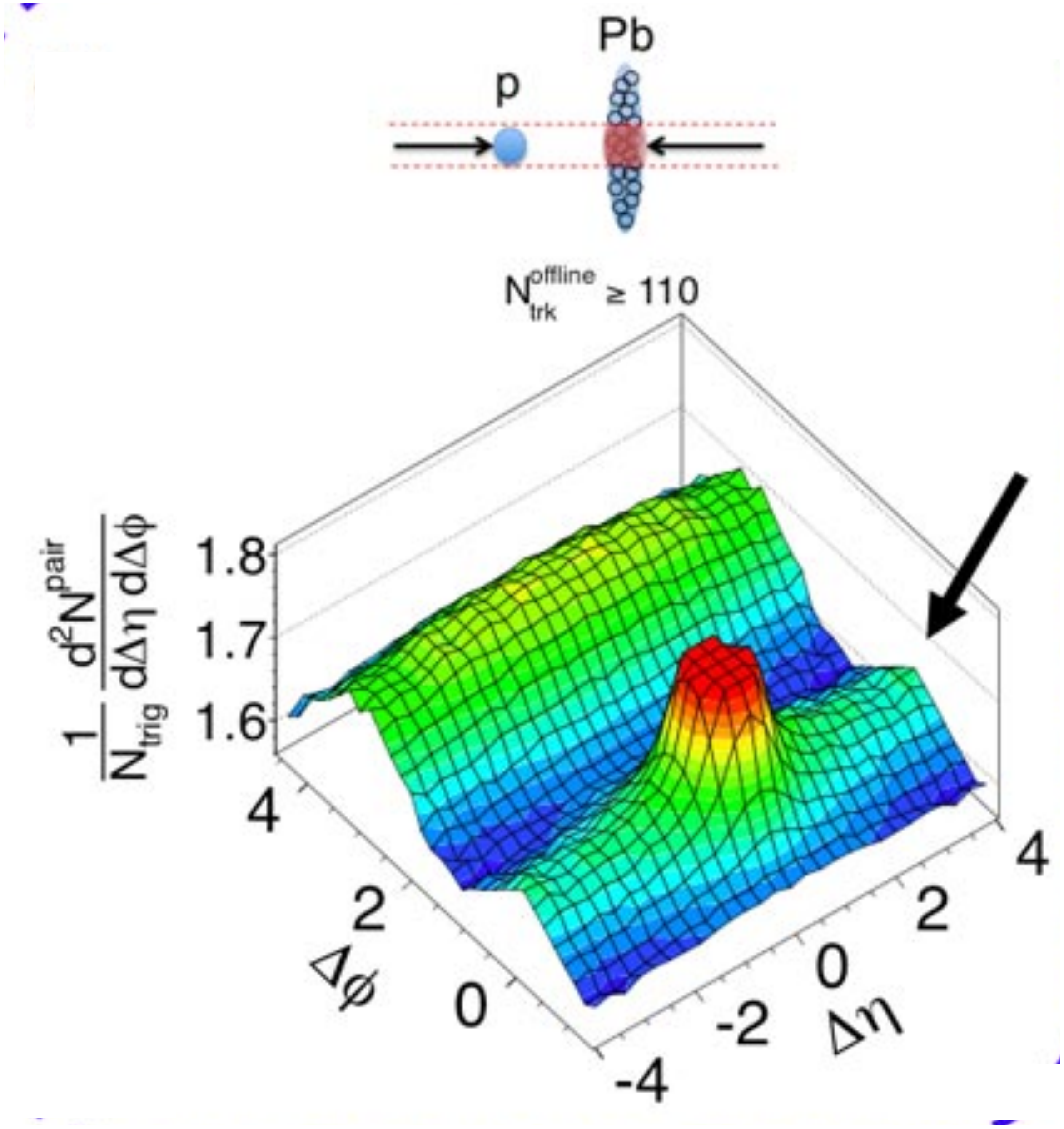
Nominal Lecture #3 Start

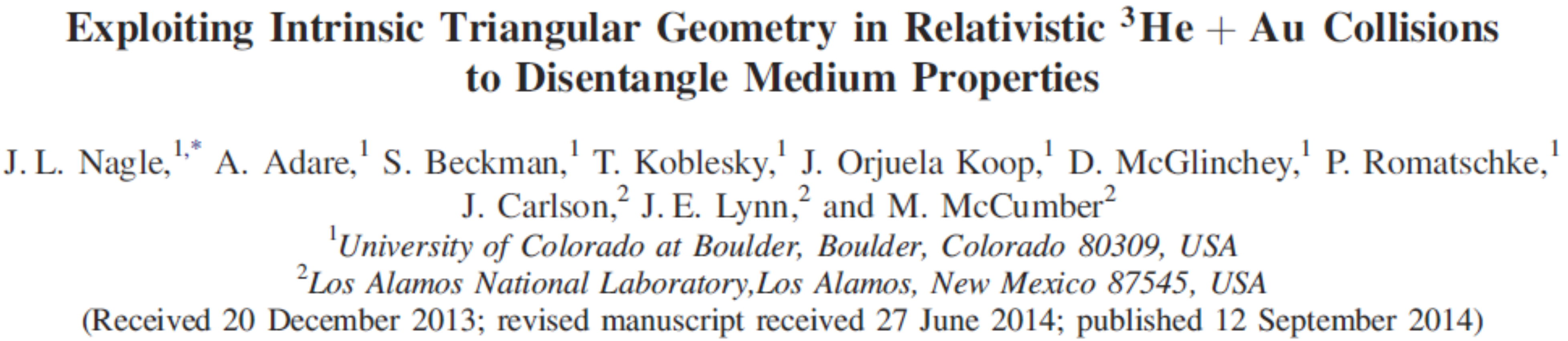
Fall 2012 Revolution – p+Pb Collisions



- Very clear ridge
- Higher moments
- Particle dependence
- Cumulants

Almost every Pb+Pb collective flow signature by ALICE, ATLAS, CMS now seen in p+Pb!

Geometry Tests at RHIC



Exploiting Intrinsic Triangular Geometry in Relativistic ^{3}He + Au Collisions to Disentangle Medium Properties

J. L. Nagle,[1,*] A. Adare,[1] S. Beckman,[1] T. Koblesky,[1] J. Orjuela Koop,[1] D. McGlinchey,[1] P. Romatschke,[1]
J. Carlson,[2] J. E. Lynn,[2] and M. McCumber[2]
[1]*University of Colorado at Boulder, Boulder, Colorado 80309, USA*
[2]*Los Alamos National Laboratory,Los Alamos, New Mexico 87545, USA*

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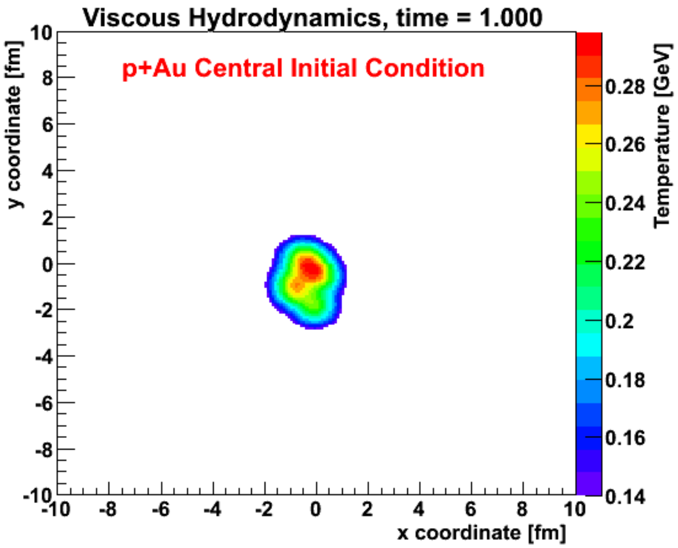
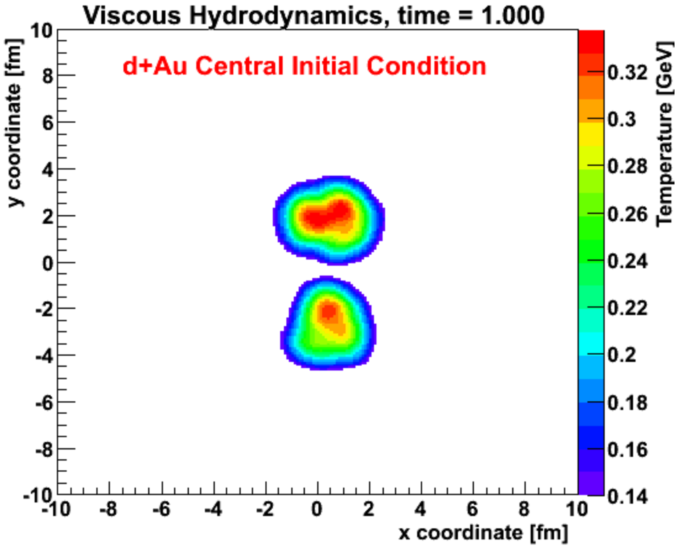
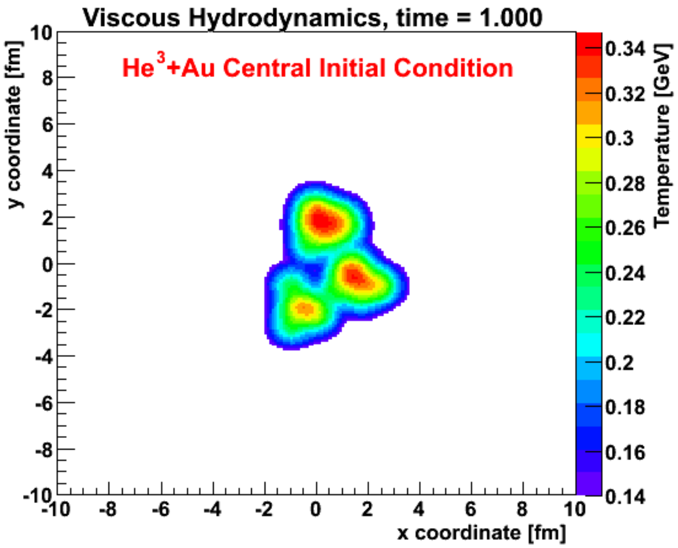
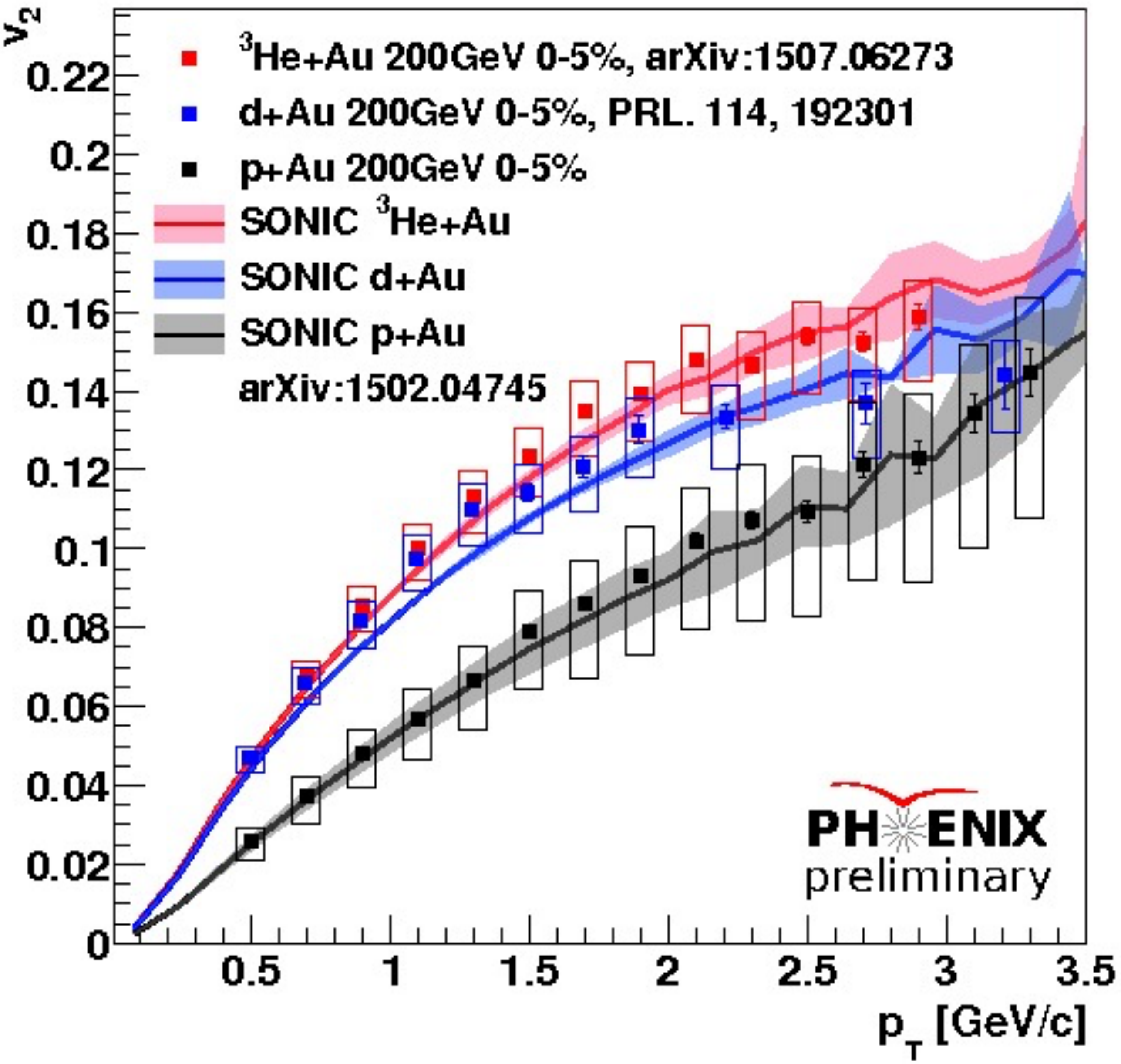
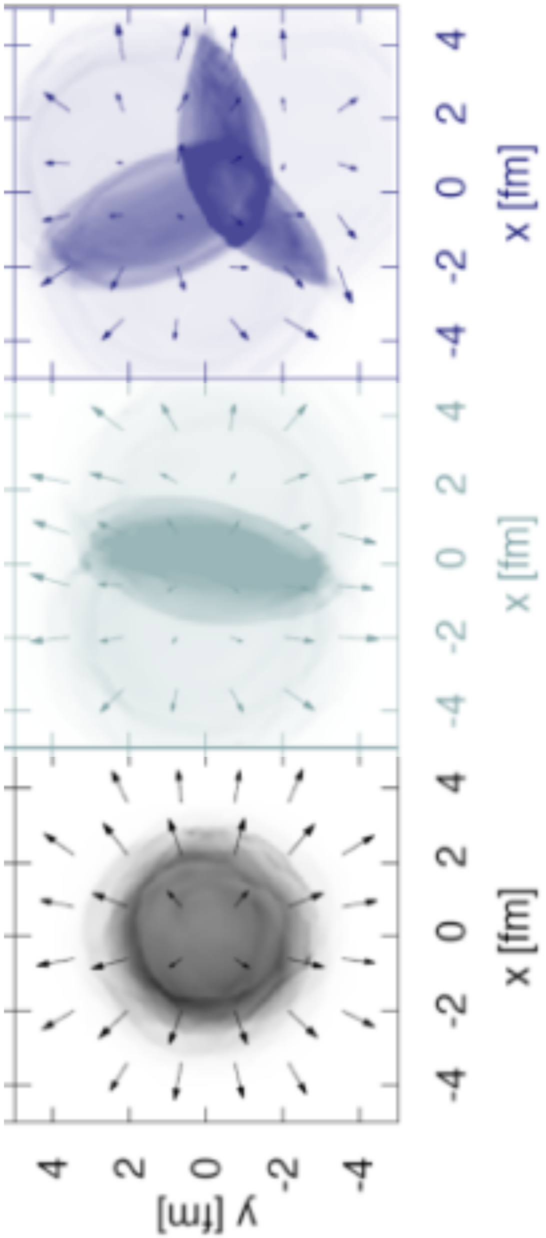






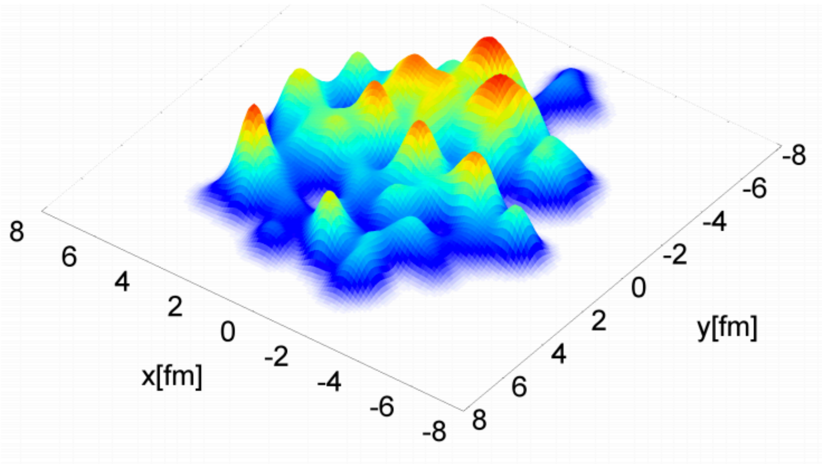
Glauber +Hydrodynamics+Cascade Predictions



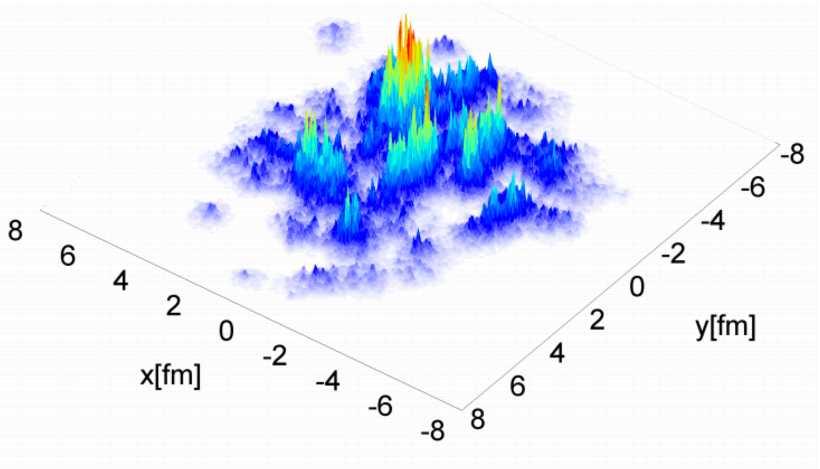


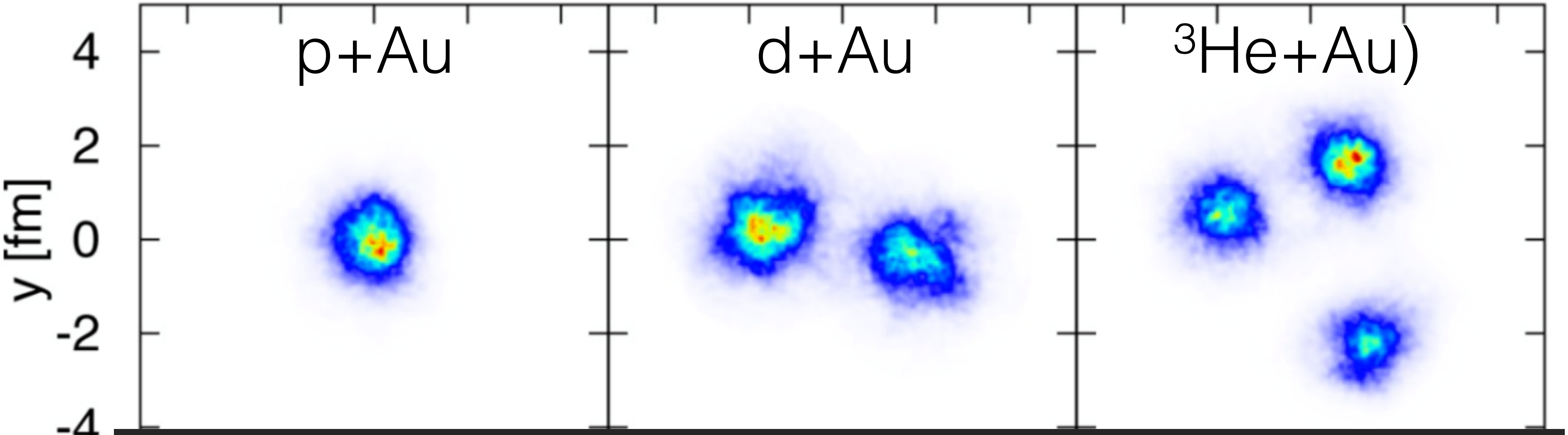
Initial Geometry Uncertainty

MC Glauber



IPGlasma





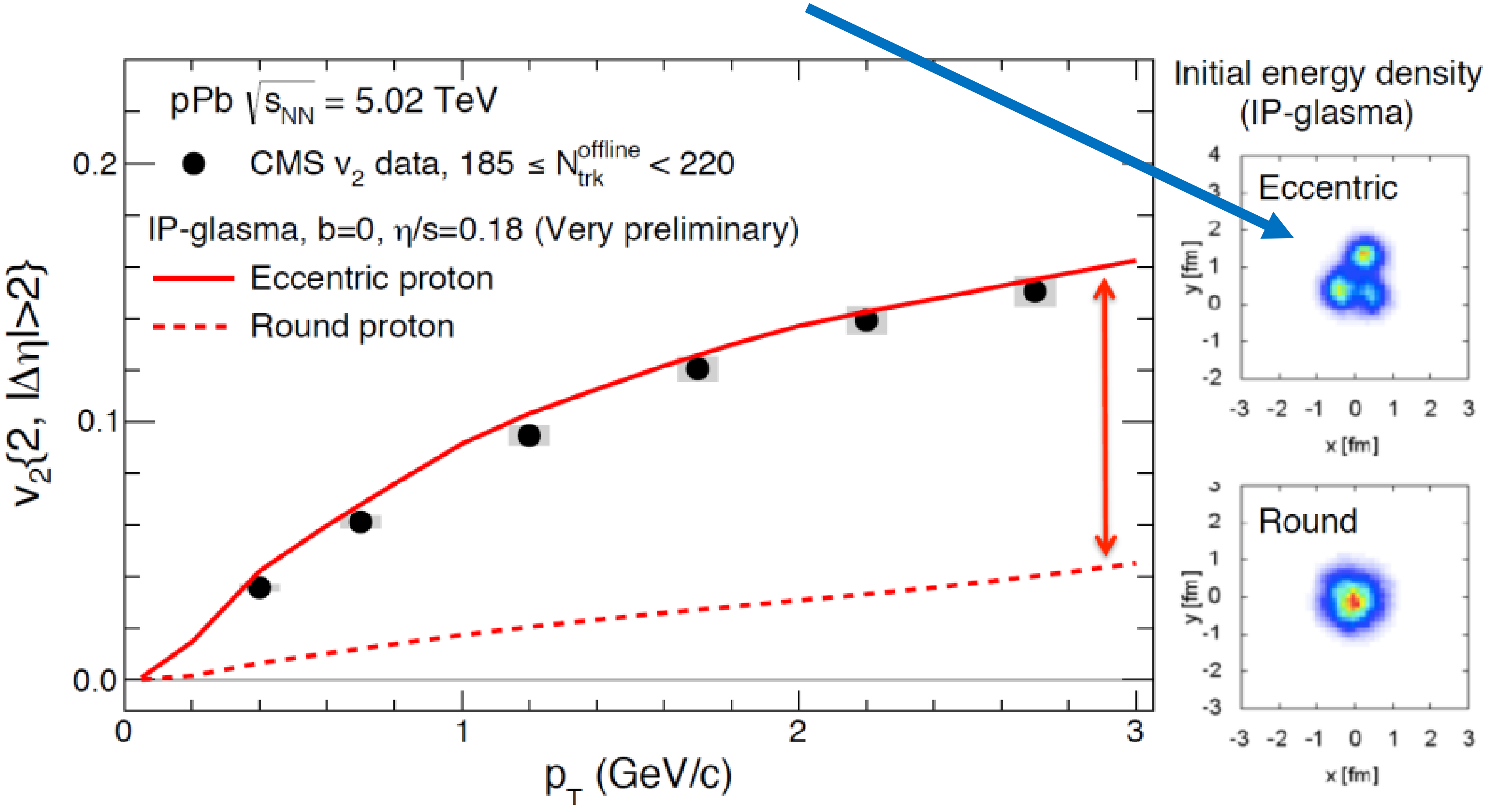
$\varepsilon_2^{\text{IPGlasma}} = 0.10$
$\varepsilon_2^{\text{Glauber}} = 0.23$

$\varepsilon_2^{\text{IPGlasma}} = 0.59$
$\varepsilon_2^{\text{Glauber}} = 0.54$

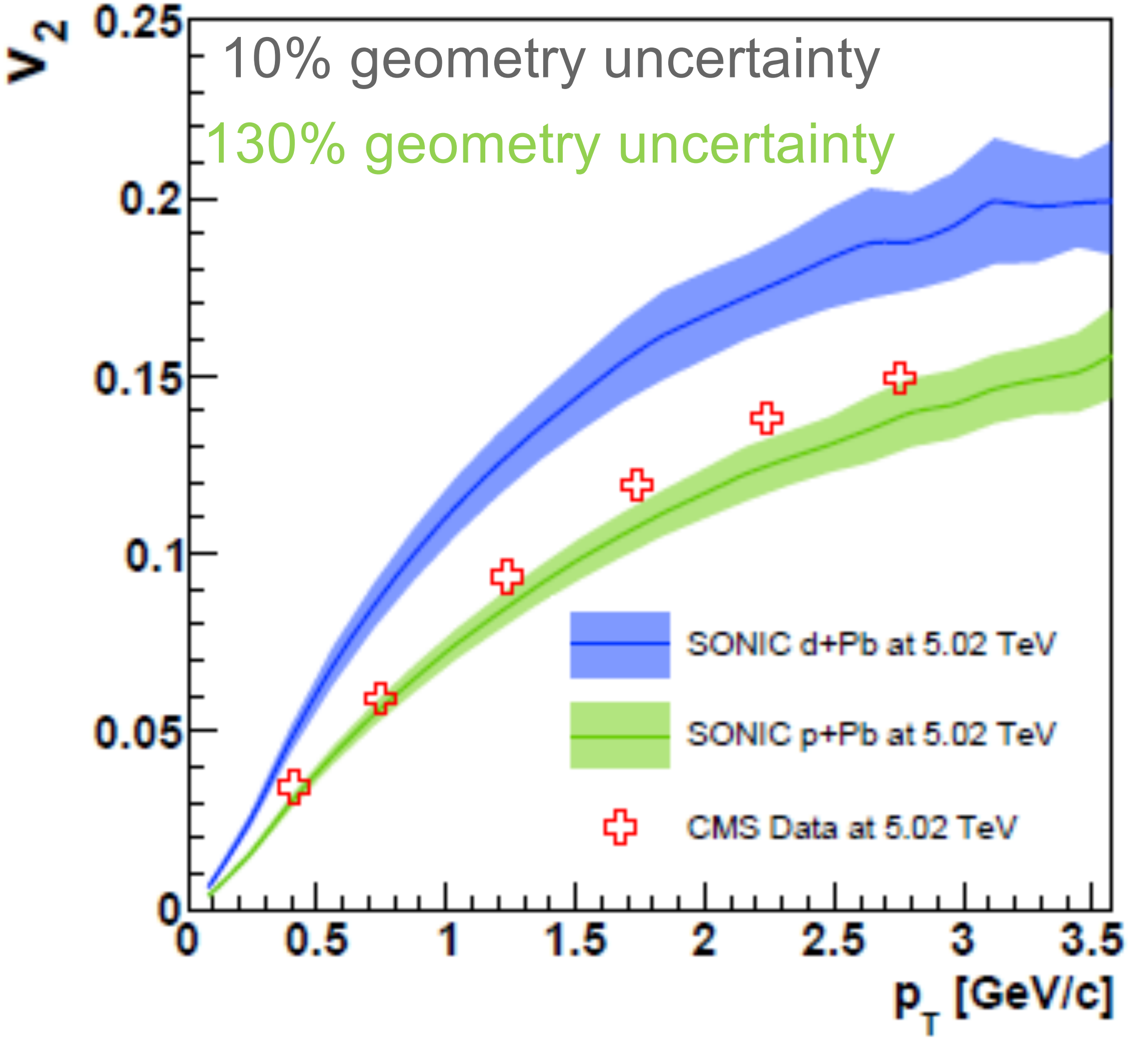
$\varepsilon_2^{\text{IPGlasma}} = 0.55$
$\varepsilon_2^{\text{Glauber}} = 0.50$

In p+A, proton substructure matters

Not ^{3}He but rather 3 constituent quarks



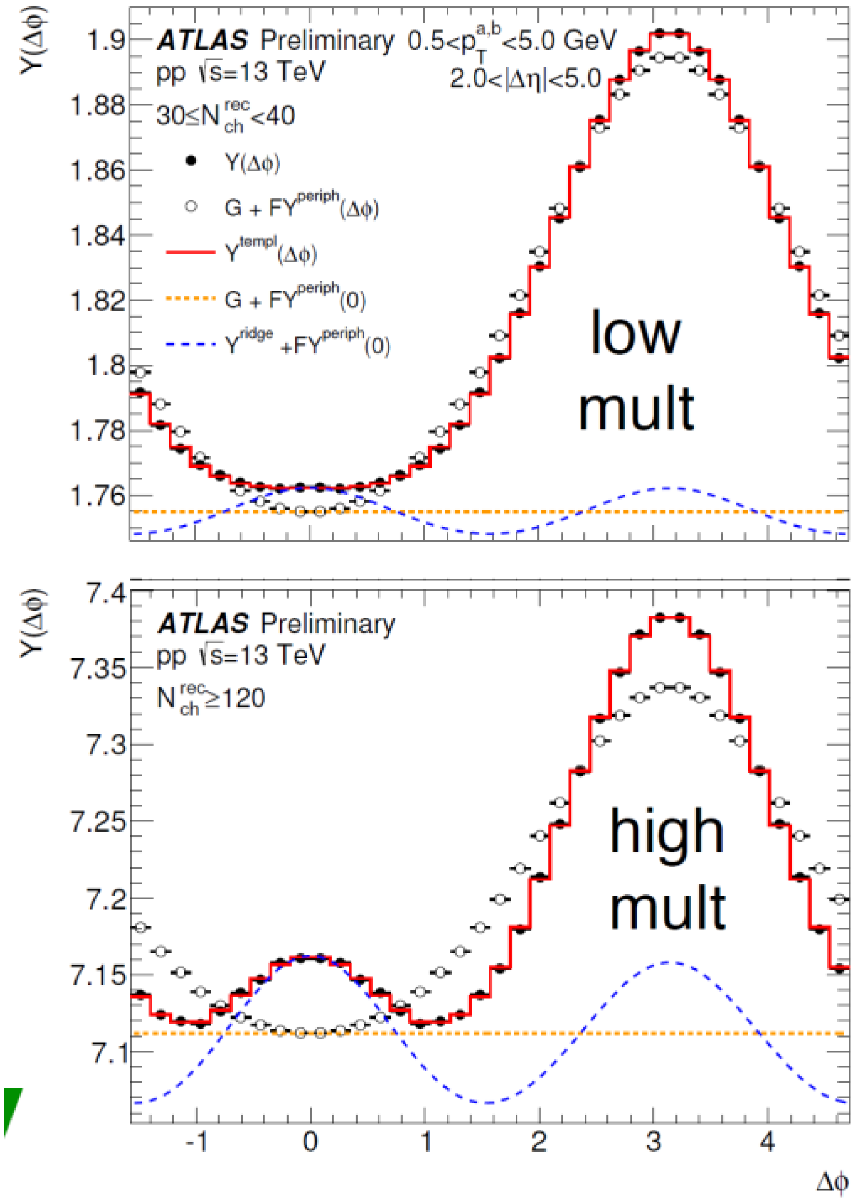
Benefits of an LHC d+Pb Run



Basic scientific method – constrain hydrodynamic inputs with d+Pb, and then use them to constrain proton substructure in p+Pb

New p+p @ 13 TeV (!) data

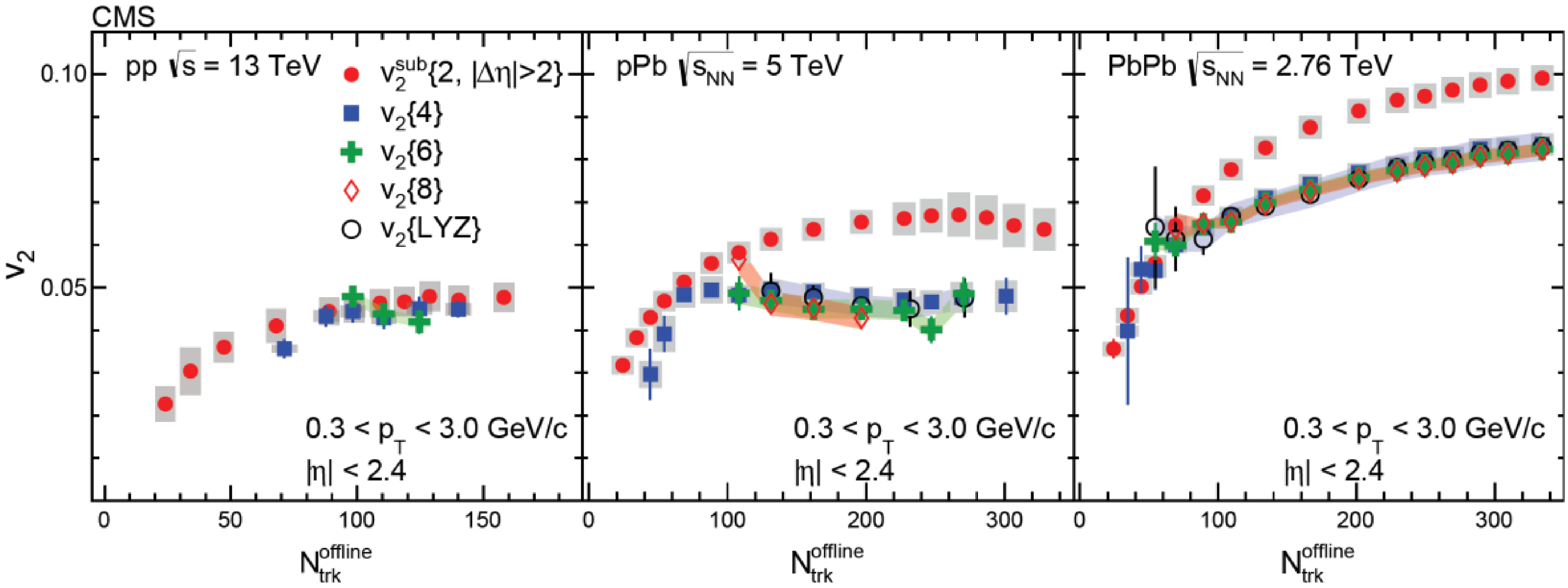
13 TeV pp



Ridge correlation clear observed in high multiplicity events.

However, it may also remain just under the surface in regular p+p events – big question!

LHC – p+p is now the hottest small topic!

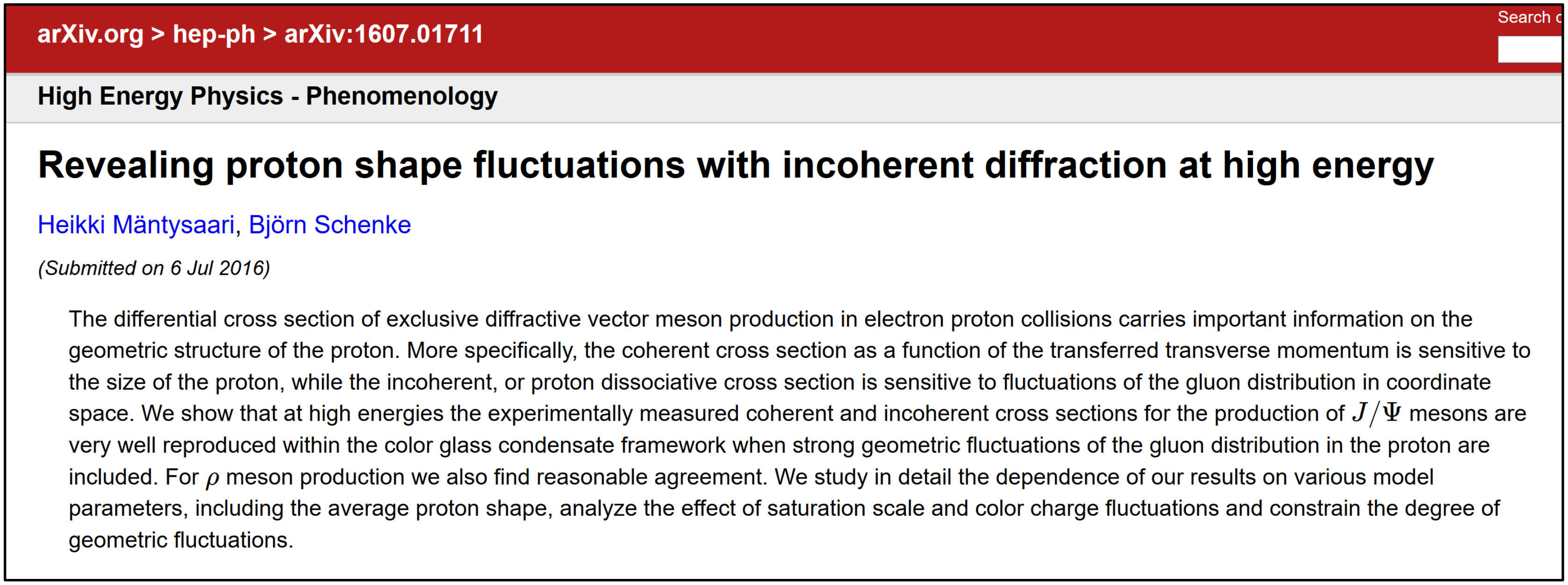


Splitting in Pb+Pb from mostly Gaussian fluctuations

$v\{2\}^2 = \langle v\rangle^2 + \sigma^2$
$v\{4\}^2 = \langle v\rangle^2 - \sigma^2$

What is really happening in p+p is unclear…

Proton Imagined on the Yoctosecond Time Scale



arXiv.org > hep-ph > arXiv:1607.01711

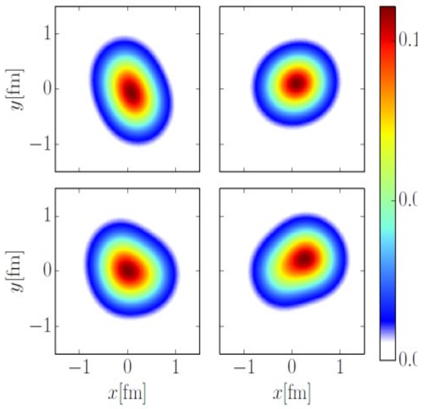
High Energy Physics - Phenomenology

Revealing proton shape fluctuations with incoherent diffraction at high energy

Heikki Mäntysaari, Björn Schenke

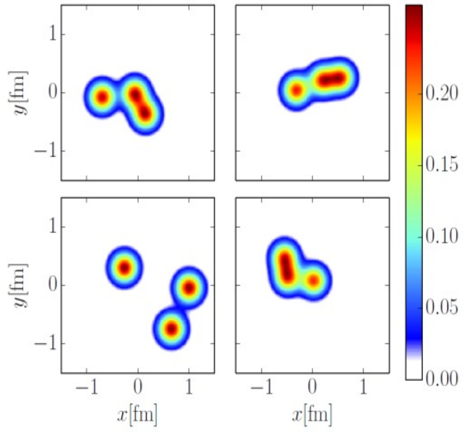
(Submitted on 6 Jul 2016)

The differential cross section of exclusive diffractive vector meson production in electron proton collisions carries important information on the geometric structure of the proton. More specifically, the coherent cross section as a function of the transferred transverse momentum is sensitive to the size of the proton, while the incoherent, or proton dissociative cross section is sensitive to fluctuations of the gluon distribution in coordinate space. We show that at high energies the experimentally measured coherent and incoherent cross sections for the production of J/Ψ mesons are very well reproduced within the color glass condensate framework when strong geometric fluctuations of the gluon distribution in the proton are included. For ρ meson production we also find reasonable agreement. We study in detail the dependence of our results on various model parameters, including the average proton shape, analyze the effect of saturation scale and color charge fluctuations and constrain the degree of geometric fluctuations.

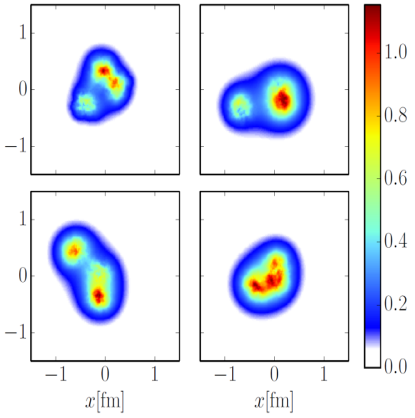


(b) $B_{qc} = 1.0\ \mathrm{GeV}^{-2}, B_q = 3.0\ \mathrm{GeV}^{-2}$

FIG. 3: Examples of proton density profiles wi
parametrizations used in this work.



(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$



. 4: Illustration of the proton density profile (1.0 − r$V(x,y)/N_c$) obtained from the IP-Glasma framework parameters $B_{qc} = 3.0\ \mathrm{GeV}^{-2}, B_q = 0.3\ \mathrm{GeV}^{-2}$ and $m = 0.4$ GeV.

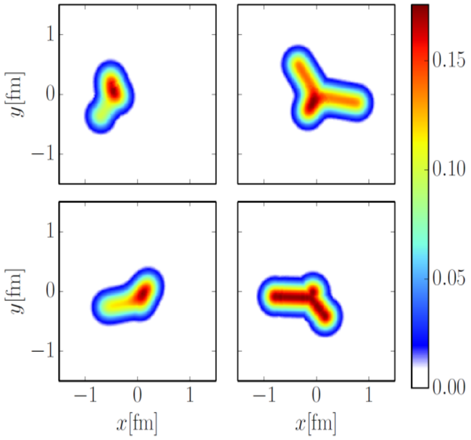


FIG. 5: Example density profiles of the “stringy proton” in the transverse plane with parameters $B_t = 4.2\ \mathrm{GeV}^{-2}, B_r = 0.6\ \mathrm{GeV}^{-2}$

https://arxiv.org/abs/1607.01711

Hydrodynamics Applied to p+p

Small, but very dense system
Huge radial expansion can lead to cavitation (bulk viscosity important)

With smooth proton geometry, high multiplicity correlates with small impact parameter and eventually circular shape!

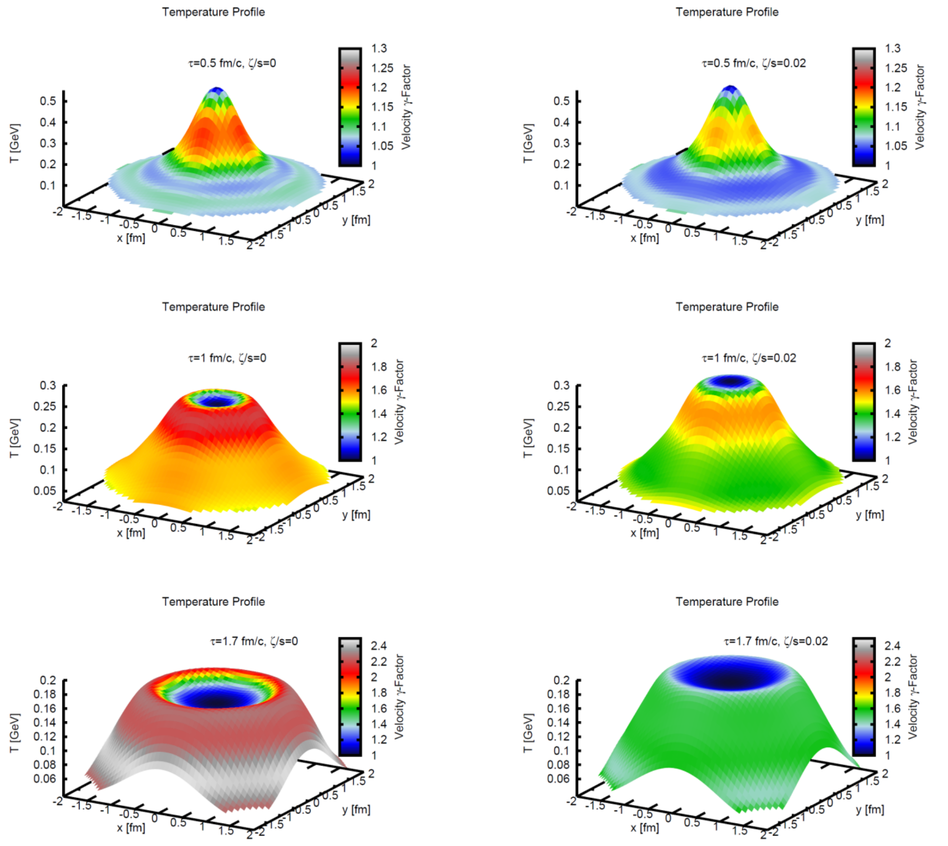
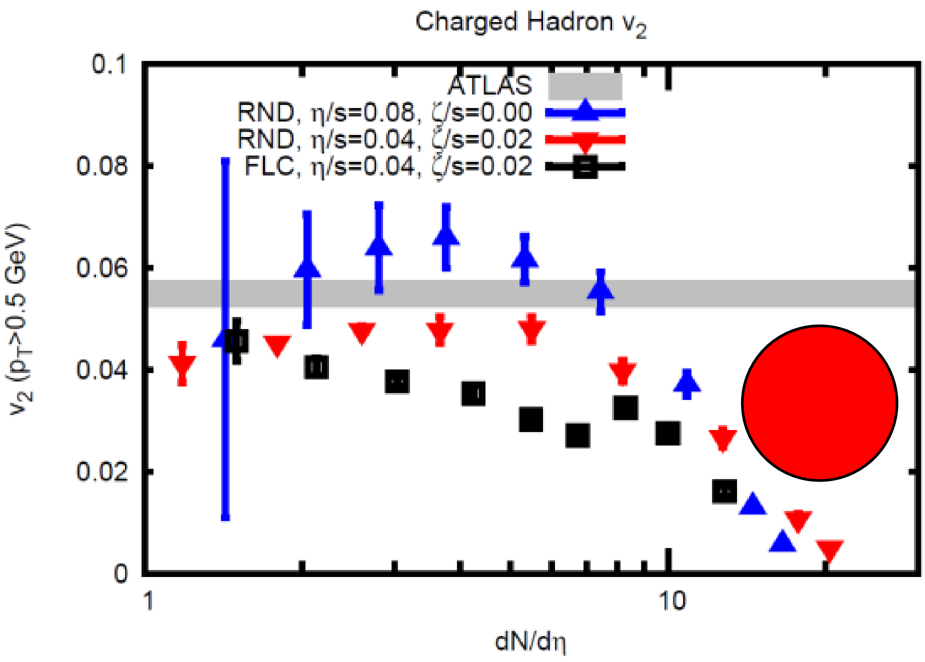
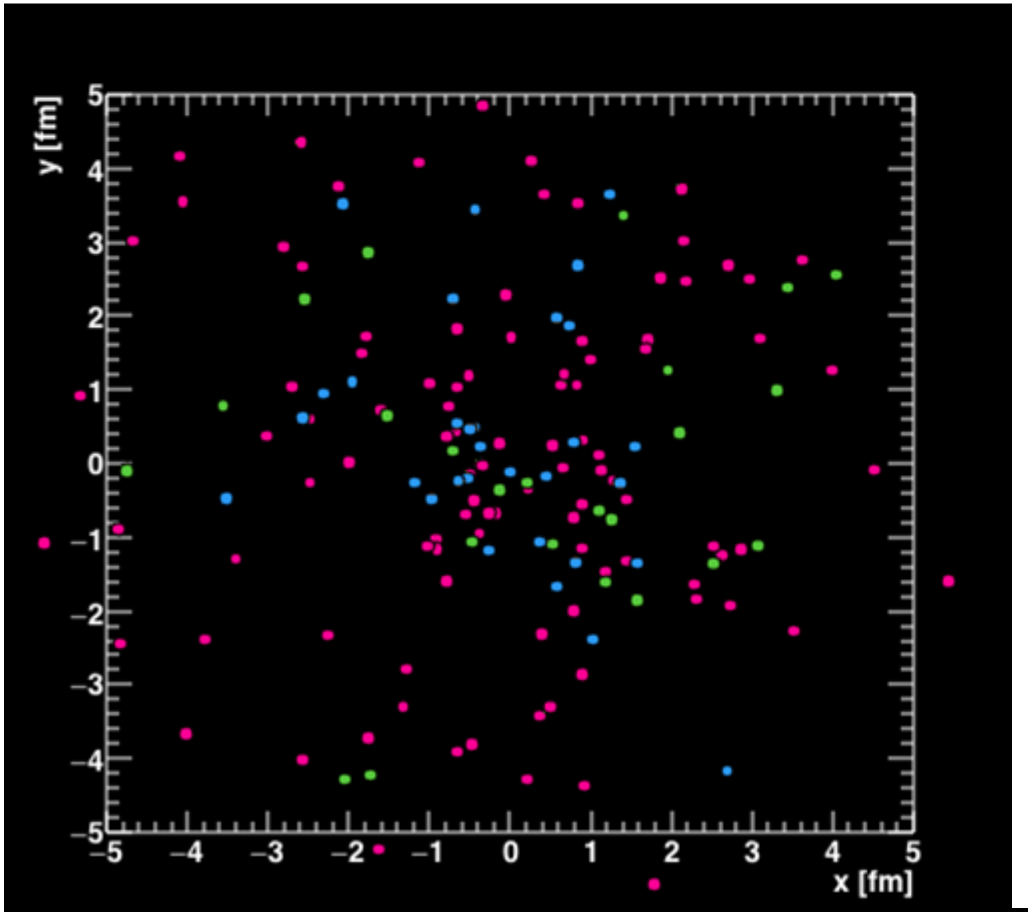


FIG. 4. Time-snapshot of the temperature distribution in the transverse plane, with color coding corresponding to the local fluid velocity $|\mathbf{v}|$ (in terms of $\gamma = \frac{1}{\sqrt{1-\mathbf{v}^2}}$). Left panels show results without bulk viscosity, while right panels are for $\frac{\zeta}{s} = 0.02$.



https://arxiv.org/abs/1512.05354

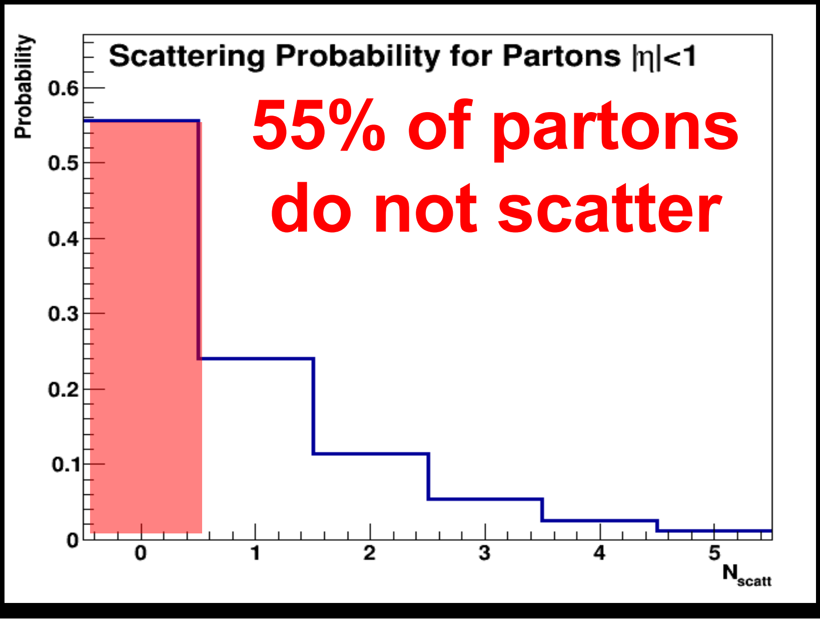


Revisiting Parton Kinetic Theory Models

Central p+Au @ 200 GeV

~ 200 partons
AMPT has all (anti)quarks
m < 30 MeV/c^2
<u>and zero gluons</u>!

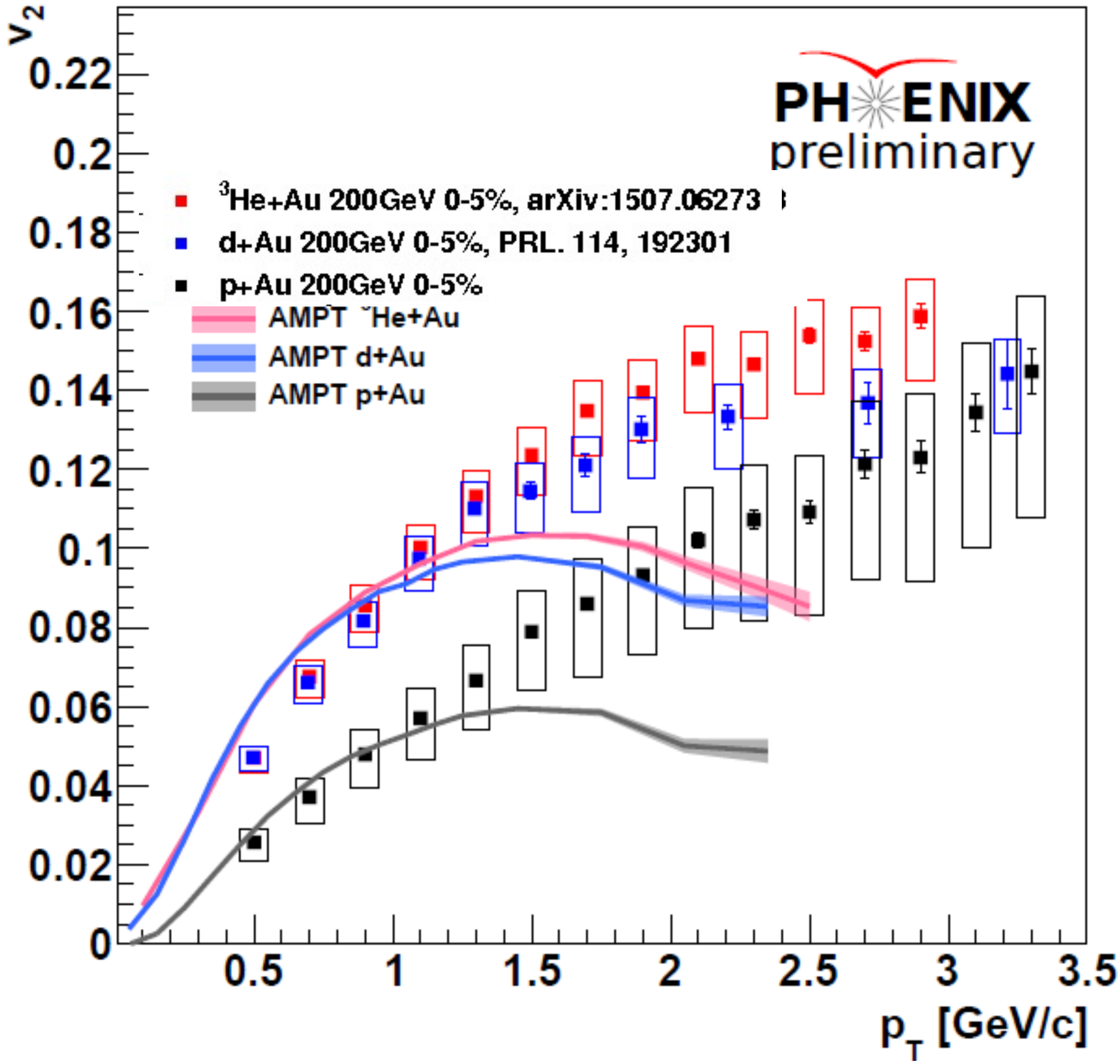
~ 45 parton-parton scattering


Scattering Probability for Partons |η|<1

55% of partons do not scatter

Not approximating flow through many collisions. Azimuthal dependence to scatter probability…

Parton Cascade (AMPT)



Modified Initial Glauber including ^{3}He wavefunction

(same I.C. as SONIC)

String melting

Lots of partons

σ= 1.5 mb

Hadron Cascade

Orjuela Koop *et al*. http://arxiv.org/abs/1501.06880

What does the future hold?

RHIC d+Au energy scan (200, 62, 39, 20 GeV)

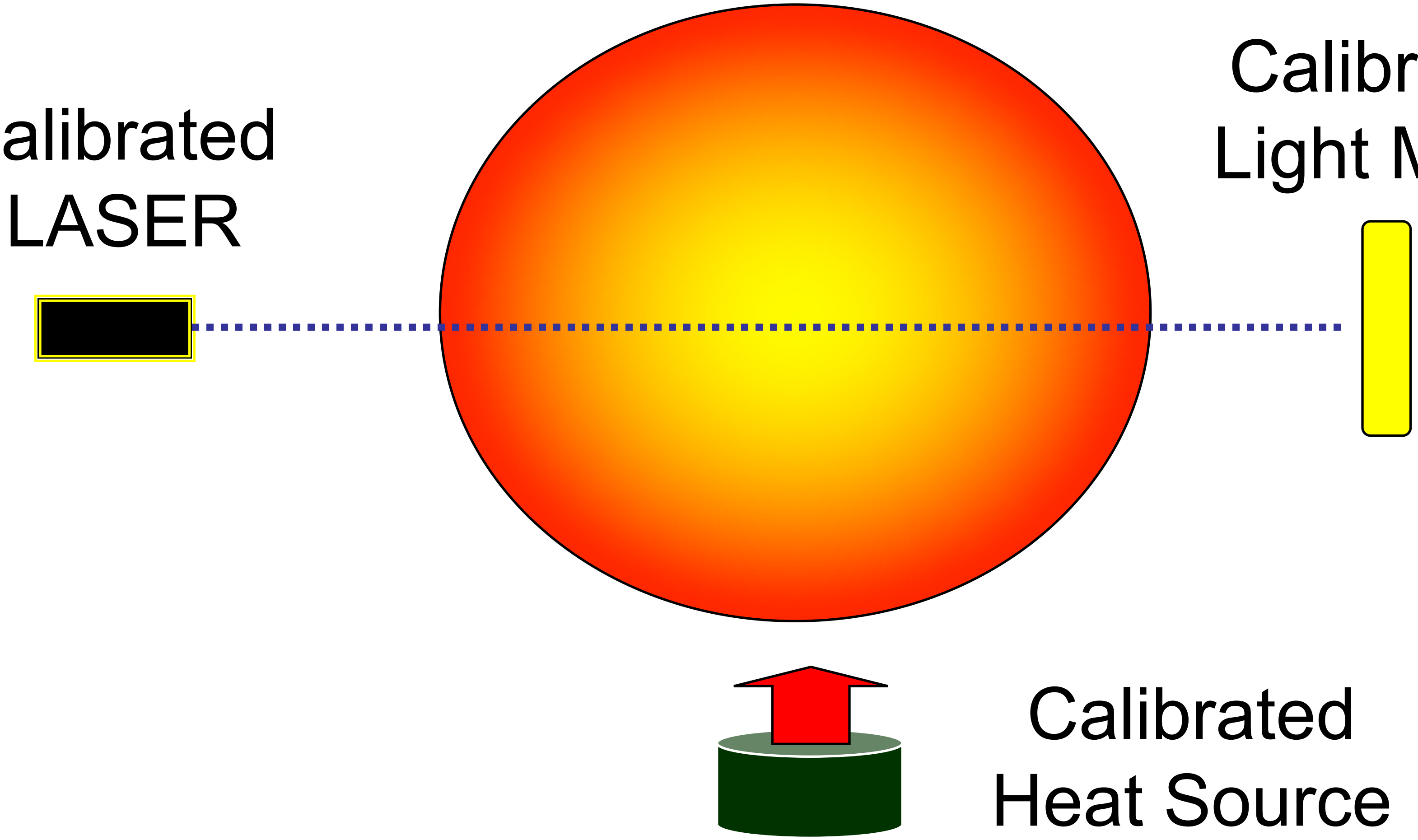
LHC p+p really just first quantitative results, more to come in the near future…

Full confrontation with theory and new developments

Jet Quenching

Probing the Matter

Matter we want to study

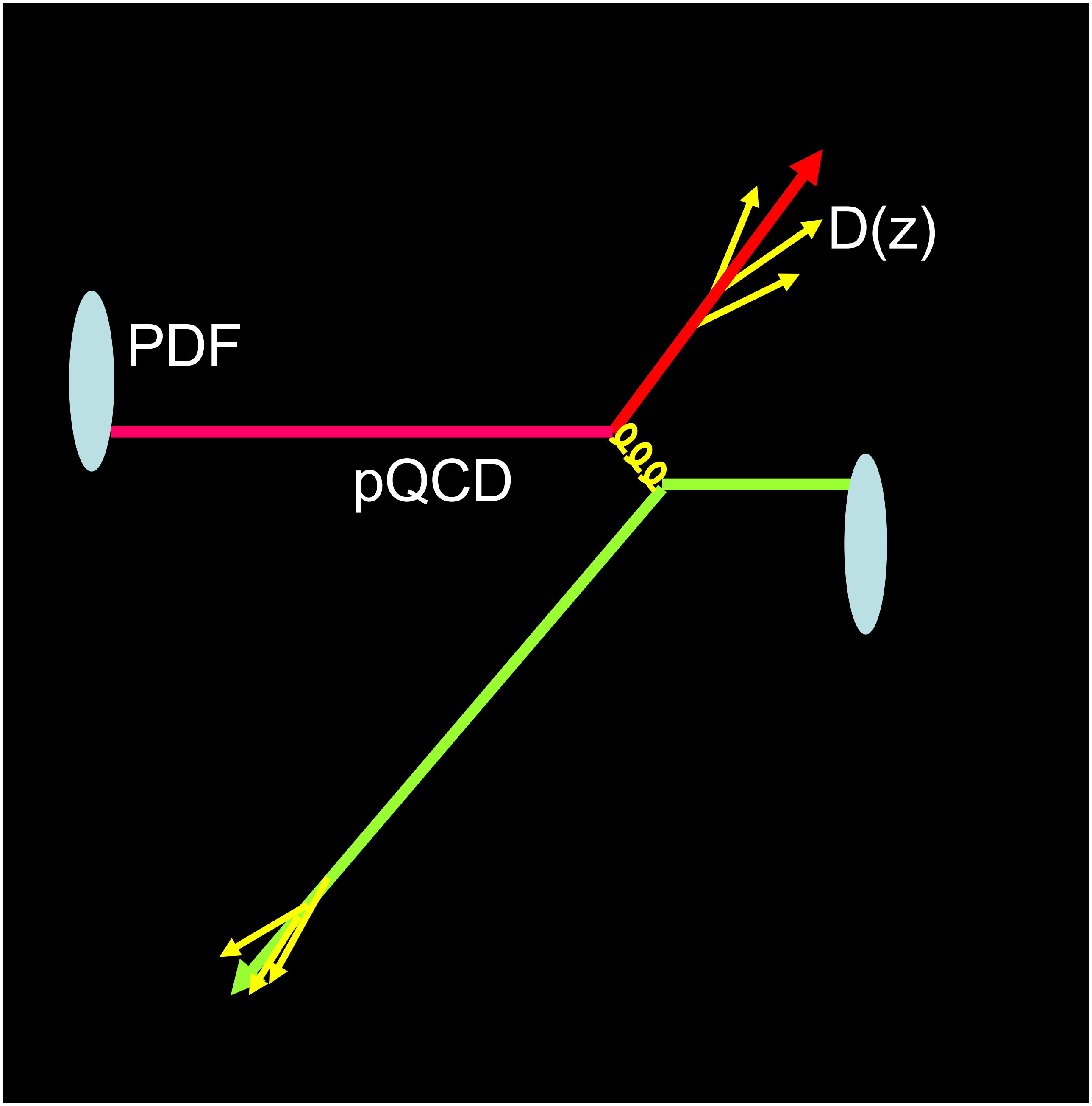


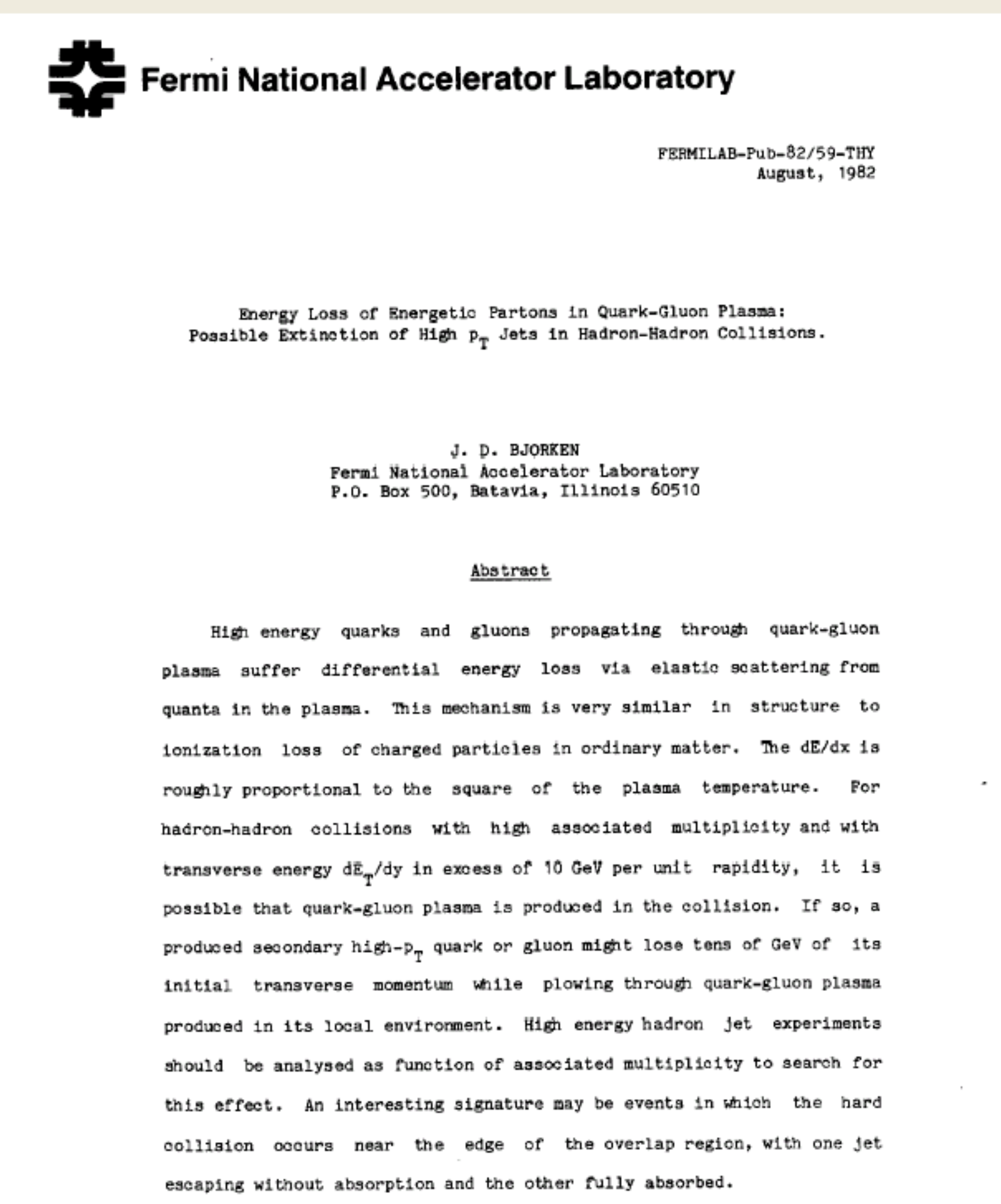
Calibrated
LASER

Calibrated
Light Meter

Calibrated
Heat Source

Autogenerated Quark “LASER”





Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

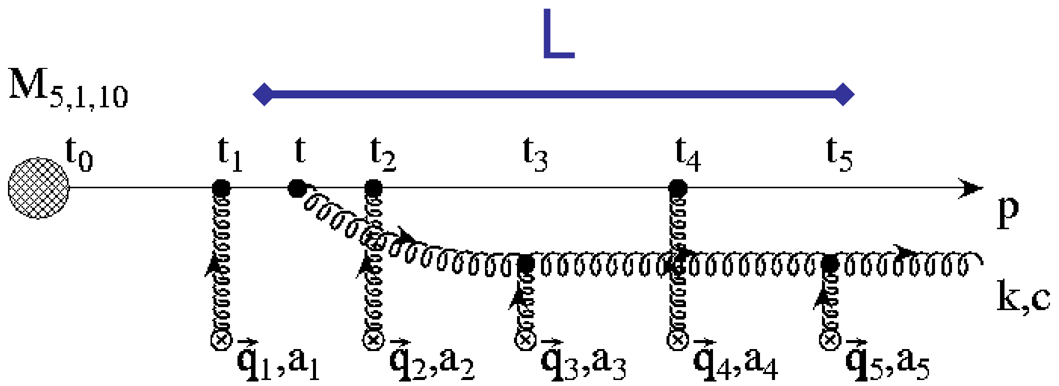
Abstract

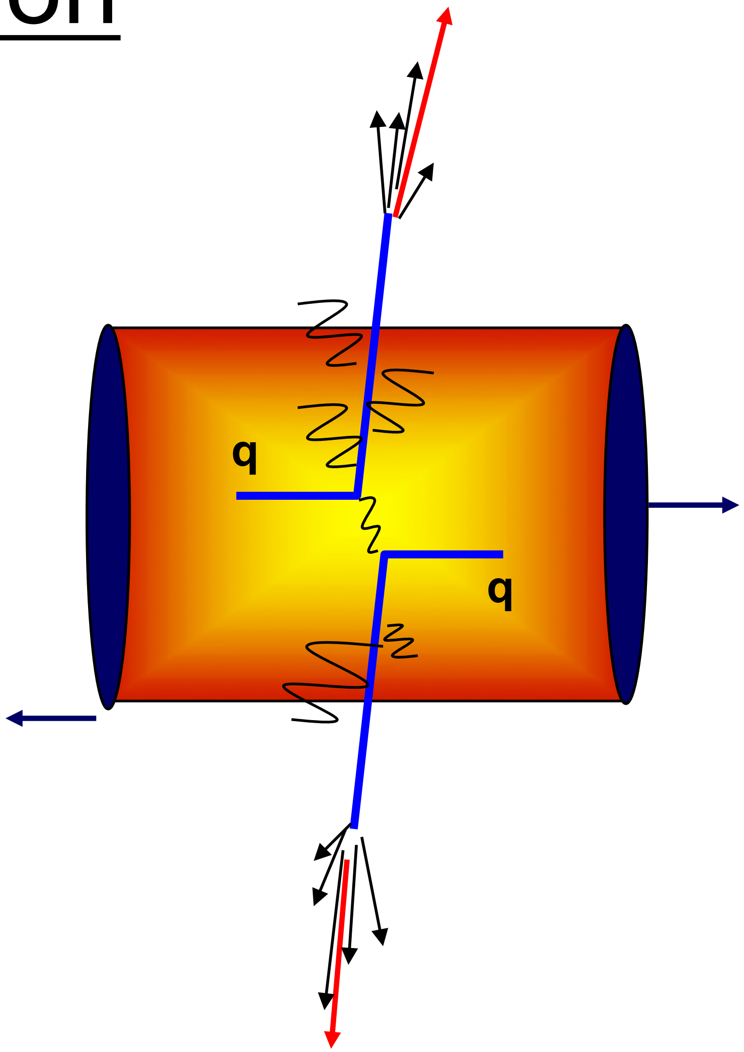
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Gluon Radiation

Partons are expected to lose energy via induced gluon radiation in traversing a dense partonic medium.

Coherence among these radiated gluons can lead to $\Delta E\ \alpha\ L^2$





Look for an effective modification in the jet fragmentation properties.

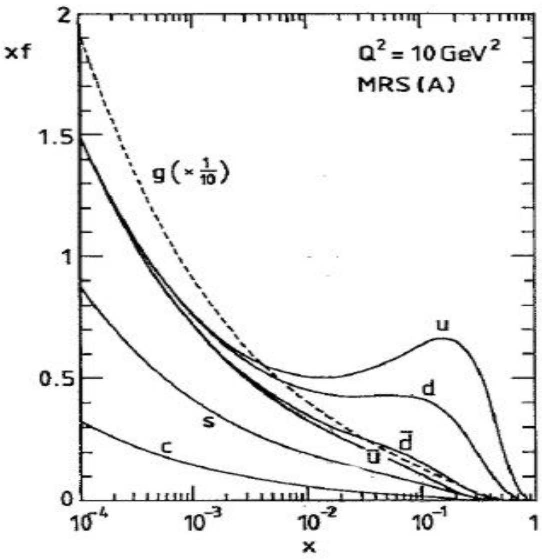
Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

pQCD + Factorization + Universality

In heavy ion collisions we can calculate the yield of high p_T hadrons

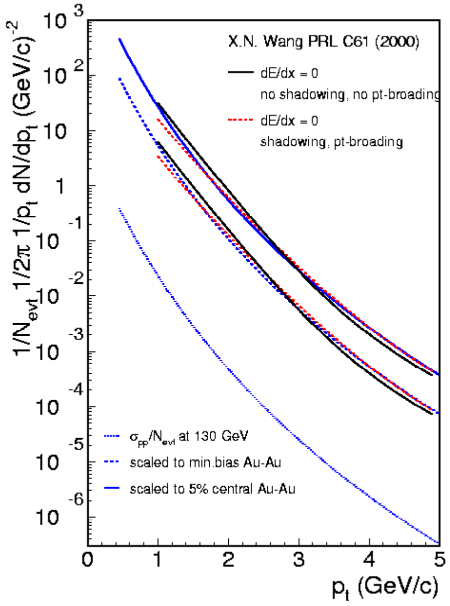
$$\overset{\downarrow}{E_h} \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c\, dx_a\, dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) \underline{f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)}\; \underline{D_{h/c}(z_c, Q_c^2)} \frac{\hat{s}}{\pi z_c^2} \underline{\frac{d\sigma^{(ab\to cd)}}{d\hat{t}}} \delta(\hat{s}+\hat{u}+\hat{t})$$

Flux of incoming partons (structure functions) from Deep Inelastic Scattering

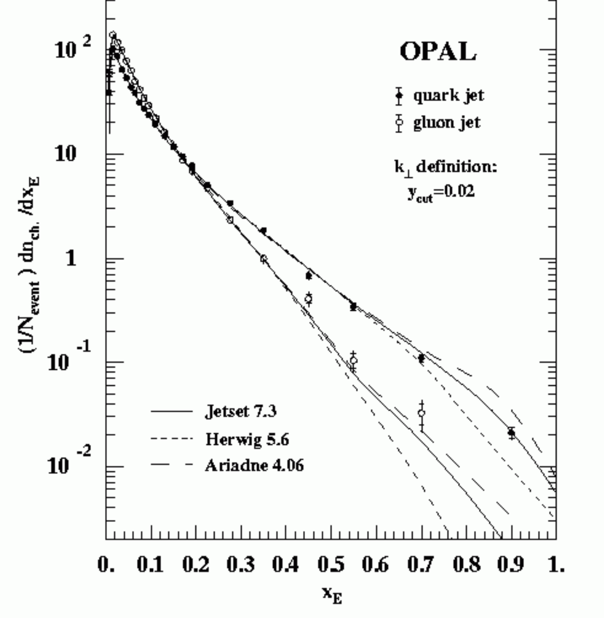


Perturbative QCD

$${}_{AA}(b_c) = {}_{pp} \;{}^{b_c}_{0}\; db^2 T_{AA}$$



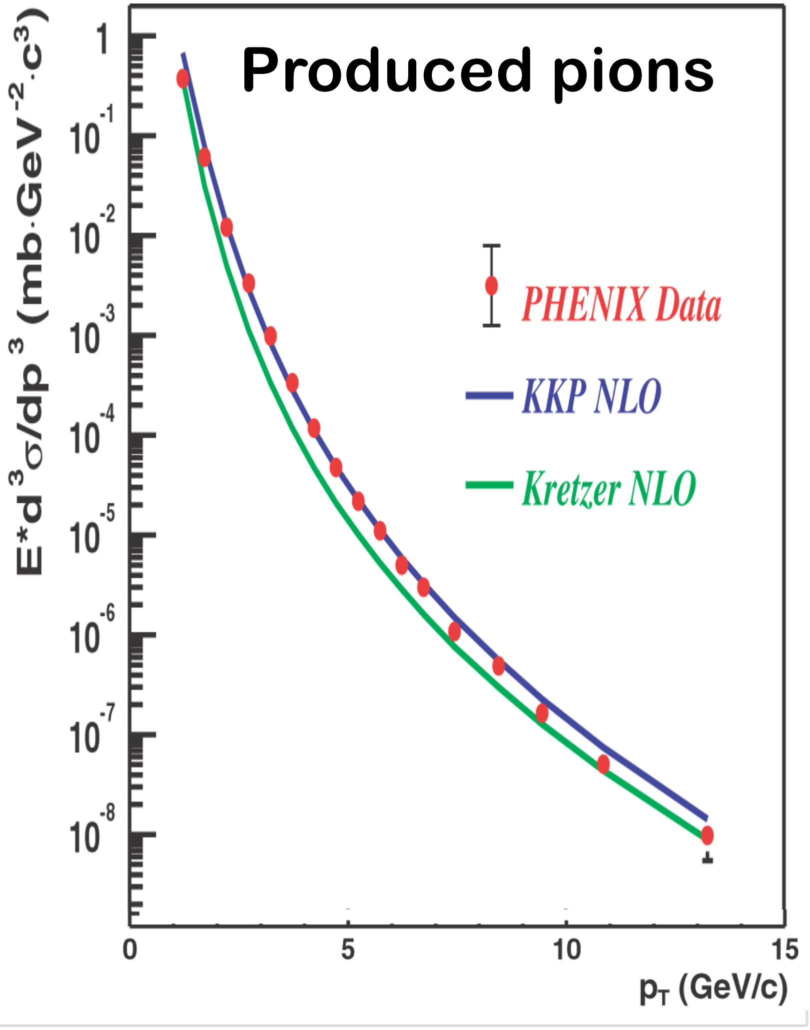
Fragmentation functions D(z) in order to relate jets to observed hadrons

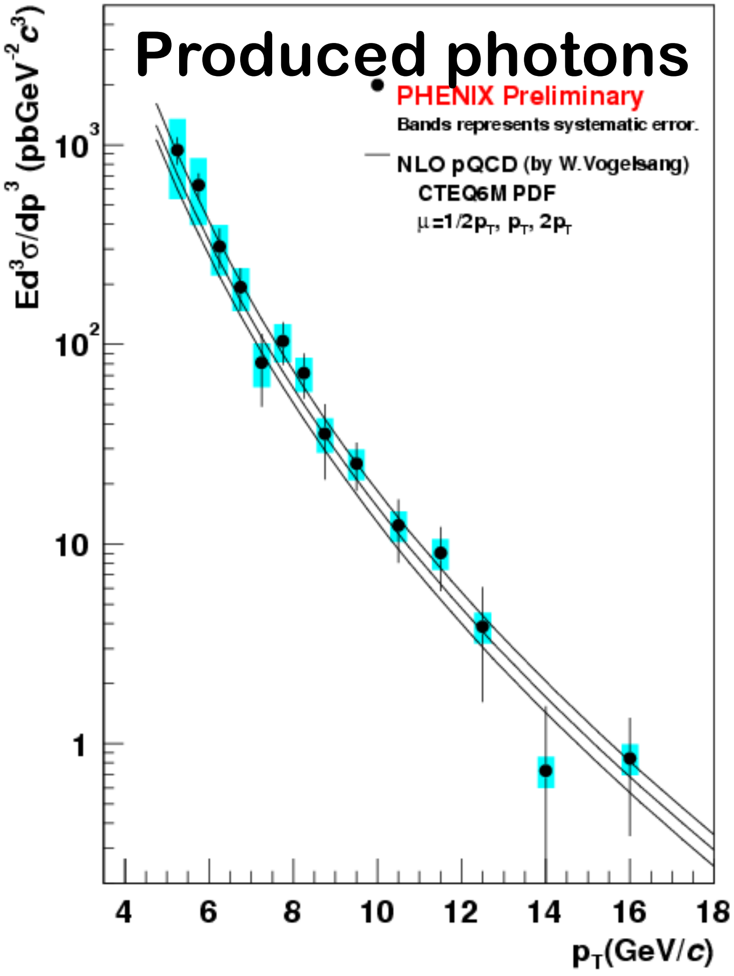


Calibrating Our Probes

High energy probes are well described in proton-proton reactions by NLO Perturbative QCD.

Single Hadrons and Photons



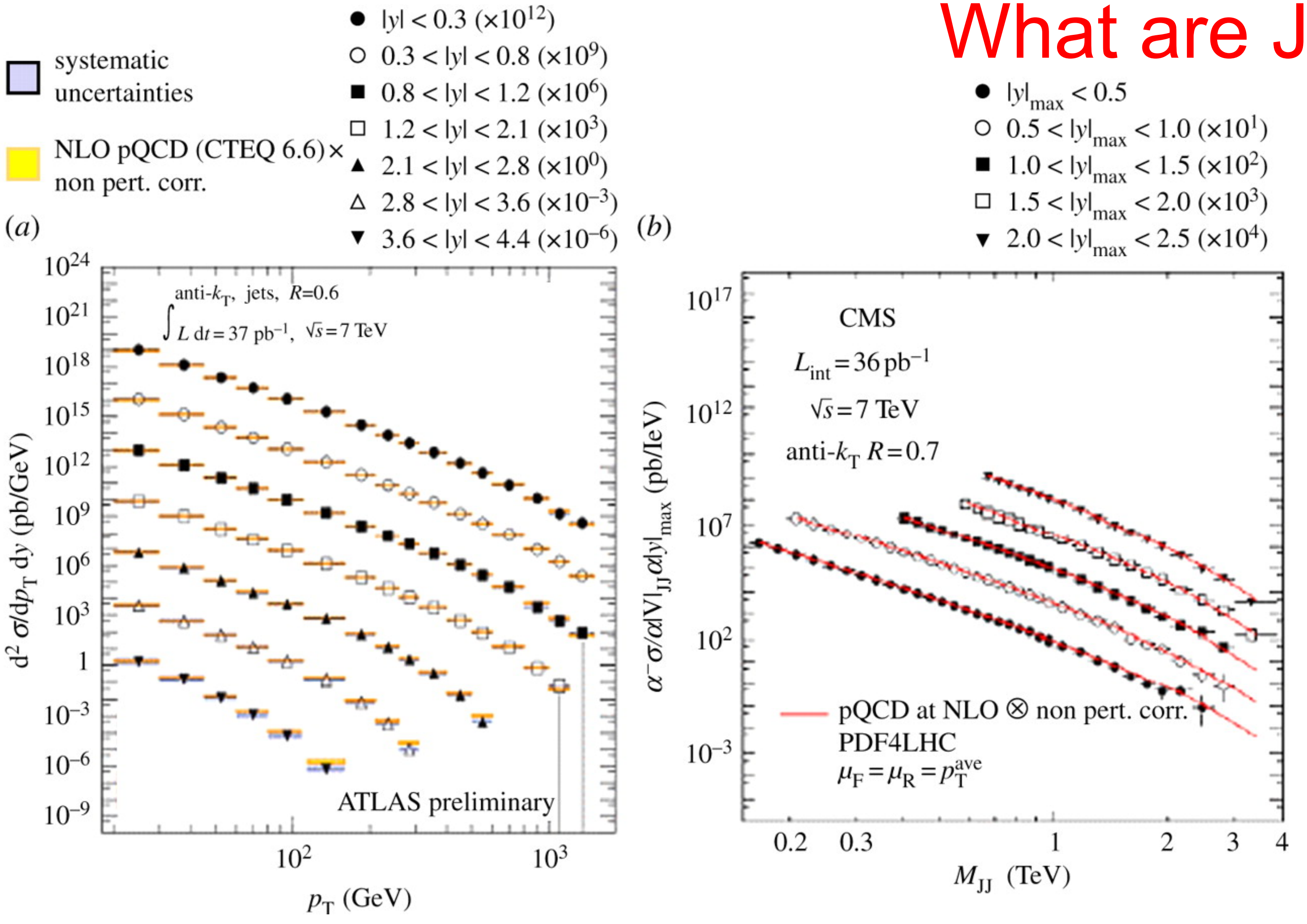


Calibrating Our Probes

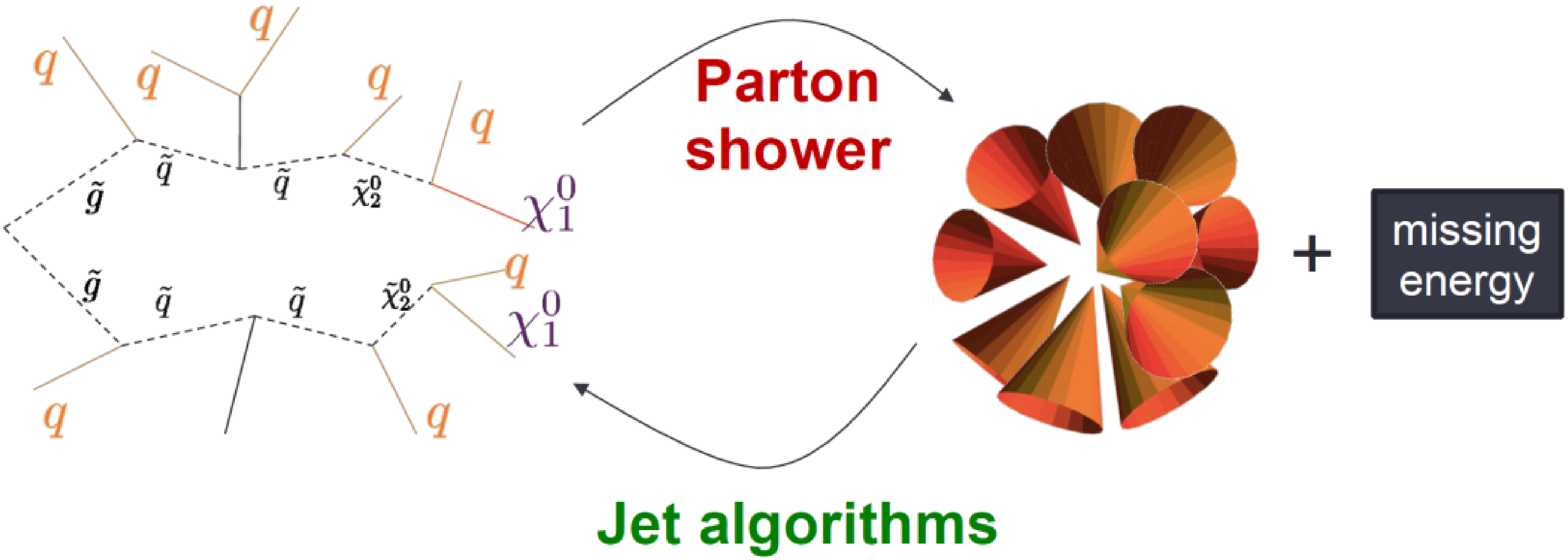
High energy probes are well described in proton-proton reactions by NLO Perturbative QCD.

Reconstructed Jets

What are Jets?



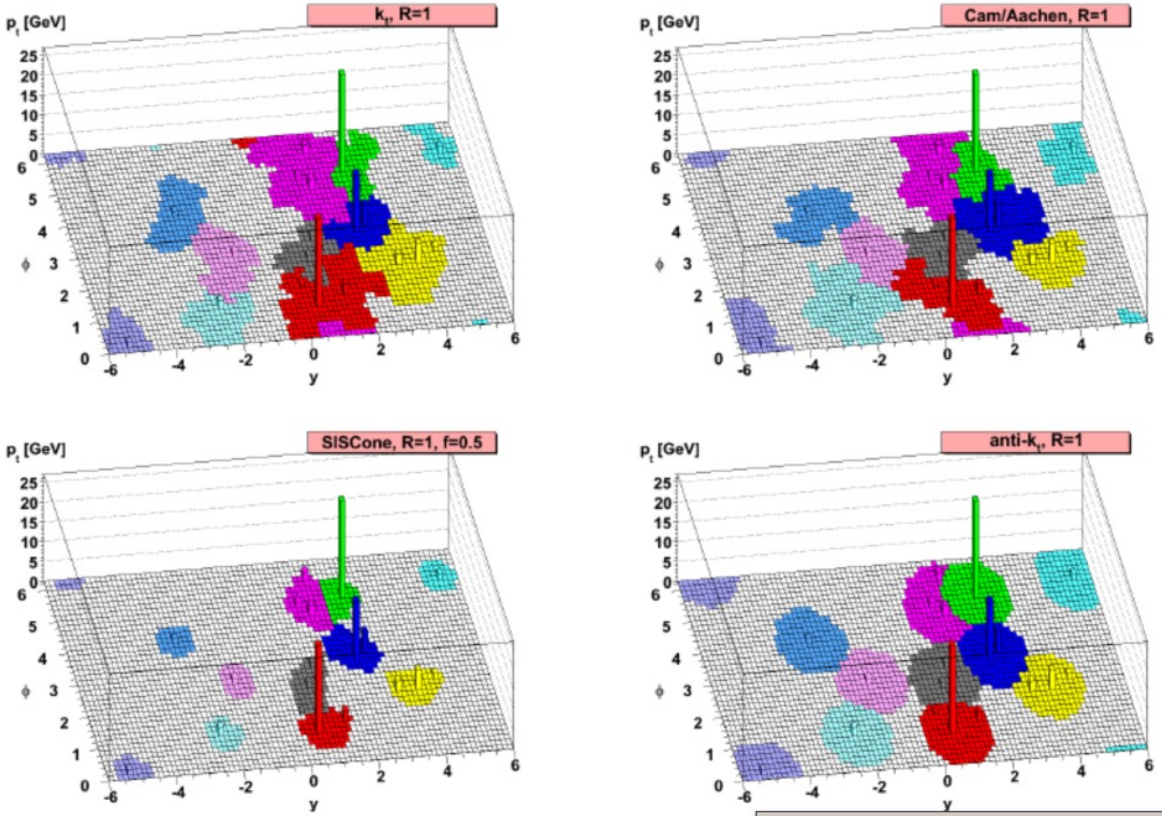
Jets-to-Parton Map



Jet algorithm sums the energy (typically in calorimeters) and can approximate catching an individual parton’s energy.

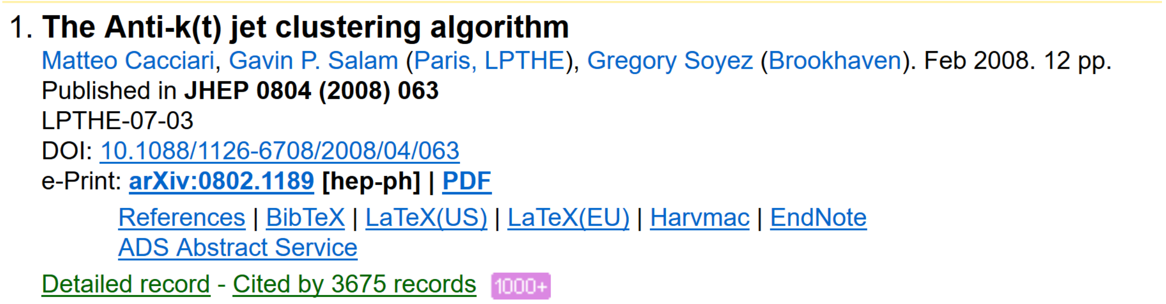
Very useful in particle physics, but often used in a different way in heavy ion physics.

Jet Algorithms



Cacciari, Salam, Soyez JHEP 0804:063 (2008)

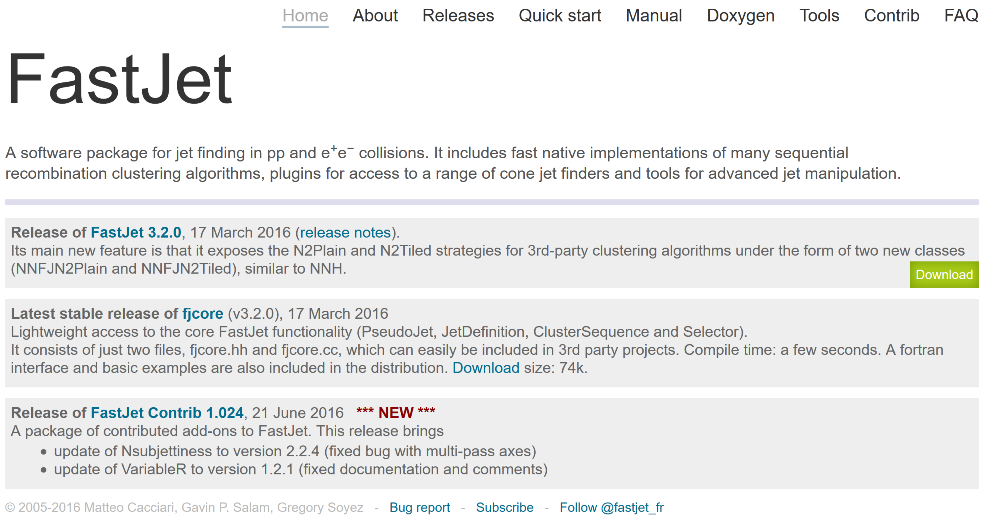
Different methods to “group” energies.



1. **The Anti-k(t) jet clustering algorithm**
Matteo Cacciari, Gavin P. Salam (Paris, LPTHE), Gregory Soyez (Brookhaven). Feb 2008. 12 pp.
Published in **JHEP 0804 (2008) 063**
LPTHE-07-03
DOI: 10.1088/1126-6708/2008/04/063
e-Print: **arXiv:0802.1189** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 3675 records 1000+

FastJet Code Publicly Available

http://fastjet.fr/



FastJet

A software package for jet finding in pp and e^+e^- collisions. It includes fast native implementations of many sequential recombination clustering algorithms, plugins for access to a range of cone jet finders and tools for advanced jet manipulation.

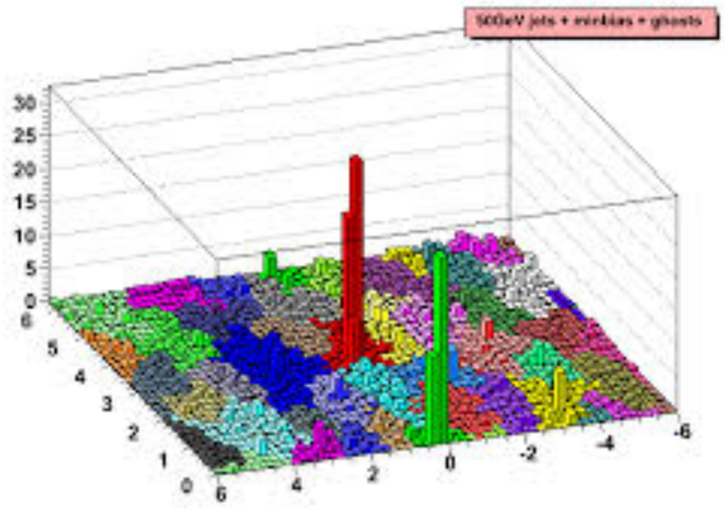
Release of FastJet 3.2.0, 17 March 2016 (release notes).
Its main new feature is that it exposes the N2Plain and N2Tiled strategies for 3rd-party clustering algorithms under the form of two new classes (NNFJN2Plain and NNFJN2Tiled), similar to NNH.

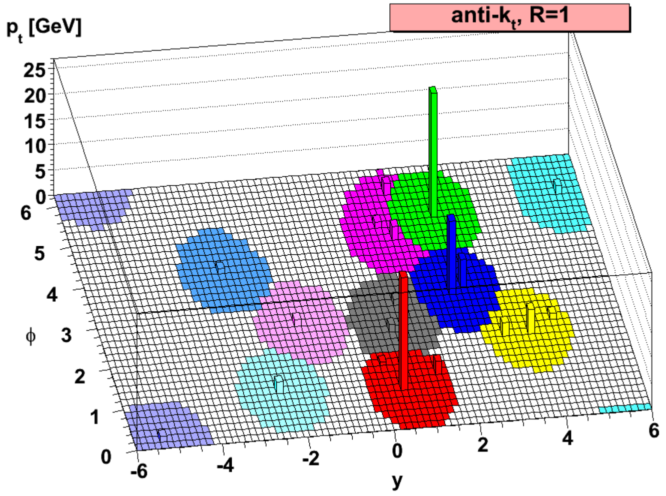
Latest stable release of fjcore (v3.2.0), 17 March 2016
Lightweight access to the core FastJet functionality (PseudoJet, JetDefinition, ClusterSequence and Selector).
It consists of just two files, fjcore.hh and fjcore.cc, which can easily be included in 3rd party projects. Compile time: a few seconds. A fortran interface and basic examples are also included in the distribution. Download size: 74k.

Release of FastJet Contrib 1.024, 21 June 2016 ***** NEW *****
A package of contributed add-ons to FastJet. This release brings

- update of Nsubjettiness to version 2.2.4 (fixed bug with multi-pass axes)
- update of VariableR to version 1.2.1 (fixed documentation and comments)

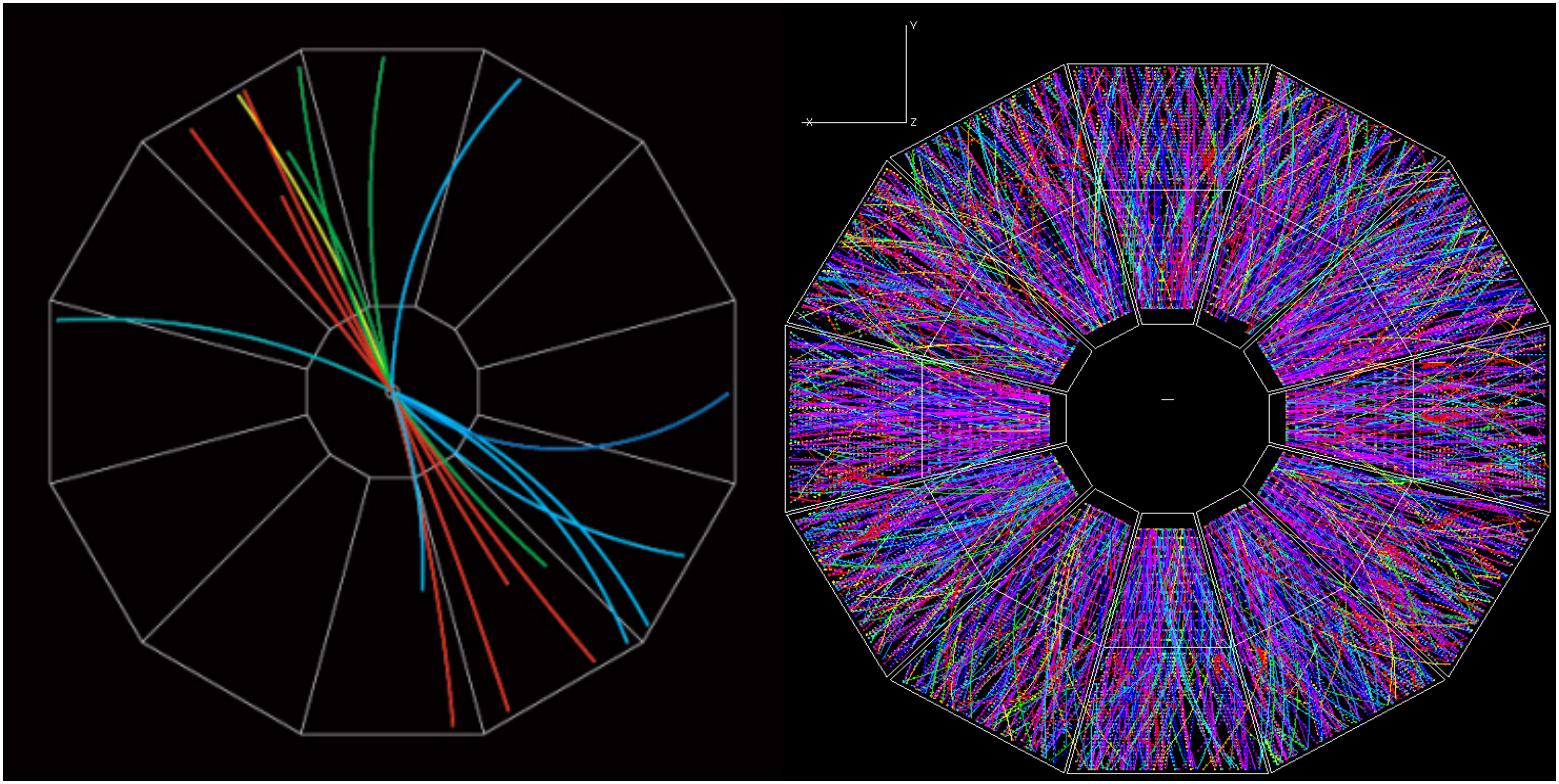
© 2005-2016 Matteo Cacciari, Gavin P. Salam, Gregory Soyez - Bug report - Subscribe - Follow @fastjet_fr





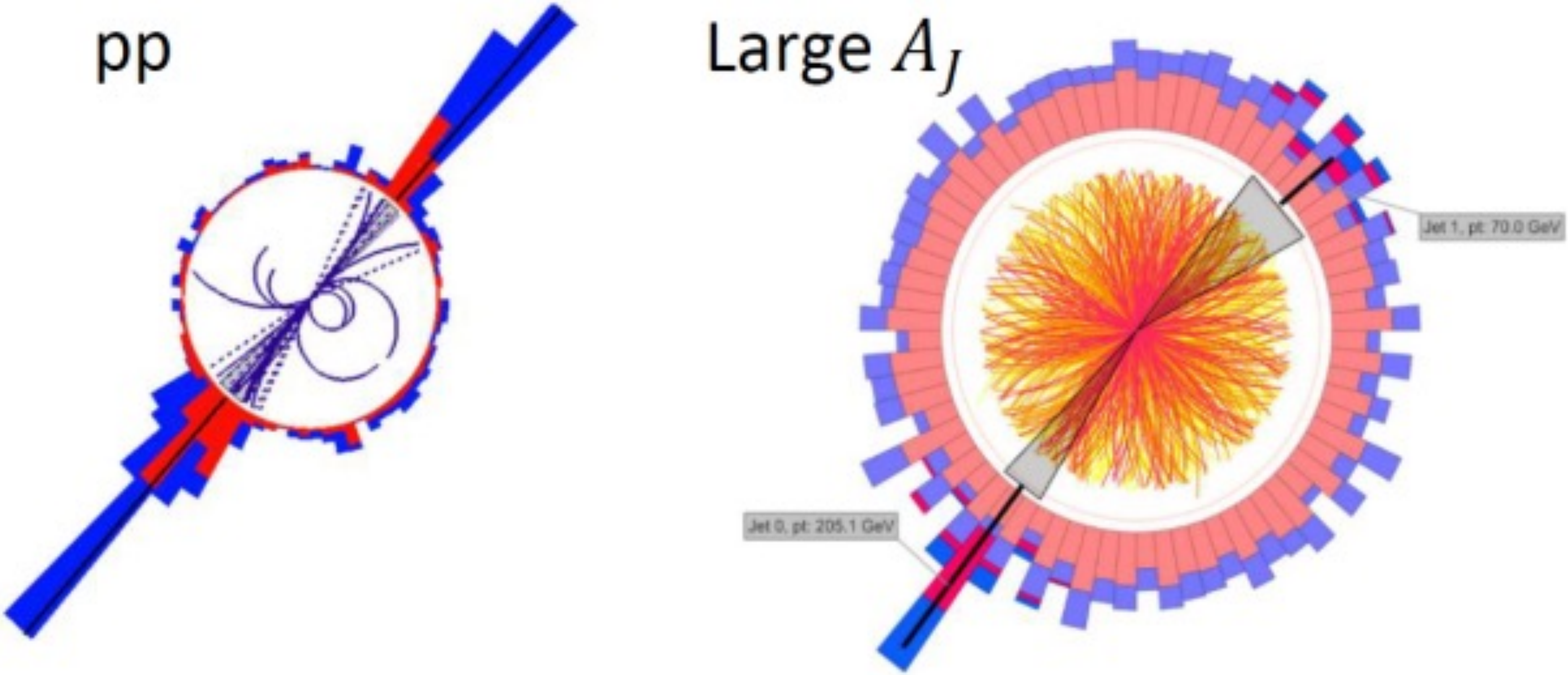
- R.D. Field, Applications of perturbative QCD A lot of detailed examples.
- R. K. Ellis, W. J. Stirling and B. R. Webber, QCD and Collider Physics
- CTEQ, Handbook of Perturbative QCD
- CTEQ website.
- John Collins, The Foundation of Perturbative QCD Includes a lot new development.
- Yu. L. Dokshitzer, V. A. Khoze, A. H. Mueller and S. I. Troyan, Basics of Perturbative QCD More advanced discussion on the small-x physics.

Jets in Heavy Ions



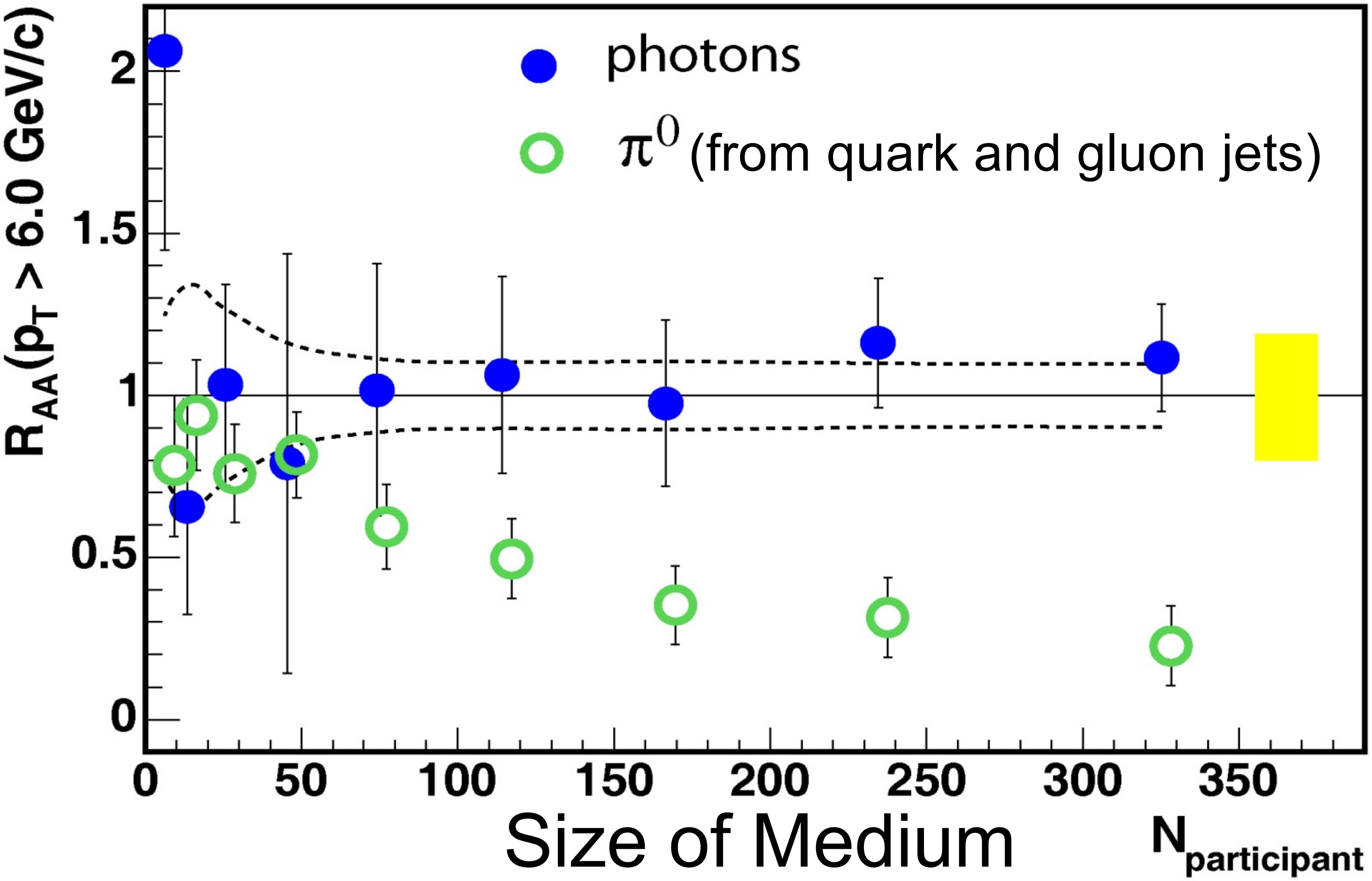
Start with single hadrons, then go to jets.

Much Higher Energy Jets at the LHC

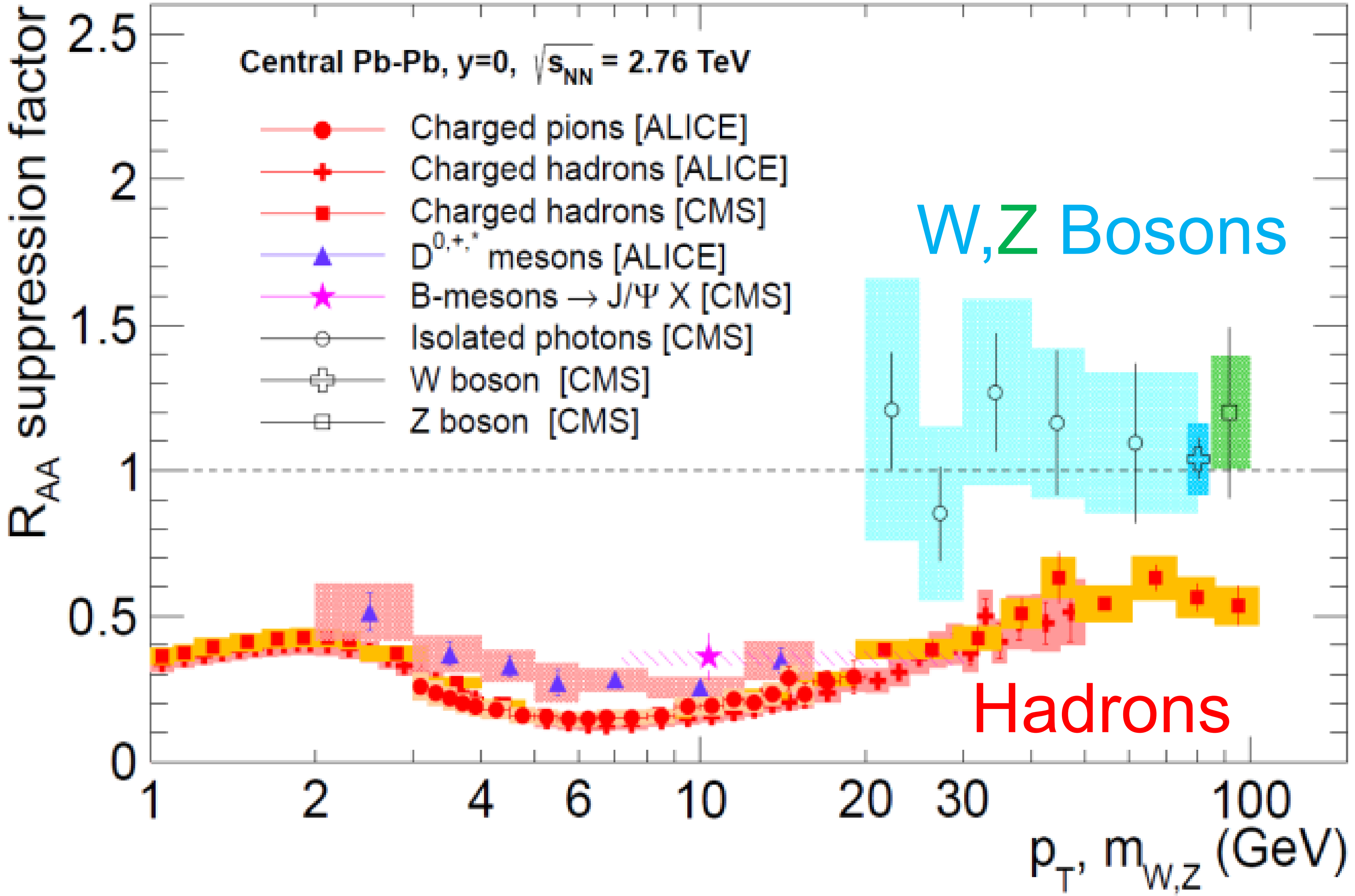


Nuclear Modification Factor

$$R_{AA}(p_T, y; b) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \times d^2\sigma_{pp}/dydp_T} = \frac{\text{A+A yield}}{\text{Scaled p+p yield}}$$

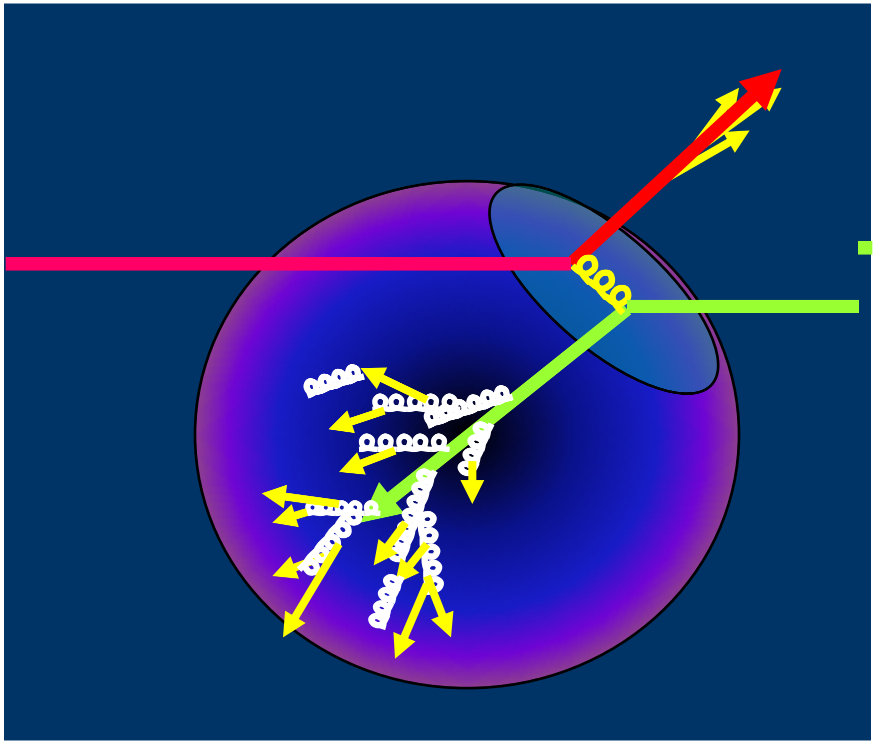


Photons unaffected by medium, pizeros suppressed


Central Pb-Pb, y=0, $\sqrt{s_{NN}}$ = 2.76 TeV
Charged pions [ALICE]
Charged hadrons [ALICE]
Charged hadrons [CMS]
$D^{0,+,*}$ mesons [ALICE]
B-mesons → J/Ψ X [CMS]
Isolated photons [CMS]
W boson [CMS]
Z boson [CMS]
W,Z Bosons
Hadrons
R_{AA} suppression factor
0
0.5
1
1.5
2
2.5
1
2
4
6
10
20
30
100
p_T, $m_{W,Z}$ (GeV)

Opaque Medium – Jet Quenching

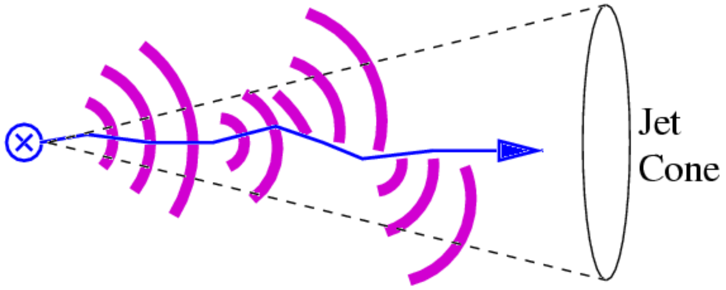
Massive induced gluon radiation thermalizes the parton energy.



Example – 100 GeV quark shot through medium and comes out the other side as large number of hadrons. Thermalized? or Collective Modes?

Wider Angular Distribution

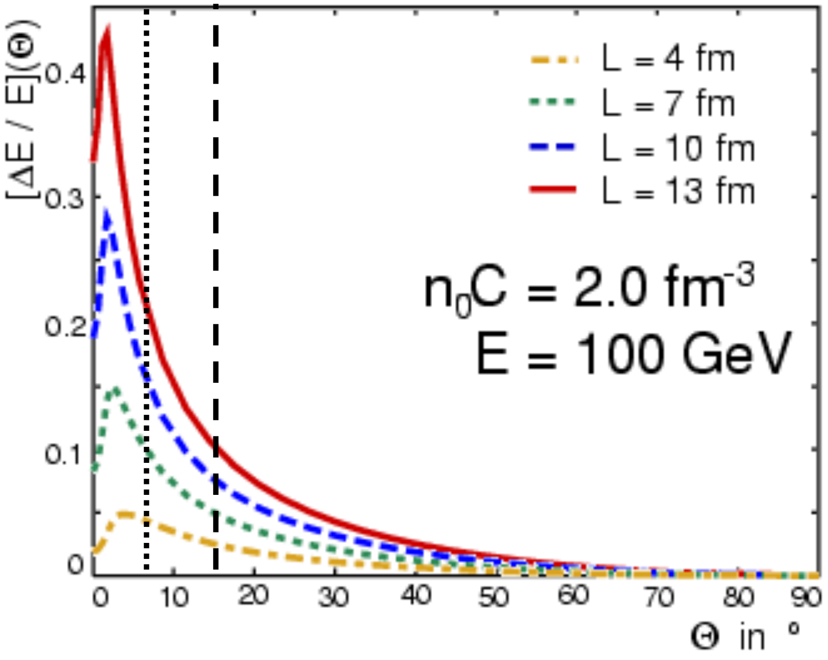
The induced gluon radiation may be measurable due to the broader angular energy distribution than from the jet.



$\theta<20^0$ - 80% of jet energy contained
5% loss of energy outside

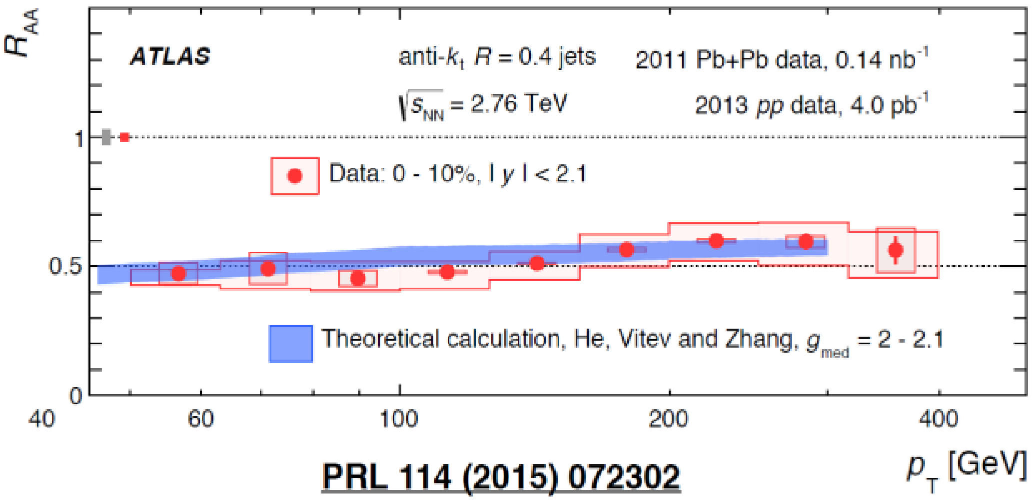
$\theta<12^0$ - 70% of jet energy contained
8% loss of energy outside

Possible observation of reduced "jet" cross section from this effect depending on the jet algorithm R value.



U.A. Wiedemann, hep-ph/0008241.
BDMS, hep-ph/0105062.

Jet Observables

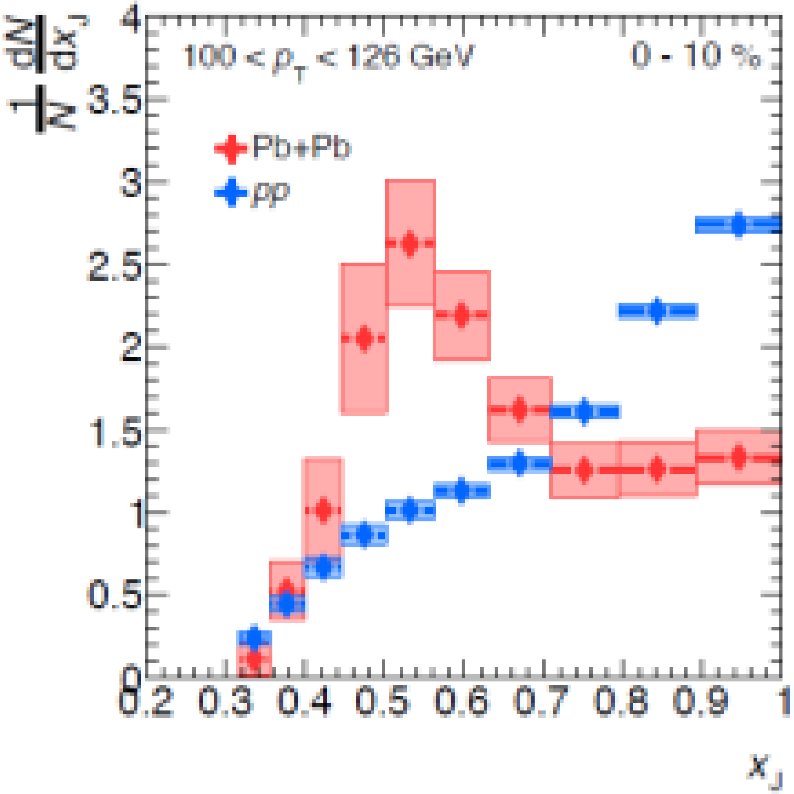


PRL 114 (2015) 072302

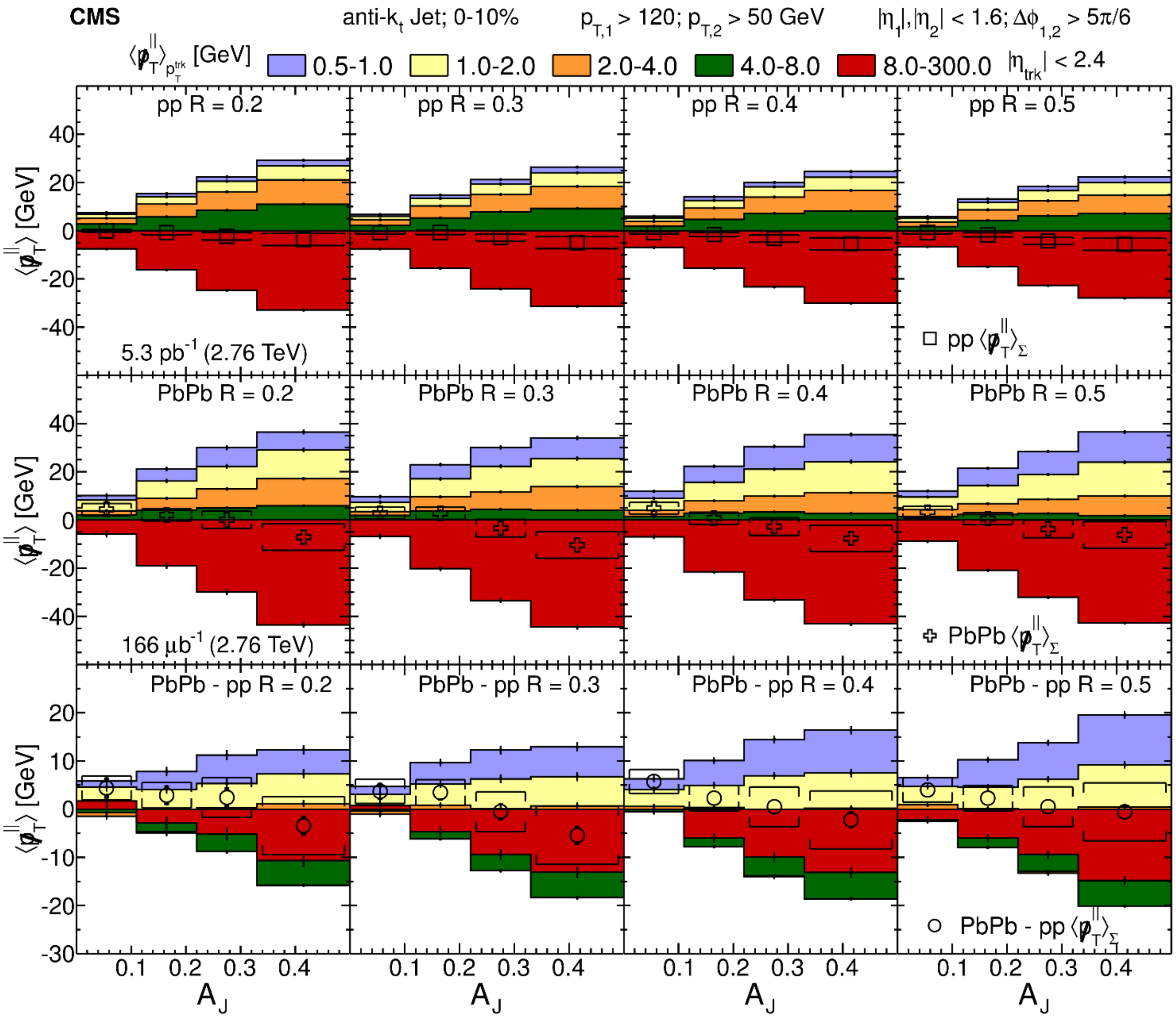
Single jets (R=0.4)
are suppressed.

Massive change to
dijet distribution.

At Leading Order,
dijets should be
transverse energy
balanced.



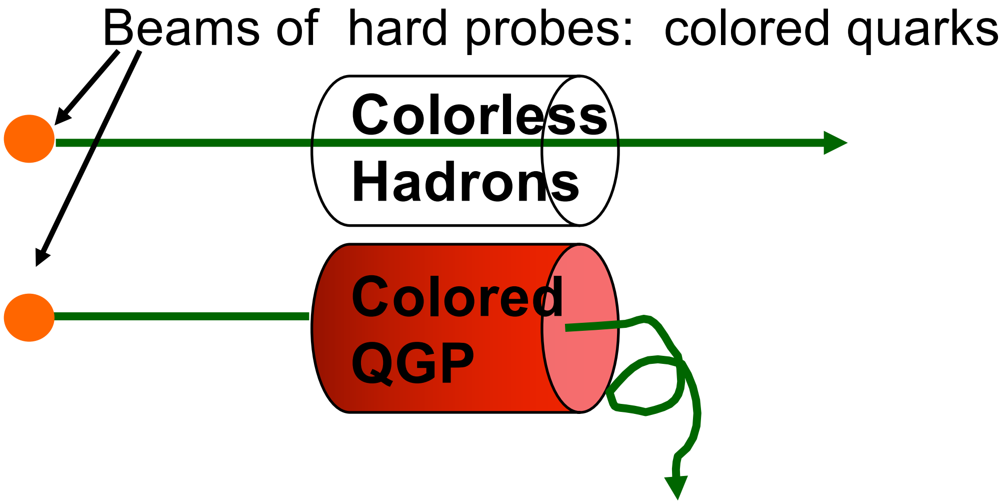
Jet Energy Redistributed



Experiment is out in front of theory…

Confined vs Deconfined Color?

Are we sensitive to deconfinement?



Beams of hard probes: colored quarks

Colorless Hadrons

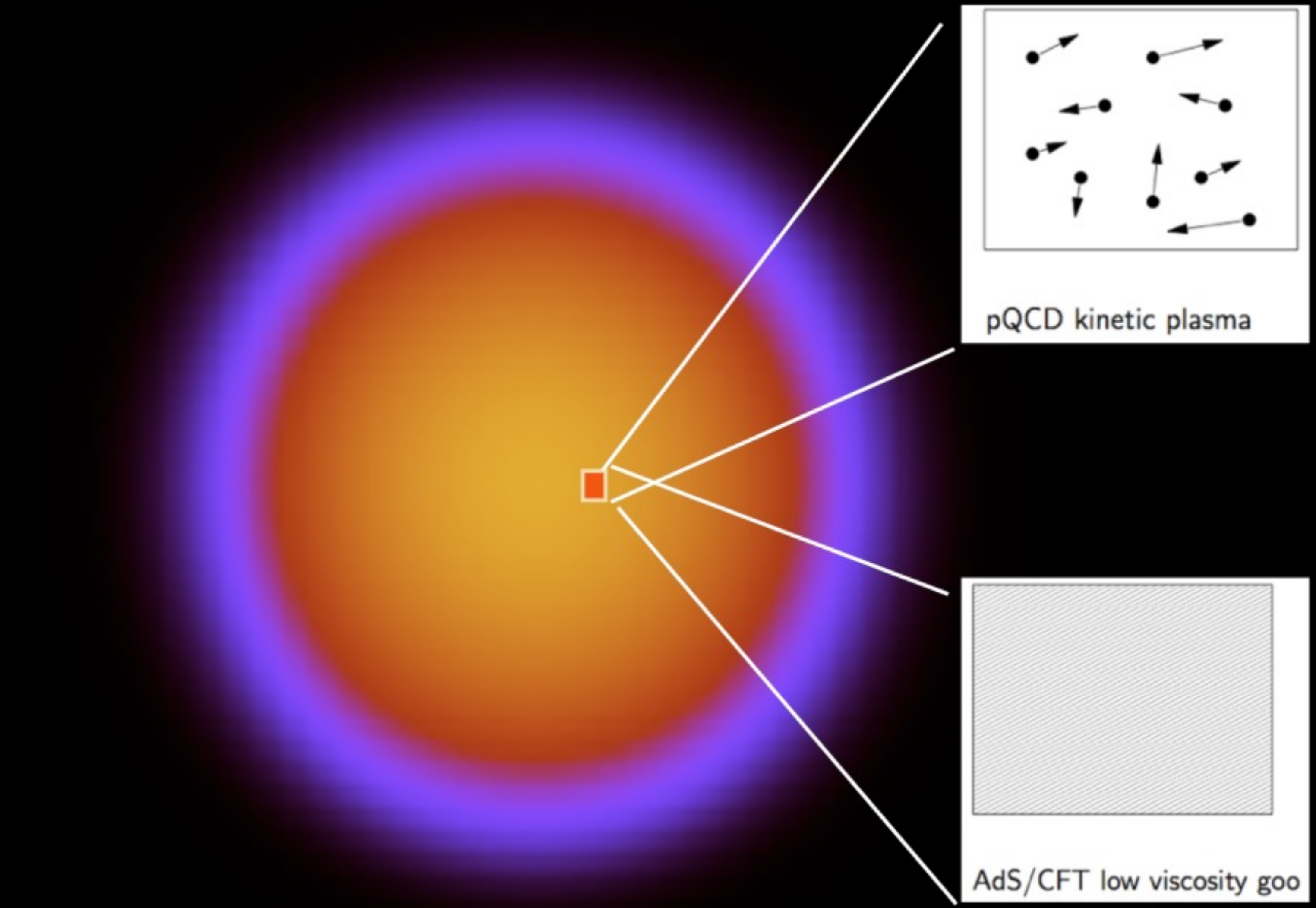
Colored QGP

Not really !

If the coherent energy loss scale is large, then we probe short distances and would “see” the color charges inside hadrons anyway (like in DIS).

Only if the energy loss scale is small would we be sensitive, but this does not seem to be our regime.

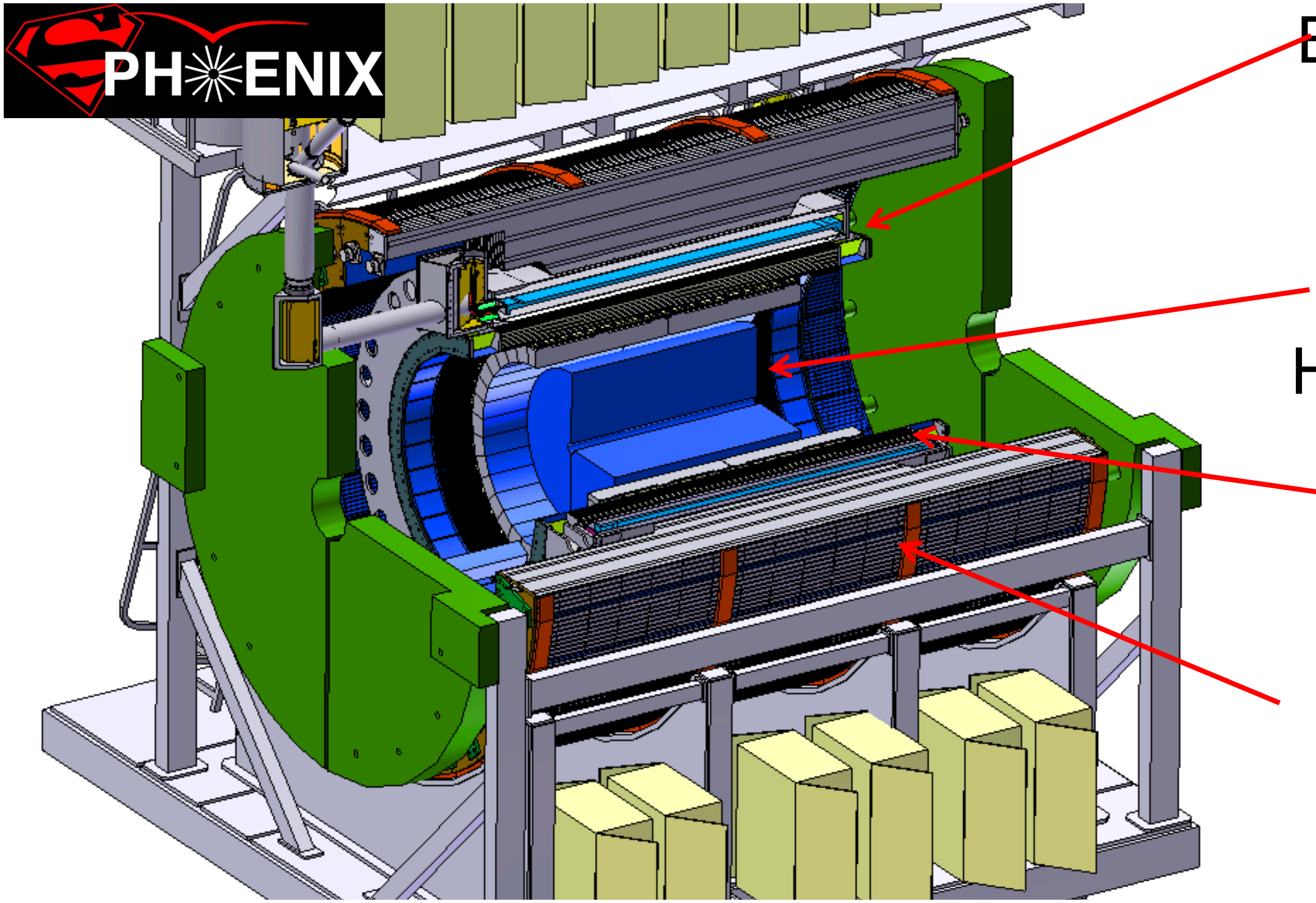
How does QGP work?



from Thomas Schafer

Use probes at multiple scales to study QGP's microscopic structure

A New Detector at RHIC



BaBar Magnet 1.5 T

Coverage |η| < 1.1

All silicon tracking
Heavy flavor tagging

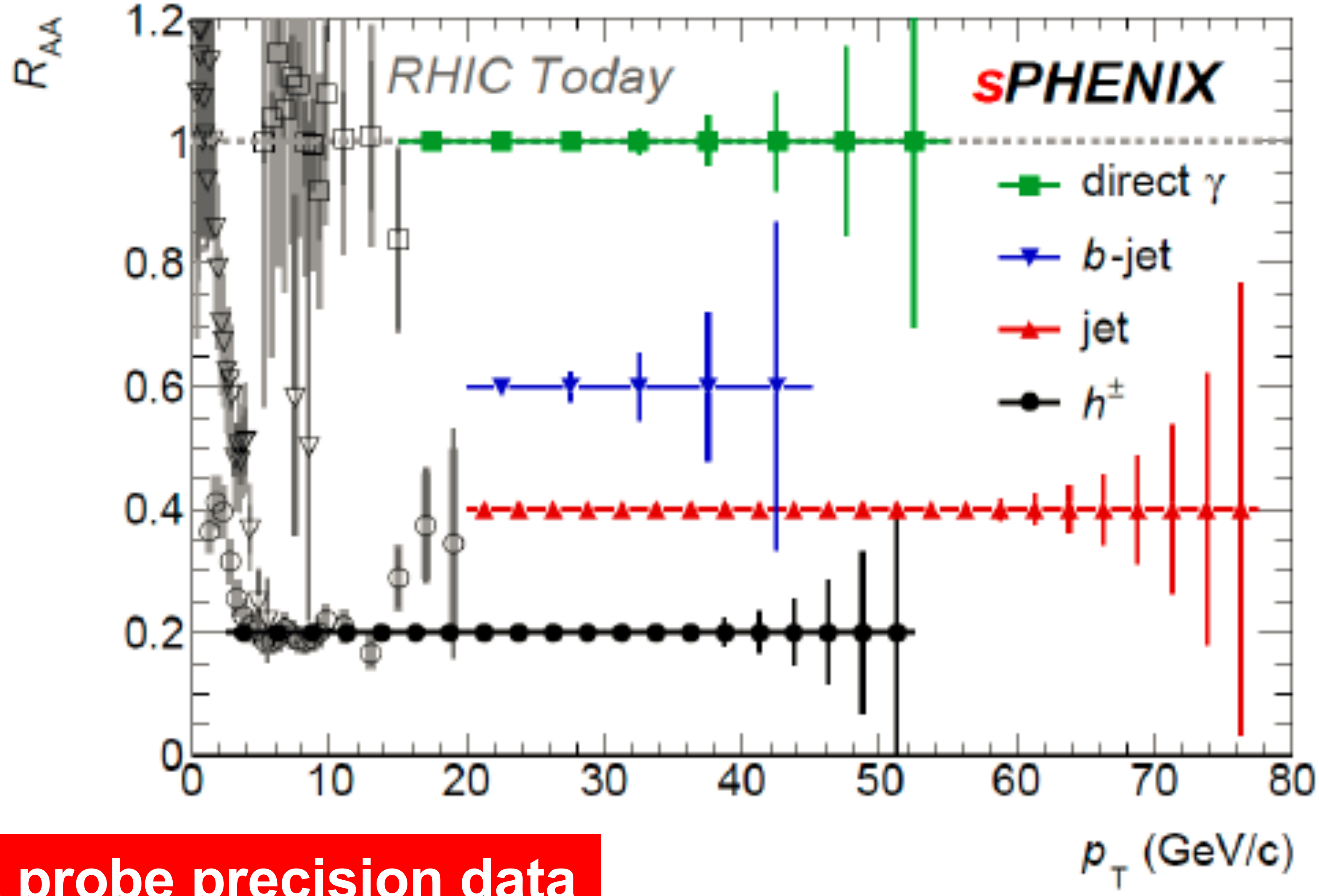
Electromagnetic
Calorimeter

Hadronic
Calorimeter

High data acquisition rate capability, 15 kHz

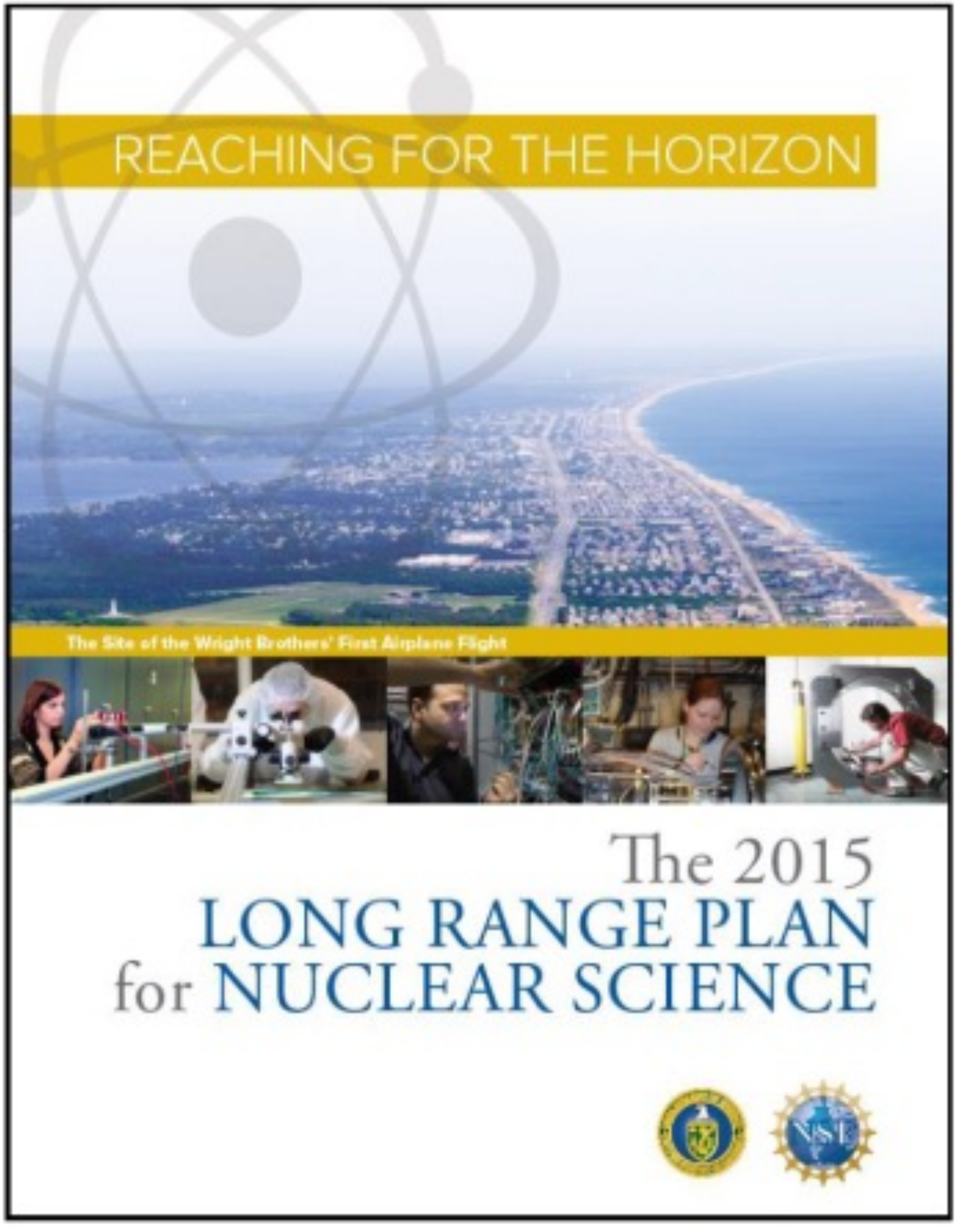
Sampling 0.6 trillion Au+Au interactions in one-year
Maximizing efficiency of RHIC running

Precision Imaging of QGP Over Key Kinematics



Jet probe precision data
RHIC – 2021-2022
LHC – 2020-2023

The Future



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Well worth reading for young people…

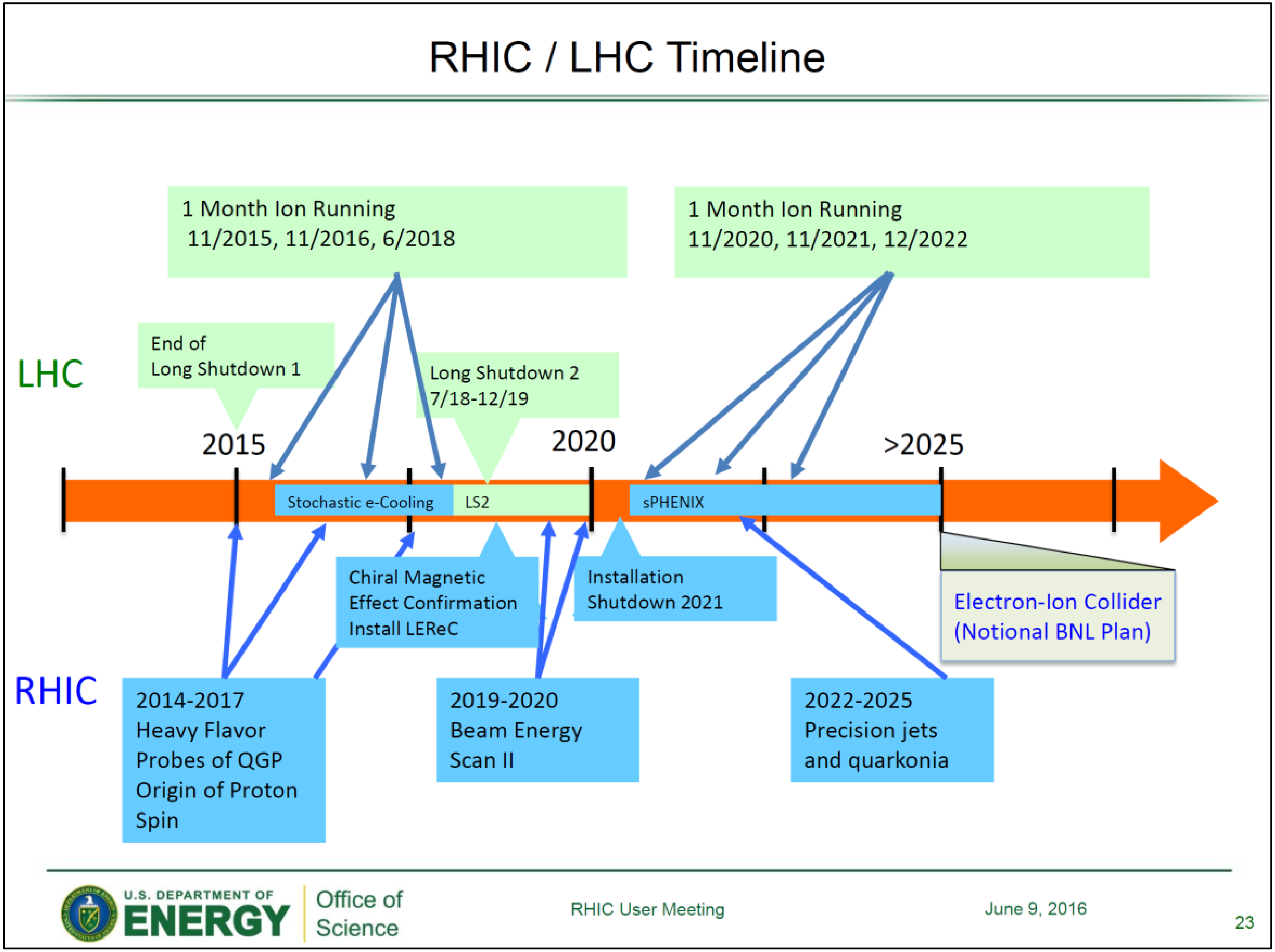
A roadmap for the future. Note that large \$0.5 - \$1.5B projects take 7-15 years at least.

Capitalize on key investments.

Future facilities.

science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

DOE Shown Heavy Ion Timeline



RHIC / LHC Timeline

LHC

End of
Long Shutdown 1

1 Month Ion Running
11/2015, 11/2016, 6/2018

Long Shutdown 2
7/18-12/19

1 Month Ion Running
11/2020, 11/2021, 12/2022

2015

2020

>2025

Stochastic e-Cooling

LS2

sPHENIX

RHIC

2014-2017
Heavy Flavor
Probes of QGP
Origin of Proton
Spin

Chiral Magnetic
Effect Confirmation
Install LEReC

2019-2020
Beam Energy
Scan II

Installation
Shutdown 2021

2022-2025
Precision jets
and quarkonia

Electron-Ion Collider
(Notional BNL Plan)

U.S. DEPARTMENT OF ENERGY | Office of Science

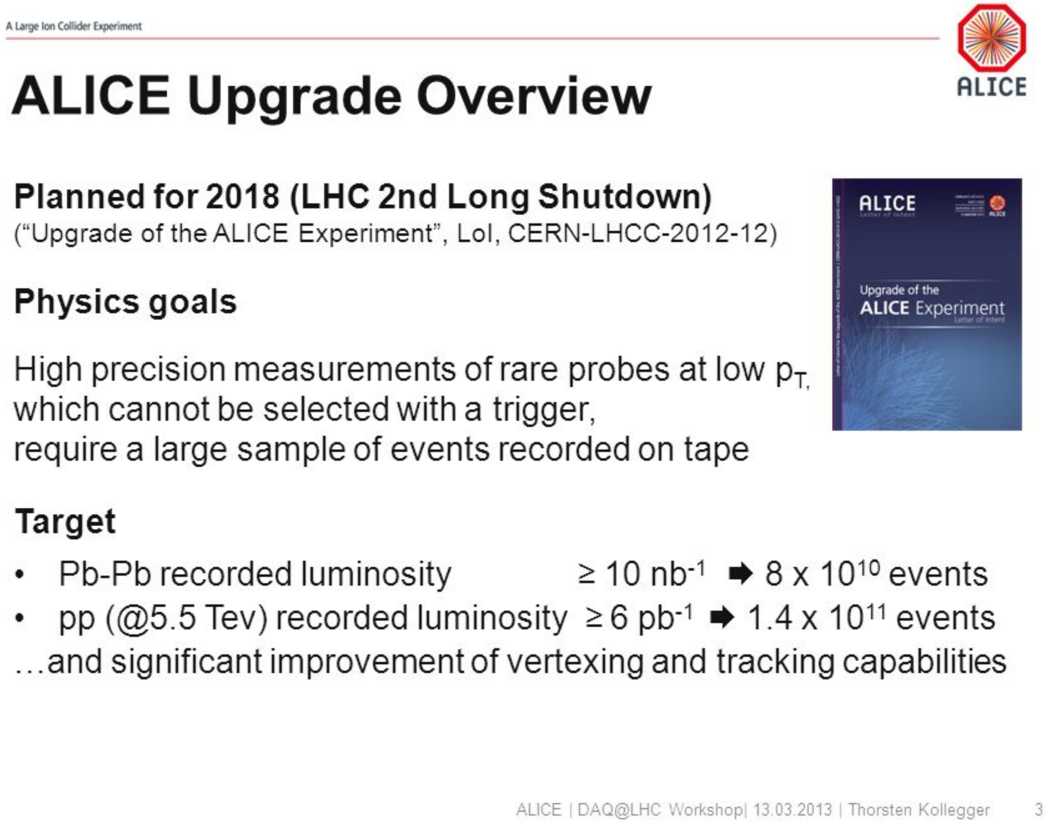
RHIC User Meeting

June 9, 2016

23

LHC Super-High Luminosity (statistics, statistics, statistics)

Major heavy ion related upgrades – ALICE will have enormous event samples for all soft → hard observables



A Large Ion Collider Experiment

ALICE Upgrade Overview

Planned for 2018 (LHC 2nd Long Shutdown)
("Upgrade of the ALICE Experiment", LoI, CERN-LHCC-2012-12)

Physics goals

High precision measurements of rare probes at low p_T, which cannot be selected with a trigger, require a large sample of events recorded on tape

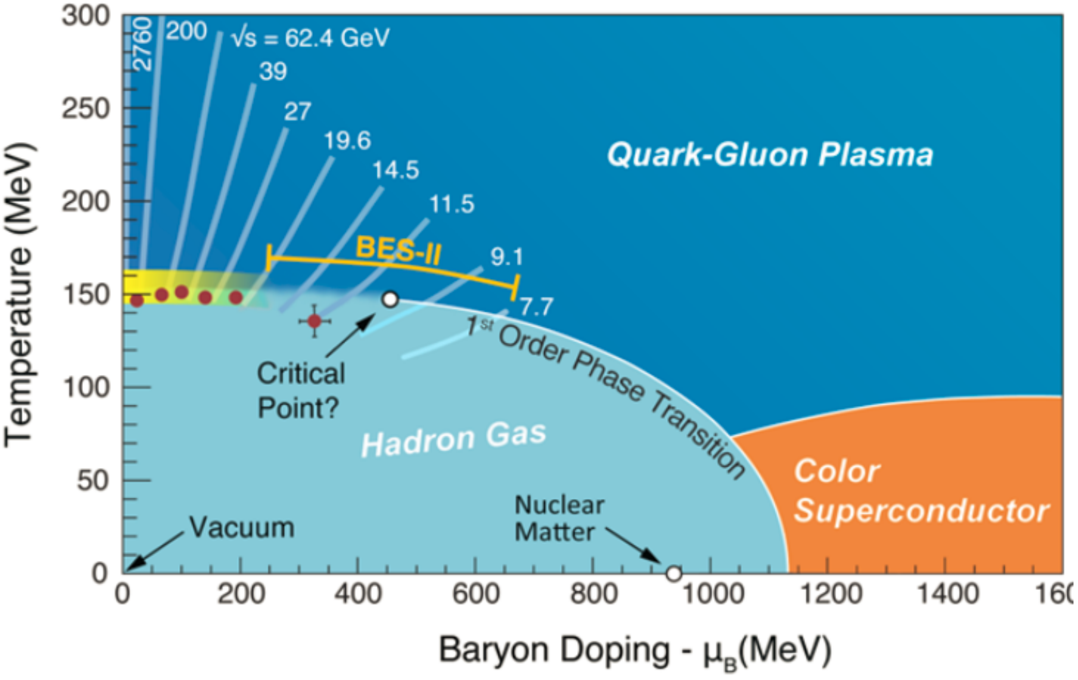
Target

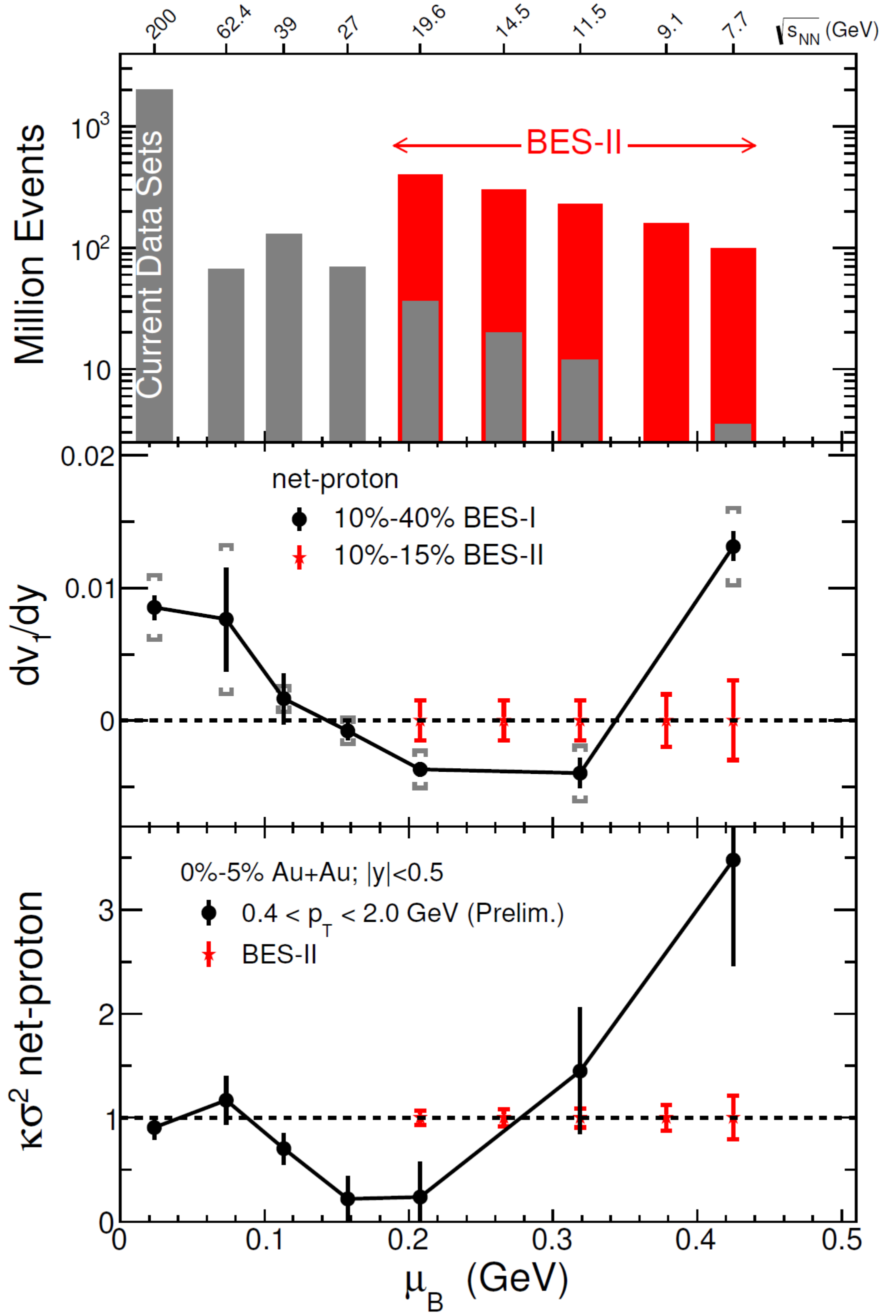
- Pb-Pb recorded luminosity ≥ 10 nb^{-1} ➡ 8 x 10^{10} events
- pp (@5.5 Tev) recorded luminosity ≥ 6 pb^{-1} ➡ 1.4 x 10^{11} events

…and significant improvement of vertexing and tracking capabilities

ALICE | DAQ@LHC Workshop| 13.03.2013 | Thorsten Kollegger 3

Beam Energy Scan – Phase II

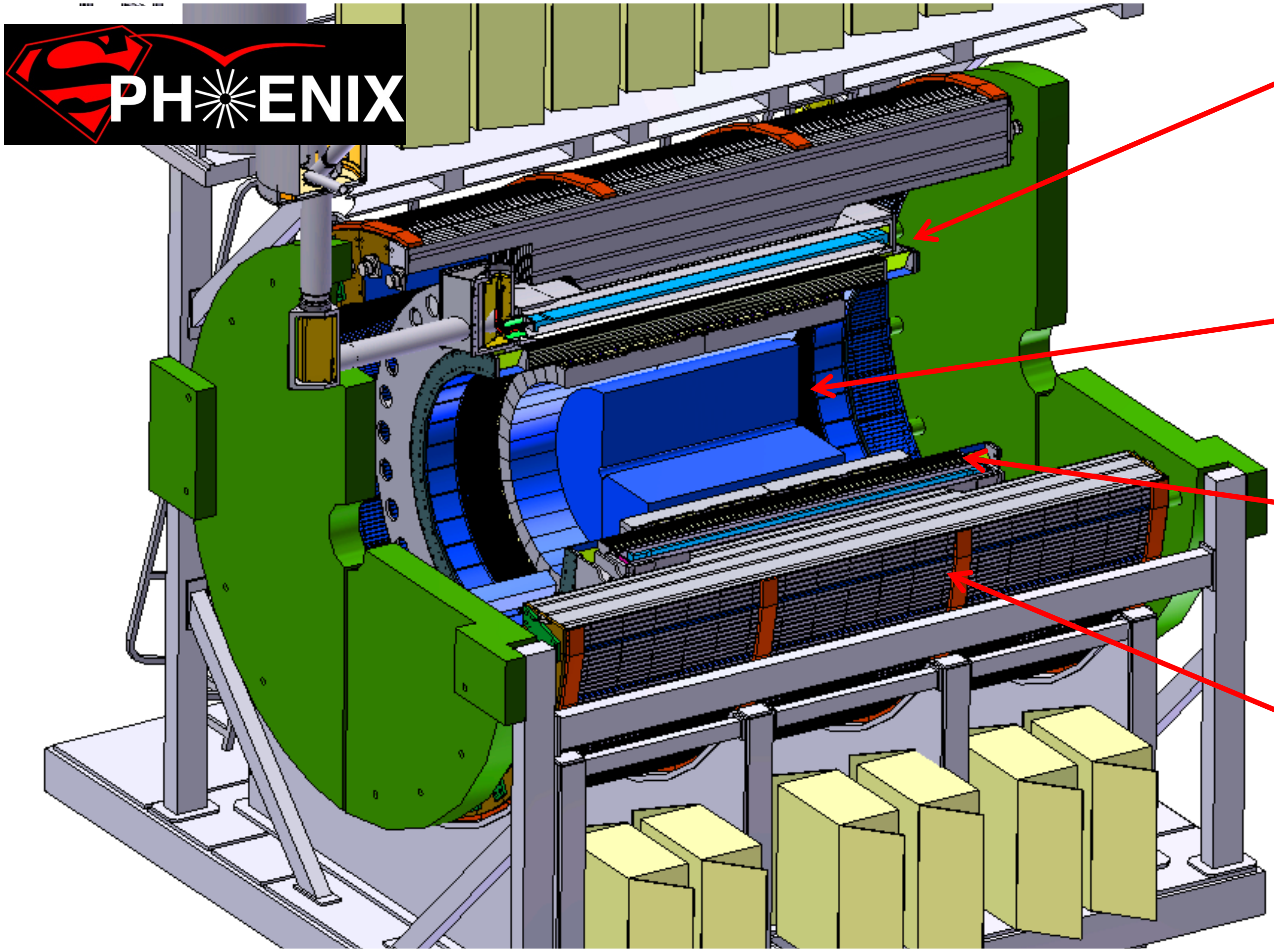




Accelerator upgrade to increase luminosity at these lower energies.

New precision in phase diagram mapping.

A New Detector at RHIC



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Calorimeter

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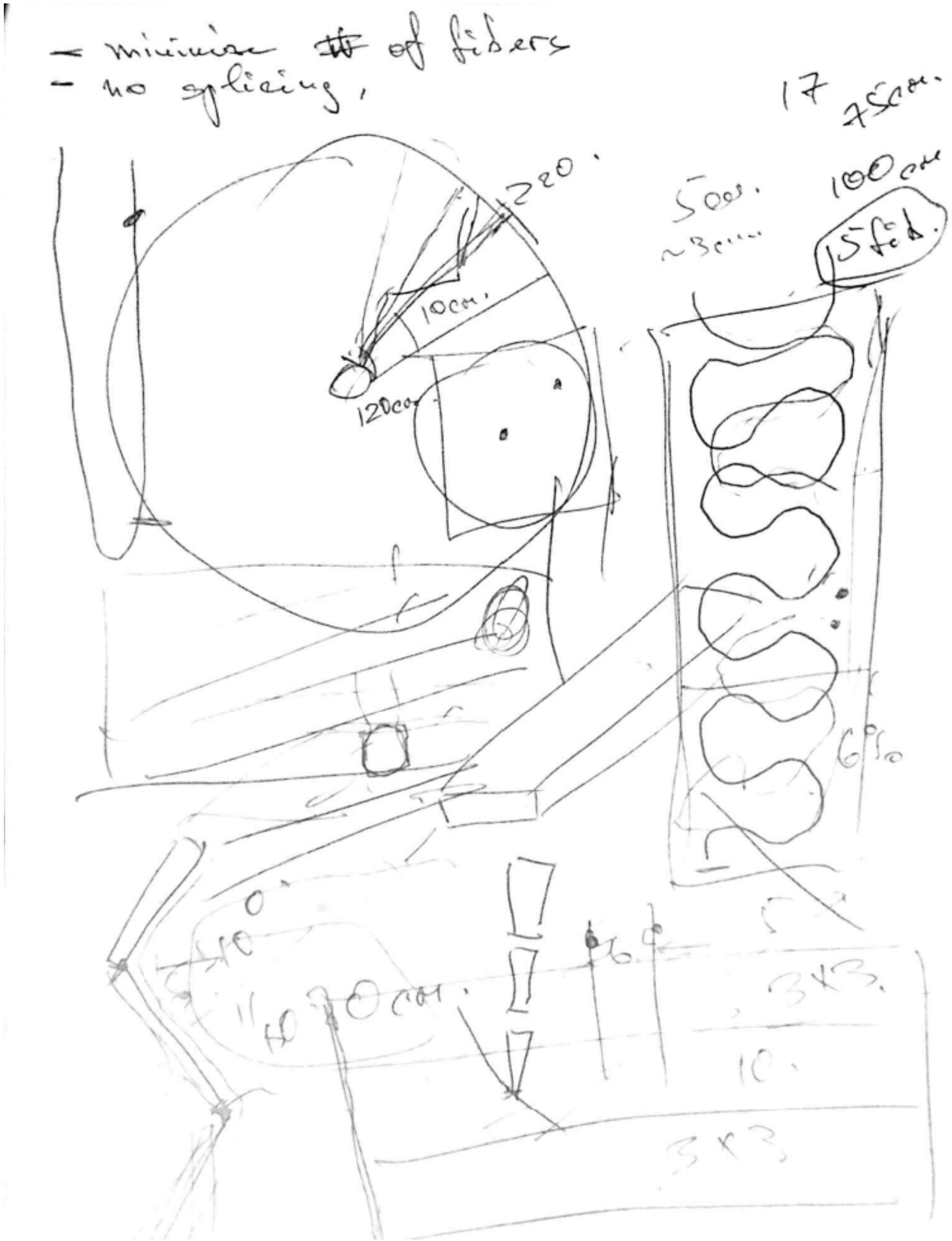
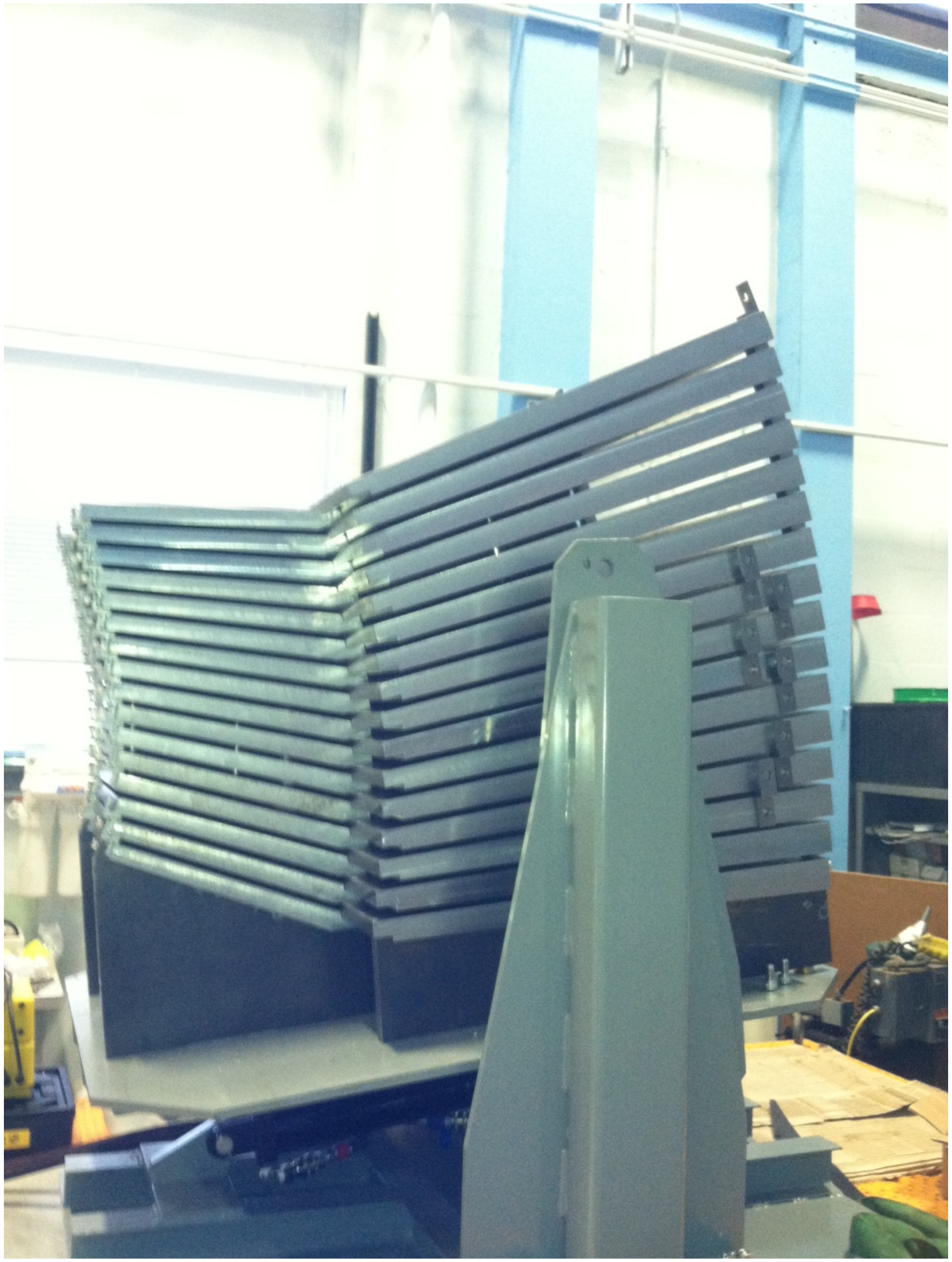
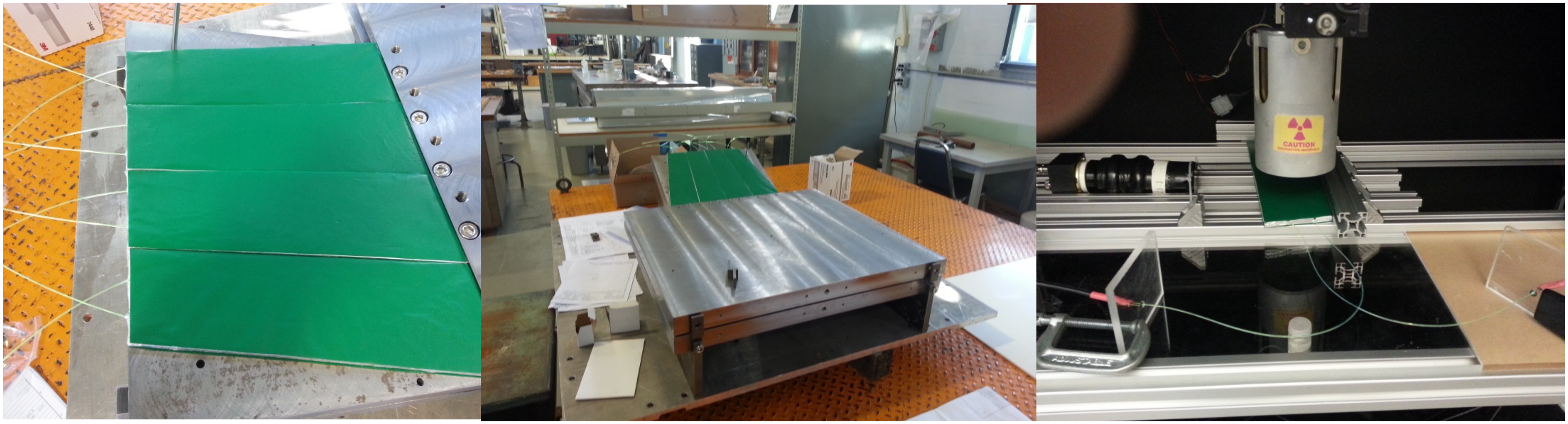
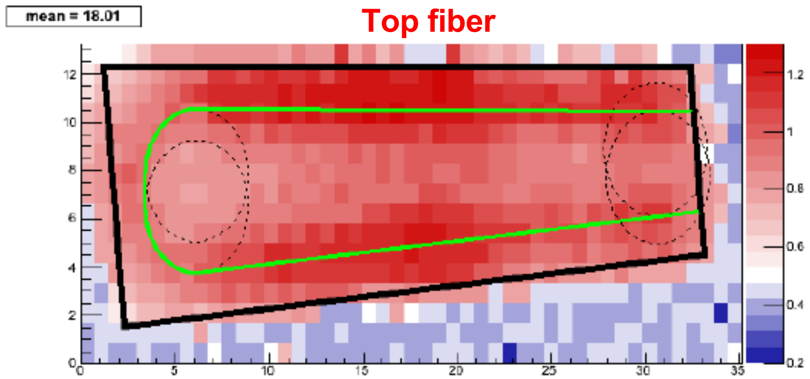
Maximizing efficiency of RHIC running

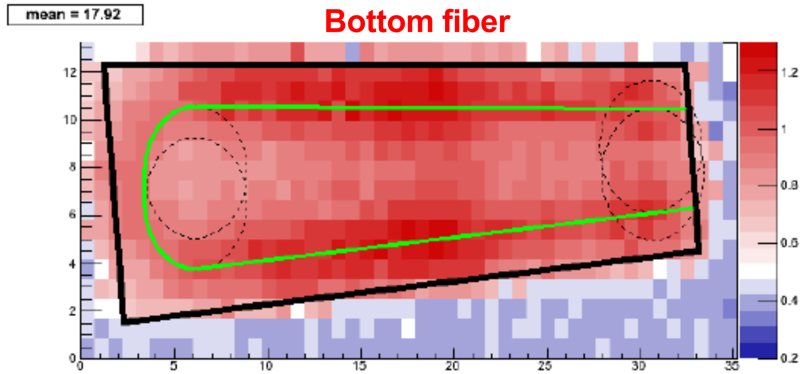
Napkin Drawing → Prototype → Detector → Physics

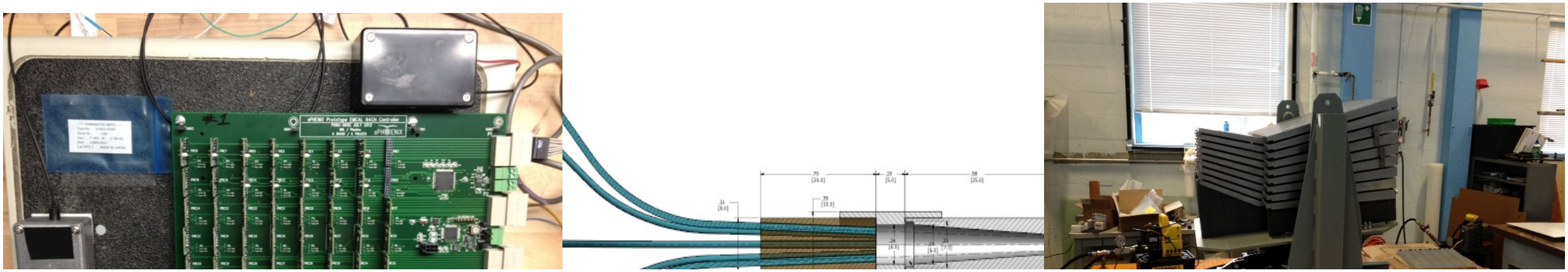










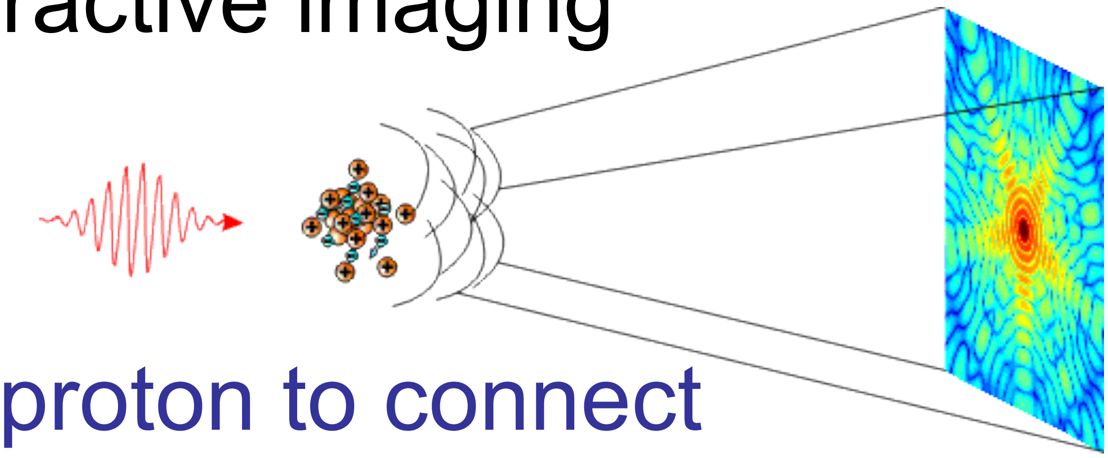


If you have the chance to get involved in hardware (even a little) it is well worth while.

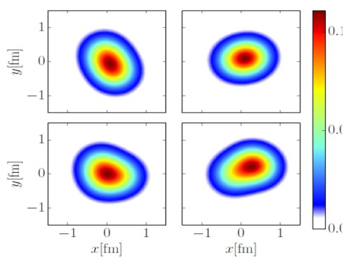
Electron-Ion Collider

Exciting future program.
Very broad (lectures last week).

One example – diffractive imaging

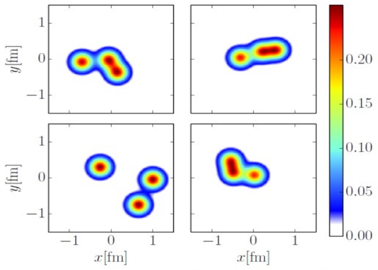


Can we image the proton to connect to our measurements of flow in p+p, p+A?

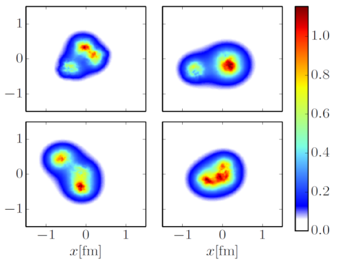


(b) $B_{qc} = 1.0$ GeV^{-2}, $B_q = 3.0$ GeV^{-2}

FIG. 3: Examples of proton density profiles wi
parametrizations used in this work.



(a) $B_{qc} = 3.3$ GeV^{-2}, $B_q = 0.7$ GeV^{-2}



. 4: Illustration of the proton density profile (1.0 − r $V(x,y)/N_c$) obtained from the IP-Glasma framework parameters $B_{qc} = 3.0$ GeV^{-2}, $B_q = 0.3$ GeV^{-2} and $m = 0.4$ GeV.

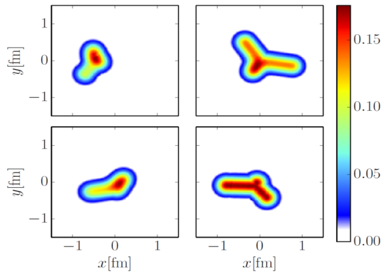


FIG. 5: Example density profiles of the "stringy proton" in the transverse plane with parameters $B_t = 4.2$ GeV^{-2}, $B_r = 0.6$ GeV^{-2}

Stay Curious

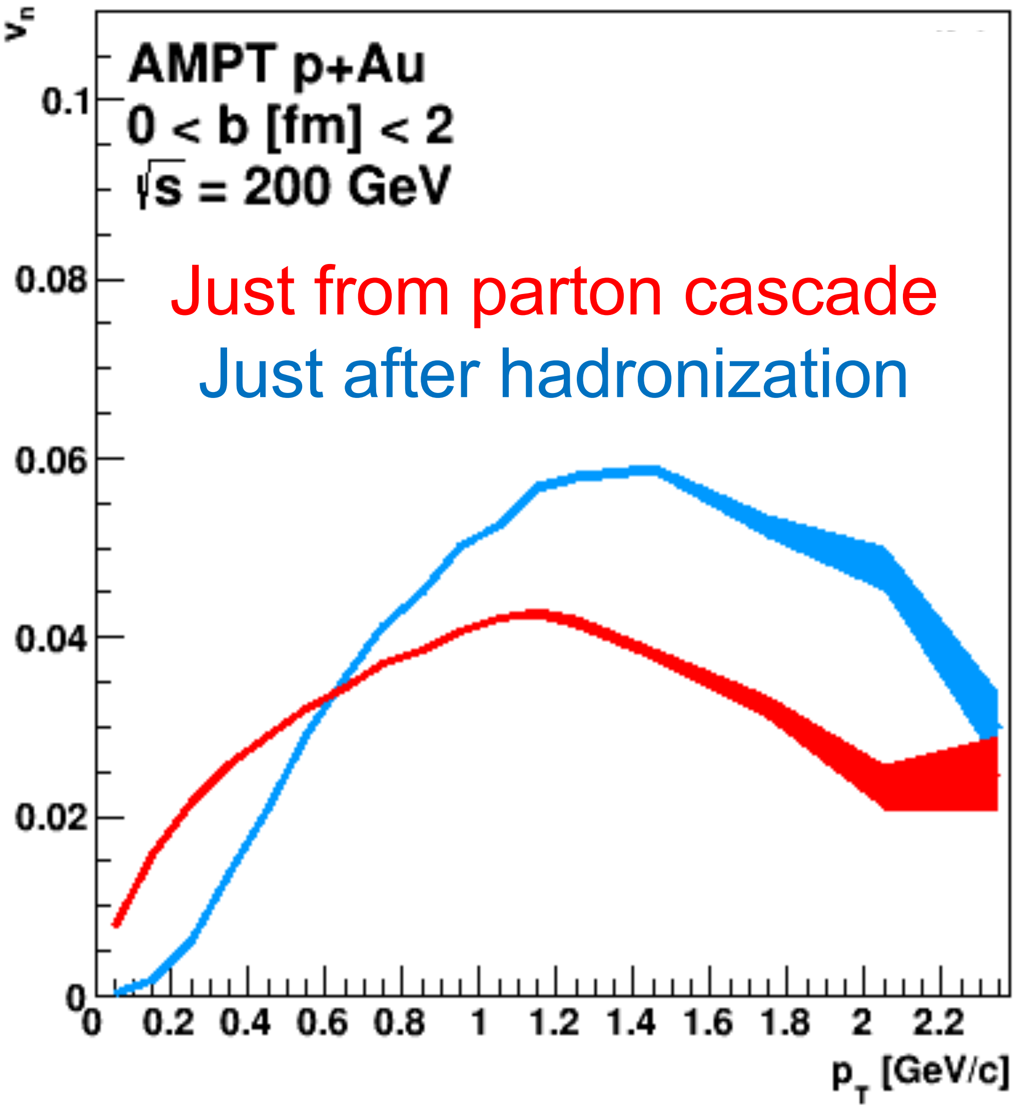
Nominal Lectures

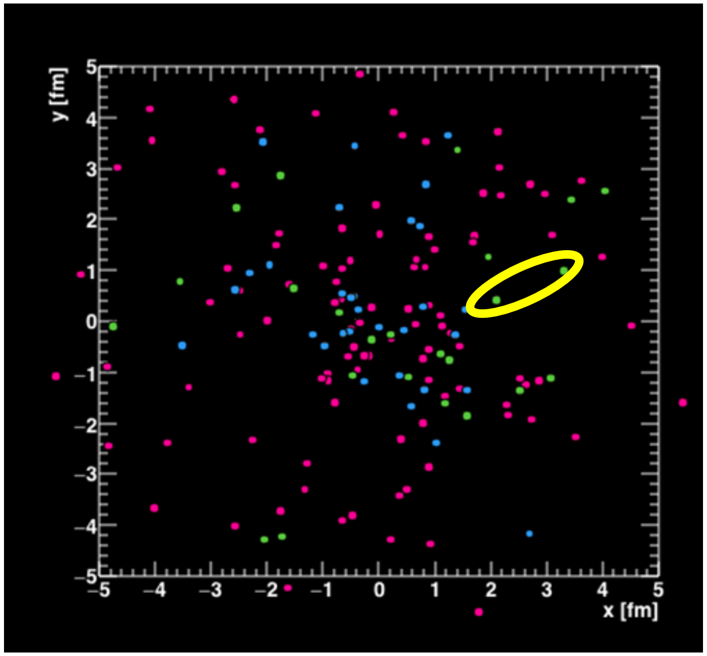
Fini

Extra Slides

Hadronization in AMPT

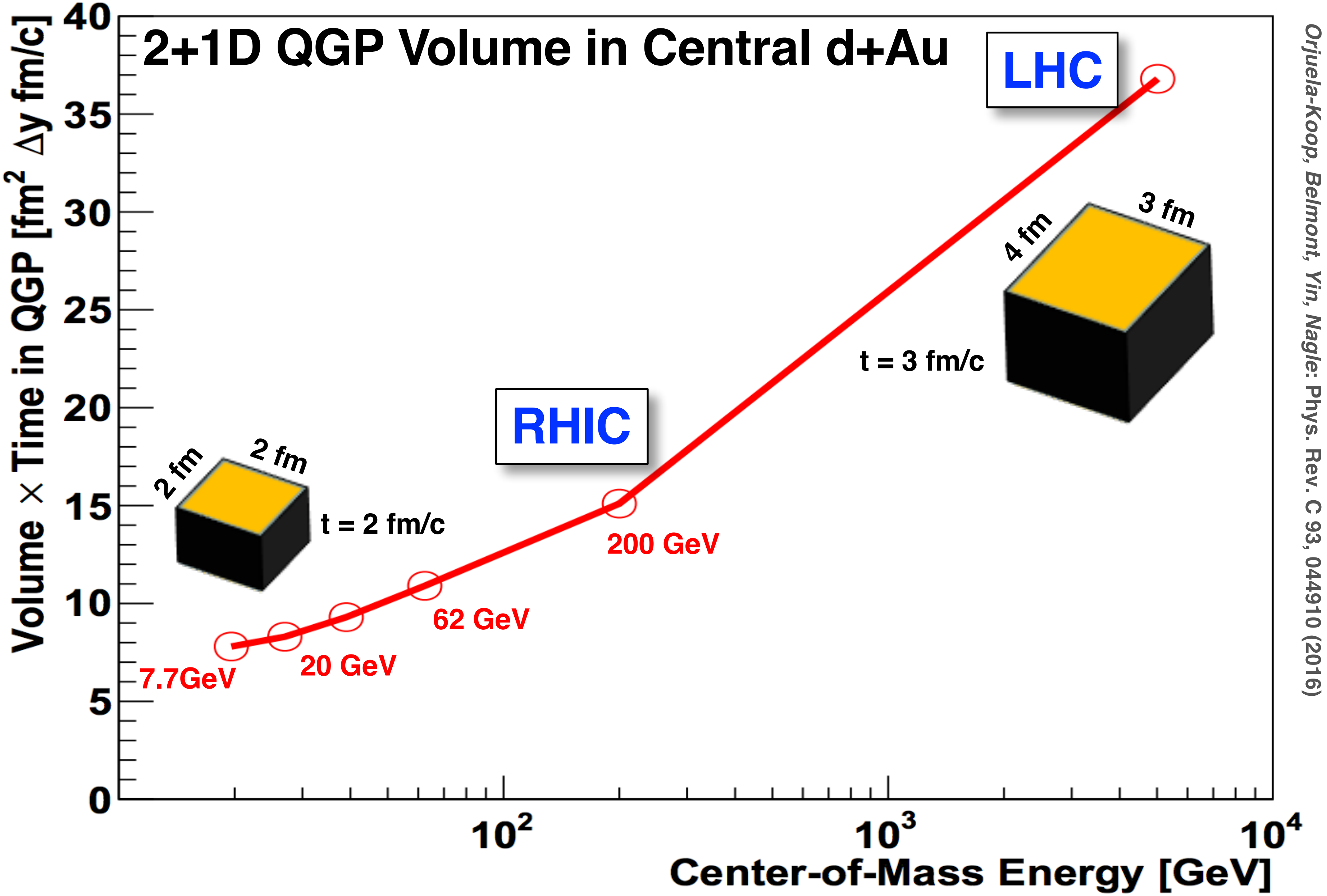
200 quarks/antiquarks → ~ 100 mesons



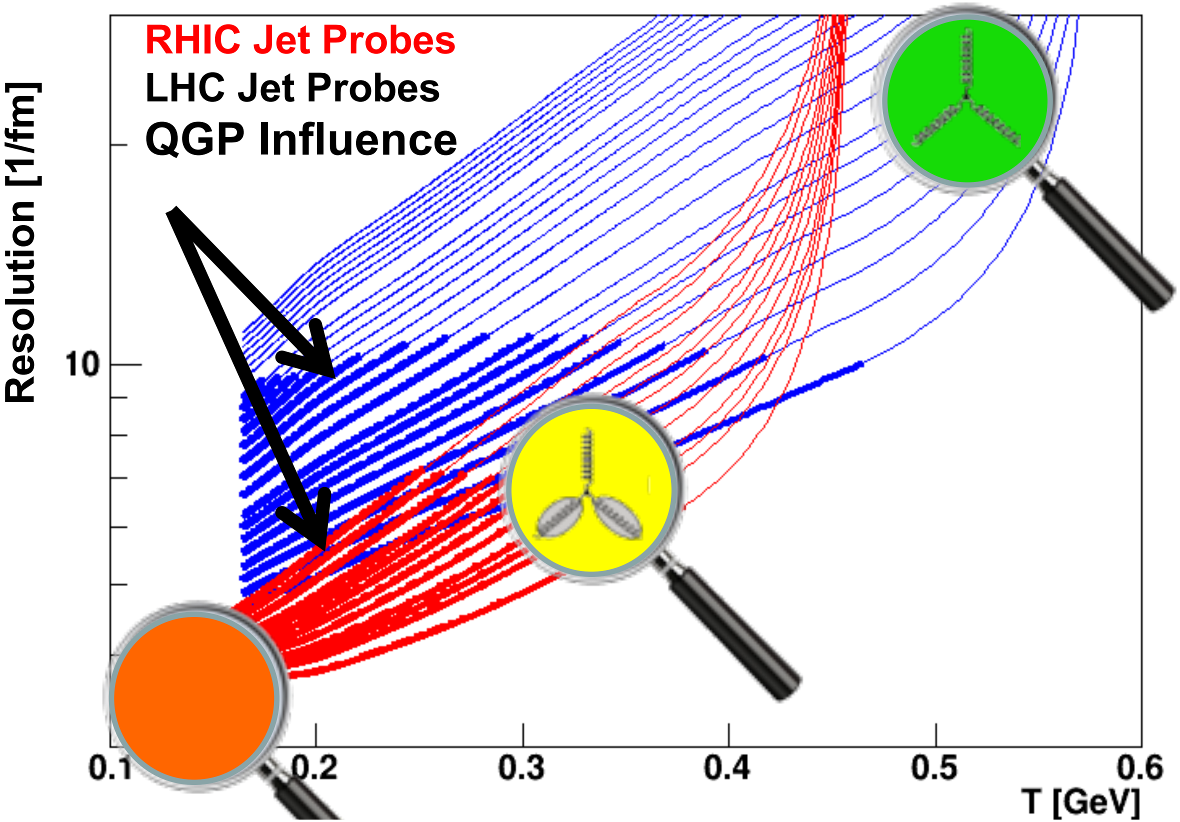


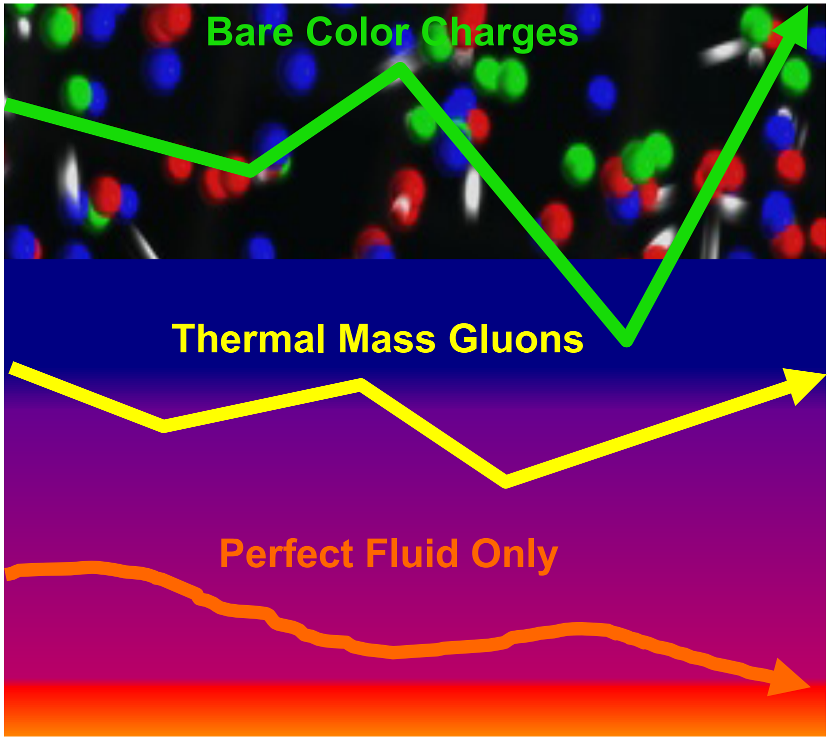
Coalescence just by closest spatial partner (no momentum space)

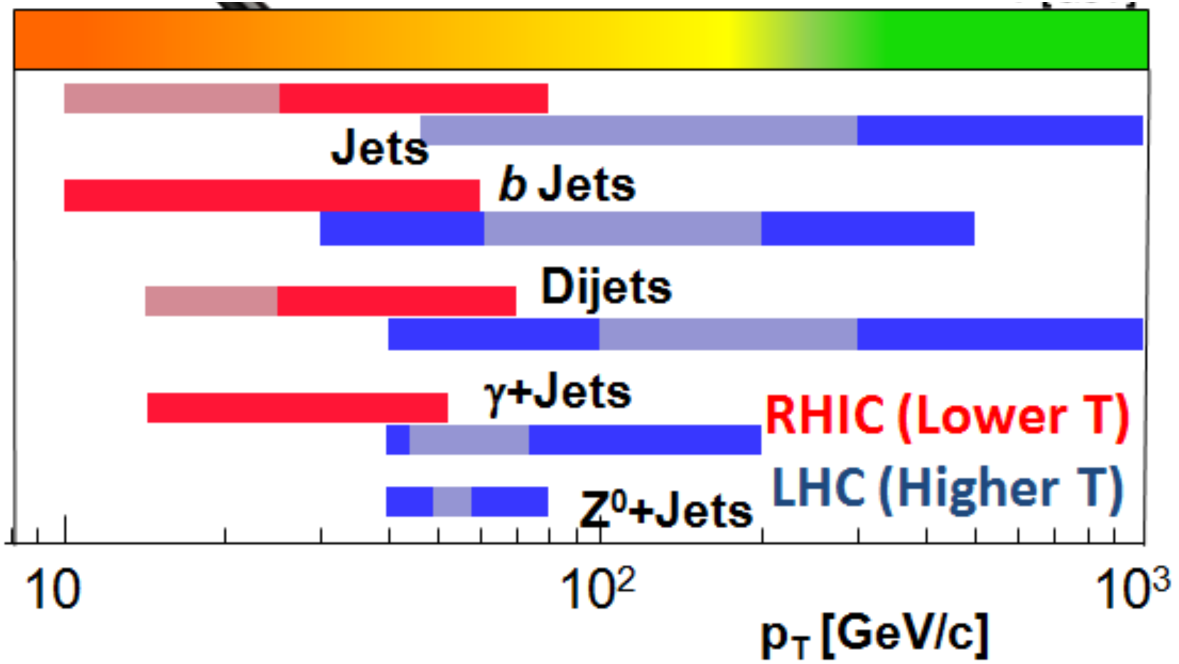
Hydrodynamic Results for d+Au Energy Scan



Orjuela-Koop, Belmont, Yin, Nagle: Phys. Rev. C 93, 044910 (2016)







Critical microscope resolution at RHIC.

Also, overlap between RHIC and LHC for simultaneous description.

Heavy Quarks

Why are heavy quarks so special?

QCD is flavor blind, so why are charm and beauty quarks interesting?

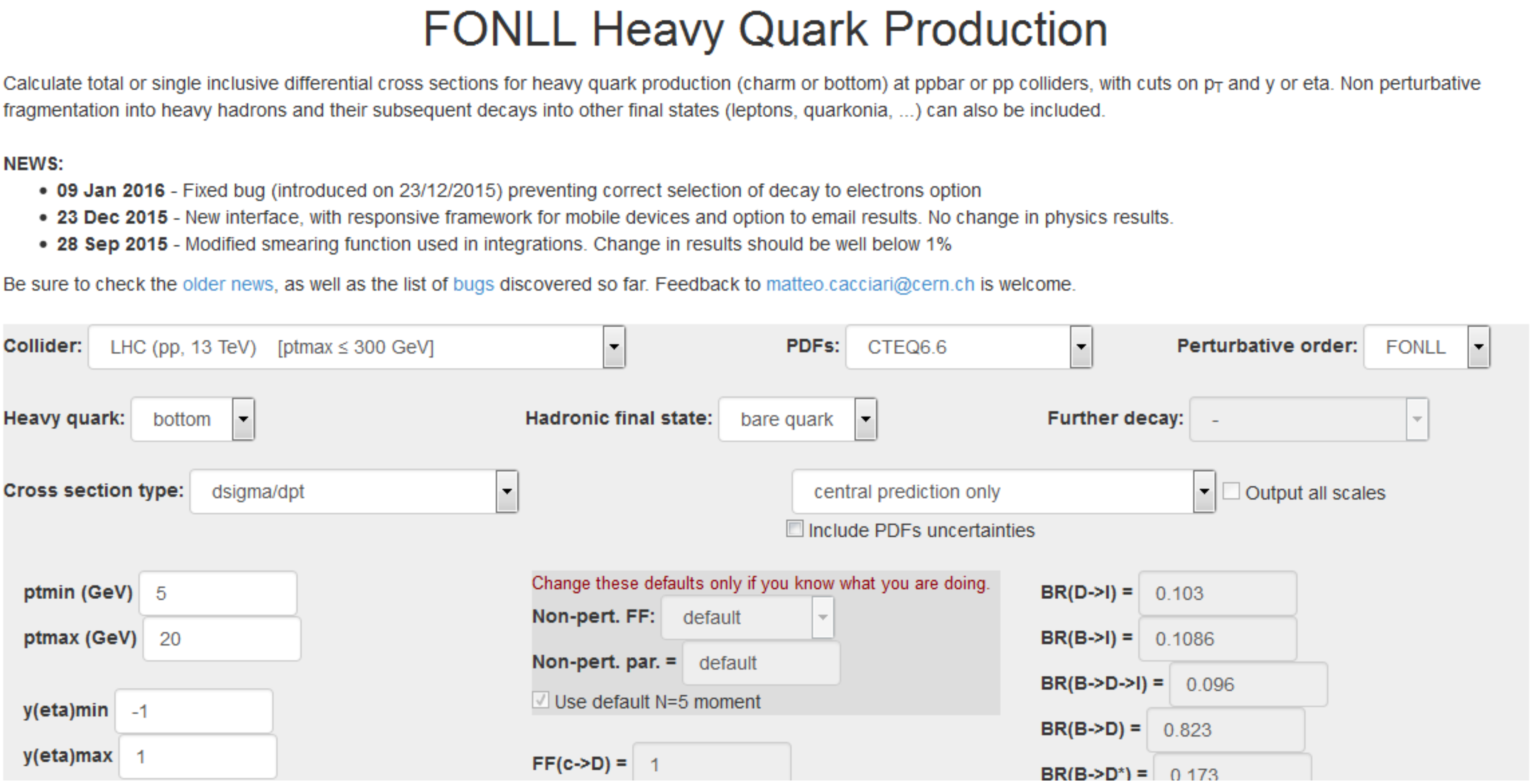
Very difficult to produce charm (beauty) quark-antiquark pairs via thermal production in the QGP

g+g → ccbar or bbbar

However, high energy gluons from the incoming nuclei can do the trick. Production dominated by “initial hard scattering” and perturbatively (pQCD) calculable even at low pT due to mass scale.

Cannot be destroyed via strong interaction with light quarks and gluons (i.e. QGP).

http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html



FONLL Heavy Quark Production

Calculate total or single inclusive differential cross sections for heavy quark production (charm or bottom) at ppbar or pp colliders, with cuts on p_T and y or eta. Non perturbative fragmentation into heavy hadrons and their subsequent decays into other final states (leptons, quarkonia, ...) can also be included.

NEWS:

- **09 Jan 2016** - Fixed bug (introduced on 23/12/2015) preventing correct selection of decay to electrons option
- **23 Dec 2015** - New interface, with responsive framework for mobile devices and option to email results. No change in physics results.
- **28 Sep 2015** - Modified smearing function used in integrations. Change in results should be well below 1%

Be sure to check the older news, as well as the list of bugs discovered so far. Feedback to matteo.cacciari@cern.ch is welcome.

Collider: LHC (pp, 13 TeV) [ptmax ≤ 300 GeV]
PDFs: CTEQ6.6
Perturbative order: FONLL
Heavy quark: bottom
Hadronic final state: bare quark
Further decay: -
Cross section type: dsigma/dpt
central prediction only
☐ Output all scales
☐ Include PDFs uncertainties

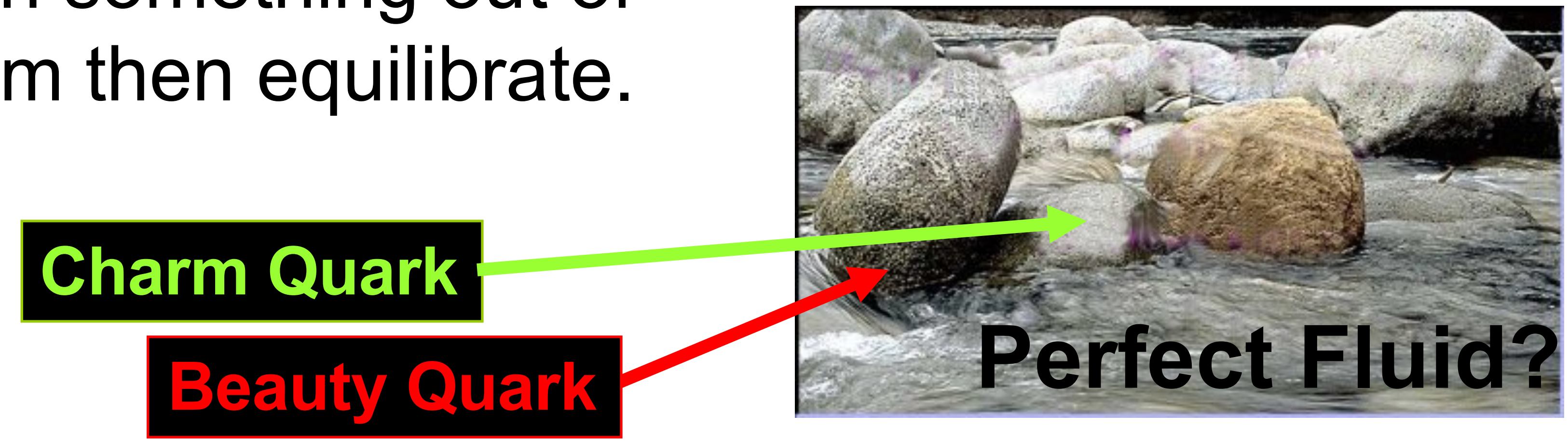
ptmin (GeV) 5
ptmax (GeV) 20
y(eta)min -1
y(eta)max 1

Change these defaults only if you know what you are doing.
Non-pert. FF: default
Non-pert. par. = default
☑ Use default N=5 moment
FF(c->D) = 1

BR(D->l) = 0.103
BR(B->l) = 0.1086
BR(B->D->l) = 0.096
BR(B->D) = 0.823
BR(B->D*) = 0.173

Alternative Fluid Probe:

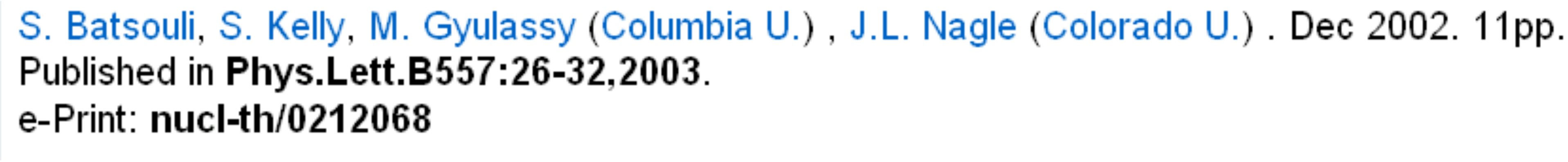
Put a pebble in the stream and watch something out of equilibrium then equilibrate.


Charm Quark

Beauty Quark

Perfect Fluid?

“Does the Charm Flow at RHIC?”

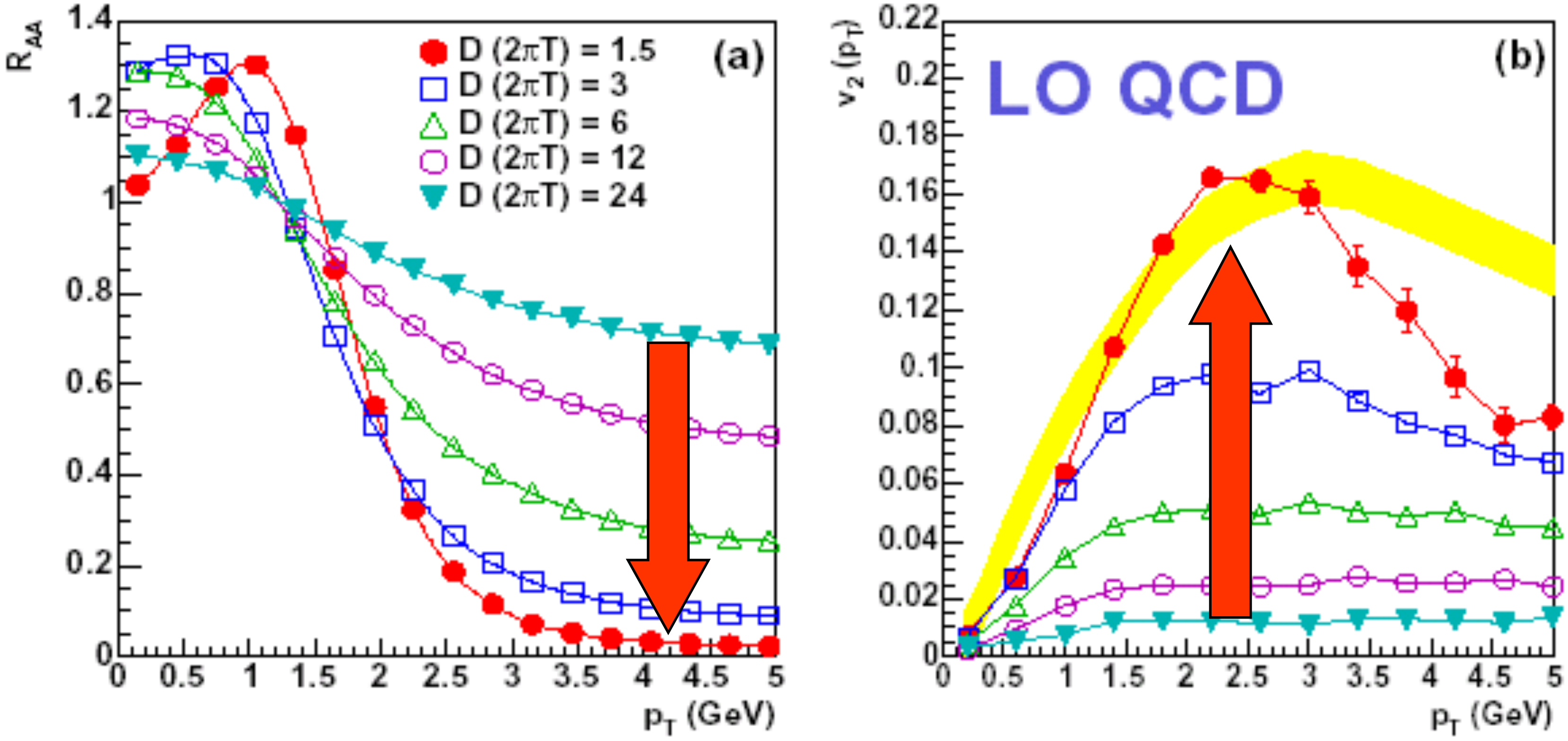

S. Batsouli, S. Kelly, M. Gyulassy (Columbia U.) , J.L. Nagle (Colorado U.) . Dec 2002. 11pp.
Published in **Phys.Lett.B557:26-32,2003.**
e-Print: **nucl-th/0212068**

At the time, many said this idea was “ridiculous”.

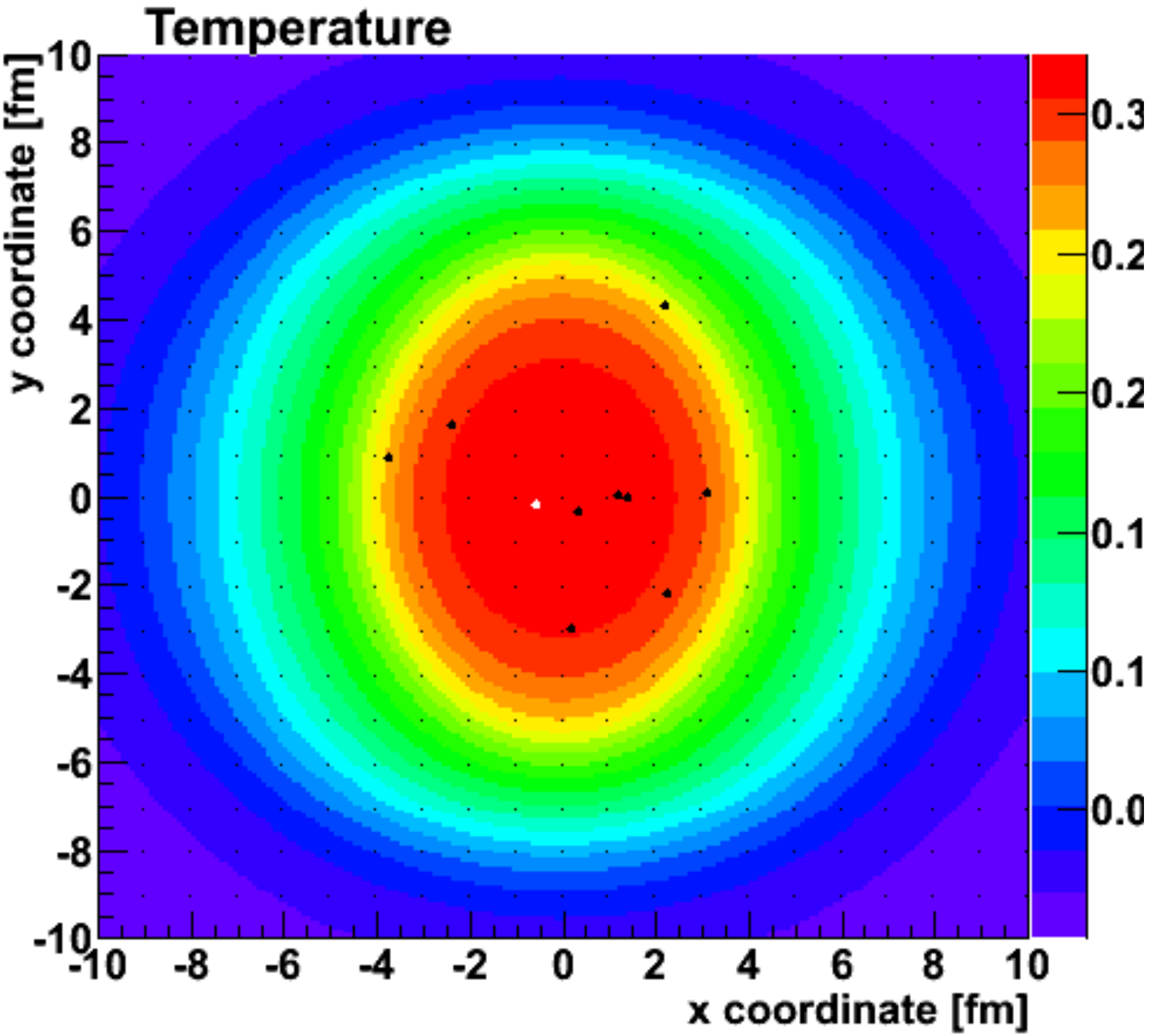
Langevin Model - Drag and Diffusion

$$\frac{dp_i}{dt} = \xi_i(t) - \eta_D p_i, \qquad \langle \xi_i(t)\xi_j(t')\rangle = \kappa\delta_{ij}\delta(t-t'). \qquad (2)$$

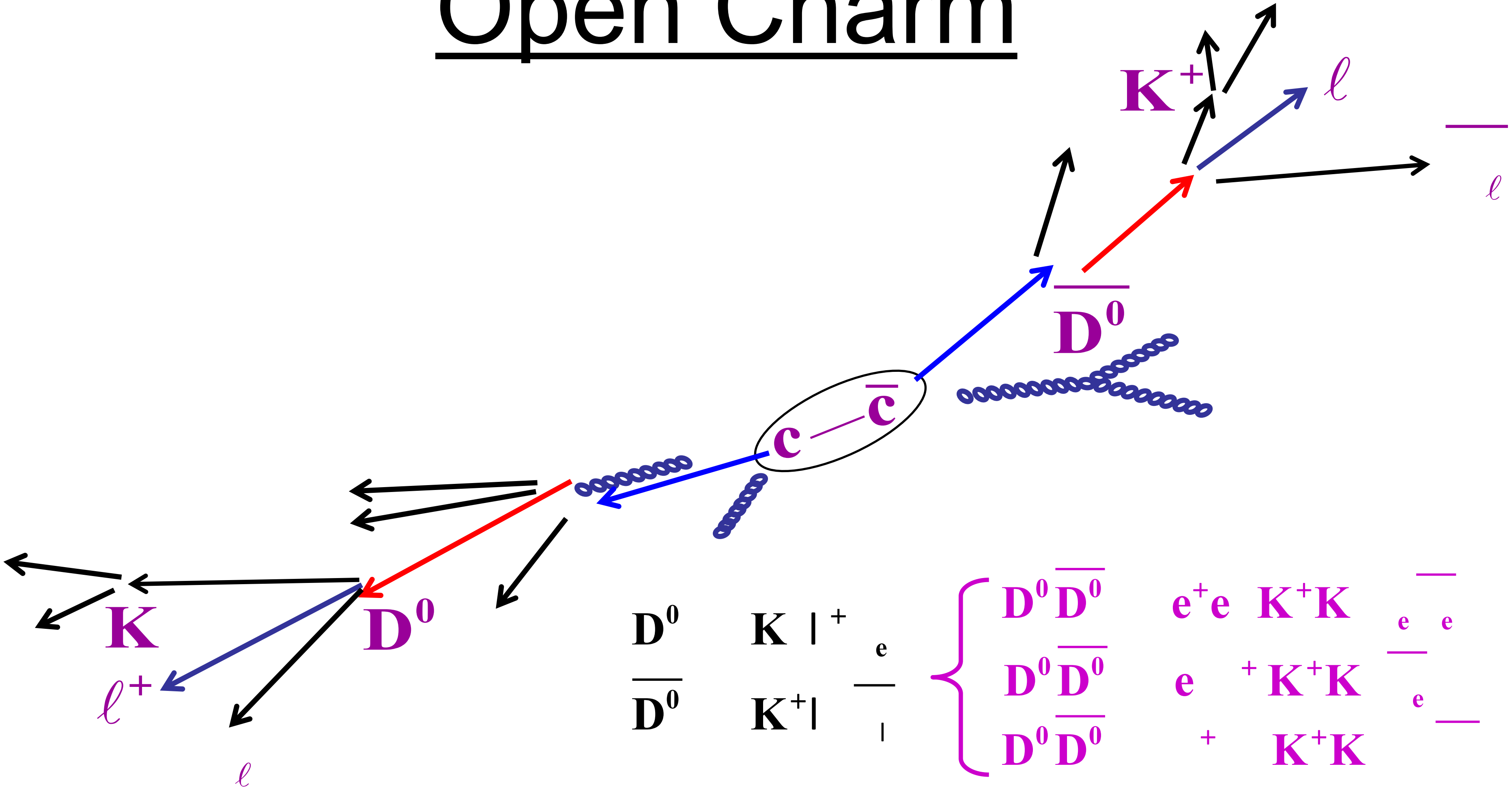
Here η_D is a momentum drag coefficient and $\xi_i(t)$ delivers random momentum kicks that are uncorrelated in time.



Teaney and Moore
http://journals.aps.org/prc/abstract/10.1103/PhysRevC.71.064904

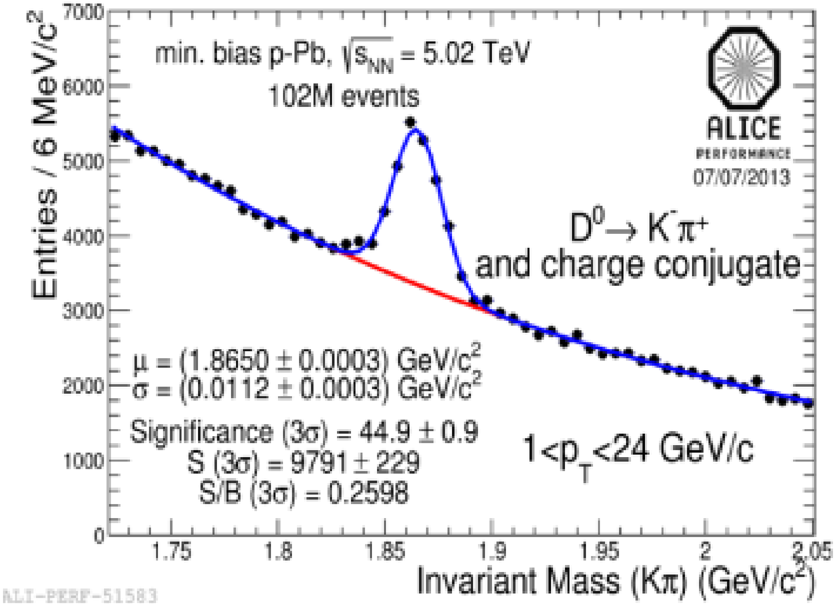

Temperature
y coordinate [fm]
x coordinate [fm]
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-8
-6
-4
-2
0
2
4
6
8
10
0.3
0.2
0.2
0.1
0.1
0.0

Open Charm

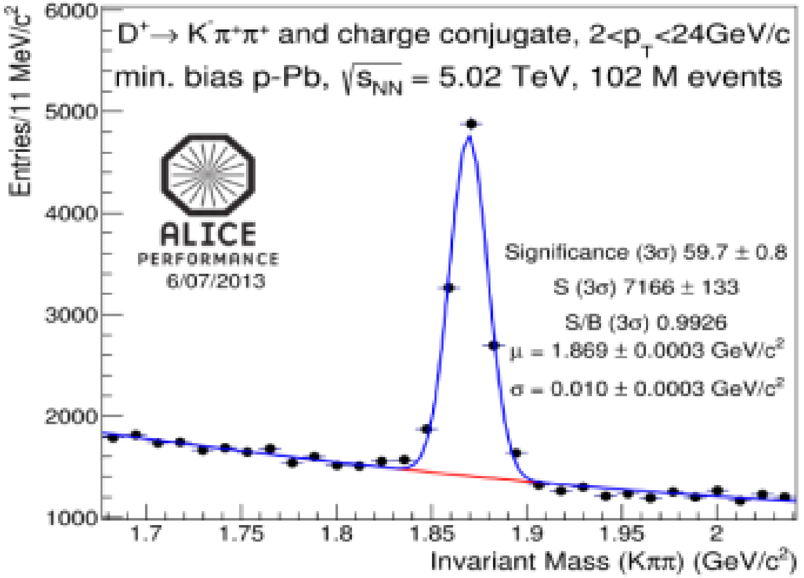


1. Measuring single leptons from semi-leptonic decay of D and B
2. Measuring D→πK and subtract combinatorics
3. Measuring the above two with a displaced vertex measurement

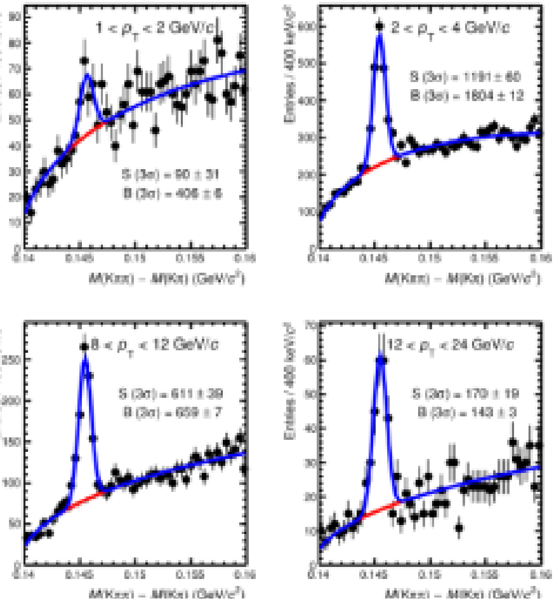
Example – Many ways to measure heavies



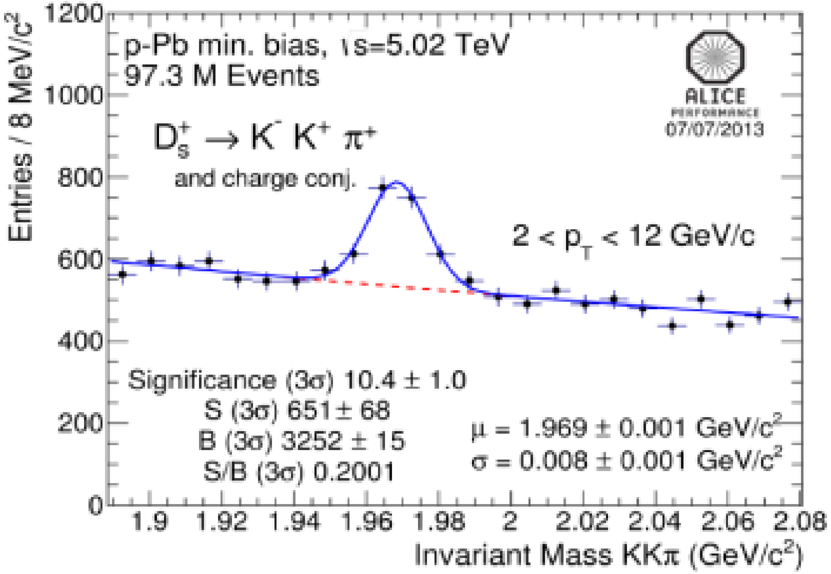
ALI-PERF-51583



p-Pb @5.02 TeV

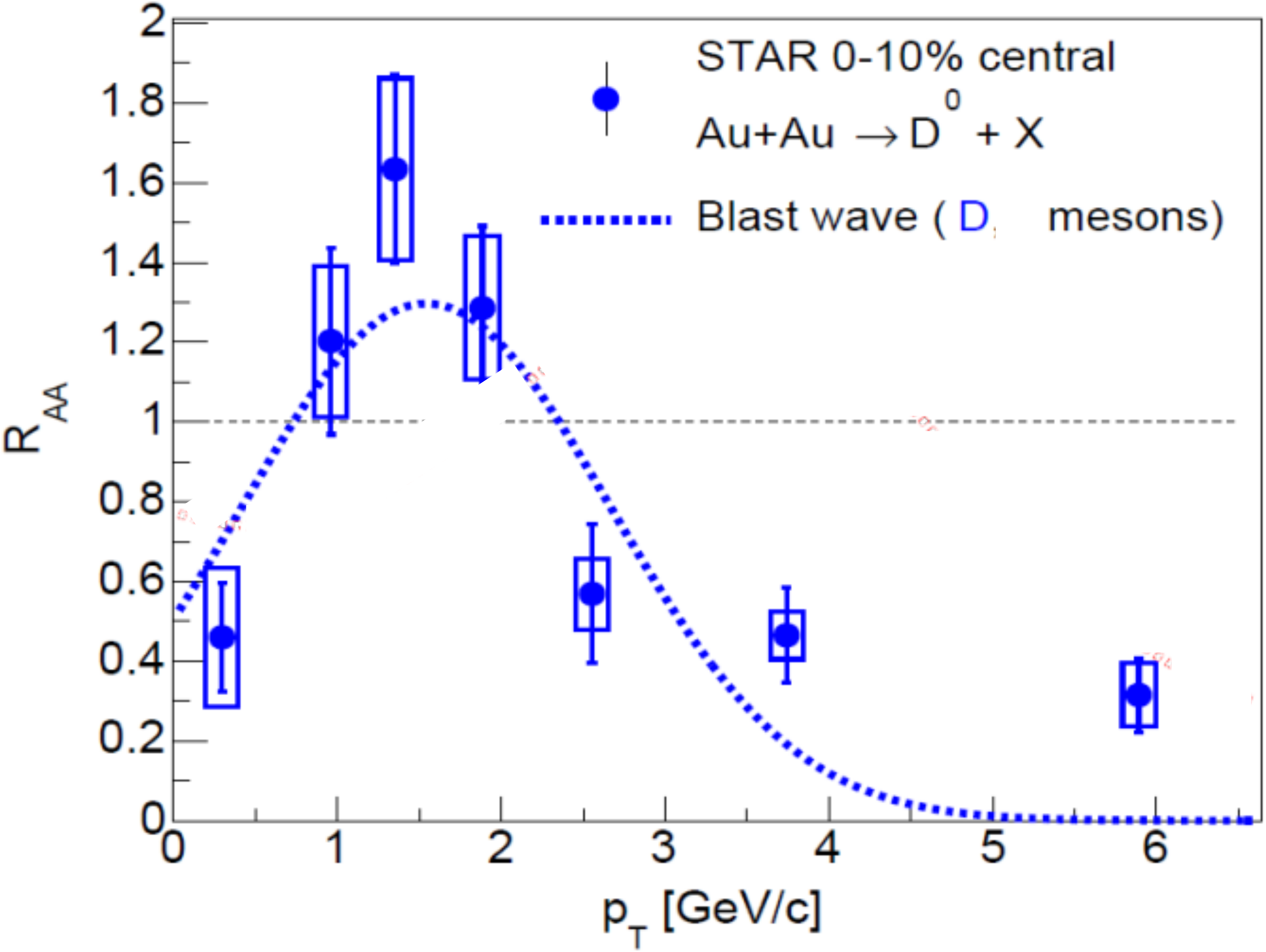


ALICE Preliminary
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
$D^{*+} \to D^0\pi^+$
and charge conjugates
94M events

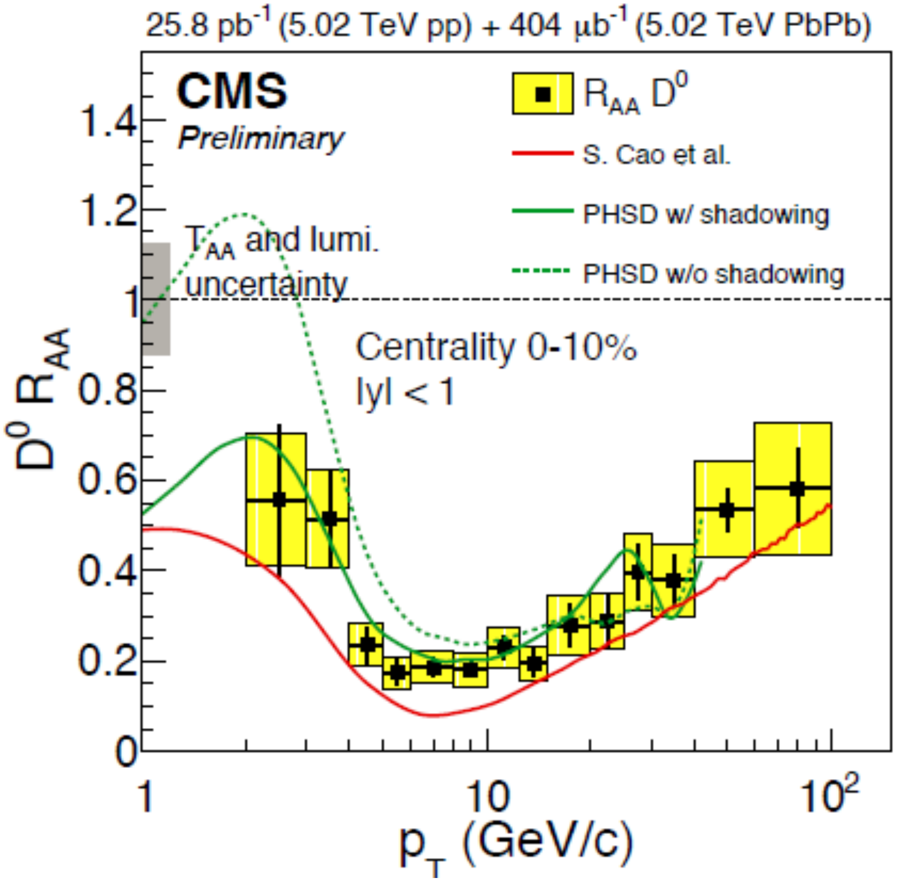


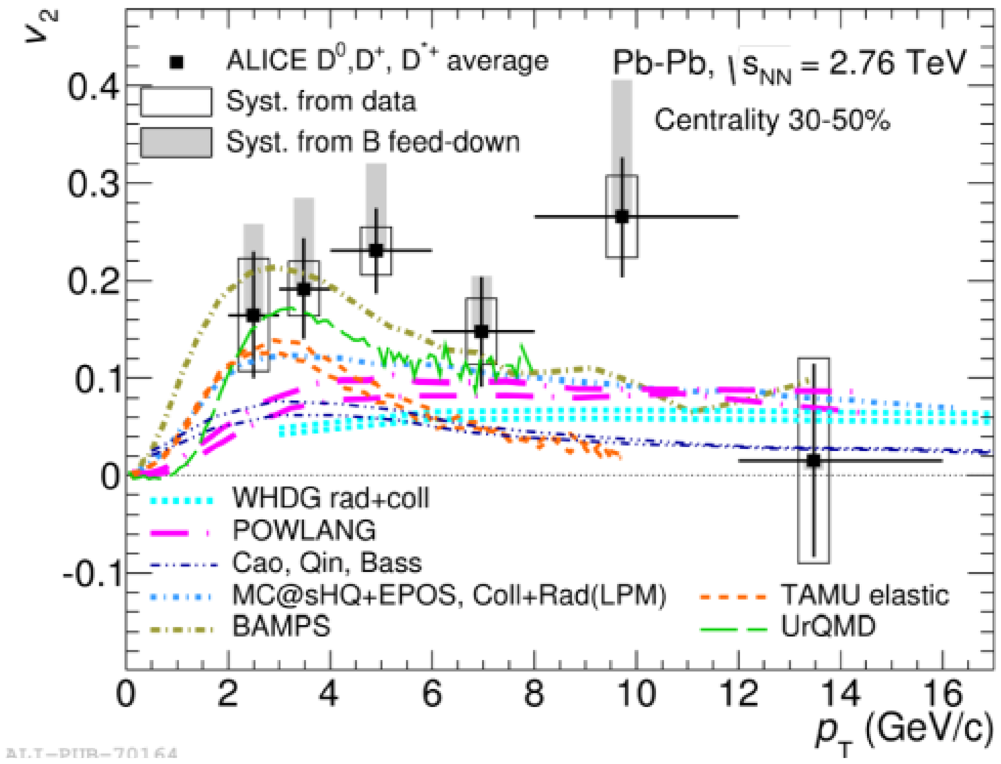
ALI-PERF-51600

Charm: Really moves with the medium



Charm: Really moves with the medium



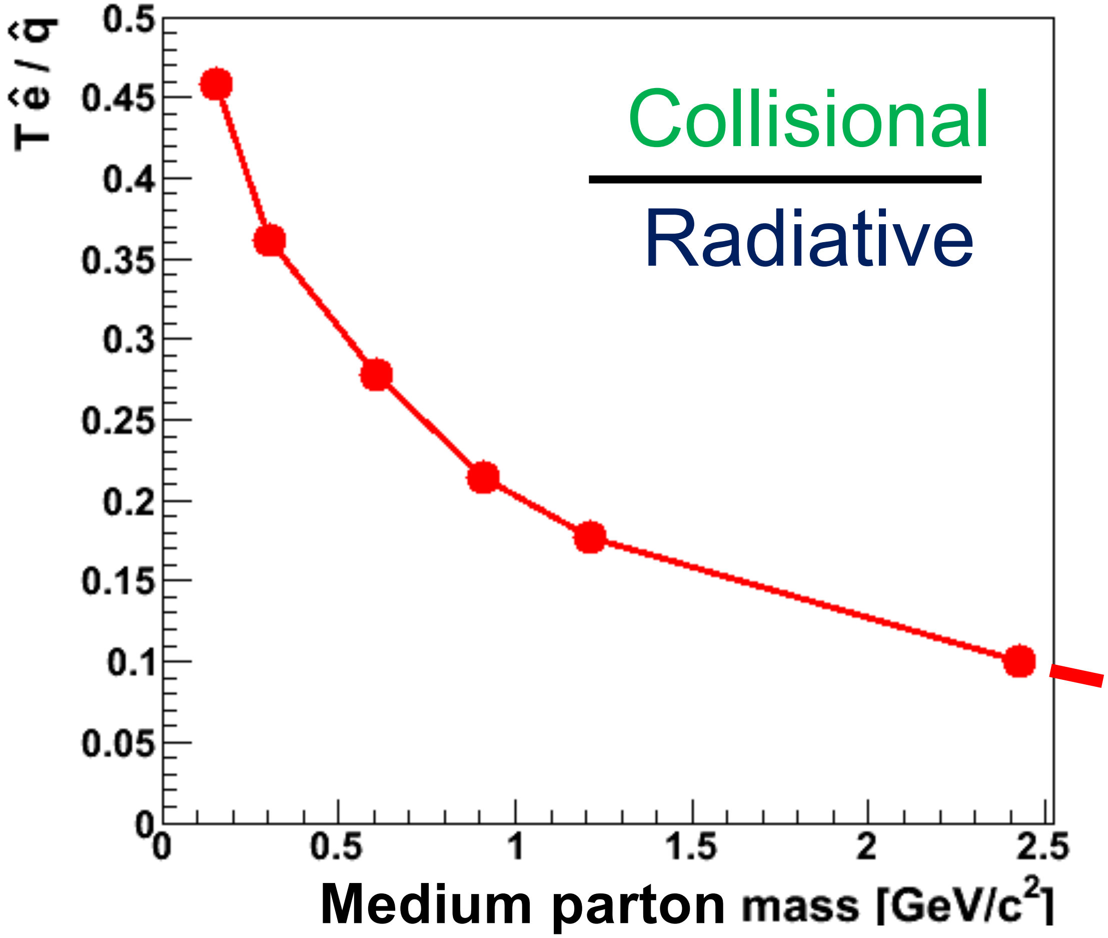


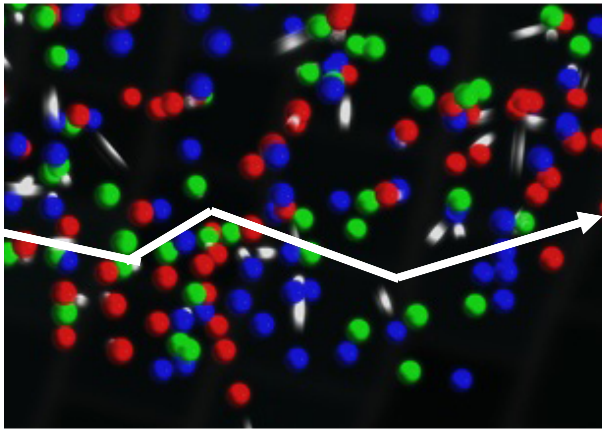
Lower momentum – drag and diffusion
Higher momentum – jet quenching energy loss

Energy Loss Mechanisms

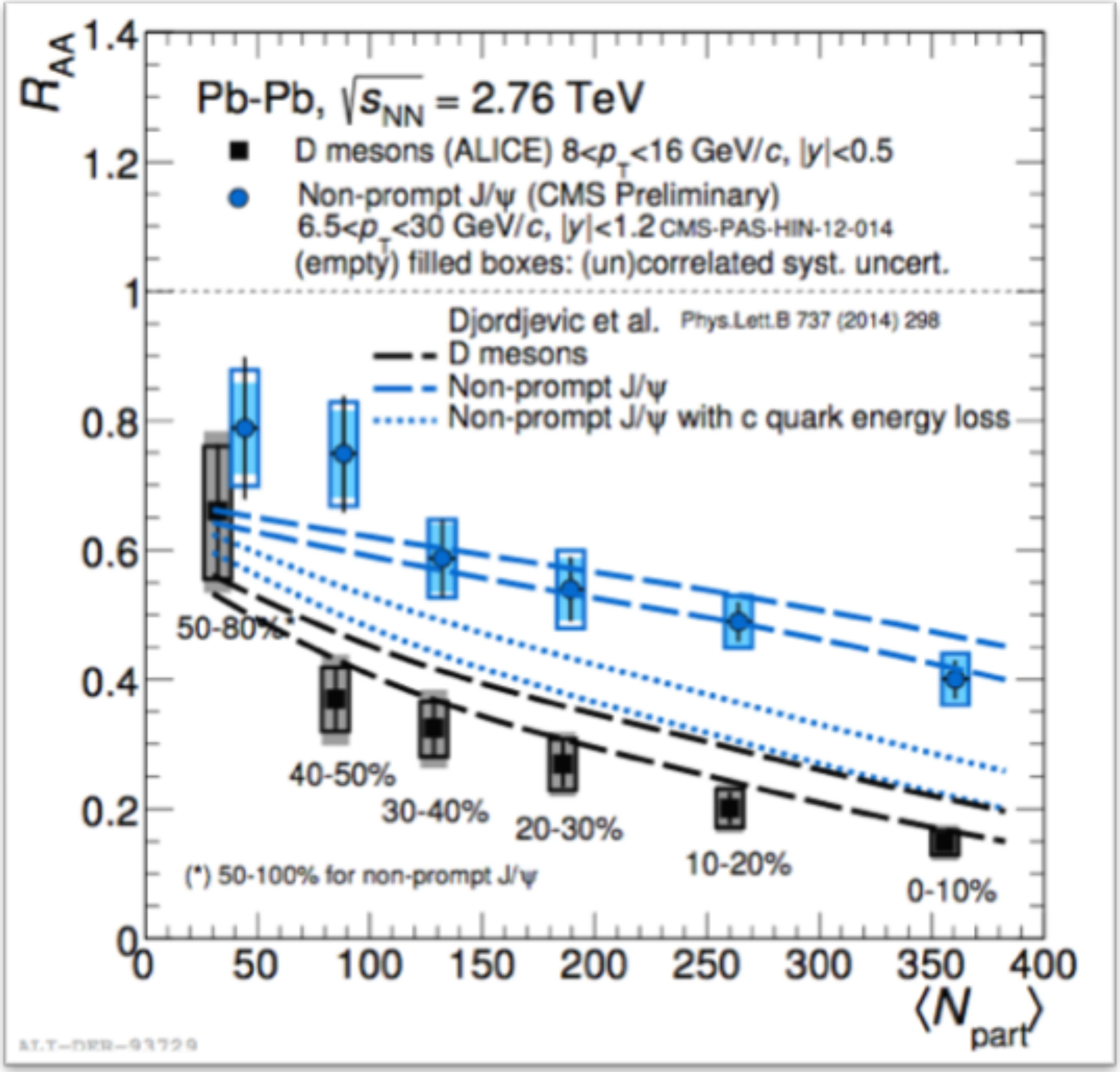
$\hat{q}$ → scattering of leading parton which then radiates

$\hat{e}$ → energy transfer from parton to QGP particle





Limit of infinitely massive scattering centers yields all radiative e-loss.

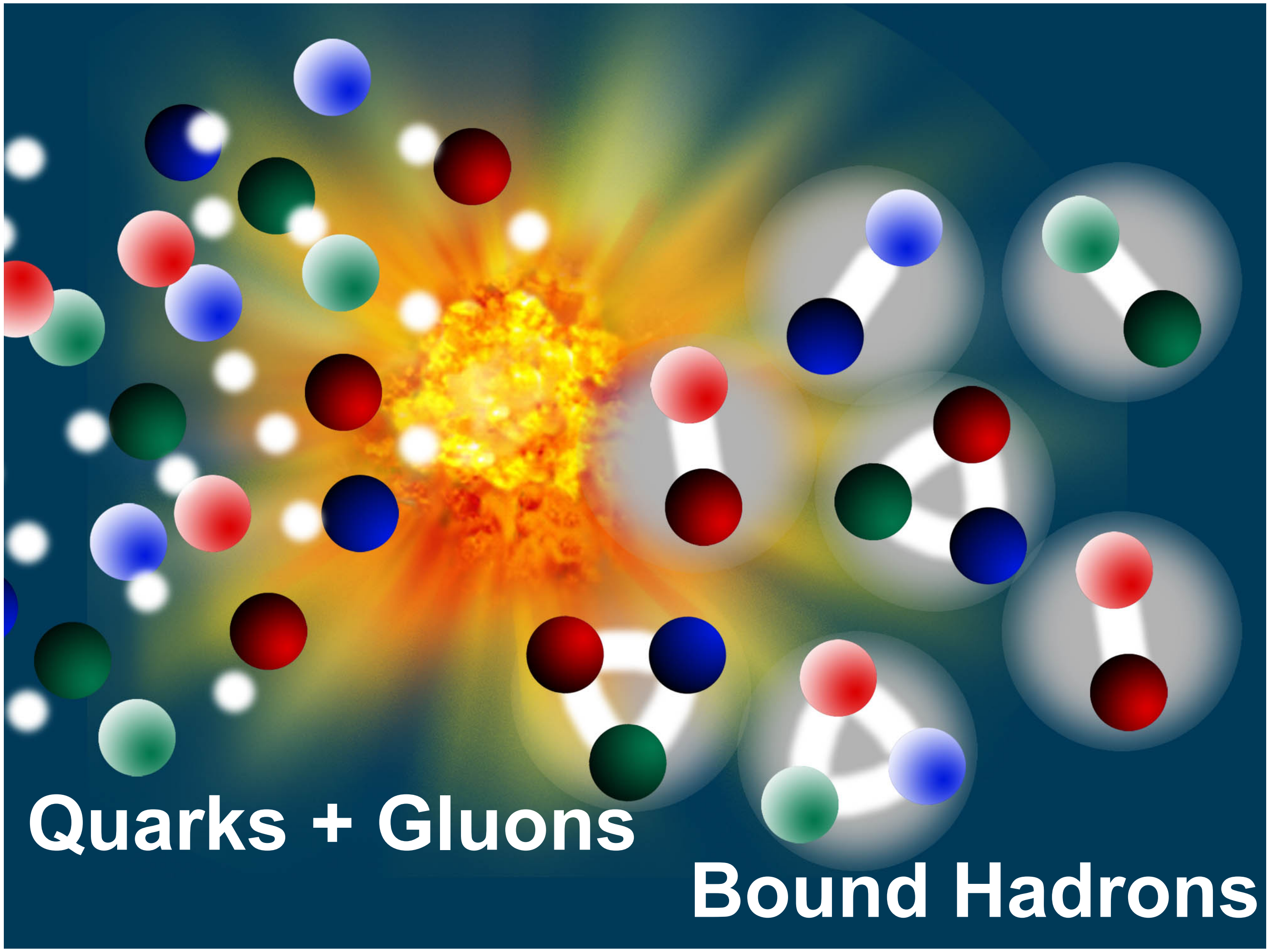


Need measurements at both RHIC and the LHC

Hadron Formation Via Coalescence

Cooper-Frye – End of Story?

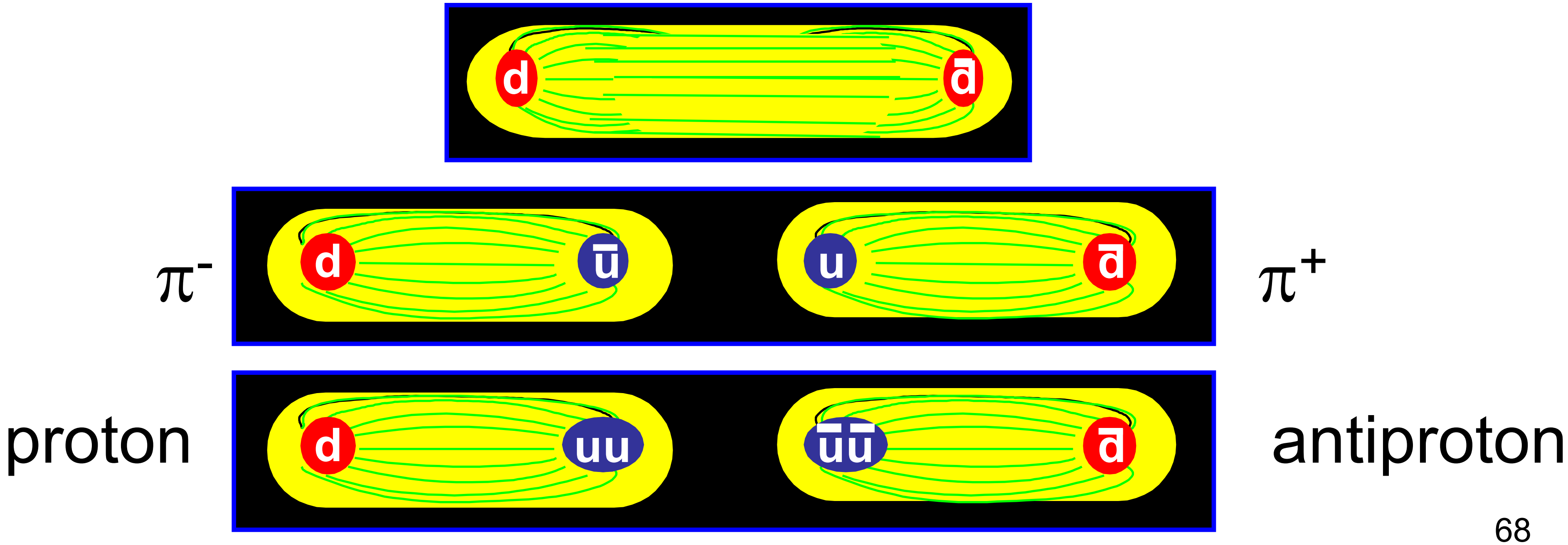
How are color neutral hadrons really formed?
Fundamental question without too many tools.



Color Strings → Hadrons

Jet fragmentation occurs when particle pairs tunnel out of the vacuum from the flux tube potential energy. Analogous to Schwinger mechanism in QED.

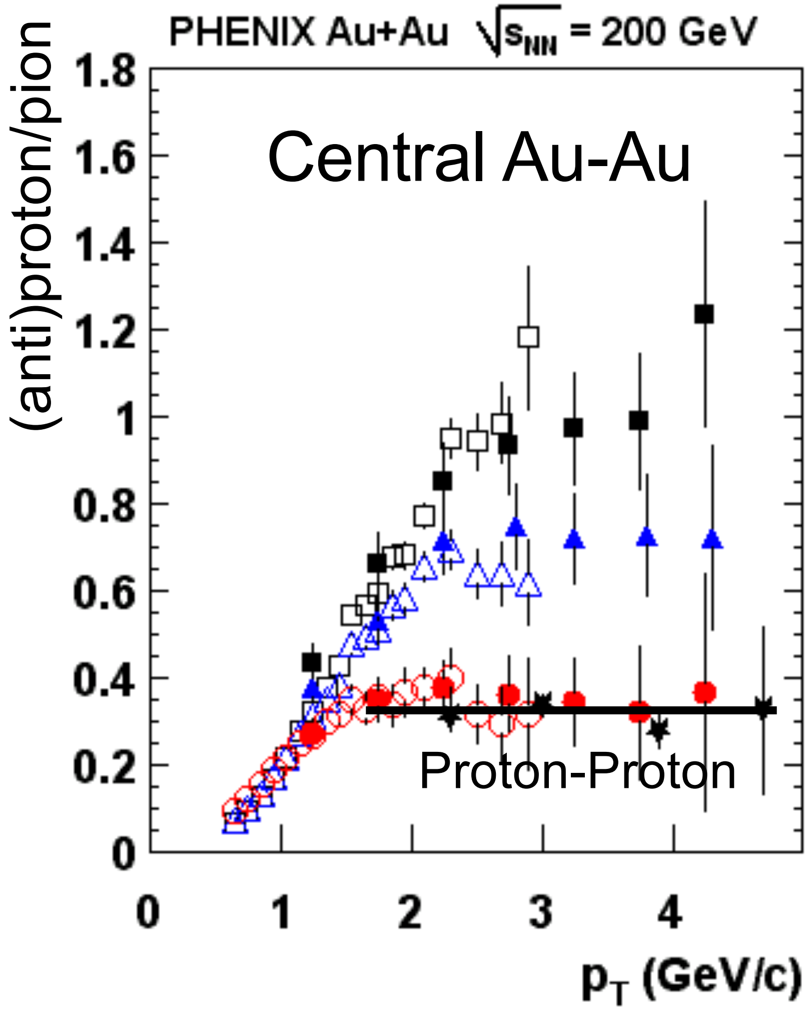
Production of $\bar{q}q$ leading to pions is much more likely than $\overline{qq}$ qq (diquark antidiquark) leading to protons and antiprotons.

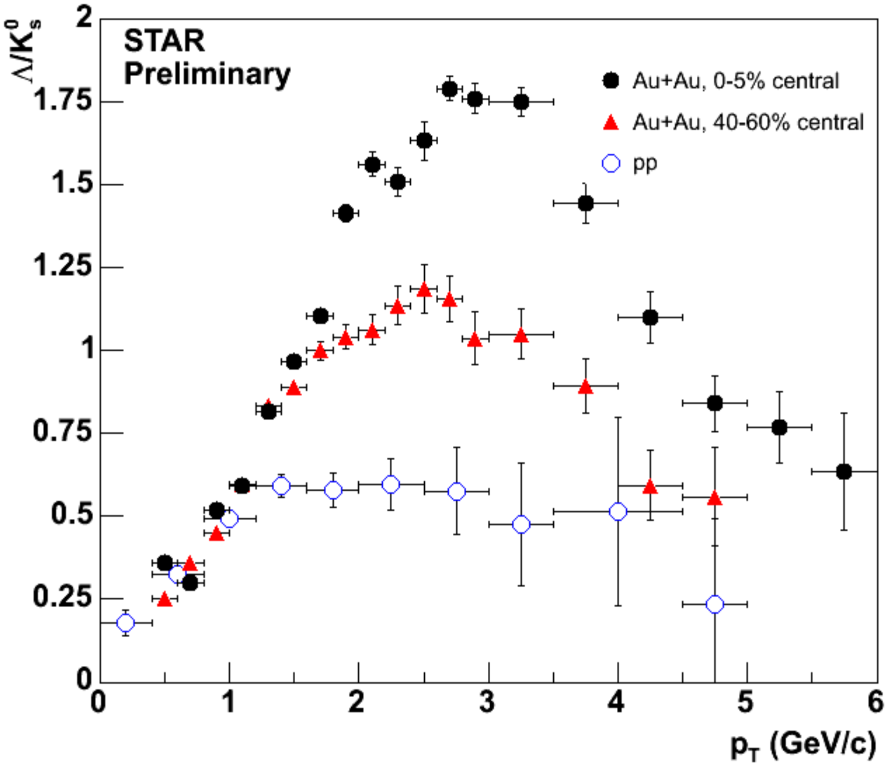


Baryon Anomaly

In proton+proton and e^+e^- reactions at moderate p_T, baryons and antibaryons are suppressed relative to mesons.

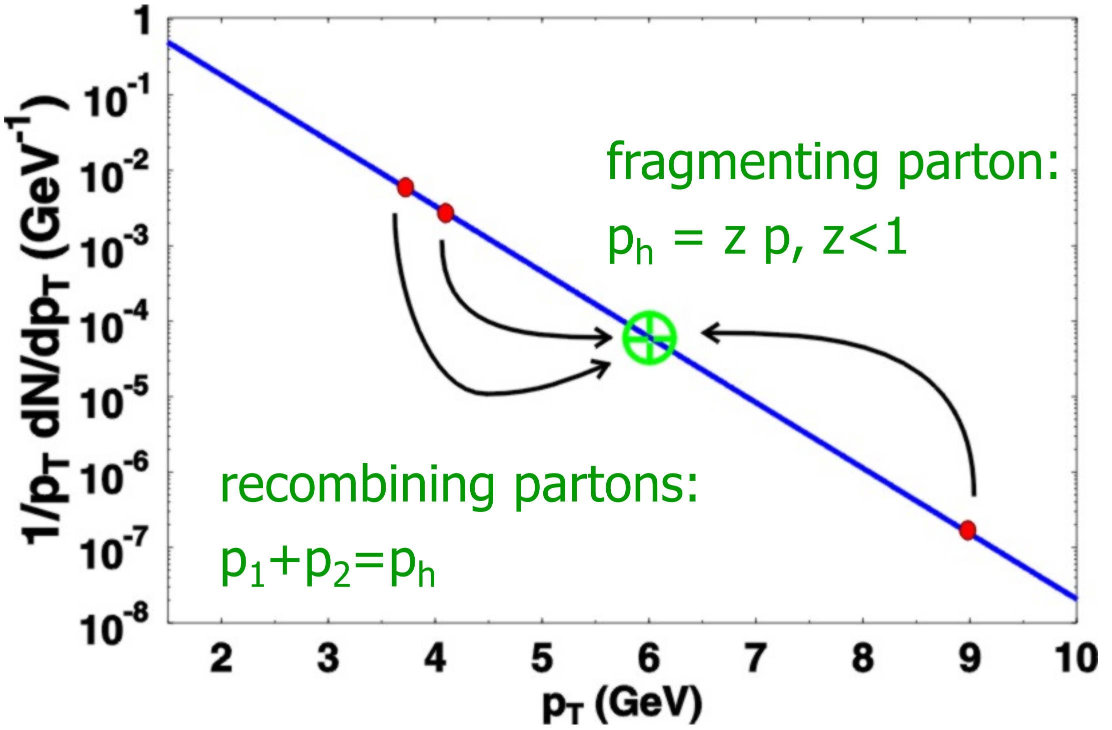
In heavy ion reactions, there is anomalous baryon production.





From Above or Below?

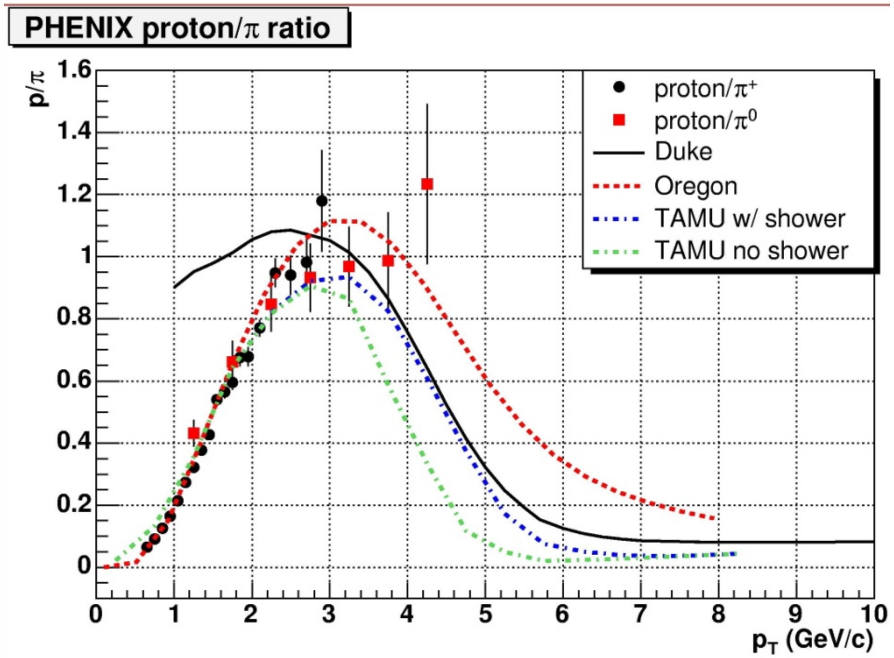
Lower p_T partons combine to form higher p_T hadrons, instead of higher p_T partons fragmenting into lower p_T hadrons.


fragmenting parton:

$p_h = z\ p,\ z<1$

recombining partons:

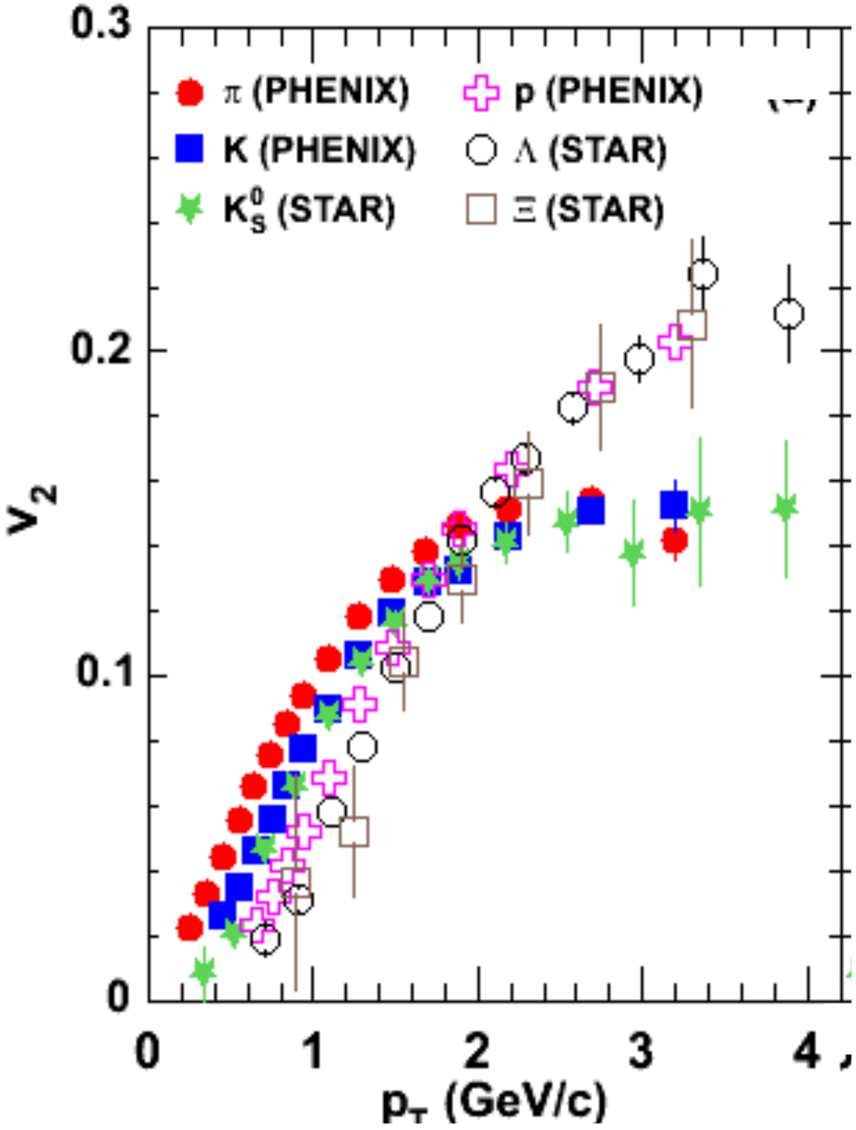
$p_1+p_2=p_h$



Qualitative explanation for baryon enhancement.

Baryon Issue in Elliptic Flow

v_2 results at low p_T agrees with hydrodynamic calculations, but at higher p_T there is a split of mesons and baryons.



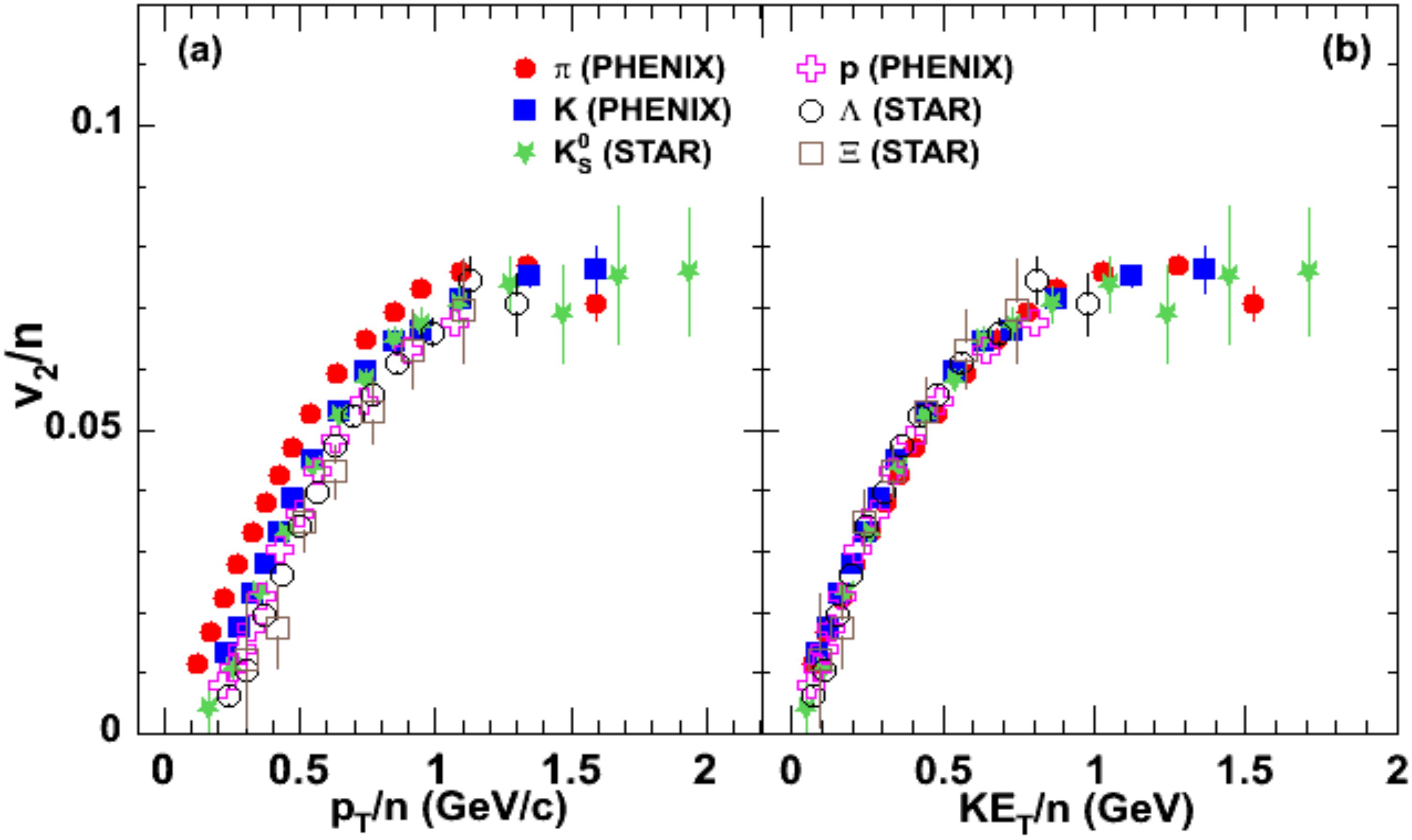
Baryons

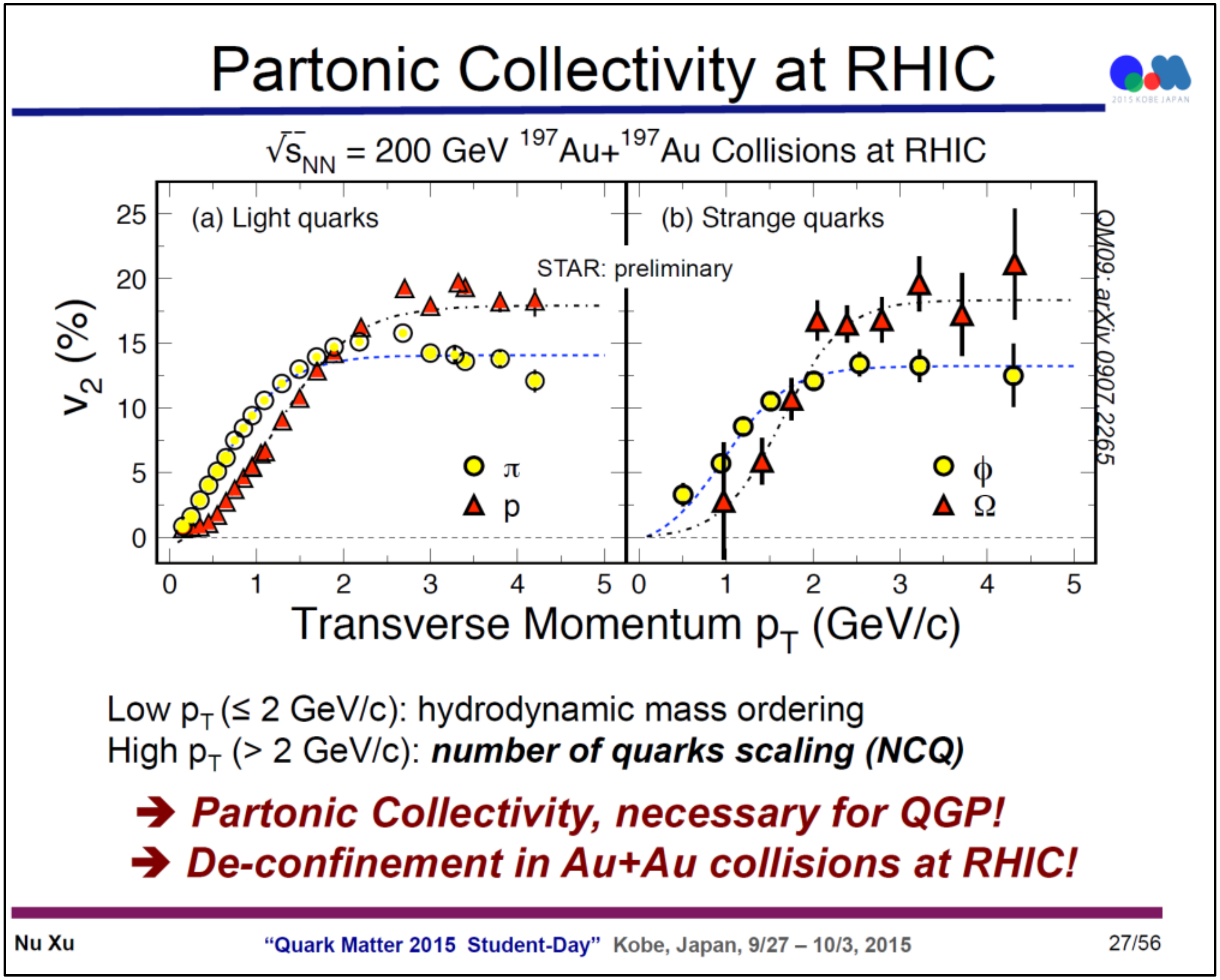
Mesons

Feature not expected from hydrodynamics + Cooper-Frye.

Rescaling by Valence Quarks

If one rescales the data by the number of valence quarks (2 for mesons and 3 for baryons), one sees a remarkable scaling!





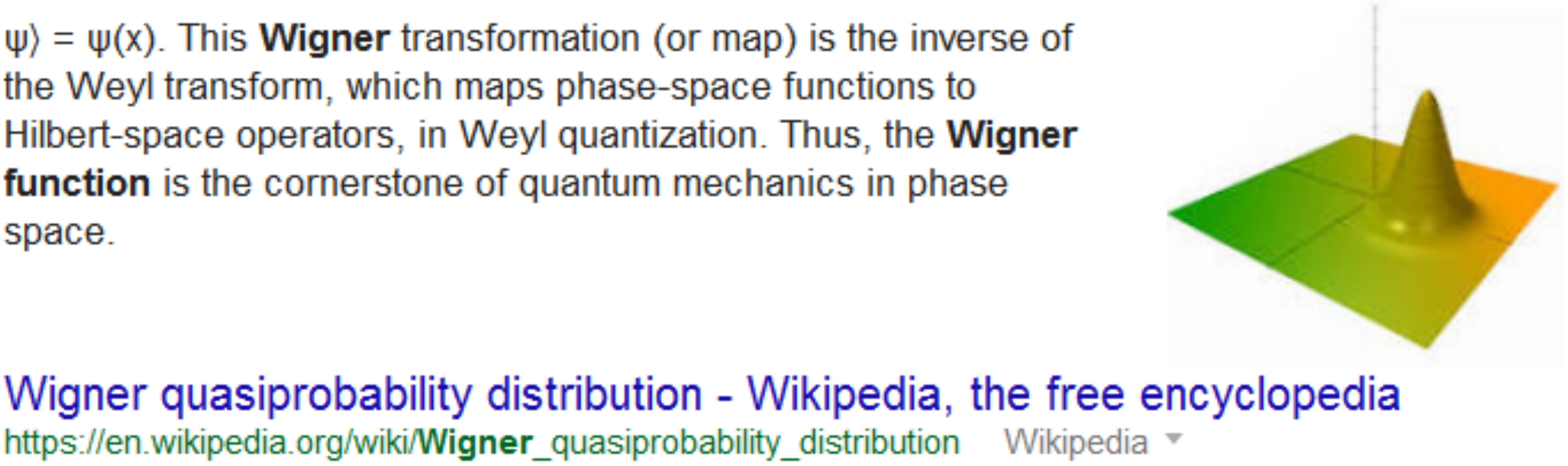
Partonic Collectivity at RHIC

Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

➔ ***Partonic Collectivity, necessary for QGP!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

Nu Xu **"Quark Matter 2015 Student-Day"** **Kobe, Japan, 9/27 – 10/3, 2015** 27/56

Too strong a conclusion in my opinion.
Mechanism of hadronization remains elusive.



ψ⟩ = ψ(x). This **Wigner** transformation (or map) is the inverse of the Weyl transform, which maps phase-space functions to Hilbert-space operators, in Weyl quantization. Thus, the **Wigner function** is the cornerstone of quantum mechanics in phase space.

Wigner quasiprobability distribution - Wikipedia, the free encyclopedia

https://en.wikipedia.org/wiki/**Wigner**_quasiprobability_distribution Wikipedia ▾

Coalescence models are very crude because we fundamentally do not know how this works in QCD.

Completely ignoring gluons.

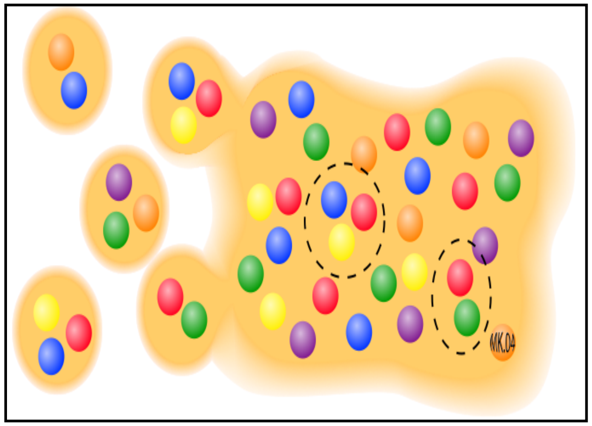
Simple harmonic oscillator potential.

Contrast Deuteron Coalescence

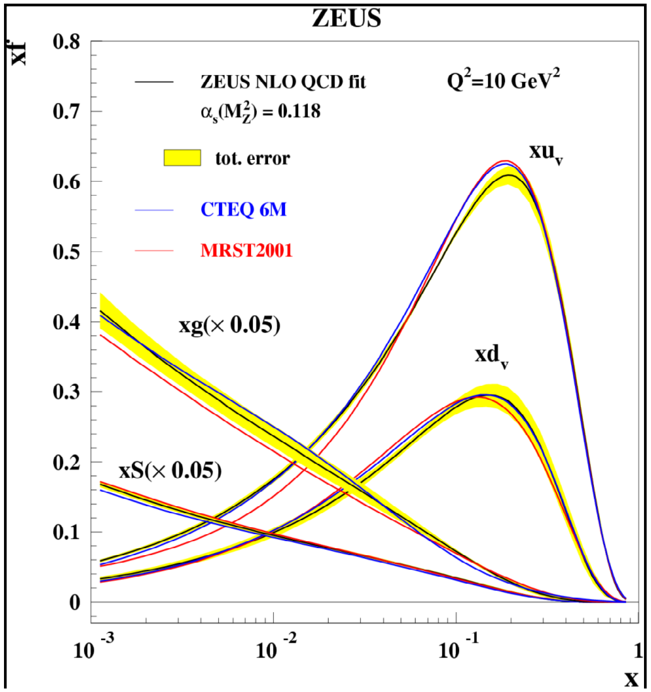
In BBN, deuteron coalescence process is well know n+p→d+γ. In heavy ion reactions, we can have off-shell n+p→d and we know the deuteron wavefunction.

What is the required space and momentum distribution of partons to form a hadron?

Very Simple Picture



Not so Simple Picture



Conclusions and Terminology

Perhaps at moderate p_T hadrons are formed from localized distribution of uncorrelated partons.

Some call it coalescence of constituent quarks?
What is a constituent quark outside a hadron? Mass?

Some call it coalescence of valence quarks?
What is a valence versus a sea quark outside a hadron?

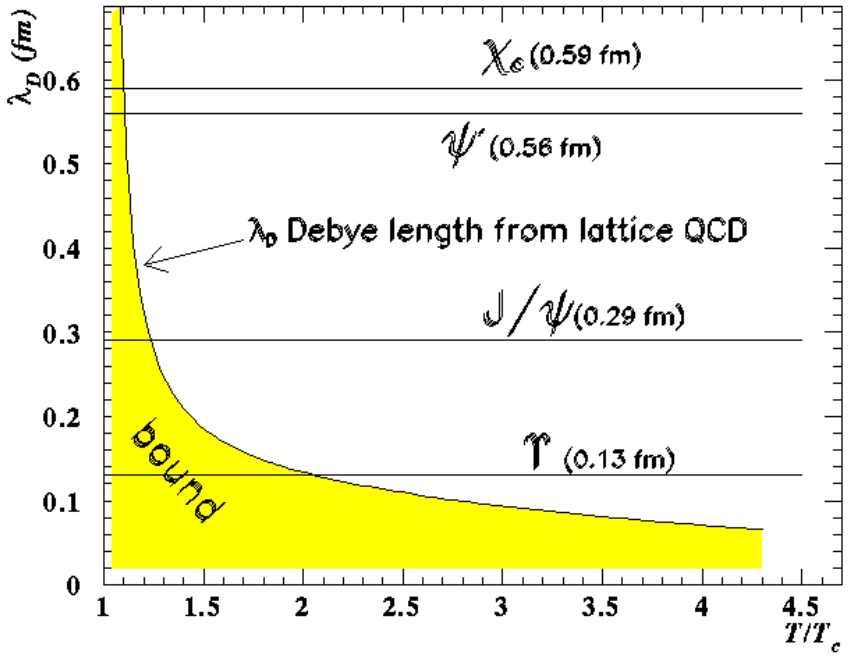
What is true is that you need a certain minimum number of objects (partons?) to have the right quantum numbers in some region of real and momentum space to form the hadron.

We still need to understand the full implications.

Heavy Quarkonia

Screening Effects

Different states “melt” at different temperatures due to different binding energies.



The ψ' and χ_c melt below or at T_c

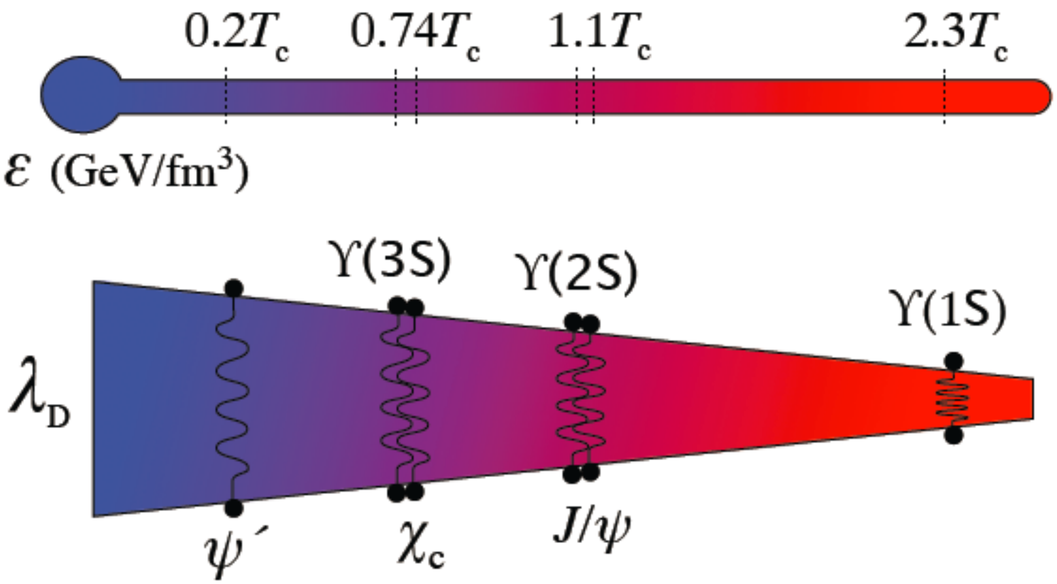
the **J/ψ** melts above T_c and

eventually the Υ(1s) melts.

state	J/	c	'	(1s)	b	(2s)	b'	(3s)
Mass [GeV}	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	---	0.74	0.15	---	---	0.93	0.83	0.74

hep-ph/0105234 - “indicate ψ' and the χ_c dissociate below the deconfinement point.”

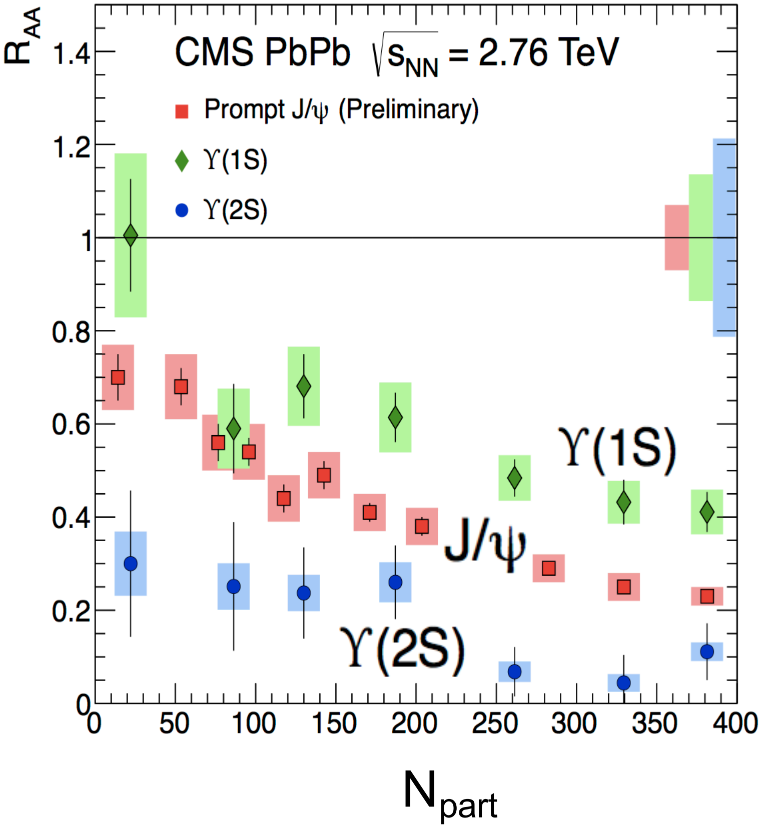
Quarkonia Thermometer



Many states constrains the temperature

PHENIX, STAR, and CMS data consistent with *melting* of Υ(2s,3s)

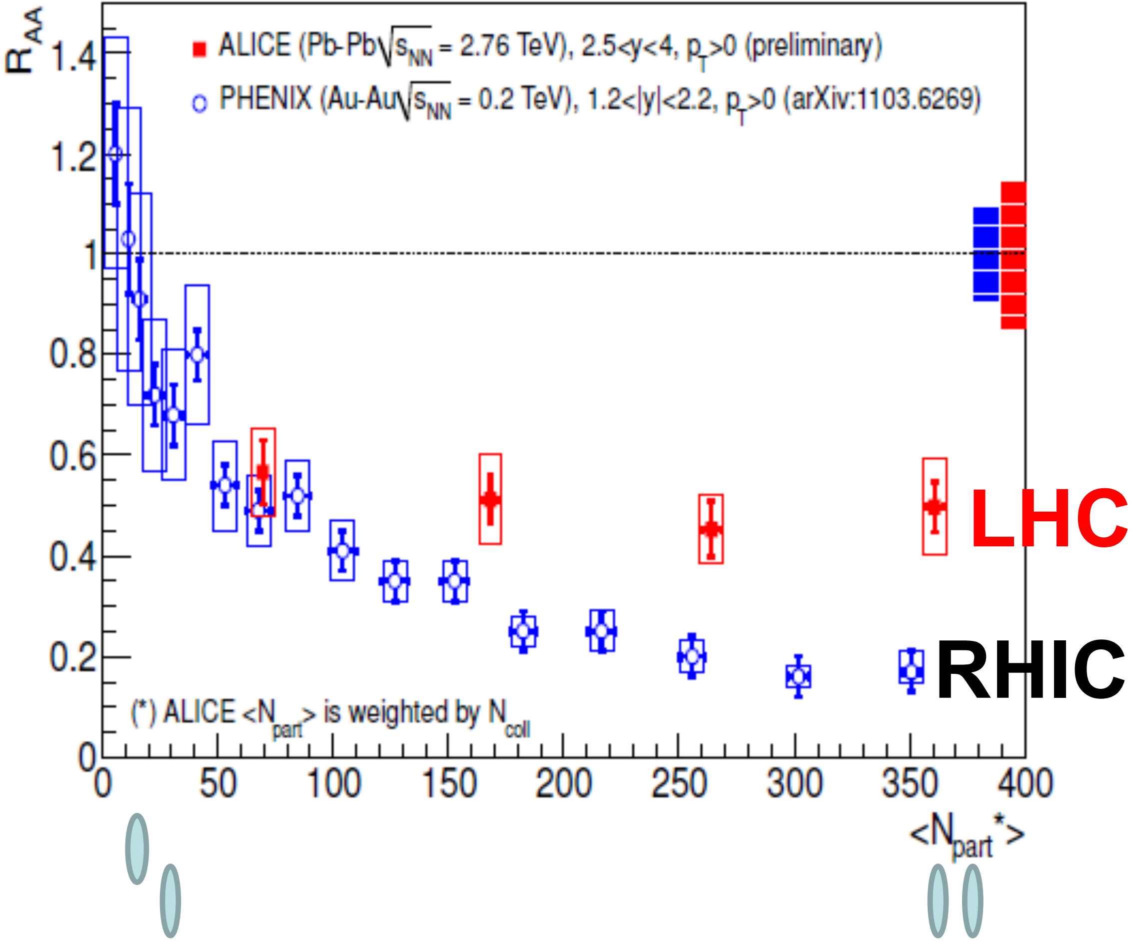
Need more statistics



Quarkonia

Bound states of cc and bb can be *Debye color screened* in the QGP as one increases the temperature (melting)

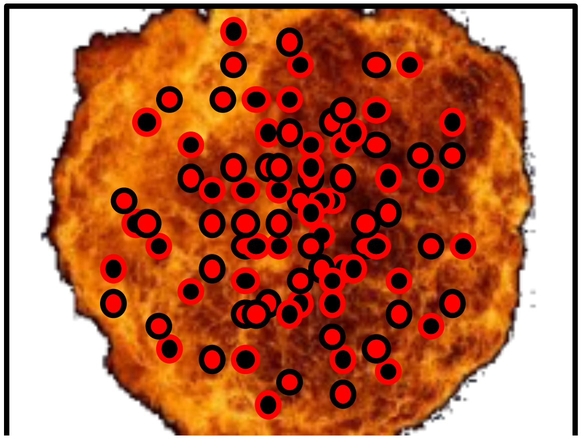
J/ψ Suppression



Bizarre twist

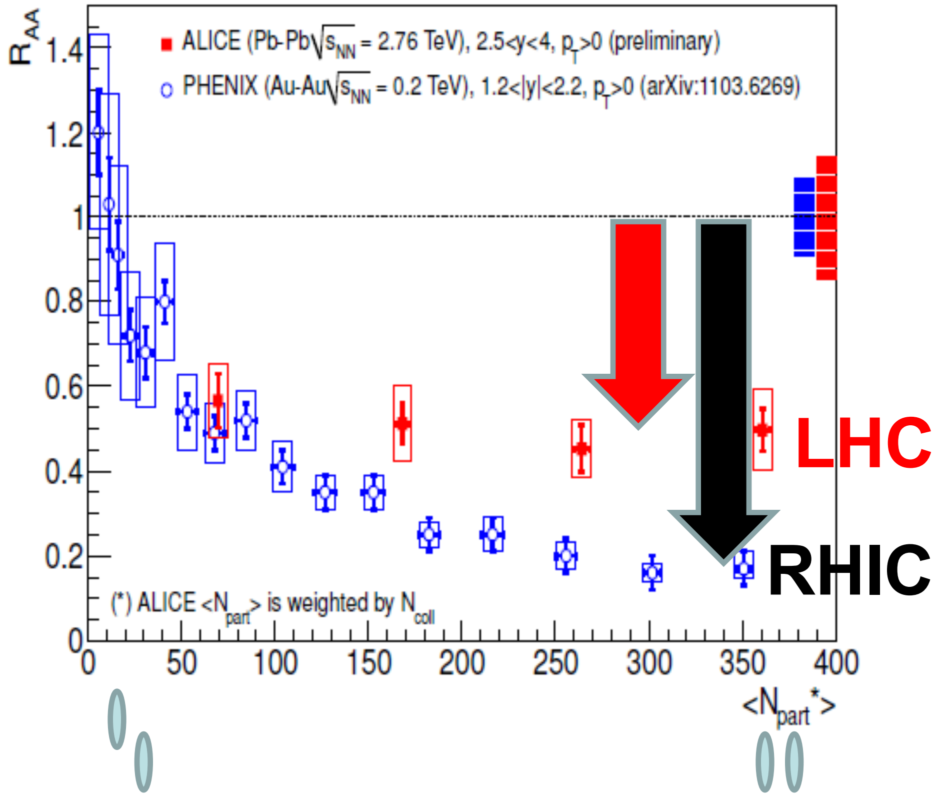
Less suppression at LHC with higher temperature.

Quark deconfinement and charm recombination at



Heavy Quarkonia Recombination

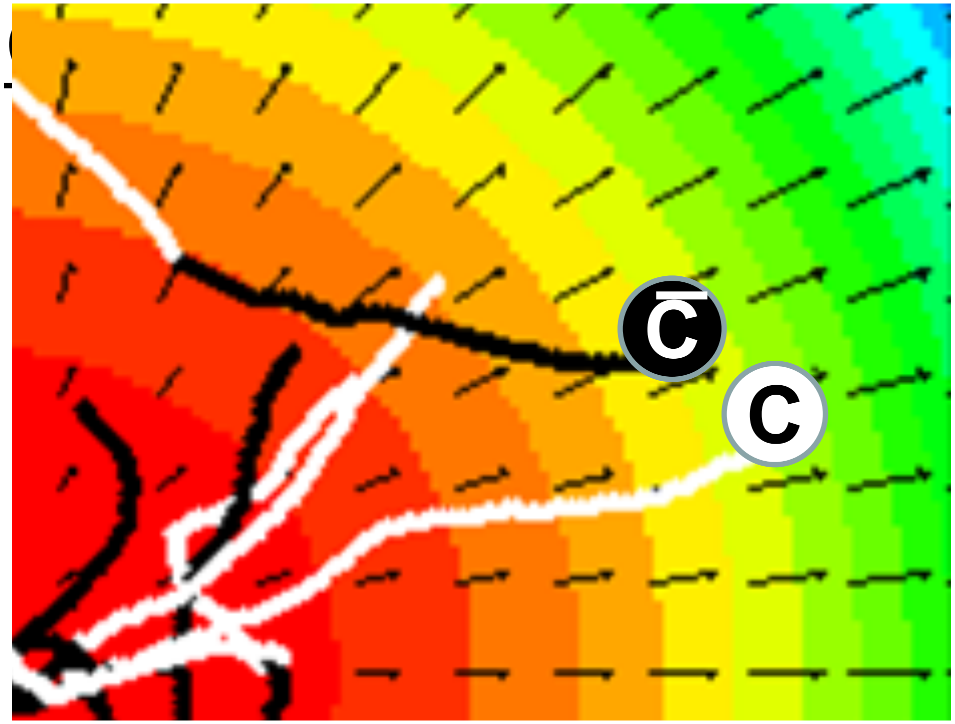
J/ψ Suppression



Less J/ψ suppression at LHC with higher temperature

Charm recombination dominant effect, not screening.

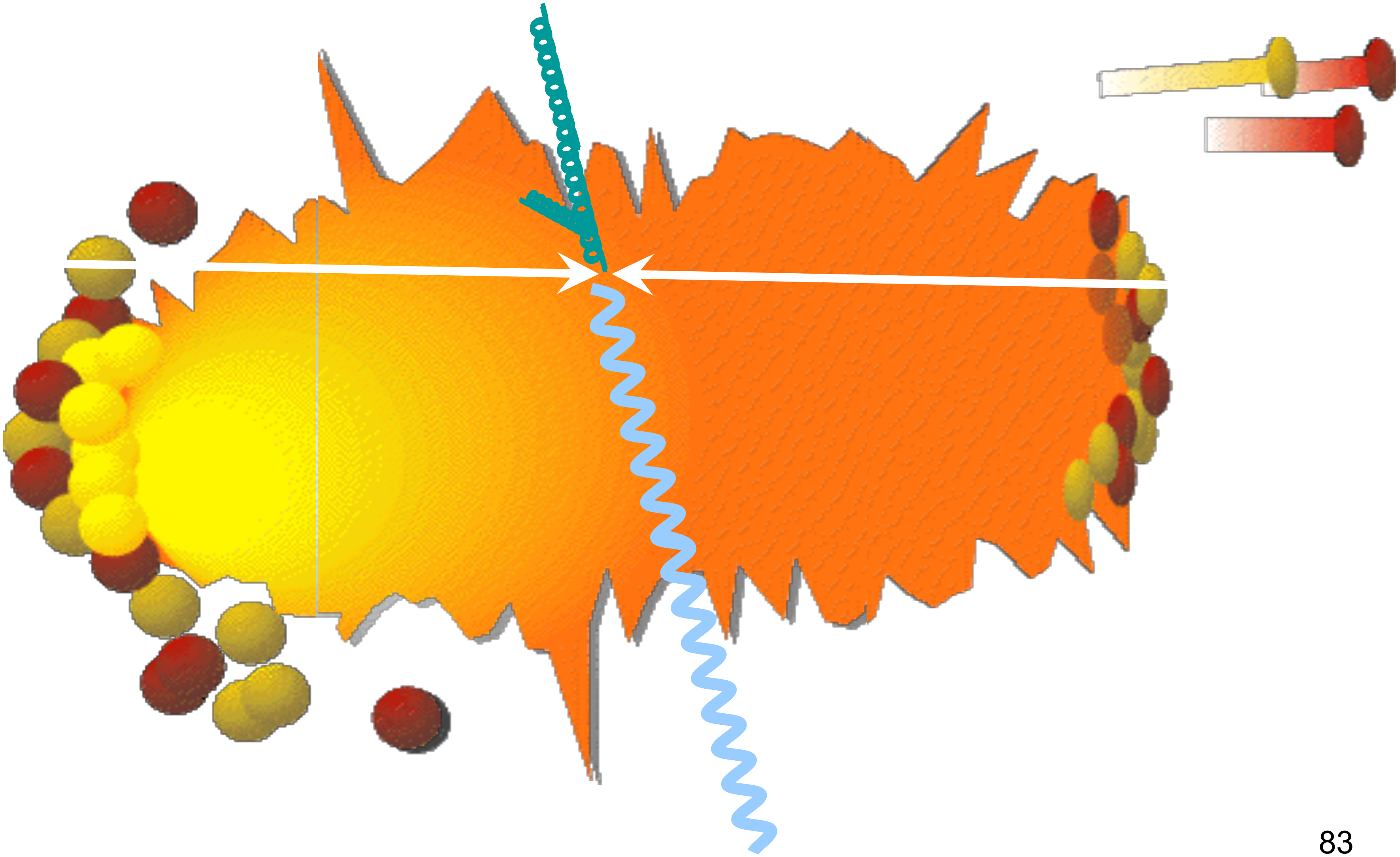
Look to Upsilons for Debye Screening,
no recombination at RHIC



Collected Randomness

Probes of the Medium

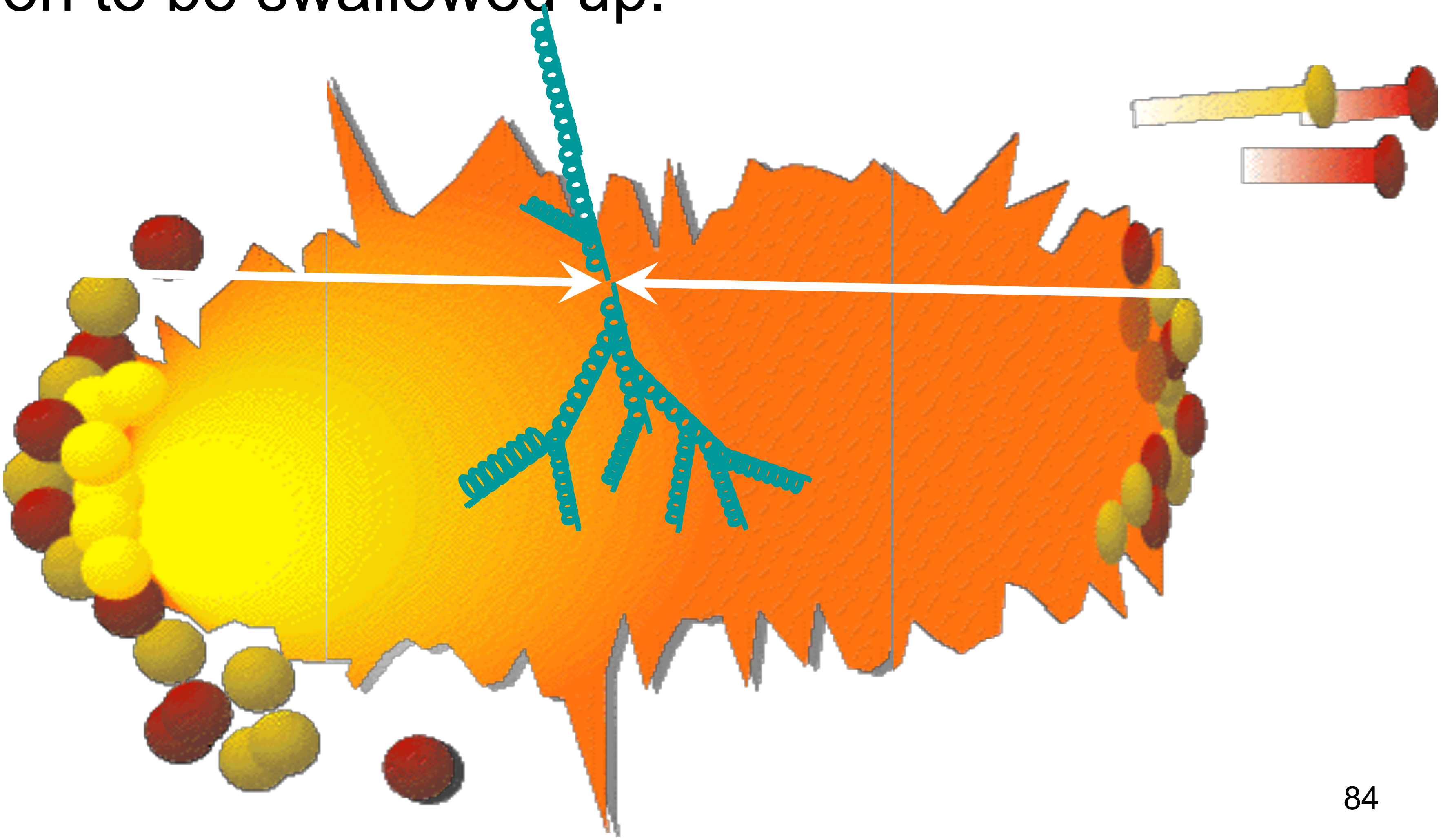
Sometimes a high energy photon is created in the collision. We expect it to pass through the plasma without pause.



Probes of the Medium

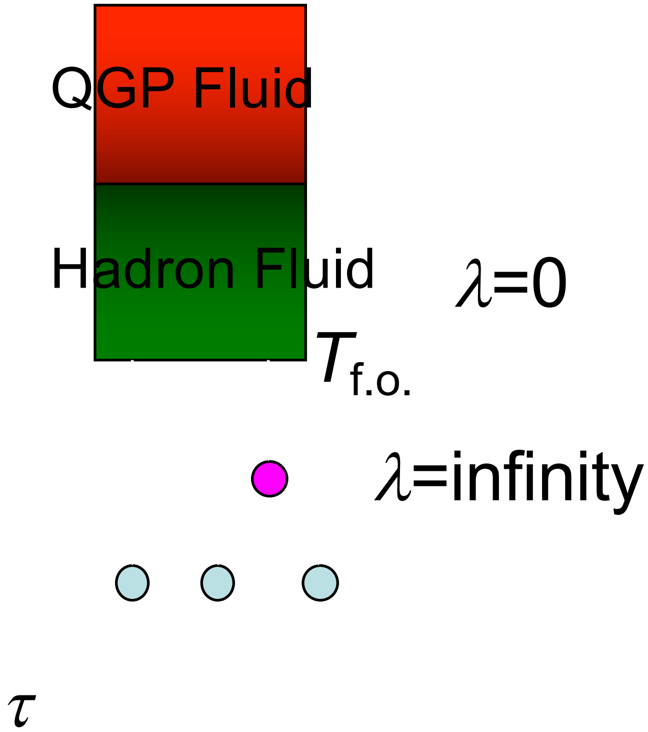
Sometimes we produce a high energy quark or gluon.

If the plasma is dense enough we expect the quark or gluon to be swallowed up.



Need translation from thermodynamic variables to particle spectra to be observed.

Sudden freezeout
(Cooper-Frye formula)



QGP Fluid

Hadron Fluid

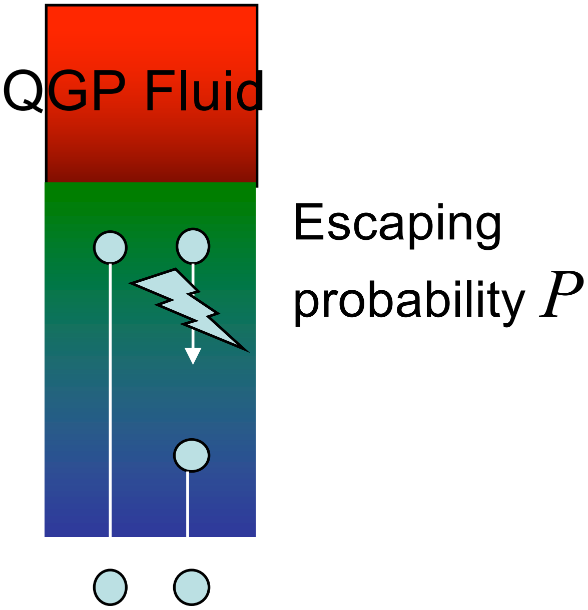
λ=0

$T_{\mathrm{f.o.}}$

λ=infinity

τ

Continuous particle
emission (Hirano, Hama)

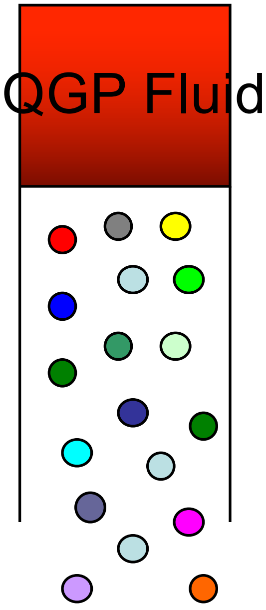


QGP Fluid

Escaping
probability P

$f_{\mathrm{free}}(x,p)=Pf(x,p)$

Hadronic afterburner
via Boltzmann eq.



QGP Fluid

Hadronic
Cascade
(RQMD,
UrQMD)

Teaney,
Lauret,
Shuryak
Bass,
Dumitru
…

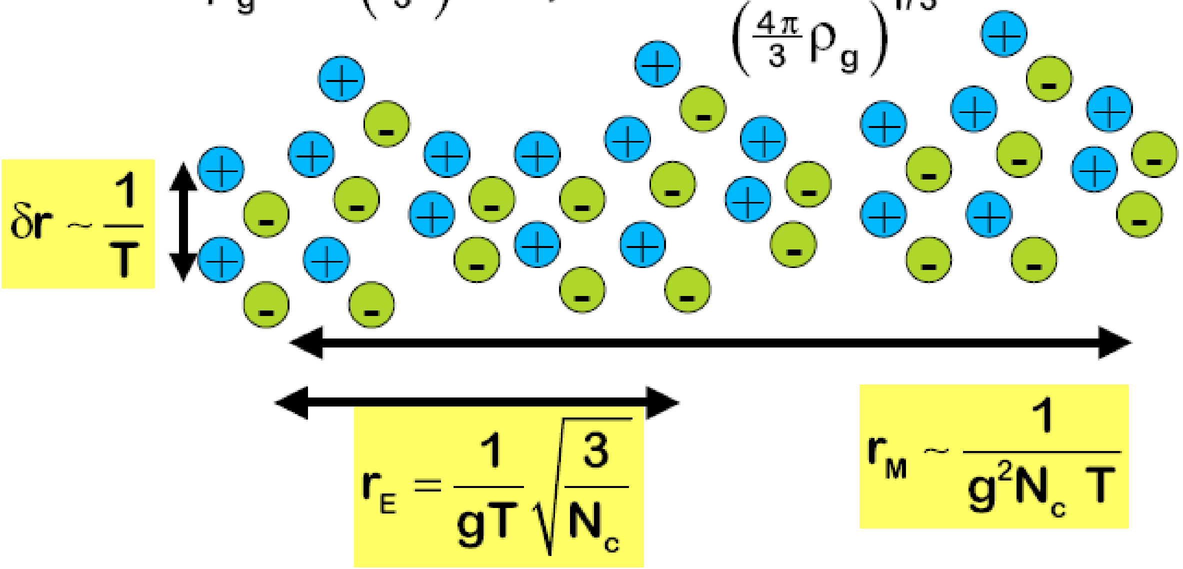
Why is α=0.3 strong coupling for sQGP thermodynamics?

While α=0.3 is weak coupling for high pt dynamics?

Weak QGP dielectric plasma length scales: $\frac{1}{T} \ll \frac{1}{gT} \ll \frac{1}{g^2T}$

Interparton Δr << Chromo-electric Debye cloud << Magnetic screen

$$\rho_g \approx 2\left(\frac{N_c}{3}\right)^2 T^3, \quad \delta r \approx \frac{1}{\left(\frac{4\pi}{3}\rho_g\right)^{1/3}}$$



$$\delta r \sim \frac{1}{T}$$

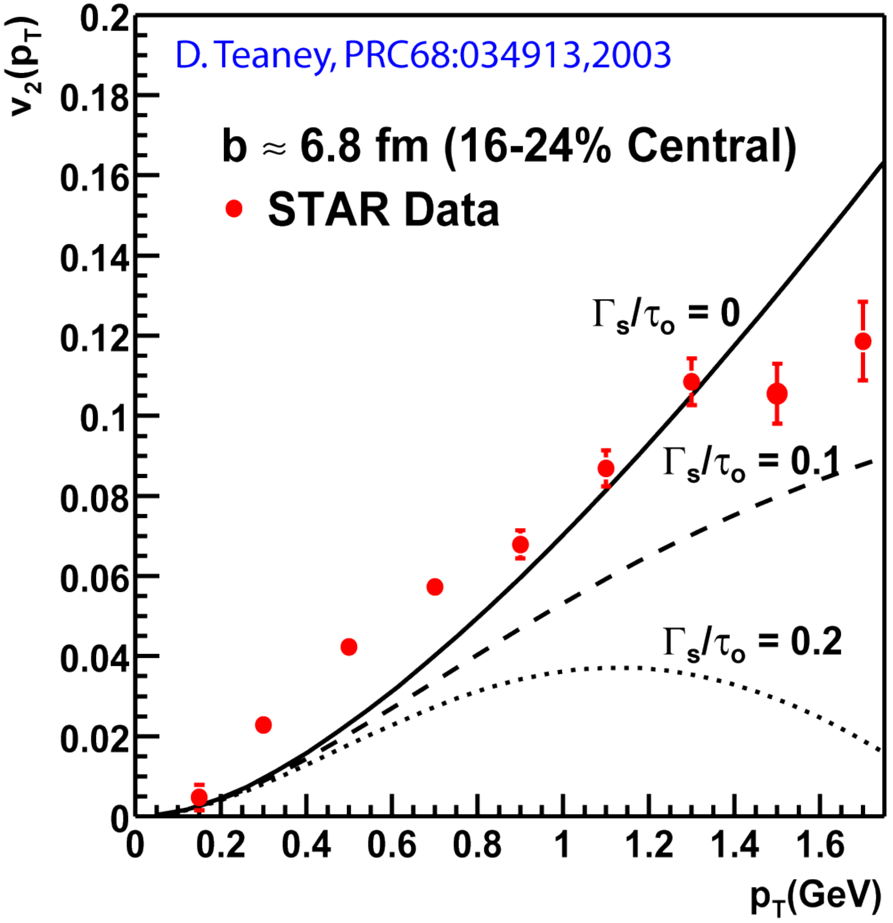
$$r_E = \frac{1}{gT}\sqrt{\frac{3}{N_c}}$$

$$r_M \sim \frac{1}{g^2 N_c T}$$

Navier Stokes

One attempt: D. Teaney

1st correction to thermal distribution function of an expanding gas $\Rightarrow$ estimate viscous corrections to spectra and elliptic flow using boost invariant blast wave model



$\Gamma_s = 4\eta/3sT$ (sound attenuation length)

pQCD: $\Gamma_s/\tau = 0.18/(\tau T) \sim 0.18$
(for $\alpha_s = 0.5$?)

AdS/CFT: $\Gamma_s/\tau = 1/(3\pi\tau T) \sim 0.11$

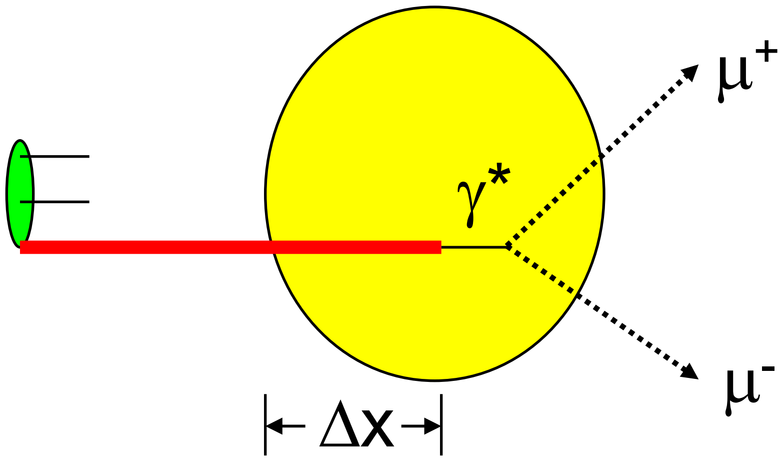
What we urgently need is viscous hydro but experts tell us this is really hard $\Rightarrow$ 3 years away (always?)

Lack of Proof $\neq$ Proof of Lack

Initial State Energy Loss

E866 at Fermilab

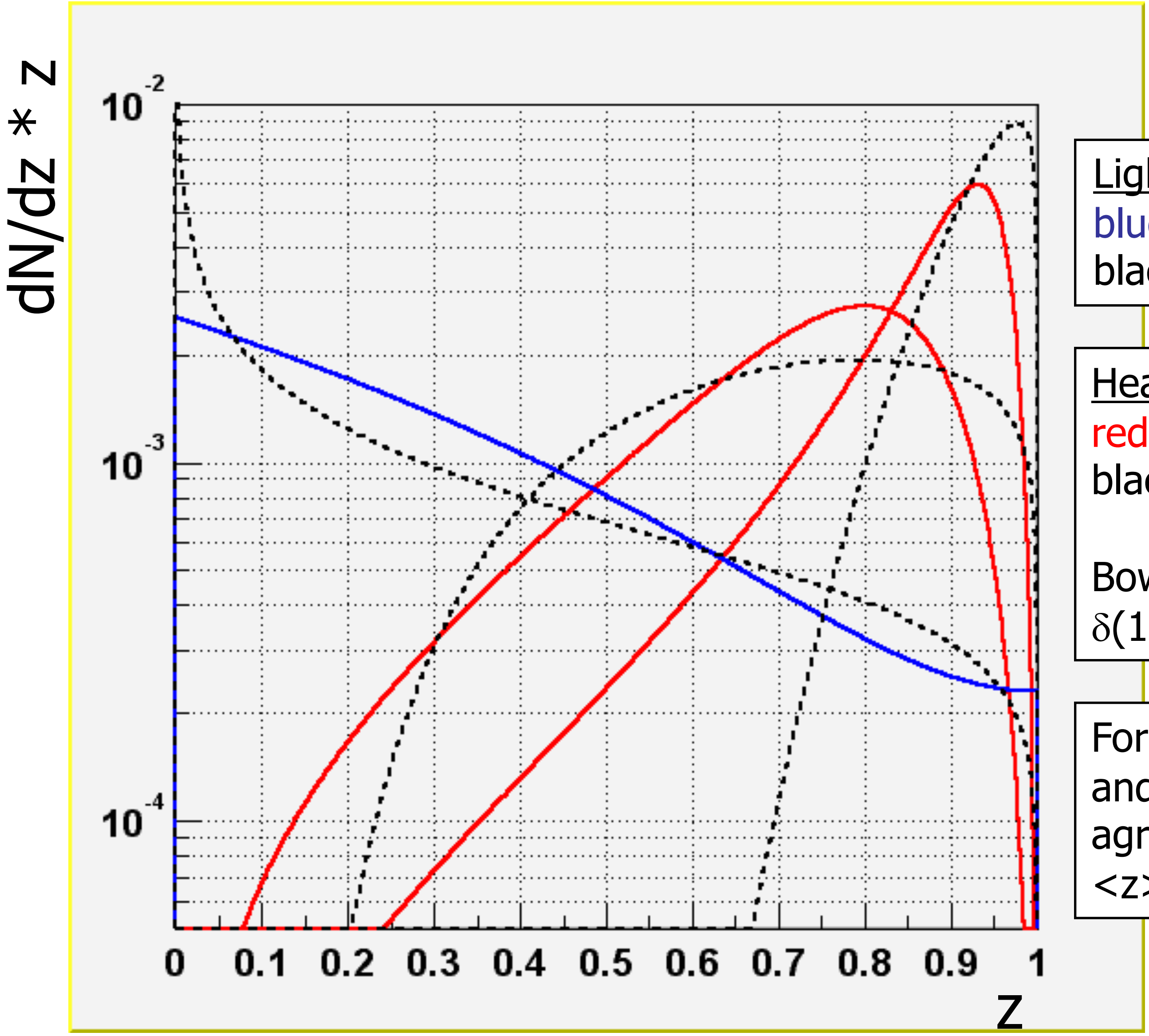
Drell-Yan production in proton-A collisions is sensitive to parton energy loss.



Need to separate shadowing from energy loss, and then
$-dE/dx = 2.32 \pm 0.52 \pm 0.5$ GeV/fm

hep-ex/0109014

Fragmentation Functions



Light quarks (u,d)
blue = Fields-Feynman
black dash = Lund fragmentation

Heavy quarks (c,b)
red = Peterson function
black dash = Lund fragmentation

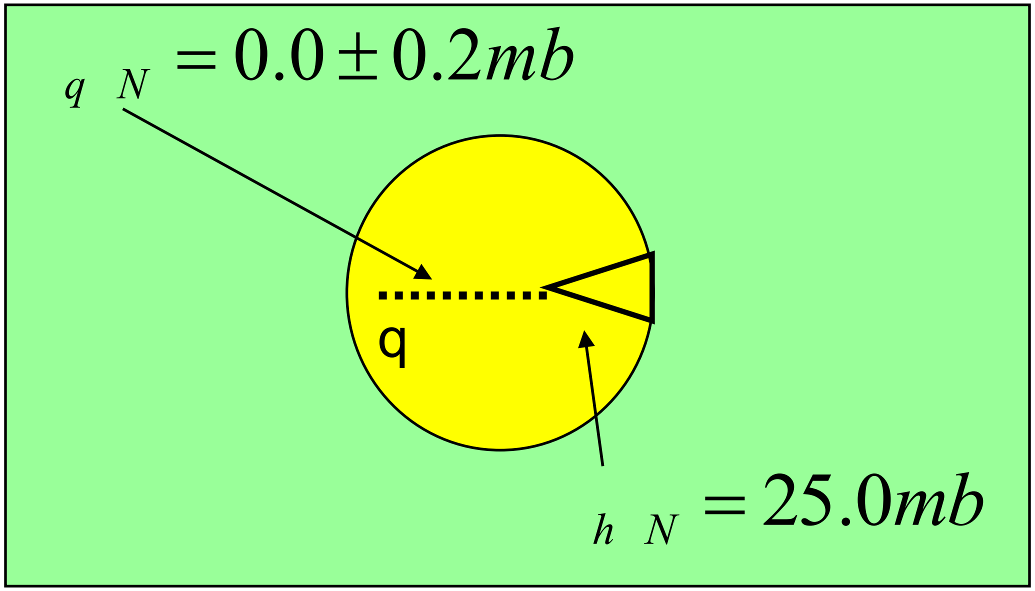
Bowler correction not shown
$\delta(1-z)$ is obvious

For charm quarks, the Peterson and Lund fragmentation roughly agree and give an average $\langle z \rangle \sim 0.8$.

Hadron Re-interaction

HERMES considers an alternative description.

Suppression due to quark-nucleon scattering ($t < t^{\pi}_{f}$) and hadron-nucleon scattering ($t > t^{\pi}_{f}$).



$$t_f = c\ (1 \quad z)$$

A hadron with large z originates from a quark emitting only a few gluons. The emission of only a few gluons corresponds to a small formation time.
Opposite to other models!

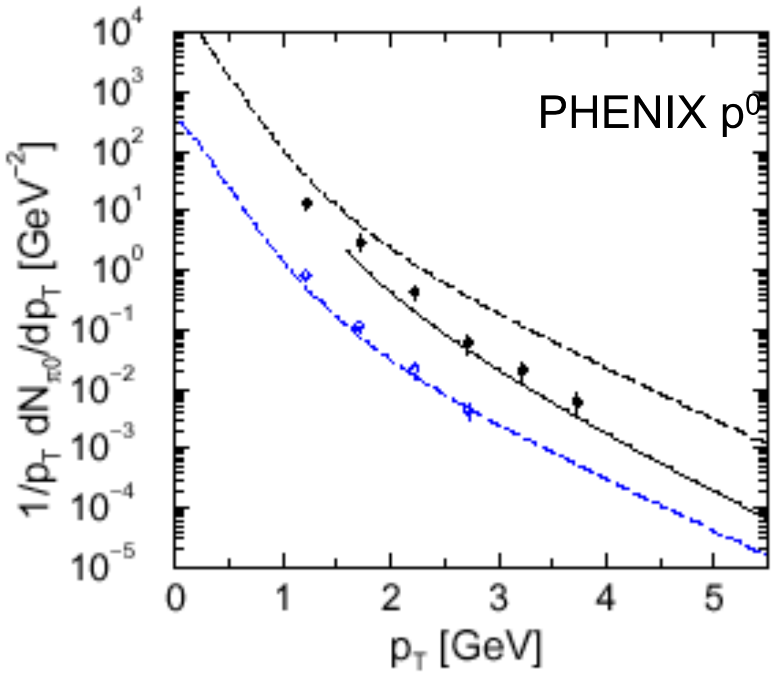
They consider good agreement with N^{14} data in a model in which the "interaction of the struck quark with the nuclear medium is very small."

hep-ex/0012049

Hadronization Time Scales

What if the quark or gluon jet begins to fragment inside the medium?

Then the fragmented hadrons can interact with the hadron gas medium, rescatter, and thus suppression high momentum hadrons.



Hadronization time =
time to build up the hadronic wavefunction

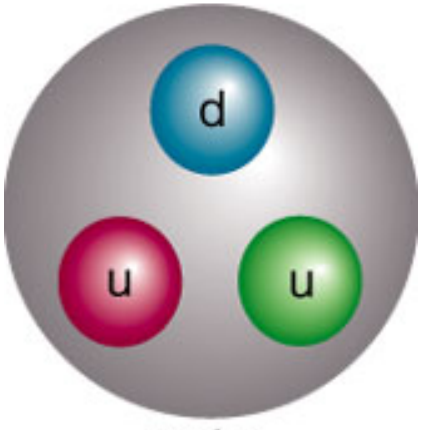
τ (light) ~ 1.2 (E/GeV) * fm/c

Nuclear systems are excellent laboratories for testing formation time issues. However, calculations seem to have factors of 2 floating around.

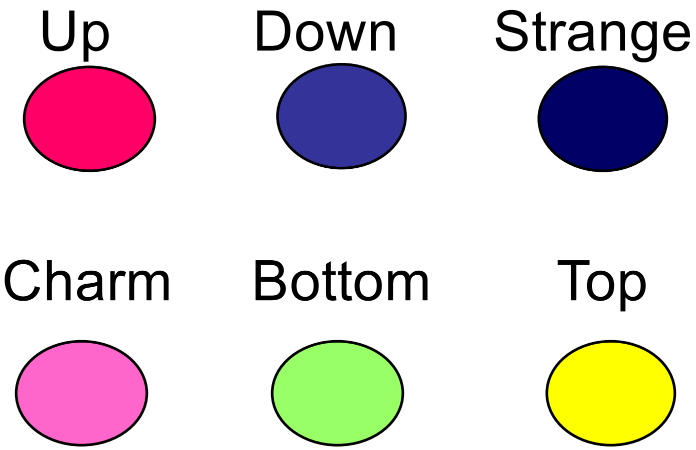
Gallmeister et al., nucl-th/0202051

Quarks, Gluons and the Strong Interaction

Proton is a composite object
made of quarks and gluons.

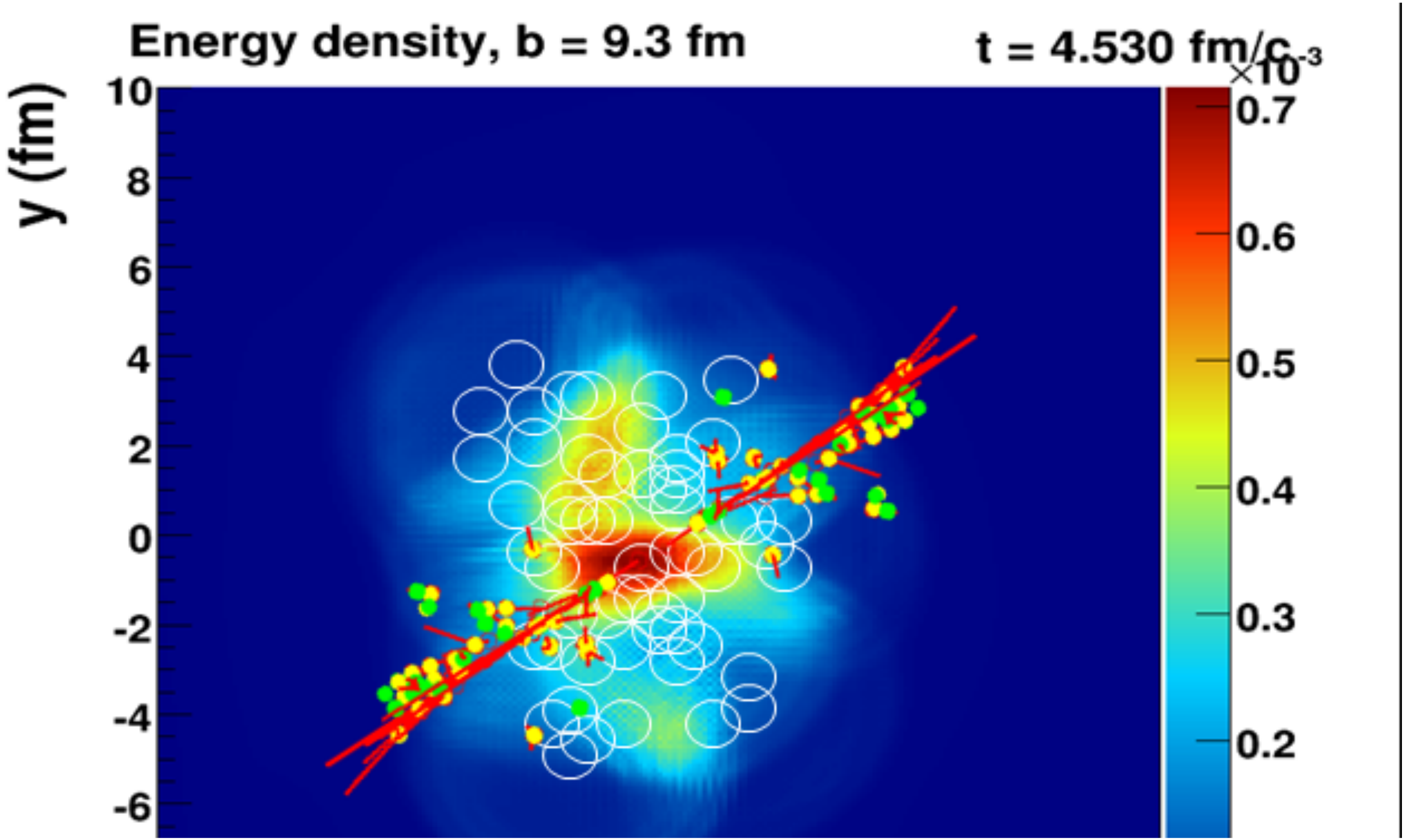


“Three quarks on a lark.” James Joyce



Up Down Strange

Charm Bottom Top

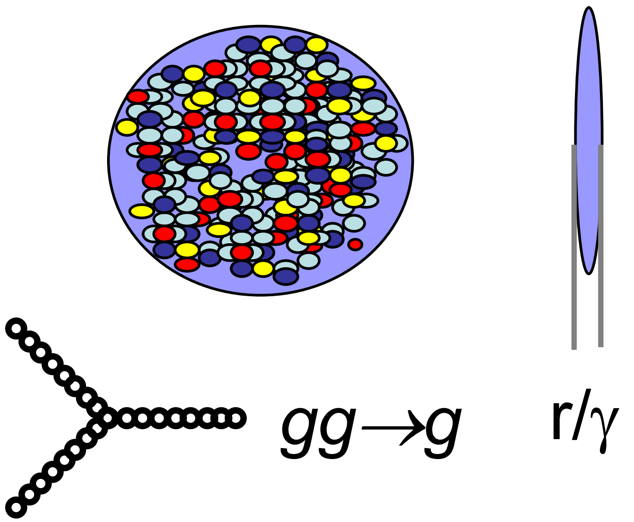


High energy back-to-back quarks (jets) can blast out through the fluid.

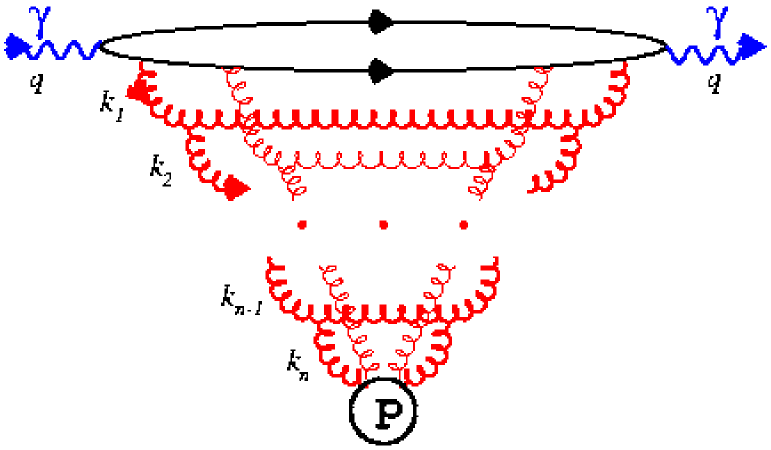
These jets → bound quark states too.

Gluon Saturation

probe rest frame



target rest frame



Transverse size of the quark-antiquark cloud is determined by $r \sim 1/Q \sim 2\ 10^{-14}$cm/ Q (GeV)

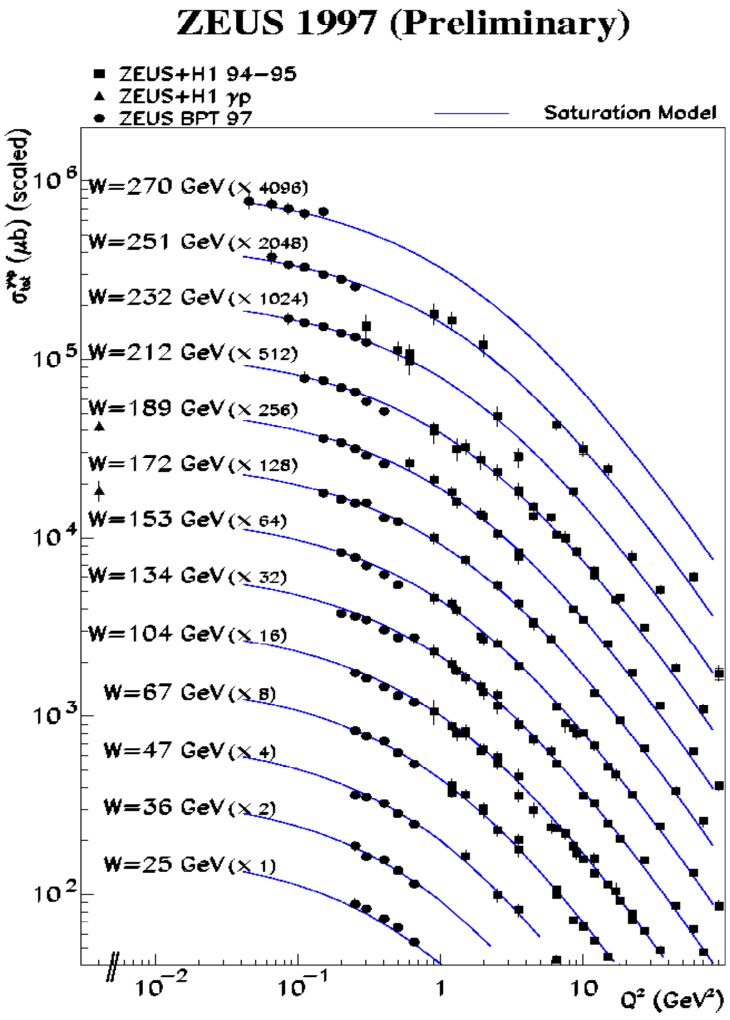
Wavefunction of low x gluons overlap and the self-coupling gluons fuse, thus saturating the density of gluons in the initial state

Fluctuations from dipole increase and the unitary limit of the photon cross section in deep inelastic scattering is the equivalent to saturation.

[1] J.P Blaizot, A.H. Mueller, Nucl. Phys. B289, 847 (1987).

Saturation in the Proton

HERA deep inelastic scattering data has been interpreted in the context of gluon saturation models.



Lowest x data is at modest Q^2 (should QCD+DGLAP work?)

Recent HERA running may not resolve these issues since machine changes limit the coverage at low-x.

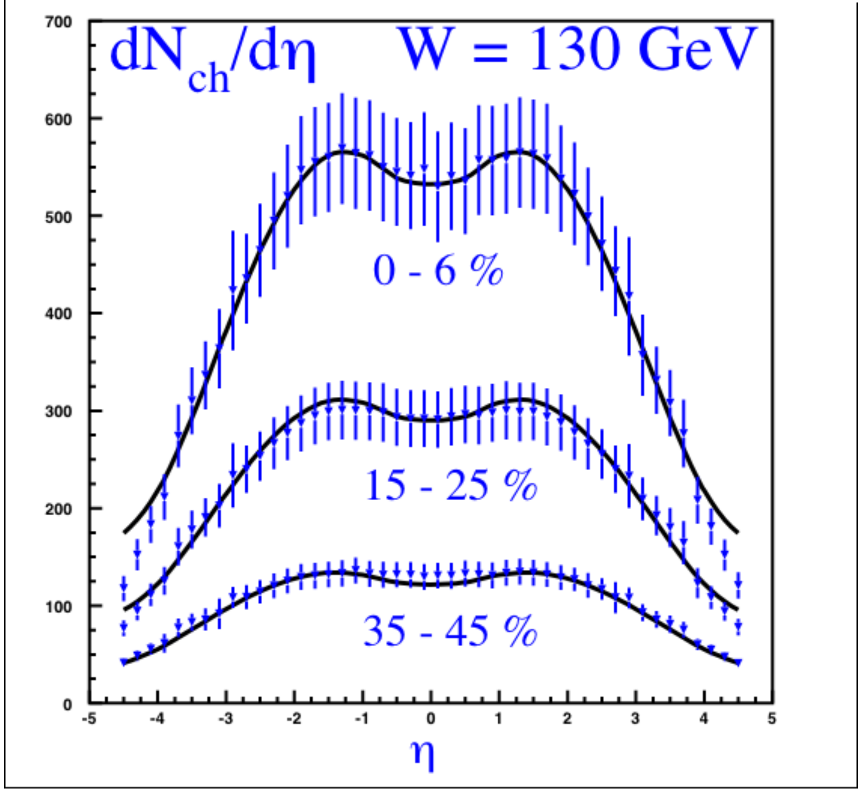
Future Electron-Ion Collider at RHIC or HERA upgrade may be necessary.

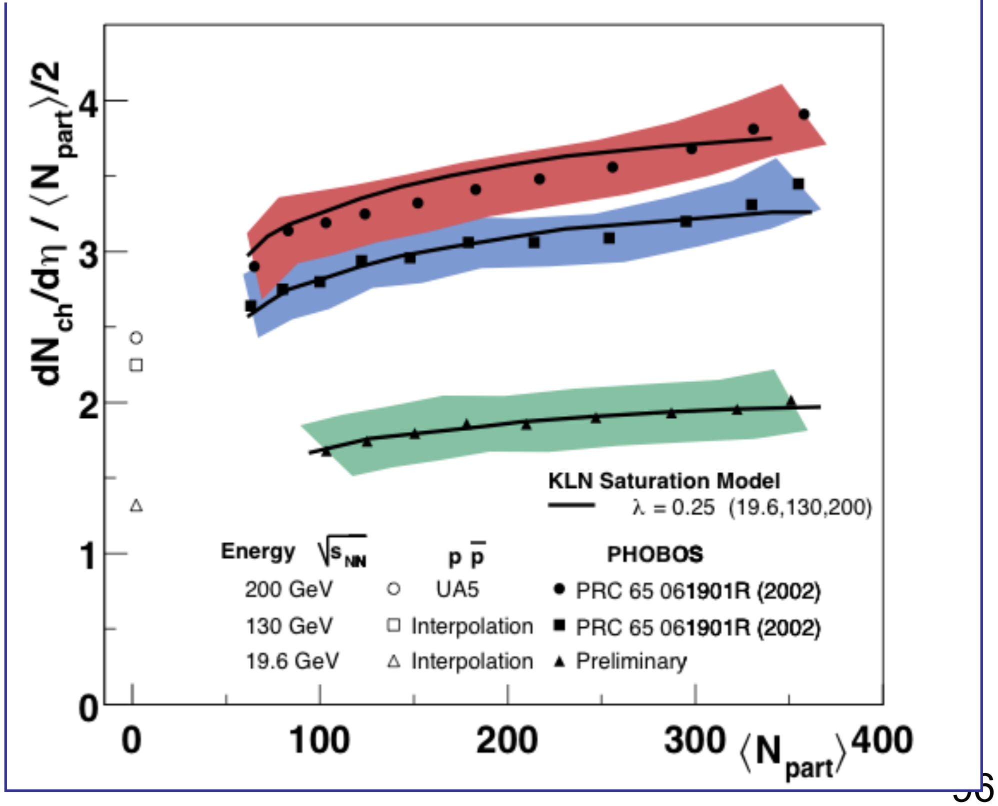
K. Golec-Biernat, Wuesthoff, others

Experimental Comparisons

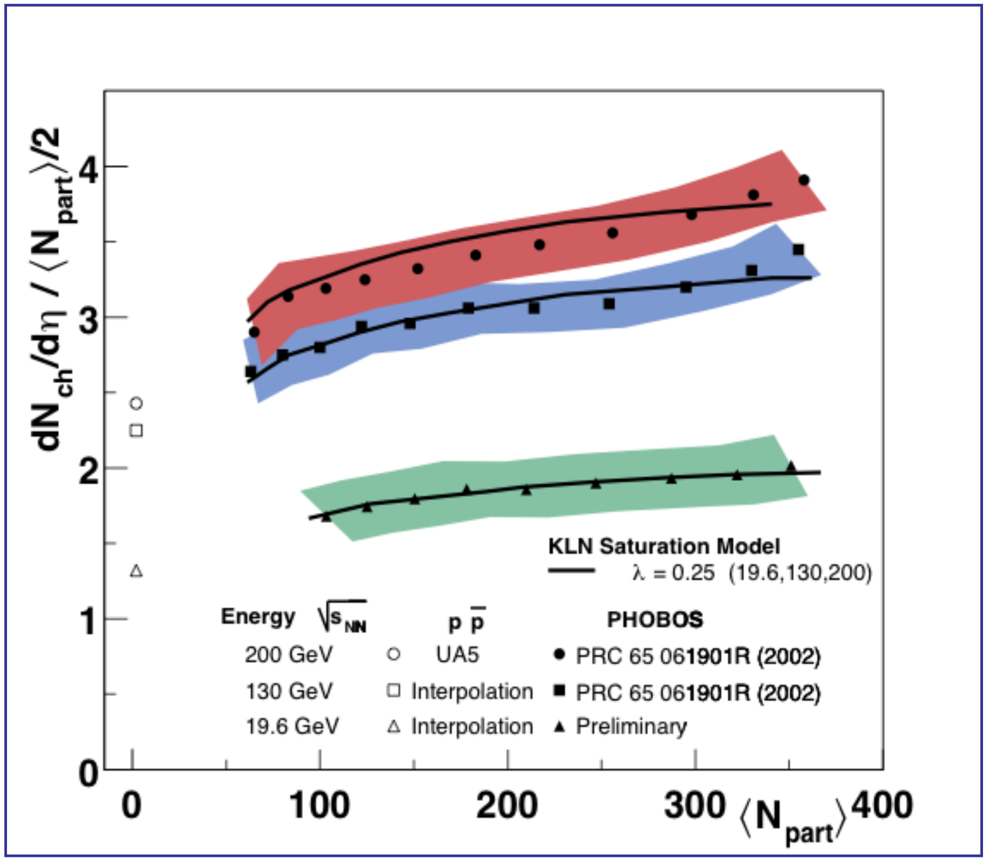
In this saturation regime (sometimes termed the Color Glass Condensate), with one parameter (saturation scale Q_s) defines the physics. In this classical approximation one can calculate the collision output distribution of gluons. If one assumes a mapping of partons to hadrons, one can compare with data.

$$\frac{dN}{d} = \frac{\cosh y}{\sqrt{m_T^2 / p_T^2 + \sinh^2 y}} \cdot cN_{part} \; \frac{s}{s_o}^{\overline{\;\;}\,2} \cdot e^{\;\;|y|} \ln \frac{Q_s^2 e^{\;\;|y|}}{{}^{2}_{QCD}} \cdot \; 1+ \;|y|\; 1 \;\; \frac{Q_s}{\sqrt{s}} e^{\;\;|y|/2} \;{}^{4}$$





Saturation Regime?

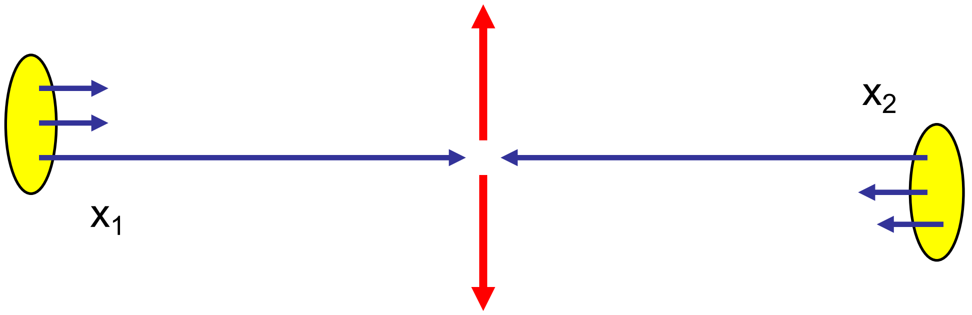


The agreement appears impressive, but at the lowest energy one is no where near the saturation condition.

Also, when the particle yield is matched, the transverse energy per particle is a factor of 2 too large. Perhaps this is longitudinal work, but no detailed calculation accounts for this yet.

Lower x?

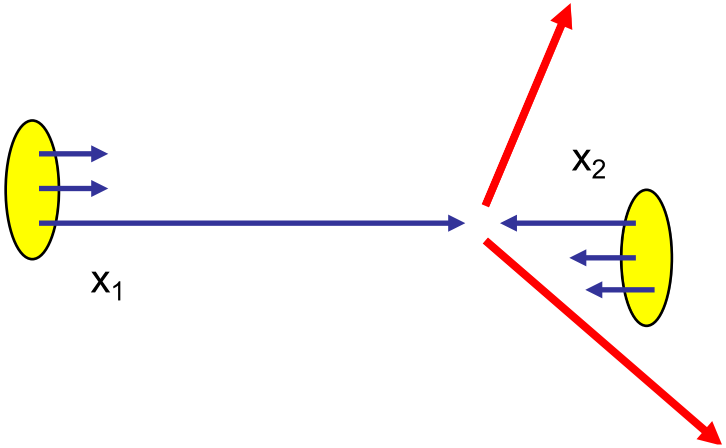
For a 2 ←→ 2 parton scattering process (LO), if both partons scatter at 90 degrees, then $x_1 = x_2 = 2p_T/E_{cm}$



$p_T \sim 2$ GeV
$E_{cm} \sim 200$ GeV
$x \sim 0.04$

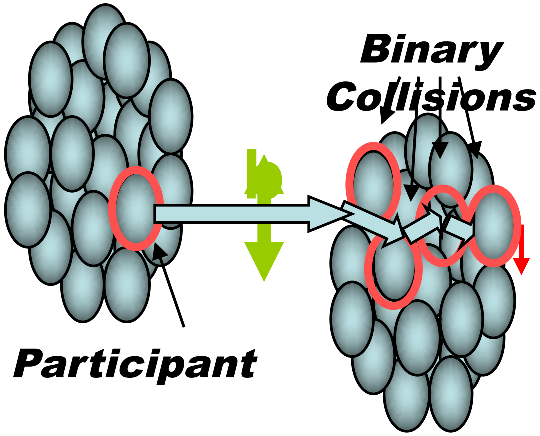
One can probe lower x values if x1 >> x2 and look at particles away from 90 degrees (forward rapidity).

Rapidity y=0 (x~0.01), y=2.0 (x~0.001), y=4.0 (x~0.0001) for pT ~ 2 GeV.



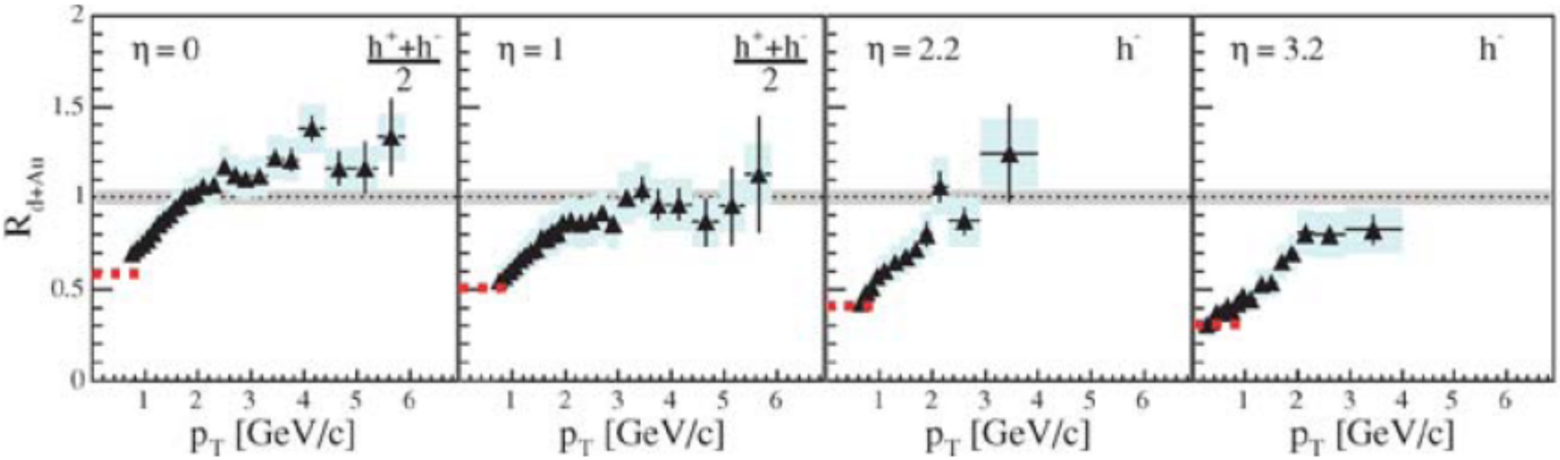
Suppression Factor R

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d}{T_{AA} d^2 \quad {}^{NN} / dp_T d}$$



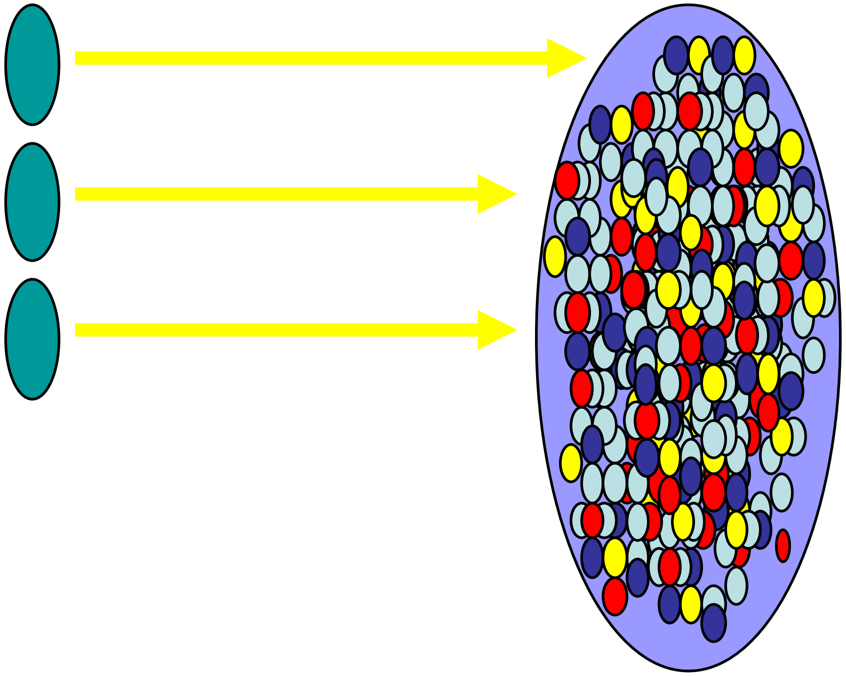
R = 1 (binary collision scaling)

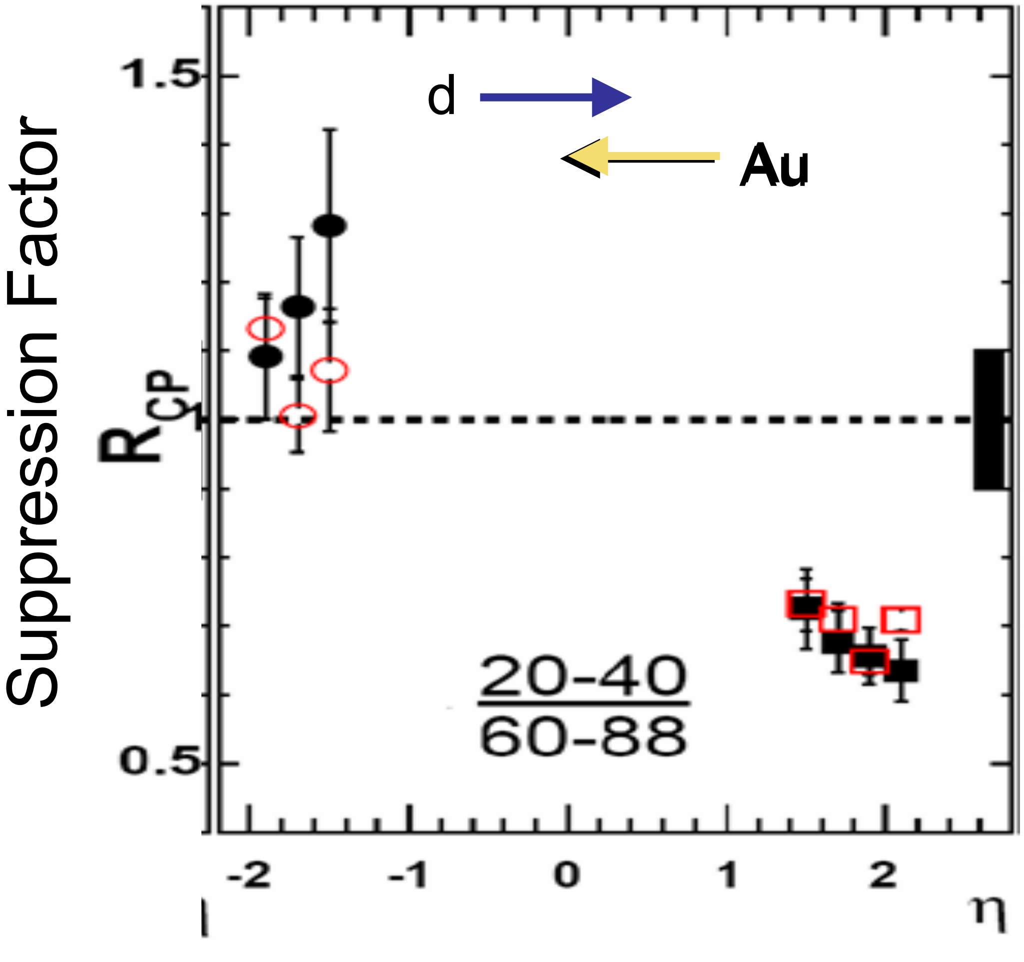
In deuteron-Gold collisions, forward rapidity probes low x in the Gold nucleus. BRAHMS observes a suppression of particles that could be related to saturation of the gluon density in the Gold nucleus.



d+Gold Probes

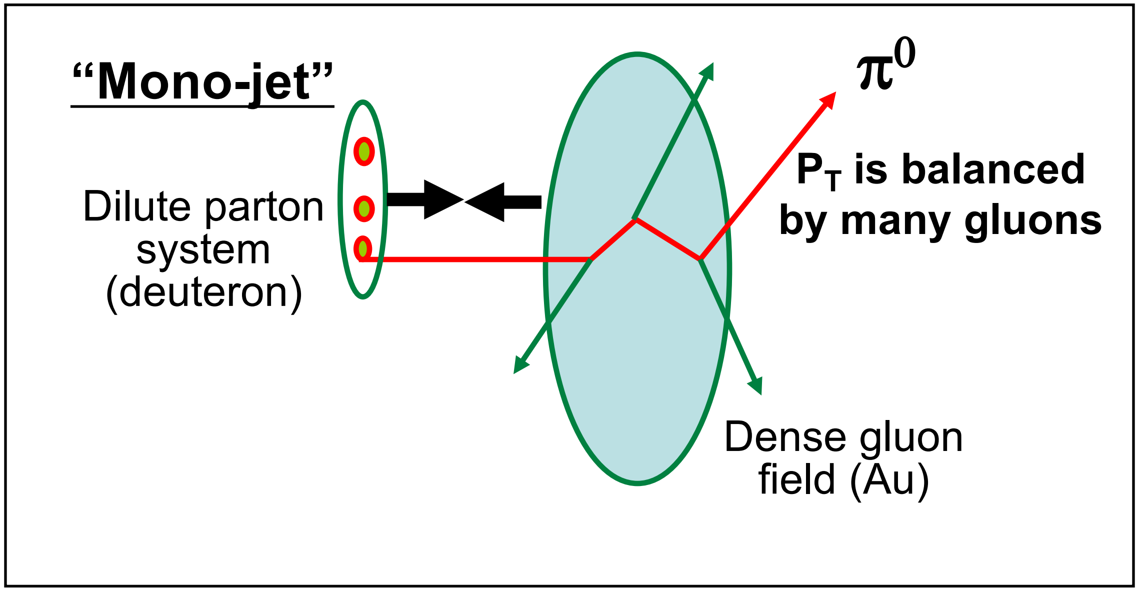
Suppression of forward hadrons generically consistent with saturation of low-x gluons.





x ~ 10^{-1} x ~ 10^{-2} x ~ 10^{-3}

MonoJets?



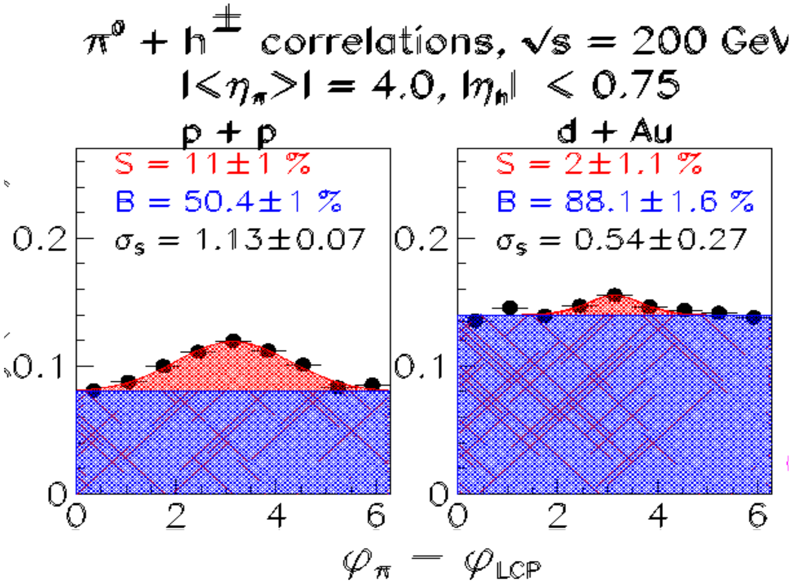
“Mono-jet”

Dilute parton
system
(deuteron)

π^0

P_T is balanced by many gluons

Dense gluon
field (Au)



STAR Experiment

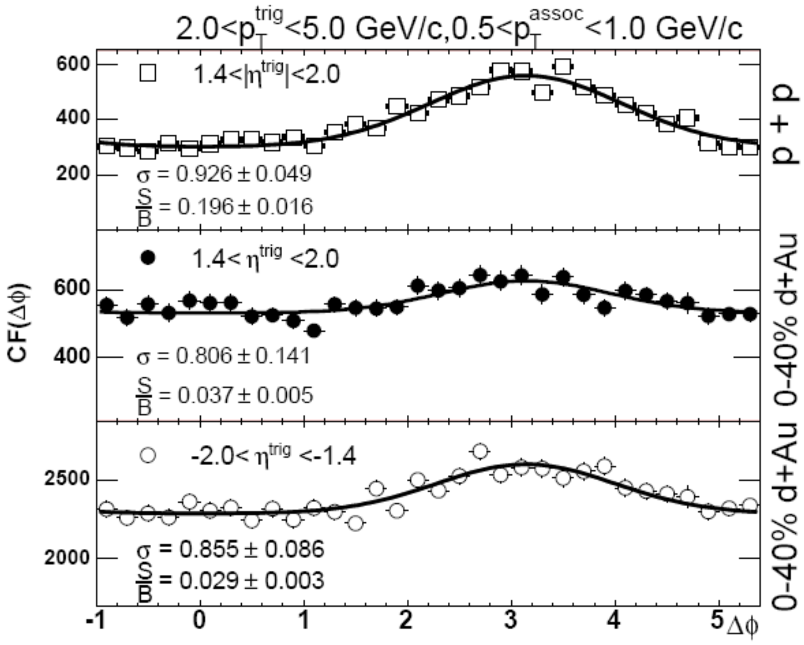
Tagged photons and jets at forward angles will give precise information on x dependence of saturation effect.

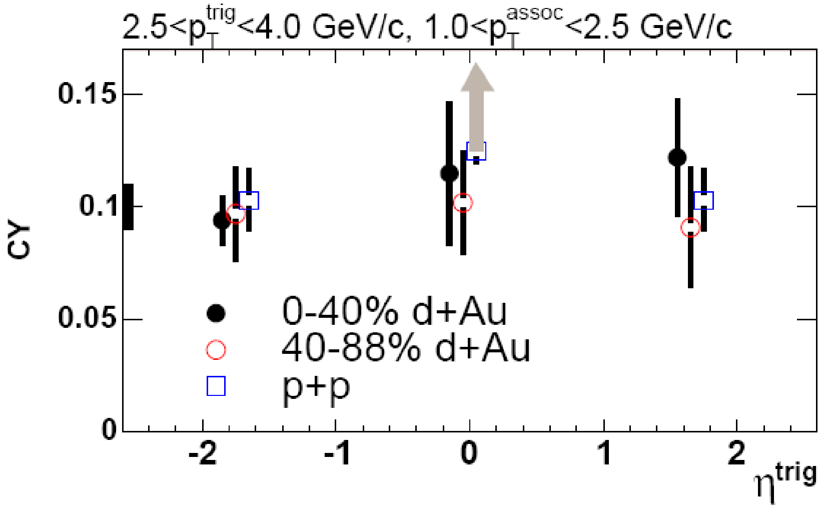
No MonoJets at y=2?

PHENIX has measured the correlation between y=2 hadrons and y=0 hadrons.

There appears to be no decrease in away side partners as predicted by saturation models.

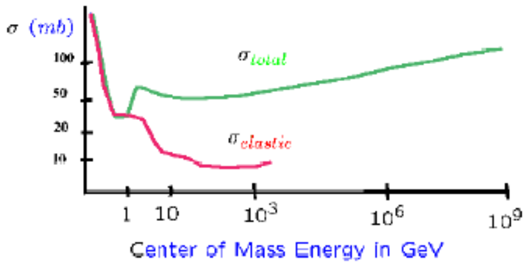
However, these predictions were for more forward rapidity (probing lower x) regions.



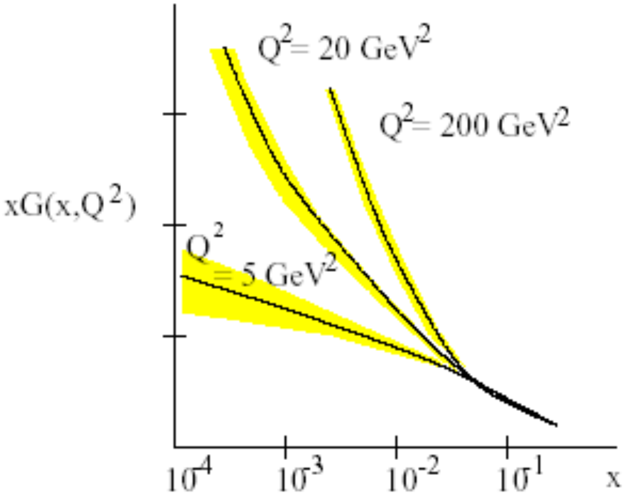


What do they have in common?

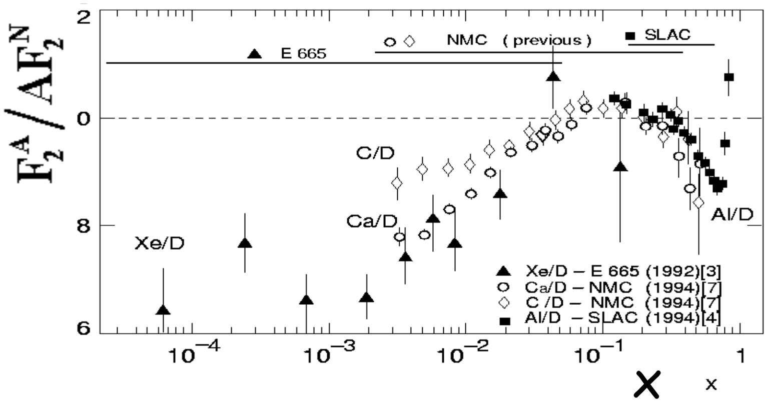
1. Scaling of the total p-p cross section



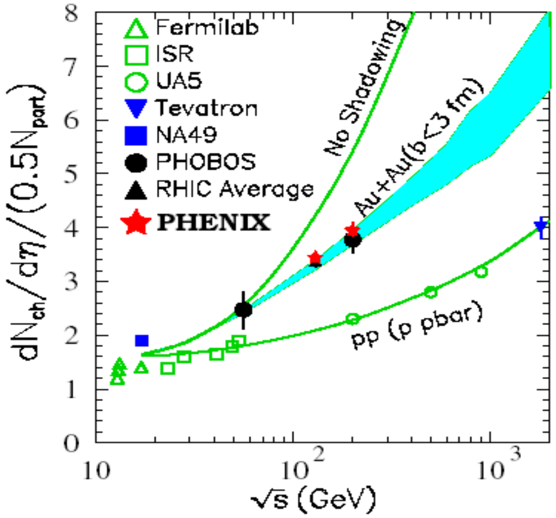
2. Growth of low x gluons in the proton



3. Shadowing of structure functions in nuclei



4. Particle production in nucleus-nucleus reactions

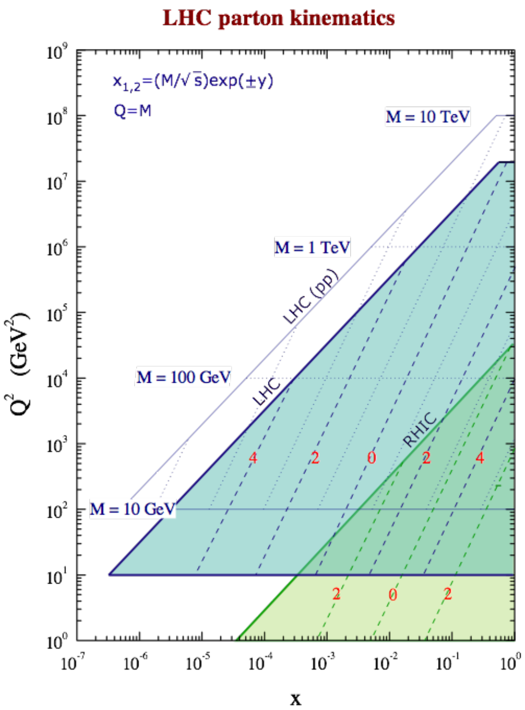


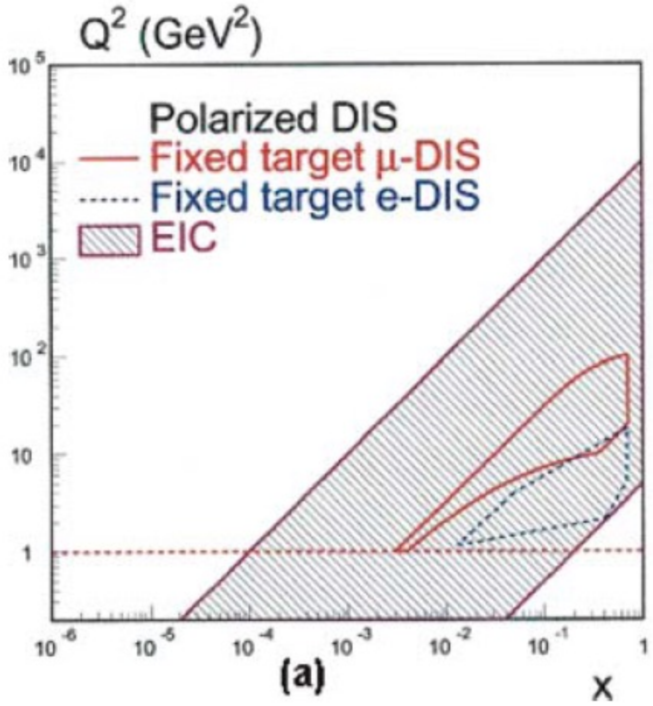
Saturation Summary

Interesting hints at non-linear saturation effects of partons in protons at HERA. Current HERA running does not focus on this physics, and facility will soon be shut down.

Interesting hints in proton (deuteron) nucleus reactions at RHIC, but at a rather soft scale. Photon Jet or Jet Jet correlations that pin down x_1 and x_2 may shed more light.

Key future is much larger x reach at high Q^2 at the LHC, or with Deep Inelastic Scattering at future electron ion collider (EIC or eRHIC).





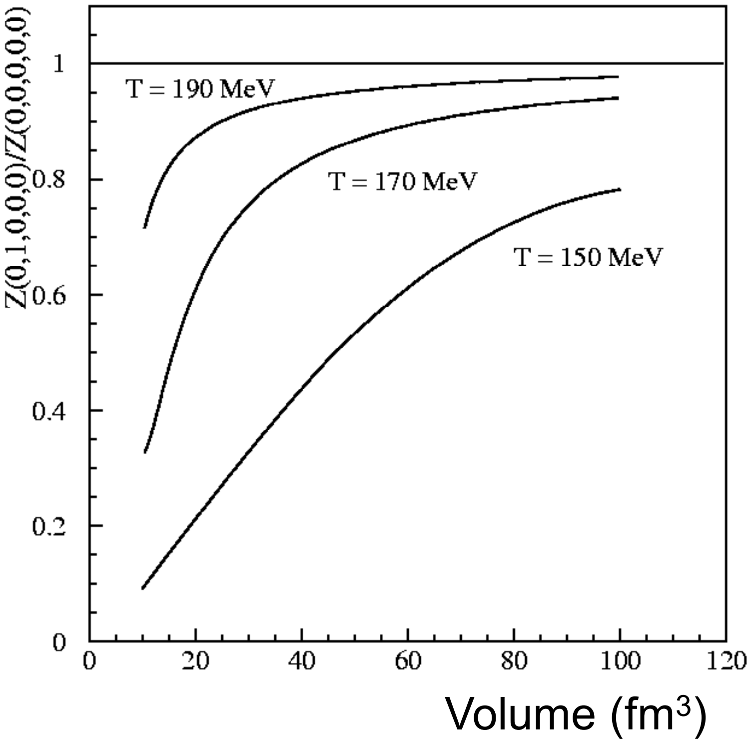
Canonical Ensemble

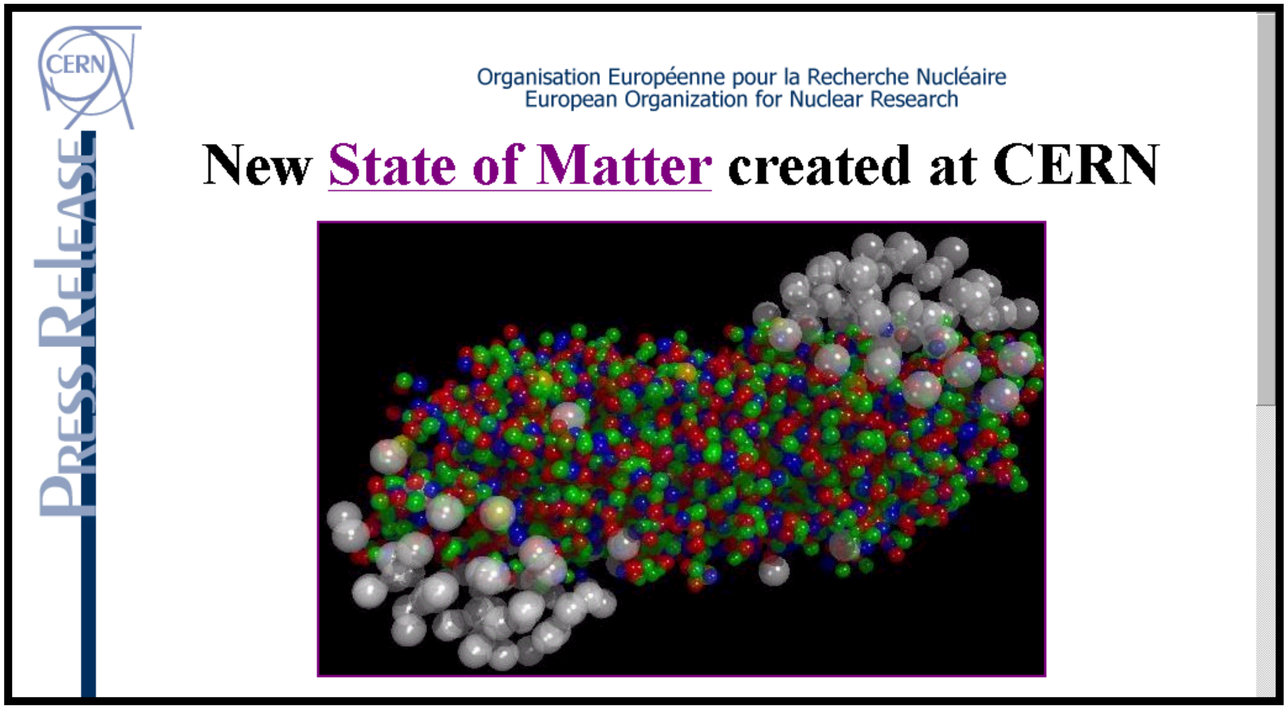
Statistical Model using Grand Canonical Ensemble

One can use the GCE even when energy and other quantum numbers are conserved. The temperature and chemical potentials simply reflect characteristics of the system. Fluctuation calculations are not valid.

If the volume of the system is large, GCE is appropriate. For small volumes, you must conserve quantum numbers (for example strangeness) in every event !

Thus the Canonical Ensemble is relevant. In the CE, strangeness is suppressed for very small volumes and reaches the GCE limit for large volumes.





PRESS RELEASE

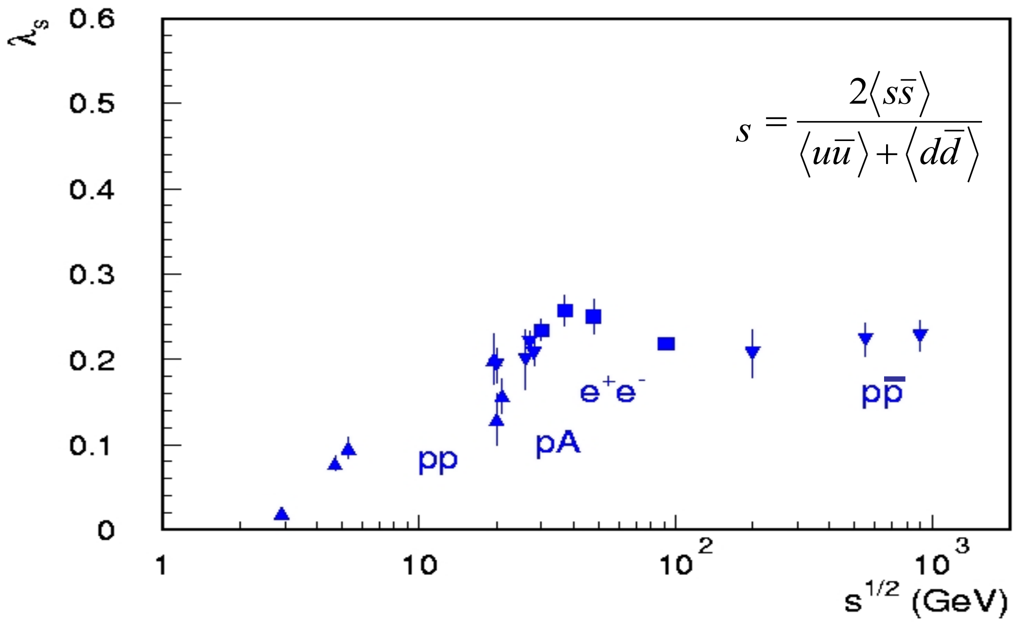
Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

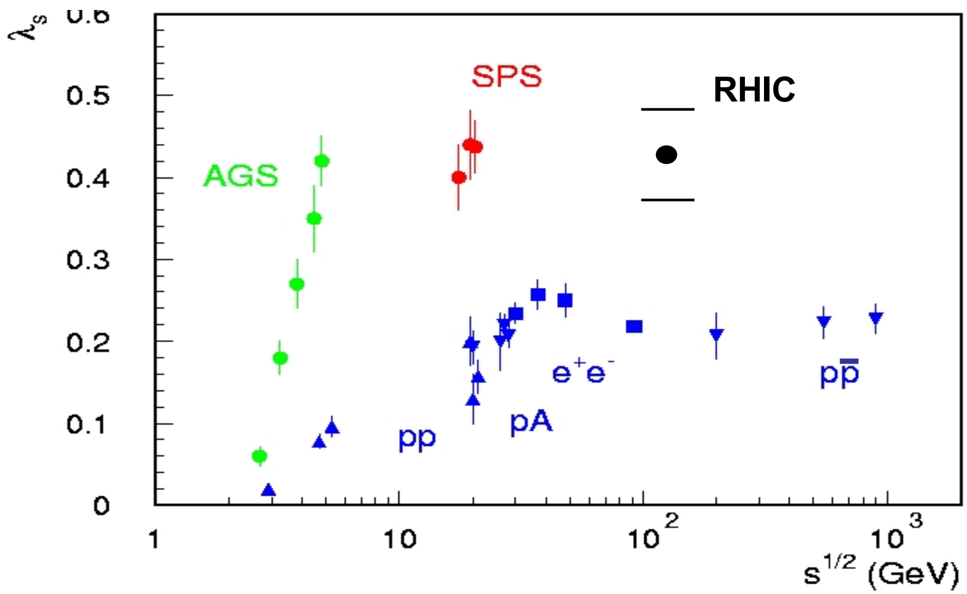
New State of Matter created at CERN

“A particularly striking aspect of this apparent ‘chemical equilibrium’ at the quark-hadron transition temperature is the observed enhancement of hadrons containing strange quark relative to proton-included collisions.

Since the hadron abundances appear to be frozen in at the point of hadron formation, this enhancement signals a new and faster strangeness-producing process before or during hadronization, involving intense rescattering among quarks and gluons.”

Strangeness Suppression



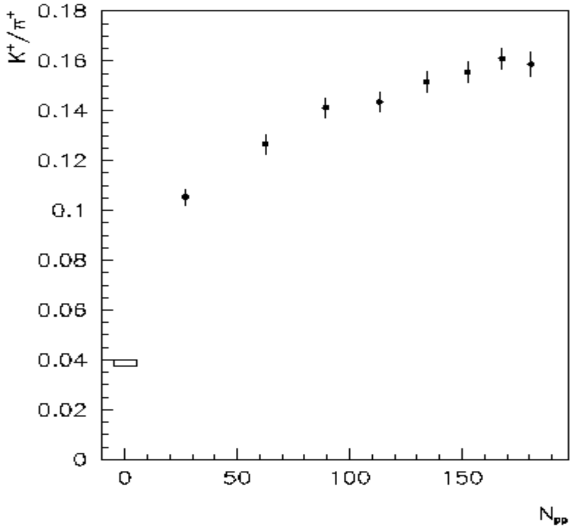


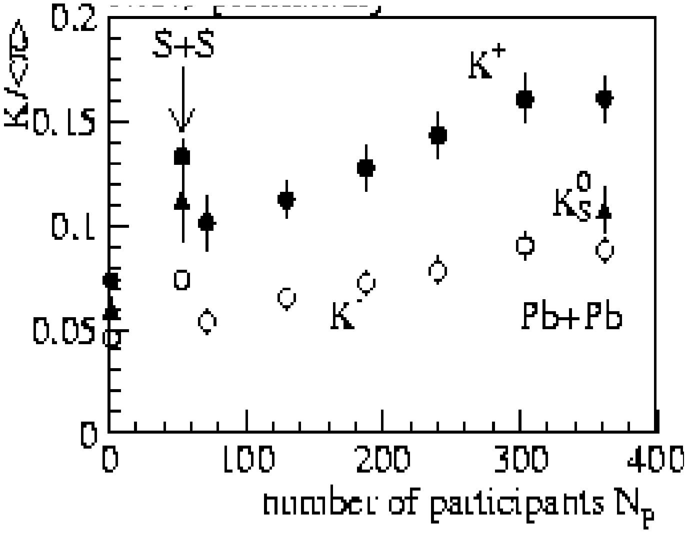
Becattini et al hep-ph/0011322, hep-ph/0002267

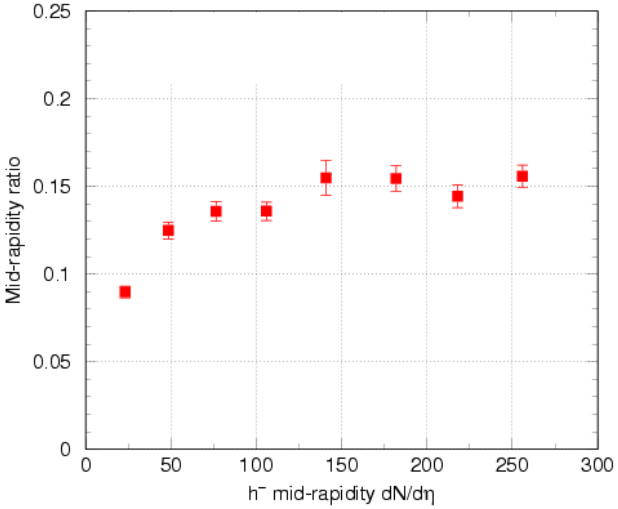
Strange Patterns

The enhancement of total strangeness appears quite similar at AGS, SPS, and now RHIC !

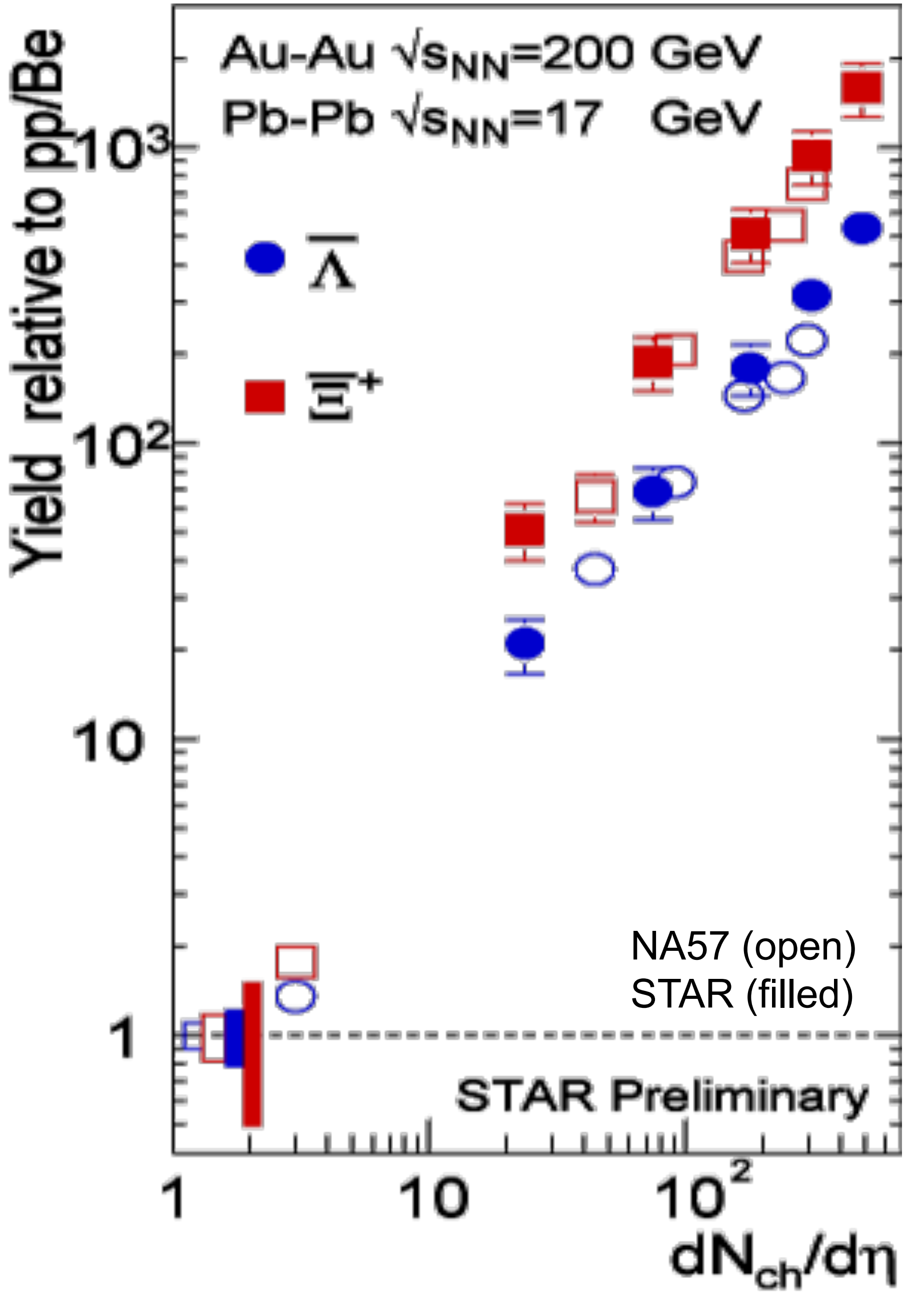
This challenges any model QGP model for enhancement. All systems are approaching something that looks statistically equilibrated, and we already see this trend in proton induced collisions.







Strangeness Enhancement

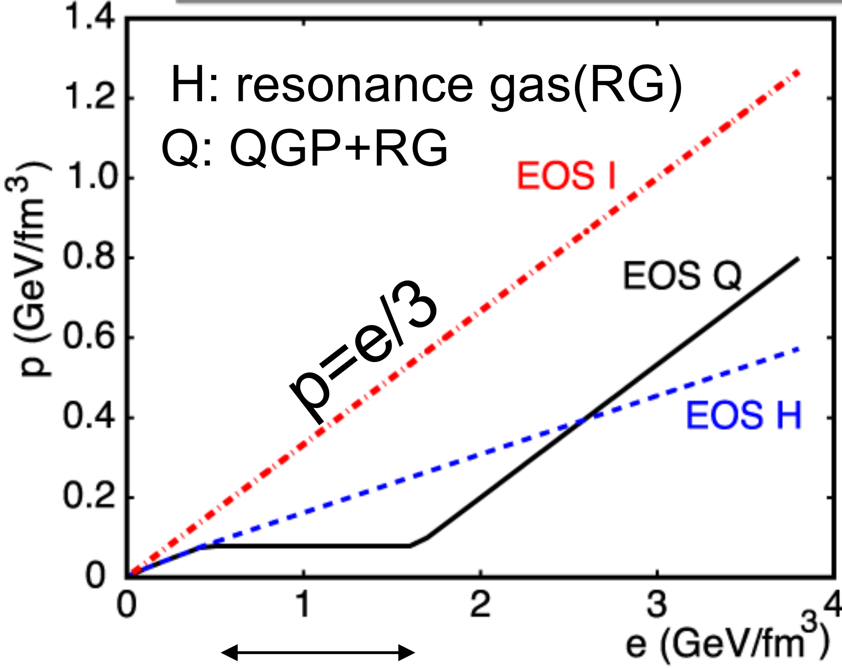


NA57 (open)
STAR (filled)

Equation of State

One can test many kinds of EoS in hydrodynamics.

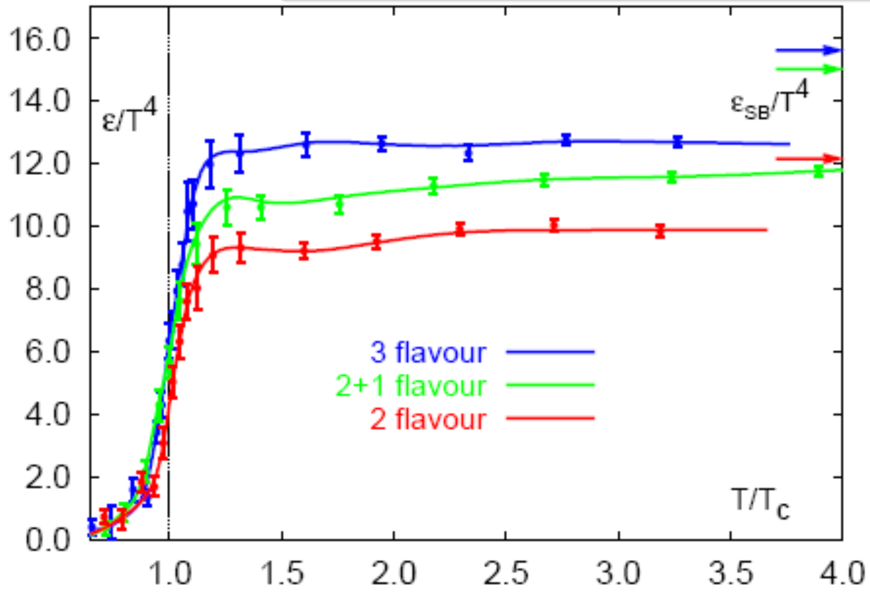
Typical EoS in hydro model



From P.Kolb and U.Heinz('03)

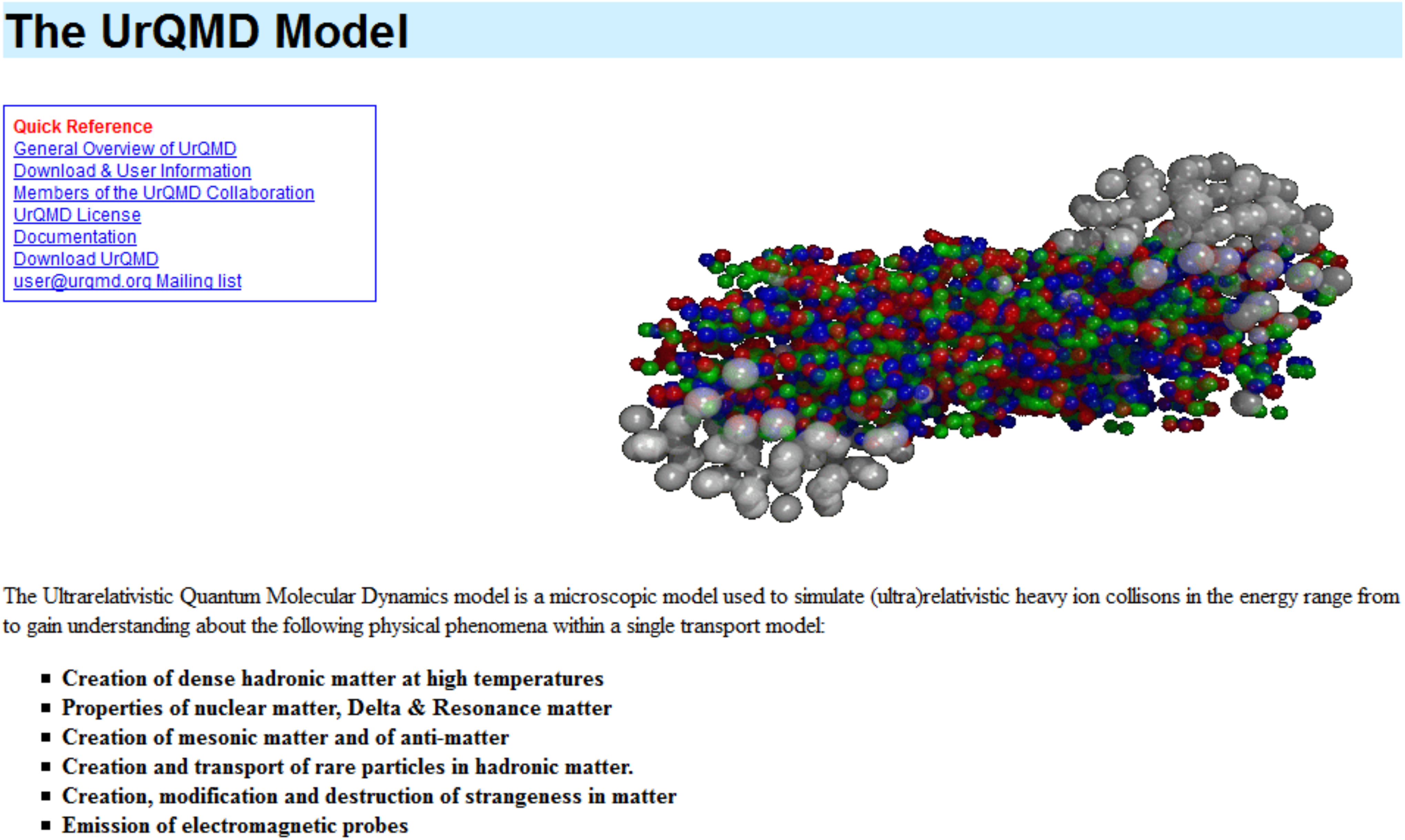
Latent heat

Lattice QCD simulations



F.Karsch *et al.* ('00)

https://urqmd.org/

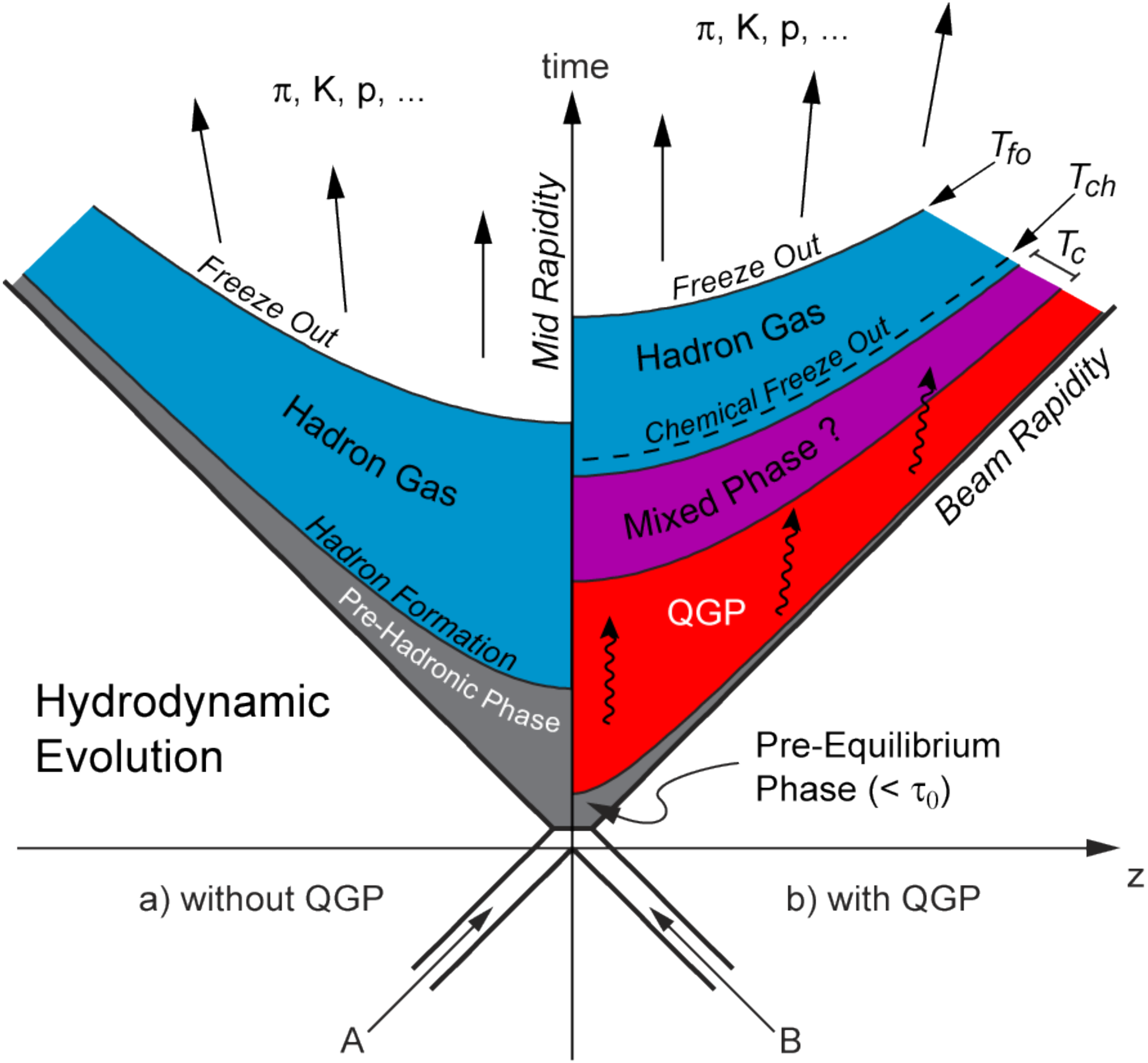


The UrQMD Model

Quick Reference
General Overview of UrQMD
Download & User Information
Members of the UrQMD Collaboration
UrQMD License
Documentation
Download UrQMD
user@urqmd.org Mailing list

The Ultrarelativistic Quantum Molecular Dynamics model is a microscopic model used to simulate (ultra)relativistic heavy ion collisons in the energy range from to gain understanding about the following physical phenomena within a single transport model:

- **Creation of dense hadronic matter at high temperatures**
- **Properties of nuclear matter, Delta & Resonance matter**
- **Creation of mesonic matter and of anti-matter**
- **Creation and transport of rare particles in hadronic matter.**
- **Creation, modification and destruction of strangeness in matter**
- **Emission of electromagnetic probes**


time
π, K, p, ...
π, K, p, ...
Mid Rapidity
Freeze Out
Freeze Out
T_{fo}
T_{ch}
T_c
Hadron Gas
Hadron Gas
Chemical Freeze Out
Mixed Phase ?
QGP
Beam Rapidity
Hadron Formation
Pre-Hadronic Phase
Hydrodynamic Evolution
Pre-Equilibrium Phase (< τ_0)
z
a) without QGP
b) with QGP
A
B

Limiting Temperature

The very rapid increase of hadron levels with mass yields an exponential level density

$$\rho(m) \quad \frac{dn}{dm} \sim m^a e^{m/T_H}$$

$$\rho(m) \; e^{\; m/T} dm$$

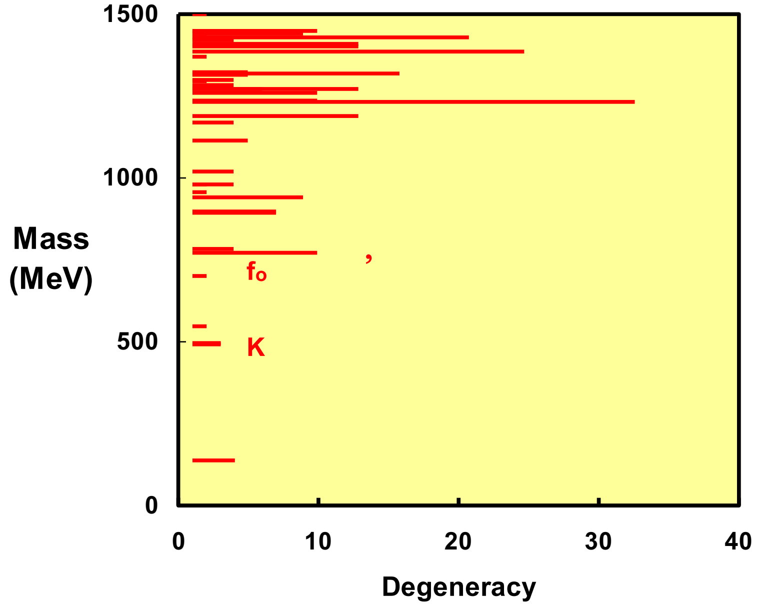
$$\sim \; m^a e^{m(\frac{1}{T_H} \;\; \frac{1}{T})} dm$$

and would thus imply a "limiting temperature"

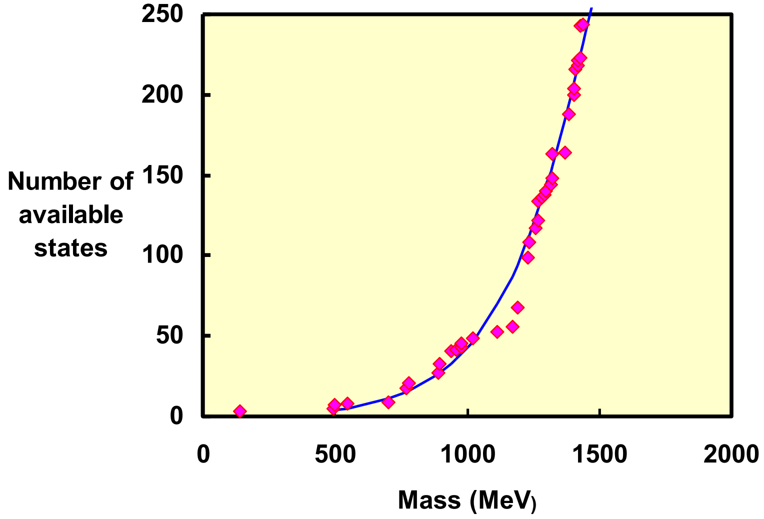
T_H ~ 170 MeV

Hagedorn, S. Fraustchi, Phys.Rev.D3:2821-2834,1971

Hadron 'level' diagram



Density of States vs Energy

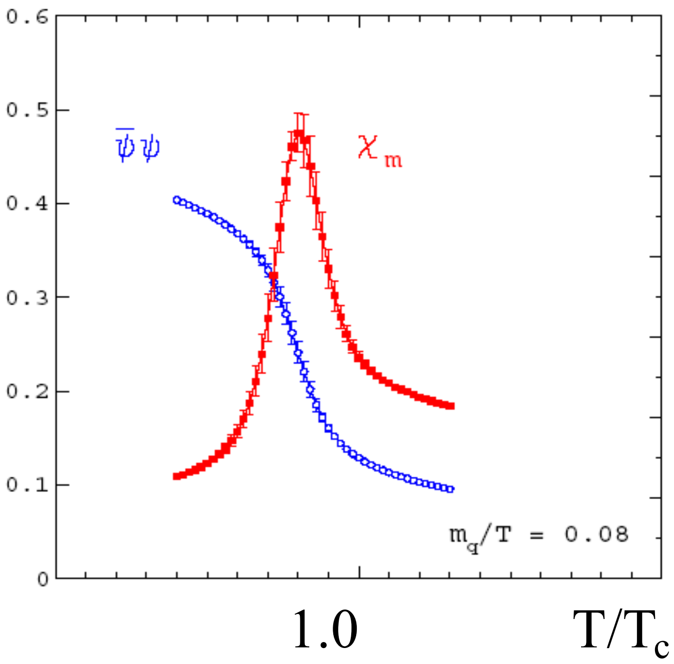


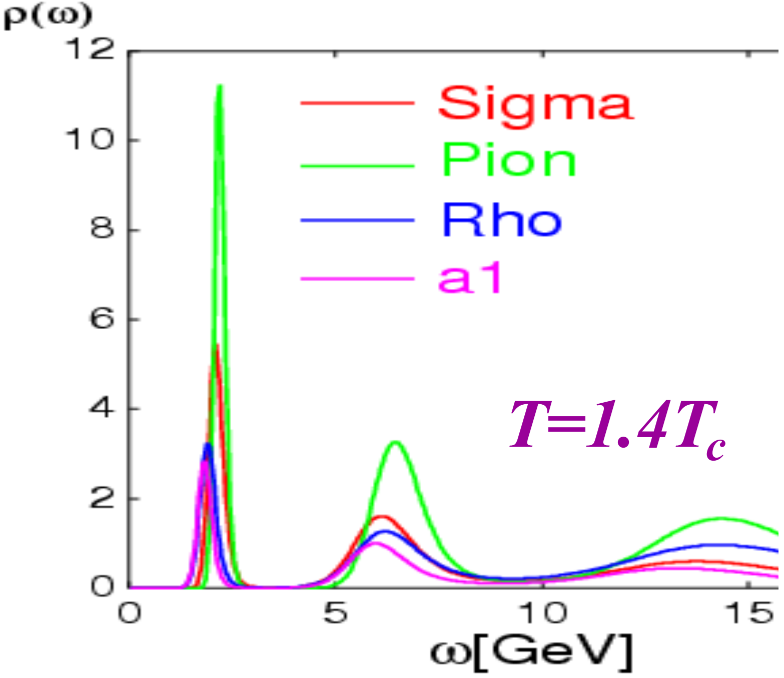
Approximate Chiral Symmetry

Up and Down quarks have very small neutral current masses (< 15 MeV). These masses are of interest to electroweak symmetry breaking (i.e. Higgs).

However, there is spontaneous breaking of chiral symmetry in the QCD vacuum we live in. A condensate of qqbar pairs results in the observed hadronic masses.

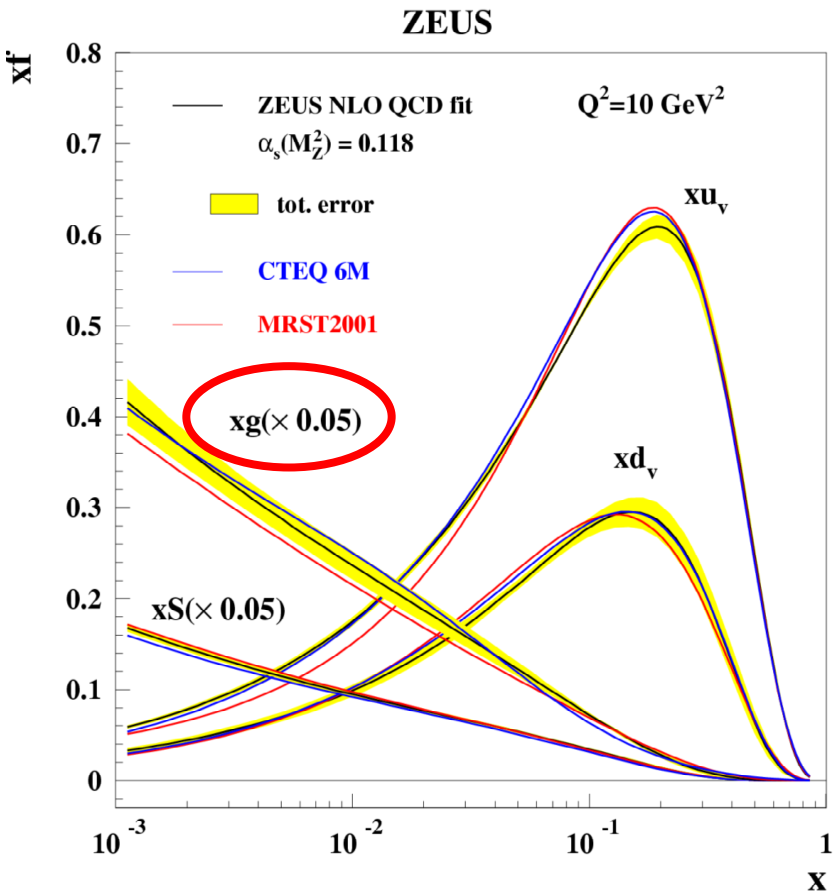
At high temperature this condensate goes away and thus hadronic masses should change near the transition.





What Are
We Colliding -
Protons and Nuclei?

Limitless Gluons?



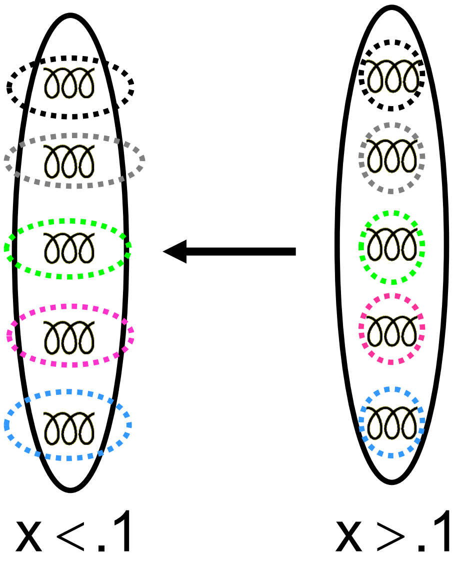
When protons are viewed at short wavelength, there is a large increase in low x gluons.

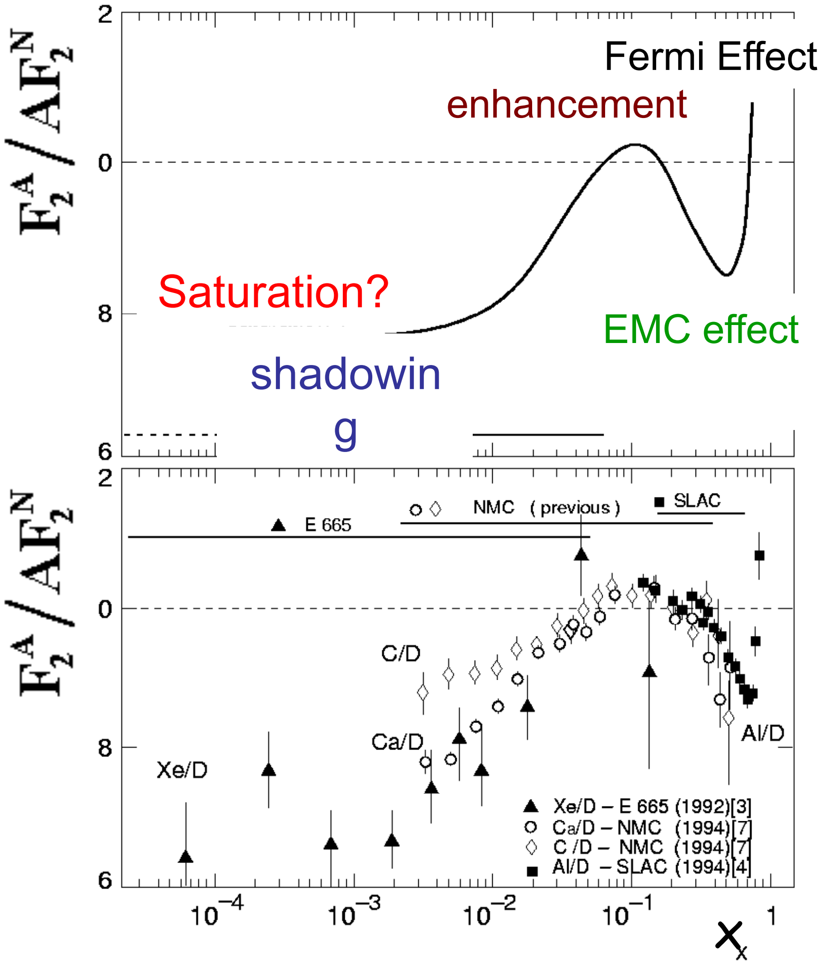
Is there a limit to the low x gluon density?

What about Nuclei?

Nucleon structure functions are known to be modified in nuclei.

Can be modeled as recombination effect due to high gluon density at low x (in the frame where the nucleus is moving fast).





RHIC probes **x** $\frac{2p_T}{\sqrt{s}} > 10^{2}$

Gluon Number Density

Gluon number density:

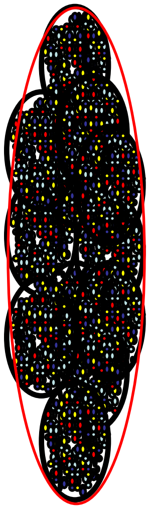
$$\rho_g = A\, xG_N(x,Q^2)/\pi R^2$$

Gluon density depends on the nuclear overlap area ($\pi R^2 \alpha A^{2/3}$) and the momentum scale (Q^2) since DGLAP evolution requires:

$$G(x, Q^2) \sim \ln (Q^2 / \Lambda_{QCD}{}^2)$$

HERA tests gluon density in the proton at very low x. RHIC can test similar gluon density at significantly higher x values. LHC heavy ion collisions probe even higher gluon densities.

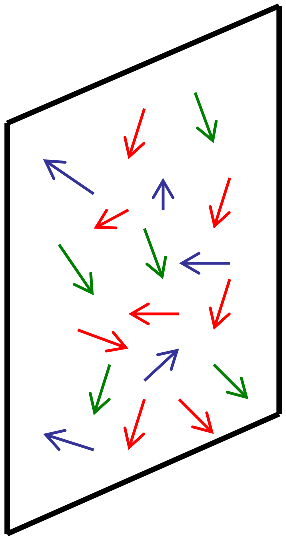
Gluon Saturation – Fields Only



Put many nucleons into a nucleus and Lorentz boost to the infinite momentum frame

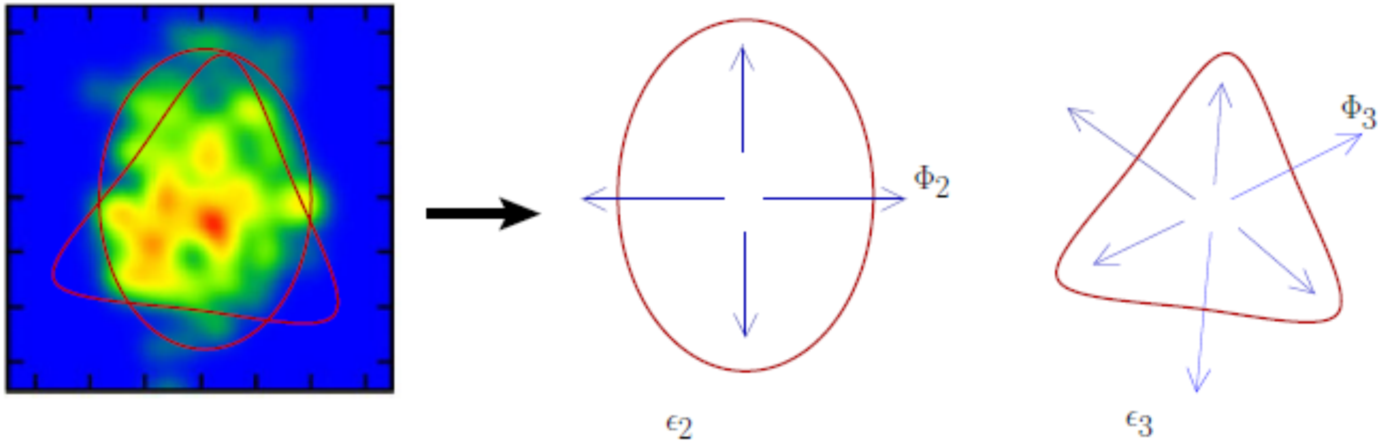
Creates a 2-dimensional sheet of very high density color charges set by a saturation scale.

$$Q_s^2(x,A) \approx 1\,\mathrm{GeV}^2 \left(\frac{10^{-4}}{x}\right)^{0.3} A^{0.3}$$

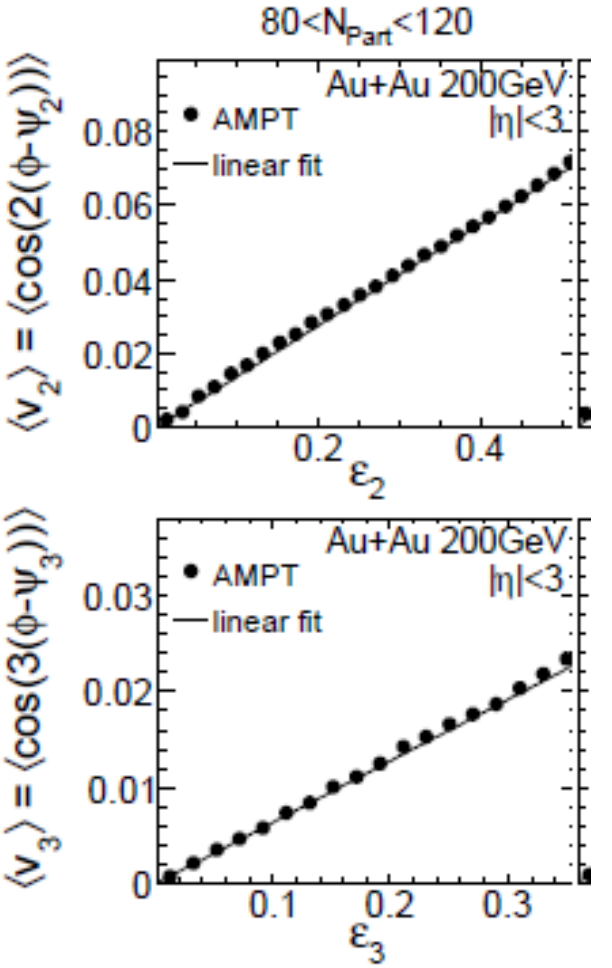


High density of gluons (saturation) allows for the simplification of Quantum Chromodynamics

Color fields can be described as classical wave solutions to the Yang-Mills equation



Spatial eccentricity e2, e3 (equa



$$\varepsilon_3 \equiv \frac{\sqrt{\langle r^2 \cos(3\phi_{\mathrm{part}})\rangle^2 + \langle r^2 \sin(3\phi_{\mathrm{part}})\rangle^2}}{\langle r^2 \rangle}$$

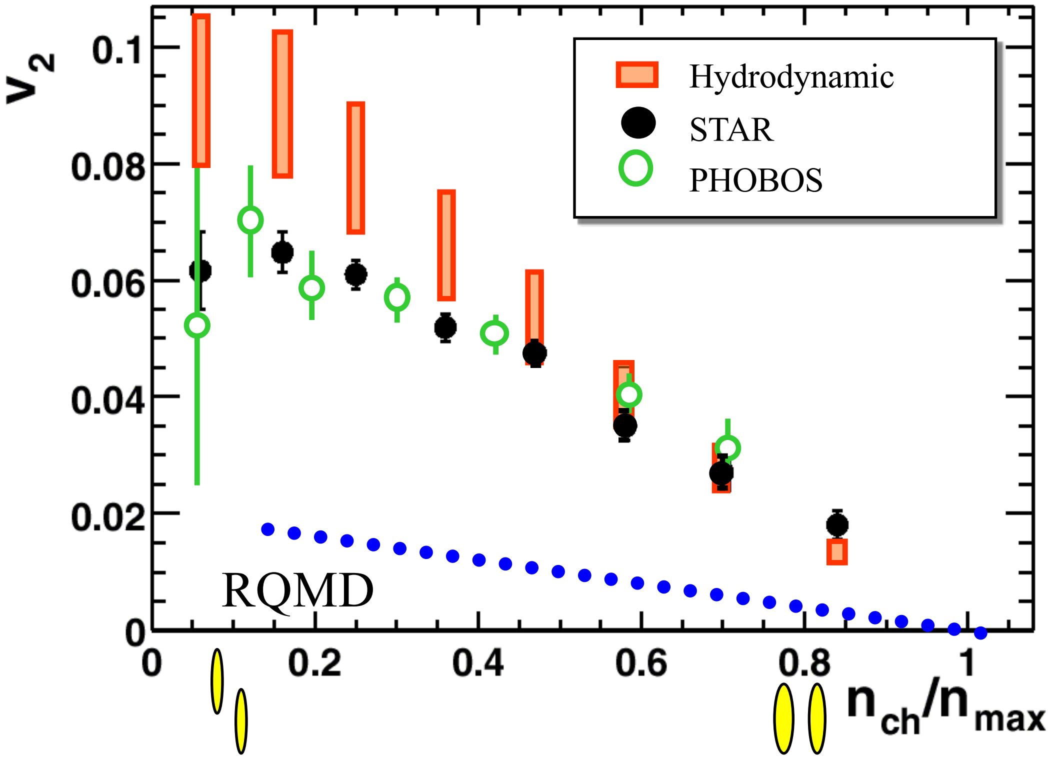
$$v_3 \equiv \langle \cos(3(\phi - \psi_3)) \rangle$$

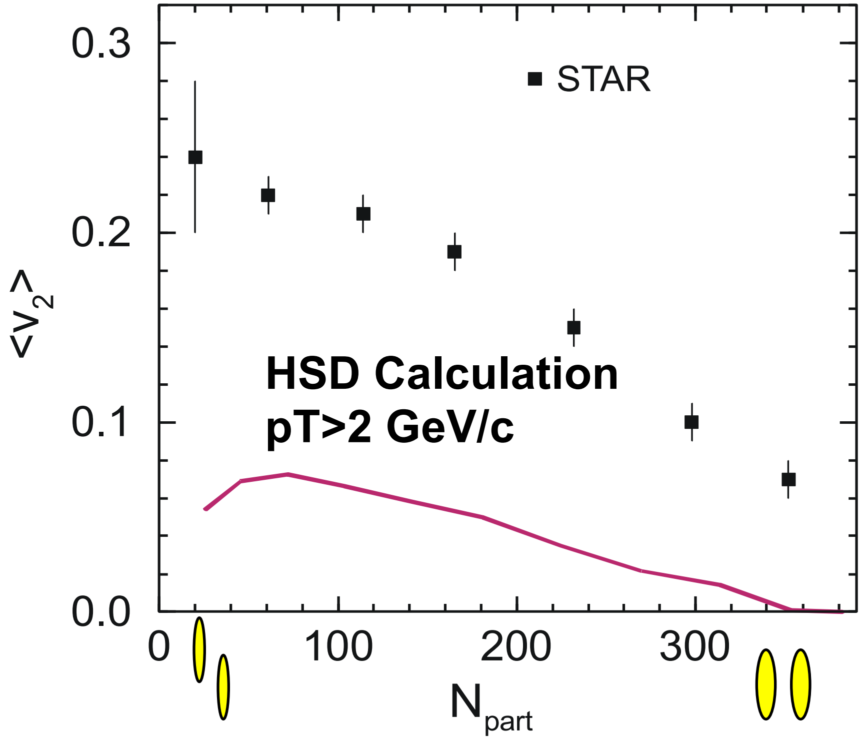
Interesting side note on AMPT

Hadron Gas ?

What interactions can lead to equilibration in < 1 fm/c?

Hadronic transport models (e.g. RQMD, HSD, ...) with hadron formation times ~1 fm/c, fail to describe data.

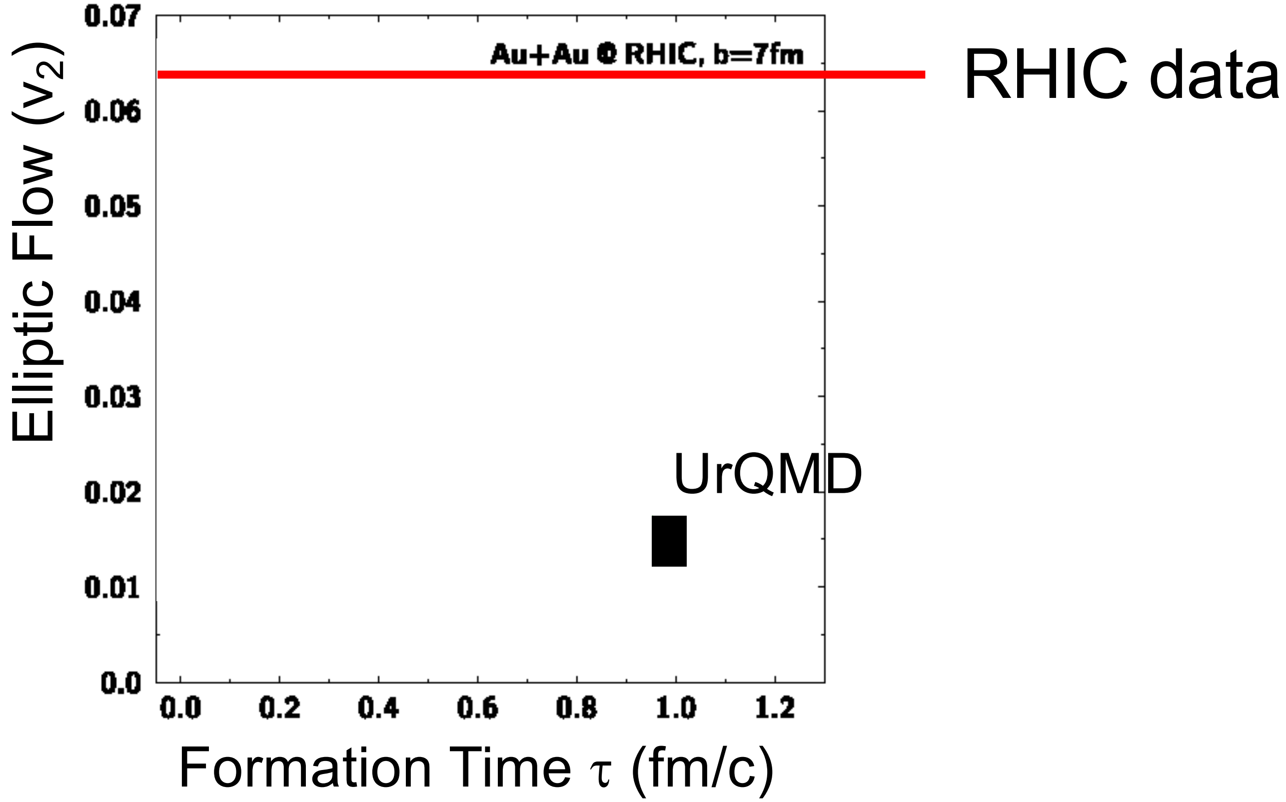




Clearly the system is not a hadron gas. Not surprising.

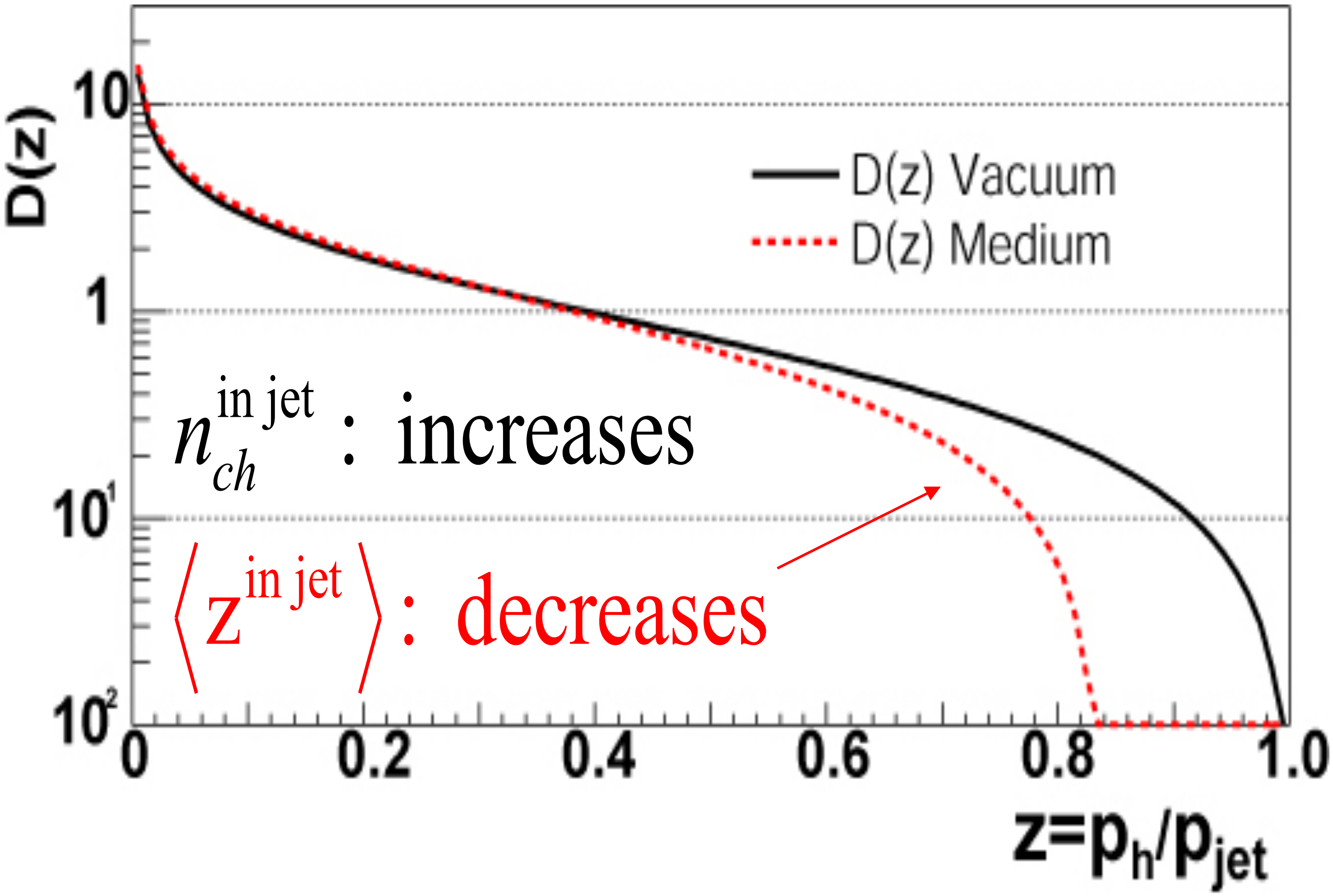
Hadron Formation Time

These string + hadronic transport models under-predict the collective motion by a factor of 4-10.



Only if we violate quantum mechanics and allow hadronic wavefunctions to fully form in τ→0 can we reproduce the data.

Modified Fragmentation



$n_{ch}^{\text{in jet}}$: increases

$\left\langle z^{\text{in jet}} \right\rangle$: decreases

What have we learned?

Jet quenching is experimentally so dramatic, sometimes we forget to ask what in detail we have learned.

1. The most basic thing we learn is the time integrated density of color charges for scattering that induces radiation.

$$\Delta E_{GLV} \approx \frac{9}{4}\alpha_s^3 \pi C_R \left(\frac{1}{\pi R^2} \frac{dN_g}{dy} \right) \left\{ \mathrm{Log} \frac{2E}{\mu^2 L} \right\} L(\phi)$$

Assuming only radiative energy loss, matching the high pT hadron suppression, indicates dN/dy(gluons) ~ 1000 or possibly dN/dy(quarks,gluons) ~ 2000.

Soft Singularity

“In the presently available RHIC range $p_T < 15$ GeV a reliable quantitative prediction of quenching can hardly be made. It is the soft singularity that causes instability of the pQCD description.” BDMS

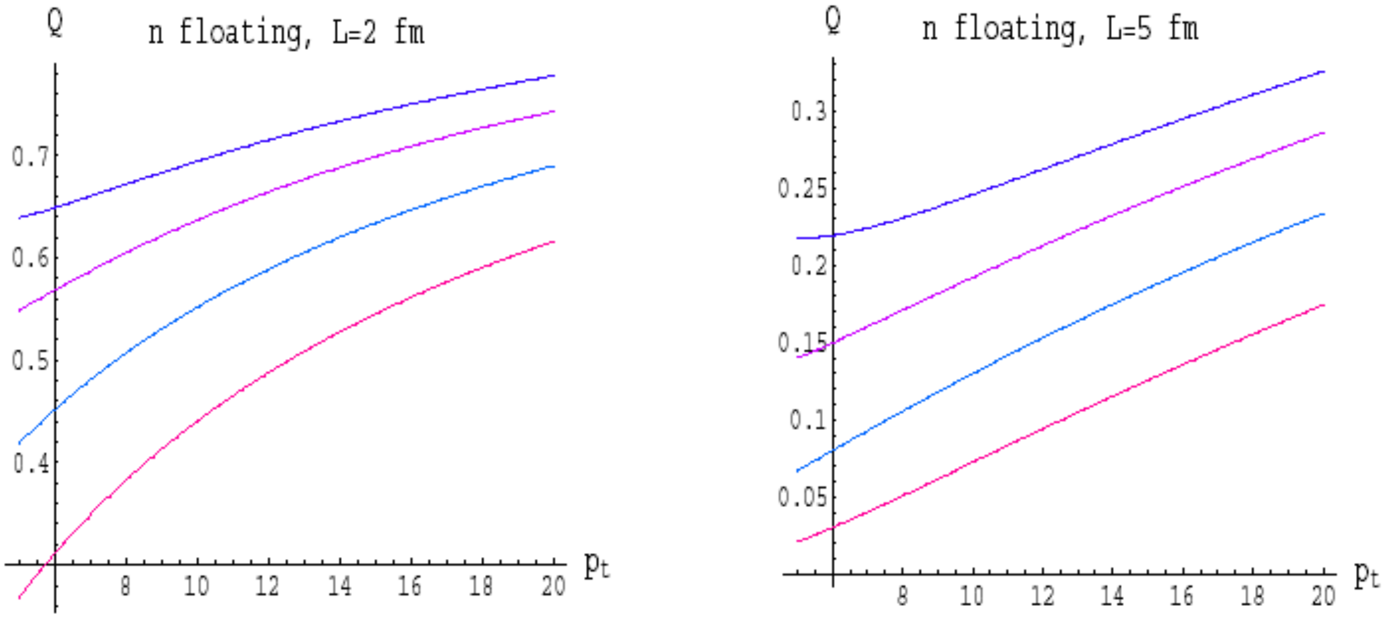
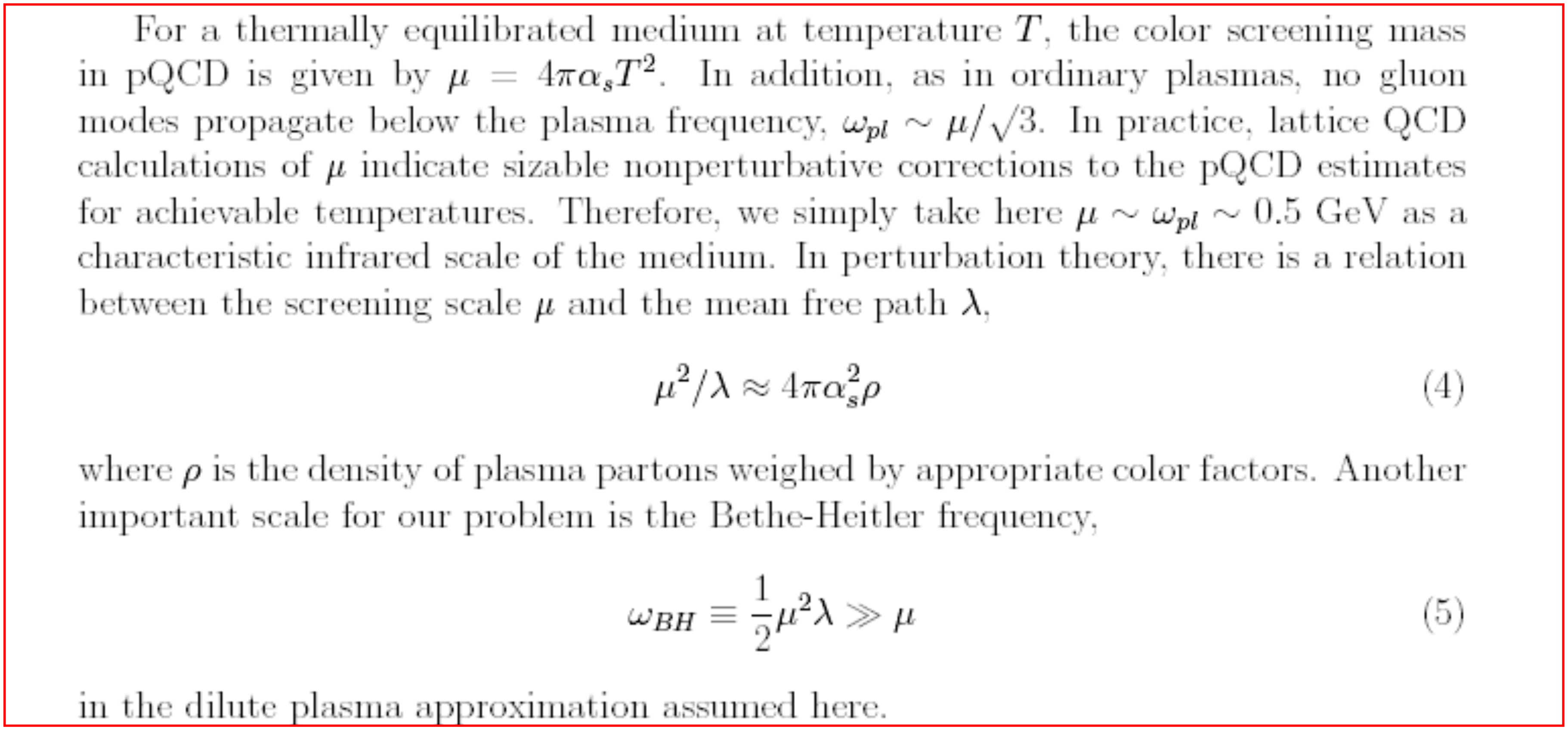


Figure 3: “Infrared” dependence of the quenching factor for hot medium. The curves (from bottom to top) correspond to the gluon energy cuts 0, 100, 300 and 500 MeV.

Plasmon Cutoff

No gluon modes propagate below the plasma frequency.
Provides a potential natural scale for the infrared cutoff.



For a thermally equilibrated medium at temperature T, the color screening mass in pQCD is given by $\mu = 4\pi\alpha_s T^2$. In addition, as in ordinary plasmas, no gluon modes propagate below the plasma frequency, $\omega_{pl} \sim \mu/\sqrt{3}$. In practice, lattice QCD calculations of μ indicate sizable nonperturbative corrections to the pQCD estimates for achievable temperatures. Therefore, we simply take here $\mu \sim \omega_{pl} \sim 0.5$ GeV as a characteristic infrared scale of the medium. In perturbation theory, there is a relation between the screening scale μ and the mean free path λ,

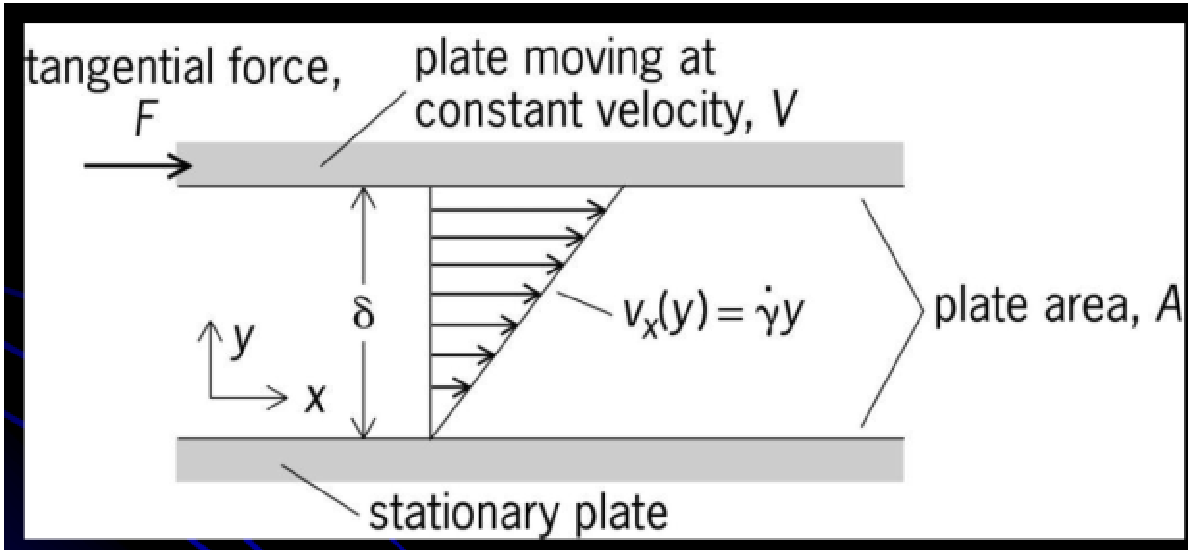
$$\mu^2/\lambda \approx 4\pi\alpha_s^2\rho \tag{4}$$

where ρ is the density of plasma partons weighed by appropriate color factors. Another important scale for our problem is the Bethe-Heitler frequency,

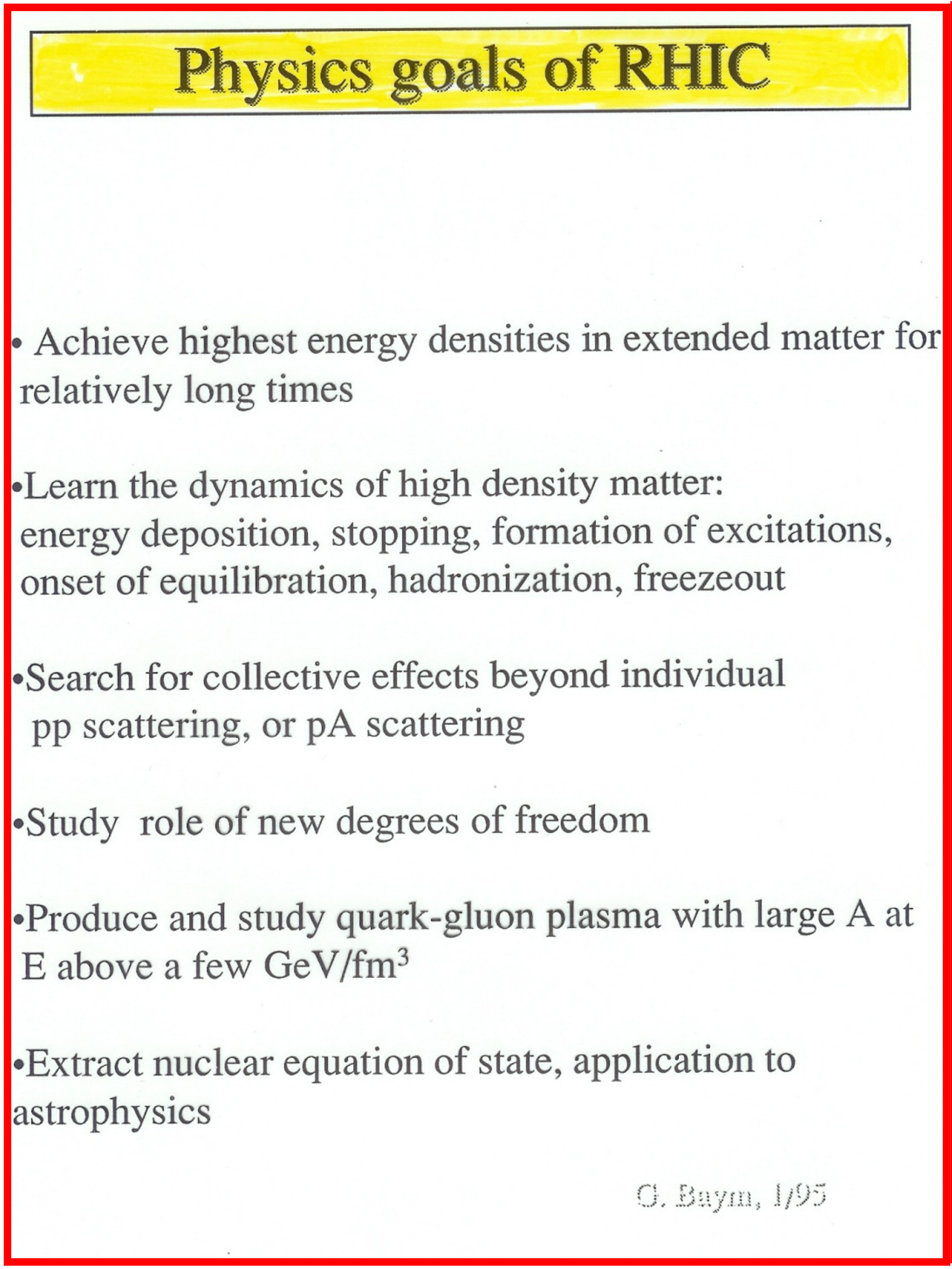
$$\omega_{BH} \equiv \frac{1}{2}\mu^2\lambda \gg \mu \tag{5}$$

in the dilute plasma approximation assumed here.

No gluon modes propagate below the plasma frequency.
This would also then be true for 0th order gluon radiation –
normal hadronization process !



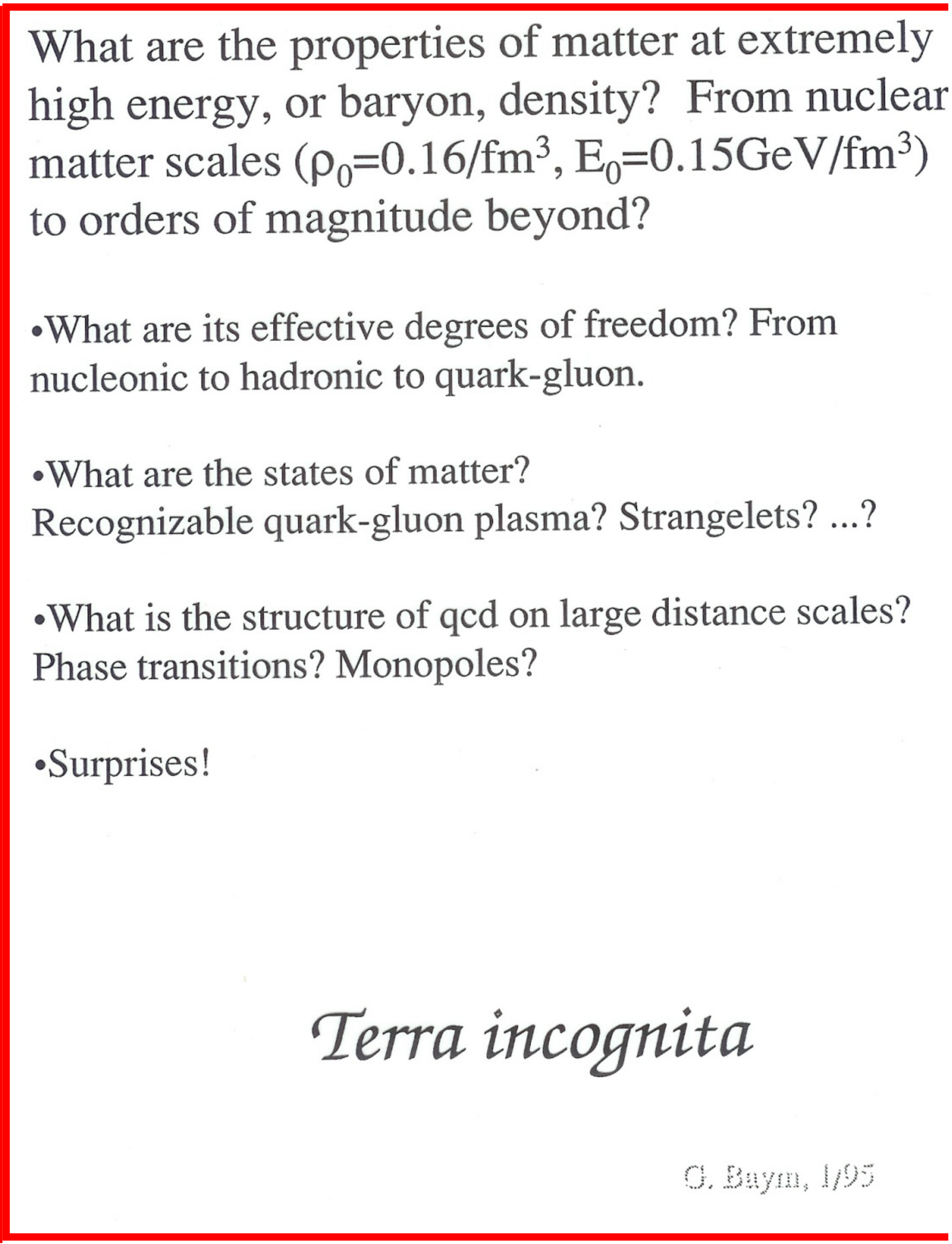
Shear viscosity characterizes quantitatively the resistance of the liquid or gas to displacement of its layers



Physics goals of RHIC

- Achieve highest energy densities in extended matter for relatively long times
- Learn the dynamics of high density matter: energy deposition, stopping, formation of excitations, onset of equilibration, hadronization, freezeout
- Search for collective effects beyond individual pp scattering, or pA scattering
- Study role of new degrees of freedom
- Produce and study quark-gluon plasma with large A at E above a few GeV/fm^3
- Extract nuclear equation of state, application to astrophysics

G. Baym, 1/95



What are the properties of matter at extremely high energy, or baryon, density? From nuclear matter scales (ρ_0=0.16/fm^3, E_0=0.15GeV/fm^3) to orders of magnitude beyond?

- What are its effective degrees of freedom? From nucleonic to hadronic to quark-gluon.
- What are the states of matter? Recognizable quark-gluon plasma? Strangelets? ...?
- What is the structure of qcd on large distance scales? Phase transitions? Monopoles?
- Surprises!

Terra incognita

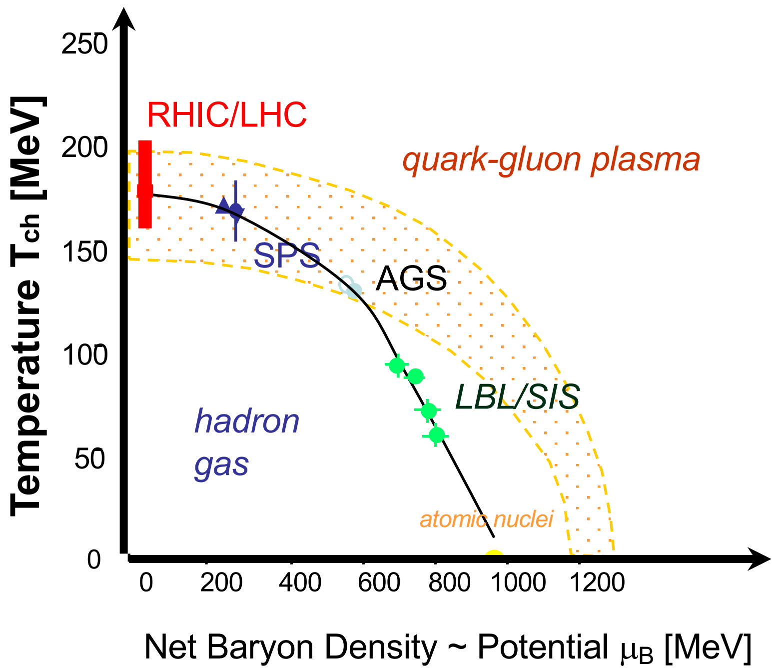
G. Baym, 1/95

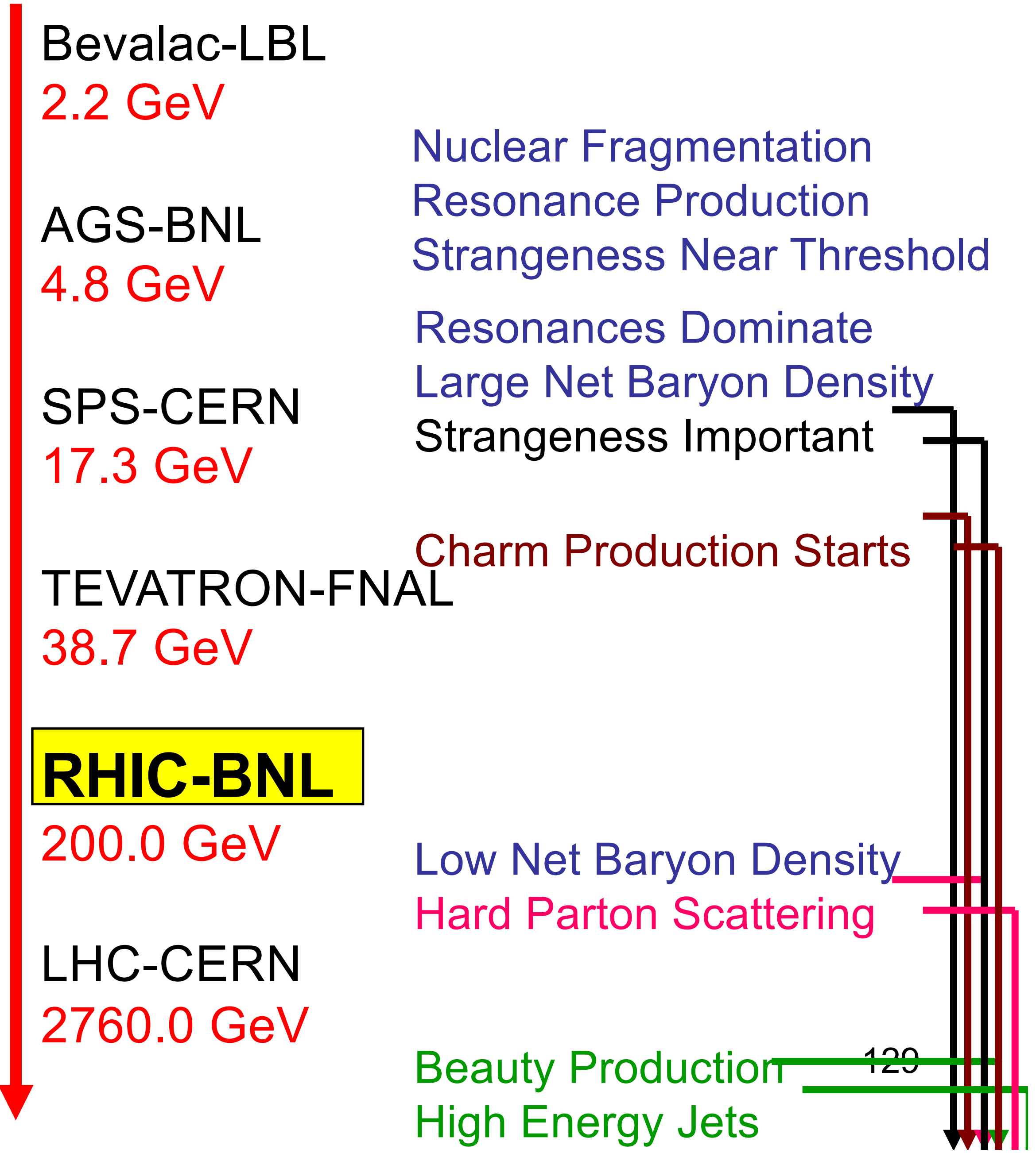
Changing the Medium, New Probes

Many basic goals of the field have remained the same over the last 20 years.

However, the character of the system created is a strong function of energy.

Many new probes and theoretical handles are available at higher energies.





Bevalac-LBL
2.2 GeV

AGS-BNL
4.8 GeV

SPS-CERN
17.3 GeV

TEVATRON-FNAL
38.7 GeV

RHIC-BNL
200.0 GeV

LHC-CERN
2760.0 GeV

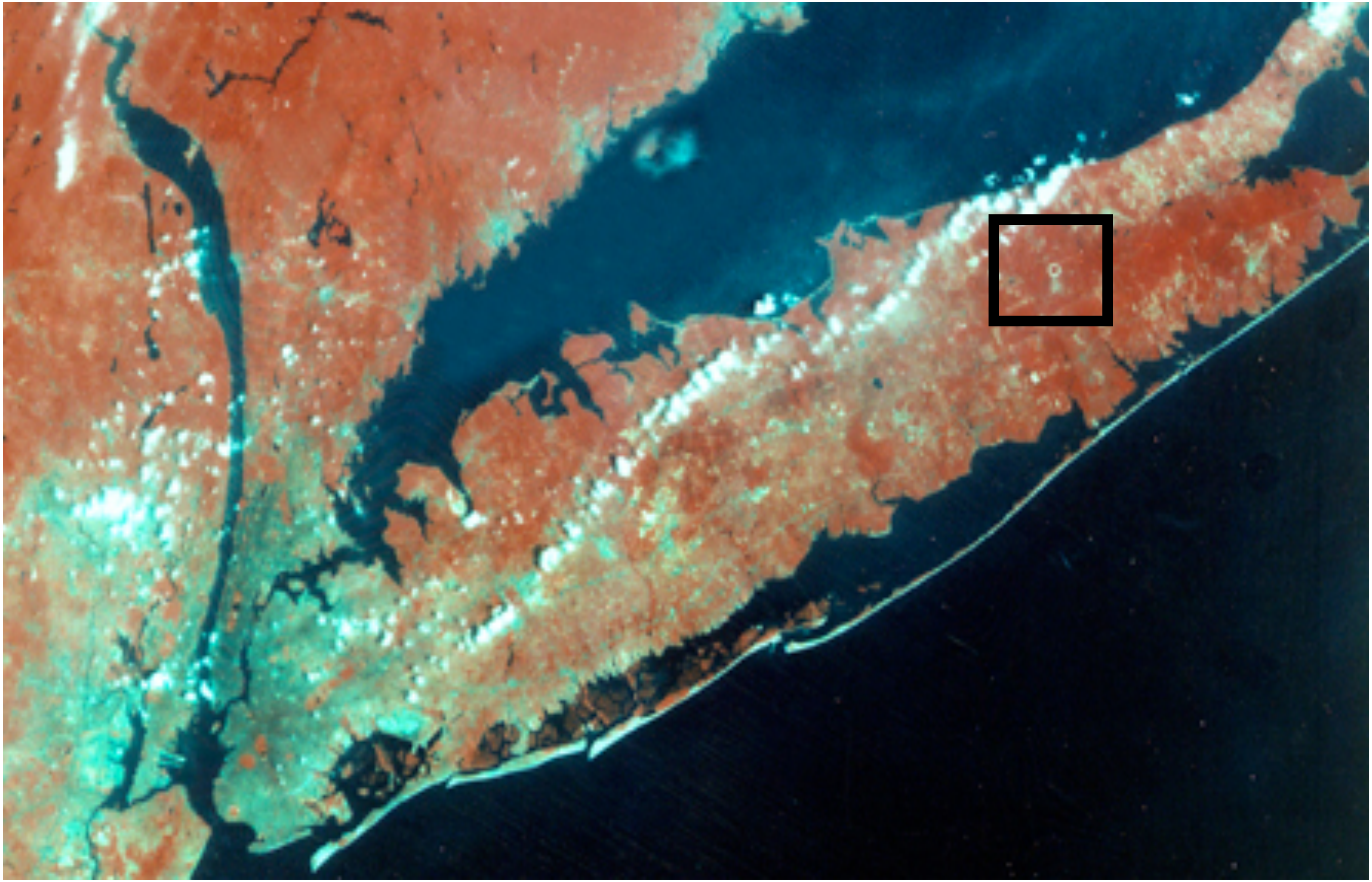
Nuclear Fragmentation
Resonance Production
Strangeness Near Threshold

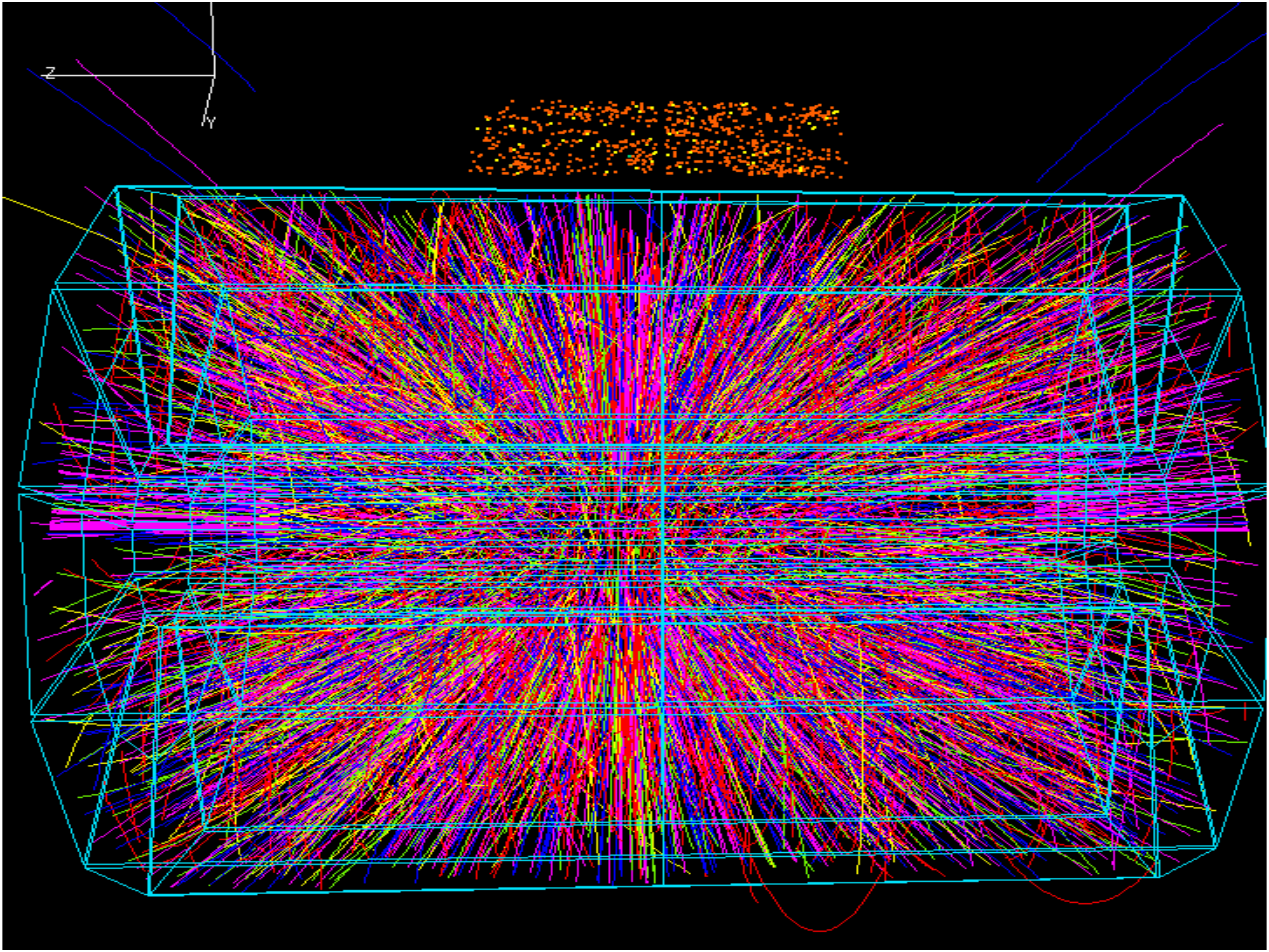
Resonances Dominate
Large Net Baryon Density
Strangeness Important

Charm Production Starts

Low Net Baryon Density
Hard Parton Scattering

Beauty Production
High Energy Jets




Z
Y

End of the World!

Can be dismissed with some basic General Relativity

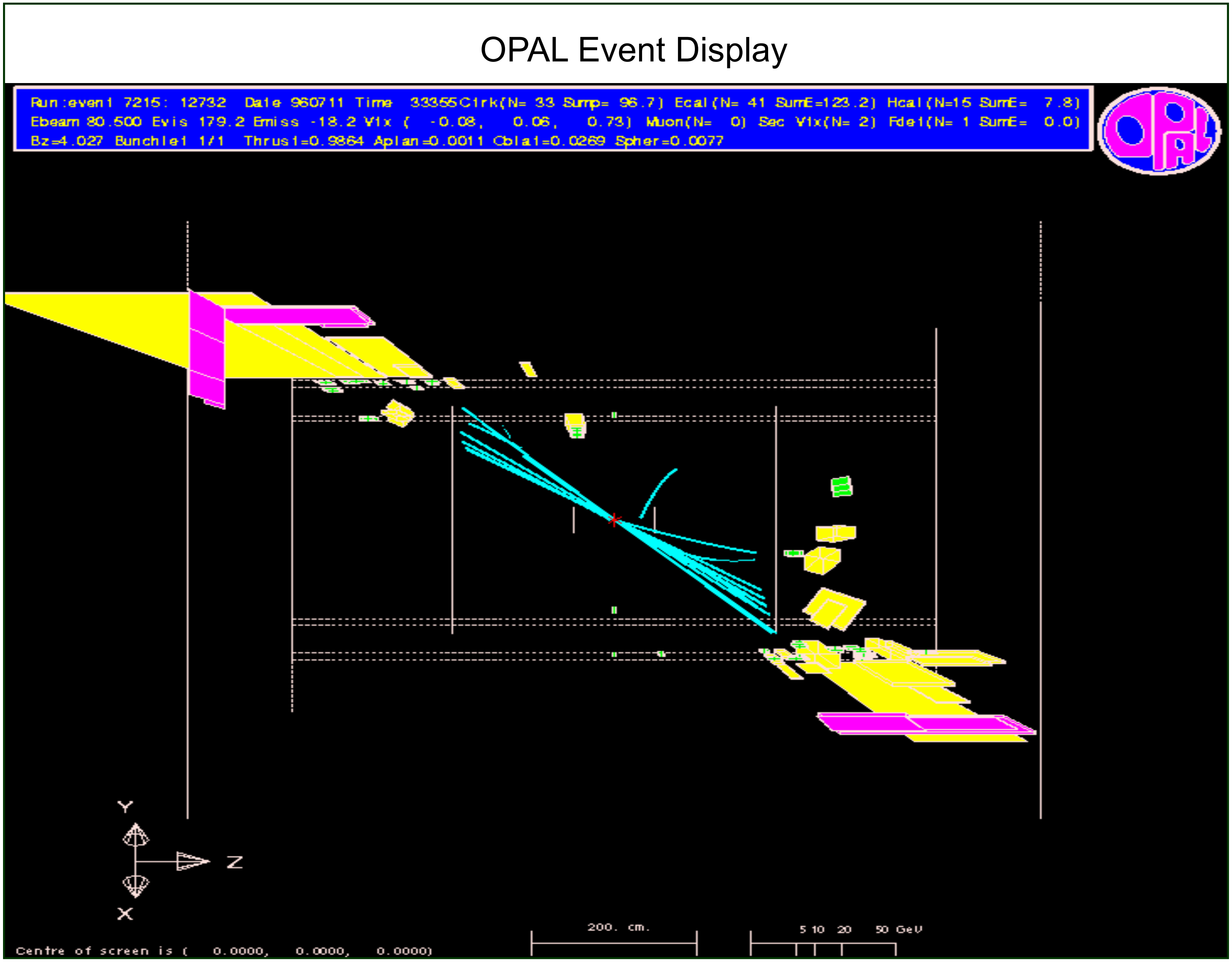
$$R_S = {}^{2GM}\!/\!_{c^2} = 10^{49}\, meters$$

much less than Planck length !

$$R = 10^{15}\, meters$$

Even if it could form, it would evaporate by Hawking Radiation in 10^{-83} seconds !

Start with Simpler System

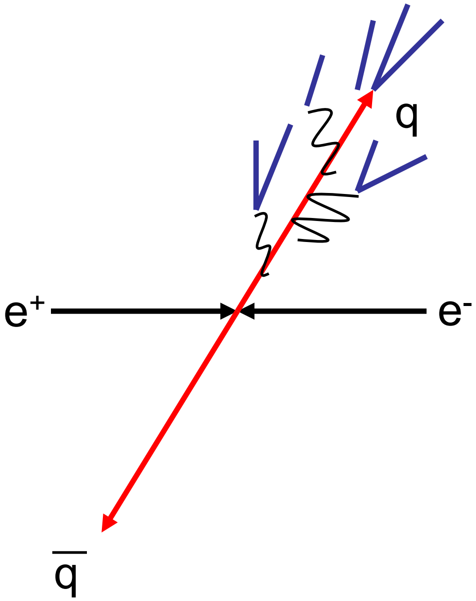


OPAL Event Display

```
Run:event 7215: 12732  Date 960711 Time  33355Ctrk(N= 33 Sump= 96.7) Ecal(N= 41 SumE=123.2) Hcal(N=15 SumE=  7.8)
Ebeam 80.500 Evis 179.2 Emiss -18.2 Vtx (  -0.08,   0.06,   0.73) Muon(N=  0) Sec Vtx(N= 2) Fdet(N= 1 SumE=  0.0)
Bz=4.027 Bunchlet 1/1  Thrust=0.9864 Aplan=0.0011 Oblat=0.0269 Spher=0.0077
```

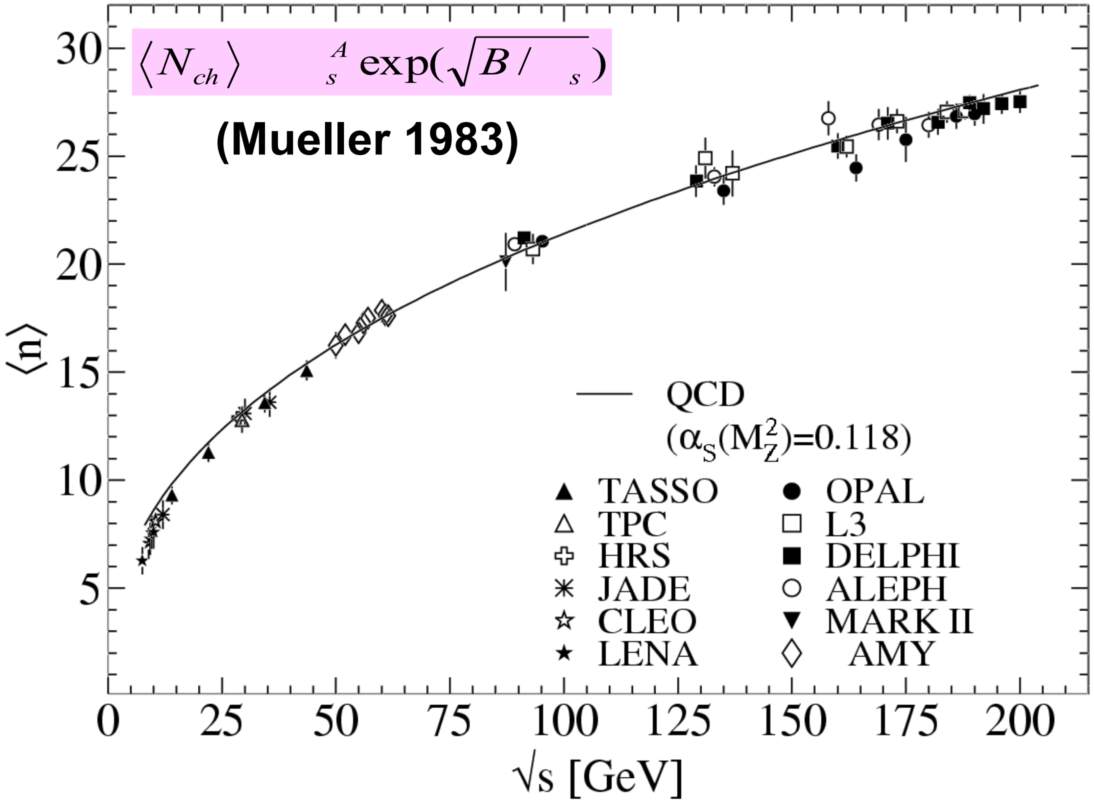
Electron-Positron Annihilation

e+e- → $q\bar{q}$ → hadron jets



Quark radiates gluons and eventually forms hadrons in a jet cone.

QCD calculation of gluon multiplicity times a hadron scale factor gives excellent agreement with data.



Bjorken Energy Density

- At $t=t_{form}$, the hatched volume contains all particles w/ $b<dz/t_{form}$:

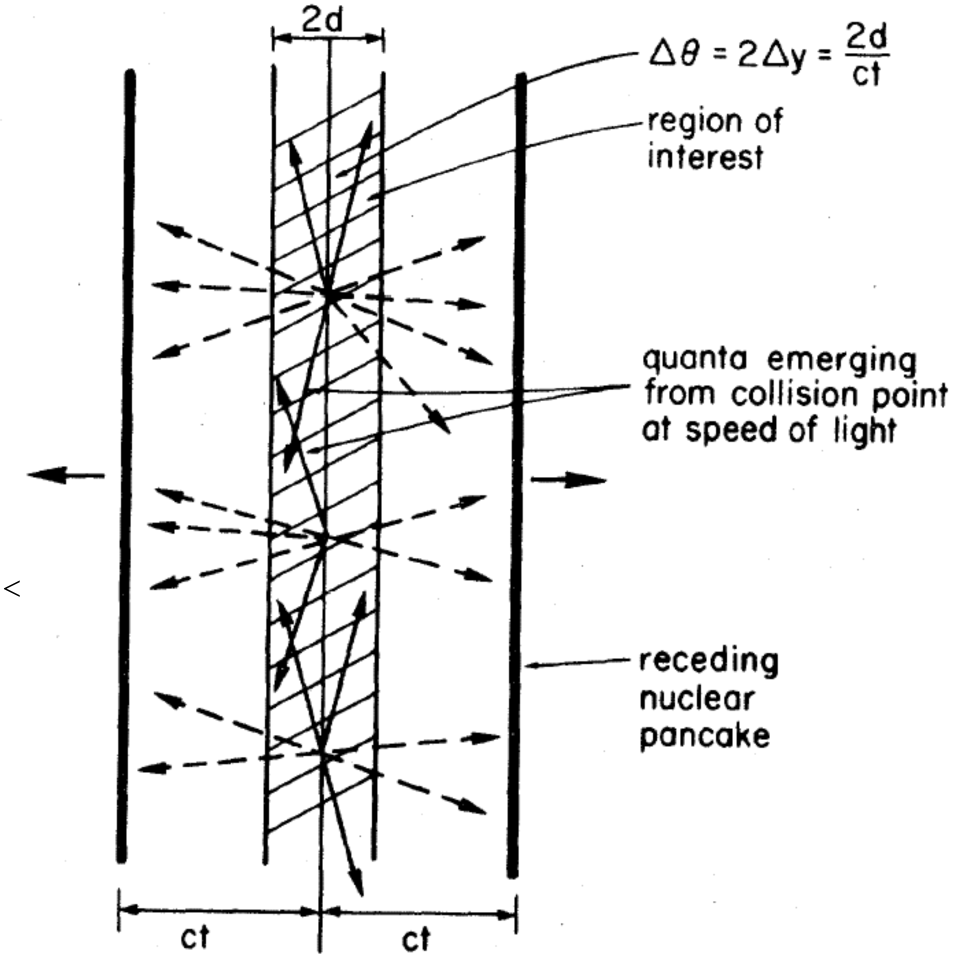
$$dN = \frac{dz}{t_{form}}\frac{dN}{d_{\|}} = \frac{dz}{t_{form}}\frac{dN}{dy};(dy = d_{\|} @ y = 0)$$

- At $y=b_{\|}=0$, $E=m_T$, thus:

$$\left\langle \ (t_{form})\right\rangle = \frac{E}{V} = \frac{dN < m_T >}{dz\ \ A} = \frac{dN(t_{form})}{dy}\frac{< m_T >}{t_{form}\ \ A}$$

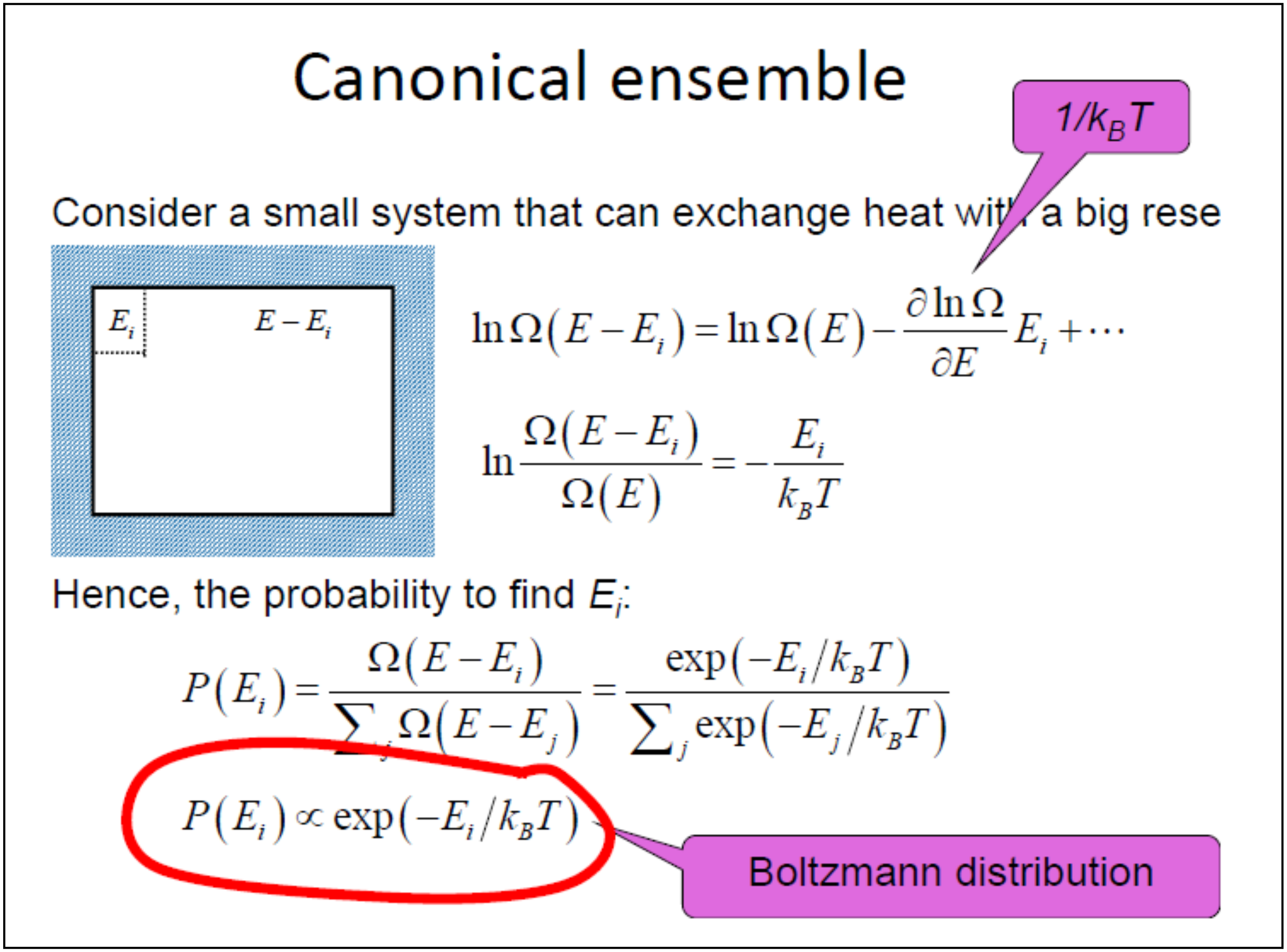
- We can equate $dN<m_T>$ & dE_T and have:

$$\left\langle \ _{BJ}(t_{form})\right\rangle = \frac{1}{t_{form}\ \ A}\frac{dE_T(t_{form})}{dy}$$



Two nuclei pass through one another leaving a region of produced particles between them.

Side Comment on Phase Space and Boltzmann



Canonical ensemble

$1/k_BT$

Consider a small system that can exchange heat wit a big rese

$$\ln\Omega(E-E_i) = \ln\Omega(E) - \frac{\partial \ln\Omega}{\partial E} E_i + \cdots$$

$$\ln\frac{\Omega(E-E_i)}{\Omega(E)} = -\frac{E_i}{k_BT}$$

Hence, the probability to find E_i:

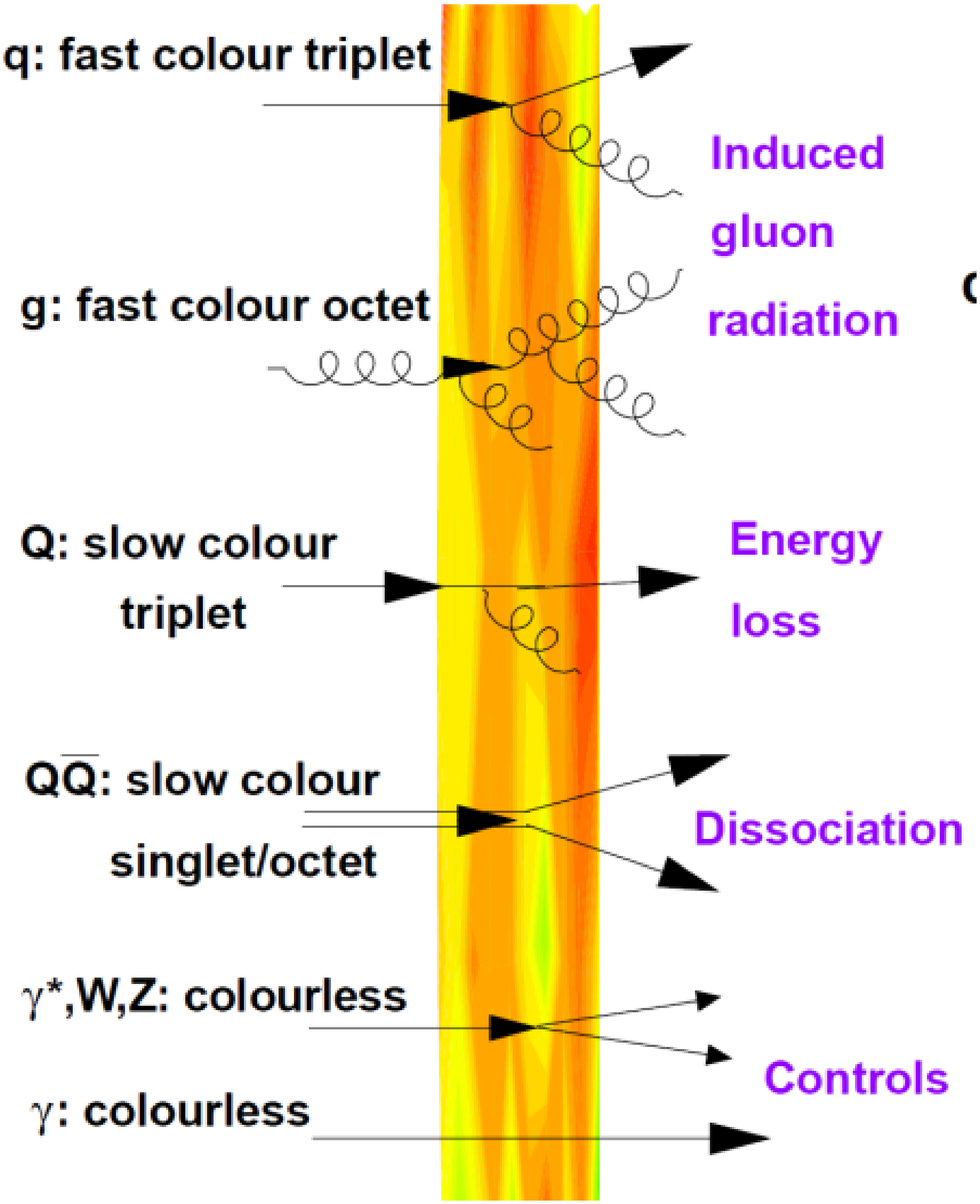
$$P(E_i) = \frac{\Omega(E-E_i)}{\sum_j \Omega(E-E_j)} = \frac{\exp(-E_i/k_BT)}{\sum_j \exp(-E_j/k_BT)}$$

$$P(E_i) \propto \exp(-E_i/k_BT)$$

Boltzmann distribution

Warning signs…

What are the odds on either of these plates?



q: fast colour triplet

g: fast colour octet

Induced

gluon

radiation

Q: slow colour

triplet

Energy

loss

$Q\bar{Q}$: slow colour

singlet/octet

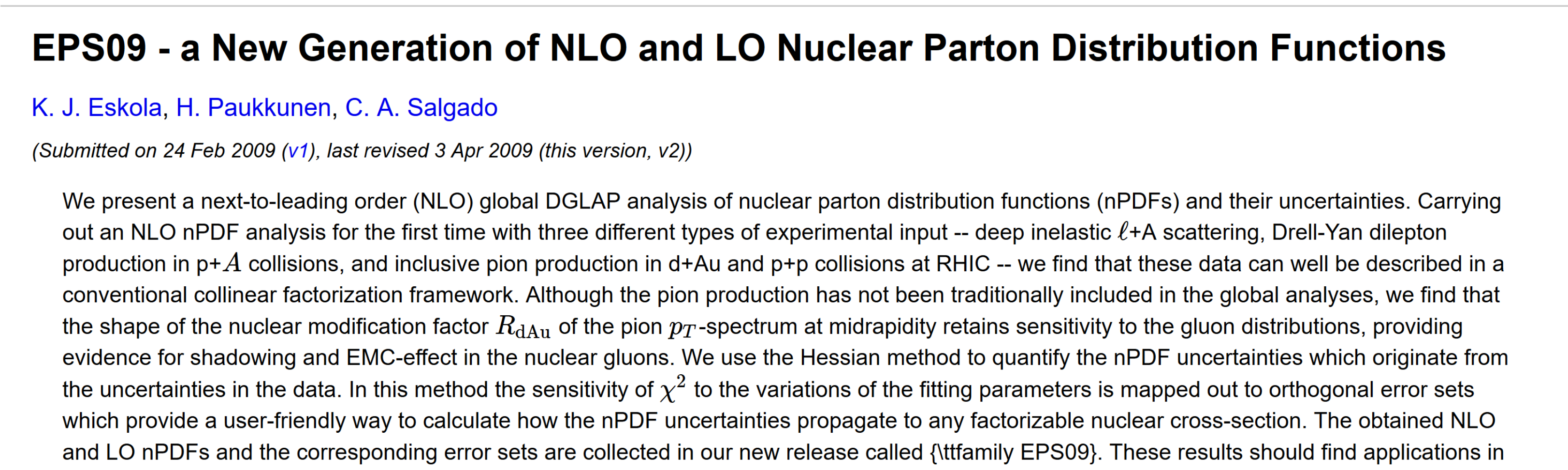
Dissociation

γ^*,W,Z: colourless

γ: colourless

Controls

http://arxiv.org/abs/0902.4154

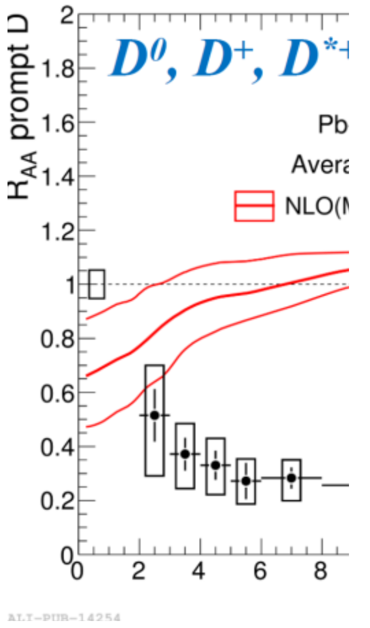


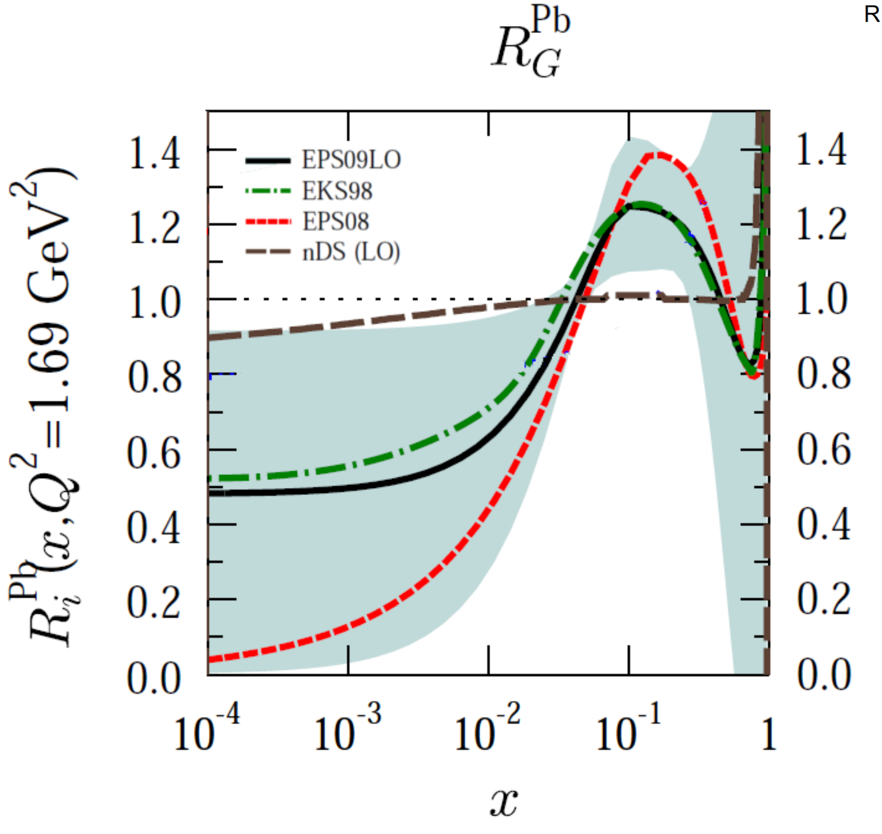
EPS09 - a New Generation of NLO and LO Nuclear Parton Distribution Functions

K. J. Eskola, H. Paukkunen, C. A. Salgado

(Submitted on 24 Feb 2009 (v1), last revised 3 Apr 2009 (this version, v2))

We present a next-to-leading order (NLO) global DGLAP analysis of nuclear parton distribution functions (nPDFs) and their uncertainties. Carrying out an NLO nPDF analysis for the first time with three different types of experimental input -- deep inelastic ℓ+A scattering, Drell-Yan dilepton production in p+A collisions, and inclusive pion production in d+Au and p+p collisions at RHIC -- we find that these data can well be described in a conventional collinear factorization framework. Although the pion production has not been traditionally included in the global analyses, we find that the shape of the nuclear modification factor $R_{\rm dAu}$ of the pion p_T-spectrum at midrapidity retains sensitivity to the gluon distributions, providing evidence for shadowing and EMC-effect in the nuclear gluons. We use the Hessian method to quantify the nPDF uncertainties which originate from the uncertainties in the data. In this method the sensitivity of χ^2 to the variations of the fitting parameters is mapped out to orthogonal error sets which provide a user-friendly way to calculate how the nPDF uncertainties propagate to any factorizable nuclear cross-section. The obtained NLO and LO nPDFs and the corresponding error sets are collected in our new release called {\ttfamily EPS09}. These results should find applications in RHIC.



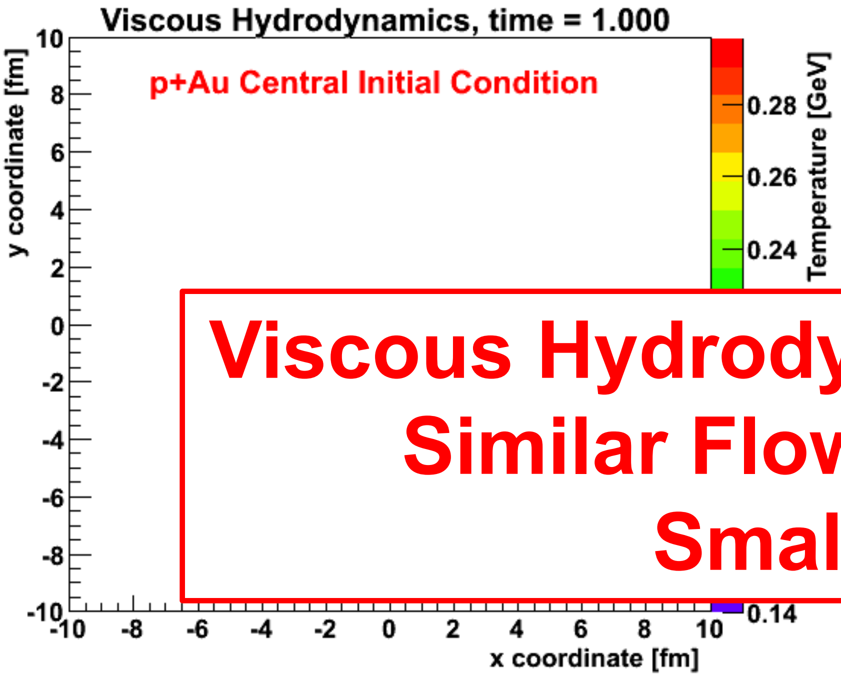


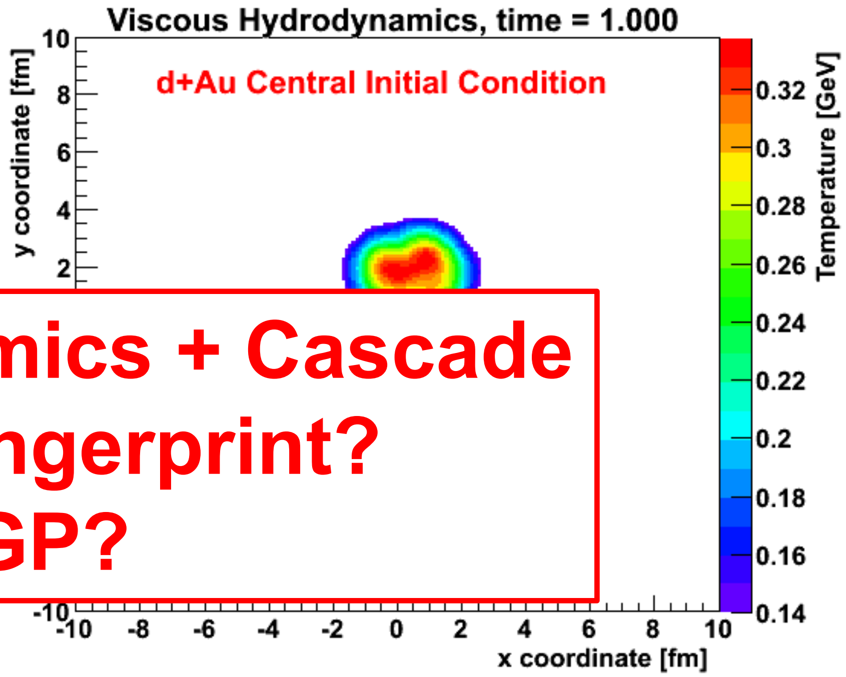
Pocket equation (good

X1 = x2 = 2 x (sqrt(m2

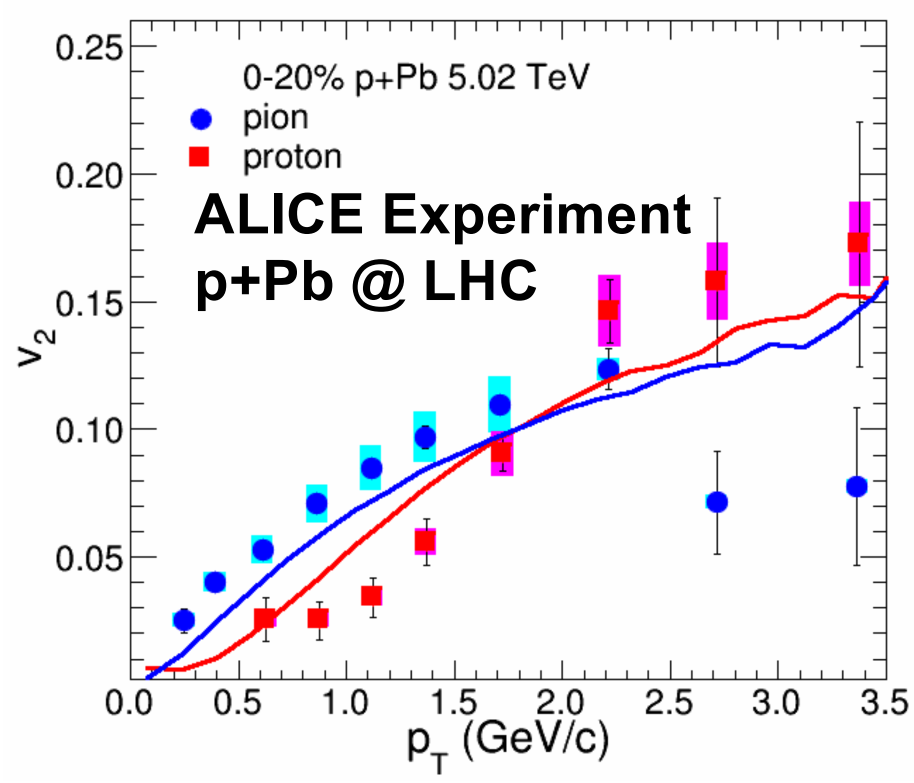
LHC charm / beauty at

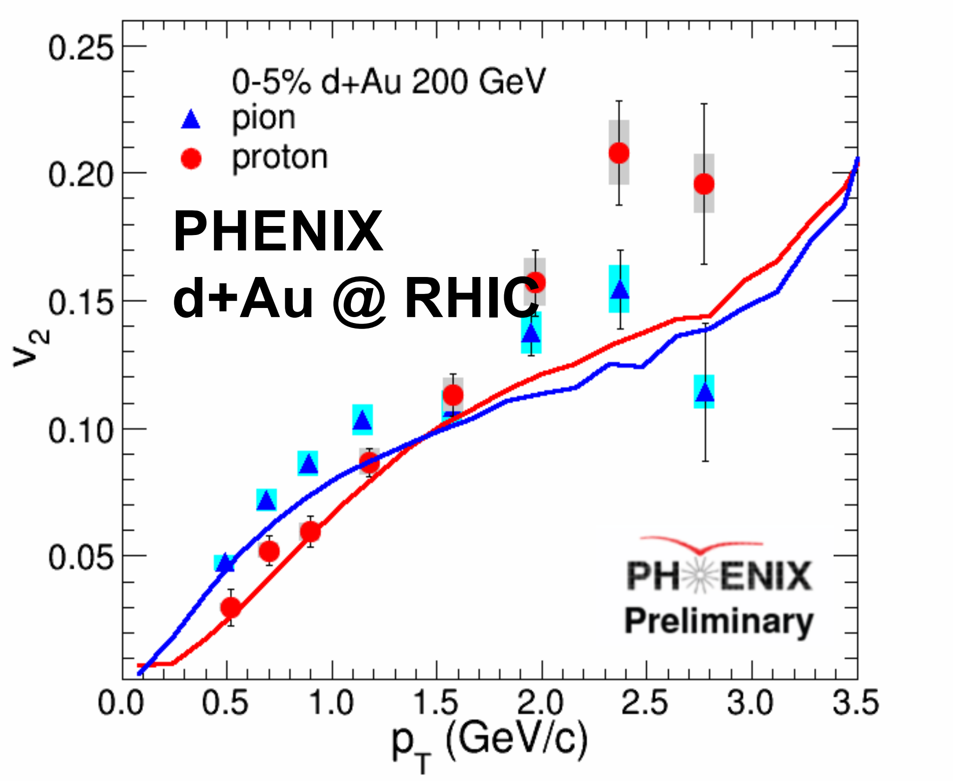
X1 = 0.001 (0.002)

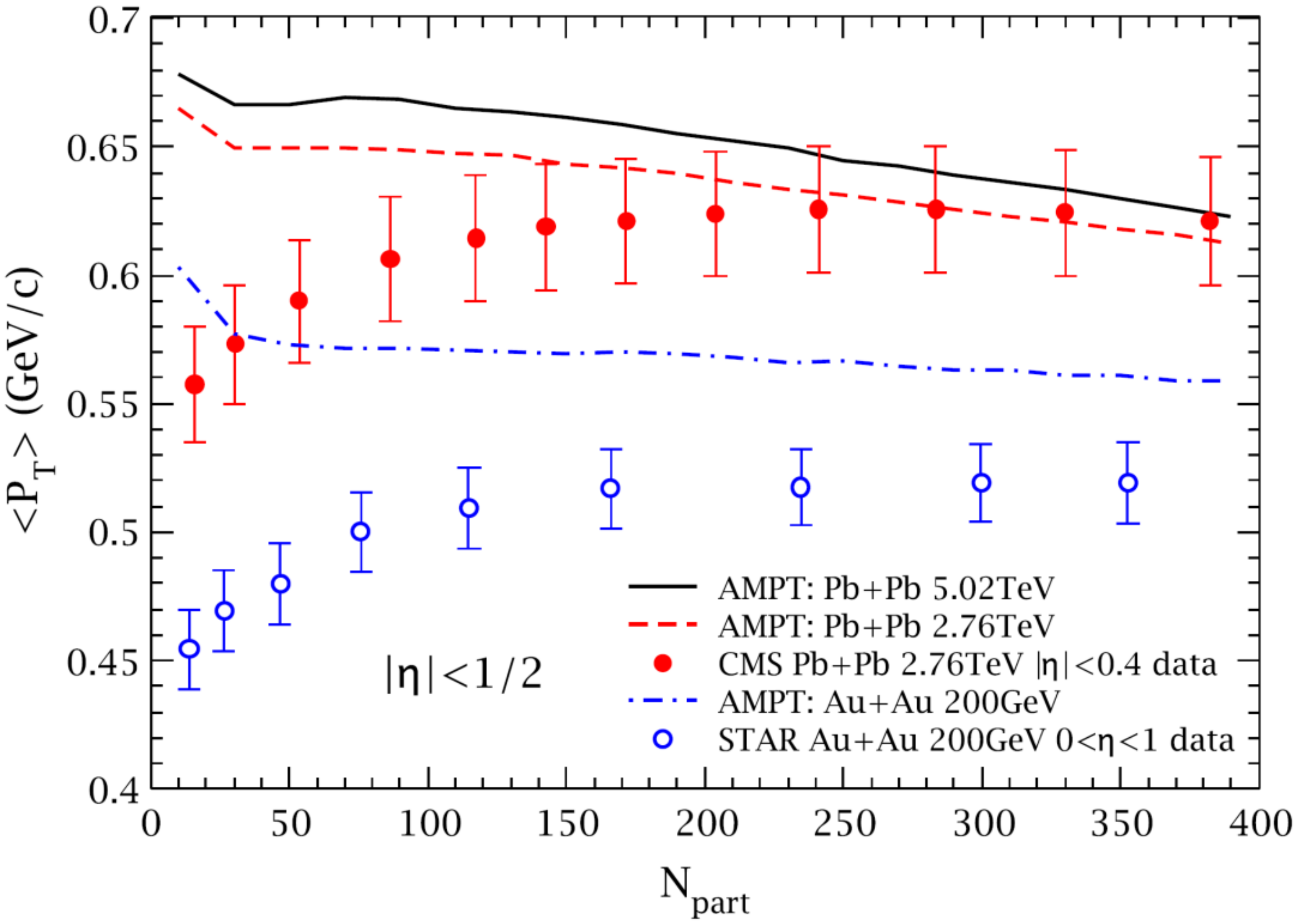




Viscous Hydrodynamics + Cascade
Similar Flow Fingerprint?
Small QGP?

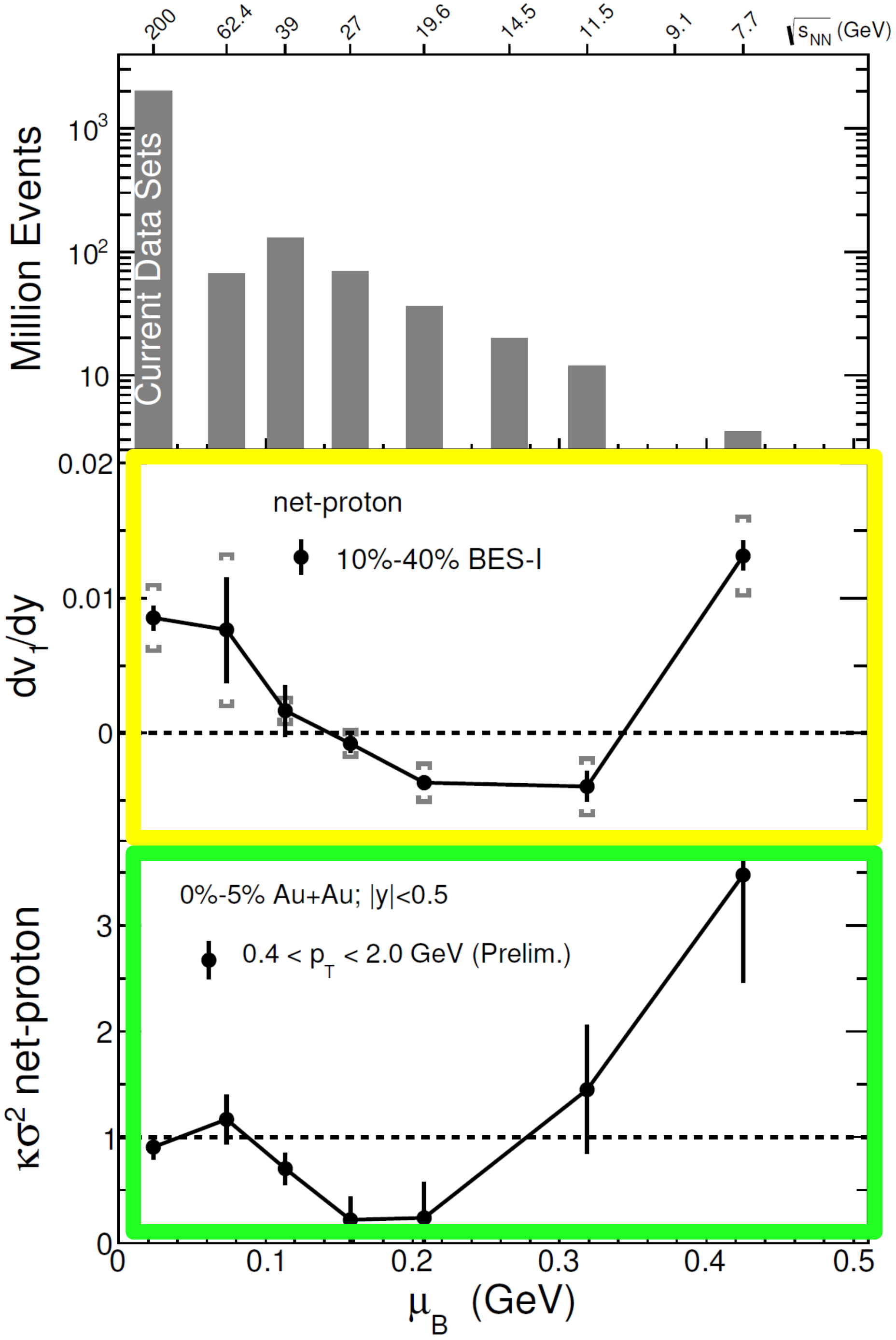






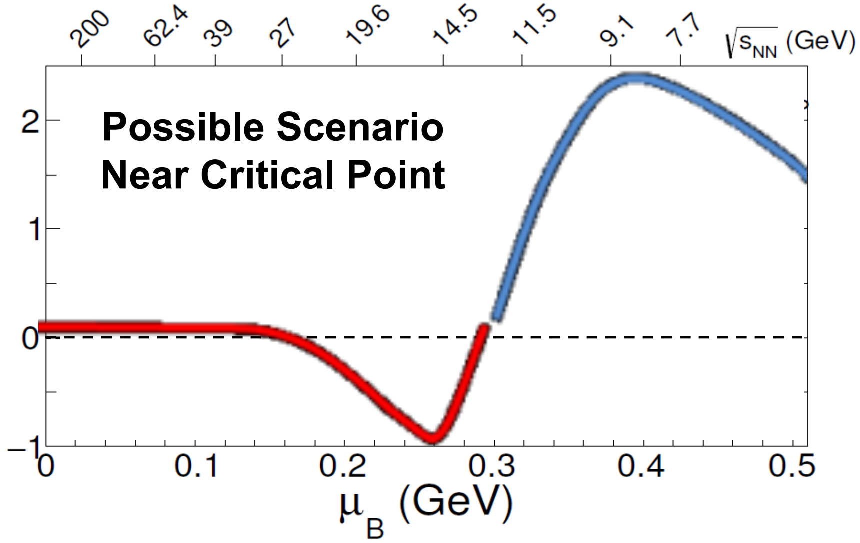
0.7
0.65
0.6
0.55
0.5
0.45
0.4
$<P_T>$ (GeV/c)
0
50
100
150
200
250
300
350
400
N_{part}
|η|<1/2
AMPT: Pb+Pb 5.02TeV
AMPT: Pb+Pb 2.76TeV
CMS Pb+Pb 2.76TeV |η|<0.4 data
AMPT: Au+Au 200GeV
STAR Au+Au 200GeV 0<η<1 data

Critical Point Hints



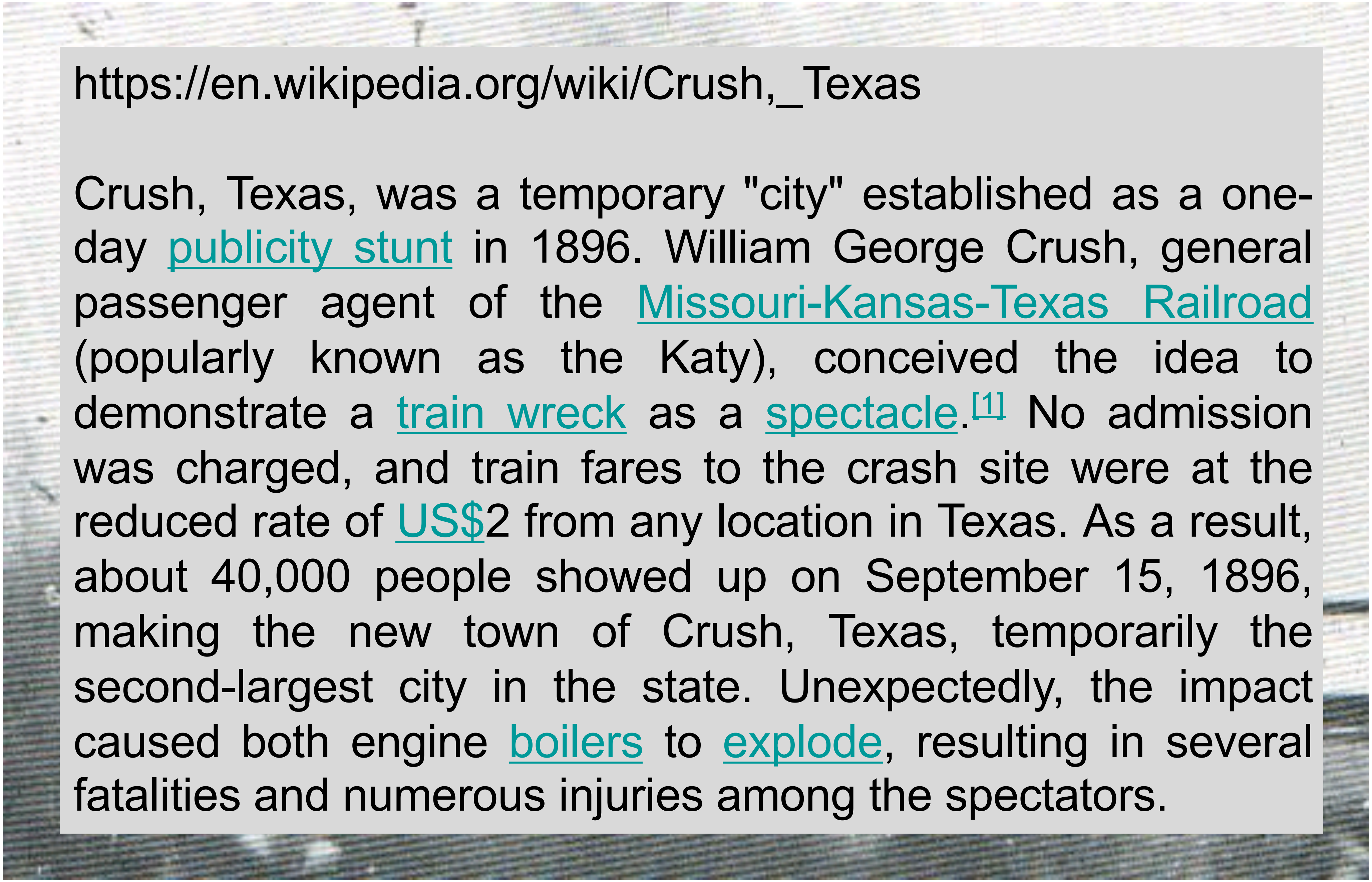
Minimum in v_1 slope was predicted as consequence of the softening of the equation of state in the transition region.

Net-proton fluctuations, proximity to critical point?



BES-2 Data Taking 2019-2020

Kinetic Energy → Thermal Energy



https://en.wikipedia.org/wiki/Crush,_Texas

Crush, Texas, was a temporary "city" established as a one-day publicity stunt in 1896. William George Crush, general passenger agent of the Missouri-Kansas-Texas Railroad (popularly known as the Katy), conceived the idea to demonstrate a train wreck as a spectacle.[1] No admission was charged, and train fares to the crash site were at the reduced rate of US$2 from any location in Texas. As a result, about 40,000 people showed up on September 15, 1896, making the new town of Crush, Texas, temporarily the second-largest city in the state. Unexpectedly, the impact caused both engine boilers to explode, resulting in several fatalities and numerous injuries among the spectators.

Simplest Goals

Frank Wilczek:

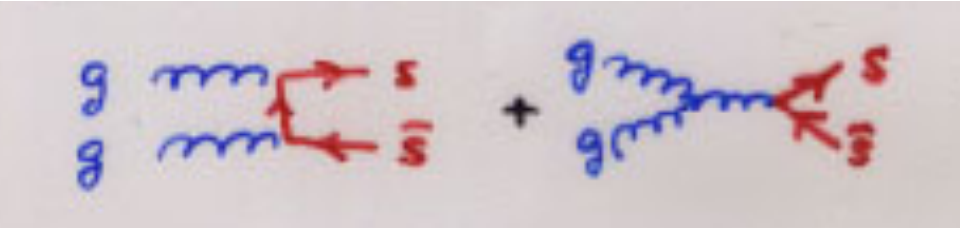
“In the quest for evidence of the quark-gluon plasma, there are two levels to which one might aspire. At the first level, one might hope to observe phenomena that are very difficult to explain from a hadronic perspective but have a simple qualitative explanation based on quarks and gluons.

But there is a second, more rigorous level that remains a challenge for the future. Using fundamental aspects of QCD theory, one can make quantitative predictions for the emission of various kinds of “hard” radiation from the quark gluon plasma. We will not have done justice to the concept of *weakly* interacting plasma of quarks and gluons until some of the predictions are confirmed by experiment.”

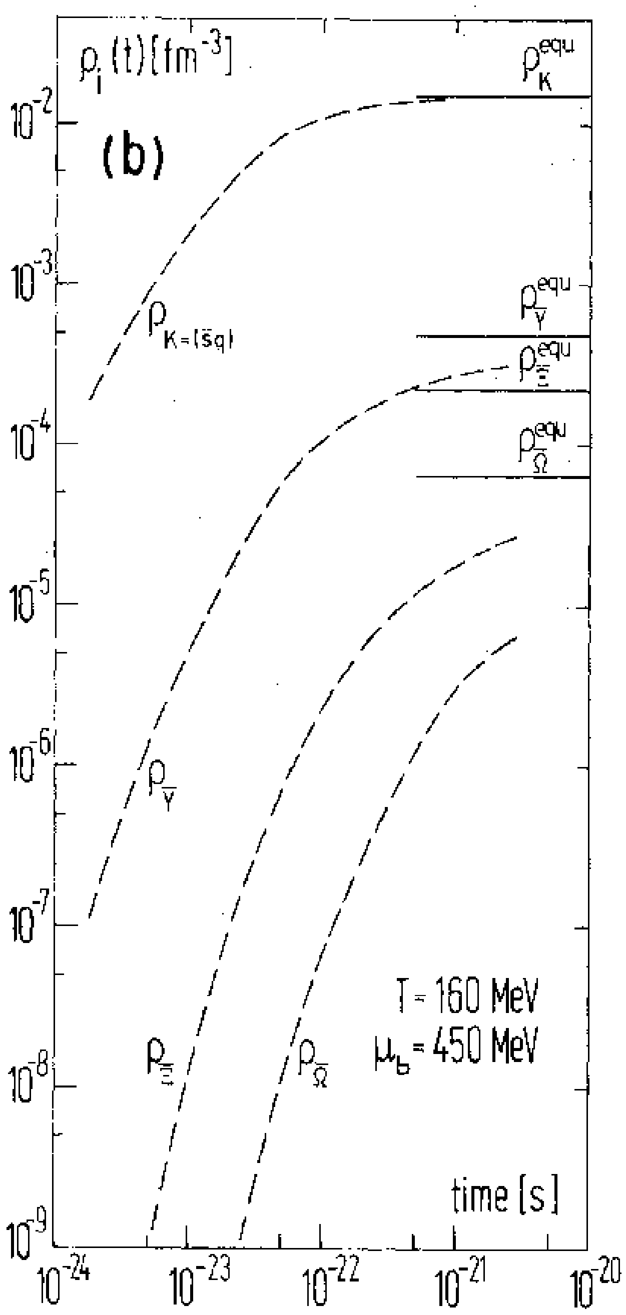
Strangeness Enhancement

Hadronic rescattering can equilibrate overall strangeness (ie. K^+, K^-, Λ) in **10-100 fm/c** and strange antibaryons (Λ, Ξ, Ω) in over **1000 fm/c** !

Quark-gluon plasma may equilibrate all strange particles in **3-6 fm/c** !



Heavy Ion collision lifetime is of order **10-15 fm/c** before free streaming.

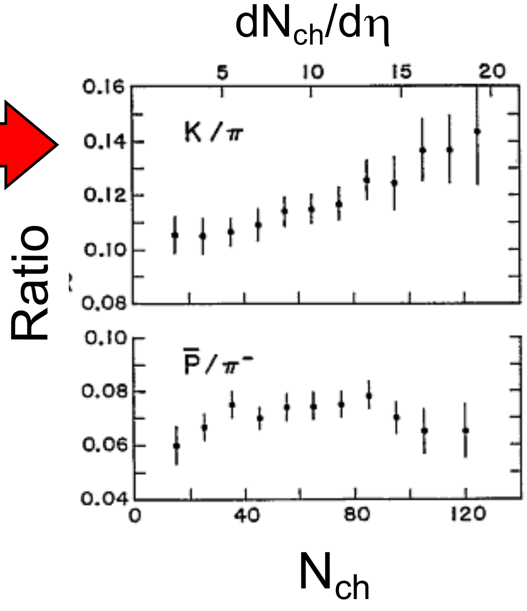


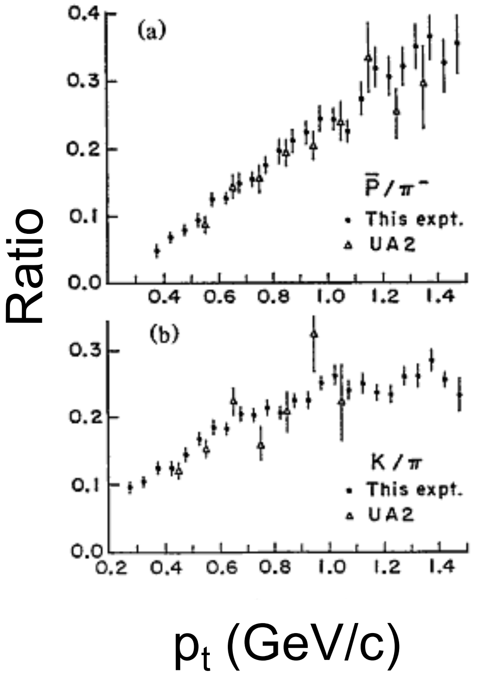
Strangeness Enhancement

Strangeness is enhanced in high multiplicity pp events, but not up to statistical equilibrium.

Experiment E735

K/π

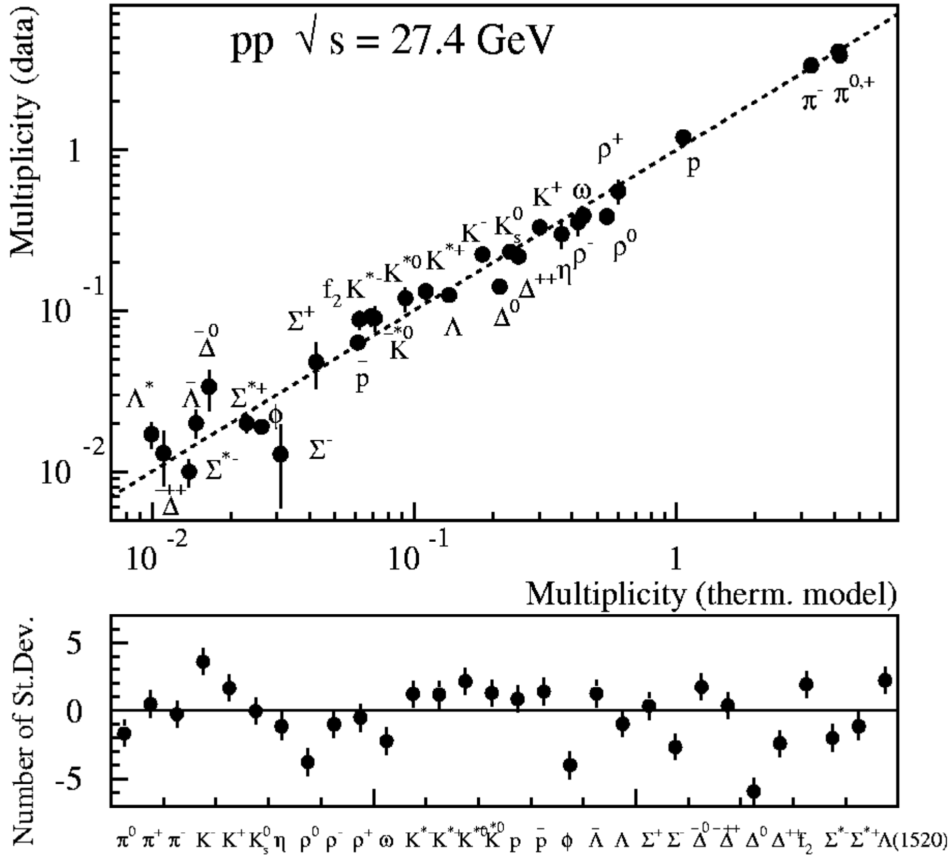


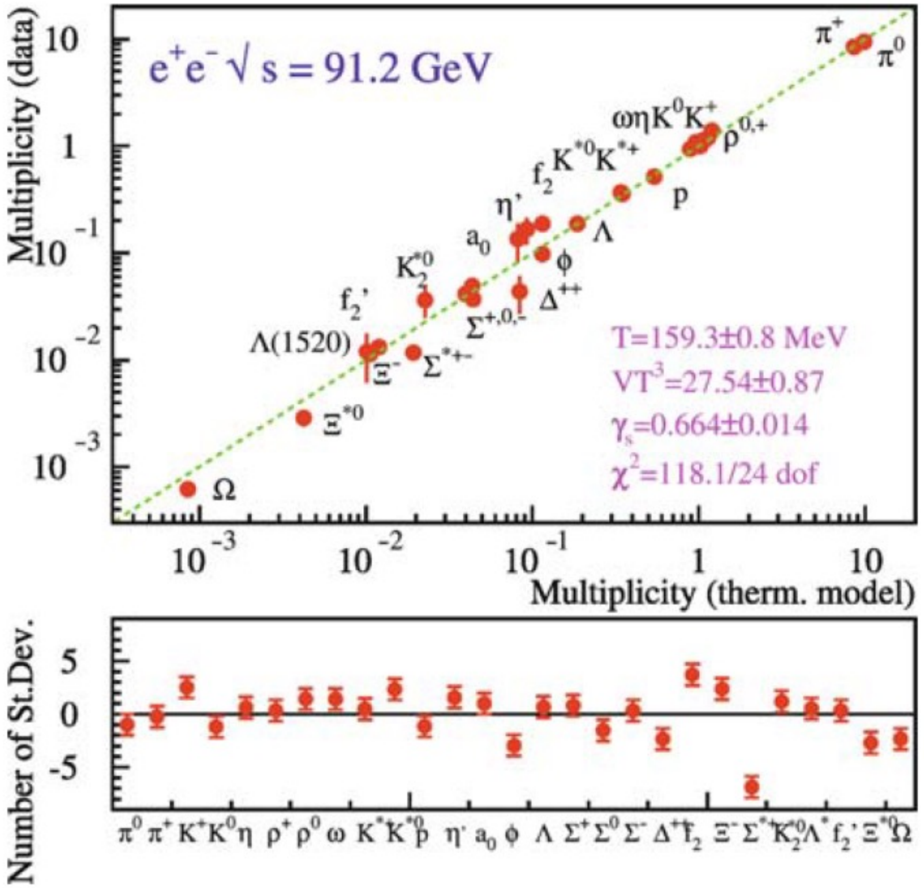


Watch out for autocorrelations. Higher multiplicity events have gluon jets which have higher strangeness!

Autocorrelations in small systems is an issue we will revisit.

Thermal / Statistical Model





The statistical model works,
with a remaining strangeness suppression.
Phase space population or equilibration?

Grand Canonical Ensemble

We start out with a system completely out of equilibrium and lots of kinetic energy.

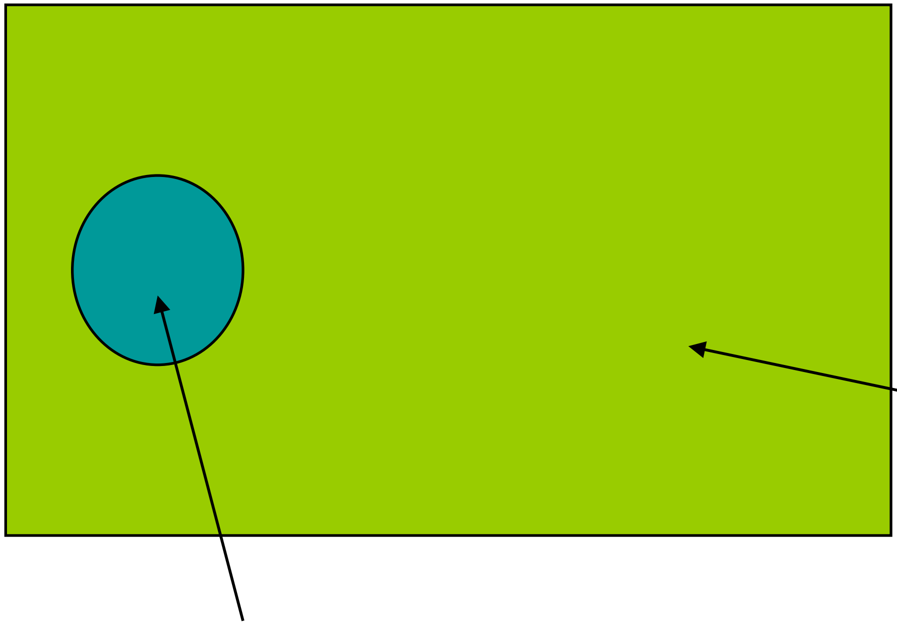
We can try to use the Grand Canonical Ensemble to calculate the abundances of all the final measured particles.

$$\bar{n}_s = \frac{1}{e^{(\ \ _s\ \ \ \ )/kT} \pm 1}$$

Fermions or Bosons

Depends on Temperature and Chemical Potential.

Grand Canonical Ensemble

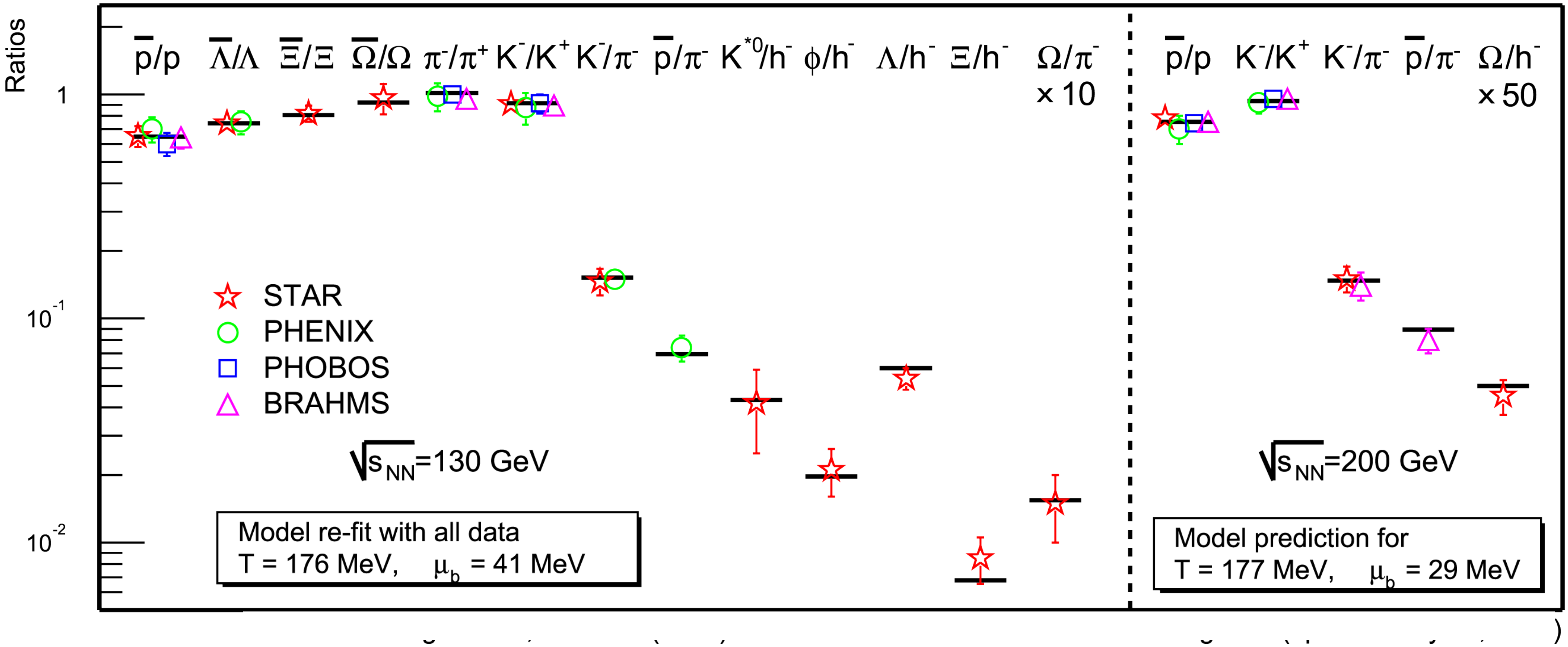


My system.

Infinite heat bath with which my system can exchange energy and particles, hence we have a temperature and chemical potential.

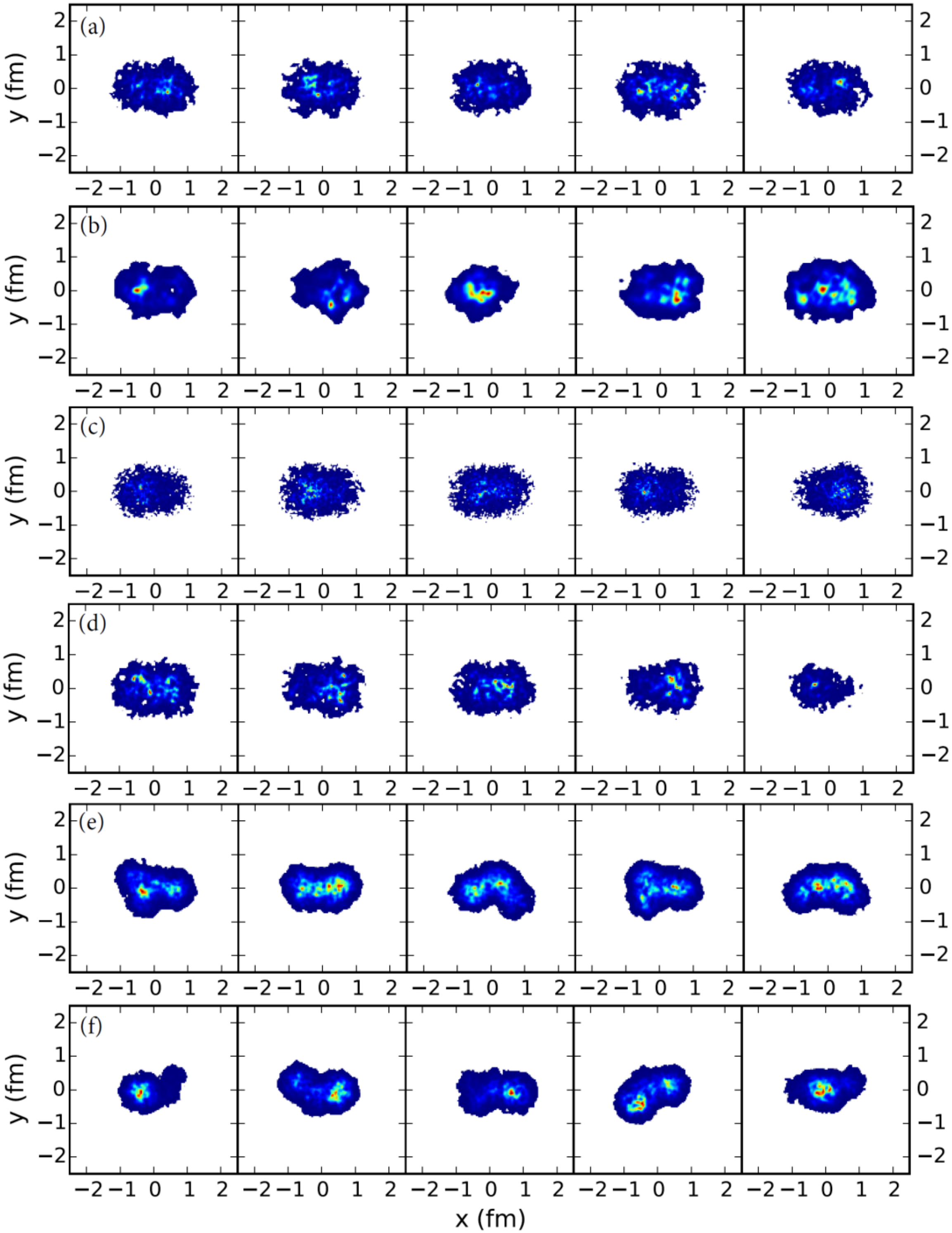
$$N_i \qquad g_i V \; \frac{d^3 p}{(2\quad)^3} \, \frac{1}{e^{(\sqrt{p^2+m^2}\qquad {}_B)/T} \pm 1}$$

Heavy Ions GCE



Works very well again, but now almost no additional suppression of strangeness.

Consider canonical ensemble in smaller systems?


(a)
(b)
(c)
(d)
(e)
(f)
y (fm)
x (fm)
−2 −1 0 1 2

The Proton

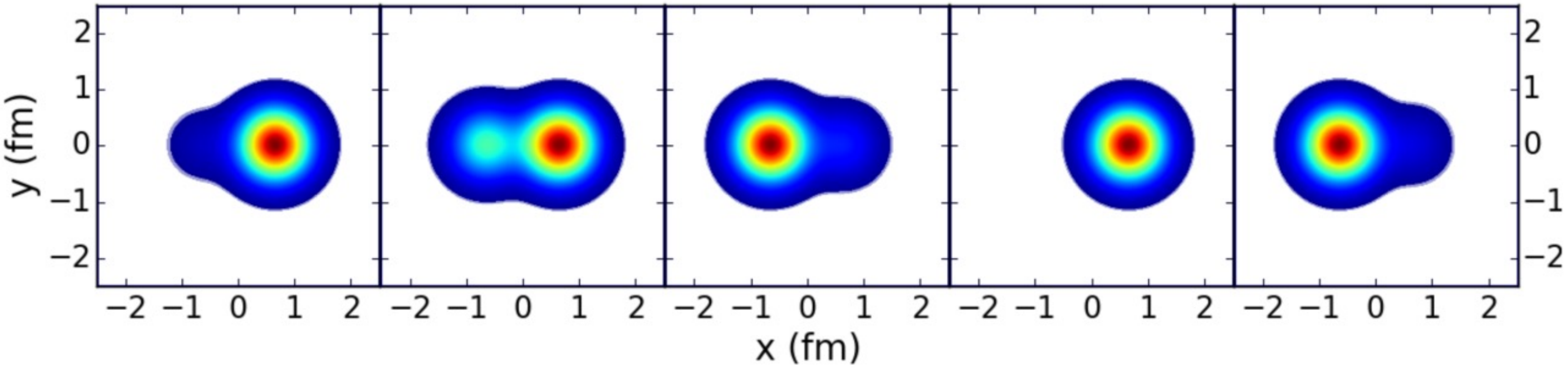


FIG. 2: Contour plots of the initial entropy density for five randomly selected p+p collisions at $\sqrt{s} = 200\,\text{GeV}$ and impact parameter $b = 1.3\,\text{fm}$, computed with the MC-Glauber model using a smooth Gaussian nucleon density profile for collision detection and including multiplicity fluctuations in the deposited entropy.

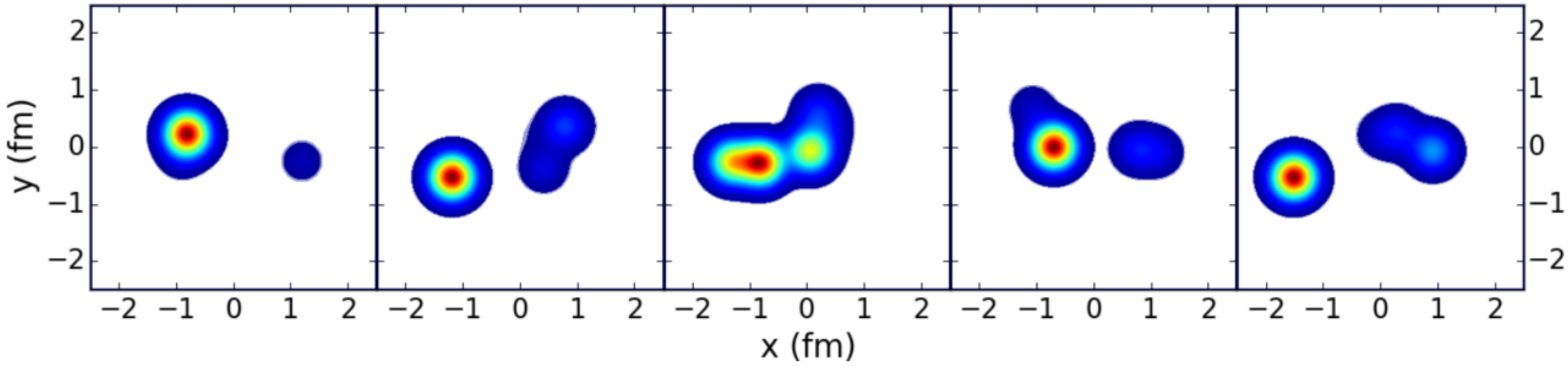
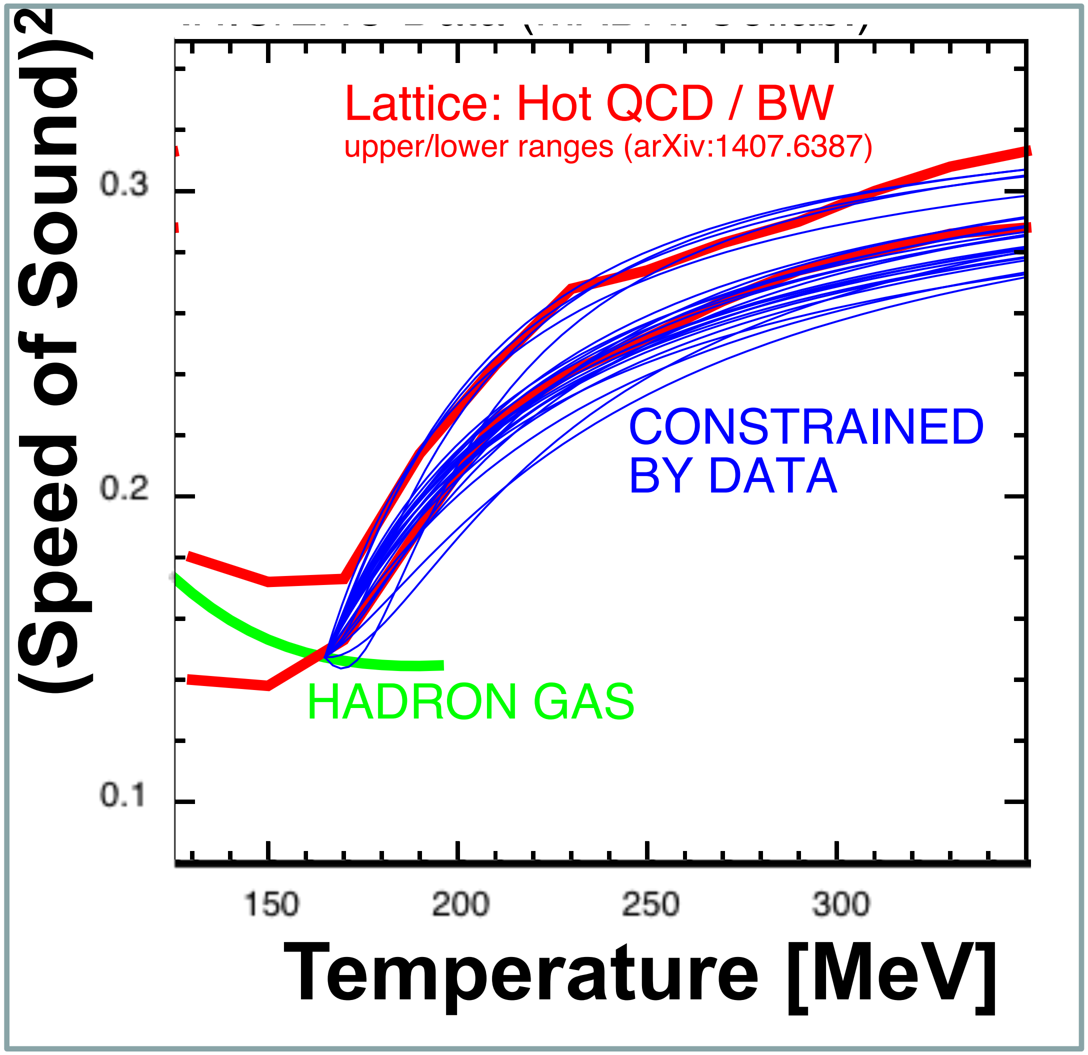


FIG. 4: Contour plots of the initial entropy density for five randomly selected p+p collisions at $\sqrt{s} = 200\,\text{GeV}$ and impact parameter $b = 1.3\,\text{fm}$, computed with the MC-Glauber model using quark subdivision of the nucleon density profile for both collision detection and entropy deposition, including additional multiplicity fluctuations in the deposited entropy. See text for model description and discussion.

https://arxiv.org/abs/1605.09418

Global Constraint Analysis

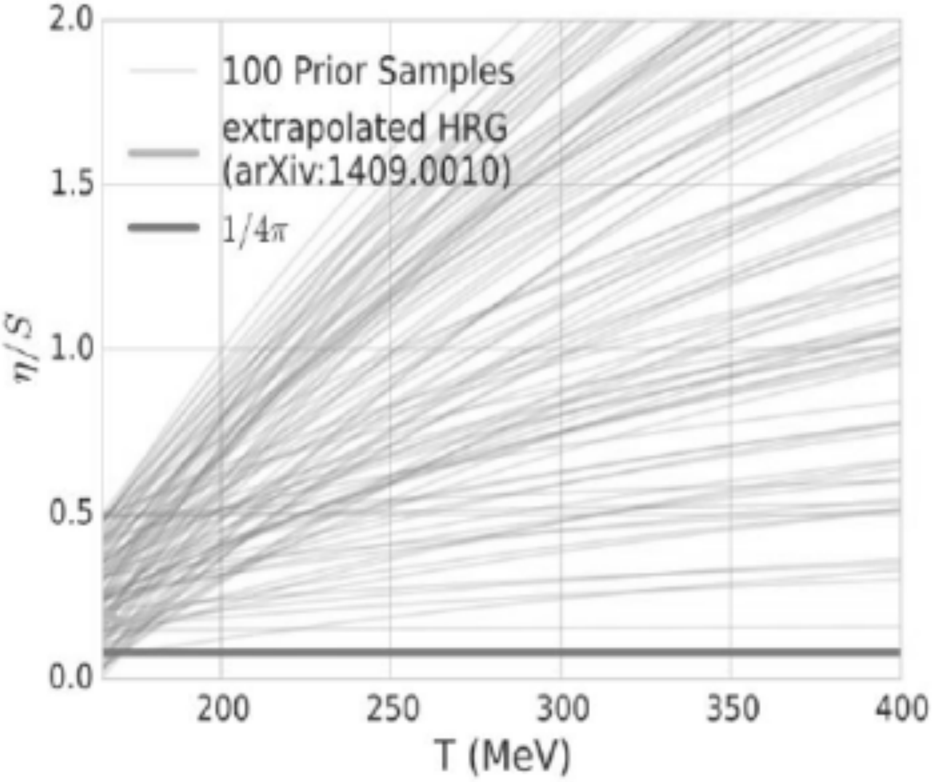


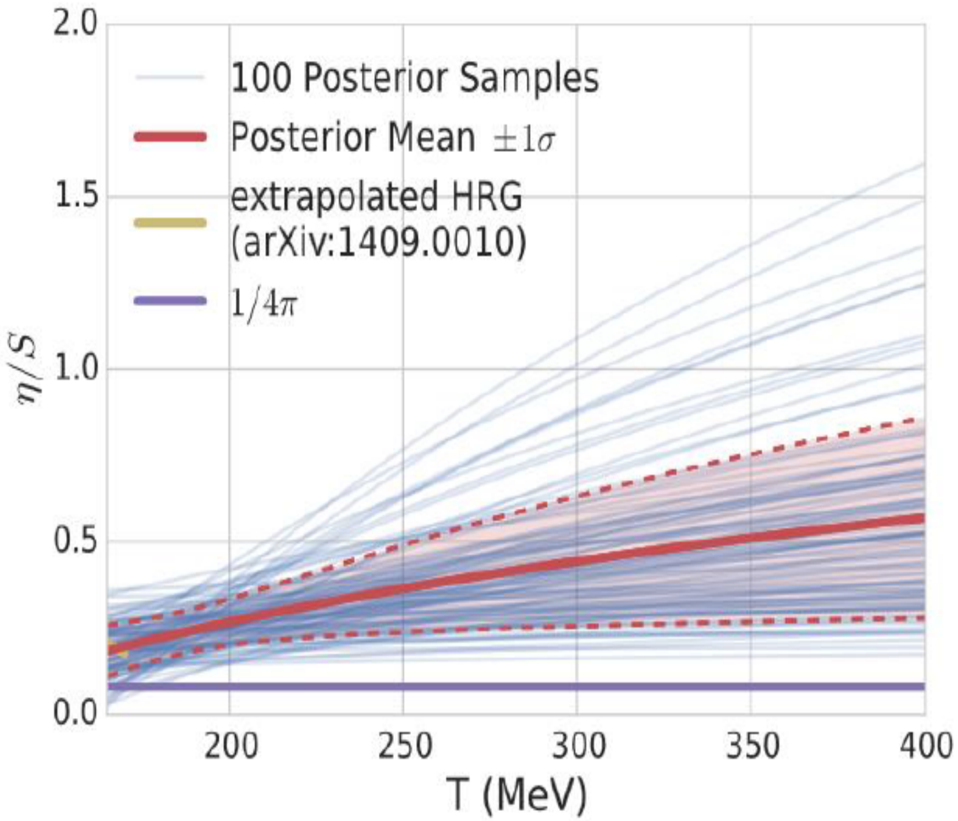
Global constraint methods using Bayesian sampling as done in Climate Modeling for example.

Includes particle spectra, elliptic flow, two-particle quantum correlations, …

Experimental confirmation of Lattice QCD Equation of State

Global Constraint Analysis



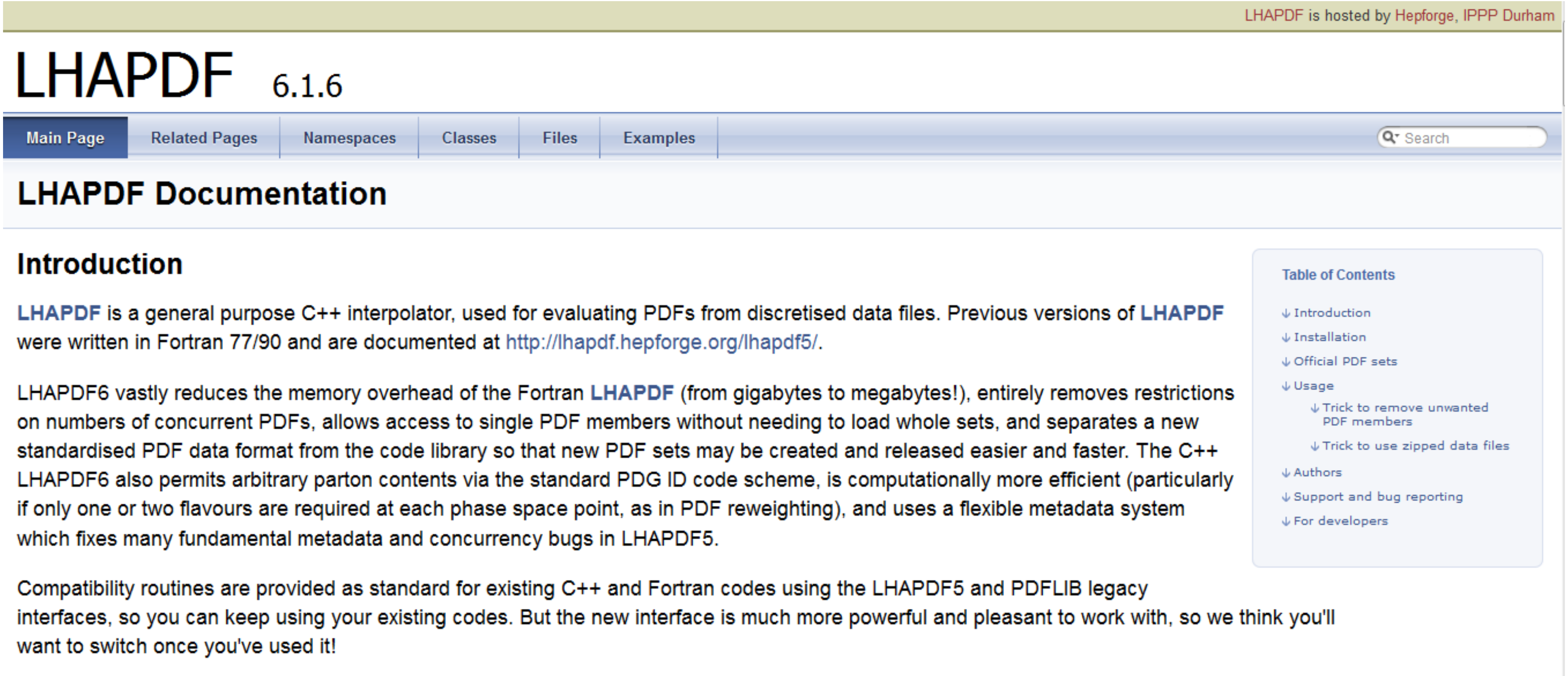


Expect η/s to increase at higher temperatures even just from running of α_s

Key lesson about when and when not to include scenarios (story of High Voltage Power Lines)…


I'M LOOKING FOR MY QUARTER I DROPPED!
DID YOU DROP IT HERE?
NO, I DROPPED IT TWO BLOCKS DOWN THE STREET!
THEN WHY ARE YOU LOOKING FOR IT HERE?
BECAUSE THE LIGHT IS BETTER HERE!
?

https://lhapdf.hepforge.org/



LHAPDF is hosted by Hepforge, IPPP Durham

LHAPDF 6.1.6

LHAPDF Documentation

Introduction

LHAPDF is a general purpose C++ interpolator, used for evaluating PDFs from discretised data files. Previous versions of **LHAPDF** were written in Fortran 77/90 and are documented at http://lhapdf.hepforge.org/lhapdf5/.

LHAPDF6 vastly reduces the memory overhead of the Fortran **LHAPDF** (from gigabytes to megabytes!), entirely removes restrictions on numbers of concurrent PDFs, allows access to single PDF members without needing to load whole sets, and separates a new standardised PDF data format from the code library so that new PDF sets may be created and released easier and faster. The C++ LHAPDF6 also permits arbitrary parton contents via the standard PDG ID code scheme, is computationally more efficient (particularly if only one or two flavours are required at each phase space point, as in PDF reweighting), and uses a flexible metadata system which fixes many fundamental metadata and concurrency bugs in LHAPDF5.

Compatibility routines are provided as standard for existing C++ and Fortran codes using the LHAPDF5 and PDFLIB legacy interfaces, so you can keep using your existing codes. But the new interface is much more powerful and pleasant to work with, so we think you'll want to switch once you've used it!

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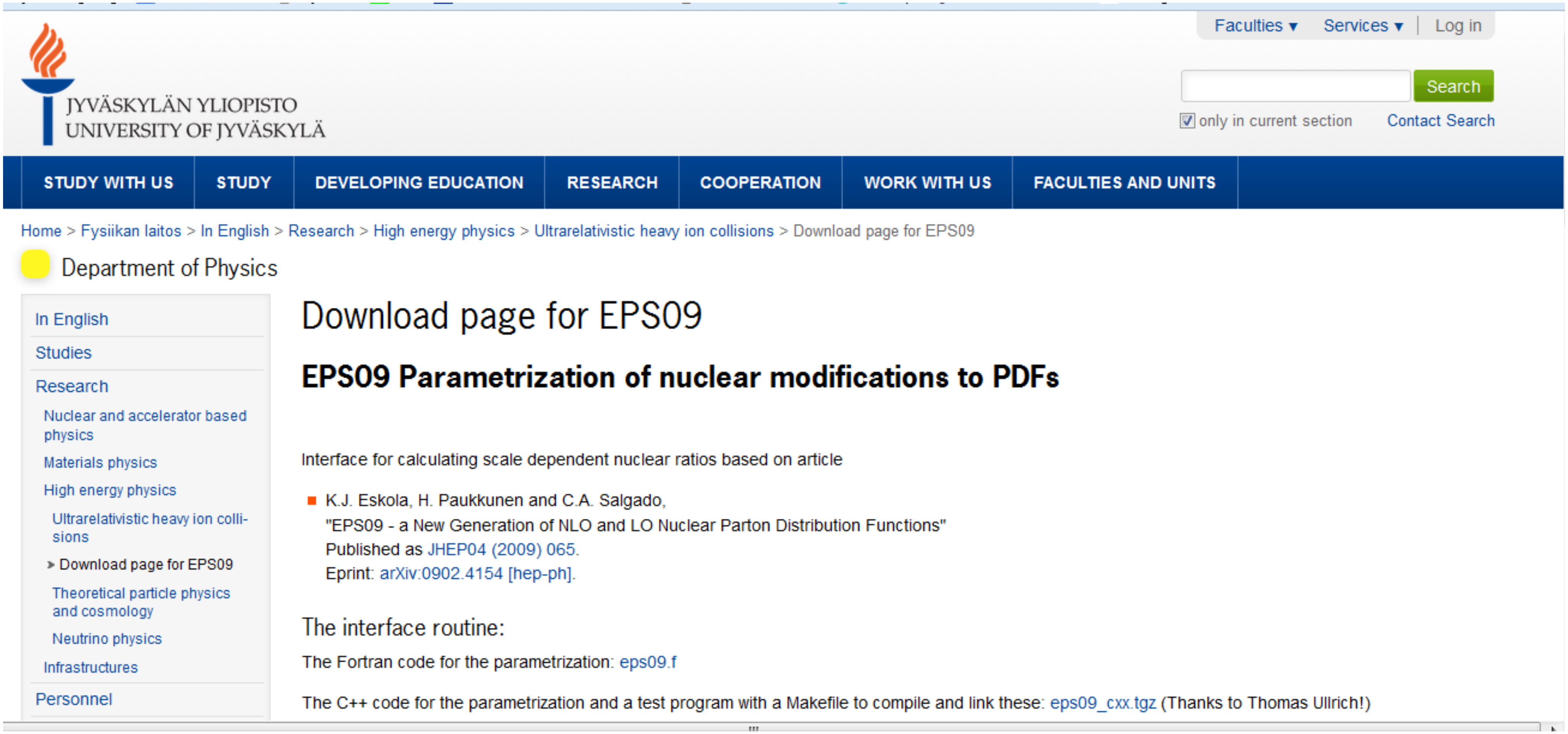
- ↓Official PDF sets
- ↓Usage
  - ↓Trick to remove unwanted PDF members
  - ↓Trick to use zipped data files
- ↓Authors
- ↓Support and bug reporting
- ↓For developers

https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/eps09



Download page for EPS09

EPS09 Parametrization of nuclear modifications to PDFs

Interface for calculating scale dependent nuclear ratios based on article

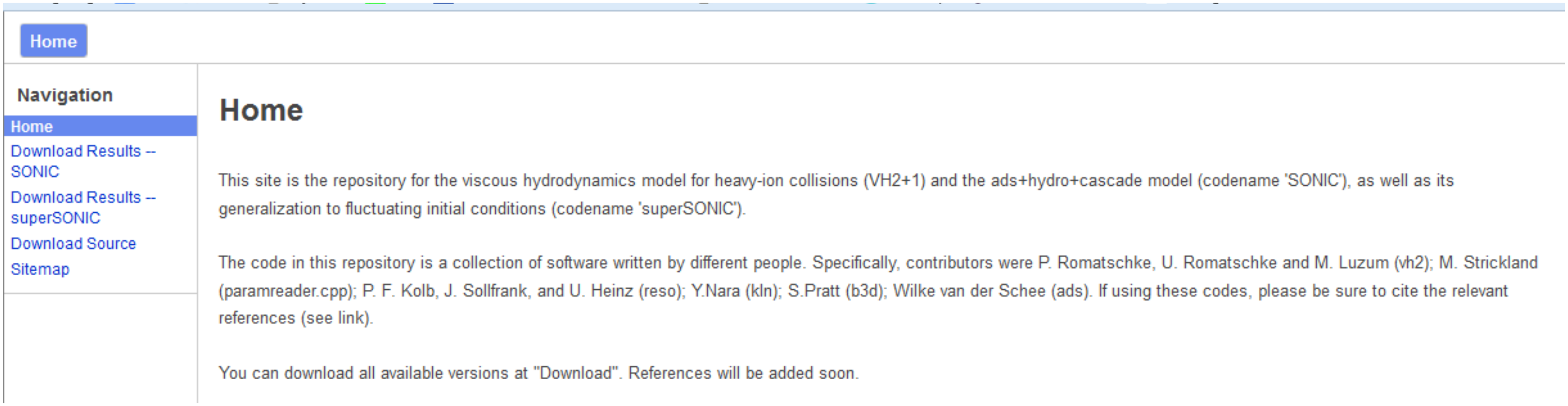
- K.J. Eskola, H. Paukkunen and C.A. Salgado,
  "EPS09 - a New Generation of NLO and LO Nuclear Parton Distribution Functions"
  Published as JHEP04 (2009) 065.
  Eprint: arXiv:0902.4154 [hep-ph].

The interface routine:

The Fortran code for the parametrization: eps09.f

The C++ code for the parametrization and a test program with a Makefile to compile and link these: eps09_cxx.tgz (Thanks to Thomas Ullrich!)

https://sites.google.com/site/revihy/



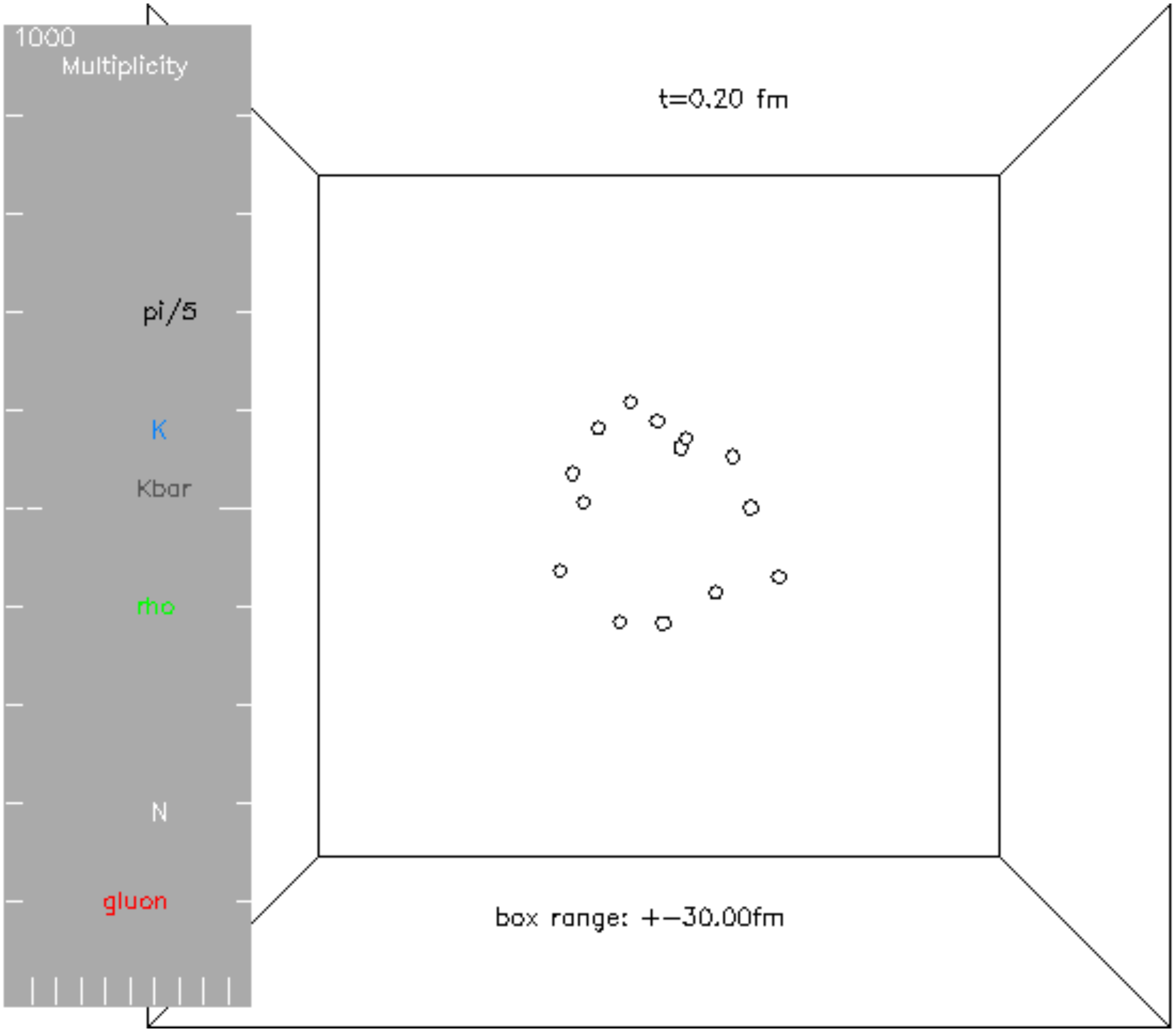
Home

This site is the repository for the viscous hydrodynamics model for heavy-ion collisions (VH2+1) and the ads+hydro+cascade model (codename 'SONIC'), as well as its generalization to fluctuating initial conditions (codename 'superSONIC').

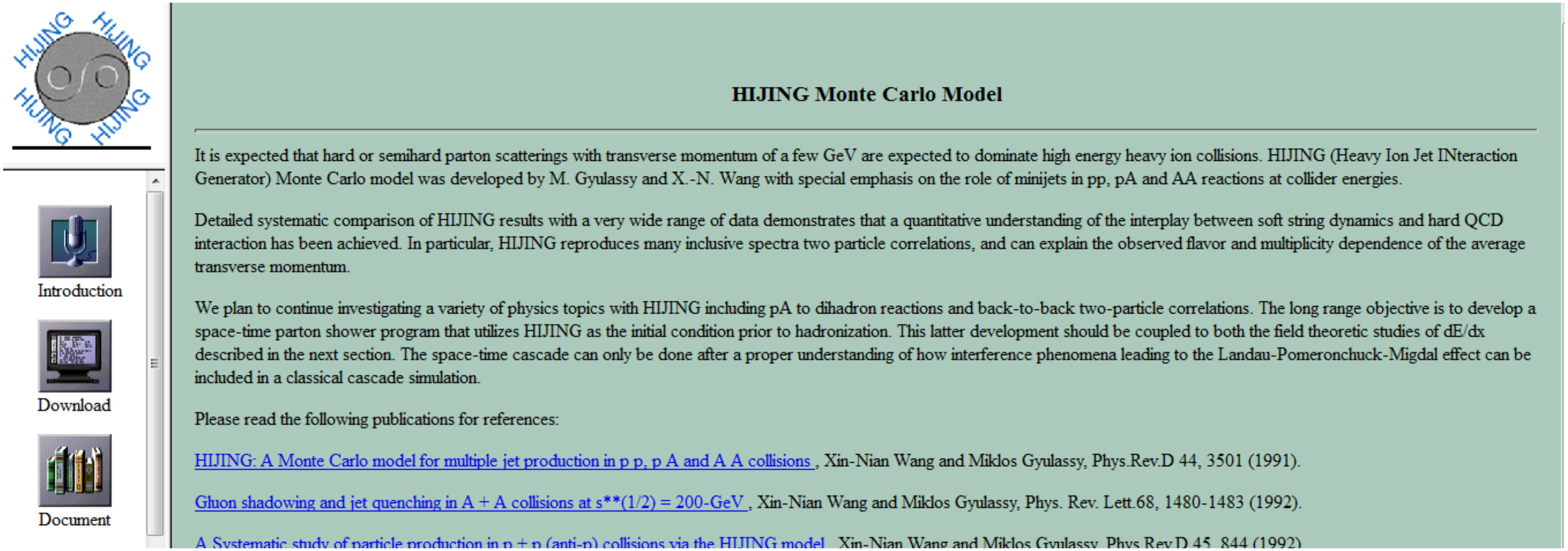
The code in this repository is a collection of software written by different people. Specifically, contributors were P. Romatschke, U. Romatschke and M. Luzum (vh2); M. Strickland (paramreader.cpp); P. F. Kolb, J. Sollfrank, and U. Heinz (reso); Y.Nara (kln); S.Pratt (b3d); Wilke van der Schee (ads). If using these codes, please be sure to cite the relevant references (see link).

You can download all available versions at "Download". References will be added soon.

Version without string melting…



http://ntc0.lbl.gov/~xnwang/hijing/index.html



HIJING Monte Carlo Model

It is expected that hard or semihard parton scatterings with transverse momentum of a few GeV are expected to dominate high energy heavy ion collisions. HIJING (Heavy Ion Jet INteraction Generator) Monte Carlo model was developed by M. Gyulassy and X.-N. Wang with special emphasis on the role of minijets in pp, pA and AA reactions at collider energies.

Detailed systematic comparison of HIJING results with a very wide range of data demonstrates that a quantitative understanding of the interplay between soft string dynamics and hard QCD interaction has been achieved. In particular, HIJING reproduces many inclusive spectra two particle correlations, and can explain the observed flavor and multiplicity dependence of the average transverse momentum.

We plan to continue investigating a variety of physics topics with HIJING including pA to dihadron reactions and back-to-back two-particle correlations. The long range objective is to develop a space-time parton shower program that utilizes HIJING as the initial condition prior to hadronization. This latter development should be coupled to both the field theoretic studies of dE/dx described in the next section. The space-time cascade can only be done after a proper understanding of how interference phenomena leading to the Landau-Pomeronchuck-Migdal effect can be included in a classical cascade simulation.

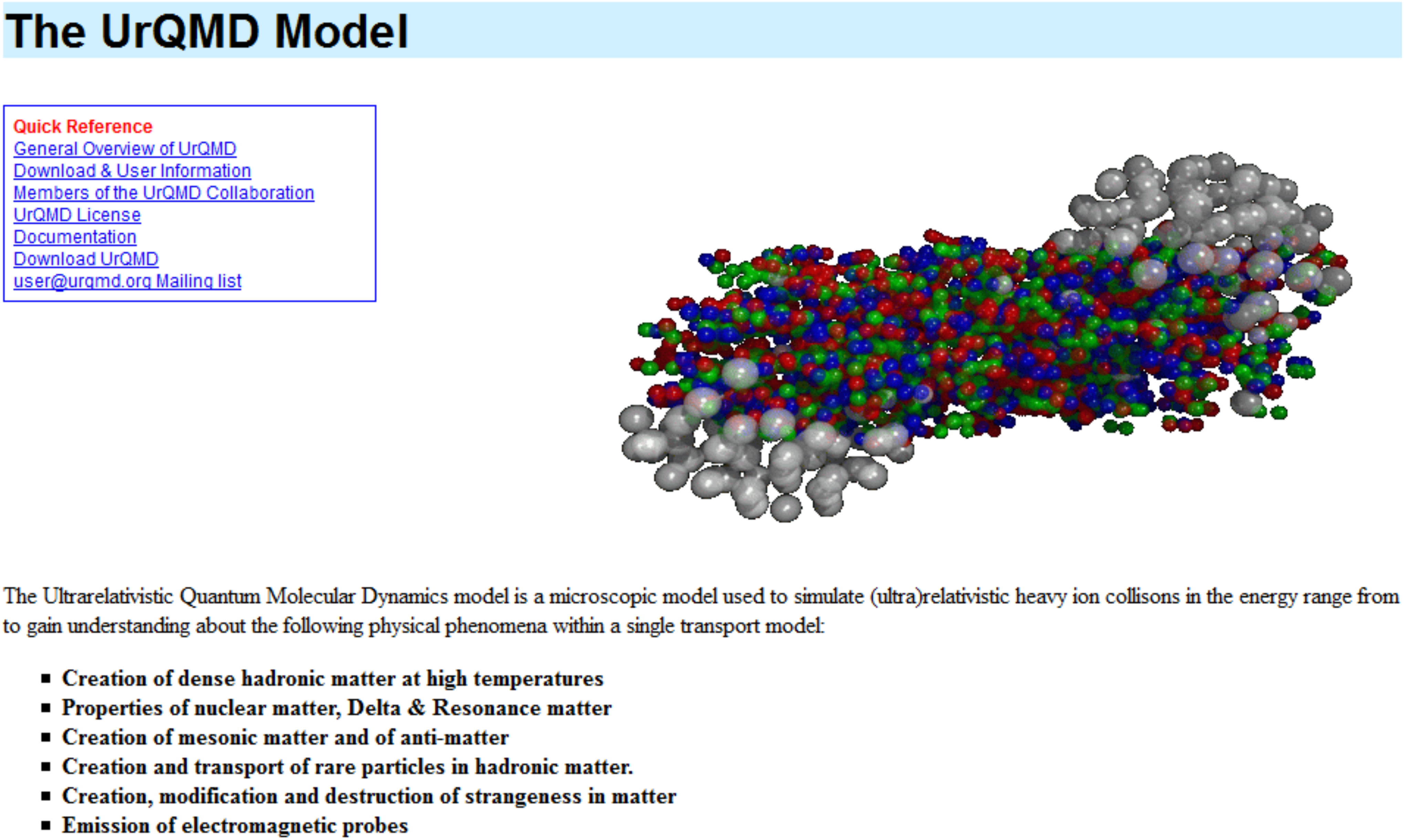
Please read the following publications for references:

HIJING: A Monte Carlo model for multiple jet production in p p, p A and A A collisions , Xin-Nian Wang and Miklos Gyulassy, Phys.Rev.D 44, 3501 (1991).

Gluon shadowing and jet quenching in A + A collisions at s**(1/2) = 200-GeV , Xin-Nian Wang and Miklos Gyulassy, Phys. Rev. Lett.68, 1480-1483 (1992).

A Systematic study of particle production in p + p (anti-p) collisions via the HIJING model , Xin-Nian Wang and Miklos Gyulassy, Phys.Rev.D 45, 844 (1992).

https://urqmd.org/



The UrQMD Model

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The Ultrarelativistic Quantum Molecular Dynamics model is a microscopic model used to simulate (ultra)relativistic heavy ion collisons in the energy range from
to gain understanding about the following physical phenomena within a single transport model:

- **Creation of dense hadronic matter at high temperatures**
- **Properties of nuclear matter, Delta & Resonance matter**
- **Creation of mesonic matter and of anti-matter**
- **Creation and transport of rare particles in hadronic matter.**
- **Creation, modification and destruction of strangeness in matter**
- **Emission of electromagnetic probes**