Two Lectures on Quark-Gluon Plasma

Lecture 2

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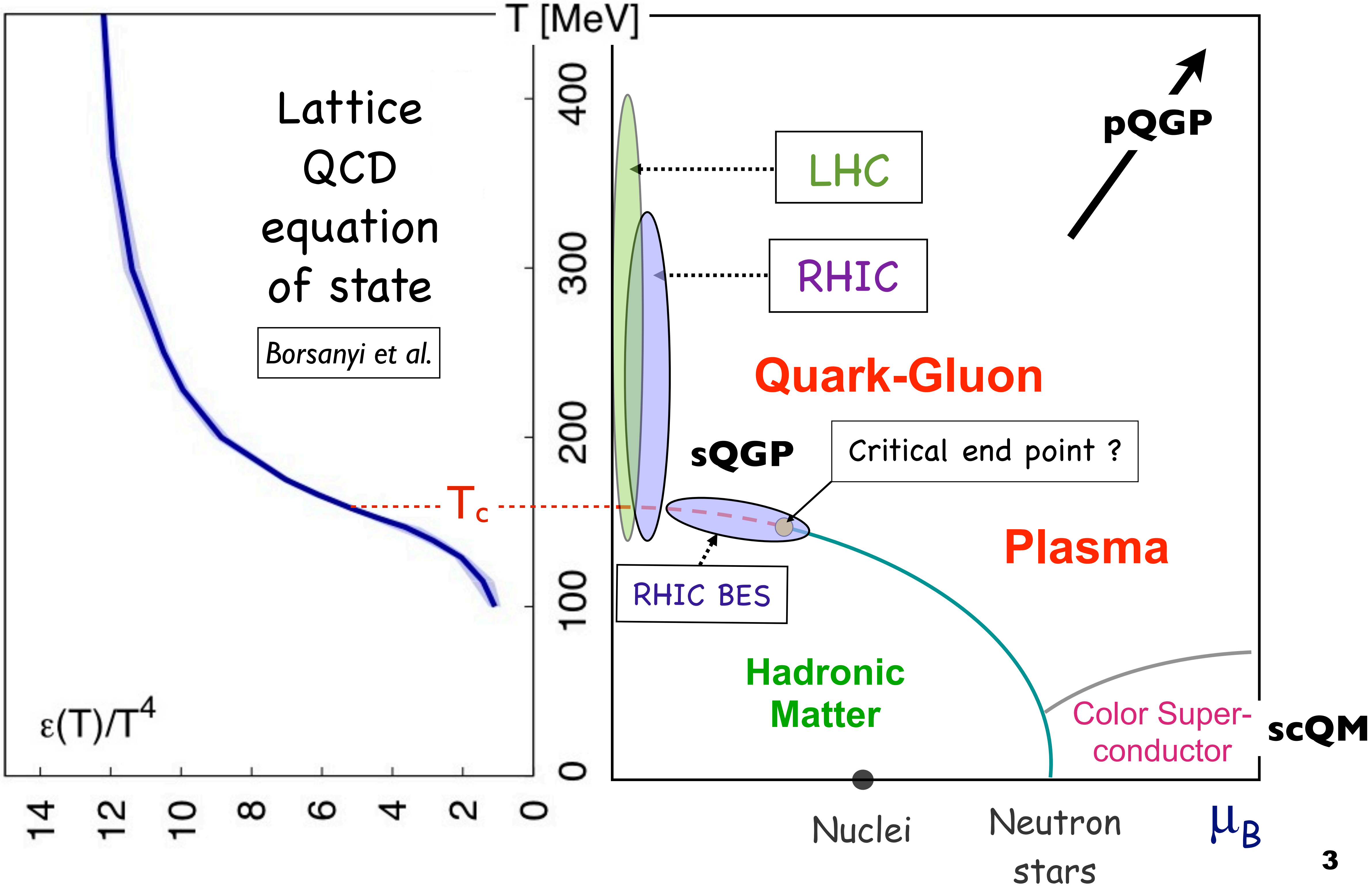
National NP Summer School

Santa Fe - July 16-17, 2012

Tomorrow

Lecture 2
Probing the QGP
in Relativistic
Heavy Ion Collisions

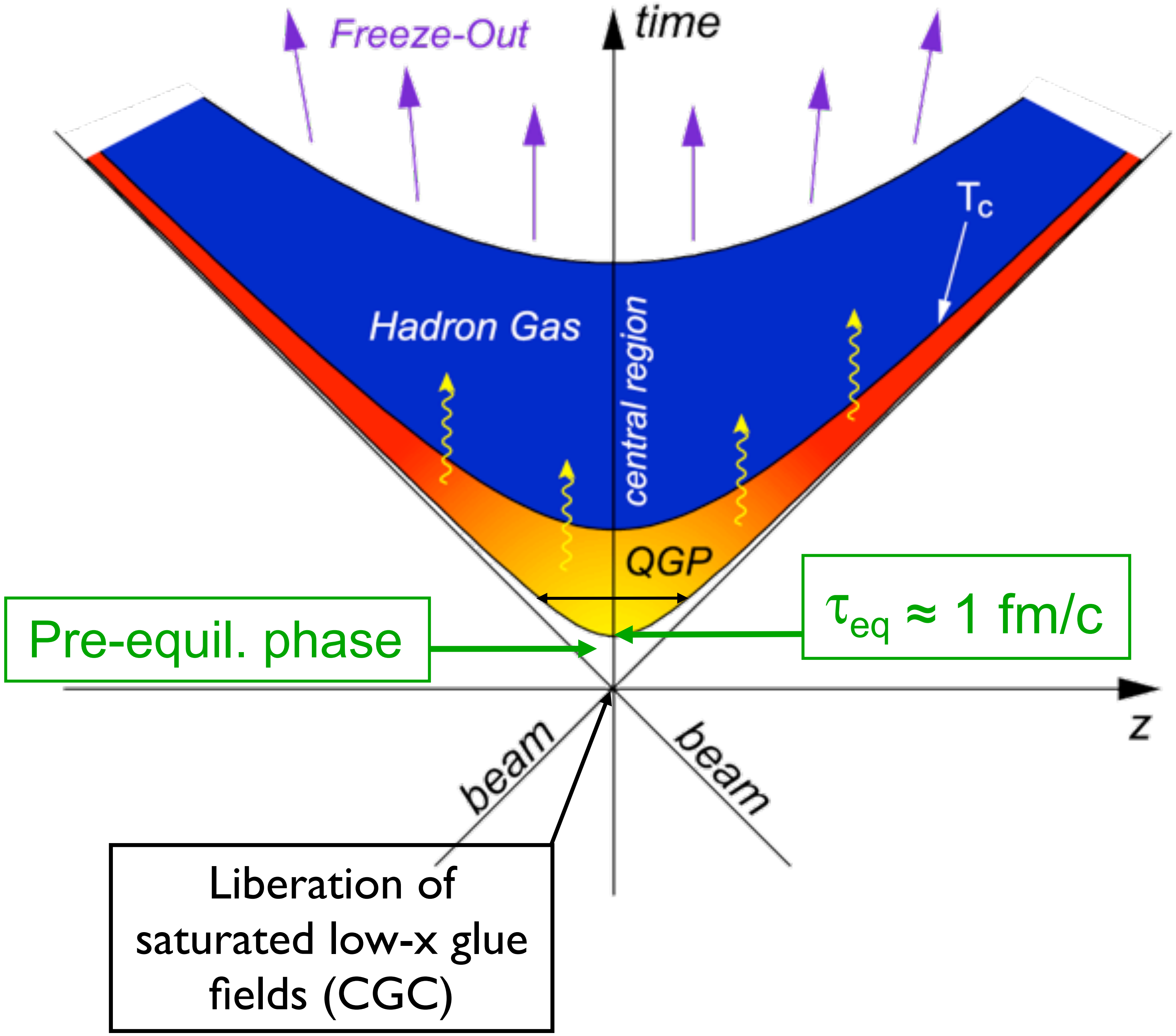
QGP Landscape



Part 1

Formation and Evolution of the QGP

Space-time picture



Pre-equil. phase

$\tau_{eq} \approx$ 1 fm/c

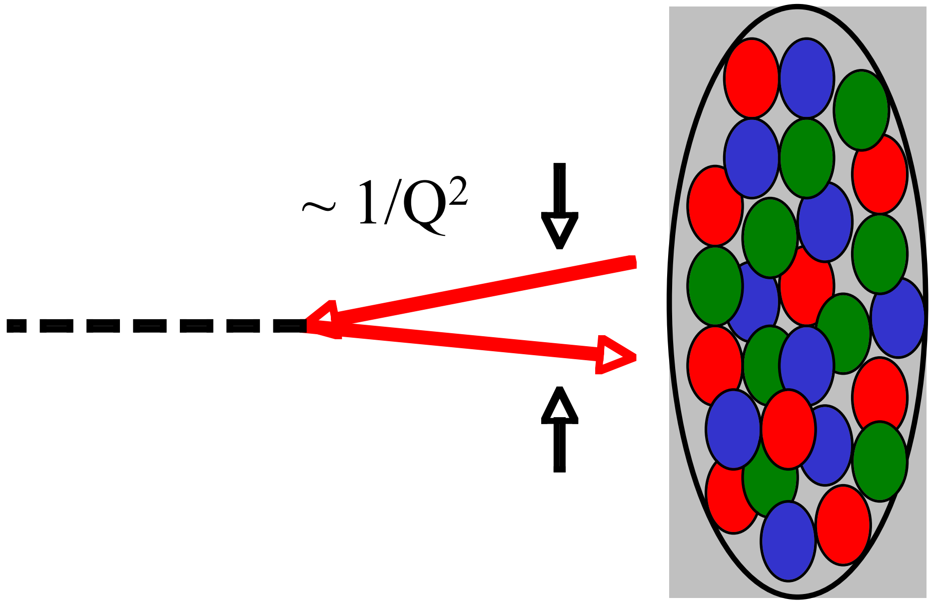
Liberation of saturated low-x glue fields (CGC)

$$s(\tau) \sim \frac{dN(\tau)/dy}{dV(\tau)/dy} \le \frac{(dN/dy)_{\text{final}}}{\pi R^2 \tau}$$

RHIC:
$s_0 \approx 33\ \text{fm}^{-3}$
$T_0 \approx 275$ MeV

LHC:
$s_0 \approx 75\ \text{fm}^{-3}$
$T_0 \approx 360$ MeV

Gluon saturation



$\Rightarrow Q_s^2(x, A)$

Gribov, Levin, Ryskin ’83

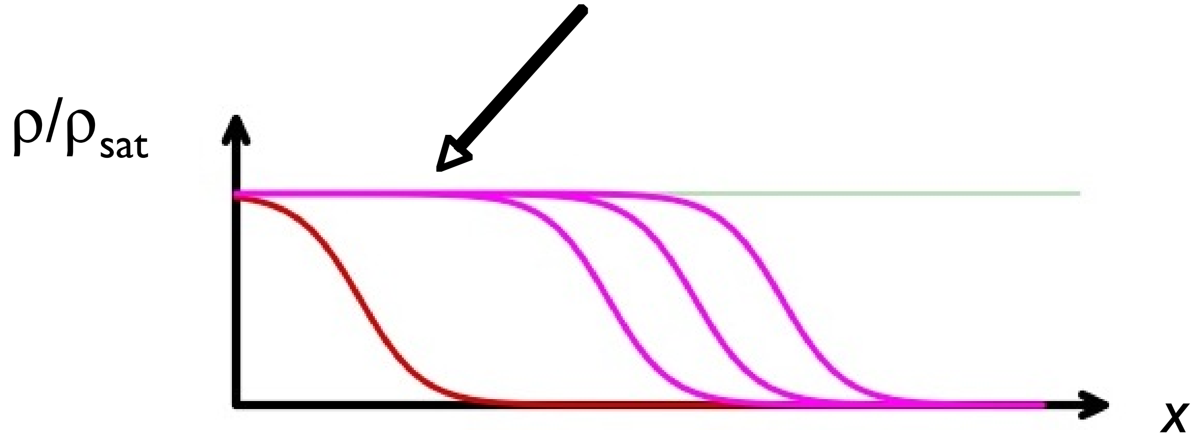
Blaizot, A. Mueller ’87

McLerran, Venugopalan ‘94

$$\text{gluon density} \times \text{area} \sim \frac{A^{1/3} x^{-0.3}}{Q_s^2} \approx 1$$

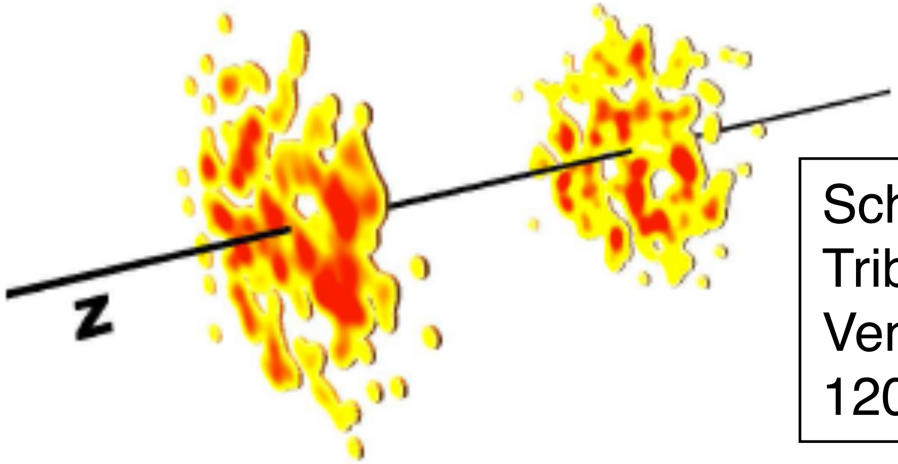
Universal saturated state at small x: $Q_s >> \Lambda_{QCD}$

“Color glass condensate” (CGC)

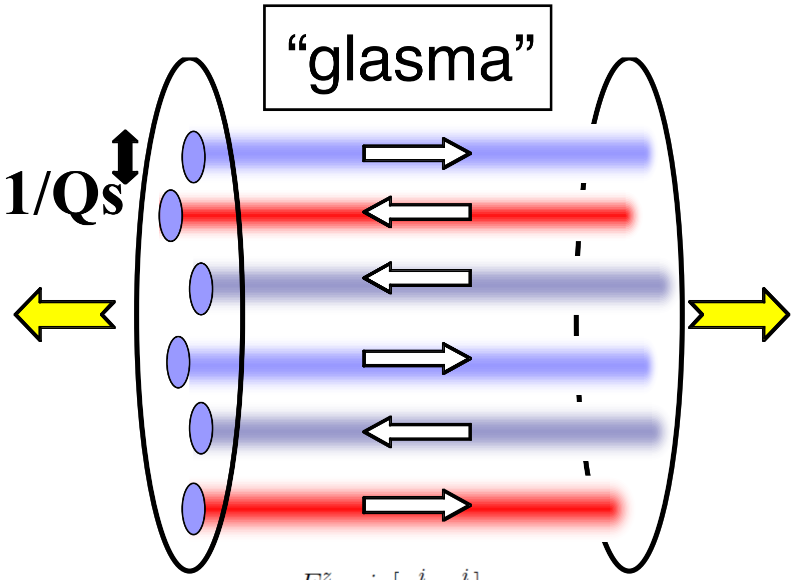


Evolution in *x* is described by BK or JIMWLK equations. Location of the onset of saturation is determined by fluctuations (Iancu, Peschanski,…)

Color charge densities of two colliding Au nuclei at top RHIC energy



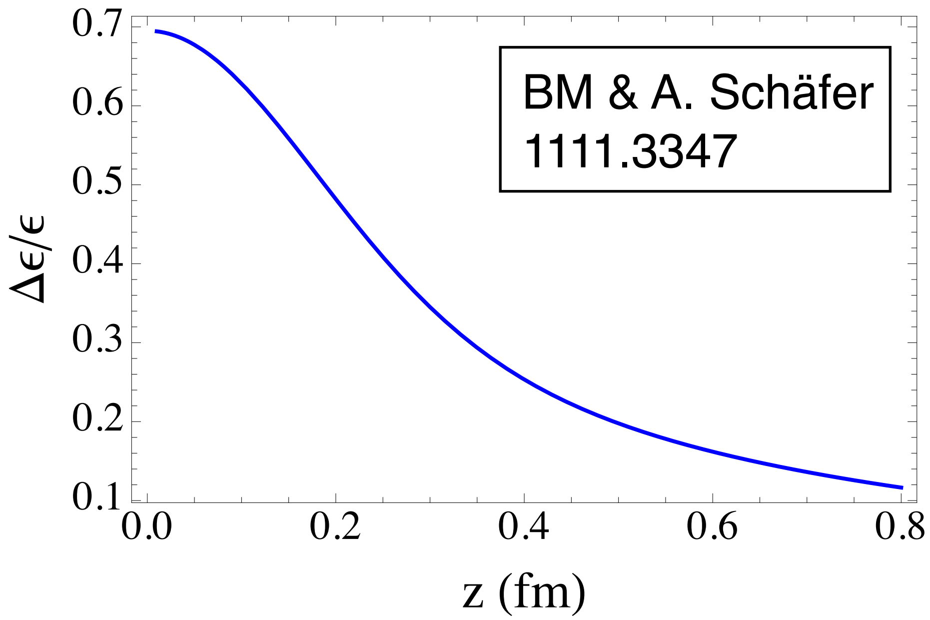
Schenke,
Tribedy &
Venugopalan
1206.6805



“glasma”

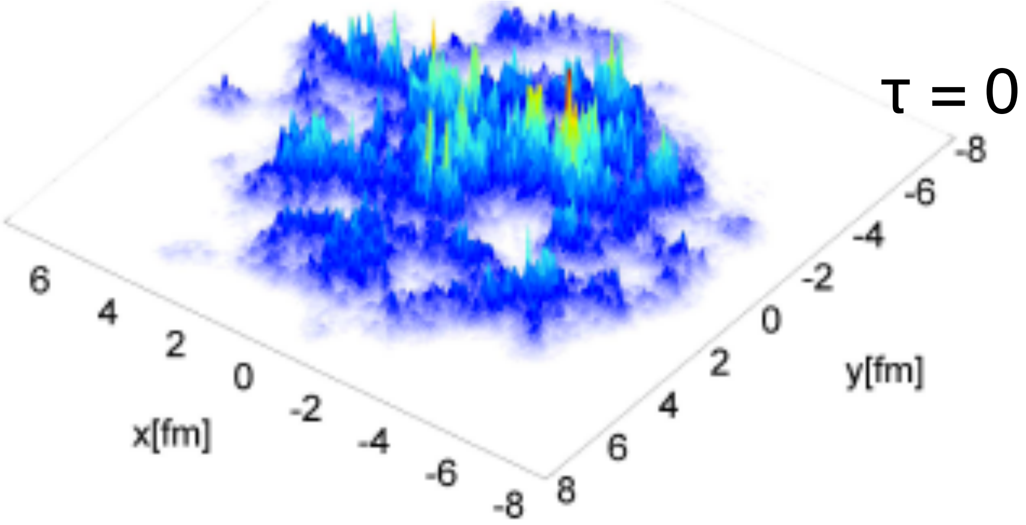
$E^z = ig[\alpha_1^i, \alpha_2^i]$
$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$

$$\Delta\varepsilon(z) = \langle \varepsilon(z)\varepsilon(0)\rangle - \langle \varepsilon(0)\rangle^2$$



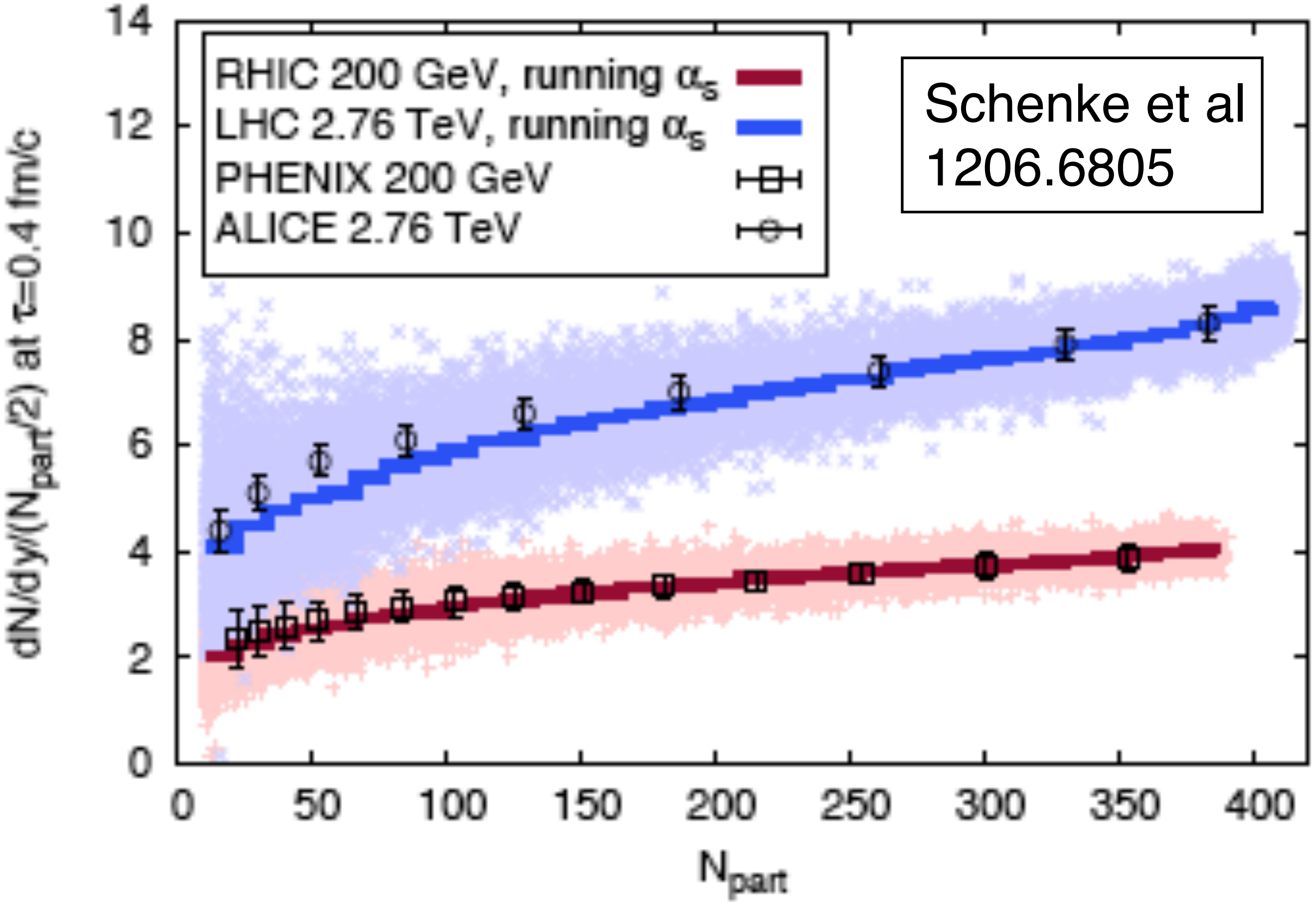
BM & A. Schäfer
1111.3347

Transverse distribution of the initial energy density



τ = 0

Gluon multiplicities (x 2/3) at τ = 0.4 fm/c

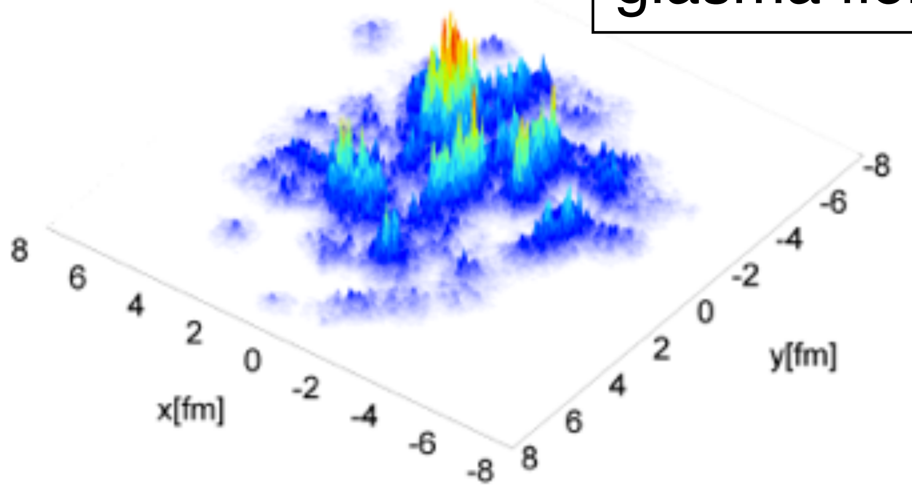


Schenke et al
1206.6805

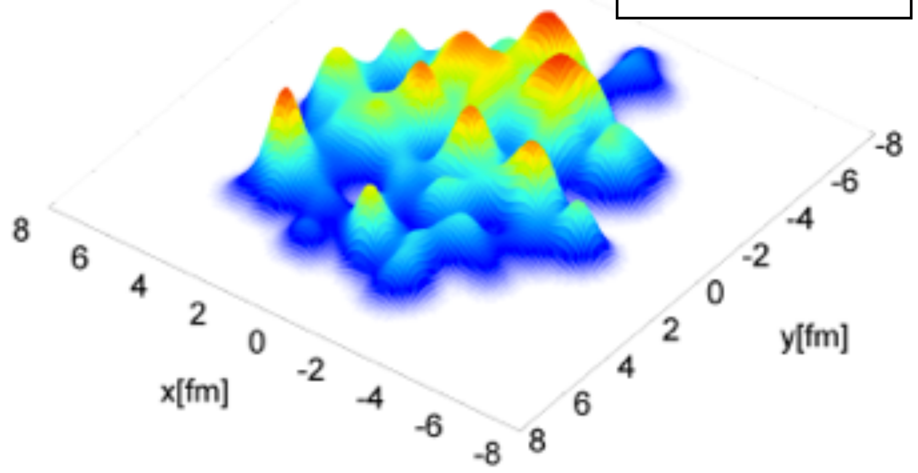
Absolute number may be questionable (no quarks, no equilibration, no hadrons) but the trend with N_{part} and √s is right.

Transverse sections of the local energy density at τ = 0.4 fm/c

glasma fields



nucleons



Part 2

Probes of the QGP

Probes of hot QCD matter

Which **properties of hot QCD matter** can we hope to determine from relativistic heavy ion data (RHIC and LHC, maybe FAIR) ?

$$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$$

Equation of state: spectra, coll. flow, fluctuations

$$c_S^2 = \partial p / \partial \varepsilon$$

Speed of sound: multiparticle correlations

$$\eta = \frac{1}{T} \int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$$

Shear viscosity: anisotropic collective flow

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+i}(y^-) F_i^{a+}(0) \right\rangle \\
\hat{e} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle i\partial^- A^{a+}(y^-) A^{a+}(0) \right\rangle \\
\hat{e}_2 &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+-}(y^-) F^{a+-}(0) \right\rangle
\end{aligned}\right\}$$

Momentum/energy diffusion:
parton energy loss, jet fragmentation

$$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln \left\langle E^a(x) E^a(0) \right\rangle$$

Color screening: Quarkonium states

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Color screening: Quarkonium states

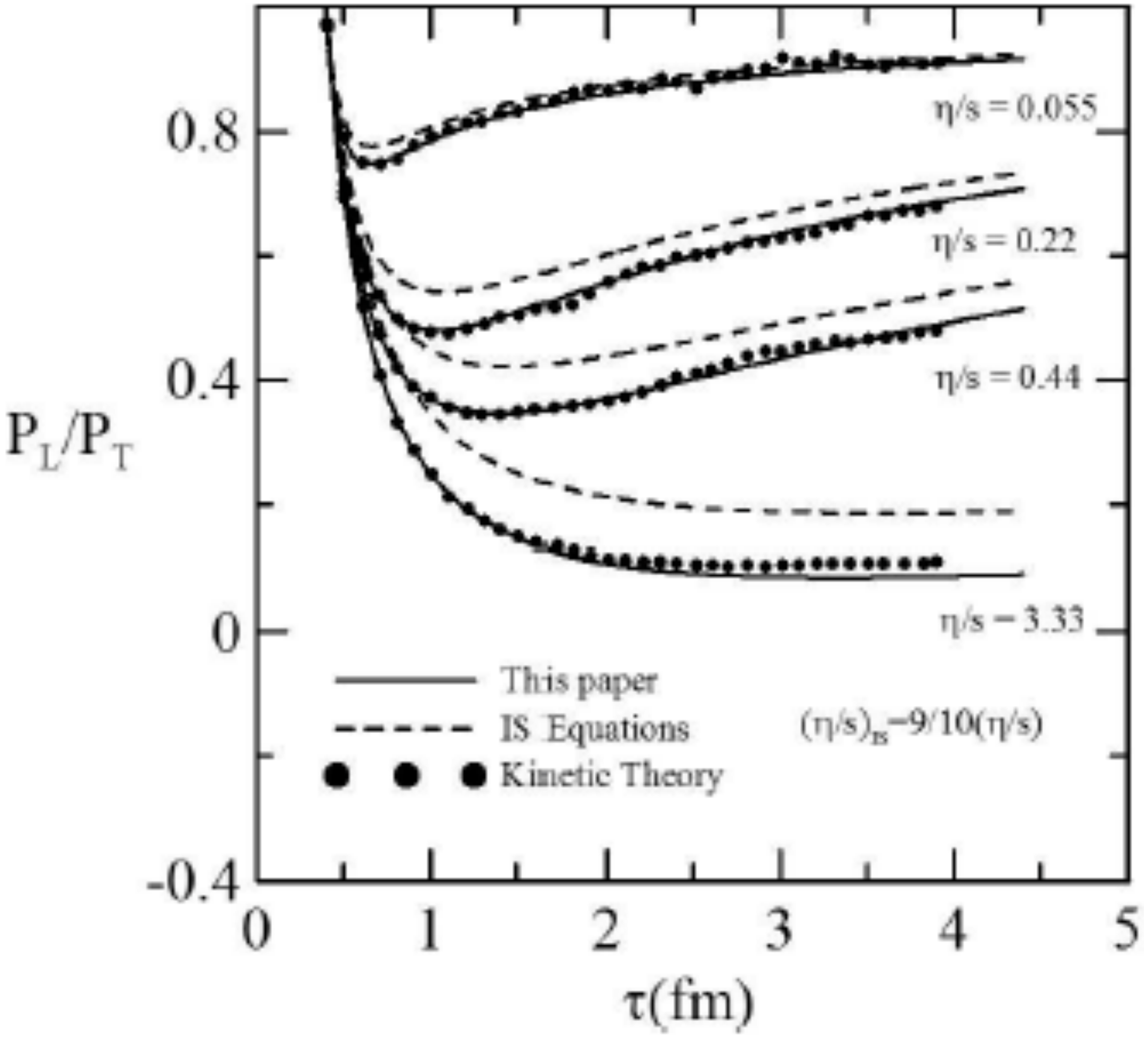
Part 2
The Liquid QGP

2^{nd} order relativistic hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

η = Shear viscosity

$$\tau_\Pi\left[\frac{d\Pi^{\mu\nu}}{d\tau} + \left(u^\mu\Pi^{\nu\lambda} + u^\nu\Pi^{\mu\lambda}\right)\frac{du^\lambda}{d\tau}\right] = \eta\left(\partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace}\right) - \Pi^{\mu\nu}$$



Excellent approximation of Boltzmann transport; negligible uncertainties due to:

- Bulk viscosity
- QCD Equation of state

Main input parameters:

- η/s
- Initial energy density profile
- Equilibration time τ_0

Perfect fluid

In gauge theories with a gravity dual, dissipation is dominated by absorption of gravitons on the black brane. This leads to the universal relation

$$\boxed{\frac{\eta}{s} \geq \frac{\hbar}{4\pi}}$$

Kovtun, Son & Starinets PRL 94 (2005) 111601

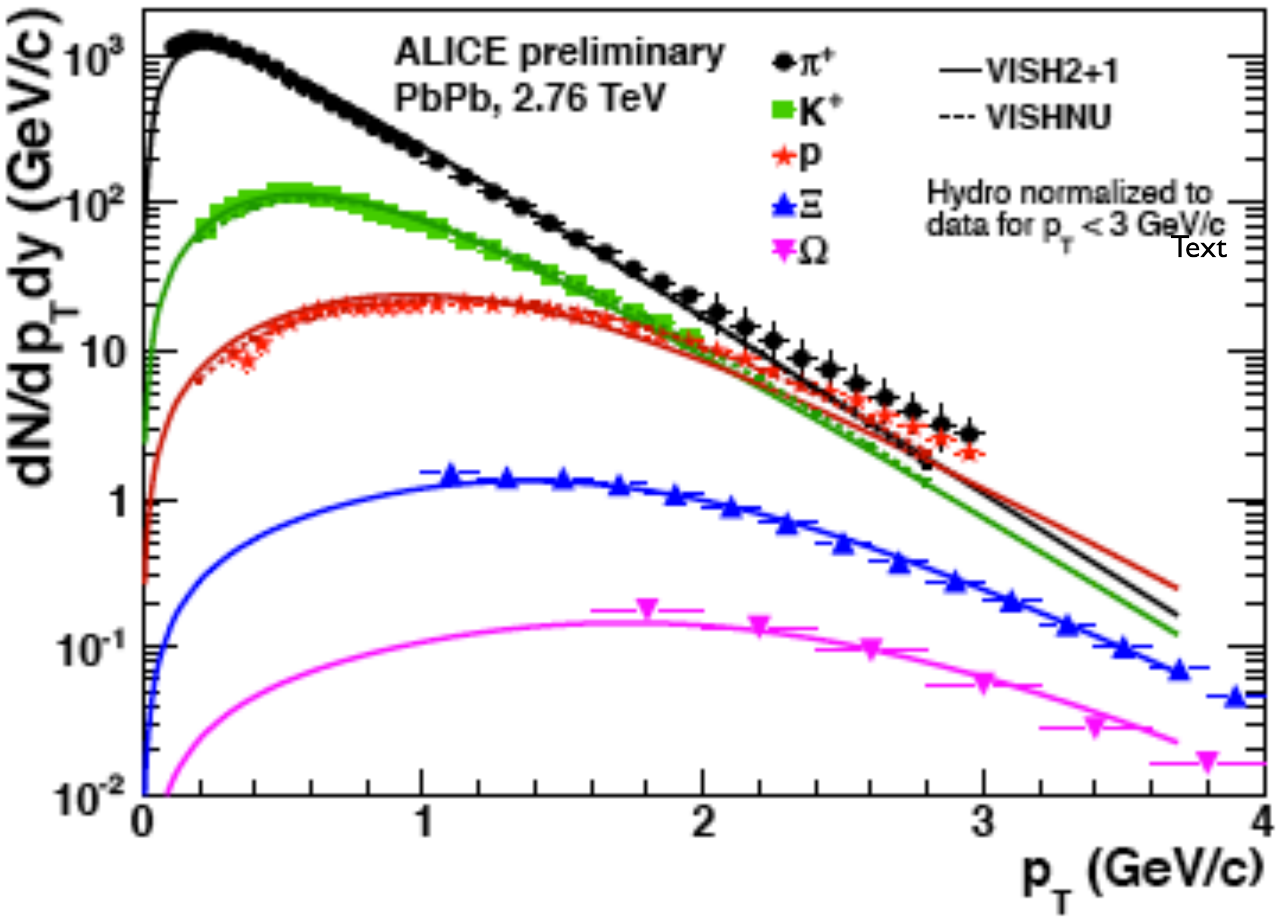
KSS bound is not completely universal, can be violated in dual gravity theories involving higher derivative (non-GR) terms. It is far below η/s of any known material (except QGP and ultra-cold fermionic atoms with unitary interactions).

A similar bound is found in kinetic theory from unitarity limit of cross sections and uncertainty relation [Danielewicz & Gyulassy (1985)]:

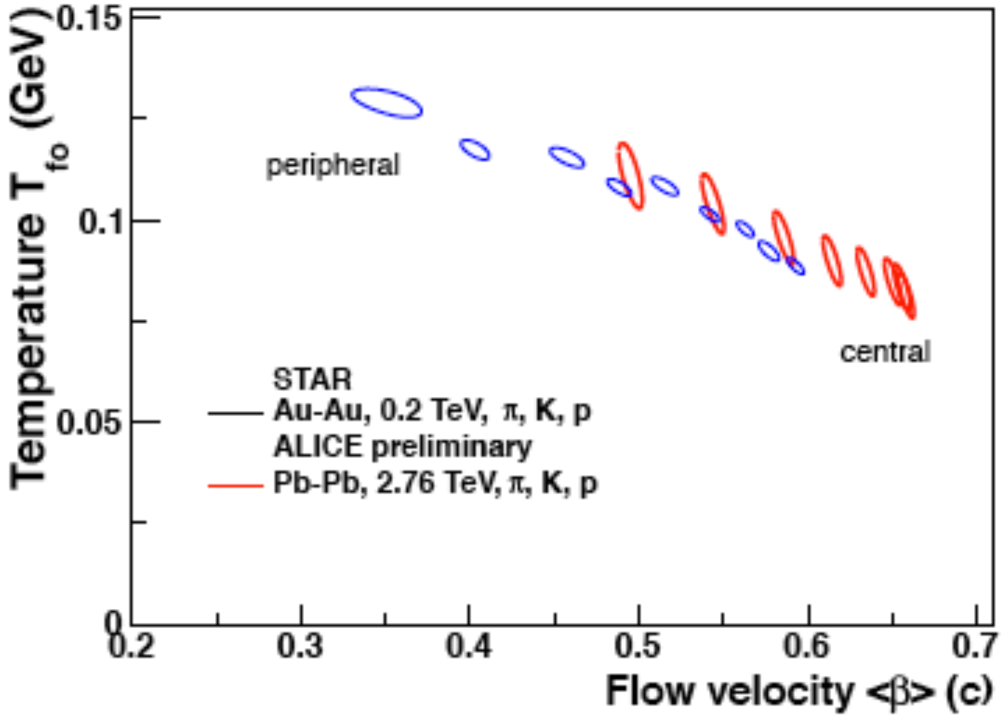
$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f \approx \frac{1}{12} s(\bar{p} \lambda_f) \quad \rightarrow \quad \frac{\eta}{s} \approx \frac{\bar{p} \lambda_f}{12} \geq \frac{\hbar}{12}$$

Hydro describes spectra @ LHC

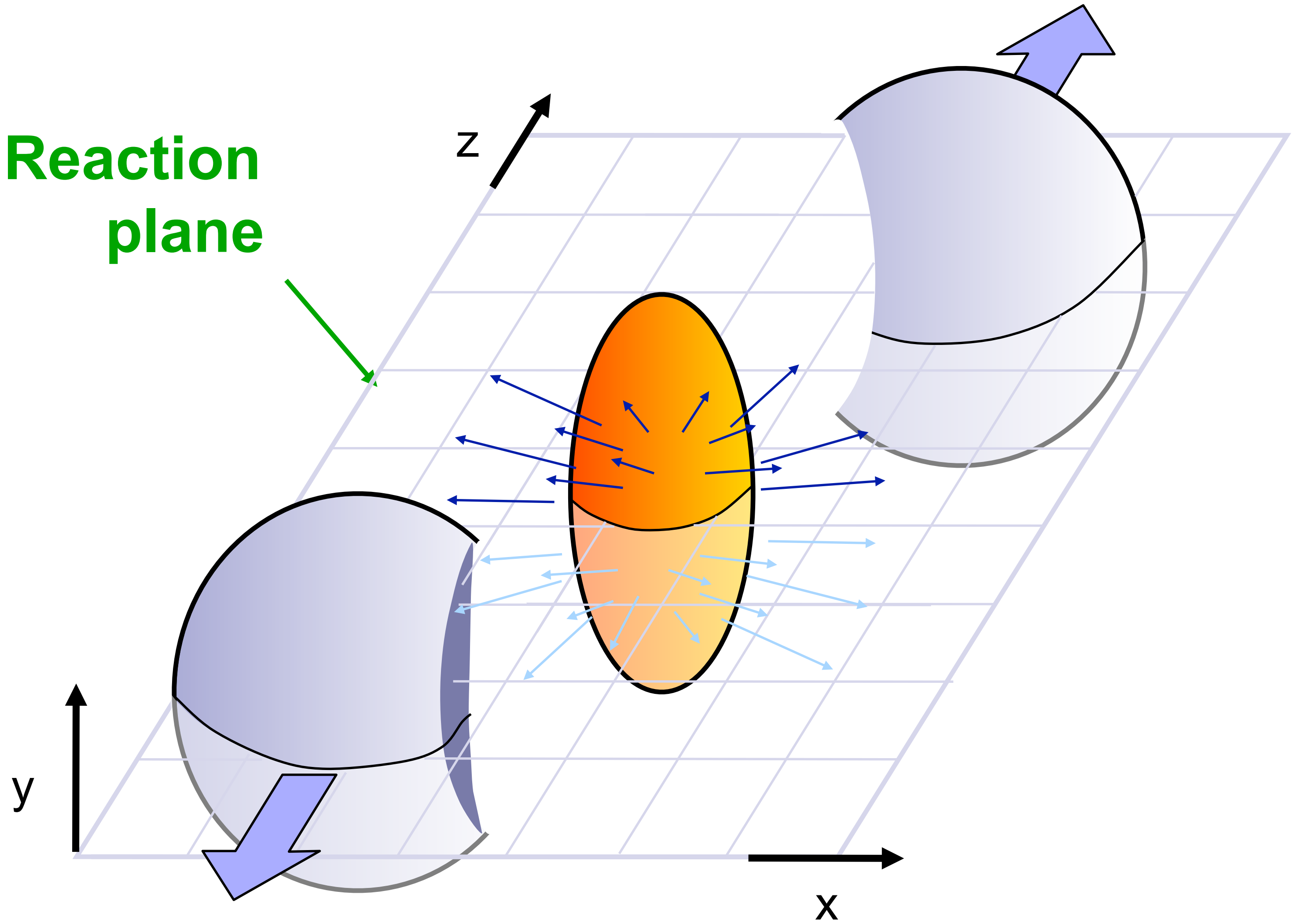
Identified particle spectra show clear evidence of thermalization and flow.



Kinetic freeze-out is cooler and faster flowing than @ RHIC.

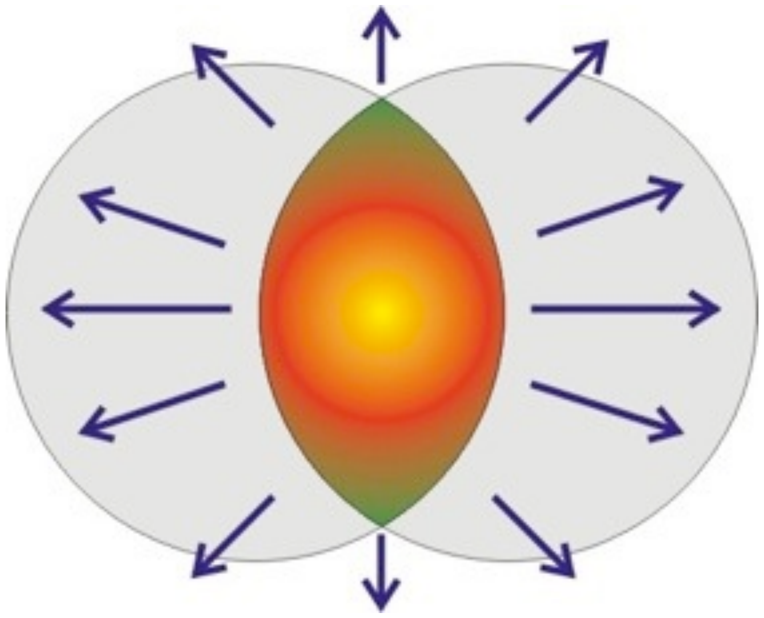


Elliptic Flow (v_2)



$v_2 = \cos(2\phi)$

coefficient of the azimuthal distribution



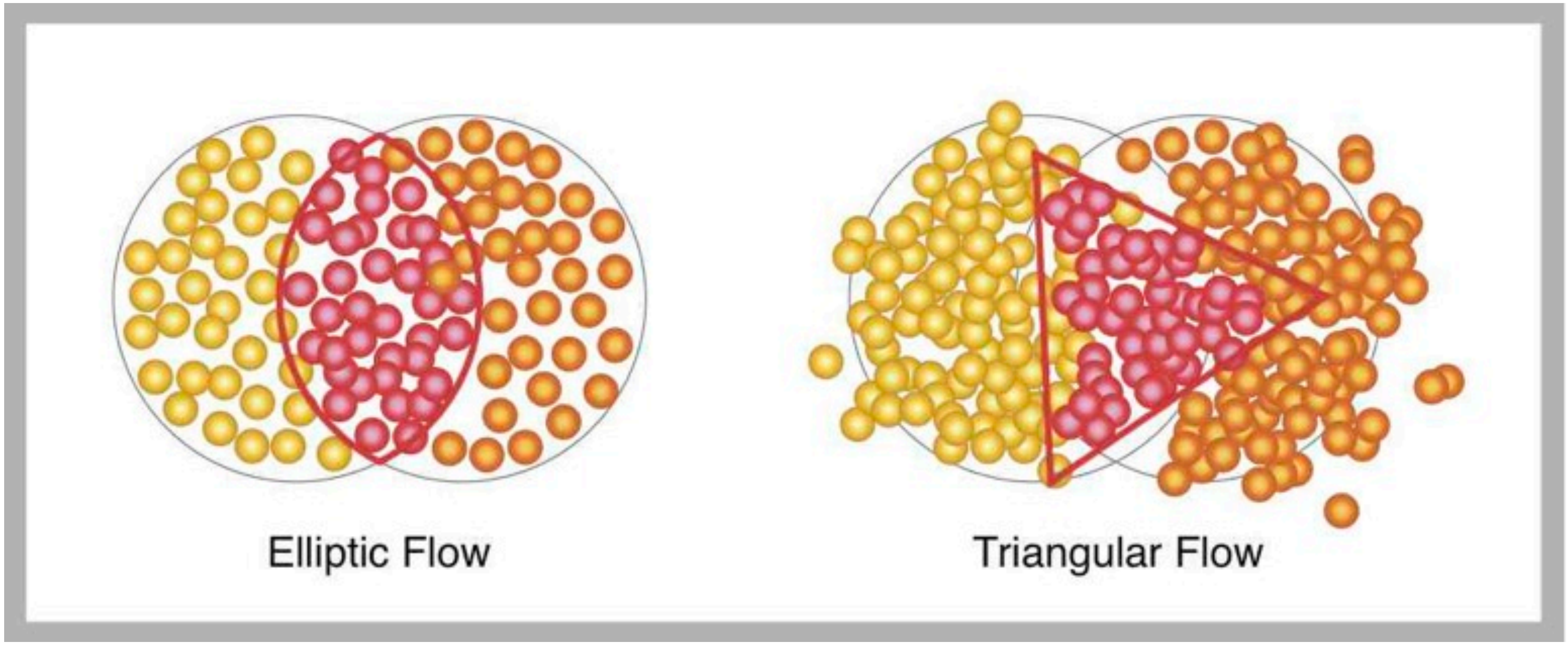
$\nabla P(\leftrightarrow) > \nabla P(\updownarrow)$

Hydrodynamics:

Flow is generated by ∇P

Event by event

Initial state generated in A+A collision is grainy
event plane ≠ reaction plane
⇒ eccentricities ε_1, ε_2, ε_3, ε_4, etc. ≠ 0



⇒ flows v_1, v_2, v_3, v_4,...

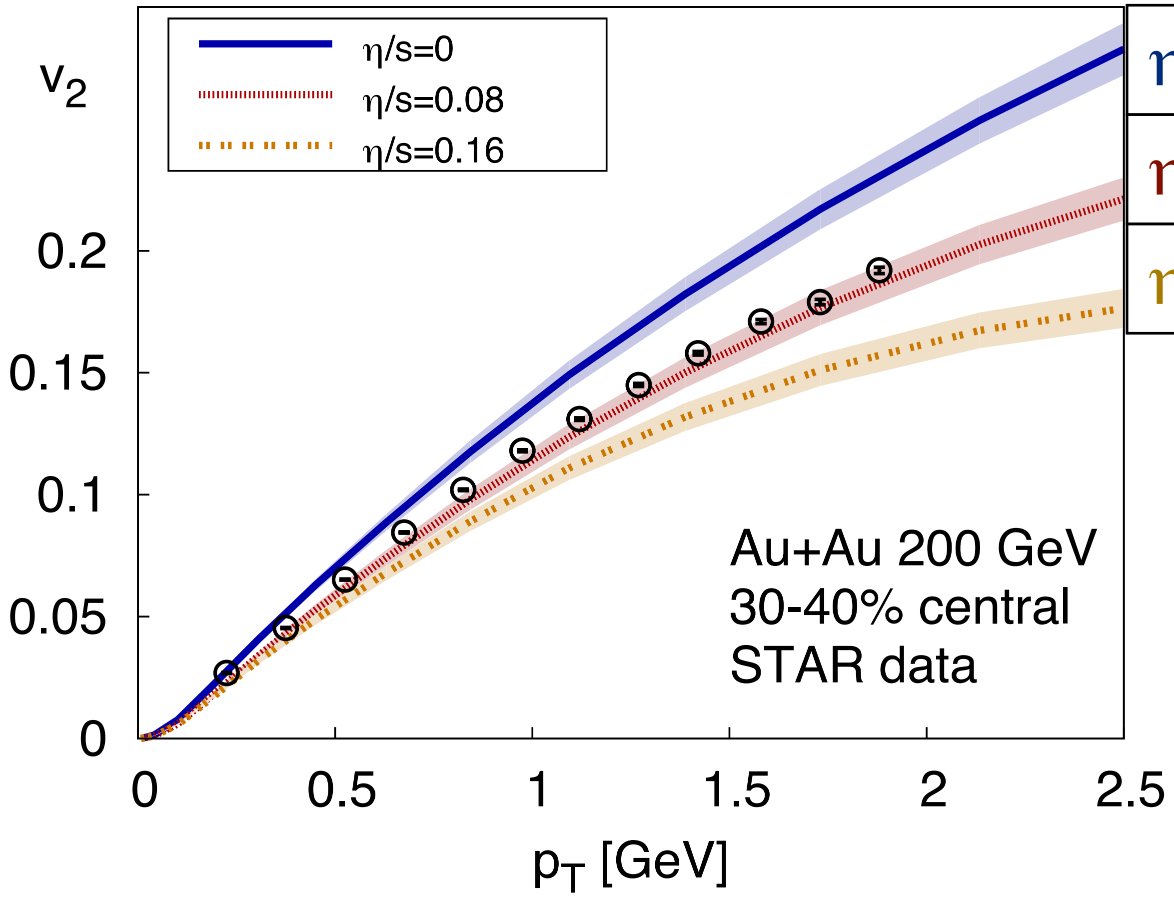
Elliptic flow "measures" η_{QGP}

Schenke, Jeon, Gale, PRL 106 (2011) 042301

Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$\eta/s \rightarrow 1/4\pi$

aka: the "perfect" liquid

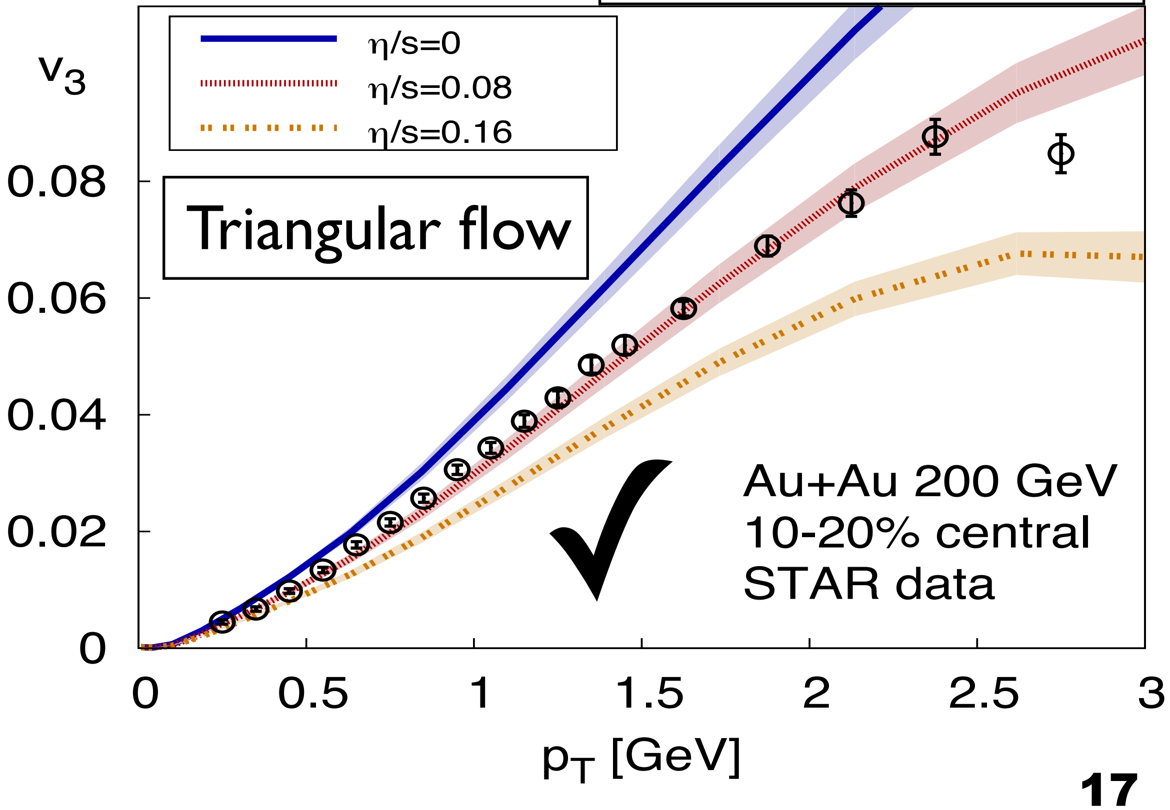


$\eta/s = 0$

$\eta/s = 1/4\pi$

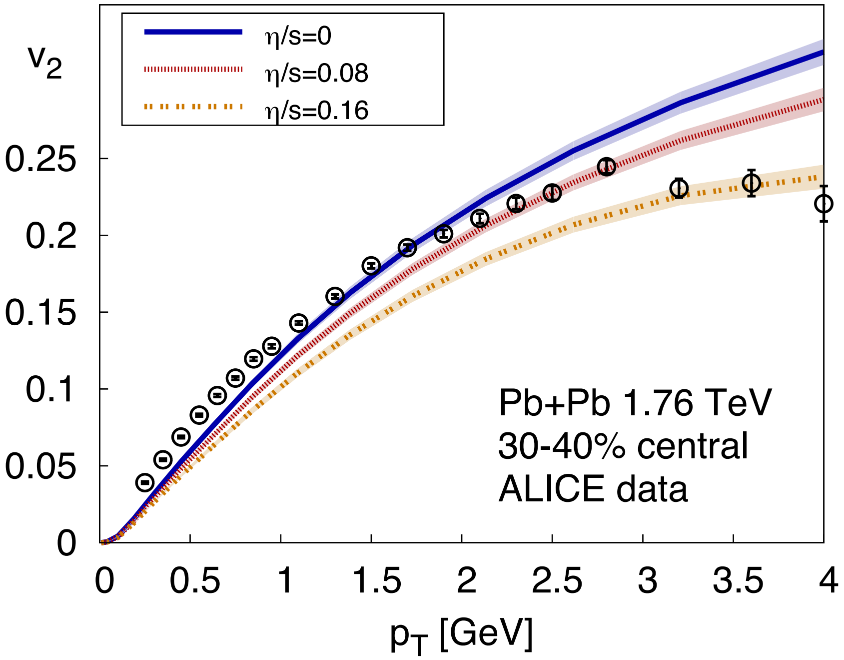
$\eta/s = 2/4\pi$

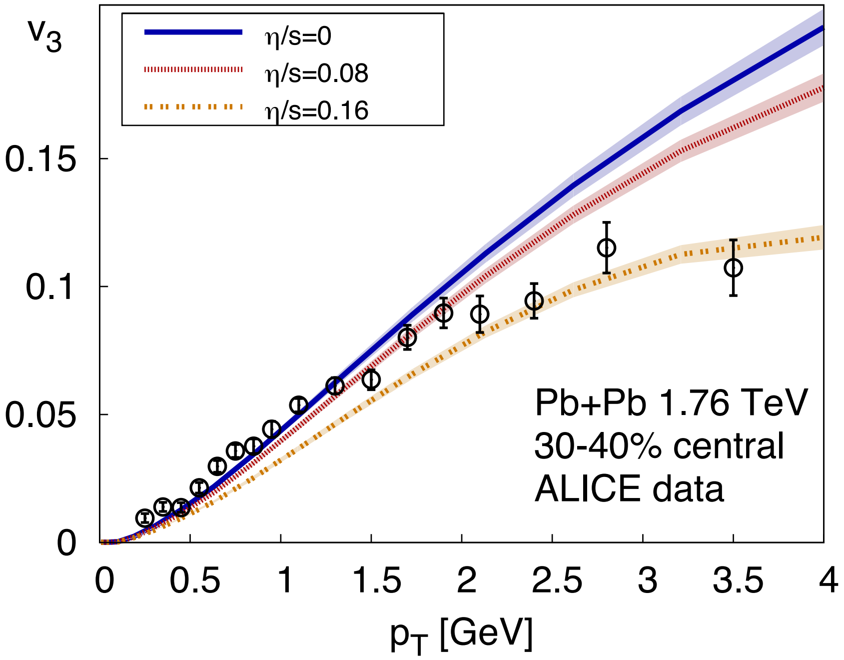
Consistency check:

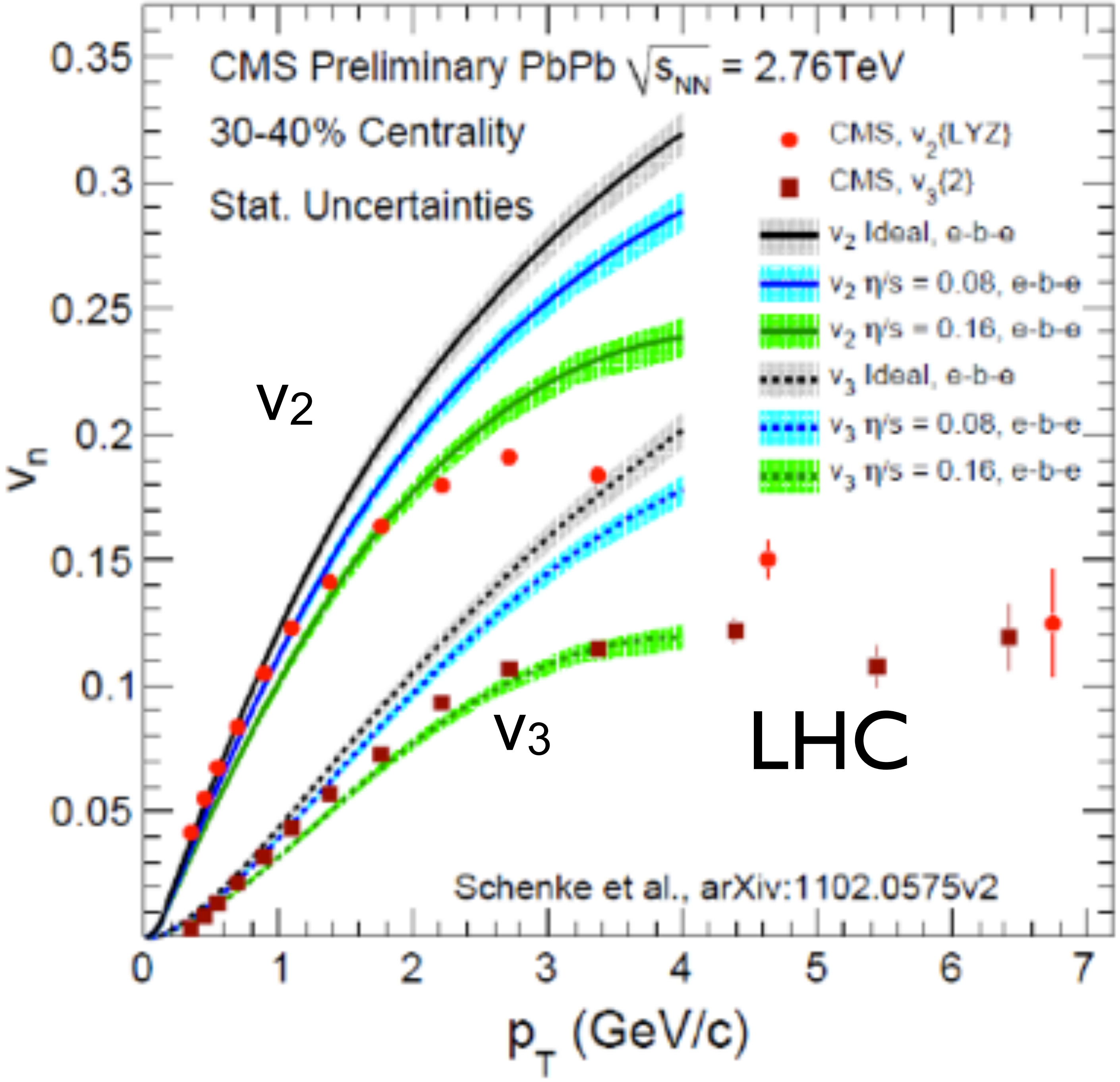


v_2 & v_3 @ LHC

Flow results agree nicely with RHIC

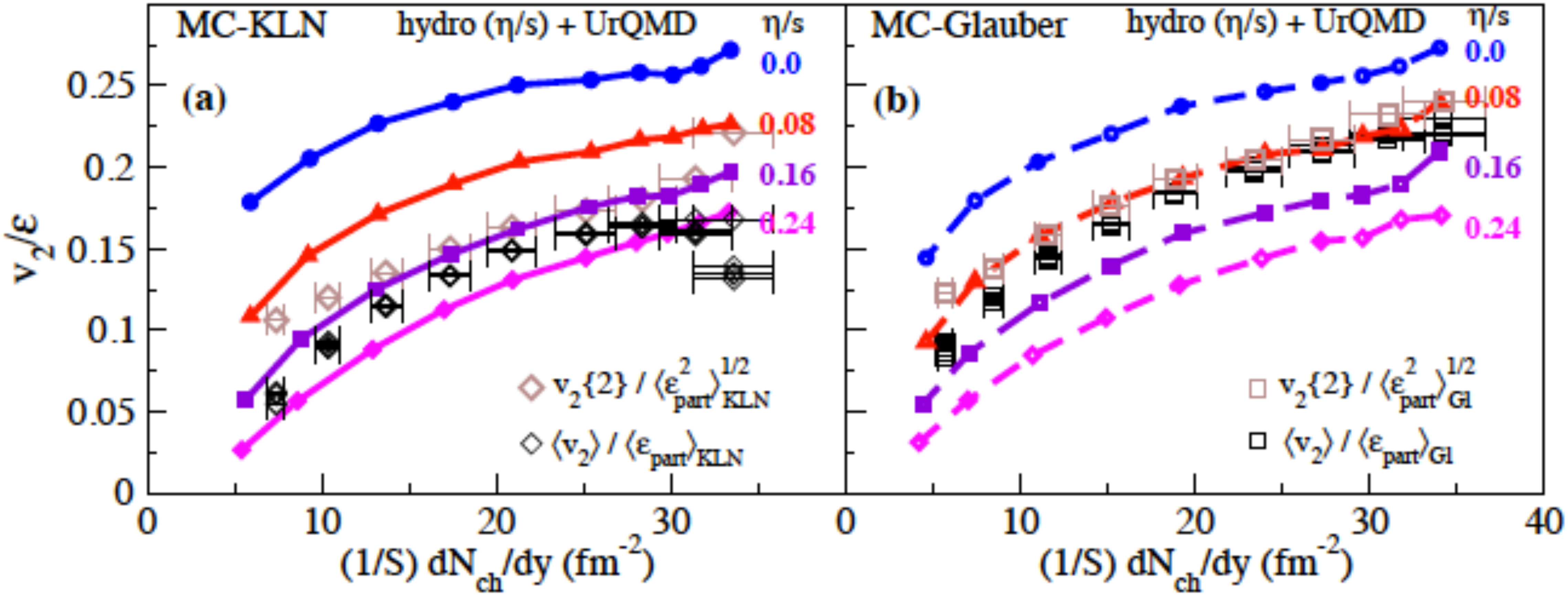






Shear viscosity

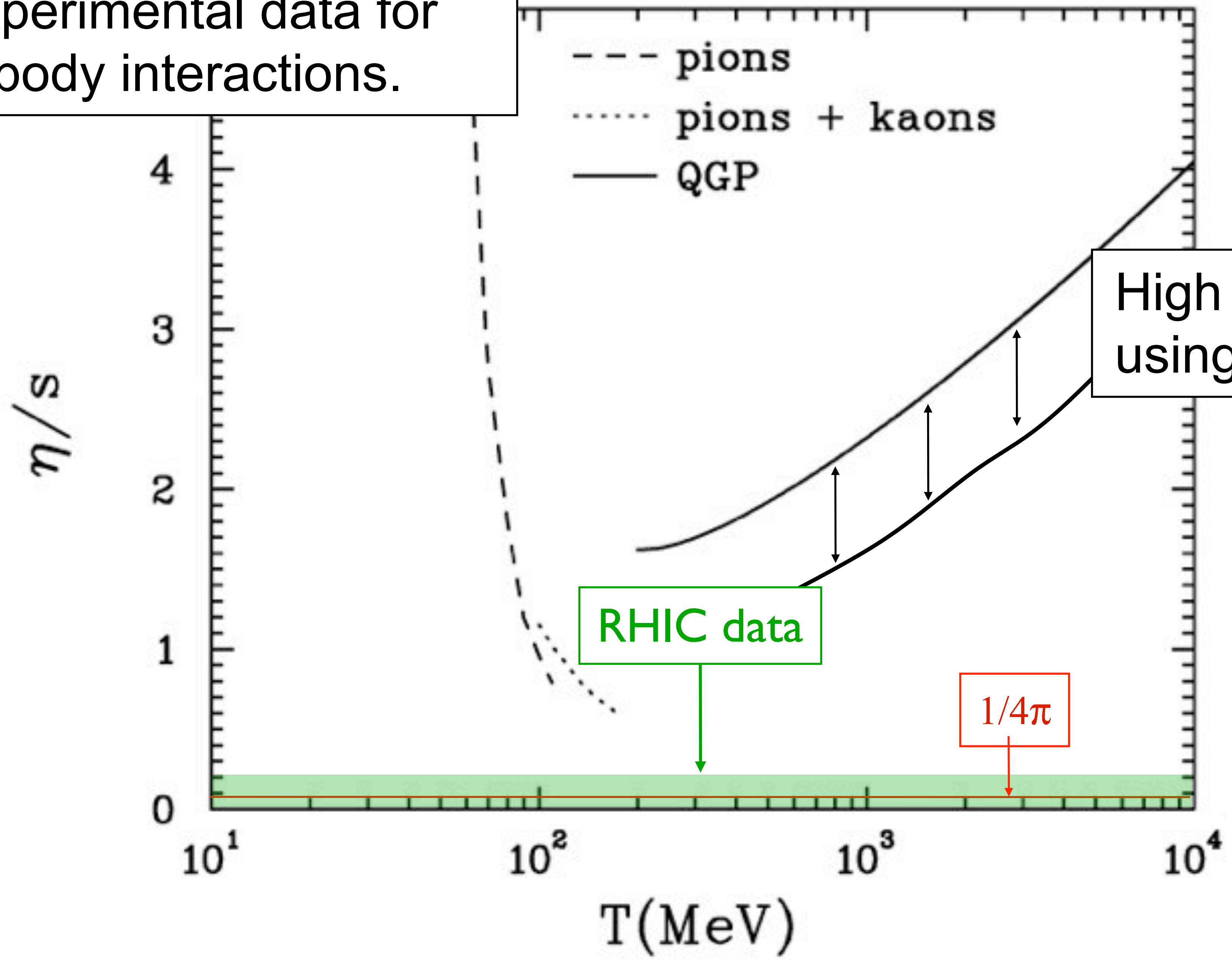
Song, Bass, Heinz, Hirano, Shen, PRL 106 (2011) 192301



Conclusion: $1 \leq 4\pi\eta/s \leq 2.5$

Remaining uncertainty mainly due to initial density profile

Viscosity of QCD matter



Low T viscosity using experimental data for 2-body interactions.

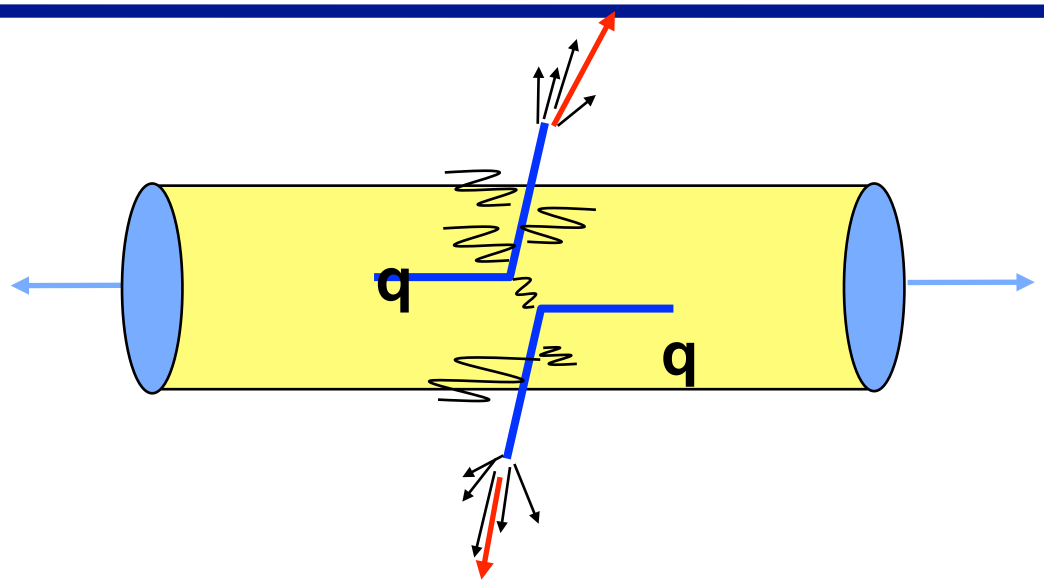
High T viscosity using perturb. QCD

RHIC data

$1/4\pi$

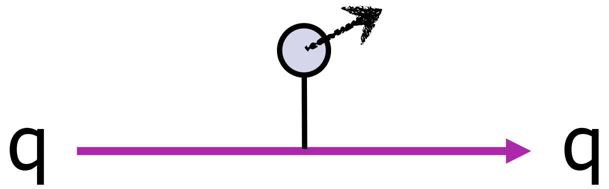
Part 3
The Opaque QGP

Parton energy loss in QCD

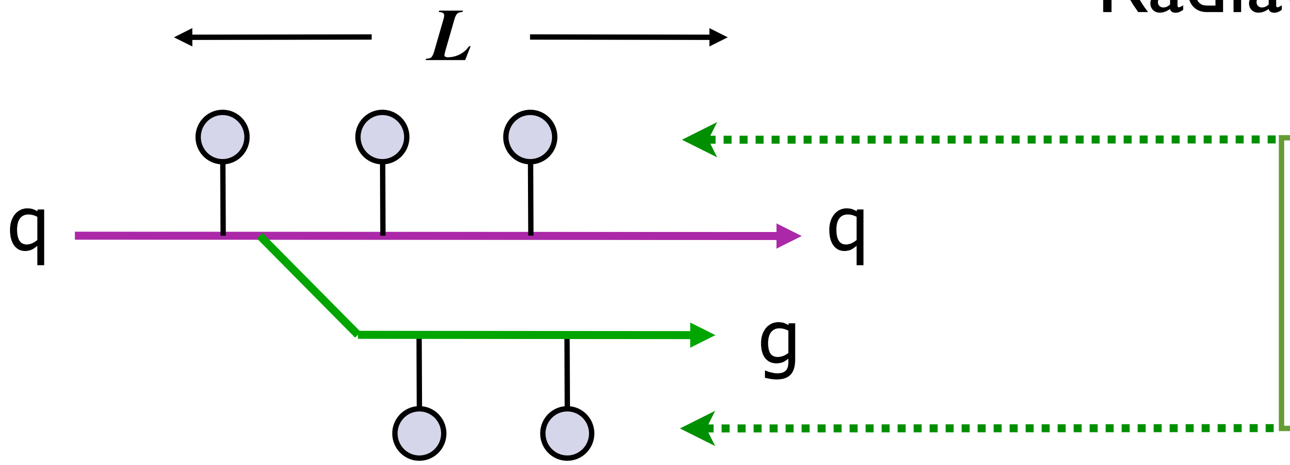


Elastic energy loss:

$$\frac{dE}{dx} = -C_2\,\hat{e}$$



Radiative energy loss:



Scattering centers

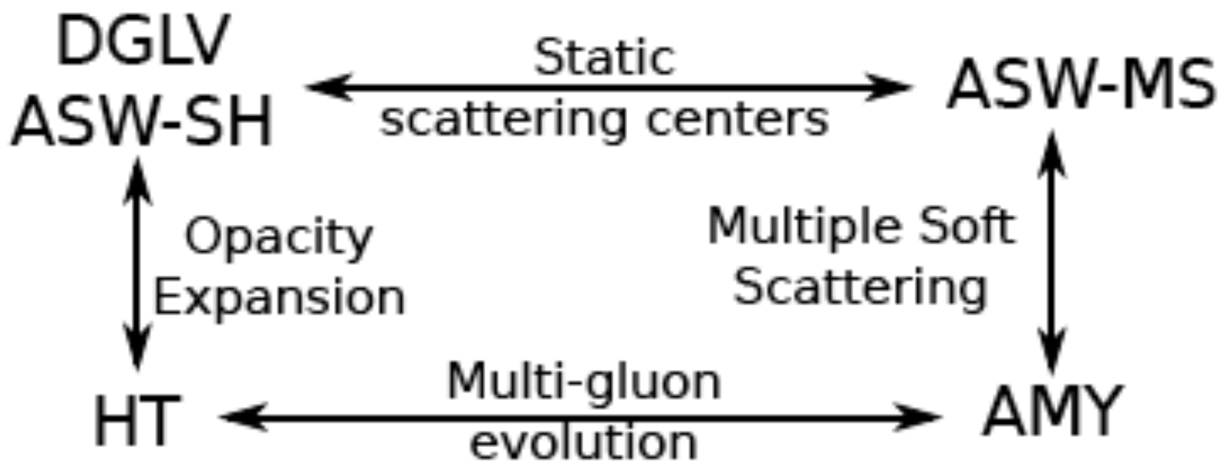
⇔ color charges

$$\frac{dE}{dx} = -C_2\,\hat{q}\,L \qquad \hat{q} = \rho\int q^2\,dq^2\,\frac{d\sigma}{dq^2} = \int dx^-\left\langle F_i^{+}(x^-)F^{+i}(0)\right\rangle$$

Review: A. Majumder & M. van Leeuwen, arXiv:1002.2206

pQCD formalism

Landscape of QCD jet quenching formalisms: [see: Armesto et al. arXiv:1106.1106; the “QCD Brick Report”]



DGLV
ASW-SH

Static scattering centers

ASW-MS

Opacity Expansion

Multiple Soft Scattering

HT

Multi-gluon evolution

AMY

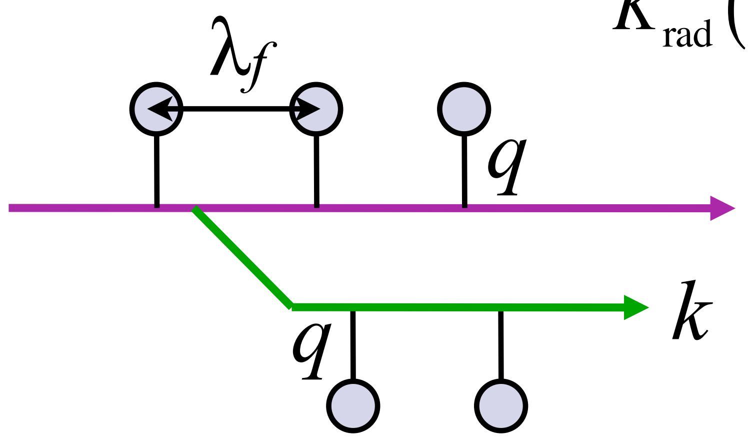
Example: DGLV

$$x\frac{dN_g^{\mathrm{DGLV}}}{dx}=\frac{2C_R\alpha_s}{\pi^3}\frac{L}{\lambda_f}\int d^2q\,d^2k\,\frac{\mu^2}{\left(q^2+\mu^2\right)}K_{\mathrm{rad}}(k,q)\int_0^L dz\,K_{\mathrm{LPM}}(k,q;z)\,\rho(z)$$

$$K_{\mathrm{rad}}(k,q)=\frac{\vec{k}\cdot\vec{q}(k-q)^2-\beta^2\vec{q}\cdot(\vec{k}-\vec{q})}{\left[(k-q)^2+\beta^2\right]\left(k^2+\beta^2\right)}\quad \text{with}\quad \beta^2=m_g^2+x^2M_q^2$$

$$K_{\mathrm{LPM}}(k,q;z)=1-\cos\left(\frac{(k-q)^2+\beta^2}{2xE}z\right)$$

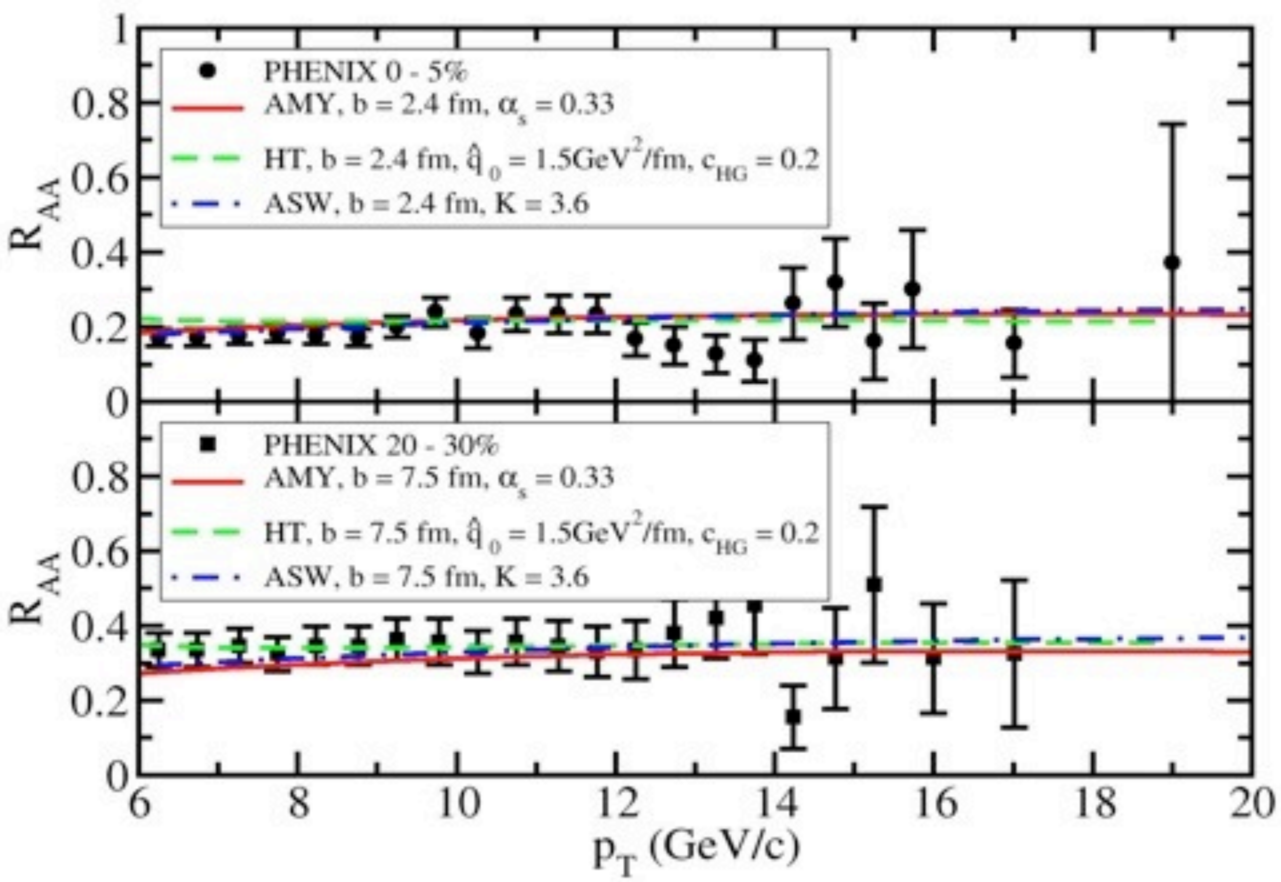
LPM coherence effect



Towards measuring $\hat{q}$

Good fits for light hadrons can be obtained for all energy loss models with 3-D hydro evolution, ***but...***

Bass, Gale, Majumder, Nonaka, Qin, Renk & Ruppert

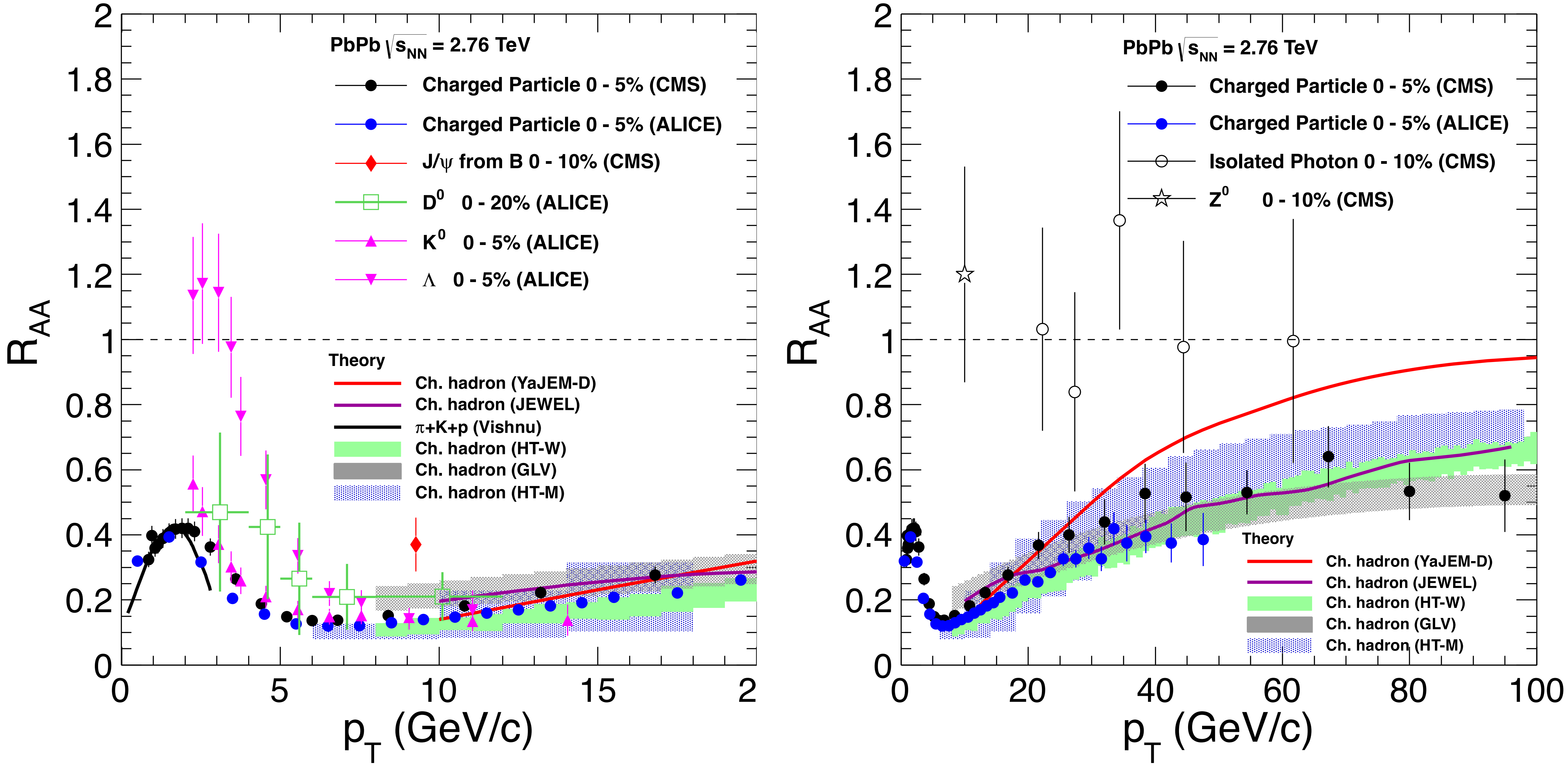


Transport parameter $\hat{q}$ deviates by more than factor 2 between different implementations.

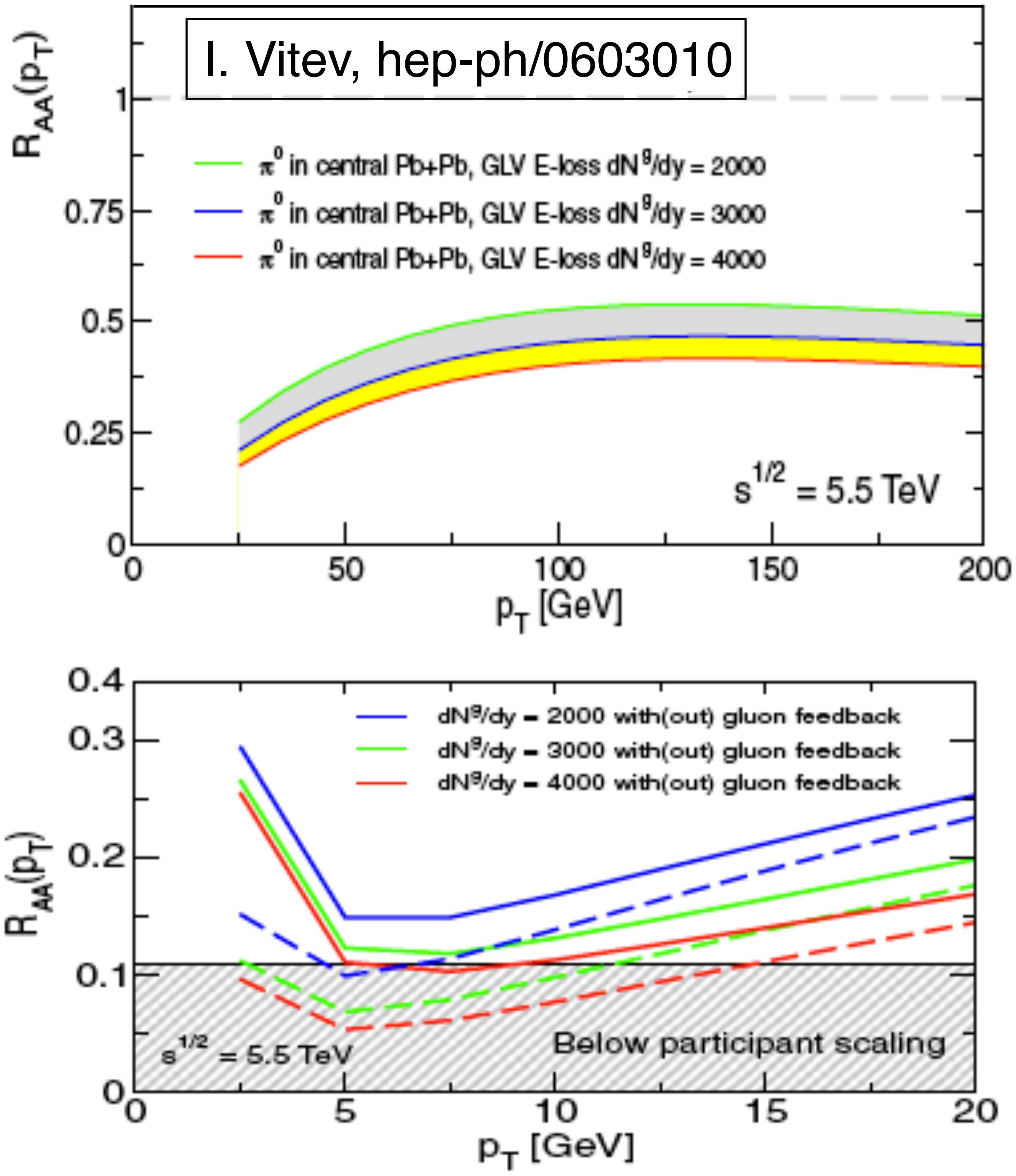
Caused by differences in the cut-offs in collinear approximation used in all implementations of gluon radiation.

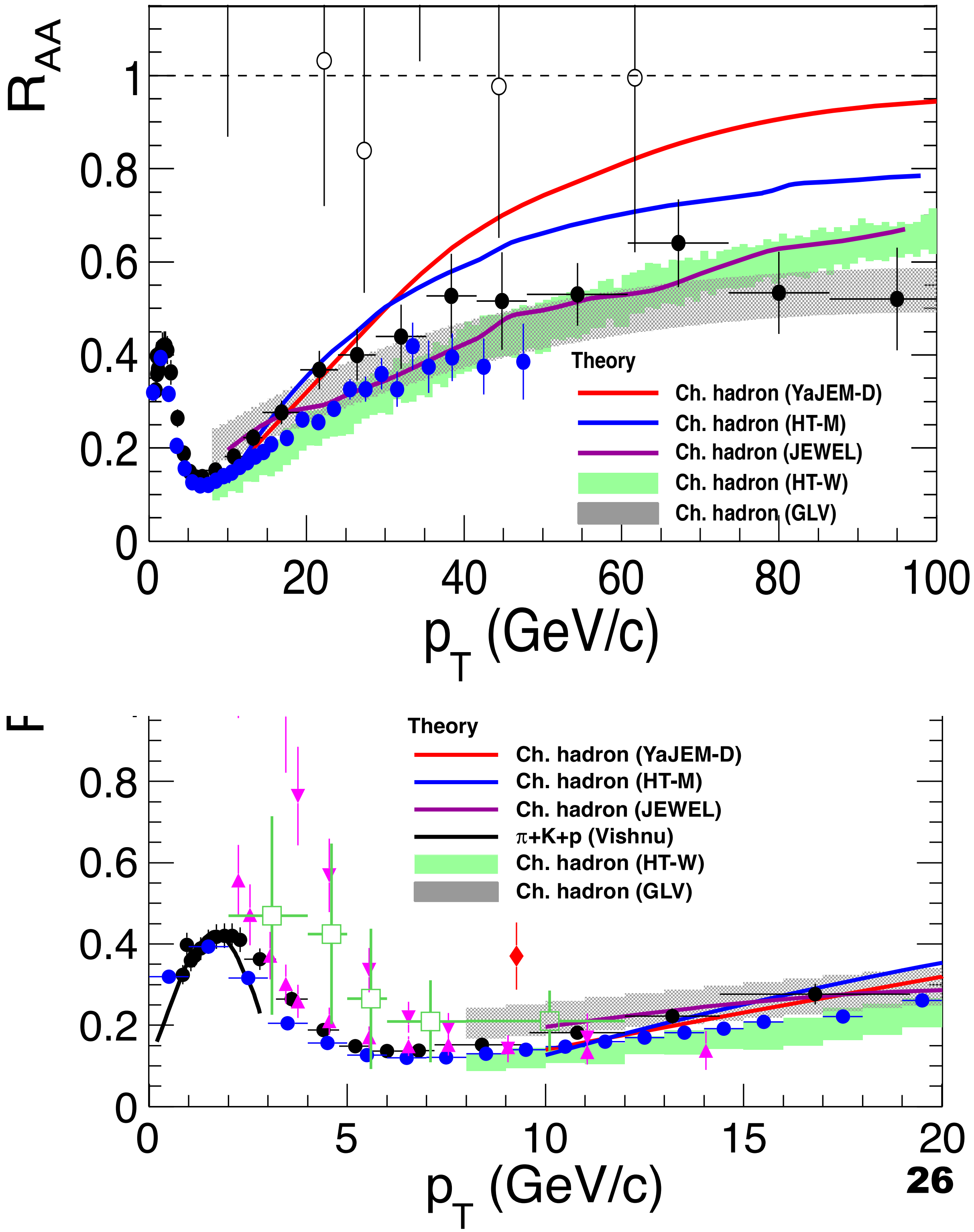
MC implementations required to accurately simulate energy loss

Jet quenching at LHC



Vitev “nailed it”


I. Vitev, hep-ph/0603010



Connecting jets with the medium

Hard partons probe the medium via the density of colored scattering centers:

$$\hat{q} = \rho \int q^2 dq^2 \left(d\sigma / dq^2 \right) \sim \int dx^- \left\langle F^{\perp +}(x^-) F_\perp^+(0) \right\rangle$$

If kinetic theory applies, thermal gluons are quasi-particles that experience the same medium. Then the shear viscosity is:

$$\eta \approx \frac{1}{3} \rho \left\langle p \lambda_f(p) \right\rangle = \frac{1}{3} \left\langle \frac{p}{\sigma_{tr}(p)} \right\rangle$$

In QCD, small angle scattering dominates:

$$\sigma_{tr}(p) \approx \frac{2\hat{q}}{\langle p \rangle^2 \rho}$$

With $\langle p \rangle \sim 3T$ and $s \approx 3.6\rho$ (for gluons) one finds:

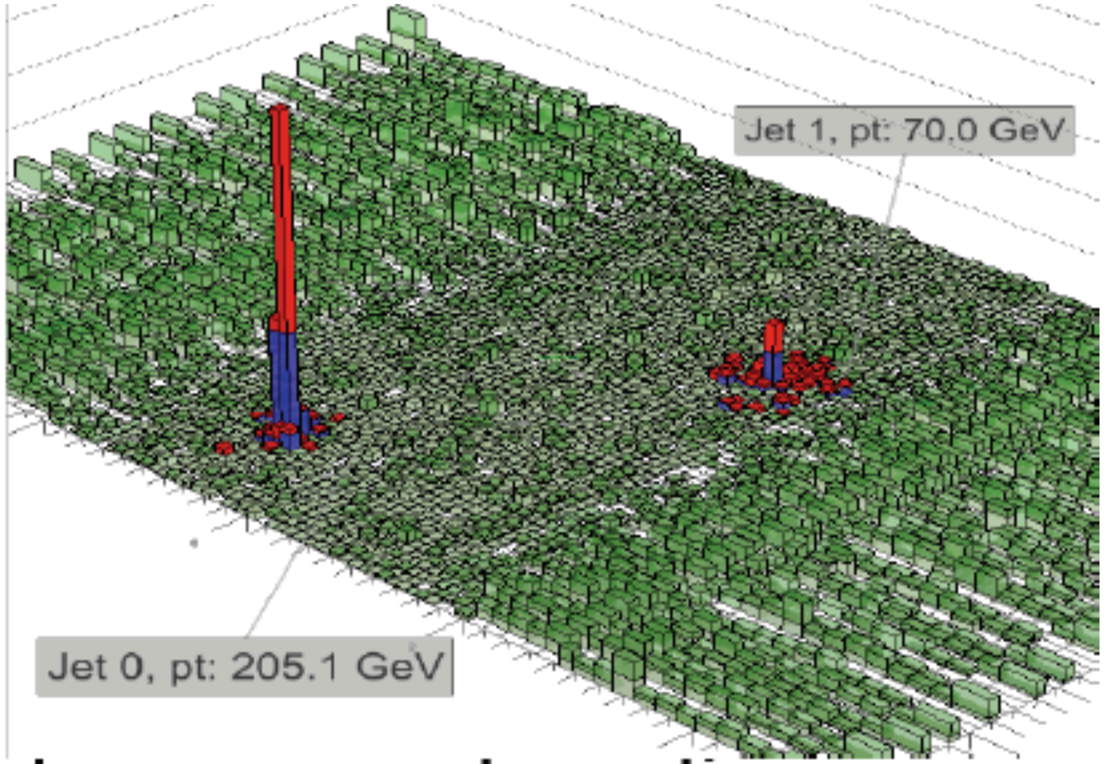
$$\boxed{\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}}$$

A. Majumder, BM, X-N. Wang,
PRL 99 (2007) 192301

From RHIC data: $T_0 \approx 335\ \mathrm{MeV},\ \hat{q}_0 \approx 2.8\ \mathrm{GeV}^2/\mathrm{fm} \ \rightarrow (\eta / s)_0 \approx 0.10$

Di-jets

- Dijet selection:
  - $|\eta^{Jet}| < 2$
  - Leading jet $p_{T,1} > 120\mathrm{GeV}/c$
  - Subleading jet $p_{T,2} > 50\mathrm{GeV}/c$
  - $\Delta\phi_{1,2} > 2\pi/3$

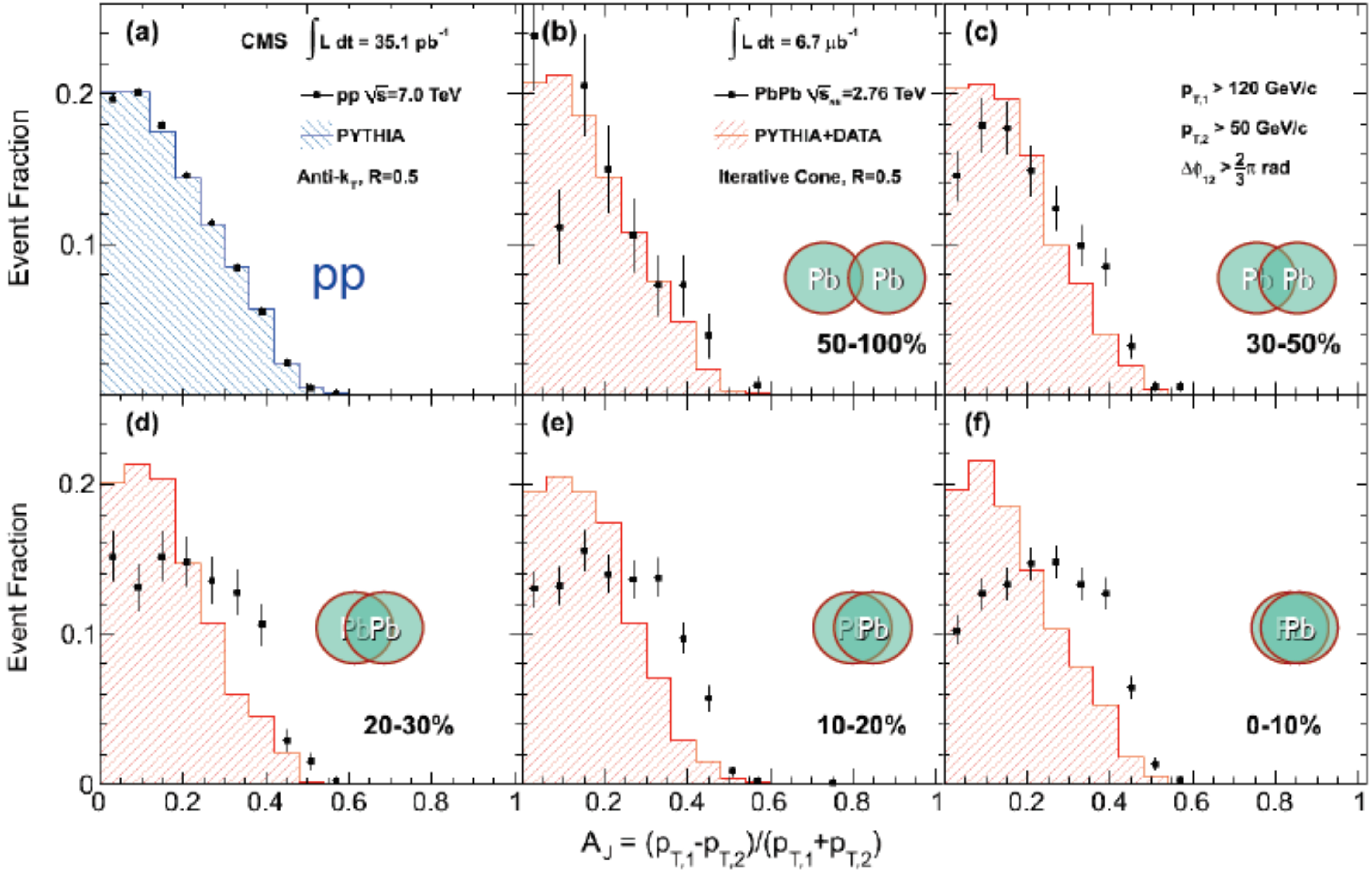


- Quantify dijet energy imbalance by asymmetry ratio:

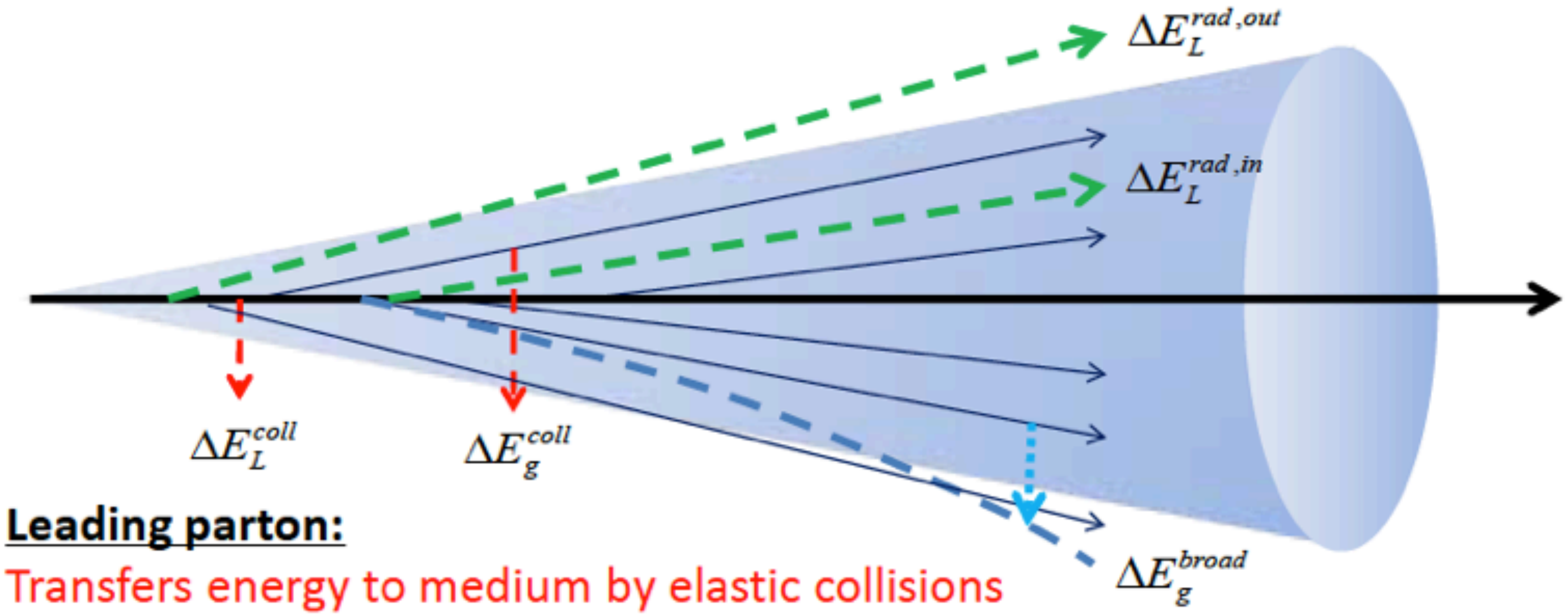
$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Removes uncertainties in overall jet energy scale

Di-jet asymmetry



Parton shower in matter



Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons scattering in the medium (*inside* and *outside* jet cone)

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Radiated gluons (*vacuum* & *medium-induced*):

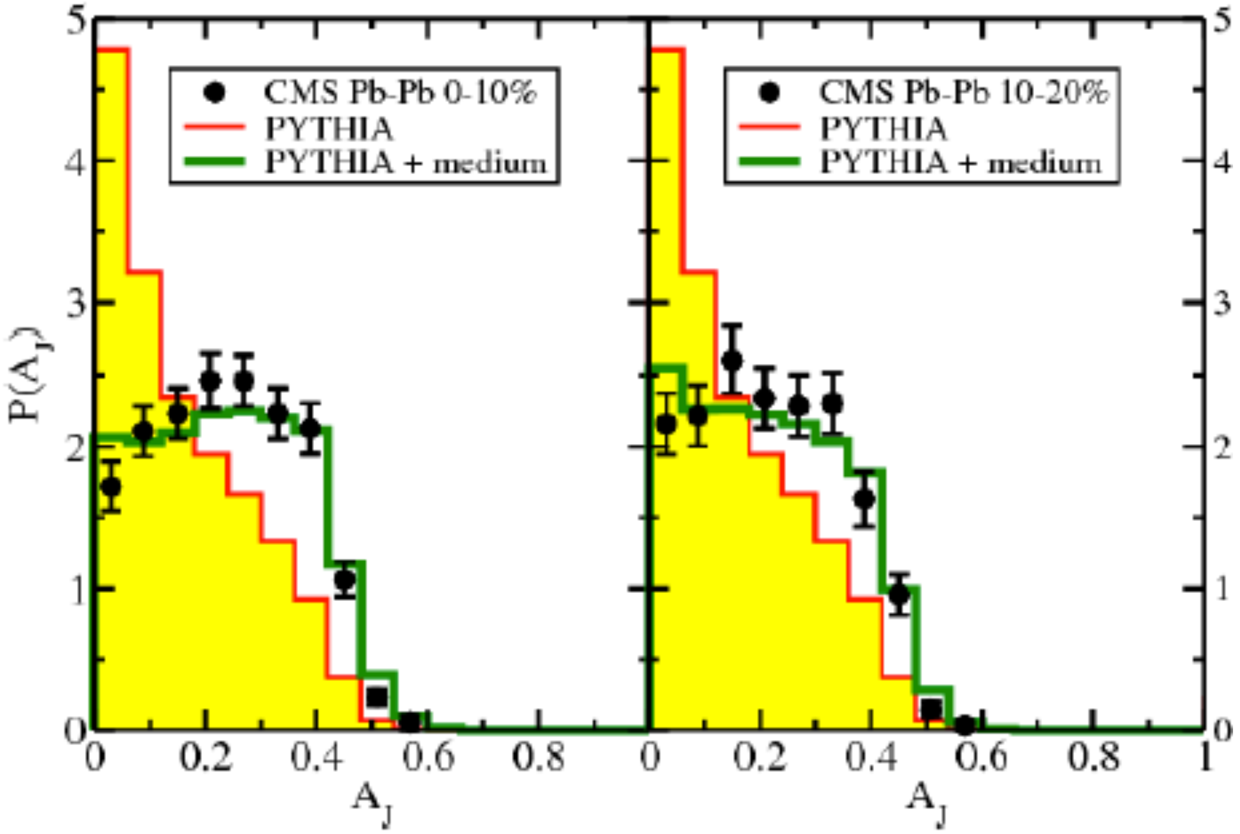
Transfer energy to medium by elastic collisions

Be kicked out of the jet cone by multiple scatterings after emission

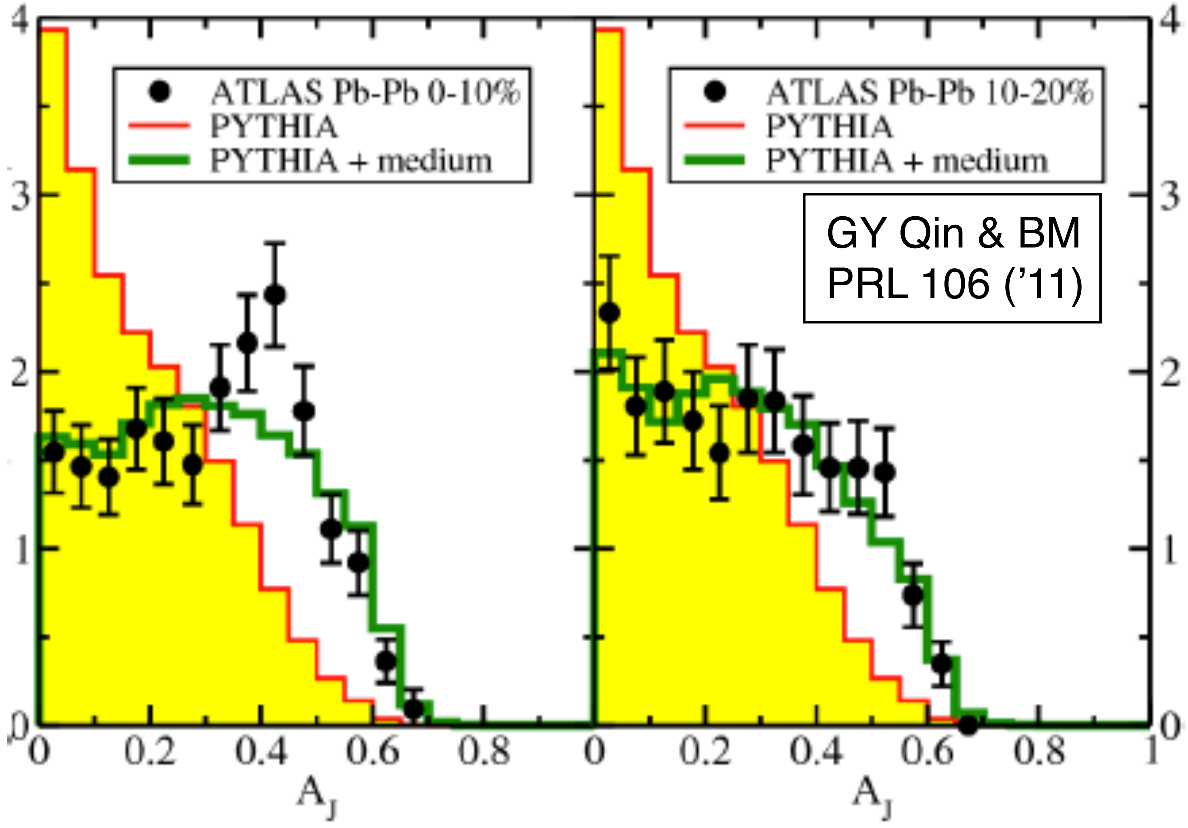
$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Di-jet asymmetry

CMS data



ATLAS data



GY Qin & BM
PRL 106 ('11)

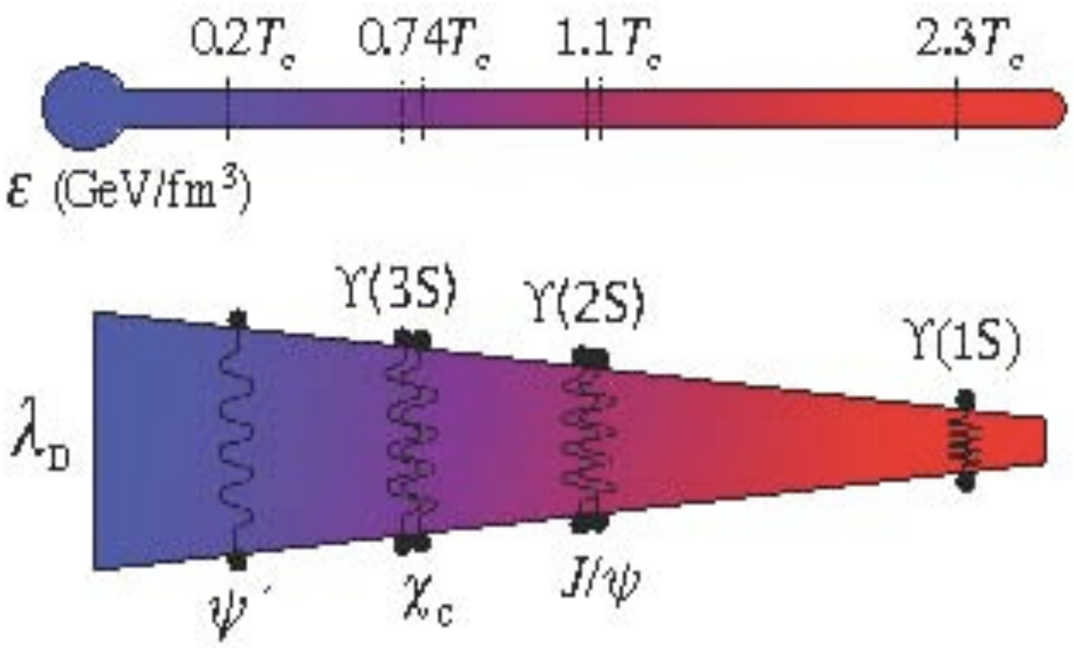
ATLAS and CMS data differ in cuts on jet energy, cone angle, etc. ATLAS results depend somewhat on precise cuts and background corrections. Theoretical fits require 20% different parameters.

Part 4
The screened QGP

Plasma screening

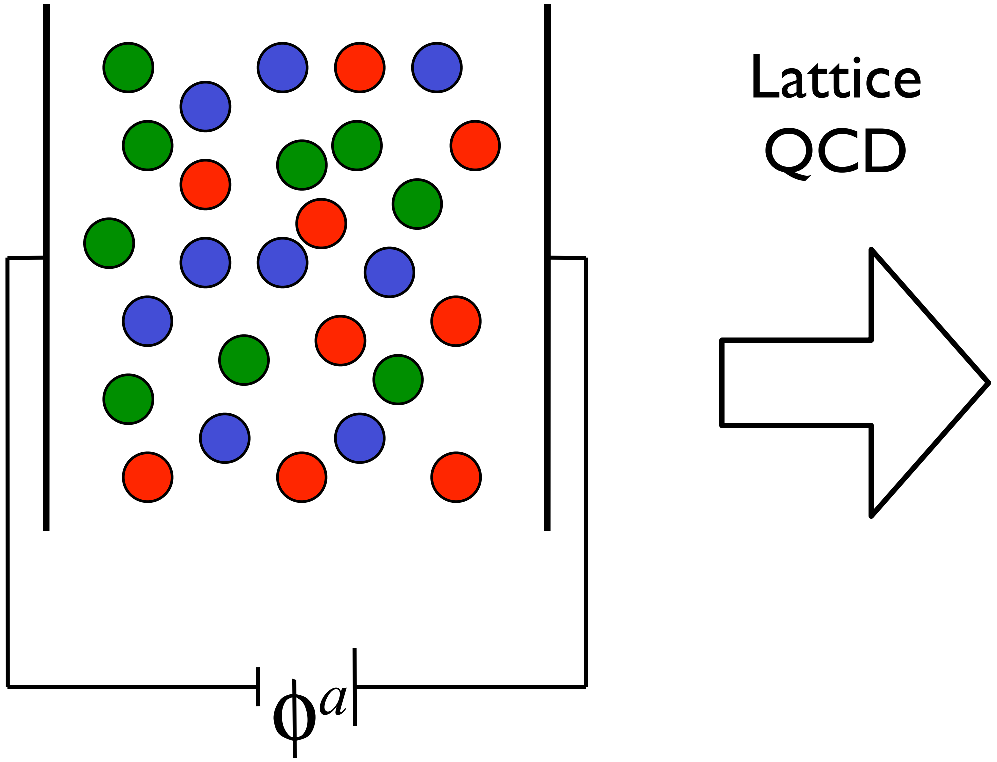
- Plasma: An globally neutral state of matter with mobile charges
- Interactions among charges of many particles spread charge over a characteristic (Debye) length ➠ (chromo-) electric screening
- Strongly coupled plasmas: Only few particles in Debye sphere ➠ Nearest neighbor correlations ↔ liquid-like properties
- *Test* QGP *screening with heavy quark bound states*

  Do they survive? Which ones?
- Ideal system: Upsilon states
- Do residual correlations enhance recombination?

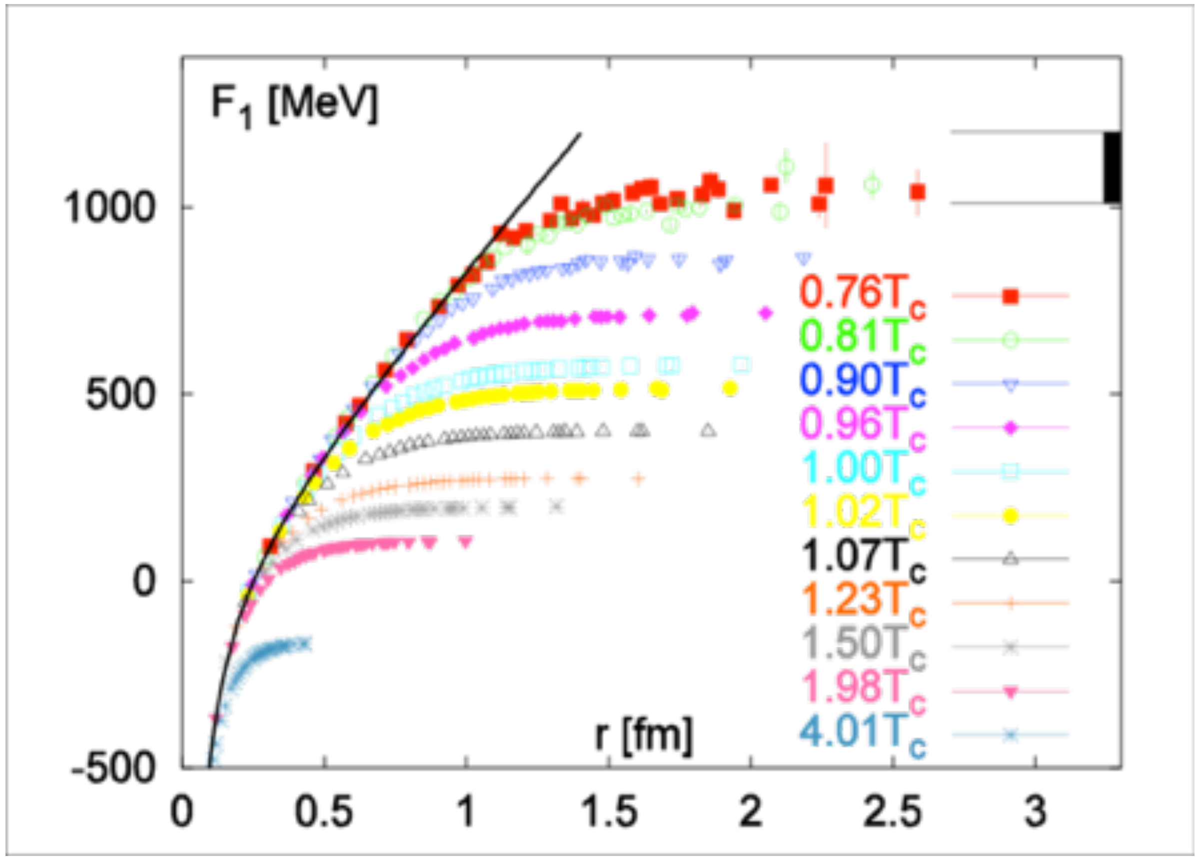


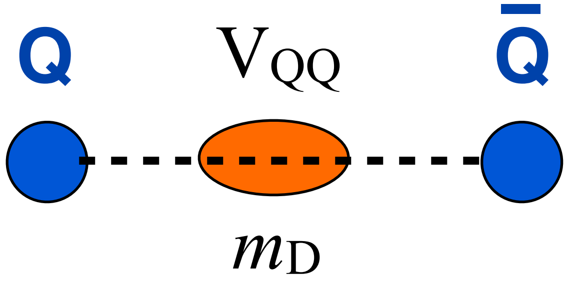
In the good old days...

... life seemed so simple:



Lattice QCD





Q V_{QQ} **$\bar{Q}$**

m_D

$m_D \sim gT$

The real story...

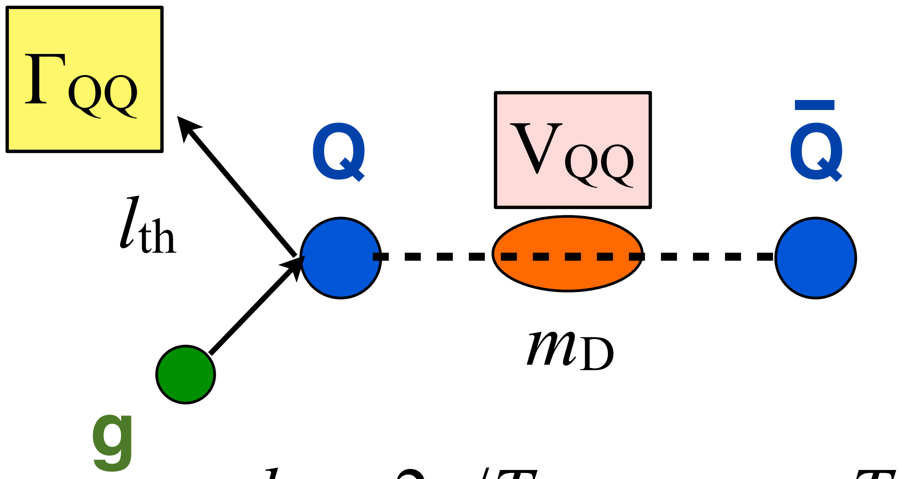
...is more complicated that just m_D.

Q-Qbar bound state interacts with medium elastically and inelastically!

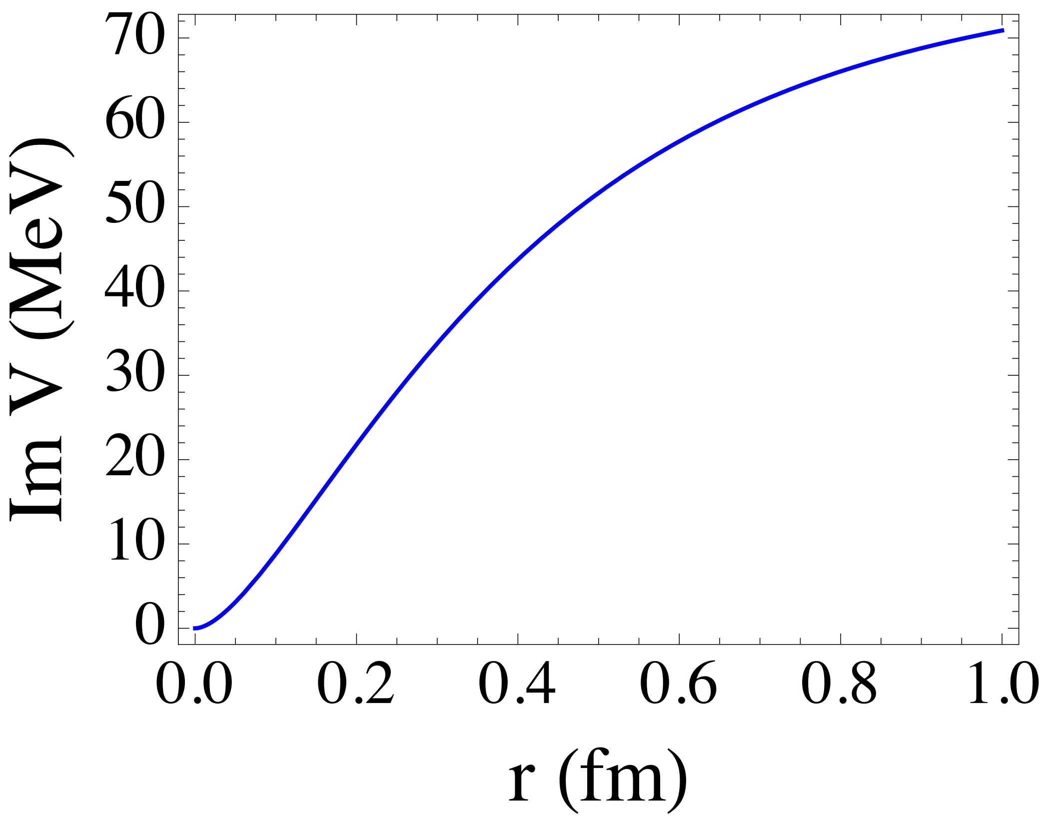
$$i\hbar\frac{\partial}{\partial t}\Psi_{Q\bar{Q}} = \left[\frac{p_Q^2 + p_{\bar{Q}}^2}{2M} + V_{Q\bar{Q}} - \frac{i}{2}\Gamma_{Q\bar{Q}} + \eta\right]\Psi_{Q\bar{Q}}$$

Strickland, arXiv:1106.2571, 1112.2761;
Akamatsu & Rothkopf, arXiv:1110.1203

➠ heavy-Q energy loss and Q-Qbar suppression cannot be separated

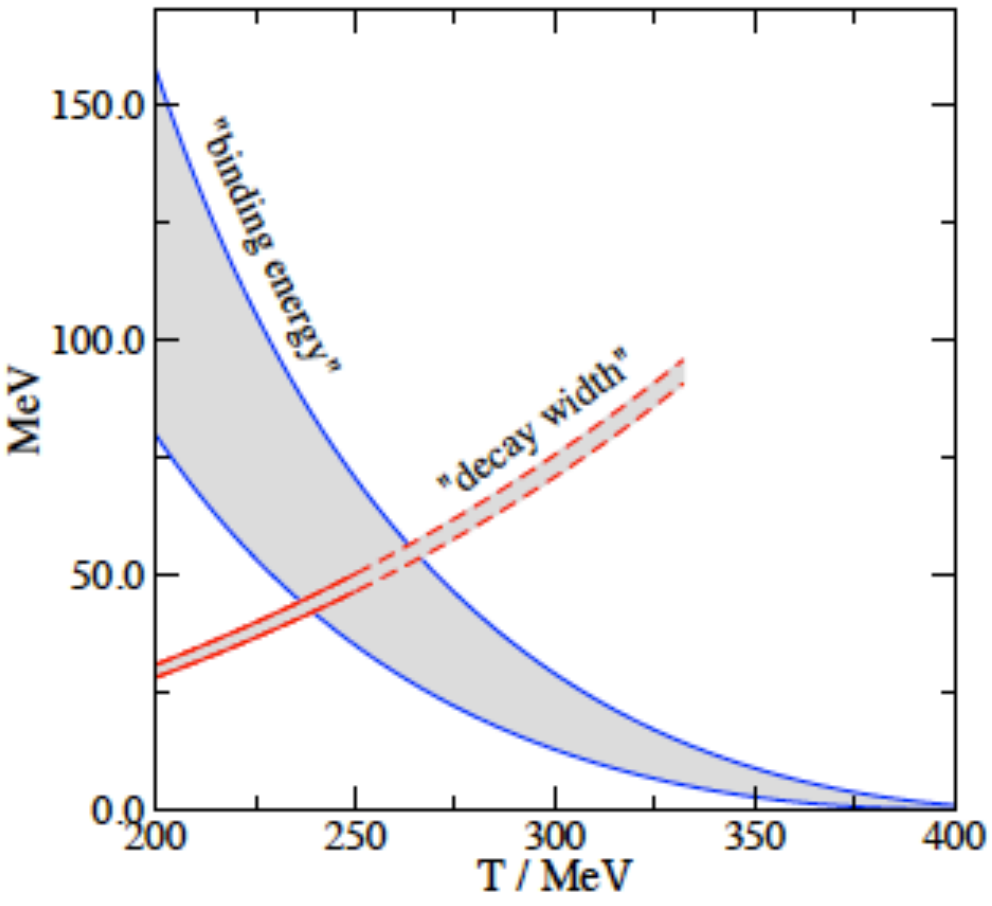


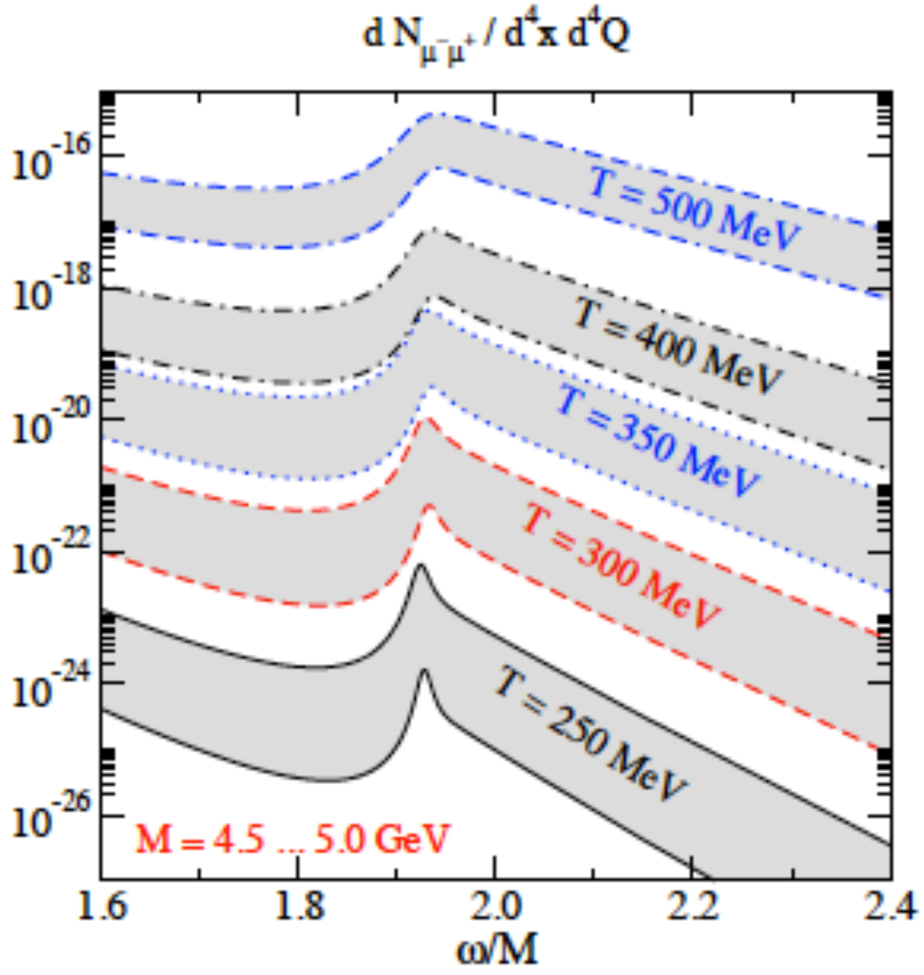
$l_{th} \sim 2\pi/T, \quad m_D \sim gT$



ϒ melting revisited

Decreasing QQ binding due to screening and increasing width due to thermal gluon absorption lead to gradual melting of quarkonium states [here ϒ(1s)]. See M. Laine, arXiv:1108.5965. Similar to ρ^0 melting at SPS?

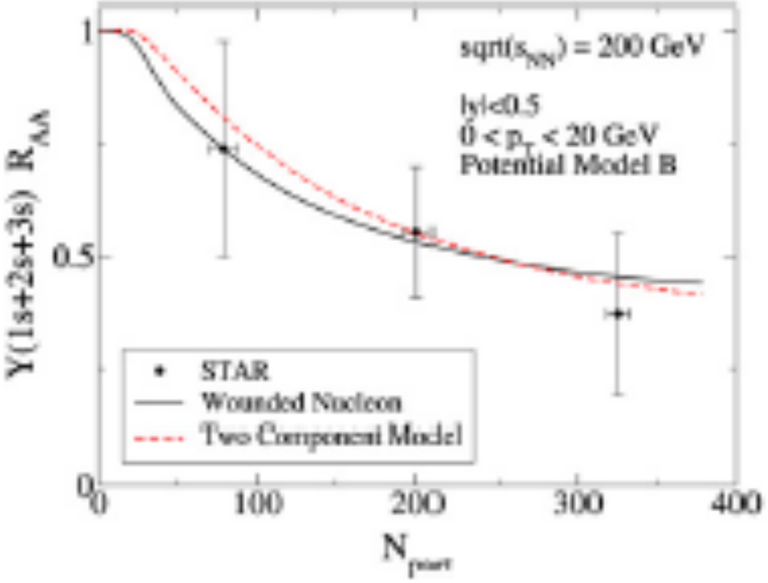


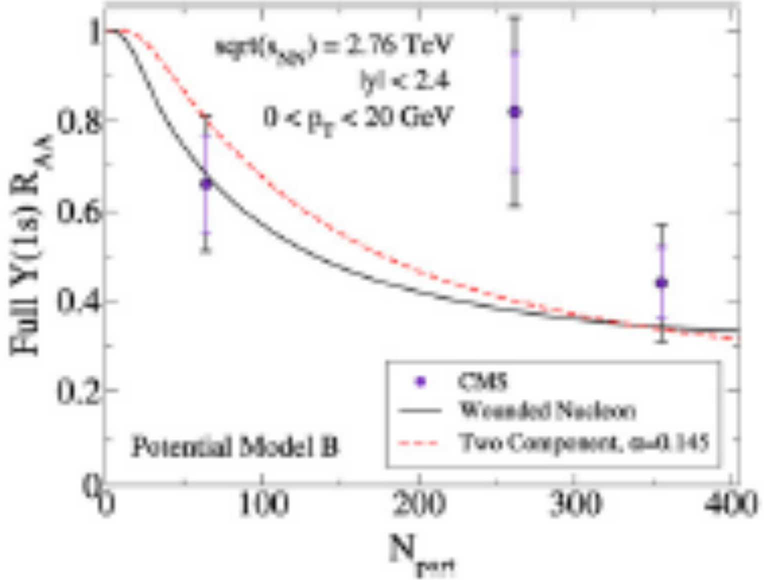


State of art

Tour de force calculation of ϒ suppression by M. Strickland, PRL 107, 132301 (2011):

- Re(V), Im(V) in anisotropic HTL / NRQCD + T-dep. confining pot.
- Schrödinger equation for ϒ states ➠ E_{QQ} , Γ_{QQ}
- Anisotropic (viscous) hydrodynamics for medium evolution
- Time integrated suppression factor: $R_{AA} = \exp\left(- \int_{\tau_{\text{form}}}^{\tau_f} \Gamma_{QQ}(\tau, x_\perp, \xi)\, d\tau \right)$





Borghini & Gombeaud, arXiv - 1109.4271:

Treat dipole transitions between QQ states induced by thermal gluons dynamically.

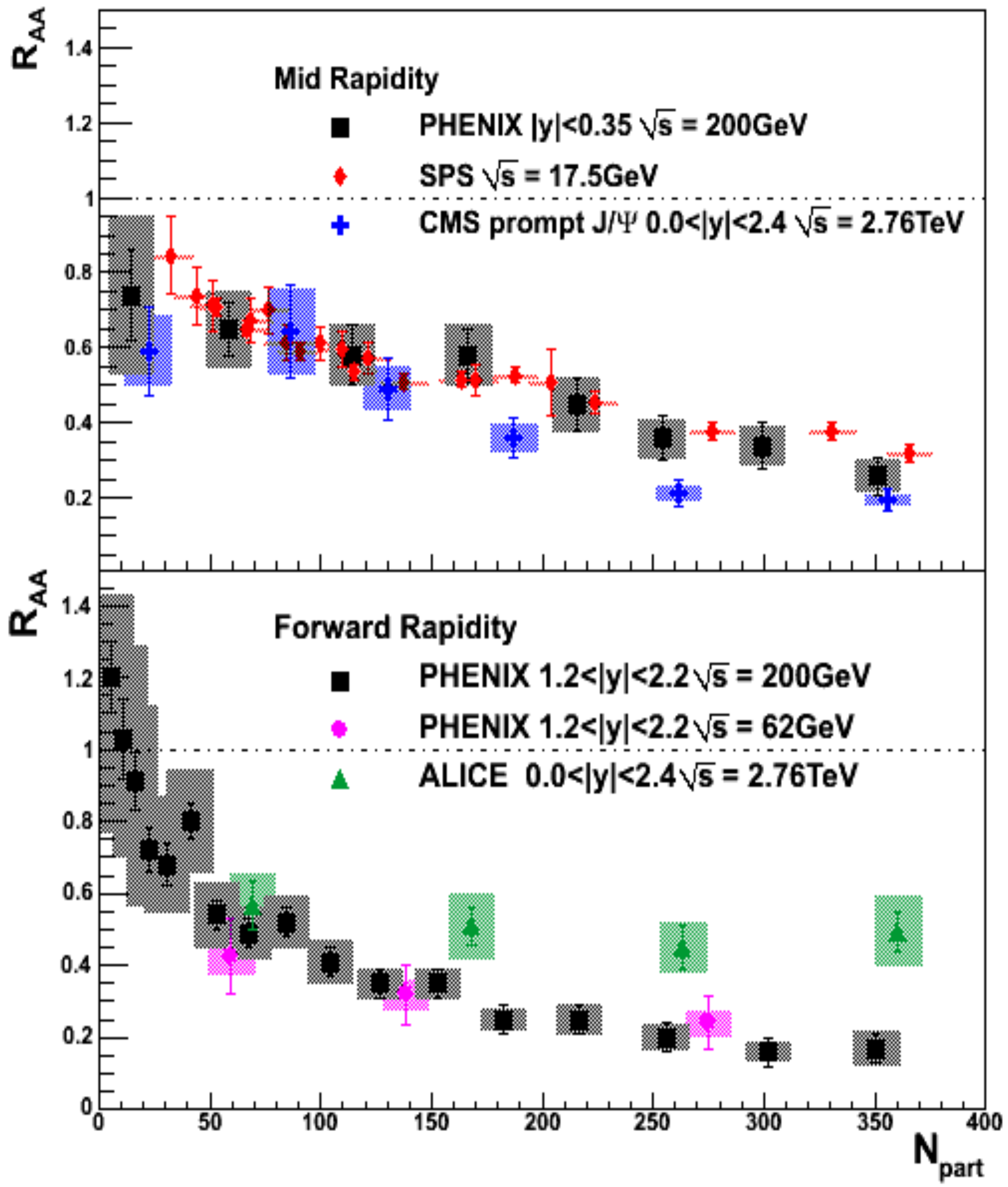
J/ψ suppression

Bewildering observations:

RHIC - more suppression at forward rapidity

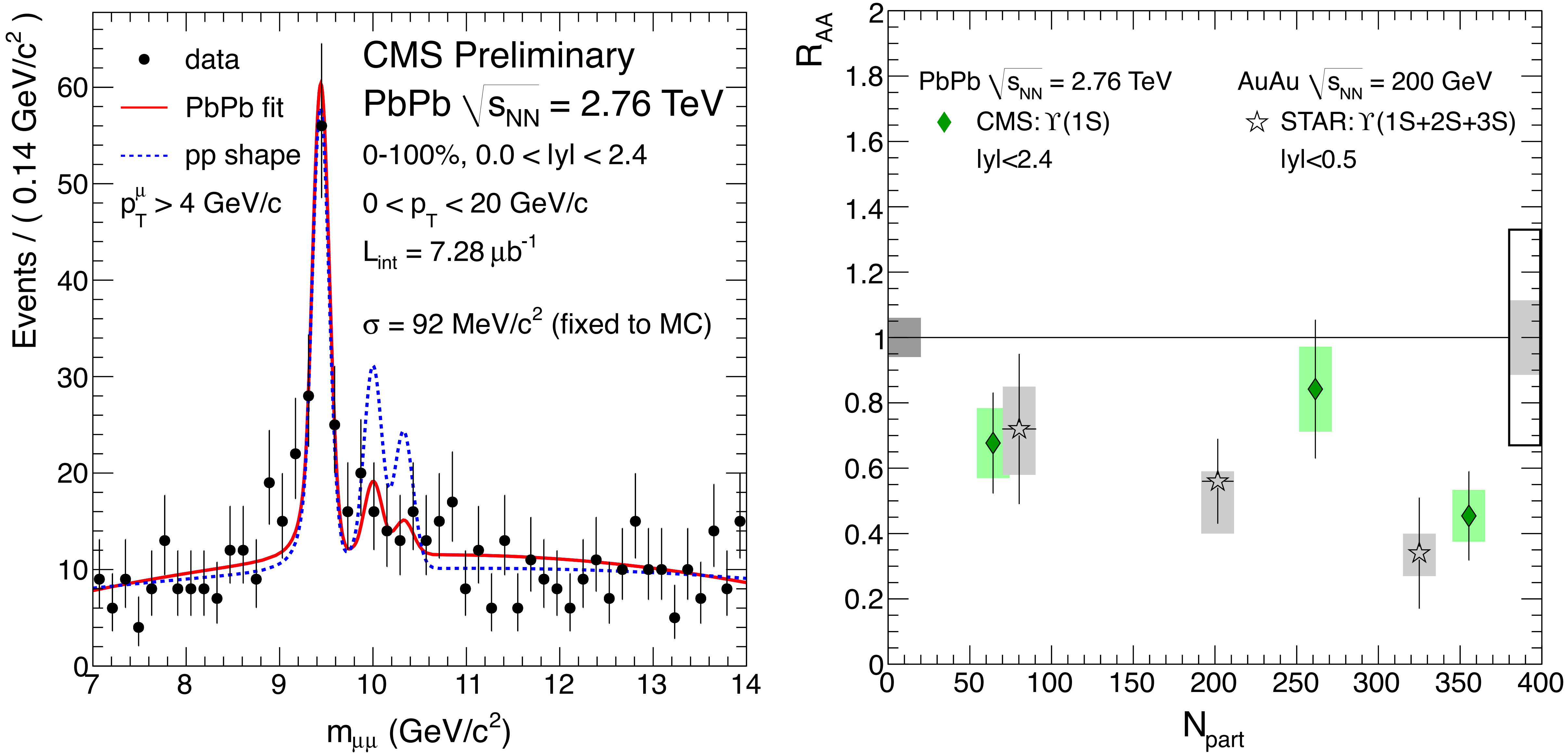
LHC - more suppression at central rapidity

Same suppression at SPS and RHIC at midrapidity



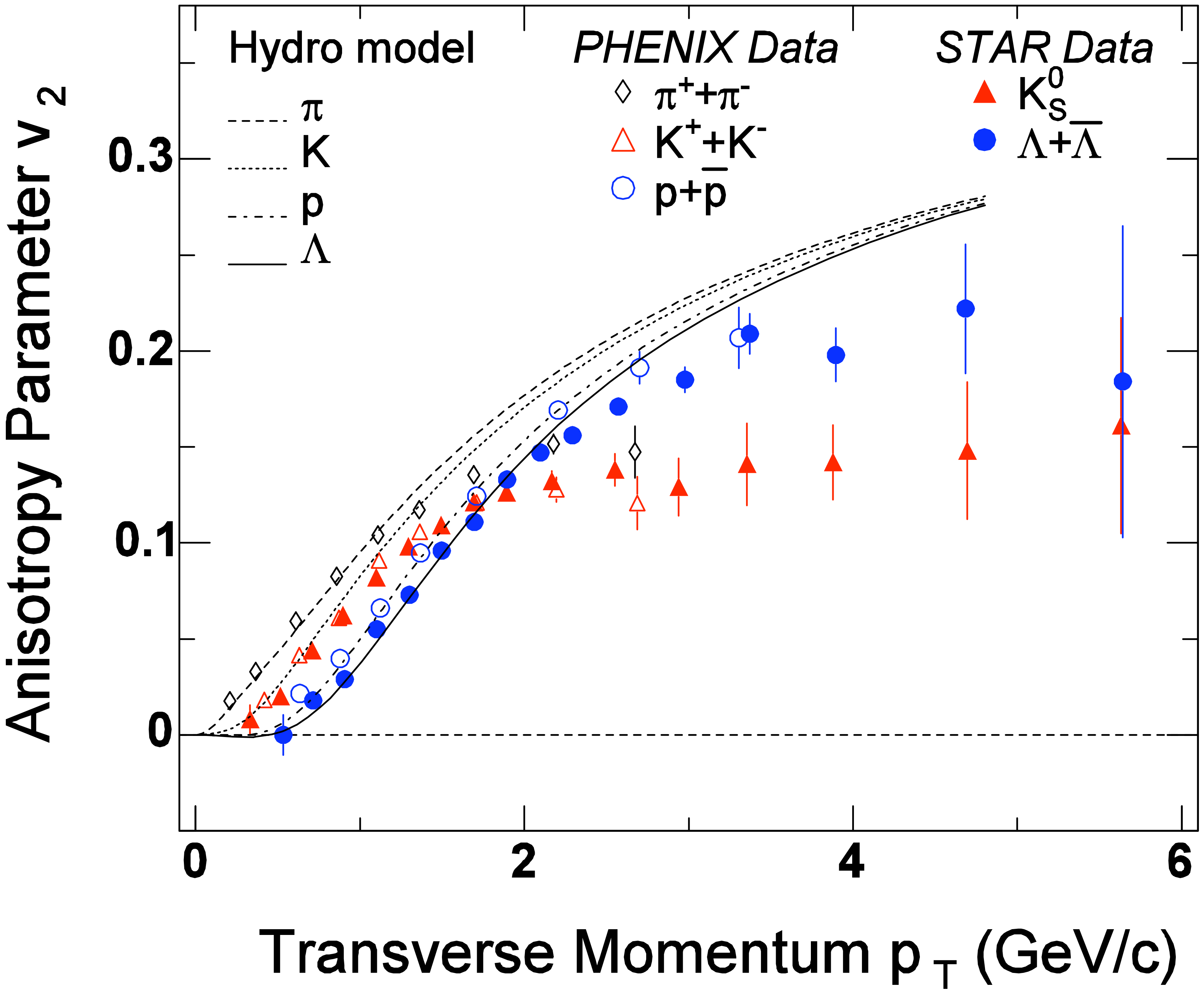
Υ suppression

Differential suppression of Υ states clearly observed

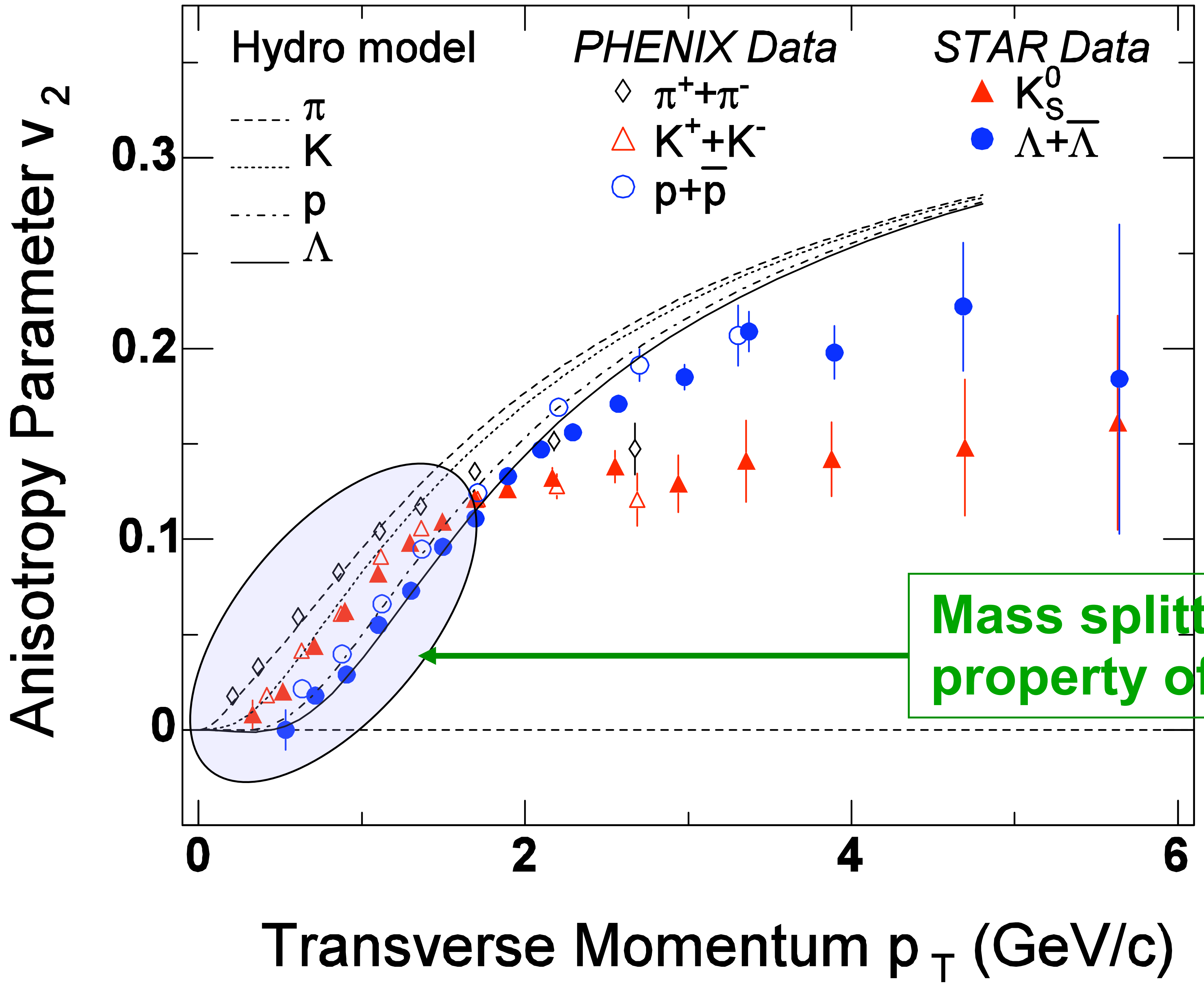


Epilogue
Hadronization
of the QGP

$v_2(p_T)$ vs. hydrodynamics

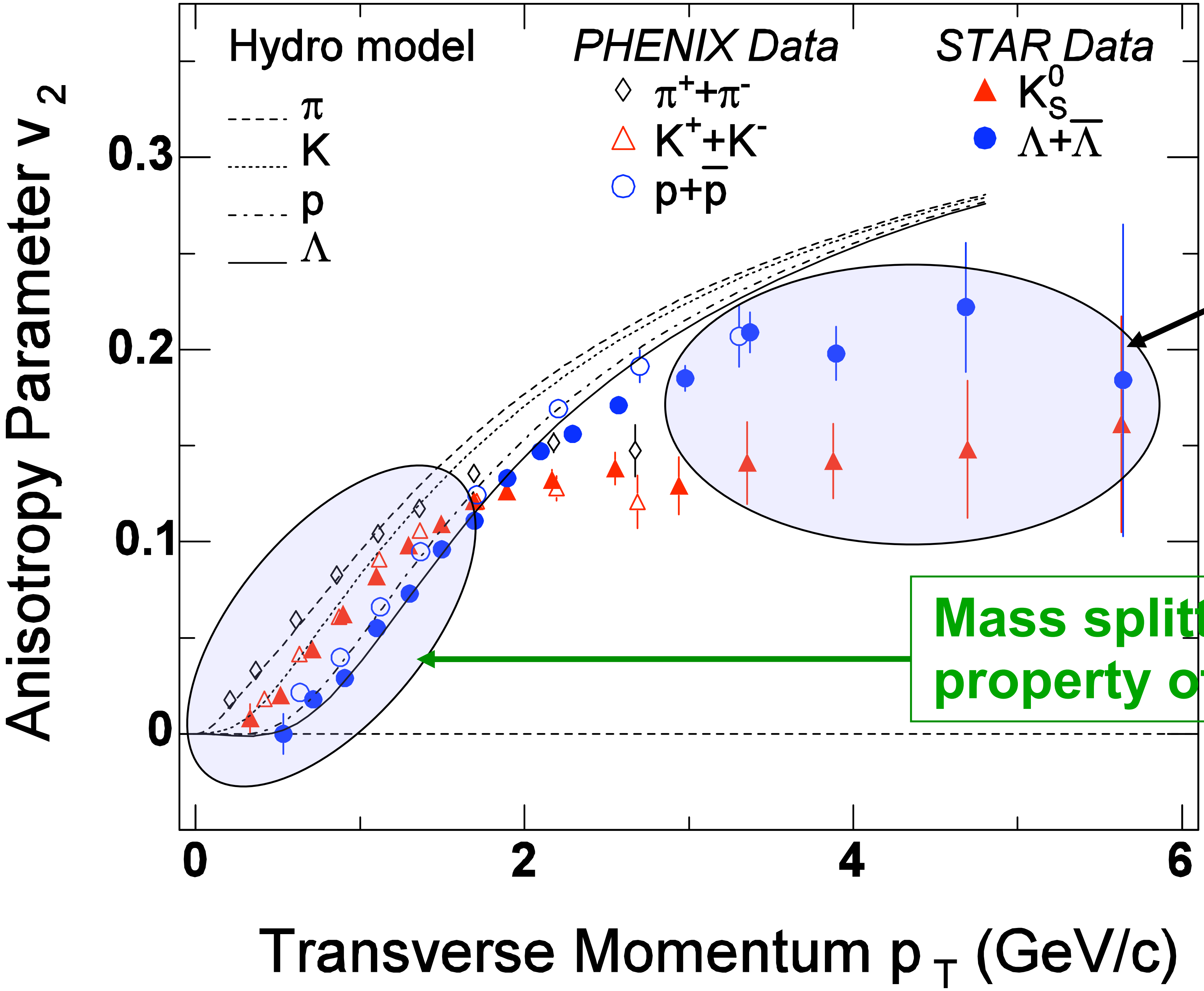


$v_2(p_T)$ vs. hydrodynamics



Mass splitting characteristic property of hydrodynamics

$v_2(p_T)$ vs. hydrodynamics



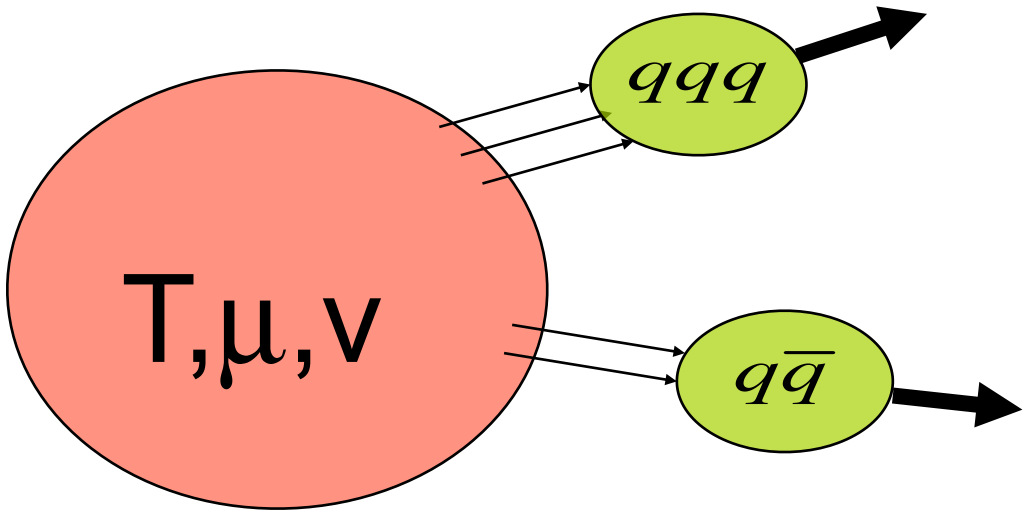
Failure of ideal hydrodynamics tells us how hadrons form

Mass splitting characteristic property of hydrodynamics

Bulk hadronization

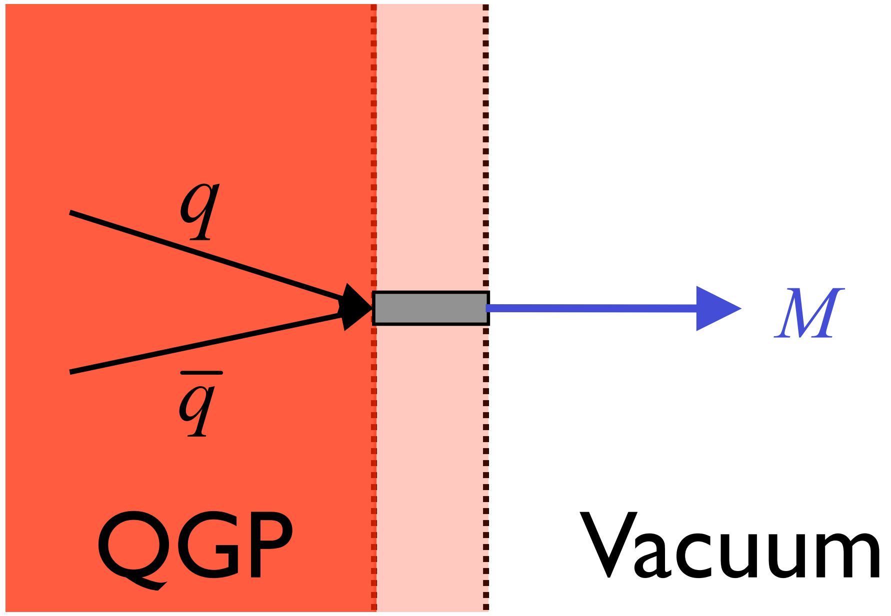
Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons

Sudden recombination



$$p_B \approx 3 p_Q$$

$$p_M \approx 2 p_Q$$

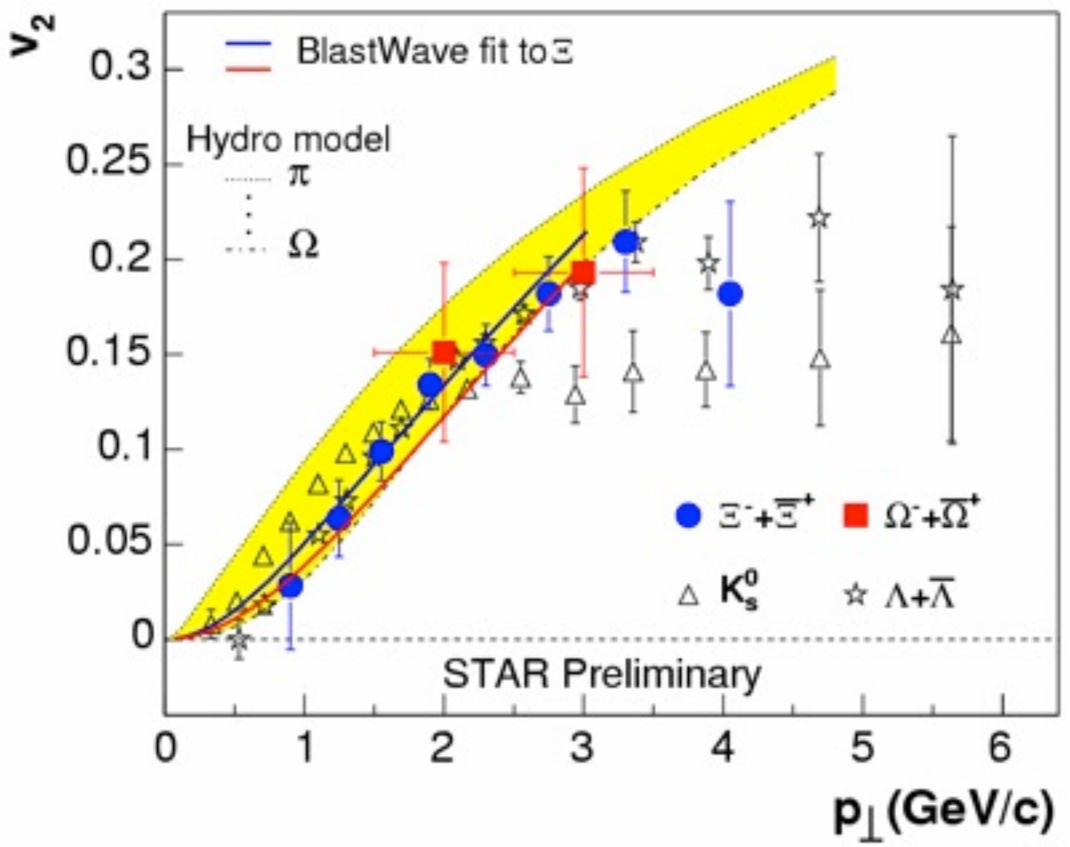


$$v_2^M(p_t) = 2 v_2^Q\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3 v_2^Q\left(\frac{p_t}{3}\right)$$

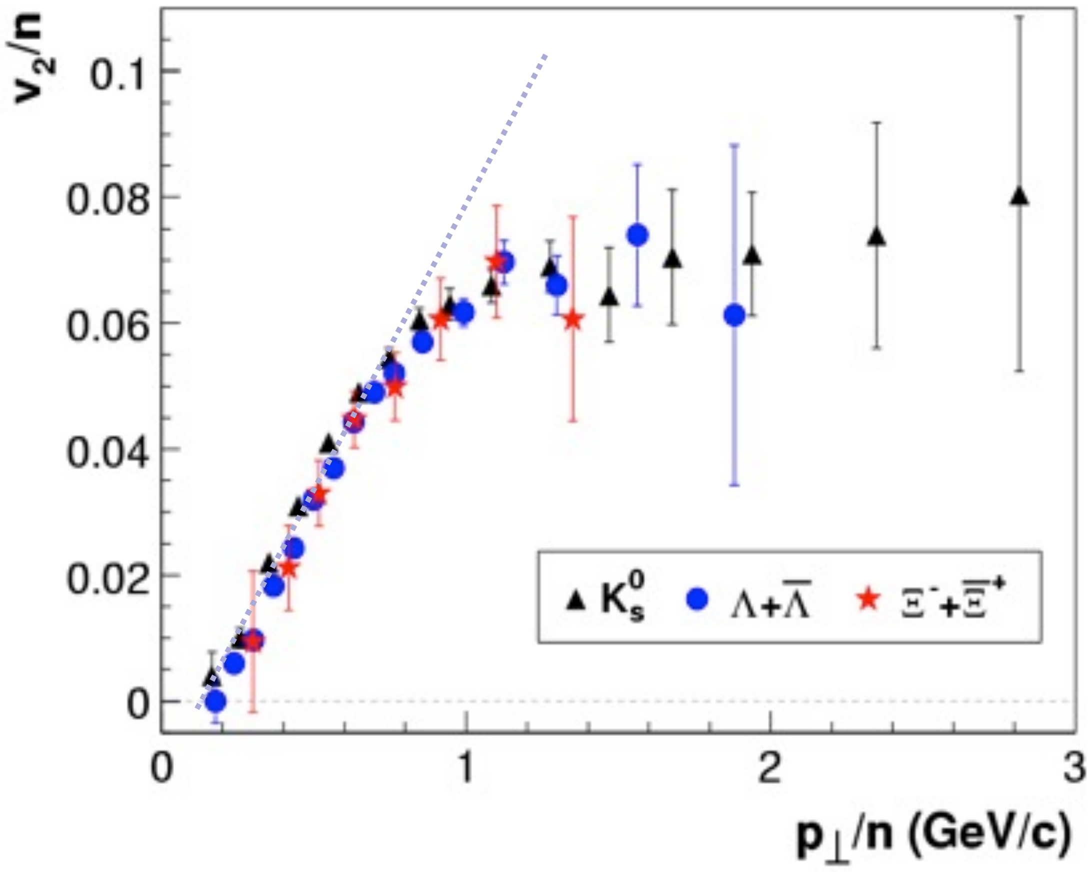
Quark number scaling of v_2

$$\frac{1}{2} v_2^M(p_t) = v_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3} v_2^B(p_t) = v_2^Q\left(\frac{p_t}{3}\right)$$



Quark number scaling of v_2

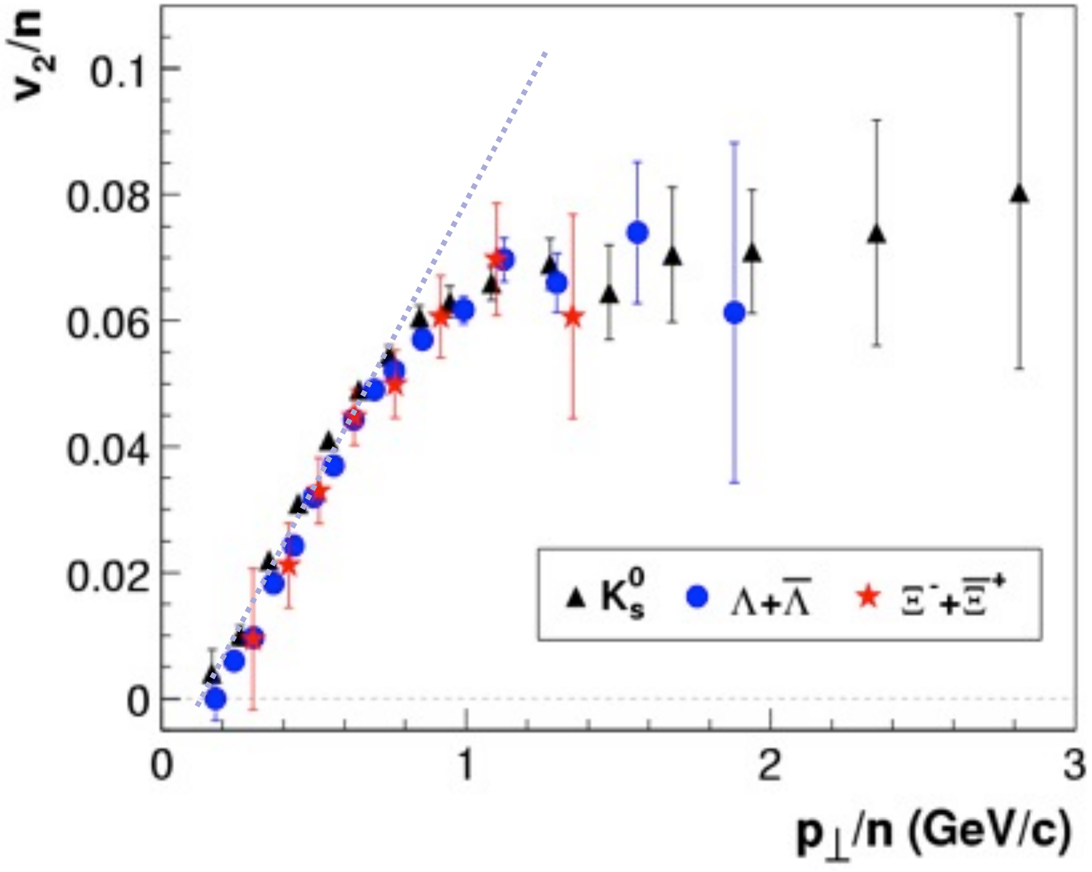
$$\frac{1}{2}\mathrm{v}_2^M(p_t) = \mathrm{v}_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3}\mathrm{v}_2^B(p_t) = \mathrm{v}_2^Q\left(\frac{p_t}{3}\right)$$

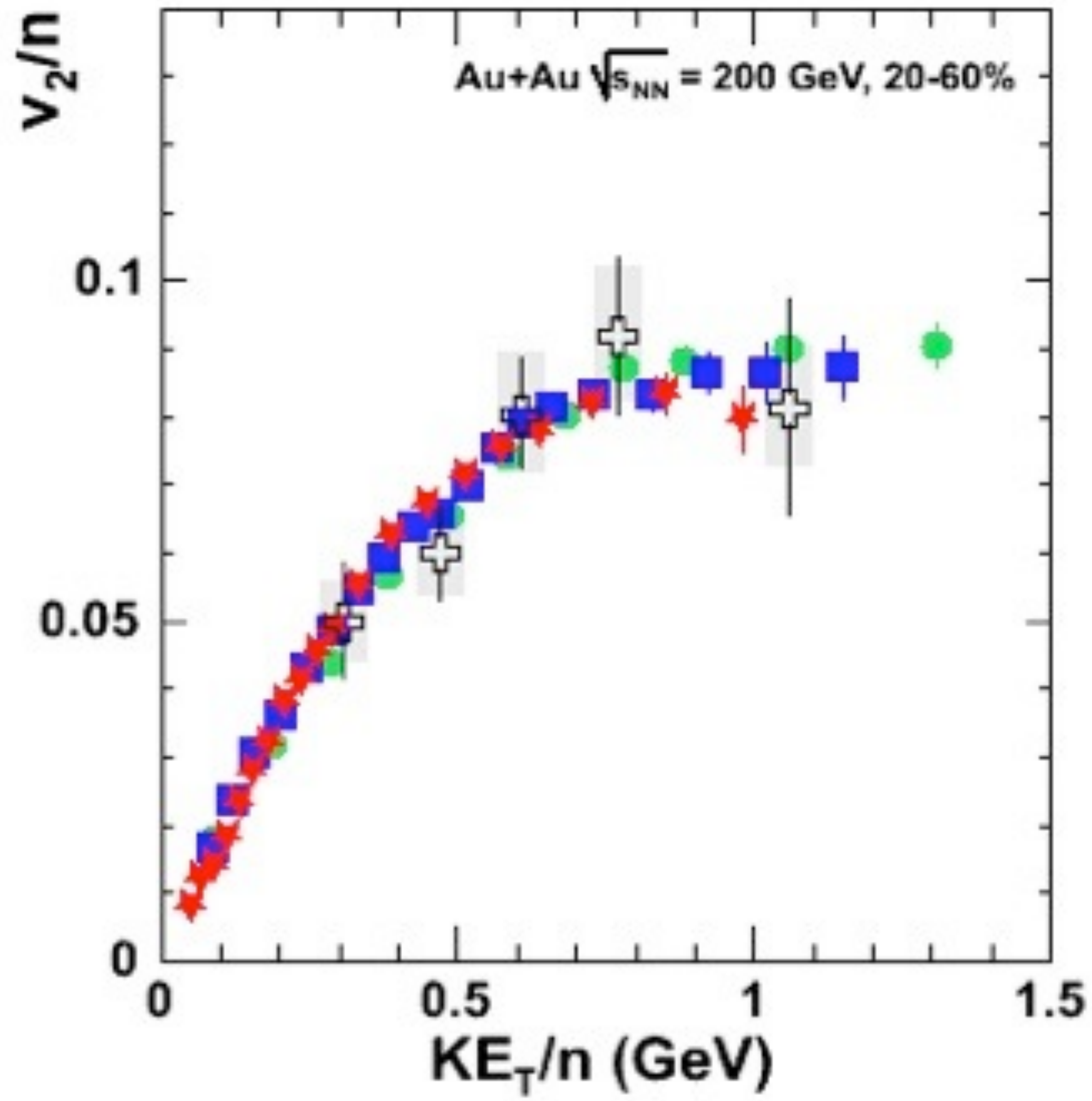


Emitting medium is composed of unconfined, flowing quarks.

Quark number scaling of v_2

$$\frac{1}{2} v_2^M(p_t) = v_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3} v_2^B(p_t) = v_2^Q\left(\frac{p_t}{3}\right)$$



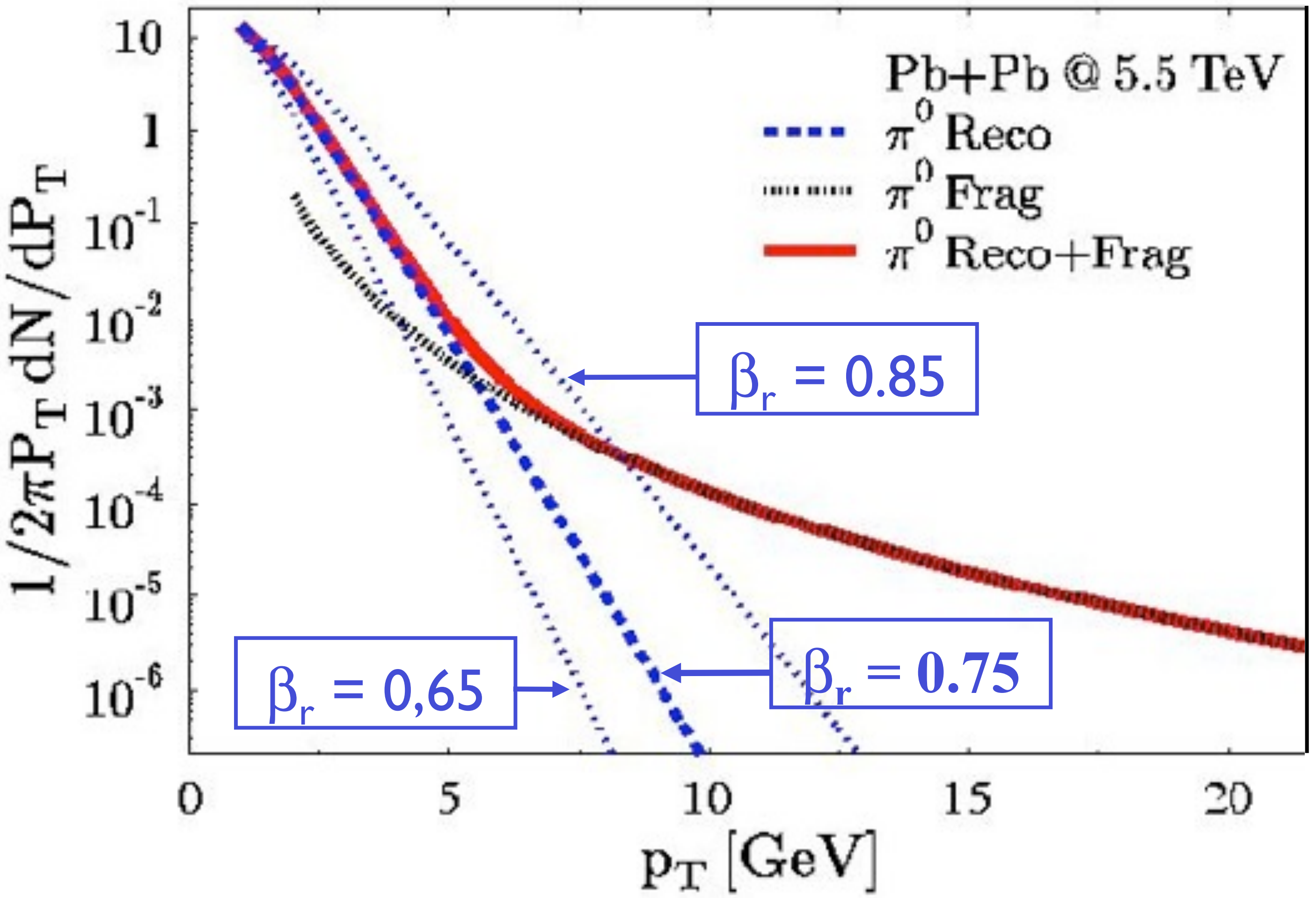


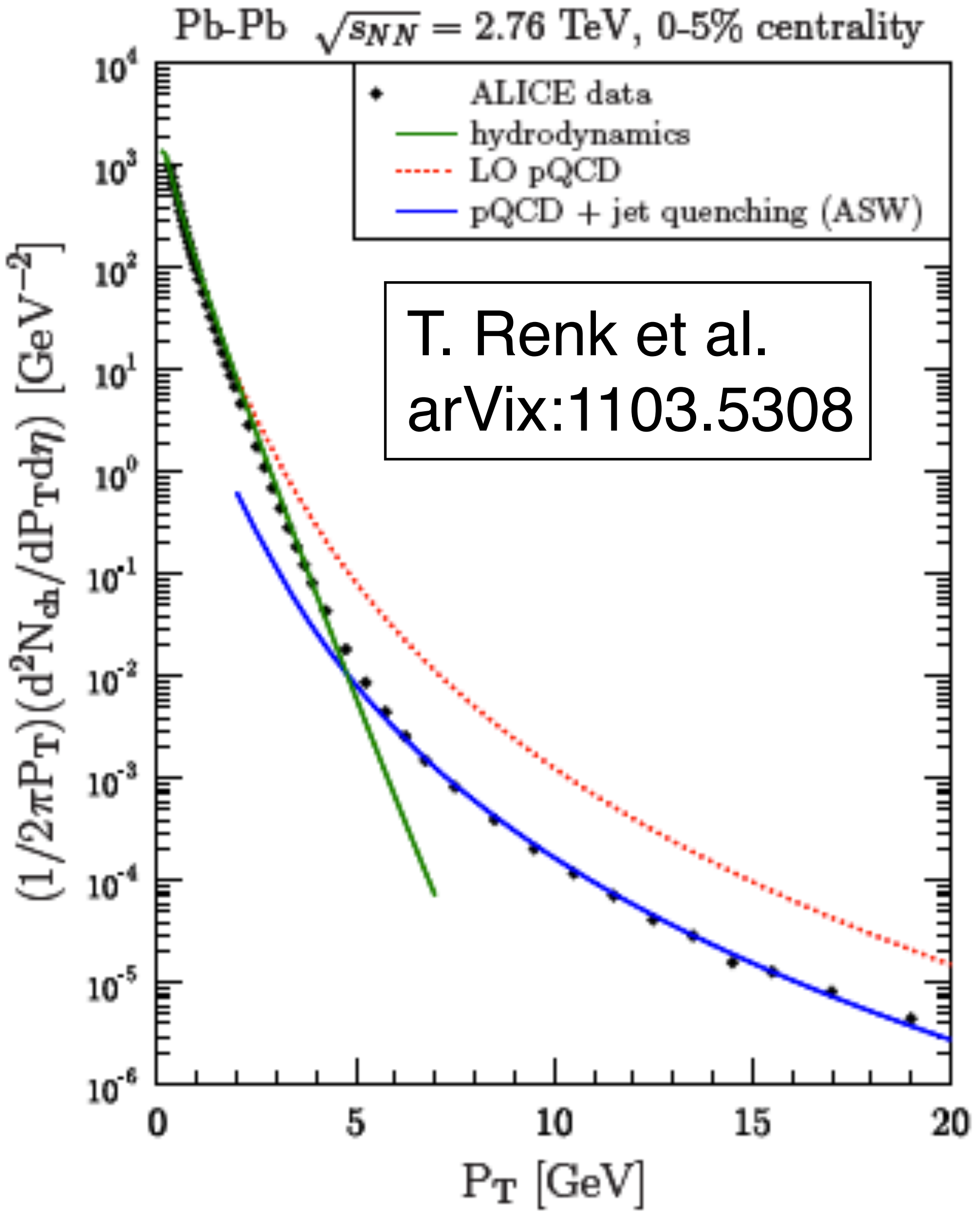
Emitting medium is composed of unconfined, flowing quarks.

Hadron production at the LHC

Recombination + fragmentation with parton energy loss prediction was right on the mark

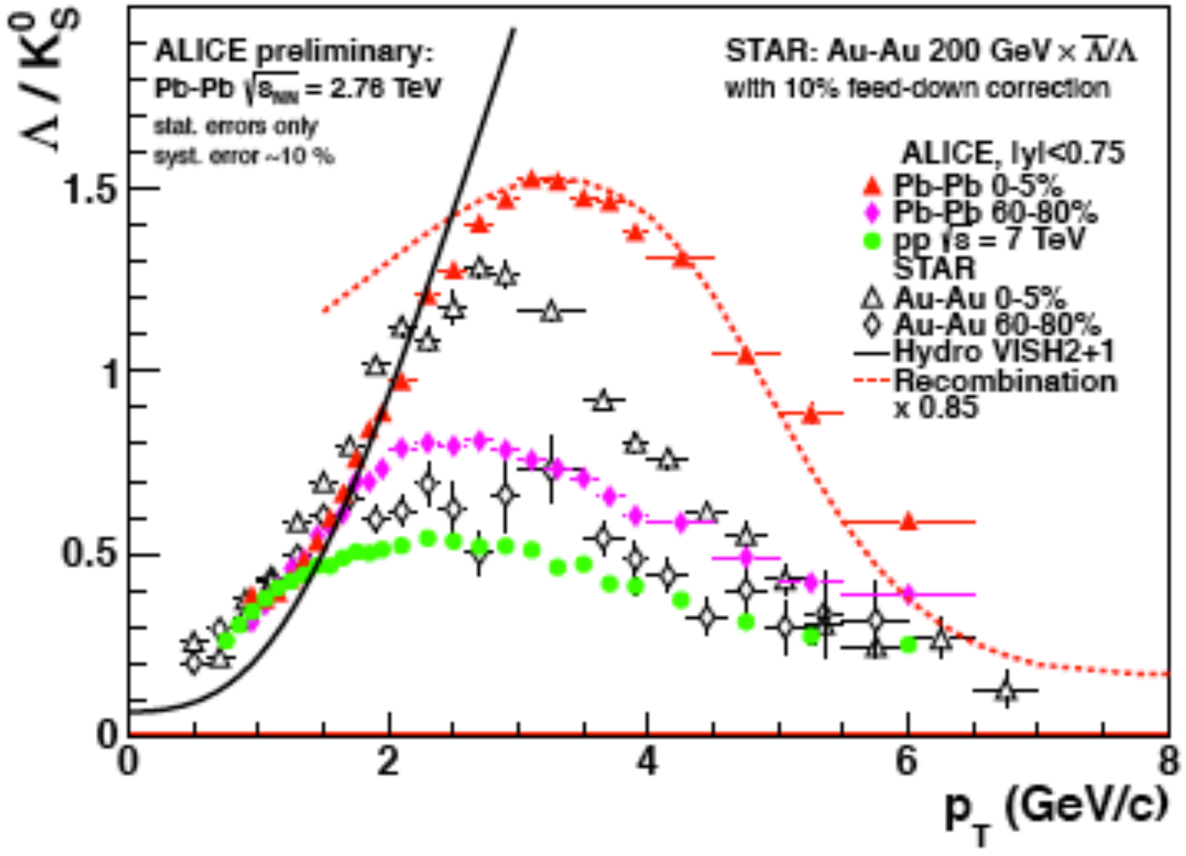
R.J. Fries & BM, nucl-th/0307043

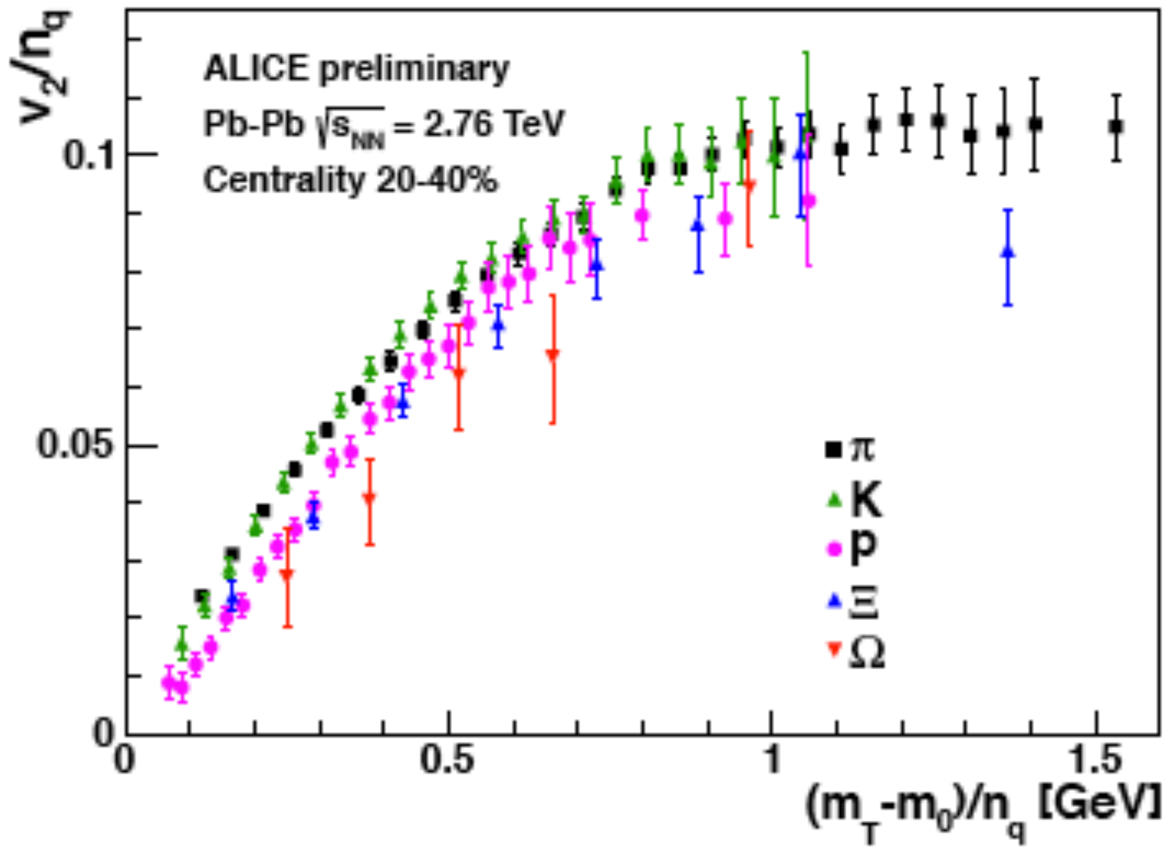




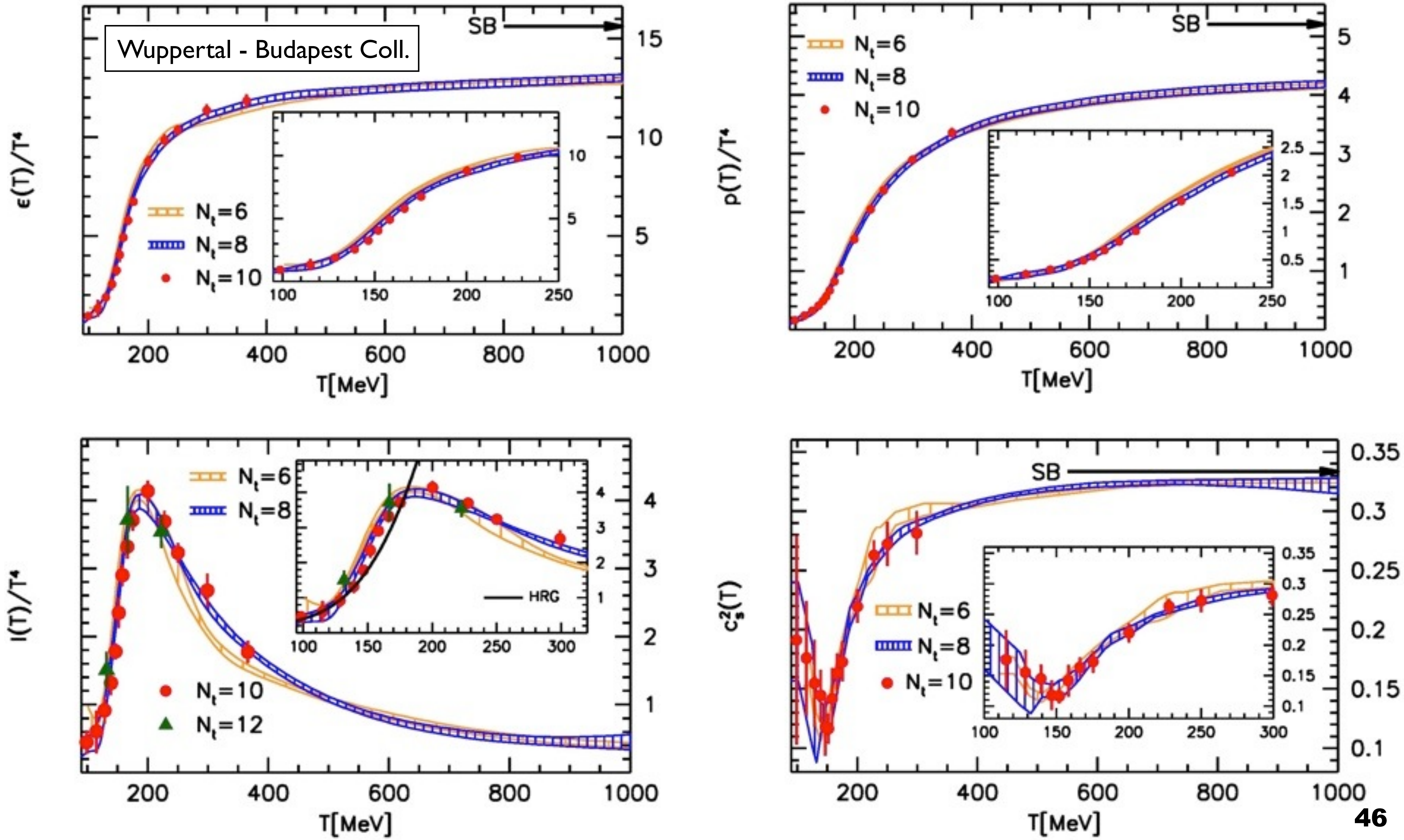
T. Renk et al.
arVix:1103.5308

Recombination at LHC?





Lattice QCD - 2010

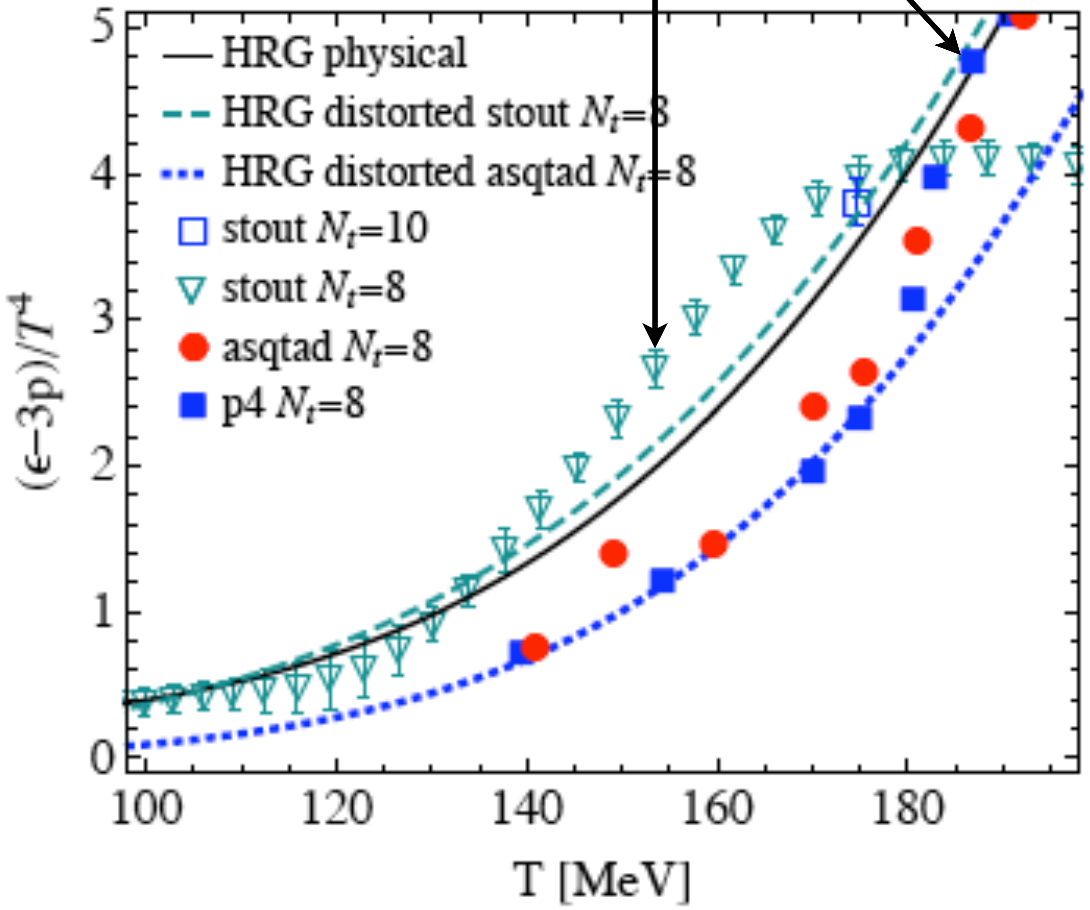


Below T_c - the HRG

Lines: Hadron resonance gas (HRG)

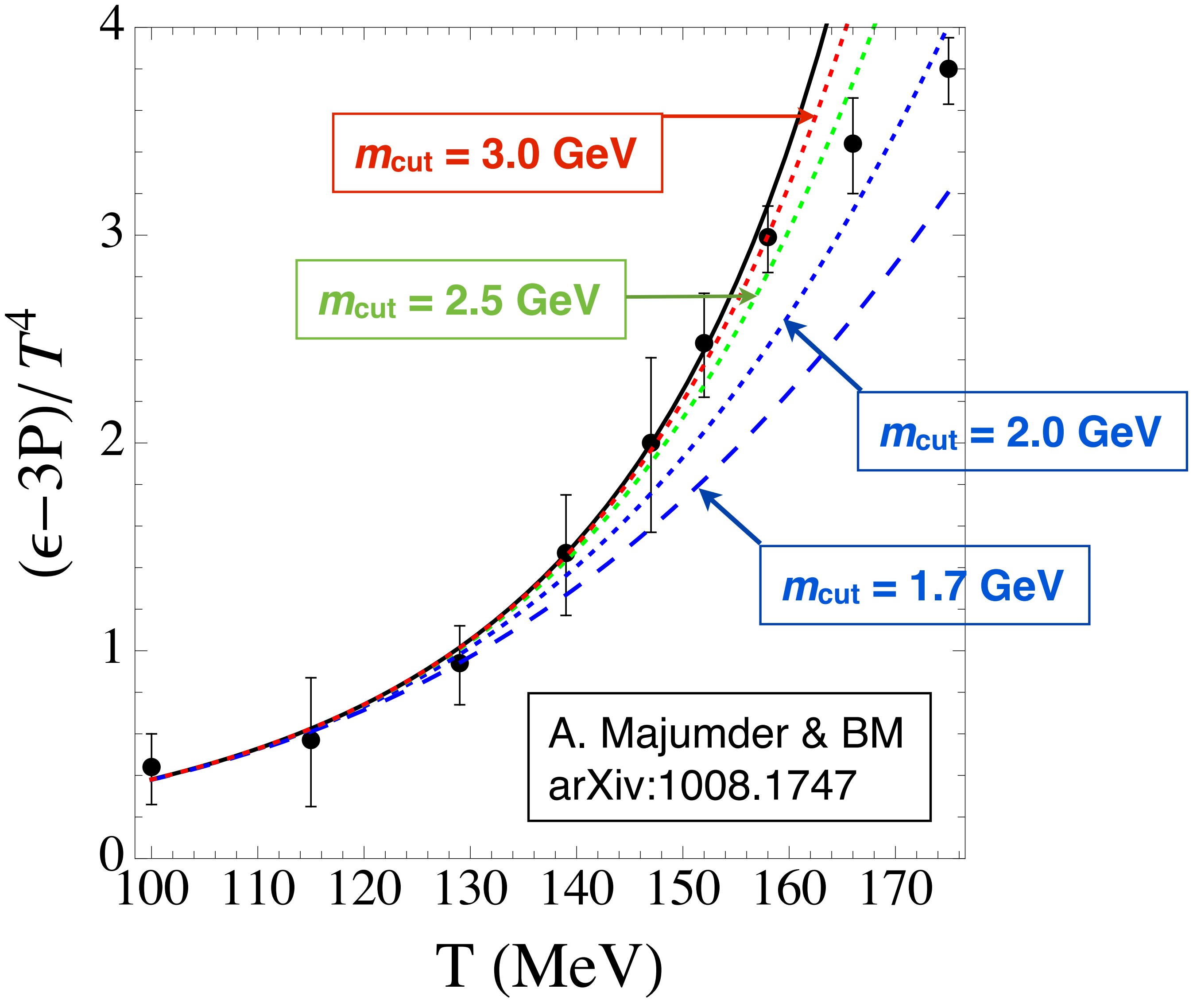
Data points: Lattice QCD (Wu-Bu)

LQCD lies above HRG for T > 140 MeV



Hadrons up to at least 2.5 GeV (maybe 3 GeV) mass contribute

$$\rho(m) = A\,(m^2+m_0^2)^{-5/4}\,e^{bm}$$



A. Majumder & BM
arXiv:1008.1747