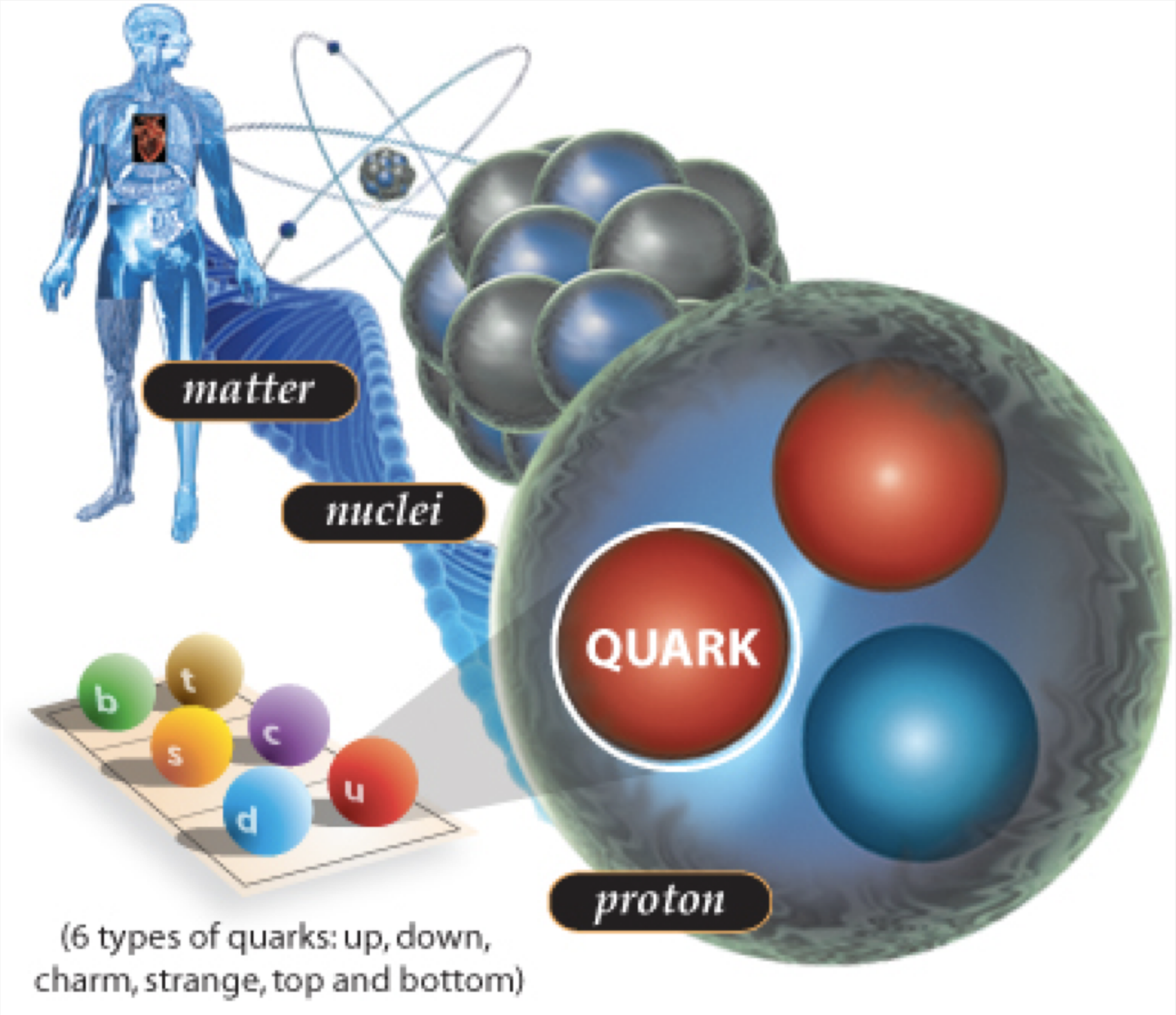
HADRONIC STRUCTURE EXPERIMENTAL

Anselm Vossen

OUTLINE

- Motivation
- Basics of hard scattering experiments
- Partonic structure of the unpolarized nucleon
  - Quarks
  - Gluons
  - Sea
- Longitudinal structure
- Transverse structure
- Fragmentation functions

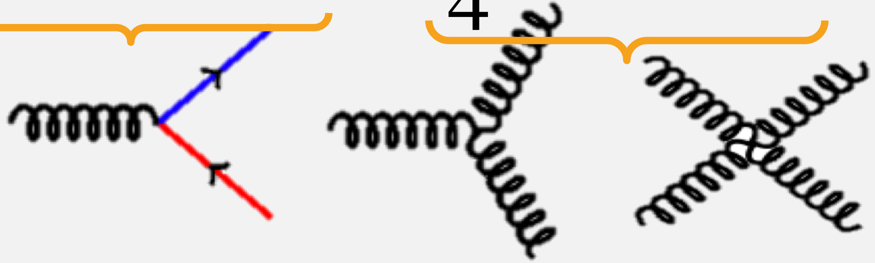
STUDY "WHAT HOLDS THE WORLD TOGETHER IN ITS INMOST FOLDS" (GOETHE'S FAUST)



THEORY OF STRONG INTERACTIONS: QUANTUM CHROMODYNAMICS

$$L_{QCD} = \overline{q}(i\gamma^{\mu}\partial_{\mu} - m)q - g(\overline{q}\gamma^{\mu}T_a q)A_{\mu}^{a} - \frac{1}{4}G_{\mu\nu}^{a}G_{a}^{\mu\nu}$$

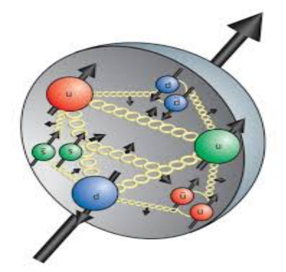
$$G_{\mu\nu}^{a} = \partial_{\mu}A_{\nu}^{a} - \partial_{\nu}A_{\mu}^{a} + f_{bc}^{a}A_{\mu}^{b}A_{\nu}^{c}$$



- Salient features like Color confinement of QCD not evident from Lagrangian!
- Proton is a QCD laboratory!

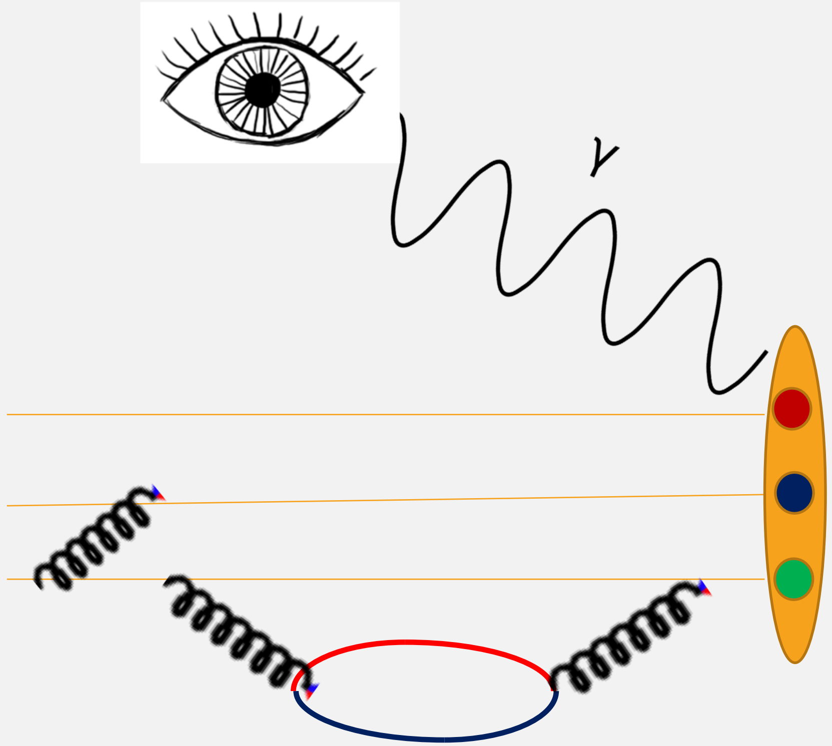
Setting the scale: Energy Matters!

system	constituents	$\Sigma_i\, m_i c^2$	Δmc^2	$\frac{\Delta mc^2}{\Sigma_i\, m_i c^2}$
atom	p + e	1 GeV	10 eV	10^{-8}
nucleus	p + n	2 GeV	2 MeV	10^{-3}
nucleon	3 quarks	~ 20 MeV	1 GeV	10^{2}



- Properties are dominated by interactions among ~massless quarks
- Deep intellectual challenges / complicated numerical analyses / extensive experimental effort required to understand this!
- Hadronic structure→Hadron dynamics

PROBING A HIGHLY RELATIVISTIC, STRONGLY INTERACTING SYSTEM

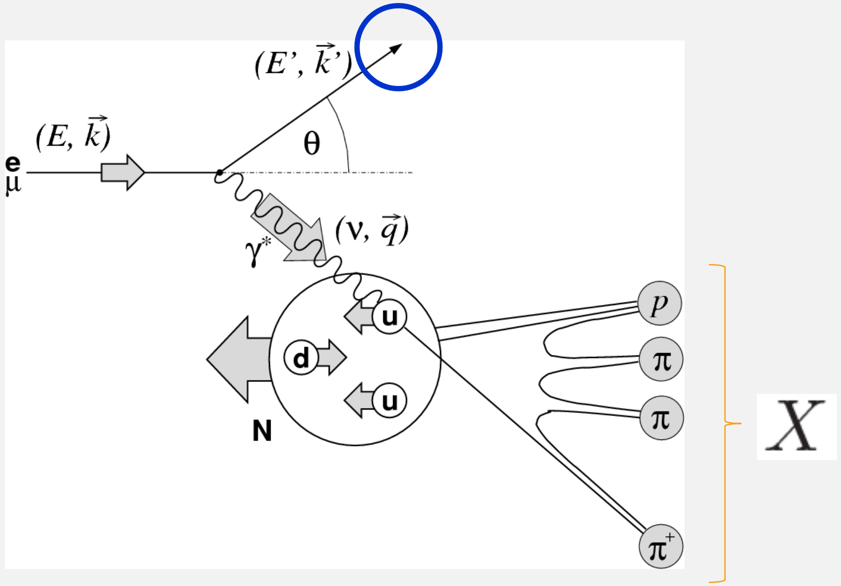


Parton picture:
(Feynman 1969)
High energy scattering can be treated as scattering from many point-like sources
- partons

- **Asymptotic freedom** in high energy scattering Infinite momentum frame
  - → probe wavefunction on the lightcone
  - suppresses transverse components
-

TOOLS OF THE TRADE SEMI INCLUSIVE DEEP INELASTIC SCATTERING

Inclusive DIS



Identified particles in final state

LO parton picture valid at high $Q^2 \gg 1$ GeV^2

- At fixed beam energy need two variables to characterize DIS event, e.g. $Q^2, \nu \rightarrow x$ in scaling regime
  - $l^\mu = (E, \vec{k}), \boldsymbol{\nu} = E - E'$
  - $\boldsymbol{Q^2} = 4EE' \sin^2 \frac{\theta}{2}$:"hard scale" of the probe
  - $\boldsymbol{x} = \frac{Q^2}{2M_n\nu}$: bjorken **scaling variable**, in partonic picture momentum fraction of the struck parton

TOOLS OF THE TRADE SEMI INCLUSIVE DEEP INELASTIC SCATTERING

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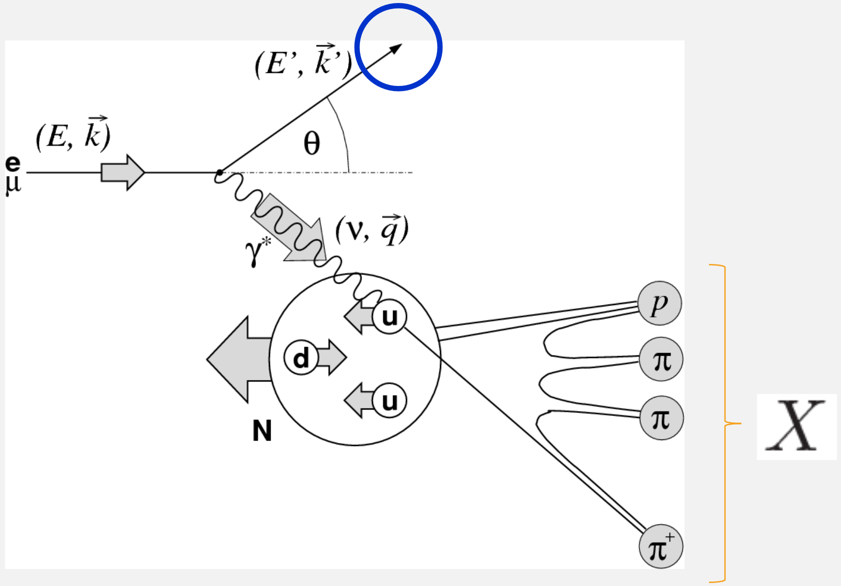
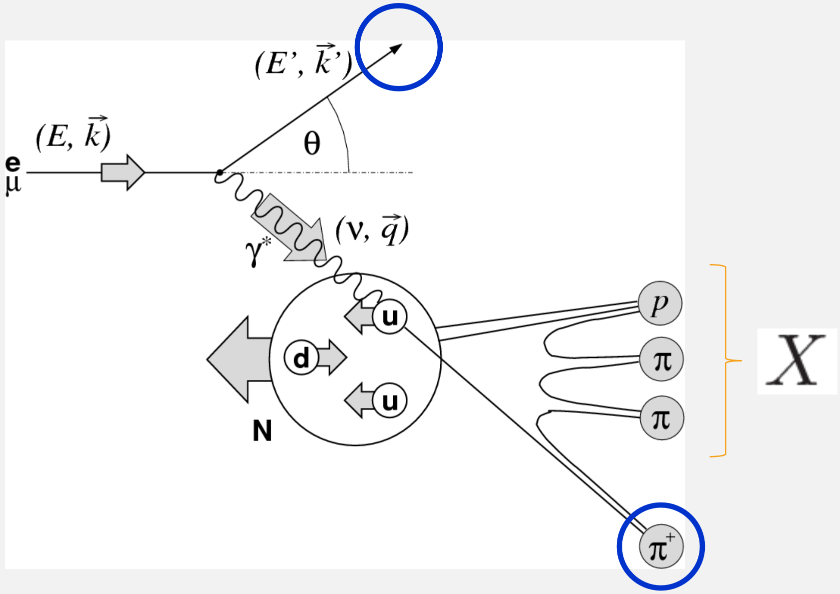


Semi-inclusive DIS (SIDIS)



Identified particles in final state

LO parton picture at high Q², **W**
(W mass of the hadronic system)

- At fixed beam energy need two variables to characterize DIS event, e.g. Q²,ν → x in scaling regime
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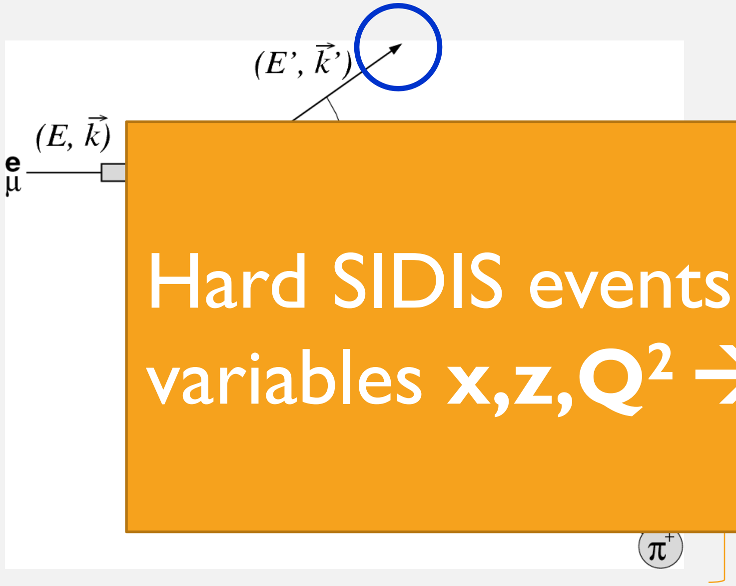
  - $\boldsymbol{z} = E_h/E_q(lab)$: fractional energy the hadron is carrying

TOOLS OF THE TRADE SEMI INCLUSIVE DEEP INELASTIC SCATTERING

Inclusive DIS



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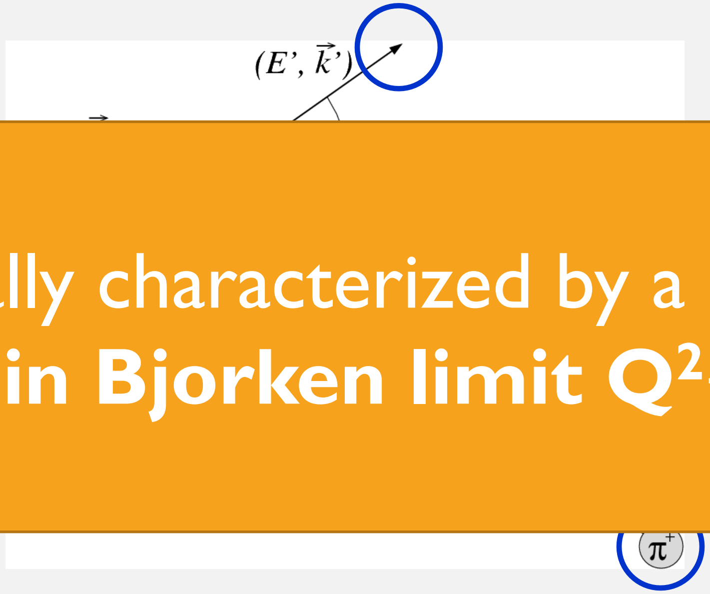


- At fixed beam energy need two variables to characterize DIS event, e.g. Q^2,ν → x in scaling regime

le" of

Hard SIDIS events usually characterized by a set of three variables **x,z,Q^2 →x,z in Bjorken limit Q^2→ ∞, x fixed (x_{Bj})**

e
momentum fraction of the struck parton

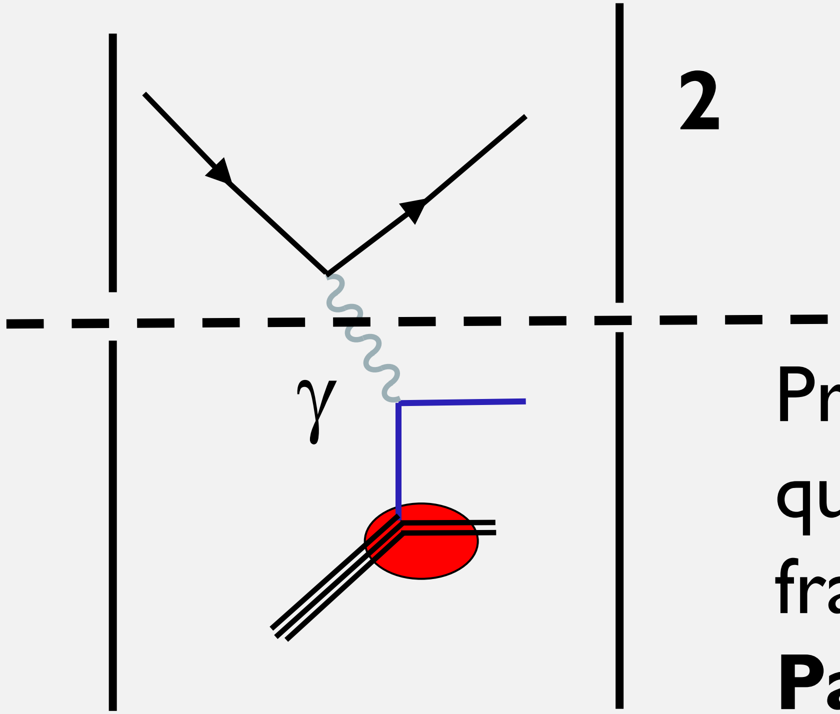
- $z = E_h/E_q(lab)$: fractional energy the hadron is carrying

Identified particles in final state

LO parton picture at high Q^2, **W**
(W mass of the hadronic system)

FACTORIZATION

$\sigma \propto$



Described by QED

Probability of finding a quark with momentum fraction x described by **Parton Distribution Function (PDF) q(x), Universal!**

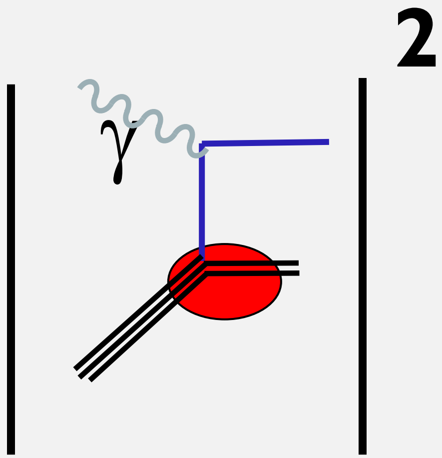
Proton Structure: Parton Distribution Function

pQCD

Fragmentation Function

$$\frac{d^2\sigma(ep \to \pi X)}{dx\, dz dQ^2} \propto q(x, Q^2) \times \frac{d\sigma^2(e\, q \to e' q')}{dx dQ^2} \times FF(z, Q^2)$$

HANDBAG DIAGRAMS



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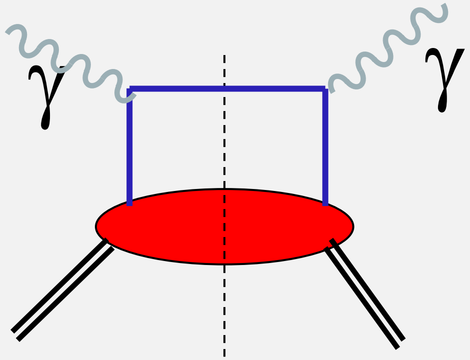


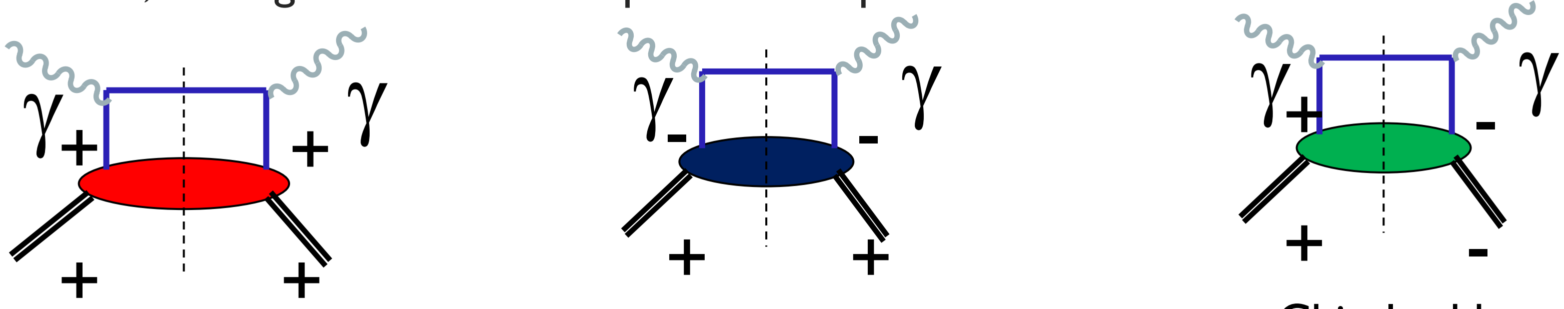
Optical Theorem:

$\sigma = -\mathrm{Im}(A_{\text{forward scattering}})$

- Scattering probability ←→ QCD amplitude

HANDBAG DIAGRAMS ←→ PDFS

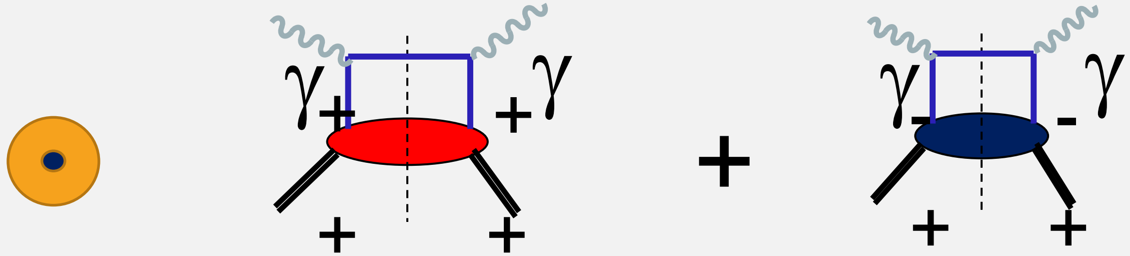
- Colinear, leading twist: three independent Amplitudes:



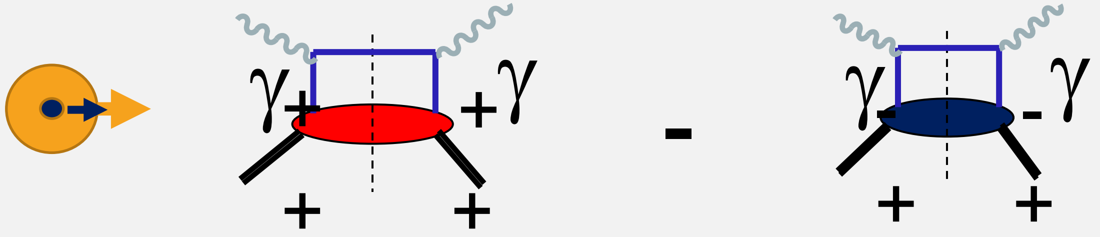
Chiral odd

- 3 PDFs

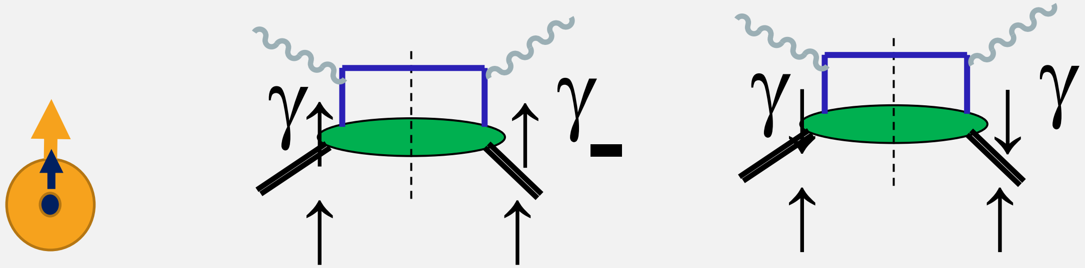
Spin averaged PDF f(x)



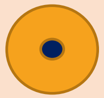
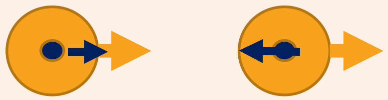
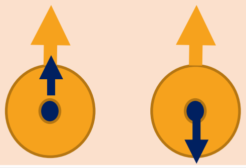
Helicity distribution function g(x)



Transversity h(x)



HANDBAG DIAGRAMS ←→ PDFS

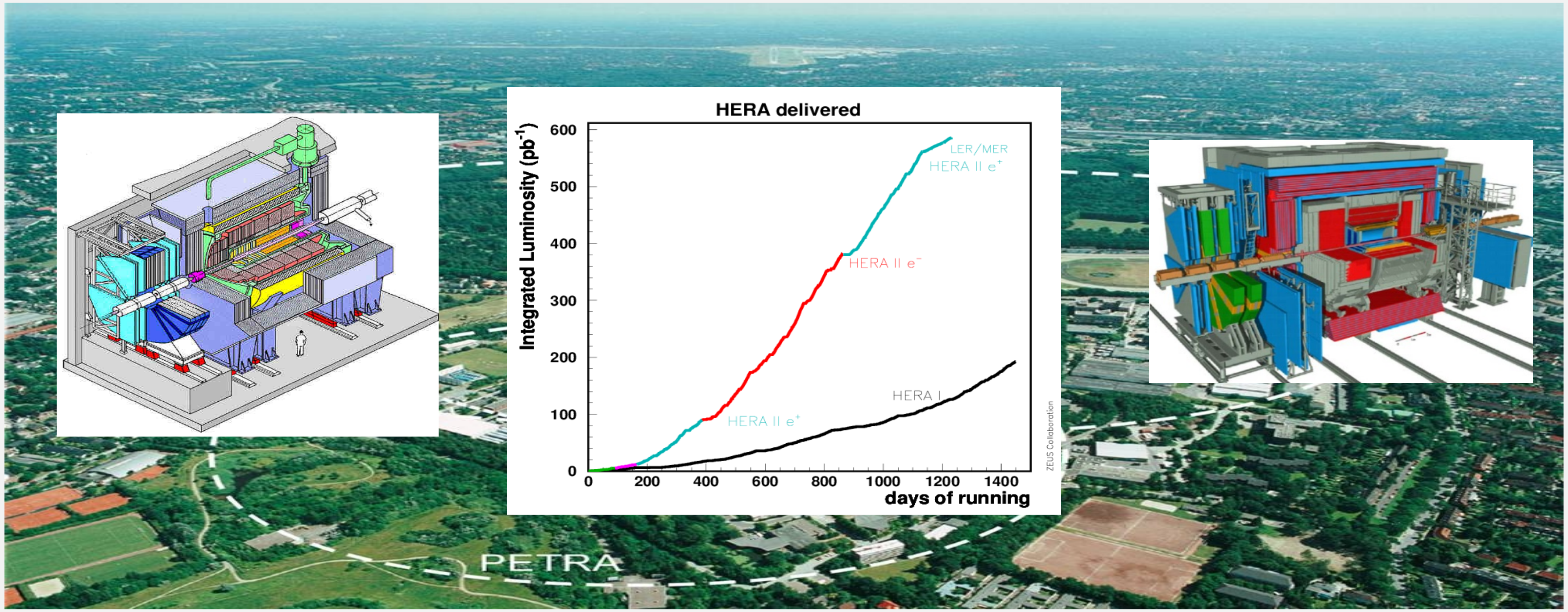
Proton Polarization → Quark Polarization ↓	Unpolarized	Longitudinal	Transverse
Unpolarized	f(x) 		
Longitudinal		g(x) 	
Transverse			h(x) 

HANDBAG DIAGRAMS ←→ PDFS

Proton Polarization → Quark Polarization ↓	Unpolarized	Longitudinal	Transverse
Unpolarized	f(x)		
Longitudinal		g(x)	
Transverse			h(x)

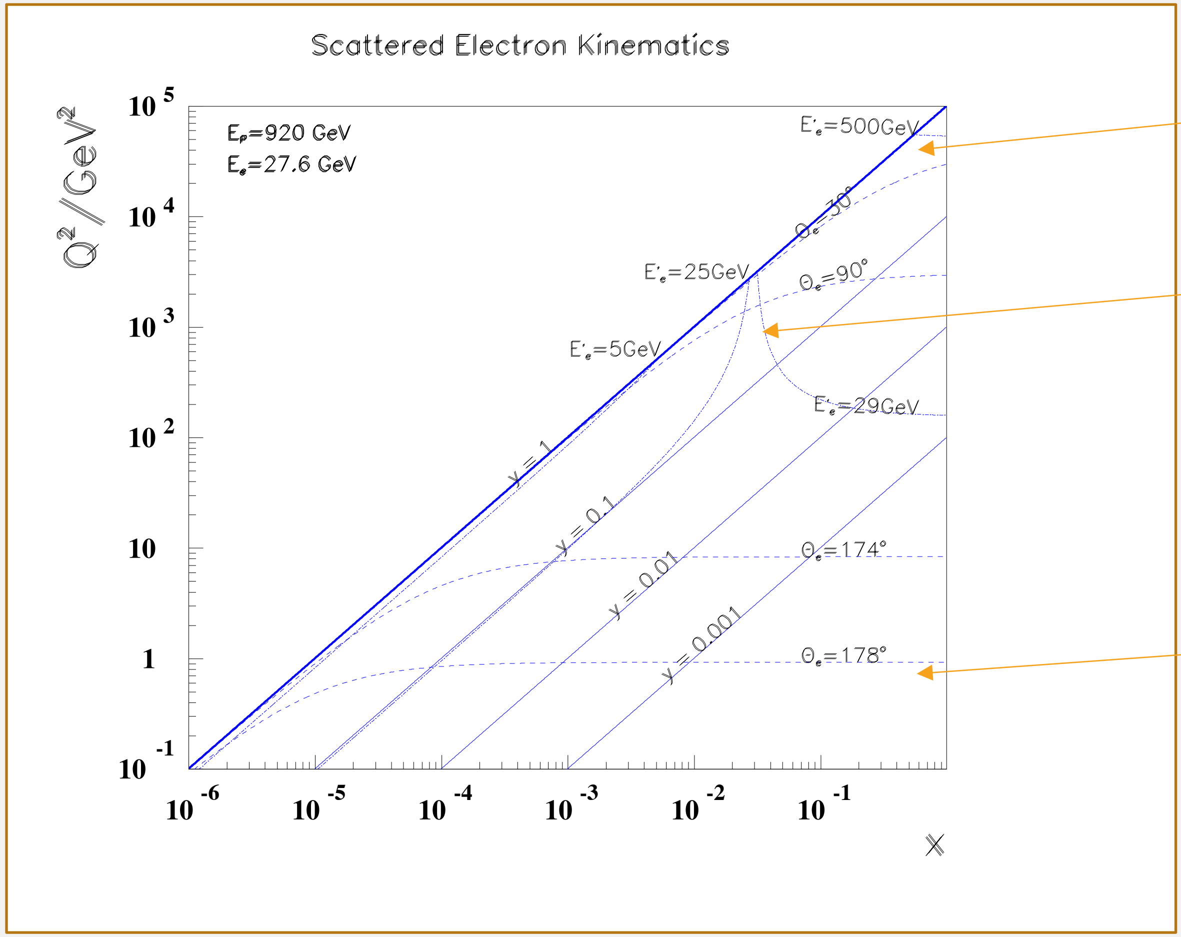
BASIS FOR f(x) EXTRACTION EP COLLIDER HERA DATA: (1992 – 2007)

- The world's only electron(positron)-proton collider at DESY, Hamburg
- Two collider experiments: H1 and ZEUS
- Total luminosity ~ 0.5 fb^{-1} per experiment
- Collider advantages: high energy, good acceptance (x,Q^2 coverage) (e.g. 320 GeV ~50 TeV beam)
- Charged and neutral current (flavour sensitivity)



- E_e = 27.6 GeV, E_p=820 GeV HERA-I , E_p = 920 GeV HERA-II (460, 575 GeV)

HERA KINEMATICS



Backward scattering

Elastic scattering

$y = E_\gamma / E_l$

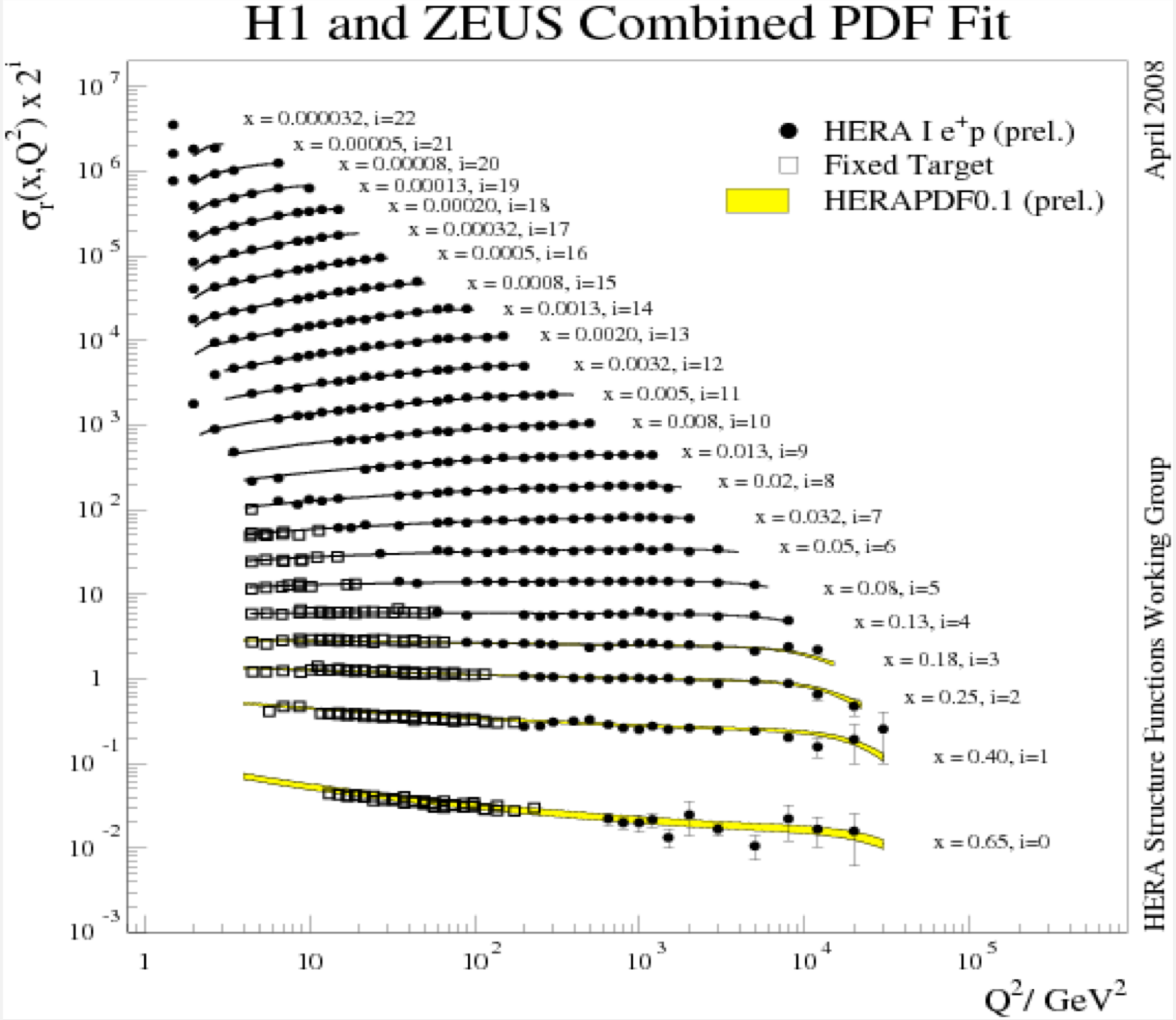
(proton at rest)

Forward scattering

- Need precise determination of electron energy
- Small Q^2 lever arm at low x

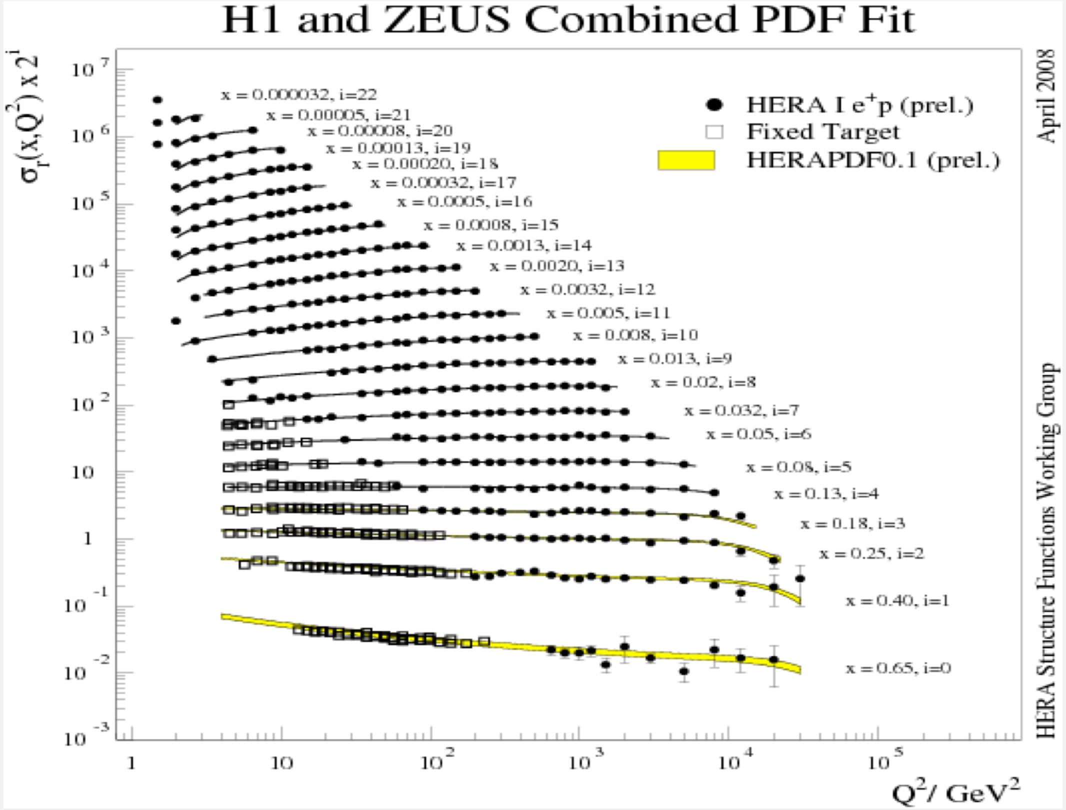
From ANL-HEP-PR-08-23

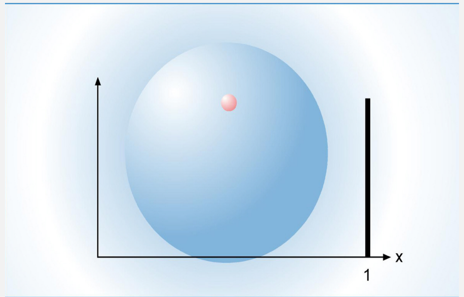
F2 AND SCALING

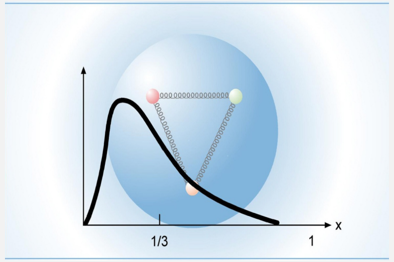


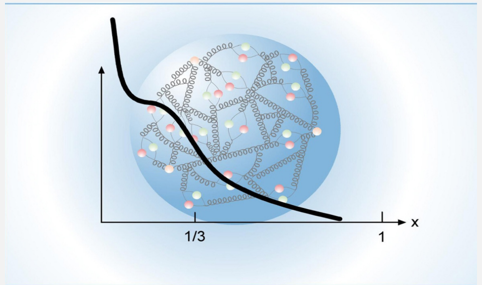
- $F_2 \propto \sum_i e_i q_i$
- $\frac{d^2\sigma}{dx dQ^2} \propto F_2\,(x, Q^2)$

F2 AND SCALING

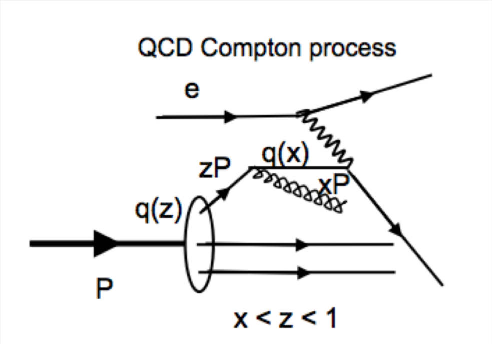


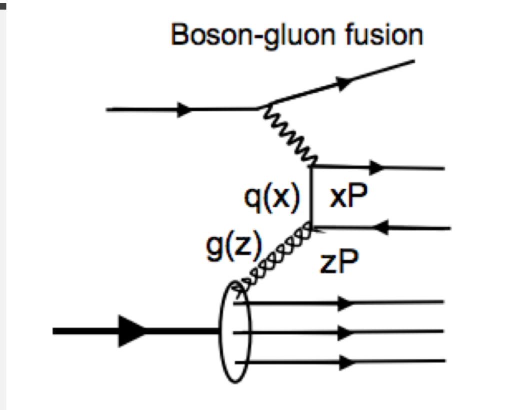


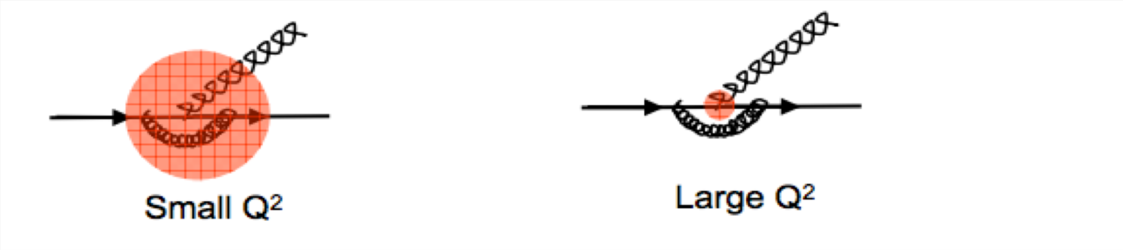




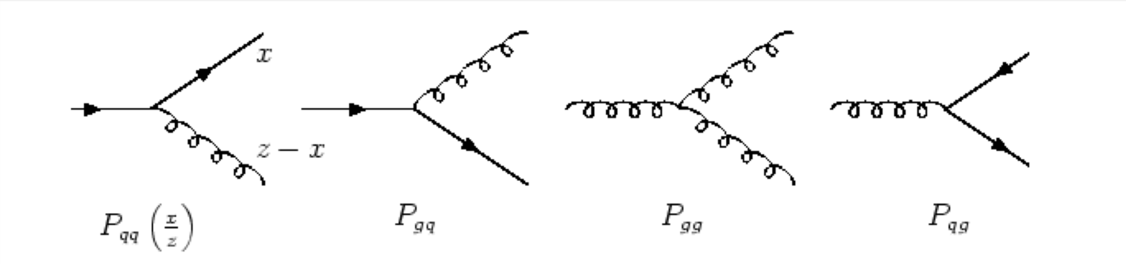
SCALING VIOLATION PROVIDES ACCESS TO GLUON DISTRIBUTION VIA DGLAP EQUATIONS





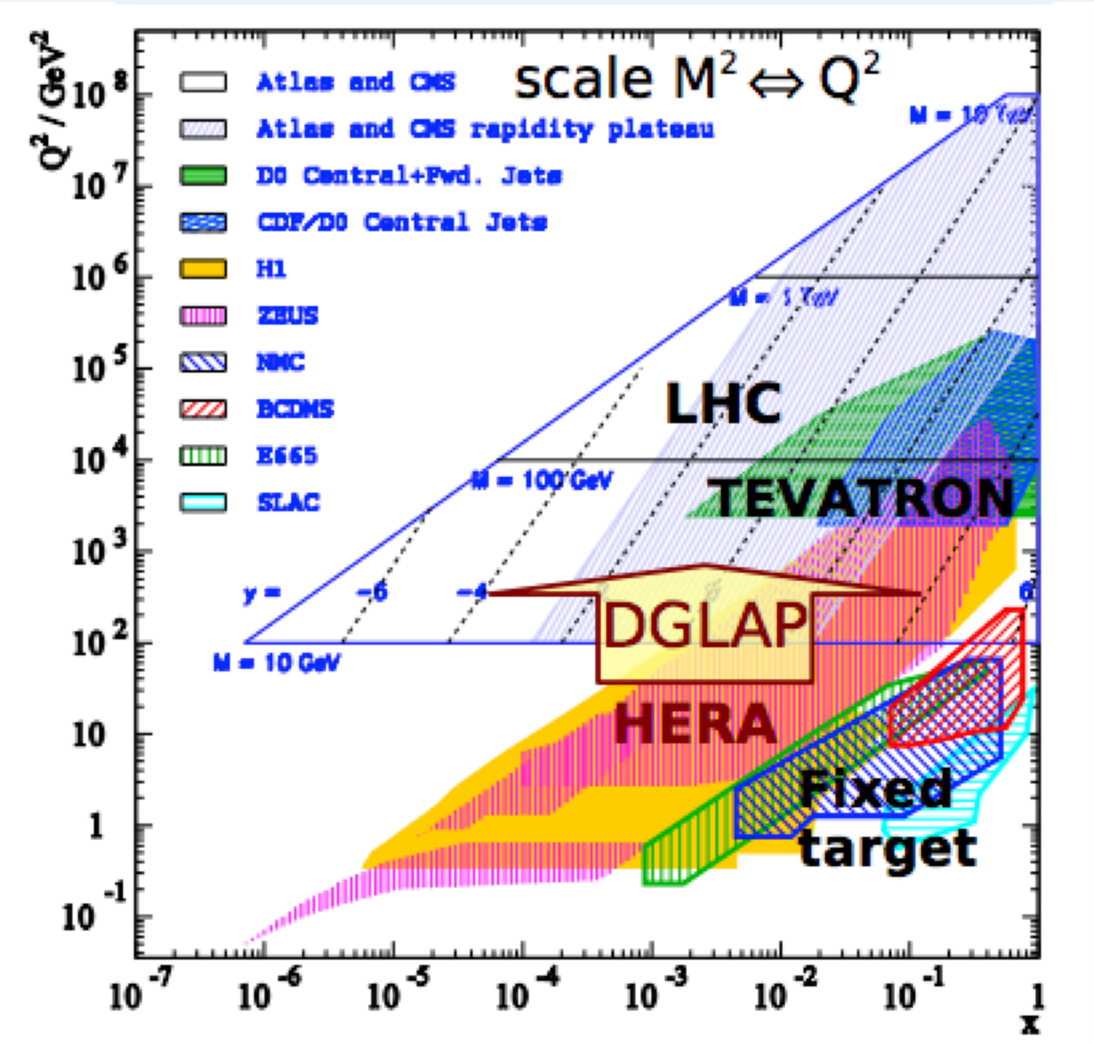


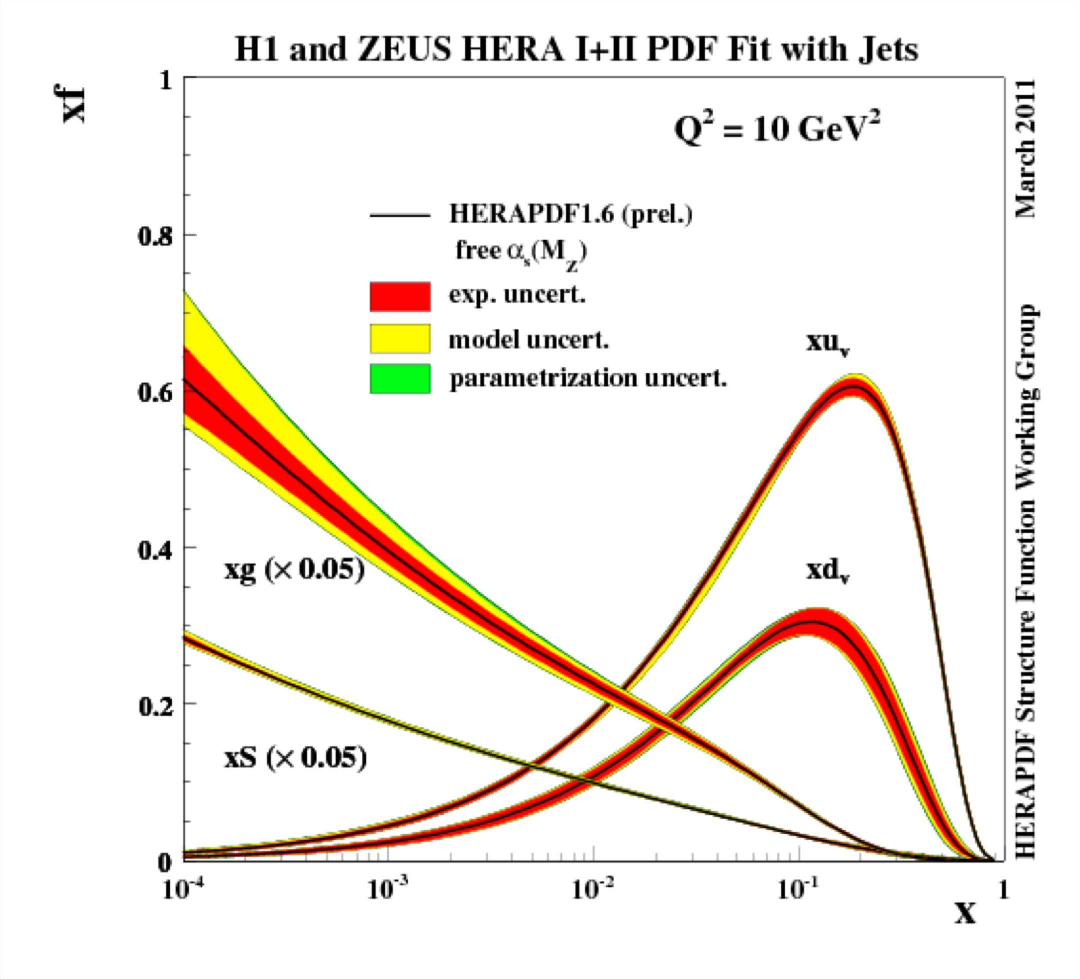
- DGLAP Equations
- $\frac{d}{dQ^2} q_i(x, Q^2) \propto q_i \otimes P_{qq}] + [g \otimes P_{qg}]$
- $\frac{d}{dQ^2} g(x, Q^2) \propto [(q_i + \bar{q}_i) \otimes P_{gq}] + [g \otimes P_{gg}]$
- $[q \otimes P] = \mathrm{P} \otimes q = \int_x^1 dy \frac{q(y,Q^2)}{y} \cdot P(\frac{x}{y})$



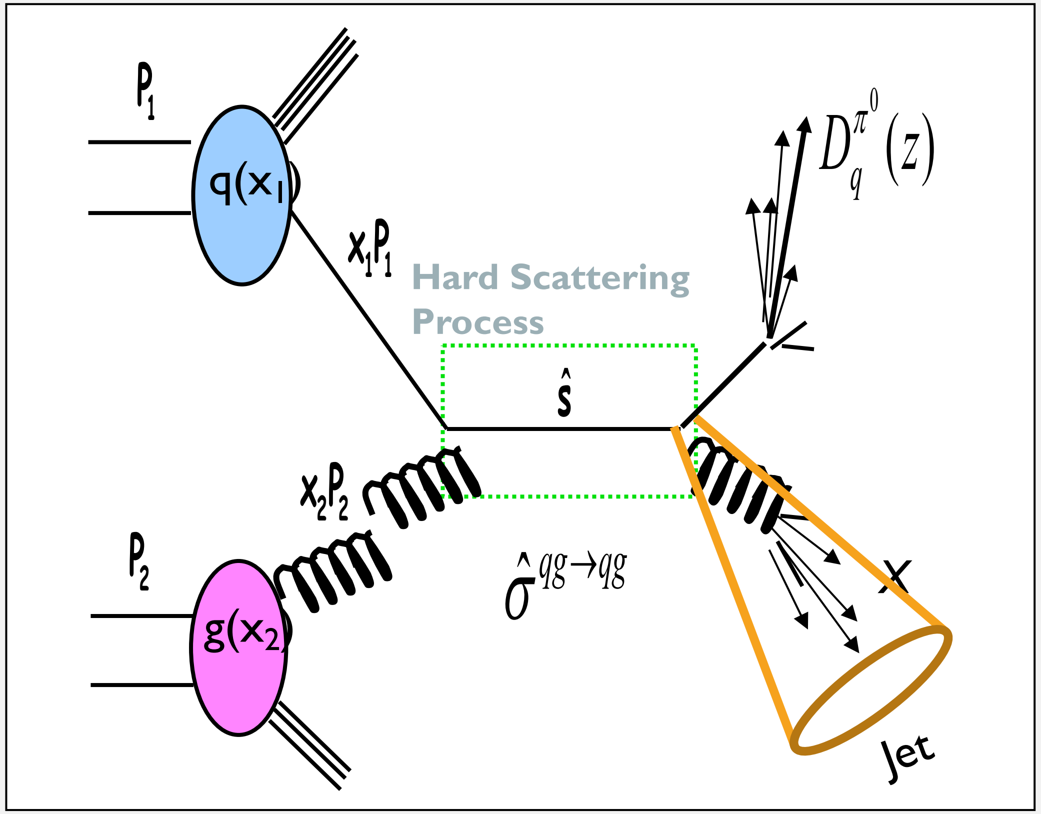
Need to know PDF at all higher x

RESULTS ON PDFS FROM HERA



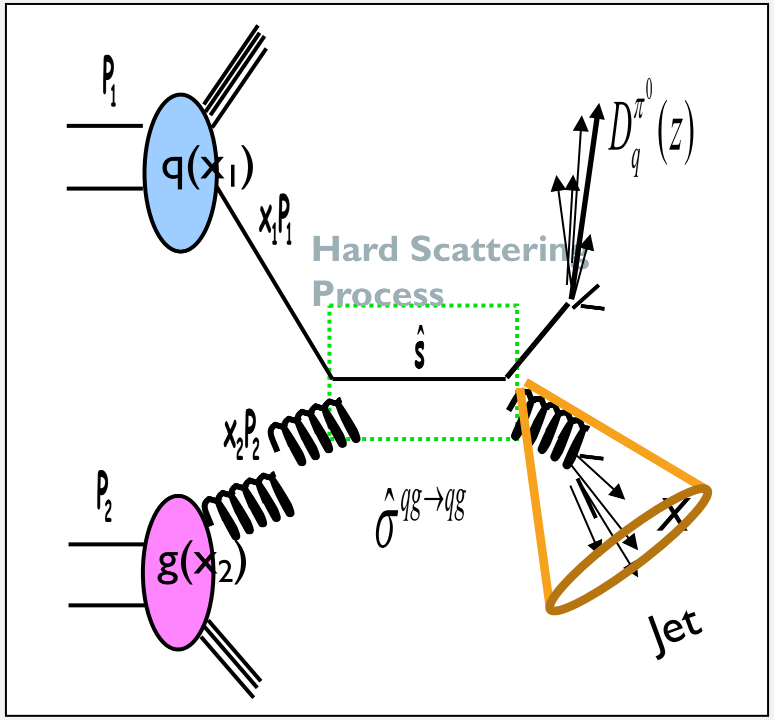


DIRECT ACCESS TO GLUON POLARIZATION AT PP COLLIDERS

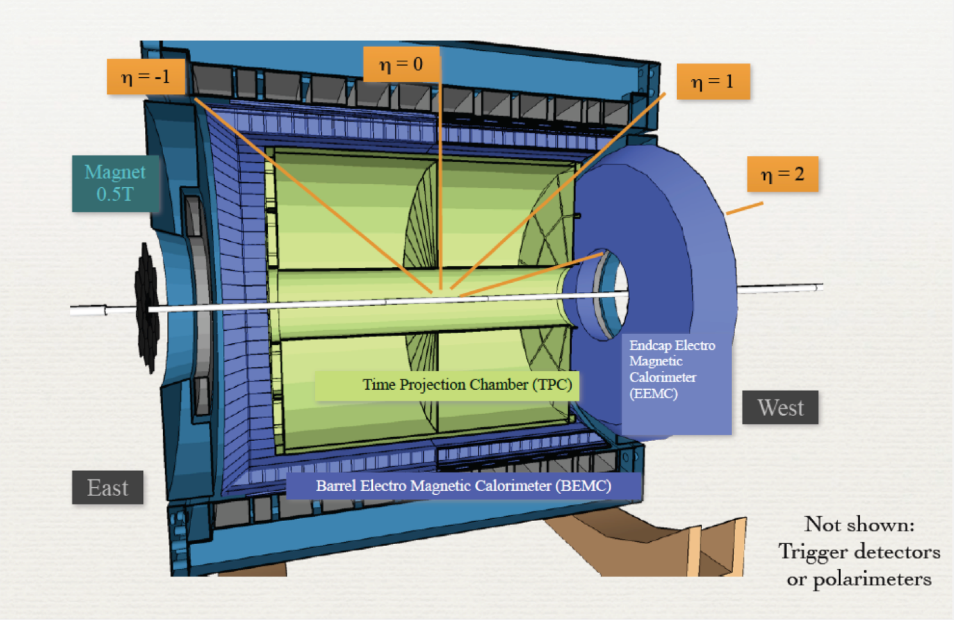


- "Parton-beam" with poorly known initial kinematics

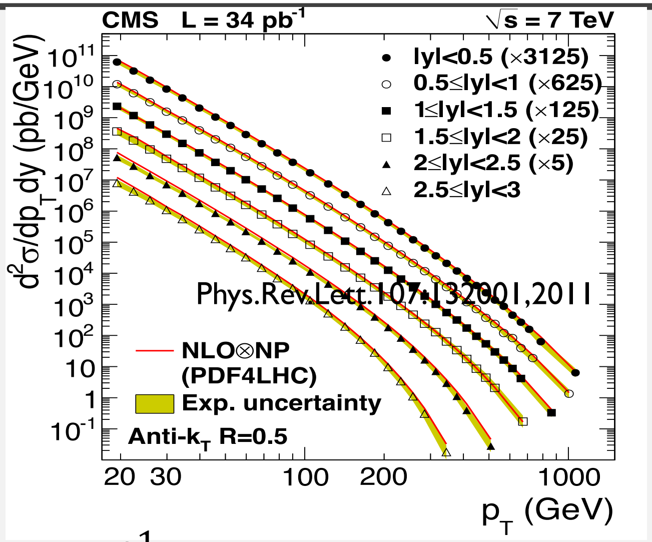
DIRECT ACCESS TO GLUON POLARIZATION AT PP COLLIDERS

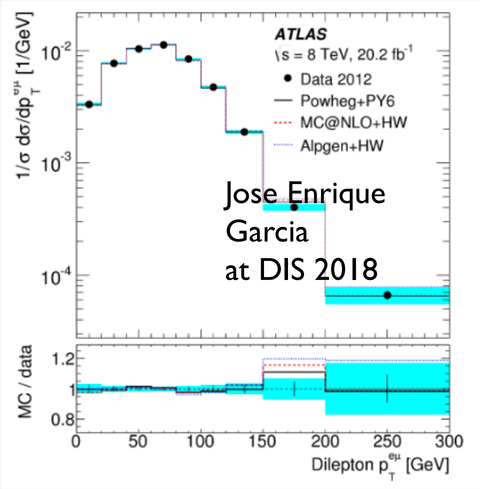


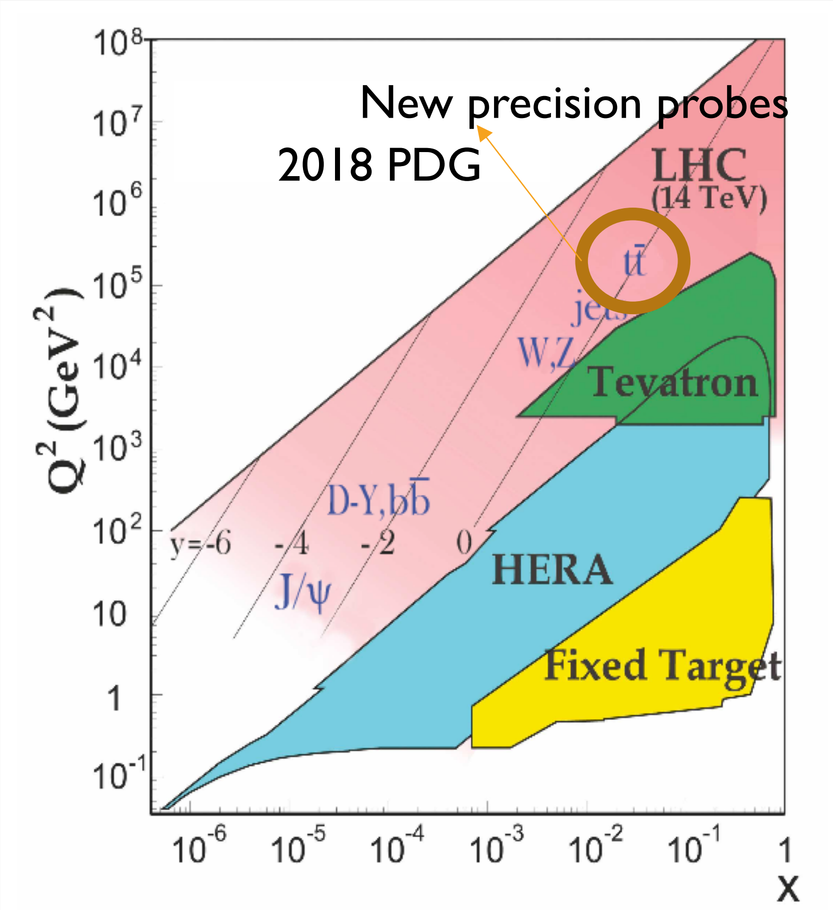
- Cannot determine **Q^2,x , need different set of variables to define kinematics**
- Initial parton kinematics unkown, use variables that are invariant under longitudinal boost:
  - **Rapidity y** (pseudorapidity η), $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right), \eta = -\ln tan\ \frac{\theta}{2}$
  - **Transverse jet momentum** p_T
  - At leading order: $\boldsymbol{x_1 = \frac{p_T}{\sqrt{s}}(e^{y_1} + e^{y_2}), x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_1} + e^{-y_2}),}$
  - **→High, (low) x: high y, high (low) p_T**



CROSS-SECTION AND MORE PROBES FROM HIGH LUMINOSITY COLLIDERS







$$\sigma \propto \sum_{ij} \int_0^1 dx_1 dx_2 f_i(x_1) f_j(x_2)\, \hat{\sigma}_{ij}$$

- Together in a global fit they provide a detailed picture
  - Multiple probes probes and kinematic regions to probe different x regions helped by high precision LHC data
  - Examples from NNPDF
    - Top-top → high x
    - W for flavor separation
    - W+c for strange quarks

INPUT FOR. NNPDF 3.0

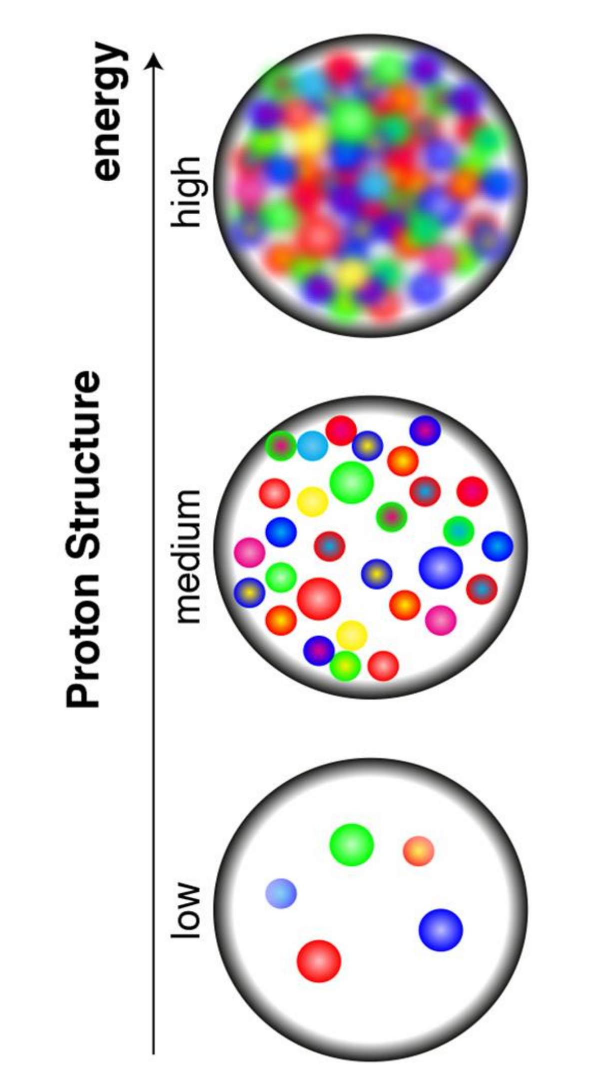
- Data used

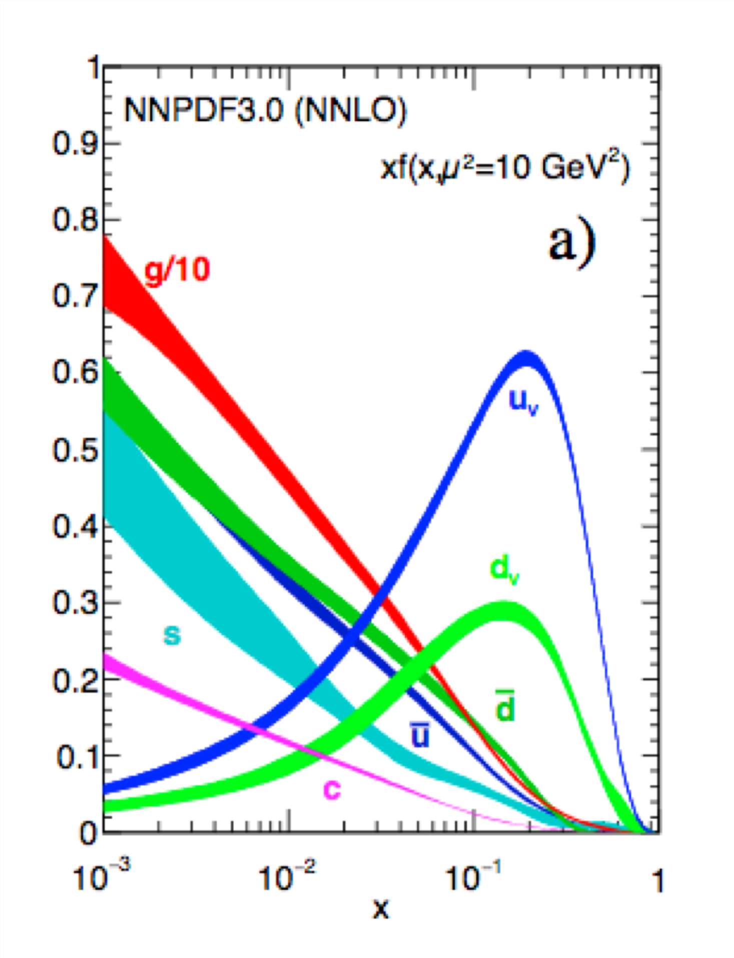
Exp.	Obs.	Ref.
E866	$\sigma^d_{\rm DY}/\sigma^p_{\rm DY}$	[48]
	$\sigma^p_{\rm DY}$	[46, 47]
E605	$\sigma^p_{\rm DY}$	[45]
CDF	$d\sigma_Z/dy_Z$	[42]
	k_t incl jets	[87]
D0	$d\sigma_Z/dy_Z$	[43]
	W electron asy (*)	[14]
	W muon asy (*)	[13]

Experiment	Obs.	Ref.	$N_{\rm dat}$
NMC	F_2^d/F_2^p	[28]	260 (121/121)
	$\sigma^{\rm NC,p}$	[29]	292 (204/204)
SLAC	F_2^p	[32]	211 (33/33)
	F_2^d	[32]	211 (34/34)
BCDMS	F_2^p	[30]	351 (333/333)
	F_2^d	[31]	254 (248/248)
CHORUS	$\sigma^{\rm CC,\nu}$	[39]	607 (416/416)
	$\sigma^{\rm CC,\bar\nu}$	[39]	607 (416/416)
NuTeV	σ_ν^{cc}	[40, 41]	45 (39/39)
	$\sigma_{\bar\nu}^{cc}$	[40, 41]	45 (37/37)
HERA	$\sigma^p_{\rm NC,CC}$ (*)	[9]	1306 (1145/1145)
	$\sigma^c_{\rm NC}$	[38]	52 (47/37)
	F_2^b (*)	[67, 68]	29 (29/29)
EMC	[F_2^c] (*)	[69]	21 (16/16)

Exp.	Obs.	Ref.	$N_{\rm dat}$
ATLAS	W, Z 2010	[49]	30 (30/30)
	W, Z 2011 (*)	[72]	34 (34/34)
	high-mass DY 2011	[50]	11 (5/5)
	low-mass DY 2011 (*)	[77]	6 (4/6)
	[Z p_T 7 TeV (p_T^Z, y_Z)] (*)	[78]	64 (39/39)
	Z p_T 8 TeV (p_T^Z, M_{ll}) (*)	[71]	64 (44/44)
	Z p_T 8 TeV (p_T^Z, y_Z) (*)	[71]	120 (48/48)
	7 TeV jets 2010	[57]	90 (90/90)
	2.76 TeV jets	[58]	59 (59/59)
	7 TeV jets 2011 (*)	[76]	140 (31/31)
	$\sigma_{\rm tot}(t\bar t)$	[74, 75]	3 (3/3)
	$(1/\sigma_{t\bar t})d\sigma(t\bar t)/y_t$ (*)	[73]	10 (10/10)
CMS	W electron asy	[52]	11 (11/11)
	W muon asy	[53]	11 (11/11)
	$W + c$ total	[60]	5 (5/0)
	$W + c$ ratio	[60]	5 (5/0)
	2D DY 2011 7 TeV	[54]	124 (88/110)
	[2D DY 2012 8 TeV]	[84]	124 (108/108)
	$W^\pm$ rap 8 TeV (*)	[79]	22 (22/22)
	Z p_T 8 TeV (*)	[83]	50 (28/28)
	7 TeV jets 2011	[59]	133 (133/133)
	2.76 TeV jets (*)	[80]	81 (81/81)
	$\sigma_{\rm tot}(t\bar t)$	[82, 88]	3 (3/3)
	$(1/\sigma_{t\bar t})d\sigma(t\bar t)/y_{t\bar t}$ (*)	[81]	10 (10/10)
LHCb	Z rapidity 940 pb	[55]	9 (9/9)
	$Z \to ee$ rapidity 2 fb	[56]	17 (17/17)
	$W, Z \to \mu$ 7 TeV (*)	[85]	33 (33/29)
	$W, Z \to \mu$ 8 TeV (*)	[86]	34 (34/30)

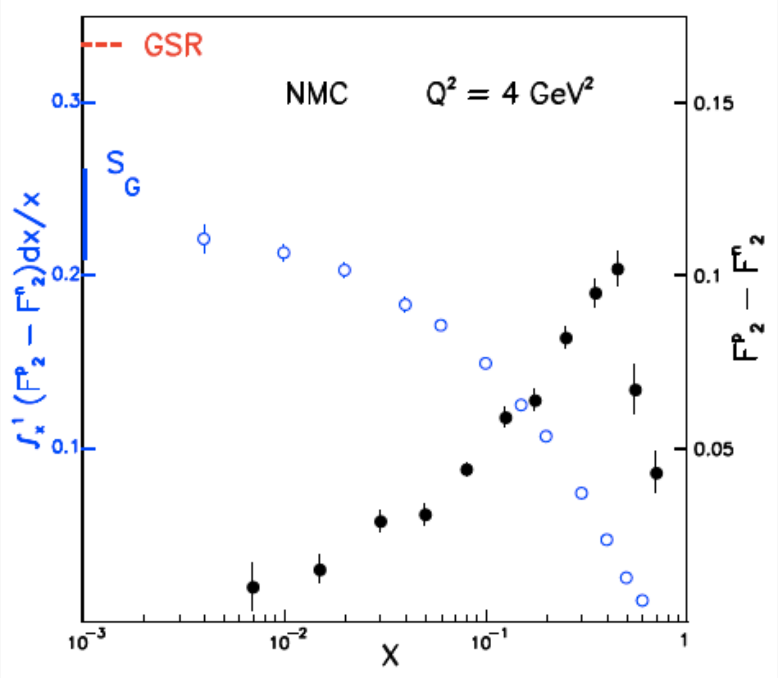
EXAMPLE OF EXTRACTED PDFS

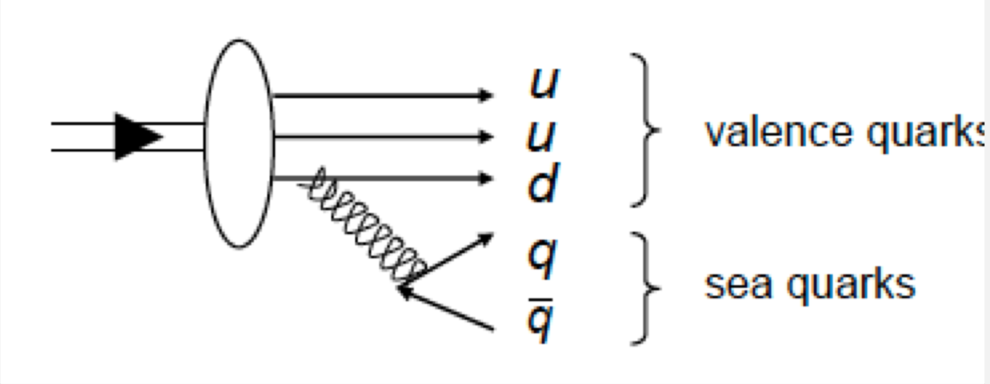




- Global fits:
- NNPDF →NNPDF3.1 ([arXiv:1706.00428](https://arxiv.org/abs/1706.00428),)
- CTEQ/CT →CT14 (**Phys.Rev. D93 (2016) no.3, 033006**)
- MSTW/MMHT →MMHT2014 (**Eur.Phys.J. C75 (2015) no.5, 204)**

TURBULENT SEA

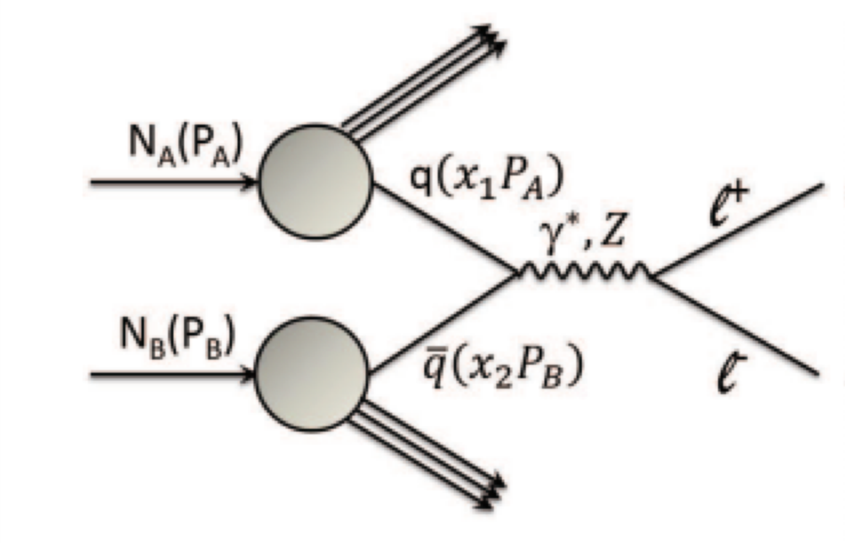


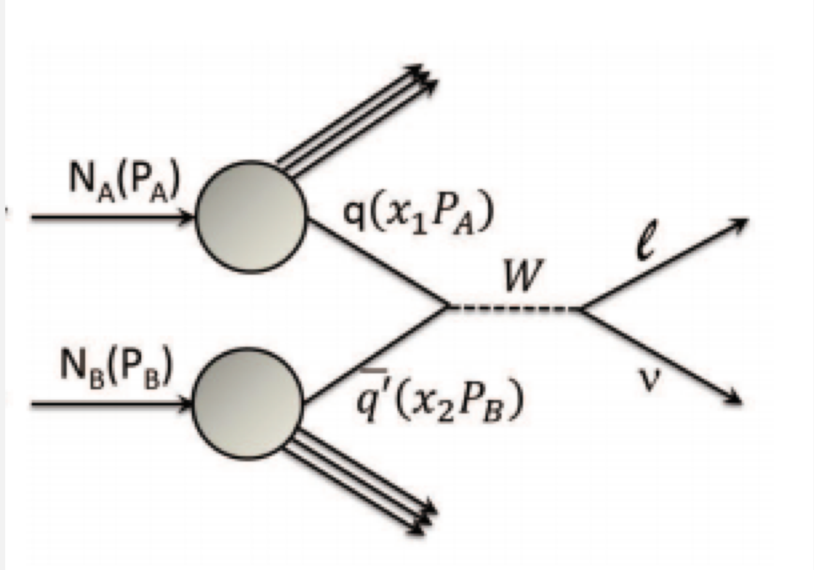


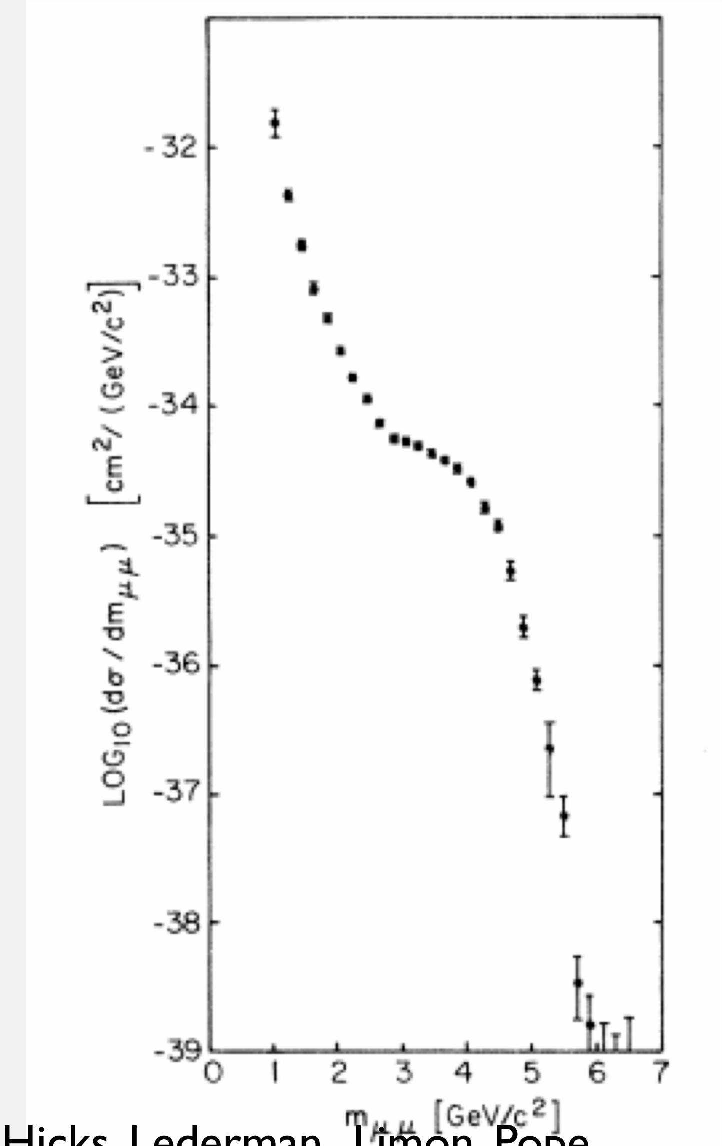
Naïve sea-quark picture

- Gottfried sum rule:
- $S_G = \int_0^1 [\frac{F_2^p(x) - F_2^n(x)}{x}]\, dx = \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))dx$
- If $(\bar{u}_p(x) = \bar{d}_p(x))$ $\boldsymbol{S_G = \frac{1}{3}}$**!**
- NMC=0.235 +/- 0.026

ACCESS TO THE SEA IN DY AND W PRODUCTION







Drell, Yan, Phys.Rev.Lett. **25** (1970) 316-320,

- Challenging measurement
  - Low cross-section
  - Background from resonances decaying in lepton pairs

Christenson, Hicks, Lederman,, Limon, Pope
Phys. Rev. Lett. 25 (1970) 1523-1526

DRELL-YAN KINEMATICS

- Drell Yan Kinematics
  - Invariant mass of the lepton pair $M = sx_t x_b$
  - "x-Feynman": $x_F = x_t - x_b = \frac{p_L}{p_{Lmax}} \approx 2p_L/\sqrt{s}$
  - Fixed target cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_\mathrm{b}dx_\mathrm{t}} = \frac{4\pi\alpha^2}{x_\mathrm{b}x_\mathrm{t}s}\sum_{q\in\{u,d,s,\dots\}} e_q^2[\bar{q}_\mathrm{t}(x_\mathrm{t})q_\mathrm{b}(x_\mathrm{b}) + \bar{q}_\mathrm{b}(x_\mathrm{b})q_\mathrm{t}(x_\mathrm{t})]$$

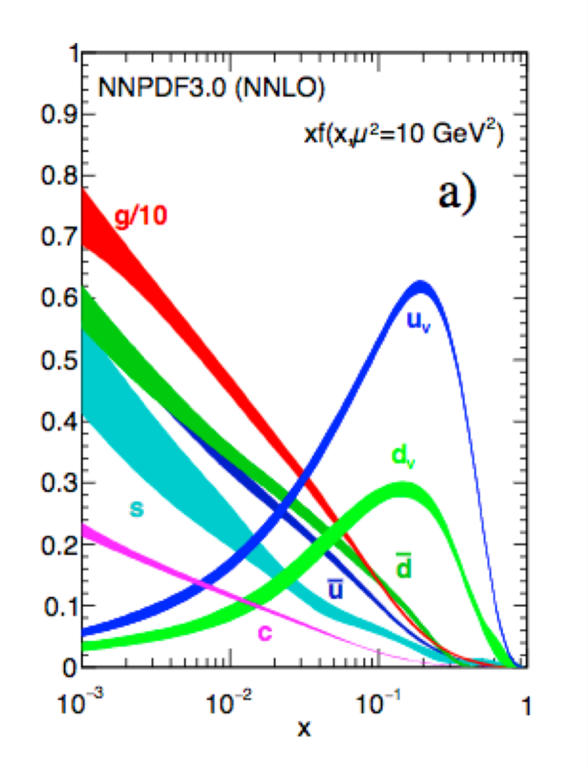
Acceptance limited

(Fixed Target, Hadron Beam)

  - u-quark dominance

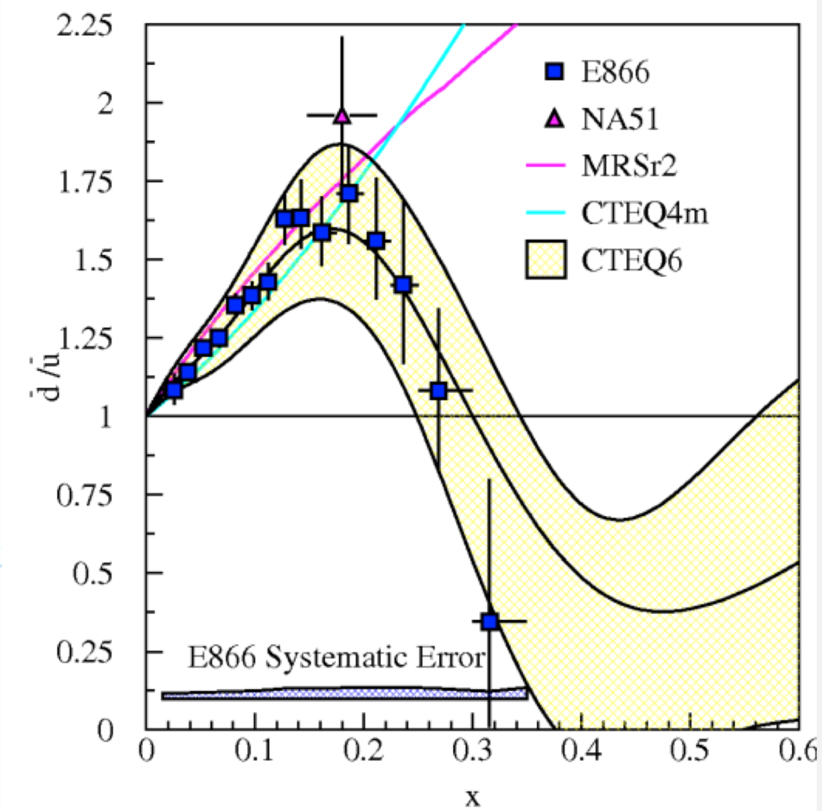
    $(2/3)^2$ vs. $(1/3)^2$

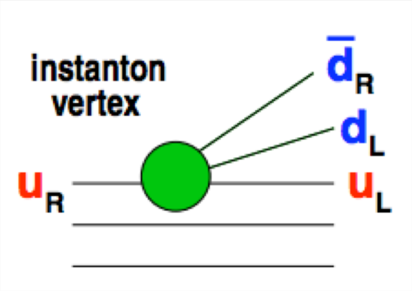
Beam	Sensitivity	Experiment
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)
Anti-Hadron	Beam antiquarks Target quarks	J-PARC, GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	COMPASS, J-PARC

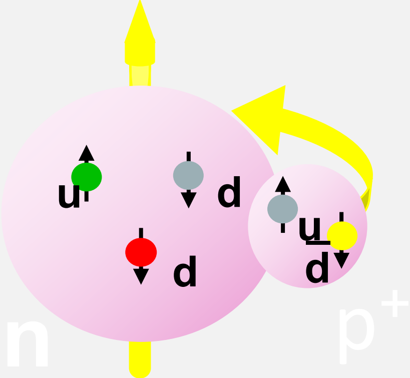


NuSea RESULTS

- E866 data qualitatively consistent w/ pion cloud, instanton and chiral quark models.







- Predicts

$$\bar{d} \geq \bar{u}$$

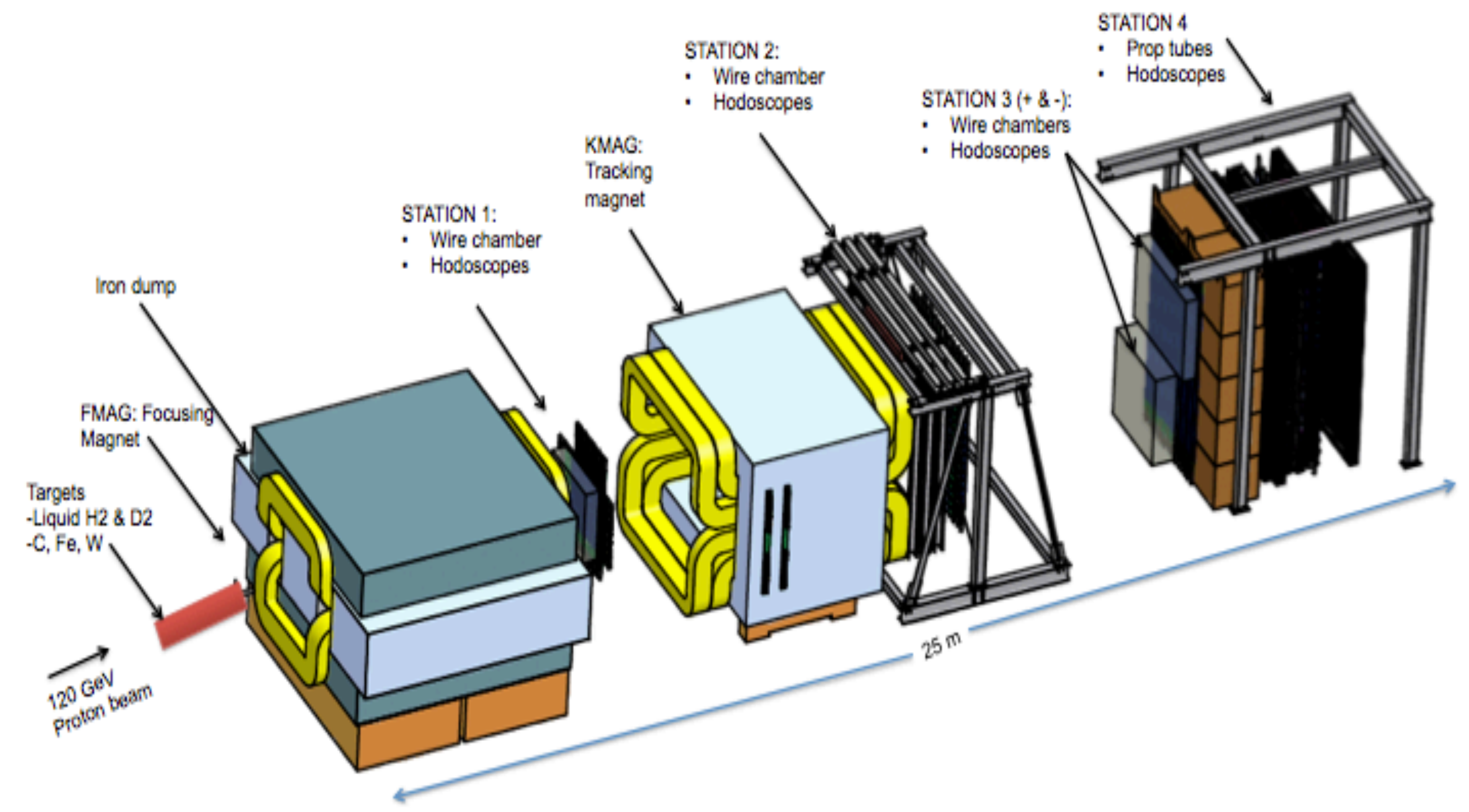
- Cannot have

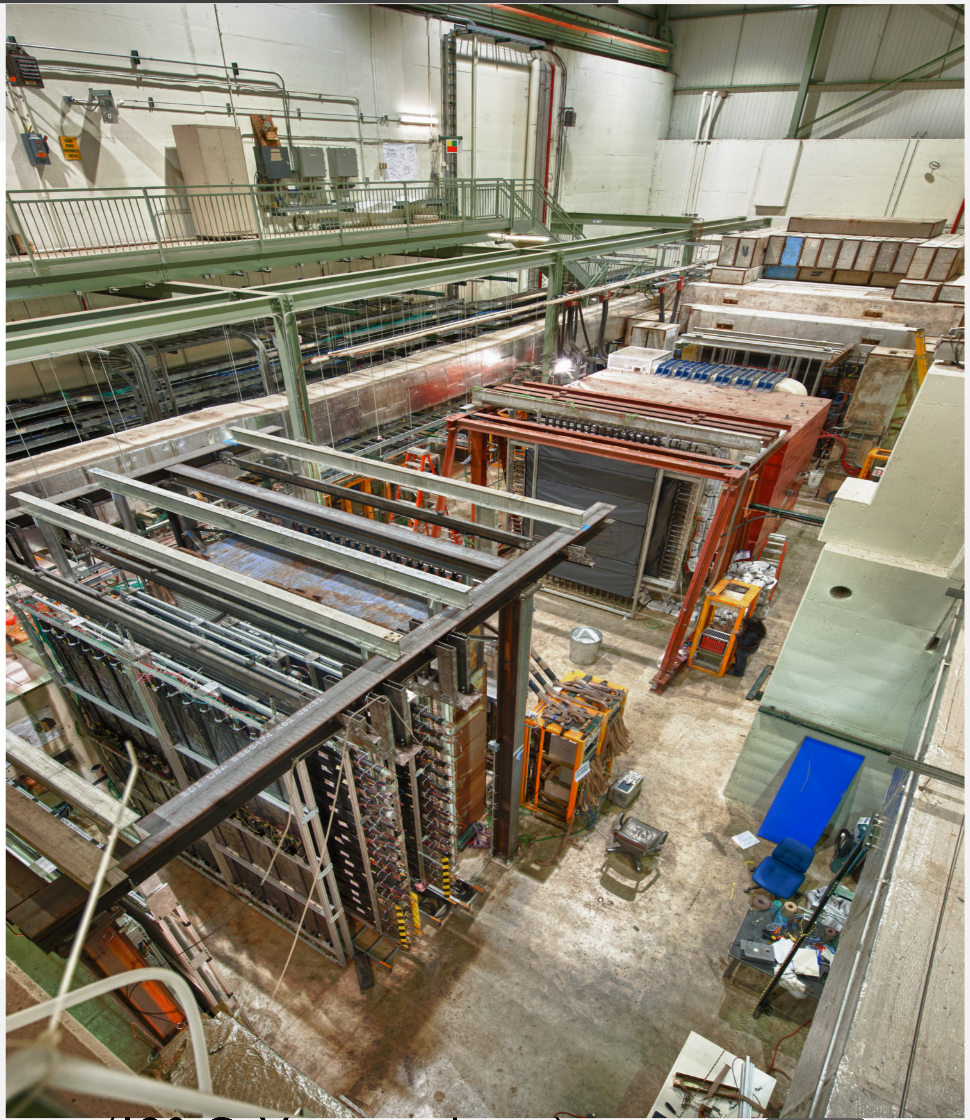
$$\bar{d} < \bar{u}$$

arxiv1007.4061

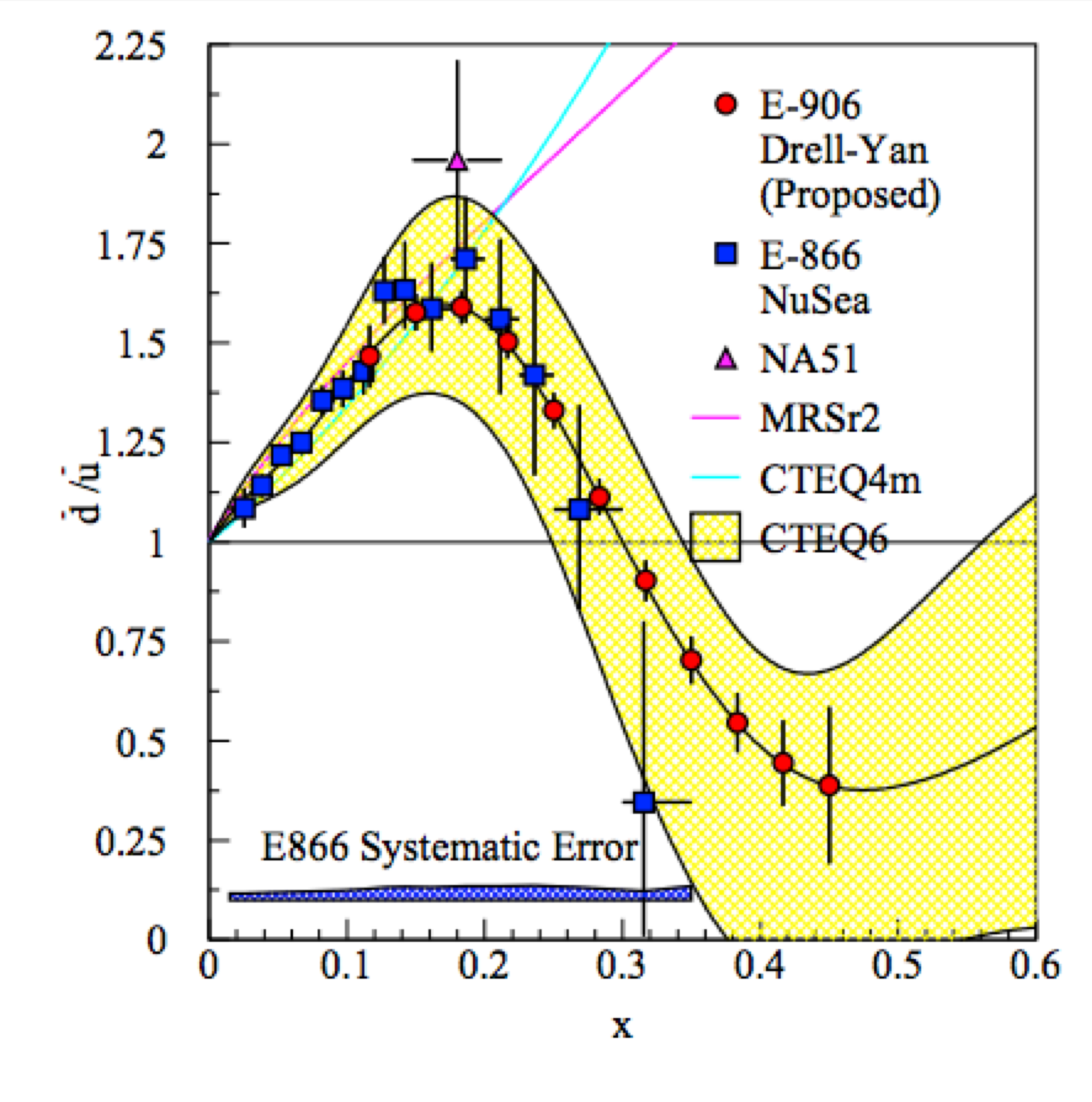
E866(NuSea) used 800 GeV proton beam

NEW: THE SEAQUEST SPECTROMETER

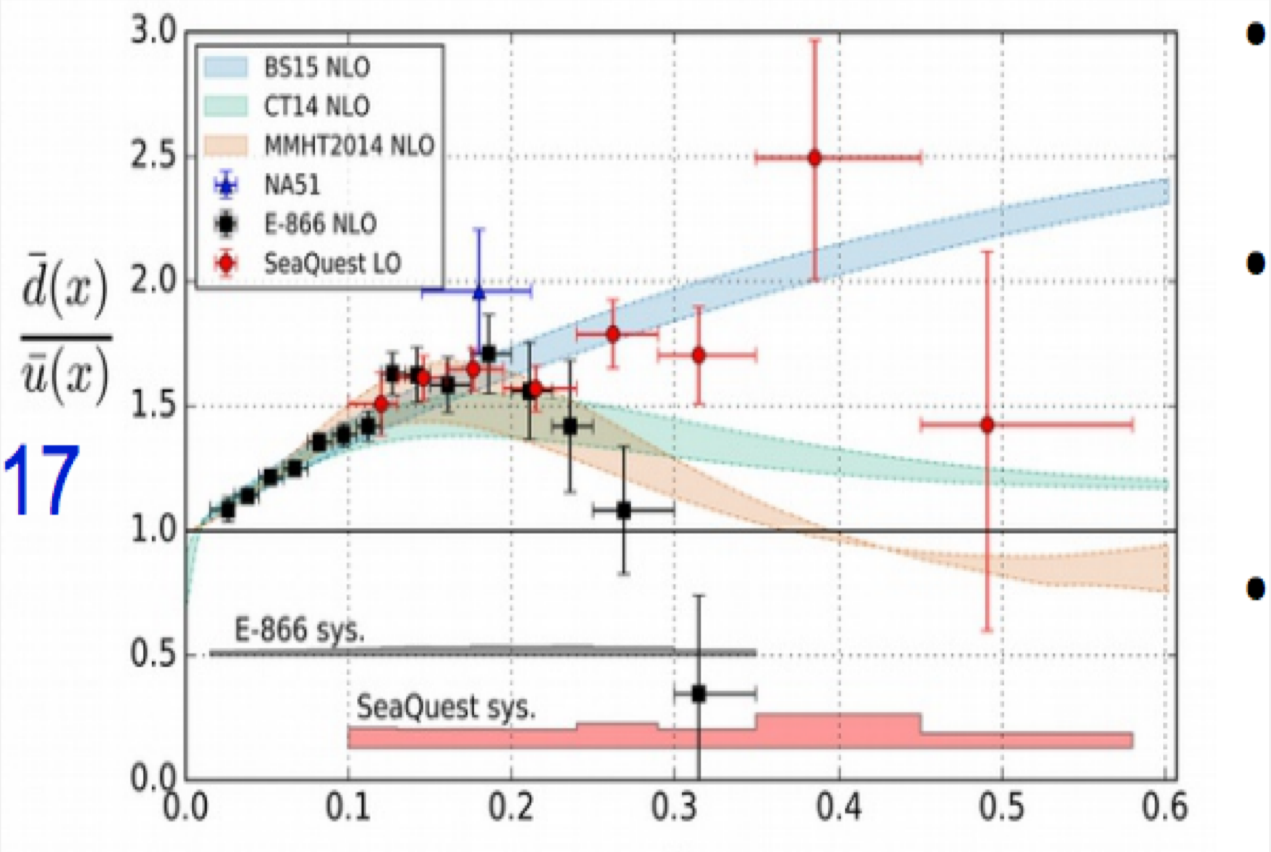




At fermilab main injector (120 GeV proton beam)

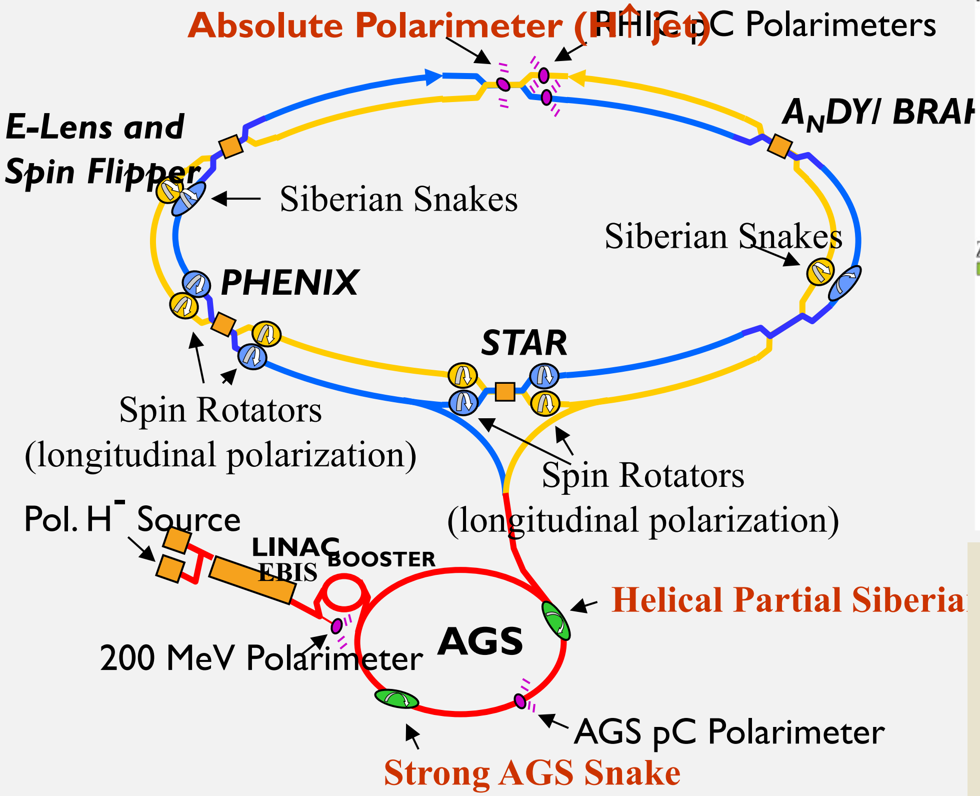


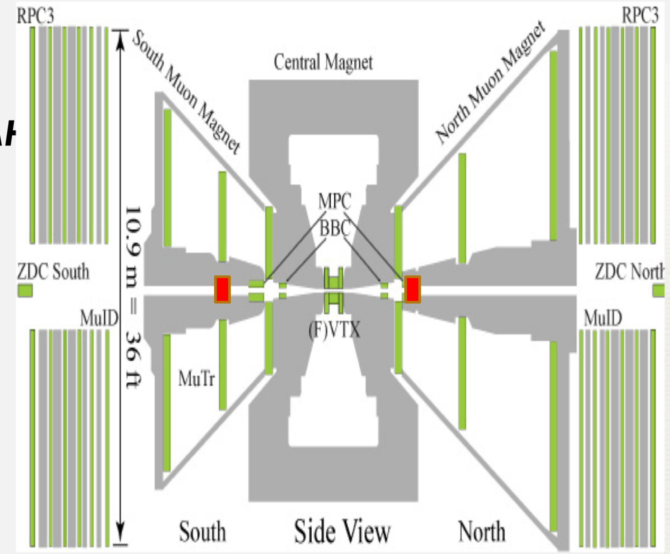
17

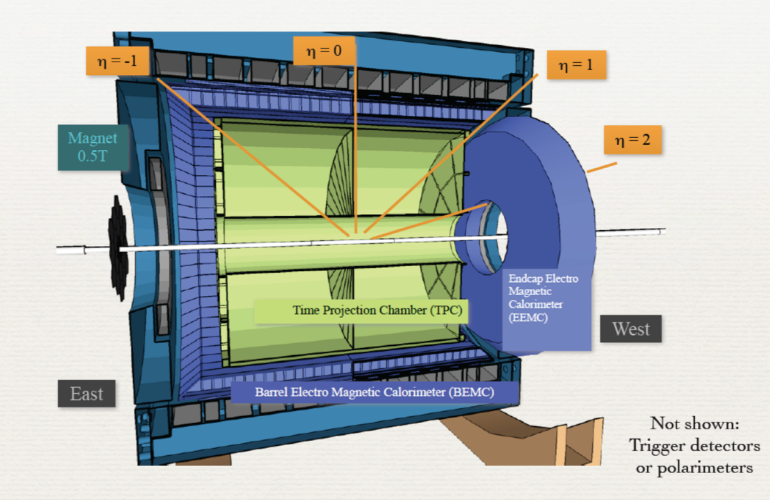


~20% of data, pre improved acceptance

RHIC: THE ONLY POLARIZED PP COLLIDER IN THE WORLD!



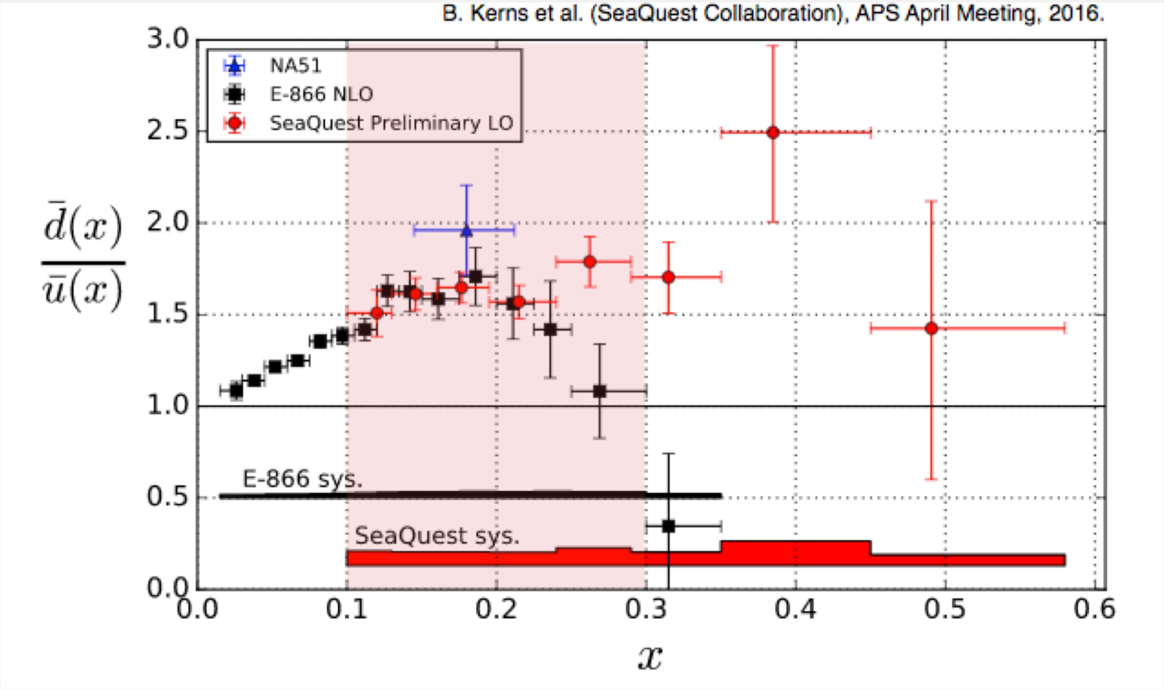


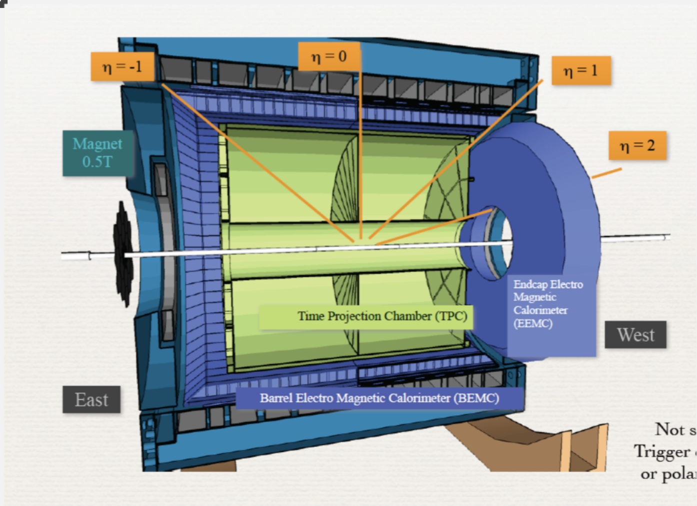


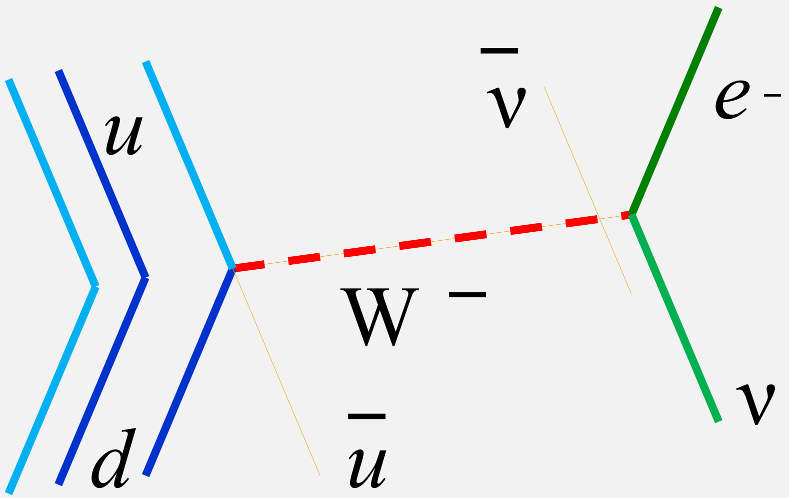
- Charged Tracks/π^0/γ in $-0.35<\eta<0.35$
- μ in $1<\eta<2$
- Forward EMC with preshower
- Pi0 channels
- High resolution/precision

- PID (Barrel) with dE/dx, TOF
- Jets in $-0.7<\eta<0.9$
- EM Jets $-1<\eta<4$
- Full Azimuth
- Forward EMC with preshower
- Jets+dijets

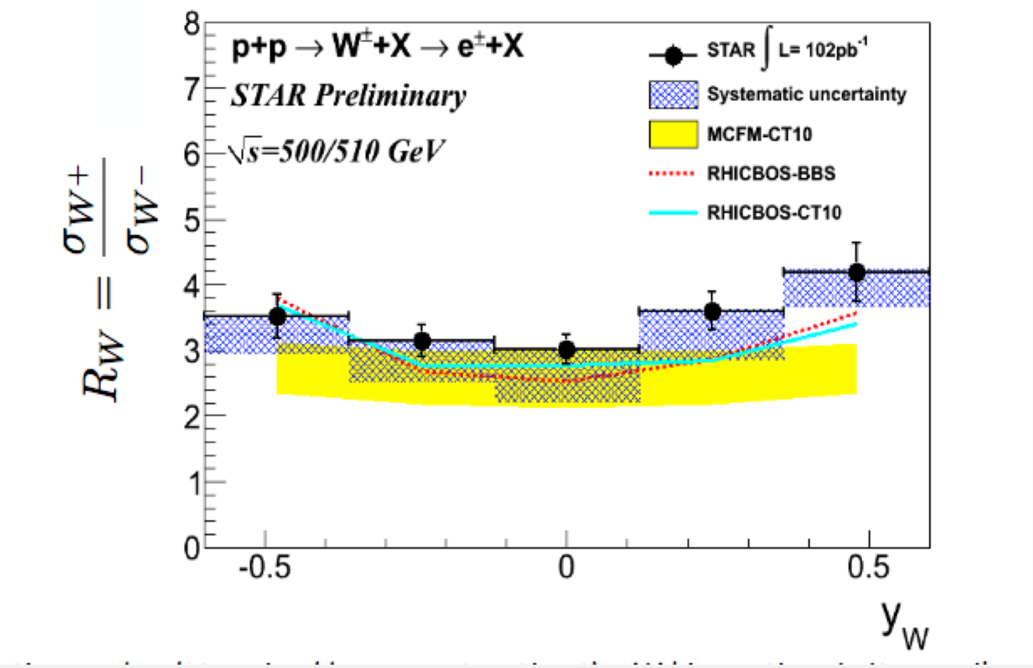
STAR KINEMATIC REACH MID-RAPIDITY

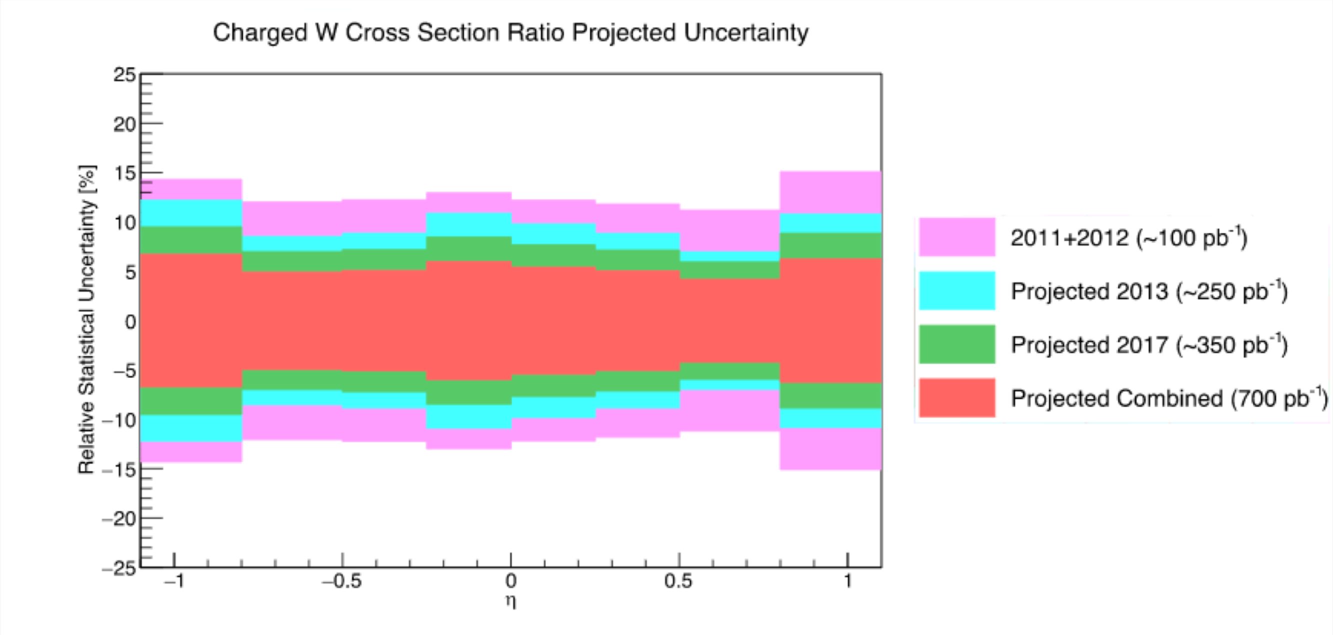






STAR RESULTS AND PROJECTIONS

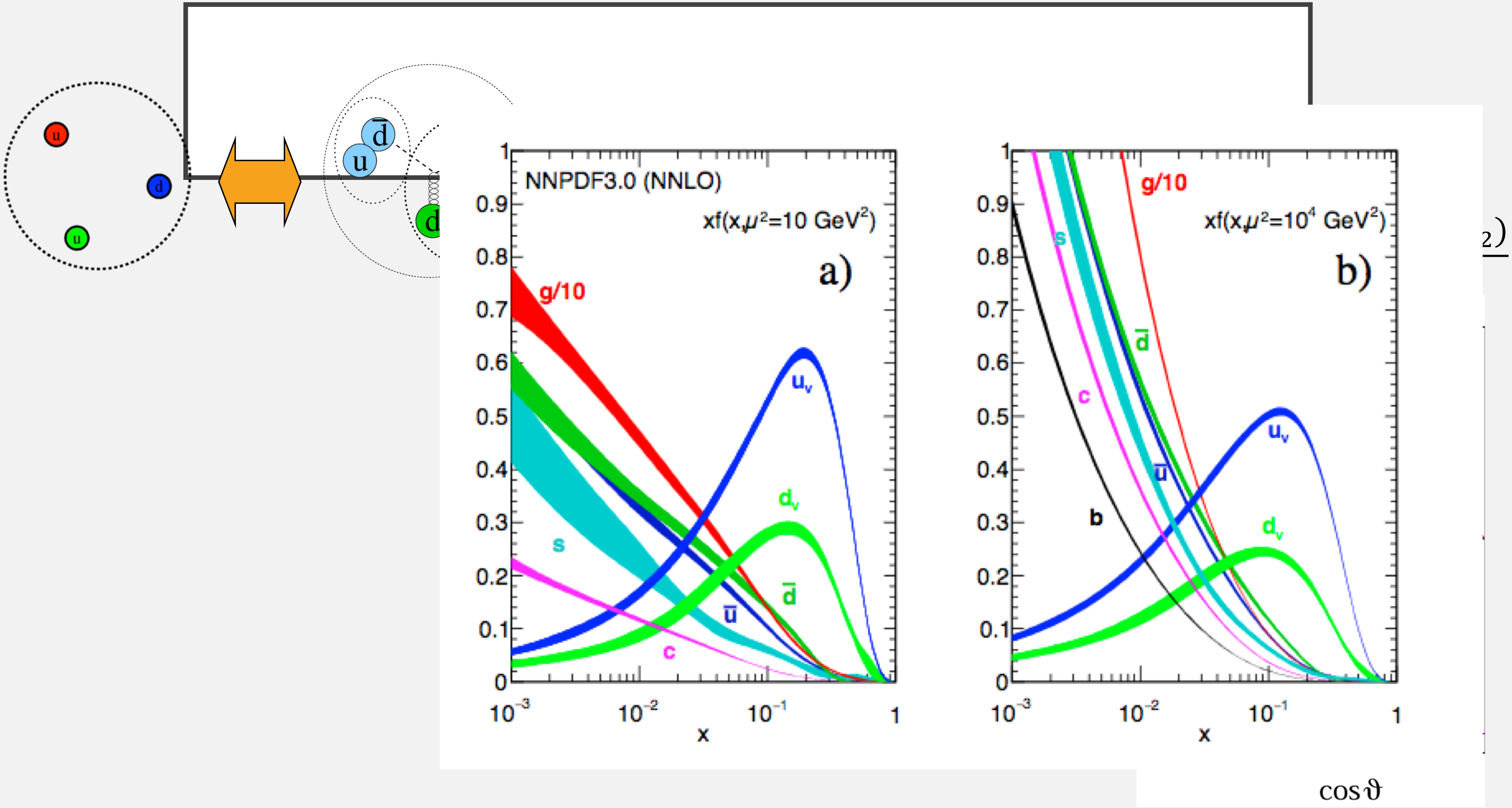


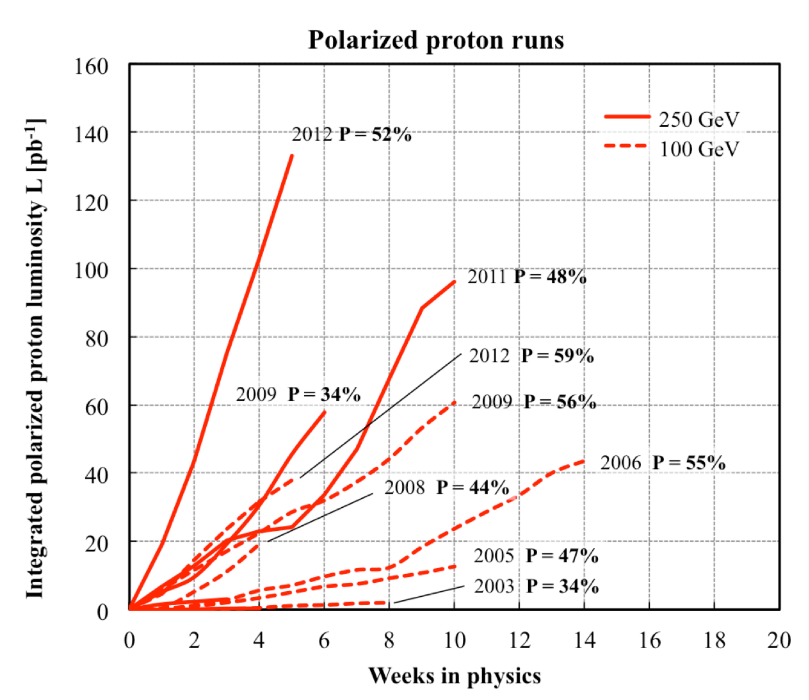


- Rapidity from 'fully reconstructed Ws'

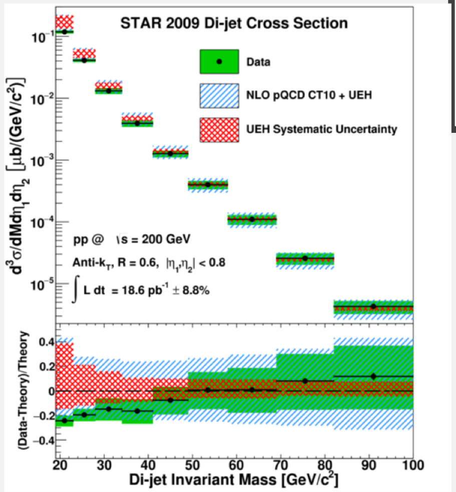
SUMMARY UNPOLARIZED PART

- Measurements of the partonic structure of the nucleon challenges challenges our understanding of QCD
- Hard scattering experiments probe the proton in a frame where it moves at the speed of light
- Factorization enables us to measure universal functions describing the parton structure (PDFs) and that have (at leading order) a probabilistic interpretation.
- Optical theorem relates PDFs to forward scattering amplitudes
- Worldwide effort to measure quark and gluon distributions precisely
- Structure of the sea still an open question


u
d
u
d̄
u
d
NNPDF3.0 (NNLO)
xf(x,μ²=10 GeV²)
a)
g/10
s
c
u_v
d_v
d̄
ū
x
xf(x,μ²=10⁴ GeV²)
b)
g/10
s
c
b
ū
u_v
d_v
d̄
x
cos ϑ



Polarized proton runs
Integrated polarized proton luminosity L [pb^-1]
Weeks in physics
250 GeV
100 GeV
2012 P = 52%
2011 P = 48%
2012 P = 59%
2009 P = 34%
2009 P = 56%
2006 P = 55%
2008 P = 44%
2005 P = 47%
2003 P = 34%
0
20
40
60
80
100
120
140
160
0
2
4
6
8
10
12
14
16
18
20



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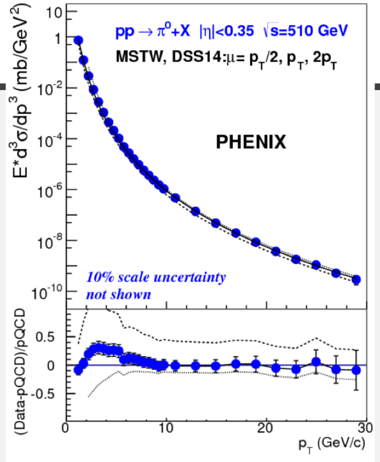

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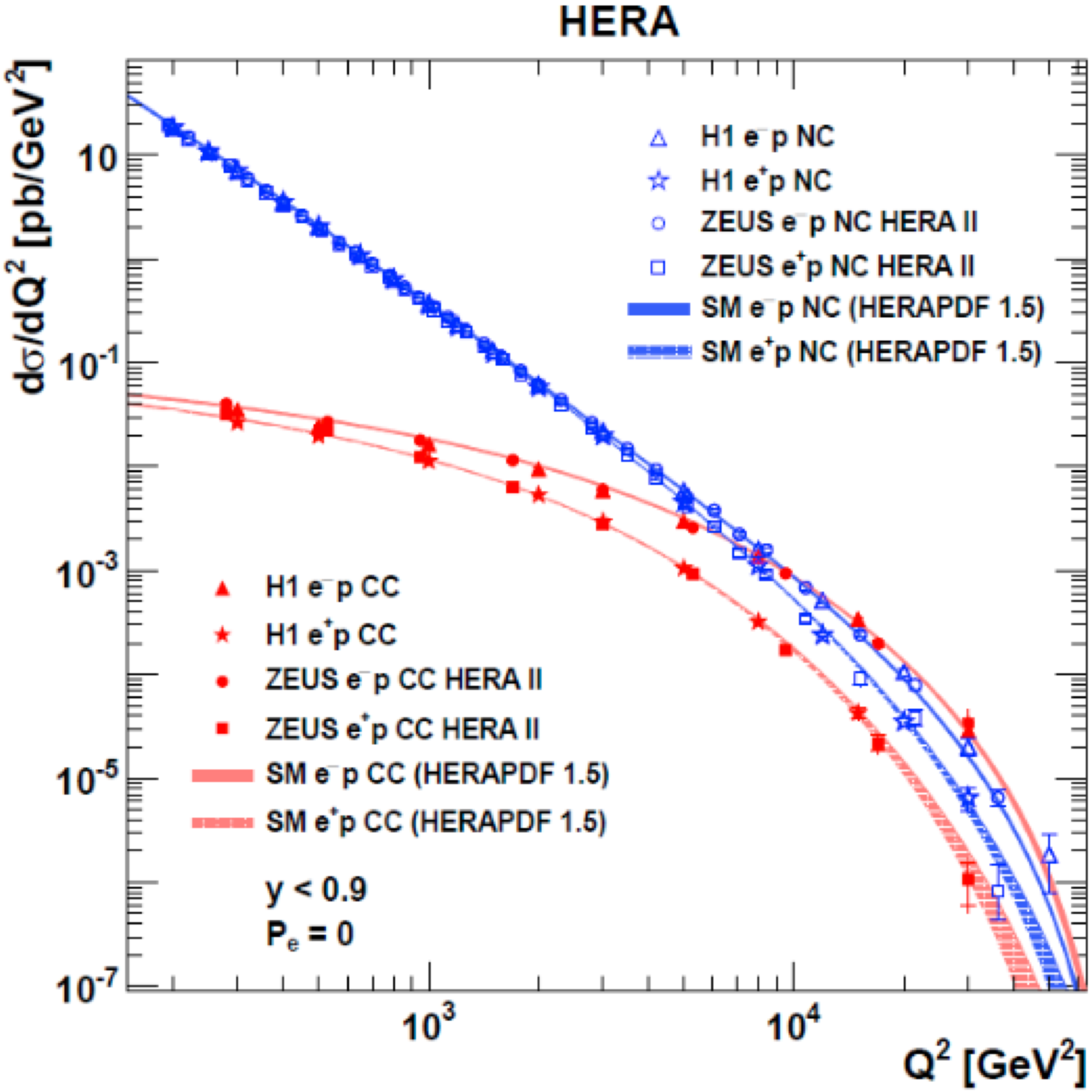

HERA
dσ/dQ² [pb/GeV²]
Q² [GeV²]
H1 e⁻p NC
H1 e⁺p NC
ZEUS e⁻p NC HERA II
ZEUS e⁺p NC HERA II
SM e⁻p NC (HERAPDF 1.5)
SM e⁺p NC (HERAPDF 1.5)
H1 e⁻p CC
H1 e⁺p CC
ZEUS e⁻p CC HERA II
ZEUS e⁺p CC HERA II
SM e⁻p CC (HERAPDF 1.5)
SM e⁺p CC (HERAPDF 1.5)
y < 0.9
Pₑ = 0