Lecture 1: introduction to hard probes; nuclear modification factor

Marco van Leeuwen,
Nikhef and Utrecht University

JET School, UC Davis, 19-21 June 2014

Universiteit Utrecht

NIKHEF

What is QCD?

What is QCD (Quantum Chromo Dynamics)?

Elementary fields: Quarks Gluons

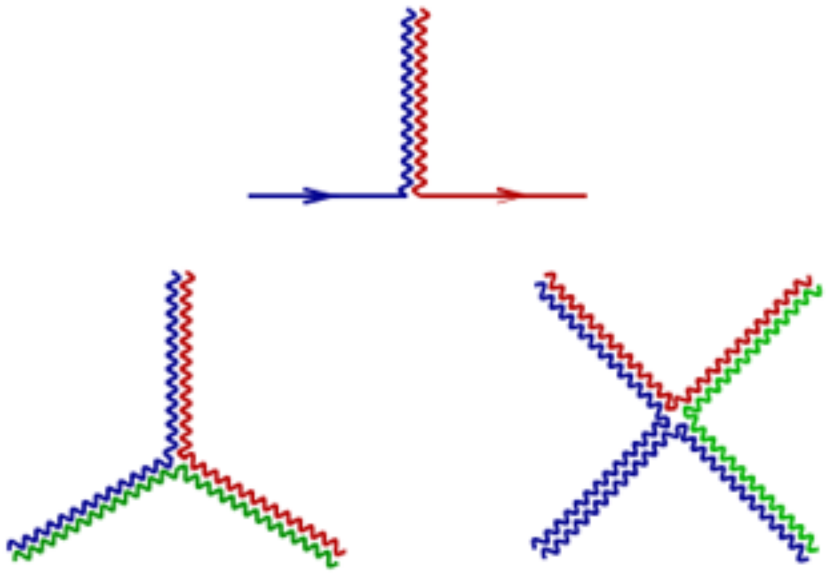
$$(q_\alpha)^a_f \begin{cases} \text{color} & a = 1,\ldots,3 \\ \text{spin} & \alpha = 1,2 \\ \text{flavor} & f = u,d,s,c,b,t \end{cases} \qquad A^a_\mu \begin{cases} \text{color} & a = 1,\ldots,8 \\ \text{spin} & \epsilon^\pm_\mu \end{cases}$$

Dynamics: Generalized Maxwell (Yang-Mills) + Dirac theory

$$\mathcal{L} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

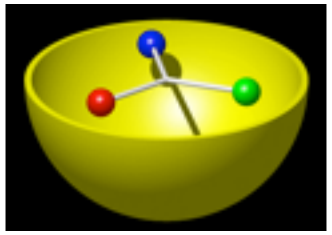
$$i\not{D}q = \gamma^\mu \left(i\partial_\mu + g A^a_\mu t^a \right) q$$



From: T. Schaefer, QM08 student talk

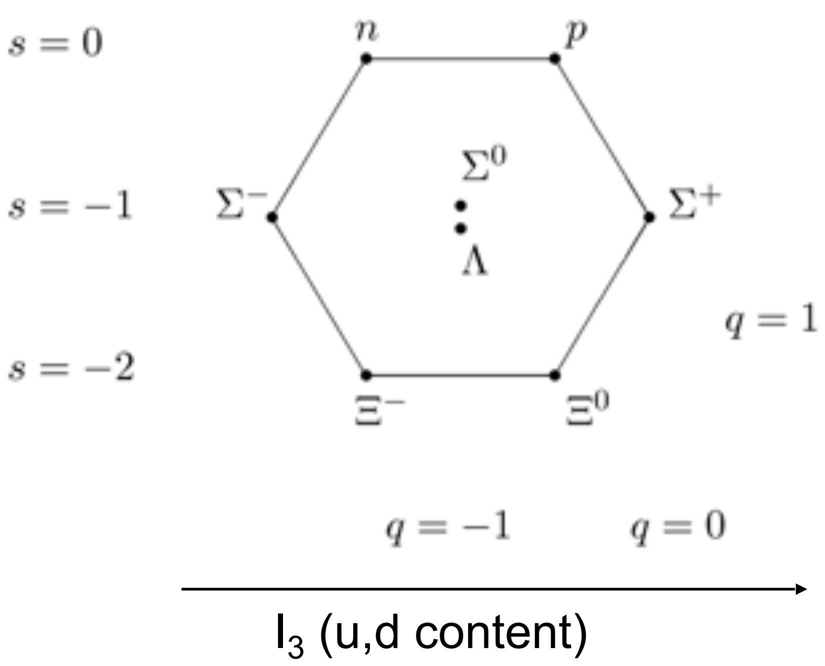
QCD and hadrons

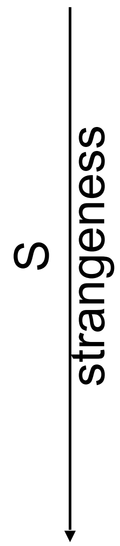
Quarks and gluons are the fundamental particles of QCD
(feature in the Lagrangian)



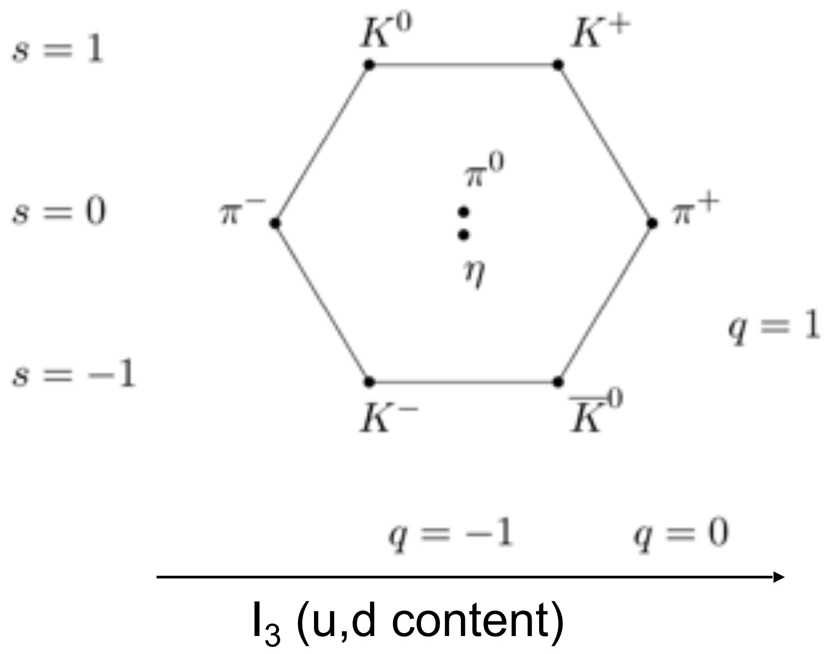
However, in nature, we observe hadrons:
Color-neutral combinations of quarks, anti-quarks

Baryon multiplet





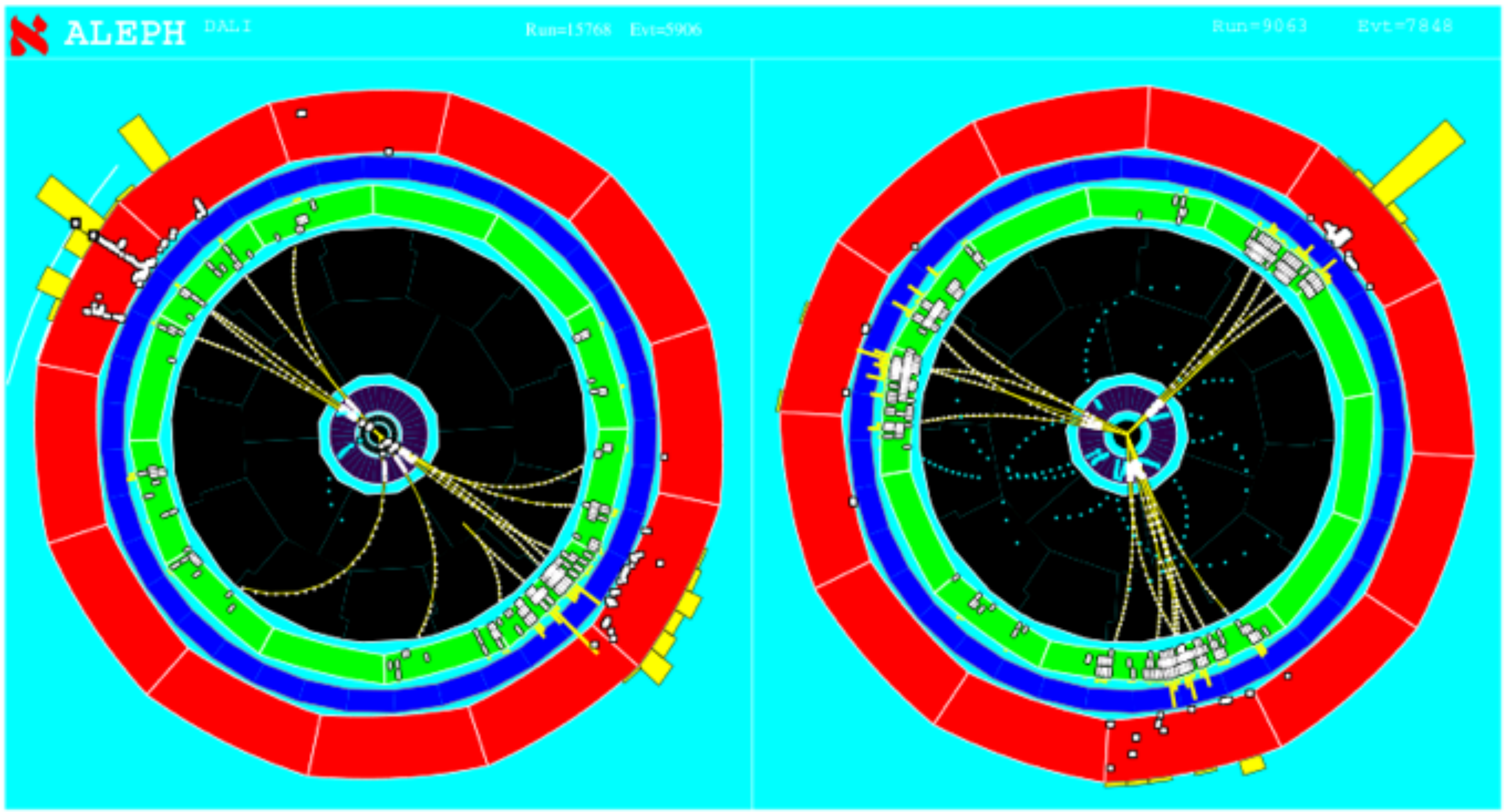
Meson multiplet

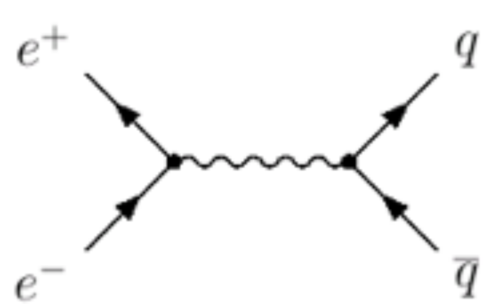


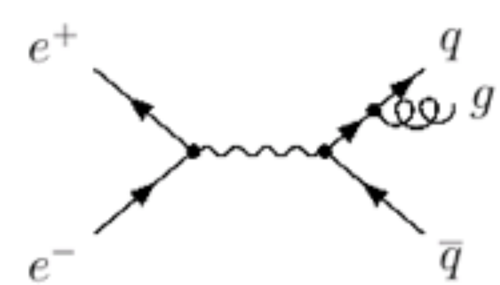
Baryons: 3 quarks

Mesons: quark-anti-quark

Seeing quarks and gluons

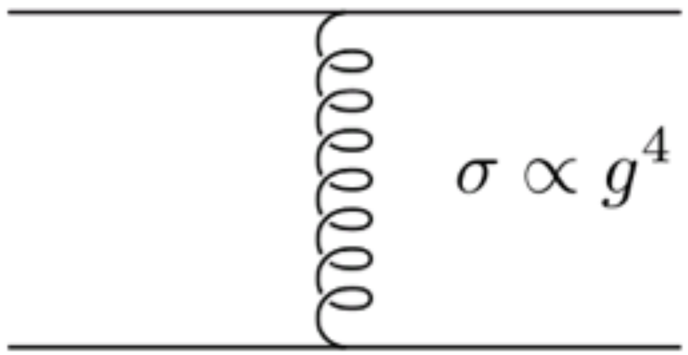






In high-energy collisions, observe traces of quarks, gluons ('jets')

How does it fit together?



$$\sigma \propto g^4 = 16\pi^2\alpha_s^2$$

Running coupling:
α_s decreases with Q^2

$$\beta_1 = (11N_c - 2n_f)/3$$

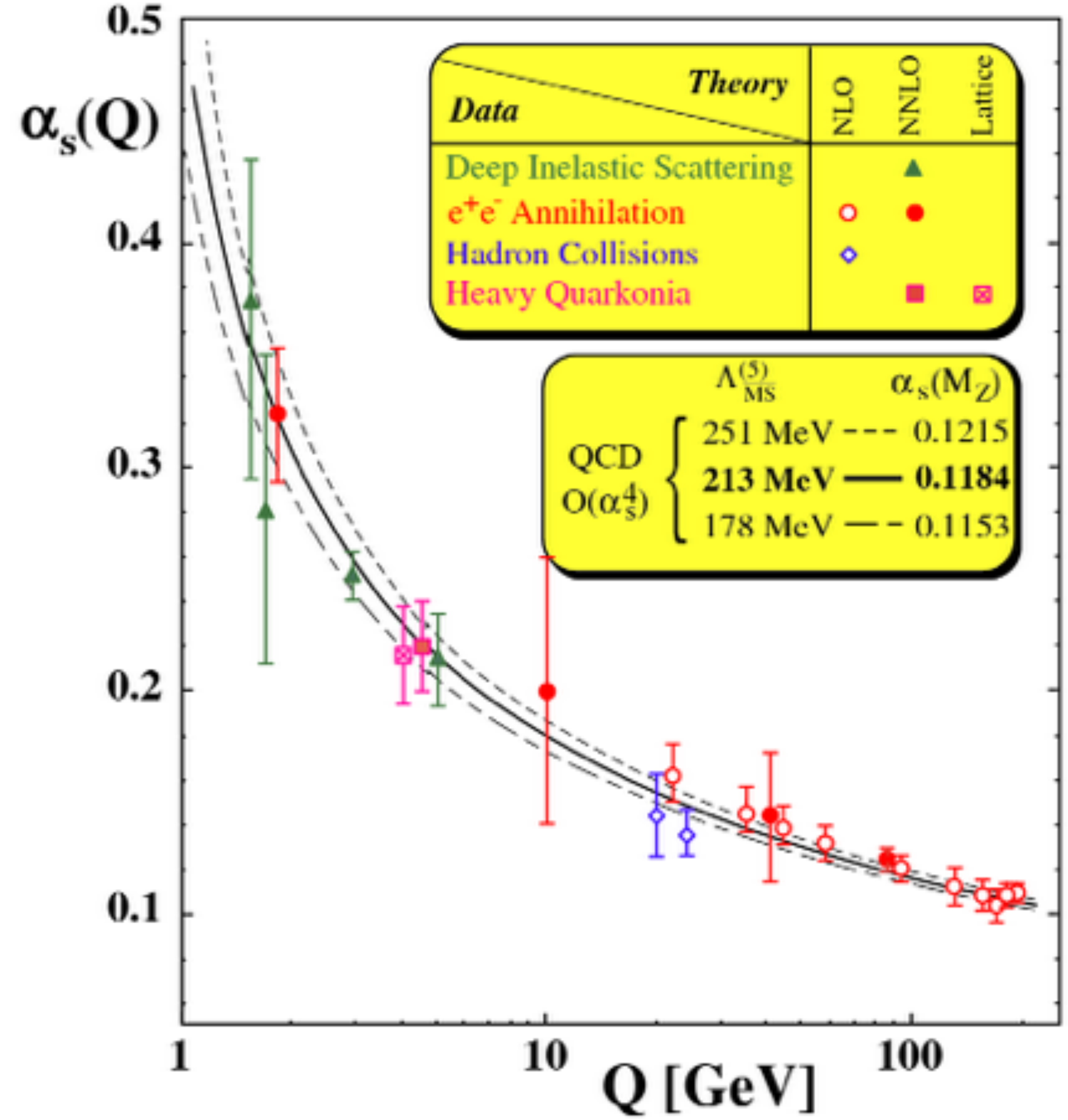
$$\alpha_s(\mu^2) = \frac{4\pi}{\beta_1 \ln(\mu^2/\Lambda_{QCD}^2)}$$

Pole at $\mu = \Lambda$

Λ_{QCD} ~ 200 MeV ~ 1 fm^{-1}

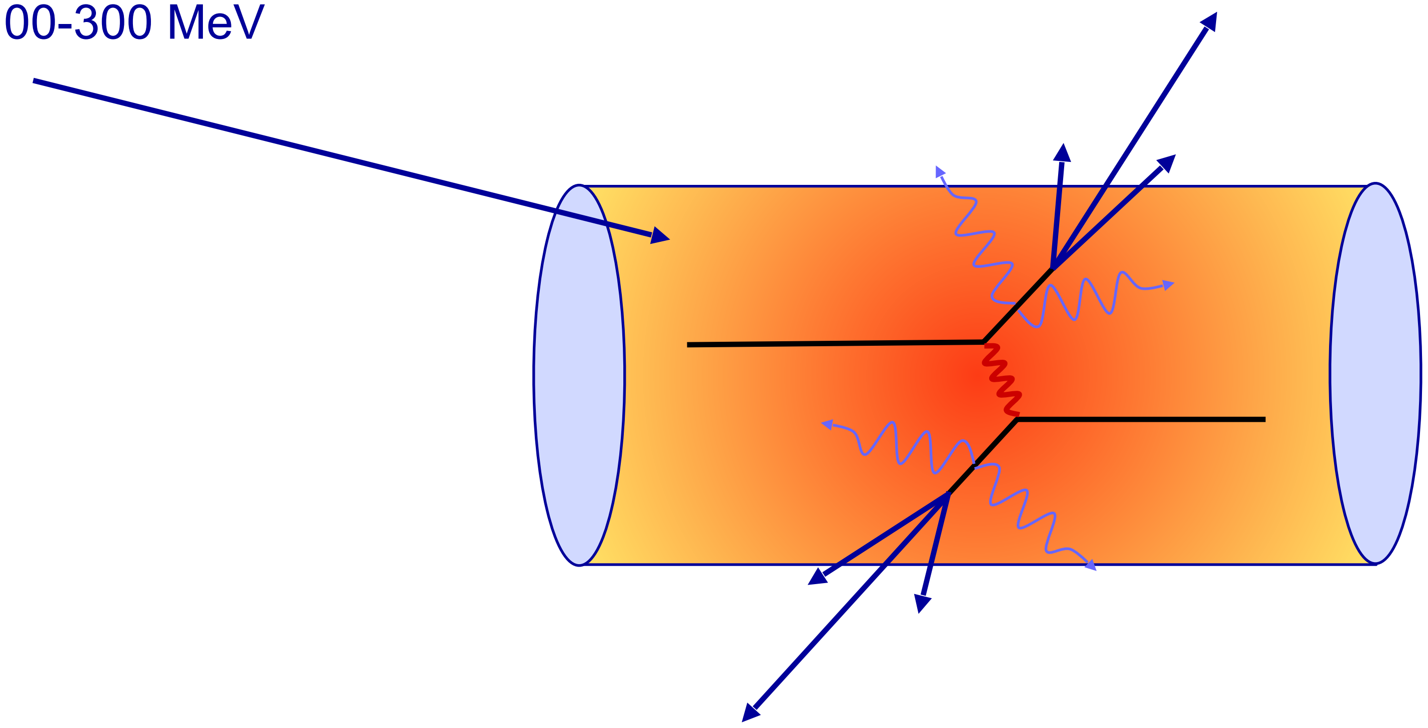
Hadronic scale

S. Bethke, J Phys G 26, R27



Soft QCD matter and hard probes

Heavy-ion collisions produce
QCD matter
Dominated by soft partons
p ~ T ~ 100-300 MeV



Hard-scatterings produce ‘quasi-free’ partons
⇒ Initial-state production known from pQCD
⇒ Probe medium through energy loss

‘Hard Probes’: sensitive to medium density, transport properties

Hard processes in QCD

- Hard process: scale Q >> Λ_{QCD}
- Hard scattering High-p_T parton(photon) Q ~ p_T
- Heavy flavour production m >> Λ_{QCD}

Factorization

Cross section calculation can be split into
- Hard part: perturbative matrix element
- Soft part: parton density (PDF), fragmentation (FF)

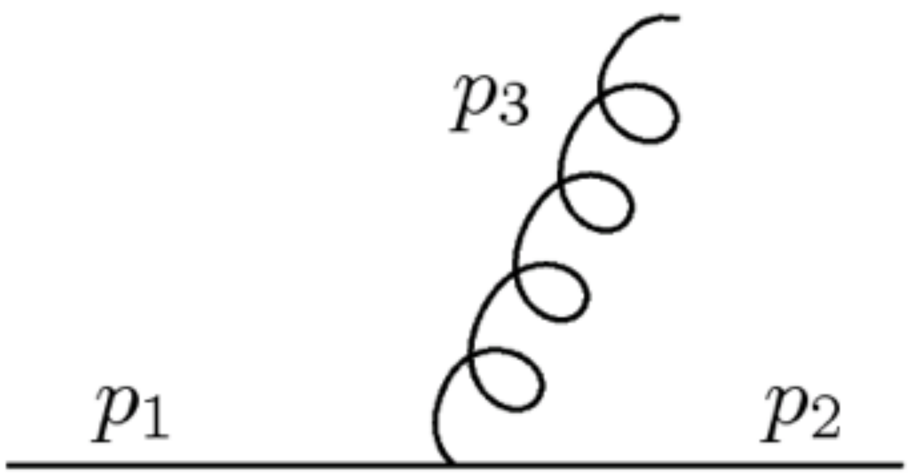
$$\frac{d\sigma_{pp}^{h}}{dy\,d^2p_T} = K \sum_{abcd} \int dx_a dx_b \underbrace{f_a(x_a,Q^2) f_b(x_b,Q^2)}_{\text{parton density}} \underbrace{\frac{d\sigma}{d\hat{t}}(ab \to cd)}_{\text{matrix element}} \underbrace{\frac{D^0_{h/c}}{\pi z_c}}_{\text{FF}}$$

QM interference between hard and soft suppressed (by Q^2/Λ^2 'Higher Twist')

Soft parts, PDF, FF are *universal*: independent of hard process

Singularities in pQCD

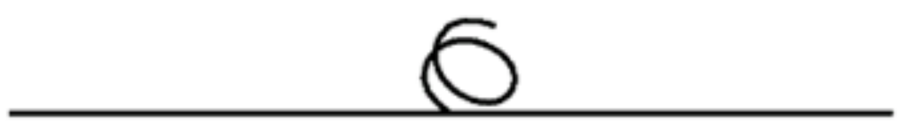
$$\frac{d^2\sigma}{dx_1 dx_2} \propto \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$



$$x_1 = 1 - \frac{2p_2 \cdot p_3}{Q^2}$$

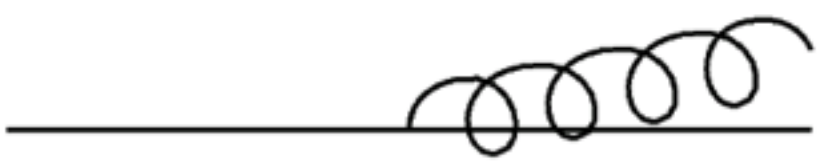
(massless case)

Soft divergence



$p_3 \to 0$

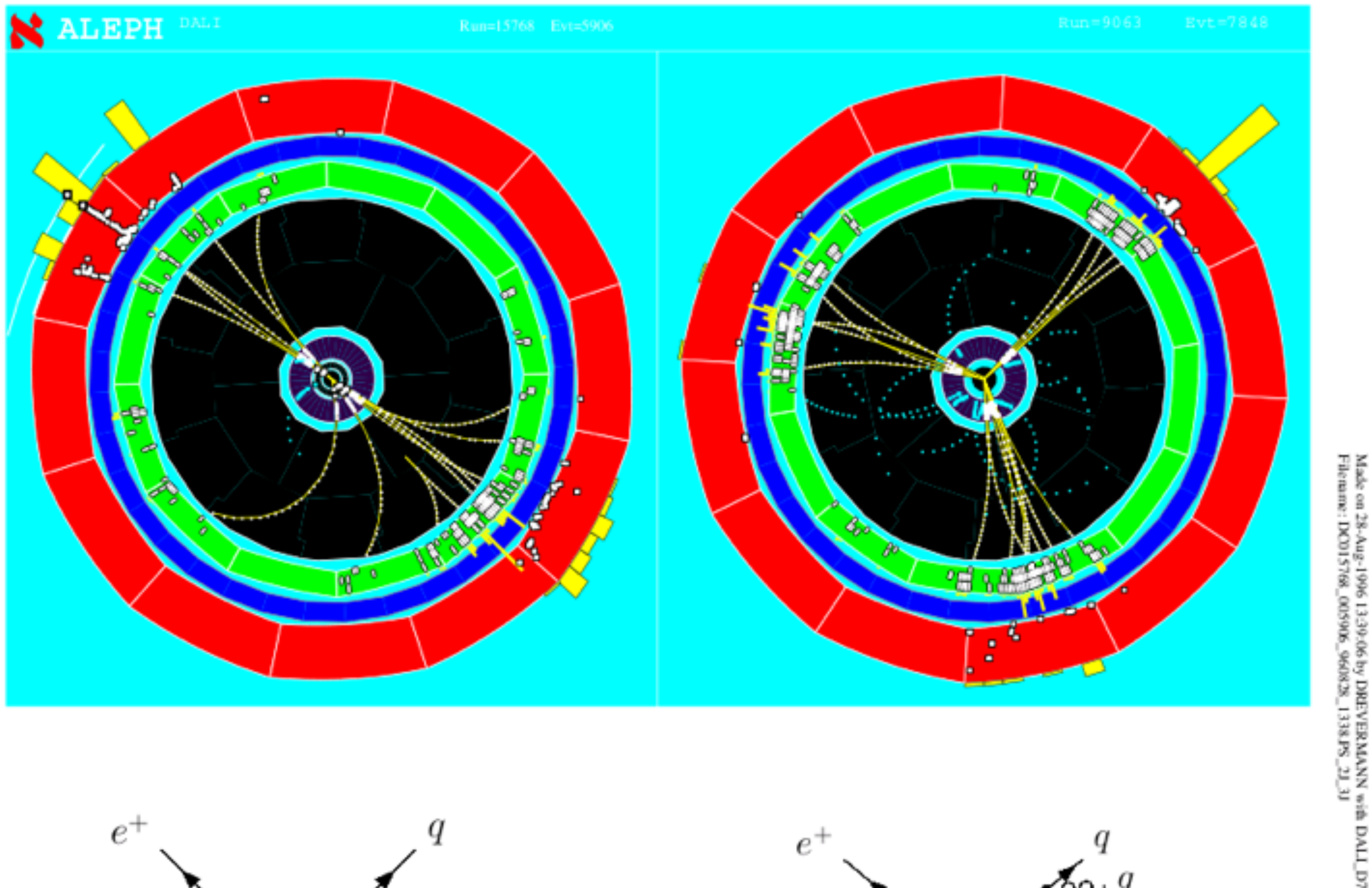
Collinear divergence

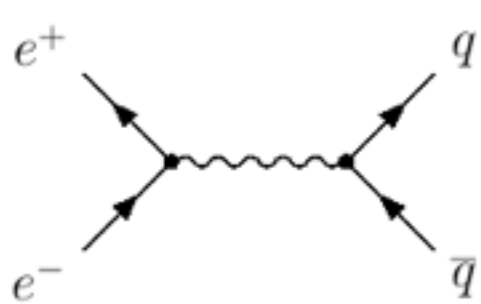


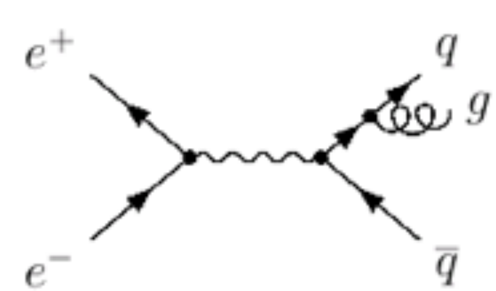
$p_2 \cdot p_3 \to 0$

Closely related to hadronisation effects

Seeing quarks and gluons





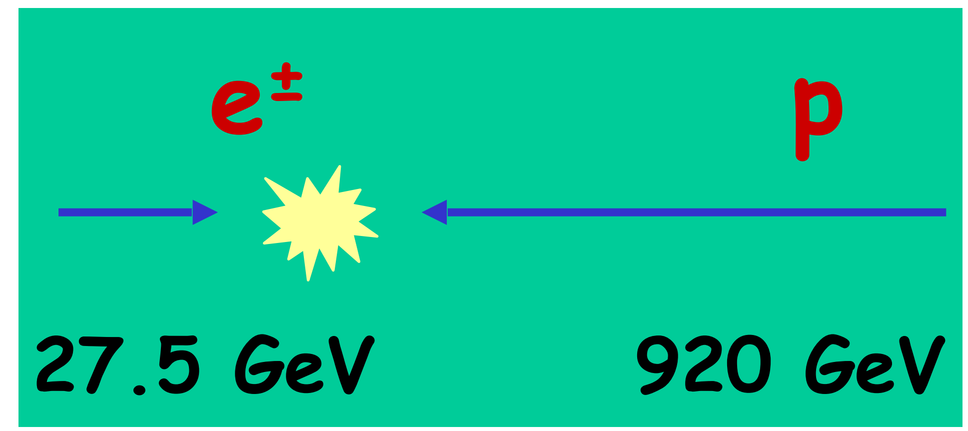


In high-energy collisions, observe traces of quarks, gluons ('jets')

The HERA Collider

The first and only ep collider in the world

Hera at DESY near Hamburg



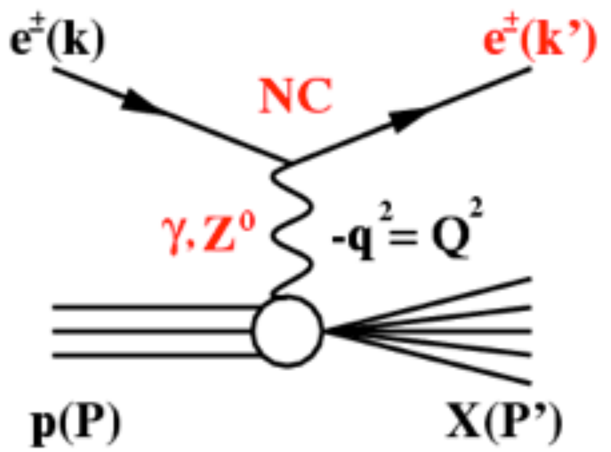
$\sqrt{s}$ = 318 GeV

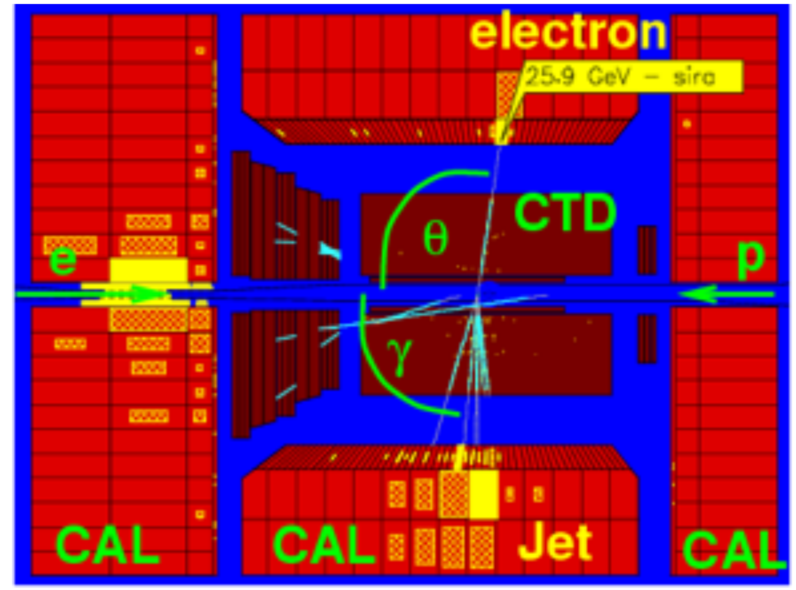
Equivalent to fixed target experiment with 50 TeV $e^{\pm}$

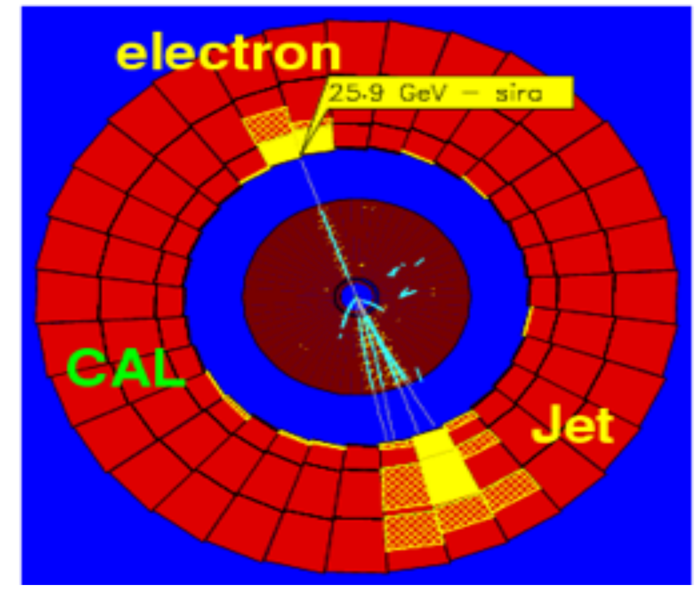
Example DIS events

NC: $e^{\pm} + p \to e^{\pm} + X,$ CC: $e^{\pm} + p \to \bar{\nu}_e(\nu_e) + X$

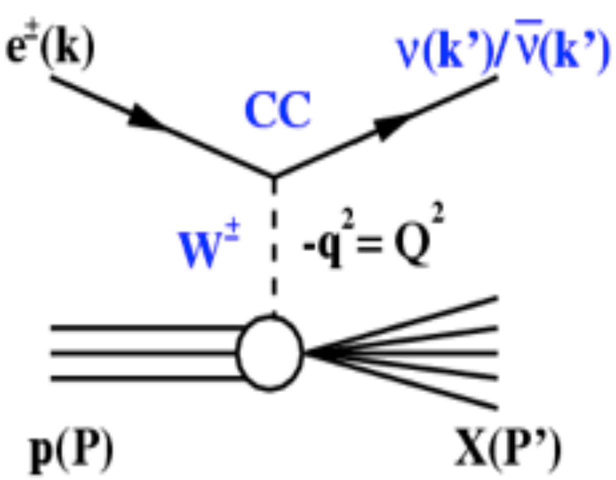
NC:

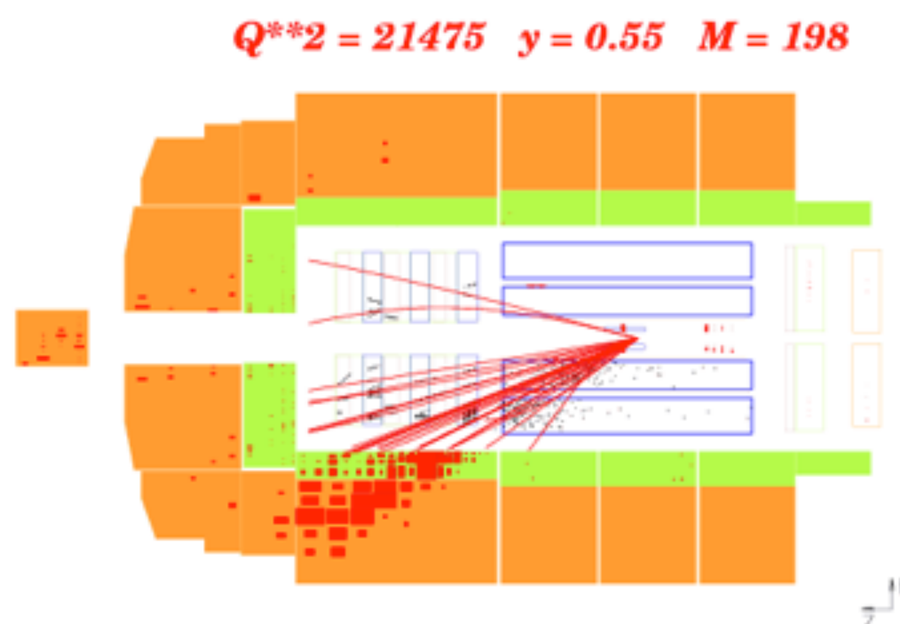


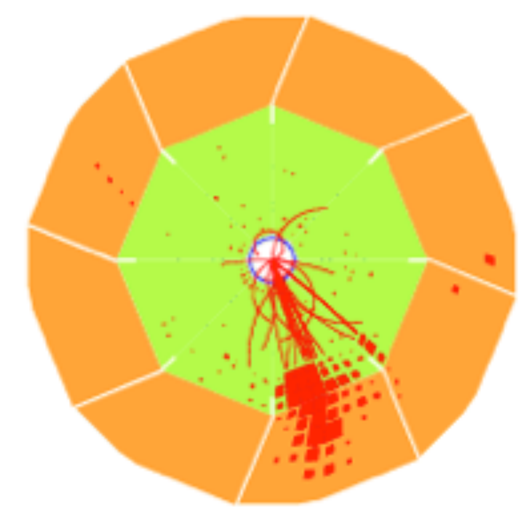




CC:

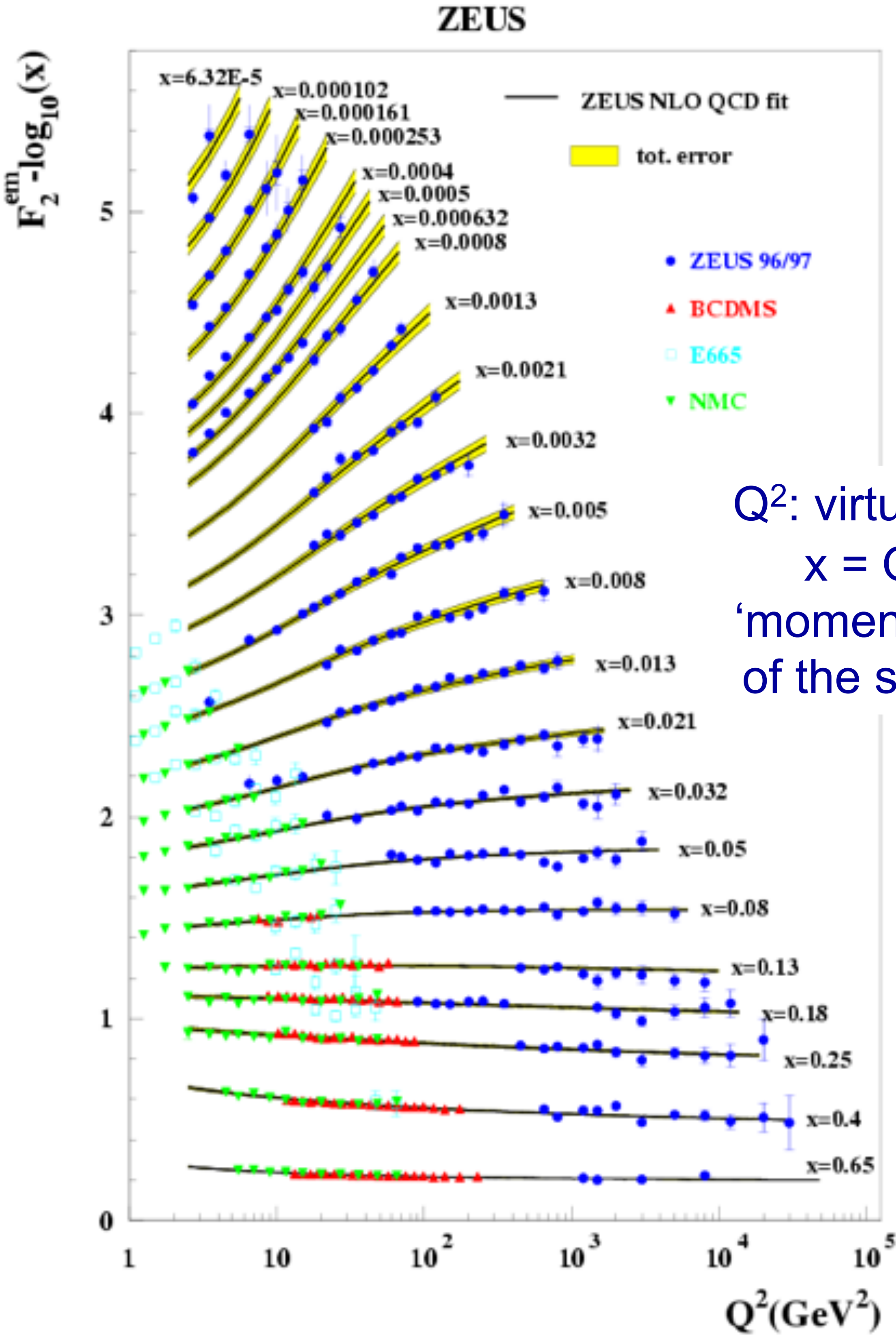






DIS: Measured electron/jet momentum fixes kinematics: x, Q^2

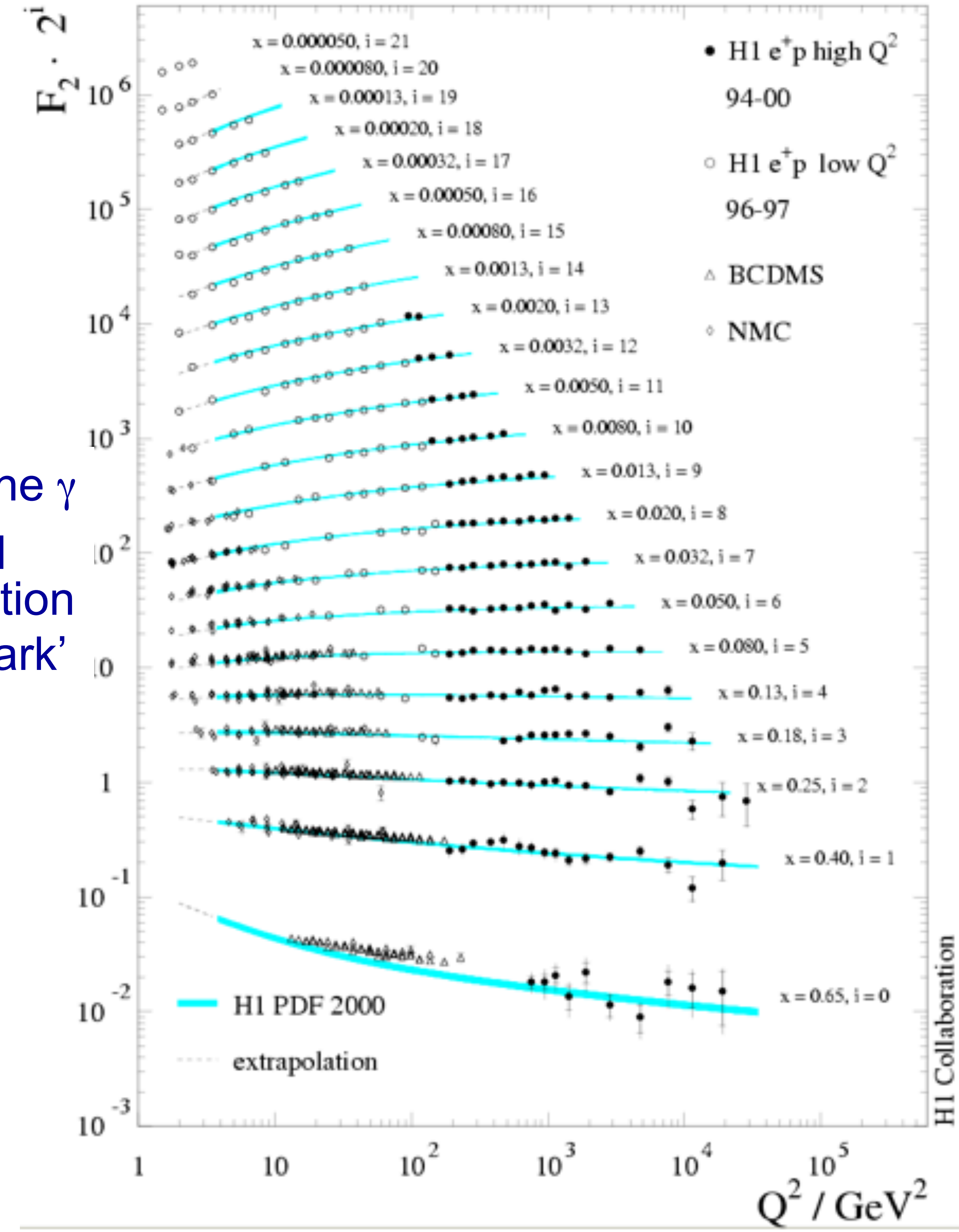
Proton structure F_2



Q^2: virtuality of the γ

$x = Q^2 / 2\,p\,q$

'momentum fraction of the struck quark'



F_2: essentially a cross section/scattering probability

Factorisation in DIS

the physical structure fct. is independent of μ_f
(this will lead to the concept of renormalization group eqs.)

both, pdf's and the short-dist. coefficient depend on μ_f
(choice of μ_f: shifting terms between long- and short-distance parts)

$$F_2(x,Q^2) = x \sum_{a=q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi} f_a(\xi,\mu_f^2) \left[\delta(1-\frac{x}{\xi}) + \frac{\alpha_s(\mu_r)}{2\pi}\left[P_{qq}\left(\frac{x}{\xi}\right)\ln\frac{Q^2}{\mu_f^2} + (C_2^q - z_{qq})\left(\frac{x}{\xi}\right)\right]\right]$$

yet another scale: μ_r
due to the renormalization
of ultraviolet divergencies

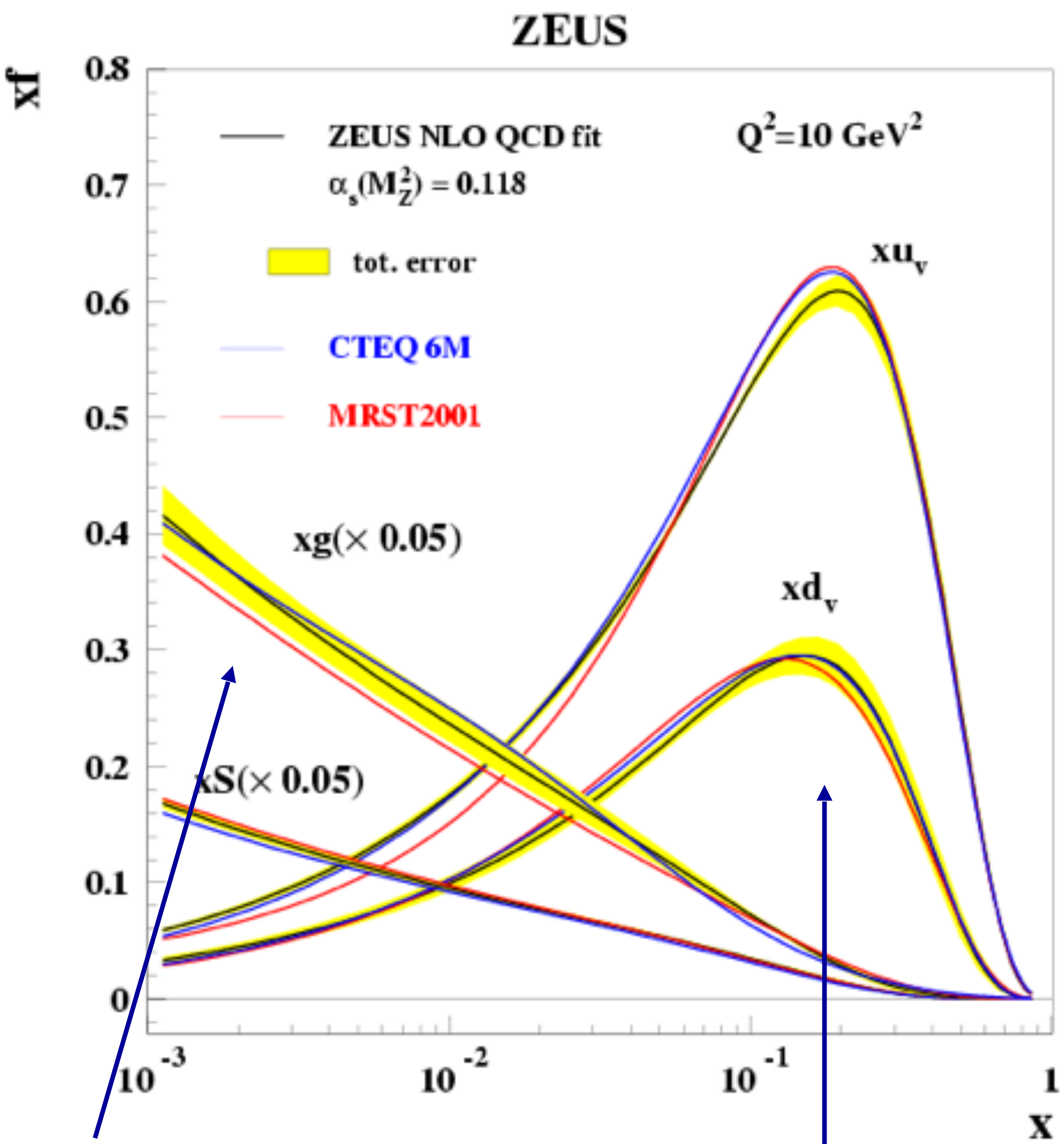
short-distance "Wilson coefficient"

choice of the factorization scheme

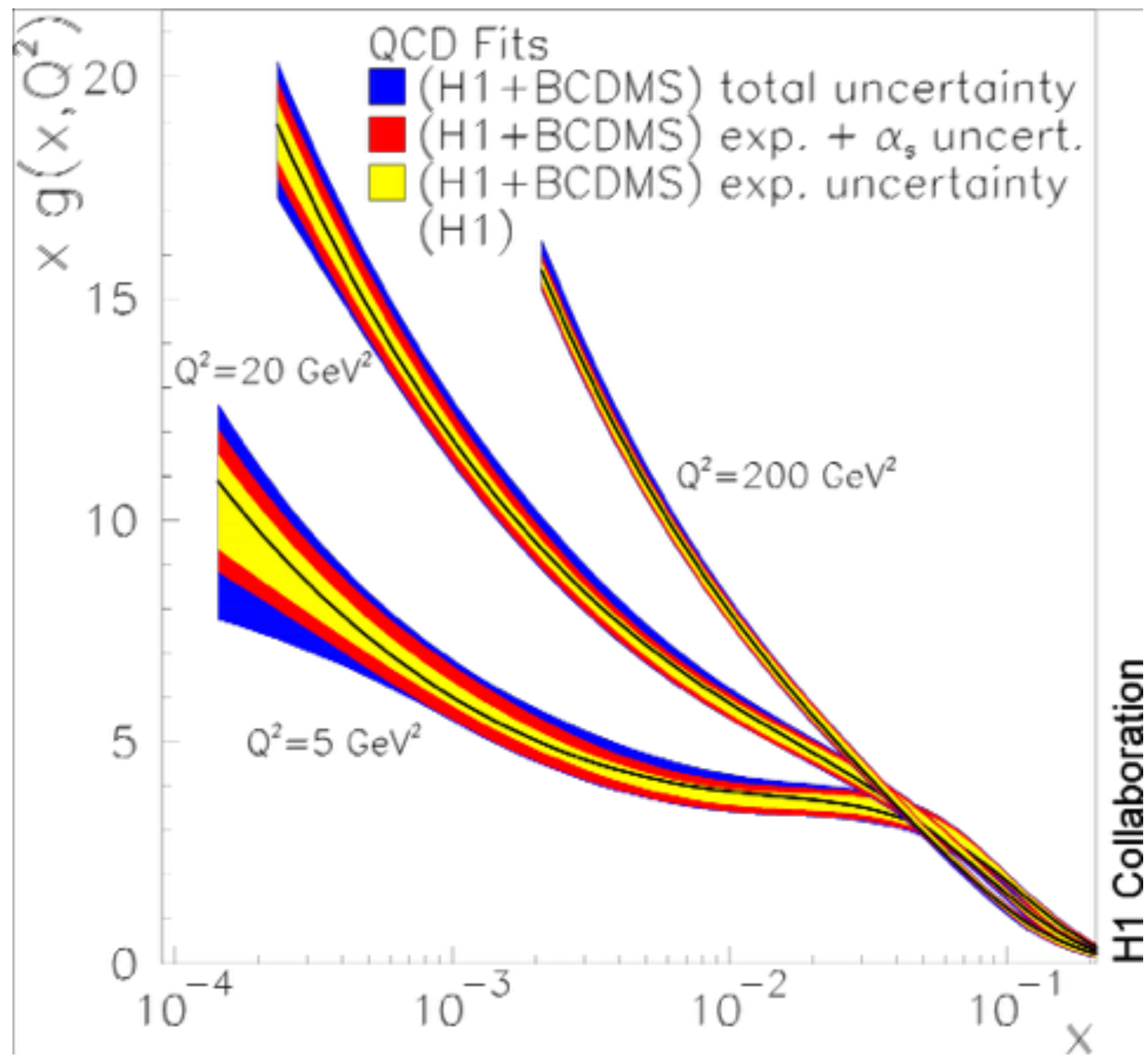
Integral over x is DGLAP evolution with splitting kernel P_{qq}

Parton density distribution

Low Q^2: valence structure



Q^2 evolution (gluons)

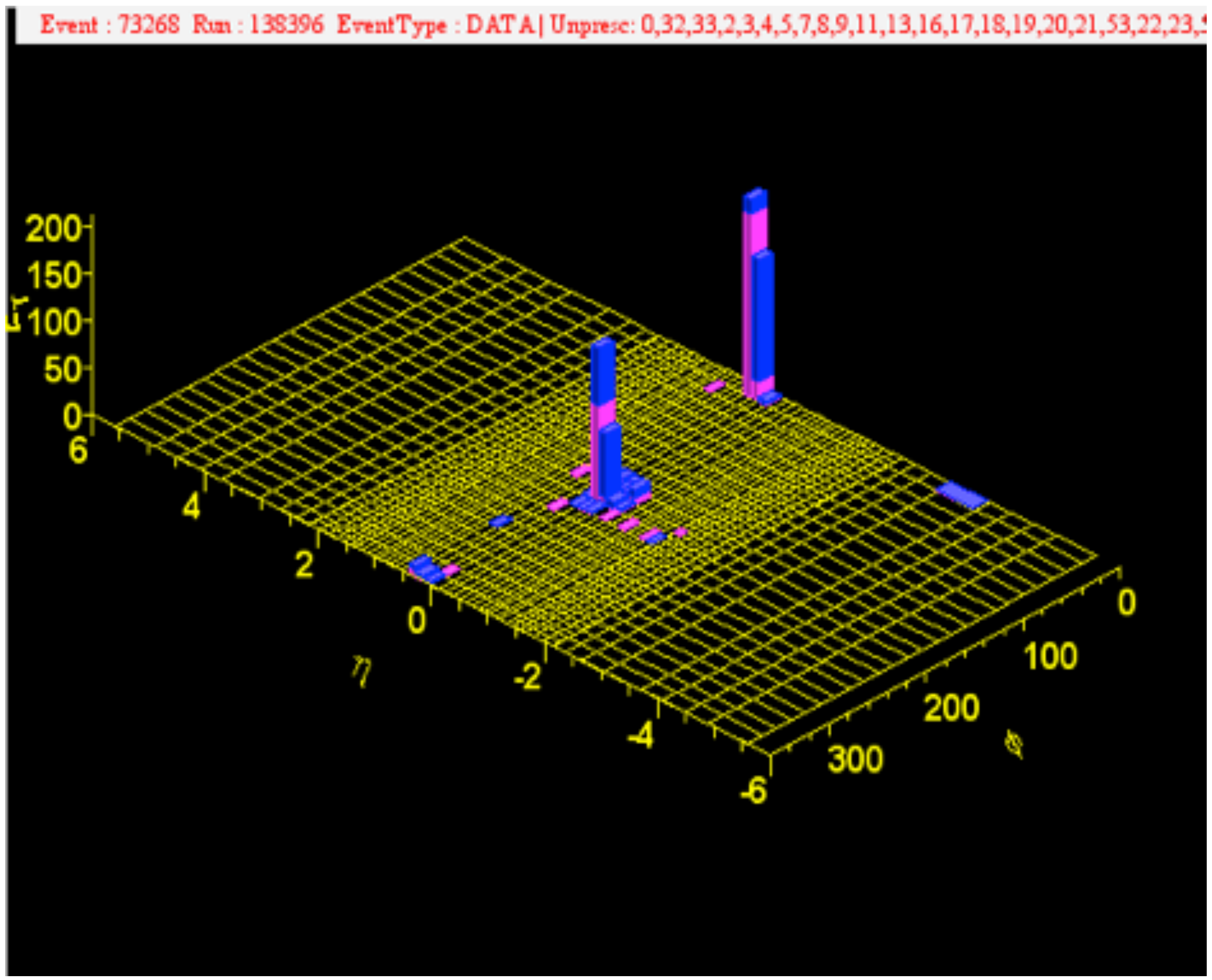


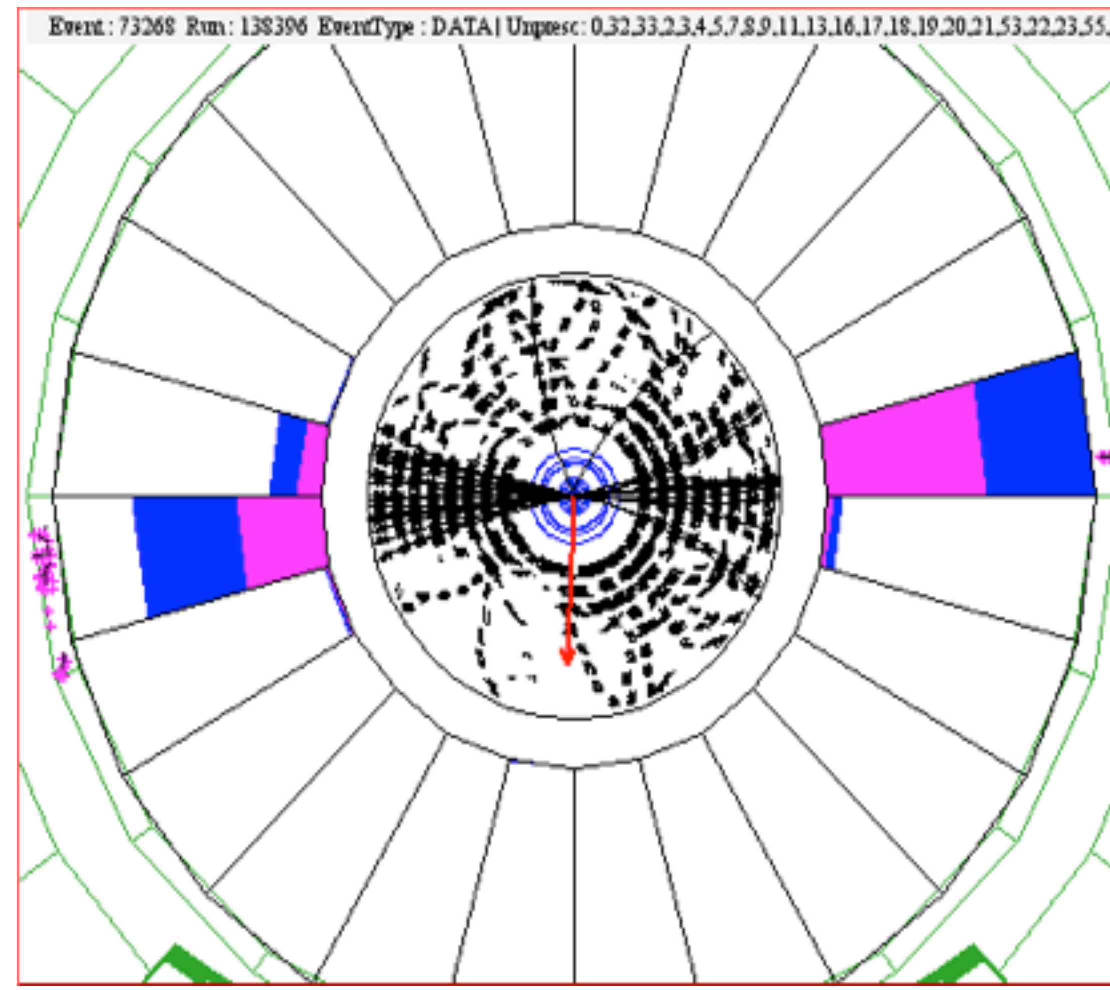
Soft gluons

Valence quarks (p = uud)
x ~ 1/3

Gluon content of proton rises quickly with Q^2

$p+\bar{p} \rightarrow$ dijet at Tevatron

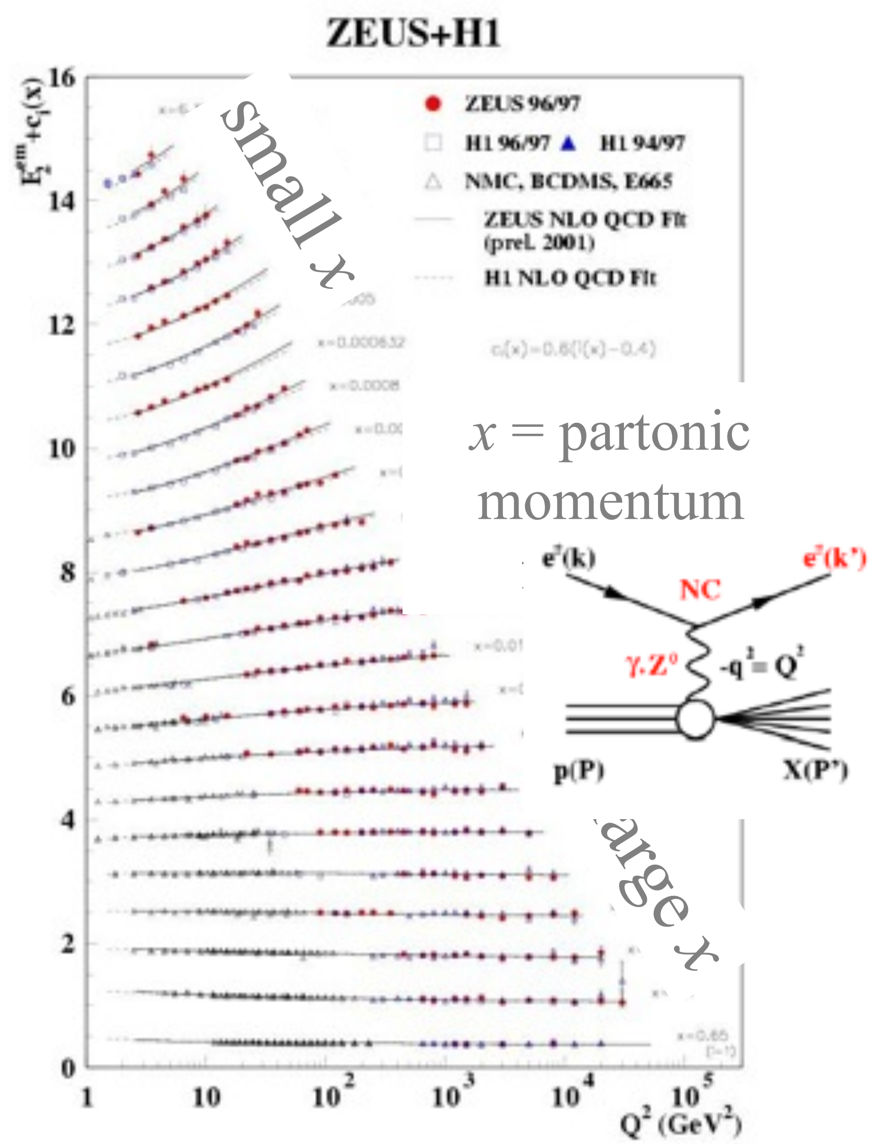




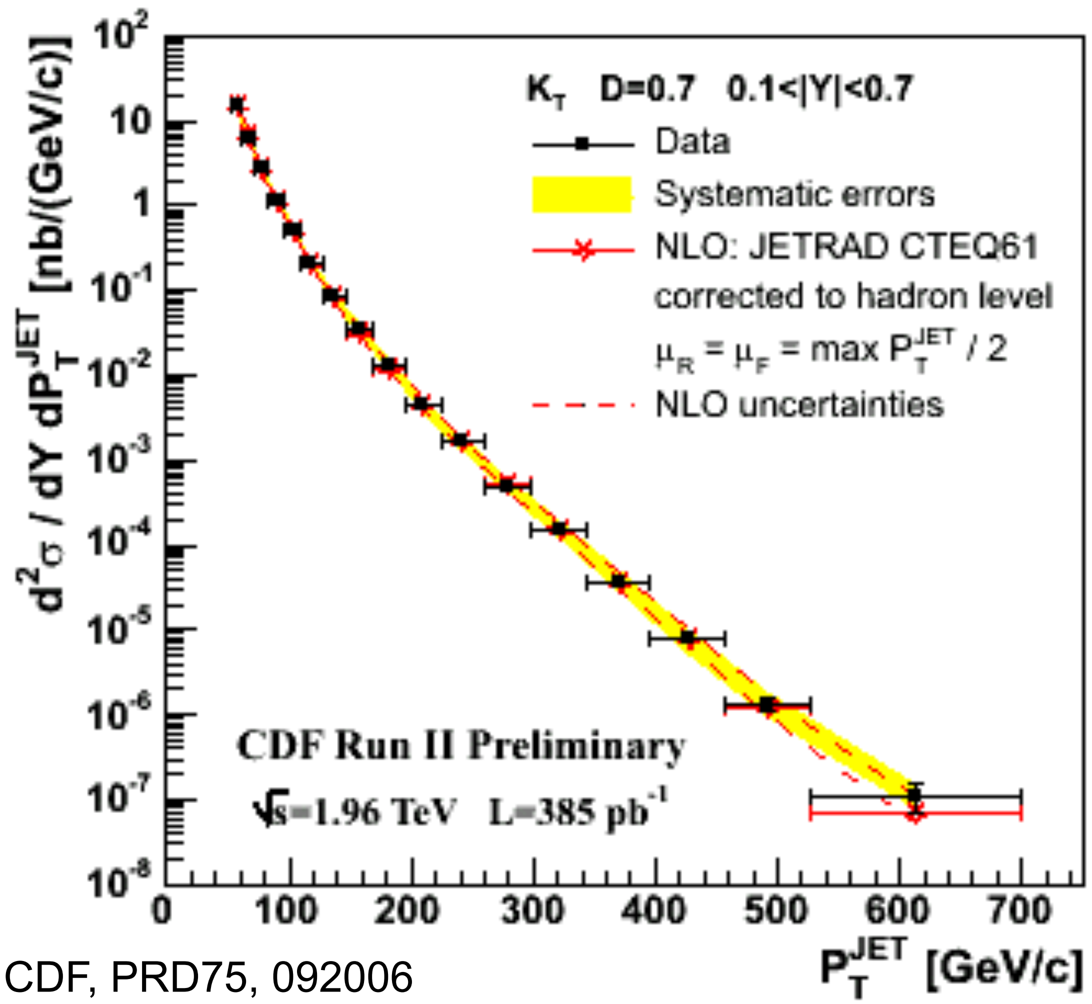
Tevatron: $p + \bar{p}$ at $\sqrt{s}$ = 1.9 TeV

Jets produced with several 100 GeV

Testing QCD at high energy

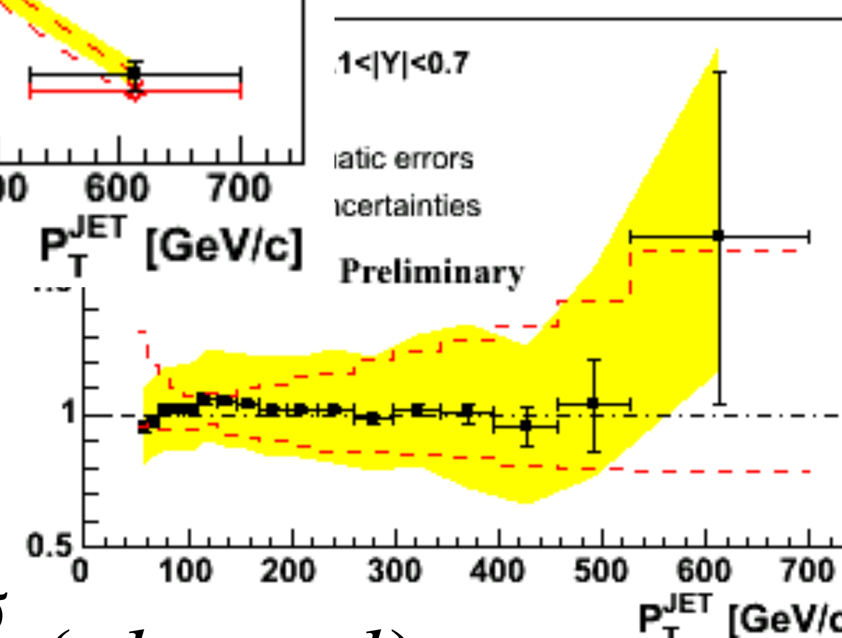


DIS to measure PDFs



CDF, PRD75, 092006

Dominant ‘theory’ uncertainty: PDFs



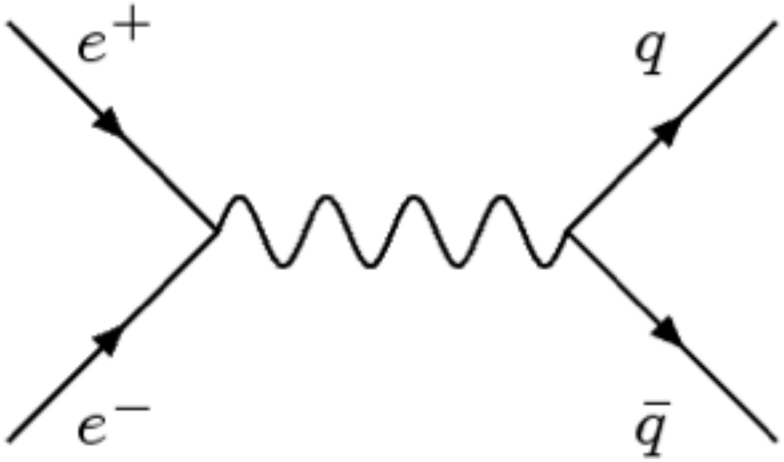
$$\frac{d\sigma_{pp}^{h}}{dy\,d^2p_T} = K\sum_{abcd}\int dx_a dx_b \underbrace{f_a(x_a,Q^2)f_b(x_b,Q^2)}_{\text{parton density}} \underbrace{\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)}_{\text{matrix element}}$$

Theory matches data over many orders of magnitude

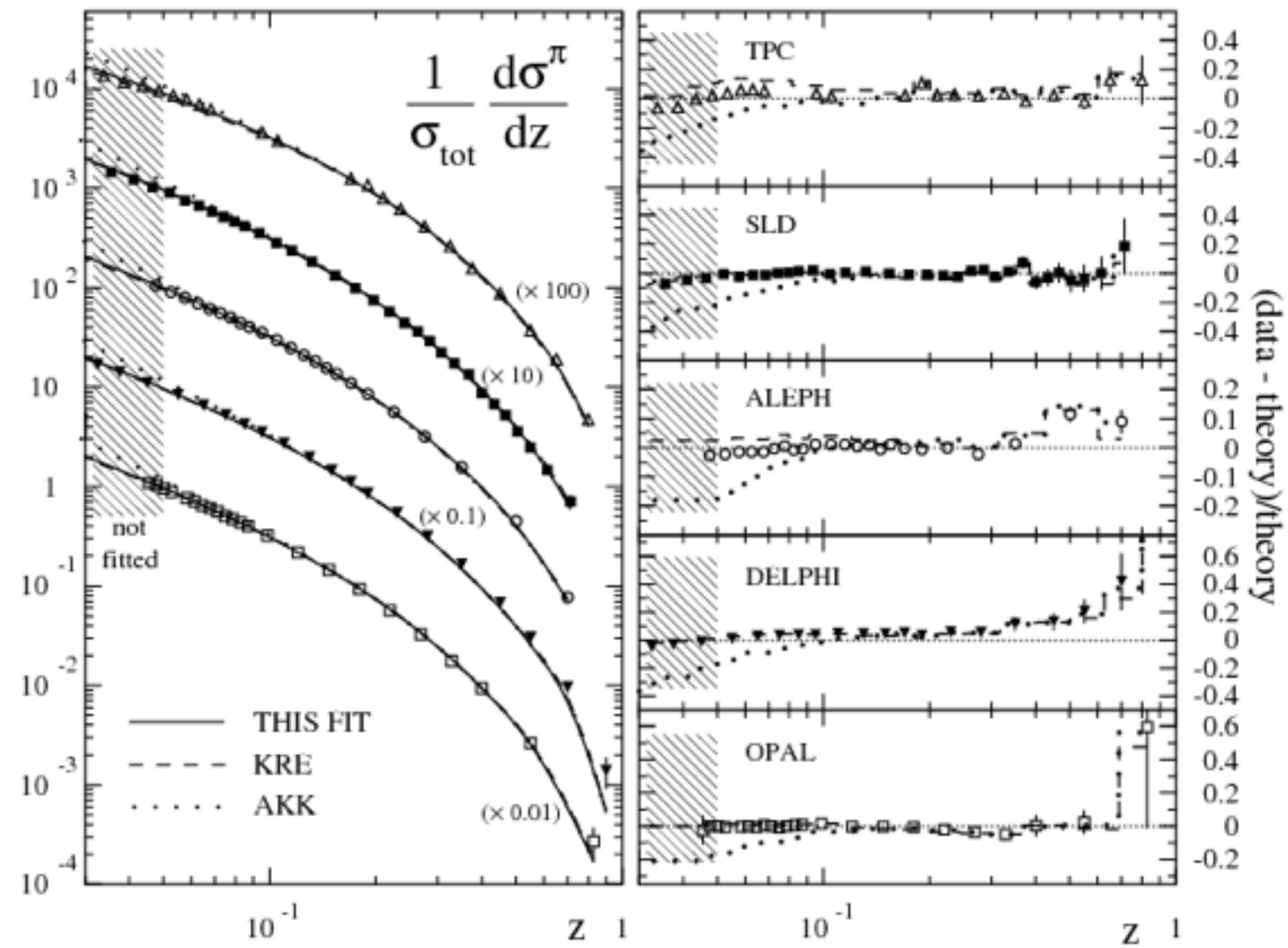
Universality: PDFs from DIS used to calculate jet-production in pp

Towards hadron production: Fragmentation Functions

$e^+e^- \rightarrow qq \rightarrow$ jets

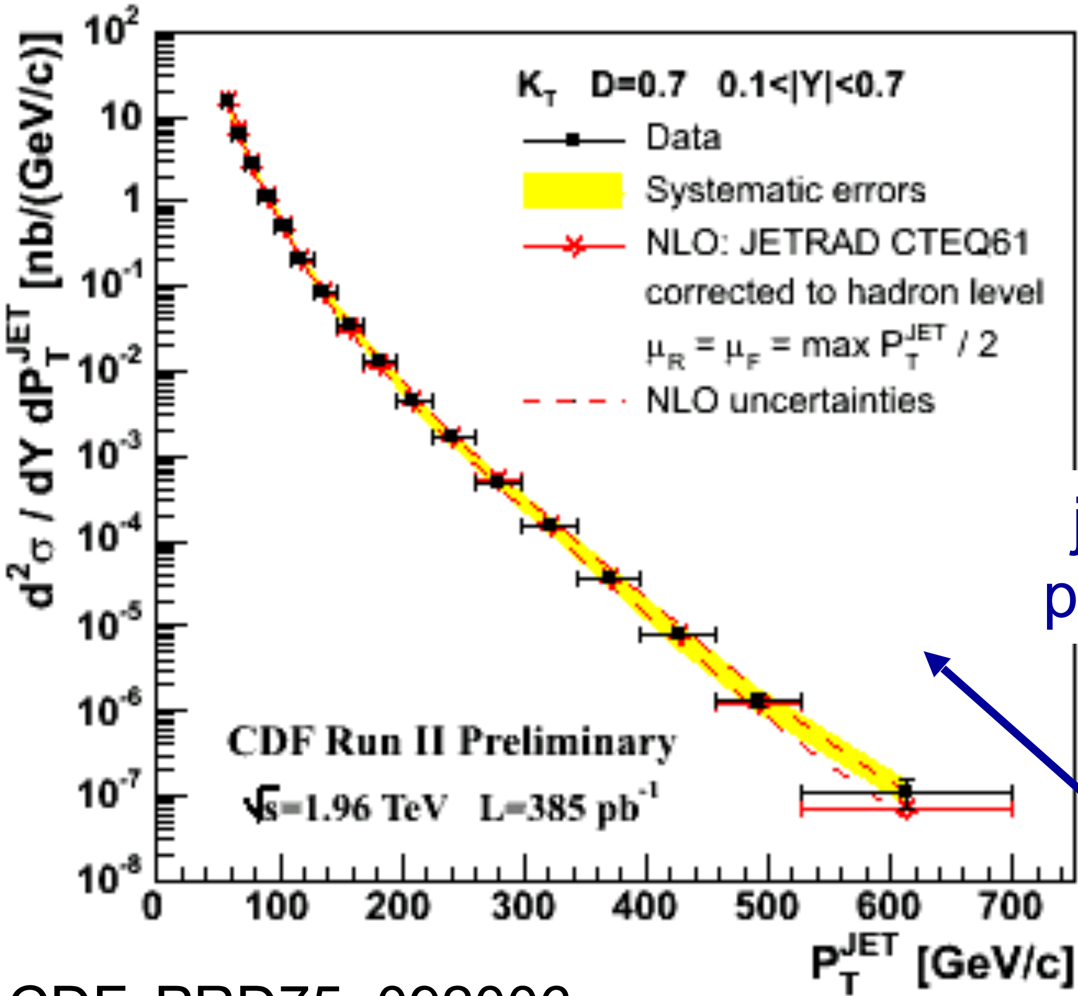


$$
\begin{aligned}
\vec{p}_{e^+} &= -\vec{p}_{e^-} \\
\vec{p}_q &= -\vec{p}_{\bar{q}} \\
p_q &= p_e
\end{aligned}
$$



Direct measurement of fragmentation functions

pQCD illustrated

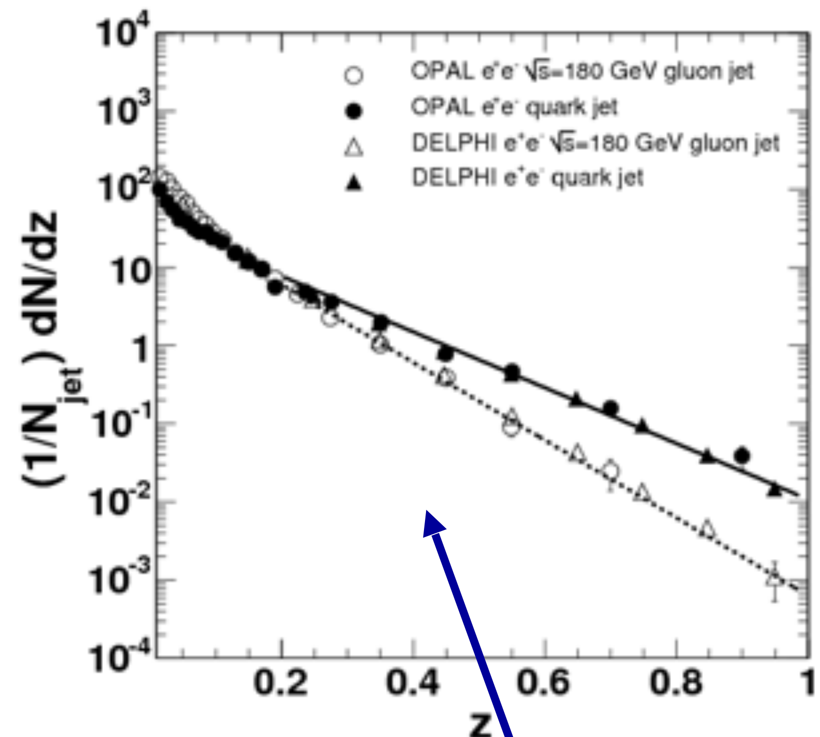


CDF, PRD75, 092006

jet spectrum ~ parton spectrum

$$\frac{dN}{\hat{p}_T d\hat{p}_T} \propto \frac{1}{\hat{p}_T^n}$$

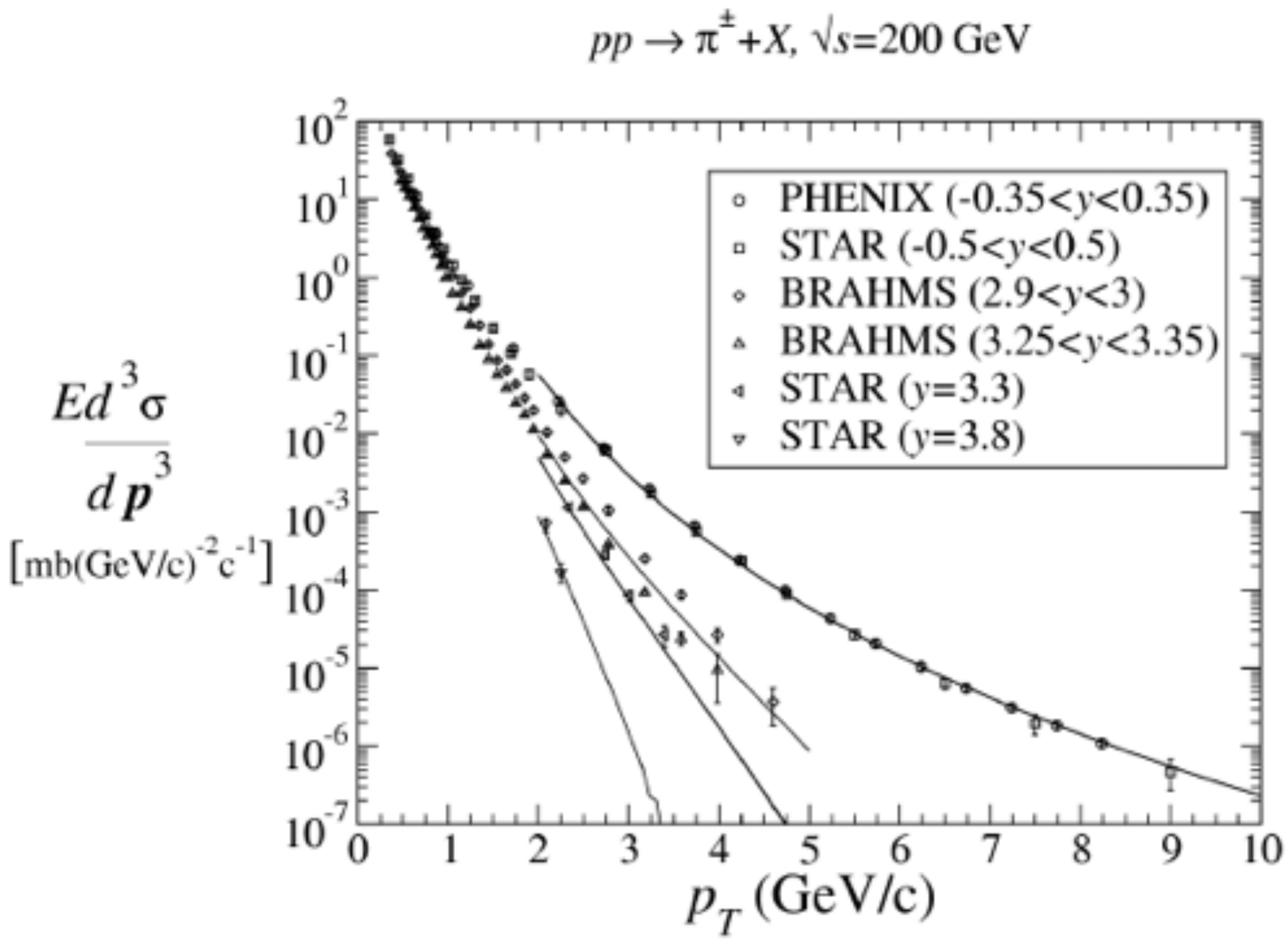
fragmentation

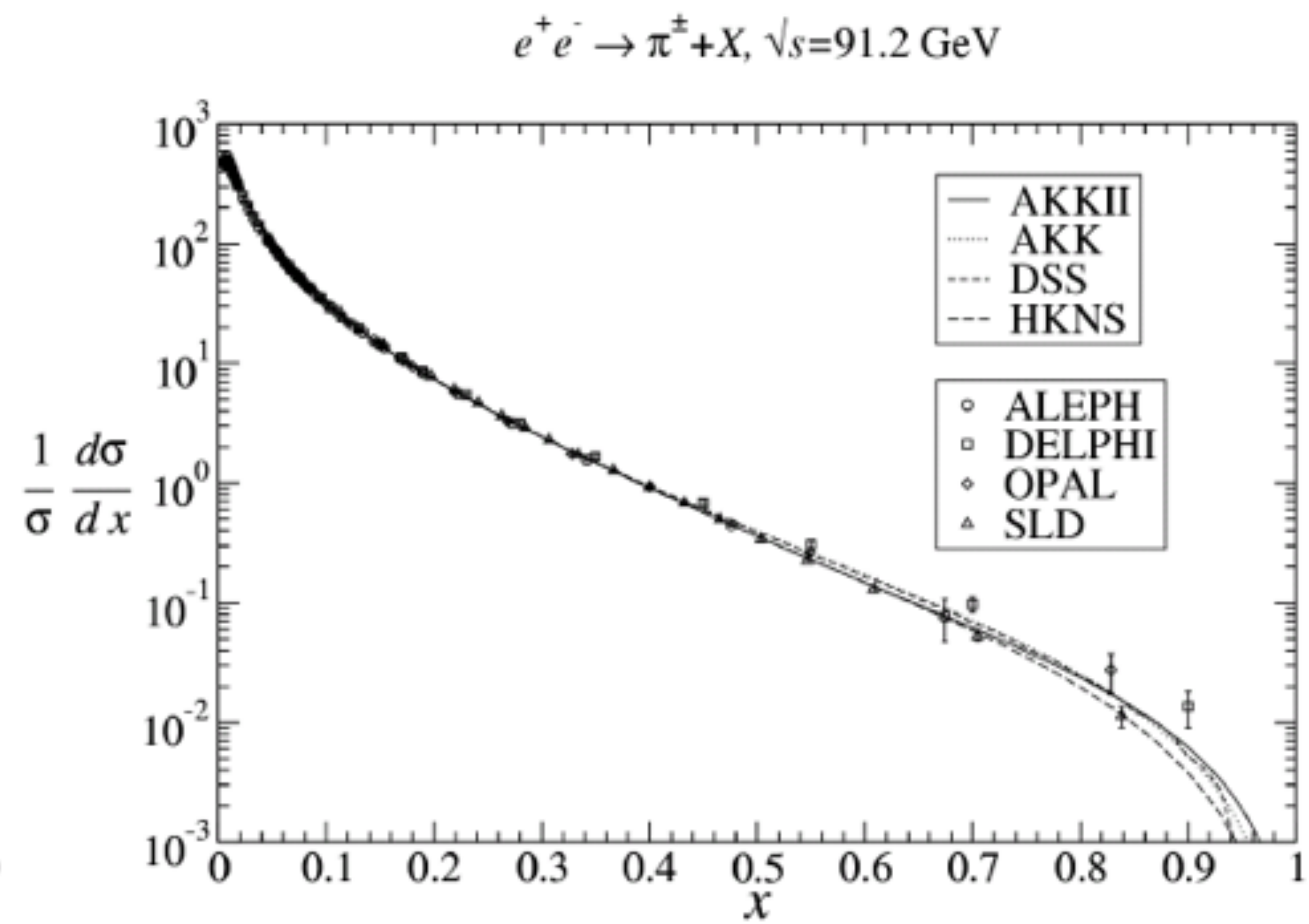


$$z = \frac{p_{T,hadron}}{P_{jet}}$$

$$\frac{d\sigma_{pp}^{h}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2)\frac{d\sigma}{d\hat{t}}(ab \to cd)\frac{D_{h/c}^0}{\pi z_c}$$

Note: difference p+p, $e^+ + e^-$

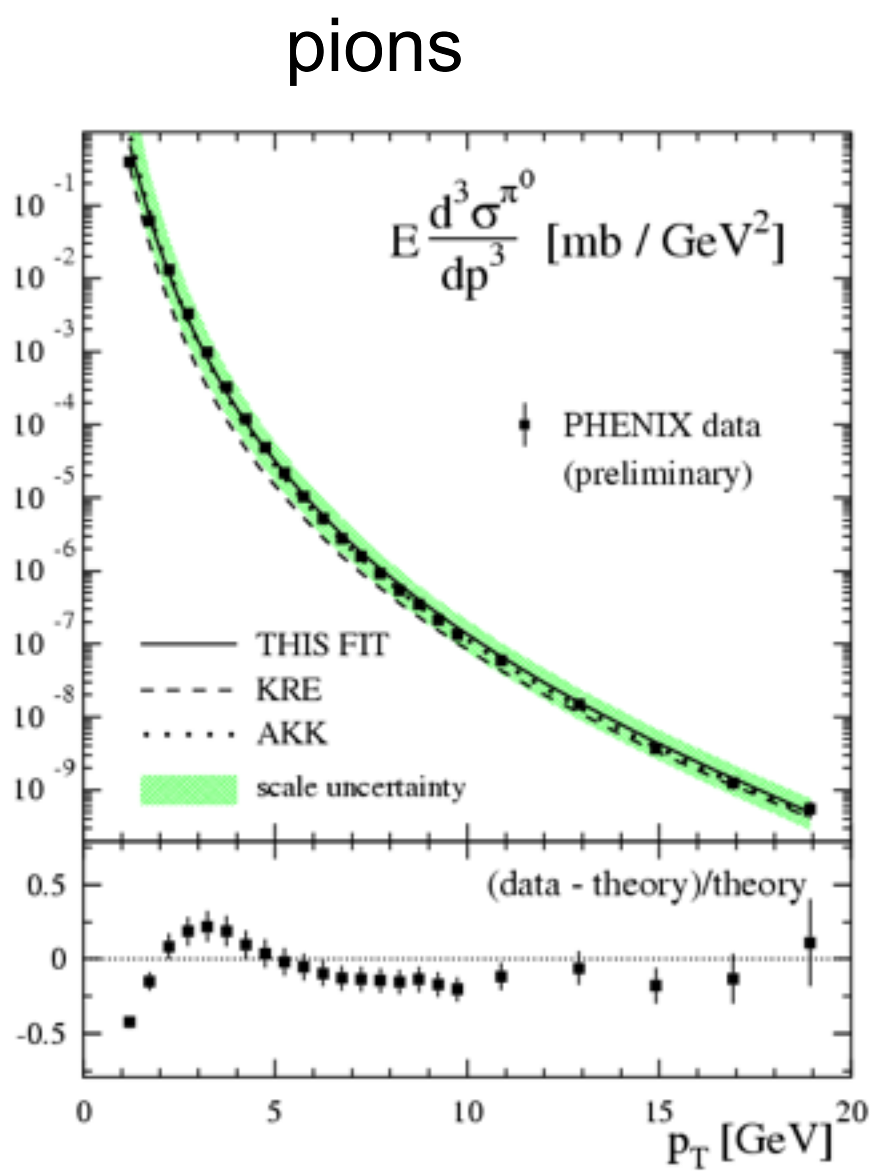


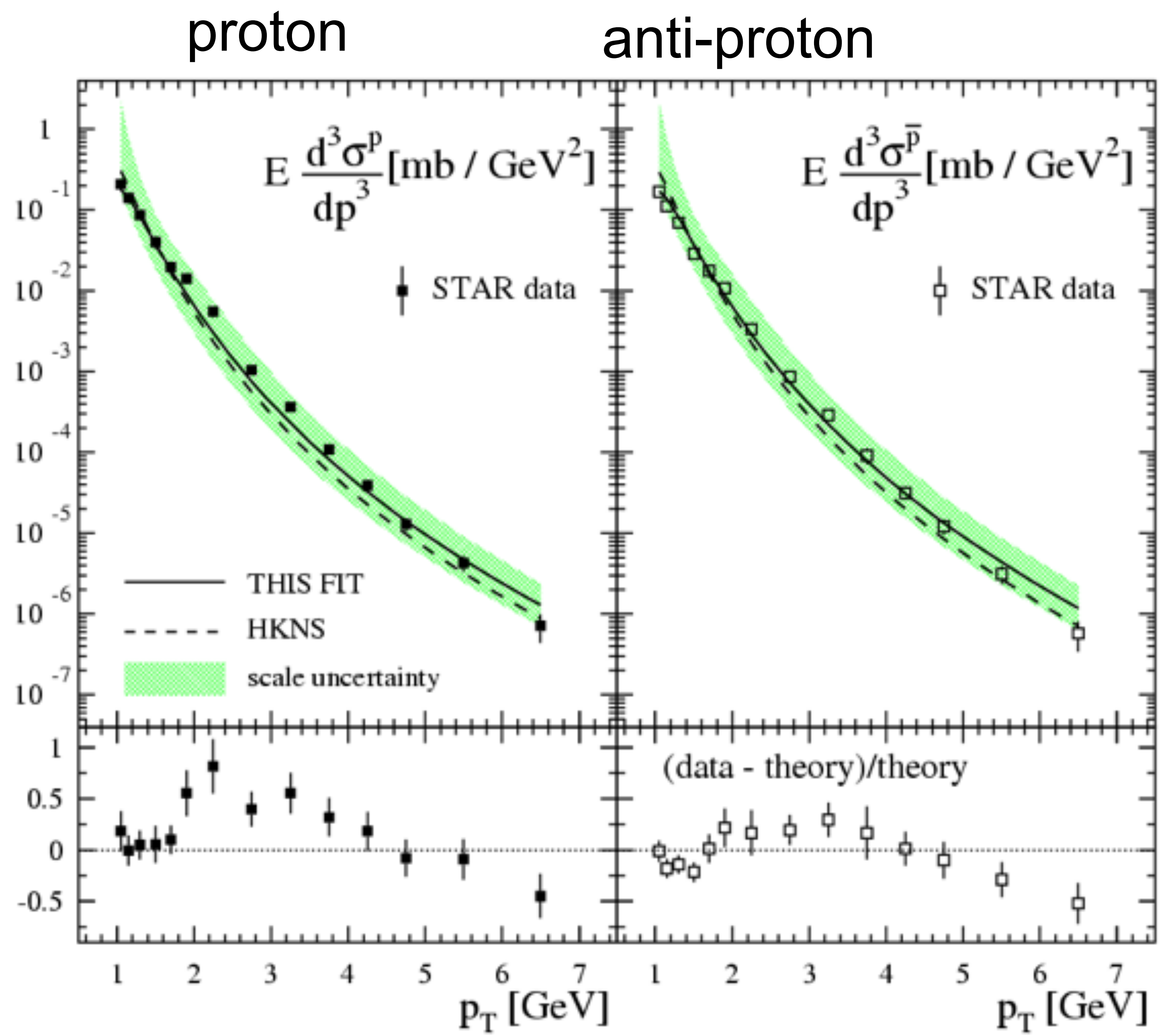


p+p: steeply falling jet spectrum
Hadron spectrum convolution
of jet spectrum with fragmentation

$e^+ + e^-$ QCD events: jets
have p=1/2 √s
Directly measure frag function

Global analysis of FF





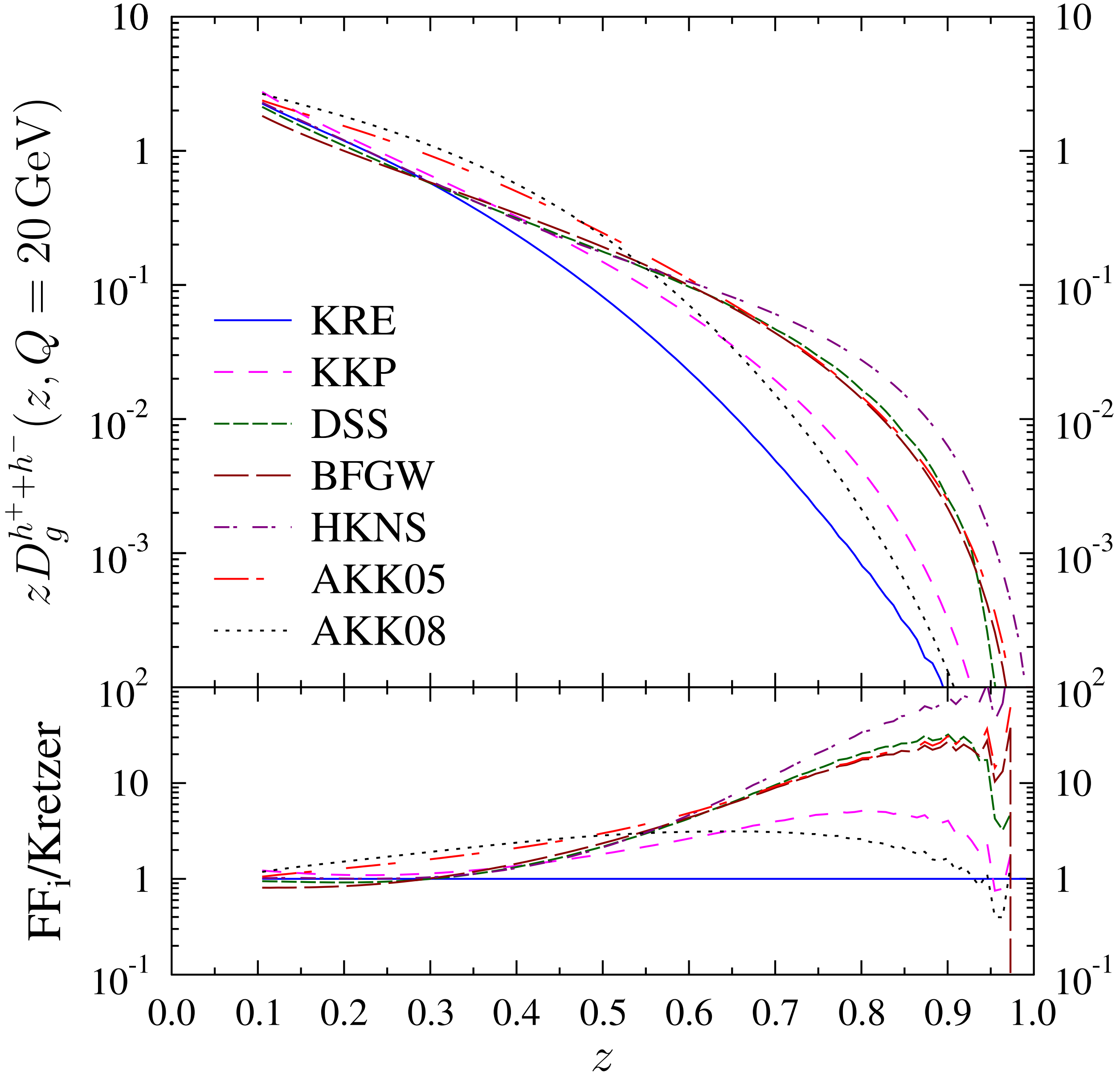
De Florian, Sassot, Stratmann, PRD 76:074033, PRD75:114010

Global analysis: use measurements, mostly e^+e^- at different $\sqrt{s}$;
fit with initial distribution + DGLAP evolution

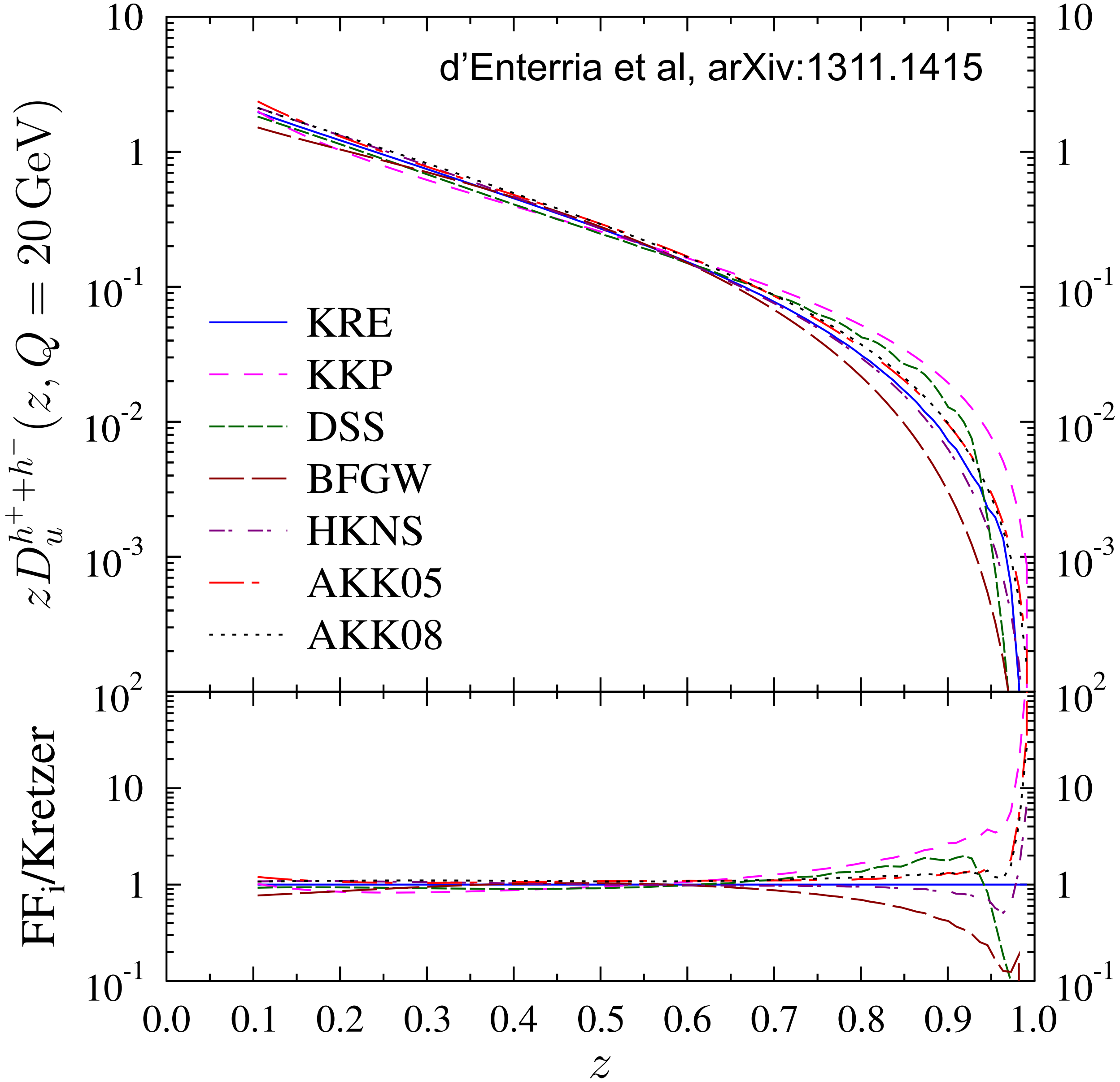
Some FF fits include RHIC data to constrain gluon fragmentation

Fragmentation function fits

Gluon fragmentation



quark (u) fragmentation



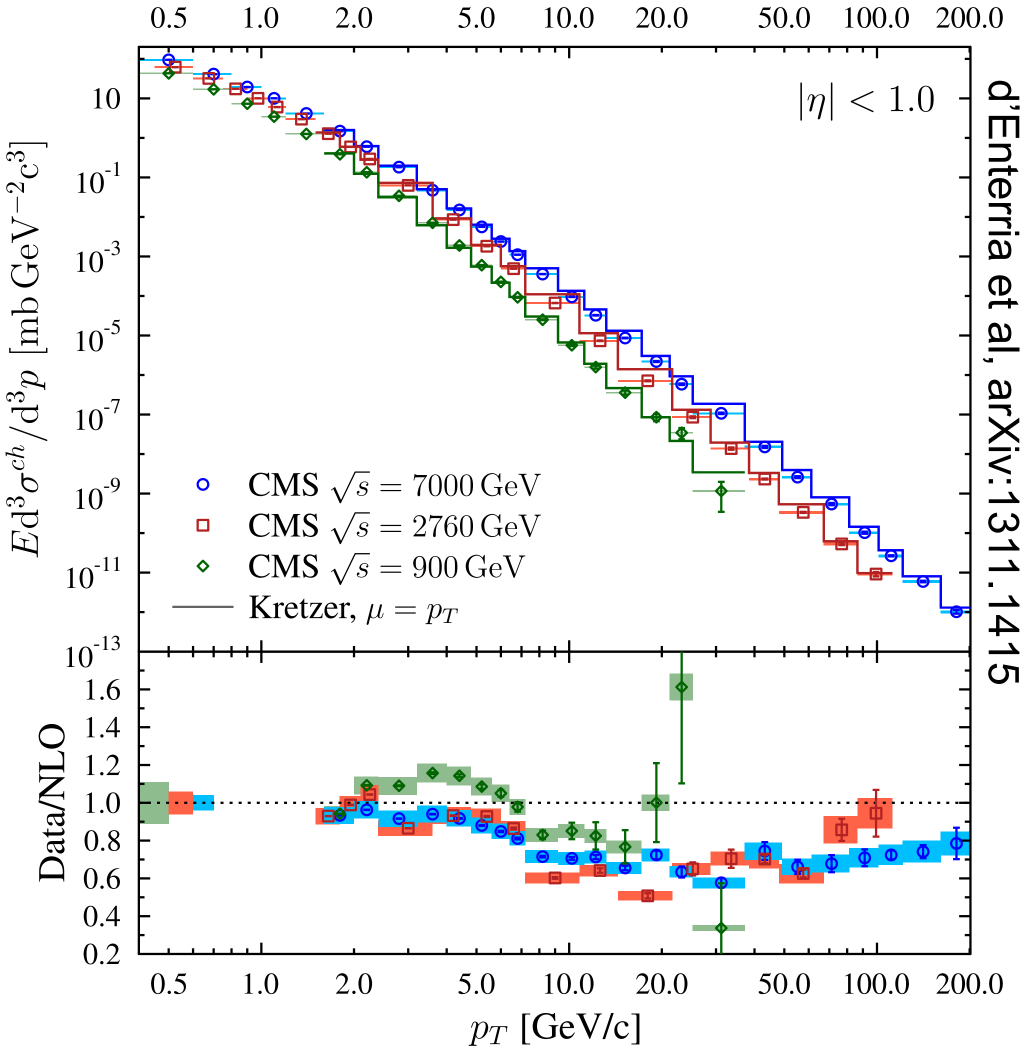
Fragmentation function fits based on e^+e^-:

large uncertainty in gluon fragmentation

Some groups use hadron production to further constrain FFs

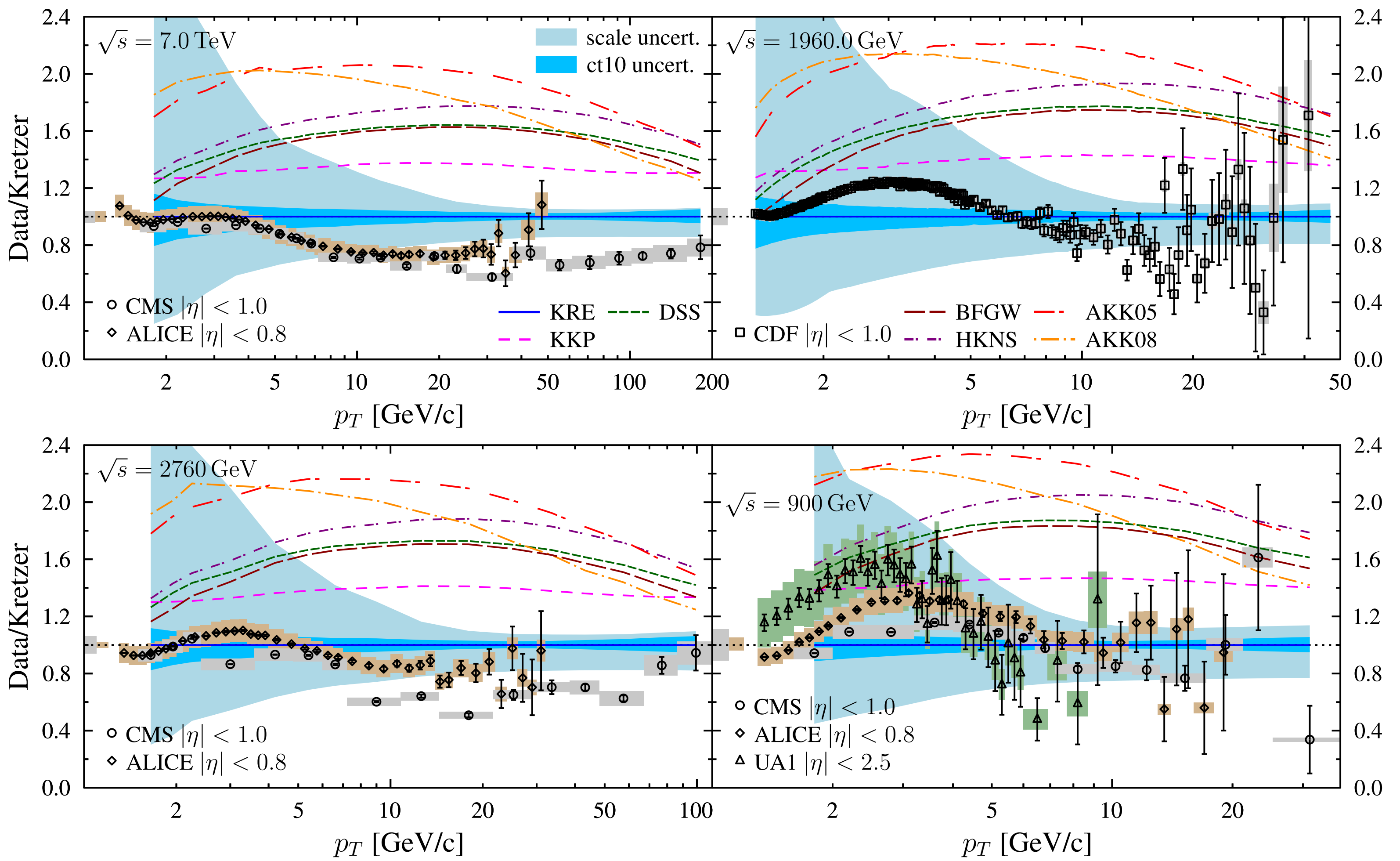
Adding the LHC data in the game

Kretzer fragmentation



d'Enterria et al, arXiv:1311.1415

Ratios data/theory with uncertainties



Factor ~2 spread of results due to FF parameterisations

Mostly due to uncertainty in gluons: next step: use data to constrain gluon FF

Also note: large scale uncertainties at $p_T < 5$ GeV

RHIC and LHC

RHIC, Brookhaven

Au+Au $\sqrt{s_{NN}}$= 200 GeV

First run: 2000

STAR, PHENIX,
PHOBOS, BRAHMS

LHC, Geneva

Pb+Pb $\sqrt{s_{NN}}$= 2760 GeV

First run: 2009/2010

Currently under maintenance
Restart 2015 with higher energy:
pp $\sqrt{s}$ = 13 TeV, PbPb $\sqrt{s_{NN}}$ = 5.12 TeV

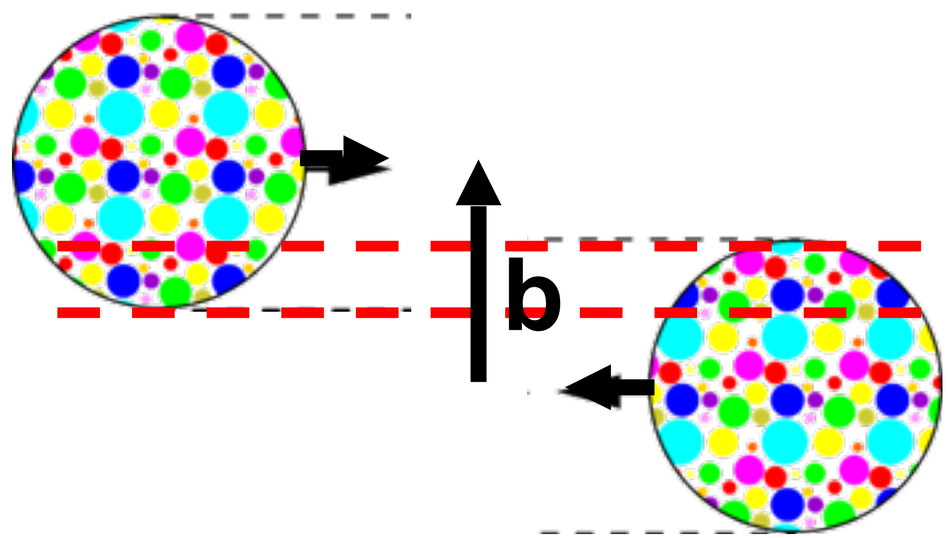
ALICE, ATLAS,
CMS, (LHCb)

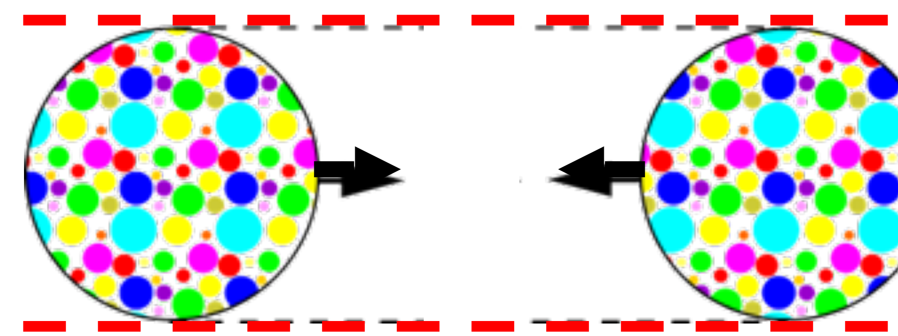
Intermezzo: Centrality

Nuclei are large compared to the range of strong force

Peripheral collision | Central collision

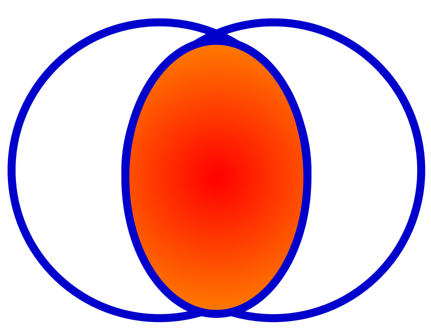
top/side view:

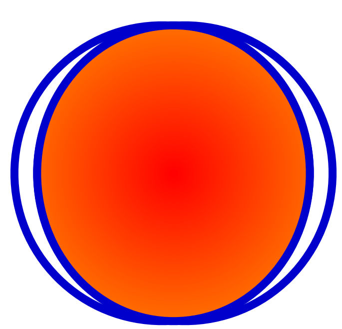




b finite | b~0 fm

front view:

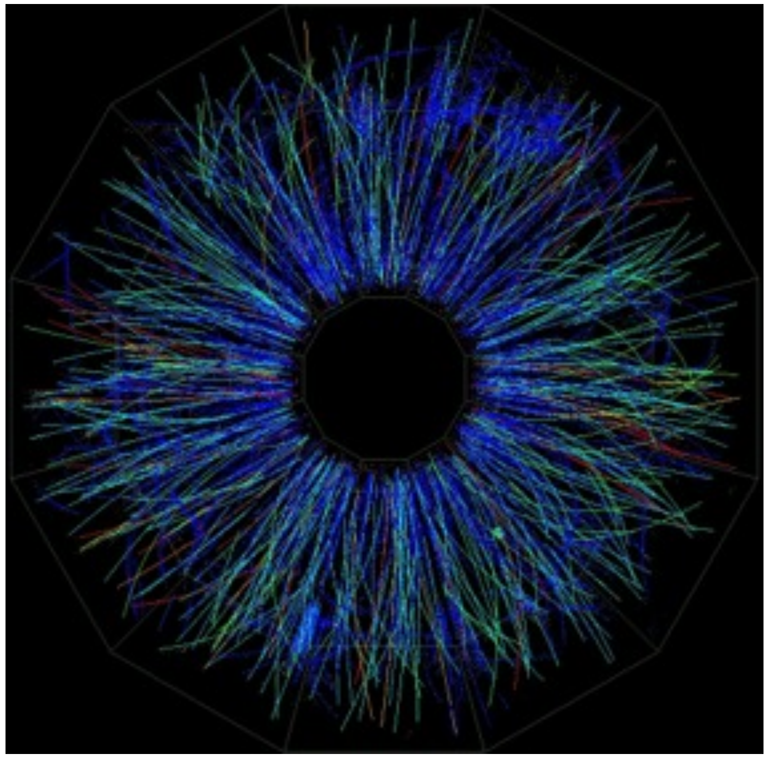


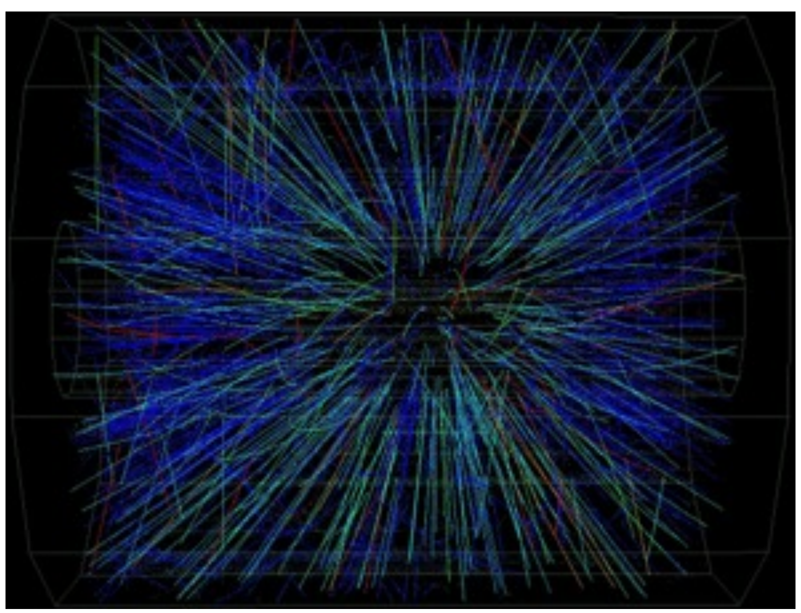


Size of reaction zone, density depends on centrality:
Expect smaller/no QGP effects in peripheral collisions

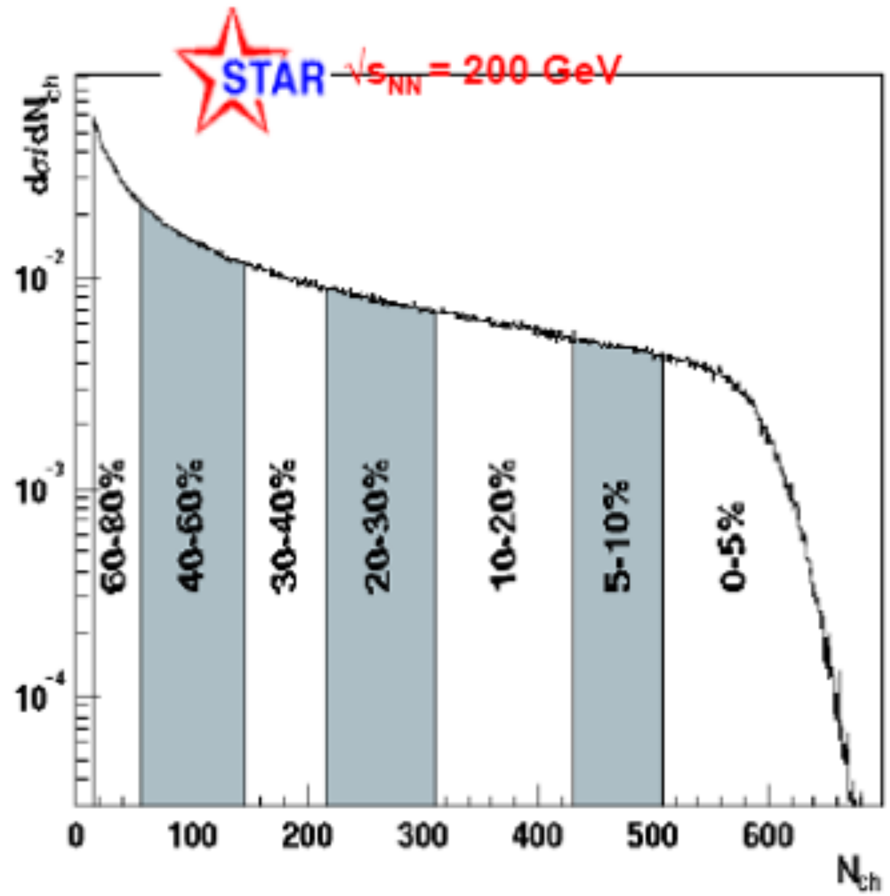
Centrality continued

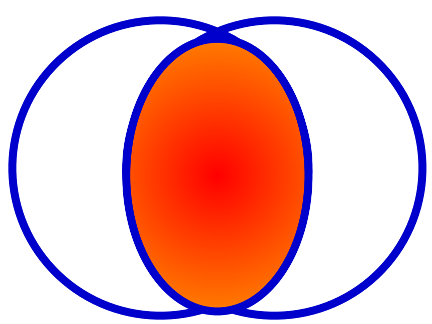
peripheral

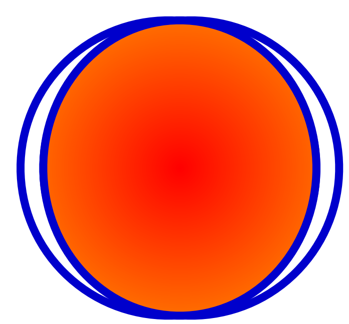




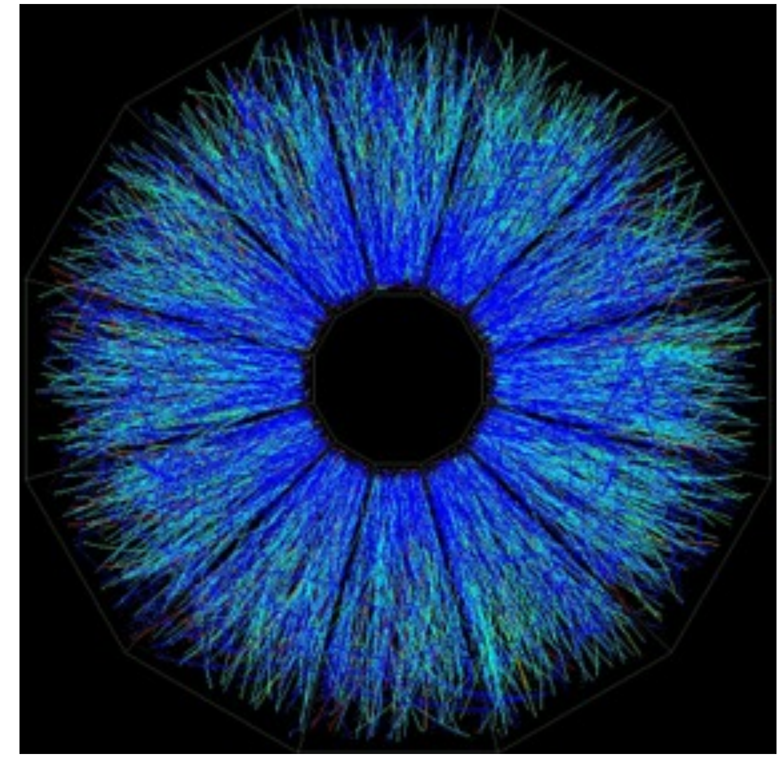
Multiplicity distribution

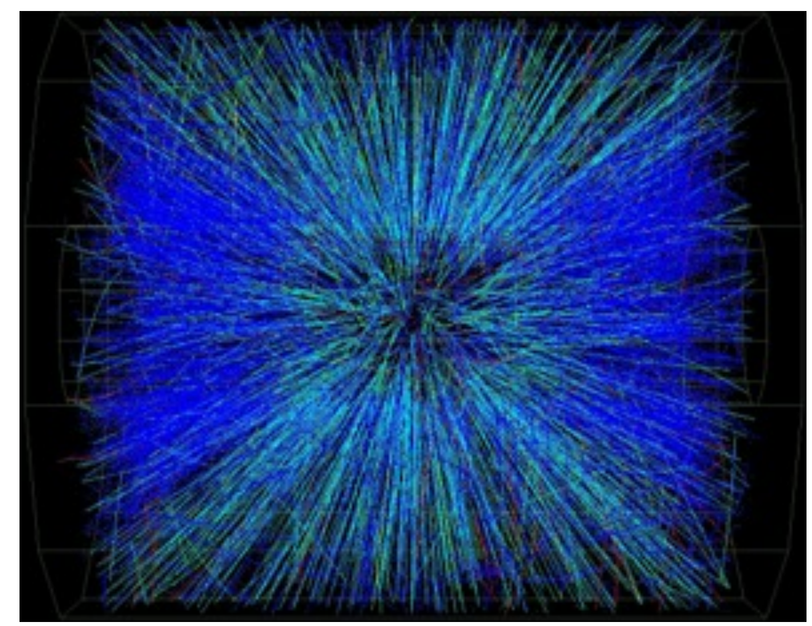






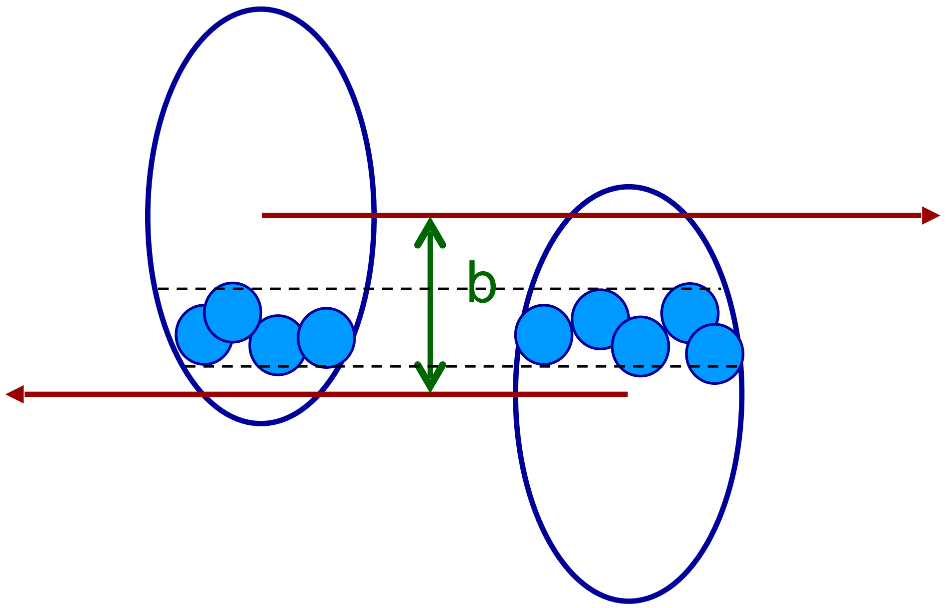
central





Experimental measure of centrality: multiplicity

Nuclear geometry: N_{part}, N_{coll}

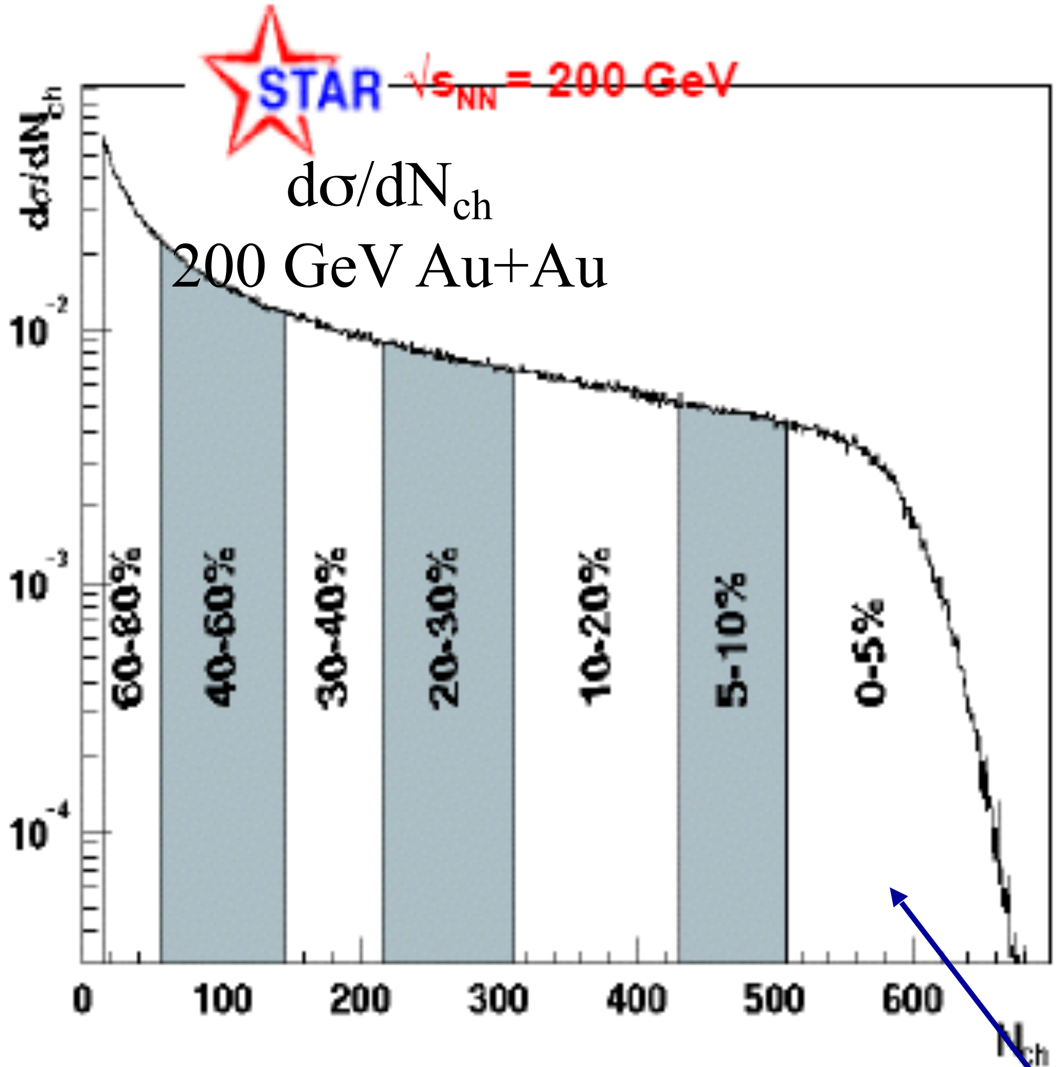


Two limiting possibilities:

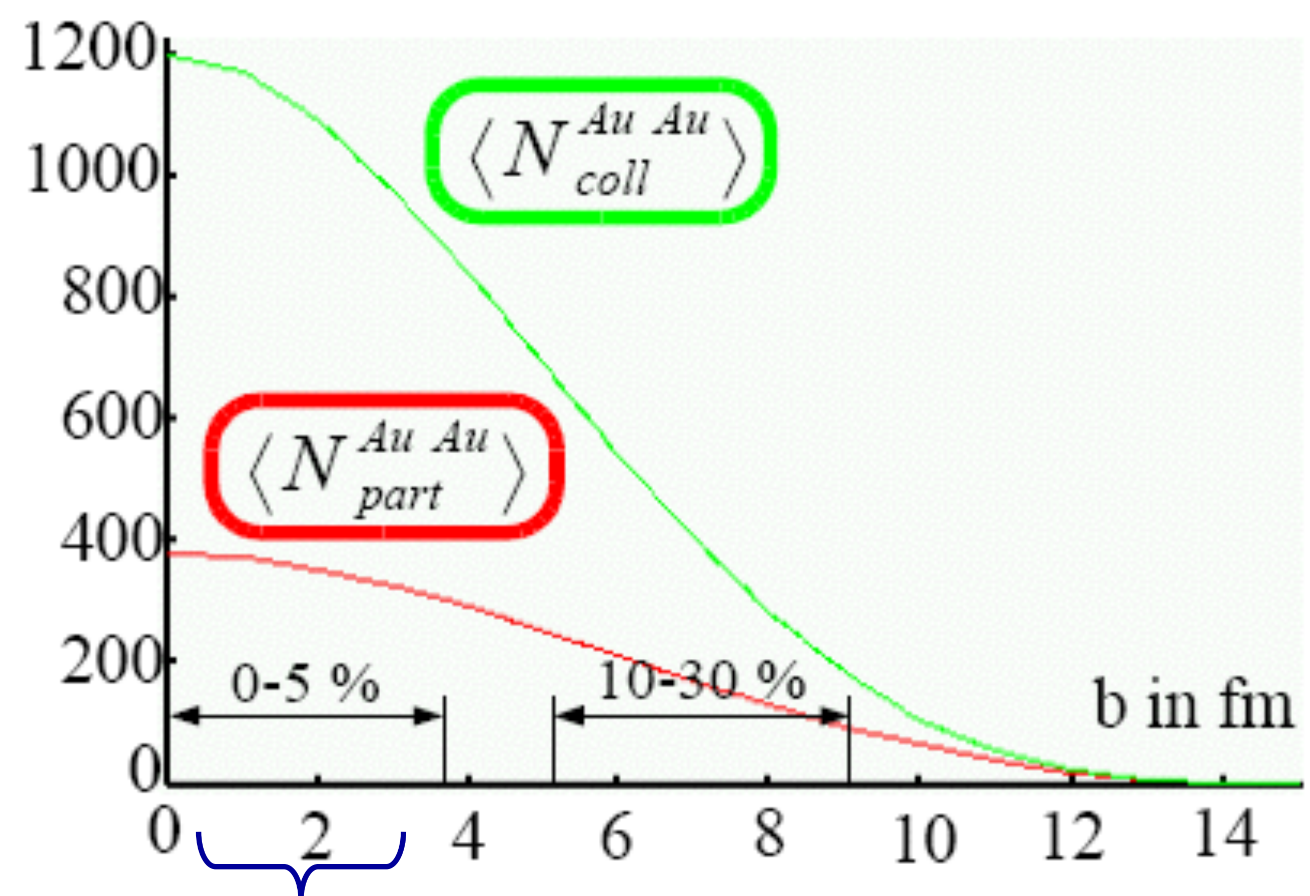
- Each nucleon only **interacts once**, 'wounded nucleons'
  $N_{part} = n_A + n_B$ (ex: 4 + 5 = 9 + …)
  Relevant for **soft production**; long timescales: $\sigma \propto N_{part}$
- Nucleons **interact with all** nucleons they encounter
  $N_{coll} = n_A \times n_B$ (ex: 4 x 5 = 20 + …)
  Relevant for **hard processes**; short timescales: $\sigma \propto N_{bin}$

Centrality dependence of hard processes

Total multiplicity: soft processes



Binary collisions weight
towards small impact parameter

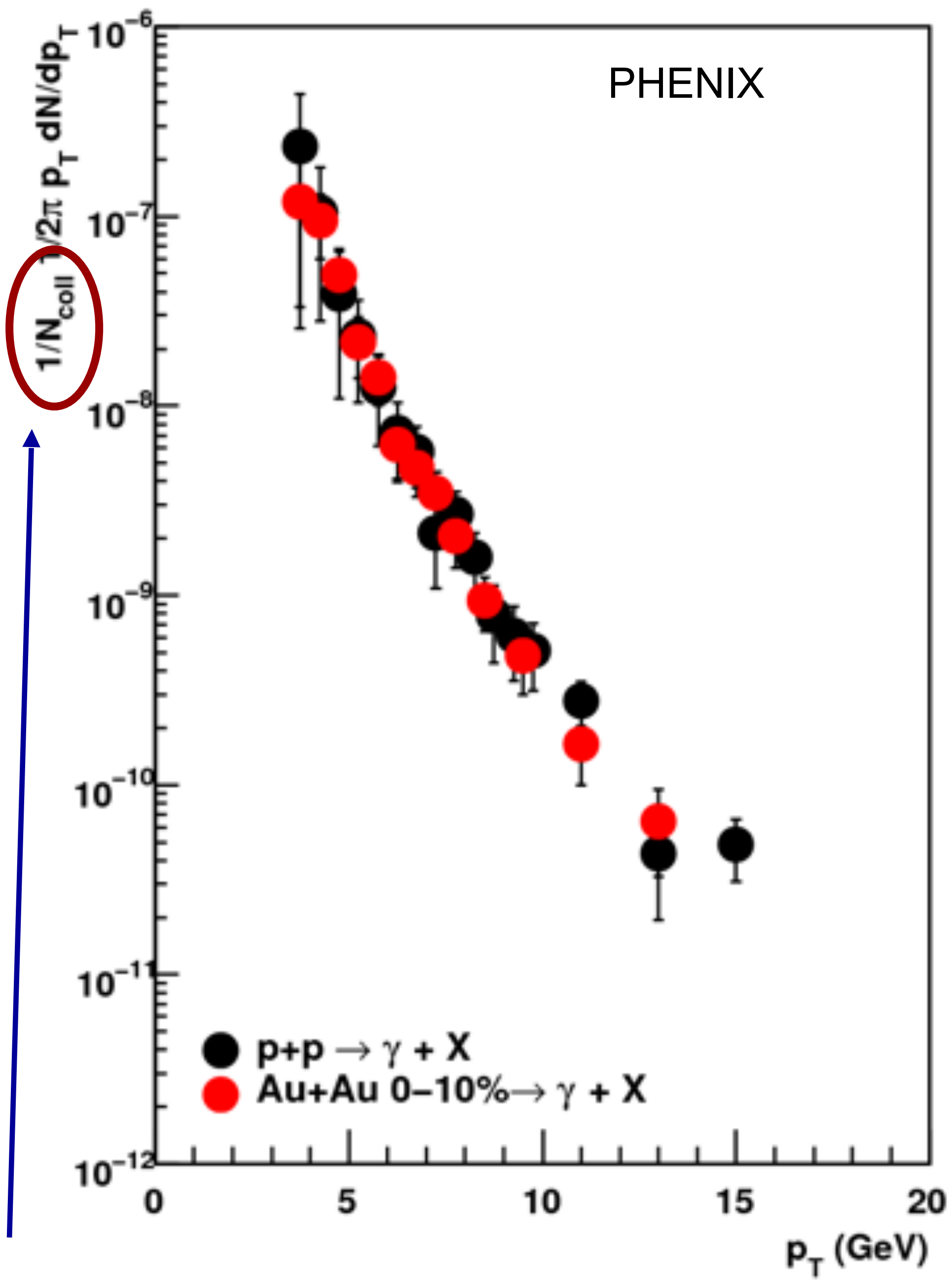


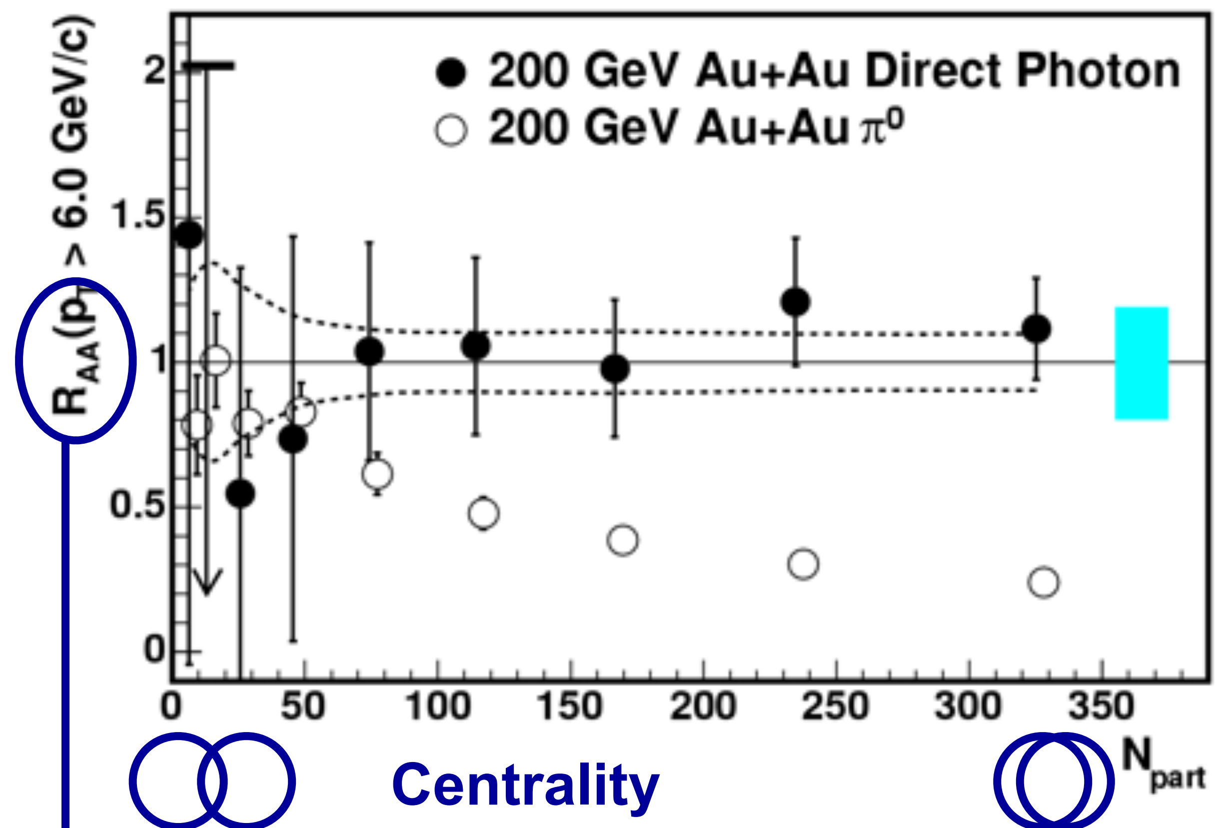
Rule of thumb for A+A collisions (A>40)
40% of the hard cross section
is contained in the 10% most central collisions

Testing volume (N_{coll}) scaling in Au+Au

Direct γ spectra

PHENIX, PRL 94, 232301





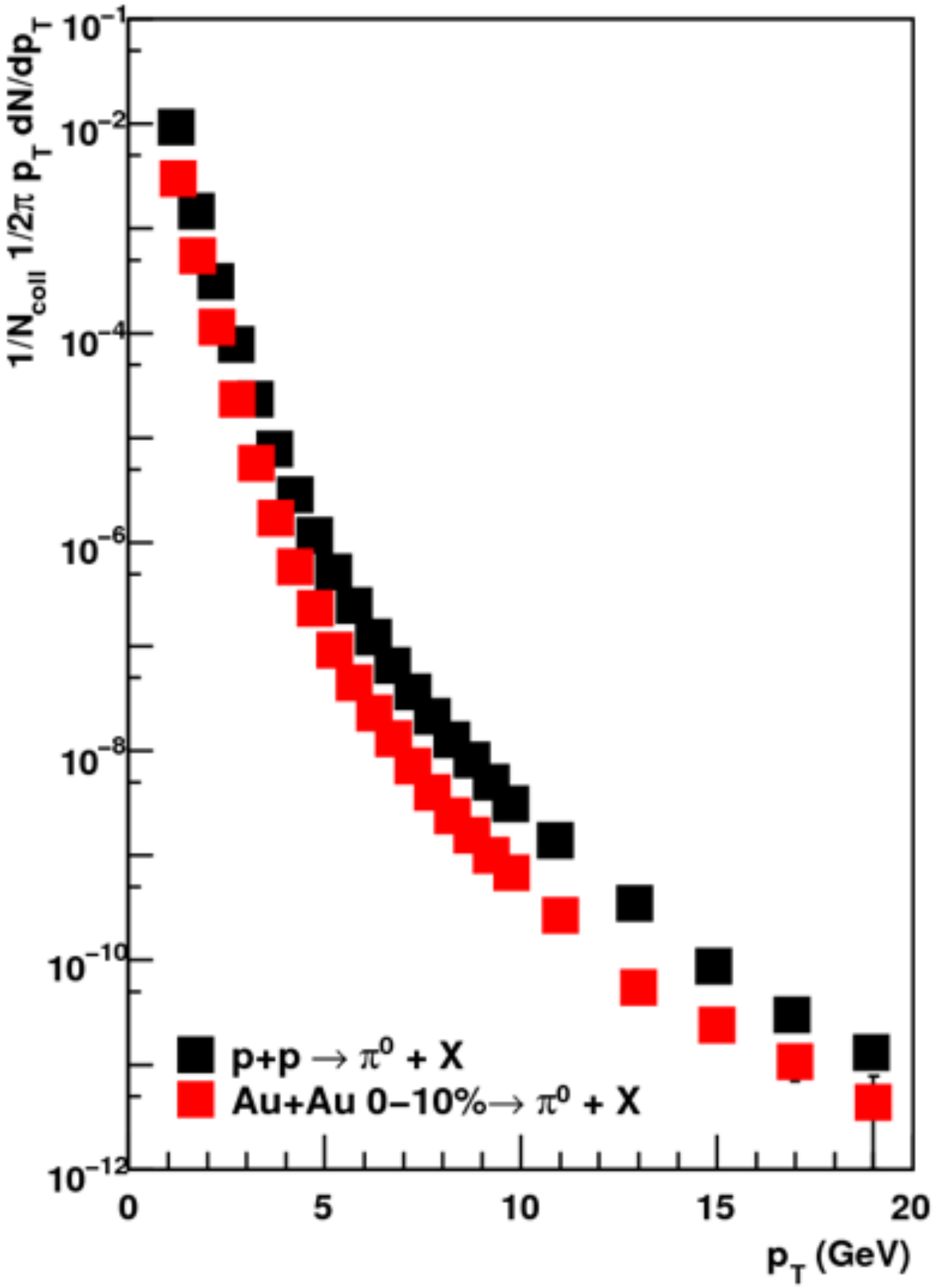
$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$

Scaled by N_{coll}

Direct γ in A+A scales with N_{coll}

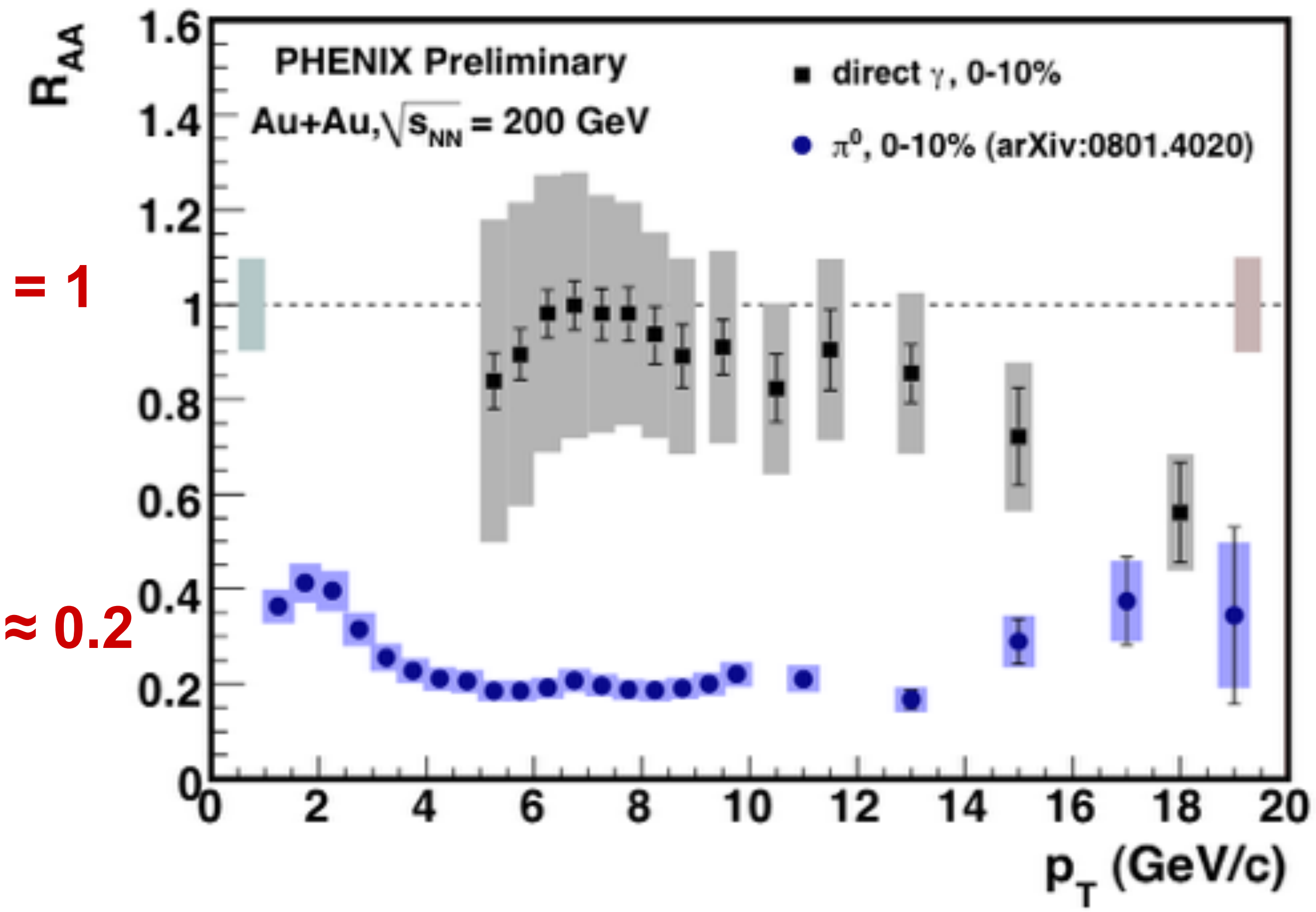
A+A initial state is incoherent superposition of p+p for hard probes

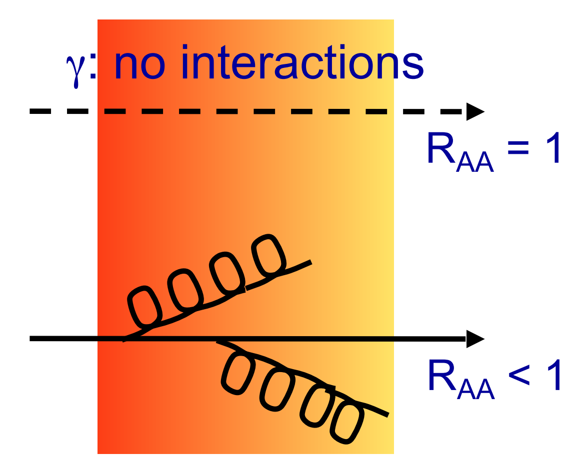
π^0 R_{AA} – high-p_T suppression



γ: R_{AA} = 1

π^0: $R_{AA} \approx 0.2$



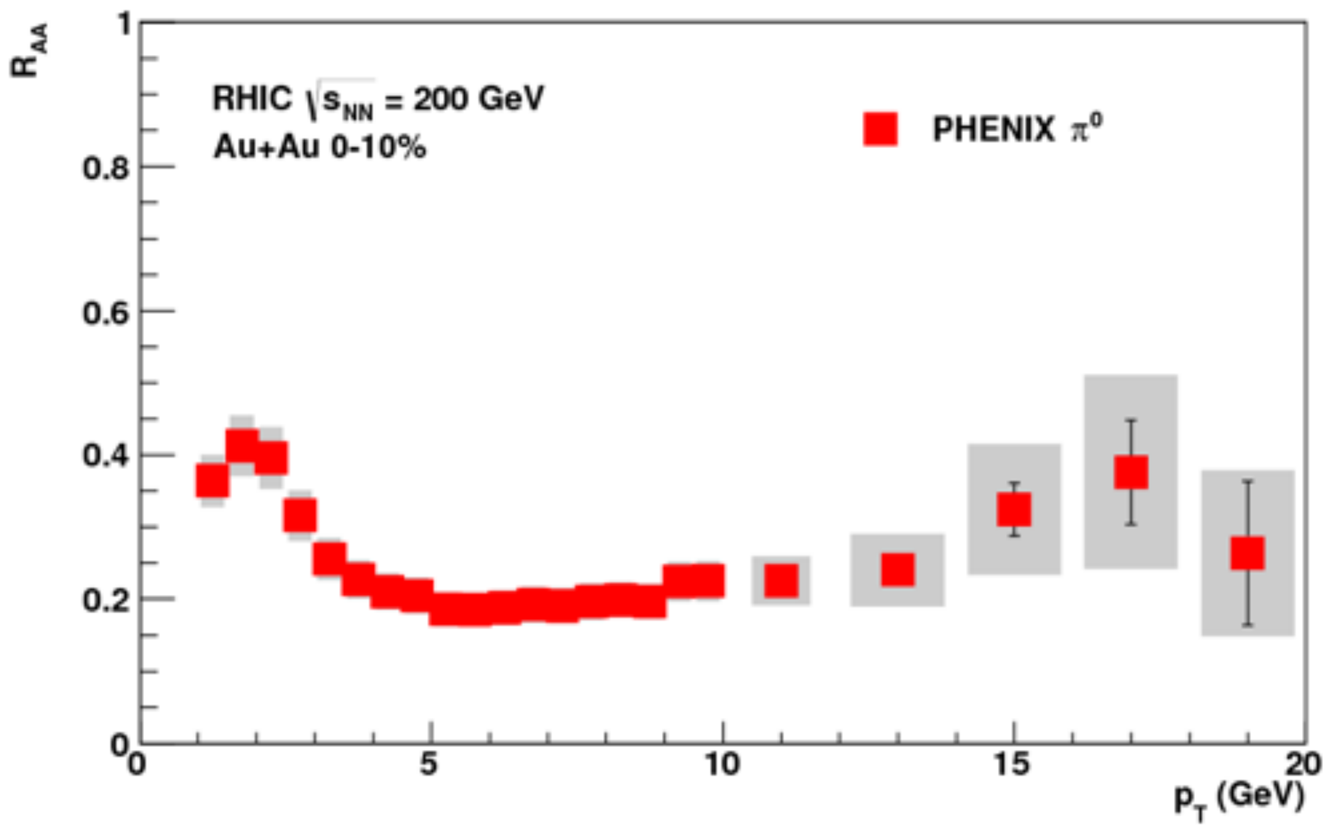


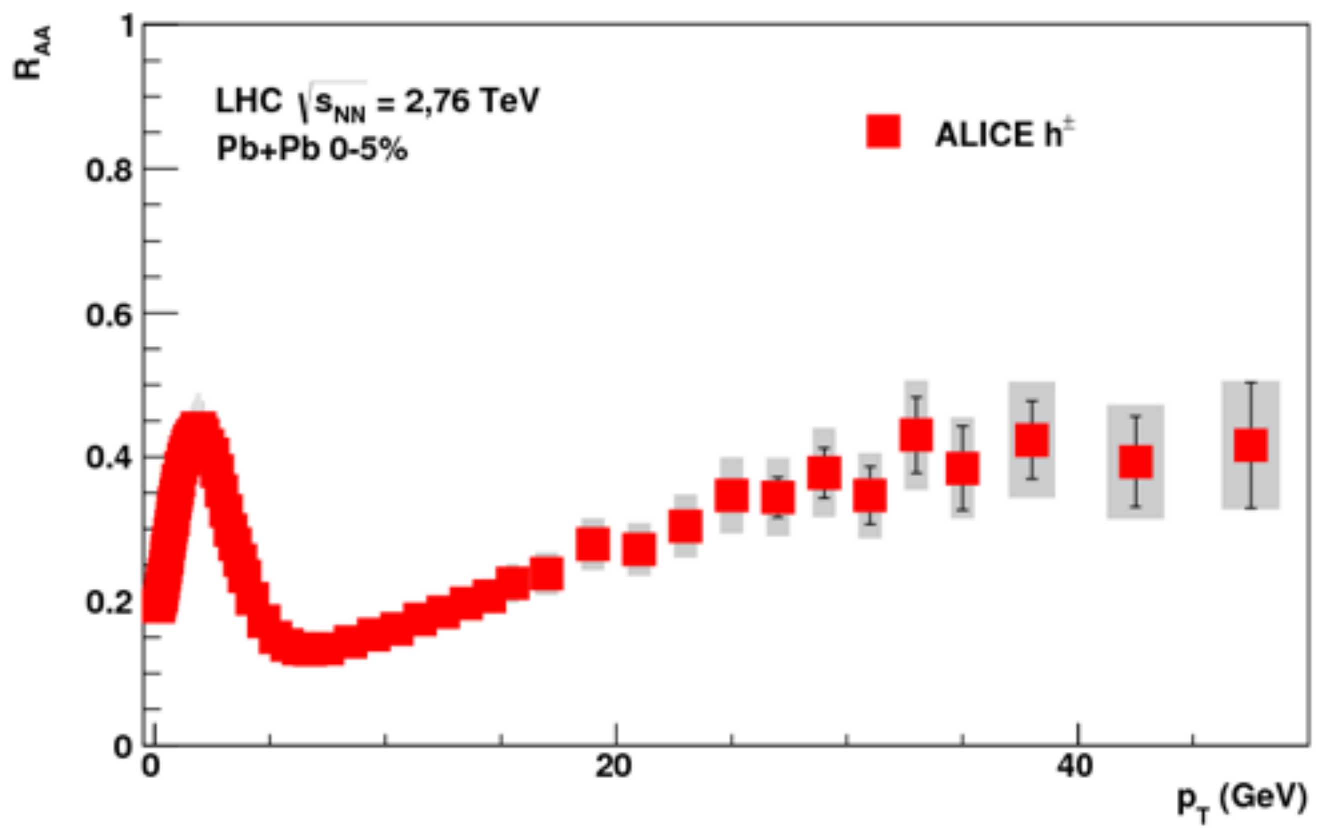
Hadrons: energy loss

Hard partons lose energy in the hot matter

Nuclear modification factor

$$R_{AA} = \frac{dN/dp_T|_{Pb+Pb}}{N_{coll}\, dN/dp_T|_{p+p}}$$





Suppression factor 2-6

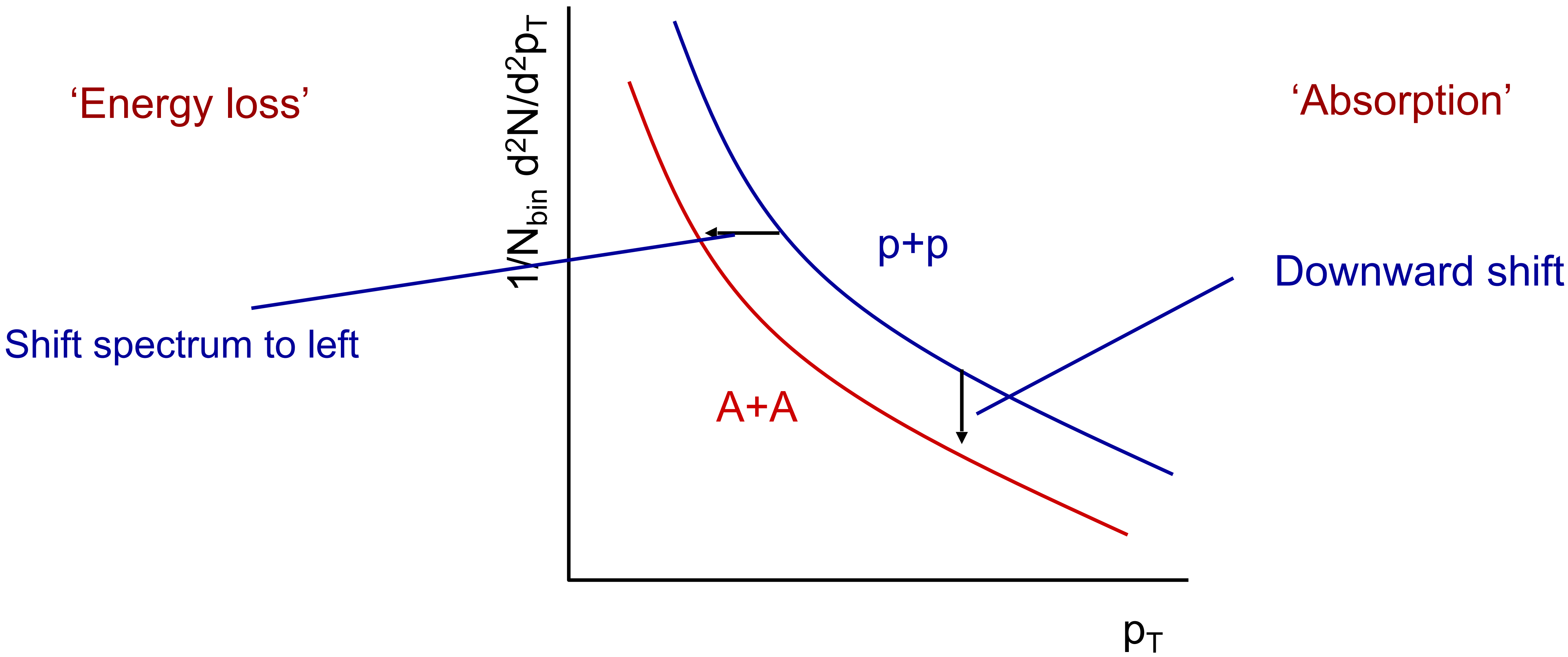
Significant p_T-dependence

Similar at RHIC and LHC?

So what does it mean?

Nuclear modification factor R_{AA}

$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$



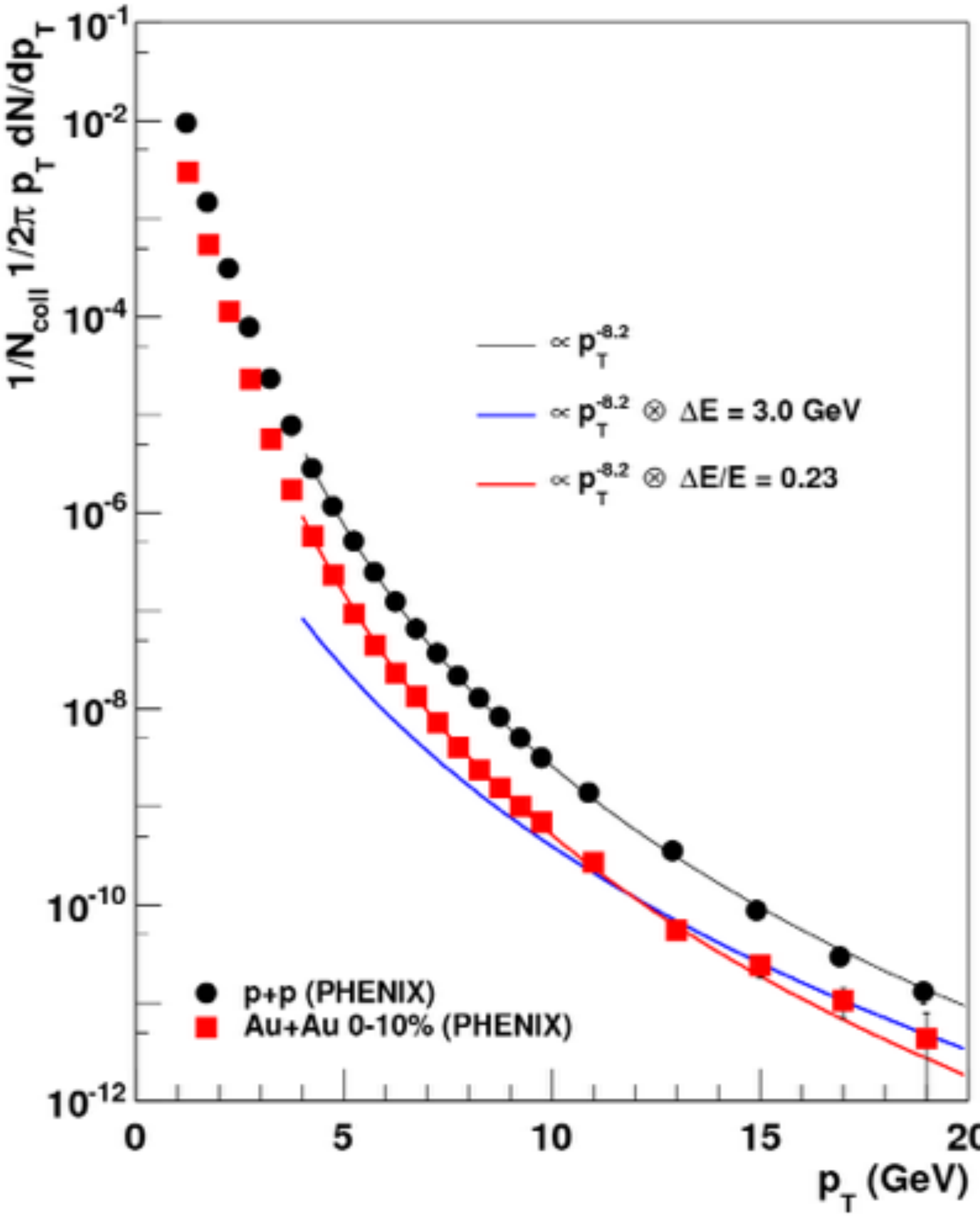
Measured R_{AA} is a ratio of yields at a given p_T

The physical mechanism is energy loss; shift of yield to lower p_T

The full range of physical pictures can be captured with an energy loss distribution P(ΔE)

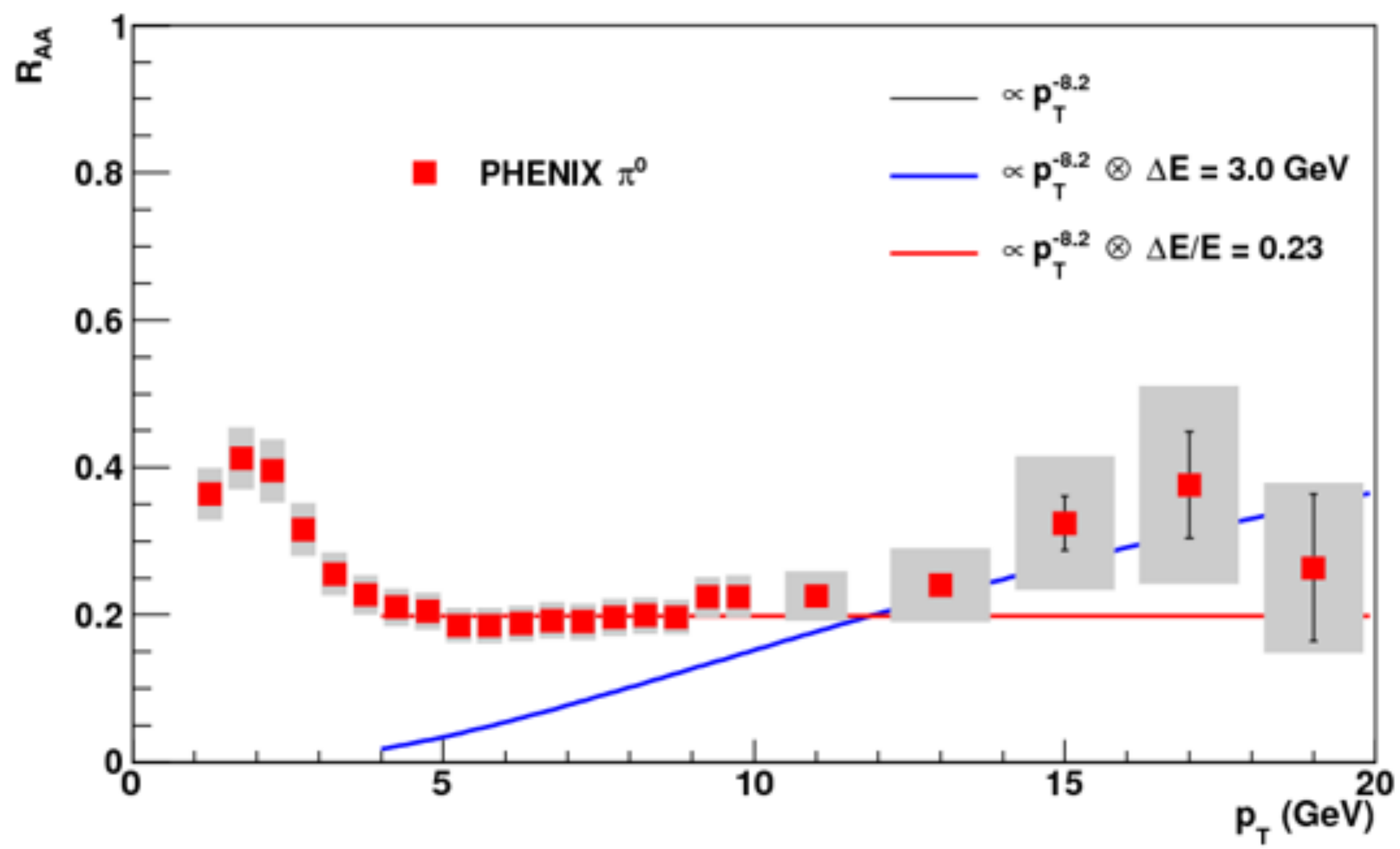
Getting a sense for the numbers – RHIC

π^0 spectra



PHENIX, PRD 76, 051106, arXiv:0801.4020

Nuclear modification factor



Oversimplified calculation:
- Fit pp with power law
- Apply energy shift or relative E loss

Not even a model !

Ball-park numbers: $\Delta E/E \approx 0.2$, or $\Delta E \approx 3$ GeV for central collisions at RHIC

From RHIC to LHC

RHIC: 200 GeV
LHC: 2.76 TeV per nucleon pair

Energy ~14 x higher

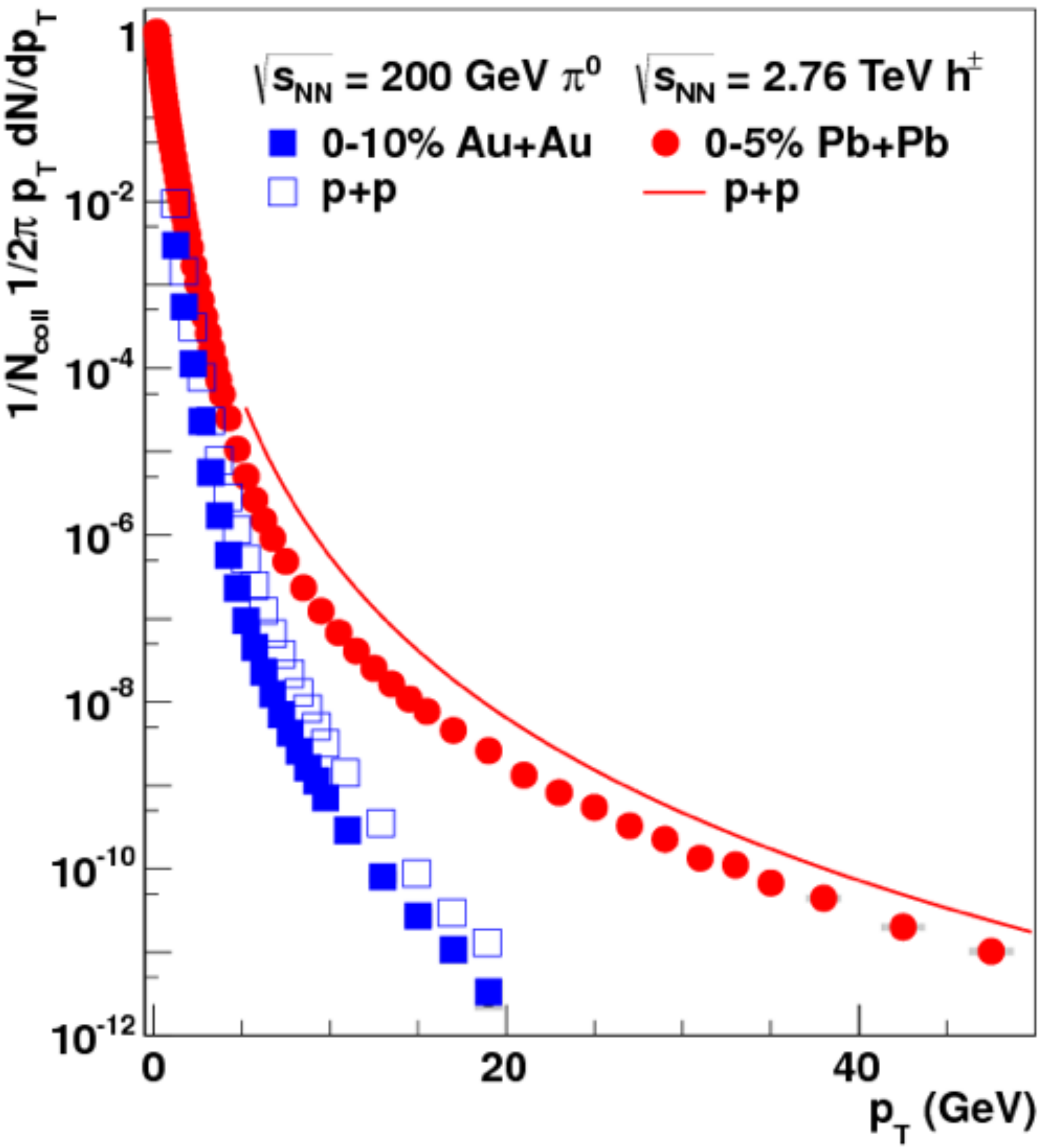
LHC: spectrum less steep, larger p_T reach

$$\frac{1}{2\pi p_T}\frac{dN}{dp_T} \propto p_T^{-n}$$

RHIC: n ~ 8.2
LHC: n ~ 6.4

Fractional energy loss:

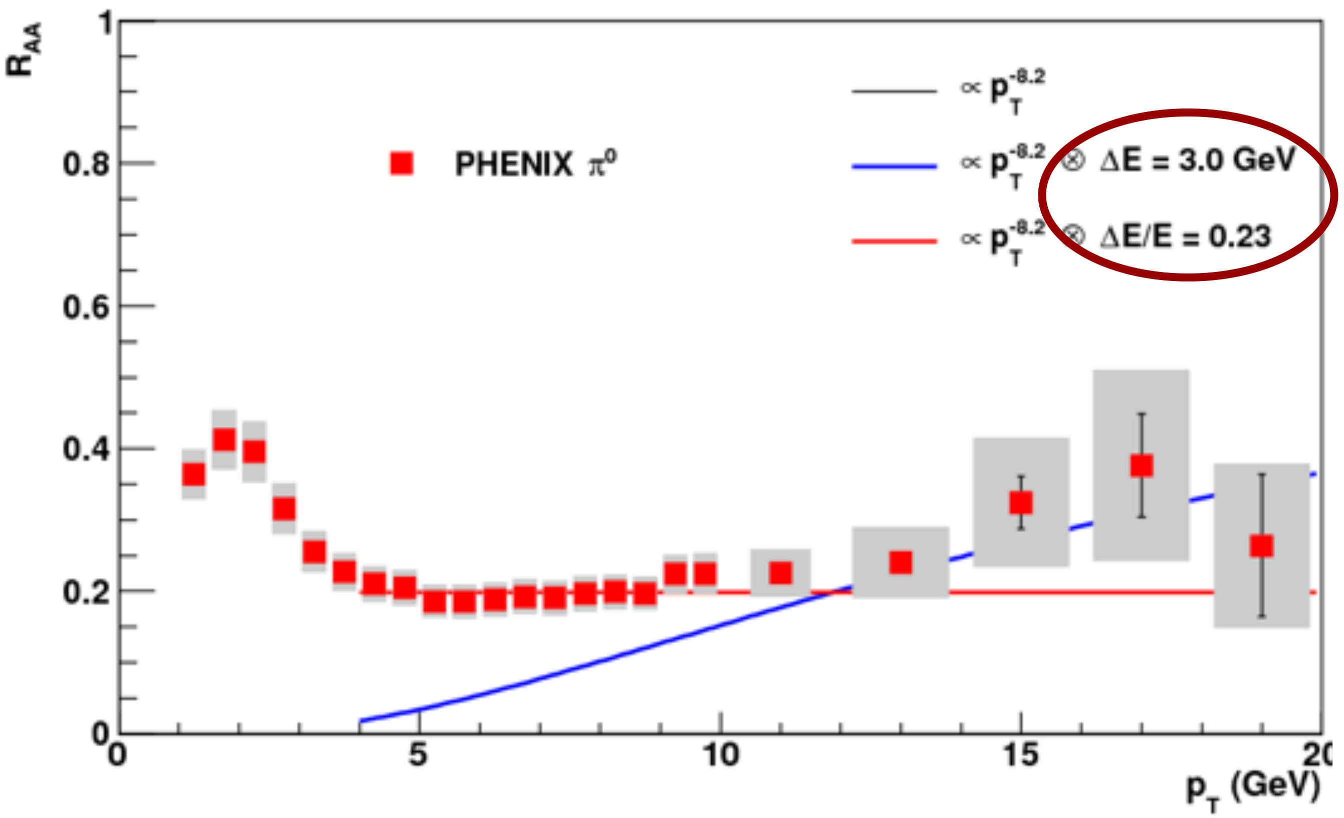
$$R_{AA} = \left(1 - \frac{\Delta E}{E}\right)^{n-2}$$



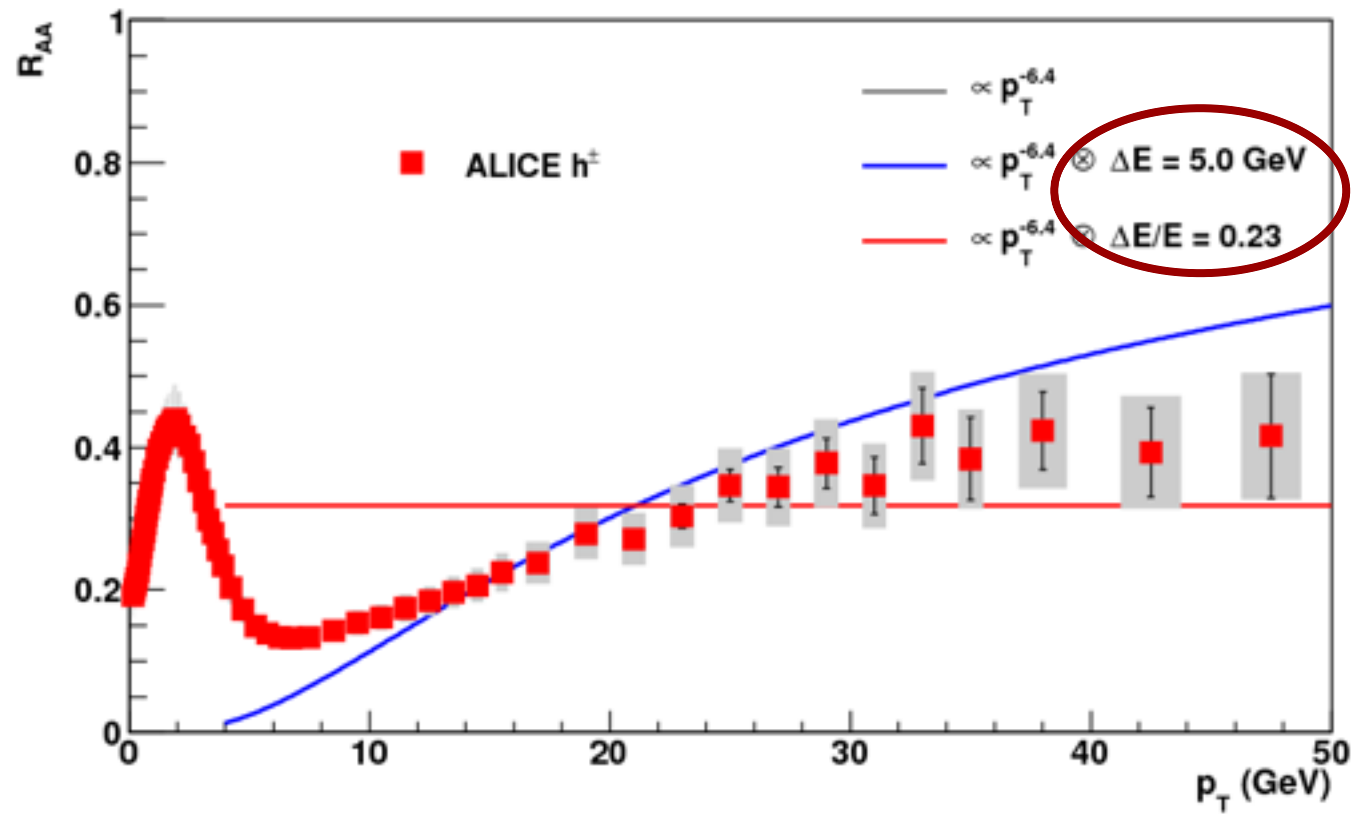
R_{AA} depends on n, steeper spectra, smaller R_{AA}

From RHIC to LHC

RHIC



LHC



RHIC: n ~ 8.2

LHC: n ~ 6.4

$$(1-0.23)^{6.2} = 0.20$$

$$(1-0.23)^{4.4} = 0.32$$

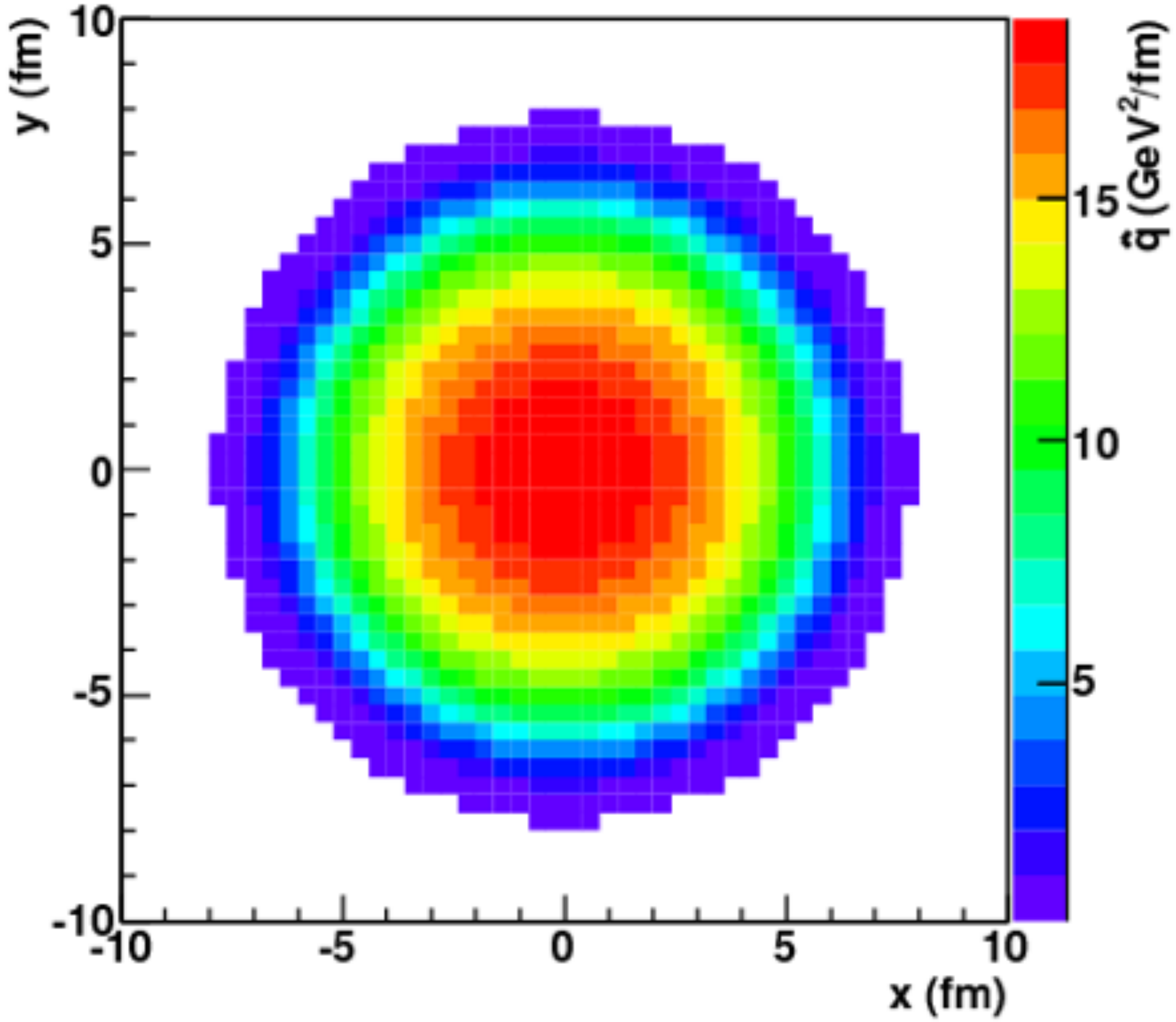
Remember: still 'getting a sense for the numbers'; this is not a model!

Towards a more complete picture

- Energy loss not single-valued, but a distribution
- Geometry: density profile; path length distribution
- Energy loss is partonic, not hadronic
  - Full modeling: medium modified shower
  - Simple ansatz for leading hadrons: energy loss followed by fragmentation
  - Quark/gluon differences

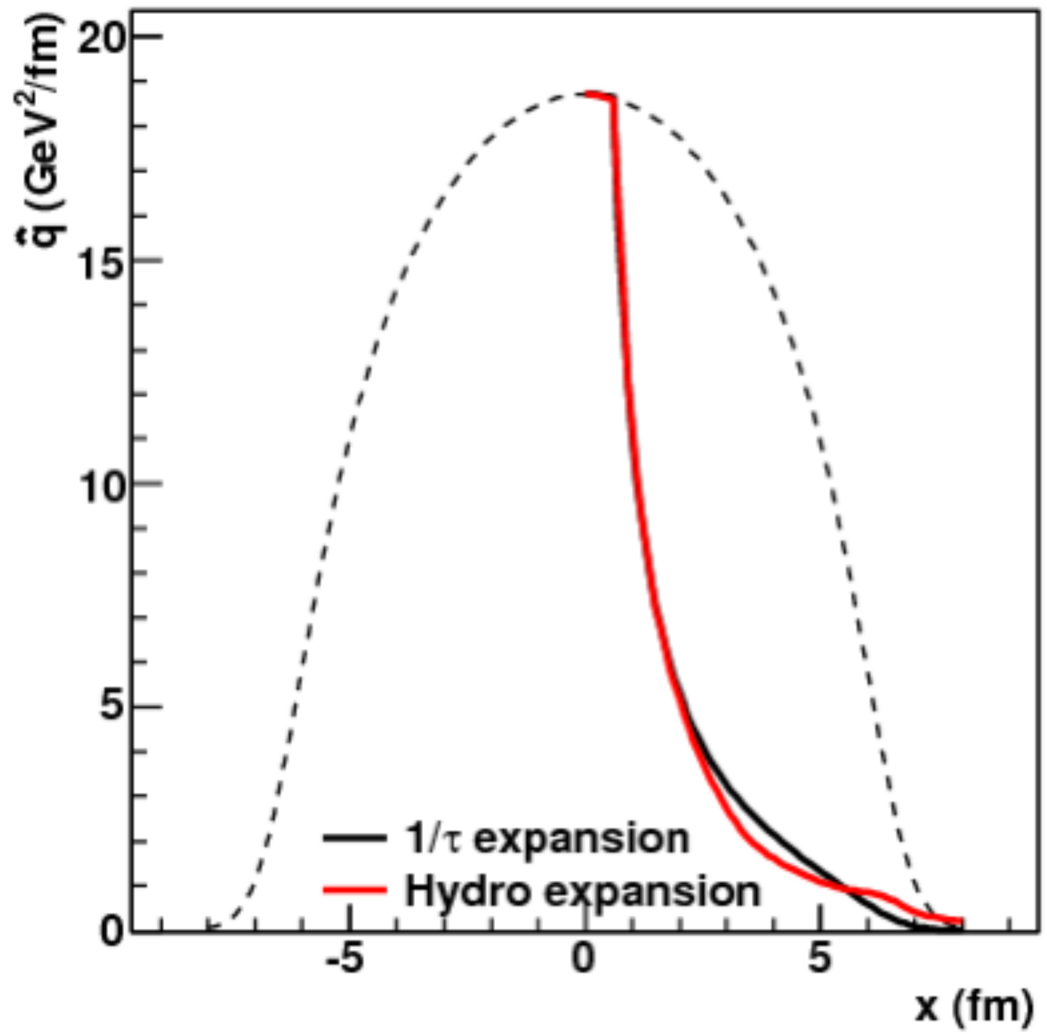
Geometry

Density profile



Profile at $\tau \sim \tau_{form}$ known

Density along parton path



Longitudinal expansion
dilutes medium
⇒ Important effect

Space-time evolution is taken into account in modeling

A simplified approach

$$\left.\frac{dN}{dp_T}\right|_{hadr} = \left.\frac{dN}{dE}\right|_{jets} \otimes P(\Delta E) \otimes D(p_{T,hadr}/E_{jet})$$

Parton spectrum	Energy loss distribution	Fragmentation (function)
$\left.\frac{dN}{dE}\right\|_{jets}$	$P(\Delta E)$	$D(p_{T,hadr}/E_{jet})$
known pQCDxPDF	extract	`known' from e^+e^-

This is where the information about the medium is

P(ΔE) combines geometry
with the intrinsic process
– Unavoidable for many observables

Notes:

- This is the simplest ansatz – most calculation to date use it (except some MCs)
- Jet, γ-jet measurements 'fix' E, removing one of the convolutions

Situation at RHIC, ca 2008

3 main calculations; comparison with same medium density profile

$$\hat{q} = \int_0^{q_{max}} dq_T^2 \; q_T^2 \frac{d\sigma}{dq_T}$$

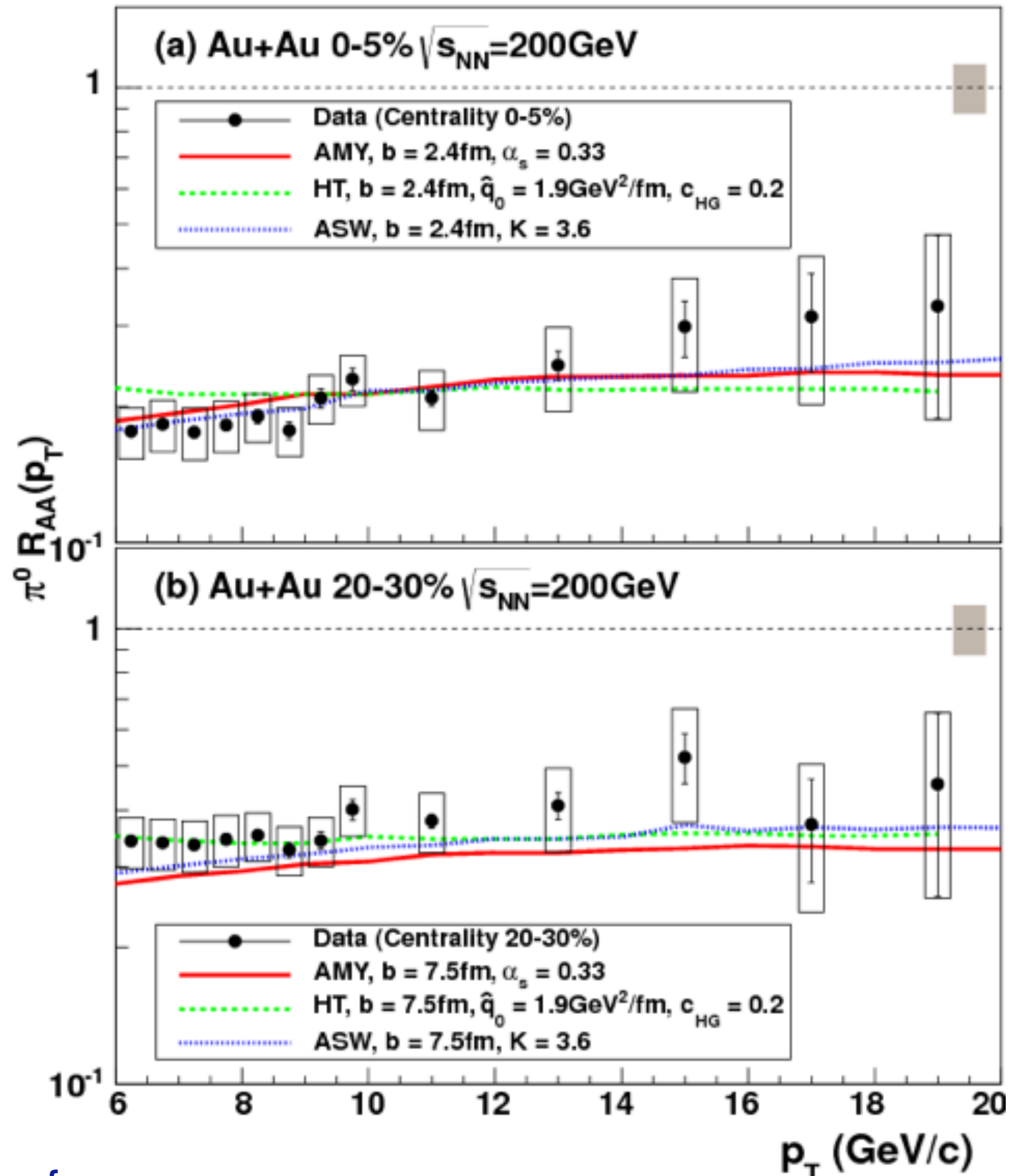
ASW: $\hat{q} = 10 - 20\ \mathrm{GeV}^2/\mathrm{fm}$

HT: $\hat{q} = 2.3 - 4.5\ \mathrm{GeV}^2/\mathrm{fm}$

AMY: $\hat{q} \approx 4\ \mathrm{GeV}^2/\mathrm{fm}$

Large density:
AMY: T ~ 400 MeV
Transverse kick: qL ~ 10-20 GeV

Large uncertainty in absolute medium density

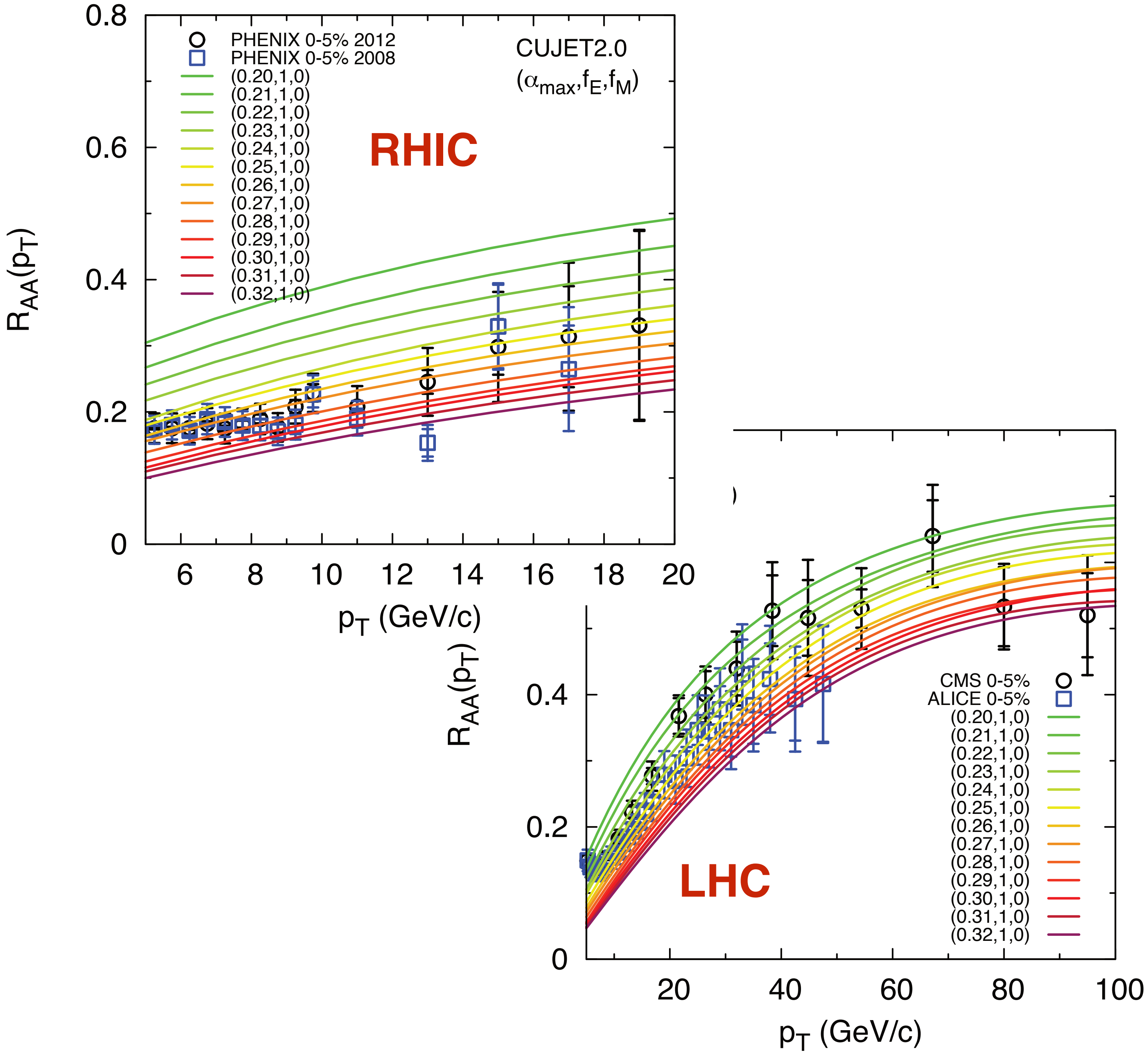


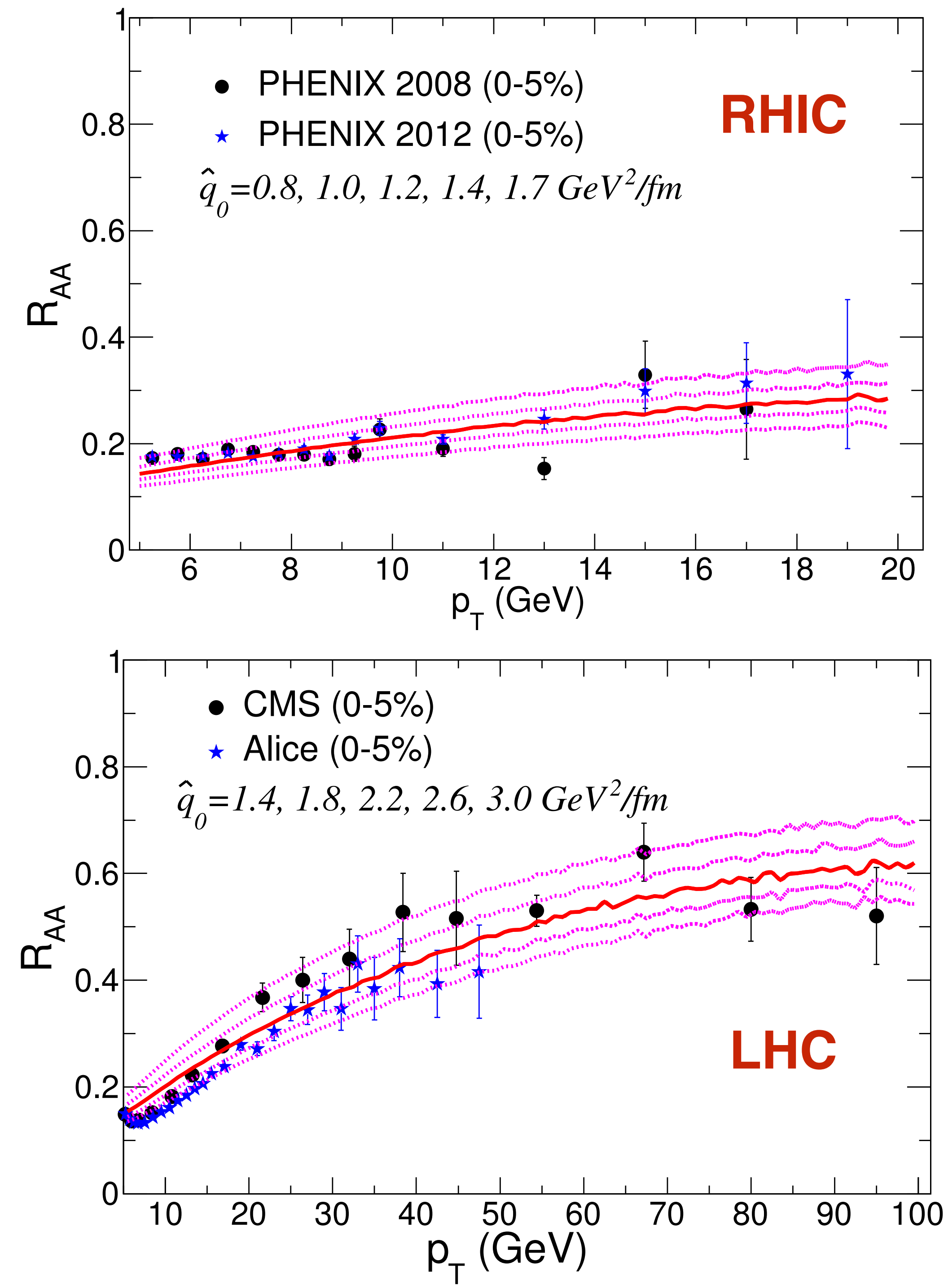
Bass et al, PRC79, 024901

PHENIX, arXiv:1208.2254

One aspect: scattering potential/momentum transfer; see recent work by Majumder, Laine, Rothkopf on lattice

RHIC and LHC





Burke et al, JET Collaboration, arXiv:1312.5003

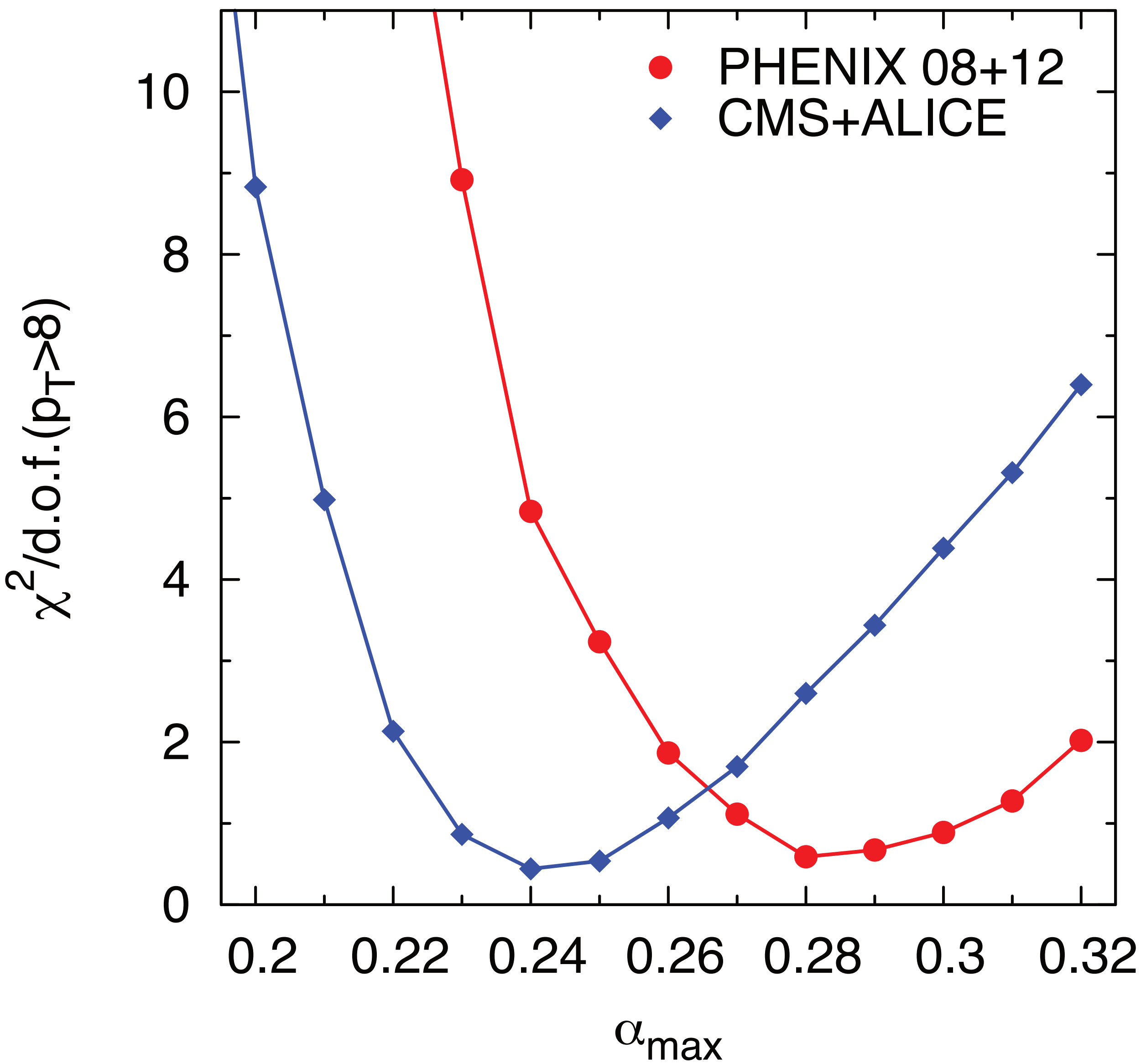
Systematic comparison of energy loss models with data

Medium modeled by Hydro (2+1D, 3+1D)

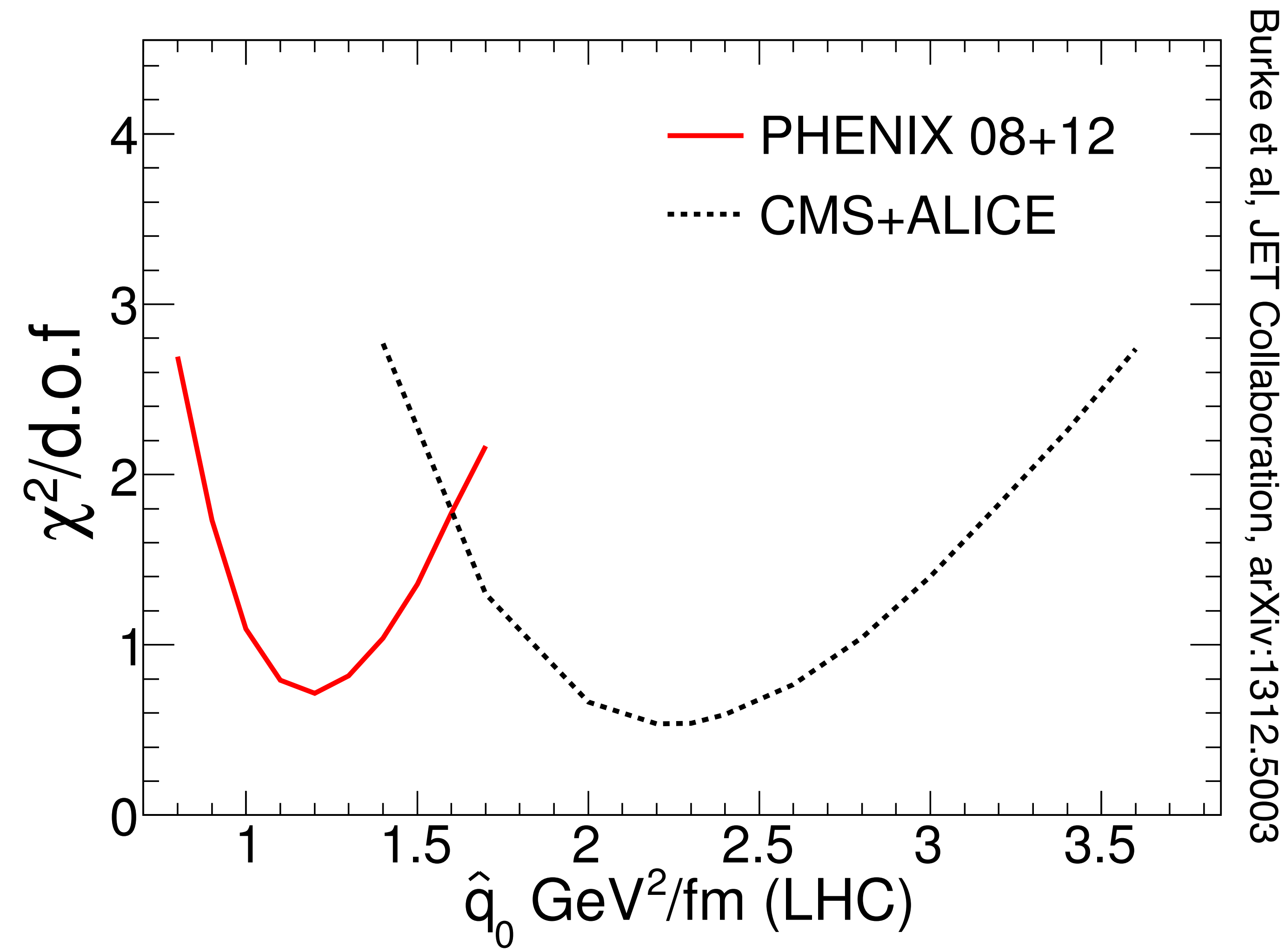
p_T dependence matches reasonably well

RHIC and LHC

CUJET 2.0



HT-BW



CUJET: α_s is medium parameter
Lower at LHC

HT: transport coeff is parameter
Higher at LHC

Summary of transport coefficient study

RHIC:

$\hat{q} = 1.2 \pm 0.3\ GeV^2/fm$

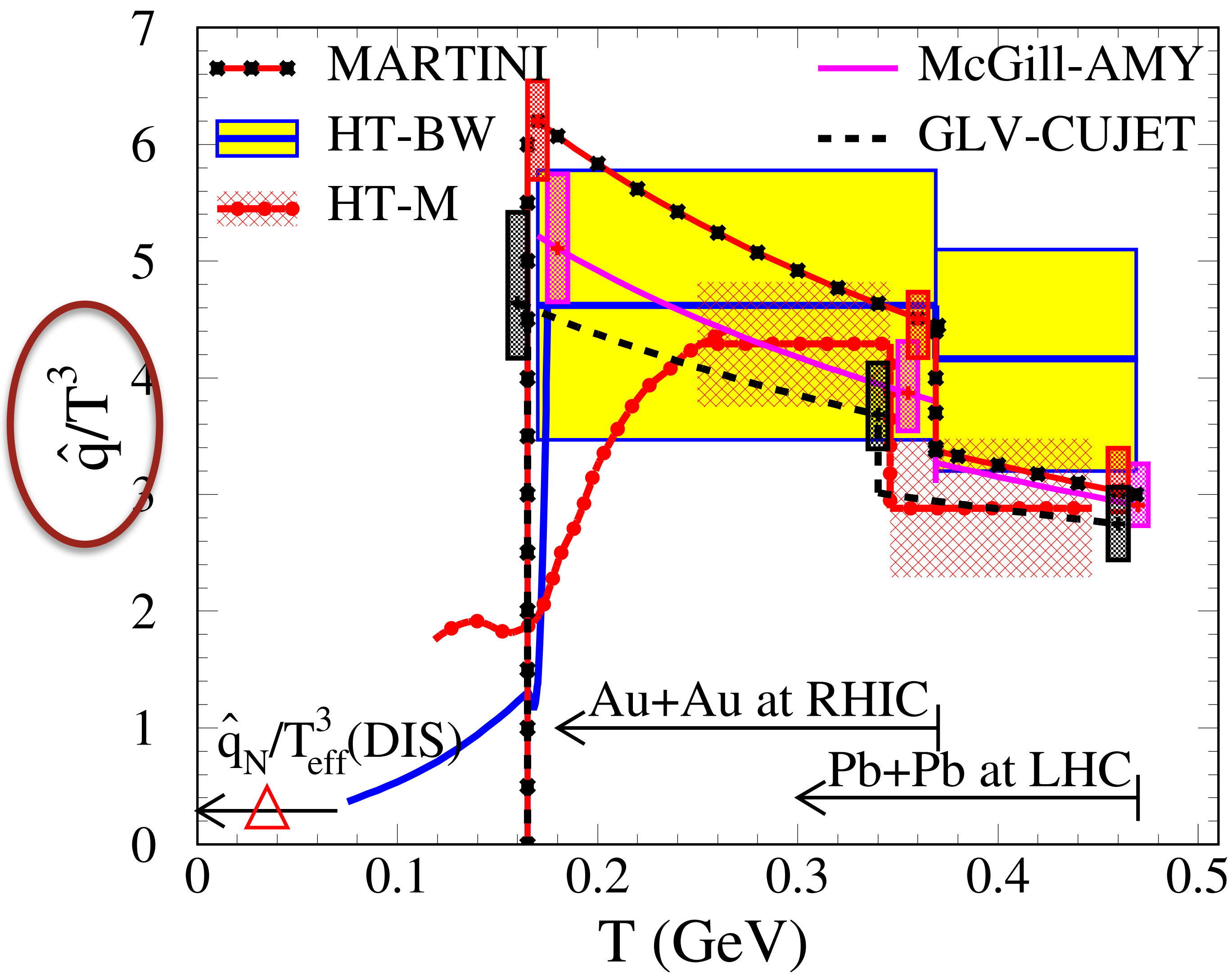
(T=370 MeV)

LHC:

$\hat{q} = 1.9 \pm 0.7\ GeV^2/fm$

(T=470 MeV)

Expect factor 2.2 from multiplicity + nuclear size



Burke et al, JET Collaboration, arXiv:1312.5003

$\hat{q}$ values from different models consistent

(NB: multiple-soft scattering omitted)

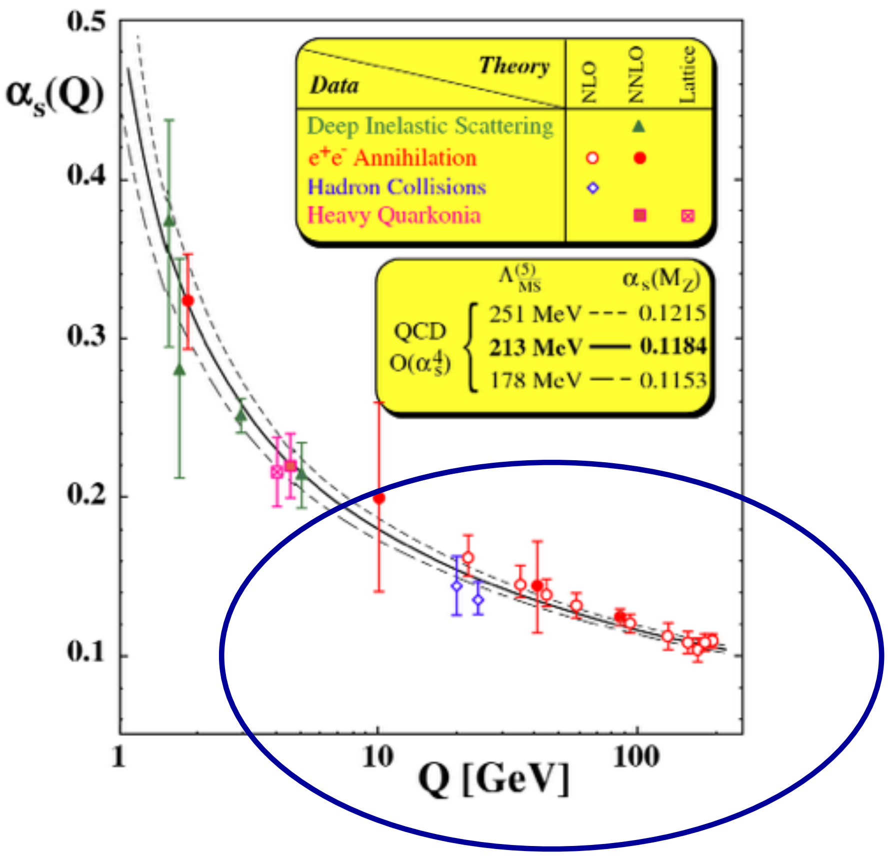
$\hat{q}/T^3$ larger at RHIC than LHC: running of α_s ?

Or: limited validity of models?

Summary

- Main tool for hard probes: factorisation
  - cross section = PDF ⊗ partonic xsec ⊗ FFs
- AA collisions: hard processes scale with N_{coll} (in absence of medium effects; e.g. photons)
- Nuclear modification factor $R_{AA} < 1$: (parton) energy loss
  - Energy loss O(5 GeV) or $\Delta E/E \sim 0.20$
  - More quantitative study: transport coefficient larger at LHC $\hat{q} \approx 1\text{–}3 \;\; GeV^2/fm$

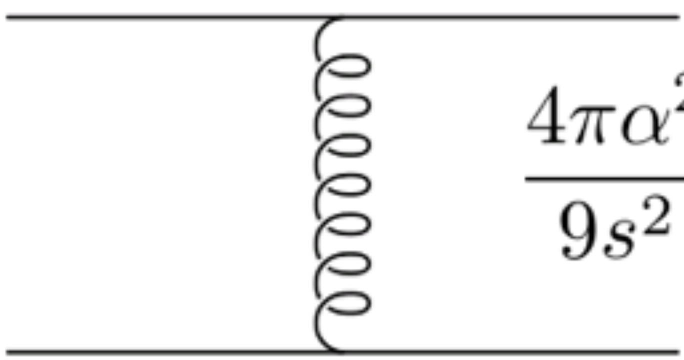
Asymptotic freedom and pQCD



At large Q^2, hard processes: calculate 'free parton scattering'

$$e^+ e^- \rightarrow q\,\bar{q}\,g$$

At high energies, quarks and gluons are manifest



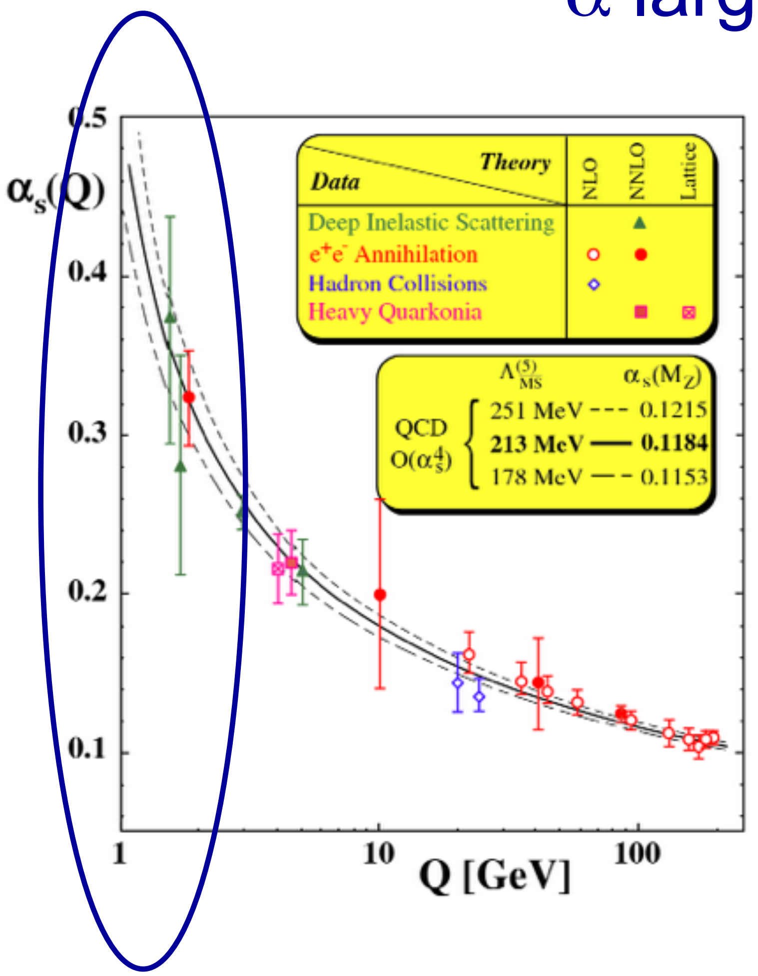
$$\frac{4\pi\alpha^2}{9s^2}\,\frac{s^2+u^2}{t^2}$$

+ more subprocesses

But need to add hadronisation (+initial state PDFs)

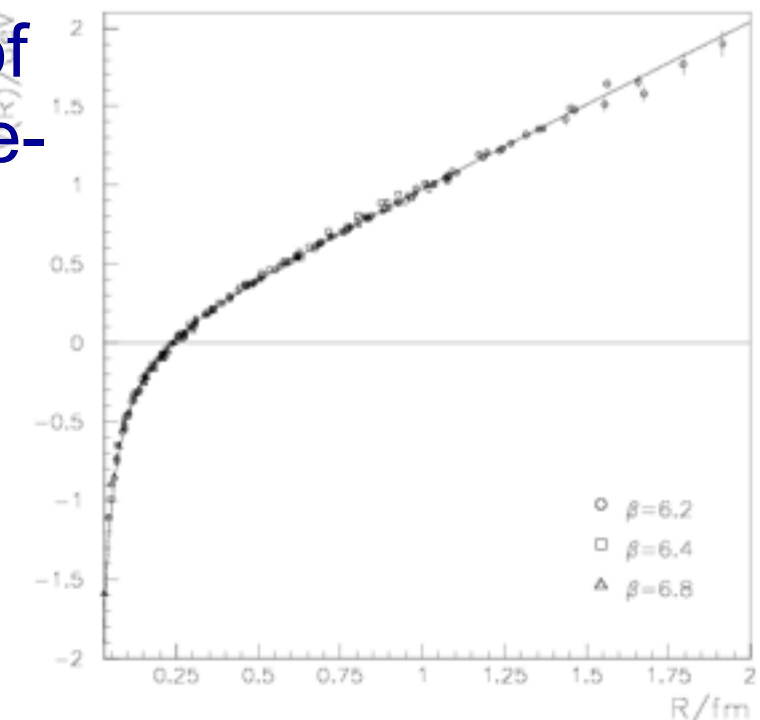
Low Q^2: confinement

α large, perturbative techniques not suitable

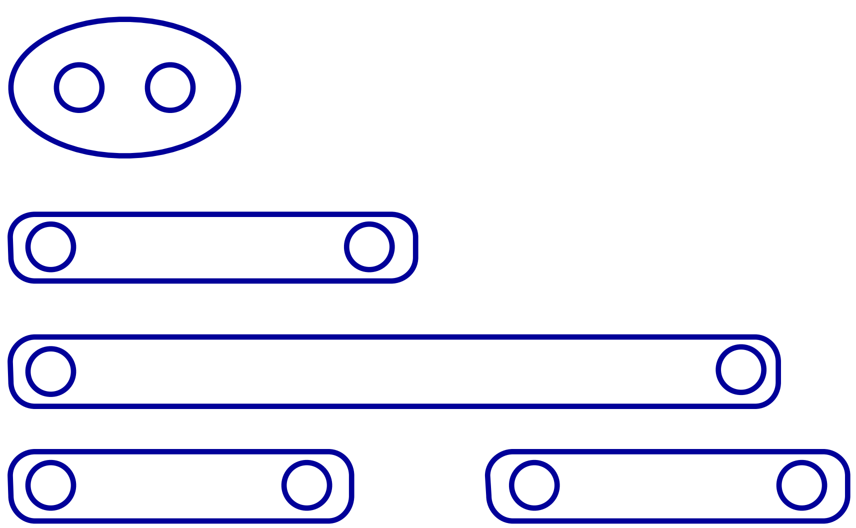


Lattice QCD: solve equations of motion (of the fields) on a space-time lattice by MC

Bali, hep-lat/9311009



Lattice QCD potential



String breaks, generate qq pair to reduce field energy