Hard Probes of the Quark Gluon Plasma
Lecture I: Introduction and pQCD

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Universiteit Utrecht

NIKHEF

General QCD references

Particle Data Group topical reviews
http://pdg.lbl.gov/2004/reviews/contents_sports.html

QCD and jets: CTEQ web page and summer school lectures http://www.phys.psu.edu/~cteq/

Handbook of Perturbative QCD, Rev. Mod. Phys. 67, 157–248 (1995)
http://www.phys.psu.edu/~cteq/handbook/v1.1/handbook.ps.gz

Gauge Theories in Particle Physics (Vol II: QCD), I.J.R. Aitchison, A.J.G. Hey

QCD and Collider Physics, R. K. Ellis, W. J. Sterling, D.R. Webber, Cambridge University Press (1996)

An Introduction to Quantum Field Theory, M. Peskin and D. Schroeder, Addison Wesley (1995)

Introduction to High Energy Physics, D. E. Perkins, Cambridge University Press, Fourth Edition (2000)

Heavy Ion references

RHIC overviews:

P. Jacobs and X. N. Wang, Prog. Part. Nucl. Phys. 54, 443 (2005)
B. Mueller and J. Nagle, Ann. Rev. Nucl. Part. Sci. 56, 93 (2006)

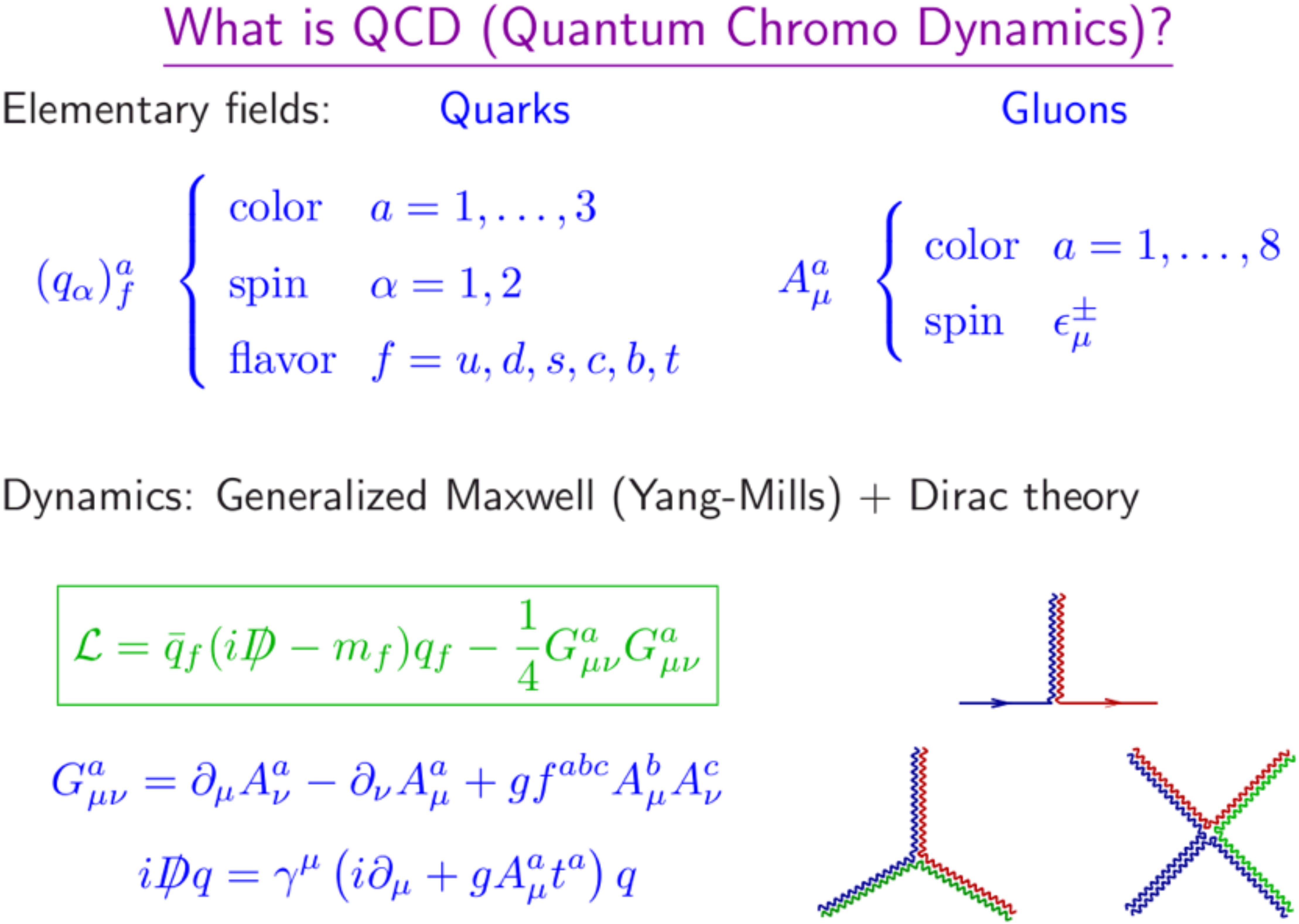
Jet quenching reviews:

M. Spousta, arXiv:1305.6400
J. Caselderrey-Solana and C. Salgado, arXiv:0712.3443
U. Wiedemann, arXiv:0908.2306
A. Majumder and M. v. L. arXiv:1002.2206
Accardi, Arleo et al, arXiv:0907.3534

RHIC experimental white papers

BRAHMS: nucl-ex/0410020
PHENIX: nucl-ex/0410003
PHOBOS: nucl-ex/0410022
STAR: nucl-ex/0501009

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

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

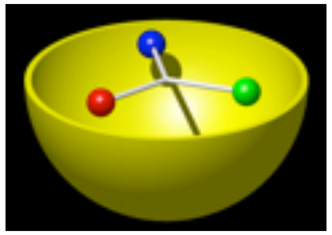
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

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

From: T. Schaefer, QM08 student talk

QCD and hadrons

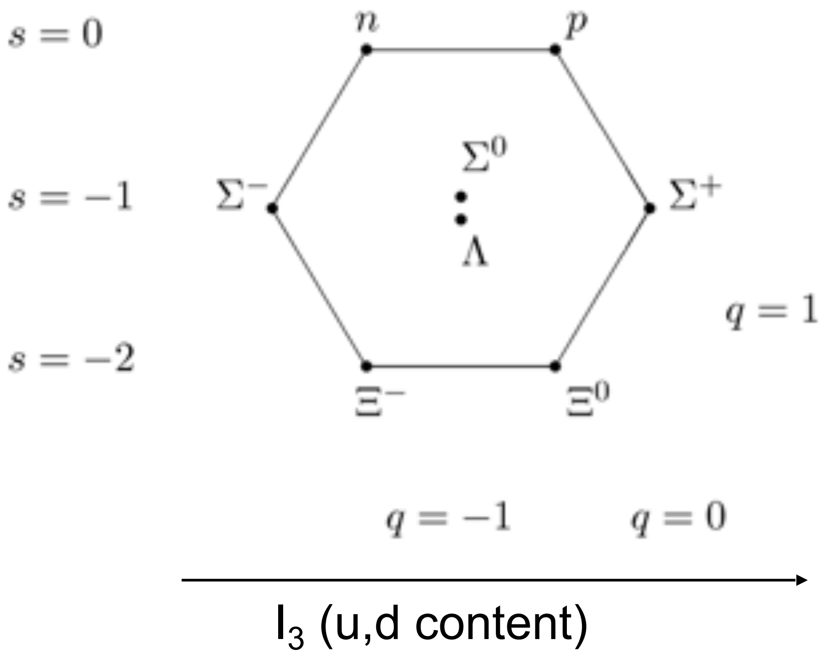
Quarks and gluons are the fundamental particles of QCD
(feature in the Lagrangian)

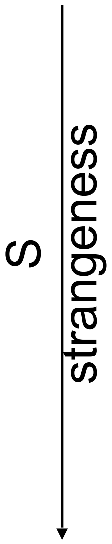


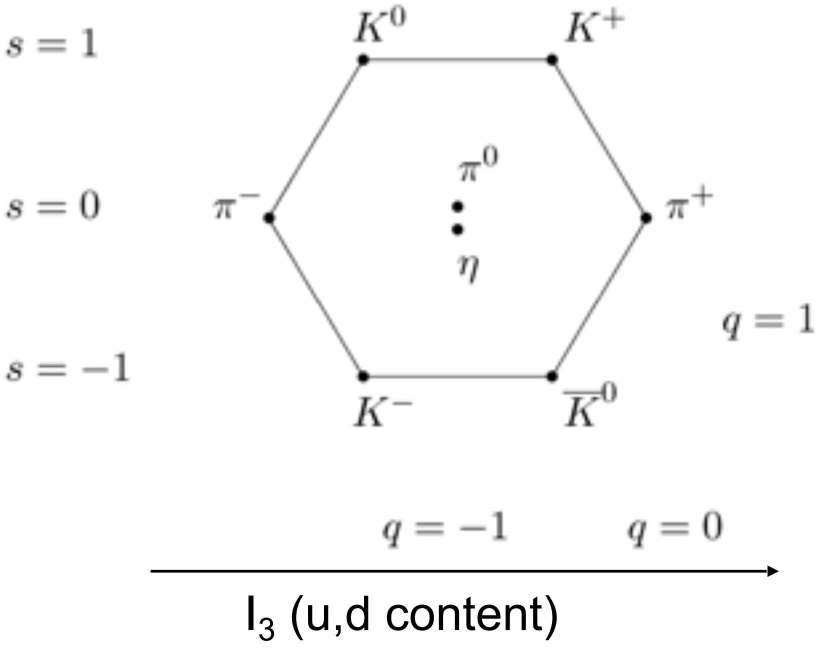
However, in nature, we observe hadrons:
Color-neutral combinations of quarks, anti-quarks

Baryon multiplet

Meson multiplet



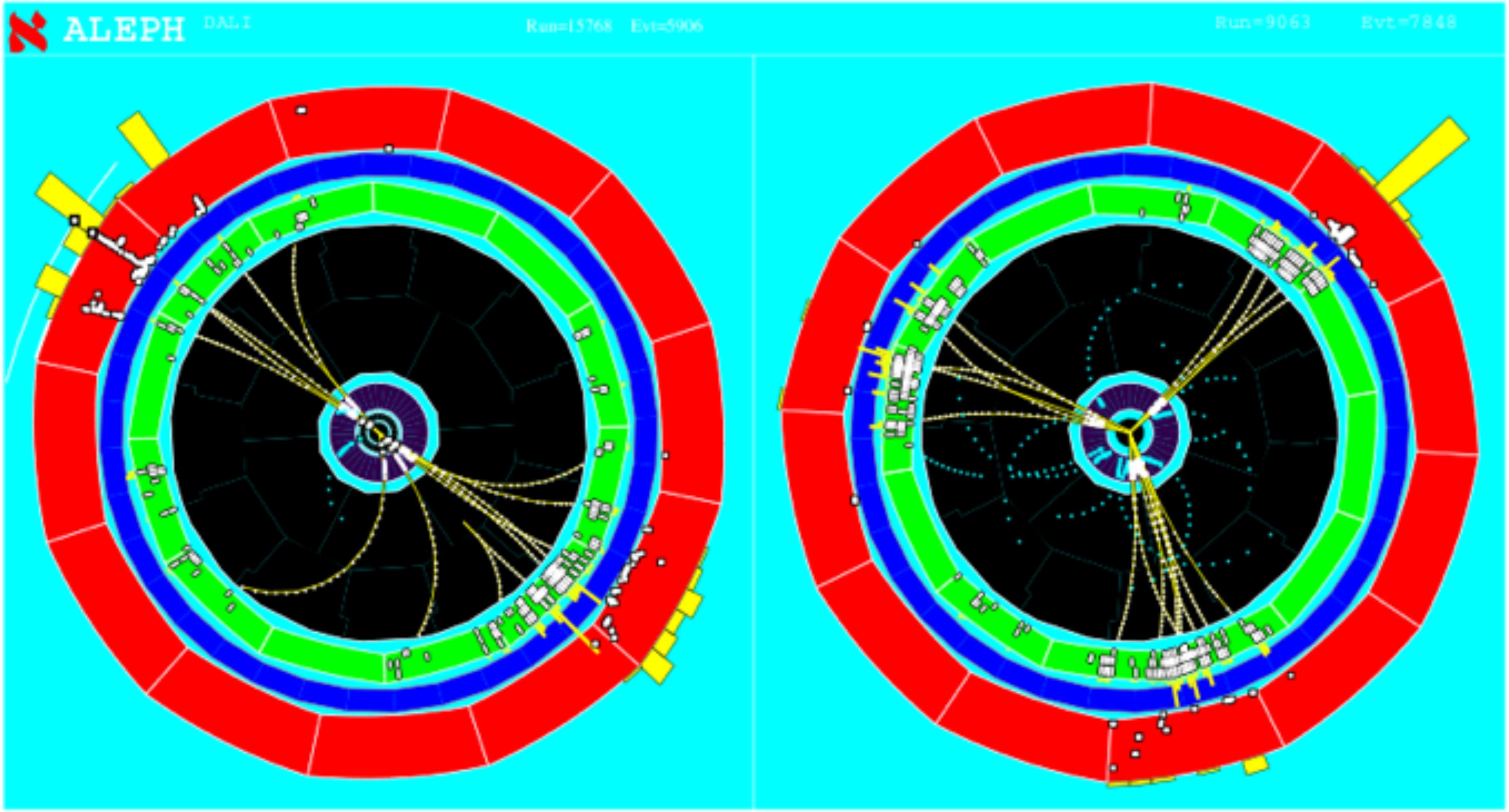




Baryons: 3 quarks

Mesons: quark-anti-quark

Seeing quarks and gluons



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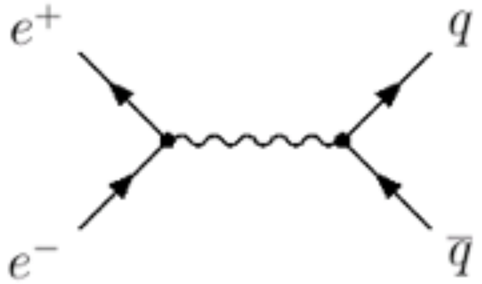
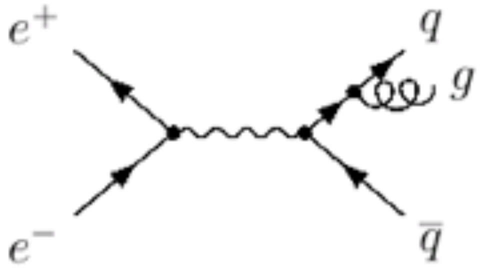
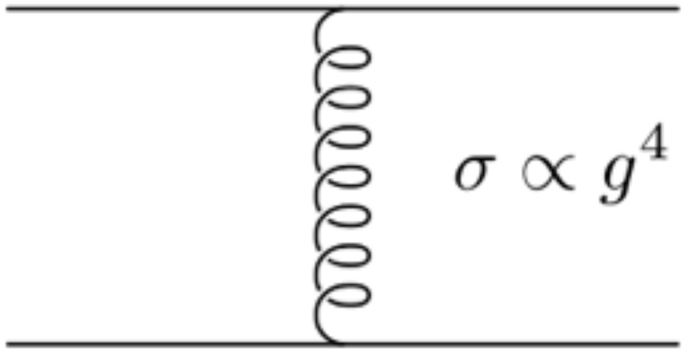




In high-energy collisions, observe traces of quarks, gluons (‘jets’)

How does it fit together?



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

Running coupling:
α_s decreases with Q^2

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

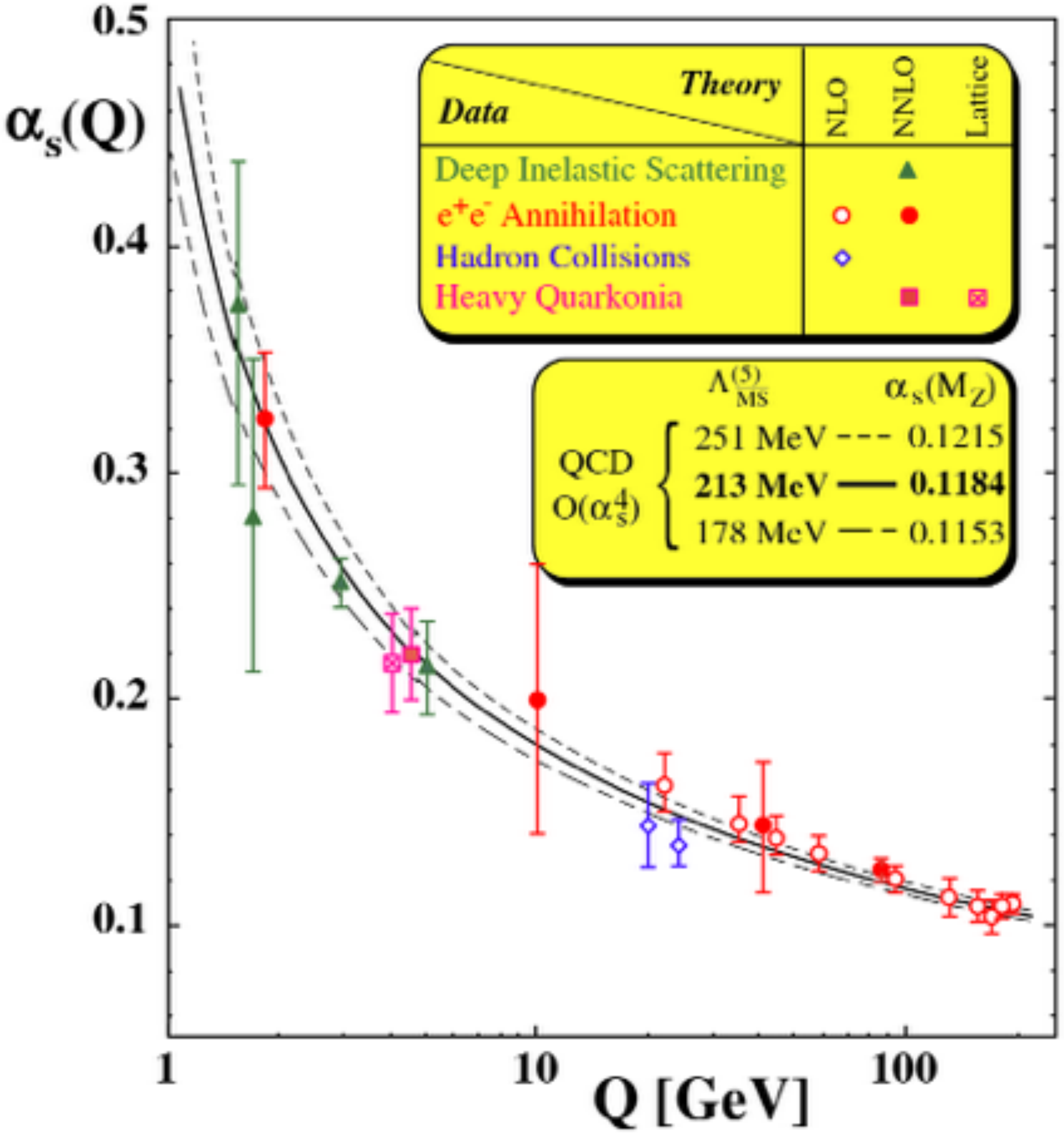
$$\alpha_s(\mu^2) = \frac{4\pi}{\beta_1 \ln(\mu^2/\Lambda^2_{QCD})}$$

Pole at $\mu = \Lambda$

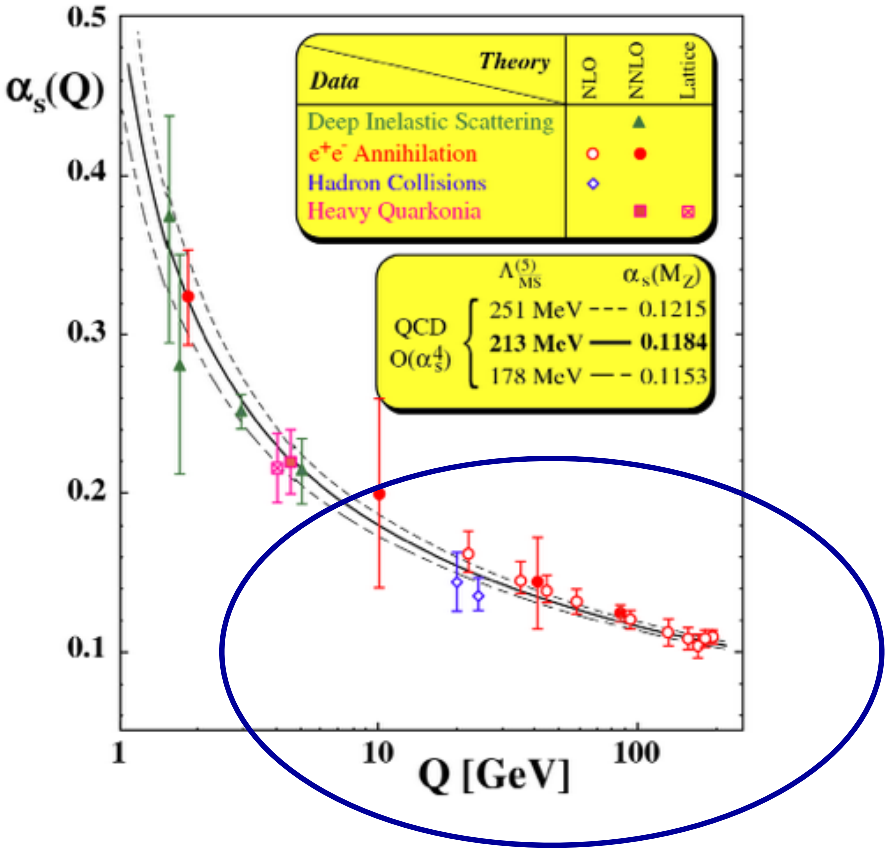
Λ_{QCD} ~ 200 MeV ~ 1 fm^{-1}

Hadronic scale

S. Bethke, J Phys G 26, R27

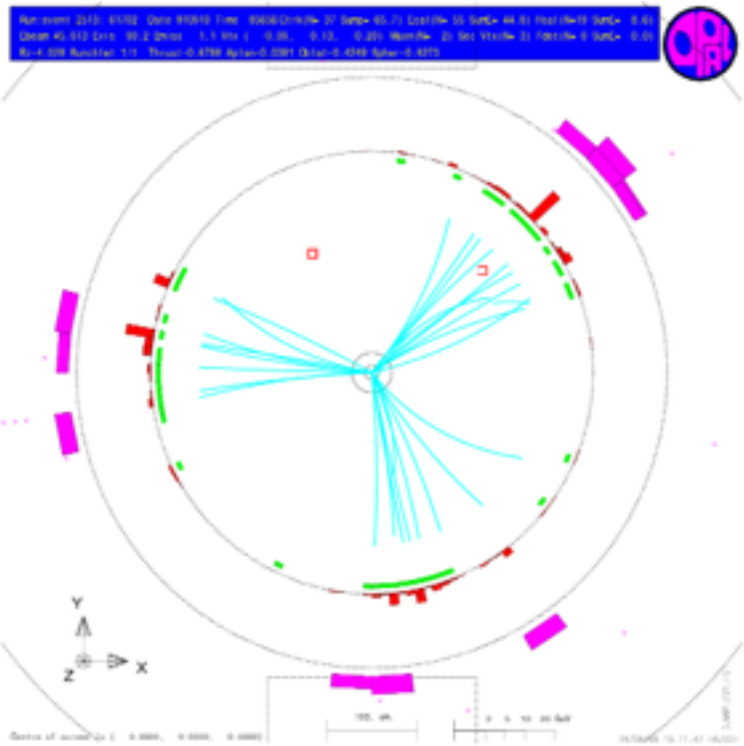


Asymptotic freedom and pQCD

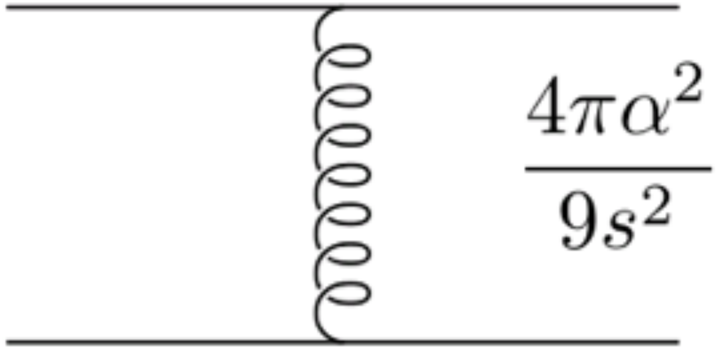


At large Q^2, hard processes: calculate ‘free parton scattering’

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



At high energies, quarks and gluons are manifest



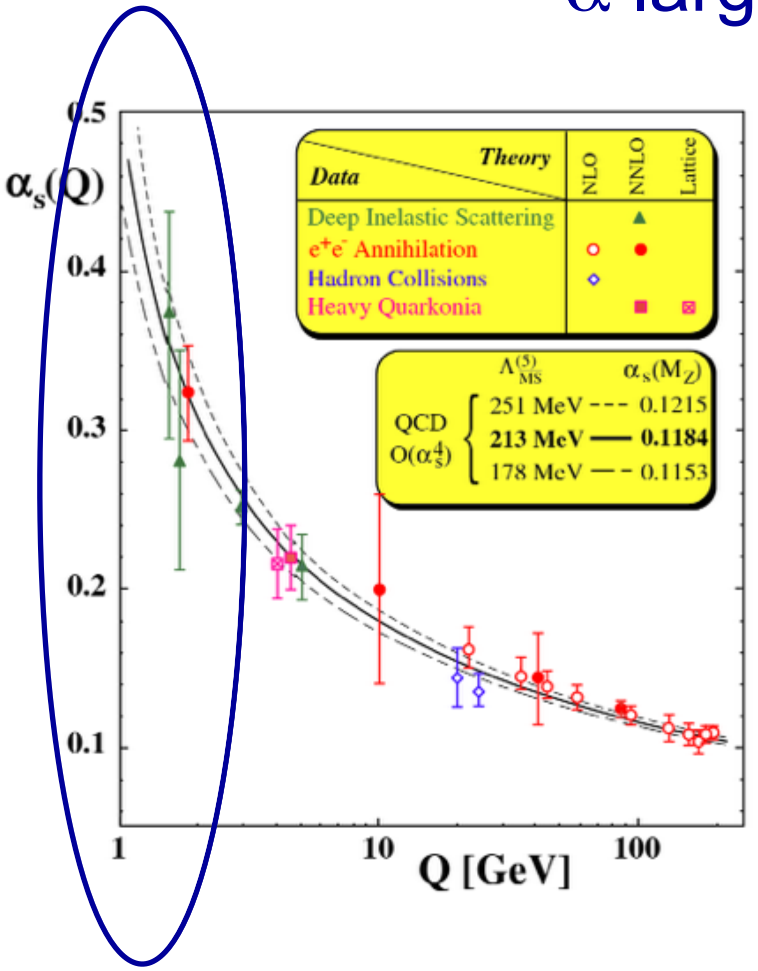
$$\frac{4\pi\alpha^2}{9s^2}\,\frac{s^2+u^2}{t^2}$$

+ more subprocesses

But need to add hadronisation (+initial state PDFs)

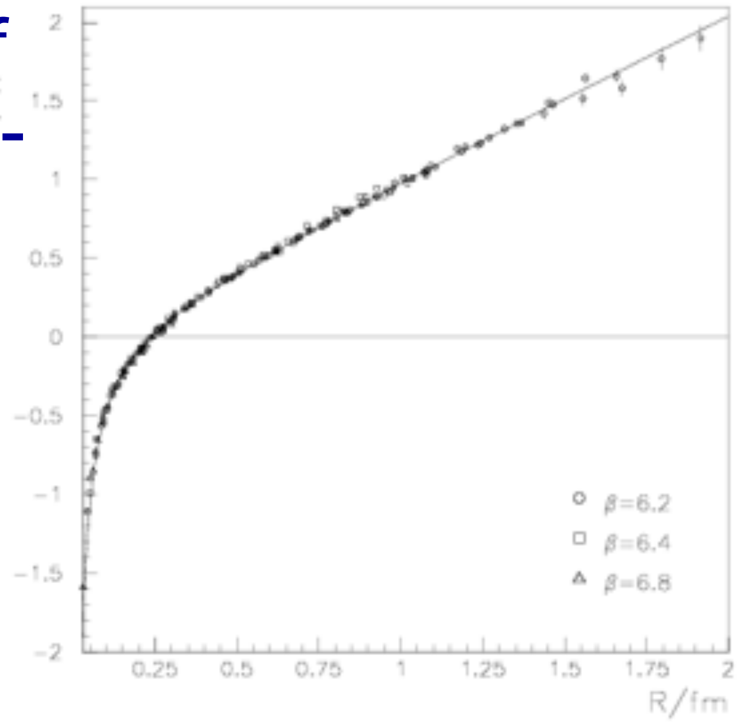
Low Q^2: confinement

α large, perturbative techniques not suitable

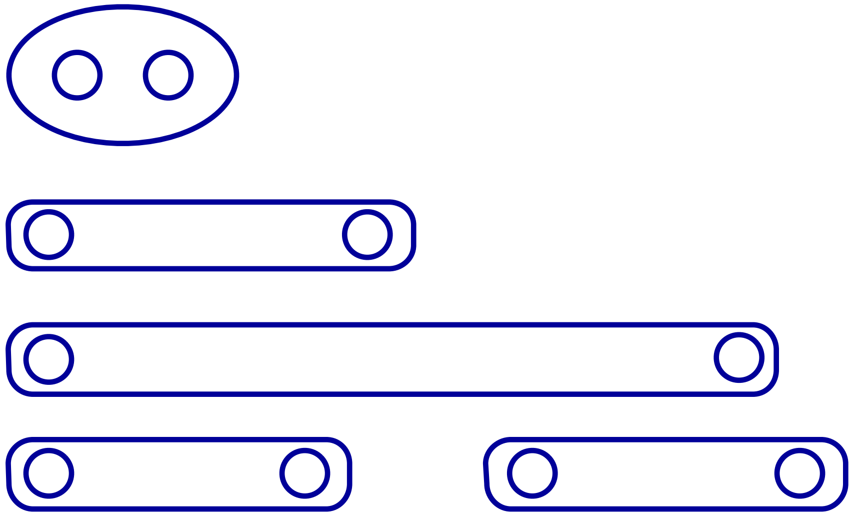


Lattice QCD: solve equations of motion (of the fields) on a space-time lattice by MC

Bali, hep-lat/9311009



Lattice QCD potential



String breaks, generate qq pair to reduce field energy

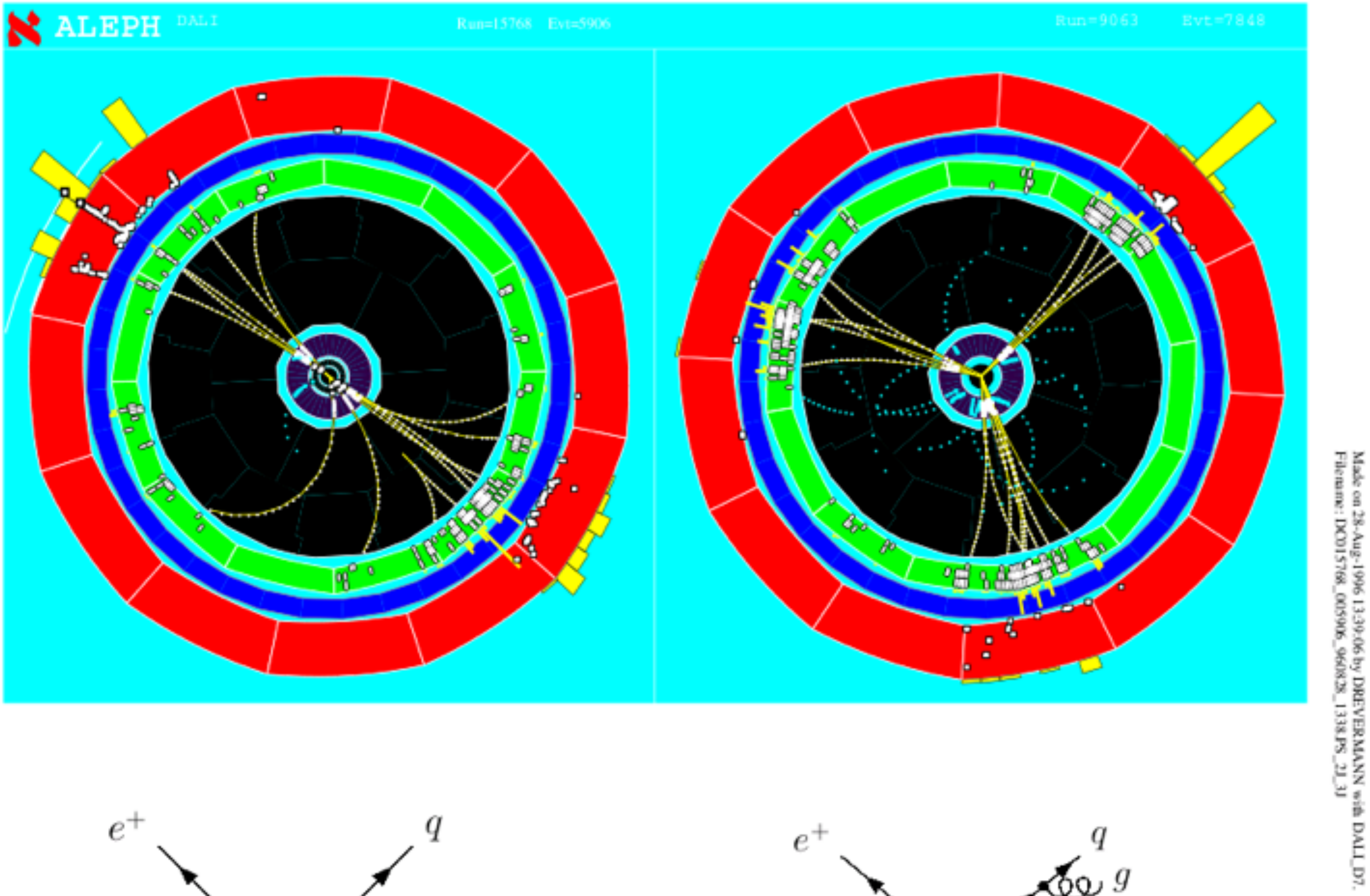
Part I: Hard processes in fundamental collisions

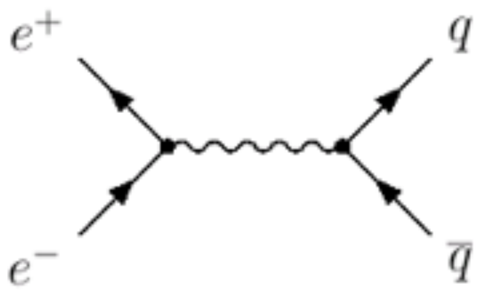
Accelerators and colliders

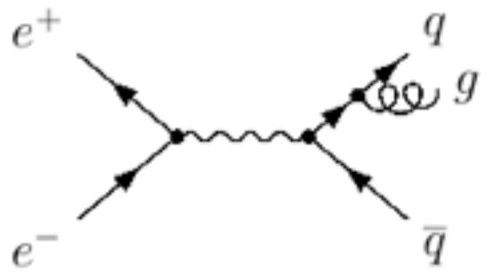
- p+p colliders (fixed target+ISR, SPPS, TevaTron, LHC)
  - Low-density QCD
  - Broad set of production mechanisms
- Electron-positron colliders (SLC, LEP)
  - Electroweak physics
  - Clean, exclusive processes
  - Measure fragmentation functions
- ep, μp accelerators (SLC, SPS, HERA)
  - Deeply Inelastic Scattering, proton structure
  - Parton density functions
- Heavy ion accelerators/colliders (AGS, SPS, RHIC, LHC)
  - Bulk QCD and Quark Gluon Plasma

Many decisive QCD measurements done

Seeing quarks and gluons



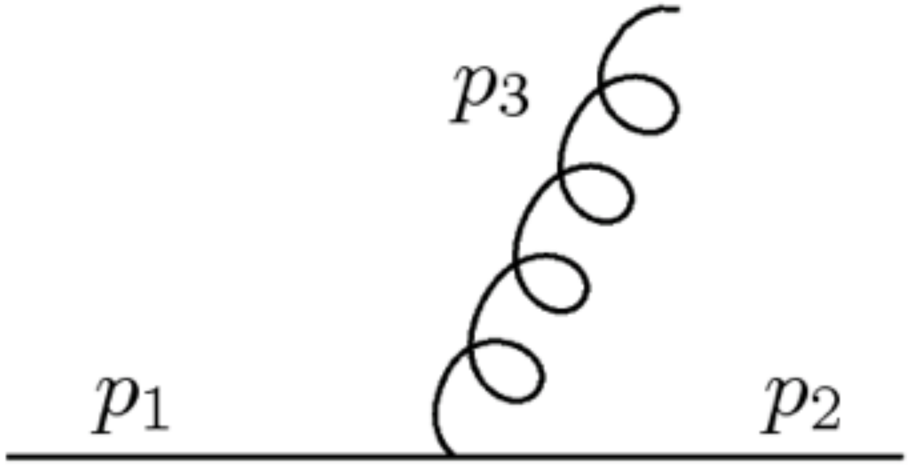




In high-energy collisions, observe traces of quarks, gluons ('jets')

Singularities in pQCD

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



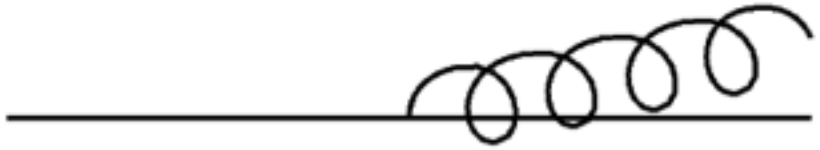
$$x_1 = 1 - \frac{2p_2 \cdot p_3}{Q^2}$$

(massless case)

Soft divergence

$p_3 \longrightarrow 0$

Collinear divergence



$p_2 \cdot p_3 \longrightarrow 0$

Closely related to hadronisation effects

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)

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

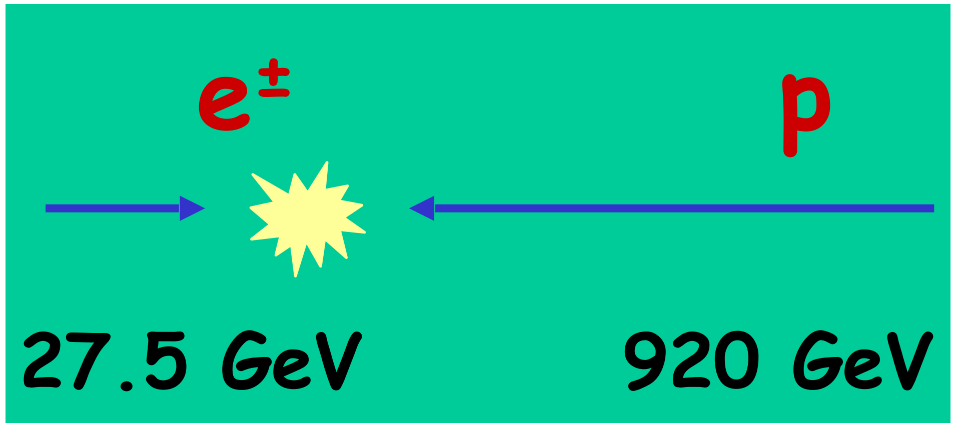
QM interference between hard and soft suppressed (by Q^2/Λ^2 'Higher Twist')

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

The HERA Collider

The first and only ep collider in the world

Hera at DESY near Hamburg



$e^{\pm}$ 27.5 GeV

p 920 GeV

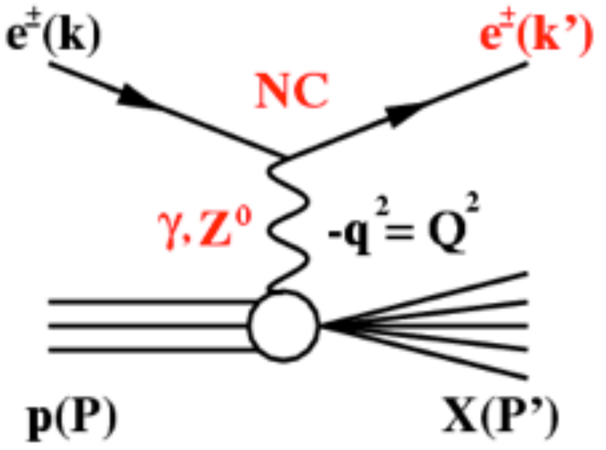
$\sqrt{s}$ = 318 GeV

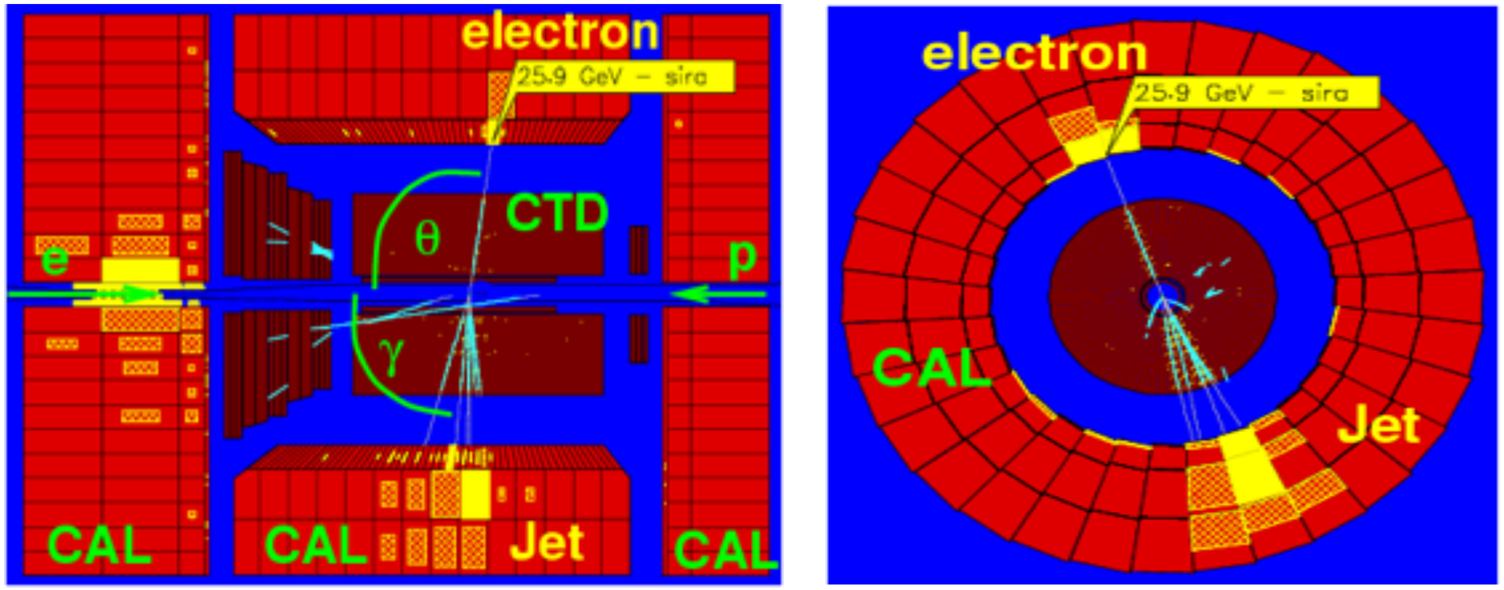
Equivalent to fixed target experiment with 50 TeV $e^{\pm}$

Example DIS events

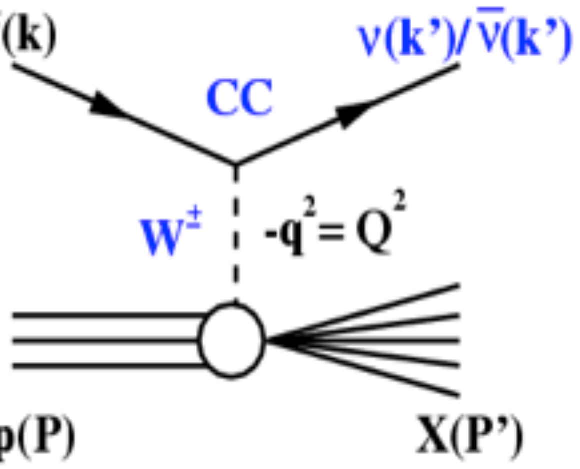
$$\mathrm{NC:}\quad e^{\pm} + p \rightarrow e^{\pm} + X, \qquad \mathrm{CC:}\quad e^{\pm} + p \rightarrow \bar{\nu}_e(\nu_e) + X$$

NC:

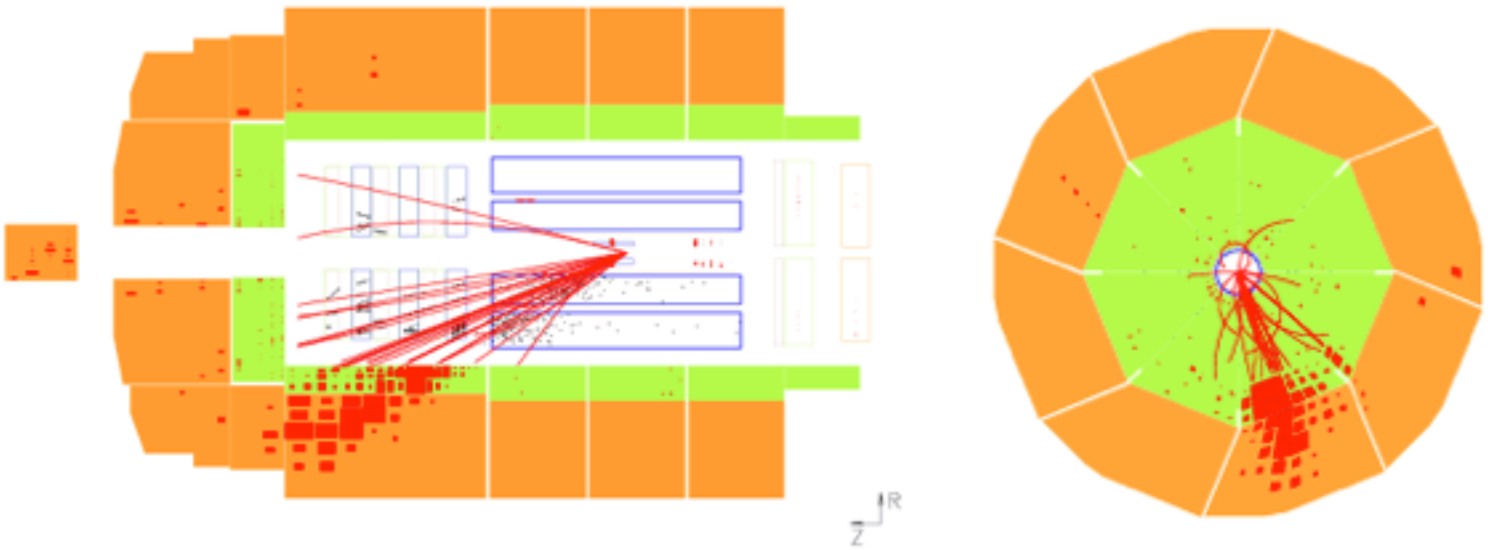




CC:

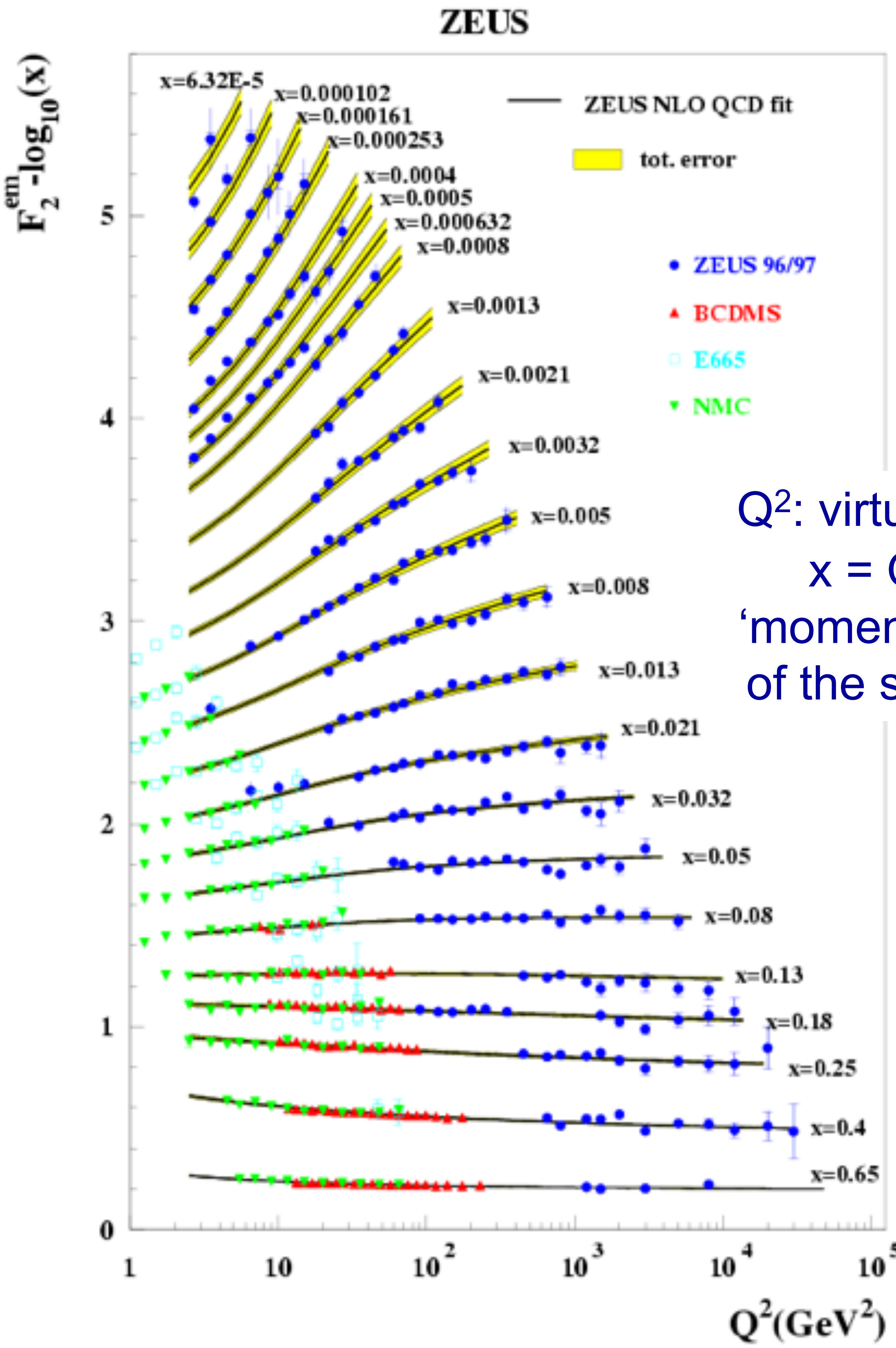


*Q**2 = 21475   y = 0.55   M = 198*



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

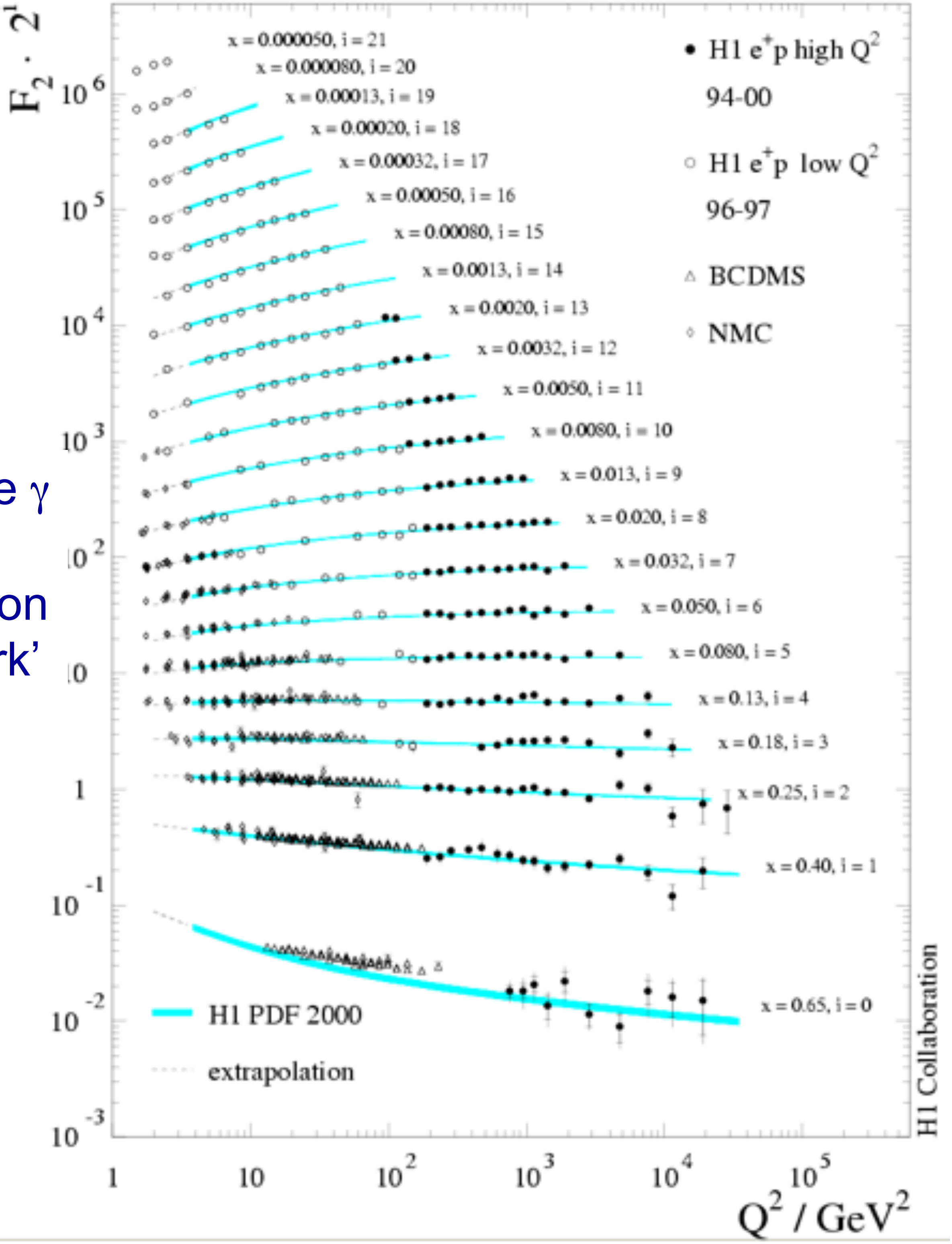
Proton structure F_2



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)

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

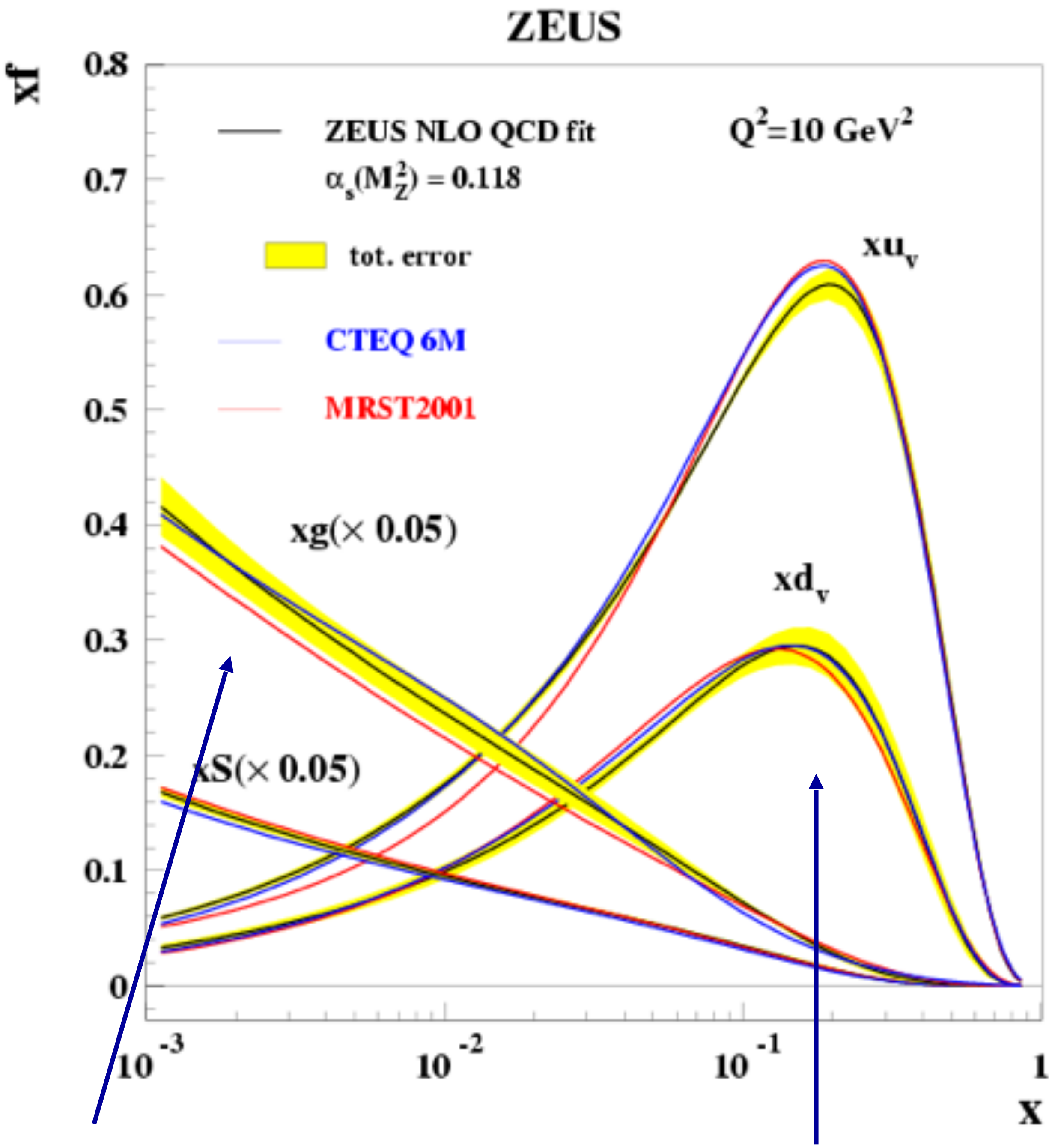
yet another scale: μ_r
due to the renormalization
of ultraviolet divergencies

choice of the factorization scheme

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

Parton density distribution

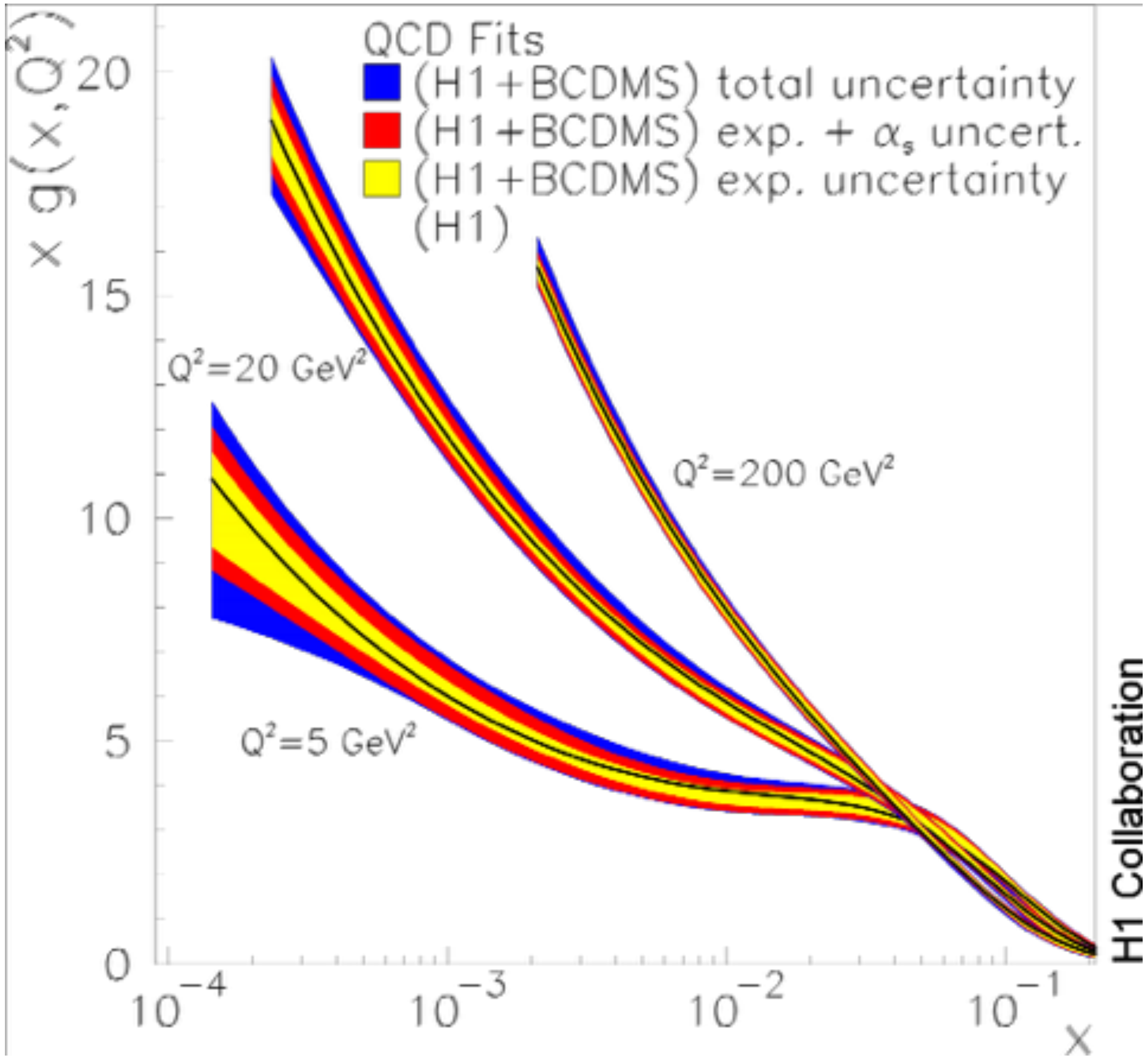
Low Q^2: valence structure



Soft gluons

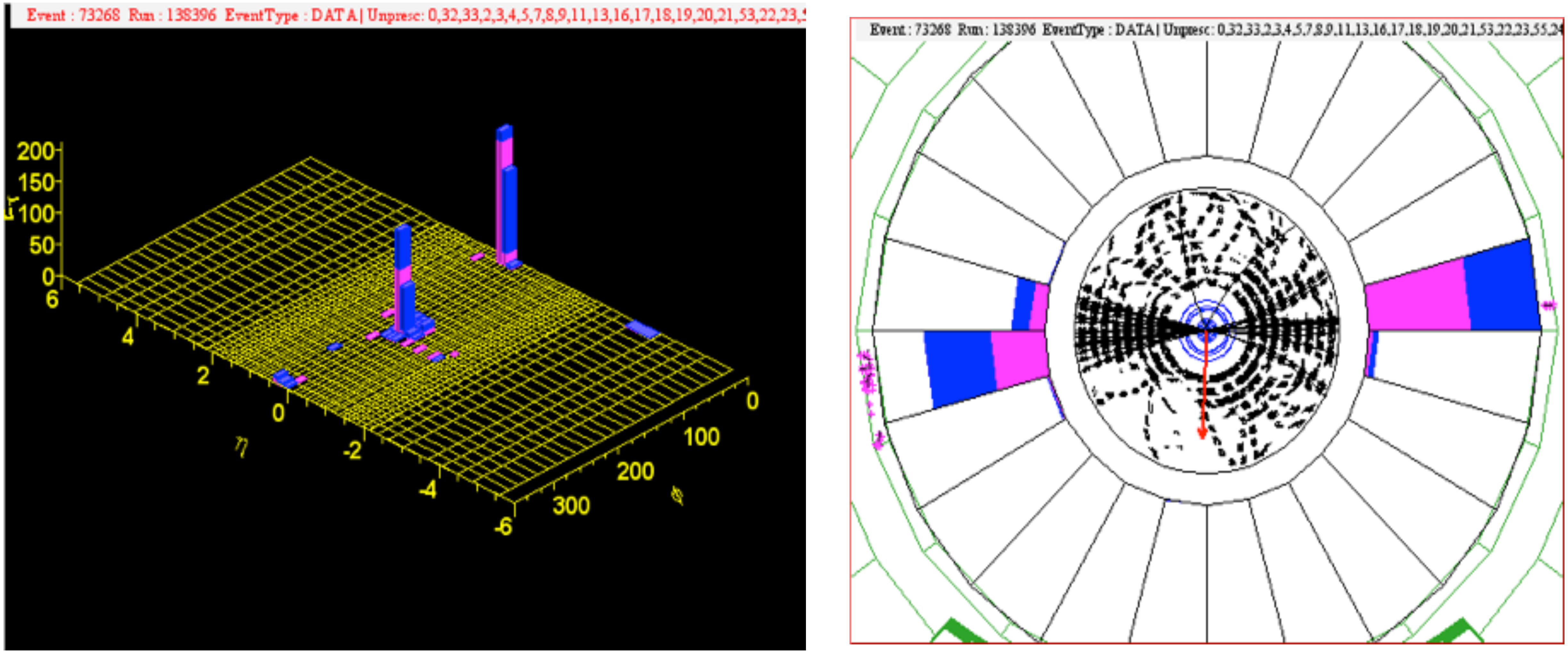
Valence quarks (p = uud)
x ~ 1/3

Q^2 evolution (gluons)



Gluon content of proton rises
quickly with Q^2

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



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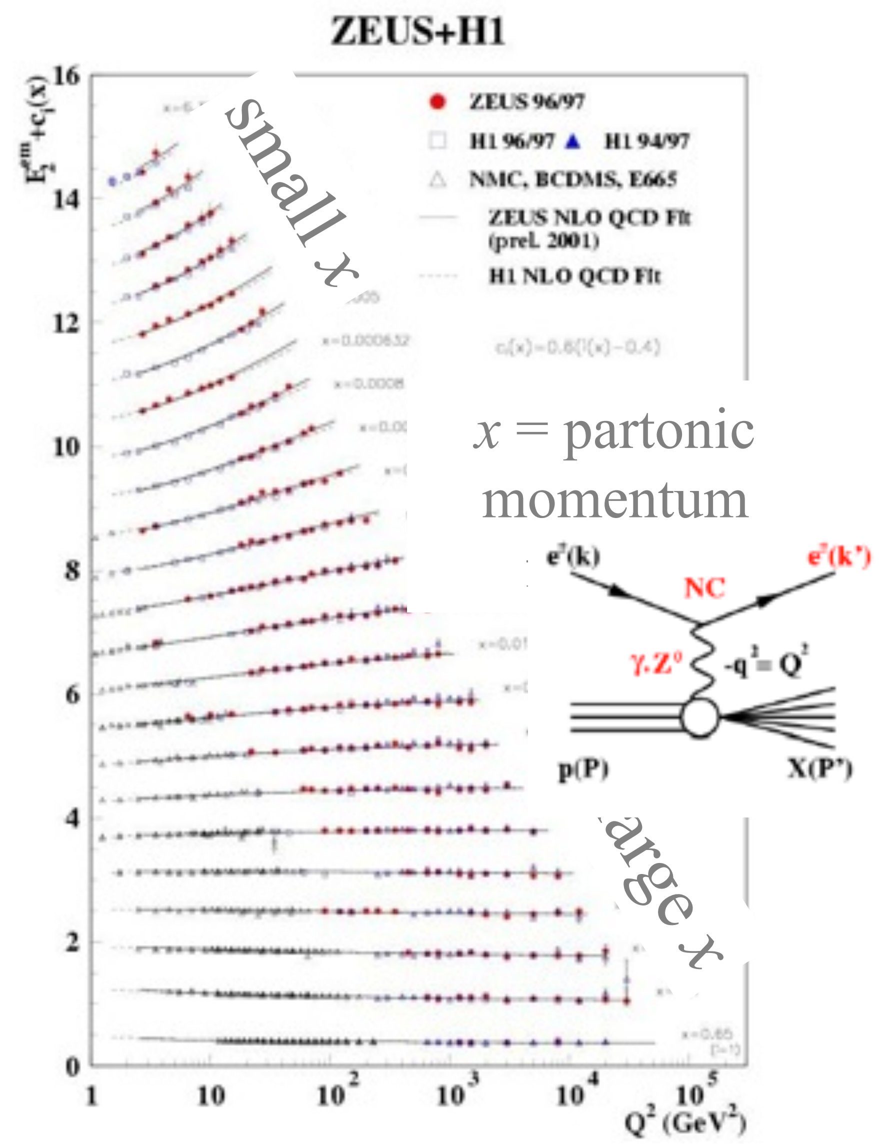
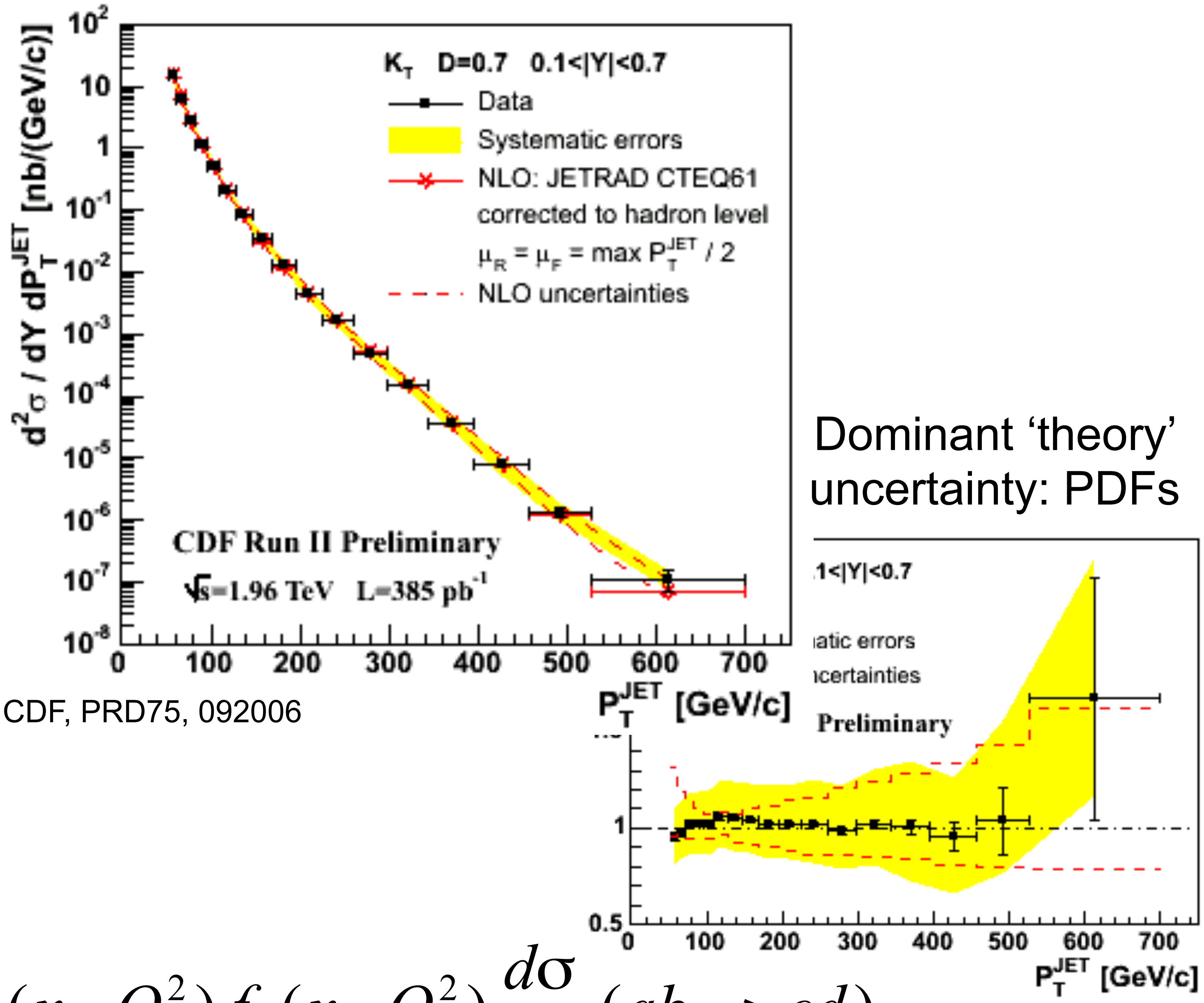
Tevatron: p + p at √s = 1.9 TeV

Jets produced with several 100 GeV

Testing QCD at high energy



DIS to measure PDFs



CDF, PRD75, 092006

Dominant 'theory' uncertainty: PDFs

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

Theory matches data over many orders of magnitude

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

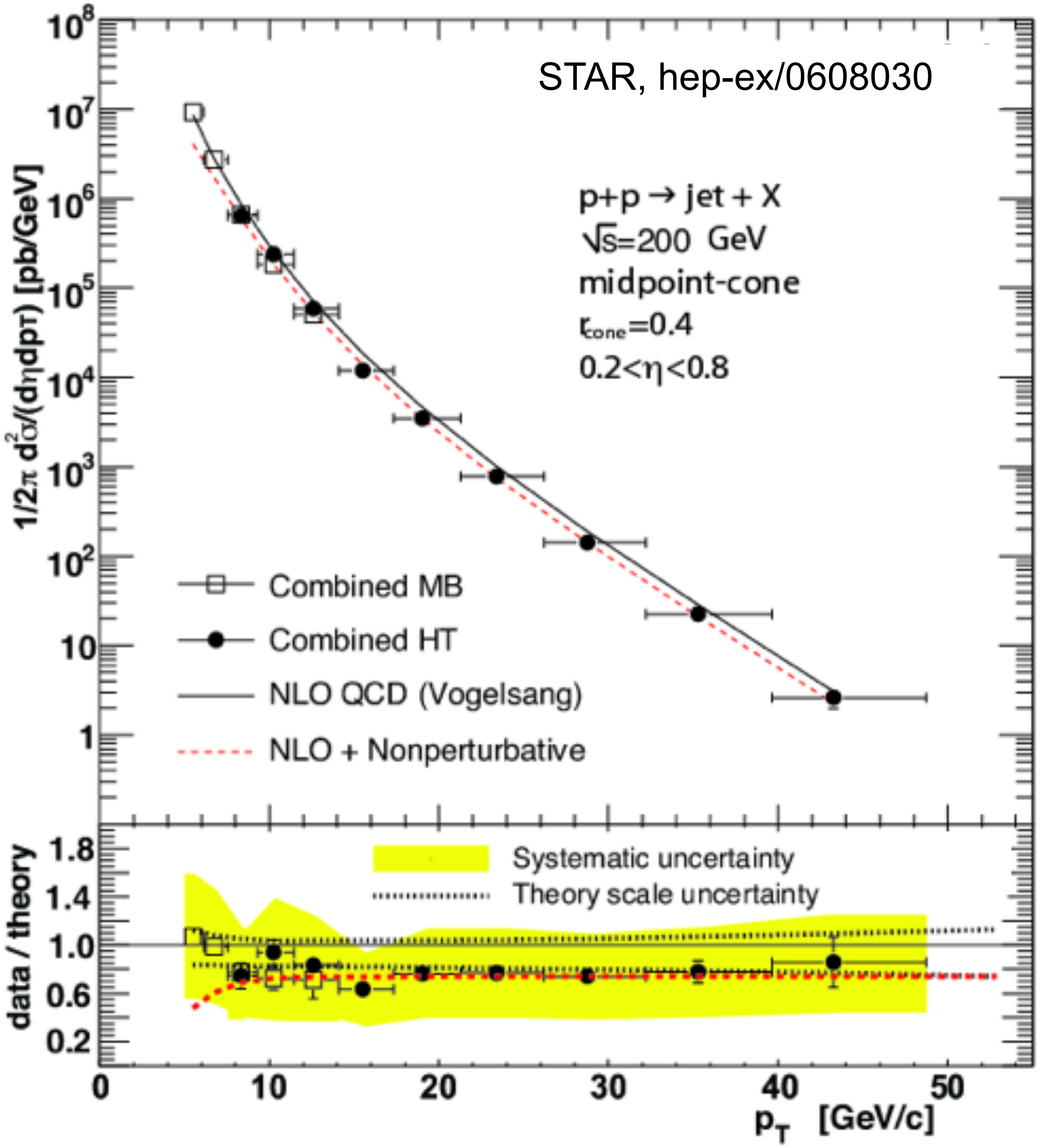
Testing QCD at RHIC with jets

RHIC: p+p at √s = 200 GeV
(recent run 500 GeV)

Jets also measured at RHIC

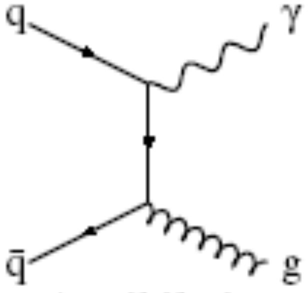
NLO pQCD also works at RHIC

However: signficant uncertainties in energy scale, both ‘theory’ and experiment

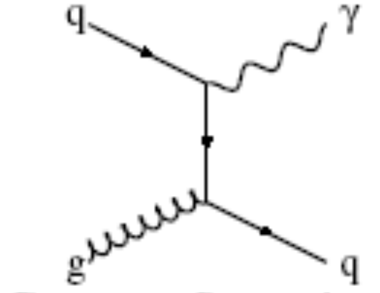

STAR, hep-ex/0608030

Direct photon basics

LO: γ does not fragment,
direct measure of partonic kinematics

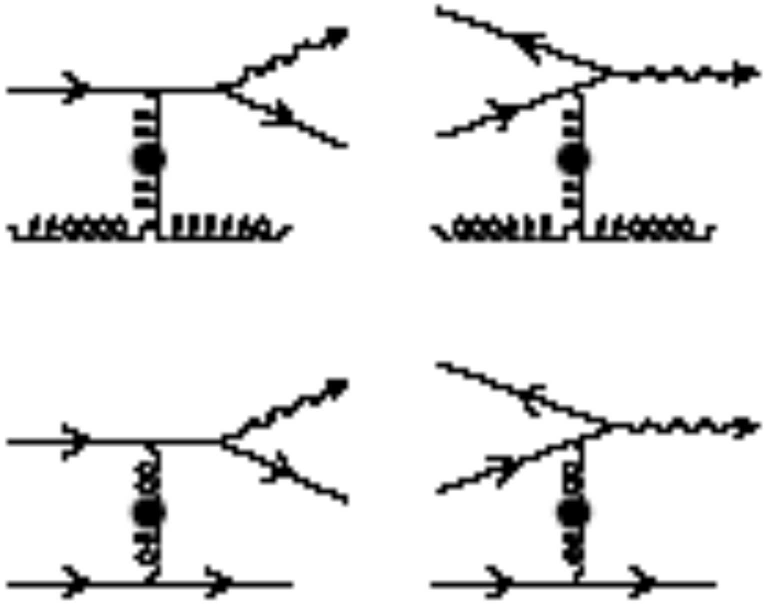


Annihilation



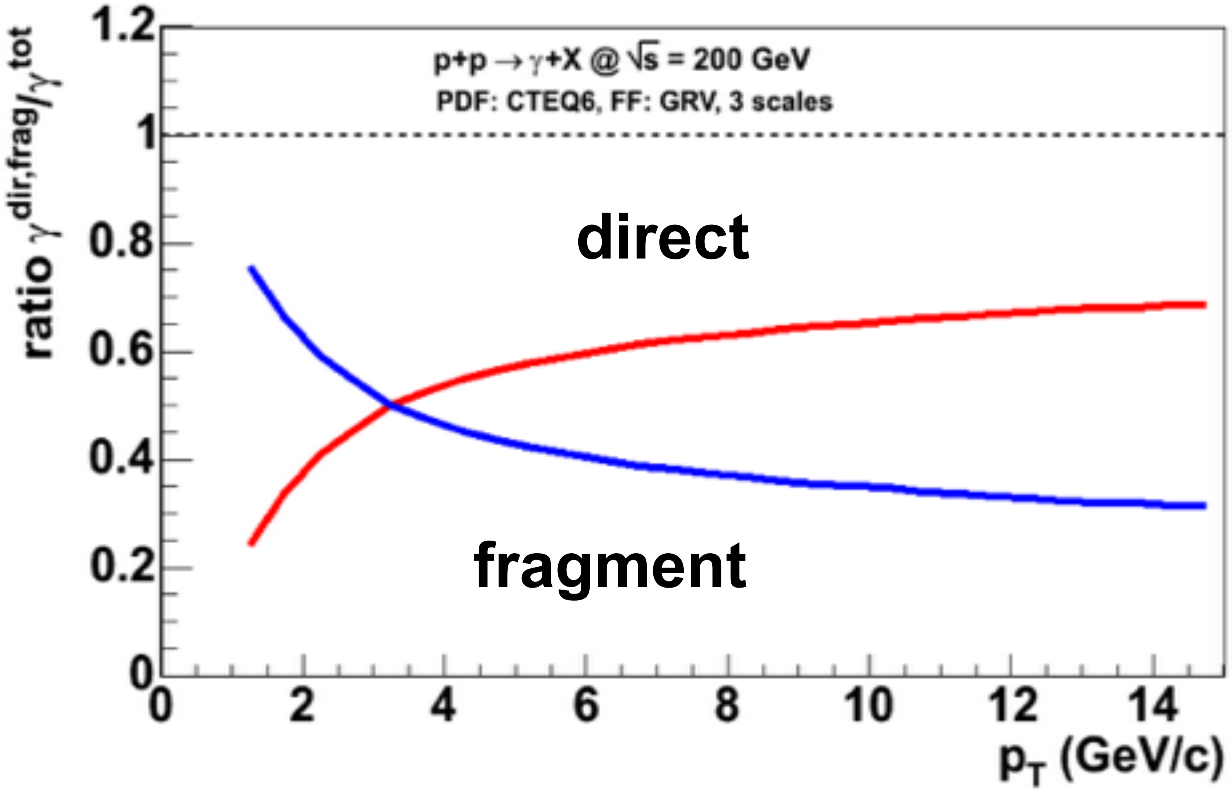
Compton Scattering

NLO: quarks radiate photons



‘fragmentation photons’

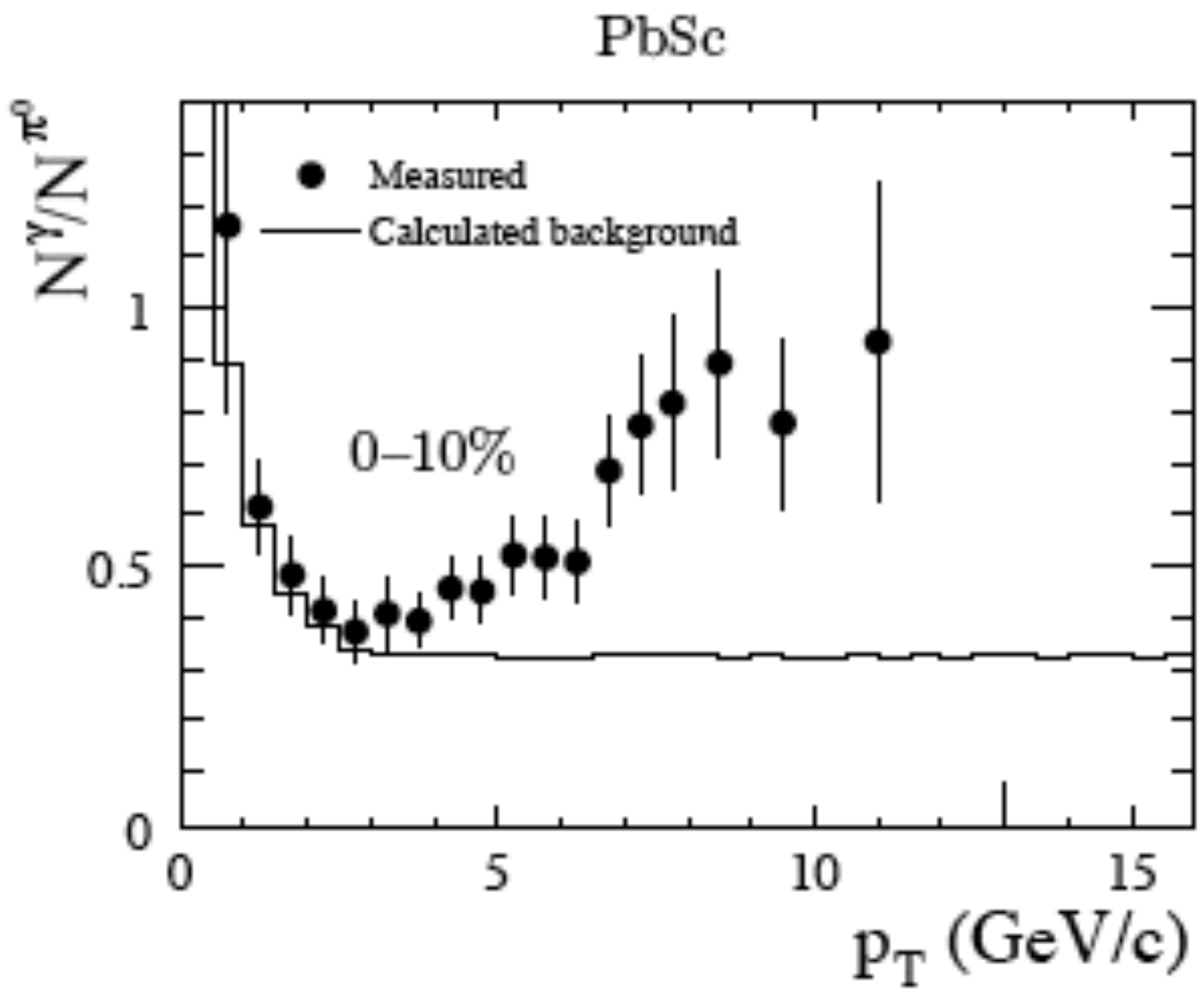
Small Rate: Yield $\propto \alpha\alpha_s$

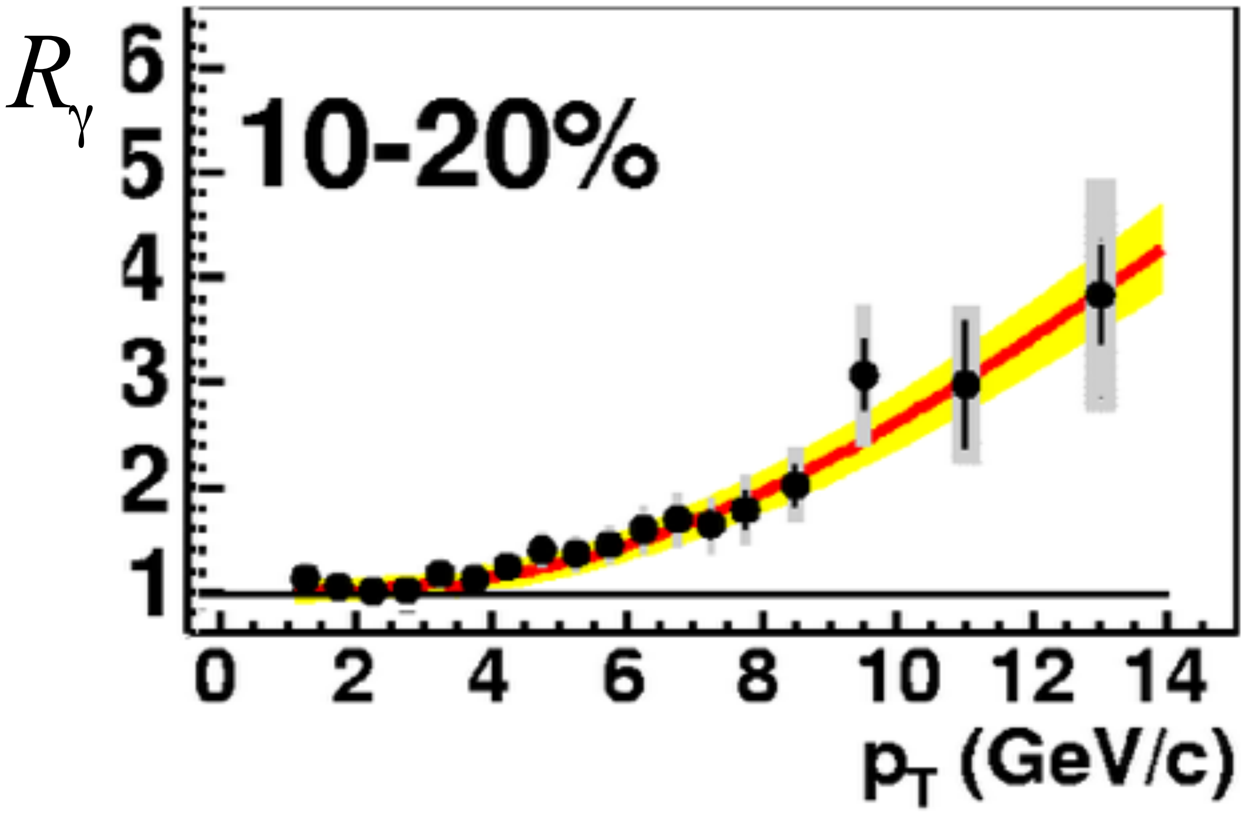


Gordon and Vogelsang, PRD48, 3136

Direct and fragmentation contribution
same order of magnitude

Experimental challenge: $\pi^0 \to \gamma\gamma$



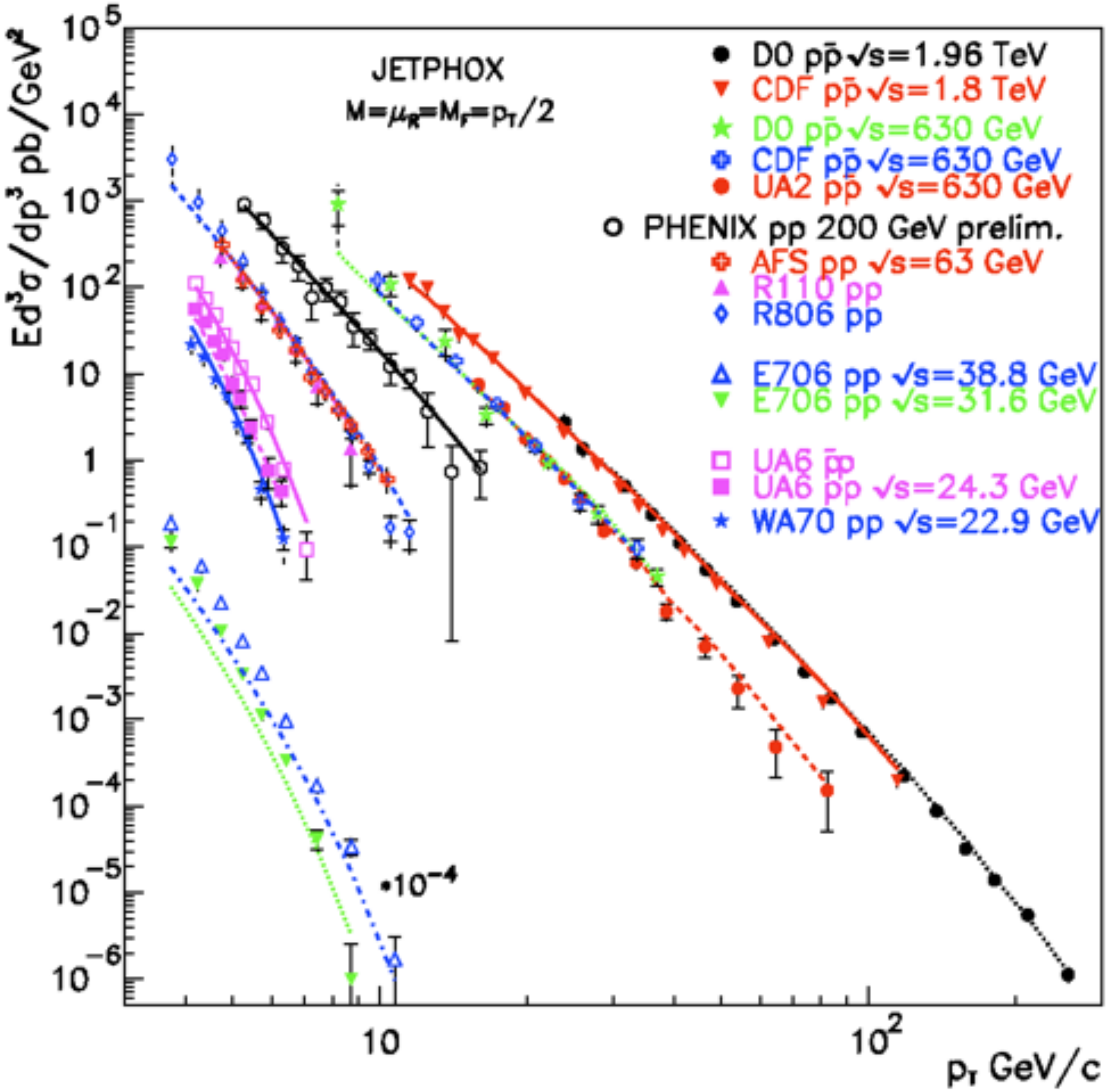


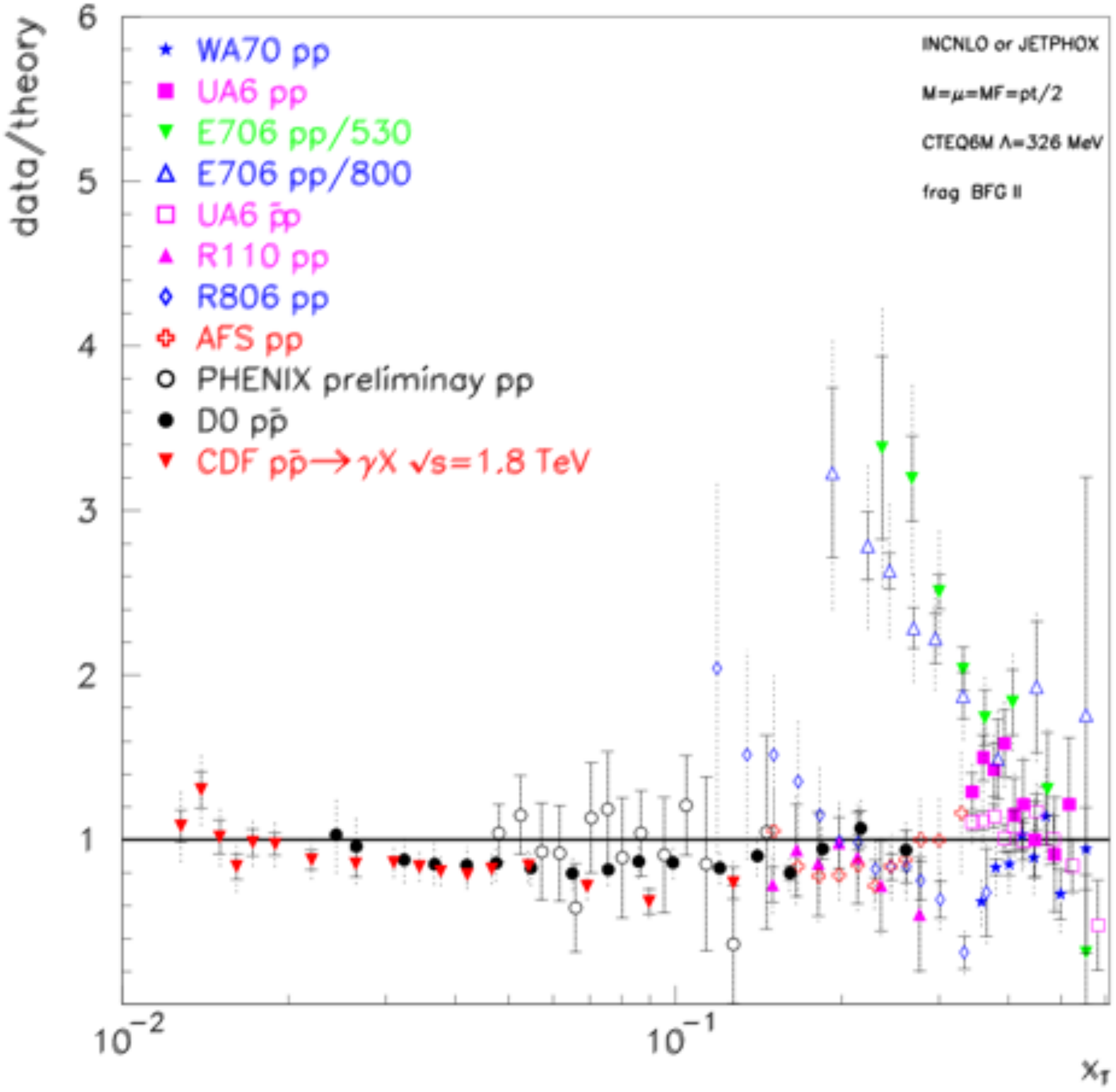
$$R_\gamma = \frac{(\gamma/\pi^0)_{\text{Measured}}}{(\gamma/\pi^0)_{\text{Background}}} \approx \frac{\gamma_{\text{Measured}}}{\gamma_{\text{Background}}}$$

Below p_T=5 GeV: decays dominant at RHIC

Direct photons: comparison to theory

P. Aurenche et al, PRD73:094007





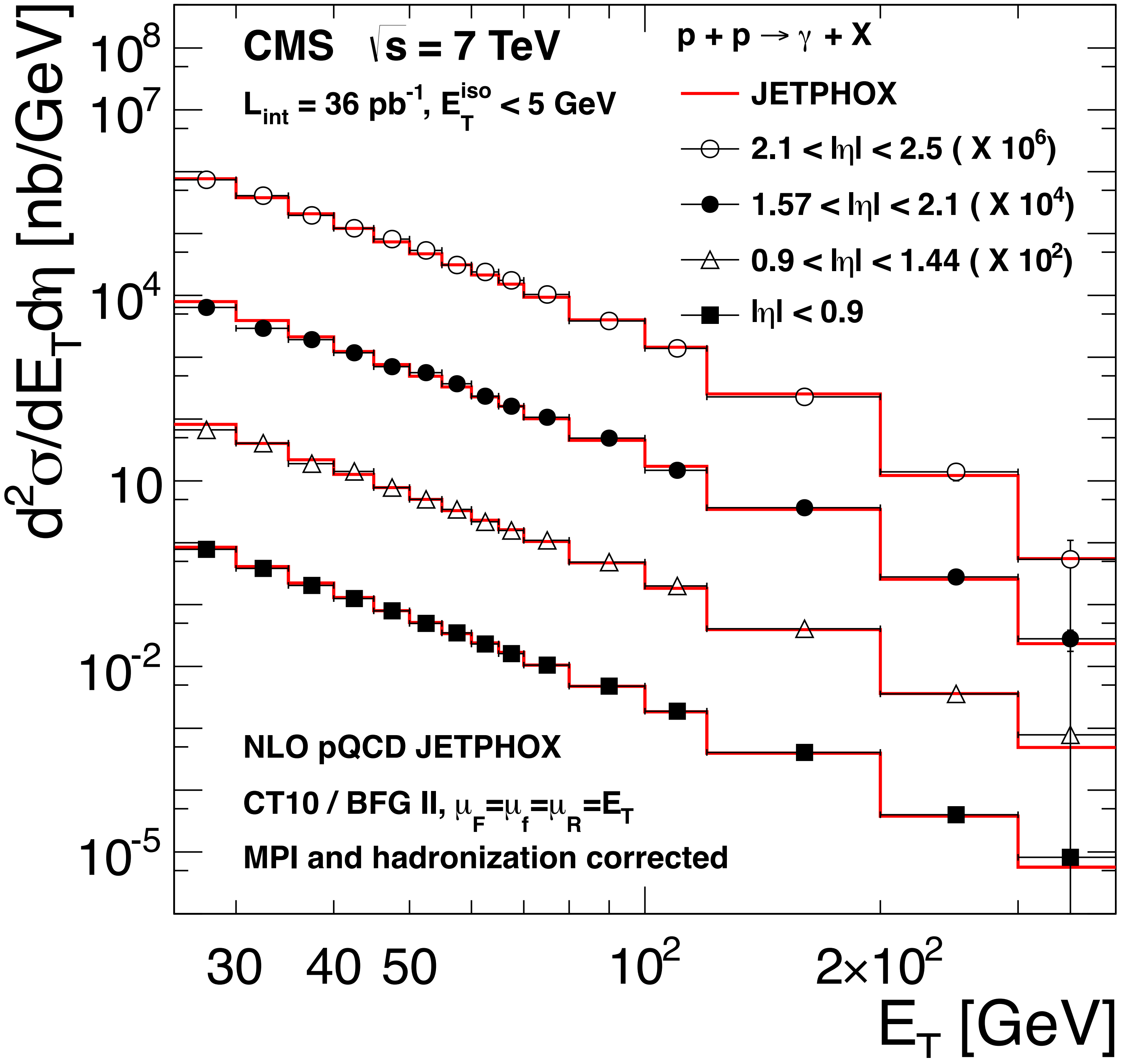
Good agreement theory-experiment

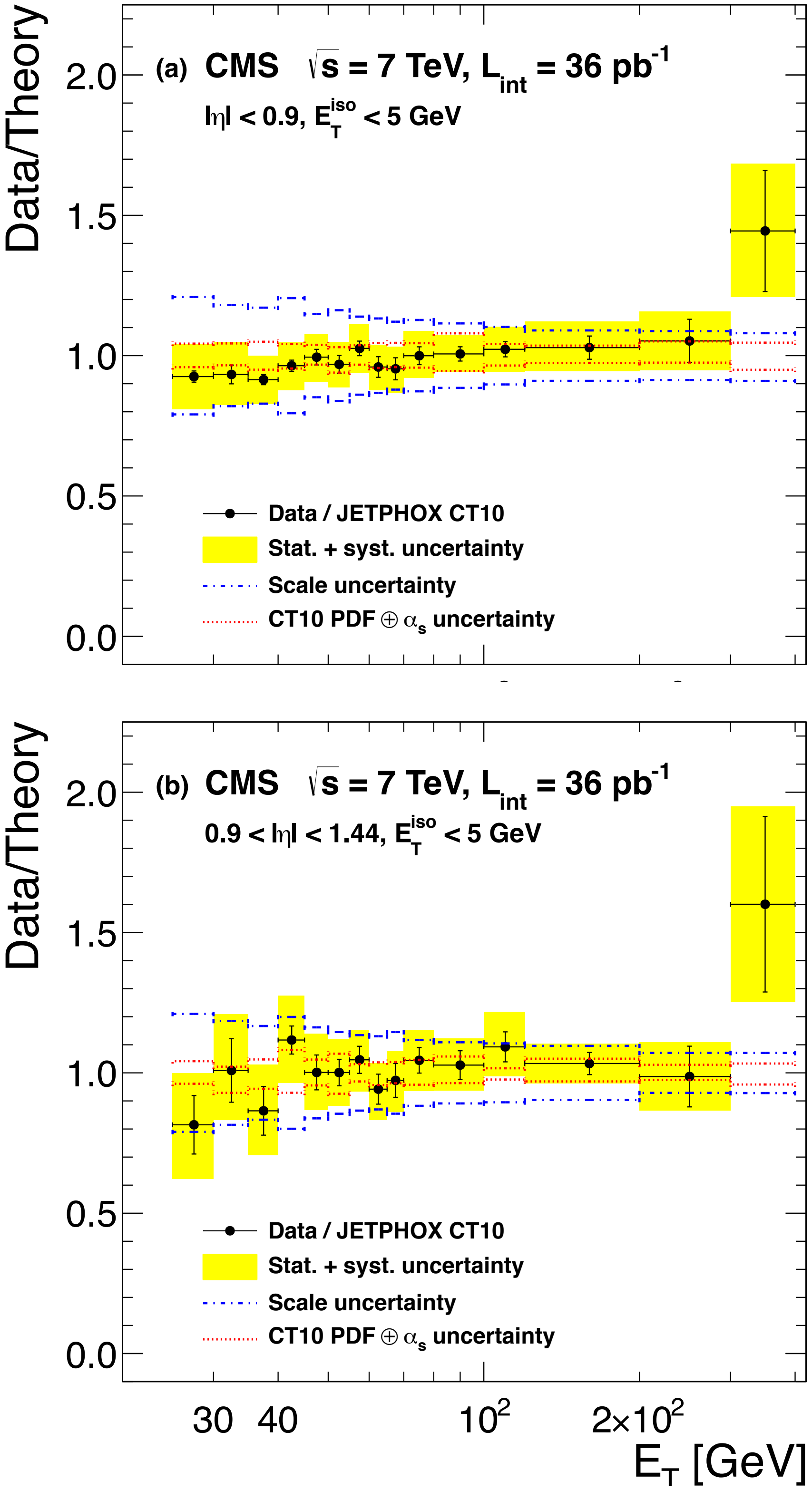
From low energy (√s=20 GeV at CERN) to highest energies (1.96 TeV TevaTron)

Exception: E706, fixed target FNAL deviates from trend: exp problem?

Direct photons LHC

(Isolated prompt photons)



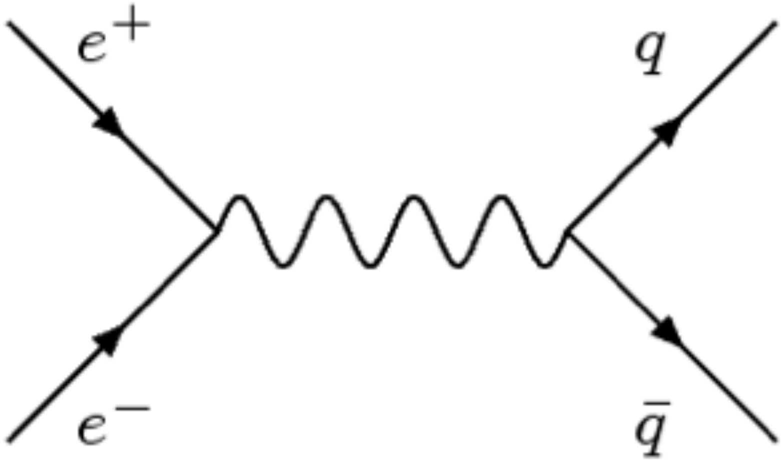


CMS, arXiv:1108.2044

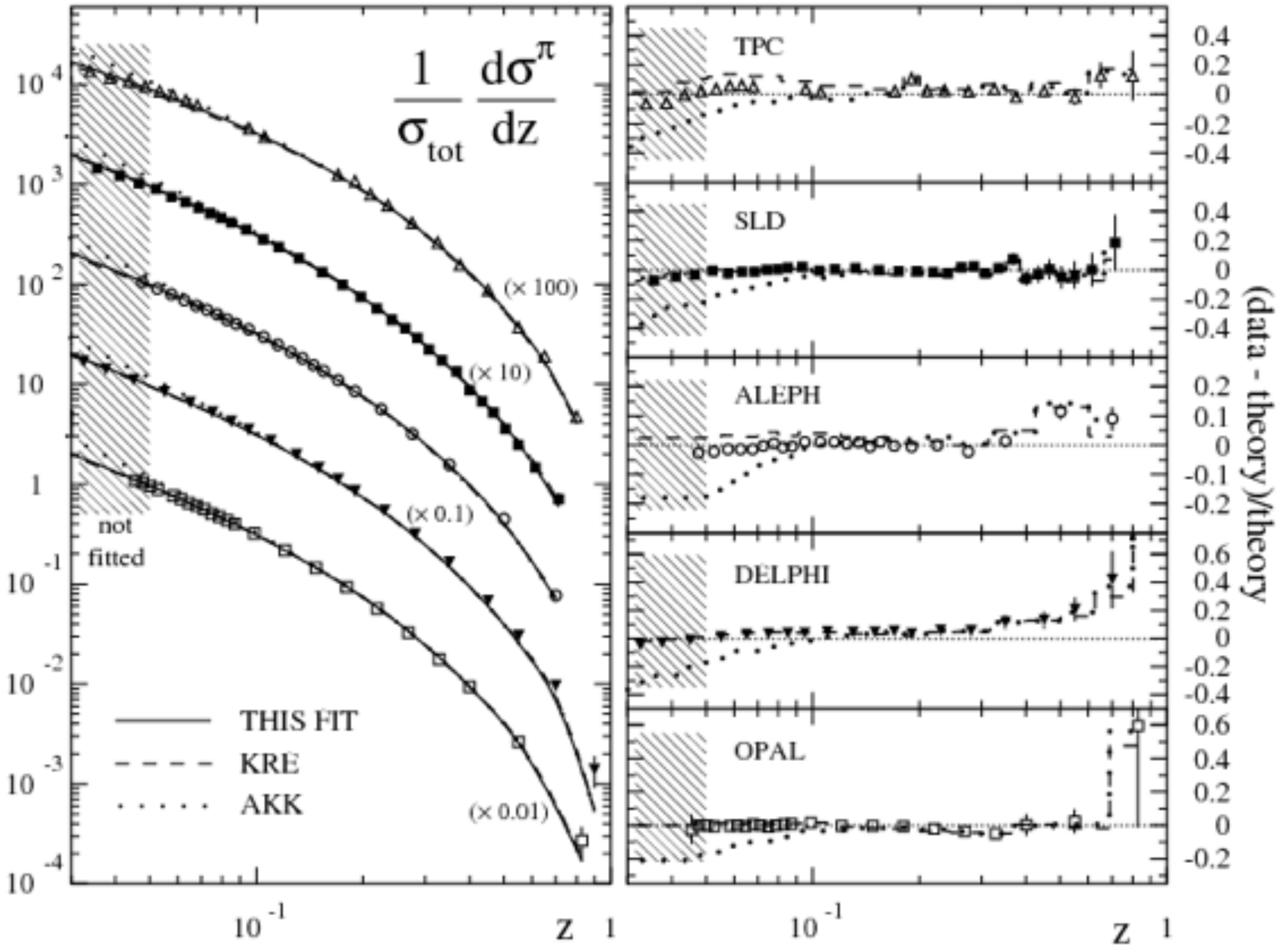
Good agreement data-theory also in p+p at LHC

Towards hadron production: Fragmentation Functions

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

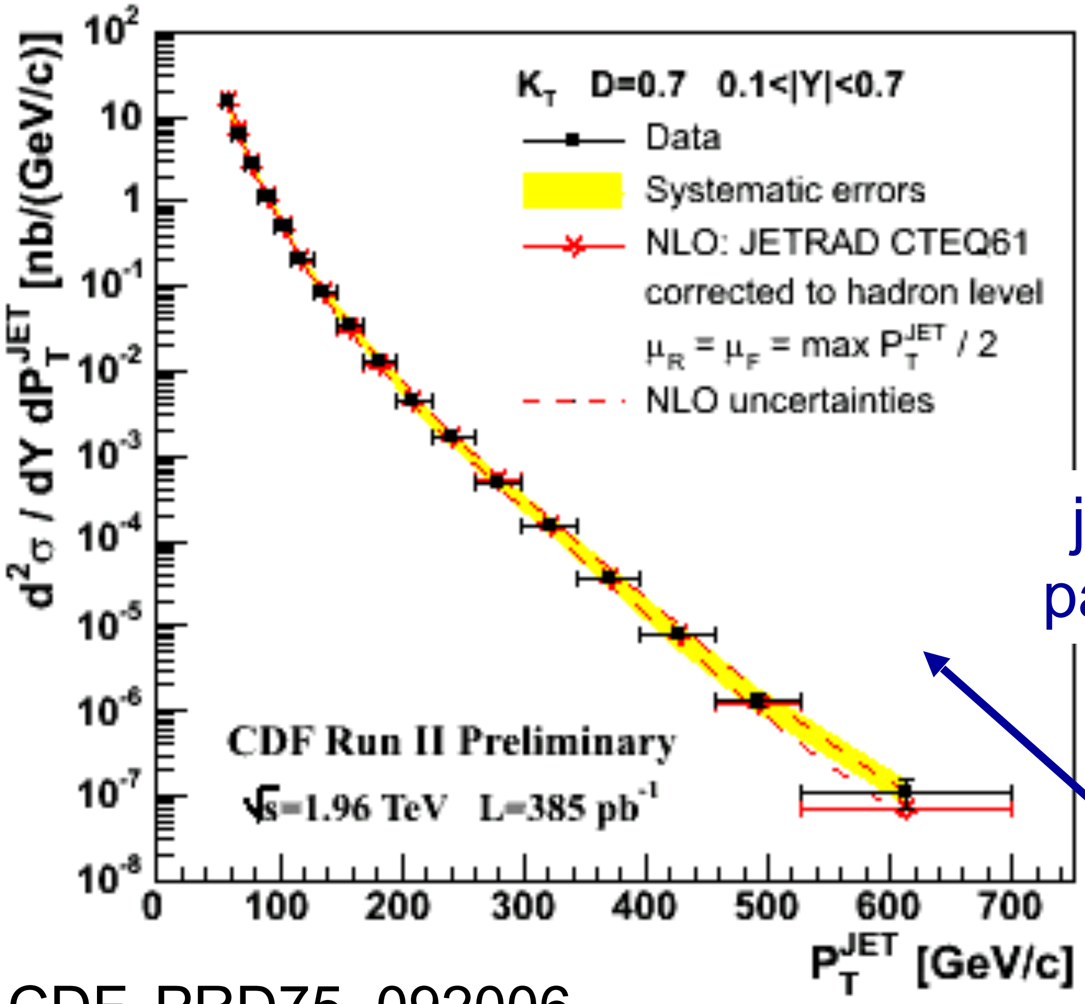


$$\begin{aligned} \vec{p}_{e^+} &= -\vec{p}_{e^-} \\ \vec{p}_q &= -\vec{p}_{\bar{q}} \\ p_q &= p_e \end{aligned}$$



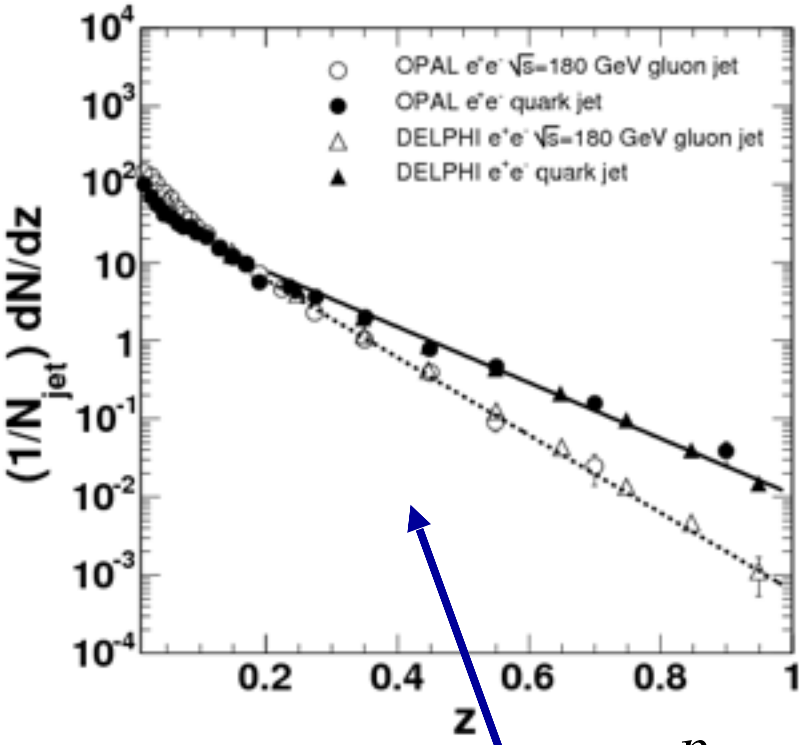
Direct measurement of fragmentation functions

pQCD illustrated



CDF, PRD75, 092006

fragmentation



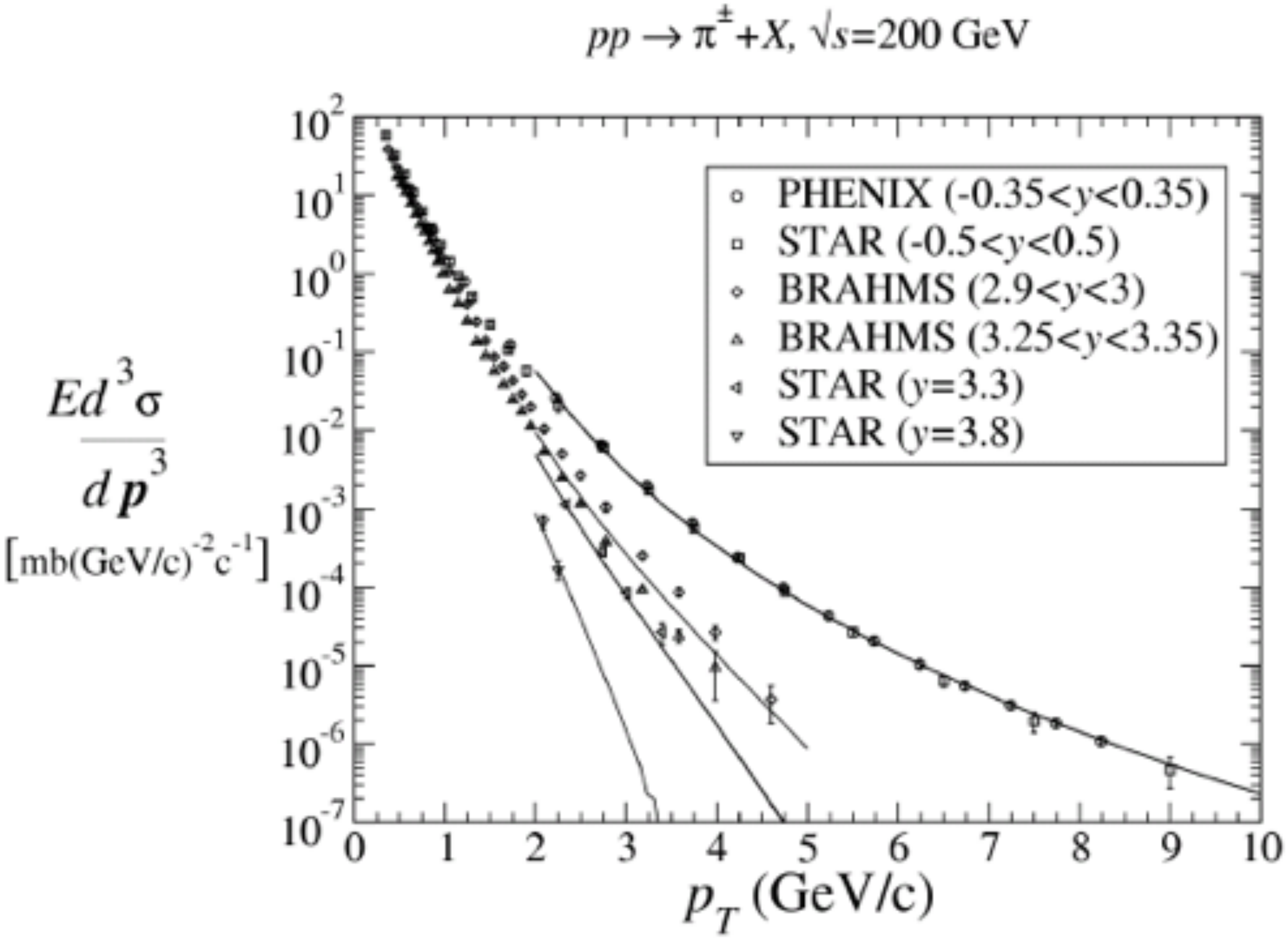
jet spectrum ~
parton spectrum

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

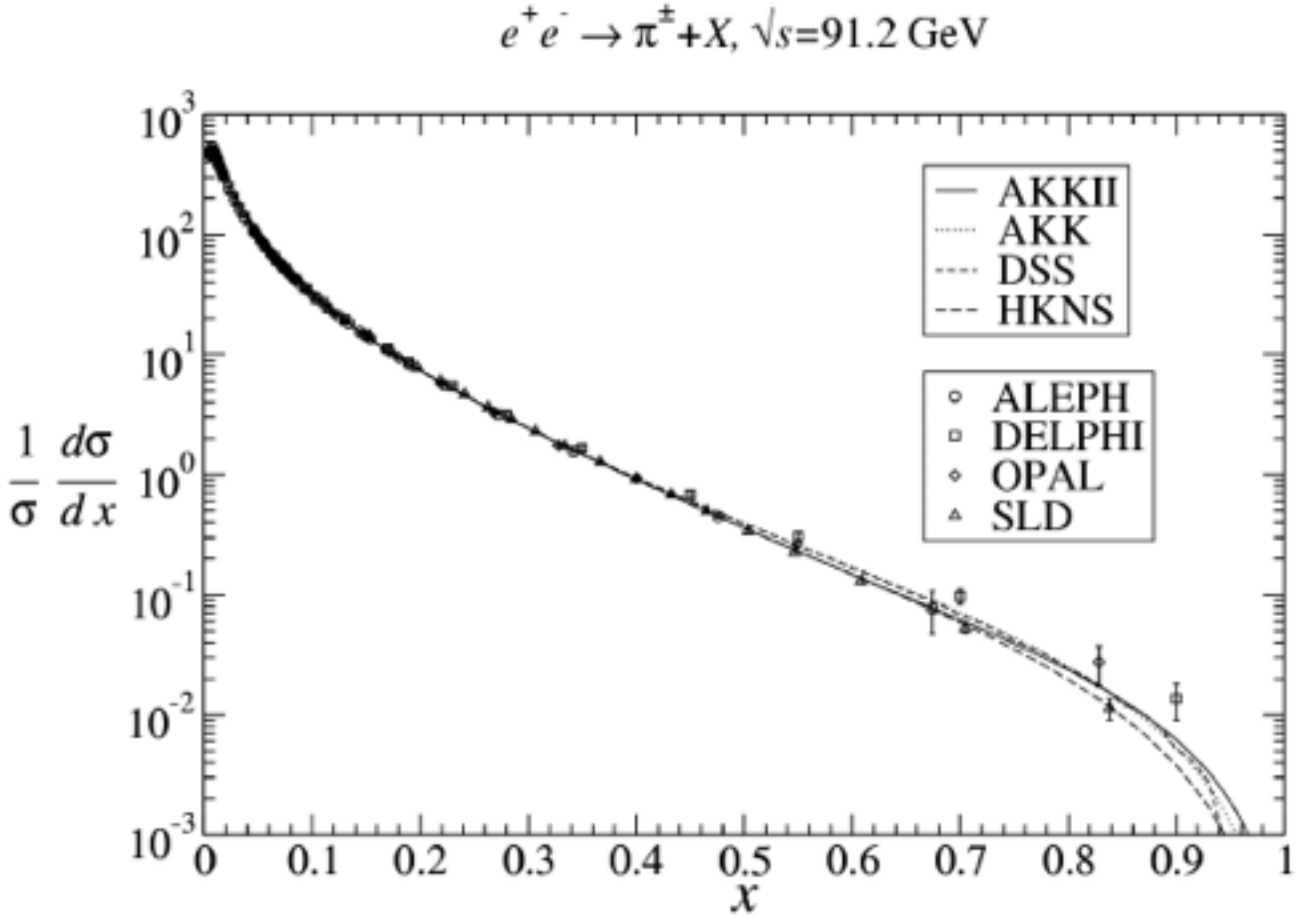
$$z = \frac{p_{T,hadron}}{P_{jet}}$$

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

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



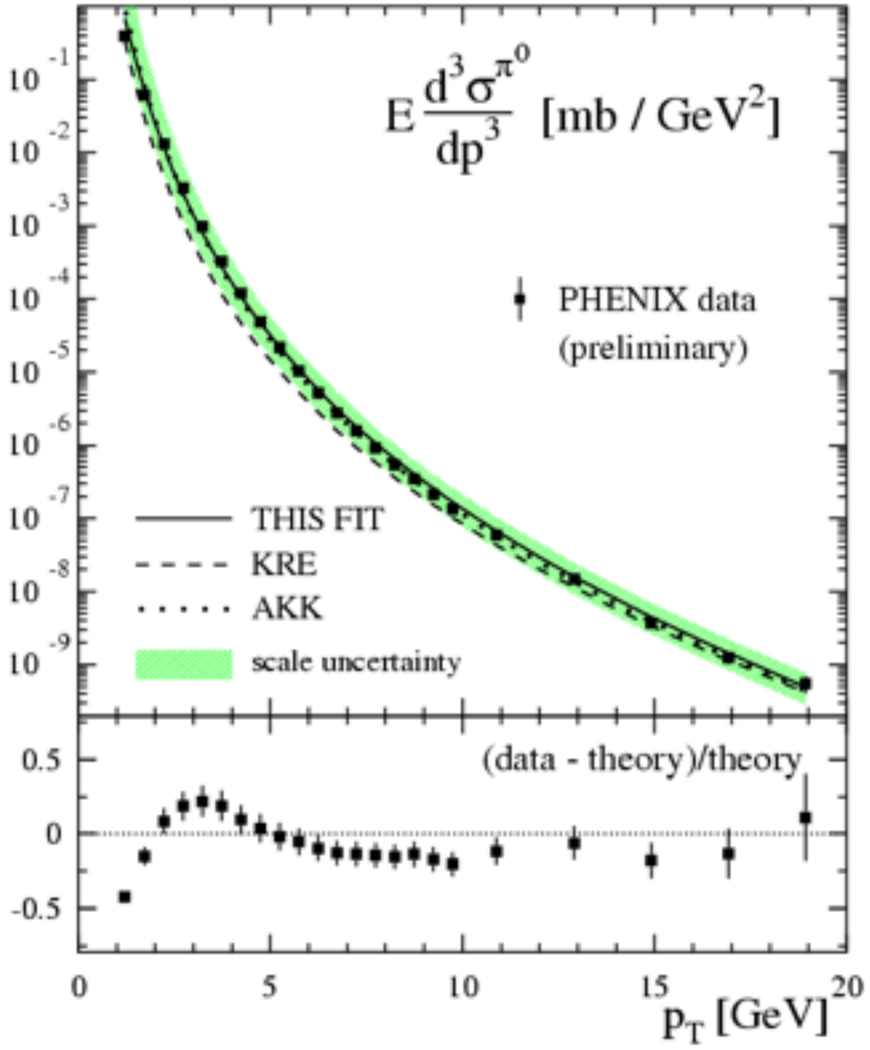
p+p: steeply falling jet spectrum
Hadron spectrum convolution
of jet spectrum with fragmentation



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

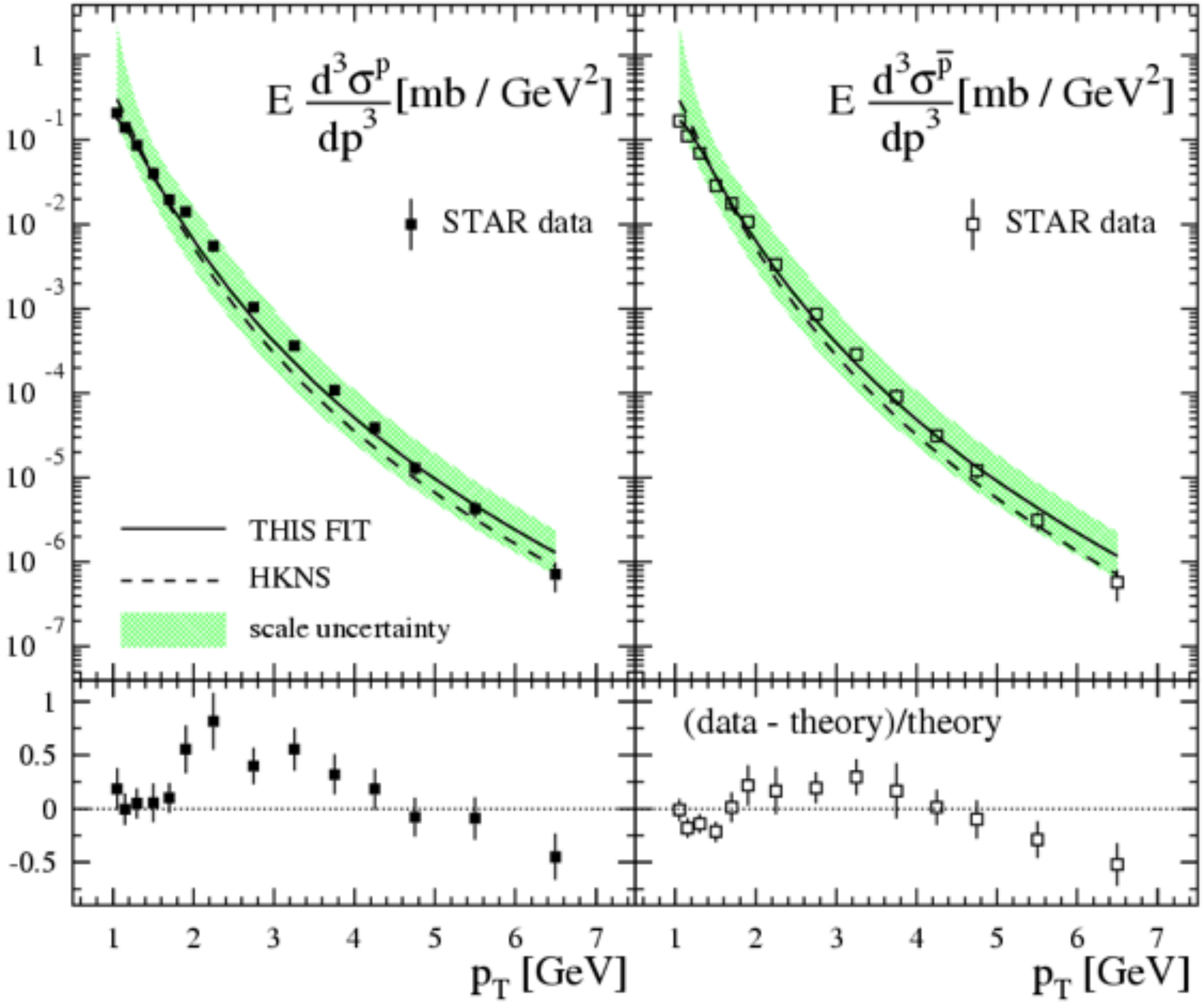
Global analysis of FF

pions



proton

anti-proton

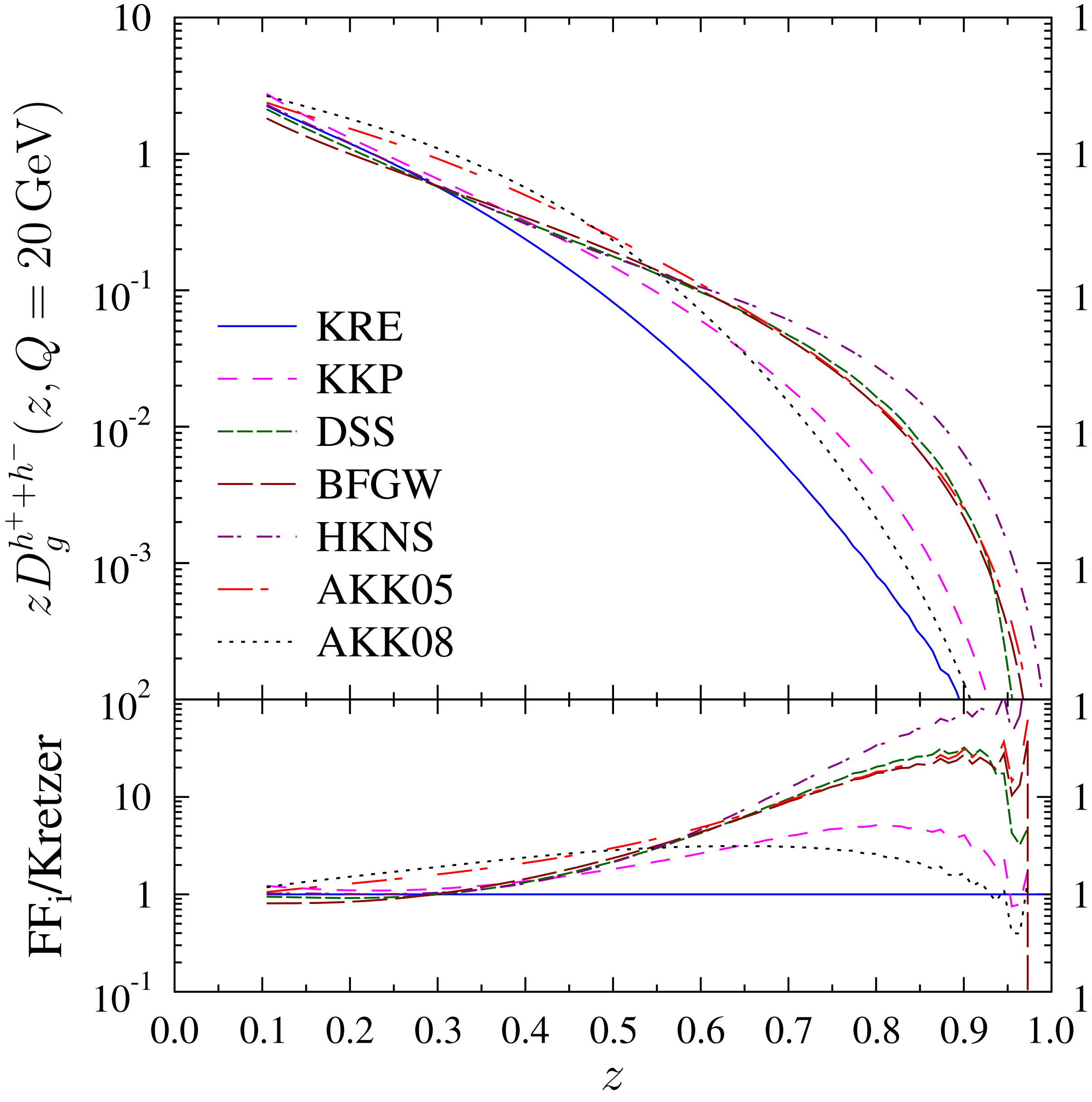


De Florian, Sassot, Stratmann, PRD 76:074033, PRD75:114010

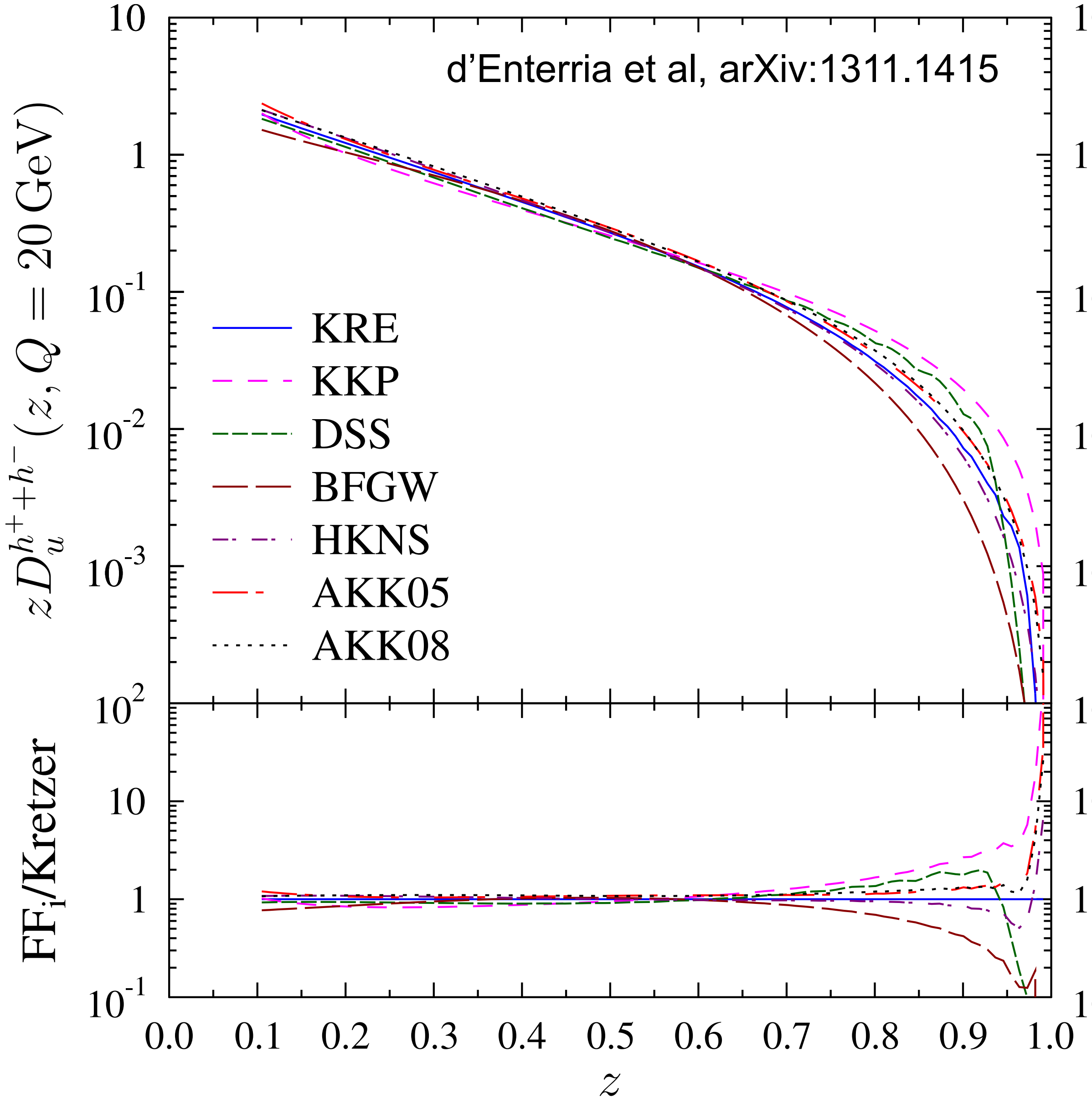
Some FF fits include RHIC data to constrain gluon fragmentation

Fragmentation function fits

Gluon fragmentation



quark (u) fragmentation

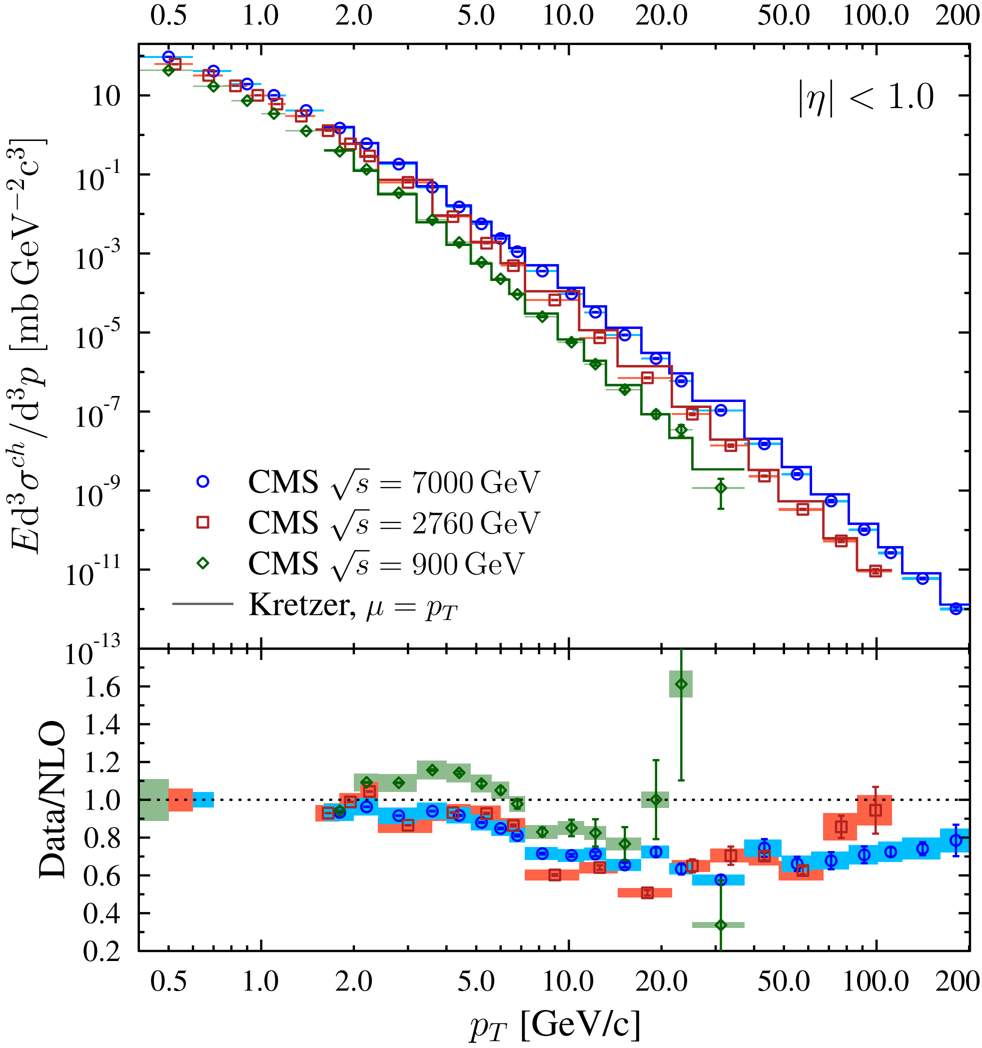


Fragmentation function fits based on e+e- have large uncertainty in gluon fragmentation

Some groups use hadron production to further constrain FFs

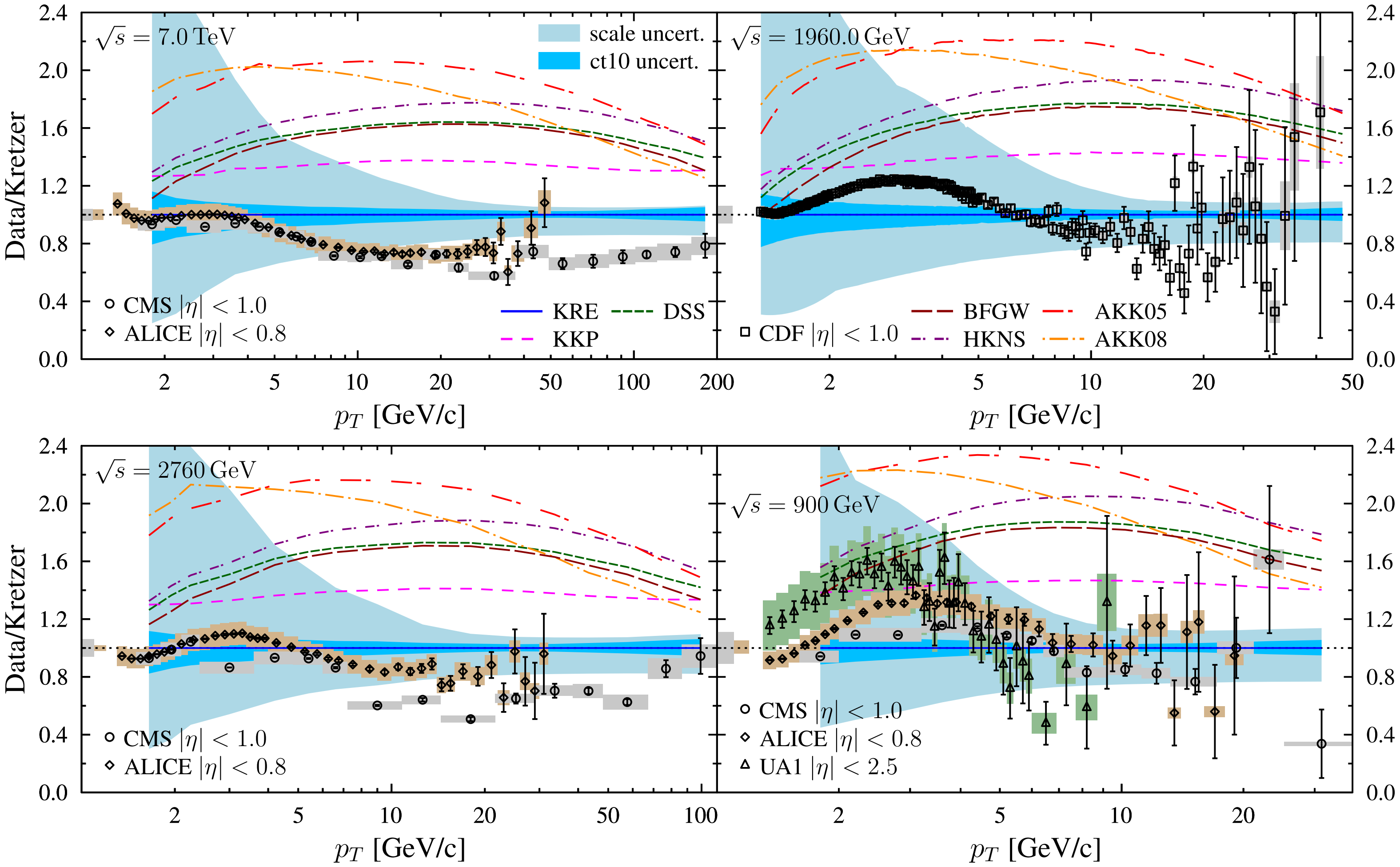
Adding the LHC data in the game

Kretzer fragmentation



d'Enterria et al, arXiv:1311.1415

Ratios data/theory with uncertainties



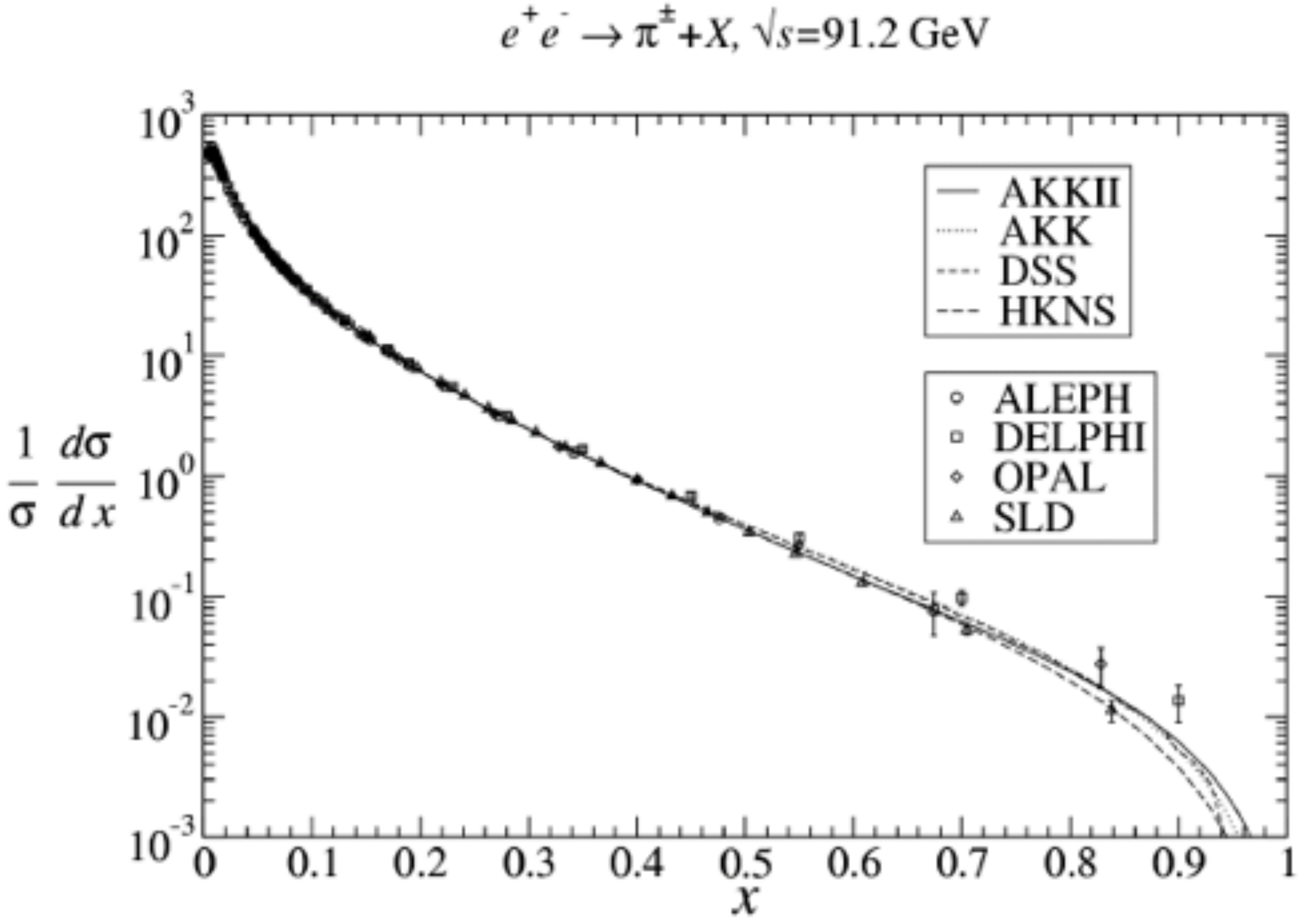
Factor ~2 spread of results due to FF parameterisations

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

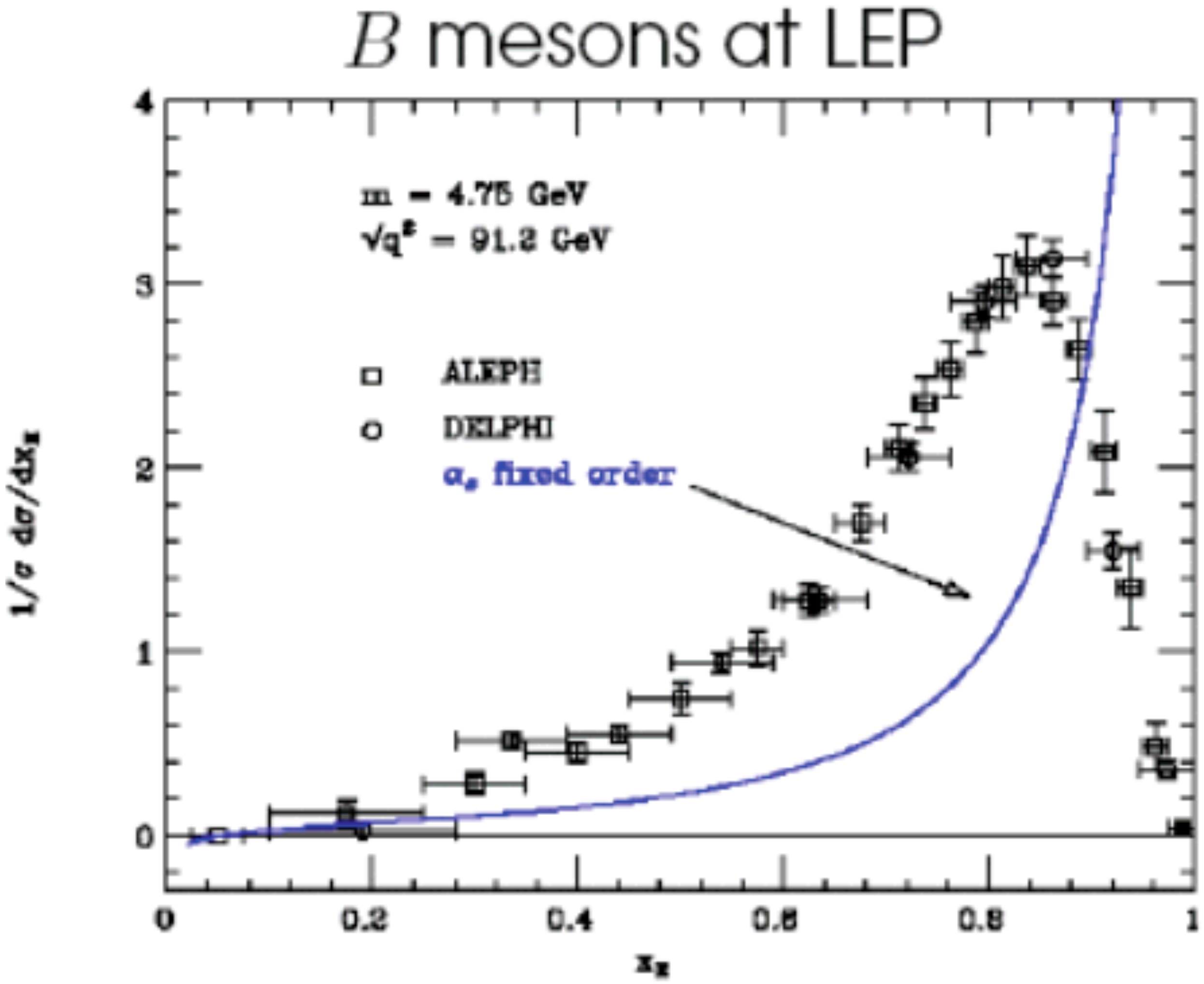
Also note: large scale uncertainties at $p_T < 5$ GeV

Heavy quark fragmentation

Light quarks



Heavy quarks

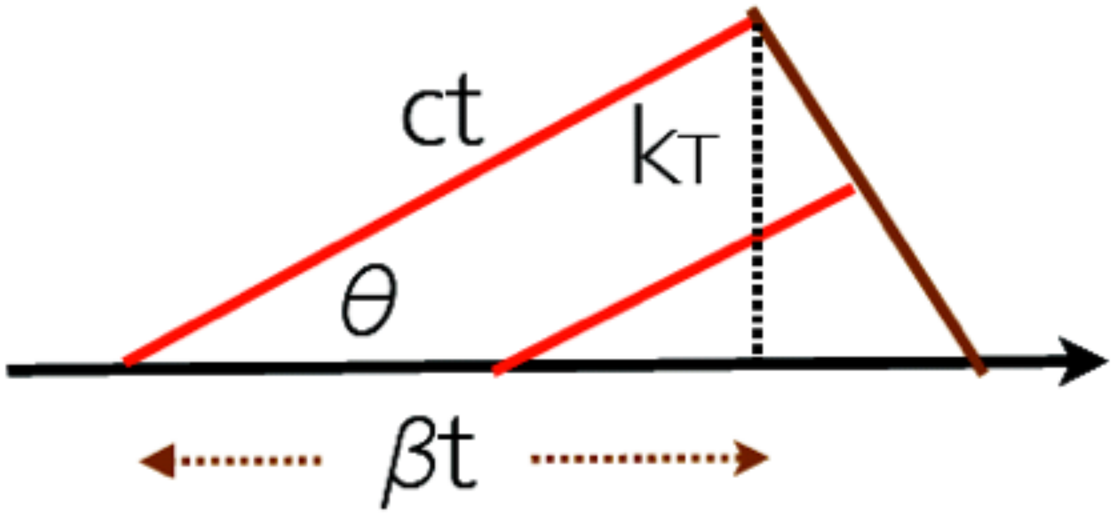


Heavy quark fragmentation: leading heavy meson carries large momentum fraction

Less gluon radiation than for light quarks, due to ‘dead cone’

Dead cone effect

Radiated wave front cannot out-run source quark



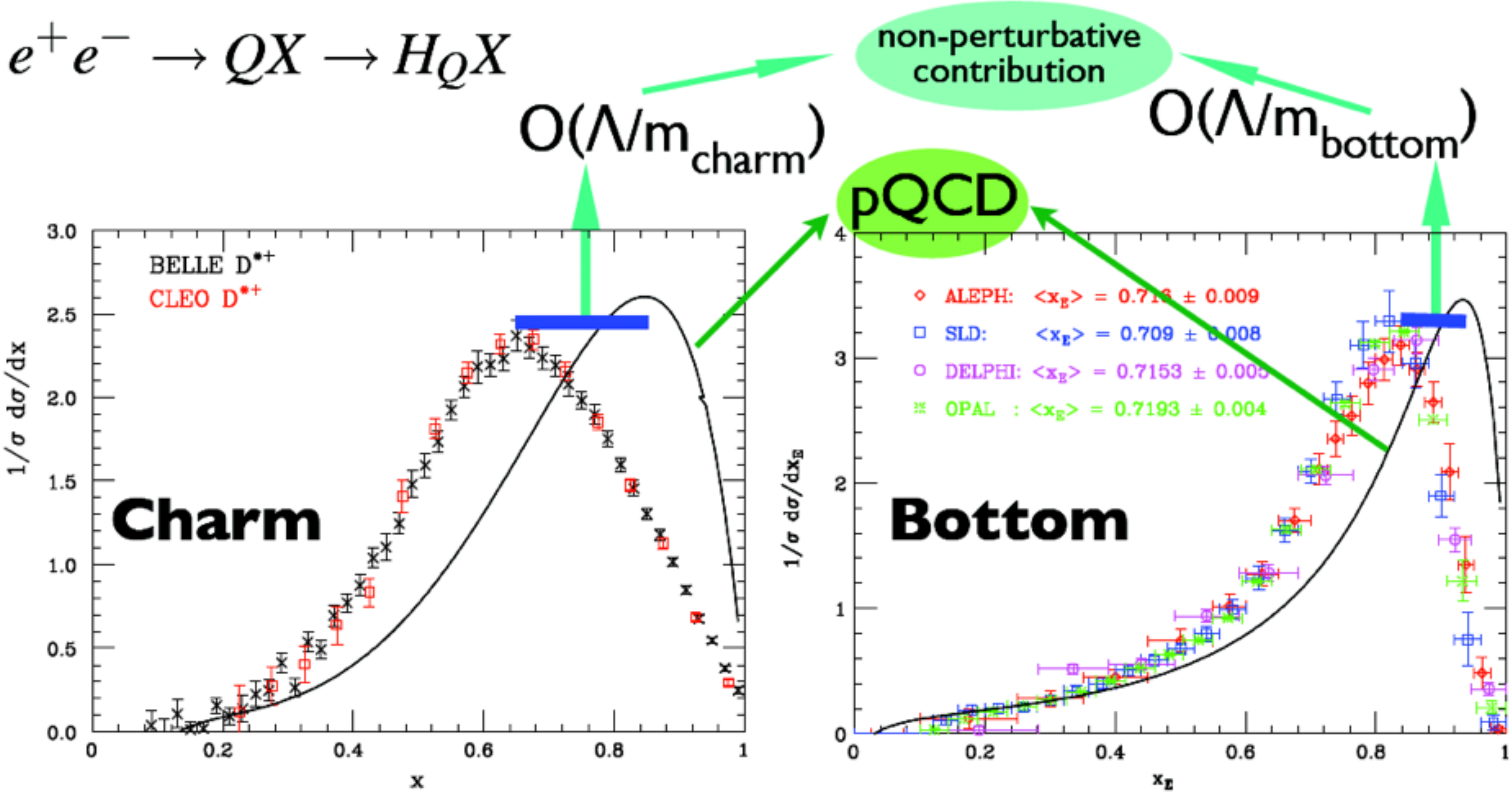
$$\sin\theta_{\mathrm{DC}} = 1 - \beta^2 = \left(\frac{M}{E}\right)^2$$

Heavy quark: $\beta < 1$

Result: minimum angle for radiation
⇒ Mass regulates collinear divergence

Heavy Quark Fragmentation II

$$e^+e^- \to QX \to H_Q X$$

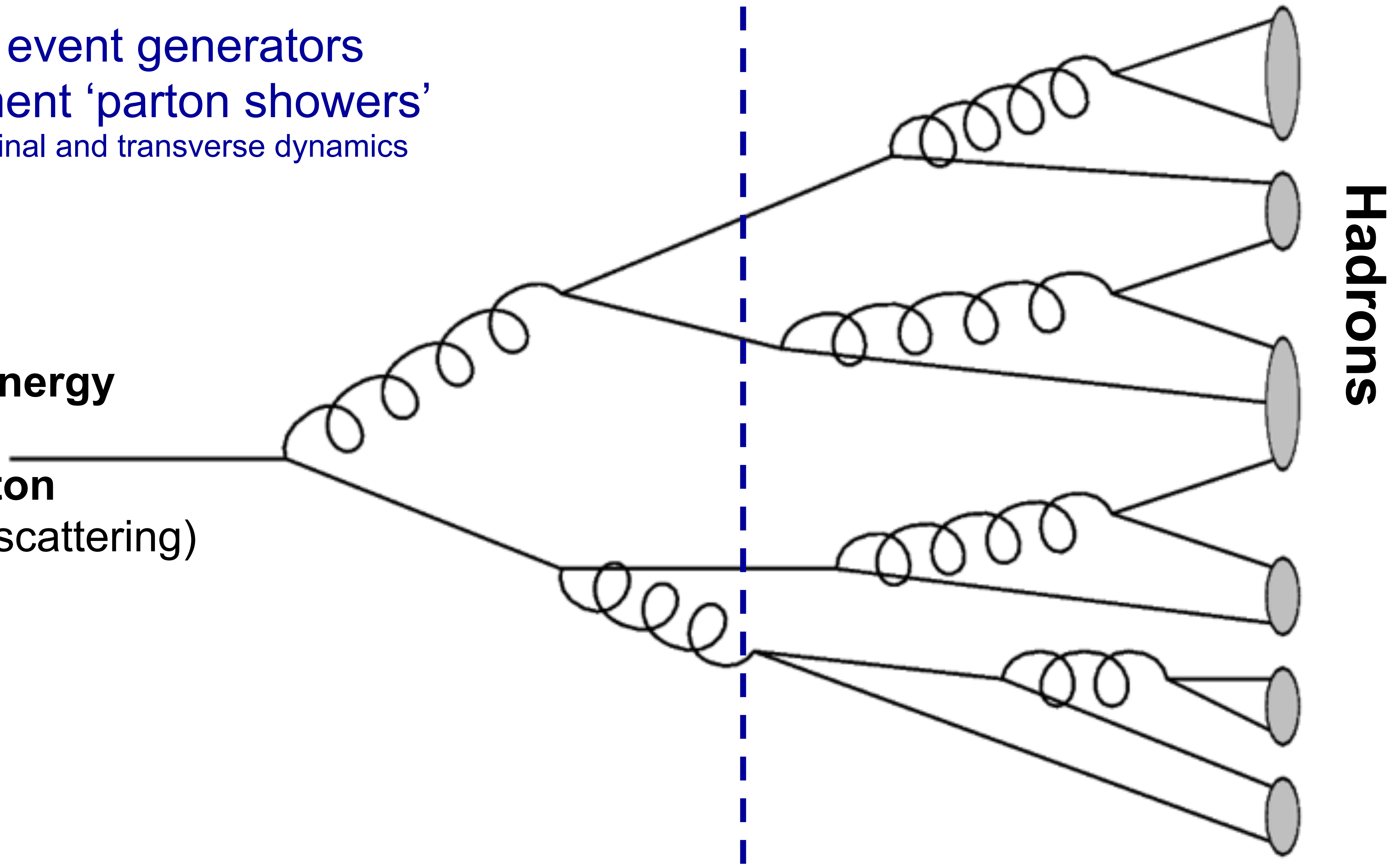


Significant non-perturbative effects seen even in heavy quark fragmentation

$$\begin{aligned}\frac{1}{\sigma}\frac{d\sigma}{dx} &= \delta(1-x)+\frac{\alpha_s(Q^2)}{2\pi}\left\{C_F+C_F\left[\ln\frac{Q^2}{m^2}\left(\frac{1+x^2}{1-x}\right)_+\right.\right.\\ &+ 2\frac{1+x^2}{1-x}\log x-\left(\frac{\ln(1-x)}{1-x}\right)_+(1+x^2)+\frac{1}{2}\left(\frac{1}{1-x}\right)_+(x^2-6x-2)\\ &+ \left.\left.\left(\frac{2}{3}\pi^2-\frac{5}{2}\right)\delta(1-x)\right]\right\}+\mathcal{O}\left(\frac{m}{Q}\right)\end{aligned}$$

Fragmentation and parton showers

MC event generators
implement 'parton showers'
Longitudinal and transverse dynamics



High-energy

parton
(from hard scattering)

large Q^2

μ_F

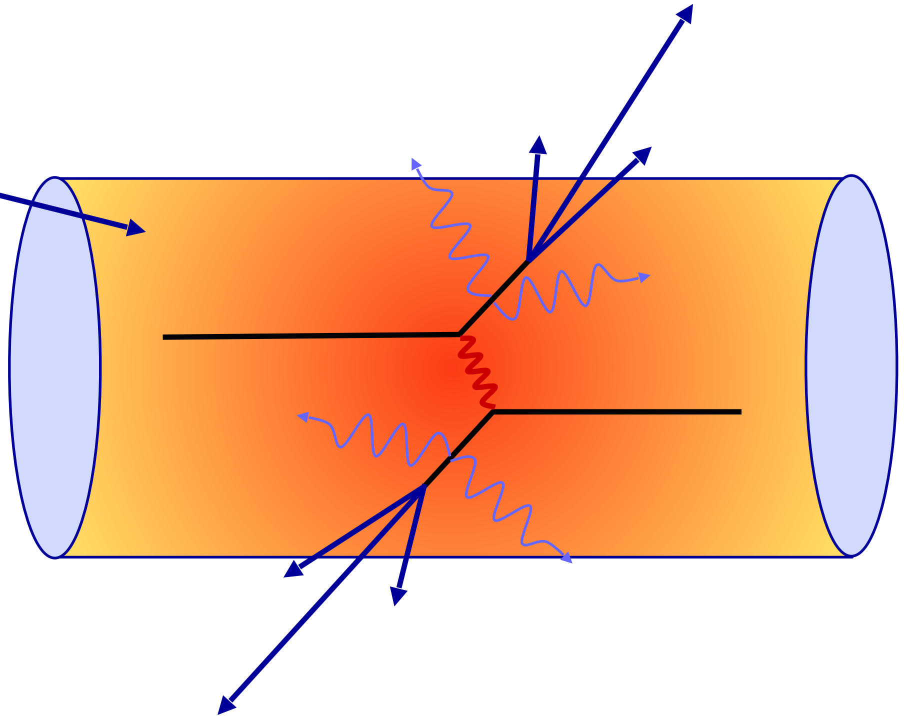
$Q \sim m_H \sim \Lambda_{QCD}$

Analytical calculations: Fragmentation Function $D(z, \mu)$ $z=p_h/E_{jet}$
Only longitudinal dynamics

Part II: Nuclear Modification Factor R_{AA}

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

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

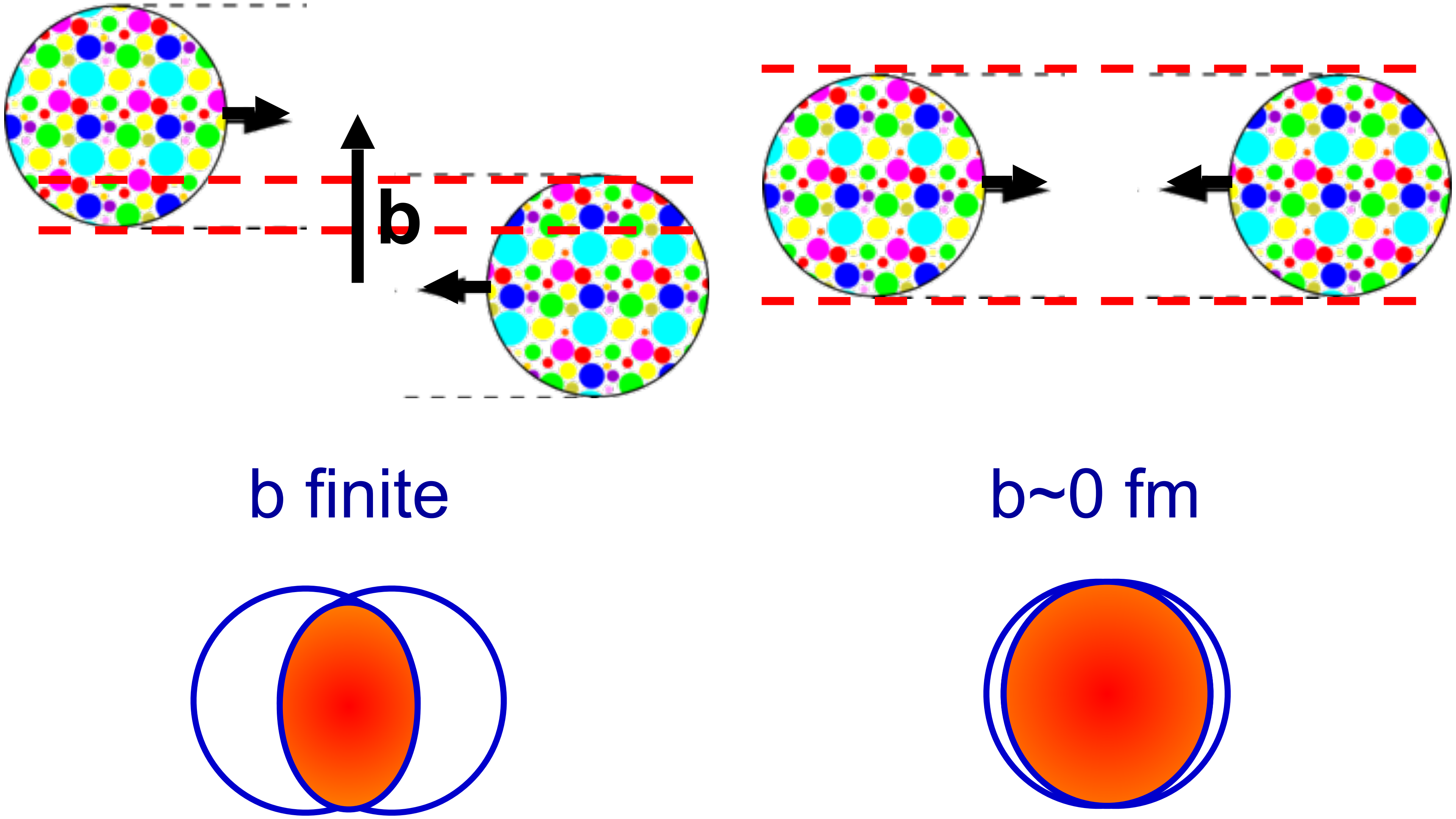
First run: 2009/2010

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

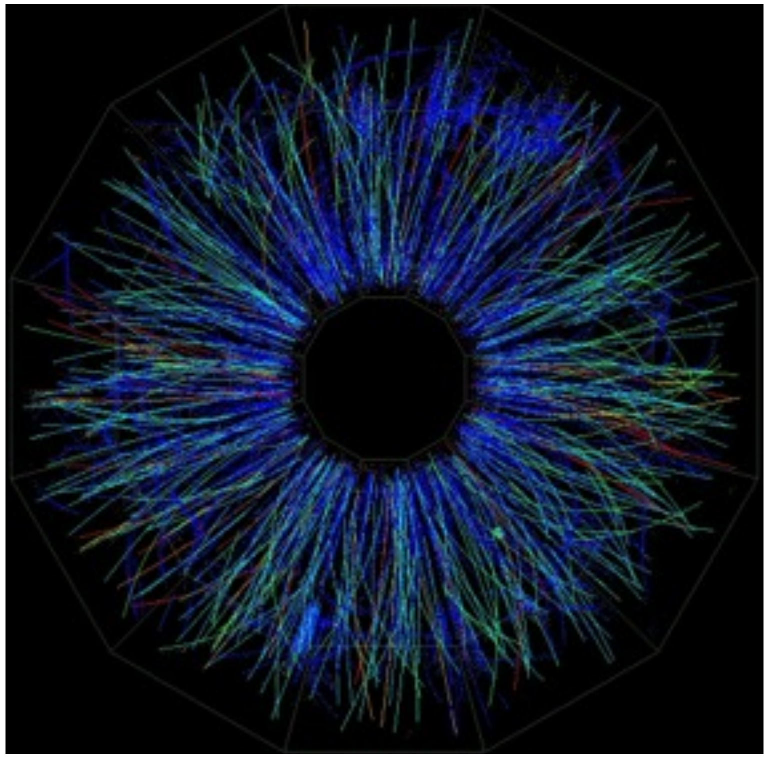
b~0 fm

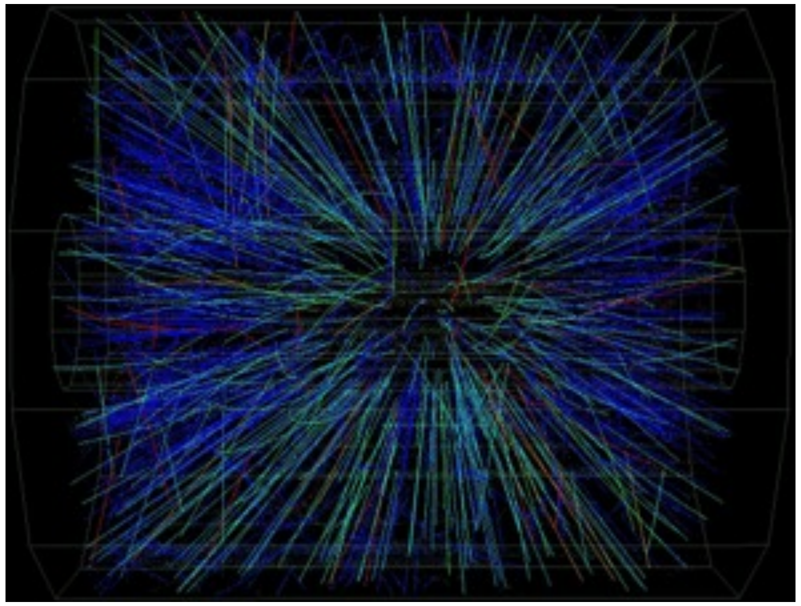
front view:

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

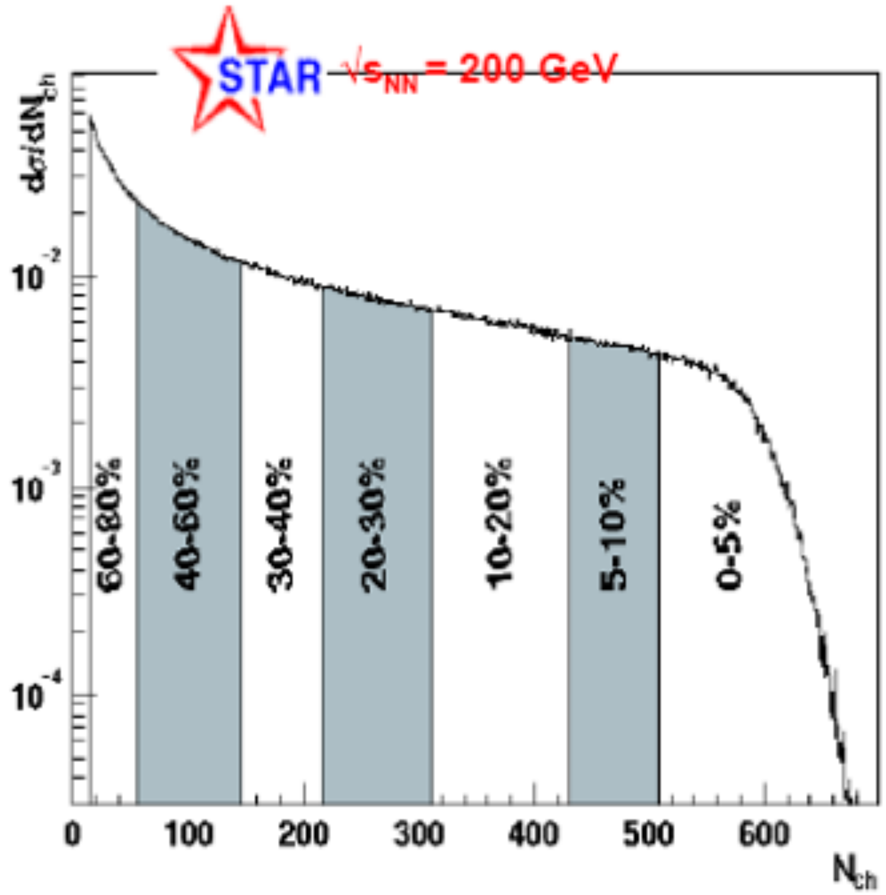
Centrality continued

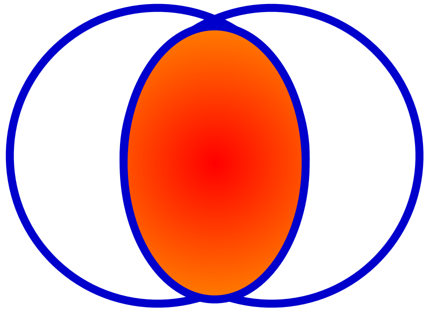
peripheral

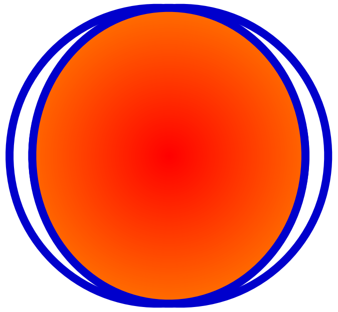




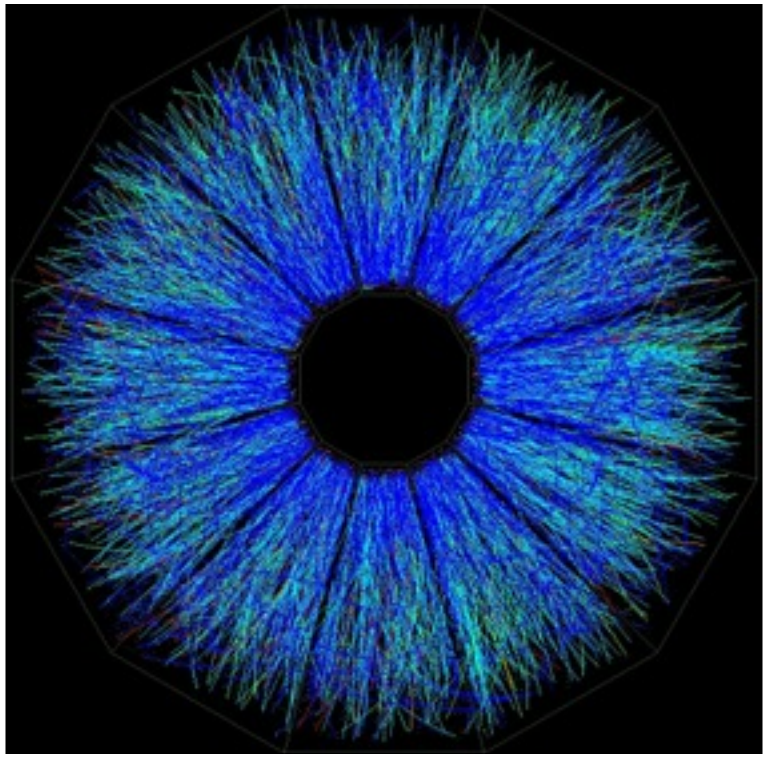
Multiplicity distribution

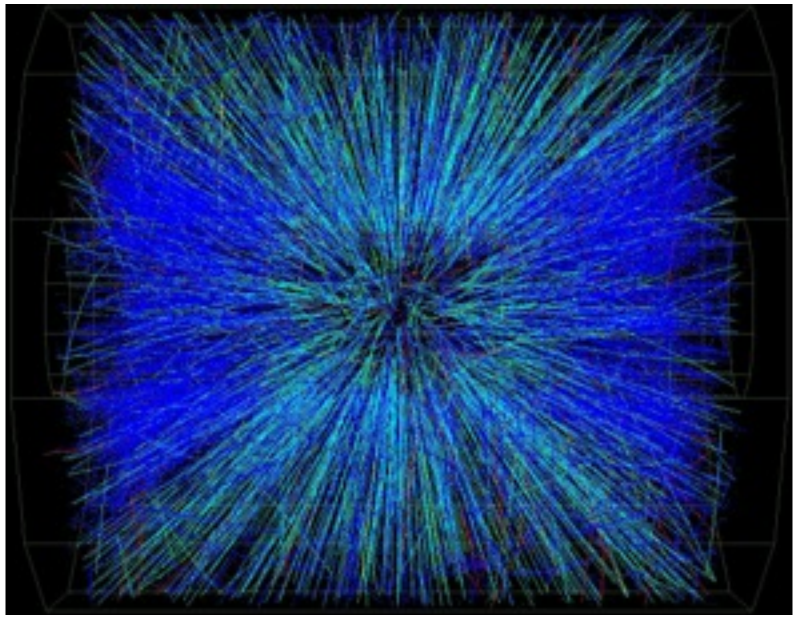






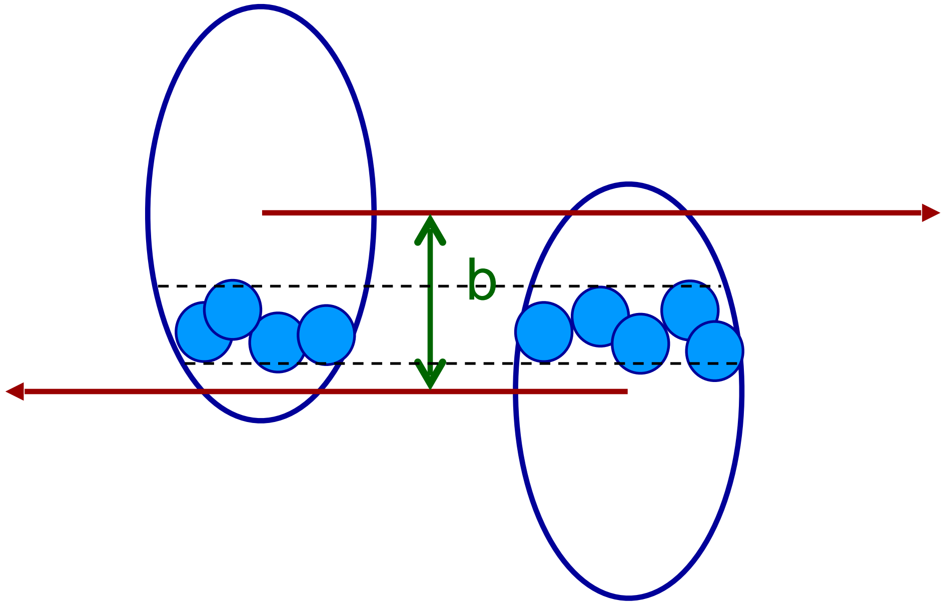
central





Experimental measure of centrality: multiplicity

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

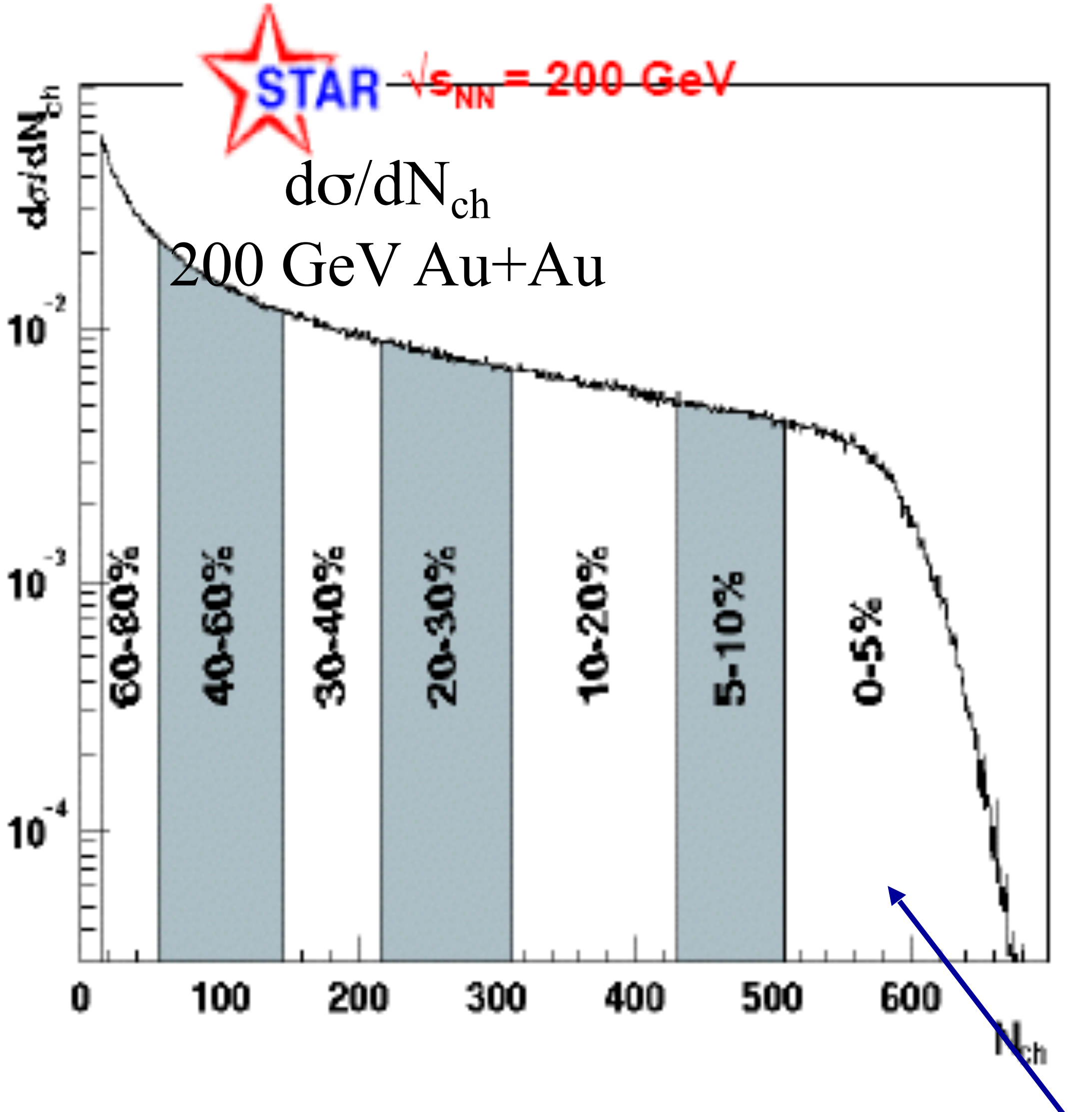


Two limiting possibilities:

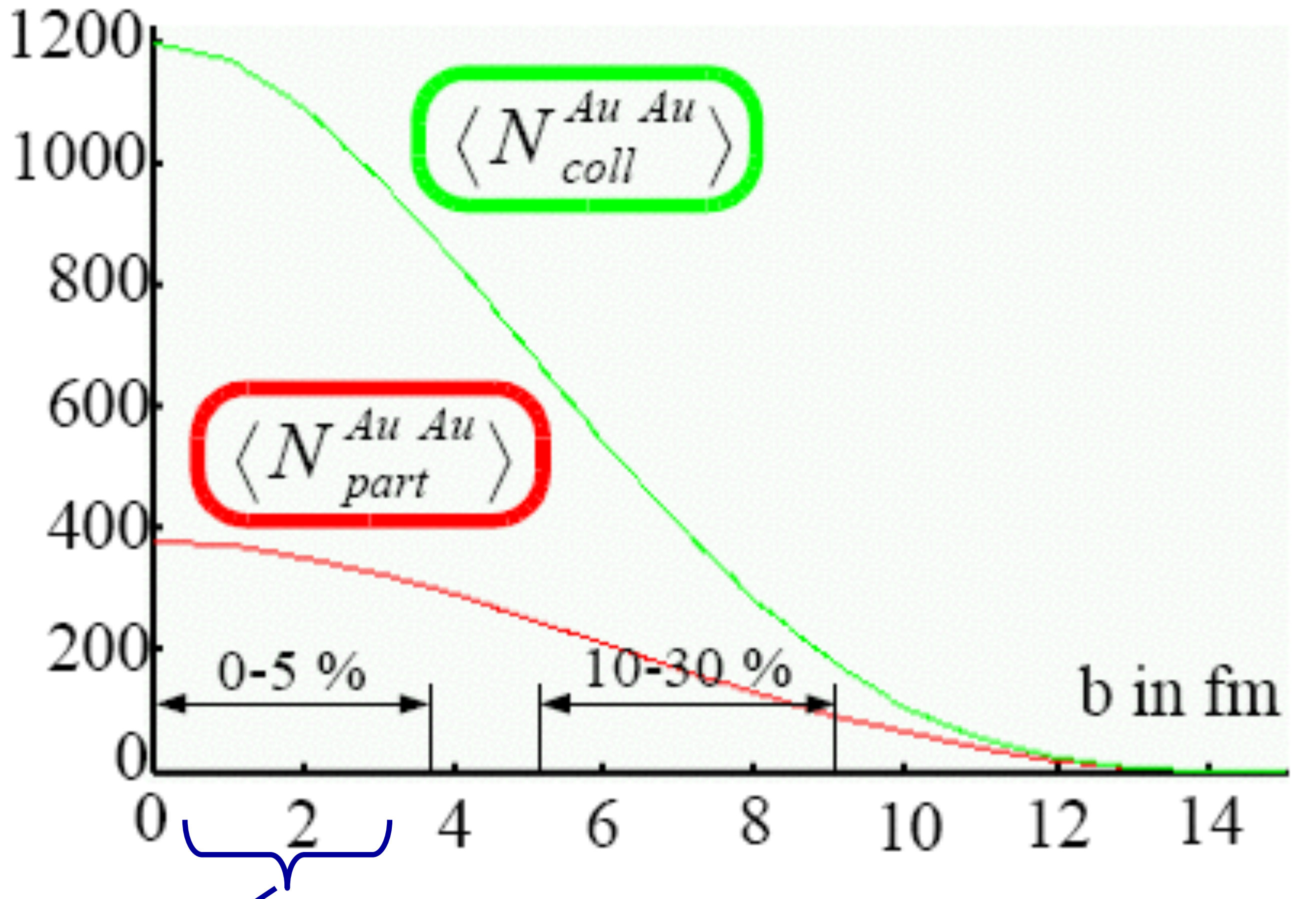
- Each nucleon only **interacts once**, ‘wounded nucleons’
  $N_{part} = n_A + n_B$ (ex: 4 + 5 = 9 + …)
  Relevant for soft production; long timescales: $\sigma \propto N_{part}$
- Nucleons **interact with all** nucleons they encounter
  $N_{coll} = n_A \times n_B$ (ex: 4 x 5 = 20 + …)
  Relevant for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

Centrality dependence of hard processes

Total multiplicity: soft processes



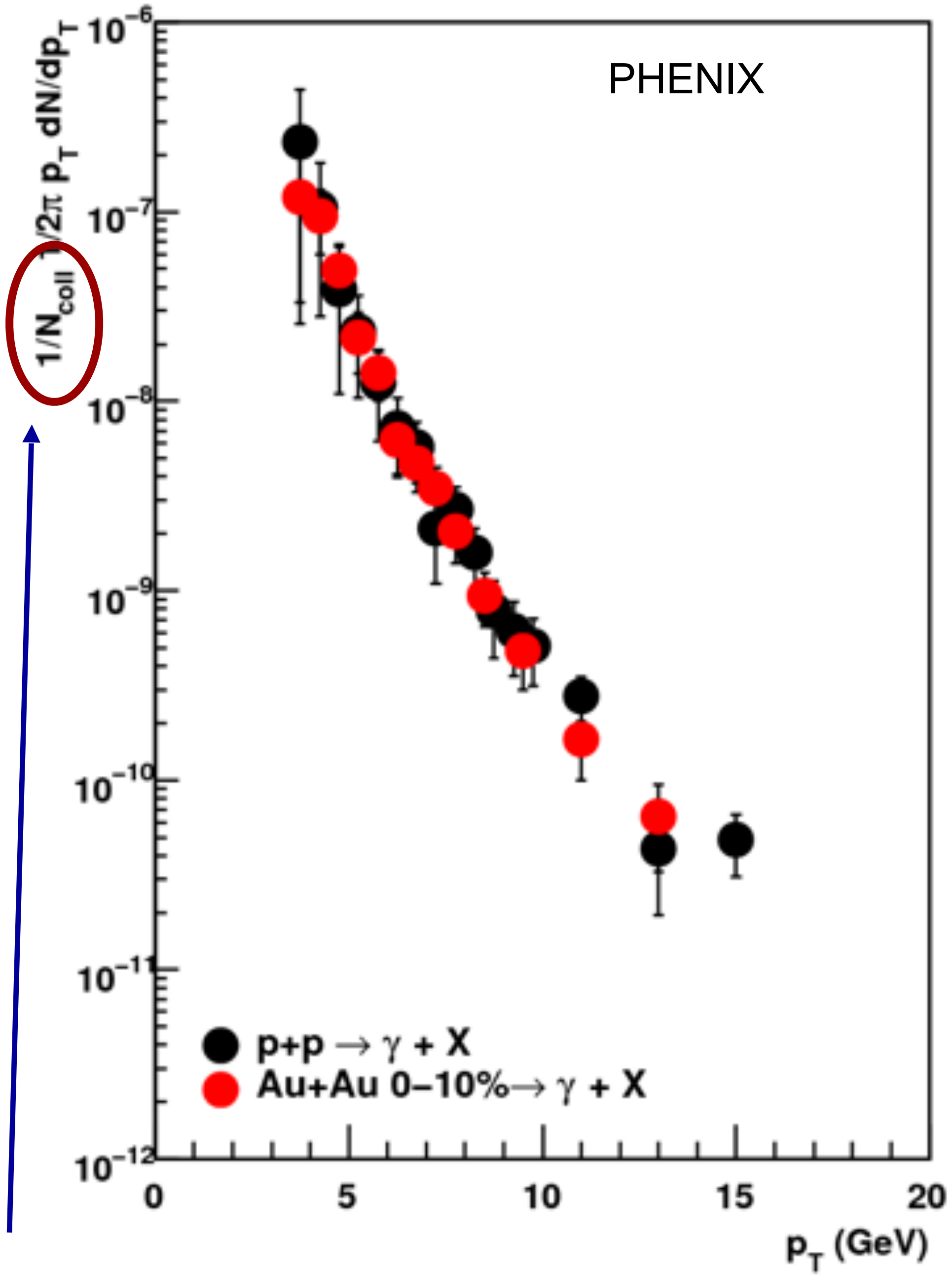
Binary collisions weight
towards small impact parameter



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

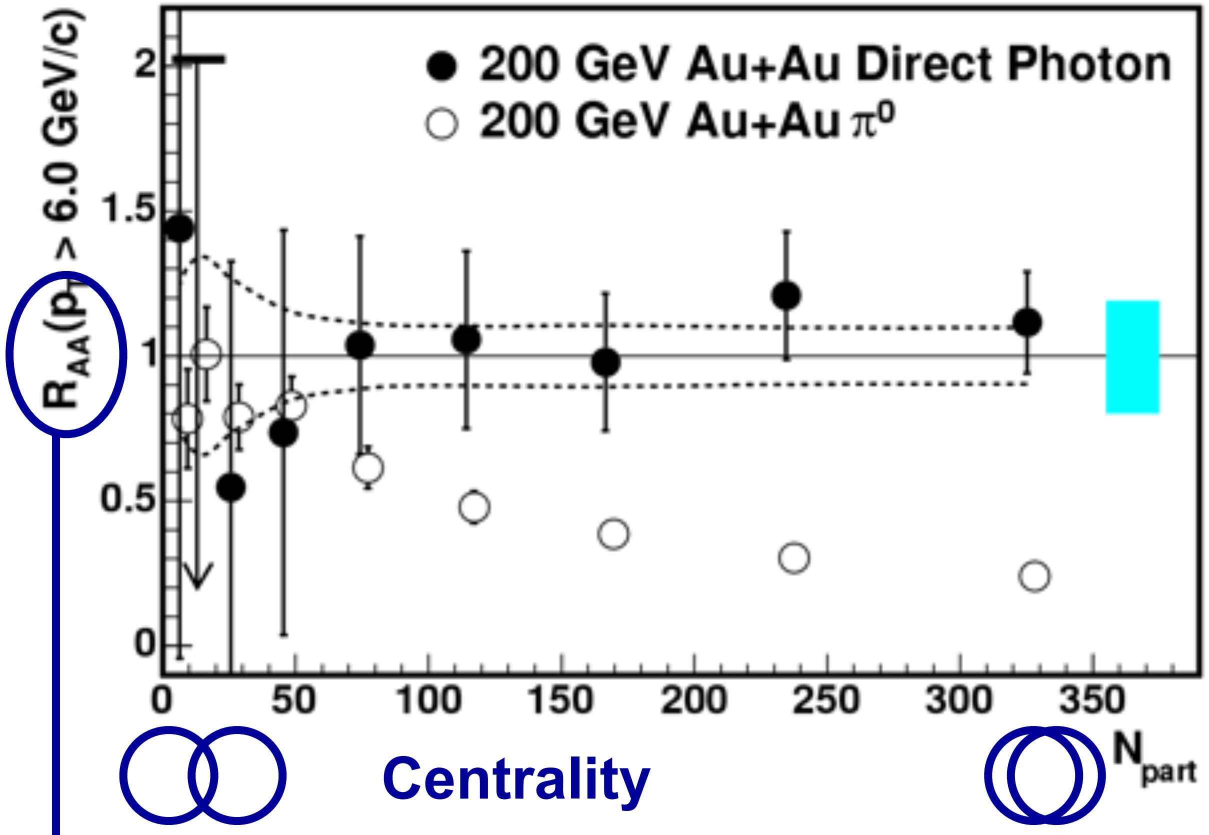
Testing volume (N_{coll}) scaling in Au+Au

Direct γ spectra



Scaled by N_{coll}

PHENIX, PRL 94, 232301

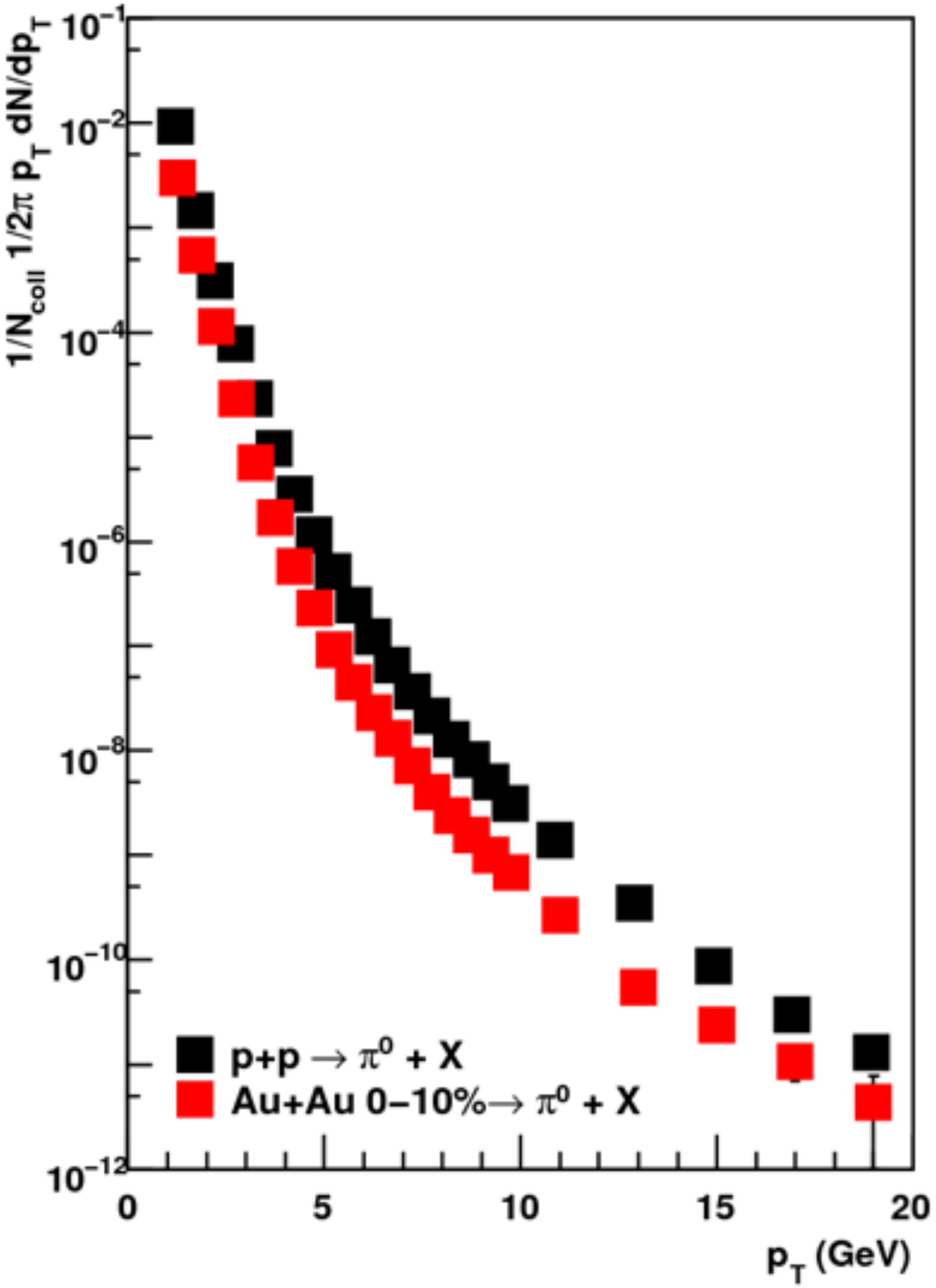


$$R_{AA} = \frac{dN/dp_T\big|_{Au+Au}}{N_{coll}\ dN/dp_T\big|_{p+p}}$$

Direct γ in A+A scales with N_{coll}

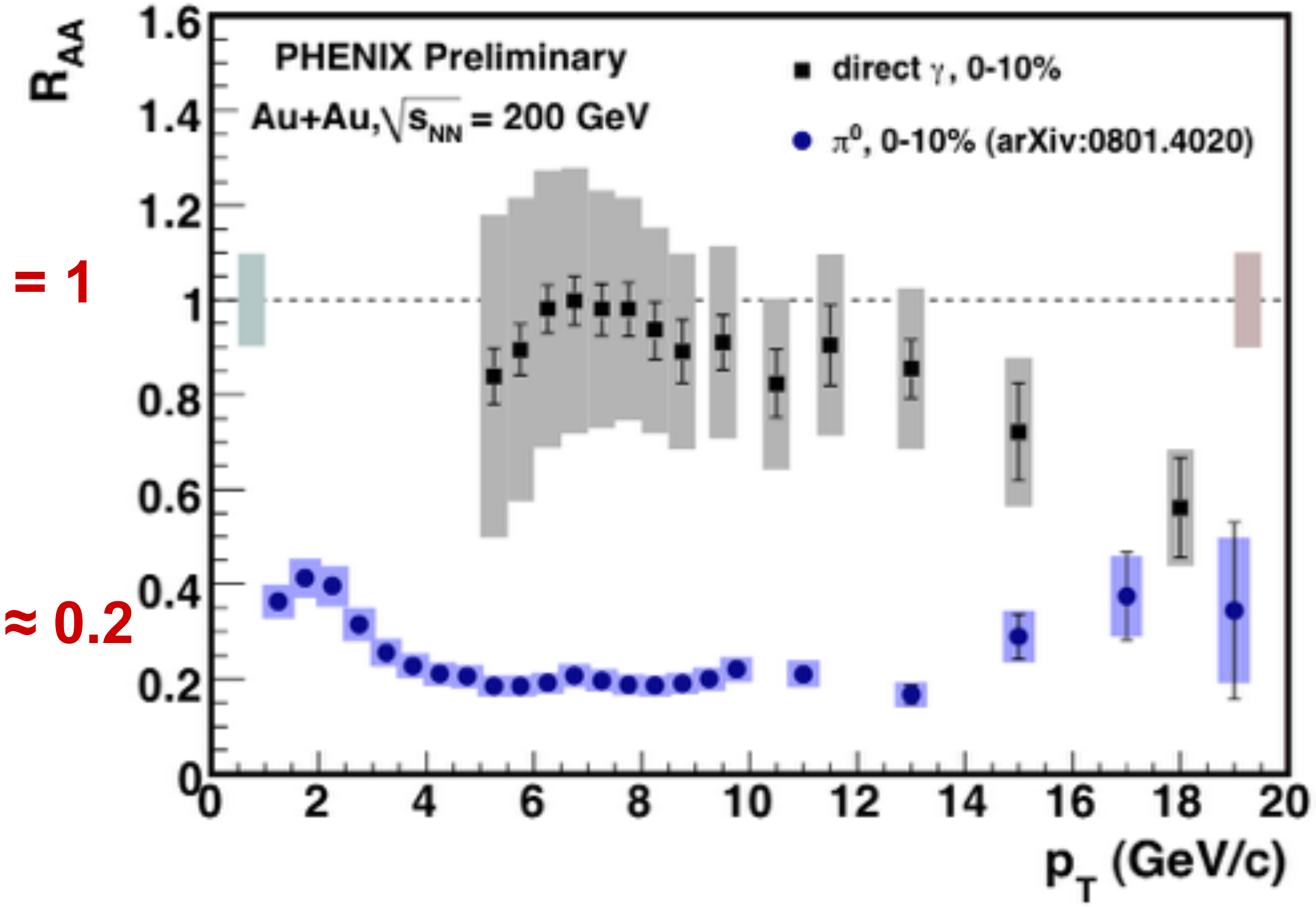
A+A initial state is incoherent superposition of p+p for hard probes

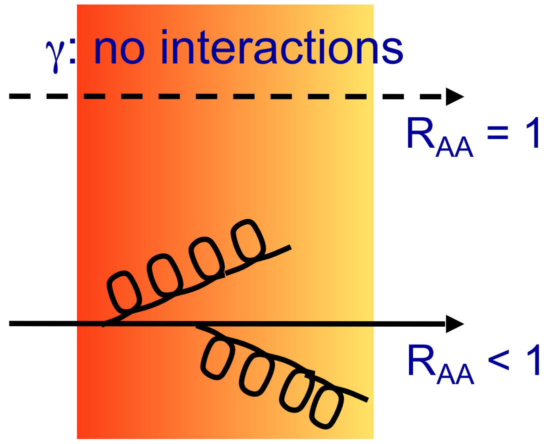
π^0 R_{AA} – high-p_T suppression



γ: $R_{AA} = 1$

π^0: $R_{AA} \approx 0.2$



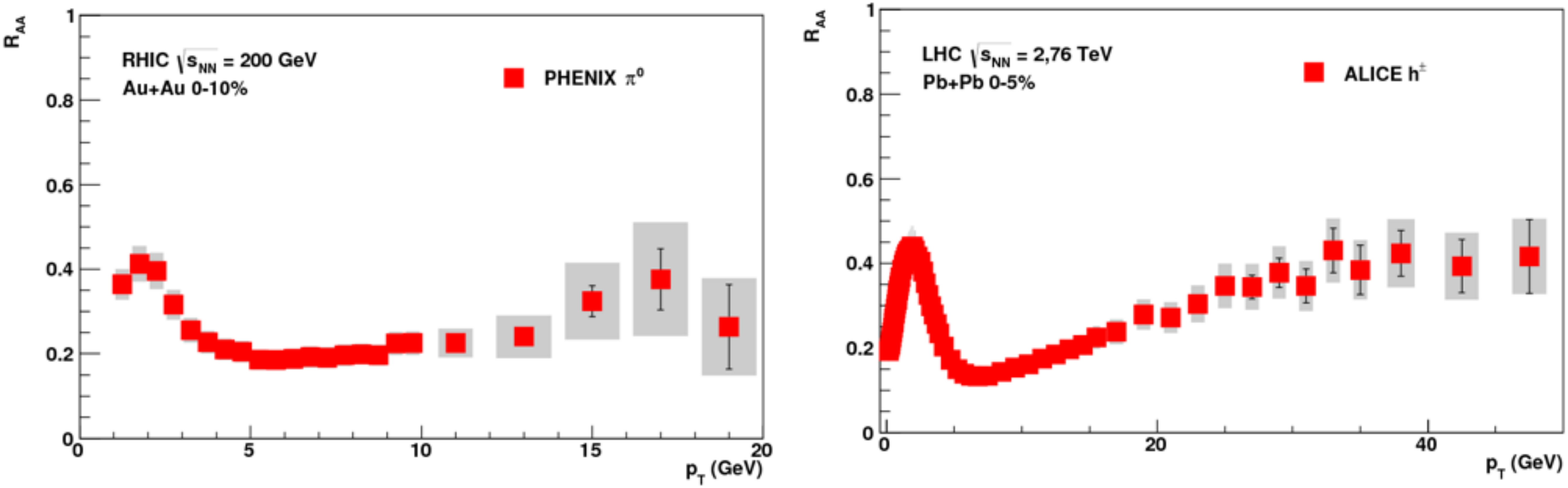


Hard partons lose energy in the hot matter

Hadrons: energy loss

Nuclear modification factor

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

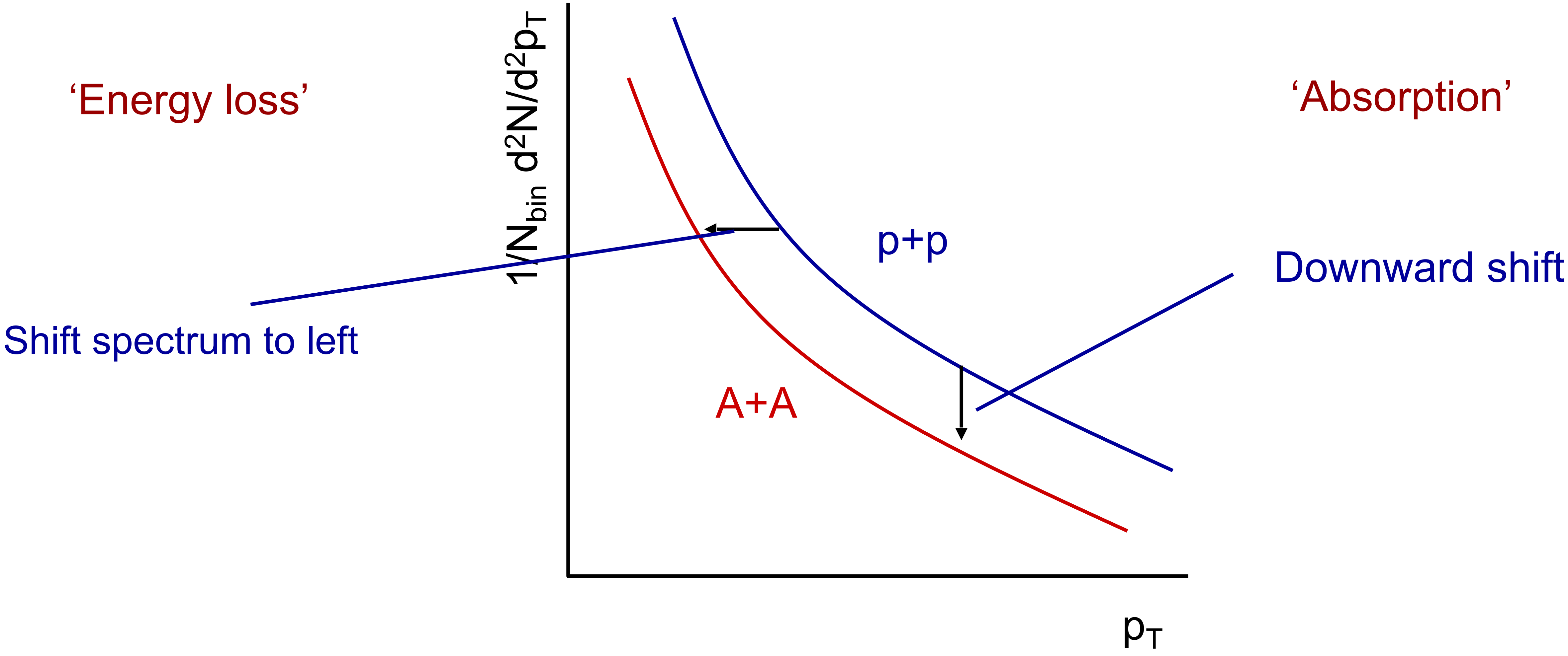


Suppression factor 2-6
Significant p_T-dependence
Similar at RHIC and LHC?

So what does it mean?

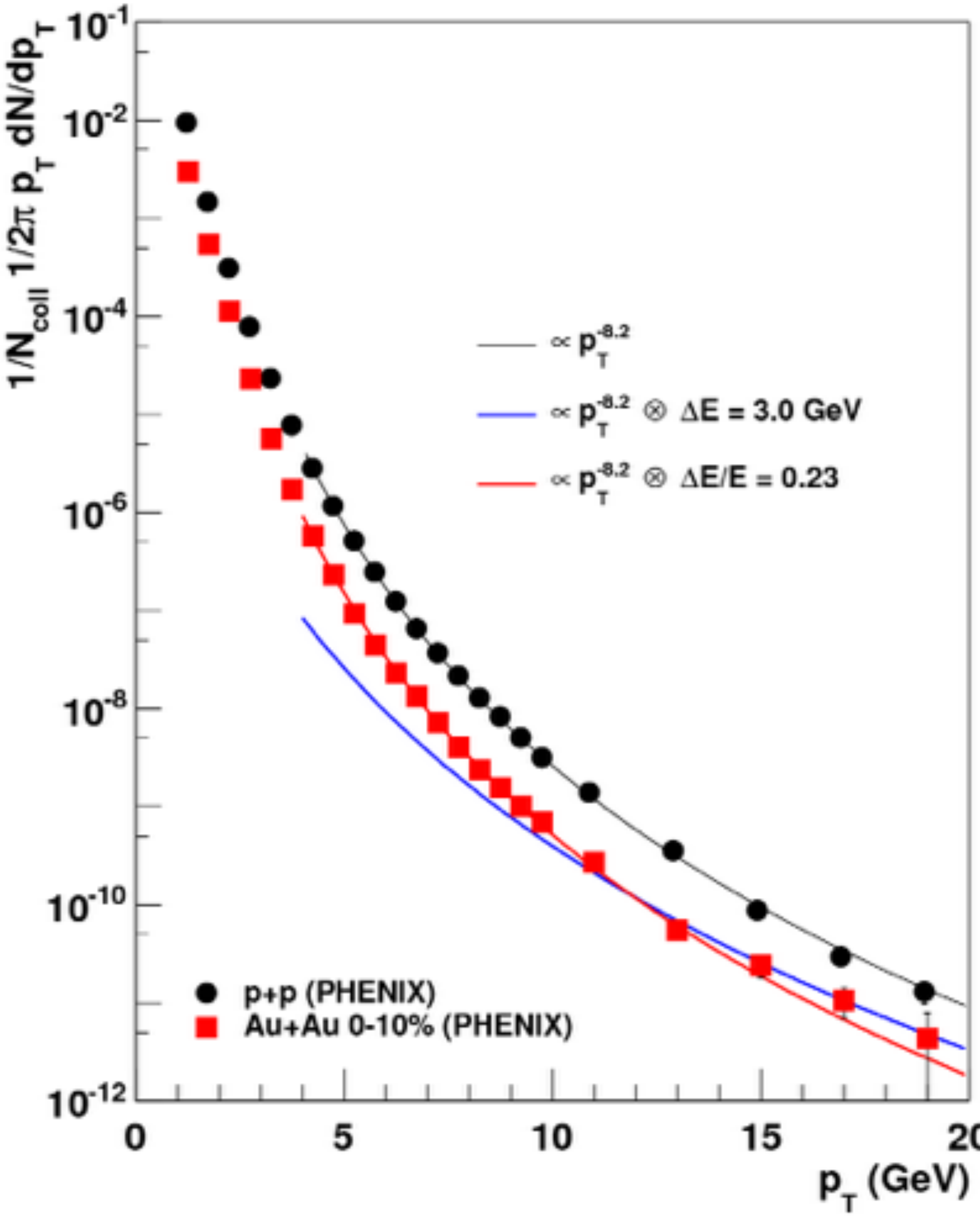
Nuclear modification factor R_{AA}

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



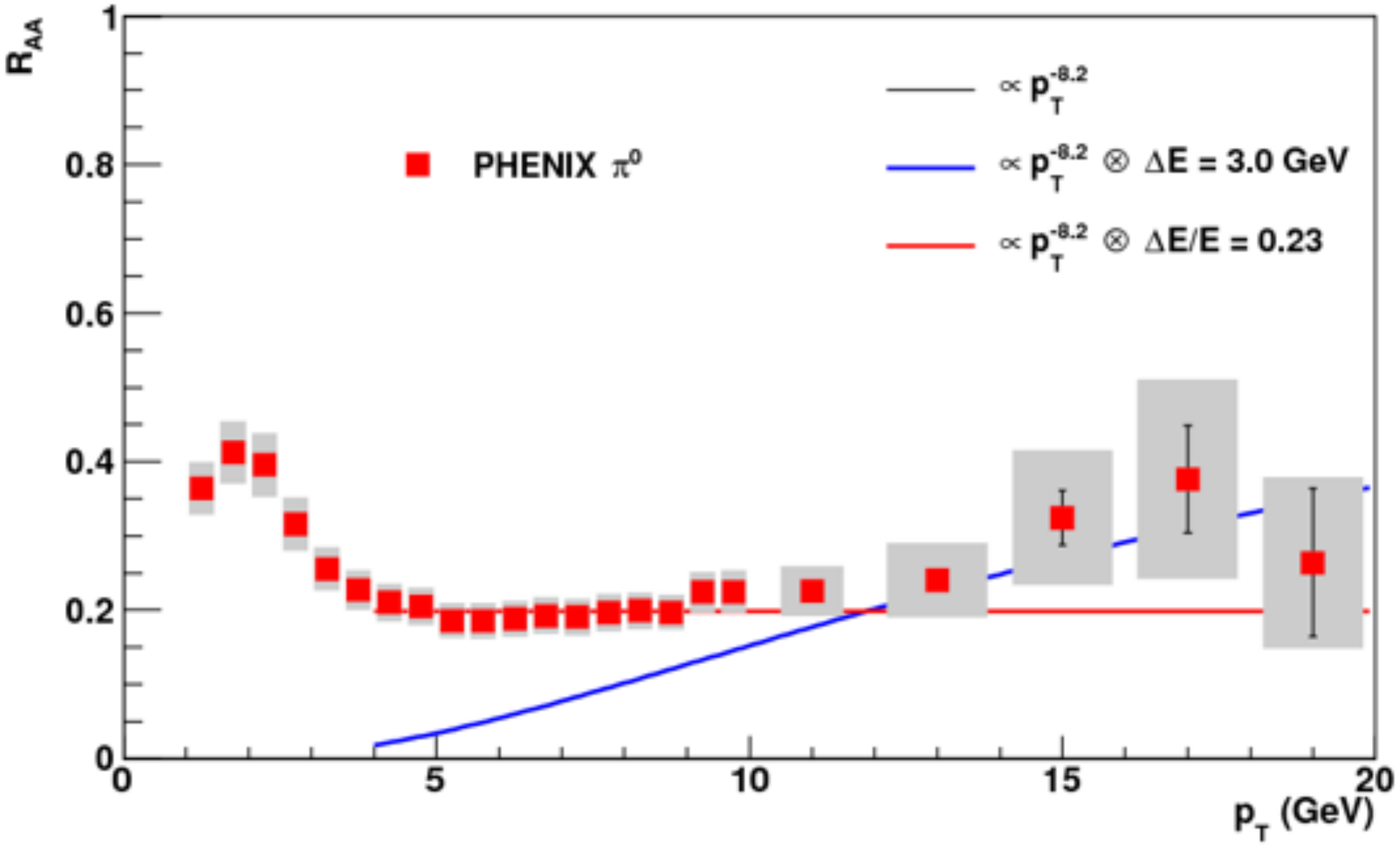
Measured R_{AA} is a ratio of yields at a given p_T
The physical mechanism is energy loss; shift of yield to lower p_T

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 ~24 x higher

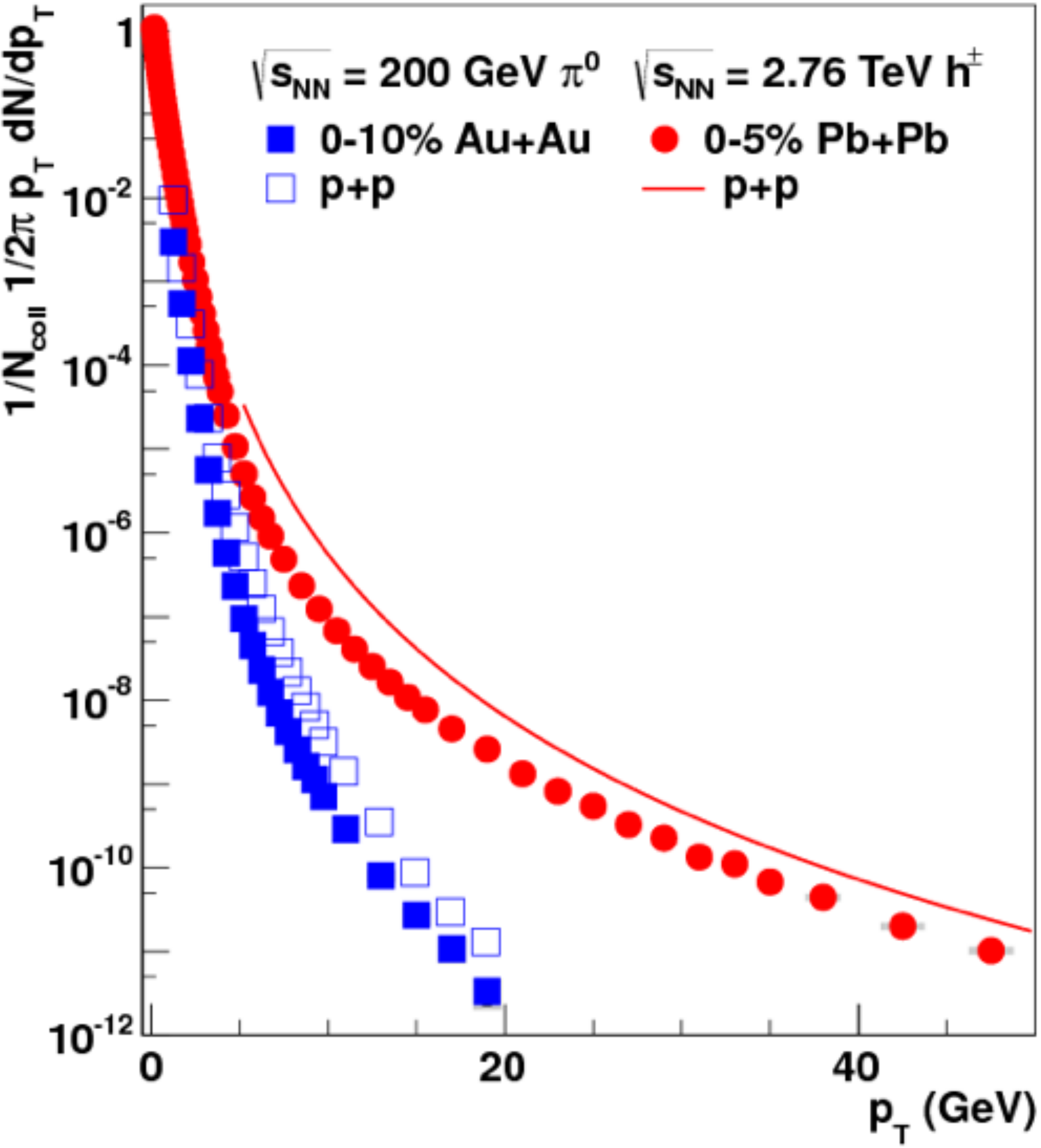
LHC: spectrum less steep,
larger p_T reach

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

RHIC: n ~ 8.2
LHC: n ~ 6.4

Fractional energy loss:

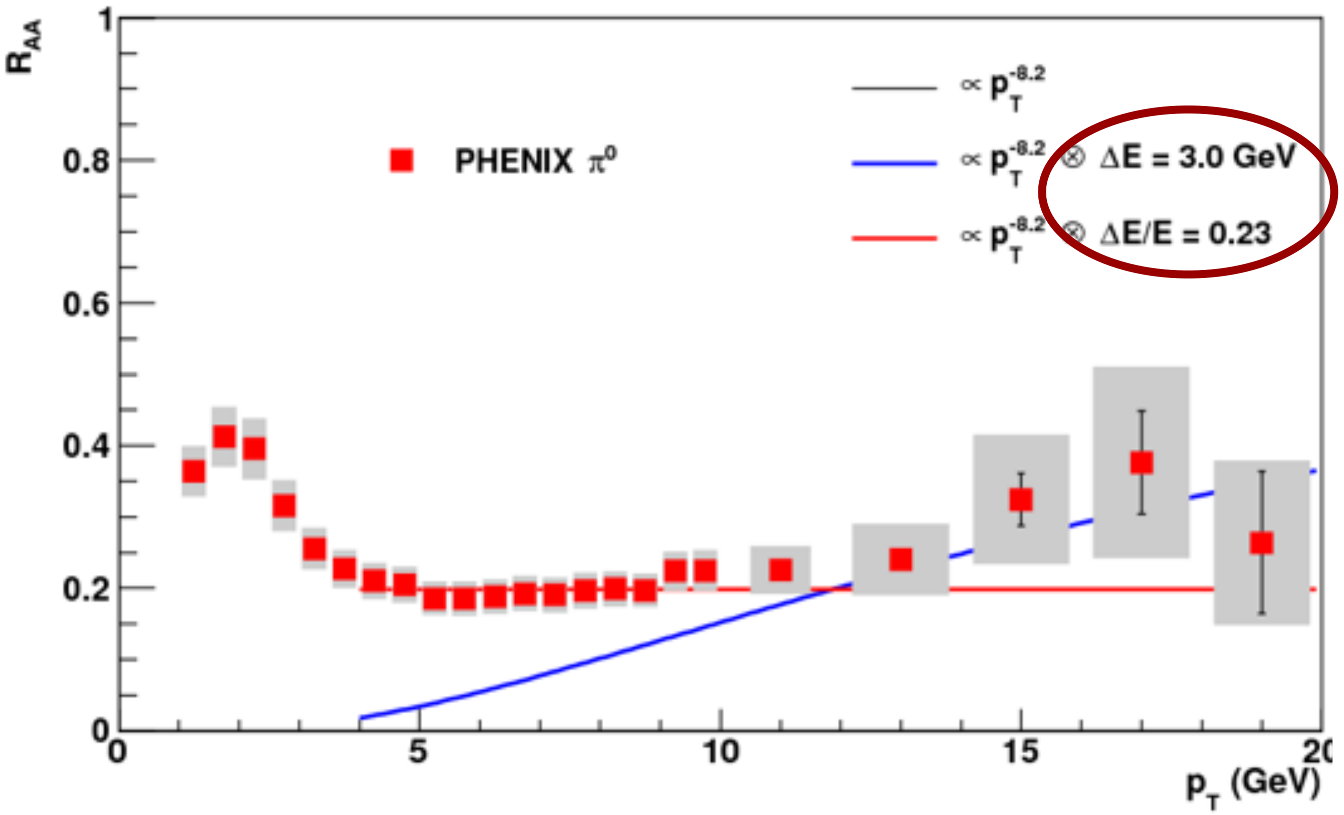
$$R_{AA} \approx \left(1 - \frac{\Delta E}{E}\right)^{n-2}$$



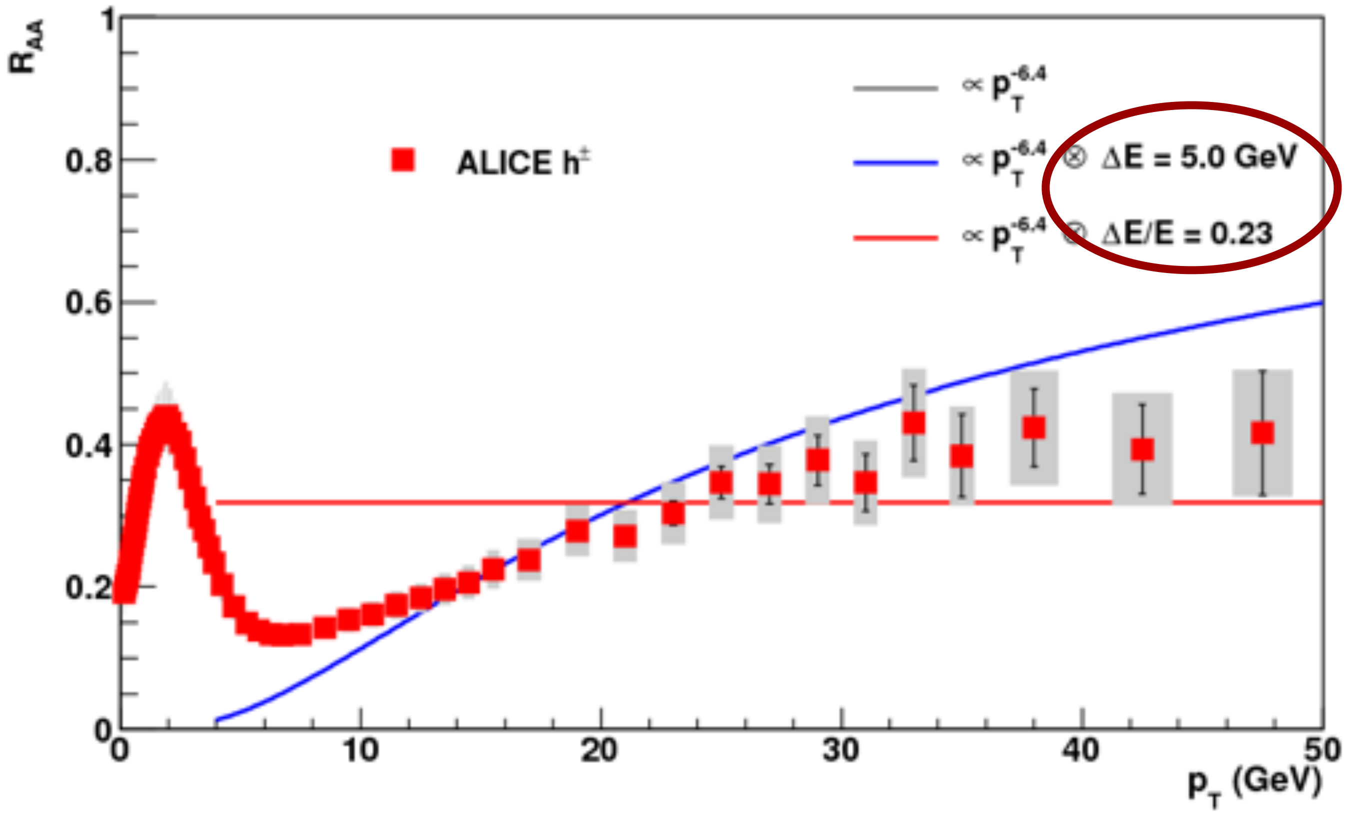
R_{AA} depends on *n*, steeper spectra, smaller R_{AA}

From RHIC to LHC

RHIC



LHC



RHIC: n ~ 8.2

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

LHC: n ~ 6.4

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

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

To be continued… in the next lecture

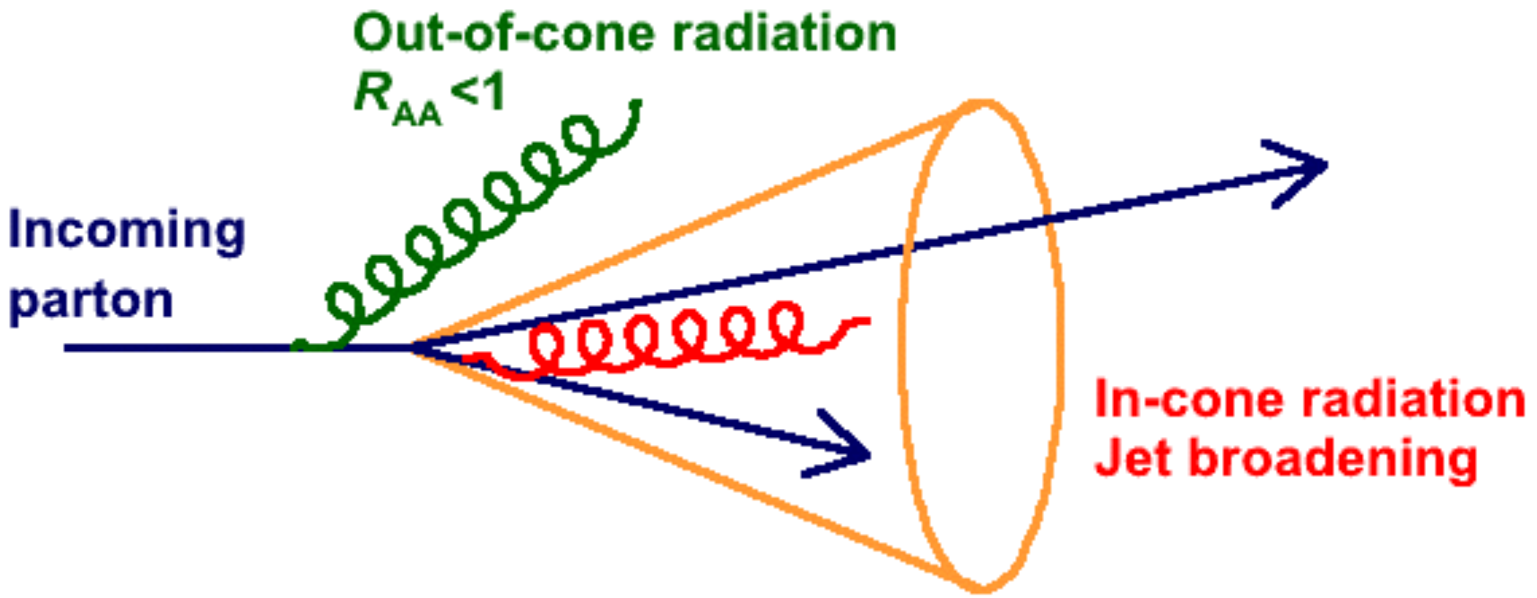
Summary

- QCD is a theory of quarks and gluons, but we observe hadrons
- Hard scattering, large Q^2: factorisation
    - Short distance and long distance physics can be separated (to some extent)
    - Short distance: perturbative QCD
    - Long distance: non-perturbative: PDFs, FFs
- Experimentally accessible ‘partonic’ observables:
    - Jets
    - Photons
- First high-Q^2 measurements in heavy ion collisions:
    - Hadron (charged particle) production: no N_{coll} scaling; energy loss
    - Photon production: N_{coll} scaling

Extra slides

Jets and parton energy loss

Motivation: understand parton energy loss by tracking the gluon radiation



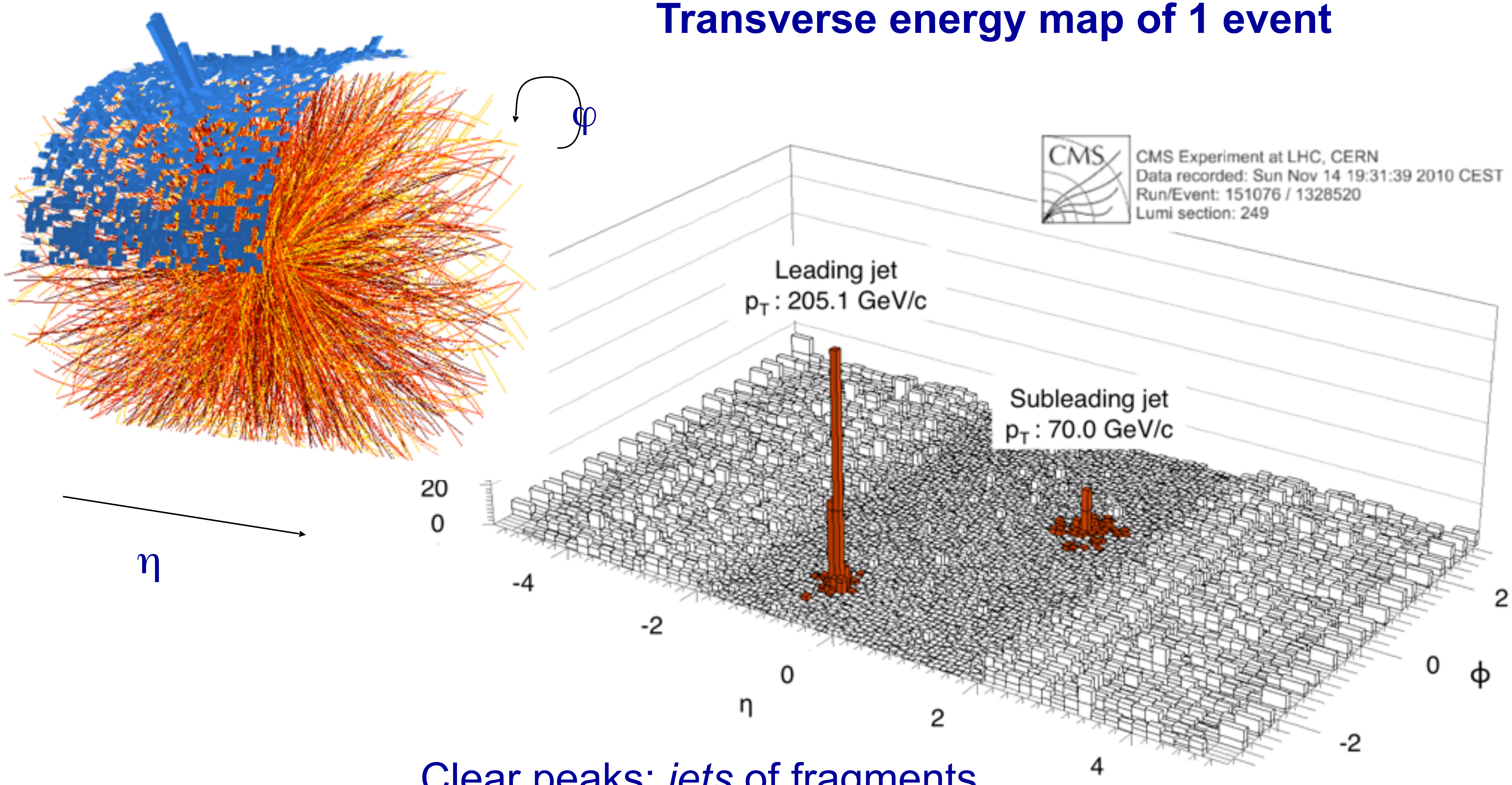
Qualitatively two scenarios:

1) In-cone radiation: $R_{AA} = 1$, change of fragmentation
2) Out-of-cone radiation: $R_{AA} < 1$

Jets at LHC

ALICE

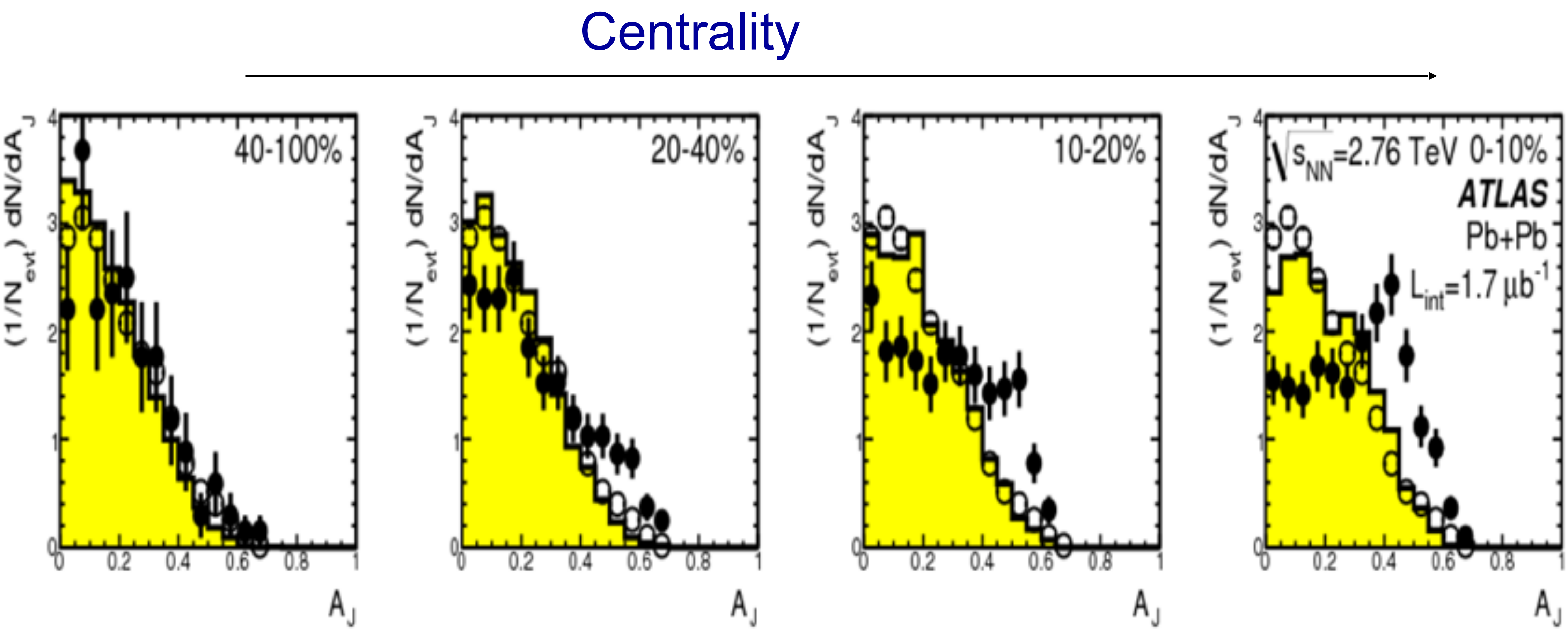
Transverse energy map of 1 event



Clear peaks: *jets* of fragments
from high-energy quarks and gluons

And a lot of uncorrelated ‘soft’ background

Jet energy asymmetry



ATLAS, arXiv:1011.6182 (PRL)

Jet-energy asymmetry

$$A_J = \frac{E_2 - E_1}{E_2 + E_1}$$

Large asymmetry seen
for central events

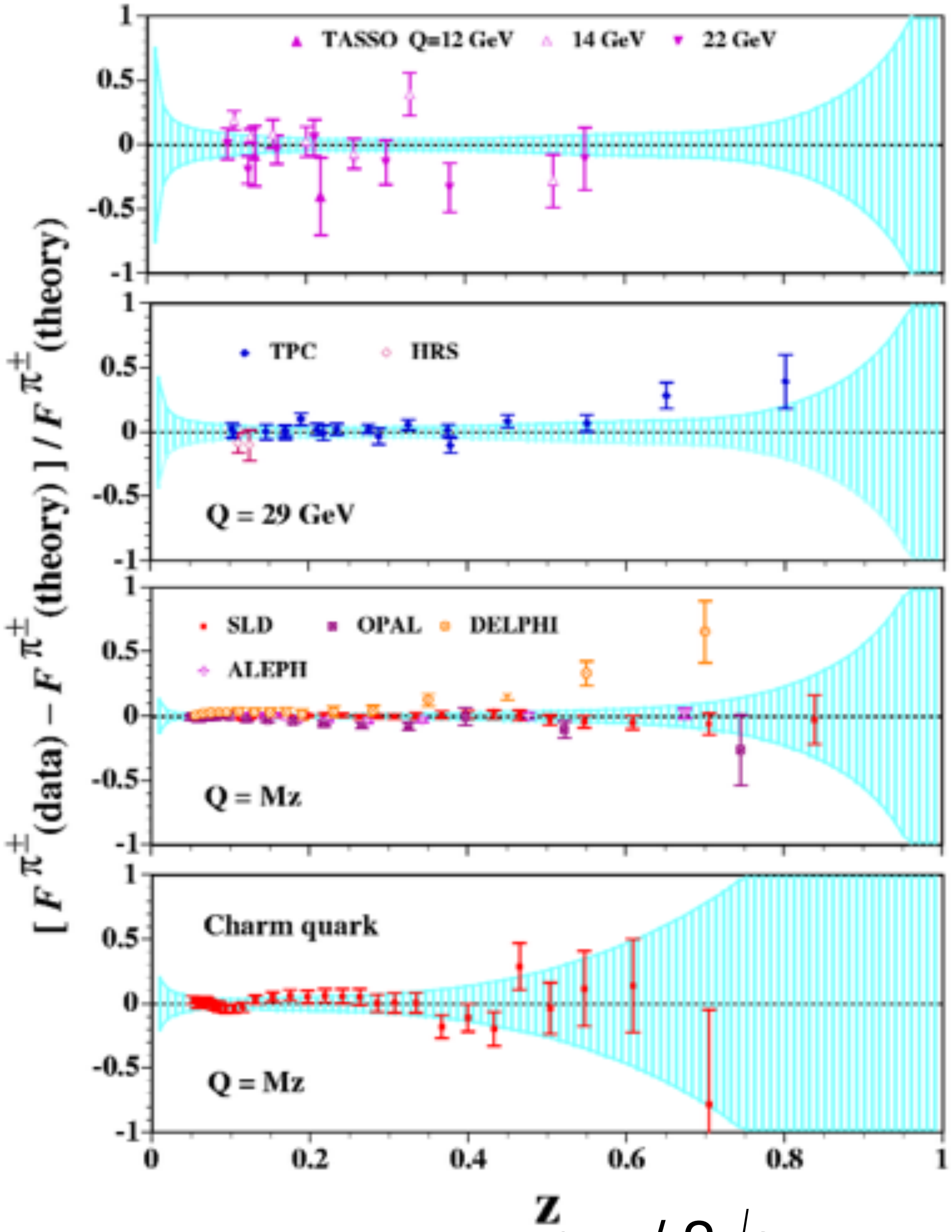
Suggests large energy loss: many GeV
~ compatible with expectations from RHIC+theory

However:

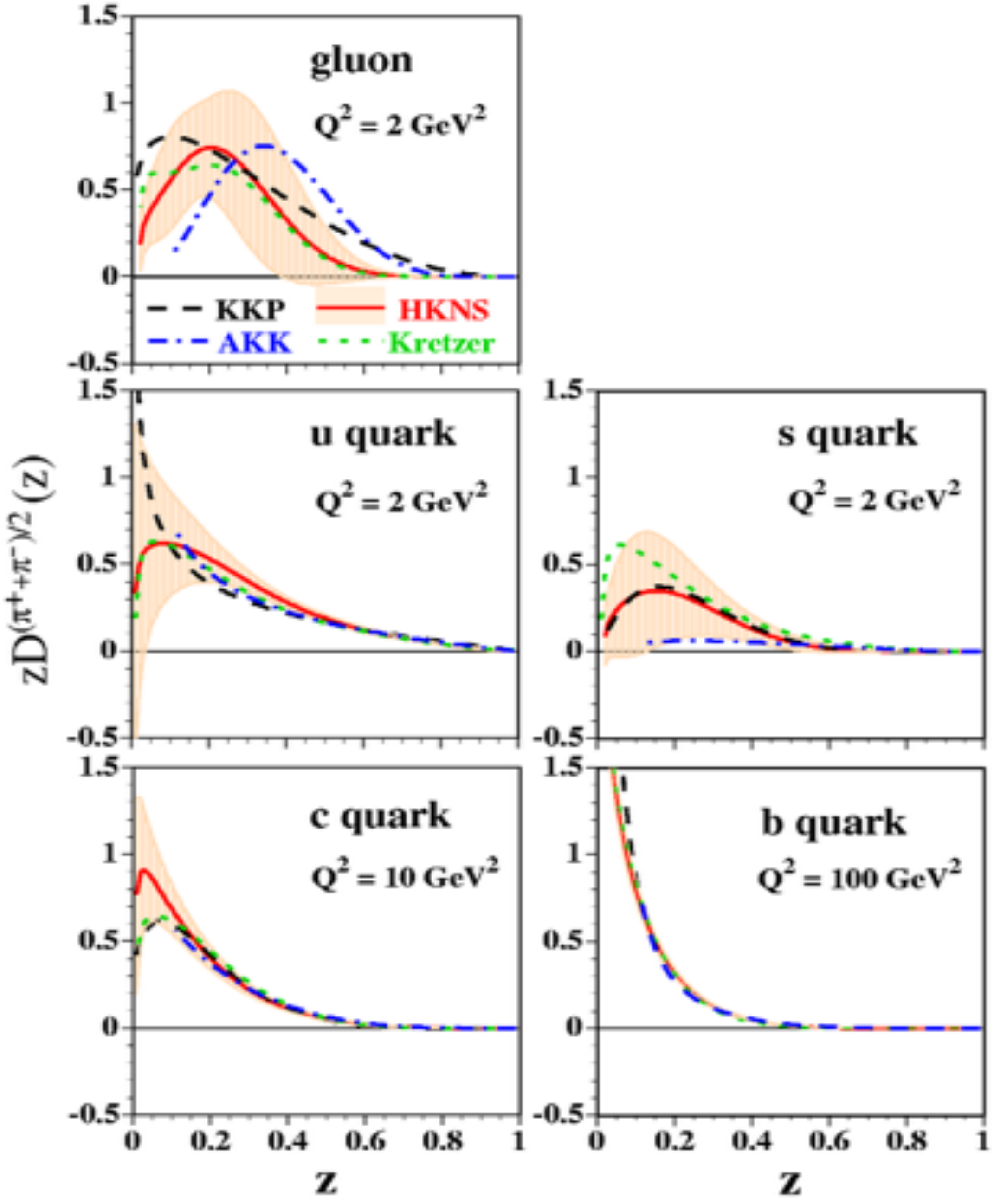
- Only measures reconstructed di-jets (don’t see lost jets)
- Not corrected for fluctuations from detector+background
- Both jets are intereracting – No simple observable

Fragmentation function uncertainties

gai, Sudo, PRD75:094009



$z=p_{T,h} / 2\sqrt{s}$



$z=p_{T,h} / E_{jet}$

Full uncertainty analysis being pursued
Uncertainties increase at small and large z