Lecture 2: p+Pb, energy loss formalisms, more differential results

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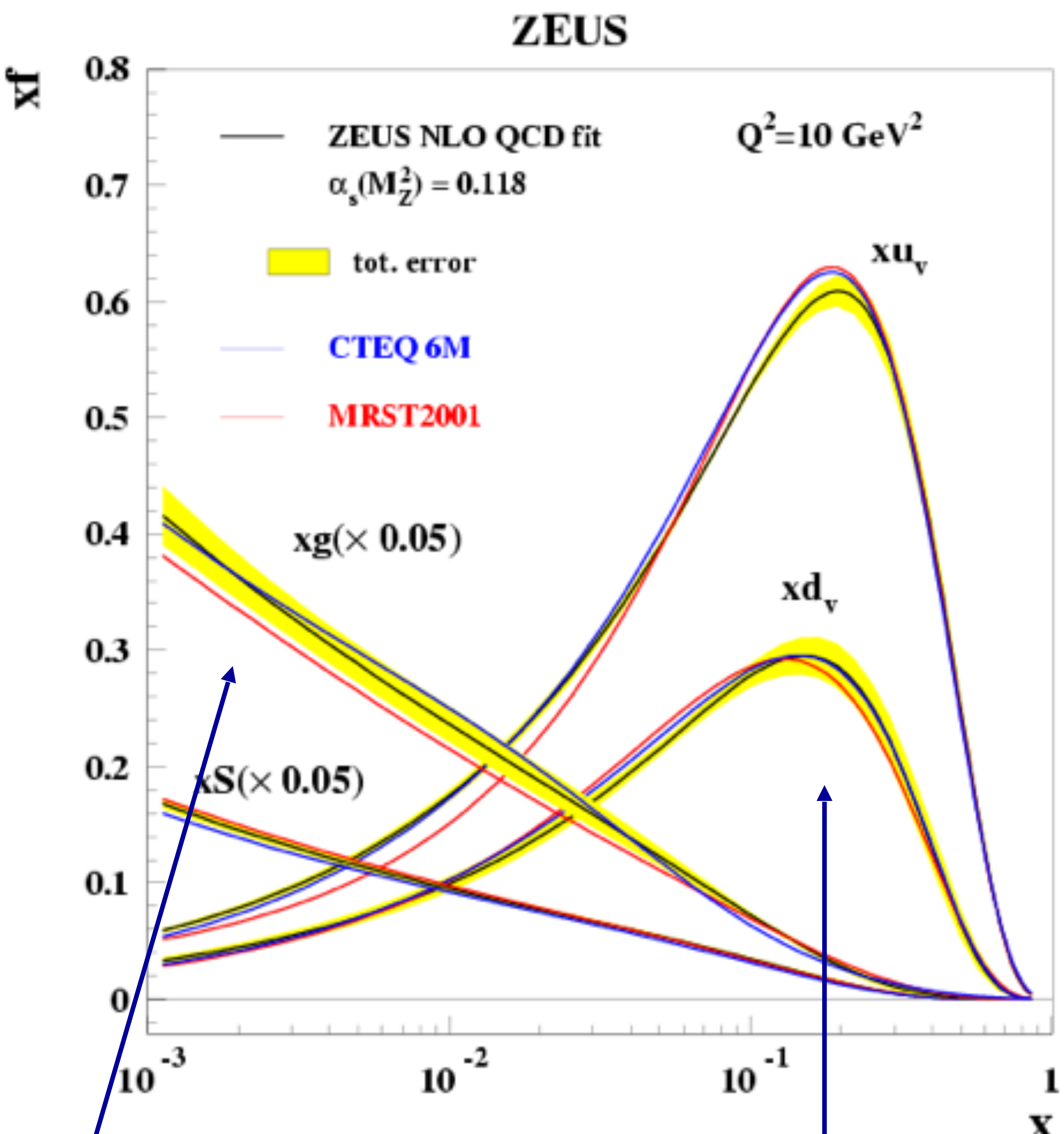
A few selected results for p+Pb at LHC

NB: no time to cover everything; mainly pointers to interesting results, see QM summary talks for more details

Parton density distribution

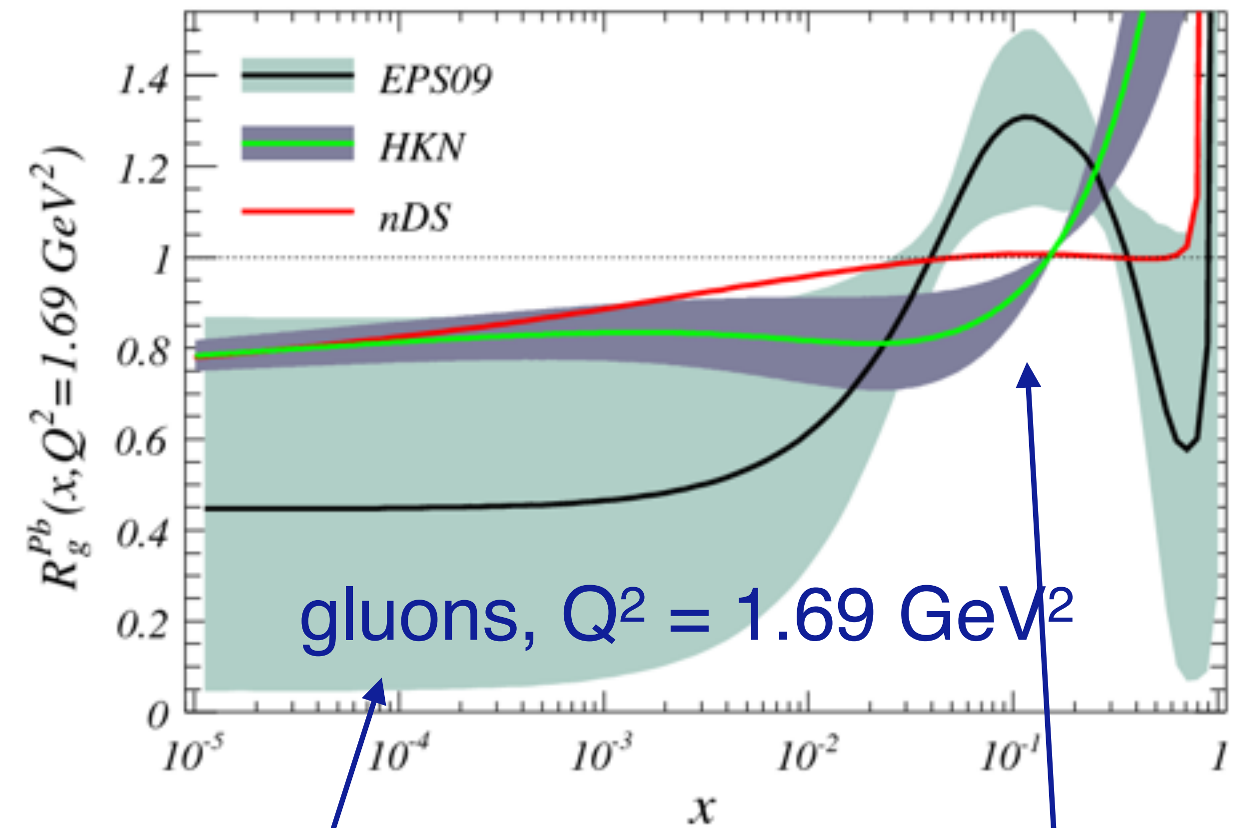
pp, low Q^2: valence structure



Soft gluons

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

Nuclei: ratio to pp



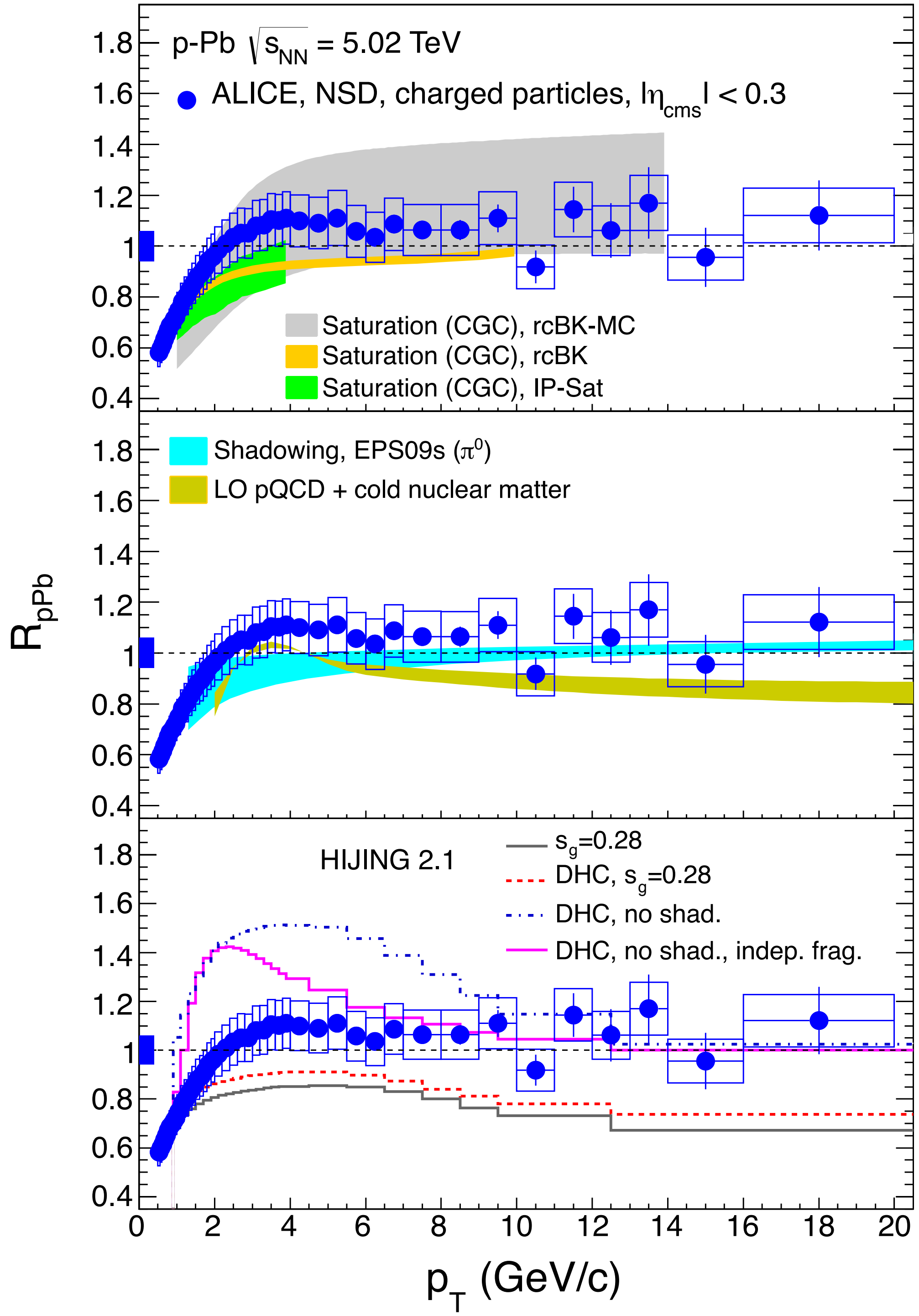
gluons, Q^2 = 1.69 GeV^2

Low-x suppression: shadowing

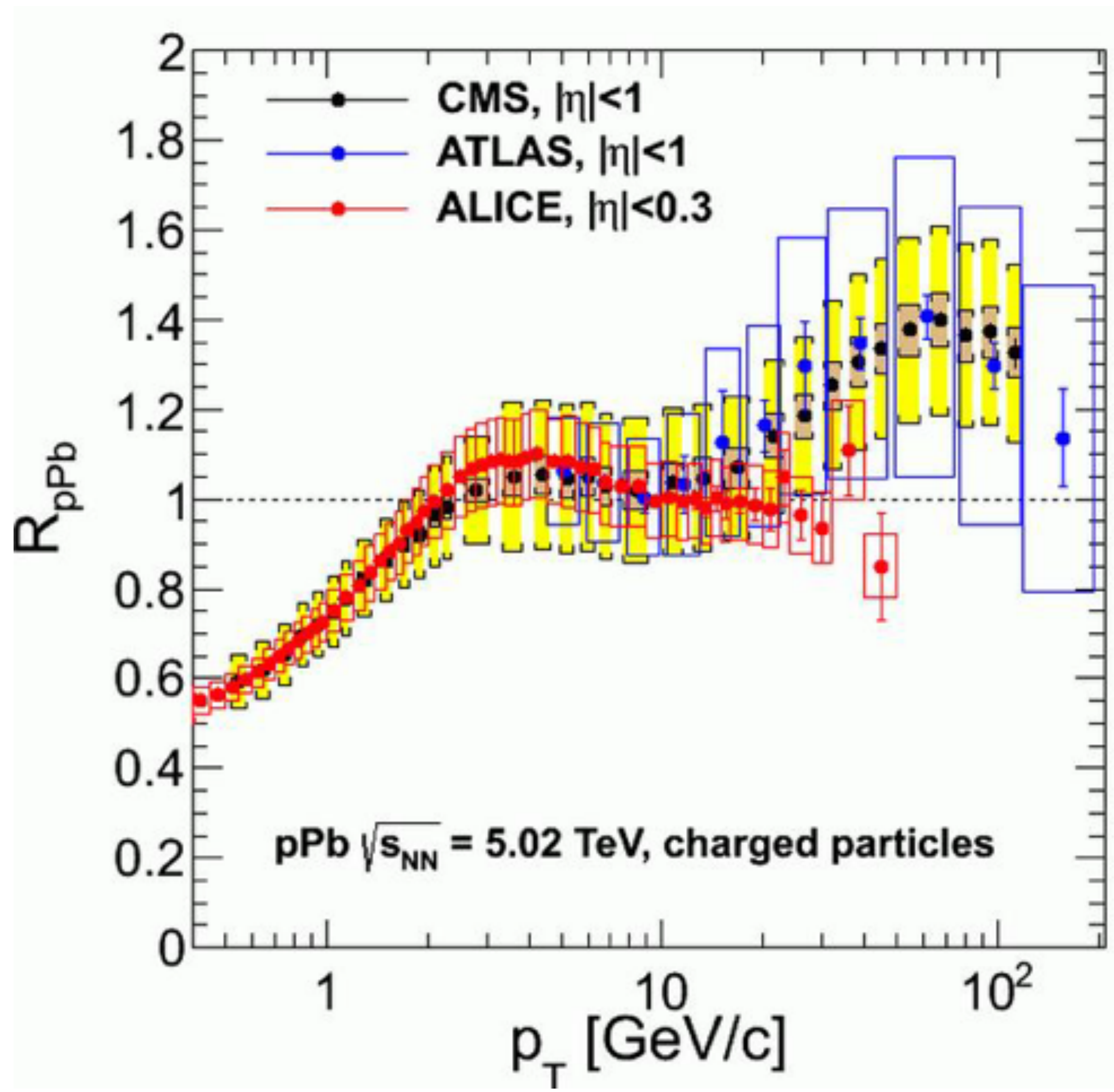
Enhancement at intermediate x: 'anti-shadowing'

Effects largest at low Q^2

Hadron R_{pPb} at LHC



ALICE, arXiv:1210.4520



CMS-HIN-12-017, ATLAS QM2014, ALICE, arXiv:1405.2737

No nuclear modification in p+Pb for hadrons $p_T \gtrsim 3$ GeV

Agrees with nuclear PDFs

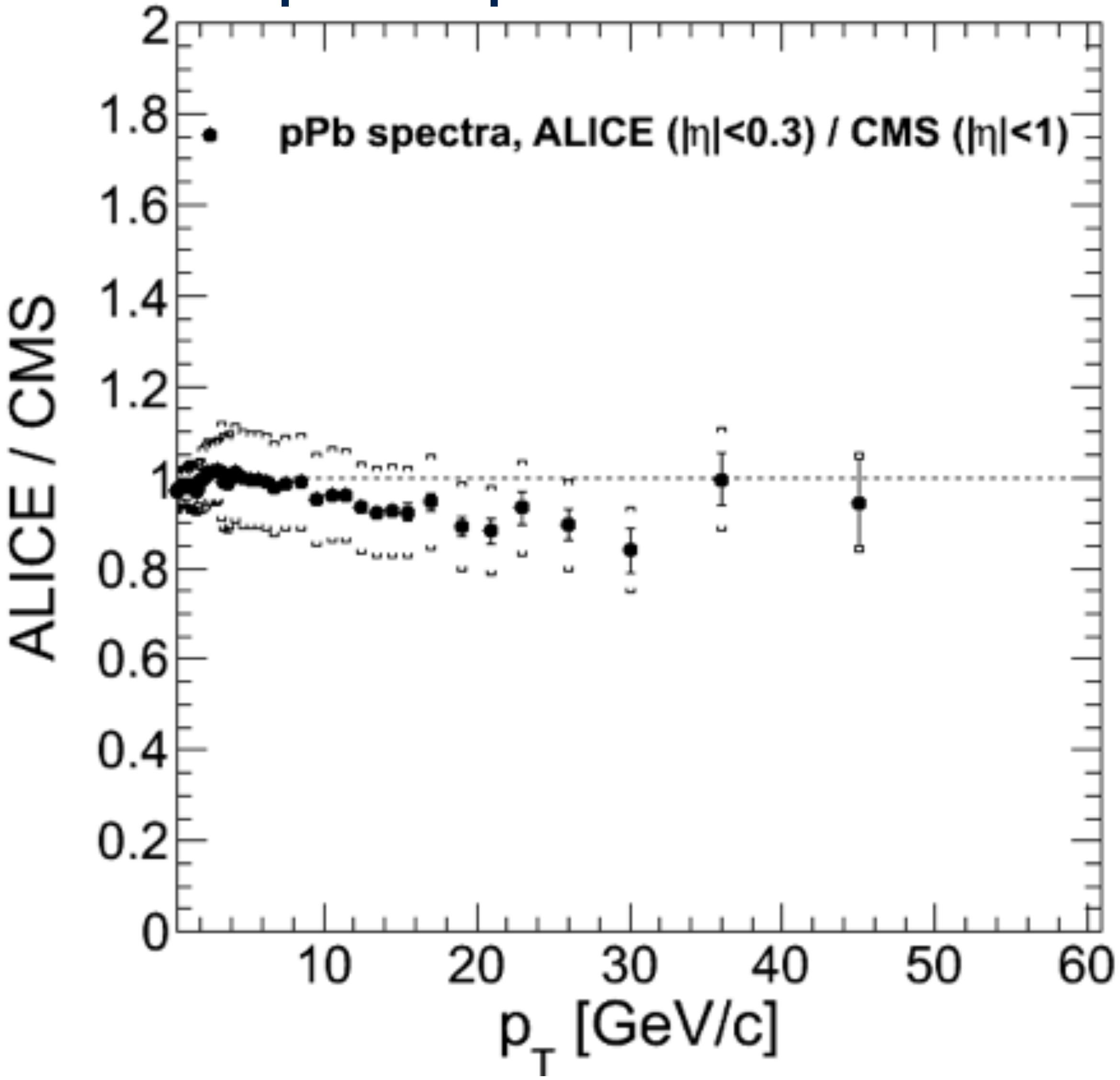
CMS, ATLAS: enhancement at $p_T > 30$ GeV

No obvious physics interpretation…

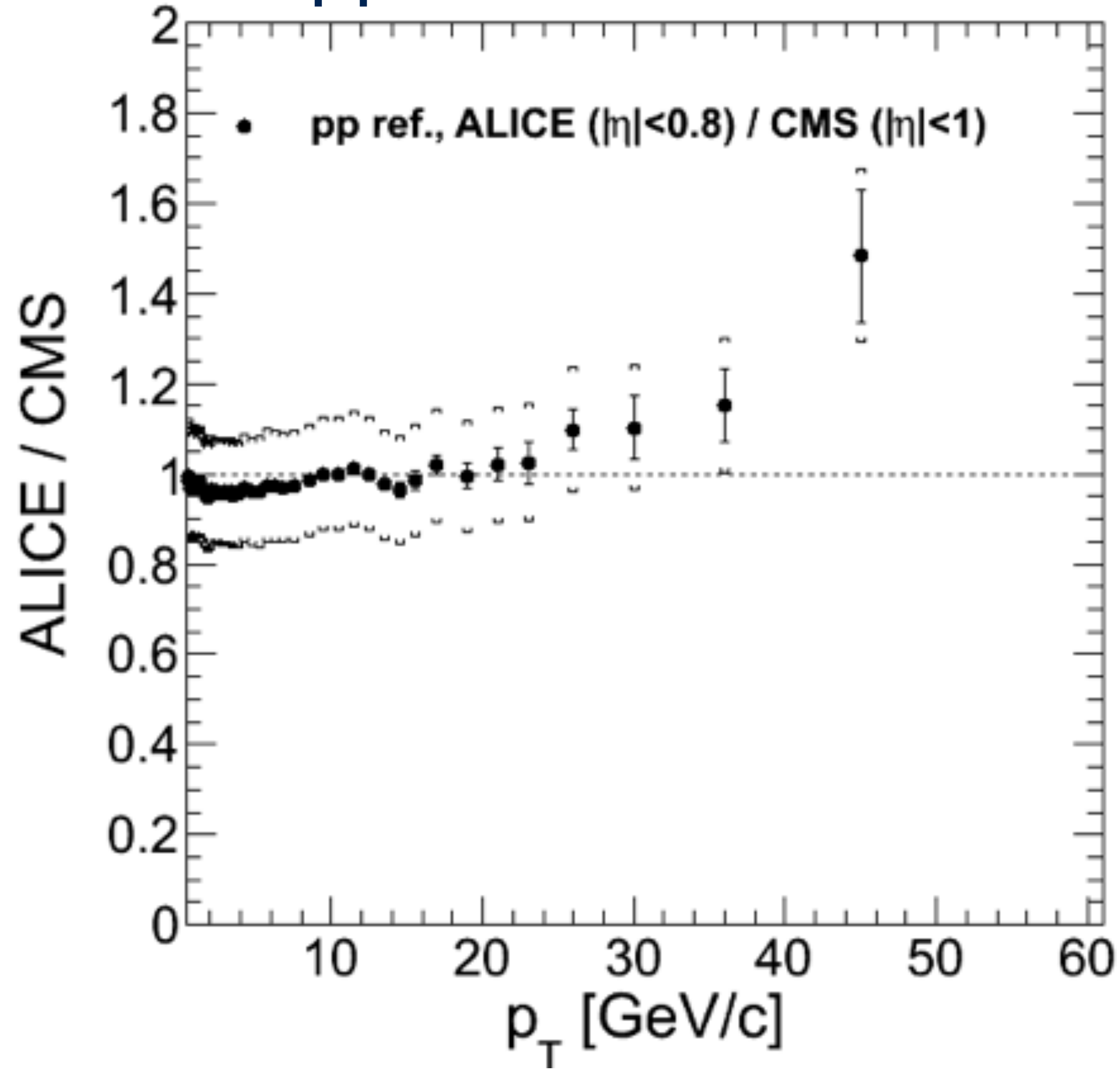
pp reference at 5.02 TeV

No pp measurements at 5.02 TeV available
All experiments use interpolations between 2.76 and 7 TeV

pPb spectra ratio



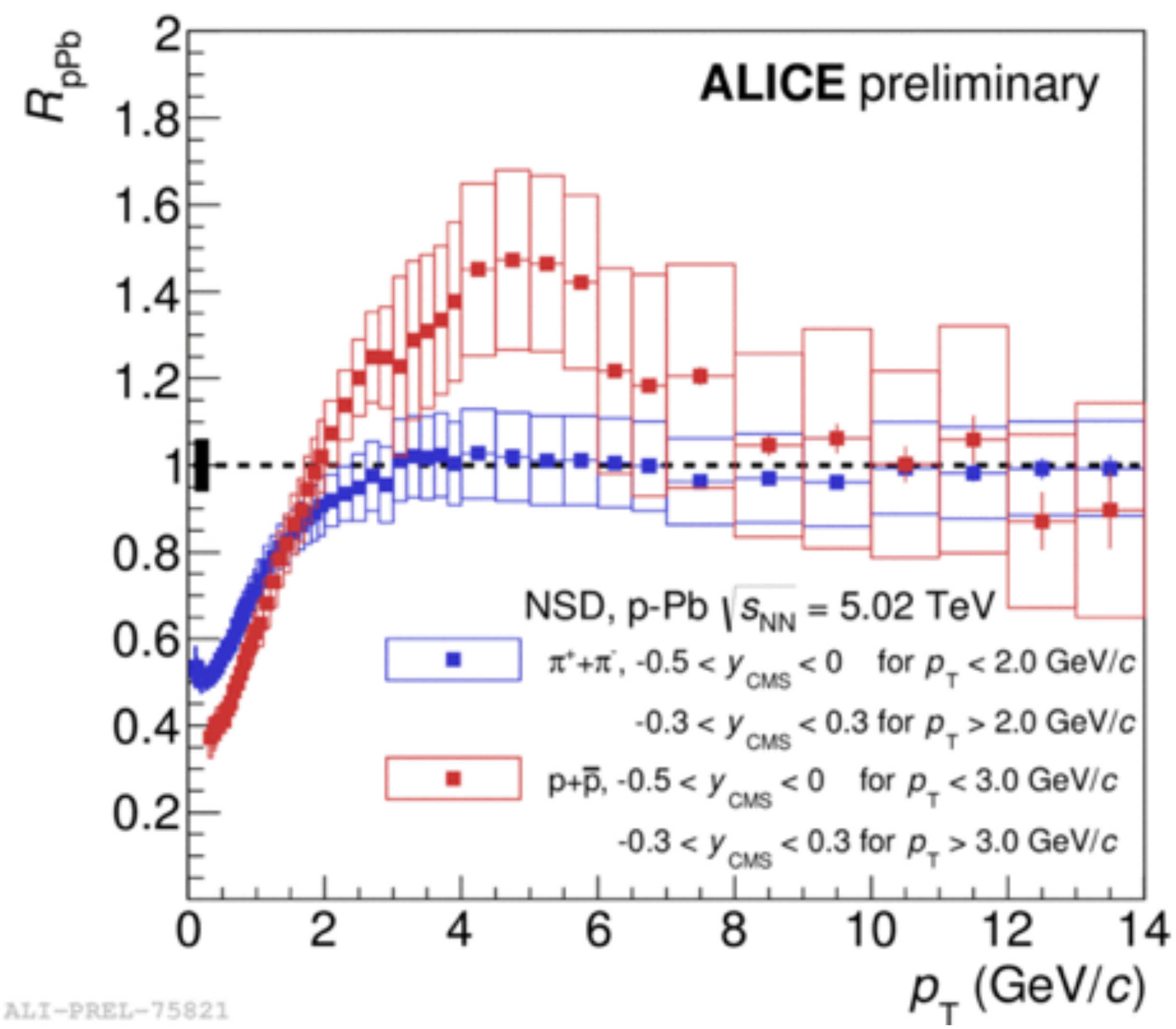
pp reference ratio

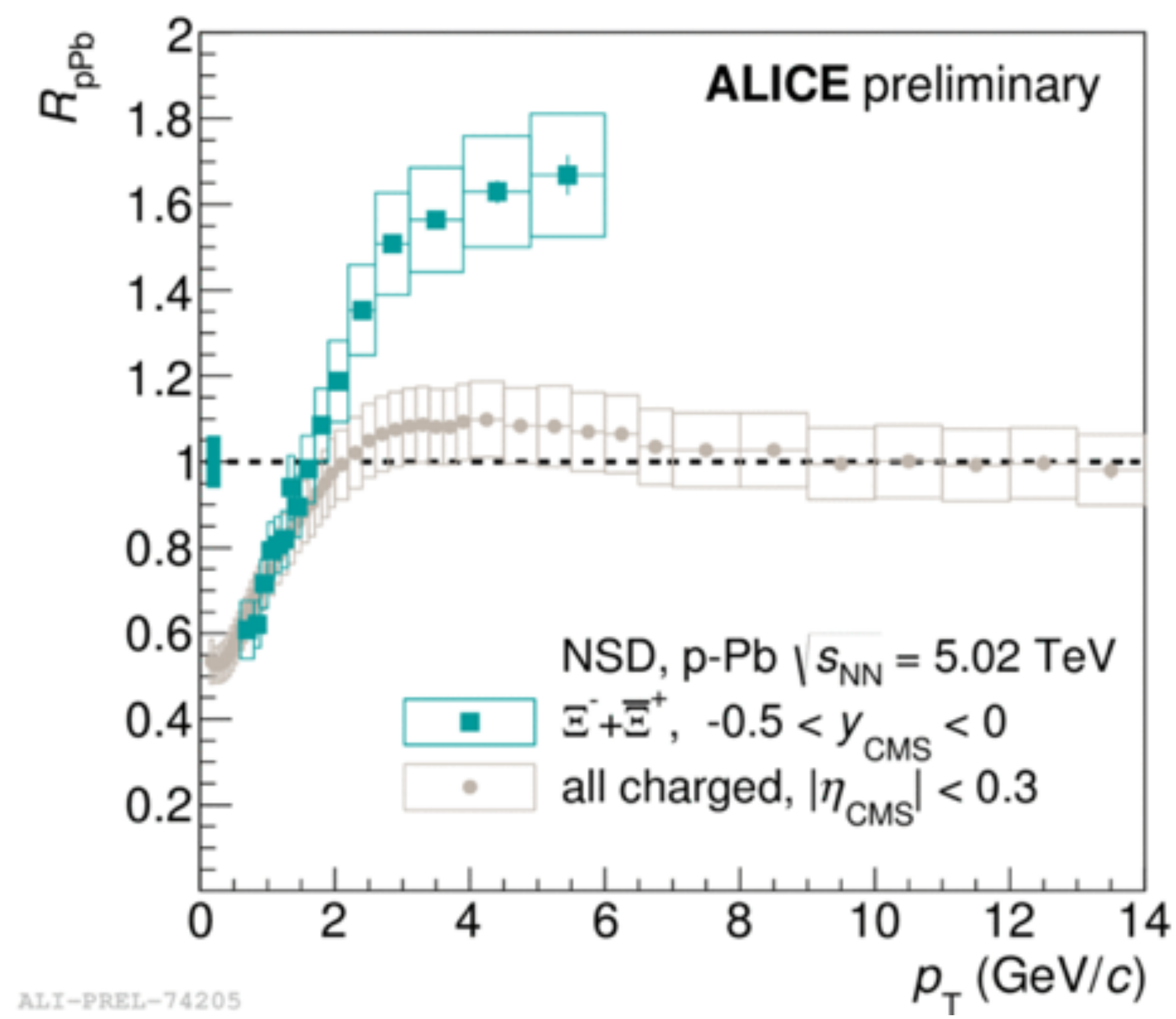


E. Appelt, Yenjie Lee @ QM2014

Largest differences in reference spectra;
revisit high-pt measurements at 2.76 and 7 TeV;
measure pp at 5.05 TeV?

Cronin effect at LHC





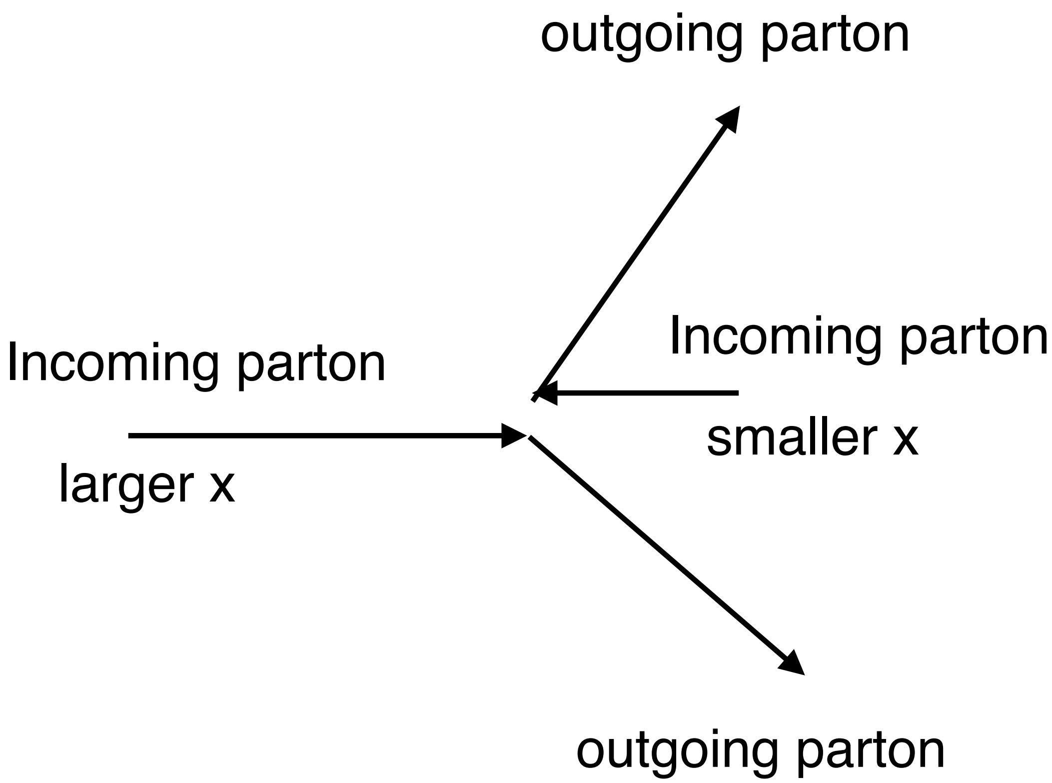
Cronin effect:

R_{pPb} shows enhancement at intermediate p_T for protons, Ξ

No large effect for π, K, Φ

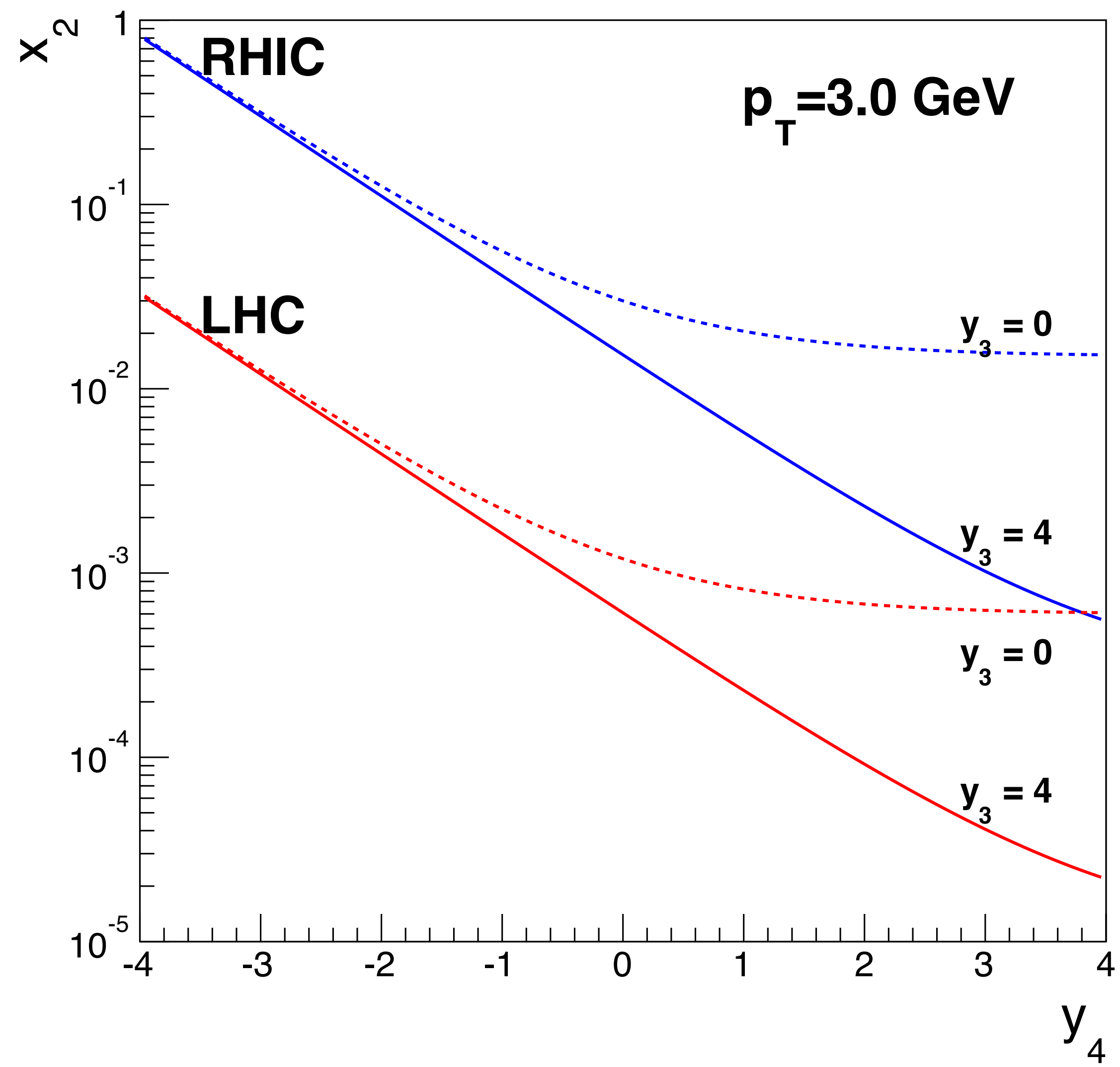
Interpretation/mechanism unclear: why does it depend on hadron type/mass?
Can it be flow-like?

Parton kinematics and x ranges



Two partons at large η, asymmetric collision: large x + small x parton

$$x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-\eta_3} + e^{-\eta_4}\right)$$

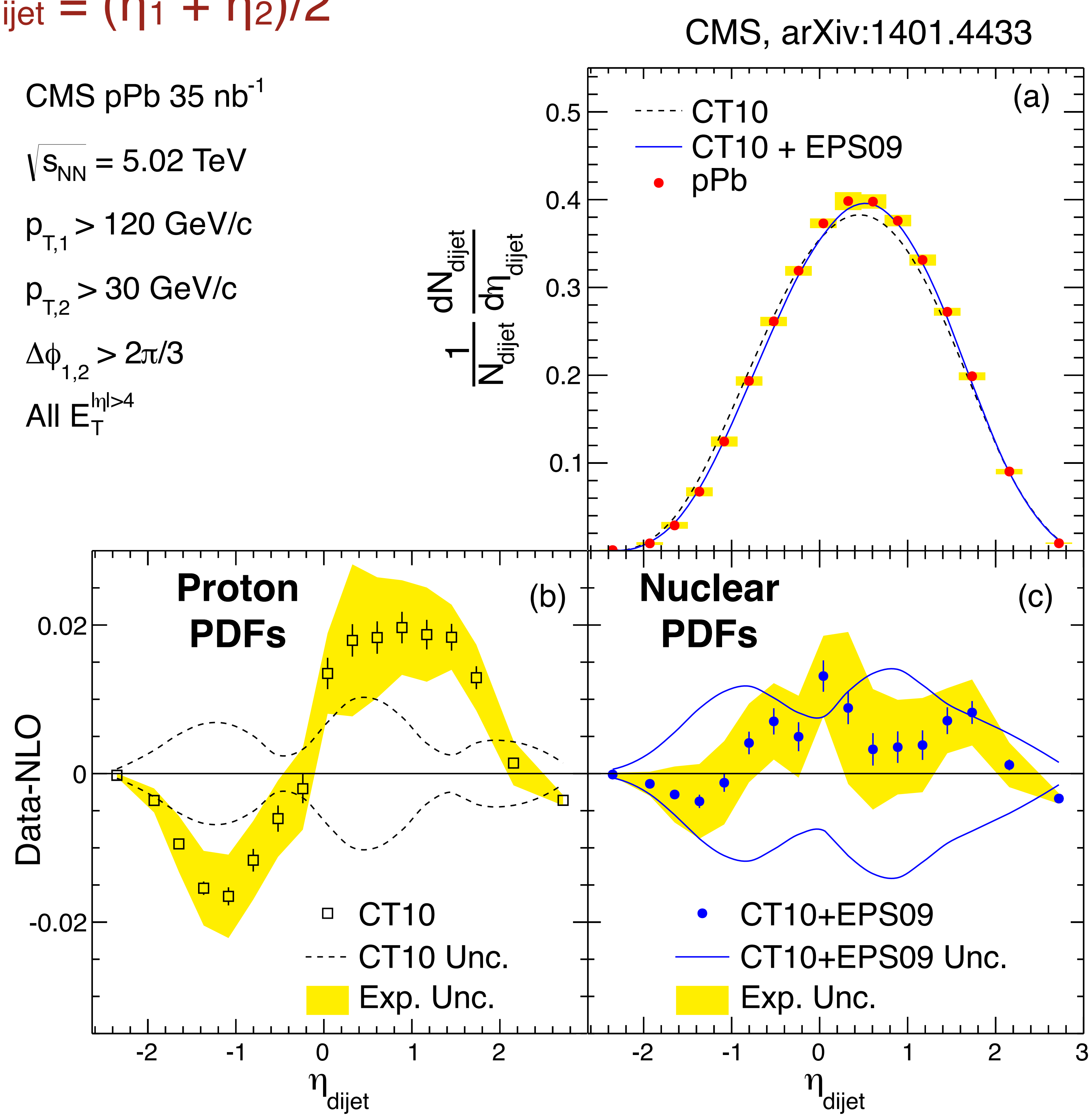


Forward rapidity is small x

LHC probes lower x than RHIC
Midrapidity at LHC ~ forward rap at RHIC

Varying *x* in p+Pb: di-jets

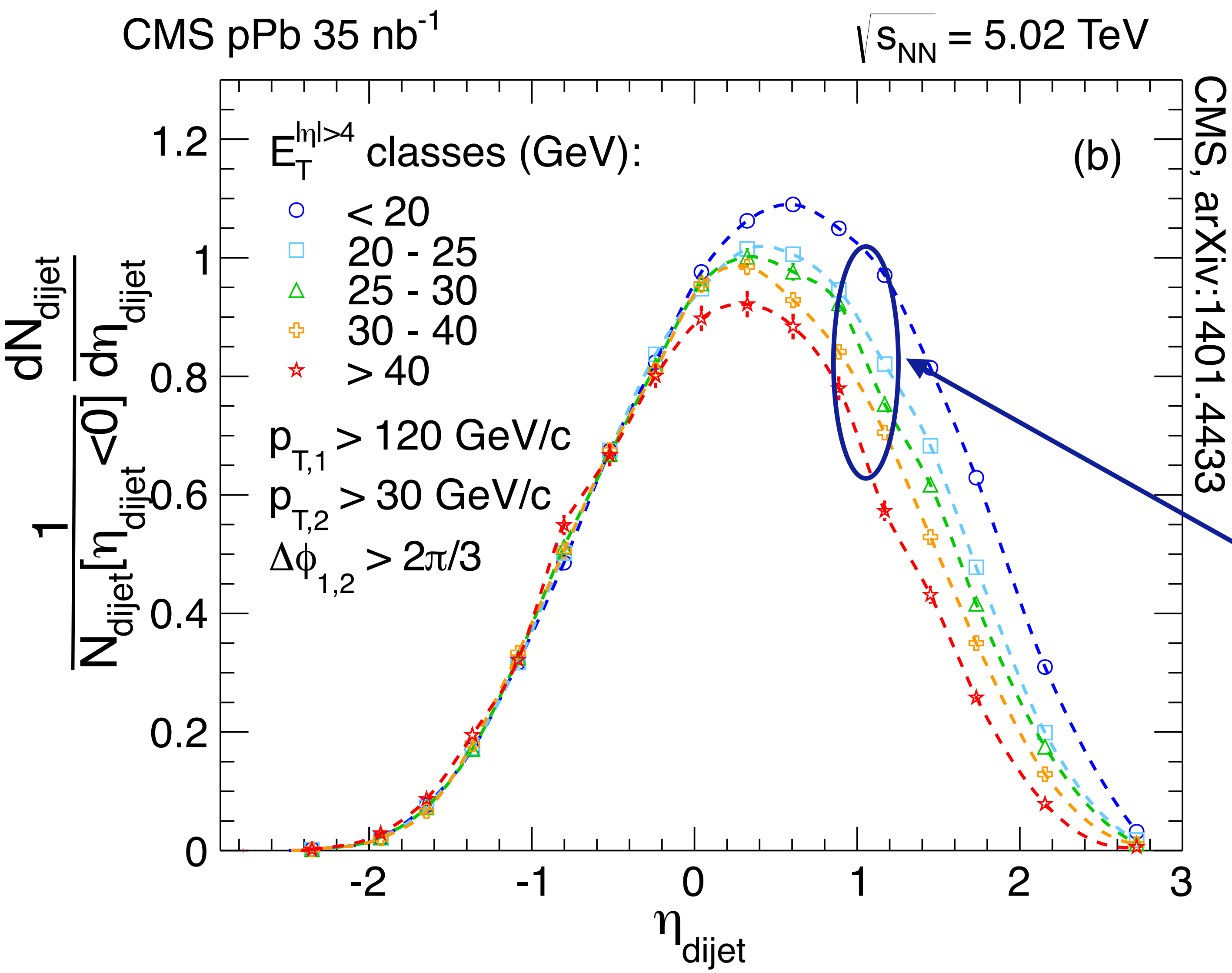
$\eta_{dijet} = (\eta_1 + \eta_2)/2$



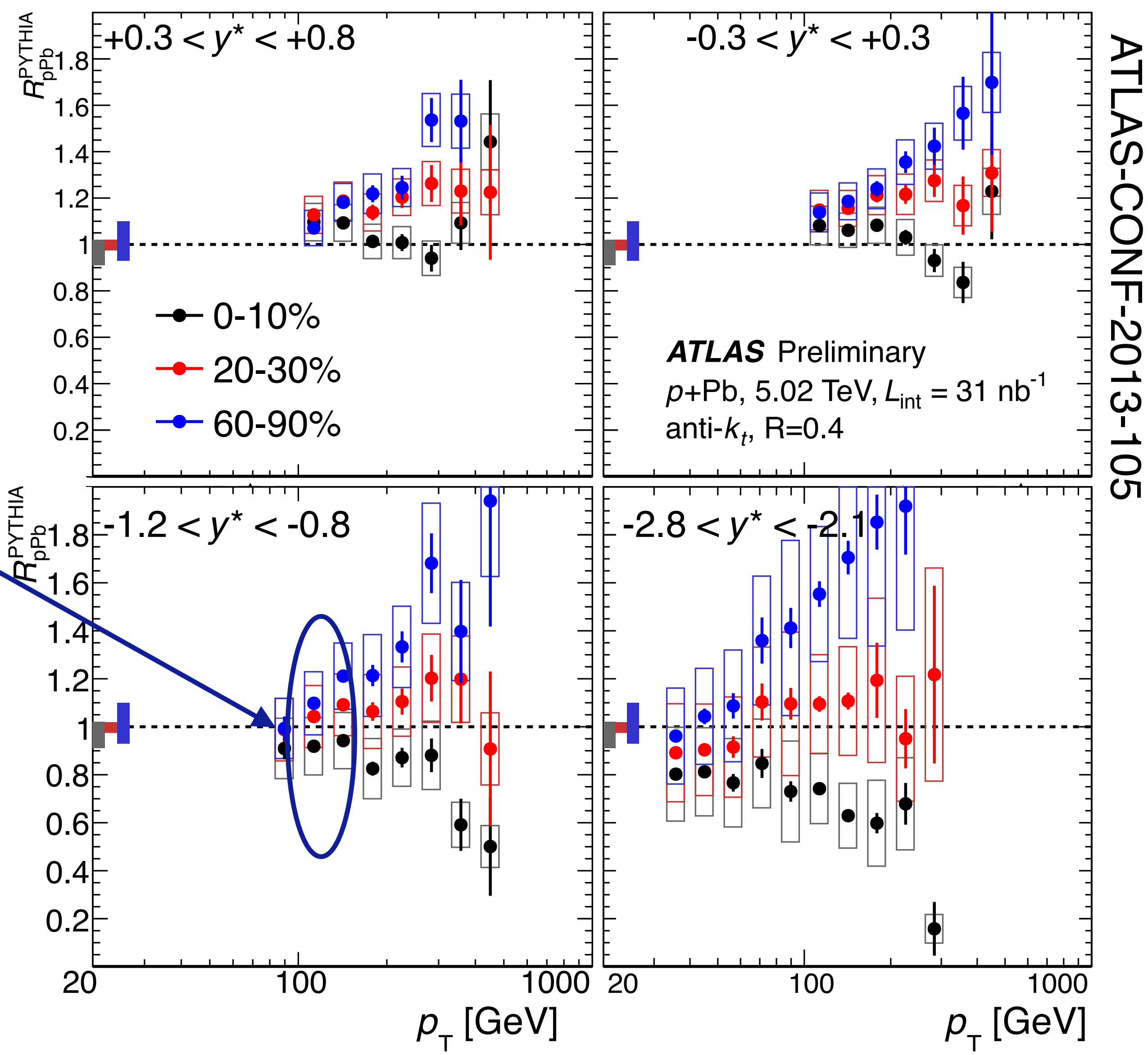
NB: asymmetric beam energies: mid-rapidity is at η~0.4

Shift of distribution to larger η agrees with nPDF expectation

Di-jet eta in event activity bins



R_{pPb}

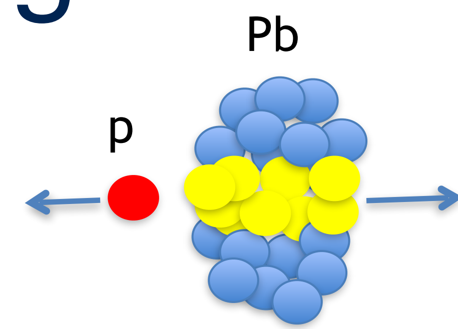


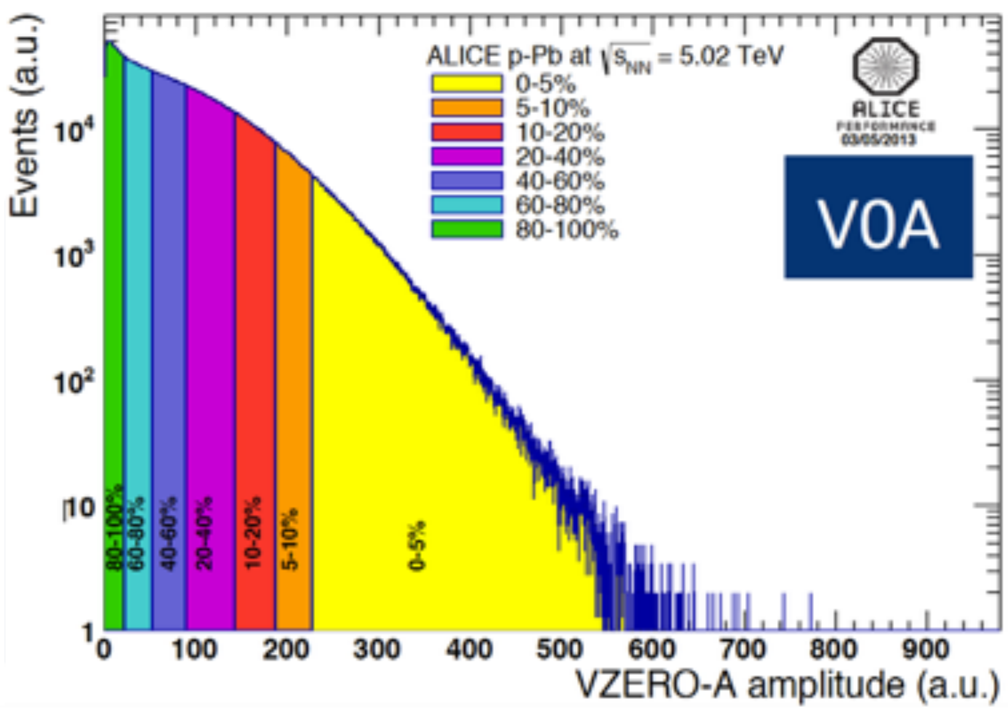
Non-trivial correlation with forward event activity: di-jet moves away from forward activity

Effect also depends on p_T

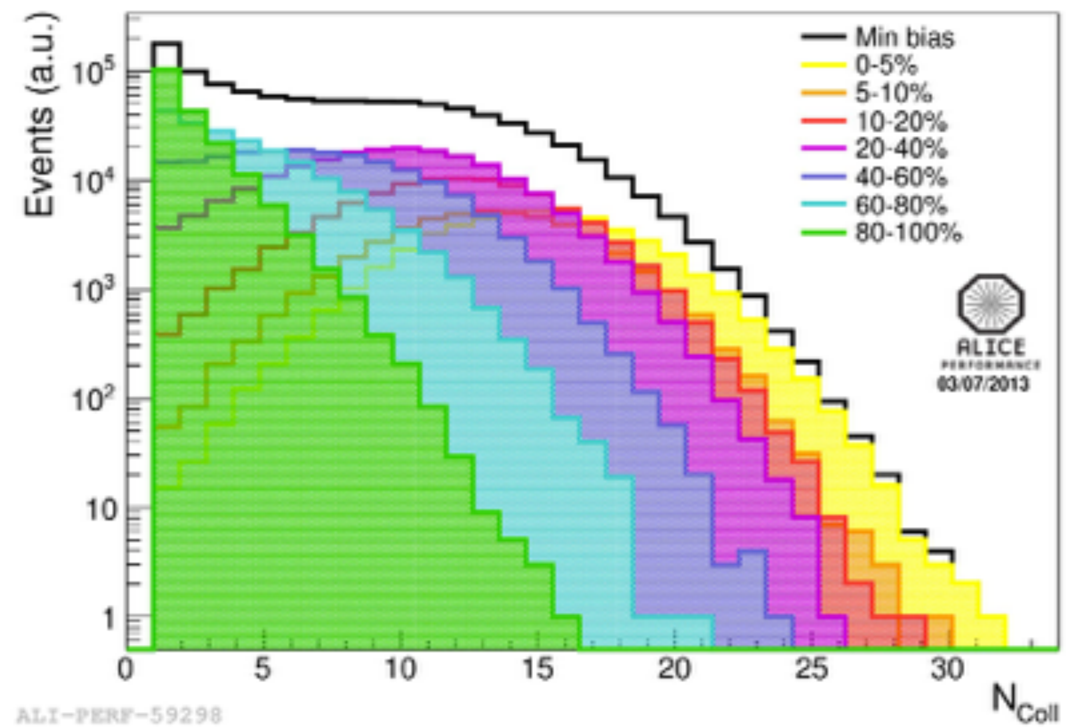
Note on centrality/geometry

Centrality: would like to vary impact parameter in experiment





Standard tool: multiplicity binning

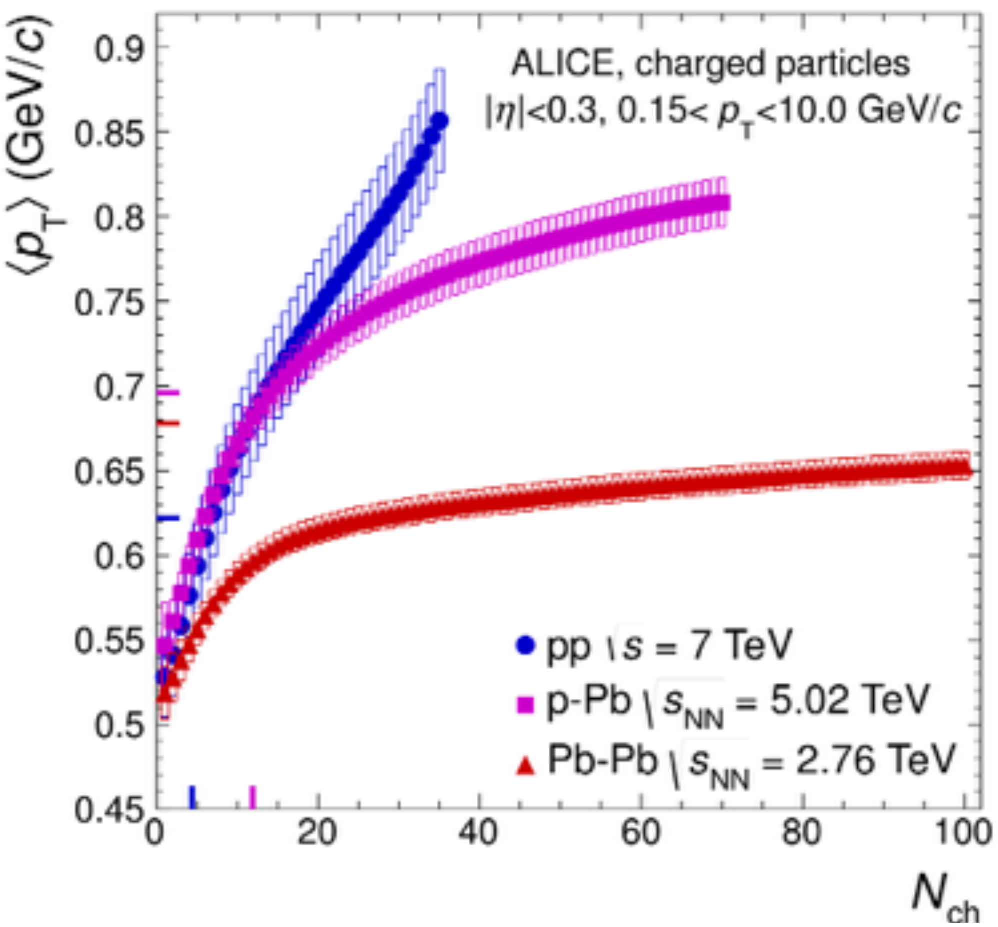


Use geometrical model (Glauber) to calculate N_{coll}

$$R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$$

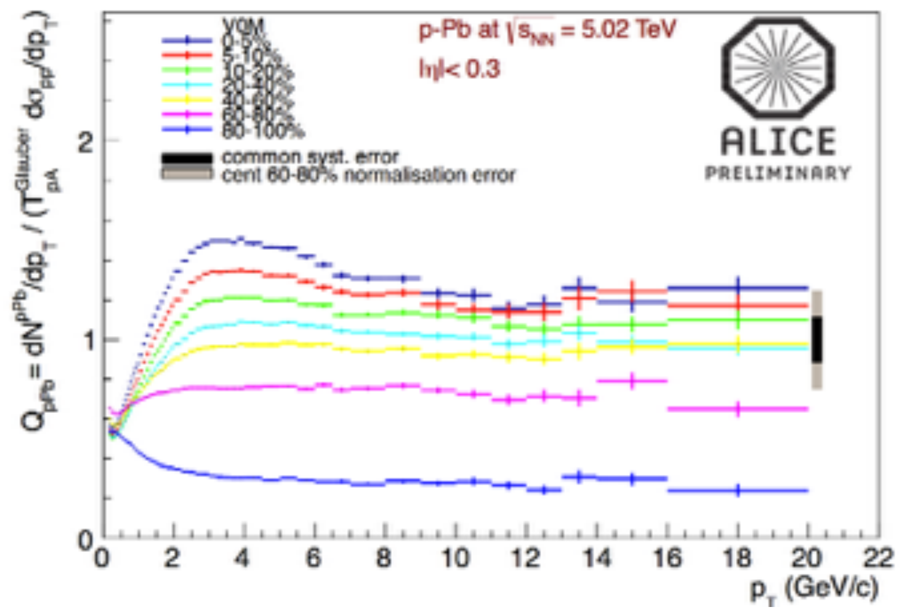
N_{coll} fluctuations within the same centrality class are large!

p+Pb centrality II

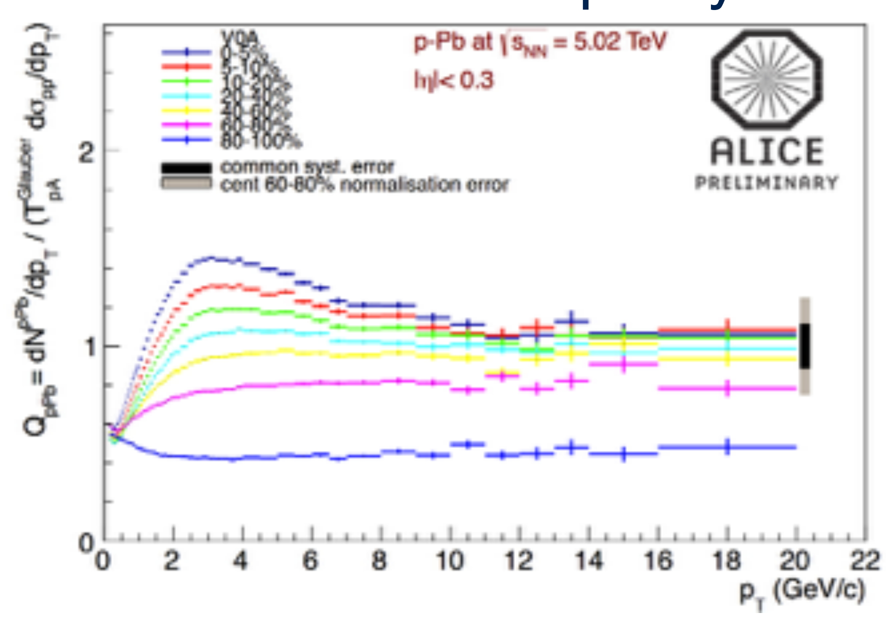


Interplay between N_{part} and higher multiplicity in individual NN collisions

Forward+backward multiplicity



Forward multiplicity



Biases affect estimation of N_{coll}, value of 'R_{pPb}'

Back to A+A and parton energy loss

Recap: transport coefficient study

RHIC:

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

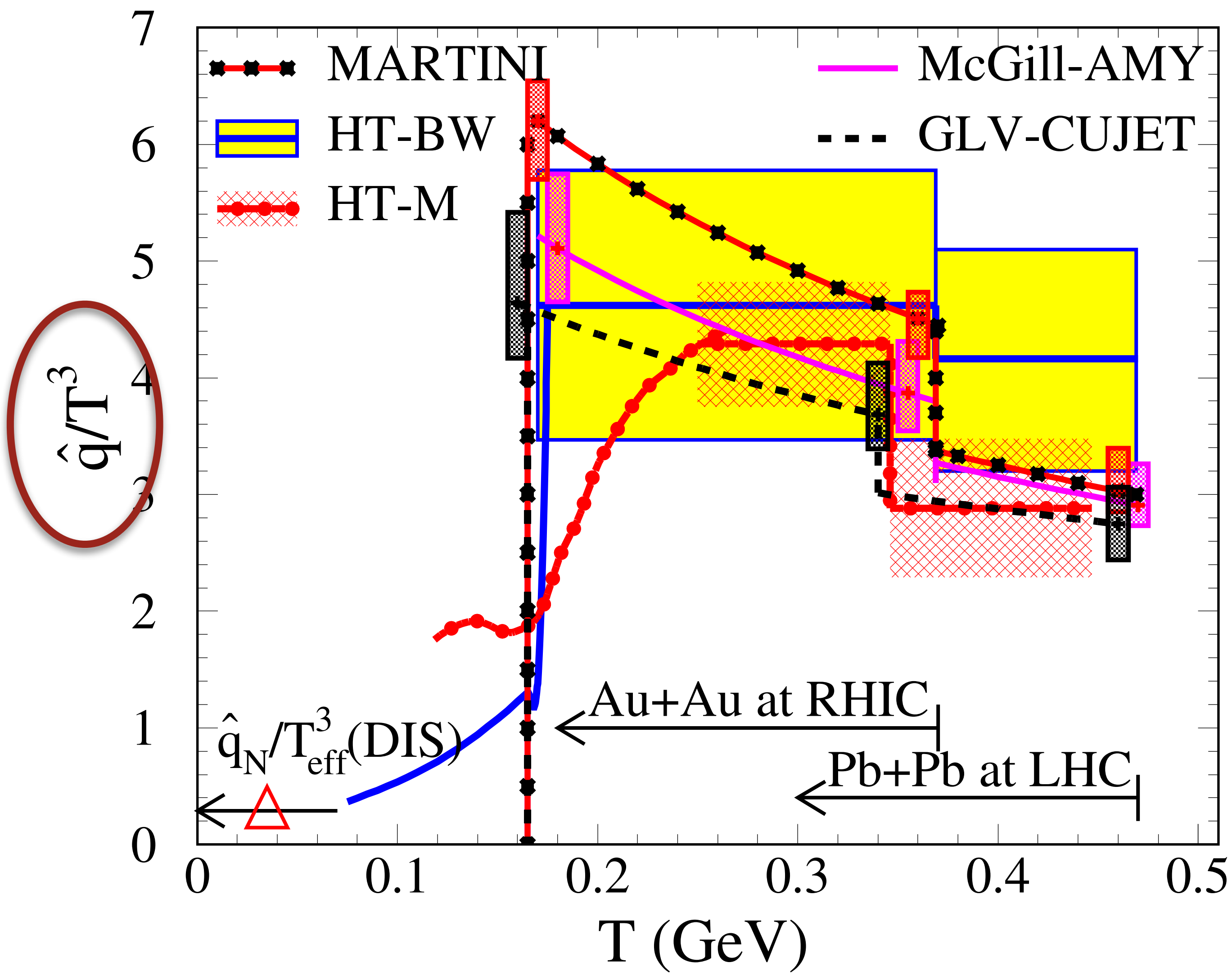
(T=370 MeV)

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?

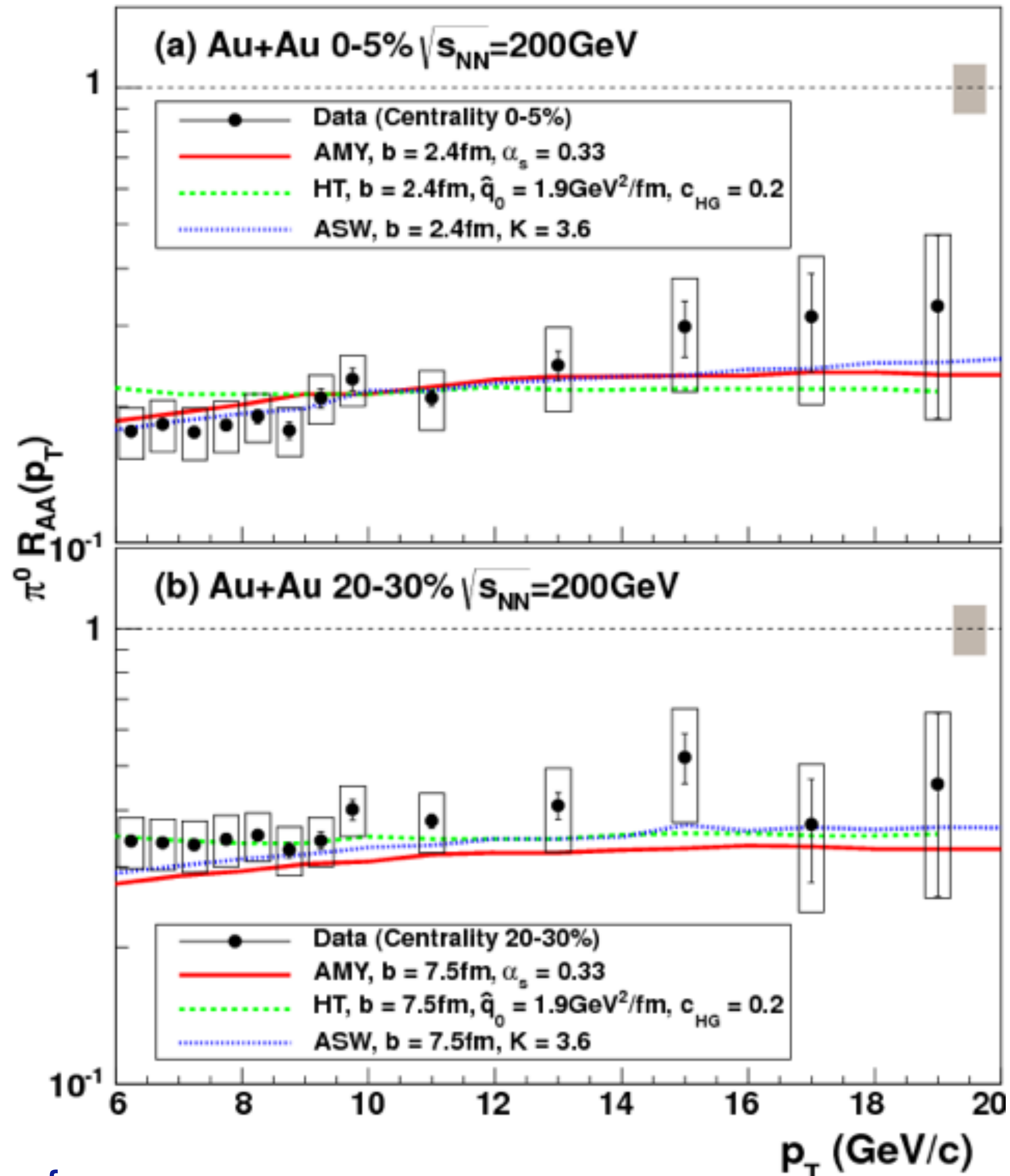
Recap: earlier study

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

ASW: $\hat{q} = 10 - 20 \text{ GeV}^2/\text{fm}$
HT: $\hat{q} = 2.3 - 4.5 \text{ GeV}^2/\text{fm}$
AMY: $\hat{q} \approx 4 \text{ GeV}^2/\text{fm}$

Large uncertainty in absolute medium density

ASW requires much larger transport coefficient



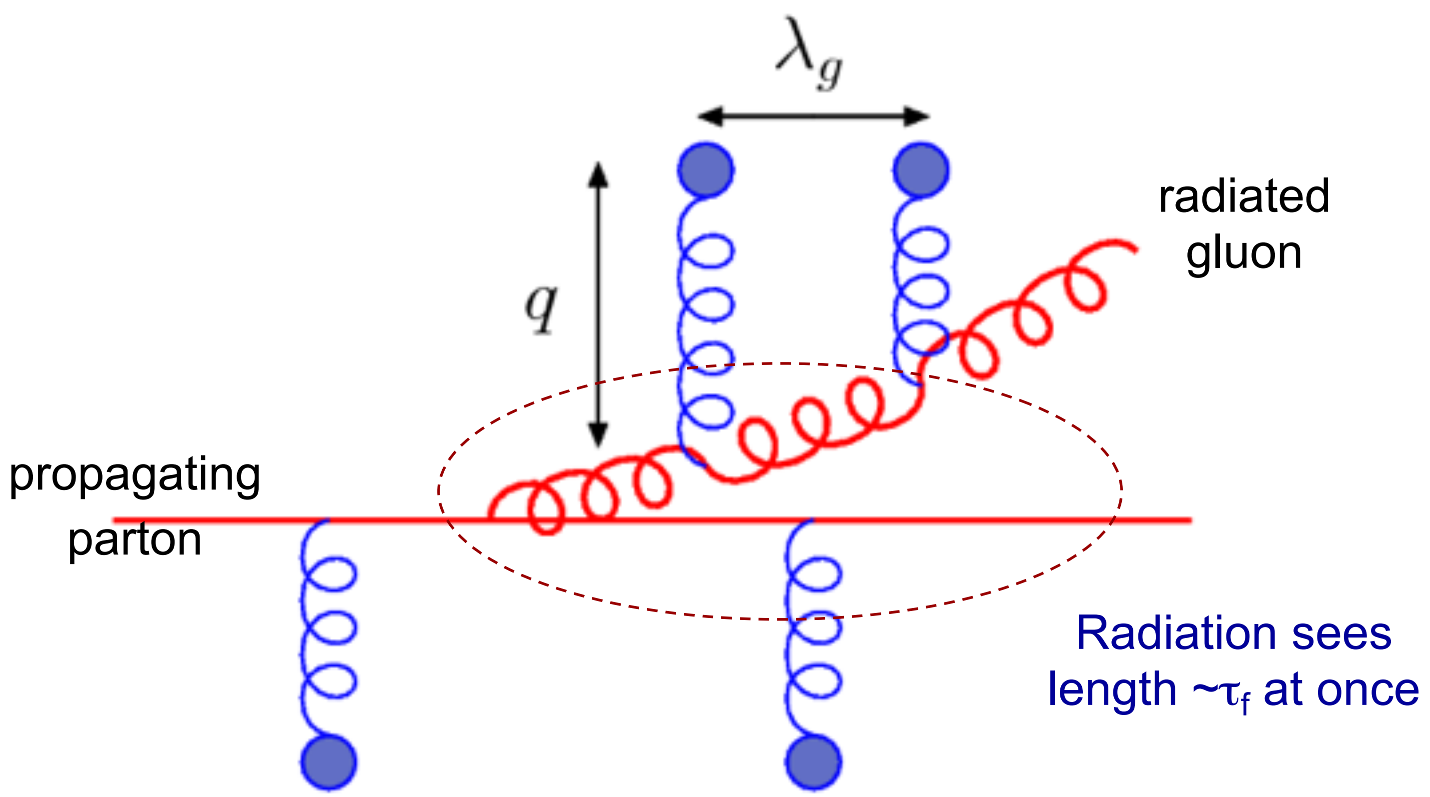
Bass et al, PRC79, 024901

PHENIX, arXiv:1208.2254

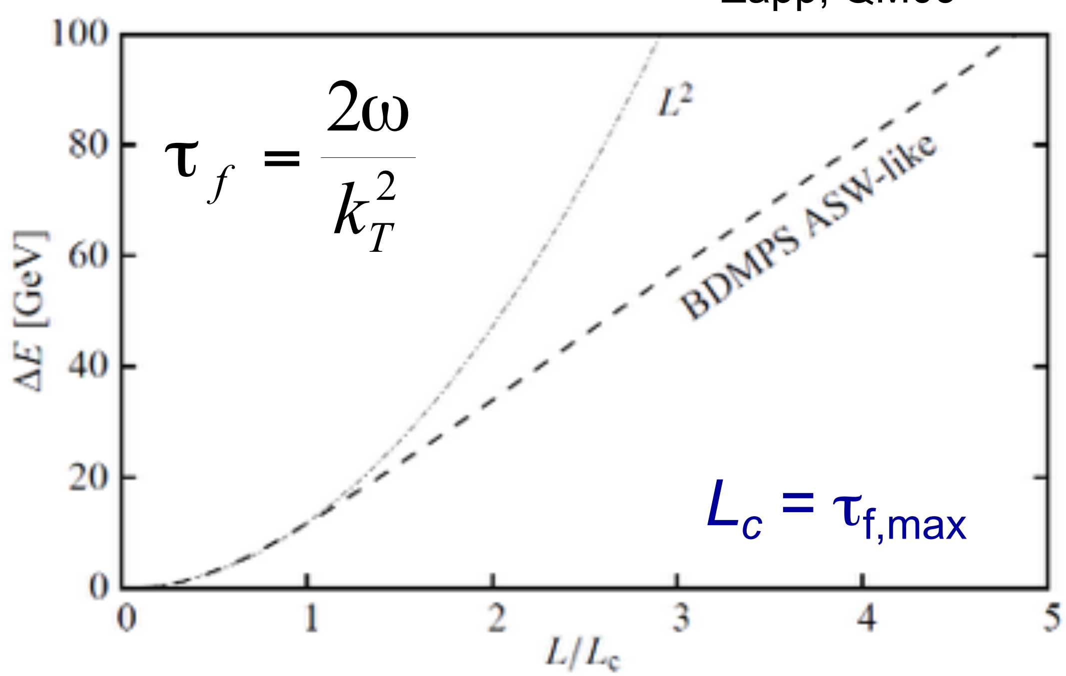
One aspect: scattering potential/momentum transfer; see recent work by Majumder, Laine, Rothkopf on lattice

Medium-induced radiation

Landau-Pomeranchuk-Migdal effect
Formation time important



Zapp, QM09



If $\lambda < \tau_f$, multiple scatterings add coherently

Energy loss depends on density: $\lambda \propto \frac{1}{\rho}$

and nature of scattering centers
(scattering cross section)

$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Transport coefficient $\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$

Four formalisms

Multiple gluon emission

- **Hard Thermal Loops (AMY)**
  - Dynamical (HTL) medium
  - Single gluon spectrum: BDMPS-Z like path integral
  - No vacuum radiation

Fokker-Planck rate equations

- **Multiple soft scattering (BDMPS-Z, ASW-MS)**
  - Static scattering centers
  - Gaussian approximation for momentum kicks
  - Full LPM interference and vacuum radiation
- **Opacity expansion ((D)GLV, ASW-SH)**
  - Static scattering centers, Yukawa potential
  - Expansion in opacity L/λ (N=1, interference between two centers default)
  - Interference with vacuum radiation

Poisson ansatz (independent emission)

- **Higher Twist (Guo, Wang, Majumder)**
  - Medium characterised by higher twist matrix elements
  - Radiation kernel similar to GLV
  - Vacuum radiation in DGLAP evolution

DGLAP evolution

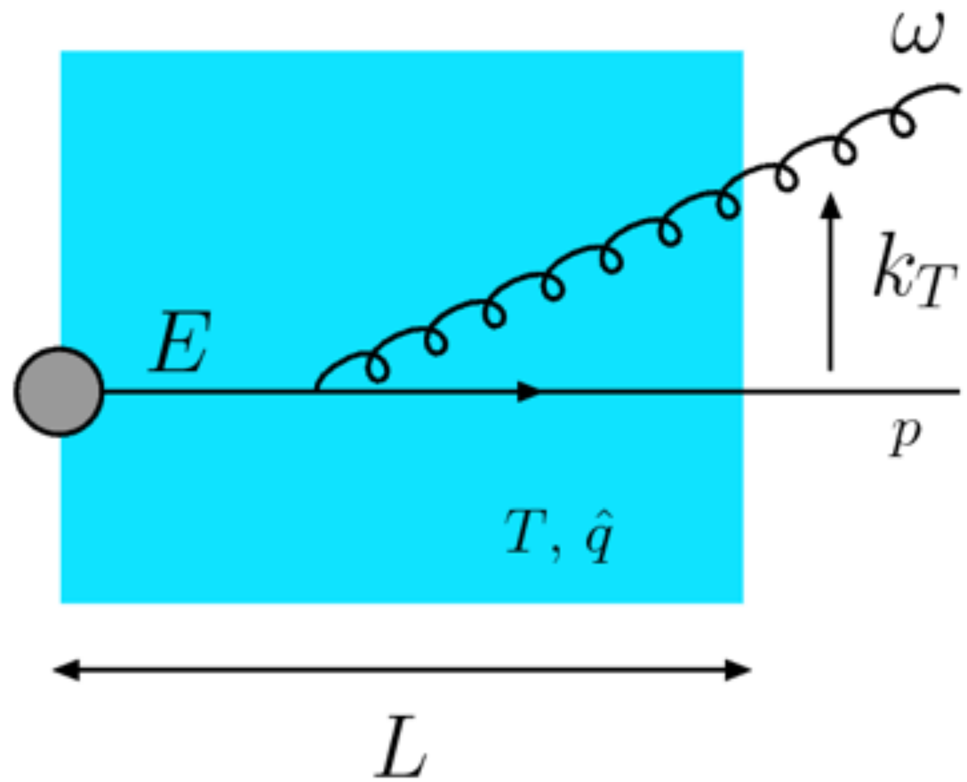
All formalisms can be related to the same BDMPS-Z path integral formalism; different approximations used

See also: arXiv:1106.1106

The Brick Problem

TECHQM: Theory-Experiment Collaboration on Hot Quark Matter

arXiv:1106.1106



Gluon(s)

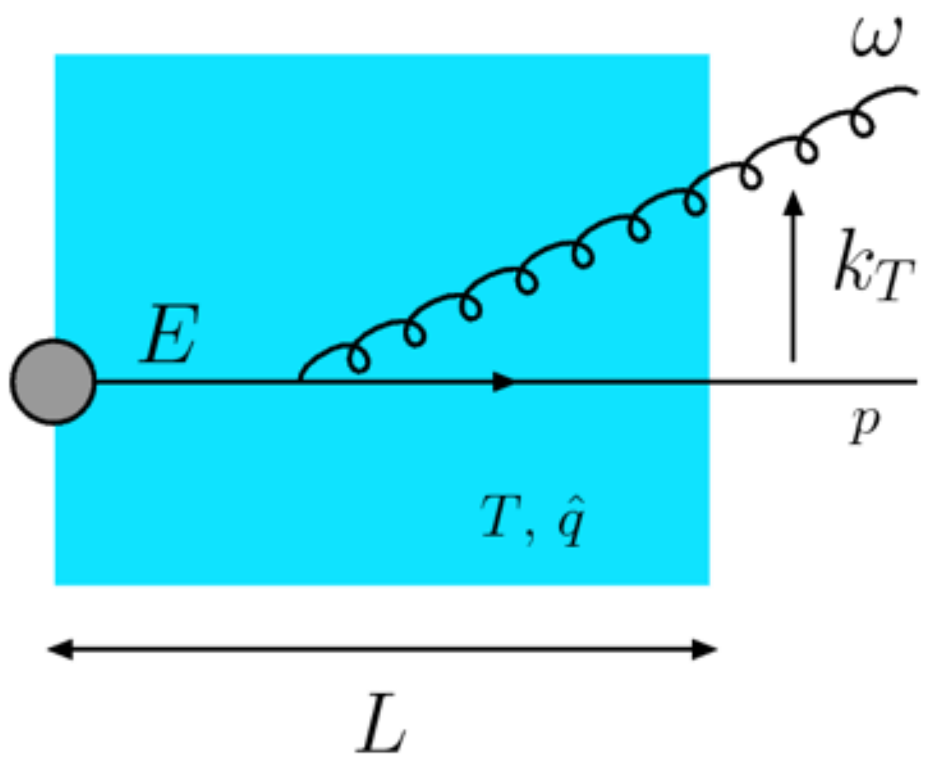
Compare energy-loss in a well-defined model system:
Fixed length *L* = 2, 5 fm
Density *T, q*
Quark, *E* = 10, 20 GeV

Compare outgoing gluon, quark distributions

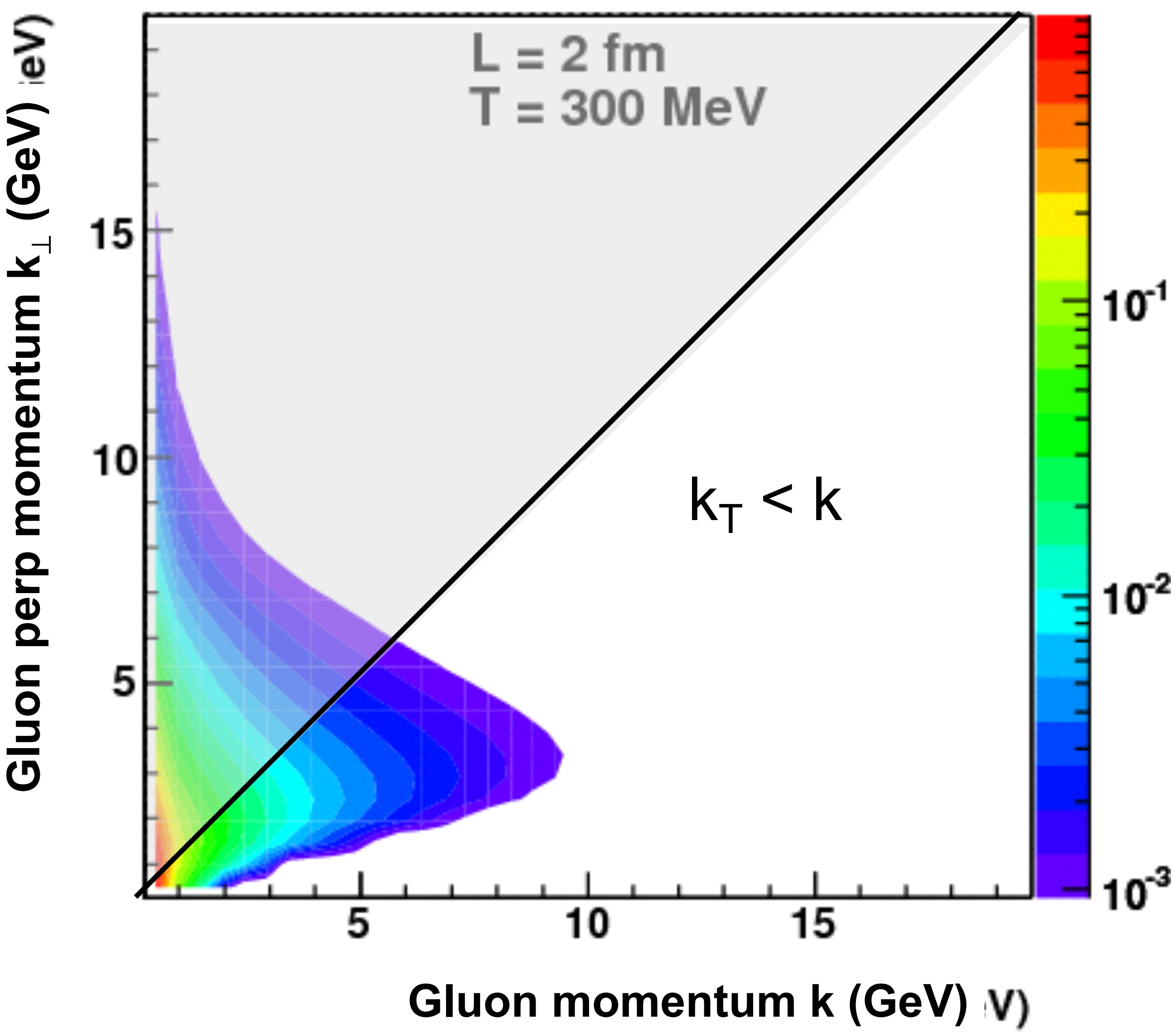
Two types of comparison:
- Same density
- Same suppression

and interpret/understand the differences

Large angle radiation



Emitted gluon distribution
Opacity expansion



Calculated gluon spectrum extends to large $k_\perp$ at small k
Outside kinematic limits

GLV, ASW, HT cut this off 'by hand'

Effect of large angle radiation

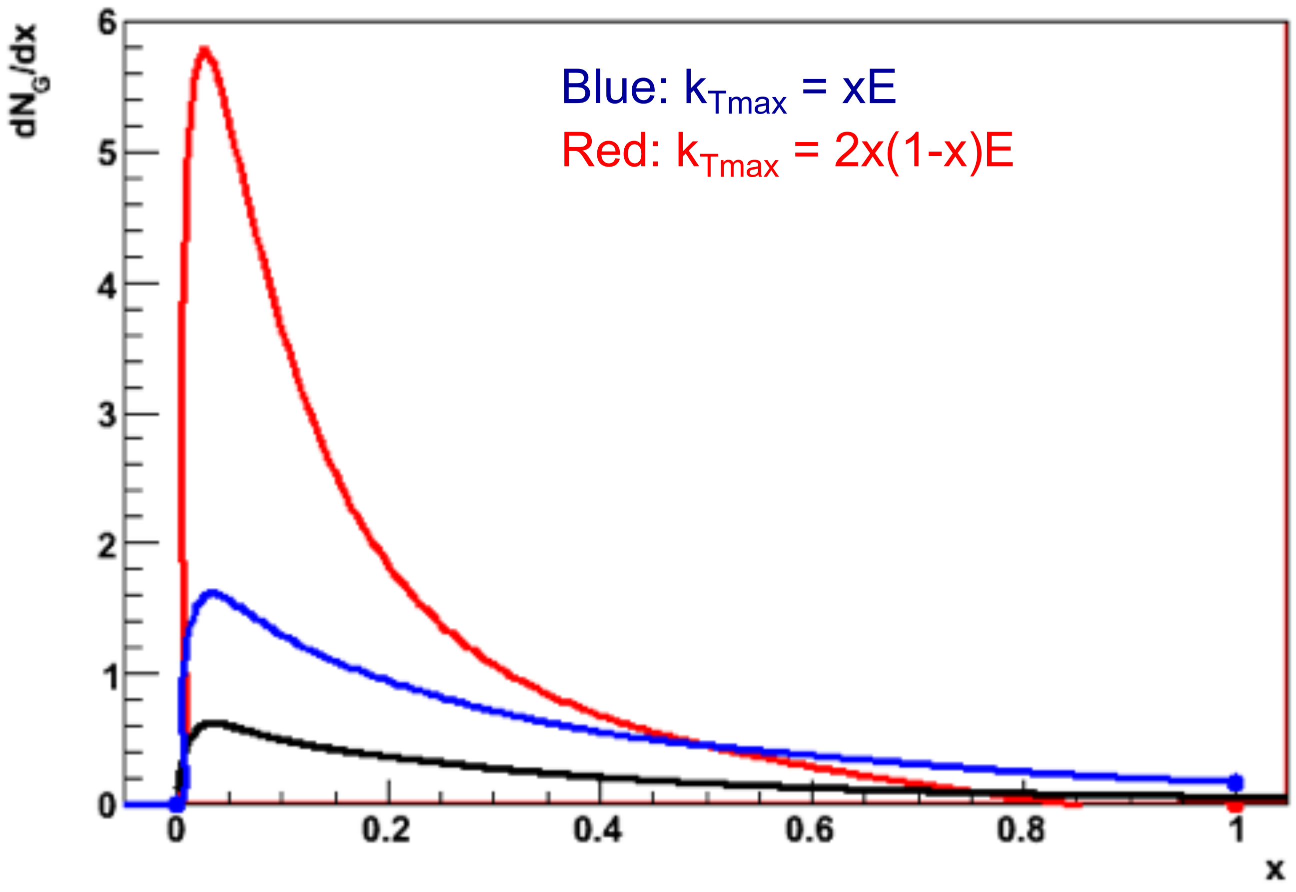
Opacity expansion formalisms

Expand in powers of $\frac{L}{\lambda}$

Different definitions of *x*:

ASW: $x_E = \frac{\omega}{E}$ GLV: $x_+ = \frac{\omega_+}{E_+}$

Single-gluon spectrum



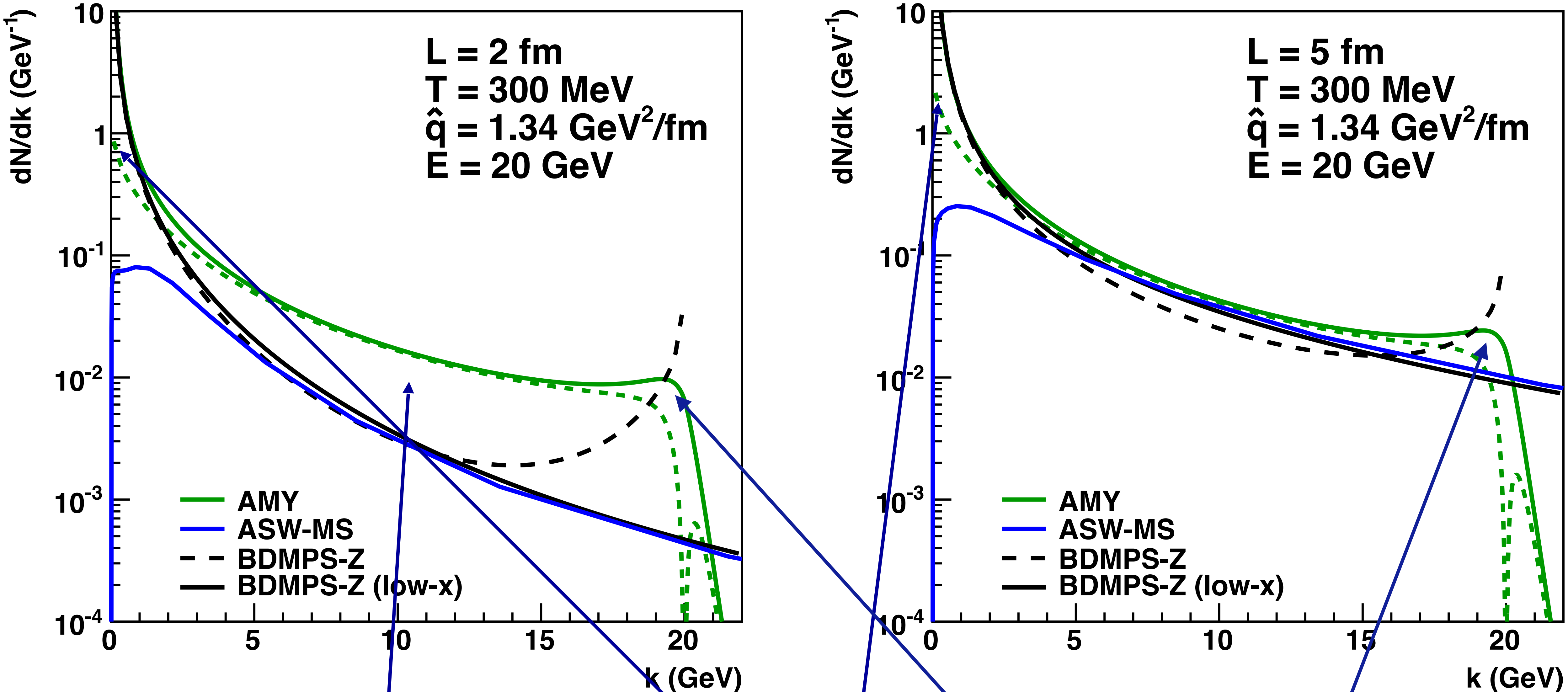
Horowitz and Cole, PRC81, 024909

Different large angle cut-offs:
$k_T < \omega = x_E E$
$k_T < \omega = 2\, x_+ E$

Factor ~2 uncertainty
from large-angle cut-off

Multiple soft scattering: BDMPS, AMY

L=2 fm Single gluon spectra L=5 fm Single gluon spectra



AMY: no large angle cut-off

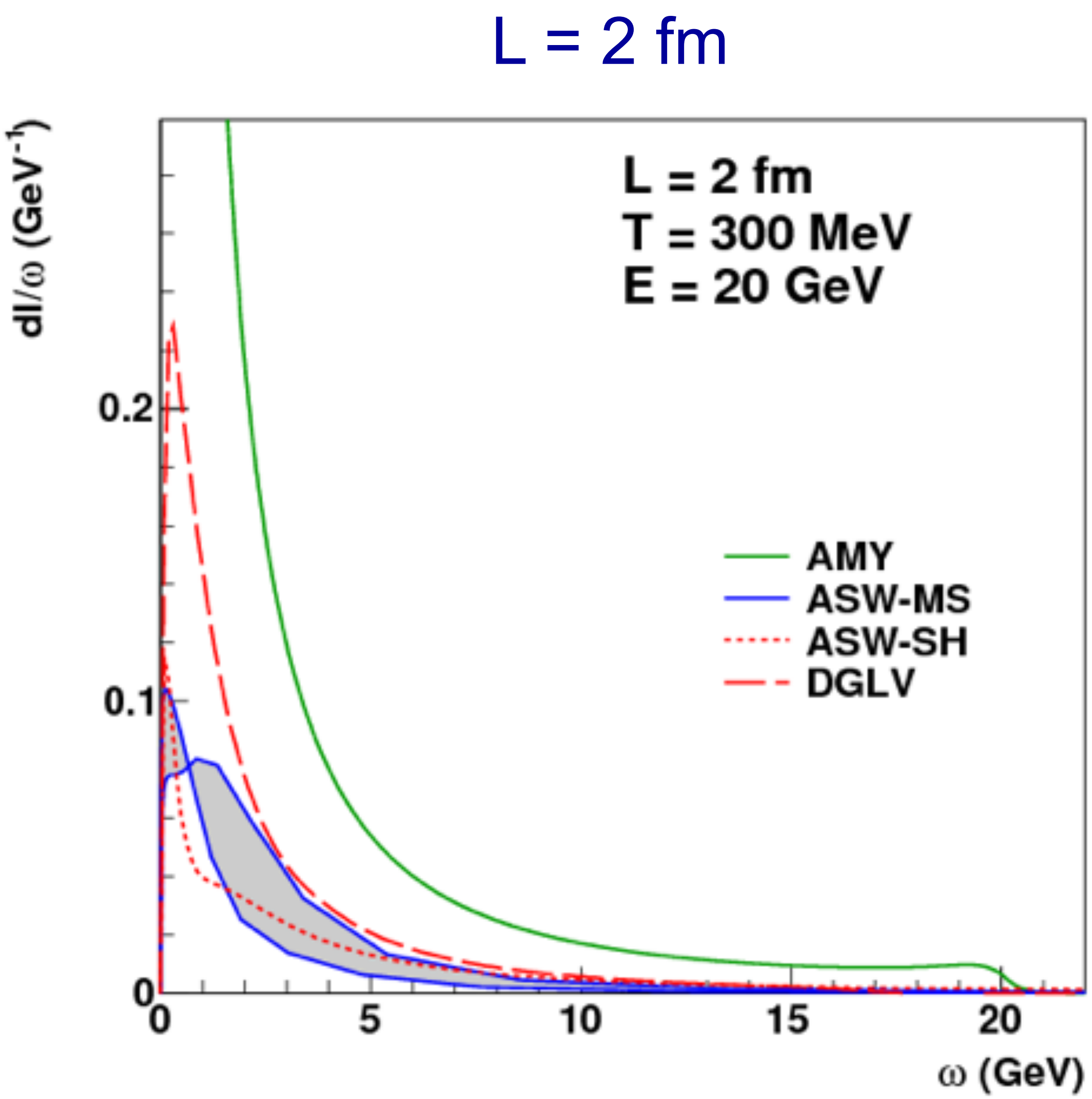
+ sizeable difference at intermediate ω at L=2 fm

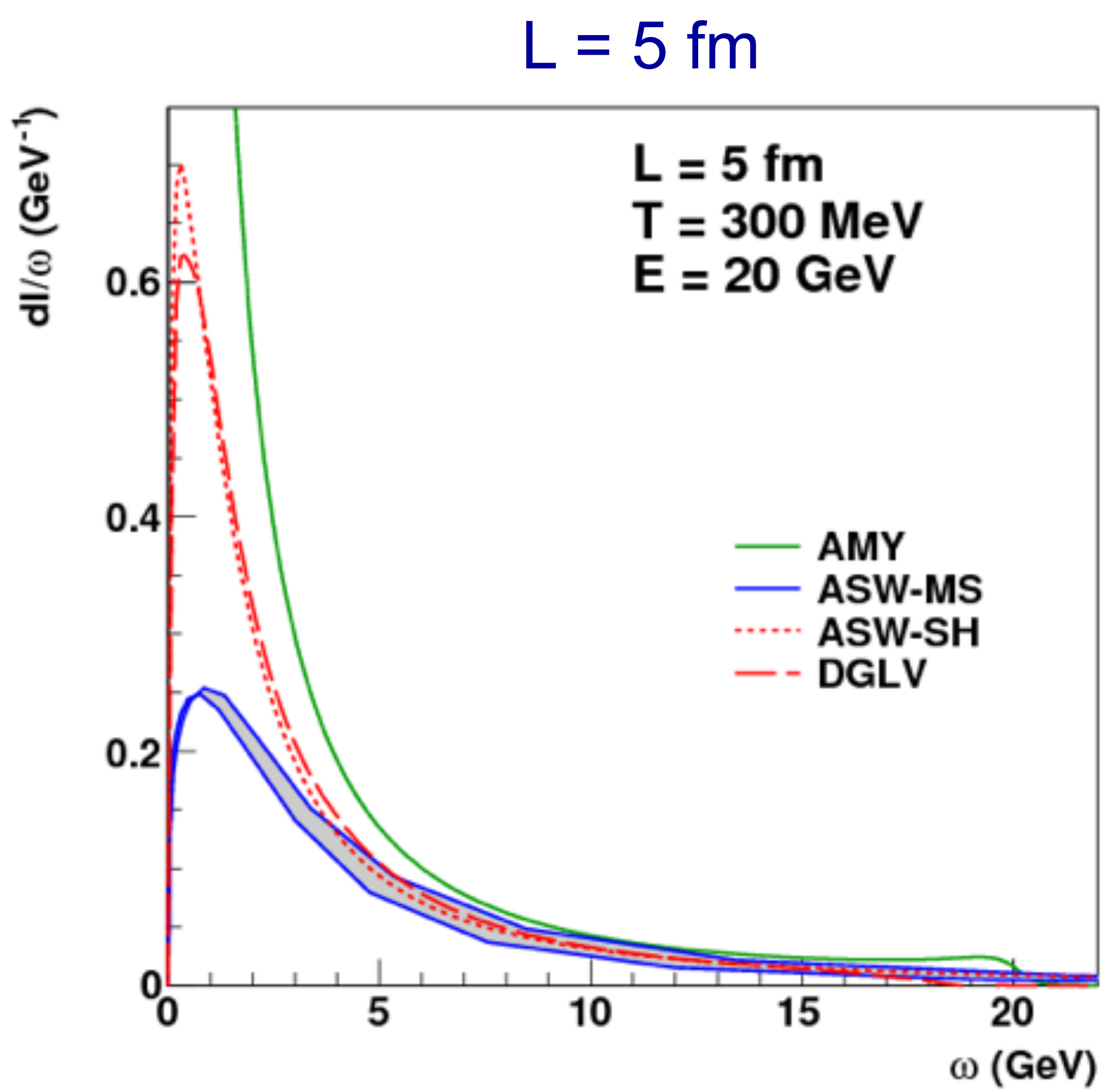
Large x treatment in AMY more accurate

Using $\hat{q}(T)$ based on AMY-HTL scattering potential

Single gluon spectra

Same temperature



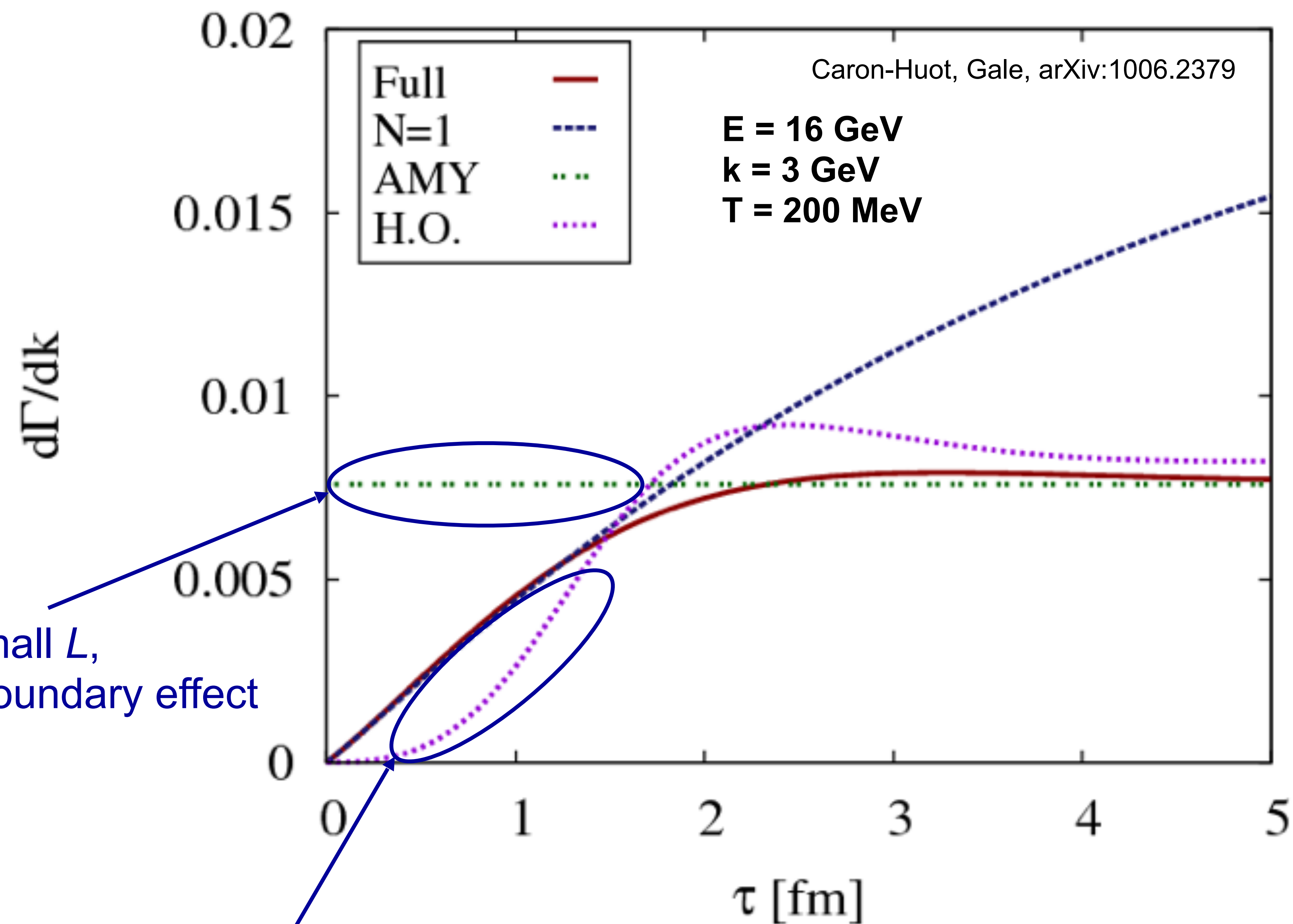


@Same temperature: AMY > OE > ASW-MS

Size of difference depends on L, but hierarchy stays

L-dependence; regions of validity?

Emission rate vs τ (=*L*)



GLV N=1
Too much radiation at large *L*
(no interference between scatt centers)

Full =
numerical solution of Zakharov path integral
= 'best we know'

AMY, small *L*,
no L^2, boundary effect

H.O = ASW/BDMPS like (harmonic oscillator)
Too little radiation at small *L*
(ignores 'hard tail' of scatt potential)

Agreement of medium density for AMY, GLV/CUJET fits is a coincidence
Multiple soft tends to give smallest E-loss, but may be most accurate?

Multiple gluon emission — Poisson ansatz

Average number of gluons:

$$\langle N_{gluon} \rangle = \int \frac{dI}{d\omega} d\omega$$

Poisson fluctuations:

$$P(n) = \frac{1}{n!} \langle N_{gluon} \rangle^n e^{-\langle N_{gluon} \rangle}$$

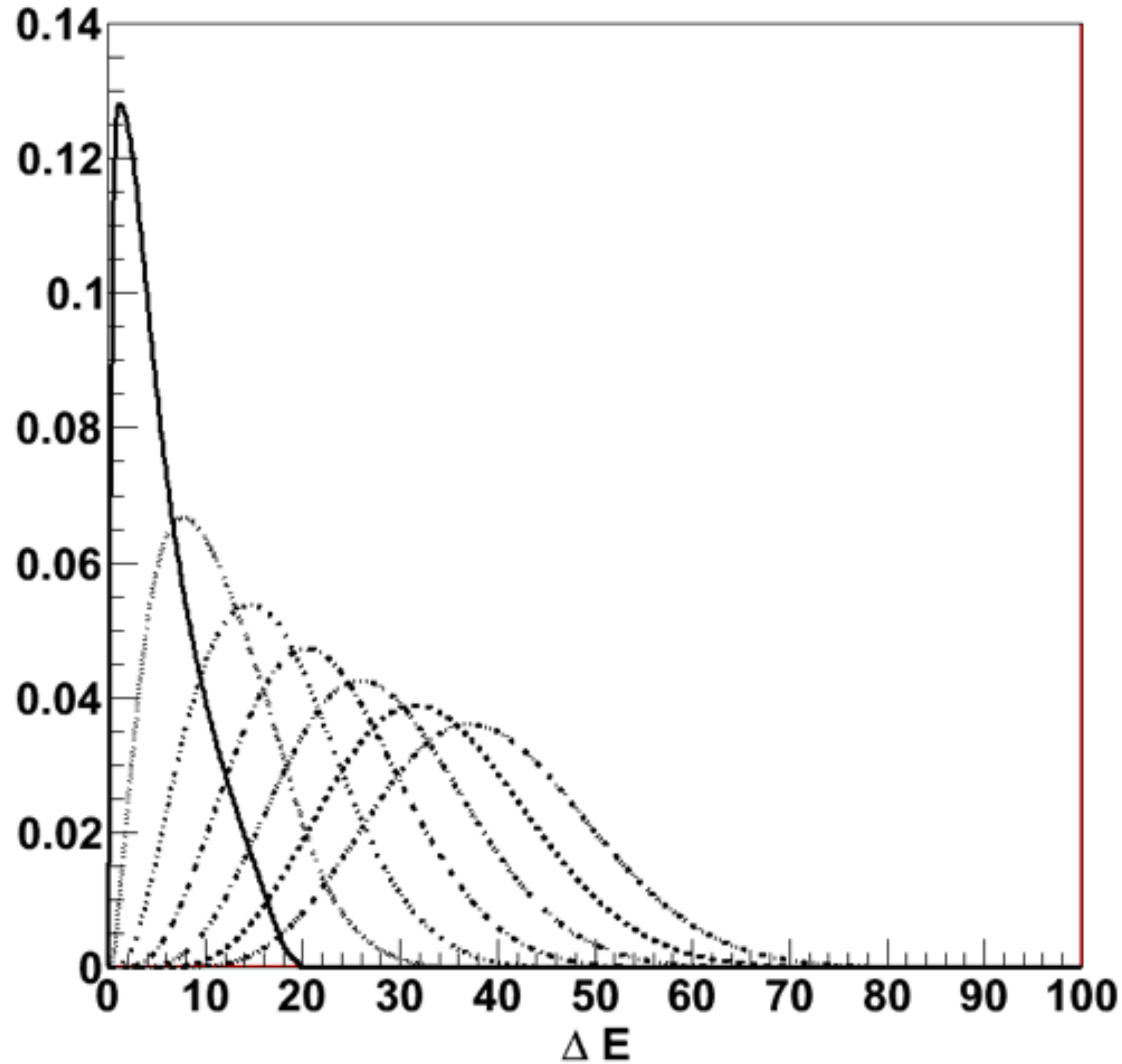
(assumed)

Total probability:

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta \left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp \left[- \int_0^{\infty} d\omega \frac{dI}{d\omega} \right]$$

$$P(\Delta E) = p_0 \delta(\Delta E) + p(\Delta E)$$

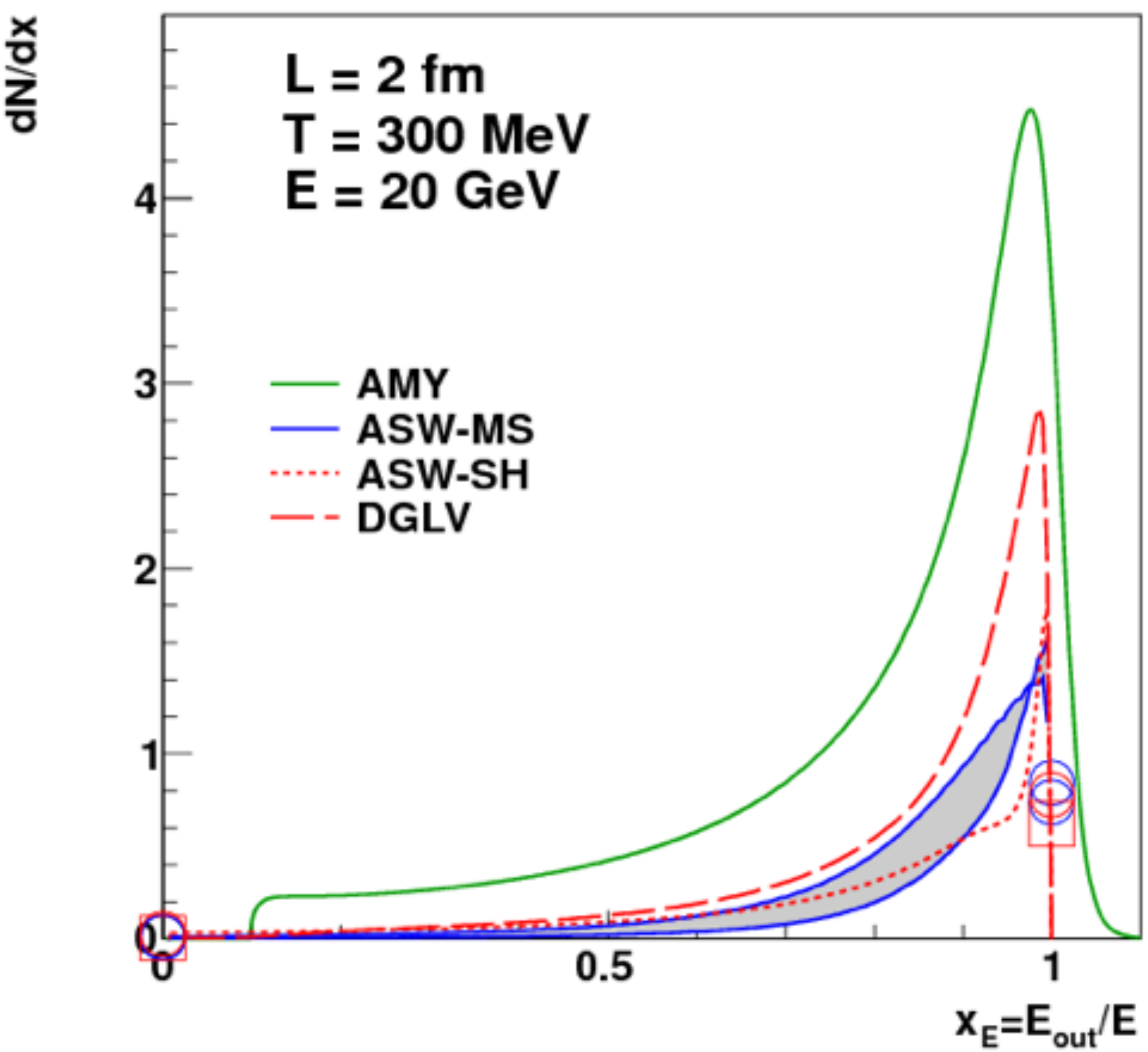
Poisson convolution example

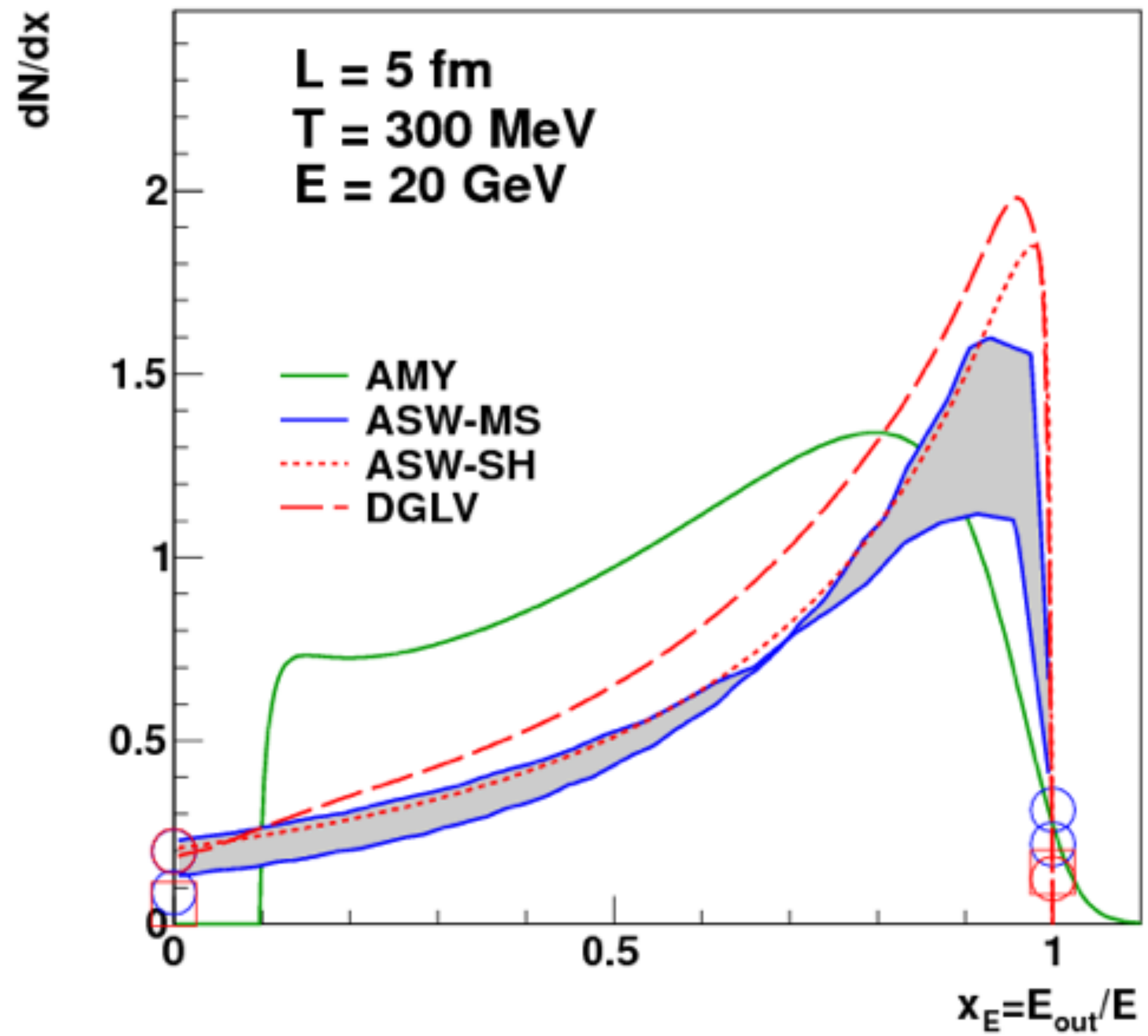


Main other approach: build into DGLAP (used for HT)

Outgoing quark spectra

Same temperature: T = 300 MeV





@Same T: suppression AMY > OE > ASW-MS

Note importance of P_0

Energy loss formalisms

- Large differences between formalisms understood
  - Large angle cut-off
  - Length dependence (interference effects)
- Mostly (?) 'technical' issues; can be overcome
  - Use path-integral formalism
  - Monte Carlo: exact *E*, *p* conservation
    - Full 2→3 NLO matrix elements
    - Include interference

Plenty of room for interesting and relevant theory work!

Current progress on:

- Interference in multiple gluon emission: 'antenna radiation'
- Some work on non-eikonal propagation
- Monte-Carlo approaches for *E*, *p* conservation (JEWEL, q-PYTHIA, YaJEM, MARTINI)

MC vs analytical approaches

Analytical approaches:

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

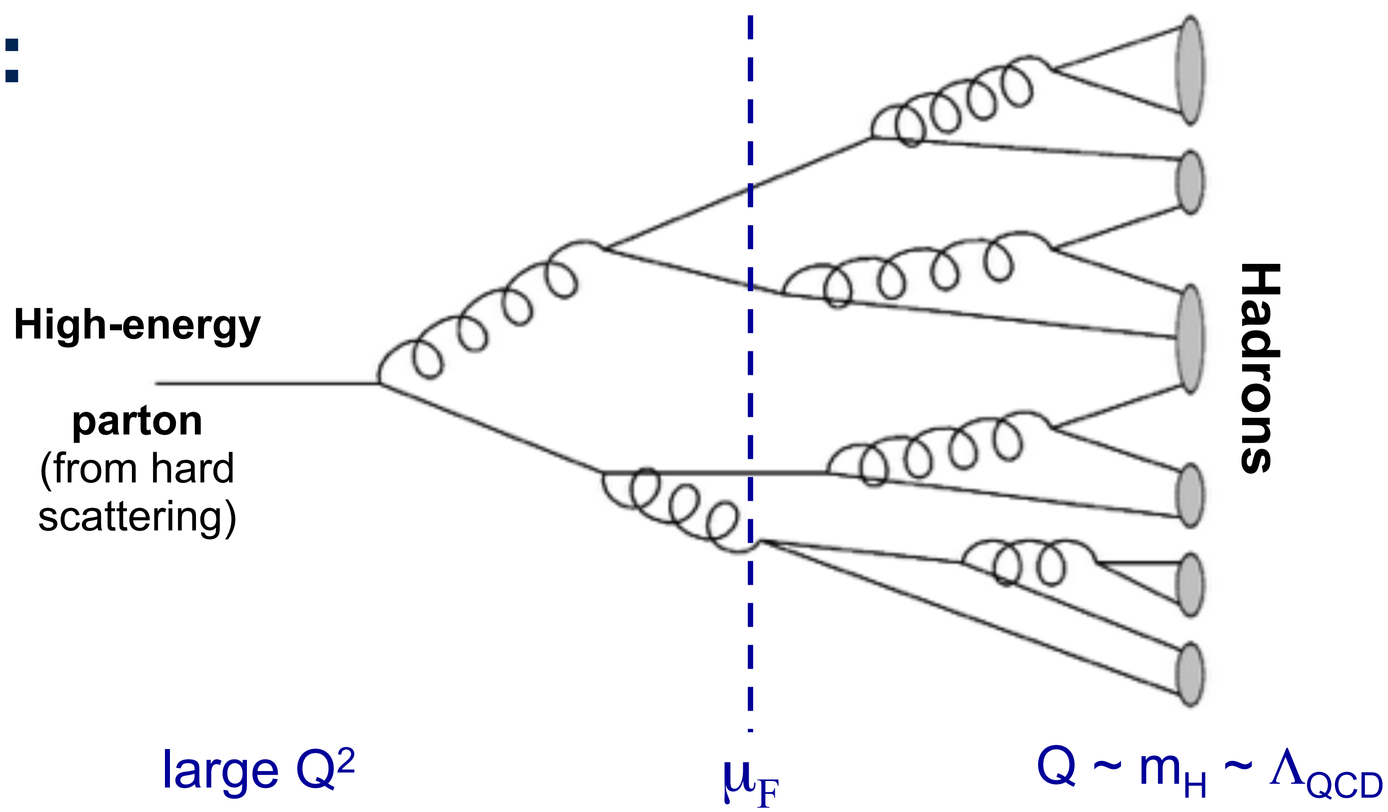
Energy loss of leading parting + fragmentation in vacuum
- radiated gluons are not tracked

Monte Carlo parton shower:

All partons tracked
(except 'soft' medium partons)

Implement medium-enhanced splitting everywhere in shower

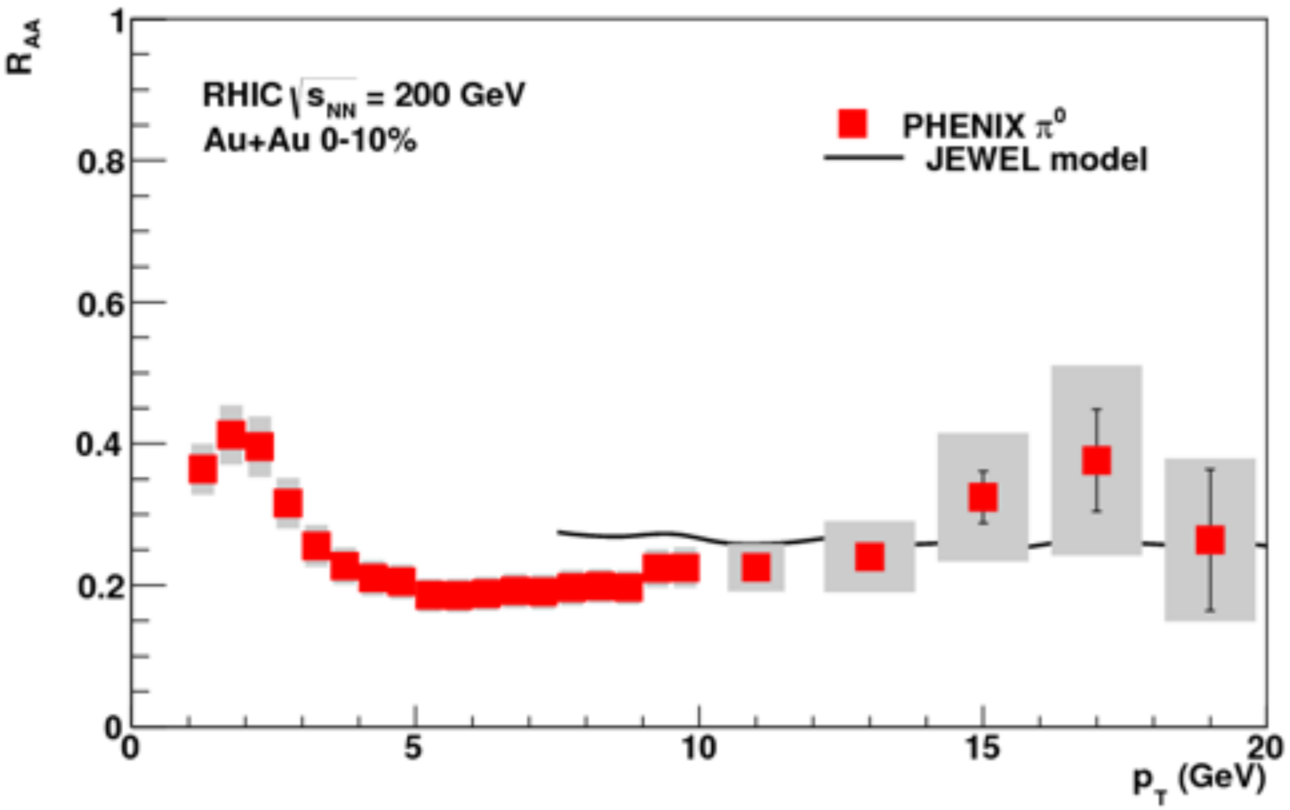
JEWEL, MARTINI,
PYQUEN, q-PYTHIA,
YAJeM

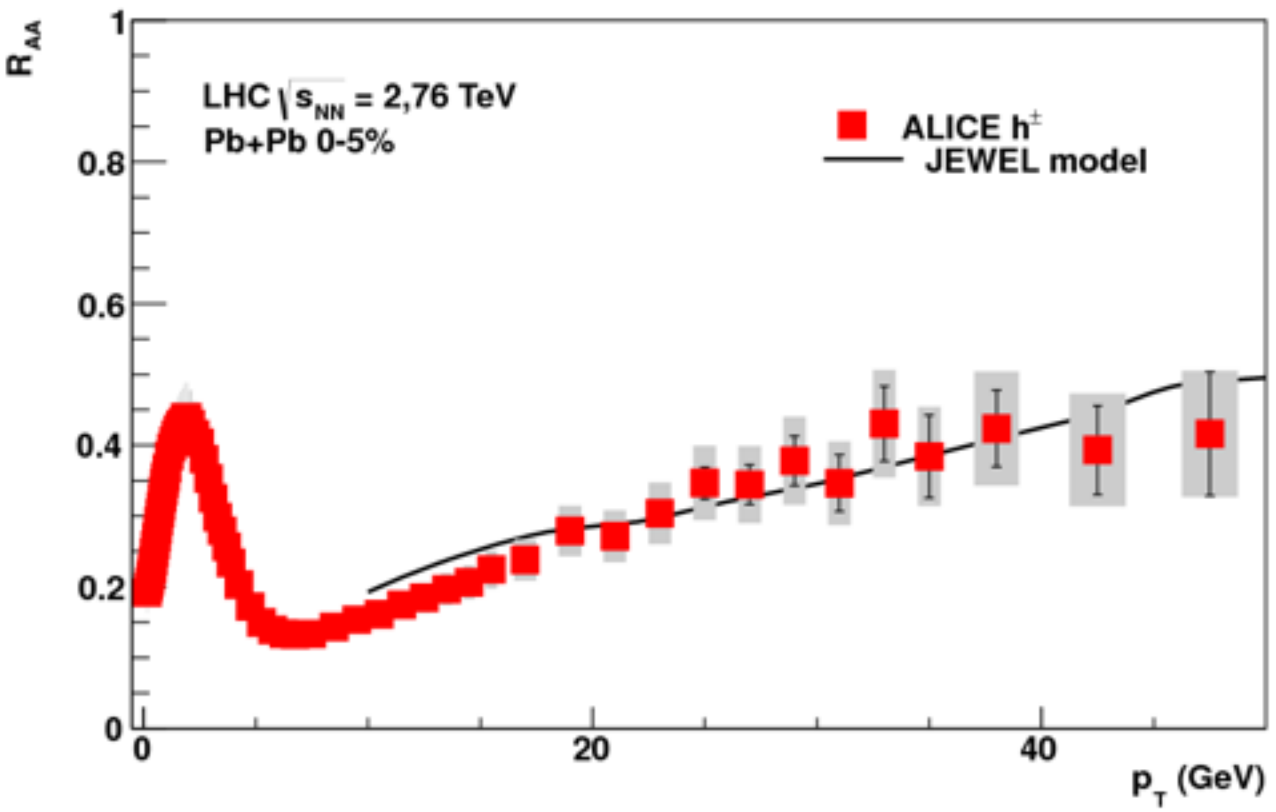


Mapping to DGLAP evolution

JEWEL: R_{AA} at LHC

JEWEL: Monte Carlo event generator with radiative+collisional energy loss
- Modified showers with MC-LPM implementation
- Geometry: expanding Woods-Saxon density





JEWEL energy loss model agrees with measurements
(tuned at RHIC, LHC ‘parameter-free’)

Effects in R_{AA}

- **Parton p_T spectra**
  - Less steep at LHC → less suppression
  - Steepness decreases with p_T: R_{AA} rises
- **Quark vs gluon jets**
  - More gluon jets at LHC → more suppression
  - More quark jets at high p_T: R_{AA} rises
- **Medium density (profile)**
  - Larger density at LHC → more suppression (profile similar?)
  - Path length dependence of energy loss
- **Parton energy dependence**
  - Expect slow (log) increase of ΔE with E → R_{AA} rises with p_T
  - Running of α_S (A Buzzatti@QM2012) ?
- **Energy loss distribution**
  - Expect broad distribution $P(\Delta E)$; kinematic bounds important

'Known', external input (Parton p_T spectra, Quark vs gluon jets, Medium density)

Energy loss theory (Medium density, Parton energy dependence, Energy loss distribution)

Determine/ constrain from measurements

Use different observables to disentangle effects contributions

Experimental 'tests' of energy loss theory

- Path length dependence
  - In- out of plane
  - Inclusive vs recoil
- Heavy vs light quarks
- Quarks vs gluons
  - Some ideas, but no clear experimental handle identified
- Distribution of radiated energy
  - Fragment distributions in jets

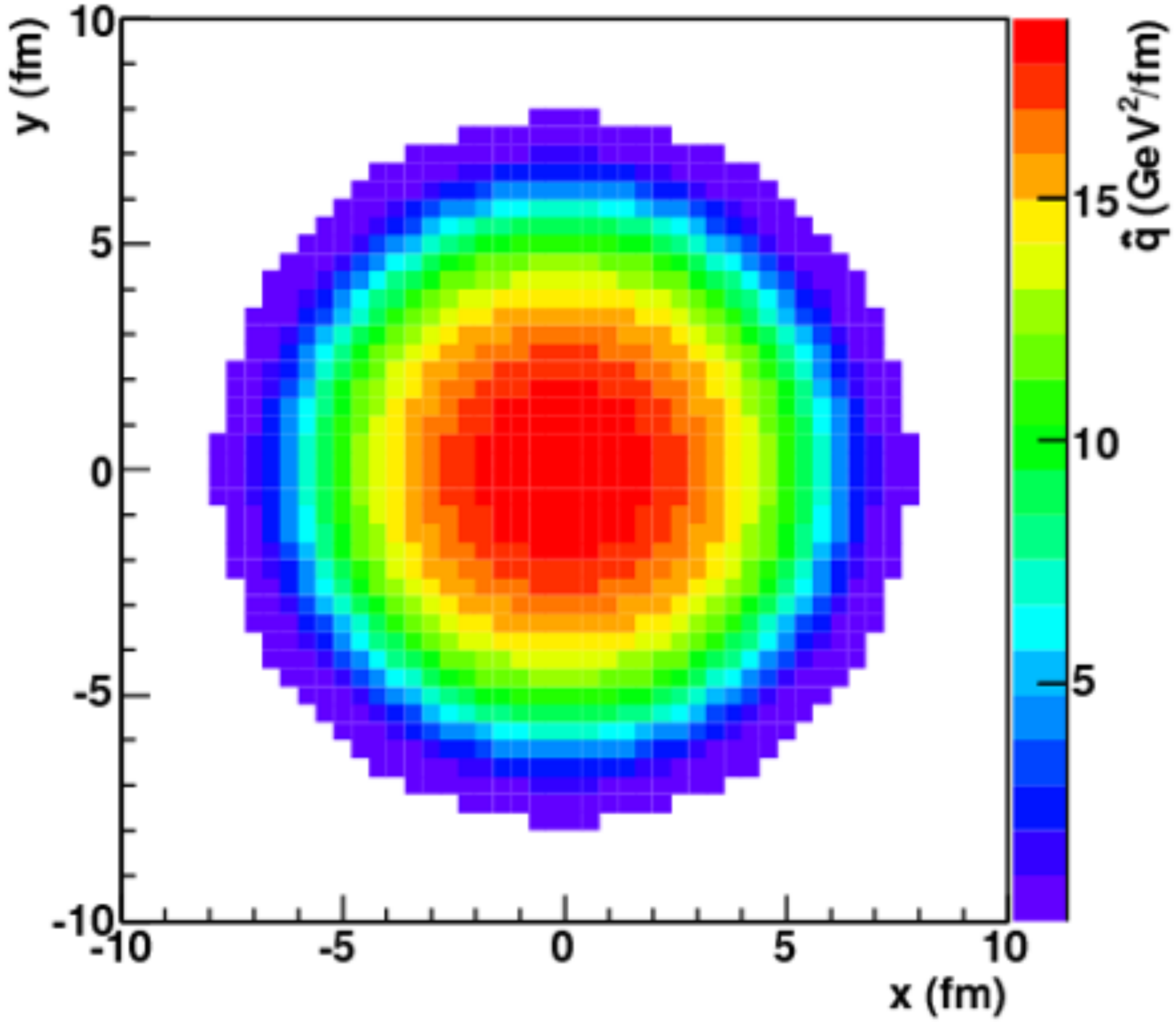
All related to mechanism of energy loss:
collisional: L
radiative: L^2,
strong coupling: L^3, q/g different

Often not possible to look for effects in isolation: most observables combine several aspects

Path length dependence

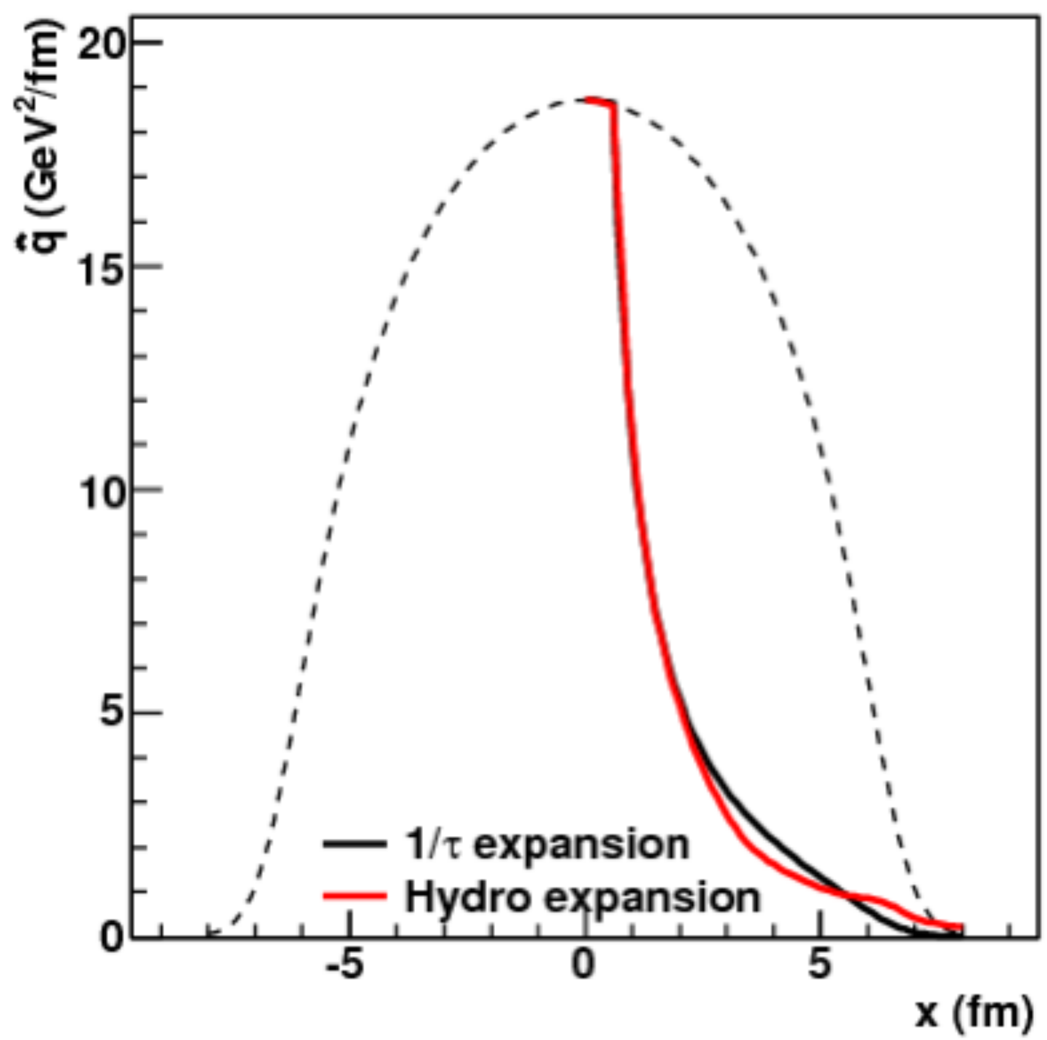
Geometry

Density profile



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

Density along parton path



Longitudinal expansion
dilutes medium
⇒ Important effect

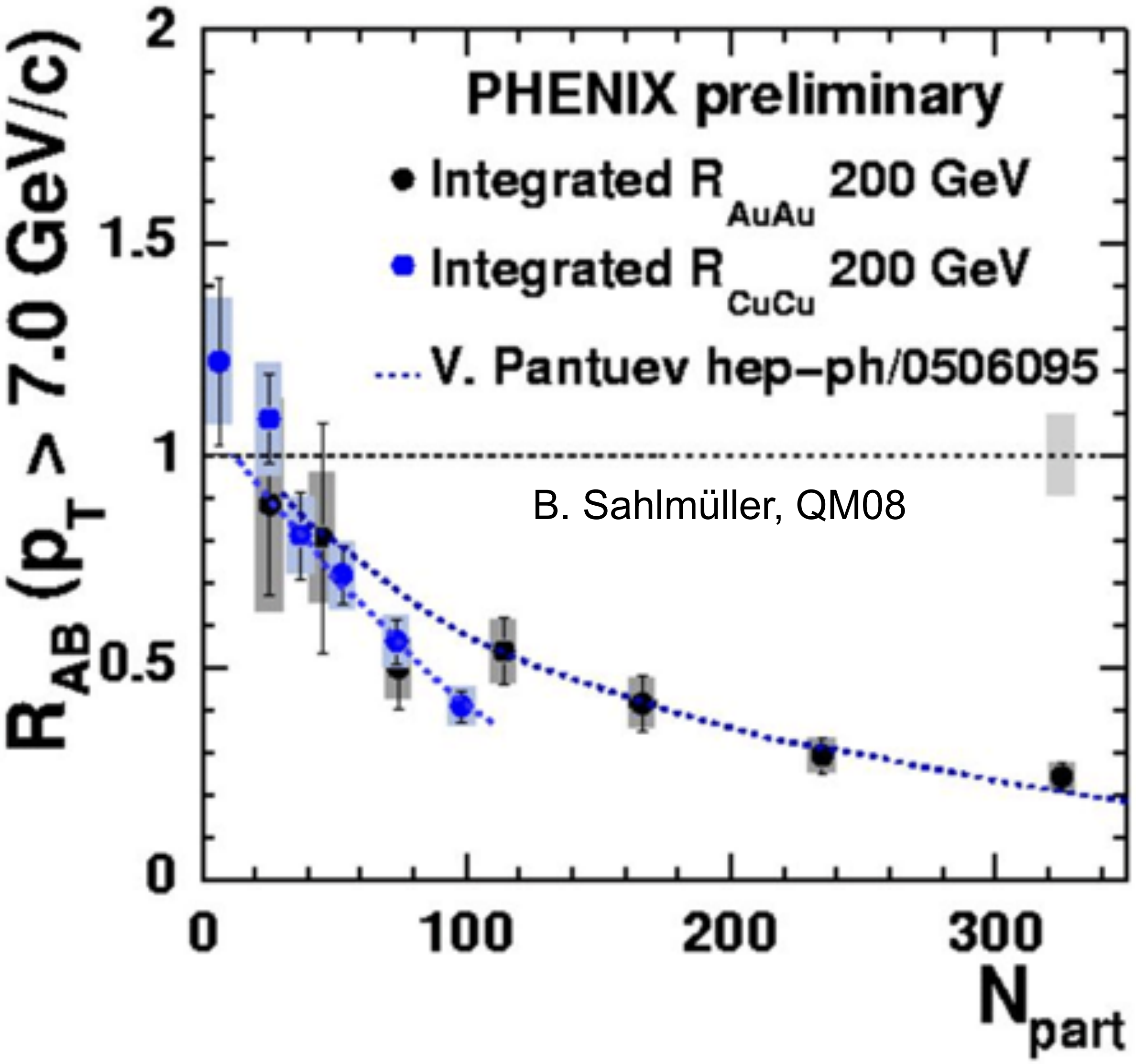
Most models take space-time evolution into account

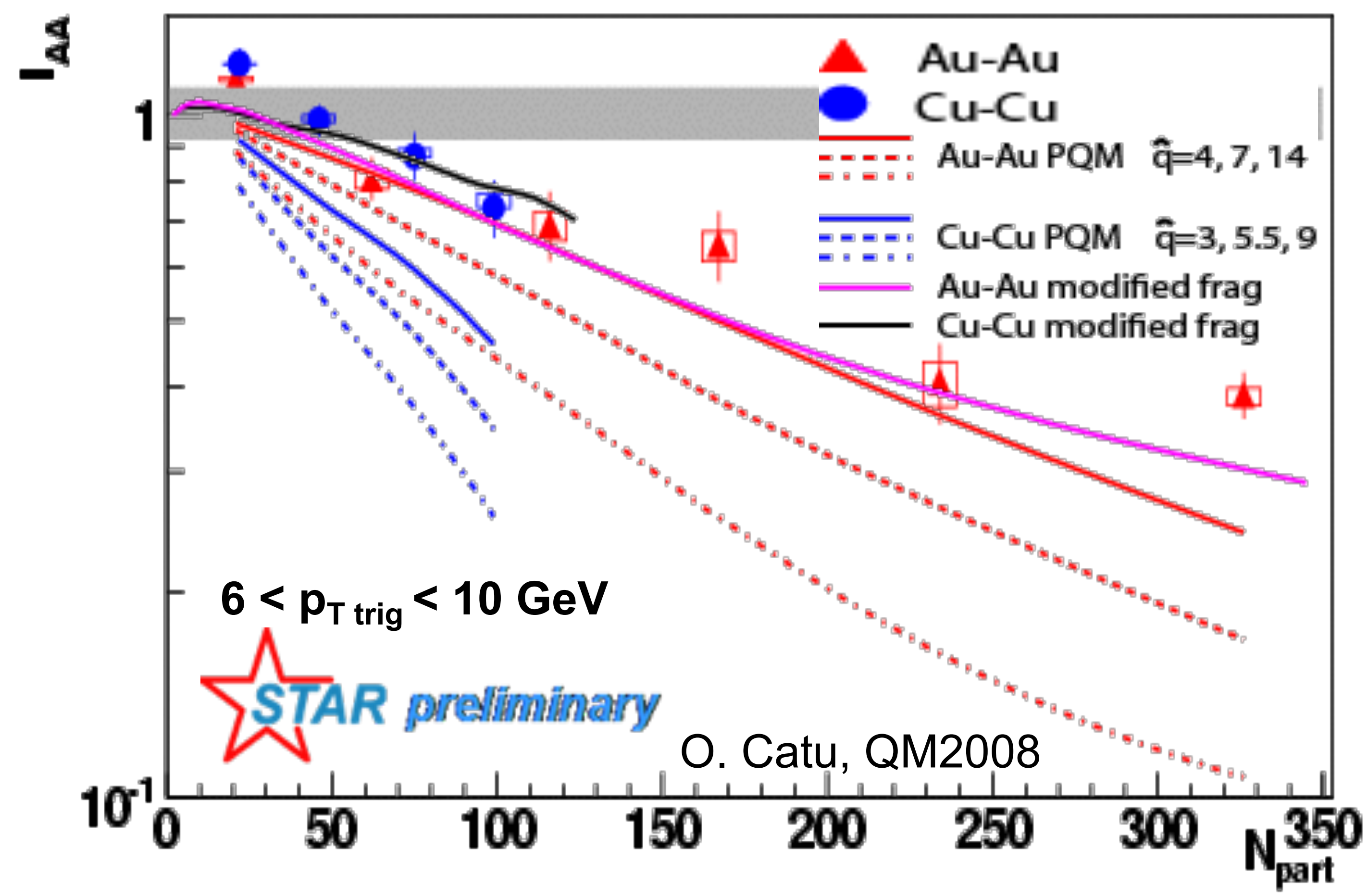
Path length I: centrality dependence

Comparing Cu+Cu and Au+Au

R_{AA}: inclusive suppression

Away-side suppression



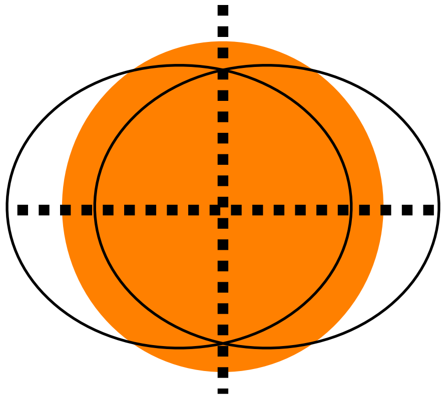


Modified frag: nucl-th/0701045 - H.Zhang, J.F. Owens, E. Wang, X.N. Wang

Quantitative constraints difficult:

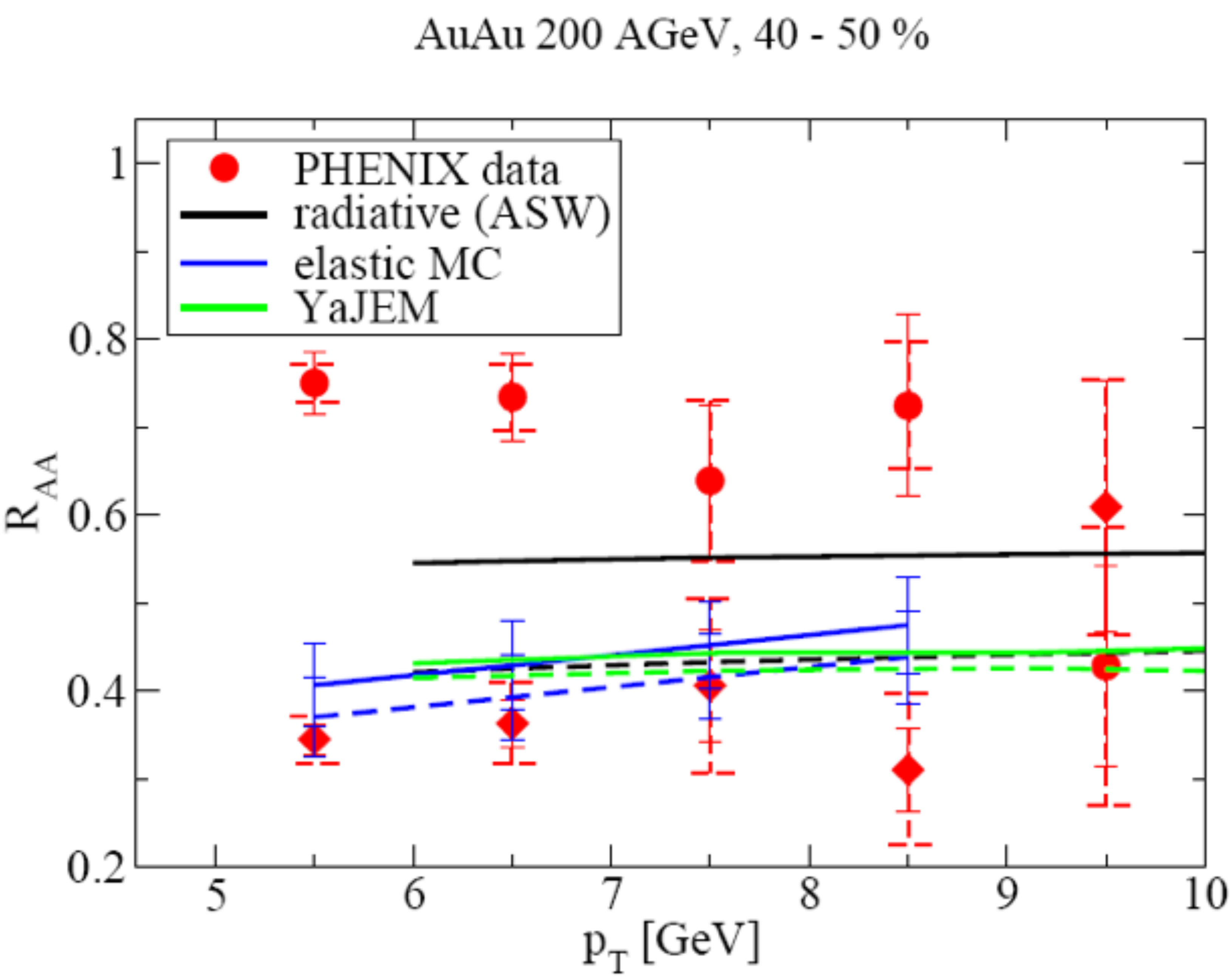
- Large experimental uncertainties for peripheral (also for theory?)
- Some freedom in centrality dependence for theory (extra parameter?)

R_{AA} vs φ and elastic eloss



Elastic E-loss gives small v_2

Data require L^2 or stronger path length dependence

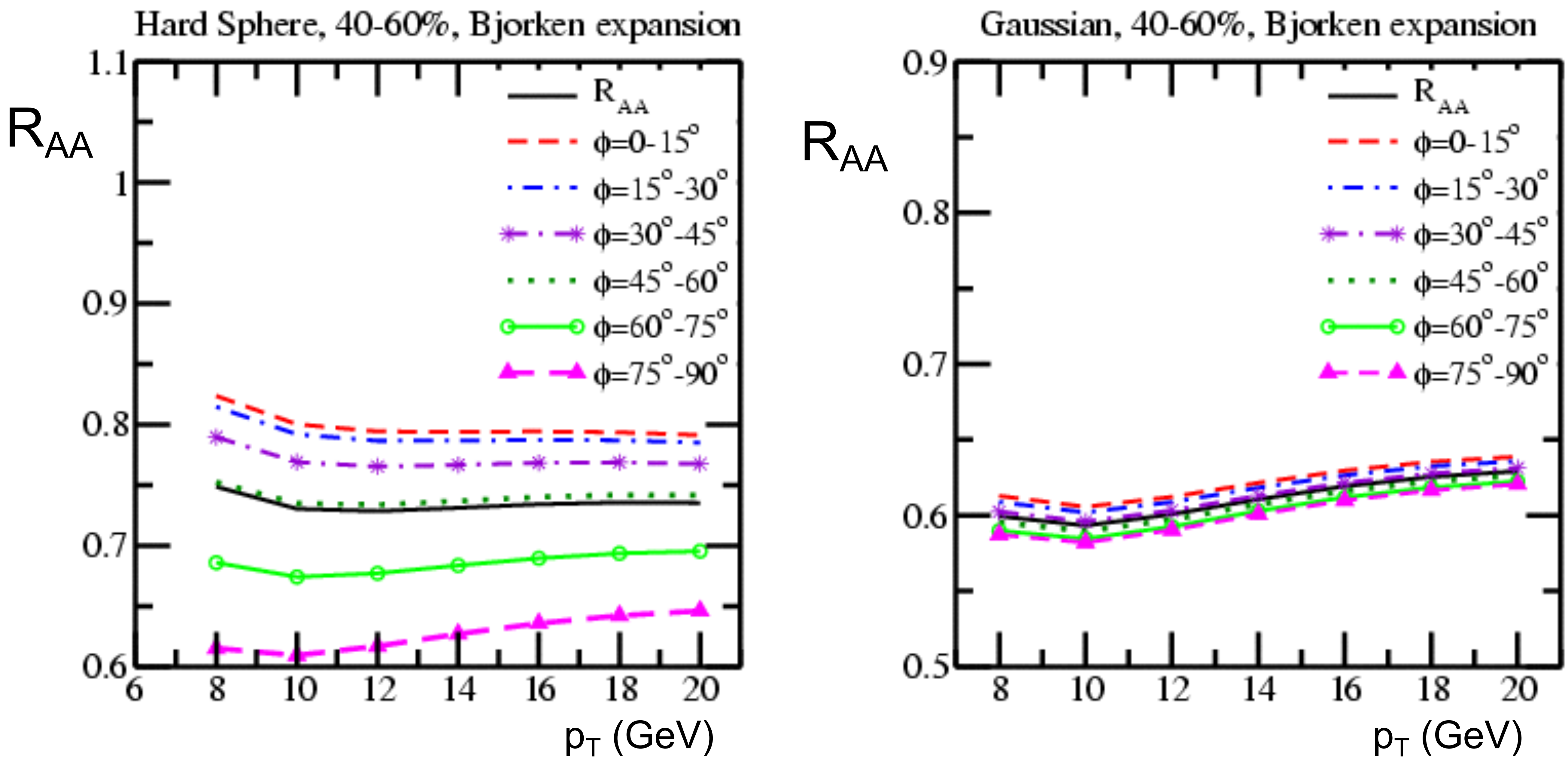


T. Renk, PRC76, 064905, J. Auvinen et al, PRC82, 051901

However, also quite sensitive to medium density evolution

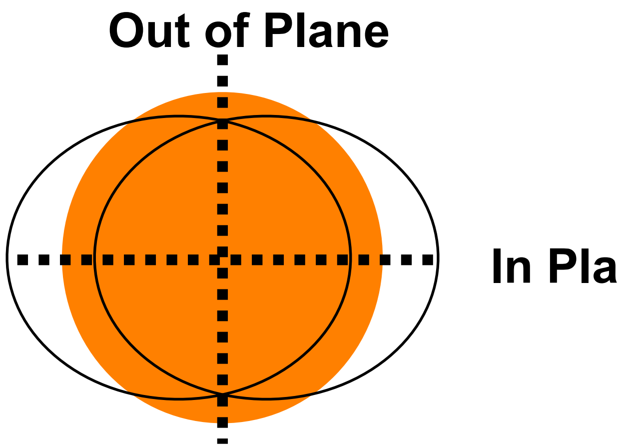
Modelling azimuthal dependence

A. Majumder, PRC75, 021901

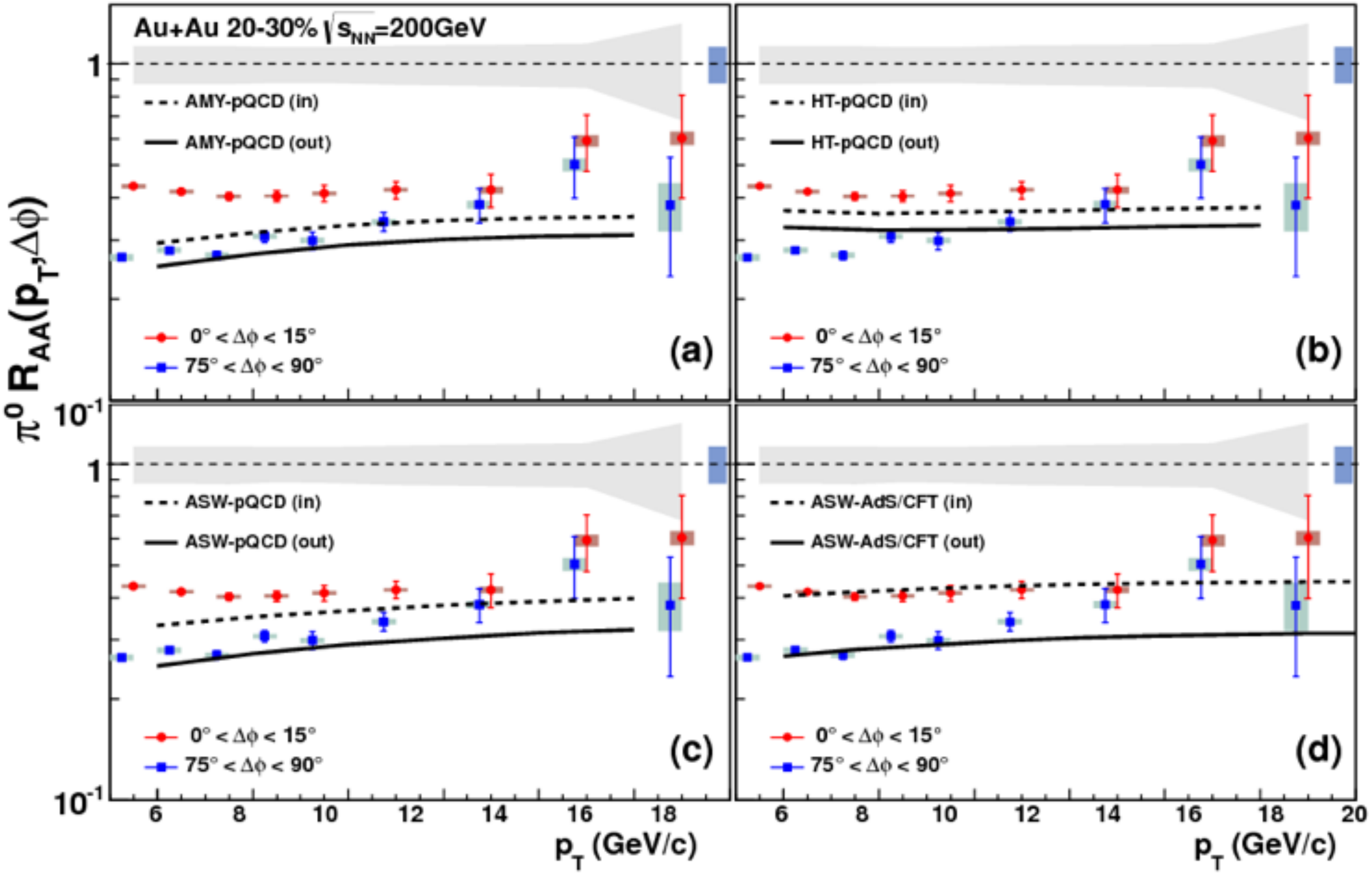


R_{AA} vs reaction plane sensitive to geometry model

Path length dependence: R_{AA} vs φ



PHENIX, arXiv:1208.2254

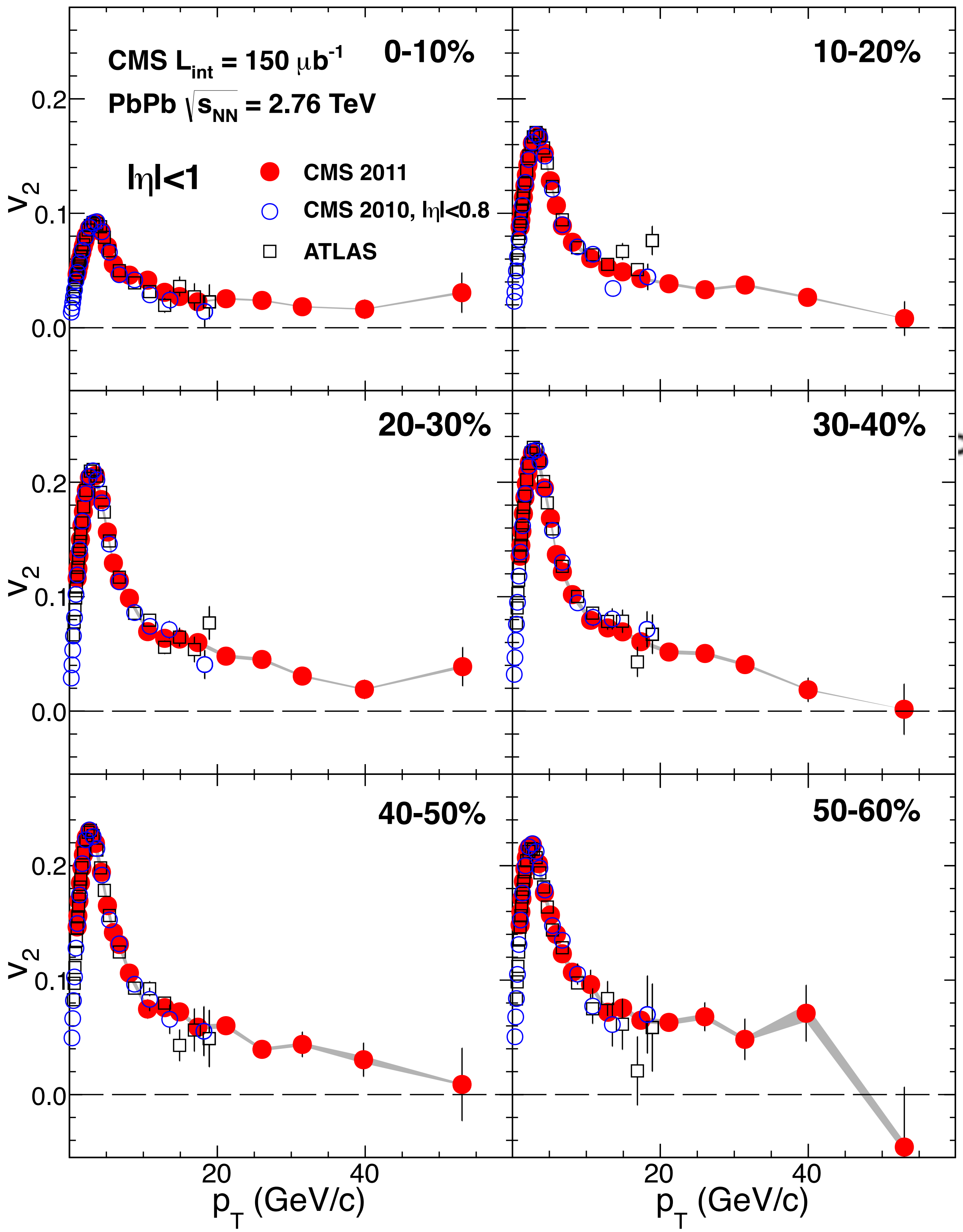


Suppression depends on angle, path length

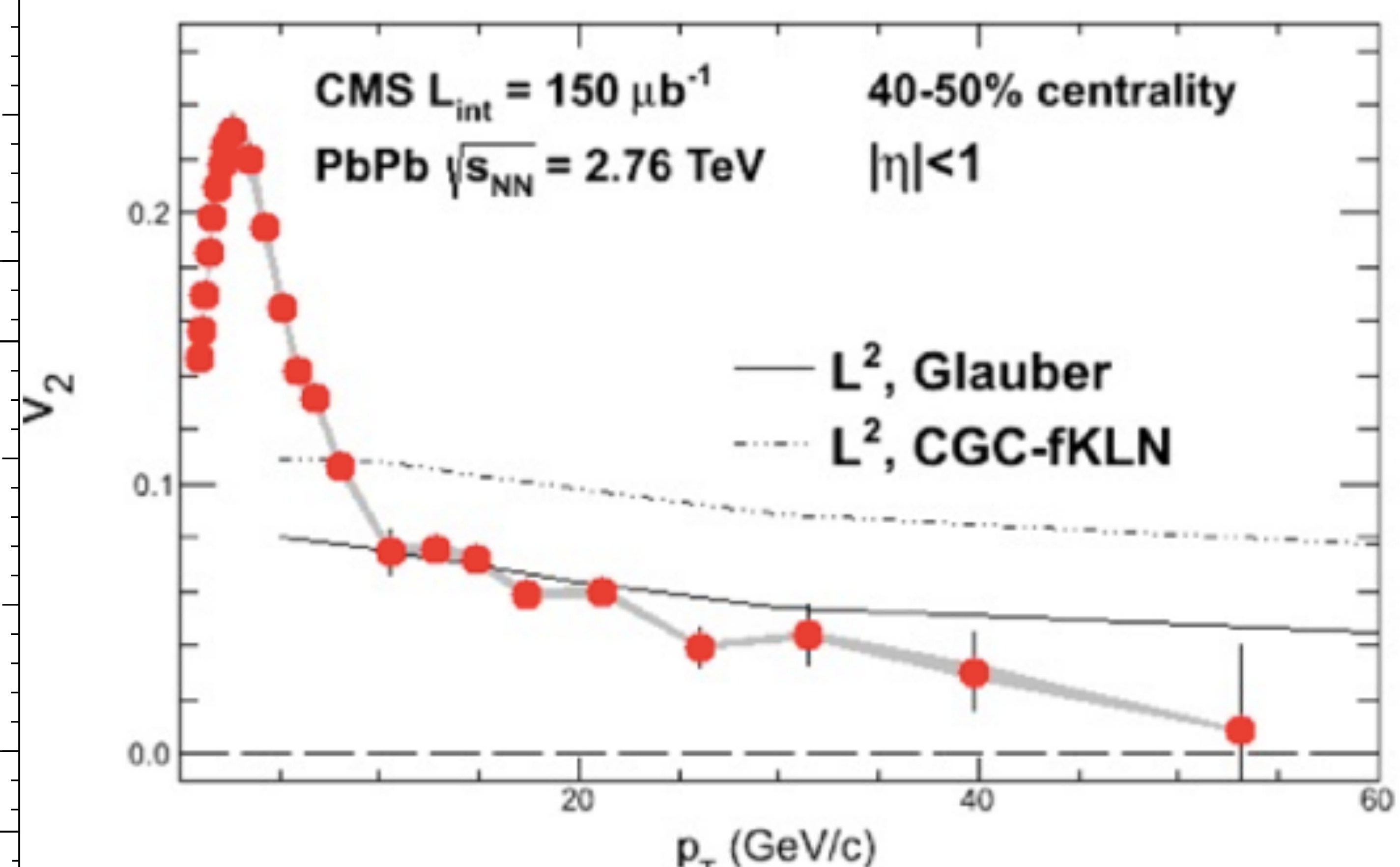
Not so easy to model: calculations give different results

Reaction plane dependence at LHC: High-p_T v_2

CMS, arXiv:1204.1850



Model: B. Betz, M. Gyulassy, arXiv:1201.0281

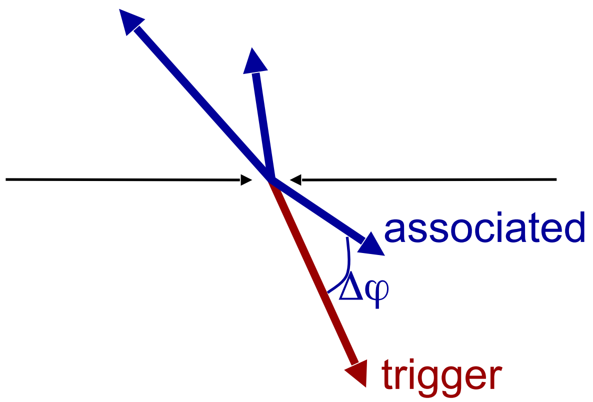


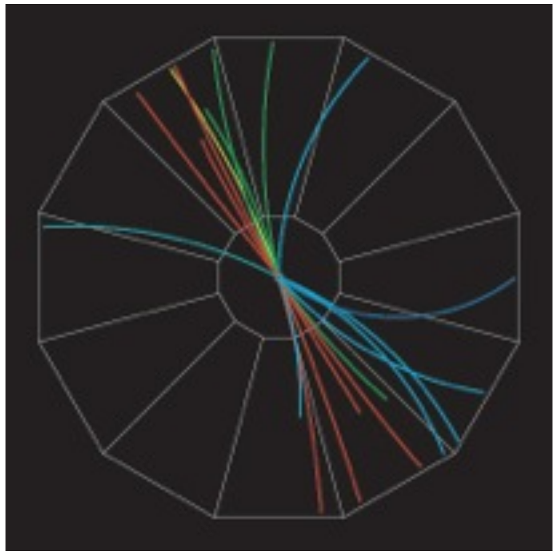
Reasonable agreement between calculation and data for p_T > 10 GeV

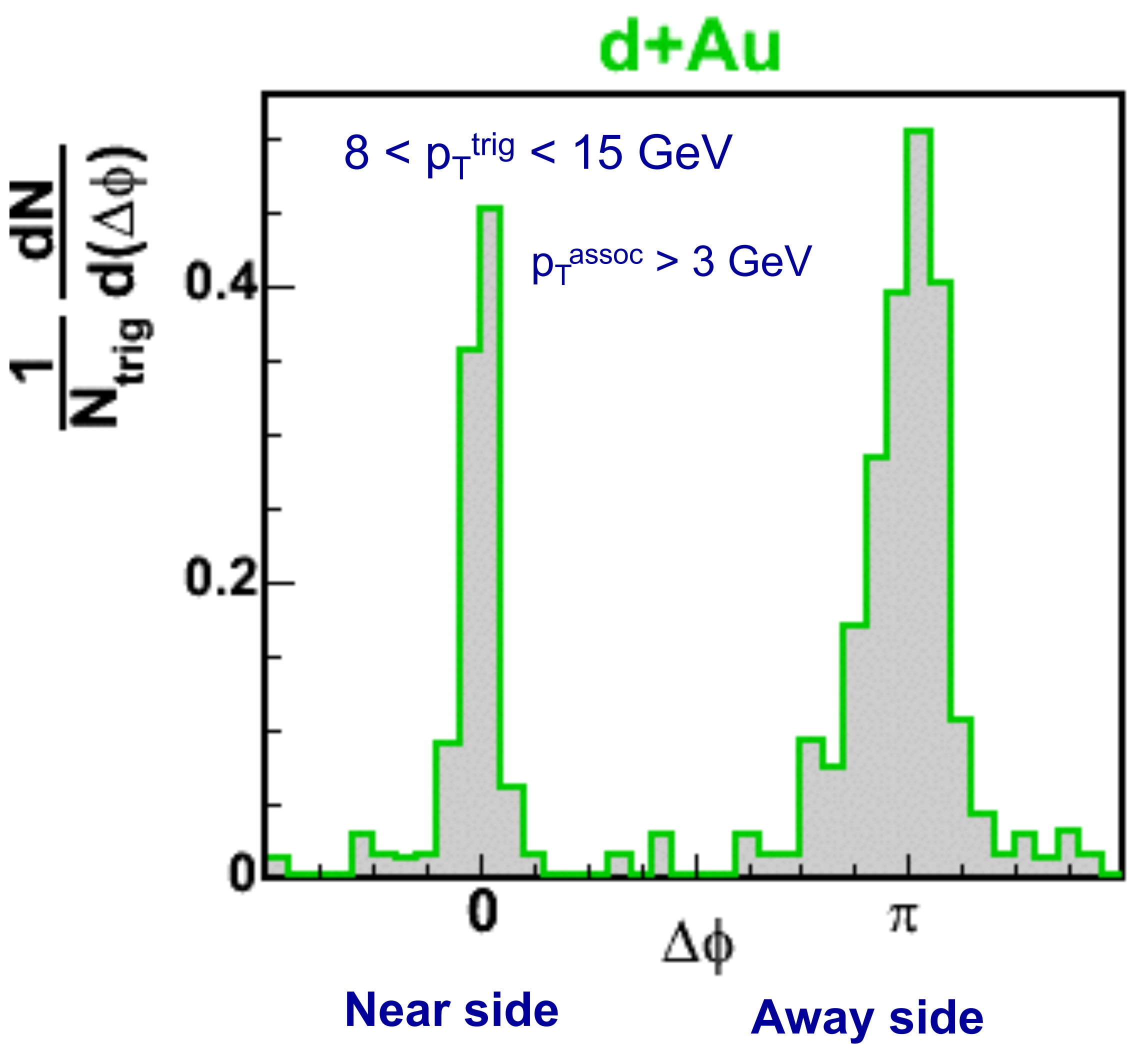
(NB: simplified geometry, E-loss;
paper claims scale-dependence of α_s main effect)

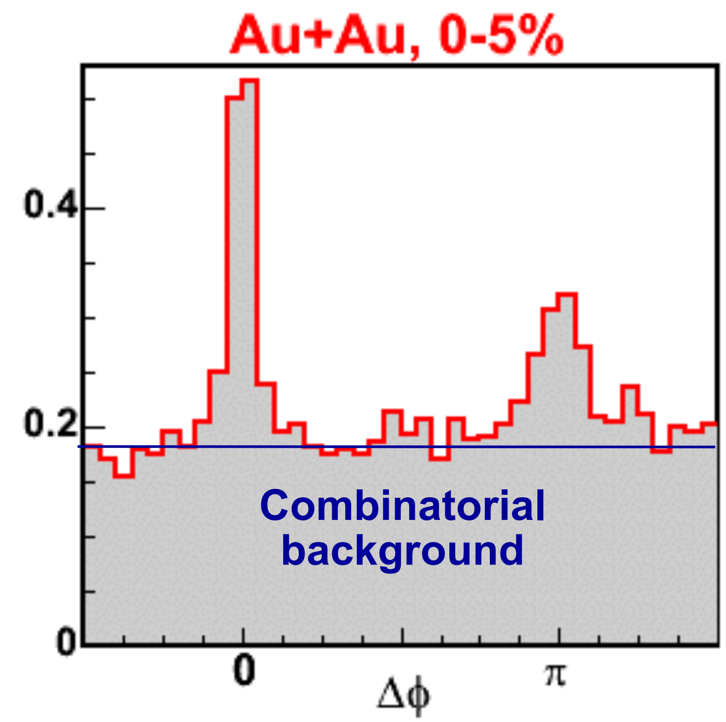
A unexpected angle on path length dependence: di-hadron correlations

Dihadron correlations



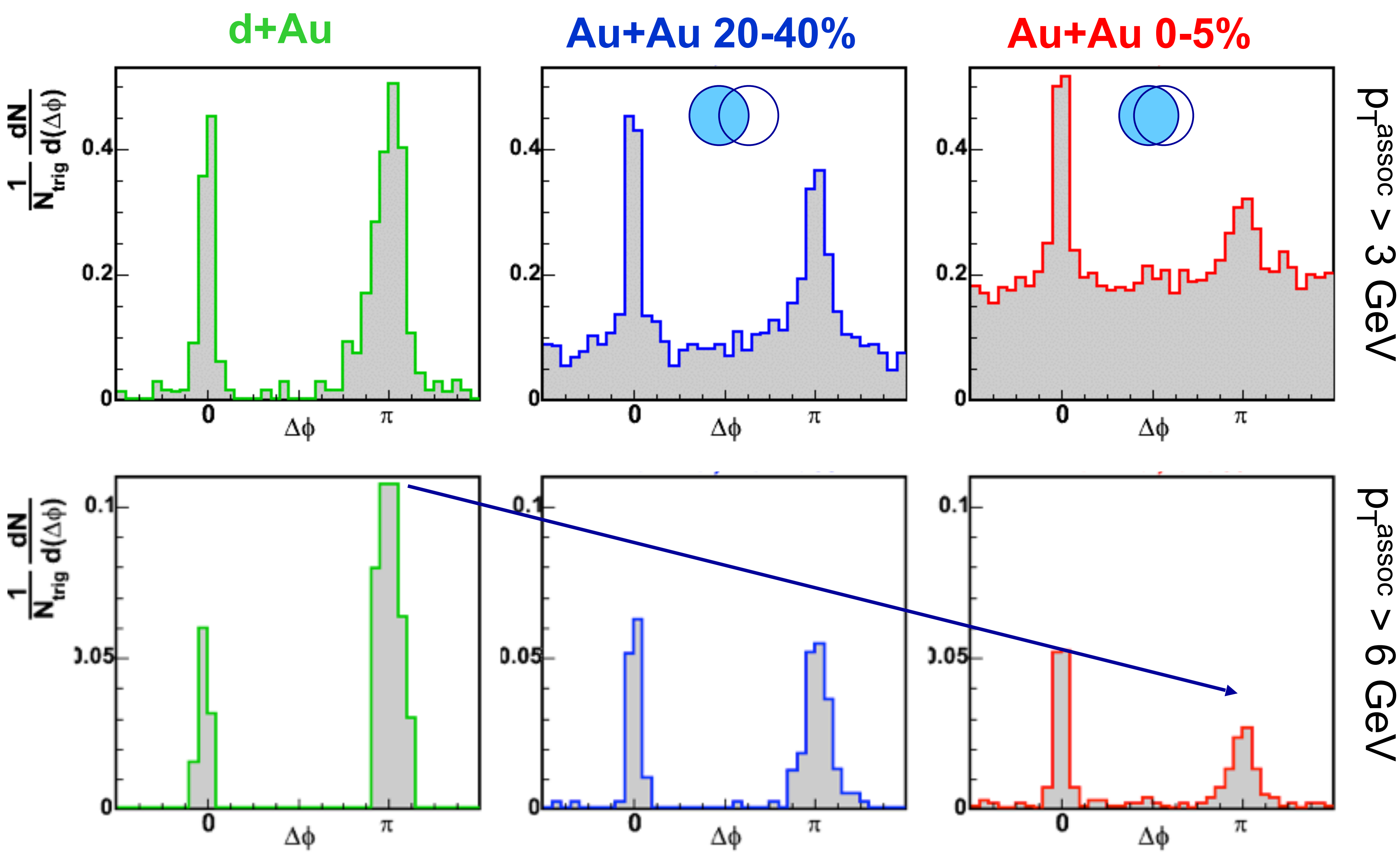






Use di-hadron correlations to probe the jet-structure in p+p, d+Au and Au+Au

Di-hadrons at high-p_T: recoil suppression



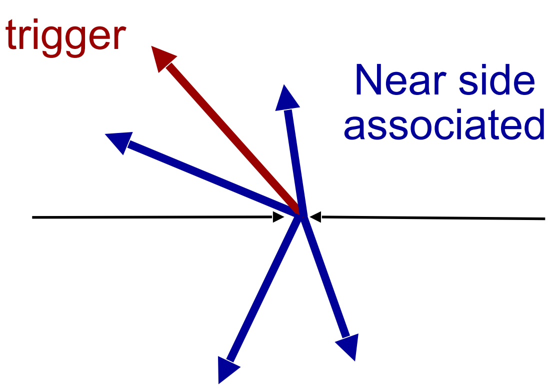
High-p_T hadron production in Au+Au dominated by (di-)jet fragmentation

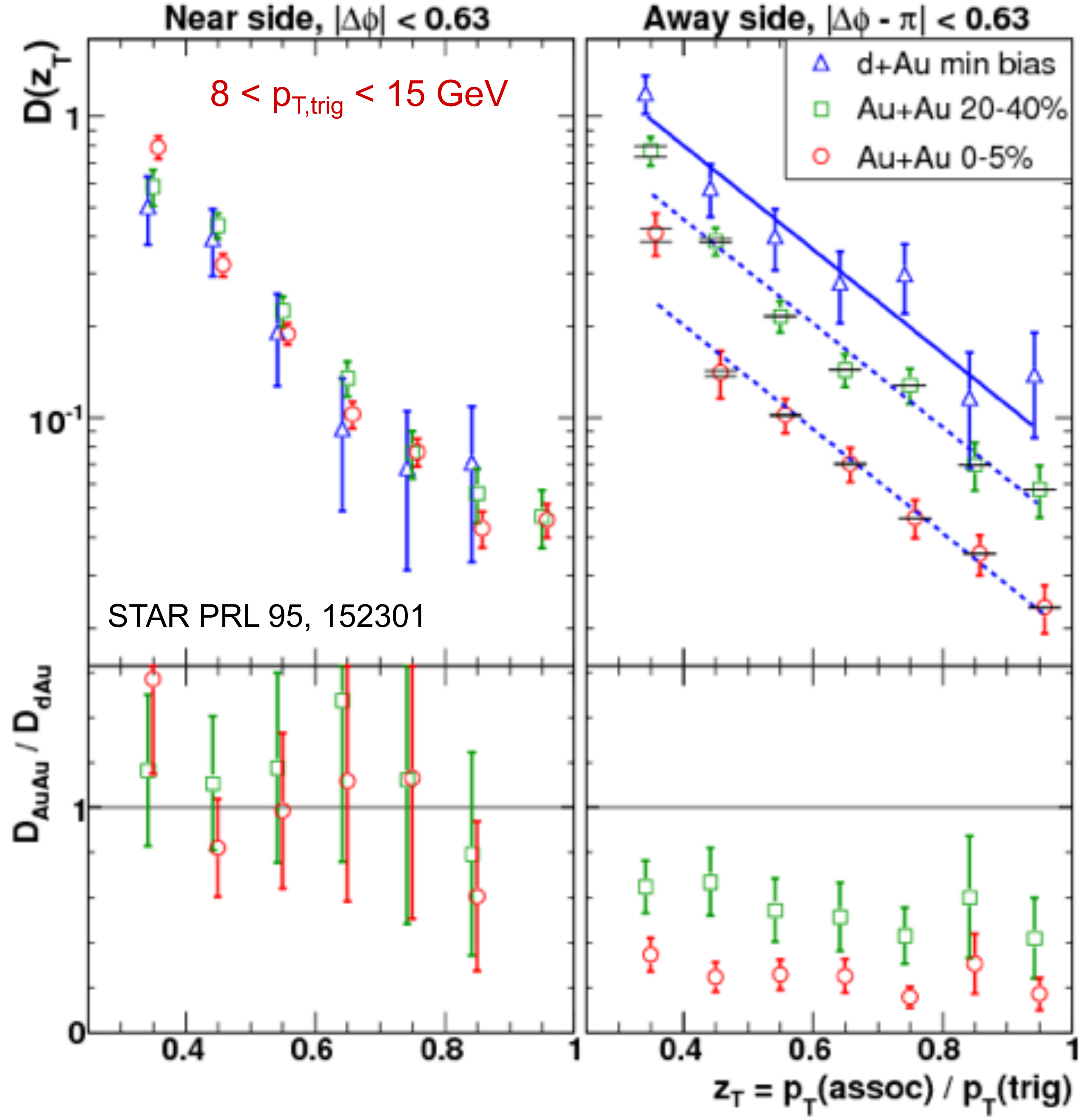
Suppression of away-side yield in Au+Au collisions: energy loss

Dihadron yield suppression

Near side

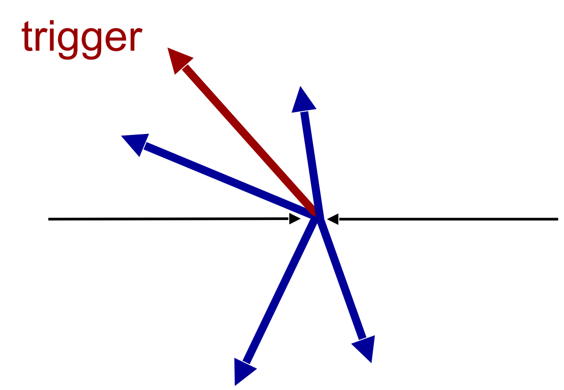
Yield of additional particles in the jet





Away side

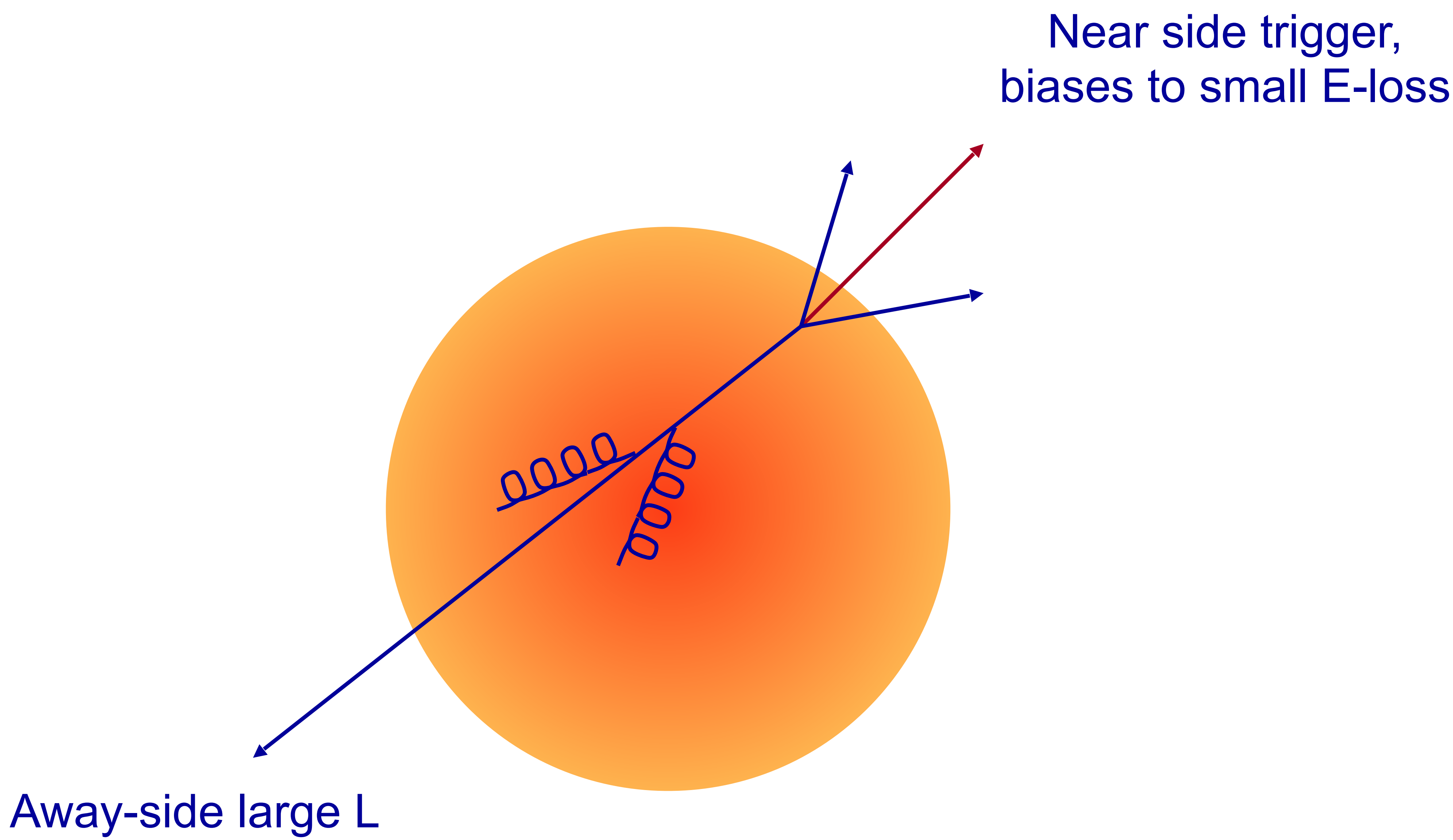
Yield in balancing jet, after energy loss



Near side: No modification
⇒ Fragmentation outside medium?

Away-side: Suppressed by factor 4-5
⇒ large energy loss

Path length II: 'surface bias'

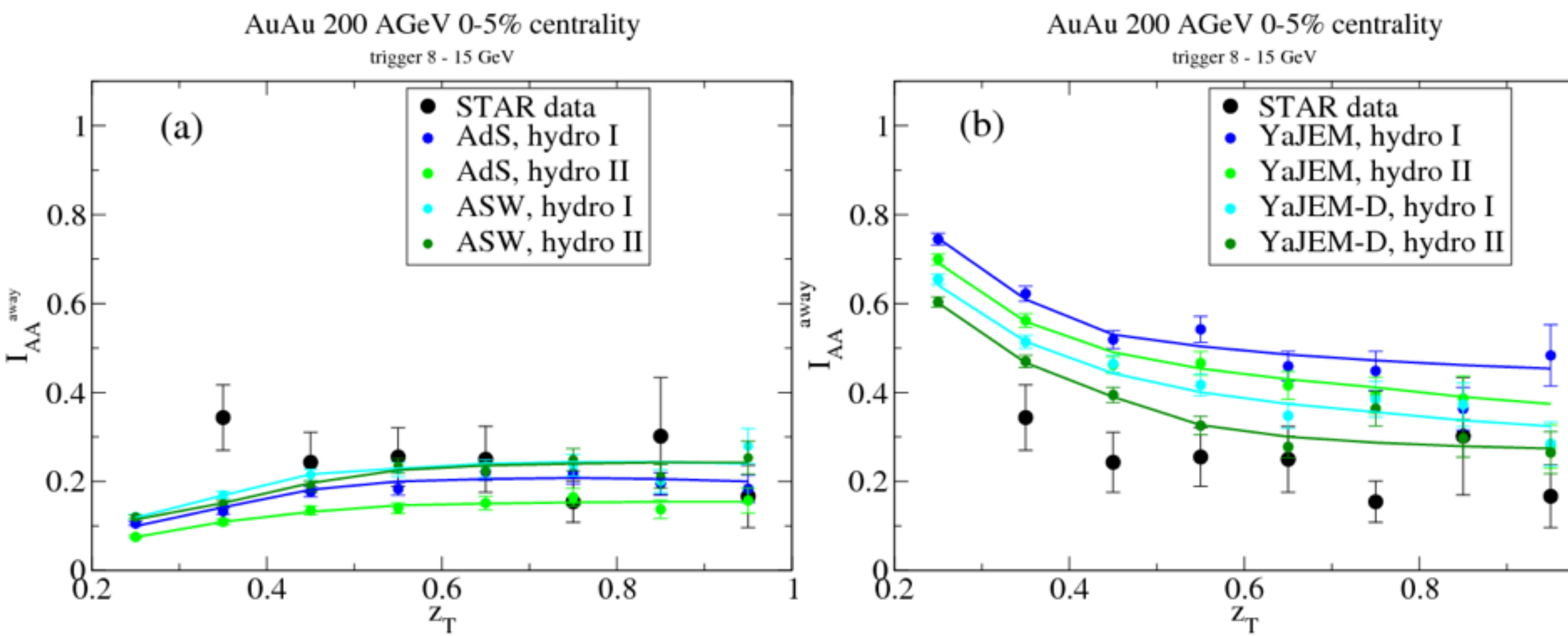


Away-side (recoil) suppression I_{AA} samples longer path-lengths than inclusives R_{AA}

NB: other effects play a role: quark/gluon composition, spectral shape (less steep for recoil)

Di-hadron modeling

Model 'calibrated' on single hadron R_{AA}



T. Renk, PRC, arXiv:1106.1740

L^2 (ASW) fits data
L^3 (AdS) slightly below

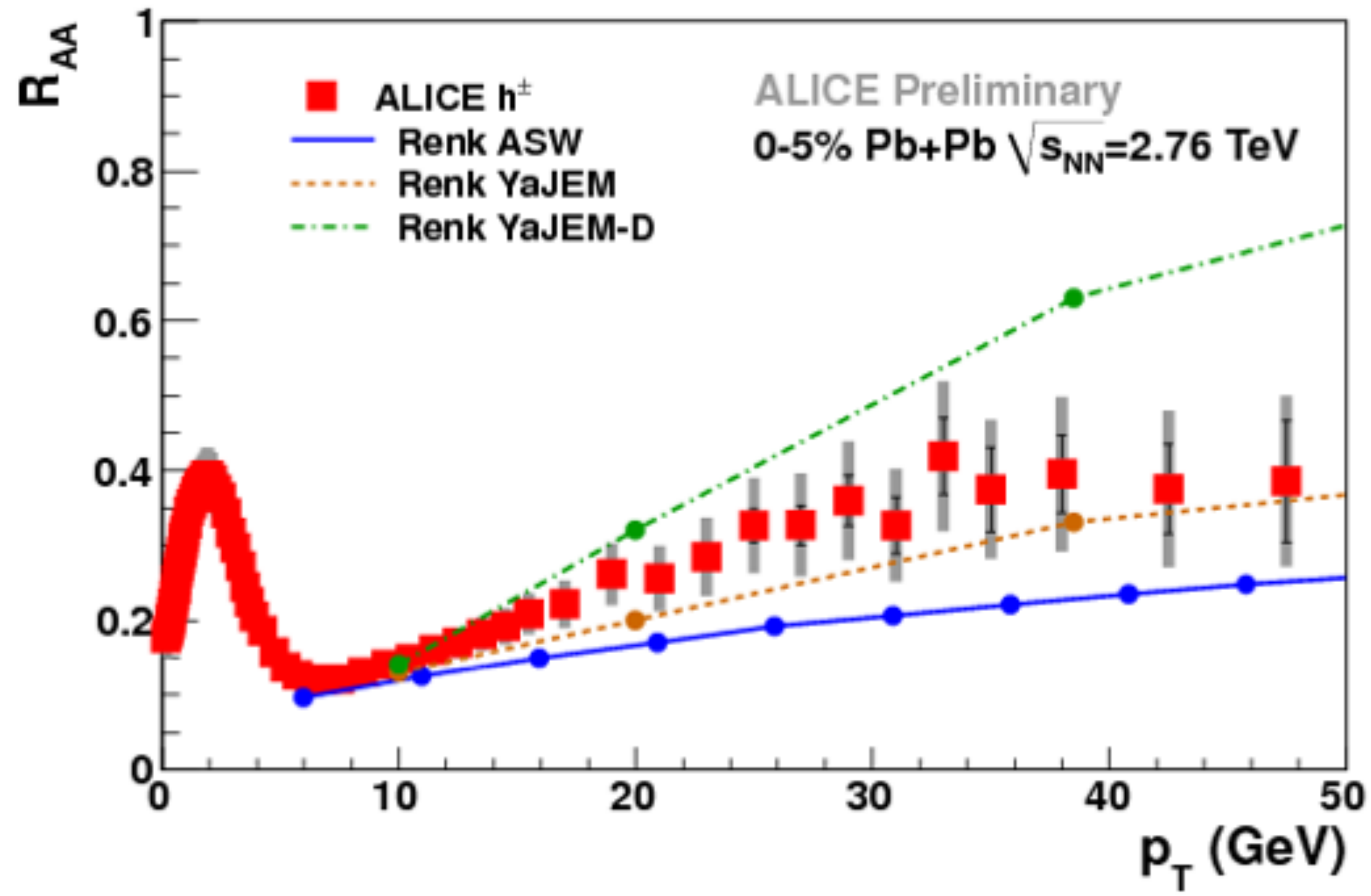
L (YaJEM): too little suppresion
L^2 (YaJEM-D) slightly above

Modified shower
generates increase at low z_T

Di-hadrons and single hadrons at LHC

Need simultaneous comparison to several measurements to constrain geometry and E-loss

Here: R_{AA} and I_{AA}

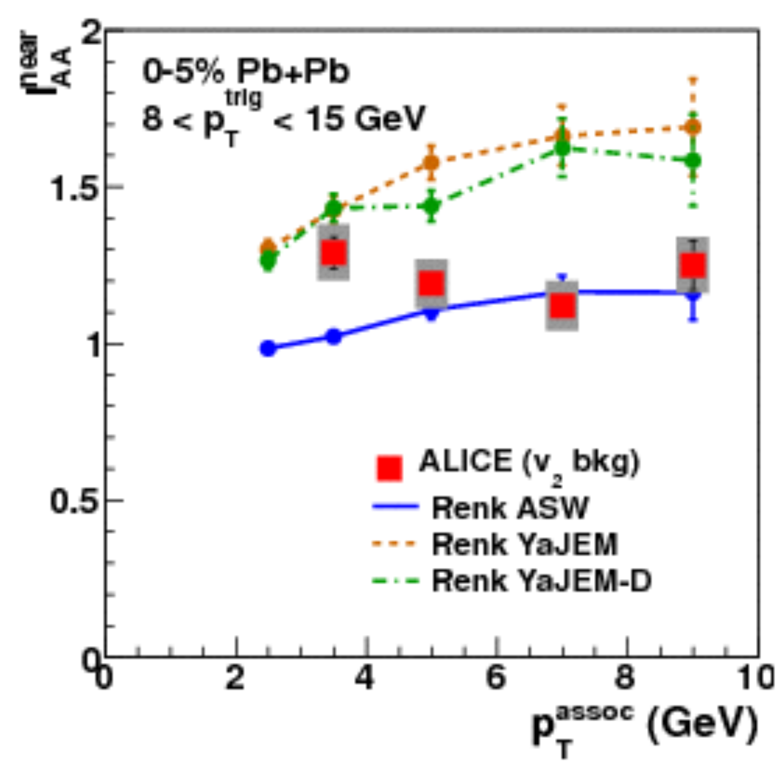


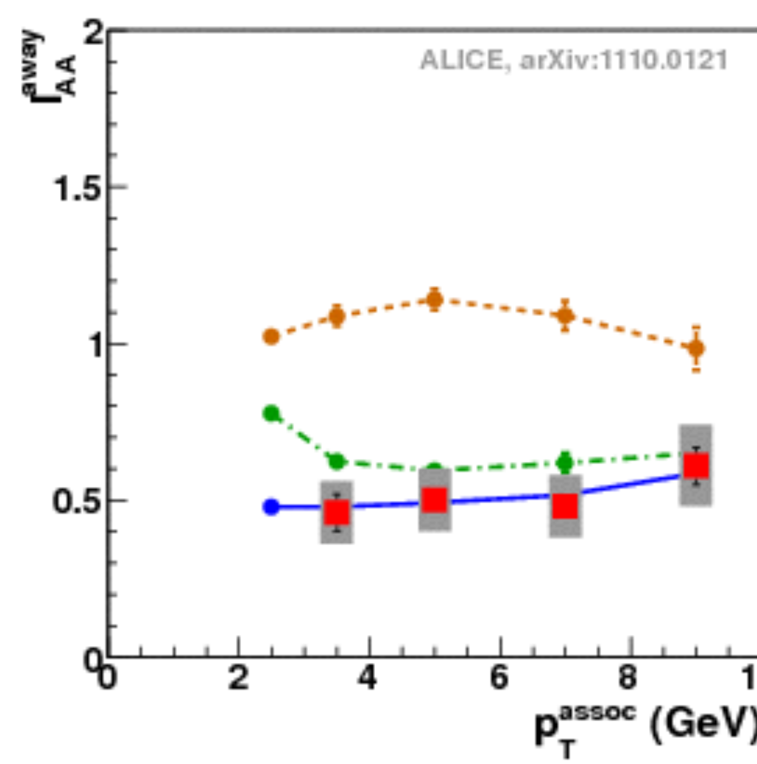
Three models:

ASW: radiative energy loss

YaJEM: medium-induced virtuality

YaJEM-D: YaJEM with L-dependent virtuality cut-off (induces L^2)





Summary

- p+Pb at LHC: some cold nuclear matter effects observed
  - Effects of nPDFs generally small, but detectable
  - $R_{pPb} = 1$, significant uncertainties at high p_T
  - + flow-like double ridge; not covered here
- Path length dependence of energy loss
  - Azimuthal dependence of jet quenching described by radiative energy loss 'L^2' dependence
    - Significant uncertainties due exact geometry
  - Recoil measurements also prefer radiative energy loss

Extra slides

Established MC models

- HIJING:
  - medium induced parton splitting process
  - complete HI events

Wang, Gyulassy, Phys. Rev. D **44** (1991) 3501

Deng, Wang, Xu, arXiv:1008.1841

- HYDJET++/PYQUEN:
  - gluon radiation sampled from BDMPS spectrum
  - elastic scattering
  - complete HI events

Lokhtin, Snigirev, Eur. Phys. J. C **45** (2006) 211

Lokhtin *et al.*, Comput. Phys. Commun. **180** (2009) 779

- JEWEL:
  - unified ME+PS description for all emissions

    work in progress
  - elastic scattering
  - simulates only parton shower + hadronisation

Zapp, Ingelman, Rathsman, Stachel, Wiedemann, Eur. Phys. J. C **60** (2009) 617

Zapp, Stachel, Wiedemann, Phys. Rev. Lett. **103** (2009) 152302

Slide from: K. Zapp, QM2011, Annecy

Established MC models

- Q-PYTHIA/Q-HERWIG:
  - modified splitting function derived from BDMPS
  - simulates only jets

Armesto, Cunqueiro, Salgado, Eur. Phys. J. C **63** (2009) 679

Armesto, Corcella, Cunqueiro, Salgado, JHEP **0911** (2009) 122

- YaJEM:
  - medium interactions transfer virtuality to partons ($\rightarrow$ radiative energy loss)
  - and degrade their energy
  - simulates only jets

Renk, Phys. Rev. C **78** (2008) 034908

Renk, Phys. Rev. C **79** (2009) 054906

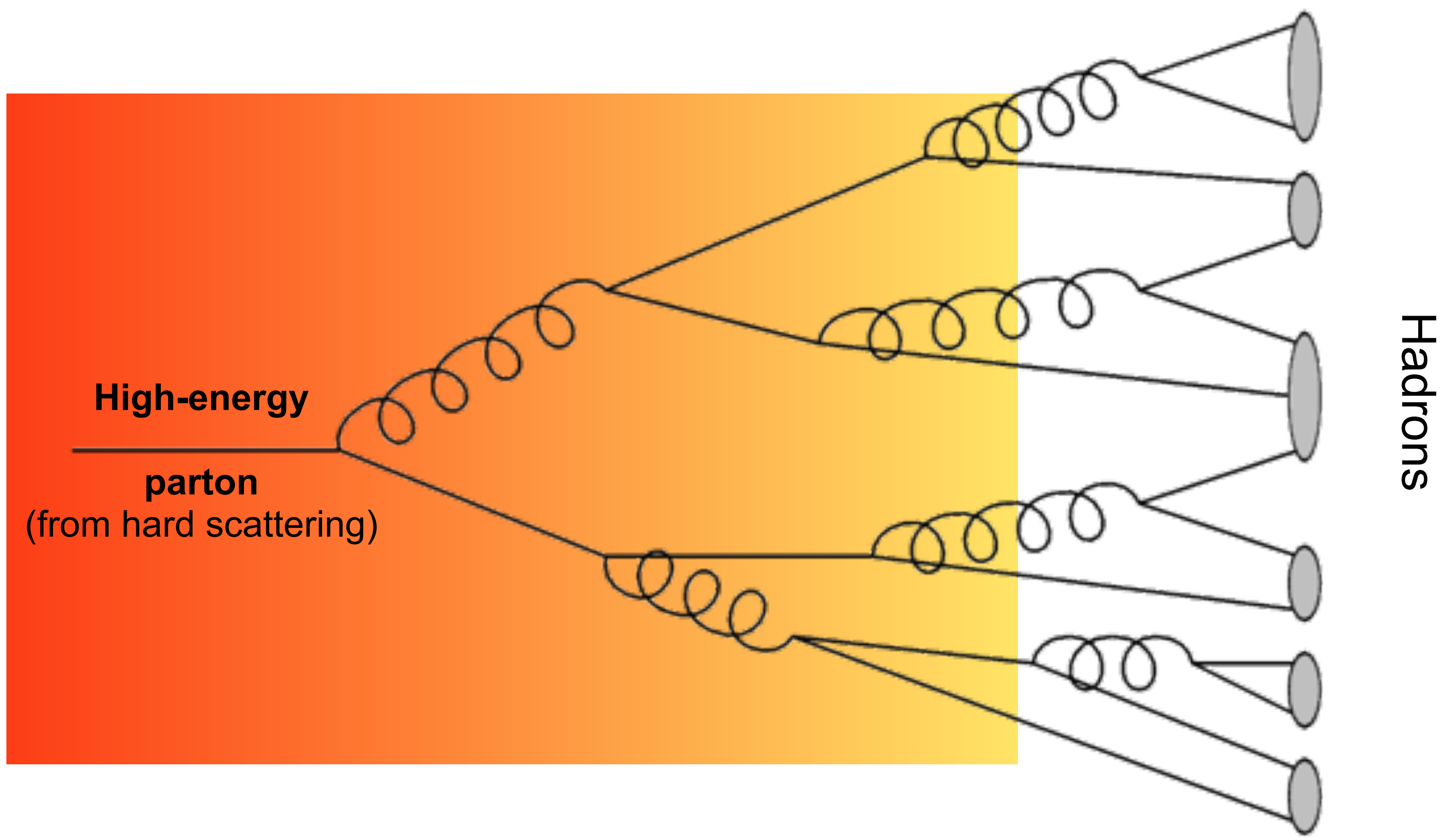
- MARTINI:
  - based on AMY transition rates
  - $+$ elastic scattering transition rate
  - simulates only jets

Schenke, Gale, Jeon, Phys. Rev. C **80** (2009) 054913

Slide from: K. Zapp, QM2011, Annecy

In-medium showers: energy loss MC

Theory calculations on previous slides: 'factorised' approach, P(ΔE) FF

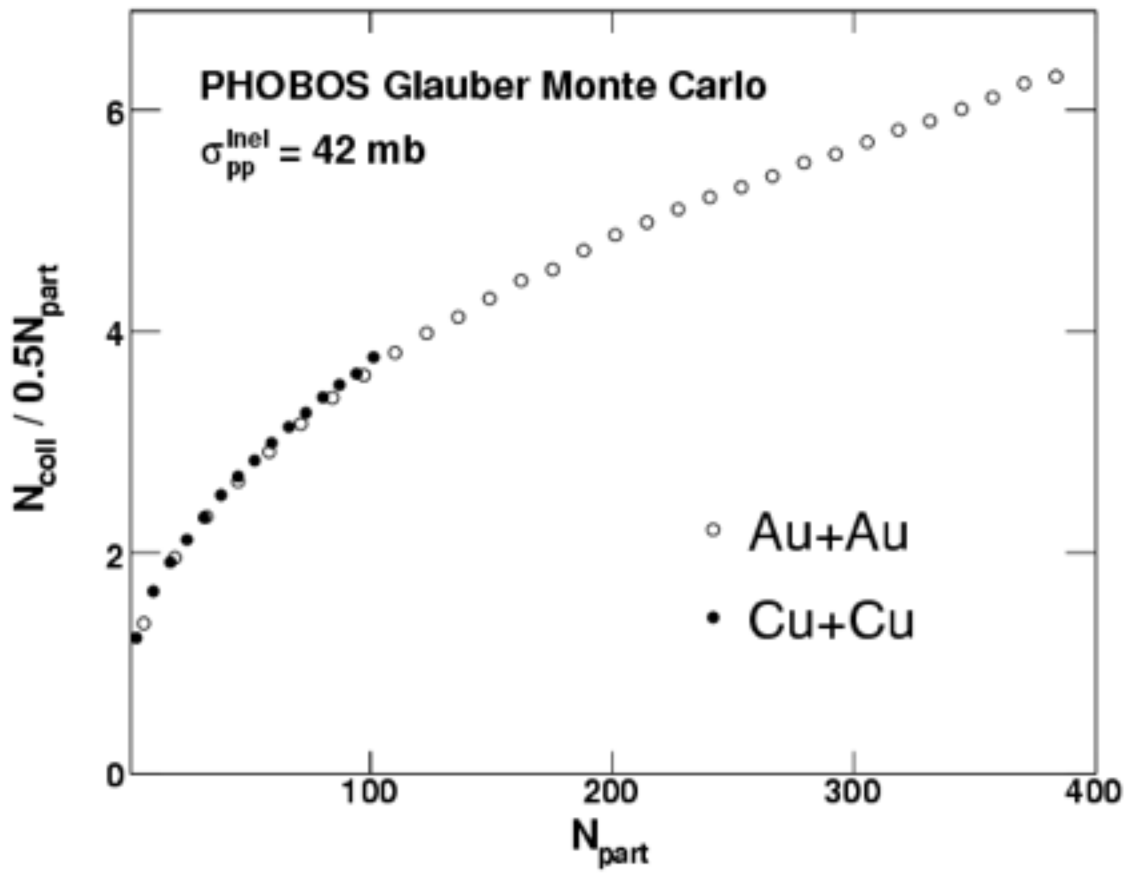


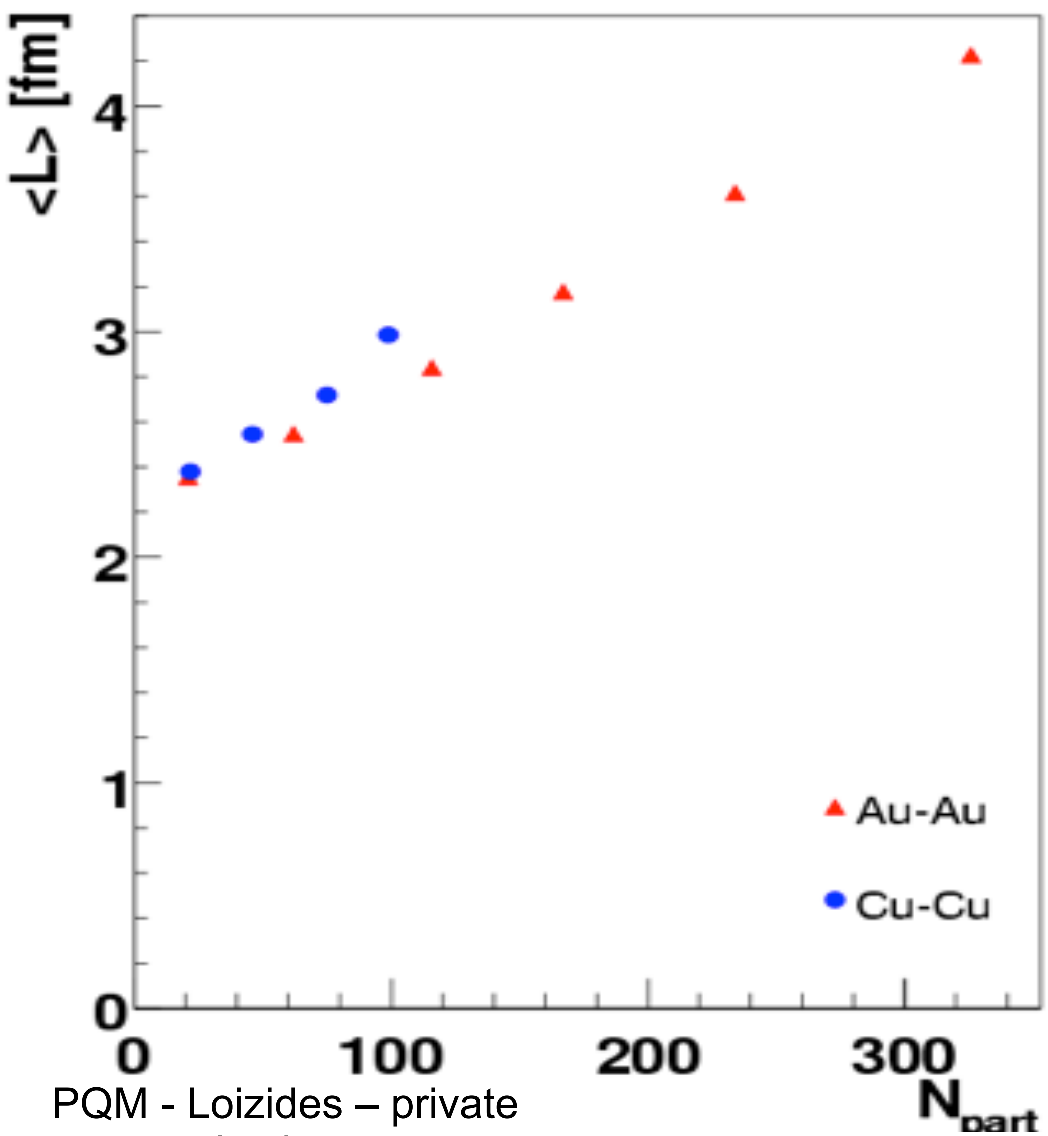
Alternative (more realistic):
in-medium shower: every radiation is affected by the medium

(N.B.: coherence effects may be more complicated; see Carlos' lectures)

Implemented in MC codes: JEWEL, YaJEM

N_{part} scaling?





PQM - Loizides – private communication

Geometry (thickness, area) of
central Cu+Cu similar to peripheral Au+Au

Cannot disentangle density vs path length