Lecture 2: Single and di-hadron measurements and energy loss modelling

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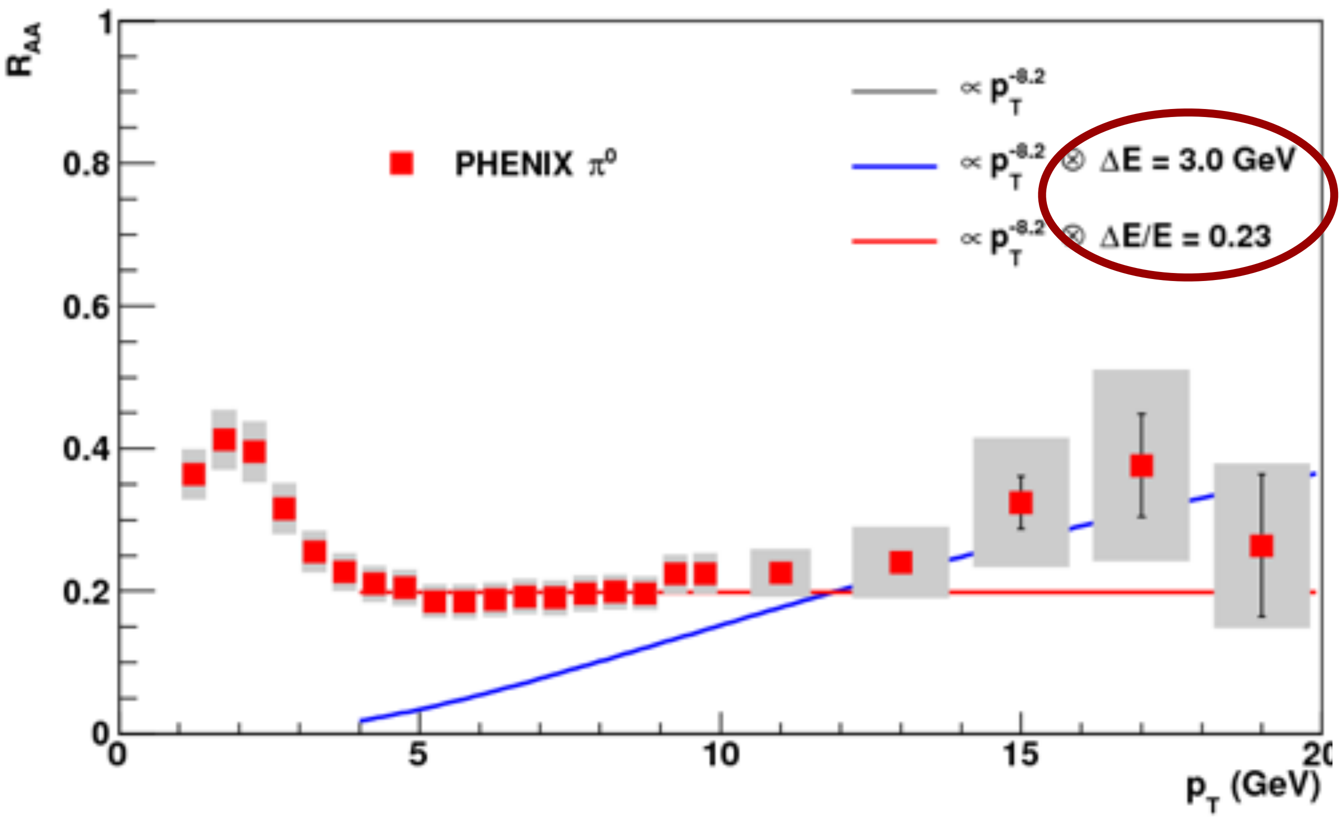
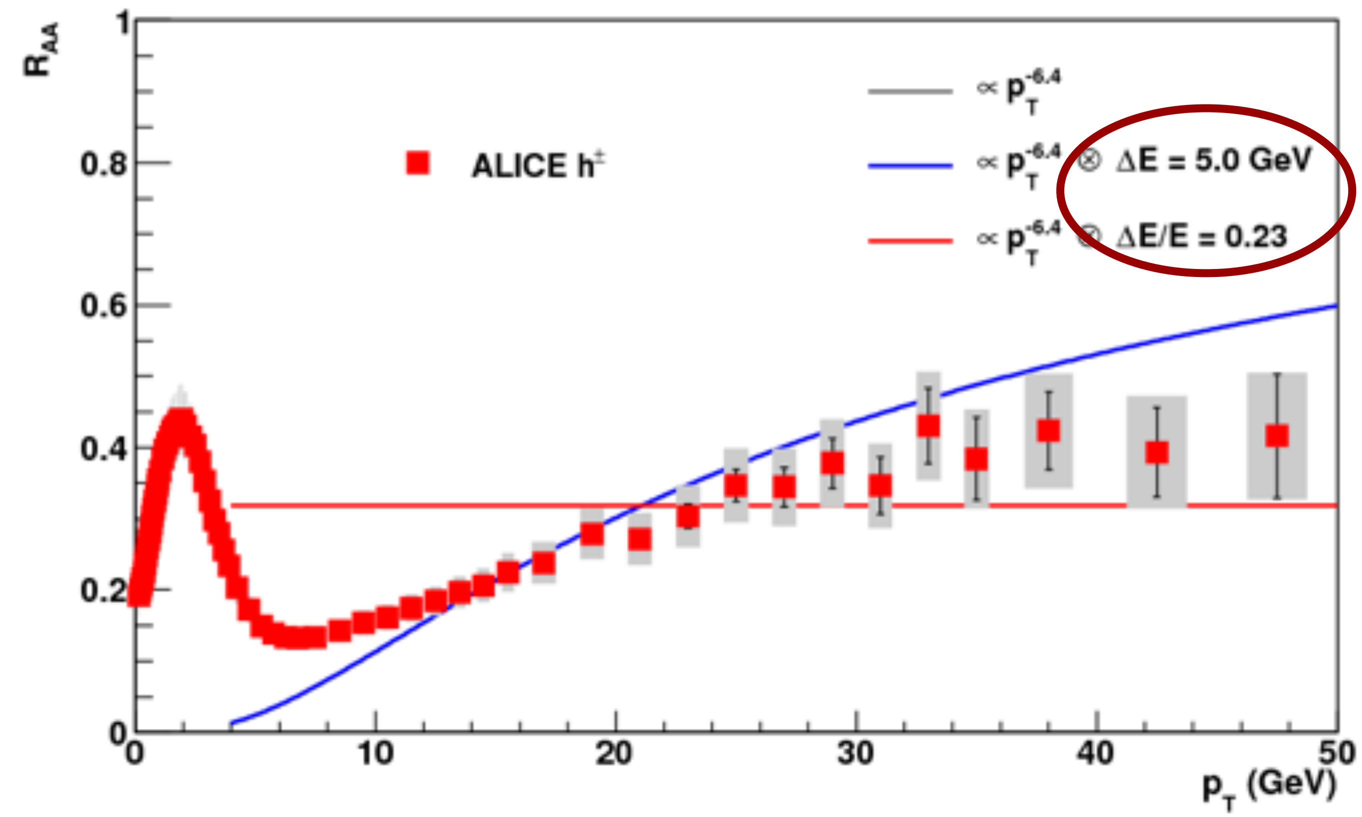
NIKHEF

From RHIC to LHC

RHIC



LHC



RHIC: n ~ 8.2

LHC: n ~ 6.4

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

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

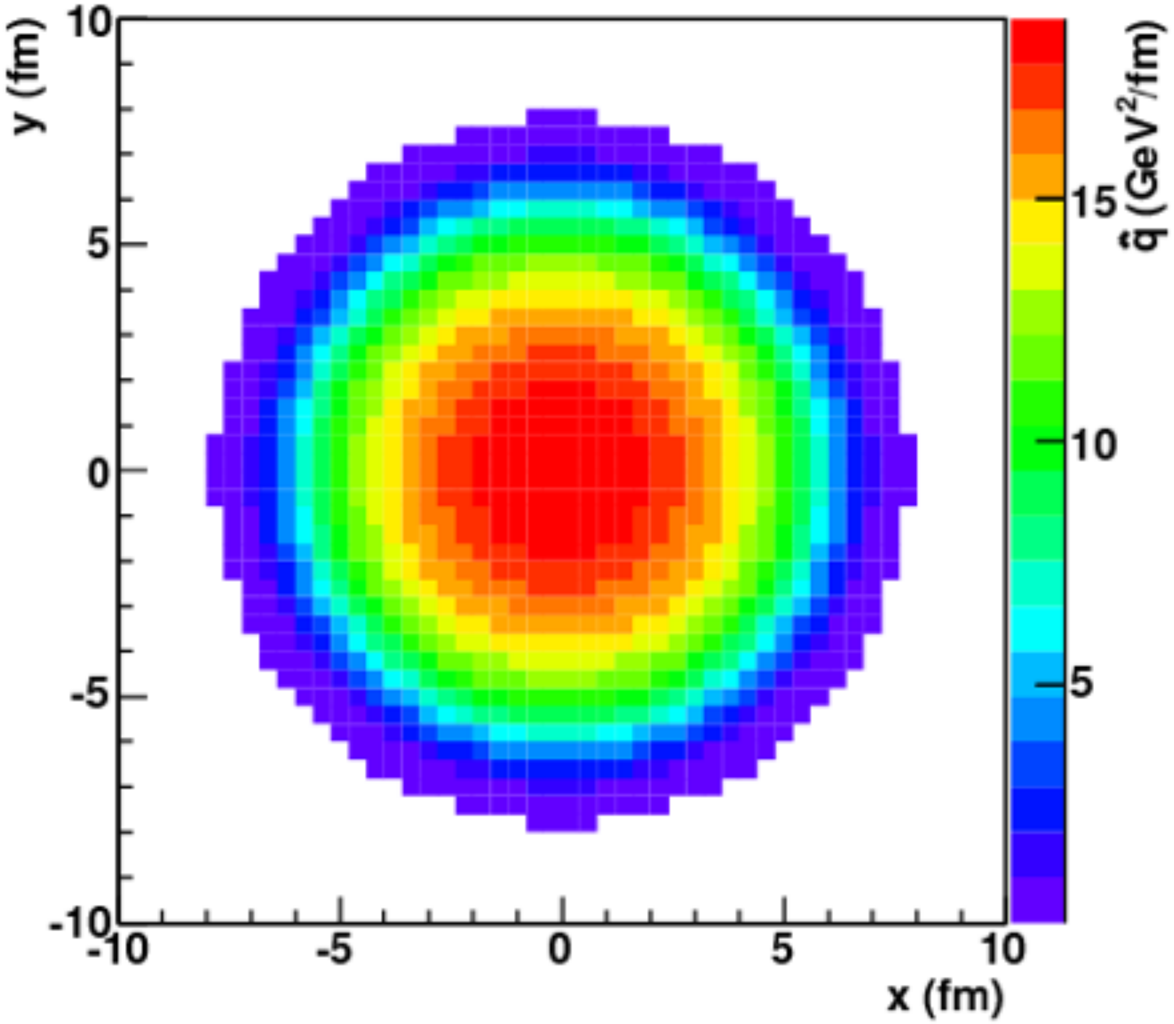
Remember: still ‘getting a sense for the numbers’; this is not a model!

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

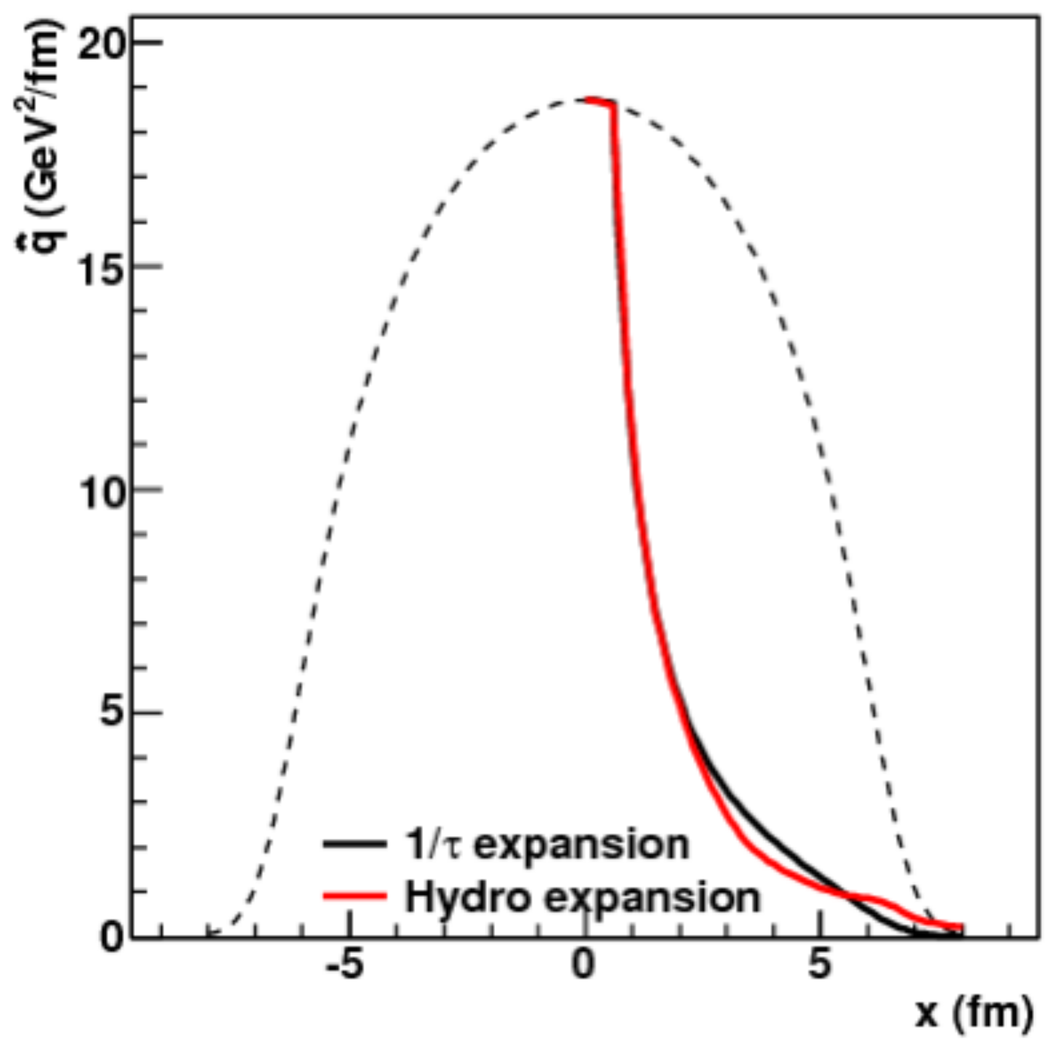
Geometry

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

Parton spectrum — Energy loss distribution — Fragmentation (function)

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

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

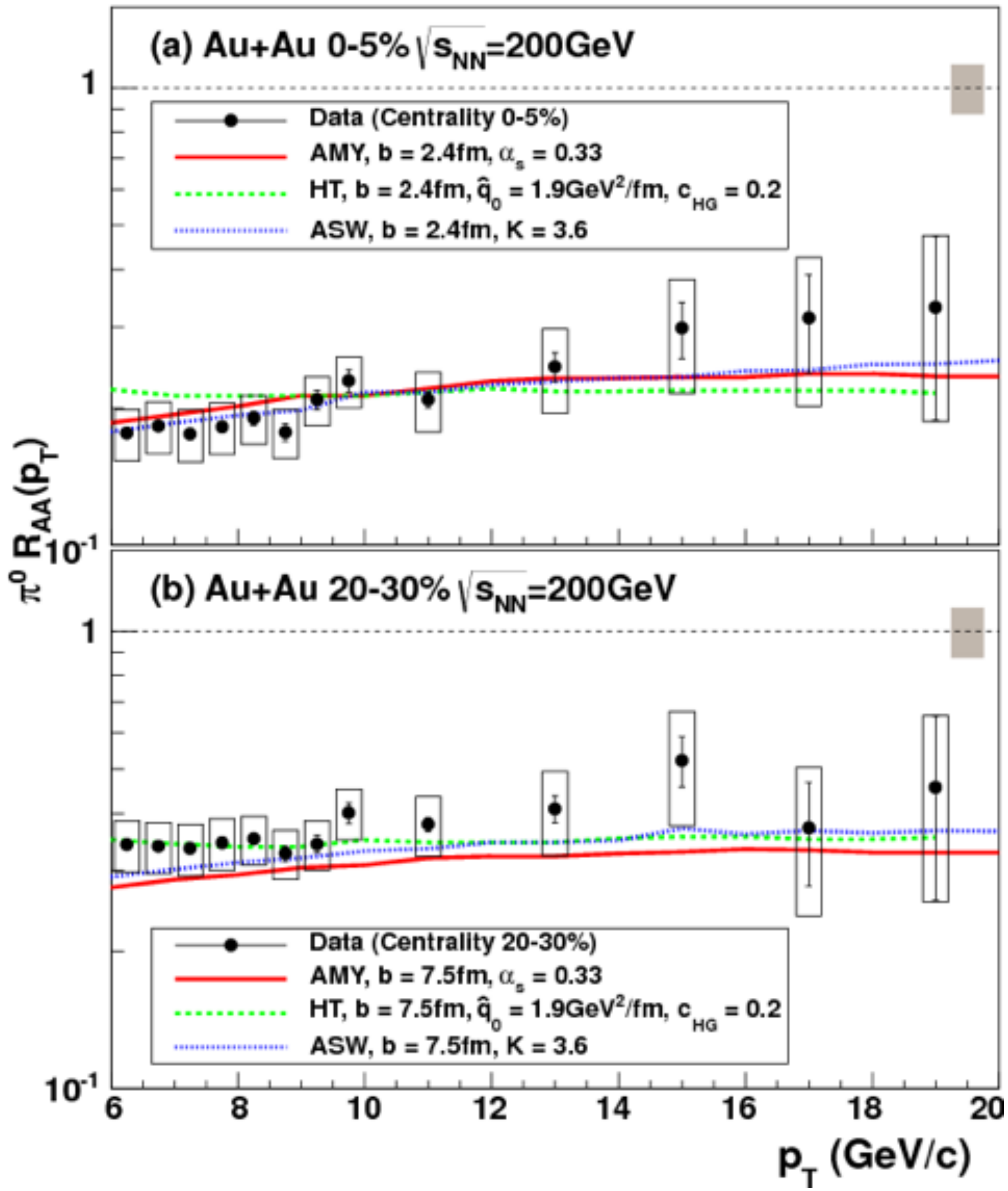
ASW: $\hat{q} = 10 - 20\ \mathrm{GeV}^2/\mathrm{fm}$

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

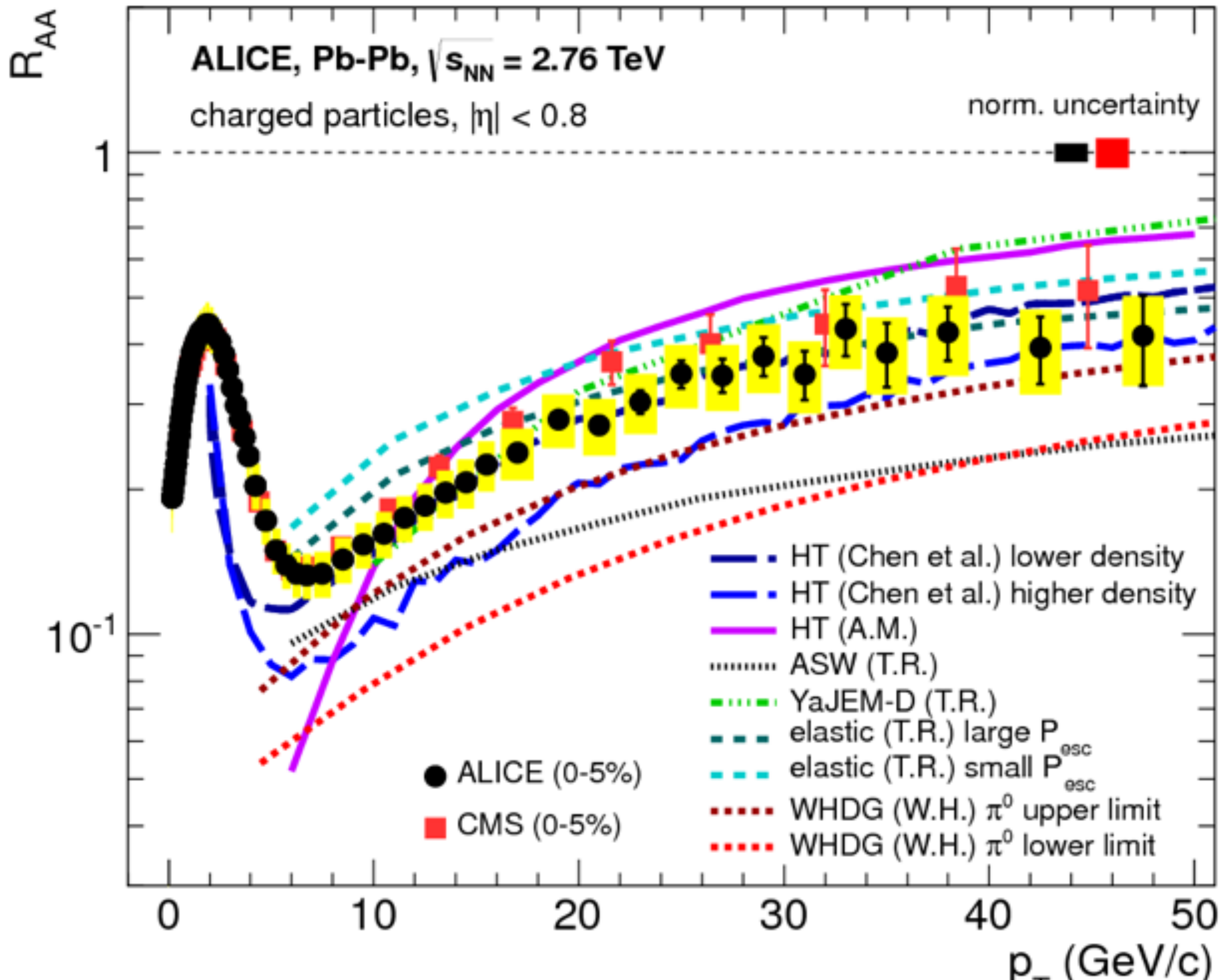
PHENIX, arXiv:1208.2254

R_{AA} at LHC & models

ALICE: arXiv:1208.2711
CMS: arXiv:1202.2554

Broad agreement between models and LHC R_{AA}

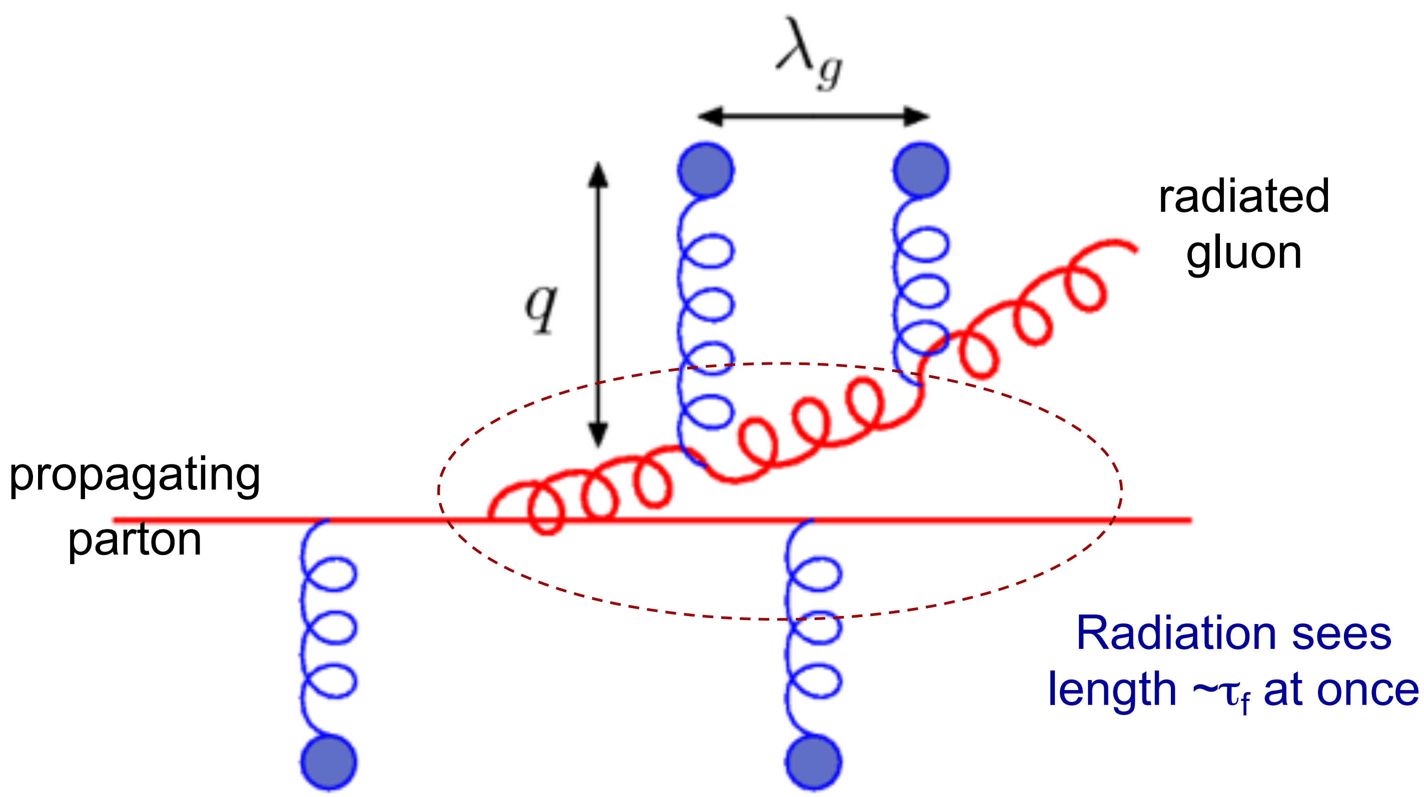
Extrapolation from RHIC tends to give too much suppression at LHC

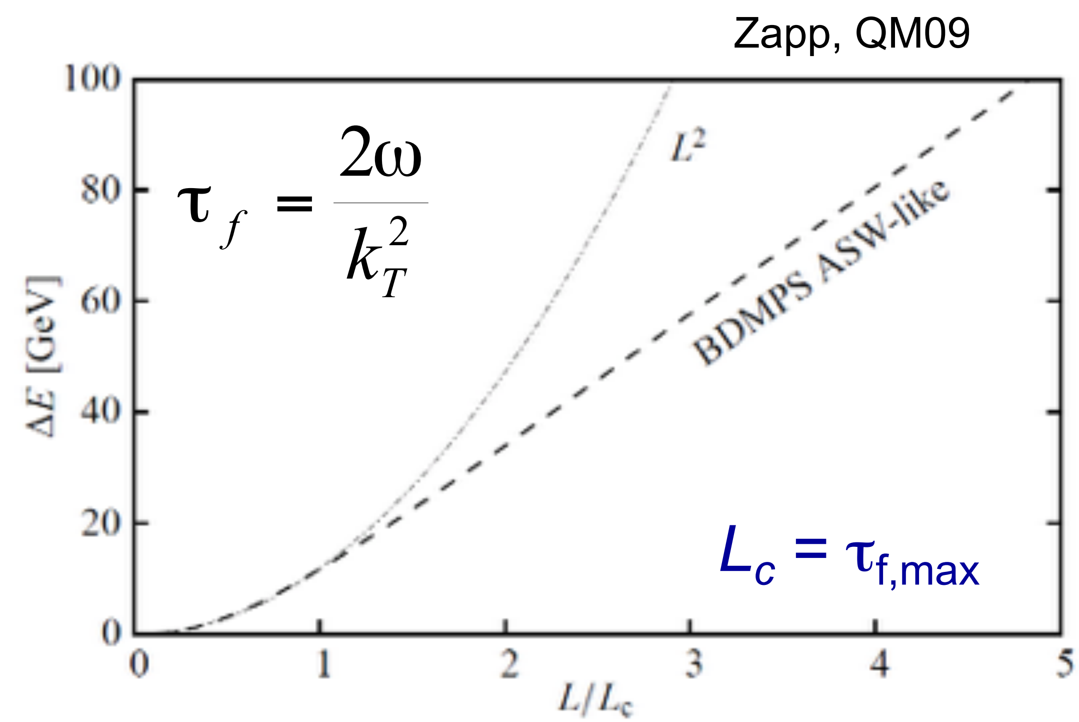


Many model curves: need more constraints and/or selection of models

Medium-induced radition

Landau-Pomeranchuk-Migdal effect
Formation time important





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

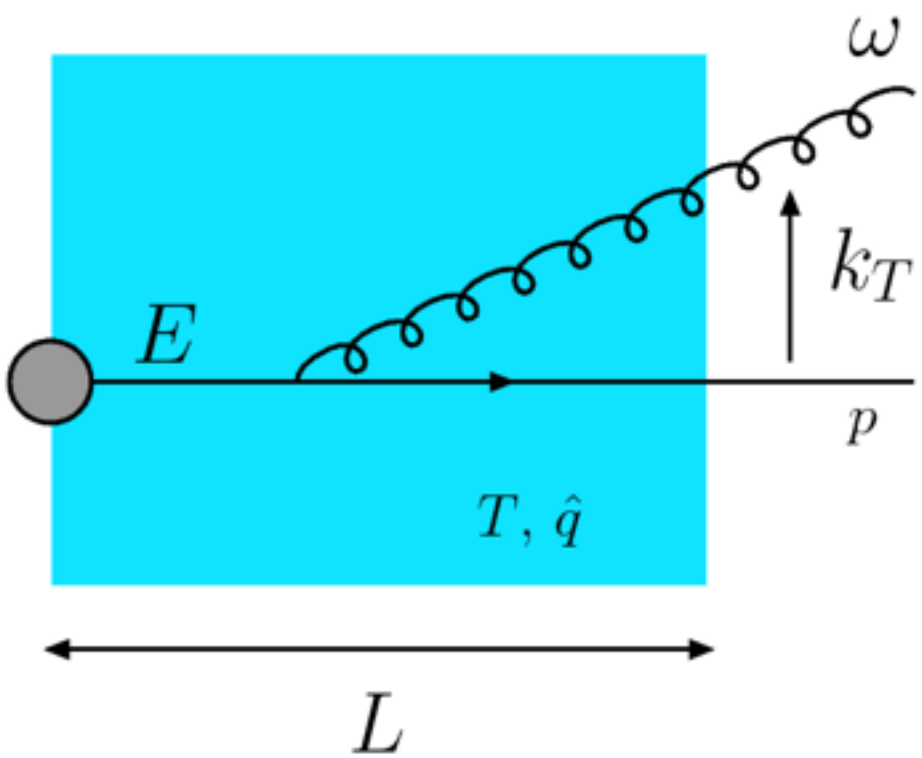
Poisson ansatz (independent emission)

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

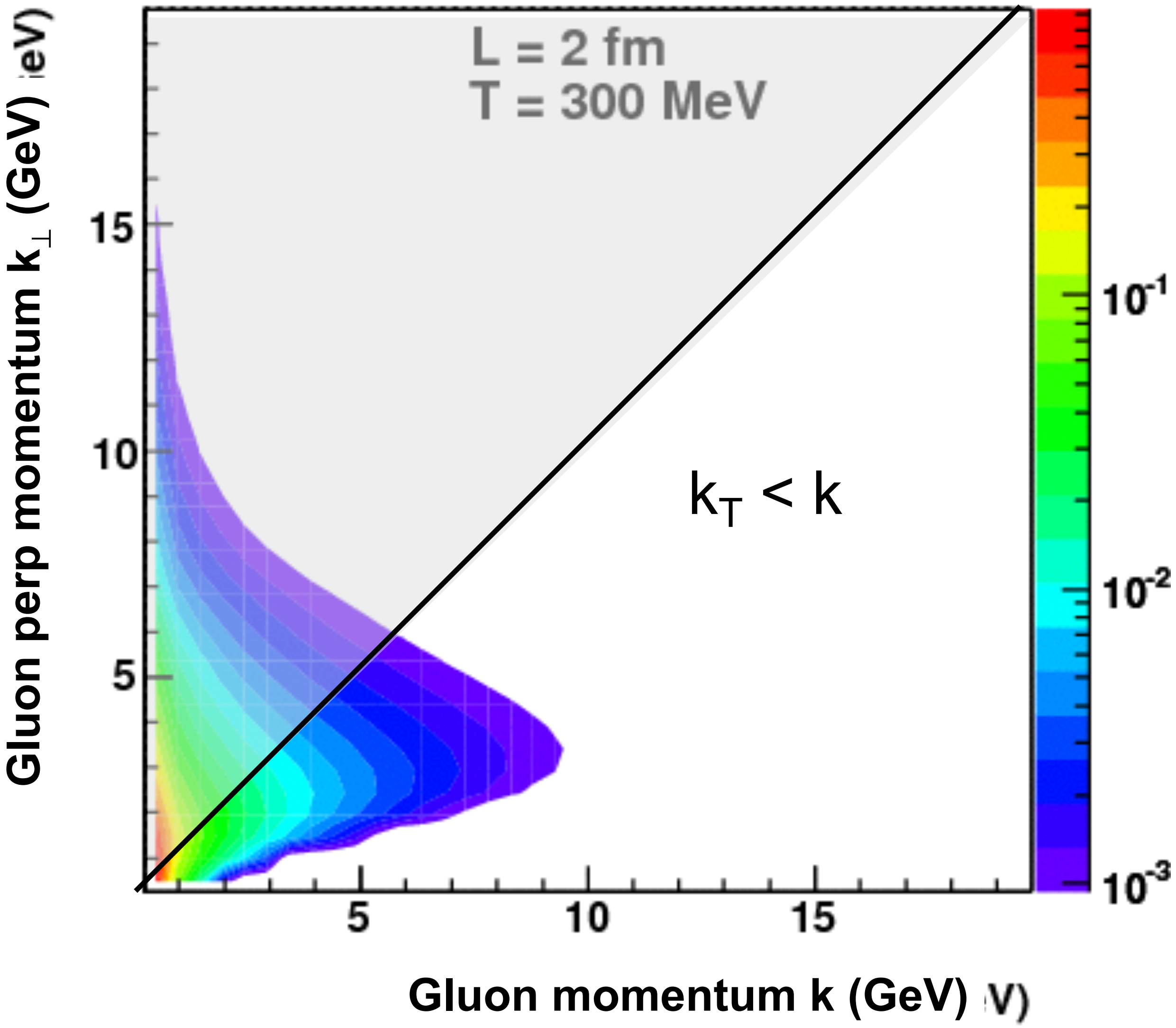
DGLAP evolution

See also: arXiv:1106.1106

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

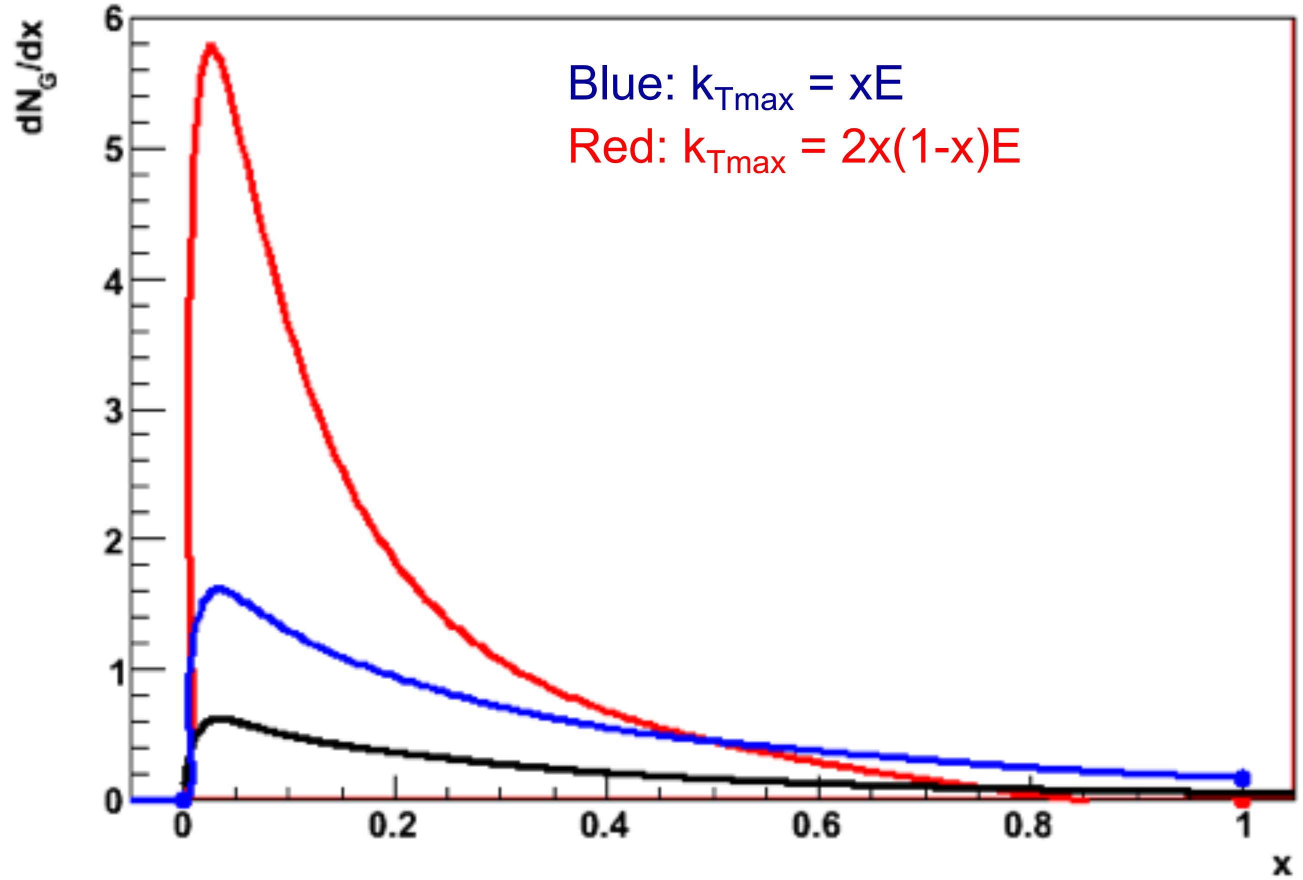
Expand in powers of $\frac{L}{\lambda}$

Different definitions of *x*:

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

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

Single-gluon spectrum

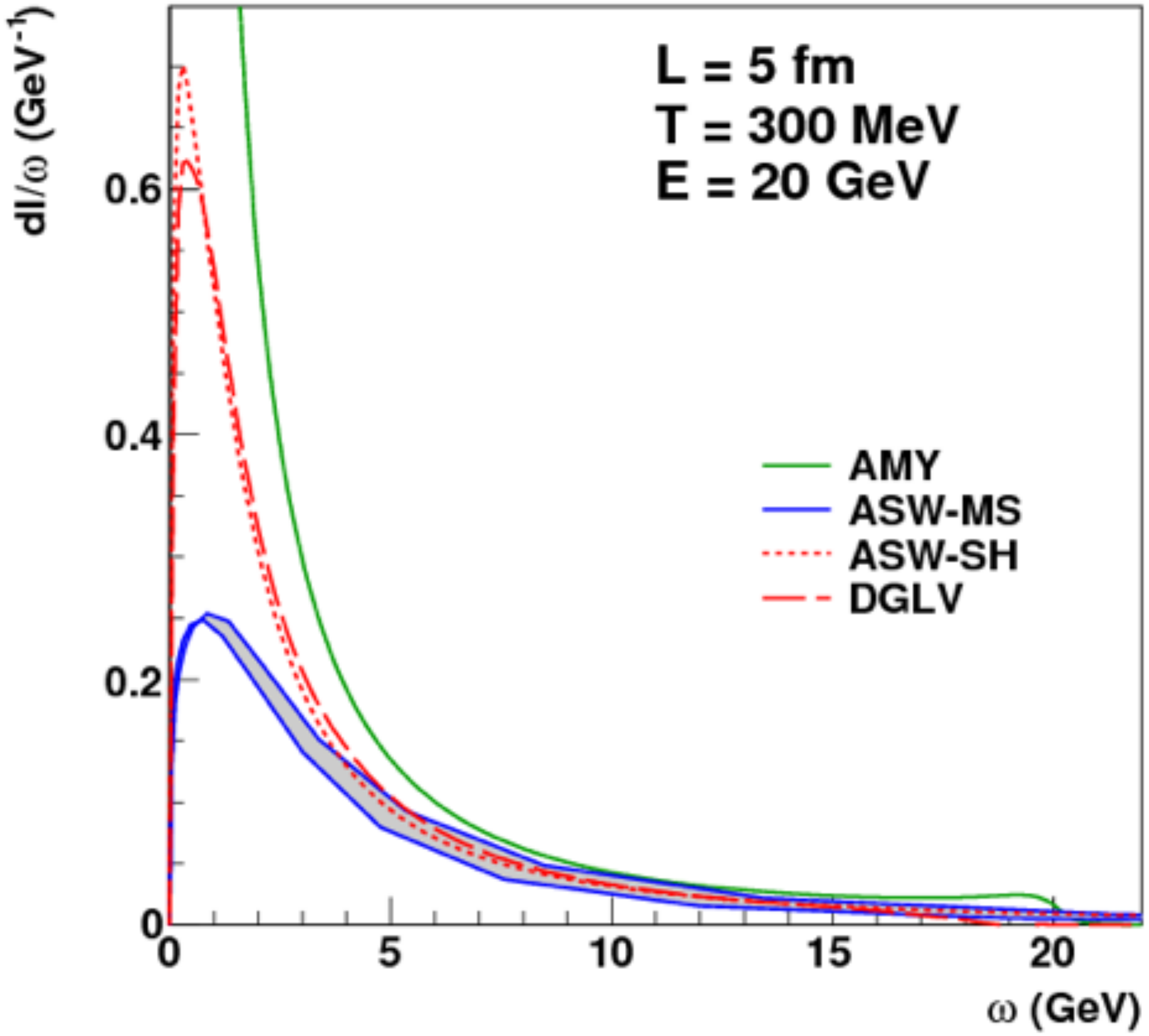


Horowitz and Cole, PRC81, 024909

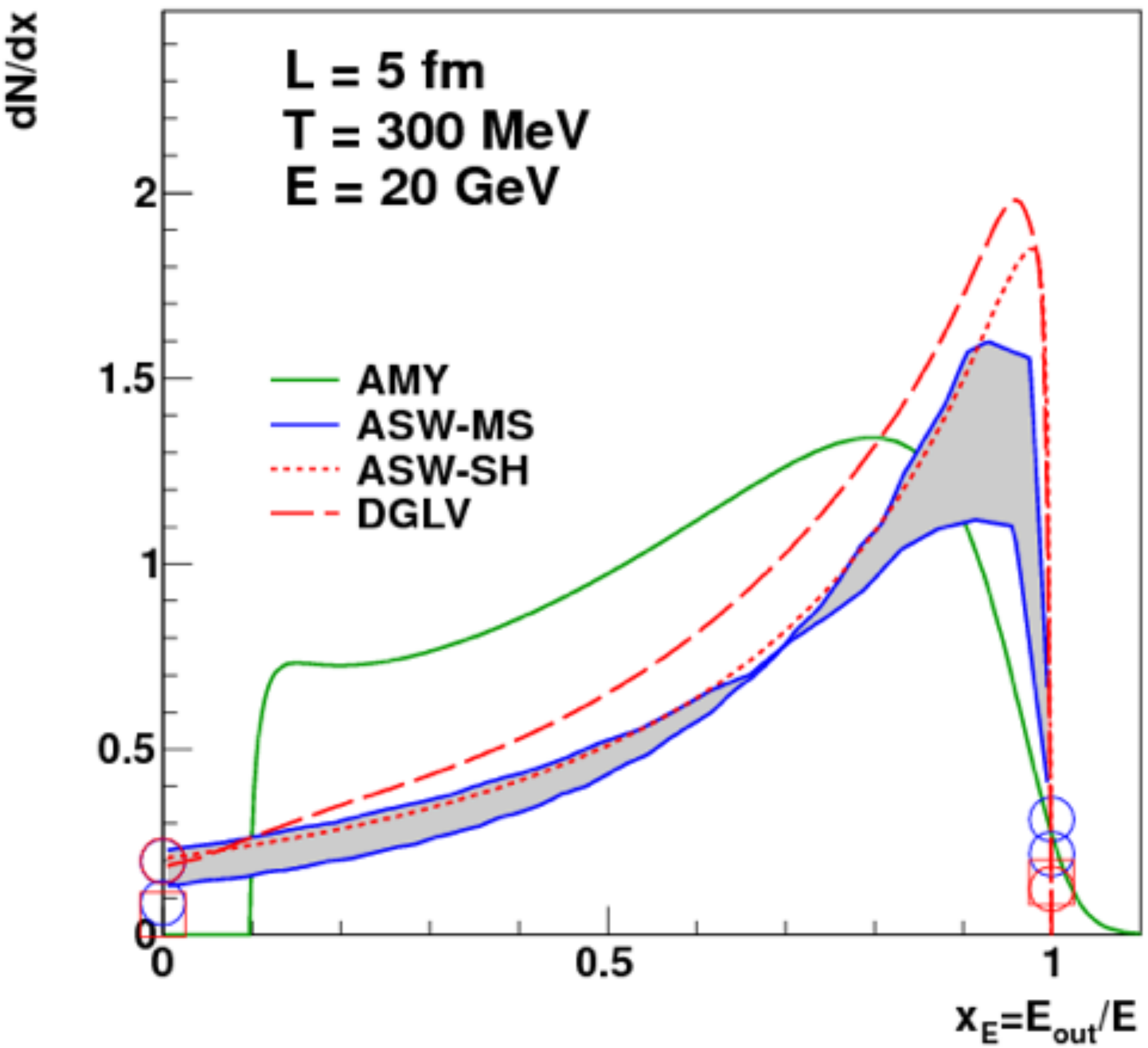
Factor ~2 uncertainty
from large-angle cut-off

Energy loss distributions

Radiated gluon distribution



Energy loss probability distribution

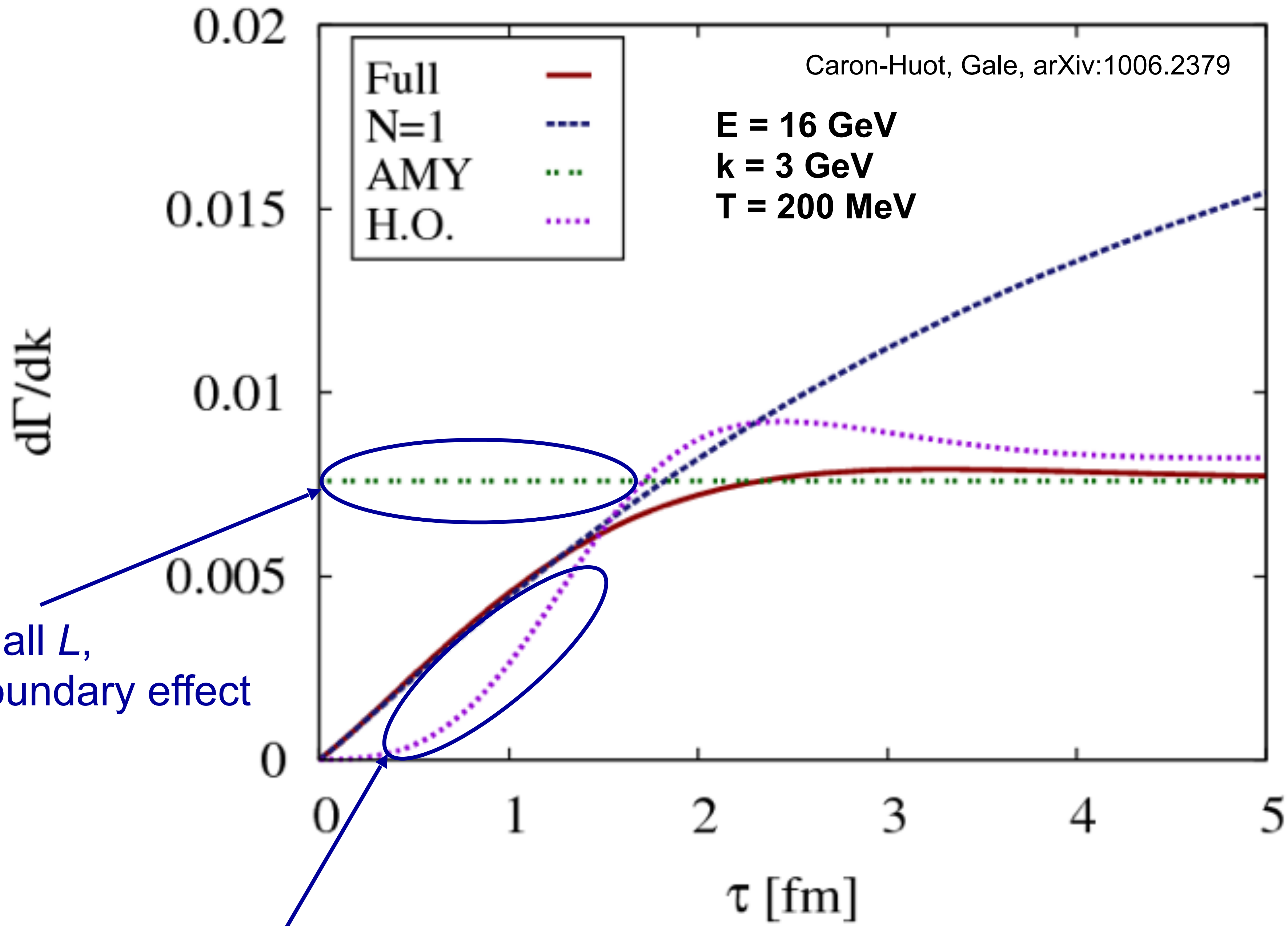


Main theory uncertainty:
Large angle radiation

Broad distribution
Significant contributions at ΔE=0, ΔE=E

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)

Energy loss formalisms

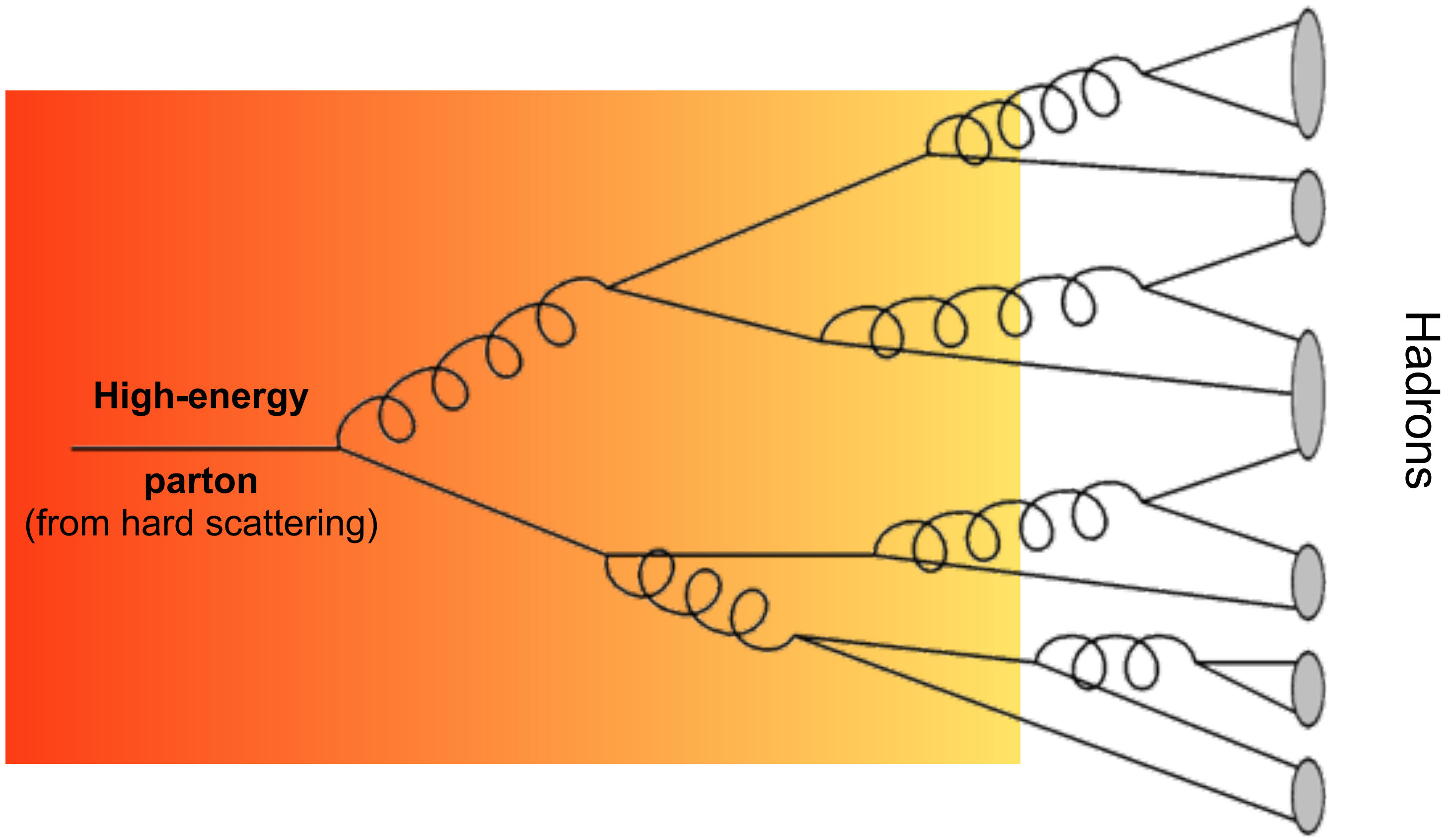
- Large differences between formalisms understood
  - Large angle cut-off
  - Length dependence (interference effects)
- Mostly (?) 'technical' issues; can be overcome
  - Use path-integral formalism
  - Monte Carlo: exact *E*, *p* conservation
    - Full 2→3 NLO matrix elements
    - Include interference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

Many new developments; see Carlos' lectures for more

Plenty of room for interesting and relevant theory work!

In-medium showers: energy loss MC

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



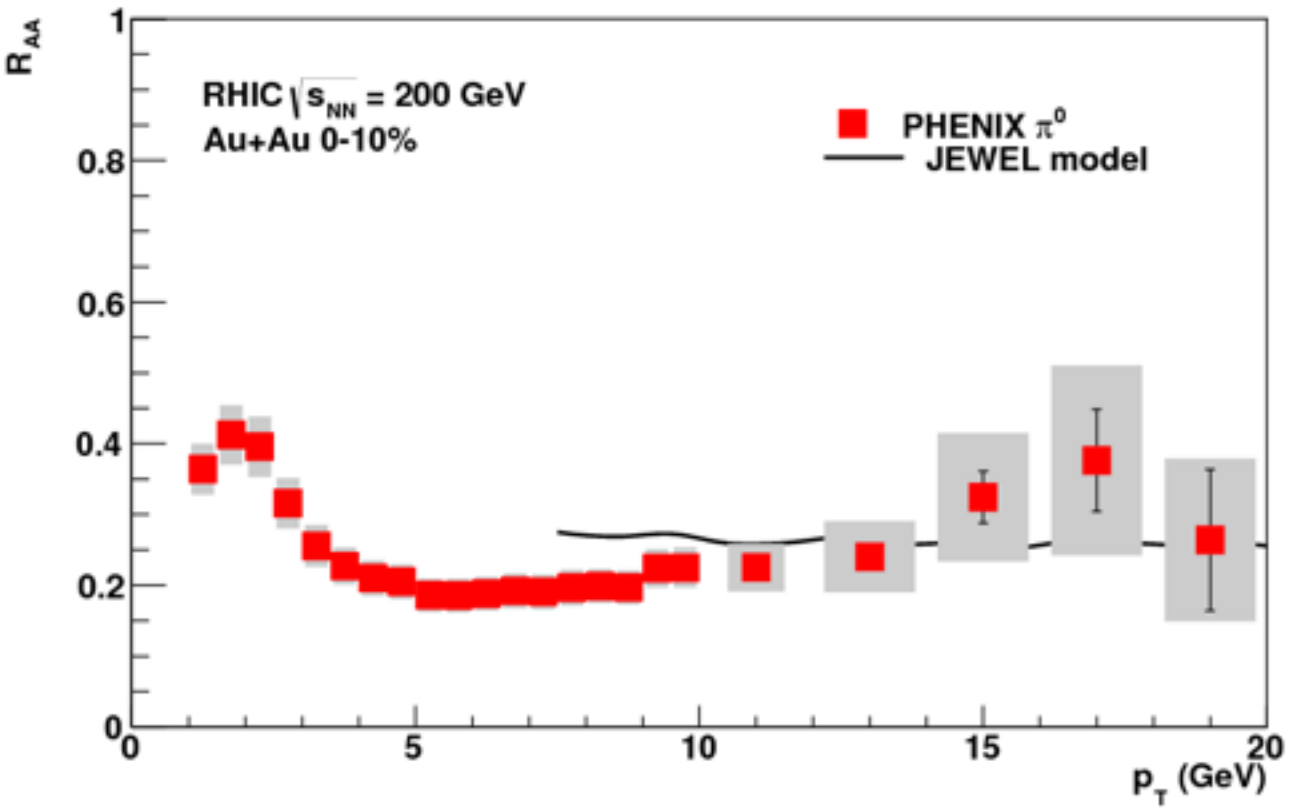
Alternative (more realistic):
in-medium shower: every radiation is affected by the medium

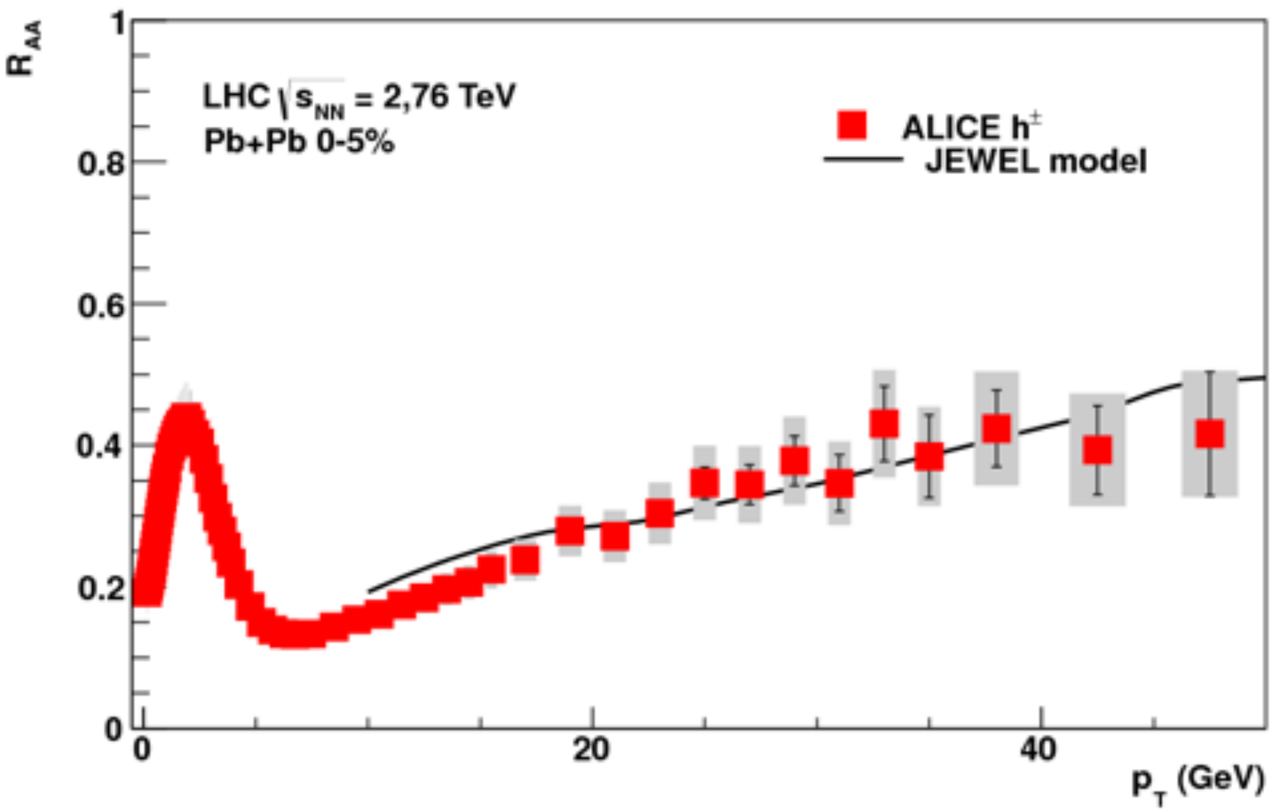
(N.B.: coherence effects may be more complicated; see Carlos’ lectures)

Implemented in MC codes: JEWEL, YaJEM

R_{AA} at LHC and JEWEL

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

Energy loss theory

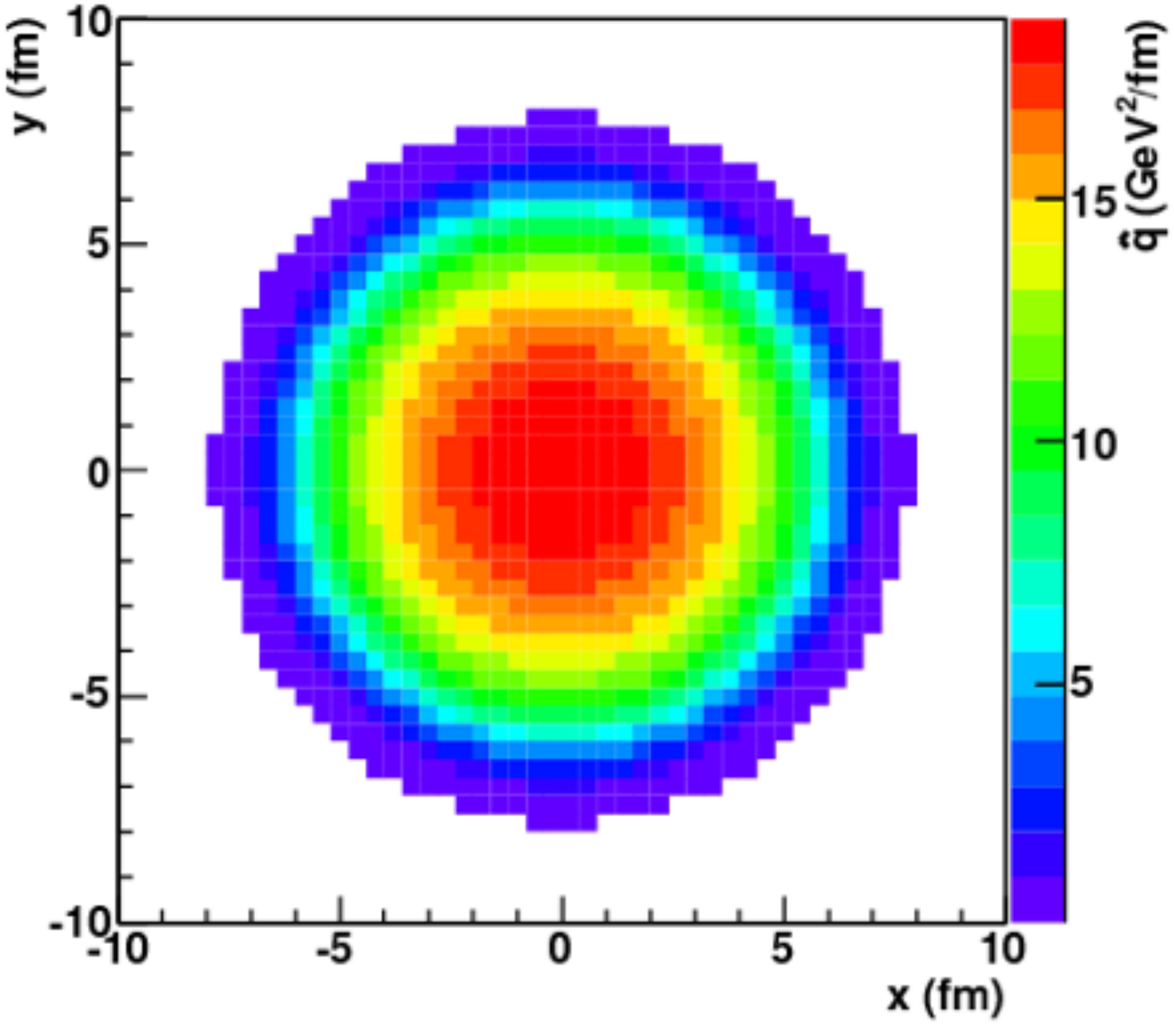
Determine/ constrain from measurements

Use different observables to disentangle effects contributions

Part II: Path length dependence

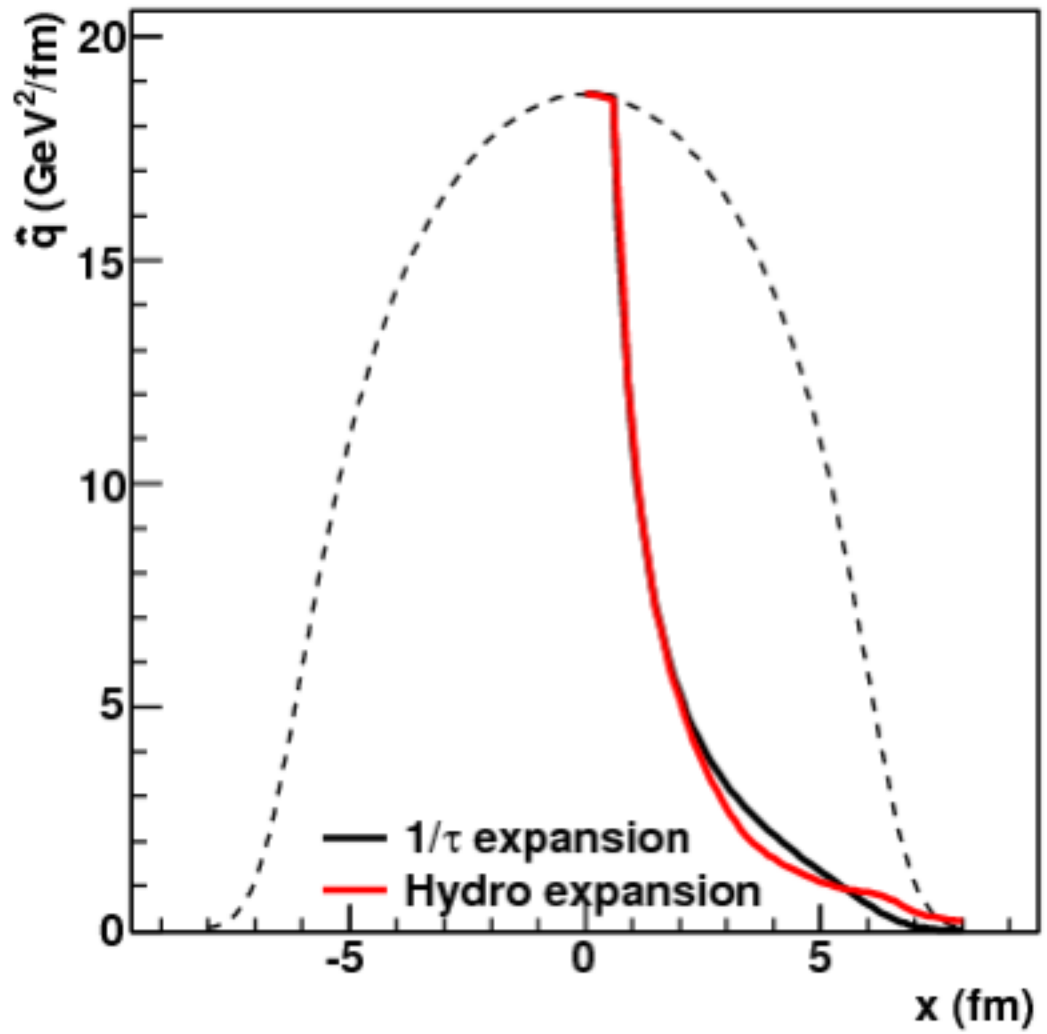
Geometry

Density profile



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

Density along parton path



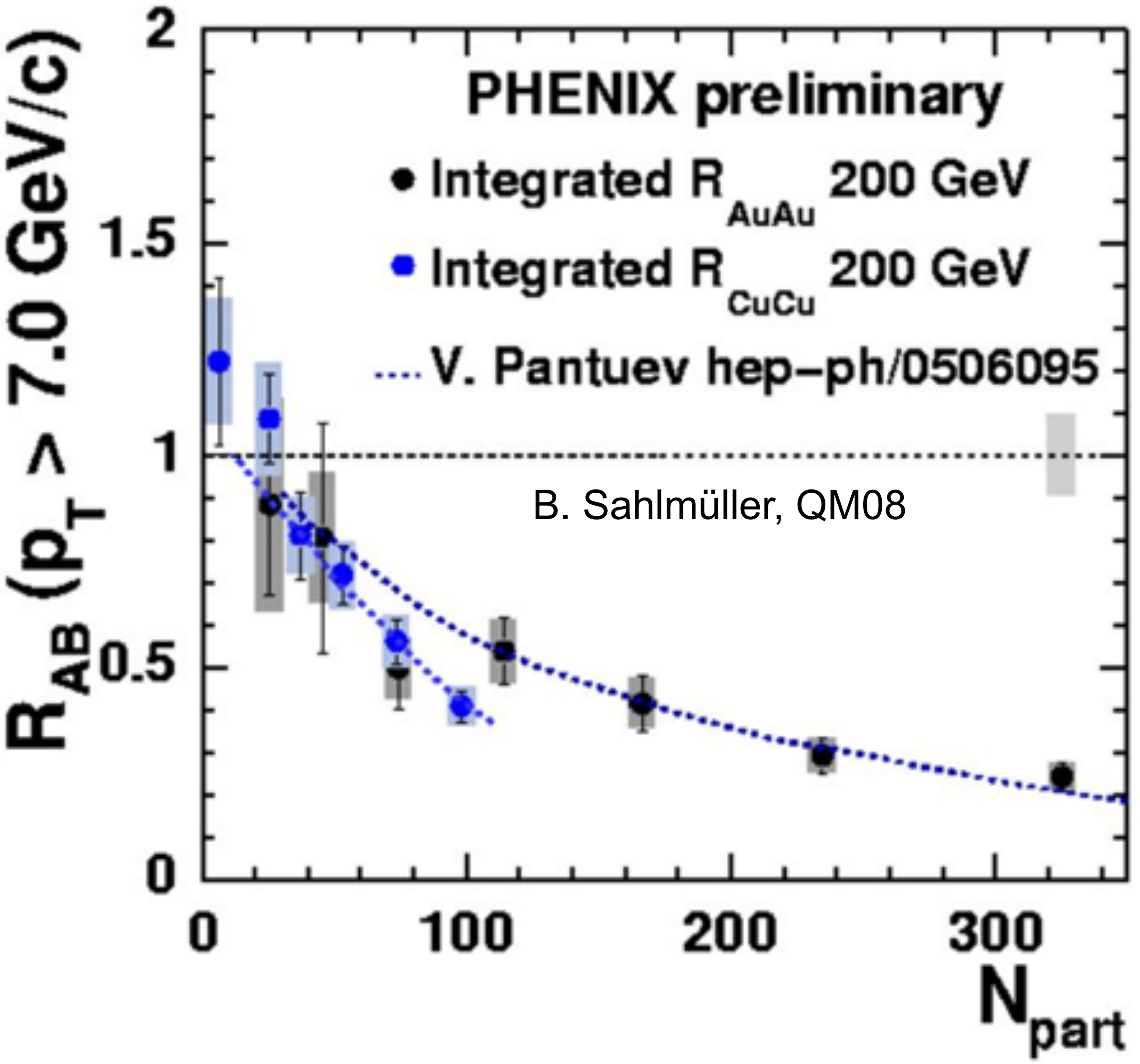
Longitudinal expansion
dilutes medium
⇒ Important effect

Most models take space-time evolution into account

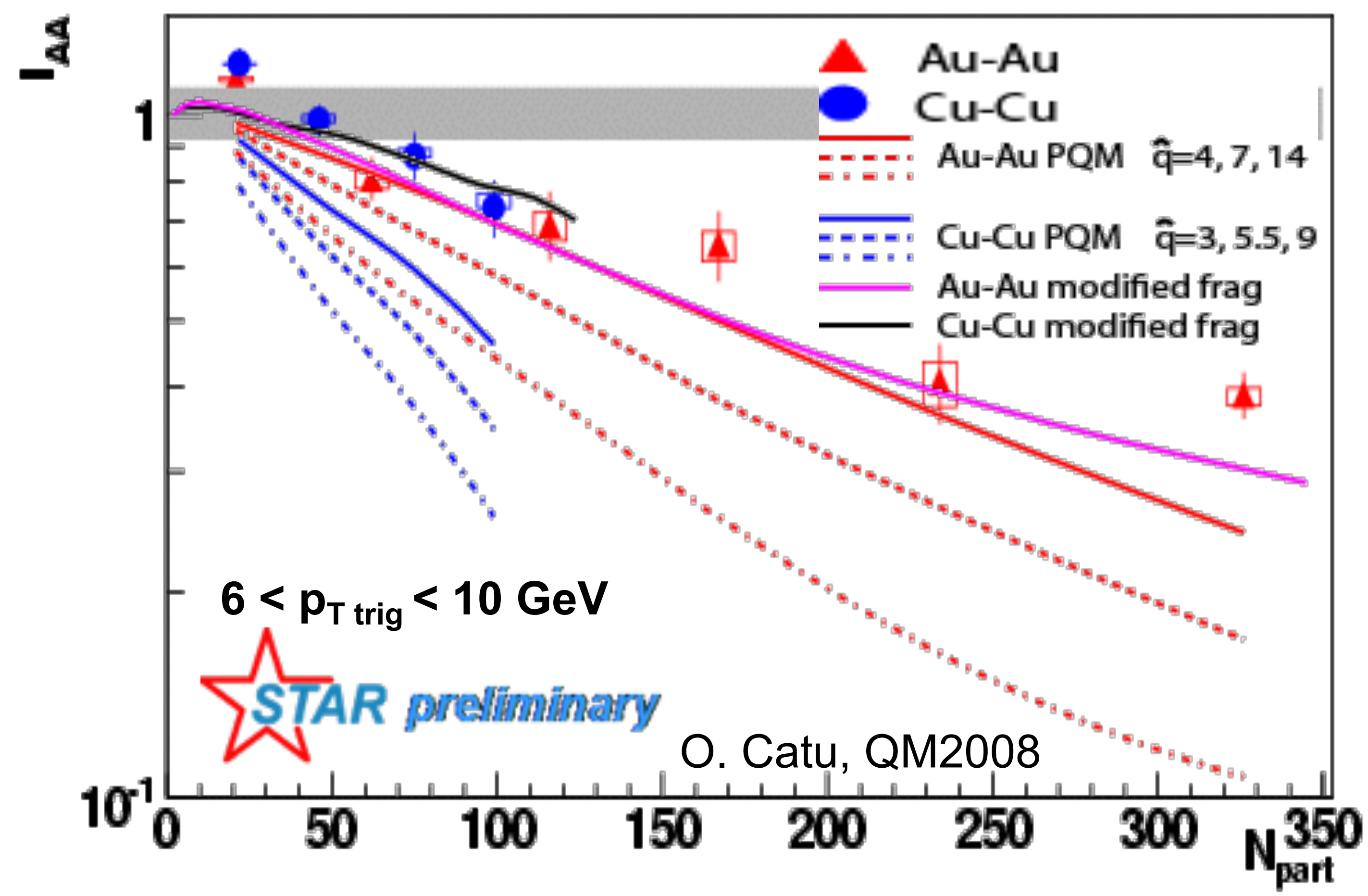
Path length I: centrality dependence

Comparing Cu+Cu and Au+Au

R_{AA}: inclusive suppression



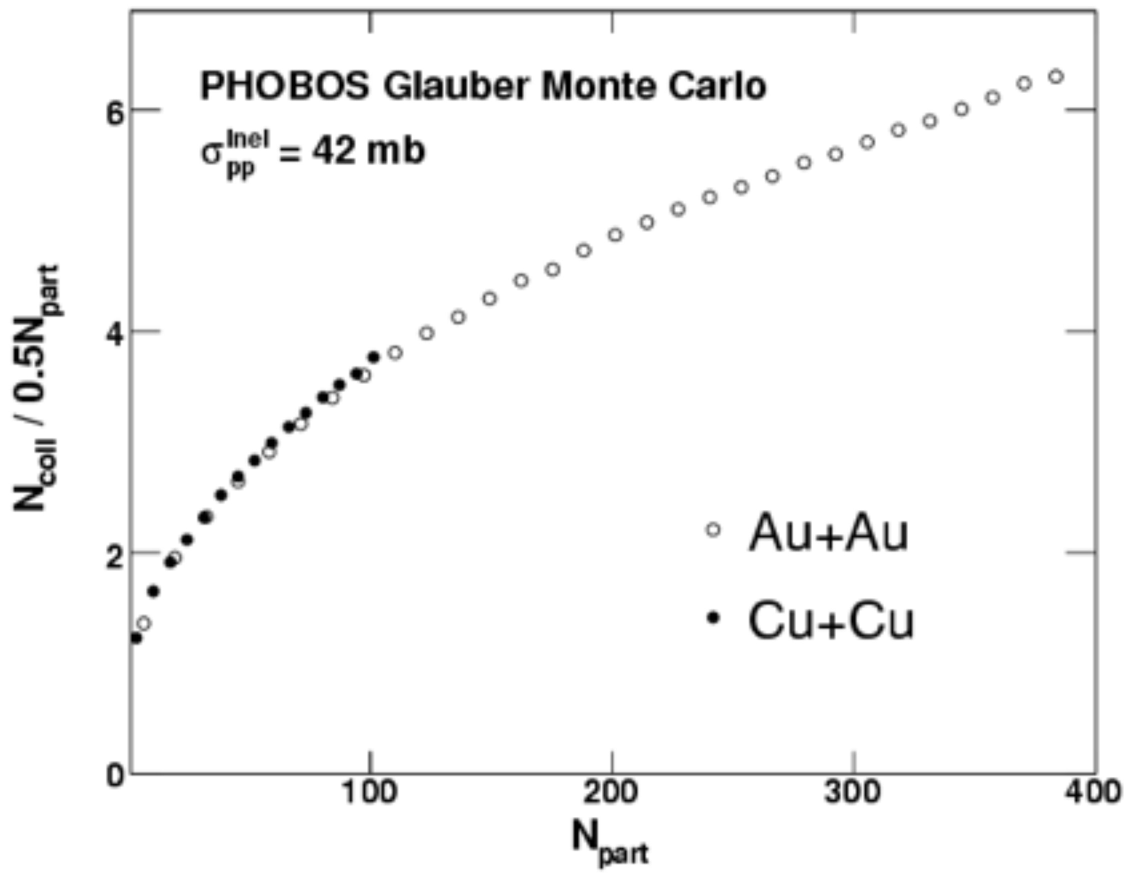
Away-side suppression

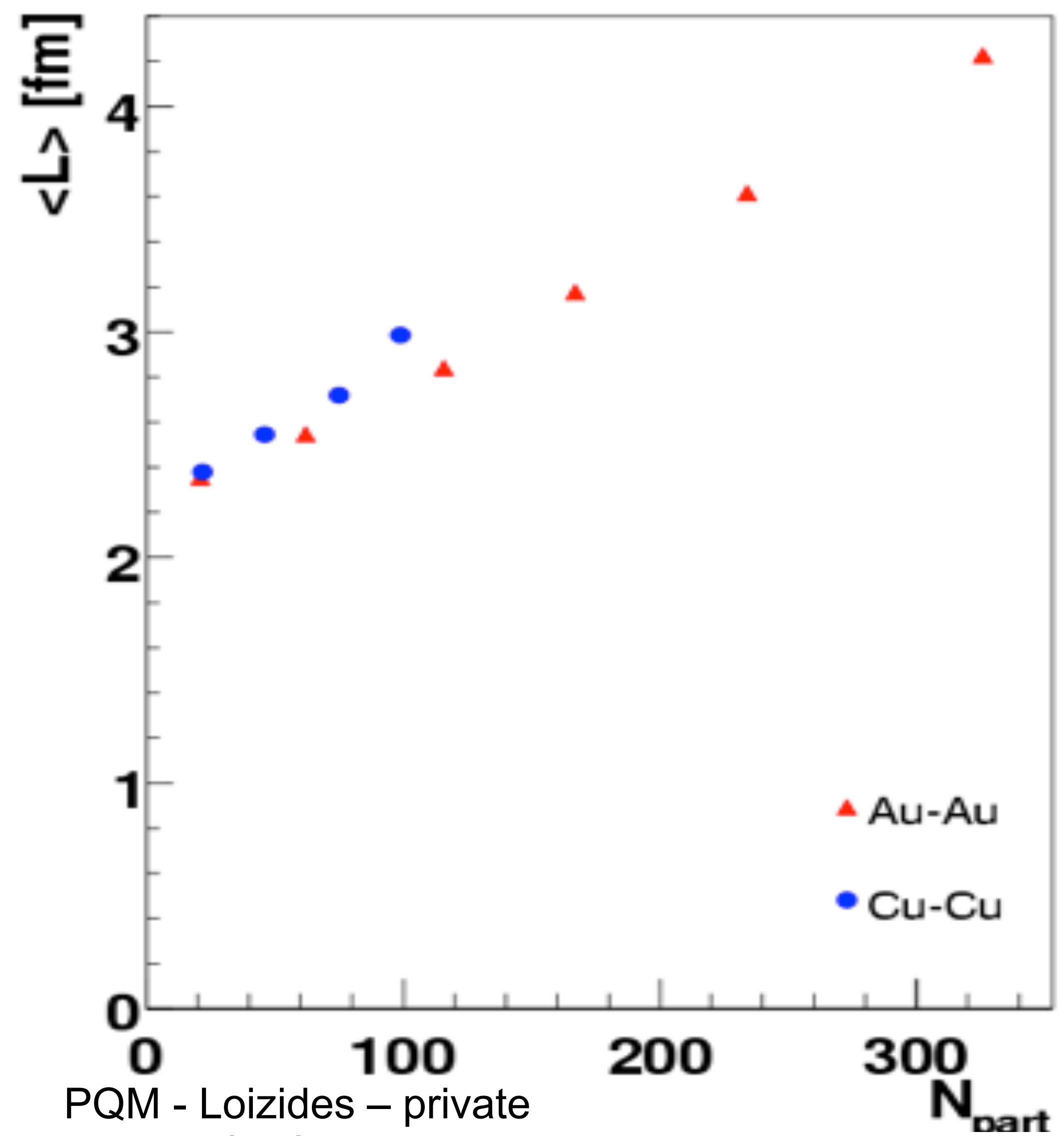


Modified frag: nucl-th/0701045 - H.Zhang, J.F. Owens, E. Wang, X.N. Wang

Inclusive and di-hadron suppression seem to scale with N_{part}

N_{part} scaling?



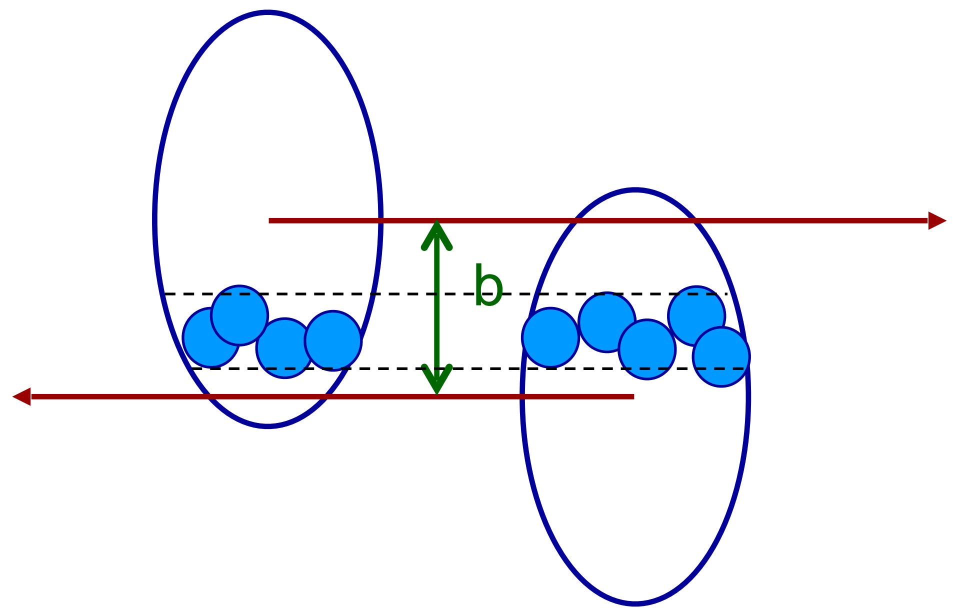


PQM - Loizides – private communication

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

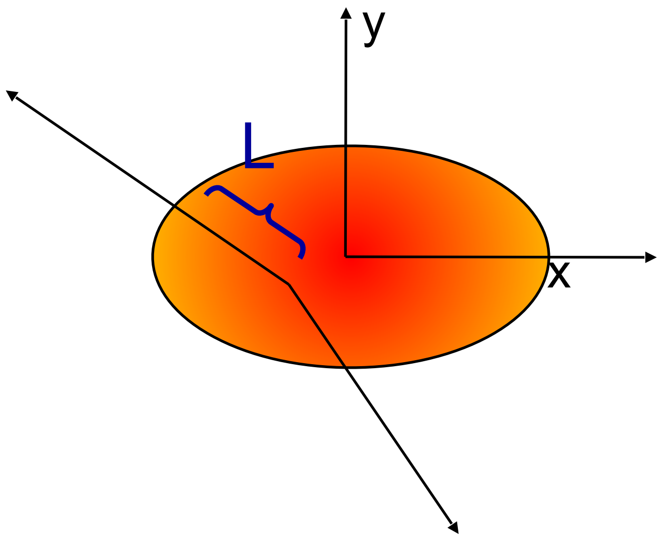
Cannot disentangle density vs path length

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



Non-central collisions: eccentric matter distribution

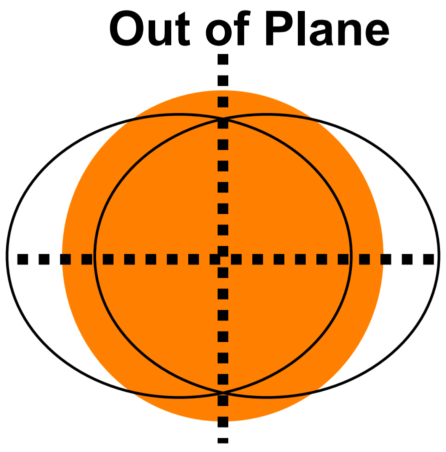
Transverse view



Density profile ρ: ρ_{part} or ρ_{coll}

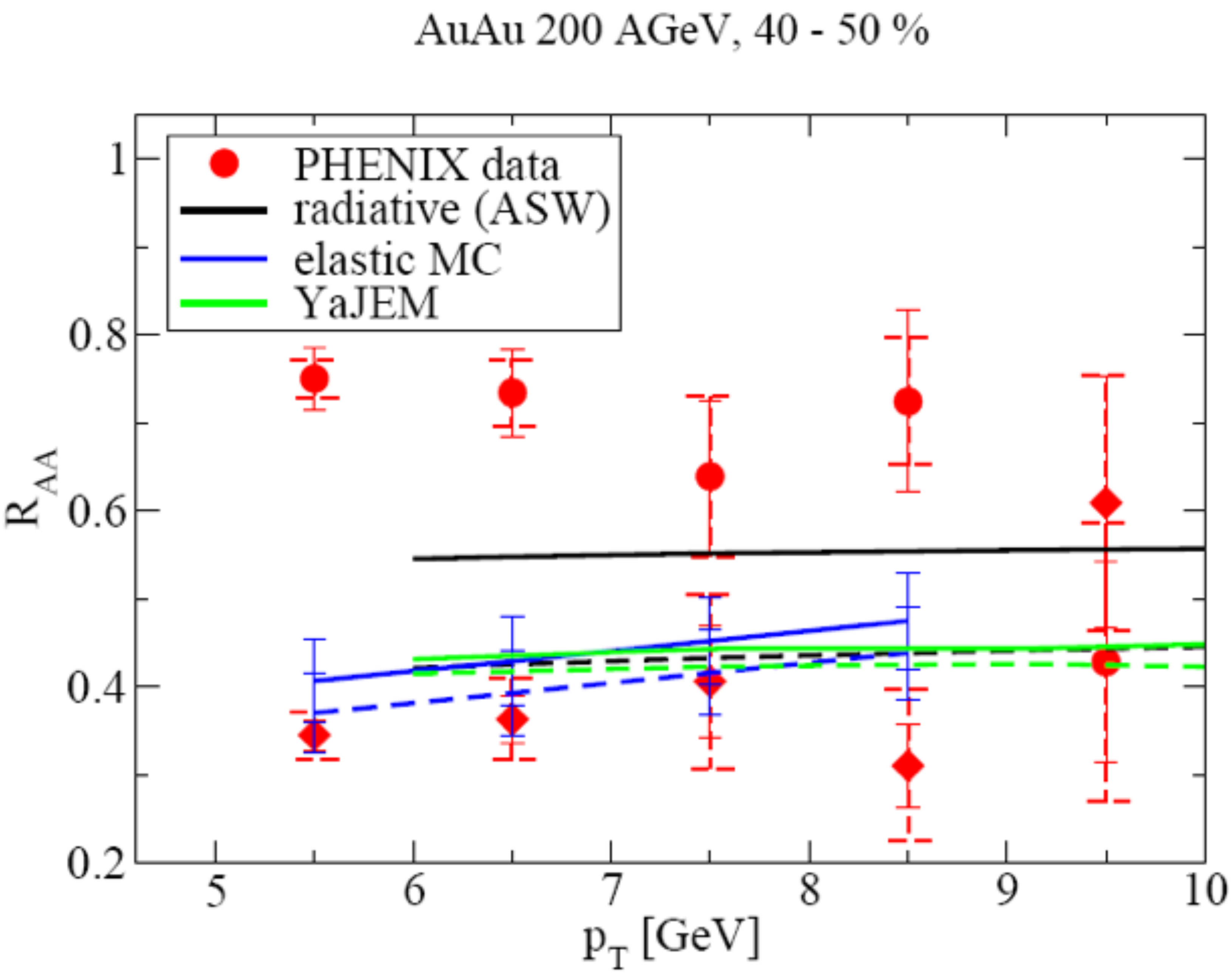
Eccentricity
$$\varepsilon = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

R_{AA} vs φ and elastic eloss



Elastic E-loss gives small v_2

Data require L^2 or stronger path length dependence

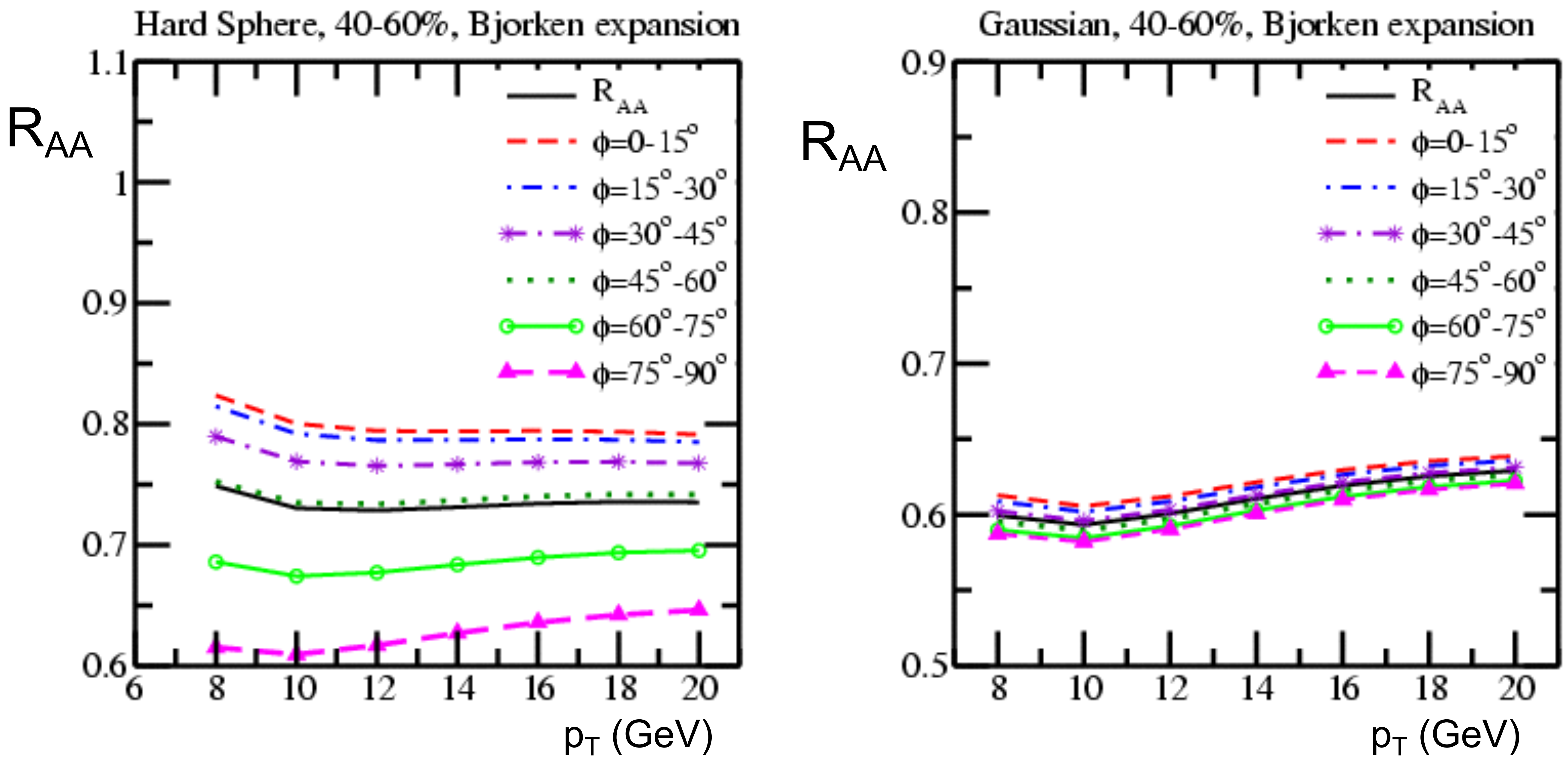


T. Renk, PRC76, 064905, J. Auvinen et al, PRC82, 051901

However, also quite sensitive to medium density evolution

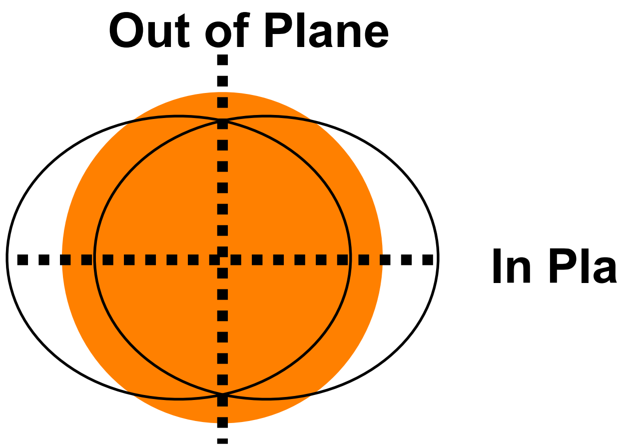
Modelling azimuthal dependence

A. Majumder, PRC75, 021901

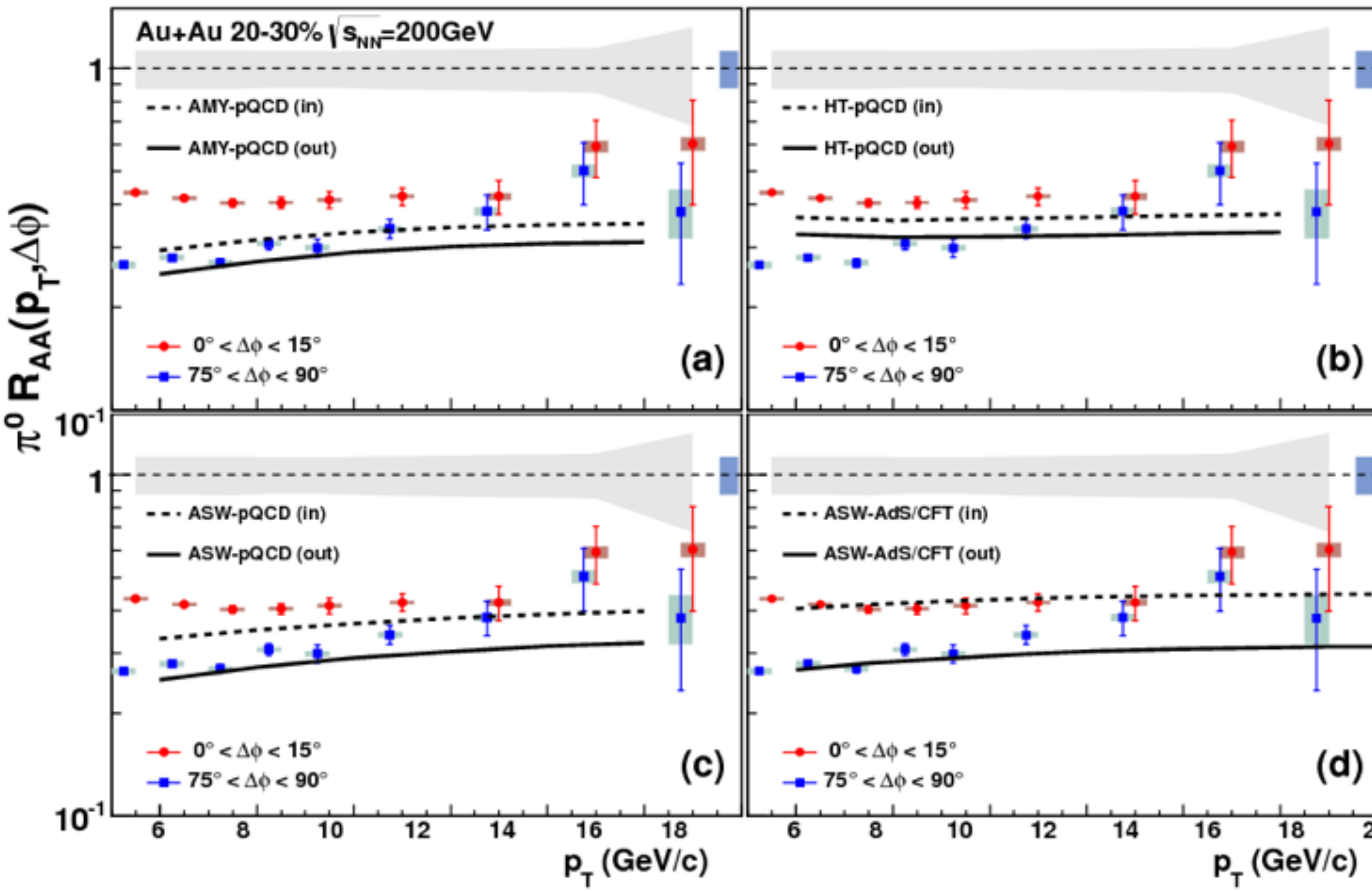


R_{AA} vs reaction plane sensitive to geometry model

Path length dependence: R_{AA} vs φ



PHENIX, arXiv:1208.2254

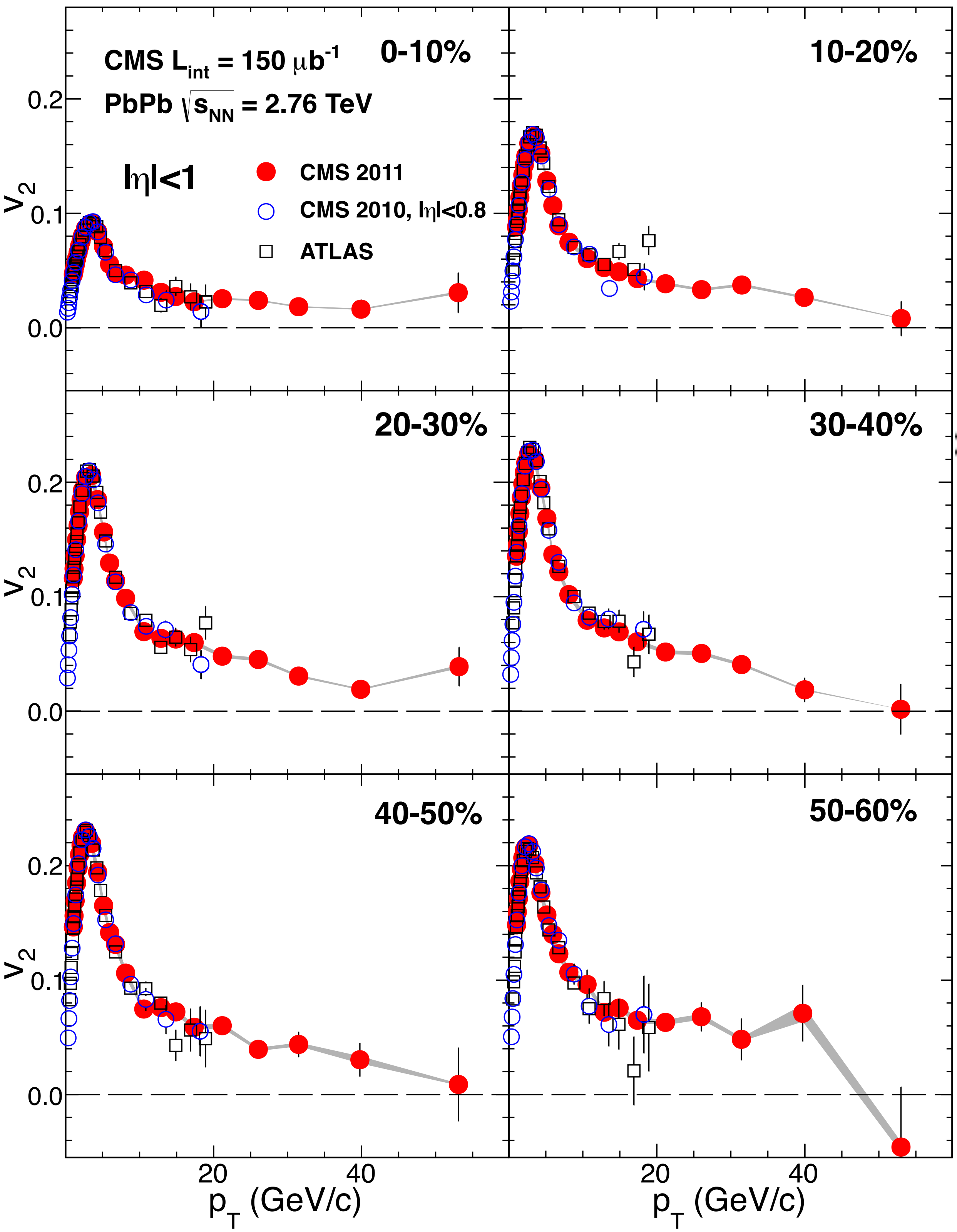


Suppression depends on angle, path length

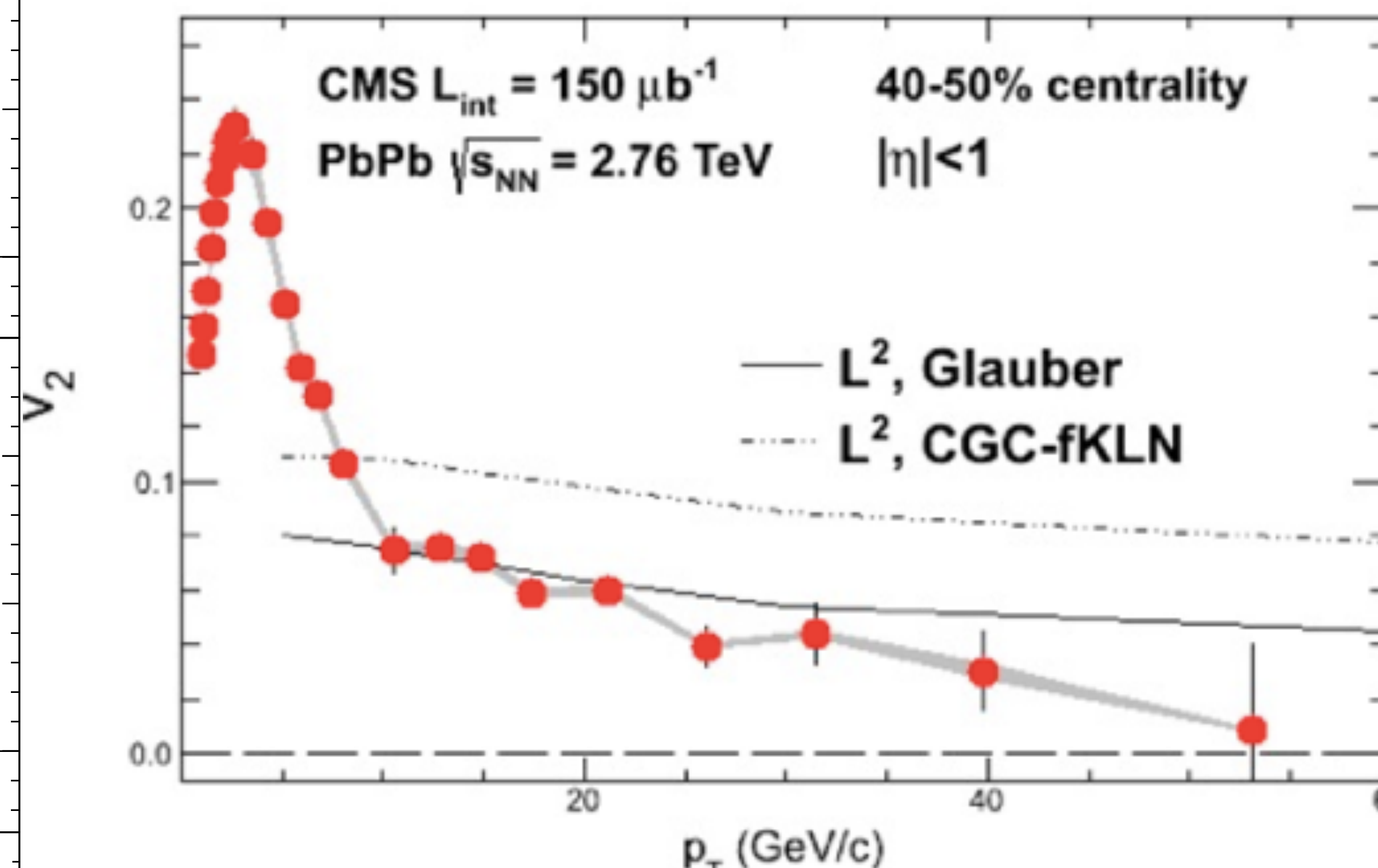
Not so easy to model: calculations give different results

Reaction plane dependence at LHC: High-p_T v_2

CMS, arXiv:1204.1850



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

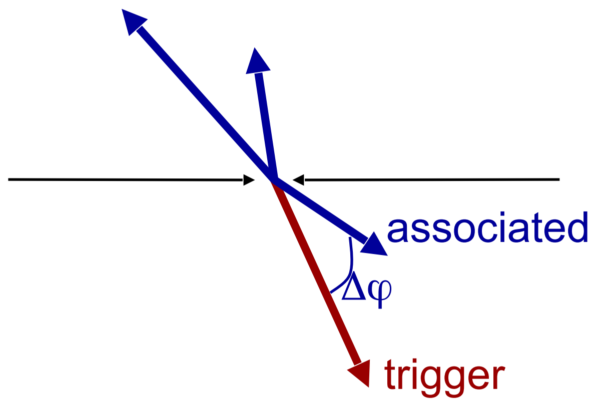


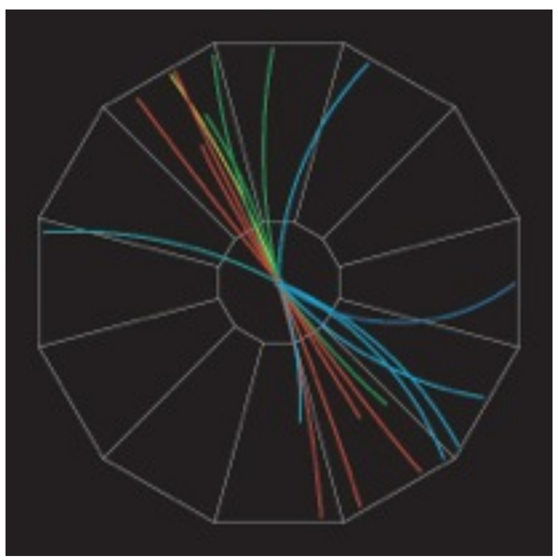
Reasonable agreement between calculation and data for $p_T > 10$ GeV

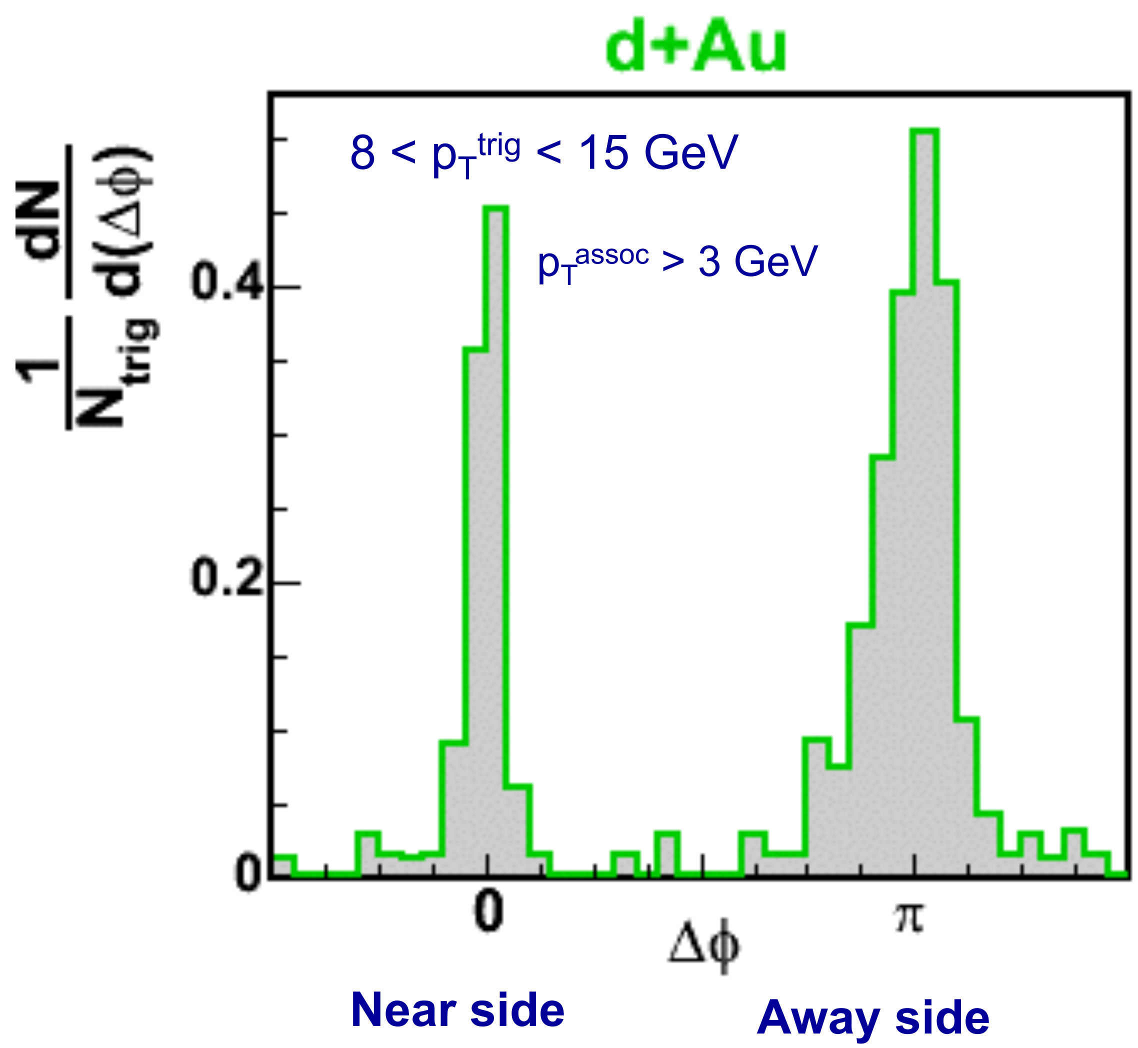
(NB: simplified geometry, E-loss;
paper claims scale-dependence of α_s main effect)

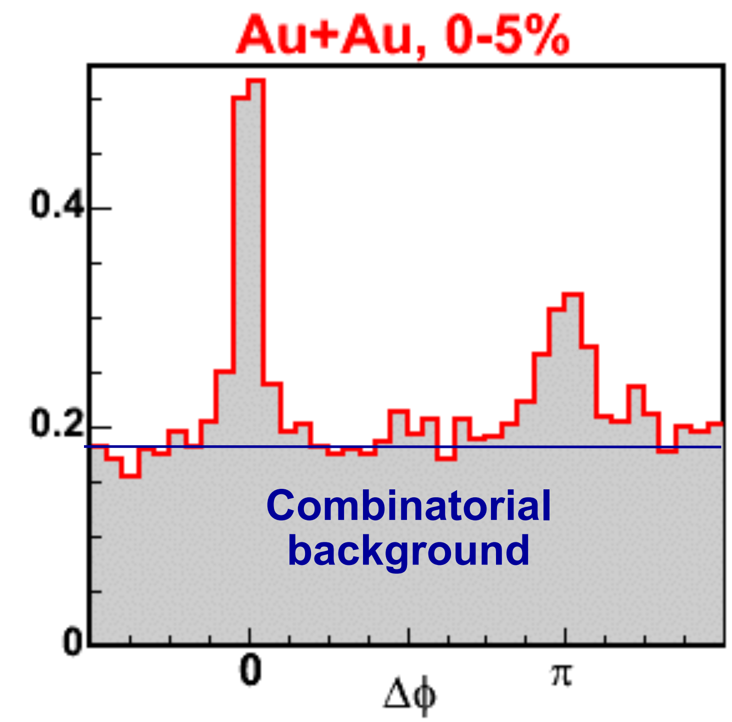
A unexpected angle on path length dependence: di-hadron correlations

Dihadron correlations



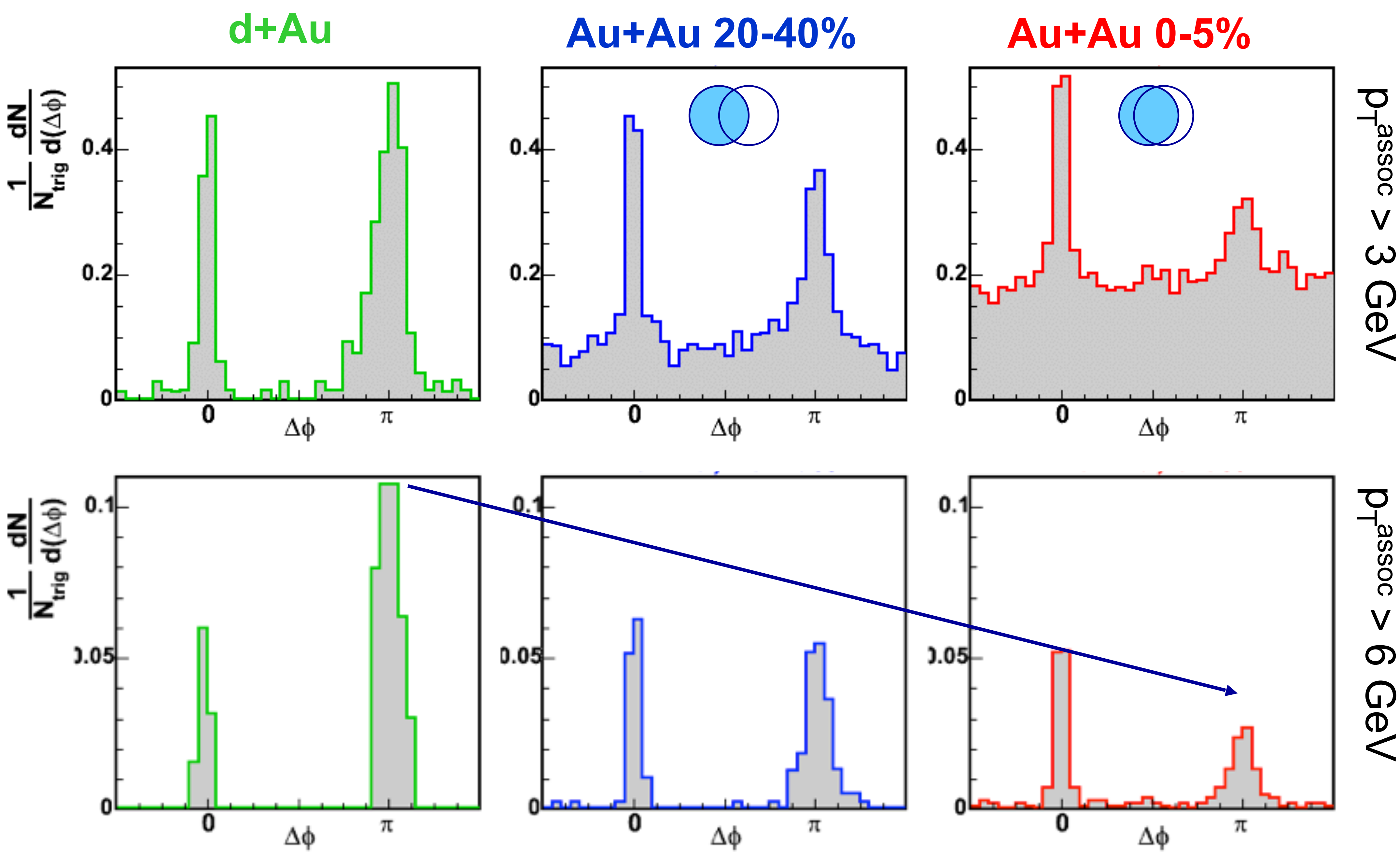






Use di-hadron correlations to probe the jet-structure in p+p, d+Au and Au+Au

Di-hadrons at high-p_T: recoil suppression



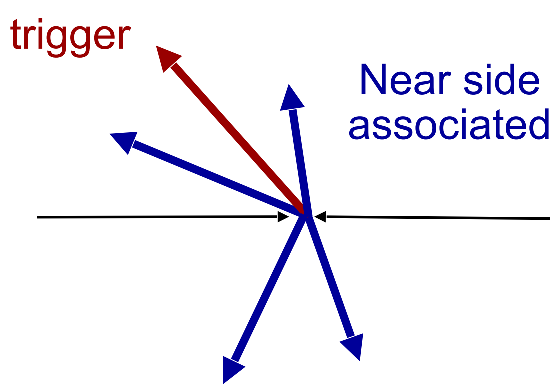
High-p_T hadron production in Au+Au dominated by (di-)jet fragmentation

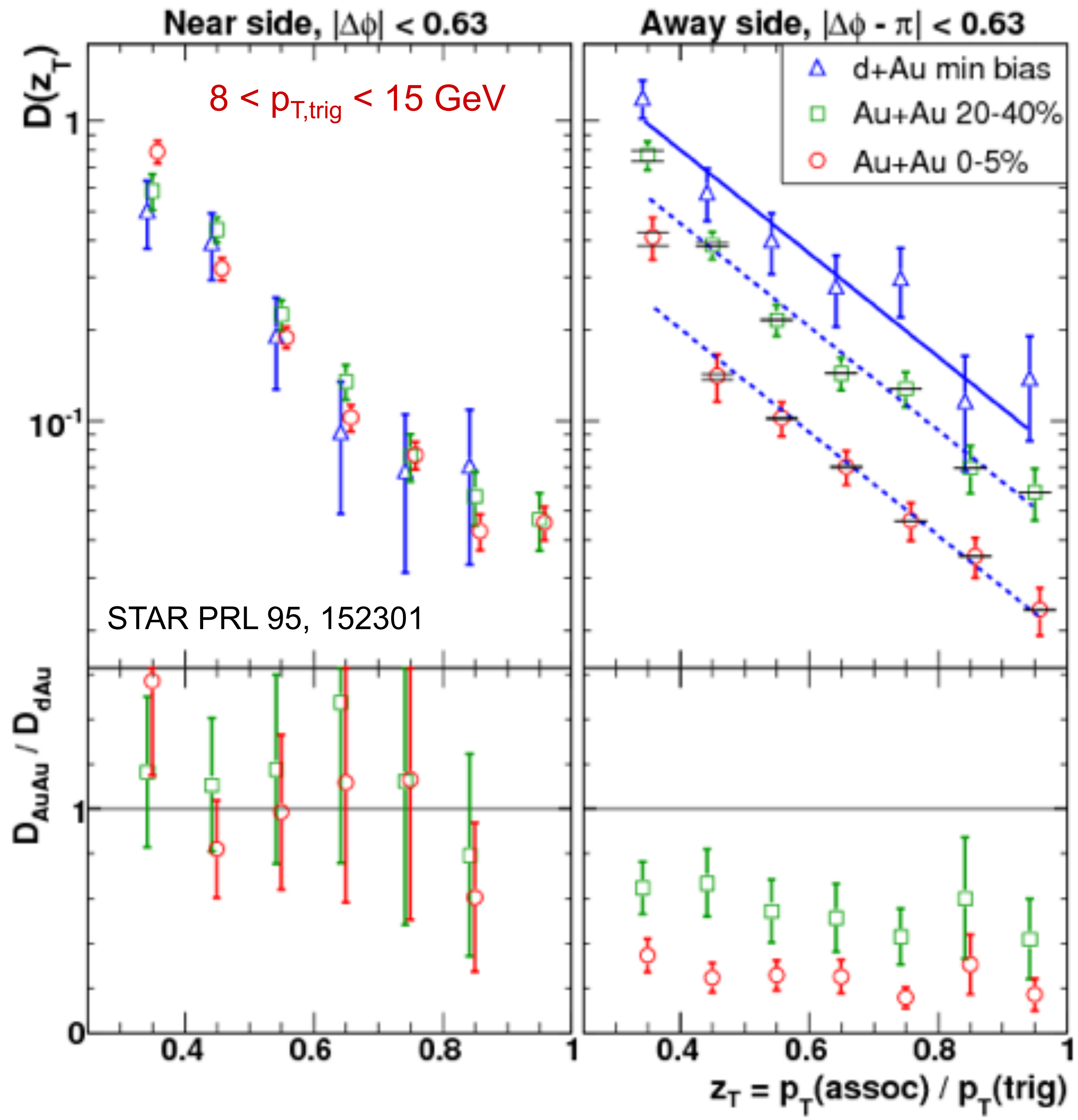
Suppression of away-side yield in Au+Au collisions: energy loss

Dihadron yield suppression

Near side

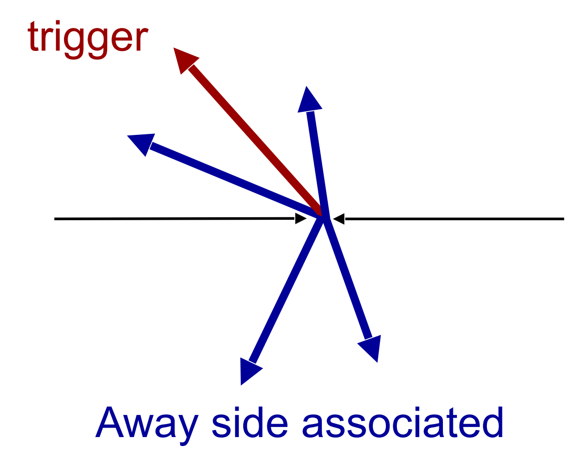
Yield of additional particles in the jet





Away side

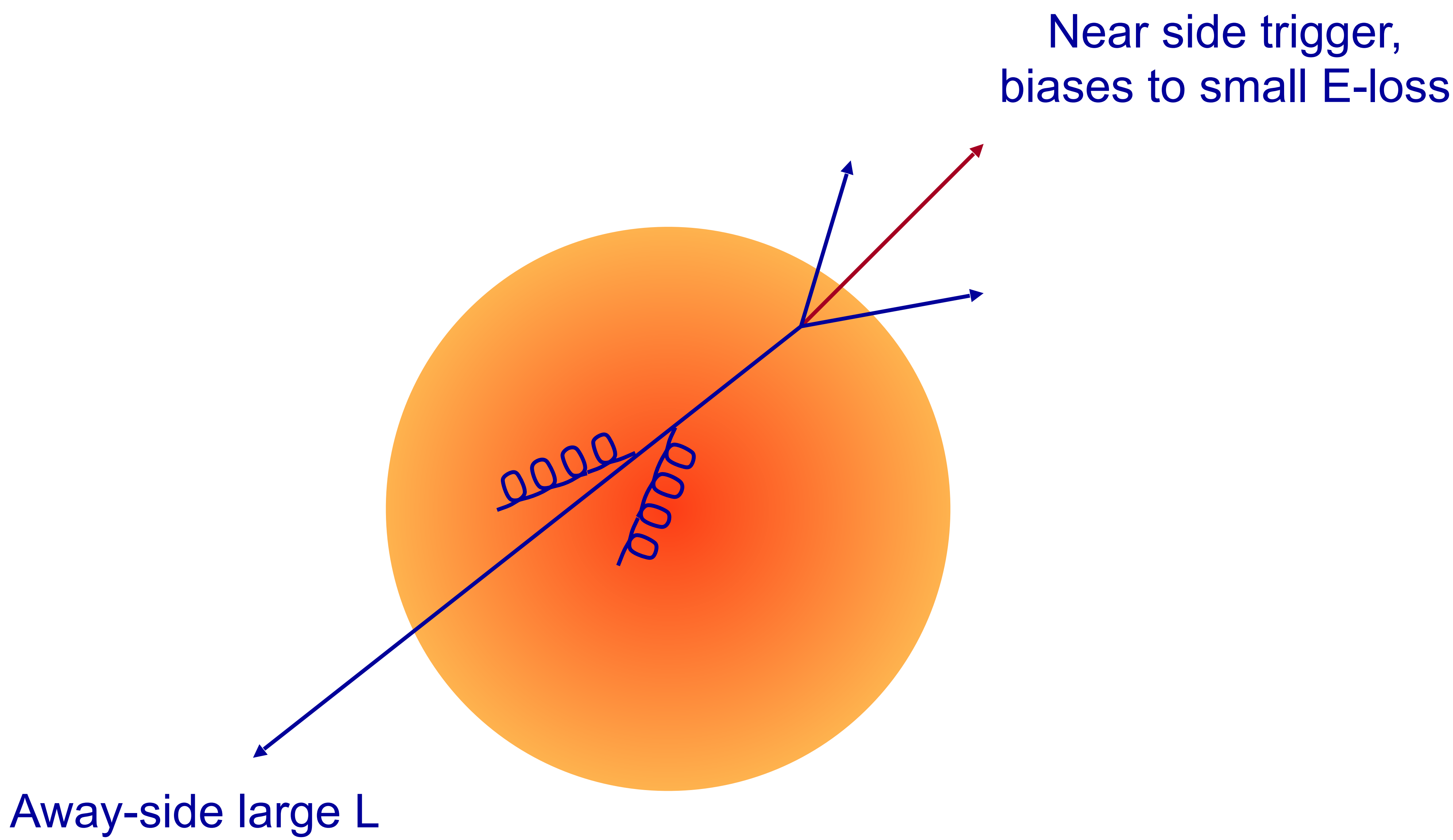
Yield in balancing jet, after energy loss



Near side: No modification
⇒ Fragmentation outside medium?

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

Path length II: 'surface bias'

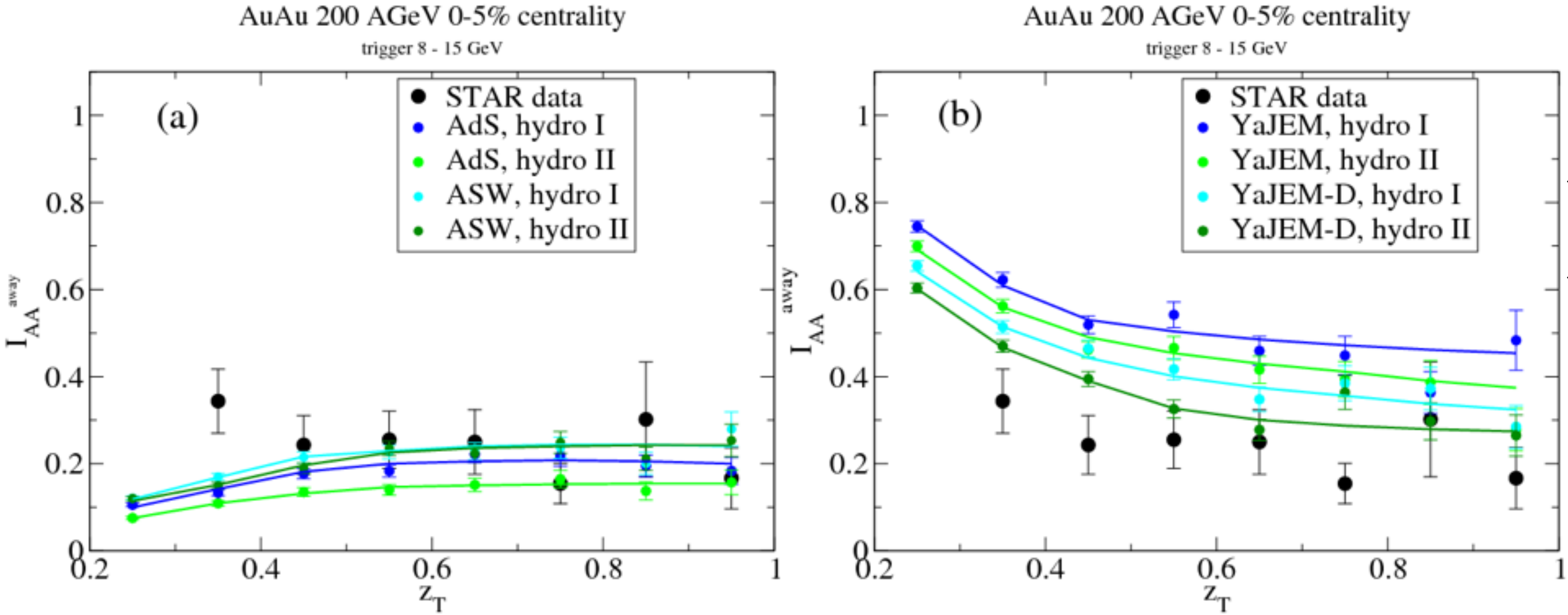


Away-side (recoil) suppression I_{AA} samples longer path-lengths than inclusives R_{AA}

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

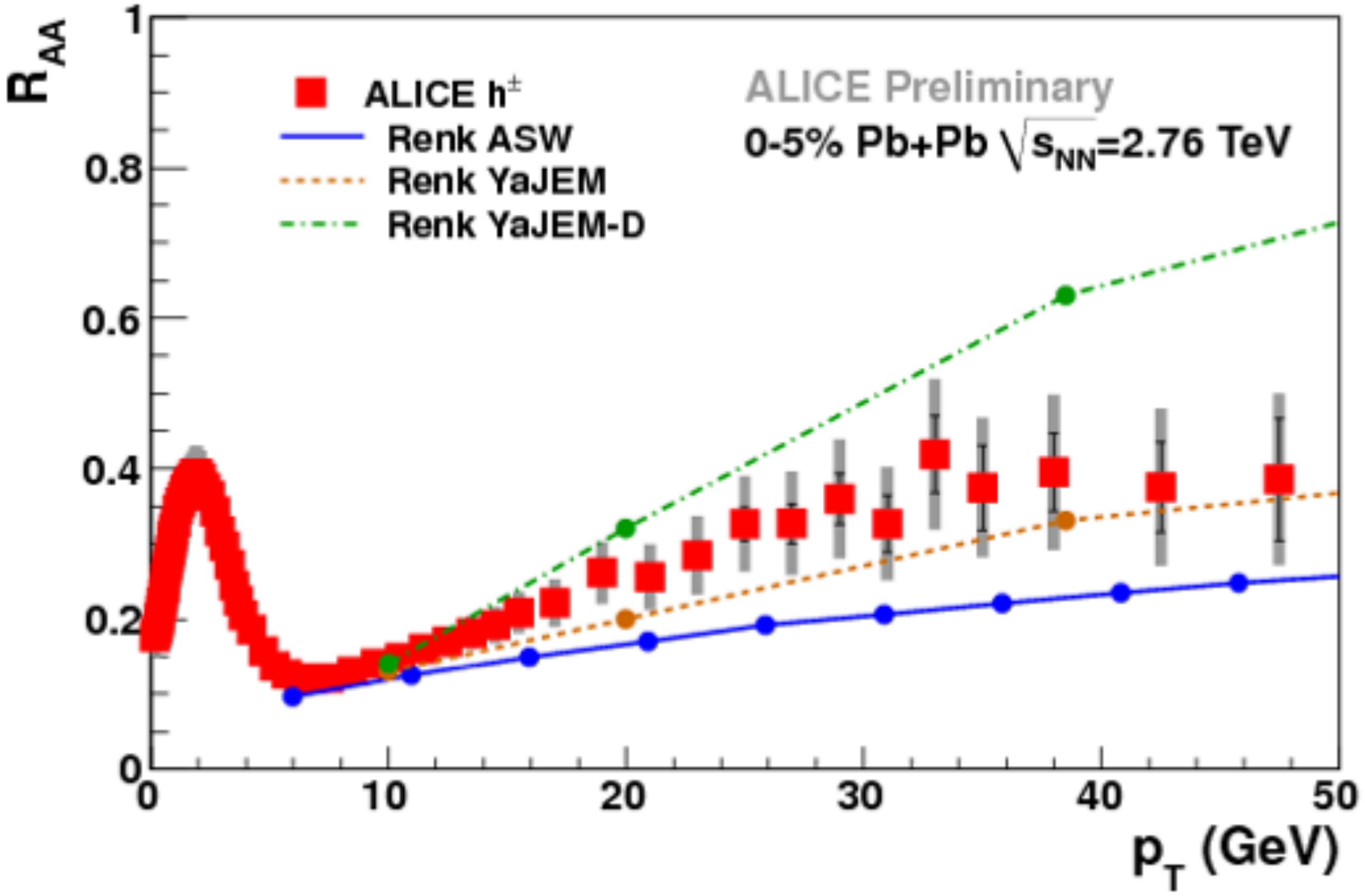
L (YaJEM): too little suppresion
L^2 (YaJEM-D) slightly above

Modified shower
generates increase at low z_T

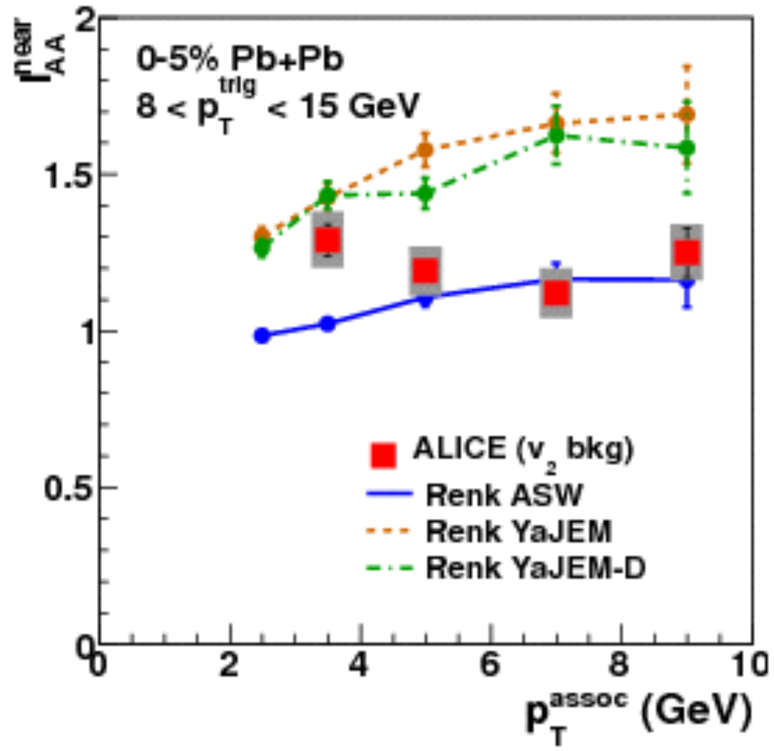
Di-hadrons and single hadrons at LHC

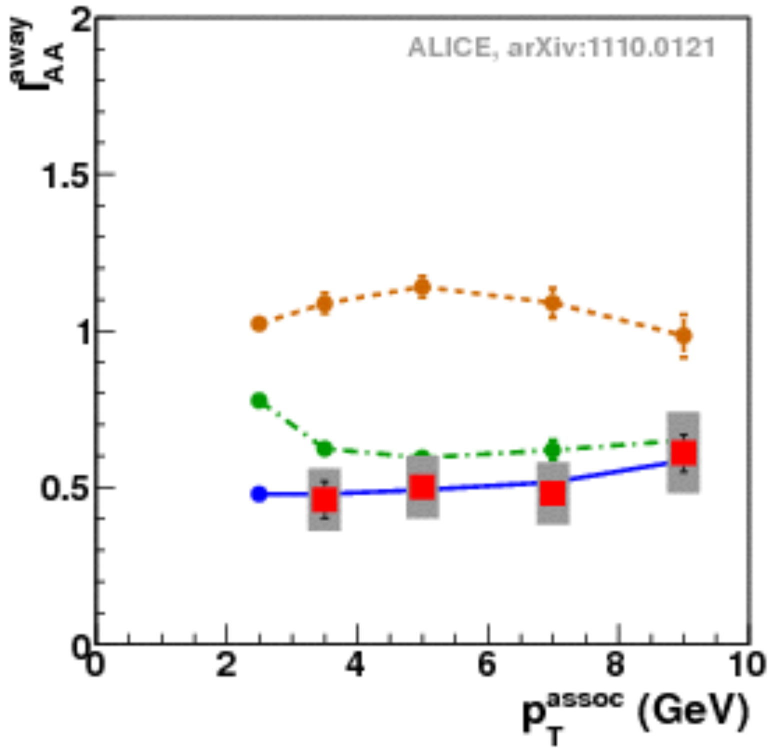
Need simultaneous comparison to several measurements to constrain geometry and E-loss

Here: R_{AA} and I_{AA}



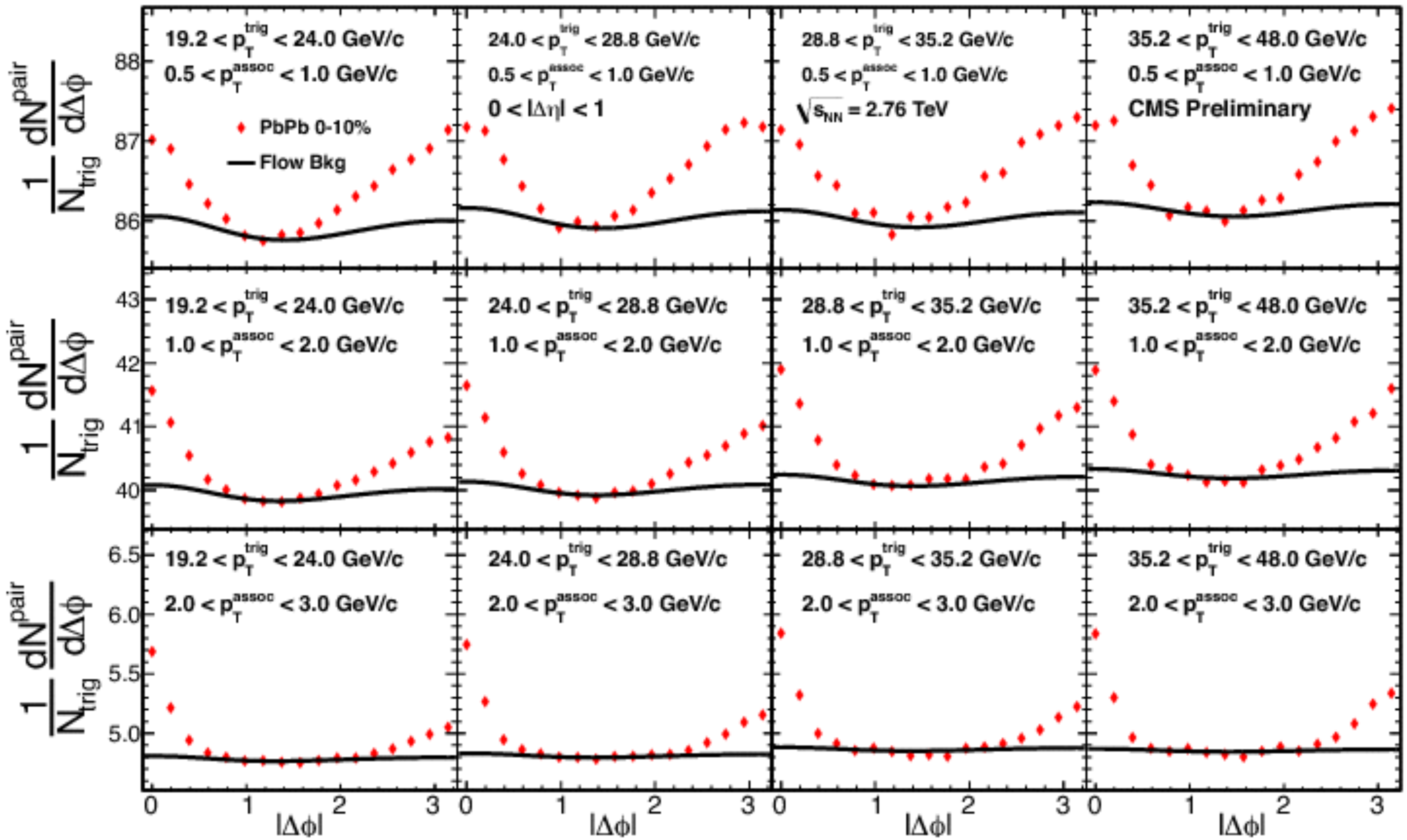
Three models:
ASW: radiative energy loss
YaJEM: medium-induced virtuality
YaJEM-D: YaJEM with L-dependent virtuality cut-off (induces L^2)





Di-hadron with high-p_T trigger

p_T^{trig} (GeV): 19.2 - 24.0 GeV 14.0 - 28.8 GeV 28.8-35.2 GeV 35.2-48.0 GeV



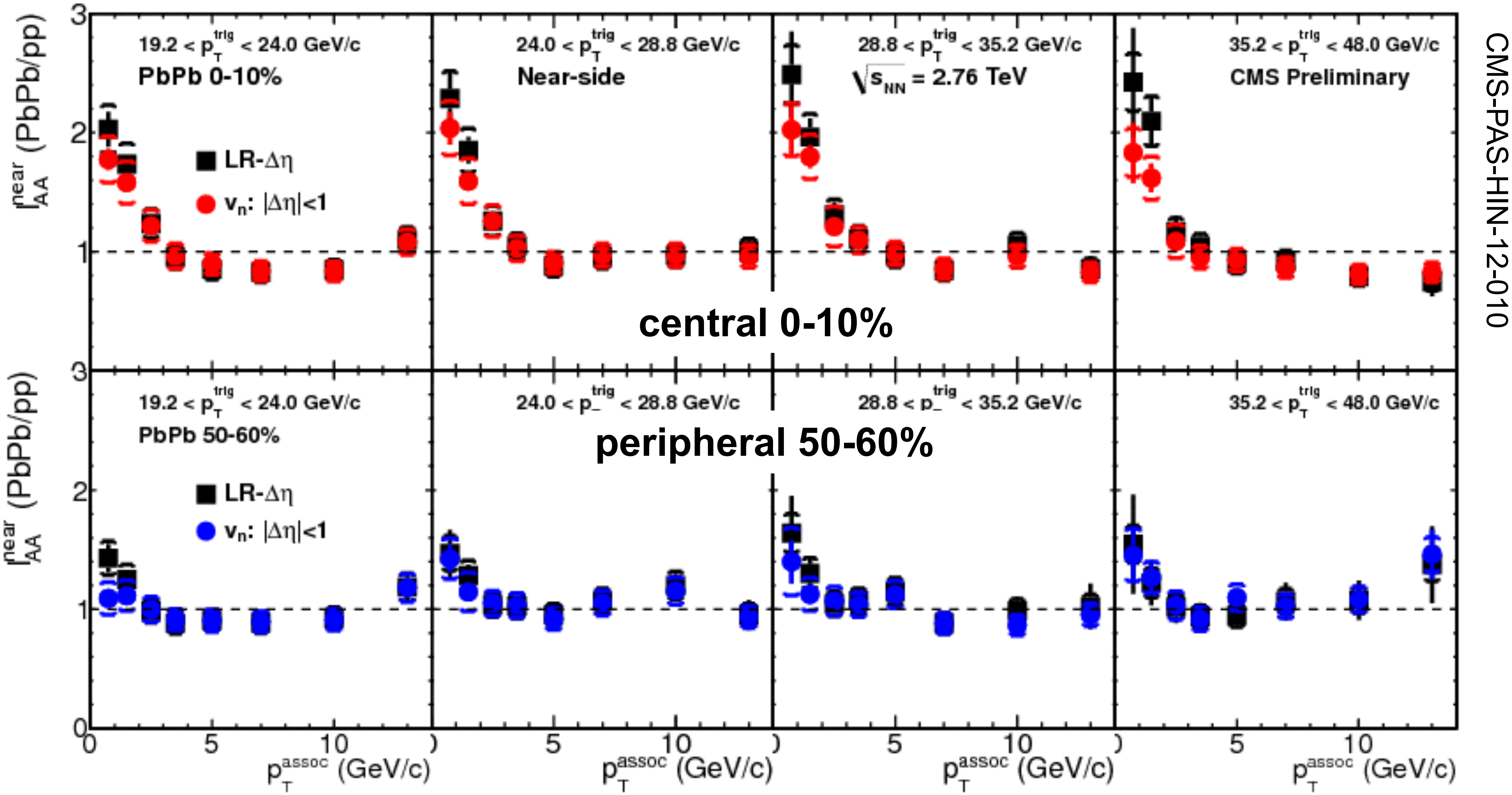
p_t^{trig} > 20 GeV at LHC: strong signals even at low p_T^{assoc} 1-3 GeV

CMS-PAS-HIN-12-010

CMS di-hadrons: near side

p_T^{trig} (GeV):

19.2 - 24.0 GeV | 14.0 - 28.8 GeV | 28.8-35.2 GeV | 35.2-48.0 GeV



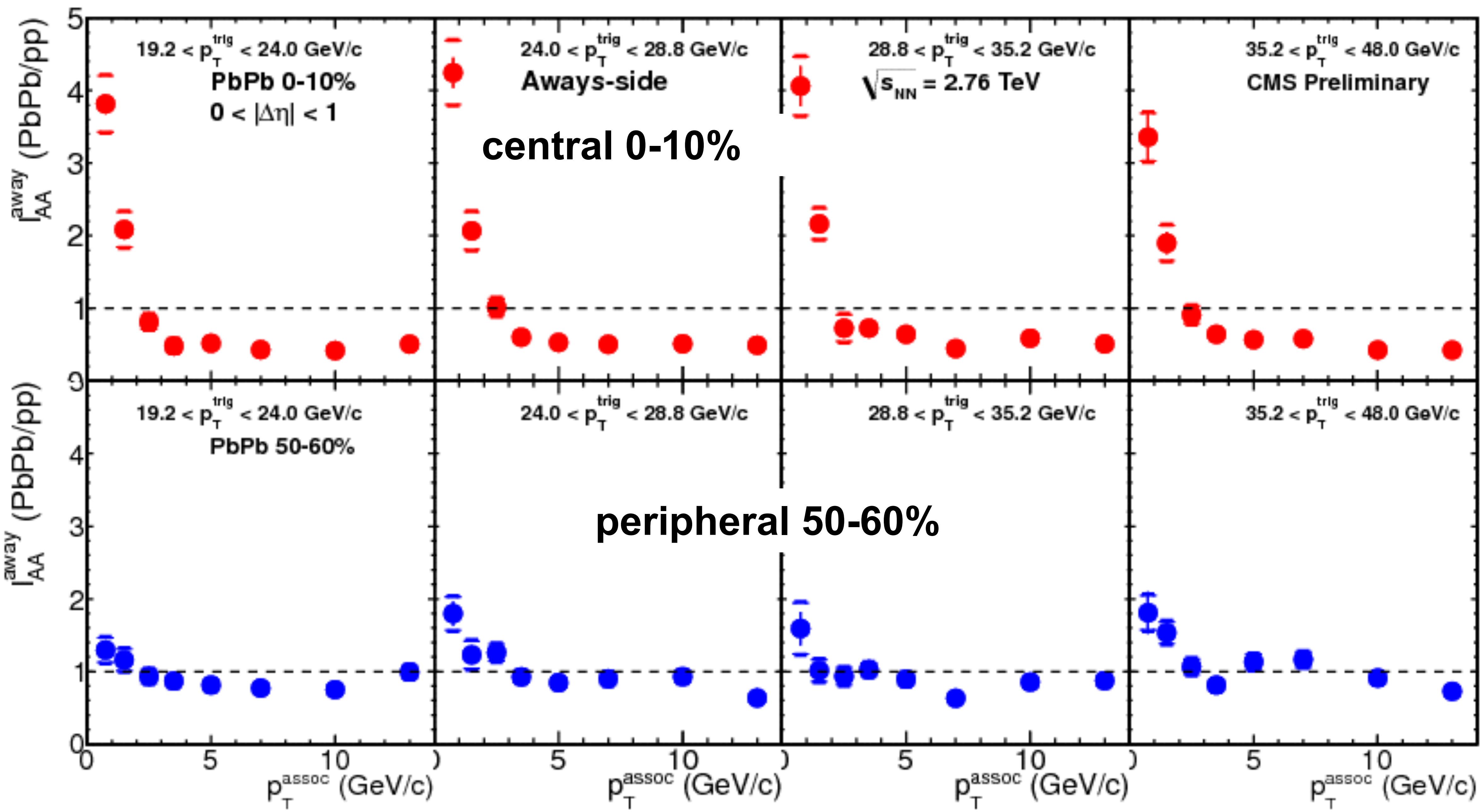
Transition enhancement → suppression @ p_T ~ 3 GeV

also compatible with I_{AA}=1 at p_T > 3 GeV?

CMS di-hadrons: away side

p_T^{trig} (GeV):

19.2 - 24.0 GeV   14.0 - 28.8 GeV   28.8-35.2 GeV   35.2-48.0 GeV



CMS-PAS-HIN-12-010

Transition enhancement → suppression @ p_T ~ 2 GeV

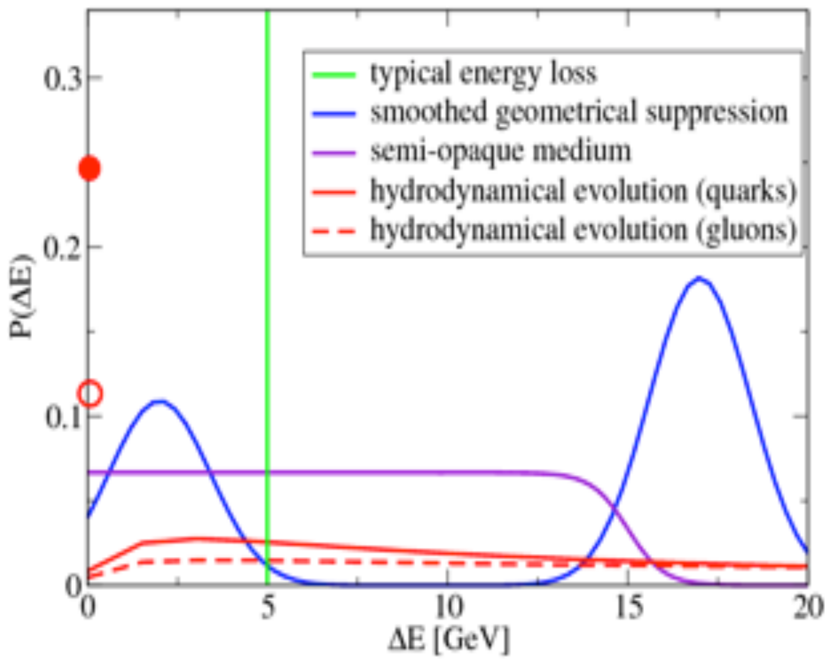
Summary R_{AA}, I_{AA}

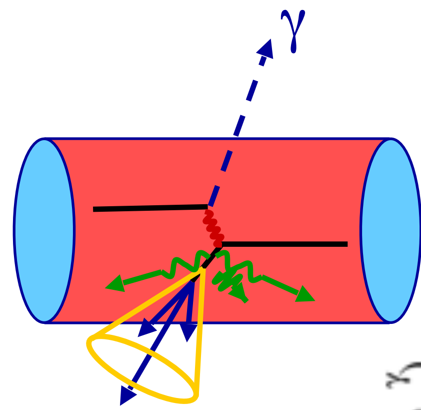
- Energy loss is a large effect: fractional loss ~0.2-0.3, several GeV
- For radiative energy loss: momentum exchange with medium ~ several GeV
- Quantitative relation between medium density and energy loss not (yet) available
- Path length dependence: L^2 strongly favoured by comparing inclusive and recoil data

Fixing the parton energy with γ-jet events

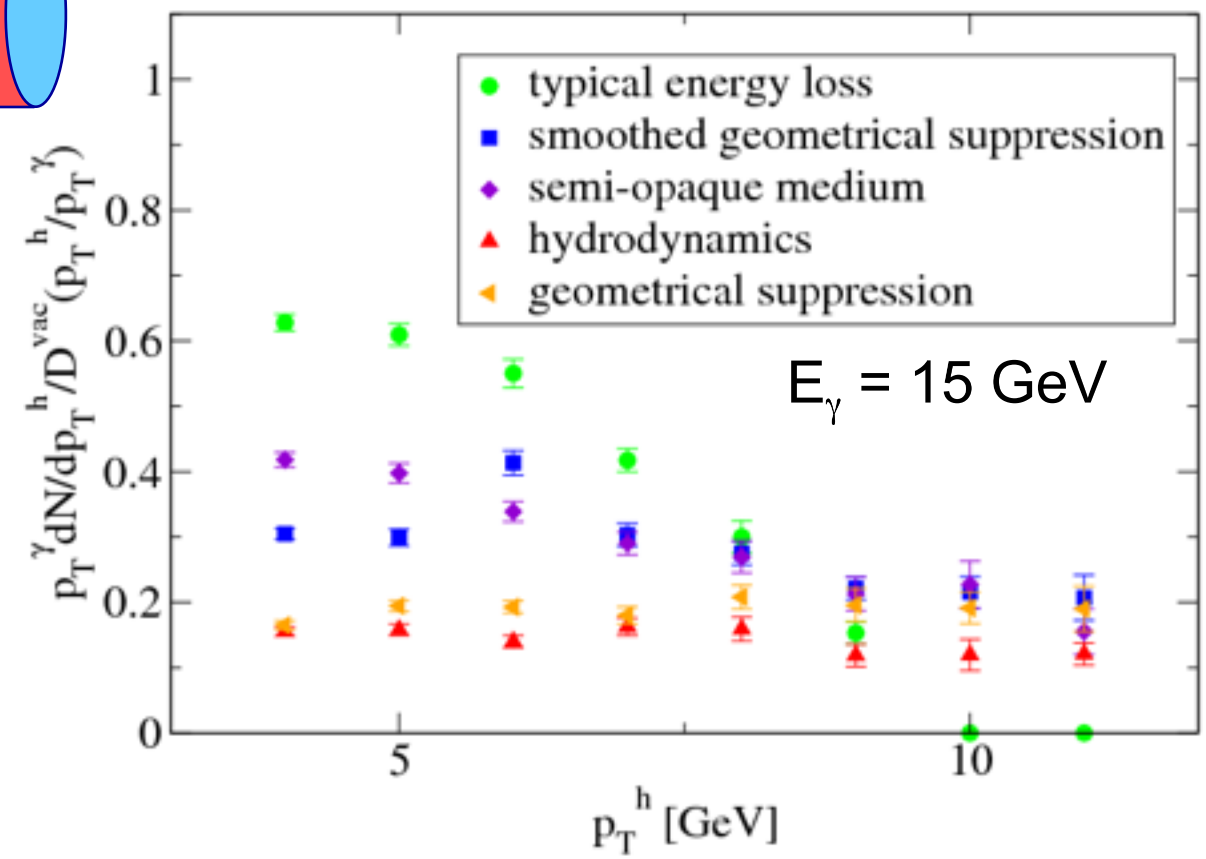
T. Renk, PRC74, 034906

Input energy loss distribution



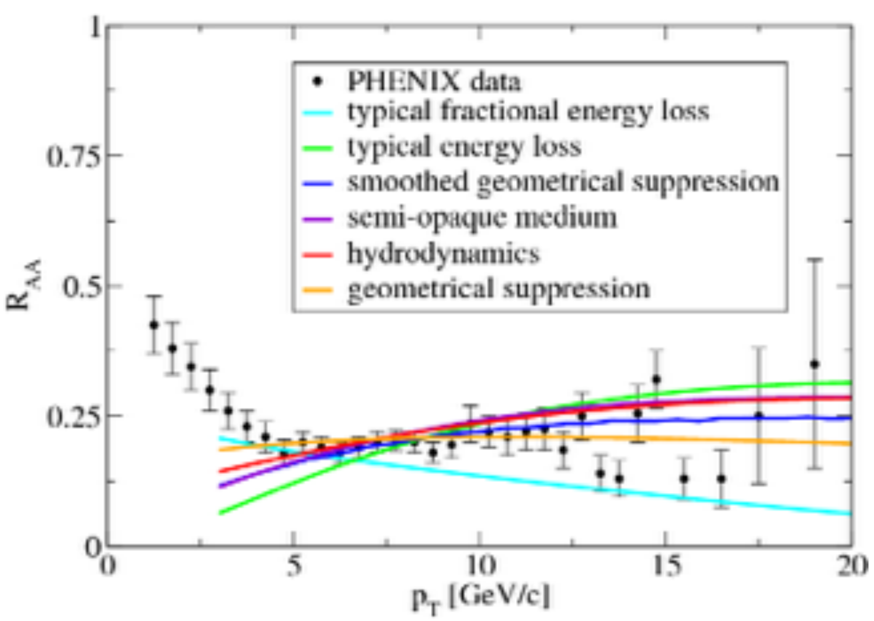


Away-side spectra in γ-jet



Away-side spectra for γ-jet are sensitive to P(ΔE)

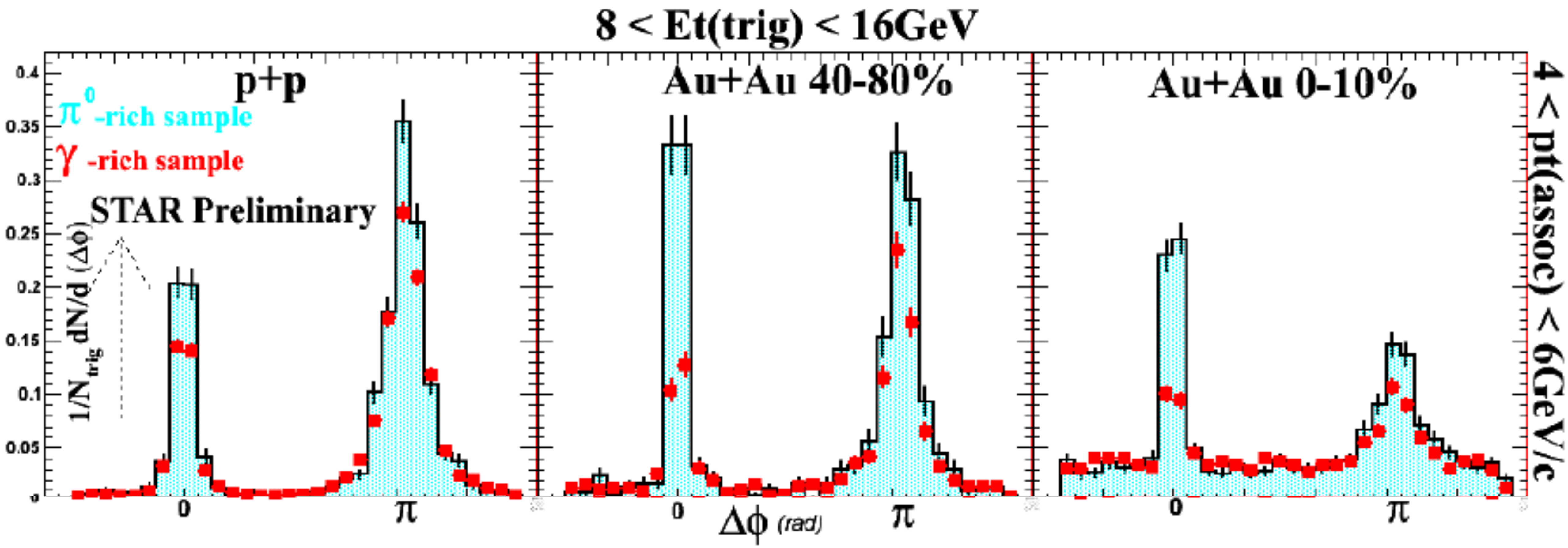
Nuclear modification factor



R_{AA} insensitive to P(ΔE)

γ-jet: know jet energy ⇒ sensitive to P(ΔE)

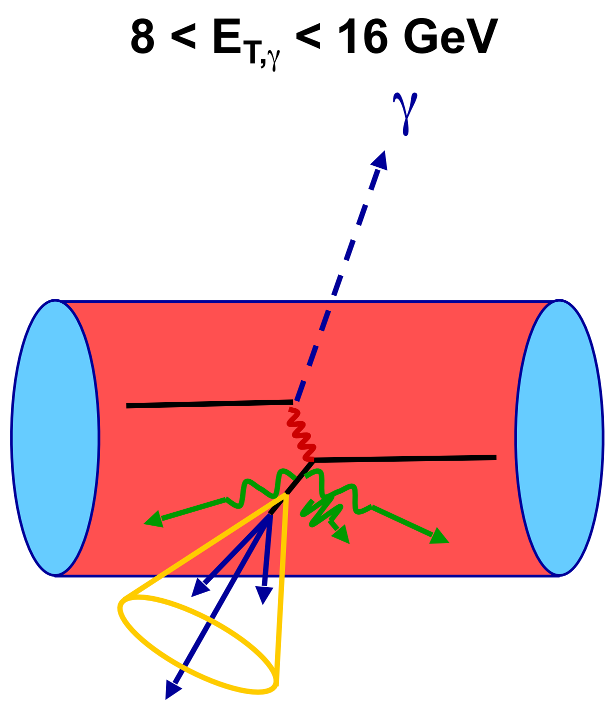
γ-jet in Au+Au

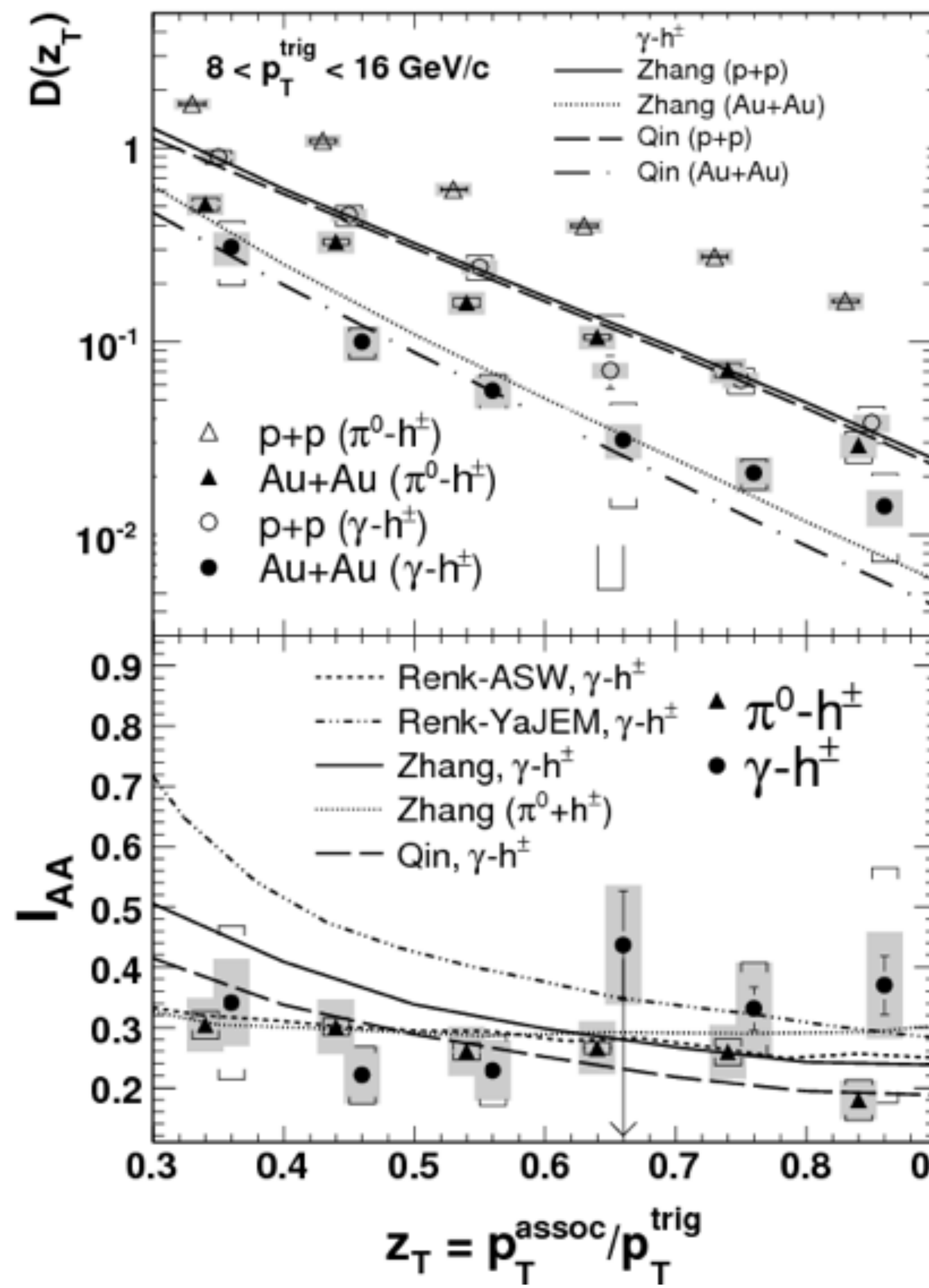


Use shower shape in EMCal to form π^0 sample and γ-rich sample

Combinatorial subtraction to obtain direct-γ sample

Direct-γ recoil suppression





STAR, arXiv:0912.1871

$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$

Large suppression for away-side: factor 3-5

Reasonable agreement with model predictions

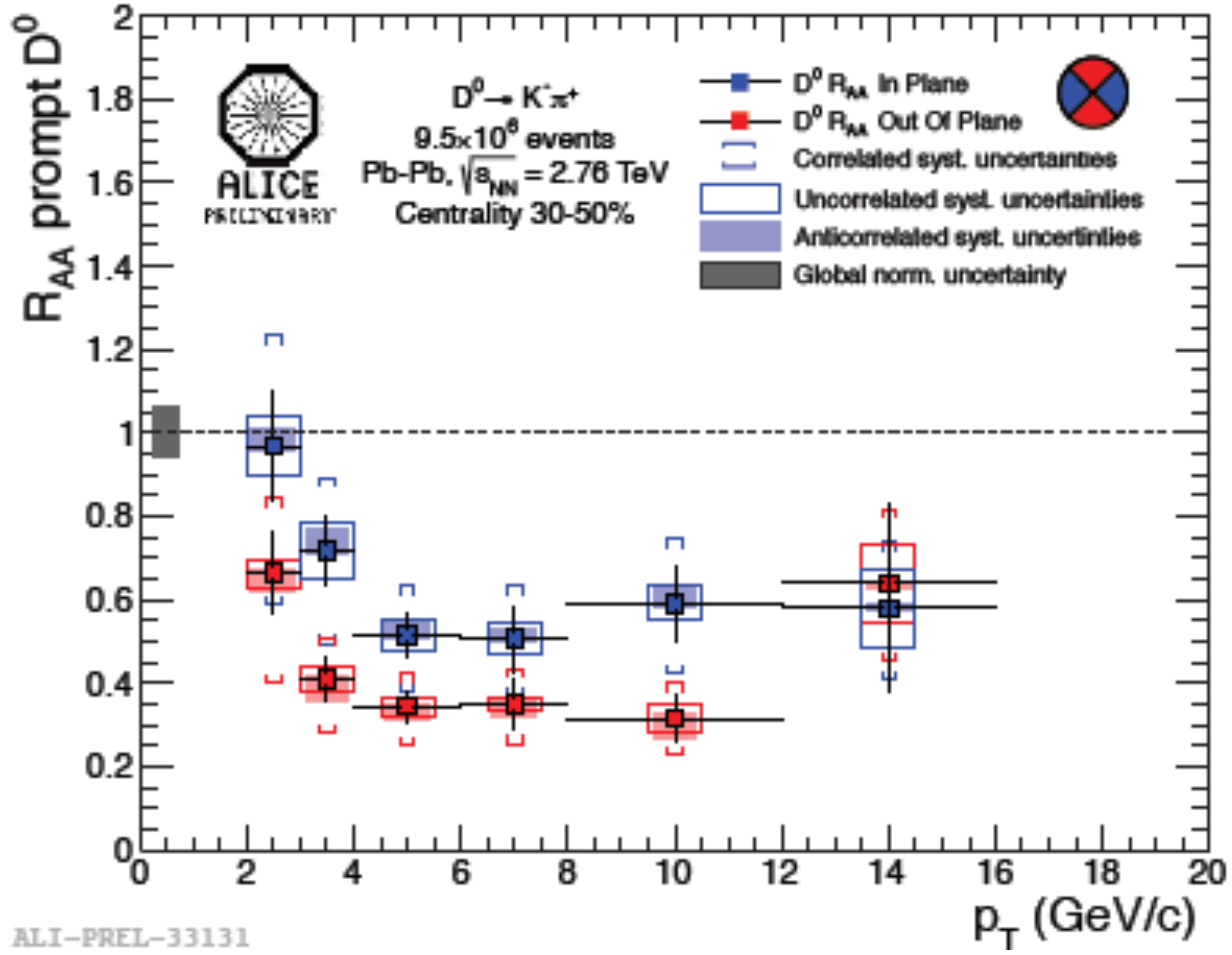
NB: gamma p_T = jet p_T still not very large

Extra slides

Questions about energy loss

- What is the dominant mechanism: radiative or elastic?
  - Heavy/light, quark/gluon difference, L^2 vs L dependence
- How important is the LPM effect?
  - L^2 vs L dependence
- Can we use this to learn about the medium?
  - Density of scattering centers?
  - Temperature?
  - Or ‘strongly coupled’, fields are dominant?

Phenomenological questions:
Large vs small angle radiation
Mean ΔE?
How many radiations?
Virtuality evolution/interplay with fragmentation?

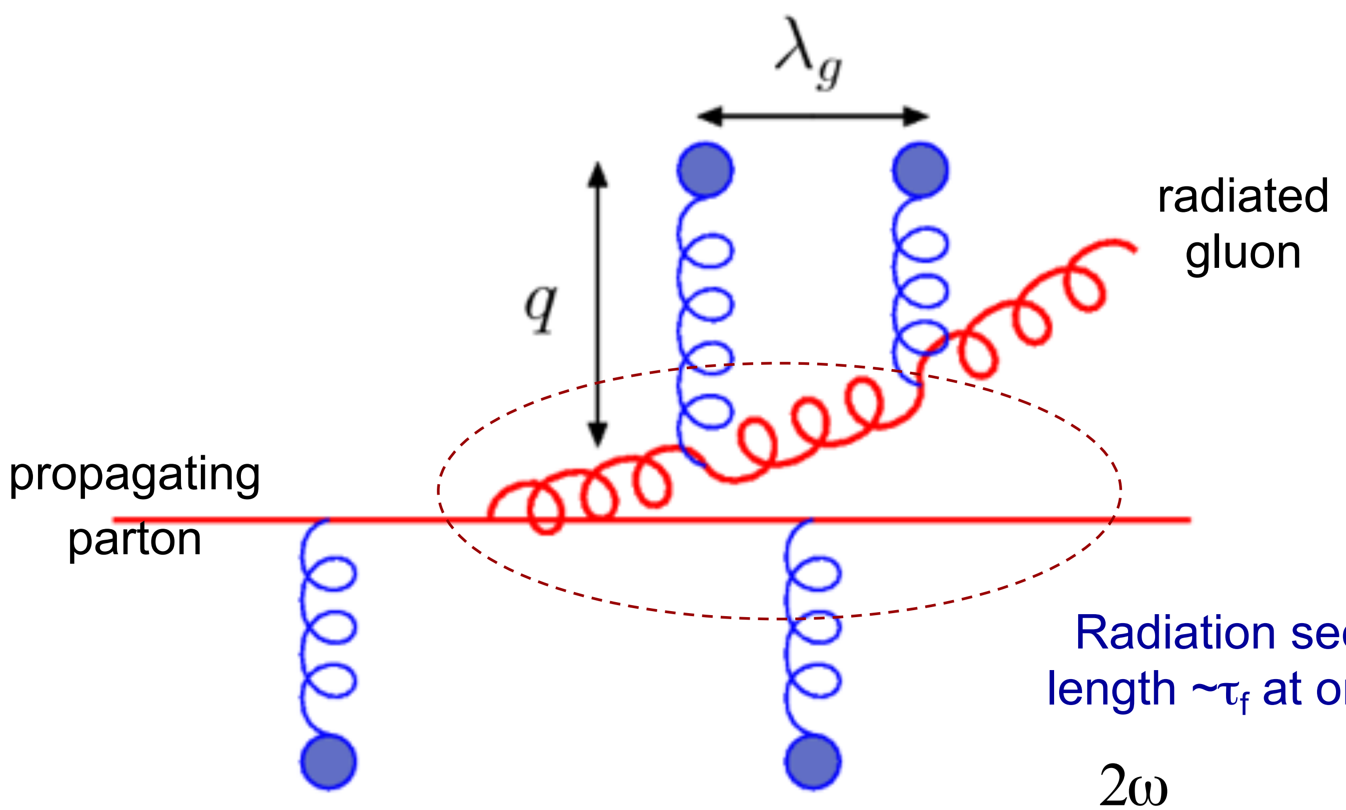


In- vs out-of-plane difference also seen for charm

→ Additional constraint for models?

Medium-induced radiation

Landau-Pomeranchuk-Migdal effect
Formation time important



Radiation sees length ~τ_f at once

$$\tau_f = \frac{2\omega}{k_T^2}$$

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

and nature of scattering centers
(scattering cross section)

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

Energy loss

$$\Delta E_{med} \sim \alpha_S C_R \hat{q} L^n F(m, E)$$

C_R: color factor (q, g)
$\hat{q}$: medium density
L: path length
m: parton mass (dead cone eff)
E: parton energy

Path-length dependence L^n
$n=1$: elastic
$n=2$: radiative (LPM regime)
$n=3$: AdS/CFT (strongly coupled)