Calibrating parton energy loss

Or: what does energy loss tell us about the medium density?

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Ingredients for a ‘realistic’ energy loss calculation

- (N)LO particle production calculation
  - PDFs, matrix elements, FF; keep track for quark and gluon jets
- Geometry: full hydro
  - Expanding Glauber probably accurate for R_{AA}
  - Event-to-event fluctuations likely important for v_2
- Energy loss model (BDMPS, GLV, HT, LBT etc)
  - For leading hadrons: fragmentation after energy loss is a good start
  - Include fluctuations

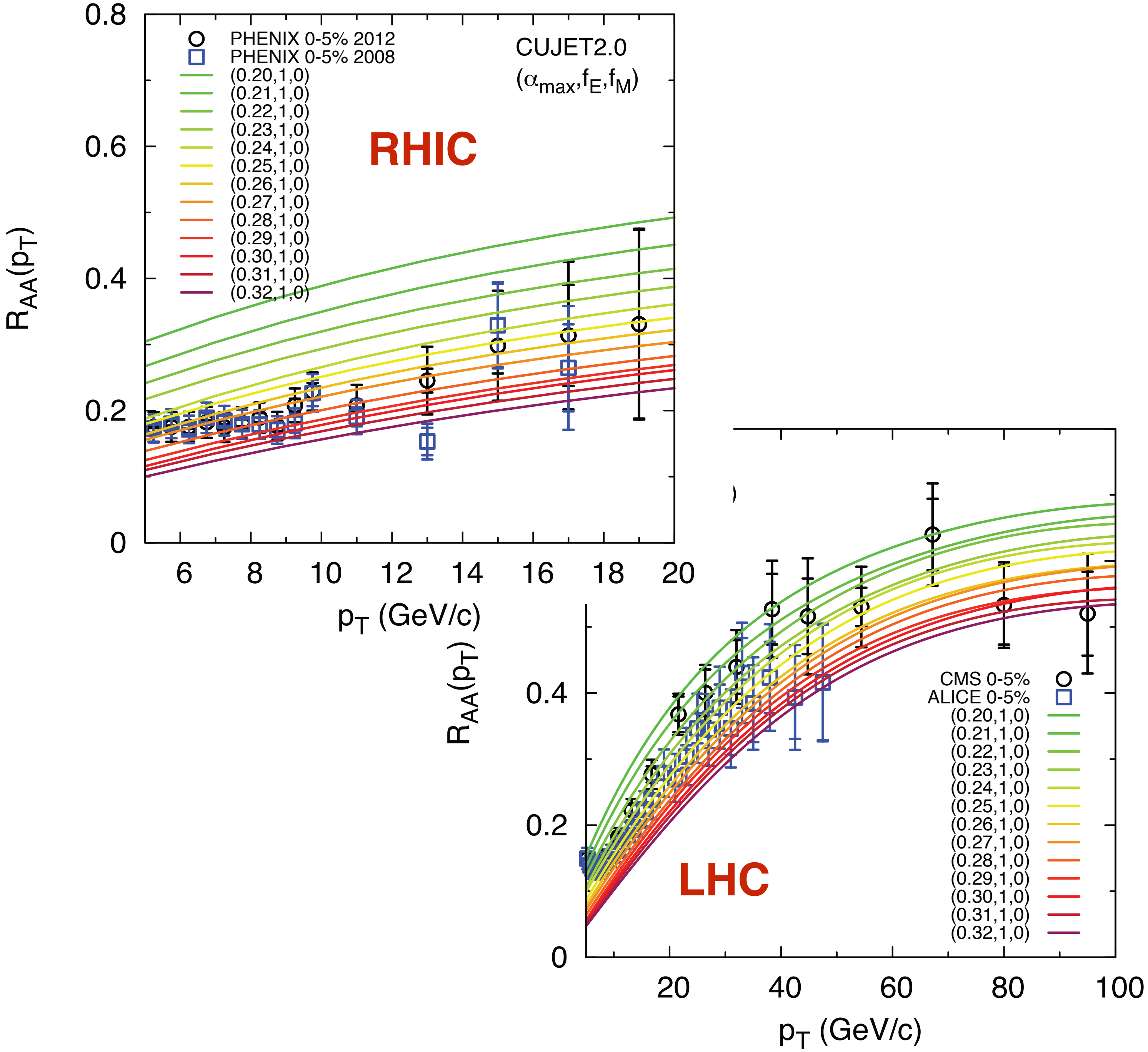
This talk: focus on single hadrons/di-hadrons

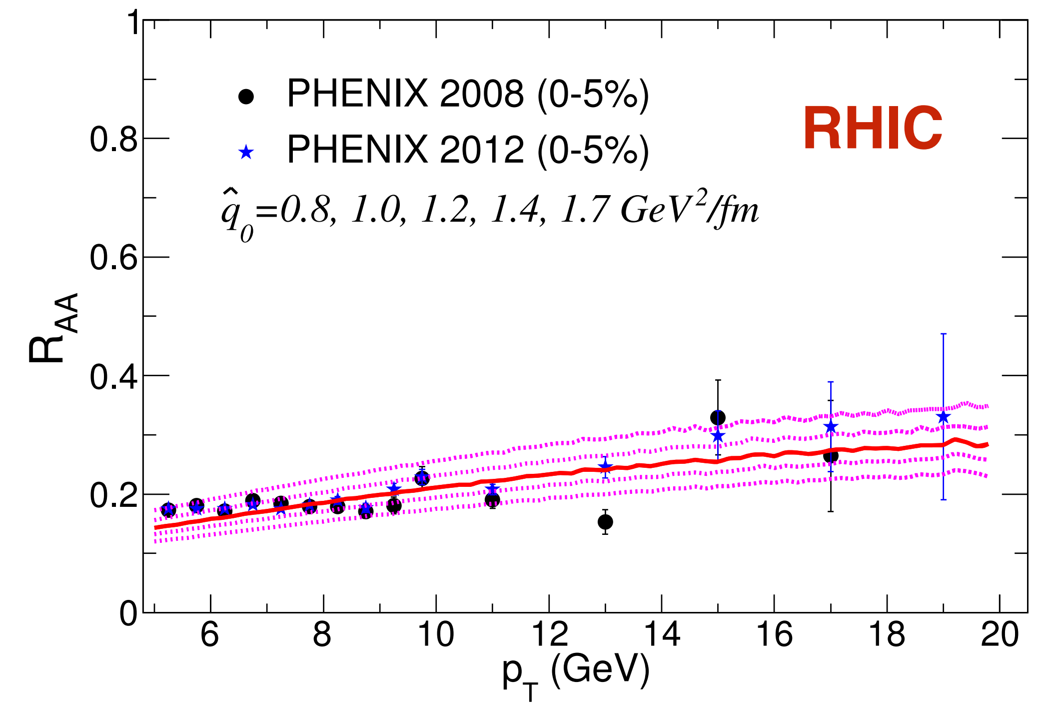
Can use independent fragmentation

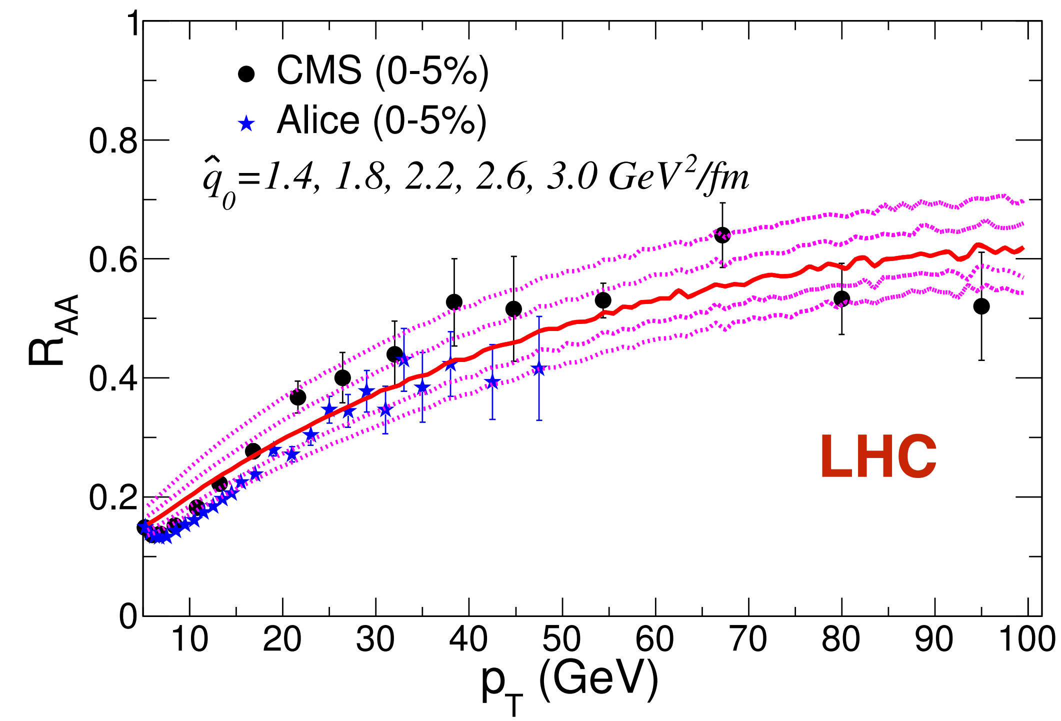
Minimal set of ingredients depends on observable

Jet observables require full shower or sophisticated analytical description

RHIC and LHC







Burke et al, JET Collaboration, arXiv:1312.5003

Systematic comparison of energy loss models with data
Medium modelled by Hydrodynamics (2+1D, 3+1D)
p_T dependence matches reasonably well

Summary of transport coefficient study

RHIC: $\sqrt{s_{NN}}$ = 200 GeV

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

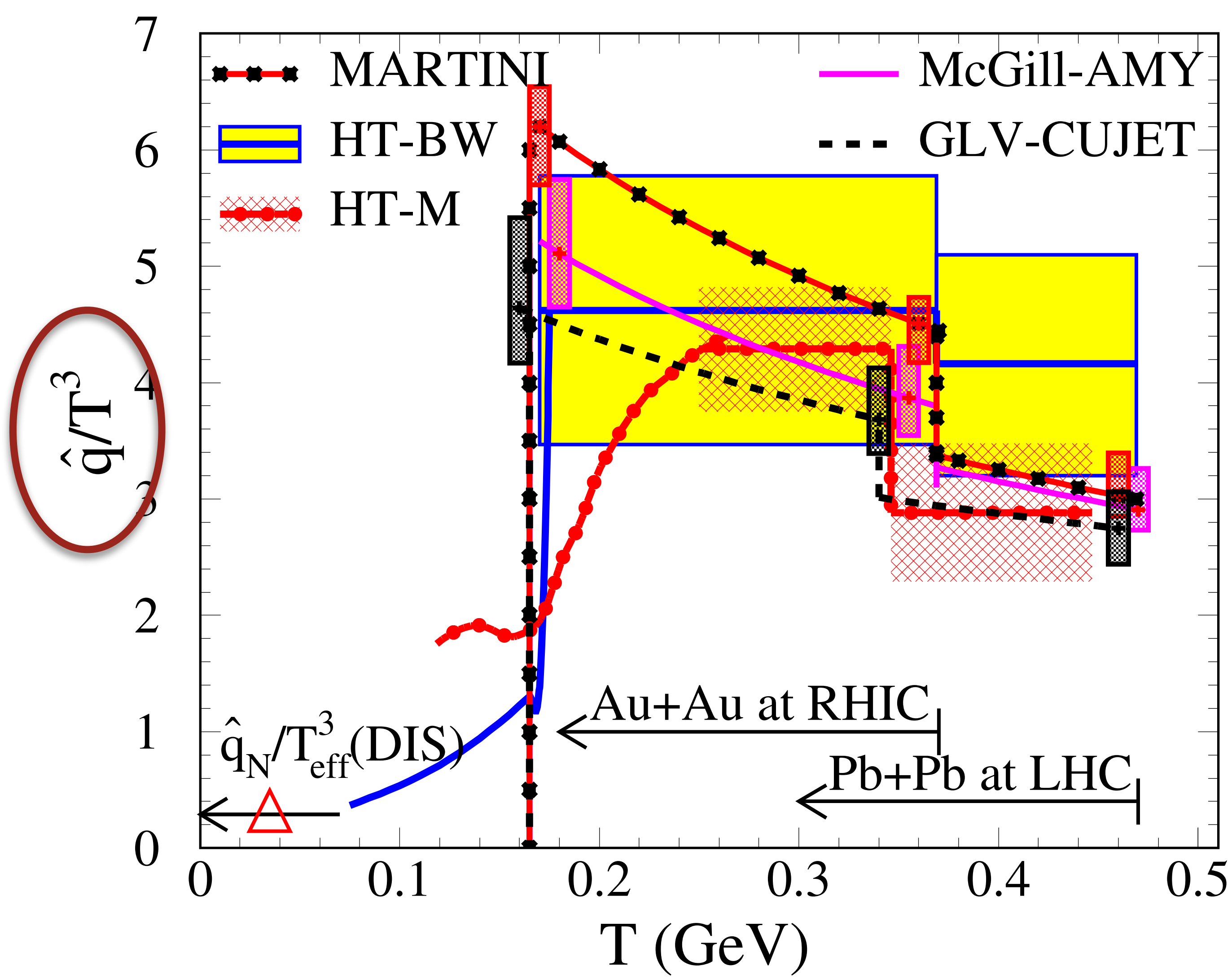
(T_i = 370 MeV)

LHC: $\sqrt{s_{NN}}$ = 2760 GeV

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

(T_i = 470 MeV)

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$



Burke et al, JET Collaboration, arXiv:1312.5003

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

Arnold and Xiao, arXiv:0810.1026

HTL expectation: $\hat{q} \approx 24\, \alpha_s^2\, T^3 \approx 2\, T^3$

Sizeable uncertainties from α_S, treatment of logs etc expected

Values found are in the right ballpark compared (p)QCD estimate

Magnitude of parton energy loss is understood

The fly in the ointment ?

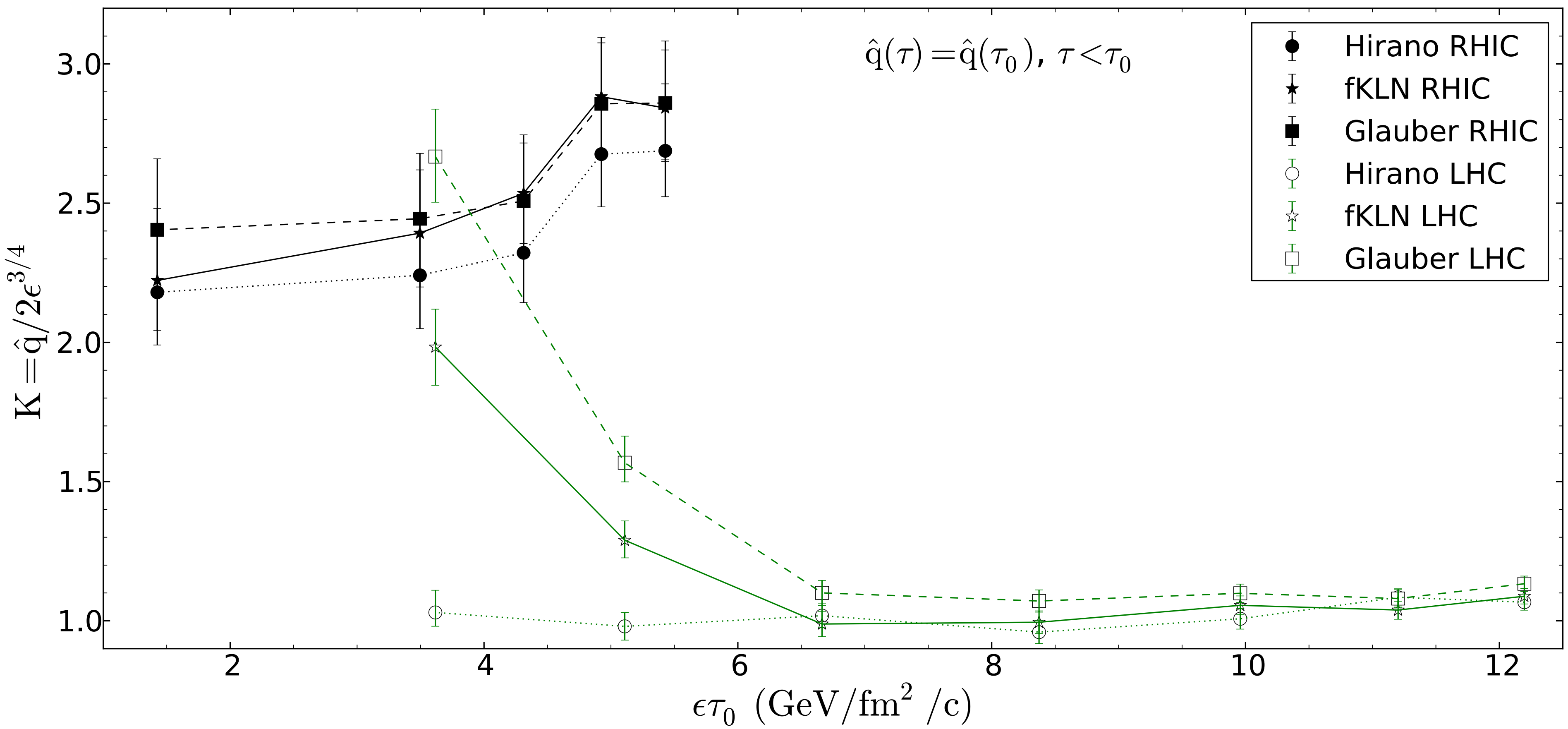
Similar fit to the data, as the JET paper, but using multiple-soft equations

Armesto et al, arXiv:1606.04837

$$\hat{q} \;=\; 2\,K\,\epsilon^{3/4}$$

$$\alpha_S \;=\; \frac{1}{3}$$

pQCD expectation:
K = 1 (by definition)

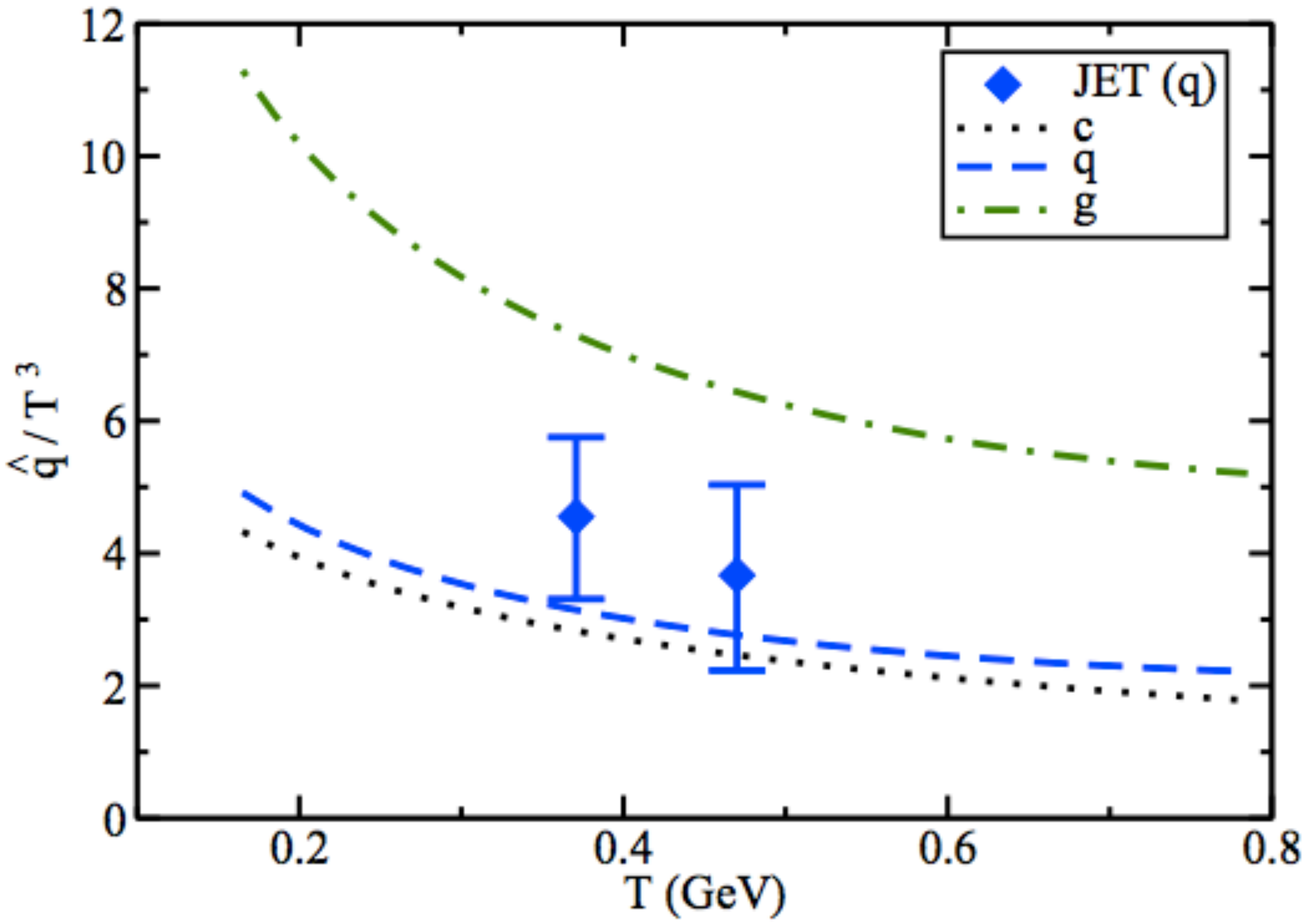


Medium: Hydrodynamics; Hirano, Luzum&Romatschke

Large difference between scale factor at RHIC and LHC

Comparison to LBT

Cao, et al, arXiv:1703.000822



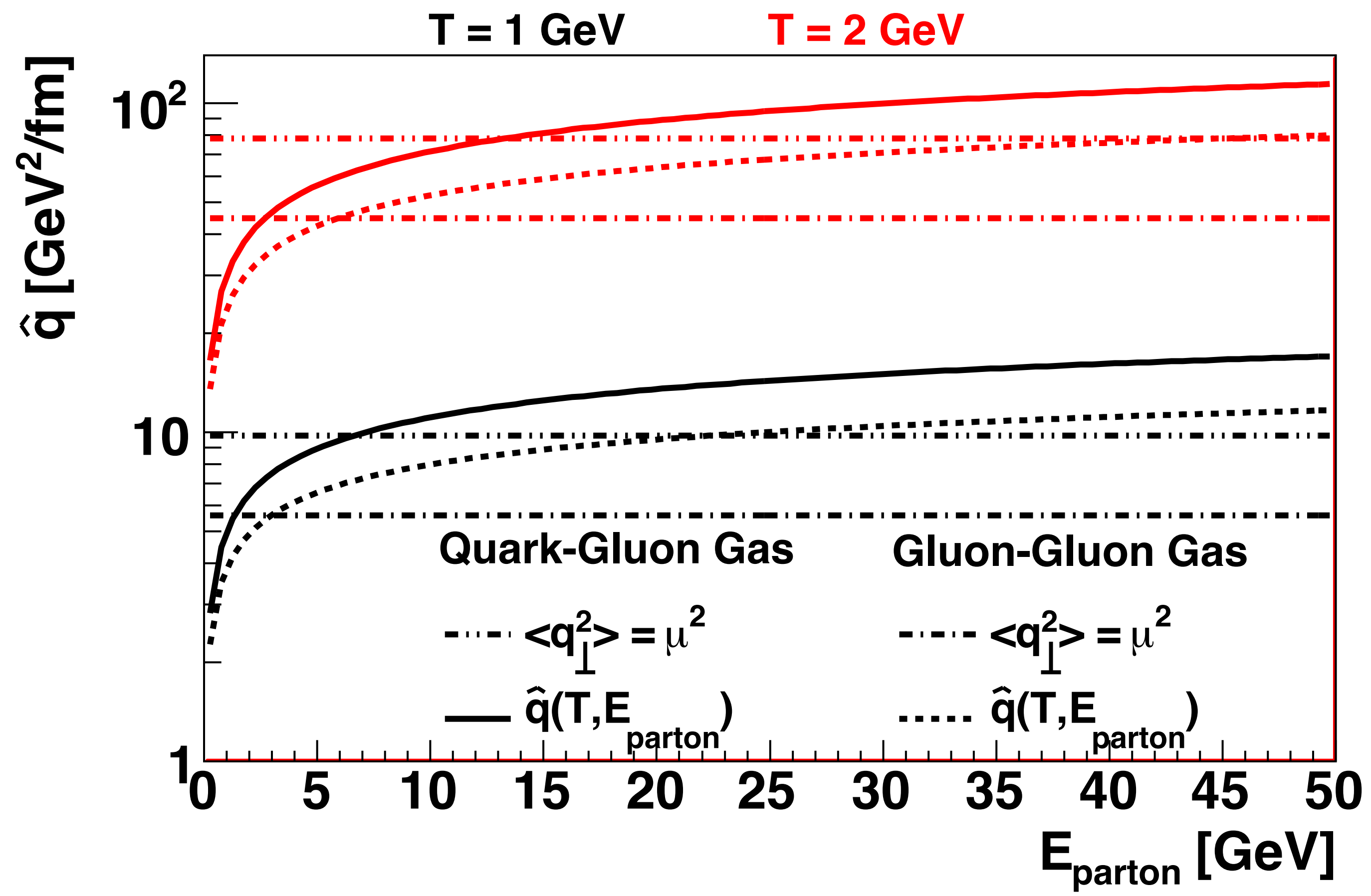
Factor ~1.5 between LBT fits and JET values; probably within uncertainties

Heavy+light energy loss

Relating qhat to medium density, or T

There are sizeable factors of uncertainty in relation $\hat{q}(T)$

- α_S
- degrees of freedom
- q_T cut-off



Some of these are intrinsic uncertainties, some are convenience

When comparing values from different authors, need to check what was used

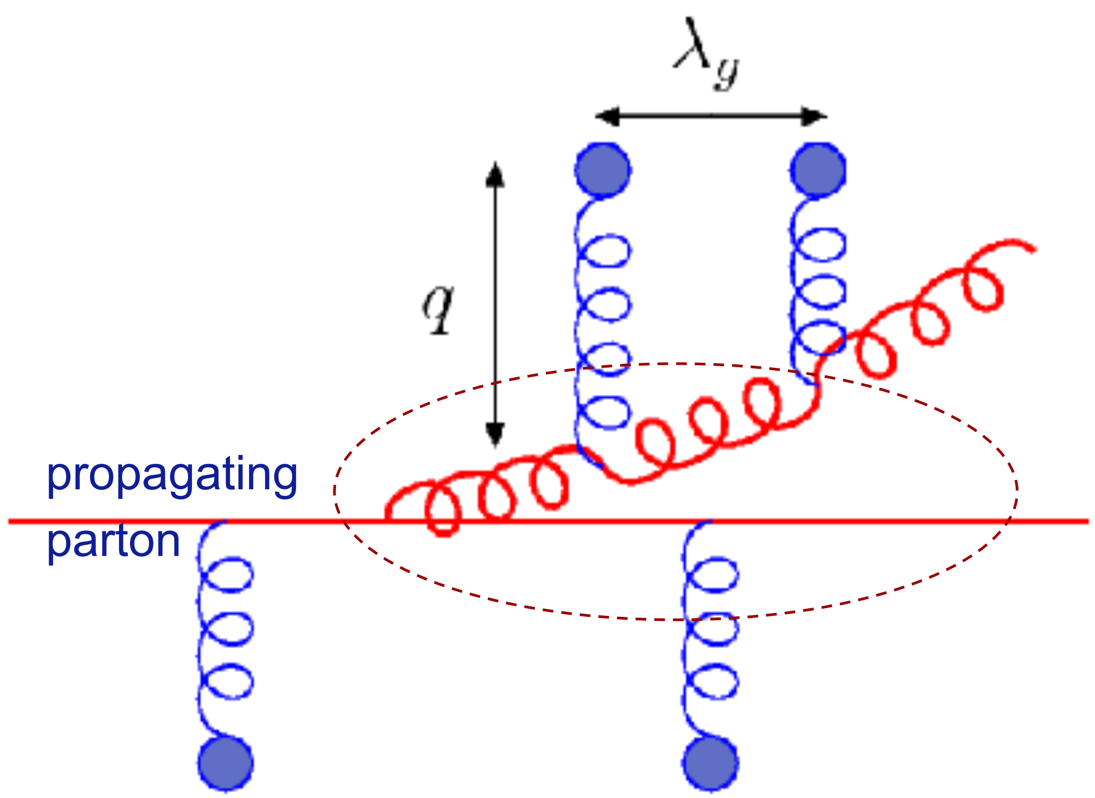
Ideally: use same convention when comparing calculations

Reminder: energy loss calculation uncertainties

Brick report; arXiv:1106.1106

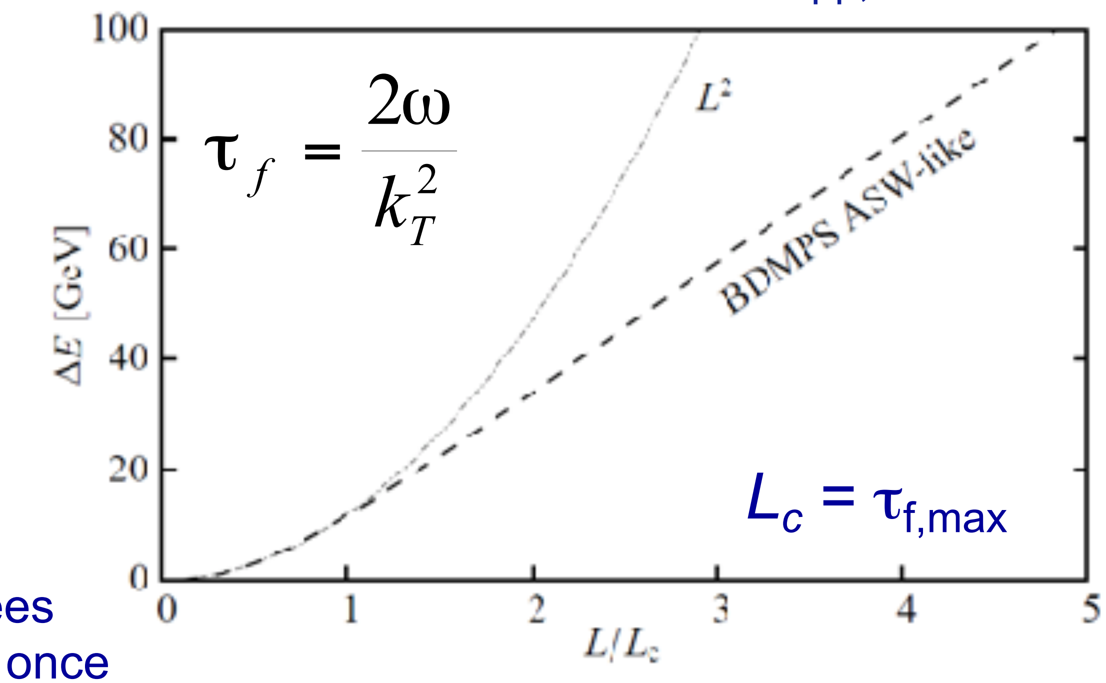
Medium-induced radiation

Landau-Pomeranchuk-Migdal effect
Formation time important



Radiation sees length $\sim\tau_f$ at once

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)

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

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

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

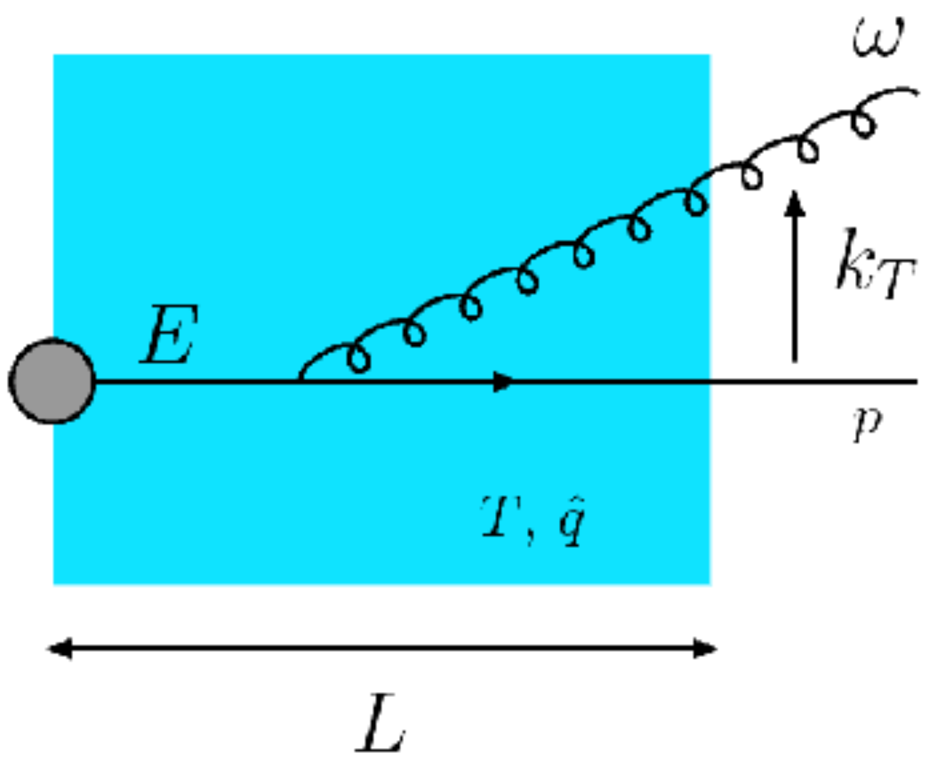
Poisson ansatz (independent emission)

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

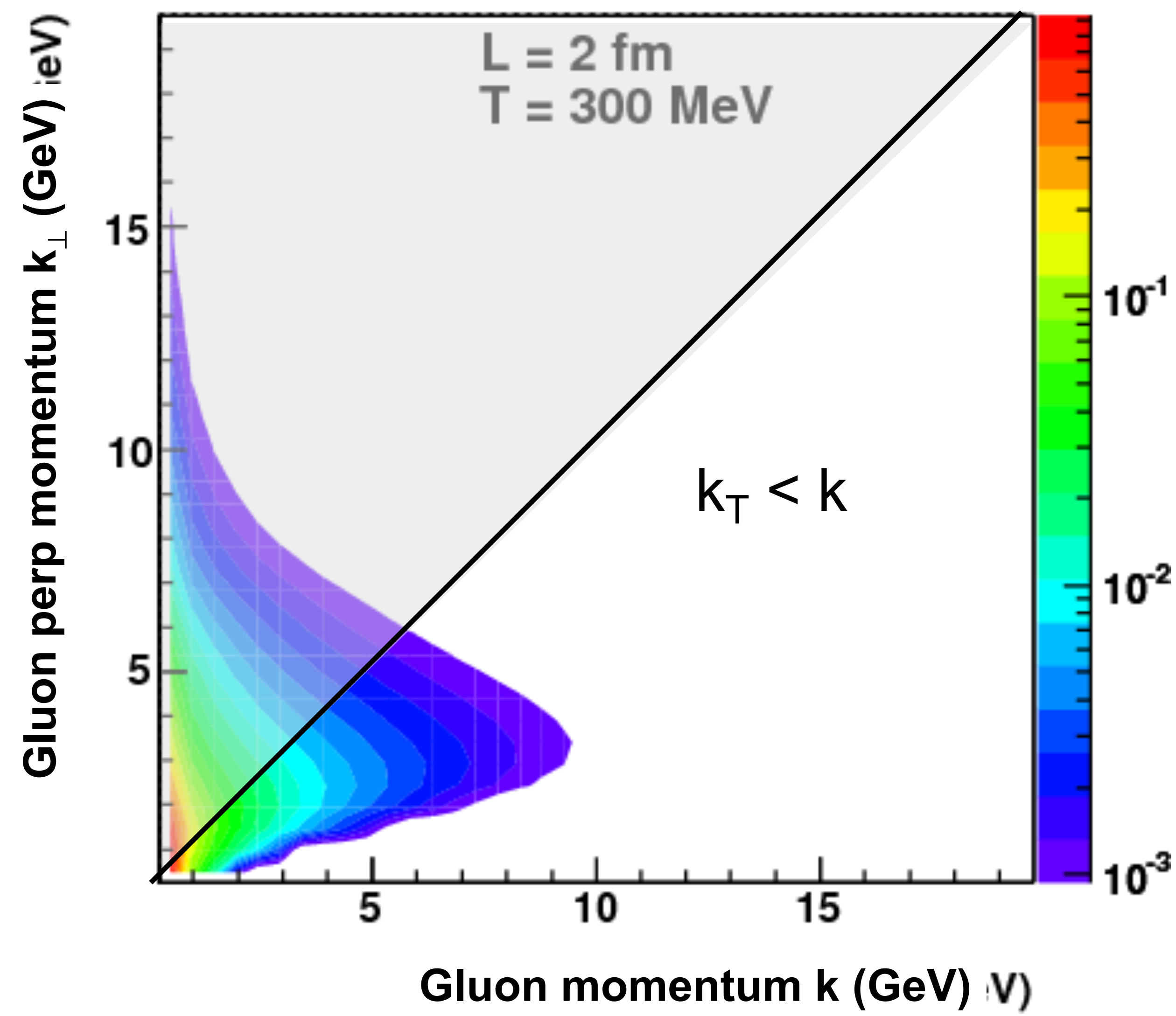
DGLAP evolution

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

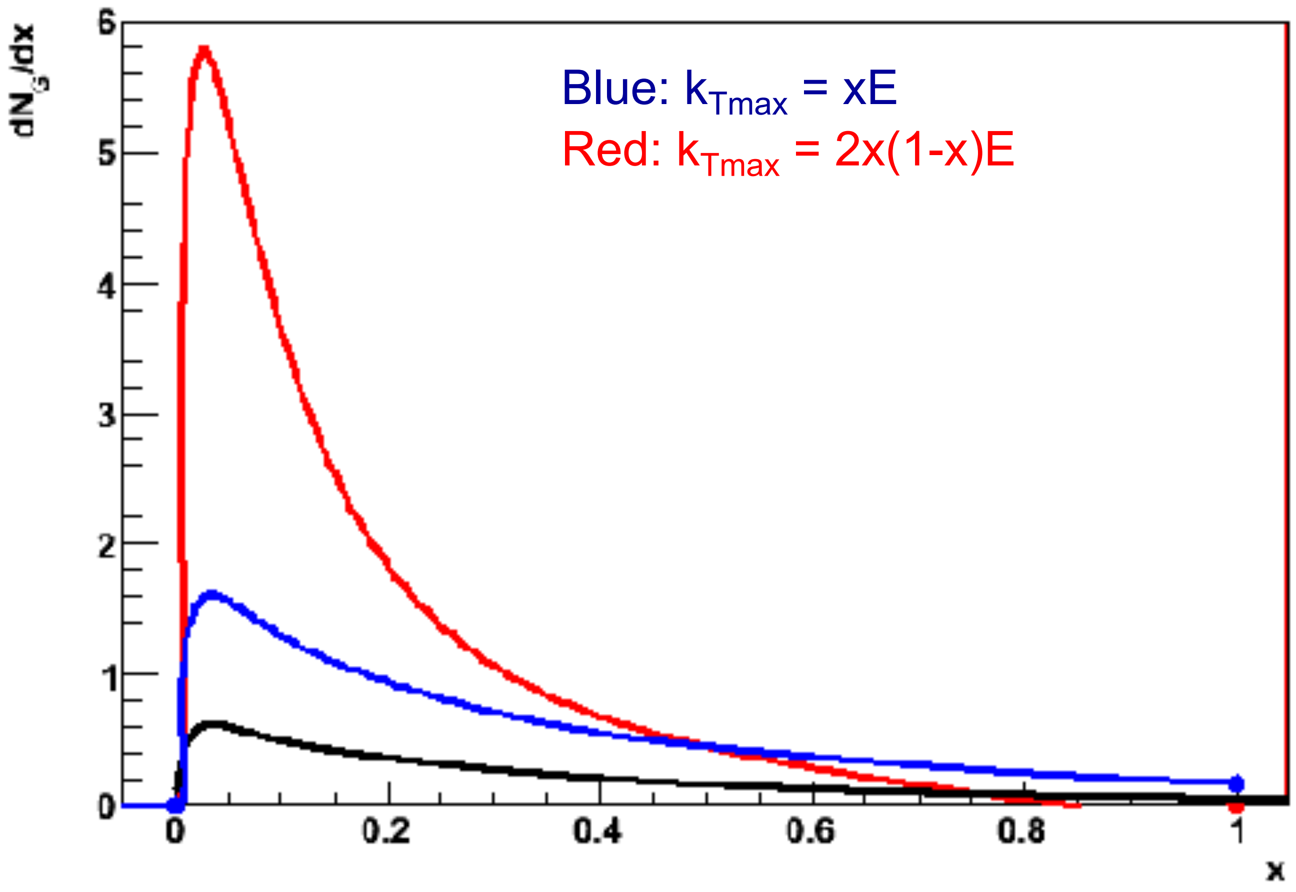
Expand in powers of $\frac{L}{\lambda}$

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

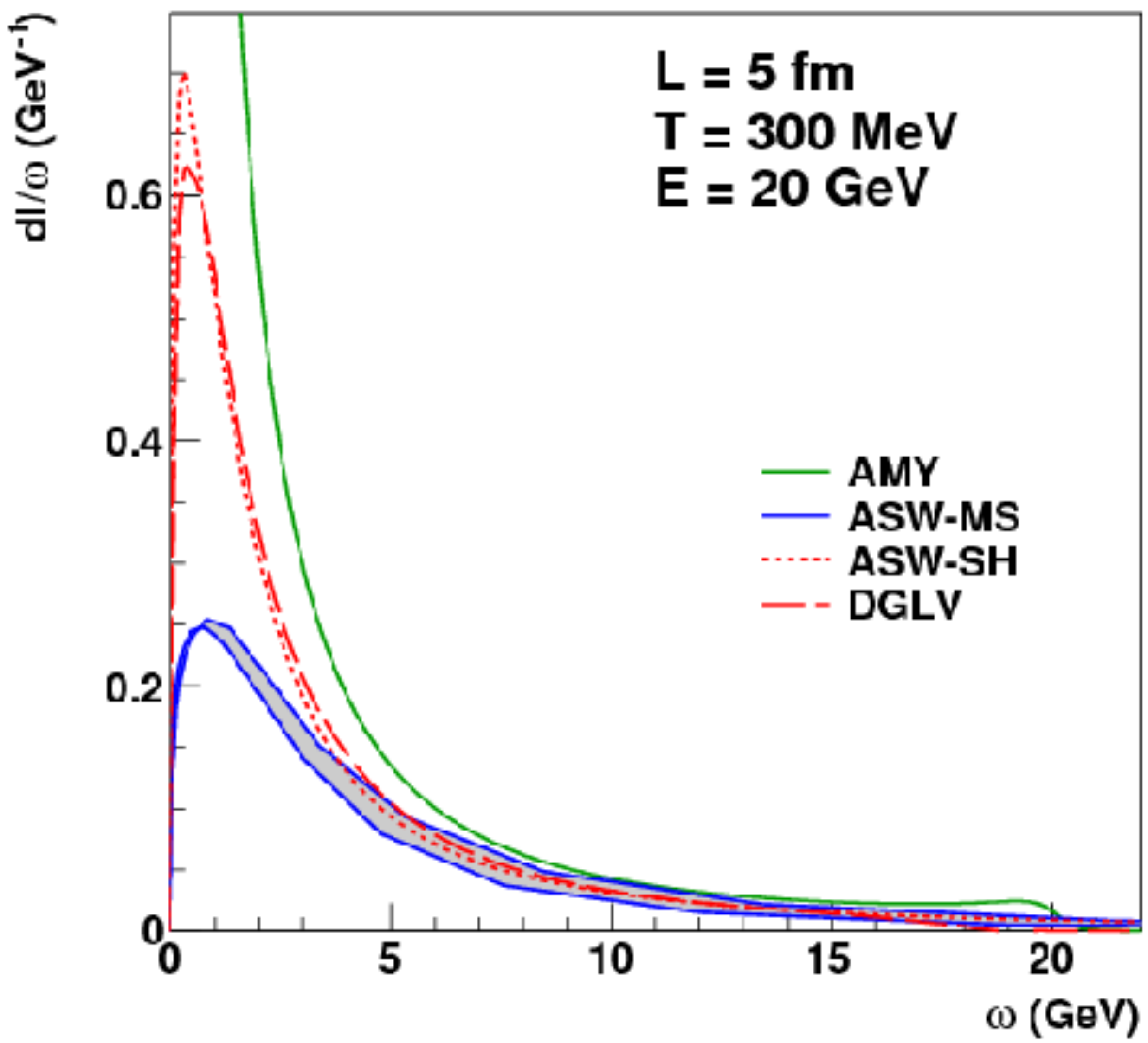


Horowitz and Cole, PRC81, 024909

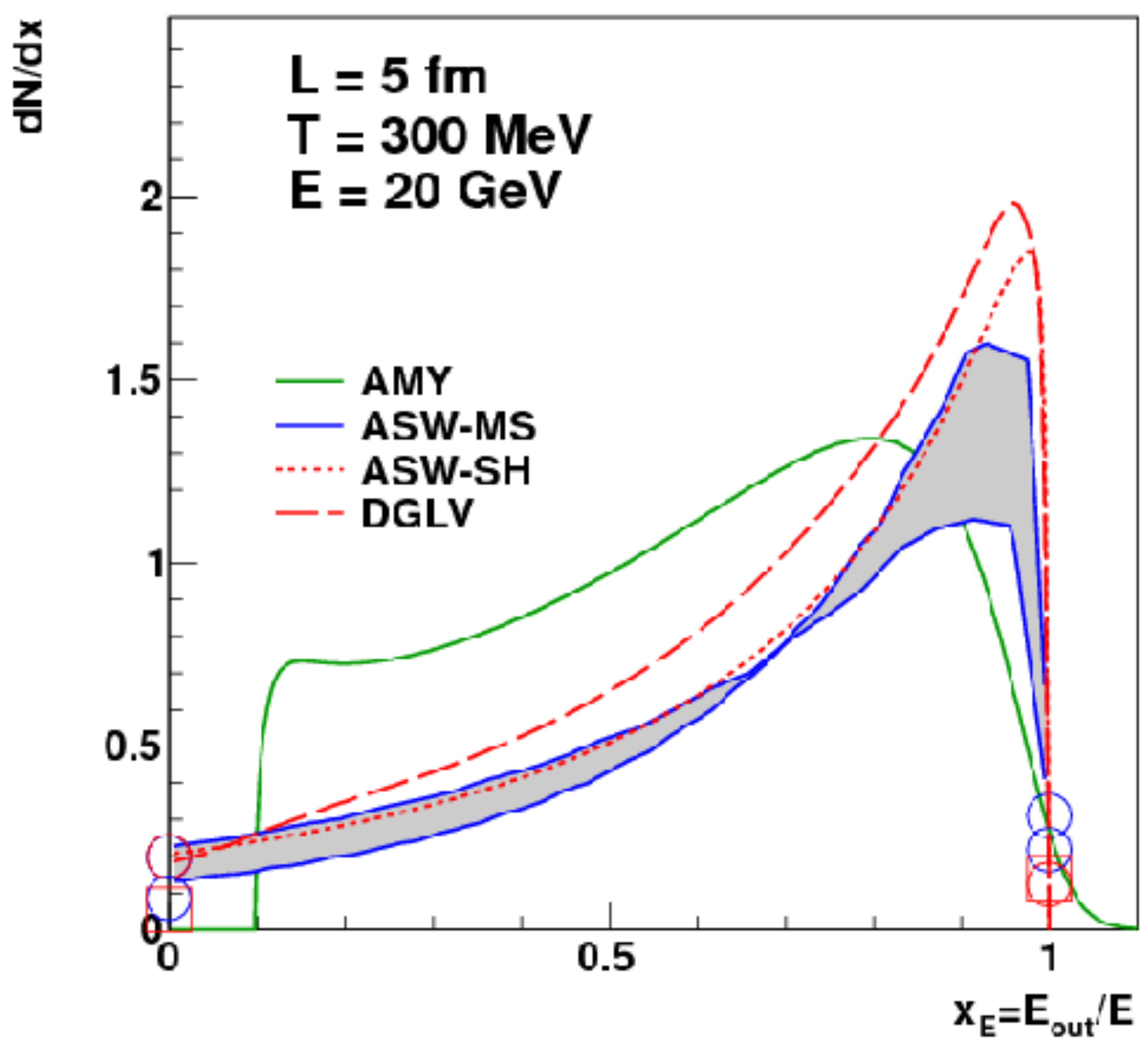
Factor ~2 uncertainty
from large-angle cut-off

Energy loss distributions

Radiated gluon distribution



Energy loss probability distribution

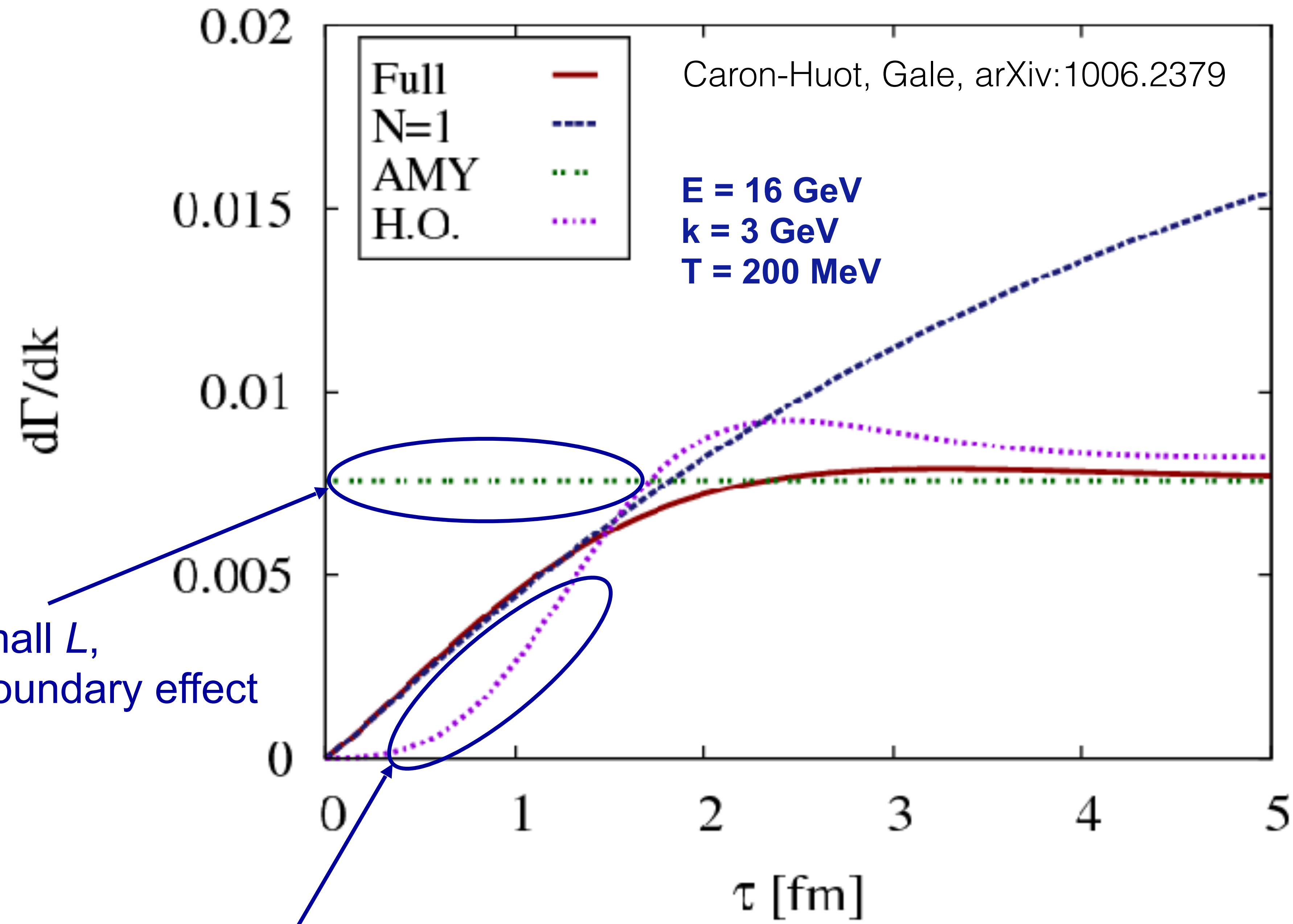


Main theory uncertainty:
Large angle radiation

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

L-dependence; regions of validity?

Emission rate vs τ (=*L*)



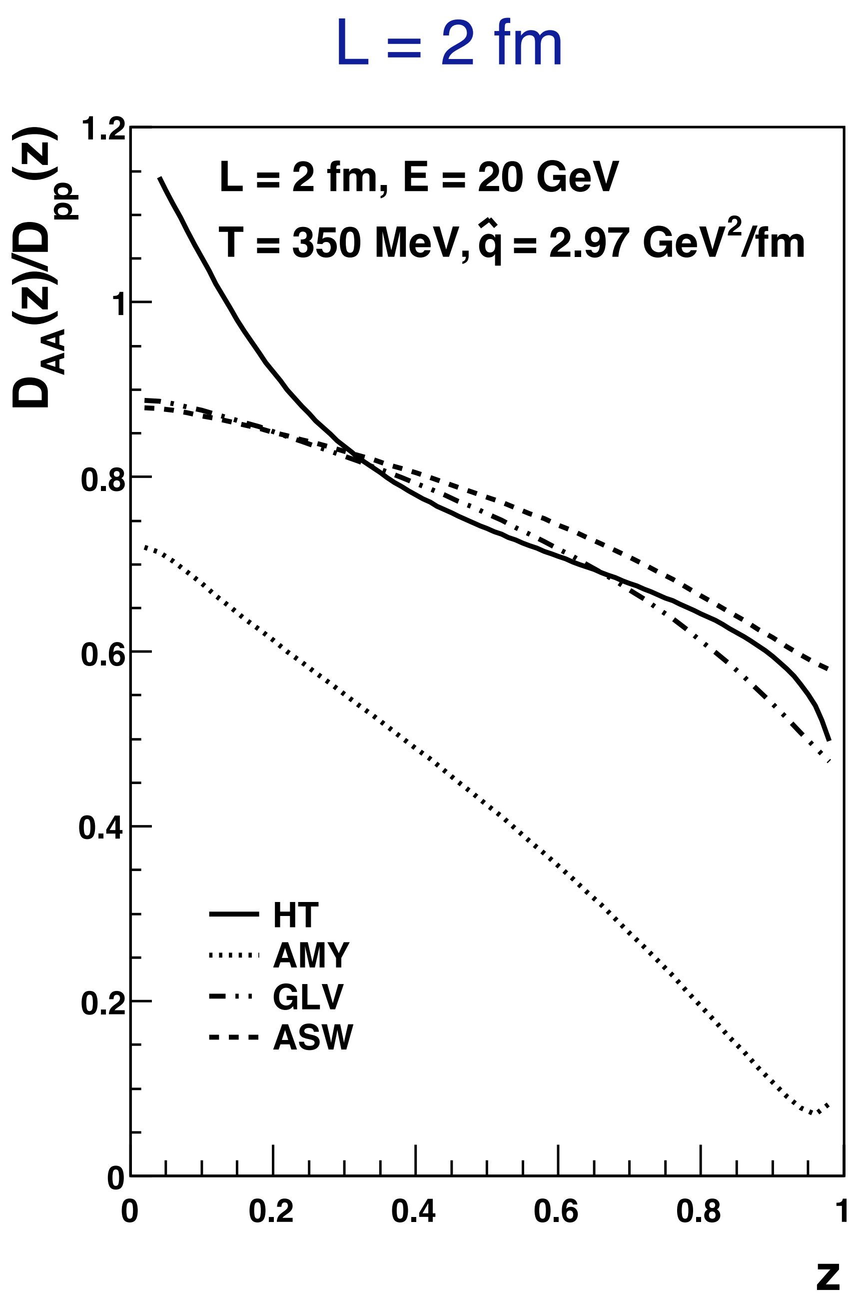
GLV N=1
Too much radiation at large *L*
(no interference between scatt centers)

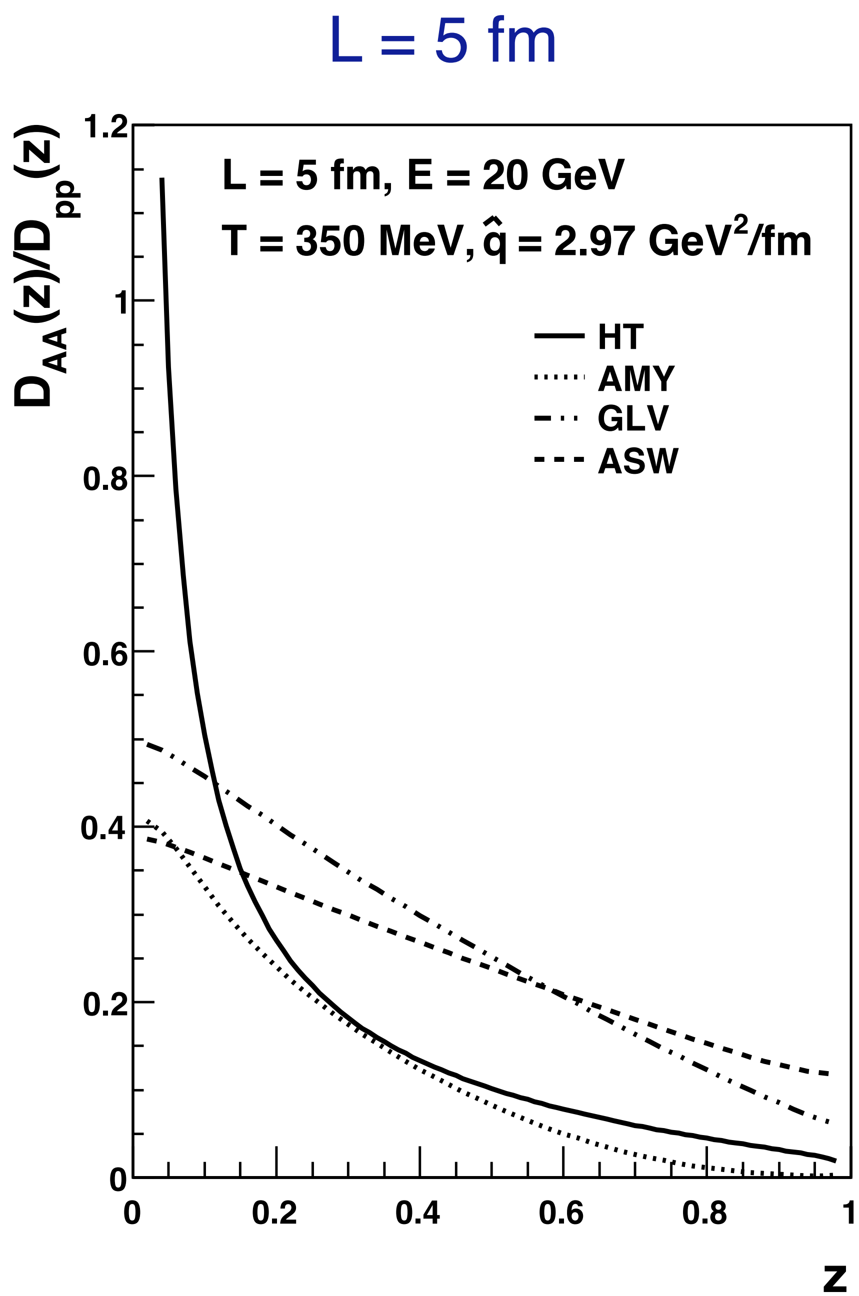
Full =
numerical solution of Zakharov path integral
= 'best we know'

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)

Comparison with Higher Twist formalism





AM, MvL, arXiv:1002.2206

Higher Twist formalism works at the level of fragmentation functions; need to fold other results with fragmentation to compare

Suppression at same rough level, different shapes

Energy loss formalisms

- Differences and similarities between formalisms understood/ categorised
  - 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 $2 \rightarrow 3$ NLO matrix elements
    - Include interference

The v_2 ‘problem’

Most likely a subtle issue; many ingredients
Corollary: cannot get away with partial modelling for v_2

CUJET

GLV-based E-loss

a_S runs, with cut-off at low Q

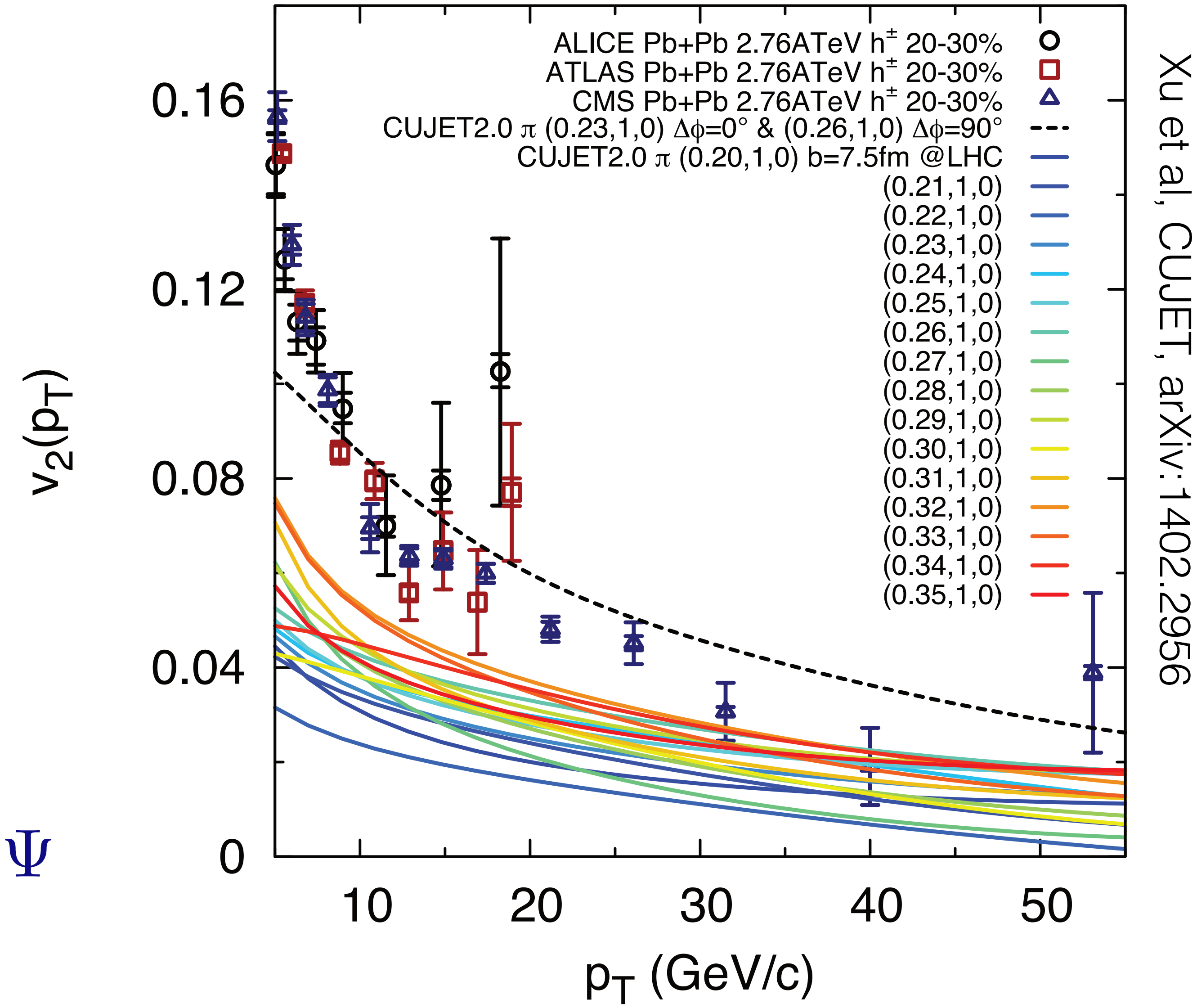
$$\alpha_s \longrightarrow \alpha_s(Q^2) = \begin{cases} \alpha_{max} & \text{if } Q \leq Q_{min} \, , \\ \dfrac{2\,\pi}{9\,\log(Q/\Lambda_{QCD})} & \text{if } Q > Q_{min} \, . \end{cases}$$

Cut-off is the main model parameter

Standard settings underpredict v_2

Black dashed line: α_{max} depends on $\phi - \Psi$
Adds v_2 'by hand'

CUJET

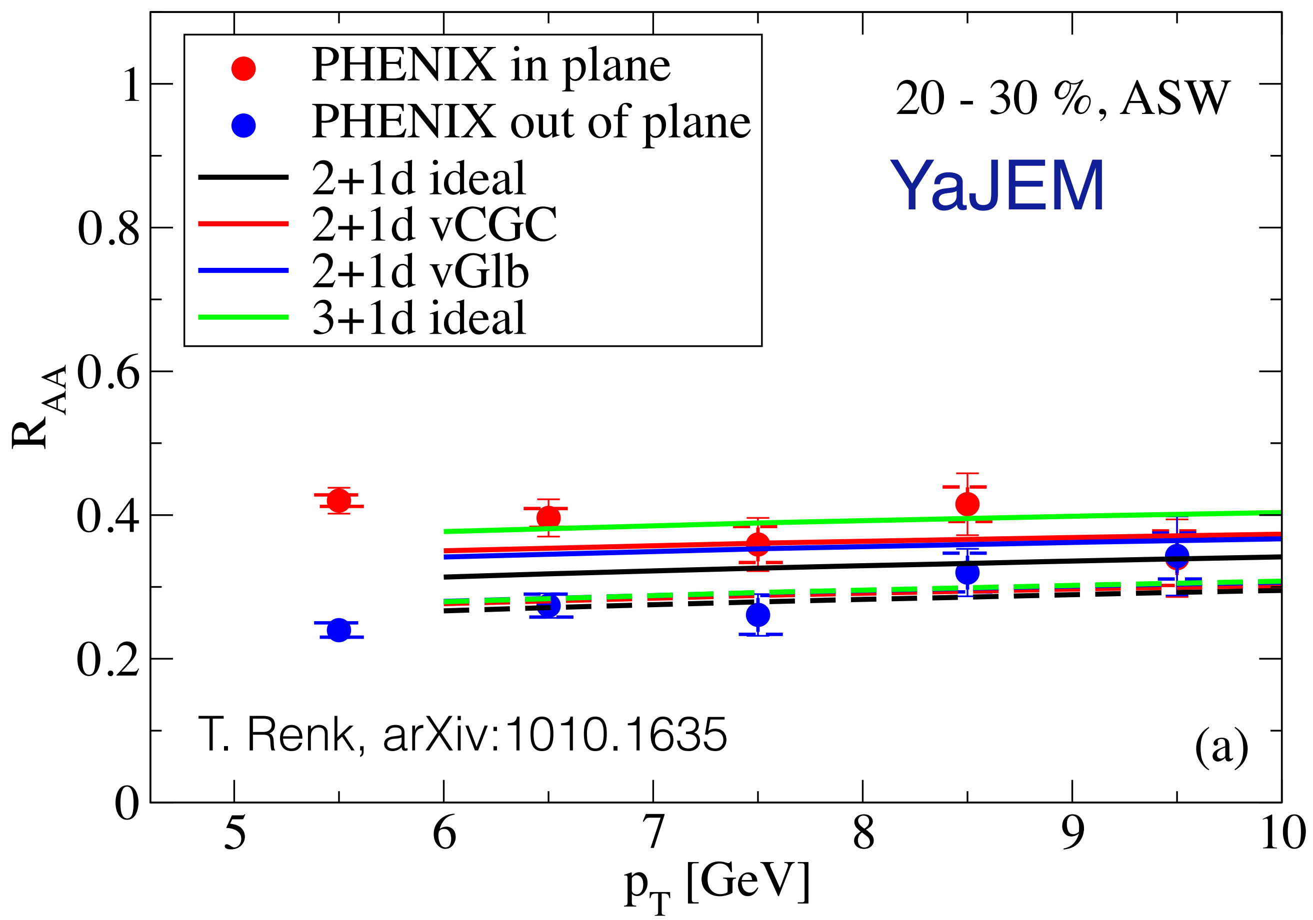


However, see also: CUJET3.0

Xu et al, arXiv:1509.00552

High-p_T v_2, R_{AA} in and out of plane

RHIC

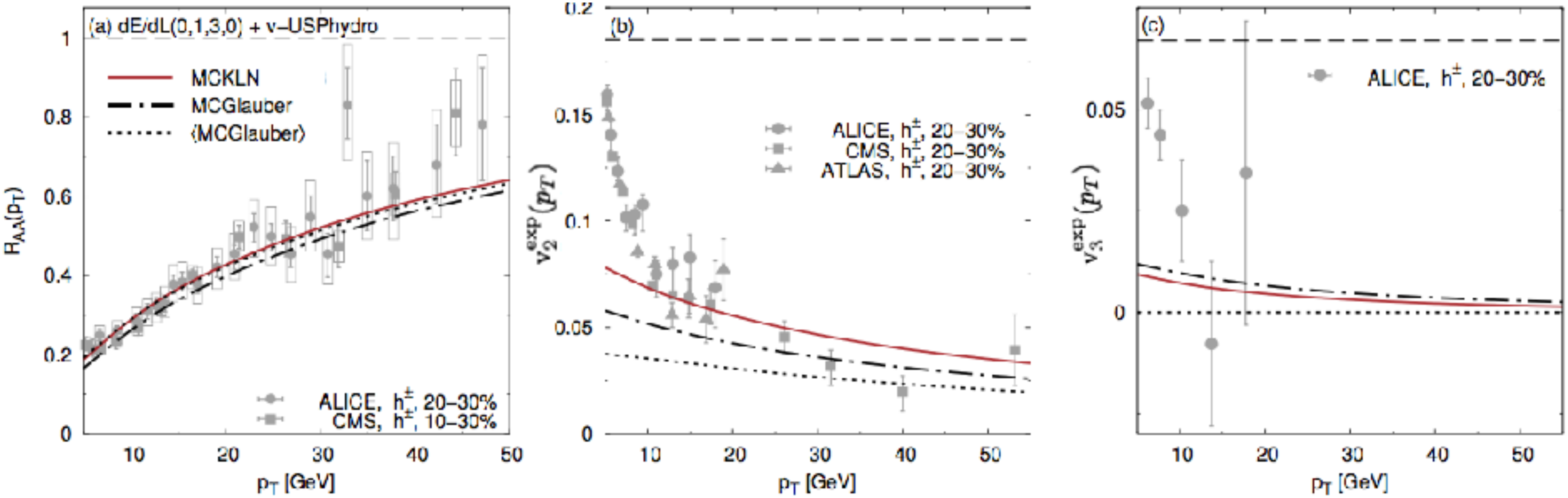


Predicted v_2 is quite sensitive to hydro settings

Needs a somewhat systematic exploration to understand whether this can constrain energy loss models and/or geometry/hydro

Noronha-Hostler et al: fluctuations

Noronha-Hostler et al, arXiv:1602.03788



Observation: high-p_T v_2 is measured wrt to low p_T v_2

$$v_n^{exp}(p_T) = \frac{\langle v_n^{soft}\, v_n^{hard}(p_T) \cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right)\right]\rangle}{\sqrt{\left\langle \left(v_n^{soft}\right)^2 \right\rangle}}$$

Basically, measure $\langle v_2^2 \rangle$

$$\frac{v_2^{exp}(p_T)}{\langle v_2^{hard}(p_T)\rangle} \simeq 1 + \frac{1}{2}\left\langle \left(\frac{\delta v_2^{soft}}{\langle v_2^{soft}\rangle}\right)^2 \right\rangle - 2\left\langle (\delta\psi_2(p_T))^2 \right\rangle$$

Fluctuations bias v_2

NB: no energy loss fluctuations; not so clear how geometry was implemented (L)

Model(ing) uncertainties for high-p_T v_2

- Initial time/treatment
- Freeze-out temperature/treatment
- Length sampling in a non-uniform medium
- Event-by-event fluctuations

When reporting a model/calculation; make sure to specify these things

Length sampling

- Energy loss scales with L^2 —> not easy to come up with a local prescription
- Gives trouble in 'medium averages'
  - e.g. for non-uniform medium, L is not unique (where do you stop)

Common prescription for BDMPS-MS:

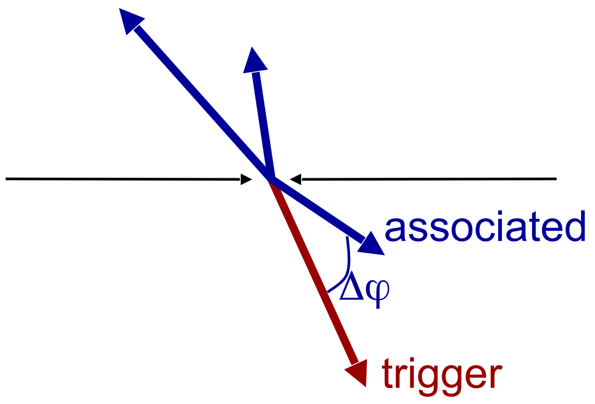
$$\omega_c = \frac{1}{2}\hat{q}L^2 \qquad \omega_c^{eff} = \int_0^{x_{max}} dx\, x\, \hat{q}(x)$$

However, also need R (related to large angle cut-off) $R = \omega_c L$

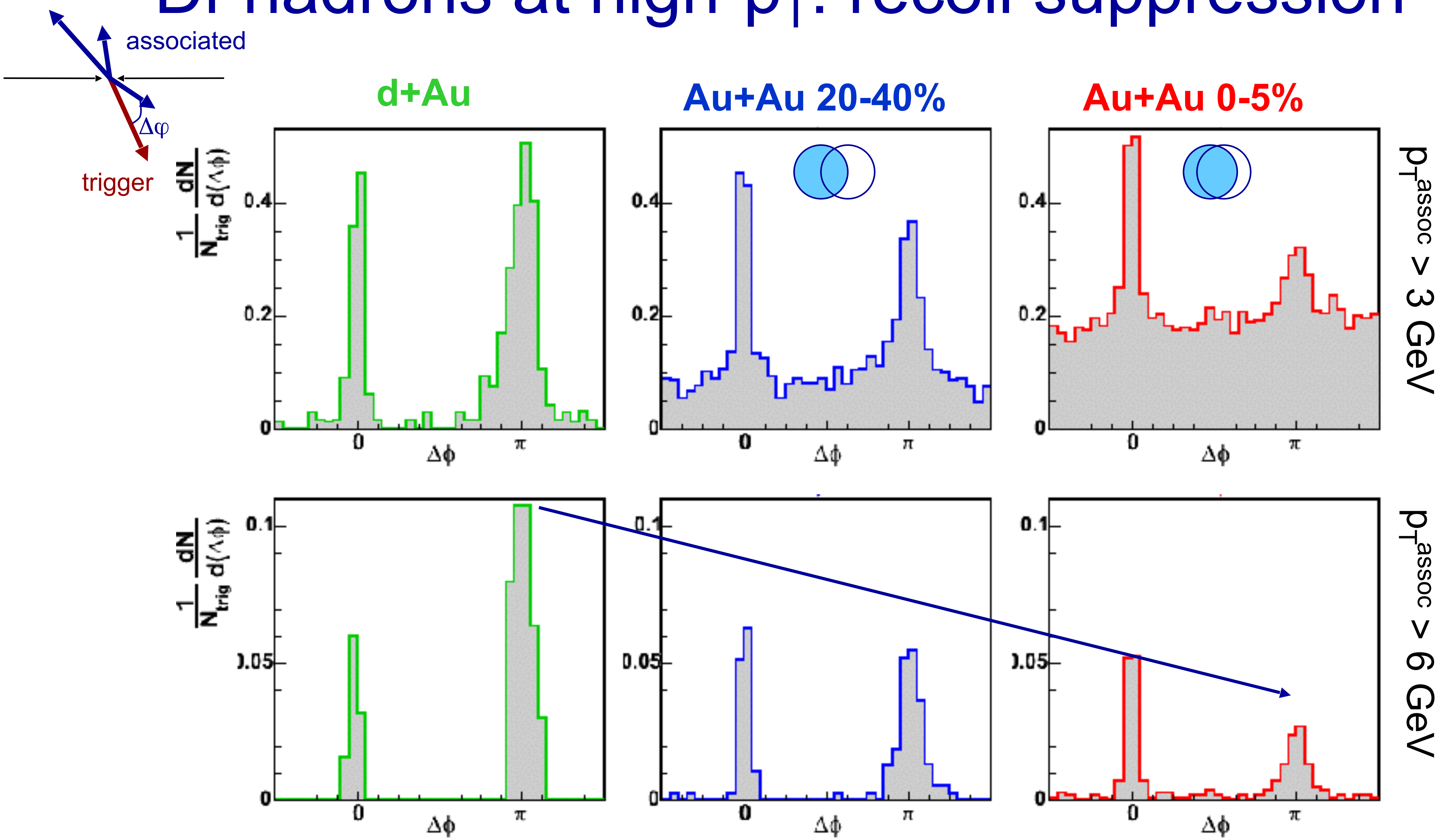
Similar for GLV, need L/lambda and mu

Probably not a fundamental issue, but needs care/need to specify what is used

Alternative handle on geometry: recoil yields, I_{AA}



Di-hadrons at high-p_T: recoil suppression



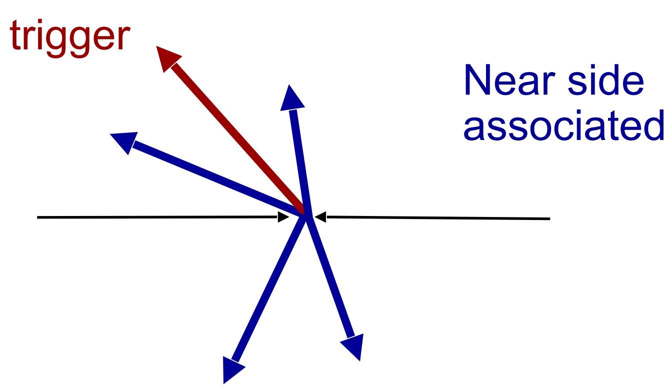
High-p_T hadron production in Au+Au dominated by (di-)jet fragmentation

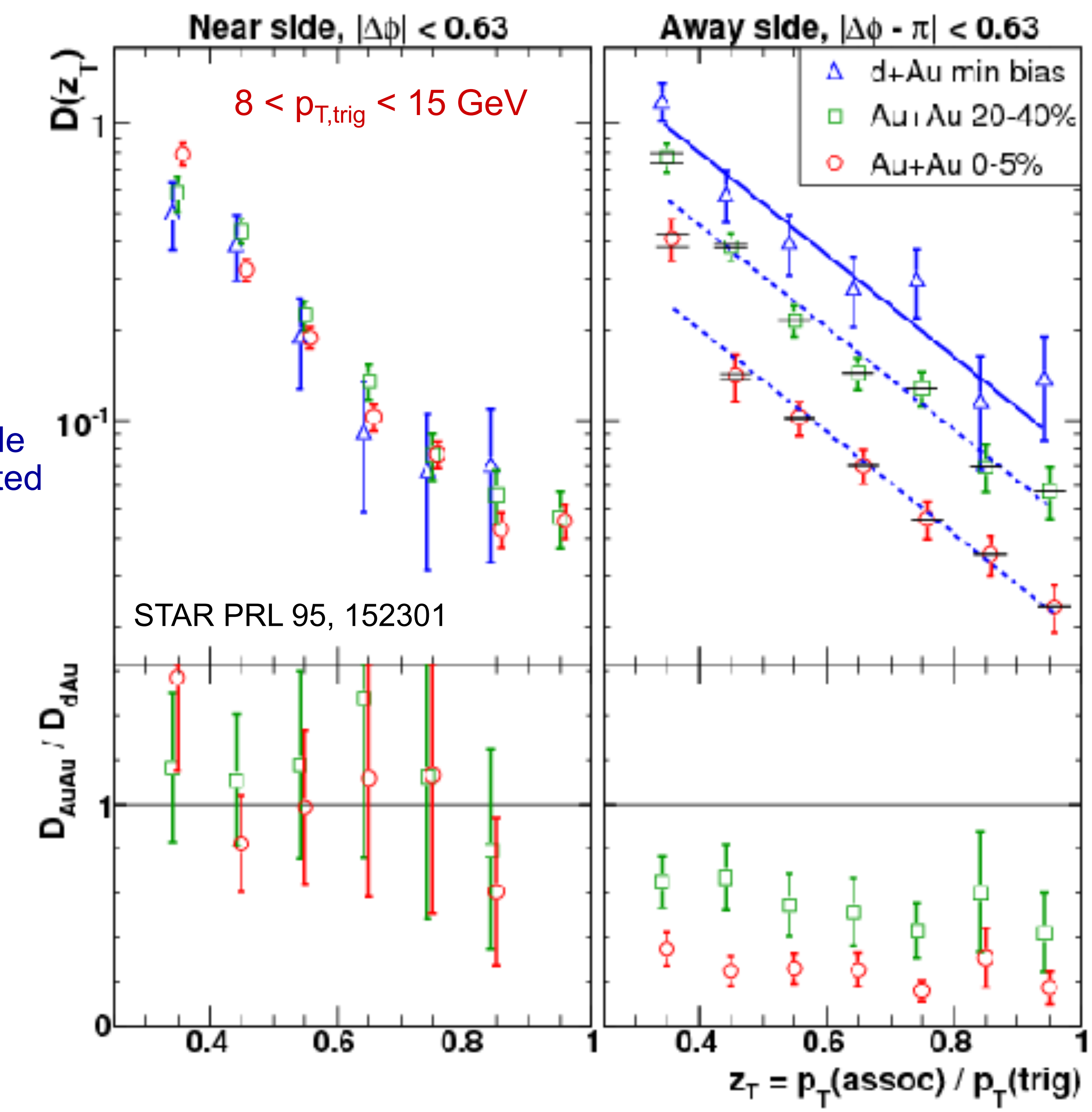
Suppression of away-side yield in Au+Au collisions: energy loss

Di-hadron yield suppression

Near side

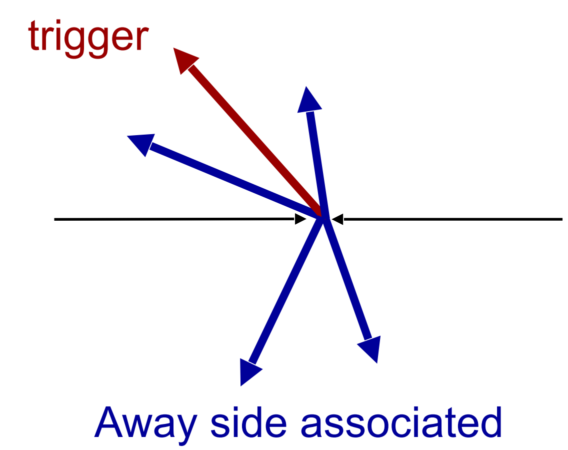
Yield of additional particles in the jet





Away side

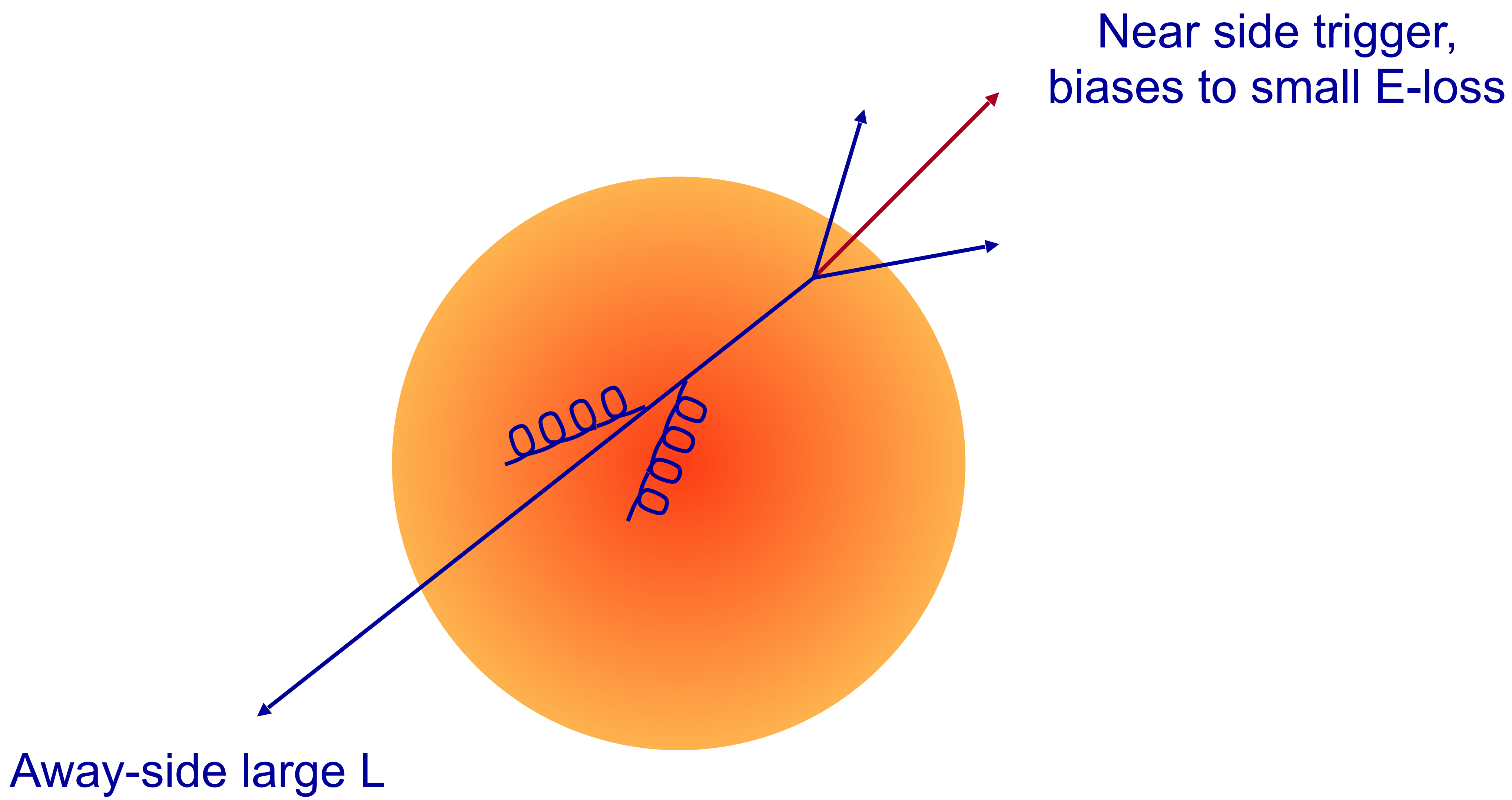
Yield in balancing jet, after energy loss



Near side: No modification
⇒ Fragmentation outside medium?

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

Path length II: 'surface bias'



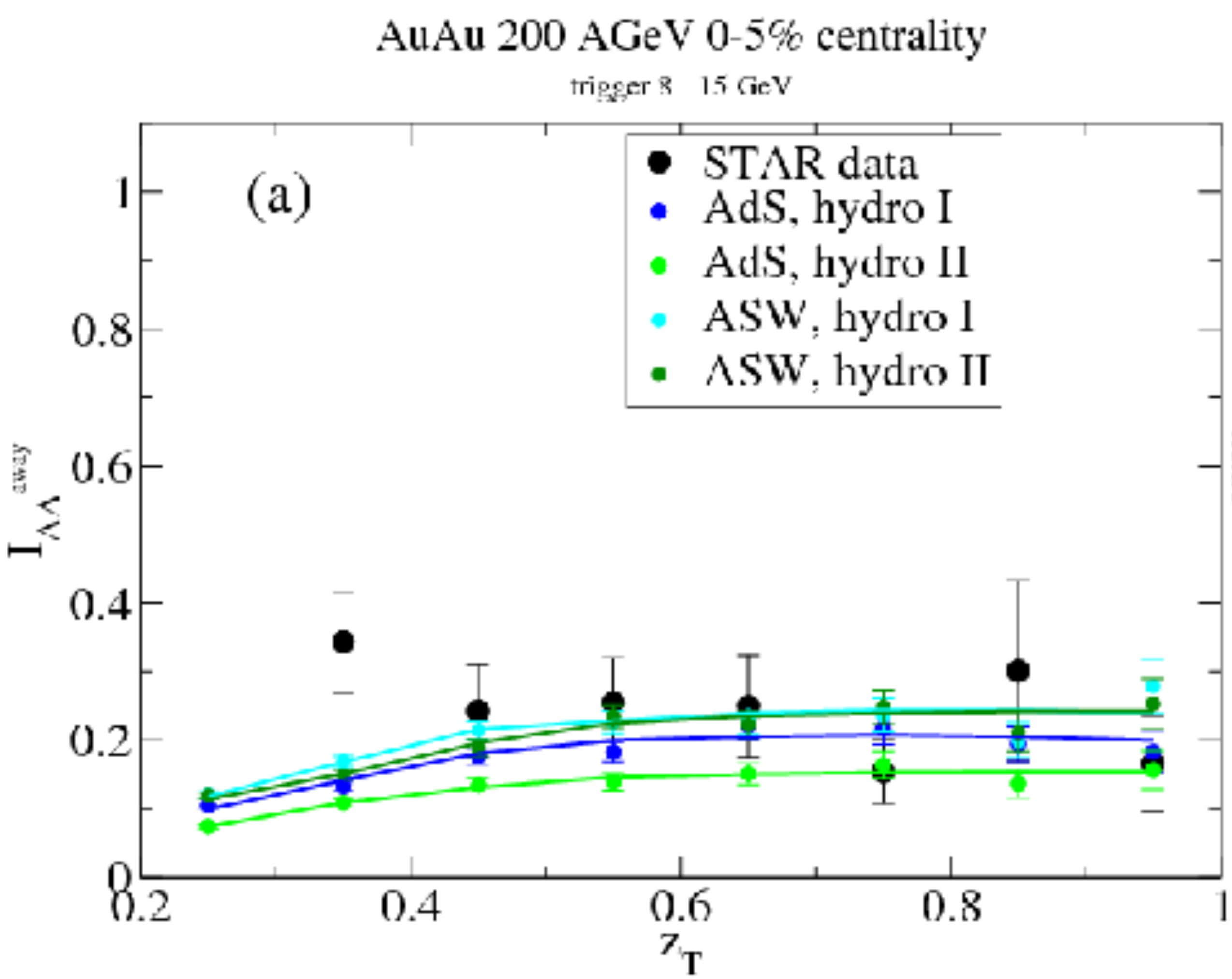
Away-side (recoil) suppression I_{AA} samples longer path-lengths than inclusive, R_{AA}

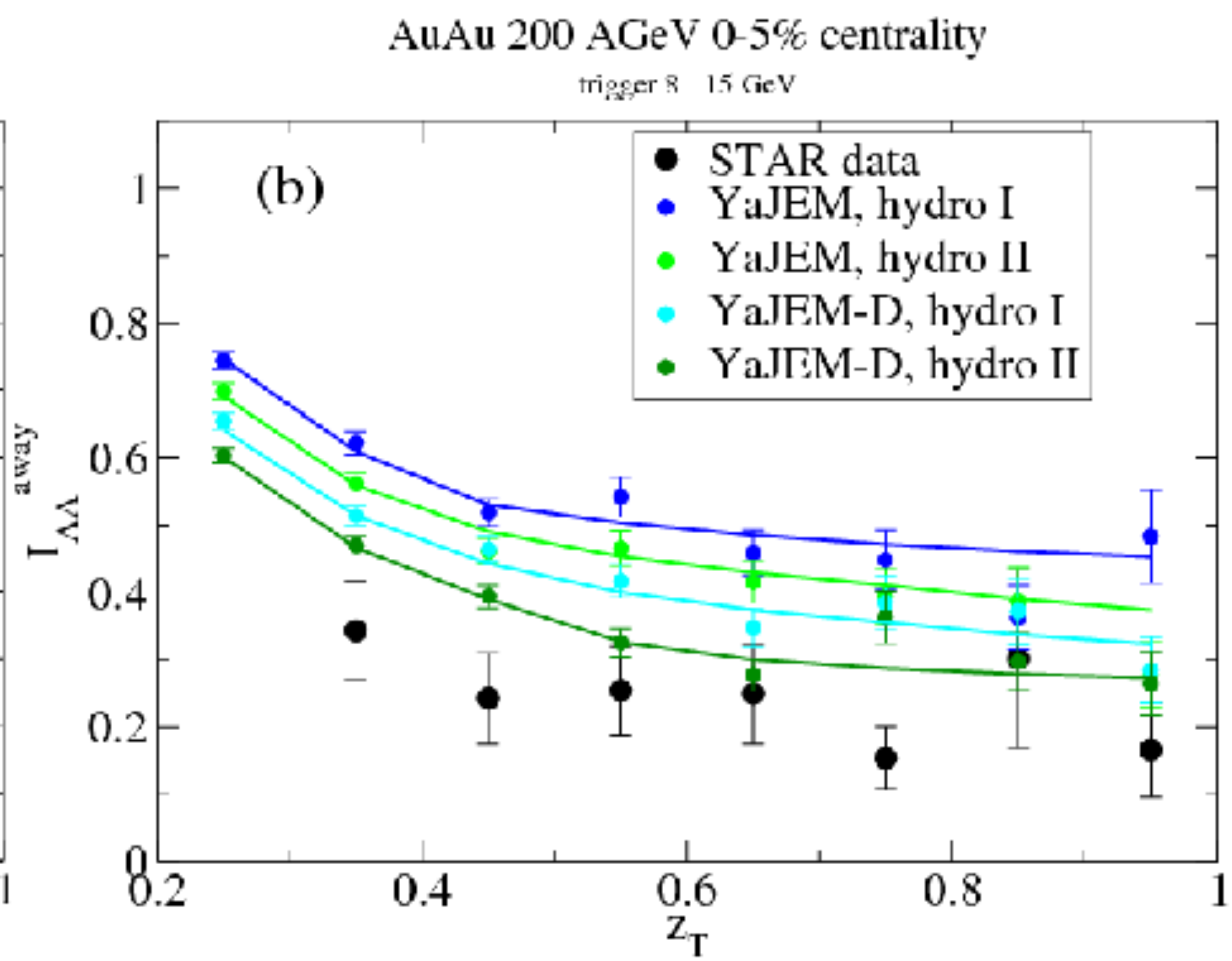
Can be modelled with the same tools as inclusive particle production

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 suppression
L^2 (YaJEM-D) slightly above

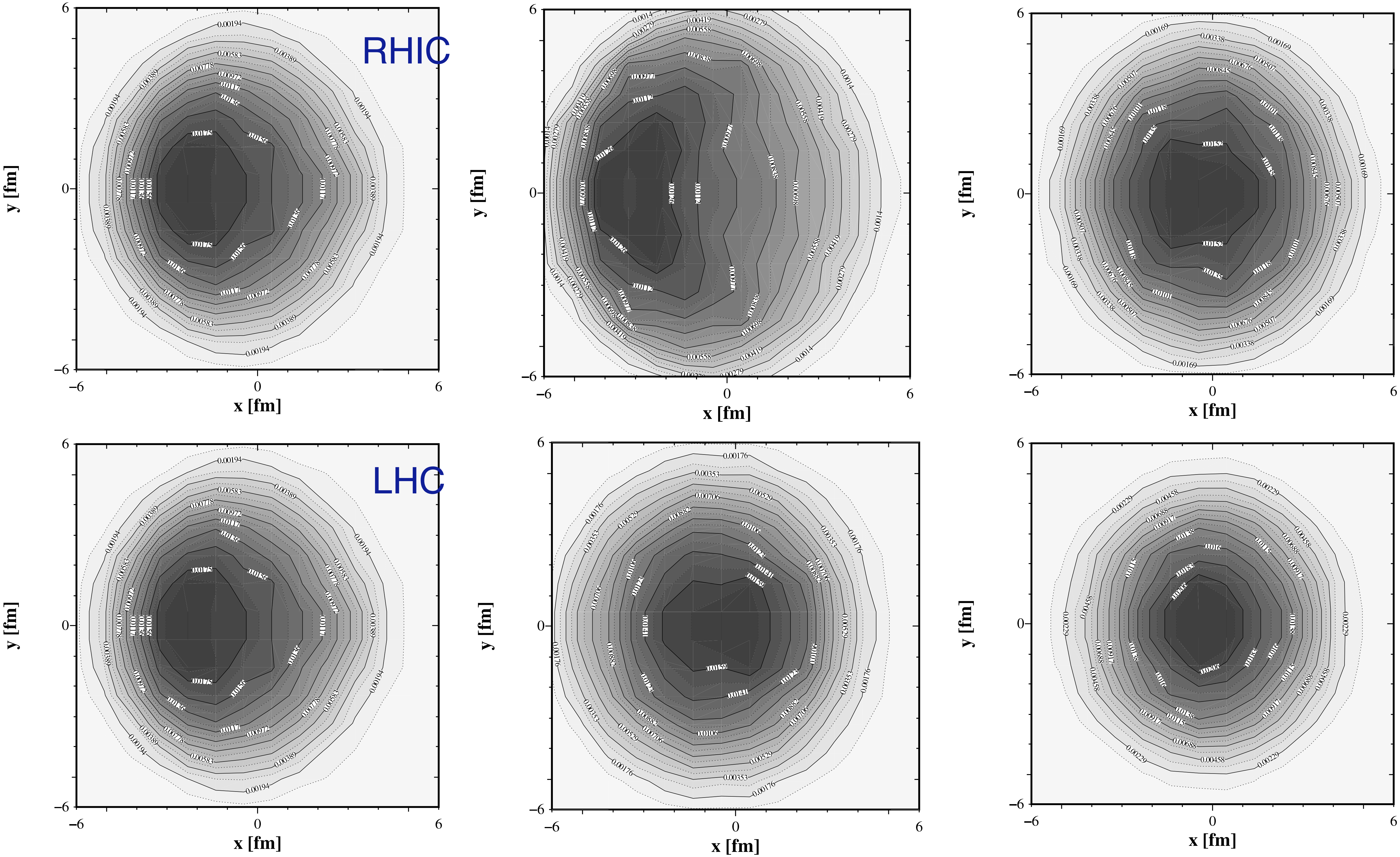
Clear sensitivity to *L* dependence

Modified shower generates increase at low z_T

Surface bias vs fluctuations

T. Renk, arXiv:1212.0646

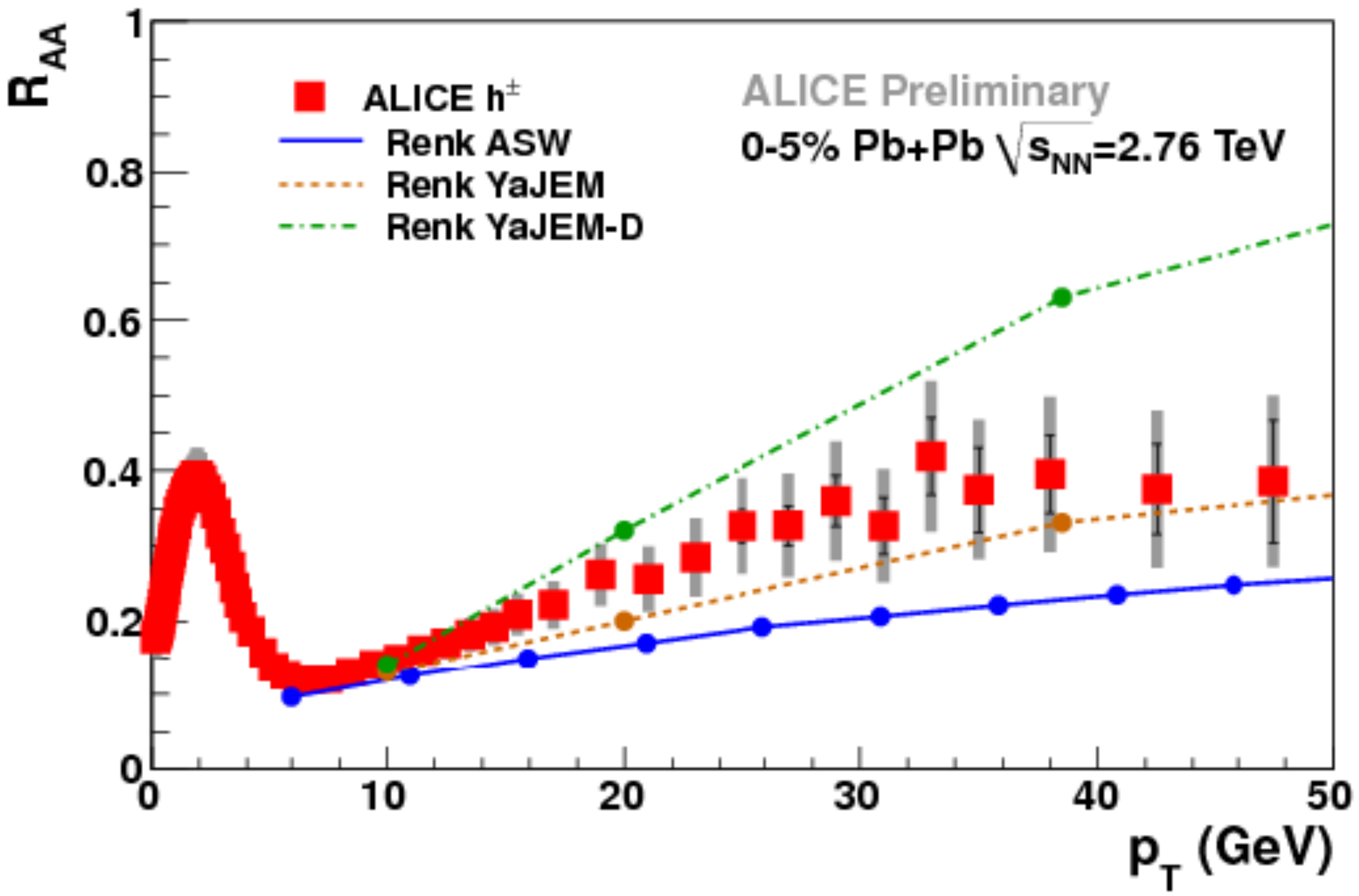
h-h | jet-h | jet-jet (A_J)



Surface bias differs between probes: largest for hadrons
and energy/collider: stronger at RHIC

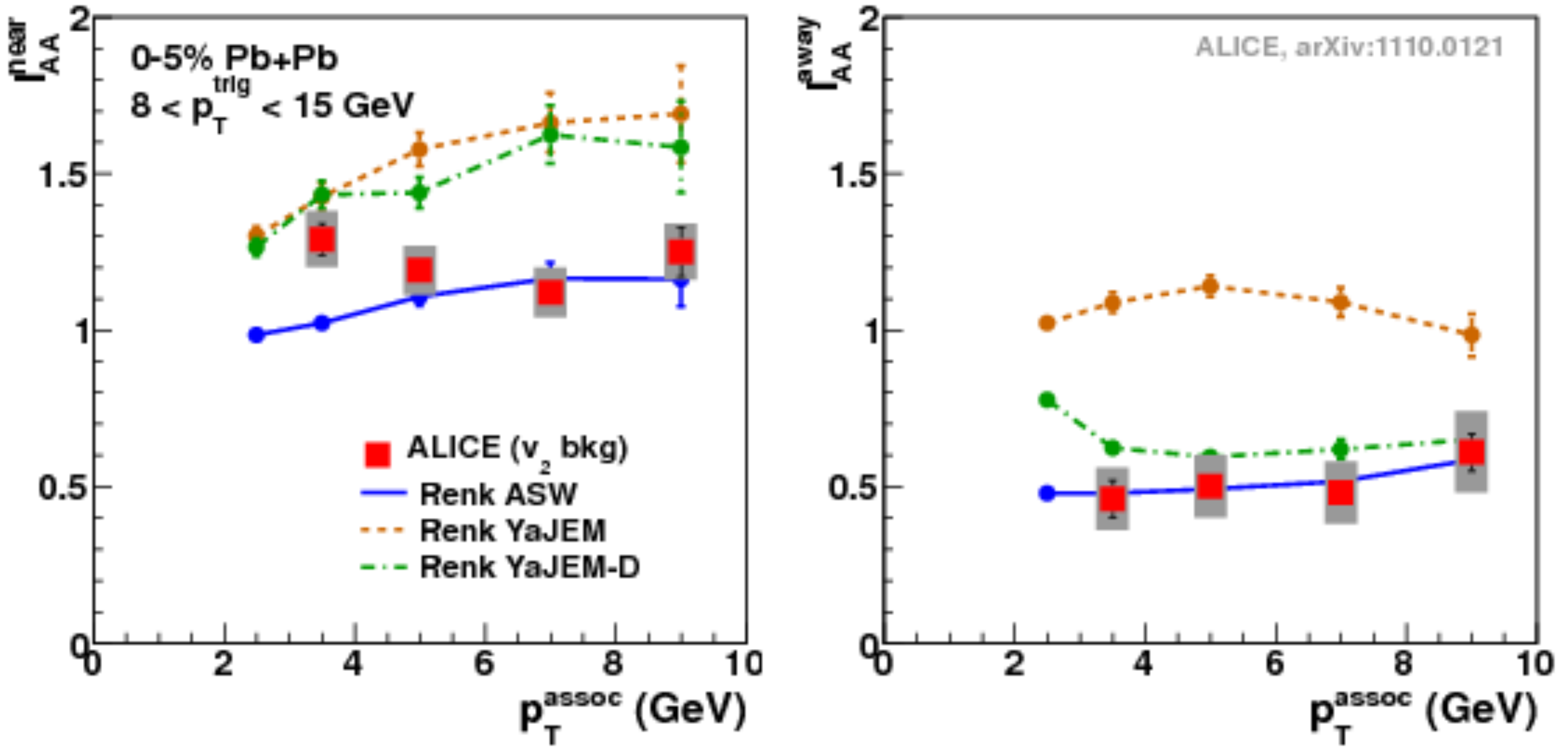
Di-hadrons and single hadrons at LHC

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



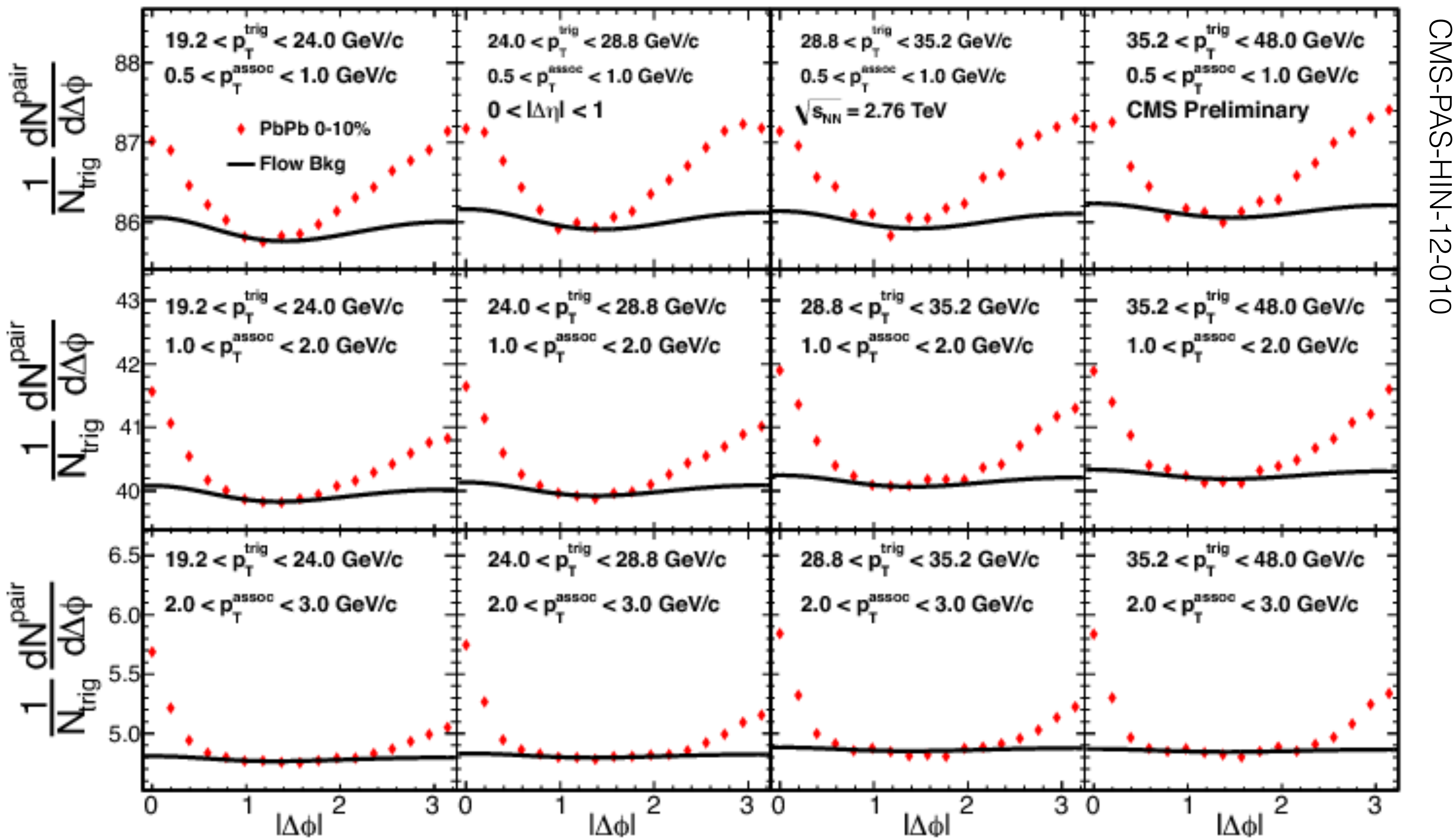
Here: R_{AA} and I_{AA}

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

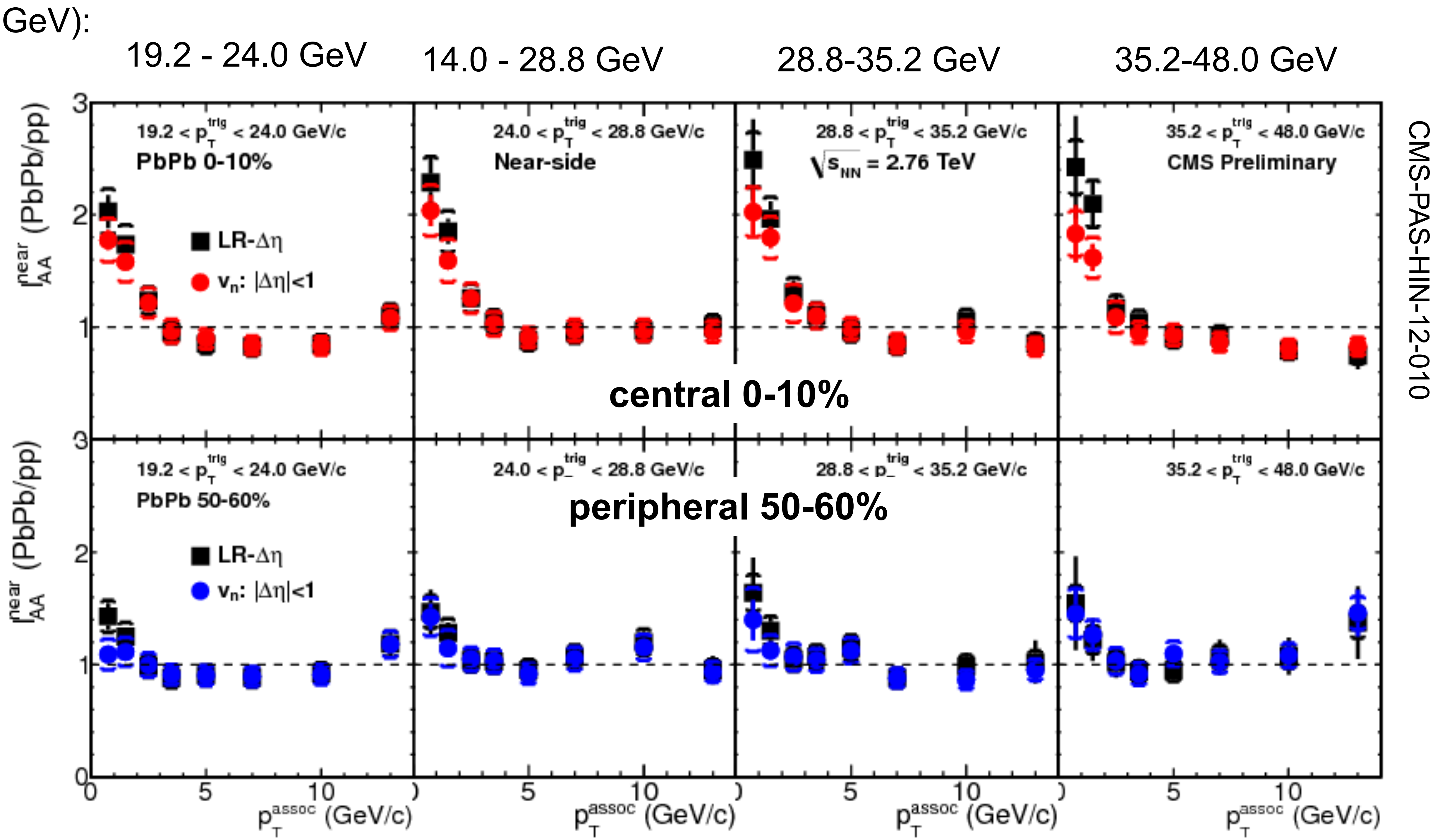
p_T^{trig} (GeV): 19.2 - 24.0 GeV 14.0 - 28.8 GeV 28.8-35.2 GeV 35.2-48.0 GeV



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

CMS-PAS-HIN-12-010

CMS di-hadrons: near side

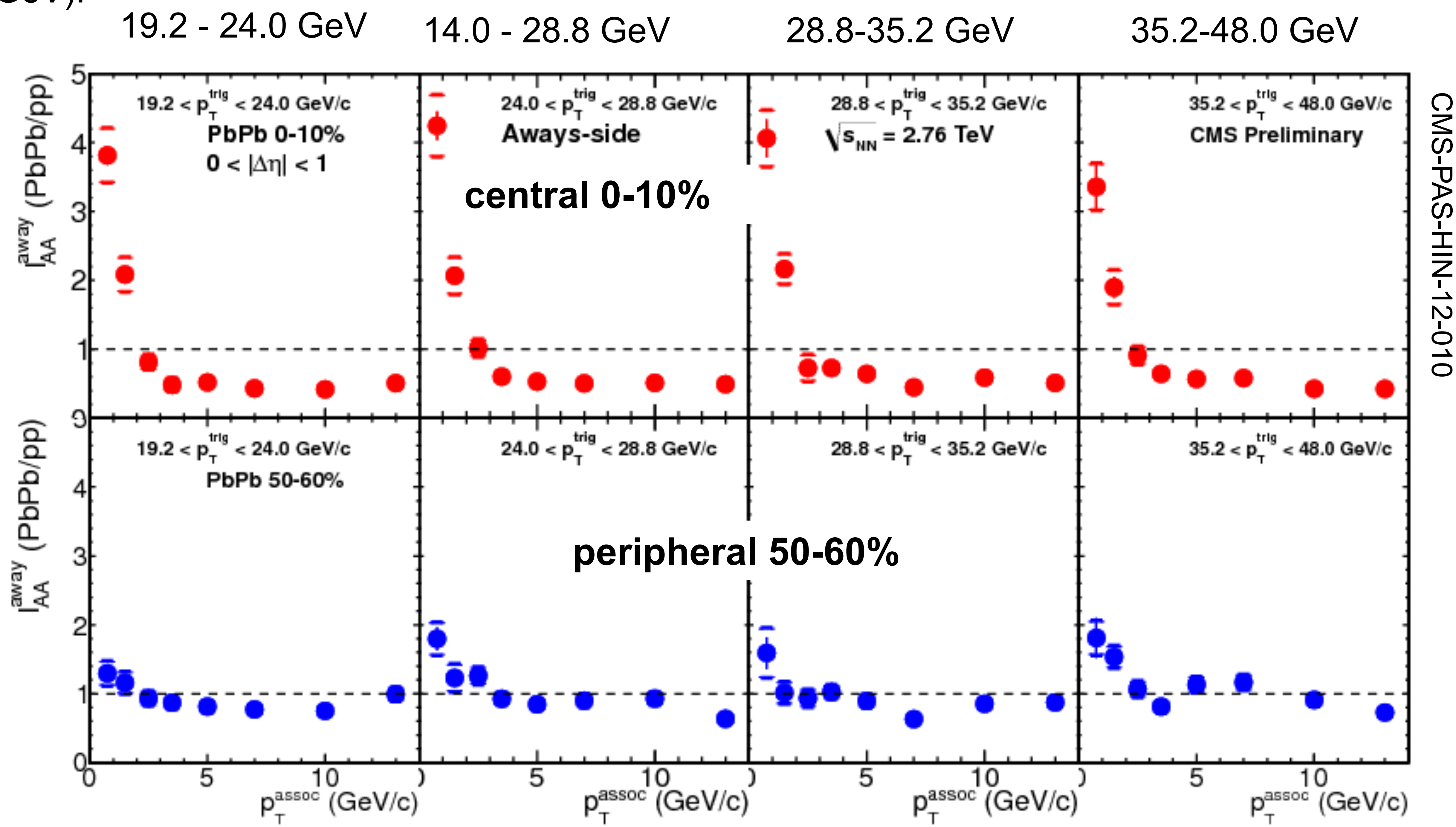


Transition enhancement → suppression @ p_T ~ 3 GeV

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

CMS di-hadrons: away side

p_T^{trig} (GeV):



Transition enhancement → suppression @ p_T ~ 2 GeV

Heavy flavour

Heavy flavour R_{AA}; mass dependence

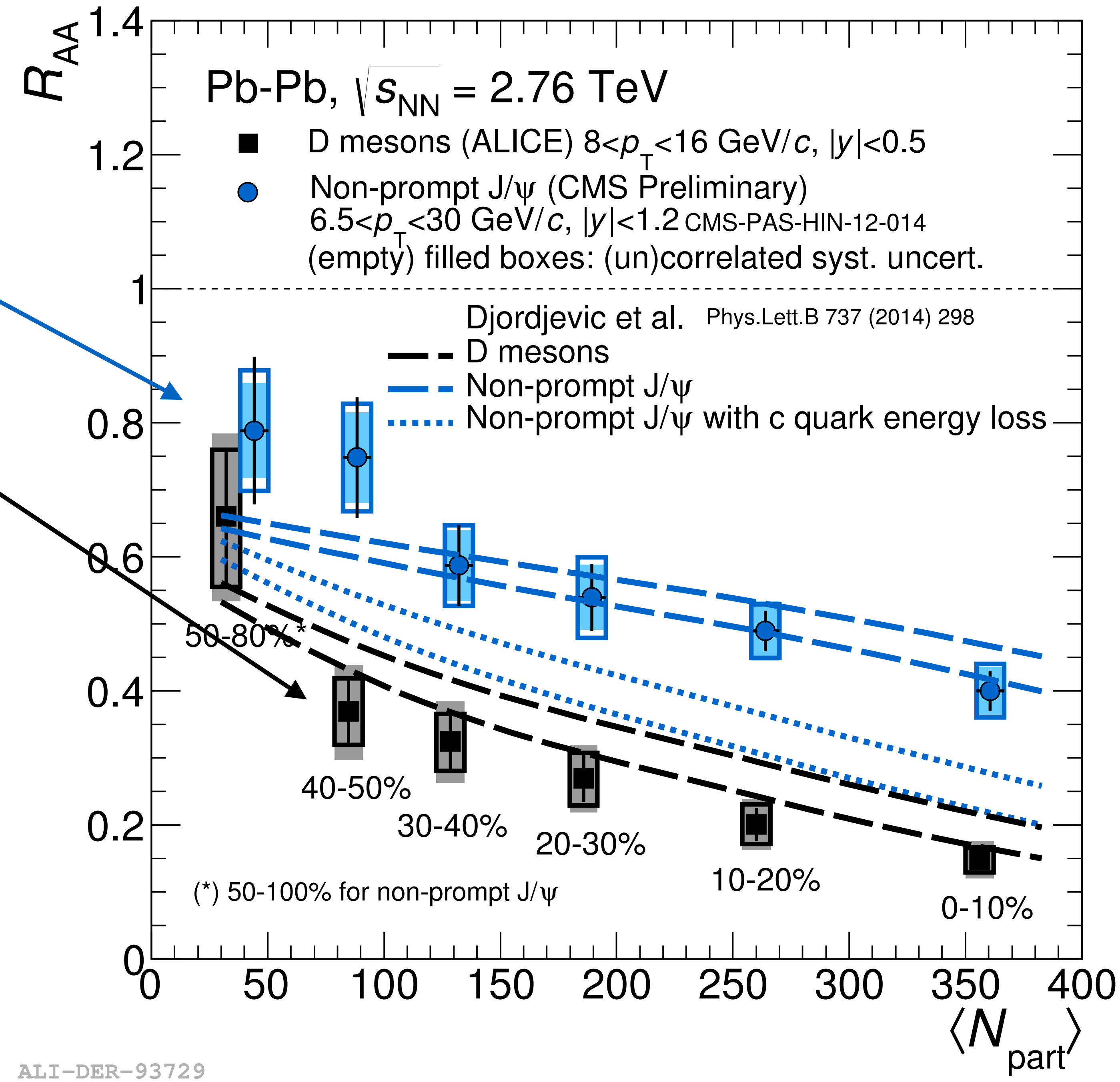
Compare
beauty: non-prompt J/Ψ
charm: D-mesons

Recent radiative (+coll) energy loss models agree well with HF data

Similarity of D meson and light hadron R_{AA} 'understood'

IMHO: importance of collisional energy loss not fully quantified

ALICE, JHEP11, 205

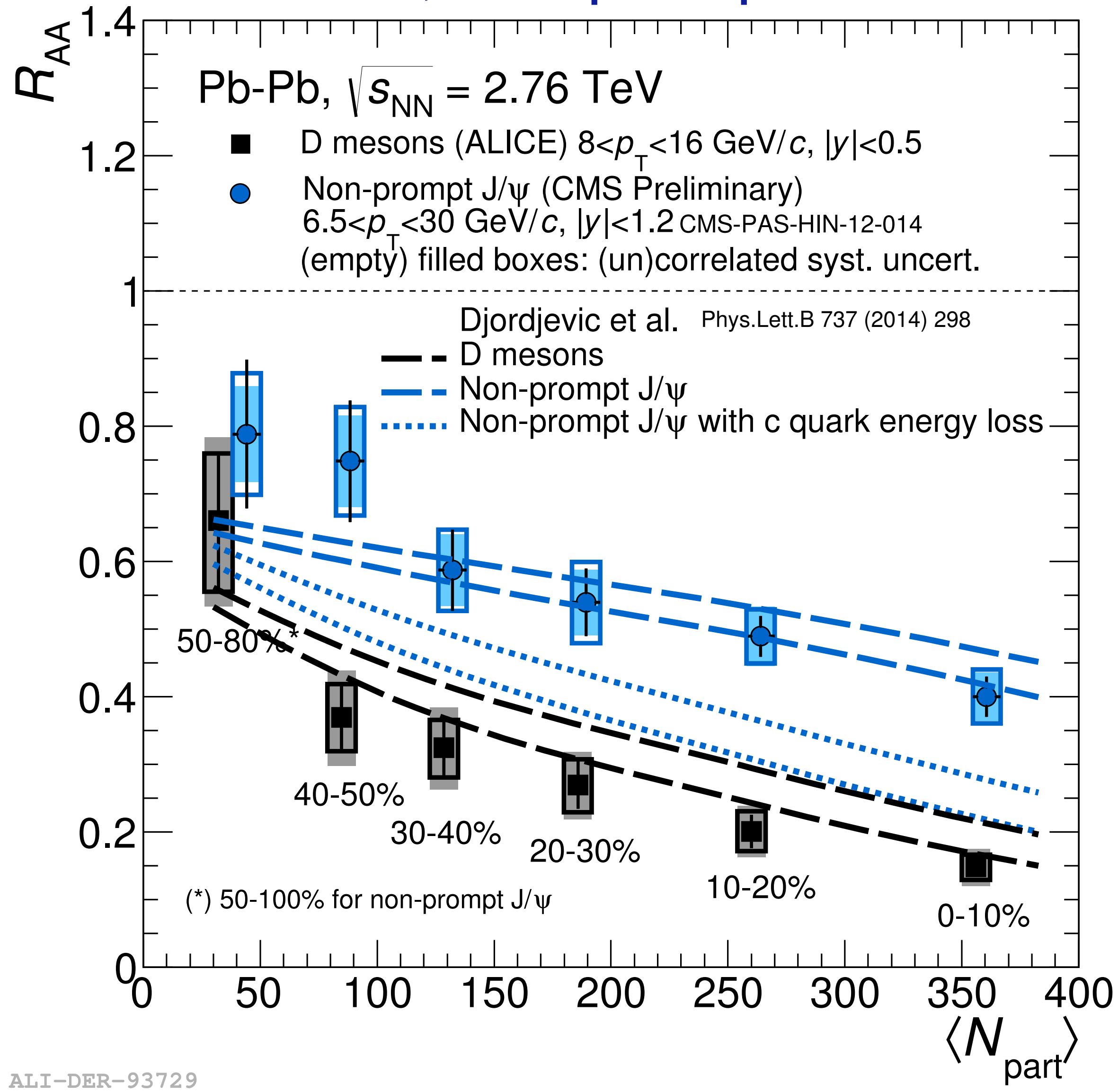


Medium model: PQM (static/expanding Glauber)

Heavy flavour

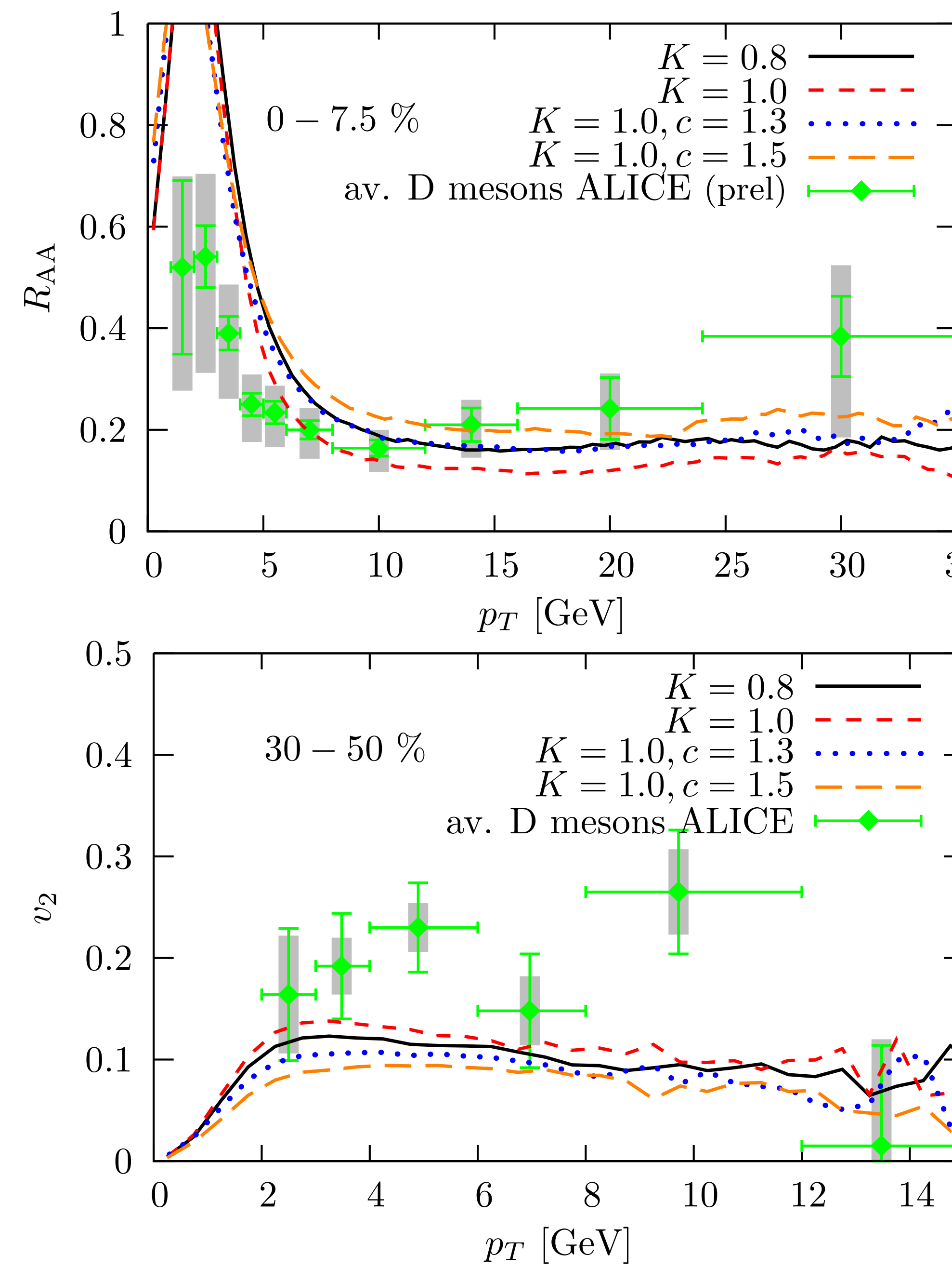
GLV-based semi-analytical

D meson, non-prompt J/Ψ R_{AA}



Djordjevic, GLV-based, arXiv:1307.4702

MC@sHQ Boltzmann transport MC



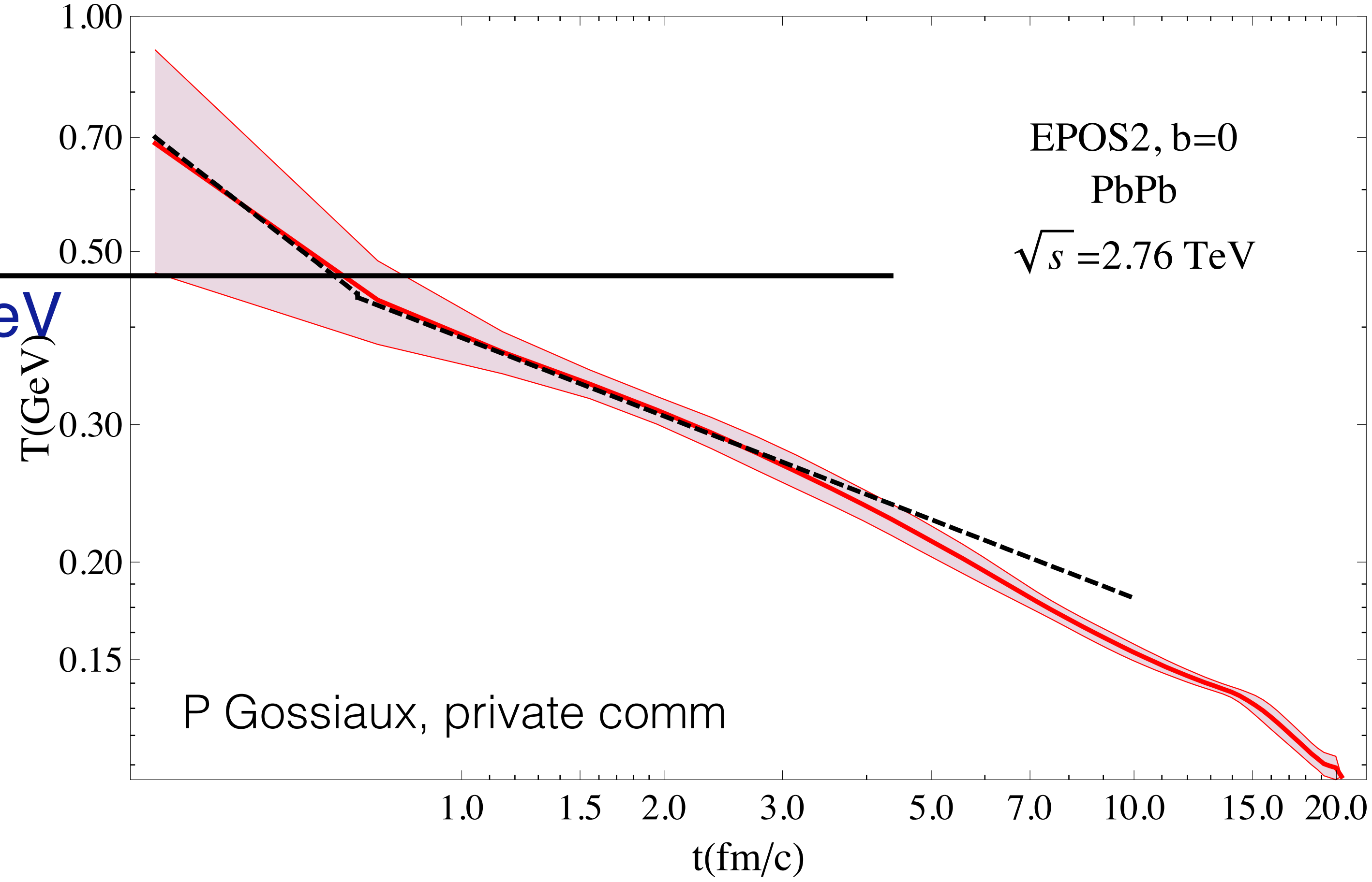
Nahrgang, Gossiaux et al, MC@sHQ, arXiv:1305.6544

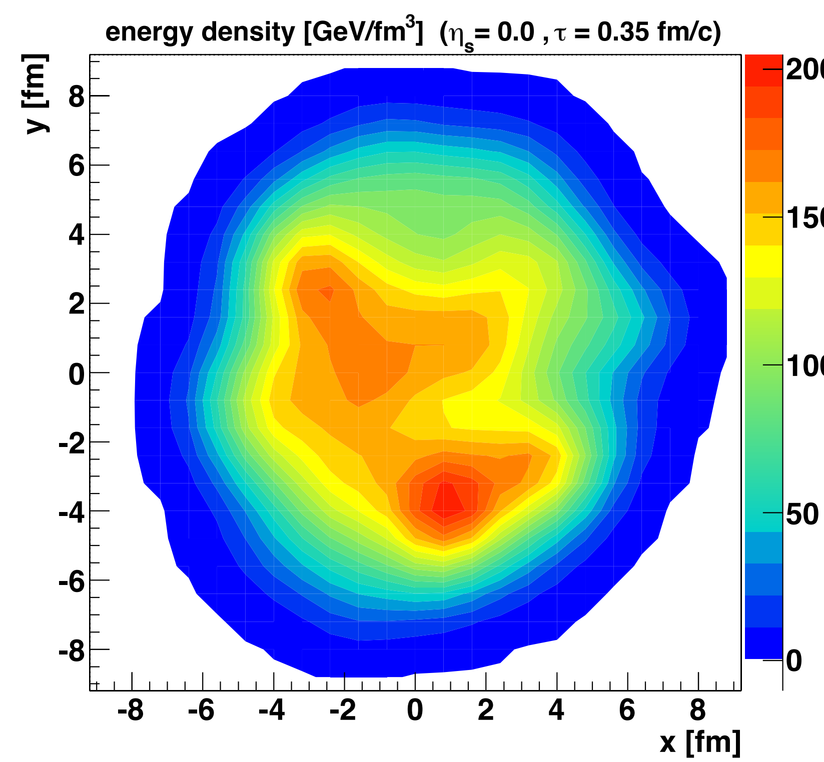
Heavy flavour well captured by models

(v_2 may be under predicted, like for light flavour)

T vs t in EPOS/MC@HQ

JET collab
T_{init} = 470 MeV





Werner, et al, arXiv:1203.5704

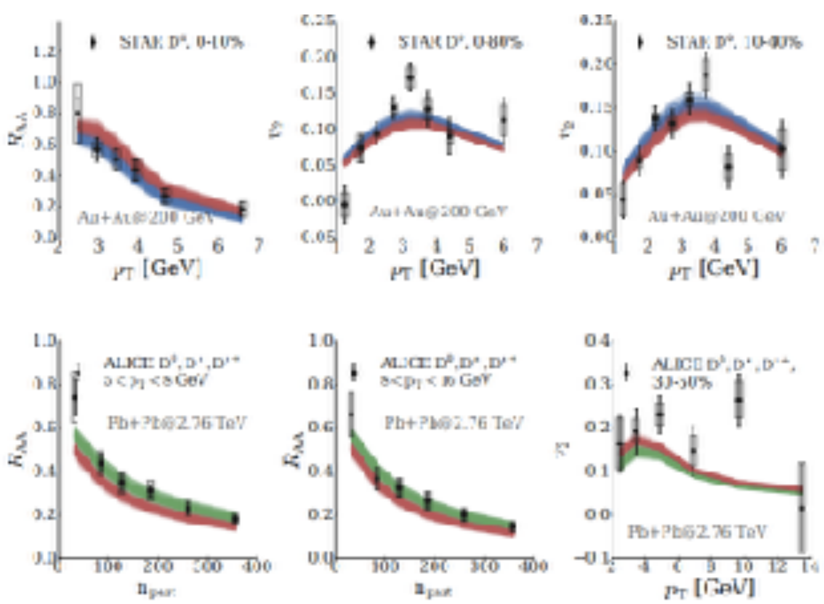
Medium parameters in MC@HQ agree well with light flavour fits

Q: how does the relation $\Delta E(T)$ compare?

Heavy Flavour diffusion coefficients

Duke fit: R_{AA}, v_2, RHIC+LHC

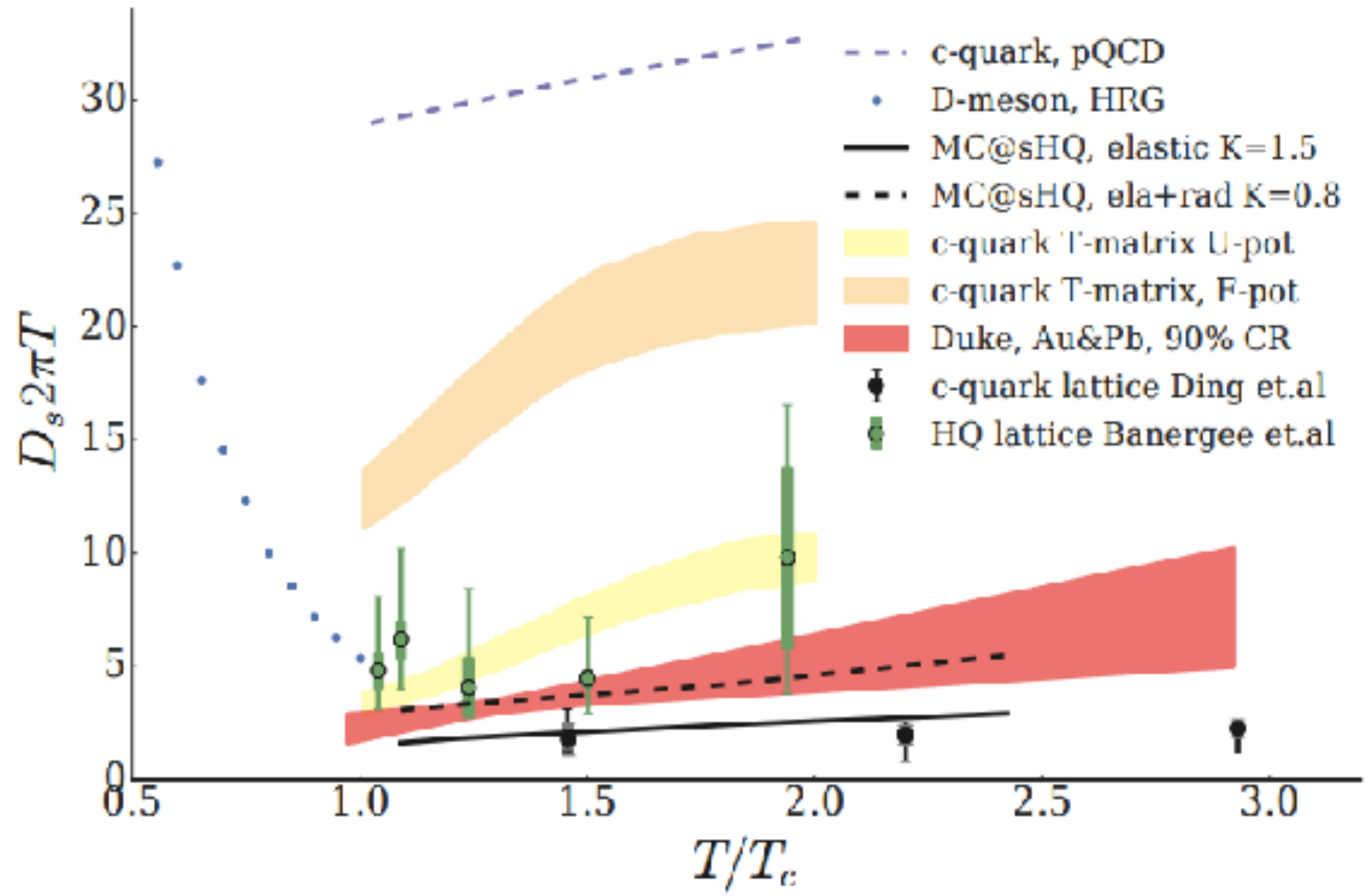
Y Xu, Quark Matter 2017



Physical model:
Linearized Boltzmann Transport

Cao et al, PRC 92, 024907

Comparison of various models/fits



F.Riek,and R.Rapp, Phys.Rev.C 82,035201(2010)

H.Ding,A.Francis,O.Kaczmarek,et.al, Phys.Rev.D 86,014509(2012)

M.He,R.J.Fries,and R.Rapp, Phys.Rev.Lett 11,112301(2013)

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First comparisons of heavy flavour transport coefficients
Still early days; work needed to understand (dis-)agreements

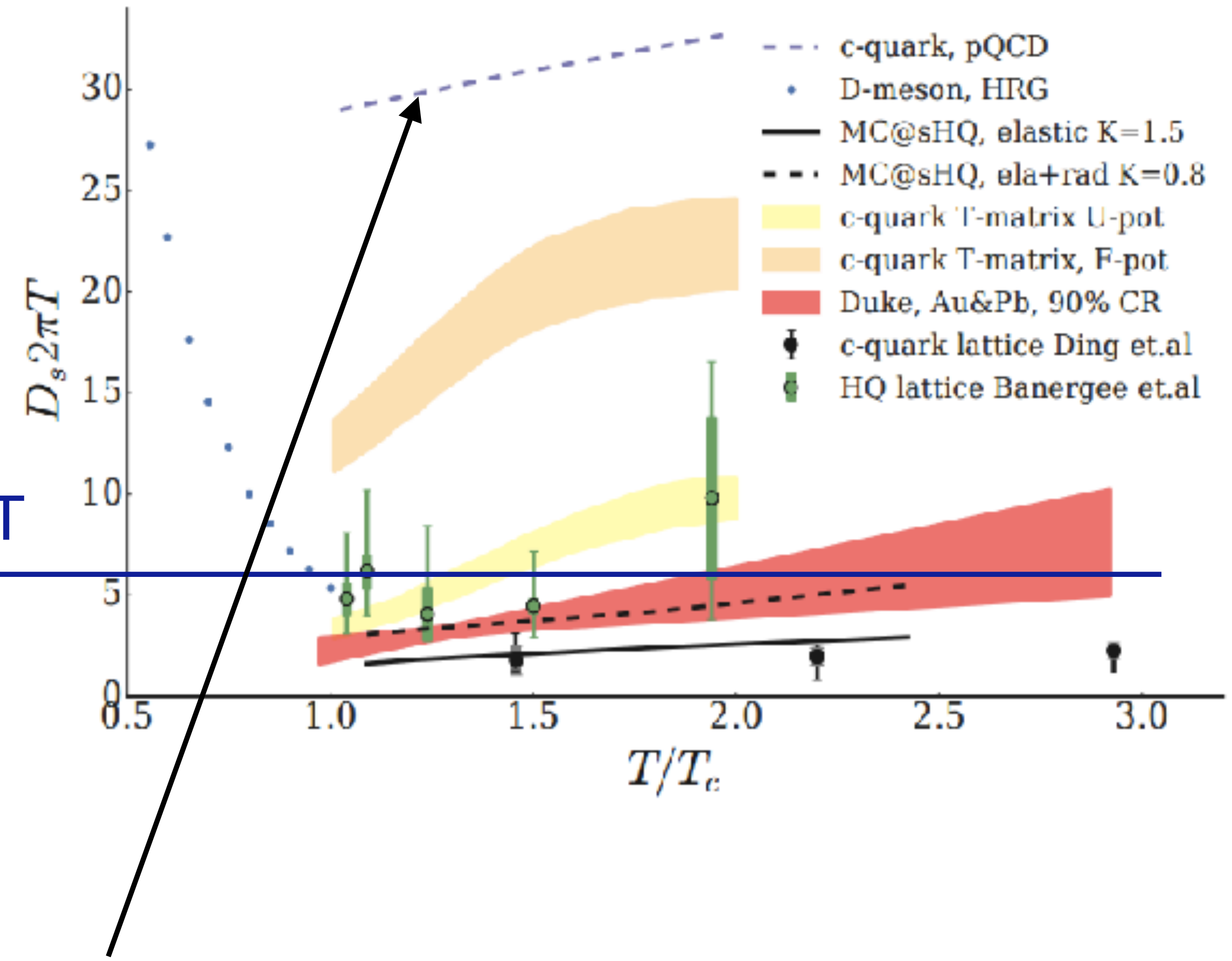
Relation D_s and $\hat{q}$

Cao, Qin, Bass, PRC 88, 044907

$$2\,\pi\,T D_s \;=\; 8\pi \frac{C_F}{C_A}\frac{T^3}{\hat{q}}$$

(approximate relation;
D_s and qhat are different regimes)

D_s = 6/2 pi T



Trying out some numbers:

qhat(T=400 MeV) = 3 GeV²/fm

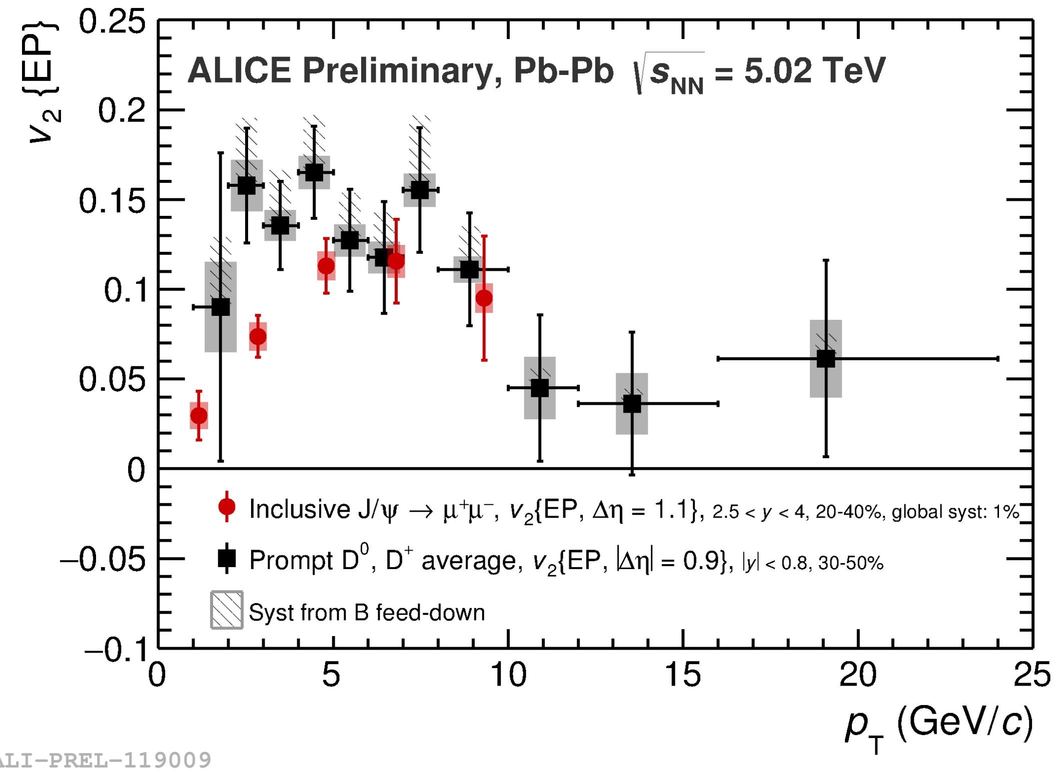
However, perturbative estimate D_s = 30/2 pi T —> qhat ~ 0.6 GeV²/fm

Why is the perturbative estimate of D_s so large?

LO: Svetitsky, PRD 37, 2484

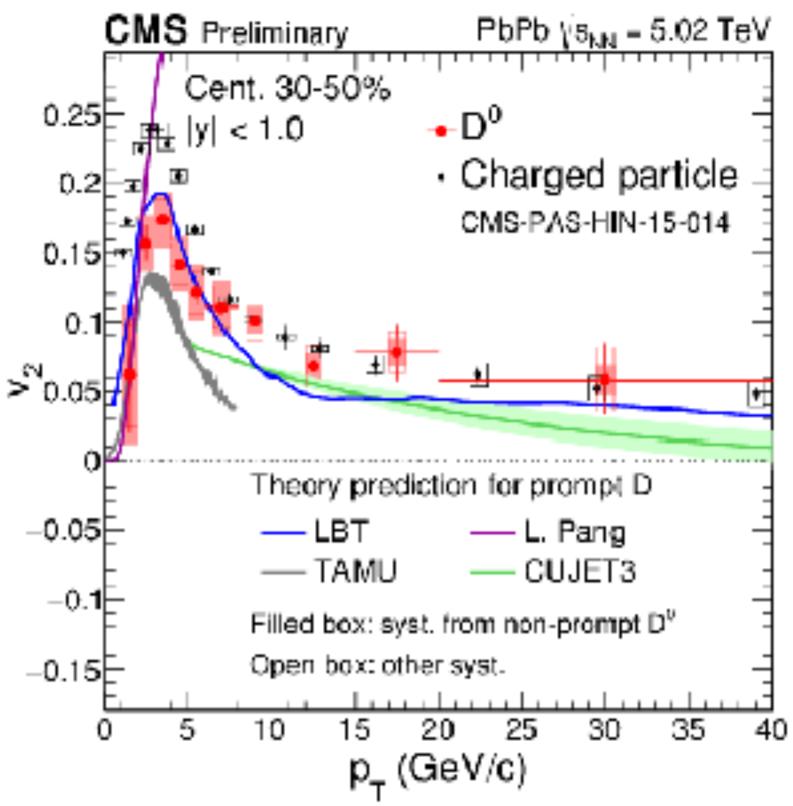
Charm v_2, v_3

J/Ψ and D meson v_2

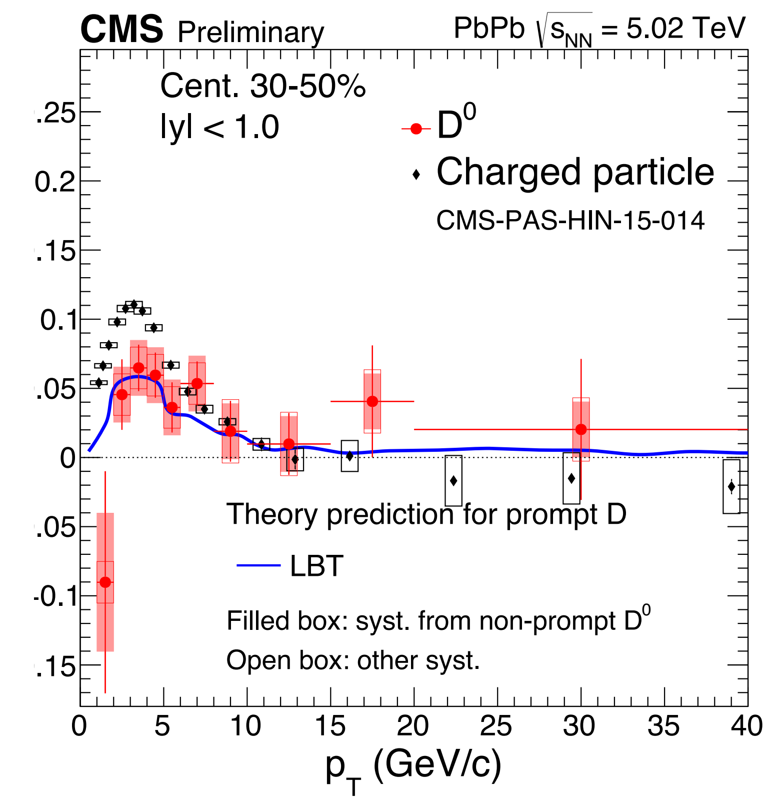


ALICE, QM2017, Barbano, Tarhini

D meson v_2



D meson v_3



Models: PRC 94 014909, PLB 735 445, JHEP 1602 169 and PRD 91 074027

LHC run 2 data for charm v_2, v_3 becoming very precise

Should revisit the fits with the new data

And compare heavy and light flavour where possible!

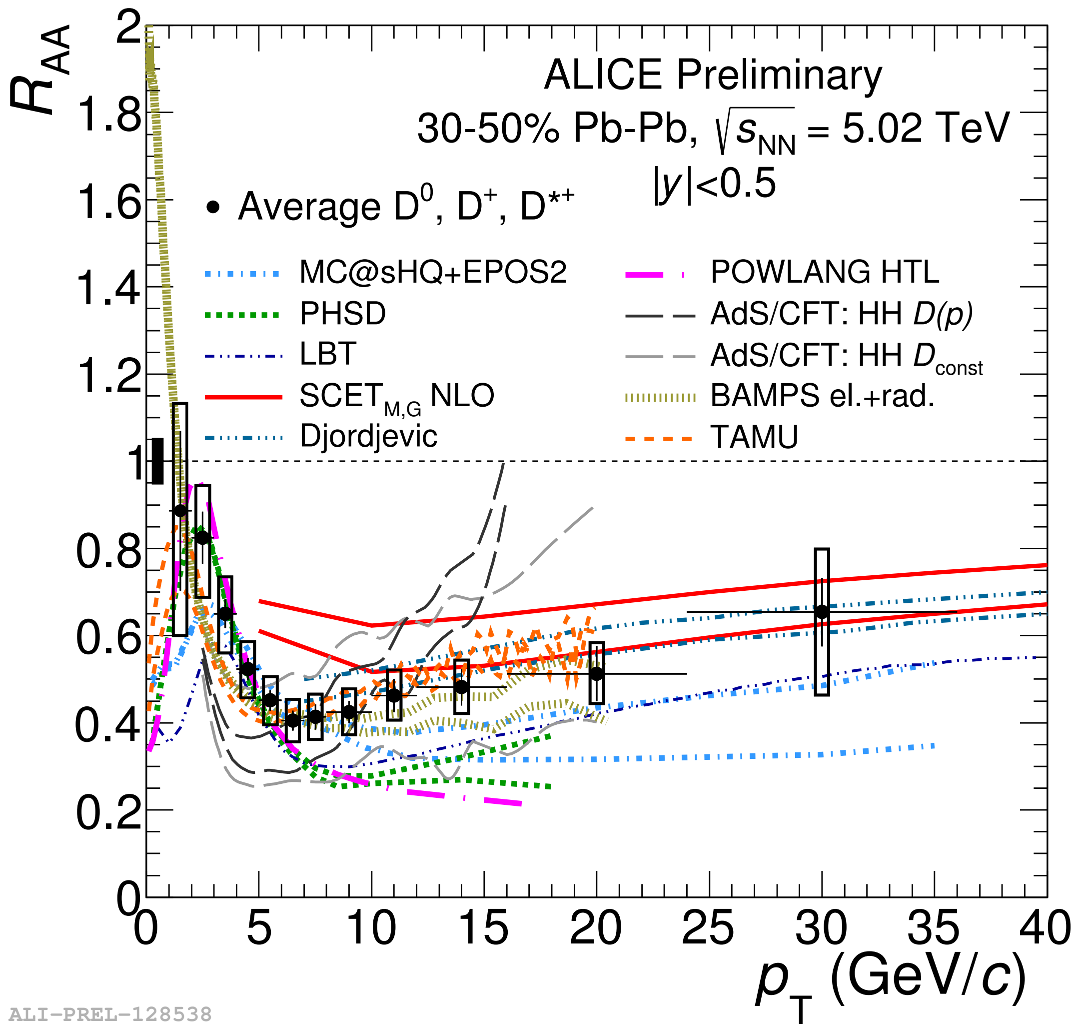
Summary

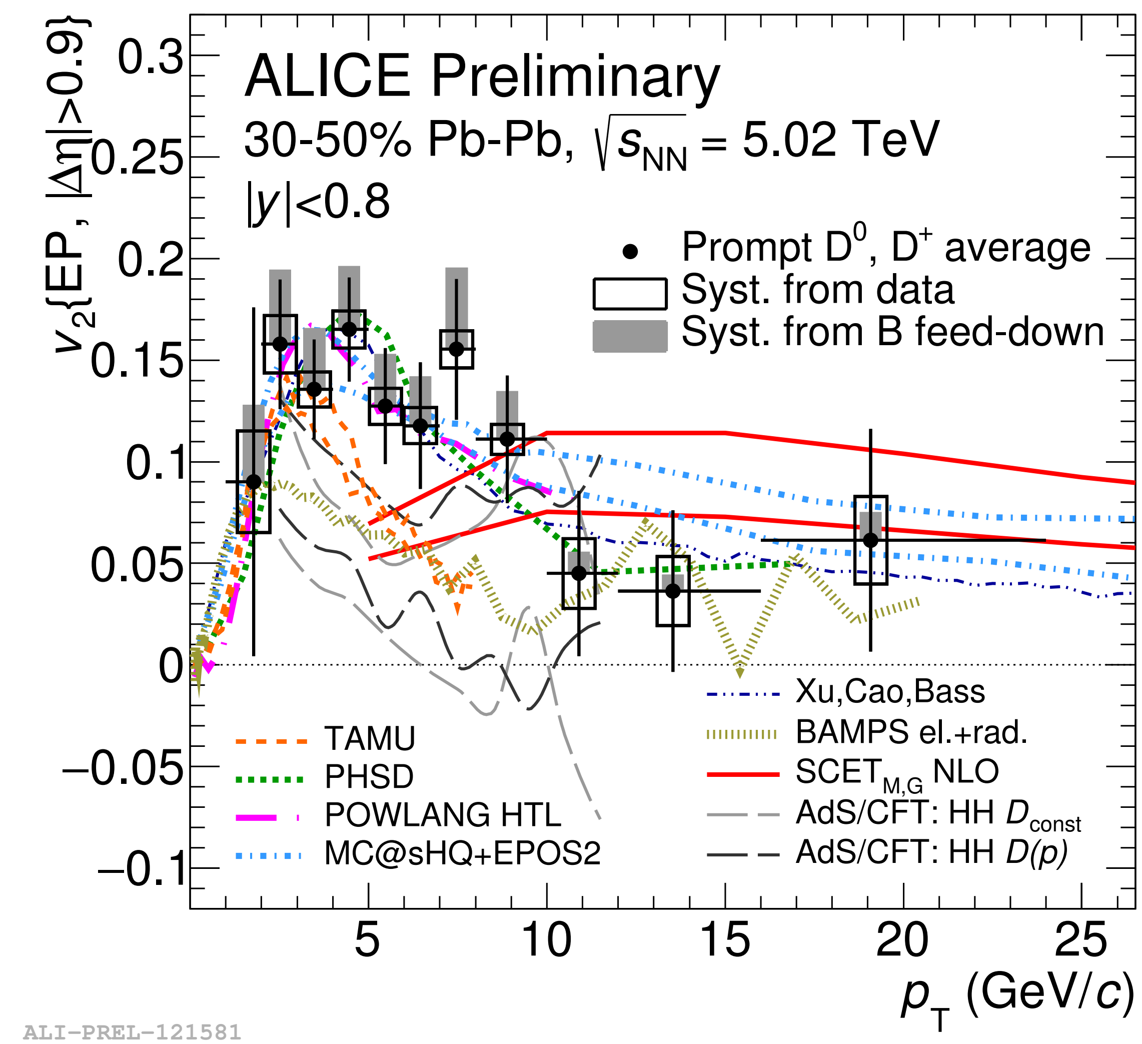
- Magnitude of energy loss understood at the semi-quantitative level
  - Several sizable uncertainties in energy loss kernels; would be nice to improve
- Some differences in convention/practice also enter the discussion: a_s, log(E/T), ndf
  - Mixed together with ‘intrinsic’ uncertainties from soft sector?
  - Can be mostly addressed by agreement on conventions
- A real (semi-)quantative test of our understanding requires multiple observables
  - R_{AA}, v_2, di-hadron, light and heavy flavour
  - Takes out some of the ‘convention uncertainties’

Thanks for your attention

Heavy flavour 5 TeV

Barbano, QM





No lack of calculations…
Only a few describe R_{AA} and v_2 at the same time

Should find out what this tells us about energy loss (modelling)

Density in EPOS/MC@sHQ

Medium density from EPOS:

ε = 150-200 GeV/fm^3

T ≈ 700 MeV

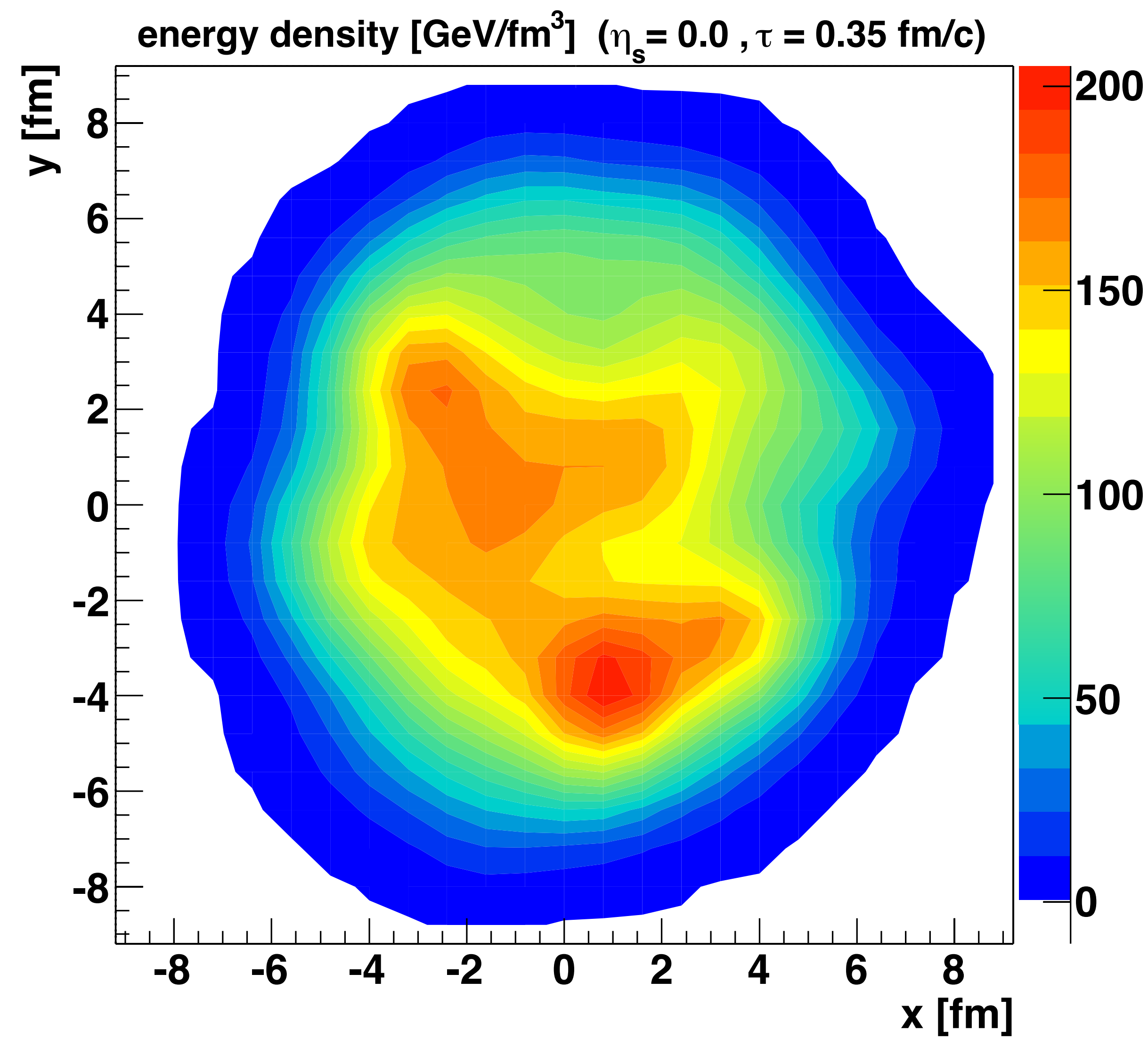
τ = 0.35 fm/c

ε = 75-98 GeV/fm^3

T ≈ 585 MeV

τ = 0.6 fm/c

Values somewhat higher than JET collaboration



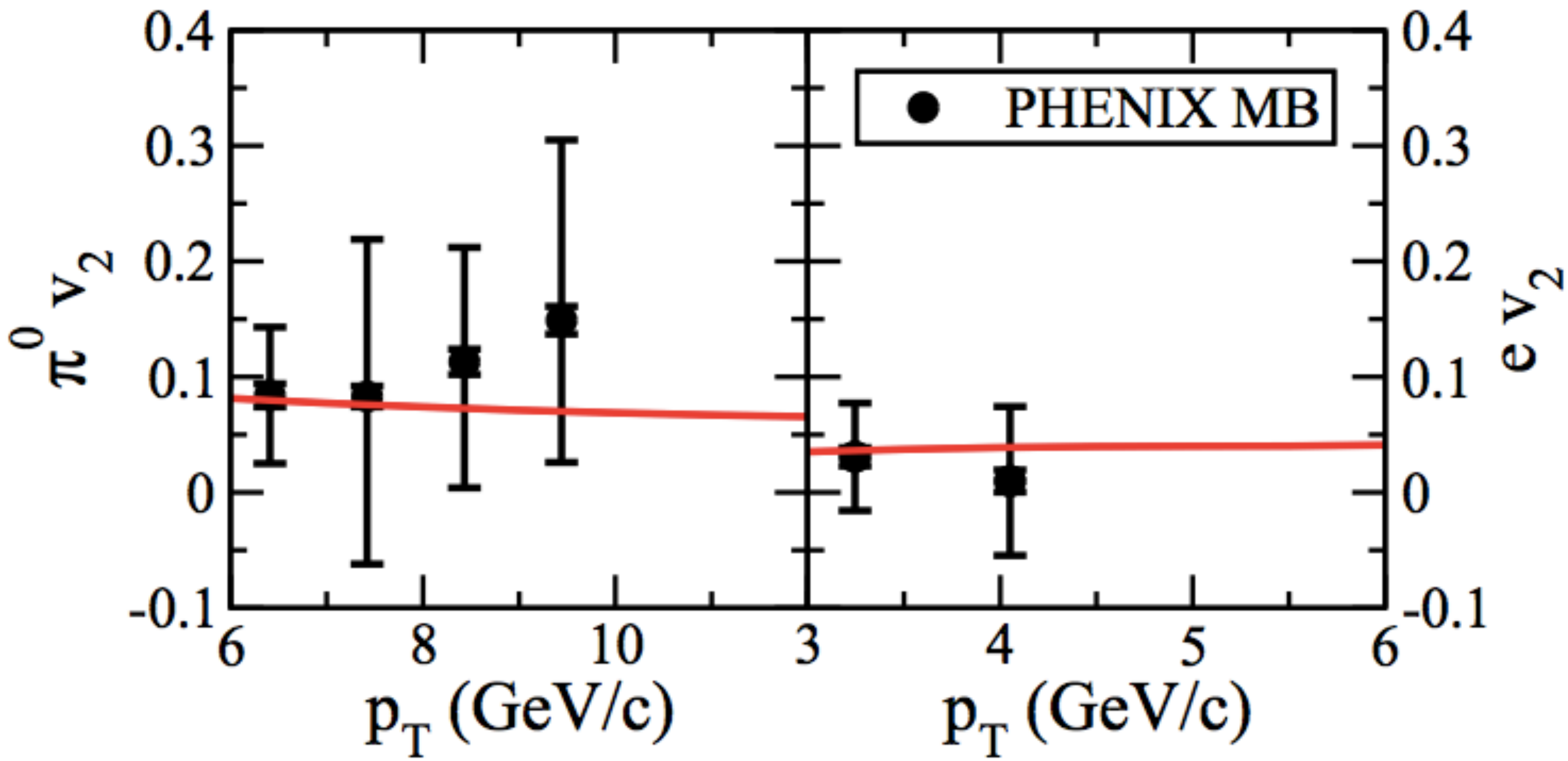
Werner, et al, arXiv:1203.5704

Caveats:

- Final value depends energy loss, density for $\tau < 0.6$ fm/c
- Energy loss model not fully benchmarked against BDMPS-Z/GLV

v_2 in Higher Twist

Qin and Majumder, arXiv:0910.3016

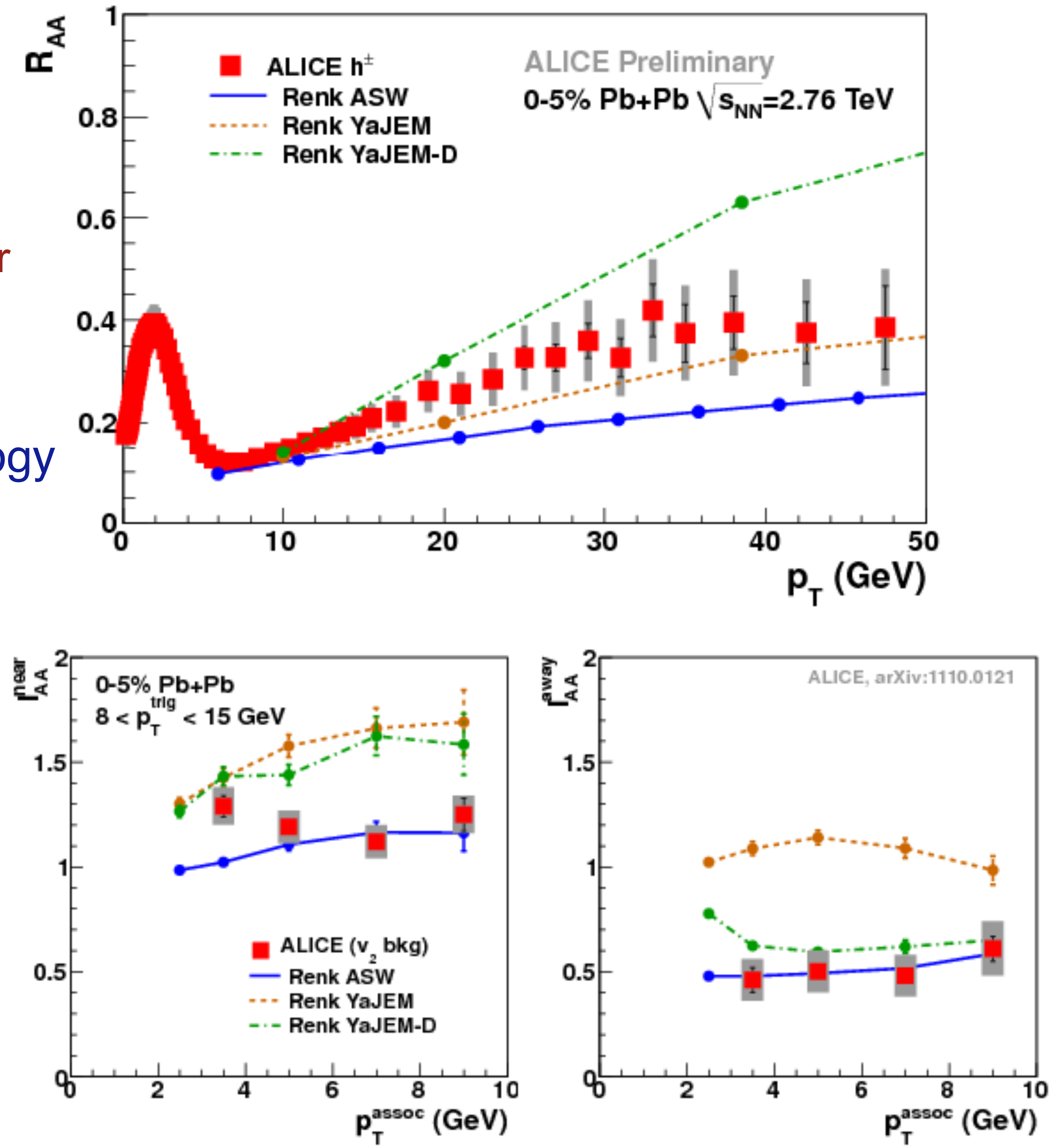


Di-hadrons and single hadrons at LHC

Simultaneous comparison to several measurements to infer geometry and E-loss behaviour

Away-side I_{AA} and R_{AA} can be calculated with the same technology

Needs a push to happen…



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

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?

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 (profile))

} Energy loss theory (Path length dependence; Parton energy dependence; Energy loss distribution)

Determine/ constrain from measurements

Use different observables to disentangle contributions

Summary/conclusion

- Measured R_{AA} is in reasonable agreement with expectations:

  $\hat{q} = 1.9 \pm 0.7\ GeV^2/fm$ at LHC, τ_0 = 0.6 fm/c

  - q/T^3 ≈ 4, HTL expectation ≈ 2, so suppression larger than expected
  - Absolute 'calibration' difficult: $\Delta E \propto \alpha_S^3 T^3$
- Other observables also fall in place: v_2, heavy flavour
- Potential to infer medium density evolution with multiple observables
  - Needs work, theory+experiment
- New tools/directions are being pursued: jets, multi-particle measurements

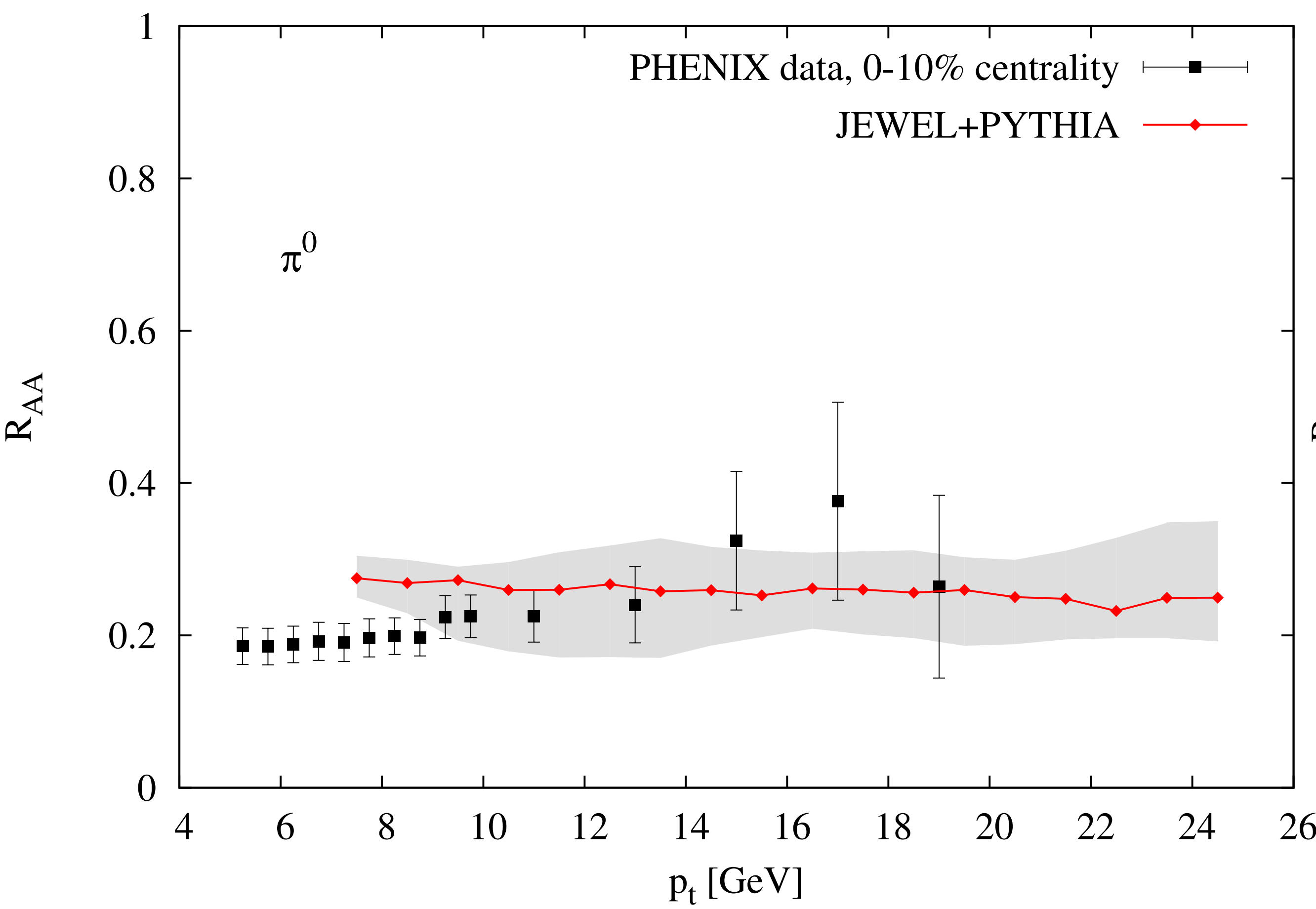
MC tools: JEWEL

Publicly available

Zapp, Krauss, Wiedemann, arXiv:1212.1599

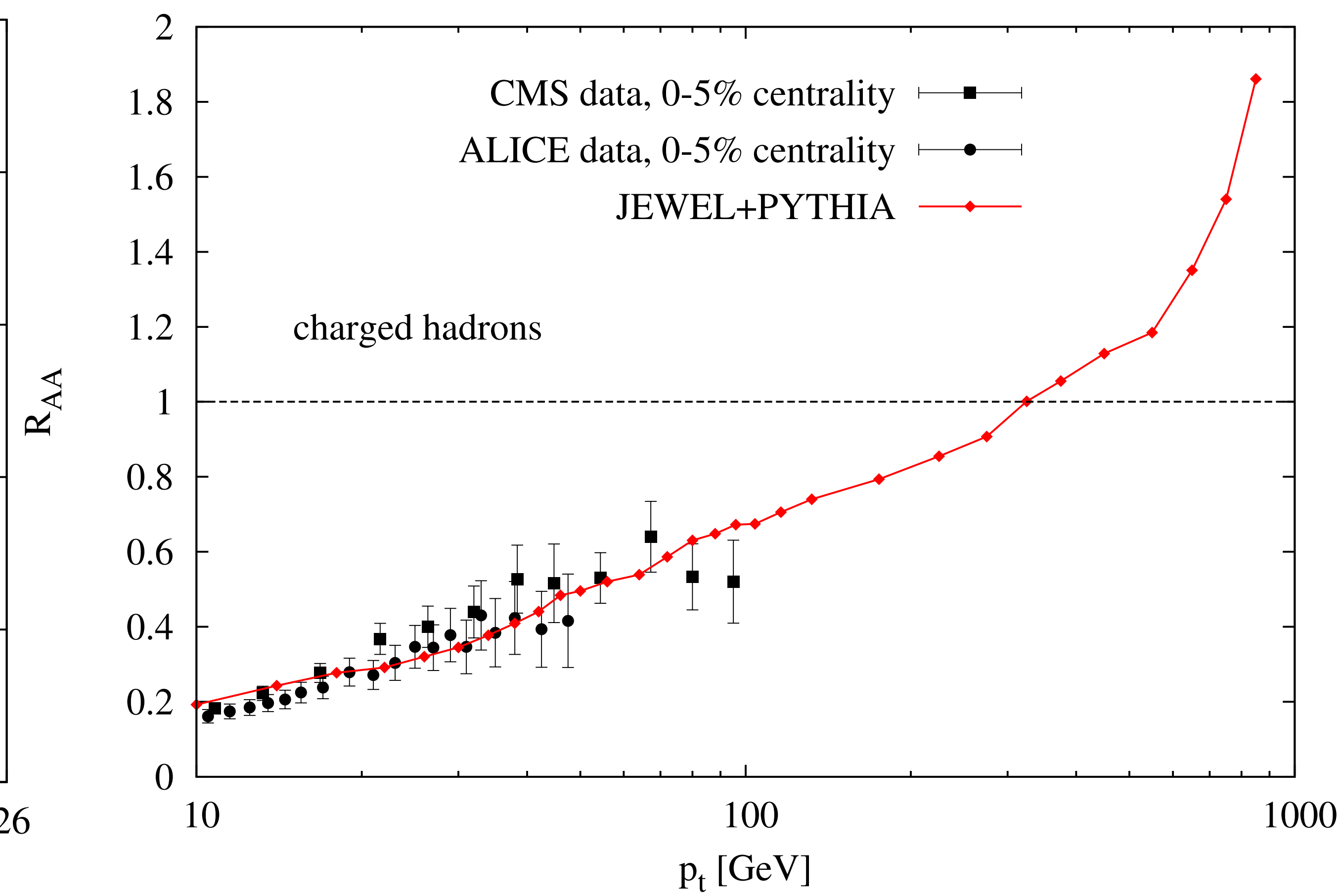
Elastic+radiative energy loss; follows BDMPS-Z in appropriate limits
Medium: Bjorken-expanding Glauber overlap

RHIC



T_i = 350 MeV @ τ_0 = 0.8 fm/c

LHC

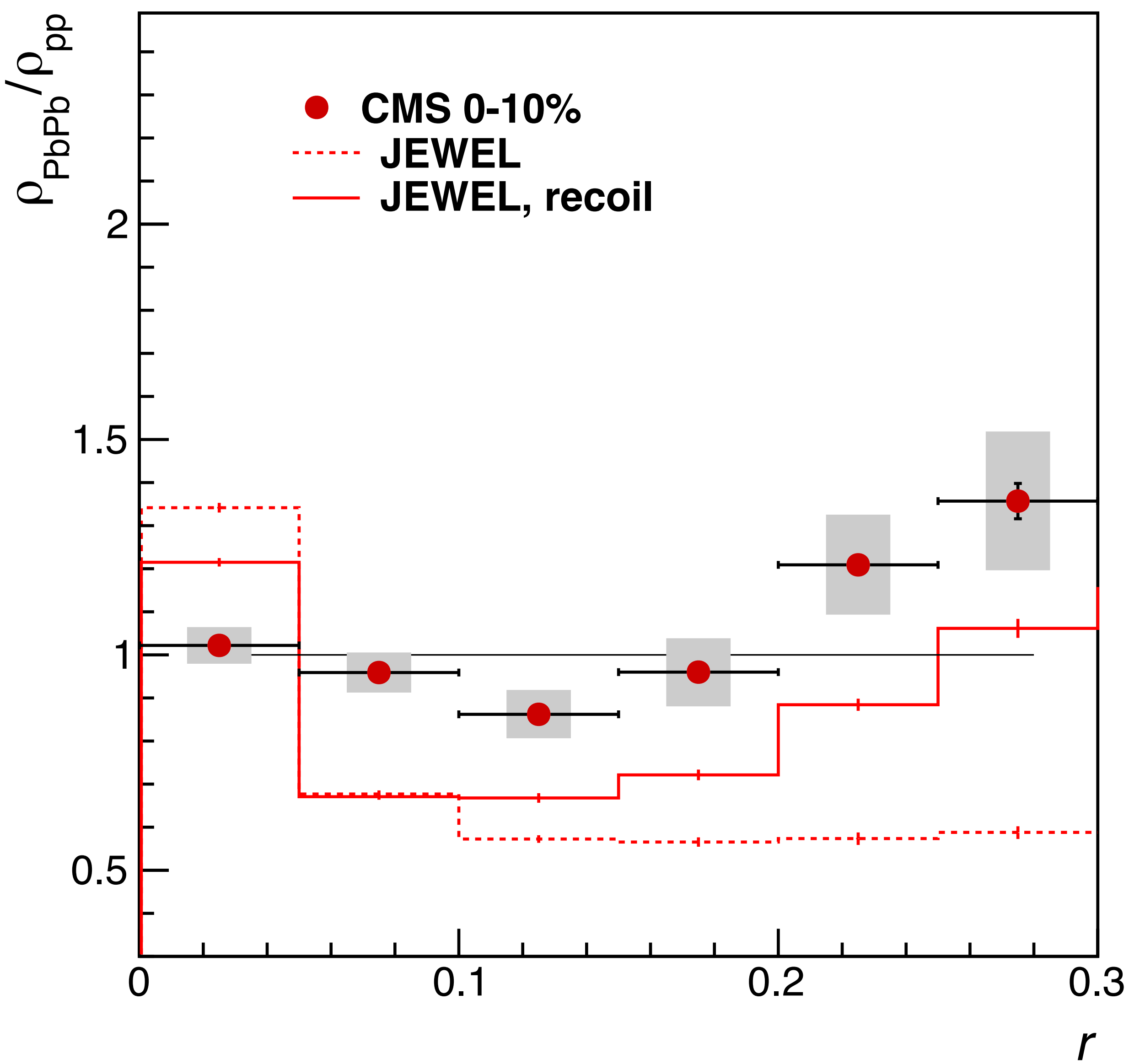


T_i = 530 MeV @ τ_0 = 0.5 fm/c

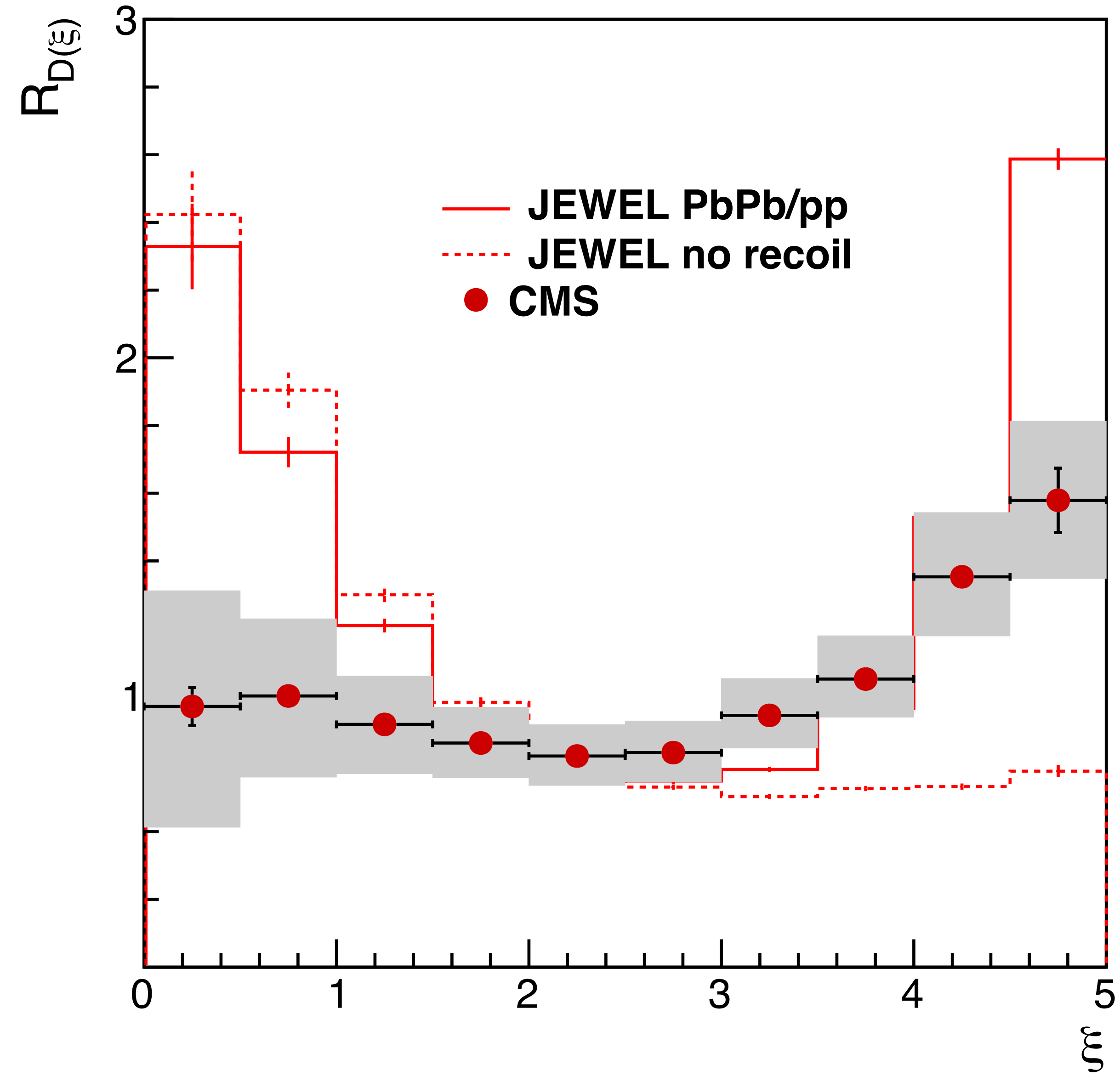
Good agreement with JET collaboration values

JEWEL jet fragmentation

Radial jet profile



Fragmentation function



MC generators allow more differential exploration of jet modification, radiated energy

NB: soft radiation model-dependent