Jet quenching: future experiments and ‘End Game’

Marco van Leeuwen, Nikhef, CERN

JETSCAPE Workshop, 5-7 January 2018
LBNL, Berkeley

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Disclaimer:
We are (I am) not in a position yet to design the End Game yet, but will try to do the next best thing….

The physics of parton energy loss — what do want/can we aim to learn?

Two broad categories: nature of energy loss mechanism and nature of the medium

Nature of the energy loss mechanism

Nature of the medium

Plus a host of technical questions, e.g. role of event-by-event/geometry fluctuations

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- Flavour dependence of energy loss
- Path length dependence of energy loss
- Interference: do jets lose energy as a single parton?
  - Also formation time effects
- Transverse broadening: relate transverse and longitudinal dynamics
  - Testing our understanding of the medium/dominant process

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Nature of the medium

- Density of the medium/value of qhat (vs temperature)
- Distribution of radiated energy; approach to thermalisation?
- Nature of the scattering centers?
  - Large angle deflection

Plus a host of technical questions, e.g. role of event-by-event/geometry fluctuations

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  - Als
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  - Te

Goal of the field: answer as many of these questions as we can, as well as we can

Technical questions have lower priority, but some may need answers to get to the interesting ones!

Corollary: connections — Need coherent modeling of multiple observables

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Part I: basic observables
‘the bread and butter’

Simple observables; program and plan

- Observables/measurements:
  - Single particle R_{AA}, v_n
  - Di-hadron, recoil suppression I_{AA}
  - Heavy flavor R_{AA}, v_n

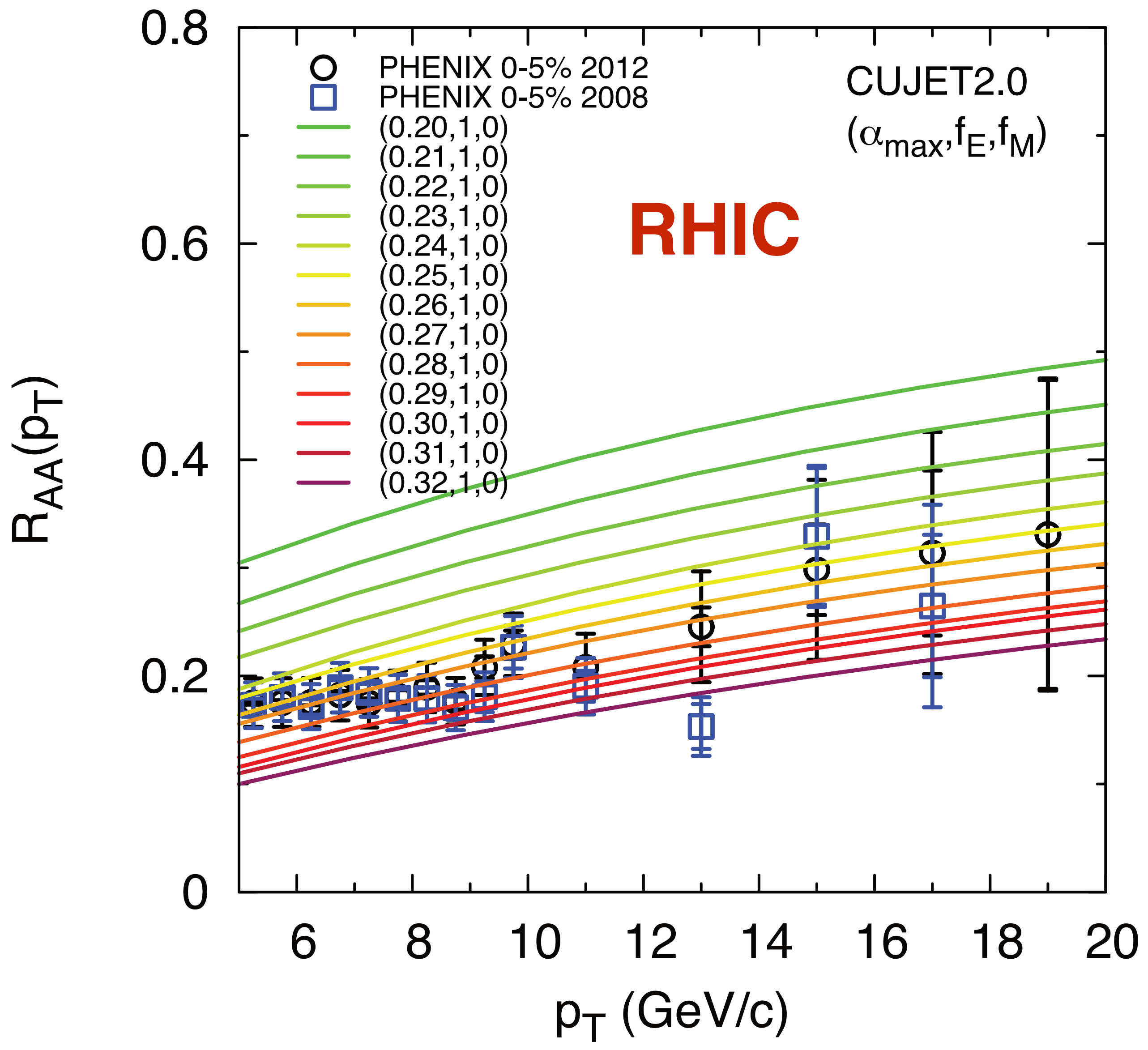
Address an important subset of the questions raised in the intro

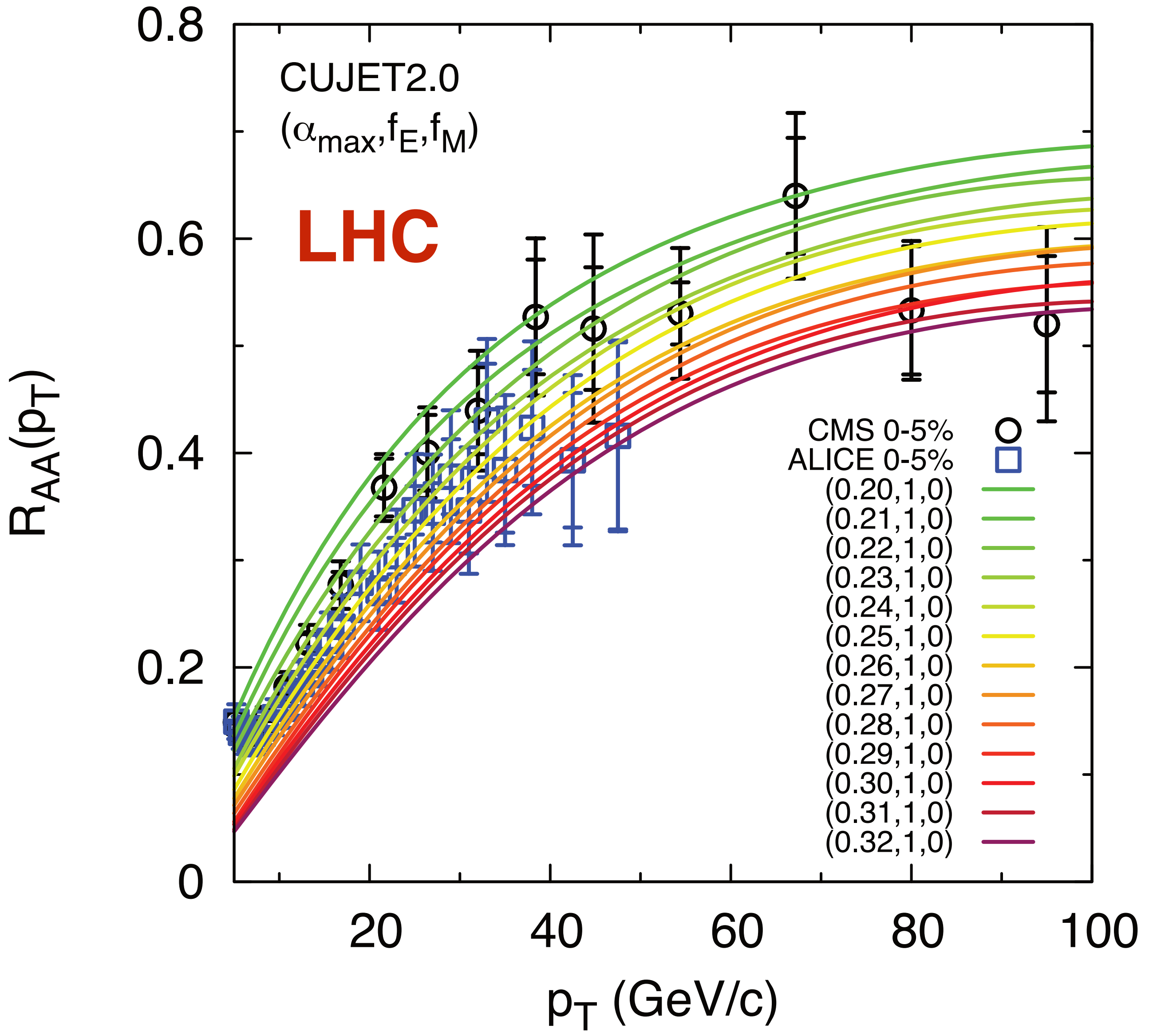
- Density of the medium: value, time evolution of qhat
- Path length dependence of energy loss
- Heavy flavour energy loss;
  dead cone effect, importance of elastic scattering vs radiation
- Scale dependence of energy loss, medium properties?

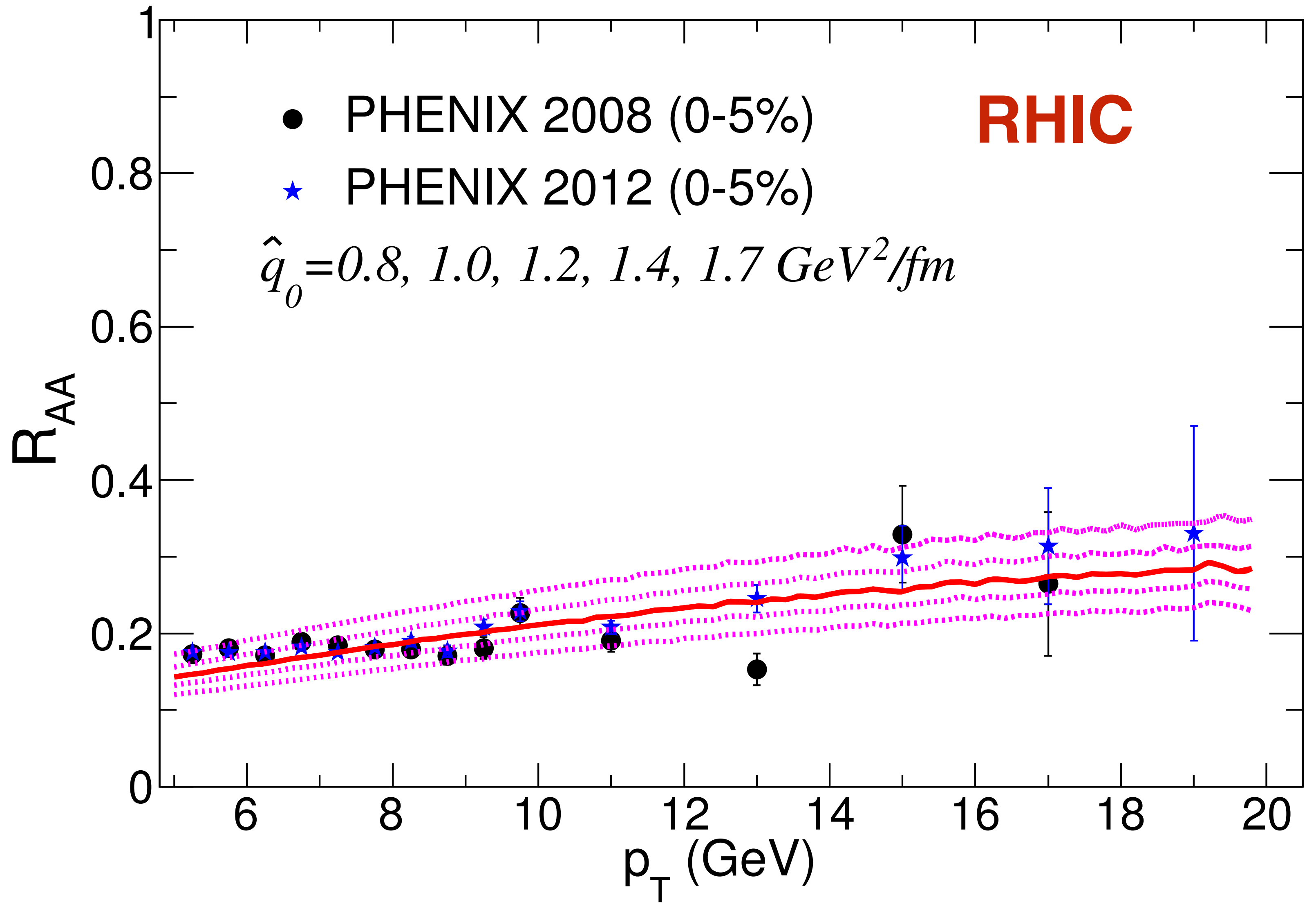
Progress to be made by:

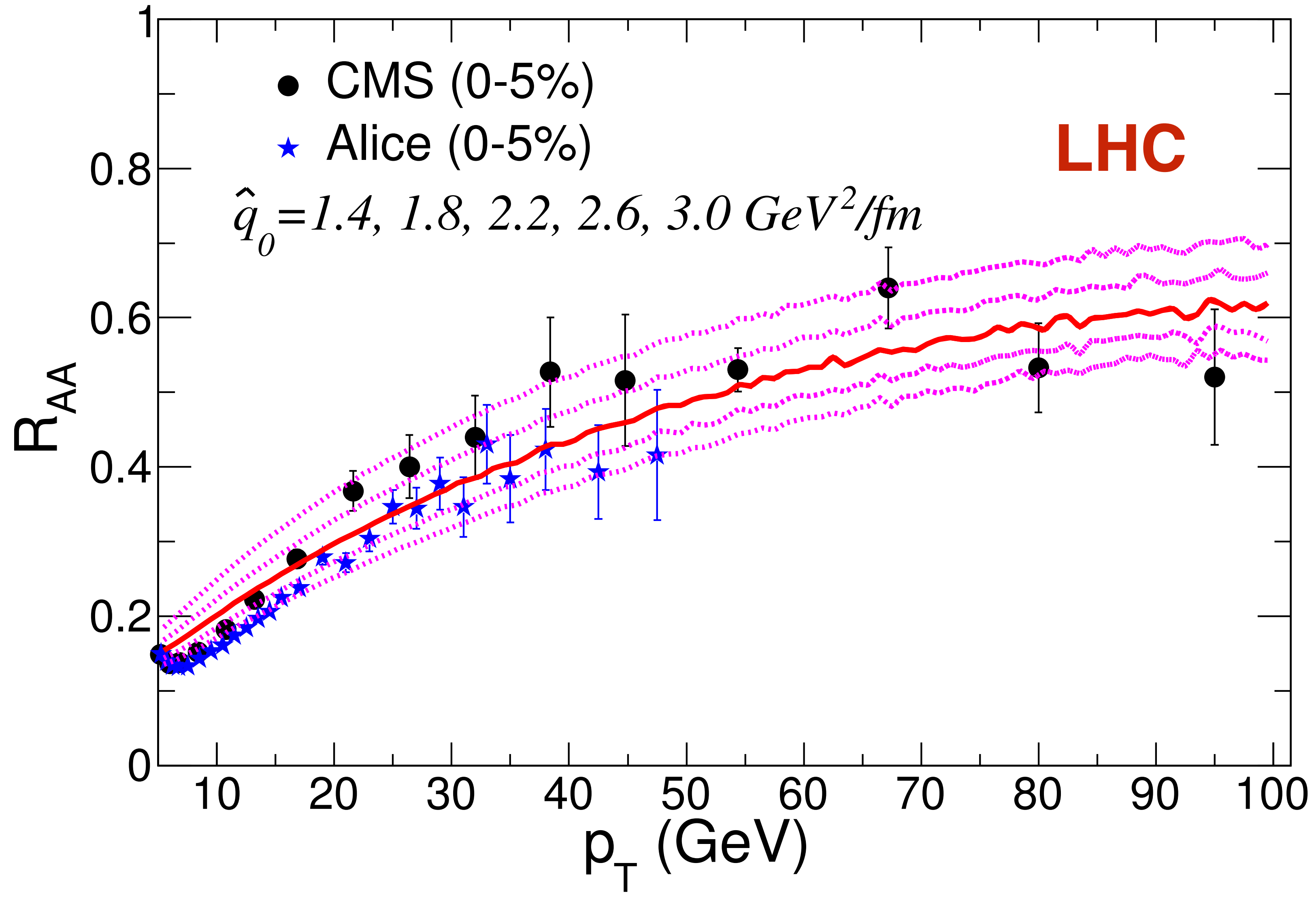
- **Coherent modeling of multiple observables**
- **Improving precision, p_T reach, comparing RHIC+LHC**

Example of a systematic exploration: 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

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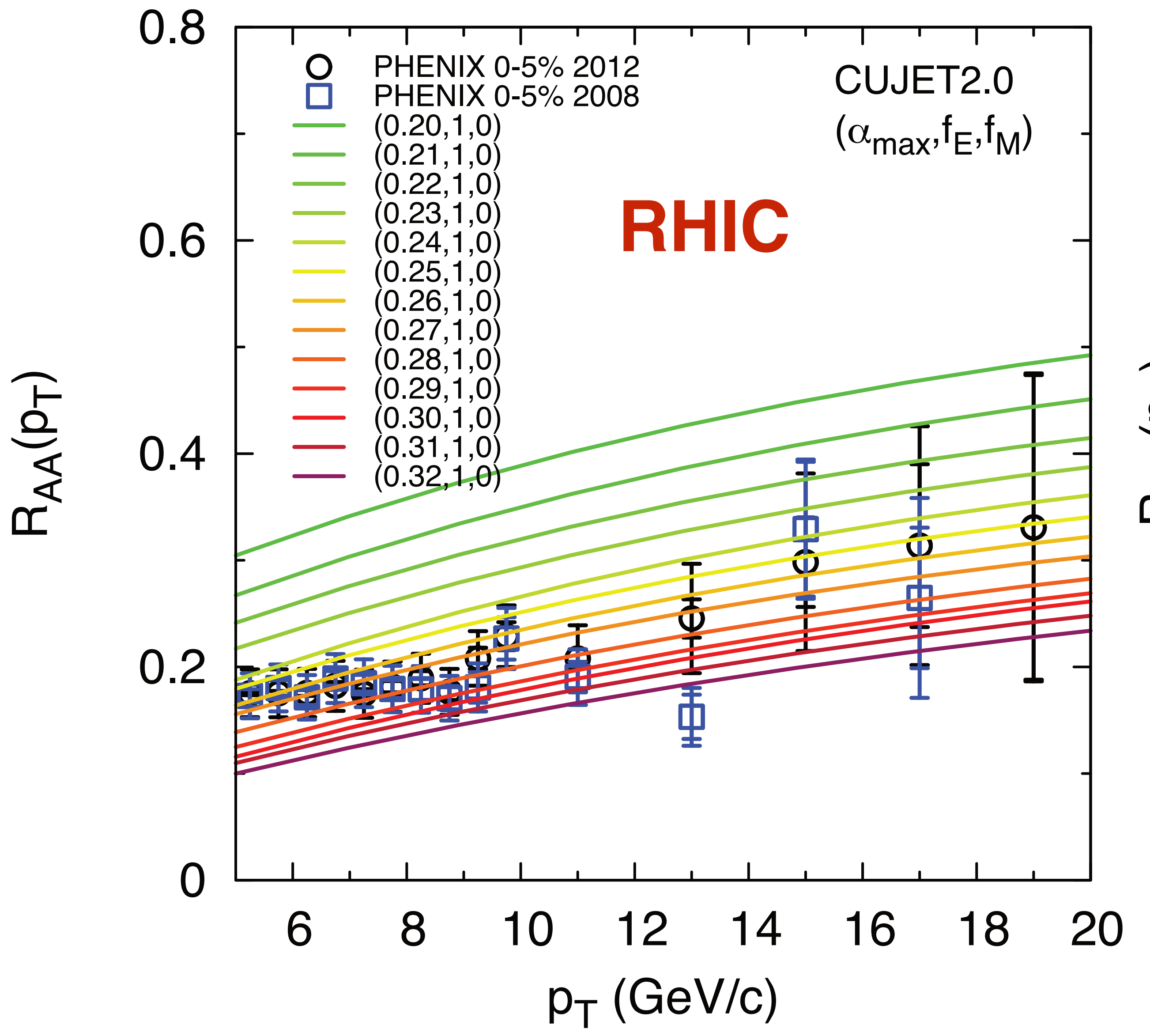

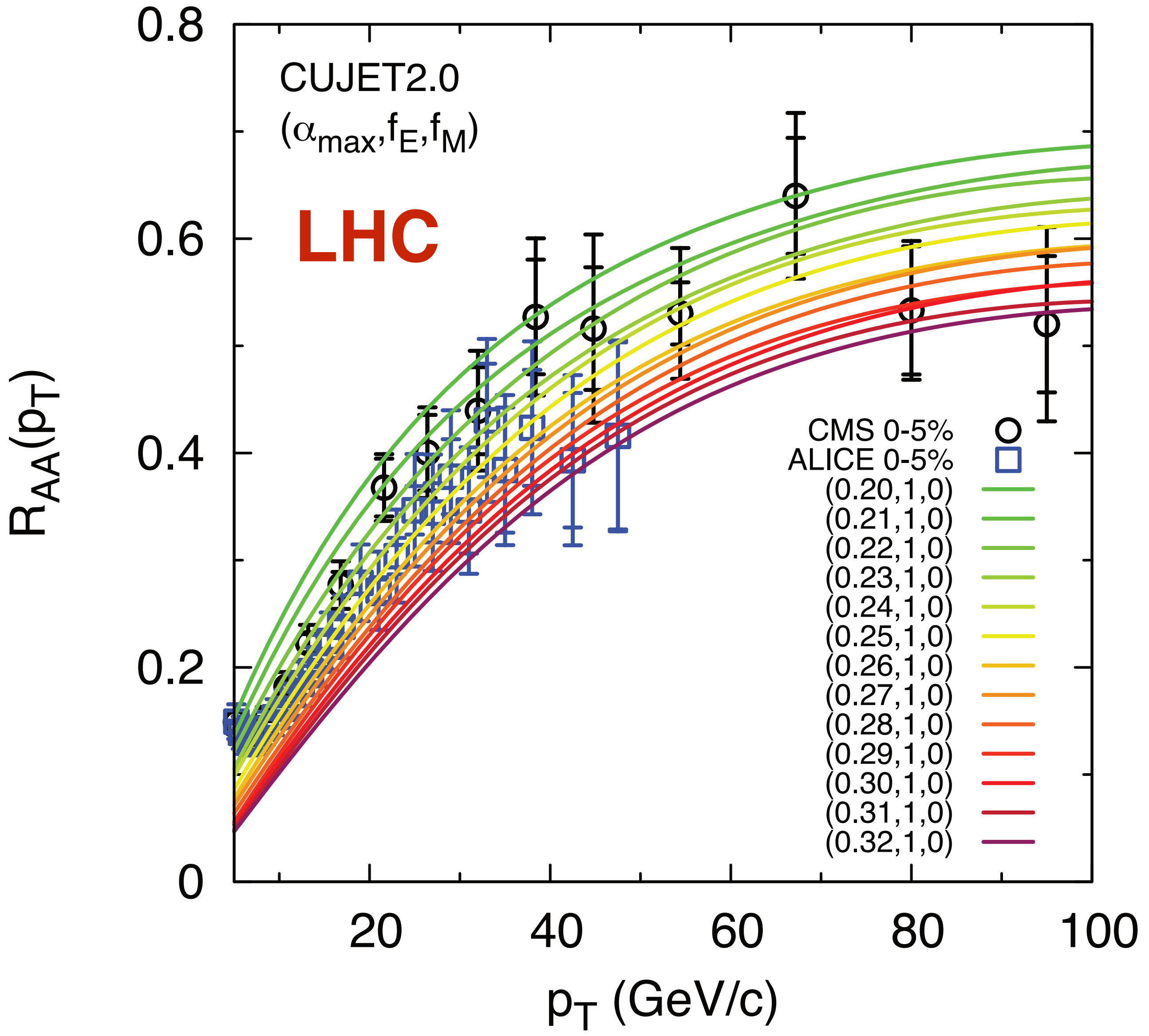

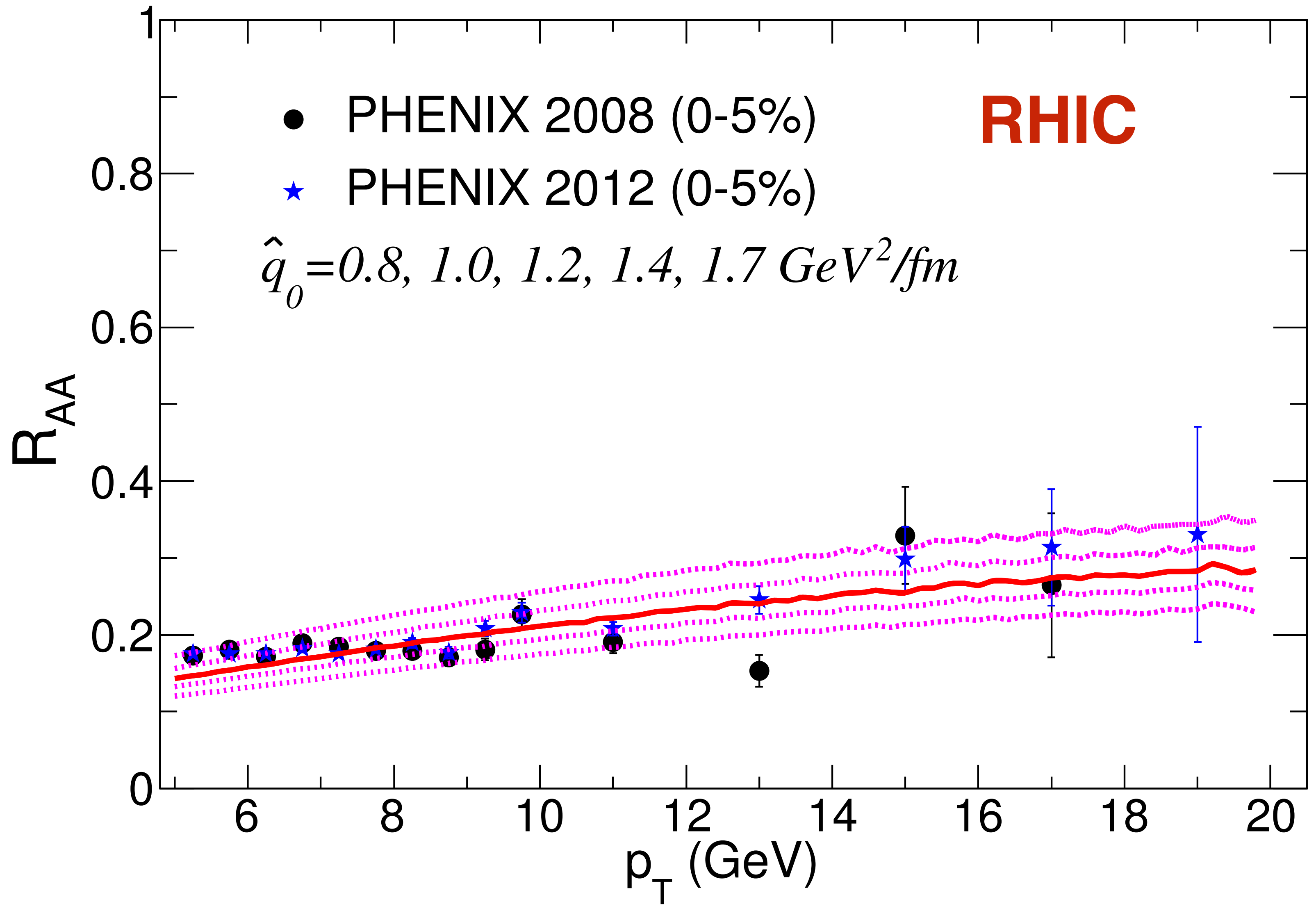

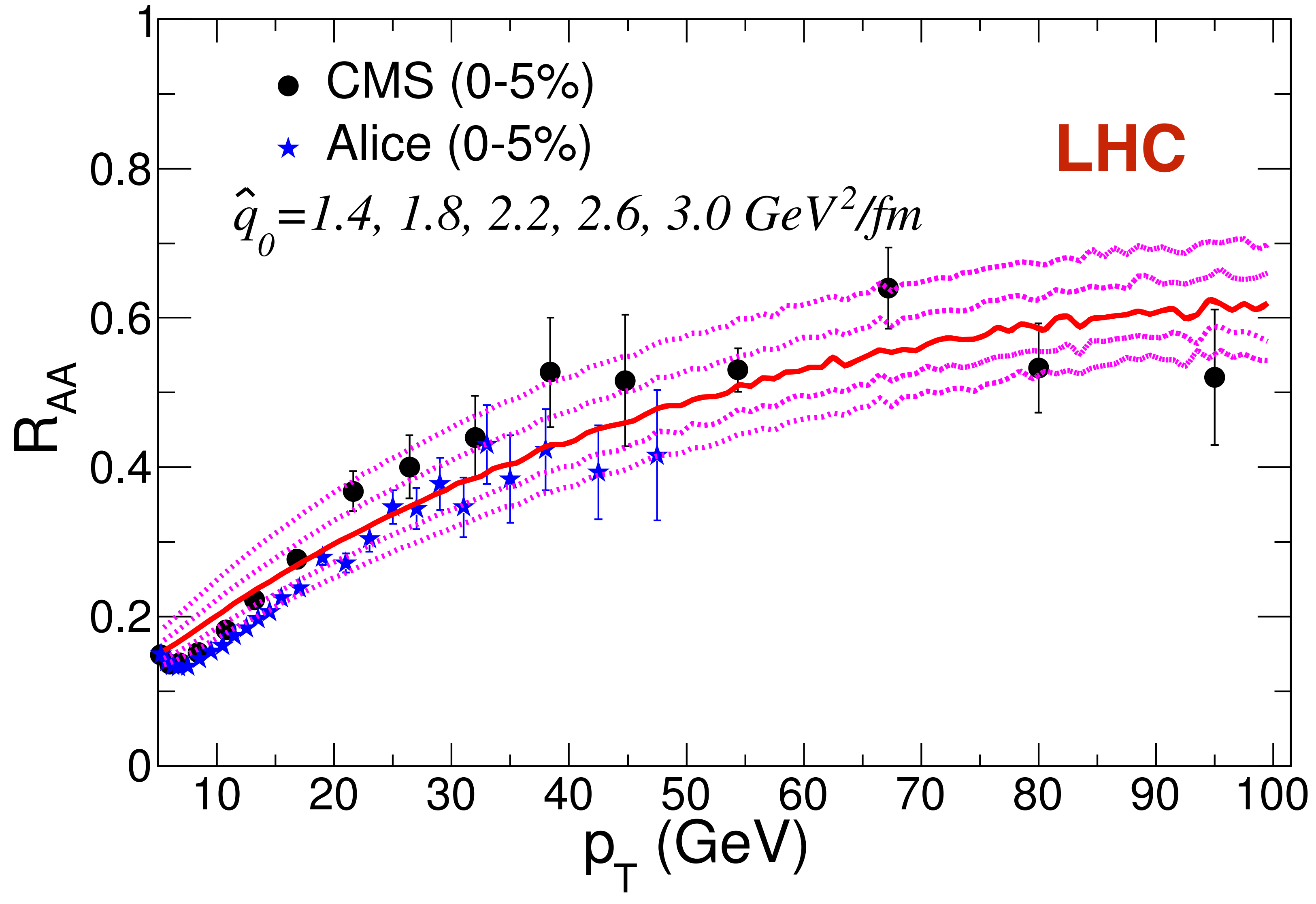

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RHIC: $\hat{q} = 1.2 \pm 0.3\ GeV^2/fm$ (T_i = 370 MeV)

LHC: $\hat{q} = 1.9 \pm 0.7\ GeV^2/fm$ (T_i = 470 MeV)

What do we learn from ‘knowing’ qhat?

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HTL expectation:

Arnold and Xiao, arXiv:0810.1026

$$\hat{q} = 2\pi C_R \alpha_S^2 N \ln\left(\frac{q_{max}^2}{m_D^2}\right) \qquad N = \frac{\zeta(3)}{\zeta(2)}\left(1 + \frac{1}{4} N_f\right) T^3$$

$$\hat{q} \approx 24 \ \alpha_S^2 \ T^3 \approx \boxed{2 \ T^3}$$

relation qhat - T depends on
number of degrees of freedom, α_S

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Conclusion for now: values are in the right ballpark — we semi-quantitatively understand parton energy loss

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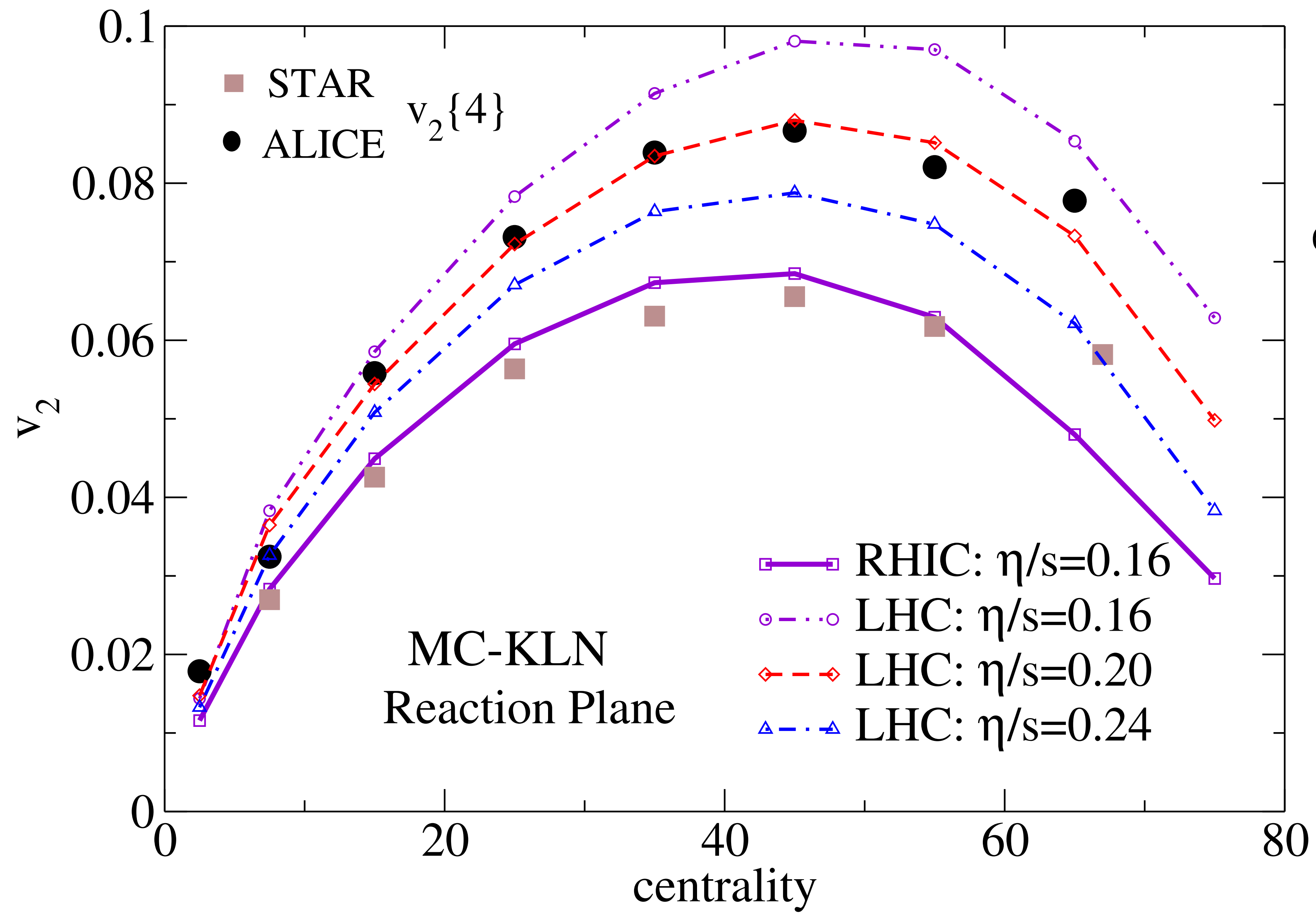
Future direction: **can we make this quantitative?**
E.g. determine number of degrees of freedom with a meaningful uncertainty?
Or constrain T-dependence of qhat?

What do we learn II: transport coefficient and viscosity

Parton gas expectation: $\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$ qhat and eta are inversely related

Majumder, Muller and Wang, PRL99, 192301

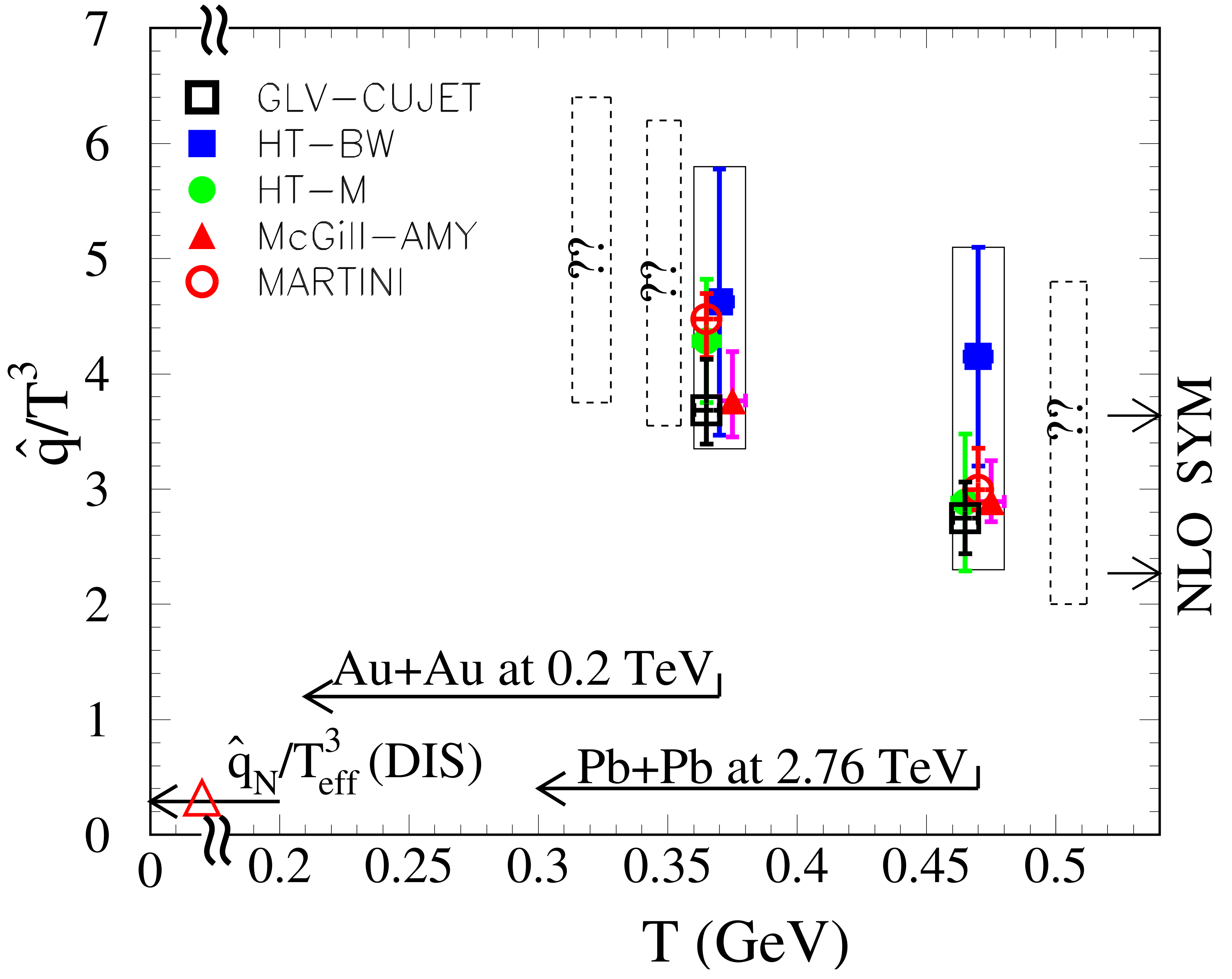
Elliptic flow



H. Song et al, PRC83, 054912

(Scaled) viscosity slightly larger at LHC

Transport coefficient from R_{AA}



Scaled transport coefficient slightly smaller at LHC

Hints of increase of η/s and decrease of q/T^3 could have a common origin?

NB: effects not significant (yet); can we narrow down the uncertainties?

More systematics: compare soft scattering formalism

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

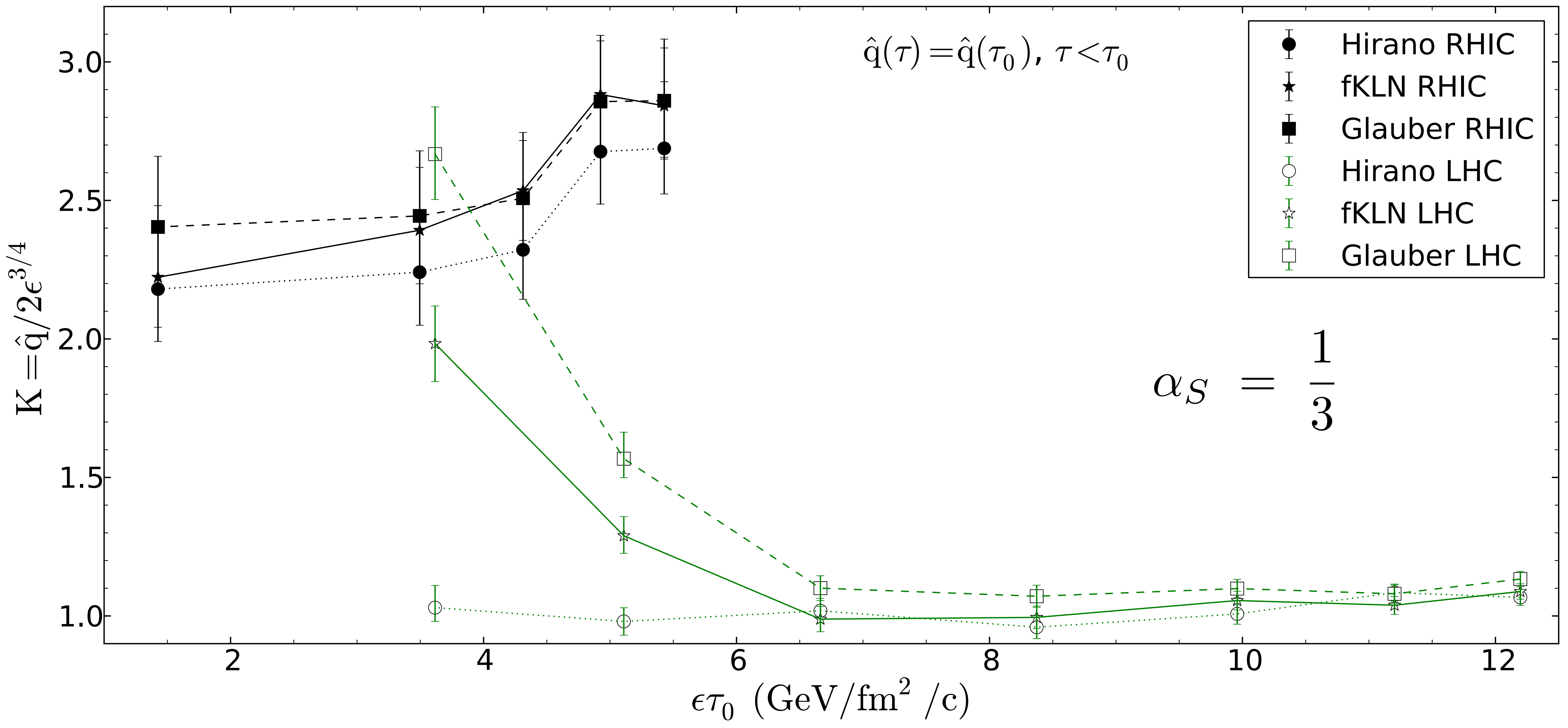
Armesto et al, arXiv:1606.04837

Energy loss: BDMPS-ASW multiple soft scattering
Medium: Hydrodynamics; Hirano, Luzum&Romatschke

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

pQCD expectation:
K = 1 (by definition)

Large difference (factor ~2)
between scale factor at RHIC and LHC

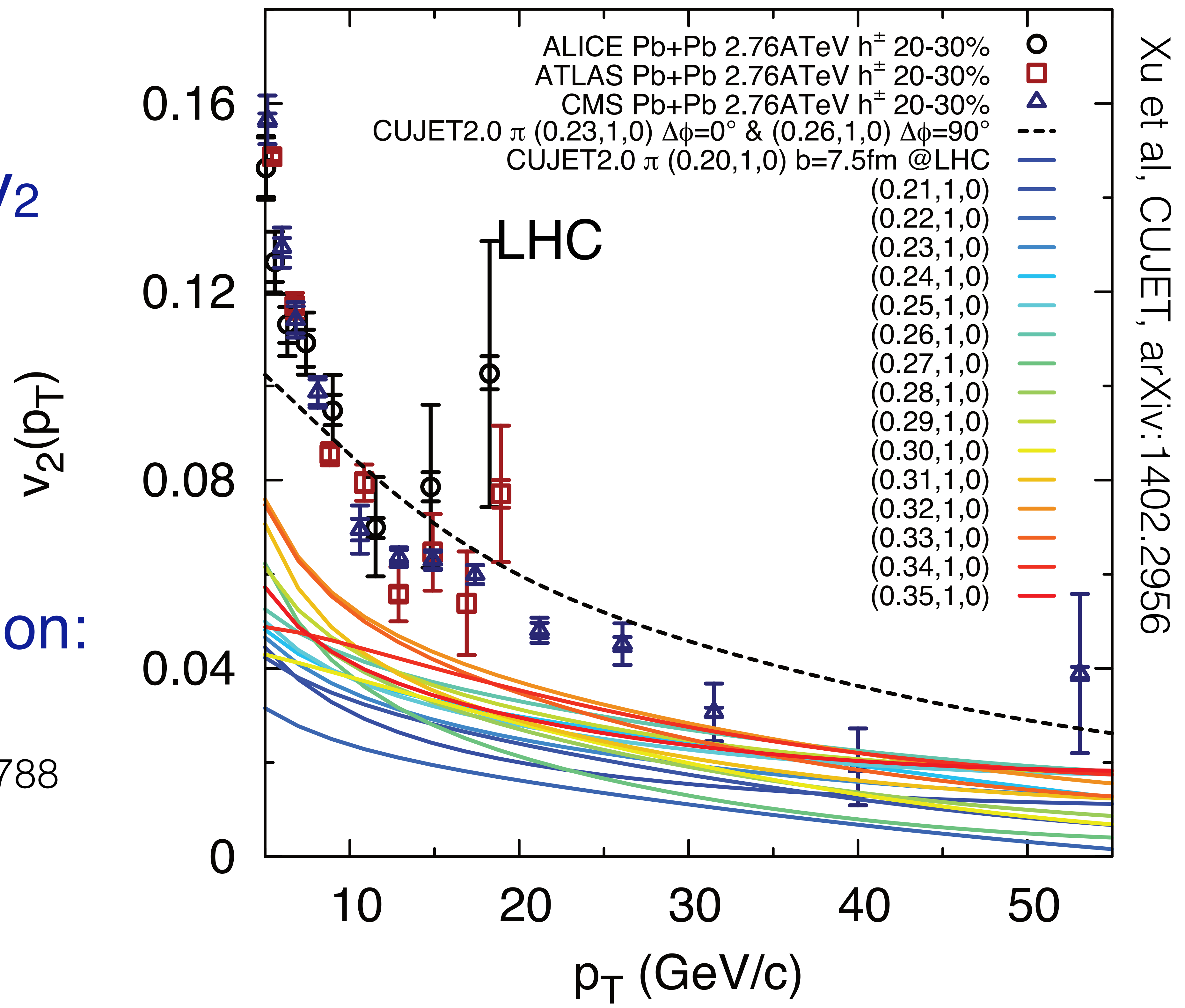


Conclusion seems different from JET collaboration work
Should follow up to find out what drives this
Points to modeling uncertainties? Can we reduce those?

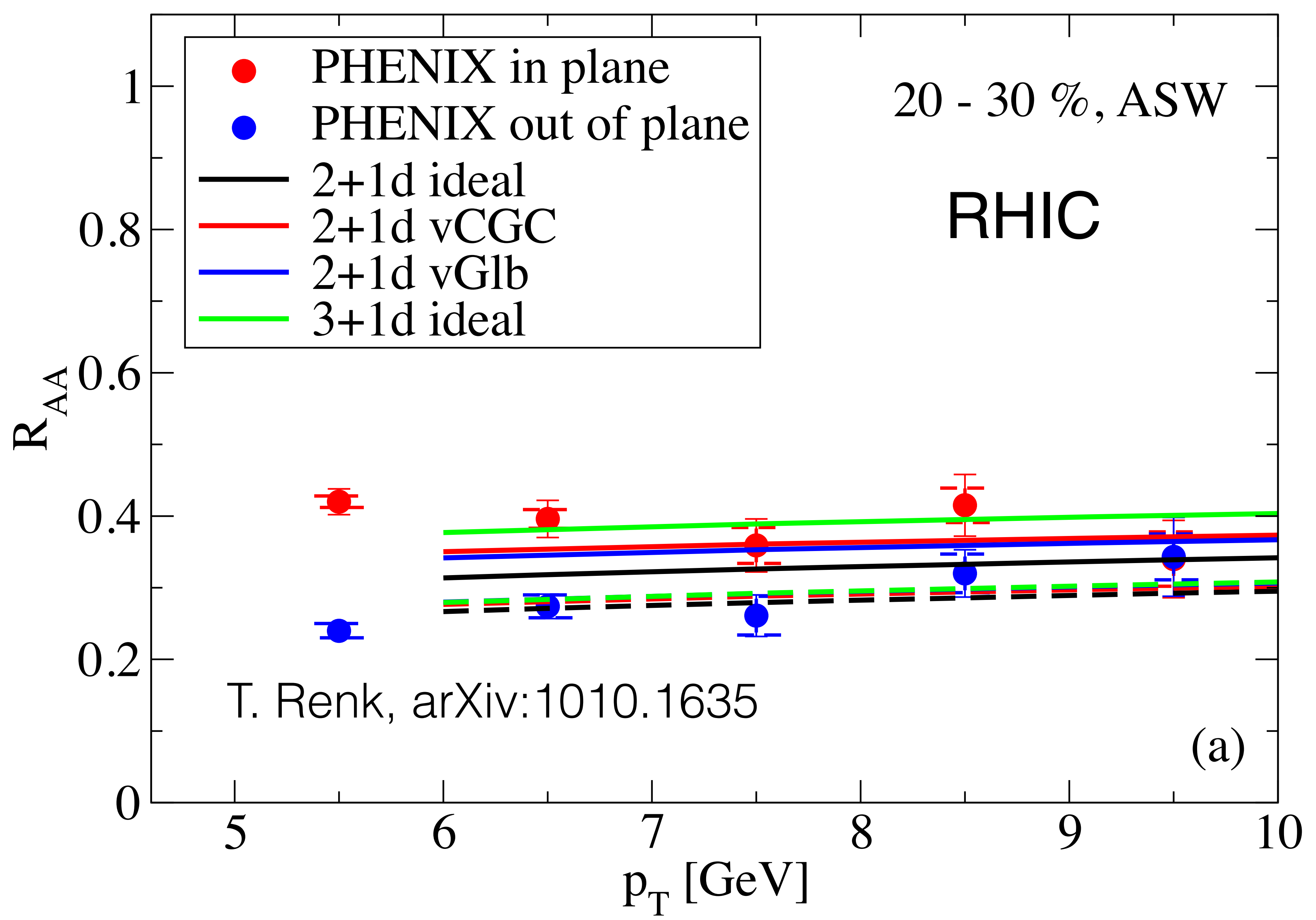
High-p_T v_2, R_{AA} in and out of plane

Current state:
Hydro+E-loss models
do not produce enough v_2

CUJET



YaJEM



Sensitive to medium evolution models
(freeze-out temp)

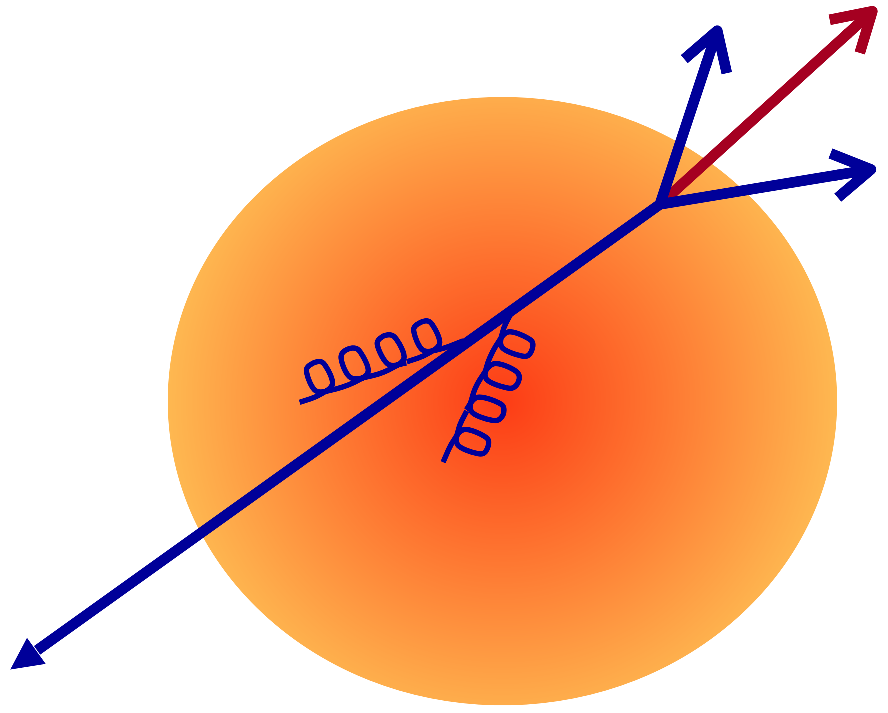
Various points under discussion:

- Effect of fluctuations
  Noronha-Hostler et al, arXiv:1602.03788
- HT gets higher v_2?
  Qin and Majumder, arXiv:0910.3016

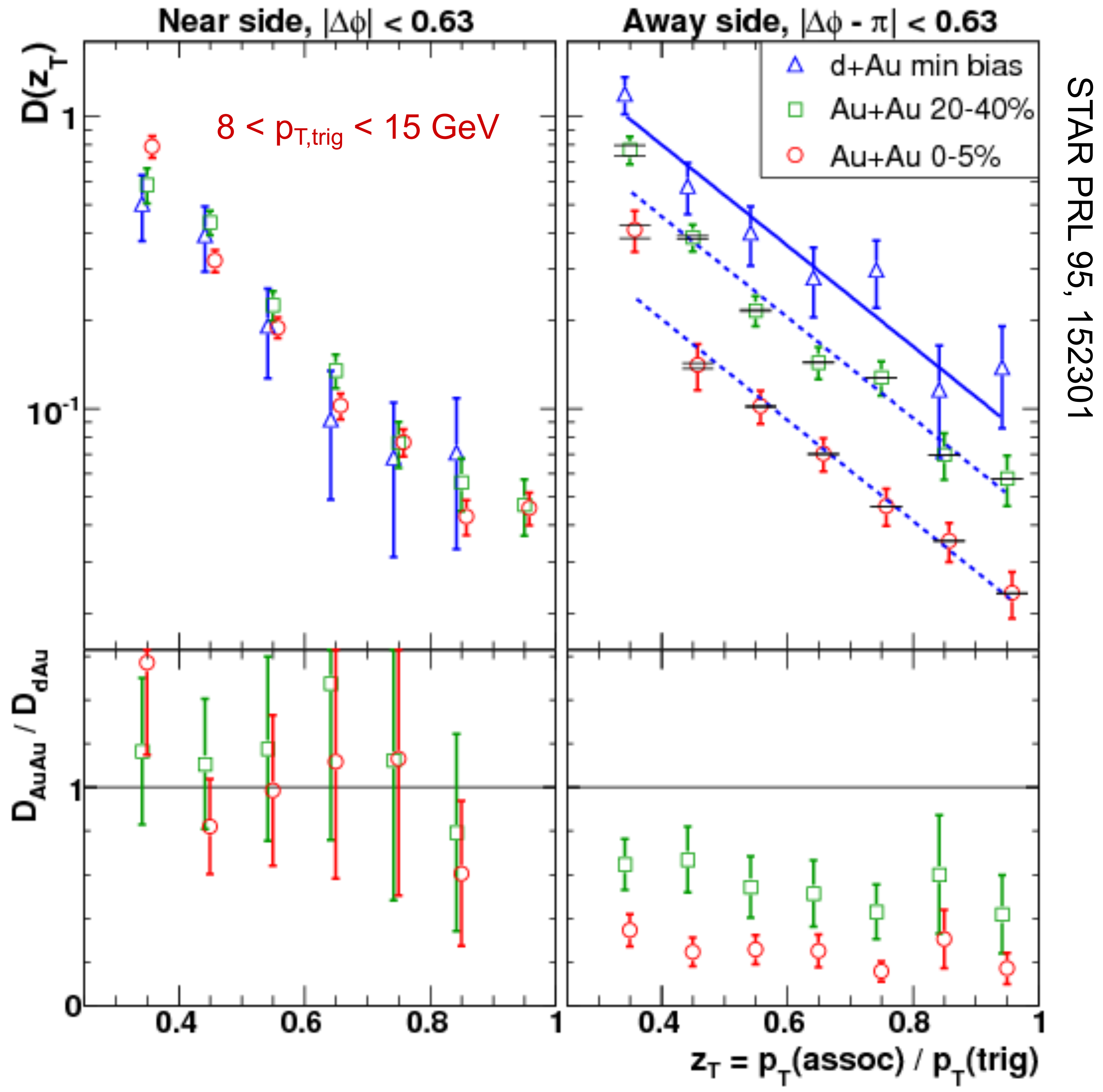
Potential with more precise data, and some effort:
Use high-p_T data to co-validate/constrain medium evolution (models)

Another handle on path length dependence: di-hadrons

Near side trigger,
biases to small E-loss



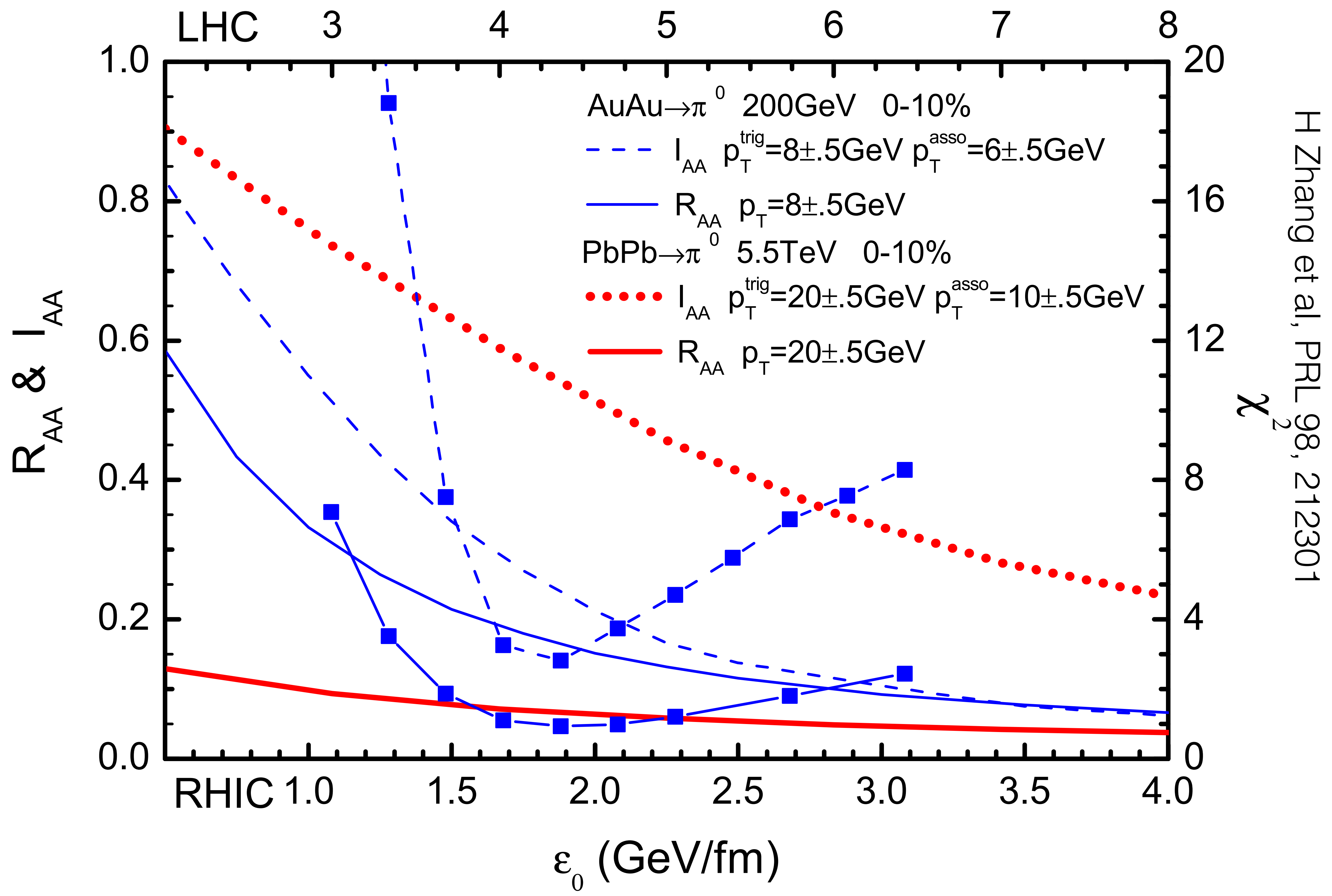
Away-side large L



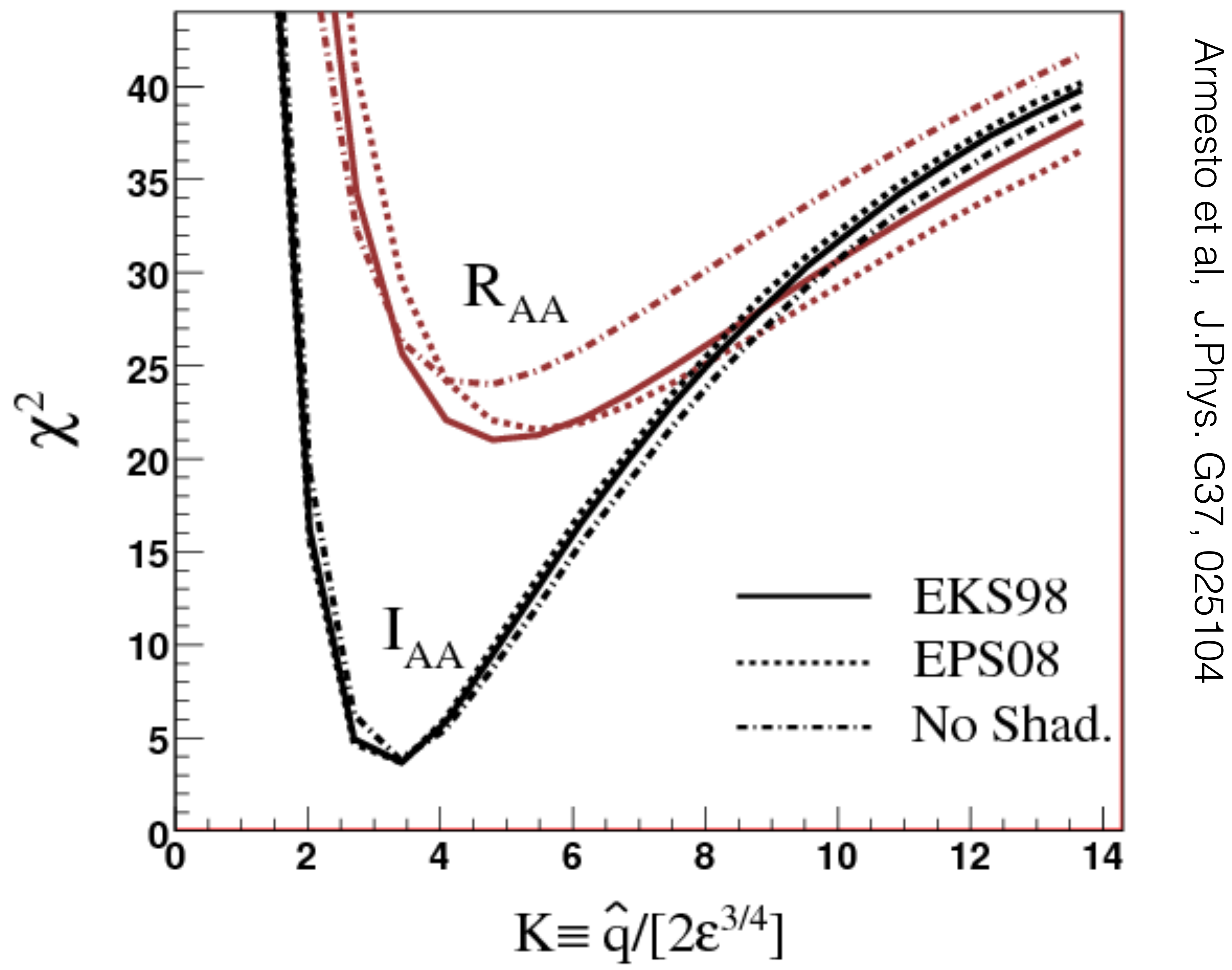
Away-side (recoil) suppression I_{AA}
samples longer path-lengths than inclusive R_{AA}

Can be modelled with the same tools as inclusive particle production

I_{AA} modeling



Medium model: Glauber profile
Energy loss: Higher Twist



Medium model: (ideal) Hydro
Energy loss: BDMPS-ASW multiple soft

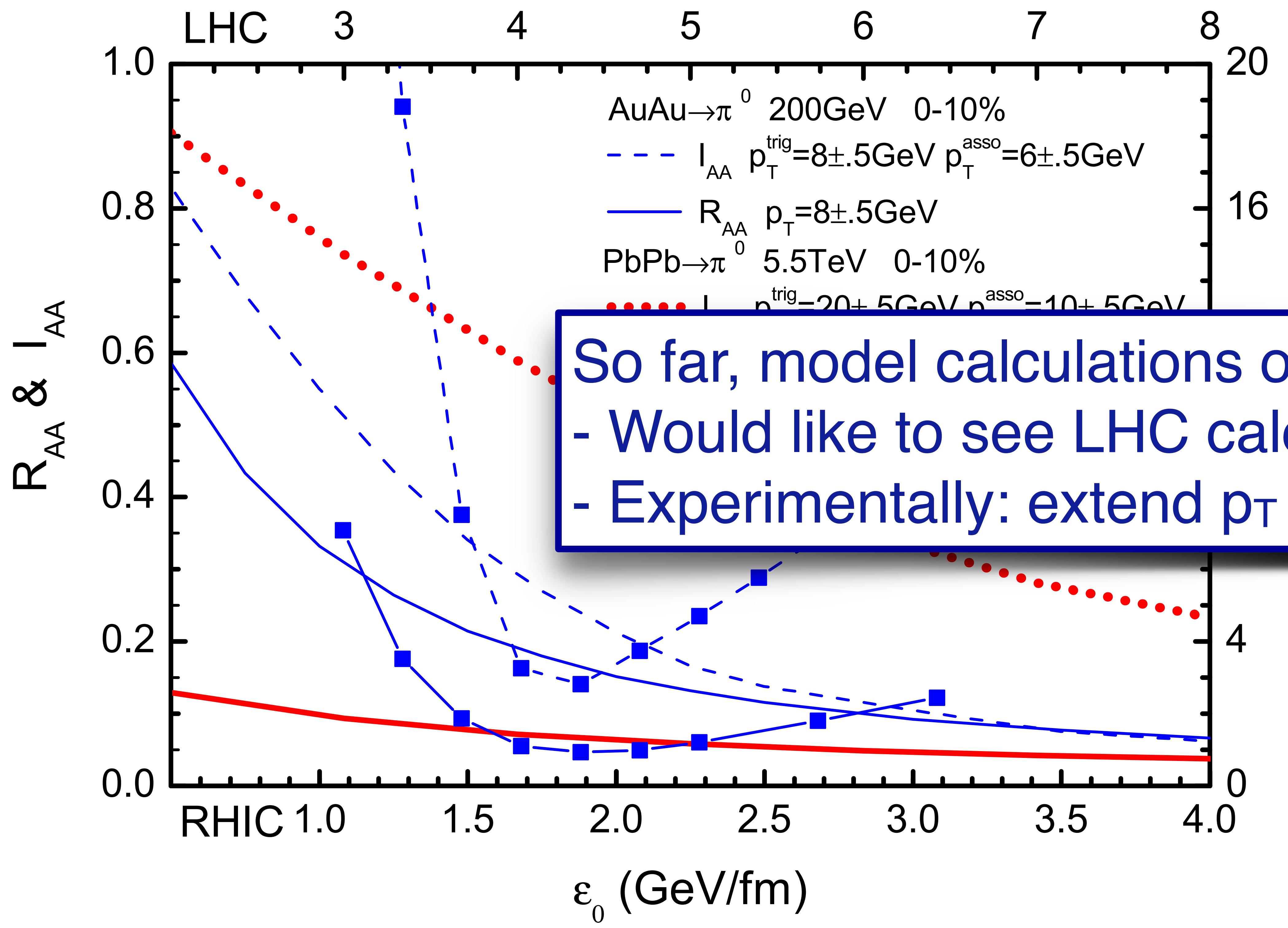
R_{AA} and I_{AA} fit with similar density

Confirms ~L^2 dependence

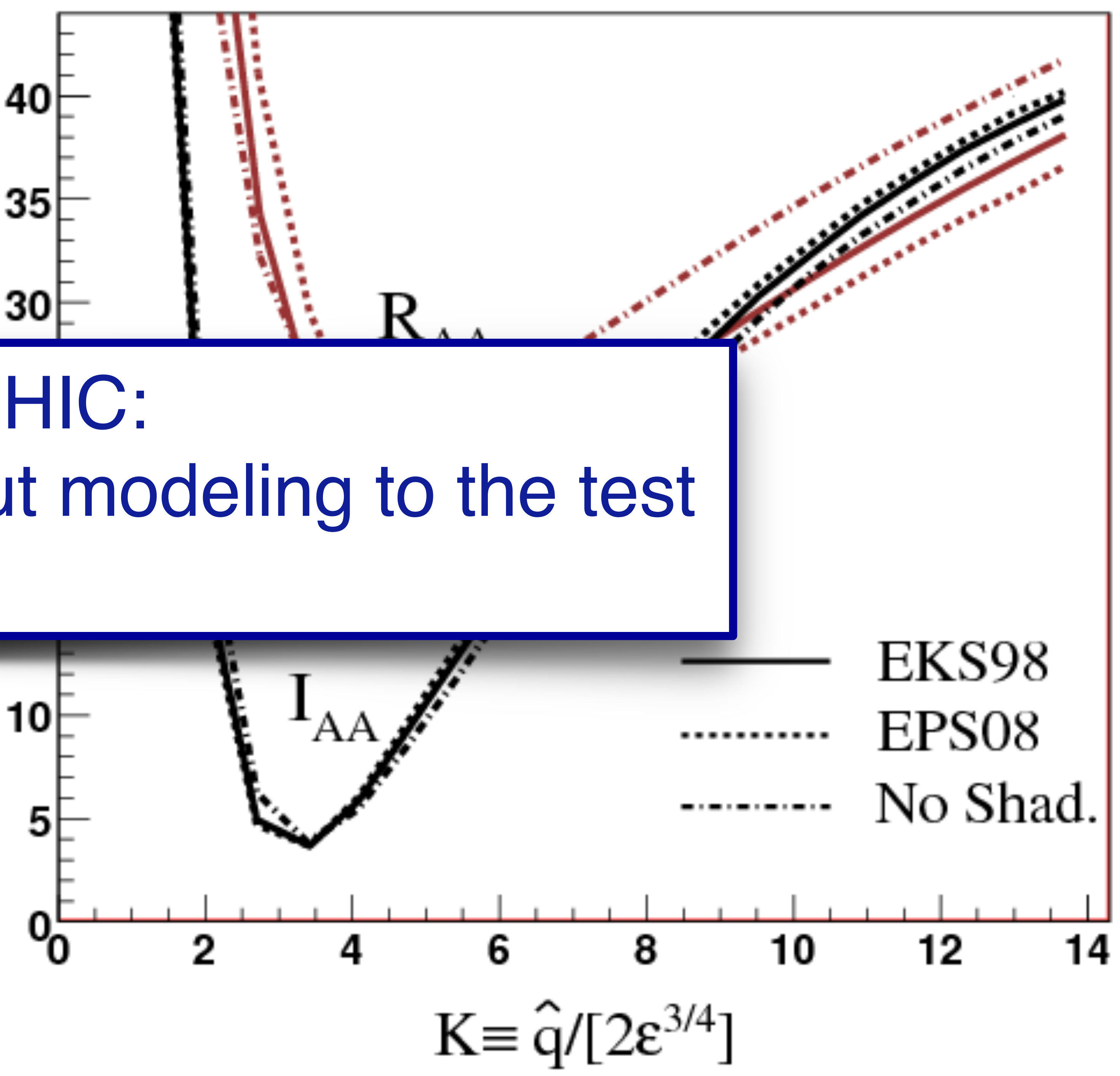
Calculations with elastic loss give too little suppression

T. Renk, PRC, arXiv:1106.1740

I_{AA} modeling



H Zhang et a... 01



Armesto et al, J.Phys. G37, 025104

So far, model calculations only exist for RHIC:
- Would like to see LHC calculations to put modeling to the test
- Experimentally: extend p_T range

Medium model: Glauber profile
Energy loss: Higher Twist

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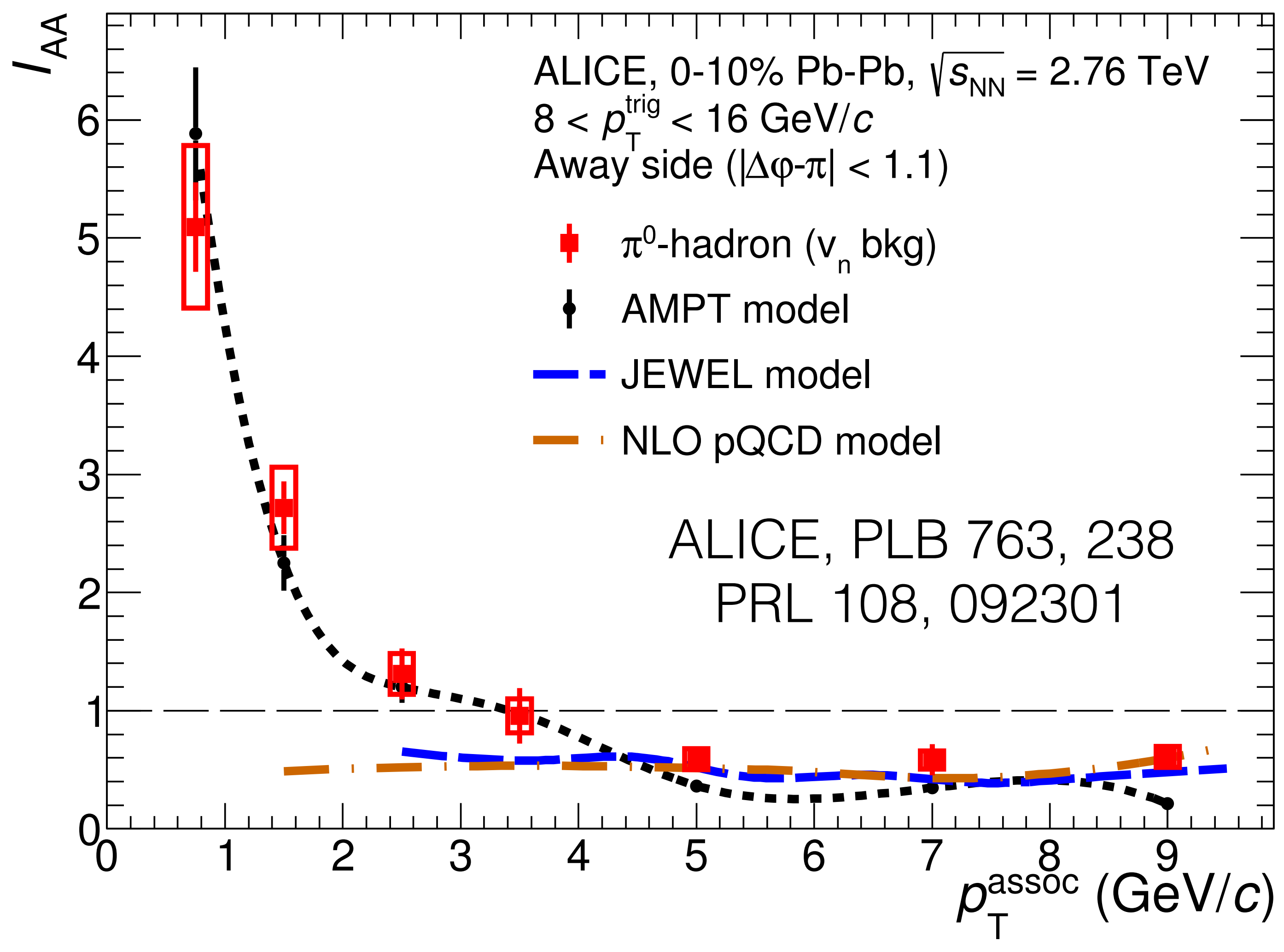
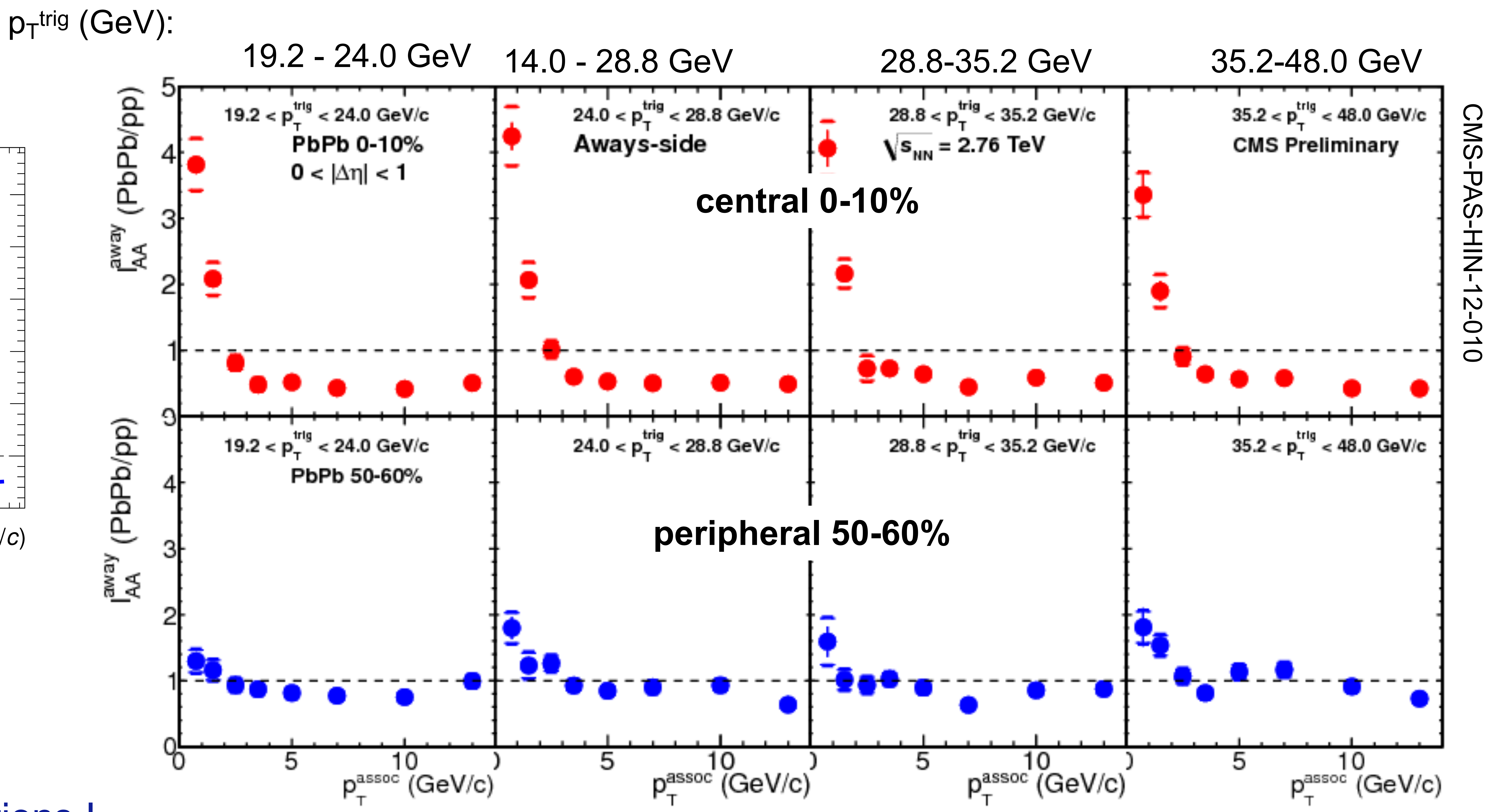
I_{AA} at the LHC





Data already exist —
it's really 'just' a matter
of running the models/calculations !

Transition enhancement → suppression @ p_T ~ 2 GeV

Heavy flavour R_{AA}; mass dependence

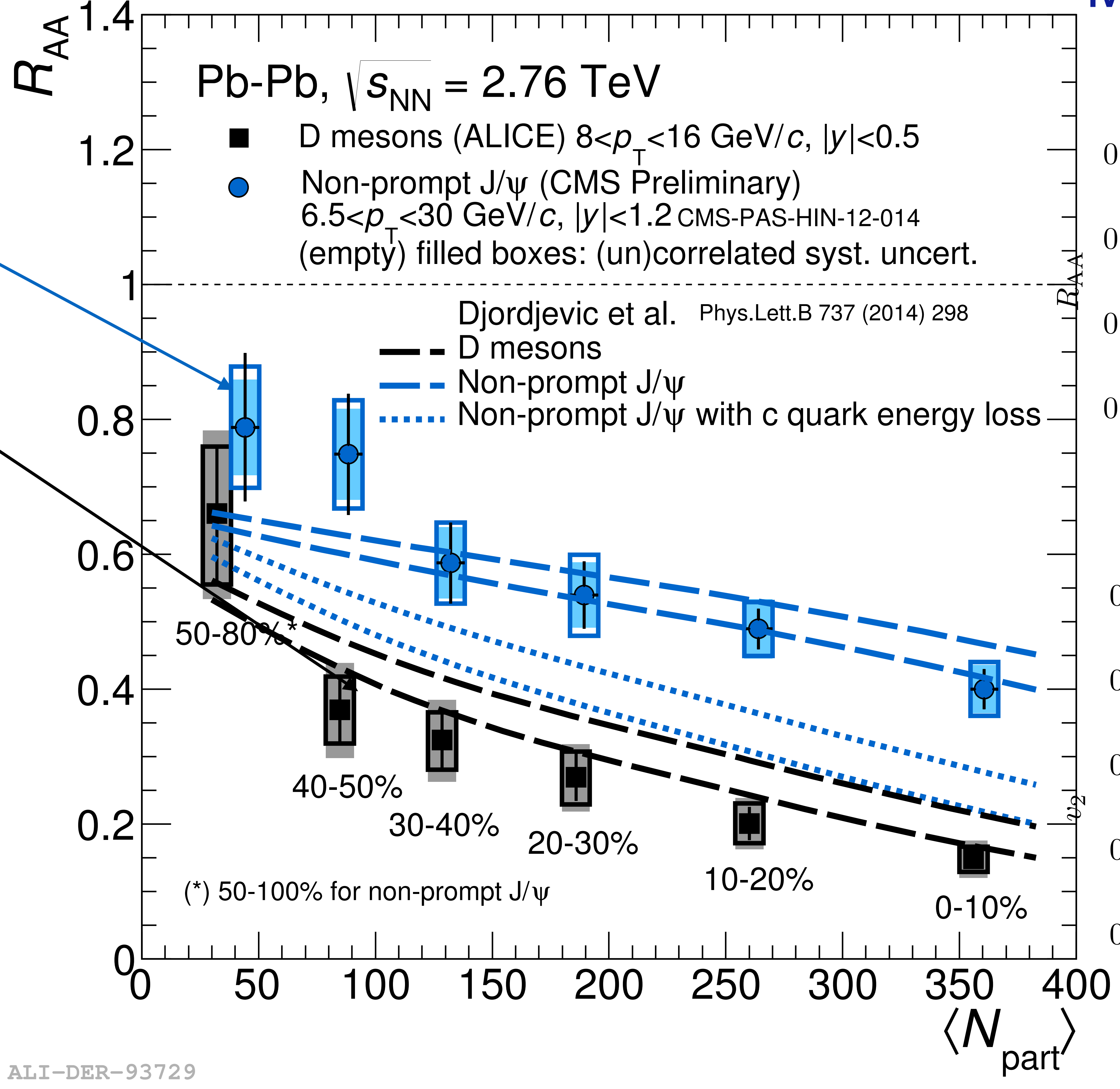
Compare
beauty: non-prompt J/Ψ
charm: D-mesons

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

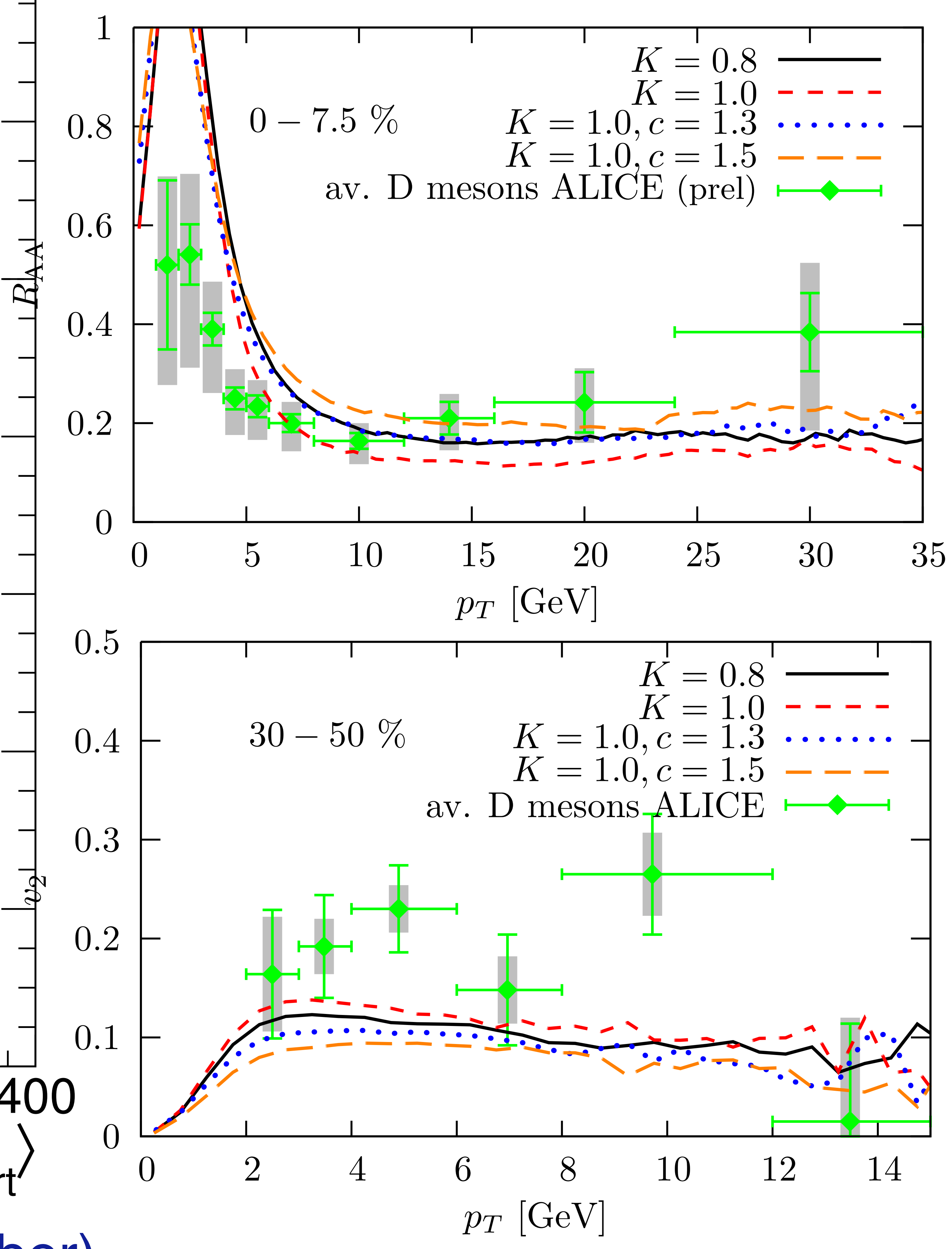
Similarity of D meson and light hadron R_{AA} 'understood'

IMHO: importance of collisional energy loss not fully quantified

ALICE, JHEP11, 205



MC@sHQ Boltzmann transport MC



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

Medium model: PQM (static/expanding Glauber)

Several groups involved with different calculations approached; rough agreement between groups

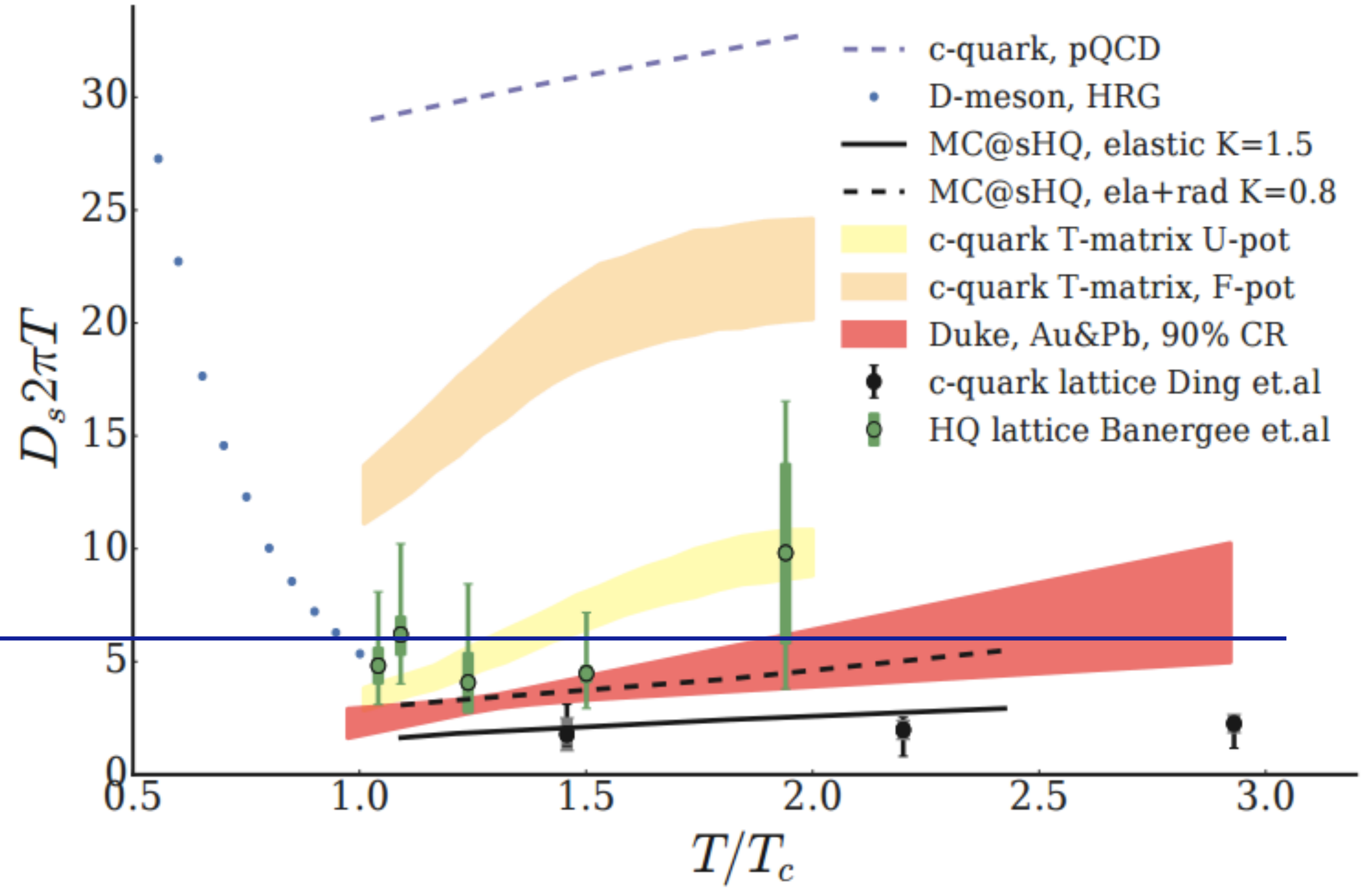
Relating heavy and light flavor modeling: D_s and $\hat{q}$

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 GeV^2/fm

However, perturbative estimate $D_s = 30/2\,\pi\,T$ —> qhat ~ 0.6 GeV^2/fm

Should connect heavy and light flavor phenomenology

E.g.: Why is the perturbative estimate of D_s so large?

LO: Svetitsky, PRD 37, 2484

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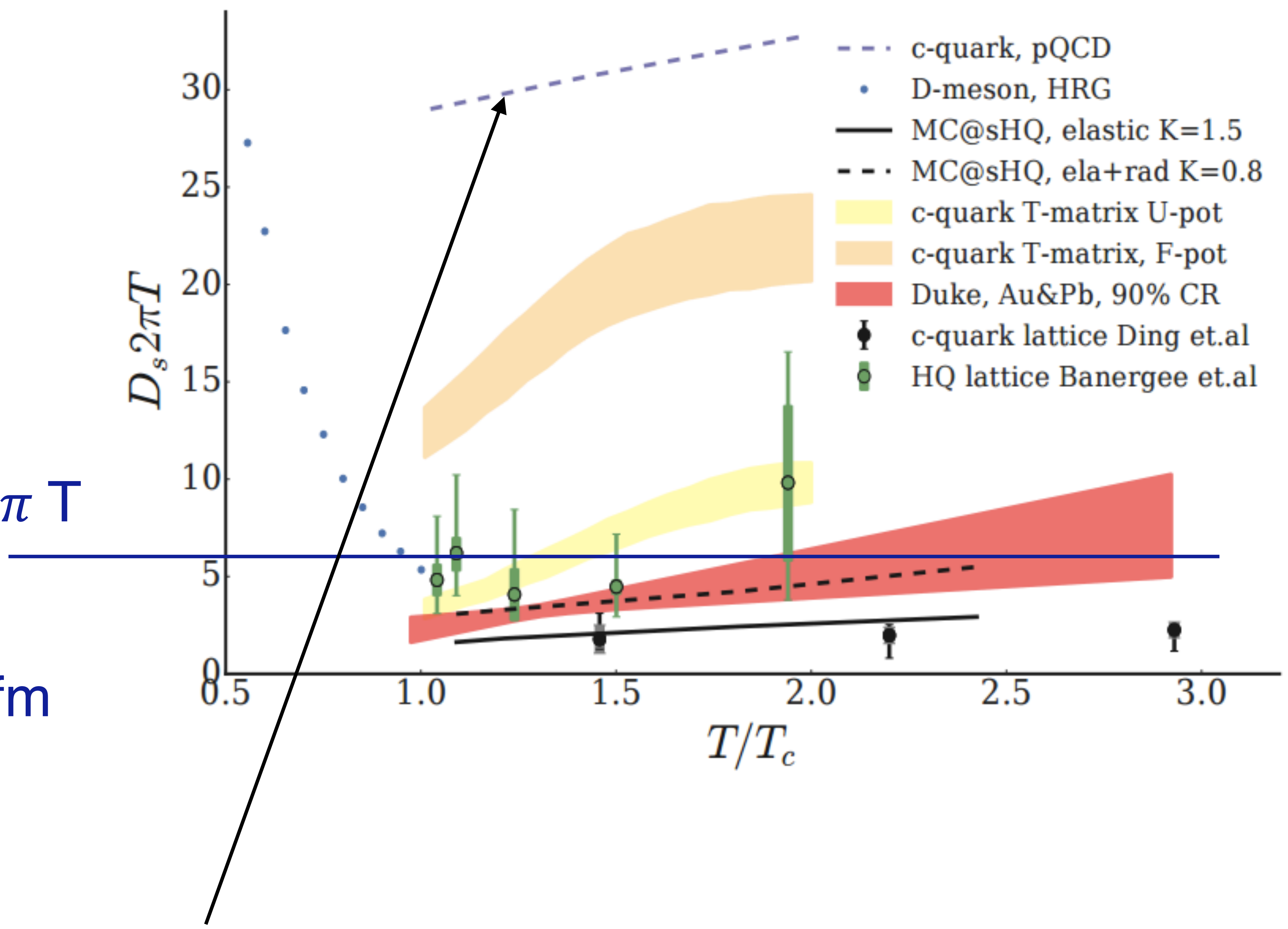

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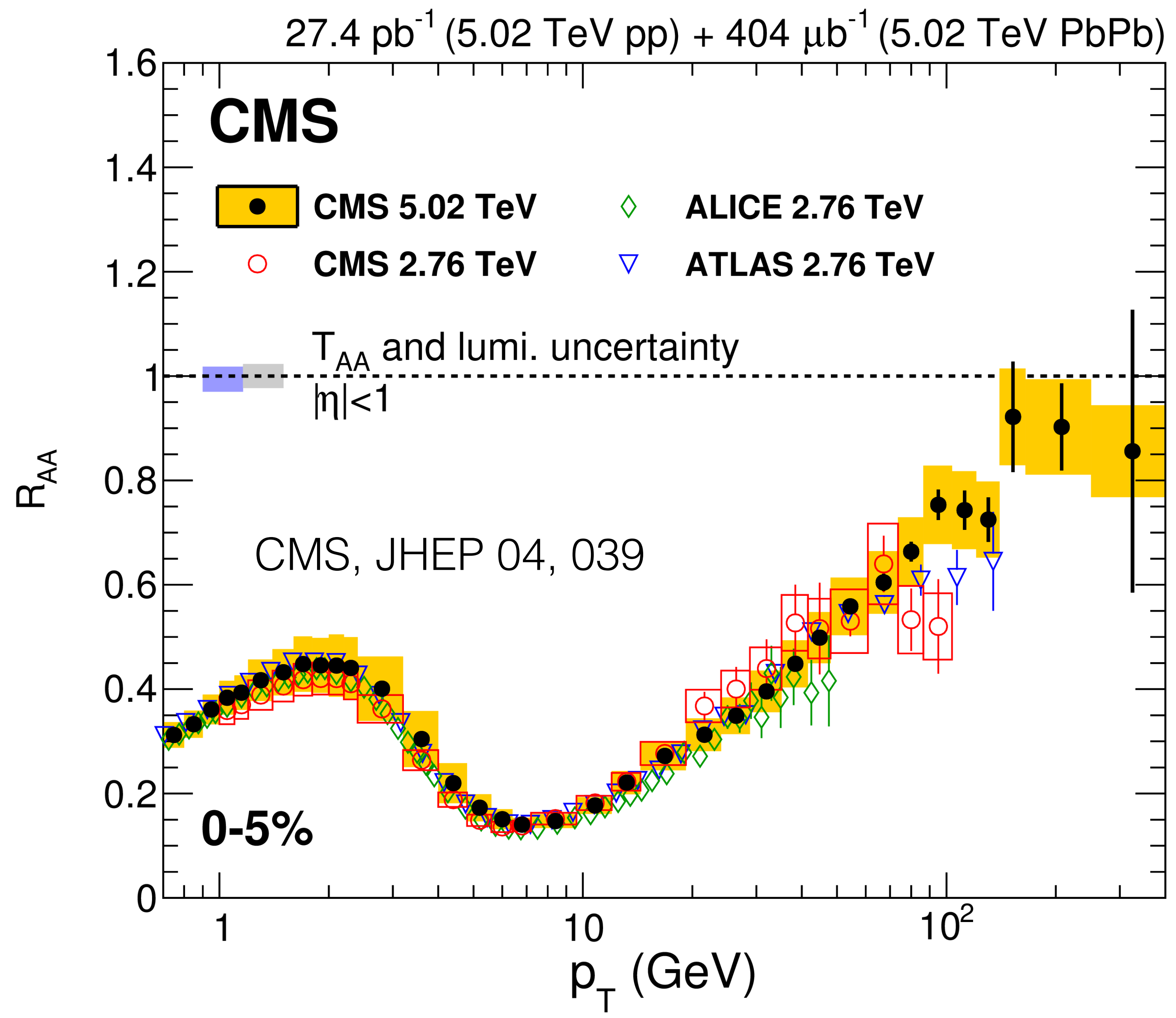
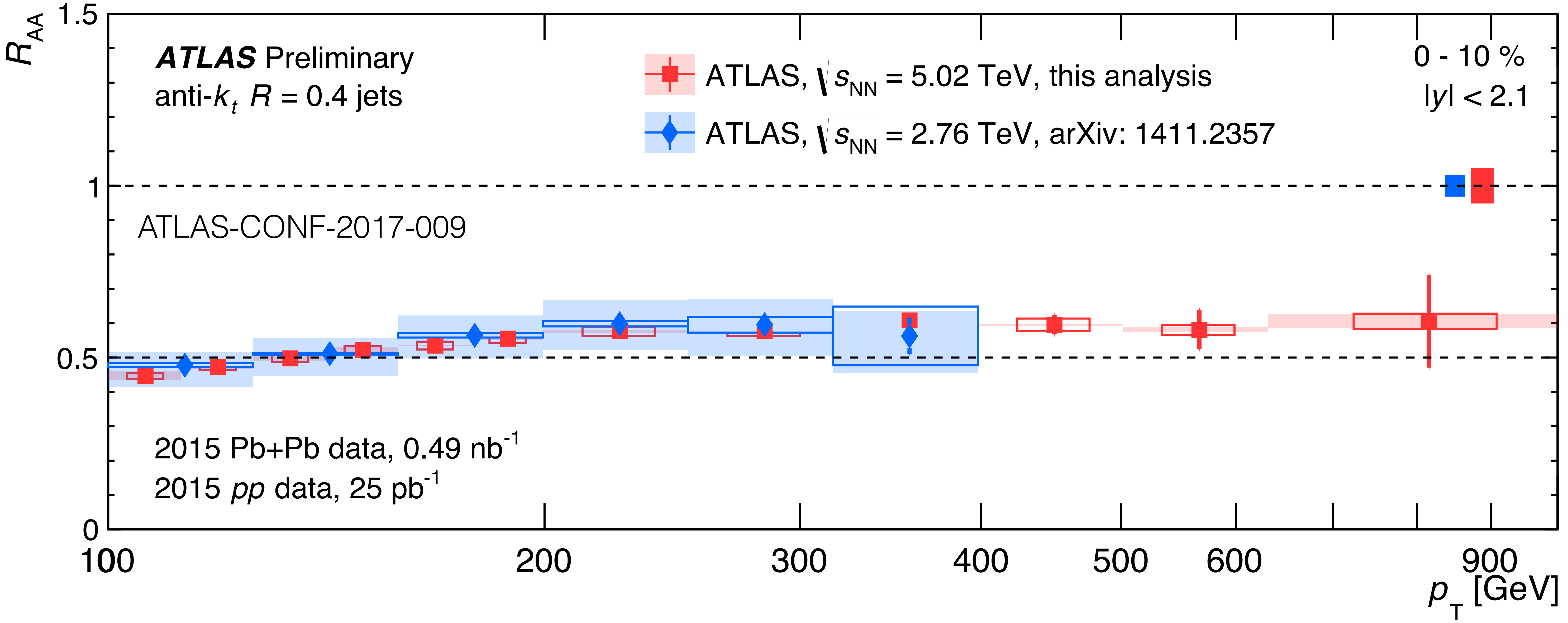
Jets: multi-parton states

High-p_T jets vs hadrons

Charged particle R_{AA}



Jet R_{AA}



Jets: $R_{AA} < 1$ out to high p_T

p_T-dependence driven by energy dependence of E-loss

Different for single particles and jets! ?

Single particles: consistent with expected constant (log E) dependence
Jets suggest increase of ΔE vs E

Tentative interpretation: in jets, multiple partons lose energy; more partons in high-E jets —> more E-loss

High-p_T jets vs hadrons

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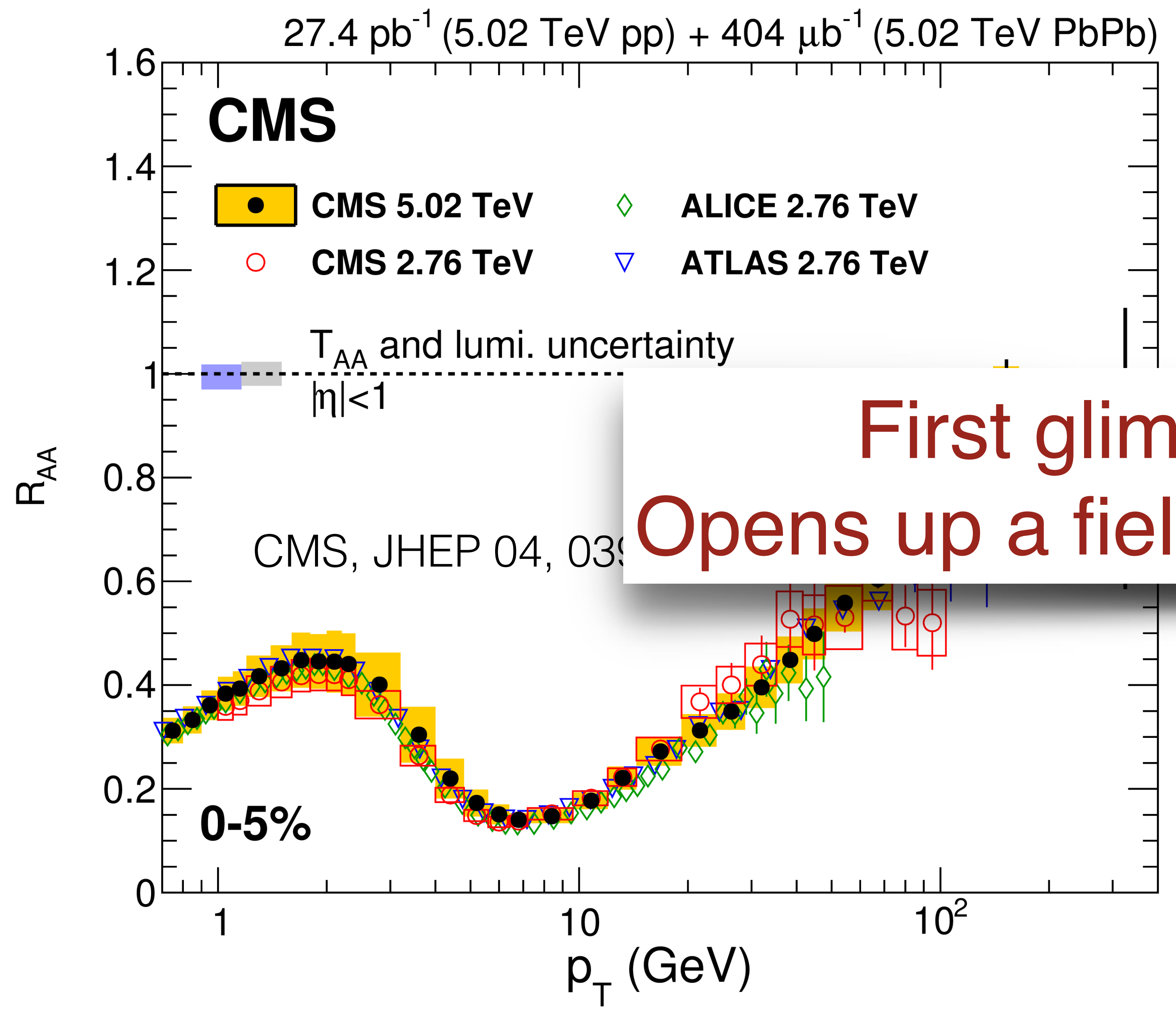
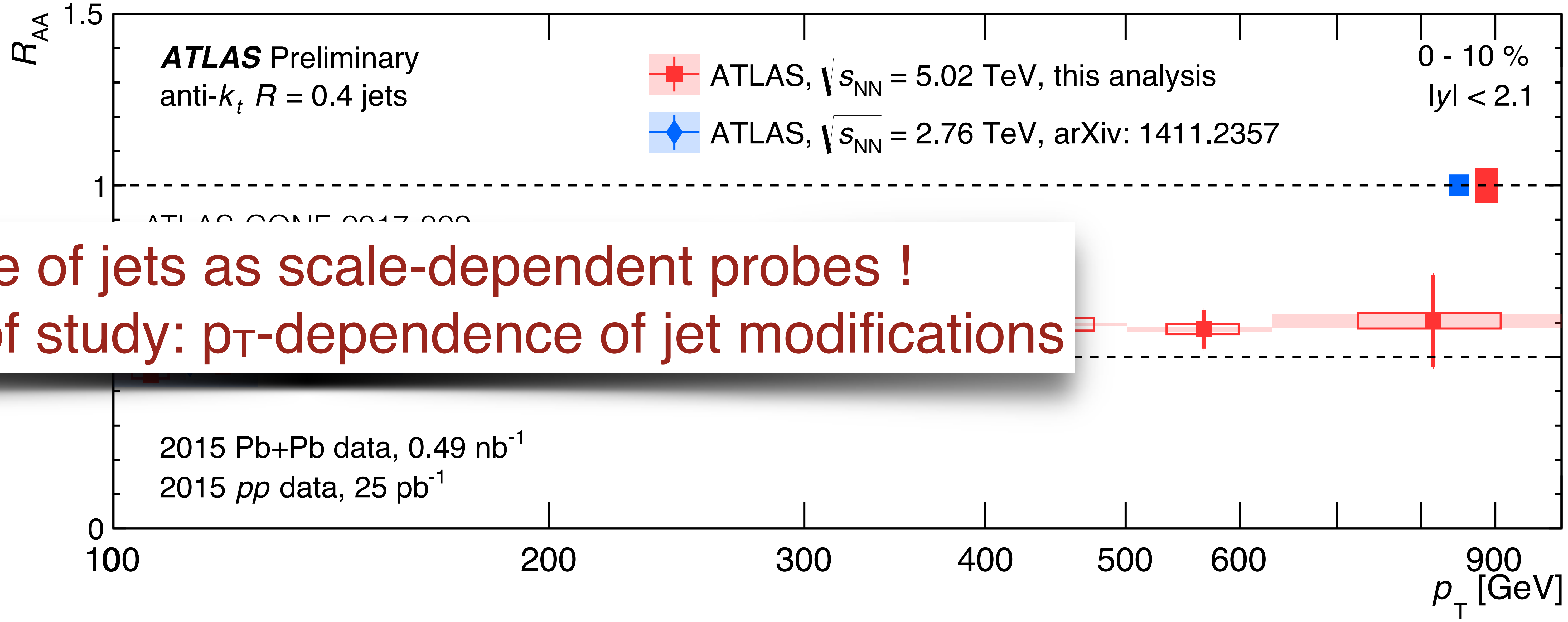


Jet R_{AA}



First glimpse of jets as scale-dependent probes !
Opens up a field of study: p_T-dependence of jet modifications

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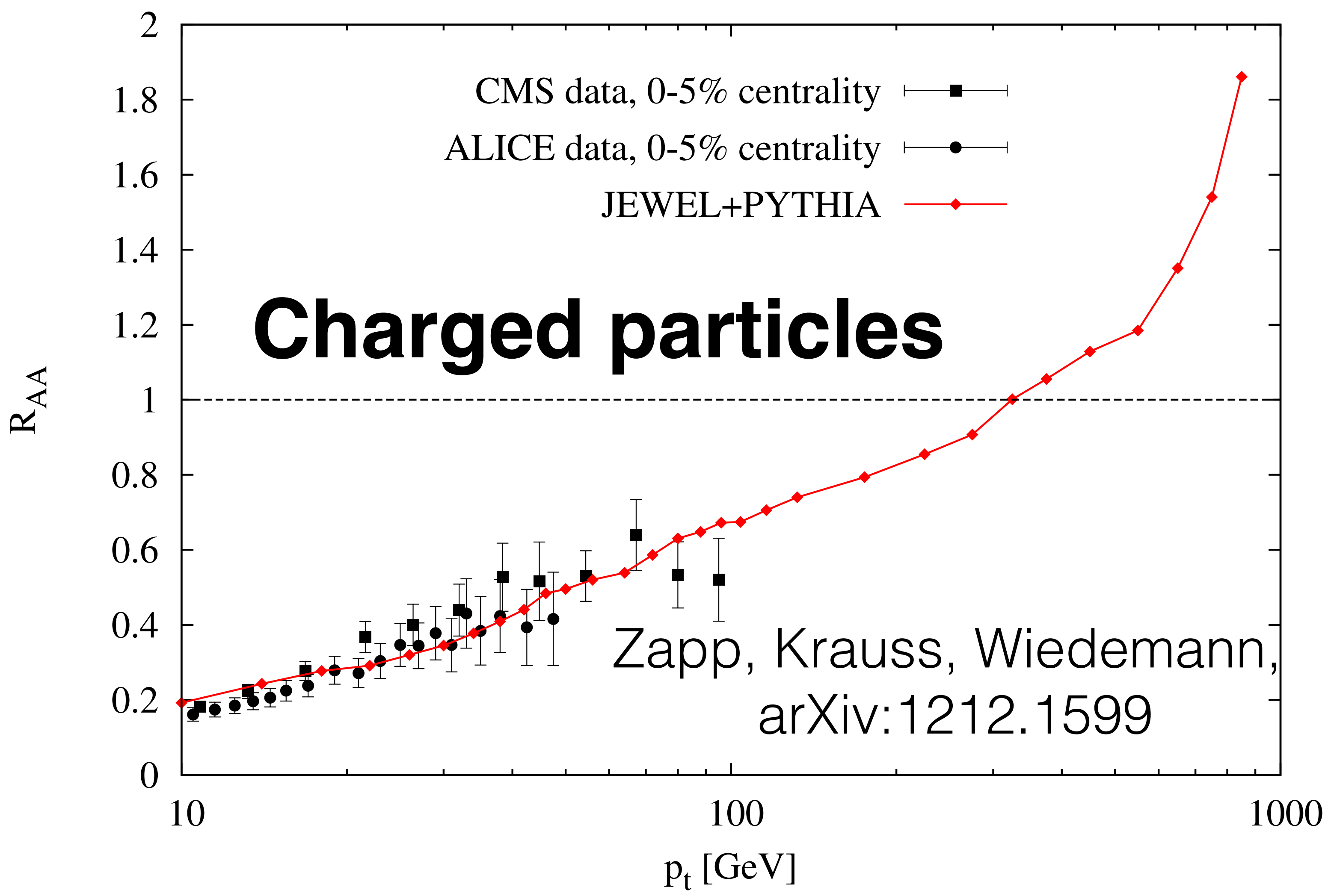
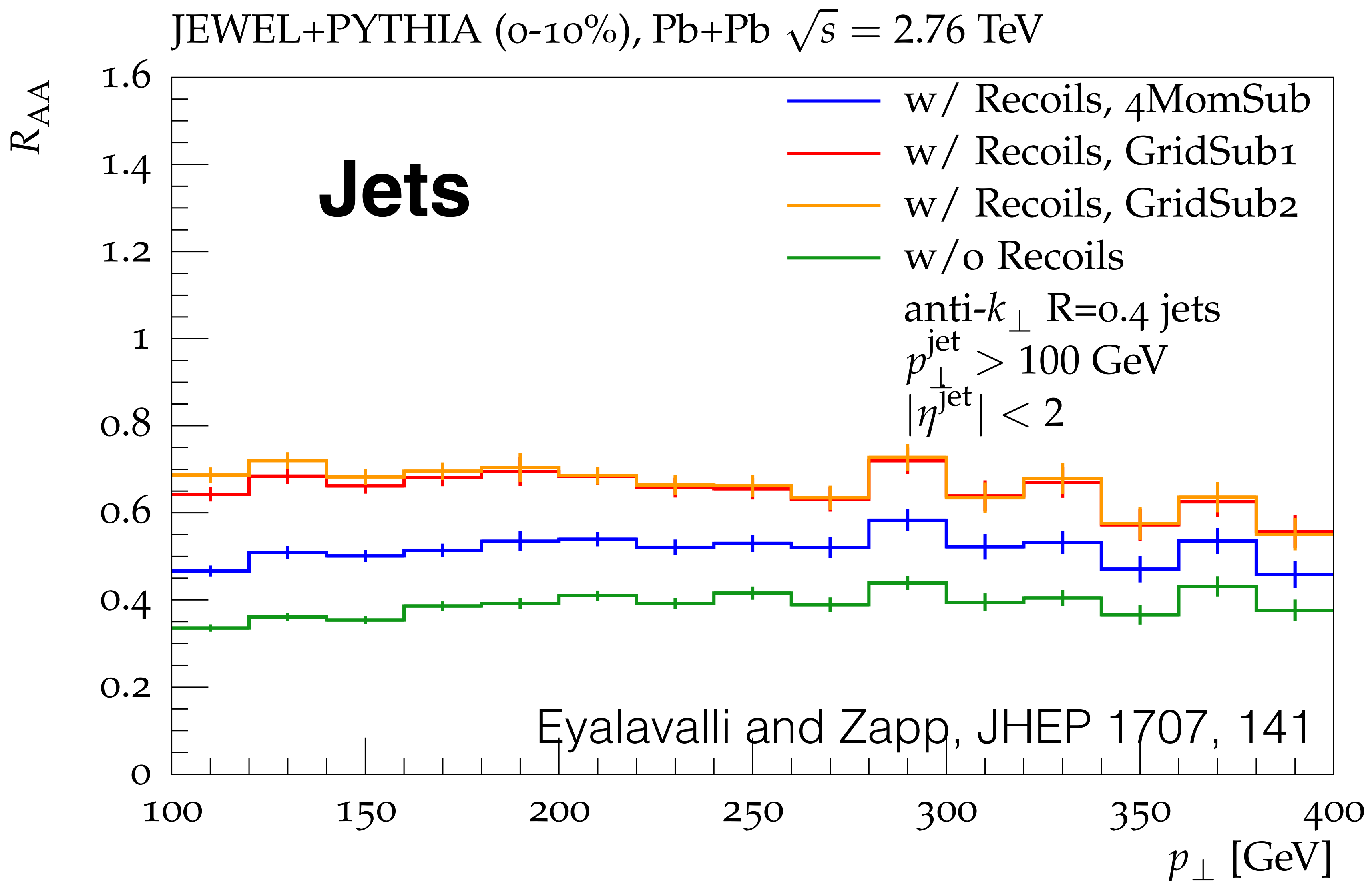
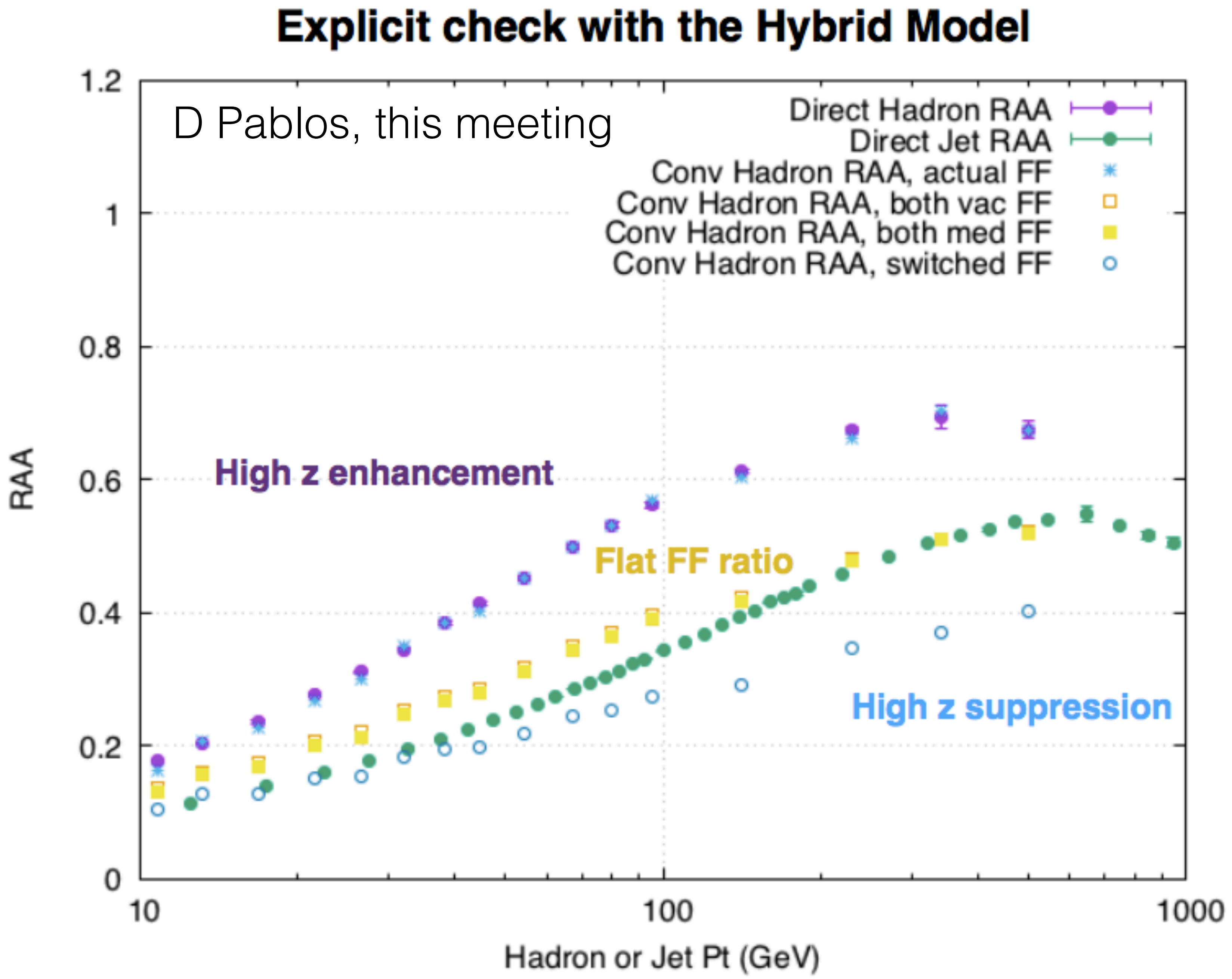
First look at the models

JEWEL





Hybrid model



JEWEL seems to capture the trends quite well

Some quantitative questions to be worked out;
e.g. increase of hadron RAA too slow at 5 TeV?

Hybrid model: similar conclusion at first sight:
increase of jet R_{AA} less steep than hadron R_{AA}
Also consistent with energy shift + small corrections?

Take home message: need large p_T range to draw strong conclusions
small range: flat vs increase hard to disentangle; limited precision of models and data

Where does the lost energy go ?

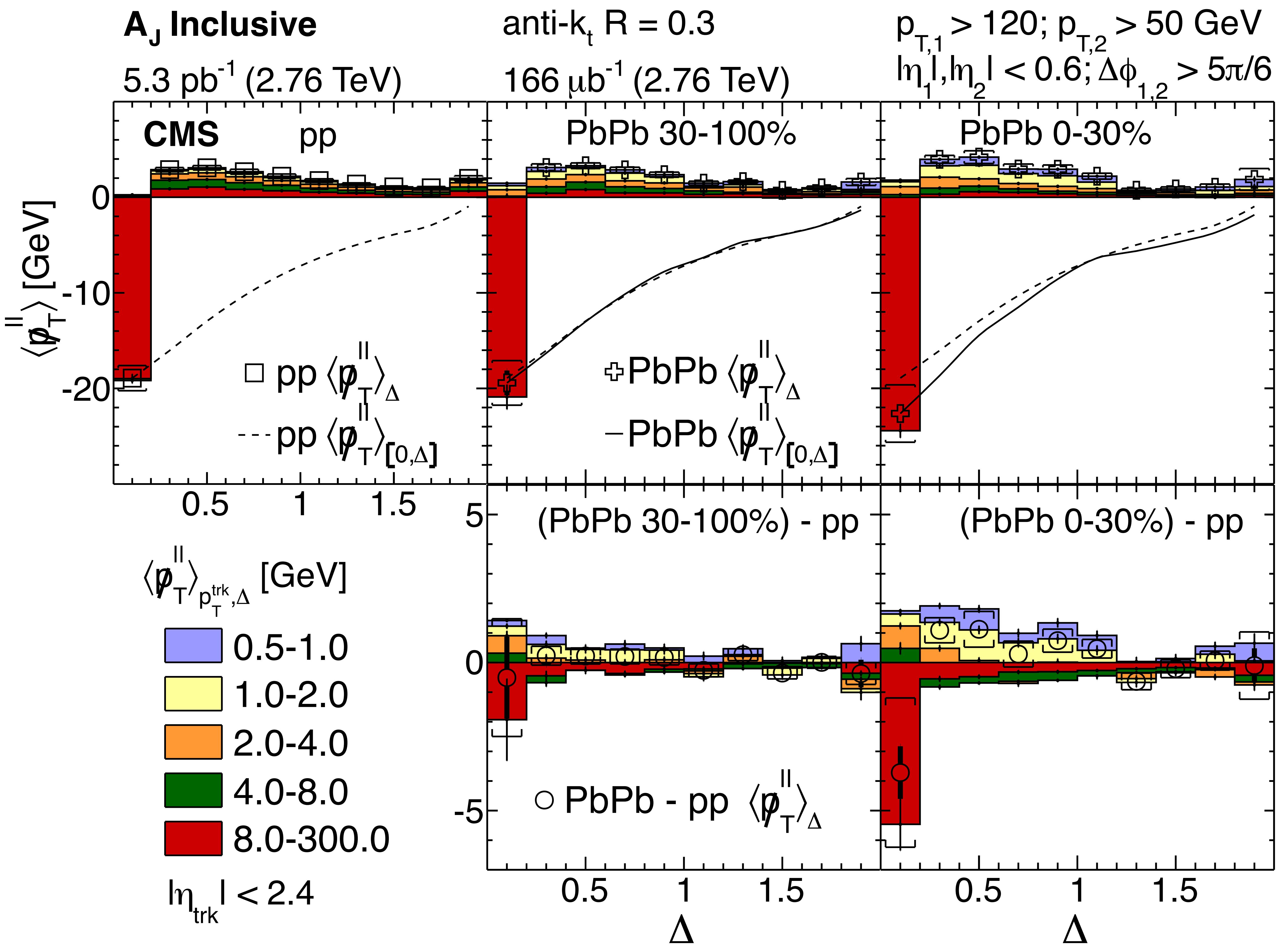
Results clearly show that lost energy goes to large angle and soft particles

Should try to go beyond this qualitative statement

- Is the transport to large-angle consistent with expectations from pQCD?
- Does it require 'thermalisation'?
- Can we learn more about coherence effects?

Several studies exist: JEWEL, Hybrid model, CCNU give partial answers…

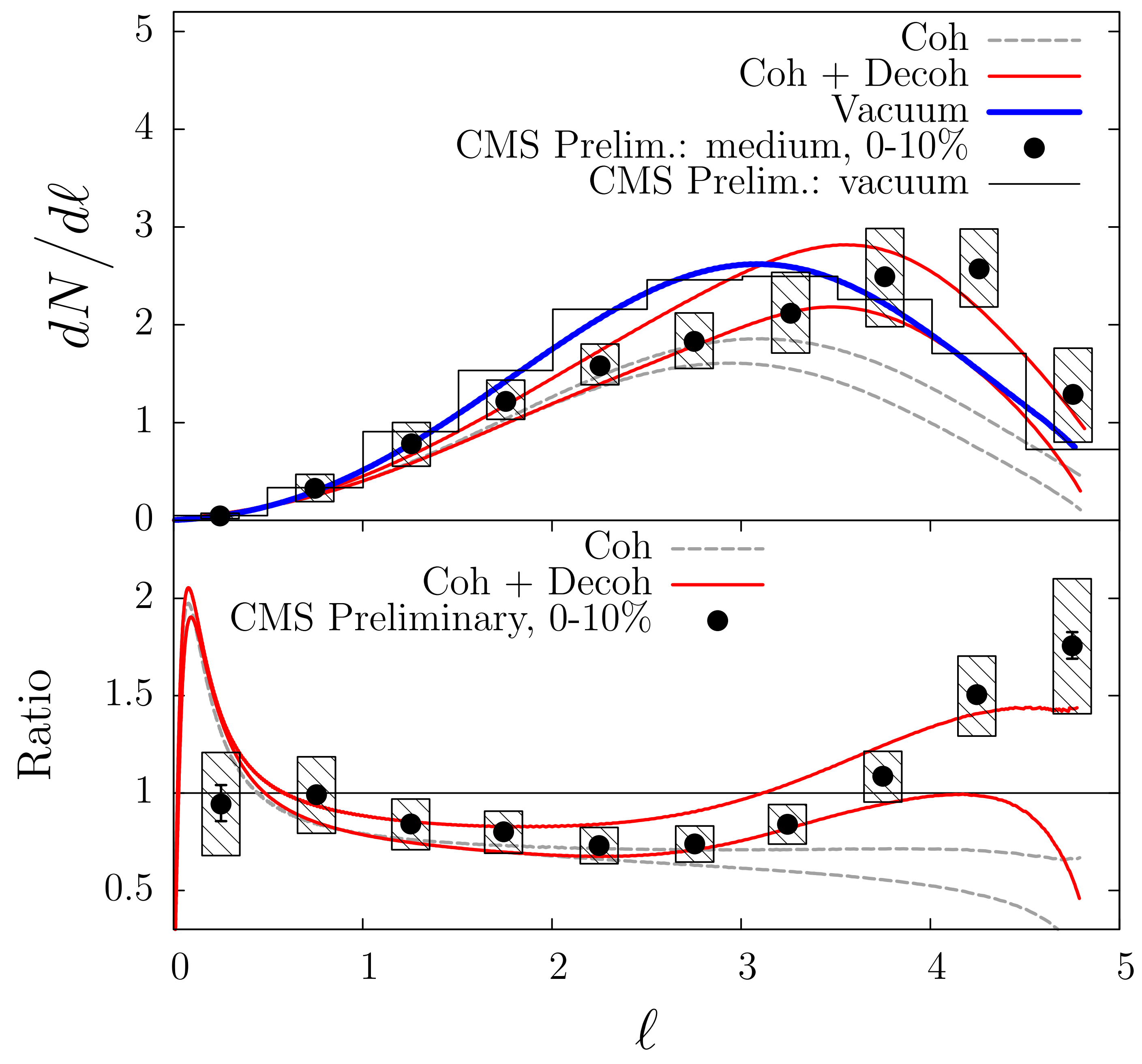
Requires careful modeling of soft physics — not easy and exploration of model uncertainties



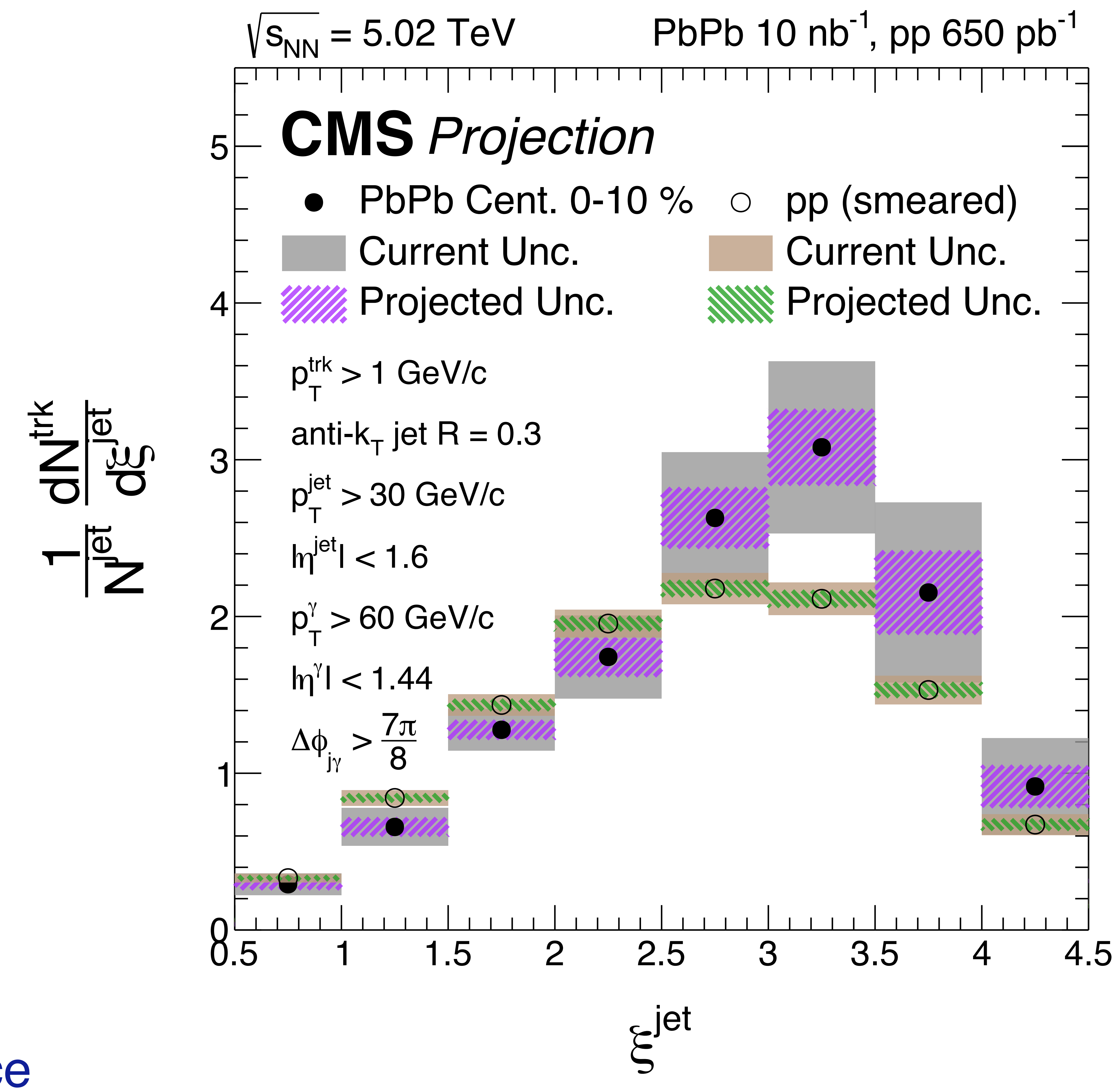
CMS, JHEP 01 (2016) 006

Fragmentation functions/hadron distributions

Mehtar-Tani and Tywoniuk, Phys. Lett. B744(2015) 284



CMS-PAS-FTR-17-002

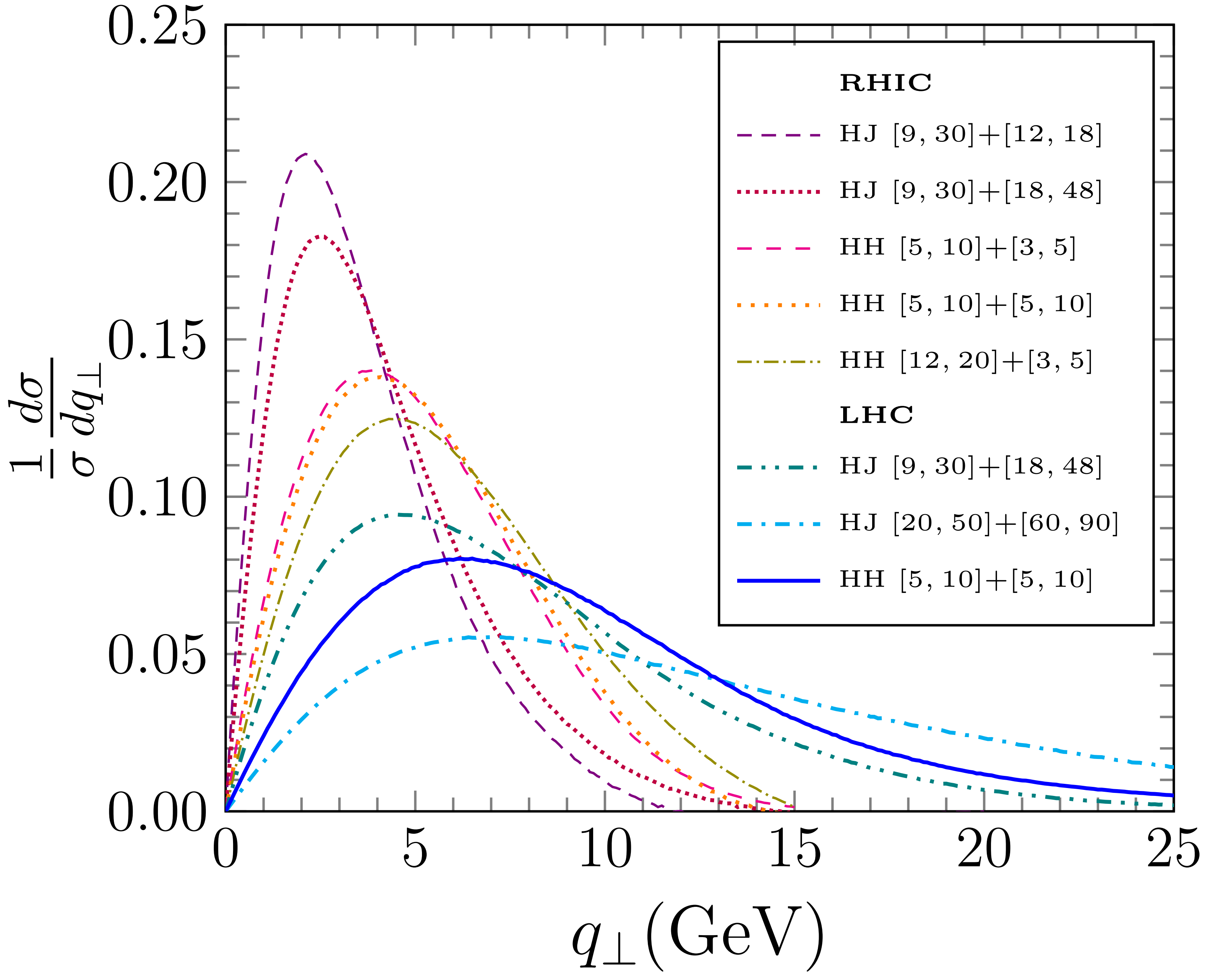


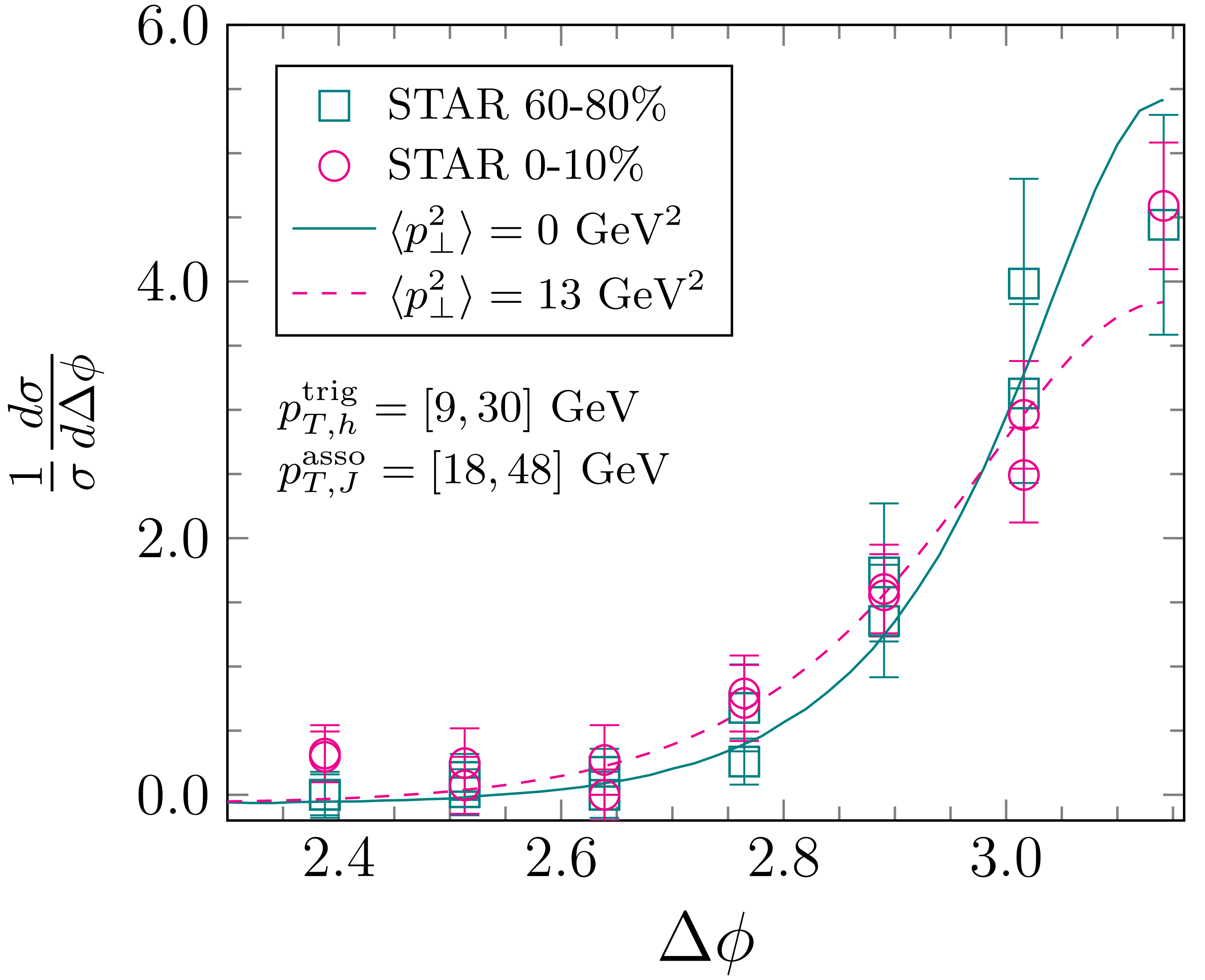
High-z: hadron vs jet R_{AA}; scale dependence of energy loss
Low-z: mechanism of thermalisation in the medium vs soft fragmentation

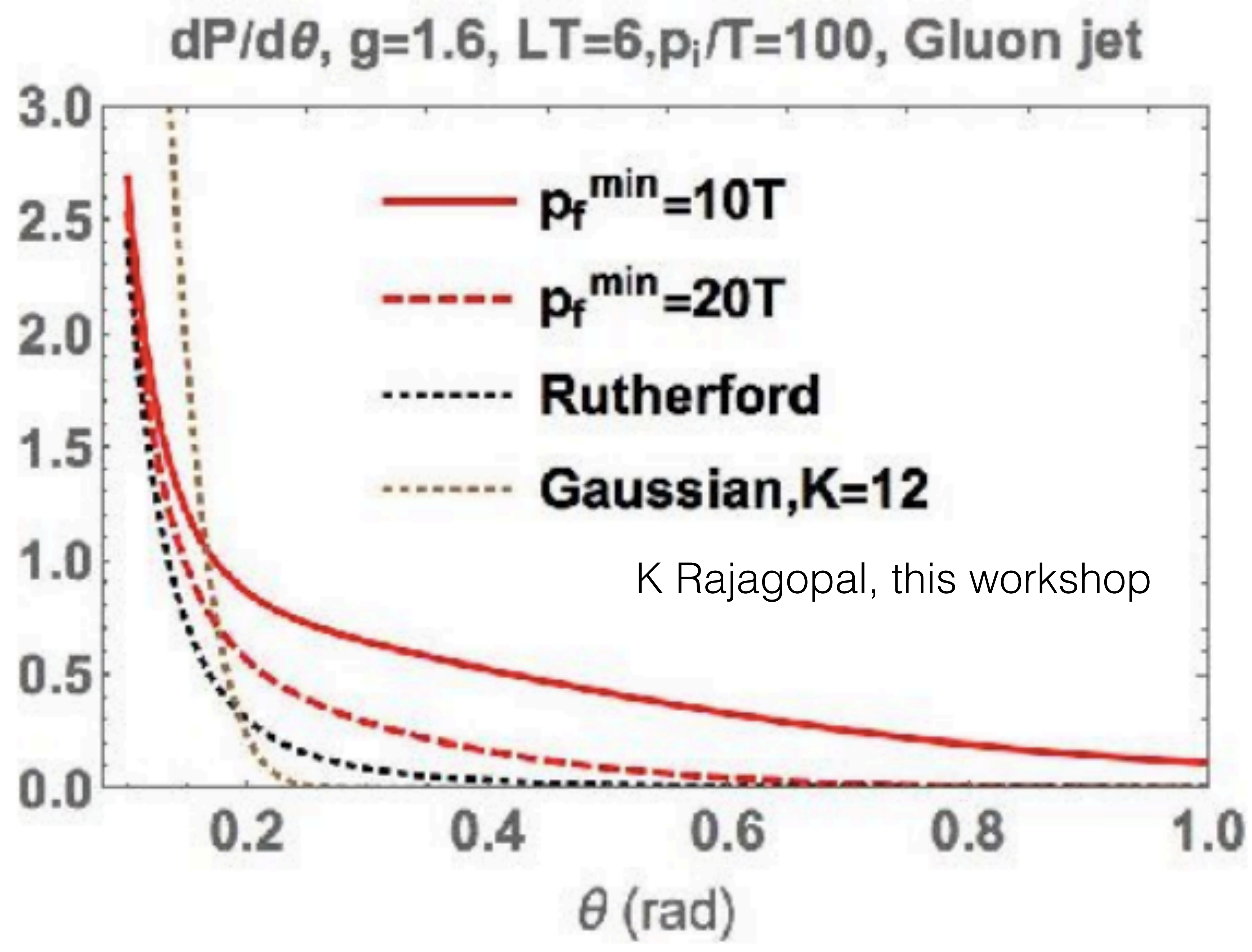
Effects tend to be small:
Experimentally: need good precision and study p_T dependence
Models: need to consider systematic uncertainties on models/missing physics

Jet acoplanarity

Chen, Qin, et al, arXiv:1607.01932







Gaussian width: sensitive to momentum broadening

Tails:'Rutherford scattering'

Relation momentum broadening - energy loss
depends on nature of medium

$$\langle q_\perp^2 \rangle = \hat{q}L \quad \hat{q} = KT^3$$

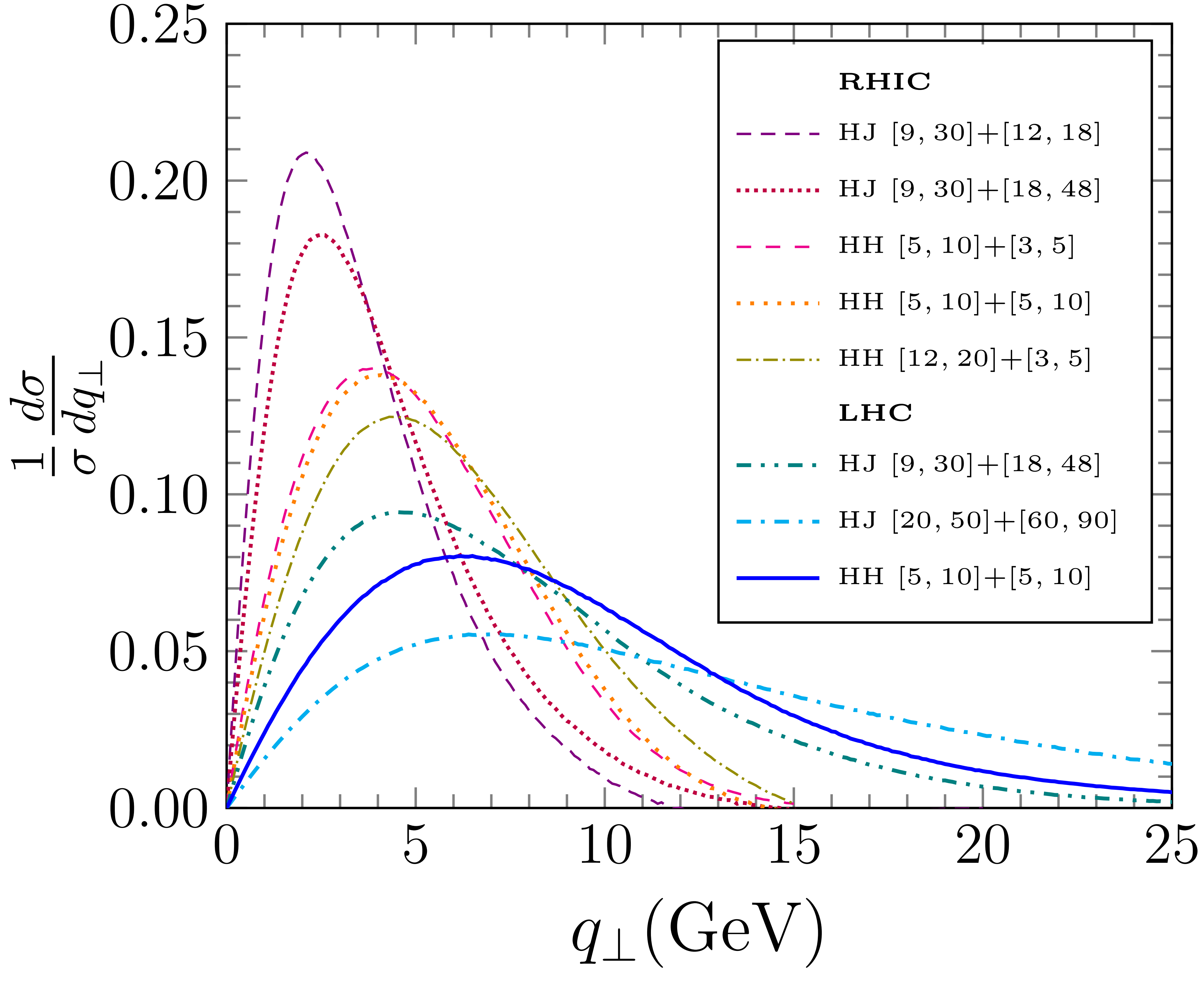
K = 2-5 in QCD
larger in strong coupling

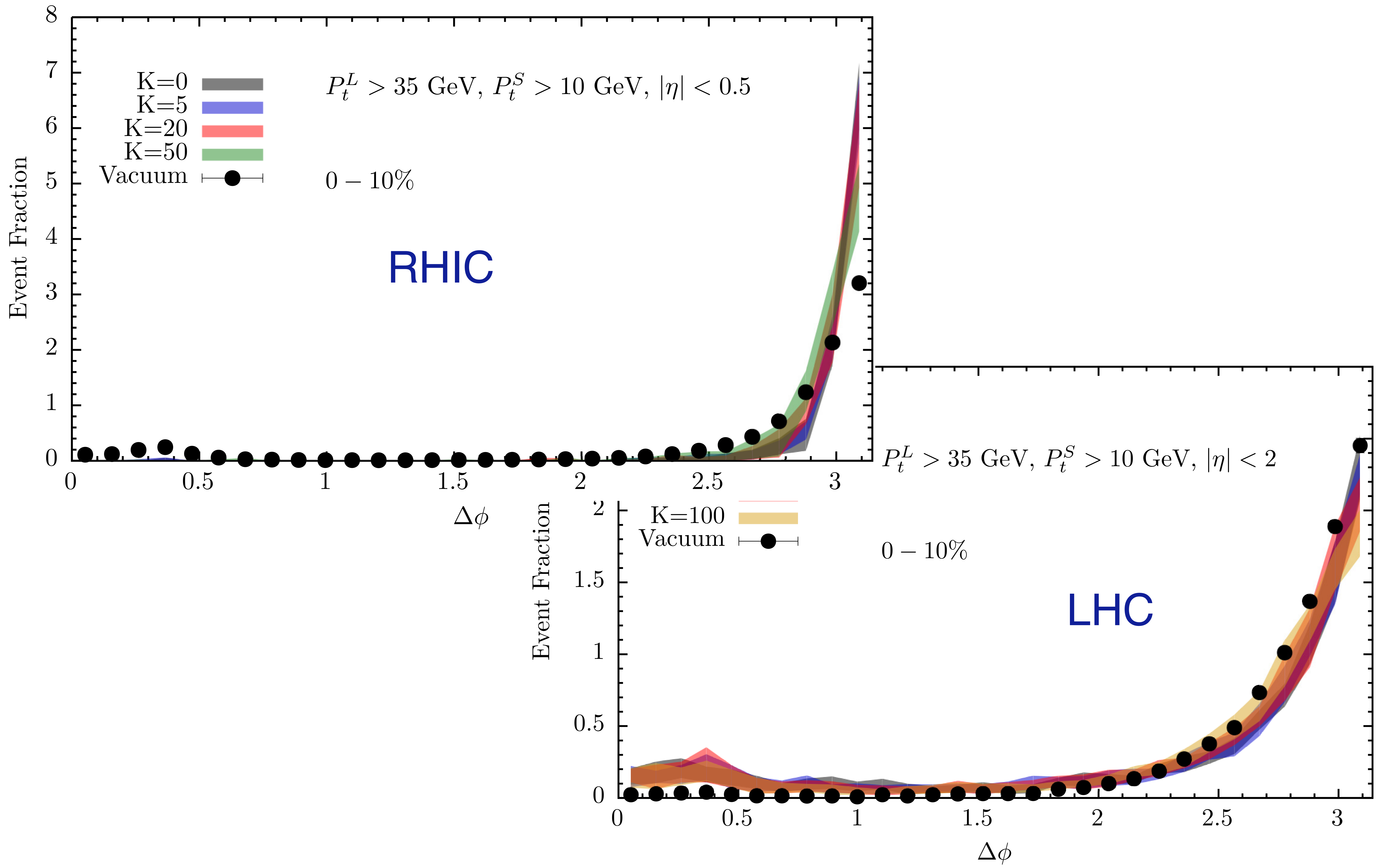
Potential for direct sensitivity
to scattering centers in the medium

Competing effects for acoplanarity: Sudakov broadening and E loss

Hybrid model, Solana et al, arXiv:1609.05842

Chen, Qin, et al, arXiv:1607.01932





Natural width of h-jet, jet-jet distributions

$$\langle q_\perp^2 \rangle = (2 - 5\ \text{GeV})^2$$

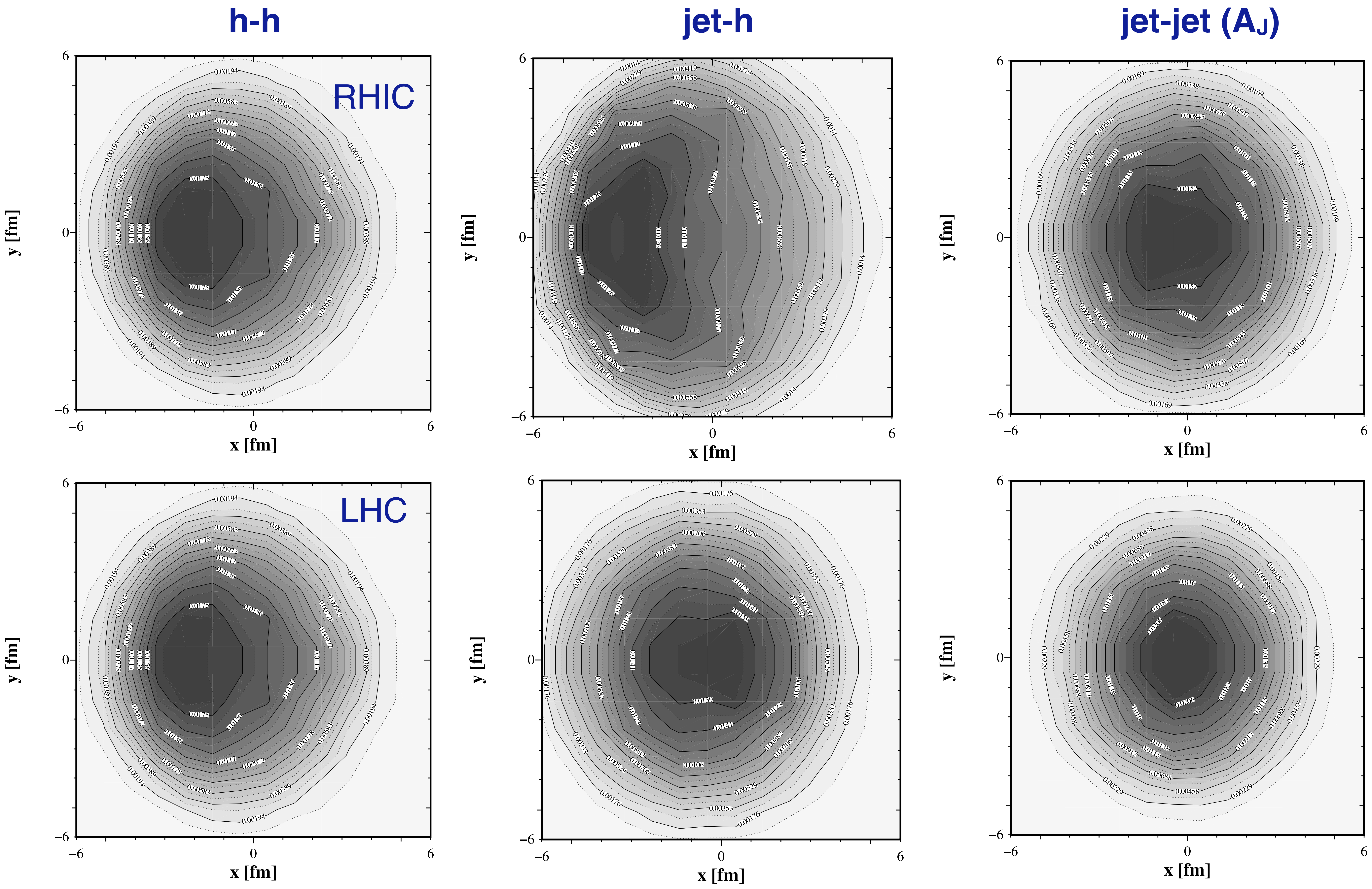
Energy loss causes narrowing (shift from high to low p_T)

Putting things together: dialing the biases

Leveraging the differences in geometric and energy loss bias in observables

Conceptually powerful, but needs simultaneous modeling of geometry, energy loss, and experimental selection

Main ingredients: surface bias vs fluctuations



T. Renk, arXiv:1212.0646

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

Using biases: examples/ideas

- Disentangle geometric effects and fluctuations
  - Inclusive vs recoil
  - gamma-jet (or EW boson-jet) vs di-jets
- Select quark/heavy quark jets
- Dial the biases to tease out the small acoplanarity signals?
- Select jets that experience a large energy loss to increase ‘signal’
  - ‘Natural’ fluctuations from geometry and the intrinsic process are very large; ‘average’ not always useful
- Explicitly study energy loss dependence on e.g. opening angle?

  Needs development/study: ideally have two classes of variables:
    - Variable(s) that preserve properties of the ‘vacuum jet’, i.e. not (much) affected by energy loss
    - Variable(s) that are explicitly sensitve to energy loss

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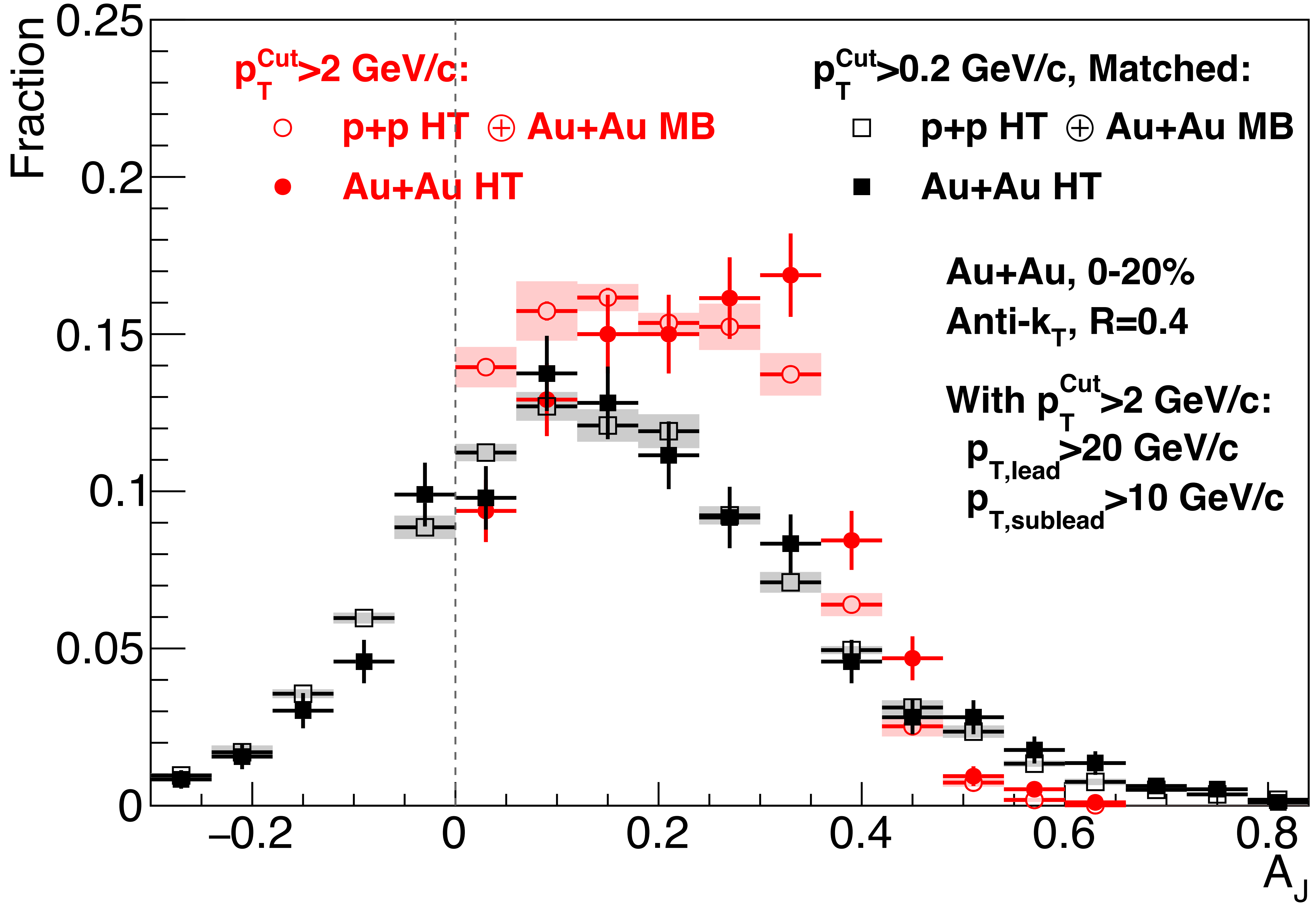
This is where jet shape variables have great potential!

Many options under study; unfortunately no time to review…

Example: A_J at RHIC

STAR, arXiv:1609.03878



Observation: di-jet imbalance small at RHIC when selecting 'hard-core jets'

Is this driven by the hard core selection?
—> Hard core selects jet (pairs) that lose little energy
Can be tested at LHC

What about other biases/effects:

- Steeper spectrum at RHIC
- Smaller overall energy loss at RHIC vs LHC?
- Quark vs gluon jets?

Promising avenue, needs follow-up to extract the physics

Example II: compare γ-jet and jet-jet

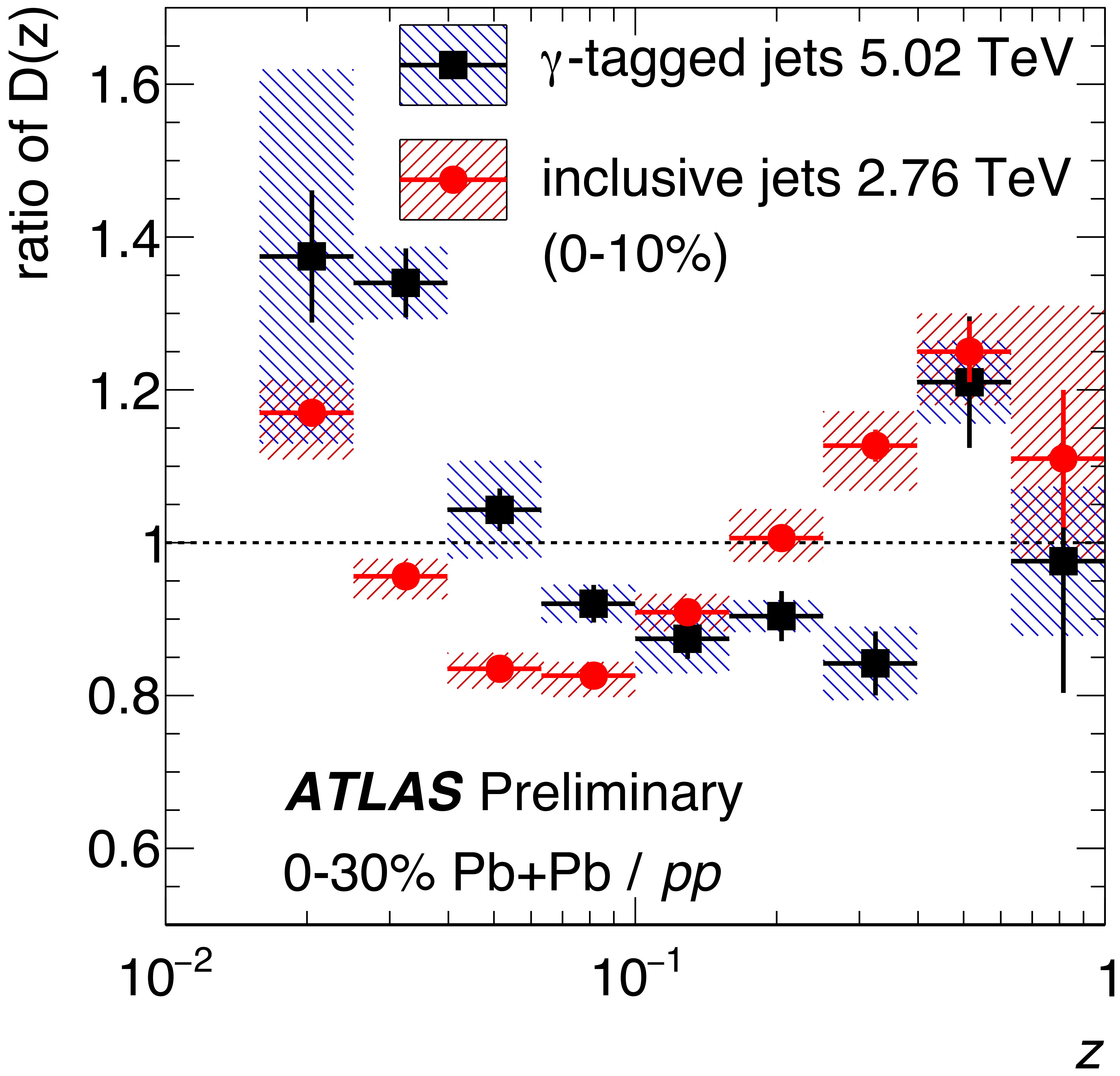
Comparing γ-jet and jet-jet changes:

- Energy loss bias
  reco jet energy is 'after energy loss'
- Flavour content
  quark vs gluon jets

Leads to difference in frag function modification

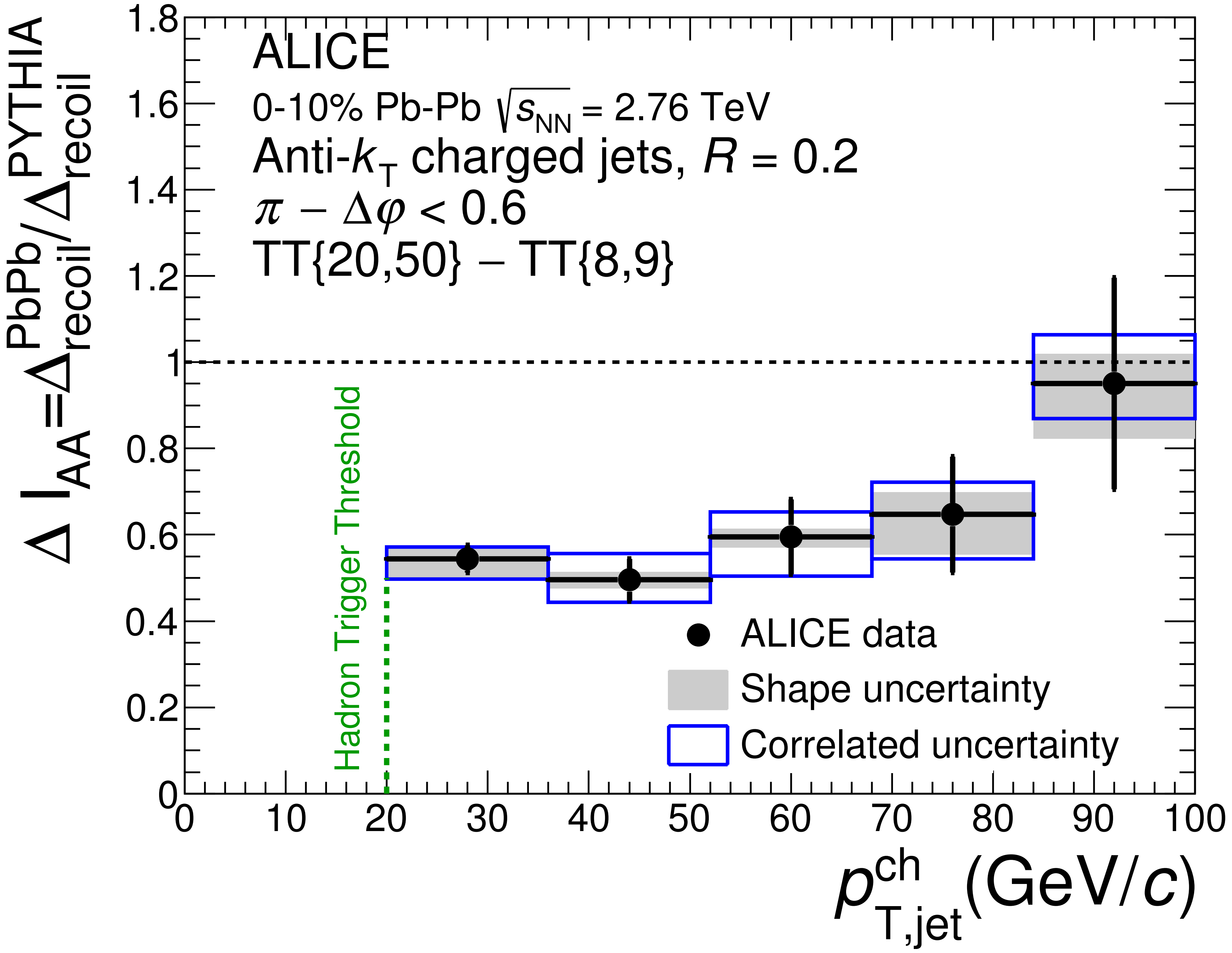
Leverage this with models + increasing data precision
to extract the physics

ATLAS-CONF-2017-074



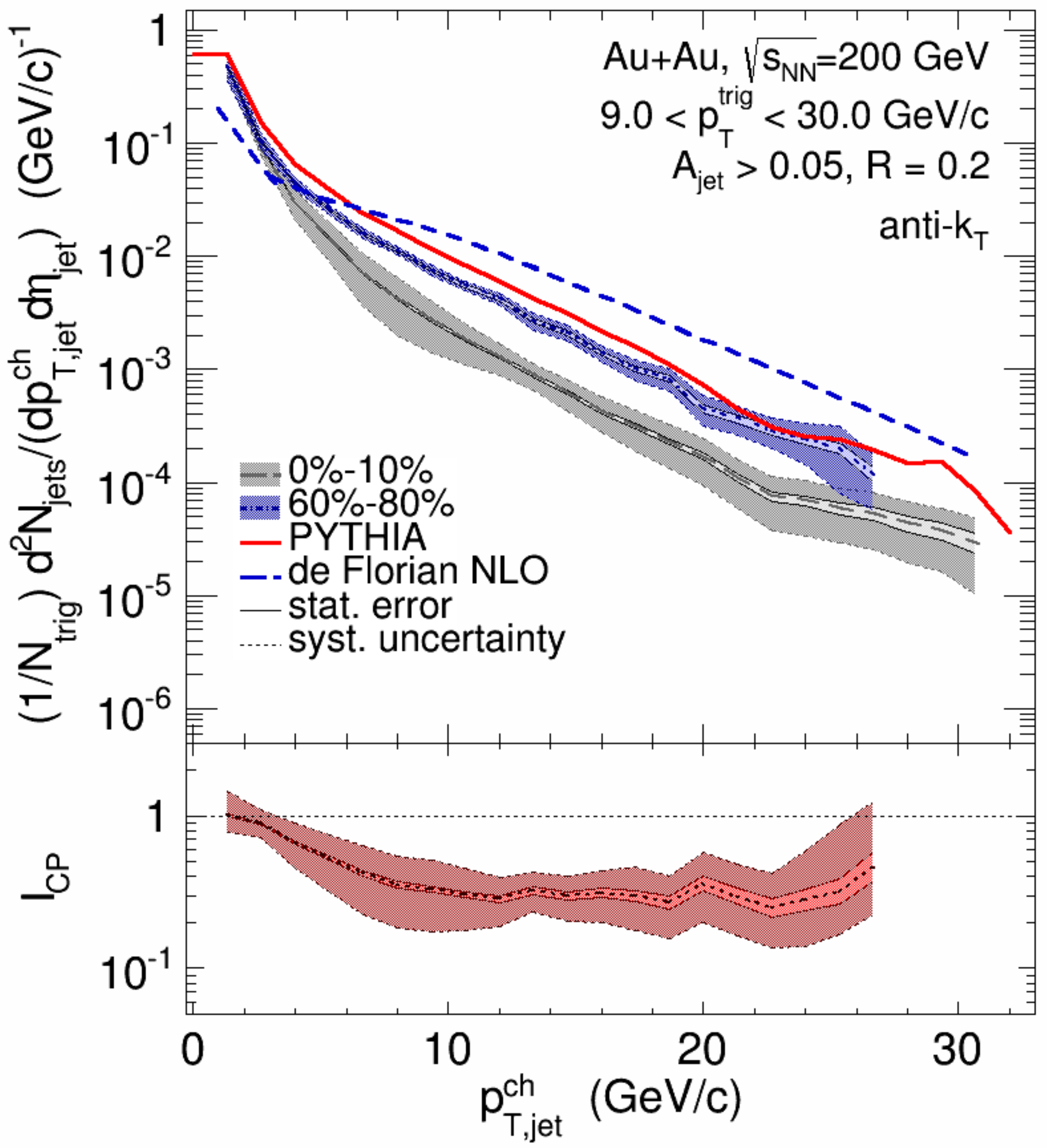
Example III: h-jet at RHIC and LHC

ALICE, JHEP 09 (2015) 170



LHC: recoil jet suppression
$\Delta I_{AA} \sim 0.5$ with R=0.2

STAR, PRC96, 024905



RHIC: recoil jet suppression
$\Delta I_{AA} \sim 0.3$ with R=0.2

Suppression numerically quite different at RHIC and LHC.
What drives this? Kinematic selection, different surface bias, …

Future experiments: HL-LHC

https://indico.cern.ch/event/647676/timetable/

HL-LHC: expect factor ~3 increase of lumi; 2.8 nb^{-1}/year

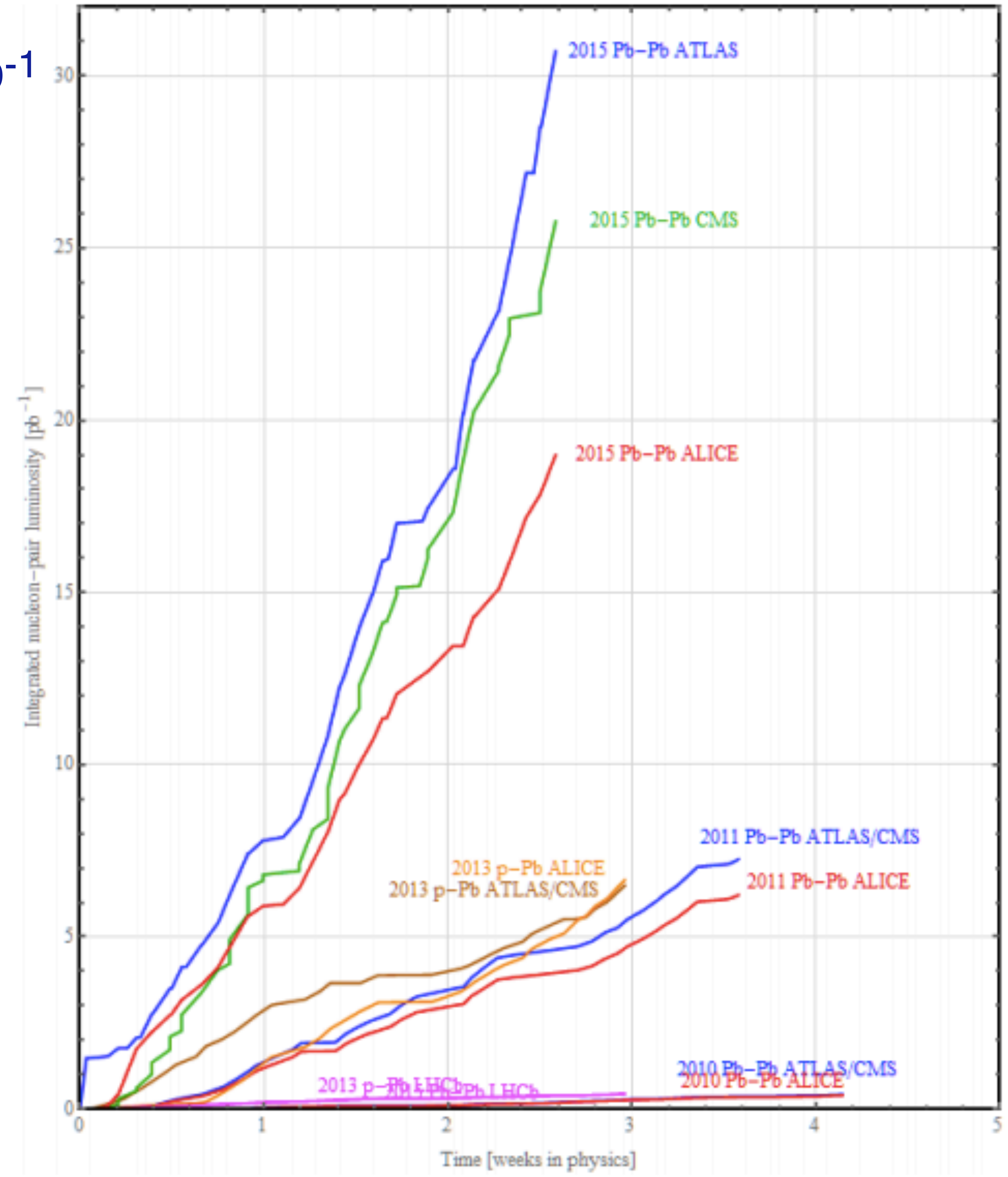
Current target lumi : 10 nb^{-1} in run 3 + 4 (2021-2029) (ALICE request)

Increase in statistics compared to run 1, 2:

- 5x for triggers in ATLAS+CMS
- 10x for triggers in ALICE
- 100x for MB-like in ALICE

LHC HI lumi over the years

0.7 nb^{-1}



J.Jowett, HL-HC workshop

1 nb^{-1} PbPb ~ 43 NN-equiv pb^{-1}

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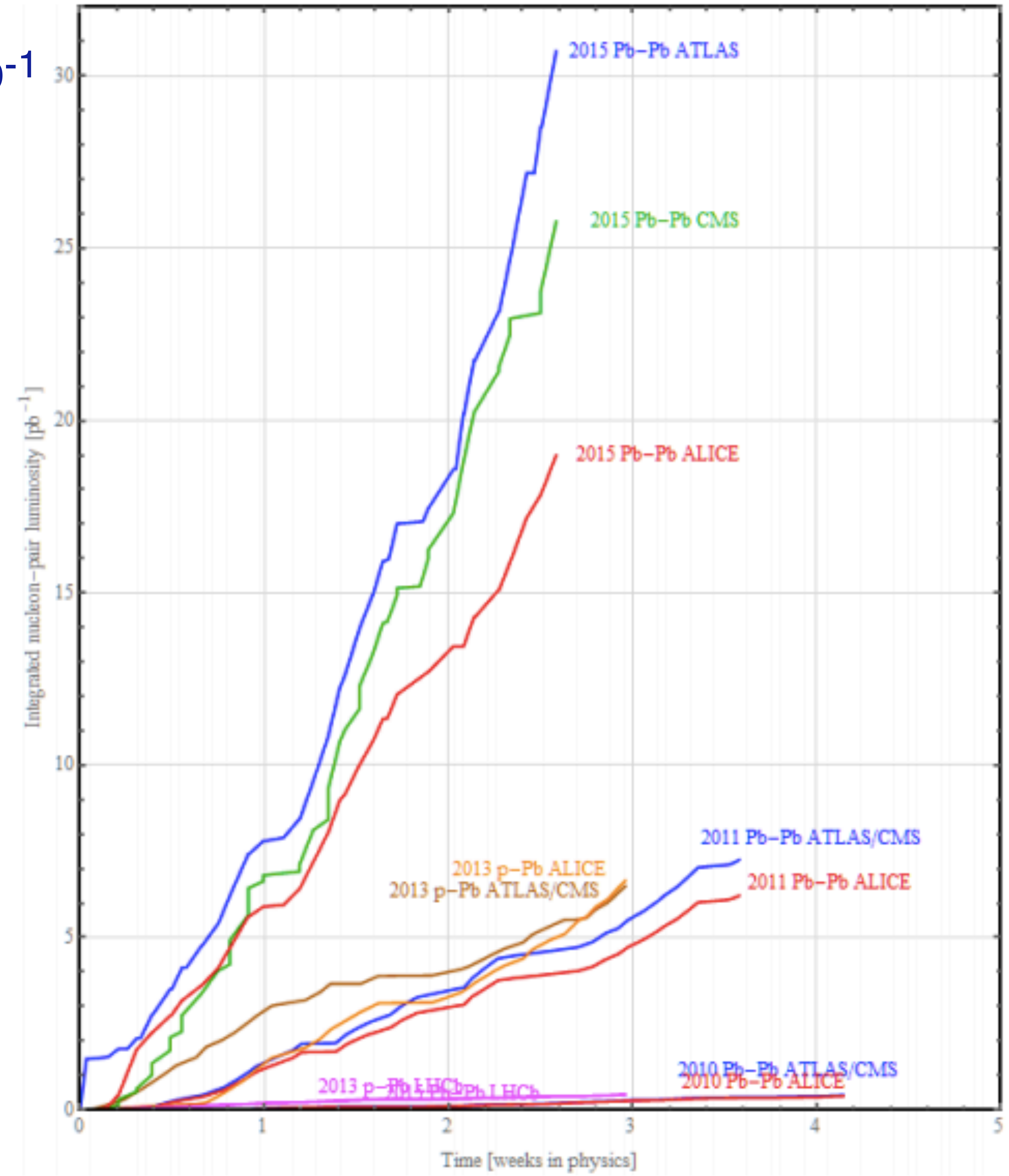
The HI program for run 3, 4 and beyond is being discussed in a series of workshops
→ European Strategy for Particle Physics

LHC HI lumi over the years

0.7 nb^{-1}



J.Jowett, HL-HC workshop

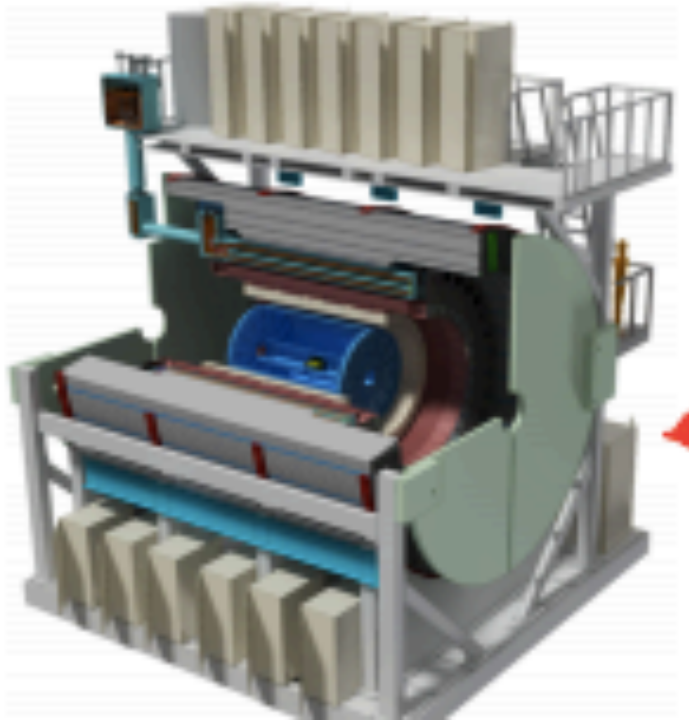
1 nb^{-1} PbPb ~ 43 NN-equiv pb^{-1}

Future experiments: sPHENIX at RHIC

Physics drives detector requirements

Physics goal	Detector requirement
High statistics for rare probes	**Accept/sample full delivered luminosity** Full azimuthal and large rapidity acceptance
Precision Upsilon spectroscopy	Hadron rejection > 99% with good $e^{+/-}$ acceptance Mass resolution 1% @ m_{Υ}
High jet efficiency and resolution	Full hadron and EM calorimetry Tracking from low to high pT
Control over parton mass	Precision vertexing for heavy flavor ID
Control over initial parton p_T	Large acceptance, high resolution photon ID
Full characterization of jet final state	High efficiency tracking for $0.2 < p_T < 40$GeV

sPHENIX



Slide from: G Roland,
CERN HI jet workshop 2017

Planned start:
2022 ~ LHC run 3

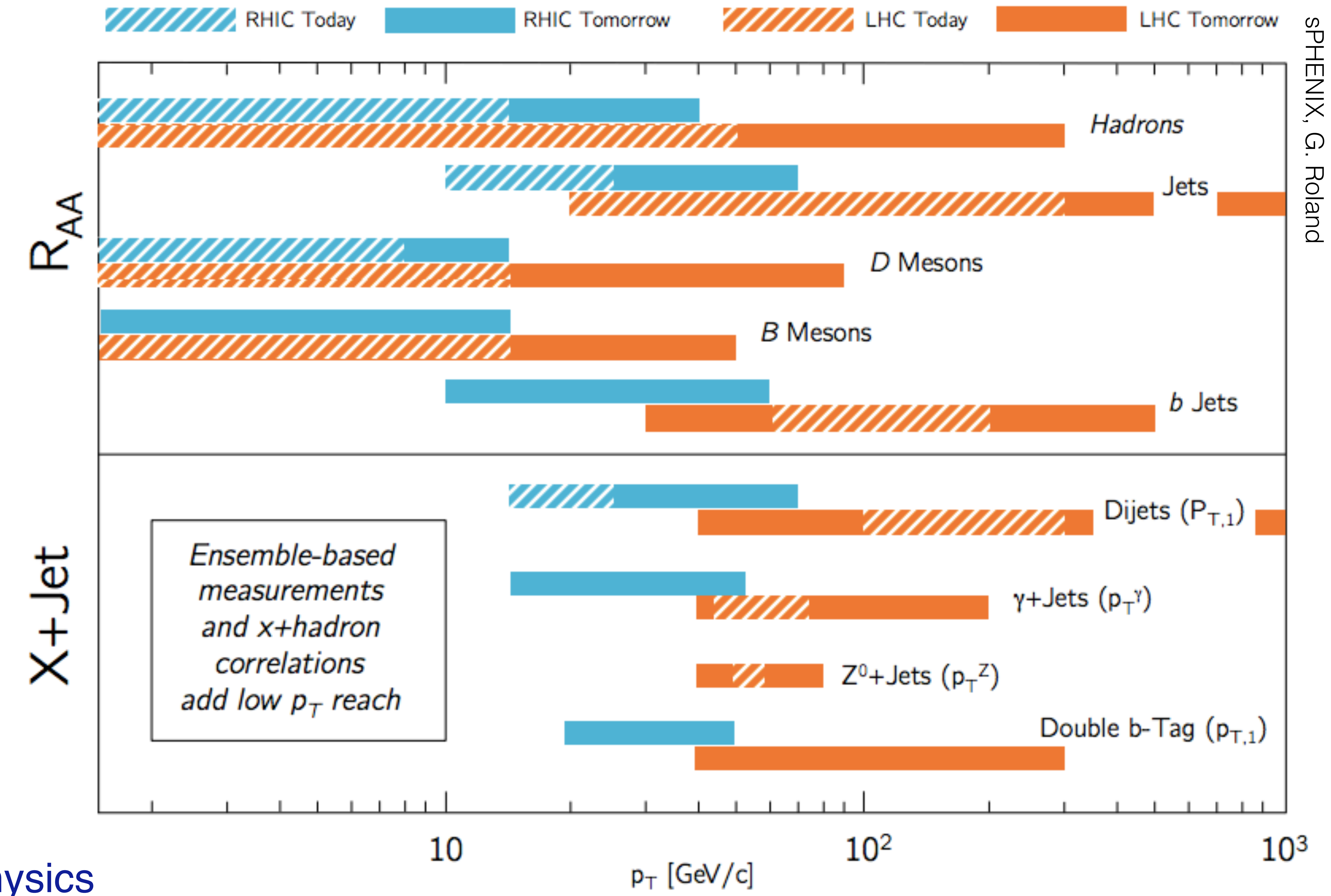
13

Instead of a summary…

Main directions

Experiment:

- Increased precision and p_T reach
  Non-trivial improvement of physics potential!
- More differential studies
  Leveraging the biases
- Better overlap between RHIC and LHC



Theory/modeling:

- Need coherent/simultaneous description
  of multiple observables to constrain the physics
- Need competing/alternative models/mechanisms to compare and contrast
  Also within a single group/code!

Thanks for your attention!

More distant future: FCC and HE-LHC

FCC
Future Circular Collider

$\sqrt{s}$ = 100 TeV for pp, $\sqrt{s_{NN}}$ = 39.4 TeV for Pb-Pb
very large project; requires new tunnel ~ 100 km

HE-LHC
High-Energy LHC

$\sqrt{s}$ = 27 TeV pp, $\sqrt{s_{NN}}$ = 10.6 TeV Pb-Pb
Earliest possible realisation 2040

More info: see HL-LHC workshops and FCC weeks, e.g.: http://fcw2018.web.cern.ch

Simple observables; how to model them?

- A lot of experience exists with simple modeling:
  - Production, energy loss, and fragmentation
  - Plus full hydro background or a good approximation in most cases
- Main advantage: keeps the model tractable (clear what is put in)
- Disadvantage: no natural extension to jet observable
  - Simple modeling may be good enough for single particle observables
  - Except, maybe via jet functions, but long and tedious road
- Also not always obvious how to implement path-length dependence in a non-uniform medium

Note: should not forget model uncertainties/freedoms
- Important part of the story; may point to new questions/directions!
- Several aspects have been explored; many connections still missing

Summary of transport coefficient study

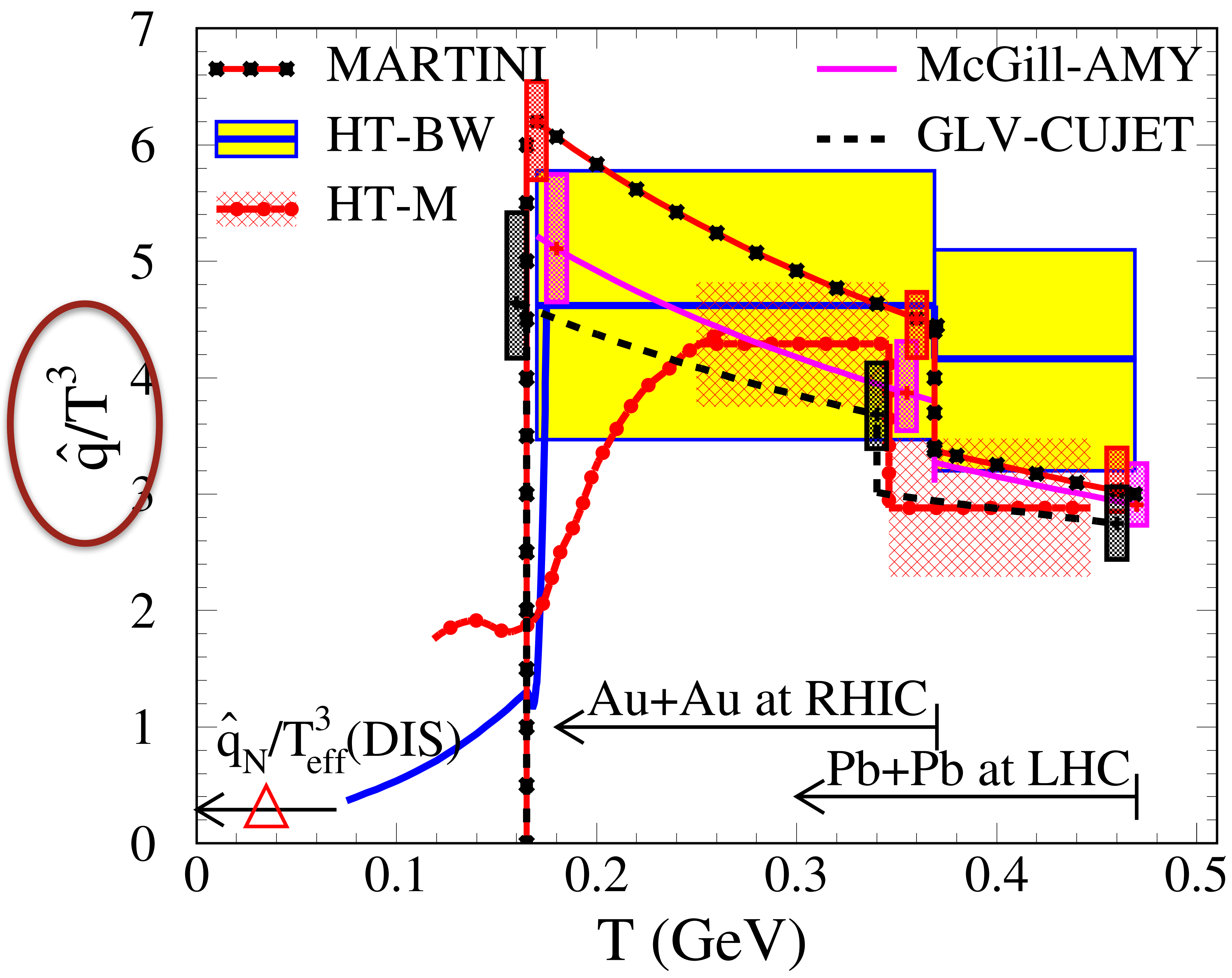
RHIC: $\hat{q} = 1.2 \pm 0.3 \ GeV^2/fm$

(T_i = 370 MeV)

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

(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

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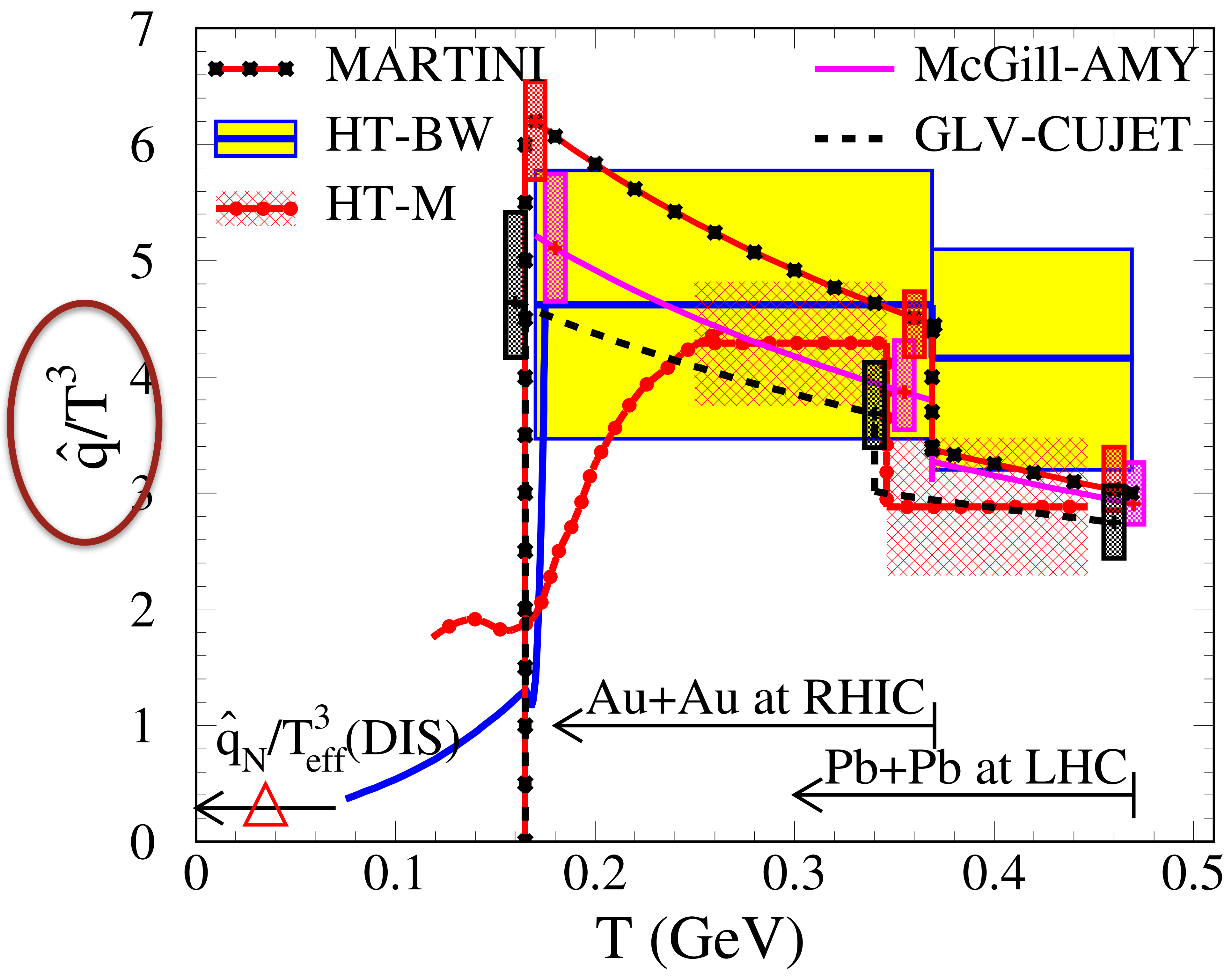

Burke et al, JET Collaboration, arXiv:1312.503

$\hat{q}$ 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

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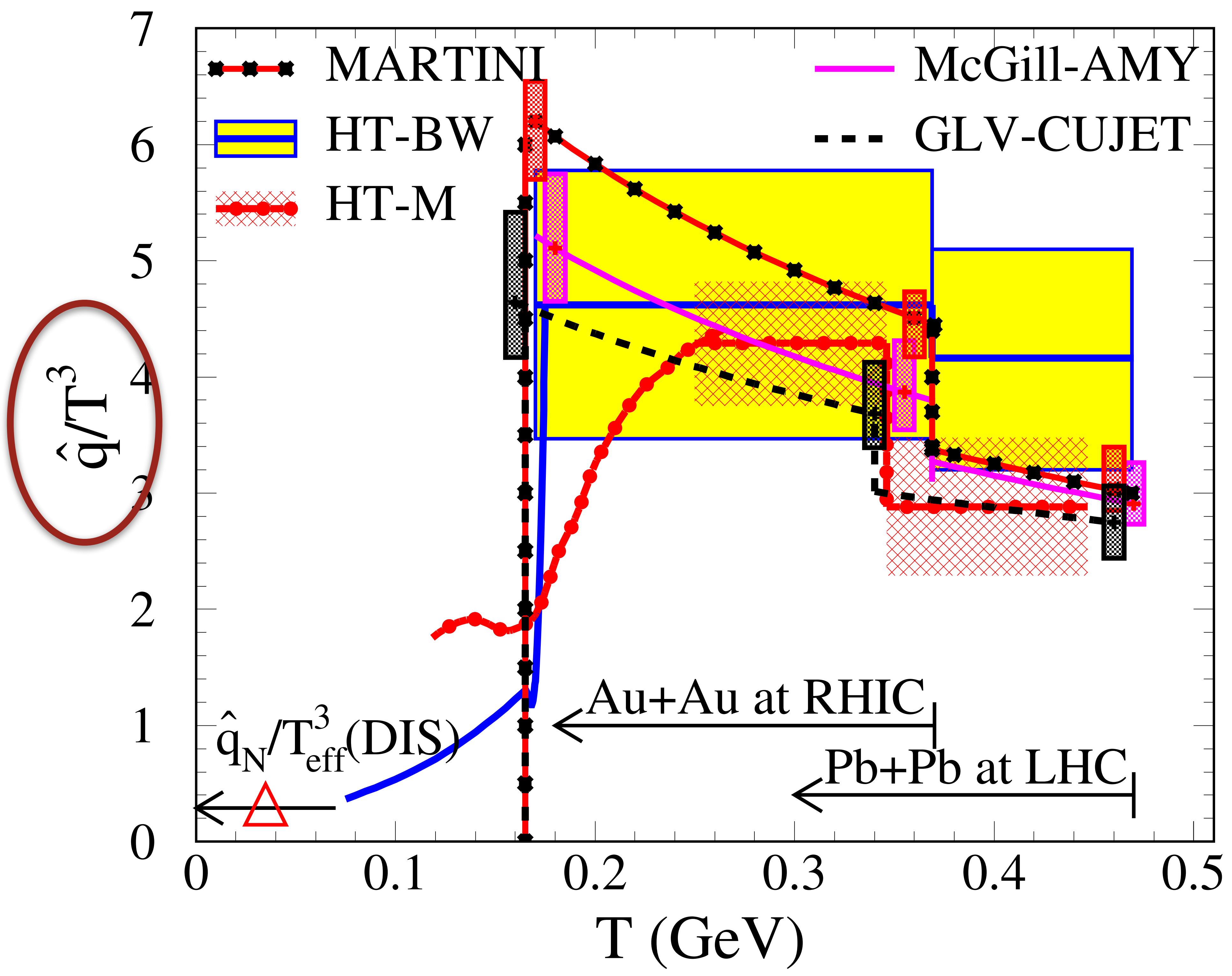

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Sizeable uncertainties from α_S, treatment of logs etc expected

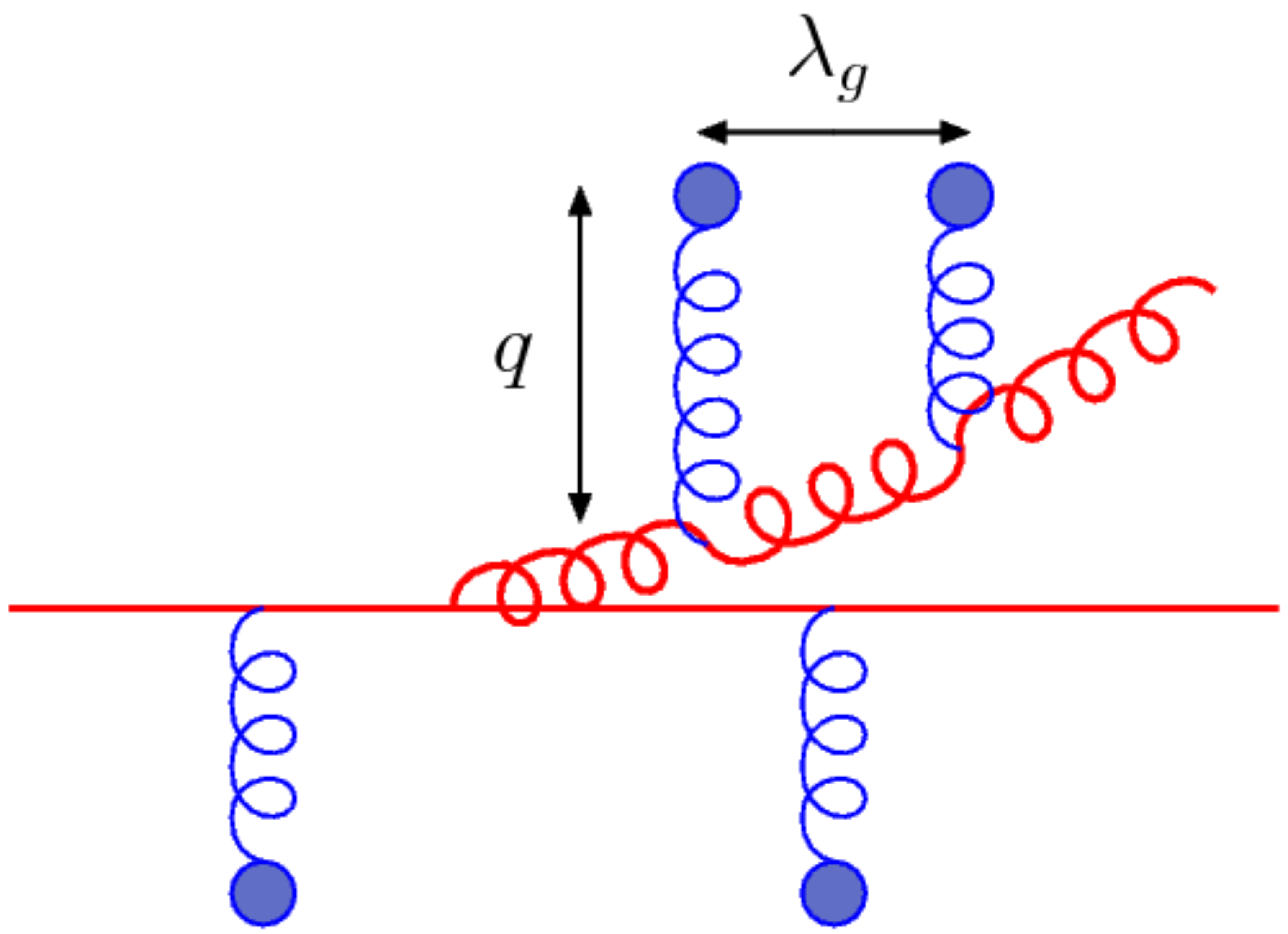
Values found are in the right ballpark compared (p)QCD estimate

Magnitude of parton energy loss is understood

Transport coefficient and viscosity

Transport coefficient:
momentum transfer per unit path length

$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda} = \rho \int dq_\perp^2 \, q_\perp^2 \frac{d^2\sigma}{dq_\perp^2}$$



$\rho \propto T^3$ $\hat{q}$ basically measures the density

Transport coefficient and viscosity

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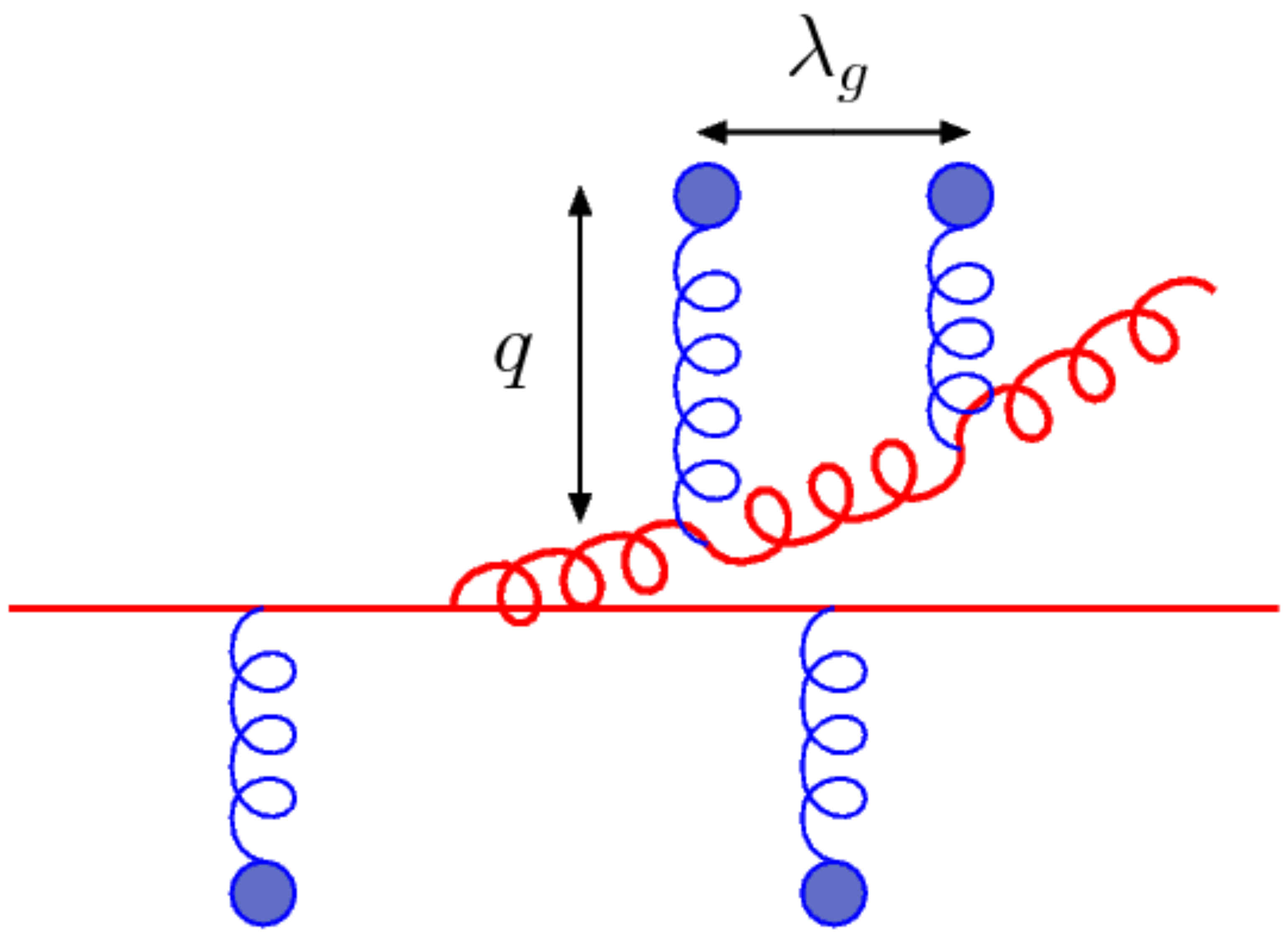

$\rho \propto T^3$ $\hat{q}$ basically measures the density

Viscosity: $\eta \propto \rho \langle p \rangle \lambda$

General relation: $\frac{\hat{q}}{T^3} \propto \left(\frac{\eta}{s}\right)^{-1}$

Transport coefficient and viscosity

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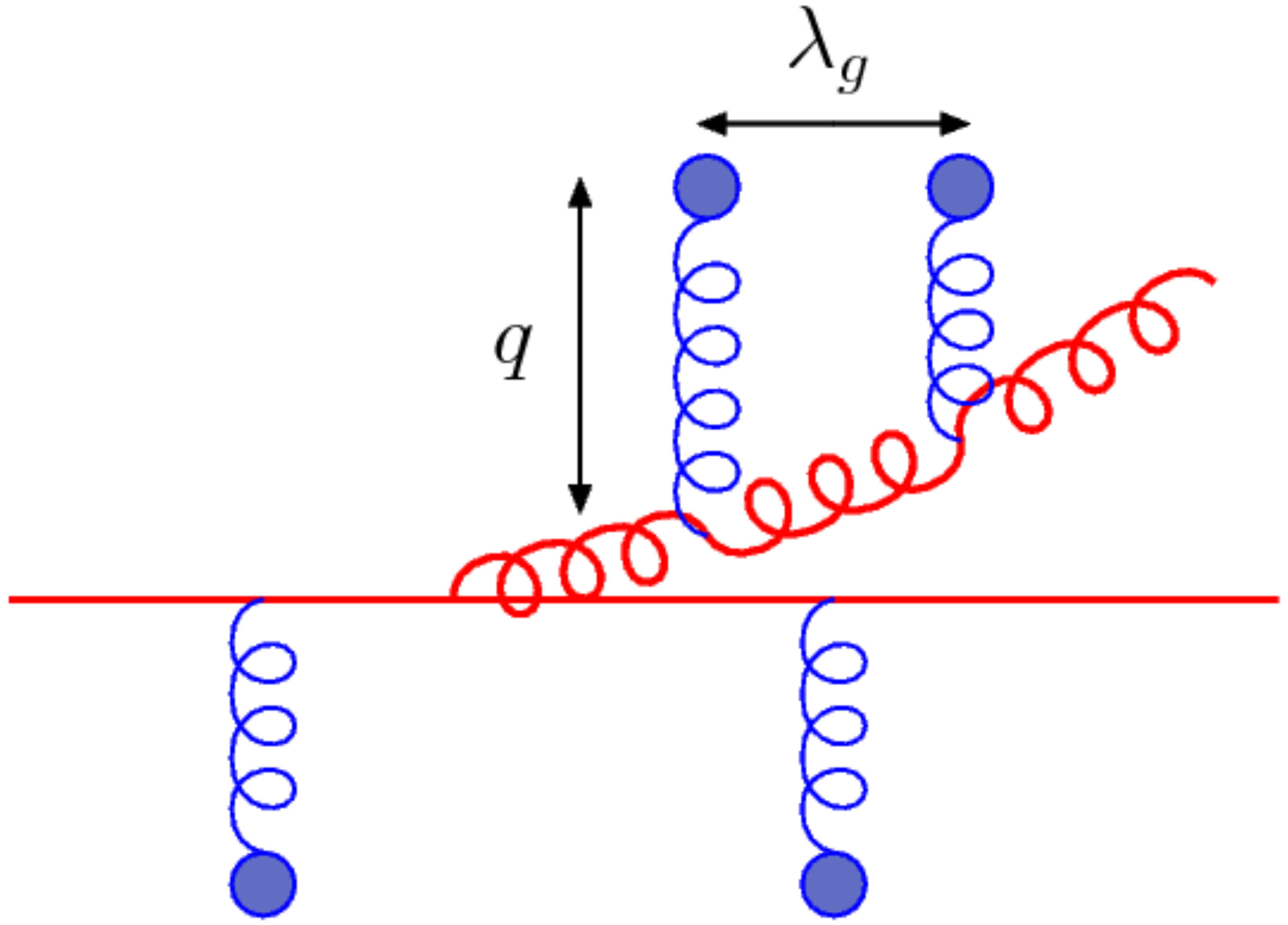


$\rho \propto T^3$ $\quad \hat{q}$ basically measures the density

Viscosity: $\eta \propto \rho \langle p \rangle \lambda$

General relation: $\dfrac{\hat{q}}{T^3} \propto \left(\dfrac{\eta}{s}\right)^{-1}$

Expect $\dfrac{\eta}{s} \approx 1.25 \dfrac{T^3}{\hat{q}}$ for a QCD medium

Majumder, Muller and Wang, PRL99, 192301

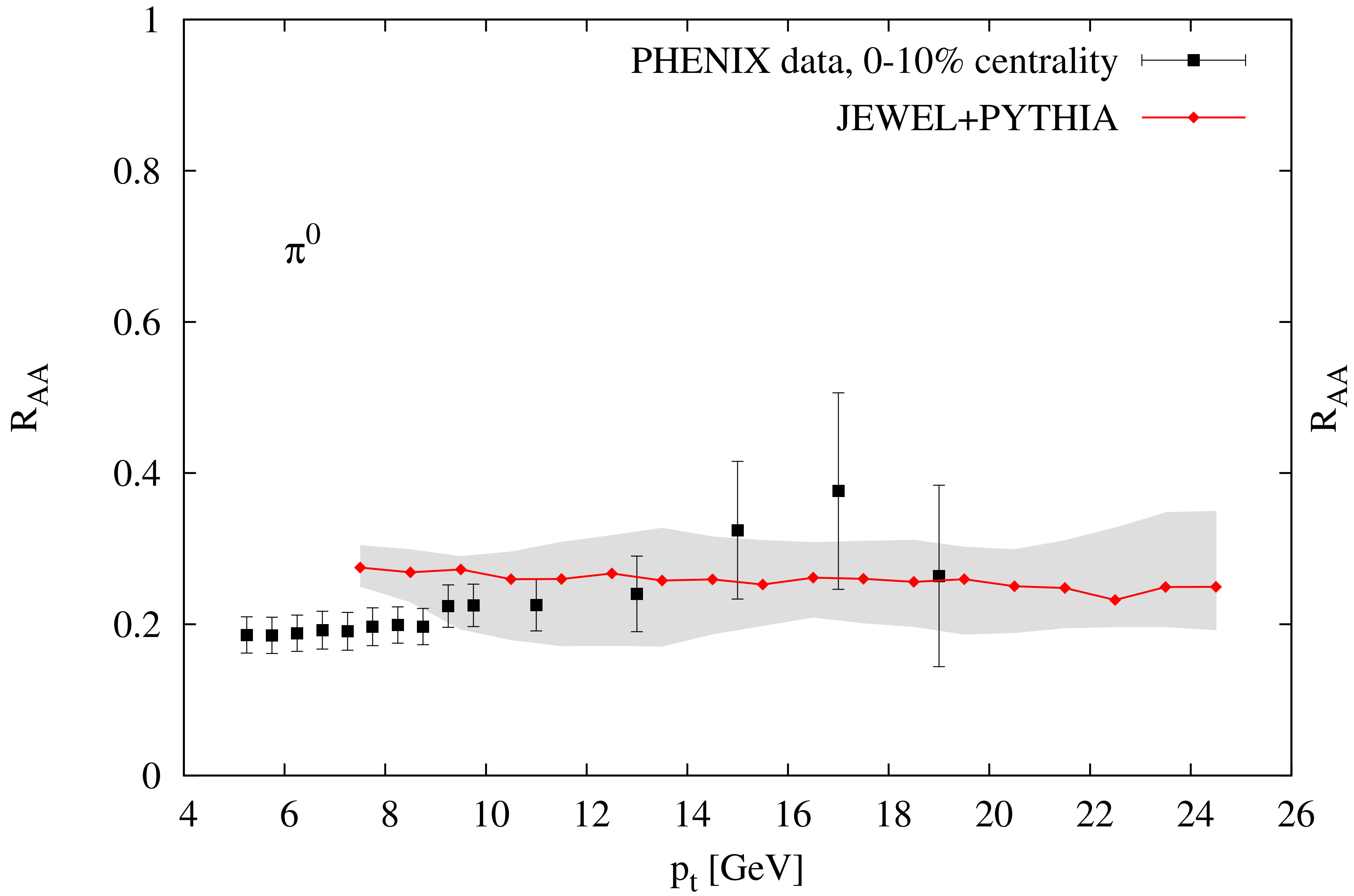
MC tools: JEWEL

Publicly available

Zapp, Krauss, Wiedemann, arXiv:1212.1599

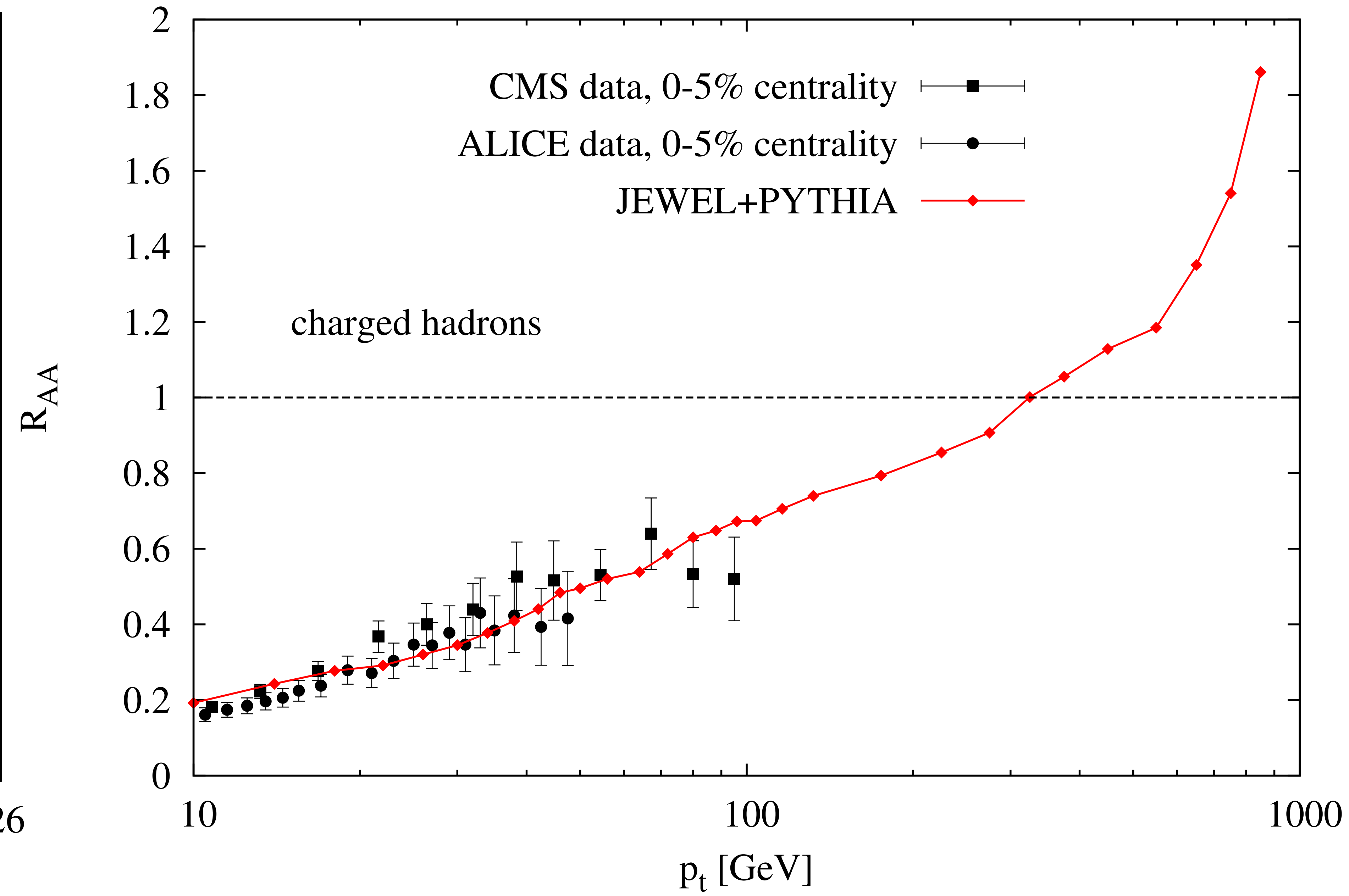
Elastic+radiative energy loss; follows BDMPS-Z in appropriate limits
Medium: Bjorken-expanding Glauber overlap

RHIC



T_i = 350 MeV @ τ_0 = 0.8 fm/c

LHC

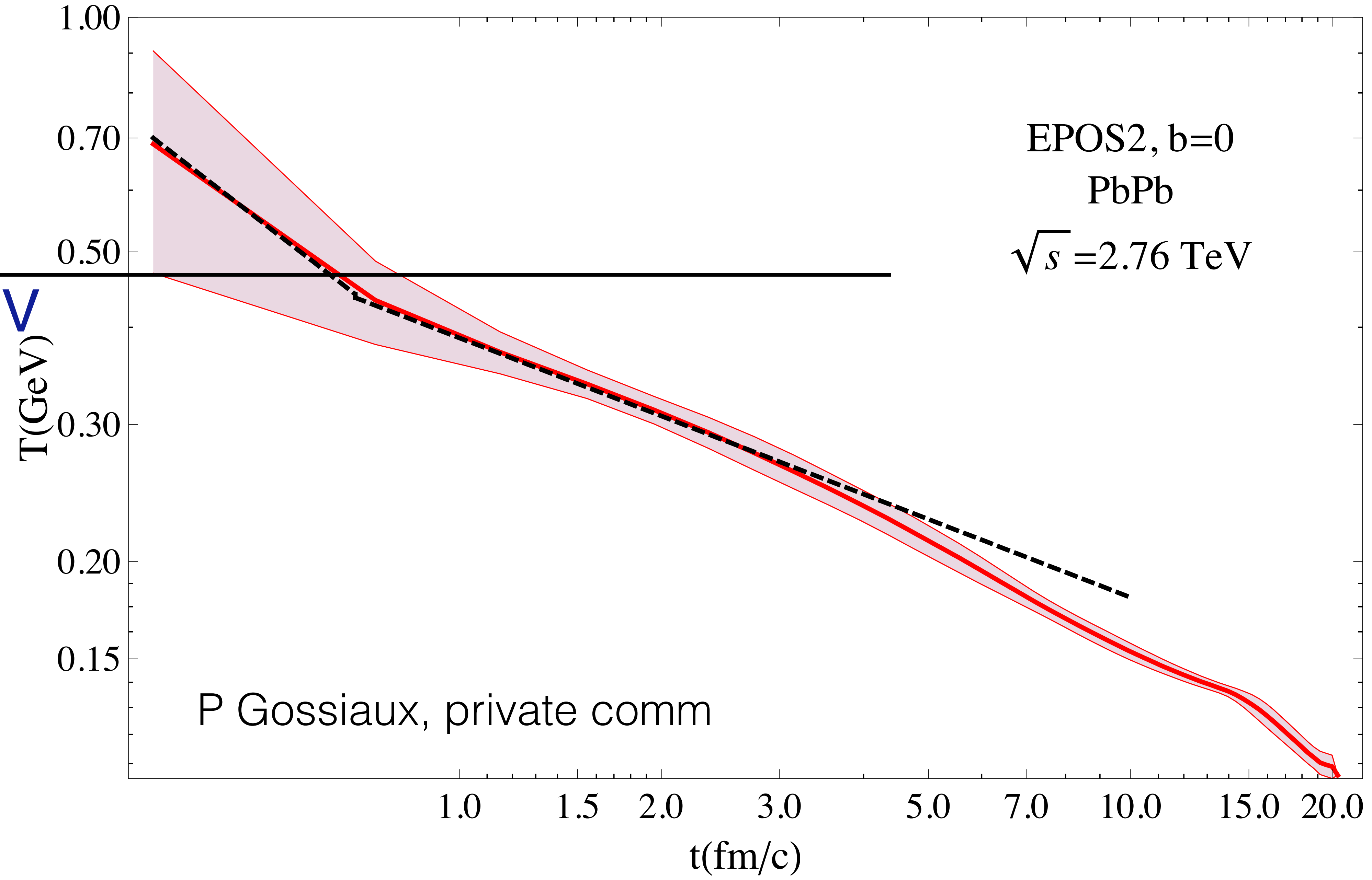


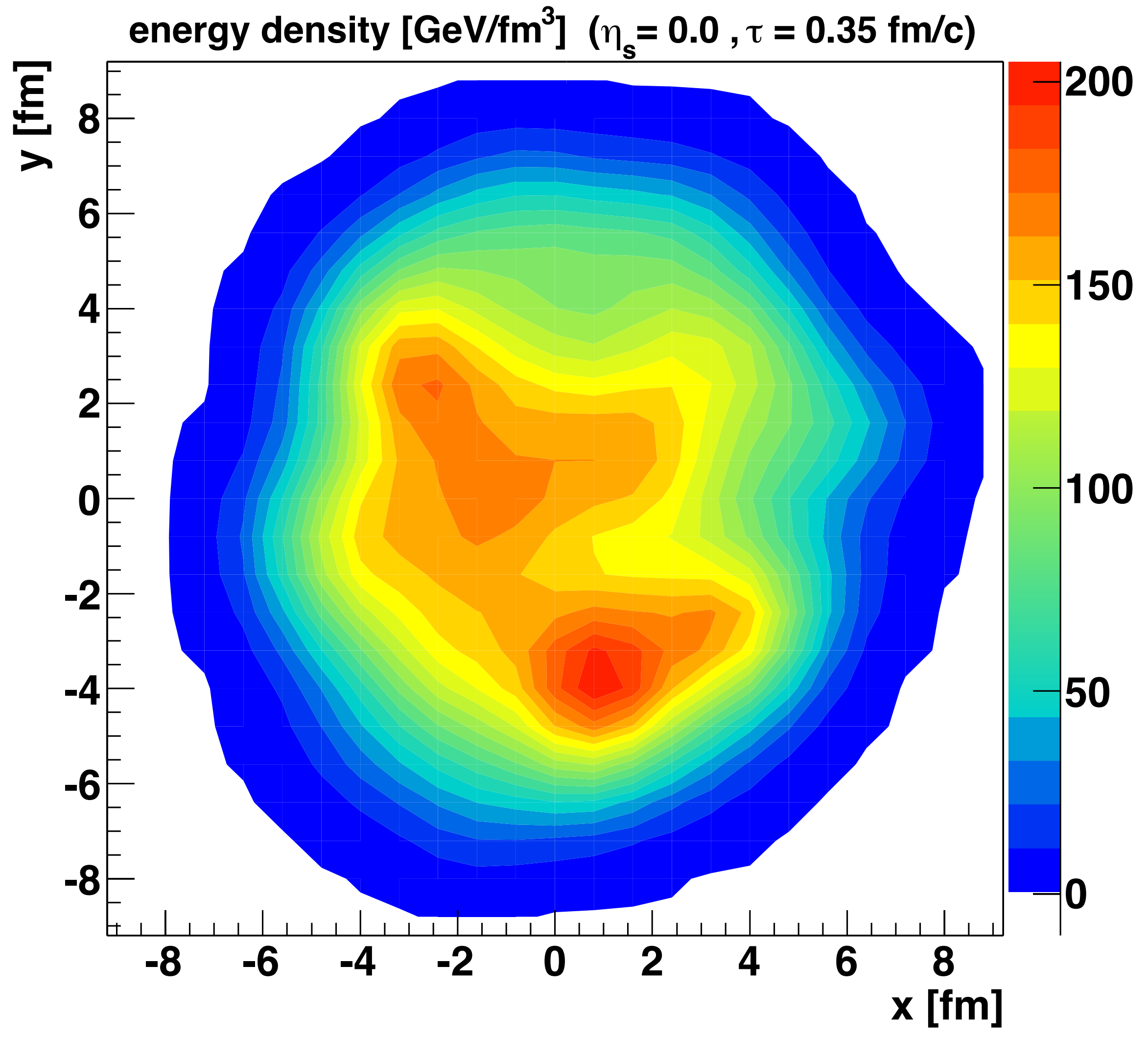
T_i = 530 MeV @ τ_0 = 0.5 fm/c

Good agreement with JET collaboration values

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?

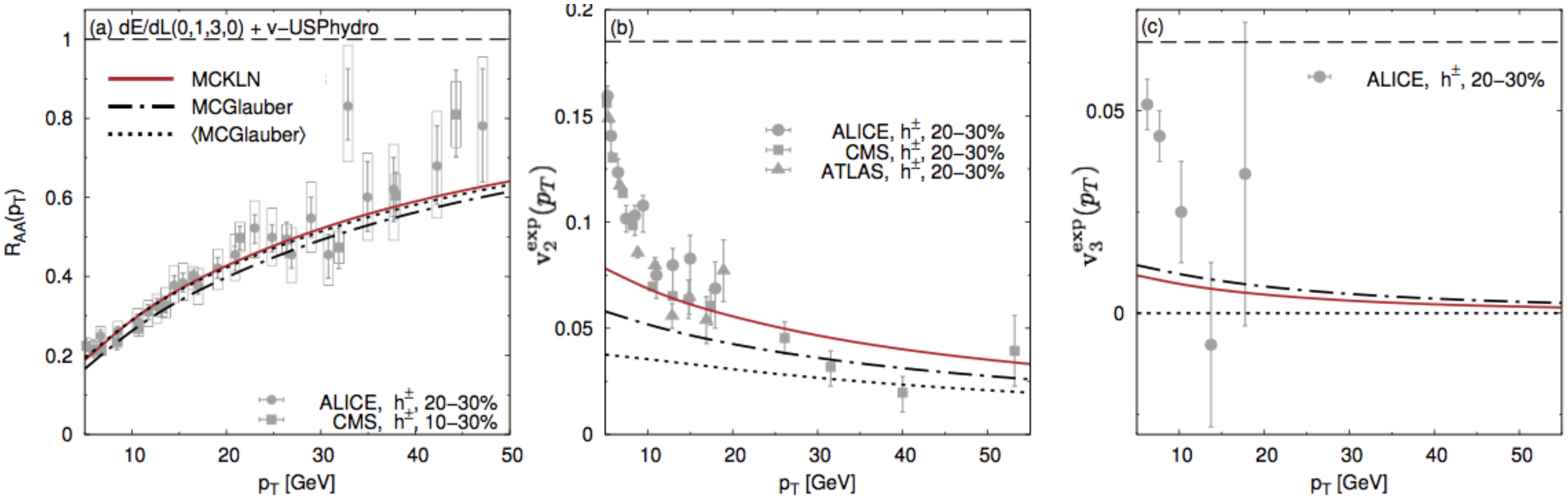
Model(ing) uncertainties for high-p_T v_2

- 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

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)

v_2 in CUJET

GLV-based E-loss

α_S runs, with cut-off at low Q

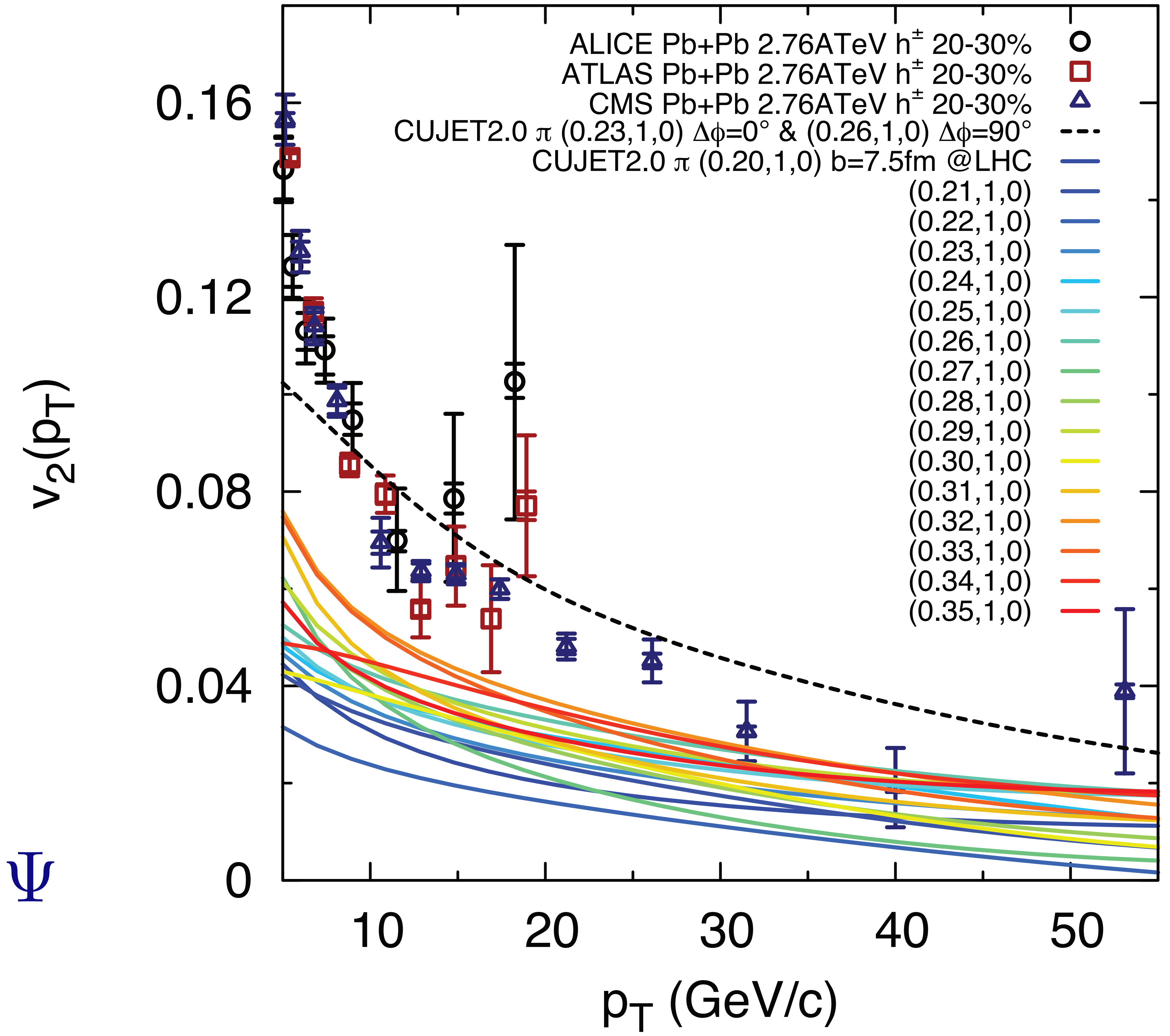
$$\alpha_s \longrightarrow \alpha_s(Q^2) = \begin{cases} \alpha_{max} & \text{if } Q \leq Q_{min} \, , \\ \dfrac{2\,\pi}{9\,\log(Q/\Lambda_{QCD})} & \text{if } Q > Q_{min} \, . \end{cases}$$

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

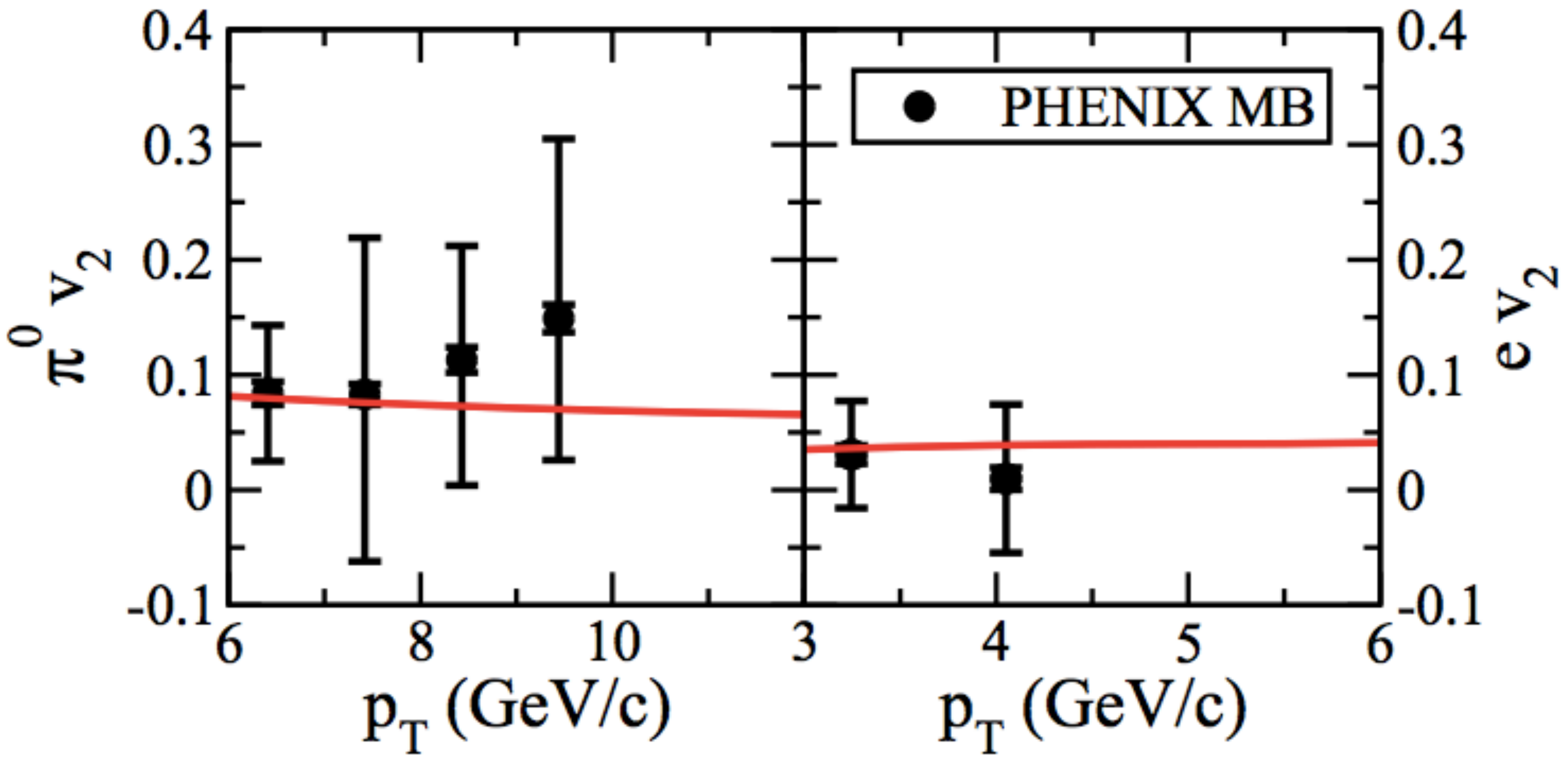


Xu et al, CUJET, arXiv:1402.2956

However, see also: CUJET3.0
Xu et al, arXiv:1509.00552

v_2 in Higher Twist

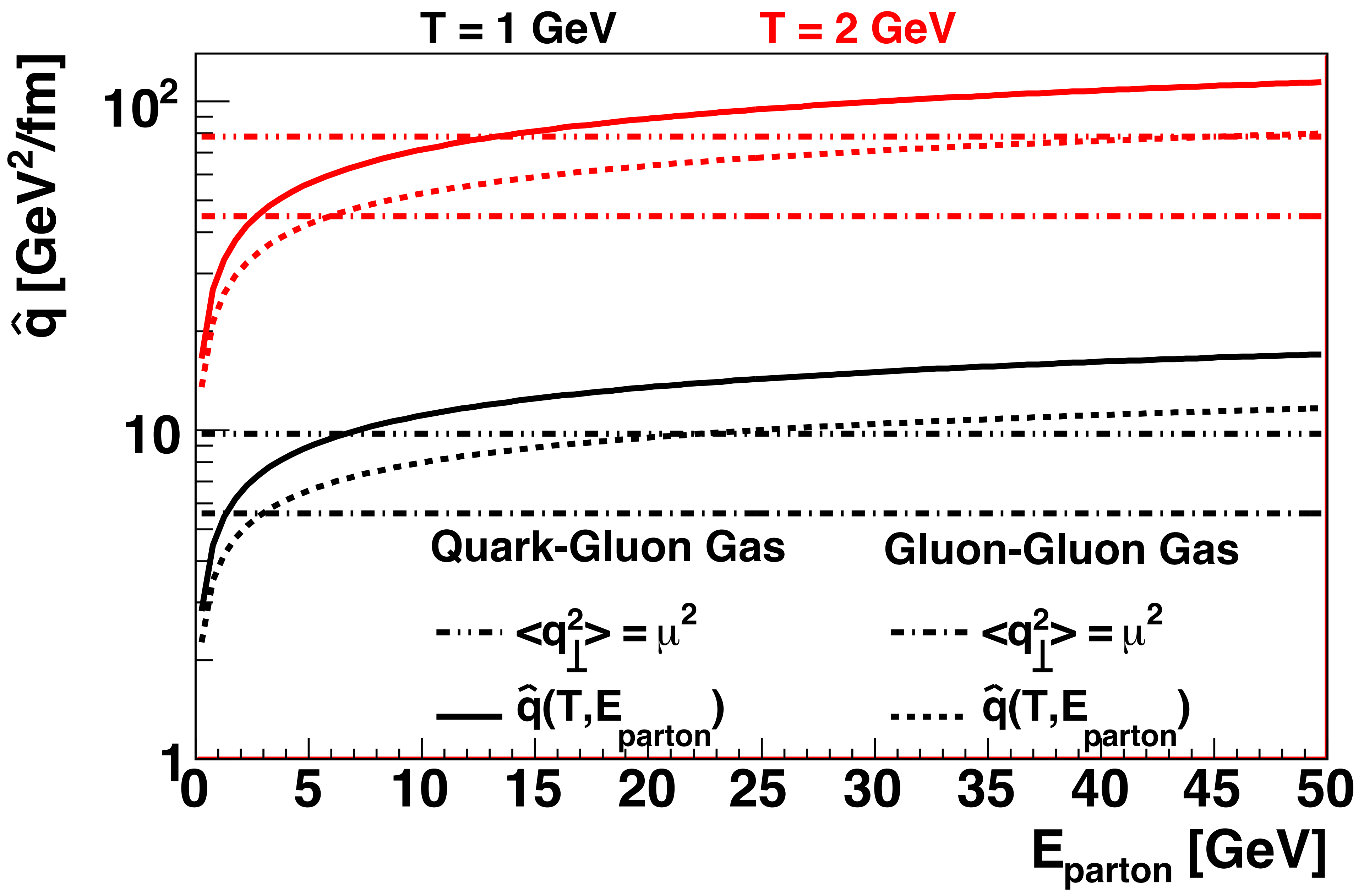
Qin and Majumder, arXiv:0910.3016



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



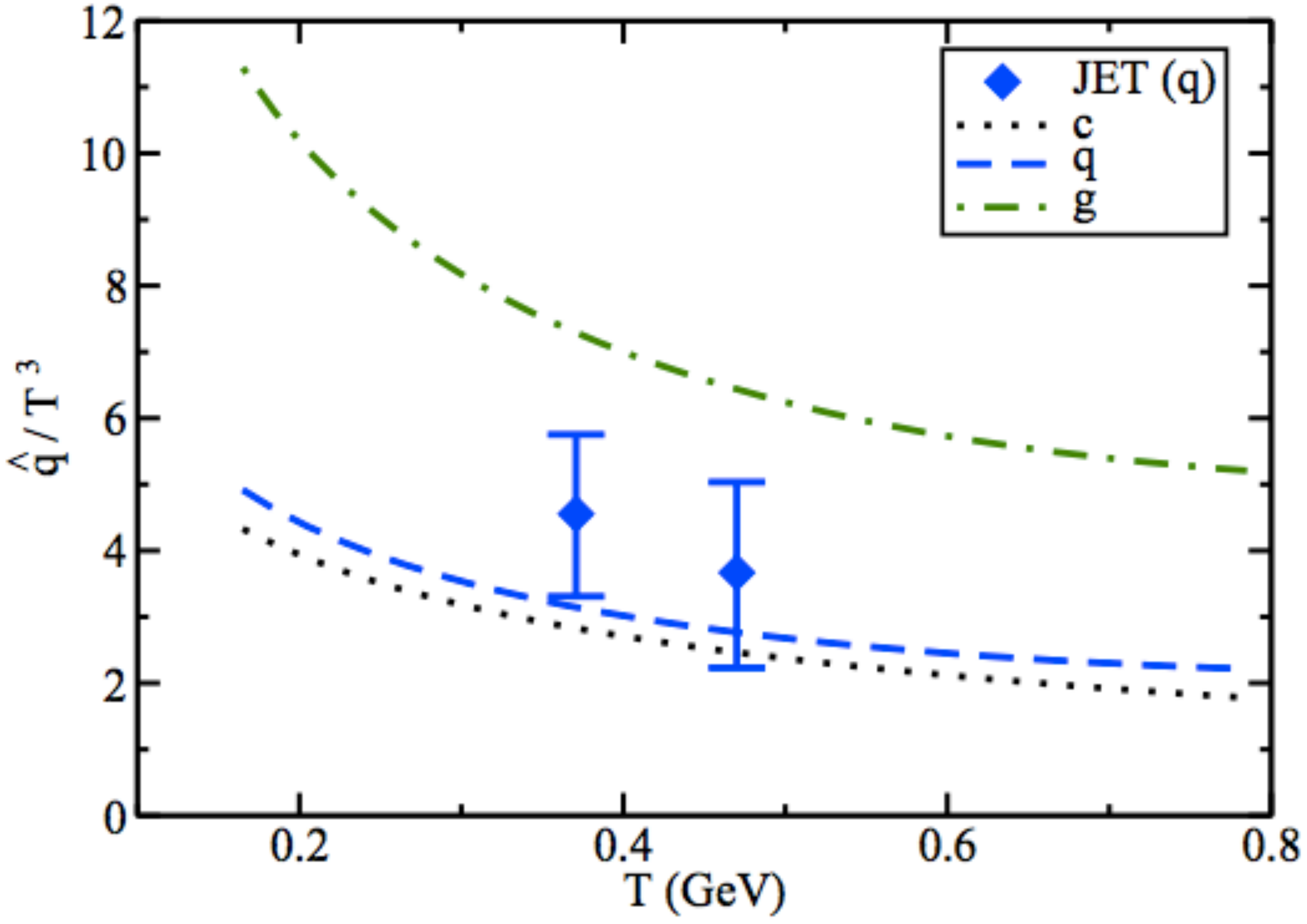
Some of these are intrinsic uncertainties, some are convenience

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

Ideally: use same convention when comparing calculations

Comparison to LBT

Cao, et al, arXiv:1703.000822

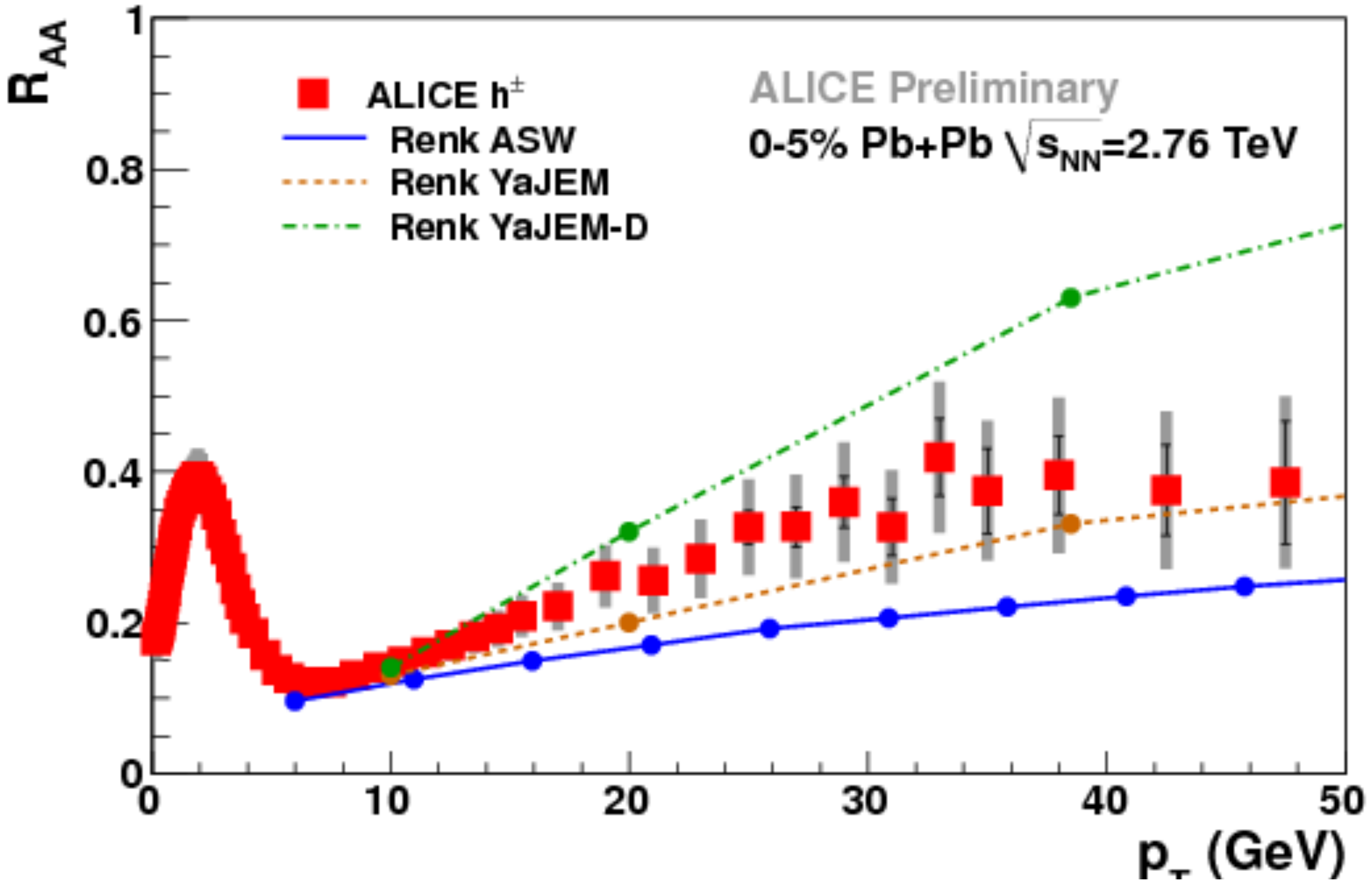


Factor ~1.5 between LBT fits and JET values; probably within uncertainties

Heavy+light energy loss

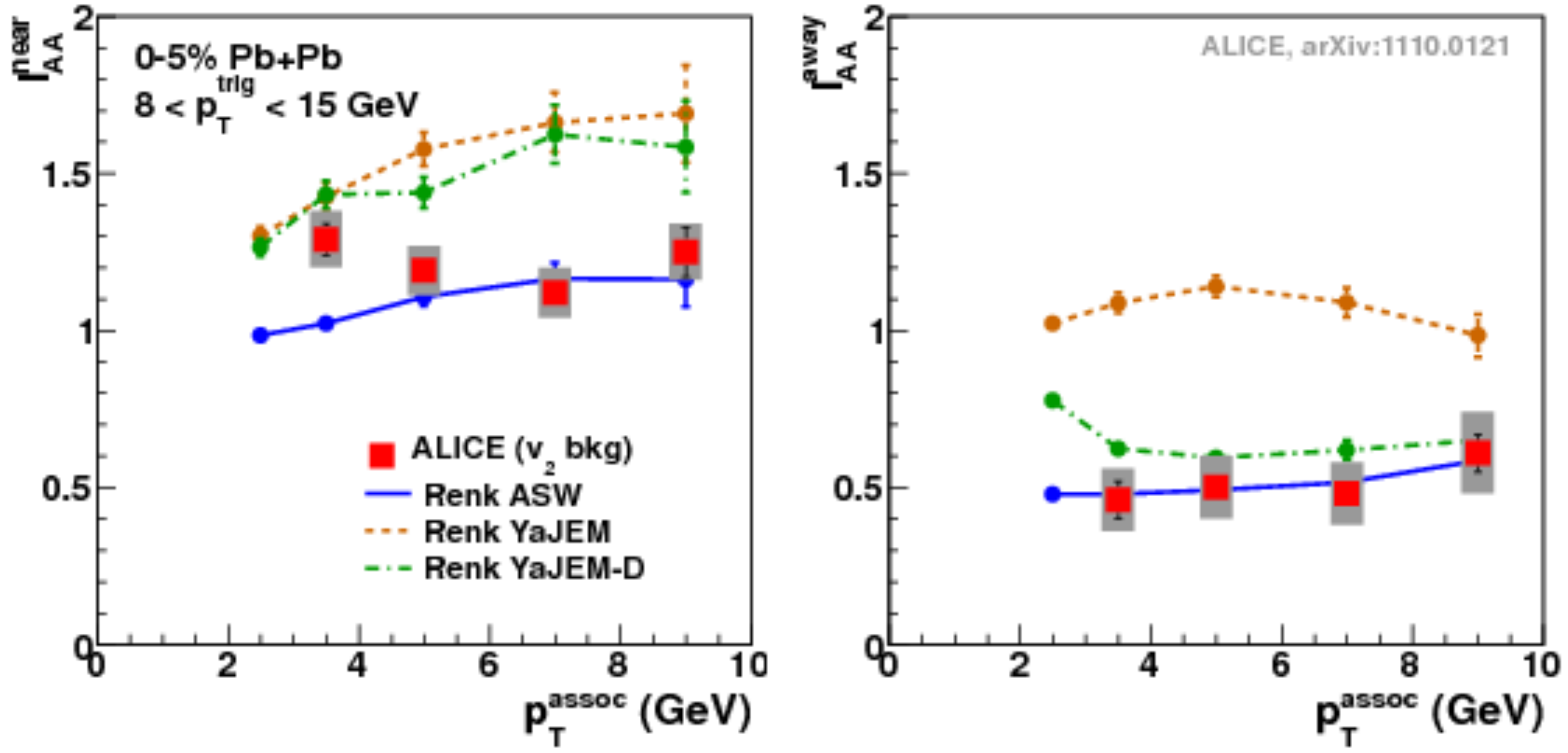
Di-hadrons and single hadrons at LHC

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



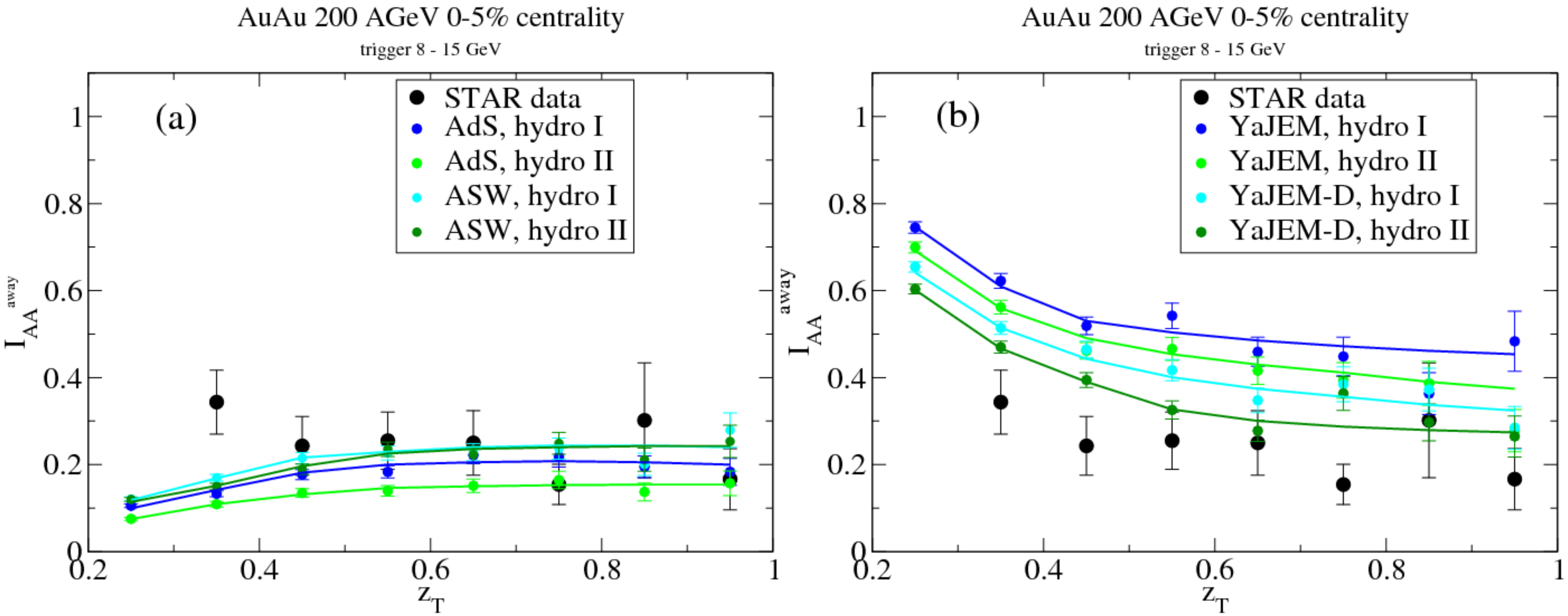
Here: R_{AA} and I_{AA}

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



Di-hadron modeling

Model ‘calibrated’ on single hadron R_{AA}



T. Renk, PRC, arXiv:1106.1740

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

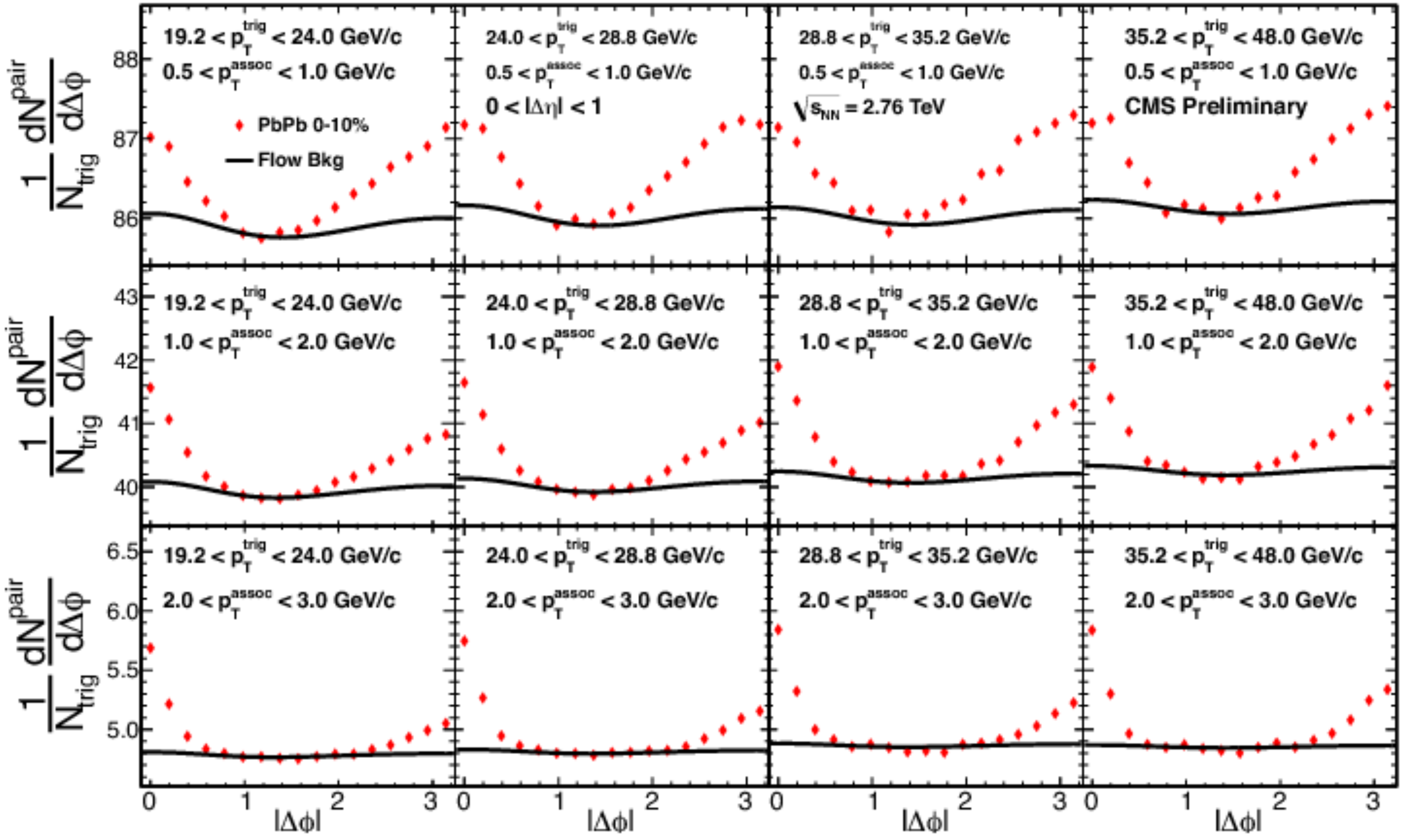
L (YaJEM): too little suppression
L^2 (YaJEM-D) slightly above

Clear sensitivity to L dependence

Modified shower
generates increase at low z_T

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



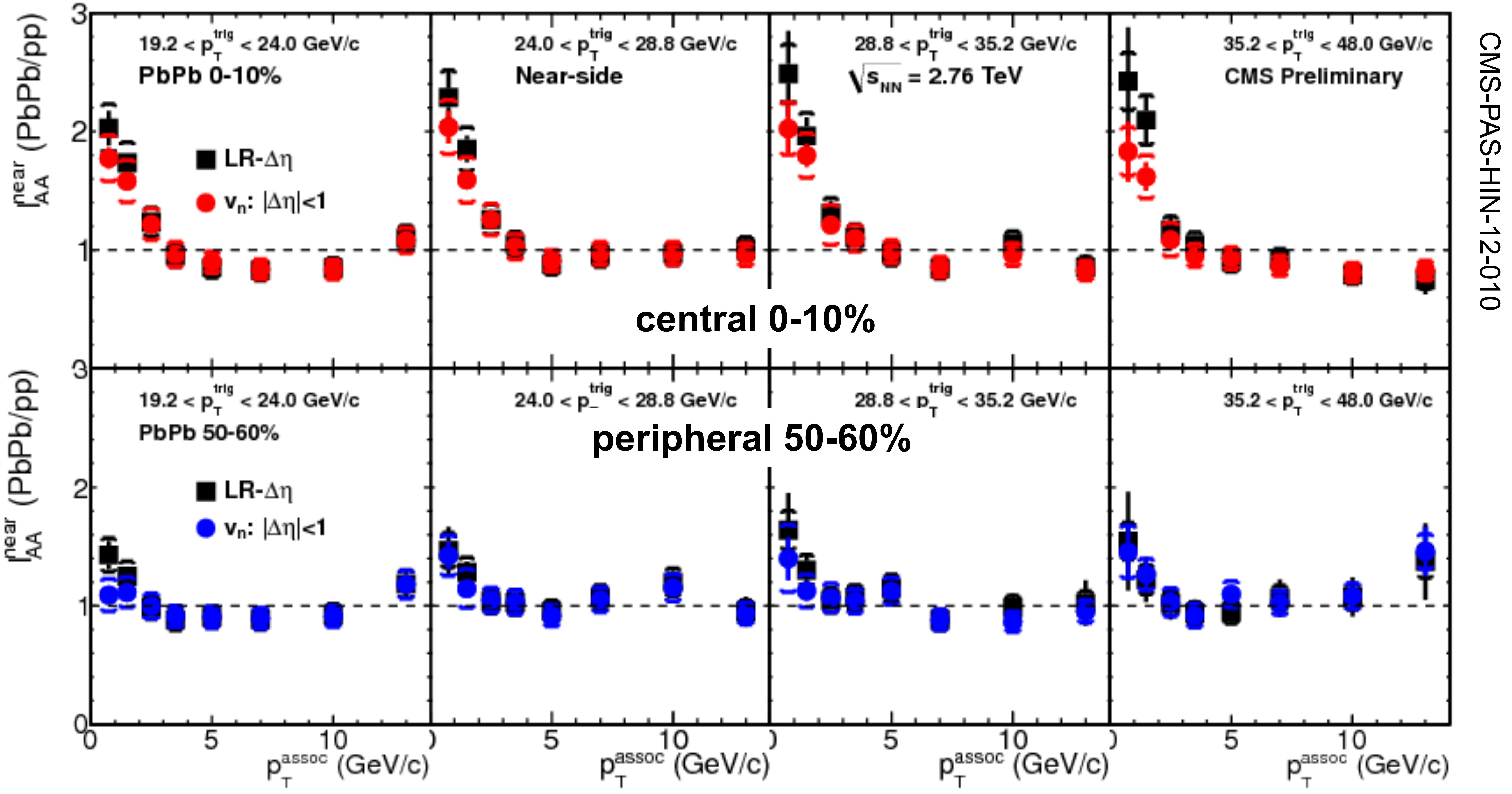
CMS-PAS-HIN-12-010

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?

Some open and partially-answered questions

Energy loss mechanism
physics of hard partons in a plasma

Flavor dependence of energy loss

Role of interference effects
Do all partons in a jet lose energy?

Scale dependence
of energy loss?

Path length dependence of energy loss
—> tomography of the medium

Thermalisation of the lost energy

Angular broadening
large-angle scattering

Nature of the medium
density, character of constituents