Hard Probes of the QGP at LHC

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Nikhef

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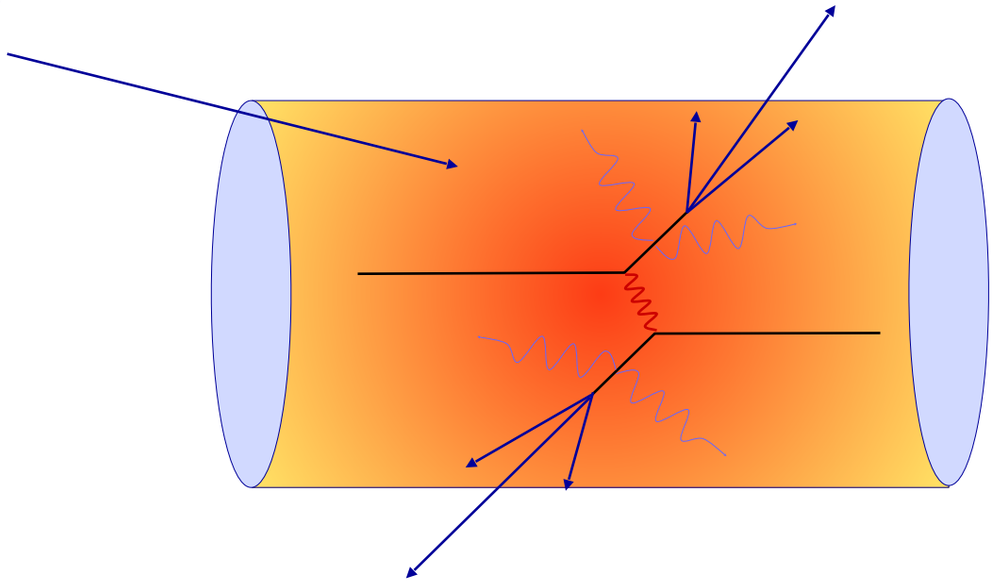
CERN

Soft QCD matter and hard probes

Heavy-ion collisions produce
QCD matter

Dominated by soft partons
p ~ T ~ 100-300 MeV



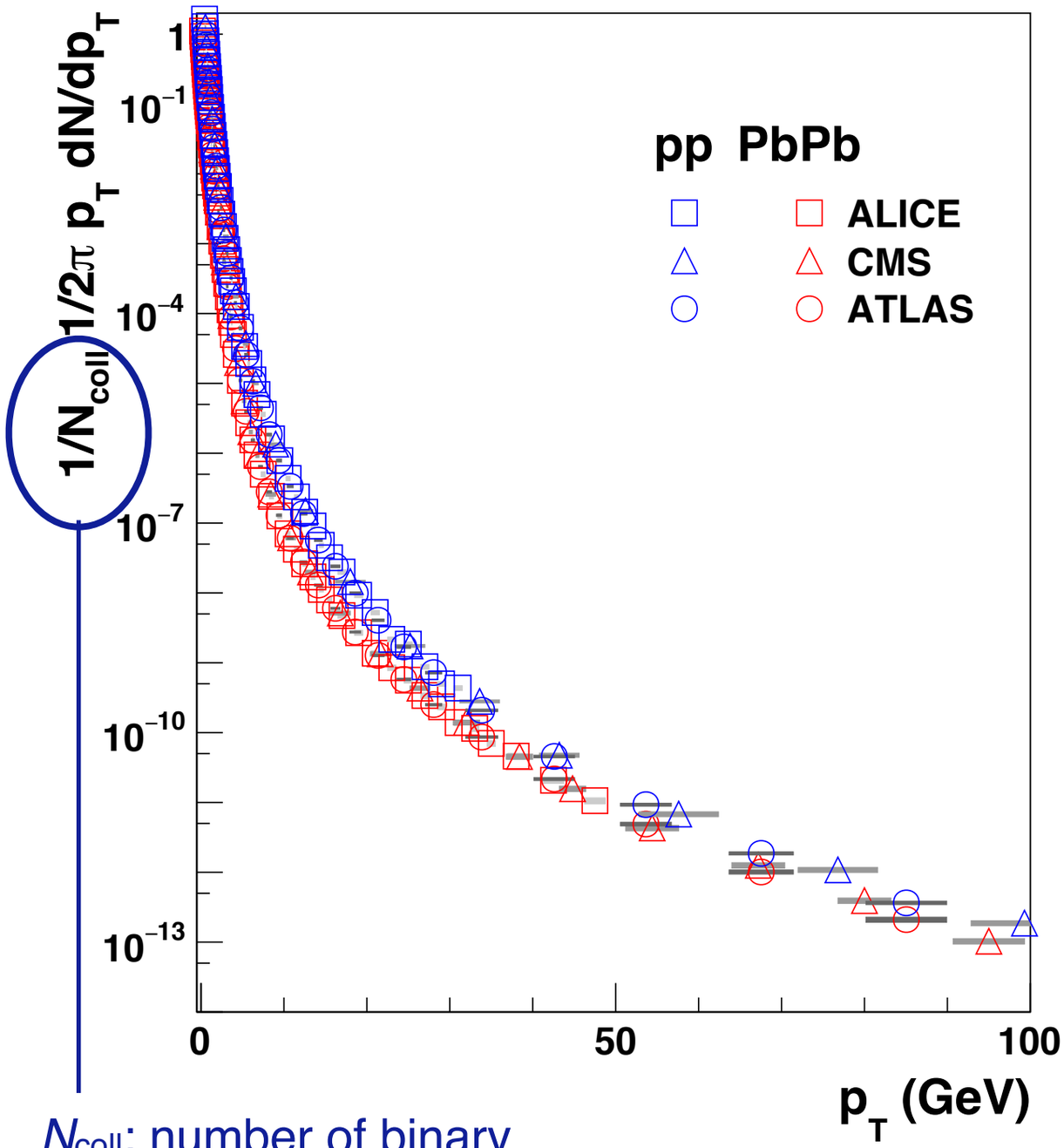
Hard-scatterings produce ‘quasi-free’ partons
⇒ Initial-state production known from pQCD
⇒ Probe medium through energy loss

‘Hard Probes’: sensitive to medium density, transport properties

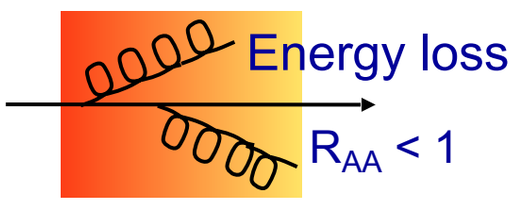
Nuclear modification: Pb+Pb

ALICE, PLB720, 52
CMS, EPJC, 72, 1945
ATLAS, arXiv:1504.04337

Charged particle p_T spectra



N_{coll}: number of binary nucleon-nucleon collisions



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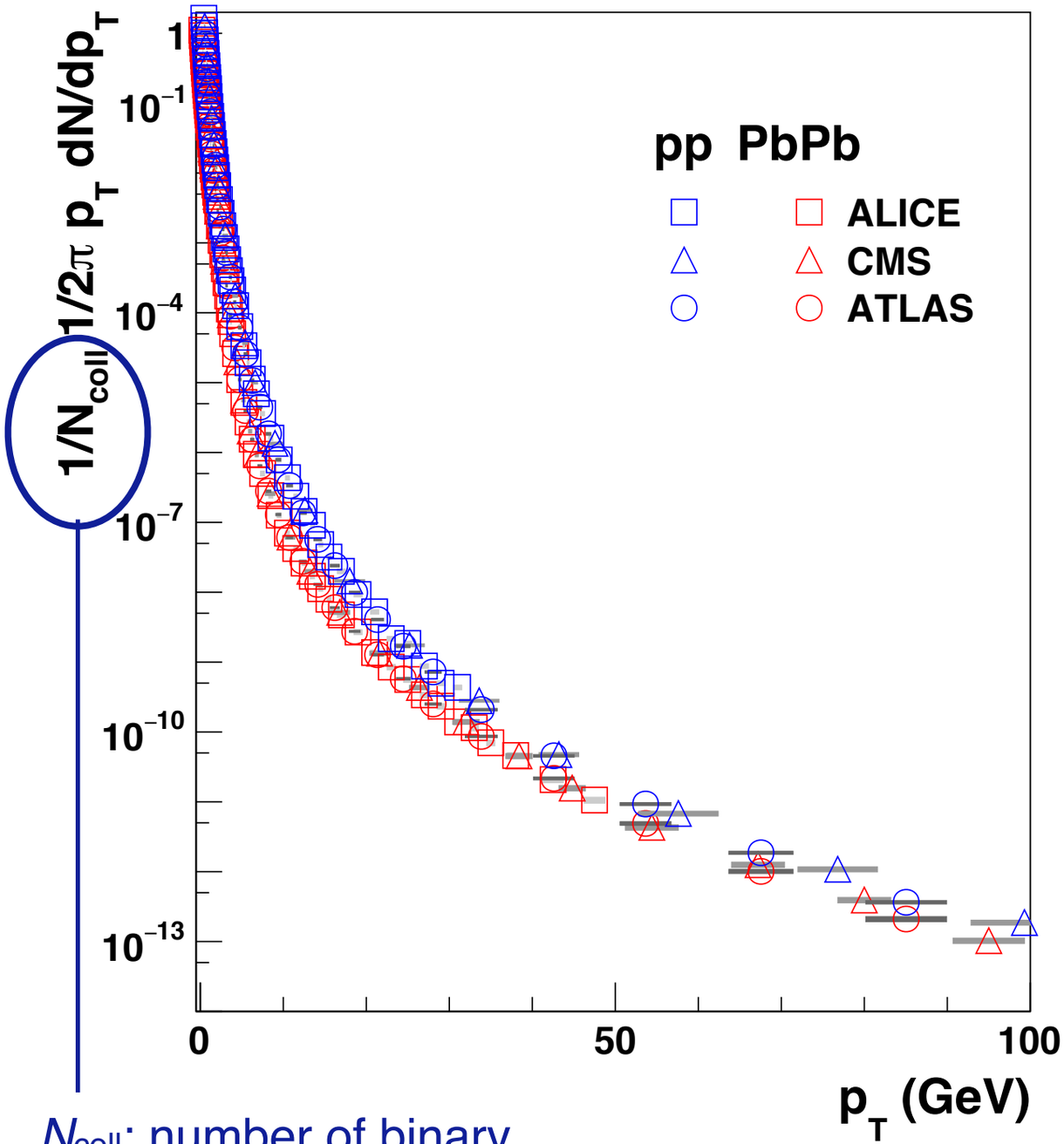

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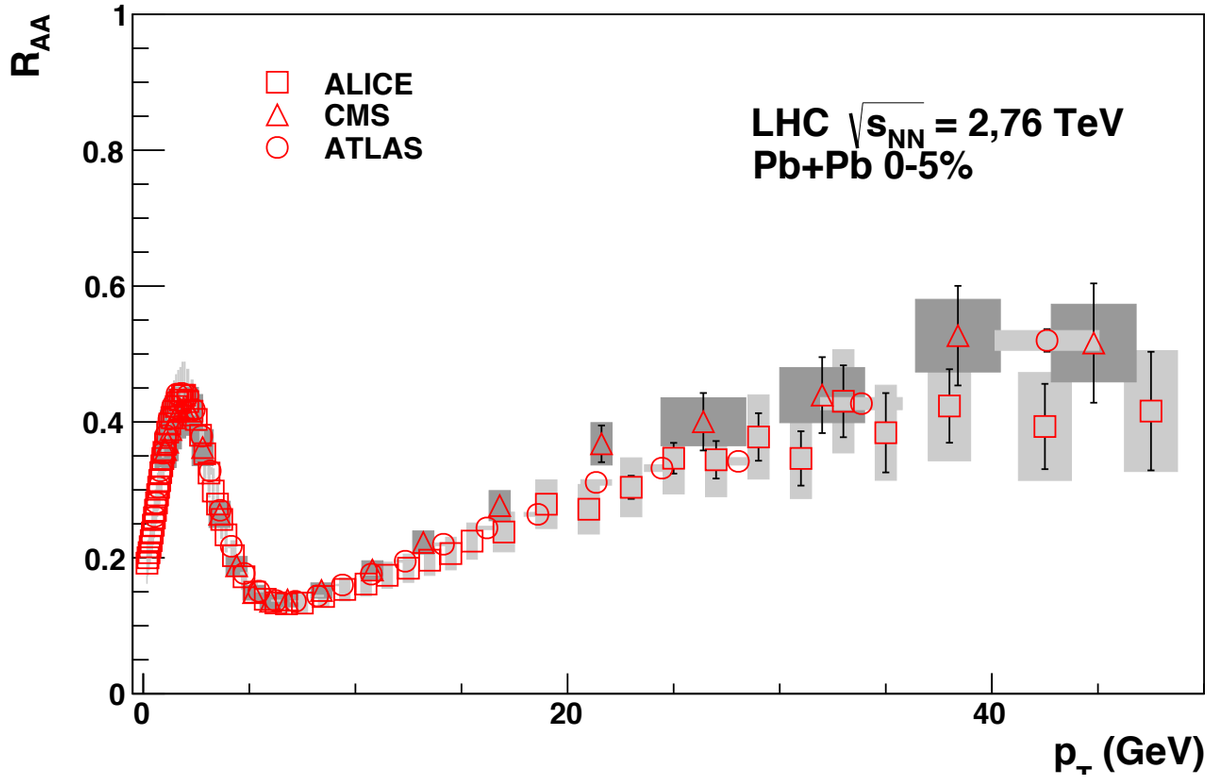
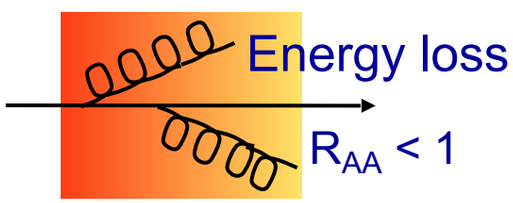


$$R_{AA} = \frac{dN/dp_T\big|_{A+A}}{N_{coll}\ dN/dp_T\big|_{p+p}}$$



Pb+Pb: clear suppression ($R_{AA} < 1$): parton energy loss

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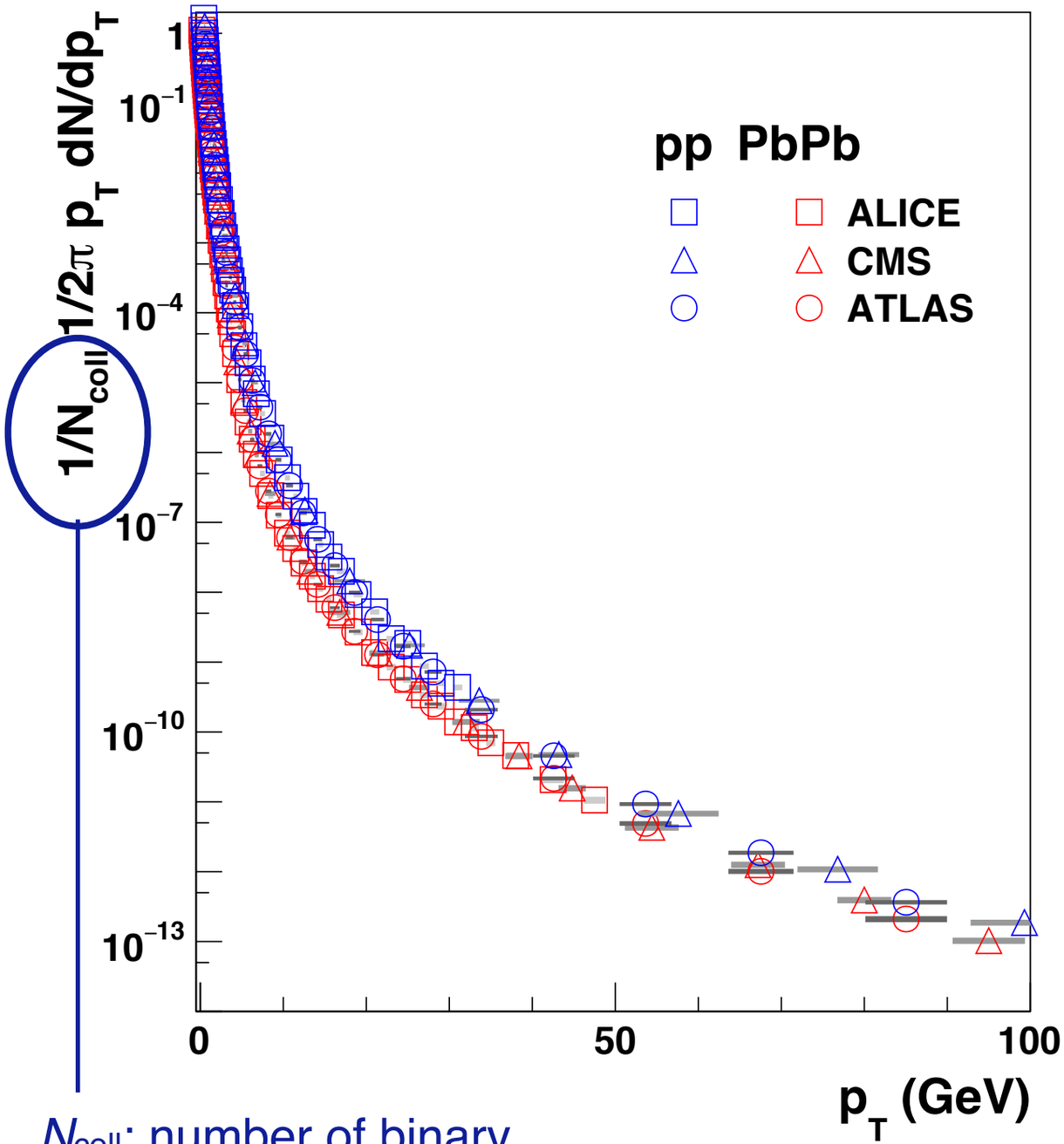

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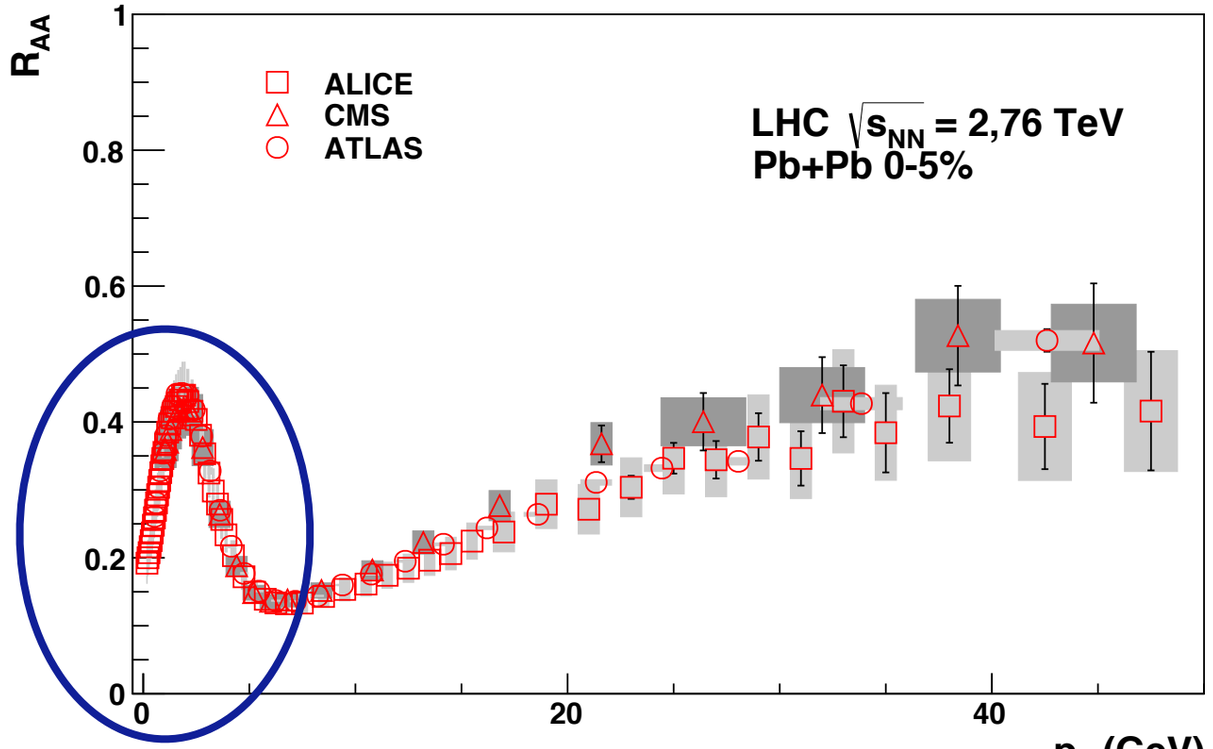
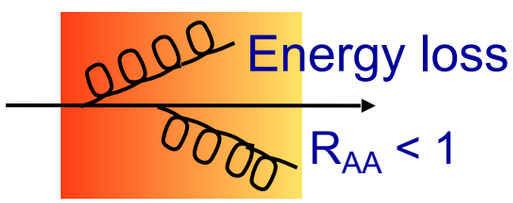


Low p_T:
soft production,
N_{part} scaling

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



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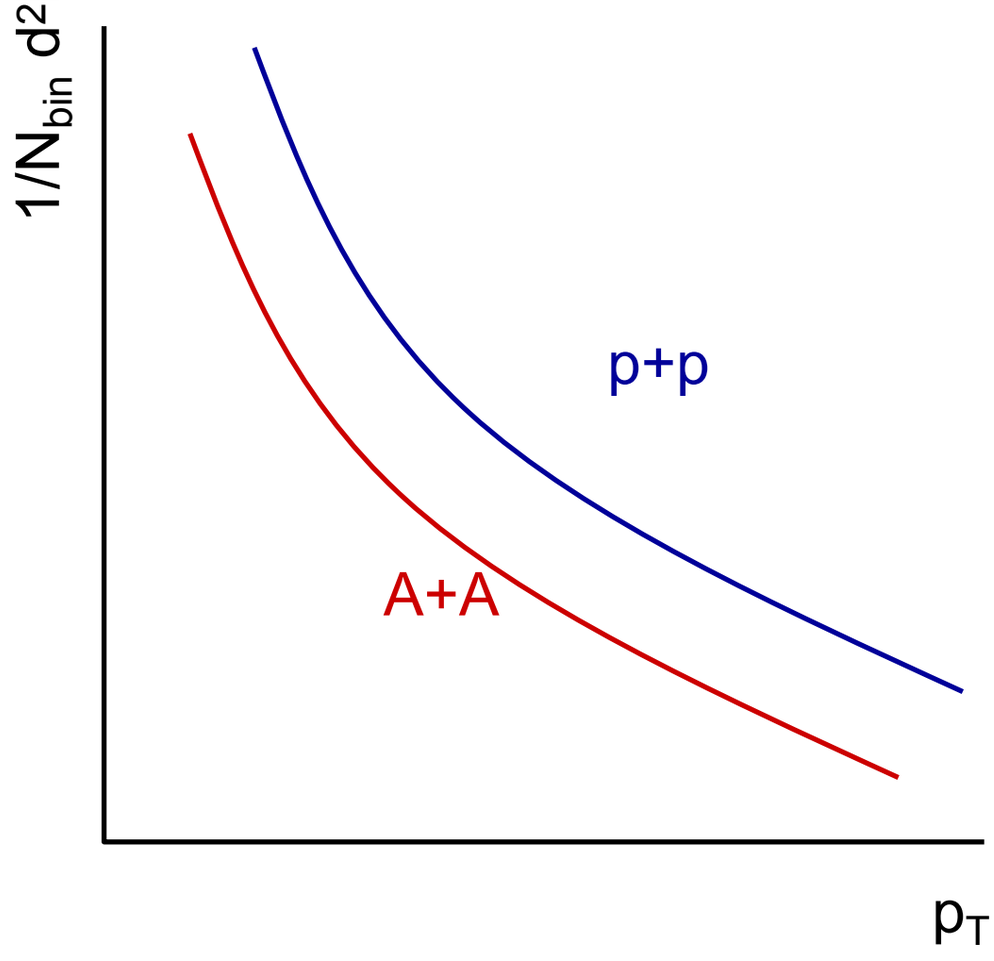

Measured R_{AA} is a ratio of yields at a given p_T

The physical mechanism is energy loss; shift of yield to lower p_T

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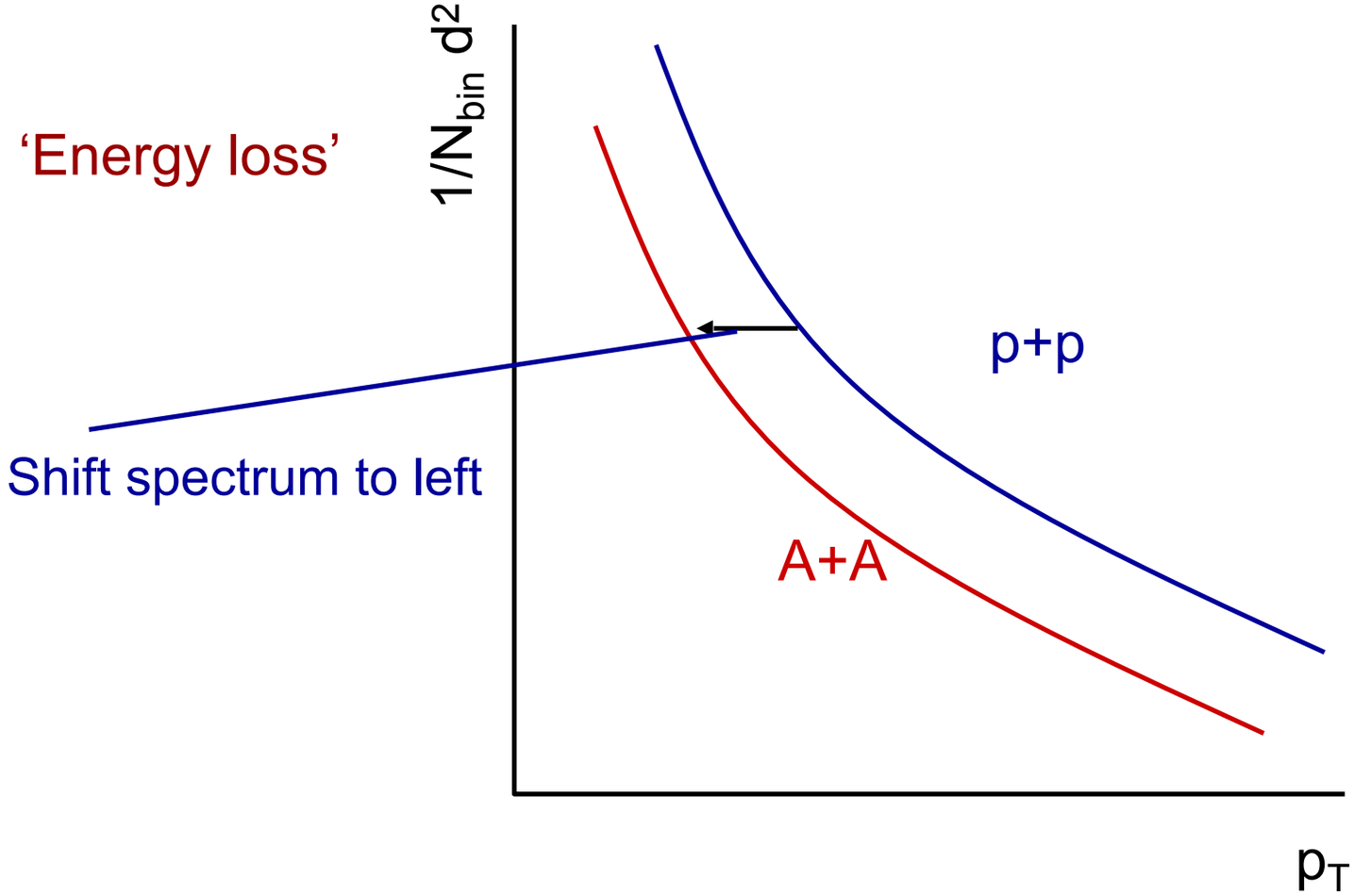

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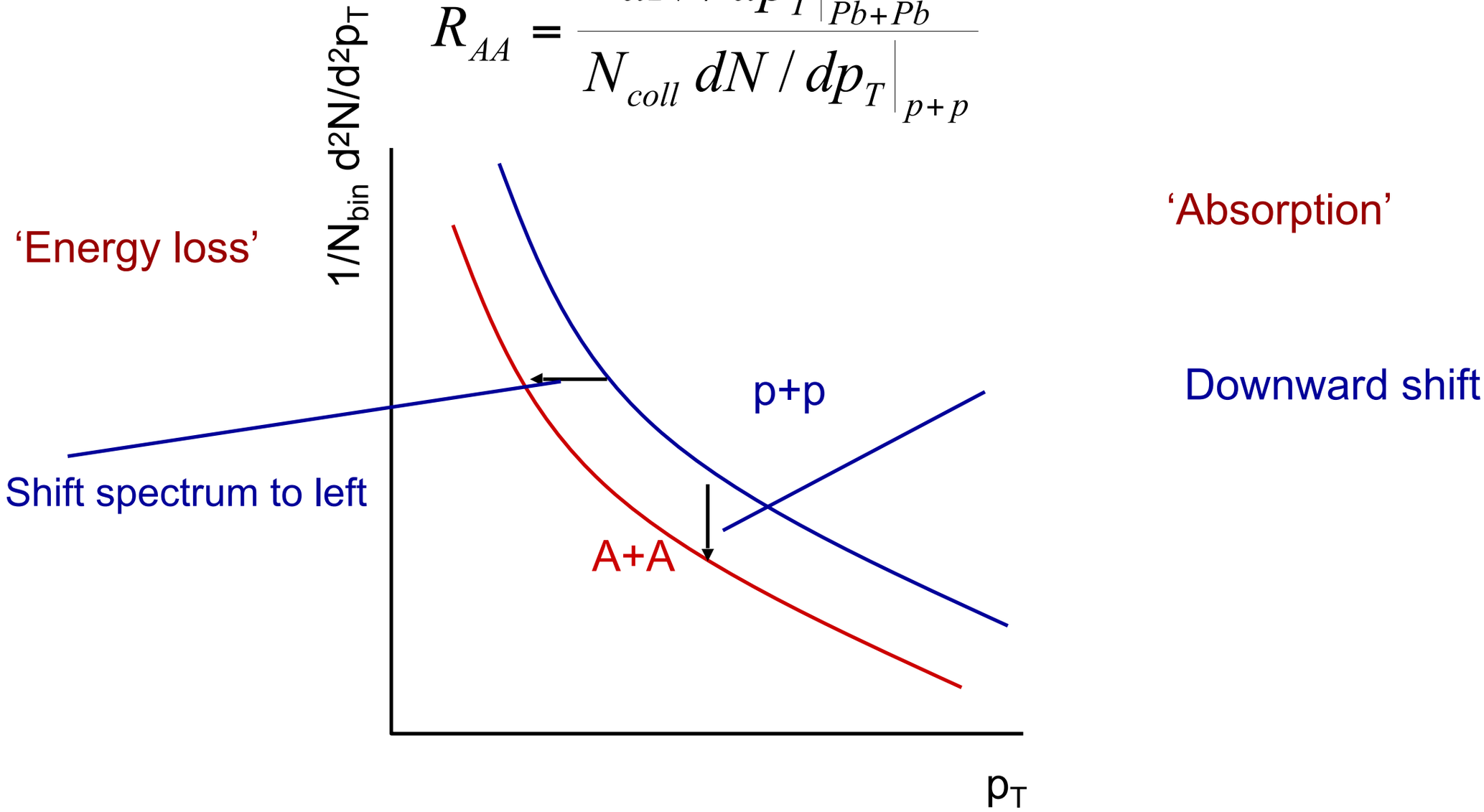

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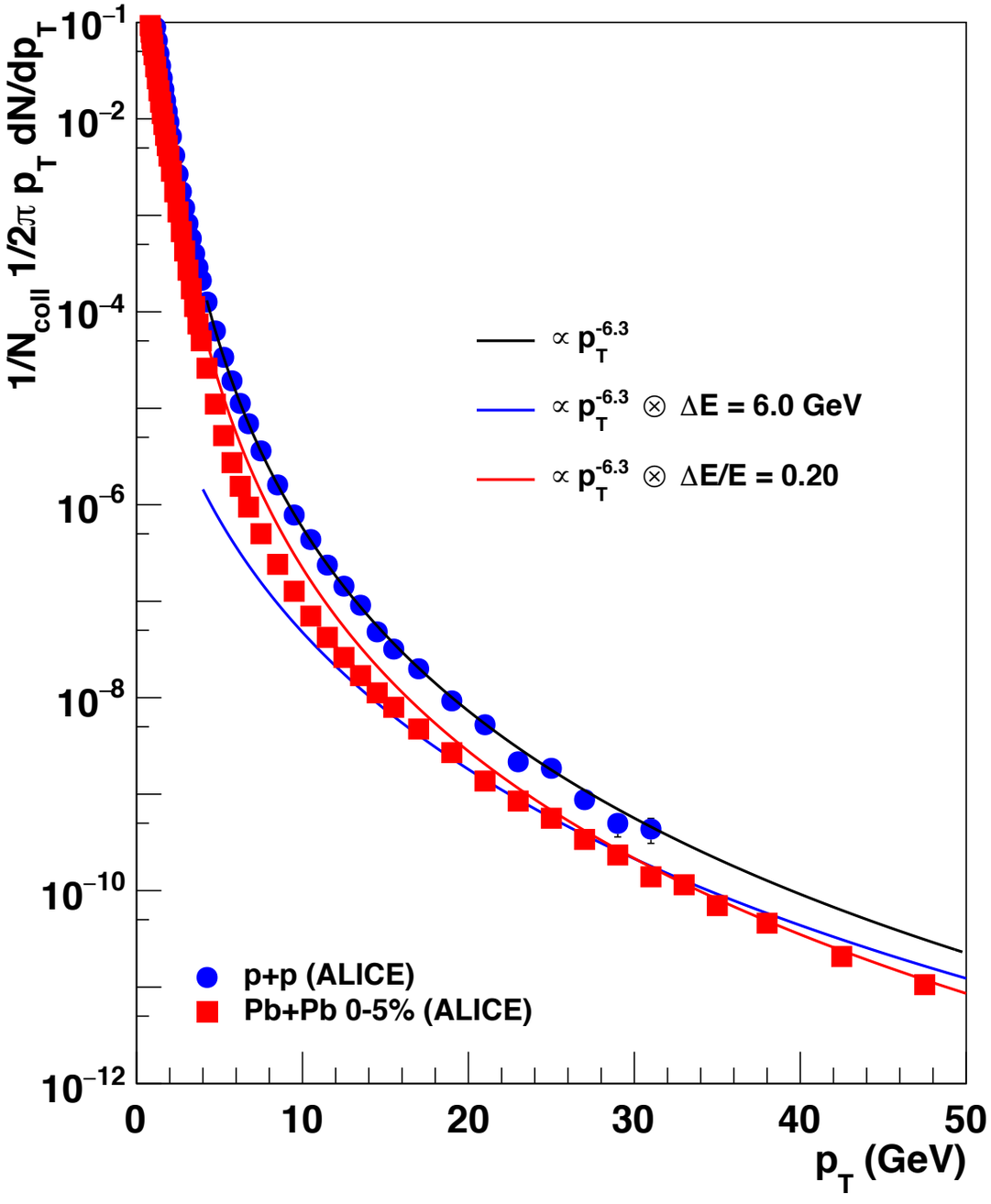
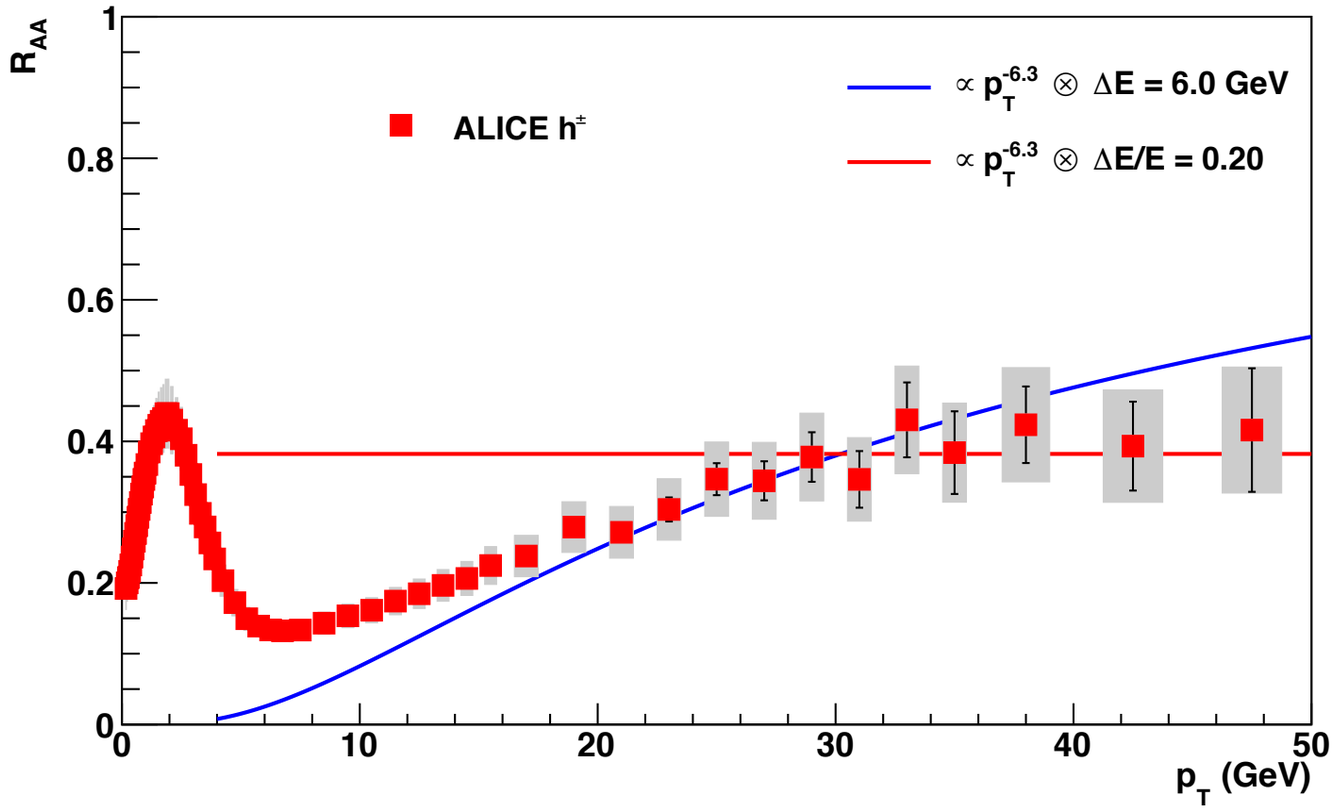
A simple fit to get started

p_T spectra



Power law exponent: 6.3

R_{AA} with two simple scenarios



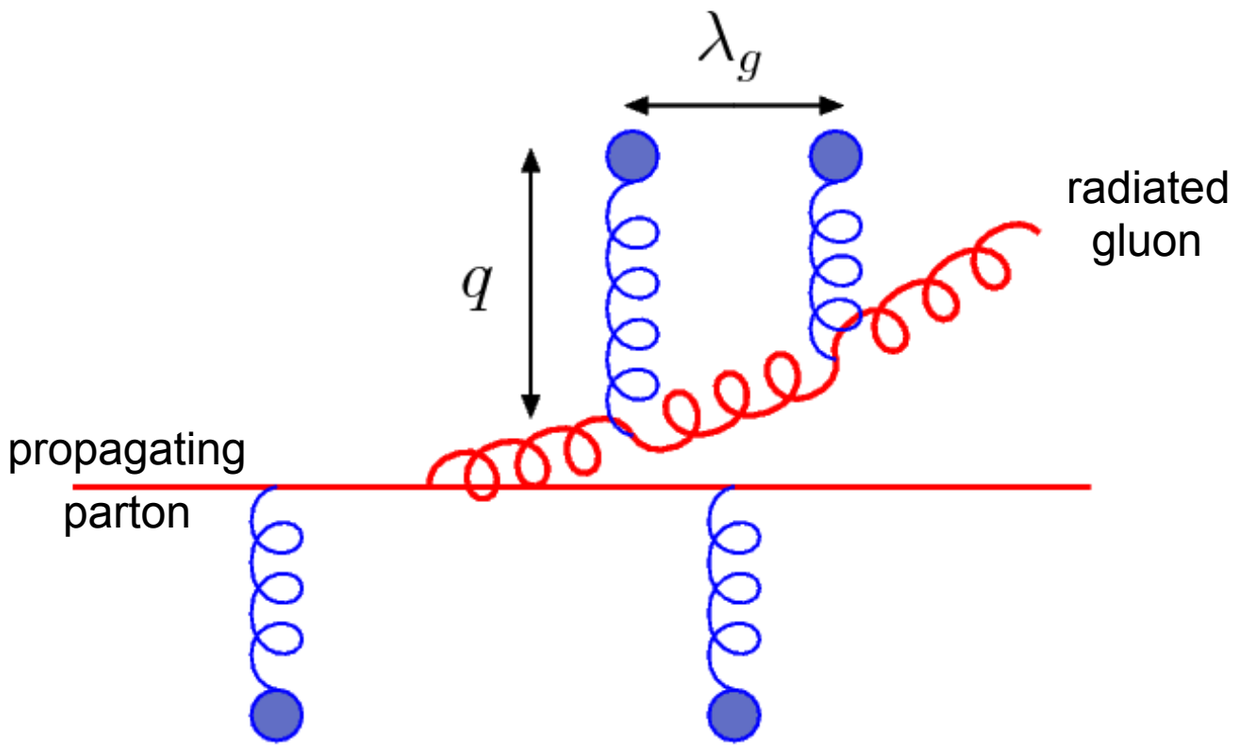
Increase of R_{AA} with p_T:
ΔE approx constant; ~ 6GeV

NB: not a full model; assumes
'hadronic' energy loss, no fluctuations, etc

Towards a more complete picture

- Geometry: couple energy loss model to model of evolution of the density (hydrodynamics)
- Energy loss not single-valued, but a 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

Medium-induced radiation



Key parameter:
Transport coefficient

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

Mean transverse kick per unit path length

Depends on density ρ through mean free path λ

$$\lambda \propto \frac{1}{\rho}$$

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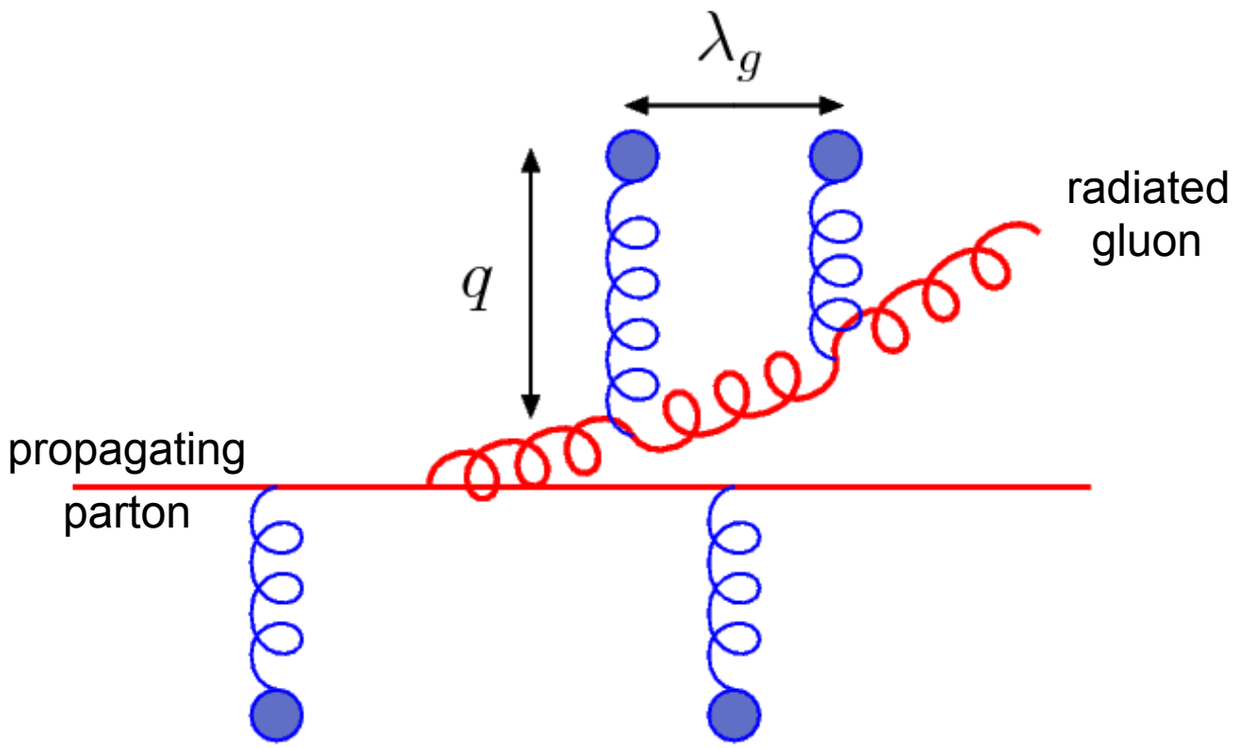

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$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Depends on density ρ through mean free path λ

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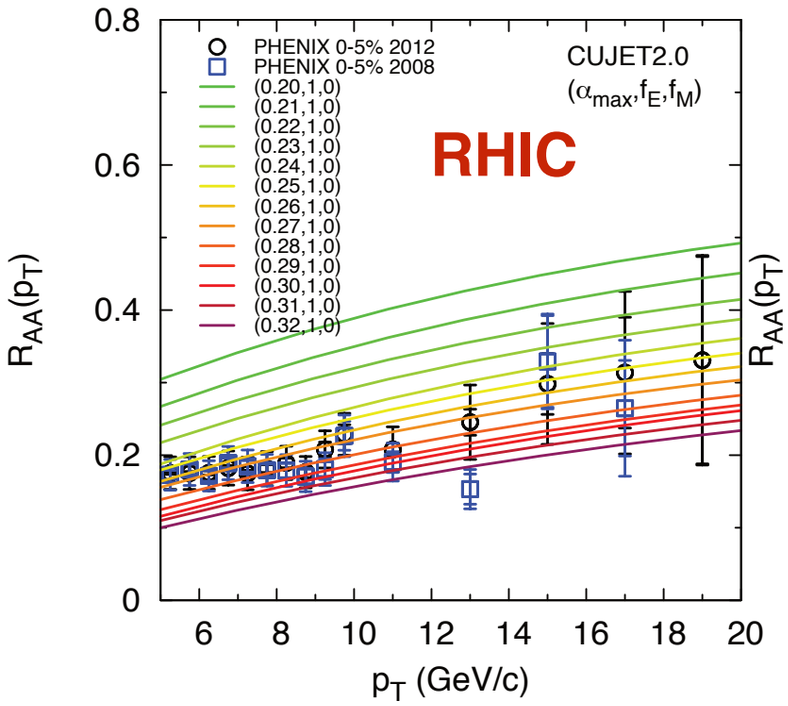
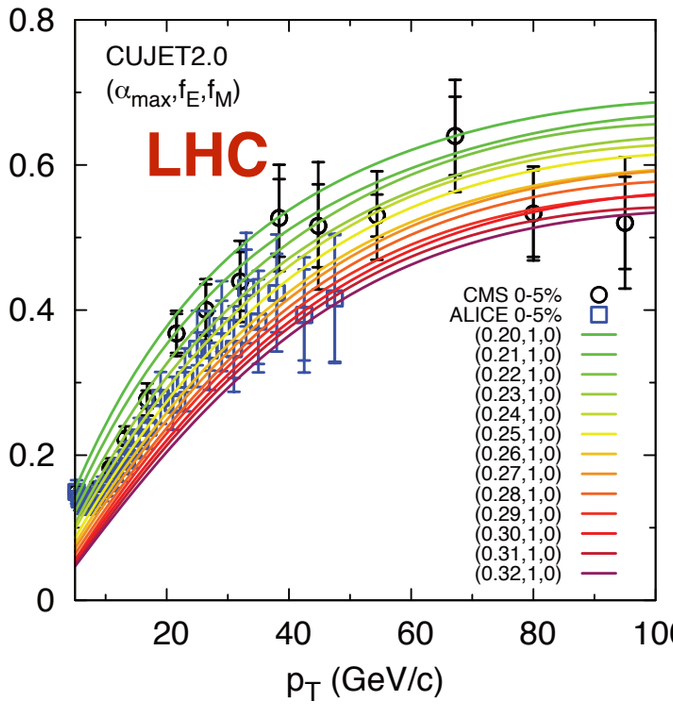
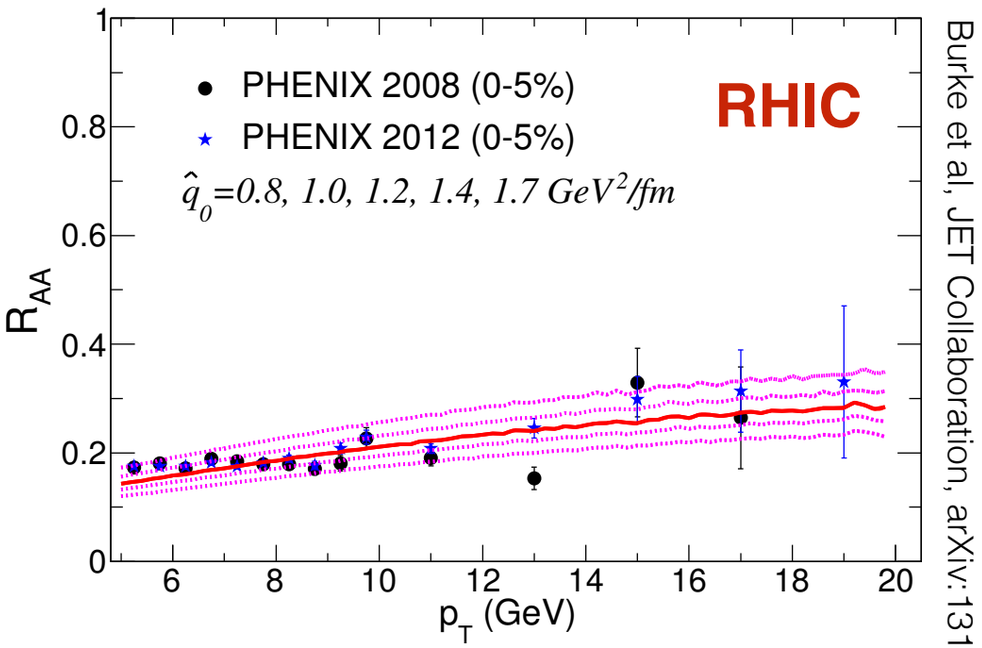
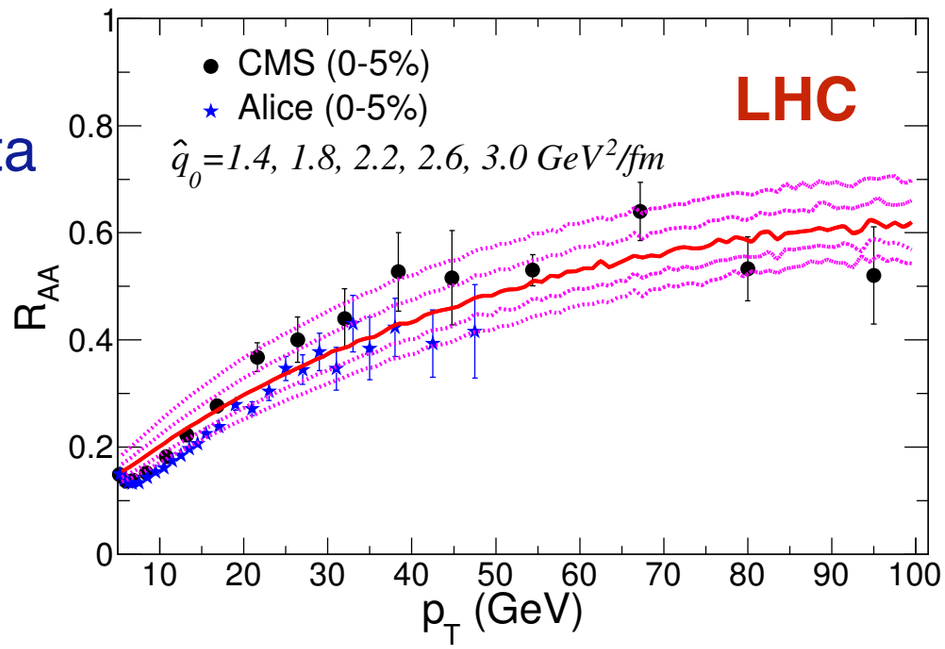
Example of a systematic exploration: RHIC and LHC







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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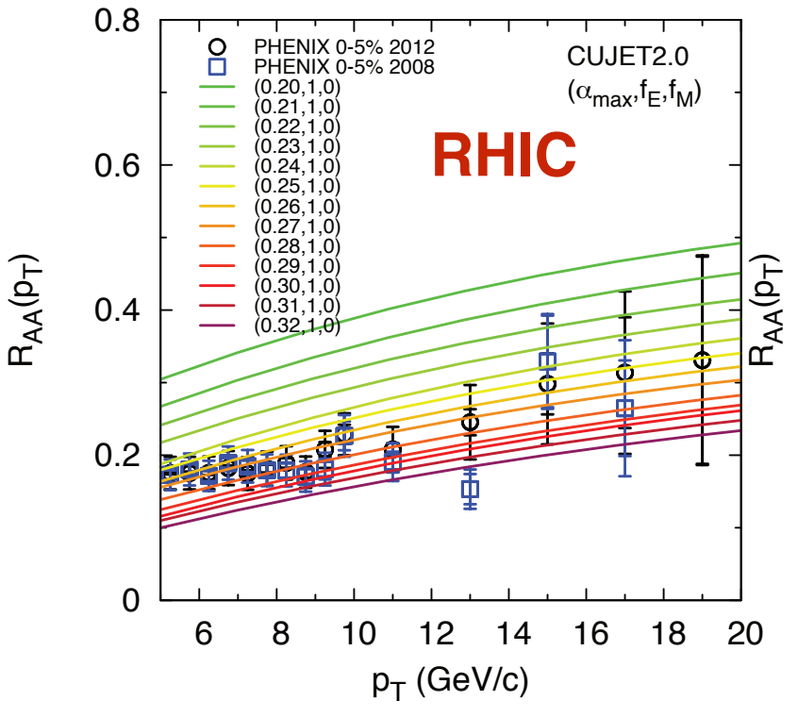

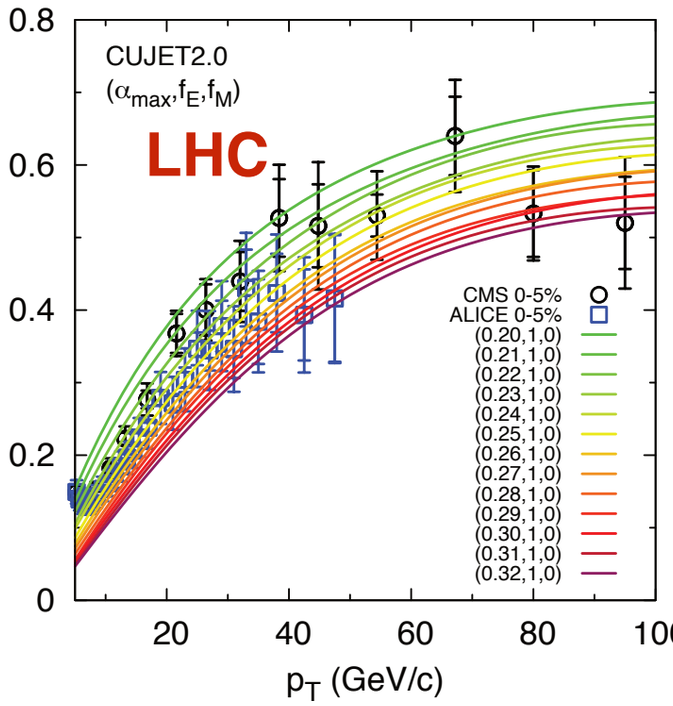

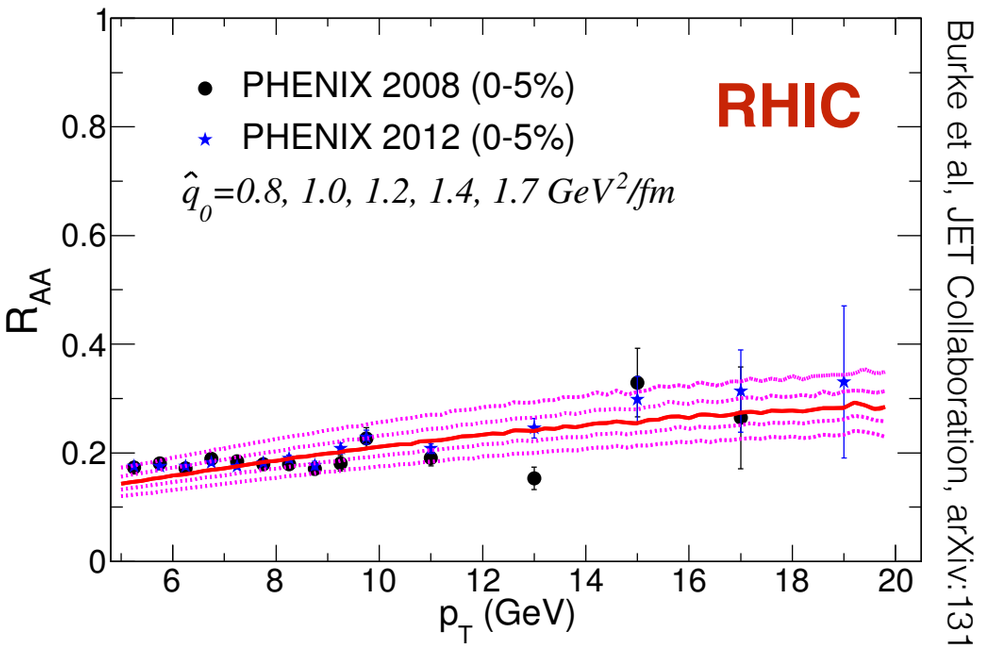

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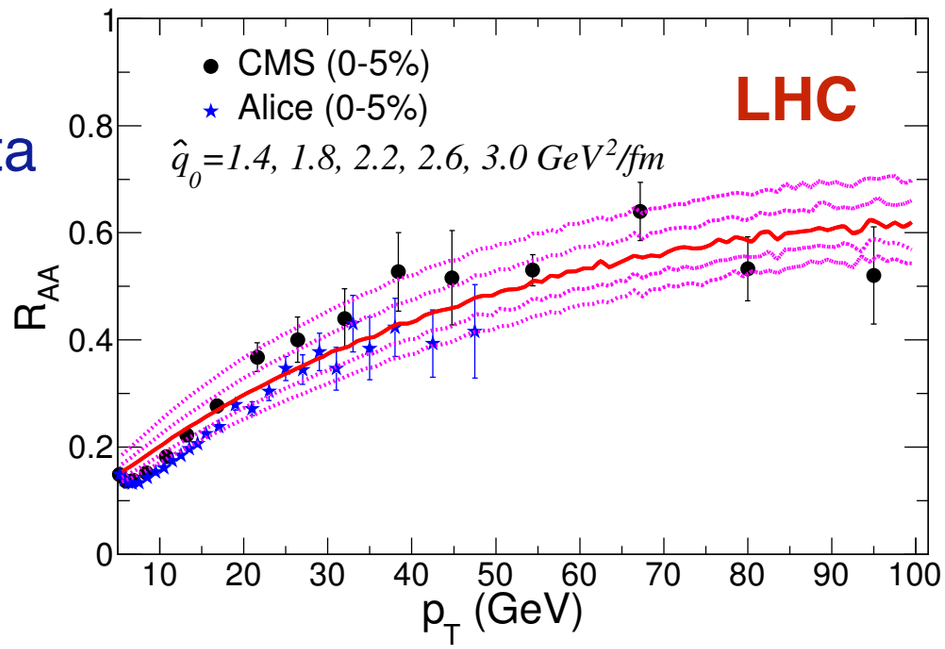

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RHIC $\hat{q} = 1.2 \pm 0.3 \ GeV^2/fm$ (T_i = 370 MeV)

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Arnold and Xiao, arXiv:0810.1026

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

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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?

Understand R_{AA}: at least one open question

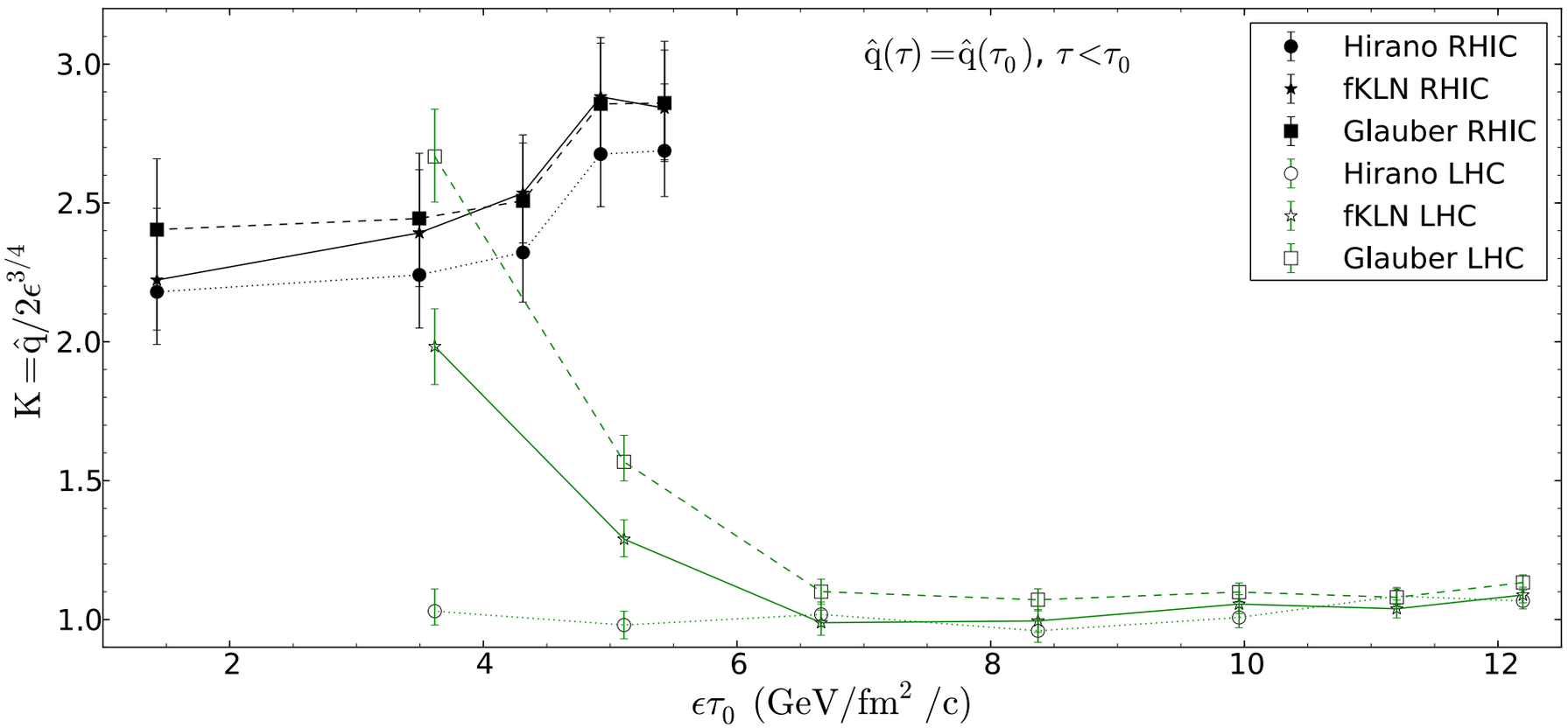
Similar fit to the data, as the JET paper, but using multiple-soft equations

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

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

pQCD expectation:
K = 1 (by definition)

Armesto et al, arXiv:1606.04837



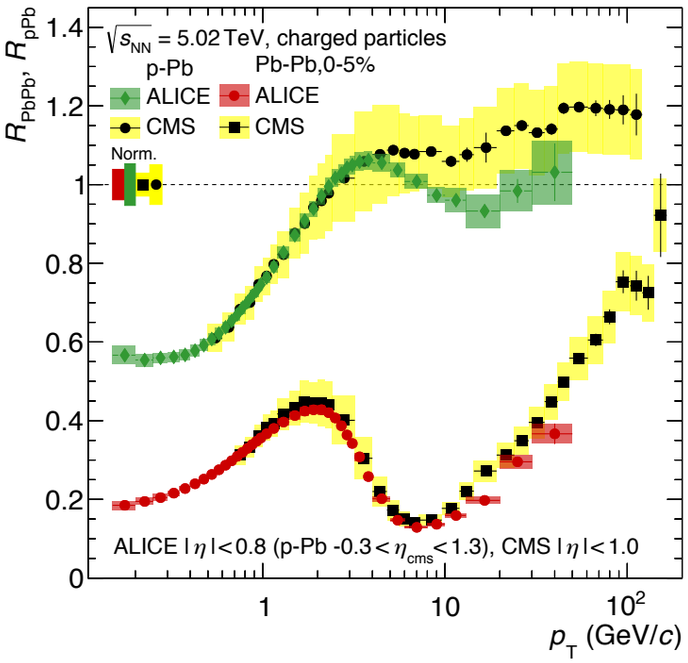
Medium: Hydrodynamics; Hirano, Luzum&Romatschke

Large difference between scale factor at RHIC and LHC

Conclusion seems different from JET collaboration work
Why? Points to modelling uncertainties? Can we reduce those?

Recent results: charged particle R_{AA} at 5 TeV

ALICE, arXiv:1802.09145
CMS, JHEP 04 (2017) 039



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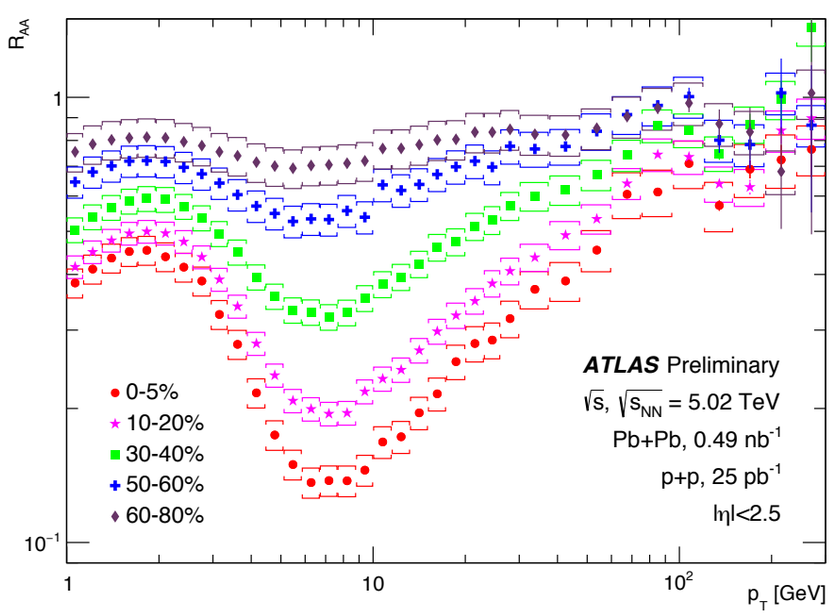

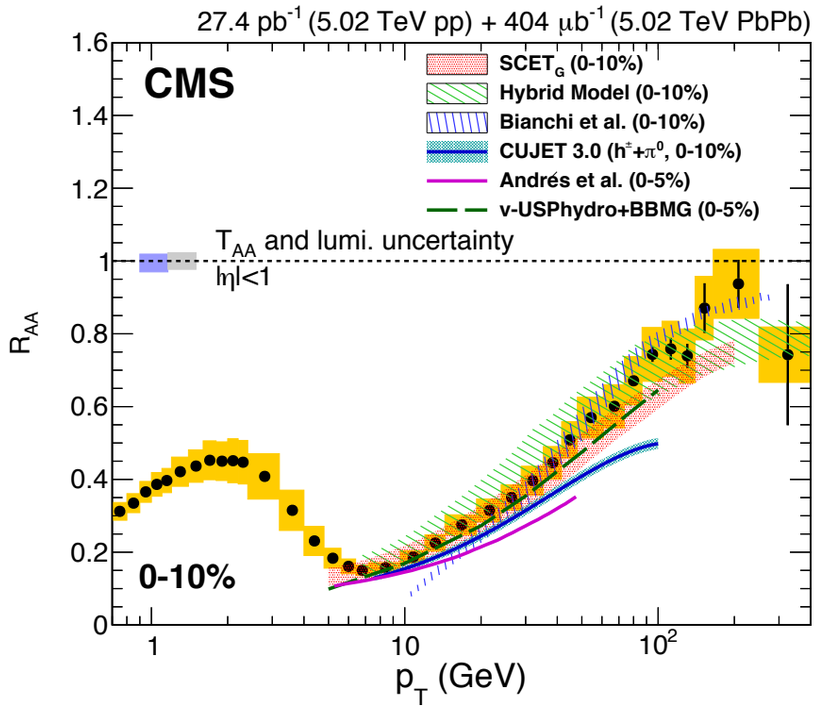

Nuclear modification factor results continue to improve uncertainties and extend p_T range

Values very similar to those from 2.76 TeV

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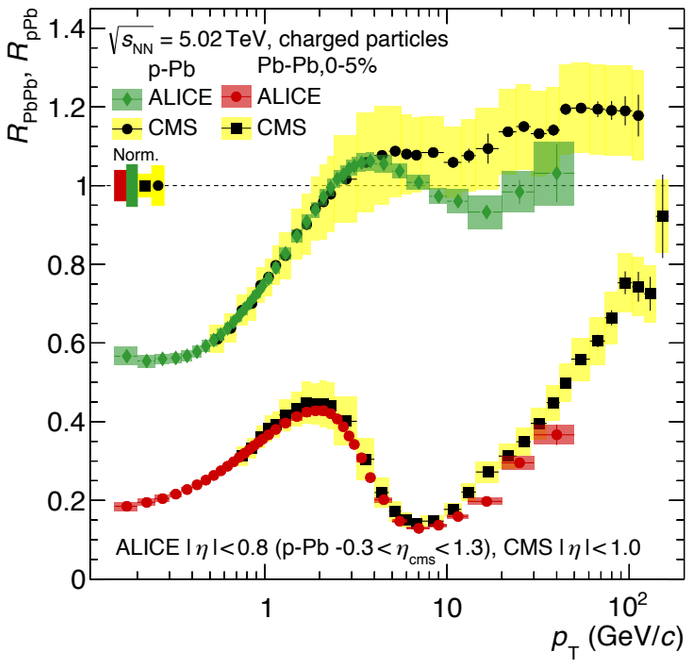

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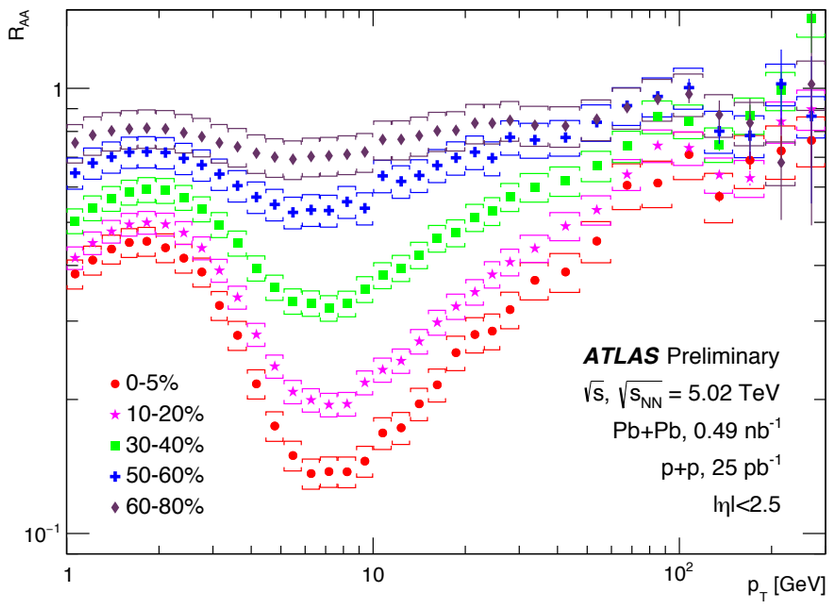
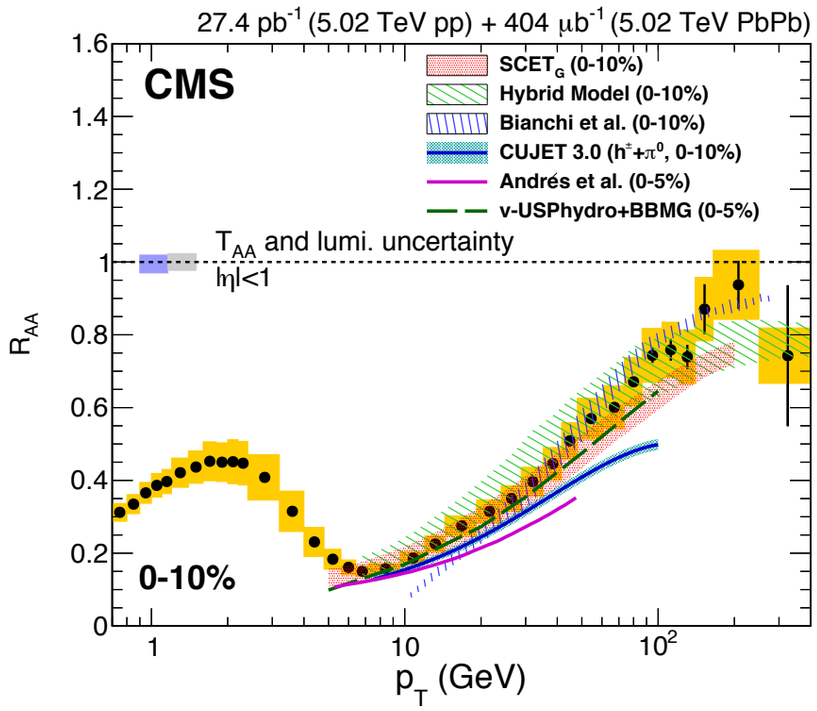




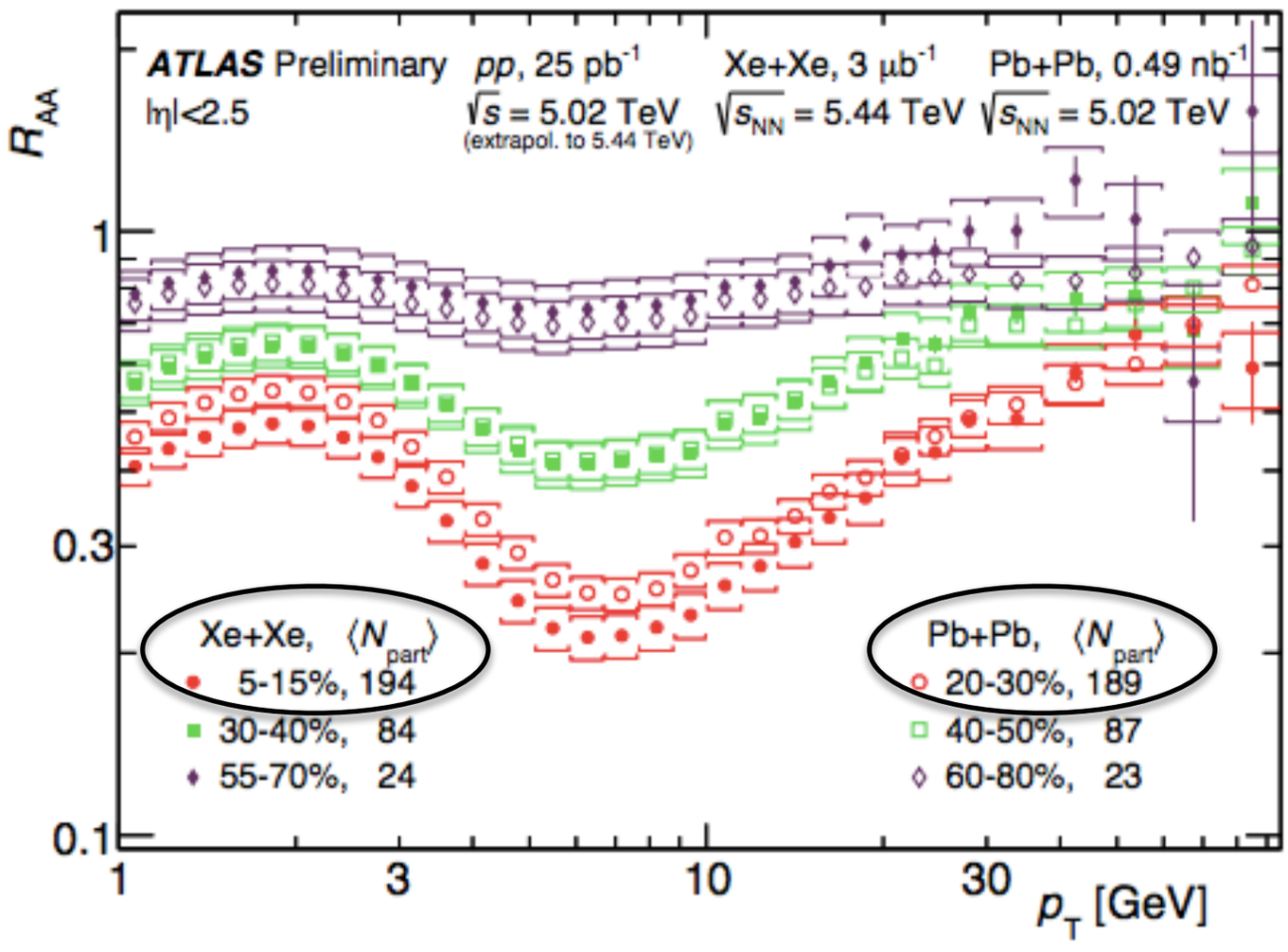
Nuclear modification factor results continue to improve uncertainties and extend p_T range

Challenge for models + field
How accurate do we expect models to be?

Values very similar to those from 2.76 TeV

Nuclear modification factor: system size dependence

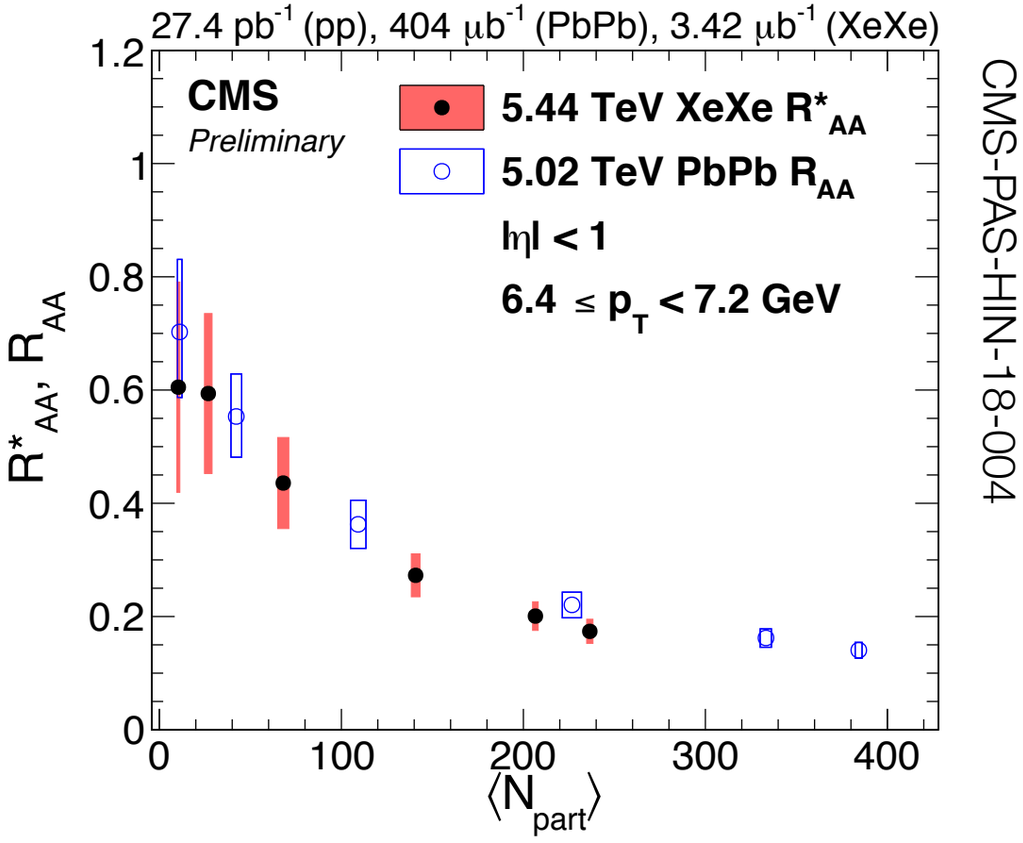
ATLAS-CONF-2018-007



Compare to PbPb at similar N_{part}; R_{AA} similar, over full p_T range

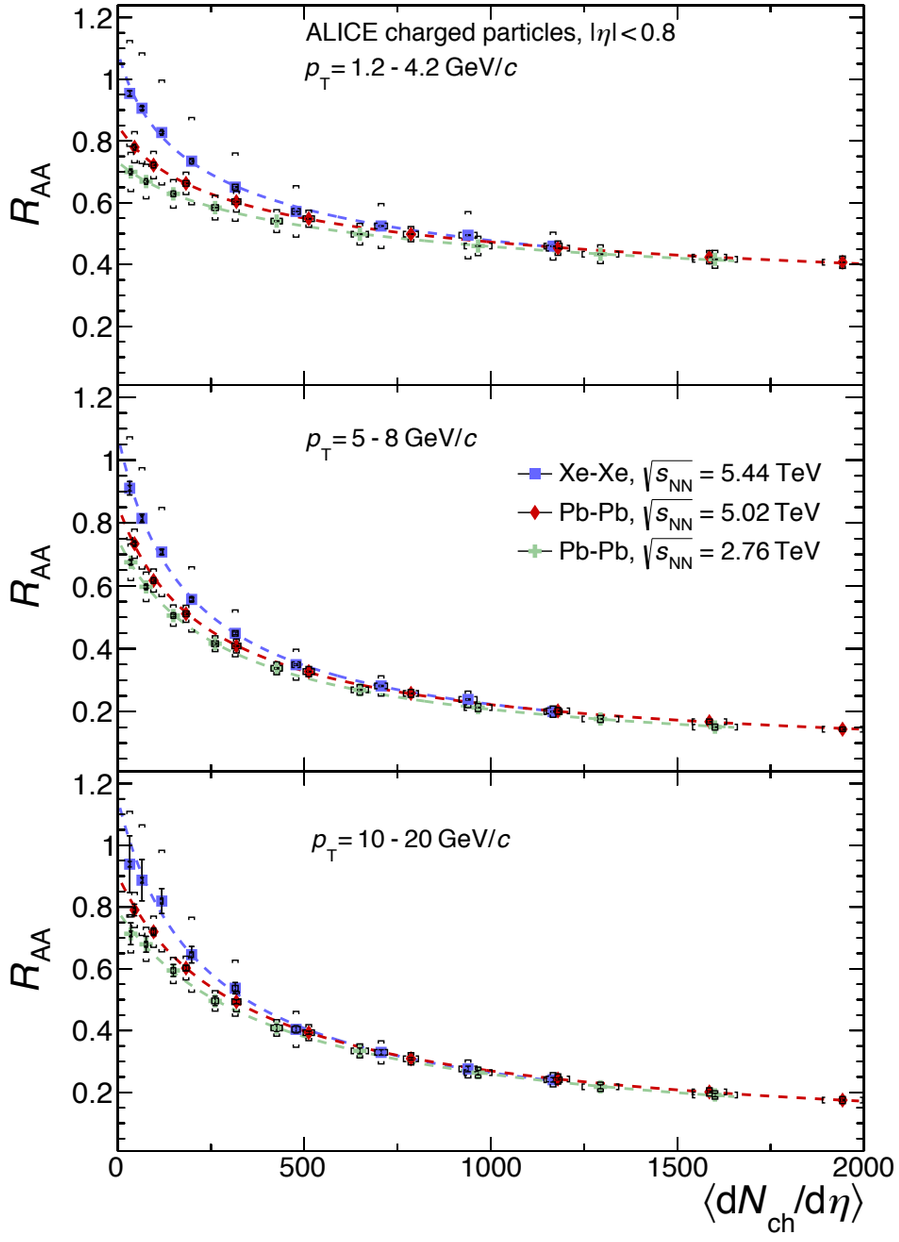
Approximate scaling with
N_{part}, or dN/dη

Nuclear modification factor: centrality dependence



Approximate scaling with N_{part}, or $dN/d\eta$

ALICE, arXiv:1805.04399



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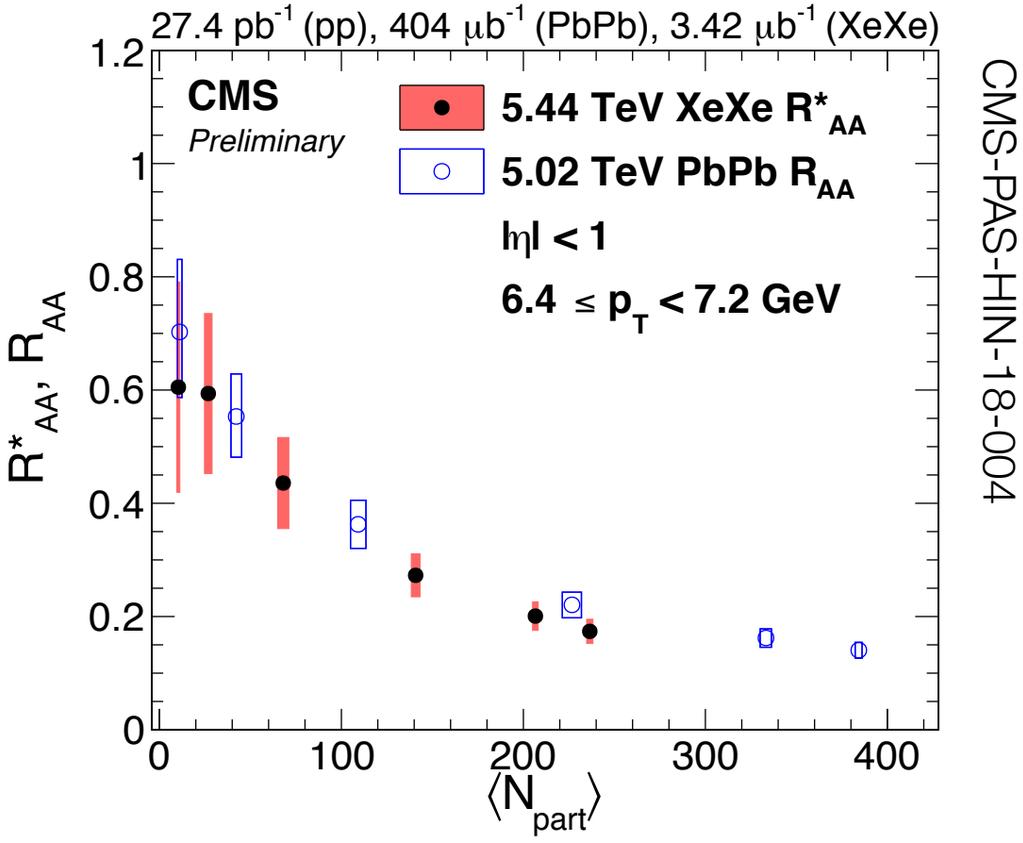

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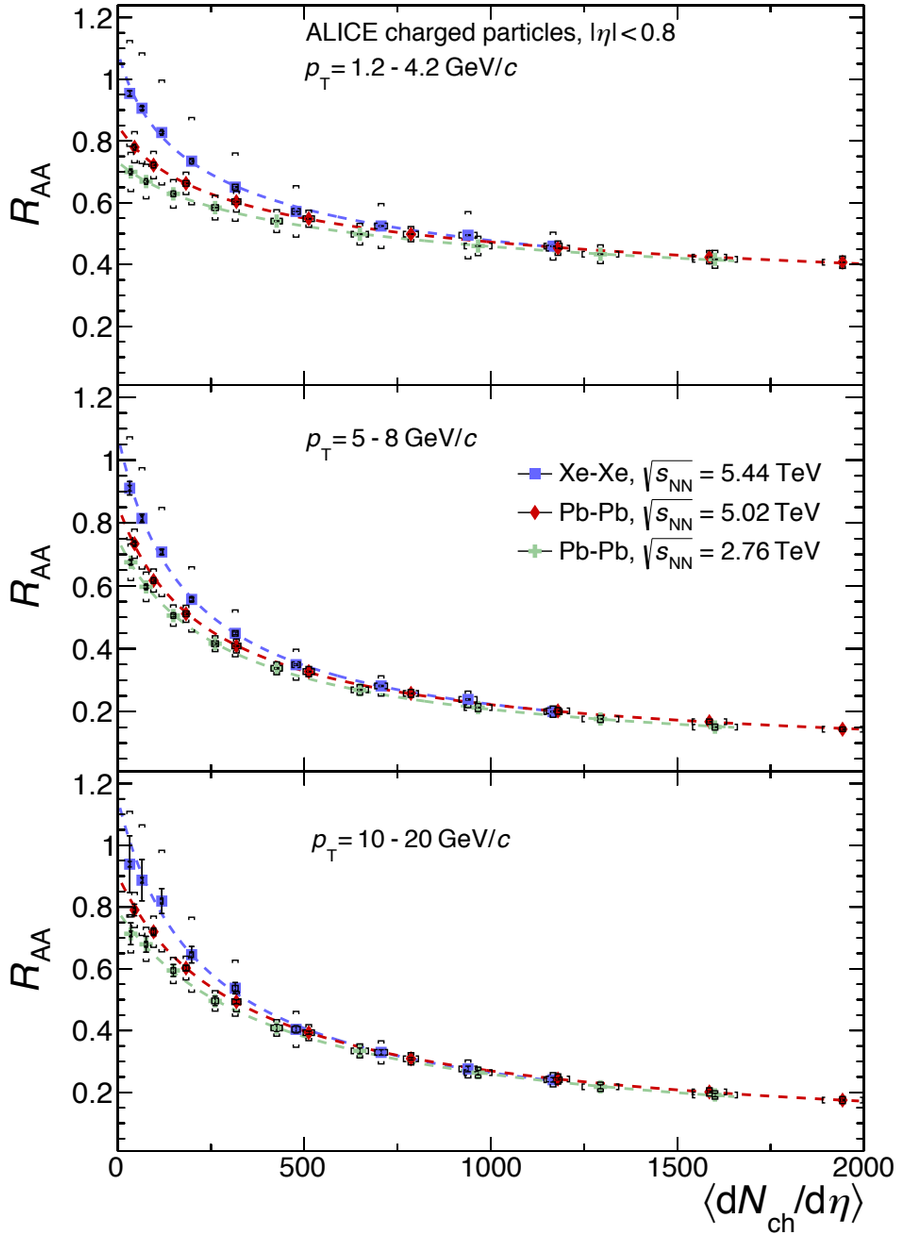

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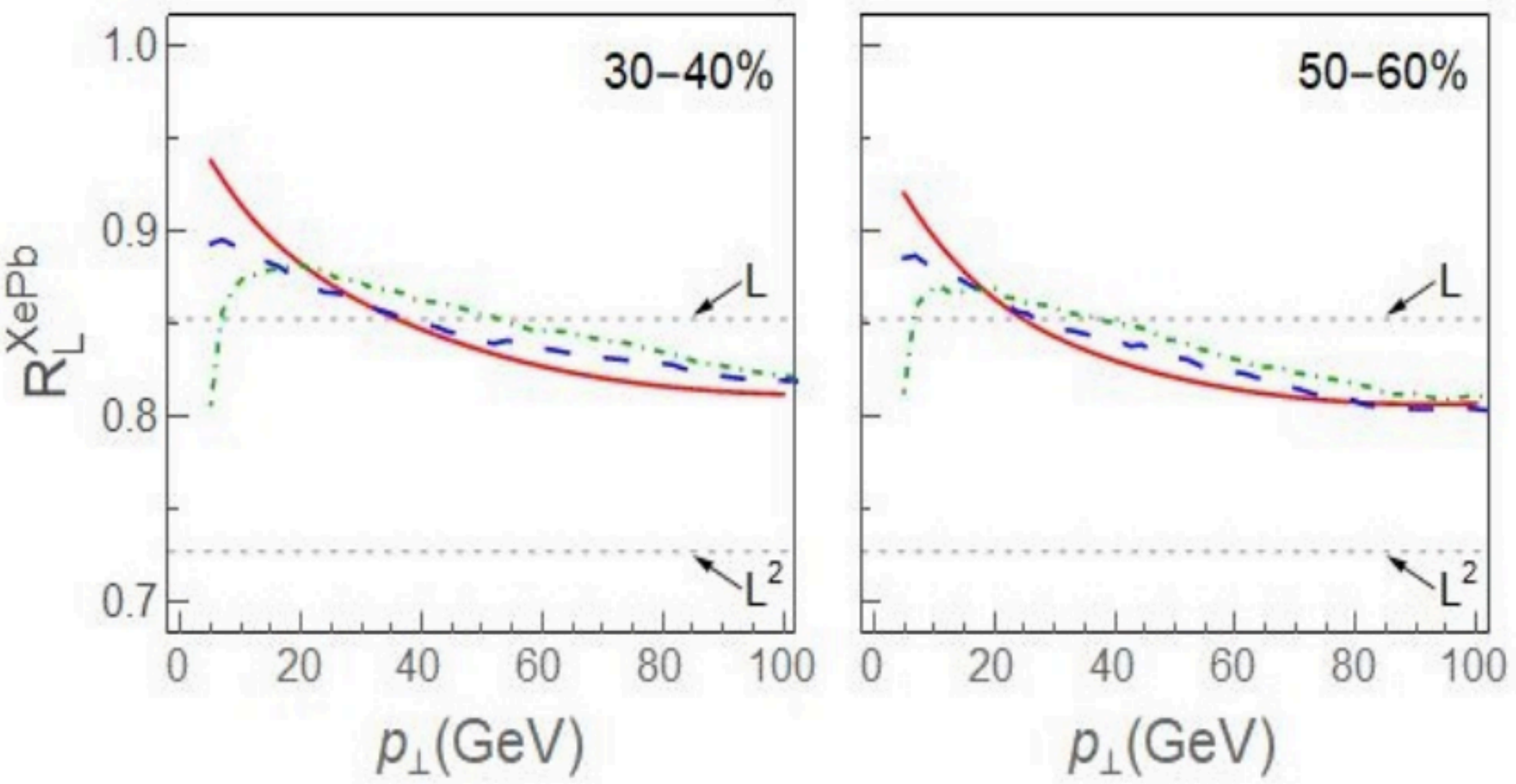
Theory/phenomenology task:
Explore constraints on density, path length dependence

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

System size dependence



New scaling proposal:

Djordjevic, arXiv:1805.04030

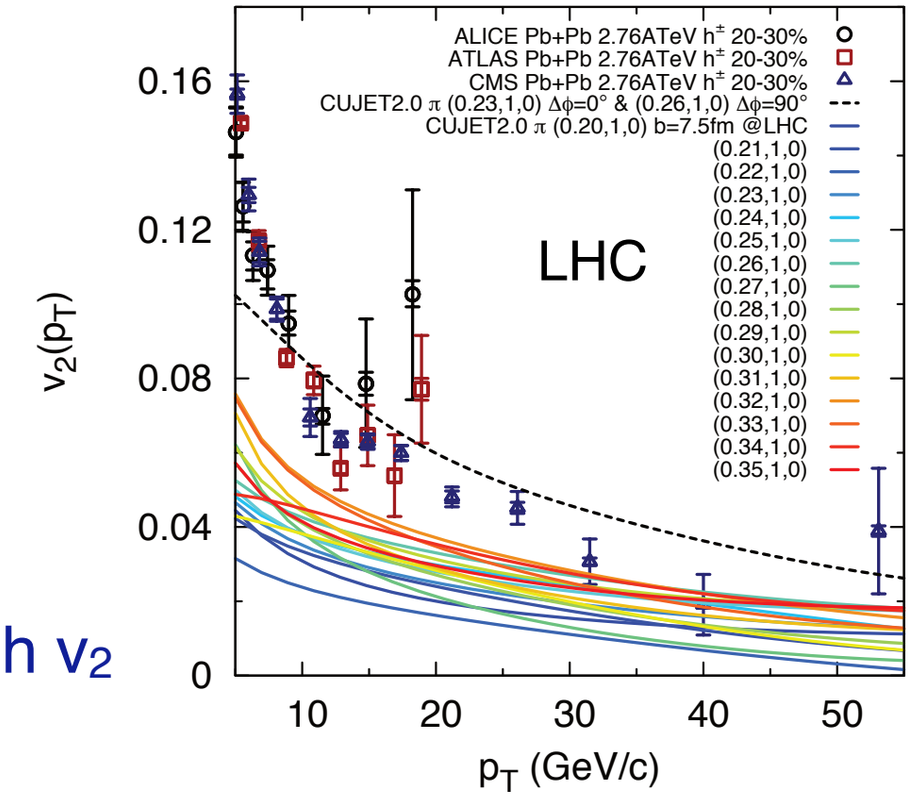
$$R_L^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \approx \frac{\xi T^a L_{Xe}^b}{\xi T^a L_{Pb}^b} \approx \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}$$

T-dependence drops out when *T* similar for equal centralities

Caveat: very approximate…

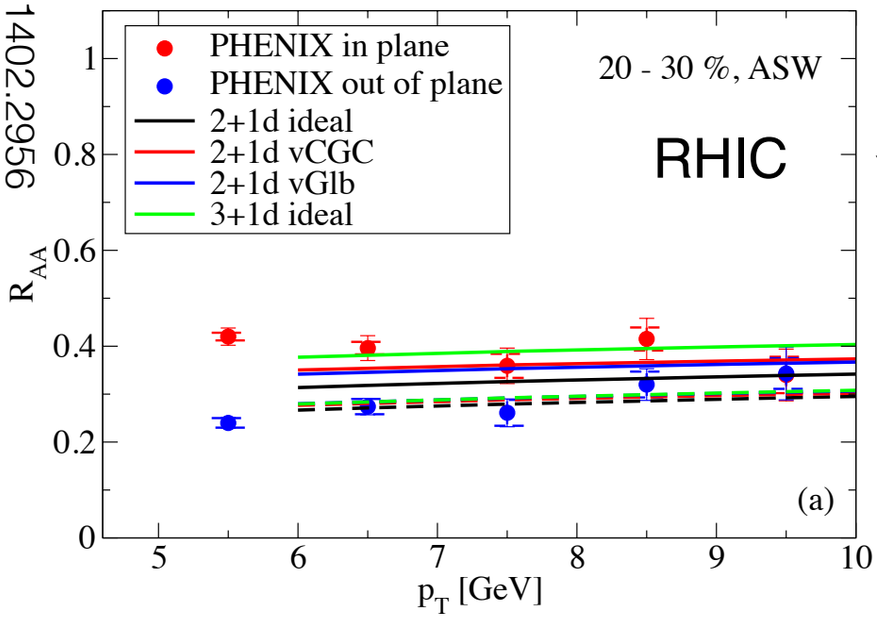
Path length dependence: high-p_T v_2, R_{AA} in and out of plane

CUJET



Xu et al, CUJET, arXiv:1402.2956

YaJEM



T. Renk, arXiv:1010.1635

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

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

See also: CUJET3.0
Xu et al, arXiv:1508.00552

Sensitive to medium evolution models
(freeze-out temp)

Path length dependence: high-p_T v_2, R_{AA} in and out of plane

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

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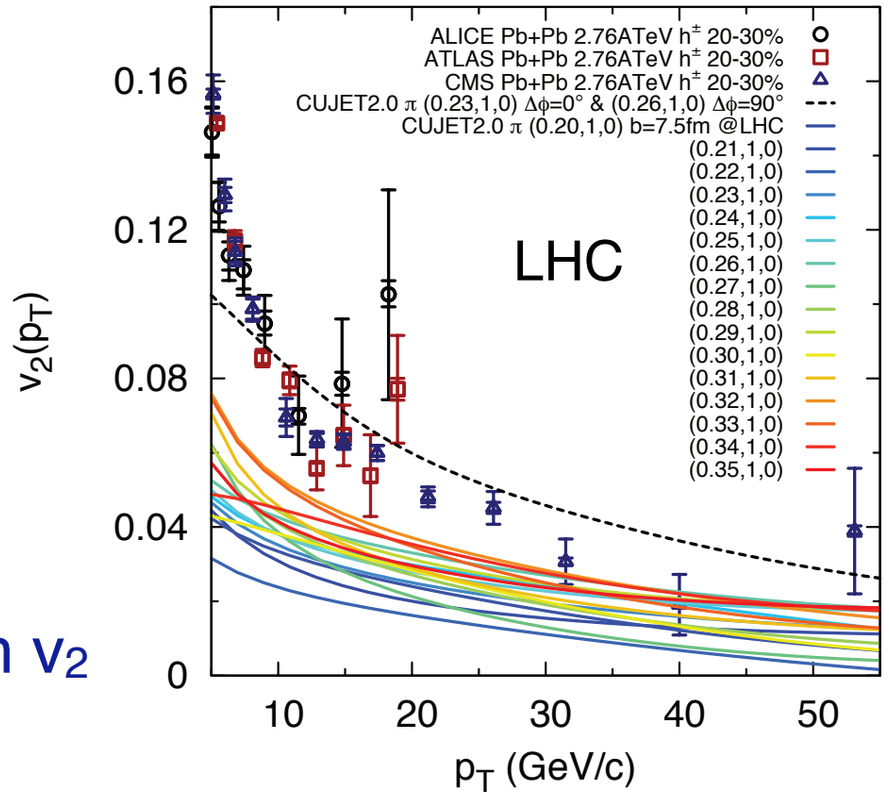

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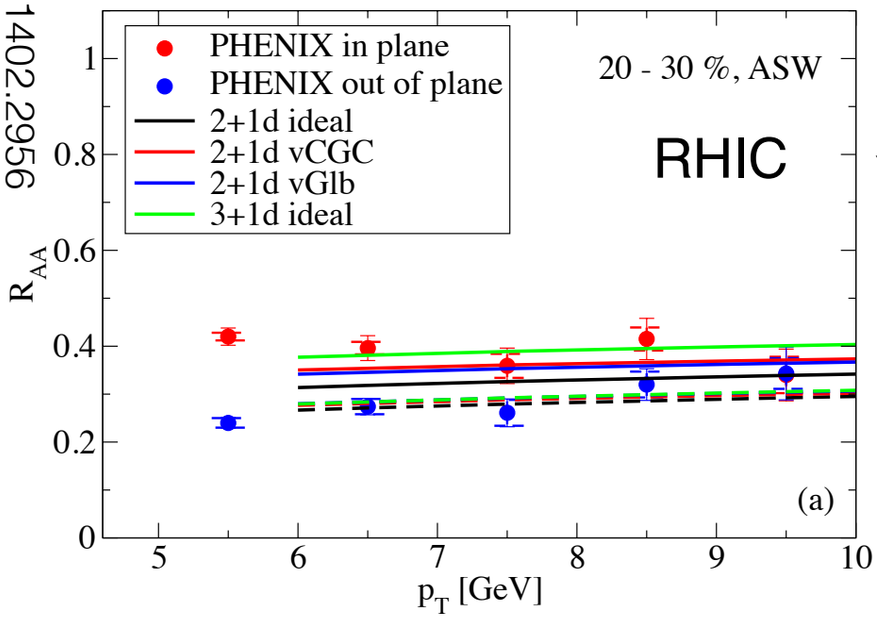

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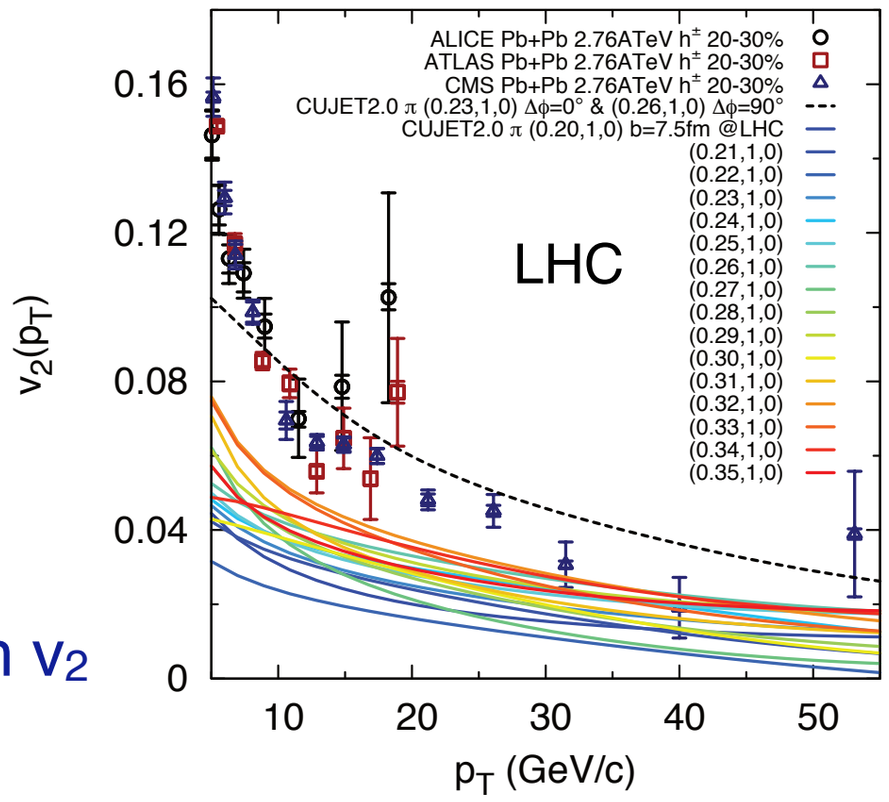

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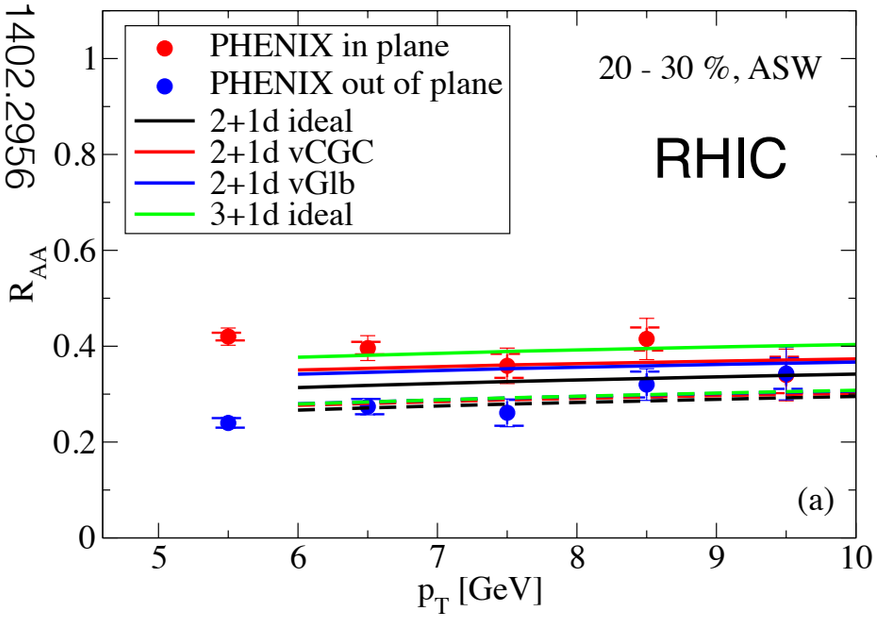

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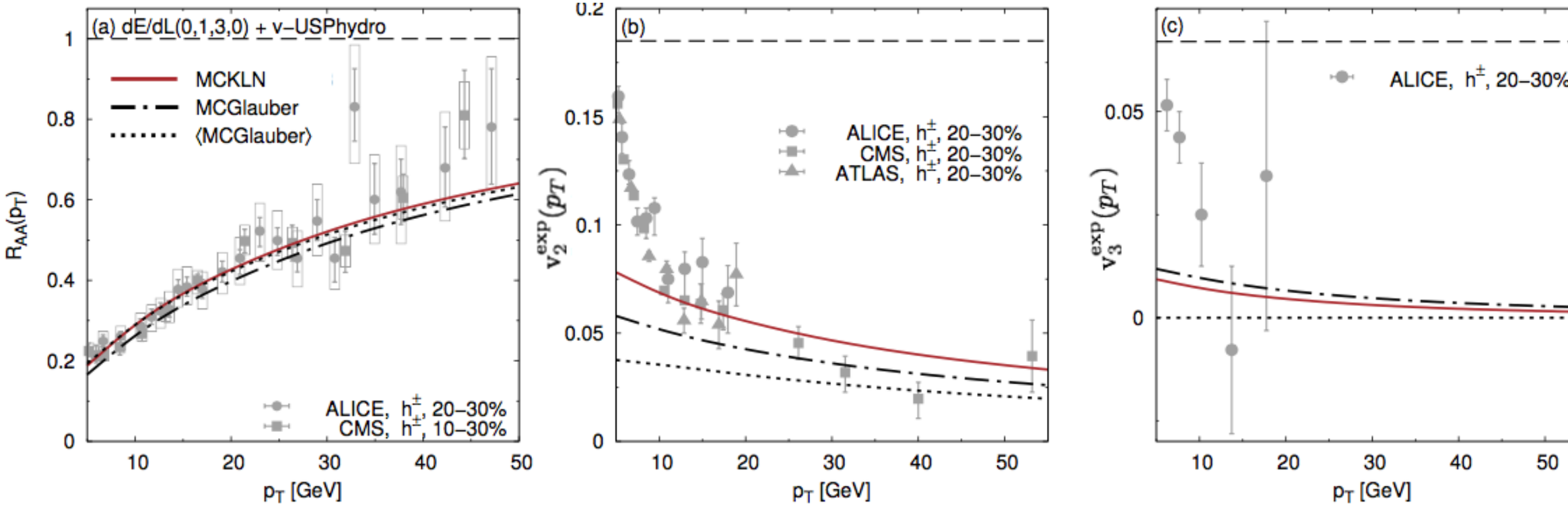
See also: CUJET3.0
Xu et al, arXiv:1508.00552

Sensitive to medium evolution models
(freeze-out temp)

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

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 $\left\langle v_2^2 \right\rangle$

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

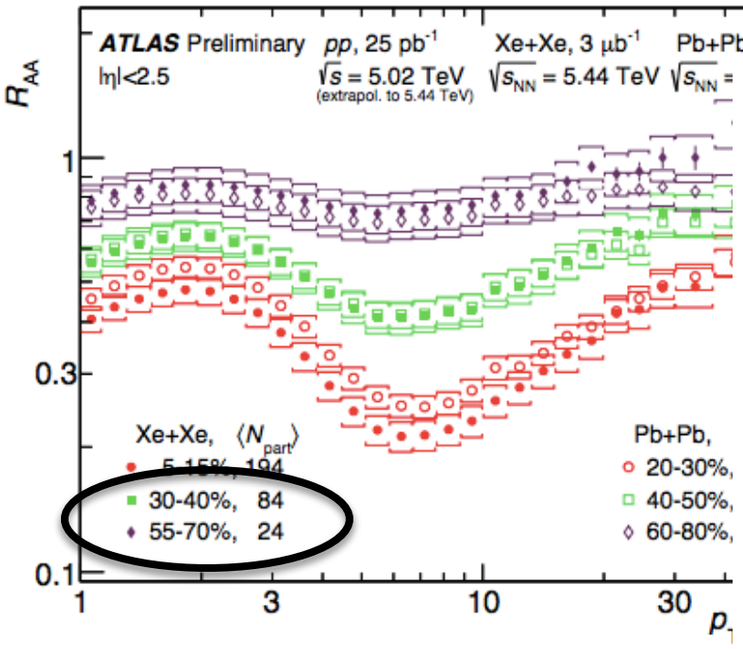
Fluctuations bias v_2

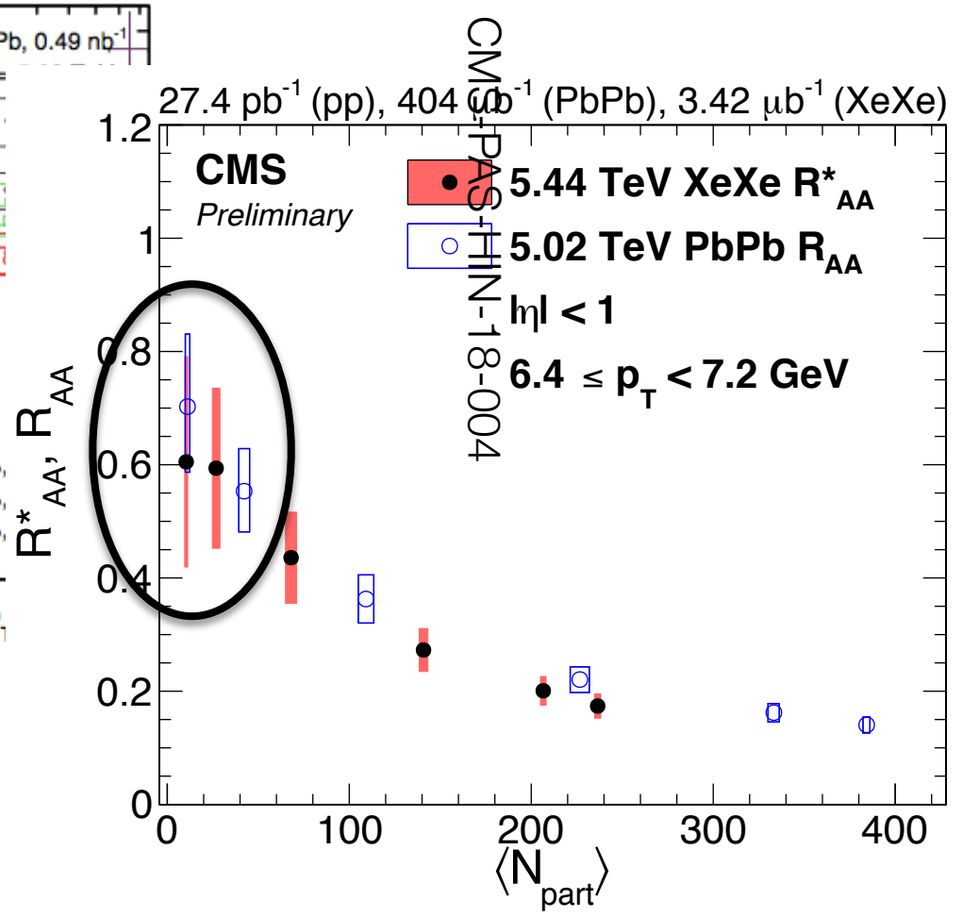
NB: no energy loss fluctuations; not so clear how geometry was implemented (L)

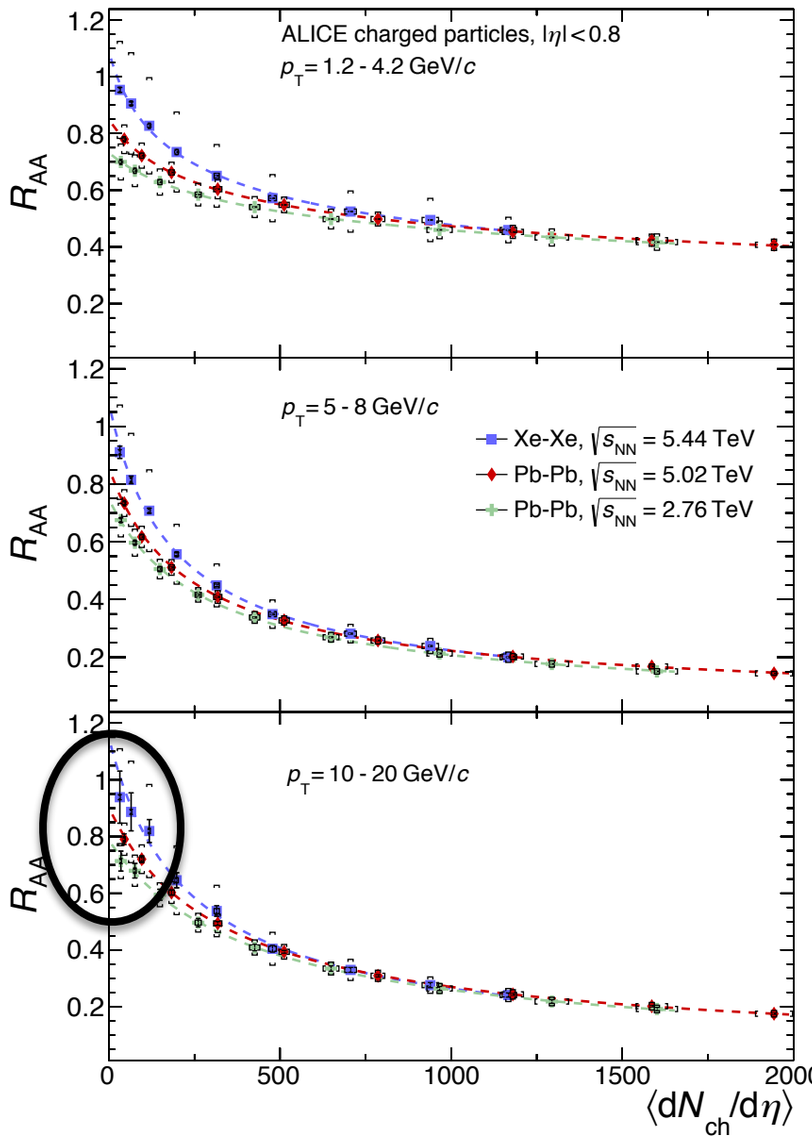
Side note: R_{AA} for peripheral events

ALICE, arXiv:1805.04399

ATLAS-CONF-2018-007







R_{AA} does not reach 1 for peripheral collisions

$N_{part} \sim 10 - 20$

Side note: R_{AA} for peripheral events

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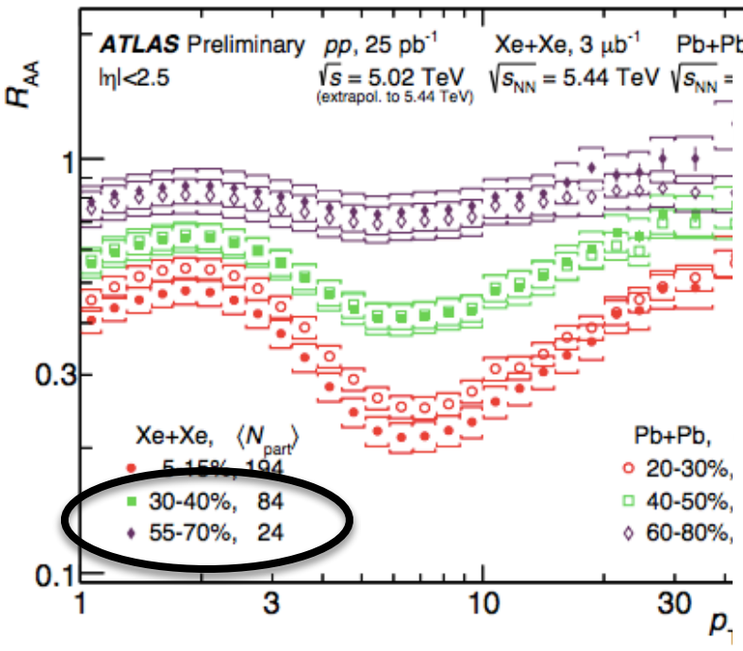
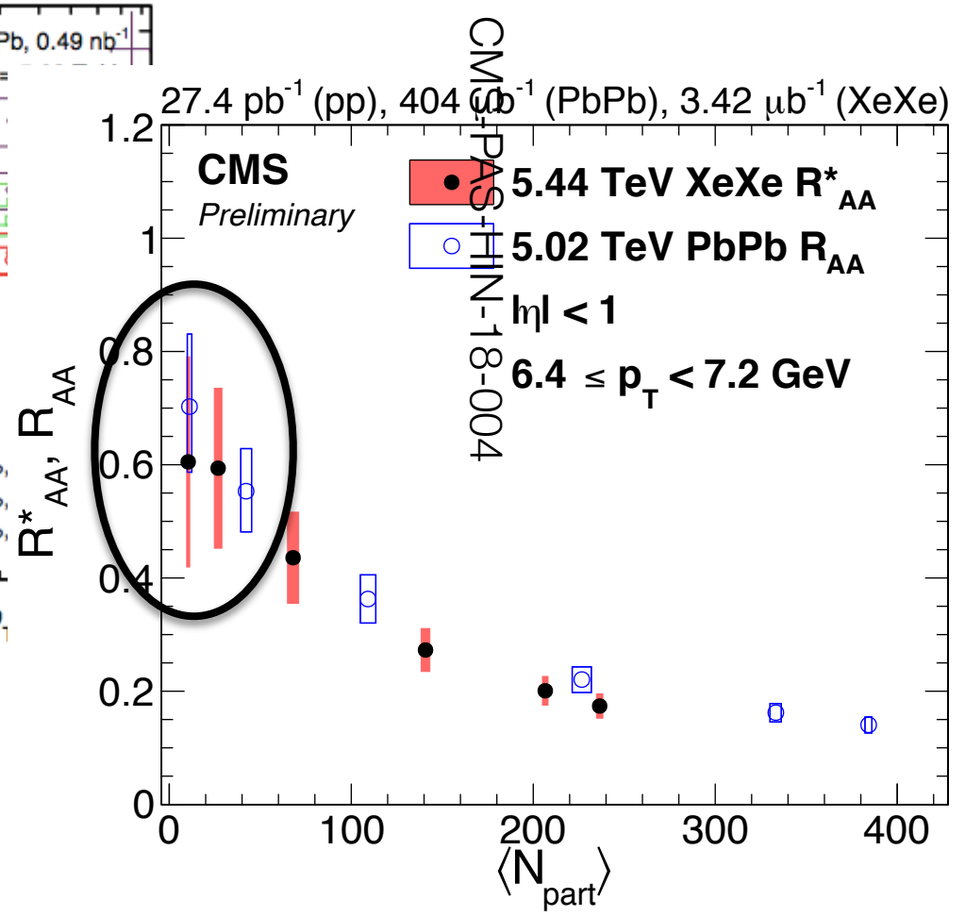
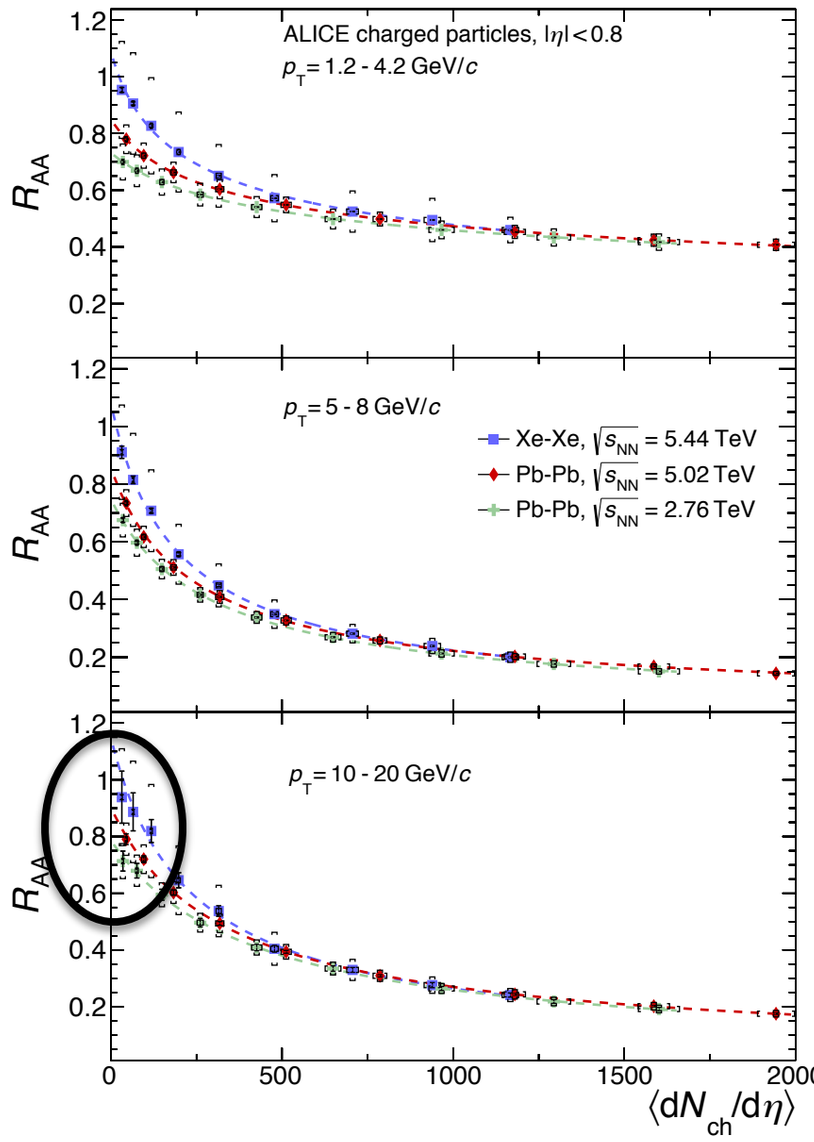
ATLAS-CONF-2018-007







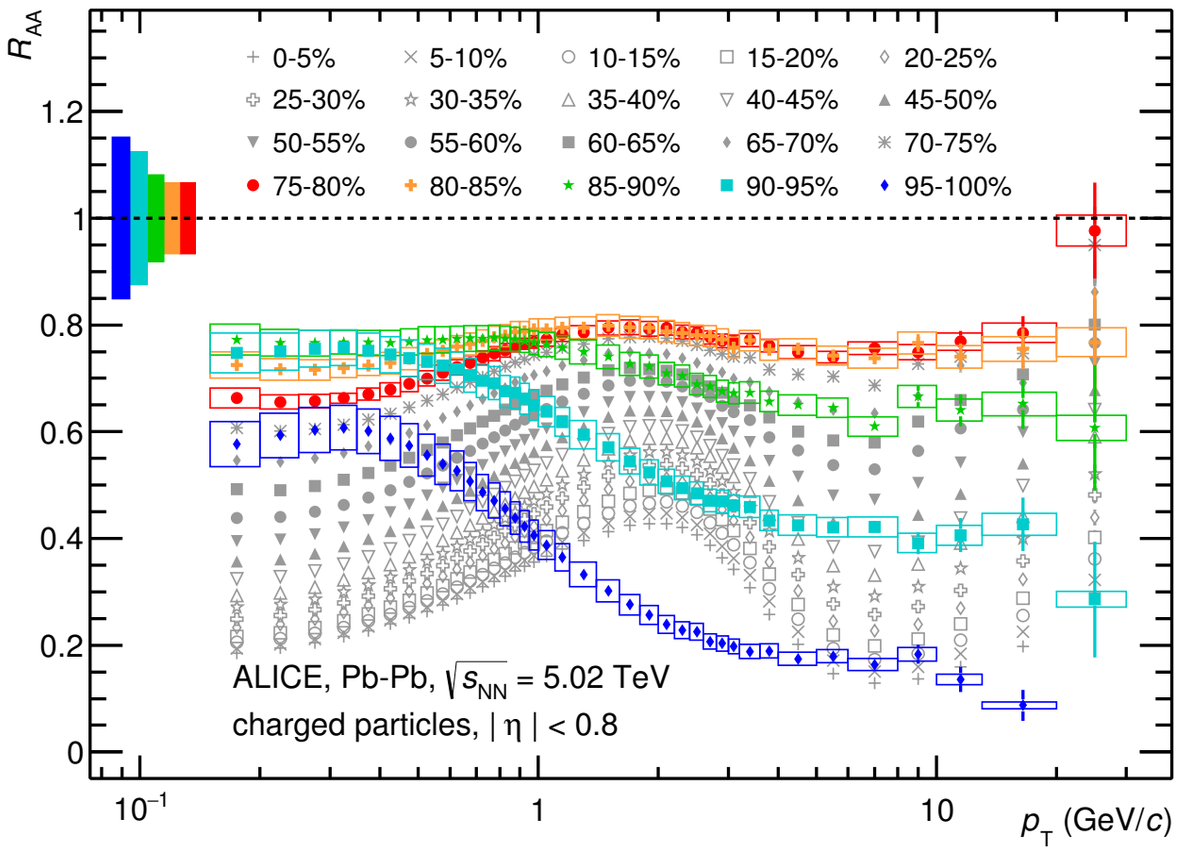
R_{AA} does not reach 1 for peripheral collisions
$N_{part} \sim 10 - 20$

Energy loss in those events? Unlikely, because $R_{pPb} \sim 1$
What else?

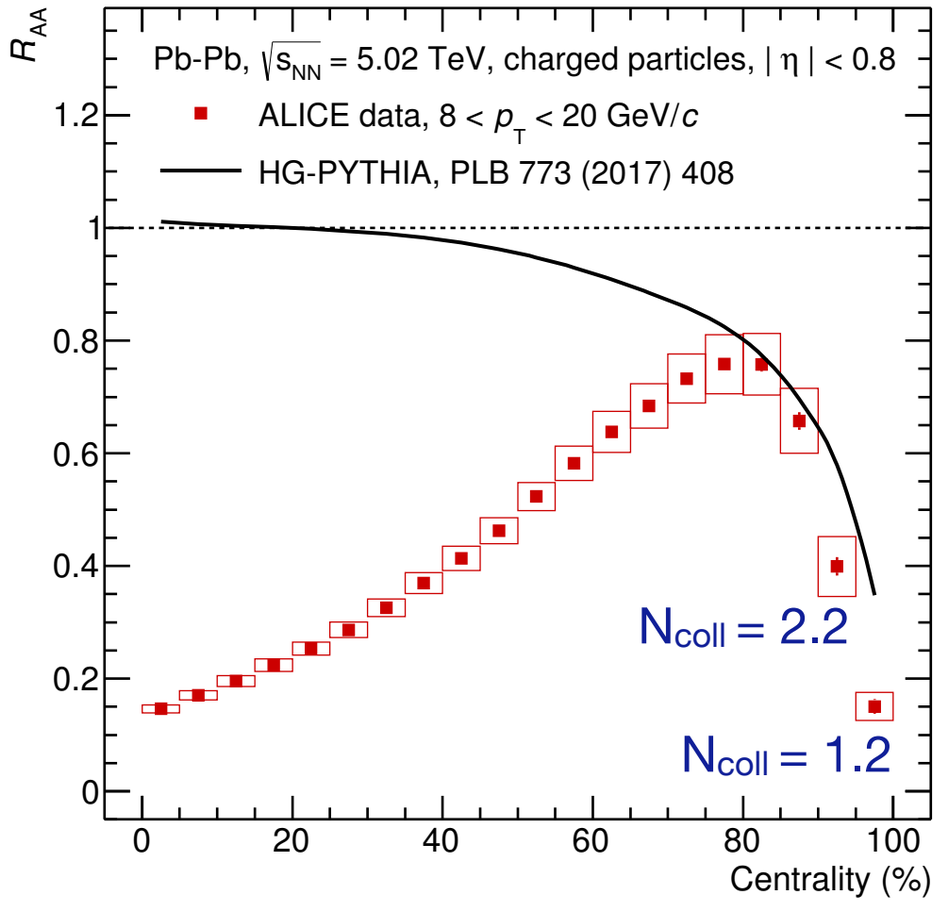
Nuclear modification in peripheral collisions

Dedicated study by ALICE: very peripheral events

R_{AA} for peripheral events



ALICE, arXiv:1805.05212



R_{AA} does not increase for centrality > 80%
but decreases; becomes p_T-dependent

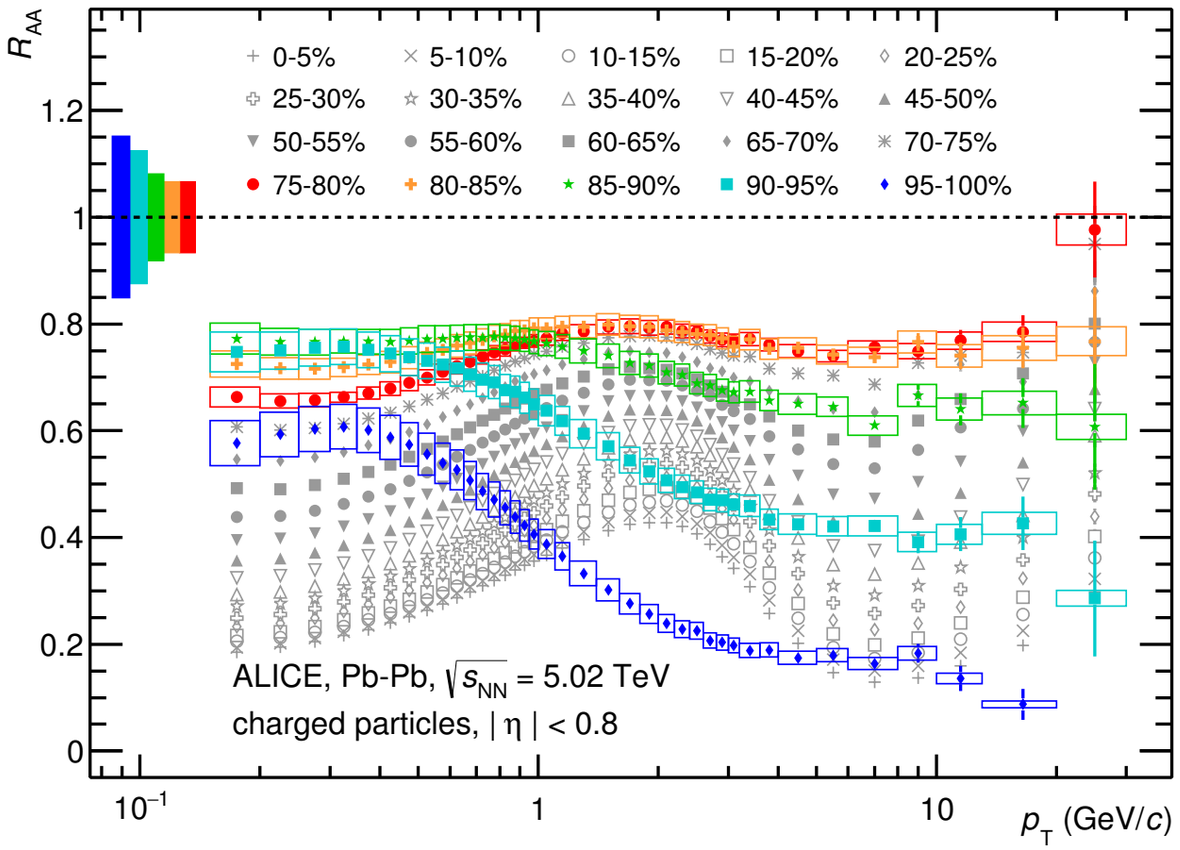
Peripheral events described by HG-Pythia
increase of pp impact parameter + multiplicity

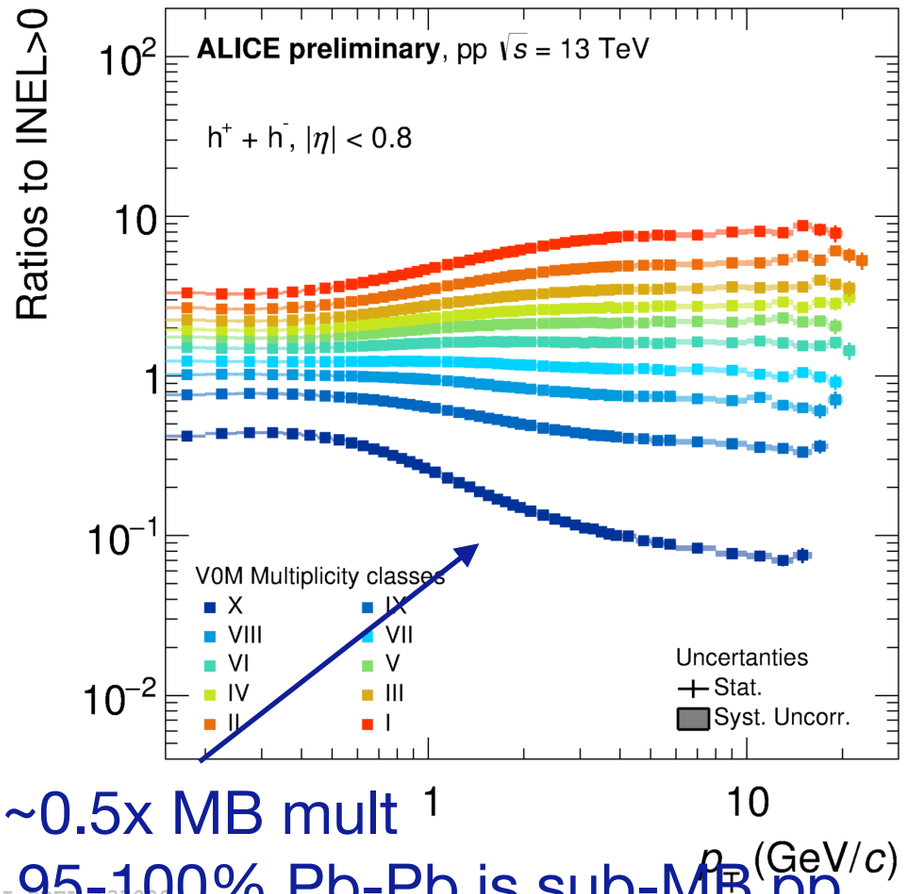
Nuclear modification in peripheral collisions

Dedicated study by ALICE: very peripheral events

R_{AA} for peripheral events

ALICE, arXiv:1805.05212





~0.5x MB mult

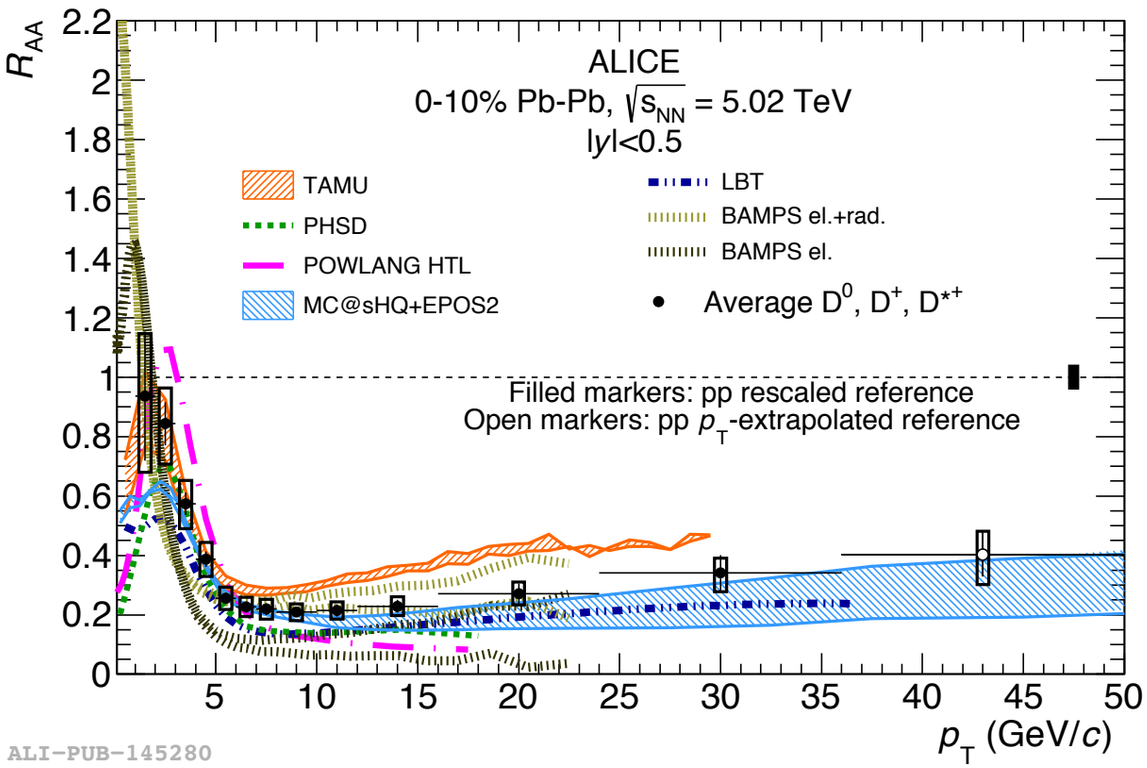
95-100% Pb-Pb is sub-MB pp

R_{AA} does not increase for centrality > 80%
but decreases; becomes p_T-dependent

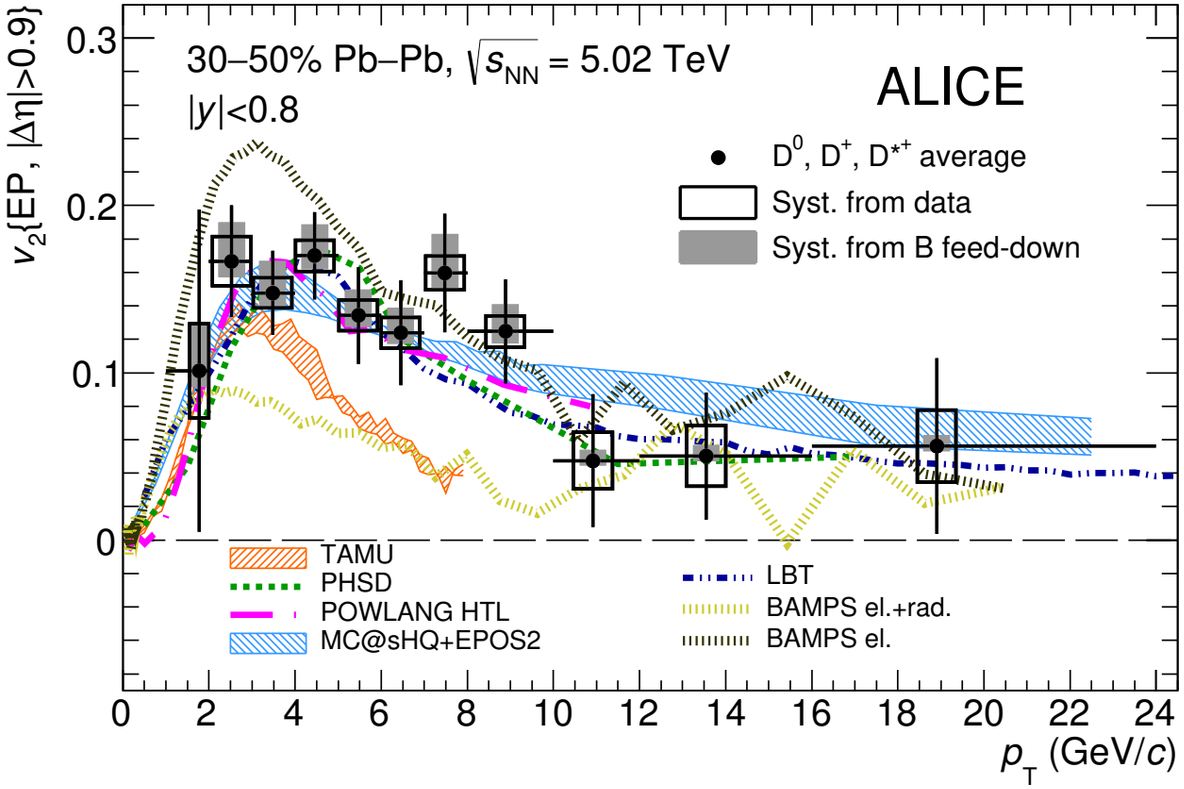
Peripheral events described by HG-Pythia
increase of pp impact parameter + multiplicity

Heavy flavour energy loss

Heavy flavor energy loss: open charm

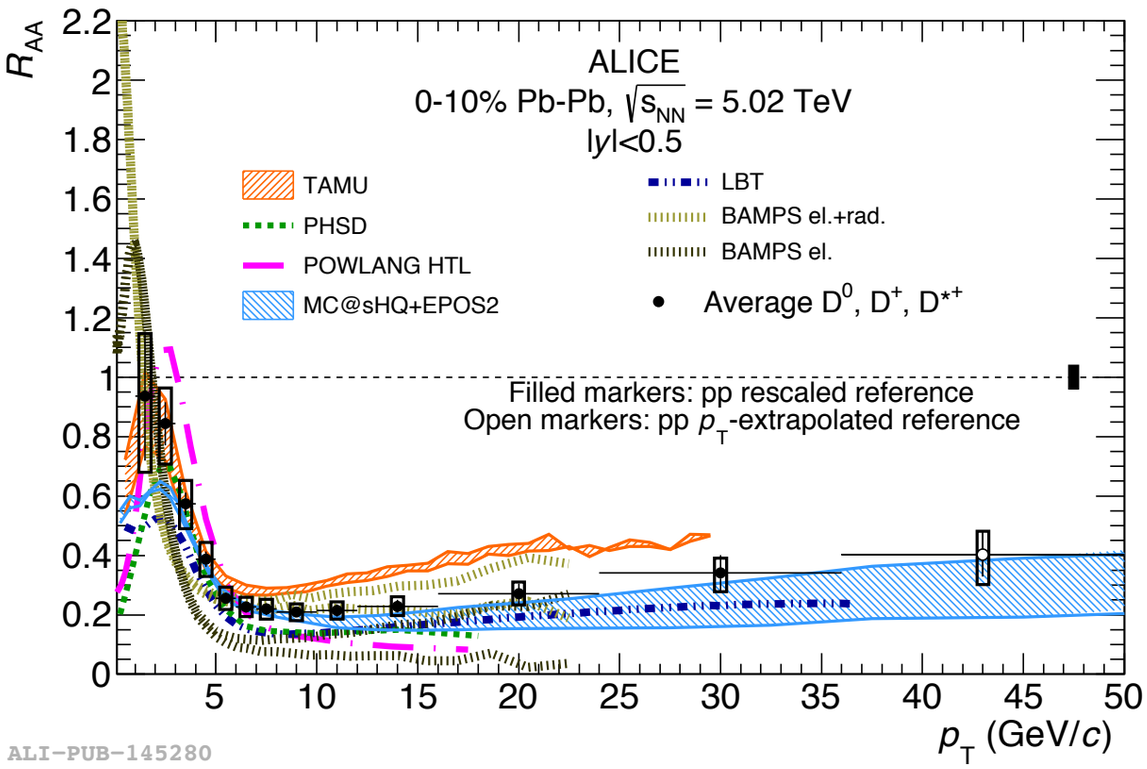


Suppression of charm mesons
similar to light flavor



Large v_2
Similar to light flavor

Heavy flavor energy loss: open charm



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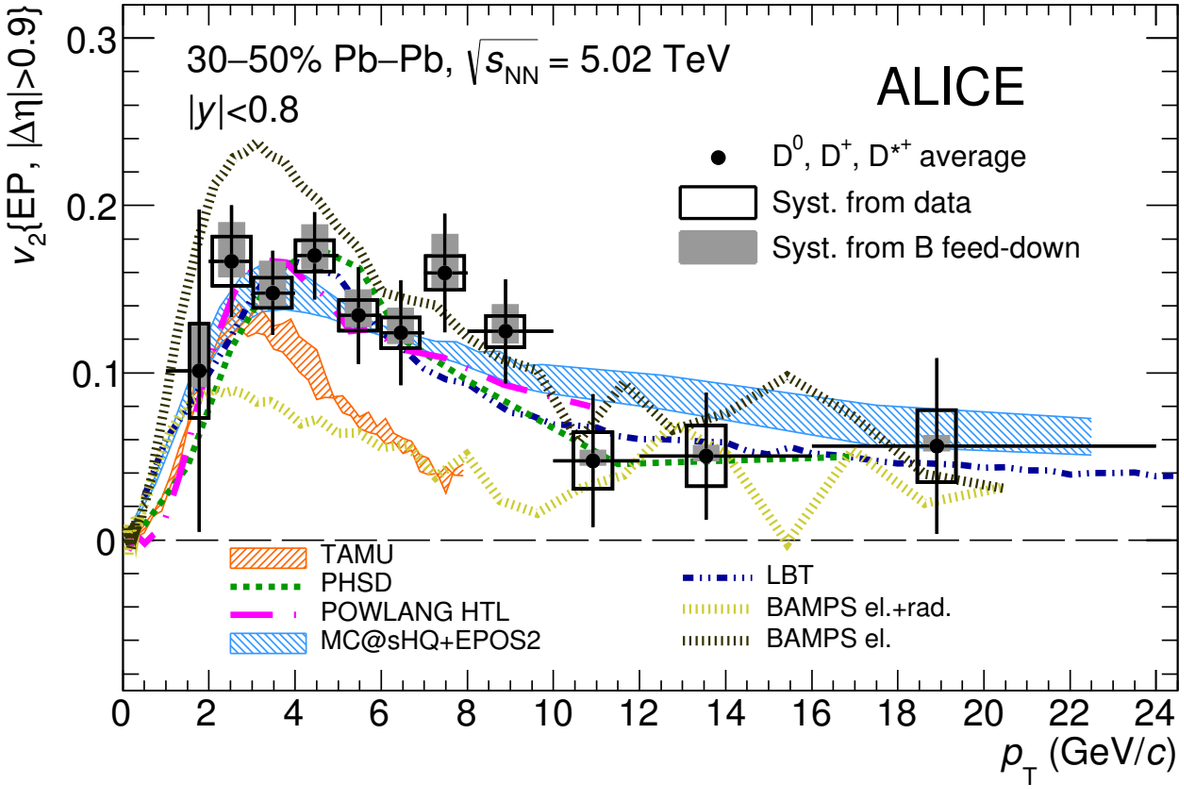


Large v_2
Similar to light flavor

Various model approaches; elastic and/or radiative energy loss
Provide good description of data; including v_2 ?

Collisional + radiative energy loss: Bayesian fit

(Picked one example to show what enters in a typical model)

Y. Xu et al, PRC 97, 014907

'Improved Langevin model':

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g.$$

Diffusion/drag (often not used/present in light flavour models)

Thermal force

Radiative loss (fluctuations are modelled as well)

Diffusion coefficient depends on *T* and *p*

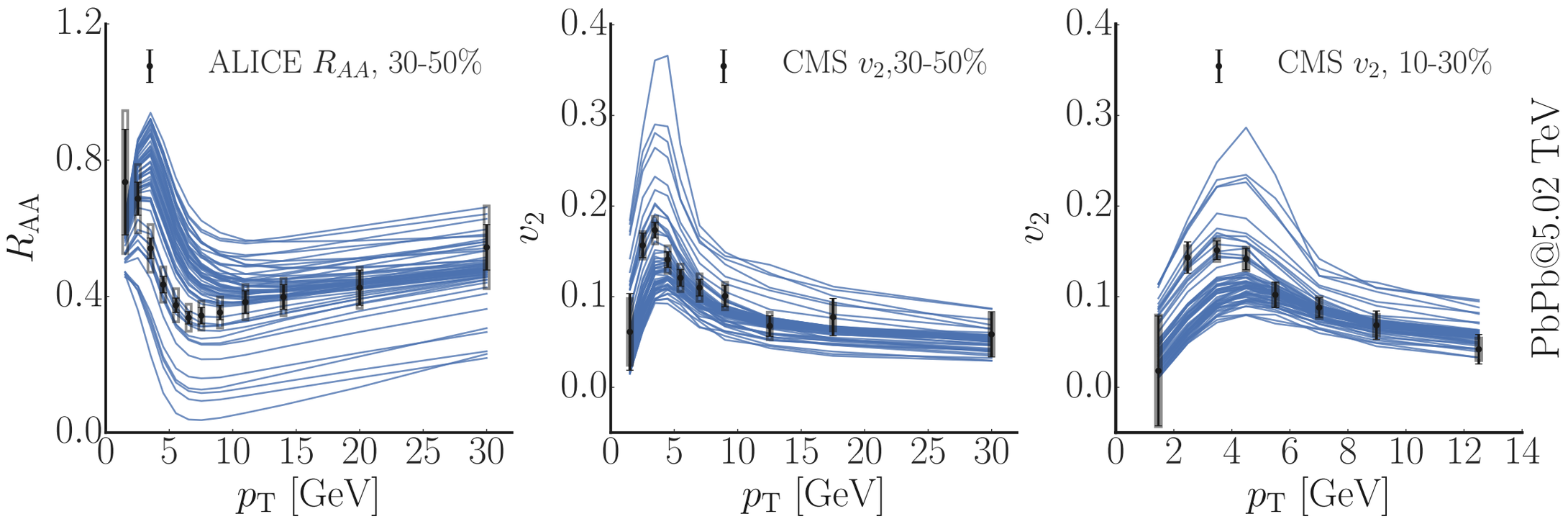
$$\eta_D = \frac{M}{T} D_s(T, \vec{p})$$

Radiative loss characterised by $\hat{q}$

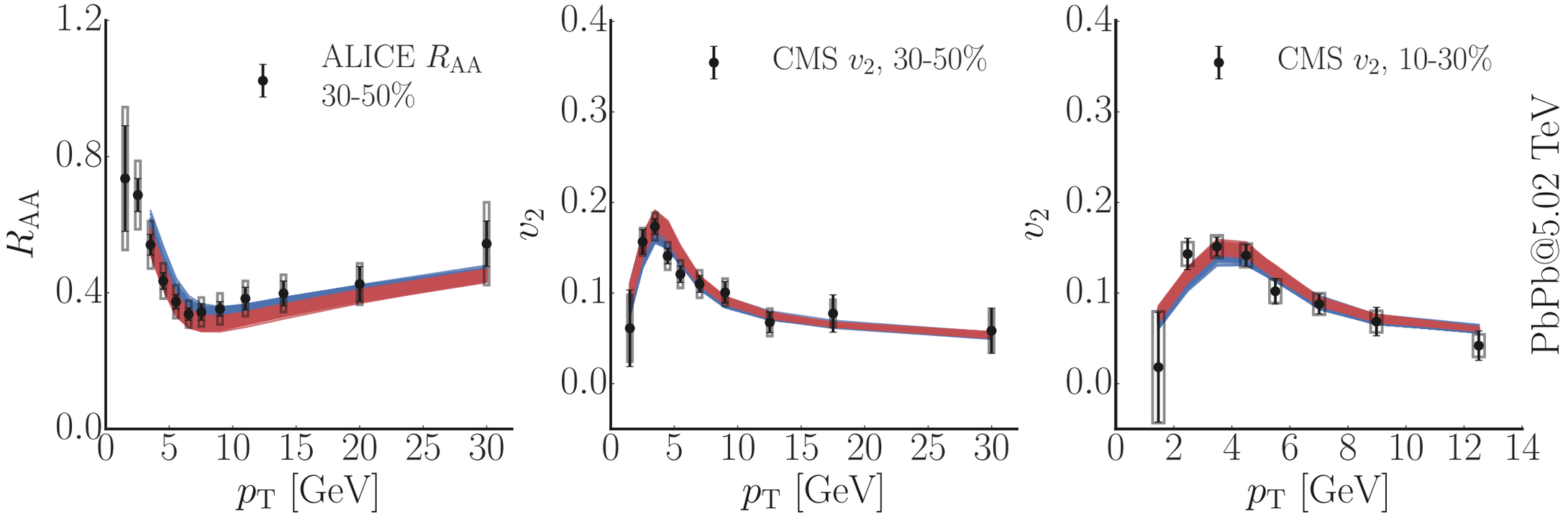
Fixed relation between $\hat{q}$ and D_s used: $D_s T = 4\frac{T^3}{\hat{q}}$

Collisional + radiative energy loss: Bayesian fit

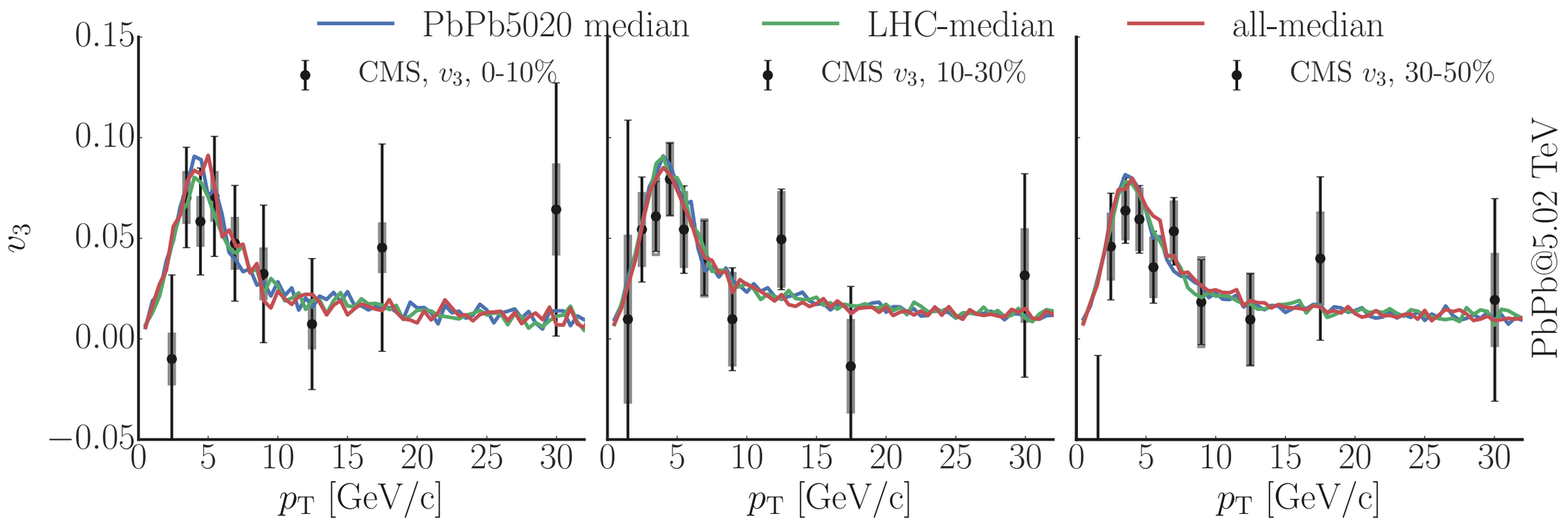
Explored parameter space:



Fit result:



Also v_3

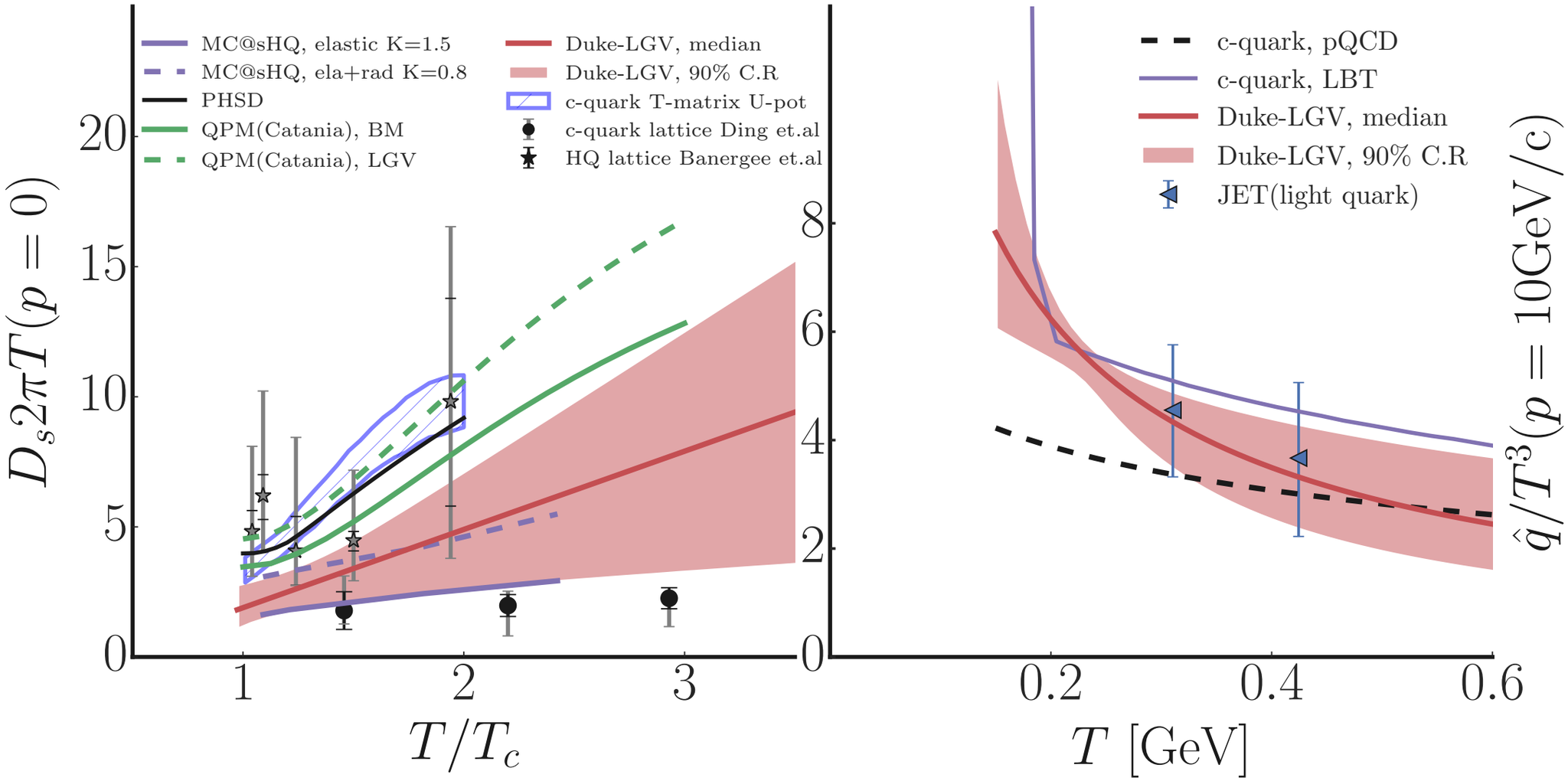


Future measurement will provide more constraints

Different p_T dependence than v_2; interplay diffusion/energy loss?

Heavy flavor transport coefficient

Y. Xu et al, PRC 97, 014907



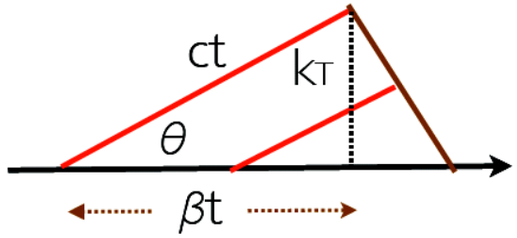
Data already provide significant constraints on *T*, *p* dependence

Agrees with light flavour: $\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$ Burke et al, JET Collaboration, arXiv:1312.5003

Some systematic uncertainties in modelling still to be explored

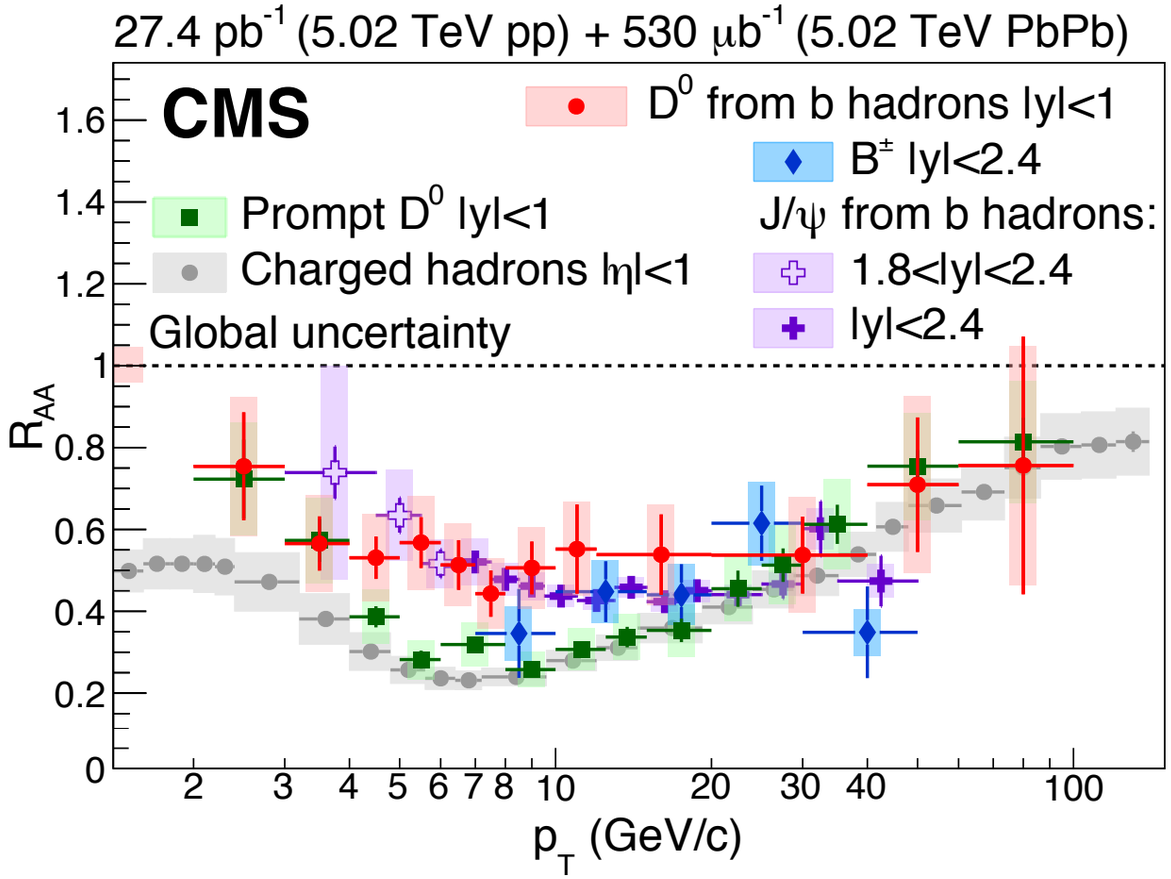
Beauty suppression

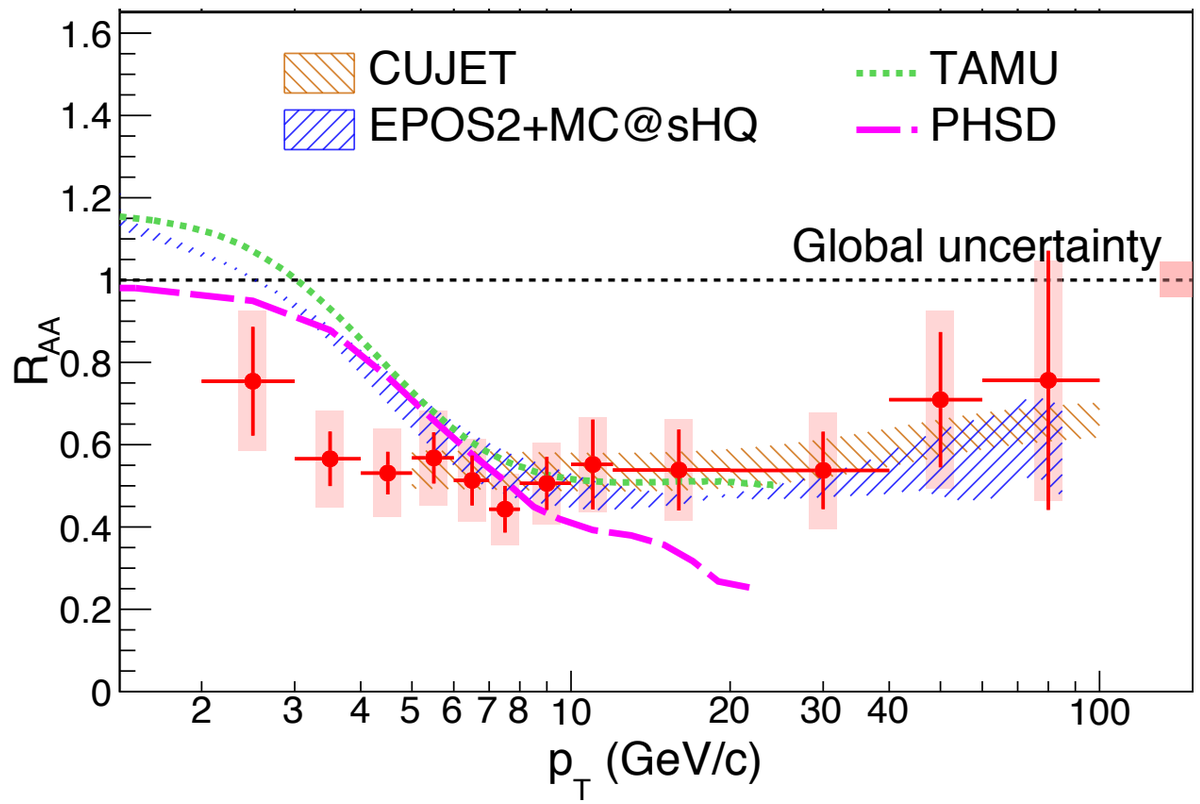
Dead cone: reduced energy loss
due to minimum radiation angle $v < c$



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

CMS, arXiv:1810.11102



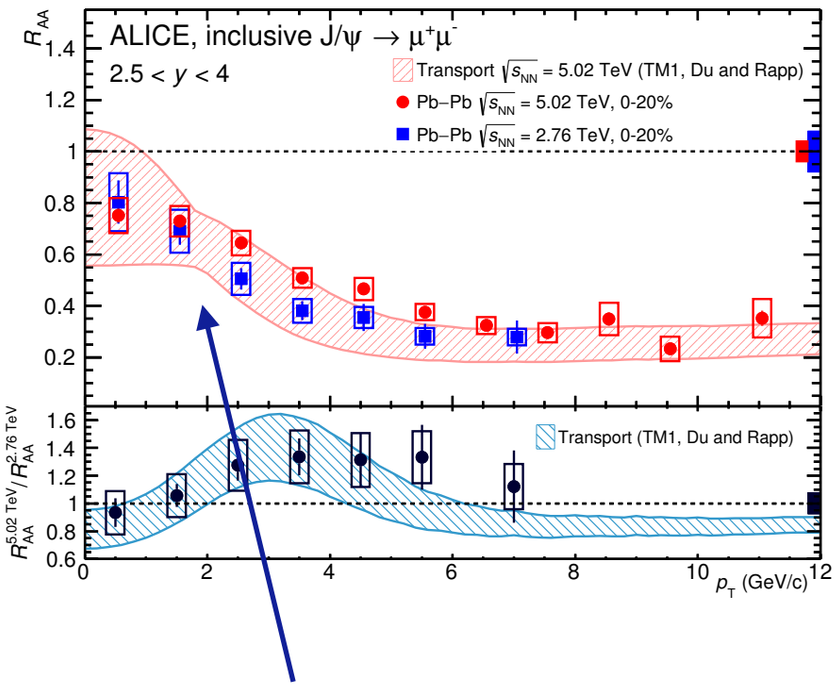


B mesons less suppressed than D meson at low p_T
As expected from dead cone effect

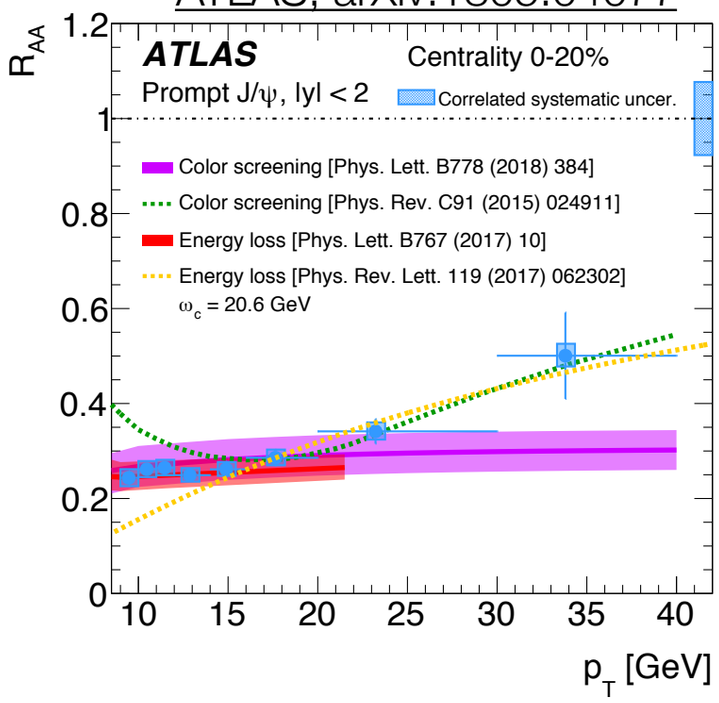
J/ψ at high p_T

J/ψ formation: contribution from recombination at low p_T
High-p_T: c-cbar with similar momentum are rare?

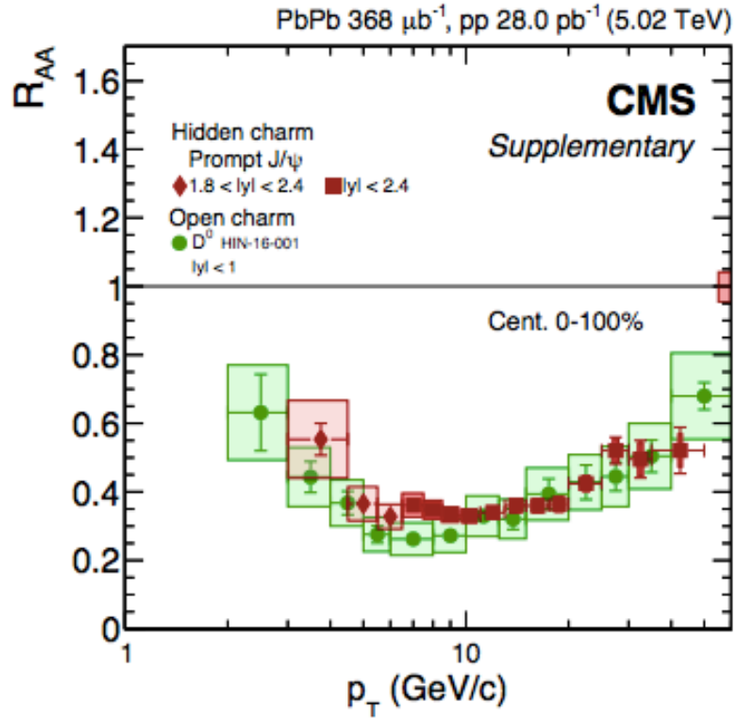
ALICE, PLB 766, 212



ATLAS, arXiv:1805.04077



Open charm and prompt J/ψ



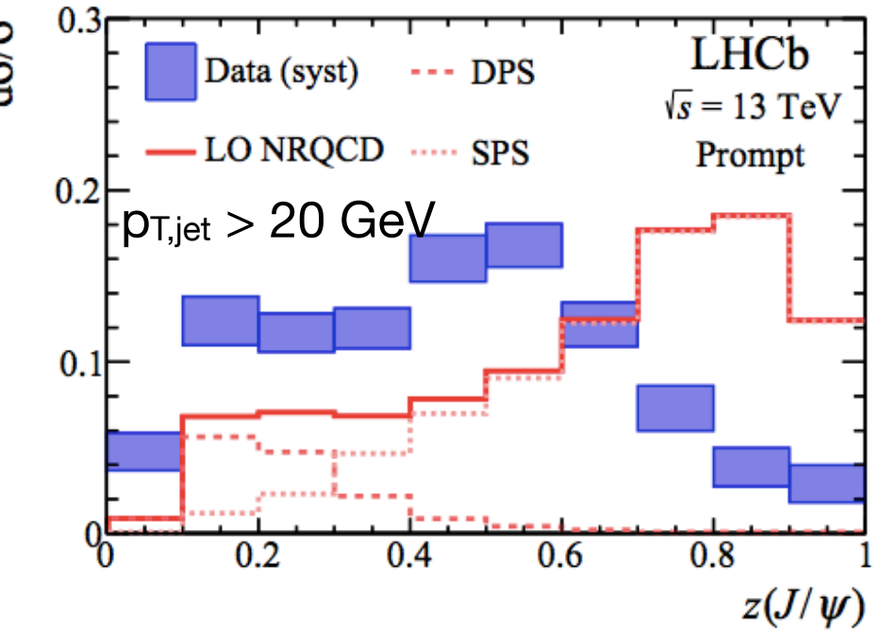
Low p_T: coalescence/recombination important

High p_T: open and hidden charm R_{AA} similar

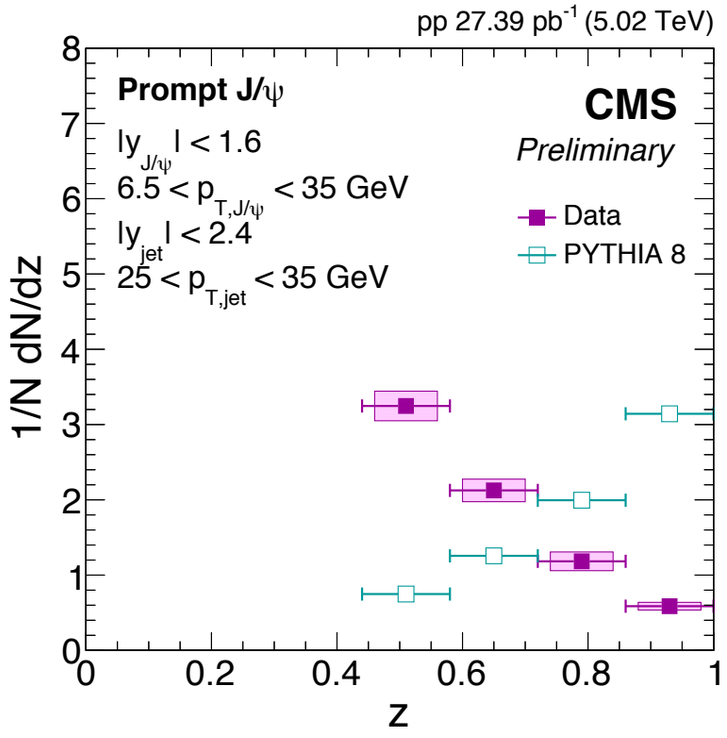
J/ψ suppression at high p_T driven by parton energy loss?

Production mechanism: J/ψ in jets

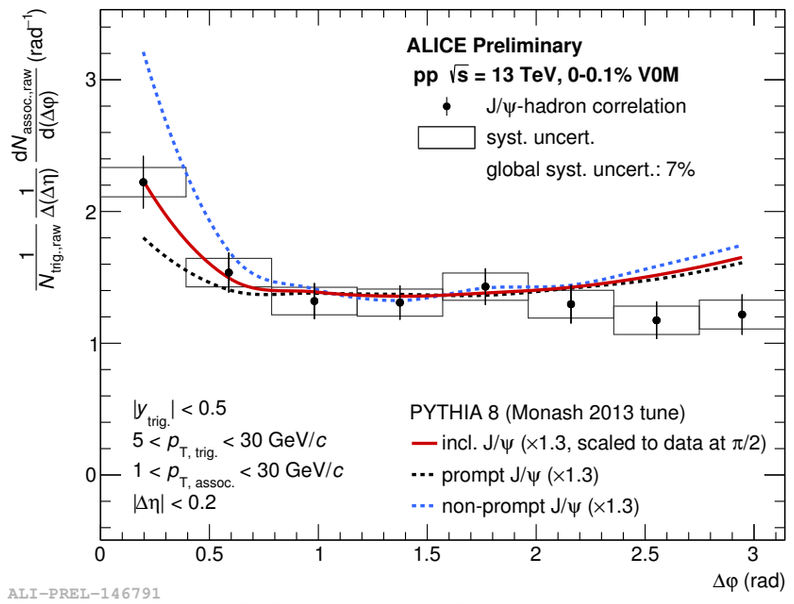
LHCb, PRL 118, 192001 (2017)



CMS-PAS-HIN-18-012



J/ψ-hadron correlations

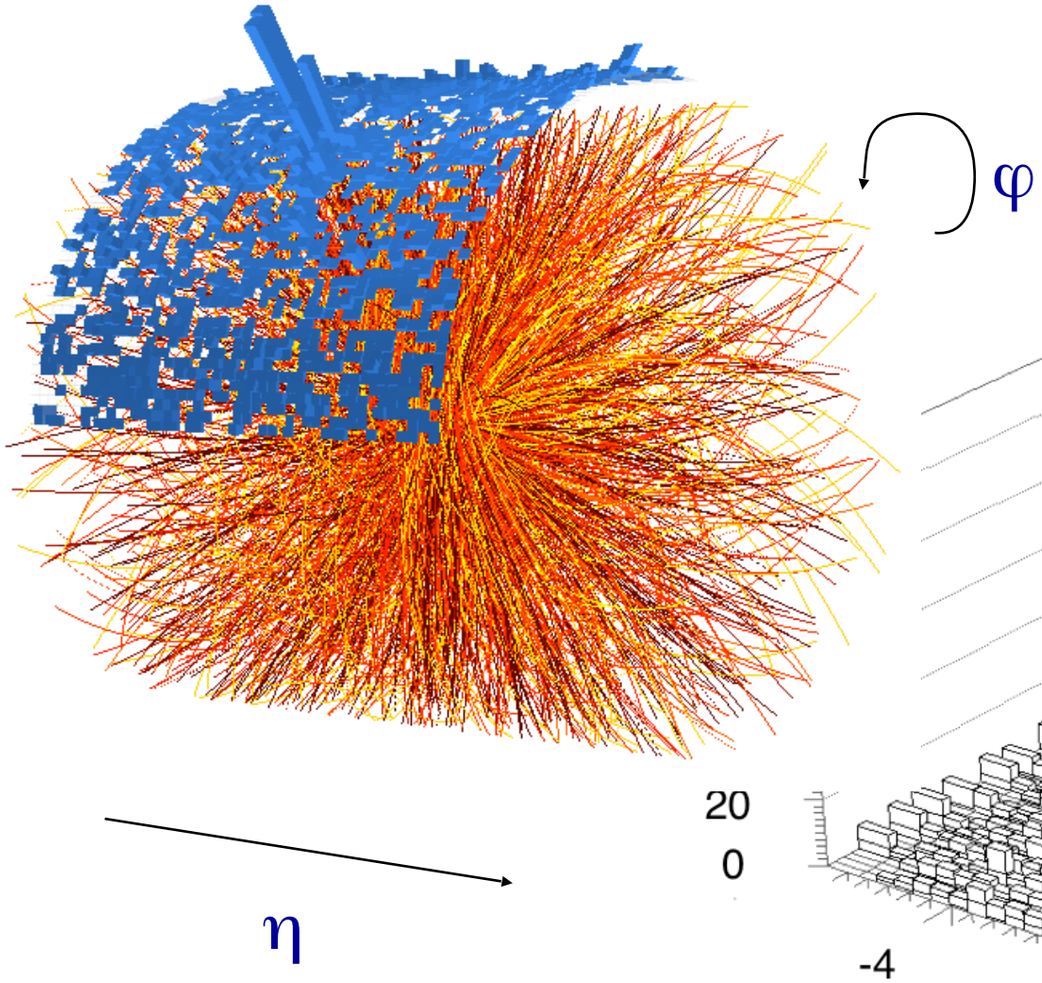


Near-side peak:
hadrons accompany the J/ψ

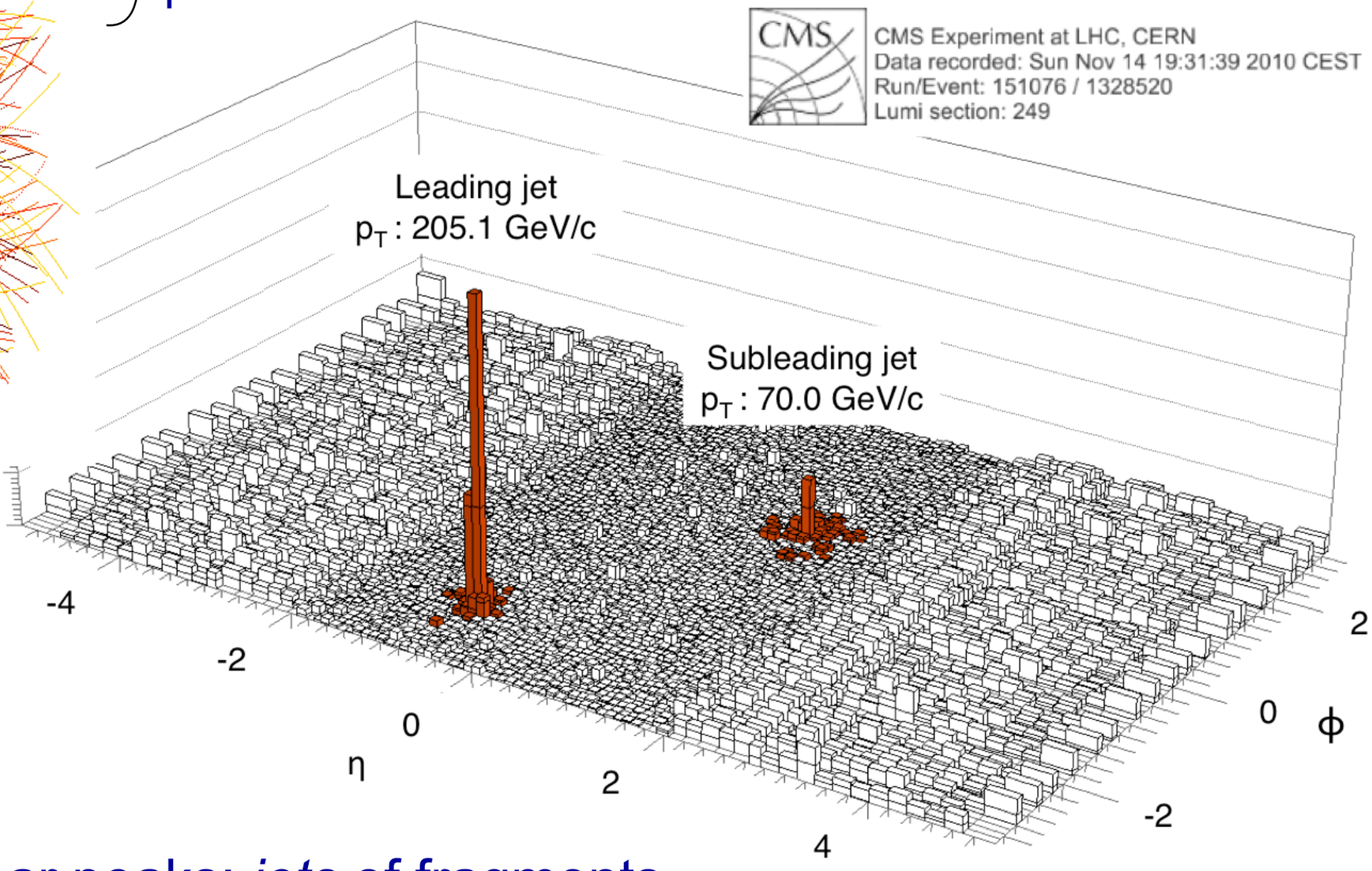
Initial expectation: color-singlet J/ψ could be produced without accompanying fragments
New insight: high-p_T J/ψ produced in jets

From single particles to jets

ALICE



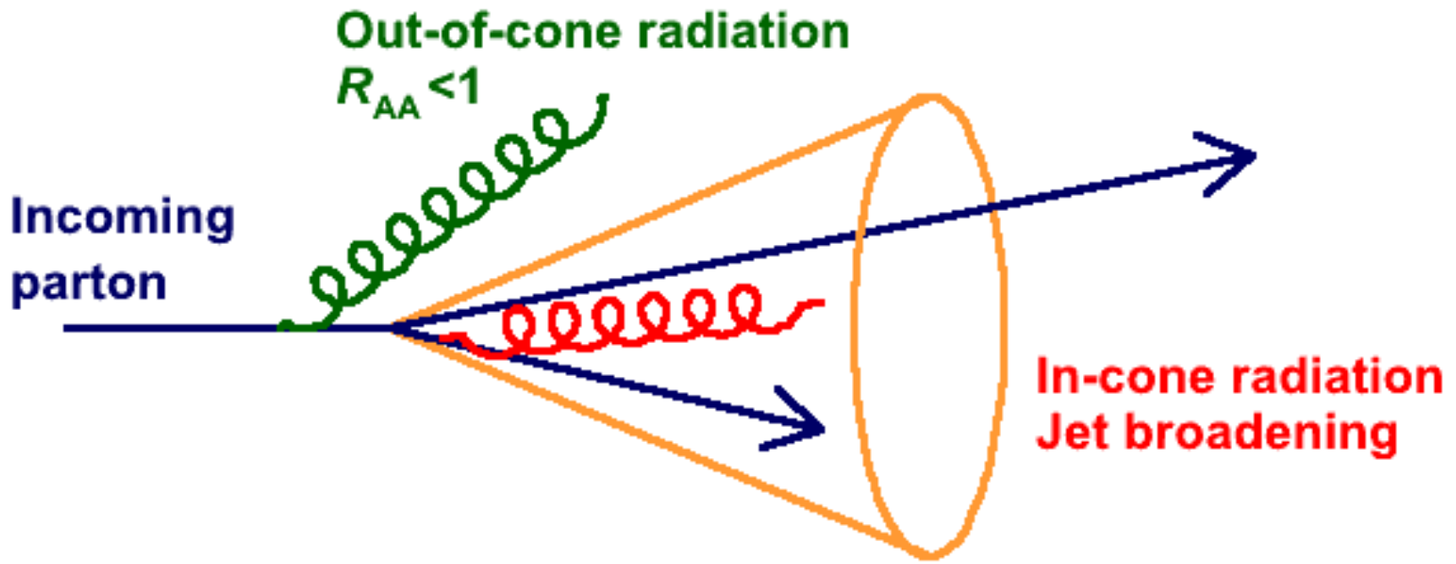
Transverse energy map of 1 event



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

Jets and parton energy loss

Motivation: understand parton energy loss by tracking the gluon radiation

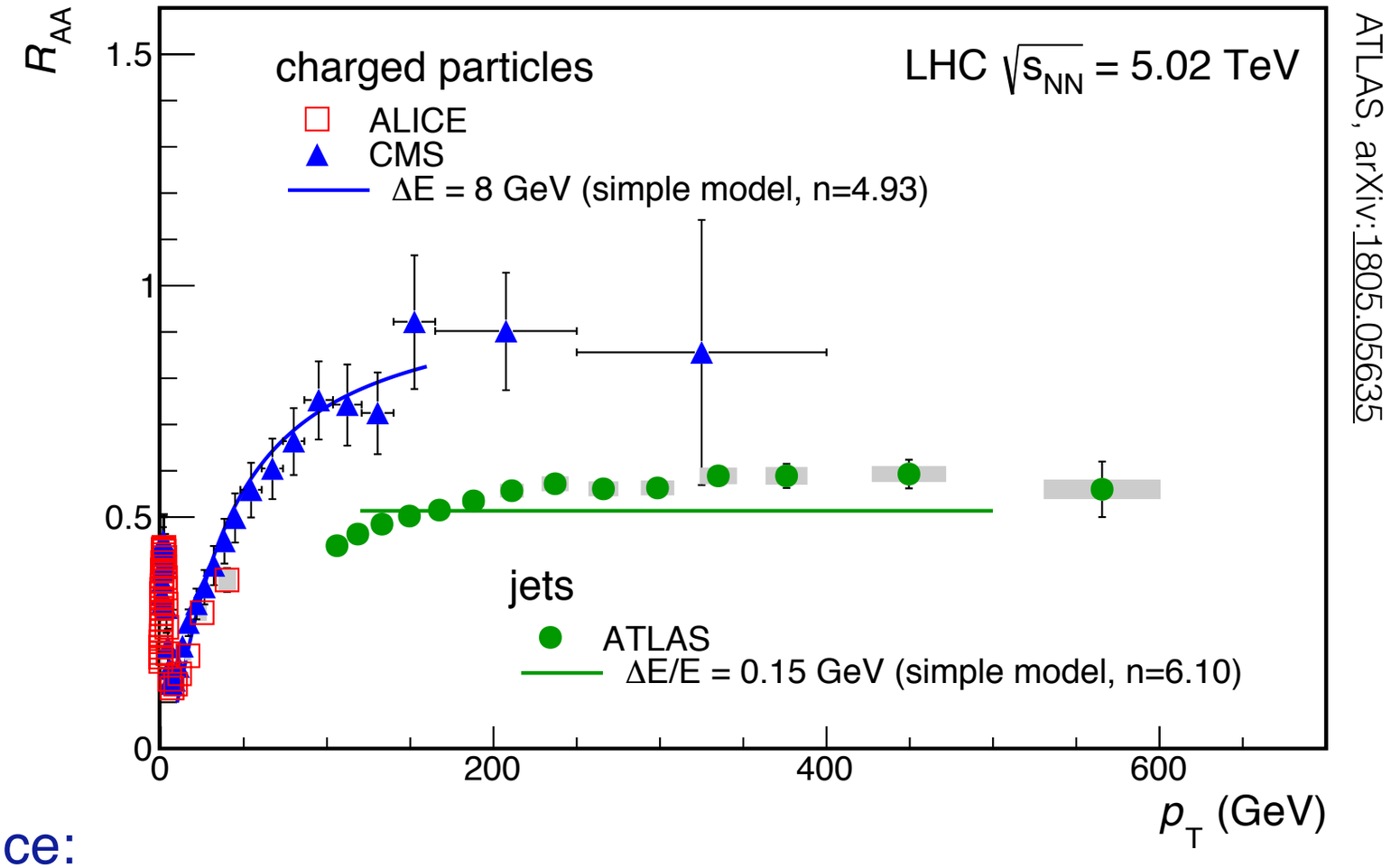


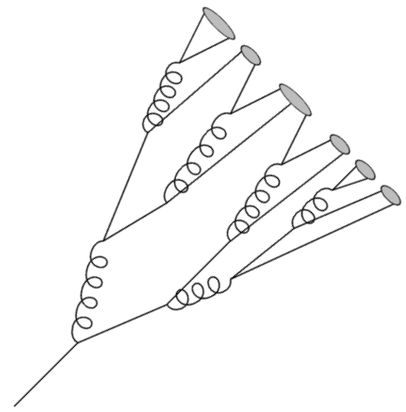
Qualitatively two scenarios:

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

More in: talk T Chujo

High-p_T hadrons vs jets





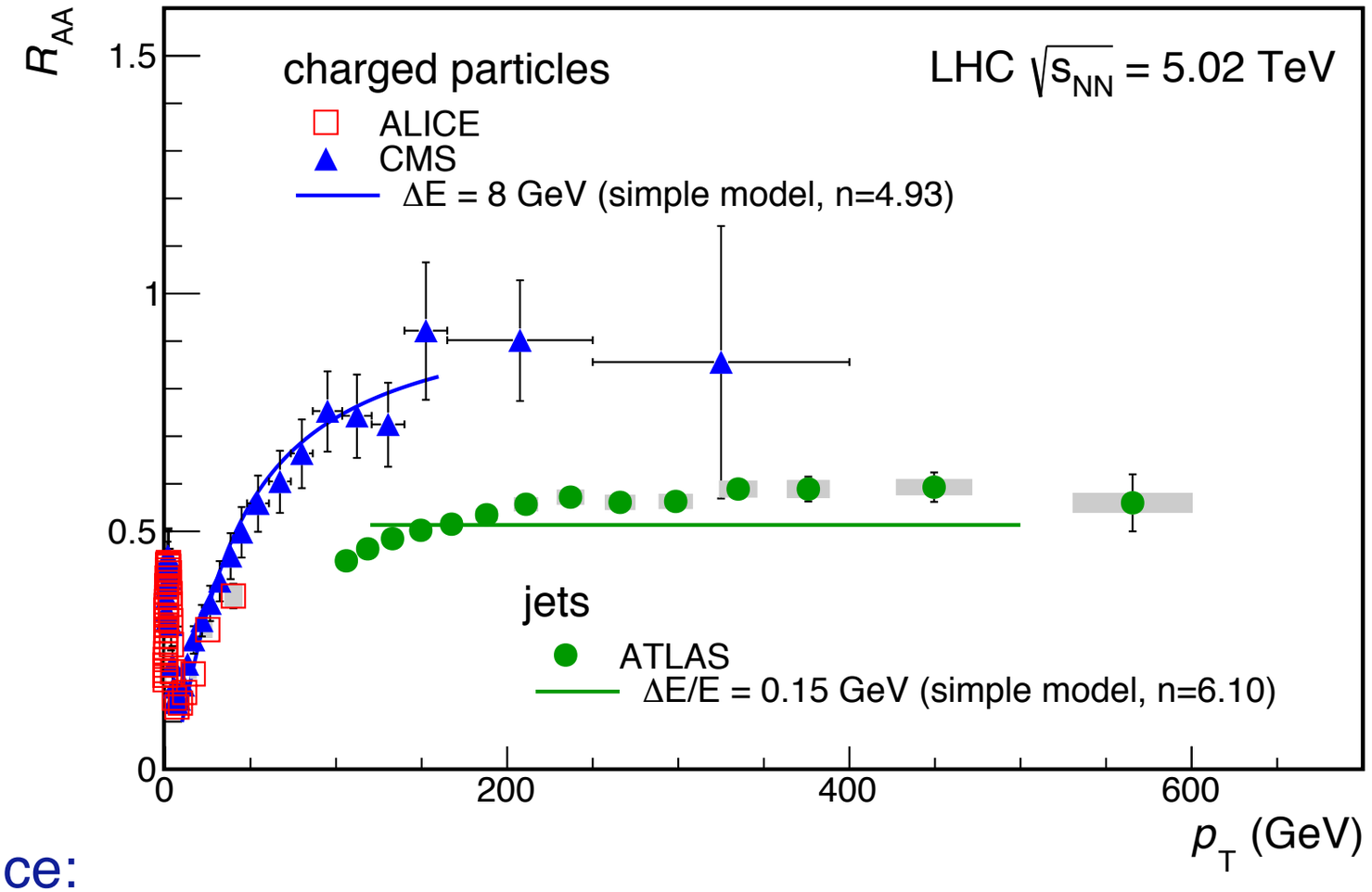
p_T-dependence:

Single particles: consistent with constant (or log E) dependence

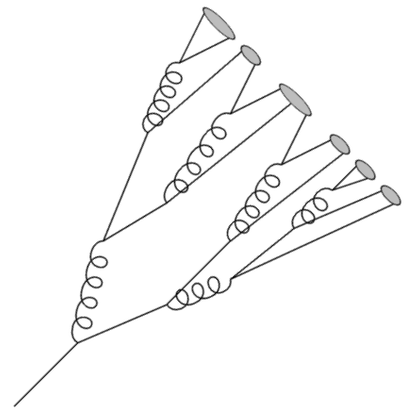
Jets: $R_{AA} < 1$ out to high p_T

Jets: suggest increase of ΔE vs E

High-p_T hadrons vs jets



ATLAS, arXiv:1805.05635



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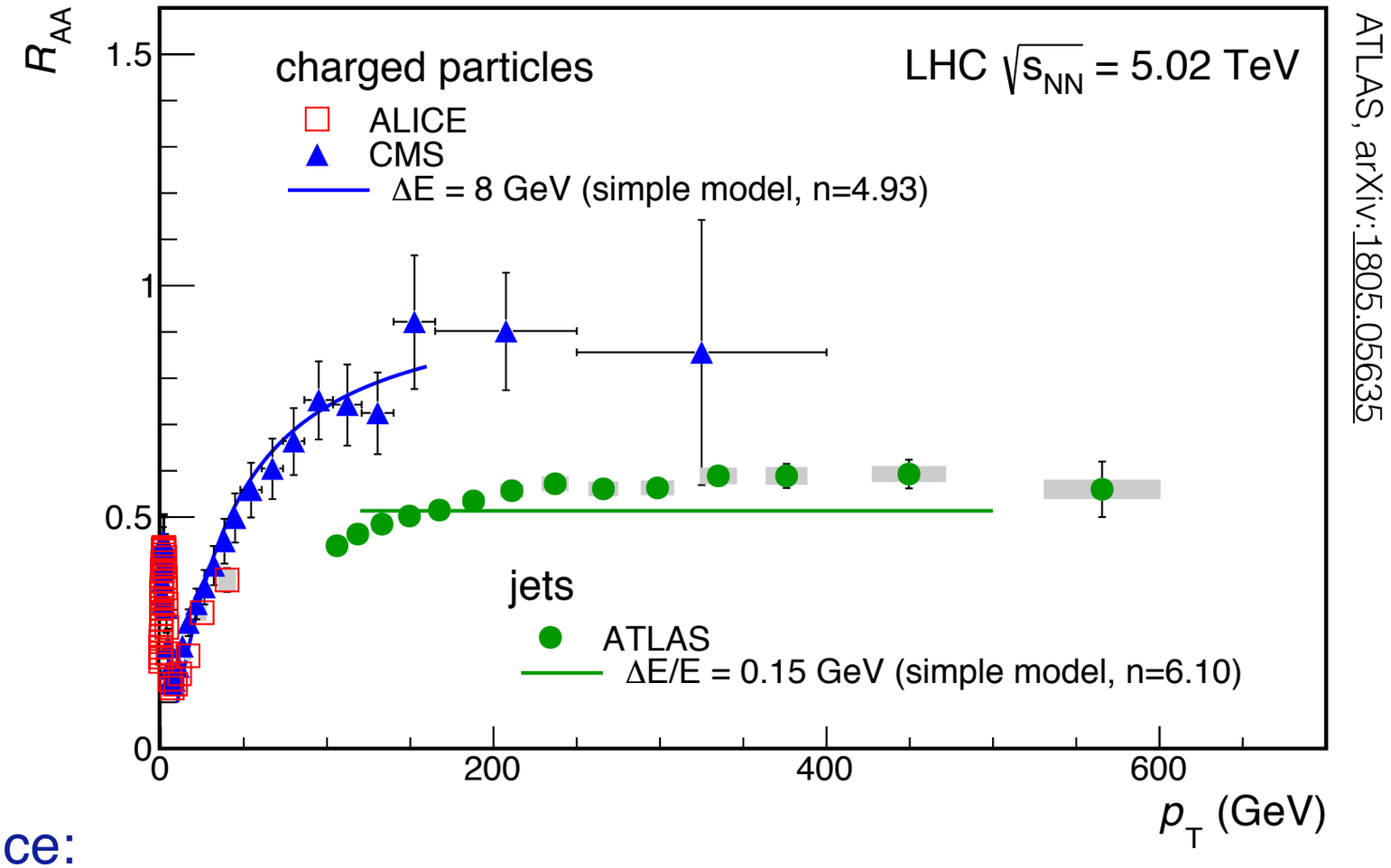
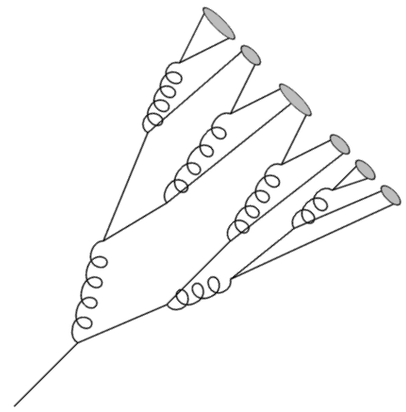
Tentative interpretation: in jets, multiple partons lose energy; more partons in high-E jets ⇒ more E-loss

High-p_T hadrons vs jets





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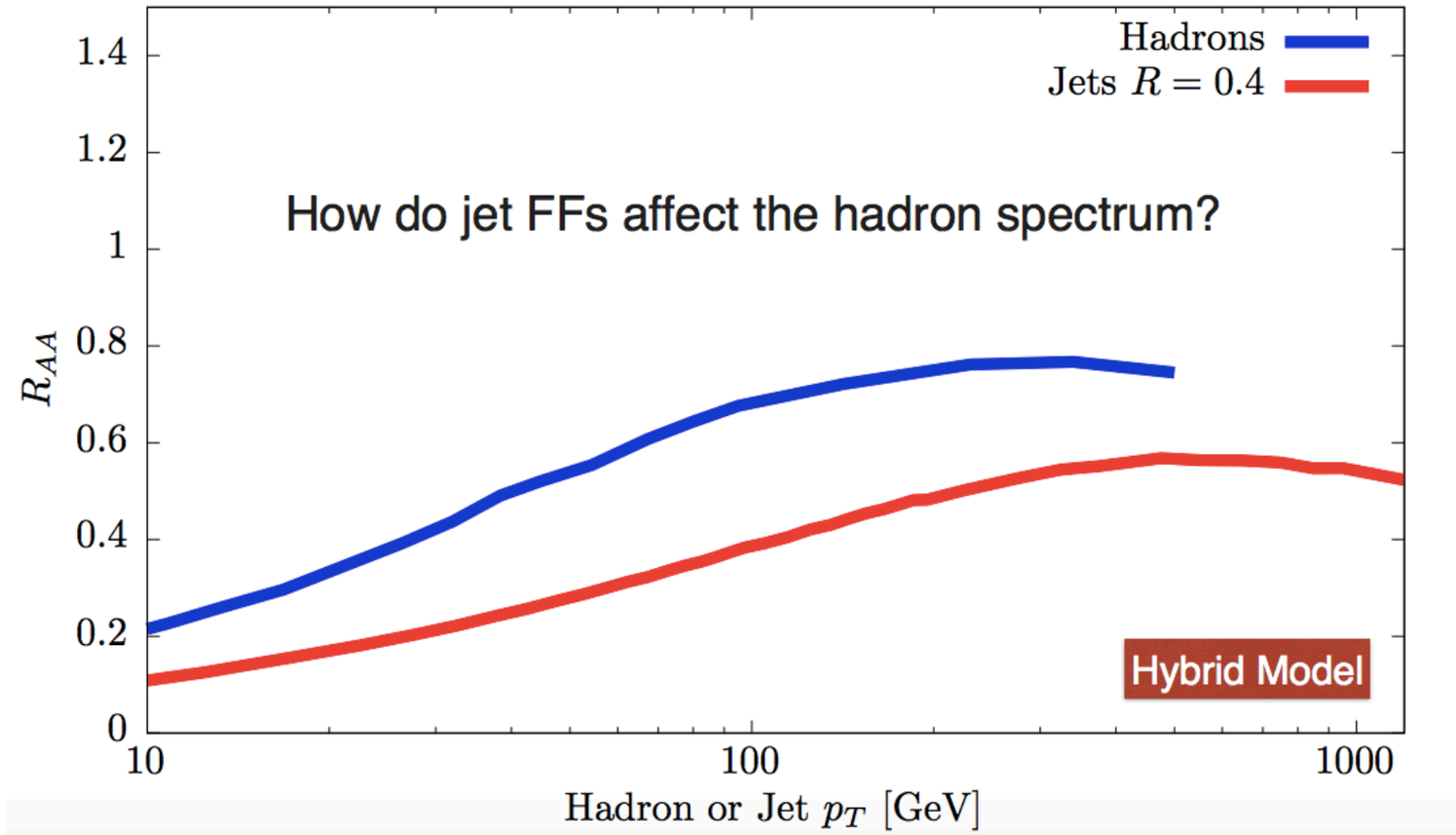
First glimpse of jets as scale-dependent probes

Opens up a field of study: p_T-dependence of jet modifications

Relating jets and hadrons: fragment distributions

Talk: D Pablos

jet R_{AA} < hadron R_{AA} (at fixed p_T)



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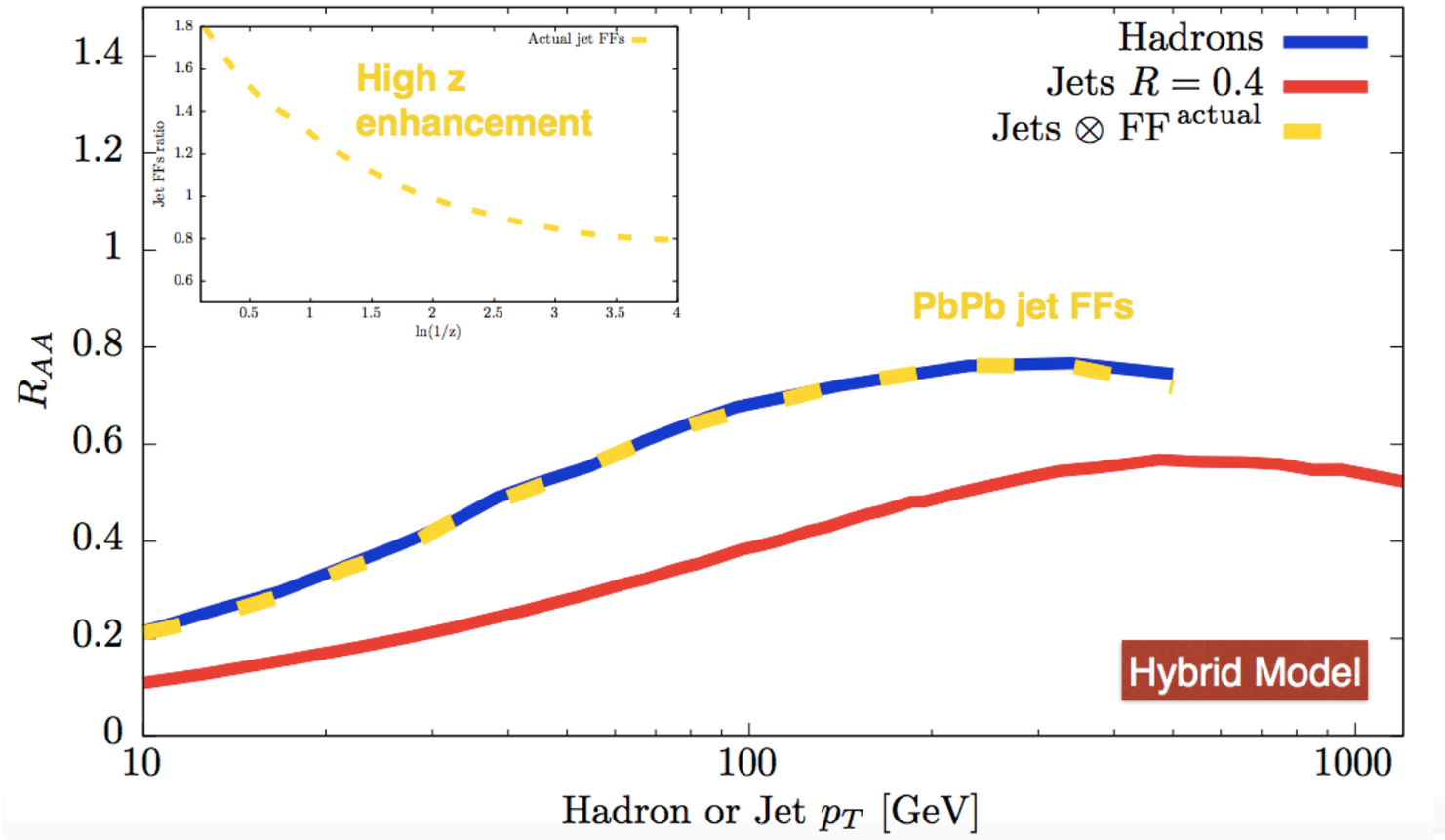
'fragmentation functions'



Note: While not 'fragmentation functions'
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fragment distributions also evolve slowly with jet pt

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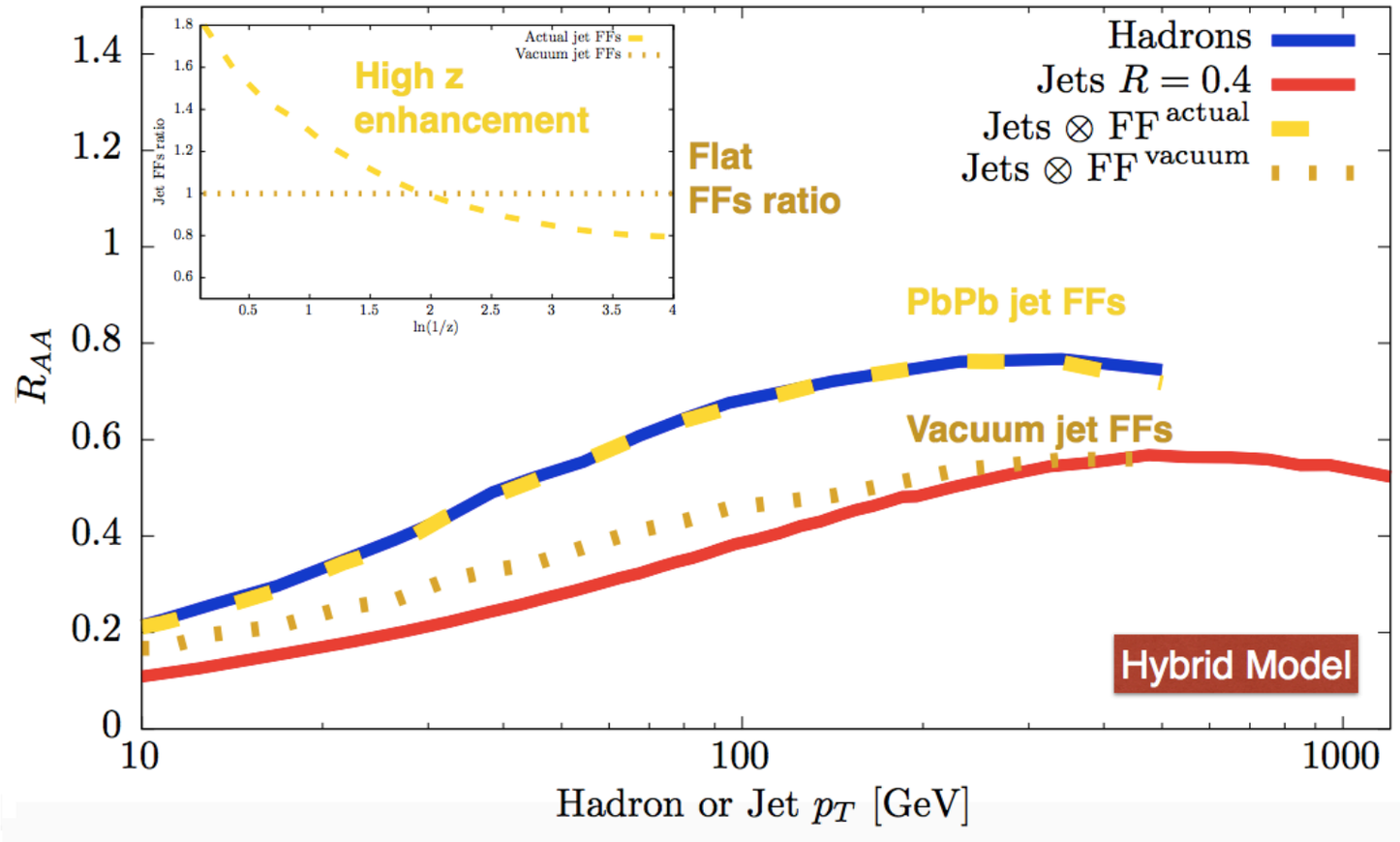

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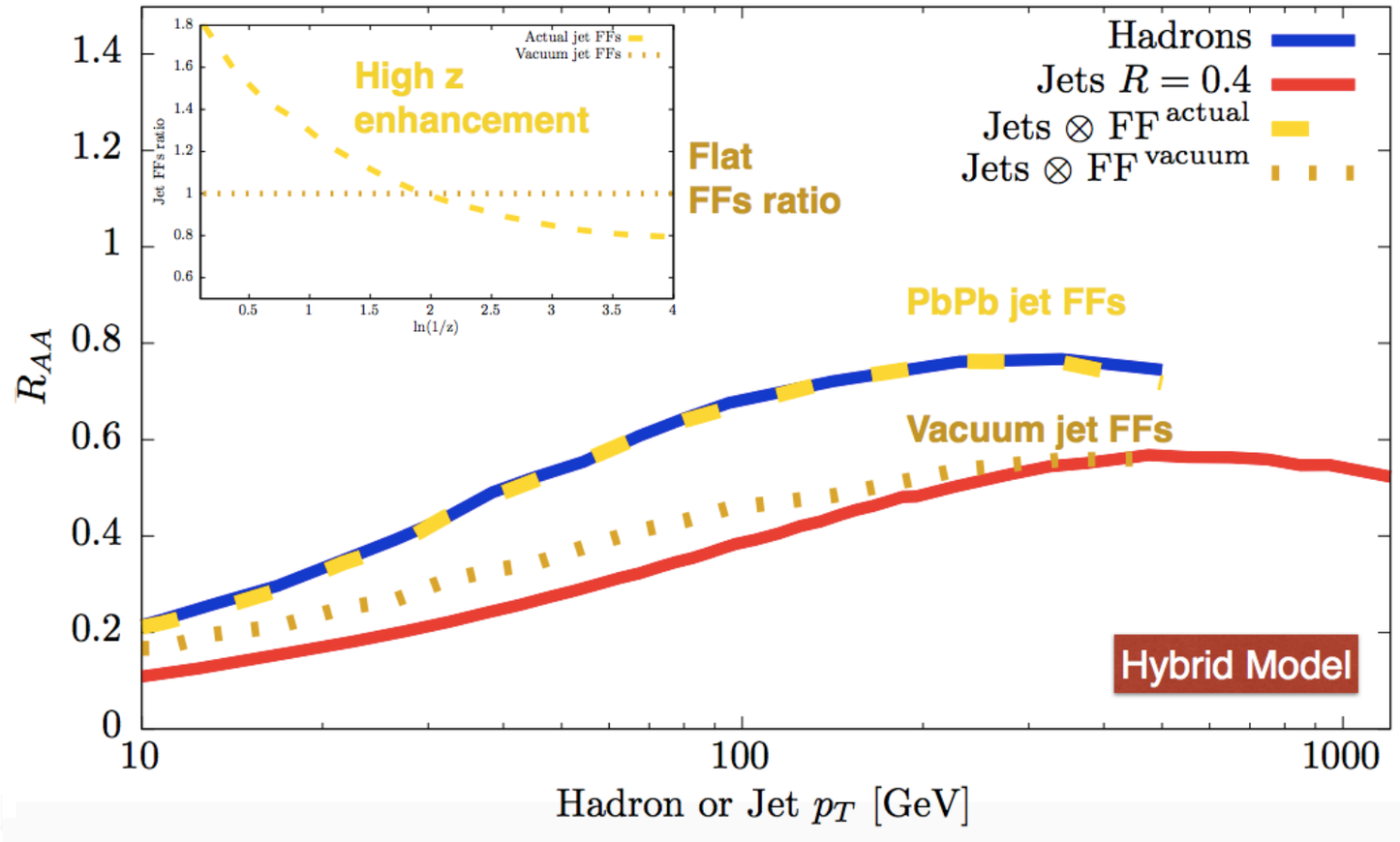

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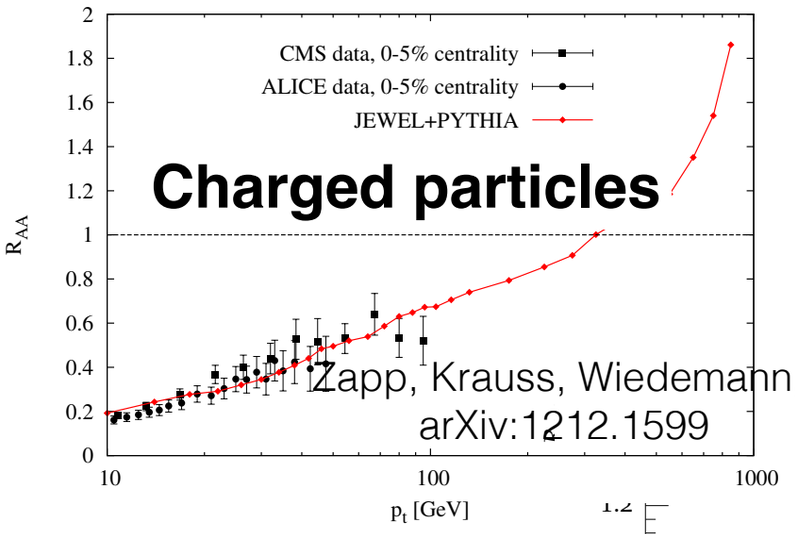
Use this to explore scale dependence of energy loss!

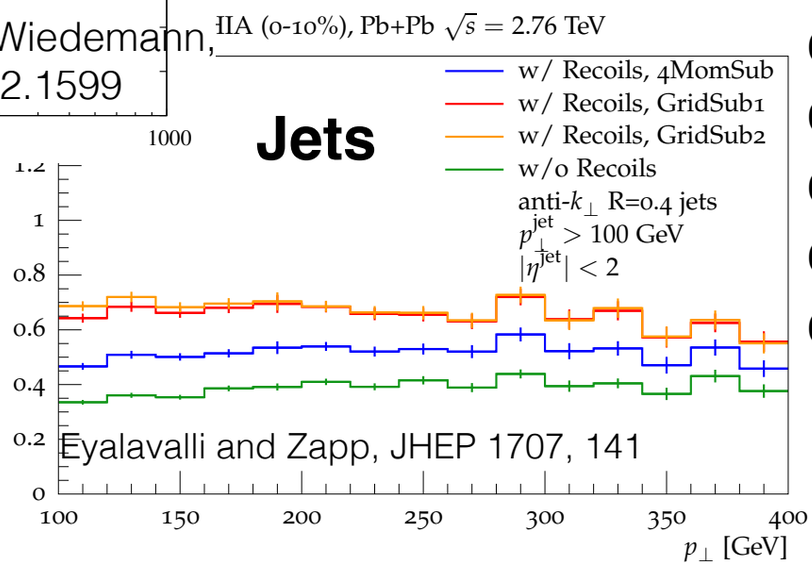
Modelling p_T dependence of jet quenching

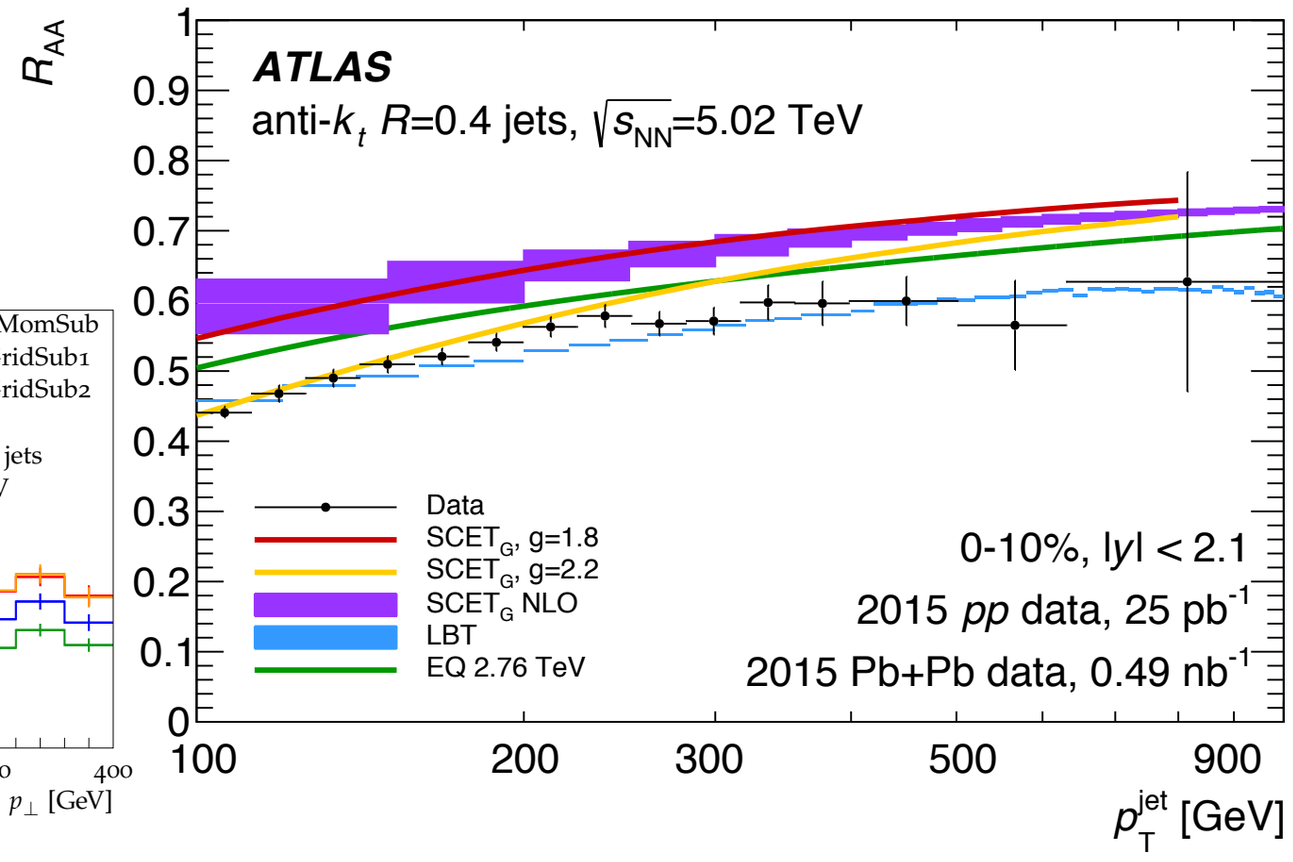
(What) does the detailed p_T dependence of jet R_{AA} tell us about energy loss?

SCET, LBT



JEWEL





Do we have enough dynamic range to answer questions about coherence, broadening, energy dependence of qhat?

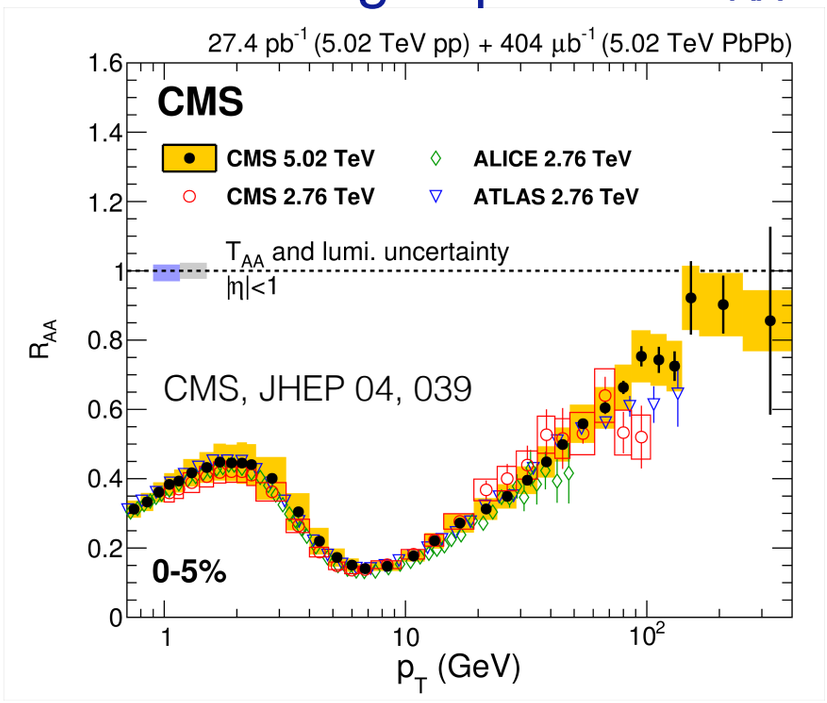
Summary: using Hard Probes to study the QGP

- Light (unidentified hadrons)
  - p_T dependence of R_{AA} understood
  - Transport coefficient qhat qualitatively agree with expectated values
  - Understanding of path length dependence can be improved
- Heavy flavour
  - Models use collisional + radiative loss: describe R_{AA} and v_2, v_3
  - Medium parameters agree with light flavour results
  - J/ψ production + interaction with medium not well understood?
  - Beauty tests dead-cone effect/angle dependence of radiation
- Jets
  - Different p_T dependence: energy loss increases with jet energy?

Thank you for your attention!

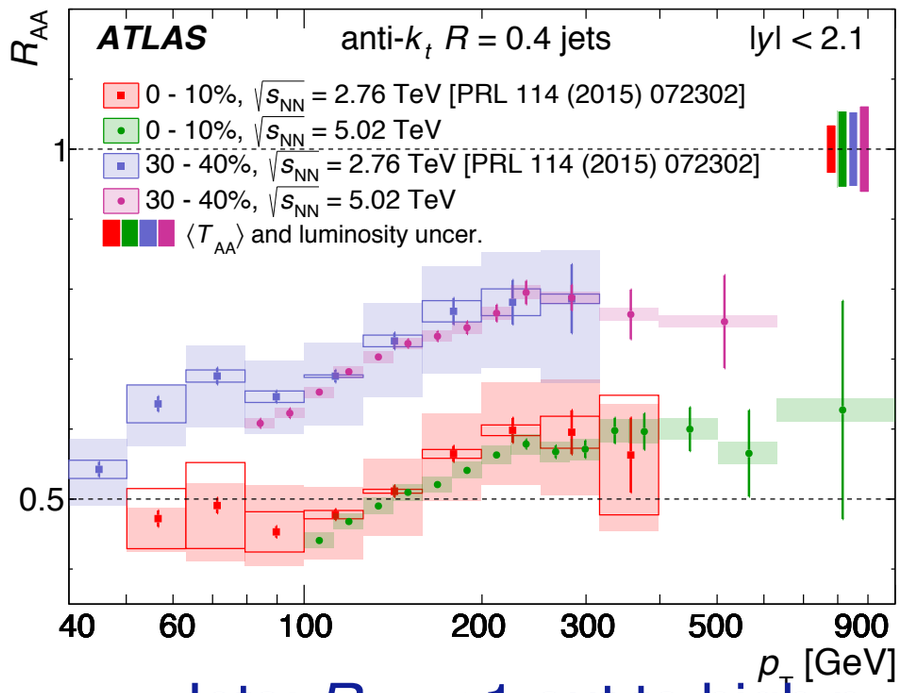
High-p_T jets vs hadrons

Charged particle R_{AA}



Jet R_{AA}

ATLAS, arXiv:1805.05635



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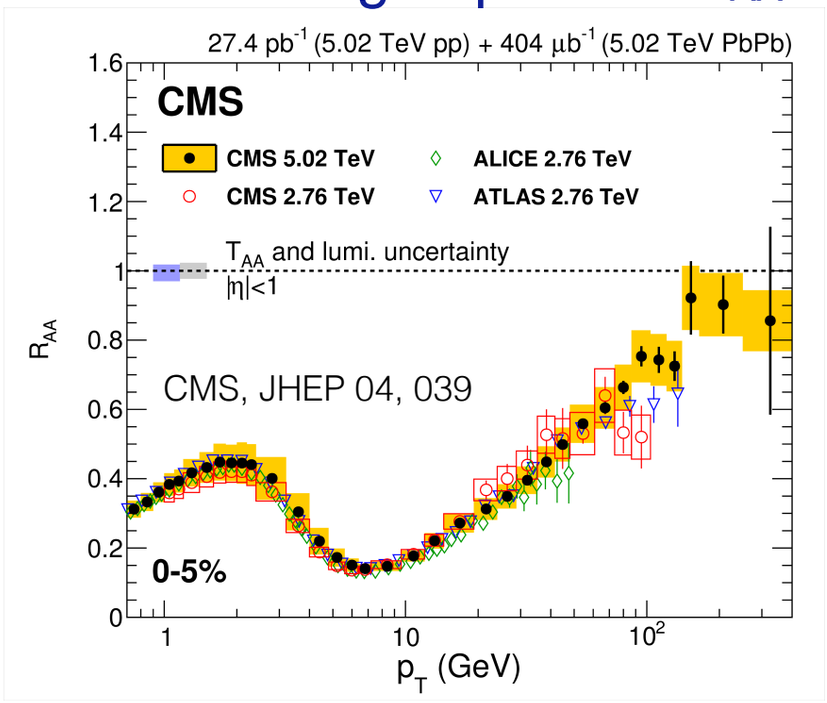

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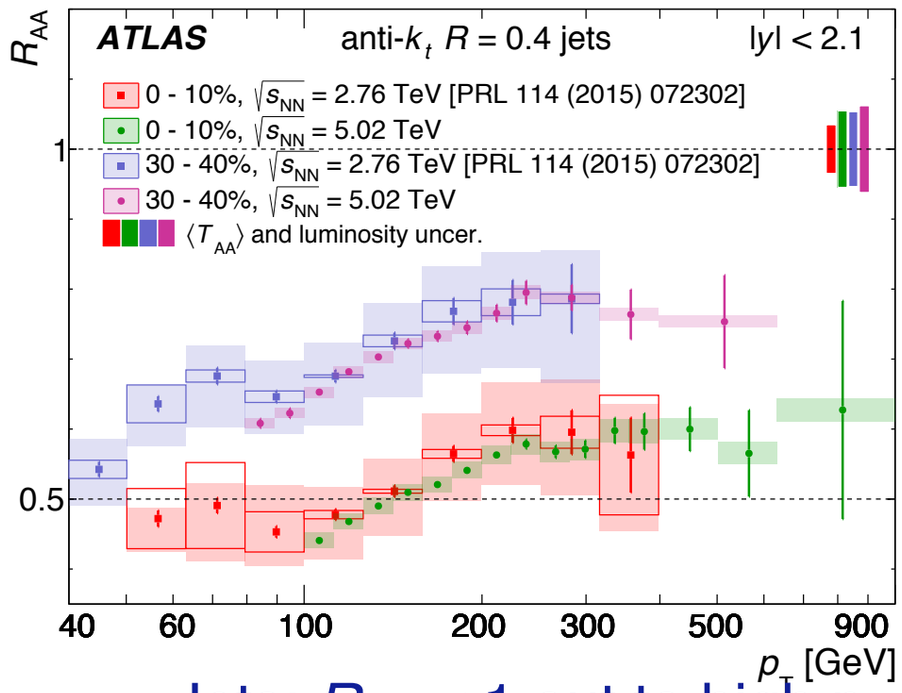

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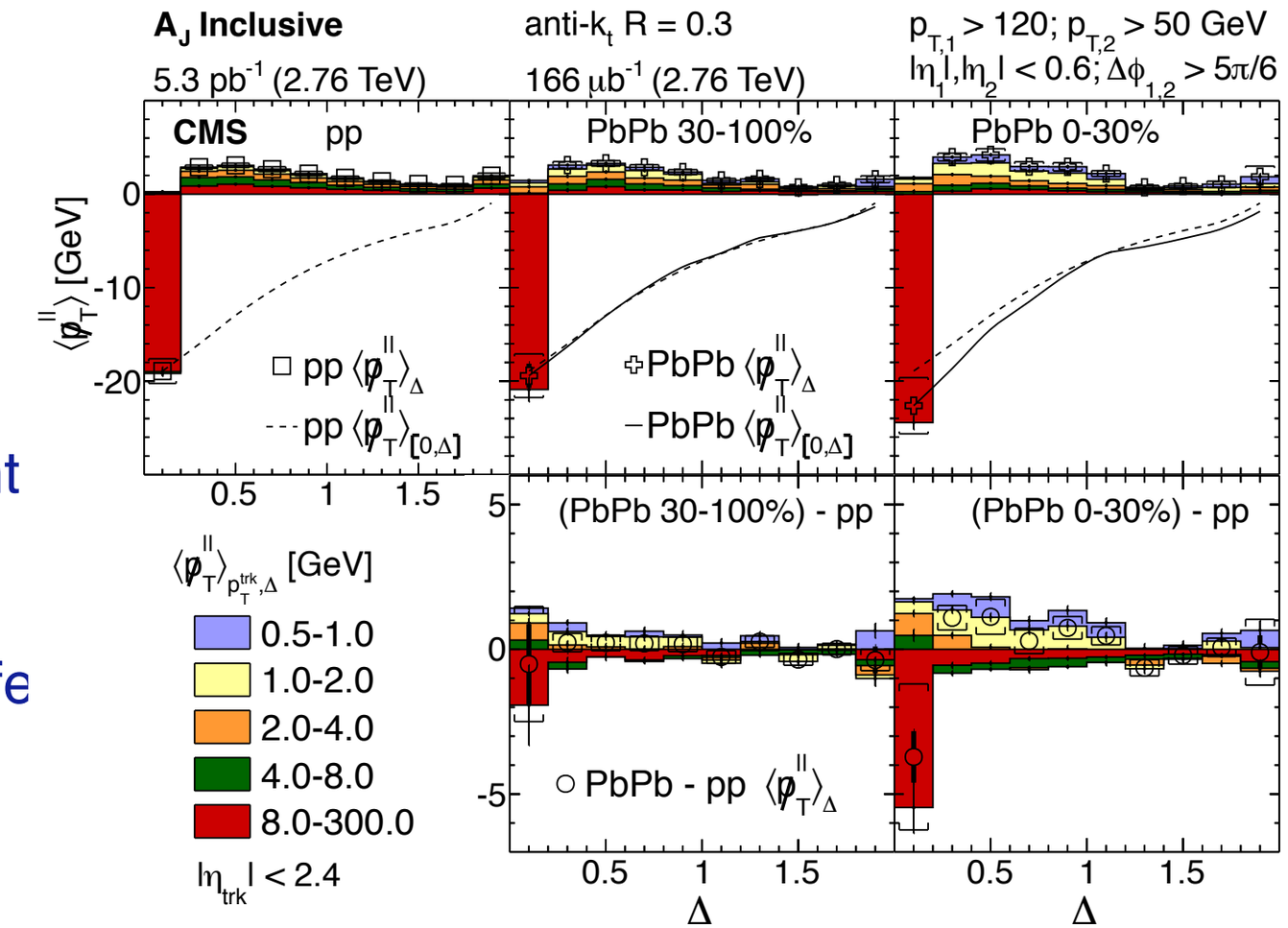
Where does the lost energy go ?

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 expectations from pQCD?
- Does it require ‘thermalisation’?
- Can we learn more about coherence effe



CMS, JHEP 01 (2016) 006

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

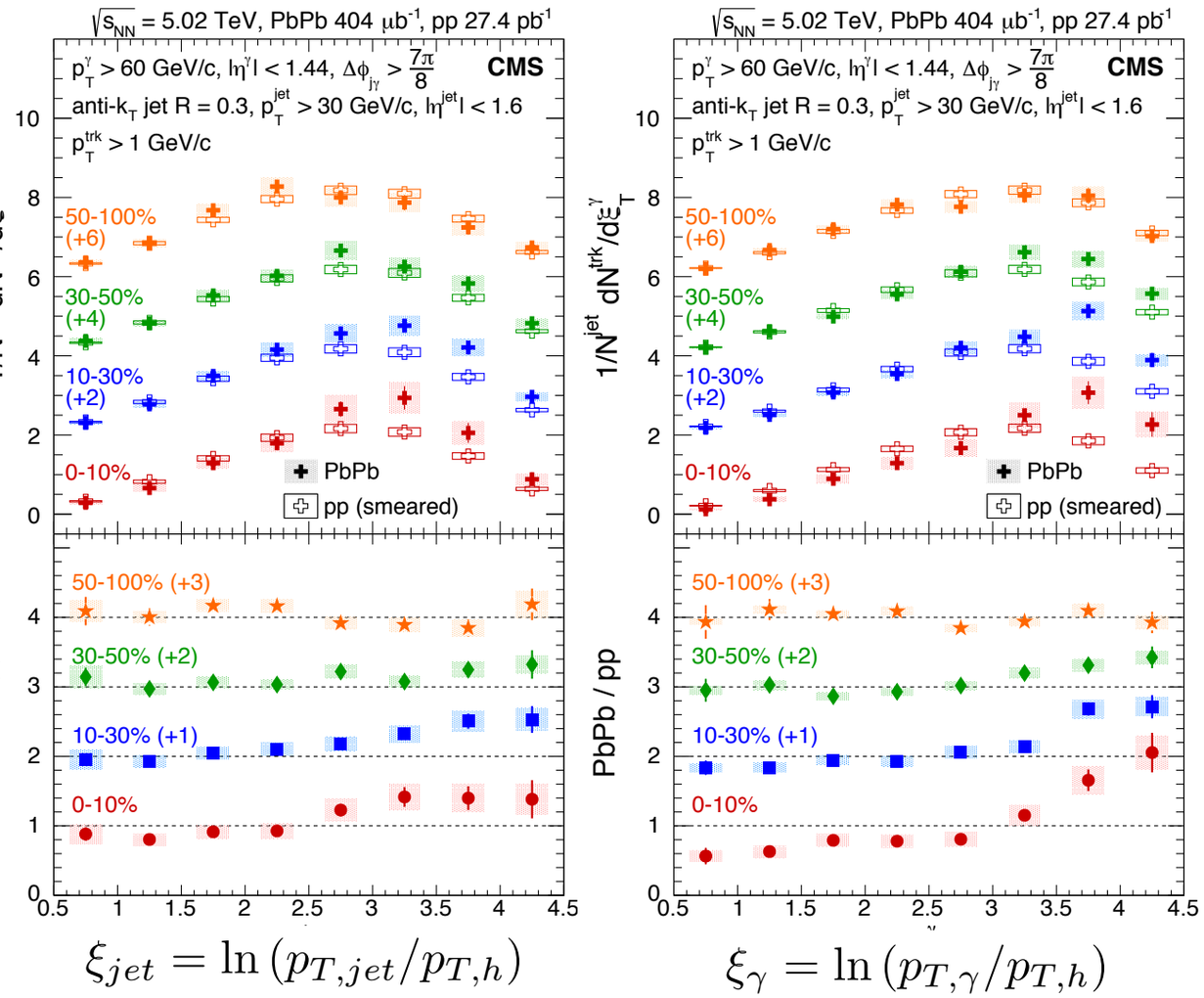
Requires careful modeling of soft physics — not easy and *exploration of model uncertainties*

Recoil fragment distributions

ATLAS-CONF-2017-074

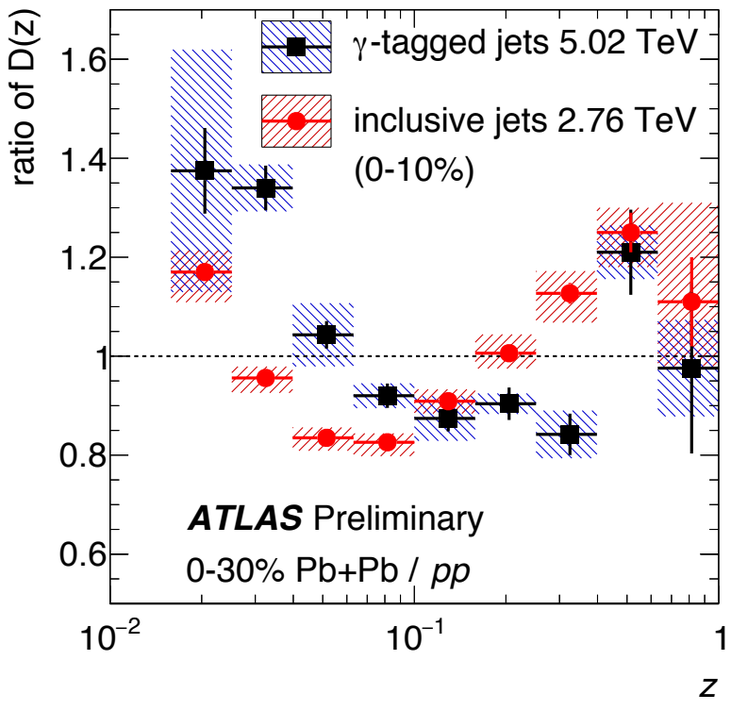
CMS, arXiv:1801.04895

Recoil fragment distributions $p_{T,\gamma}$ >60 GeV



ξ=0.7 ~ z = 0.5

Recoil fragment distributions: γ-jet and di-jet



γ-jet: suppression at high z

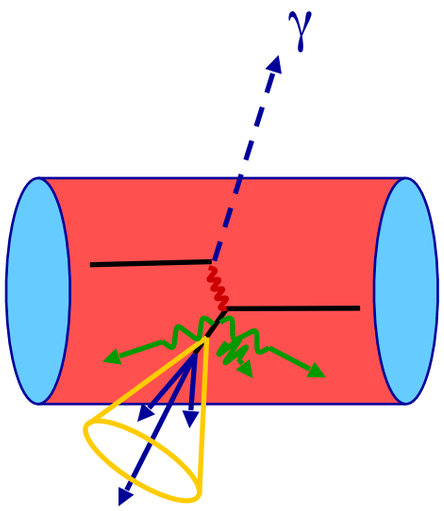
di-jet: enhancement at large z

Different bias/selection

quark vs gluon jets

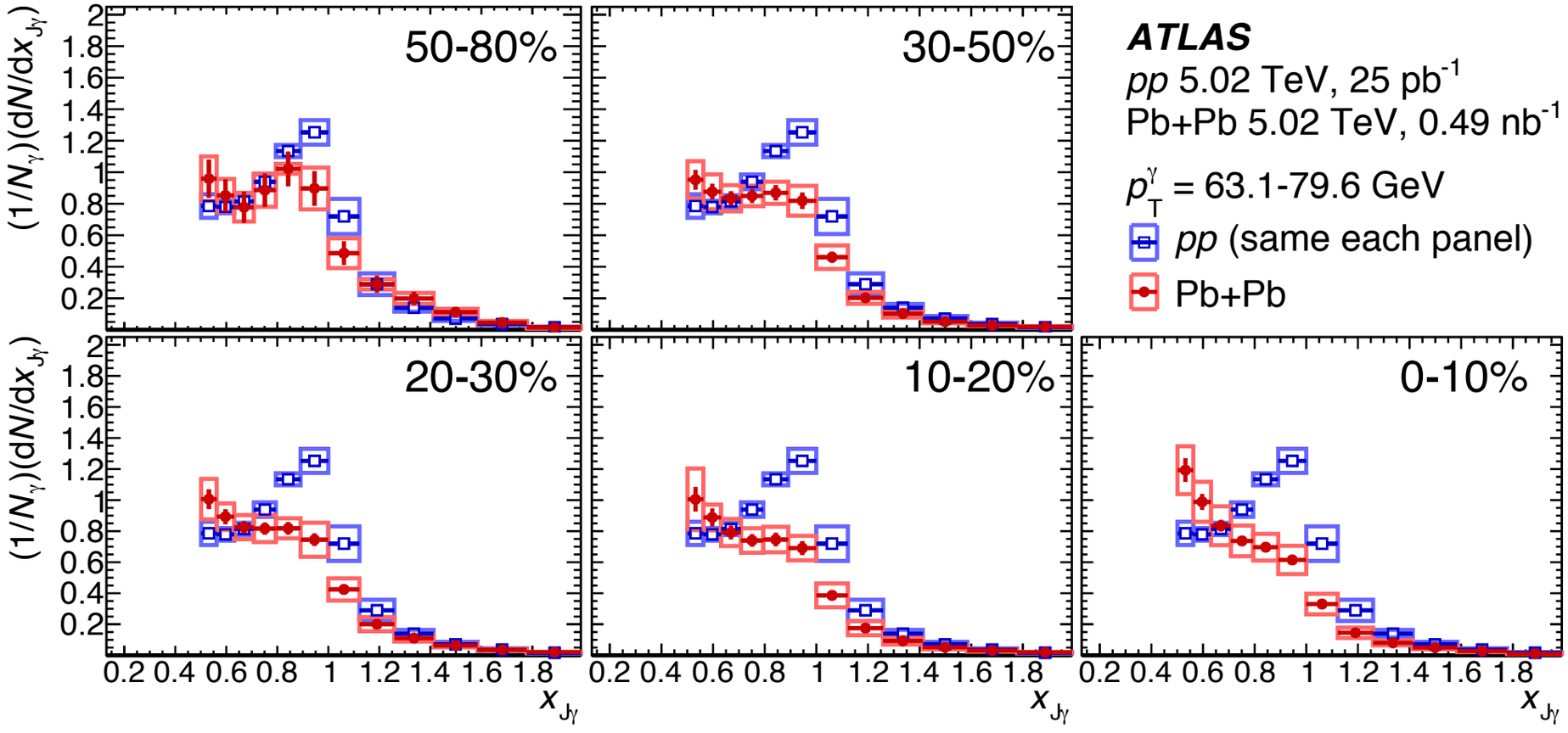
Enhancement of soft fragments; reduction of hard fragments

Gamma-jet momentum balance



Photon does not lose energy
Clean selection of initial p_T

Centrality dependence

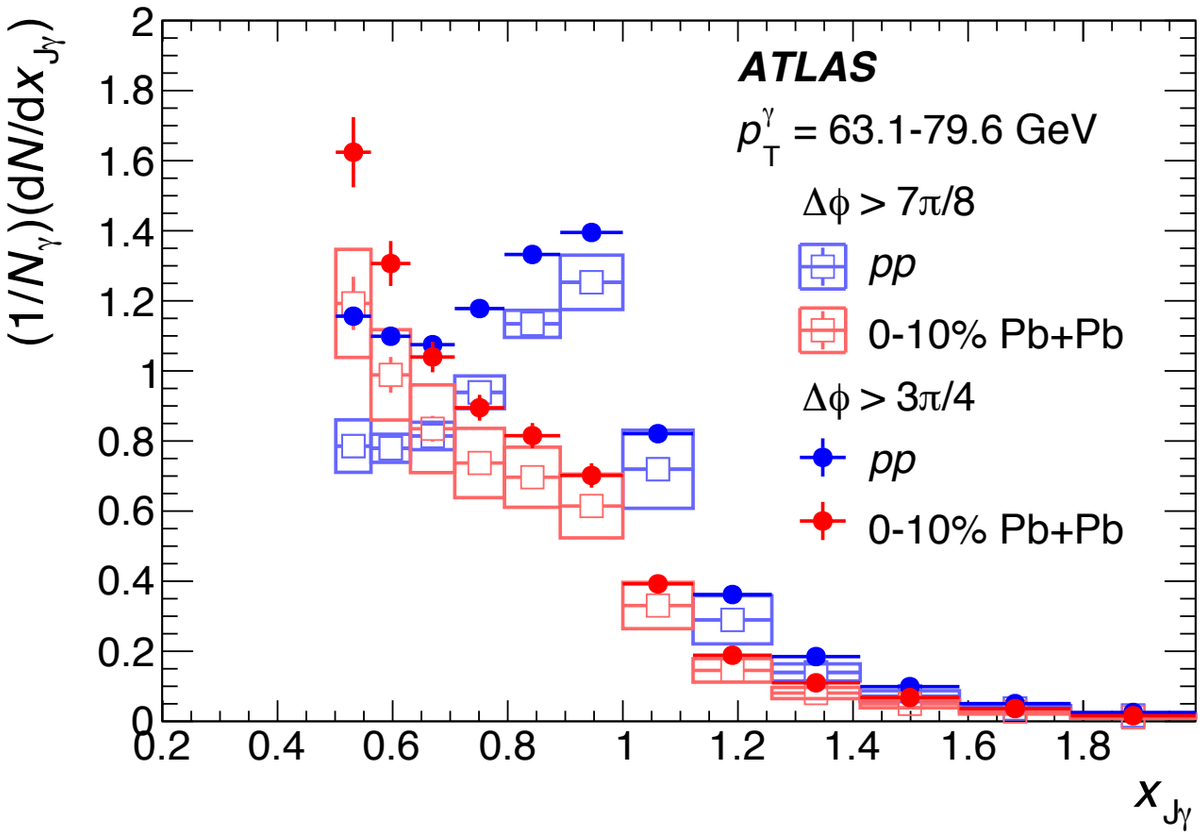


ATLAS, Phys.Lett. B789 (2019) 167-190

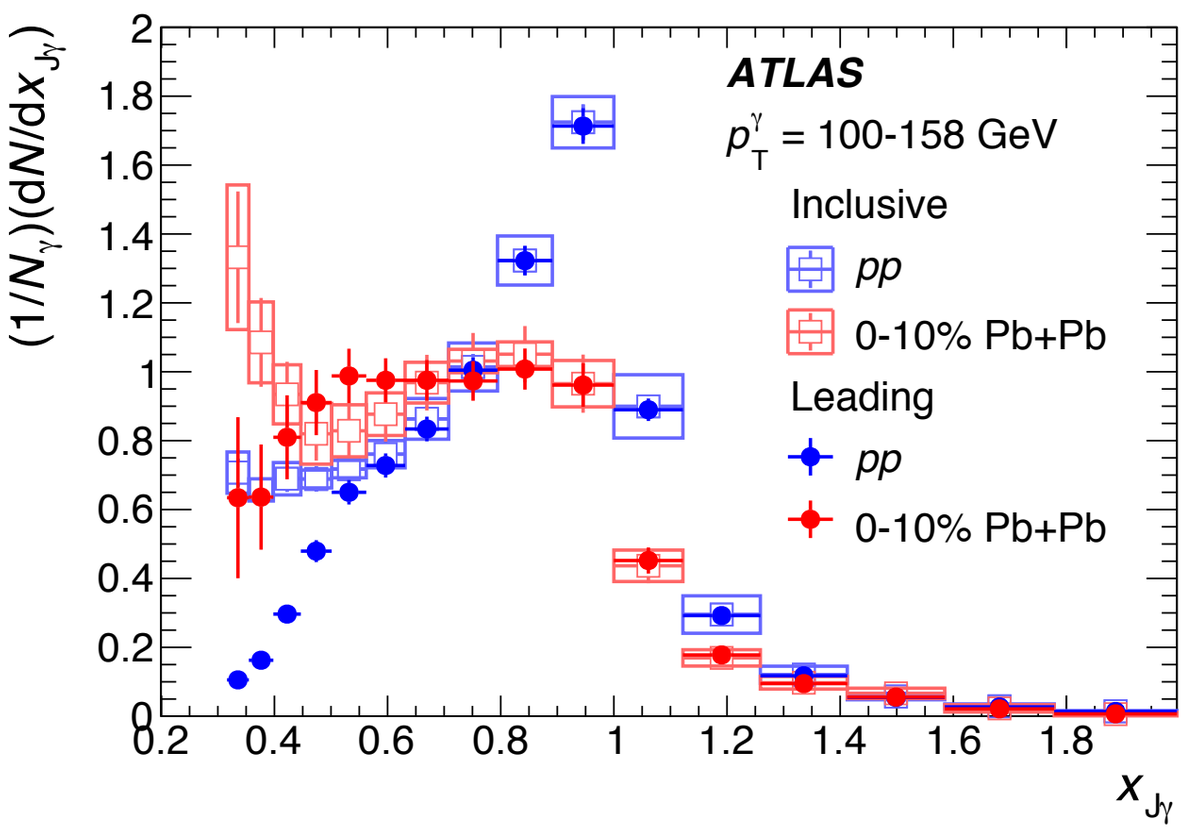
Increased asymmetry for PbPb: recoil jet loses energy

Gamma-jet momentum balance: inclusive vs leading

60 GeV trigger photon



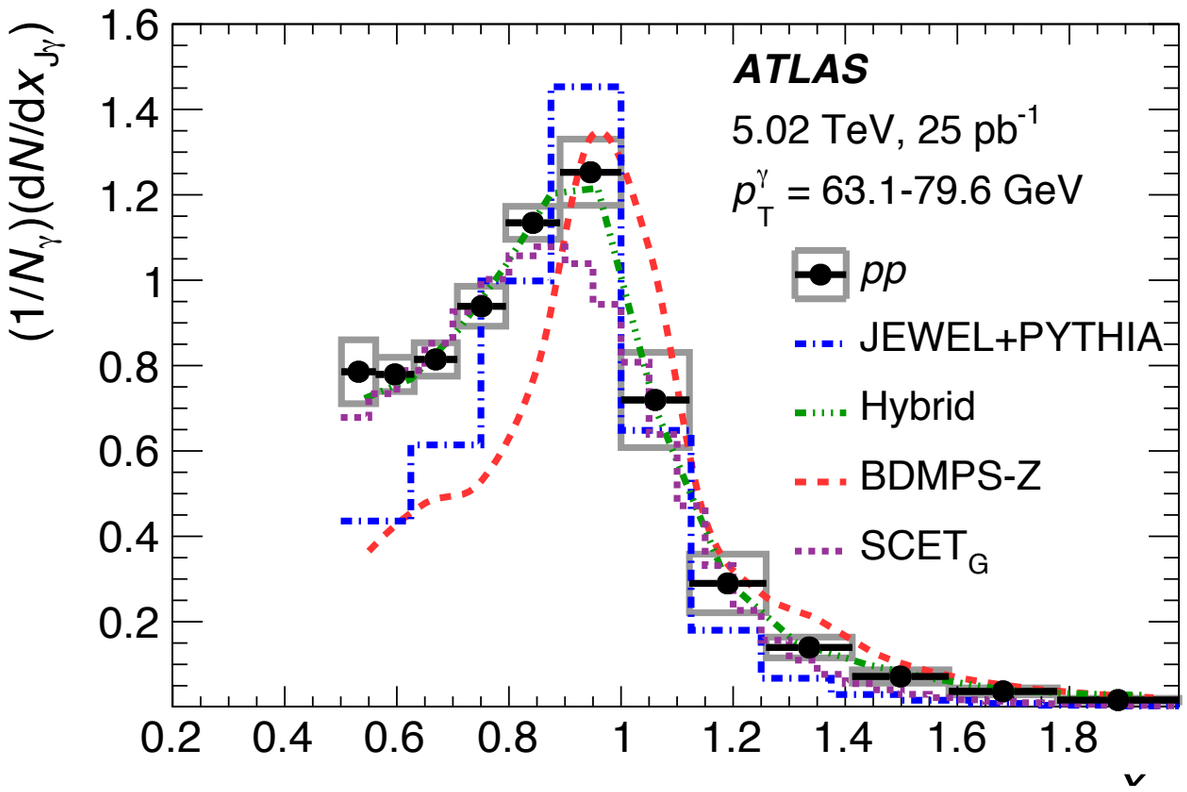
100 GeV trigger photon

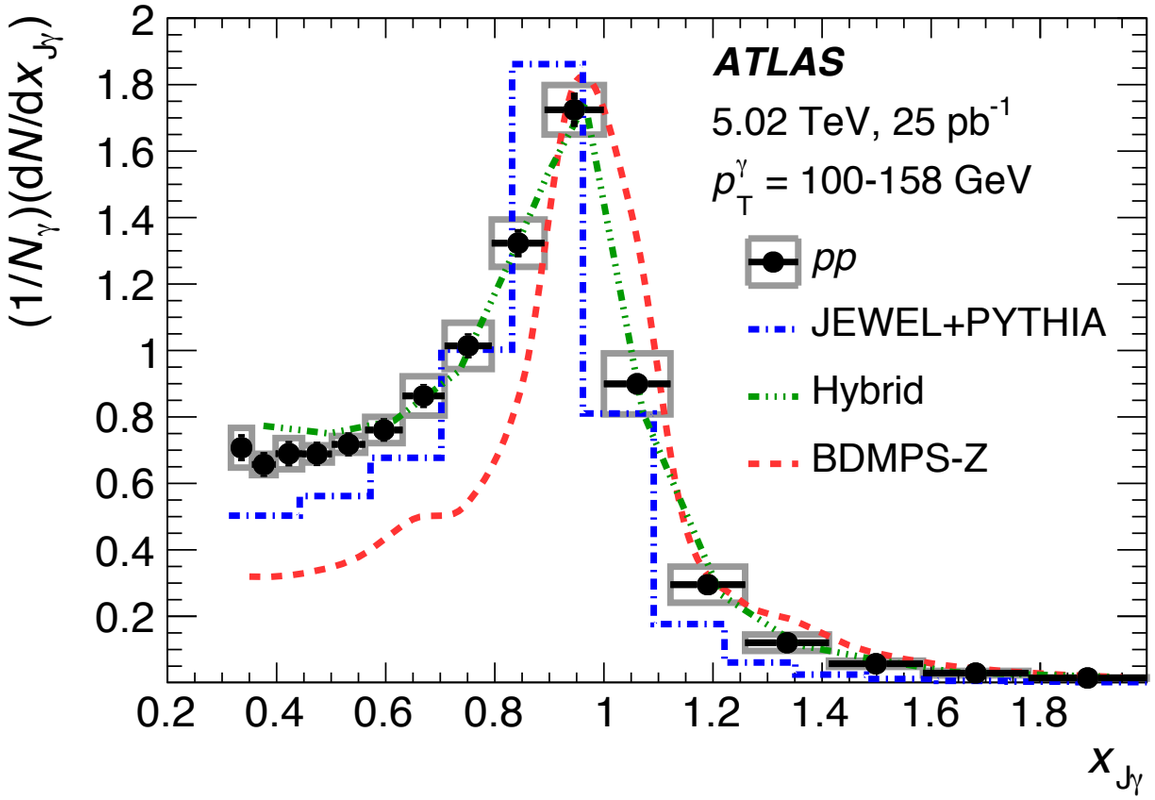


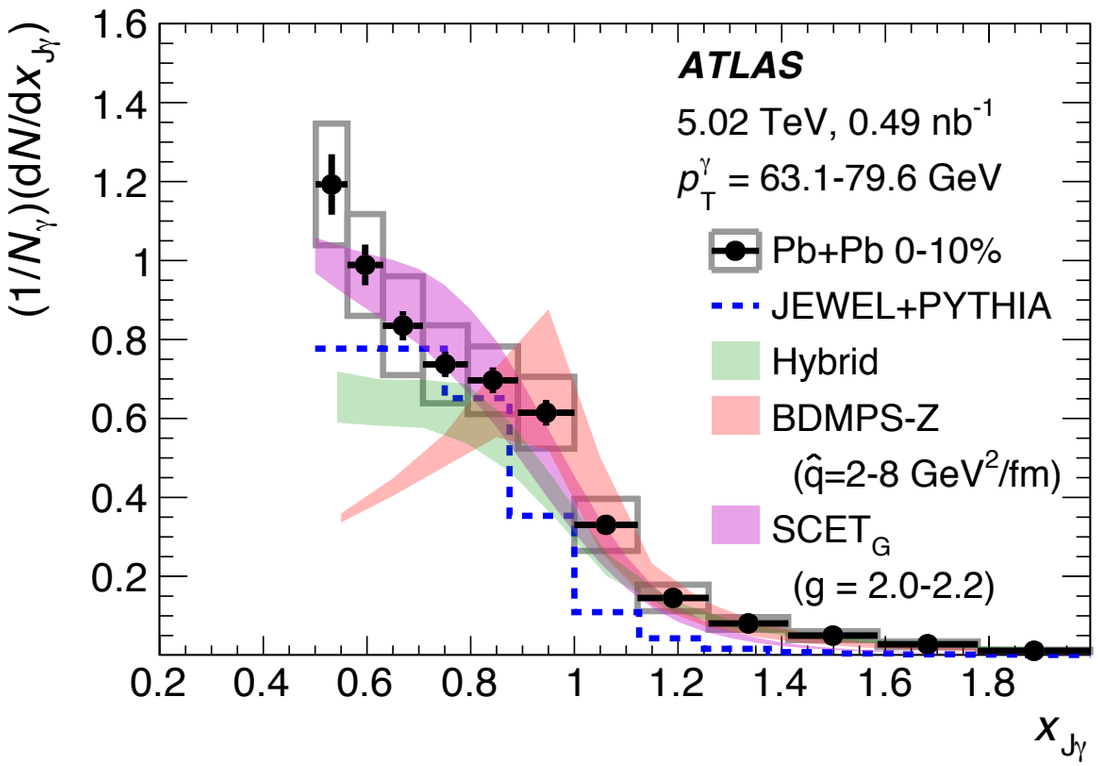
Peak at low x_{Jg} from additional jets

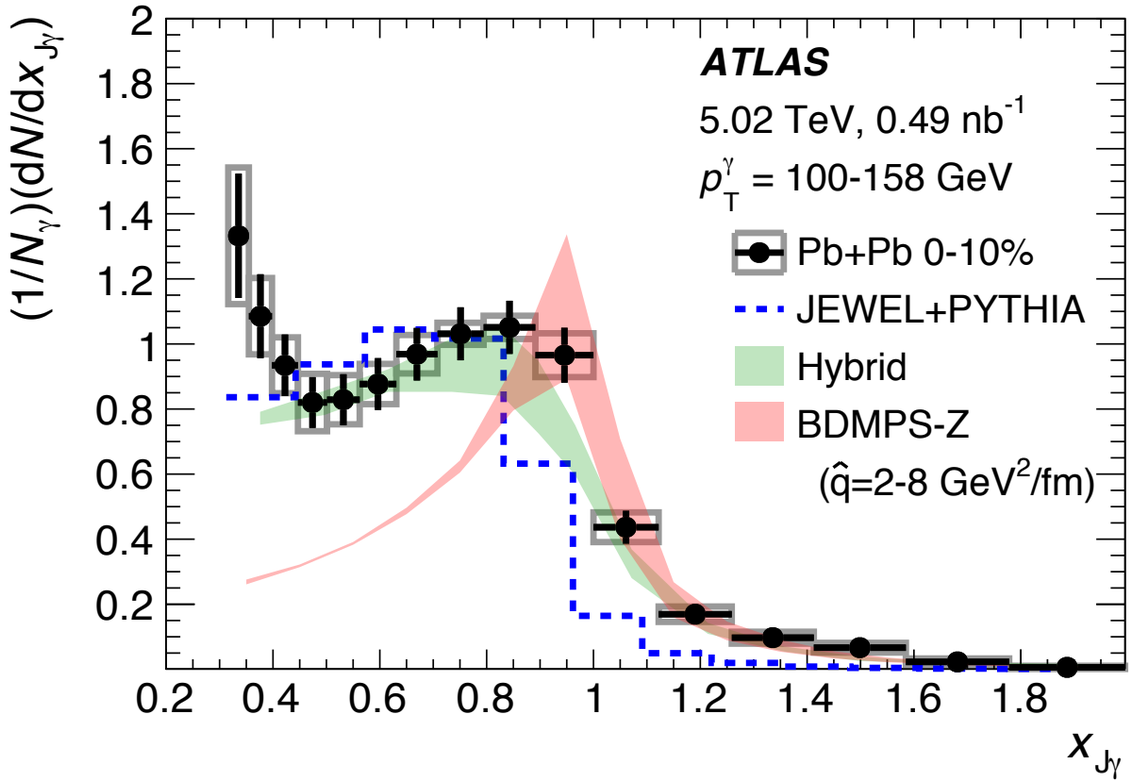
Also allows to explore energy dependence of lost energy

Model comparison



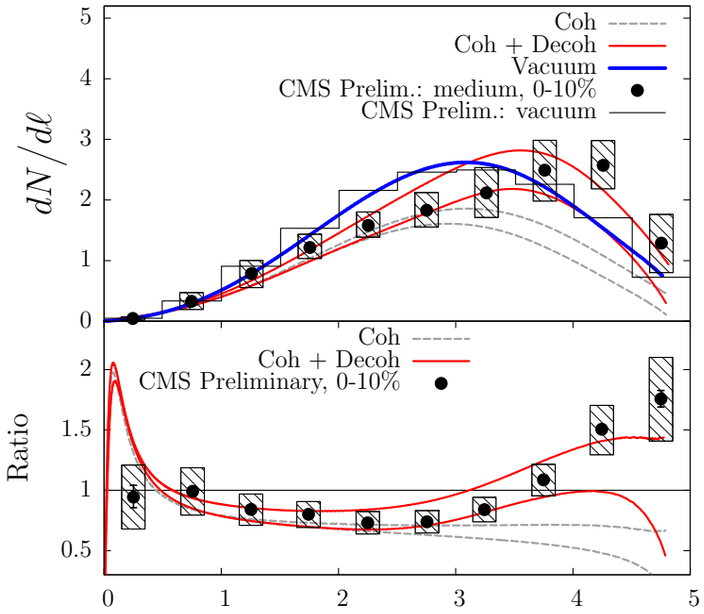




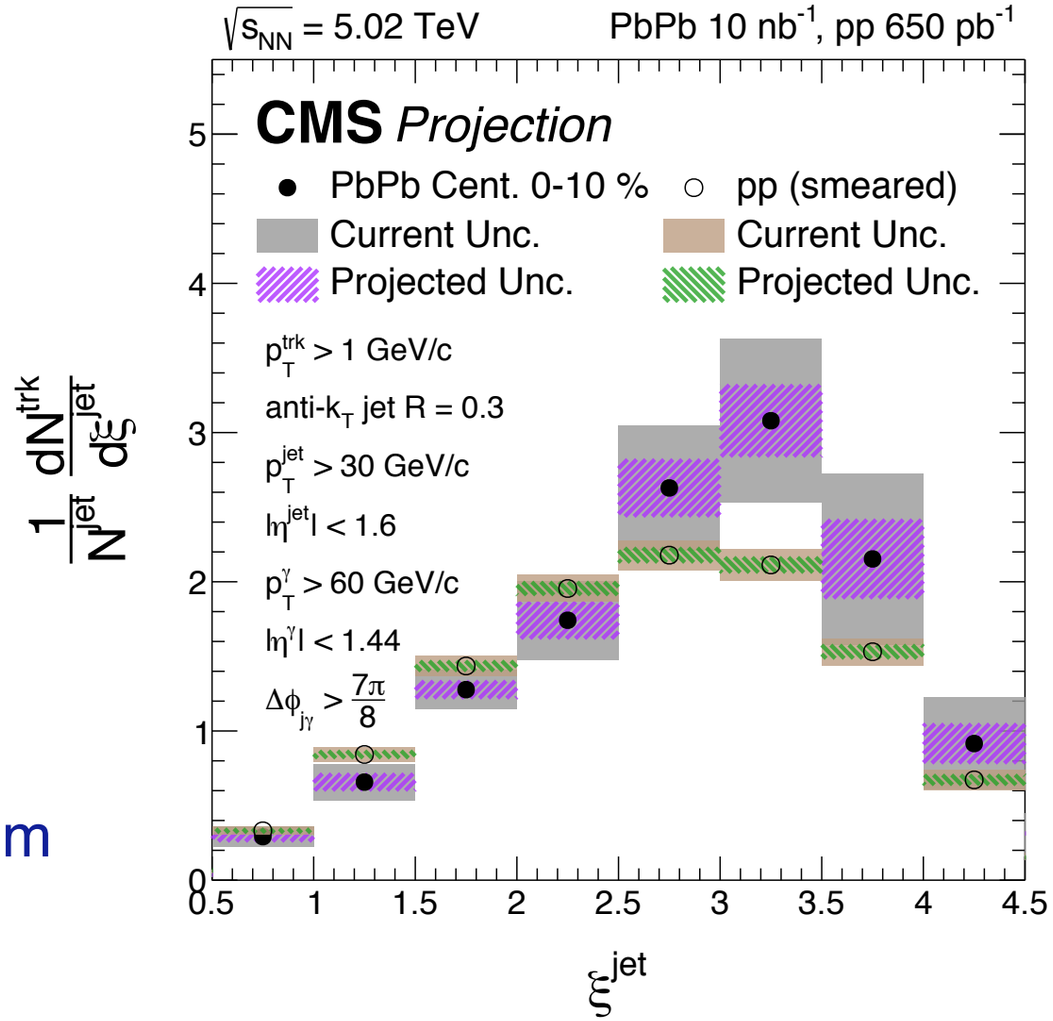


Fragmentation functions/hadron distributions

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

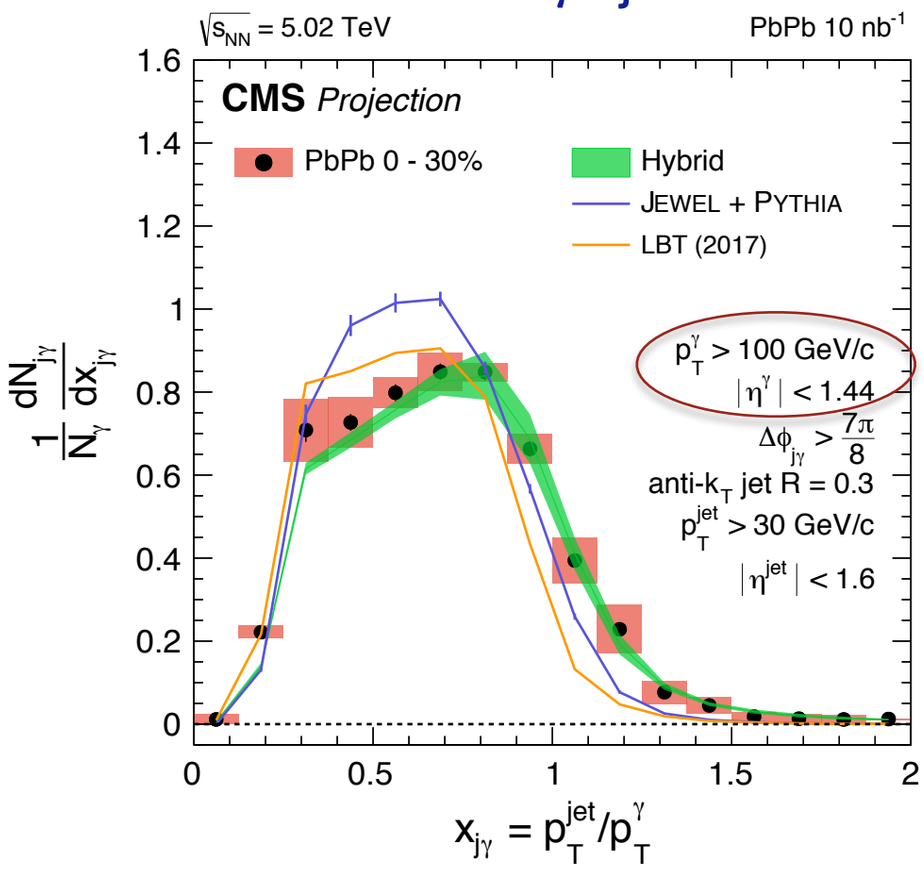
Effects tend to be small:

Experimentally: need good precision and study p_T dependence

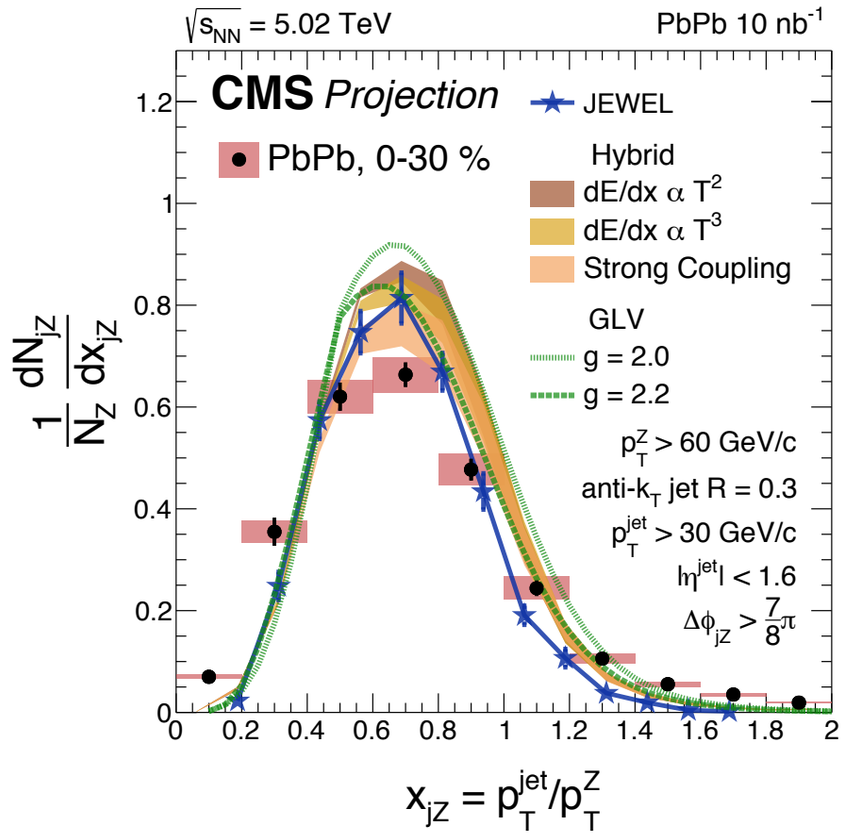
Models: need to consider systematic uncertainties on models/missing physics

Future directions: improved precision/dynamic range

γ+jet



Z+jet



Run 3+4: much improved precision; need to push modelling to make use of this!

Inclusive/average vs jet-by-jet

- Intra-jet distributions (‘fragmentation functions’, radial profile) measure **averages over a sample of jets**
- Jet shape variables (mass, angularities, z_g etc): jet-by-jet quantity, in principle sensitive to fluctuations

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Fluctuations are expected to be large:

- geometric contribution; not all partons come from the center: path length fluctuations
- intrinsic fluctuations: E-loss is a stochastic process
  - Already for a single parton
  - Could be stronger effect in jets ‘fat jets loose more energy’

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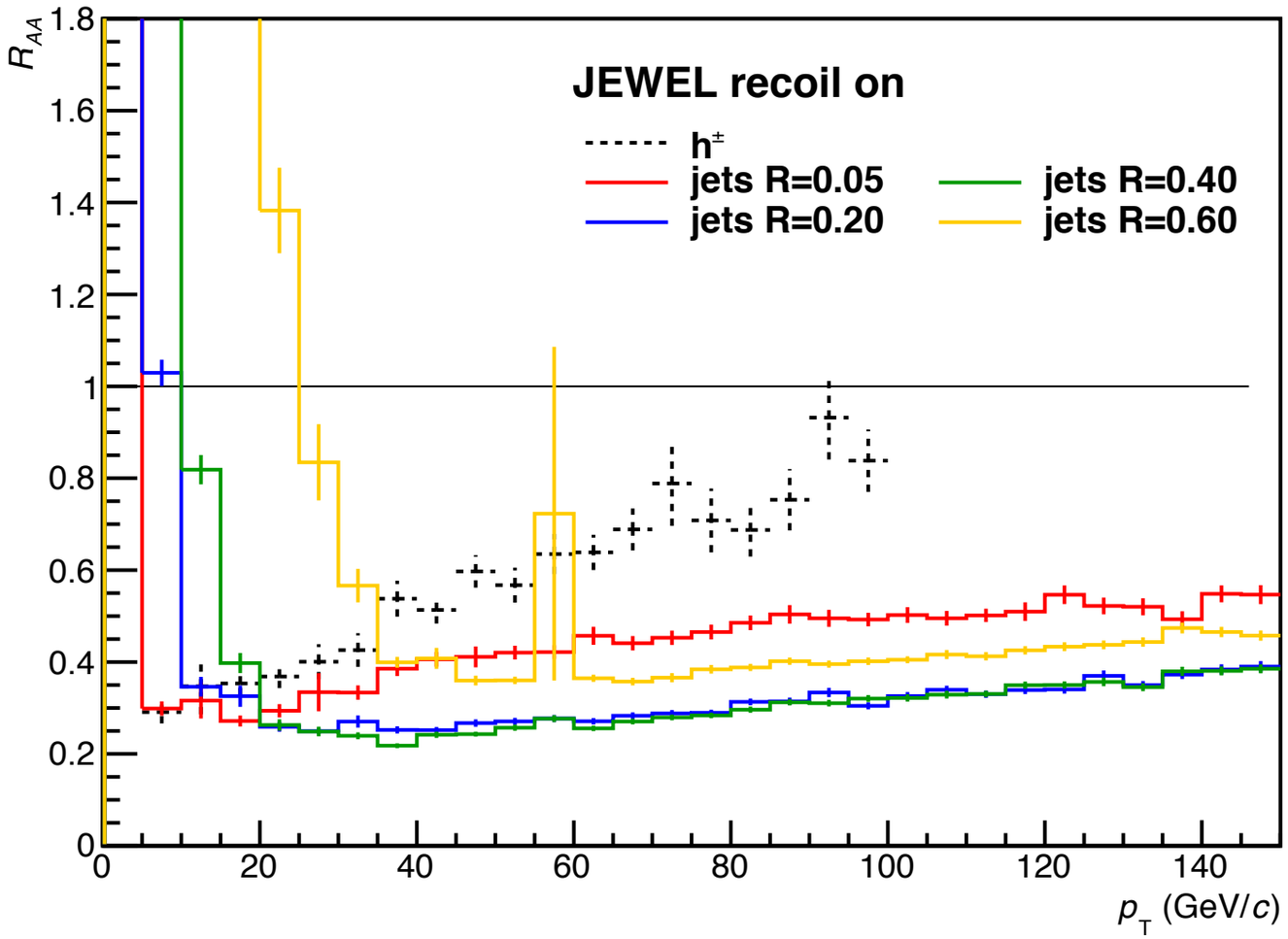
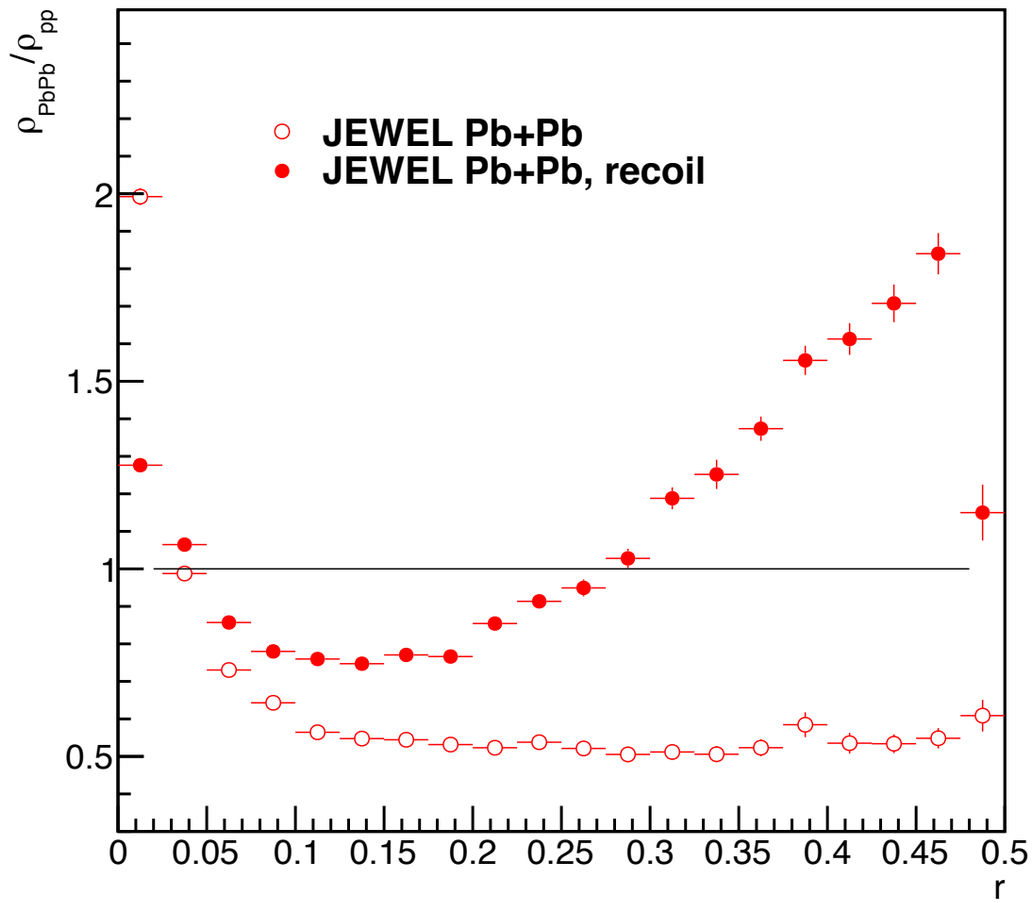
Measuring fluctuations constrains these aspects of models !

Relation radial profile and R_{AA} vs R





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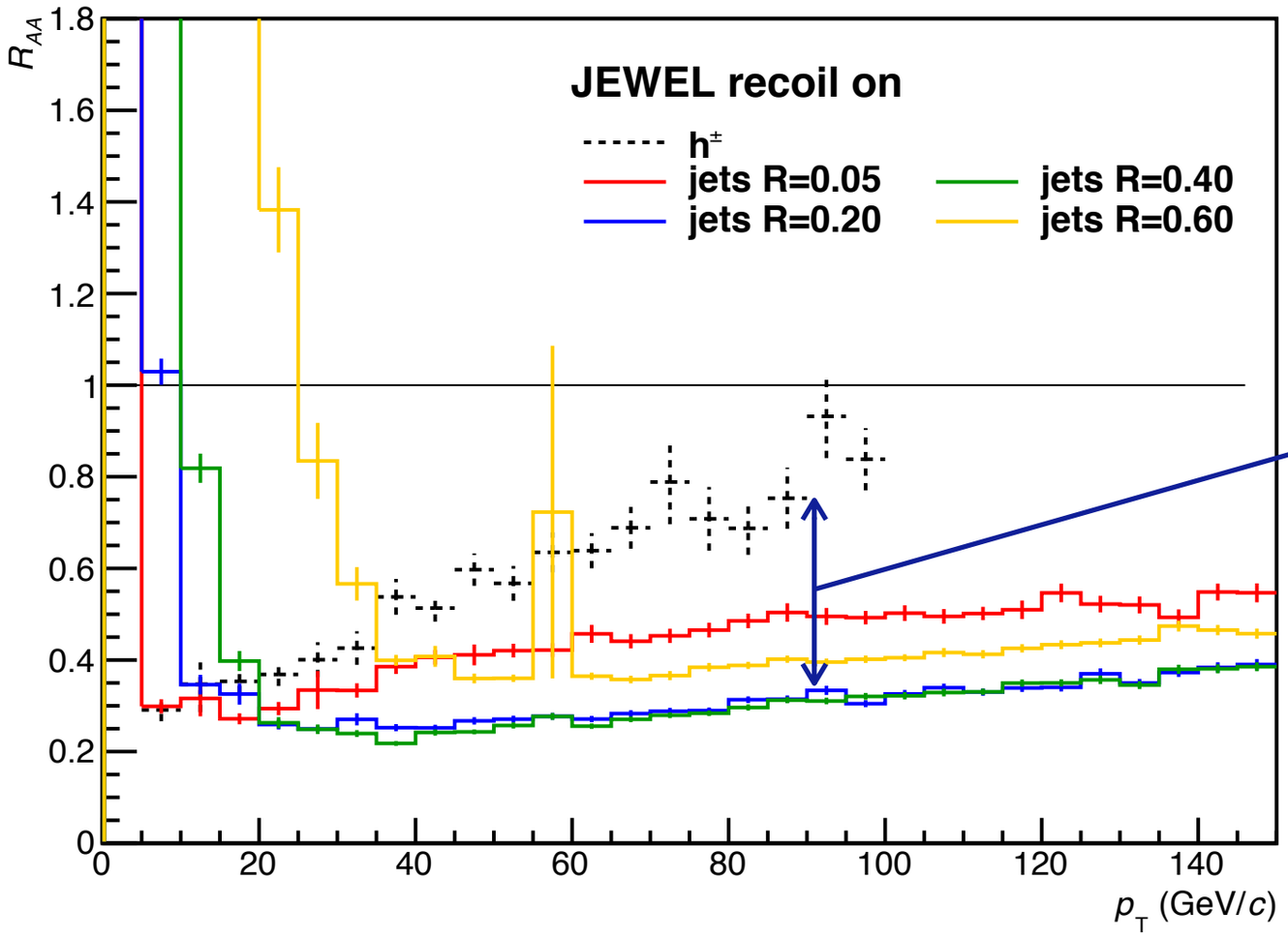

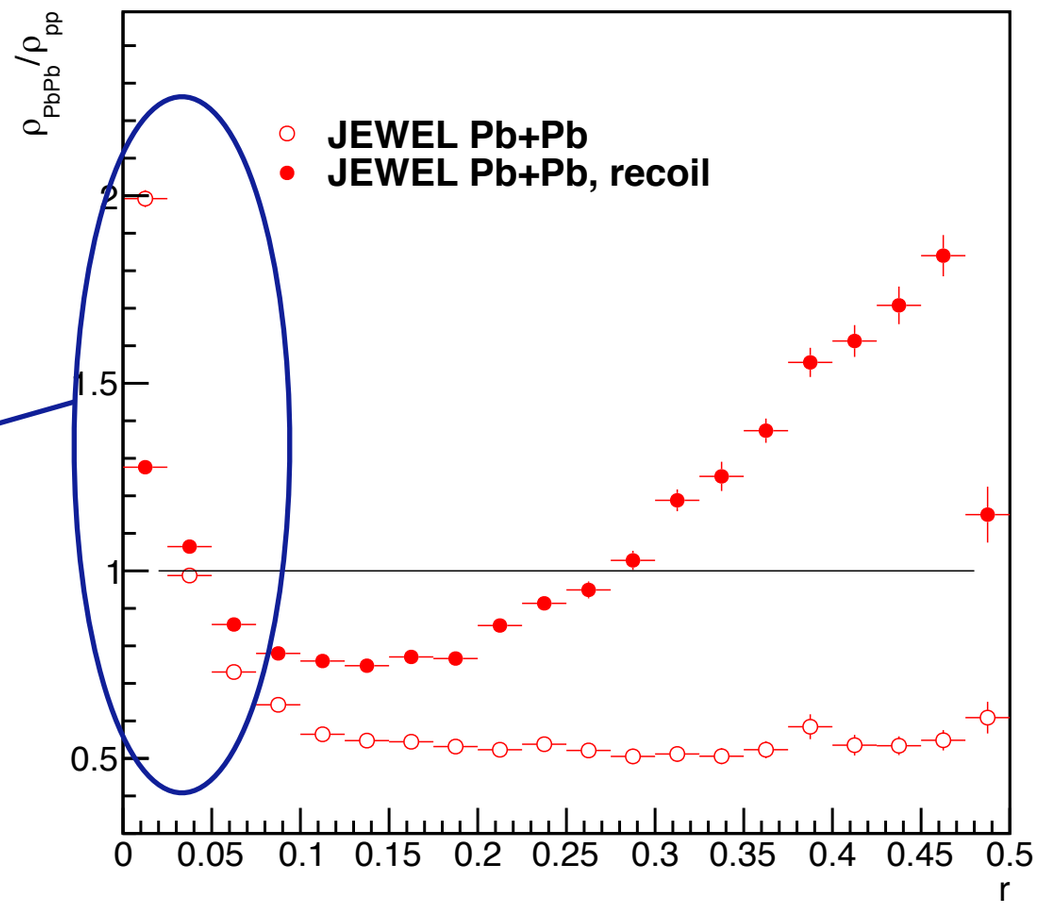

Stronger peak at small r ⇒ decrease of R_{AA} with R for R < 0.2

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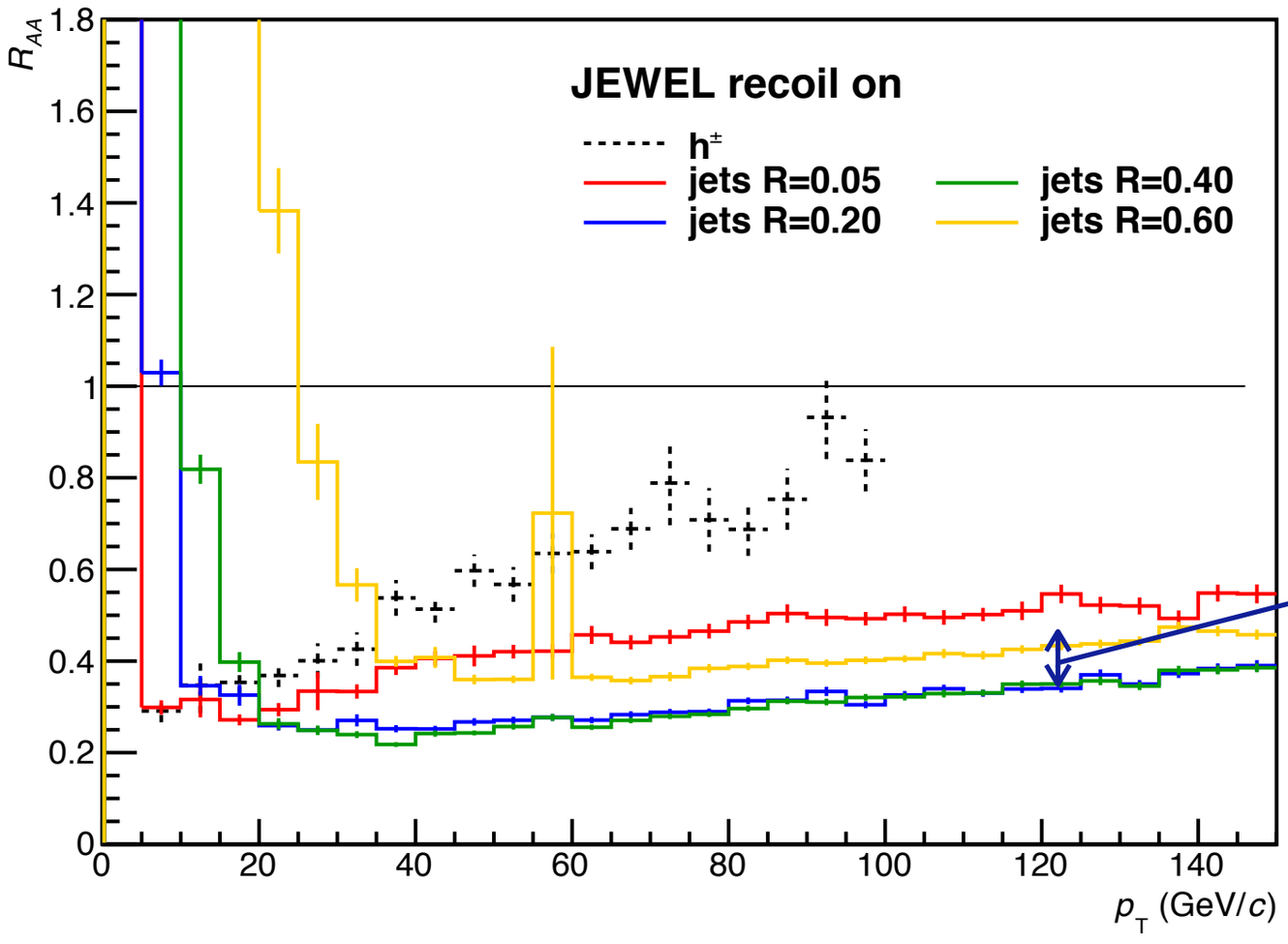
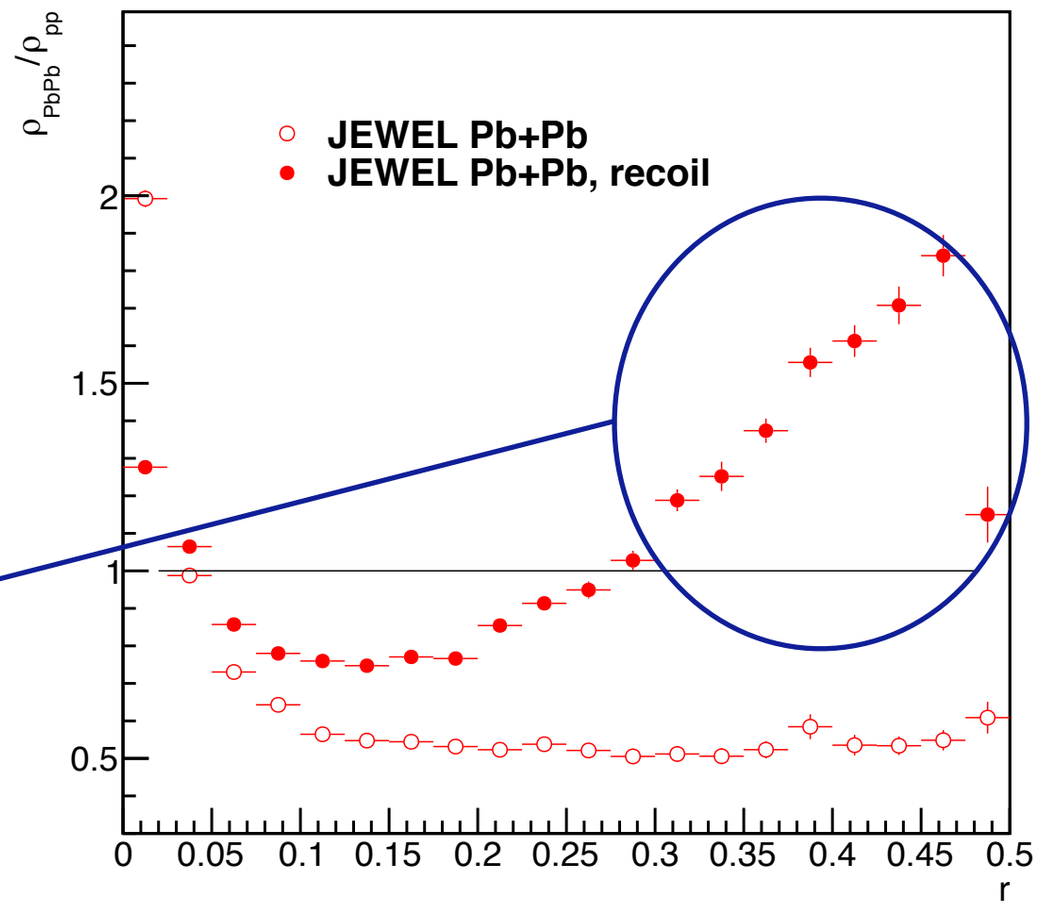
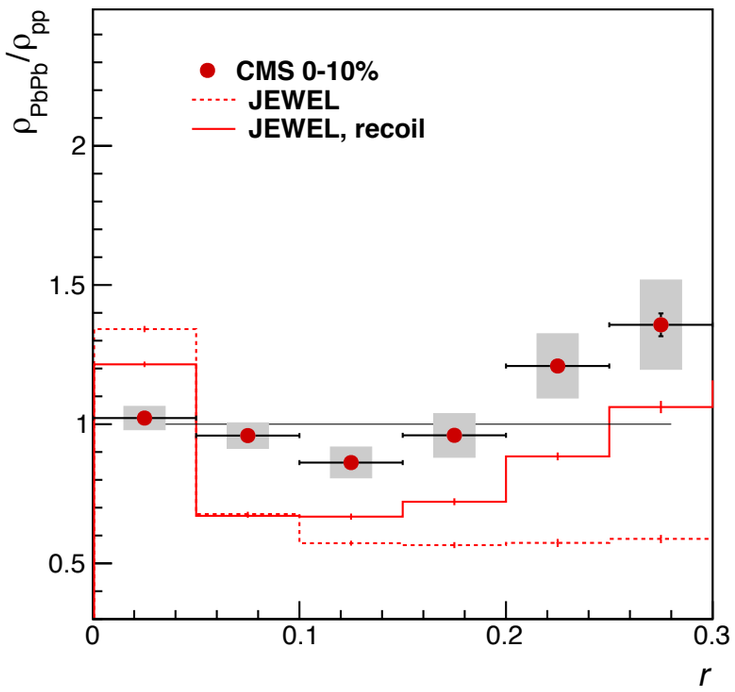




Stronger peak at small r ⇒ decrease of R_{AA} with R for $R < 0.2$

Increase of ratio at large r (only with recoil): increase of R_{AA} for $R > 0.4$
(small effect because total momentum flow is small at large R)

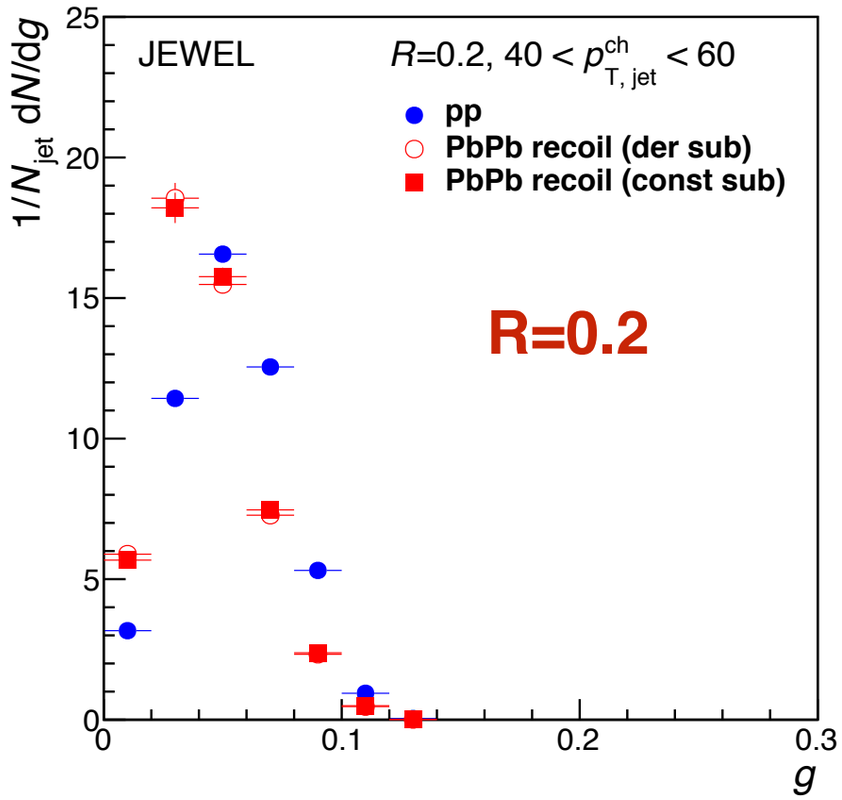
Example: girth, radial profiles



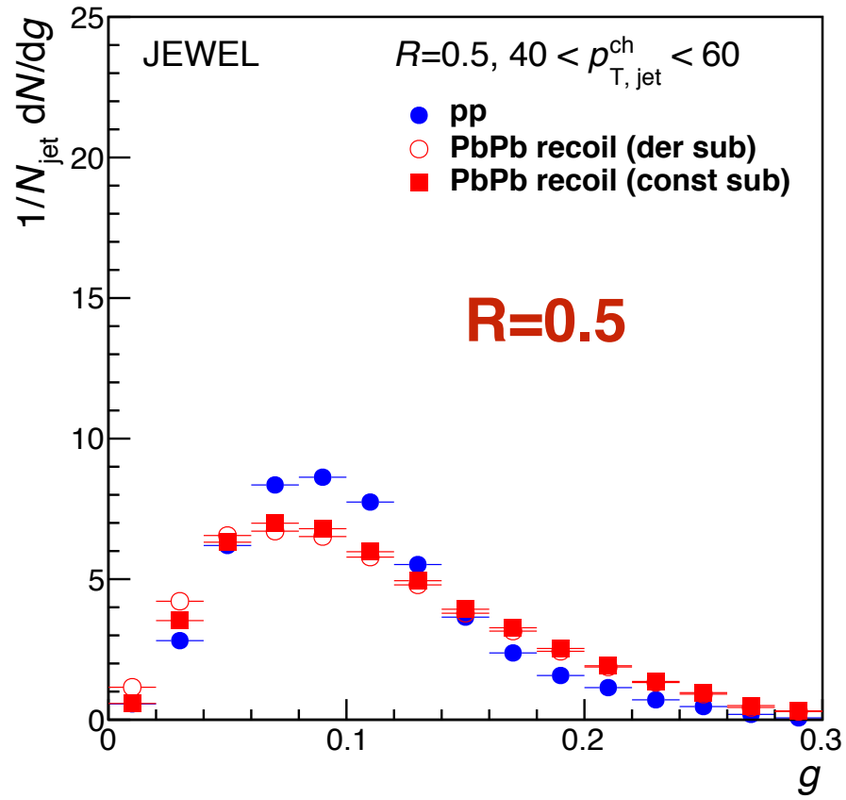
Radial profiles
('CMS jet shape')

Average over events

girth: First moment of radial profile $g = \frac{1}{p_{\perp}^{\text{jet}}} \sum_{k \in J} p_{\perp}^{(k)} \Delta R_{kJ}$



Small jet R: narrowing
mean *g* decreases

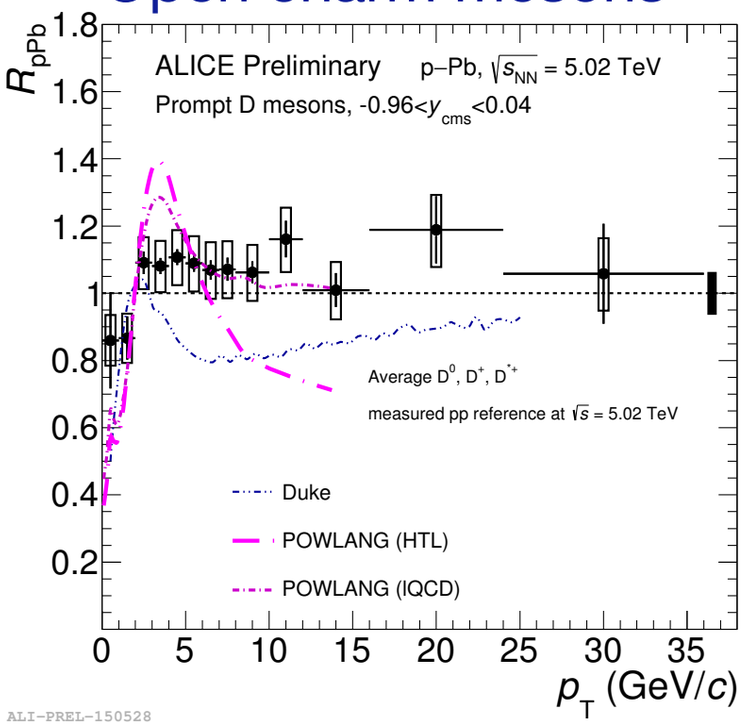


Large jet *R*: broadening
mean *g* increases

***g* is measured jet by jet**
Mean g corresponds to the profile measurement,
width of distribution contains new information

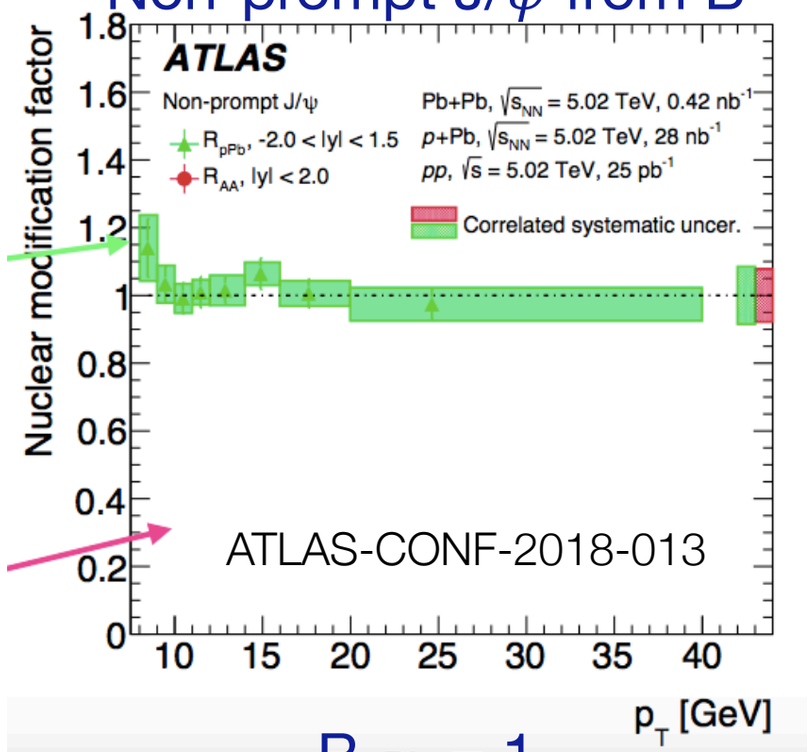
Flow without energy loss?

Open charm mesons



$R_{pPb} = 1$

Non-prompt J/ψ from B



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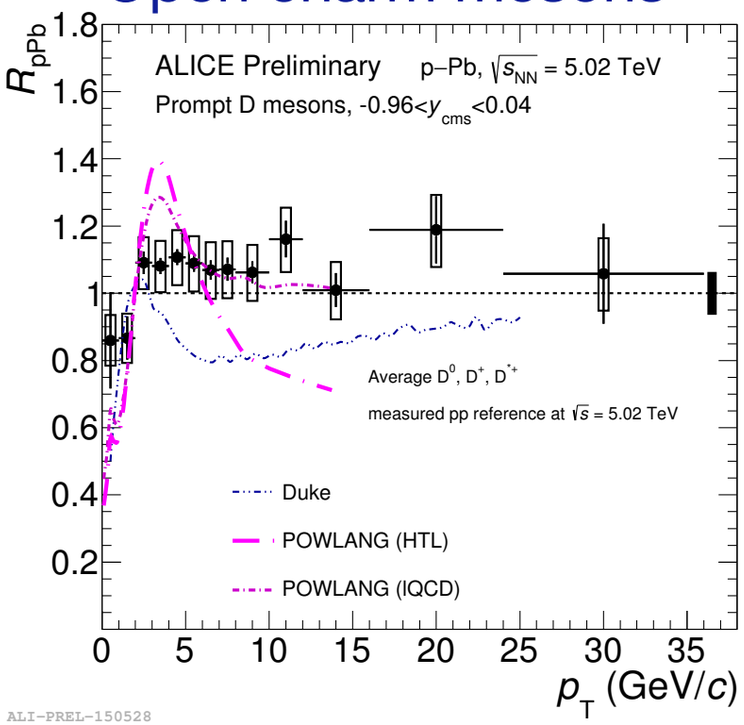

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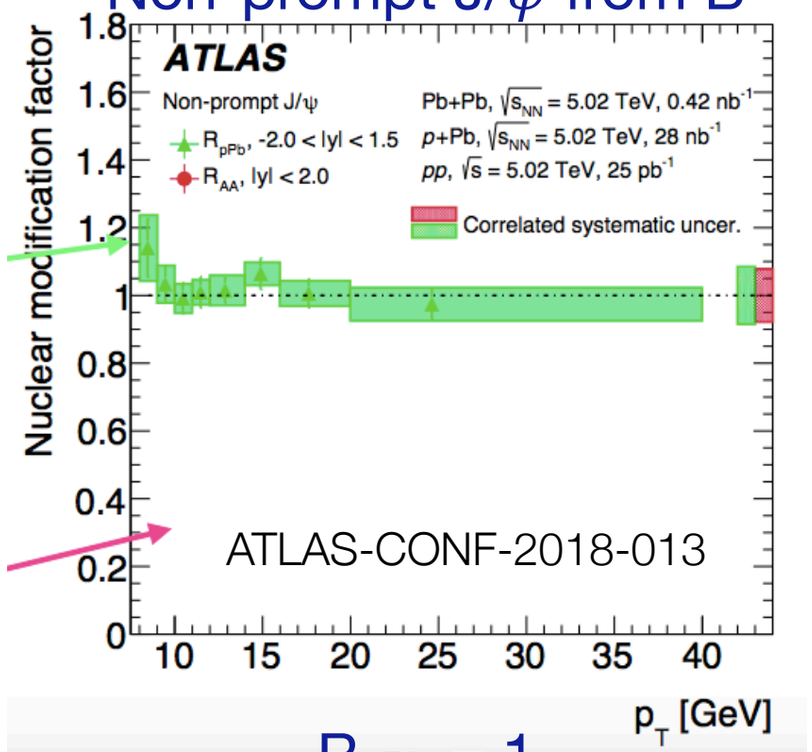
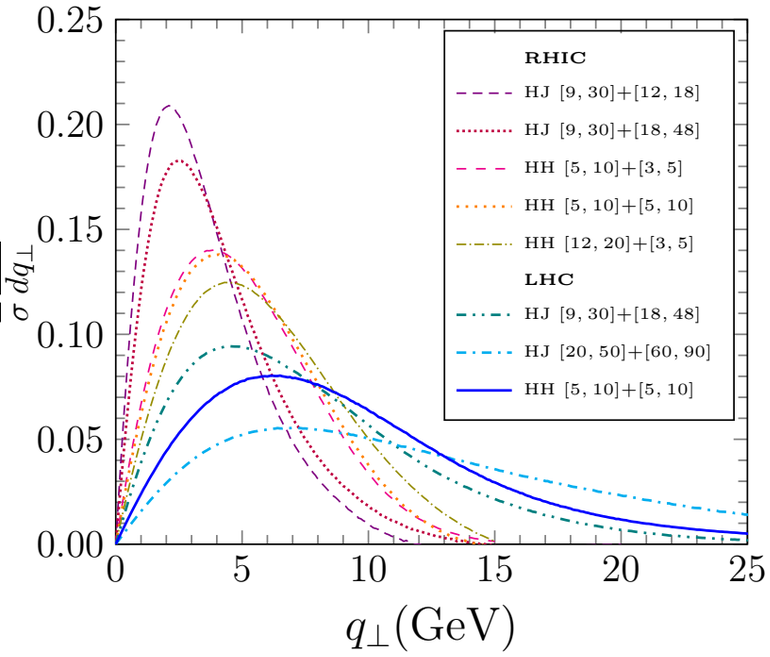


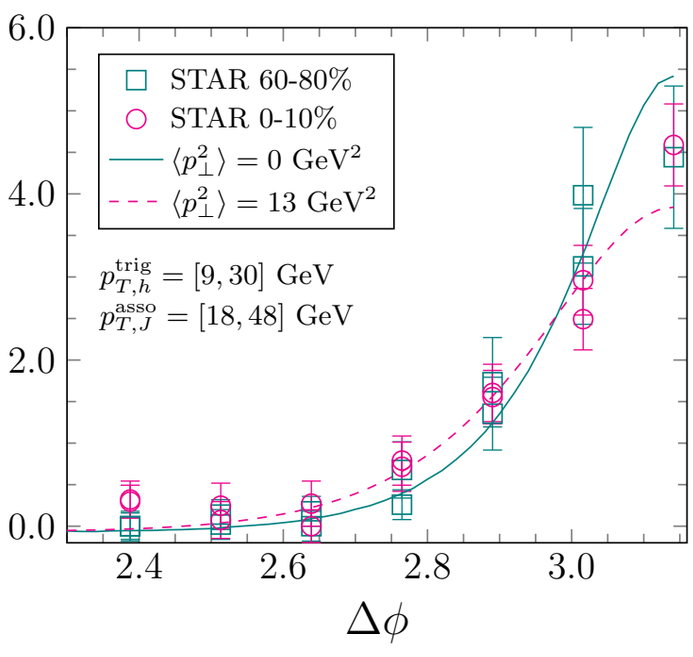
$R_{pPb} = 1$

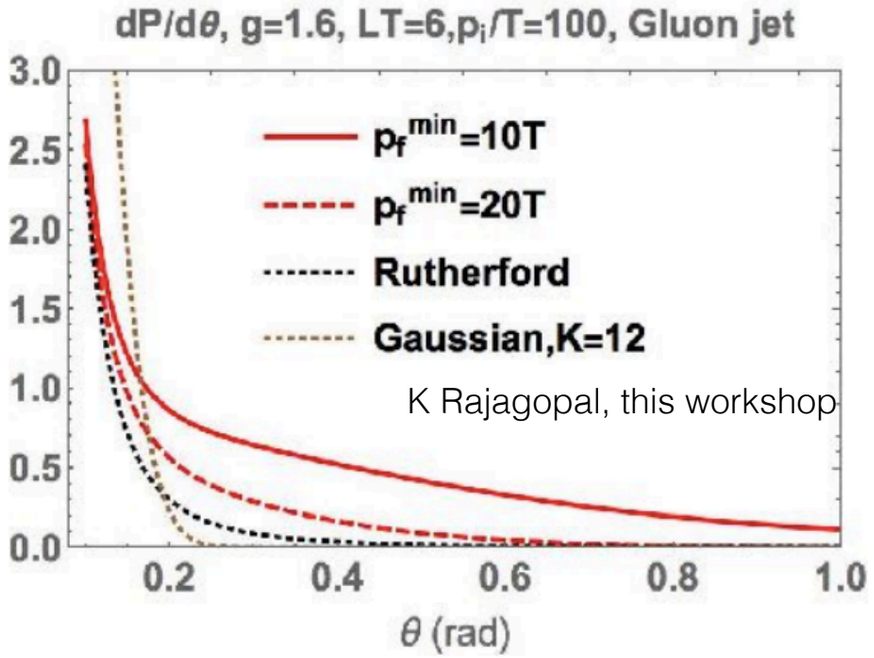
Flow from transport: need only few (elastic) scatterings to generate v_2
energy loss can be small

Transverse momentum broadening: Jet acoplanarity



Chen, Qin, et al, arXiv:1607.01932





K Rajagopal, this workshop

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

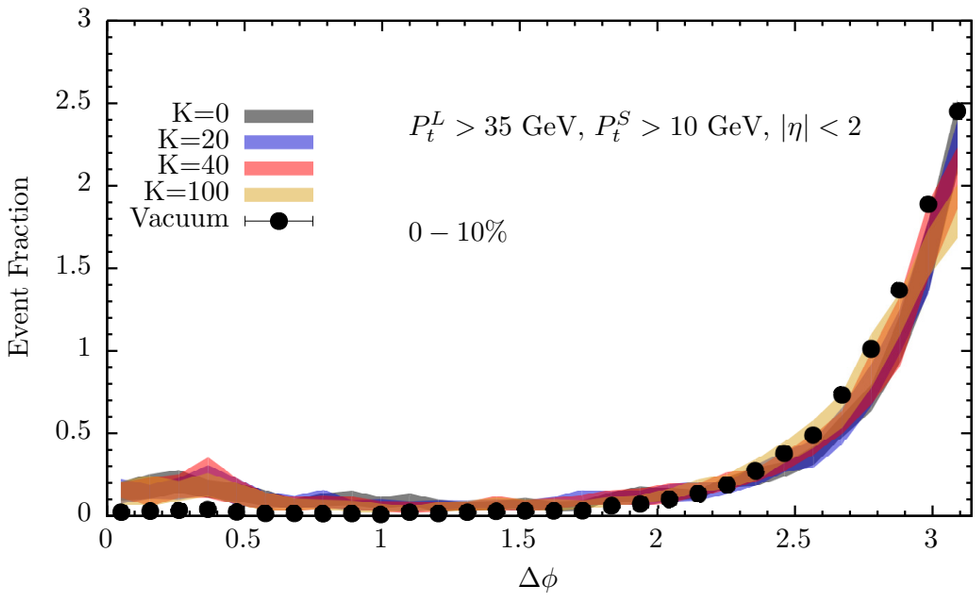
Potential for direct sensitivity to scattering centers in the medium

Exploring in-medium broadening in models

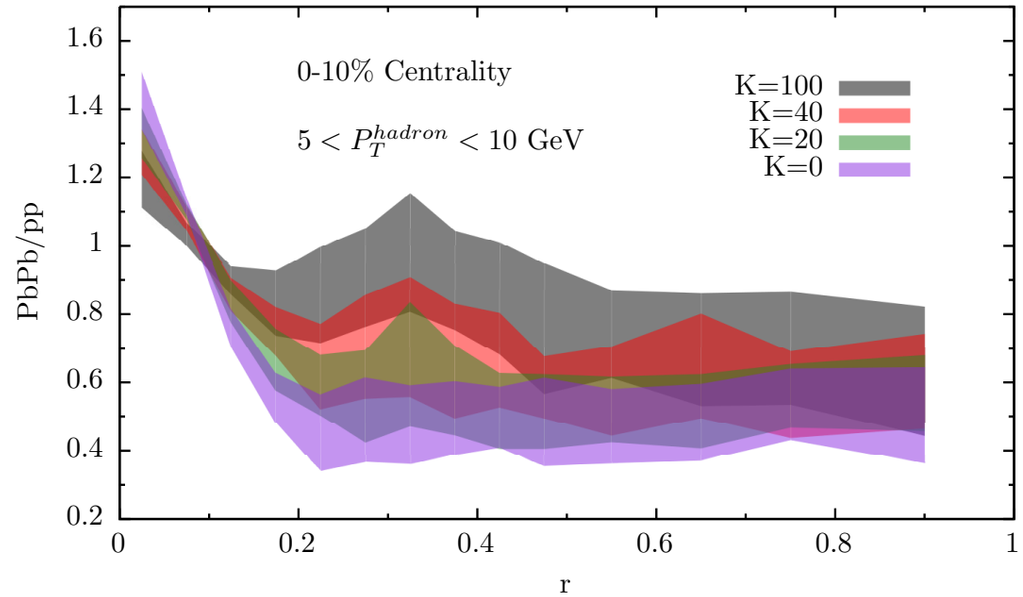
$\langle q_\perp^2 \rangle = \hat{q}L \qquad \hat{q} = KT^3$

Hybrid model, Caselderrey-Solana et al, arXiv:1609.05842, JHEP 1703 (2017)

Di-jet angle



Radial profile of recoil jet



Broadening effect small; masked by energy loss: higher energy jet more collimated

Need low p_T jets to see recoil broadening

Alternative observable: stronger/more characteristic signal?

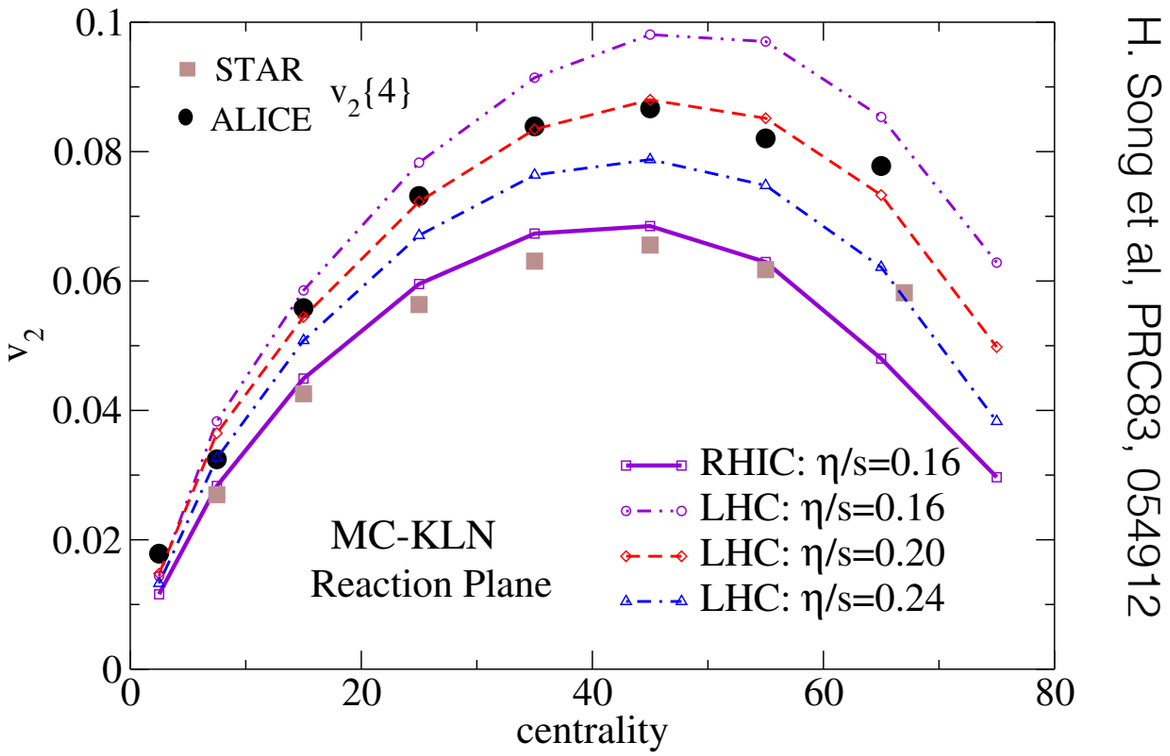
Note: *This observable is proposed as a result of the model studies*

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

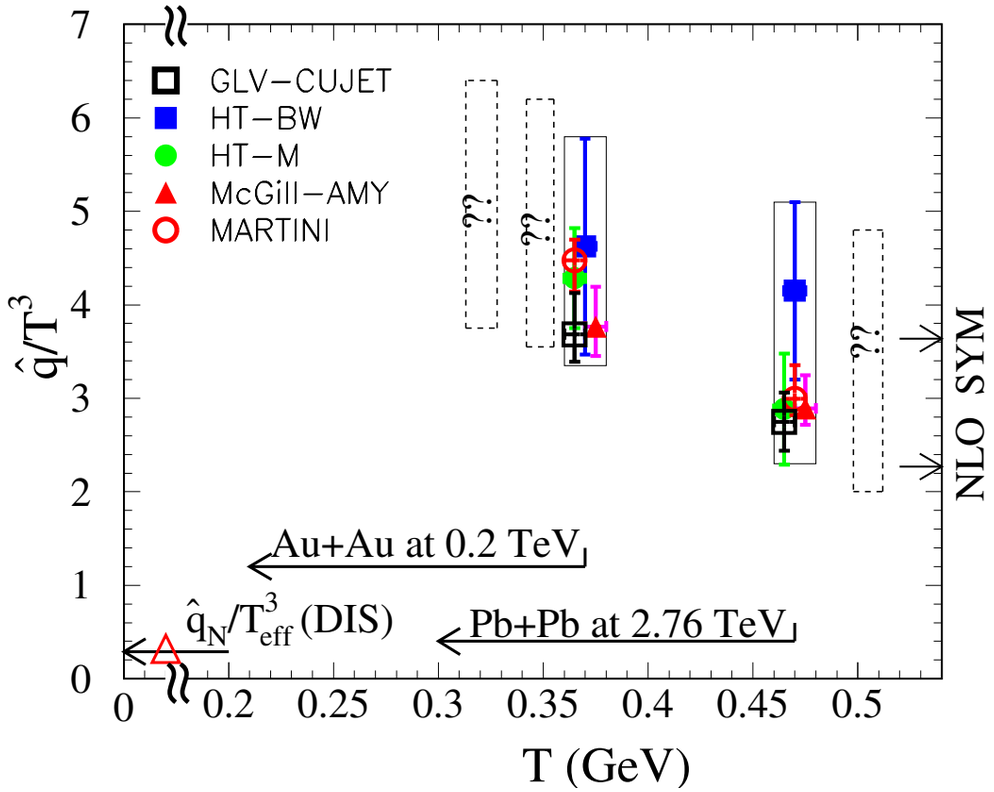
Majumder, Muller and Wang, PRL99, 192301

Elliptic flow



(Scaled) viscosity slightly larger at LHC

Transport coefficient from R_{AA}



Scaled transport coefficient slightly smaller at LHC

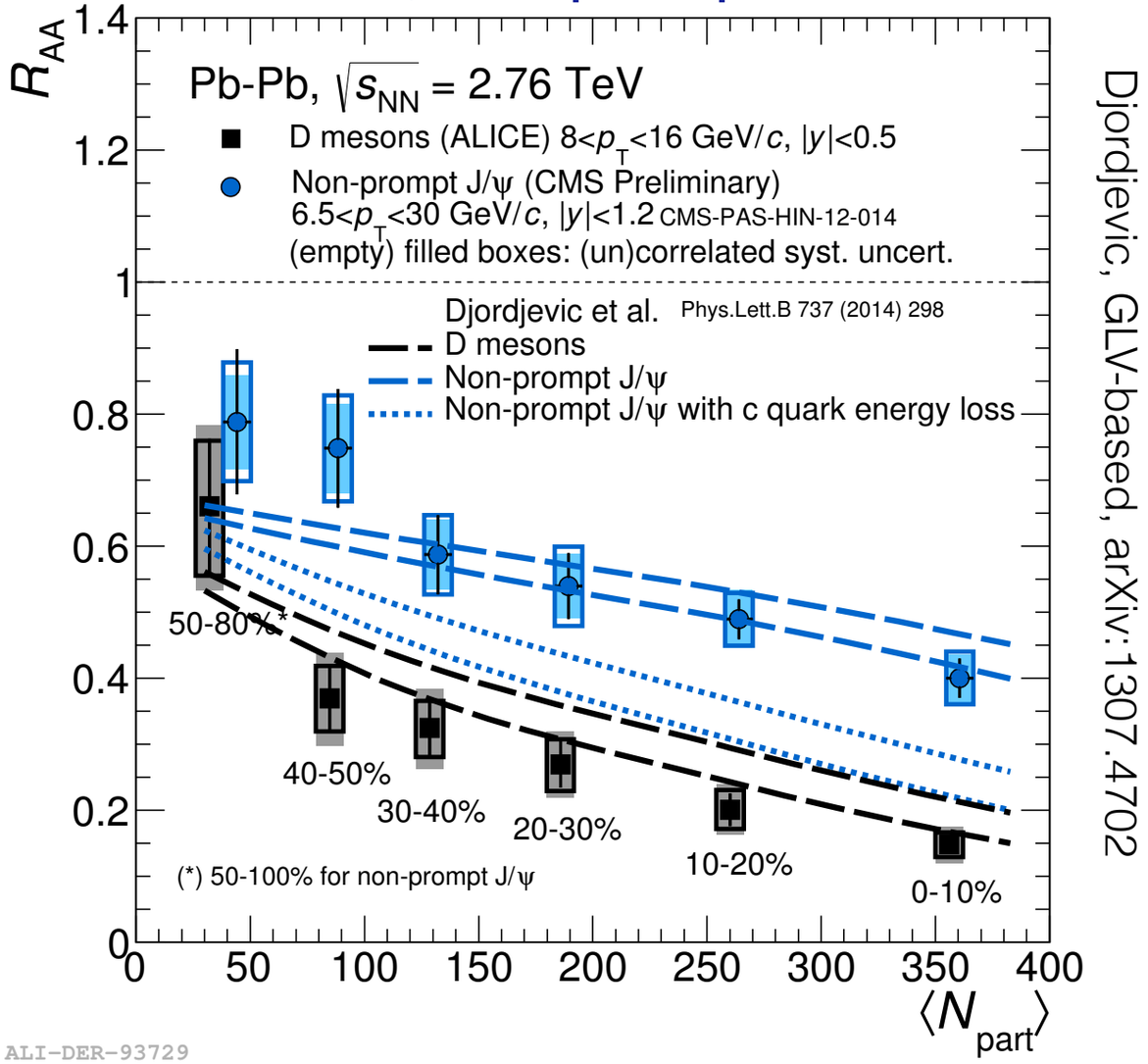
Hints of increase of η/s and decrease of q/T^3 could have a common origin?

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

Heavy flavour

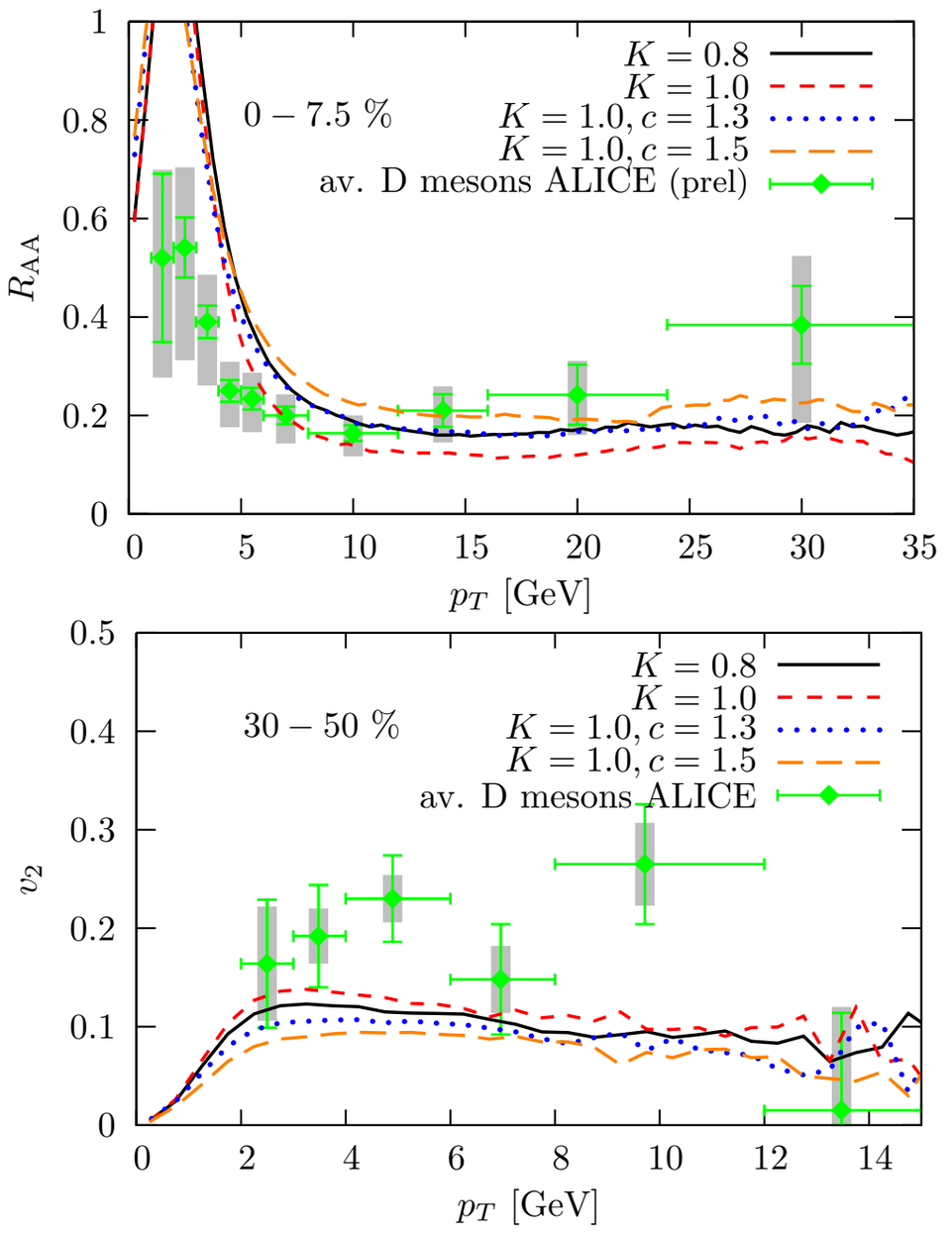
GLV-based semi-analytical

D meson, non-prompt J/Ψ R_{AA}



Djordjevic, GLV-based, arXiv:1307.4702

MC@sHQ Boltzmann transport MC



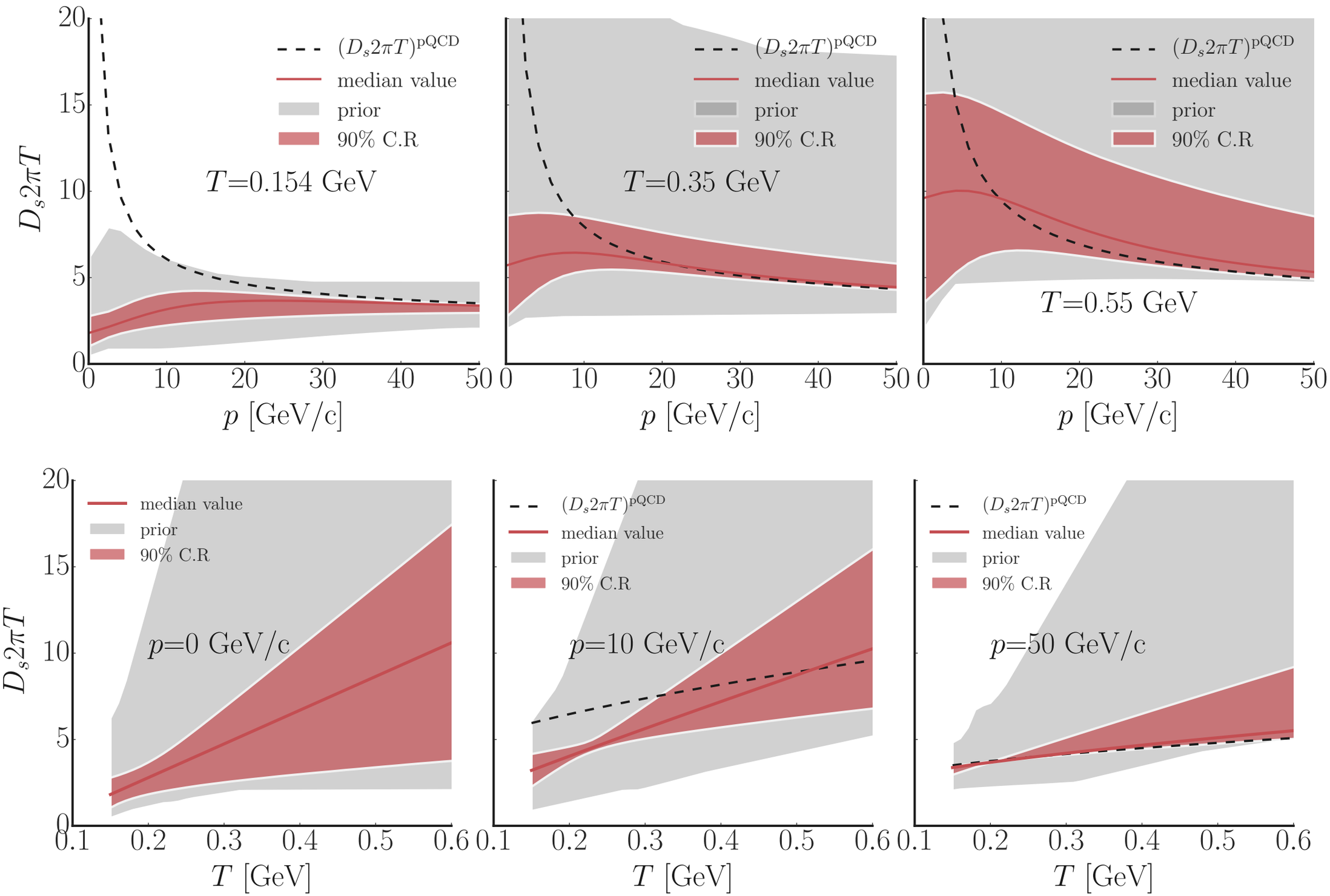
Nahrgang, Gossiaux et al, MC@sHQ, arXiv:1305.6544

Heavy flavour well captured by models

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

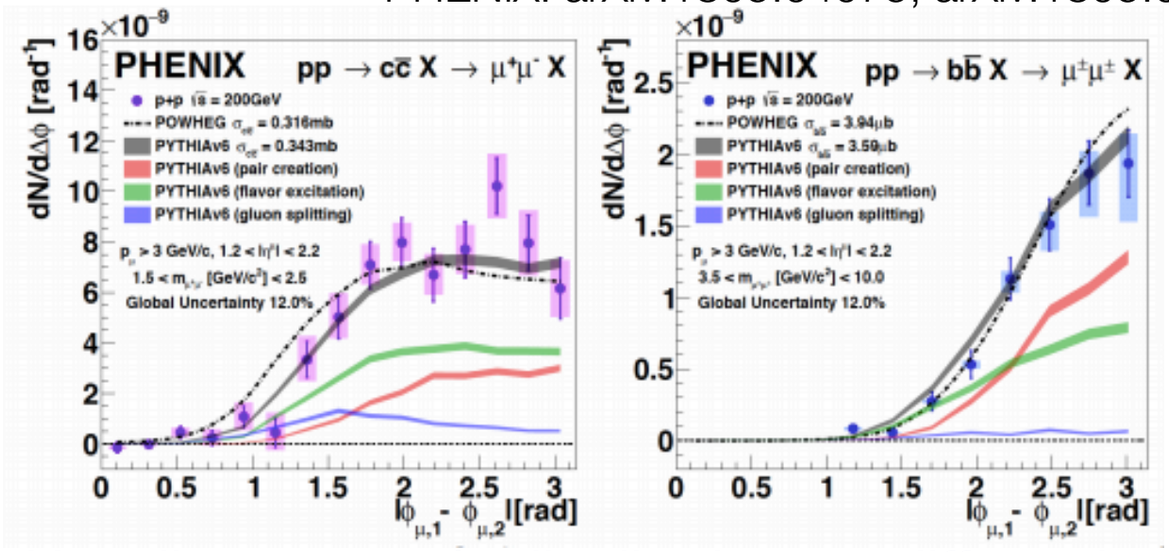
Determining the density, transport coefficient

Y. Xu et al, PRC 97, 014907

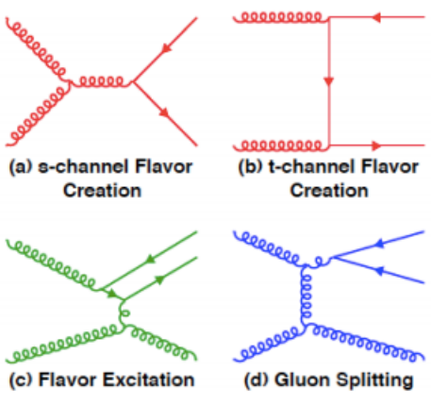


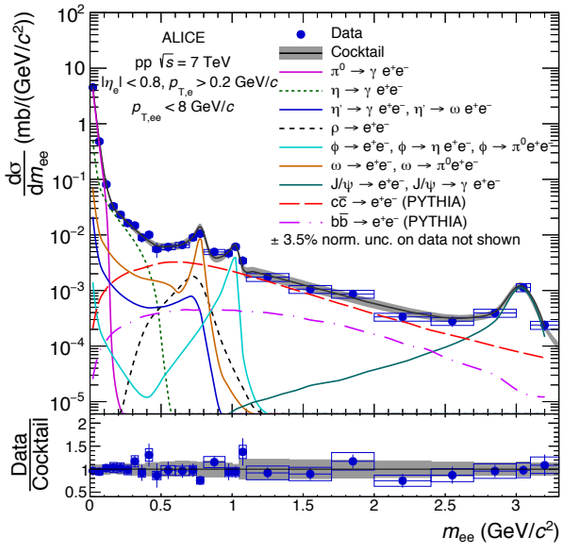
HF production dynamics: direct pairs vs gluon jets

PHENIX: arXiv:1805.04075, arXiv:1805.02448

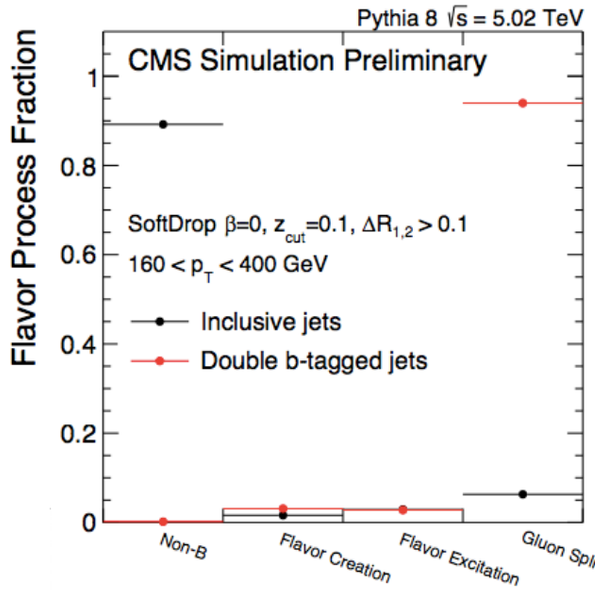


Use di-muon angle distributions to differentiate pair creation: back-to-back pairs
gluon splitting: near side pairs





electron-positron mass distribution depends on angular distributions



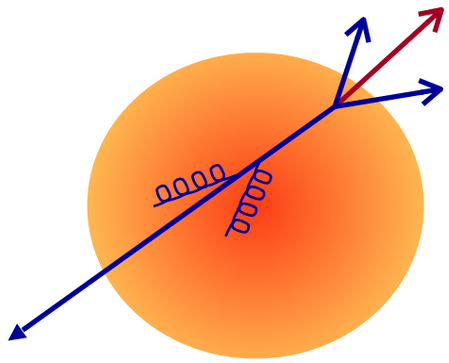
Future direction:
single vs double b-tag jets

+several new results on D mesons in jets from ALICE+CMS

Exciting prospects: use heavy flavors to tag shower prongs and follow energy loss
Multi-parton energy loss

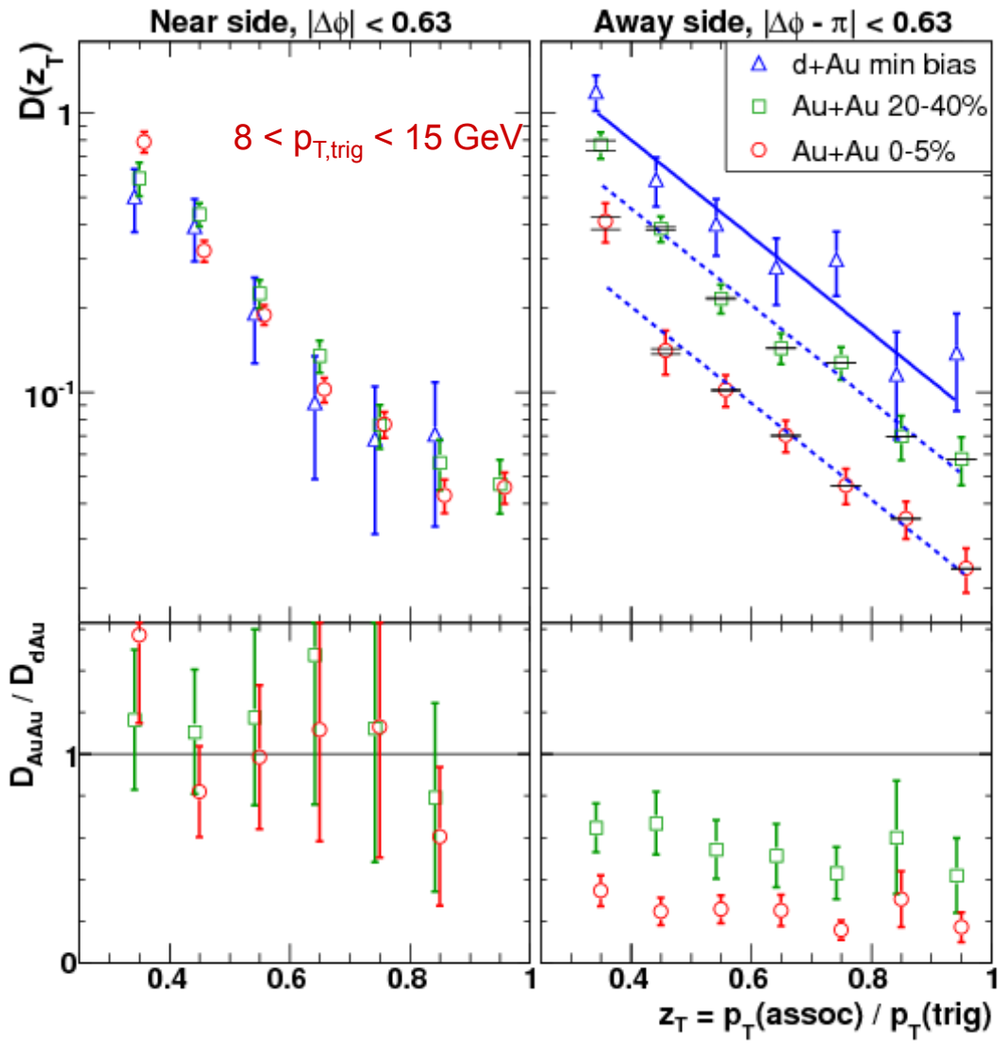
Another handle on path length dependence: di-hadrons

Near side trigger,
biases to small E-loss



Away-side large L

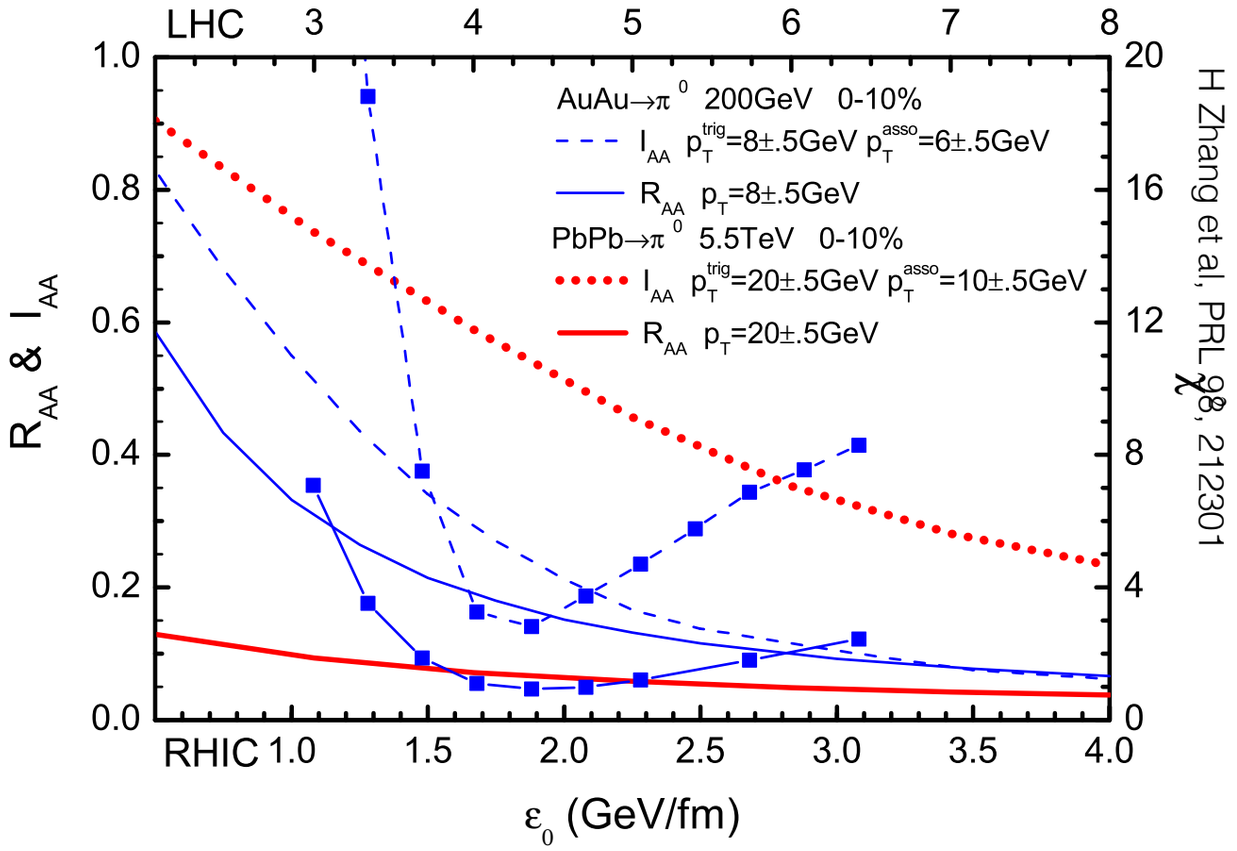
Away-side (recoil) suppression I_{AA}
samples longer path-lengths than inclusive R_{AA}



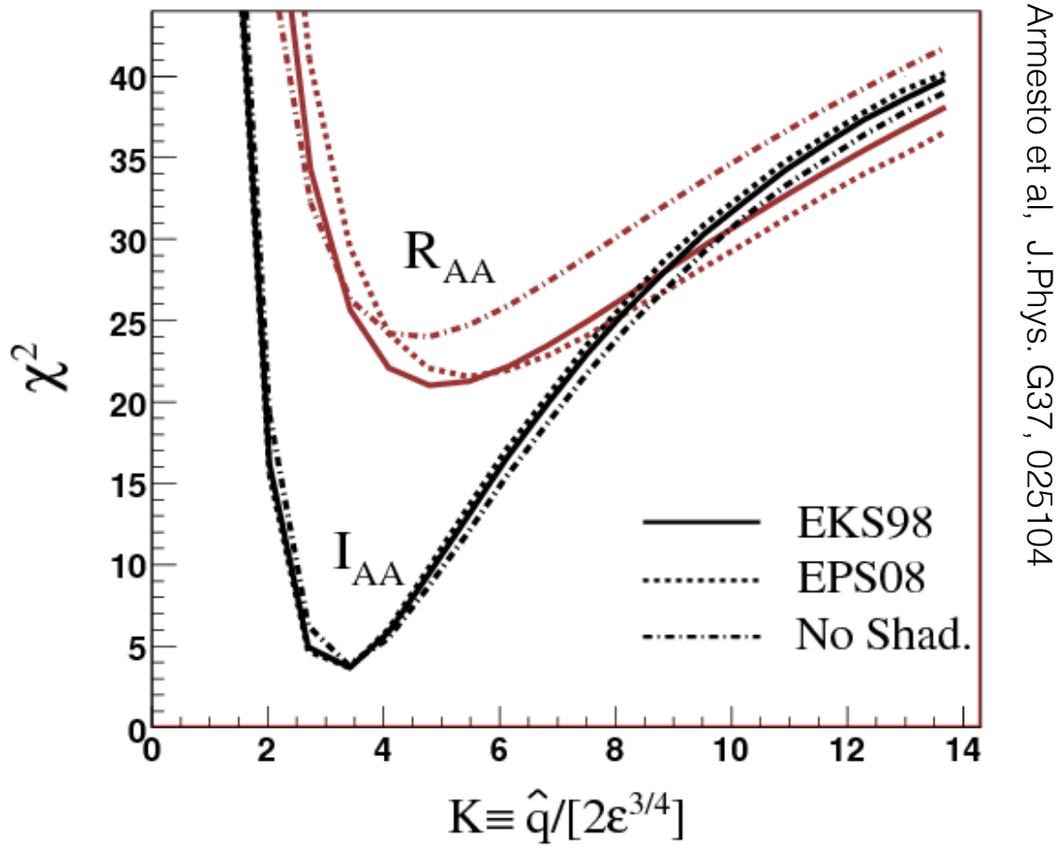
STAR PRL 95, 152301

Can be modelled with the same tools as inclusive particle production

I_{AA} modeling



Medium model: Glauber profile
Energy loss: Higher Twist

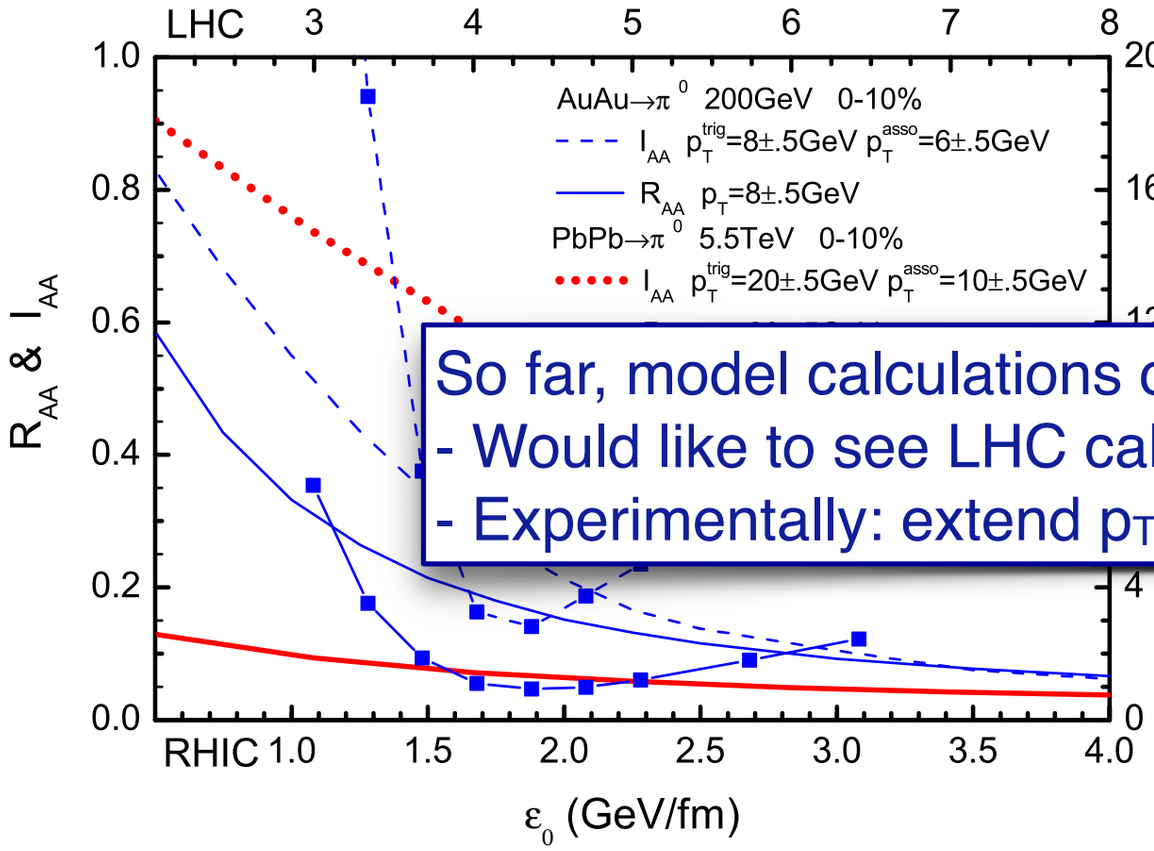


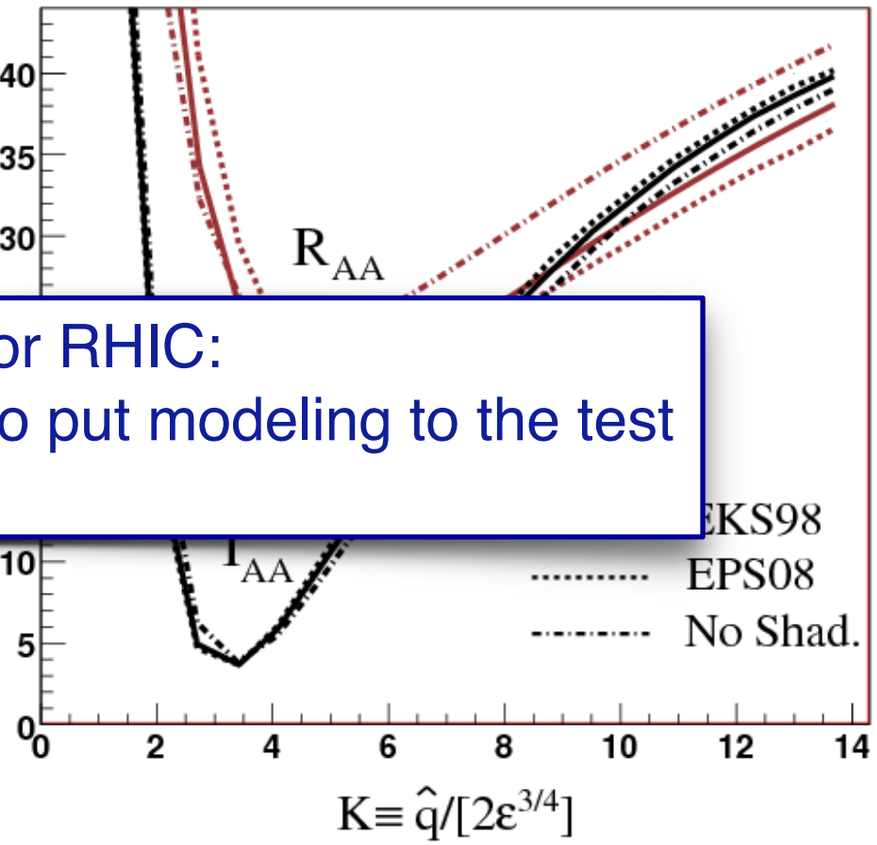
Medium model: (ideal) Hydro
Energy loss: BDMPS-ASW multiple soft

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

Confirms ~L^2 dependence

I_{AA} modeling





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

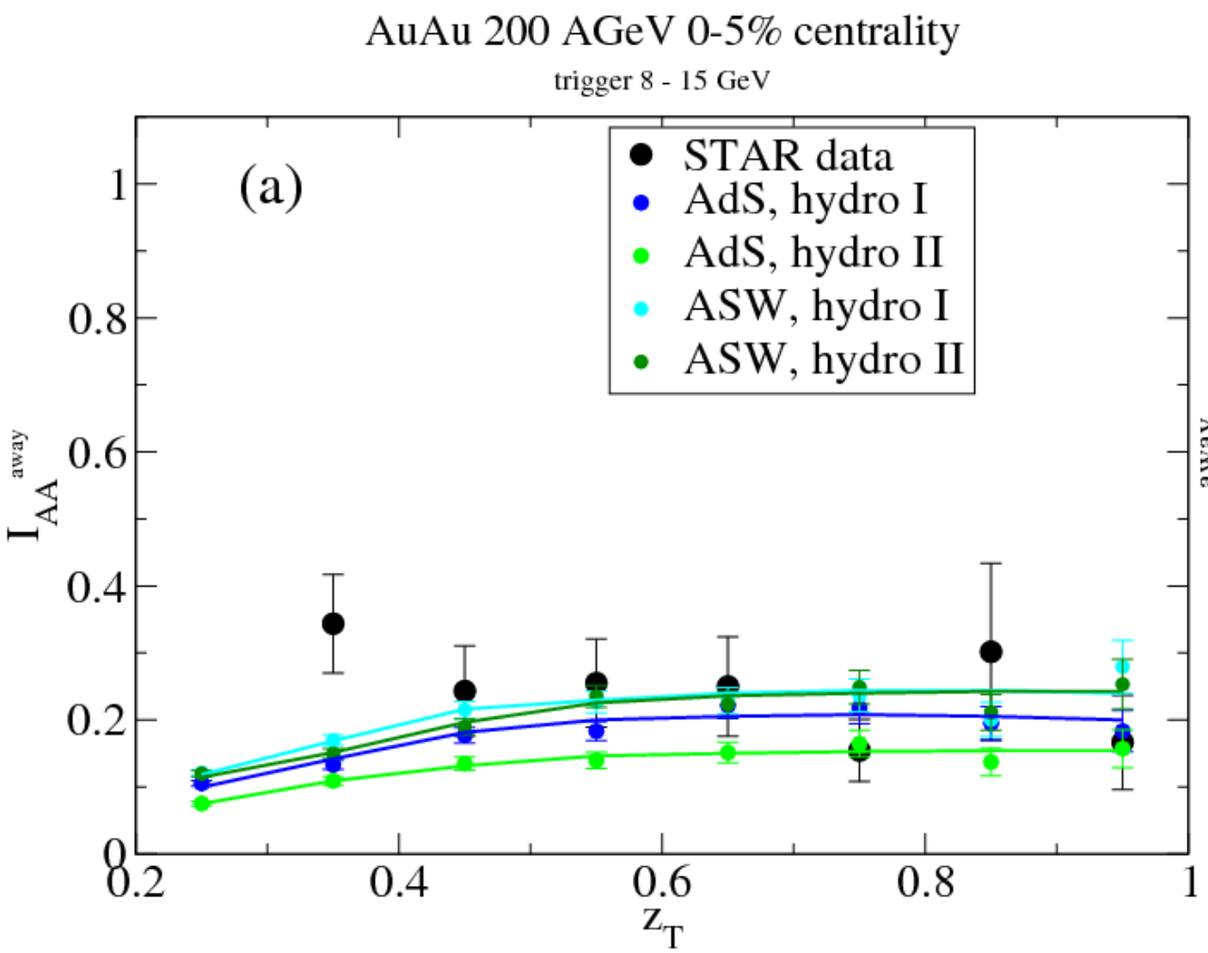
Medium model: (ideal) Hydro
Energy loss: BDMPS-ASW multiple soft

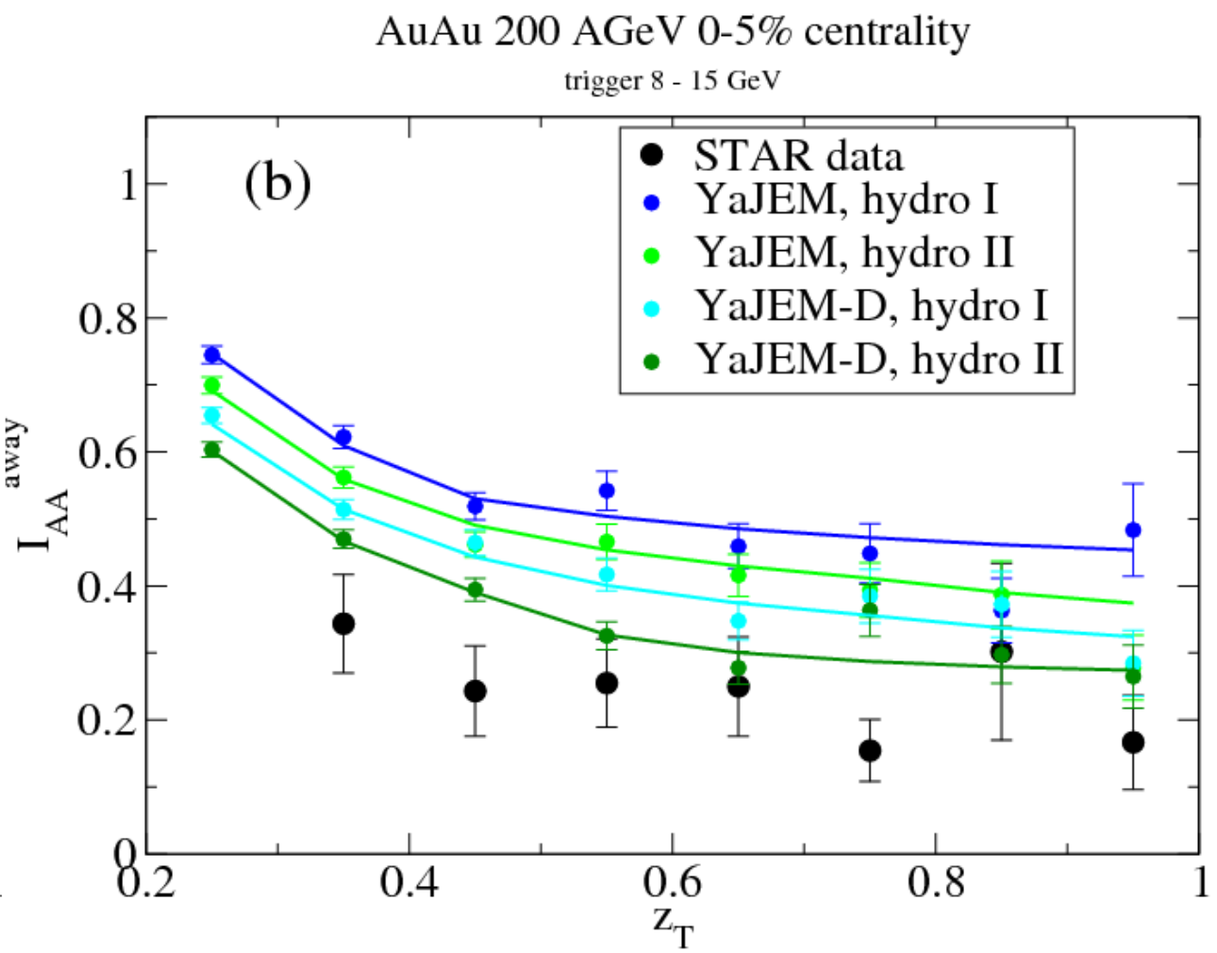
R_{AA} and I_{AA} fit with similar density

Confirms ~L^2 dependence

Di-hadron modeling

Model ‘calibrated’ on single hadron R_{AA}





T. Renk, PRC, arXiv:1106.1740

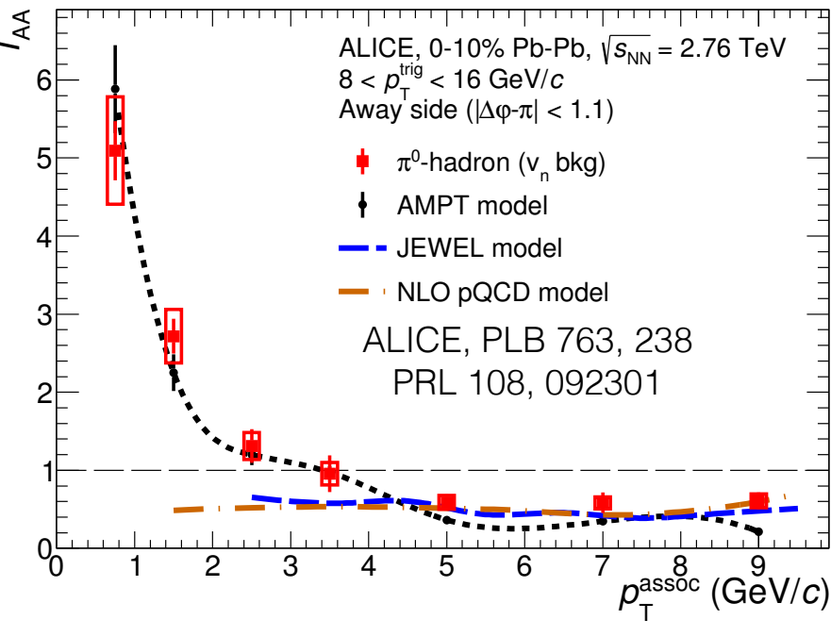
L^2 (ASW) fits data
L^3 (AdS) slightly below

Clear sensitivity to L dependence

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

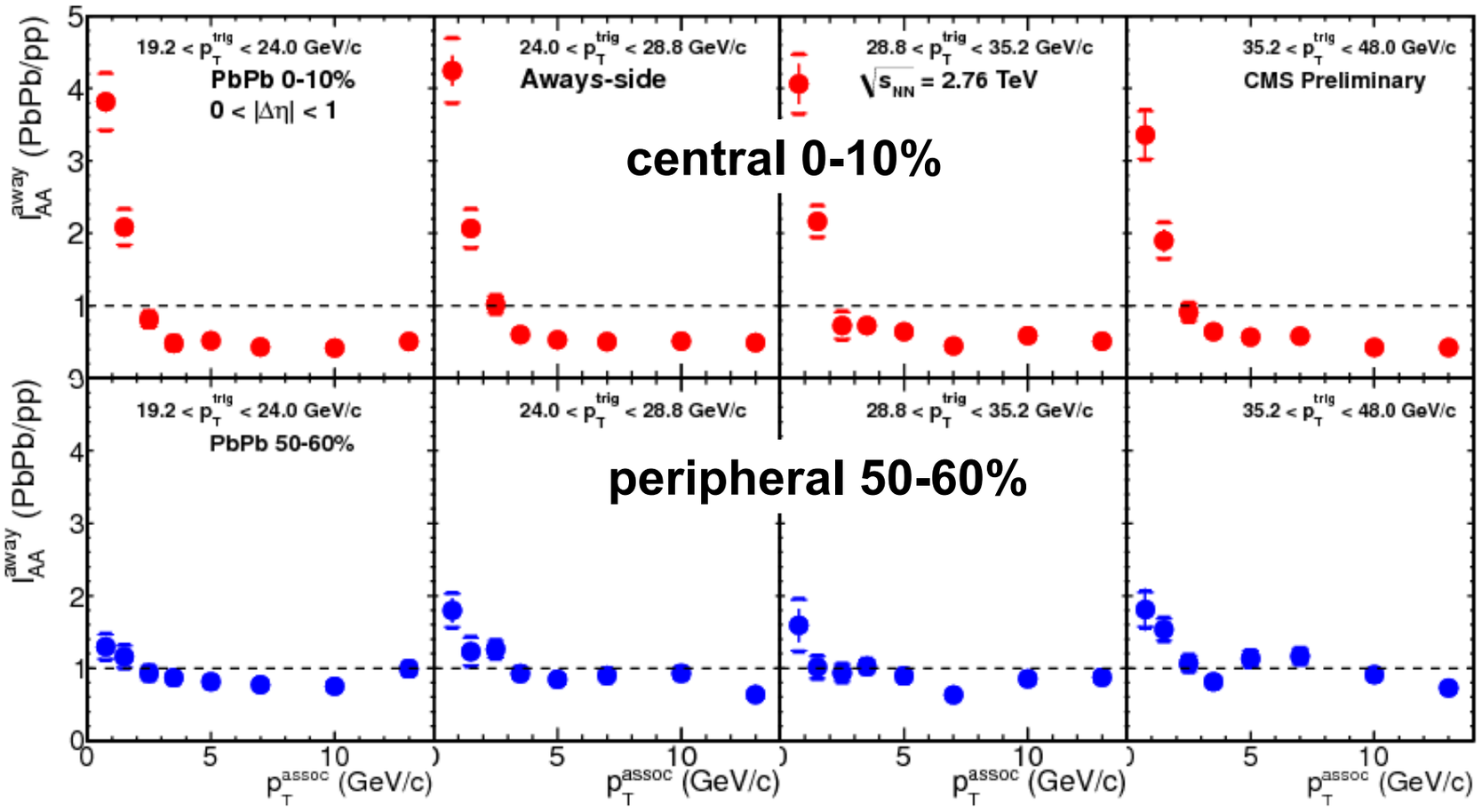
Modified shower
generates increase at low z_T

I_{AA} at the LHC



p_T^{trig} (GeV):

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



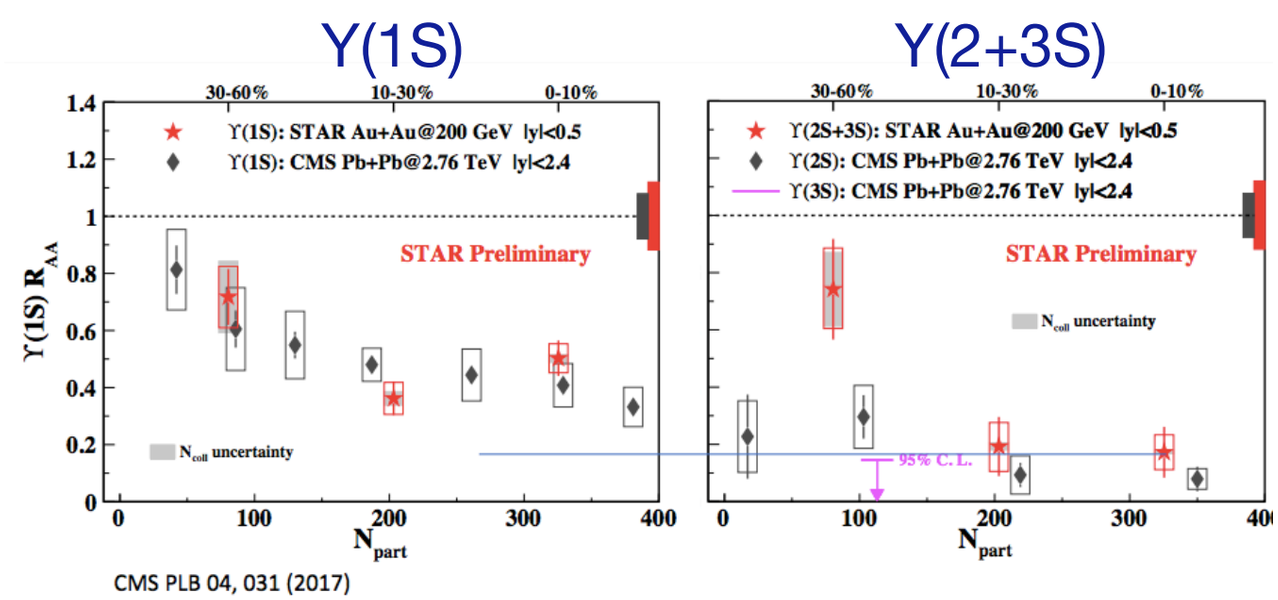
CMS-PAS-HIN-12-010

Transition enhancement → suppression @ p_T ~ 2 GeV

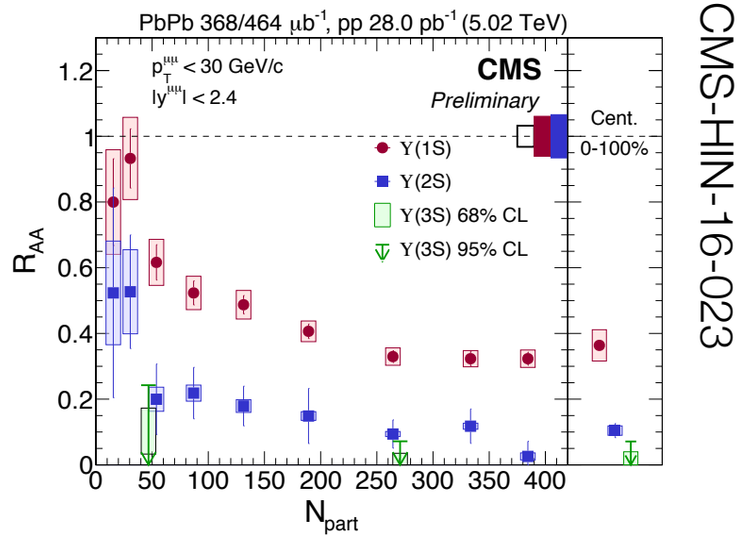
Would like to see a more systematic comparison of calculations to data
Explore p_T dependence? In- and out-of-plane?

Bottomonia melting

QM Overviews: R Ma and E Ferreiro

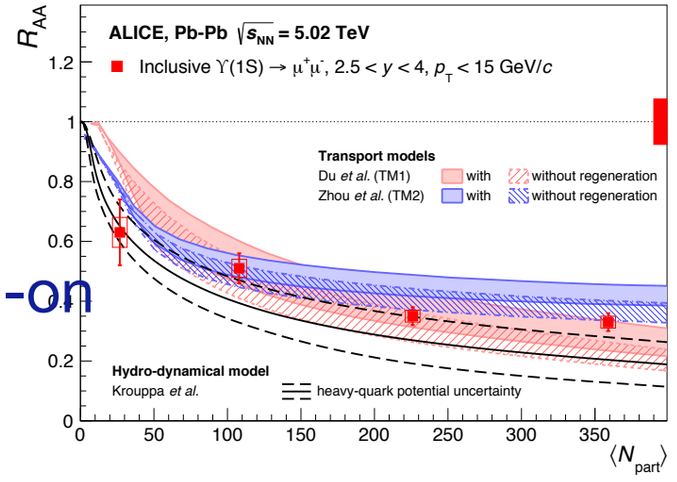


CMS PLB 04, 031 (2017)



CMS-HIN-16-023

ALICE, arXiv:1805.04387



TAMU, X. Du et al PRC 96, 054901 B. Krouppa, et al PRD 97, 016017

	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	500	240	190

	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	600	230	170

Clear hierarchy of suppression, but no sudden turn-on

- T does not change rapidly with centrality
- Average over system
- Melting sets in for $T < T_m$