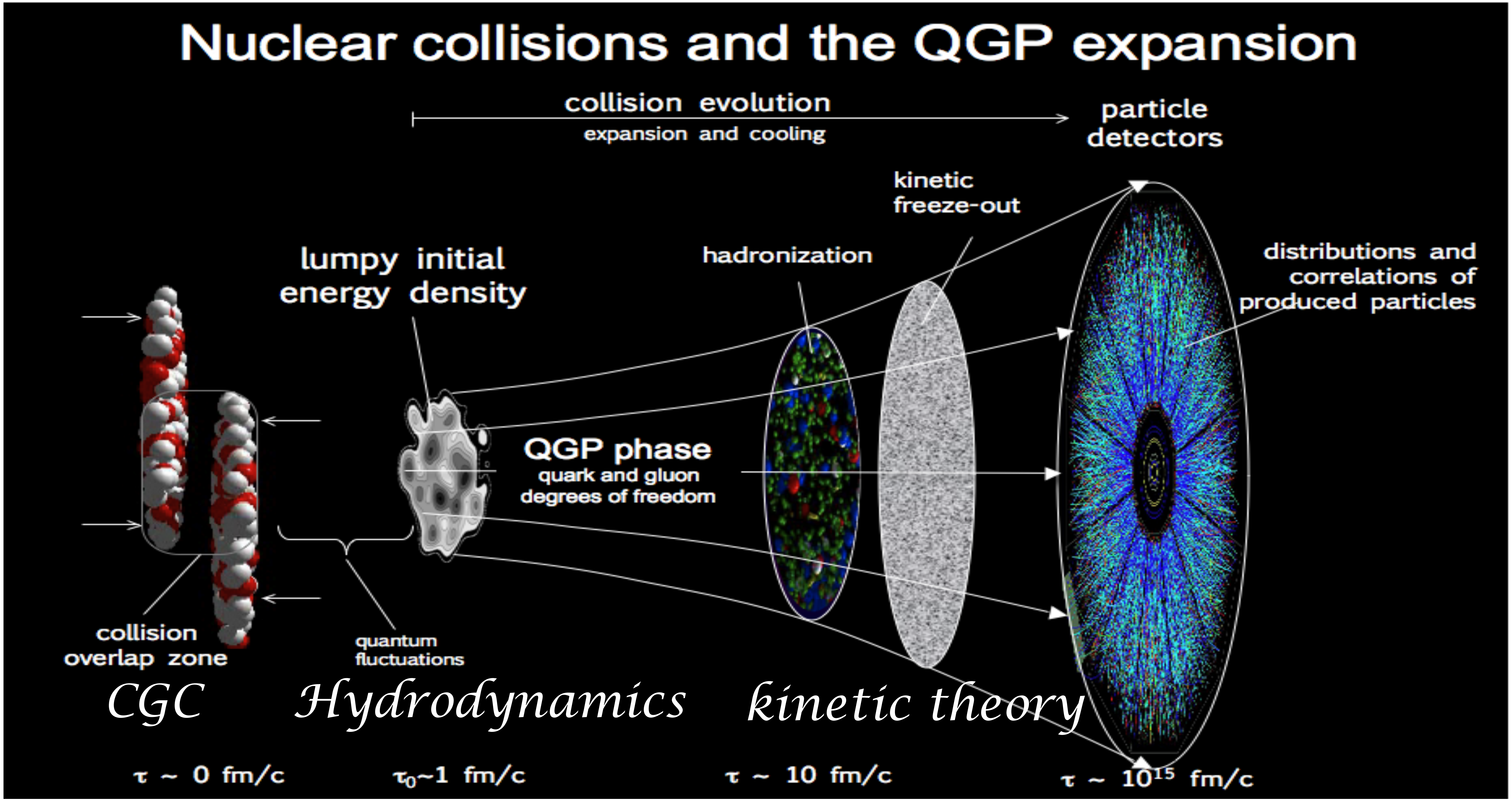
Relativistic Heavy Ions II - How strong is the coupling and can we understand the interactions?

By the end of today's talk I aim for you to be able to discuss at dinner :

What hard probes are and why we use them
What a jet is to a nuclear physicist
What "jet quenching" is
Why heavy quarks interact differently with the QGP than light quarks

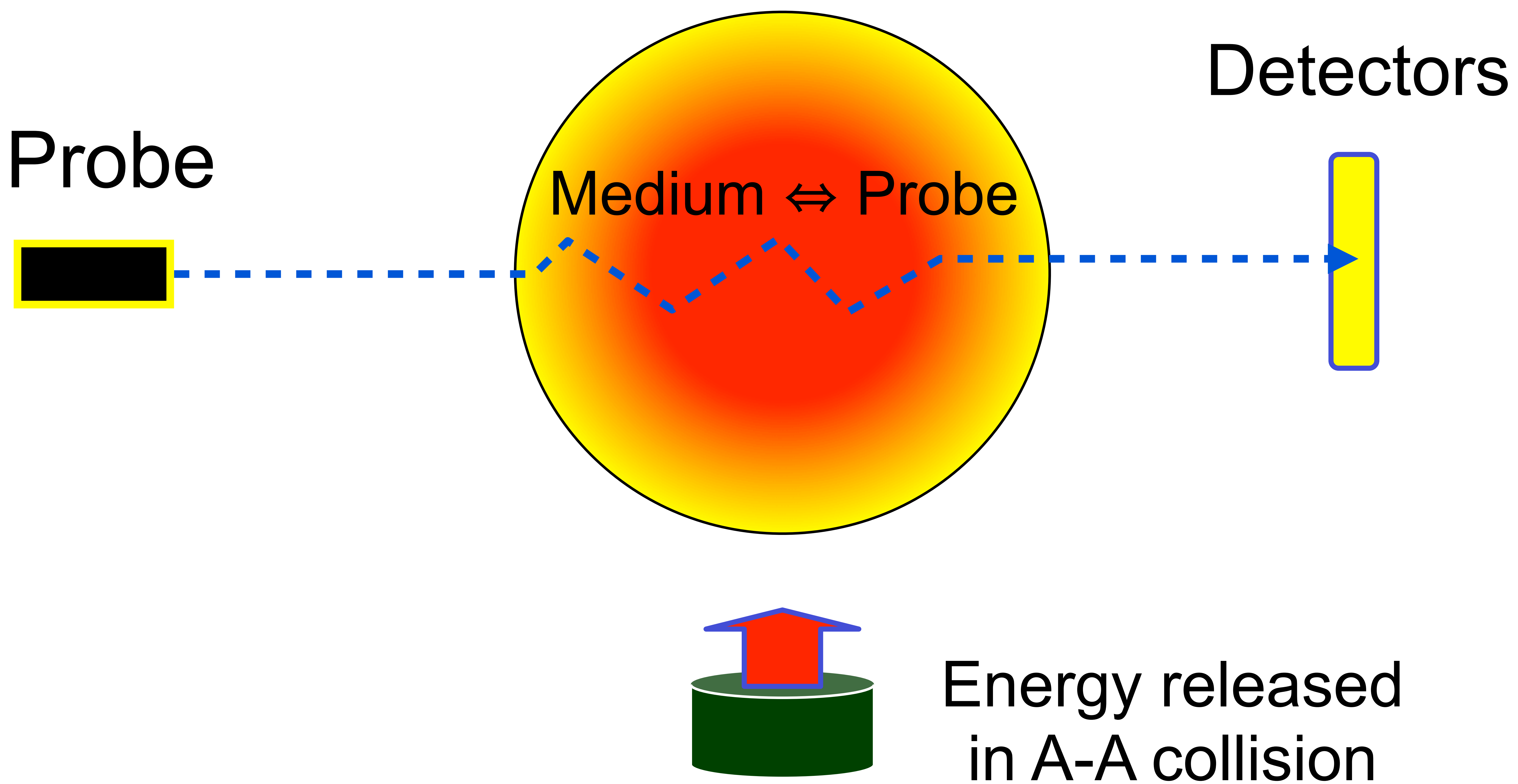
Recap of yesterday



Can we understand the nature of QGP by studying how highly energetic parton interact with it?

Defining a probe

Matter we want to study

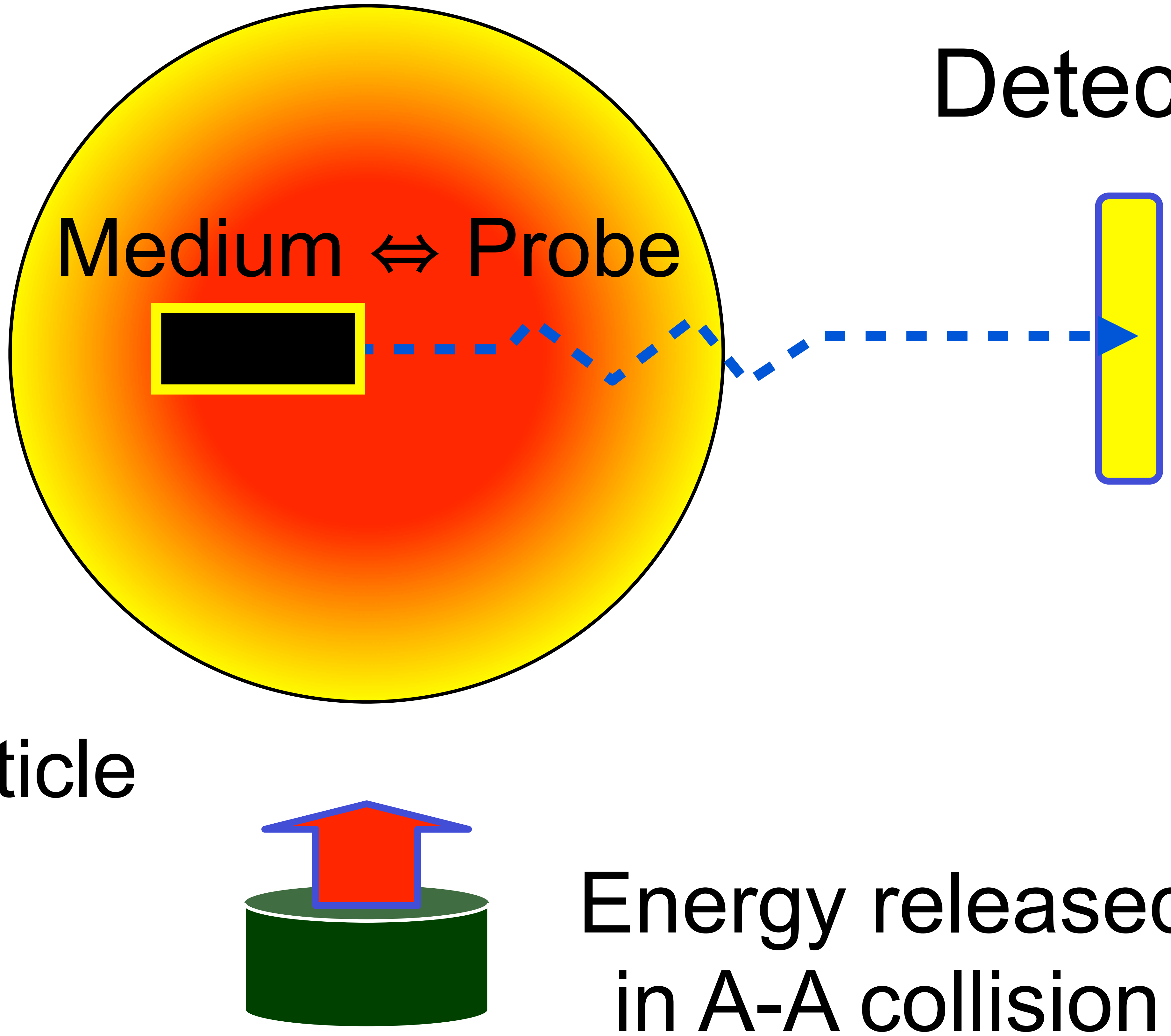


Defining a probe

Matter we want to study

Self-generated &
calibrated probes

Detectors



Hard partons (q, g)
- High momentum particle
- Heavy flavor particle
- Jet

Energy released
in A-A collision

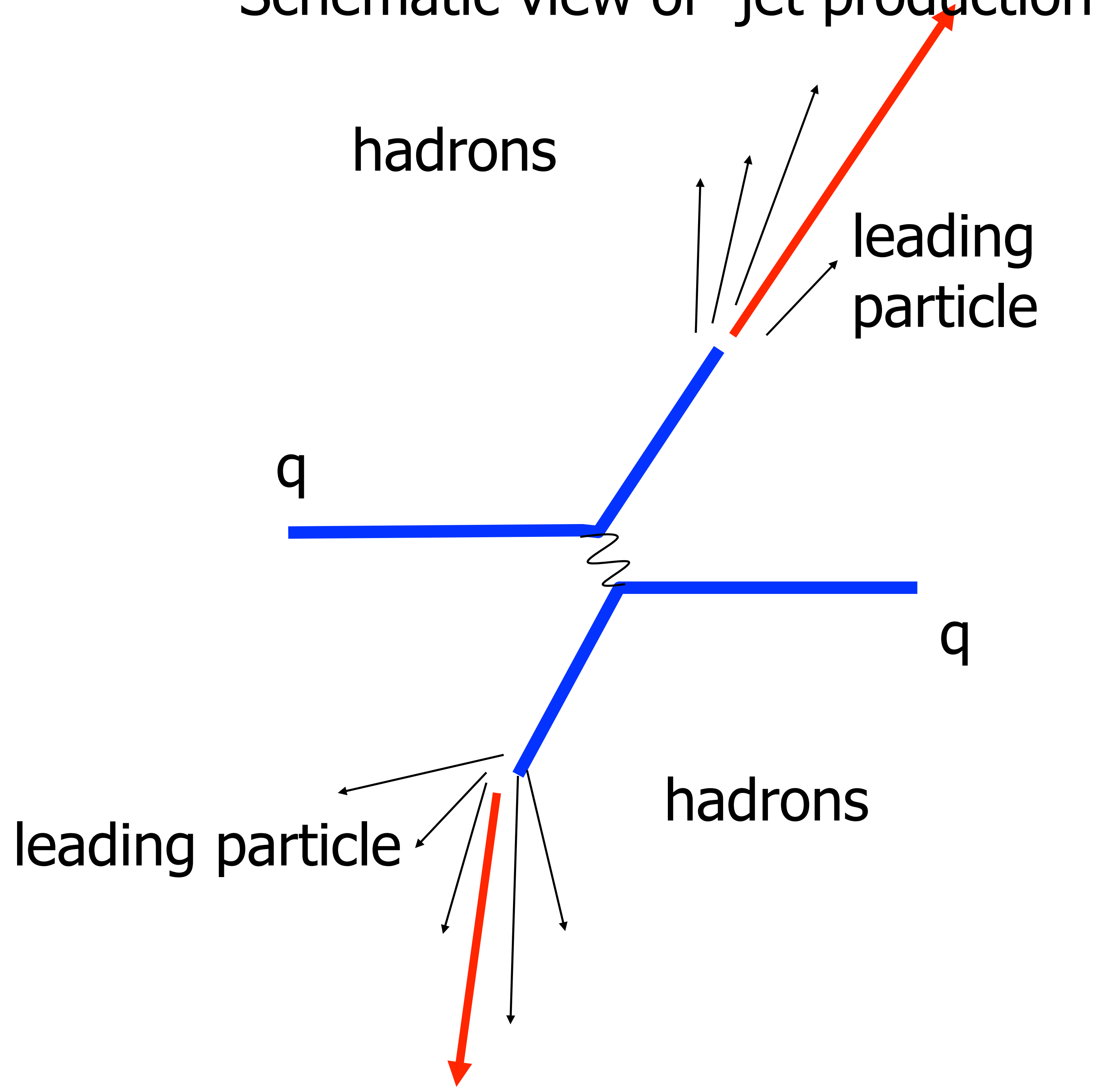
Using "hard" particles as probes

'Hard' processes have a large scale in calculation $\rightarrow$ pQCD applicable:

<u>high</u> momentum transfer Q^2

<u>high</u> transverse momentum p_T

<u>high</u> mass m (N.B.: since m>>0 heavy quark production is 'hard' process even at low p_T)



Early production in parton-parton scatterings with large Q^2

Using "hard" particles as probes

'Hard' processes have a large scale in calculation → pQCD applicable:

- high momentum transfer Q^2
- high transverse momentum p_T
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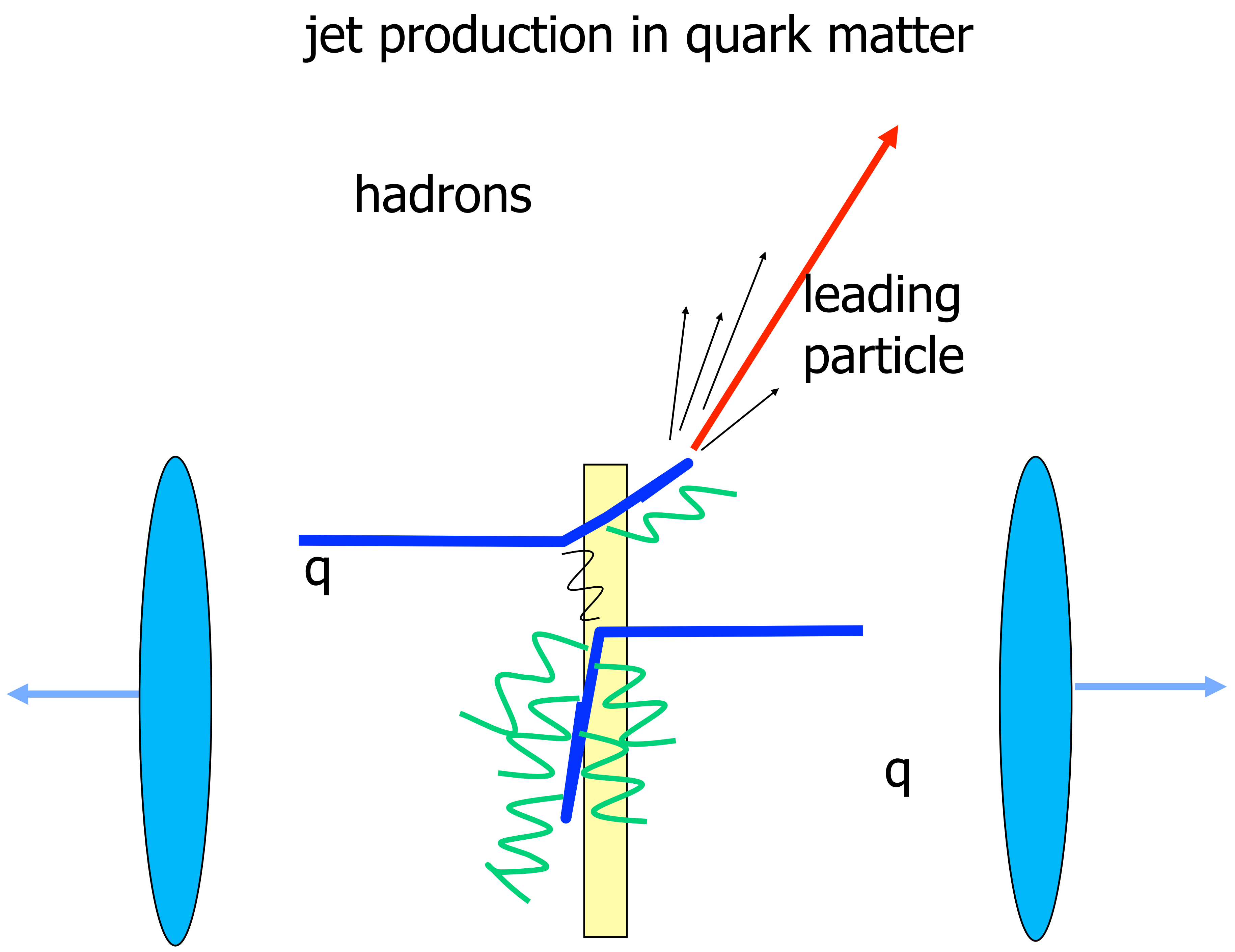
Early production in parton-parton scatterings with large Q^2

Direct interaction with partonic phases of the reaction i.e. a calibrated probe

Look for attenuation/ absorption of probe



The LHC is a hard probes machine

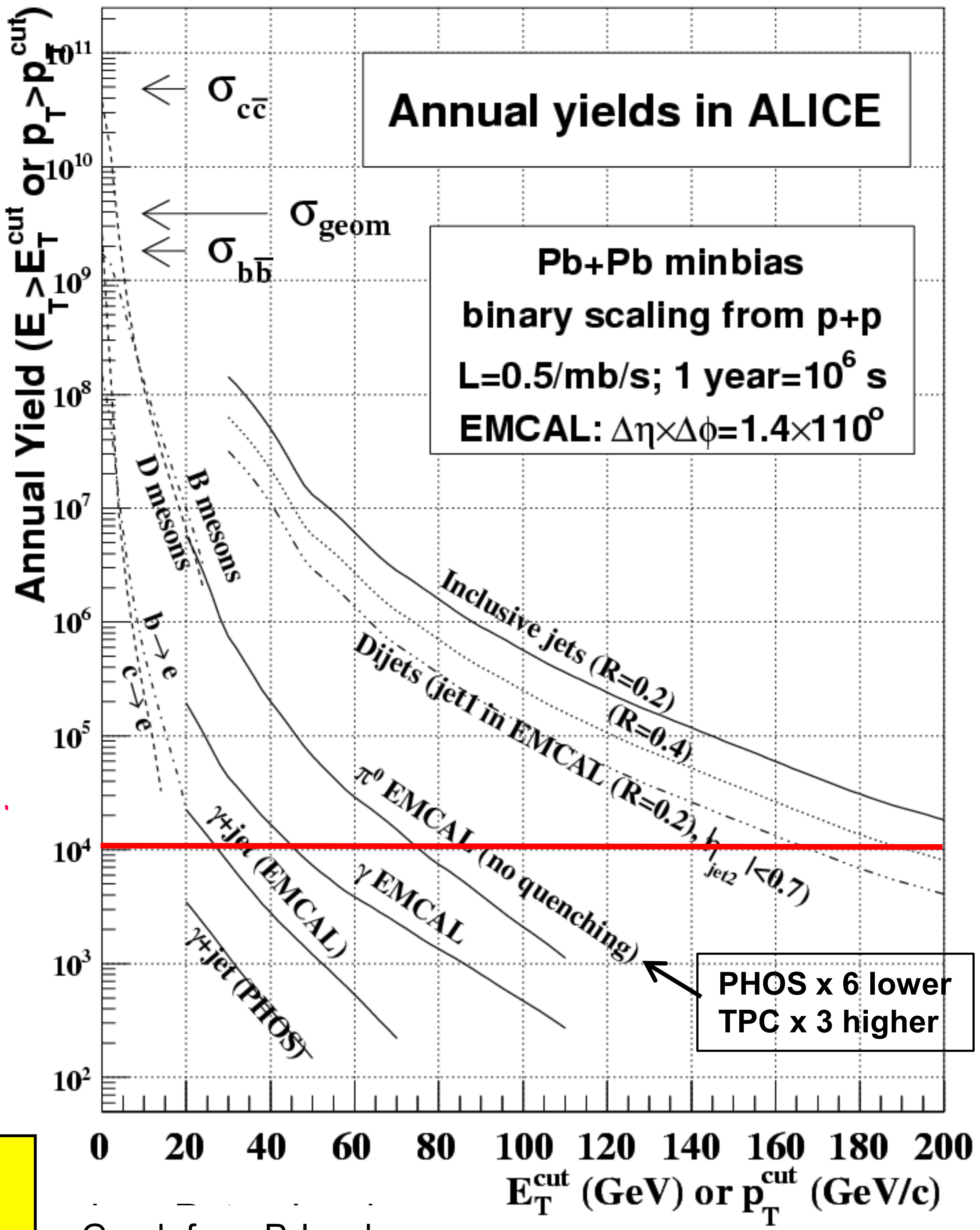
An LHC Pb-Pb year:

1 month ~ 10^6 seconds

Need 10^4 "events" in a year to make a measurement:

- inclusive jets E_T < 200 GeV
- di-jets E_T < 170 GeV
- π^0 p_T <75 GeV
- inclusive γ p_T<45 GeV
- inclusive e p_T<30 GeV

- σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)
- σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)



Graph from P.Jacobs

Hard probes are no longer rare probes

Is charm a calibrated probe?

Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0	39 ± 1 ± 1
	$D^\pm$	18 ± 1 ± 3*
	D_s	15 ± 2 ± 4
	Λ_c	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV	**Total**	130 ± 30 ± 26

Total charm production cross section per nucleon-nucleon in Au-Au consistent with that measured in pp collisions:

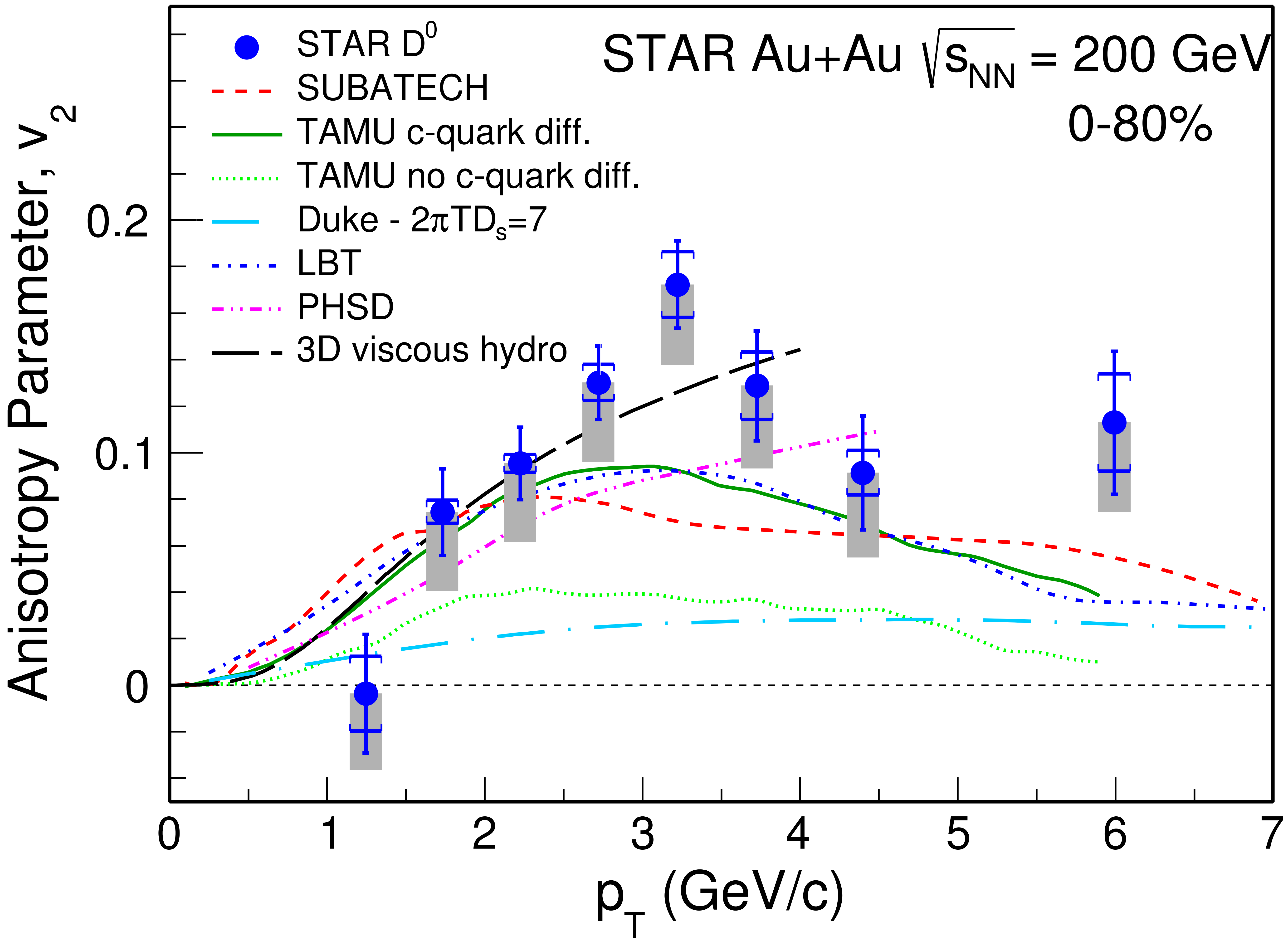
N_{coll} scaling of charm production

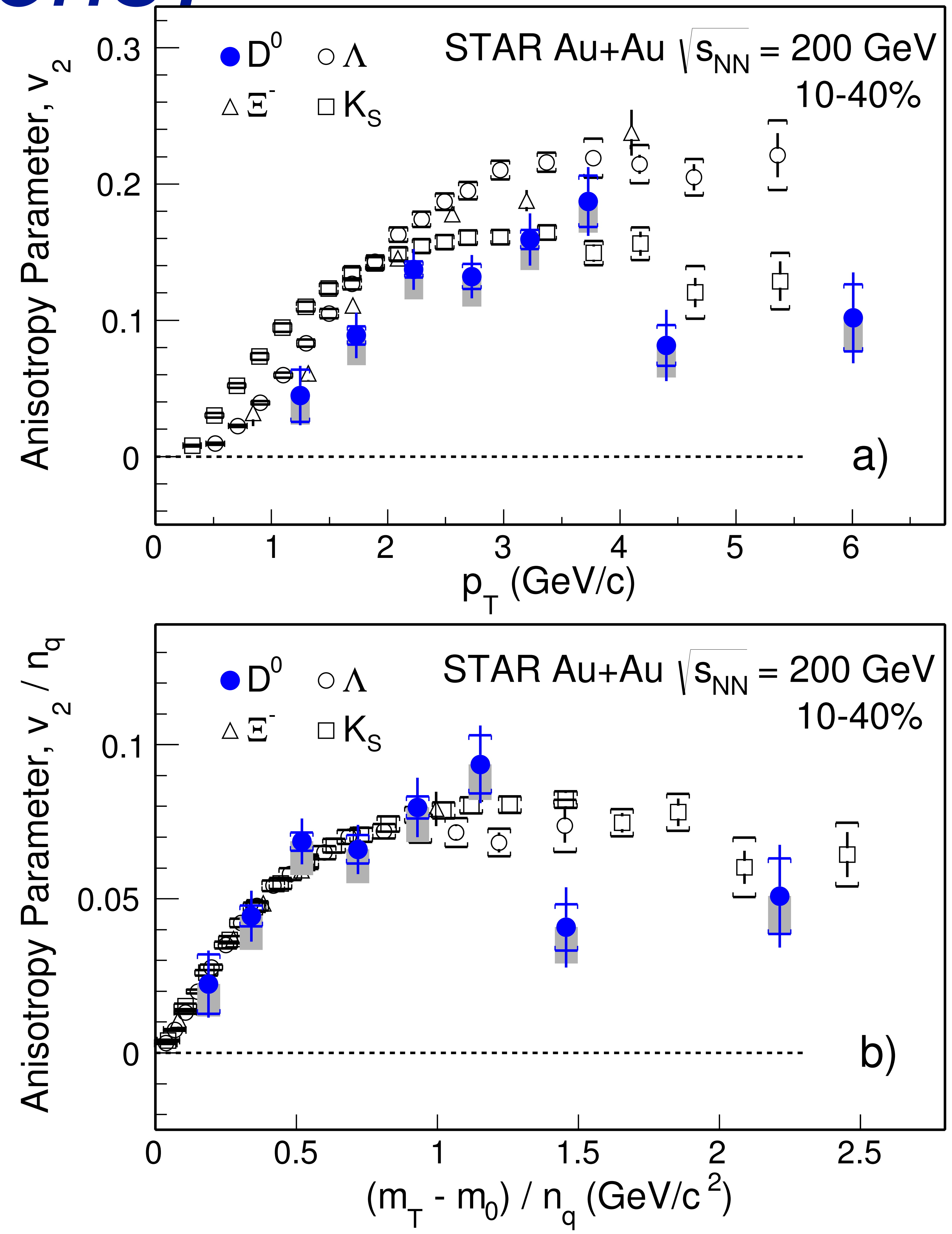
Measurement required dedicated precision vertex tracking and coverage to $p_T = 0$ GeV/c

Heavy flavor production is a calibrated probe

STAR: PRC 99 (2019) 034908, PRL 127 (2021) 092301, PRL 124 (2020) 172301, PRD 86 (2012) 071013

What about the heavy quark interactions?



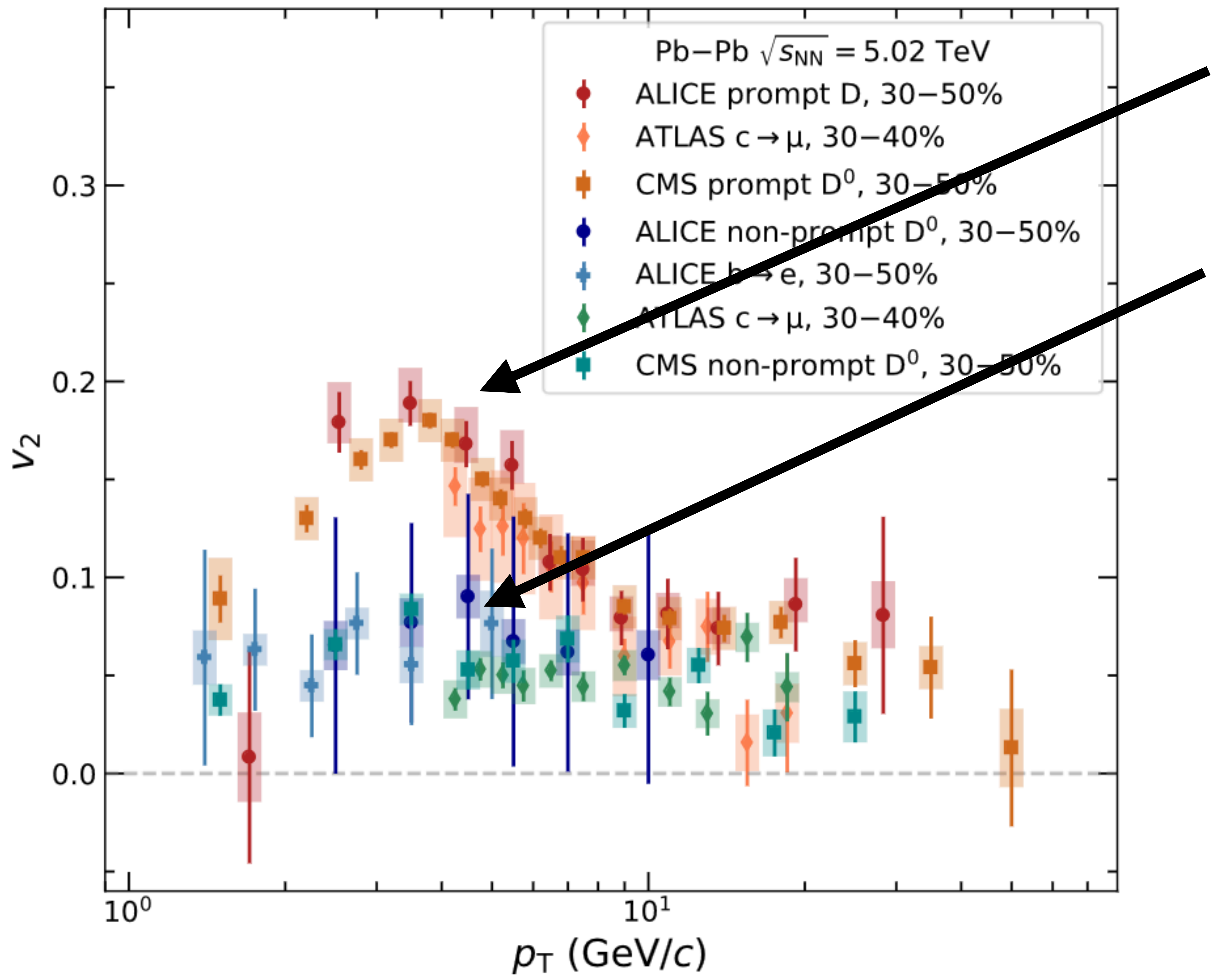


Charm hadrons also flowing
- significant rescattering
- at quark or hadronic level?

NCQ scaling of charm
- thermalization of heavy quarks

STAR: PRL 118 (2017) 212301

Even beauty is flowing



Charm flows strongly

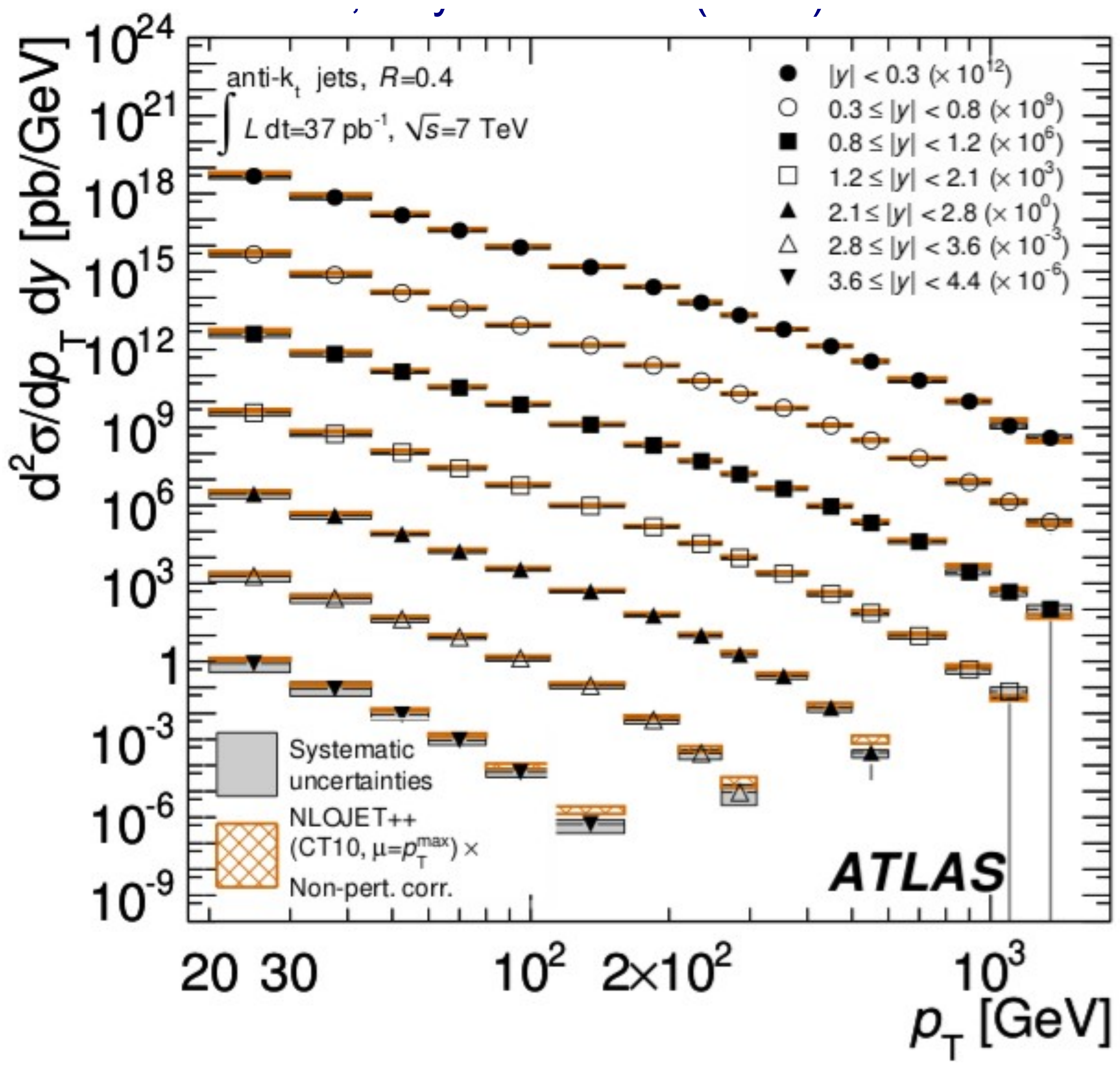
Beauty is participating in the bulk collectivity but not as strong

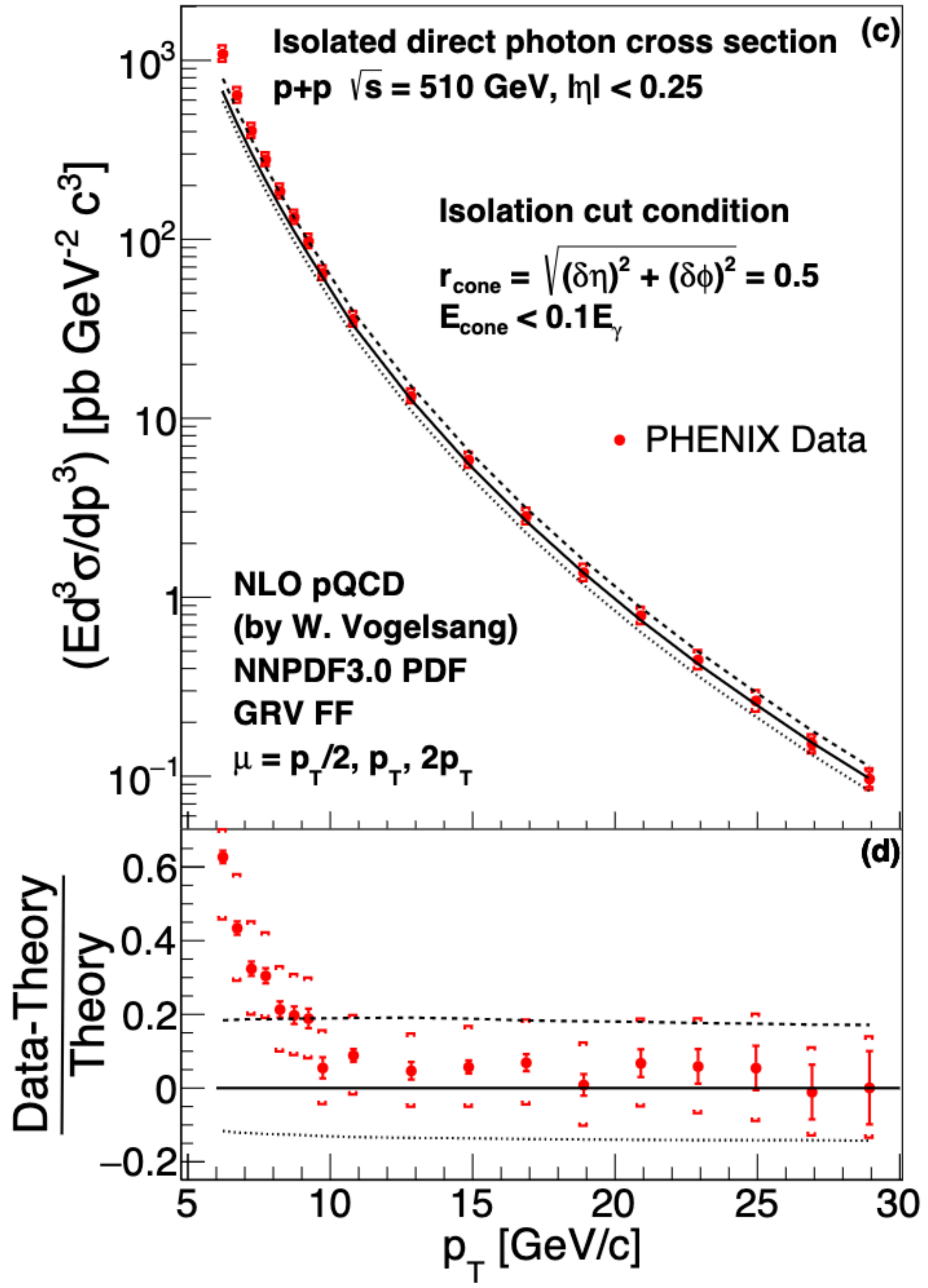
Suggests beauty only partially thermalized

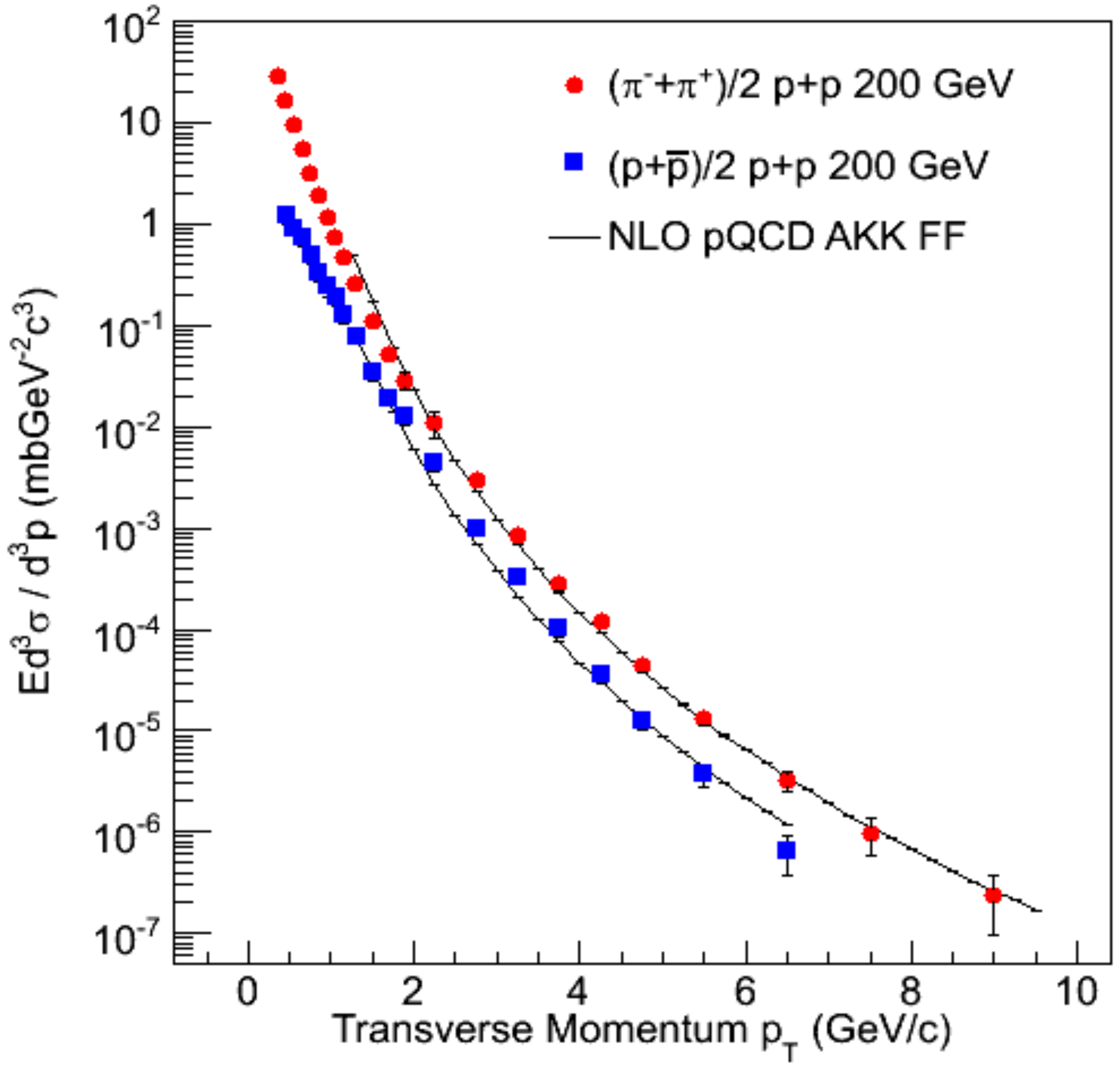
Models suggests collisional interactions needed

ALICE: PLB 813 (2021) 136054, arXiv:2307.1408, PRL 126 (2021) 162001, ATLAS: PLB 807 (2020) 135595, PLB 807 (2020) 135595, CMS PLB 816 (2021) 136253,arXiv: 2212.01363

High p_T production – a calibrated probe







Jet cross-section in p-p is well described by NLO pQCD calculations over many orders of magnitude at RHIC and LHC

Jet and particle spectra well calculated by pQCD

Minimum bias γ production in p-p well modeled

Minimum bias particle production in p-p also well modeled

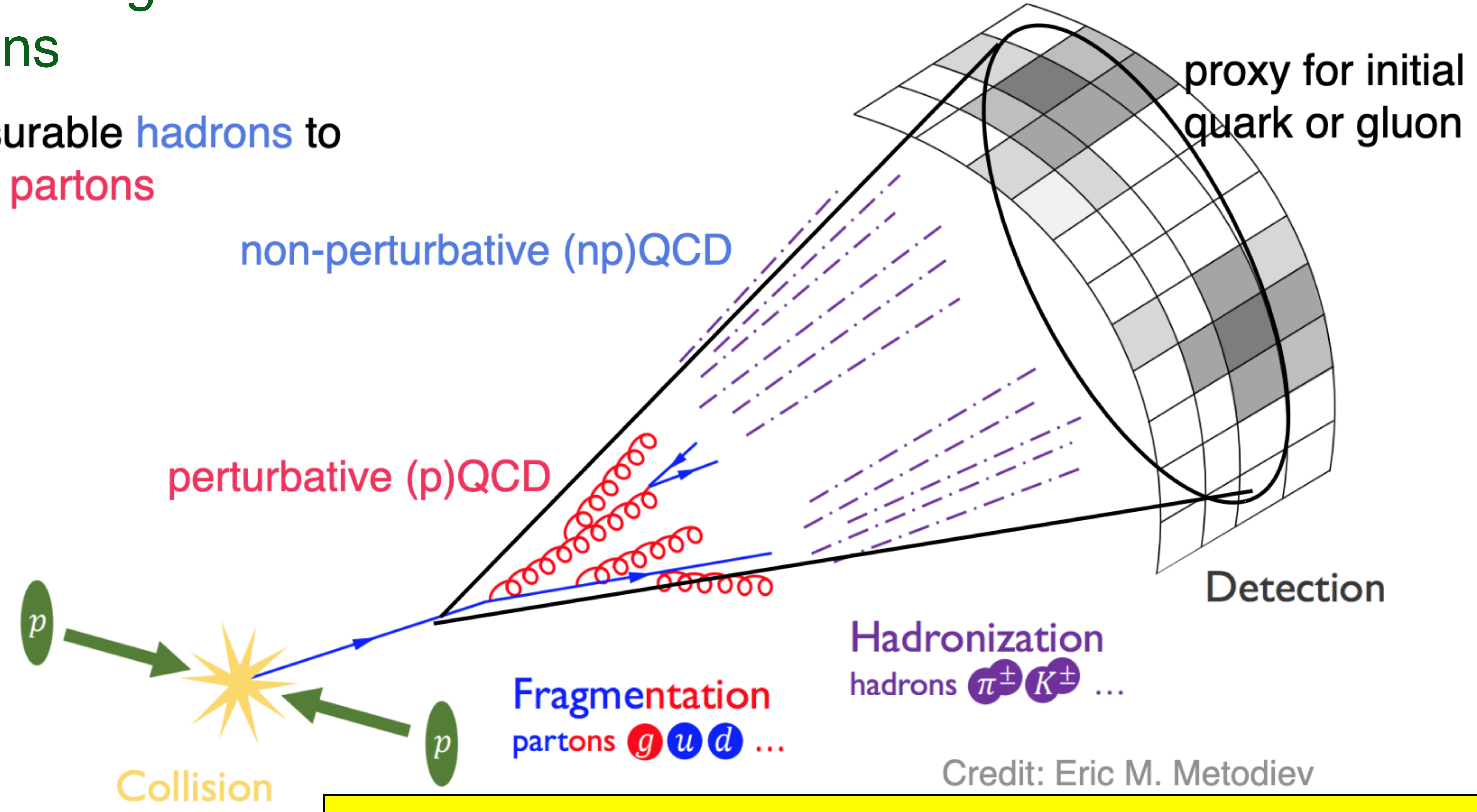
ATLAS: PRD 86 (2012) 014022, PHENIX: *PRL* 130 (2023) 25, 251901 STAR: PLB 637 (2006) 161, S. Albino et al. NPB 725 (2005) 181

Jets as tools to study QCD and the QGP

Collimated sprays of particles

- colored parton fragments and hadronizes into colorless hadrons

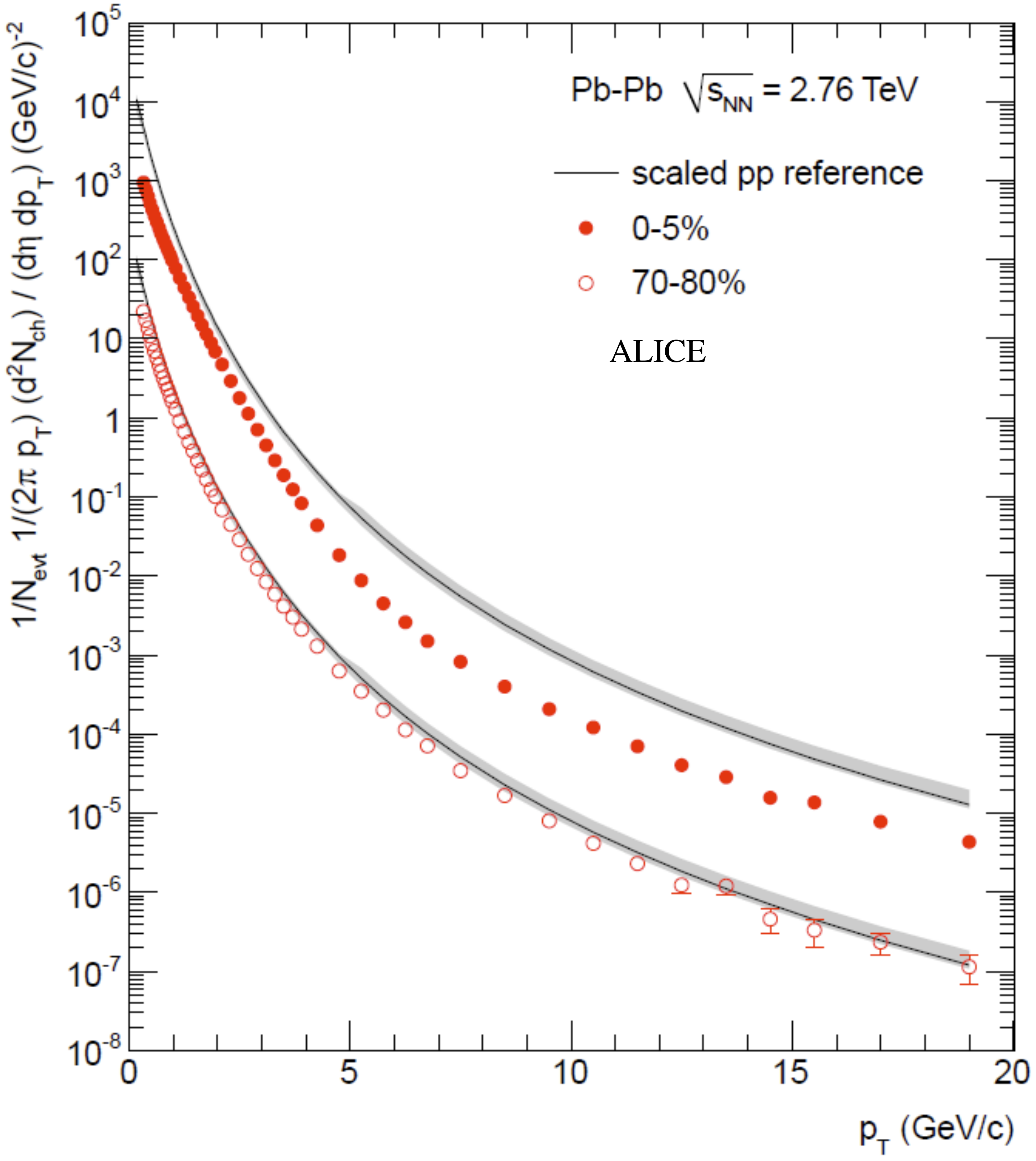
Connect measurable hadrons to unmeasurable partons

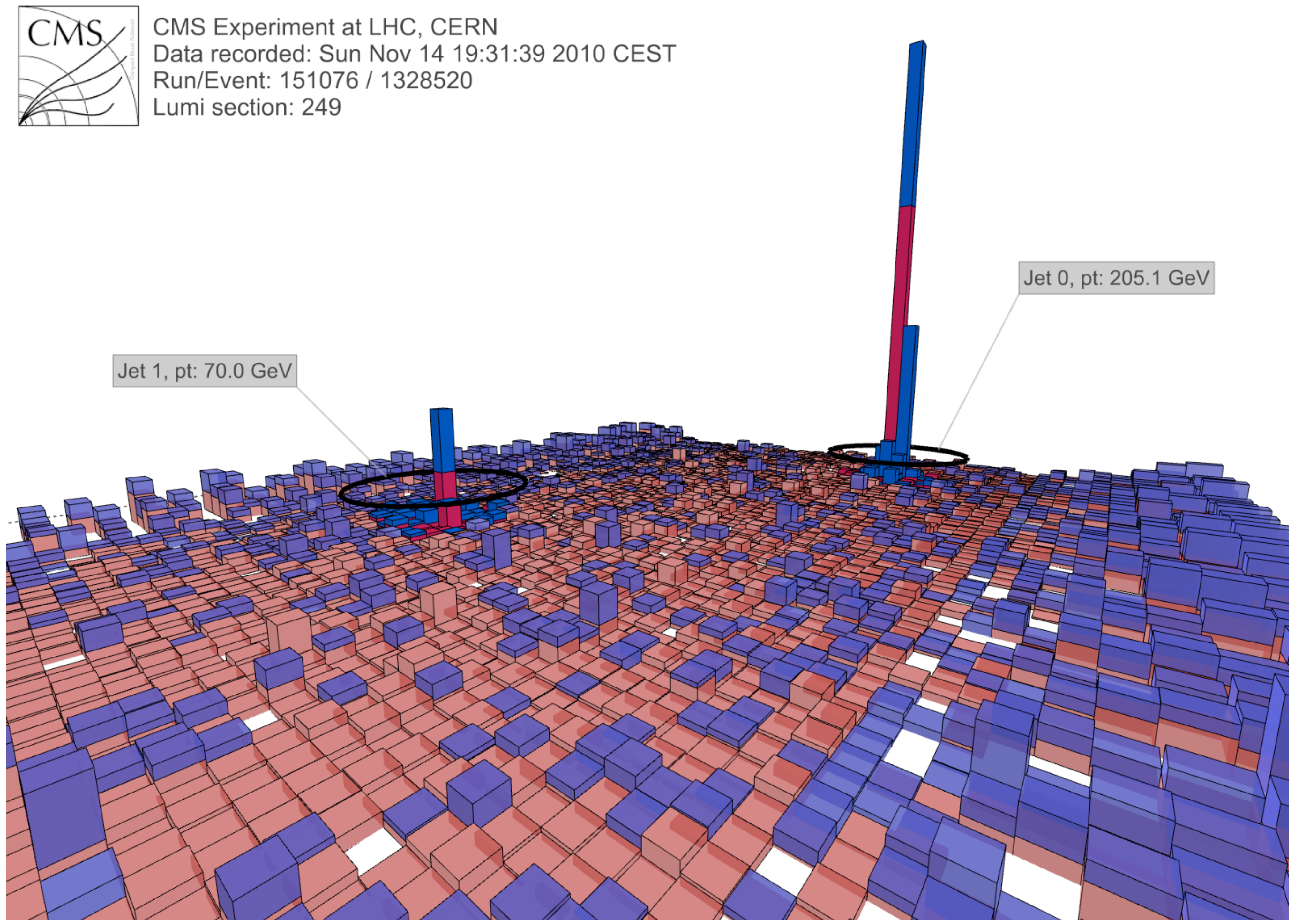


Credit: Eric M. Metodiev

Multi-scale complex dynamic objects resulting from principles of QCD

Start off simple - high p_T particles





Clear shape change at high p_T for central collisions

Even visible by eye in event displays at LHC

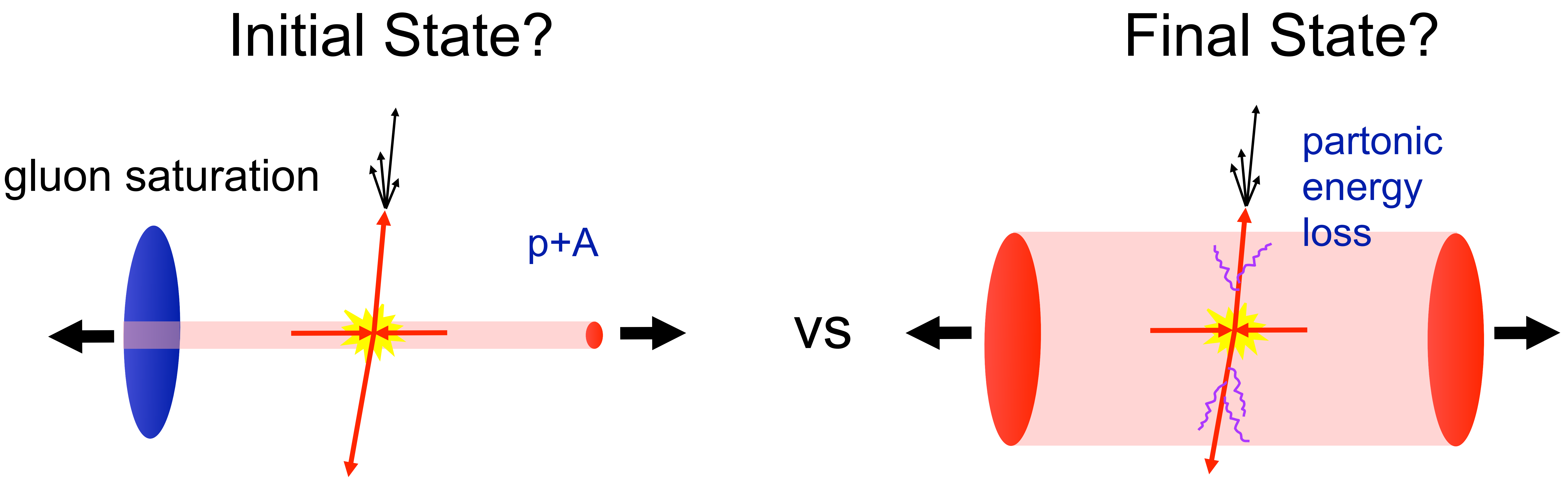
p-p reference:
Interpolation of 0.9 and 7 TeV data
7 TeV data scaled by NLO QCD calc.

ALICE PLB696 (2011)

Initial or final state effects?

A clear difference between p-p and A-A observed:

Caused by initial state (quark/gluon shadowing)
or final state (energy loss in plasma) effects?

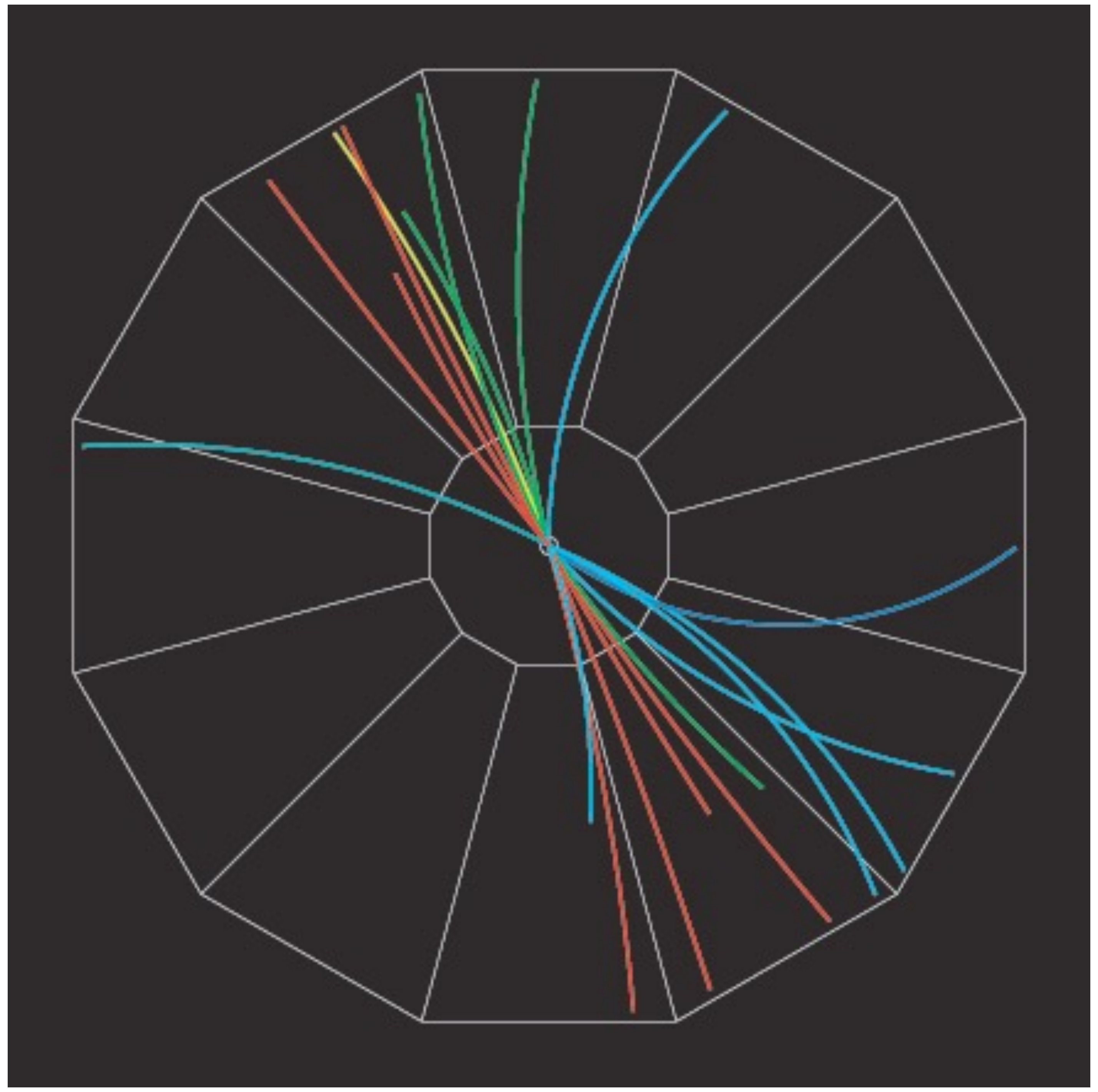


To test need collisions where no final state effects due to plasma but initial nuclear state effects present:

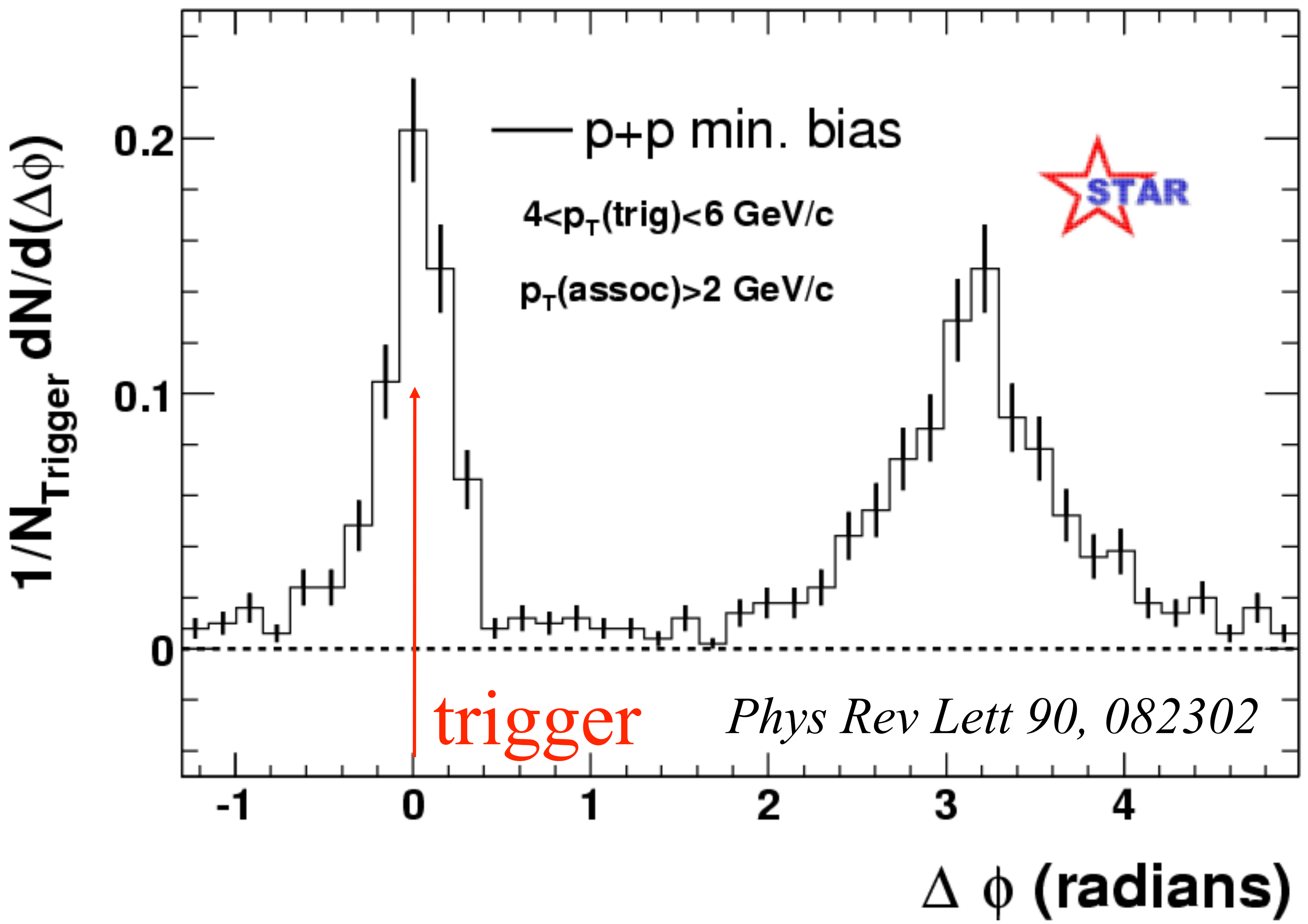
Use p-A (d-A)

Examine di-hadron correlations

p-p → dijet



min. bias p-p collisions

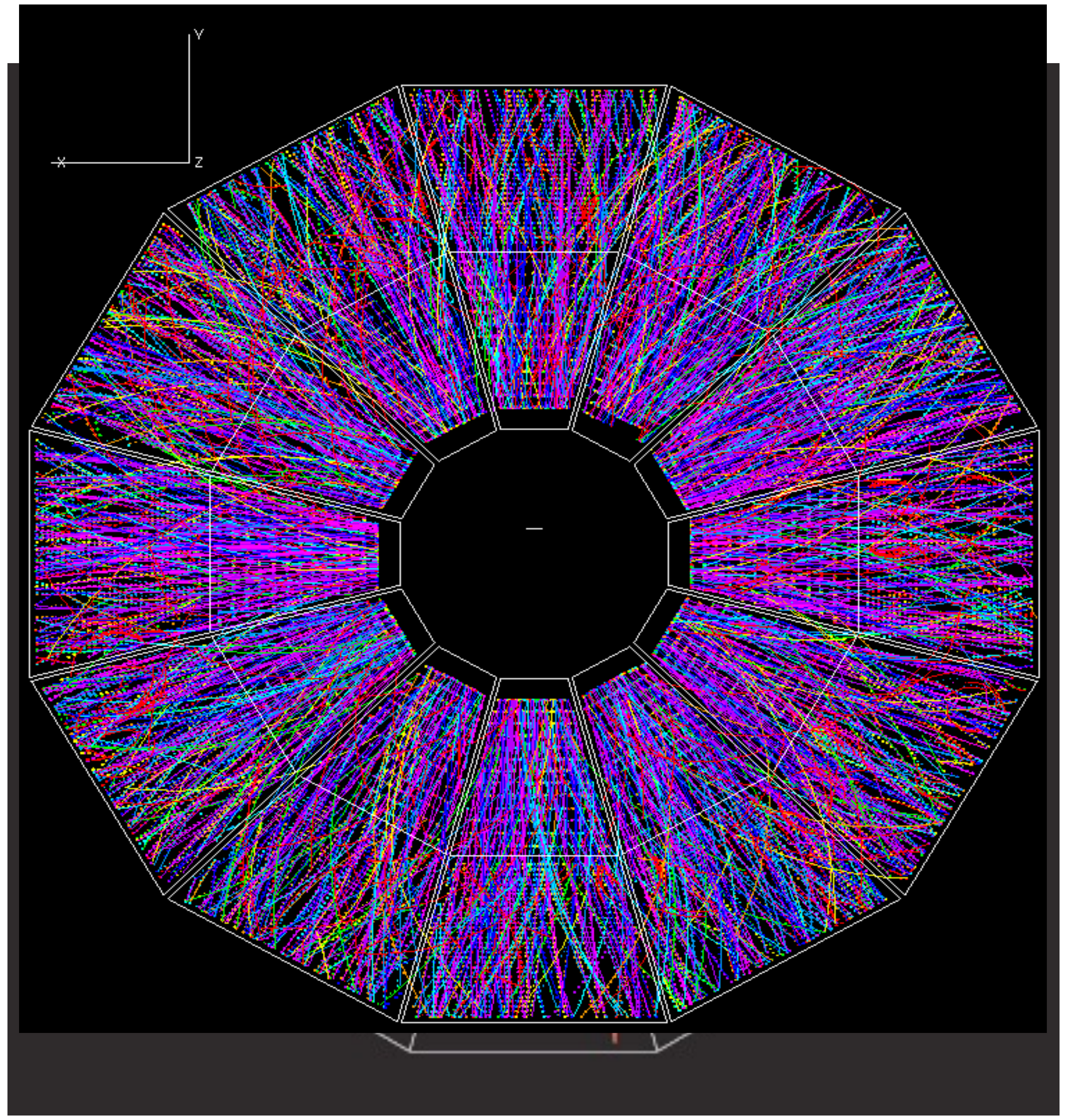


Trigger: highest p_T track
$\Delta\varphi$ distribution:

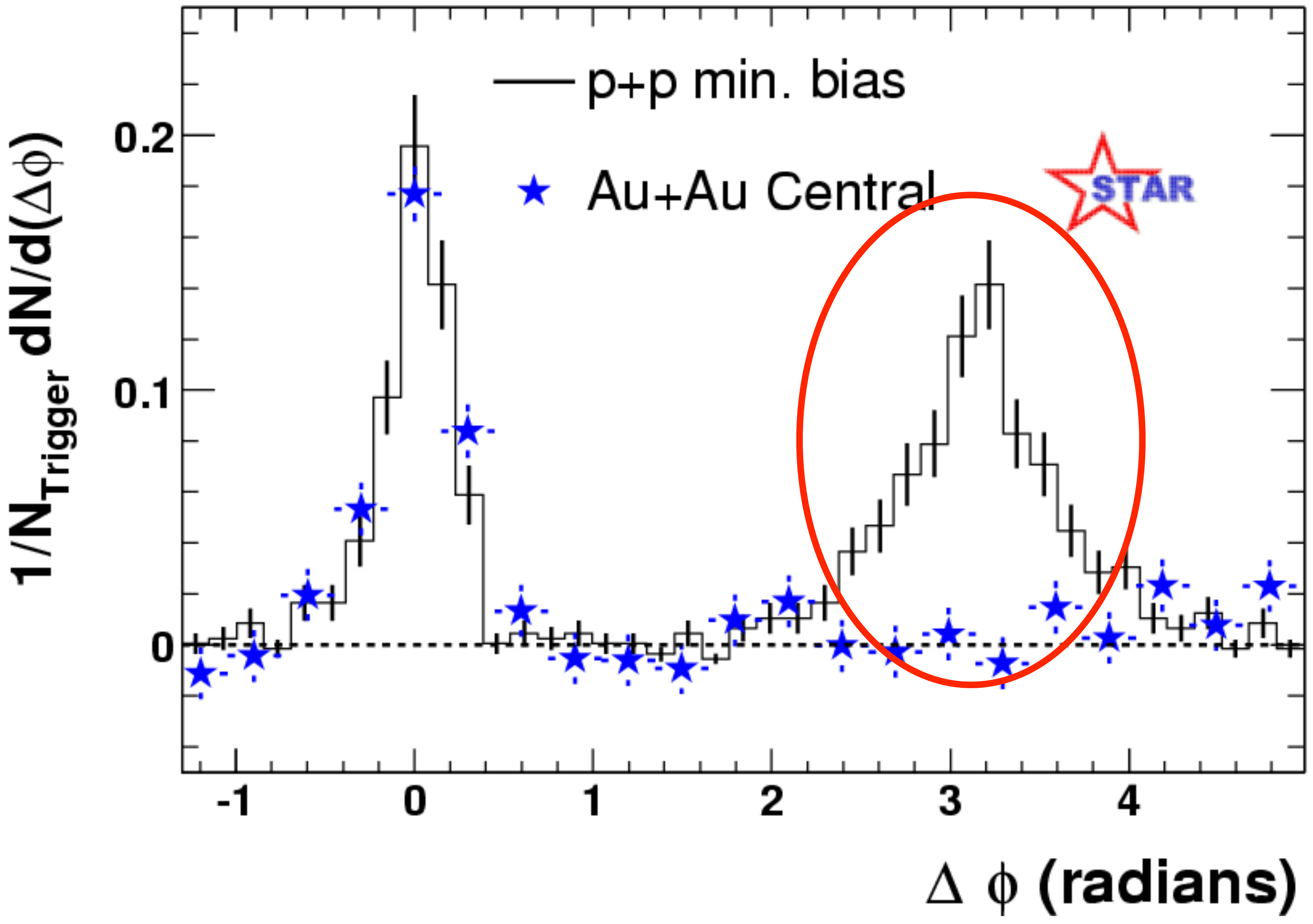
STAR: PRL 90 082302 (2003)

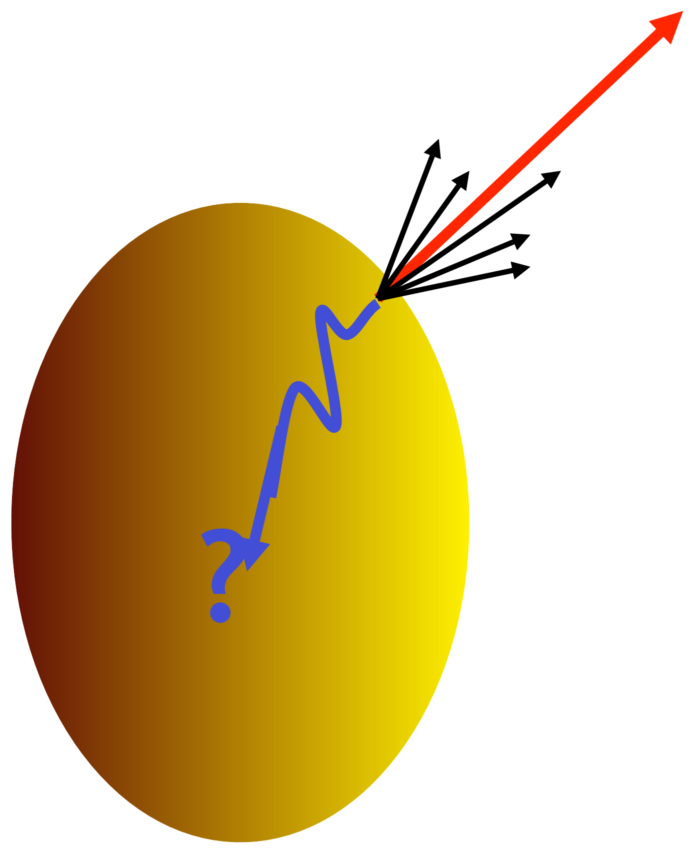
Examine di-hadron correlations

p-p → dijet



central Au-Au collisions





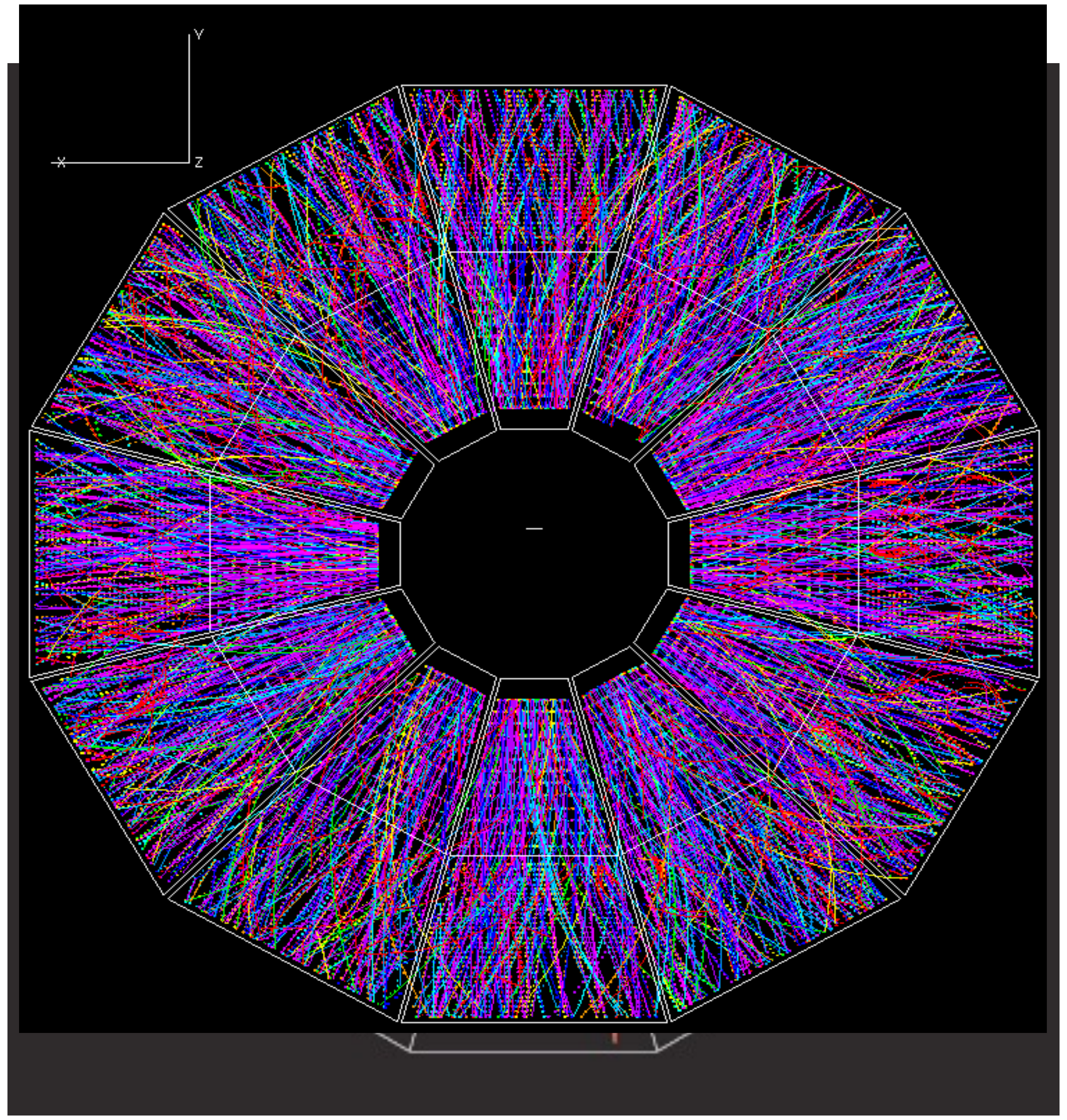
Δφ ≈ 0: central Au-Au similar to p-p

Δφ ≈ π: strong suppression in A-A

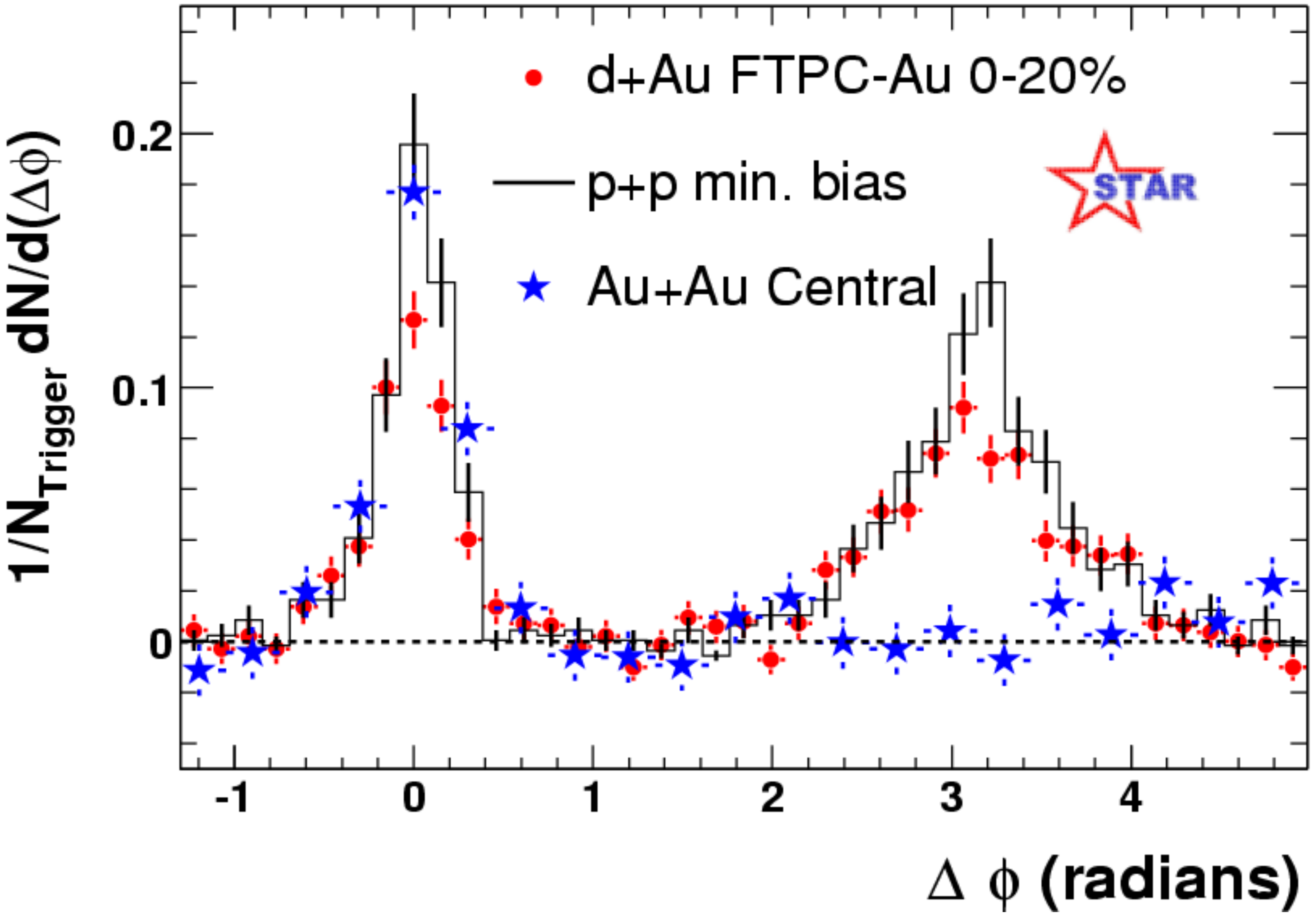
STAR: PRL 90 082302 (2003)

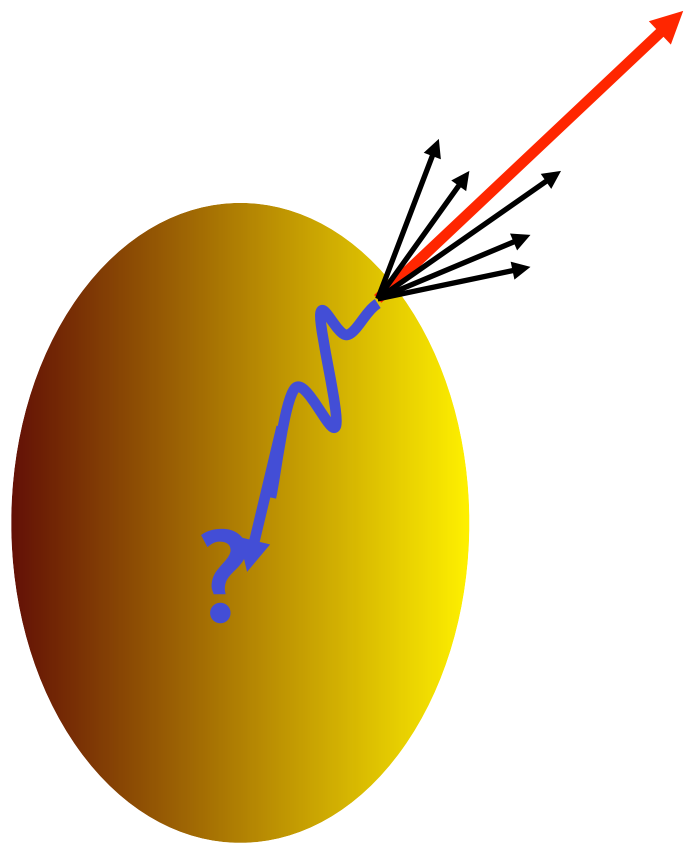
Examine di-hadron correlations

p-p → dijet



central Au-Au collisions





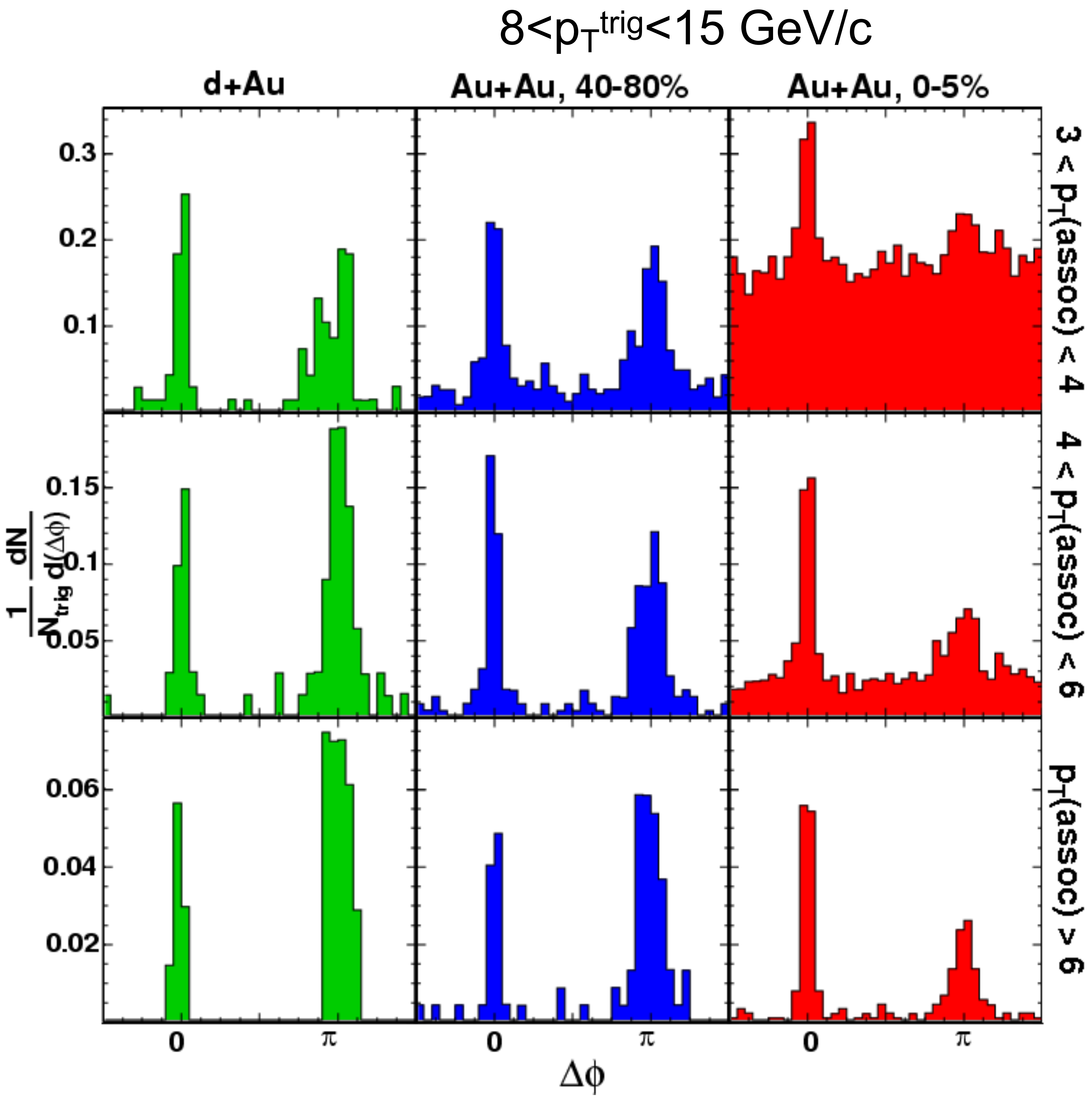
Δφ ≈ 0: central Au-Au similar to p-p

Δφ ≈ π: strong suppression in A-A

Not in d-Au - its a final state effect

STAR: PRL 90 082302 (2003)

Observation of "Punch through"



If use higher p_T particles:

Away-side peak re-emerges

Smaller in Au-Au than d-Au

Virtually no background

High energy jets *"punch through"* the medium.

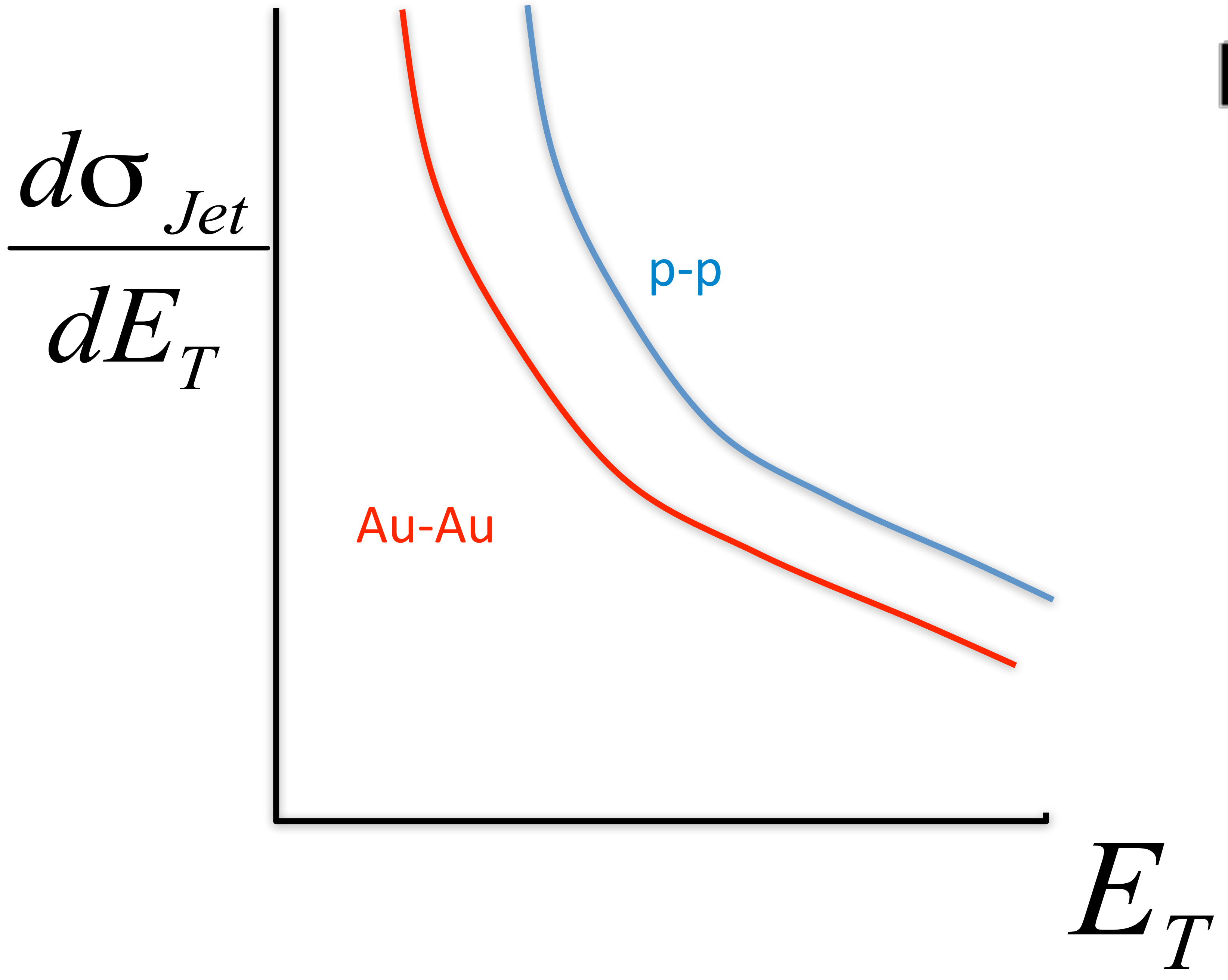
STAR PRL 97 (2006) 162301

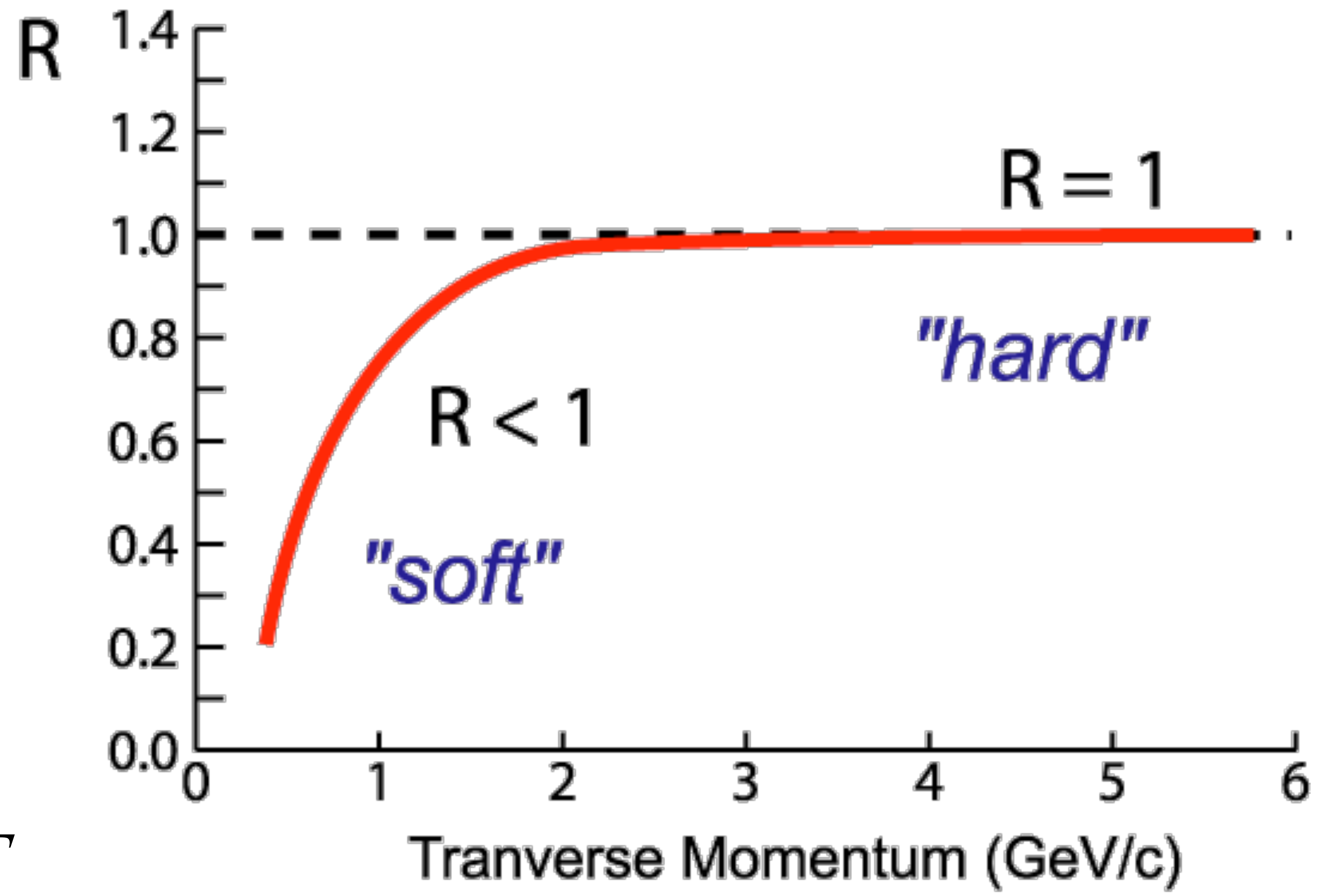
How do partons interact with the QGP?

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\times\langle N_{coll}\rangle}$$

Average number of p+p collisions in A+A collision





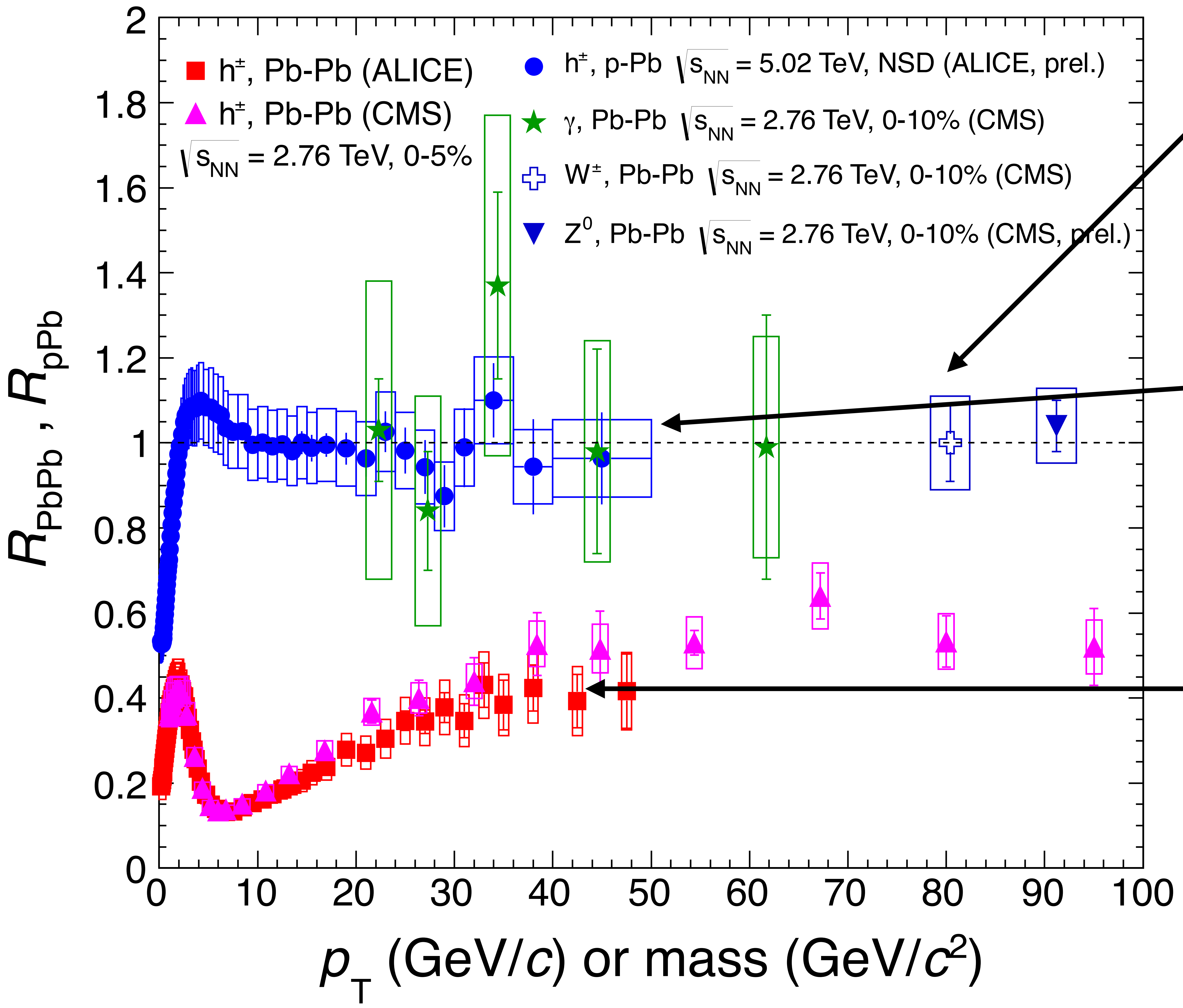
No "Effect":

R < 1 at small momenta - production from thermal bath

R = 1 at higher momenta where hard processes dominate

R<1 at high p_T if QGP affecting partons' propagation

Very strong coupling



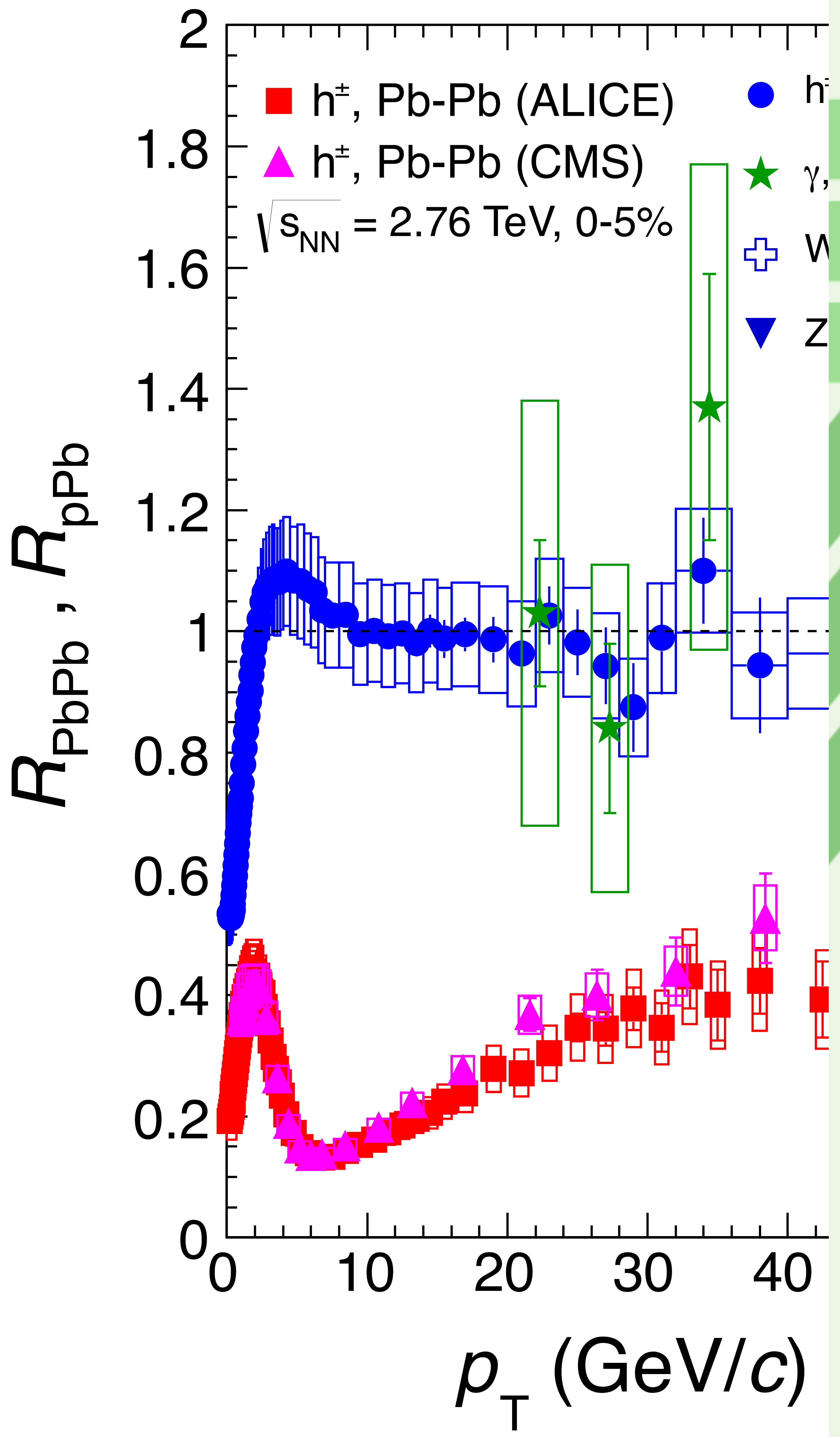
Colorless objects should not interact with colored QGP
show no suppression

Minimum p-Pb collisions don't form QGP
R_{pPb} shows no suppression

Hadrons are suppressed in central collisions
Huge: factor 5

sQGP - strongly coupled - colored objects suffer large energy loss

Very strong coupling



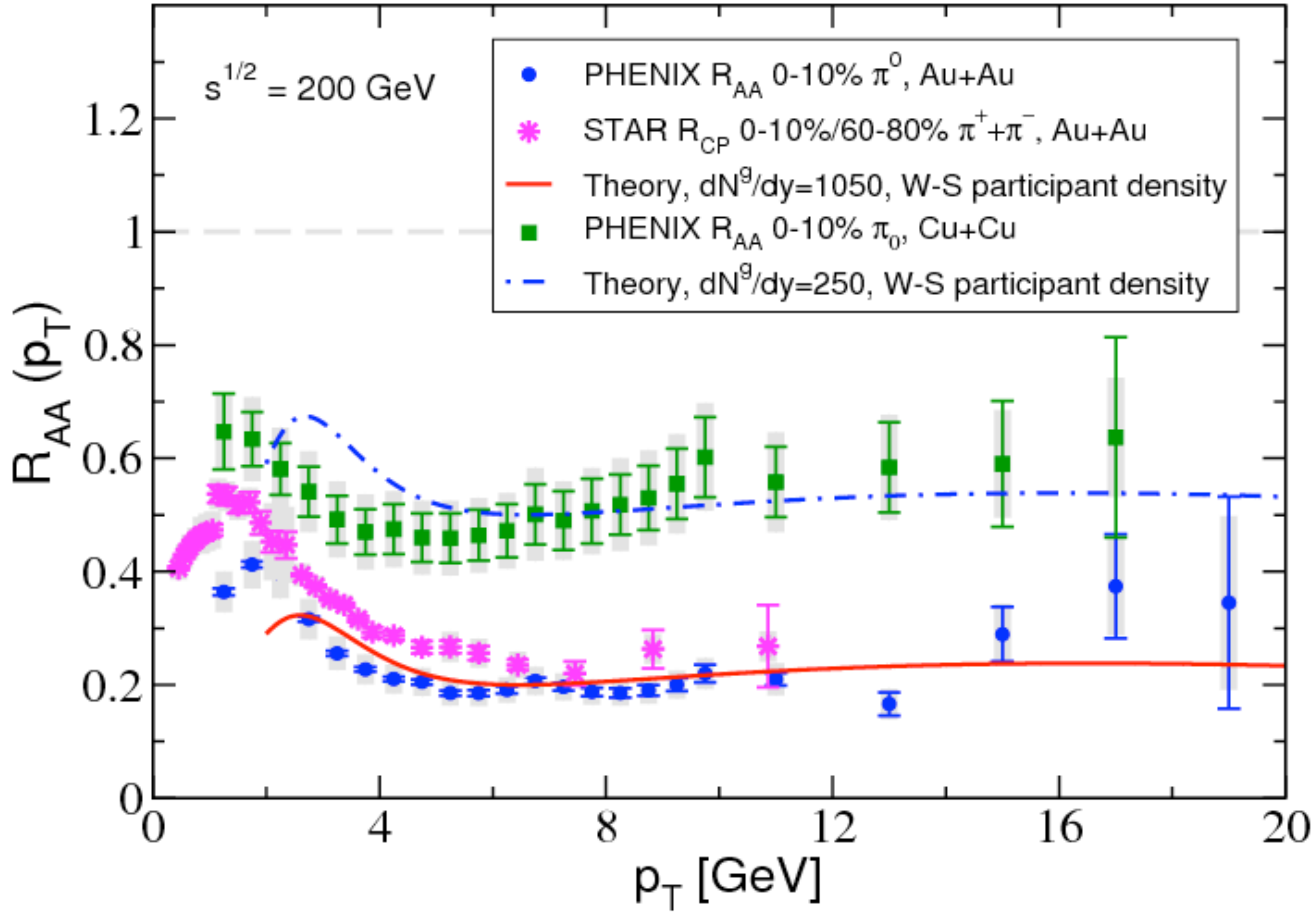
…orless objects should not …ract with colored QGP
…ow no suppression

…imum p-Pb collisions …'t form QGP
…Pb shows no suppression

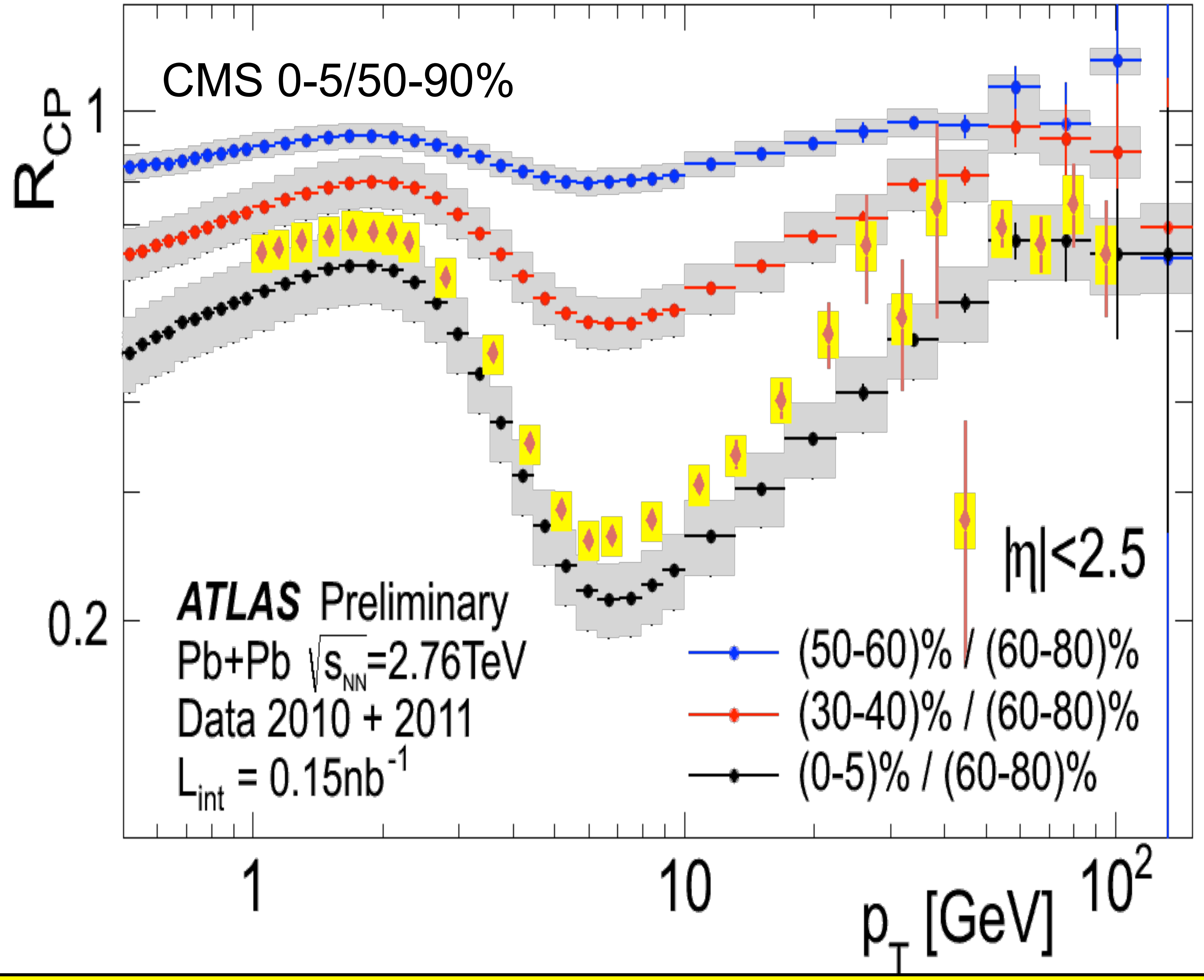
…adrons are suppressed … central collisions
Huge: factor 5

…P - strongly coupled - …ed objects suffer large energy loss

Strong suppression of high p_T particles



Collisions of heavier ions results in more quenching

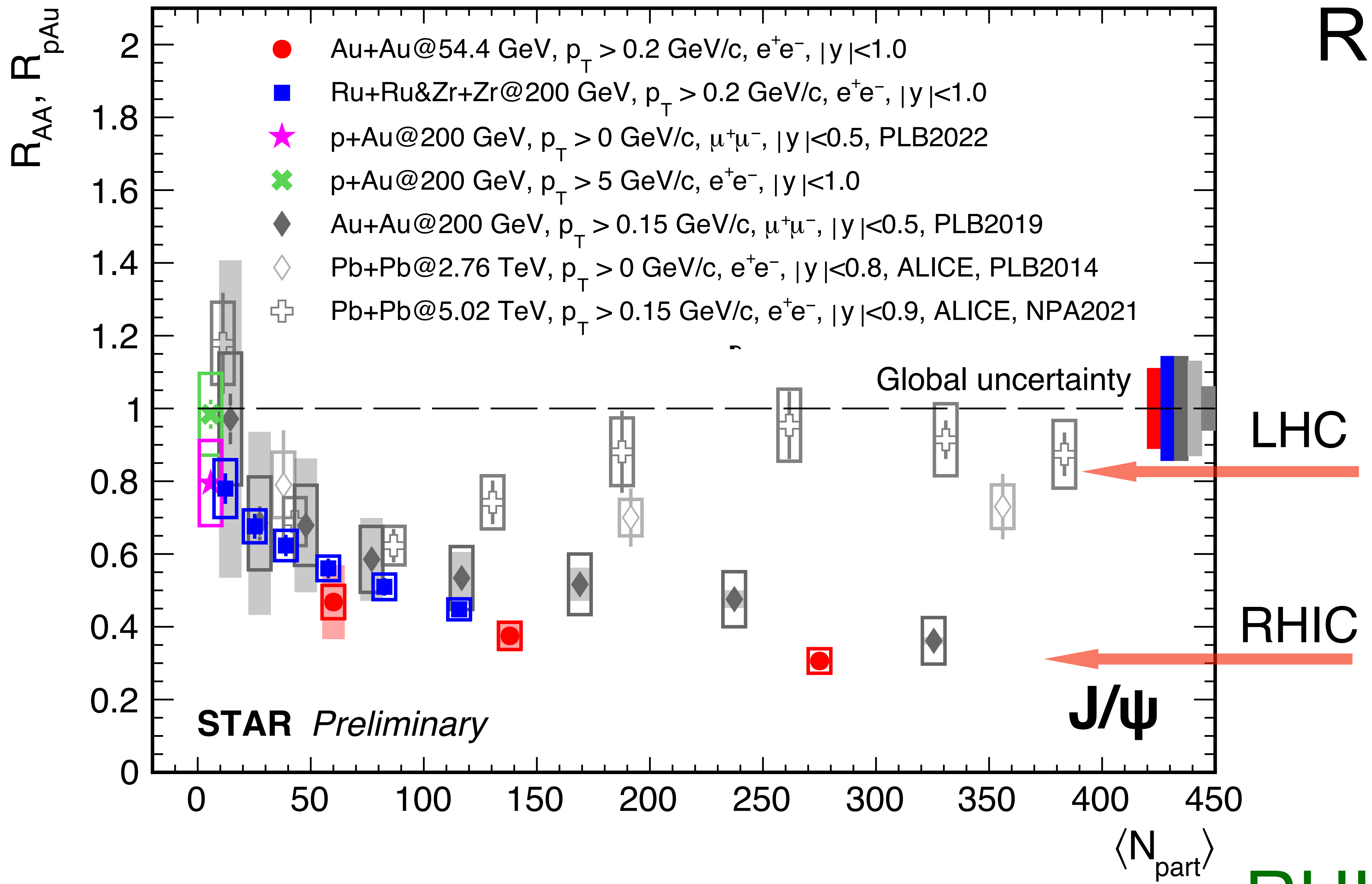


High p_T hadrons hadronize
at RHIC: from quarks
at LHC: from gluons
(larger color charge!)

Both quarks and gluons strongly coupled to the medium

What about charmonia?

Much more suppression at RHIC than at the LHC!



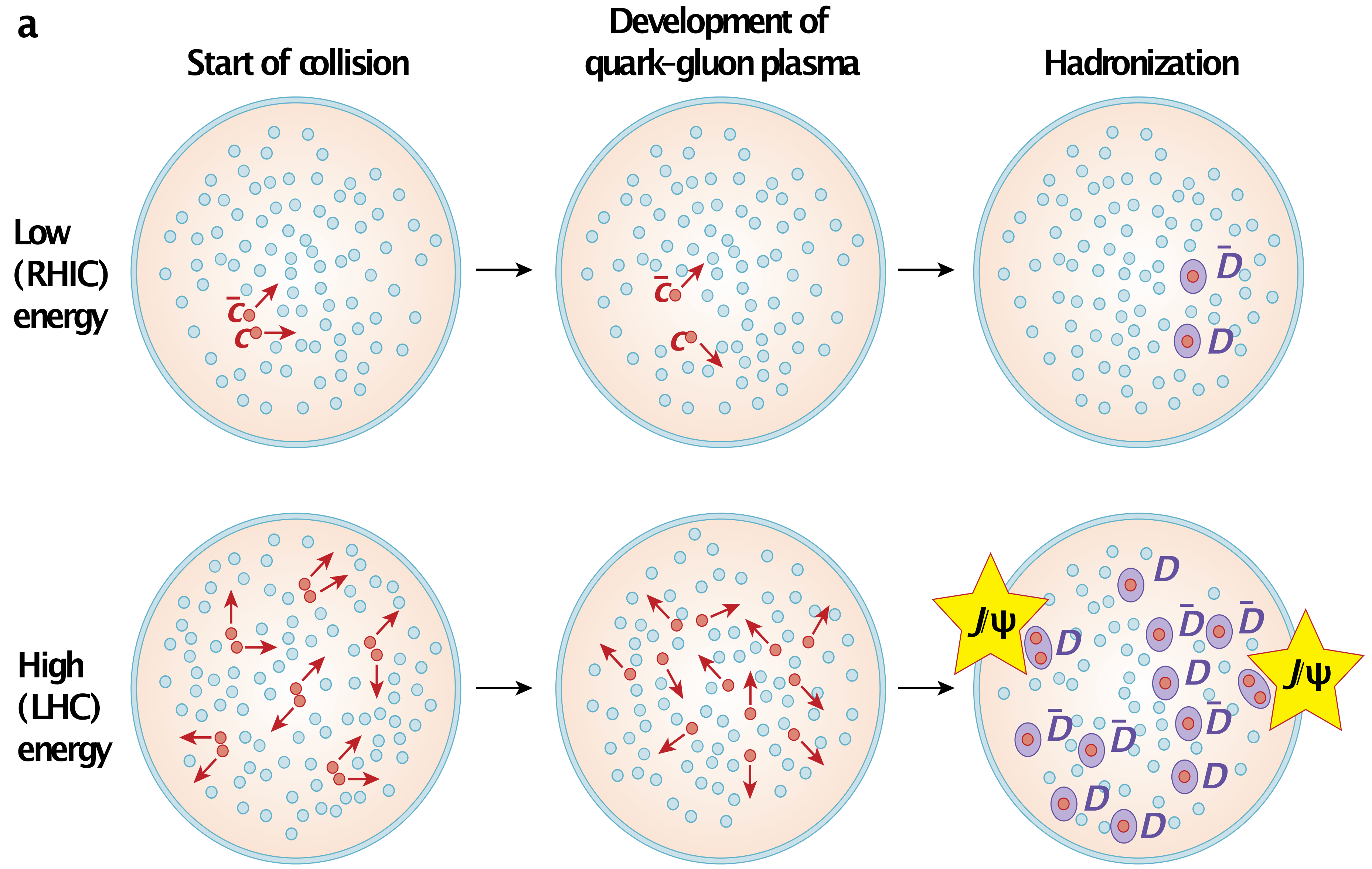
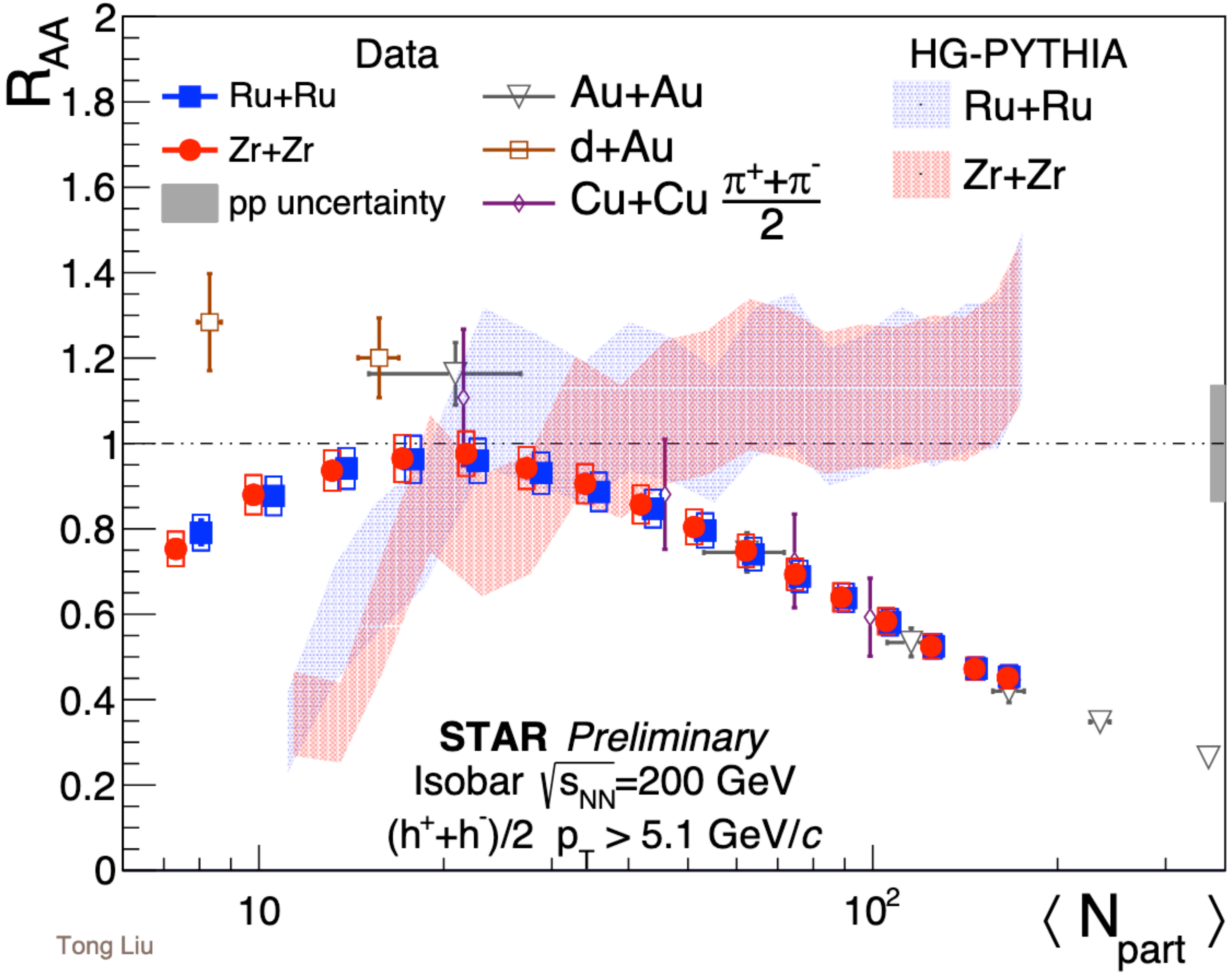


Image: P. Braun-Muzinger, J. Stachel, Nature 448 (2007) 332

J/ψ melts but also regenerates

RHIC much less regeneration in medium (few c quarks created, once melted don't reform)

Precision quenching measurements



Jet quenching linear with log(N_{part})

R_{AA} (N_{part}>20) decreases with N_{part}

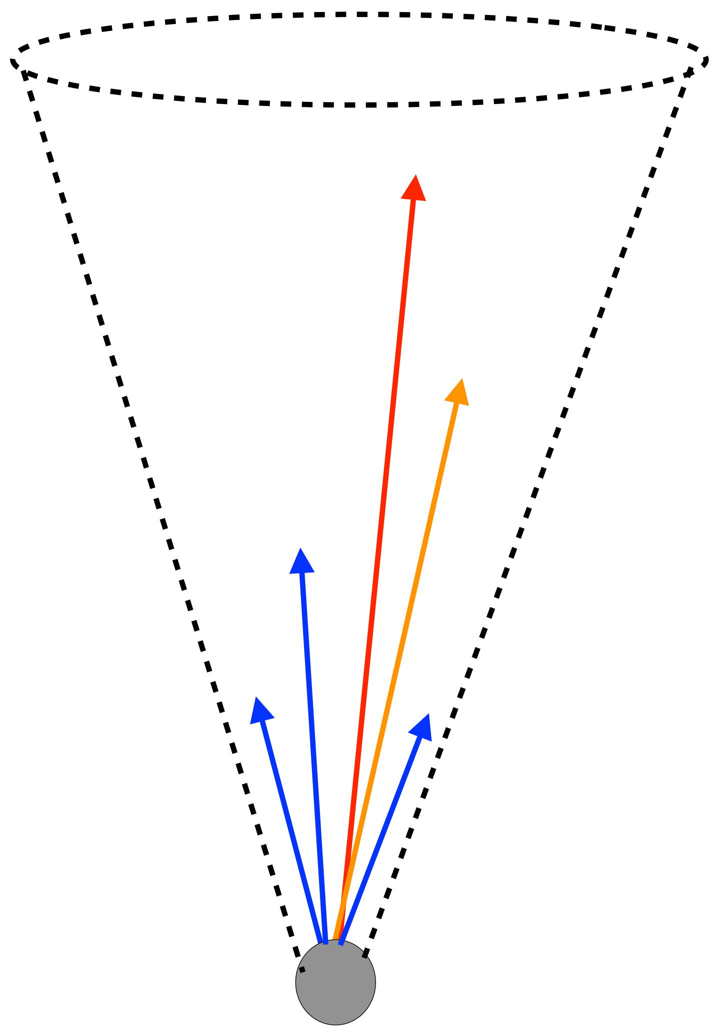
Same R_{AA} at same N_{part} regardless of system

Deviation from trend starting at $N_{part} \lesssim 20$

Event selection bias in peripheral events causes artificial suppression?

STAR: PRL 91, 172302 (2003), PRL 91, 072304 (2003), PRC 81, 054907 (2010) Loizides & Morsch, PLB 773 (2017) 408-4

What's expected from A-A jet spectrum

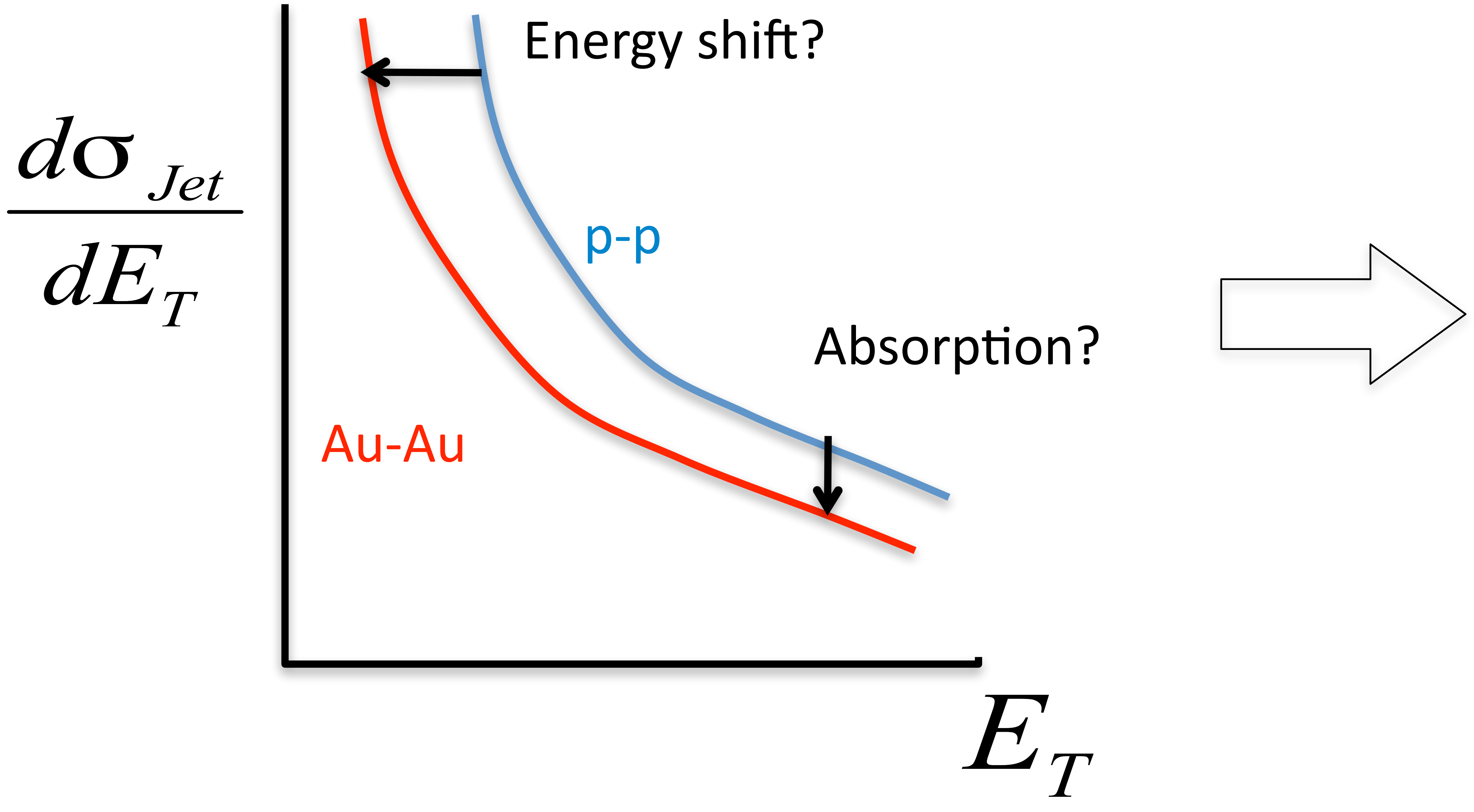


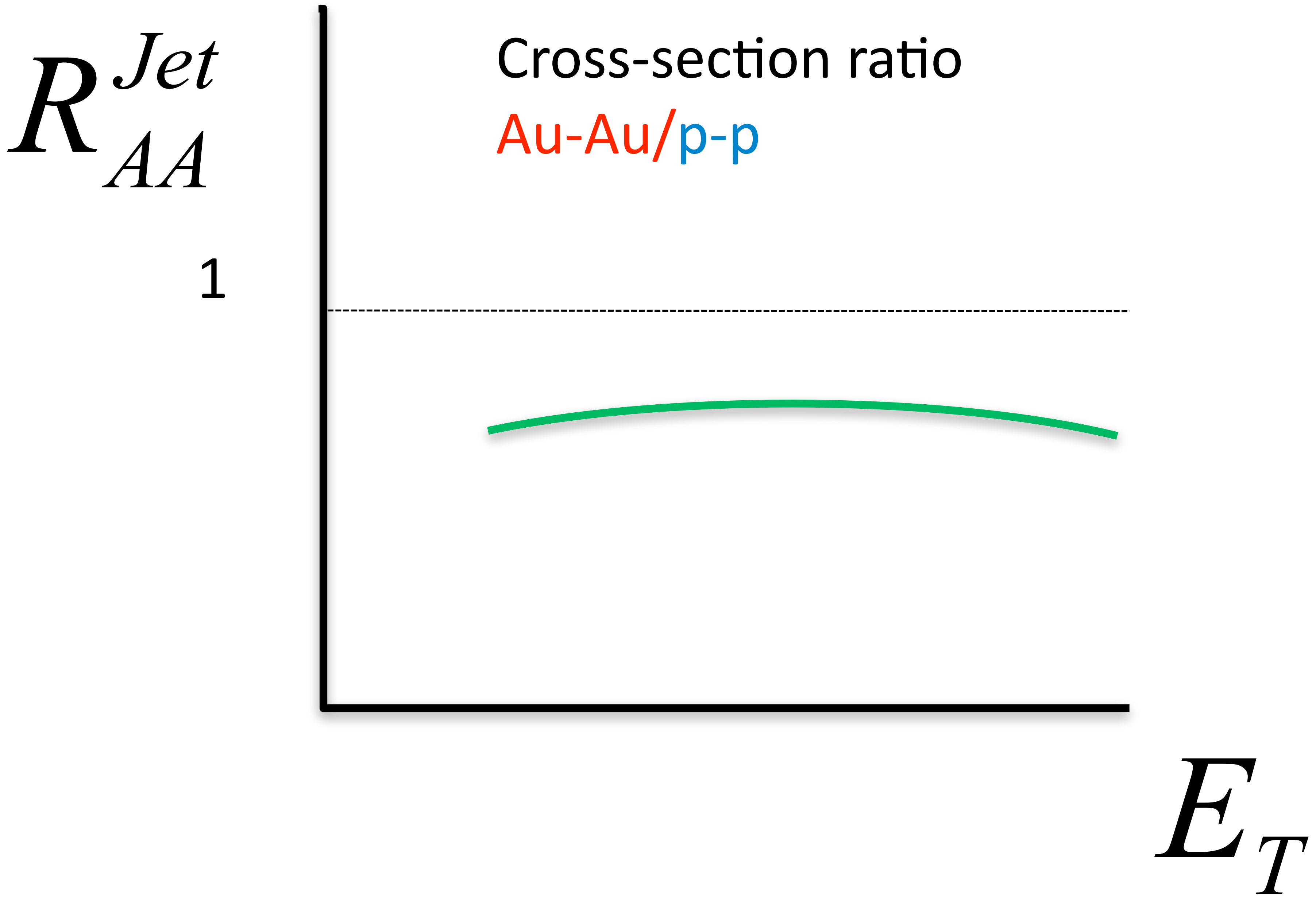
p and E MUST be conserved even with quenched jets

Study nuclear modification factor (R_{AA}) of jets

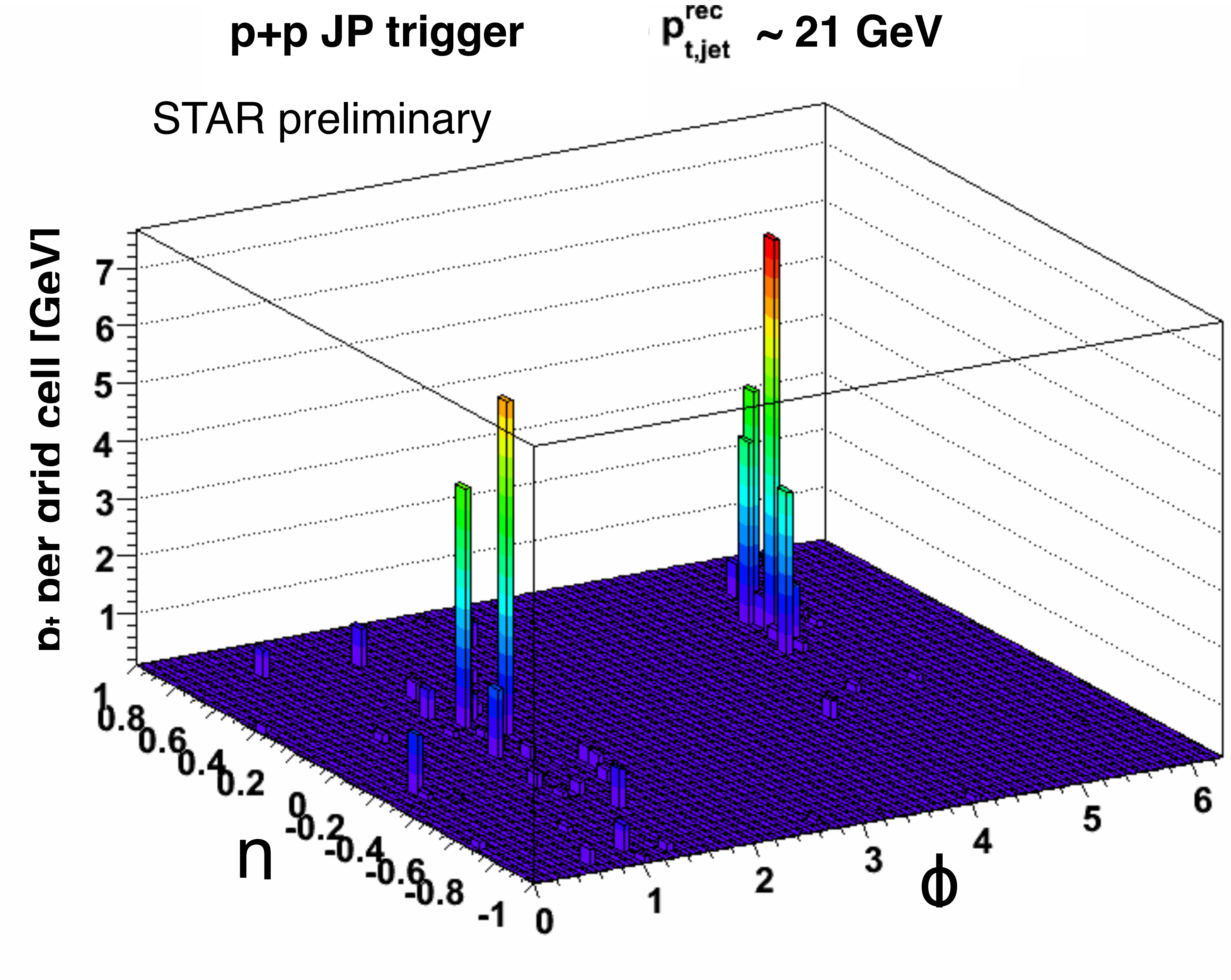
If jet reconstruction complete and unbiased R_{AA}==1

If some jets absorbed and/or not all energy recovered R_{AA}<1

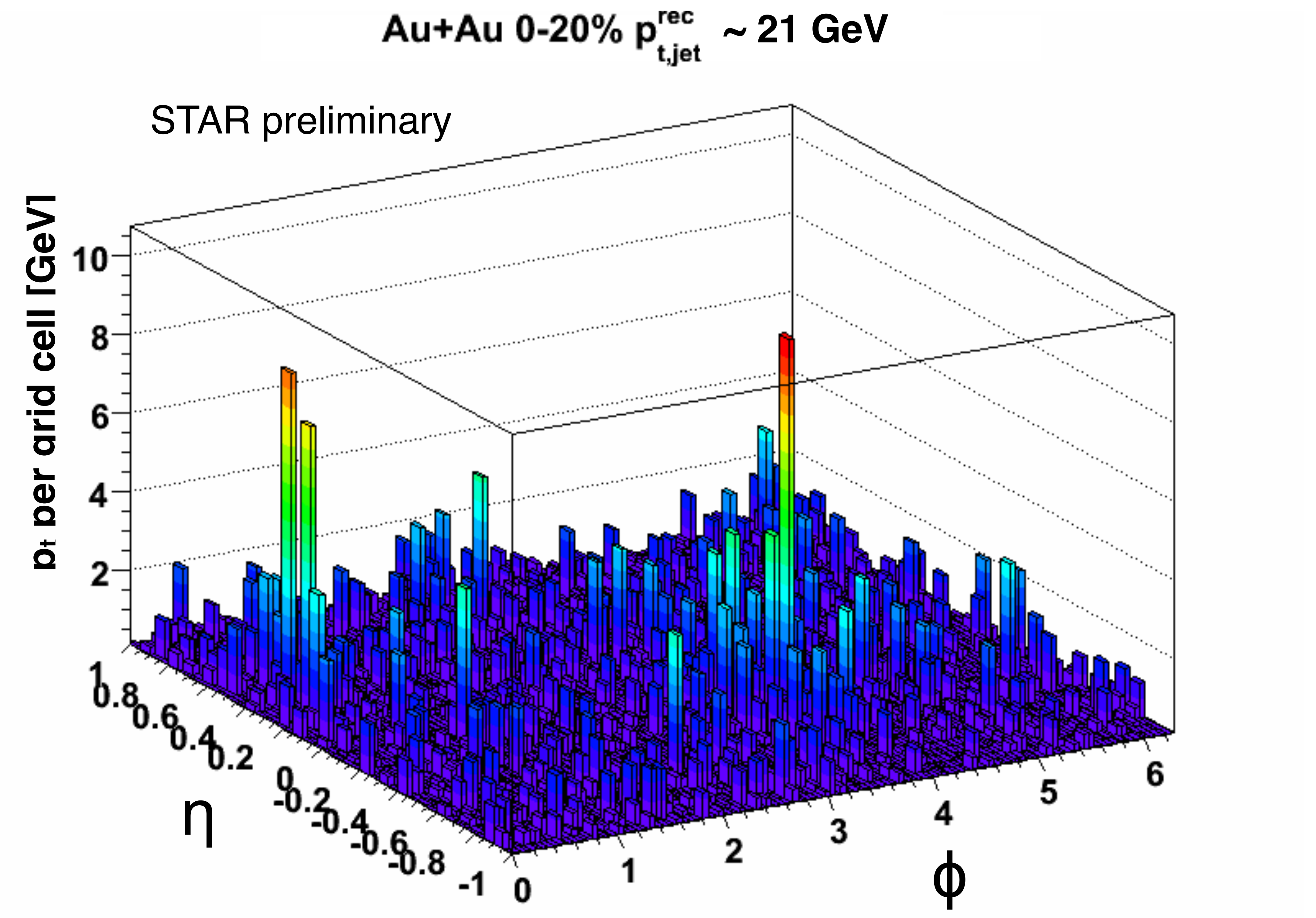




Full-jet reconstruction in HI collisions



In p-p jet clearly visible



In A-A more challenging

Underlying event background a significant challenge - magnitude and fluctuations

Challenging background in A-A events

Central Pb-Pb events has produces several thousand particles
- Most of these are not from hard scatterings

Event-by-event basis:

p_T (Jet Measured) ~ p_T (Jet) + ρ A ± $\sigma \sqrt{A}$

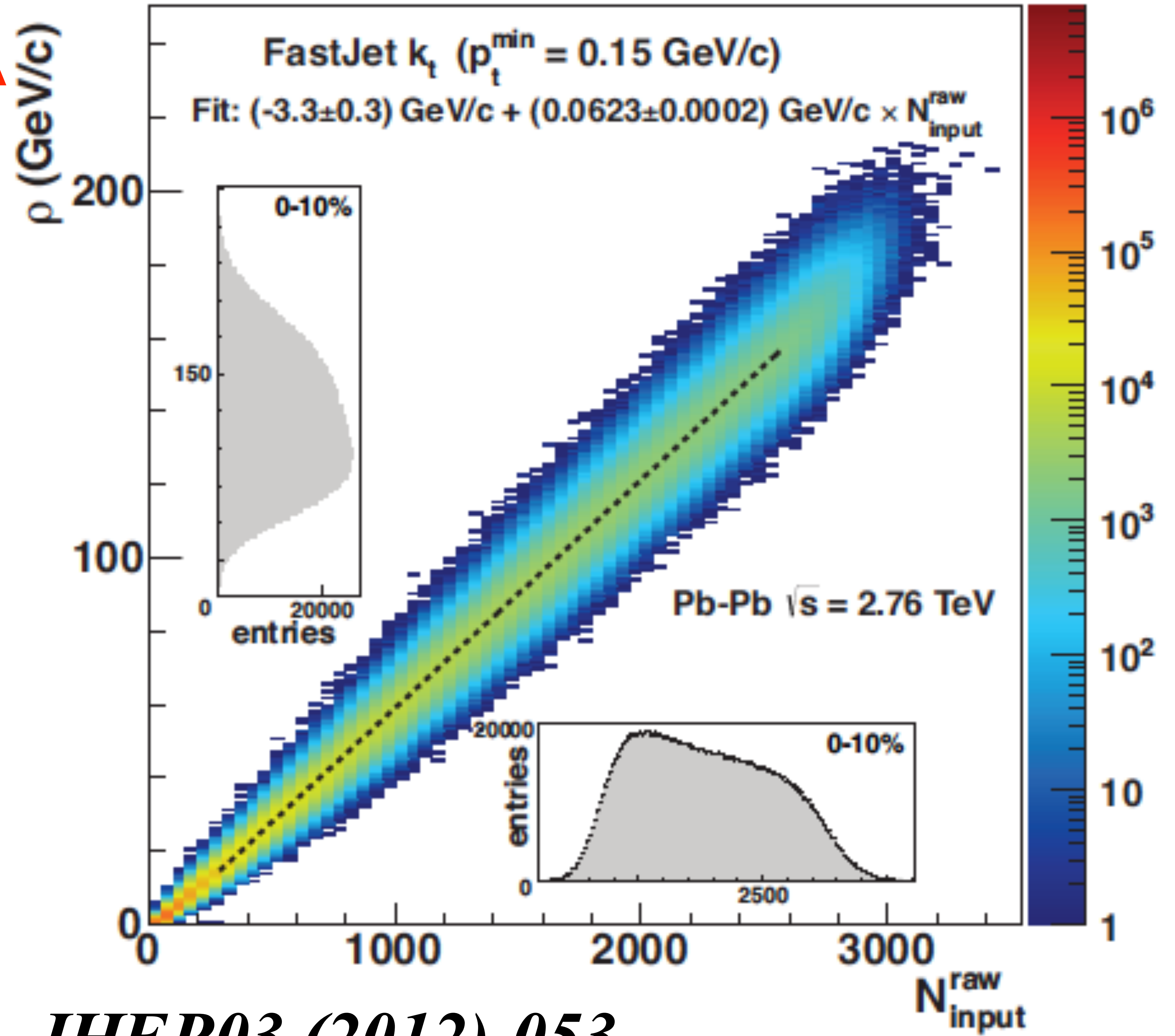
ρ - background energy per unit area

A - jet area ~ πR^2

100 GeV of uncorrelated background at the LHC in cone R=0.4 (at RHIC about factor 2 smaller)

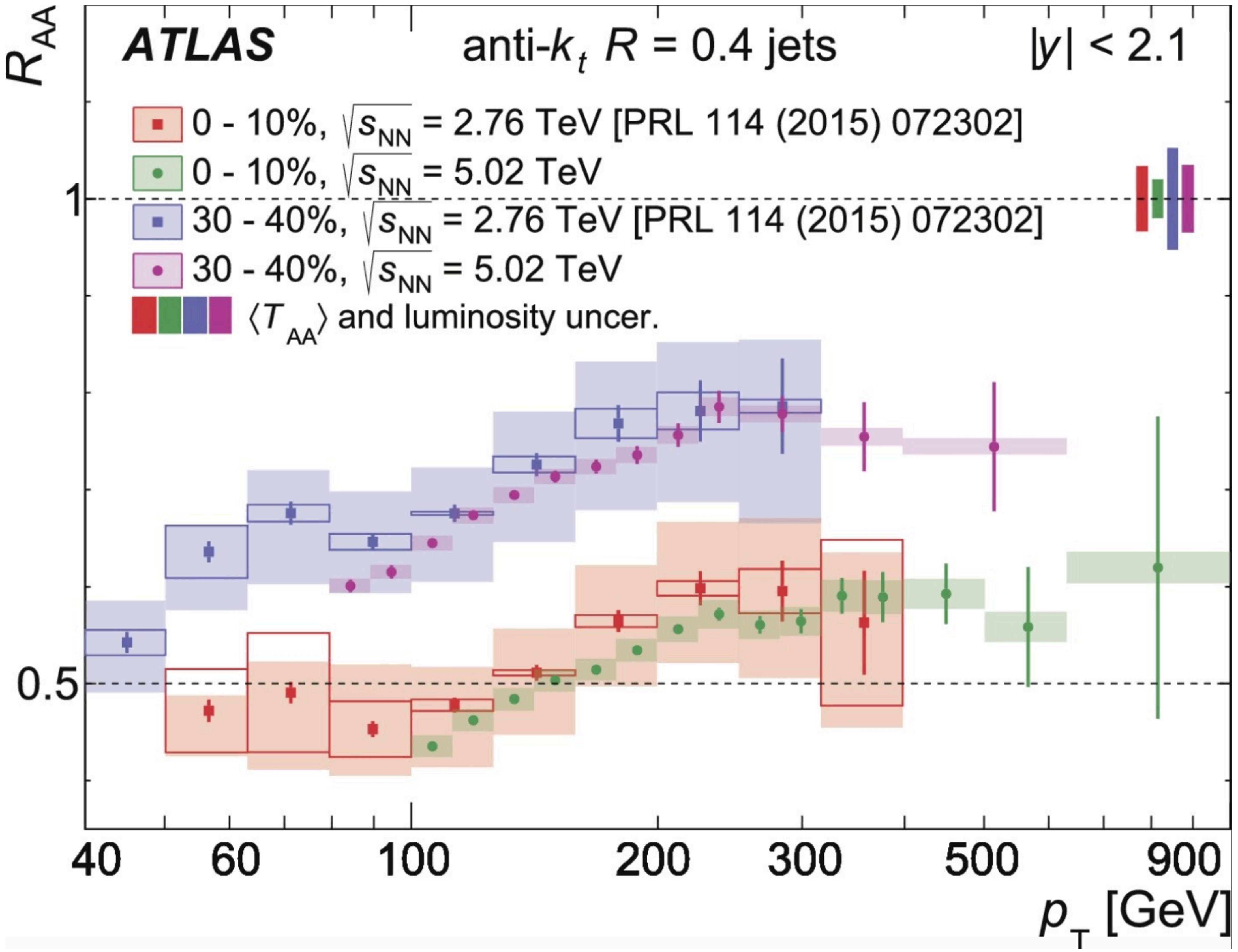
N.B. are also large fluctuations

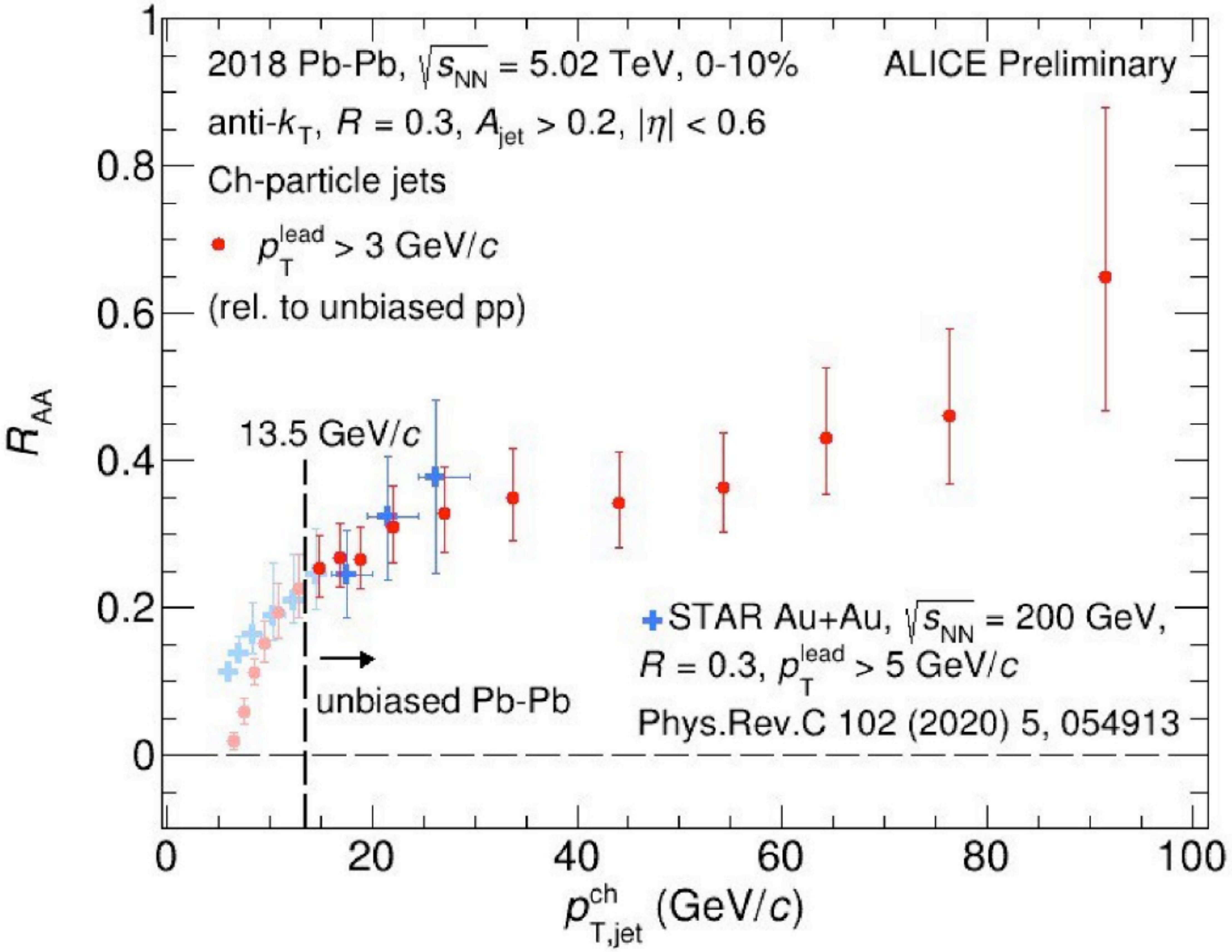
Unfolding needed to obtain initial jet p_T from any A-A measurement



JHEP03 (2012) 053

Full energy still not recovered





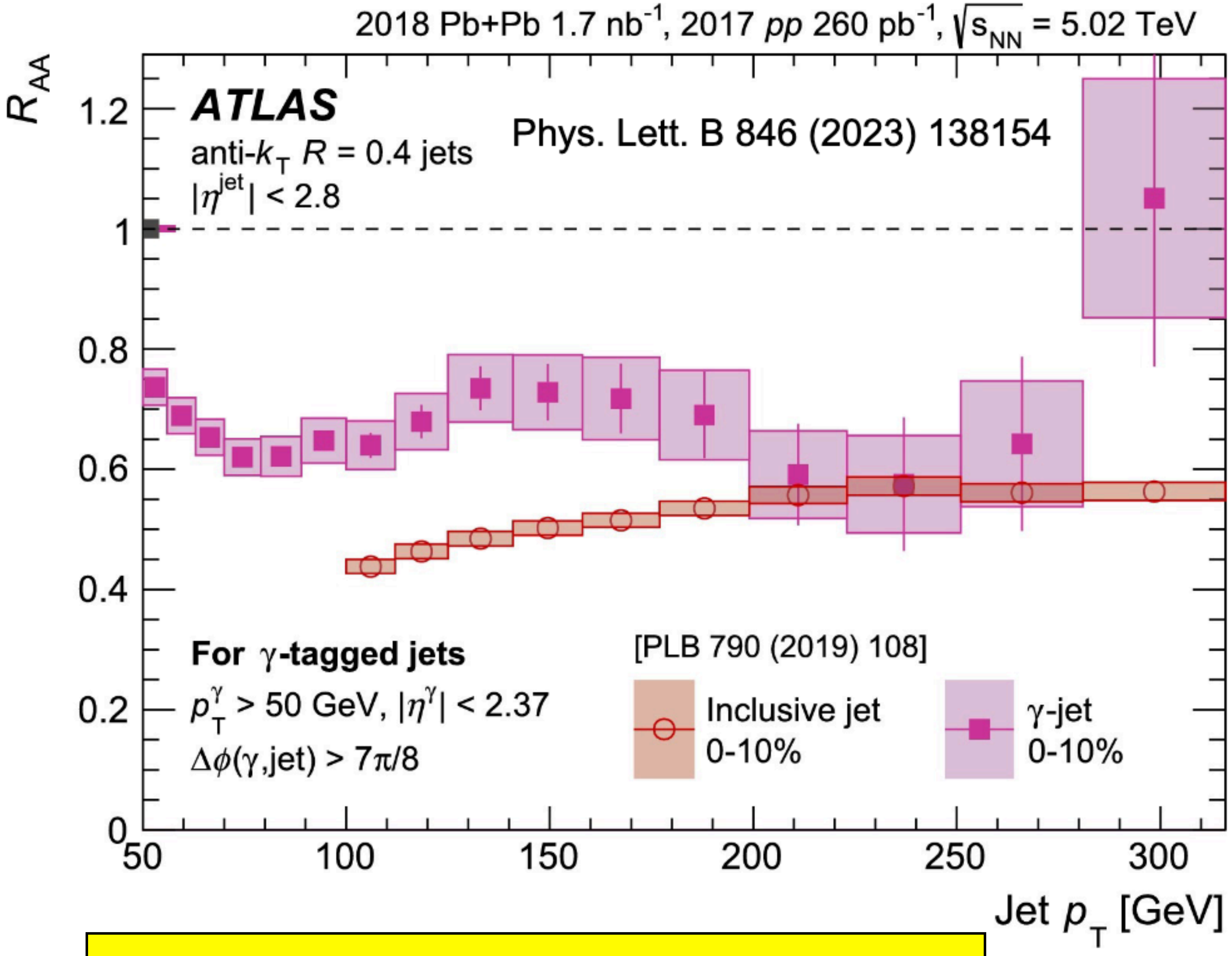
Quenched energy not recovered for R=0.4

R_{AA}(5 TeV) ~ R_{AA}(2.76 TeV) ~ R_{AA}(200 GeV)

Compensating effects of higher quenching and flatter p_T spectra

ATLAS: PLB 790 (2019) 108

Does quenching depends on parton flavor?



Energy loss dependence on color charge shown

At LHC:

Photon tagged ~ quark jet

Inclusive ~ gluon jet

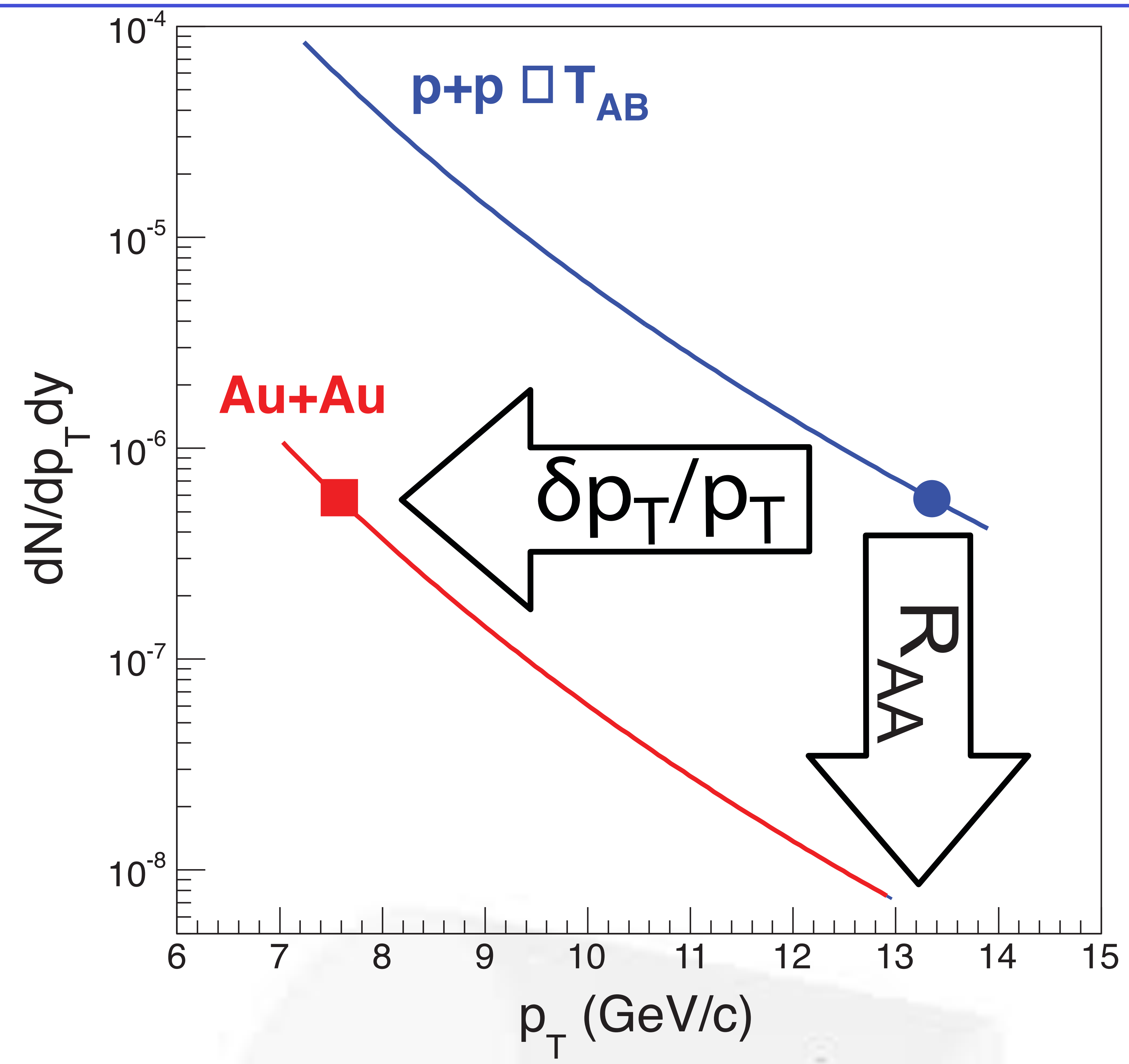
Caveat: Steepness of spectrum plays a key role

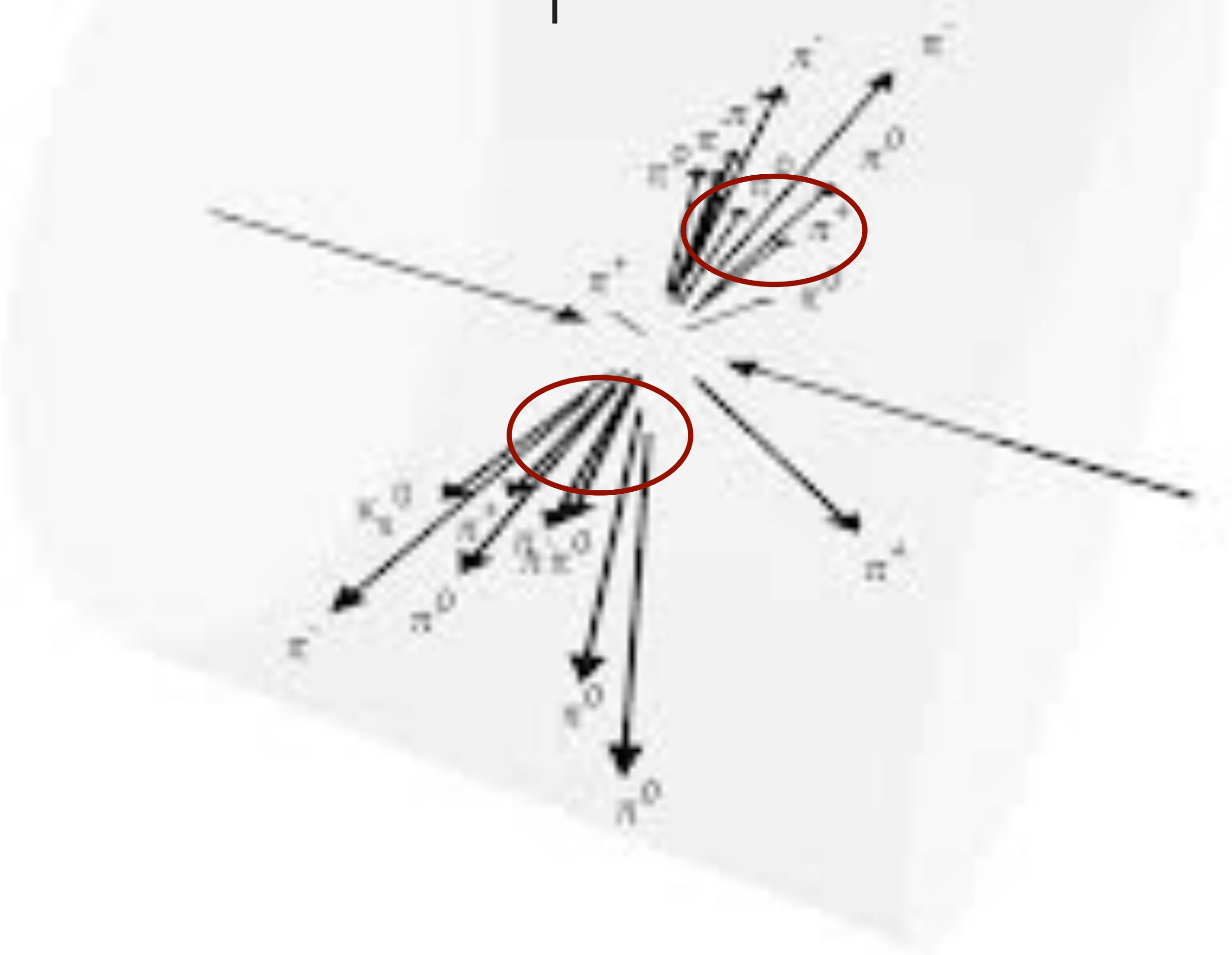
GLV approximation:

$$\frac{\Delta E}{E} \approx \frac{9C_R\pi\alpha_s^3}{4}\frac{1}{A_\perp}\frac{dN^g}{dy}L\frac{1}{E}\ln\frac{2E}{\mu^2 L}+\cdots.$$

M. Gyulassy et al. PRL 86 (2001) 2537

Di-jet energy (im)balance





Are the getting fully quenched or does each loose a little bit of energy?

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Ideally since p and E conserved

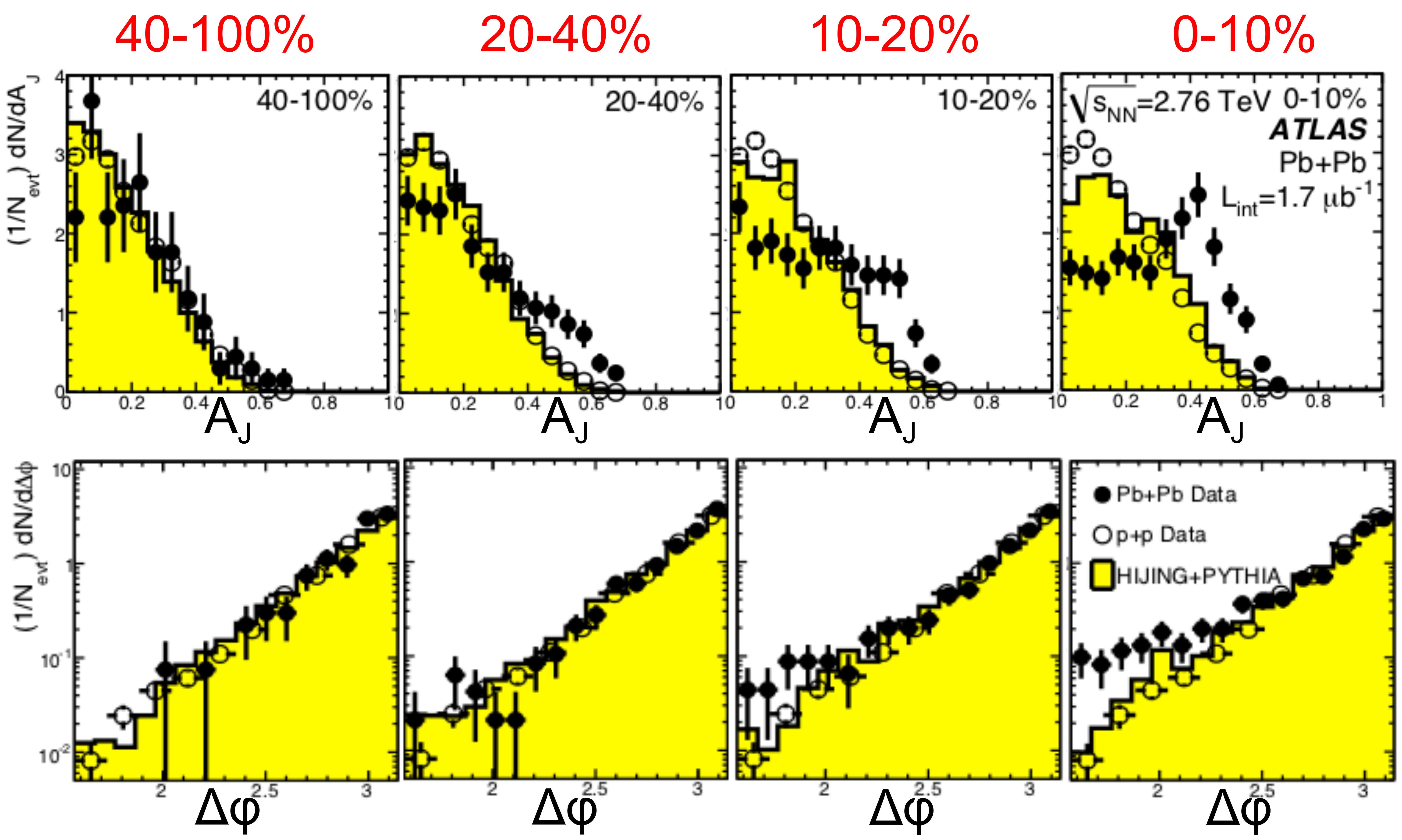
$A_J = 0$

Using jet finder some energy missed

Even for p-p $A_J \neq 0$

Compare A_J in p-p and A-A

Di-jet momentum imbalance



Energy lost of jet-by-jet basis

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta\varphi_{12} > \frac{\pi}{2}$$

Di-jet rate not significantly reduced

Significant momentum imbalance in most central events

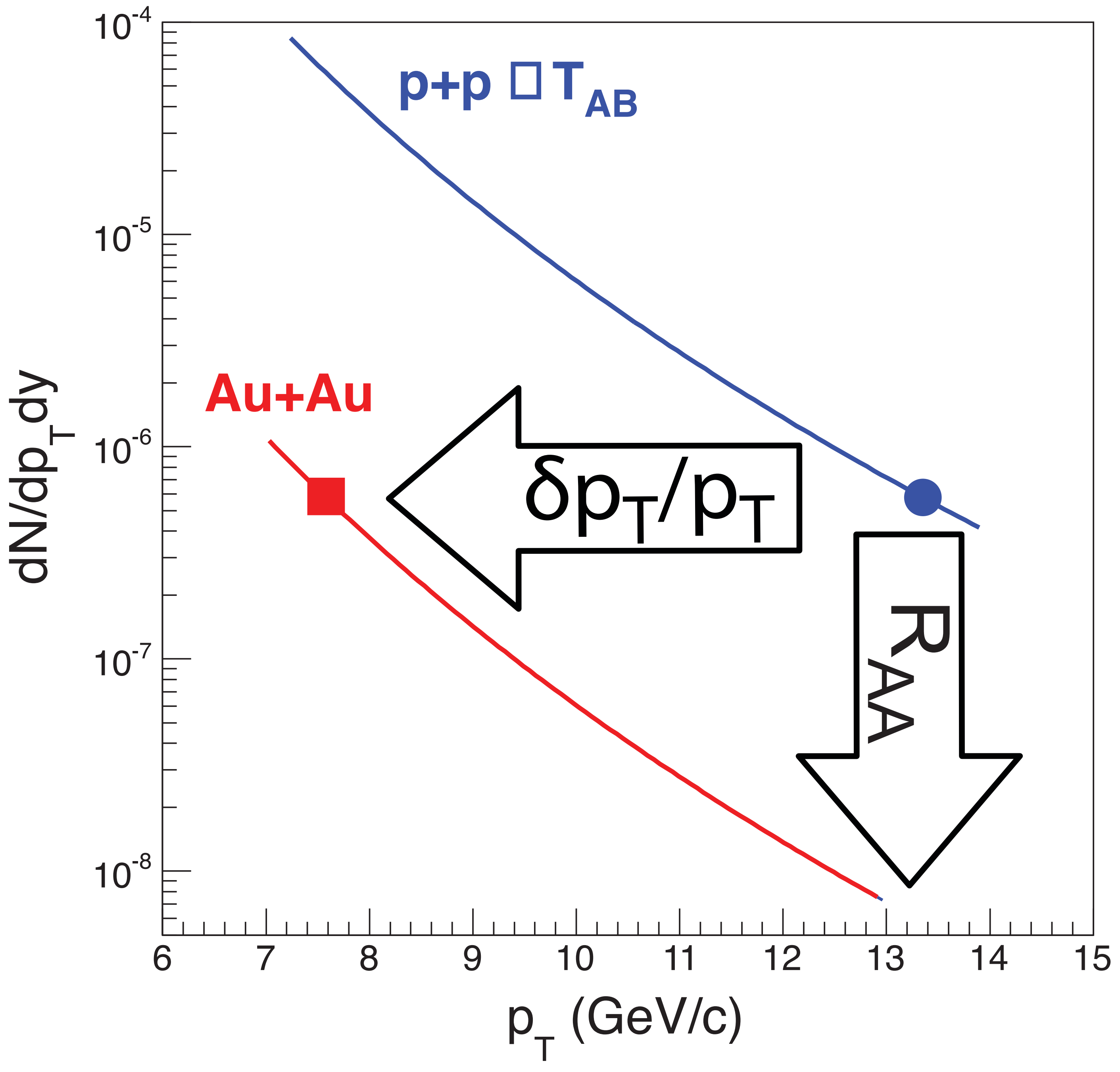
Little to no azimuthal decorrelation - likely energy loss in small steps

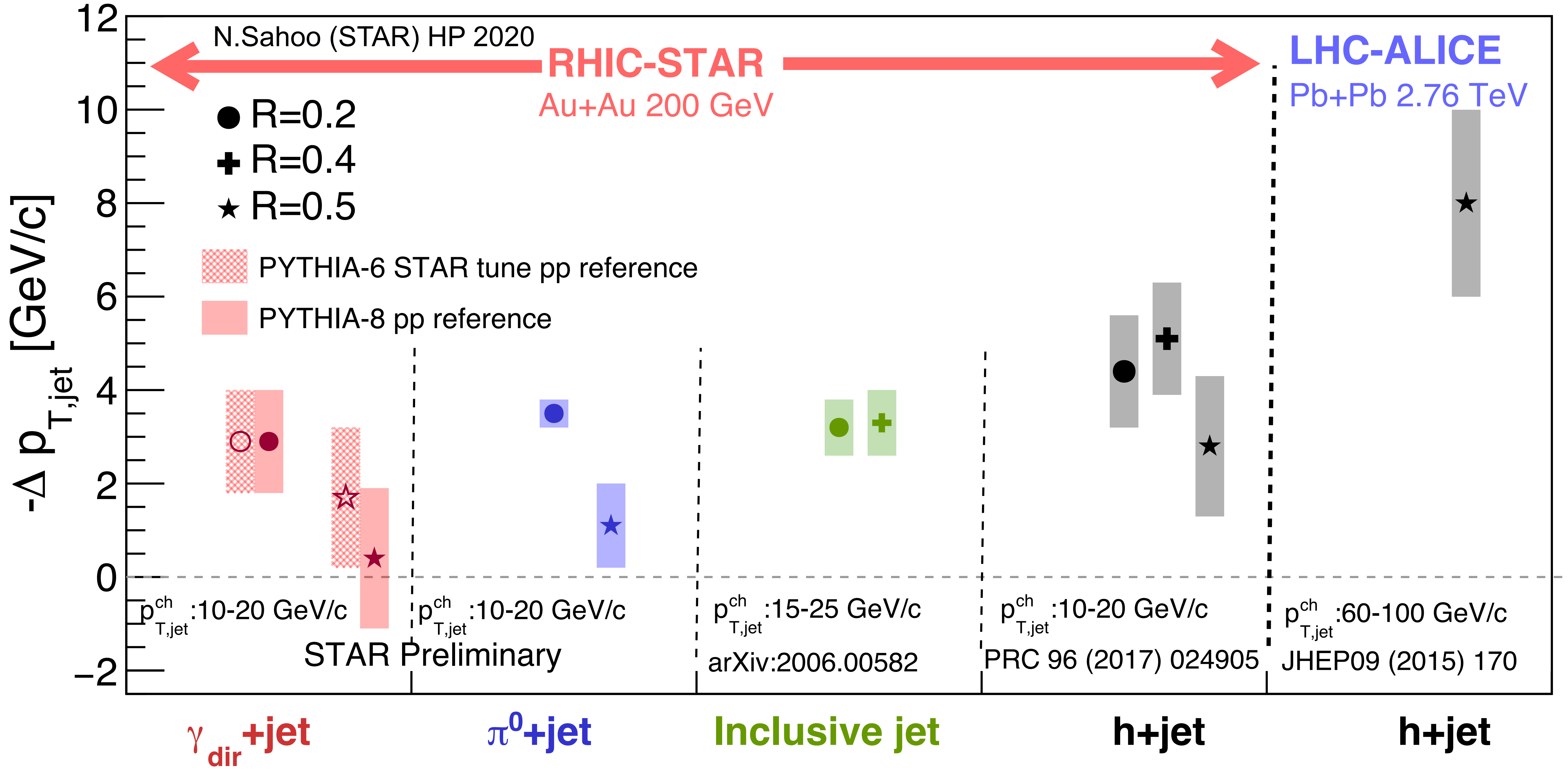
ATLAS, PRL 105 (2010) 252303
CMS, PRC 84 (2011) 024906

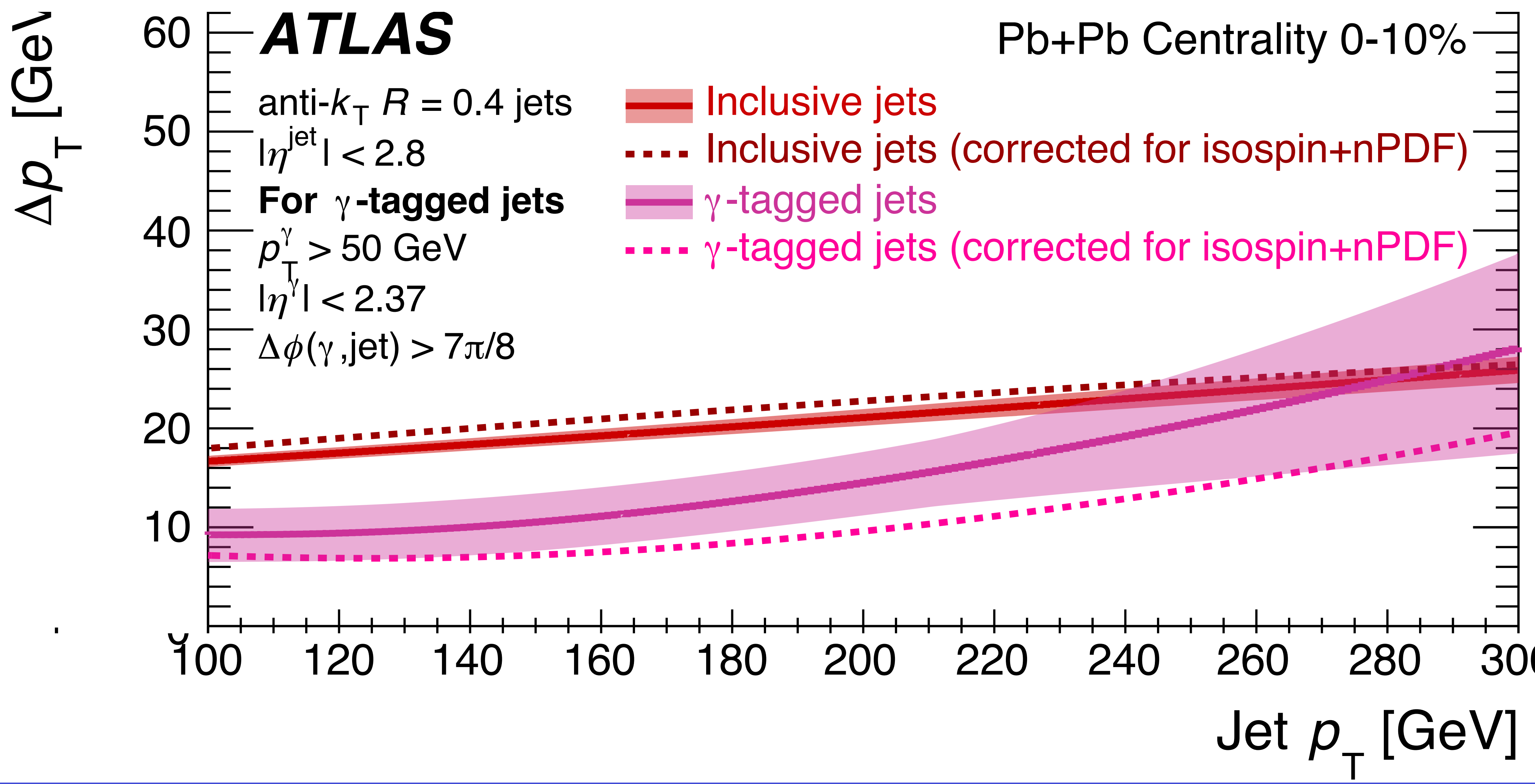
Quantifying the energy loss

Measure fractional momentum loss

$\delta p_T/p_T$ instead of R_{AA}



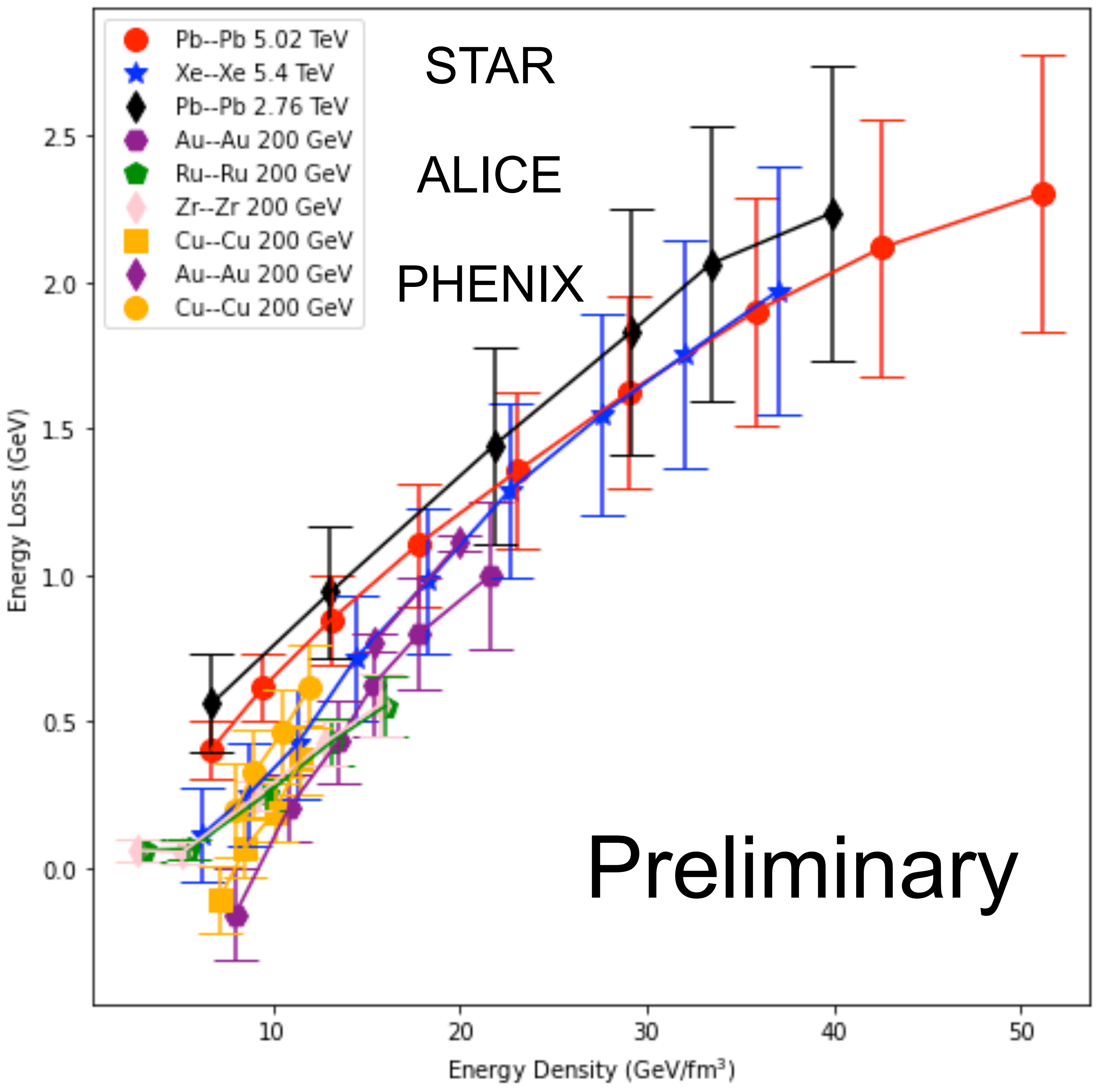




Δp_T (RHIC) < Δp_T (LHC)
Δp_T (quark) < Δp_T (g)

PHENIX: PRC 87, 034911 (2013), ATLAS: PLB 846 (2023) 138154

Energy loss vs energy density



More details on estimates see 2308.05743 J. Harris & B. Muller

E_{Loss} from shift of p_T spectra

Approximate energy density from:

$dN_{ch}/d\eta$ —> dS/dy —>

$s_f\,\tau_f = dS/dy/A_T = s_{init}\,\tau_{init}$

$\varepsilon_{init} = 3/4\; s_{init}\,T_{int}$

Correlation between E_{Loss} and ε_{init} over different species and collision energies

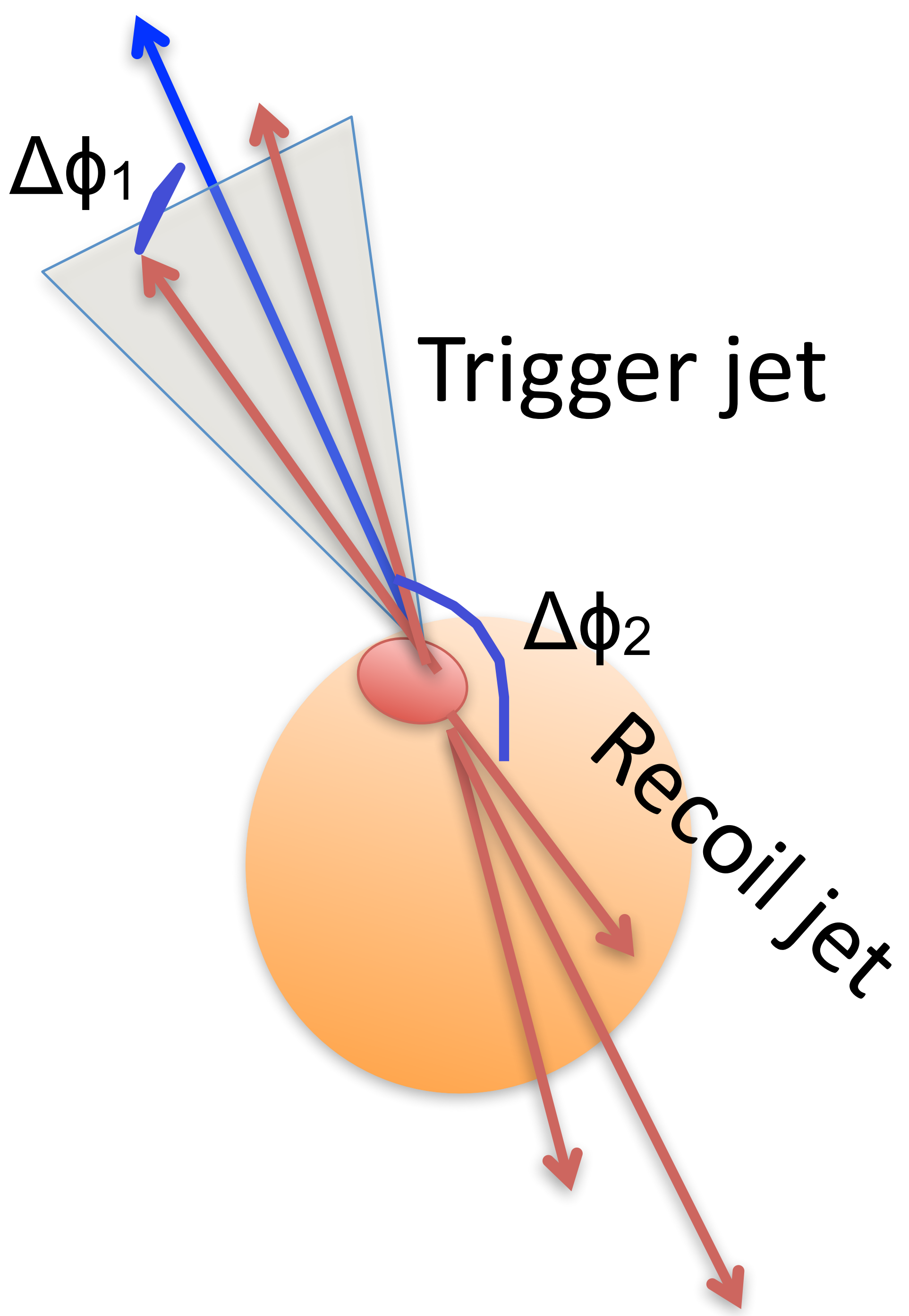
N.B. Link between entropy and charged particle density very sensitive to viscosity.

GLV approximation:

$$\frac{\Delta E}{E} \approx \frac{9C_R\pi\alpha_s^3}{4}\frac{1}{A_\perp}\frac{dN^g}{dy}L\frac{1}{E}\ln\frac{2E}{\mu^2 L} + \cdots .$$

M. Gyulassy et al. PRL 86 (2001) 2537

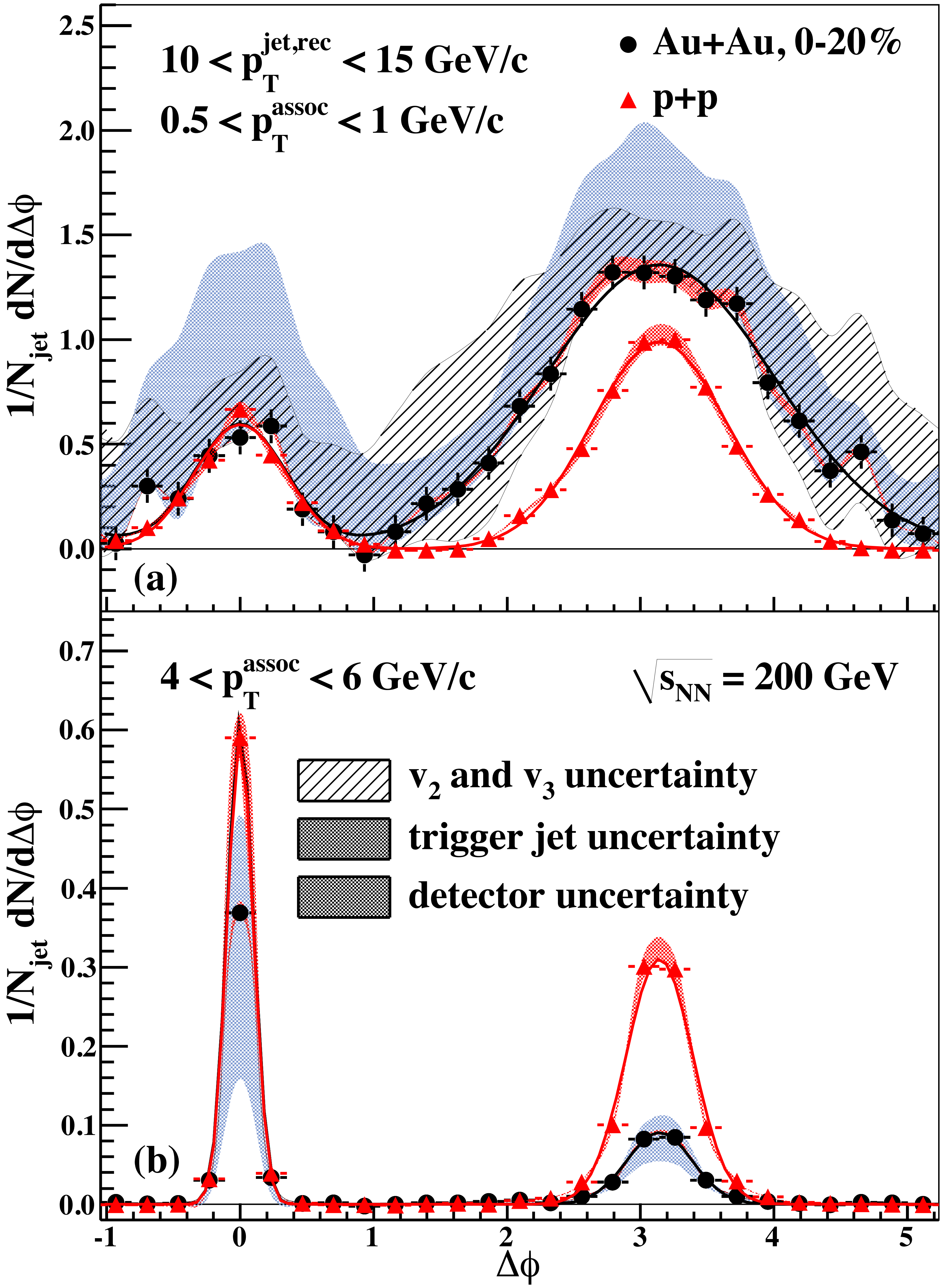
Jet-hadron correlations Au-Au vs. p-p



High Tower Trigger (HT):
tower 0.05x0.05 (ηxϕ)
with E_t> 5.4 GeV

$\Delta\phi = \phi_{Jet} - \phi_{Assoc.}$

ϕ_{Jet} = jet-axis found by Anti-k_T, R=0.4, $p_{t,cut}$>2 GeV and $p_{t,rec}$(jet)>20 GeV



Broadening of recoil-side

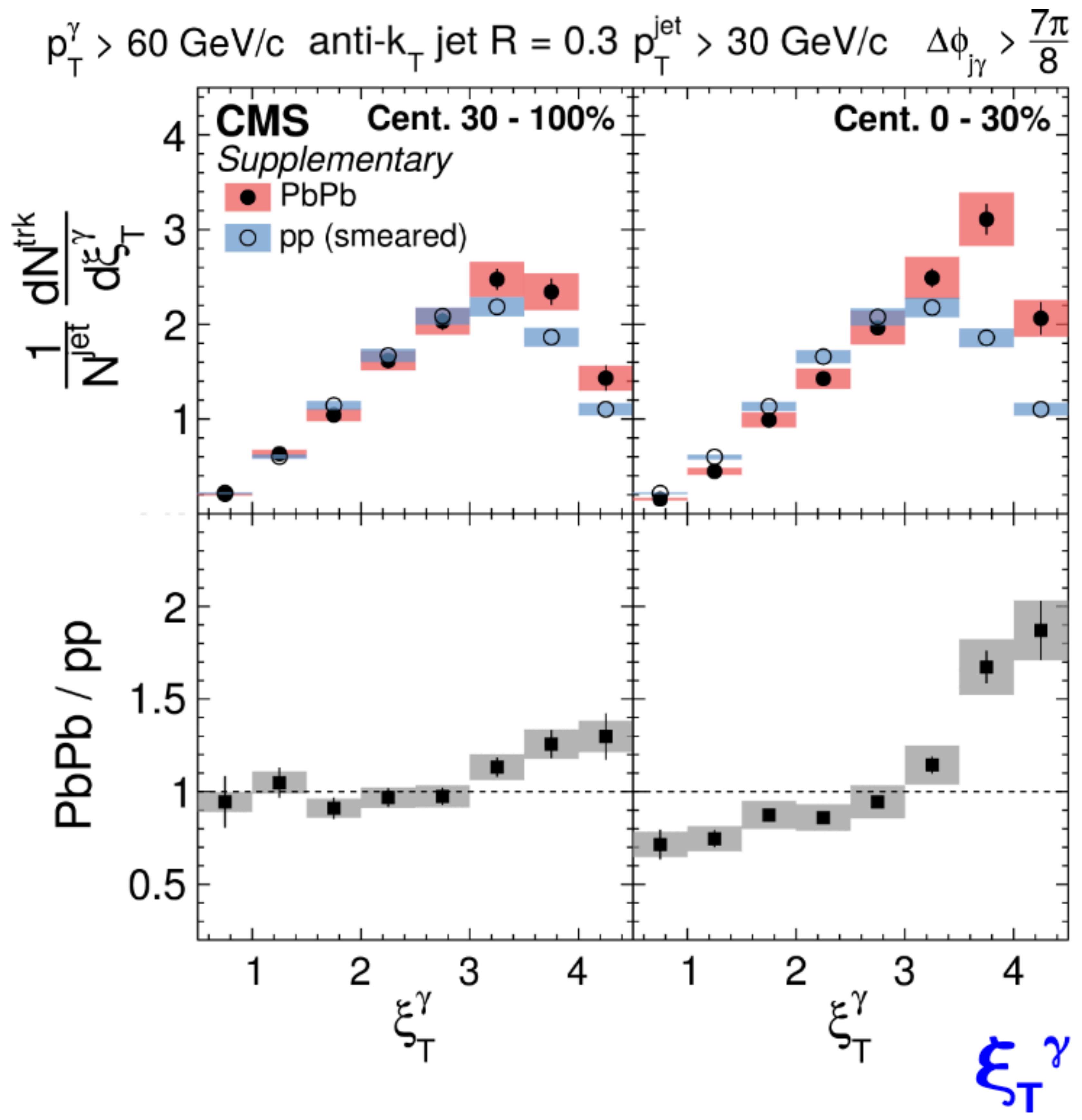
Softening of recoil-side

E remains correlated to jet axis but at large angles

Fragmentation modified as expected

STAR: PRL 112 (2014) 122301

What about at the LHC?



Reconstruct jet recoiling from high p_T photon

- since photons don't interact "know" initial parton energy

Examine fragmentation hadrons

$$\xi_T^\gamma = \ln[-|\vec{p}_T^{\,\gamma}|^2/(\vec{p}_T^{\,trk}\cdot\vec{p}_T^{\,\gamma})]$$

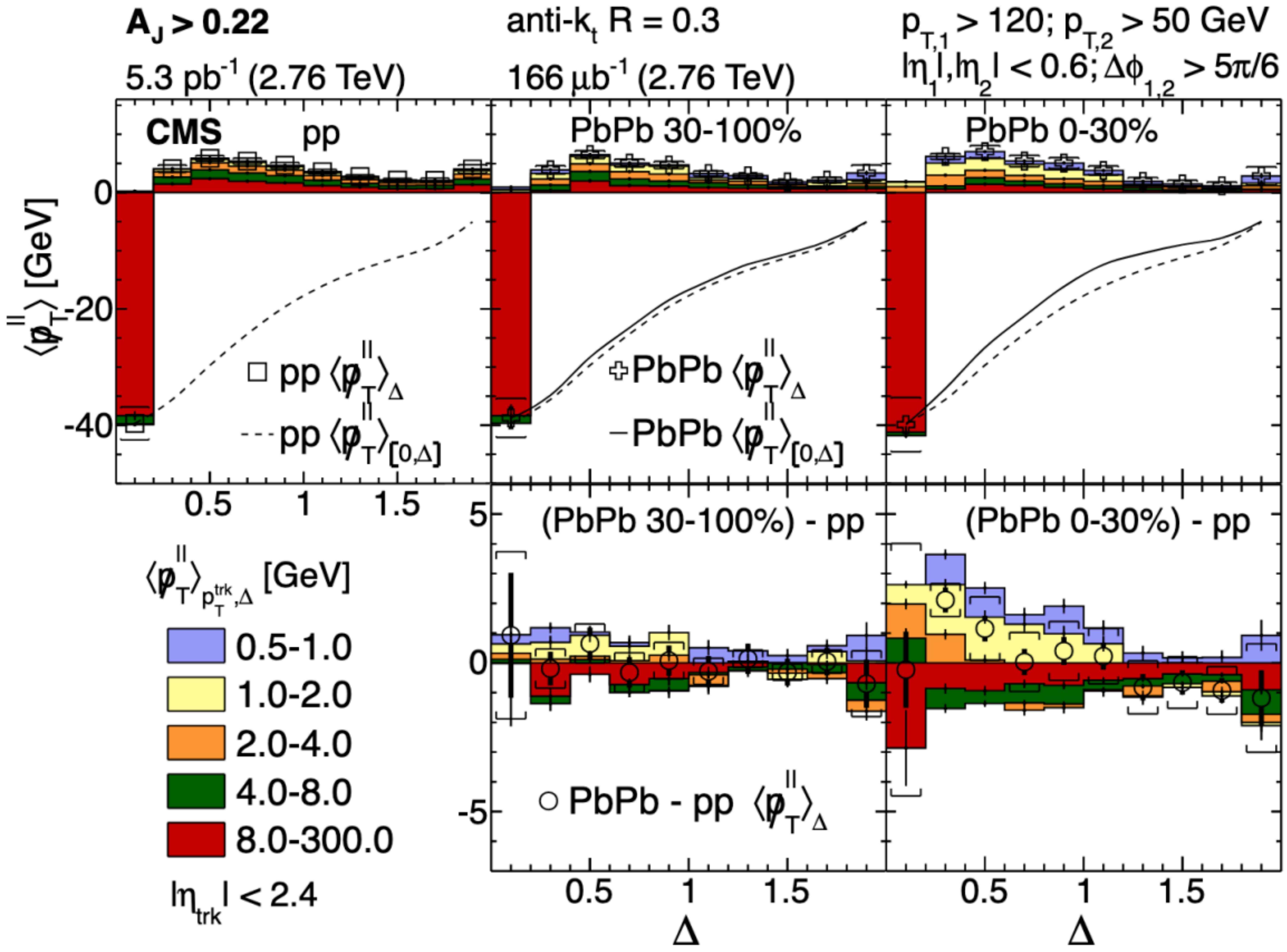
- take ratio Pb+Pb/p+p

Most of the "lost" hard particles emerge as multiple soft particles

- Jet substructure is highly modified
- Particles emerge at large R and low p_T

CMS: PRL121 (2018) 242301

Searching for quenched energy at LHC



Balancing only occurs when looking VERY far from jet axis

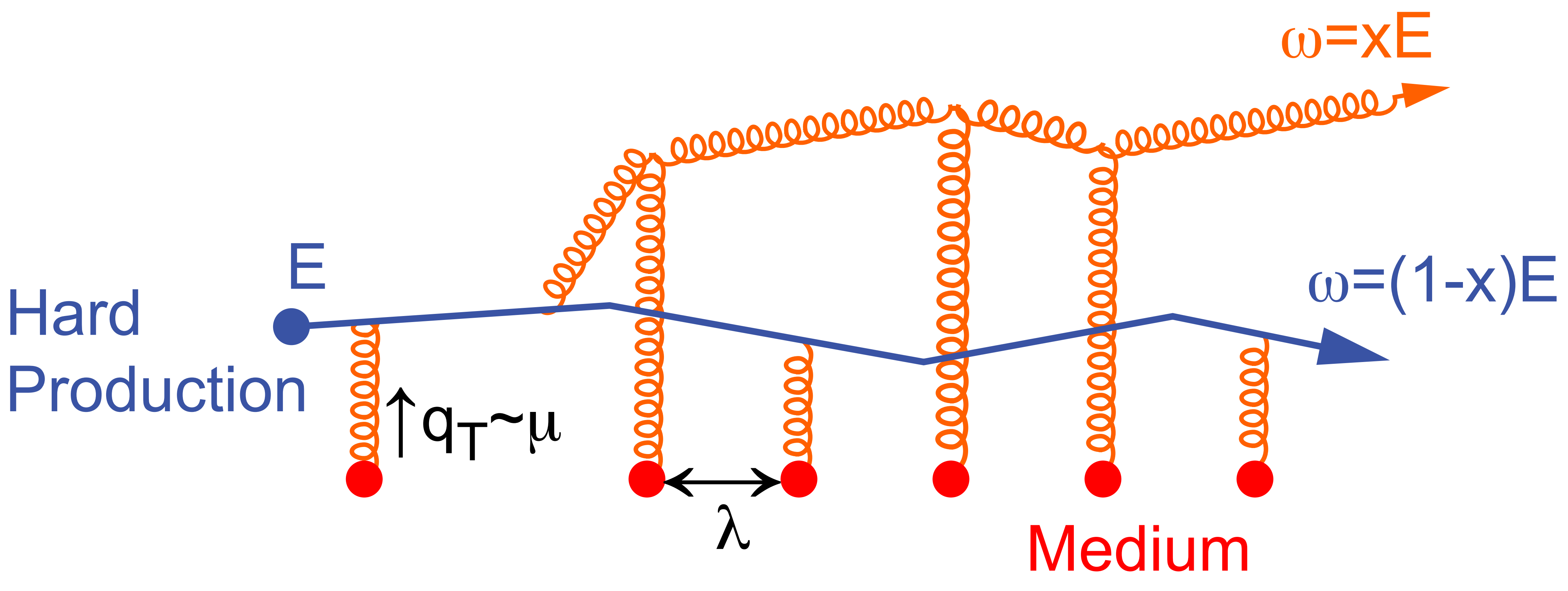
At LHC quenched energy spread over entire hemisphere!

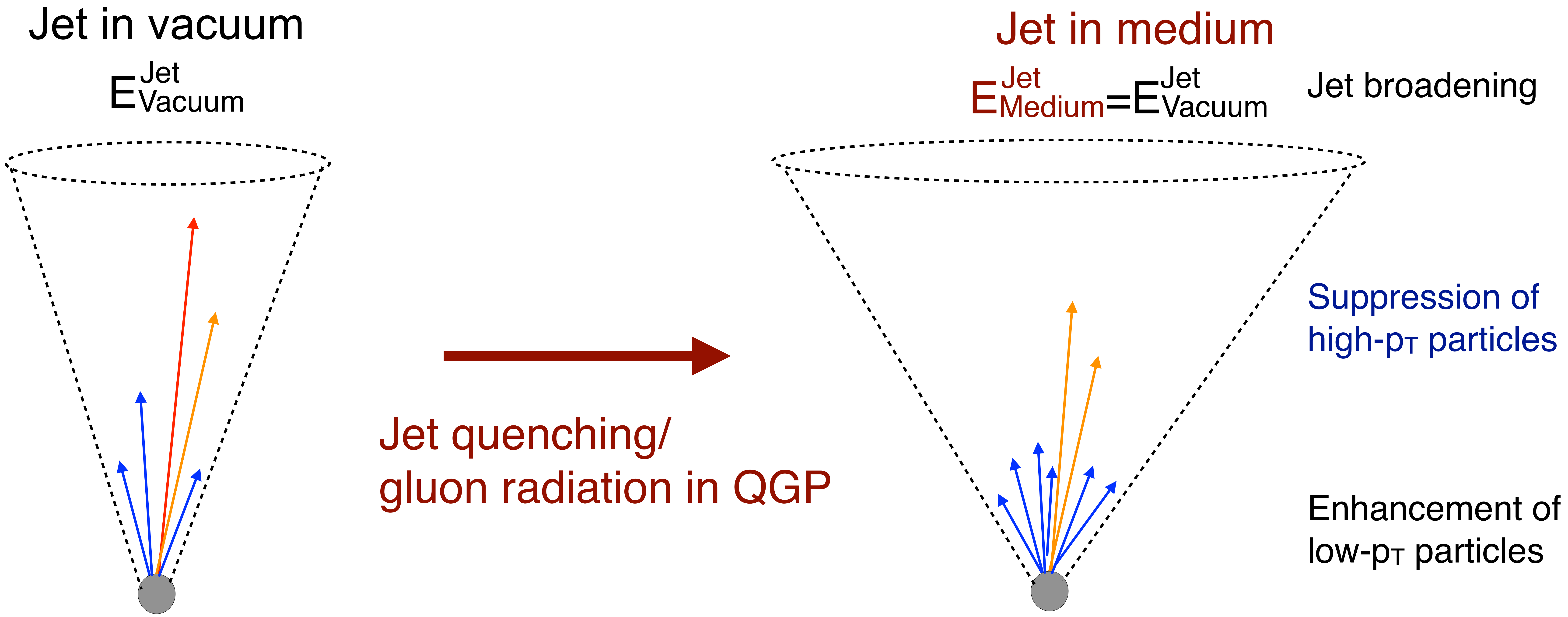
CMS: JHEP 01 (2016) 006

An initial interpretation

Jet quenching = Gluon radiation:

Multiple final-state gluon radiation off of produced hard parton induced by traversing dense colored medium



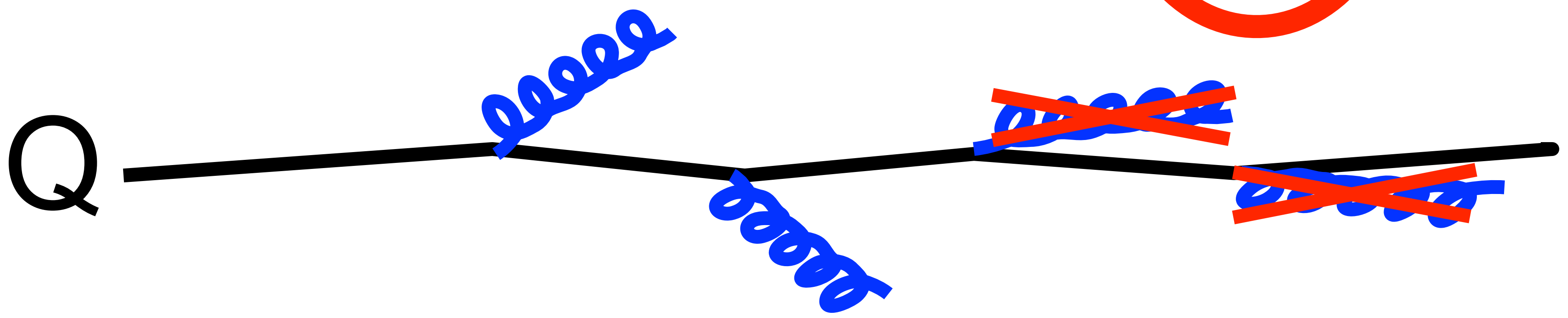


Increased particles at low p_T and large angles

What about heavy quarks?

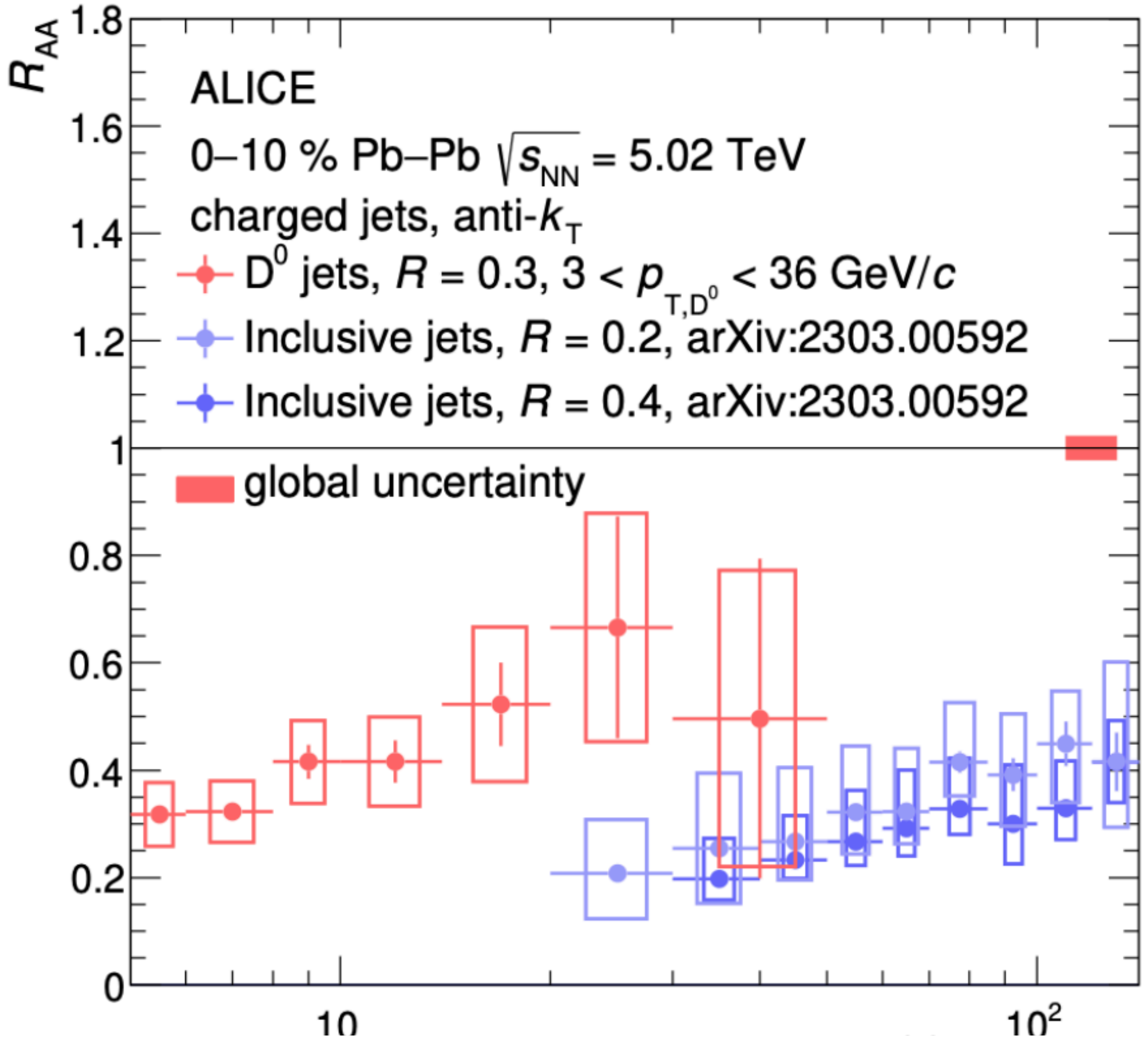
Dead cone effect implies less heavy quark energy loss in matter:

$$\omega \left.\frac{dI}{dw}\right|_{\mathrm{HEAVY}} = \frac{\omega \left.\frac{dI}{dw}\right|_{\mathrm{LIGHT}}}{\left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

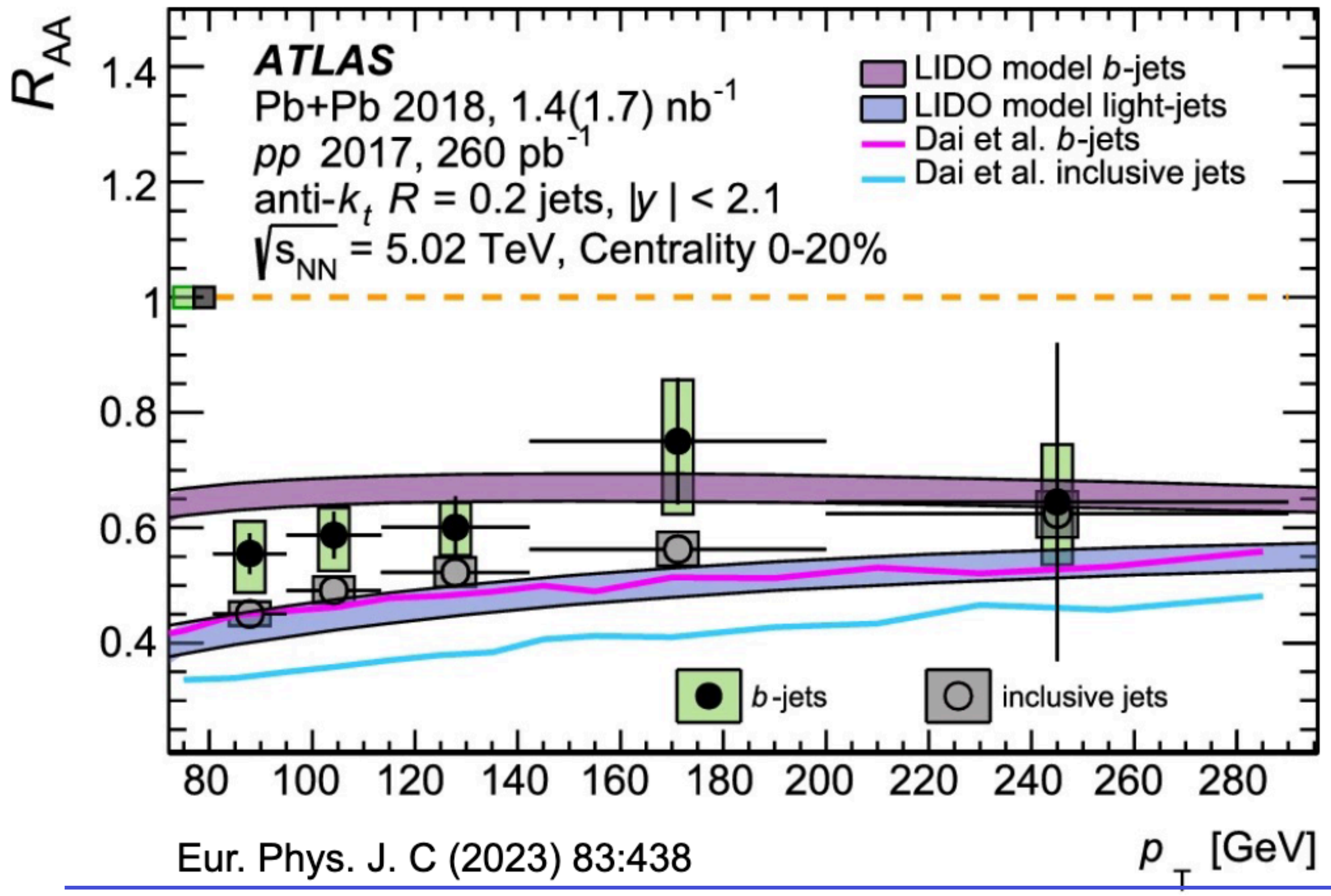


b less suppressed than c less suppressed than gluons

Caveat: Steepness of spectrum plays a key role



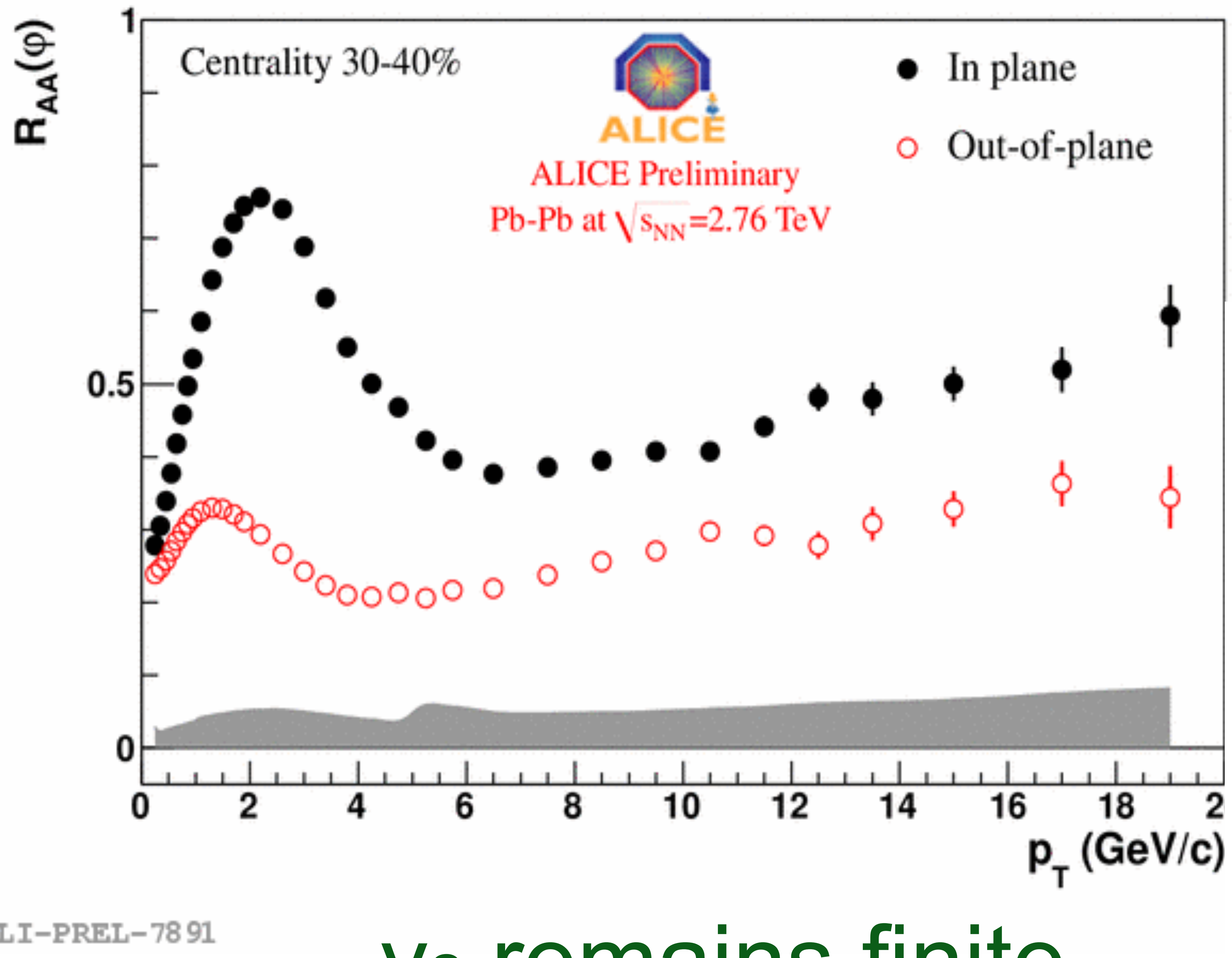
D-tagged jets



b-tagged jets

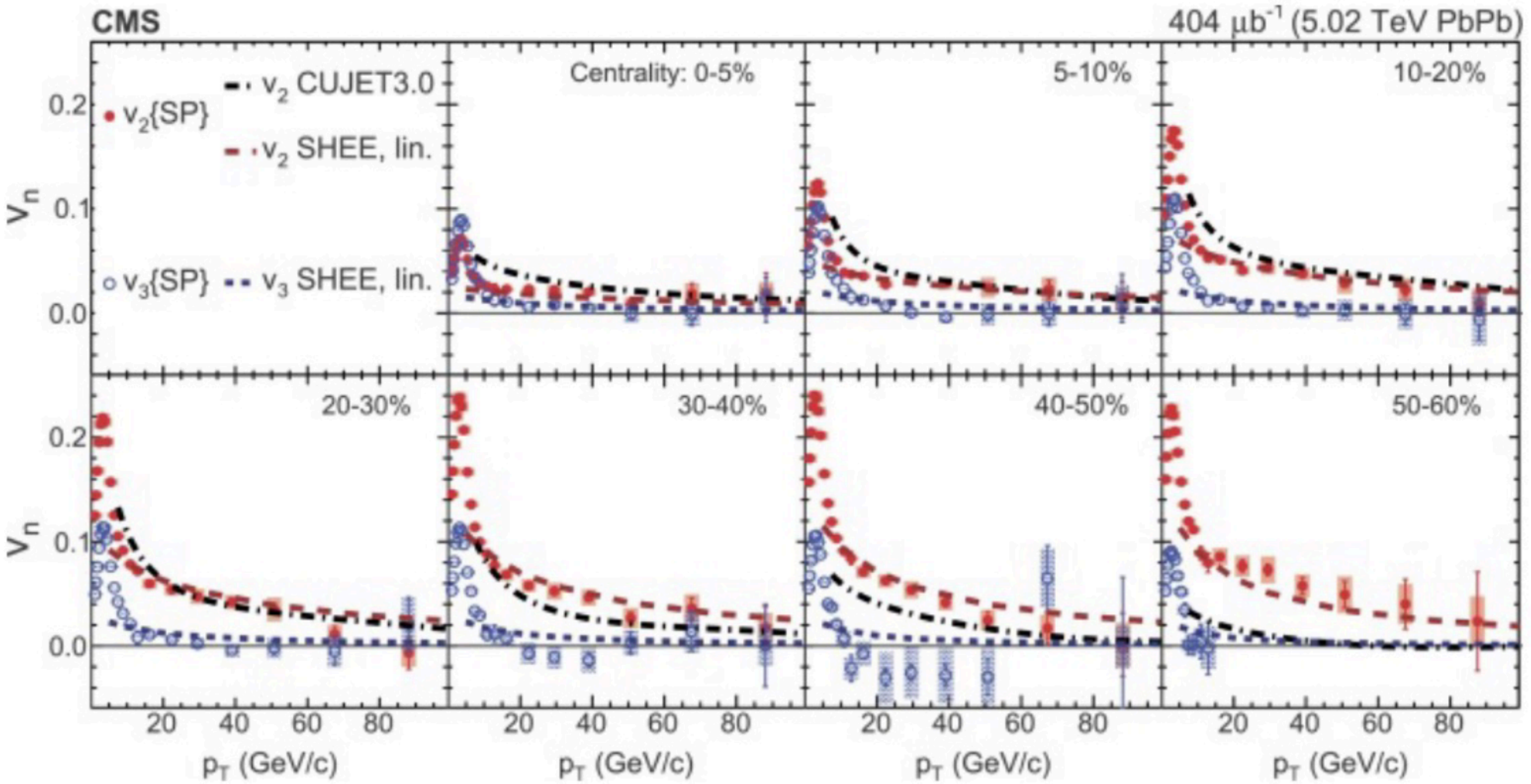
Dokshitzer and Kharzeev, PLB 519 (2001) 199

Pathlength dependence to energy loss



More suppression for charged hadrons exiting out-of-plane

- longer average path length in medium



v_2 remains finite

$v_3 = 0$

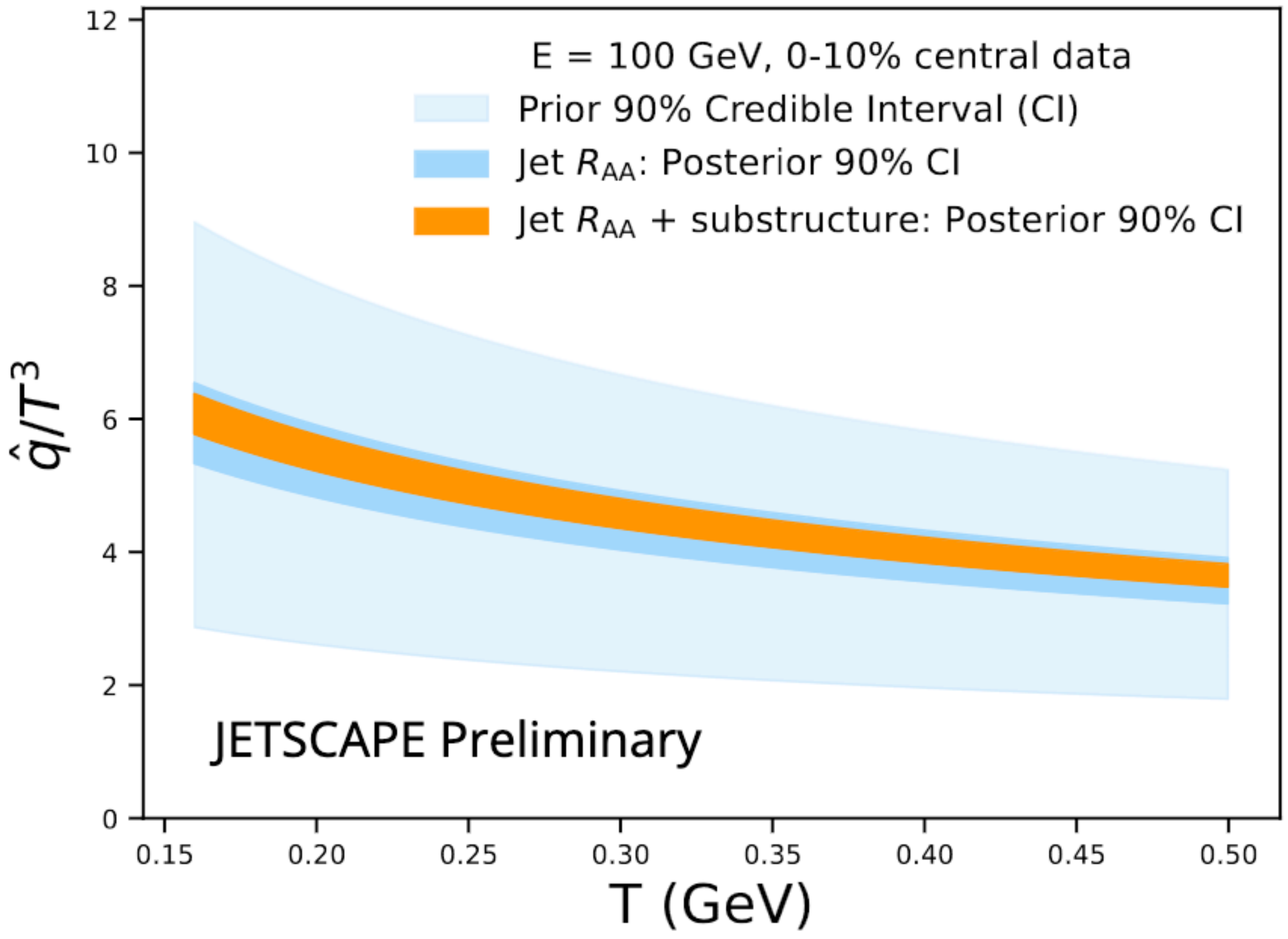
Consistent with path length dependent E_{Loss}

GLV approximation:

$$\frac{\Delta E}{E} \approx \frac{9C_R\pi\alpha_s^3}{4}\frac{1}{A_\perp}\frac{dN^g}{dy}L\frac{1}{E}\ln\frac{2E}{\mu^2 L} + \cdots .$$

CMS: PLB 776 (2018)

Determining QGP transport properties



Advances continue - especially via JETSCAPE (but not only) - exploit bayesian inference

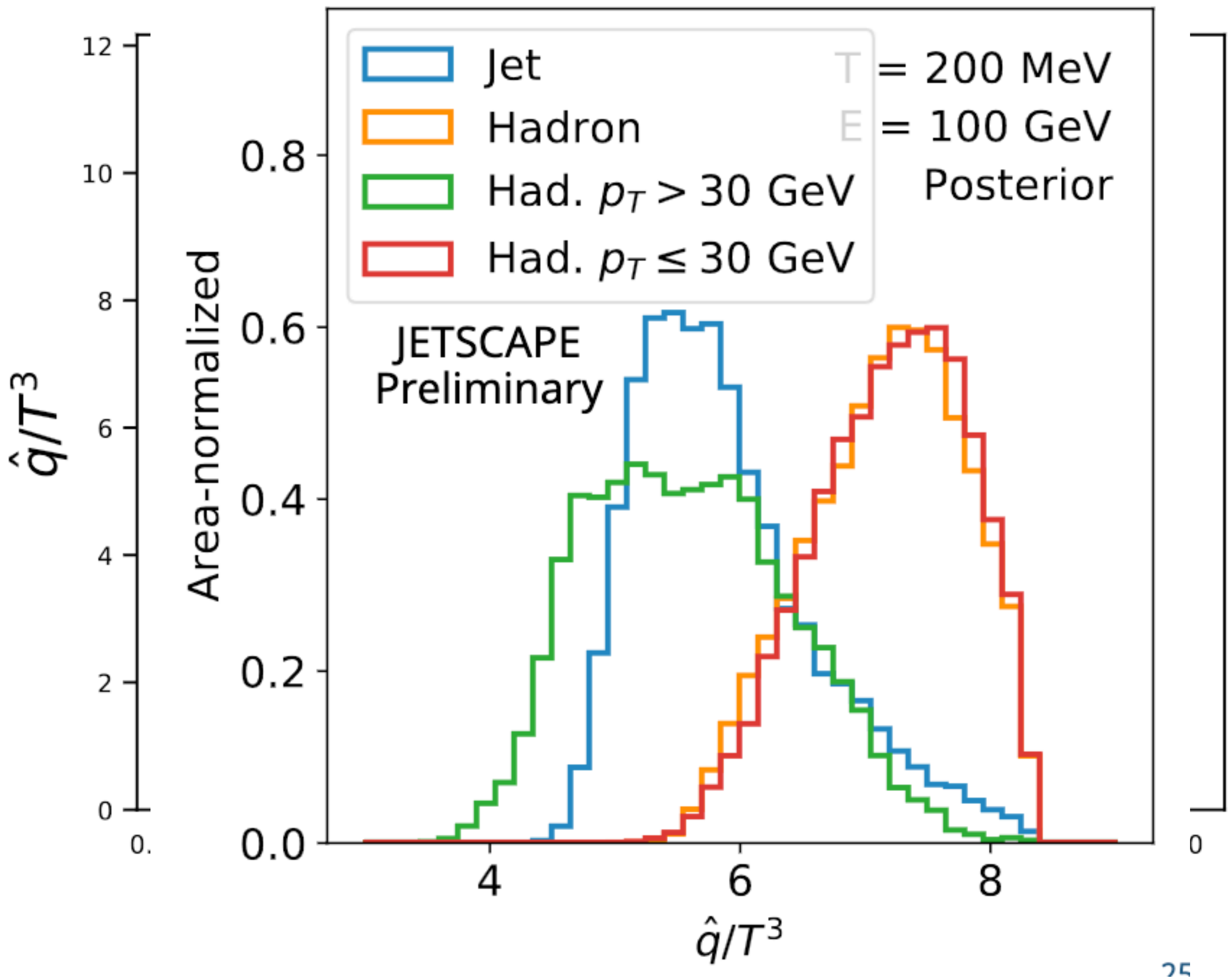
Now includes jet R_{AA} and substructure measurements

$\hat{q} = Q^2/L$ Q - mtm transfer to medium
L - path length

Most precise estimate to-date

Does the T evolution explain differences at RHIC and the LHC?

Determining QGP transport properties



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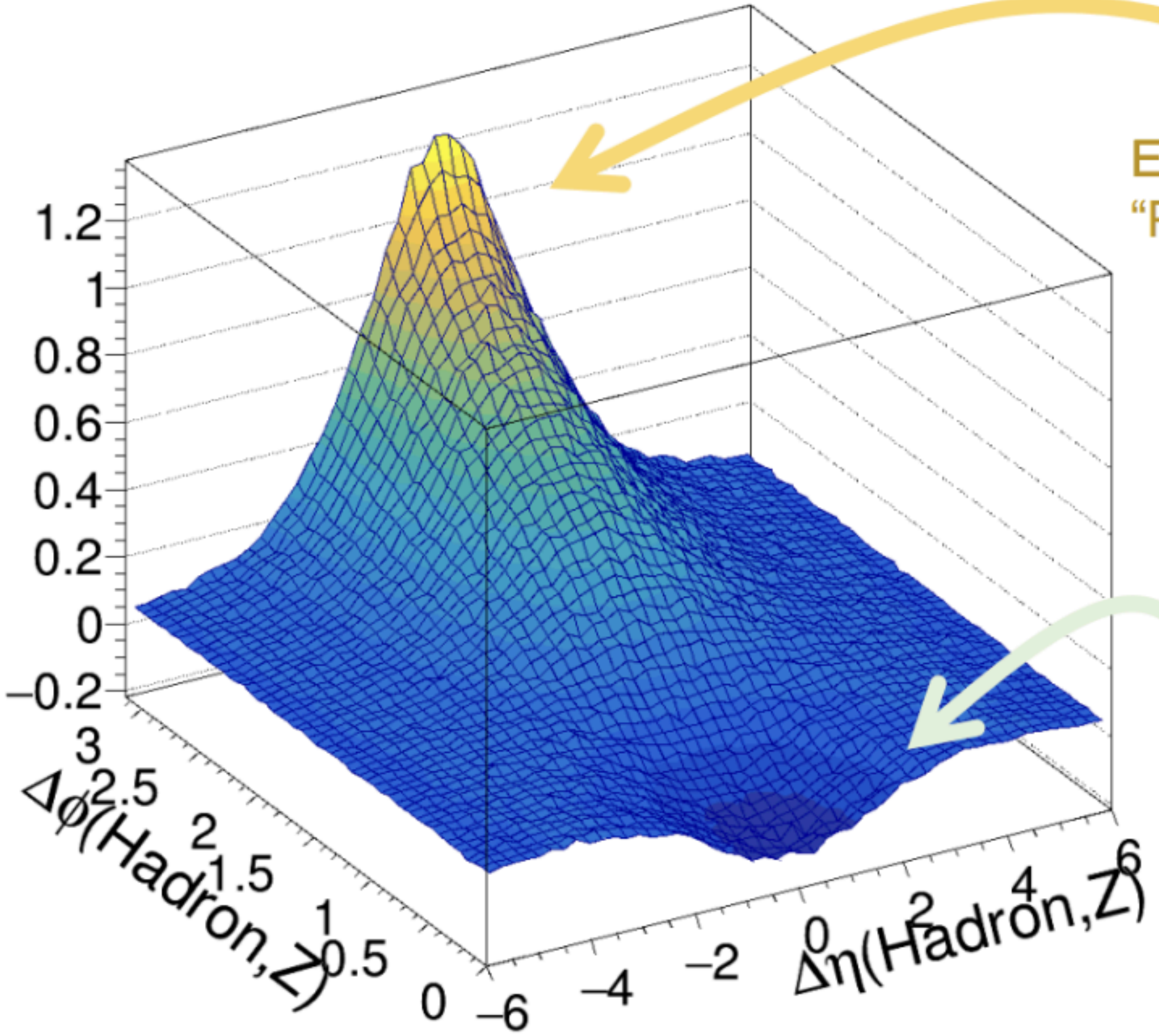
Most precise estimate to-date

Does the T evolution explain differences at RHIC and the LHC?

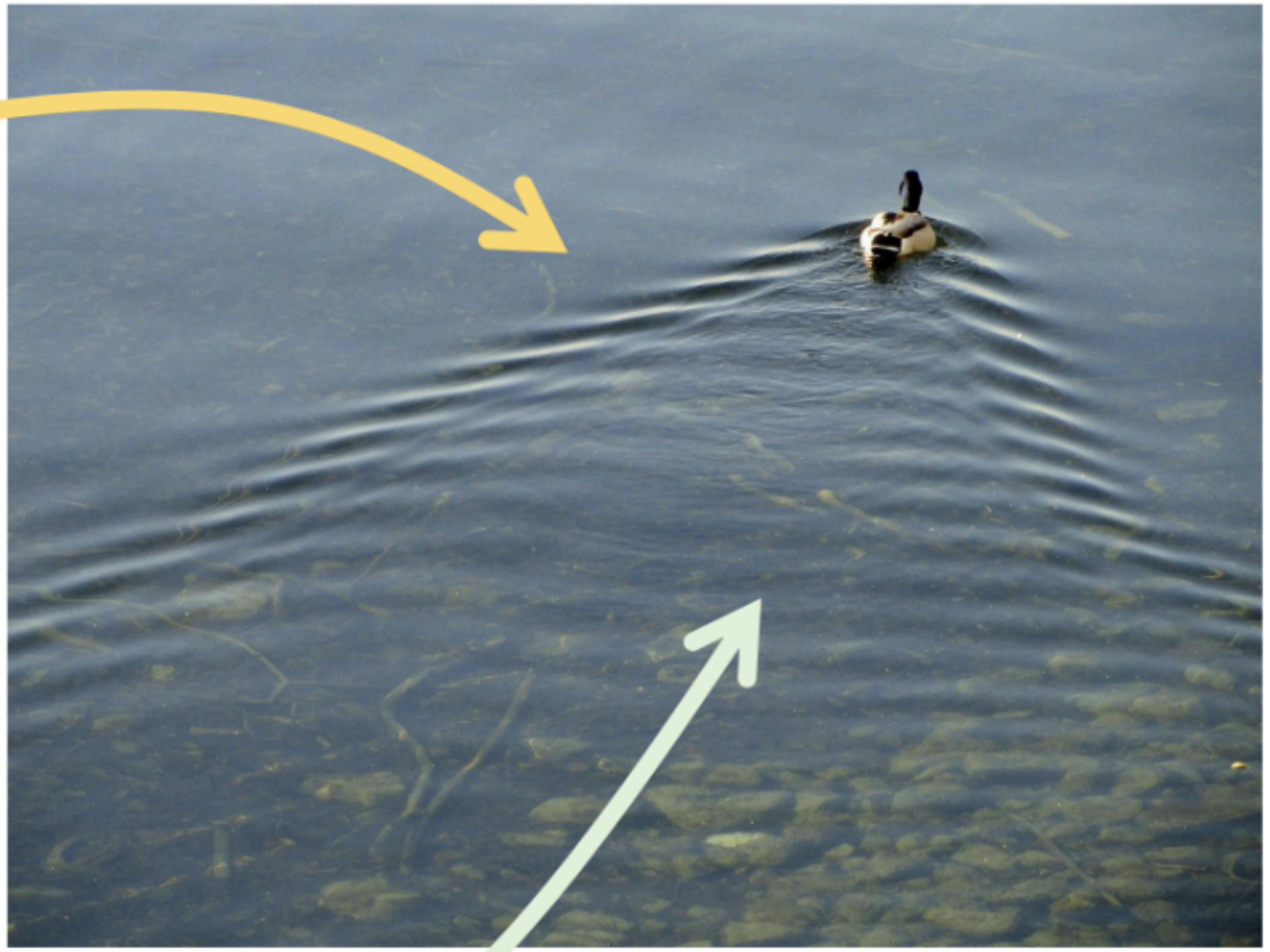
Some tension when include hadron R_{AA}

Some physics missing?
Uncertainties incorrect?
Theory uncertainty critical?
All of the above?

Does medium respond to the jet?



Enhancement of particle
"Positive wake"



Depletion of particle
"Recoil"
"QGP hole"
"Negative wake"

Position space

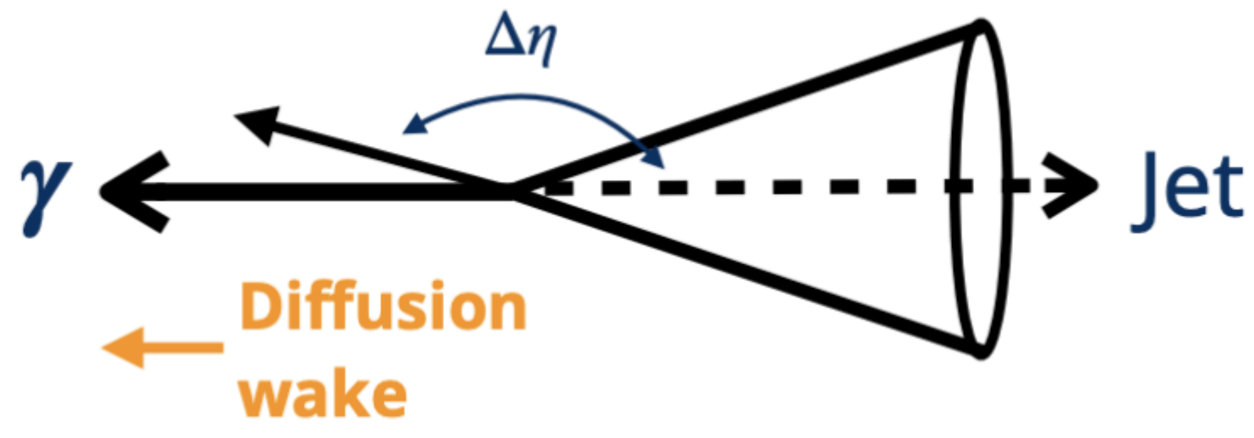
Credit: Yen-Jie Lee

Z^0 and **wake hadron** correlation in Hybrid model

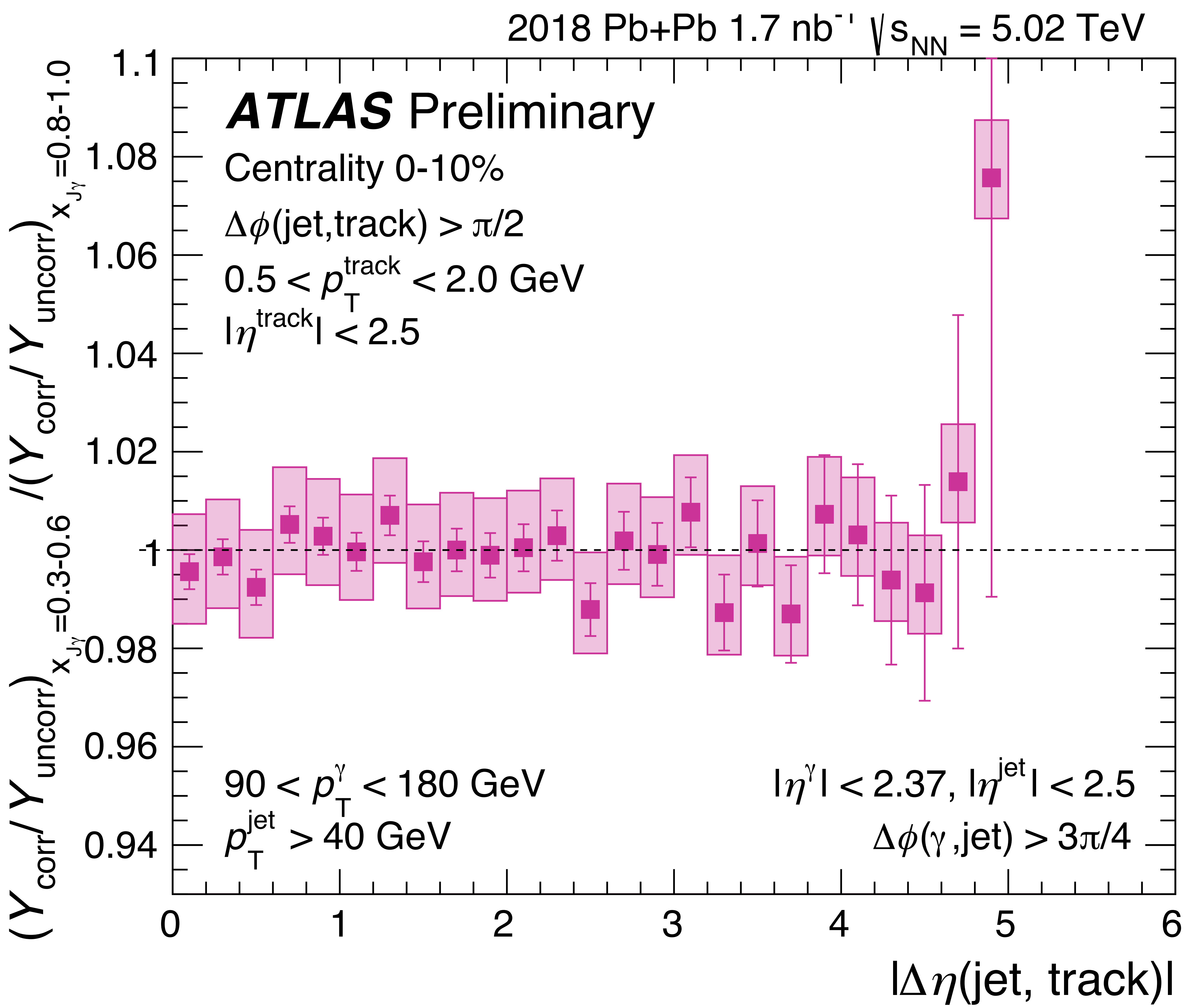
Daniel Pablo, Krishna Rajagopal, YJL

Momentum space

Diffusion Wake or Not?



Credit: R. Ehlers



Lost jet energy generates diffusion wake

—> Depleted particle production in γ direction

—> Wake larger when x_J smaller

At 95% CL wake < 0.8% perturbation of bulk

(note CoLBT predicts 0.2%)

Don't yet have sensitivity to wake effects

Summary of studies using hard probes

Hard probes verified as calibrated probes via p-p data

Charm and beauty have significant rescattering in the medium

Large suppression of high p_T hadrons in presence of a QGP

Jets reconstructed in A-A show strong suppression and modified fragmentation patterns

Energy loss depends on parton color charge, flavor, path length through the medium, and the medium's energy density

No clear evidence of medium response to energy loss

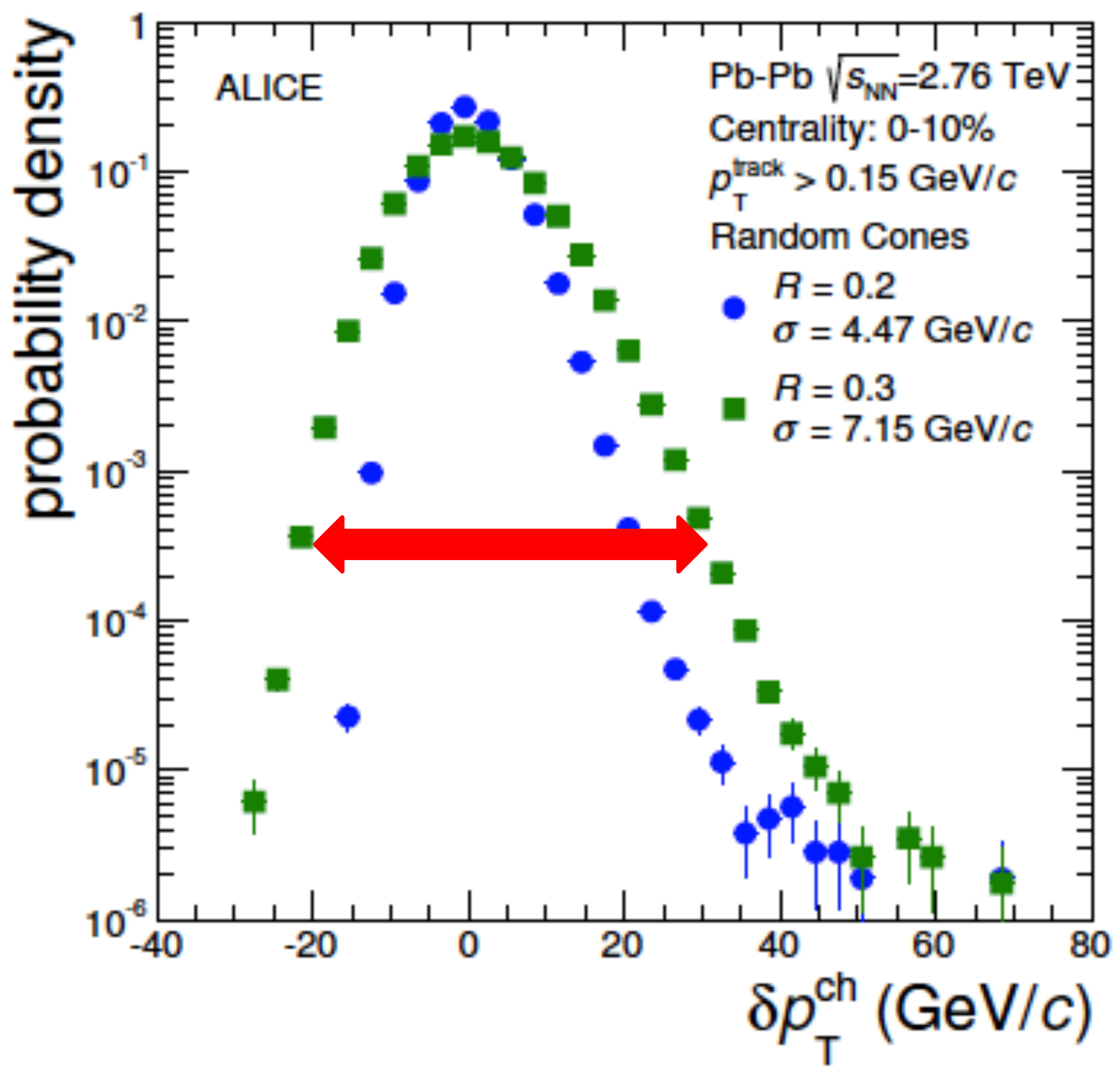
Results can be explained as due to significant partonic energy loss in the QGP before fragmentation

Tomorrow: The unexpected and unplanned physics from RHIC and the LHC

And the background fluctuates

- Background is NOT uniformly distributed within a event.
- It fluctuates from point-to-point.
- It is also correlated with the global characteristics of the events: η dependence; correlation with the event plane

JHEP 03 (2014) 013



Jet Energy Resolution

$$\delta p_T = \sum p_T^{track} - \rho \times A$$

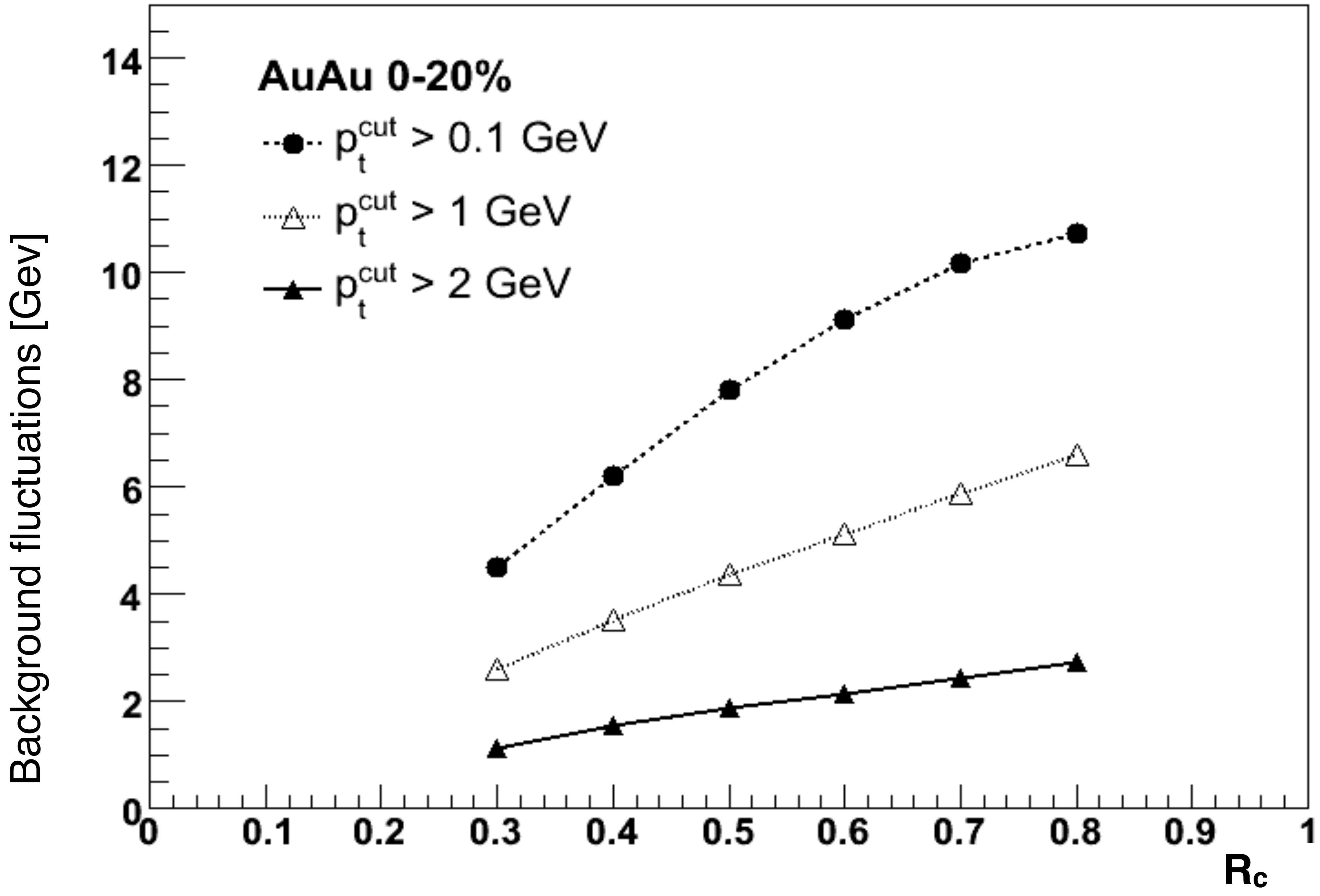
- σ~7.2 GeV/c for R = 0.3 charged jets
- Can be unfolded if known precisely

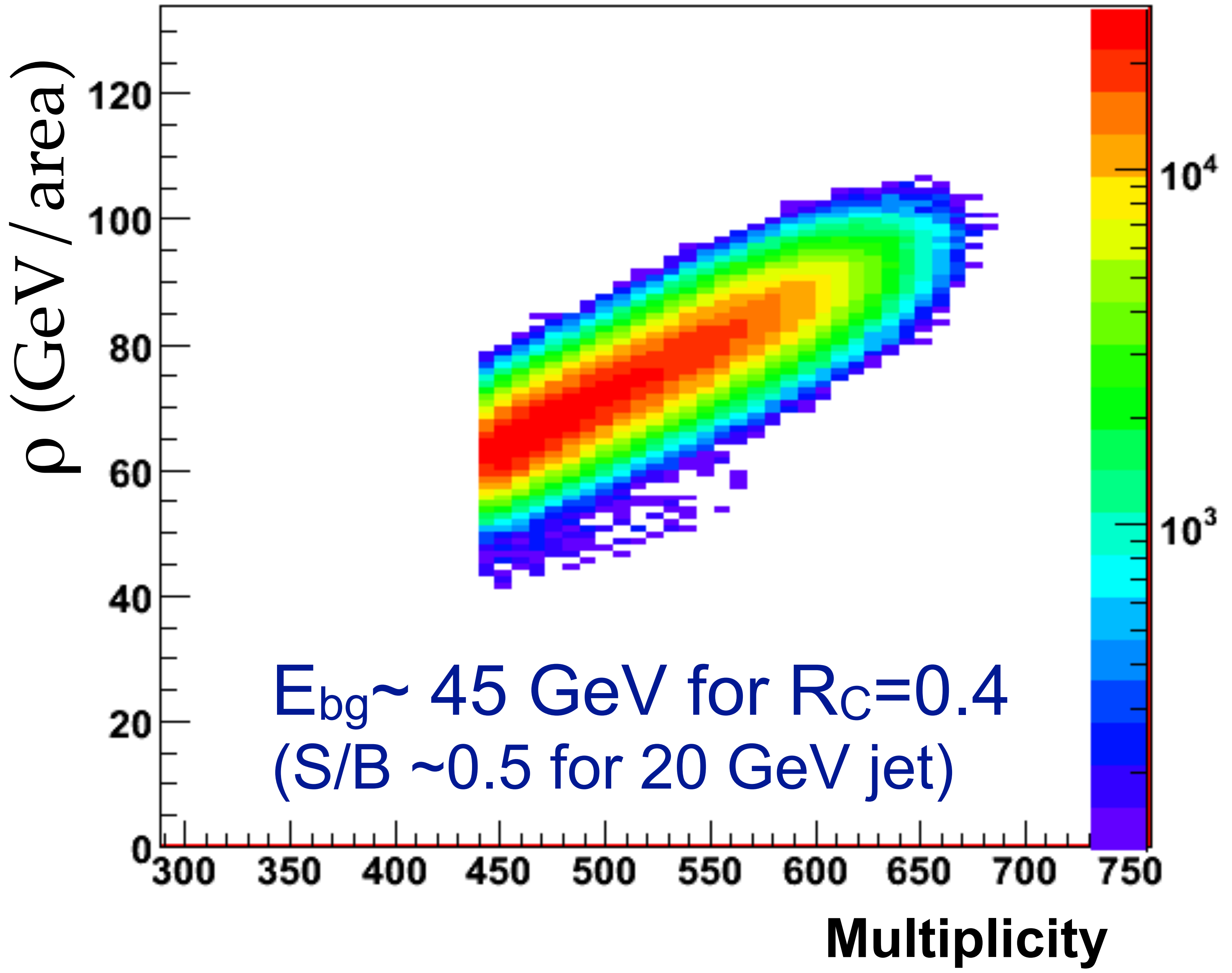
Background - central Au-Au collisions

Event-by-event basis:

p_T (Jet Measured) ~ p_T (Jet) + ρ A ± σ √A

ρ - background energy per unit area
A - jet area





E_{bg}~ 45 GeV for R_C=0.4
(S/B ~0.5 for 20 GeV jet)

Substantial region-to-region background fluctuations

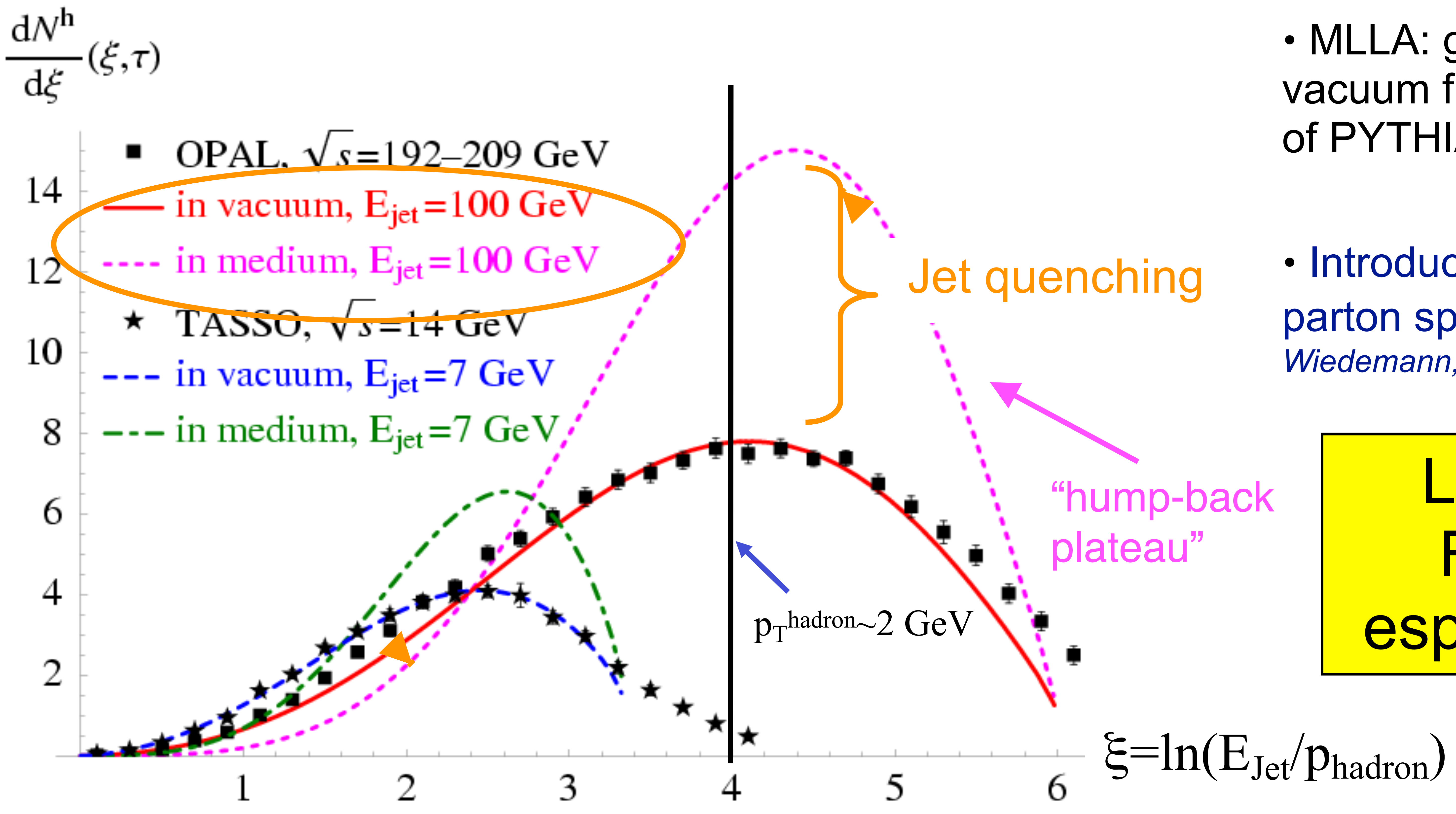
σ - comparable magnitude from FastJet and naïve random cones

Both reduced significantly by increasing p_T^{cut}

Modification of the fragmentation

p and E must be conserved so quenched energy must appear somewhere

Prediction that the fragmentation function is modified in the presence of a QGP - more and softer particles produced



- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*

Look at A-A Frag. Fnc. especially low z