Hard probes in small systems

HP'18 Student Lectures
CERN, 30 September 2018

Dennis V. Perepelitsa
University of Colorado Boulder

Hard probes in small systems

Low-x QCD

Nuclear PDFs

explore this (and other) physics

EM & Weak Probes

HF & Quarkonia

Jets

use these tools (and QGP physics?)

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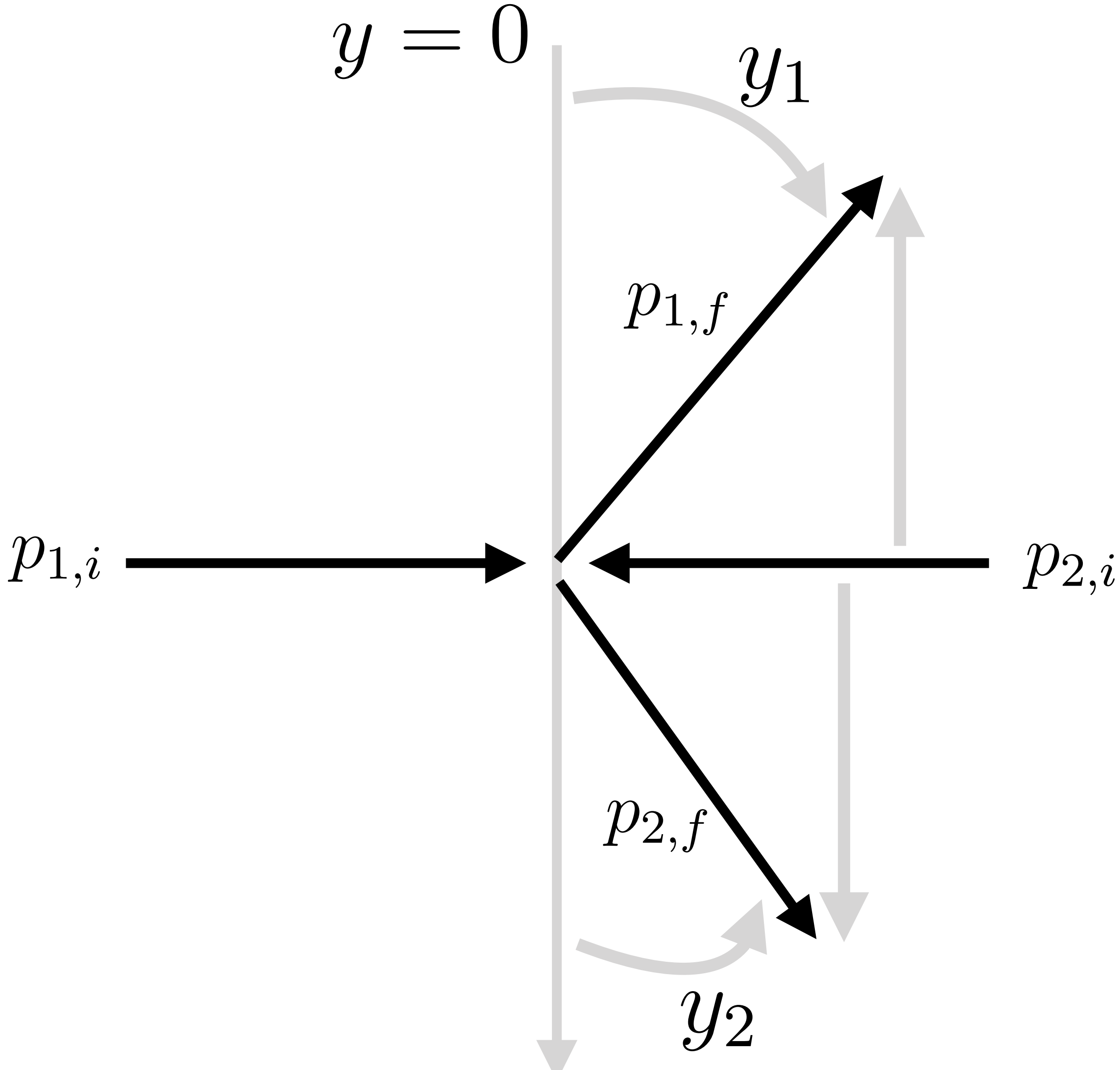
Initial state physics

Hard-soft correlations

QGP in small systems

Useful references:
A. Morsch, 12 Intl High-pT Workshop, Bergen, Oct '17
P. Steinberg, Probing Quark Gluon Matter w/ Jets, BNL, July '18
L. Bianchi, Quark Matter Student Day, Venice, May '18

2→2 parton scattering cheat sheet



Using $(E, \vec{p}_\mathrm{T}, p_z)$...

$$p_{1,i} = (x_1 E_\mathrm{beam}, \vec{0}, x_1 E_\mathrm{beam})$$

$$p_{2,i} = (x_2 E_\mathrm{beam}, \vec{0}, -x_2 E_\mathrm{beam})$$

$$p_{1,f} = (p_\mathrm{T} \cosh(y_1), \vec{p}_\mathrm{T}, p_\mathrm{T} \sinh(y_1))$$

$$p_{2,f} = (p_\mathrm{T} \cosh(y_2), \vec{p}_\mathrm{T}, p_\mathrm{T} \sinh(y_2))$$

$$p_{1,i} + p_{2,i} = p_{1,f} + p_{2,f}$$

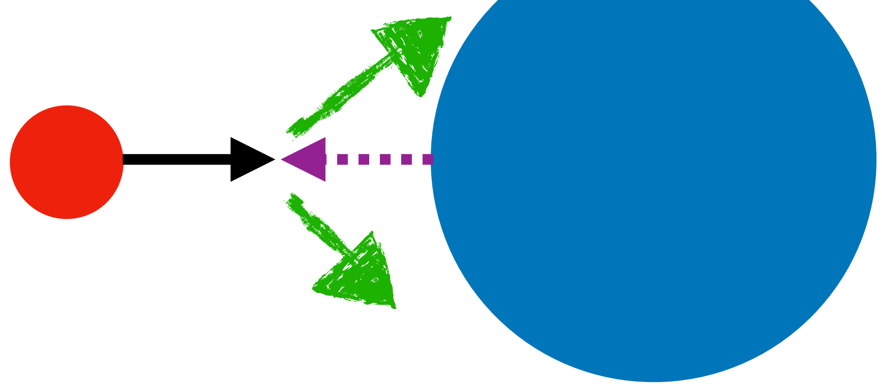
$$x_1 = p_\mathrm{T}(e^{y_1} + e^{y_2})/\sqrt{s}$$

$$x_2 = p_\mathrm{T}(e^{-y_1} + e^{-y_2})/\sqrt{s}$$

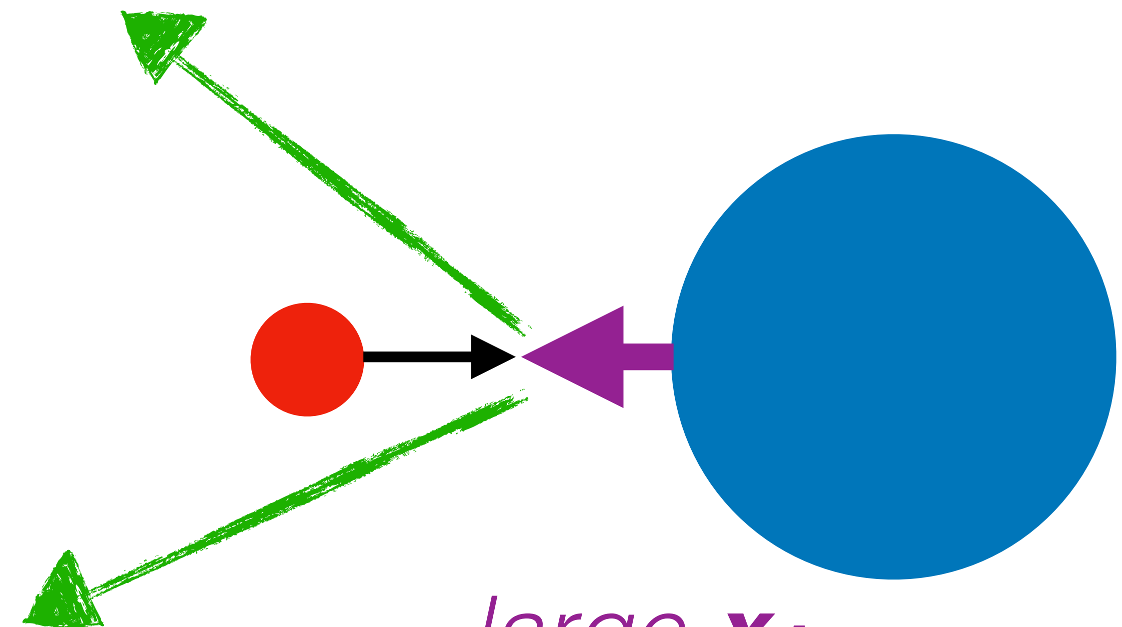
In the limit $y_1 \gg y_2$, $x_1 \approx p_\mathrm{T} e^{y_1}/\sqrt{s}$

$$\frac{1}{2}\log(x_1/x_2) = y^* = \frac{1}{2}(y_1 + y_2)$$

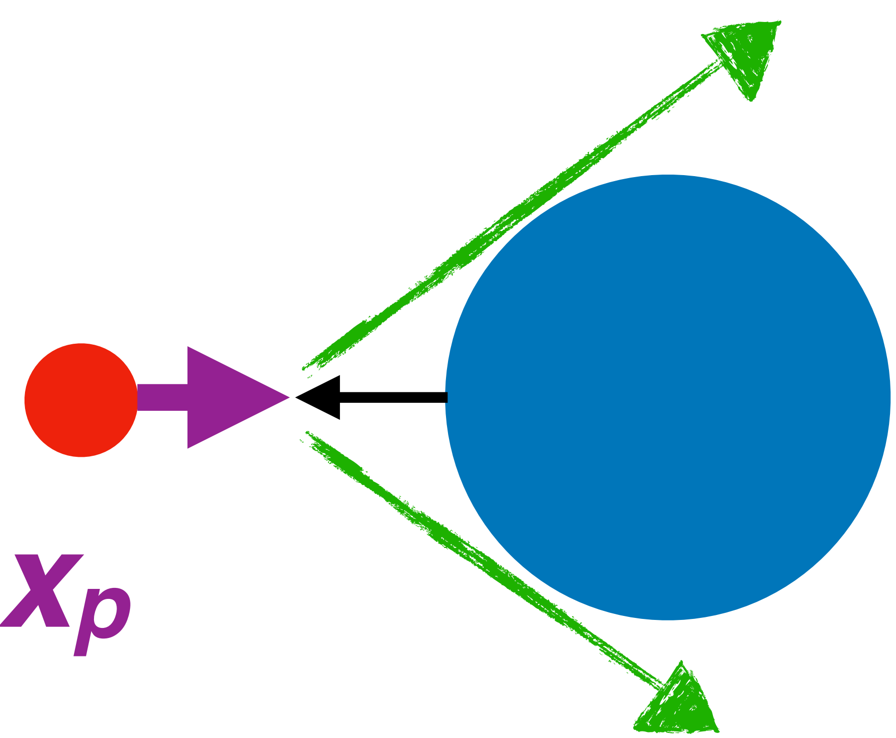
small-x & large-x



small-x_A
("forward" & low-p_T)

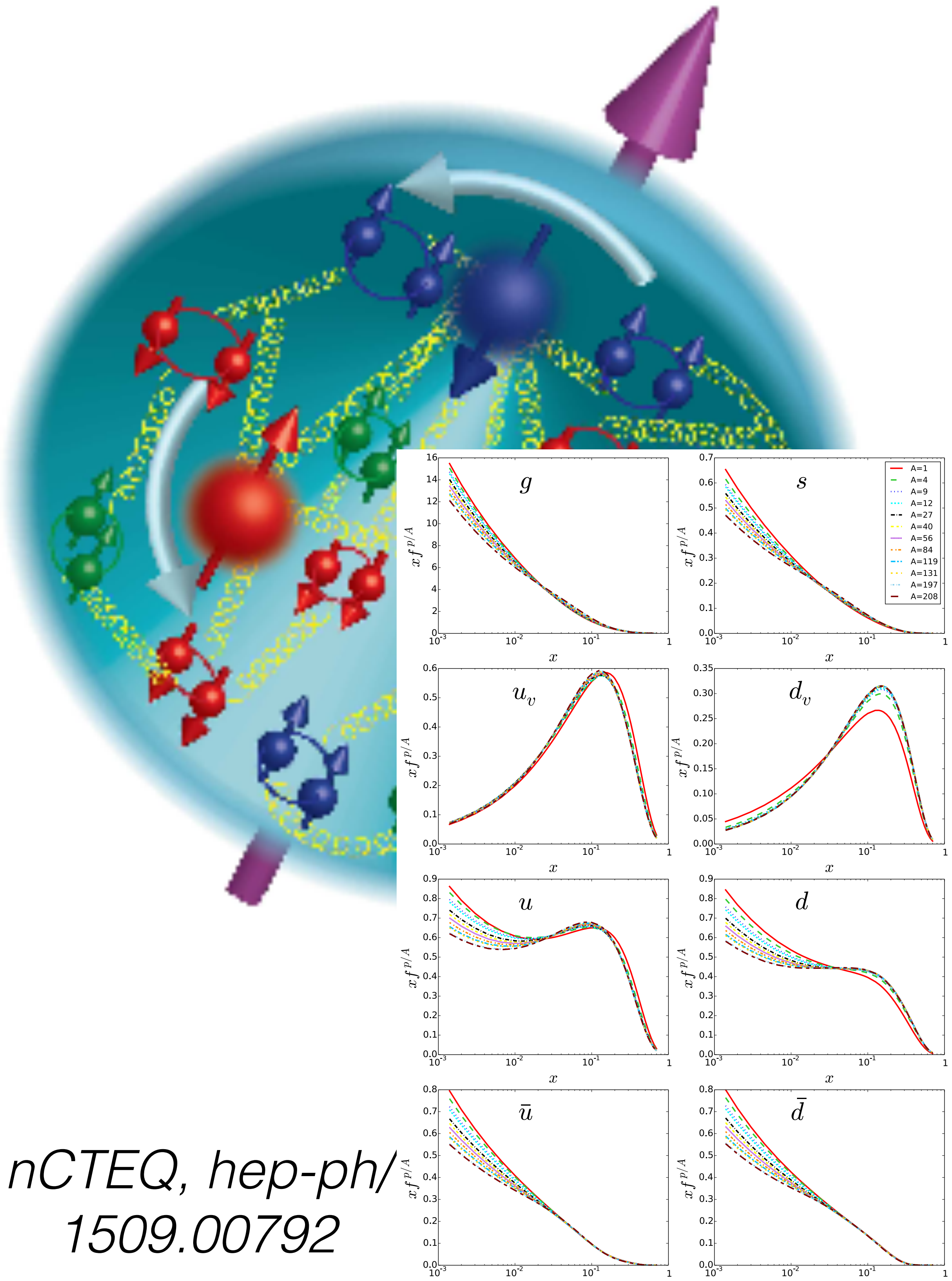


large-x_A
("backward" & high-p_T)



large-x_p

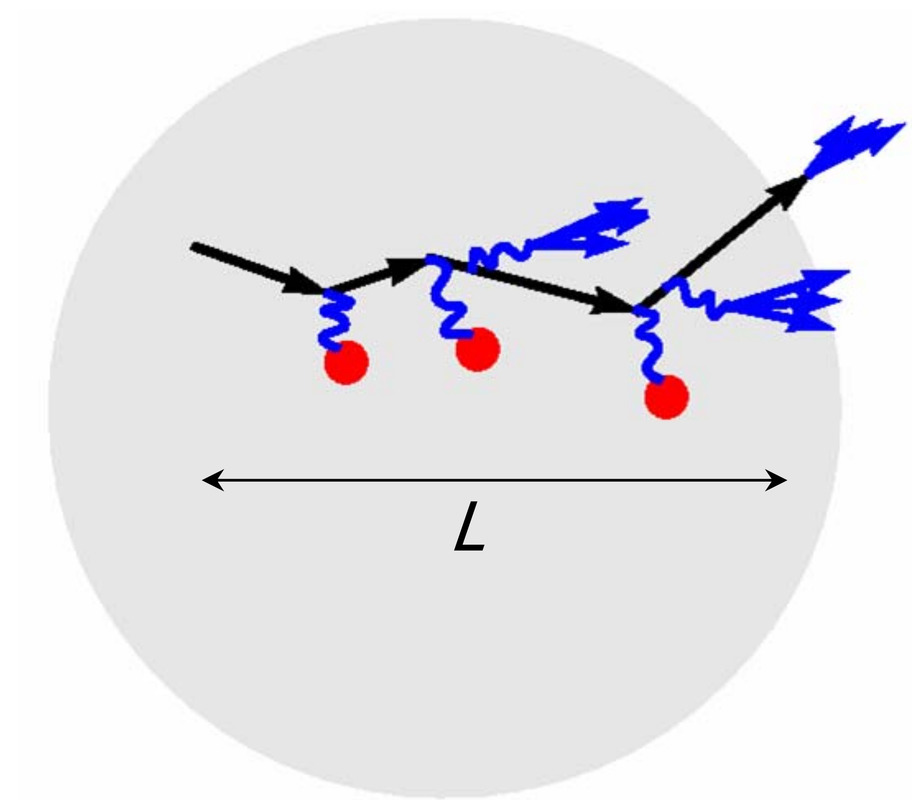
Initial state physics



nCTEQ, hep-ph/ 1509.00792

Figure 6: nCTEQ15 bound proton PDFs at the scale $Q = 10$ GeV for a range of nuclei from the free proton ($A = 1$) to lead ($A = 208$).

global nPDF picture

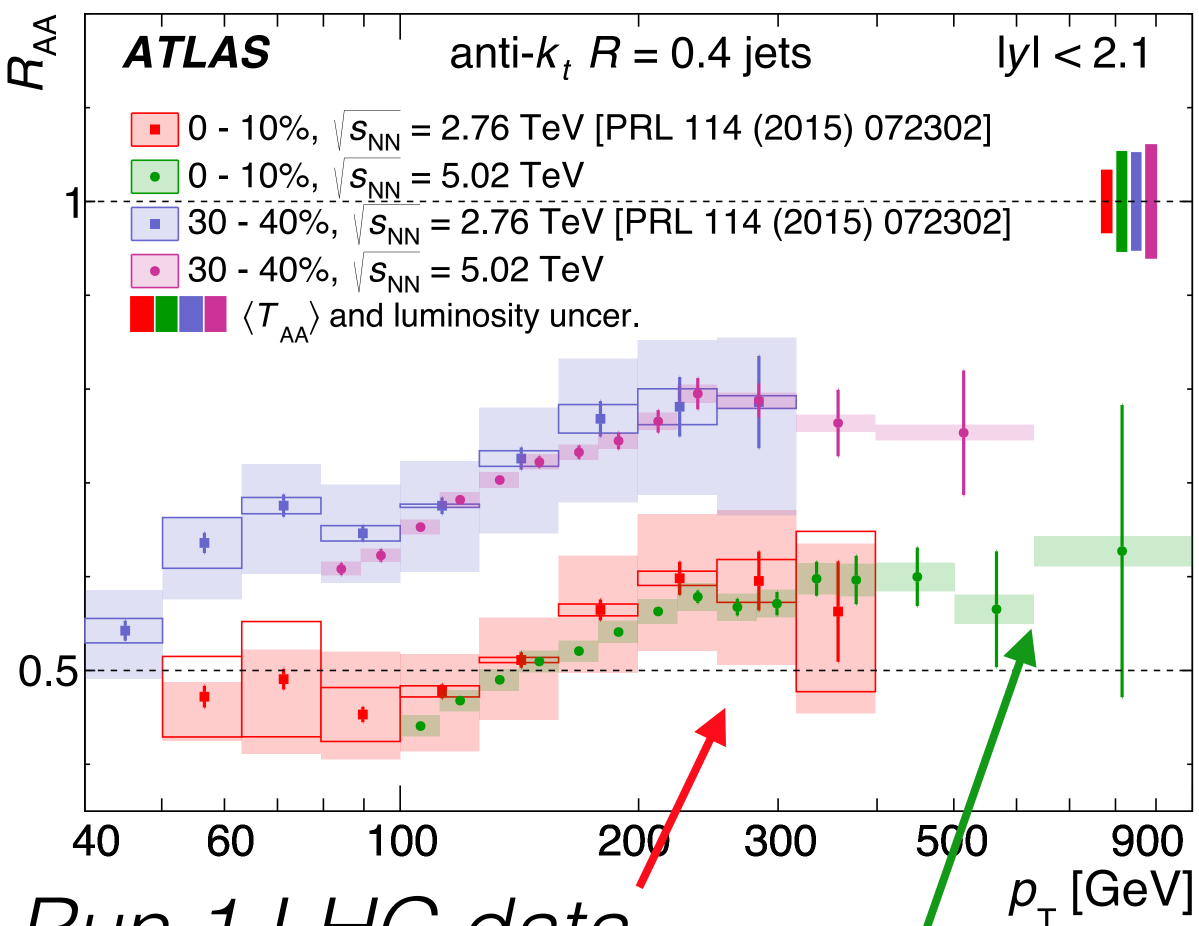


dynamical pictures of “cold nuclear matter” effects

…more in Carlos' & Sevil's talks…

context for A+A (1/2)

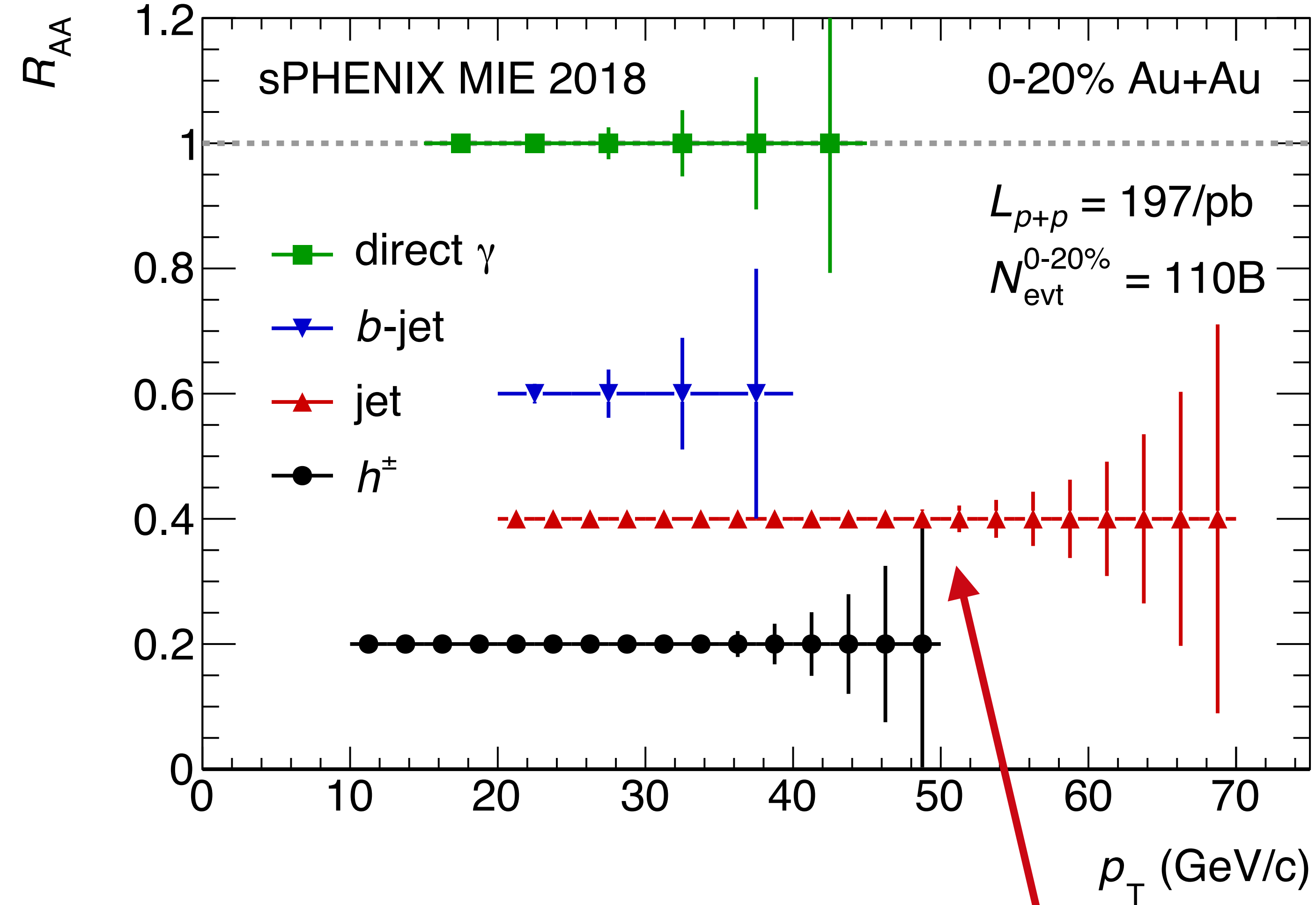
arXiv:1805.05635



Run 1 LHC data

2015 LHC data

(3x-4x more in 2018?)



E_{jet} = 1 TeV at y~0

x_A ~ 0.4 (EMC region!)

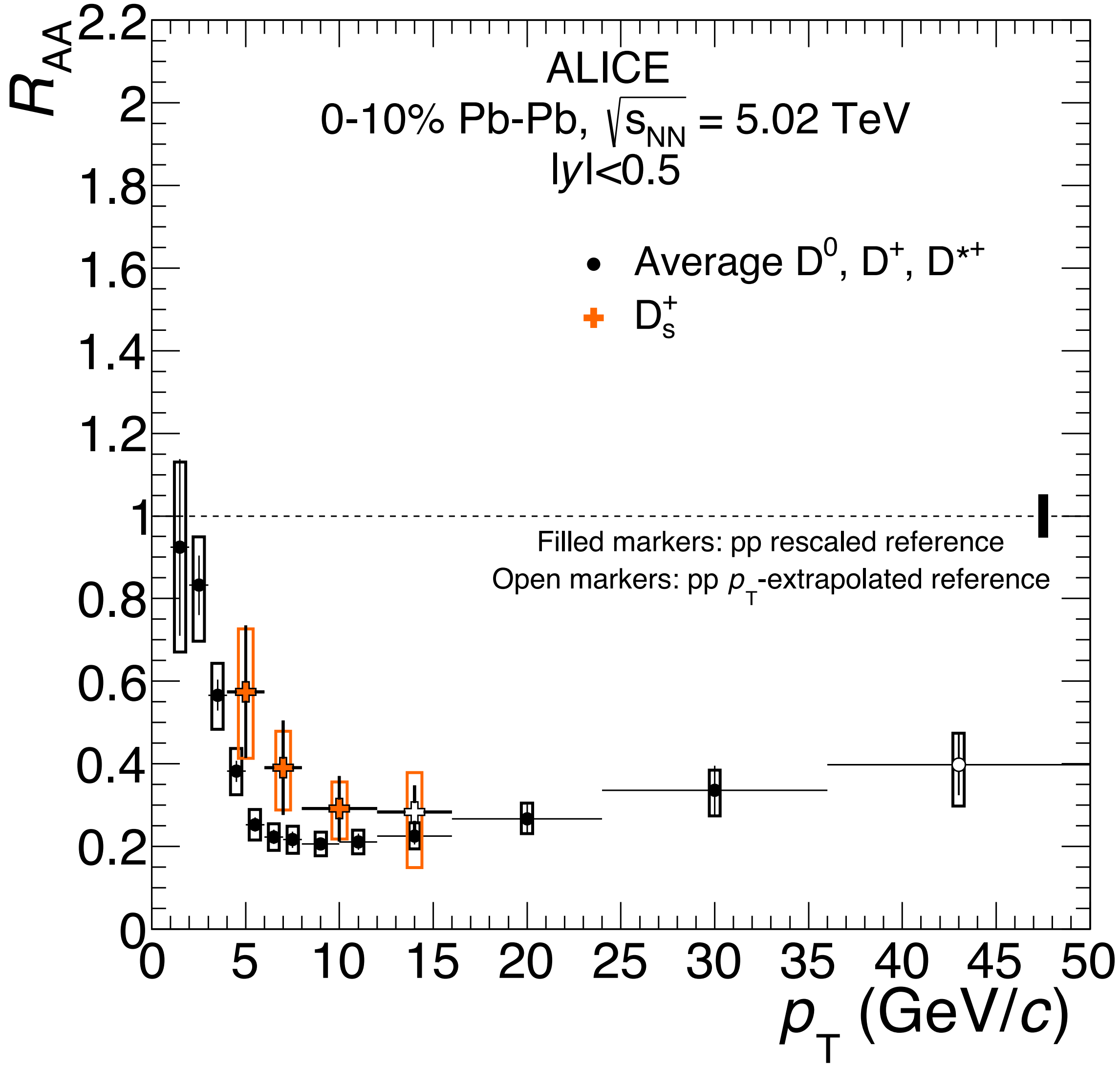
Au+Au @ RHIC-sPHENIX,

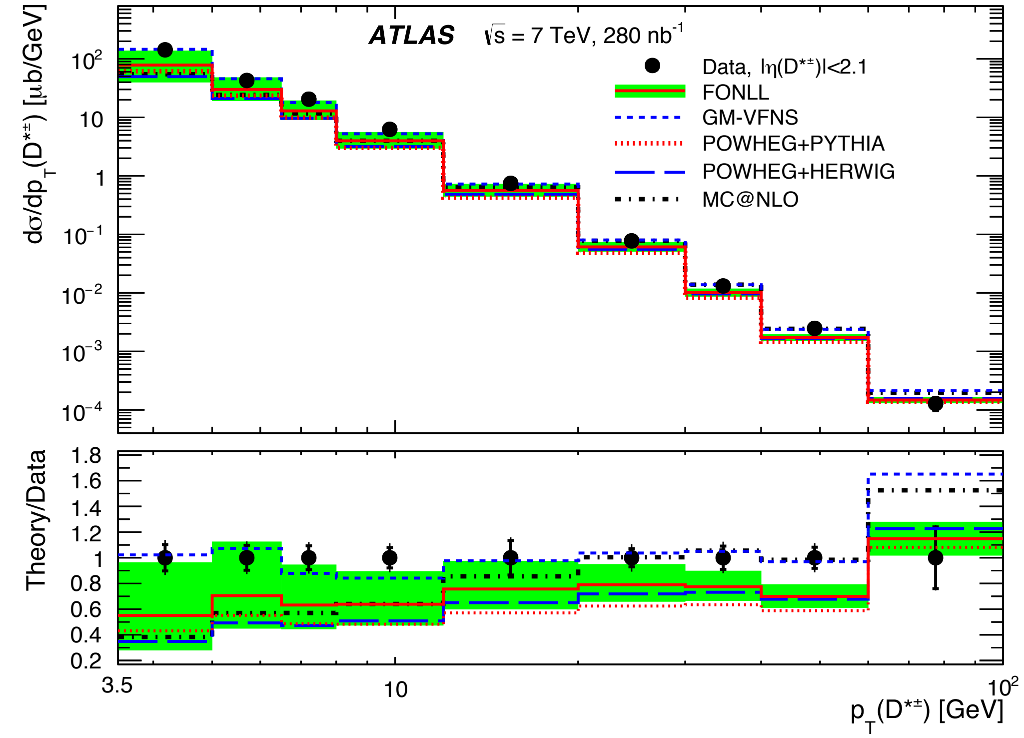
E_{jet} = 50 GeV at y~+0, x_A ~ 0.5

need <u>precise</u> constraints from p+A…

…more in Barbara & Pol's talks…

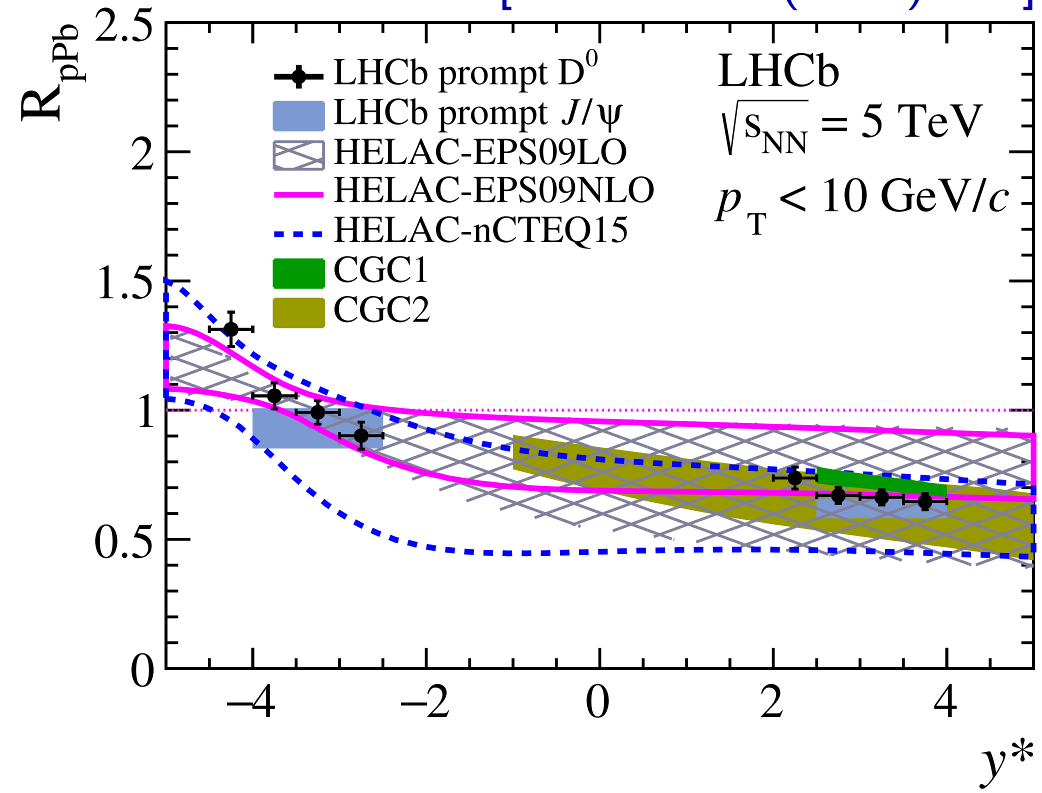
context for A+A (2/2)





Large uncertainties in FONLL calculations

[JHEP 1710 (2017) 090]



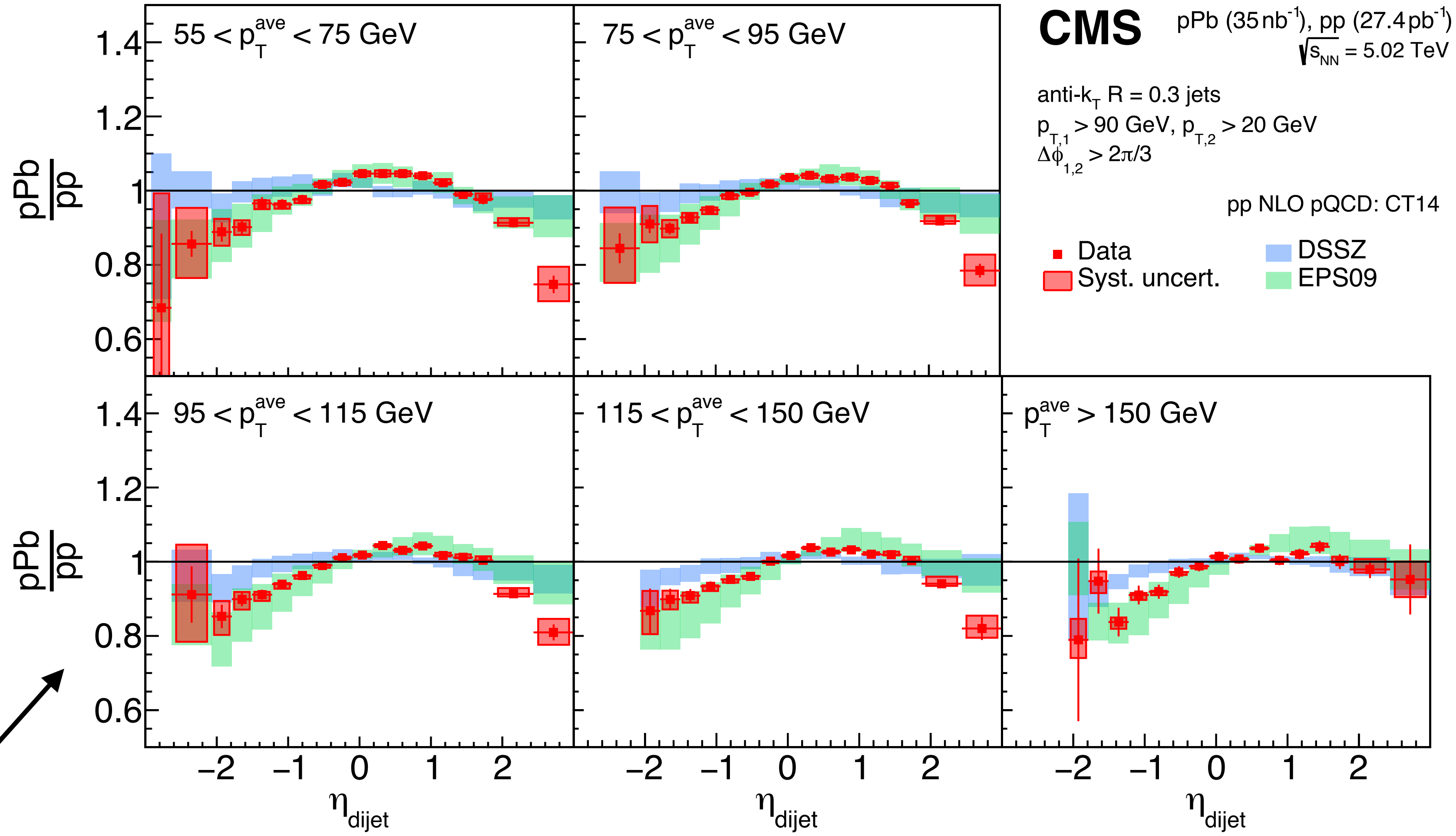
Total $c\bar{c}$ and $b\bar{b}$ created early and preserved throughout QGP evolution

➡ *very powerful, but crucial to have information directly from p+A data*

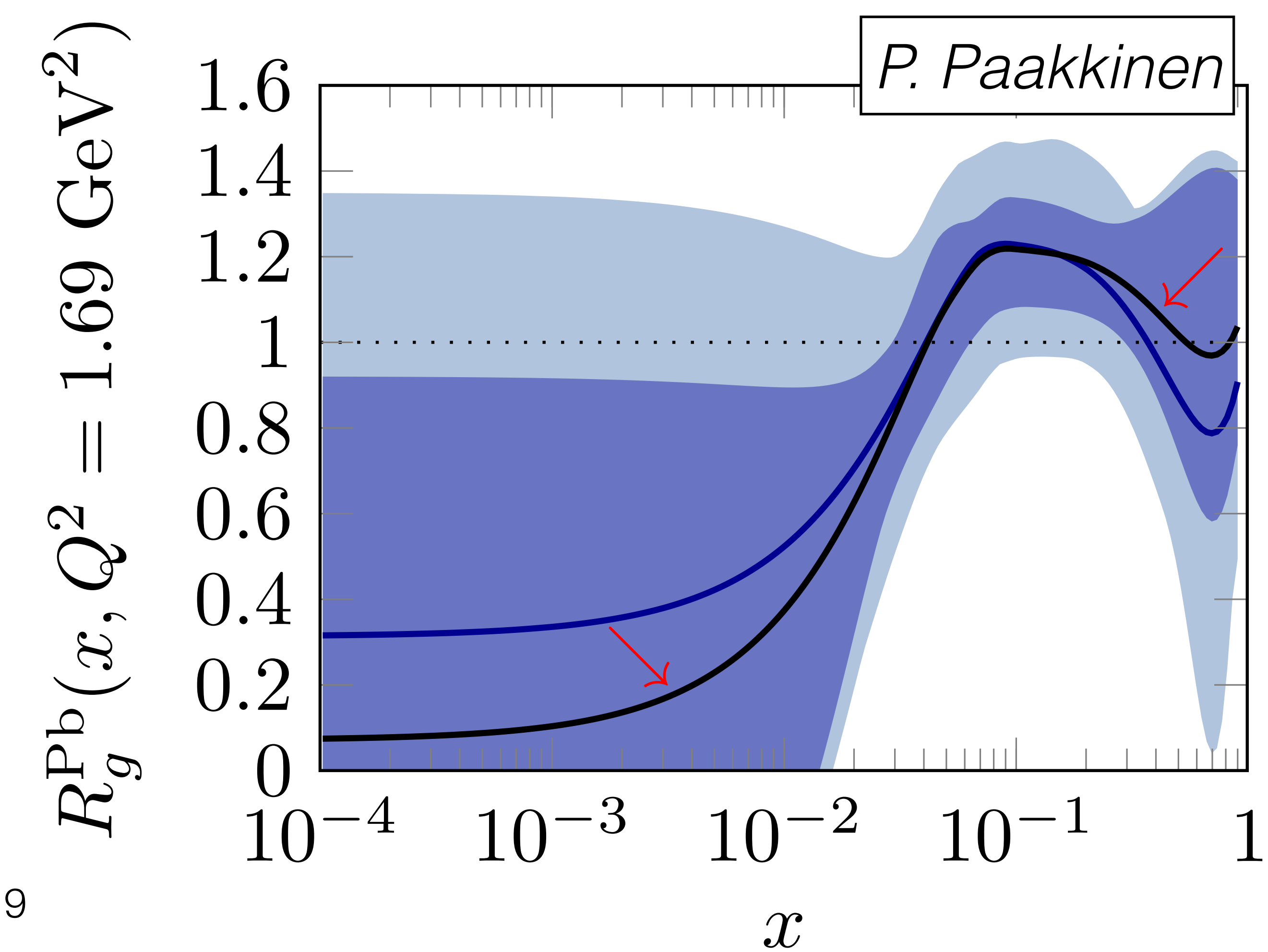
Large variation in nPDF/ saturation calculations

hard probes data in a global nPDF picture

broad (p_T, η)-dep. measurements in p+Pb/pp



impact of LHC Run 1 data on nPDF constraints

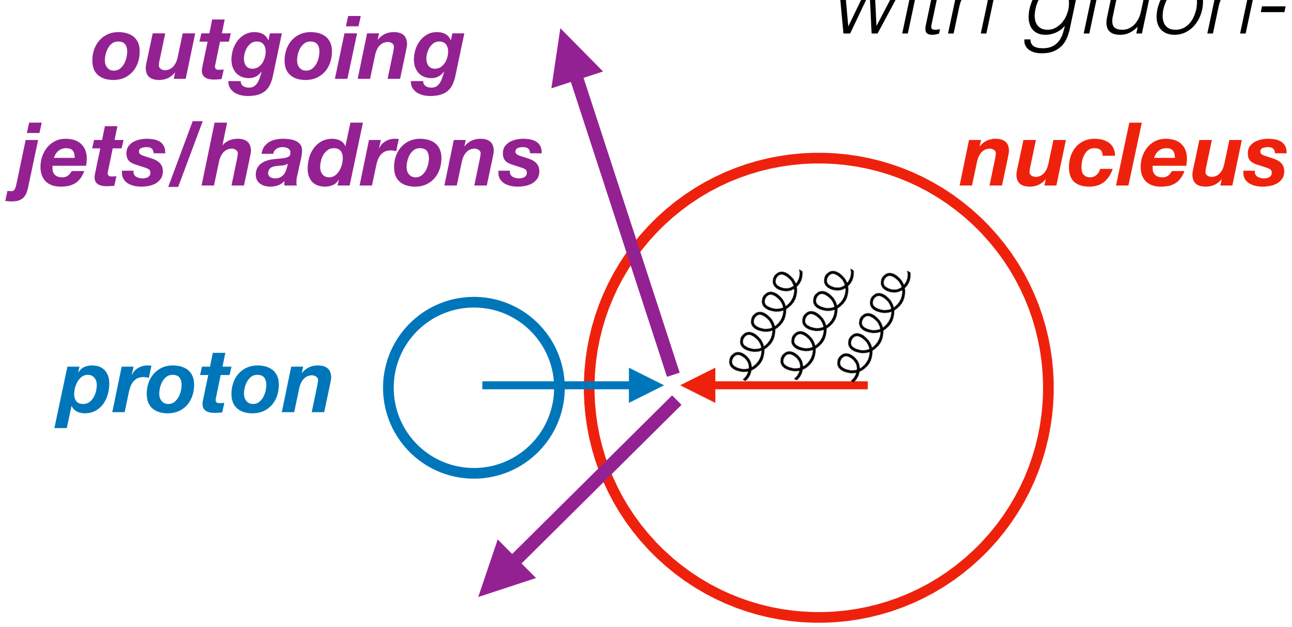


…more in Aleksander's talk…

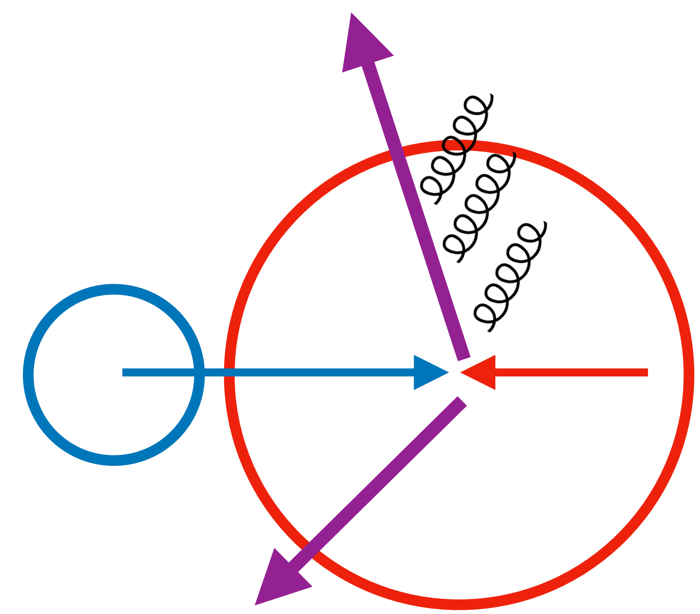
…more in Jamal’s talk…

“cold nuclear matter” dynamics

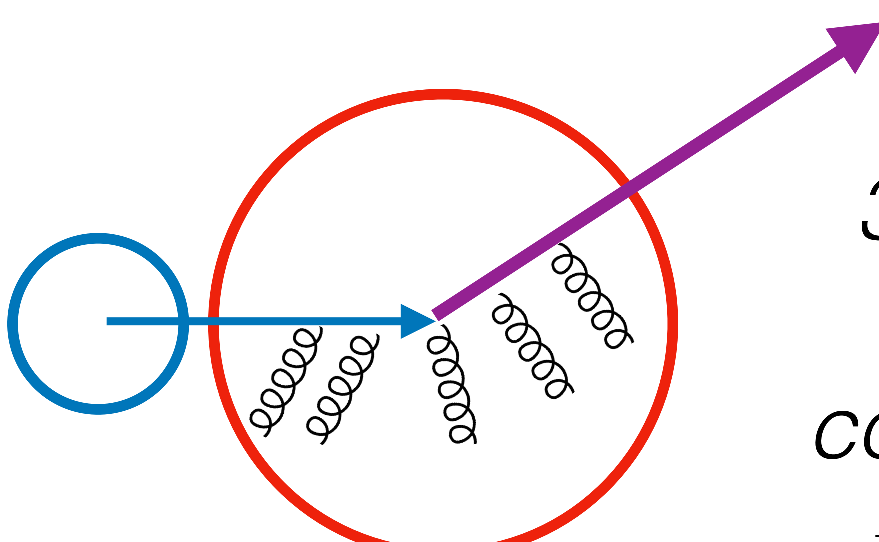
partons before and/or after hard scattering interacting with gluon-dense nucleus



1. parton-gluon interactions before hard scattering (initial state E-loss)



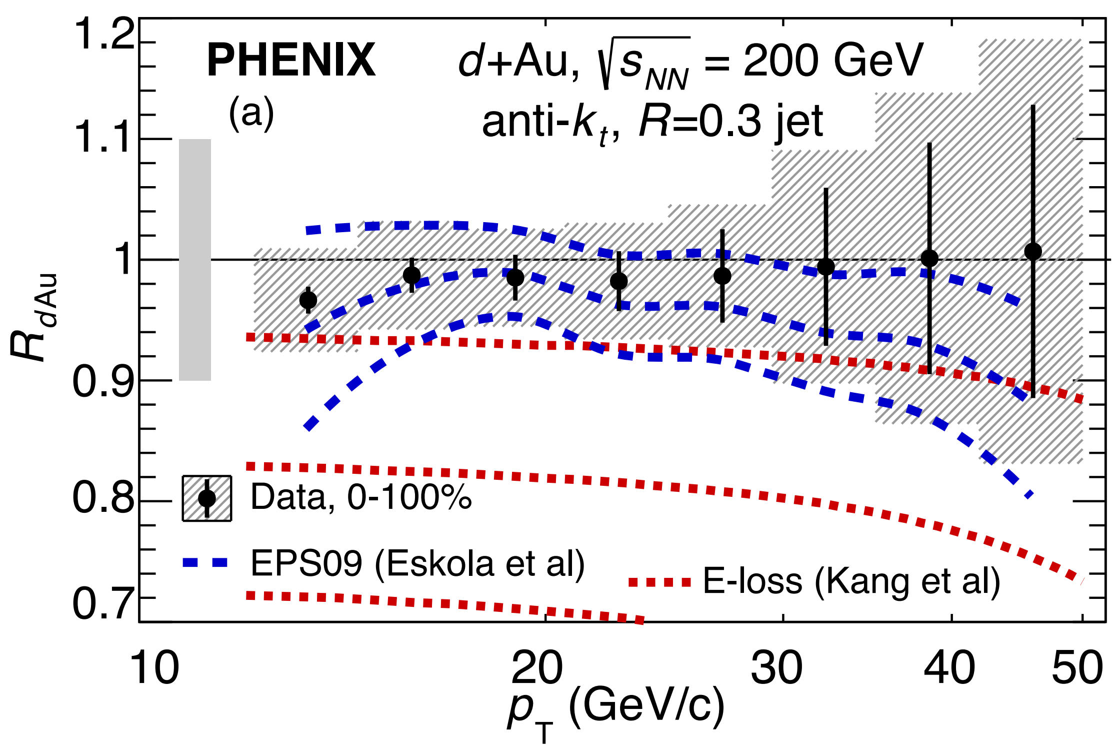
2. interactions after scattering (k_T broadening, $\Delta\phi$ decorrelation)



3. forward mono-jet production (parton in proton interacts coherently with saturated gluons)

1. initial state energy loss

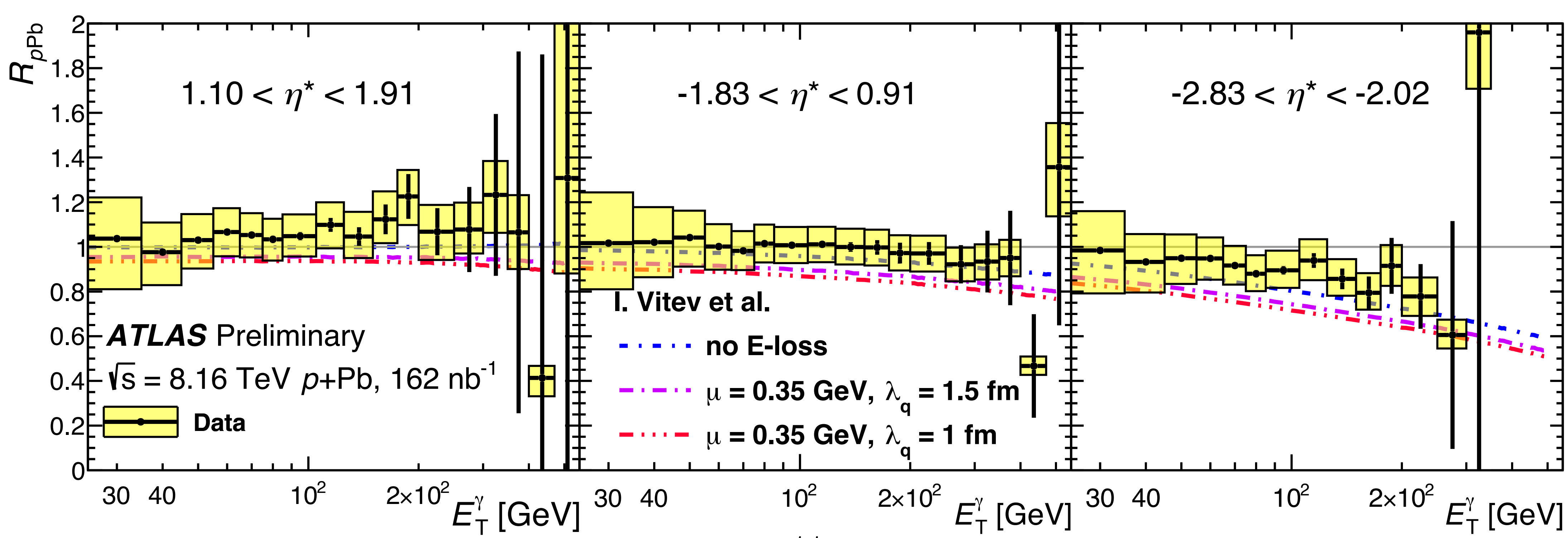
PRL 116, 122301 (2016)



important at fixed-target energies, evidence at collider energies is weaker …

Strong constraints from jets @ RHIC, photons @ LHC

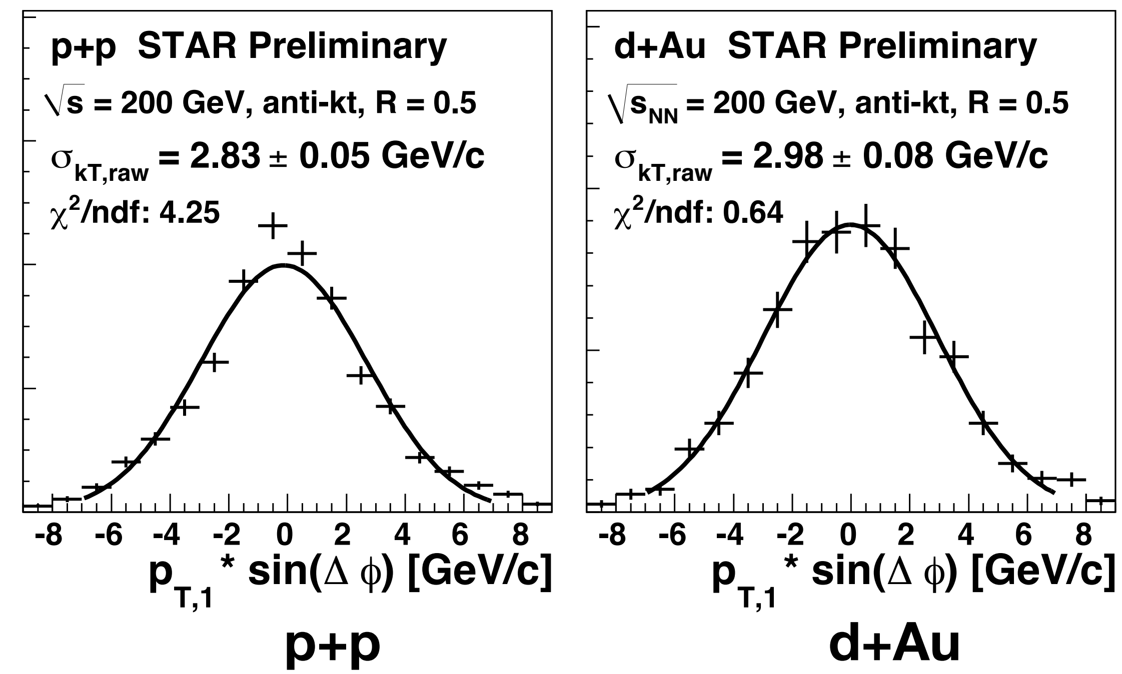
ATLAS-CONF-2017-072



2. k_T broadening

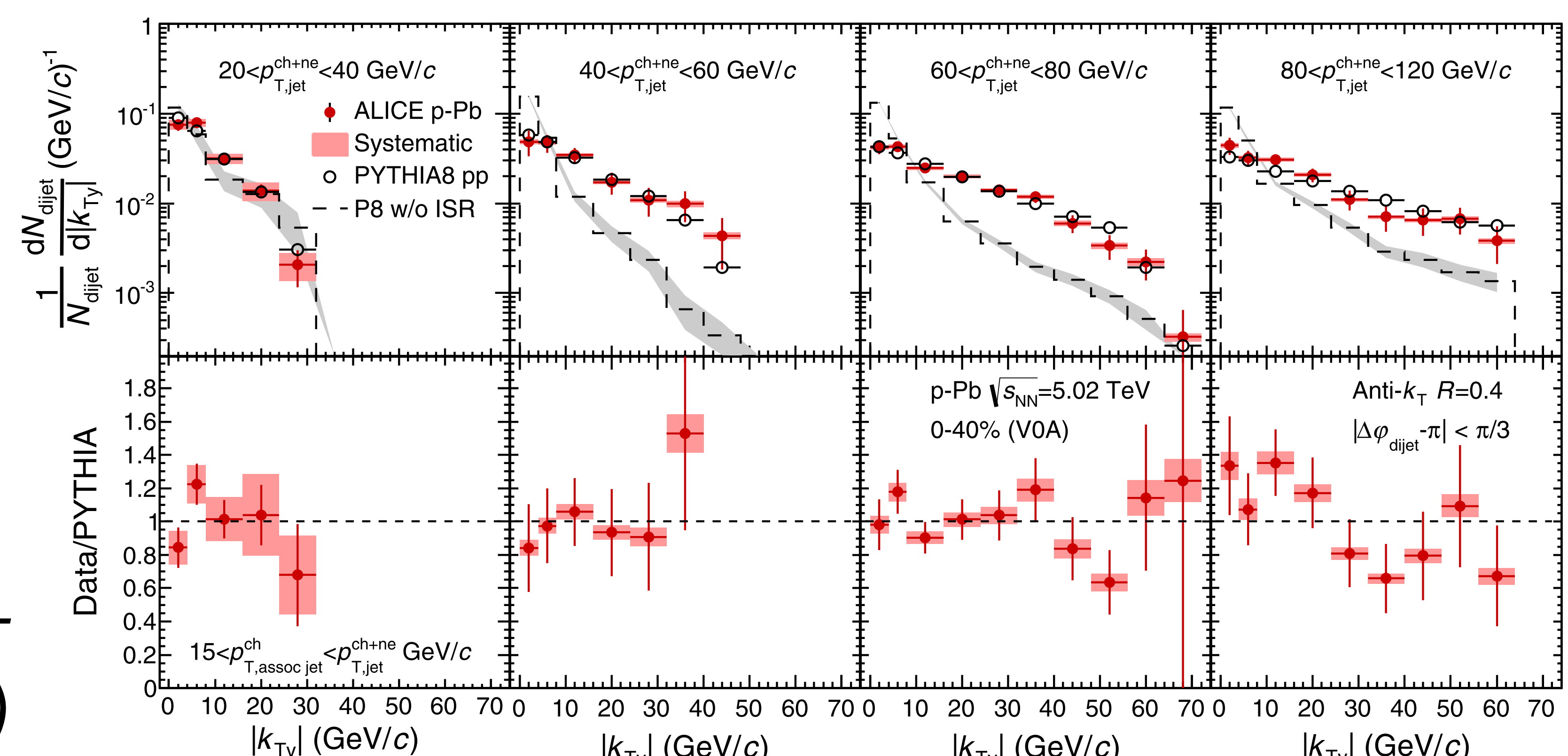
Common measurement of dijet acoplanarity in nuclear environment:

$k_{T,y} = p_T^{jet} \sin(\Delta\phi^{dijet})$



di-hadrons at STAR

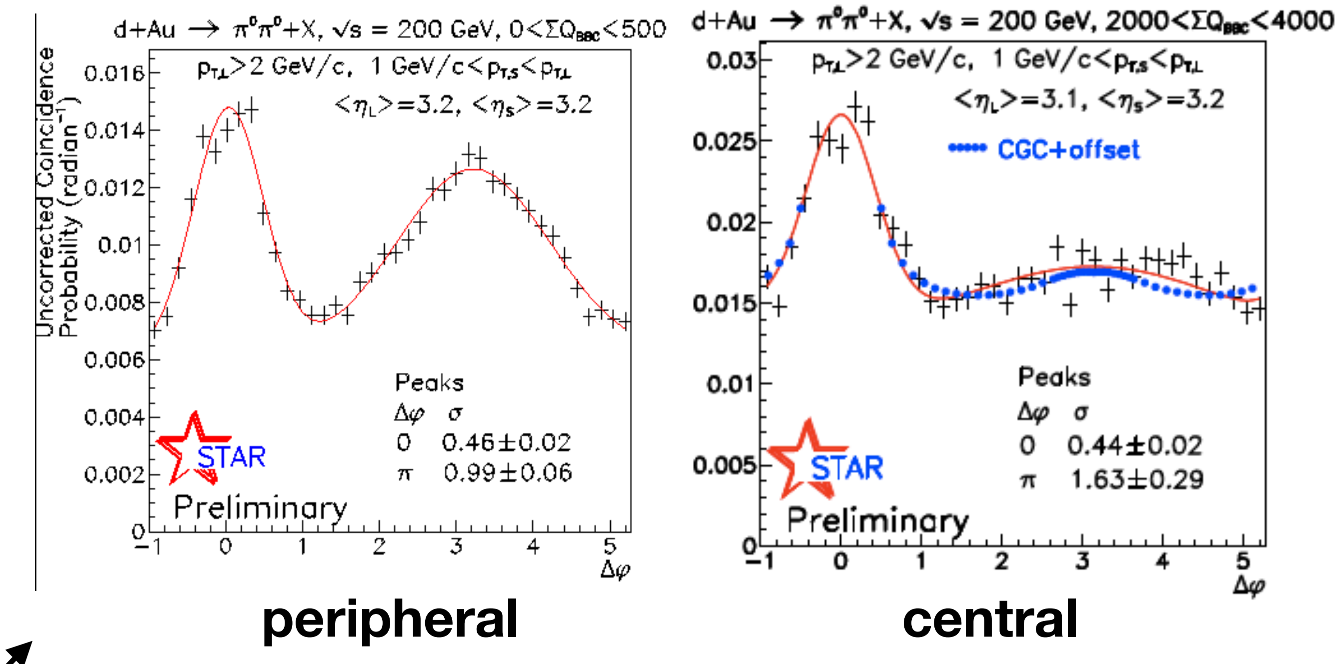
PLB 746 (2015) 385

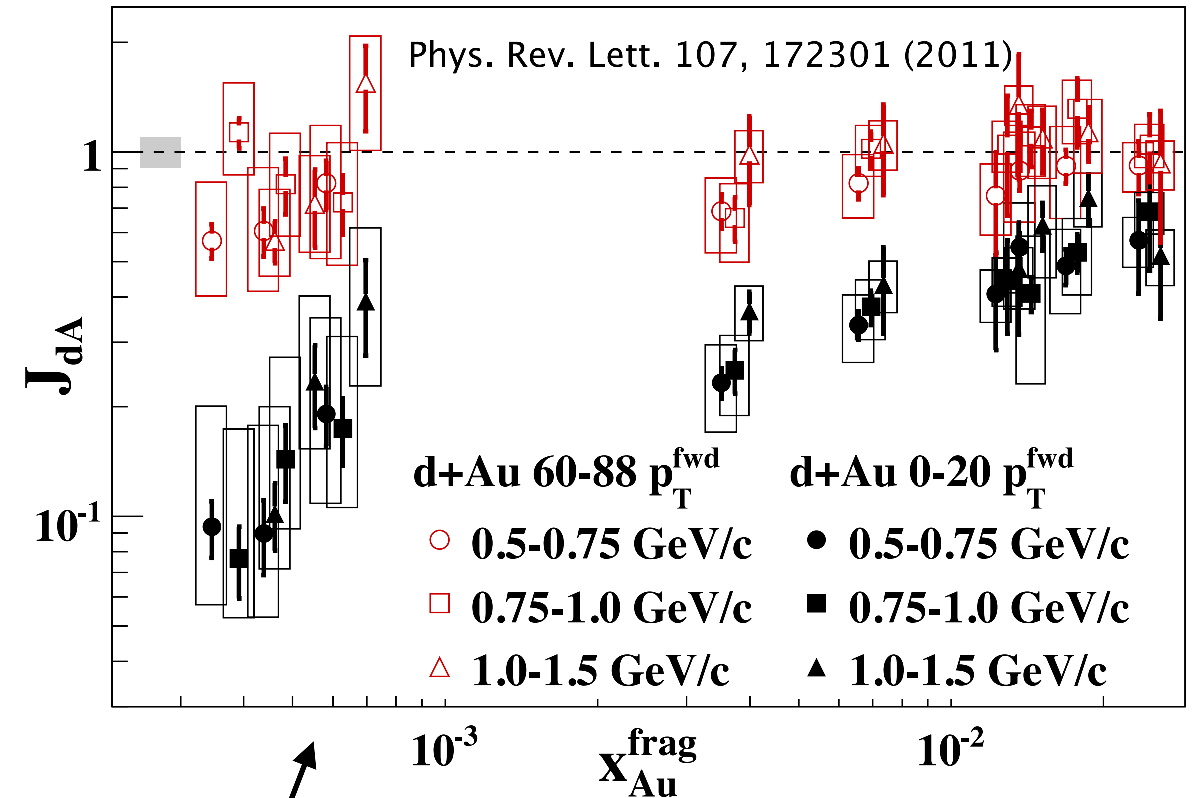


di-jets in ALICE

no strong effects (but co-mover breakup of $c\bar{c}$…?)

3. forward “mono-jet” production

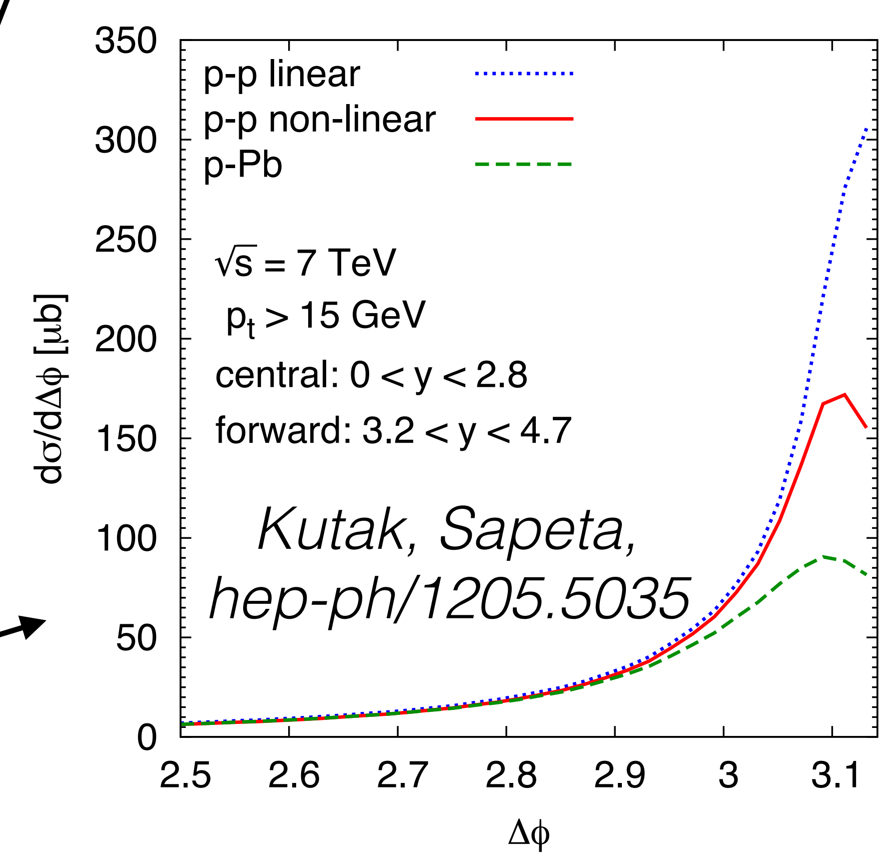




dramatic effects in d+Au at RHIC:

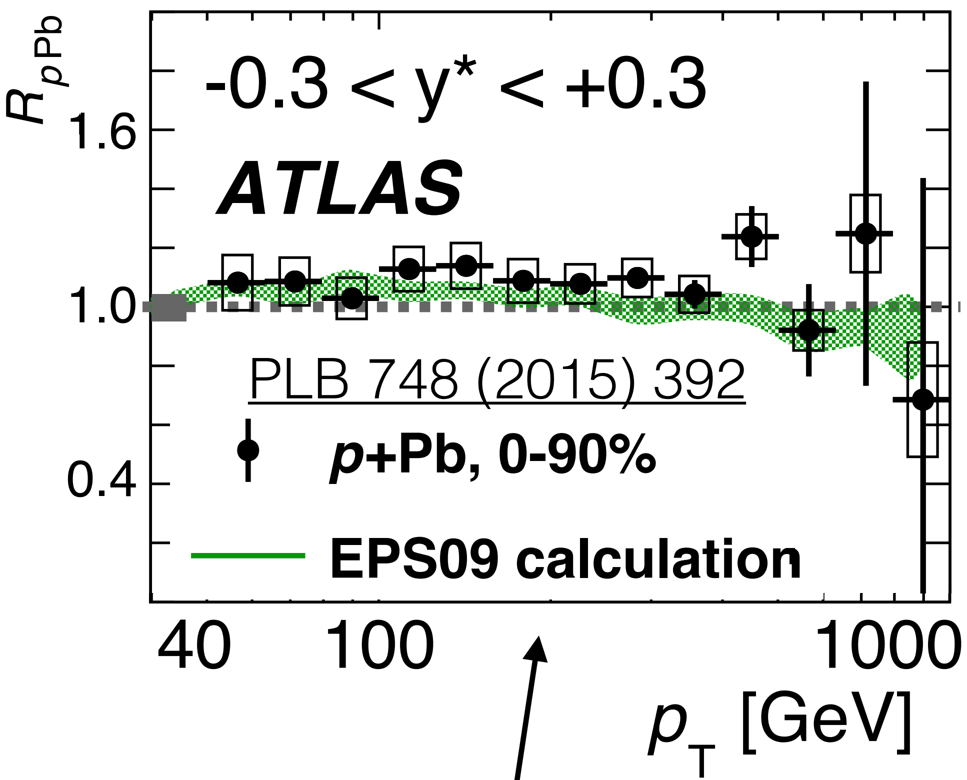
STAR forward di-hadron Δφ

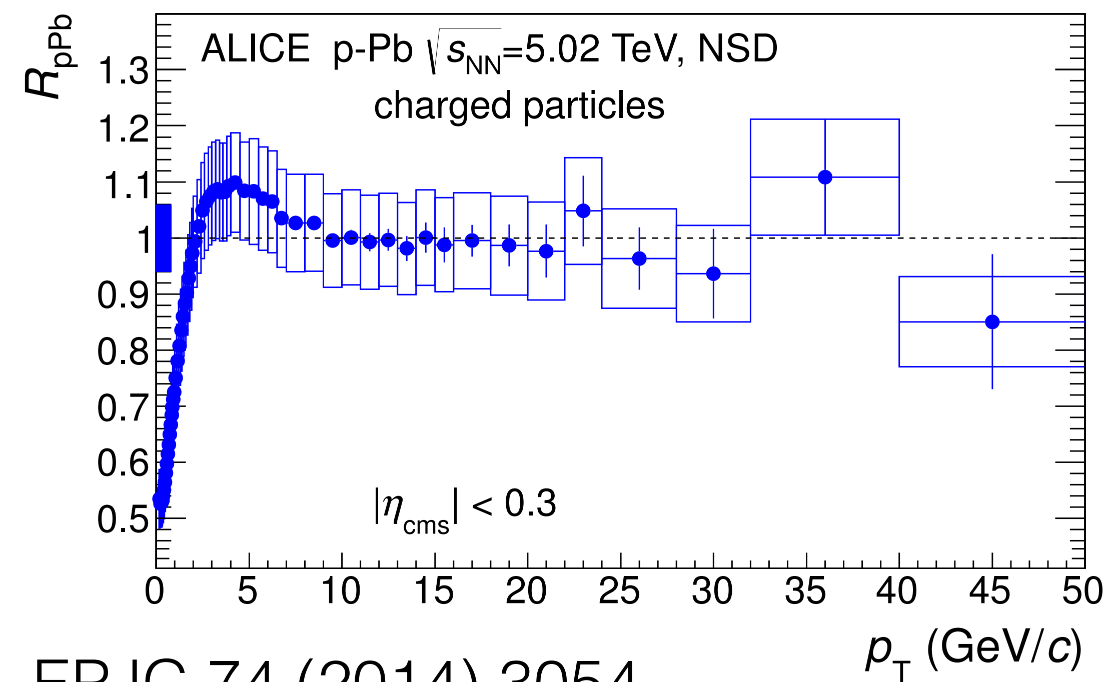
PHENIX ratio of C-F per-trigger yields



will we see saturation effects for central+forward dijets at LHC @ HP’18?

how can we explore saturation region?



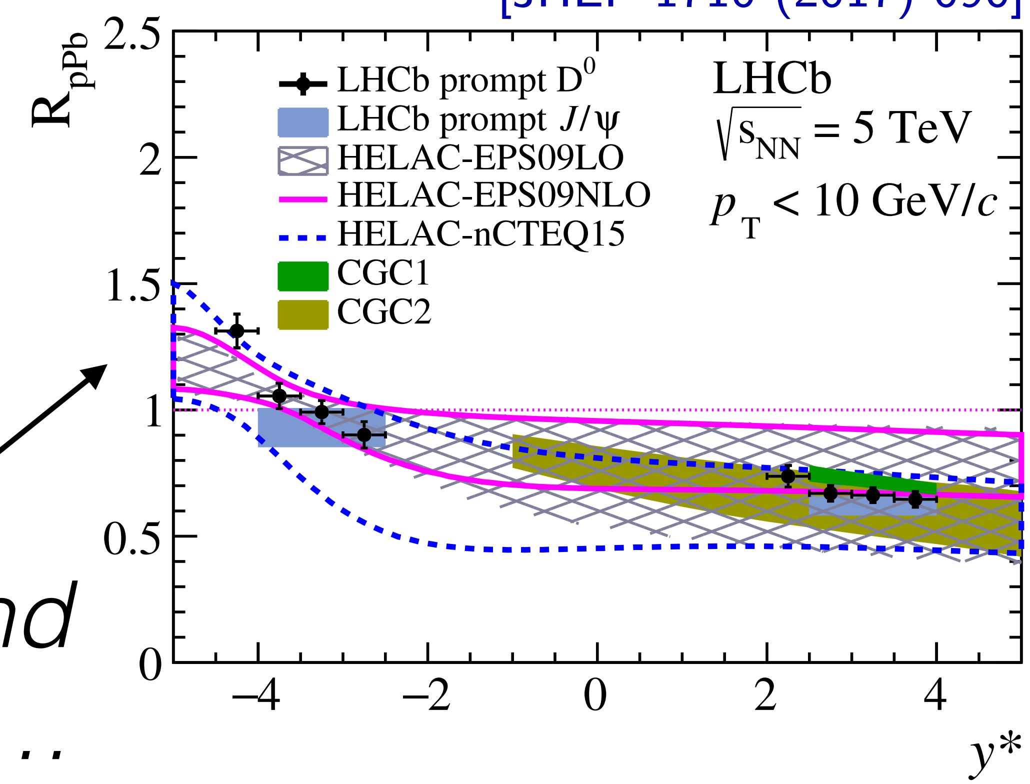


EPJC 74 (2014) 3054

jets: *minimum p_T, effects evolve away with high Q^2…*

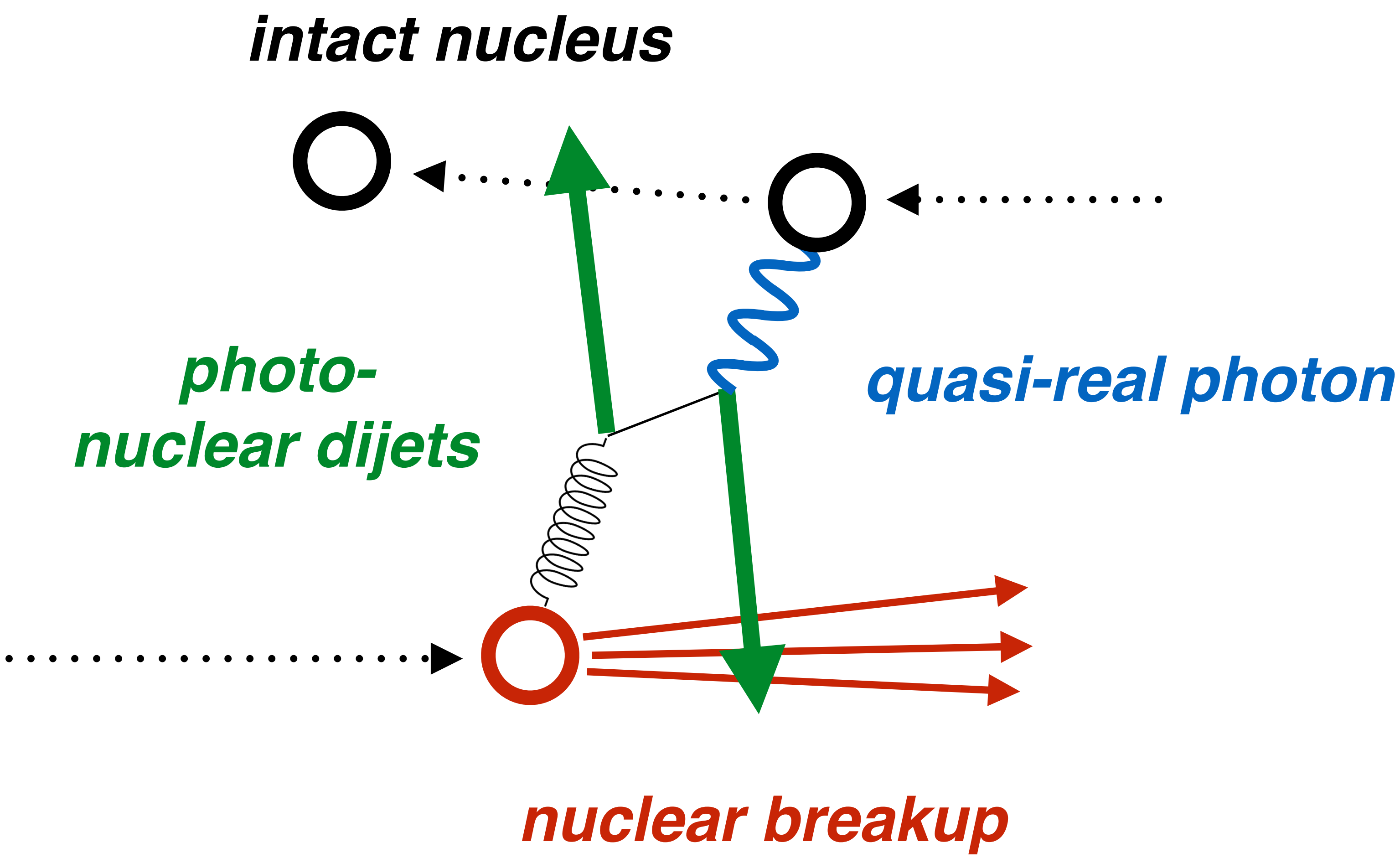
hadrons: *indirect access to parton kinematics, soft contribution…*

[JHEP 1710 (2017) 090]

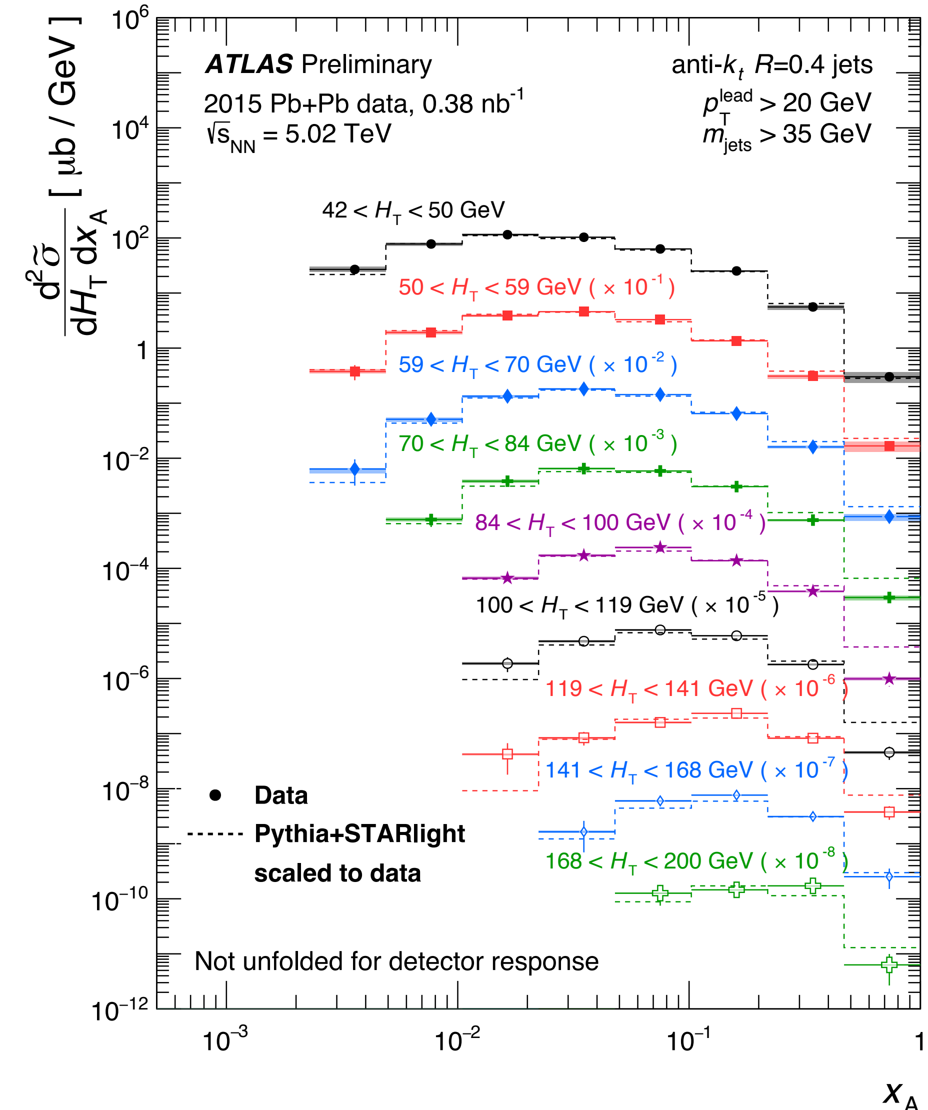


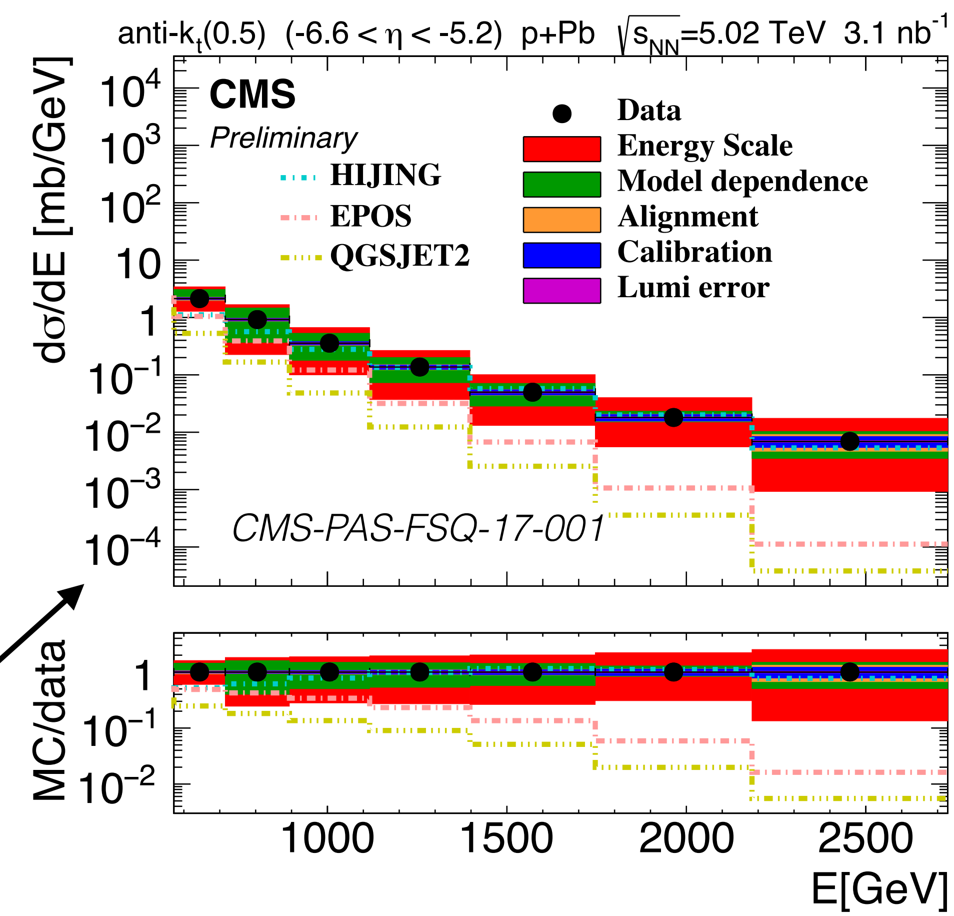
J/Ψ: *don't understand production mechanisms…*

New processes: photo-nuclear dijets in Pb+Pb w/ ATLAS



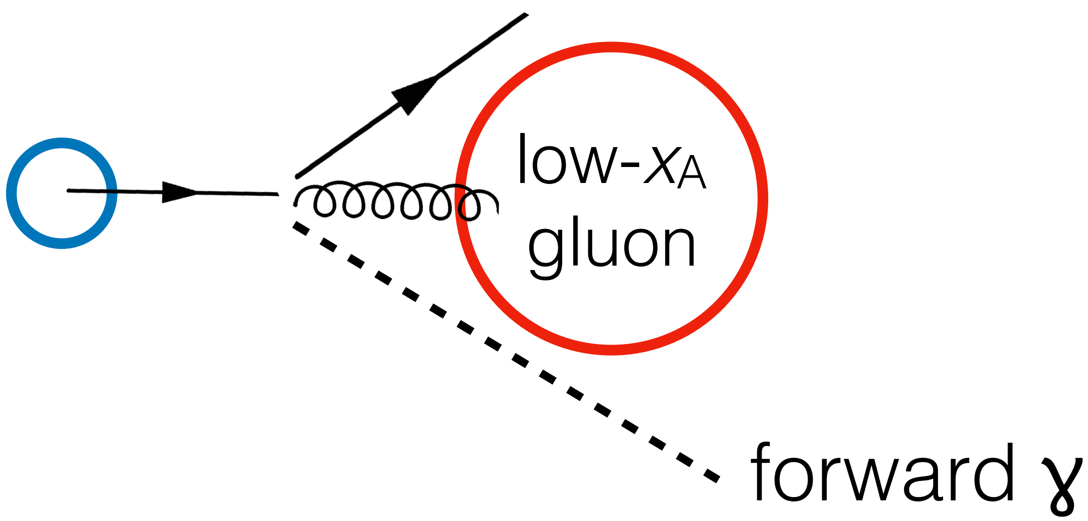
(“DIS”-like, measure to lower-p_T)

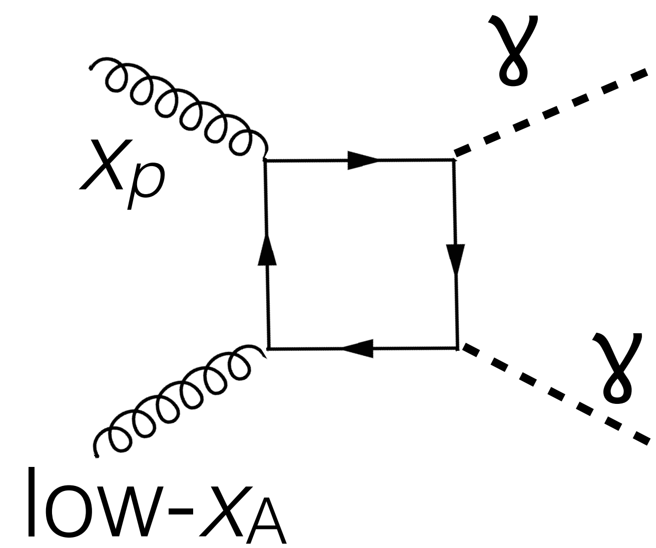




New instrumentation: very forward (y=5.2-6.6) jets in p+Pb w/ CASTOR

photons as low-x_A gluon probe

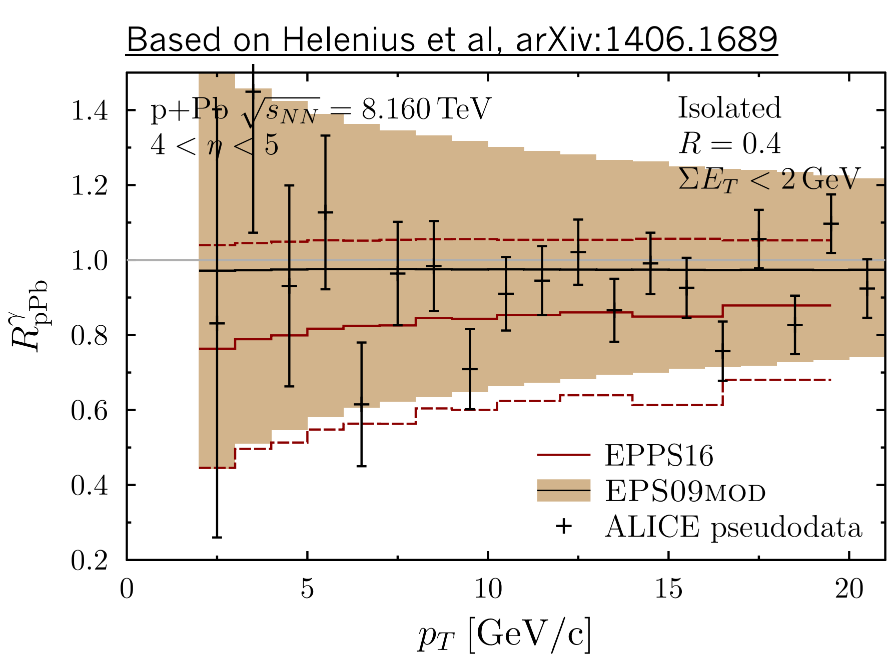


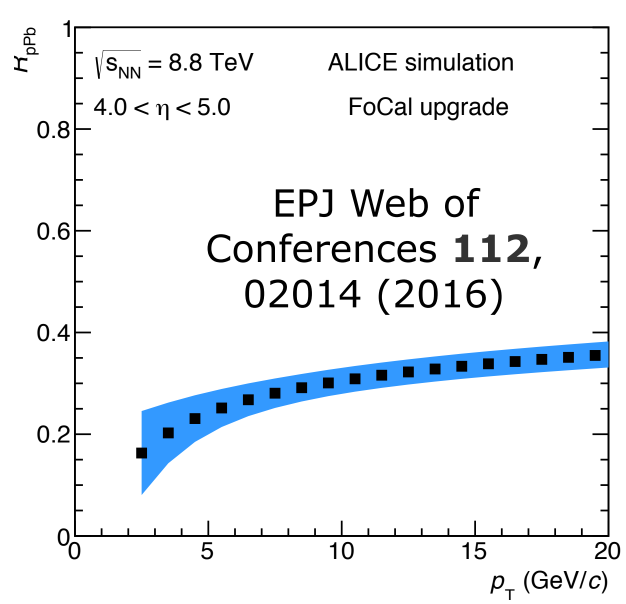


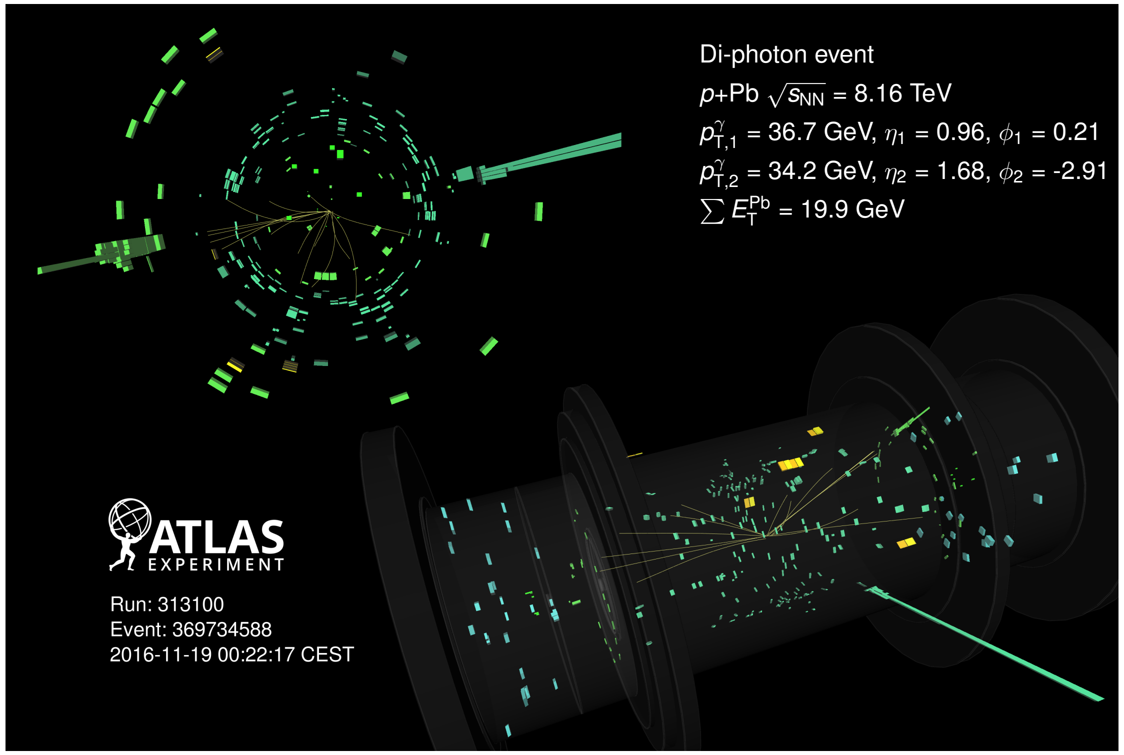
y=4-5 (ALICE FoCal upgrade)

see also LHCb & PHENIX MPC-EX

di-photon production in 8.16 TeV p+Pb @ LHC?





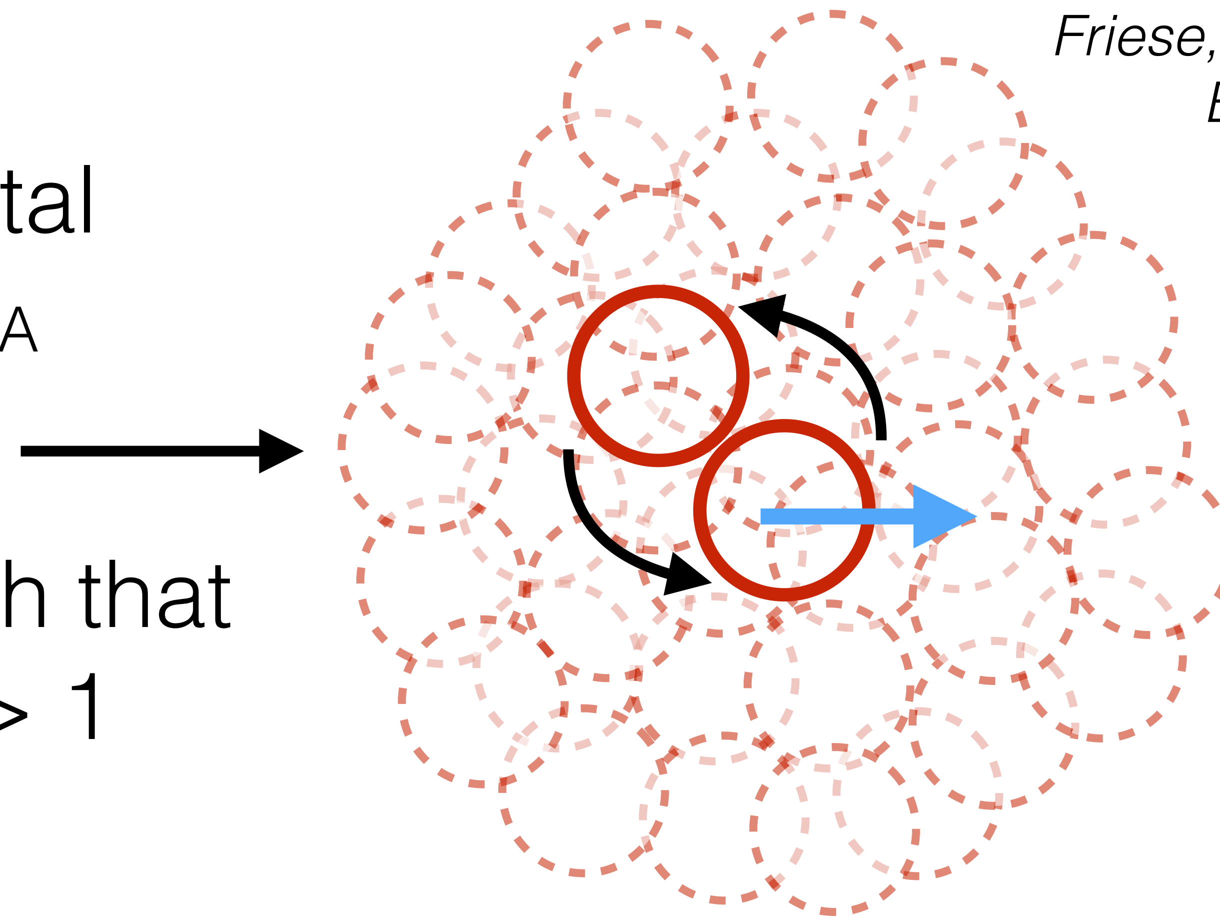


nuclear effects at large-x_A

At large-x_A, Fermi motion of nucleons in nucleus:
… but also, short-range ***p-n*** *correlations!*

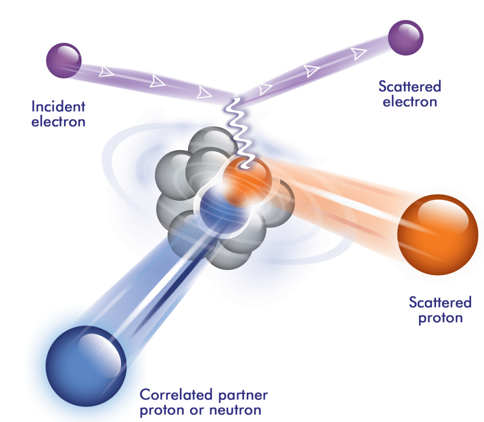
Friese, Sargsian, Strikman
EPJC 75 (2015) 534

nucleus has total momentum p_A



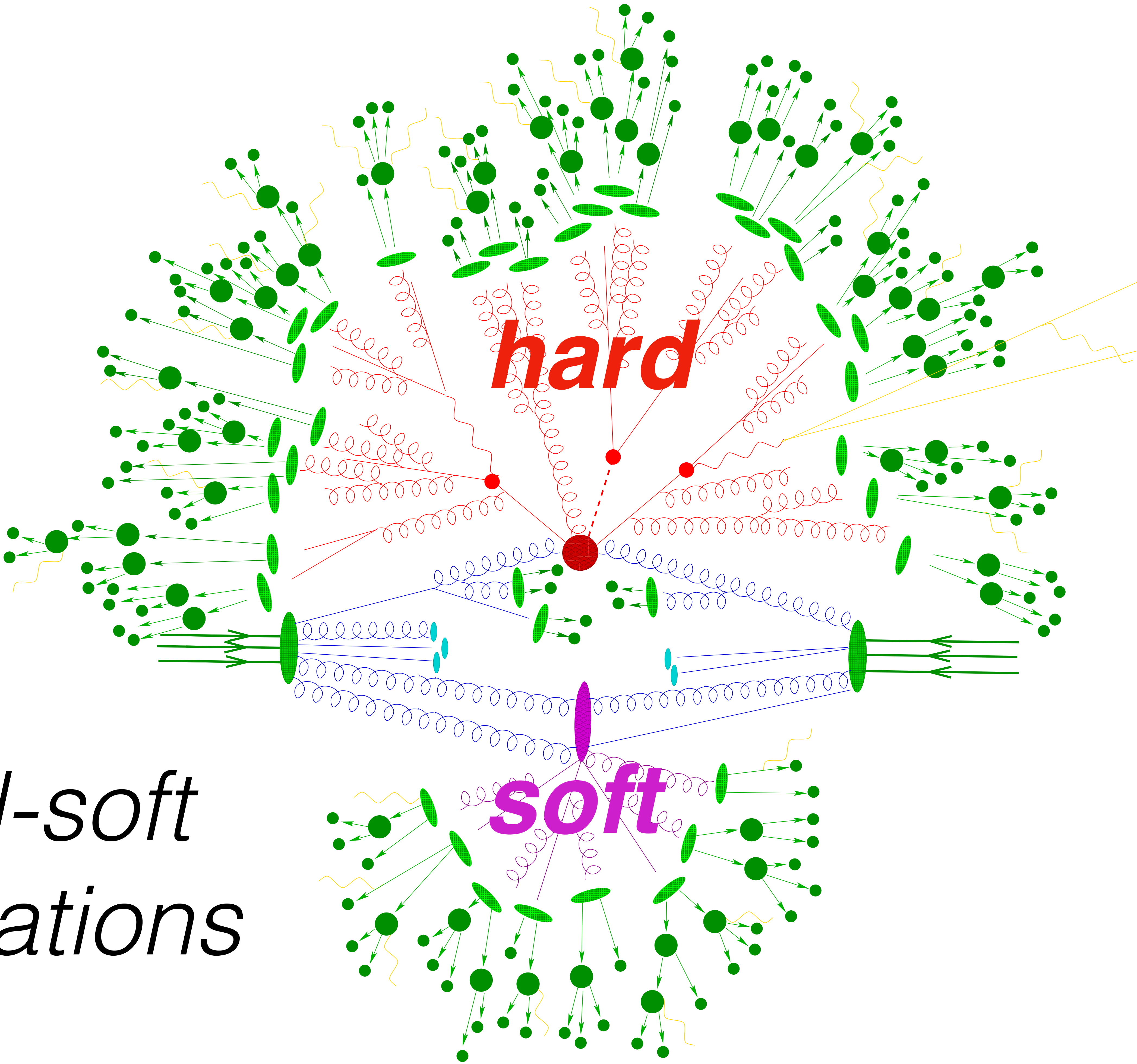
quark with p_q such that
$x_A = p_q/(p_A/A) > 1$

JLab experiments



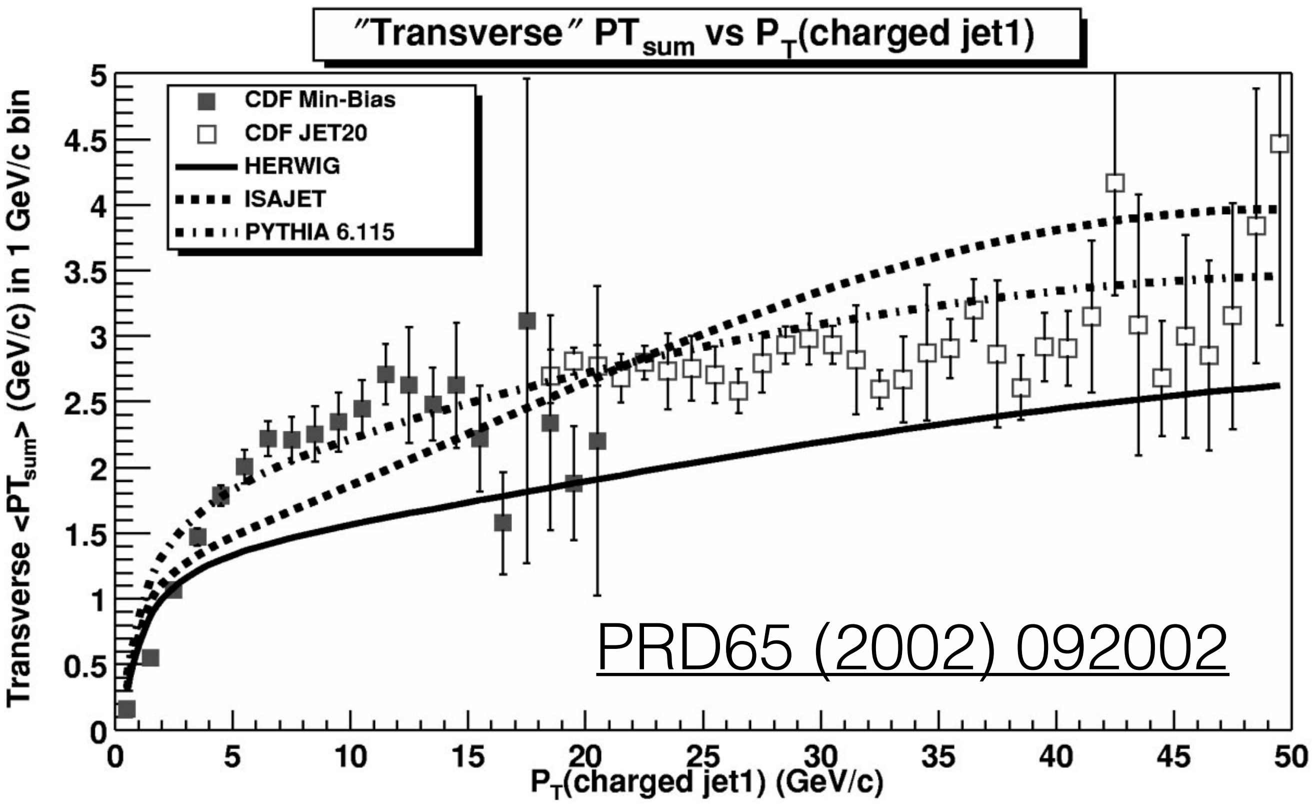
Possibility to observe $x_A > 1$ configurations!

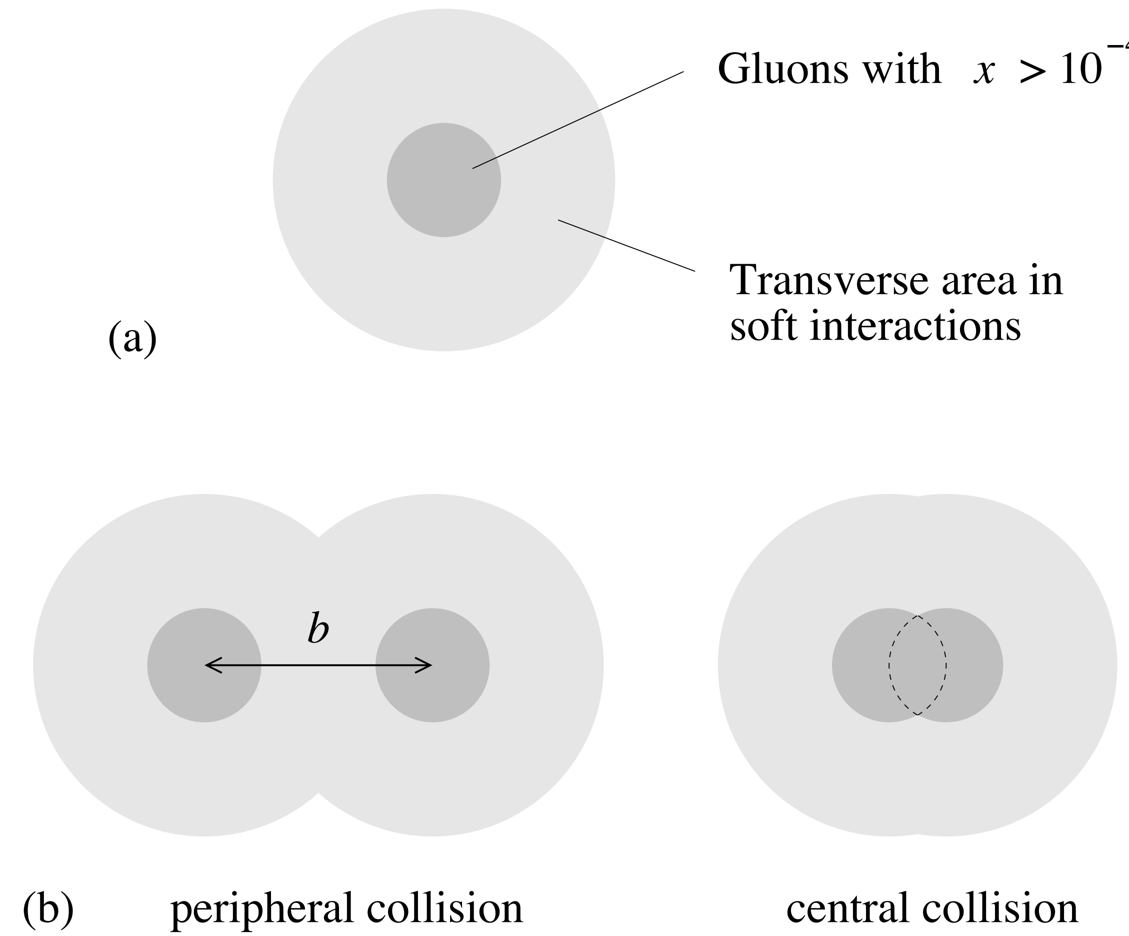
➡ *rates are sensitive to Short-Range Correlations (SRCs) in nuclei ("medium energy" physics)*



Hard-soft correlations

UE in the presence of a hard scattering





PRD83 (2011) 054012

pp (or $p\bar{p}$) collisions with a modest GeV jet or hadron produce more UE than "average" collisions

can be understood from geometric picture of proton

multi-parton interactions

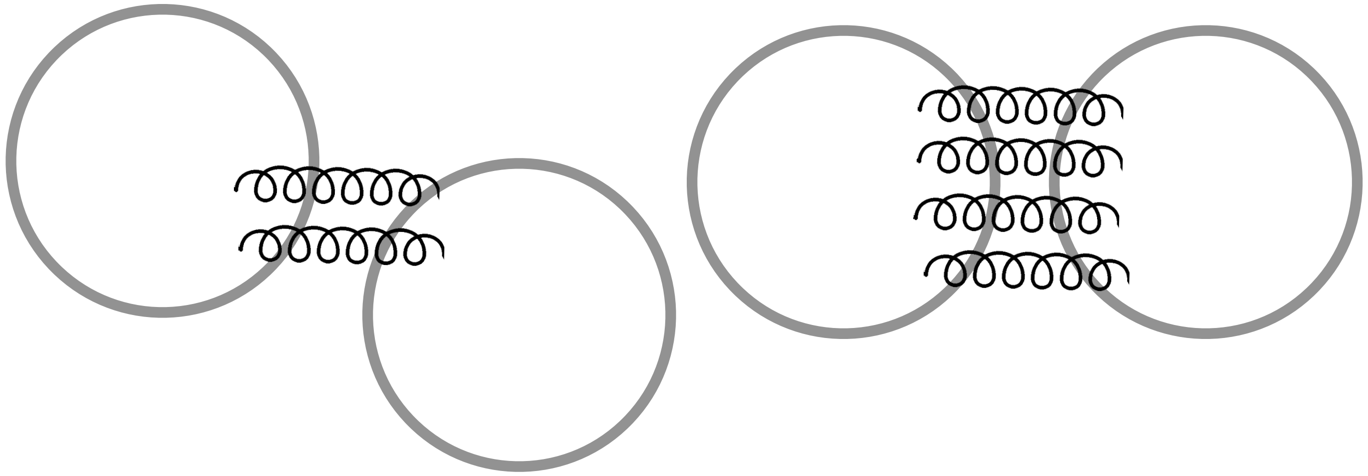
P. Skands, TASI Lectures at CU-Boulder, hep-ph/1207.2389

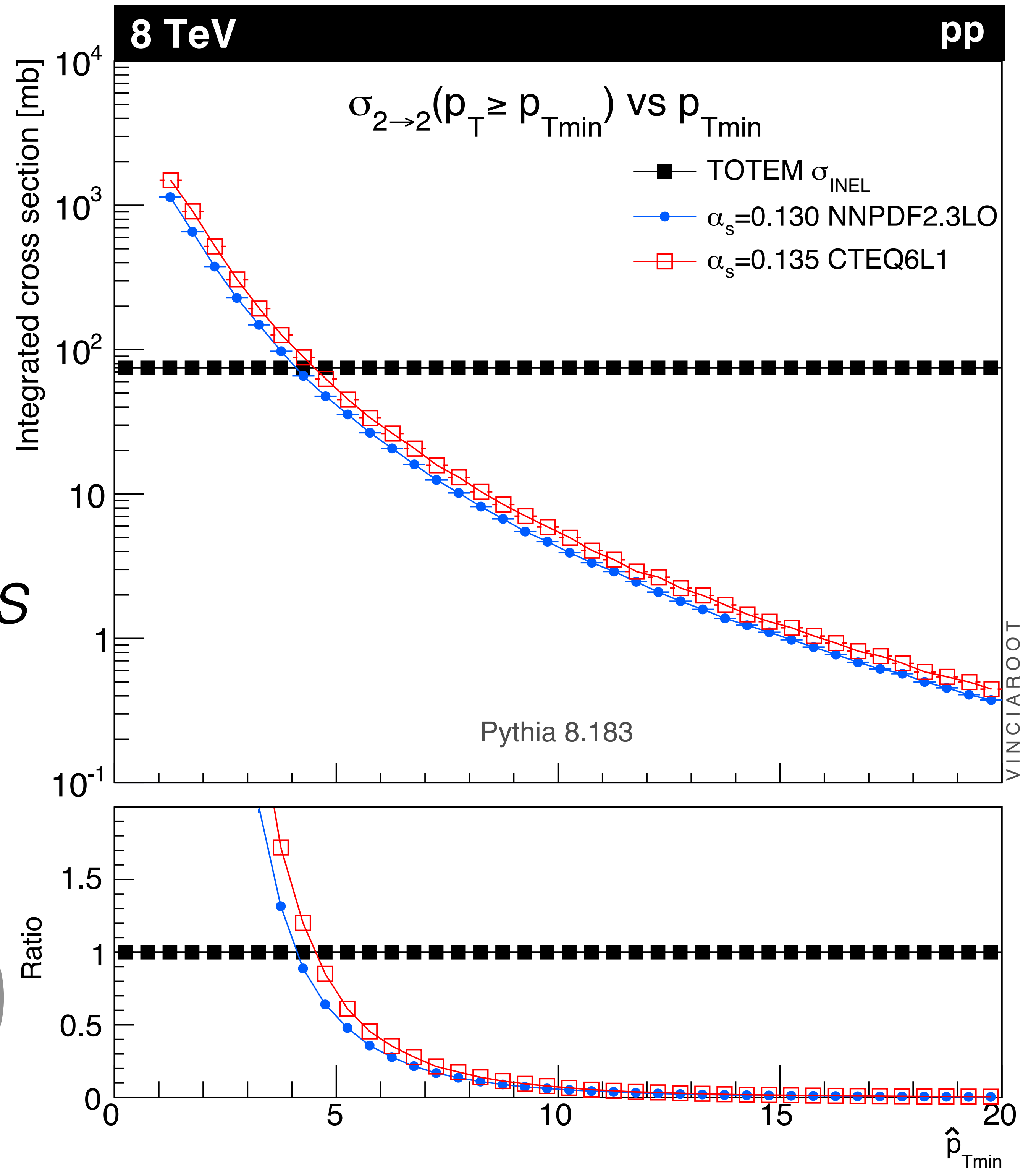
*at LHC energies, **g+g cross-sections** at small Q^2*
*≫ **total pp cross-section***

many individual g+g collisions

small overlap,
few MPI

large overlap,
many MPI



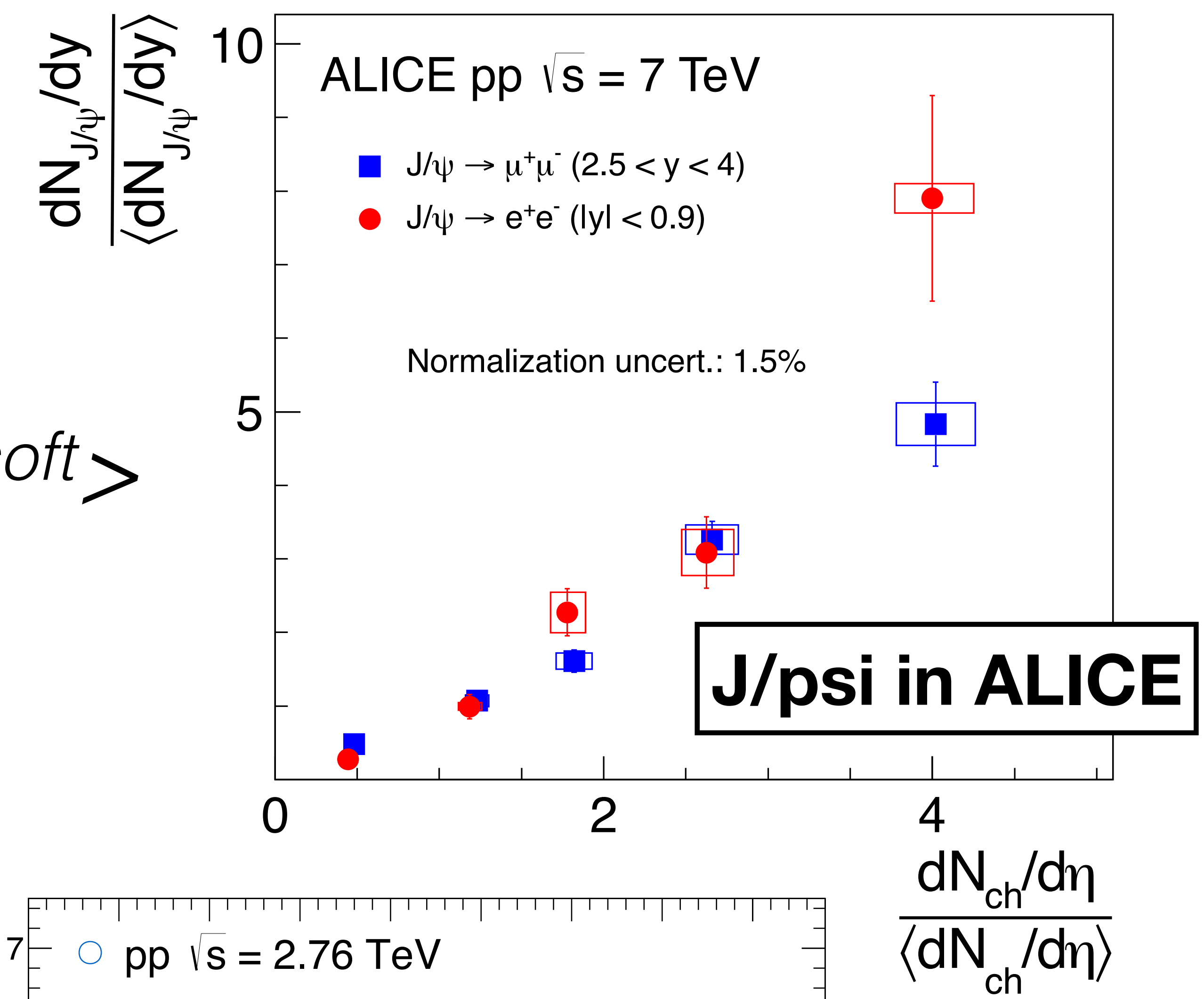


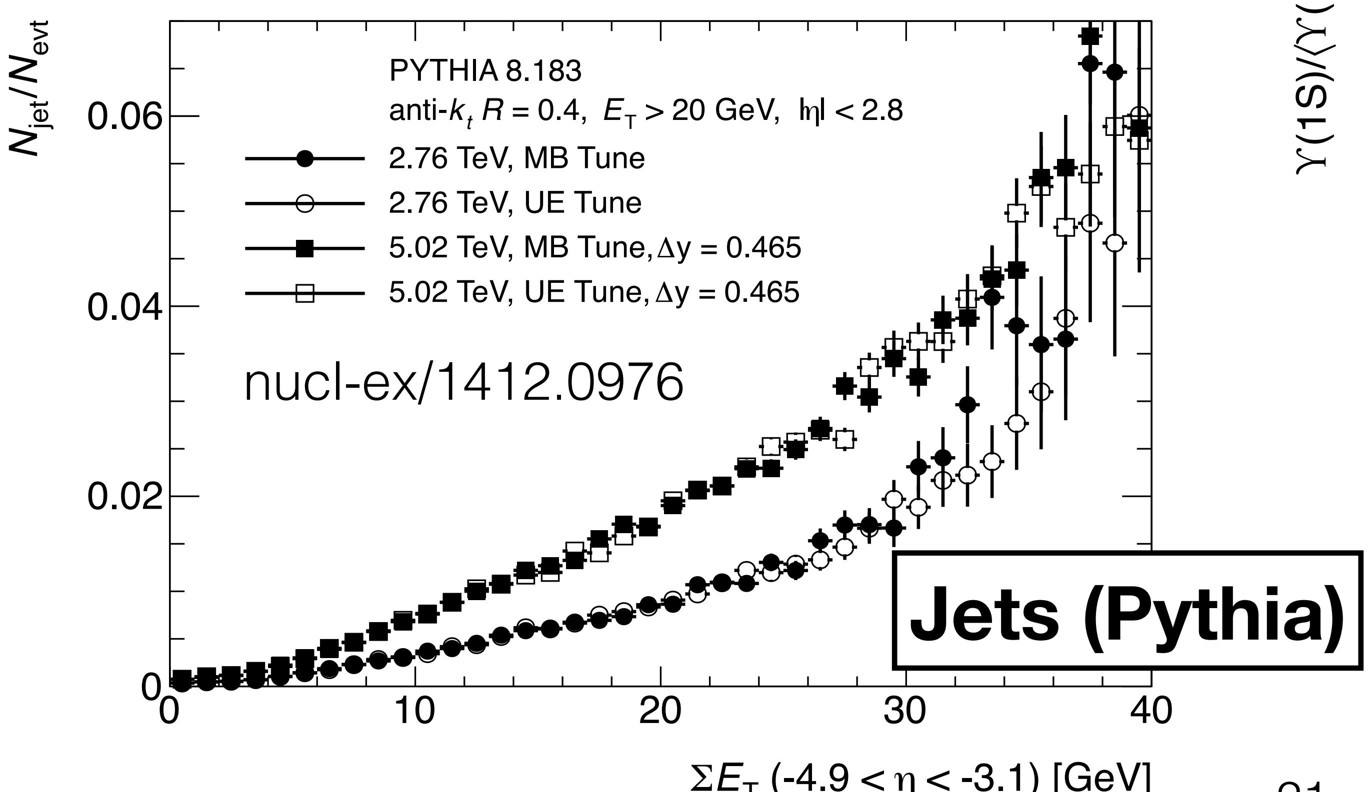
PLB712 (2012) 165

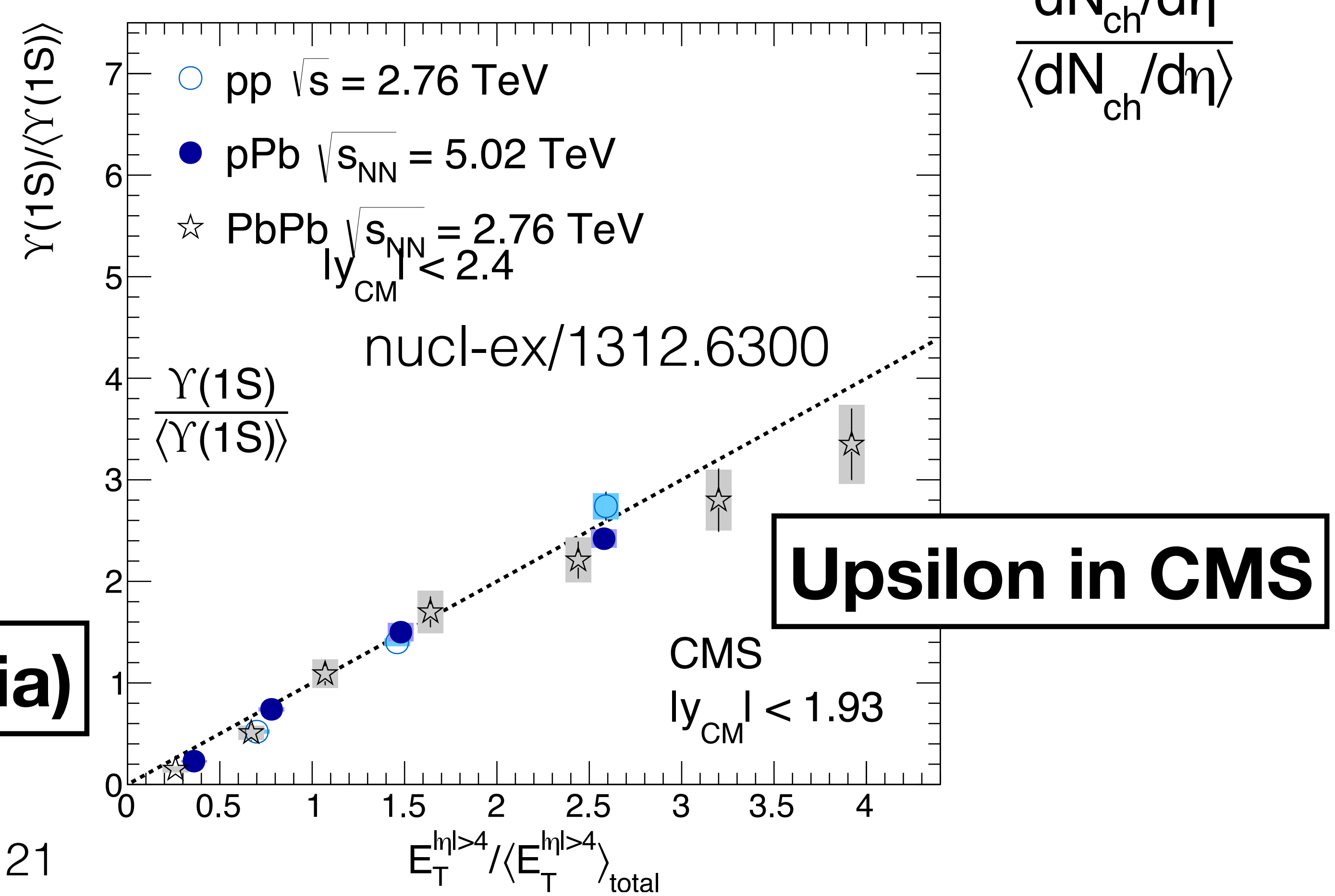
hard scattering and UE signals approximately “scale”

$$N^{hard} / \langle N^{hard} \rangle \approx E_T{}^{soft} / \langle E_T{}^{soft} \rangle$$

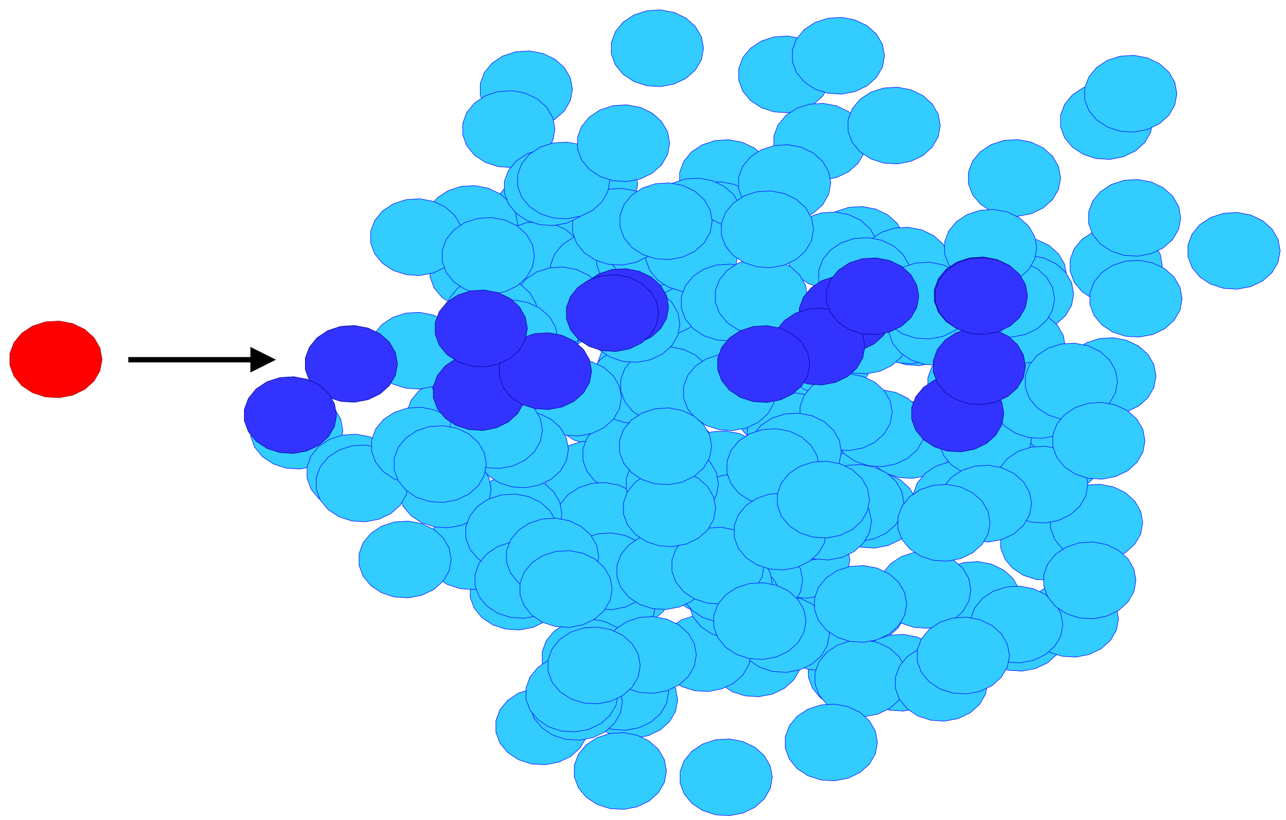
(but deviations from this are also interesting…)

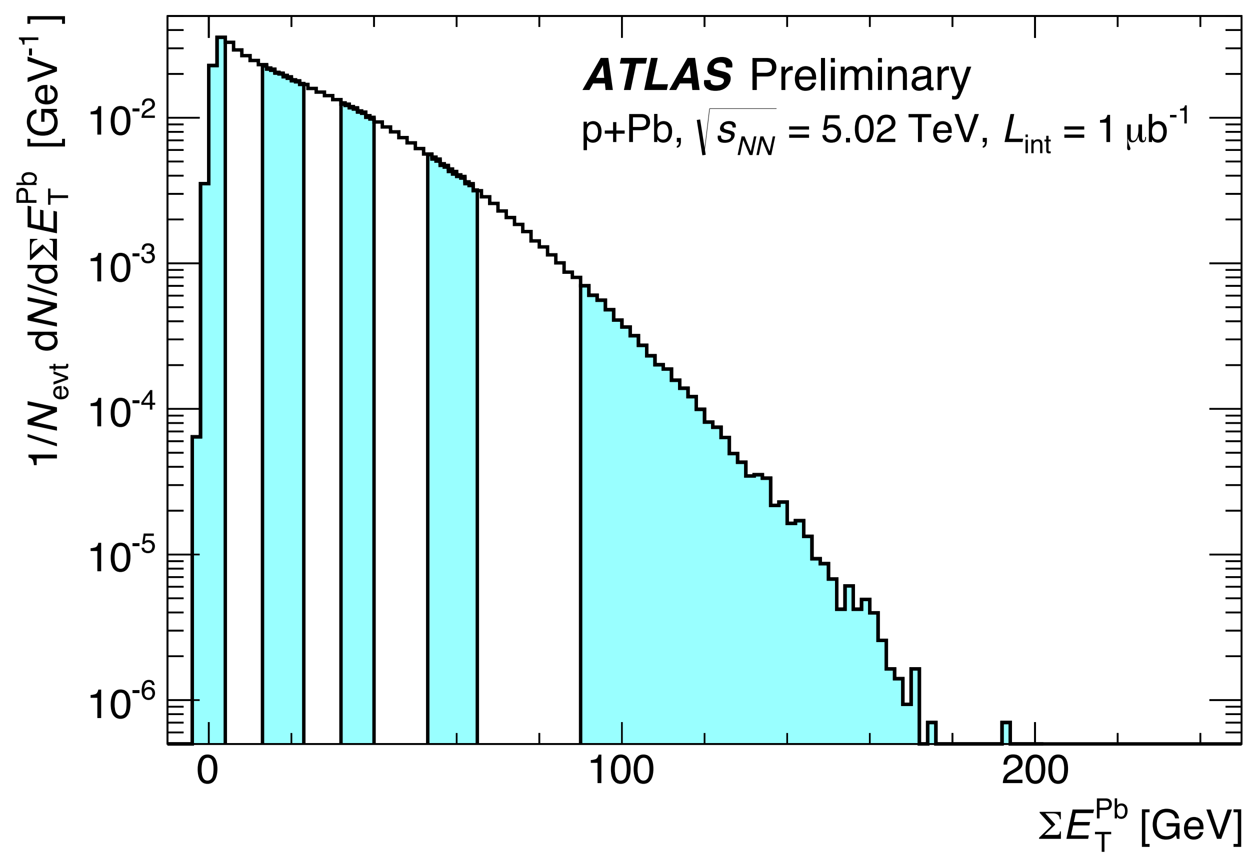






centrality w/ hard probes



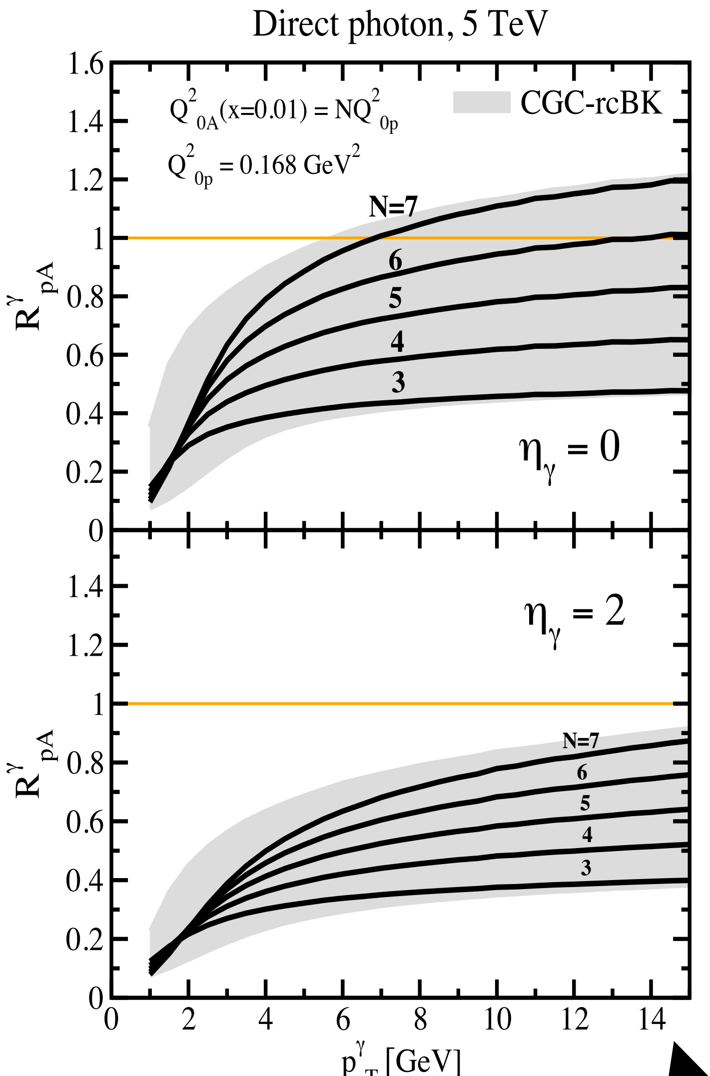


phenomenology in A+A collisions (and p+A at lower energies):

1. *relate N_{coll} & N_{part} to some <u>observed multiplicity</u> (N_{ch}, $\Sigma E_T{}^{Pb}$)*
2. *selecting on multiplicity picks out class of geometric events*

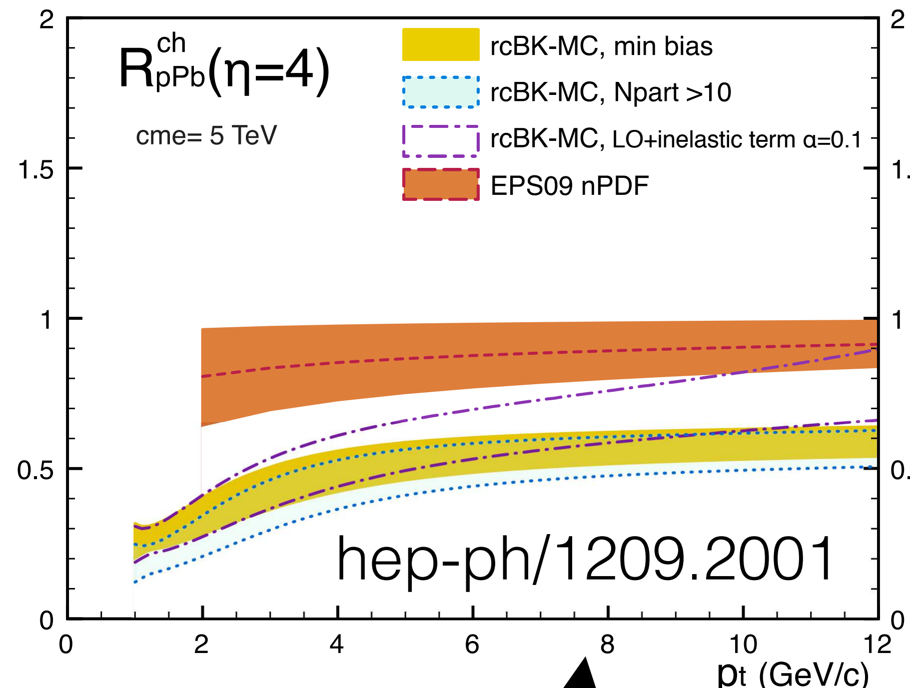
…more in Sasha Milov's talk…

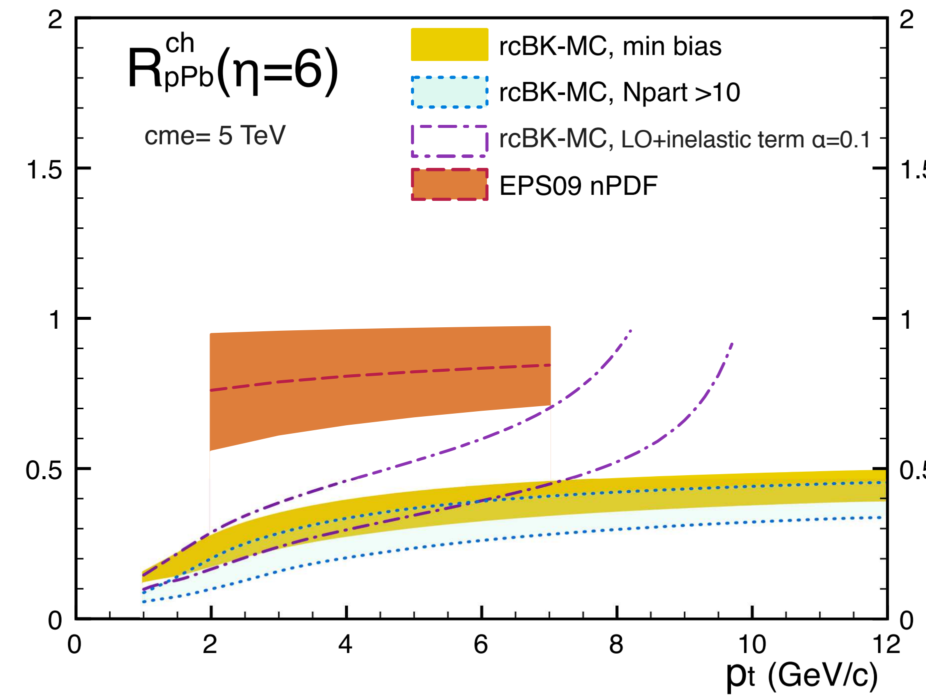
theoretical desire to have centrality in p+A…



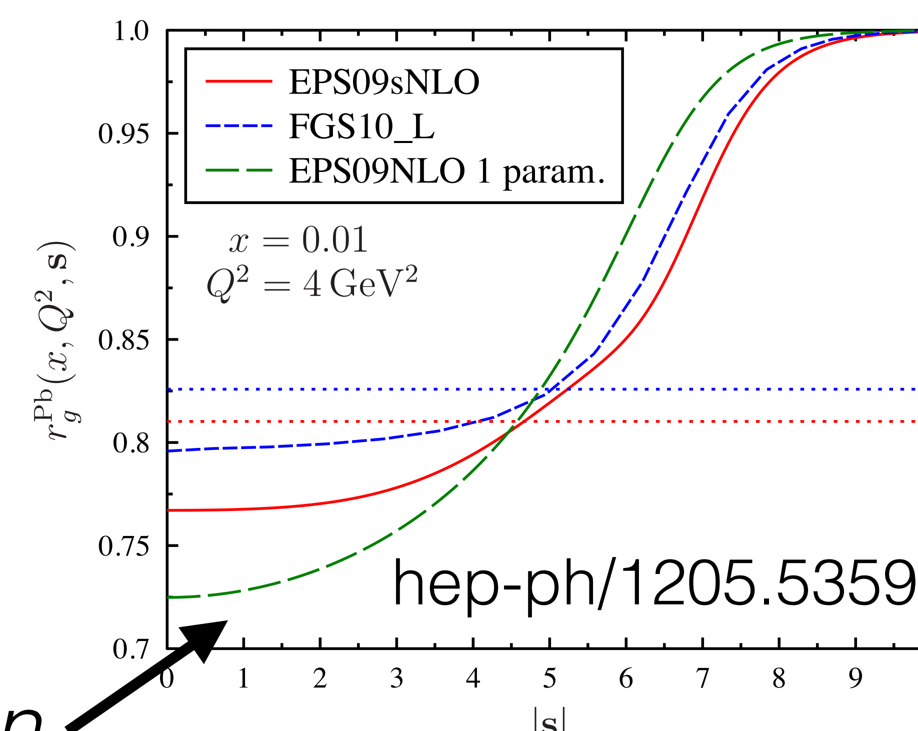
hep-ph/1210.2385

varying saturation scale for forward photon R_{pA}…





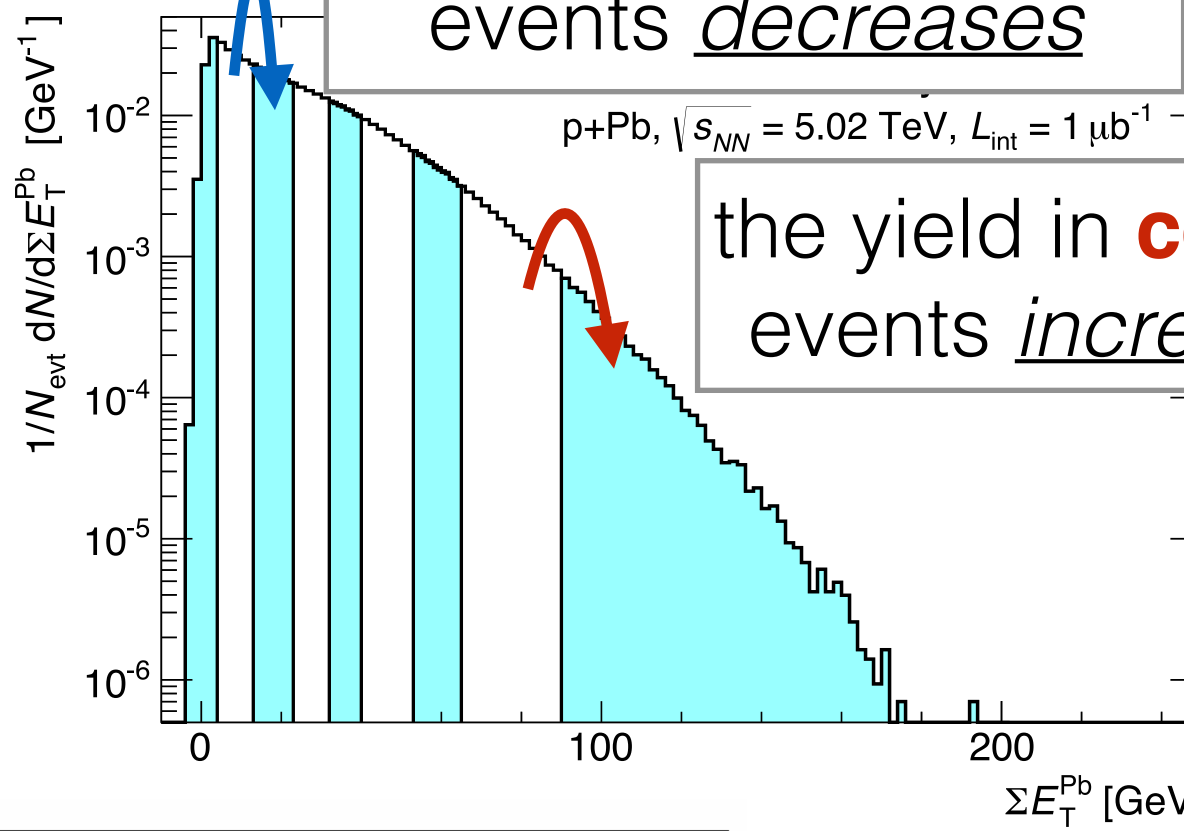
hadron spectra in CGC in central p+A…



b-dependence of nPDF modification

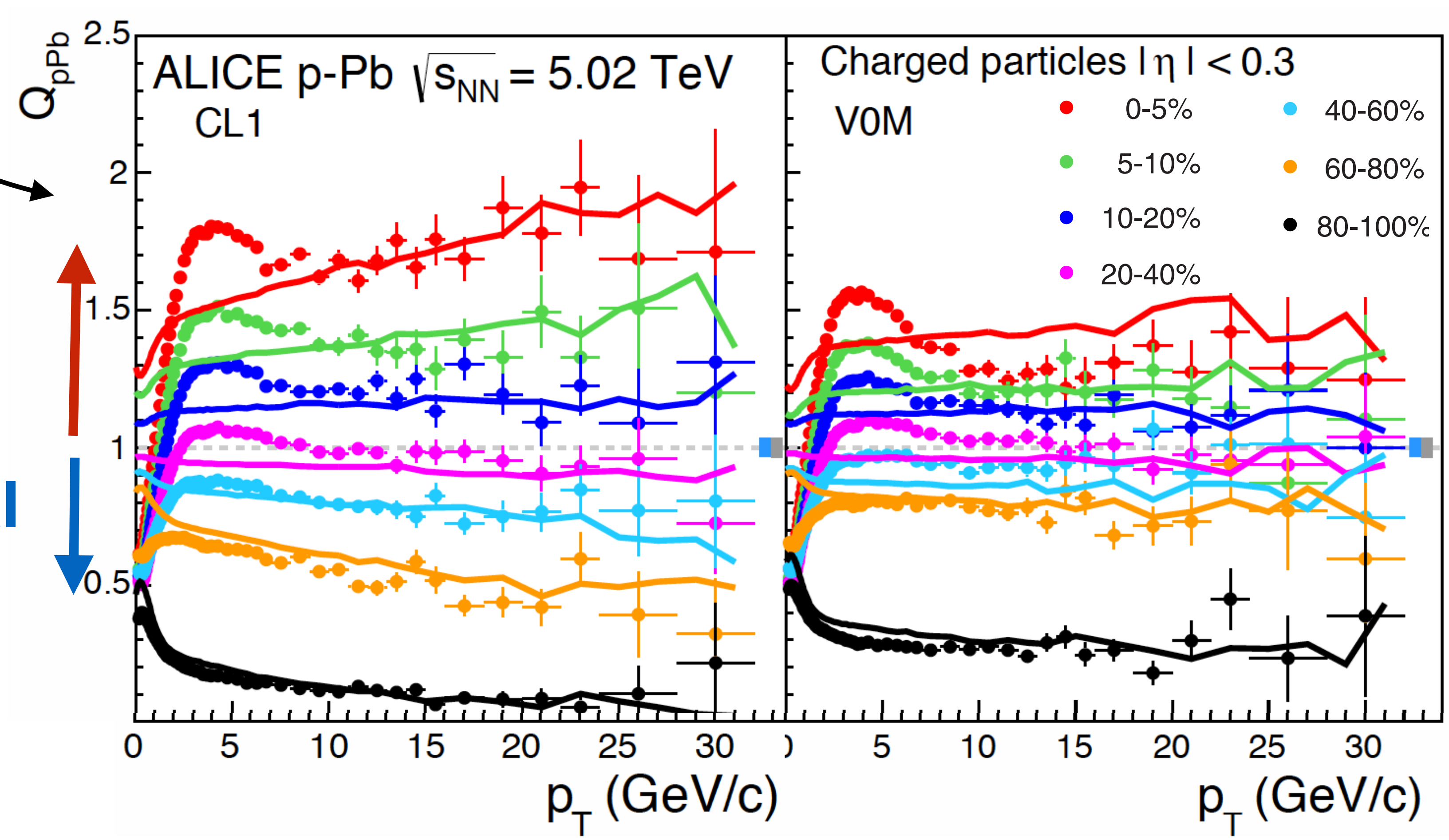
effect of hard-soft correlation…

huge effect when measuring multiplicity in the same acceptance as hard process…



central

peripheral



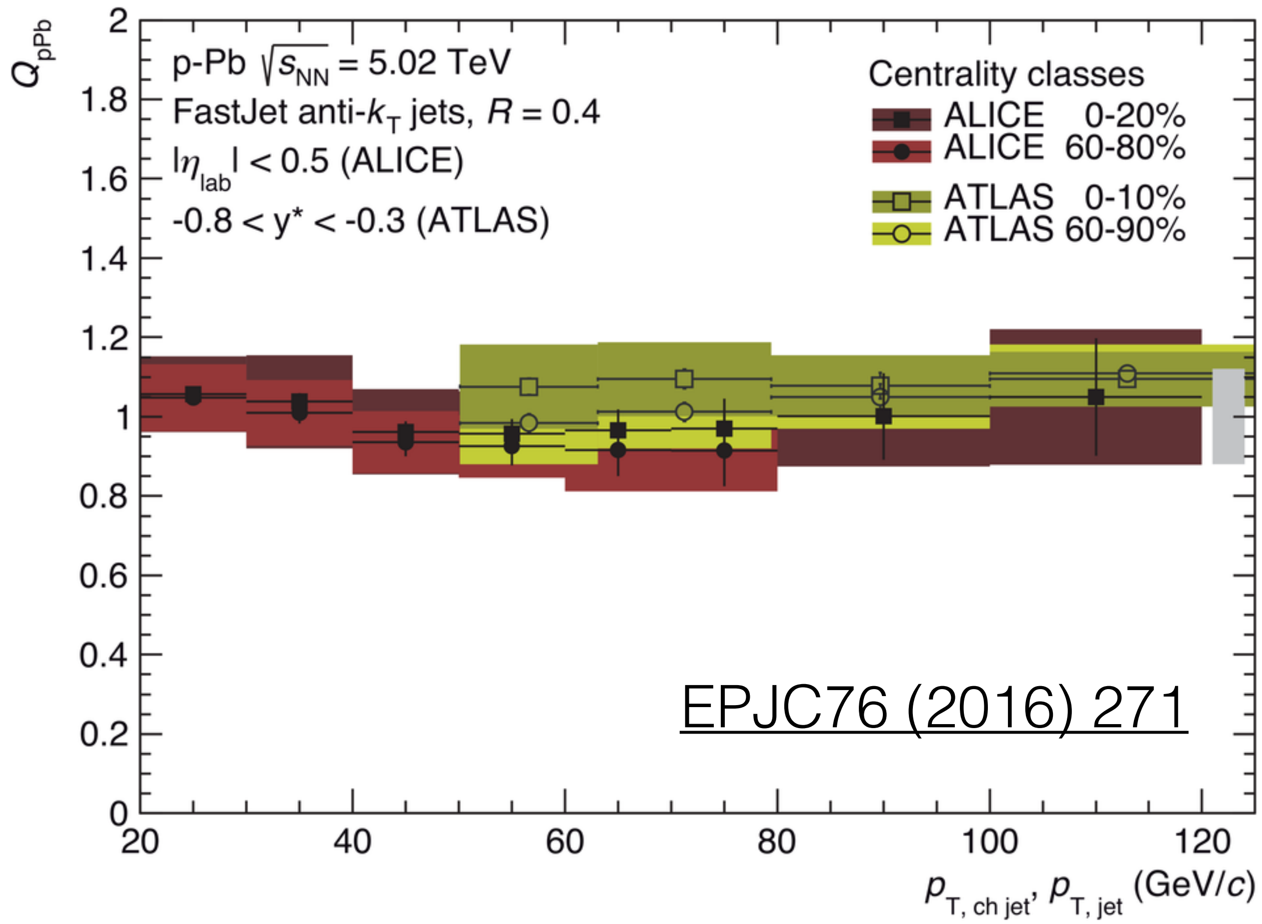
more modest effect (~20%?) w/ rapidity separation

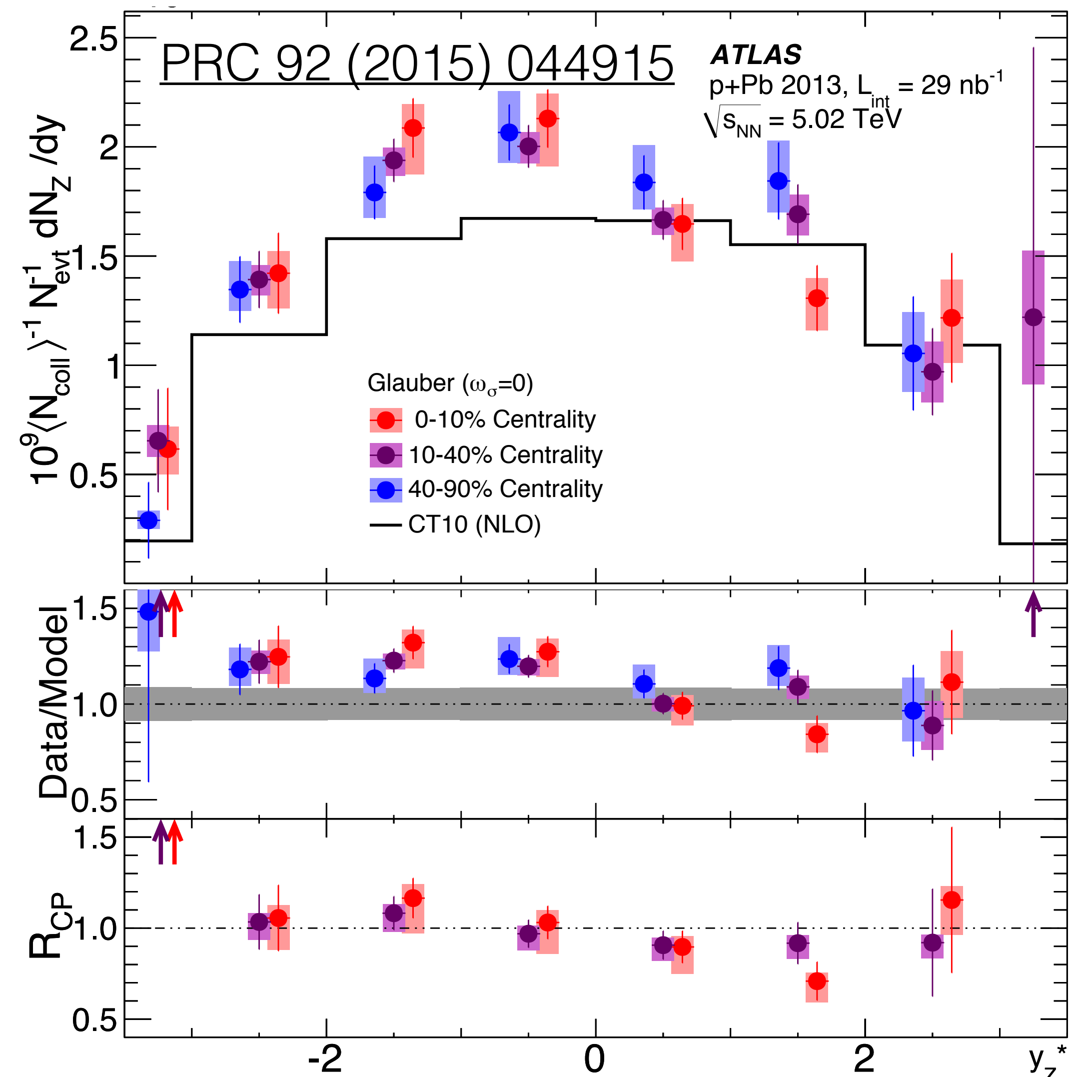
Phys. Rev. C 91 (2015) 064905

some remedies…

Z's w/ ATLAS

Jets w/ ALICE & ATLAS





"hybrid" model: use Pb-going ZDC to define centrality, translate to mid-rapidity ("Q_{pPb}")

<u>one downside</u>: lose central event sensitivity…

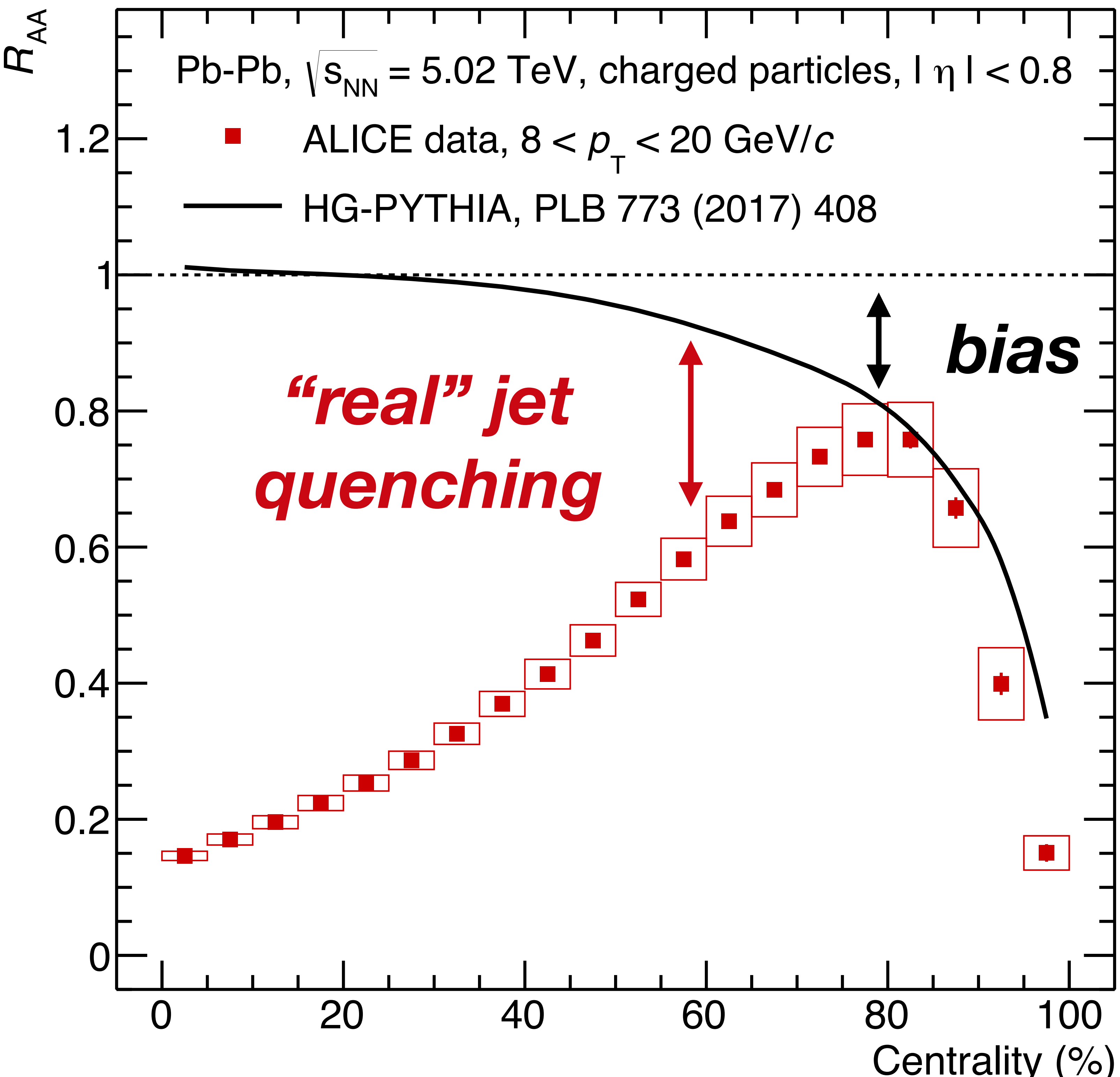
correct for Hard-UE correlation bias,

<u>one downside</u>: introduce model dependence

DVP, Steinberg, *hep/1412.0976*

see also PHENIX PRC 90 (2014) 034902

centrality bias in A+A?



from multiplicity selection

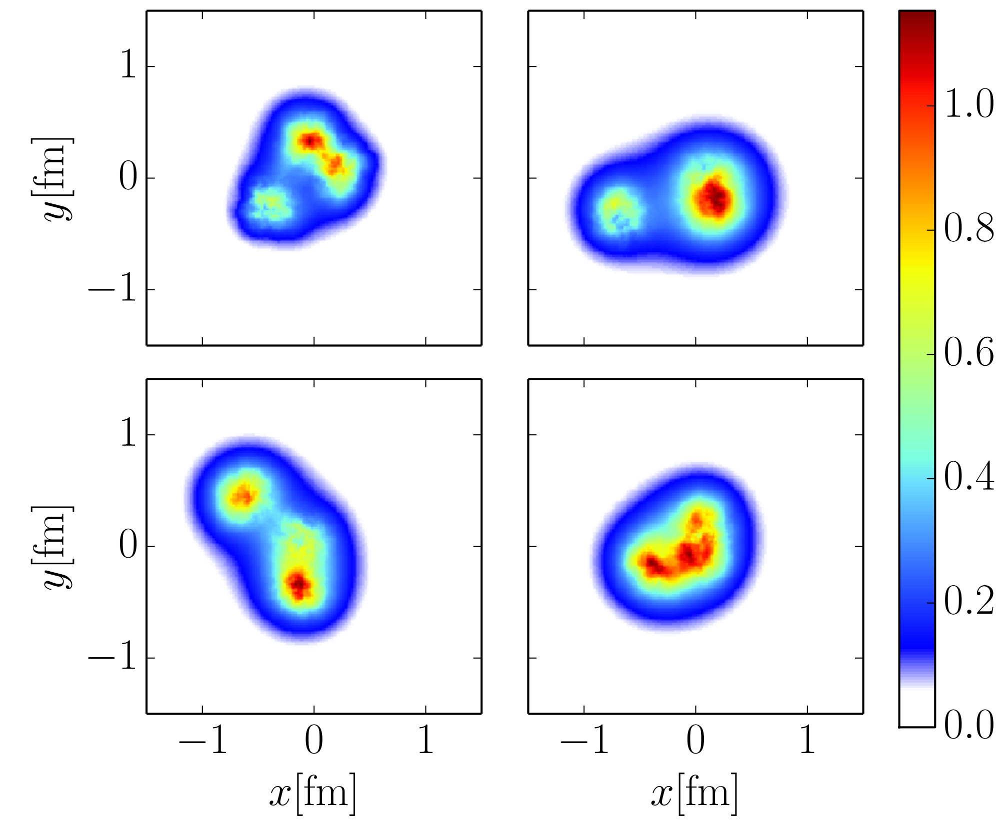
jet quenching may turn off significantly sooner than expected…

(and that models have been assuming in data…)

nucl-ex/1805.05212

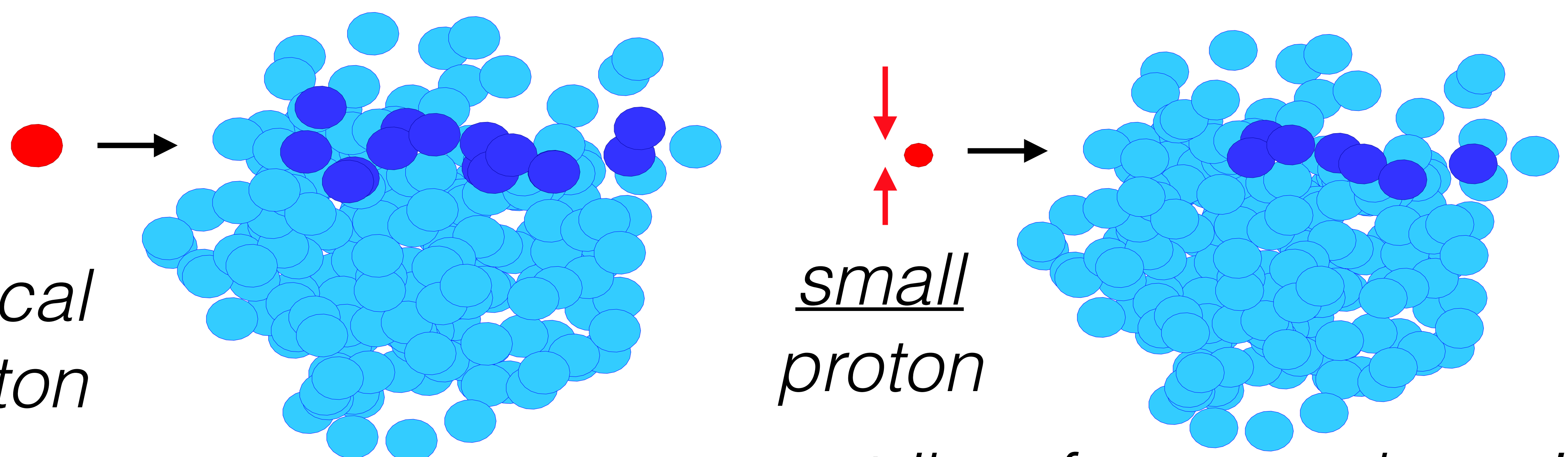
Large-x_p, >0.1: "*shrinking*" of the proton

protons size & shape fluctuates event by event



can use the nucleus to observe average changes in the proton's transverse ***size****…*

typical proton



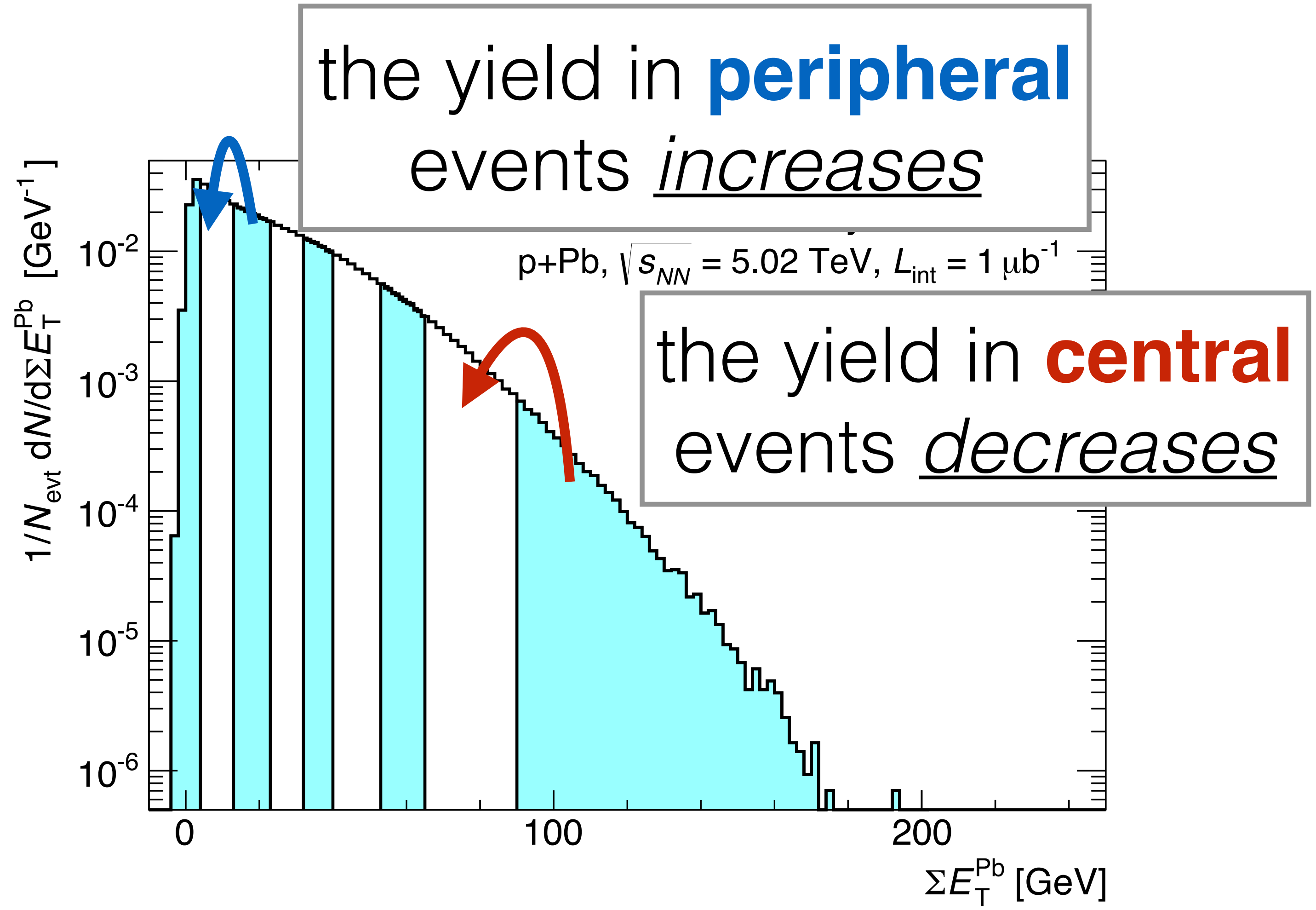
small proton

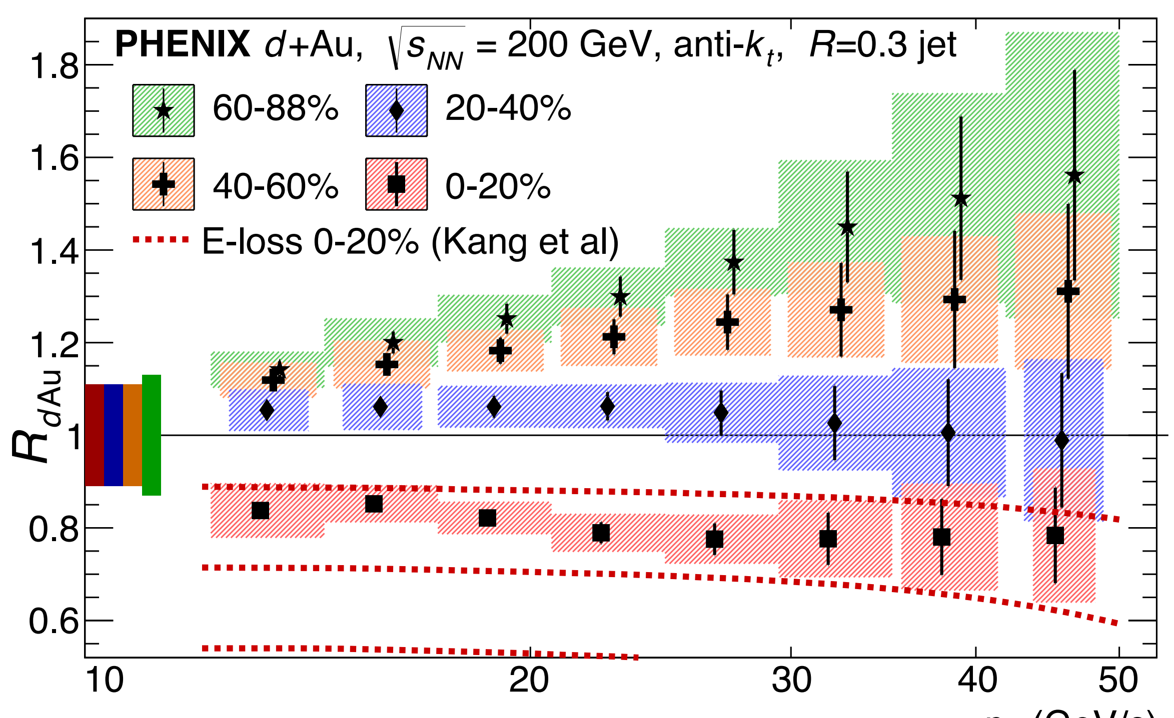
strikes fewer nucleons!

a shrinking proton manifests…

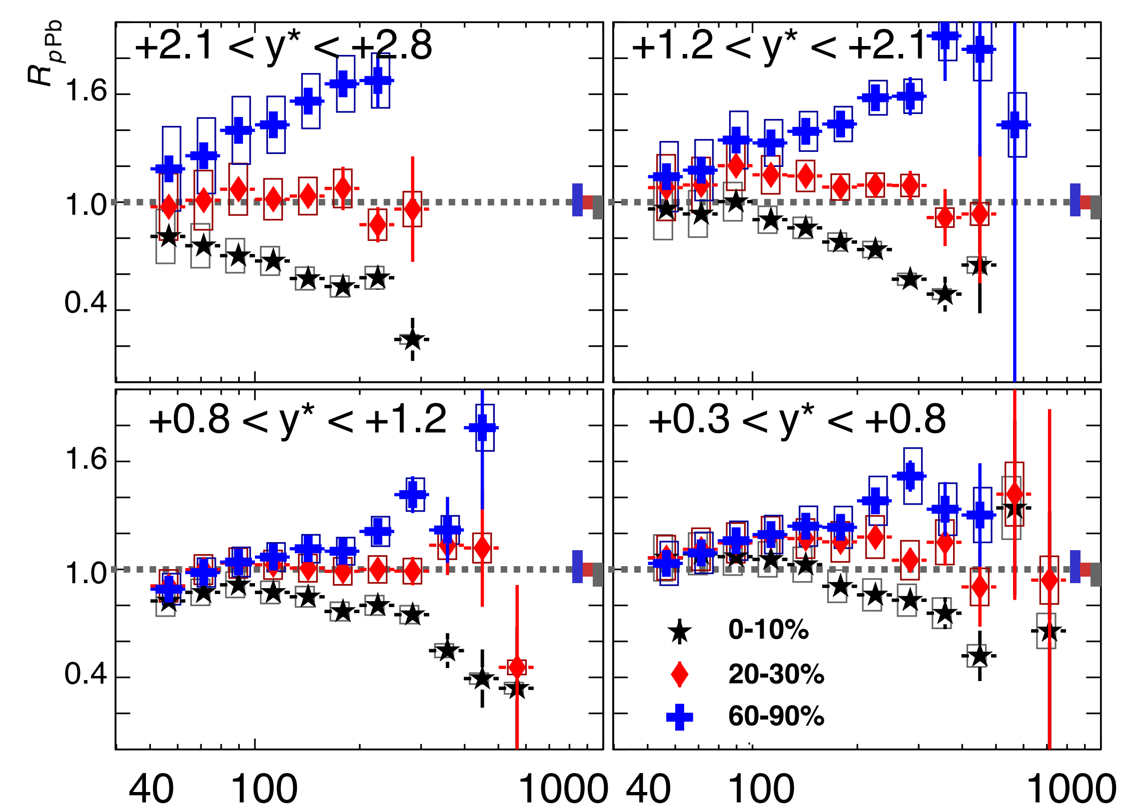
only at extreme x_p (proton dominated by a single high-E quark)

with opposite signal as the trivial "centrality bias" (peripheral ↑, central ↓)

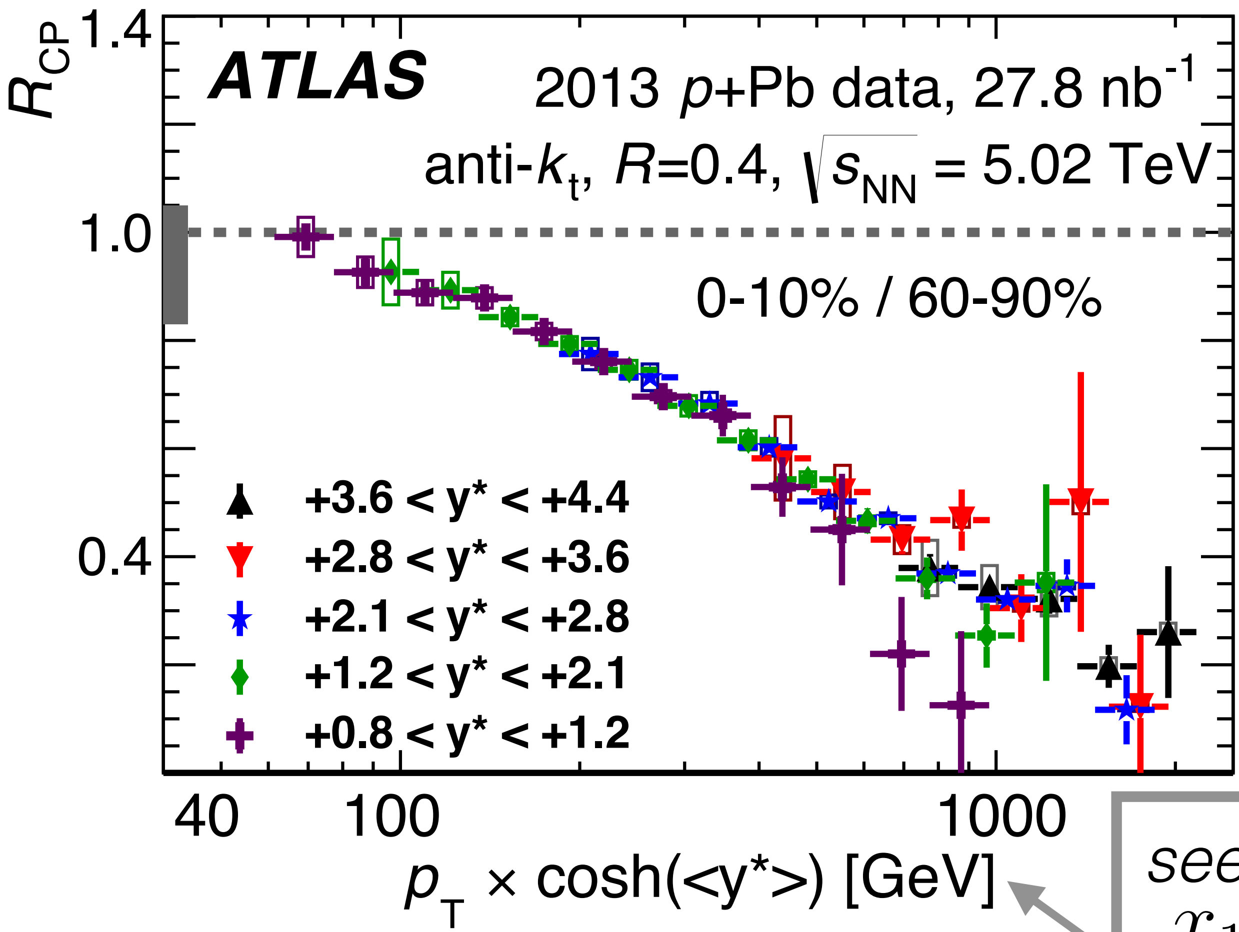


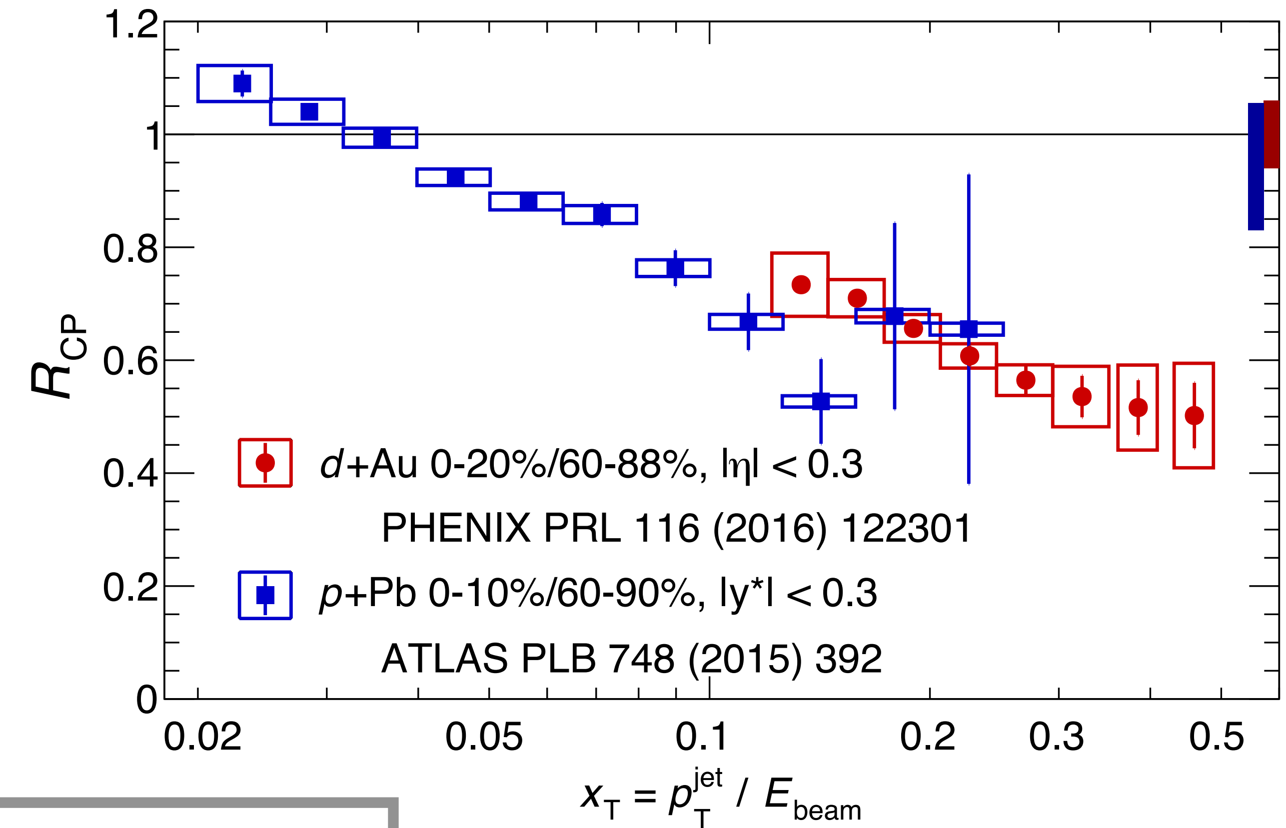


PRL 116 (2016) 122301



PLB 748 (2015) 392

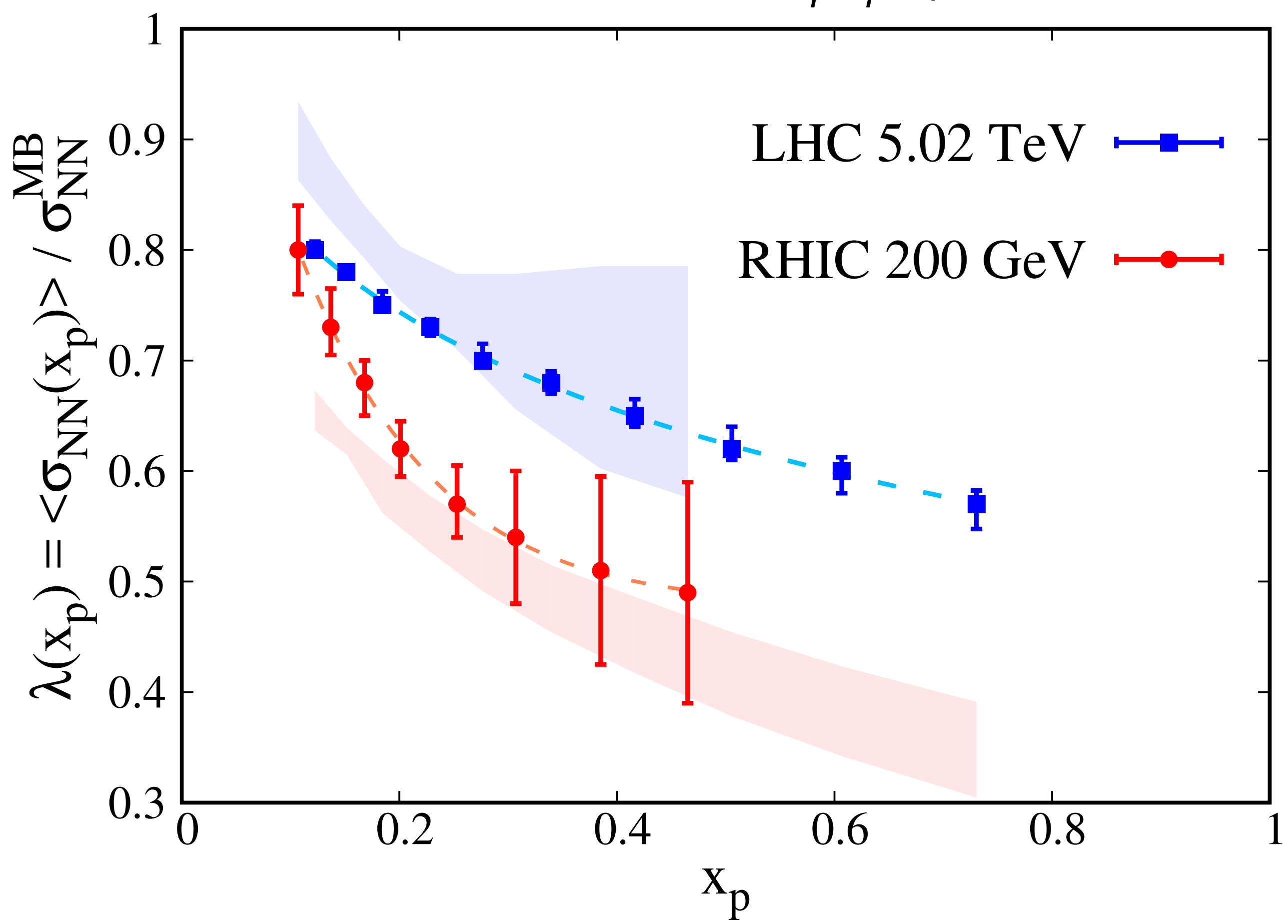




see slide 4:
$x_1 \approx p_{\mathrm{T}} e^{y_1} / \sqrt{s}$

PRC 93 (2016) 011902

hep-ph/1709.04993

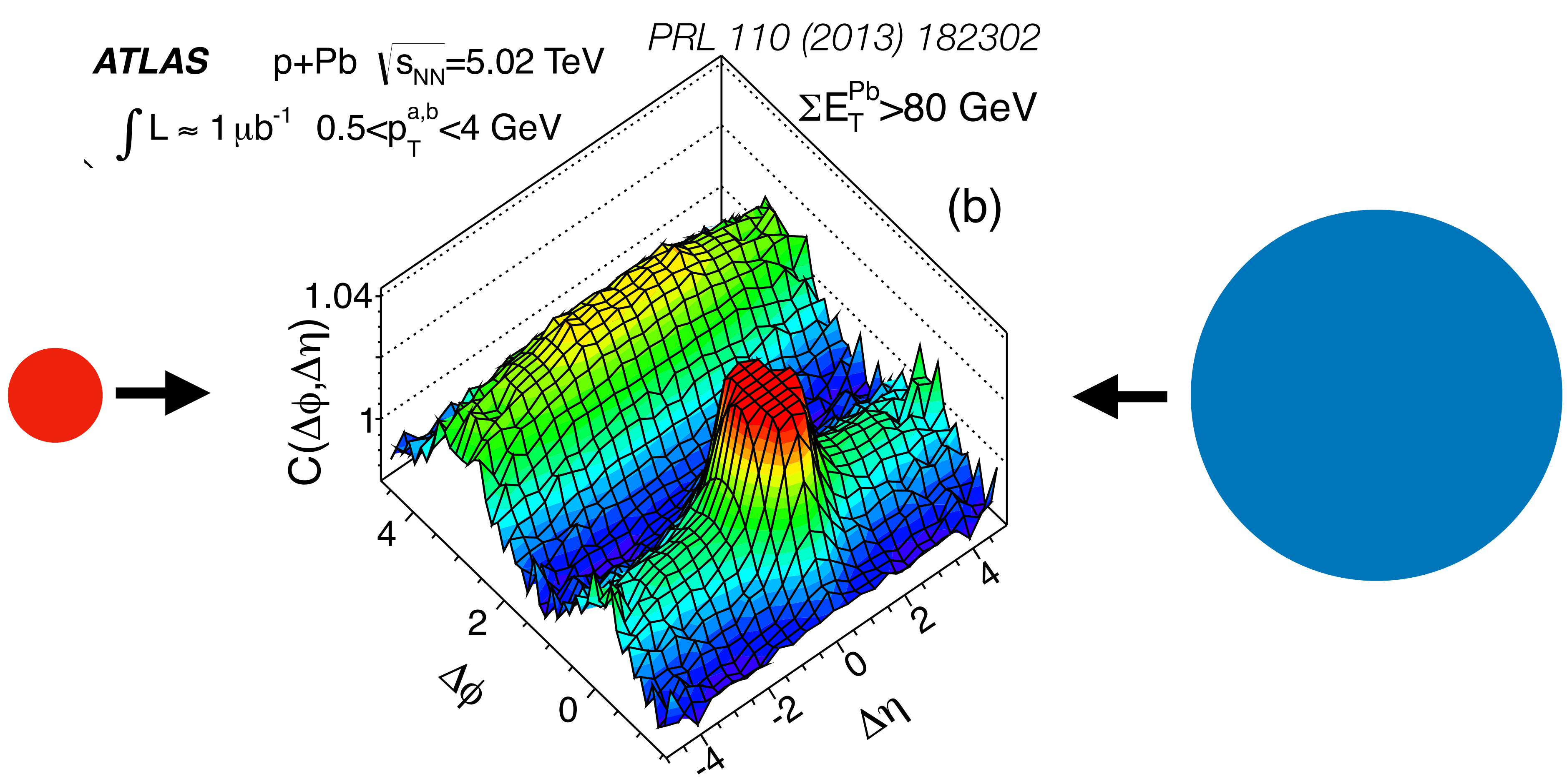


LHC data at multiple y, and LHC+RHIC data confirm shrinking is controlled by large-x_p

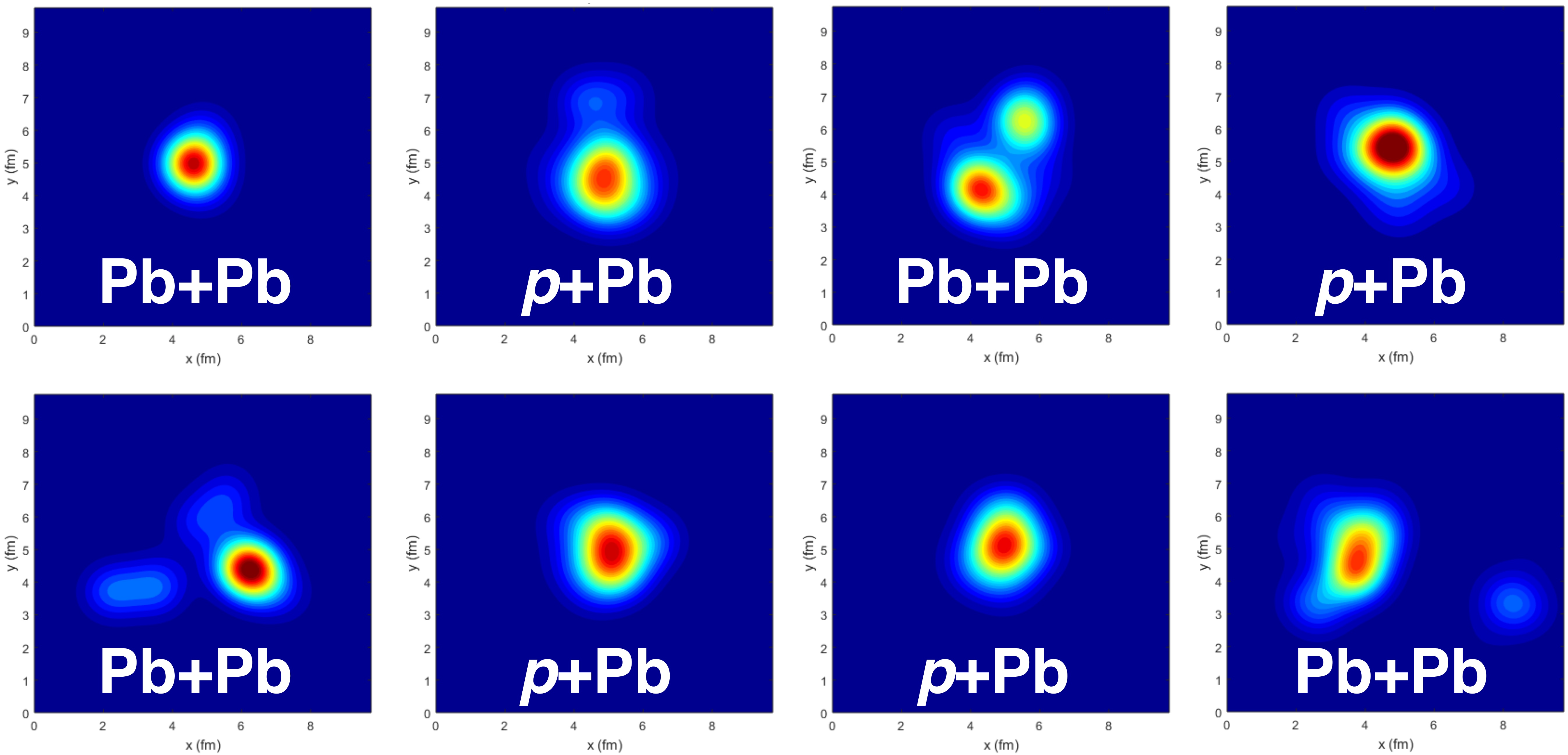
theoretical extraction on quantitive meaning of "shrinking"

See also: Armesto et al, PLB 747 (2015) 441 , Bzdak et al, PRC 93 (2016) 044901 Majumder et al, PRC 97 (2018) 054904

QGP in small systems?



where does the QGP "begin"?



0-10% *p*+A & 70-90% A+A

R. Weller and P. Romatschke, SuperSONIC

(historical) signatures of QGP formation

- Collective (hydrodynamic) expansion
- Strangeness enhancement
- Thermal radiation
- Differential quarkonia melting
- Jet quenching (incl. HF quarks)

"bulk" or soft probes

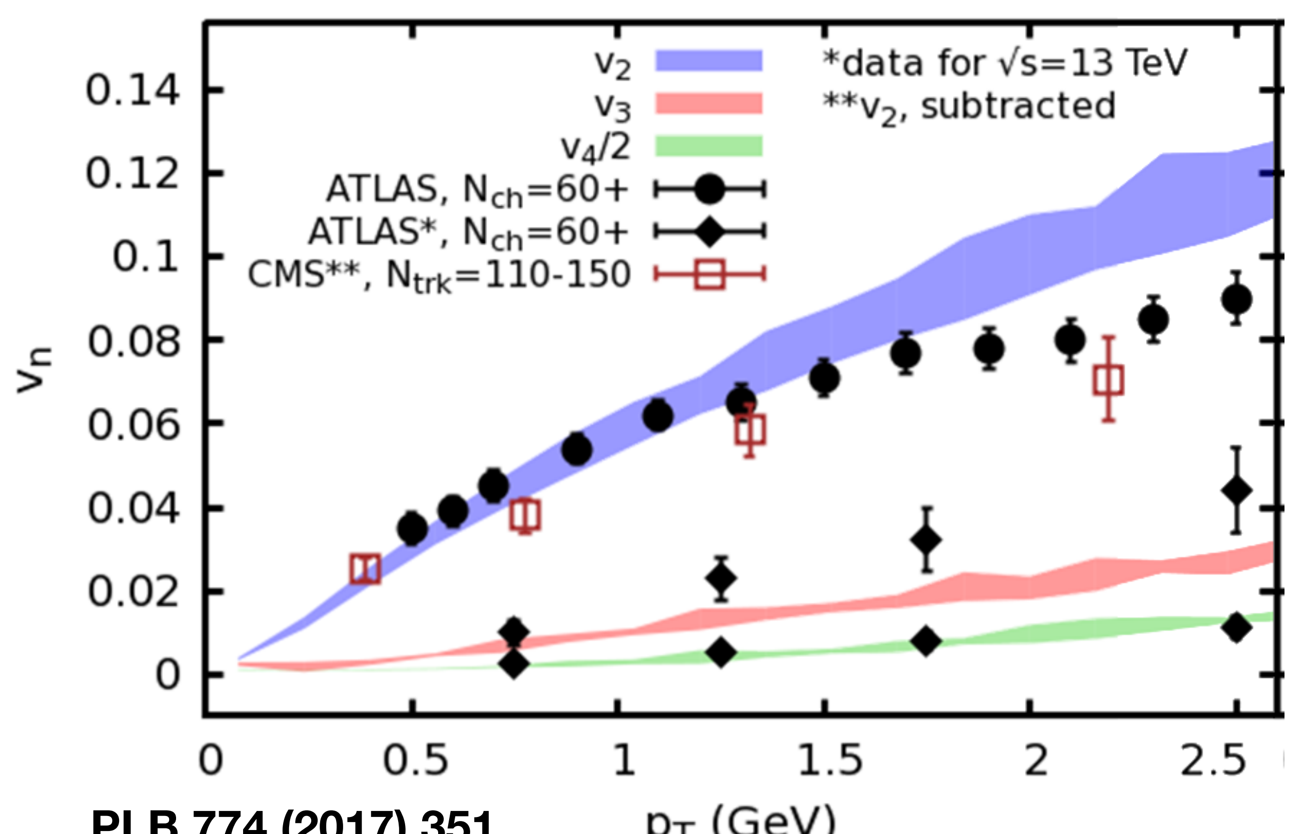
hard or EW probes

collective behavior in small systems

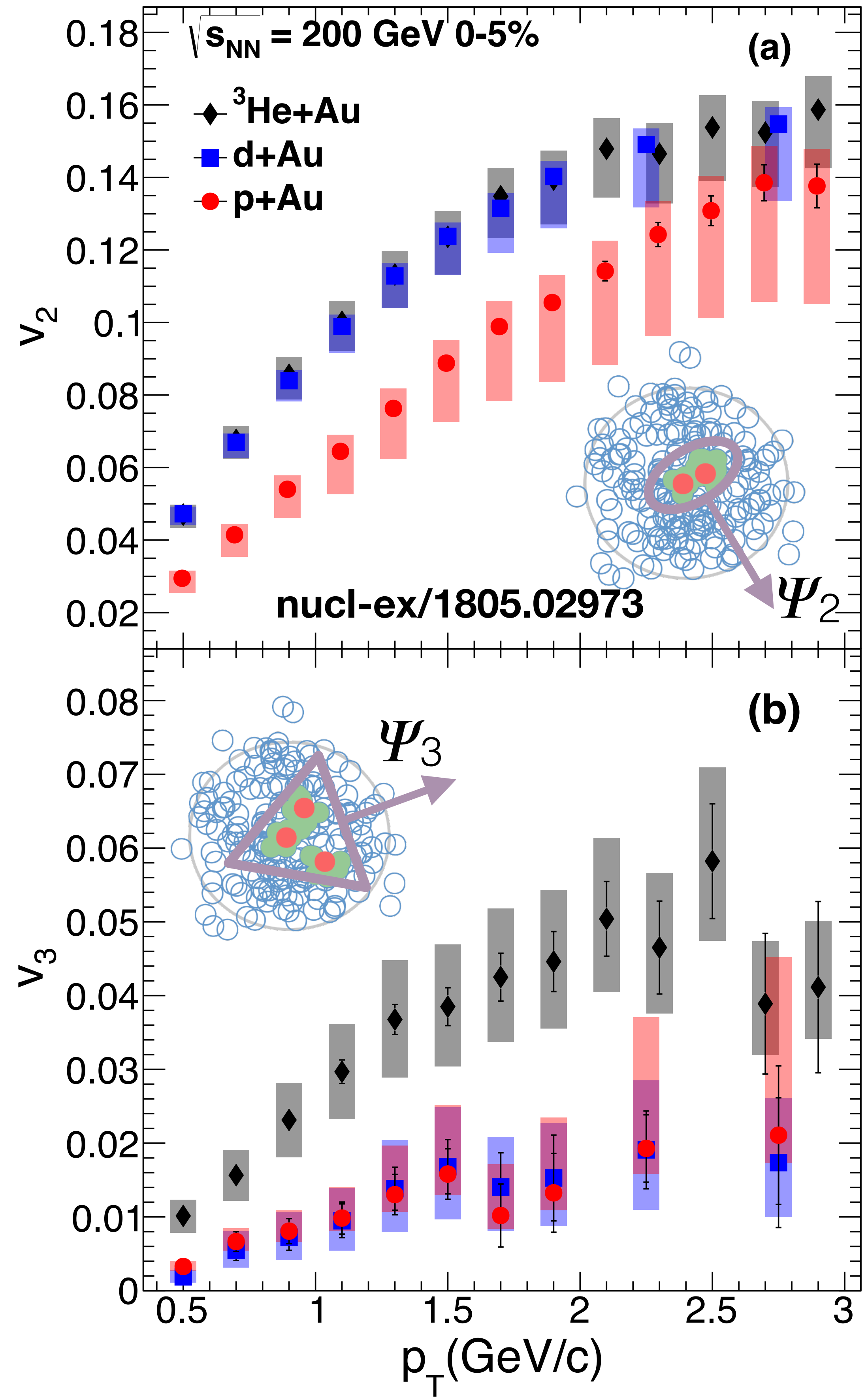
successful description of v_n in p/d/3He+A systems within AA-like hydrodynamic framework

including in pp collisions!

superSONIC for p+p, √s=5.02 TeV, 0-1%



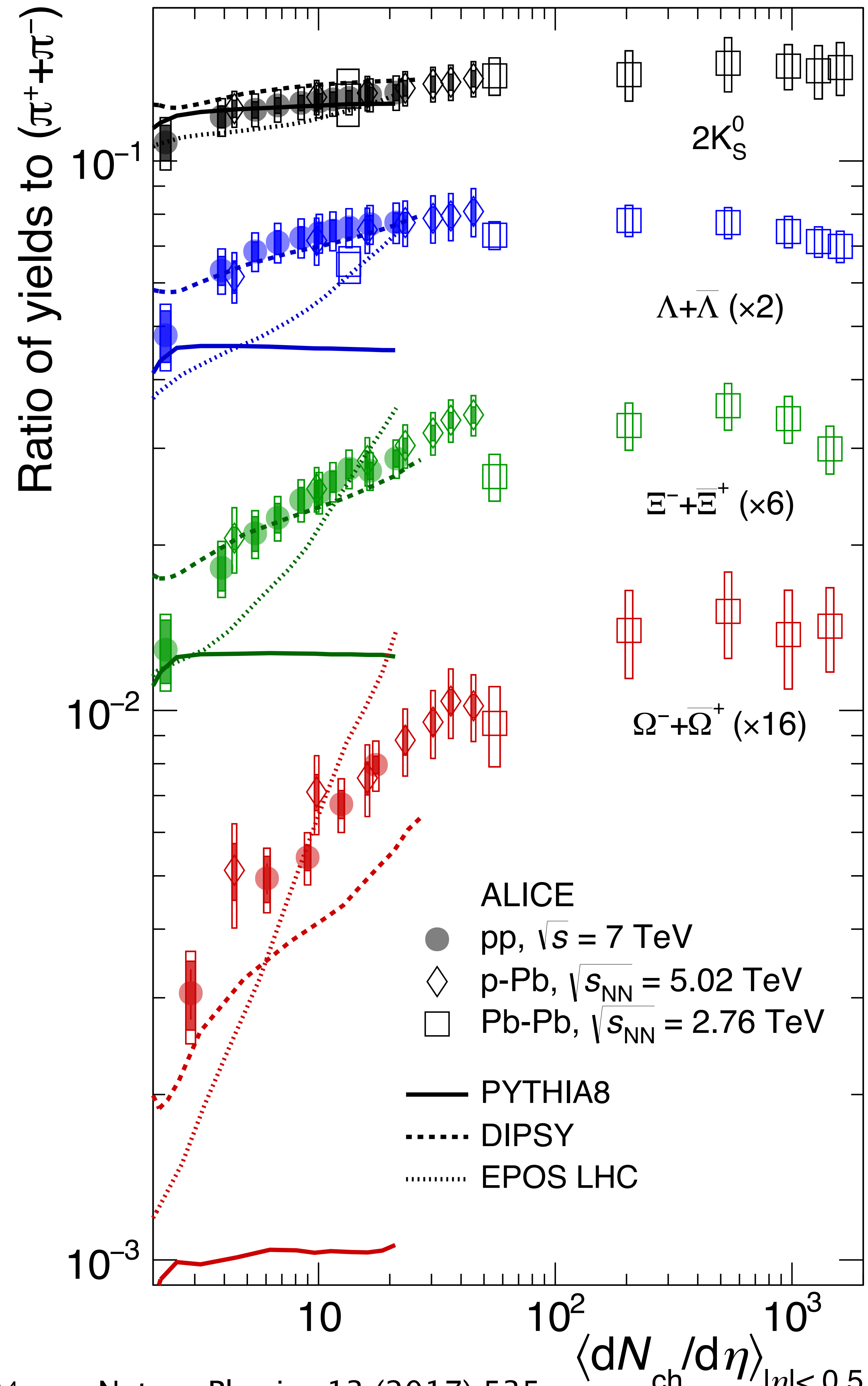
PLB 774 (2017) 351



strangeness enhancement

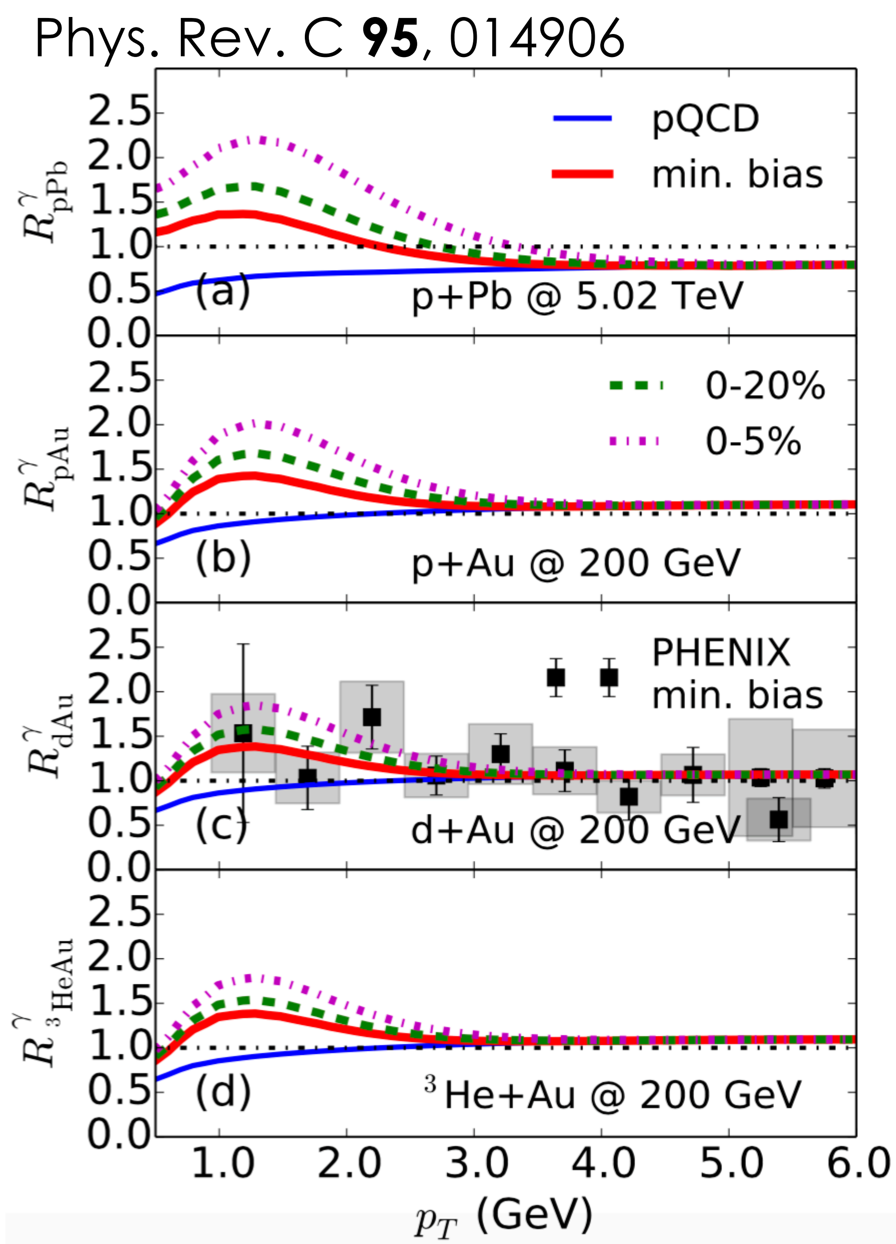
strange / light hadron yield ratios reach "AA"-like at large multiplicity…

"smooth" evolution from pp to pA to AA, with regimes overlapping

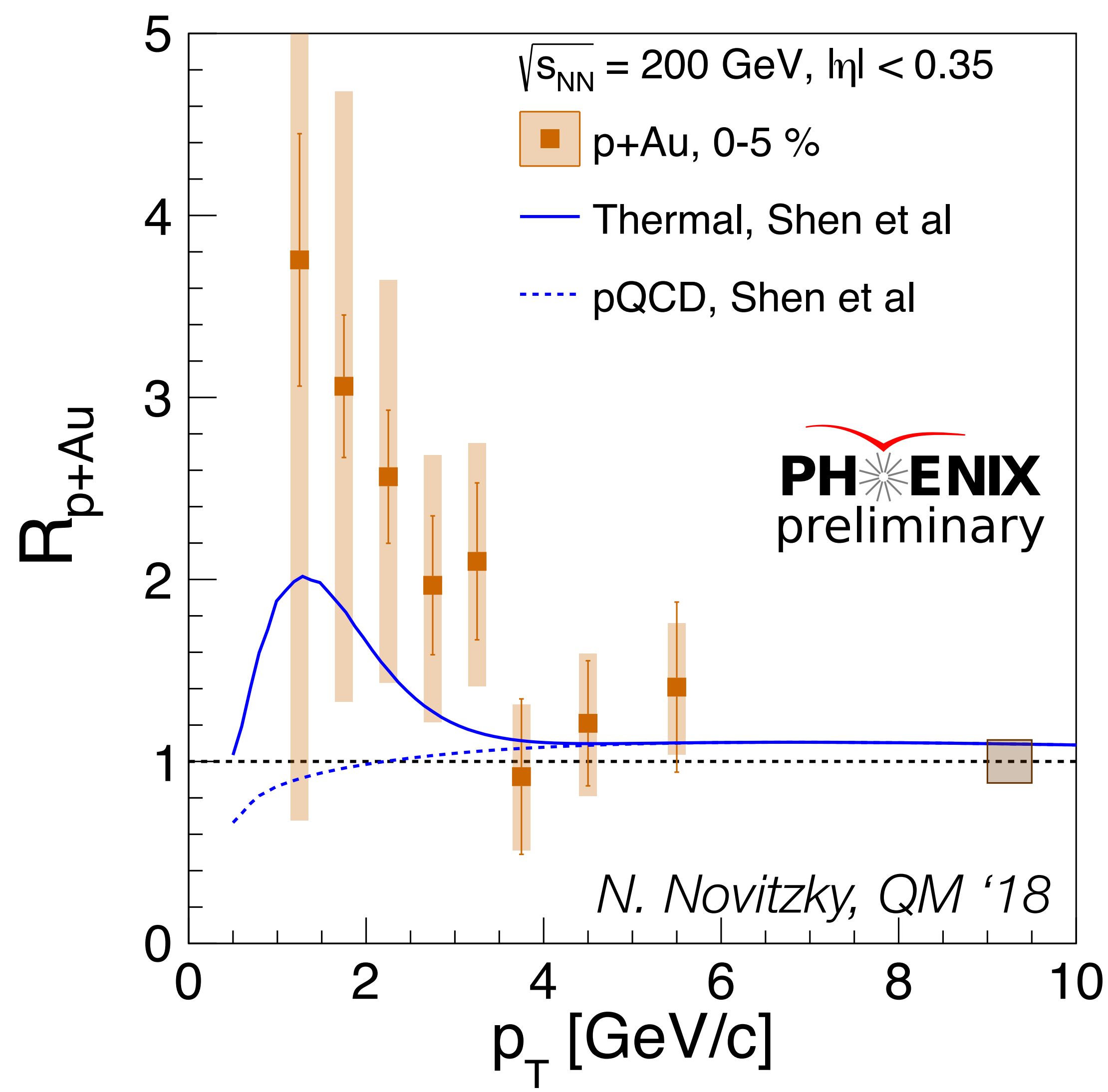


Nature Physics 13 (2017) 535

thermally radiating *p*+A system?



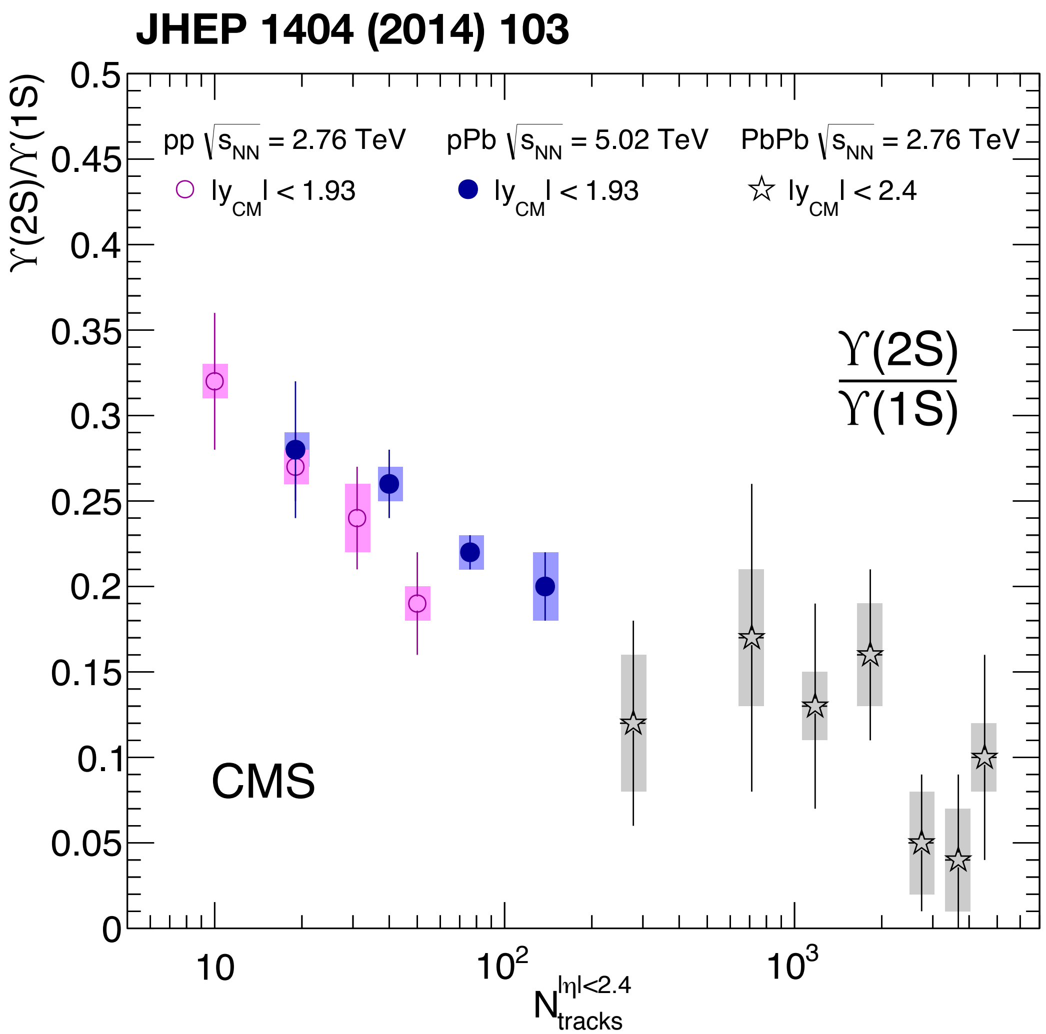
models tuned to A+A data predict thermal photon rates in small systems…

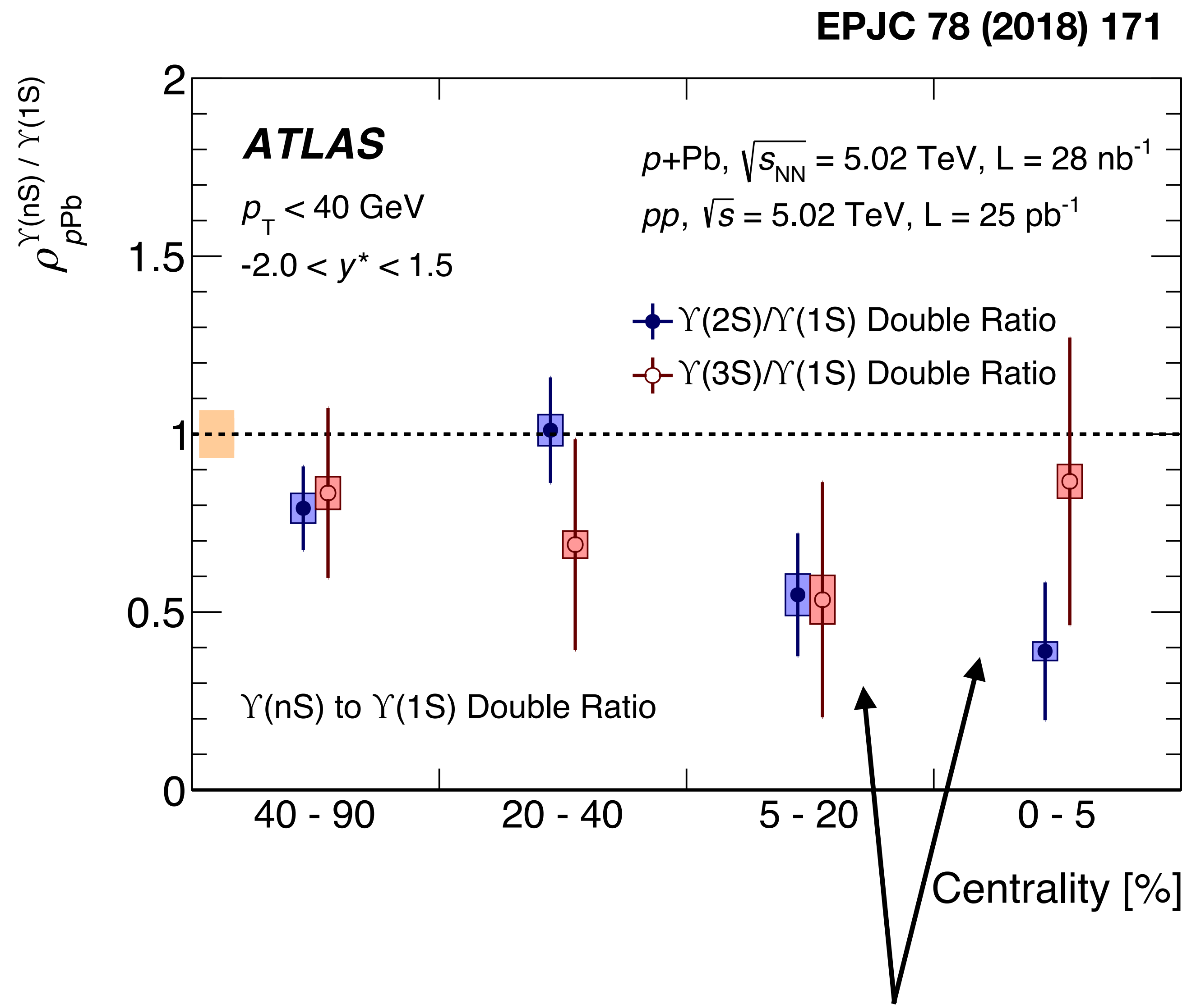


evidence of (small) thermal radiation in 0-5% p+A?

differential quarkonium melting

(focus on Upsilon @ LHC, no regeneration effects…)





relative 2S/1S yields (e.g. no absolute R_{pA} required)

$[nS/1S]^{pA}$ / $[nS/1S]^{pp}$ ratios

common trend in pp, pA, AA…

suppression in 0-20%?

(historical) signatures of QGP formation

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- ☑ Thermal radiation
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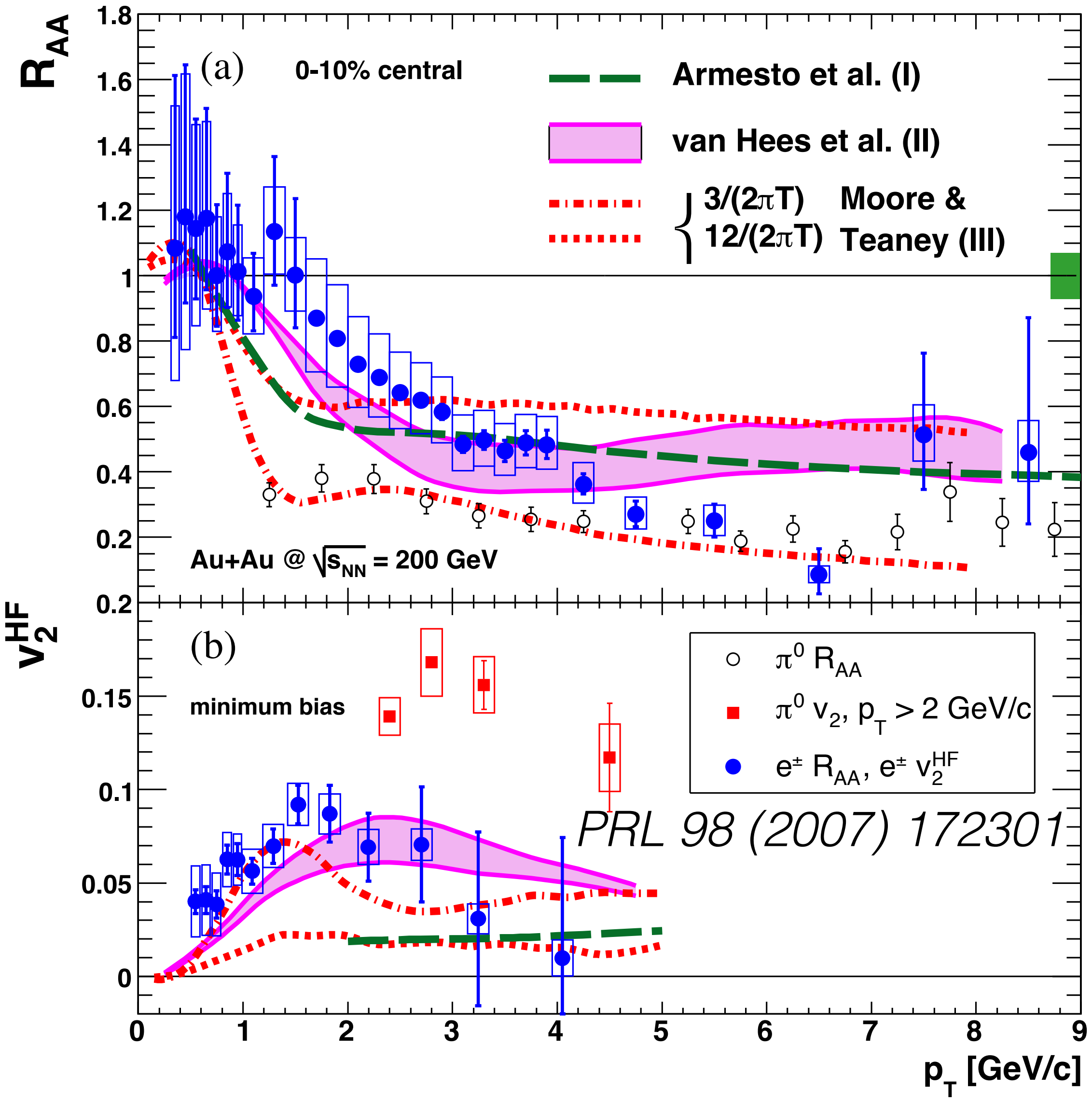
- ☐ Jet quenching (incl. HF quarks)

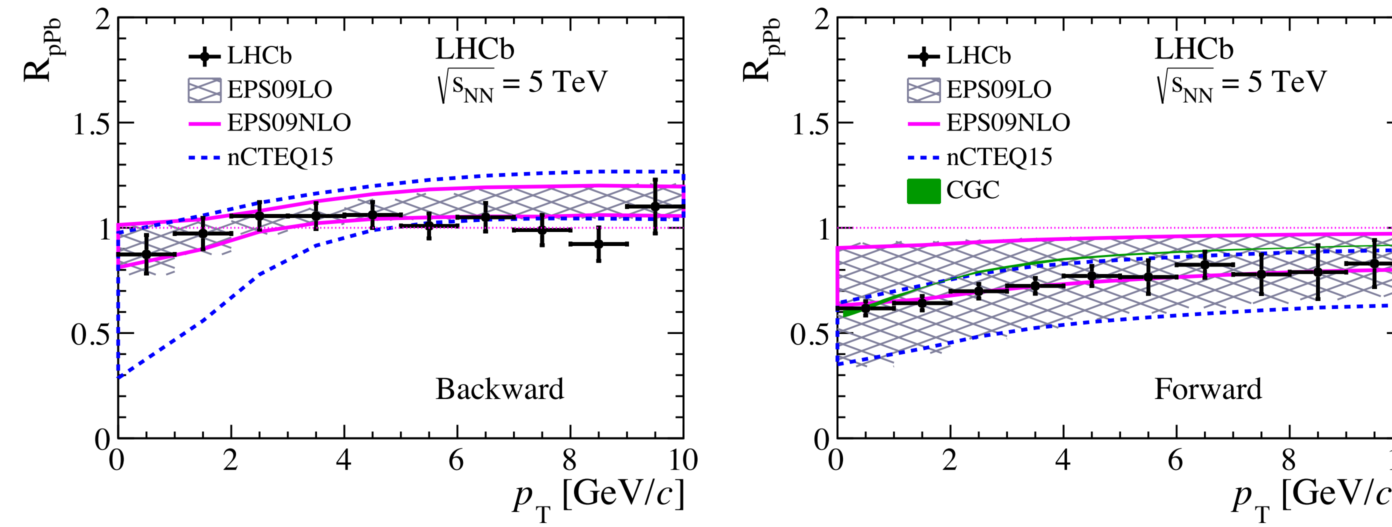
"bulk" or soft probes

hard or EW probes

collective behavior of HF quarks

JHEP 10 (2017) 090

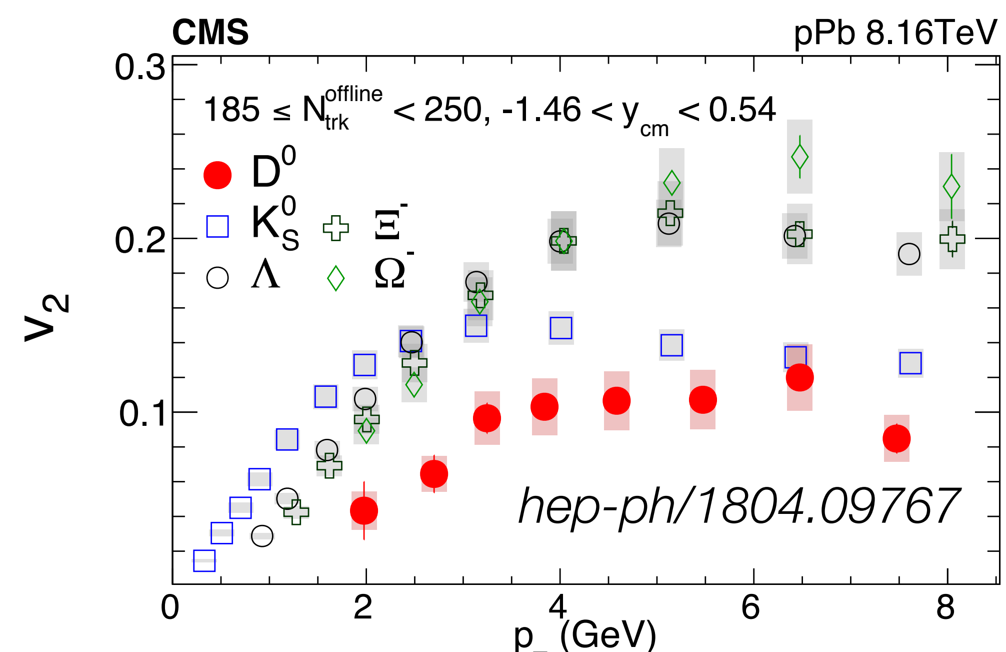




R_{pA} compatible with only nPDF / saturation effects…

substantial E-loss & flow of HF electrons in RHIC Au+Au

➡ *η/s = 1/4π bound!*



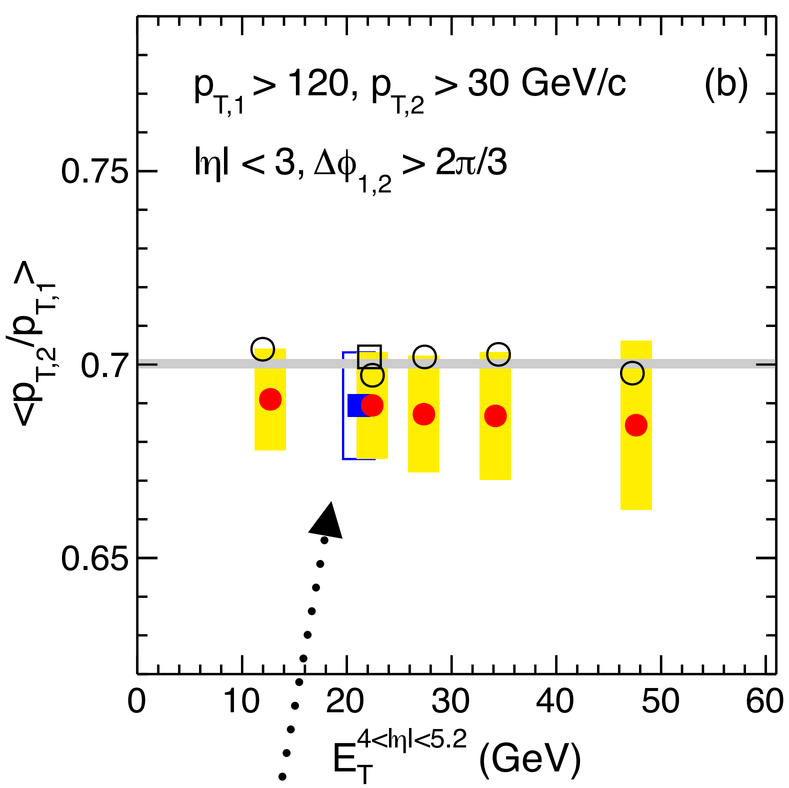
but very large "flow"(??)

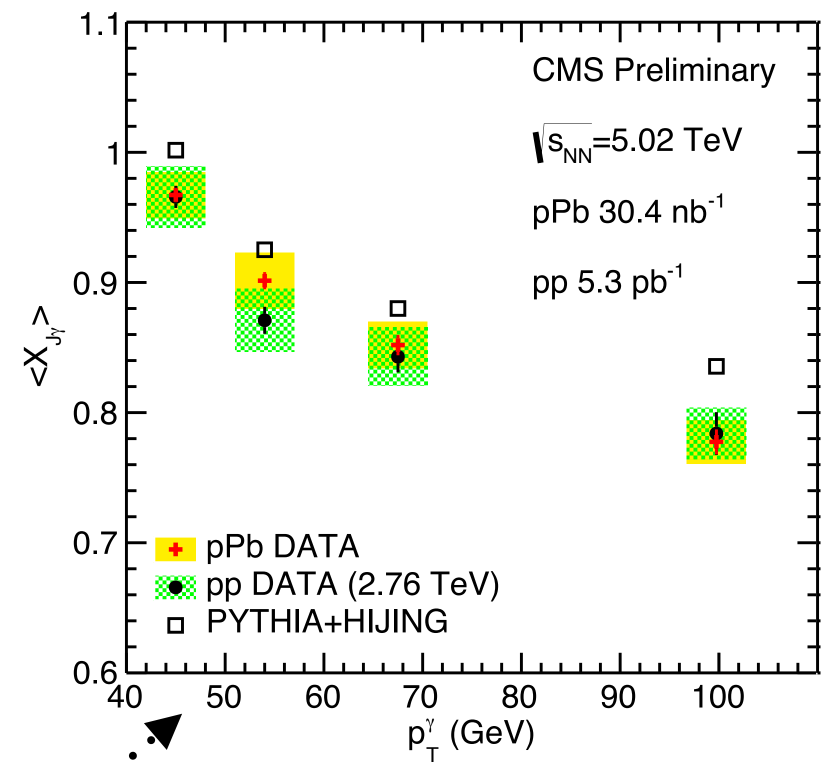
➡ *how to understand soft & hard physics together?*

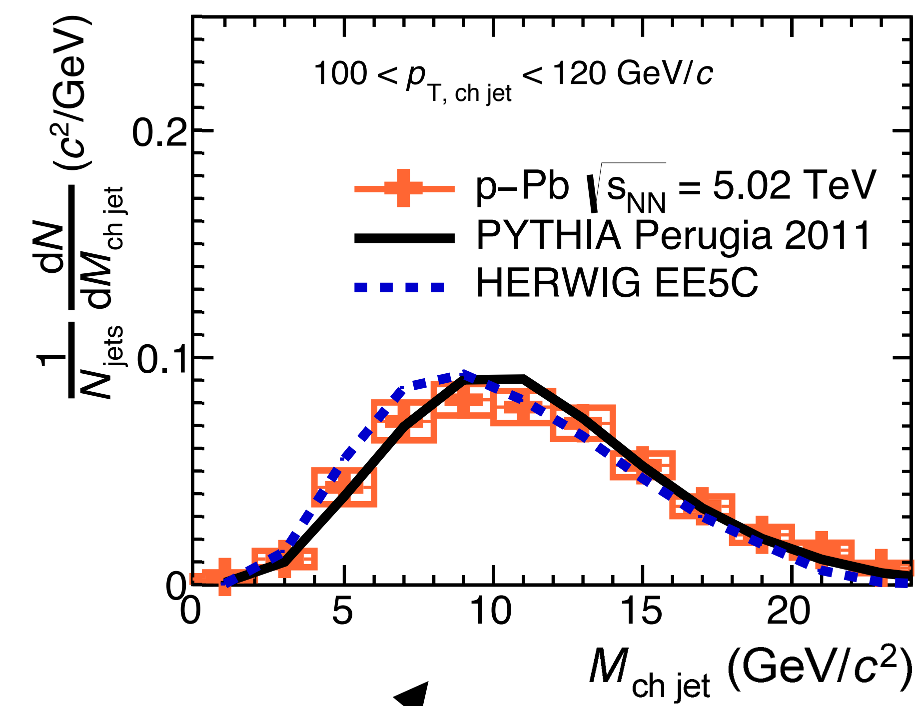
how to measure jet quenching in p+A?

- ➡ *Search for small effects (low-p_T jets / hadrons), in central collisions*
- ➡ *Central R_{pA} difficult to control systematically (and can encode large, non-jet quenching physics)*
- ➡ *Use event-by-event (or jet-by-jet) quenching observables*

E-by-*E* energy loss in 2013 data







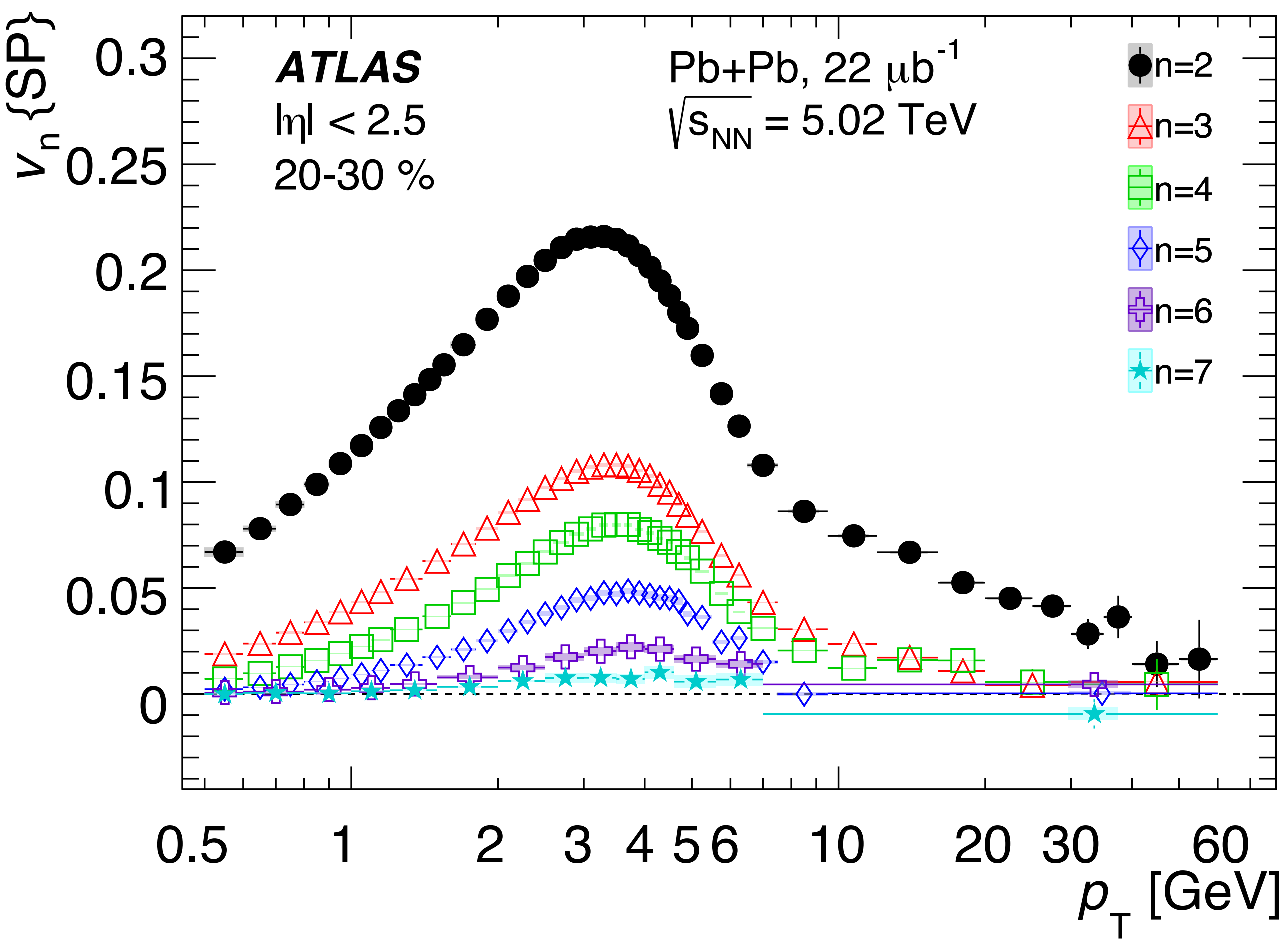
dijet and γ+jet p_T balance

quenching-sensitive jet shapes

➡ *null effect, but all at high-p_T or in “minimum bias” events*

high-p_T v_2 in ultra-central p+A?

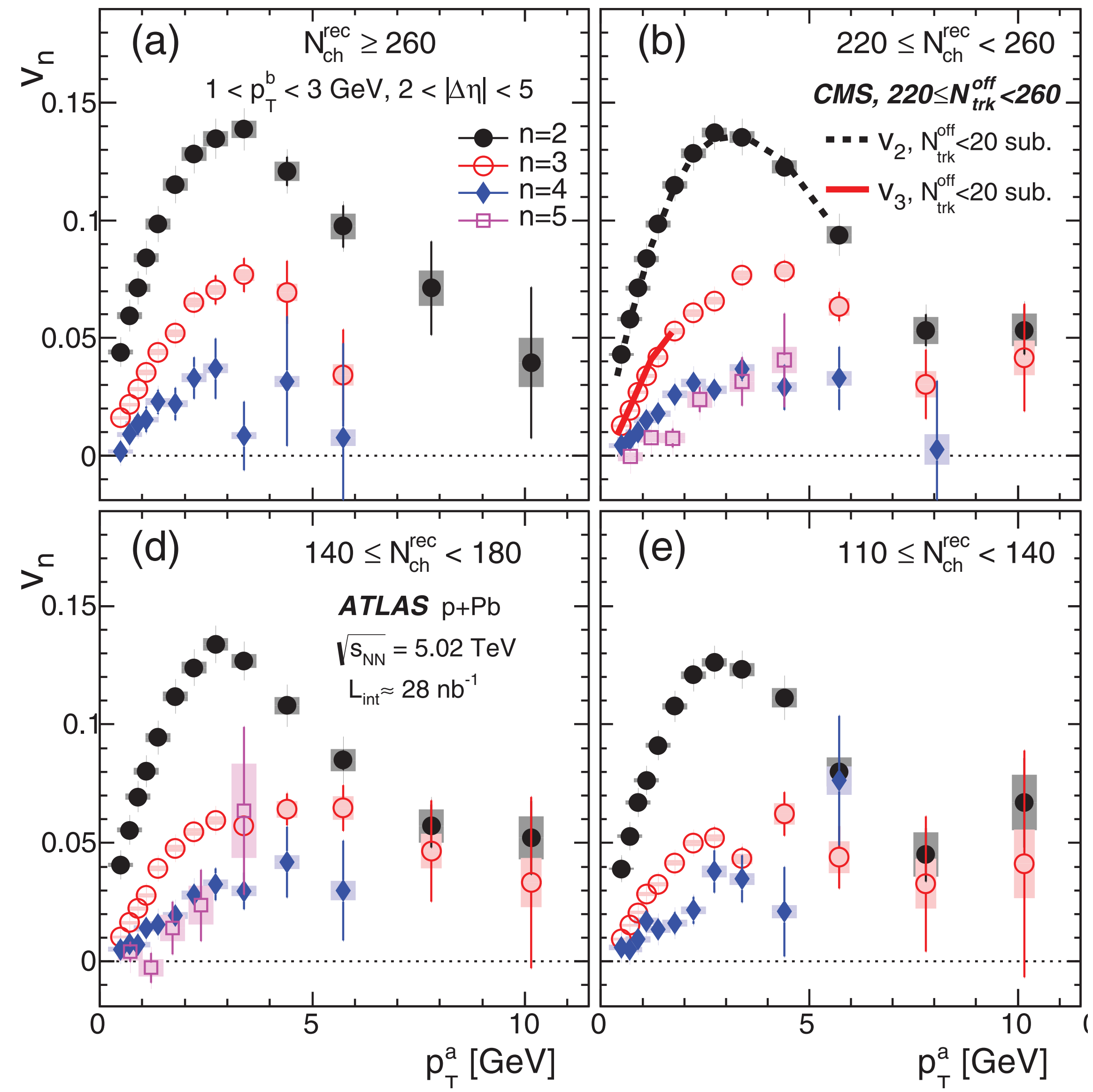
nucl-ex/1808.03951



in AA systems, high-p_T (> 10 GeV) v_2 understood as energy loss

(diff. energy loss in vs. out of plane)

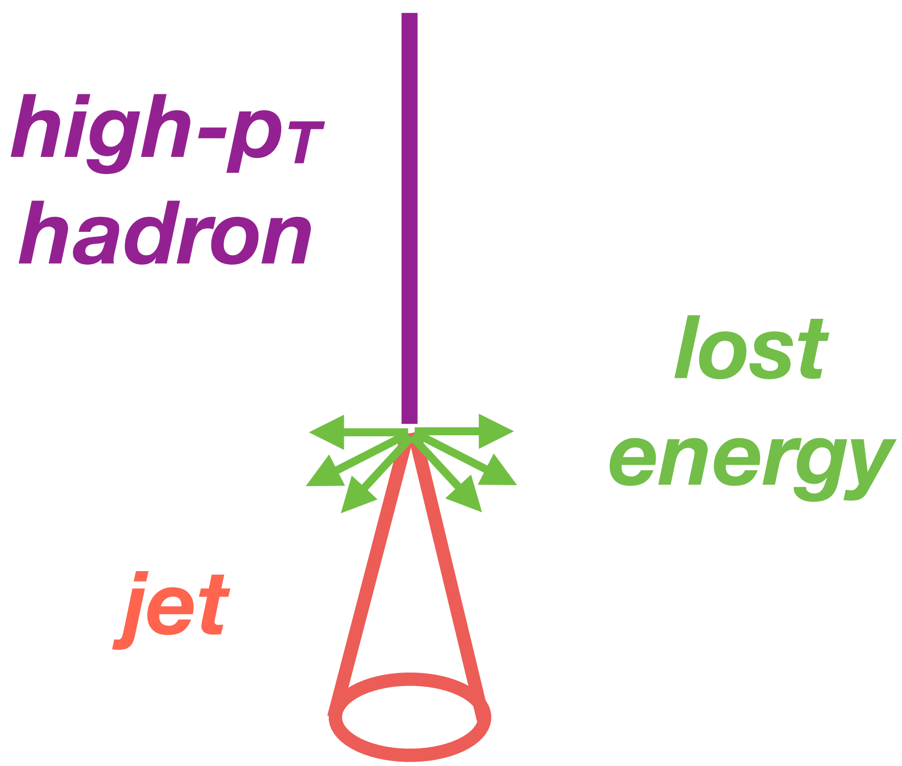
PRC 90 (2014) 044906

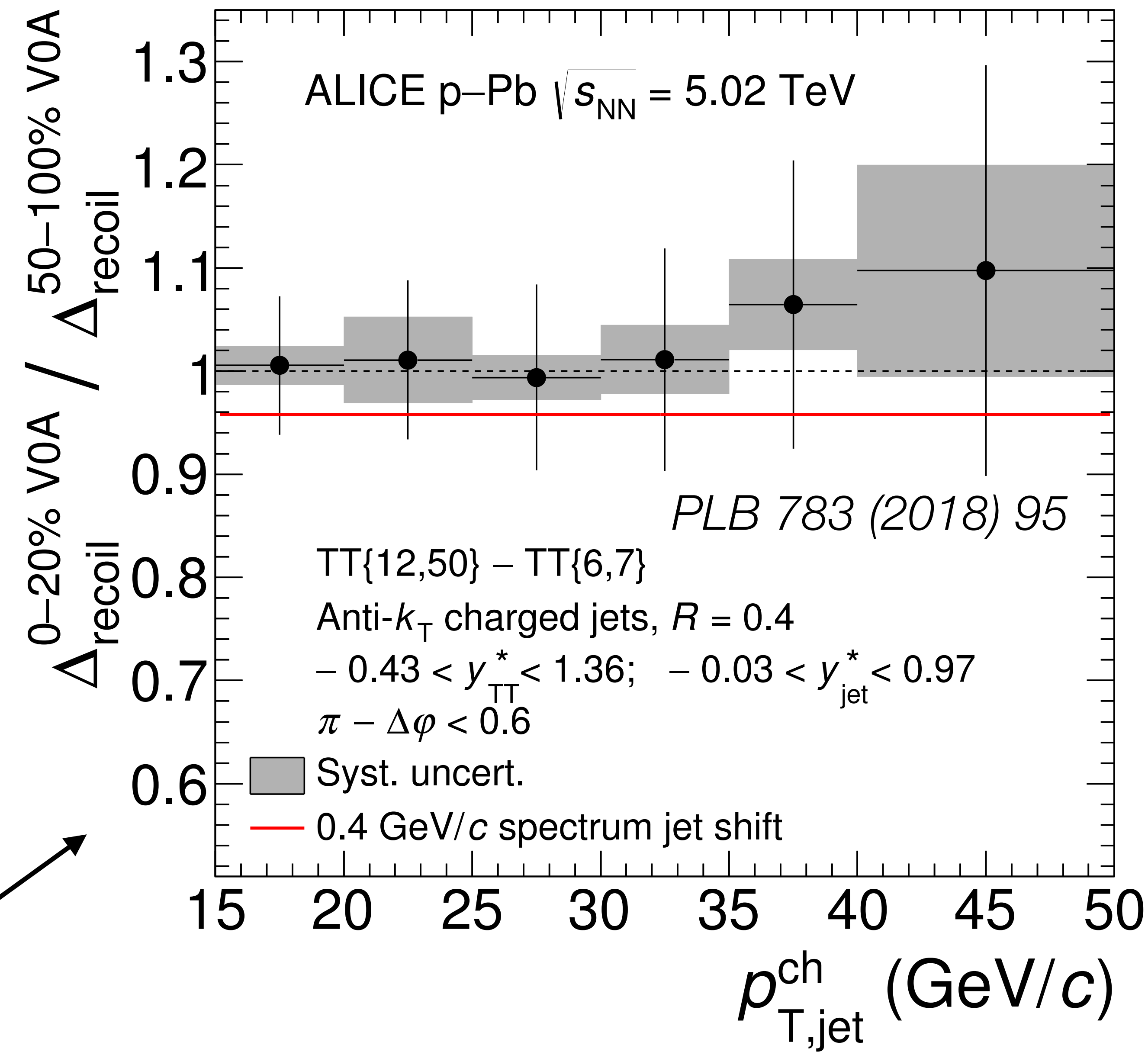


In 2013 p+Pb data, large v_2 @ p_T ~ 10 GeV in 0-1% p+Pb…

hadron+recoil jet correlations

push to lower p_T (15-50 GeV), central events (0-20%)





unmodified recoil jet p_T distributions…

sets empirical limit on out-of-cone E-loss, but some subtleties (can both jets lose E, etc.?)

jet quenching in high-mult. *pp*?

Eur. Phys. J. C (2018) 78:343
https://doi.org/10.1140/epjc/s10052-018-5826-9
THE EUROPEAN PHYSICAL JOURNAL C
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Regular Article - Experimental Physics

Observables for possible QGP signatures in central *pp* collisions

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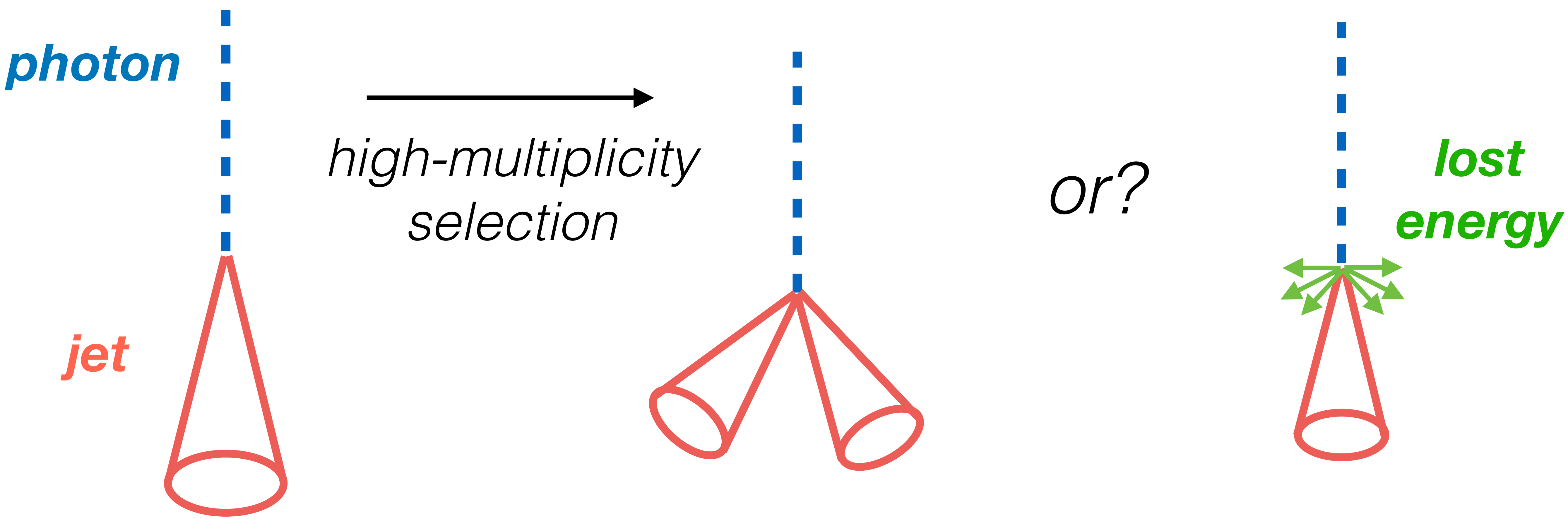

vacuum baseline

bias towards multi-jet final states

“true” E-loss

(historical) signatures of QGP formation

- ☑ Collective (hydrodynamic) expansion
- ☑ Strangeness enhancement
- ☑ Thermal radiation
- ☑ Differential quarkonia melting
- ? Jet quenching (incl. HF quarks)

"bulk" or soft probes

hard or EW probes

How should we understand these data together?

Do we understand the meaning of these in small systems?

thank you!

questions?

you can also find me at lunch…