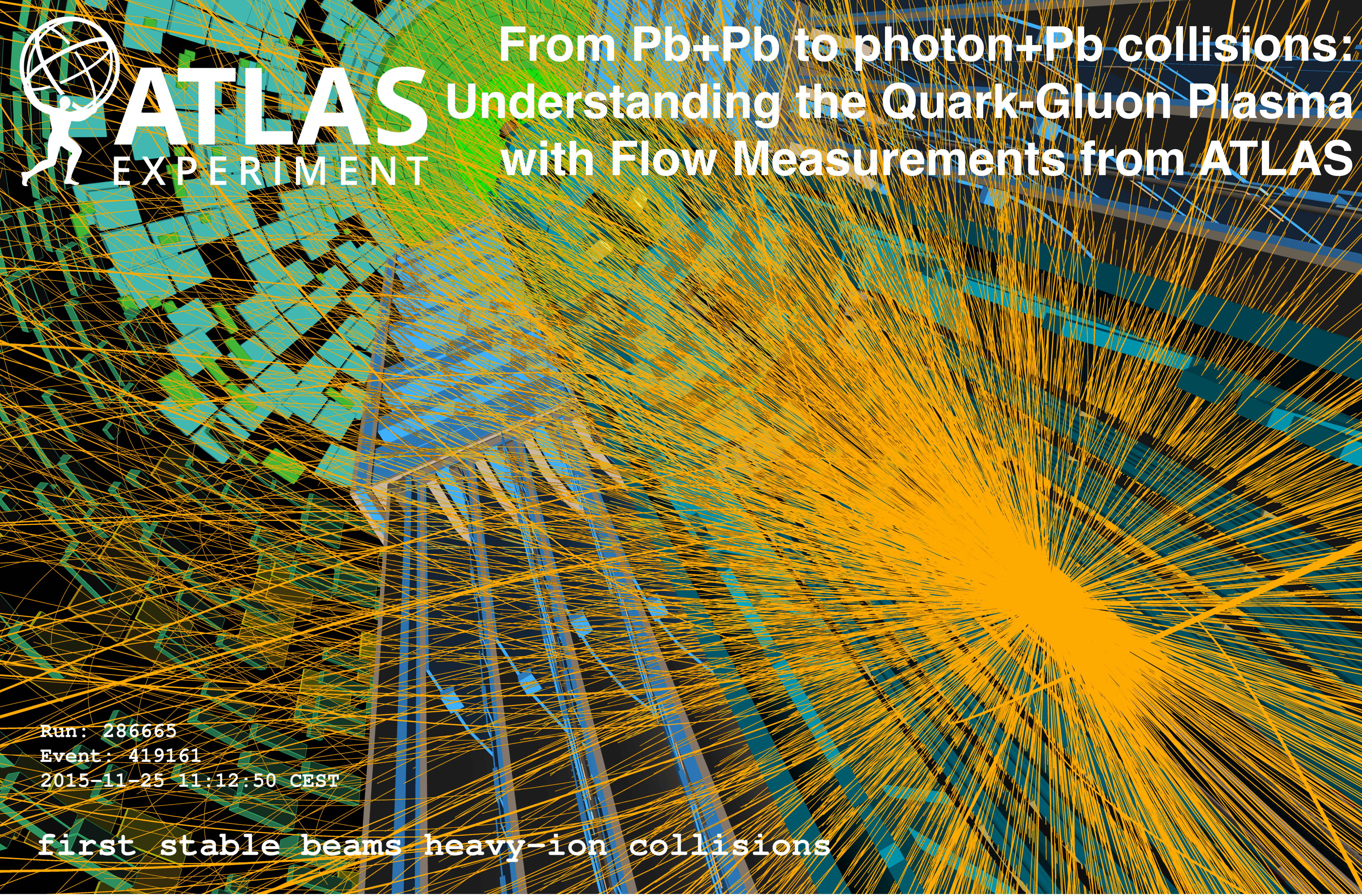
From Pb+Pb to photon+Pb collisions: Understanding the Quark-Gluon Plasma with Flow Measurements from ATLAS

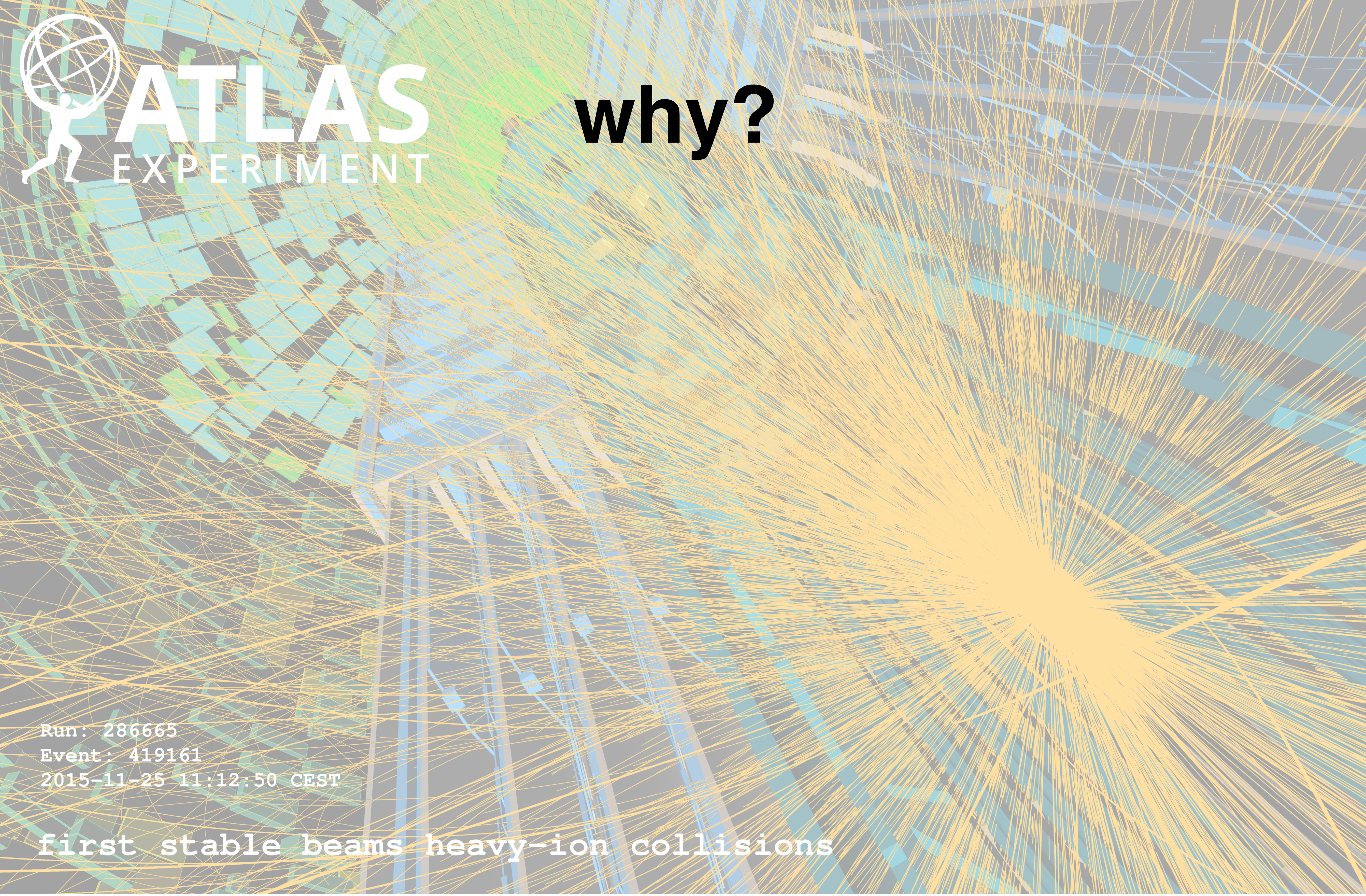


Anne M. Sickles for the ATLAS Collaboration

ILLINOIS

November 26, 2019

why?



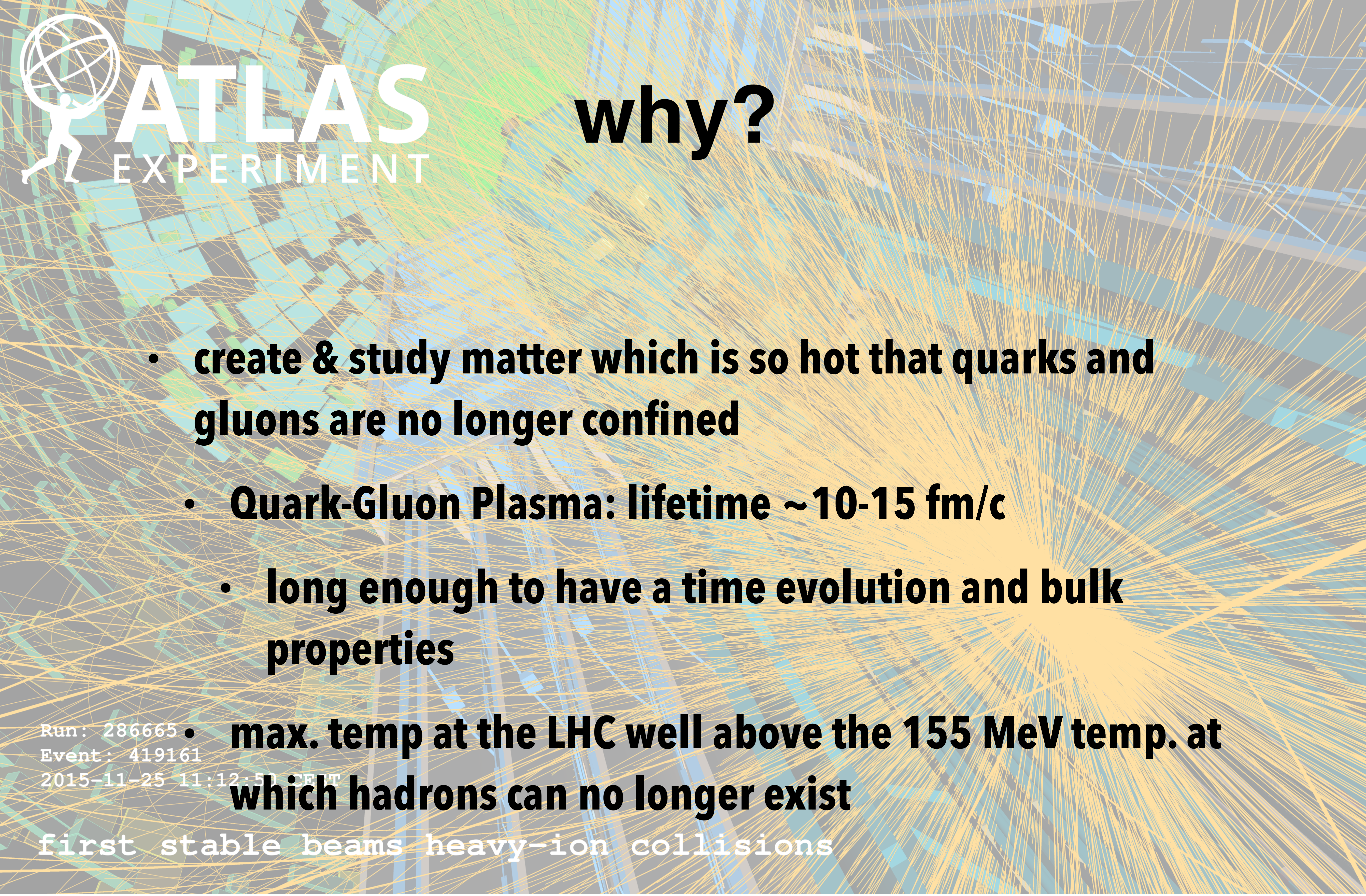
ILLINOIS

Anne M. Sickles

November 26, 2019

why?

- create & study matter which is so hot that quarks and gluons are no longer confined
  - Quark-Gluon Plasma: lifetime ~10-15 fm/c
    - long enough to have a time evolution and bulk properties
- max. temp at the LHC well above the 155 MeV temp. at which hadrons can no longer exist



goals of the heavy ion program at the LHC

slide from U. Wiedemann, European Strategy Open Symposium, May 2019

Main goals of nuclear beams programs @ HL-LHC

(as defined in HL-LHC WG5 report: arXiv:1812.06772)

1. **Characterizing the long-wavelength QGP properties** with unprecedented precision.
2. **Probing the inner workings of the QGP:** investigating microscopic parton dynamics in hot and dense QCD matter.
3. **System size dependence:** developing a unified picture of particle production and QCD dynamics from pp to AA.
4. **Exploring nuclear parton densities** in a broad (x, Q^2) range and searching for onset of parton saturation.

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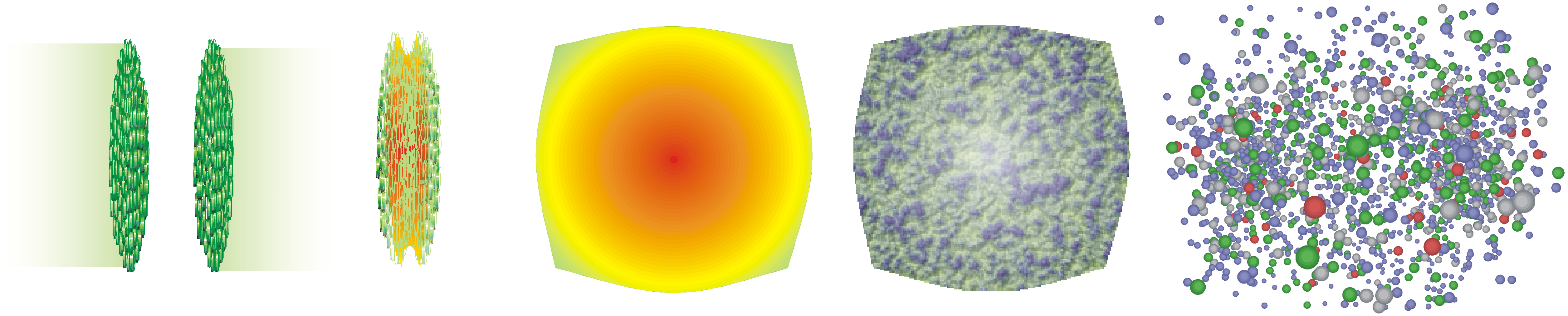
goal for today: discuss recent ATLAS measurements with sensitivity to these questions

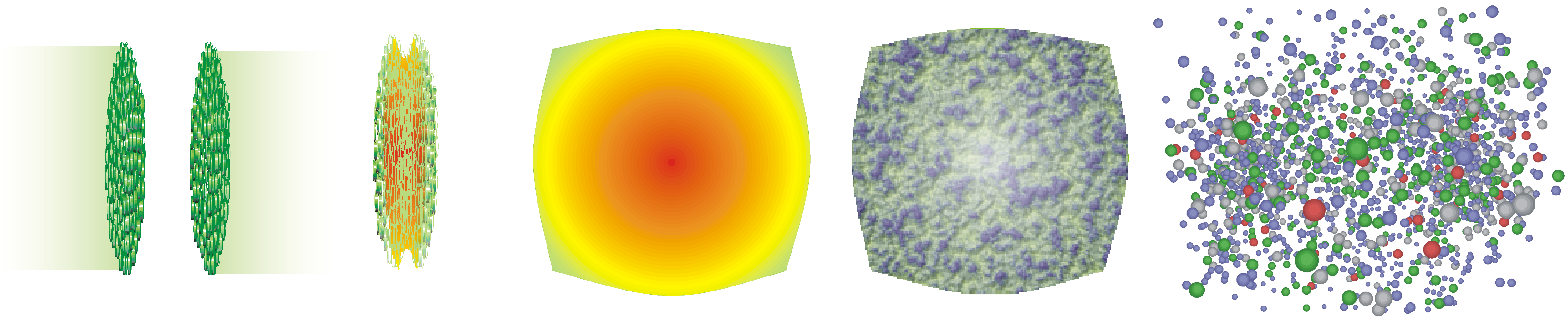
ATLAS heavy ion datasets

System	Year	$\sqrt{s_{NN}}$ [TeV]	L_{int}
Pb+Pb	2010	2.76	9 μb^{-1}
Pb+Pb	2011	2.76	0.14 nb^{-1}
p+Pb	2012	5.02	1 μb^{-1}
p+Pb	2013	5.02	29 nb^{-1}
pp	2013	2.76	4 pb^{-1}
pp	2015, 2016	13	75 nb^{-1}
pp	2015	5.02	28 pb^{-1}
Pb+Pb	2015	5.02	0.49 nb^{-1}
p+Pb	2016	5.02	0.5 nb^{-1}
p+Pb	2016	8.16	180 nb^{-1}
pp	2017	13	150 pb^{-1}
Xe+Xe	2017	5.44	3 μb^{-1}
pp	2017	5.02	272 pb^{-1}
pp	2018	13	193 pb^{-1}
Pb+Pb	2018	5.02	1.75 nb^{-1}

13 TeV pp is low pileup running used in correlation measurements

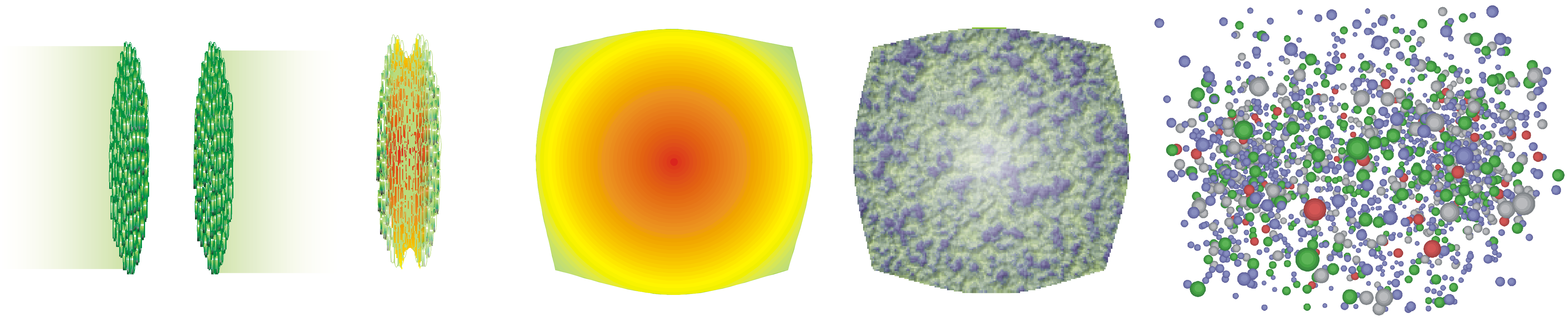


QGP phase



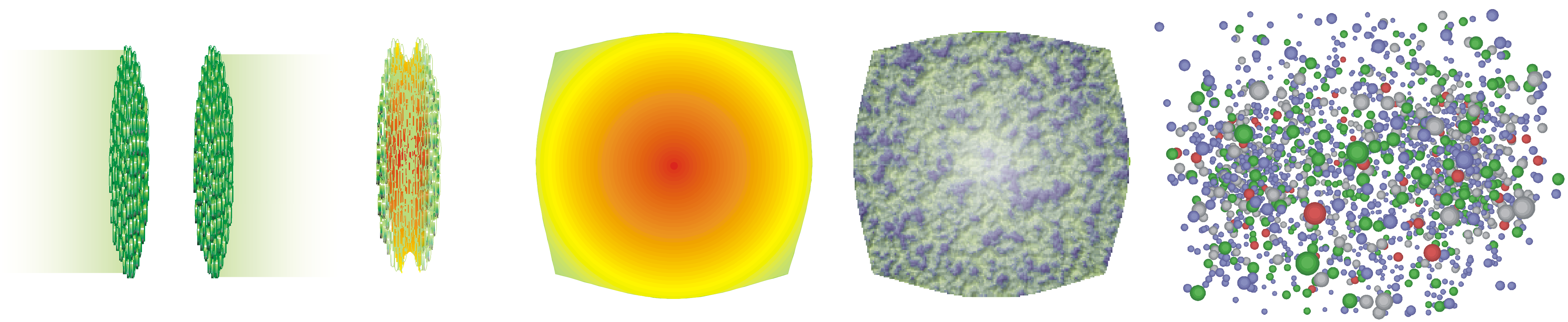
QGP phase

final state particles

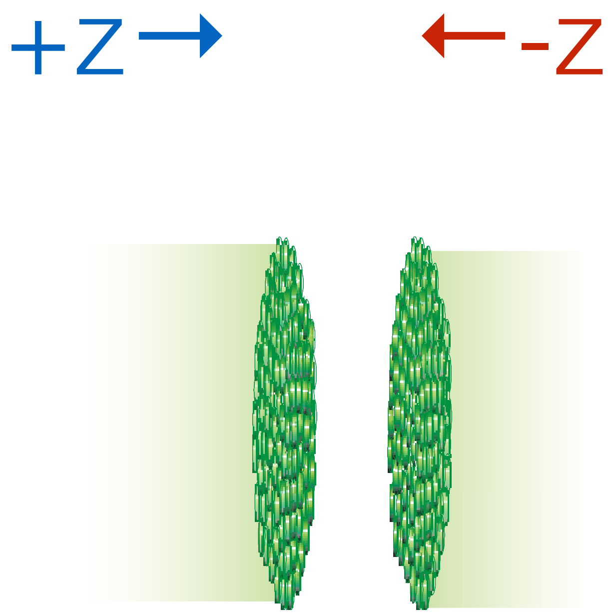


a heavy ion collision

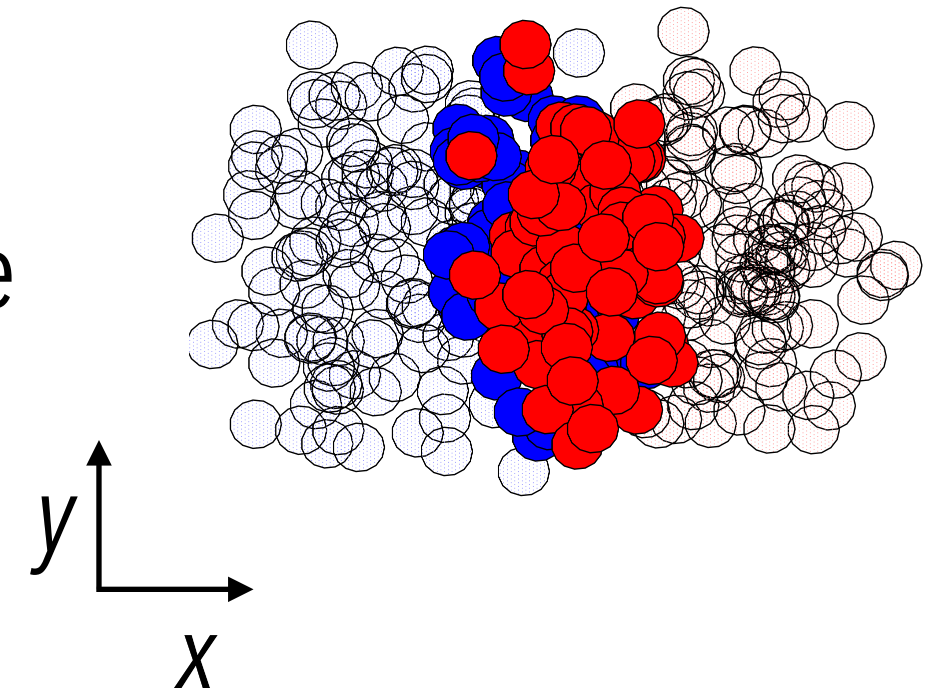
incoming nuclei QGP phase final state particles



a heavy ion collision

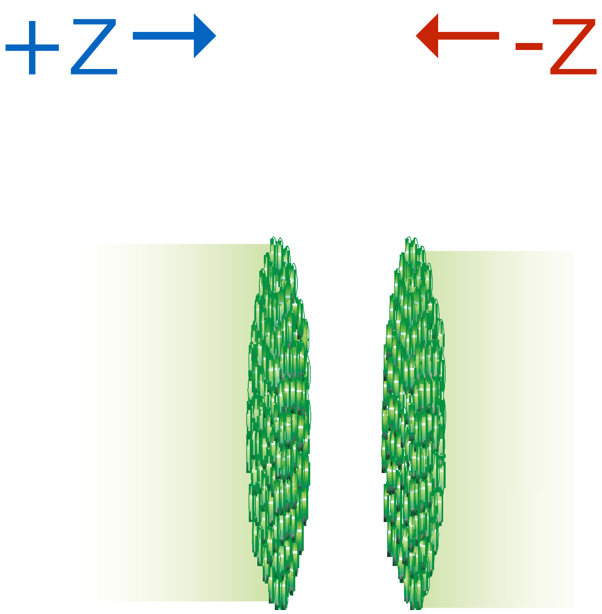


look at the *x*-*y* plane



geometry of each collision depends on **impact parameter** and **event-by-event fluctuations**

a heavy ion collision



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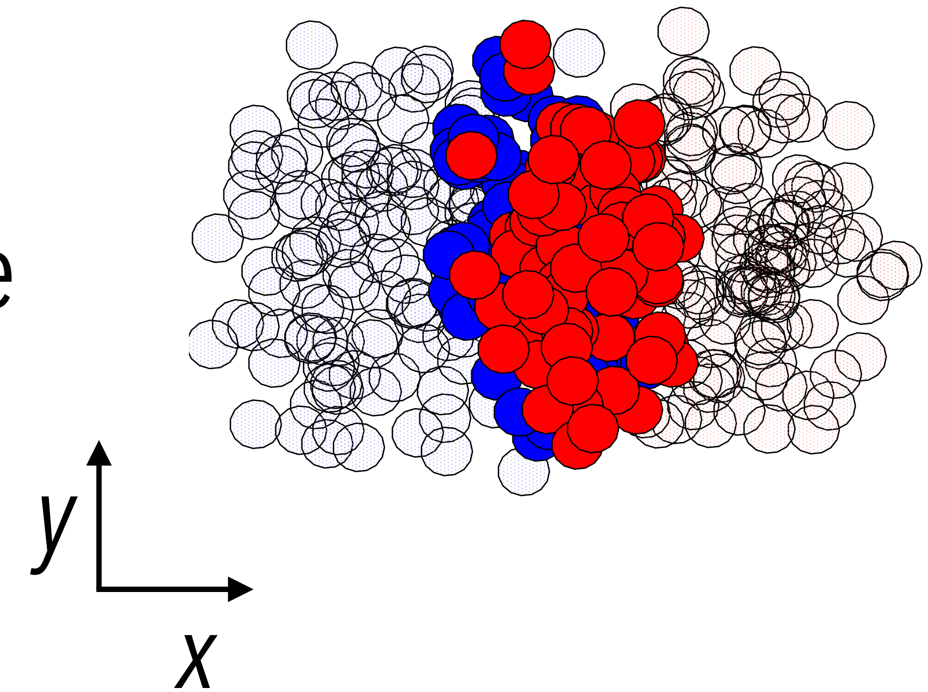
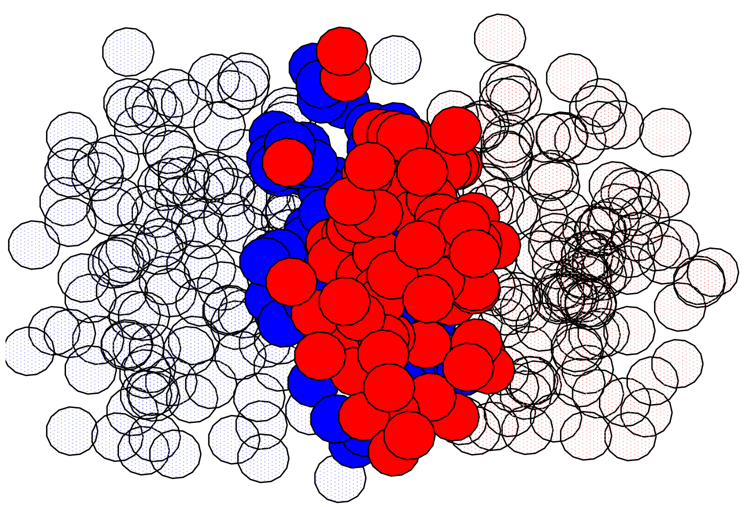


geometry of each collision depends on **impact parameter** and **event-by-event fluctuations**

observables sensitive to geometry provide a powerful tool to study the quark-gluon plasma

before the collision: orientation of the nuclei



ATLAS, PLB 707 330 (2012)

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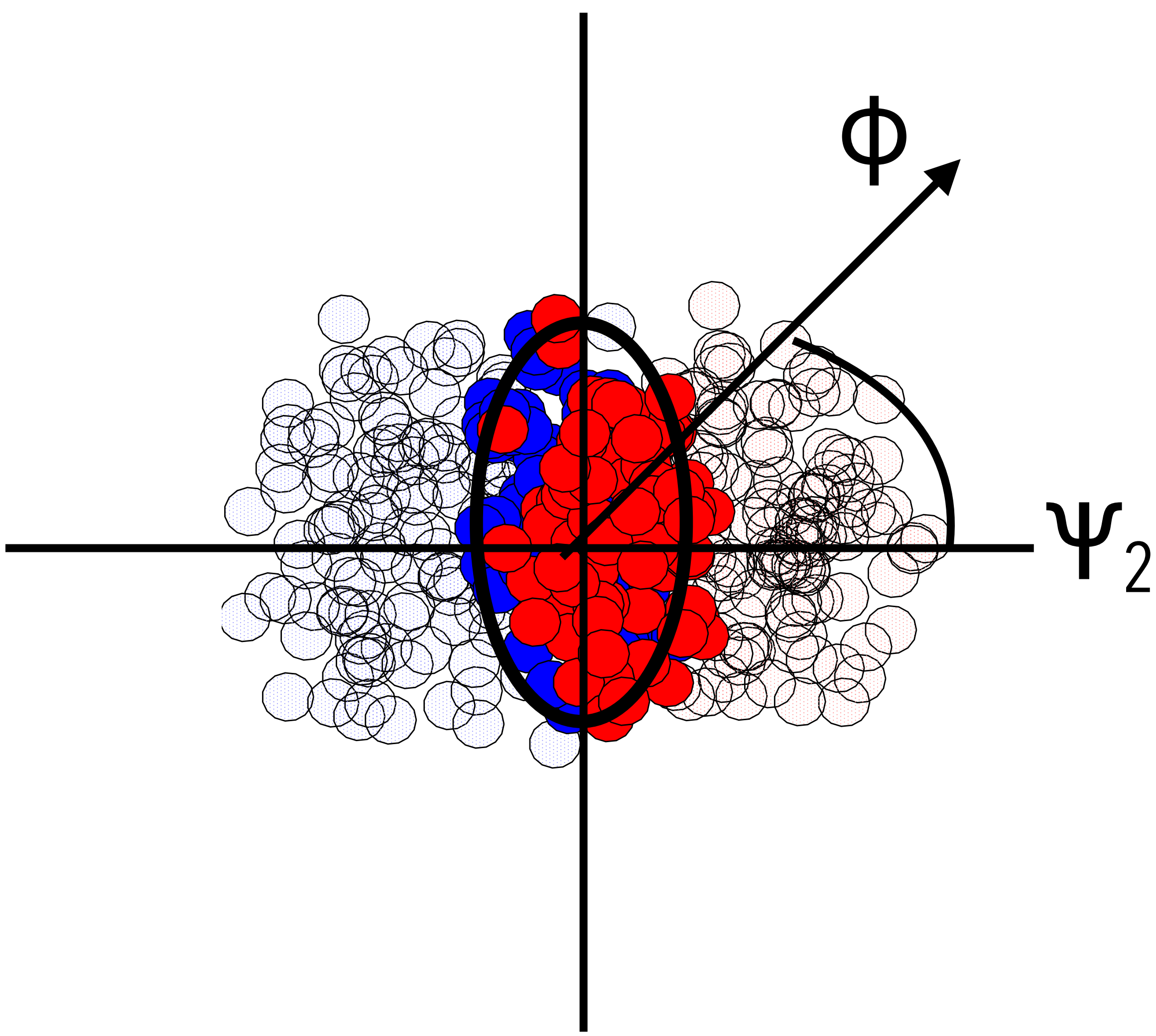
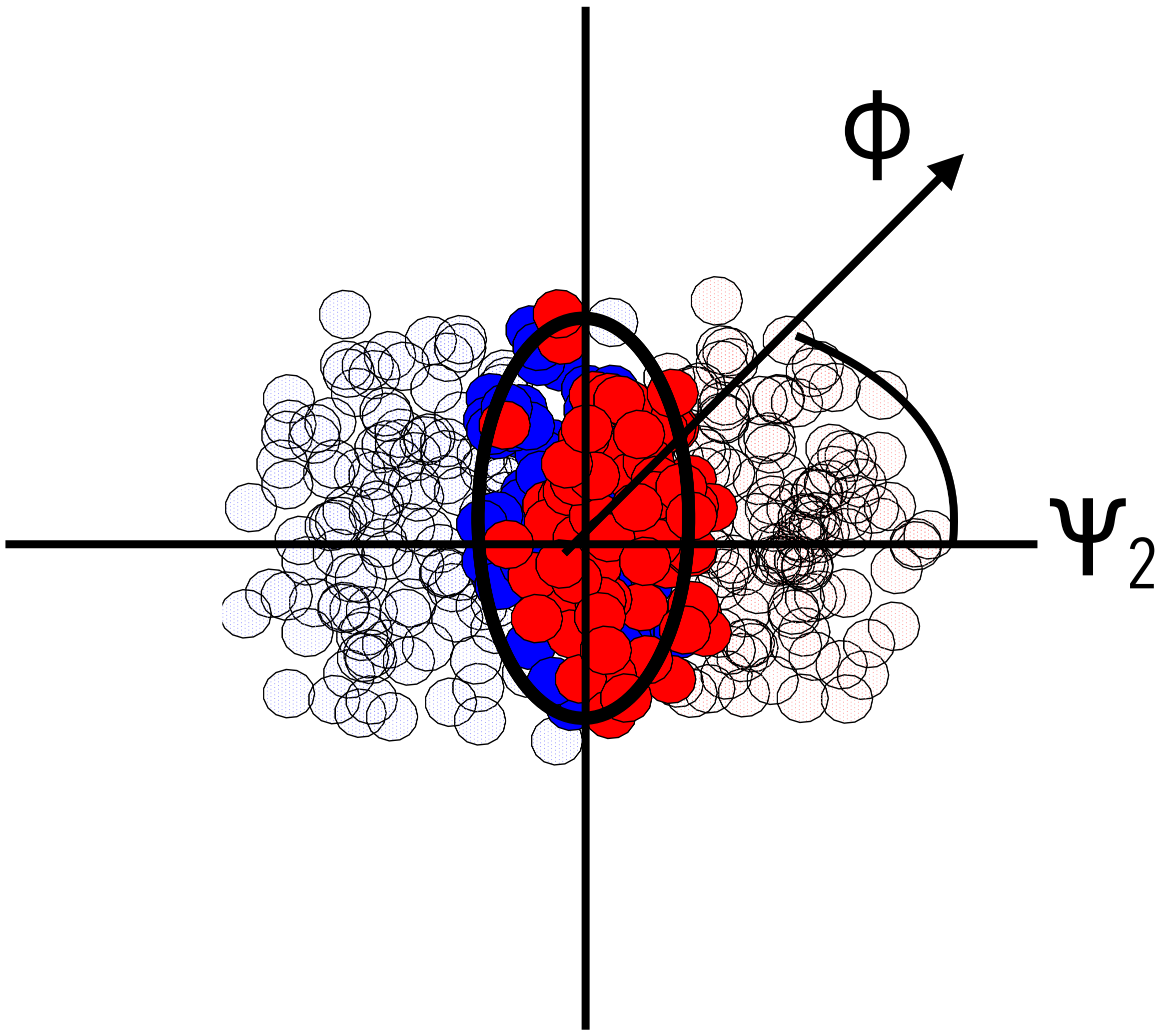
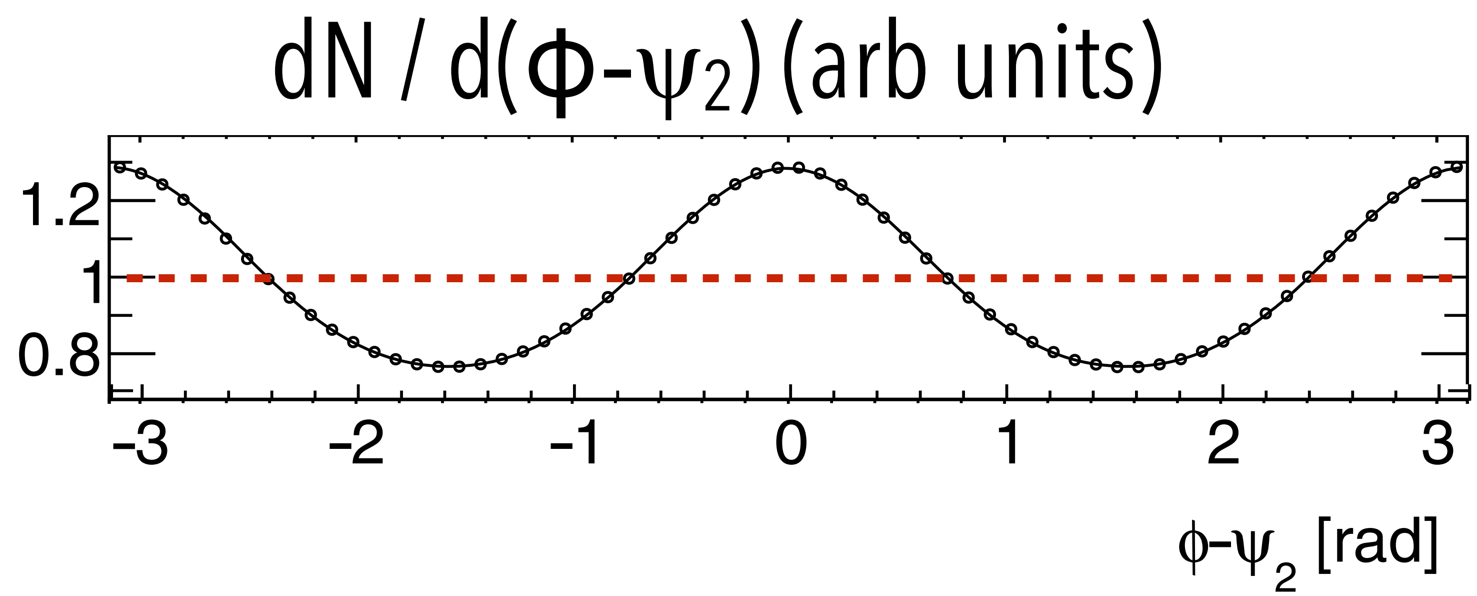


ATLAS, PLB 707 330 (2012)

before the collision: orientation of the nuclei

after the collision: angular distribution of particles

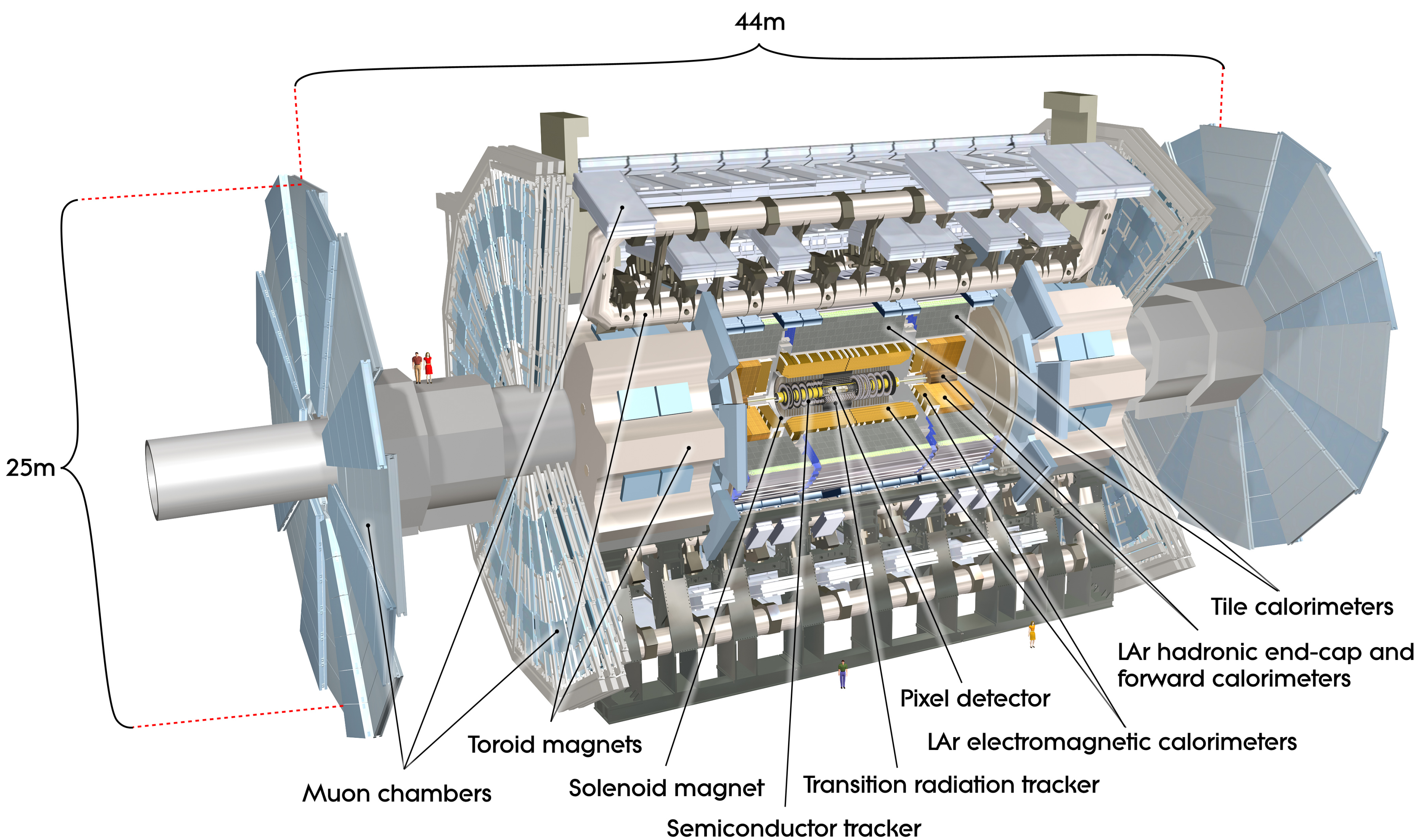




thousands of events with approximately the same impact parameter

ATLAS, PLB 707 330 (2012)

measuring anisotropy



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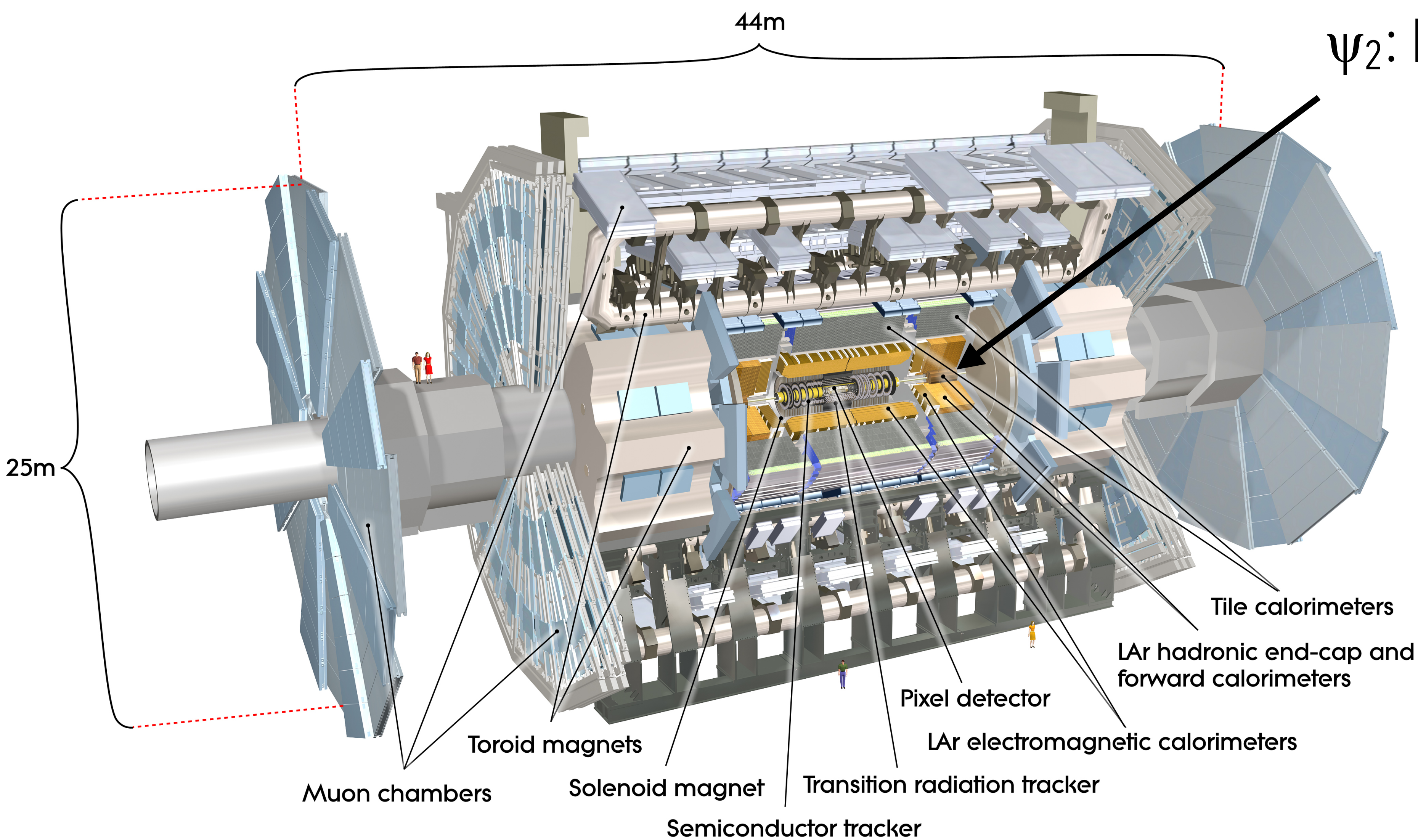
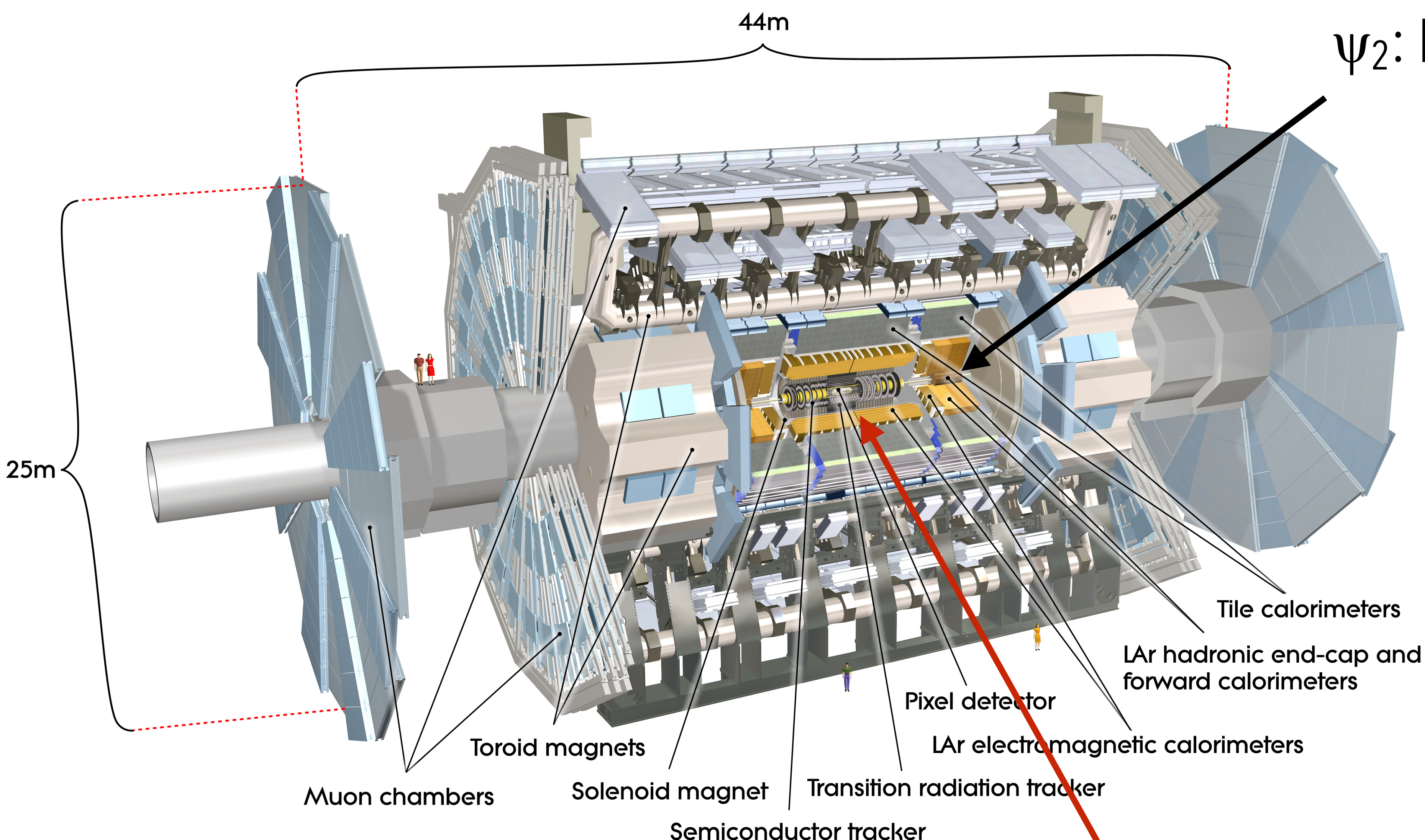


ψ_2: FCal energies, $3.2 < |\eta| < 4.9$

$$\Psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{\sum E_{\mathrm{T},i}^{\mathrm{tower}} w_i \sin(2\phi_i)}{\sum E_{\mathrm{T},i}^{\mathrm{tower}} w_i \cos(2\phi_i)}\right)$$

measuring anisotropy



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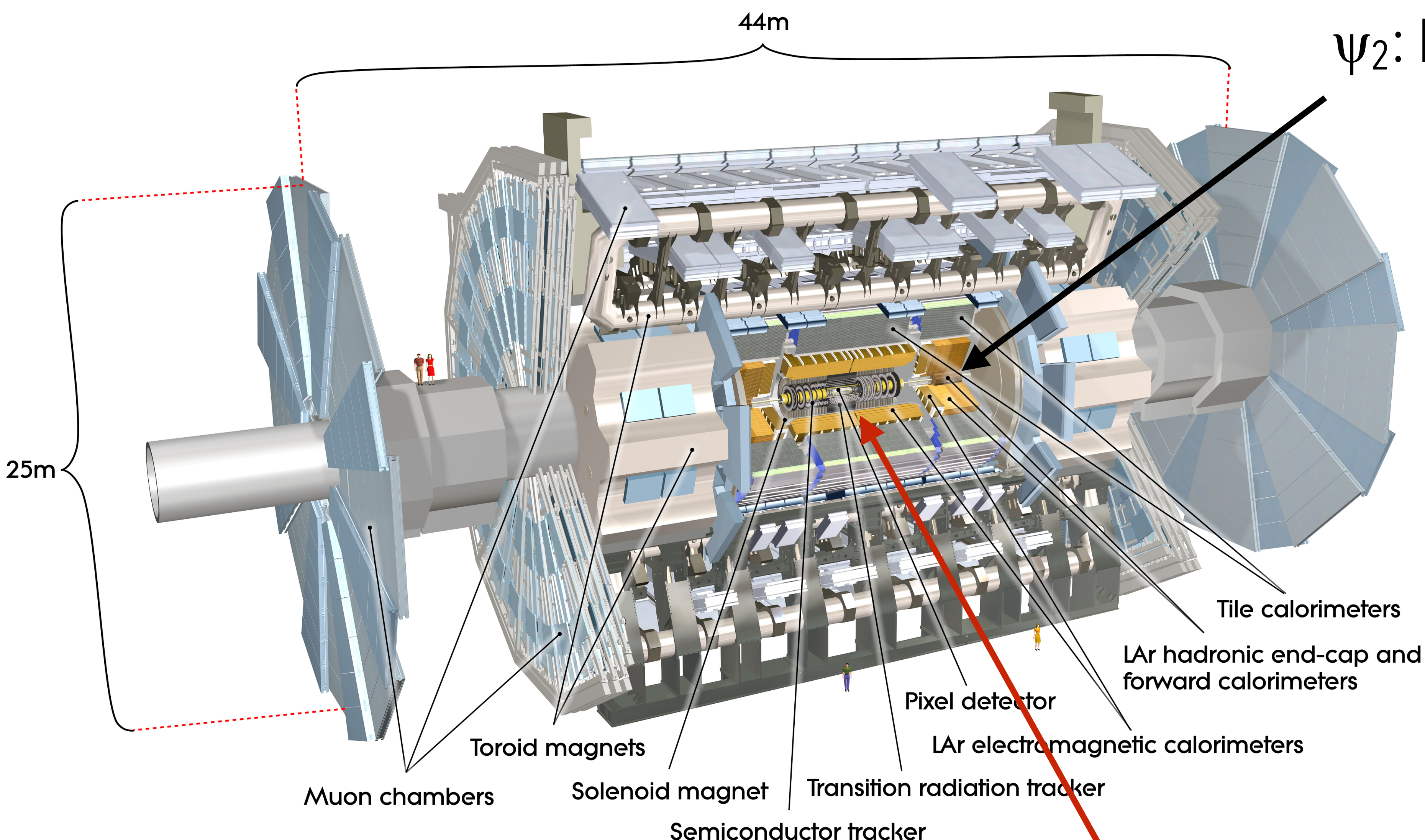

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particles: charged particles with $|\eta| < 2.5$

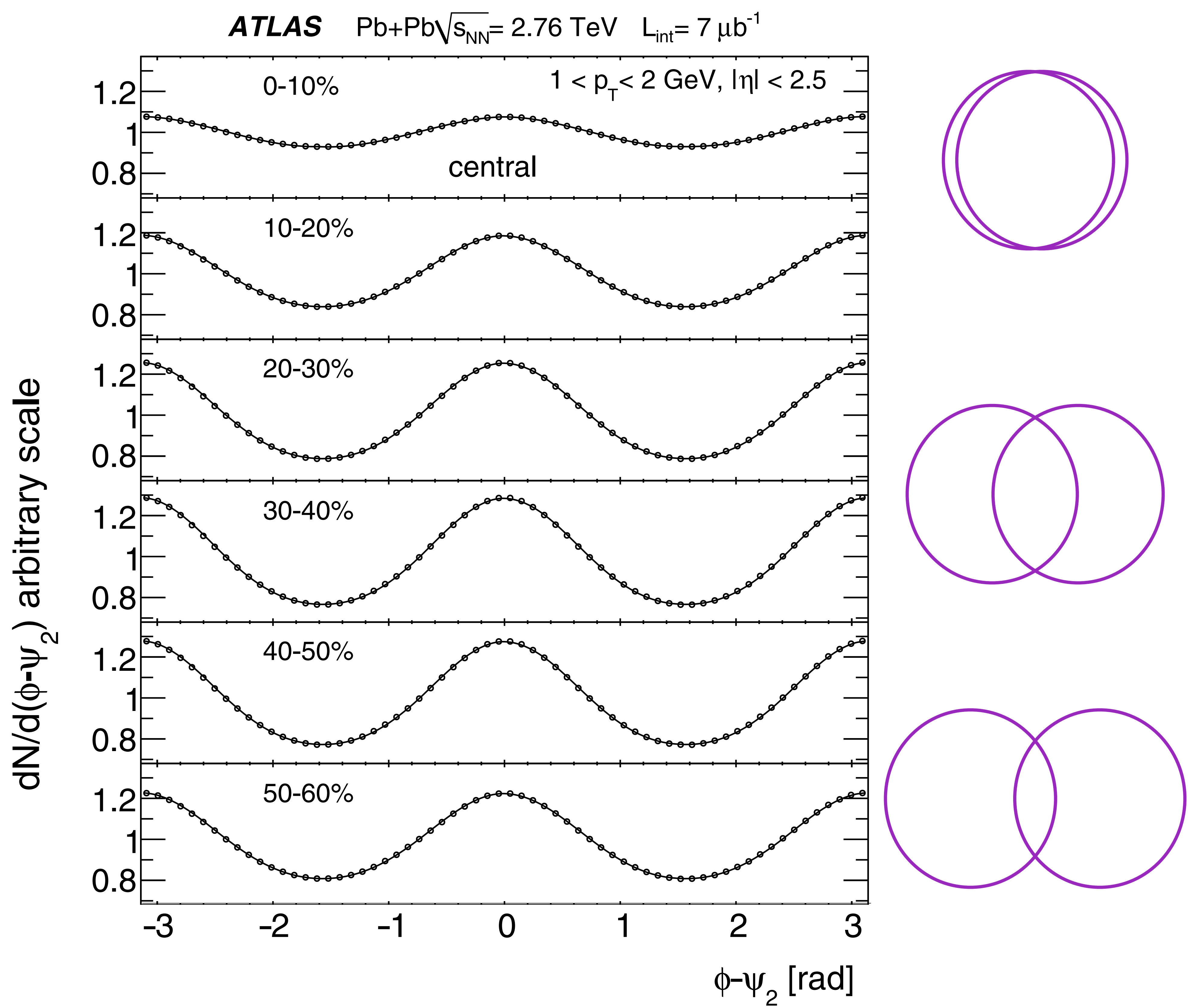
key is that these are *long range* correlations,

not associated with jets or particle decays

collision geometry

PLB 707 330 (2012)

increasing modulation

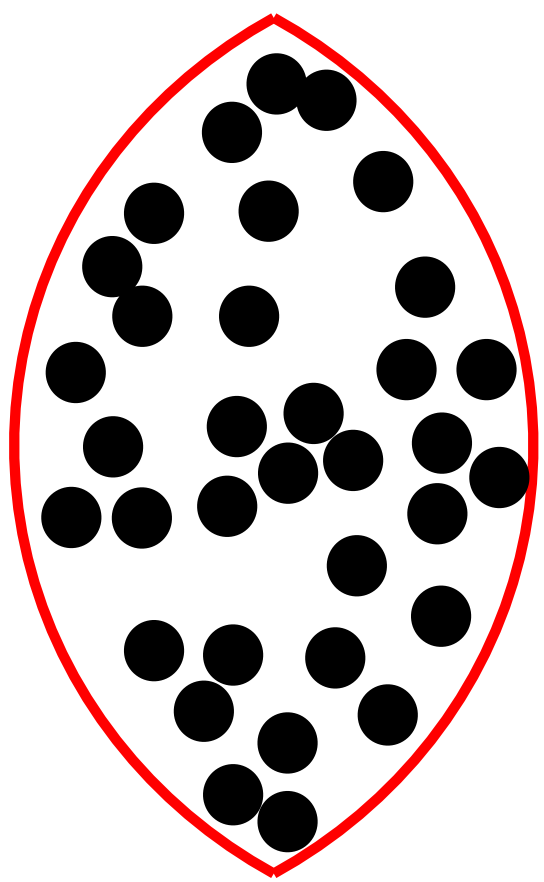


increasing eccentricity

role of interactions

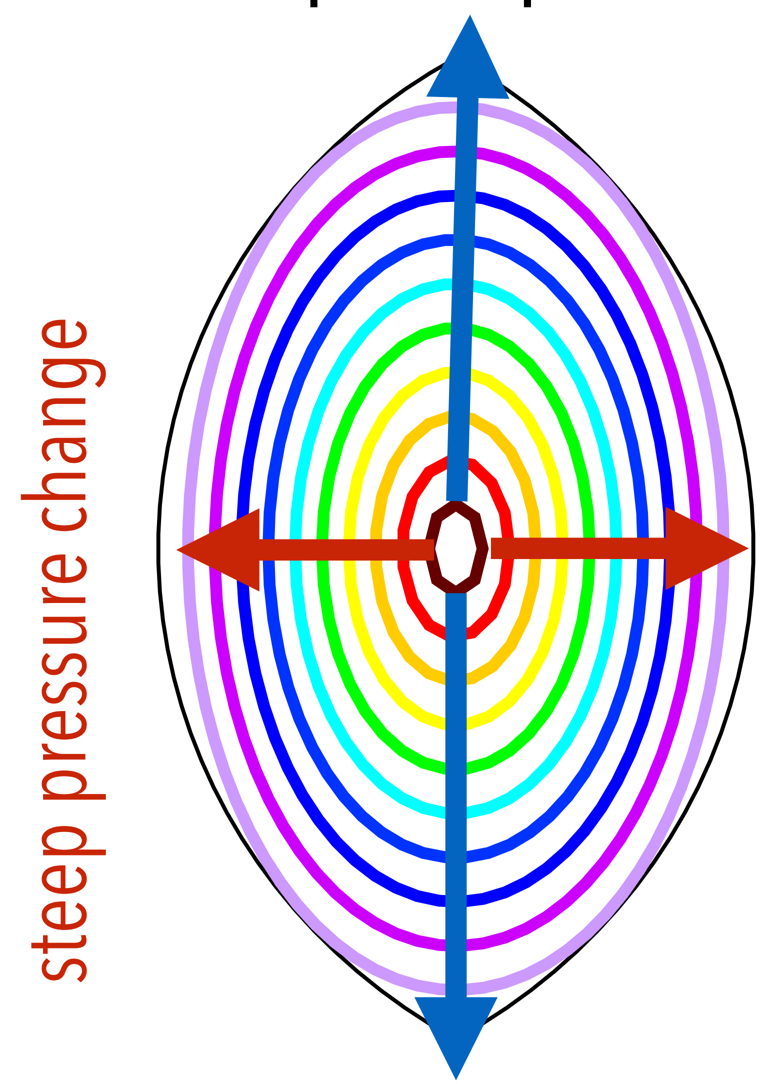
gas: minimal interactions

isotropic expansion



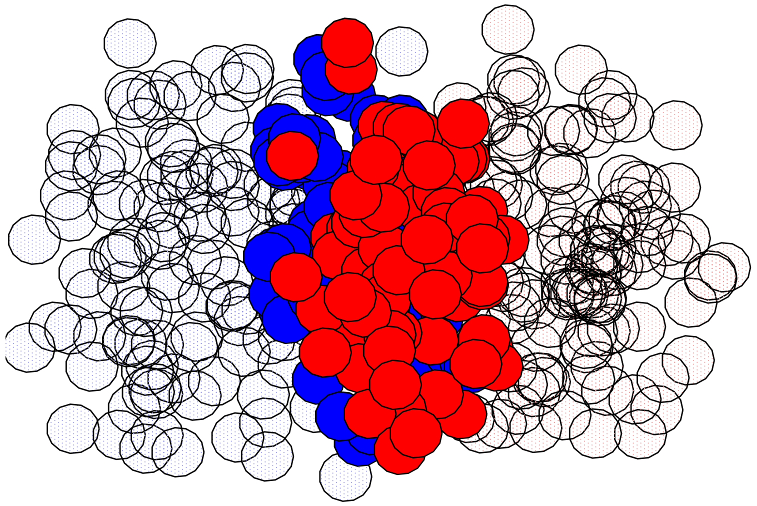
fluid: lots of interactions

anisotropic expansion

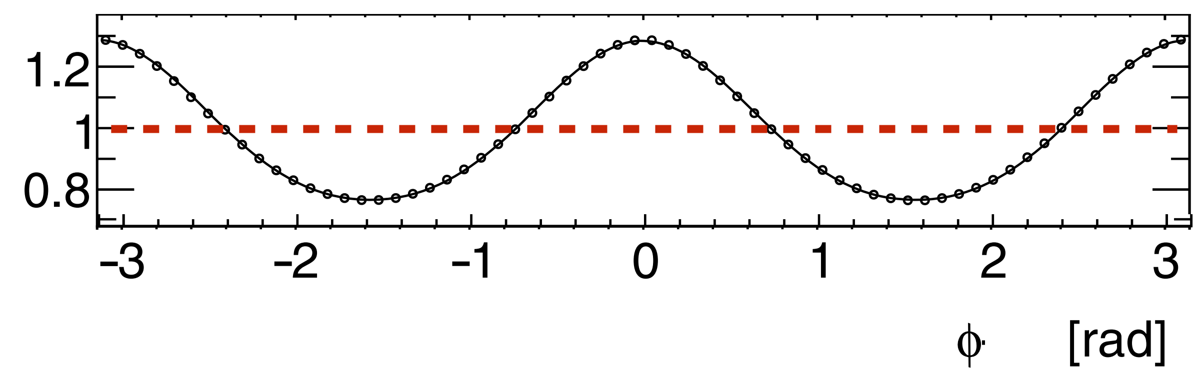


hydrodynamic modeling

eccentricity in initial state → anisotropy in final state



→



Gale, et al PRL 110 012302

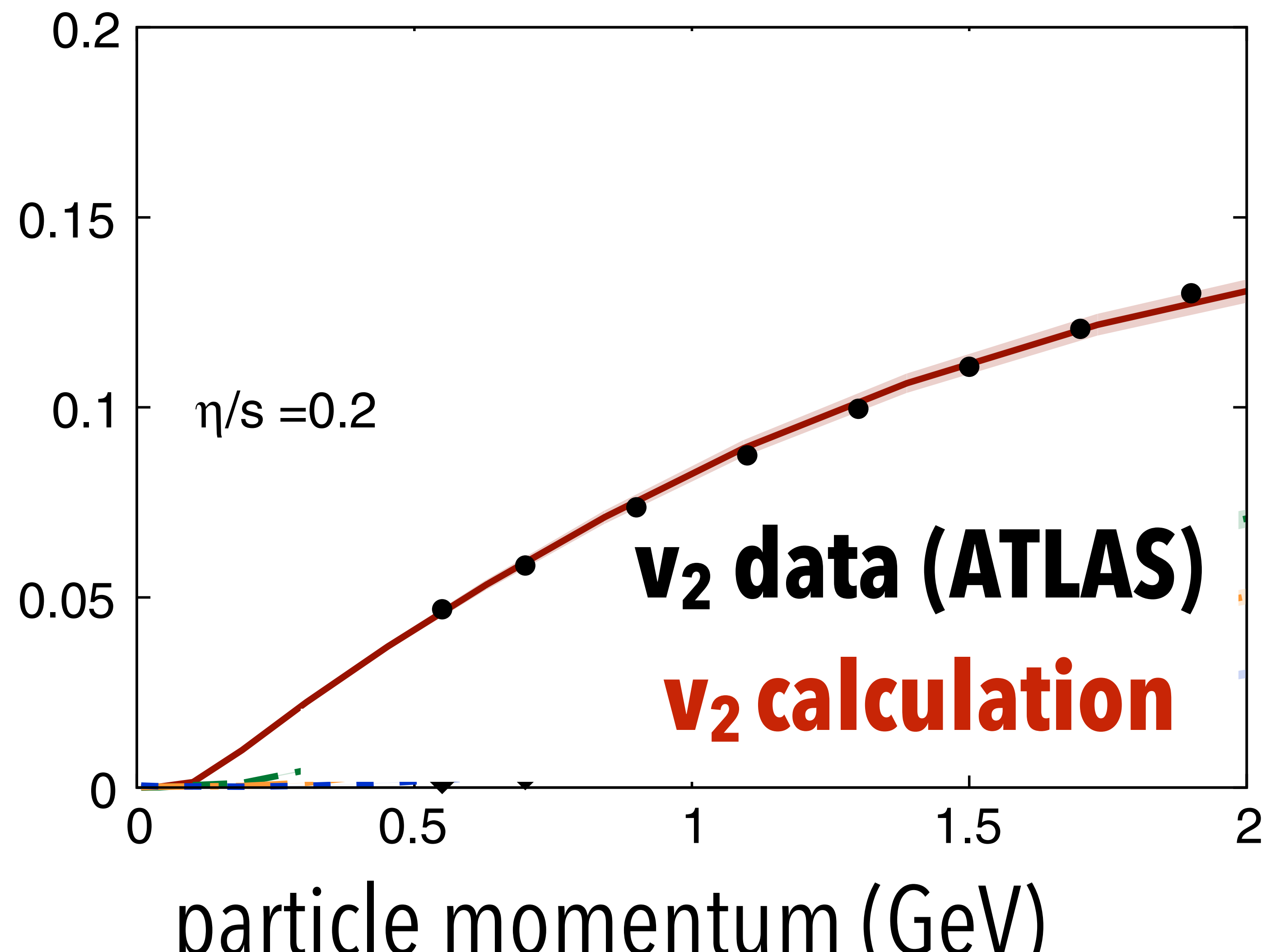
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_2)]$$

v_2 → amplitude of modulation

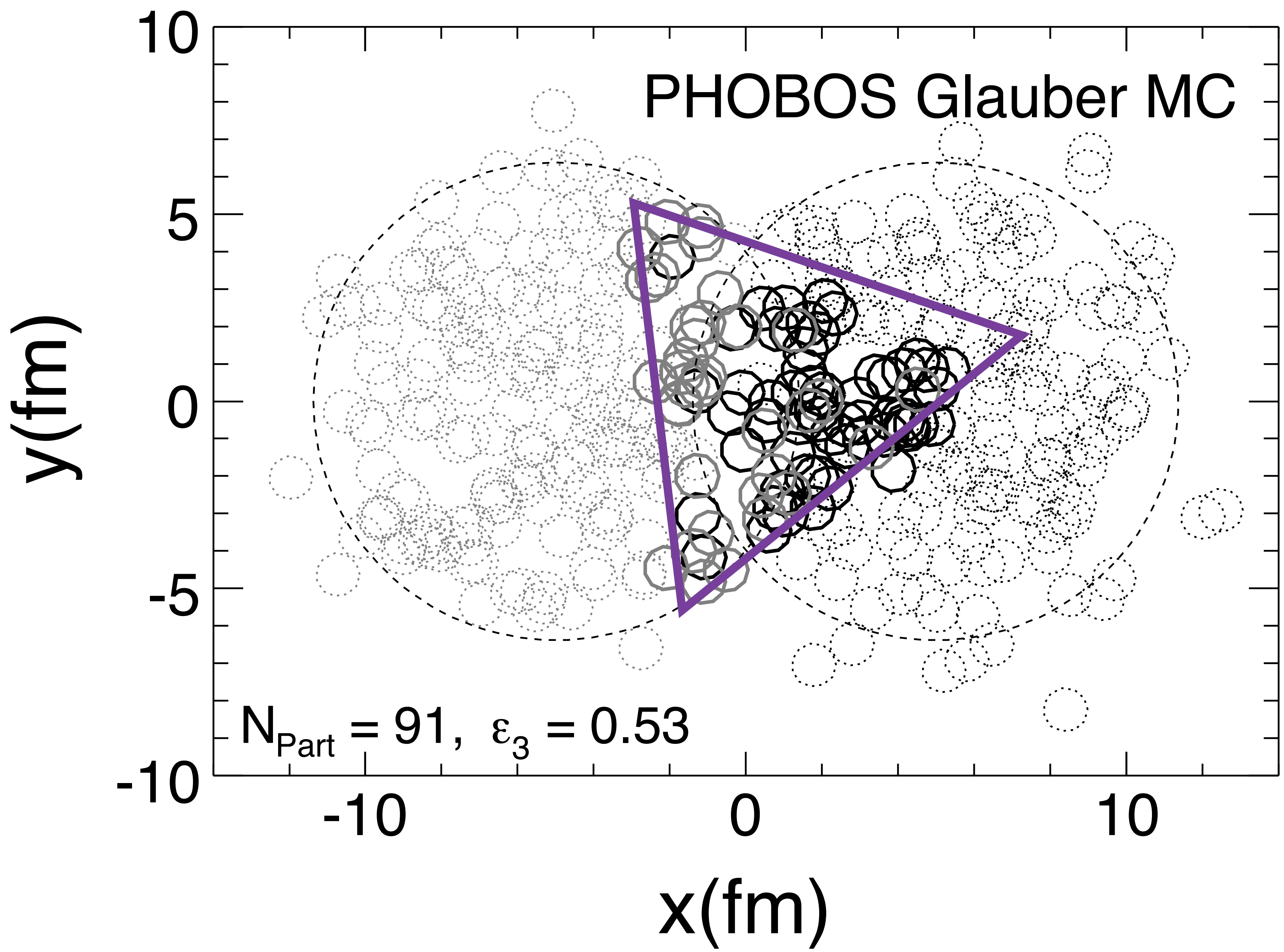
increasing viscosity reduces the observed v_2 values

η/s: shear viscosity/entropy density

ζ/s: bulk viscosity/entropy density



Alver & Roland, Phys.Rev. C81 (2010) 054905

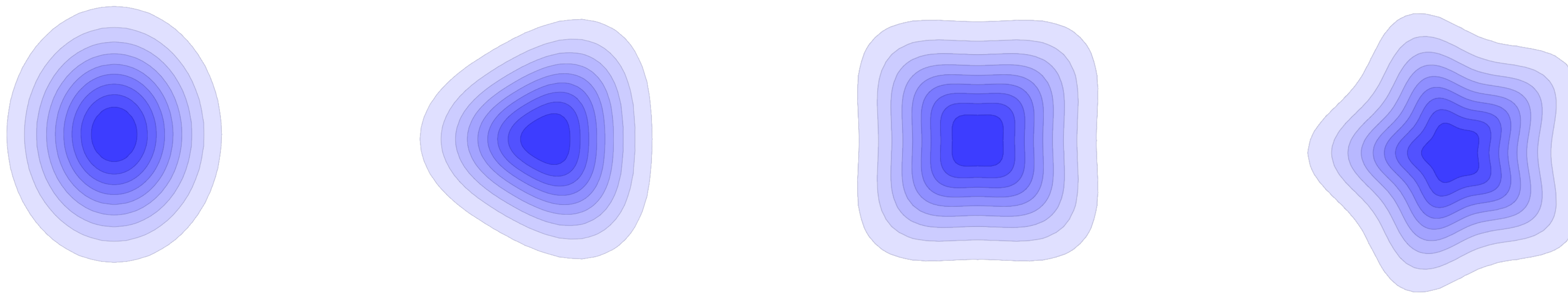


fluctuations in the nucleon position can create any shape of the initial nucleon positions

→ not just ellipticity, ε_2, but ε_3, ε_4, ...

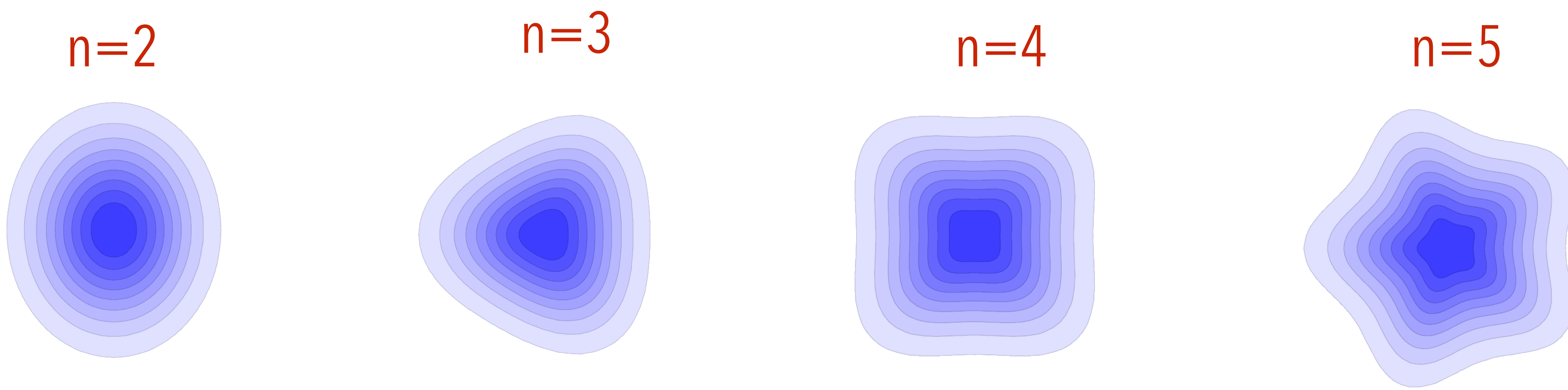
decomposing geometry

n=2 n=3 n=4 n=5



characterize the shape of a collision in terms of these eccentricities ε_n and the orientations ψ_n

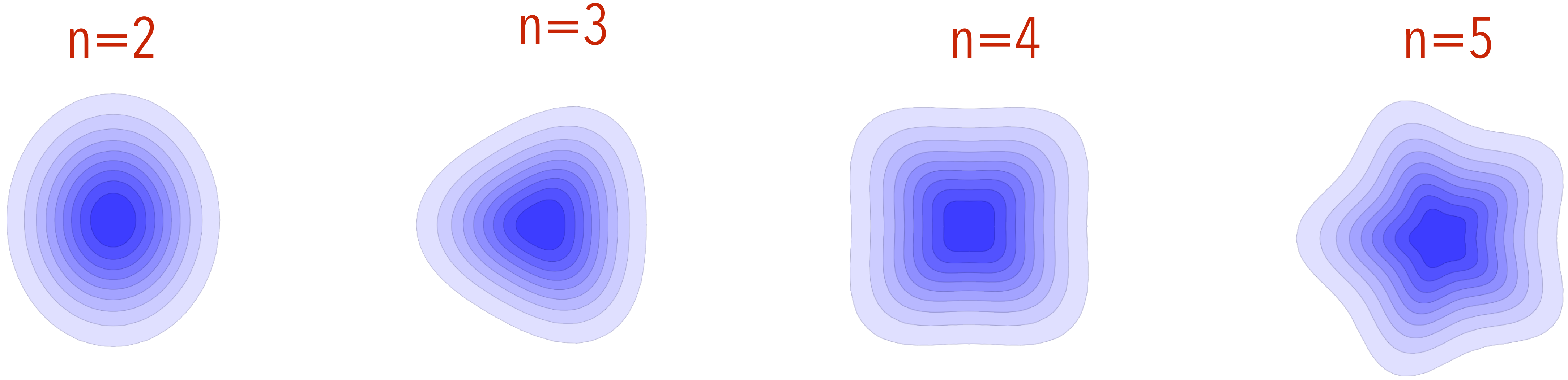
decomposing geometry



characterize the shape of a collision in terms of these eccentricities ε_n and the orientations ψ_n

particle distribution can be written as: $$\frac{dN}{d\phi} \propto 1 + 2v_N \cos[N(\phi - \Psi_N)]$$

decomposing geometry



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$\varepsilon_2 \rightarrow v_2$

$\varepsilon_3 \rightarrow v_3$

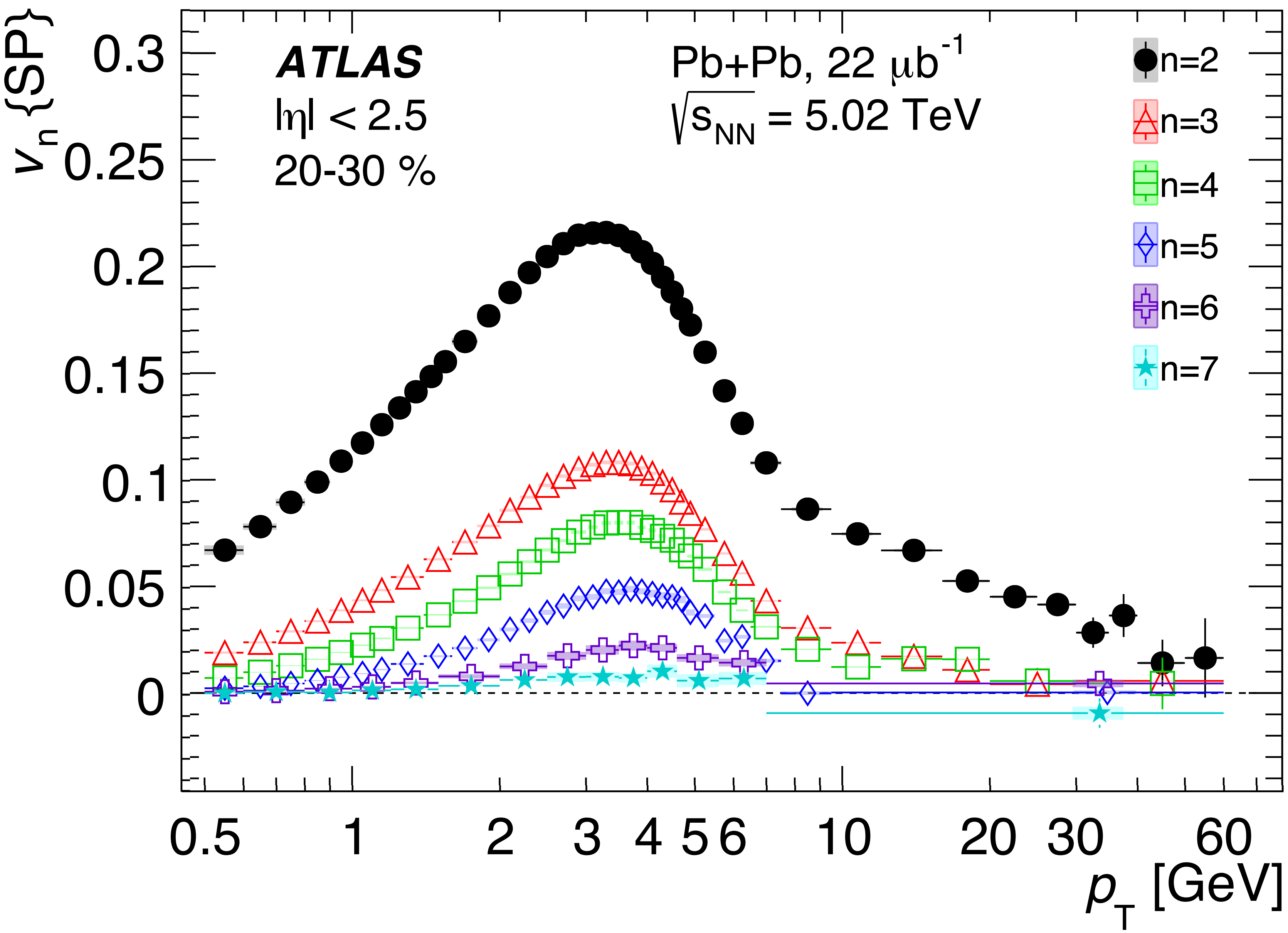
…

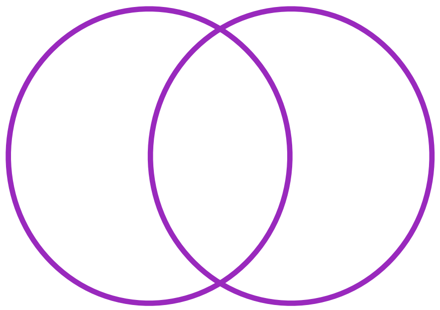
$\varepsilon_n > 2$: generated by fluctuations

larger n: v_n increasingly damped by viscosity

beautiful measurements of flow

$$\frac{dN}{d\phi} \propto 1 + 2v_N \cos[N(\phi - \Psi_N)]$$





dominance of overall elliptical shape → $v_2 > v_{n>2}$

fluctuations generate v_3 and higher

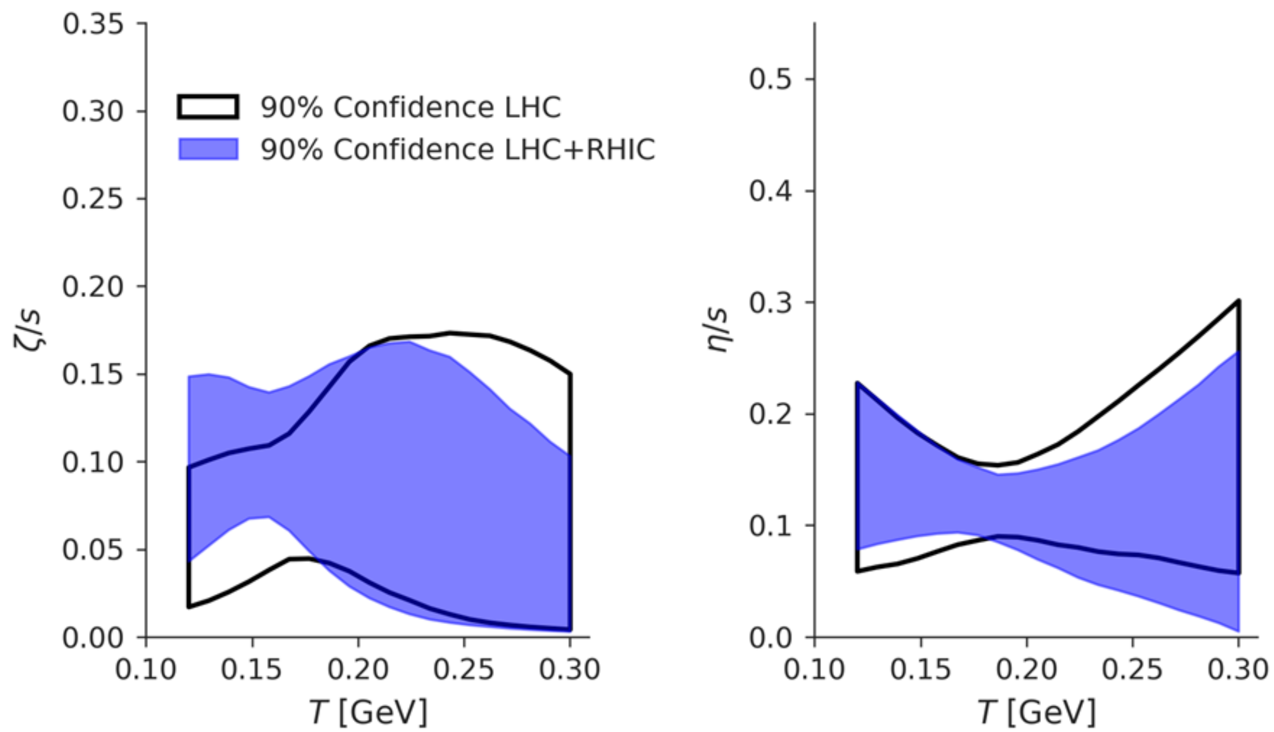
EPJC 78 (2018) 997

data constrained extractions of QGP parameters

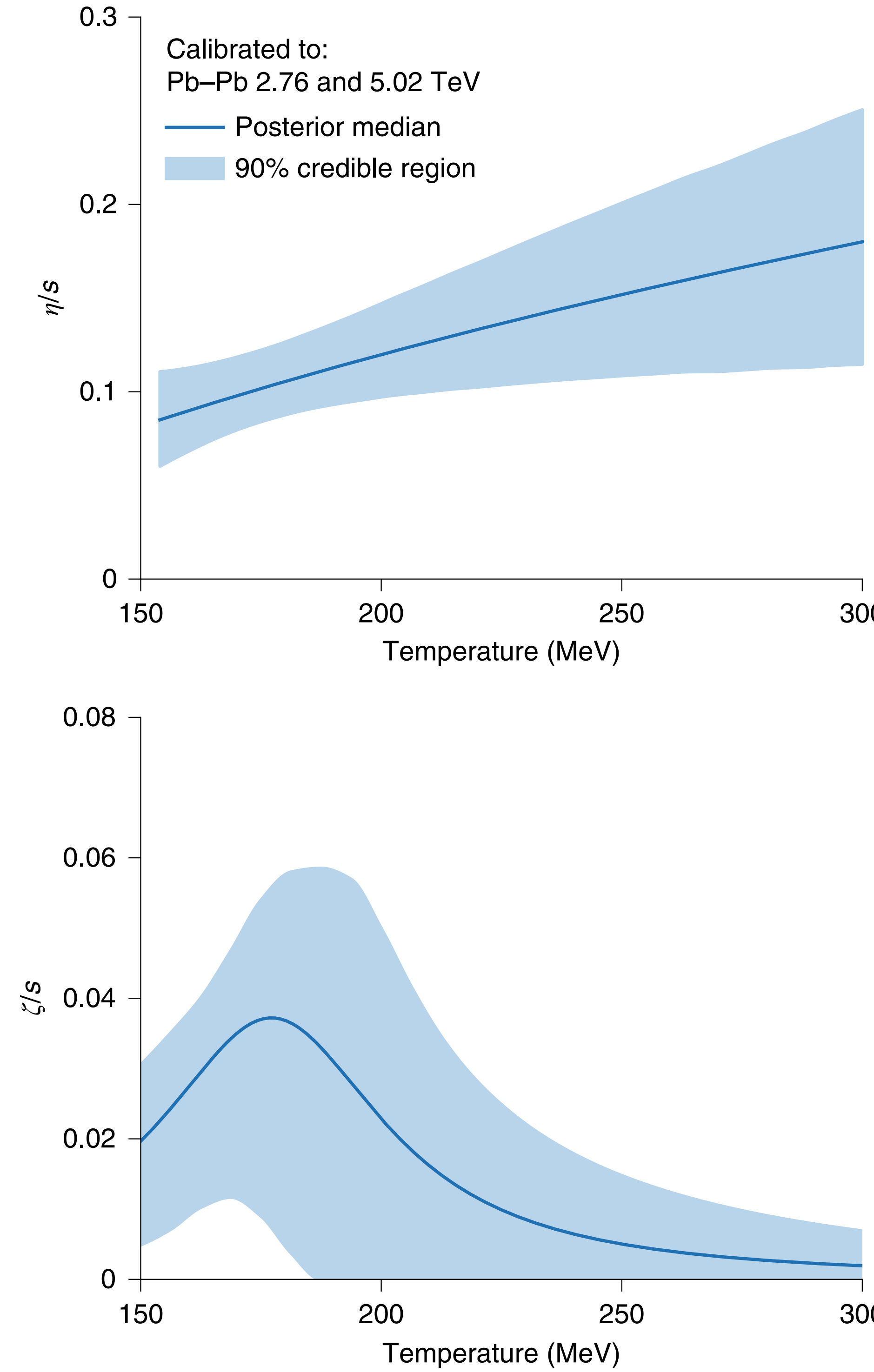
using LHC v_n data to constrain shear & bulk viscosity

Bulk viscosity

Shear viscosity



Paquet/Jetscape Quark Matter 2019

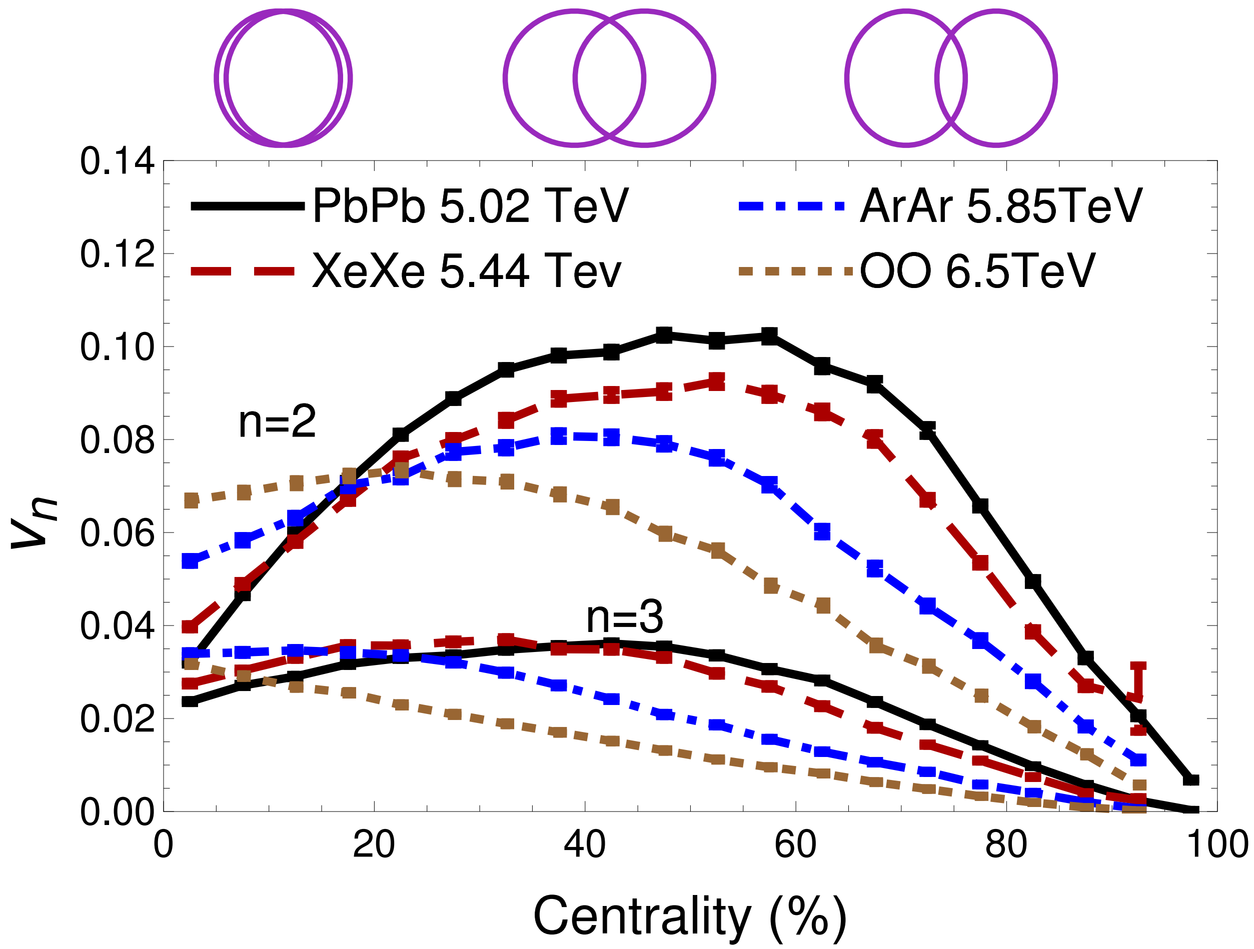


these (and other) analyses are a big step forward! but have assumptions about the form of the initial state, conversion to hadrons, …

Bernhard et al Nature Phys. 15 1113 (2019)

v_n from geometry & fluctuations

Sievert & Noronha-Hostler, PRC 100 024904 (2019)



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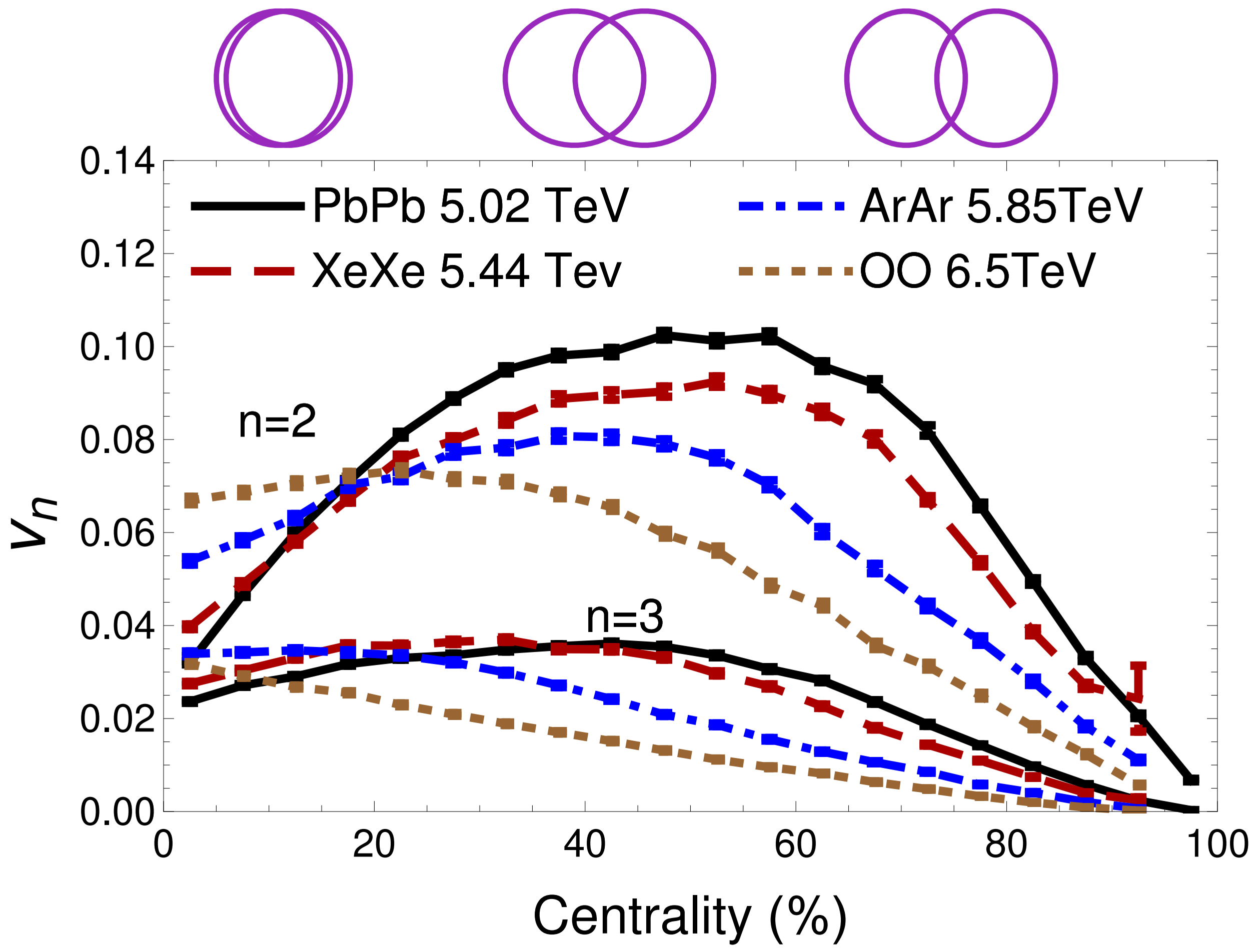

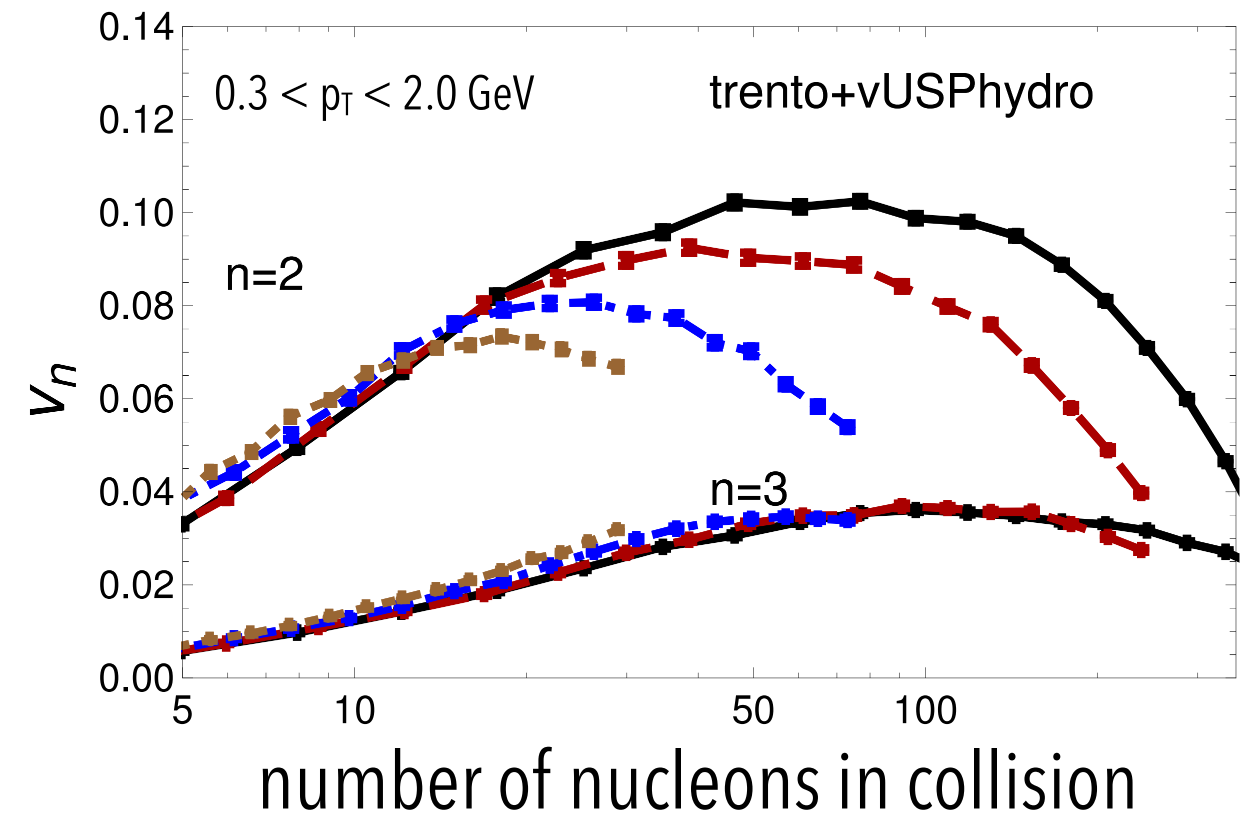

v_2: impact parameter driven, except for very small systems

v_3: always driven by fluctuations so it depends on the size of the system

two-particle correlations

$$\frac{dN}{d\phi} \propto 1 + 2v_N \cos[N(\phi - \Psi_N)]$$ correlations of particles wrt ψ_N

$$\downarrow$$

$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B} \cos(n\Delta\phi)$$ two-particle correlations

1911.04812

two-particle correlations

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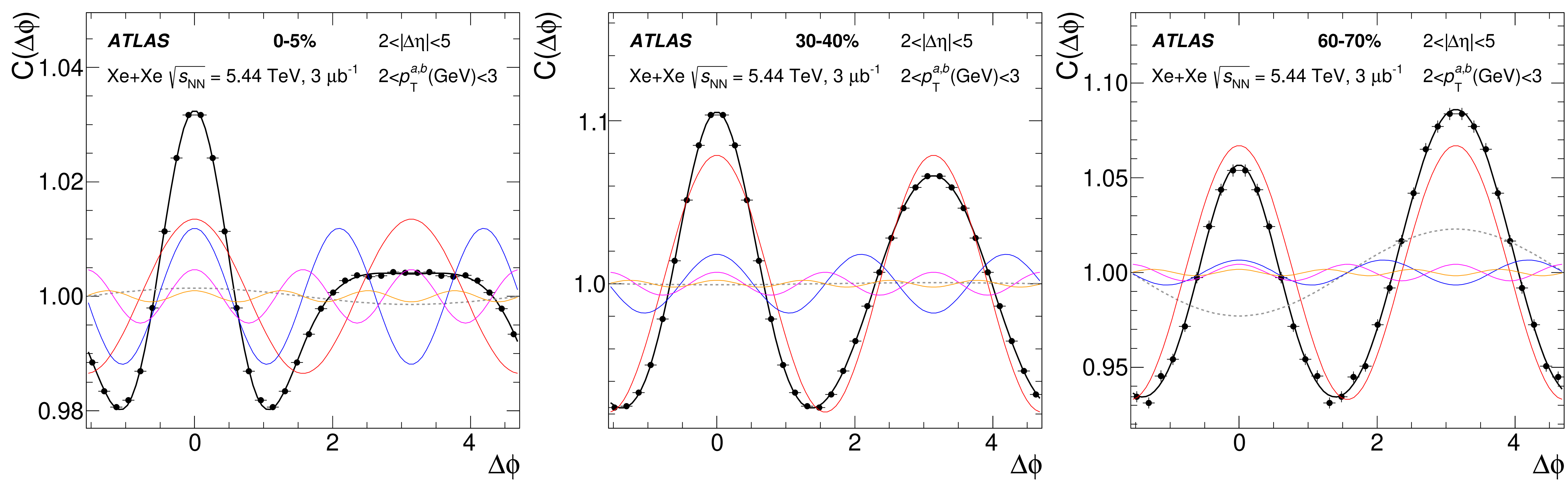


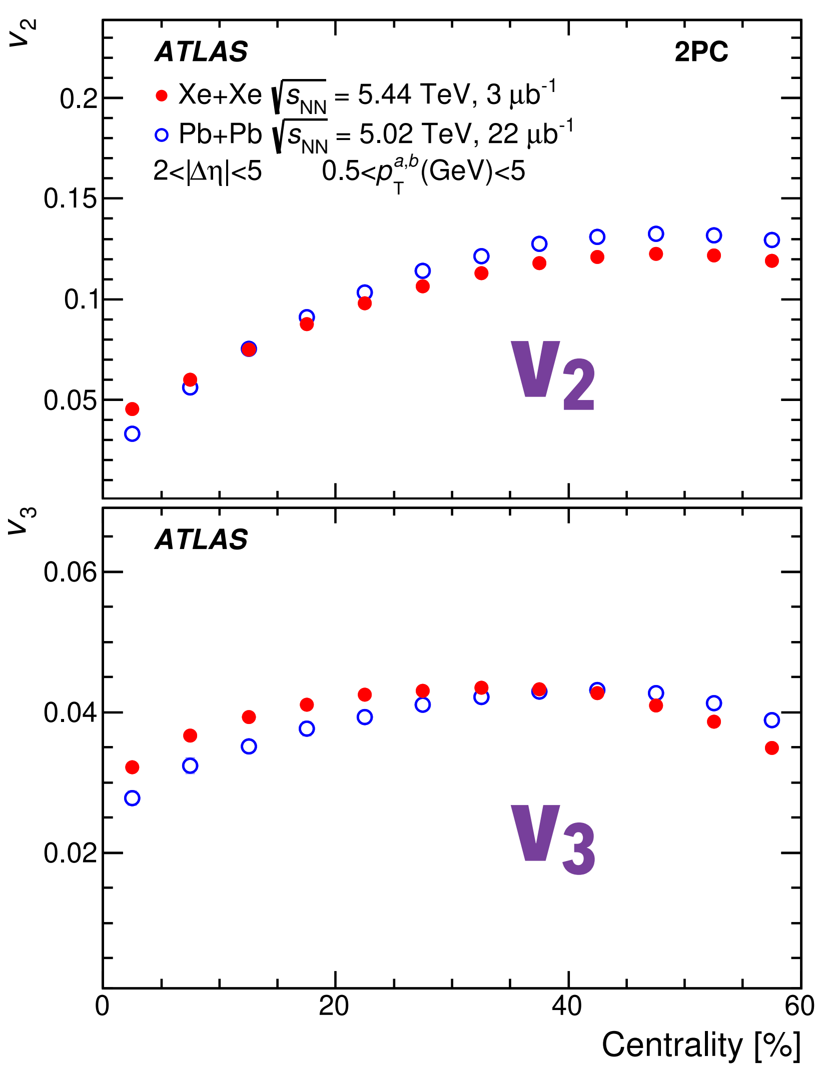
n = 2 n = 3 n = 4 n = 5

1911.04812

XeXe collisions

Xe: A = 129

Pb: A = 208



1911.04812

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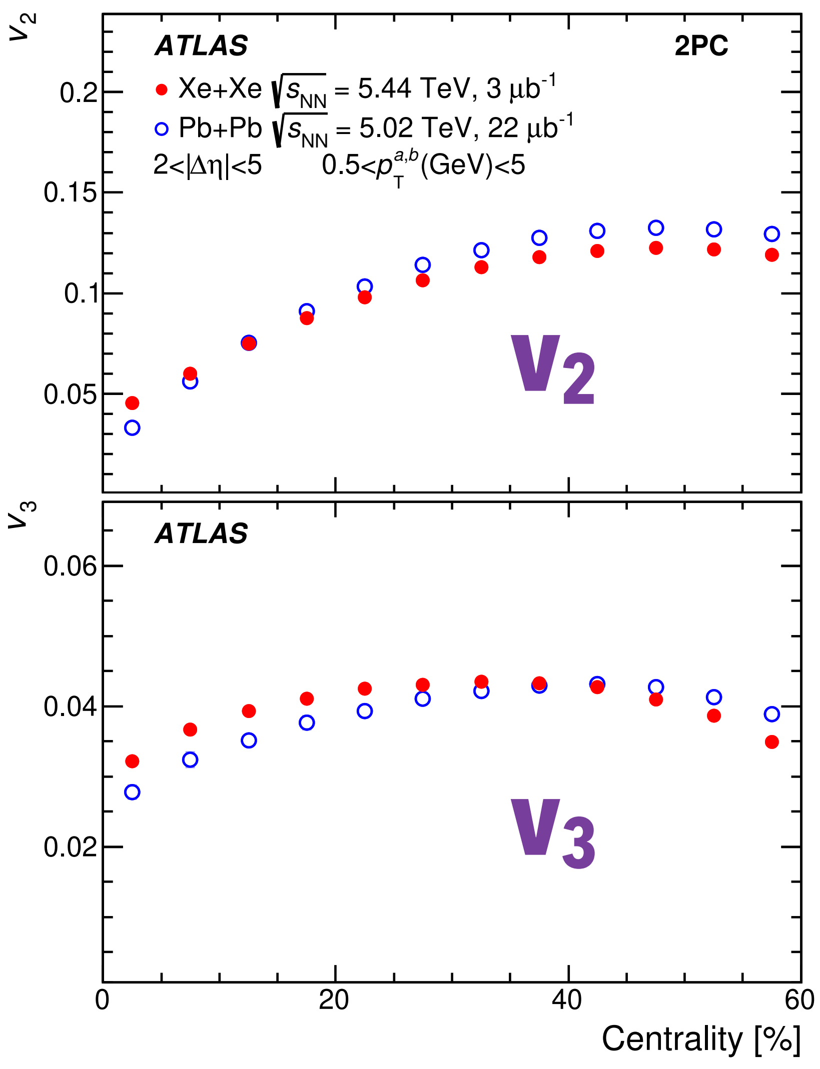
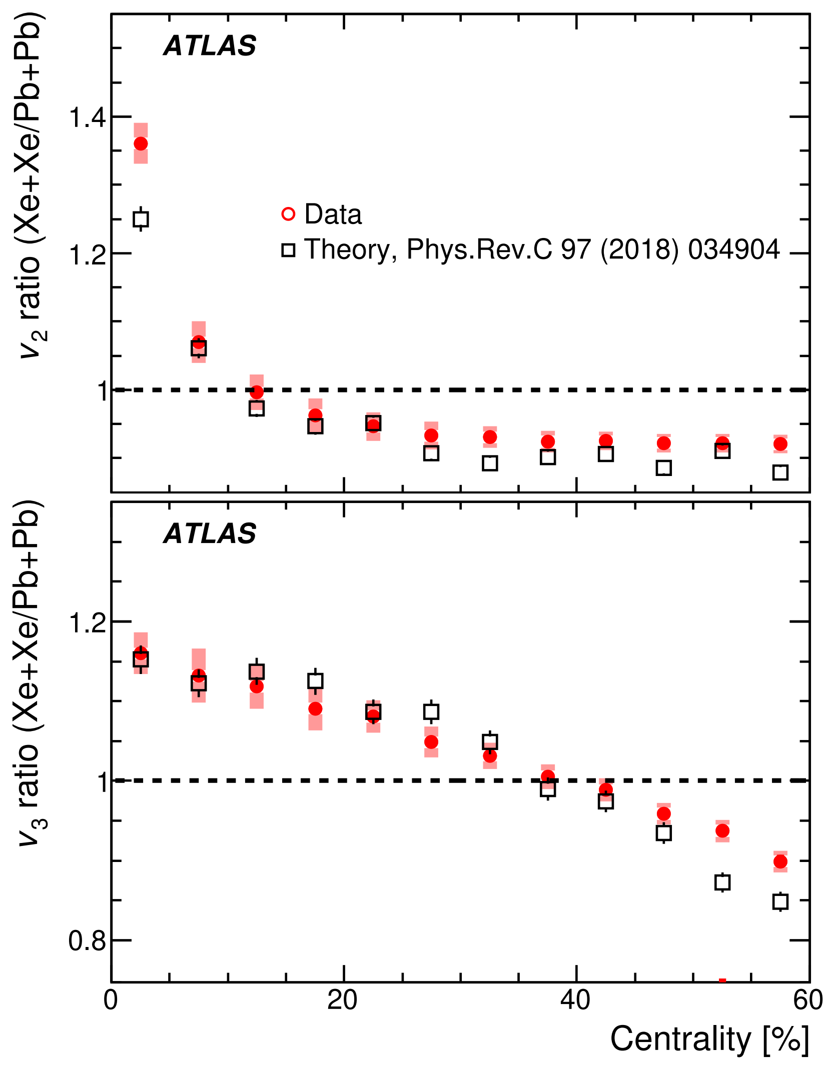


XeXe / PbPb



1911.04812

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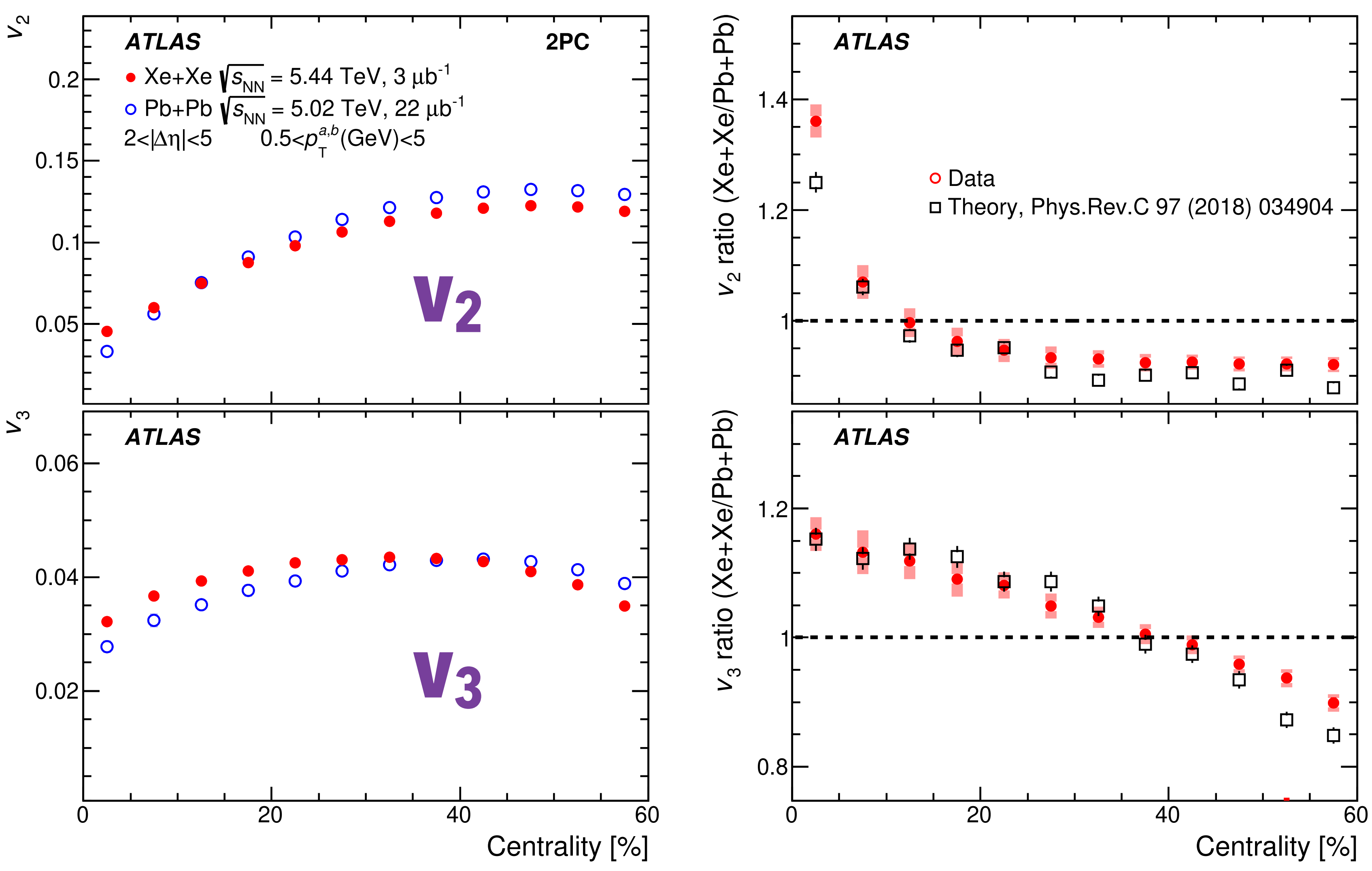

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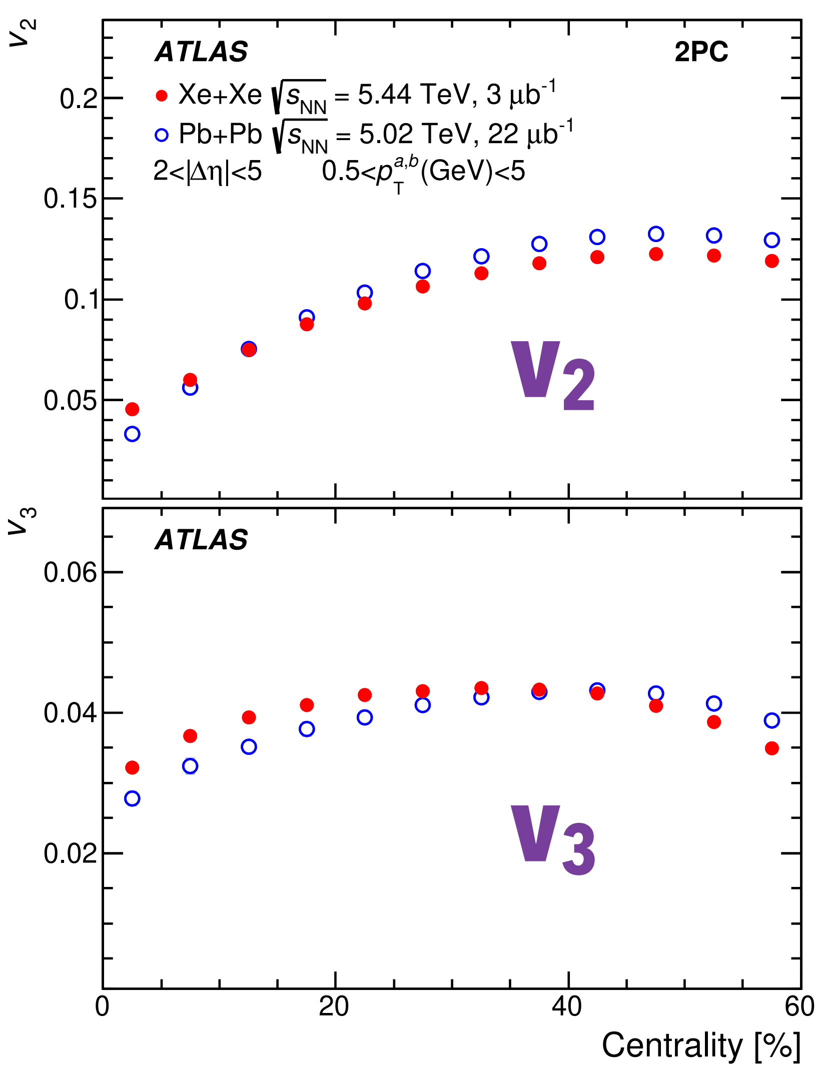

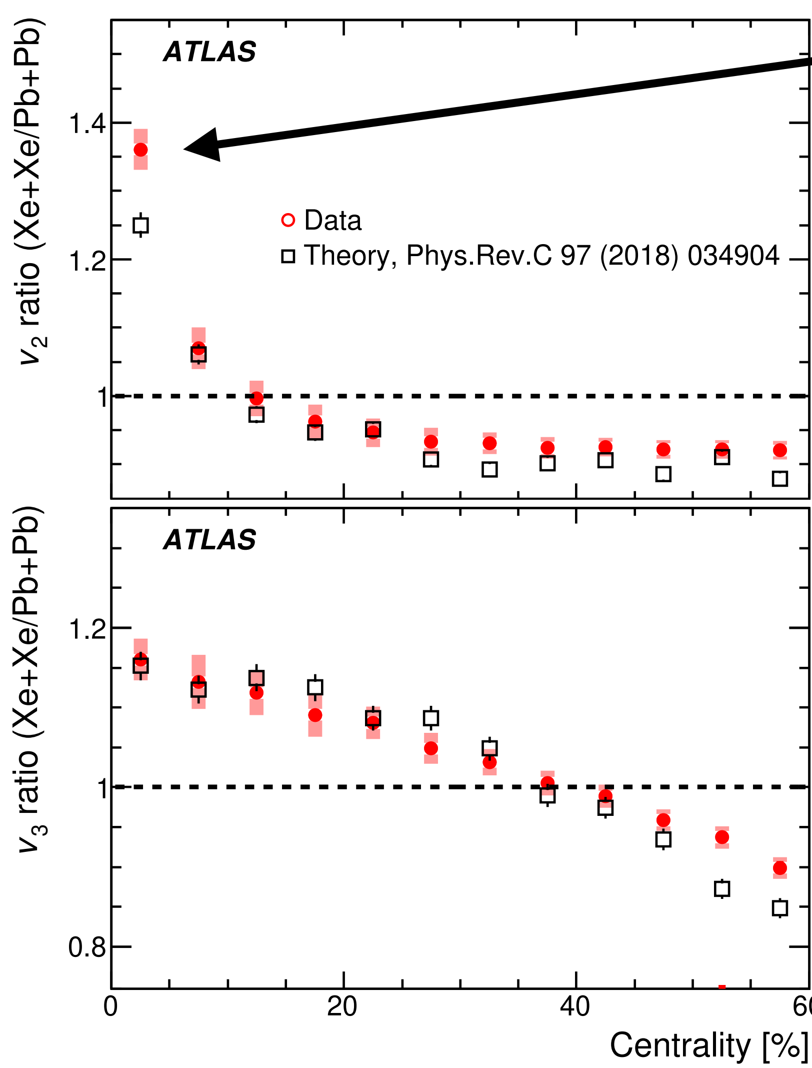

extra v_2 in central collisions

→ more fluctuations

1911.04812

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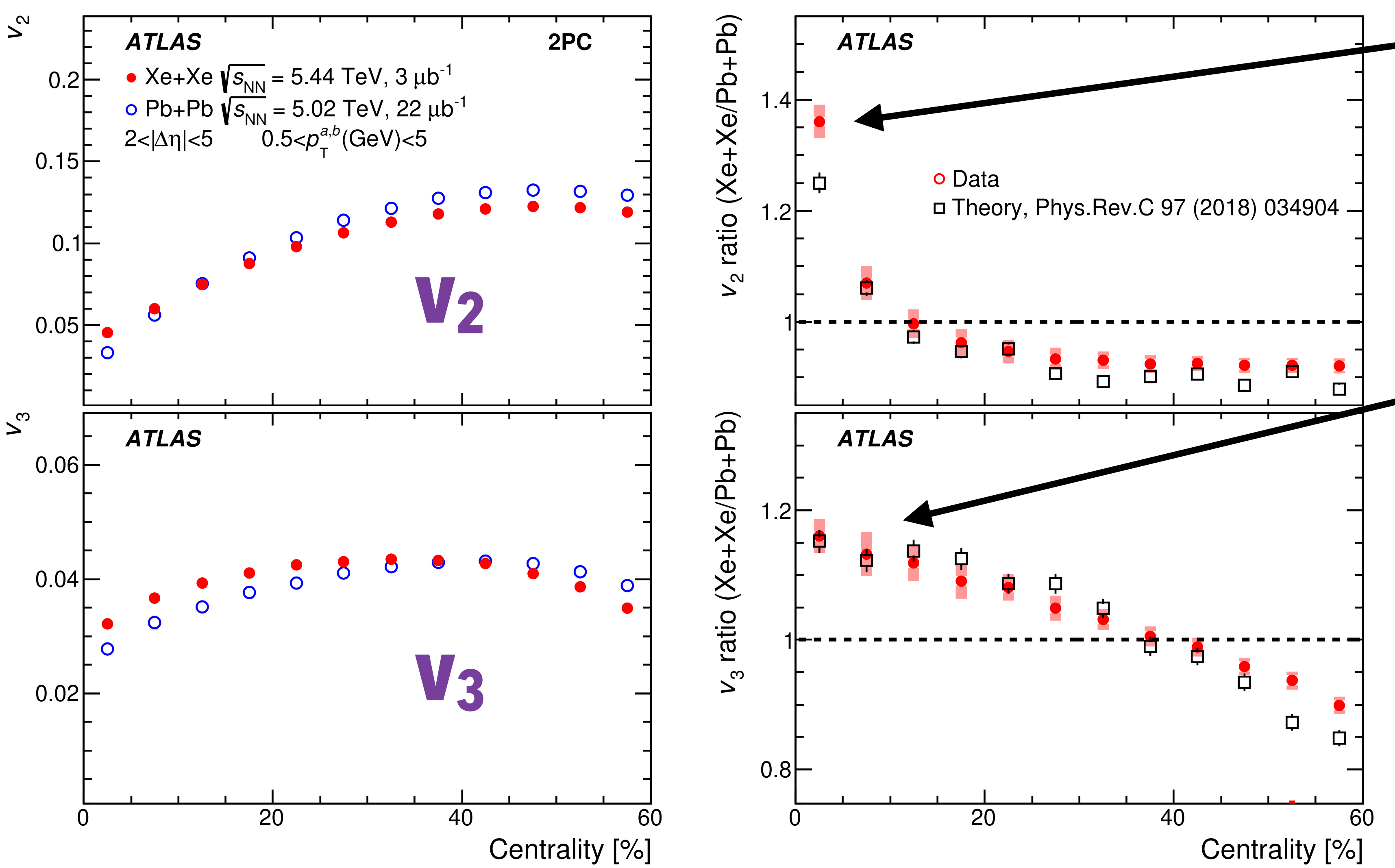
XeXe has:

XeXe / PbPb



extra v_2 in central collisions
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extra v_3 →more fluctuations

1911.04812

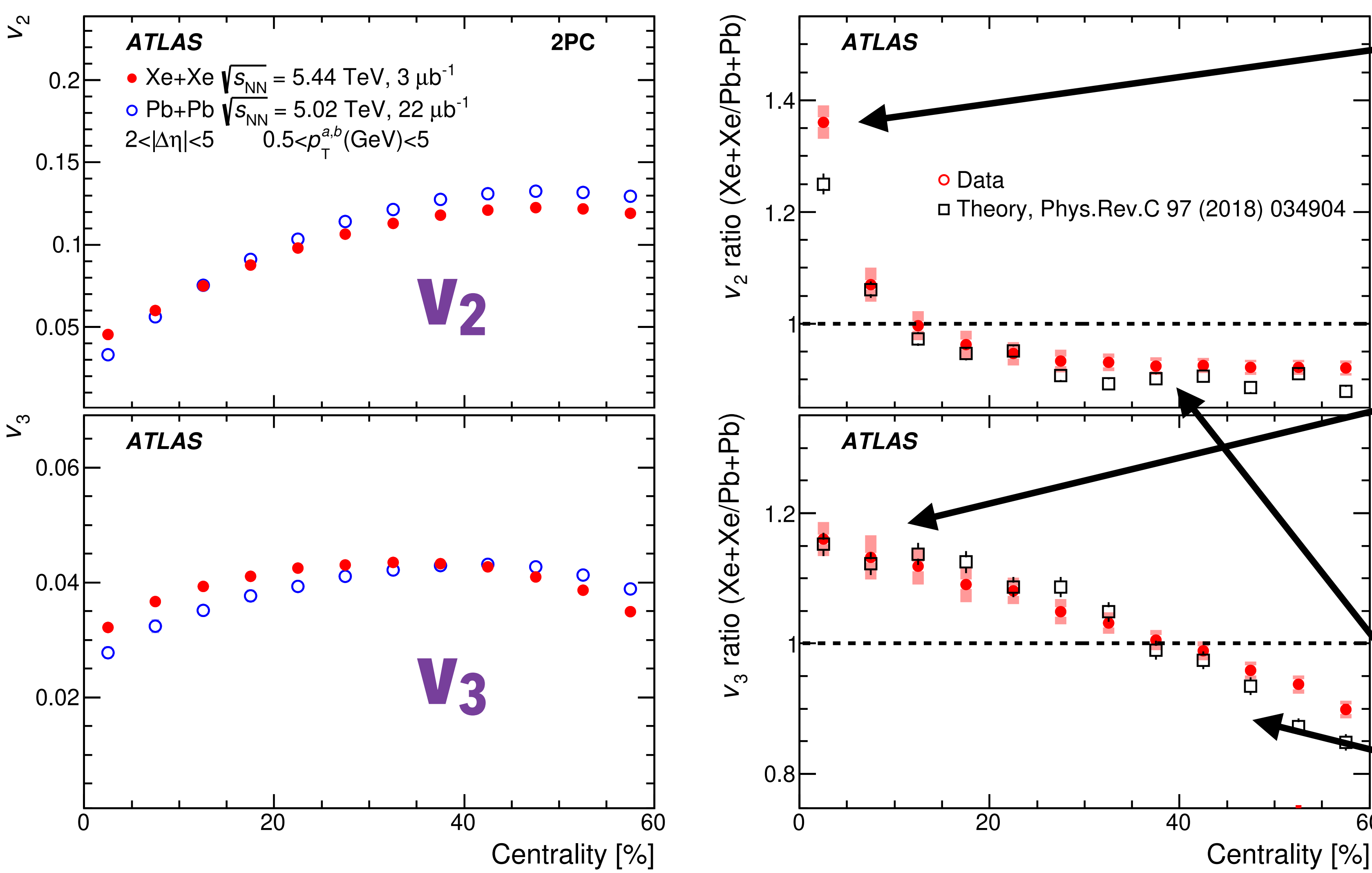
XeXe collisions

Xe: A = 129

Pb: A = 208

XeXe / PbPb

XeXe has:



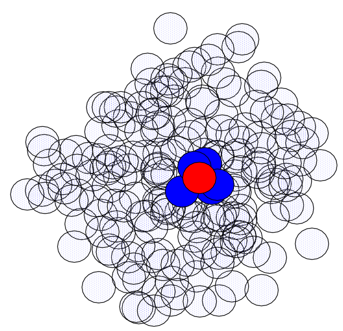
extra v_2 in central collisions $\rightarrow$ more fluctuations

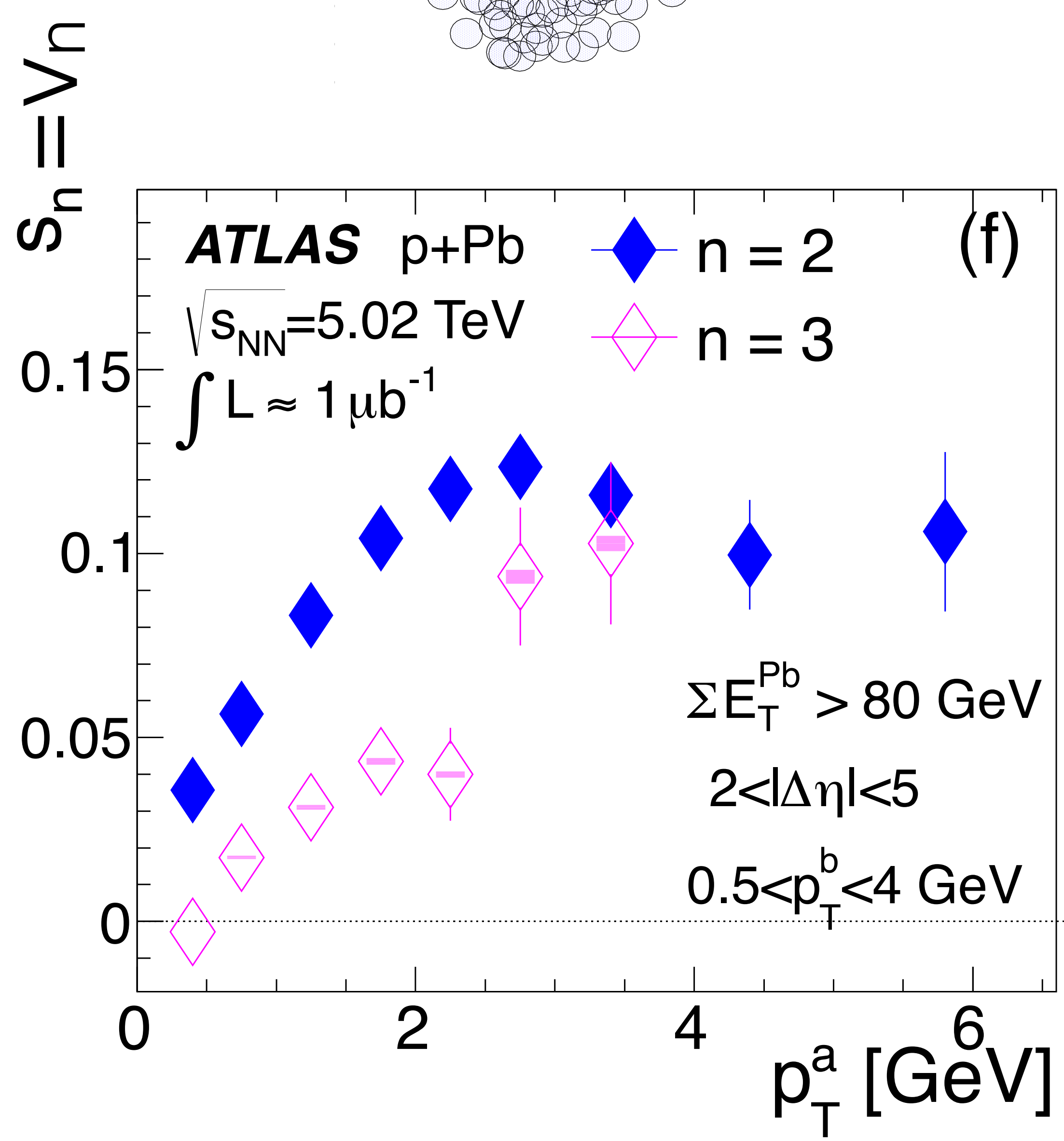
extra v_3 $\rightarrow$ more fluctuations

smaller systems: stronger effect of viscosity to reduce v_n values

1911.04812

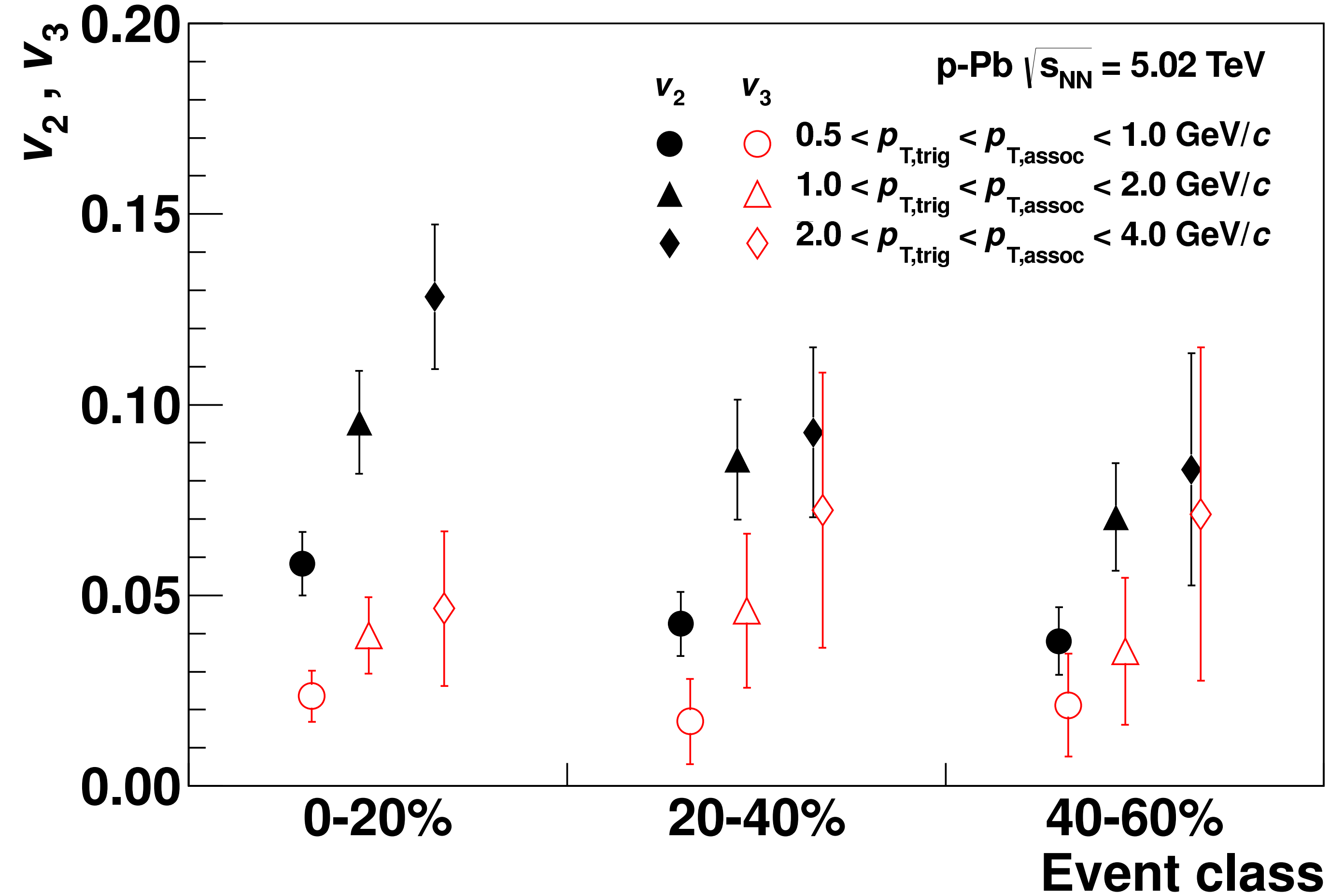
smaller system: pPb collisions





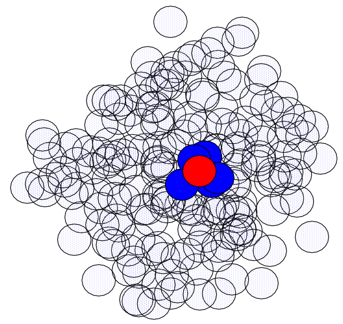
ATLAS PRL 110 182302 (2013)

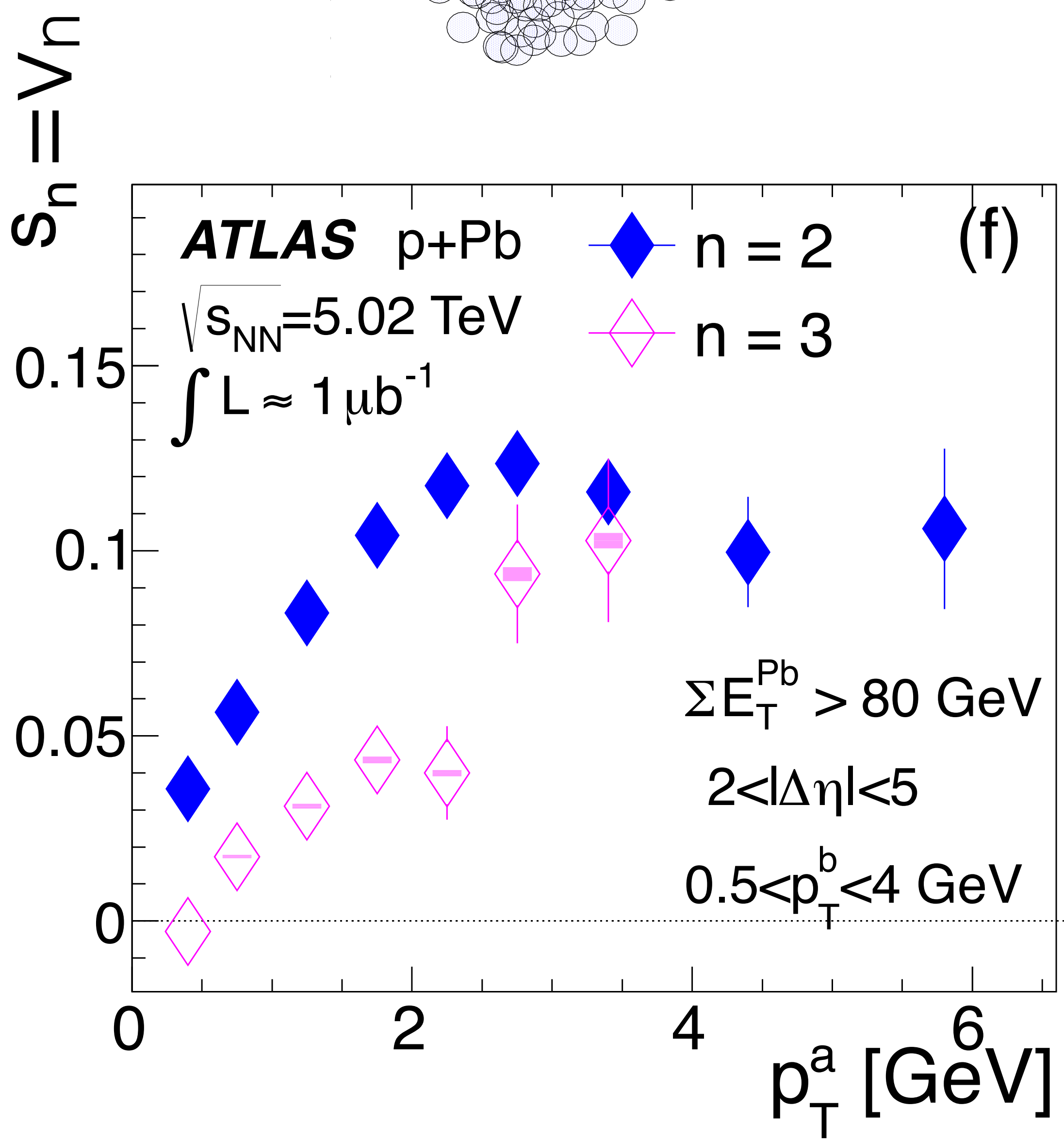
ALICE PLB 719 29



2013 surprising result: v_2 & v_3 measured in pPb collisions!

smaller system: pPb collisions





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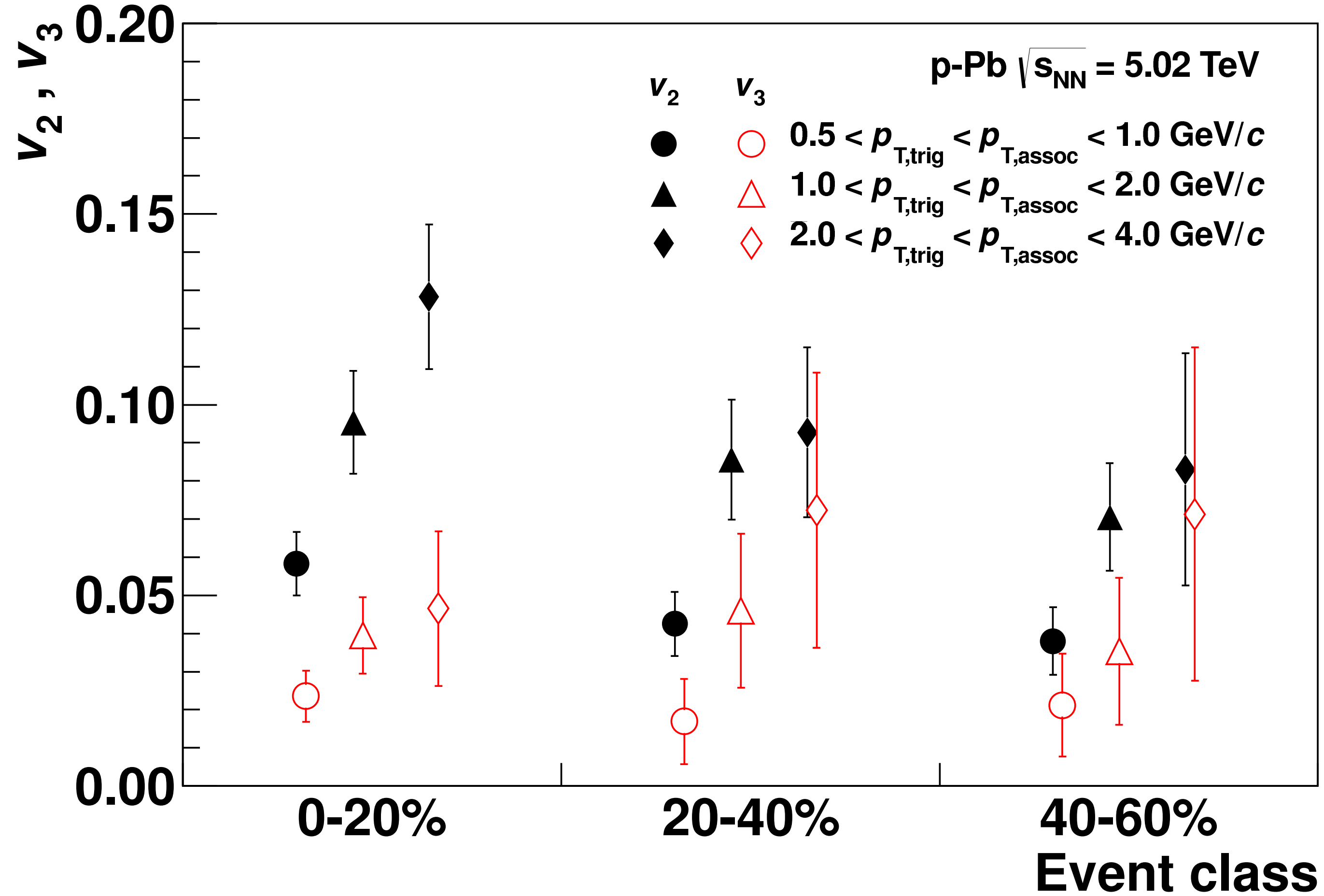
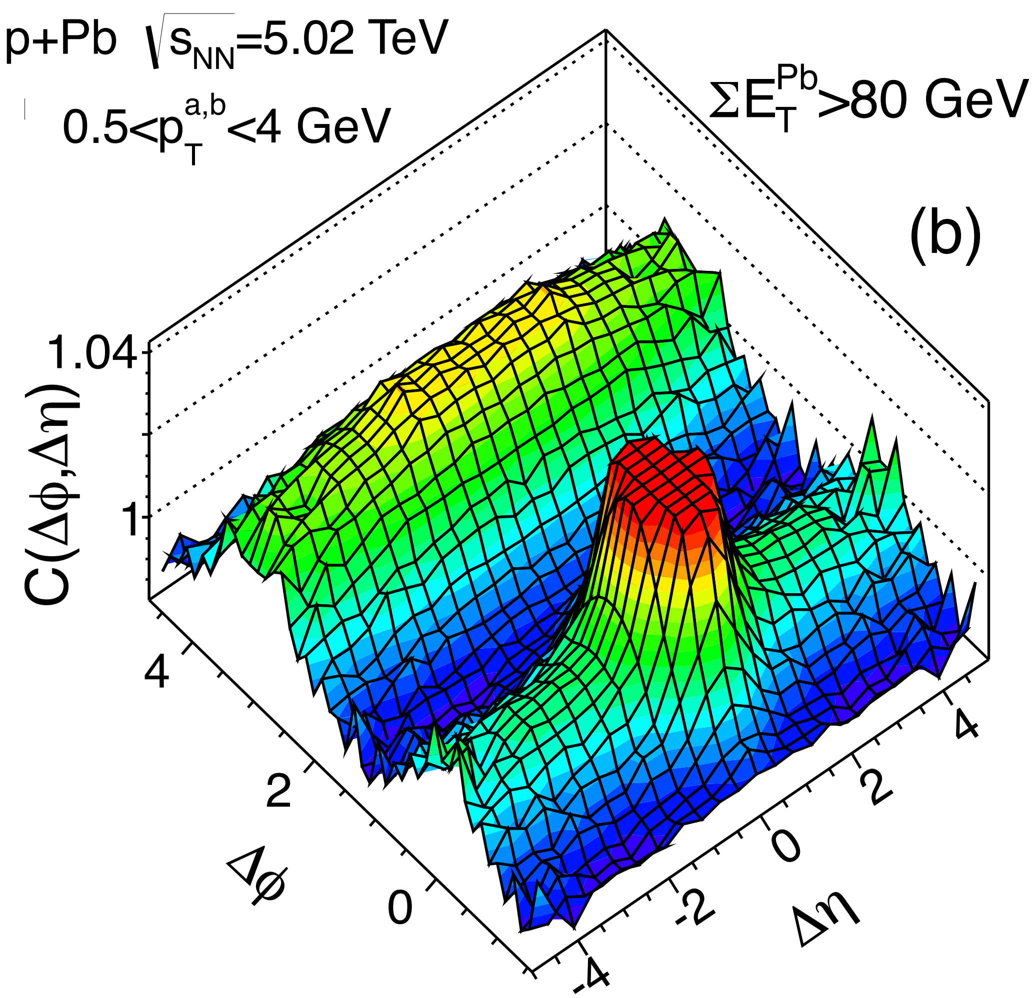
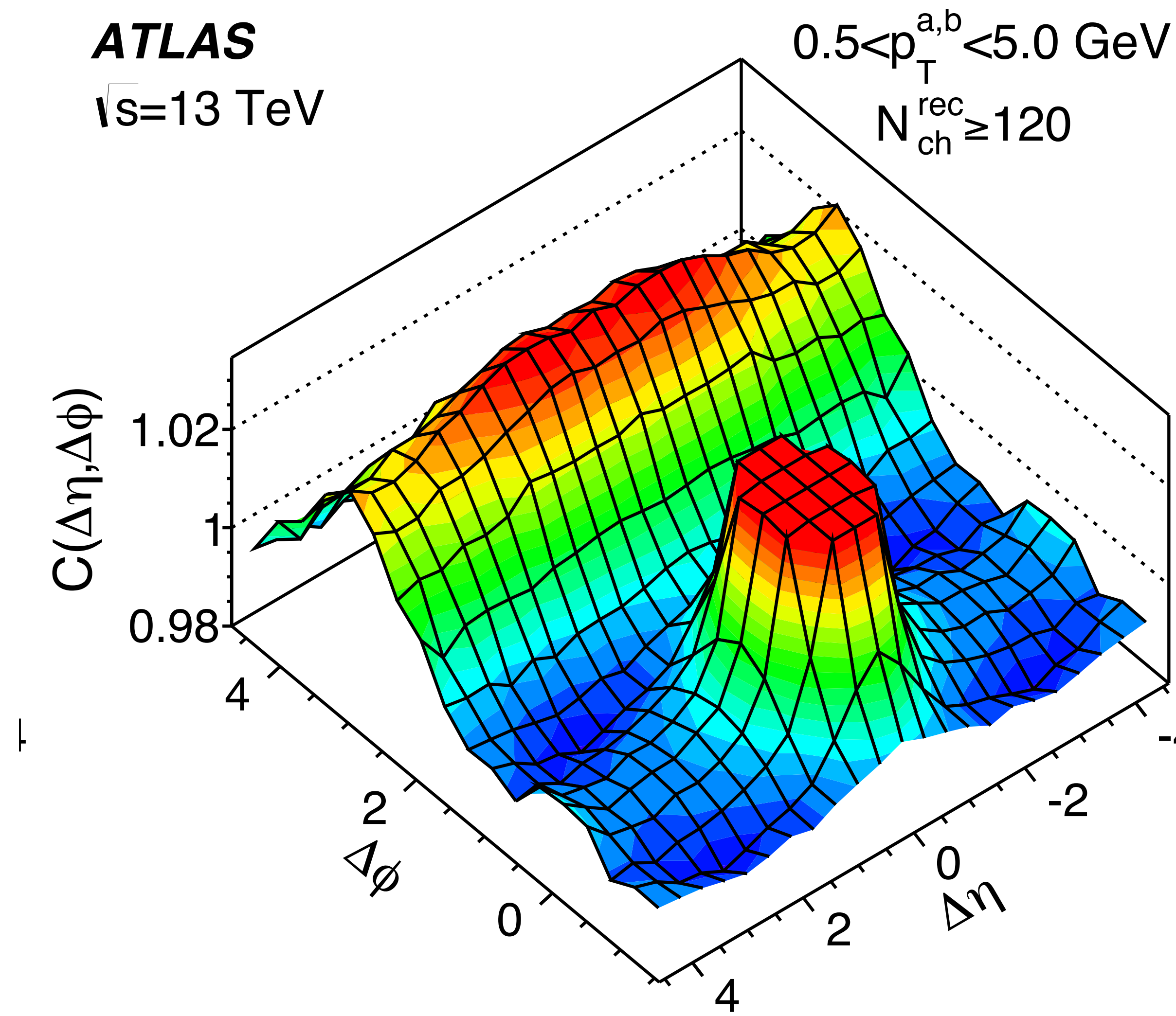


2013 surprising result: v_2 & v_3 measured in pPb collisions!

evidence for QGP formation or something else?

looking for vn in smaller systems

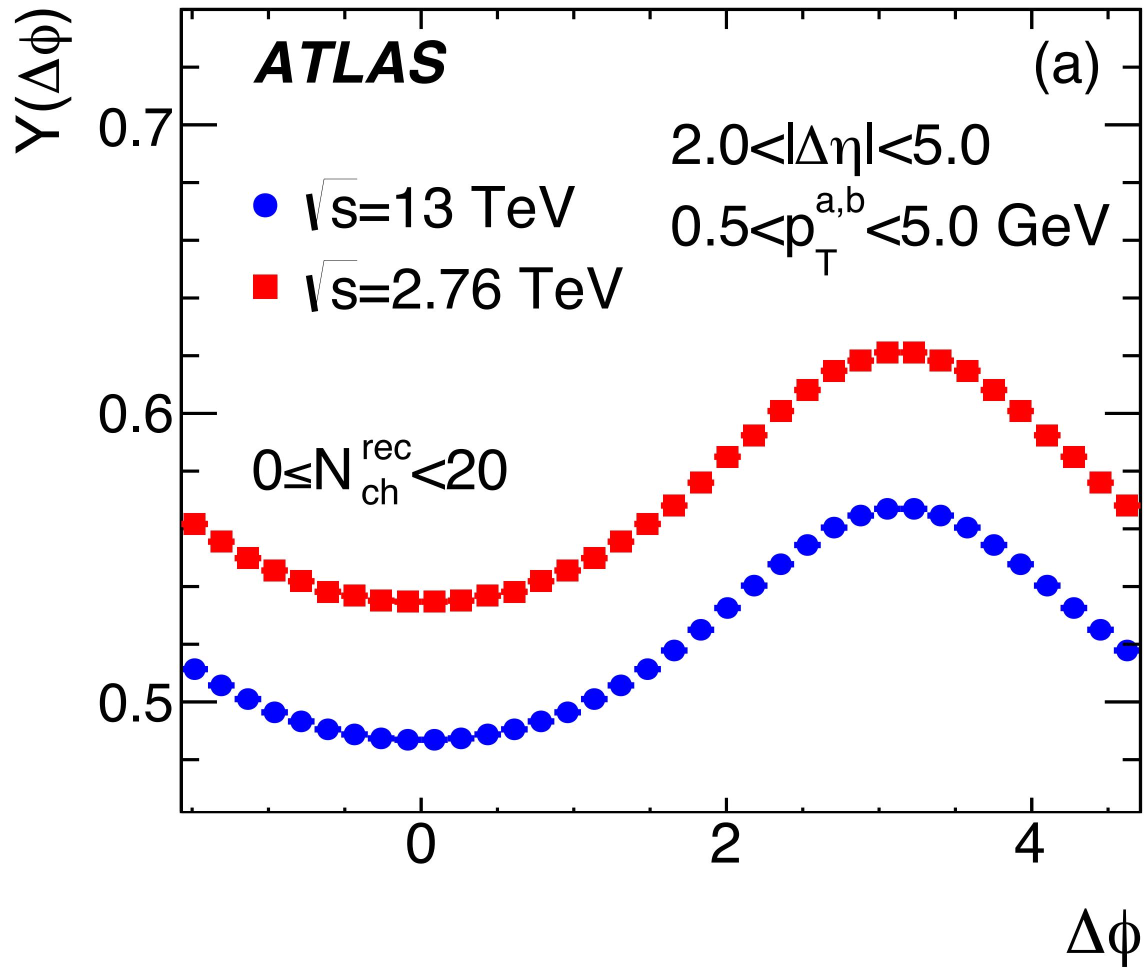




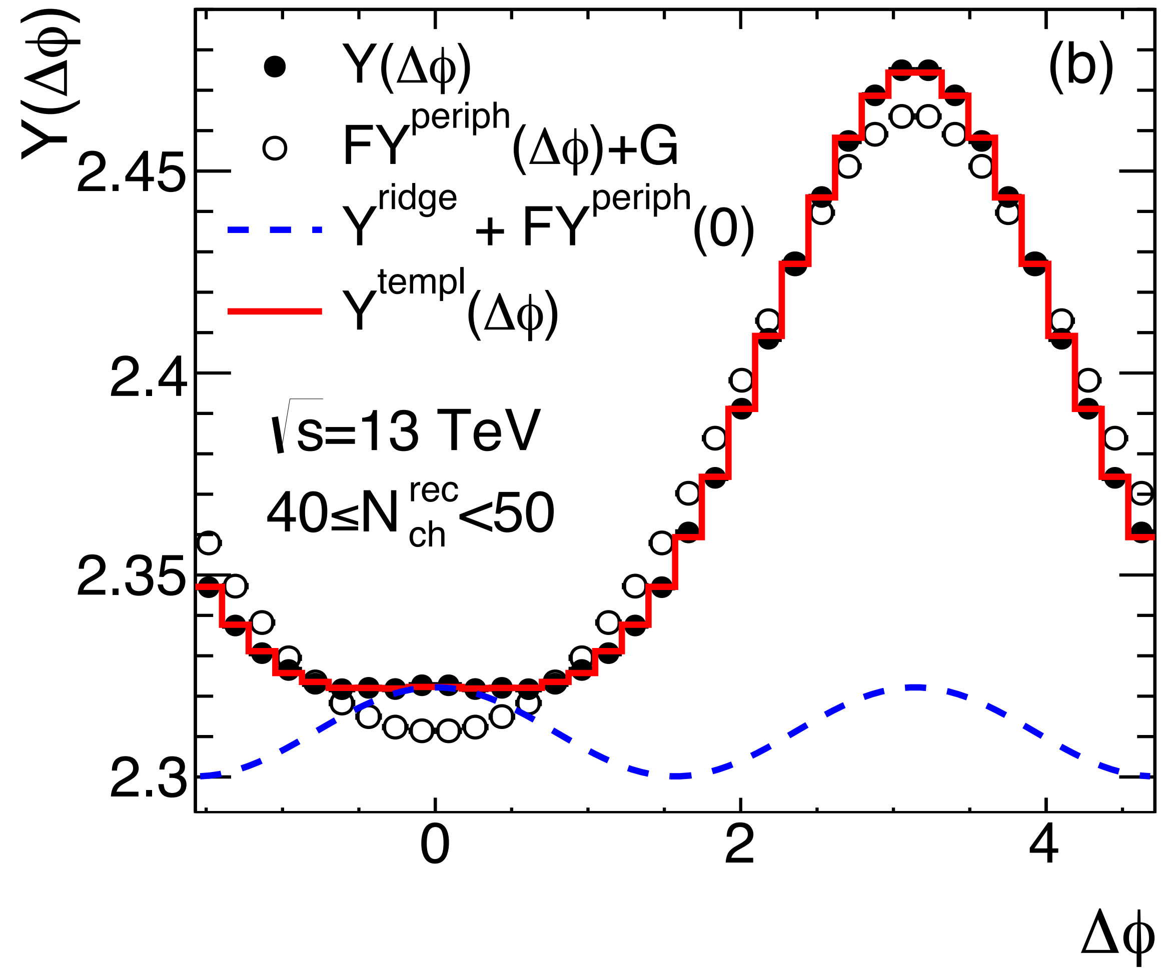
PRL 110 182302 (2013)
PRL 116 172301 (2016)

fitting procedure

$Y^{periph}(\Delta\Phi)$, $N_{ch}^{rec} < 20$



$40 < N_{ch}^{rec} < 50$



$$Y^{\rm templ}(\Delta\phi) = F\, Y^{\rm periph}(\Delta\phi) + Y^{\rm ridge}(\Delta\phi)\,,$$

$$Y^{\rm ridge}(\Delta\phi) = G\,(1 + 2v_{2,2}\cos(2\Delta\phi))\ ,$$

ATLAS PRL116 172301

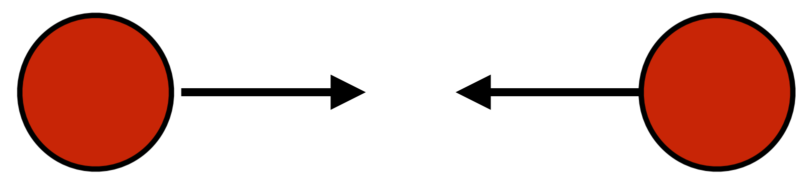
fit free parameters:

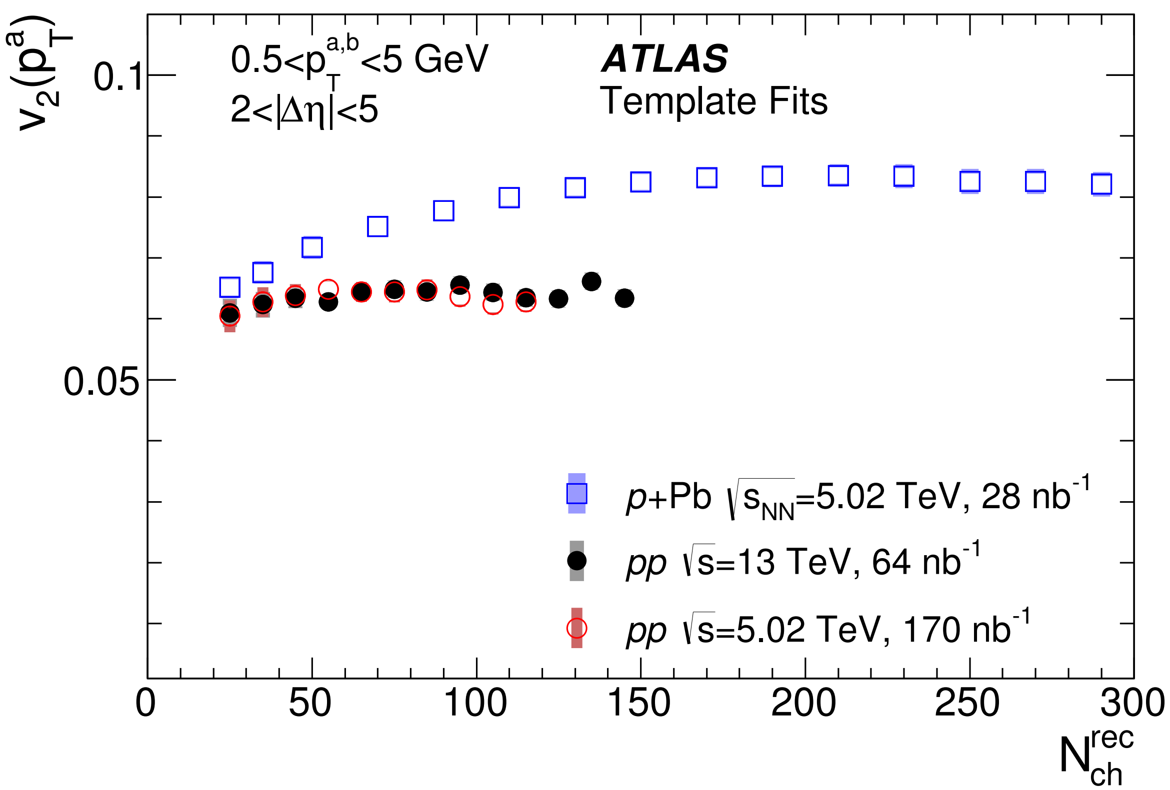
F & $v_{2,2}$

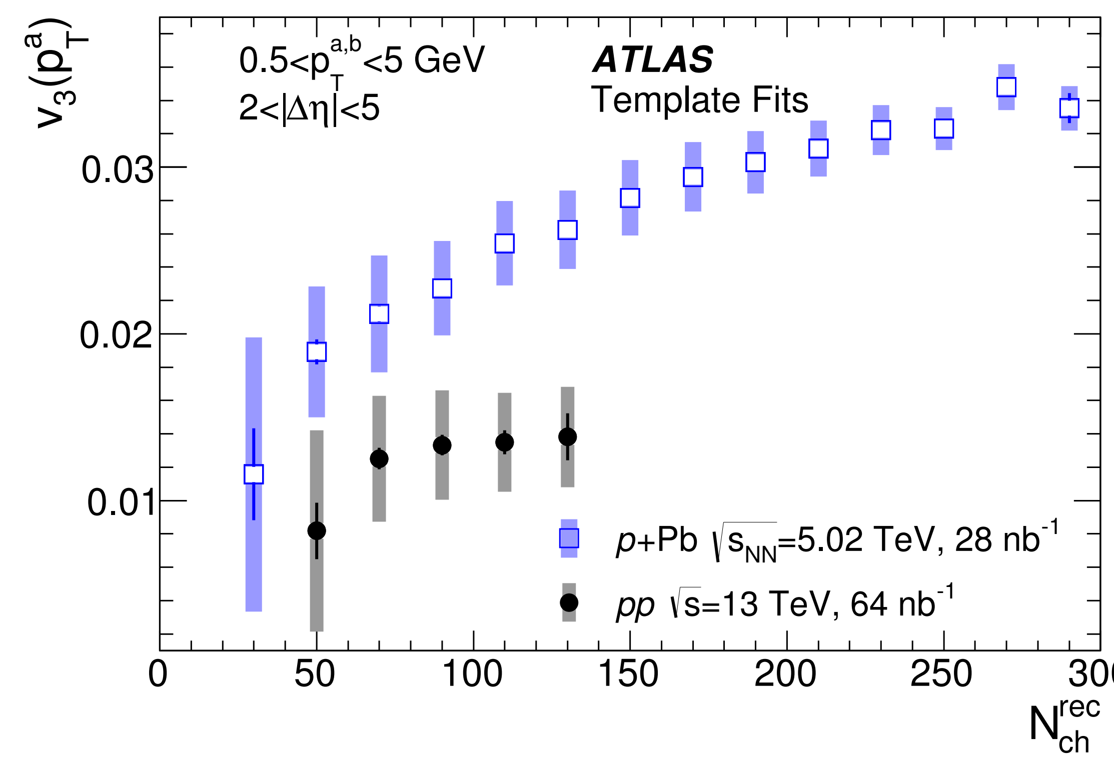
G fixed such that:

$$\int_0^\pi d\Delta\phi\ Y^{\rm templ} = \int_0^\pi d\Delta\phi\ Y$$

v_2 & v_3 in proton-proton collisions







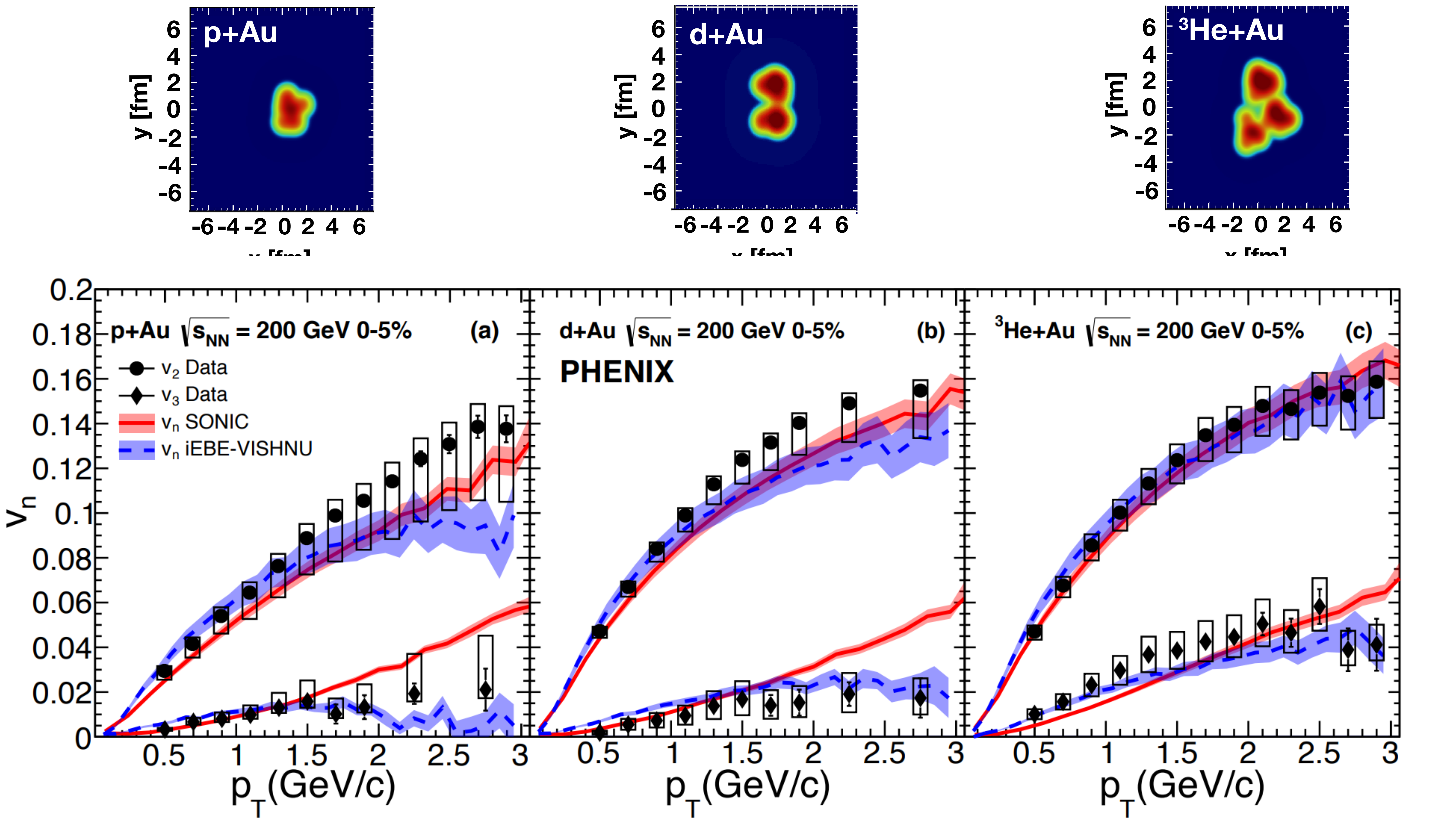
$v_{2pp} < v_{2pPb}$

$v_{3pp} < v_{3pPb}$

in pp collisions any relationship between ε_n & v_n must be given by some model of the fluctuations

PRC 96 024908 (2017)

geometry and hydrodynamics in small systems

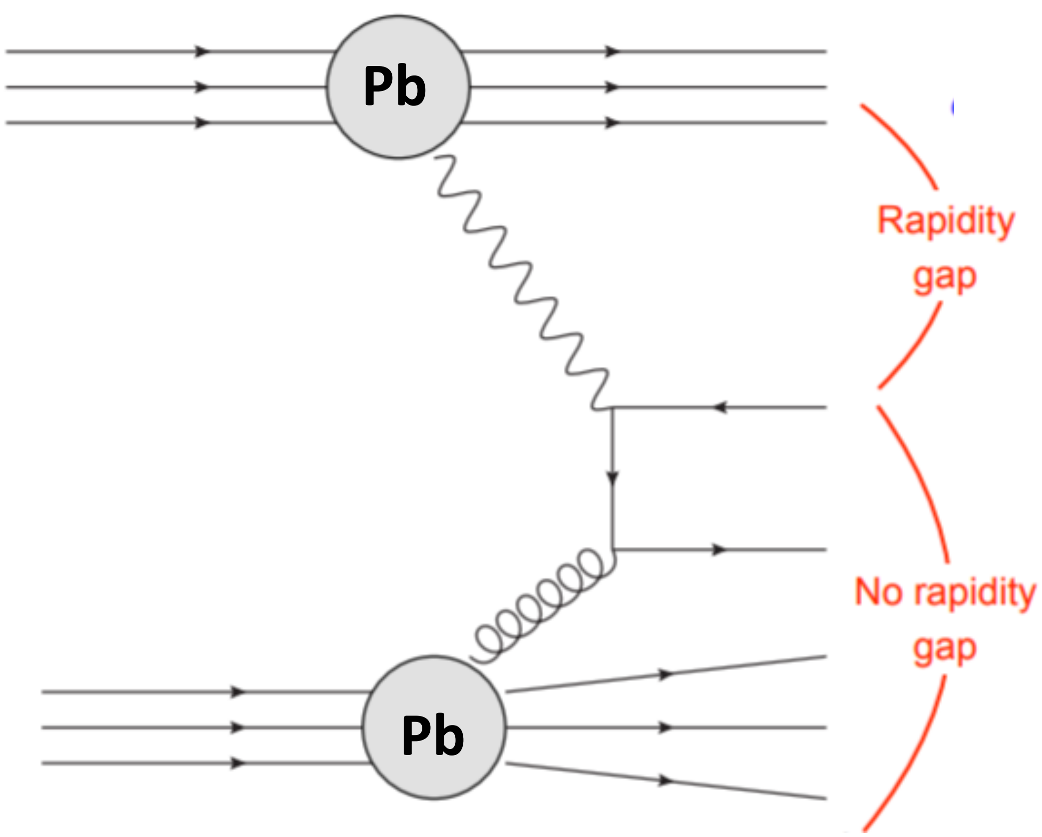


PHENIX, Nature Phys. 15 (2019) 214

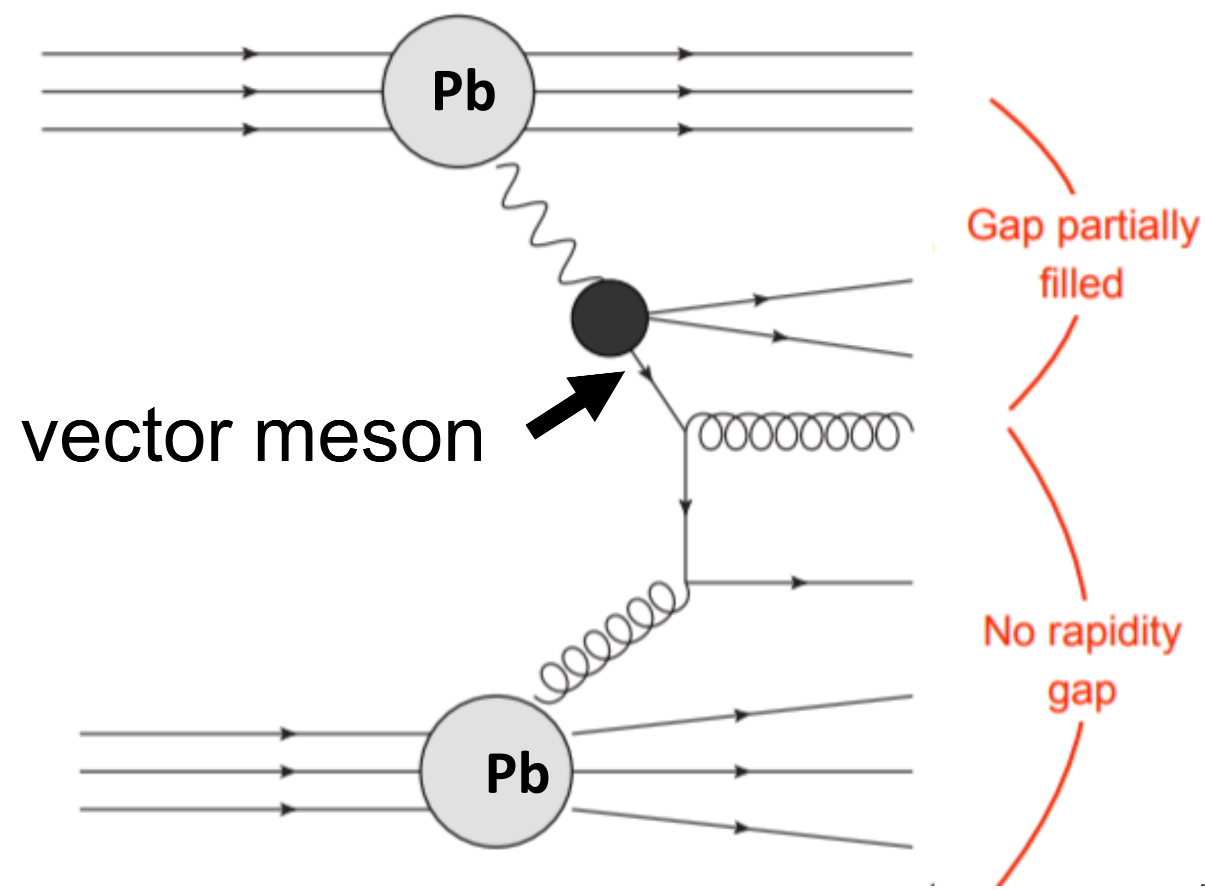
v_2, v_3 clearly tied to geometry through hydrodynamic calculations

photon-Pb collisions

direct γ-Pb collision

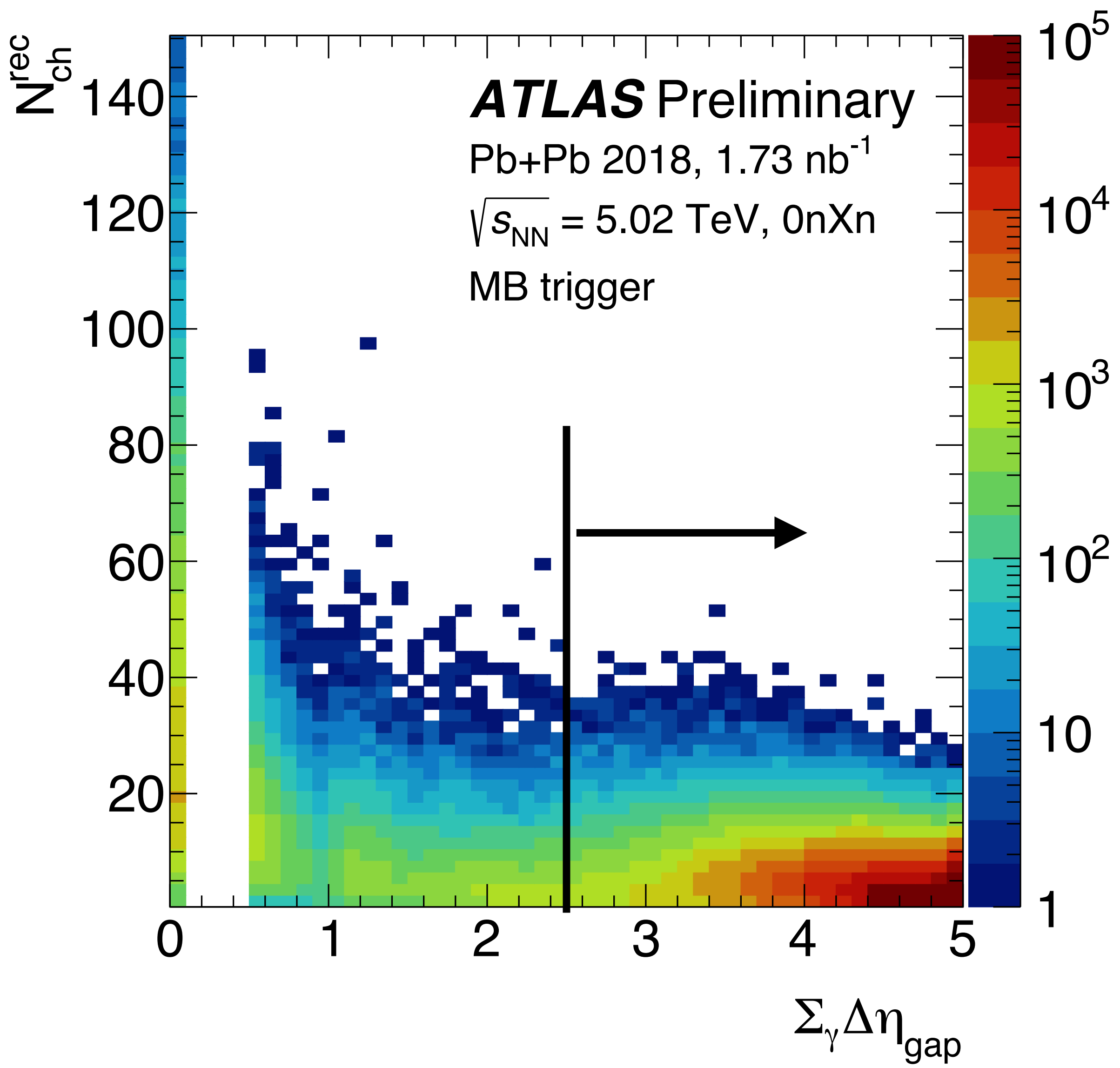


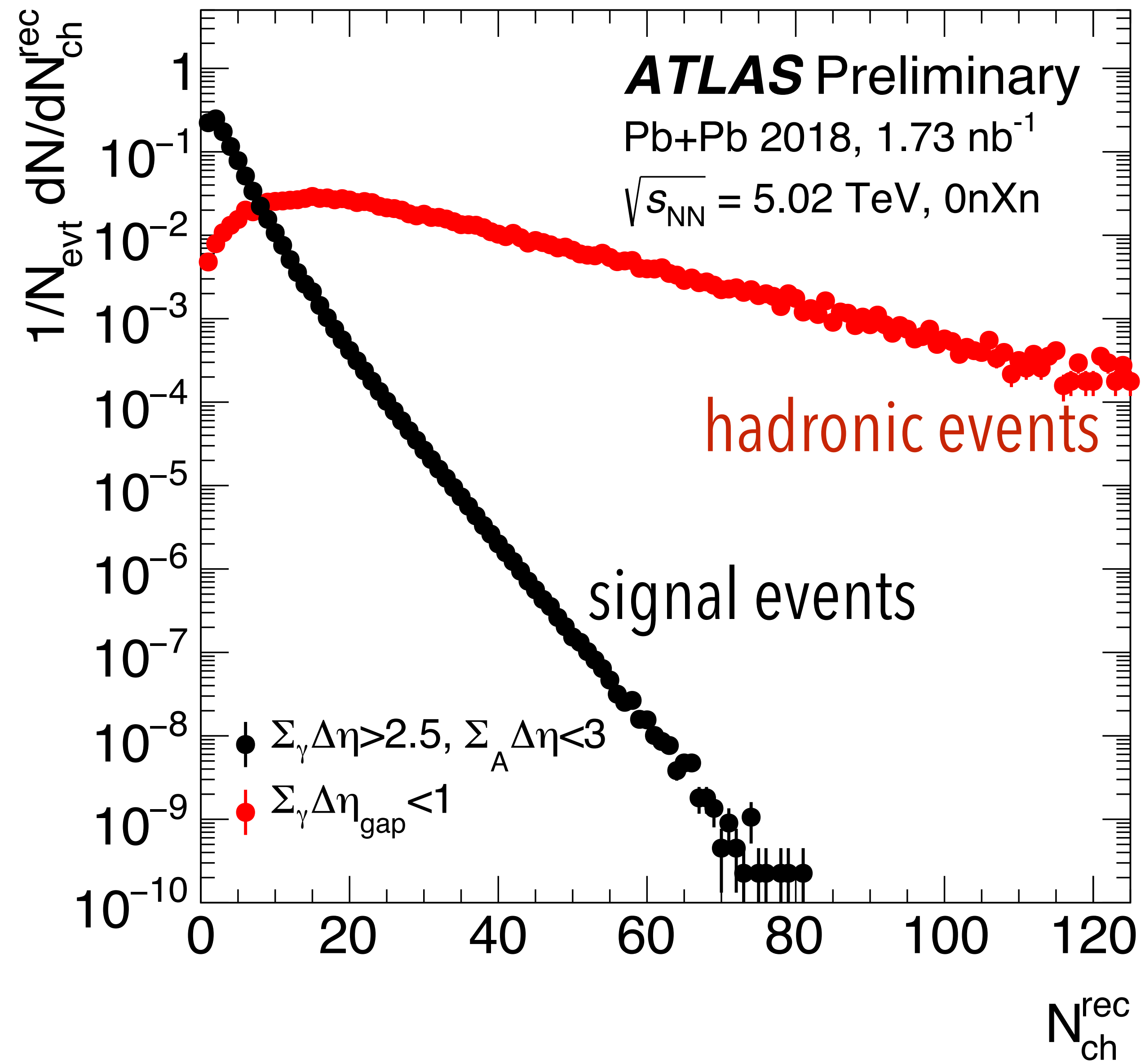
resolved γ-Pb collision



multiplicity in γ-Pb collisions

0nXn: at least 1 neutron in one ZDC and 0 in the other





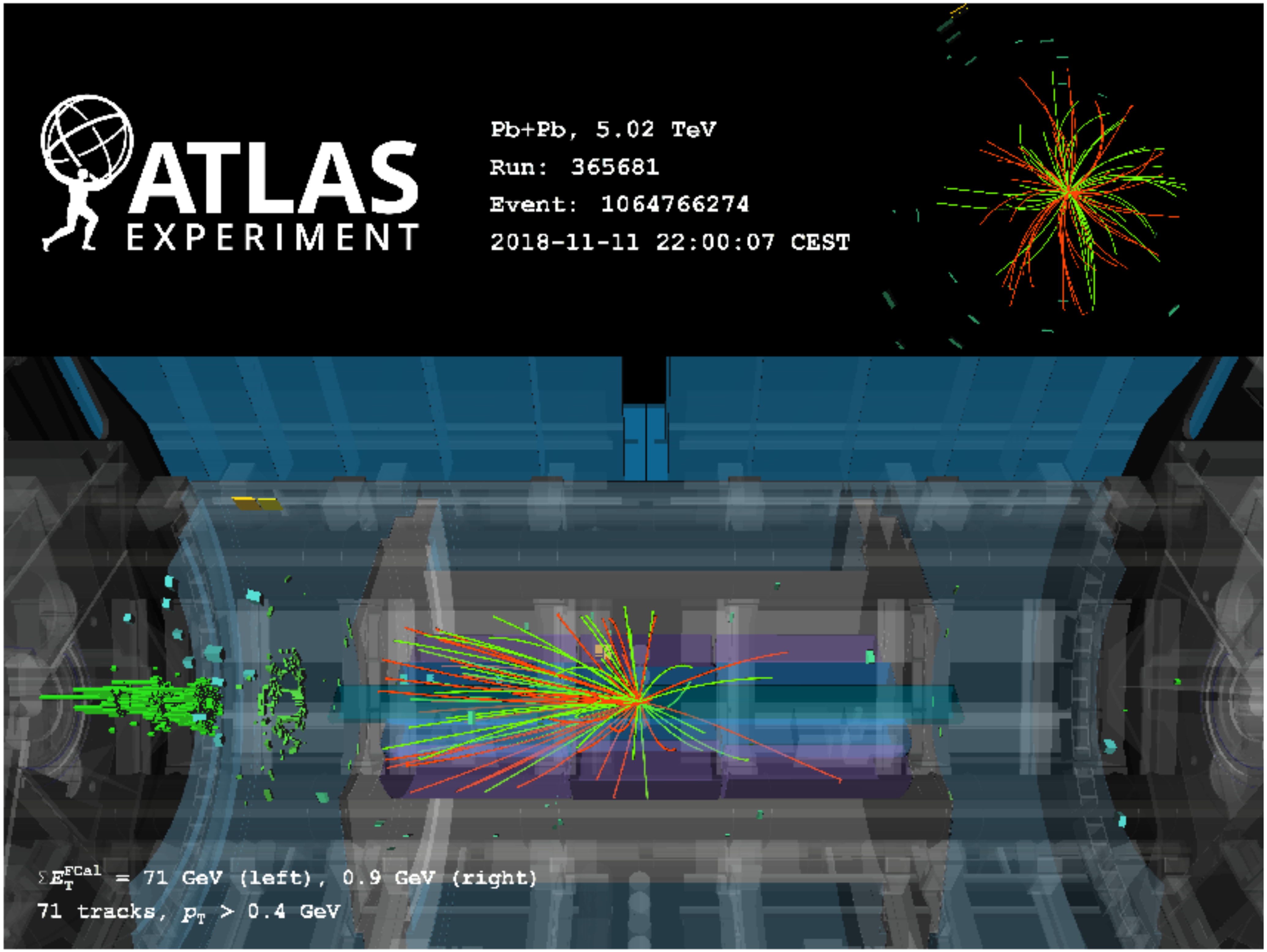
$\Sigma\Delta\eta_{gap}$: sum of all gaps (including tracks & clusters) > 0.5

require: $\Sigma_{\gamma}\Delta\eta_{gap}$: > 2.5 & $\Sigma_{A}\Delta\eta_{gap}$ < 3

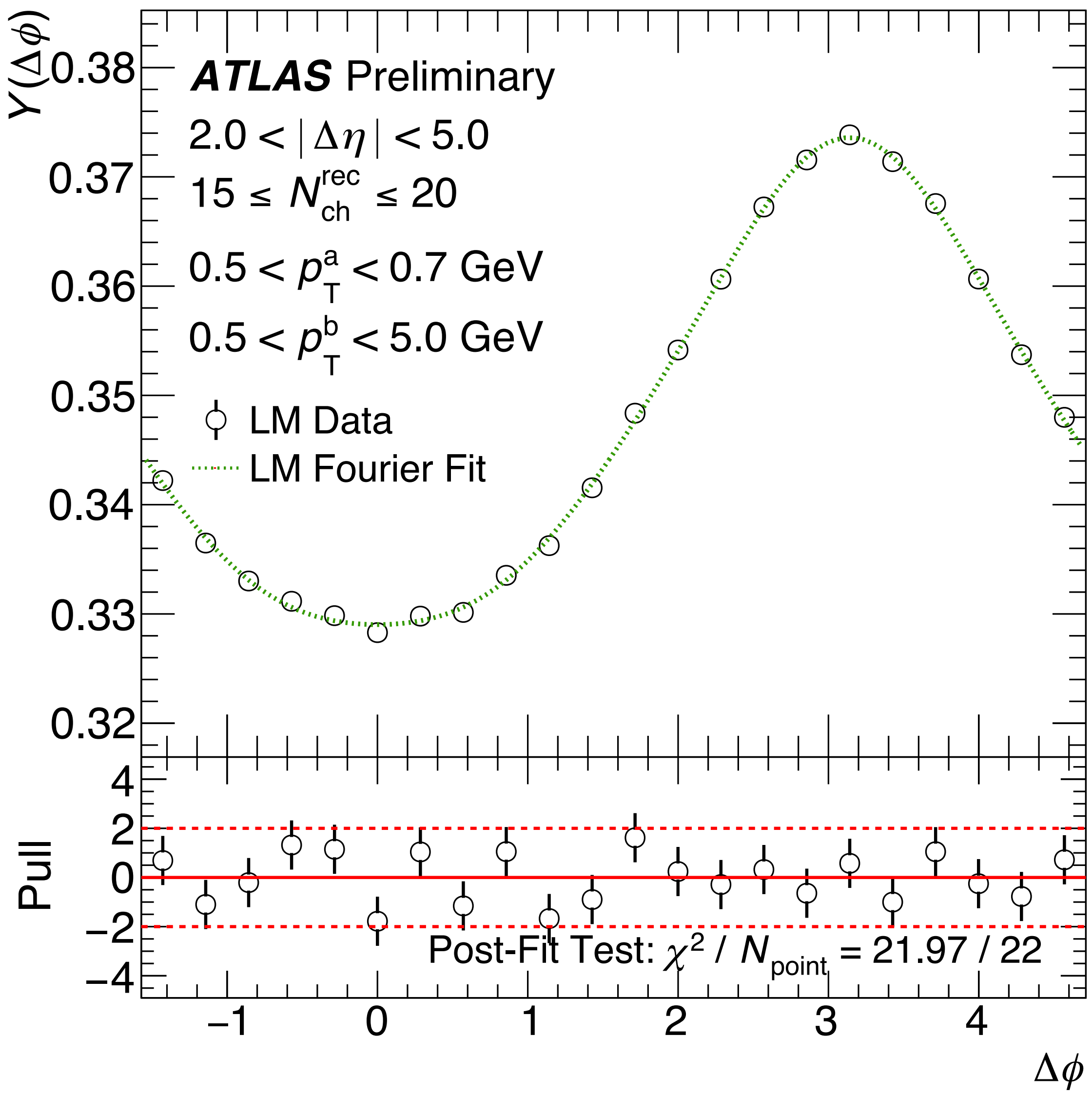
ATLAS-CONF-2019-022

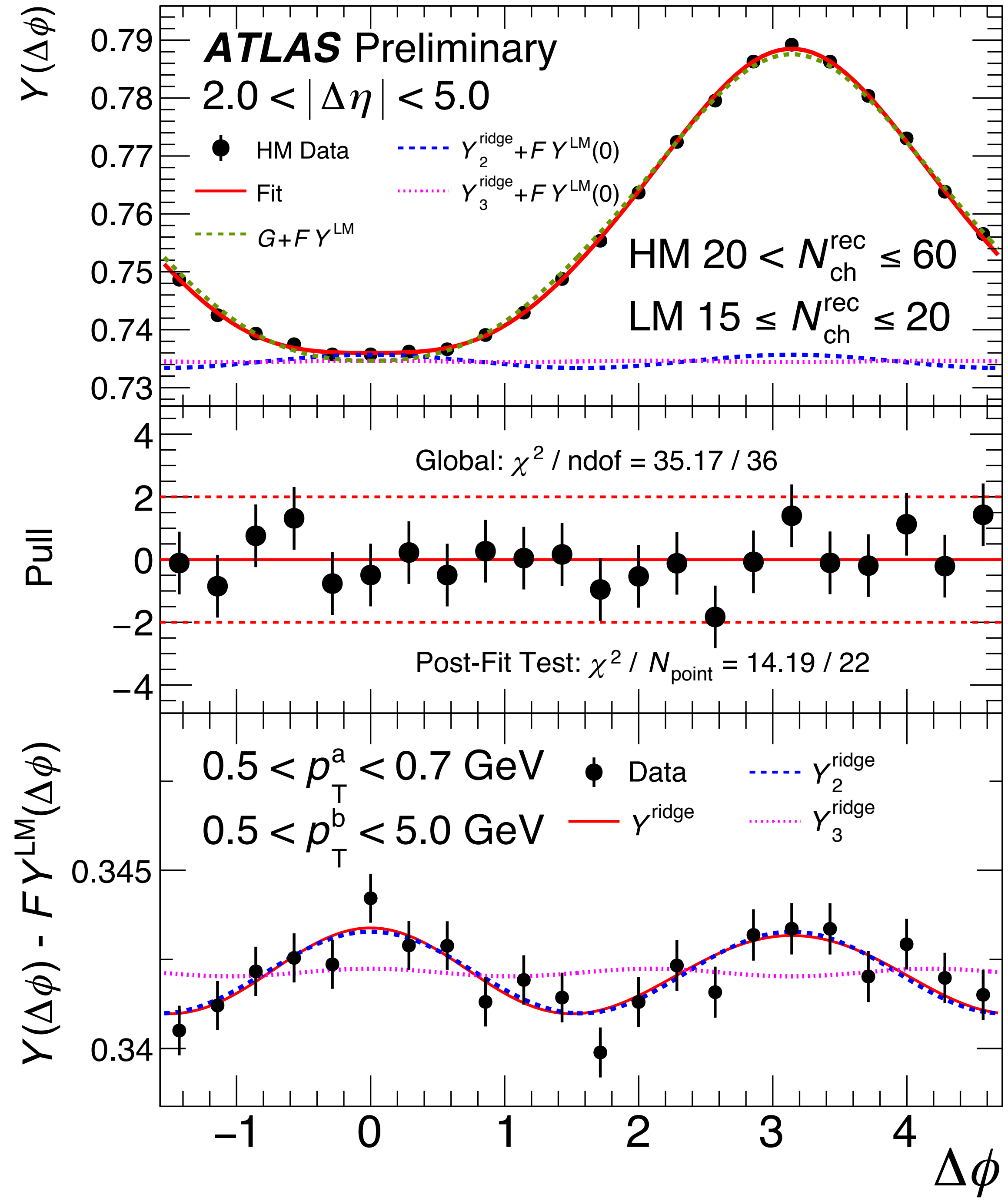
γ-Pb event display

Pb ←



→ γ

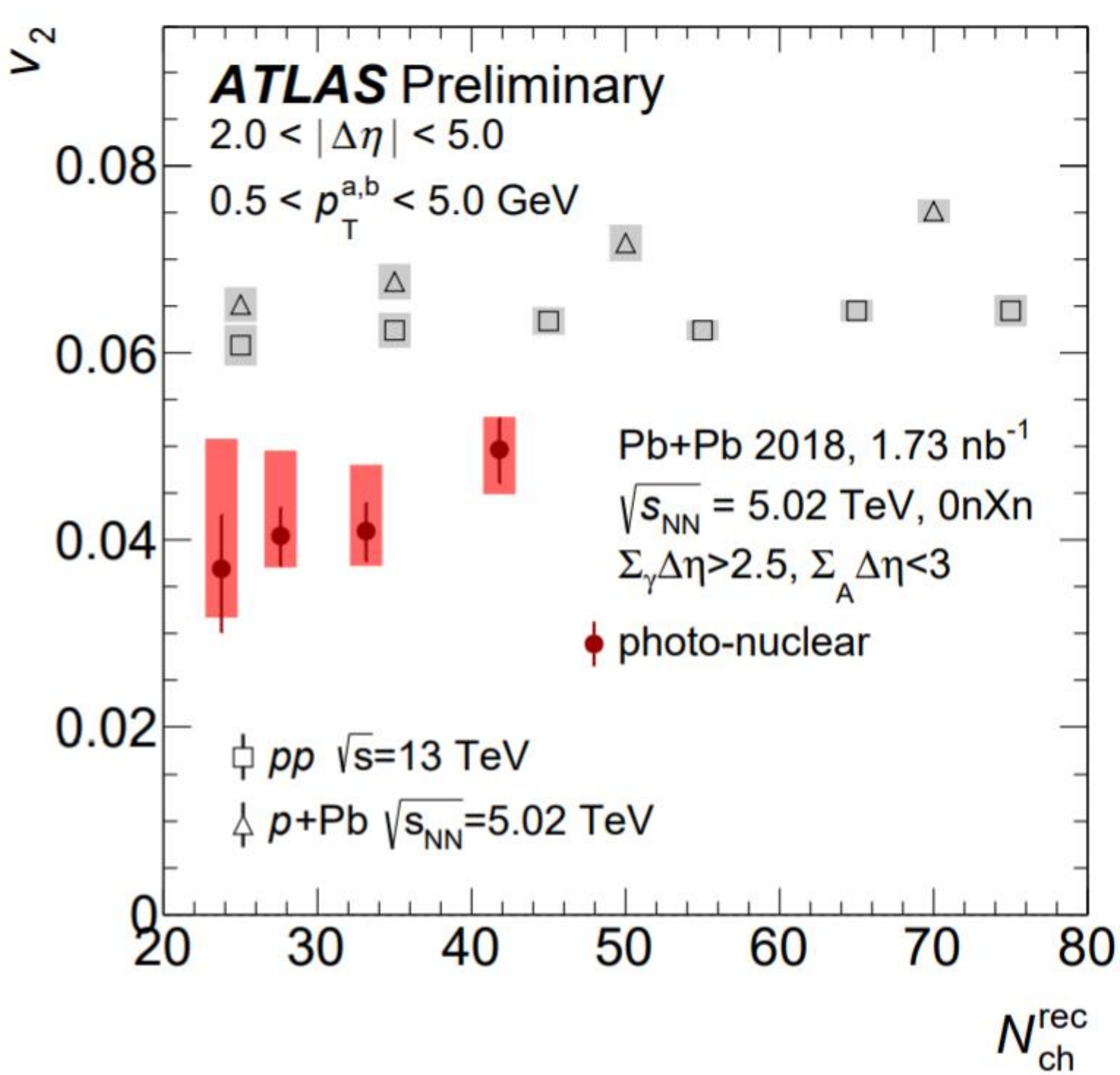


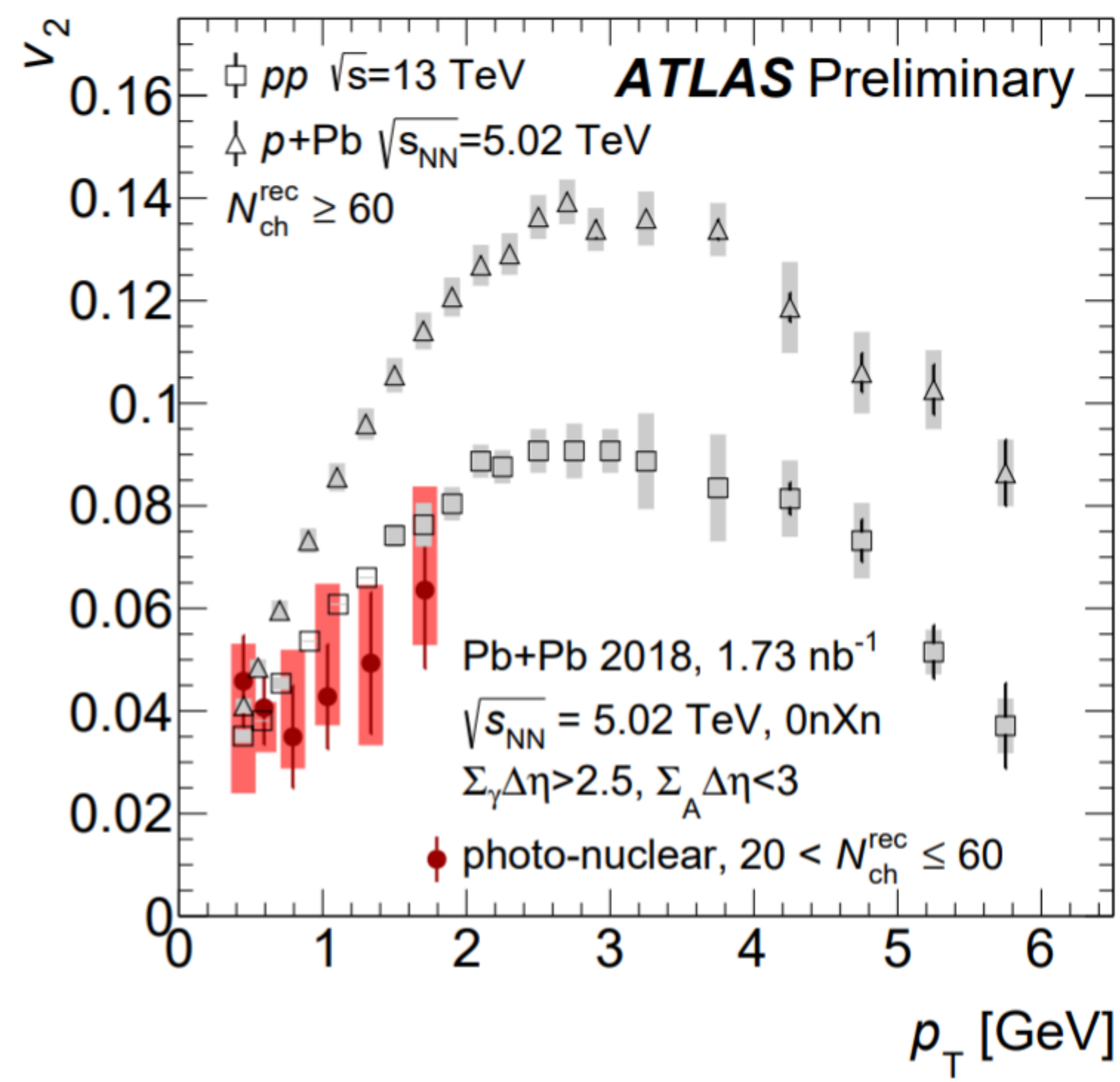


simultaneous fit to low (LM) and high (HM) multiplicity distributions

ATLAS-CONF-2019-022

v_2 in photon-nucleus collisions





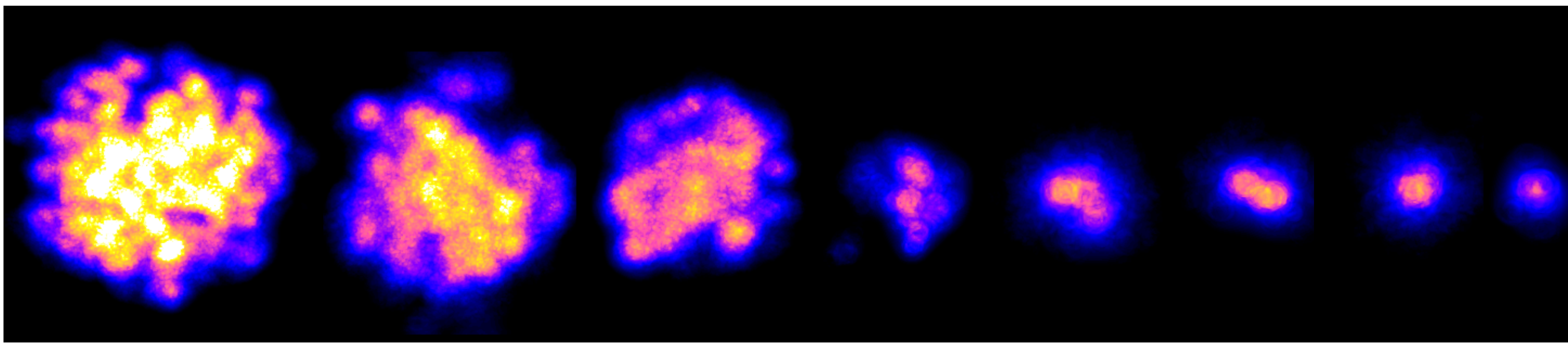
$v_2(\gamma Pb) < v_2(pp) < v_2(pPb)$

could be sensitive to different geometries than in pp/pPb collisions

ATLAS-CONF-2019-022

from Pb-Pb collisions to pp hydrodynamic calculations can describe the data

v_2 measurement in γ-Pb collisions are a provocative frontier…



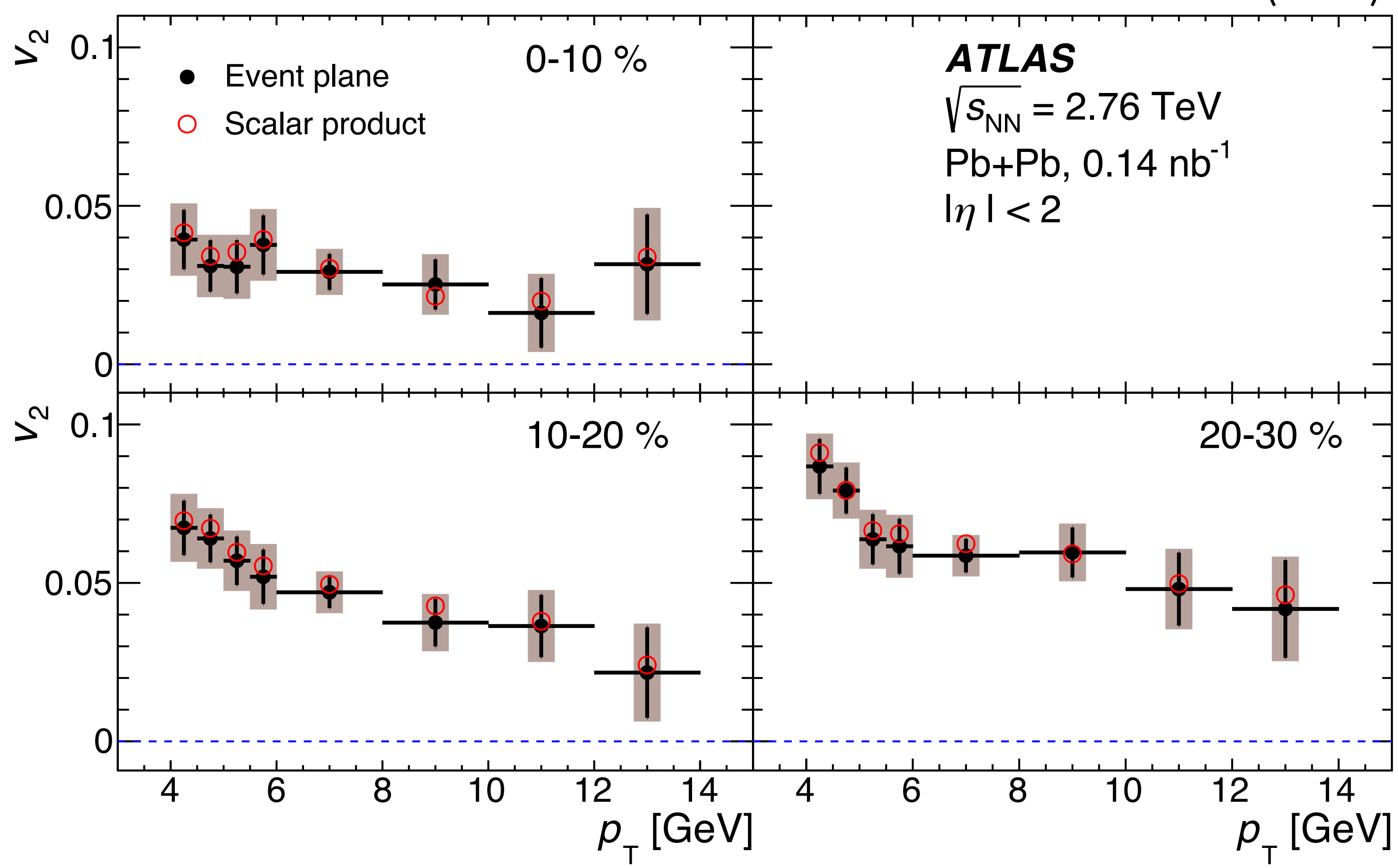
the different role of geometry and fluctuations provides an opportunity to constrain the properties of the QGP

image: C. Shen (QM19)

heavy quarks

- charm and bottom quarks are interesting because their v_n values are sensitive to how much these more massive quark flow with the QGP
- ATLAS has measured the $\mu^{\pm}$ from the decay of charm and bottom hadrons (combined)
    - observe $v_2 > 0$

PRC 98 044905 (2018)



$m_{charm} = 1.3$ GeV

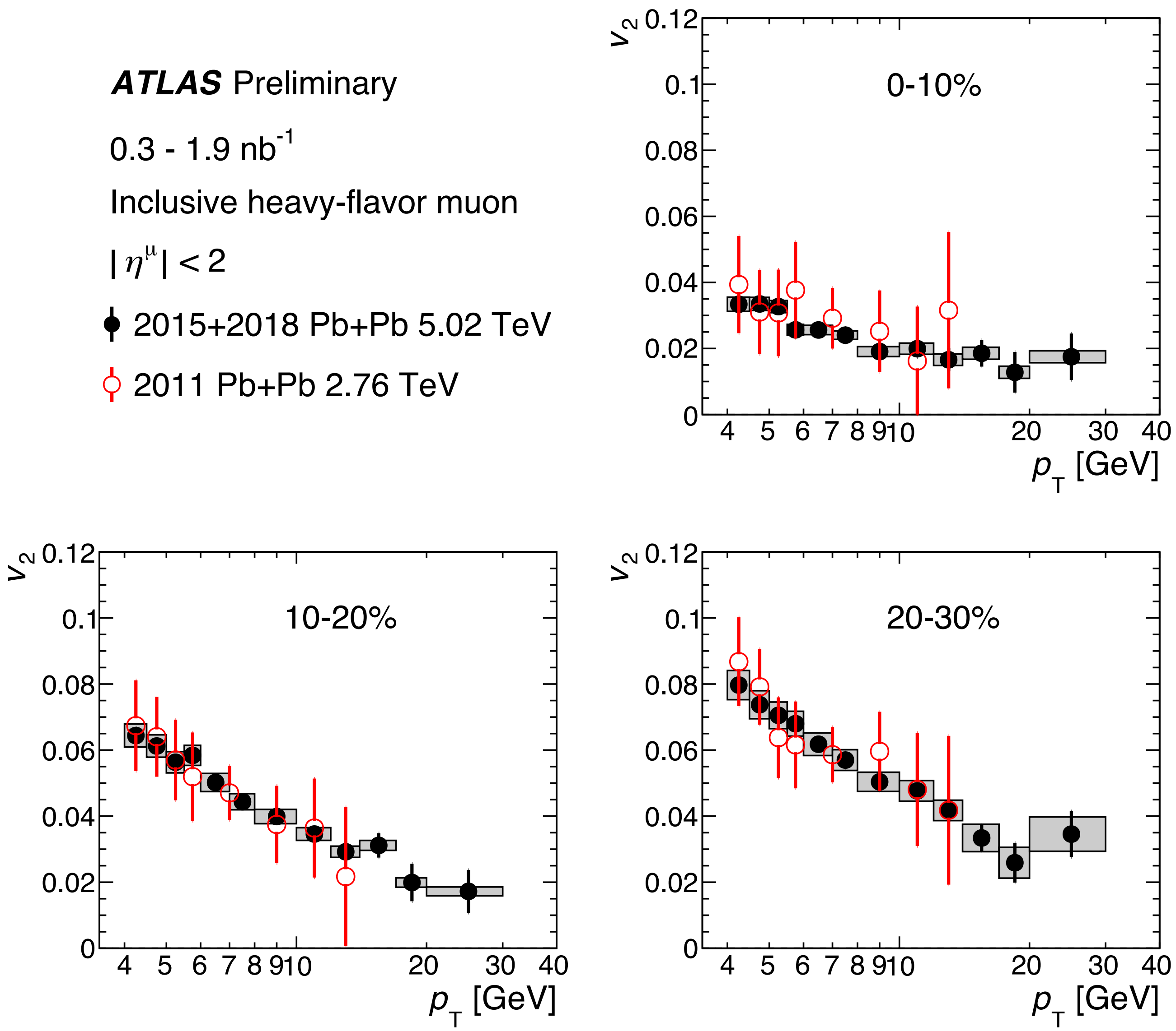
$m_{bottom} = 4.2$ GeV

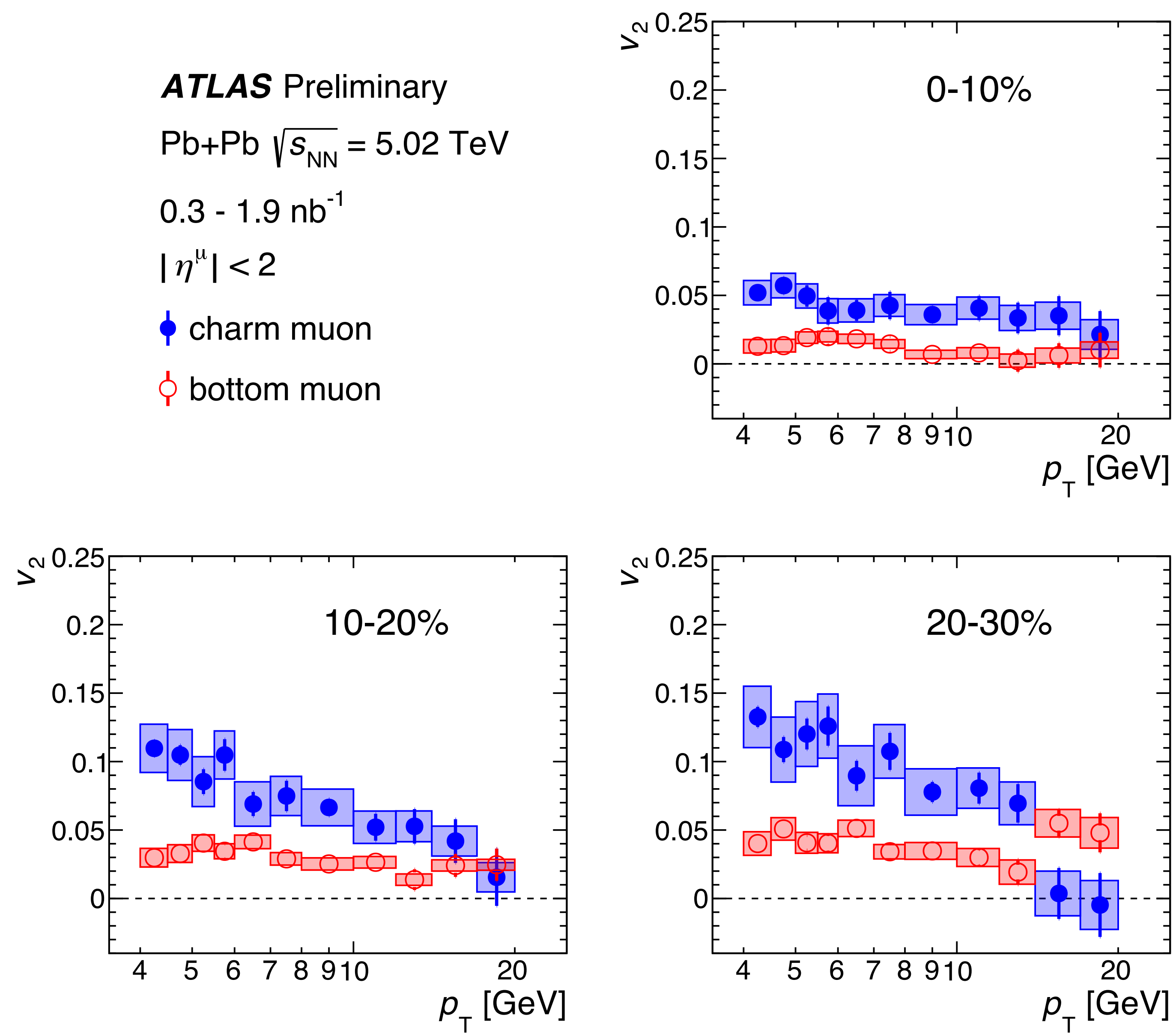
question: is the a difference in the flow due to the mass difference?

charm & bottom v_2, separately

much larger Run2 dataset!

charm v_2 > bottom v_2



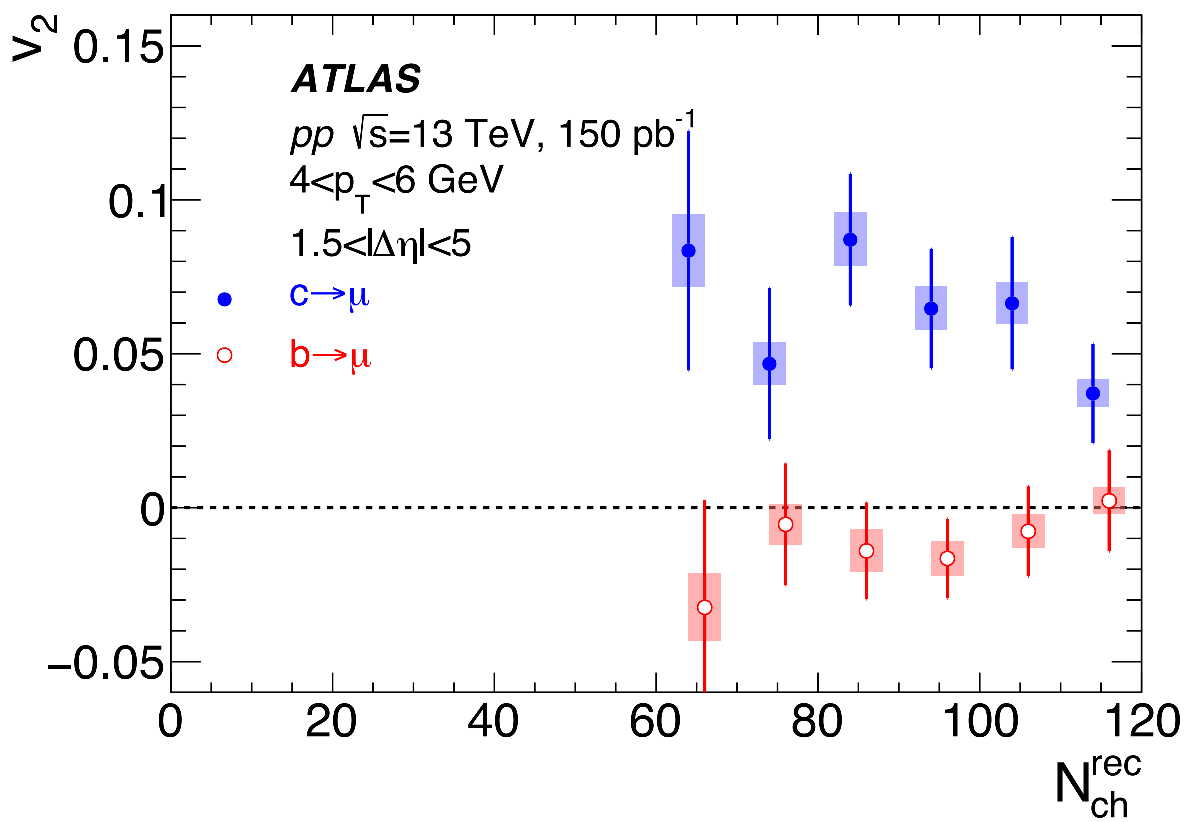


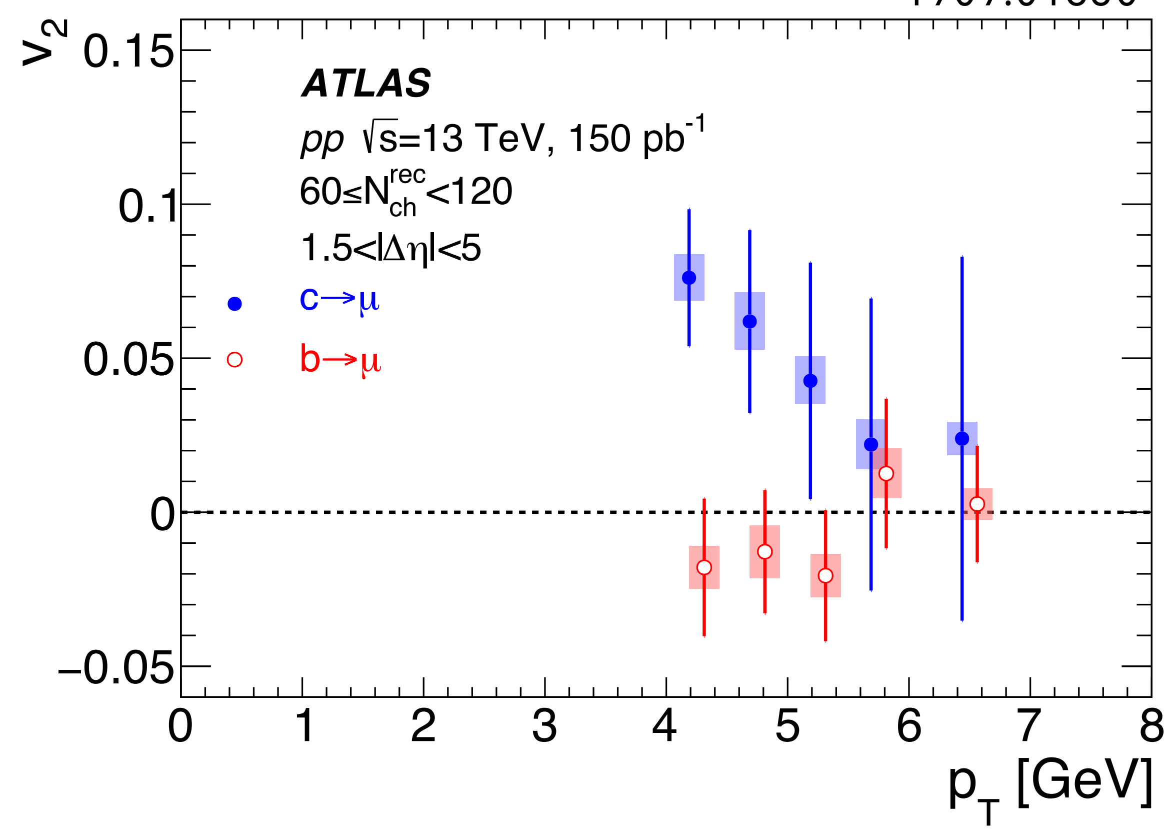
ATLAS-CONF-2019-053

charm & bottom v_2 in pp collisions

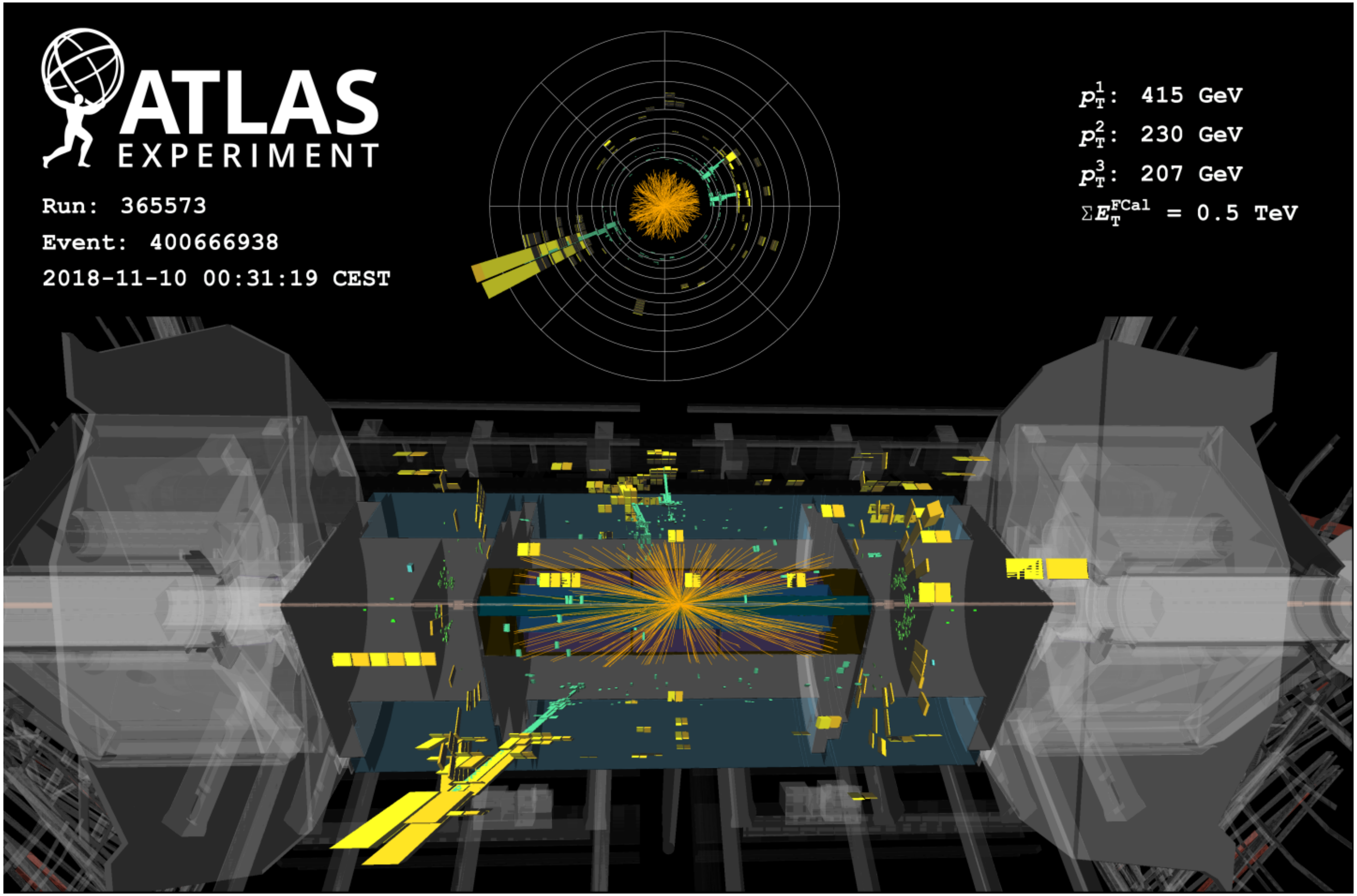
what about in pp collisions? overall v_2 is smaller than in PbPb collisions & the size of the system is also smaller

1909.01650





charm v_2 > bottom $v_2 \approx 0$

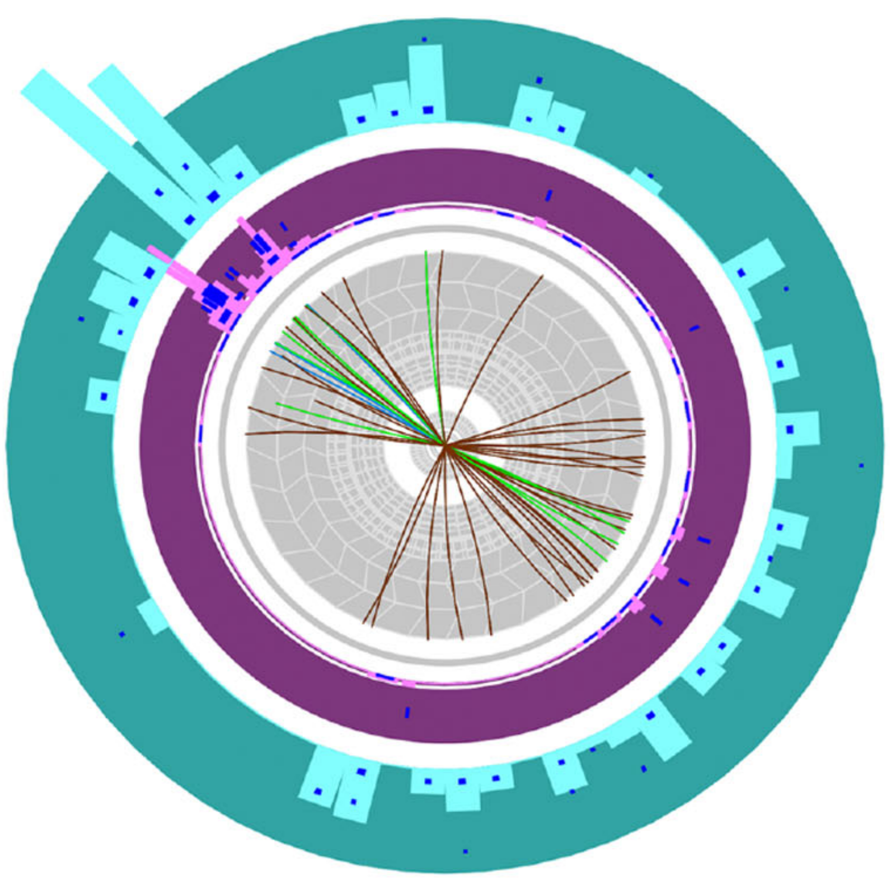


can we see how the jets experience different path lengths?

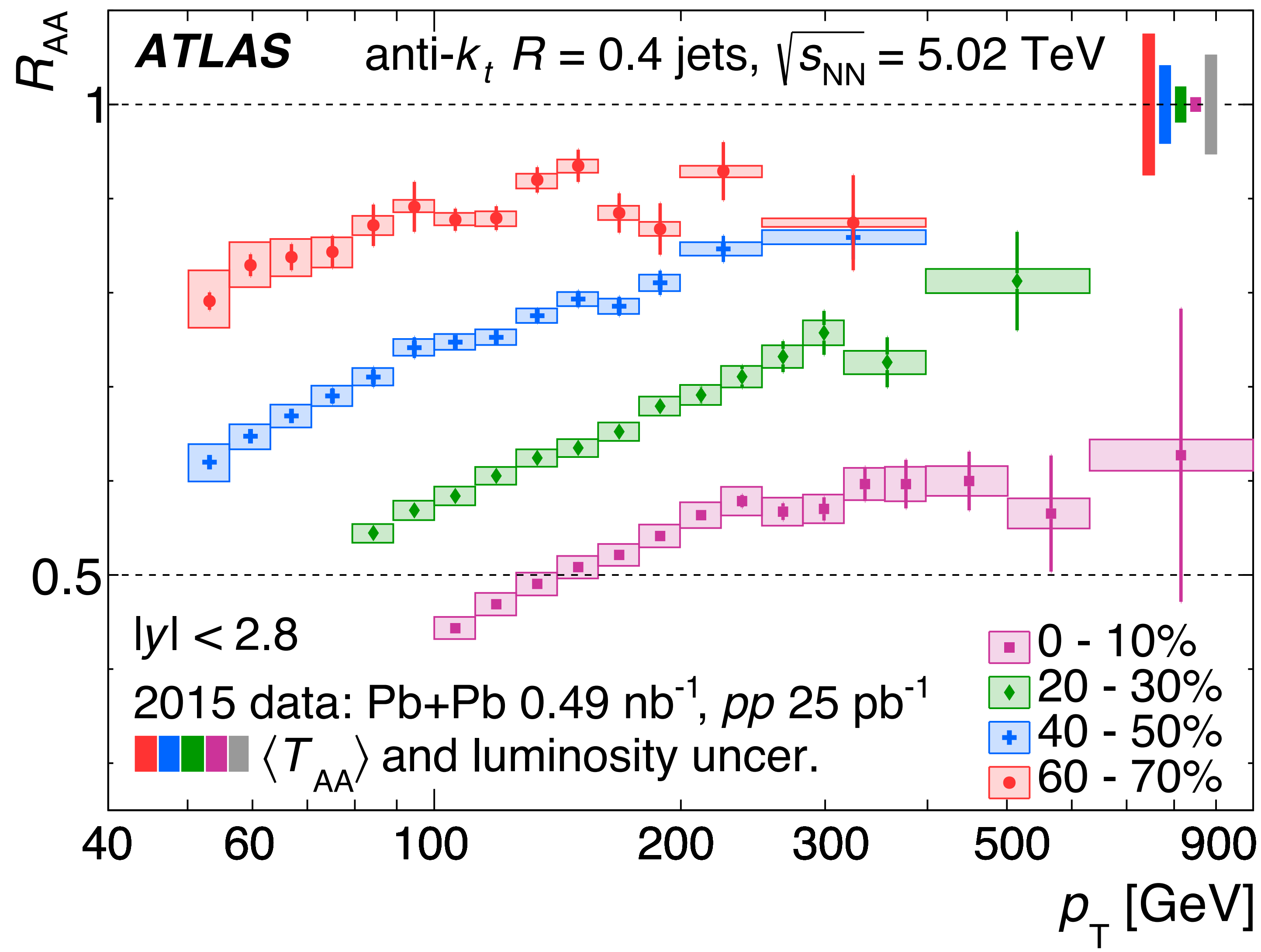
jet quenching

R_{AA} = number of jets in PbPb collisions/ pp collisions scaled by nuclear thickness function

$R_{AA} = 1 \rightarrow$ jets in PbPb collisions like pp collisions

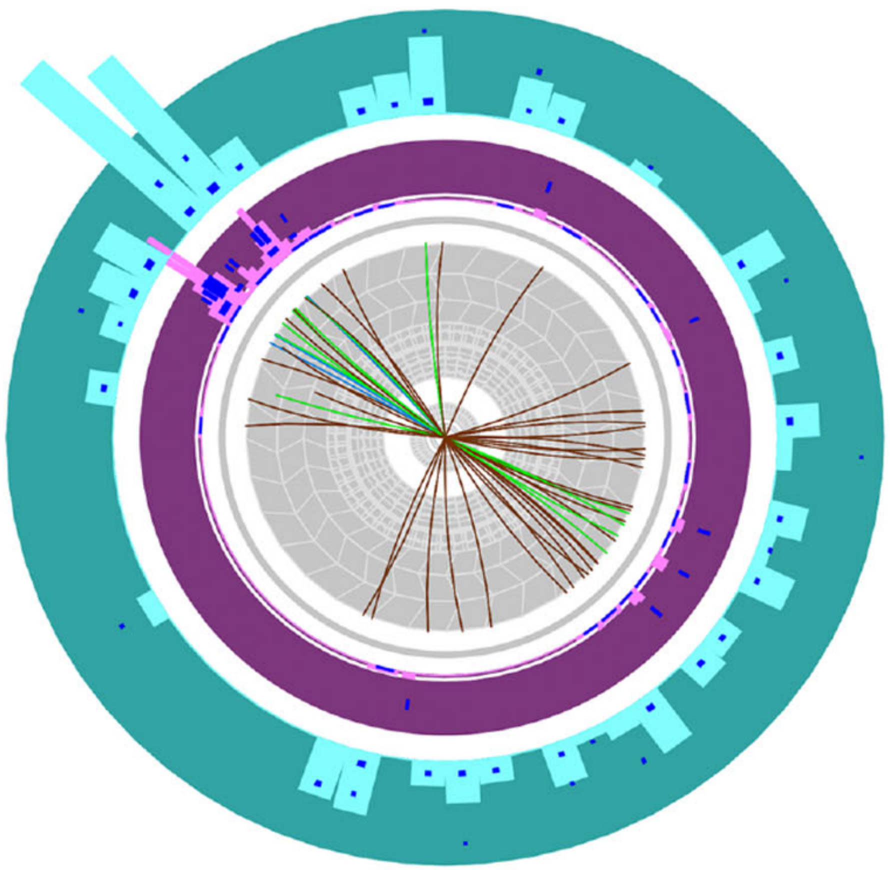


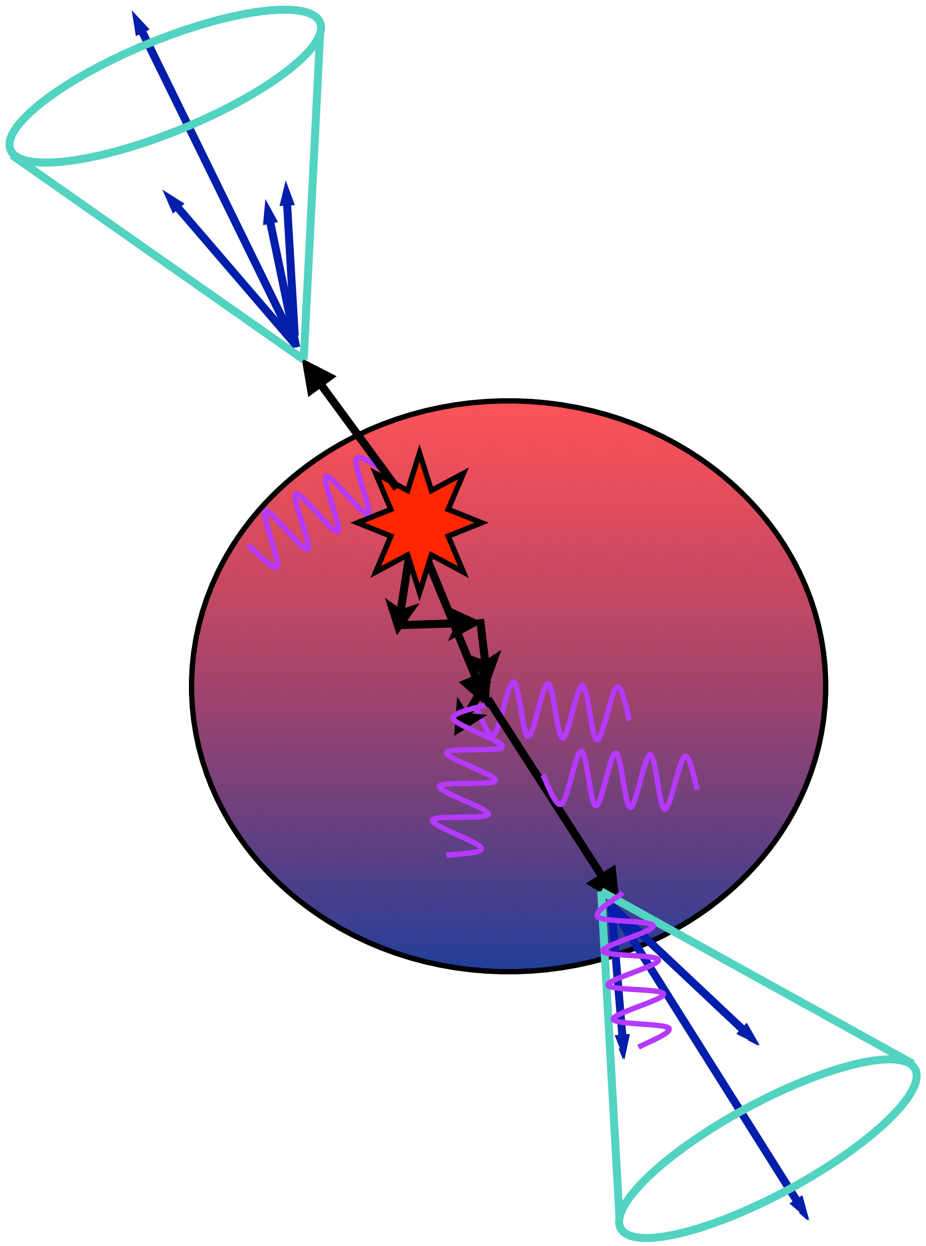
PLB 790 (2019) 108



more central collisions

picture: energy is lost from the jet cone as jets interact with the QGP

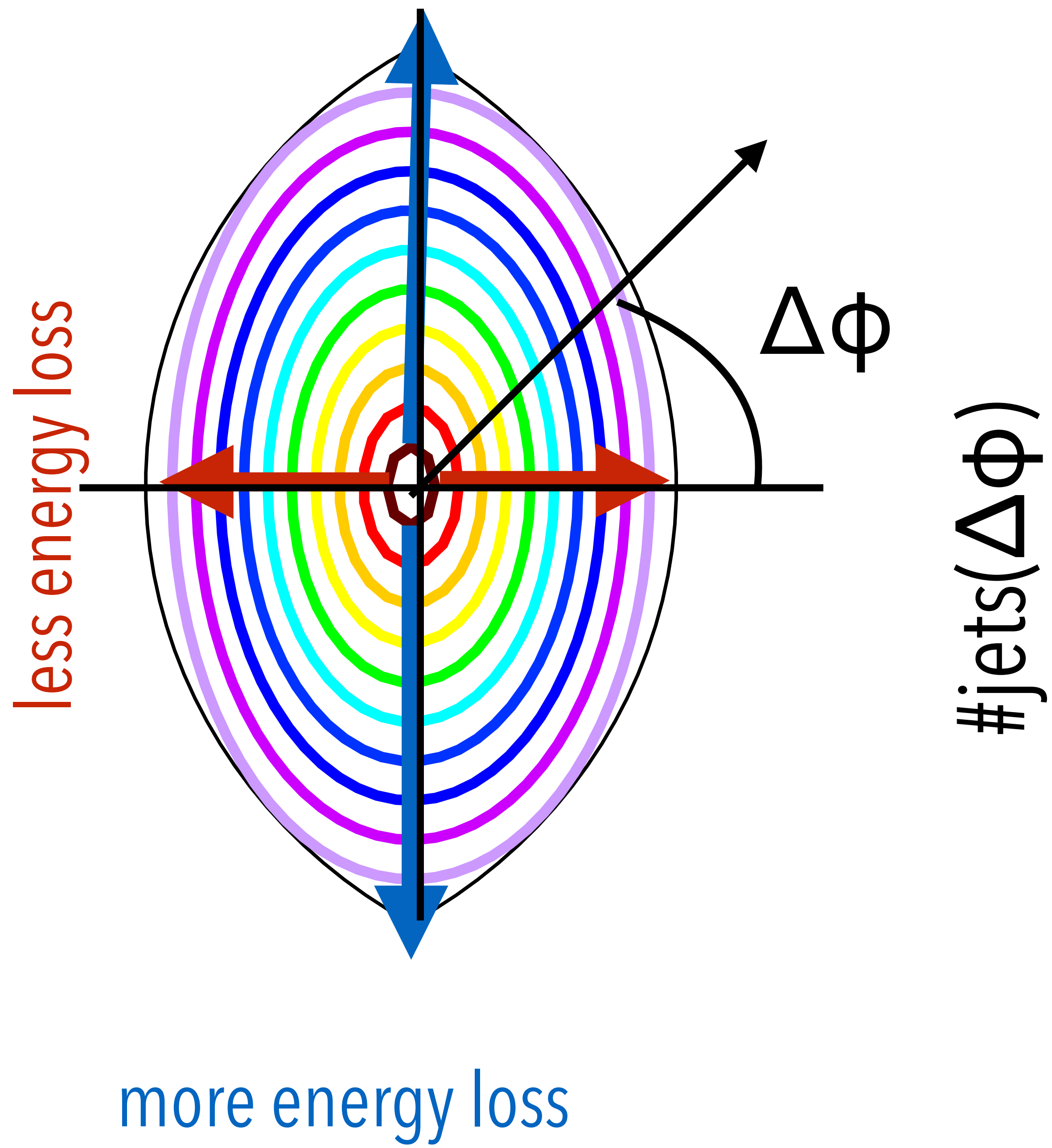




picture: energy is lost from the jet cone as jets interact with the QGP

path length dependence of jet quenching

jets of a given p_T are more likely to make it out if they go through the short side



PRL 111 152301 (2013)

path length dependence of jet quenching

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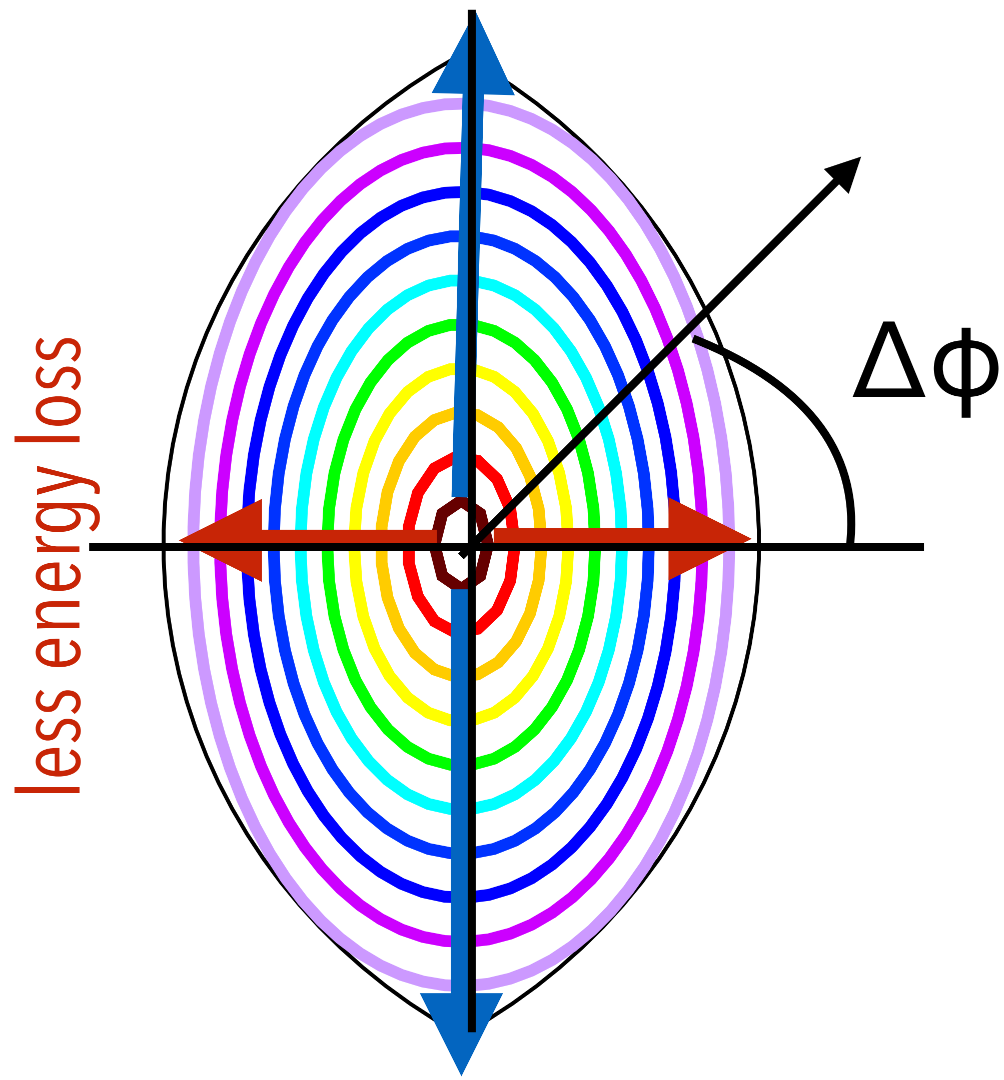
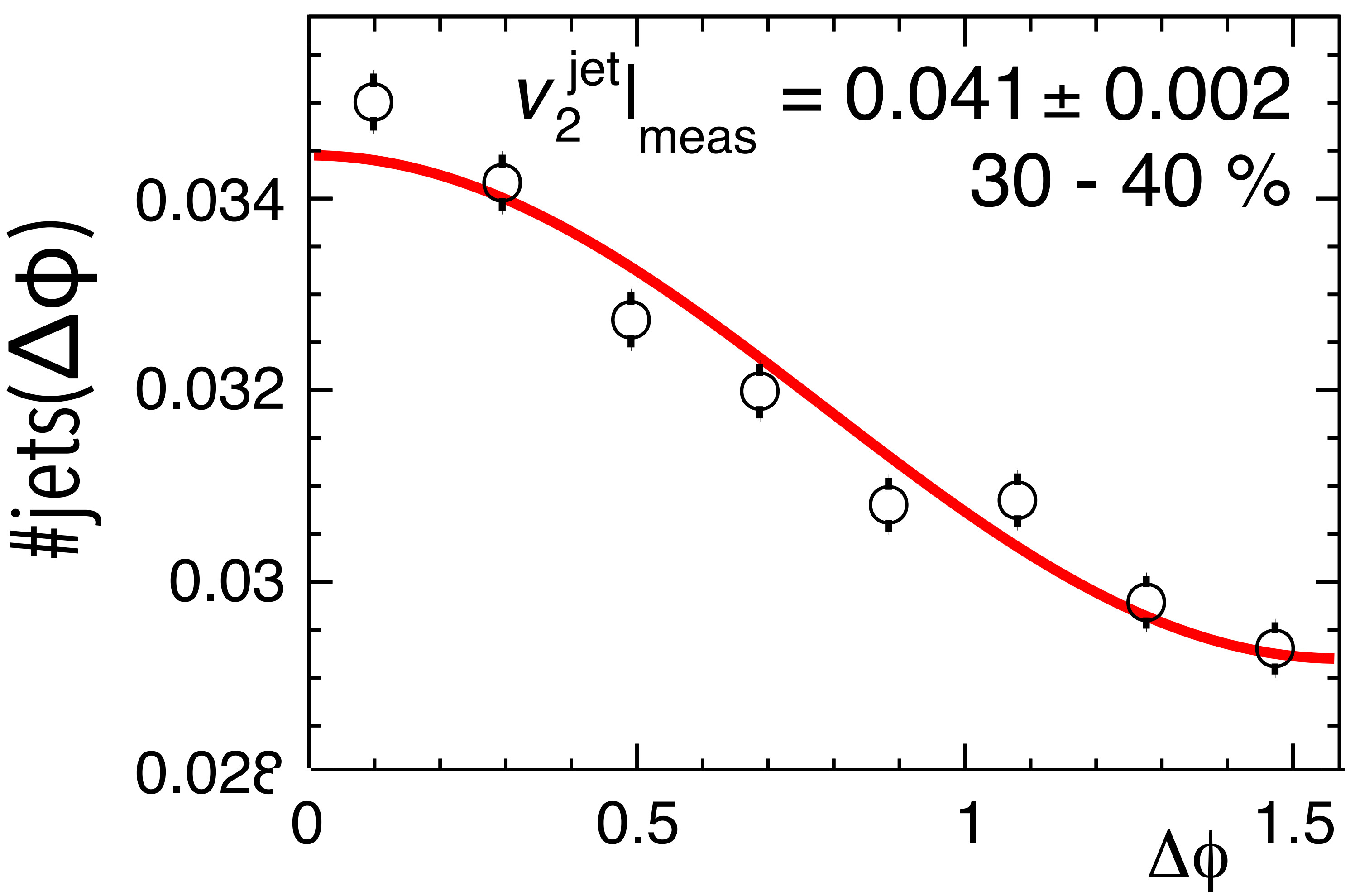


60 < p_T < 80 GeV R=0.2

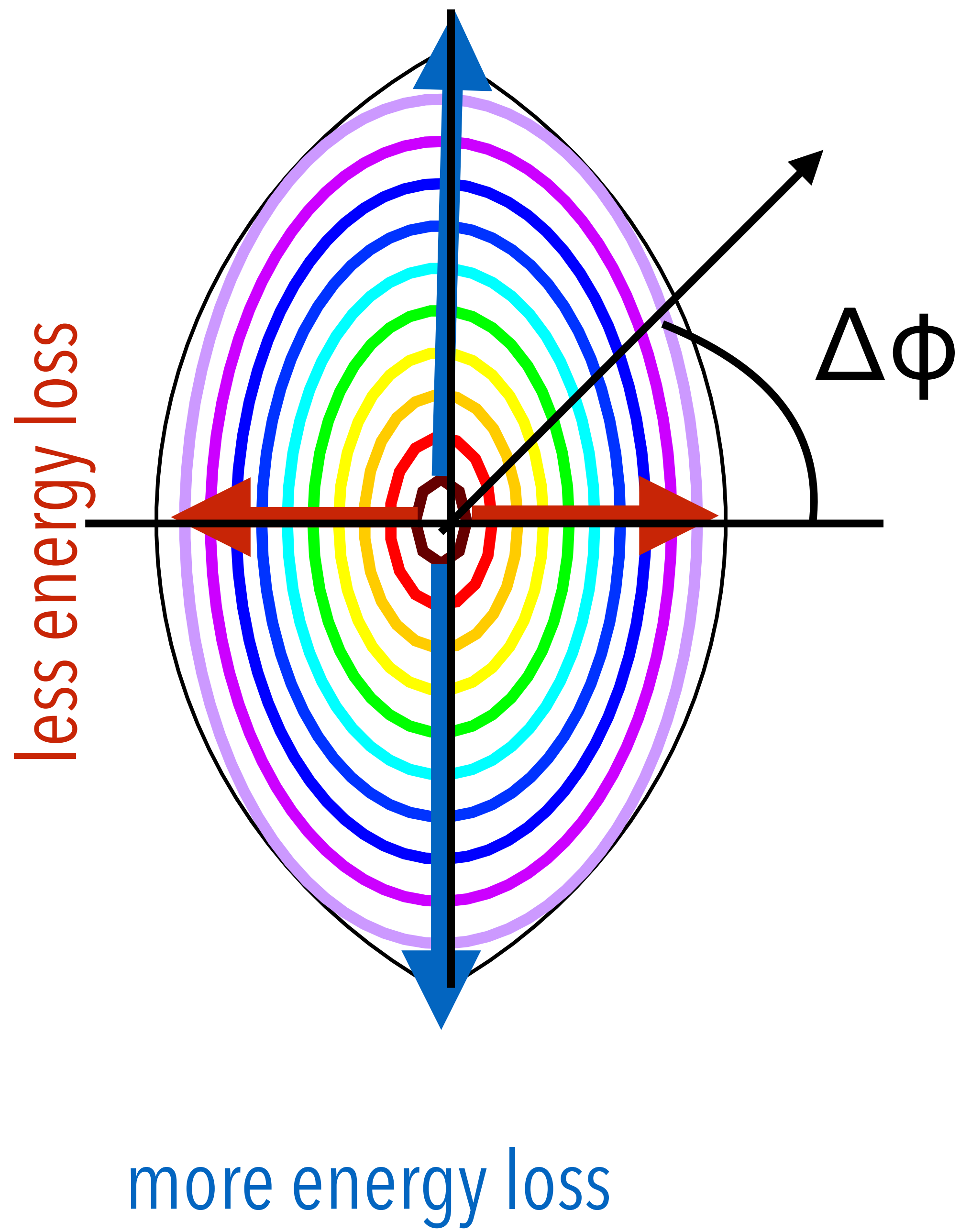


PRL 111 152301 (2013)

path length dependence of jet quenching

jets of a given p_T are more likely to make it out if they go through the short side

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$



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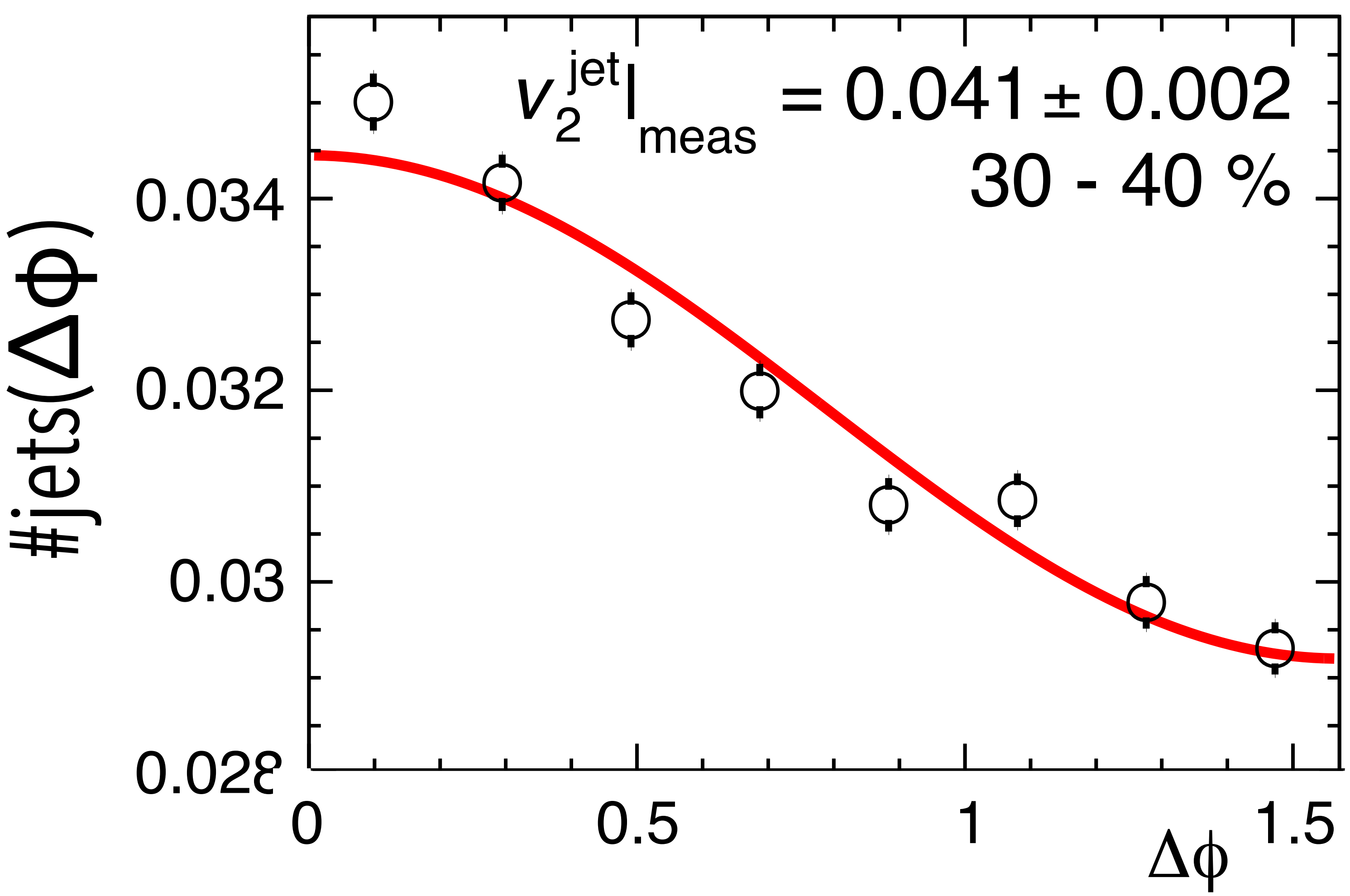
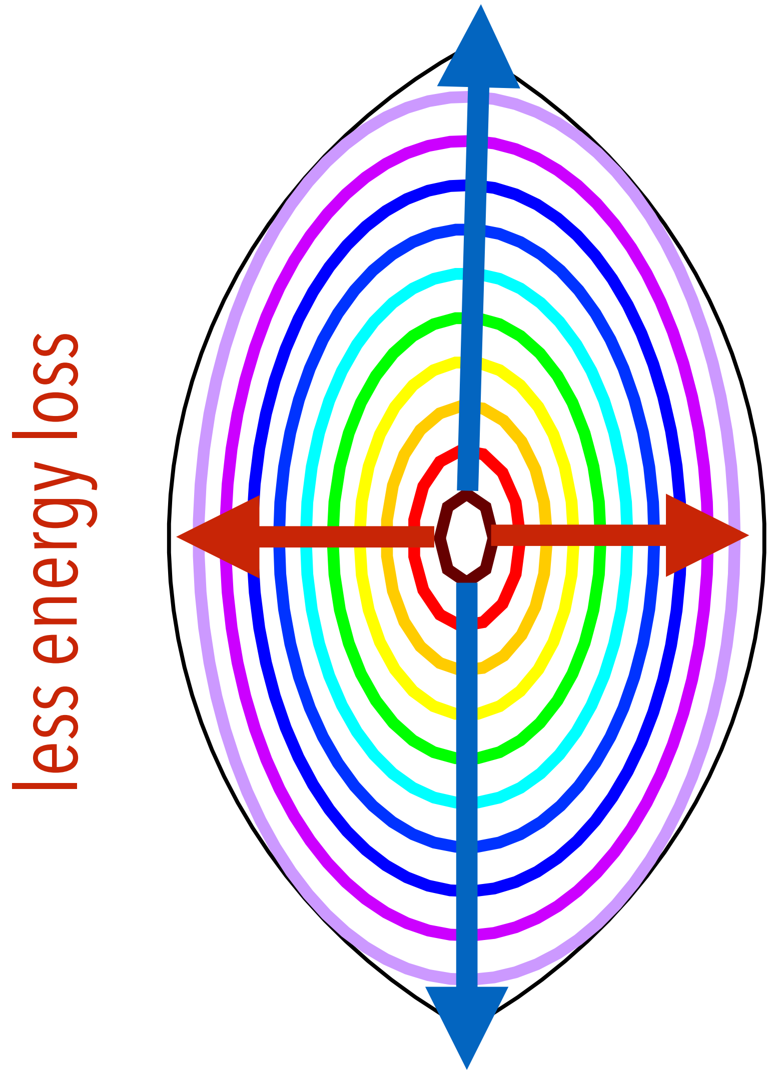
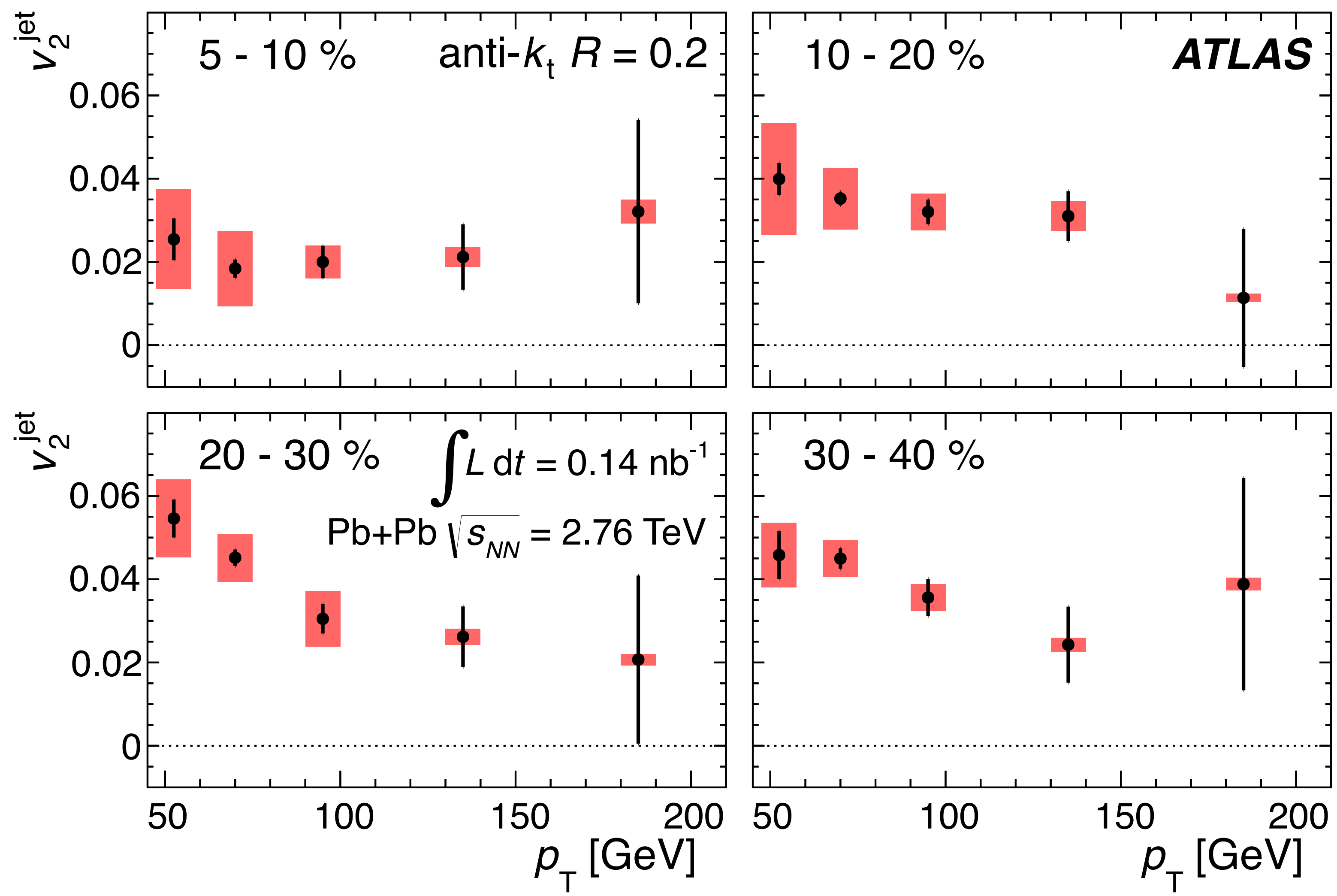


PRL 111 152301 (2013)

jets also have v_2



PRL 111 152301 (2013)

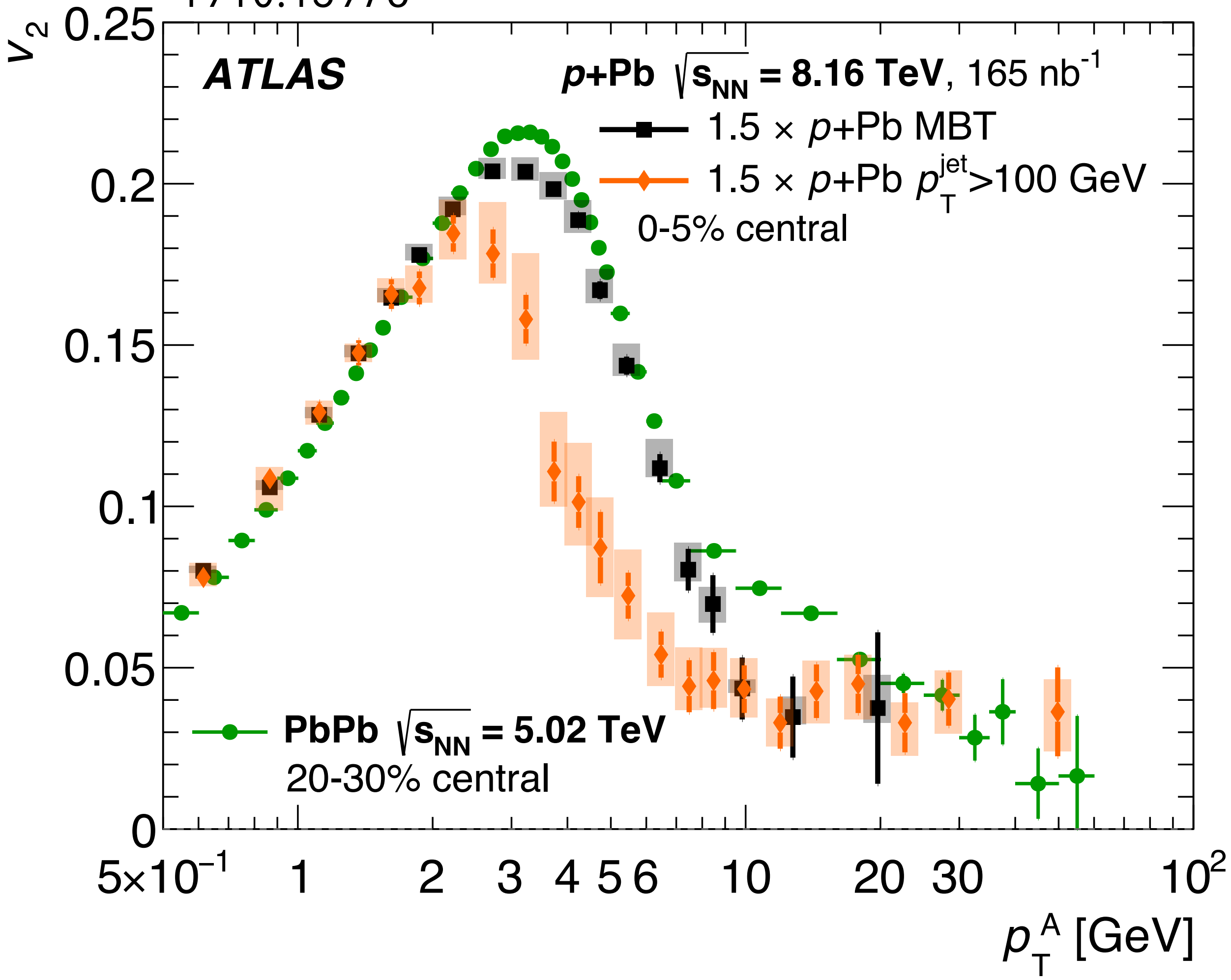


jet v_2 attributed to path length dependence of jet energy loss

but no quantitive model to explain both the R_{AA} and the v_2 of jets

pPb: v_2 without quenching

1910.13978



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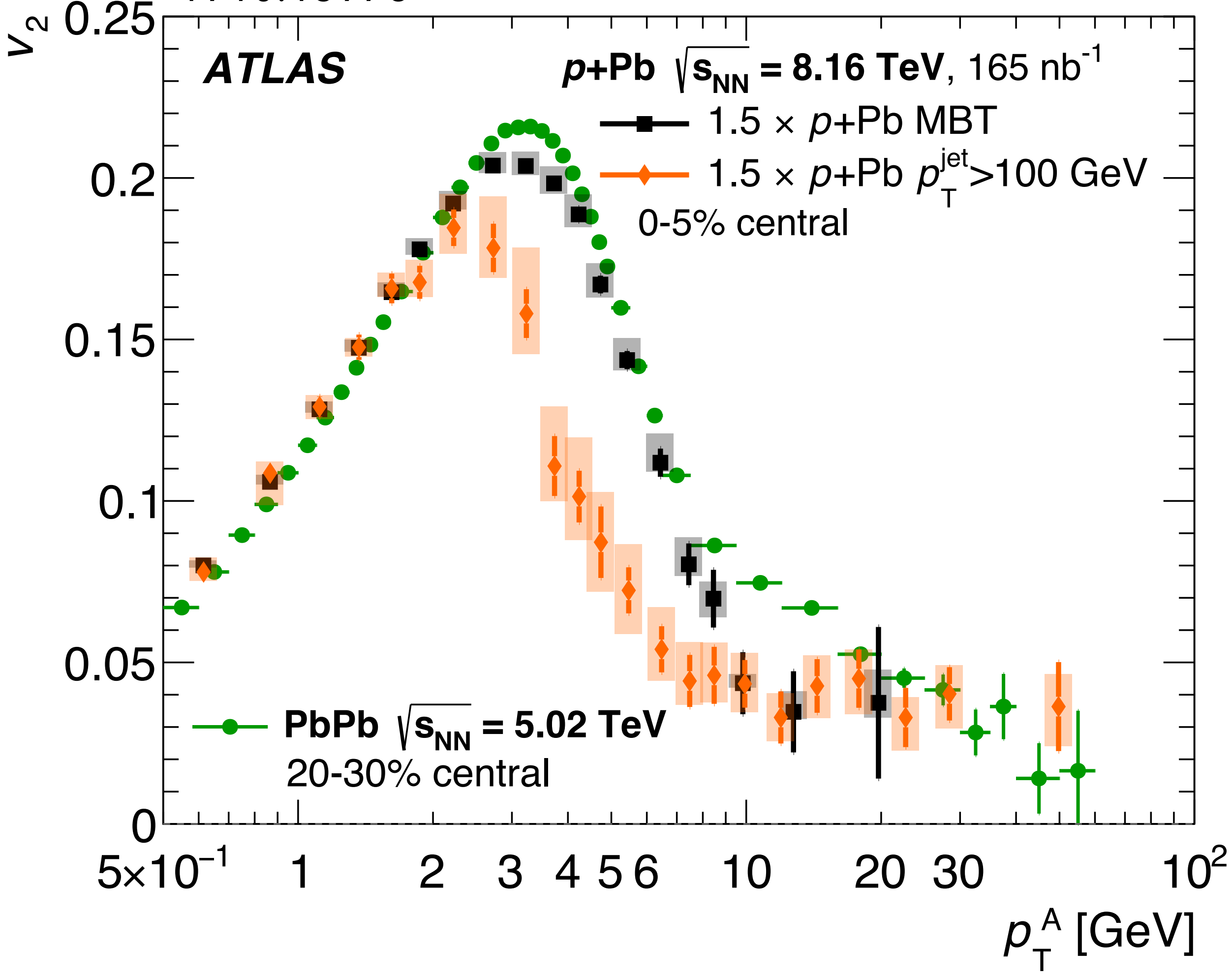
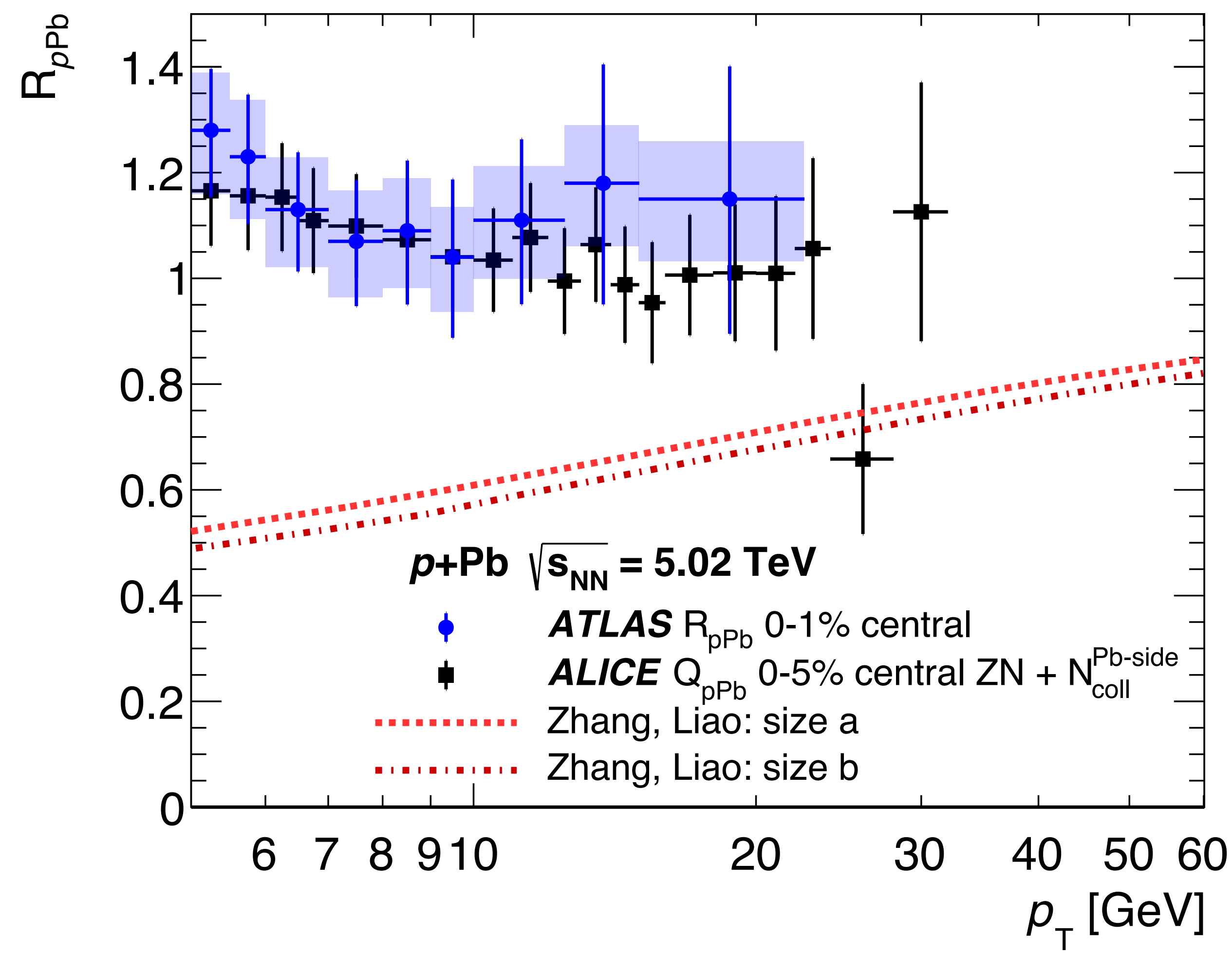
1910.13978





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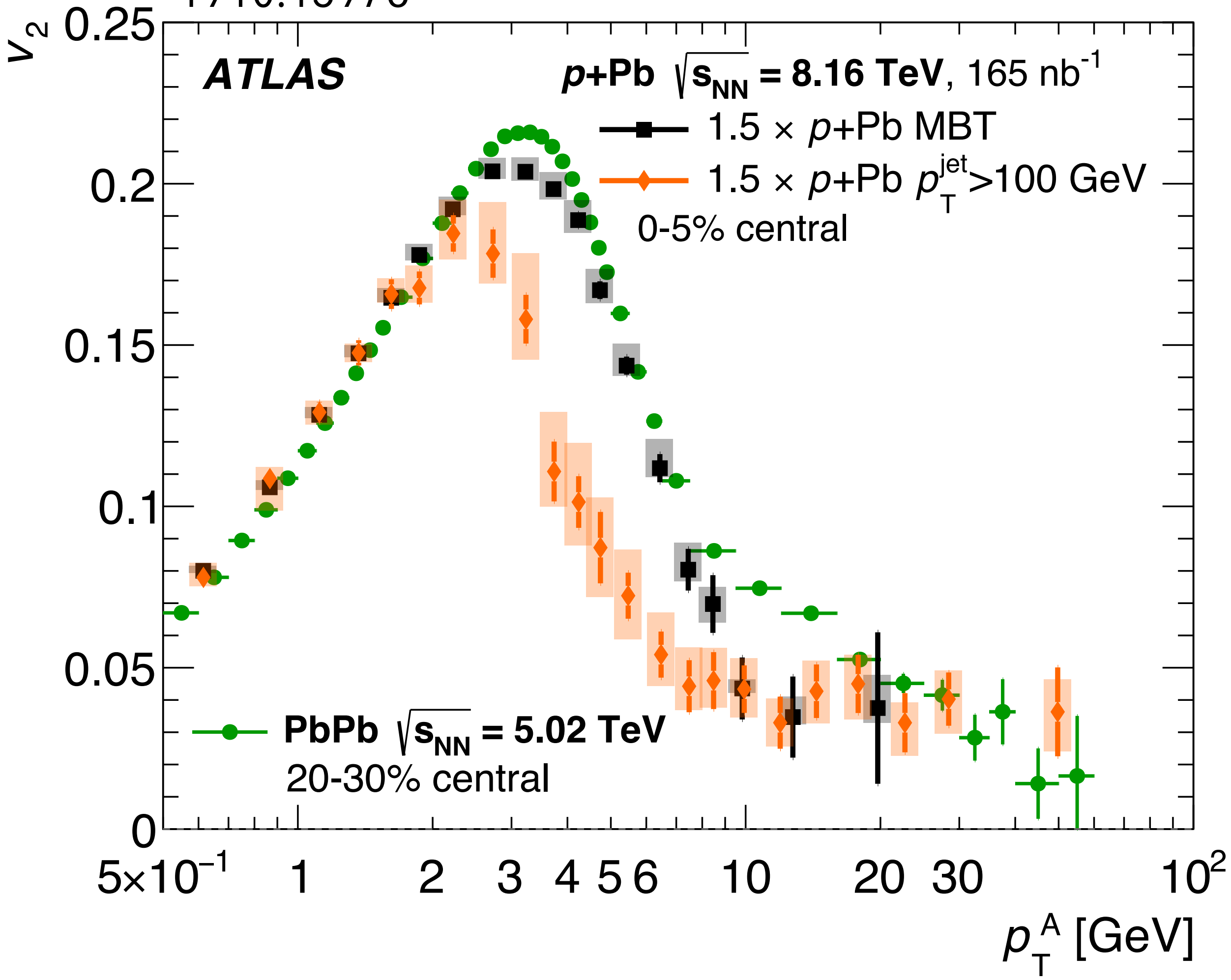
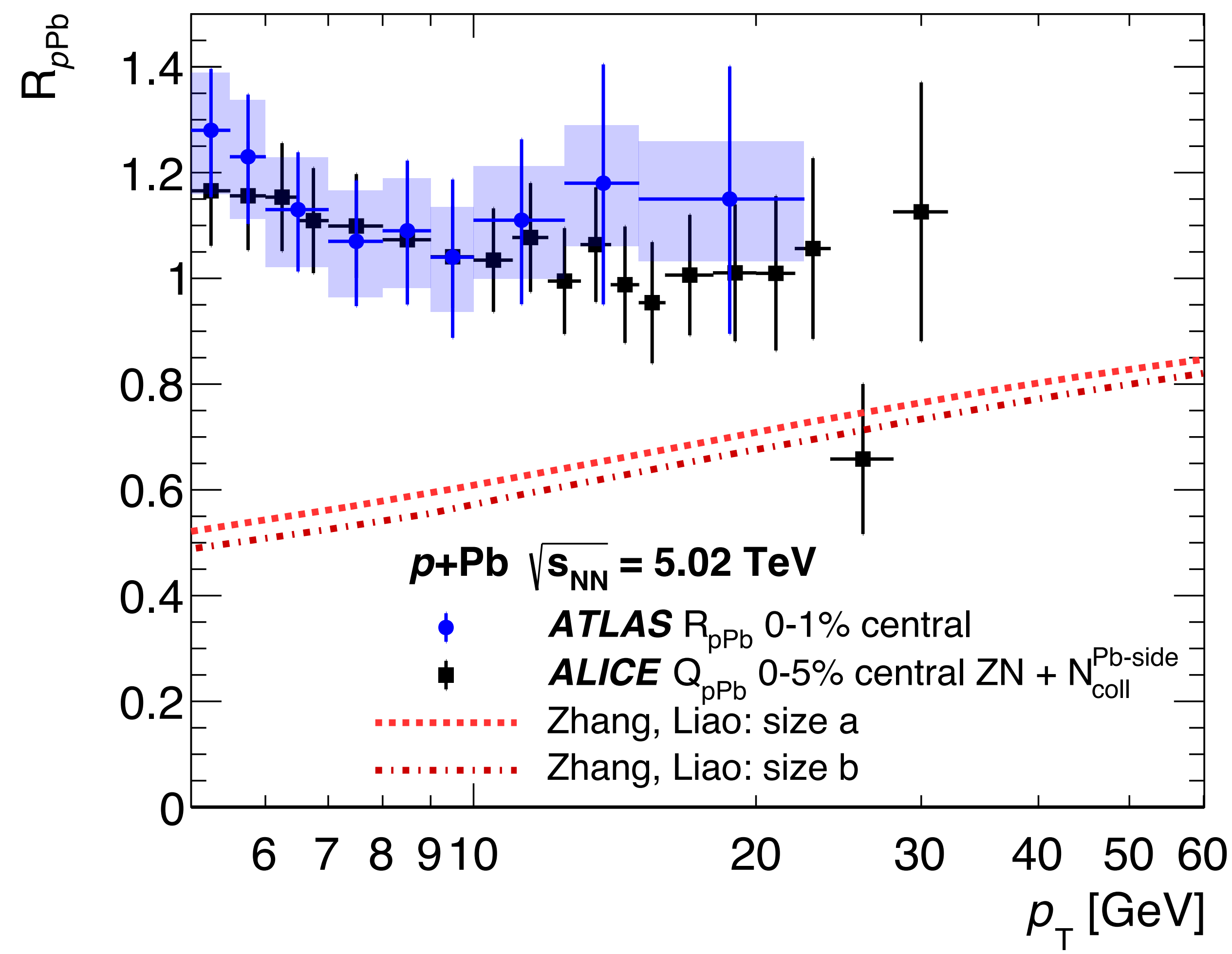
1910.13978



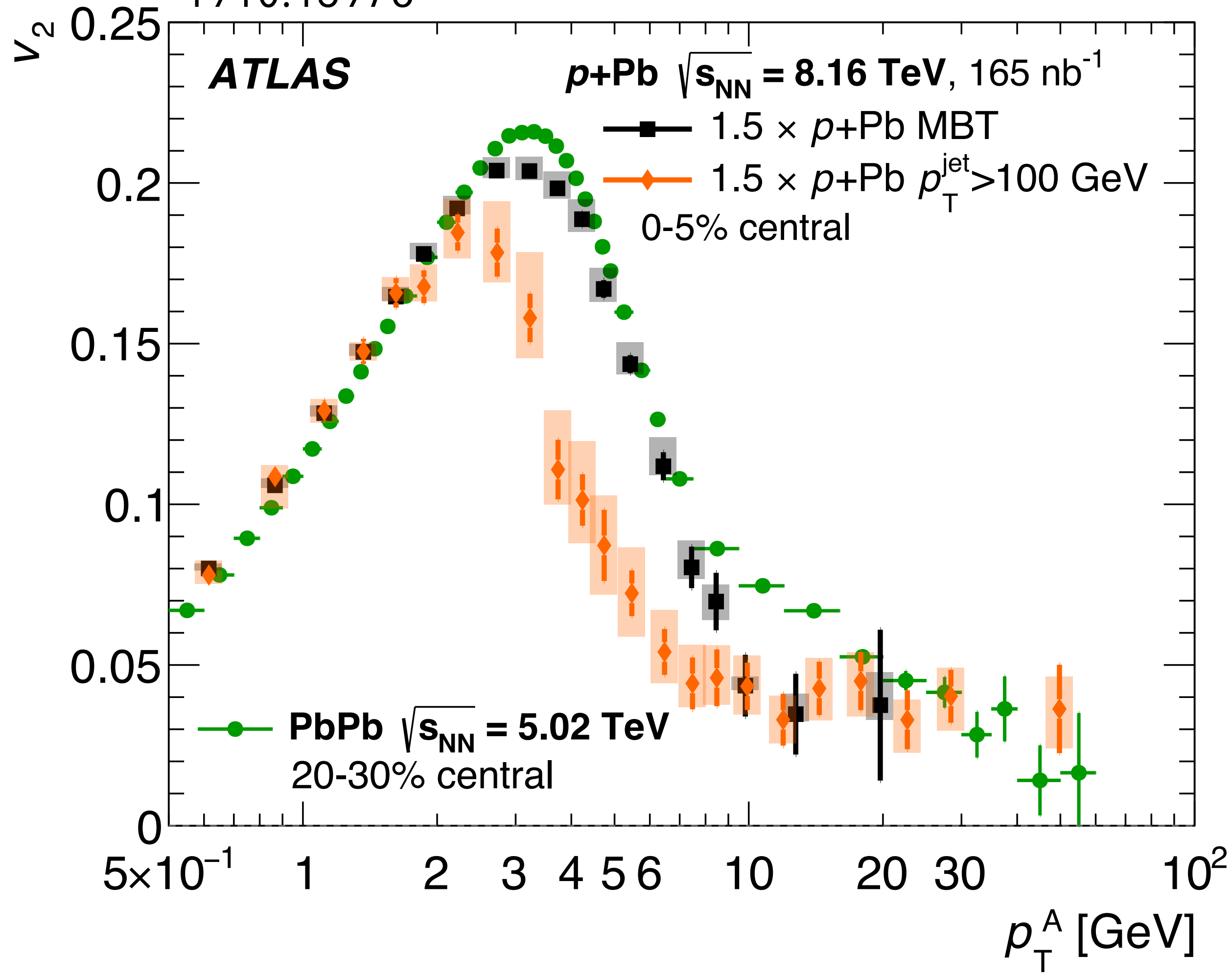


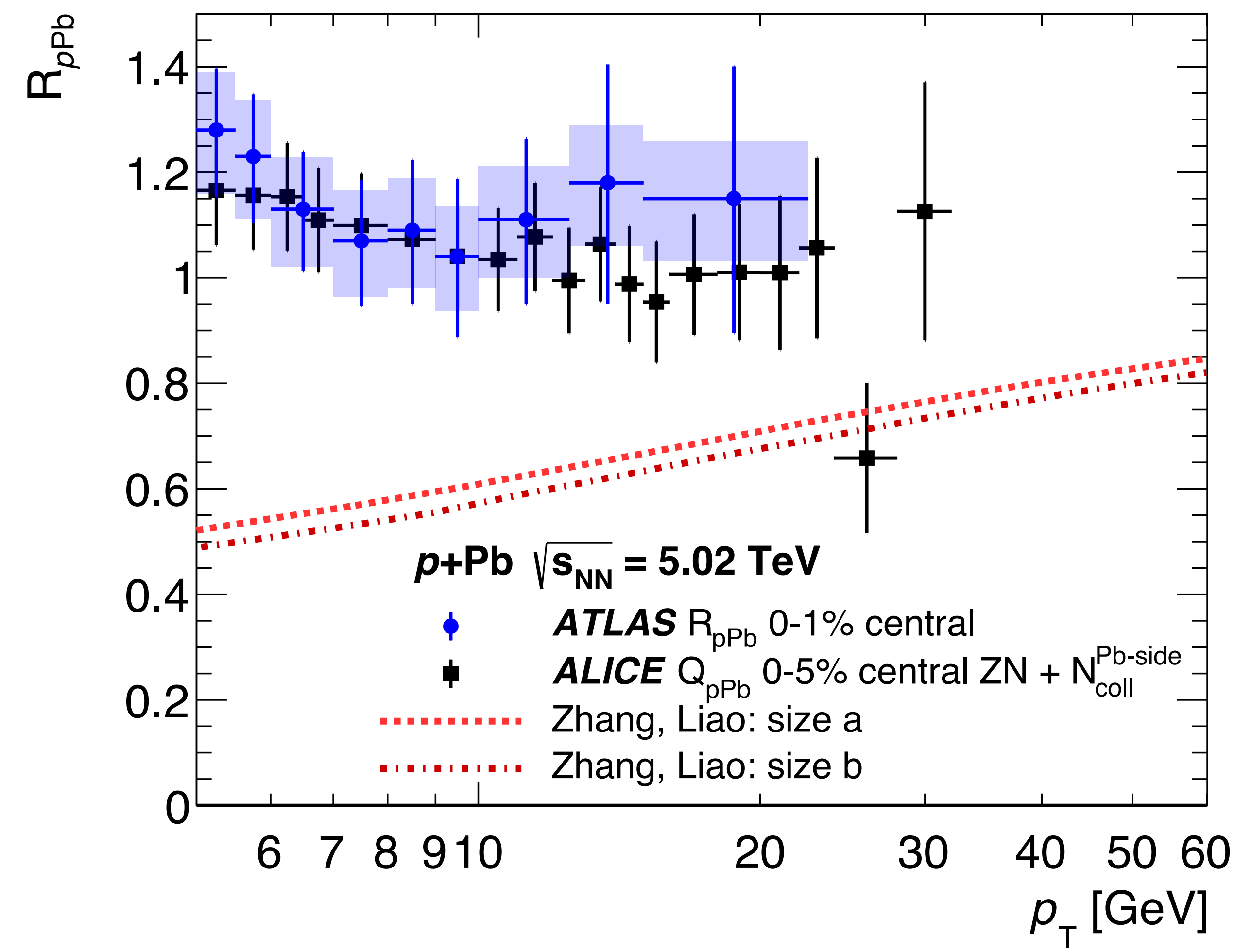
PbPb: $v_2 > 0$ & $R_{PbPb} < 1$

pPb: $v_2 > 0$ & $R_{pPb} \approx 1$

pPb: v_2 without quenching

1910.13978





PbPb: $v_2 > 0$ & $R_{PbPb} < 1$

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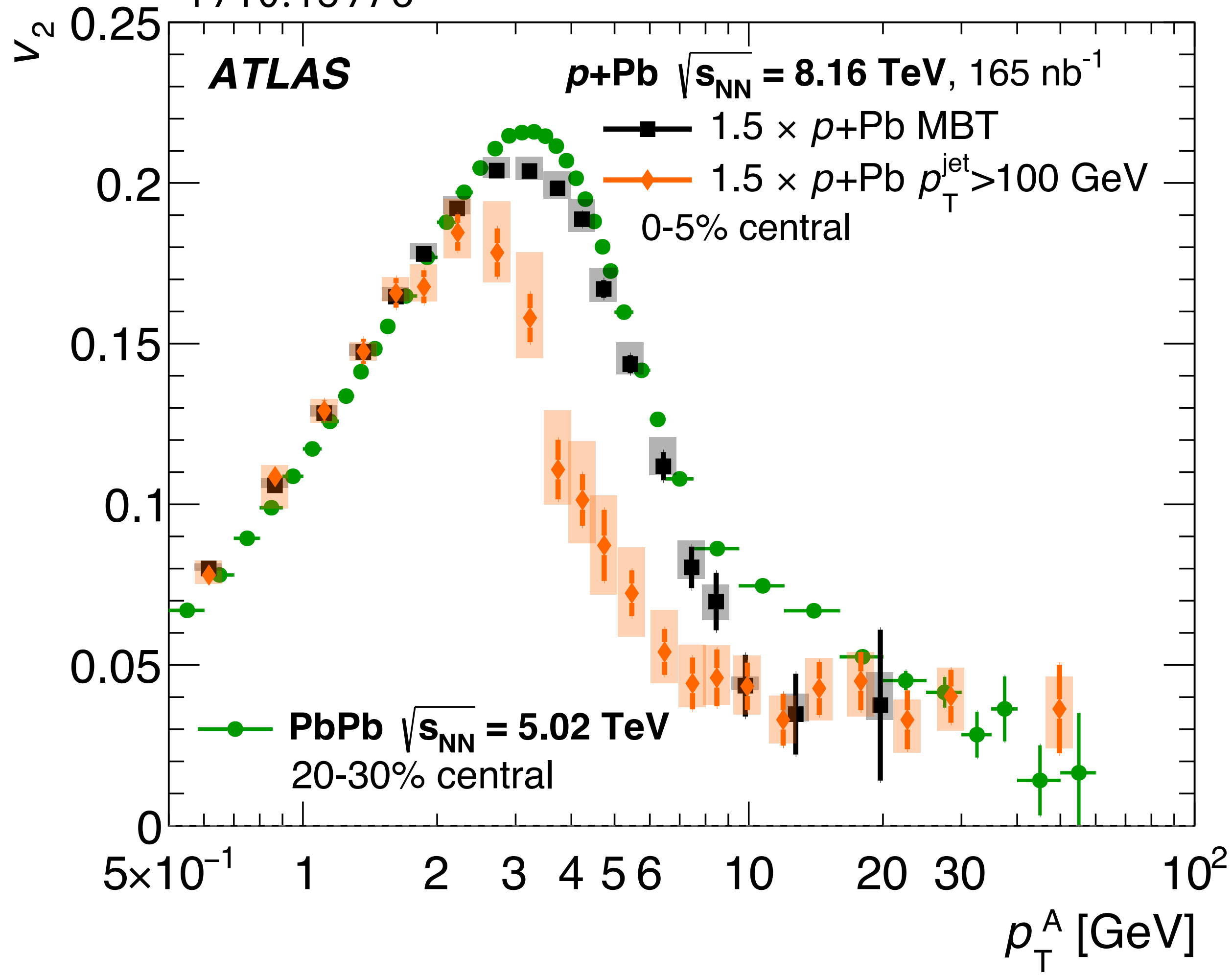
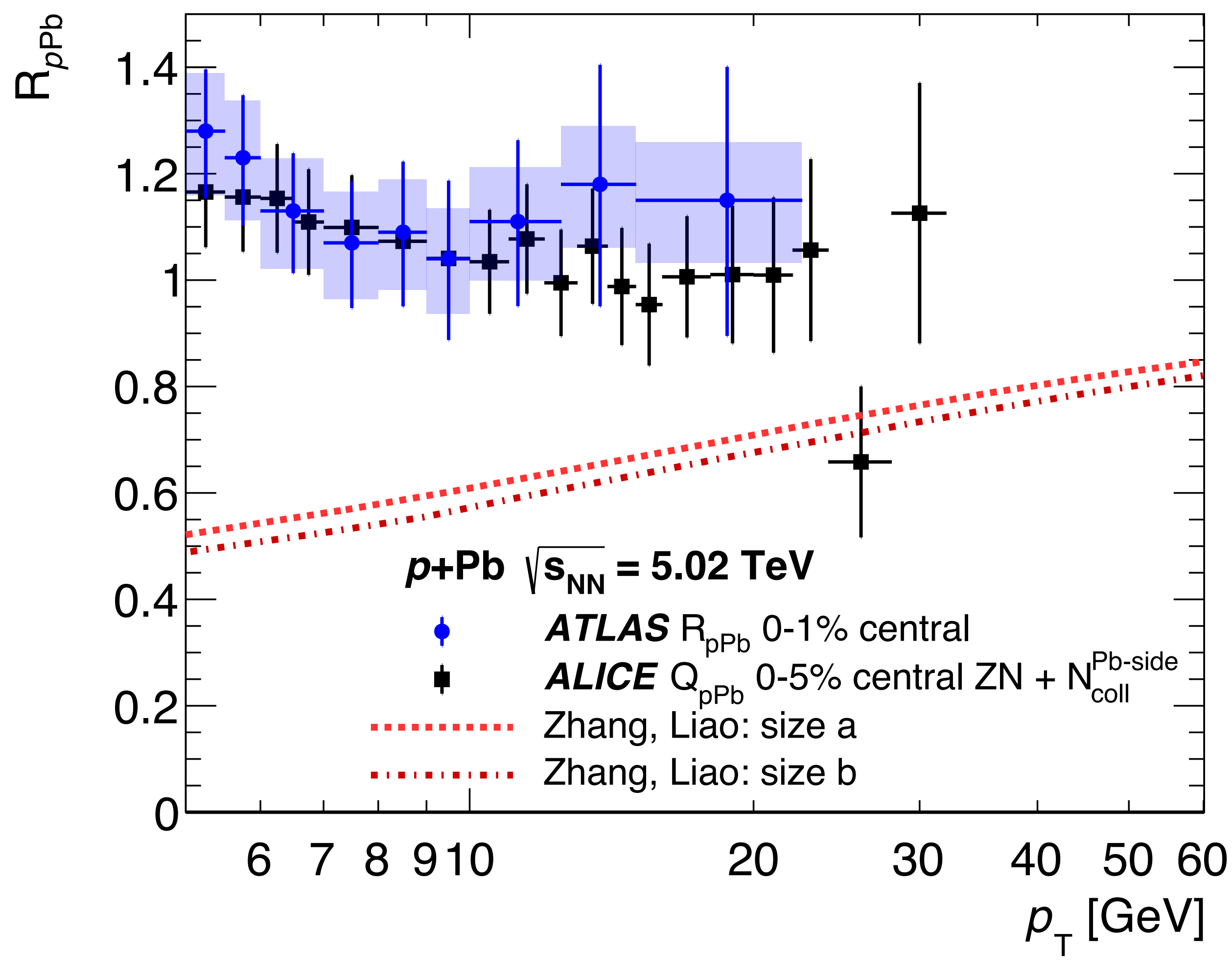
do the v_2 in PbPb and pPb collisions have the same origin?

is the picture of $\Delta E(L)$ in PbPb right?

pPb: v_2 without quenching

1910.13978





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do the v_2 in PbPb and pPb collisions have the same origin?

is the picture of $\Delta E(L)$ in PbPb right?

light ion collisions with a different geometry but the same size as pPb could help clarify this

summary

- from PbPb → pp collisions: observation of v_n describable with hydrodynamics
    - constraining the properties of the quark-gluon plasma
    - XeXe and OO collisions provide a way to understand the interplay between geometry and fluctuations
    - provocative new measurement of v_2 in γ-Pb collisions!
- differences between v_2 for charm and bottom quarks observed
    - no significant $v_2(b \rightarrow \mu)$ in pp collisions
    - opportunity to understand the dynamics of the QGP!
- similarity of v_2 at high p_T in PbPb and pPb collisions despite very different system size and jet quenching
    - not understood
    - OO collisions would provide a key guide for jet quenching in small systems

summary

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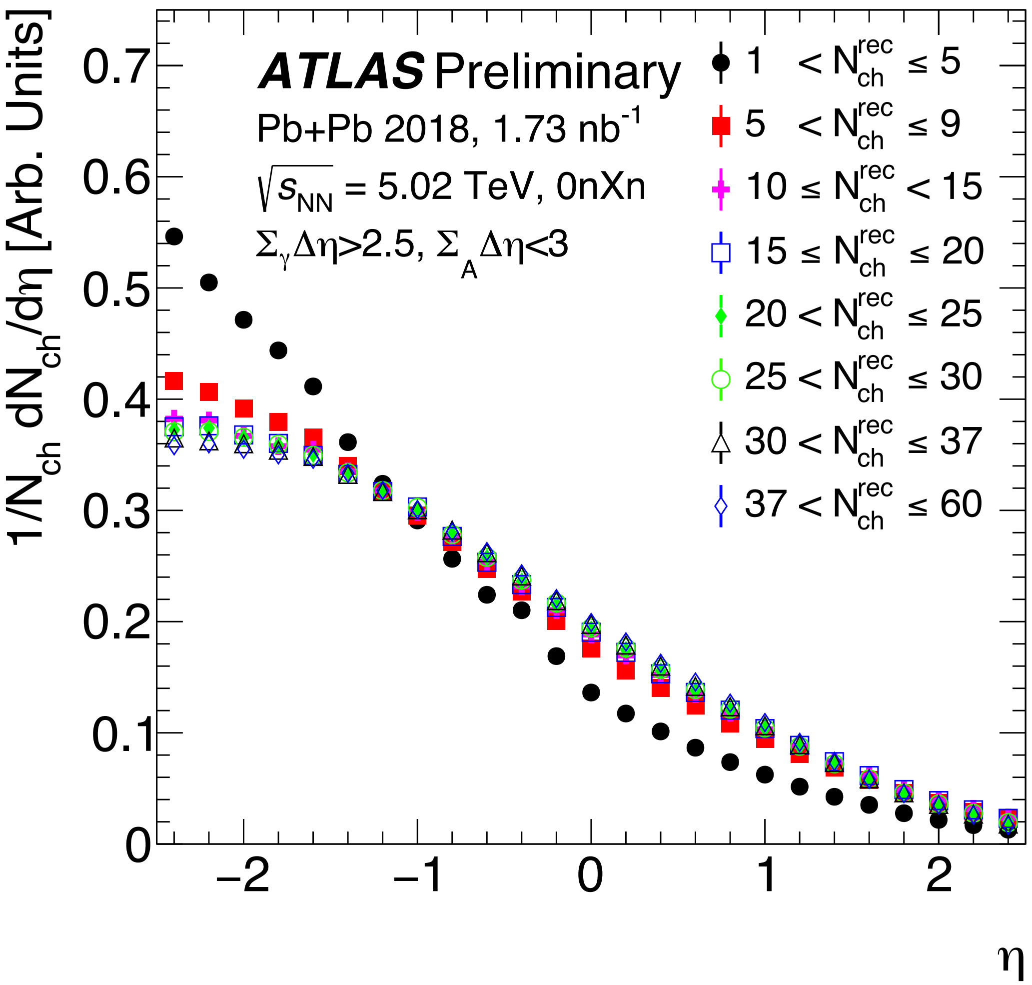
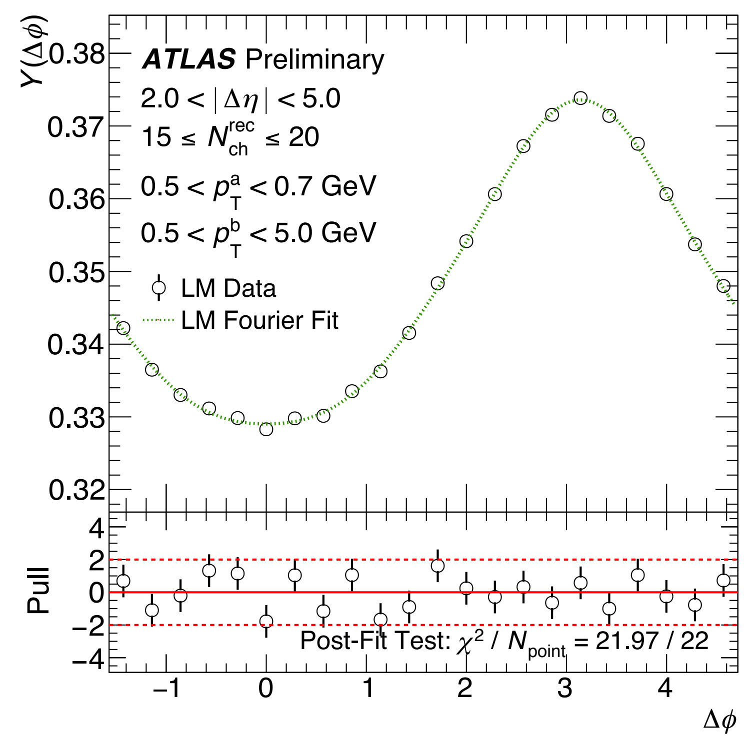
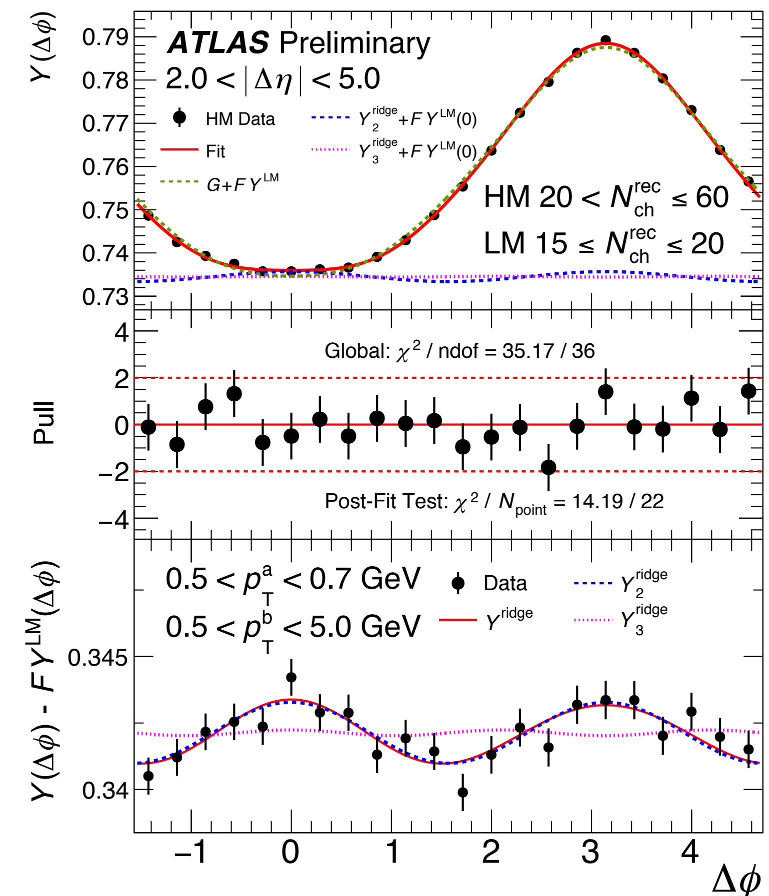
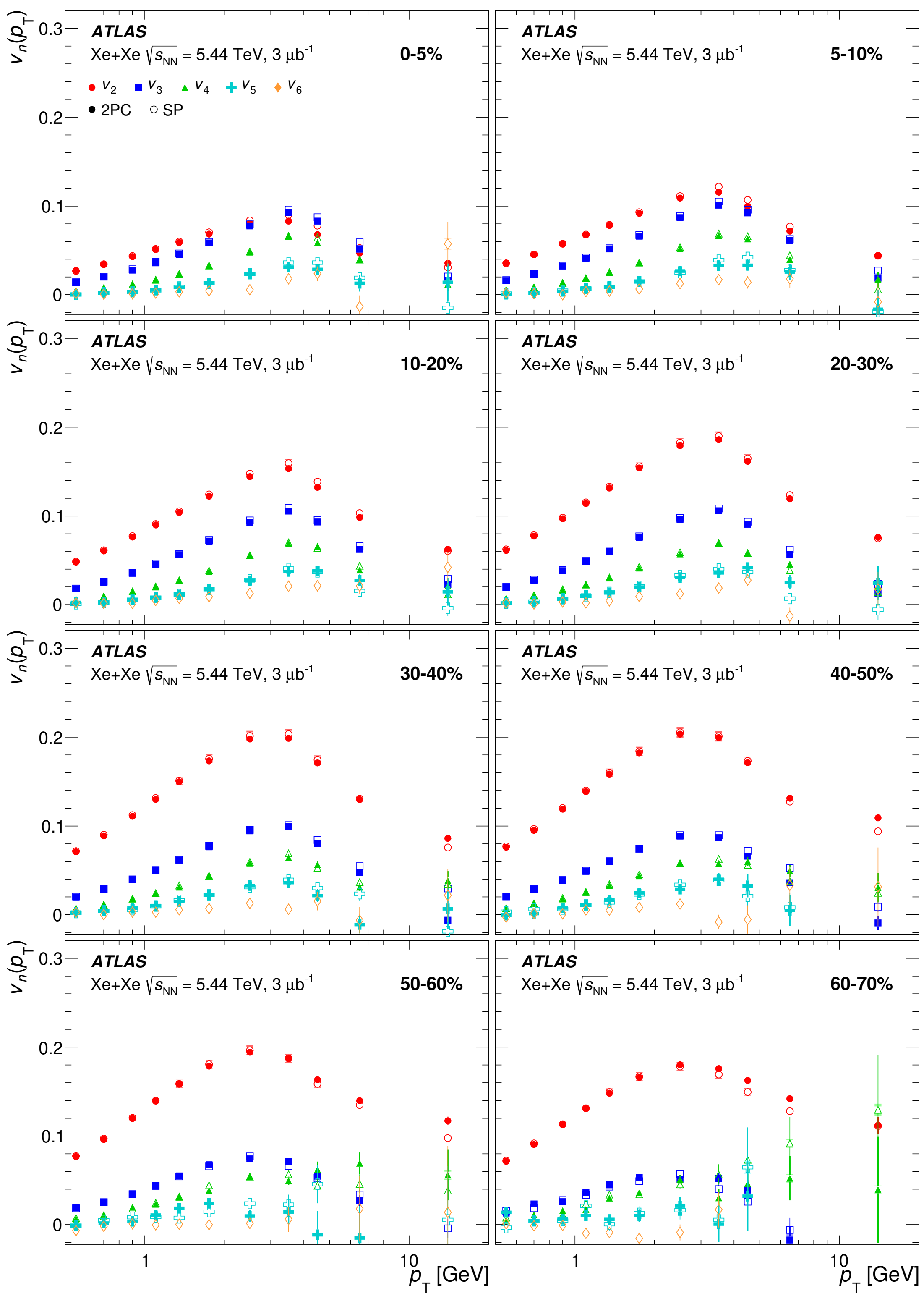
  - OO collisions would provide a key guide for jet quenching in small systems

we're looking forward to more analyses from Run 2 data and new opportunities in Run 3 backups

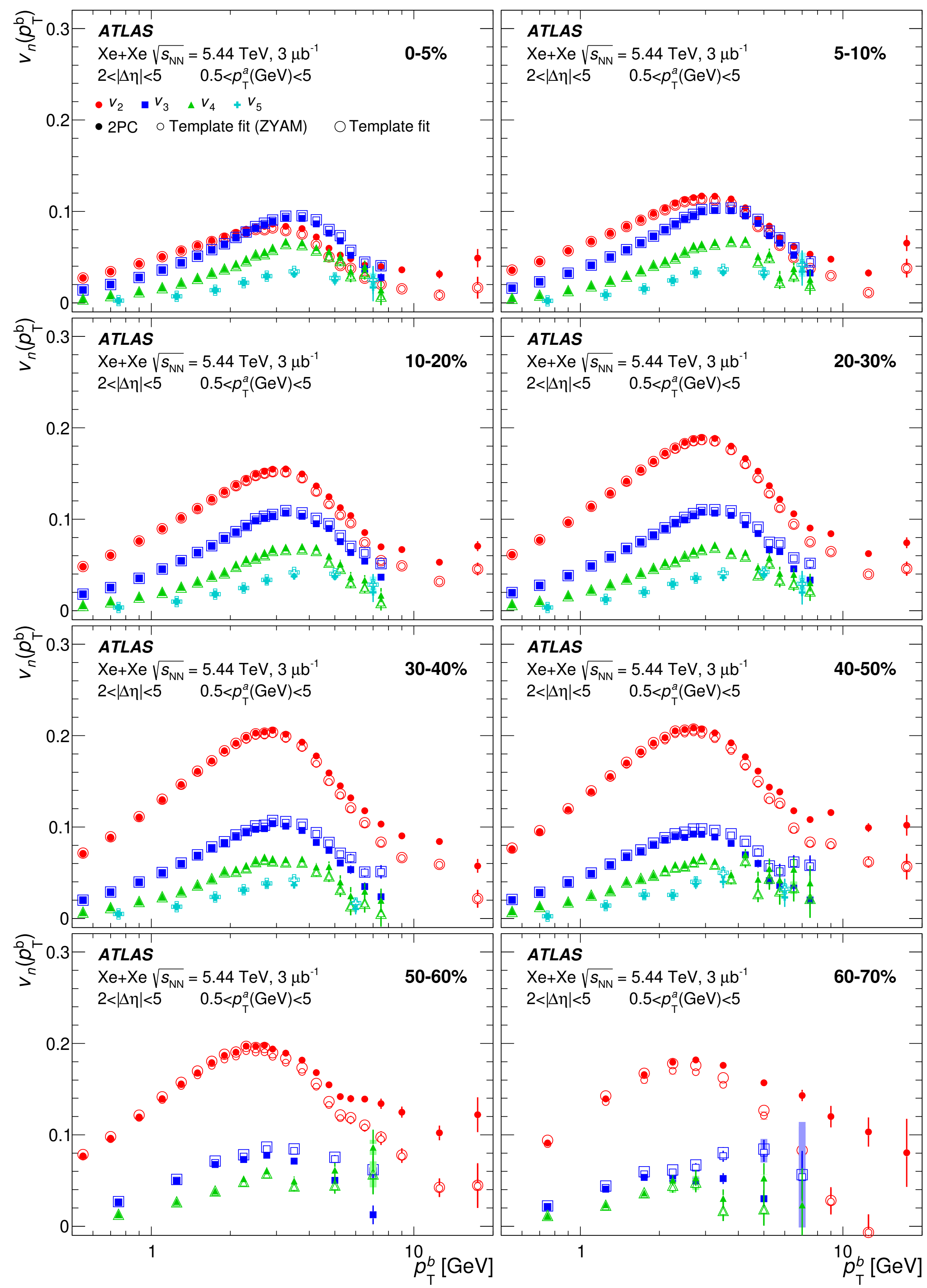

ATLAS Preliminary
Pb+Pb 2018, 1.73 nb^{-1}
$\sqrt{s_{NN}}$ = 5.02 TeV, 0nXn
$\Sigma_{\gamma}\Delta\eta$>2.5, $\Sigma_{A}\Delta\eta$<3
$1 < N_{ch}^{rec} \leq 5$
$5 < N_{ch}^{rec} \leq 9$
$10 \leq N_{ch}^{rec} < 15$
$15 \leq N_{ch}^{rec} \leq 20$
$20 < N_{ch}^{rec} \leq 25$
$25 < N_{ch}^{rec} \leq 30$
$30 < N_{ch}^{rec} \leq 37$
$37 < N_{ch}^{rec} \leq 60$
$1/N_{ch}\, dN_{ch}/d\eta$ [Arb. Units]
η


ATLAS Preliminary
$2.0 < |\Delta\eta| < 5.0$
$15 \leq N_{ch}^{rec} \leq 20$
$0.5 < p_T^a < 0.7$ GeV
$0.5 < p_T^b < 5.0$ GeV
LM Data
LM Fourier Fit
$Y(\Delta\phi)$
Pull
Post-Fit Test: χ^2 / N_{point} = 21.97 / 22
$\Delta\phi$


ATLAS Preliminary
$2.0 < |\Delta\eta| < 5.0$
HM Data
Fit
$G+F\,Y^{LM}$
$Y_2^{ridge}+F\,Y^{LM}(0)$
$Y_3^{ridge}+F\,Y^{LM}(0)$
HM $20 < N_{ch}^{rec} \leq 60$
LM $15 \leq N_{ch}^{rec} \leq 20$
$Y(\Delta\phi)$
Global: χ^2 / ndof = 35.17 / 36
Pull
Post-Fit Test: χ^2 / N_{point} = 14.19 / 22
$0.5 < p_T^a < 0.7$ GeV
$0.5 < p_T^b < 5.0$ GeV
Data
Y^{ridge}
Y_2^{ridge}
Y_3^{ridge}
$Y(\Delta\phi) - F\,Y^{LM}(\Delta\phi)$
$\Delta\phi$



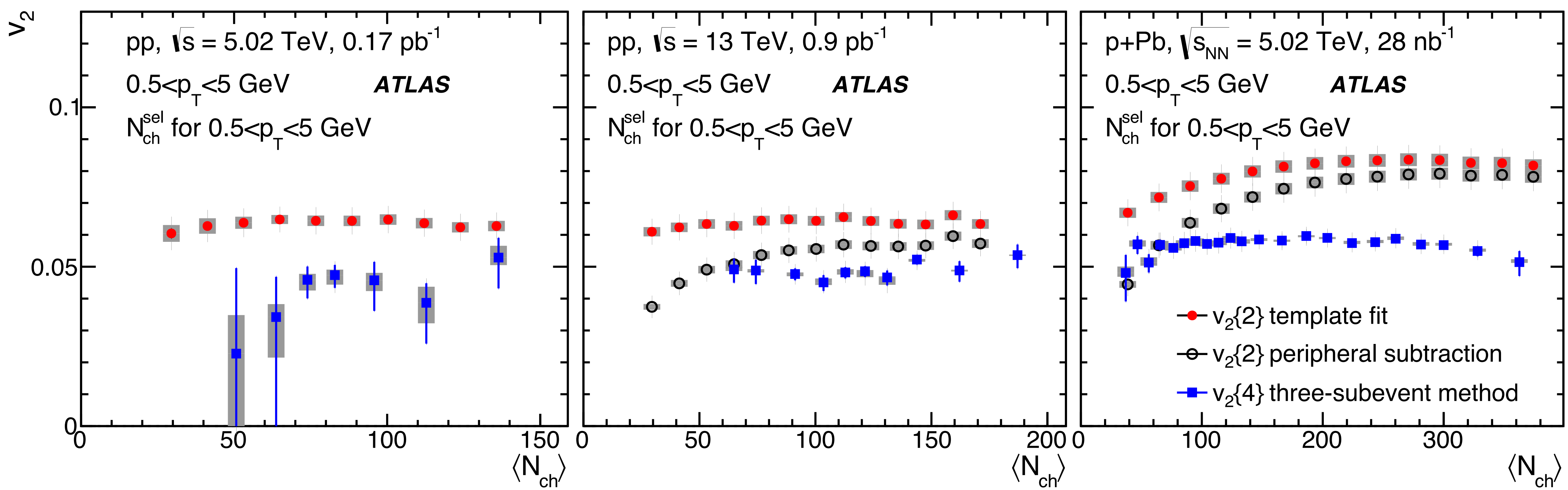
ATLAS
Xe+Xe √s_NN = 5.44 TeV, 3 μb⁻¹
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
v2 v3 v4 v5 v6
2PC SP
vn(pT)
pT [GeV]



ATLAS
Xe+Xe √s_NN = 5.44 TeV, 3 μb⁻¹
2<|Δη|<5 0.5<p_T^a(GeV)<5
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
v2 v3 v4 v5
2PC Template fit (ZYAM) Template fit
vn(p_T^b)
p_T^b [GeV]

1911.04812

template fit/4 particle correlations



1708.03559