Soft particle production and collectivity in small systems

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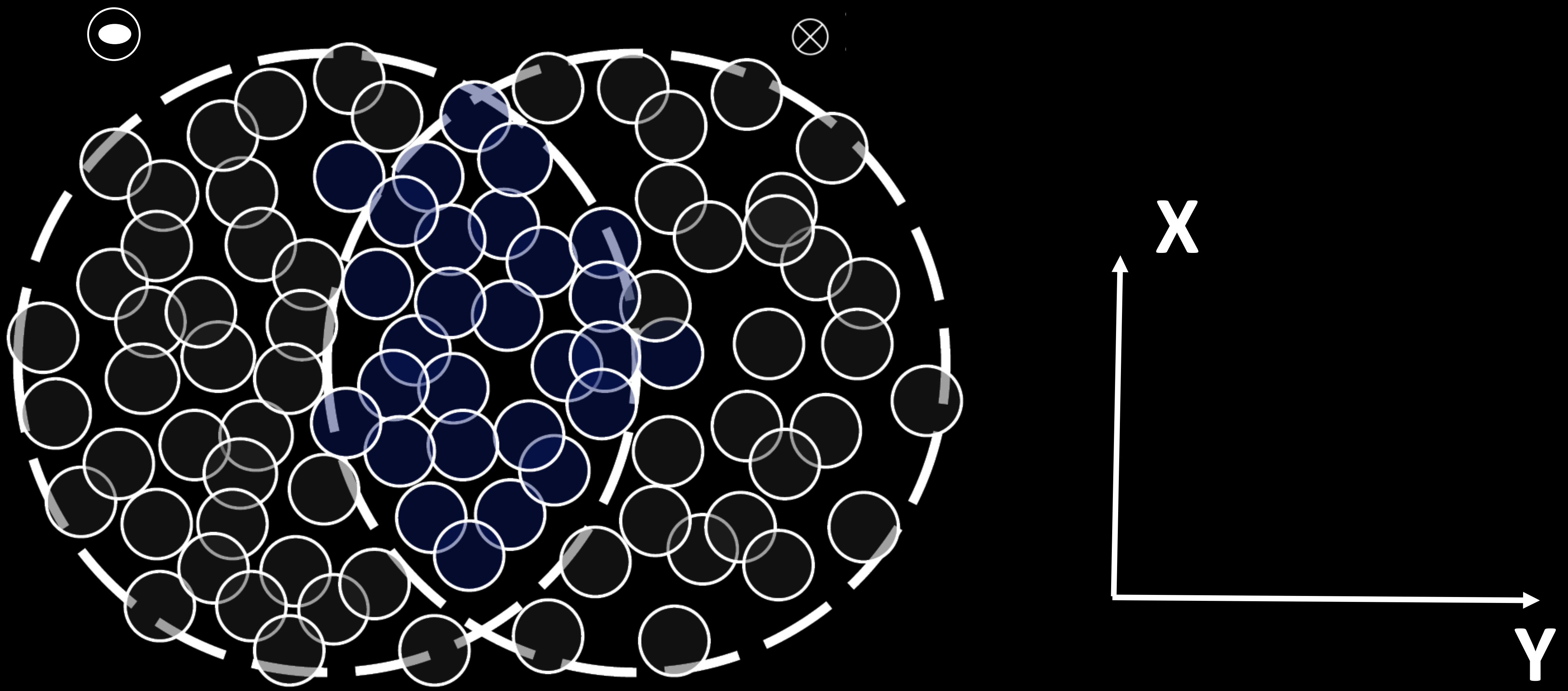
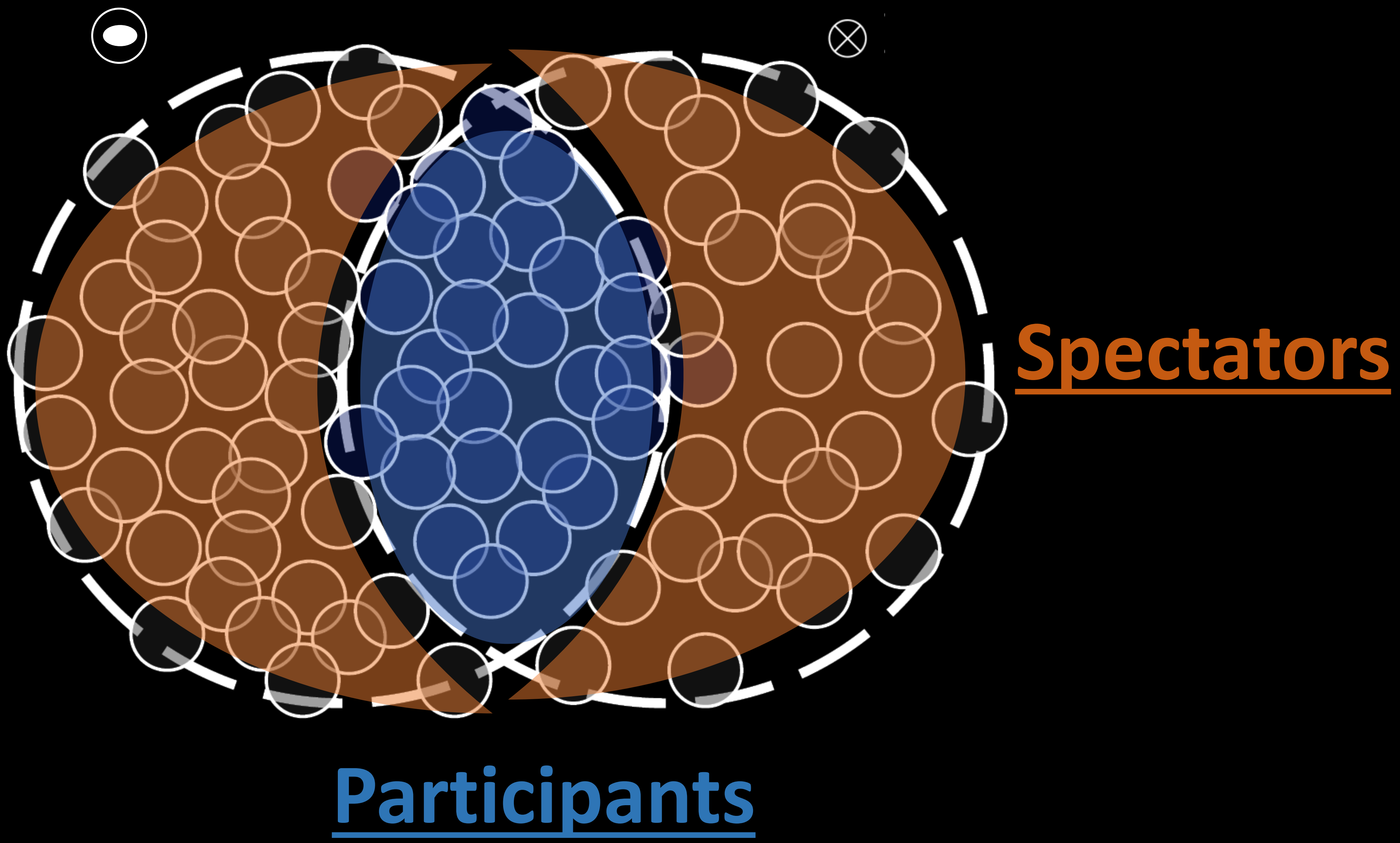
Columbia University

On behalf of:

ALICE, ATLAS, CMS, and LHCb

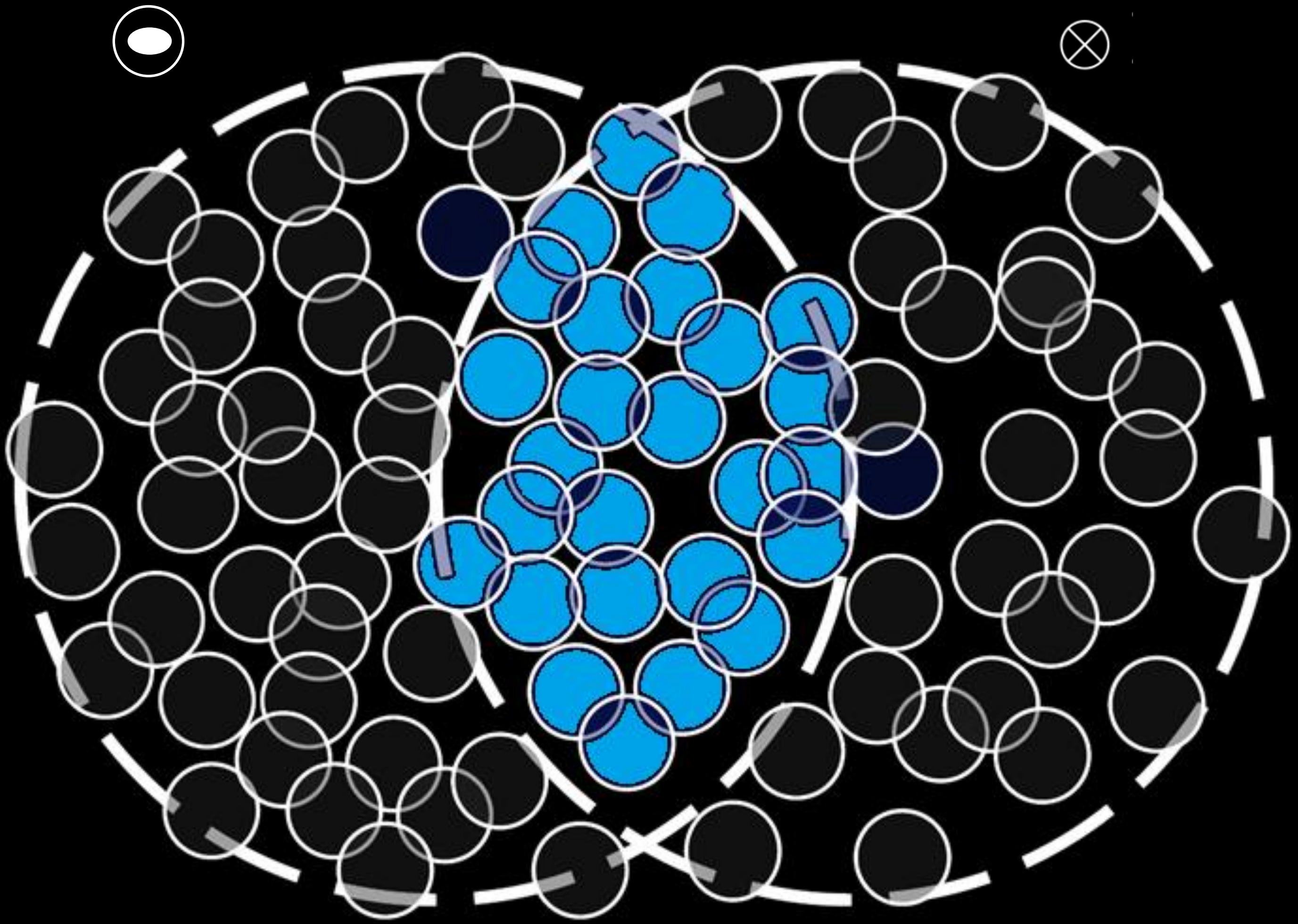
10th Edition of the Large Hadron Collider Physics Conference

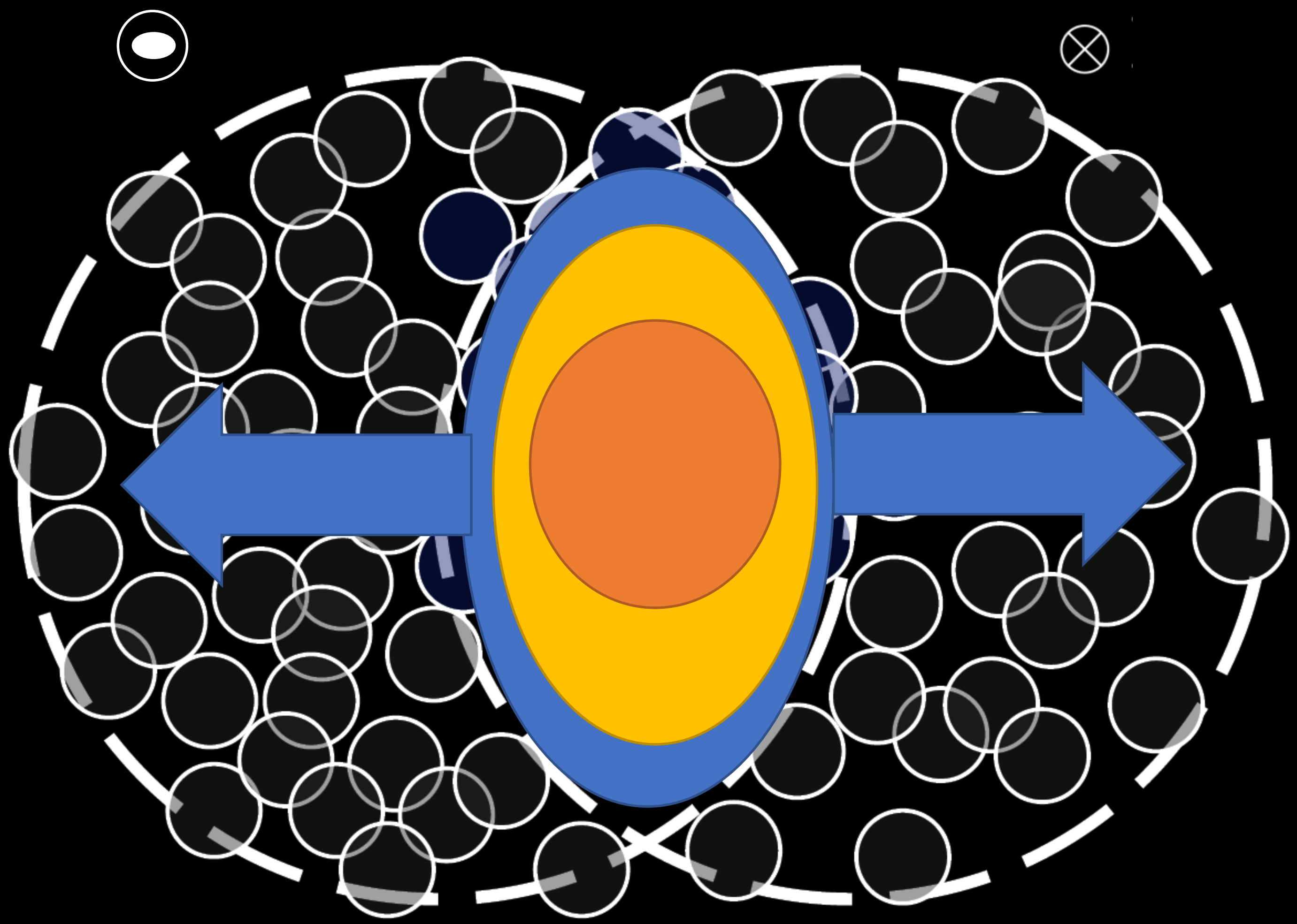

X
Y

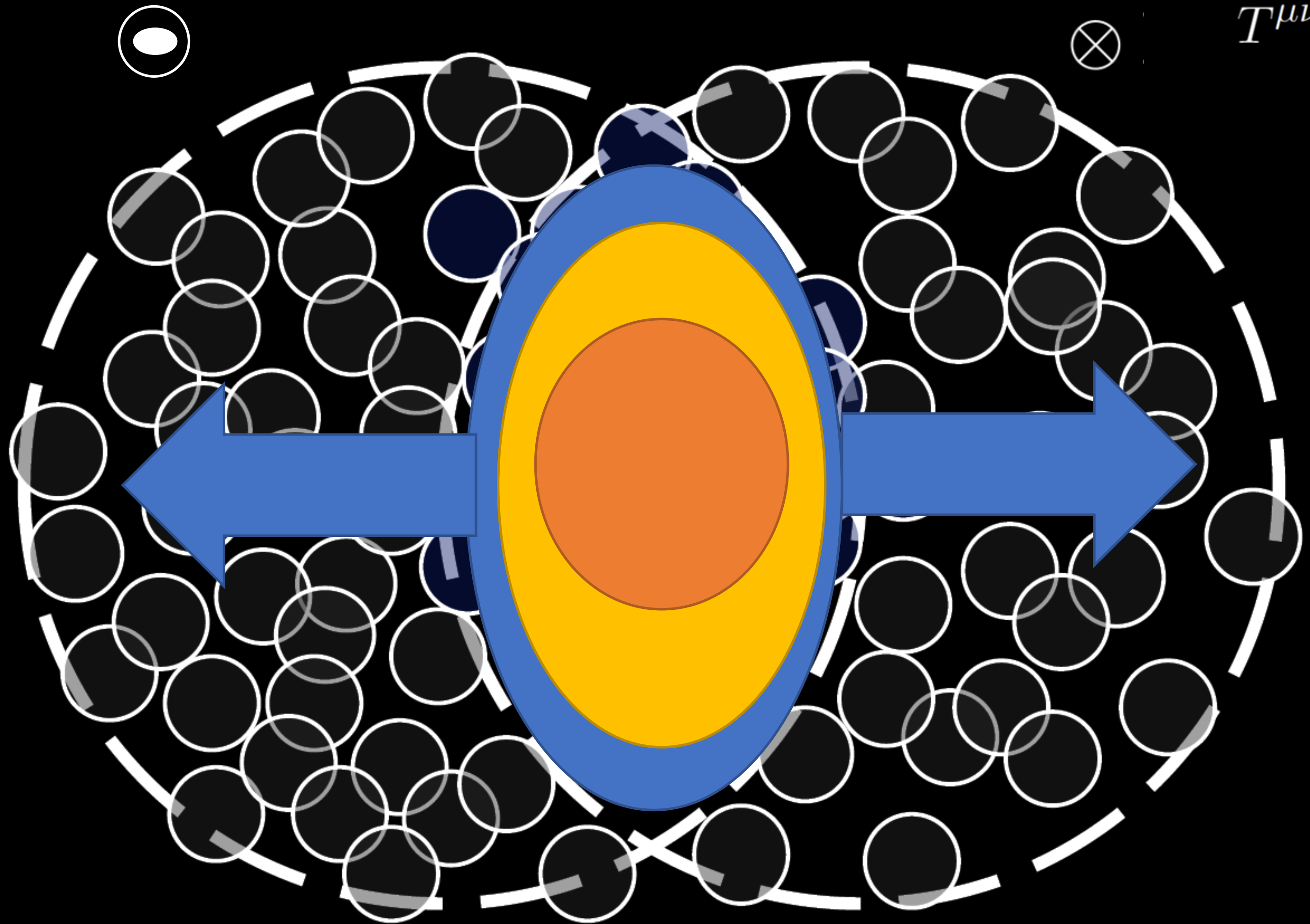


Spectators
Participants

Initial state



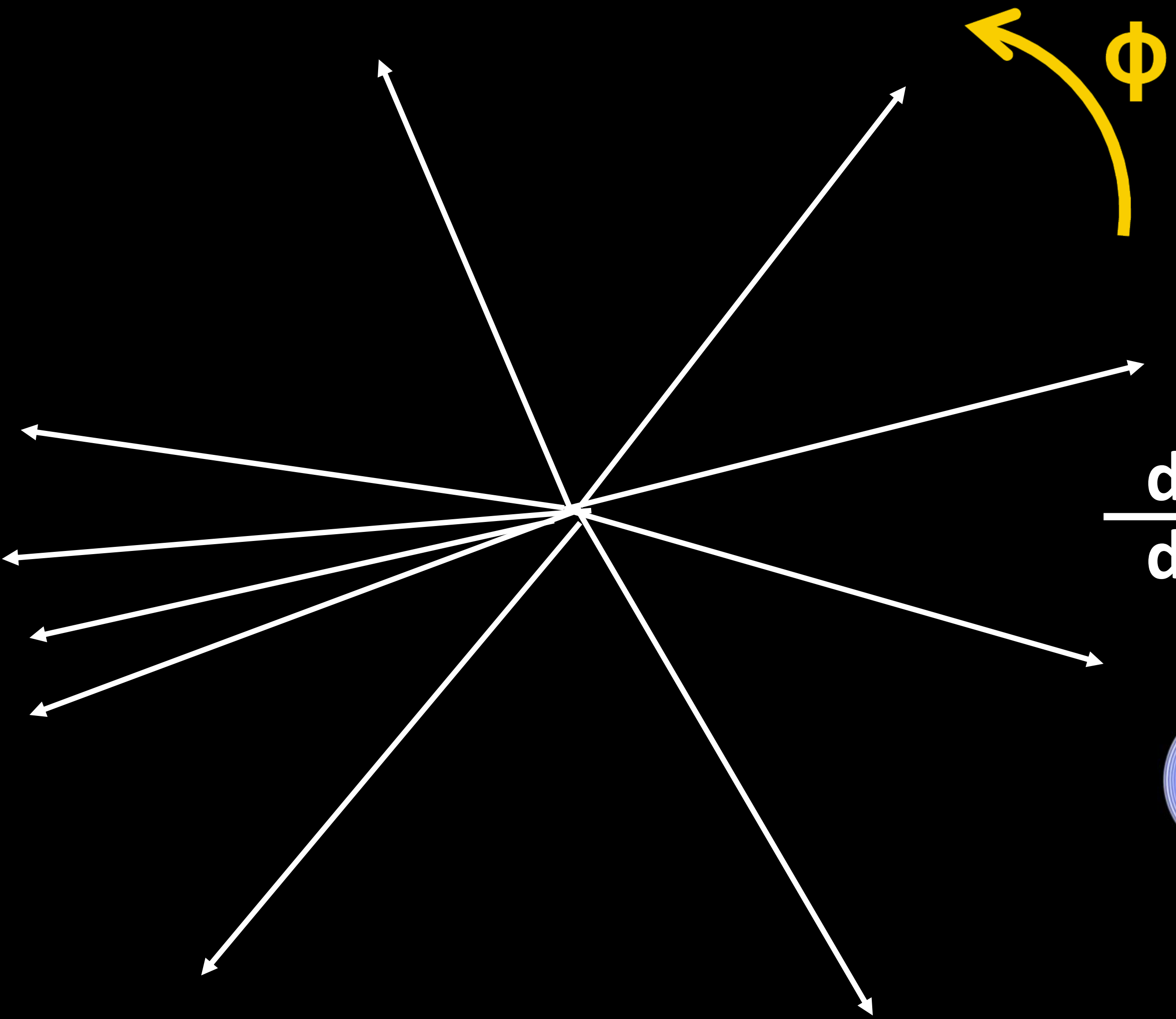




Viscous Hydrodynamics

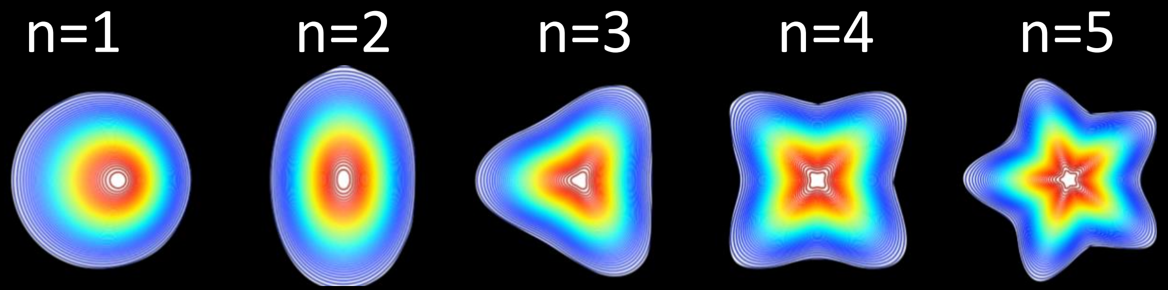
$$T^{\mu\nu} = \underbrace{\epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu}}_{\text{Ideal Hydro}} \underbrace{- \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^{\perp}_{\lambda} u^\lambda}_{\text{Viscous Hydro}}$$

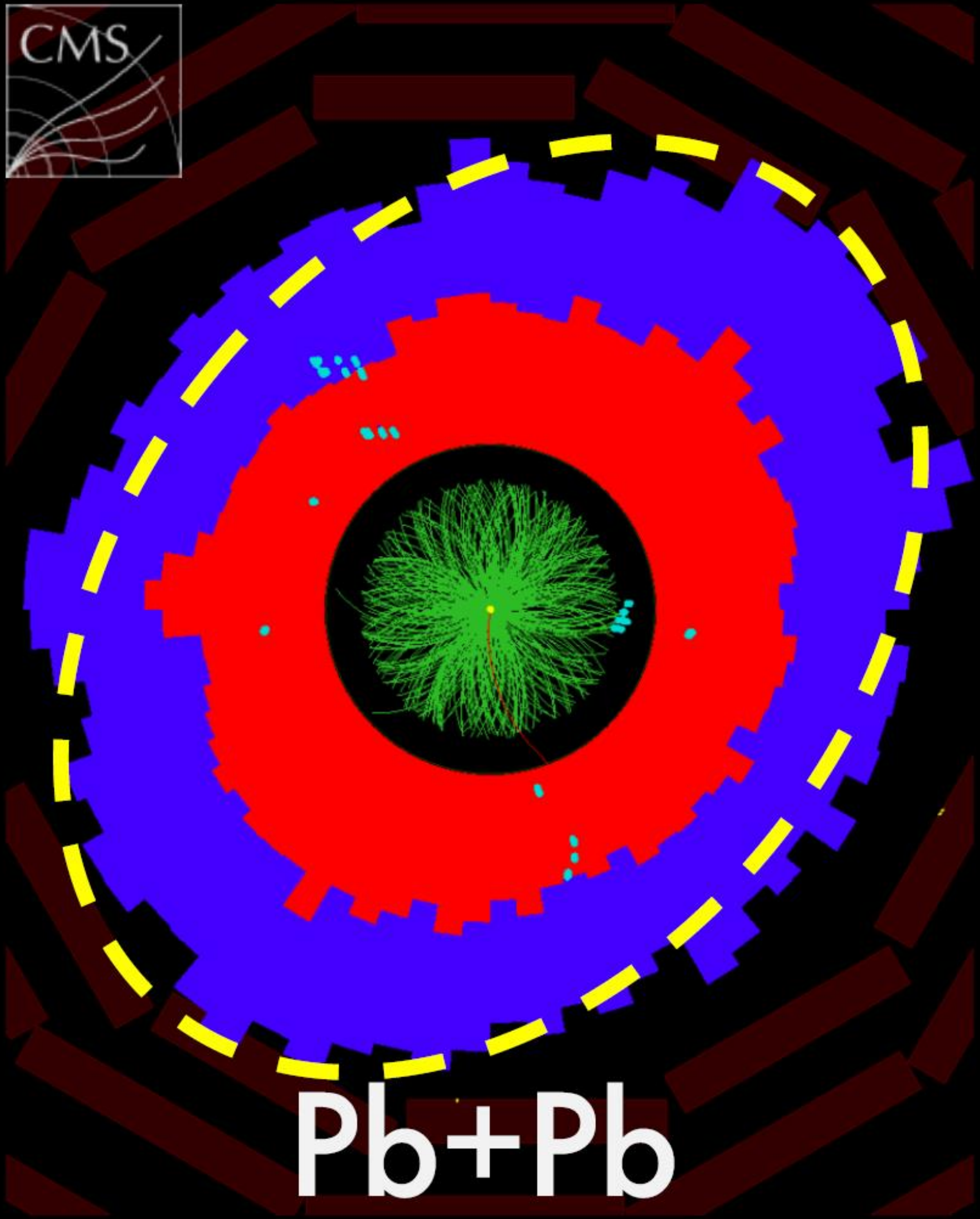
Initial state → **Hydro** → Momentum anisotropy



<u>Azimuthal anisotropy</u>

$$\frac{dN}{d\phi} \alpha \; 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + \ldots$$

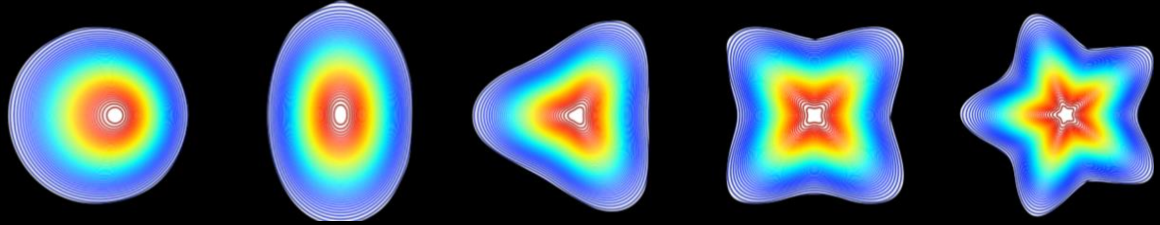




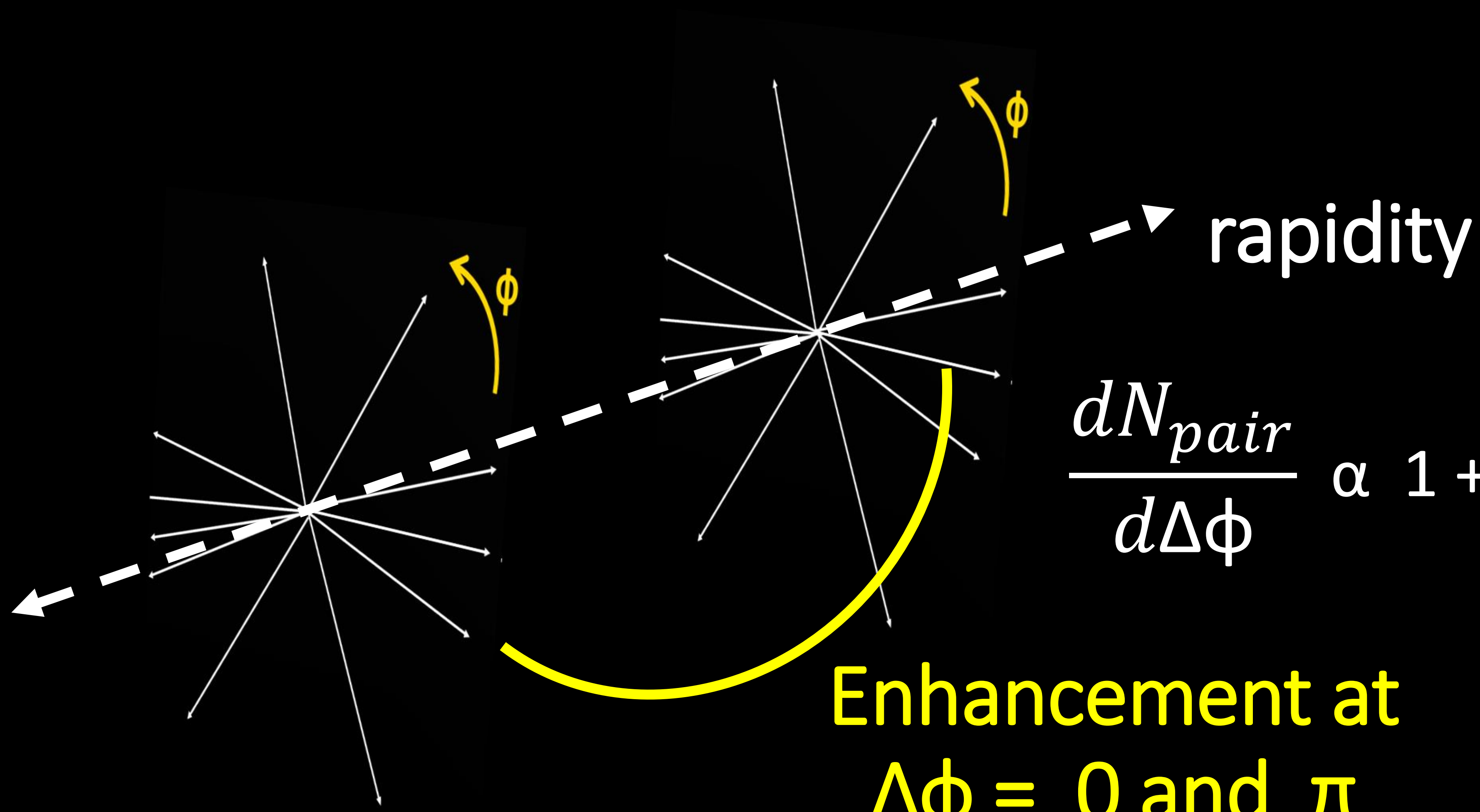
Single-particle azimuthal anisotropy

$$\frac{dN}{d\phi} \; \alpha \; 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + \ldots$$

n=1 n=2 n=3 n=4 n=5



Two-particle correlation

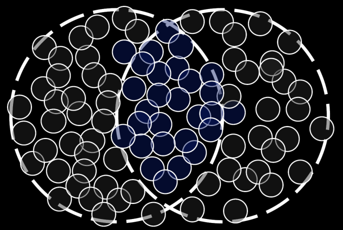


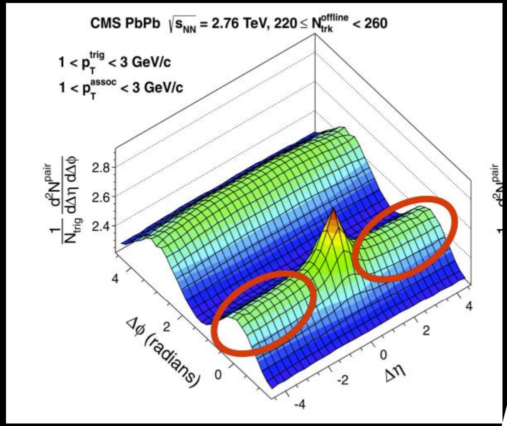
$$\frac{dN_{pair}}{d\Delta\phi} \;\alpha\; 1 + 2v_{2,2}\cos(2\Delta\phi) + ..$$

Enhancement at
$\Delta\phi =$ 0 and π

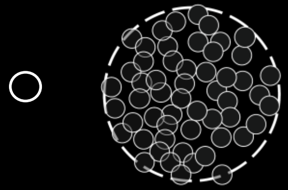
System size

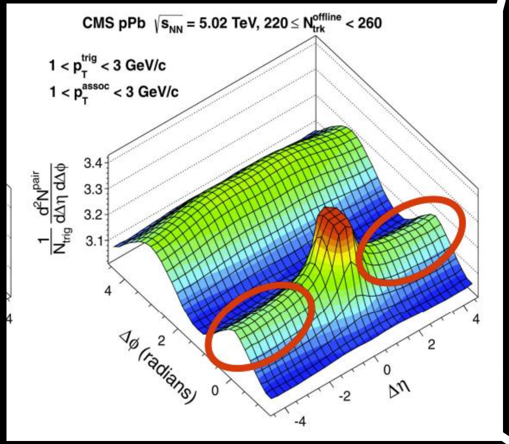
Pb+Pb

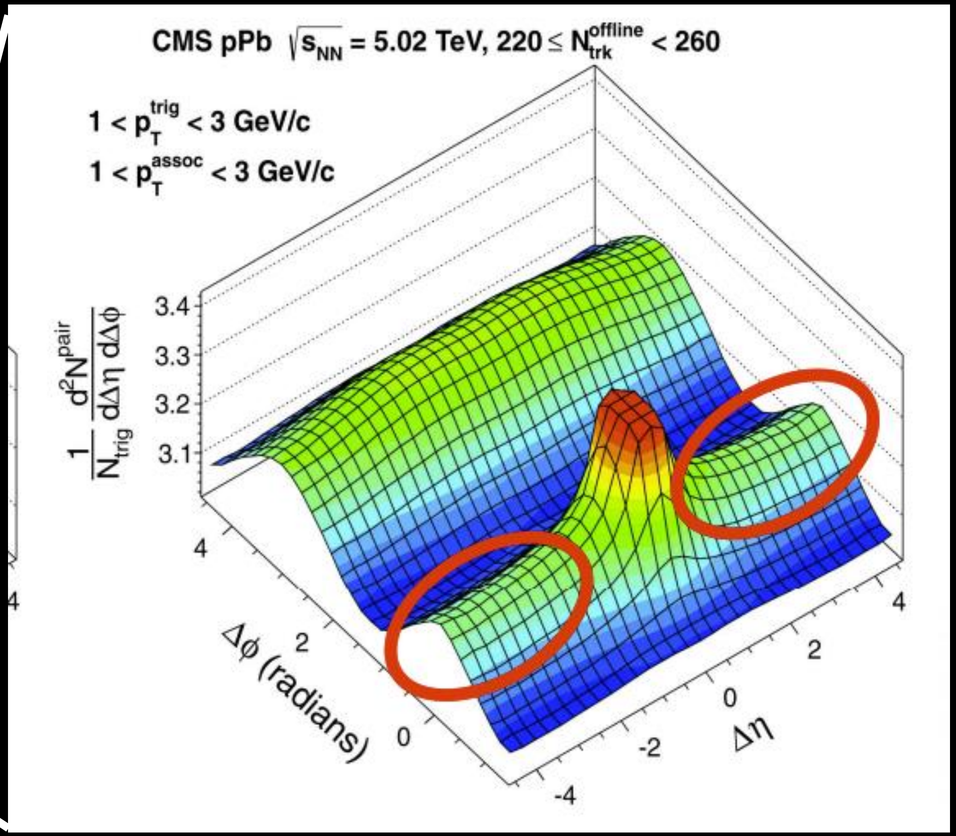




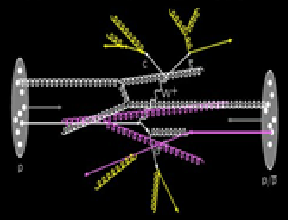
p+Pb

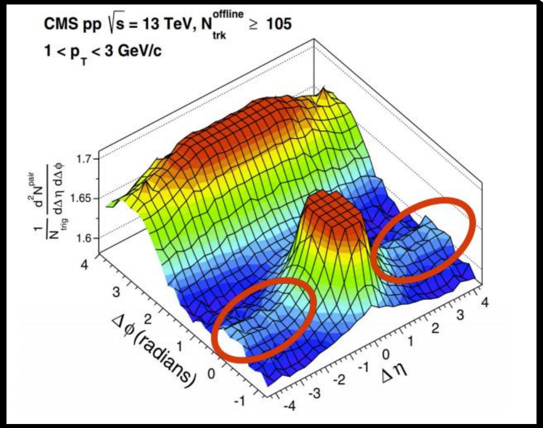






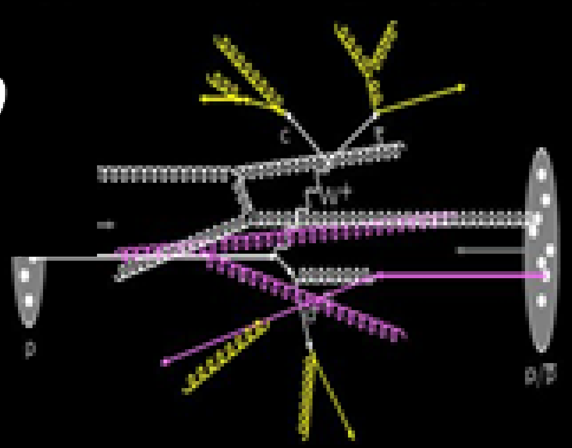
pp





I will be discussing

pp



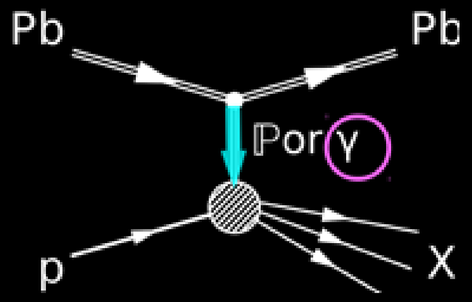
v_n-$[p_T]$ correlations in pp
CMS preliminary HIN-21-012

Longitudinal decorrelations
ATLAS preliminary ATLAS-CONF-2022-020

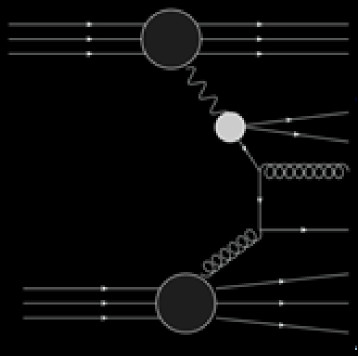
Identified hadron production with ALICE
-Identified hadron collectivity QM22
-Strangeness enhancement QM22
-Hadron resonance production QM22
-Forward strangeness arXiv:2204.13042

At the LHC

γ+*p*

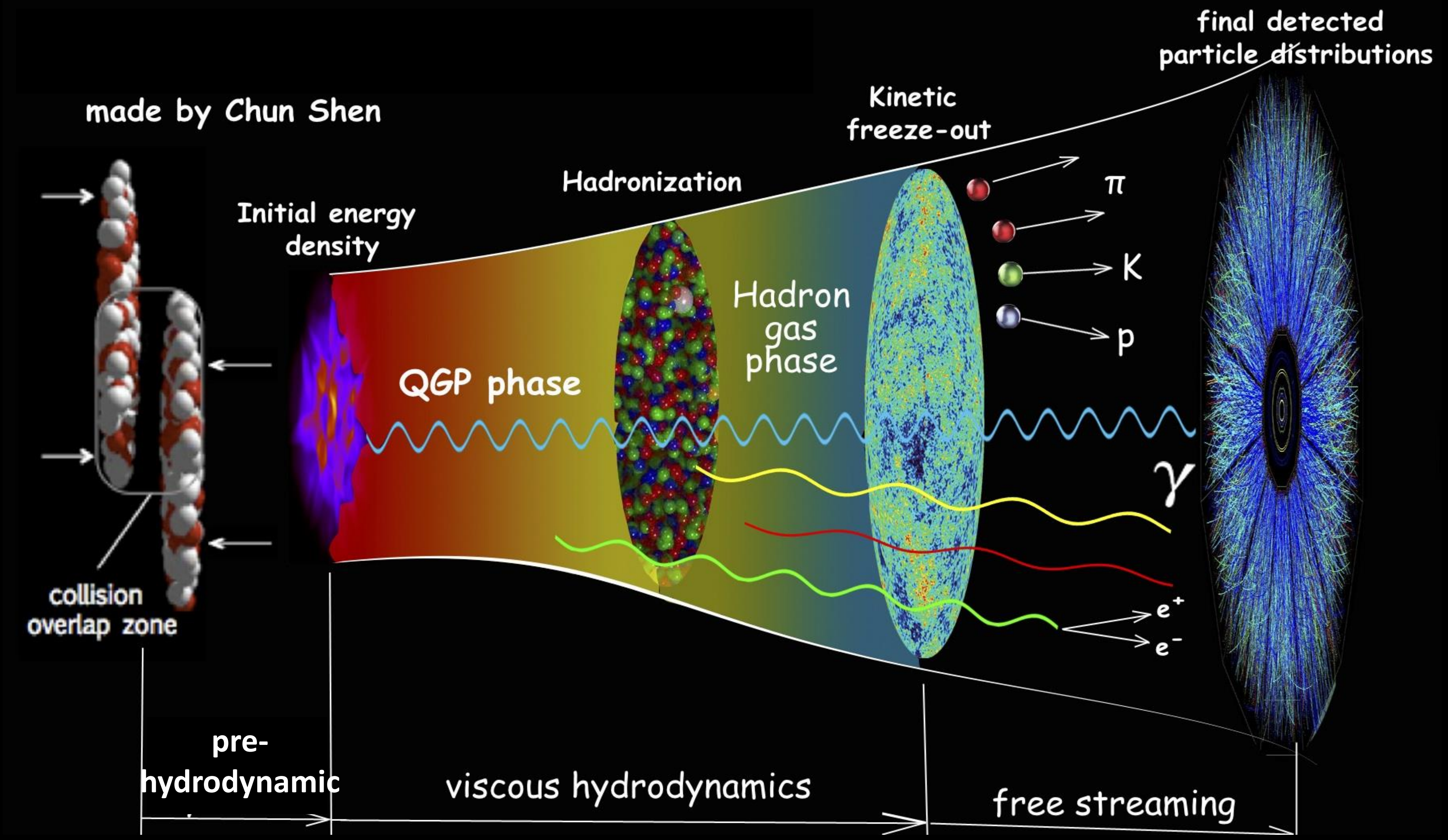


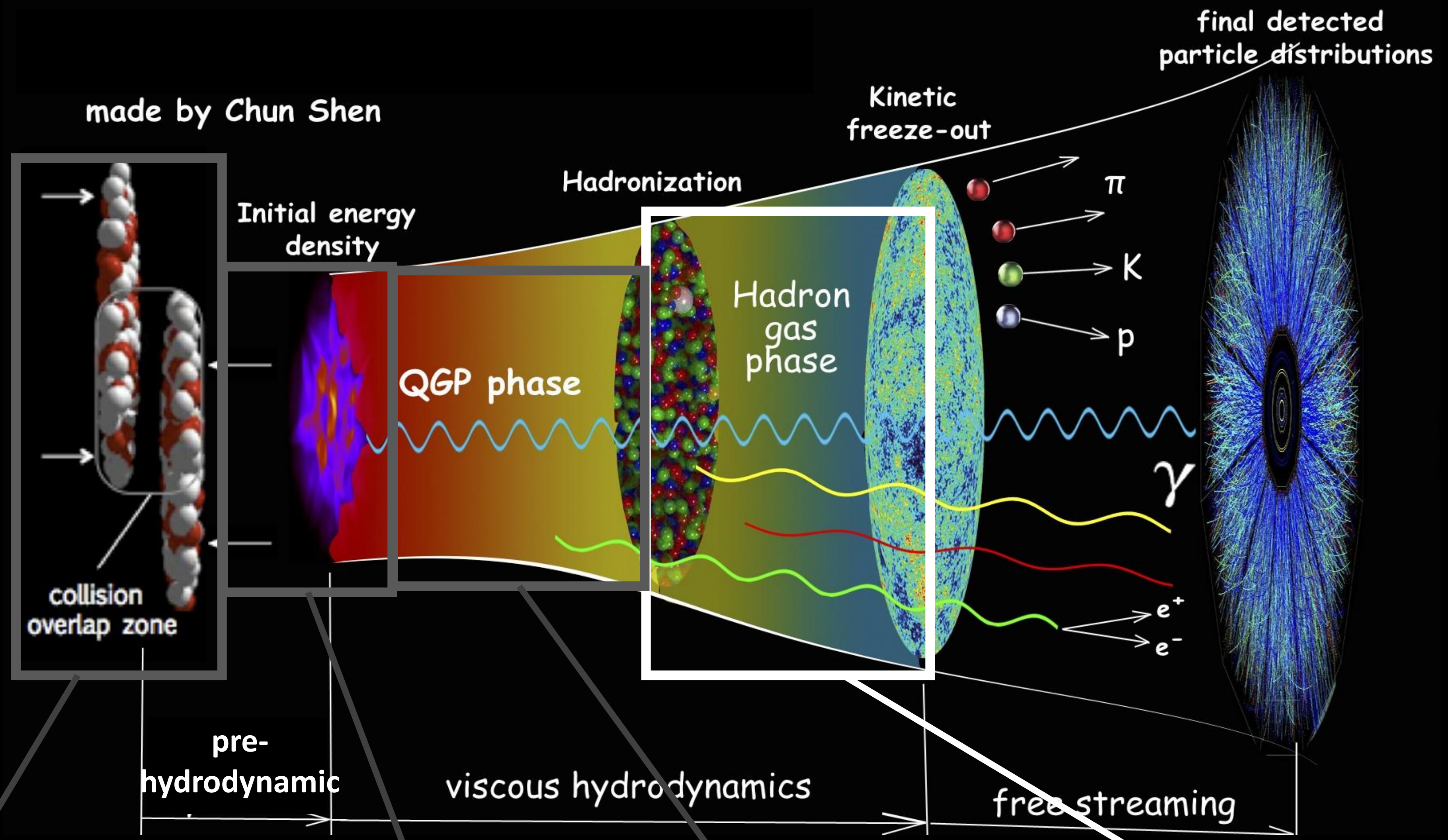
γ+A



γ+*p* collectivity
arXiv:2204.13486

γ+A collectivity
arXiv:2101.10771


made by Chun Shen
Initial energy density
Hadronization
Kinetic freeze-out
final detected particle distributions
π
K
p
Hadron gas phase
QGP phase
γ
collision overlap zone
e+
e−
pre-hydrodynamic
viscous hydrodynamics
free streaming



Hadron resonance production
QM22

v_n-$[p_T]$ correlations
HIN-21-012
Longitudinal decorrelations
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γ+p collectivity
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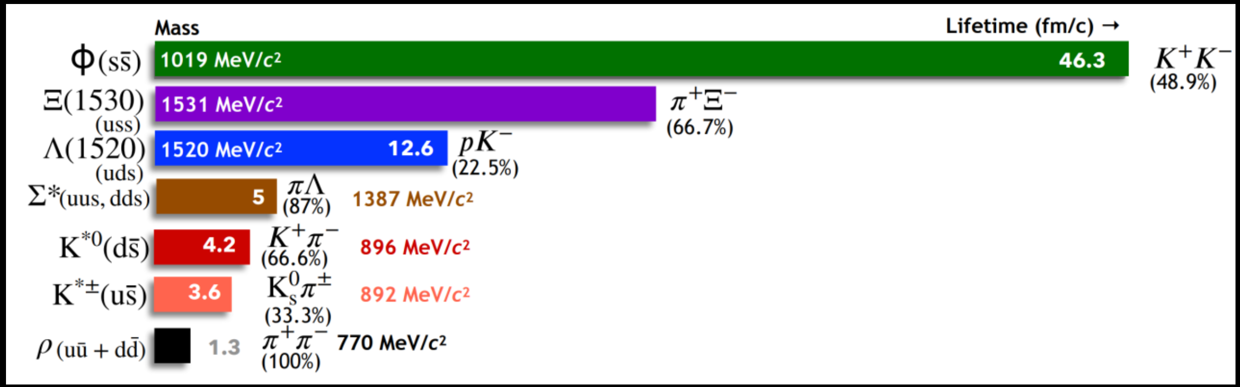
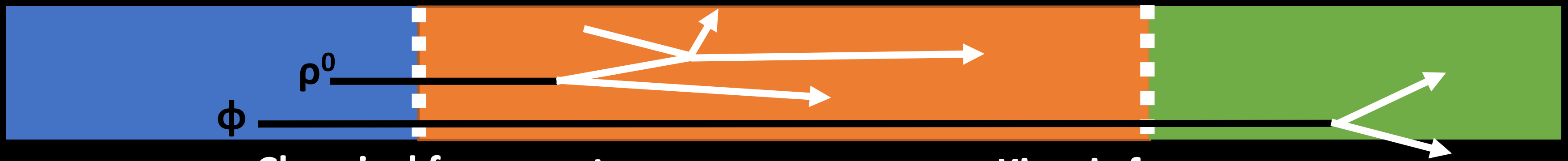
Identified hadron collectivity
QM22
Strangeness enhancement
QM22

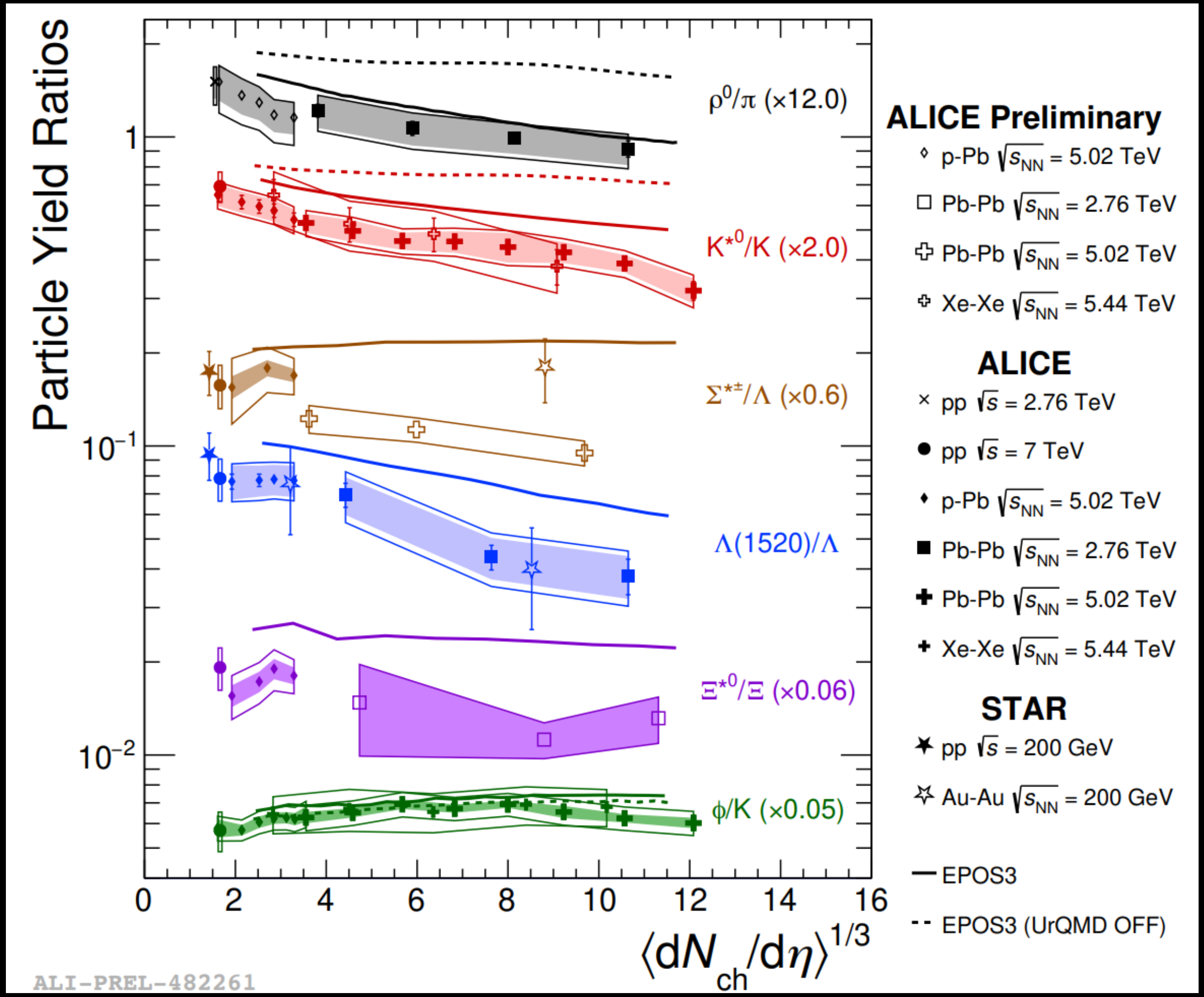
Interactions in a cooling hadronic gas

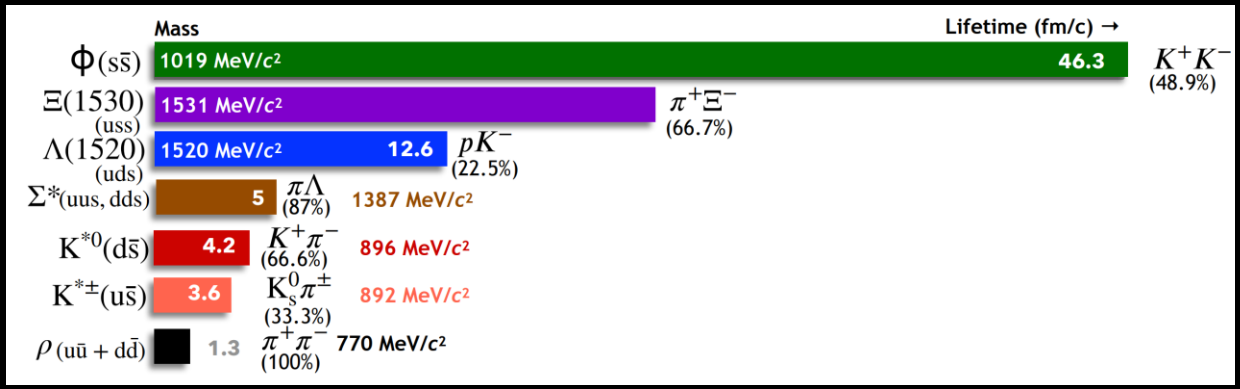




QM22 slides

Interactions in a cooling hadronic gas

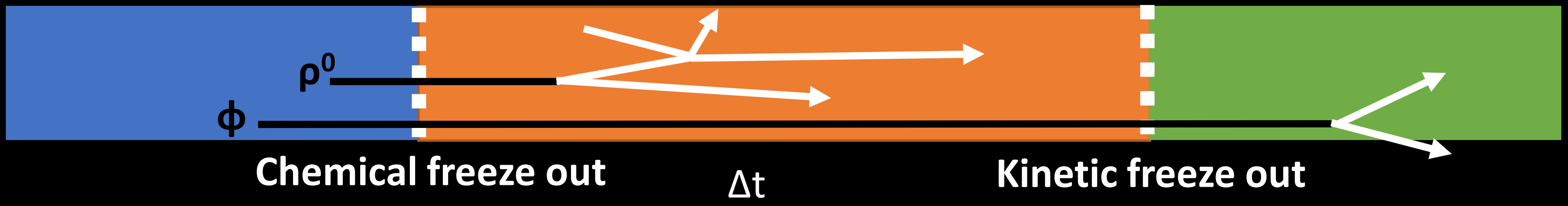




Measurements of hadron resonances probe the Δt between chemical and kinetic freeze out.

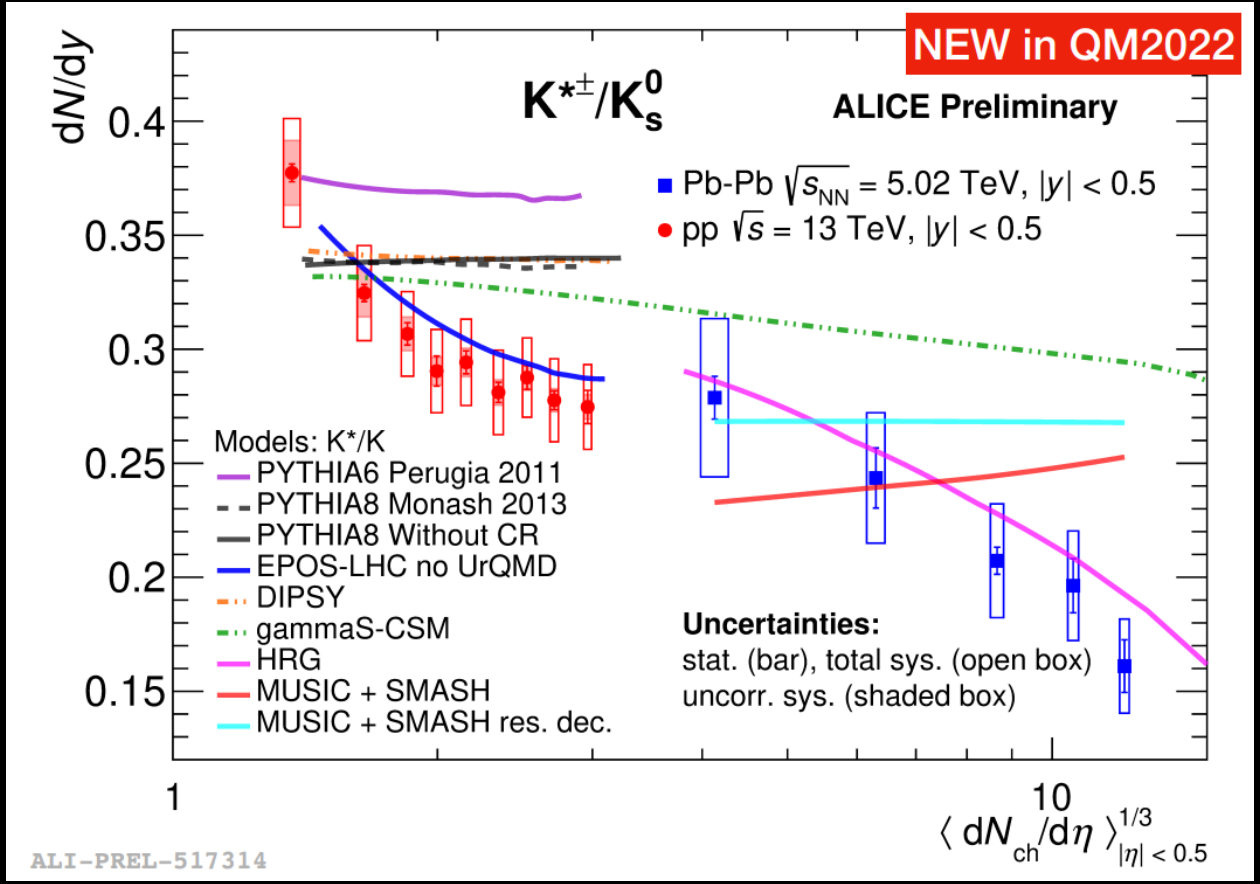
2 proposed effects in the hadronic phase

- **Regeneration -** pseudo-elastic scattering through resonance state
- **Rescattering** - elastic scattering smears out mass peak



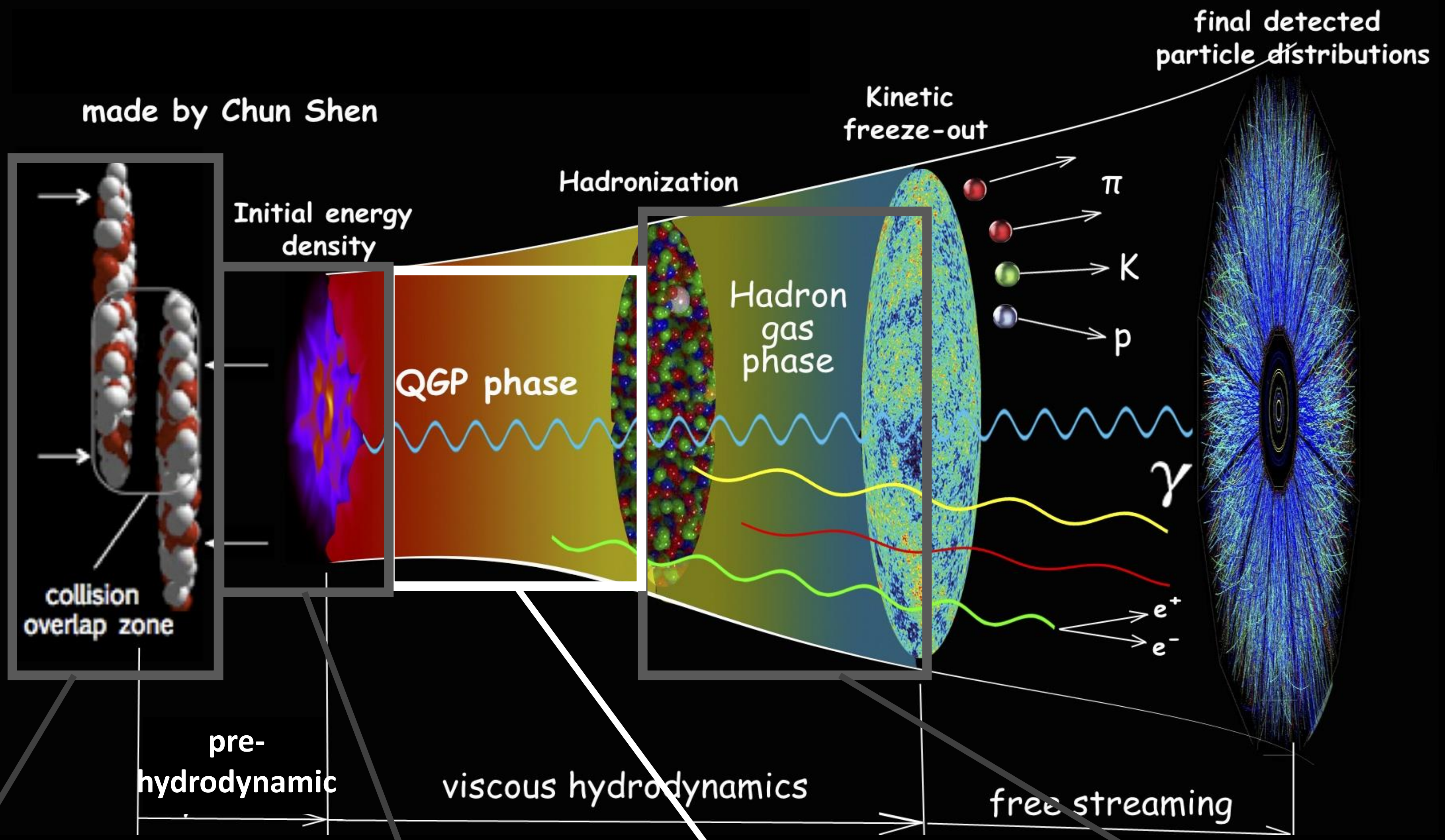
QM22 slides

A closer look at new $K^{*\pm}/K^0_S$



- Suppression of yield ratio in high multiplicity events
- Models need to include hadronic phase
- Best model descriptions are **EPOS-LHC (no UrQMD)** and **HRG.** Both include a fully simulated hadronic phase.

QM22 slides



v_n-$[p_T]$ correlations
HIN-21-012
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γ+*p* collectivity
arXiv:2204.13486
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QM22 arXiv:2204.13042

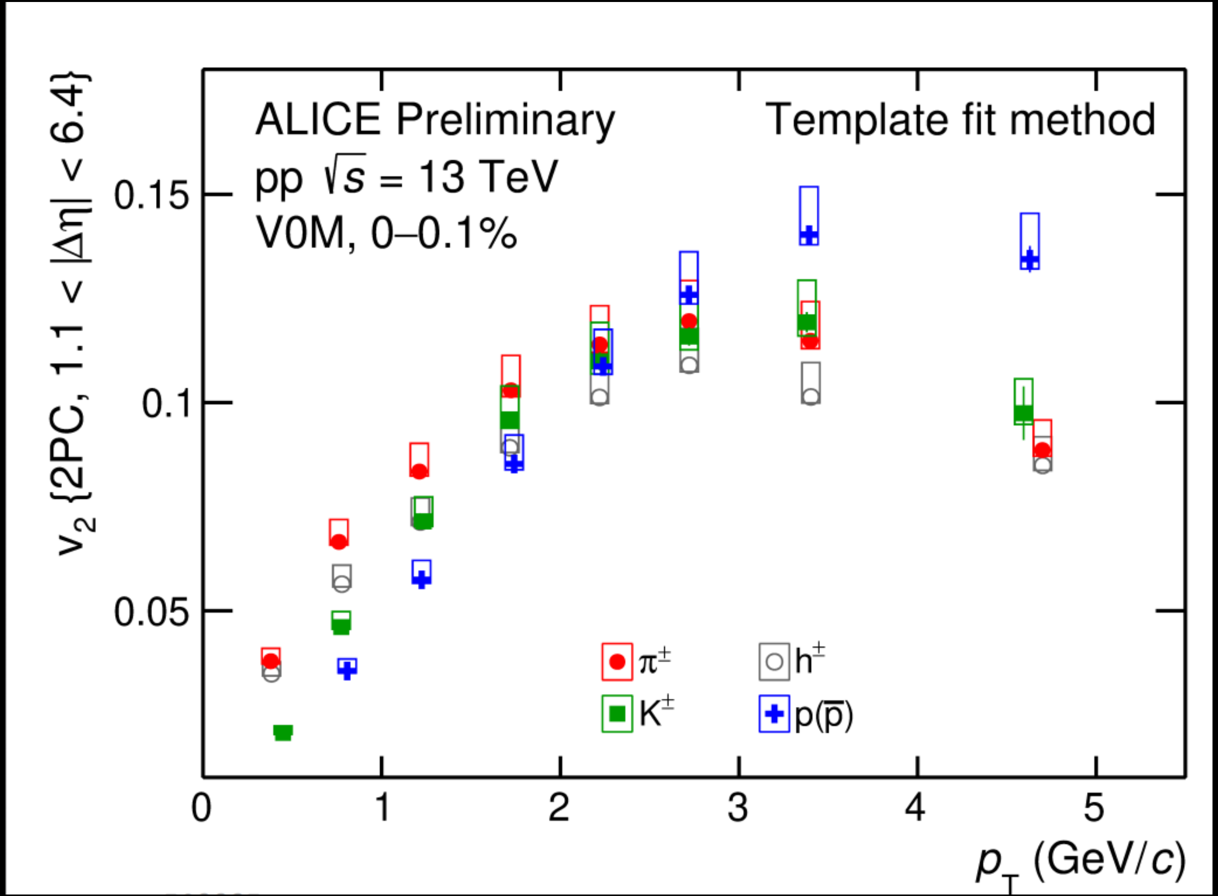
Hadron resonance production
QM22

Flow of identified particles in *pp*

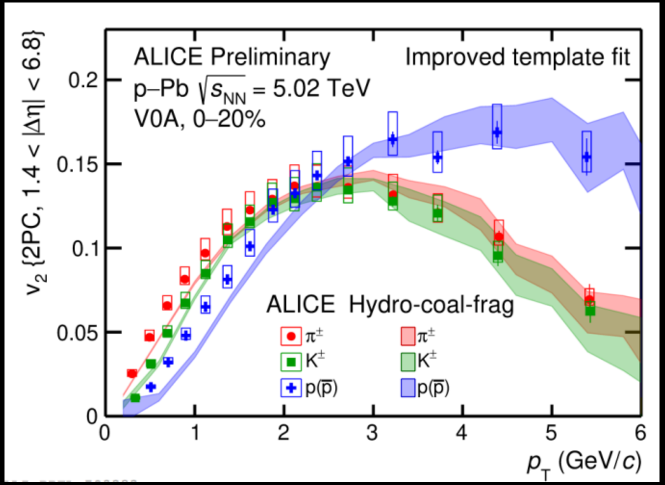
QM22 reference

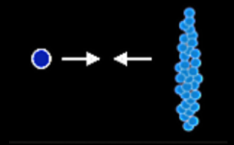
Newly observed phenomenon in *pp*

- Mass ordering at low p_T
- Baryon-meson splitting at intermediate p_T region



Nonflow removal (Template fit method) has led to clear baryon-meson grouping





To qualitatively reproduce data **above 3 GeV** models must include **quark coalescence and jet fragmentation**

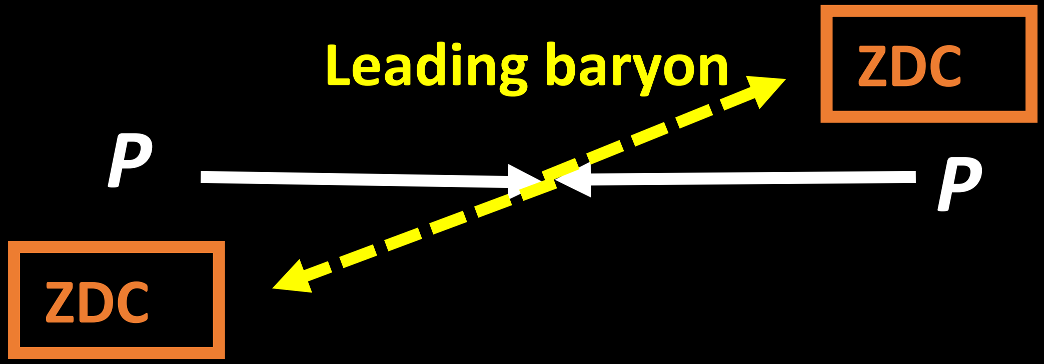
Coalescence: simplified model

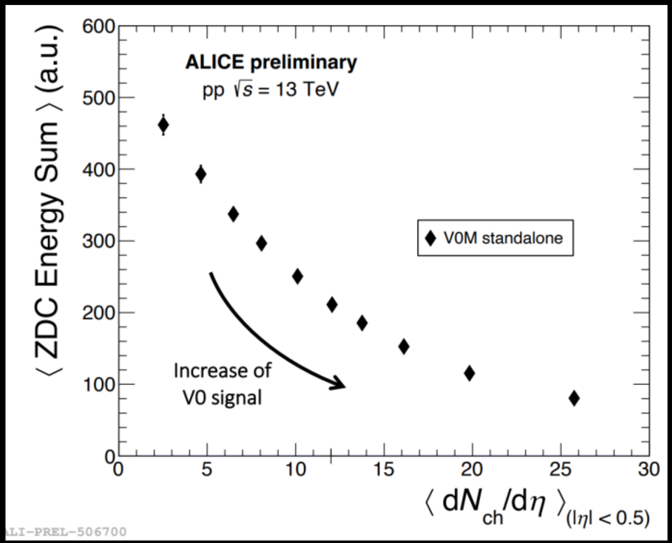
$V_2^{hadron}(p_T) = n \times v_2^{partons}(p_T/n)$

Where *n* is the number of valance quarks

Strangeness enhancement

- Thermal production of strange quarks in the QGP increase the $s\bar{s}$ content from initial content from initial collision.
- Signature of the presents and duration of QGP phase.
- Growing knowledge of the details of how the thermal productions is facilitated by temperature of the QGP and total energy deposited /system size as well as the experimental handles of such causes.



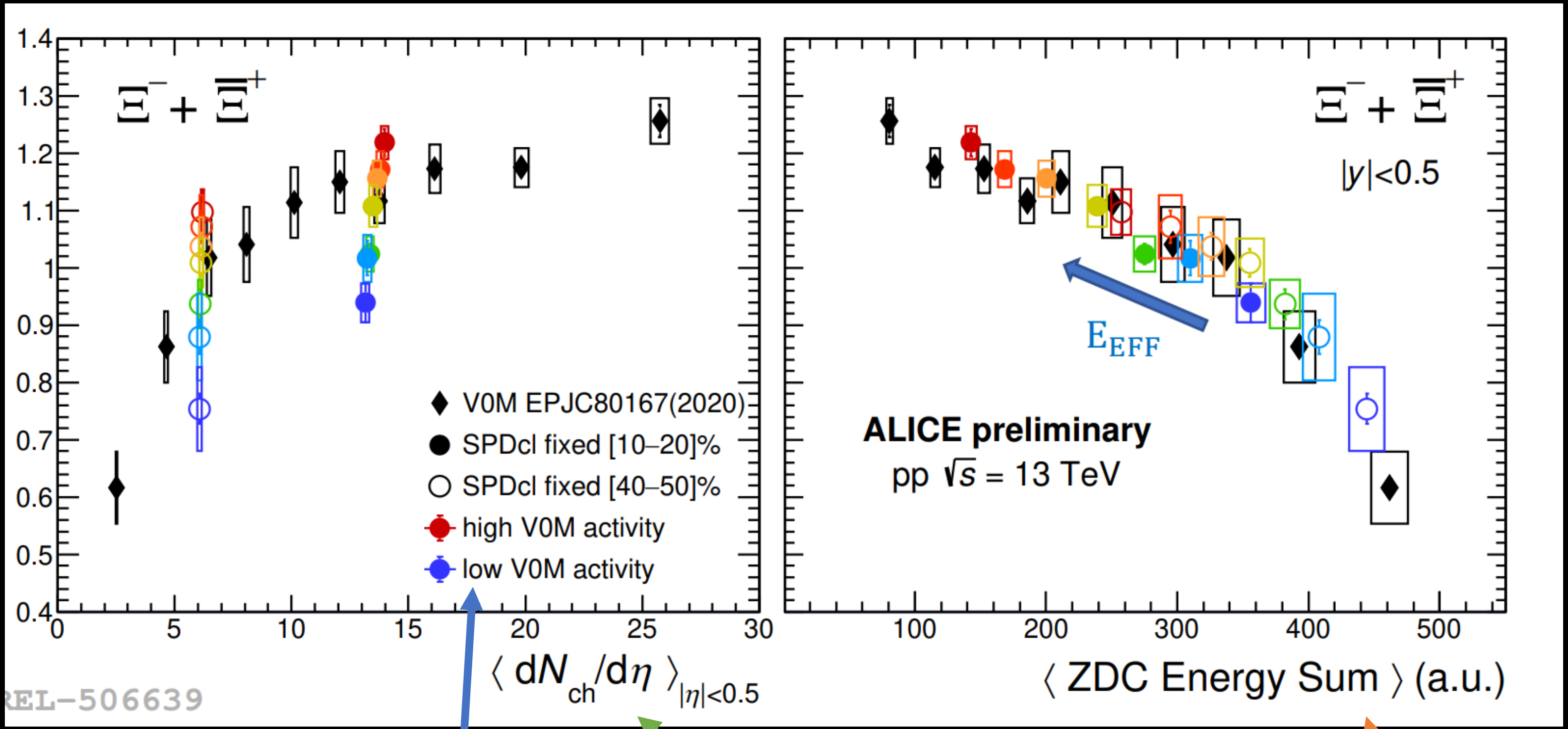


QM22 reference

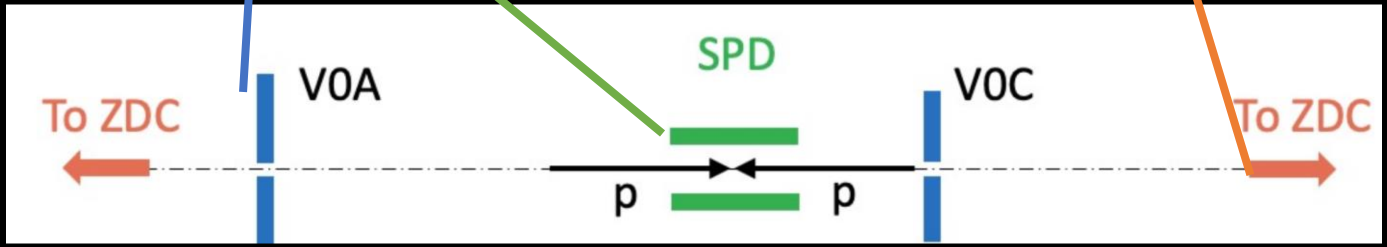
ZDC energy is anticorrelated with mid-rapidity multiplicity

Strangeness enhancement with dN_{ch}/dη and ZDC

$$\frac{Y_{\Xi^- + \bar{\Xi}^+}/\langle N_{ch}\rangle}{\langle Y_{\Xi^- + \bar{\Xi}^+}/\langle N_{ch}\rangle\rangle}$$



QM22 reference

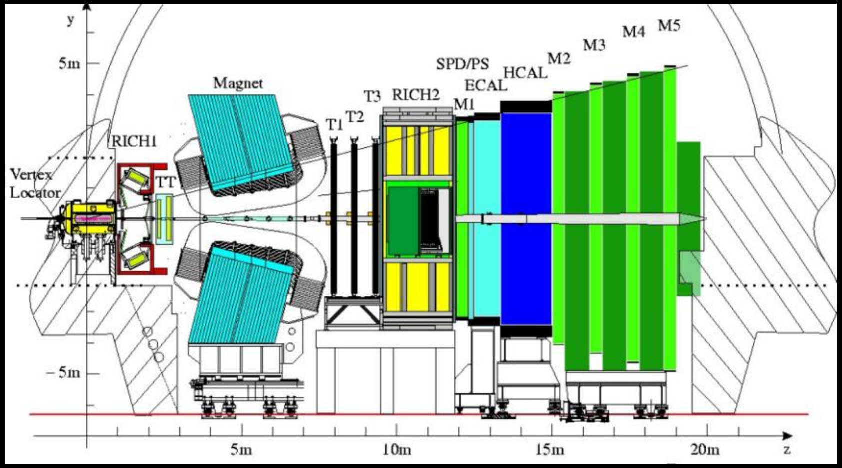


Increase in the average fraction pf strange hadrons with increasing multiplicity and decreasing ZDC energy

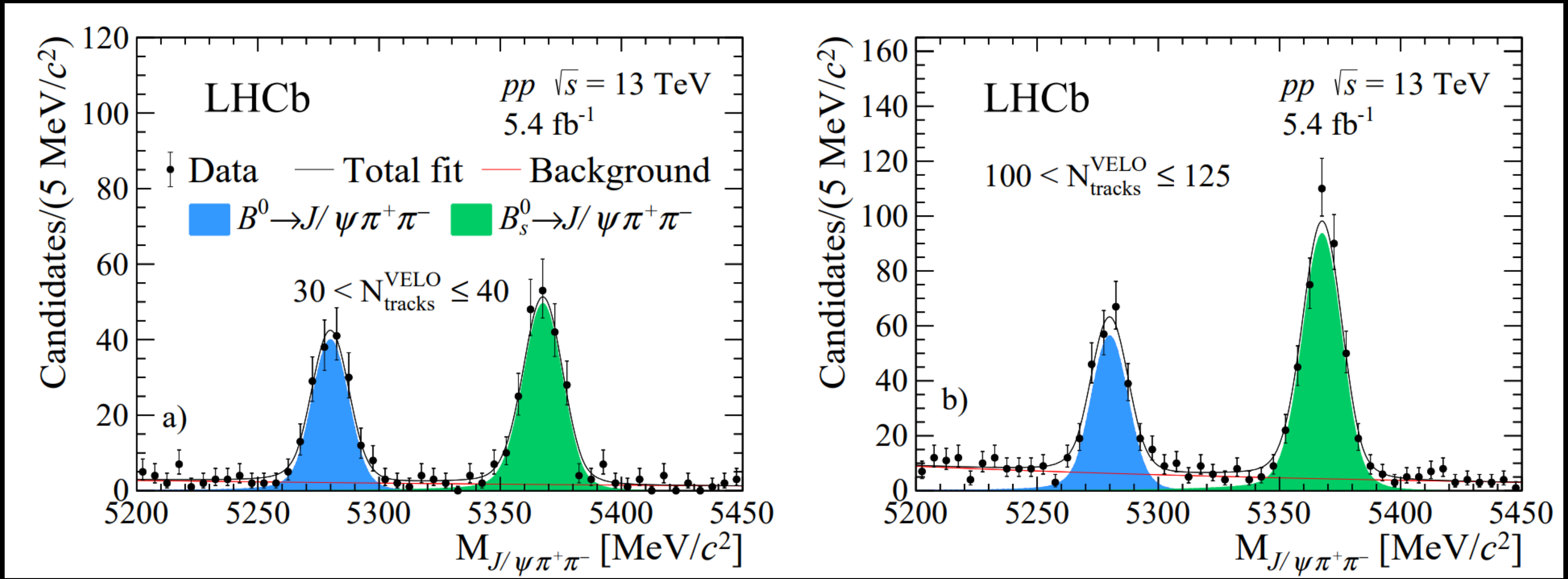
Multiplicity η <0.5 is not the whole story for strange hadrons within y<0.5

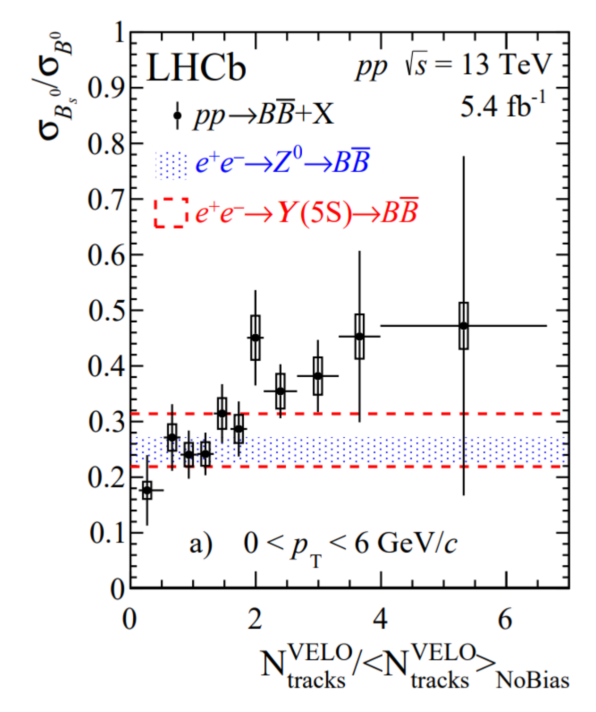
Strangeness enhancement: B_s^0/B^0 with LHCb

- Unique capabilities of LHCb to make complimentary heavy-ion-style measurements.
- Measurement of B^0_s and B^0 at forward rapidity ($2 < y < 5$) in *pp* at 13 TeV
- 3.4 sigma inclrease in B_s^0/B^0 with multiplicity



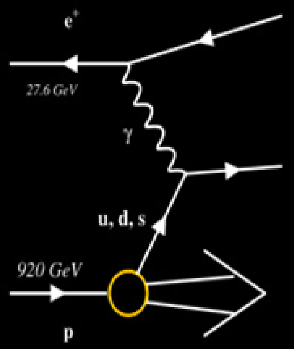
arXiv:2204.13042



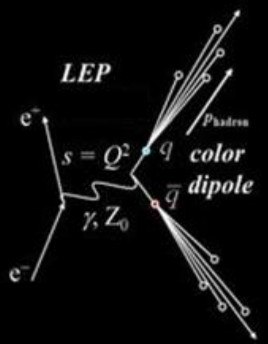


What are the minimal condition for collectivity?

e+*p*

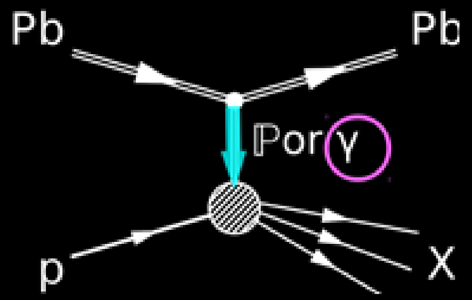


e^++e^-

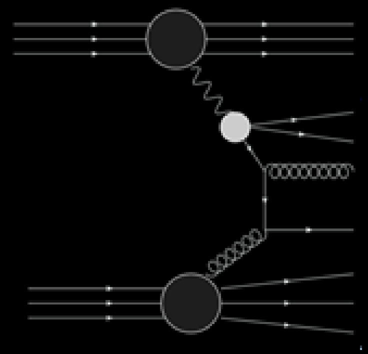


At the LHC

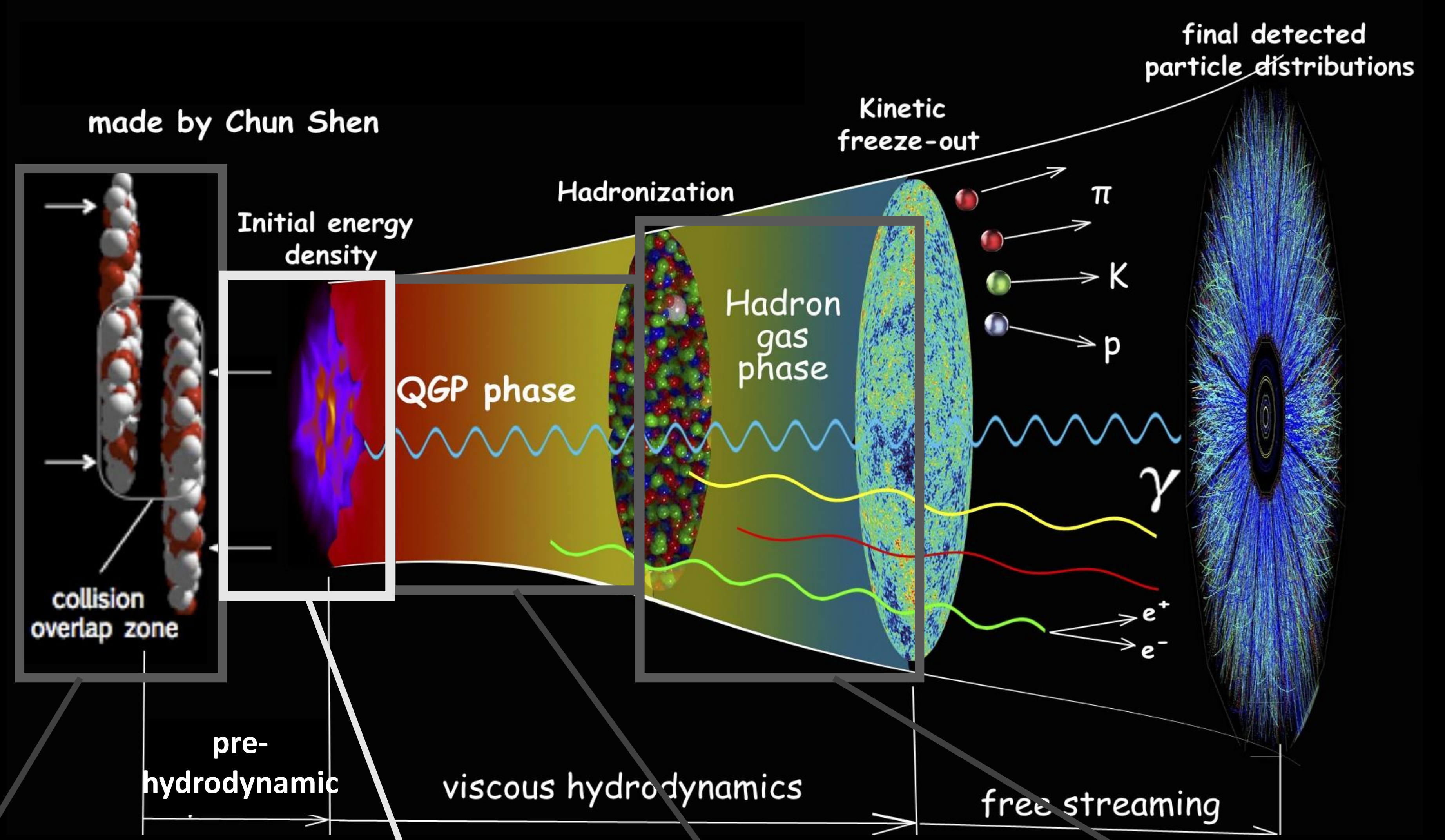
γ+*p*



γ+A



Many new searches in other small systems



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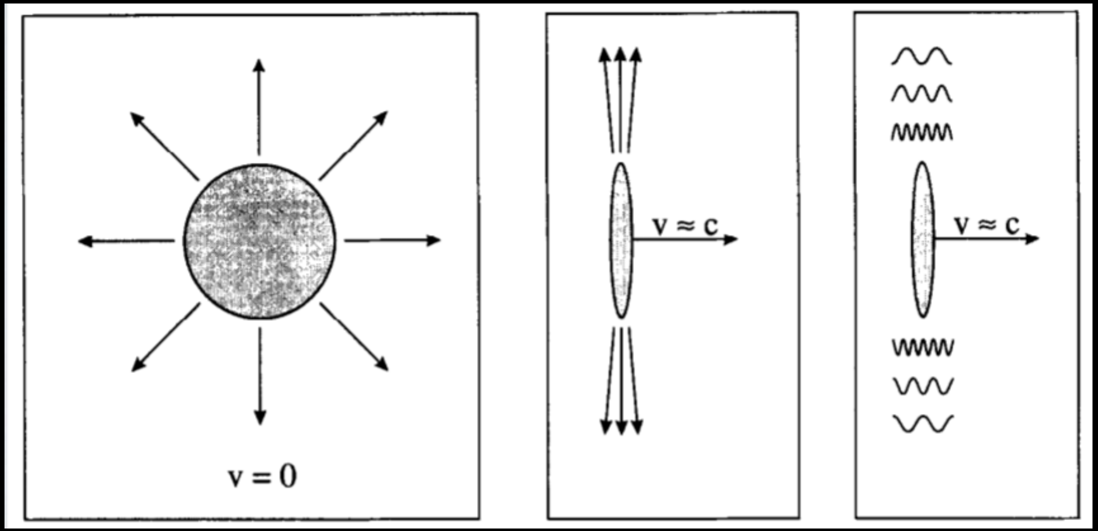
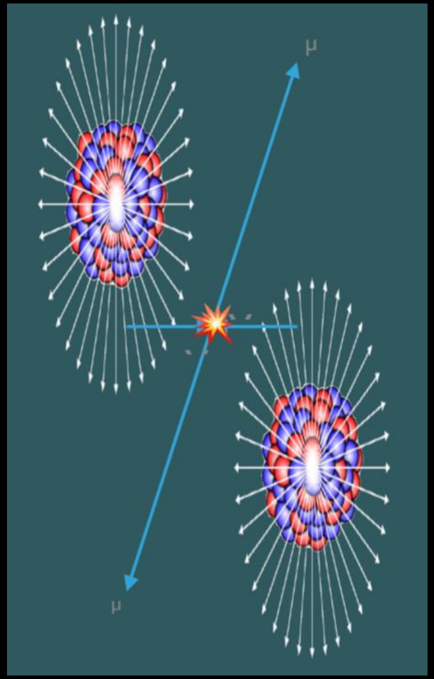
Ultra-peripheral collisions at the LHC



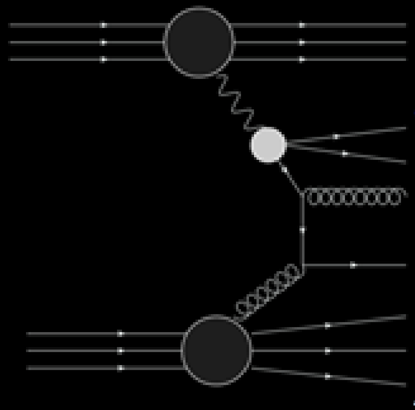
Coulomb fields of moving charges can be treated as an equivalent flux of photons which are boosted to high energies.

Photons reach energies of 10s of GeV with a 2.5 TeV Pb beam at the LHC



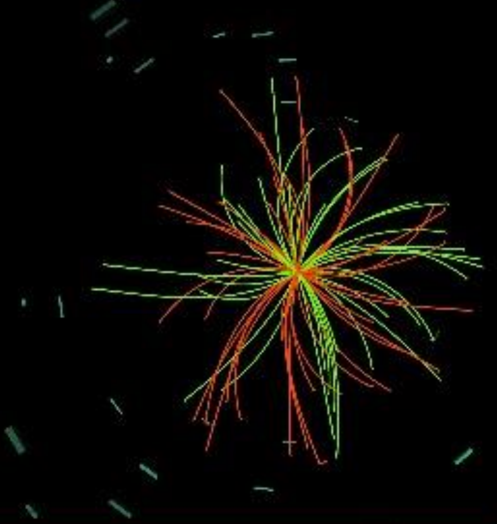
When $b > 2R_A$ two categories of interactions

- Pure EM processes
  - γγ → γγ arXiv:1904.03536 & arXiv:2008.05355
  - γγ → μμ arXiv:2011.12211
- Photo-hadron interactions
  - γ + A → A* + V
  - γ + A → X

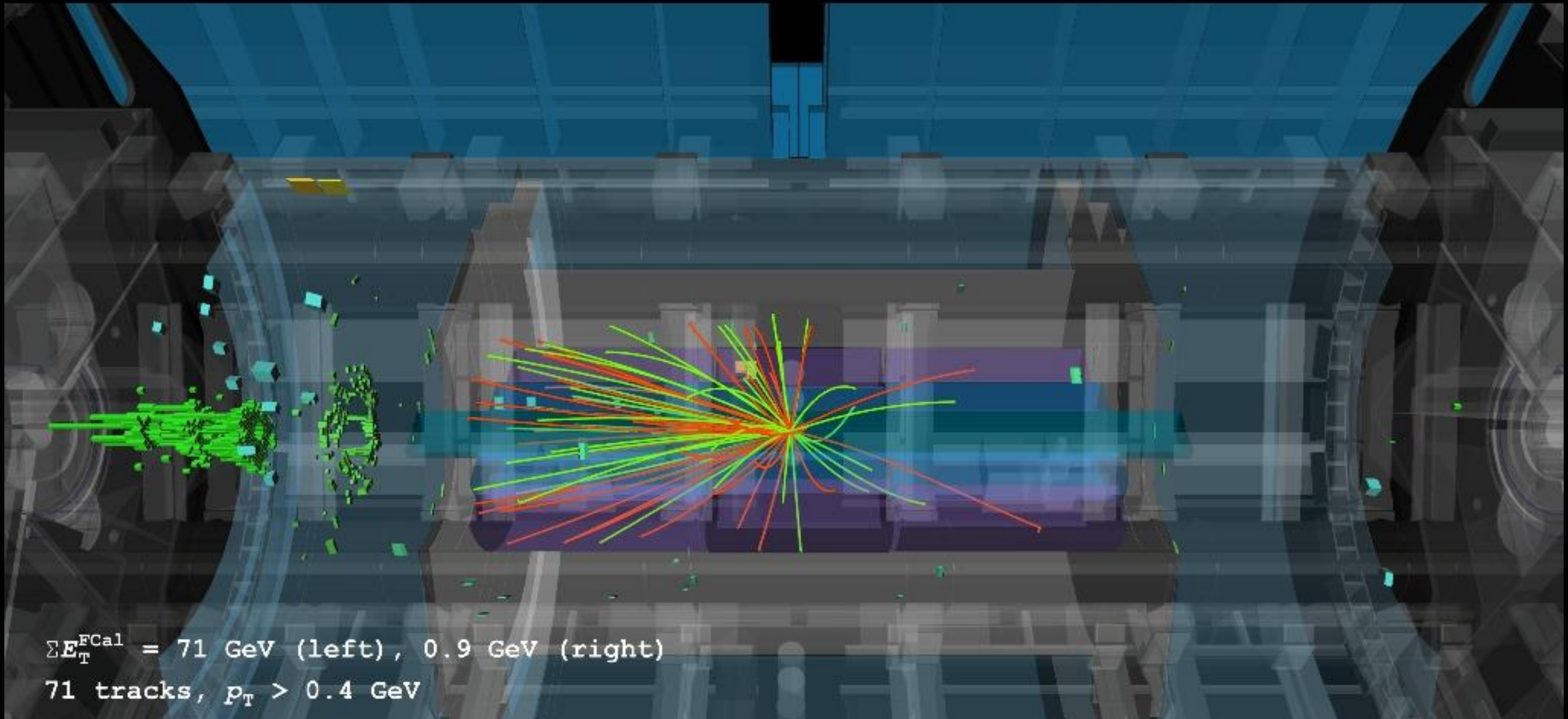


ATLAS EXPERIMENT

Pb+Pb, 5.02 TeV
Run: 365681
Event: 1064766274
2018-11-11 22:00:07 CEST



Pb going direction



photon going direction

Pb+Pb, 5.02 TeV
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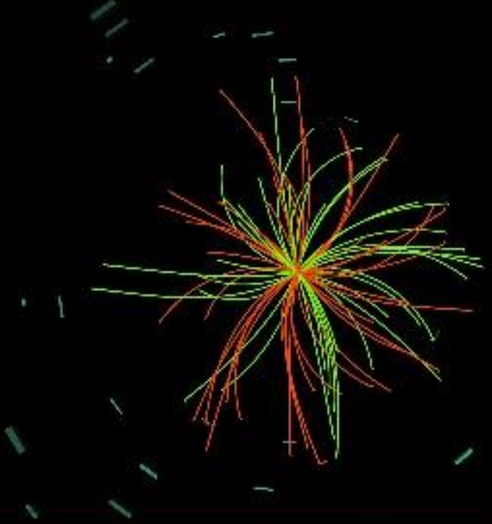
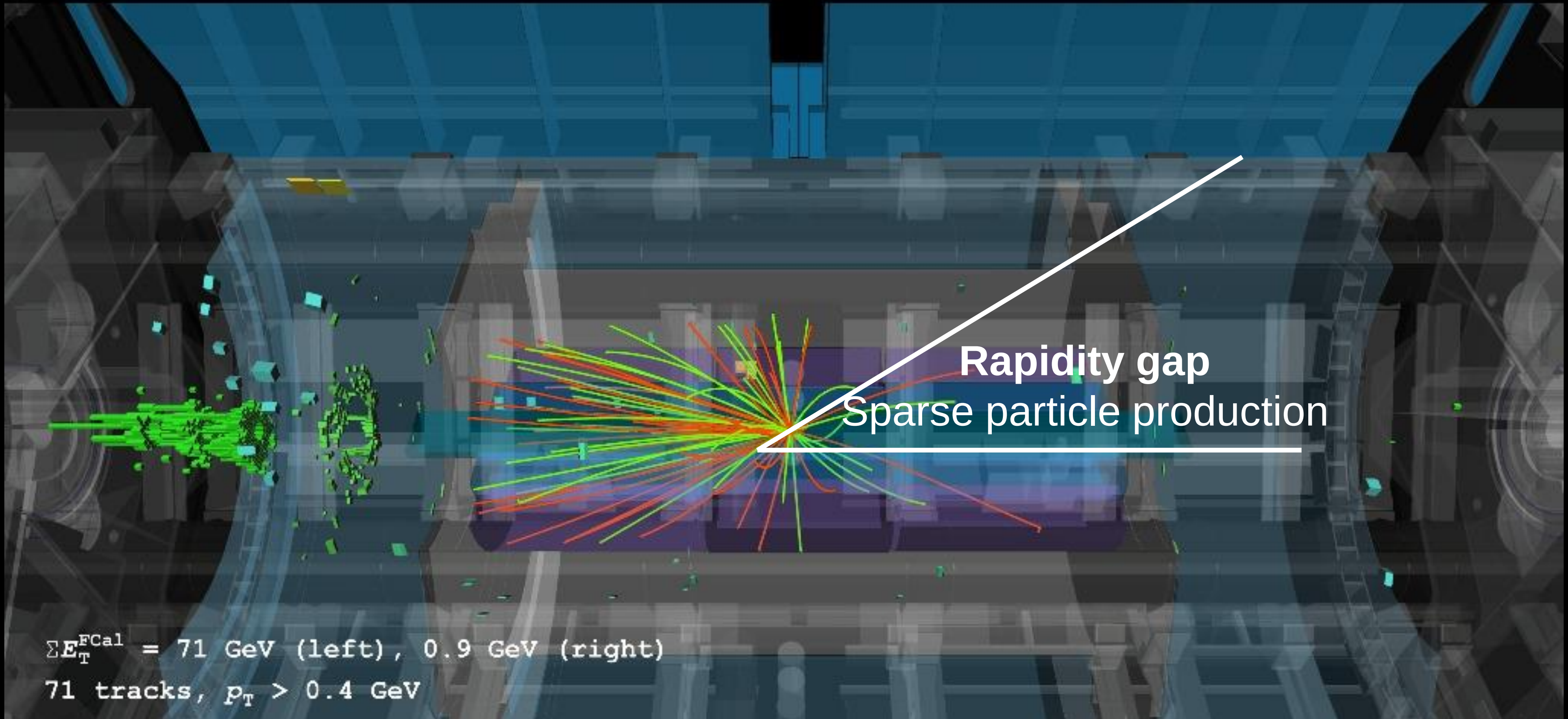


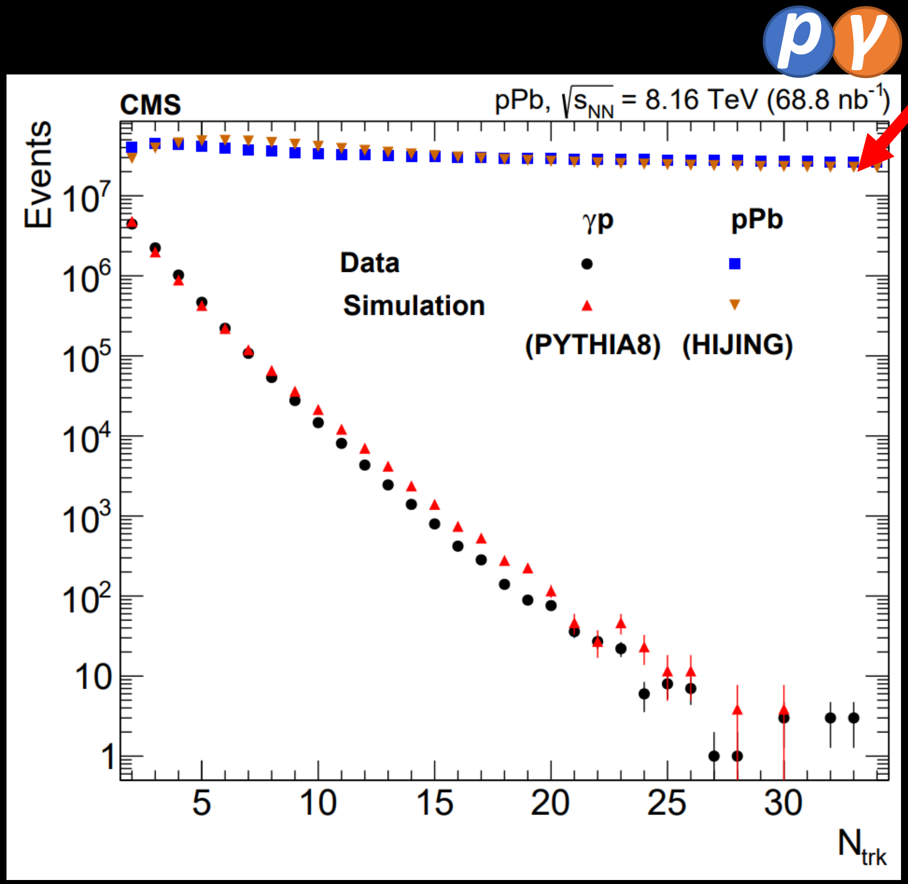
Pb going direction

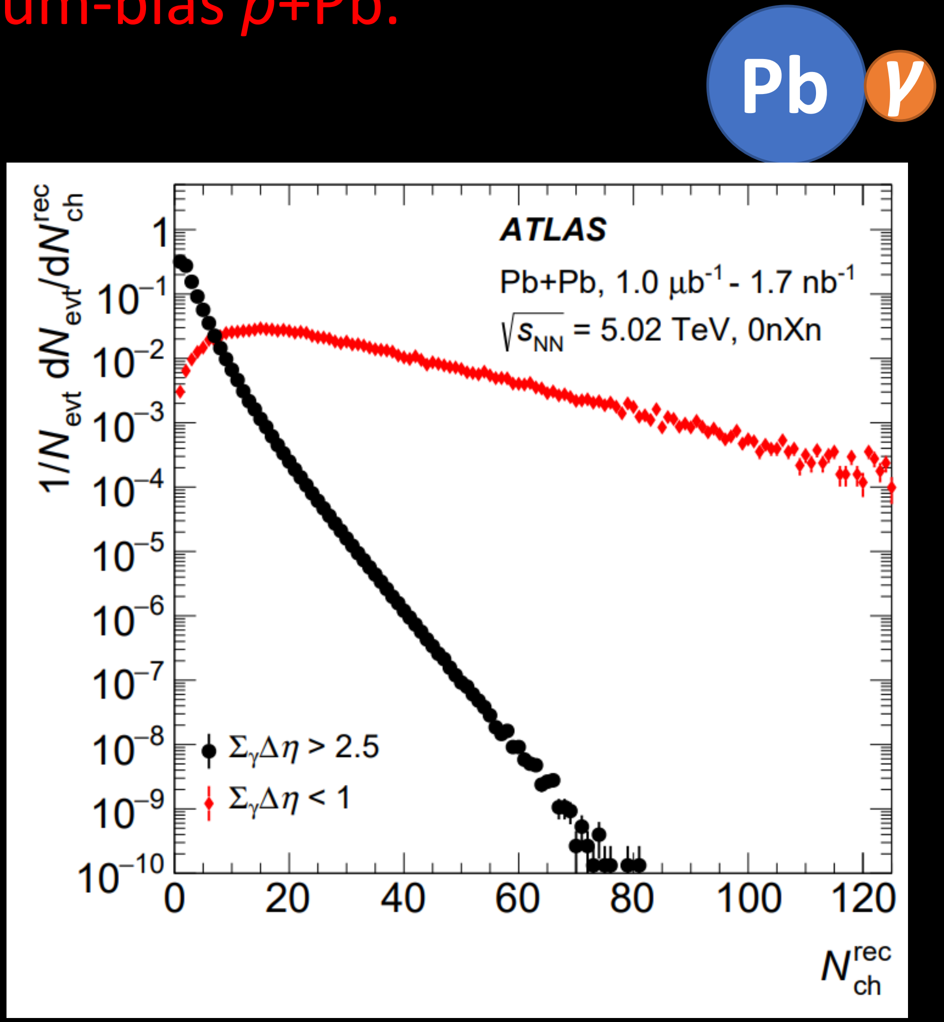


photon going direction

Charged-particle multiplicity

γ+A has a very steep multiplicity distribution and γ+*p* is even steeper compared to minimum-bias *p*+Pb.





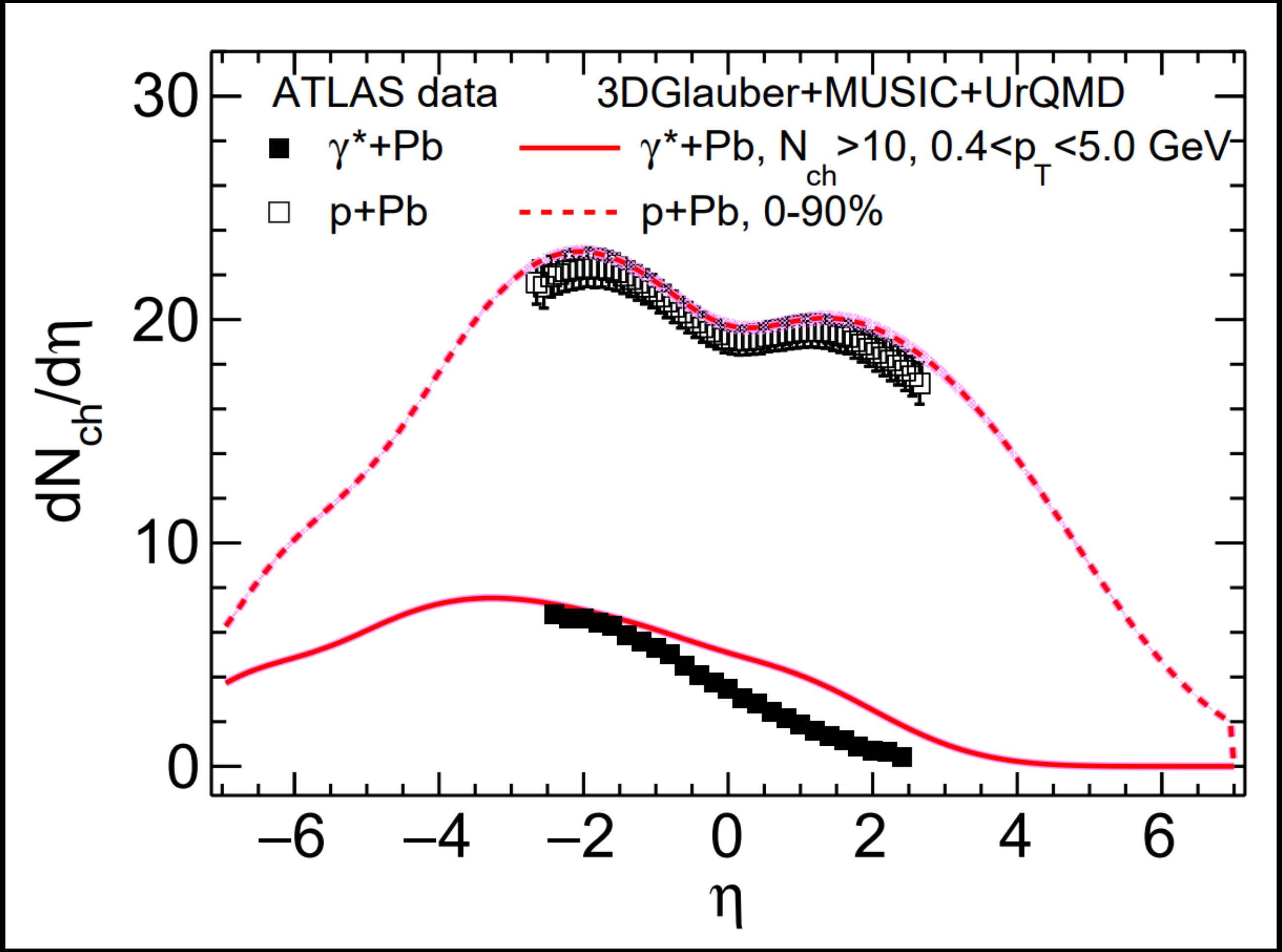
arXiv:2204.13486

arXiv:2101.10771

$dN_{ch}/d\eta$ in γA collisions

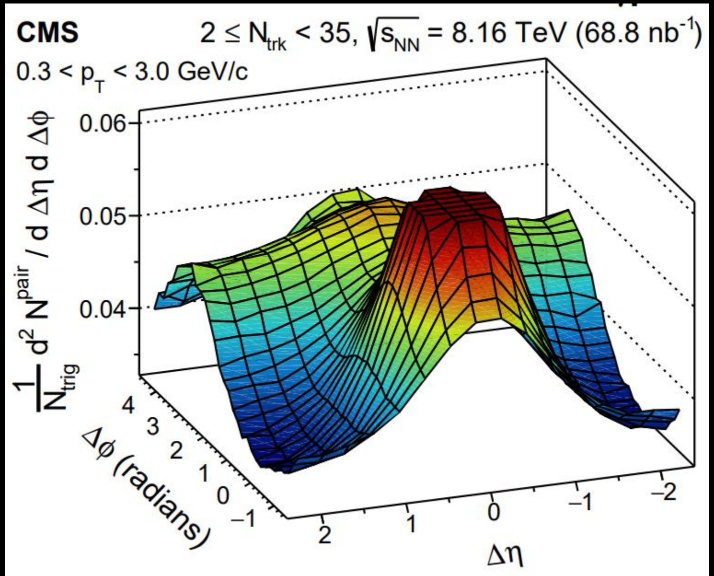
First comparisons with theory model which can describe de range of soft phenomenon in hadronic collisions

Many refinements need to be made to the theory and a proper data measurement are needed for a detailed quantitative comparison, such as…
-realistic photon-Pb impact parameter
-inclusion of direct events
-experimental event selection of theory



arXiv:2203.06094

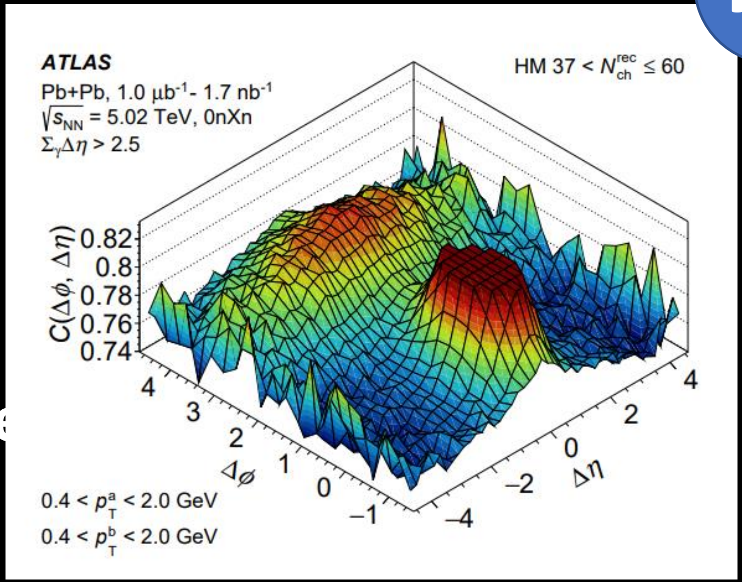
Two-particle correlation of charged tracks

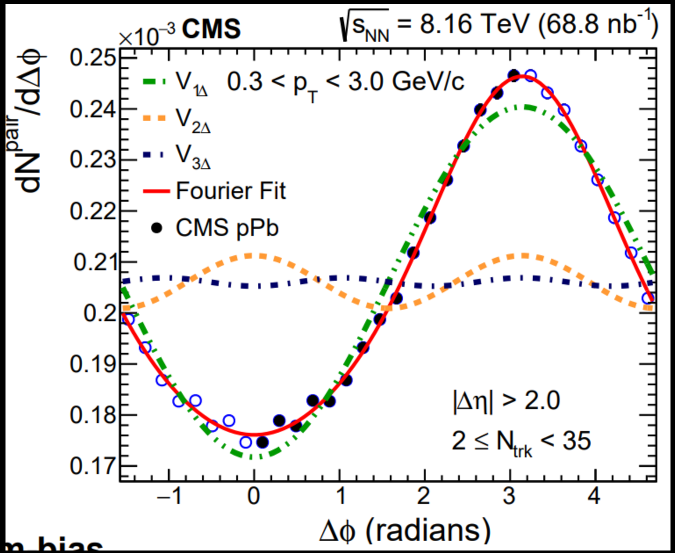


pγ

No clear nearside ridge

Pb γ





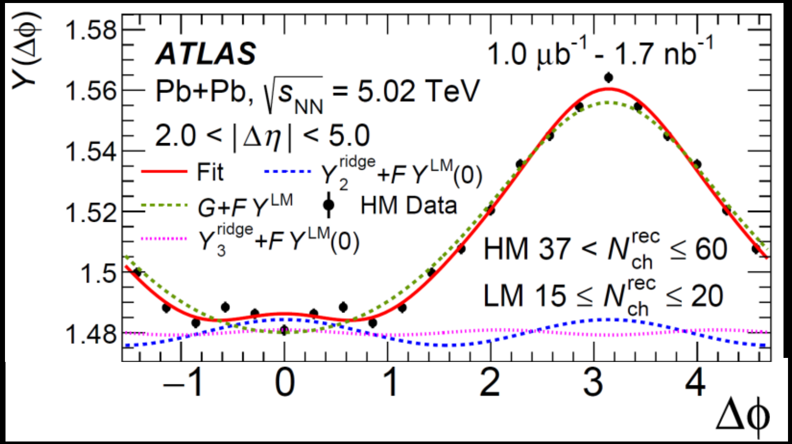
Away-side correlation

Momentum conservation

Jets

Not collective phenomenon

Termed “non-flow”

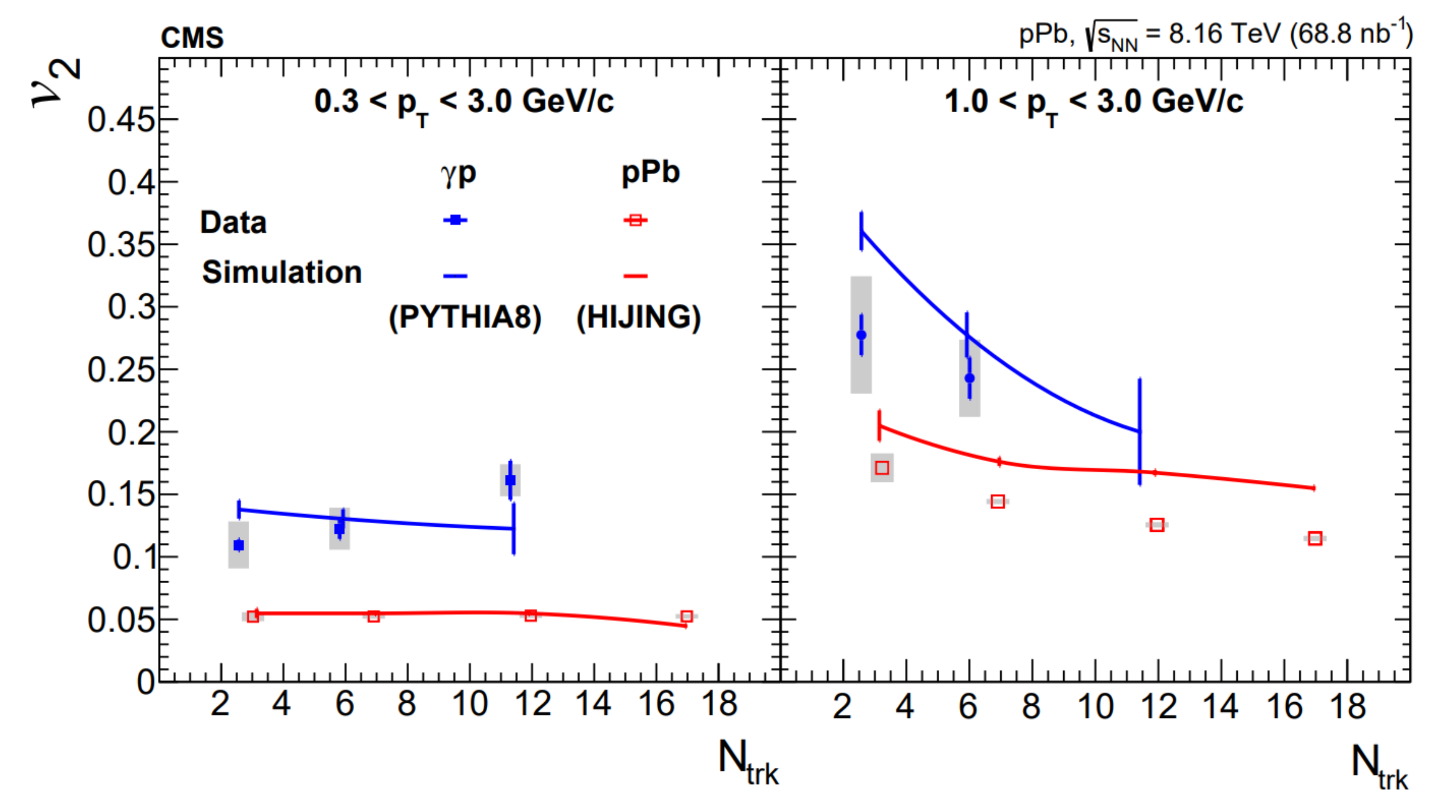


arXiv:2204.13486

Need to remove non-flow

arXiv:2101.10771

γ+p final results: $v_2(N_{ch})$



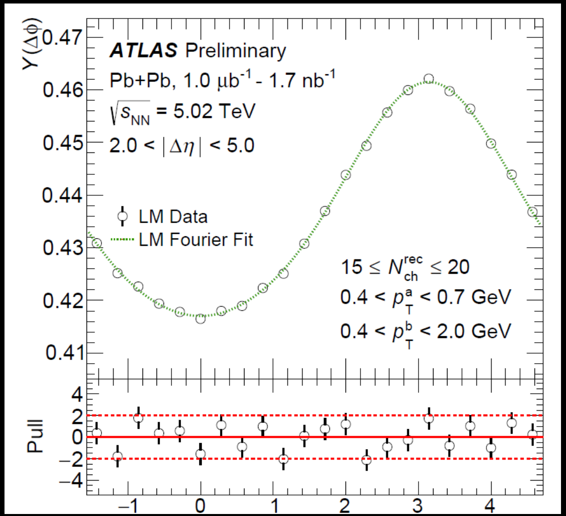
arXiv:2204.13486

- V_2 is largely a result of non-flow correlations
- Non-flow subtraction should be performed to further understand the collective effects.
- MC modeling of soft correlations is generally not perfect, thus the general agreement of data with MC with no flow is relatively weak evidence of no flow in gamma+p

Non-flow removal in γA correlations

High-multiplicity (HM) correlation data

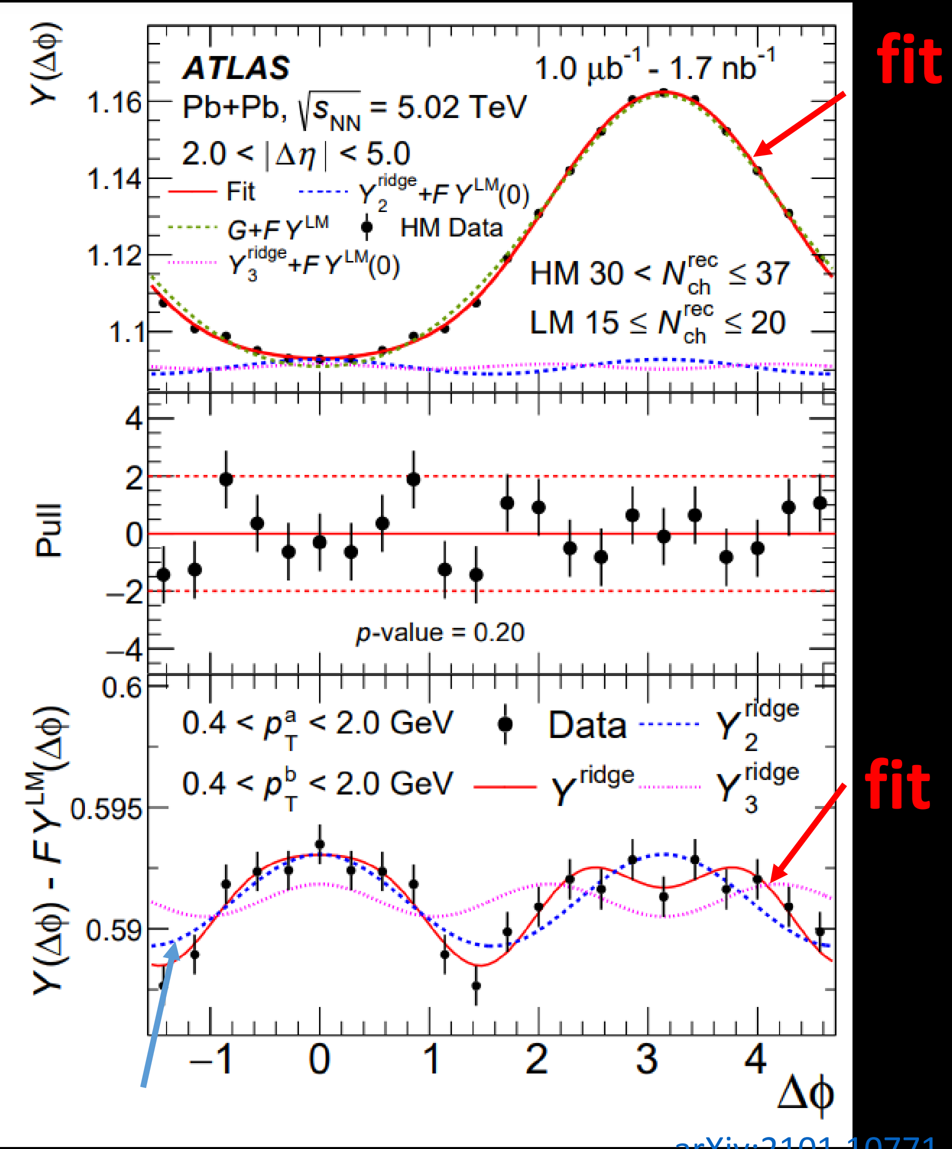
Low multiplicity (LM)
template for jet/non-flow correlation



<u>Nonflow subtraction</u>

- HM fit with LM data and flow coef.
- HM and LM assumed to have same flow shape
- Different LM selection leads to similar results

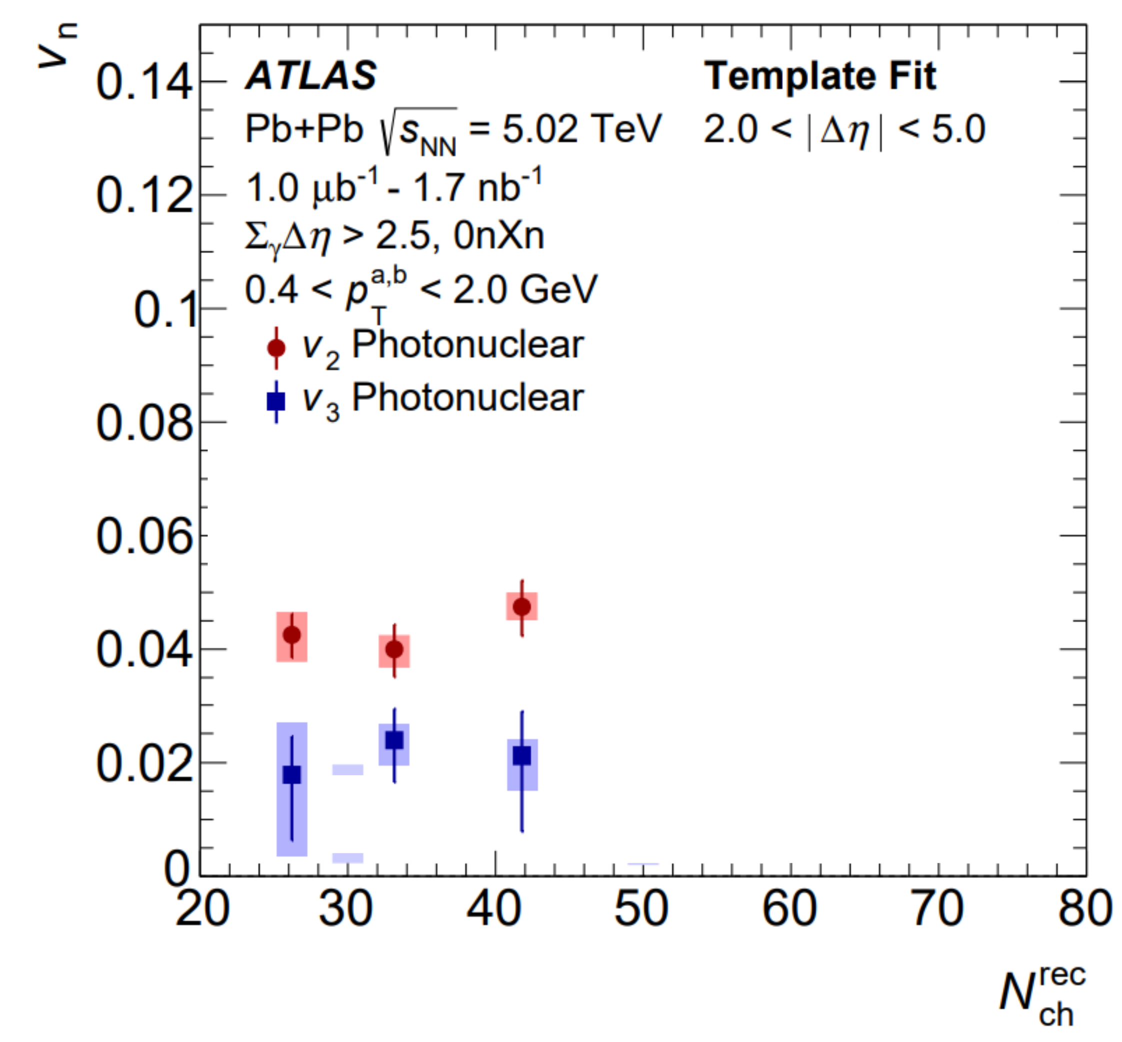
$$Y^{HM}(\Delta\phi) = FY^{LM}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{3} v_{n,n}\cos(n\Delta\phi)\right\}$$



arXiv:2101.10771

After nonflow subtraction clear cos(2Δϕ) modulation

v_n in photonuclear collisions

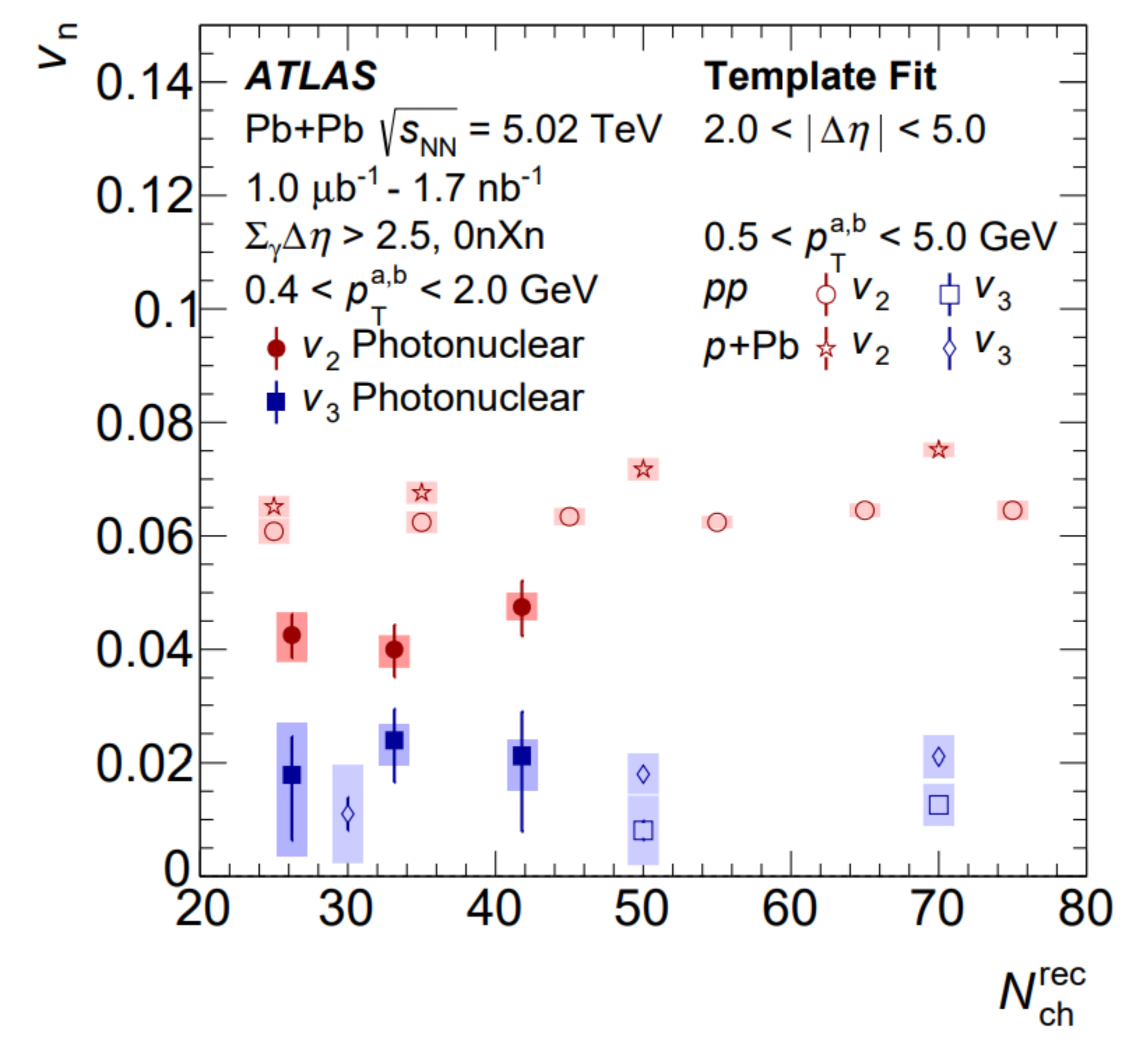


Significant nonzero v_2 and v_3 in photonuclear collisions

Flat $v_2(N_{ch})$ within statistical precision

arXiv:2101.10771

v_n in photonuclear collisions



Significant nonzero v_2 and v_3 in photonuclear collisions

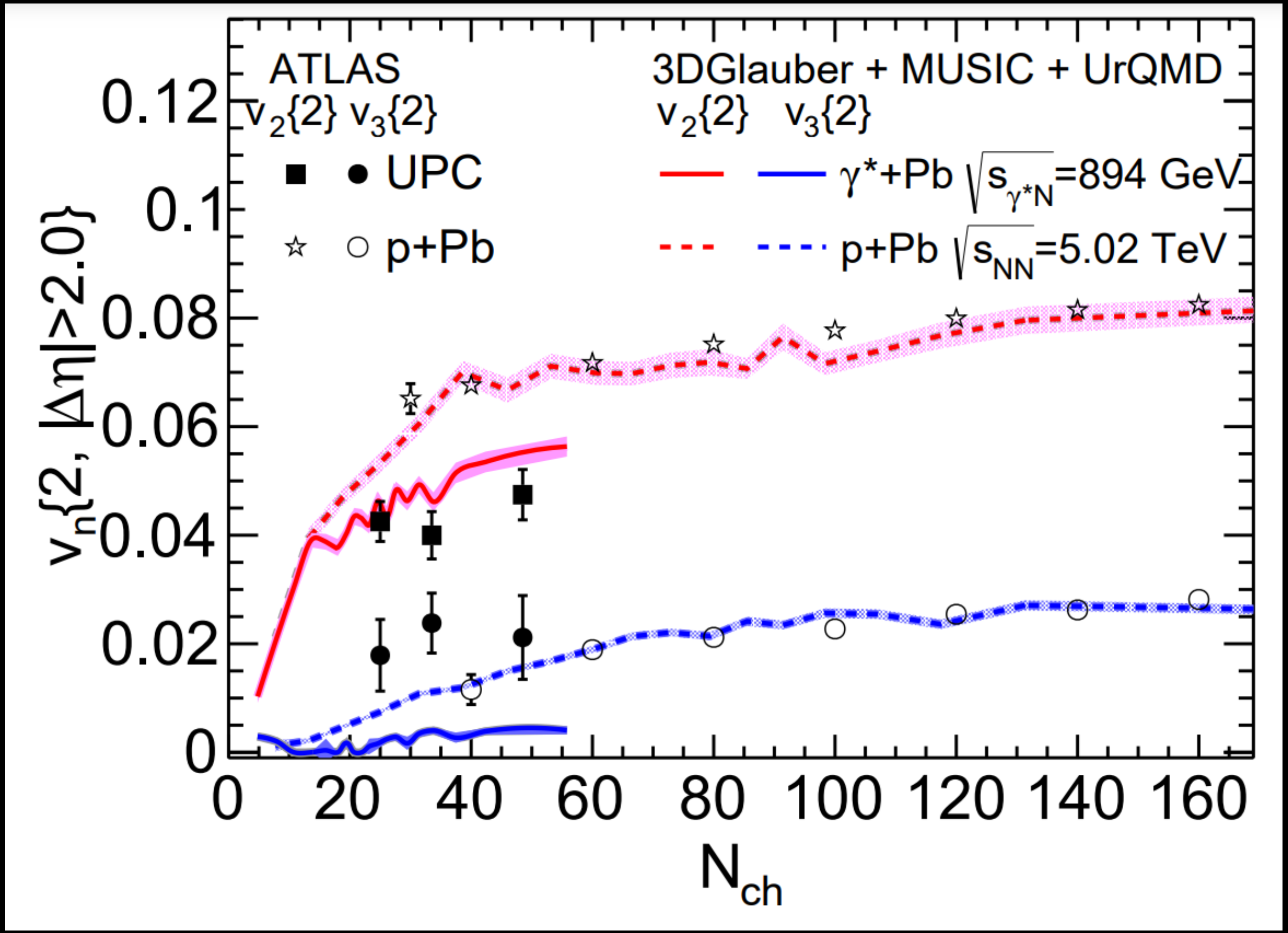
Flat $v_2(N_{ch})$ within statistical precision

Changing *pp* to $0.4 < p_T < 2.0$ is predicted to lower *pp* v_2 by ~10% which does not lead to agreement between *pp* and γA

Consistent v_3 between γA and *pp* given large uncertainties on both

arXiv:2101.10771

New γ+Pb theory comparisons



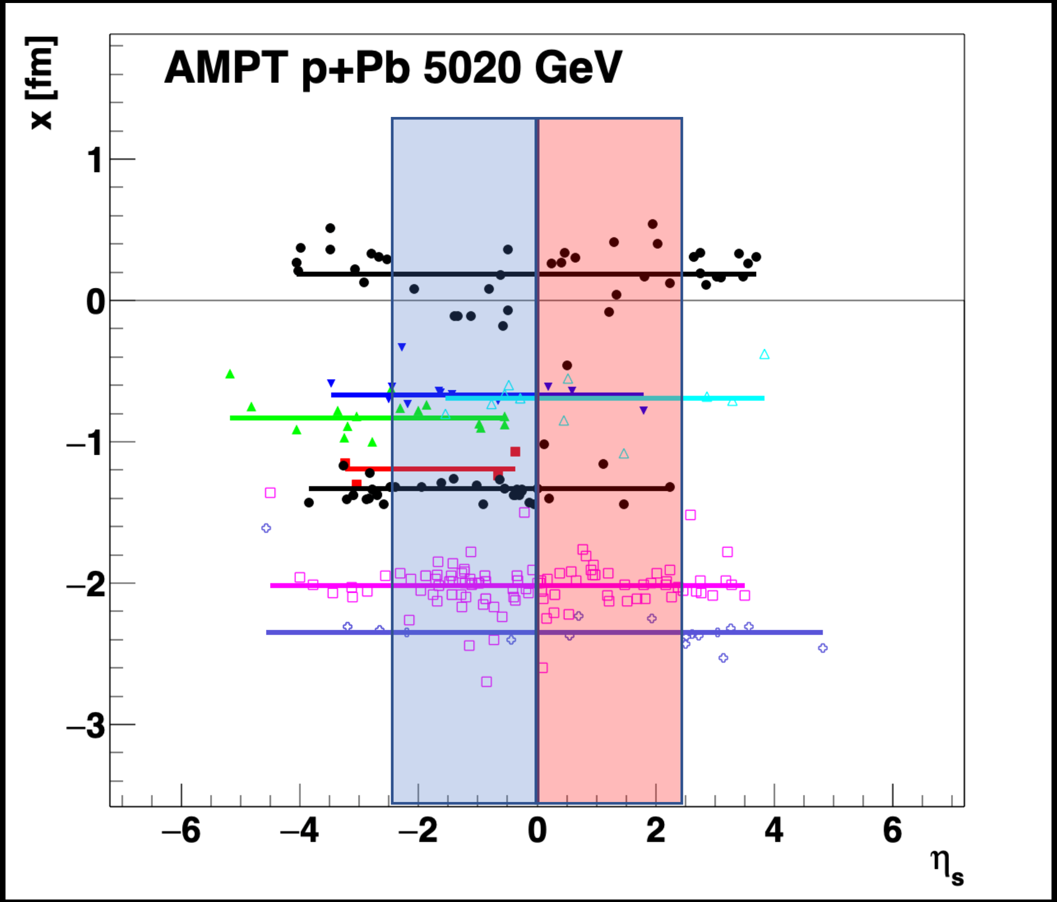
New comparison to 3DGlauber + MUSIC +UrQMD

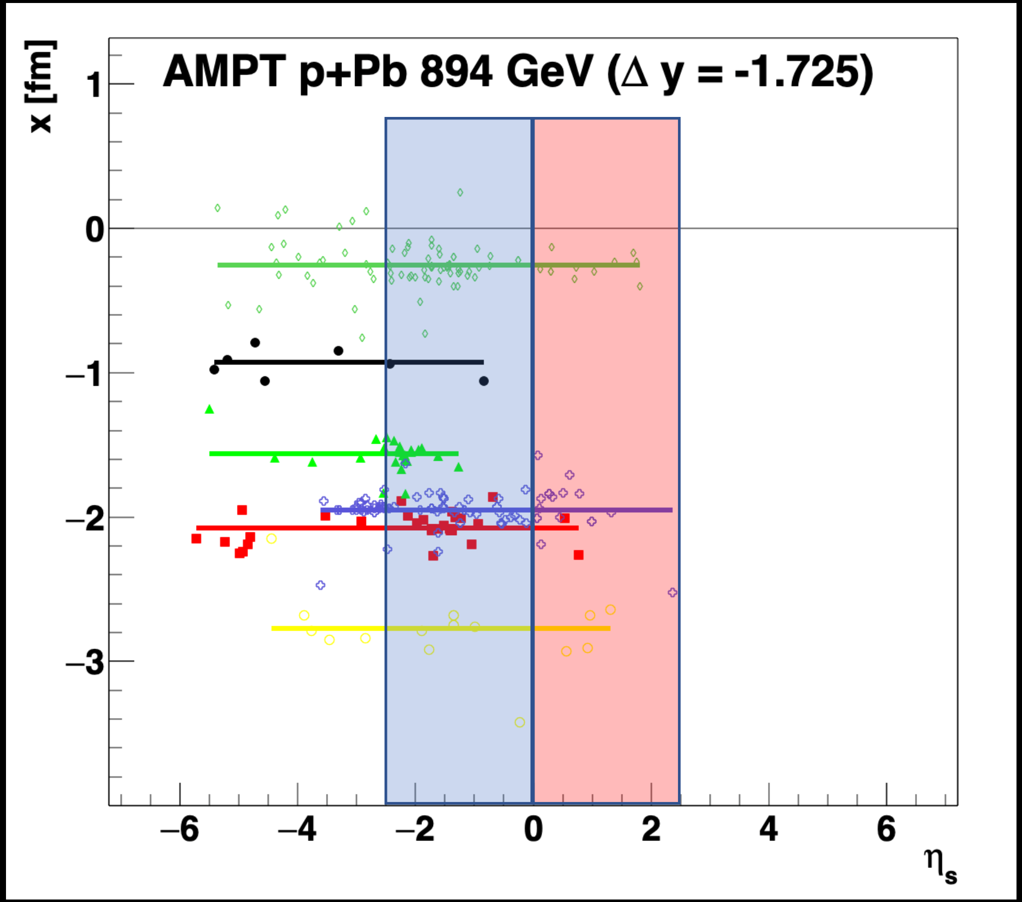
Quantitatively reproduces both p+Pb and γ+Pb simultaniously

Why is v_2 (γ *Pb) < v_2 (pPb)

arXiv:2203.06094

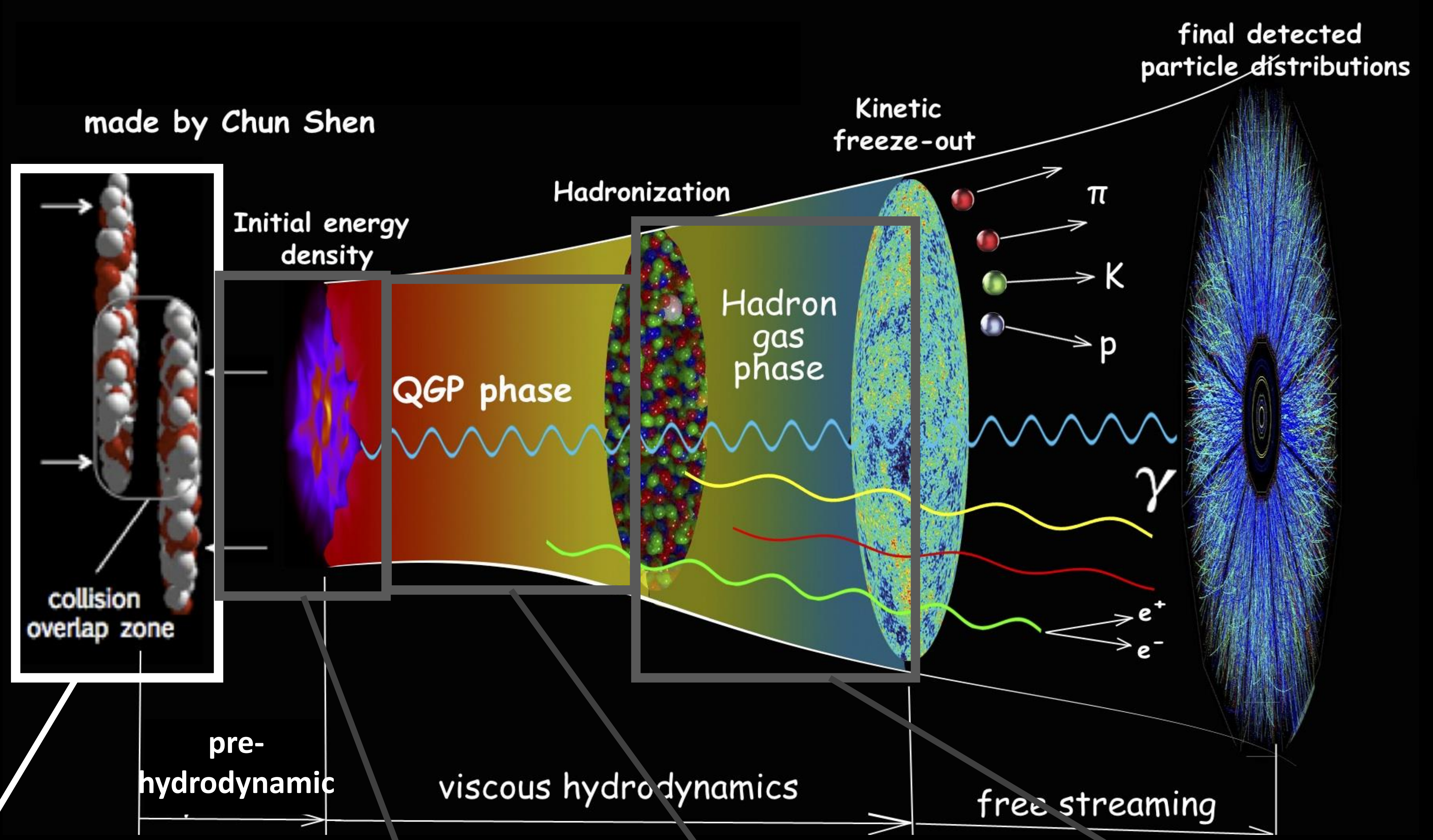
Why is v_2 (γ *Pb) < v_2 (pPb)… Boost matters!





String models can reproduce longitudinal geometry fluctuations

In a two-particle correlation, particles are selected from rapidities which can have different string geometries (decreasing the correlation)



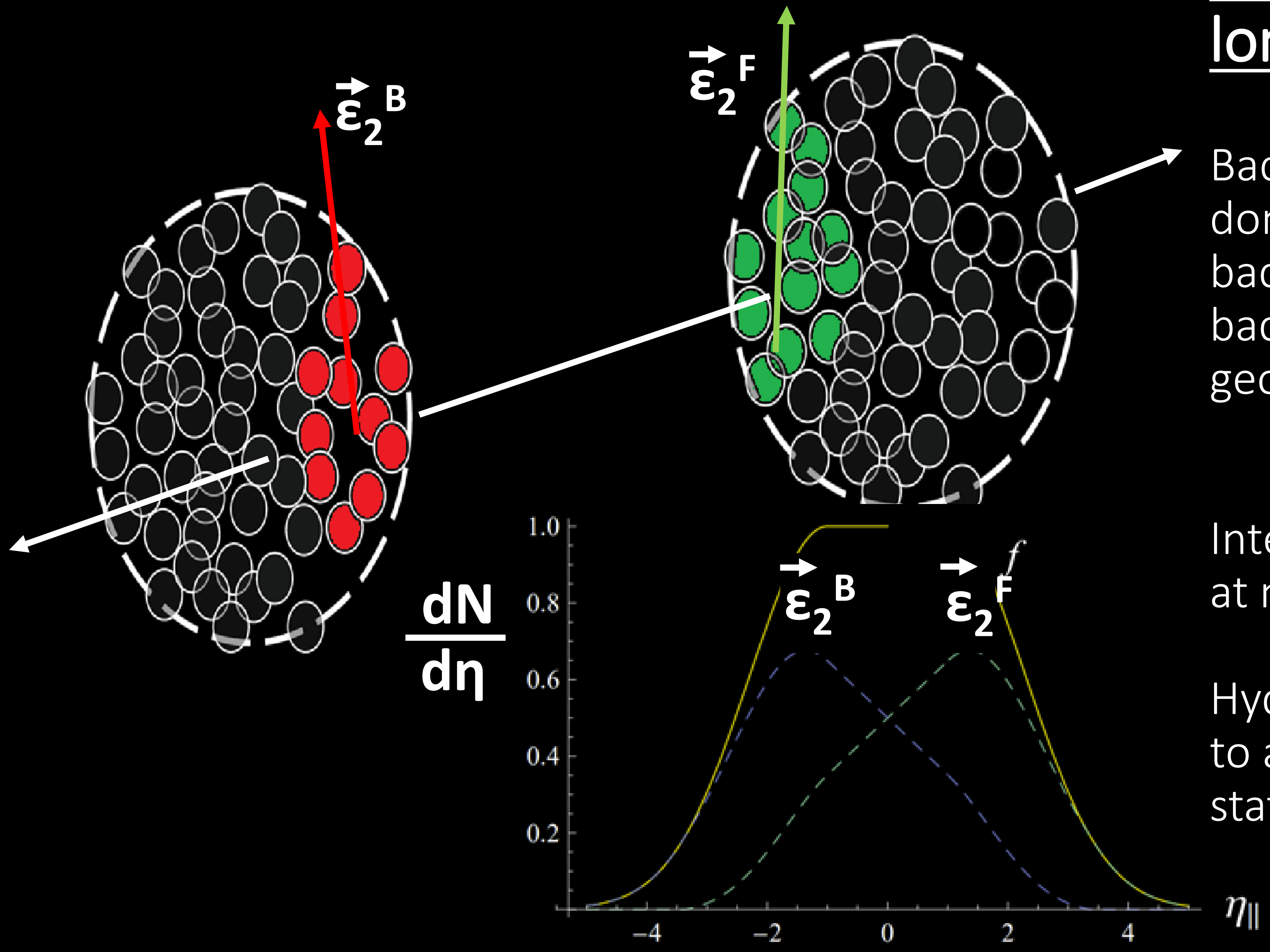
v_n-$[p_T]$ correlations
HIN-21-012
Longitudinal decorrelations
ATLAS-CONF-2022-020

γ+*p* collectivity
CMS-PAS-HIN-18-008
γ+A collectivity
arXiv:2101.10771

Identified hadron collectivity
QM22
Strangeness enhancement
QM22

Hadron resonance production
QM22

η-dependent geometry



First models of longitudinal decorrelation

Backwards-going participants dominates backwards going dN/dη and backwards-going initial-state geometry

Interpolation between geometries at mid-rapidity

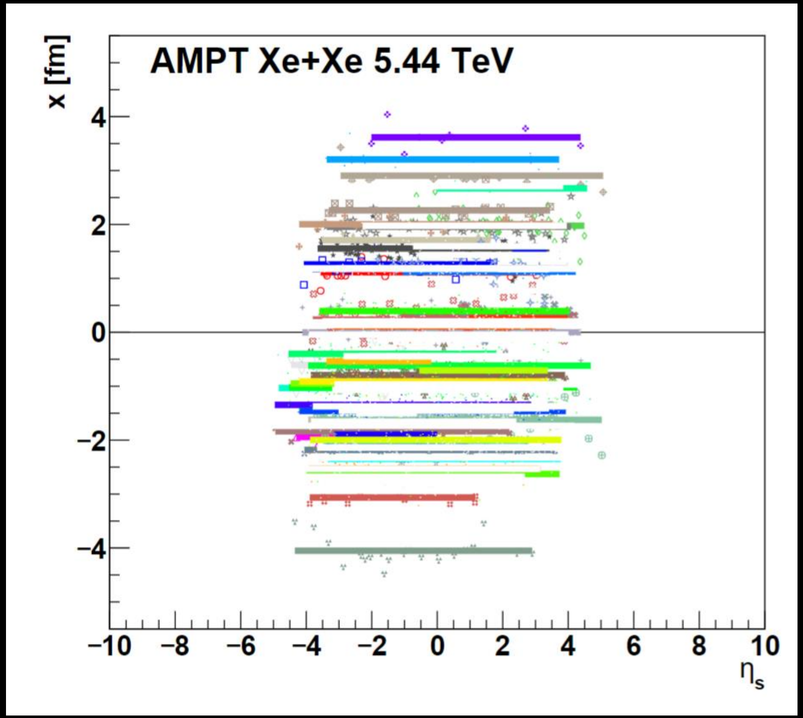
Hydrodynamic expansion gives rise to azimuthally anisotropic final-state momentum

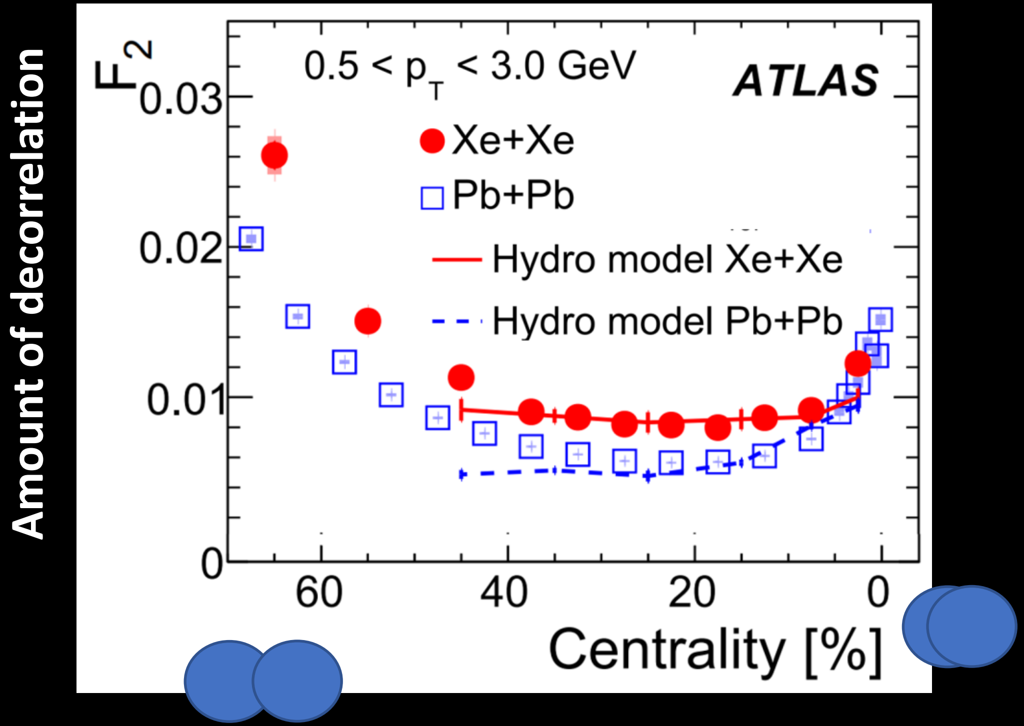
arXiv:1011.3354

String models of longitudinal decorrelation

- String-based MC Glauber models of the initial state simulate these effects out of the box
- Common models (HIJING/AMPT) produce one string per participant
- String-based initial state + hydro has shown good agreement with previous ATLAS results.

arXiv:2001.04201



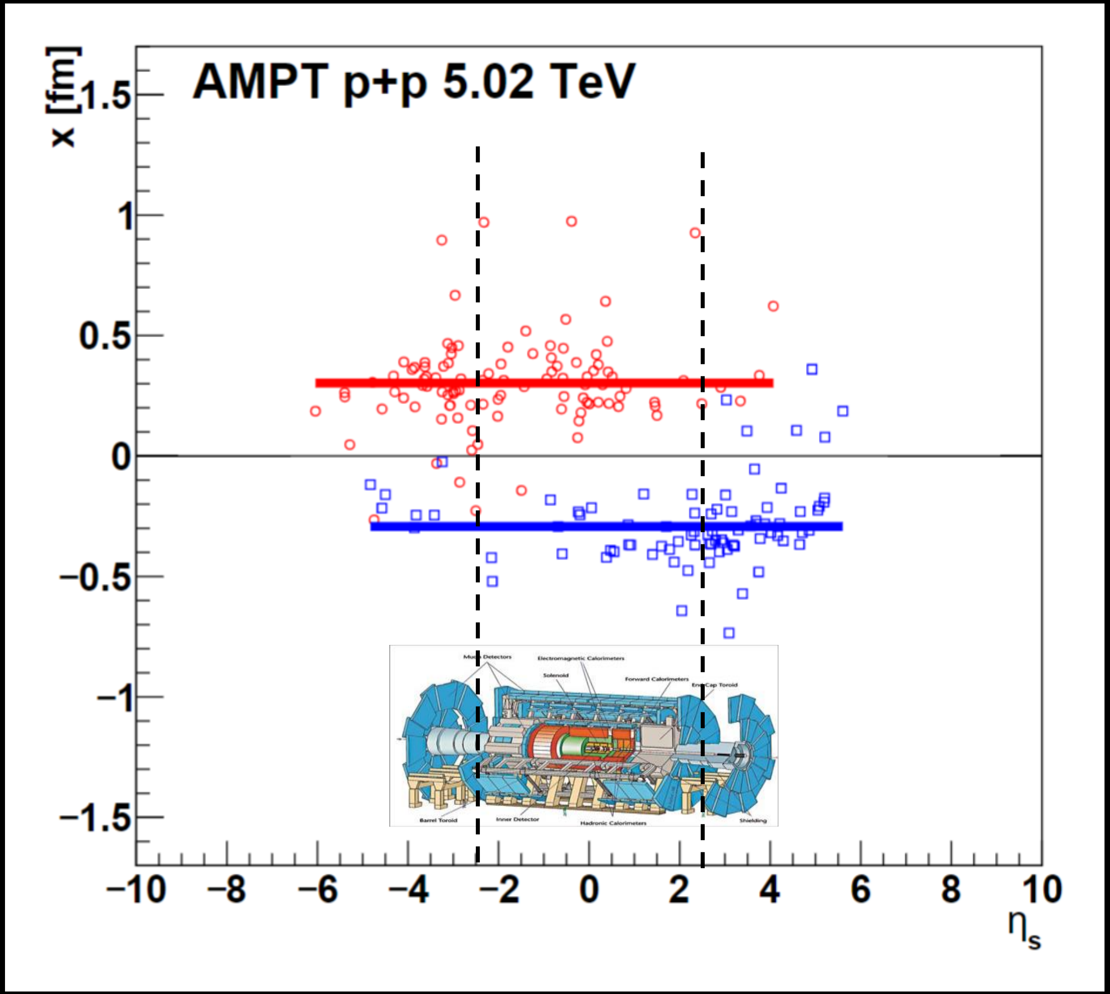


$v_{2,2} \propto 1 + F_2\eta$

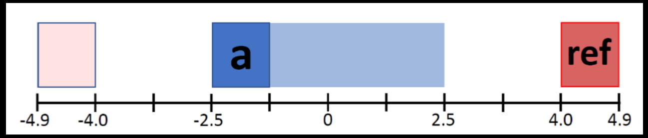
String models make straightforward prediction in *pp*

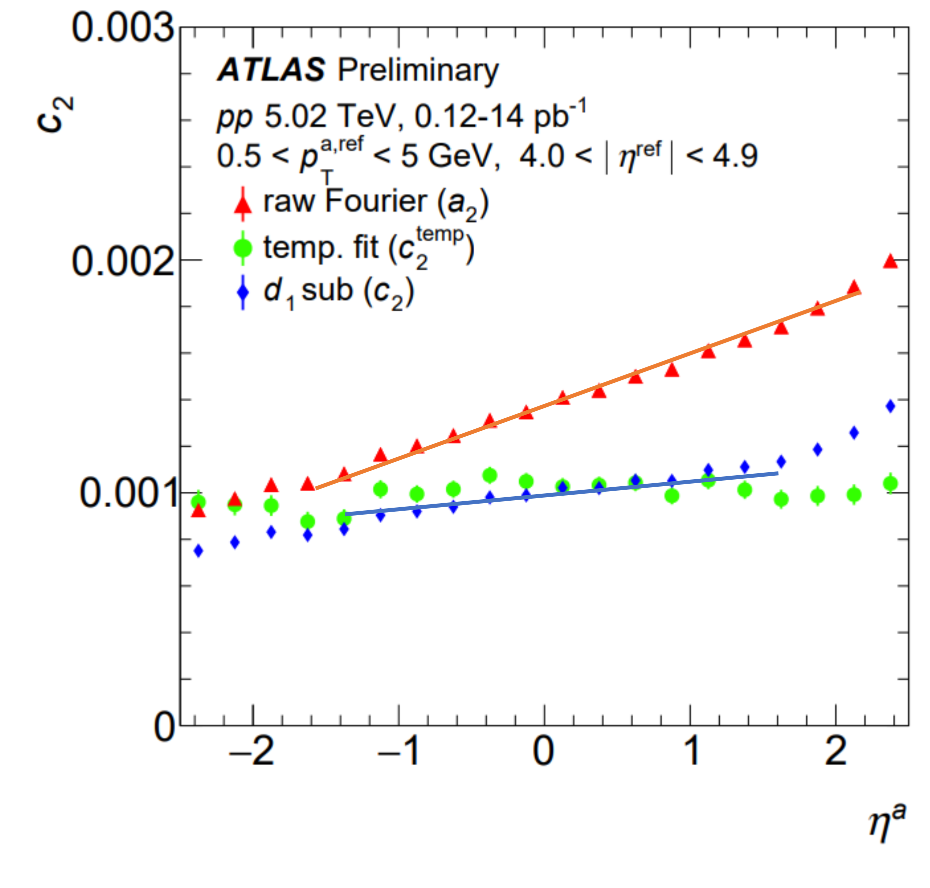
- A string per participant produces a simple model of proton-proton collisions
- Strings span the acceptance of the ATLAS inner detector.
- No variation in geometry
- **No longitudinal decorrelation**

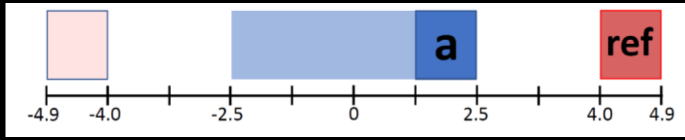
What does data say



$v_{2,2}(\eta^a)$ and non-flow subtraction







$$v_{2,2} \propto 1+F_2\eta$$

F_2 is the fractional change in correlation per a unit of rapidity

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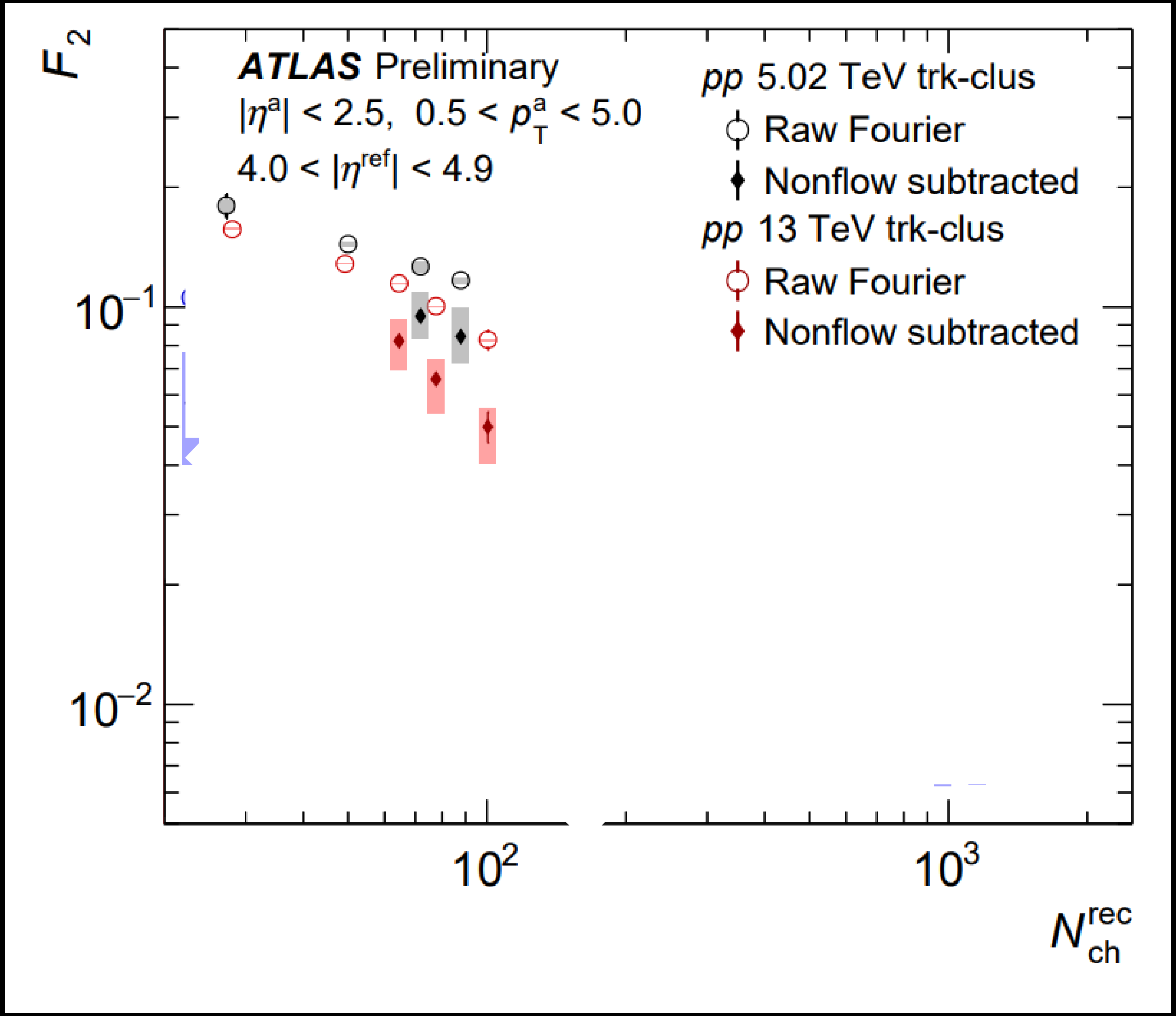
System comparison



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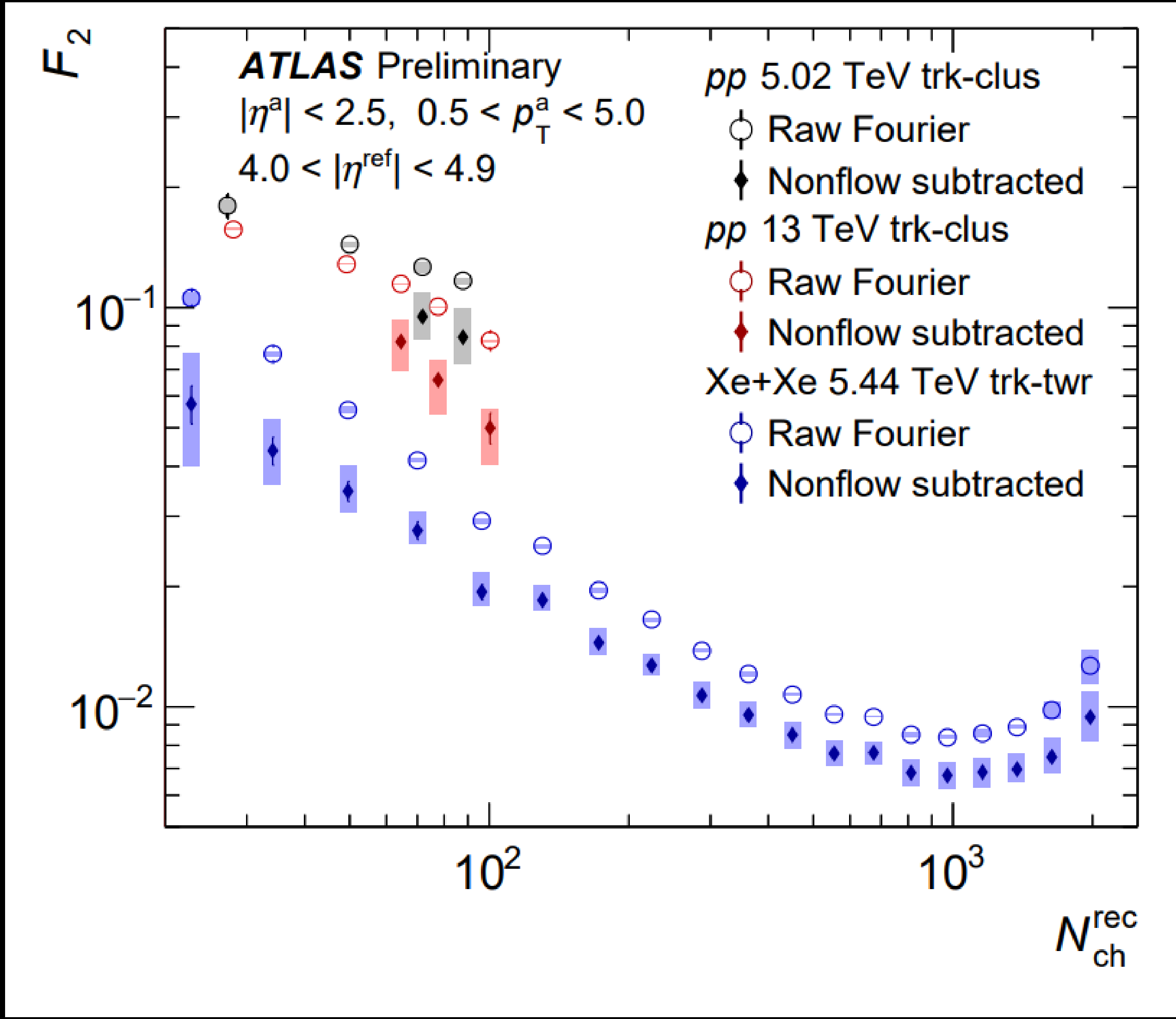
Raw results (open markers)

Non-flow subtracted results

Larger decorrelation in *pp* than Xe+Xe at similar multiplicities.

Peripheral XeXe and *pp* decorrelation follow a power-law decrease

System comparison



Raw results (open markers)

Non-flow subtracted results

Larger decorrelation in *pp* than Xe+Xe at similar multiplicities.

Peripheral XeXe and *pp* decorrelation follow a power-law decrease

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Data to AMPT comparisons

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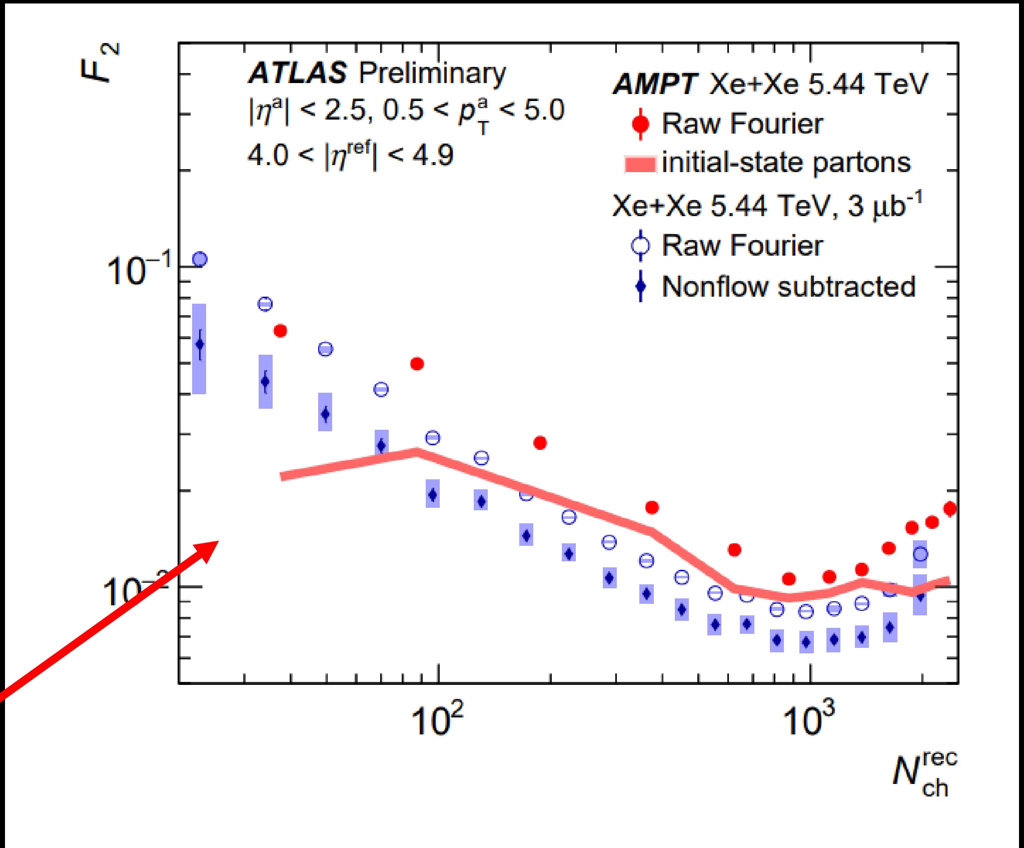
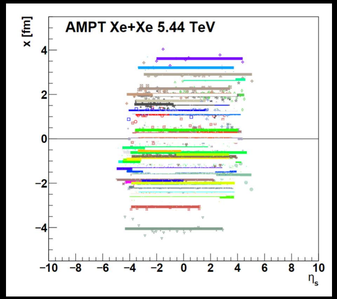
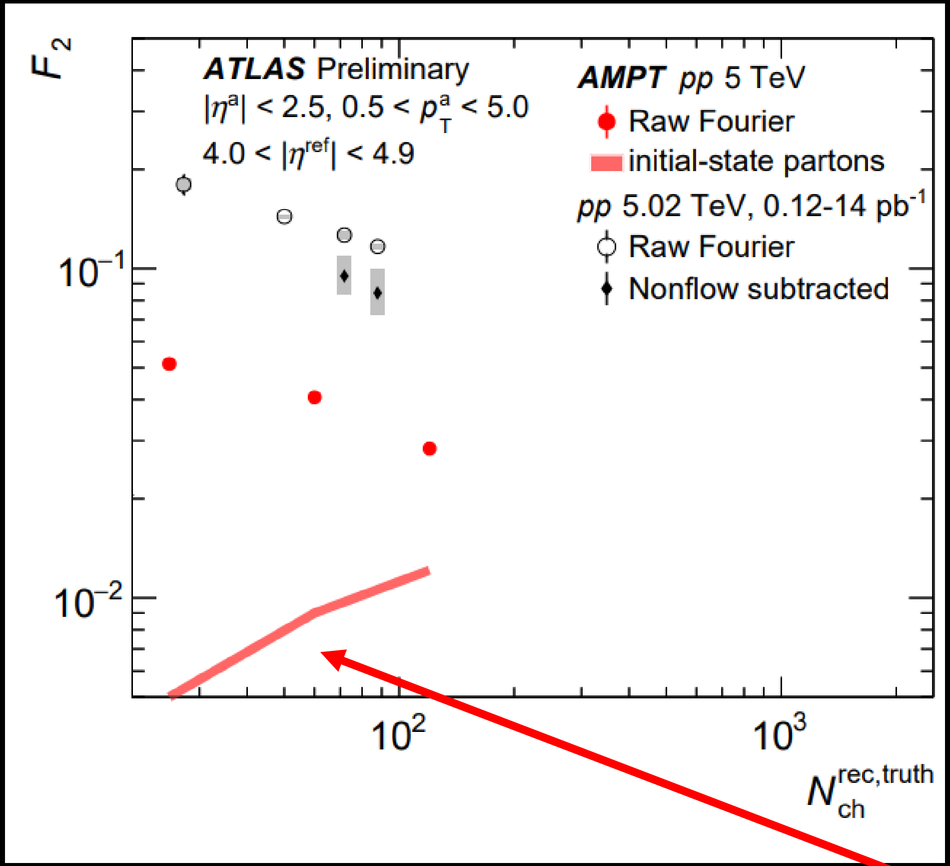


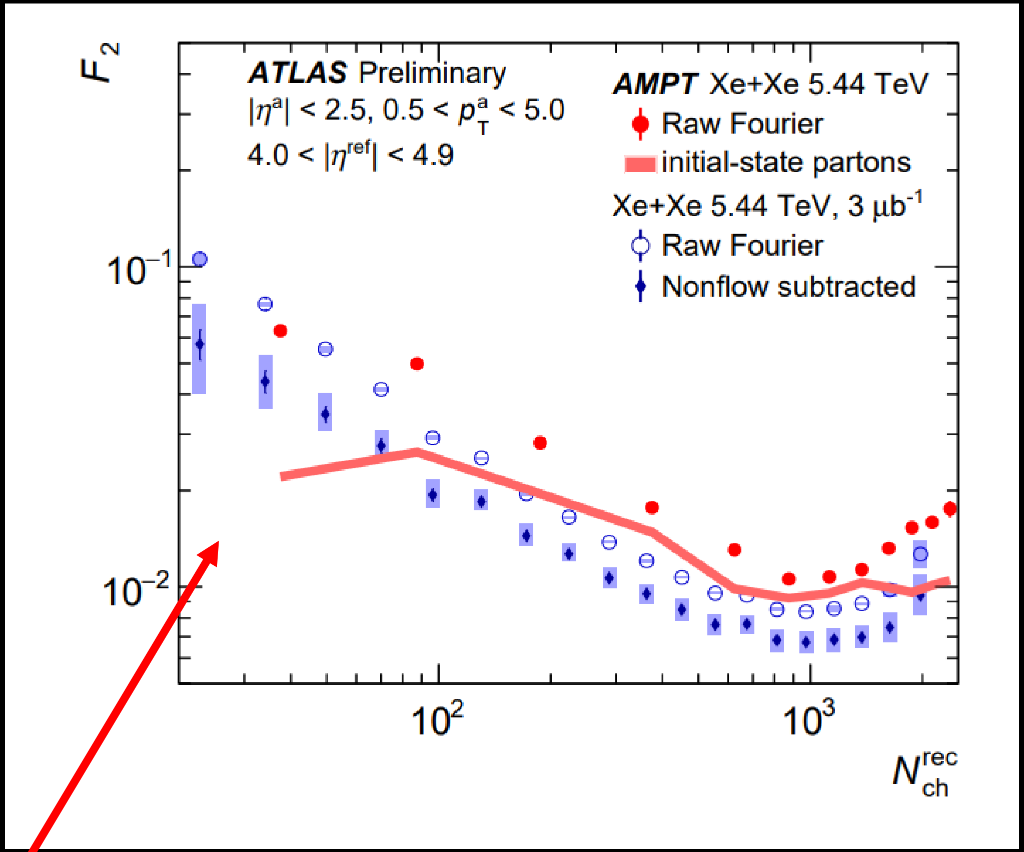


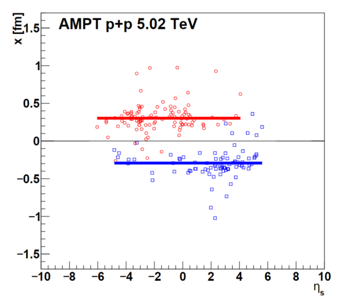
$$r_2(|\eta^a|) = \frac{\vec{\varepsilon}_2(-|\eta_s^a|) \cdot \vec{\varepsilon}_2(\eta_s^{ref})}{\vec{\varepsilon}_2(|\eta_s^a|) \cdot \vec{\varepsilon}_2(\eta_s^{ref})}$$

Data to AMPT comparisons

ATLAS-CONF-2022-020

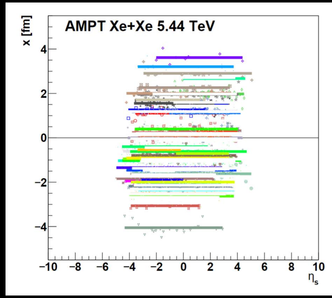






$$r_2(|\eta^a|) = \frac{\vec{\varepsilon}_2(-|\eta_s^a|) \cdot \vec{\varepsilon}_2(\eta_s^{ref})}{\vec{\varepsilon}_2(|\eta_s^a|) \cdot \vec{\varepsilon}_2(\eta_s^{ref})}$$

Low number of strings leads to small geometric decorrelation



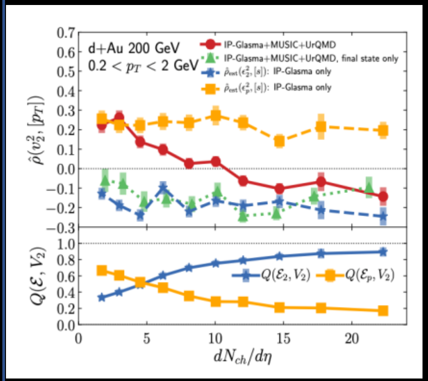
Disfavors a *pp* initial-state model with a low number of long strings

v_n-[p_T] *correlation pp* collisions

Probes the correlation between initial energy density size and shape.

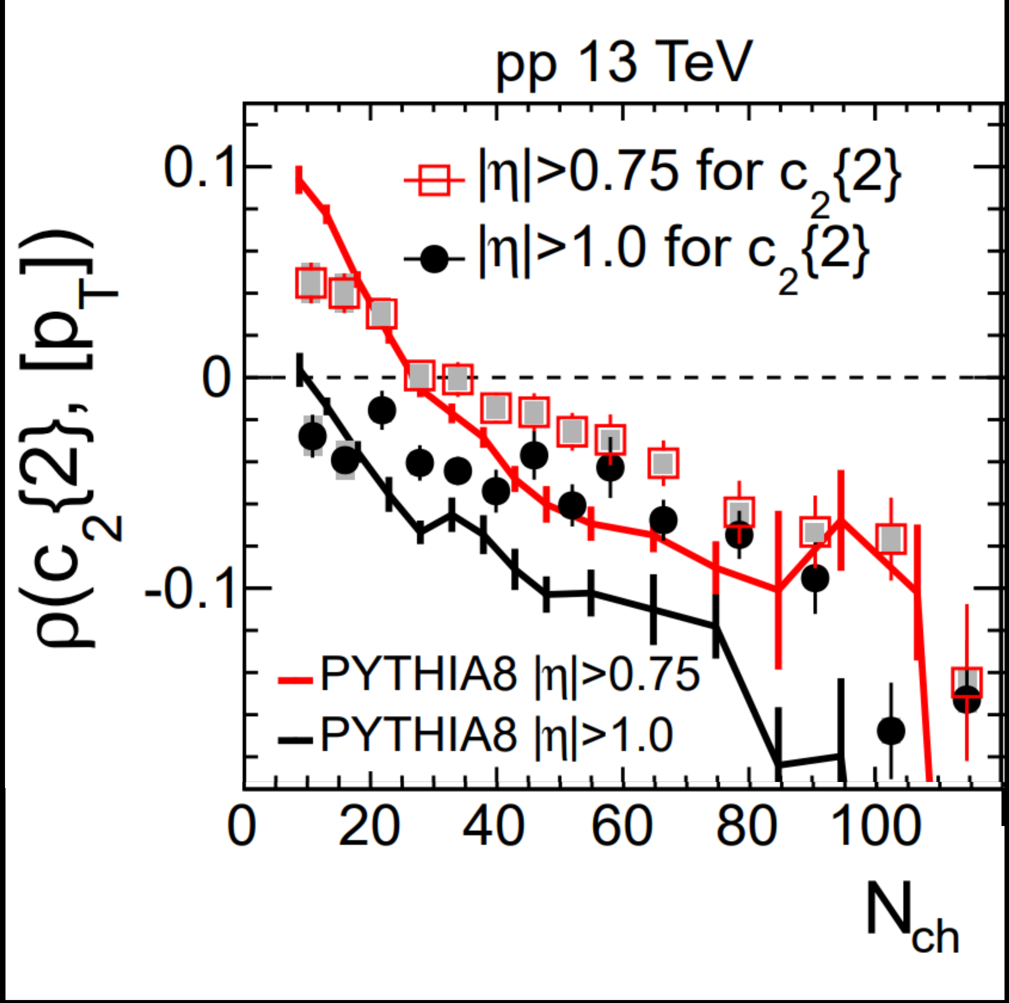
Results show a large impact from non-flow

Very challenging interpretation because similar trends are seen in PYTHIA8.



https://arxiv.org/abs/2006.15721

Sign change in v_n-[p_T] correlation was predicted to be a signature of initial-state correlations



HIN-21-012

Conclusion

Initial state
Precision measurements of pp initial-state geometry
Larger longitudinal decorrelation in pp than larger systems
Correlations between v_n-[p_T]

Novel/ultra small systems

Photonuclear v_n has a similar order of magnitude and trends as other previously measured hadronic systems

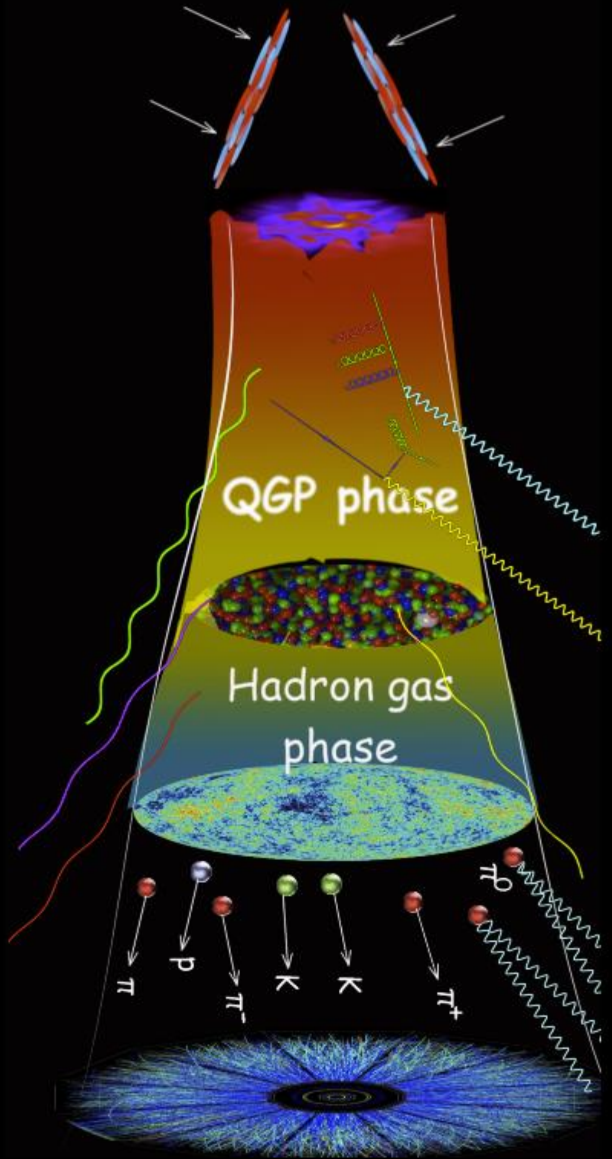
- Intuitive property of hadronic-like photonuclear collisions (photon → vector meson).
- New model comparisons that reproduce results in γ+Pb and p+Pb simultaneously and qualitatively reproduces γ+Pb dN_{ch}/dη

QGP and hadron gas expansion in proton-proton

Precision measurements of identified hadron flow

More differential measurements of the initial state effects on strangeness

Clear signature of a hadronic phase with increasing rescattering with multiplicity



Thank you

Fundamental constraints on nucleon-nucleon collisions

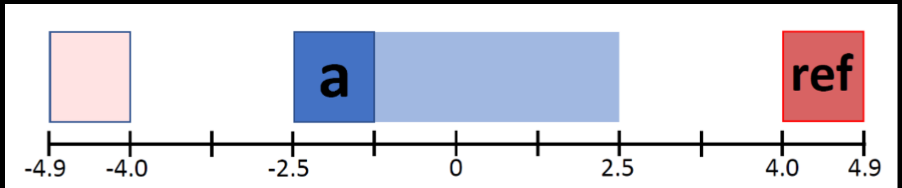
- Constrains the correlation between initial state
    1. Transverse structure and
    2. Longitudinal energy deposition / initial state momentum structure

- Longitudinal dependence of correlations is of practical importance when
    - **Comparing experimental results with different acceptances**
    - **Comparing theory and data**

Analysis overview

Systems analyzed

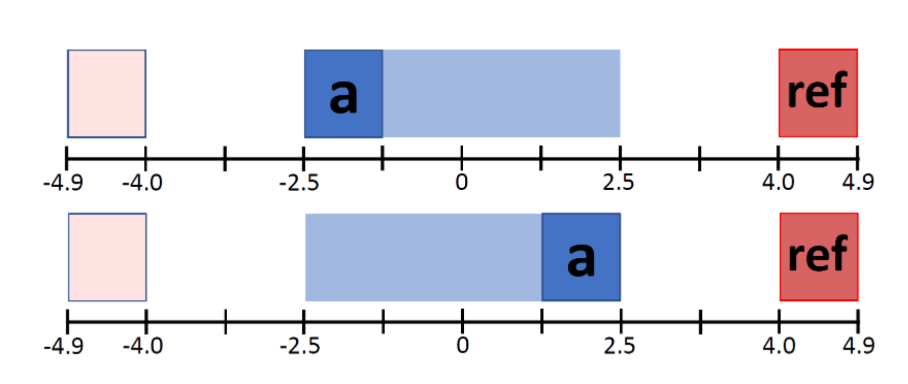
pp **13 TeV** ***pp*** **5.02 TeV** **Xe+Xe 5.44 TeV**



Analysis steps

Step 1: Two-particle correlations between Inner detector tracks and forward calorimeter

Step 2: measure Fourier moments and perform non-flow subtraction as a function of η^{a}



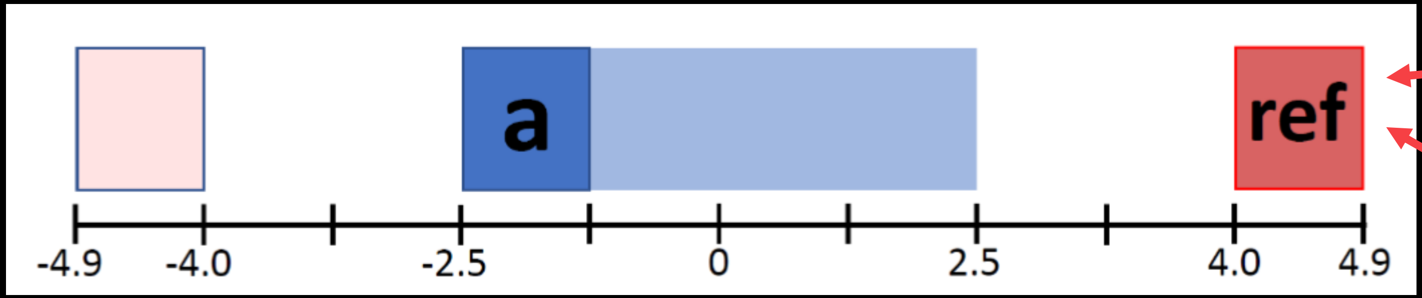
Step 3: construct ratio, $r_{n}(|\eta^{a}|)$

Step 4: Parametrize decorrelation via the slope of $r_{n}(|\eta^{a}|)$

Analysis overview

$$\Delta\phi = \underbrace{\phi^{a}}_{\eta^{a} = [-2.5,2.5]} - \underbrace{\phi^{ref}}_{\eta^{ref} = [4.0,4.9]}$$

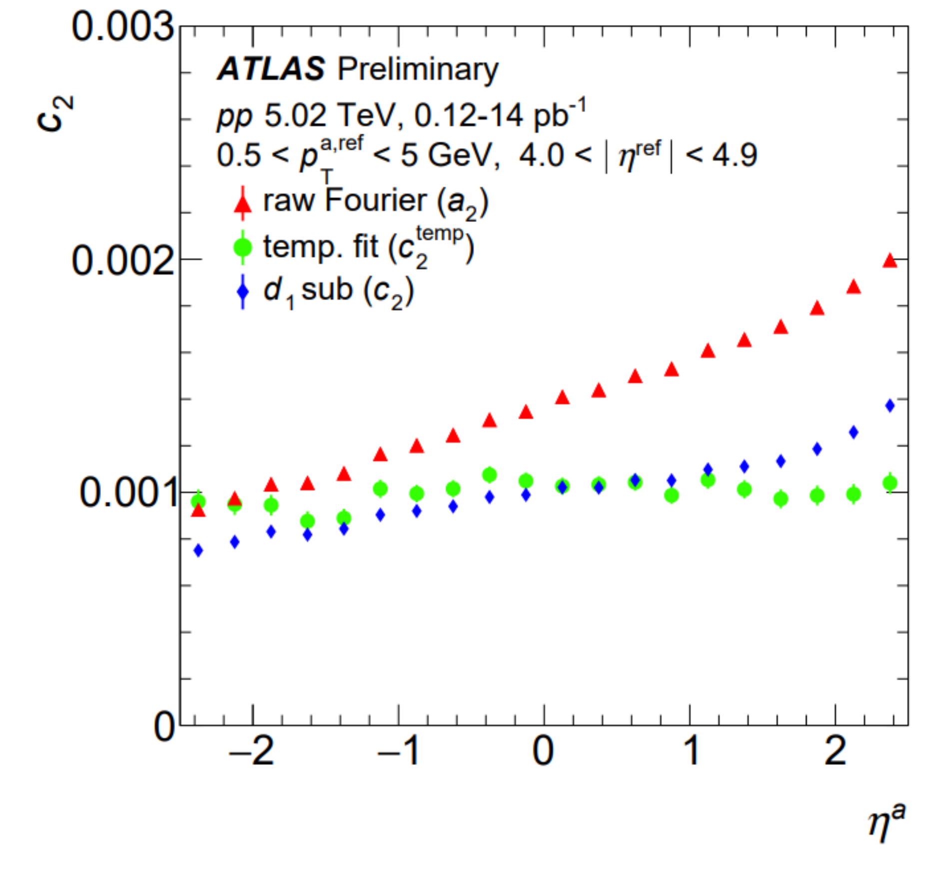
Step 1: Two-particle correlations between Inner detector tracks and forward calorimeter

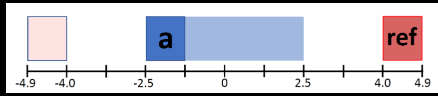


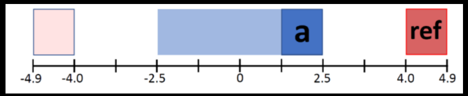
pp: calorimetric cluster

Xe+Xe: calorimetric tower

$v_{2,2}(\eta^a)$ and non-flow subtraction







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Raw Fourier moments a_2

$$Y(\Delta\phi, \eta^a) = G\left\{1 + 2\sum_{n=1}^{4} a_n(\eta^a)\cos(n\Delta\phi)\right\}$$

flow **non-flow**

$$Y(\Delta\phi, \eta^a) = G\left\{1 + 2\sum_{n=1}^{4} (c_n(\eta^a) + d_n(\eta^a))\cos(n\Delta\phi)\right\}$$

η-dependent template fit (temp. fit)

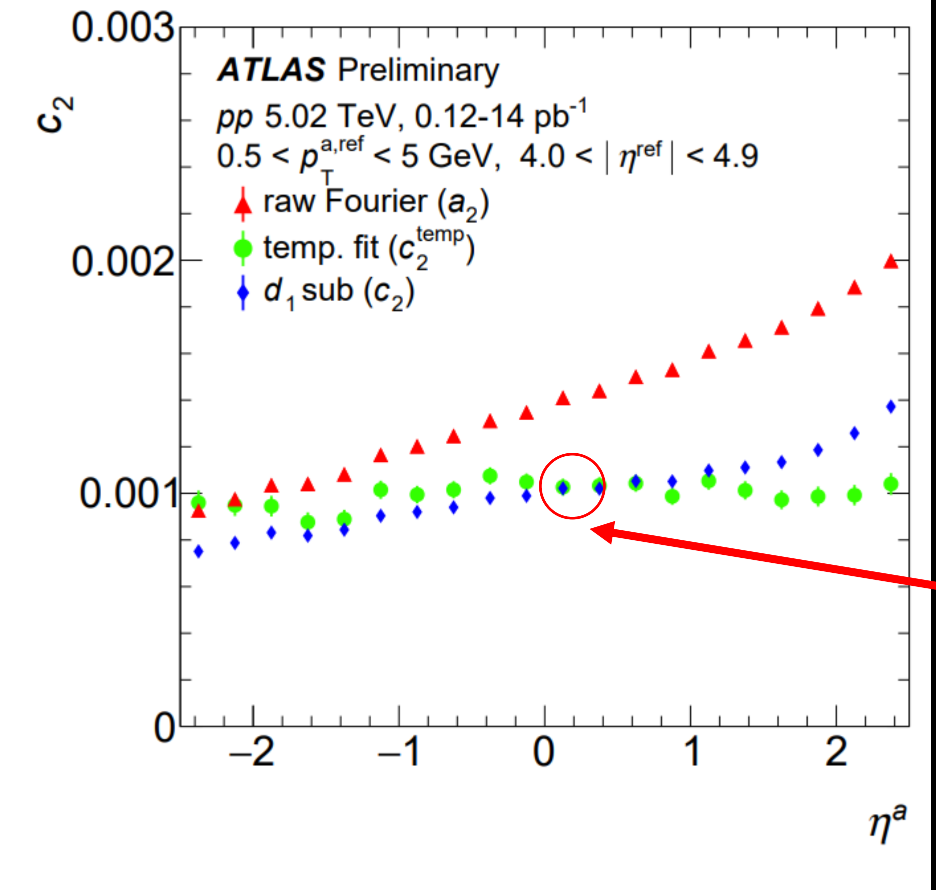
$$Y^{HM}(\Delta\phi, \eta^a) = F^{temp}(\eta^a)Y^{LM}(\Delta\phi, \eta^a) + G^{temp}(\eta^a)\left\{1 + 2\sum_{n=2}^{4} c_n^{temp}(\eta^a)\cos(n\Delta\phi)\right\}$$

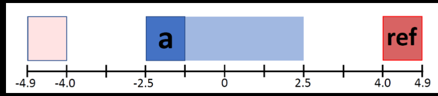
Use low multiplicity 2PC in same η^a slice as a *template* for non-flow

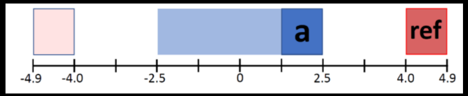
Low multiplicity reference N_{ch} = 40-60

Many assumptions in the template fit – can we compare to another method

$v_{2,2}(\eta^a)$ and non-flow subtraction







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d_1 scaling subtraction (d_1 sub.)

$$c_2(\eta^a) = a_2(\eta^a) - a_1(\eta^a)\frac{d_2|_{\eta^a=0}}{d_1|_{\eta^a=0}}(1 + [F_2^d - F_1^d]\eta^a)$$

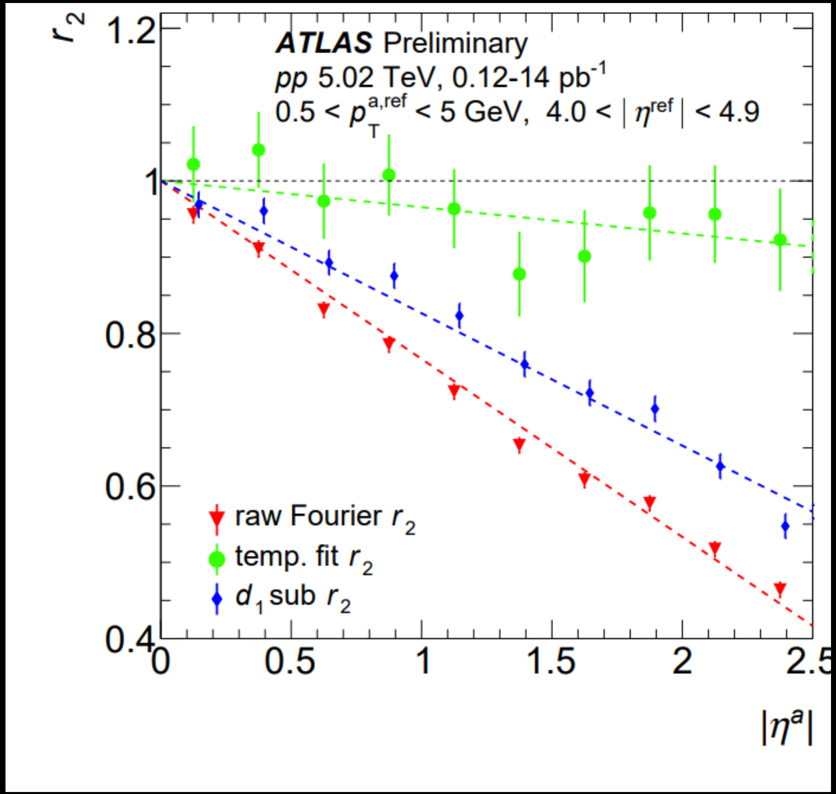
η^a independent non-flow shape
from mid-rapidity template fit results

η^a dependent correction
Build in η^a dependence with non-flow model from LM events

Differences in the subtracted results – will discuss with the full final results

Construct $r_2(|\eta^a|)$ ratio

$$r_2(|\eta^a|) = \frac{v_{2,2}(-|\eta^a|)}{v_{2,2}(|\eta^a|)}$$

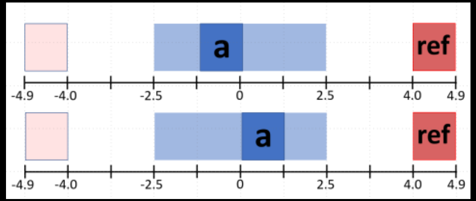


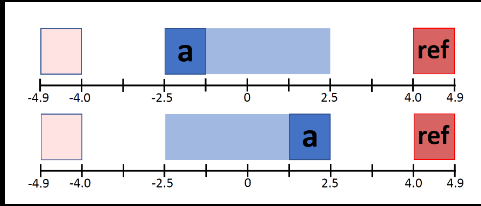
Extract the slope of r_2 with linear regression

$$F_n = \frac{\Sigma_i (1 - r_n(\eta_i))\eta_i}{2\Sigma_i \eta_i^2}$$

$$r_n(|\eta^a|) = 1 - 2F_2|\eta^a|$$

This regression is nearly identical to fitting with the above function





F_2 shown as dashed lines

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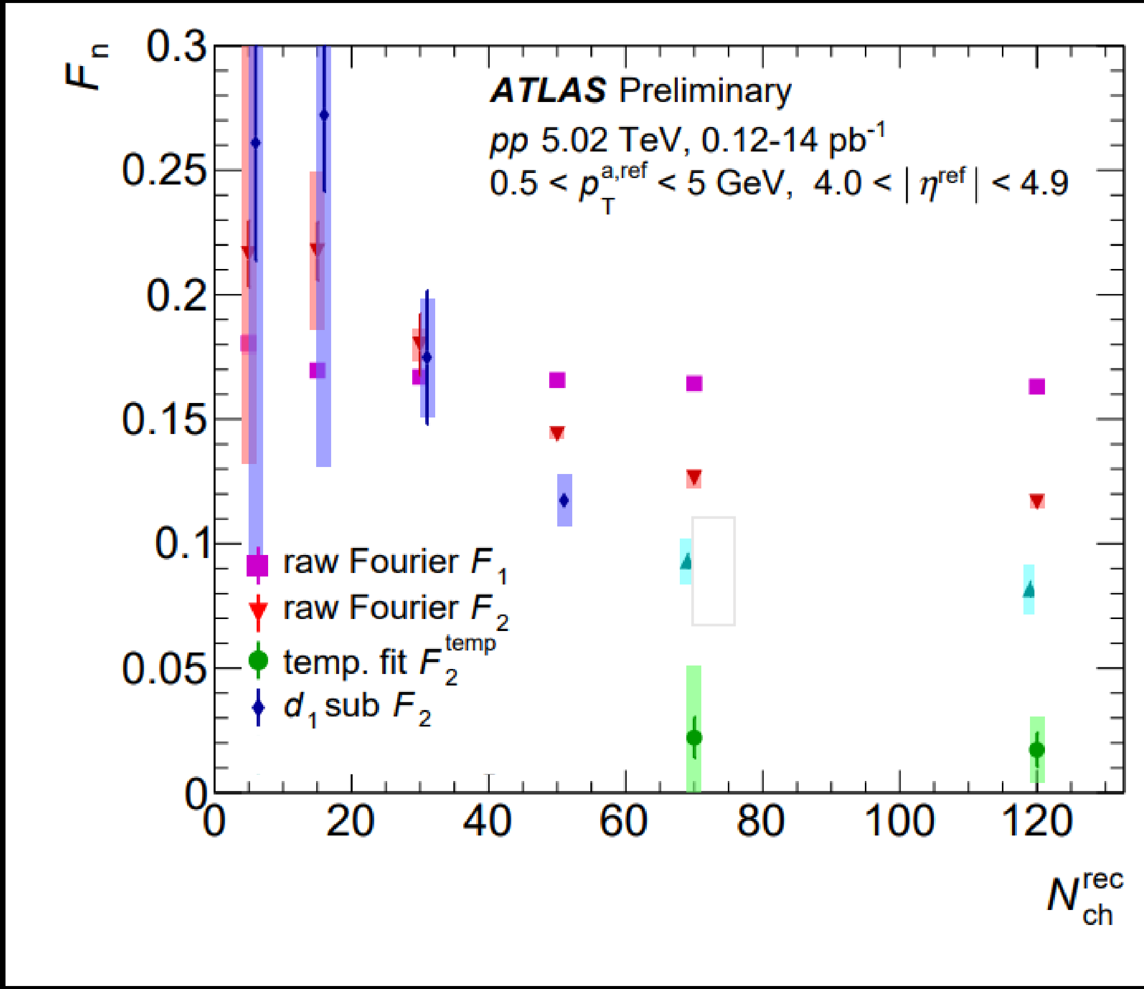
The r_n ratio measures the relative decorrelation between 2 η^a selections

F_2 provides a good description of r_2

Result in 5.02 TeV *pp* collisions



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- **Raw Fourier F_2:** a combination of flow and nonflow η^a dependence.
- **Raw Fourier F_1:** the η^a dependence of a_1. Mostly multiplicity independent
- **Template fit F_2**: Subtracts off ~85% of the raw decorrelation.
  - Template N_{ch}=40-60
- ***d_1*-scaling subtracted:** removes 1/4 of the raw decorrelation
  - Defined across the whole N_{ch} range

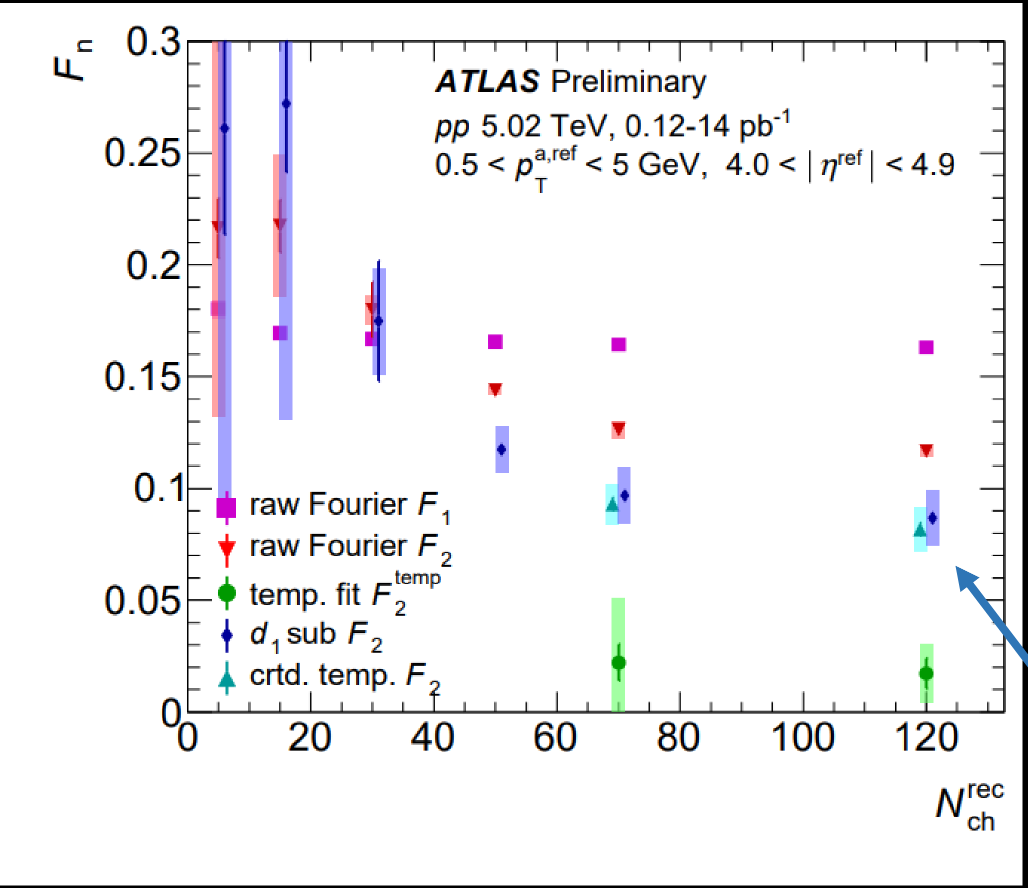
Template fit corrections

	Template fit F_2	d_1-scaling subtracted:
N_{ch}-independent non-flow shape	✓	✓
First moment is all non-flow	✓	✓
N_{ch}-independent mid-rapidity flow	✓	✓
F_n at N_{ch}=0-20 is all non-flow	X	✓
~~N_{ch}-independent flow decorrelation~~	~~✓~~	X

The template fit can be corrected for the violation of **N_{ch}-independent flow decorrelation assumption**

$$F_n^{\mathrm{HM}} \approx F_n^{\mathrm{temp}} + \rho \frac{c_n^{\mathrm{LM}}|_{\eta^a=0}}{c_n^{\mathrm{HM}}|_{\eta^a=0}} \left(F_n^{\mathrm{LM}} - F_n^{\mathrm{temp}}\right)$$

Result in 5.02 TeV *pp* collisions



ATLAS-CONF-2022-020

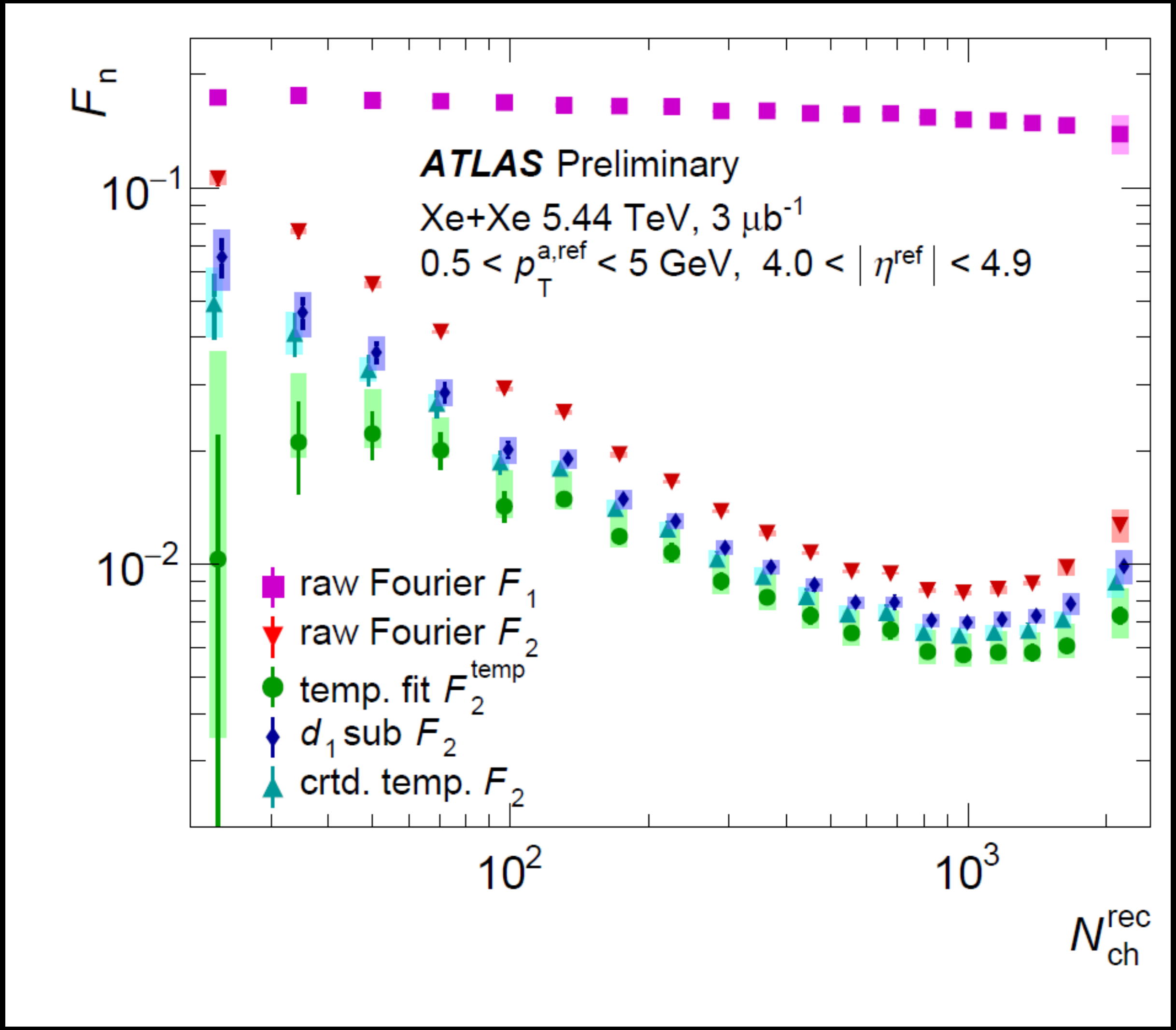
	Template fit F_2	d_1-scaling subtracted:
N_{ch}-independent non-flow shape	✓	✓
First moment is all non-flow	✓	✓
N_{ch}-independent mid-rapidity flow	✓	✓
F_n at N_{ch}=0-20 is all non-flow	X	✓
N_{ch}-independent flow decorrelation	✓	X

The template fit can be corrected for the violation of assumptions with input from the d_1-scaling subtraction

$$F_n^{\mathrm{HM}} \approx F_n^{\mathrm{temp}} + \rho \frac{c_n^{\mathrm{LM}}|_{\eta^a=0}}{c_n^{\mathrm{HM}}|_{\eta^a=0}} \left(F_n^{\mathrm{LM}} - F_n^{\mathrm{temp}}\right)$$

Given results in the d_1 subtraction, the template fit results are understandable

Results in Xe+Xe collisions



First measurement of 70~90% Xe+Xe decorrelation

Analysis differences

- Track-tower correlation
- *pp* reference for template fit and estimation of d_1 sub parameters.

Subtracted results suggest non-flow effects at all centralities This assumes

- No modification of nonflow shape
- Non-flow is the only source of first Fourier moment in correlation.

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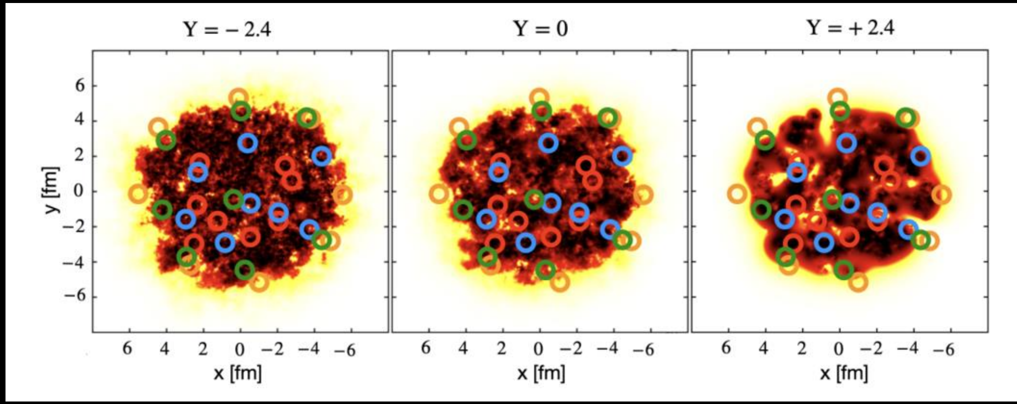
What's next: a new (precision) world

- Part of a push towards a full precision-oriented discription of collective QCD physics
- Discriminate between final and initial state effects
  - Recent work show very large initial-state azimuthal anisotropic decorrelation
  - arXiv:2201.08864
  - arXiv:2109.03512 (pure hydro)
- Future measurements of
  - multi-particle decorrelation – less sensitive to non-flow effects.
  - Photonuclear decorrelation

IP-Glasma+MUSIC+UrQMD   Schenke et al arXiv:2201.08864



AMPT+PYTHIA   Zhang et al.   arXiv:2104.05998