Applications of heavy ion physics methodology

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USTC

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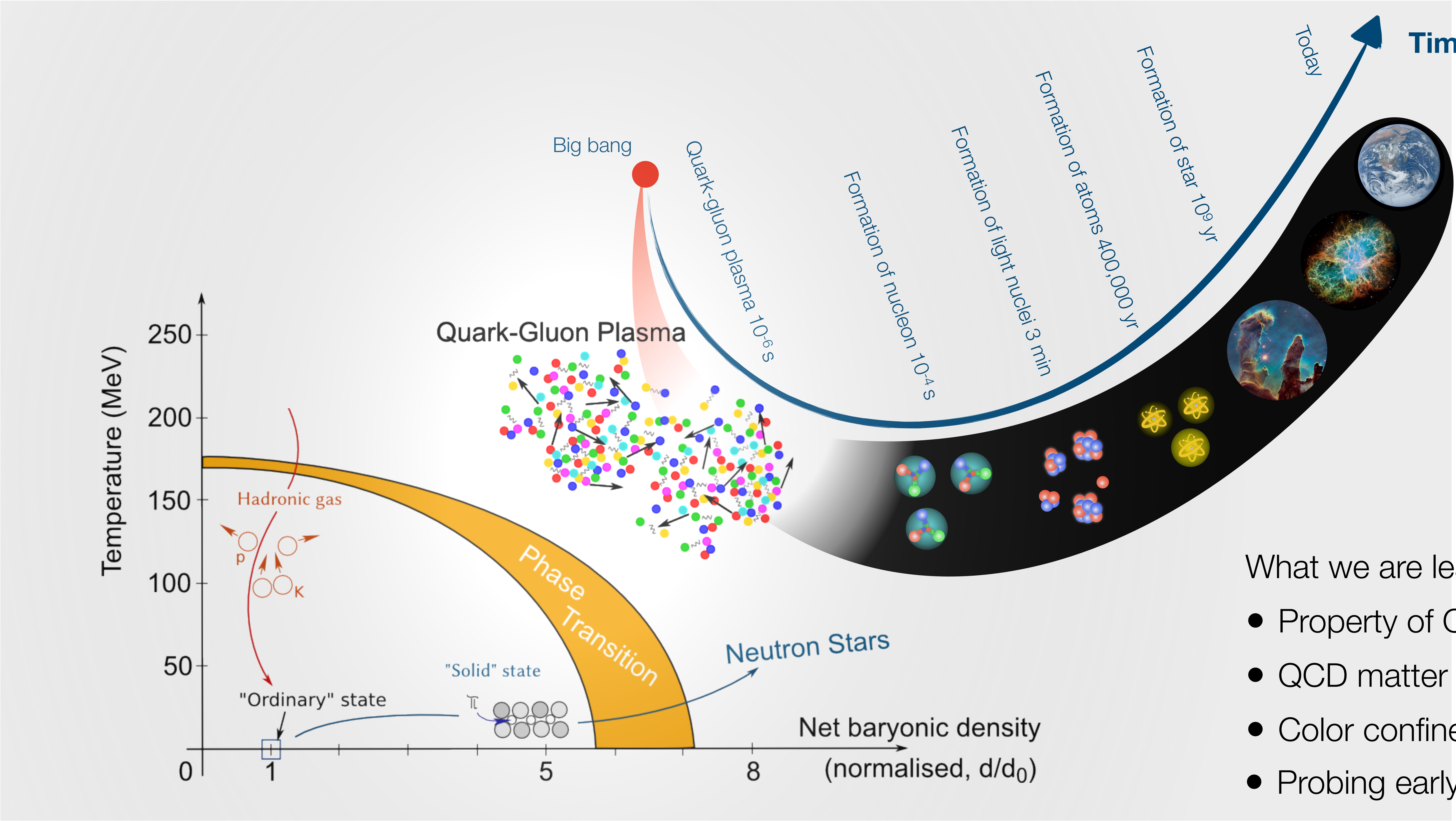
ATLAS EXPERIMENT

Hadron Physics Online Forum (HAPOF)

Quark-gluon plasma (QGP)

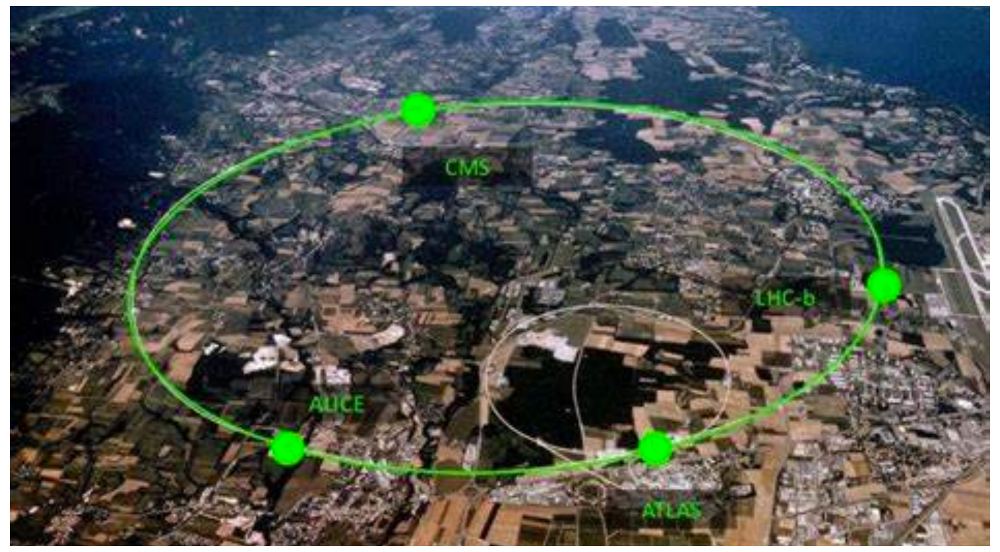


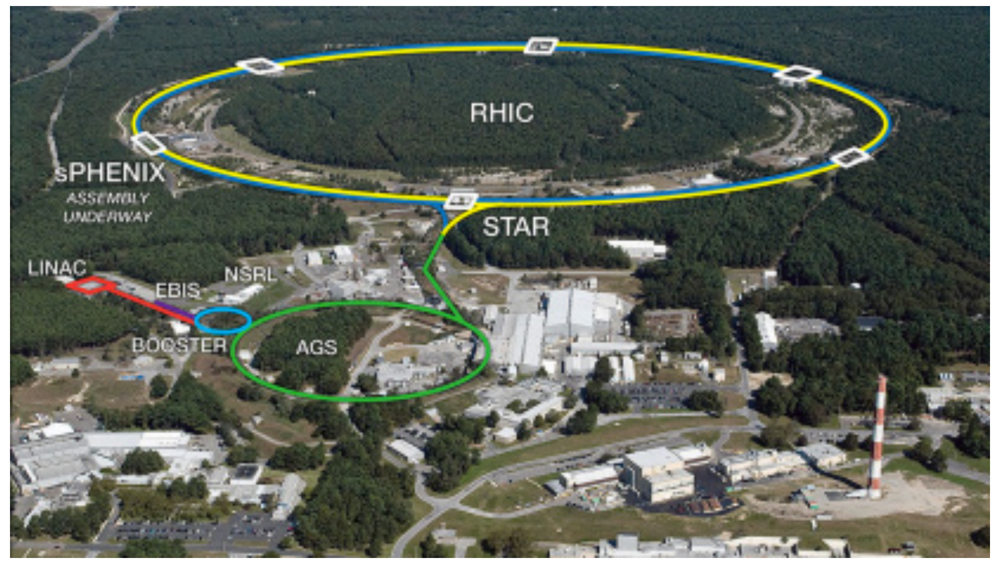
Credit: Antonin Maire, CERN-THESIS-2011-263

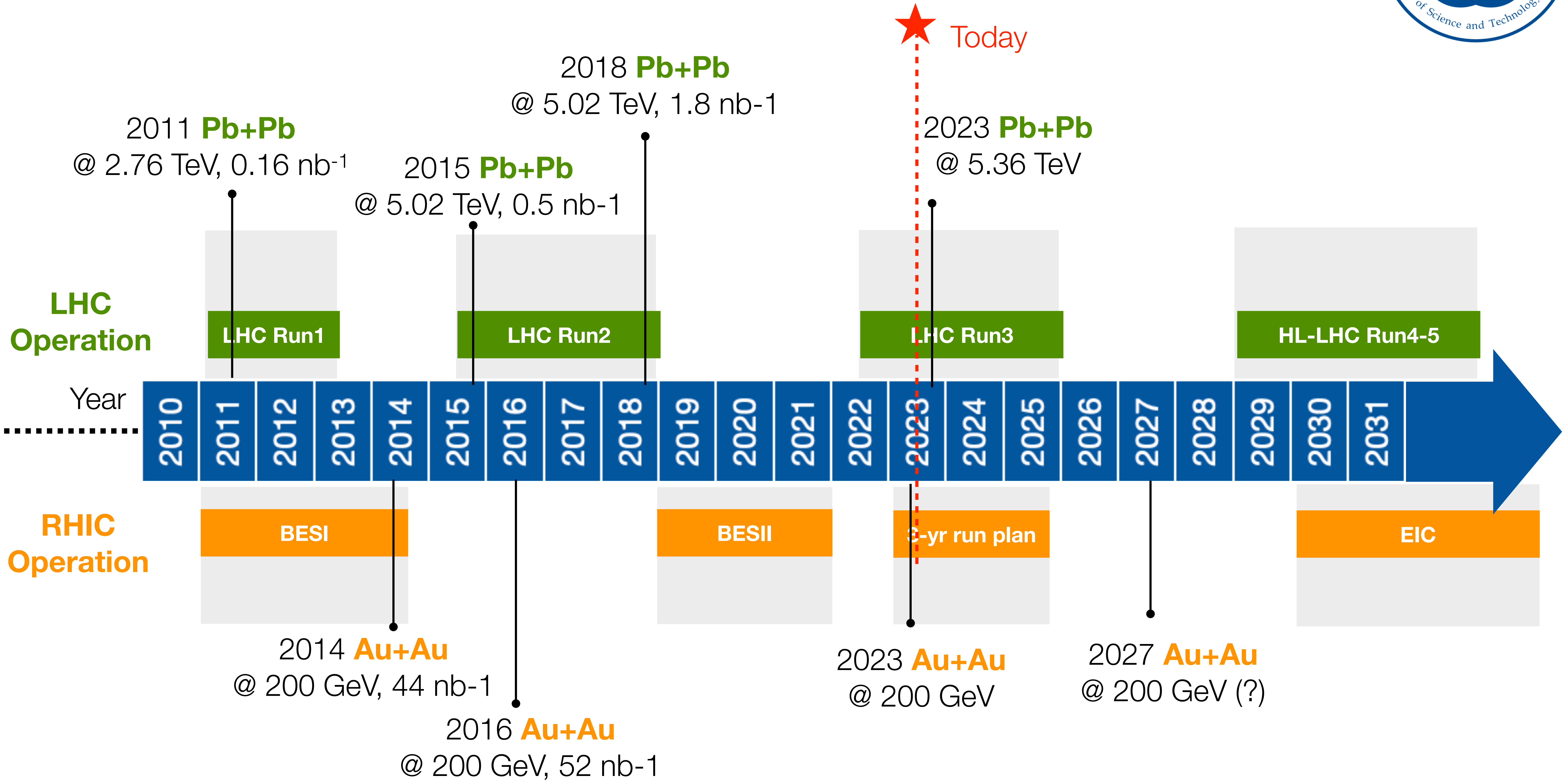
What we are learning from QGP

- Property of QGP
- QCD matter phase transition
- Color confinement
- Probing early universe

Heavy ion programs at RHIC and LHC since 2010

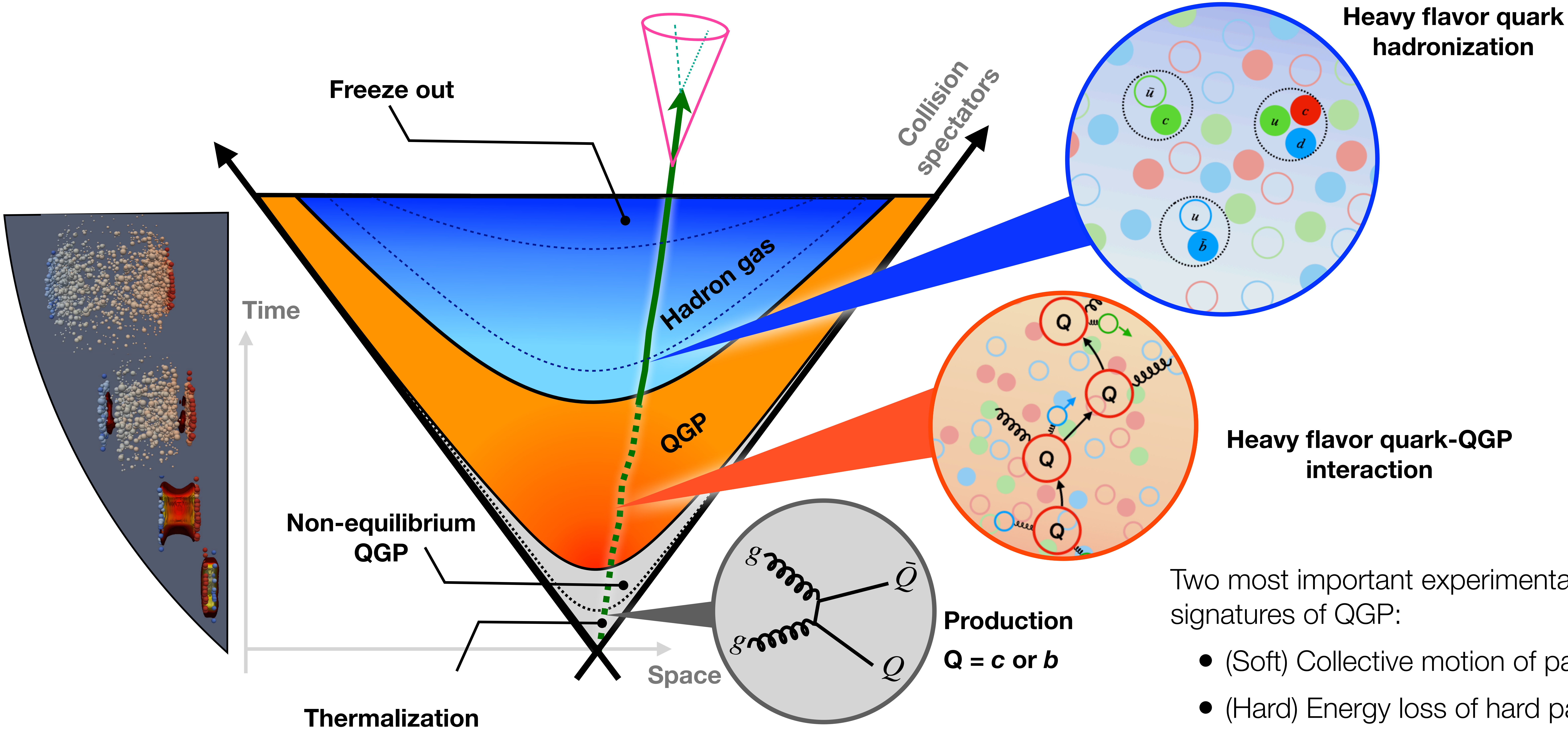






- Have we discovered QGP in experiment?
- We have defined QGP as a new phase of QCD matter!

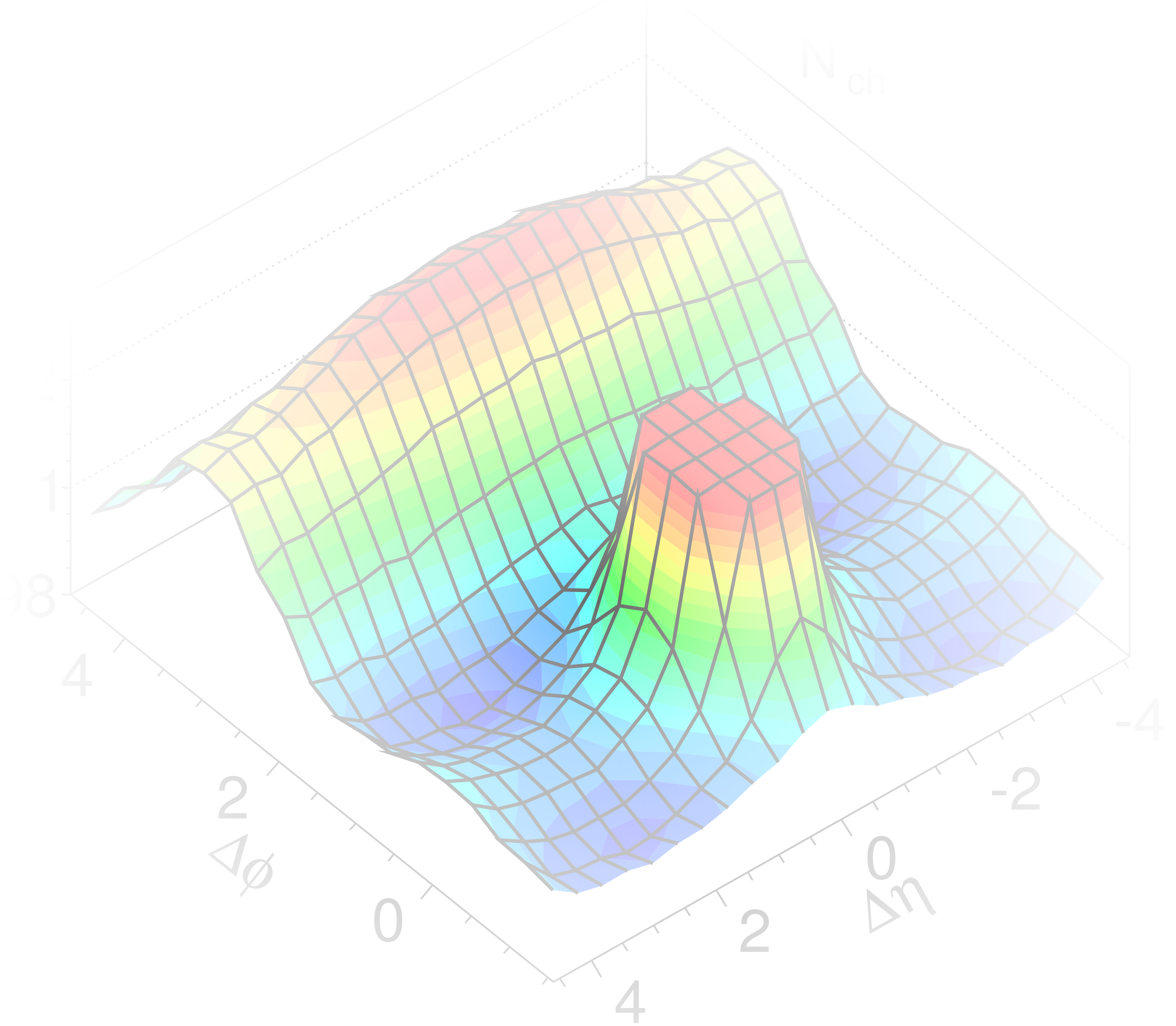
Life of QGP at collider



Two most important experimental signatures of QGP:

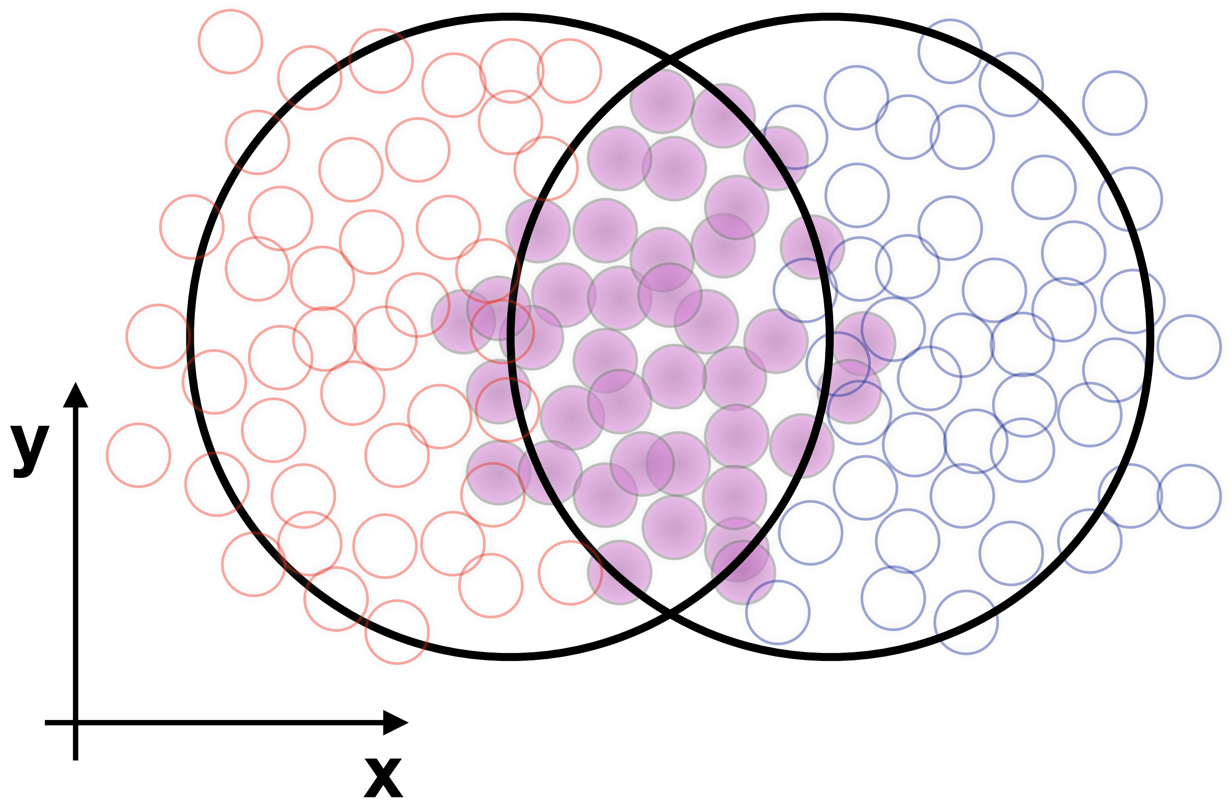
- (Soft) Collective motion of particles
- (Hard) Energy loss of hard particles

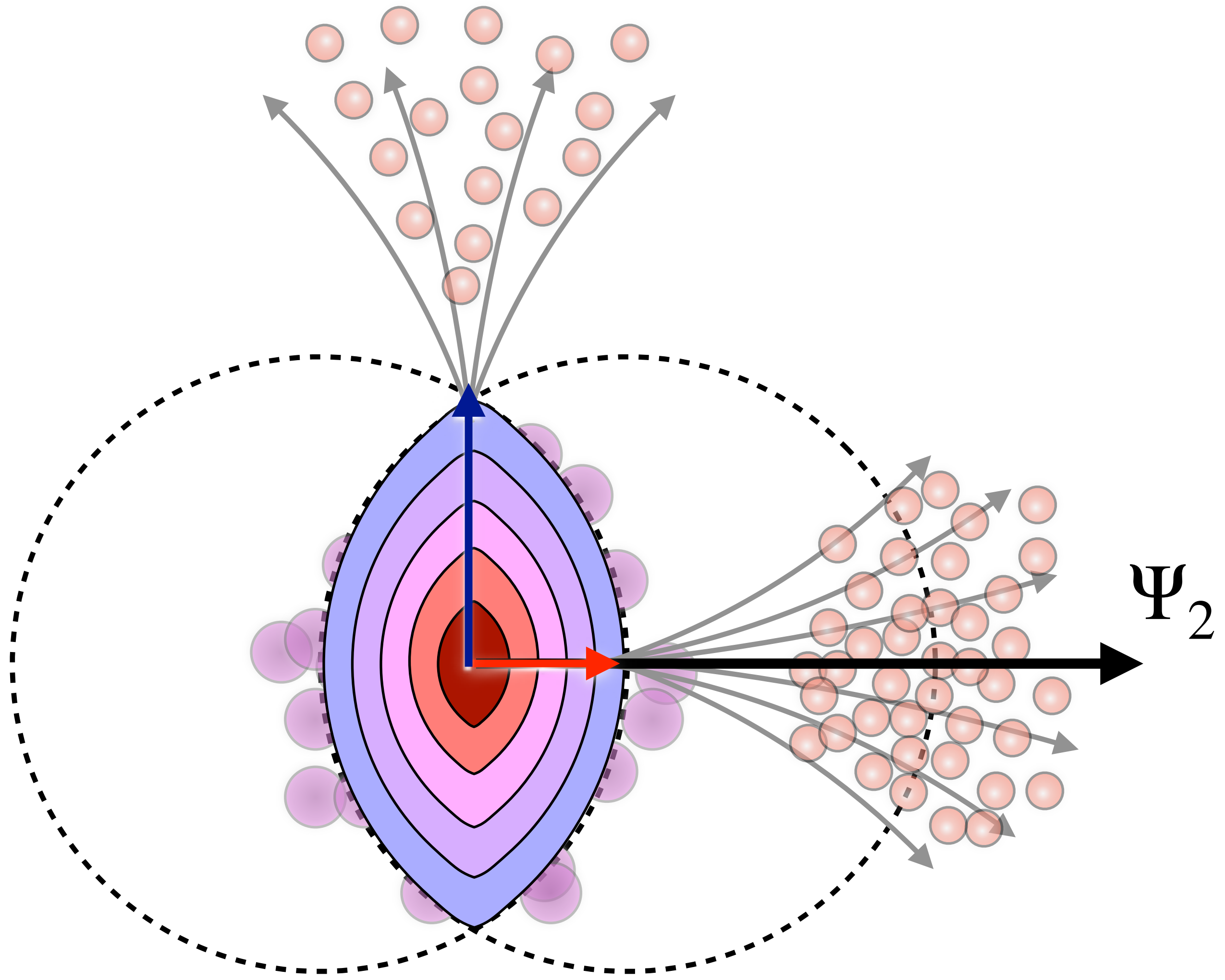
Application of **soft** sector methodology



Soft particle correlation in heavy ion collisions

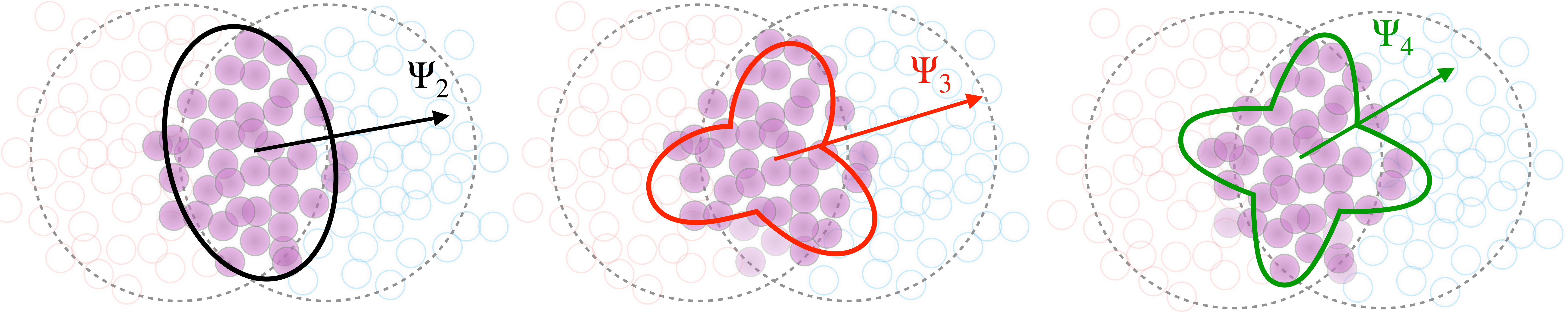
Typical Pb+Pb collision event

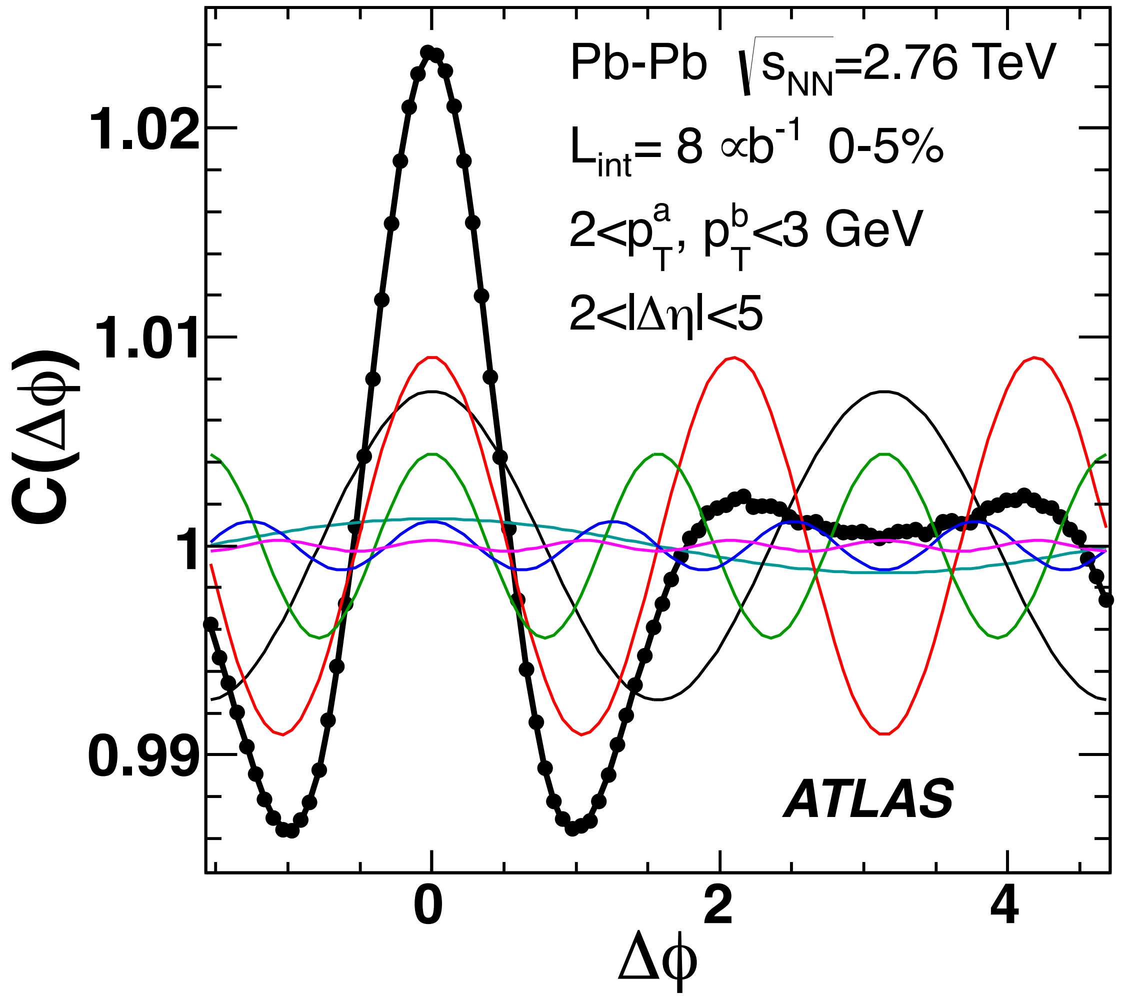




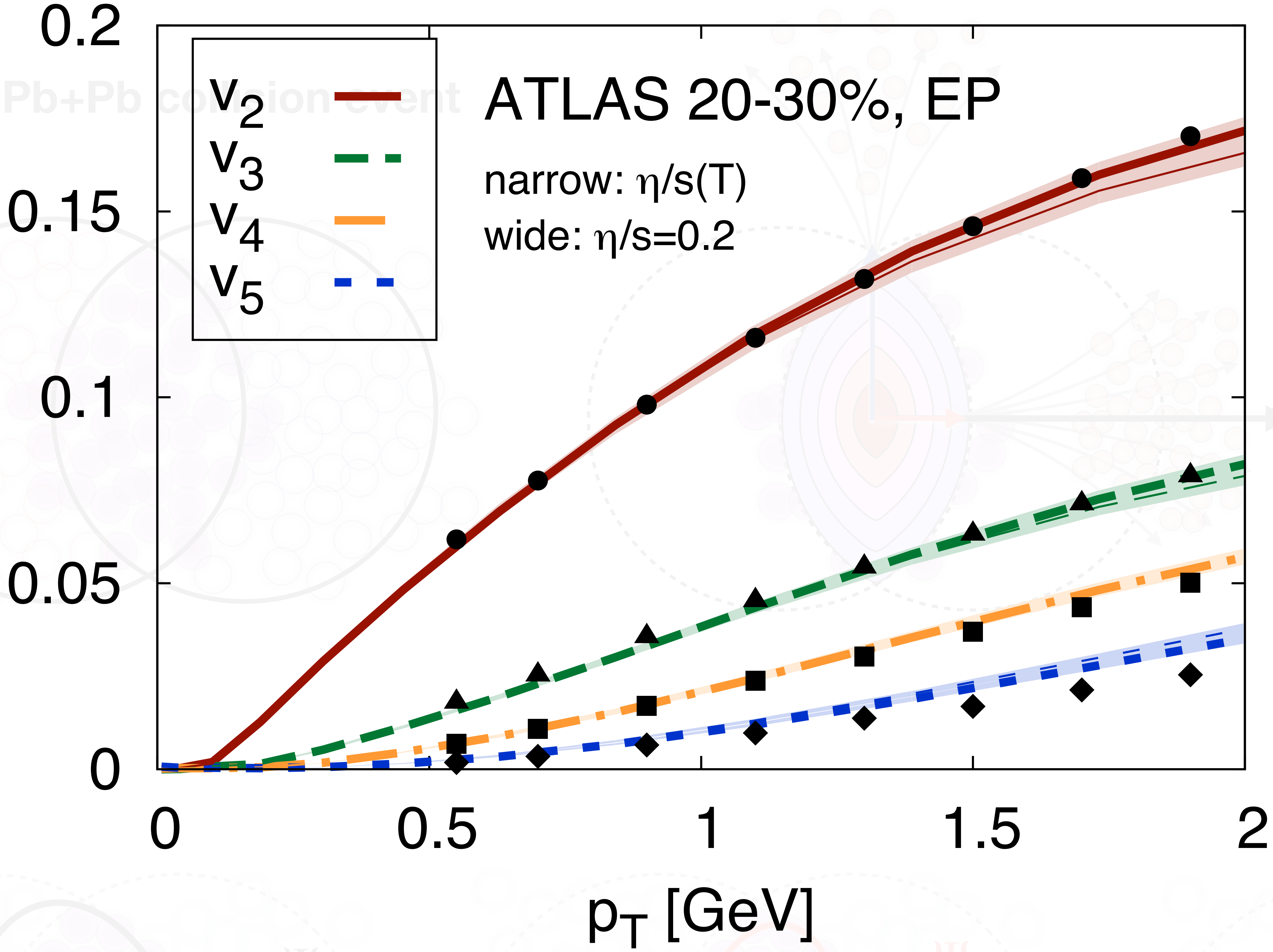
$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + \left(2\sum_n v_n \cos\left(n(\phi - \Psi_n)\right)\right)$$

$$v_n = \langle \cos(n(\phi - \Psi_n)) \rangle \sim \sqrt{\langle \cos(n(\phi_1 - \phi_2)) \rangle}$$





Soft particle correlation in heavy ion collisions



$$\frac{dN}{d\phi} \propto 1 + \left(2\sum_n v_n \cos\left(n(\phi - \Psi_n)\right)\right)$$

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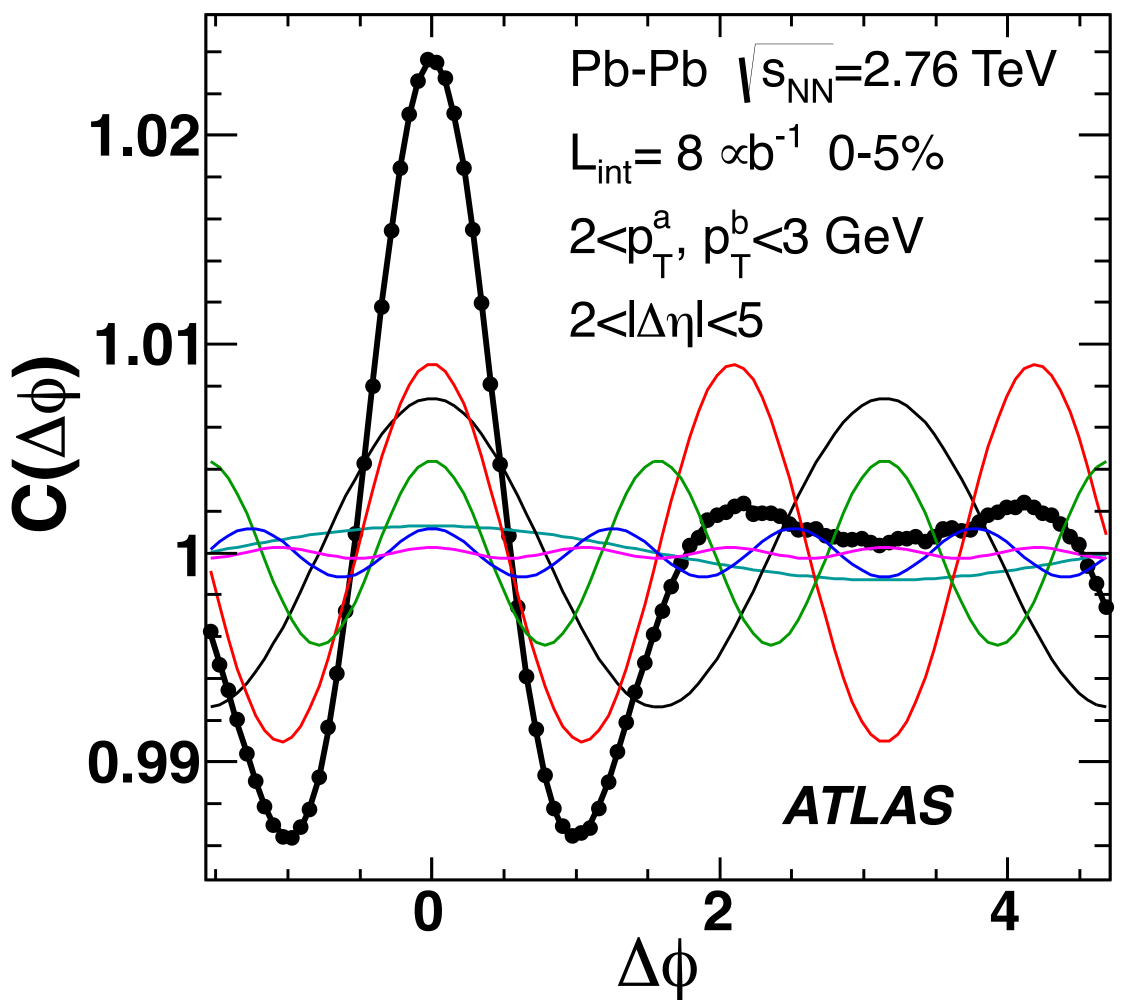
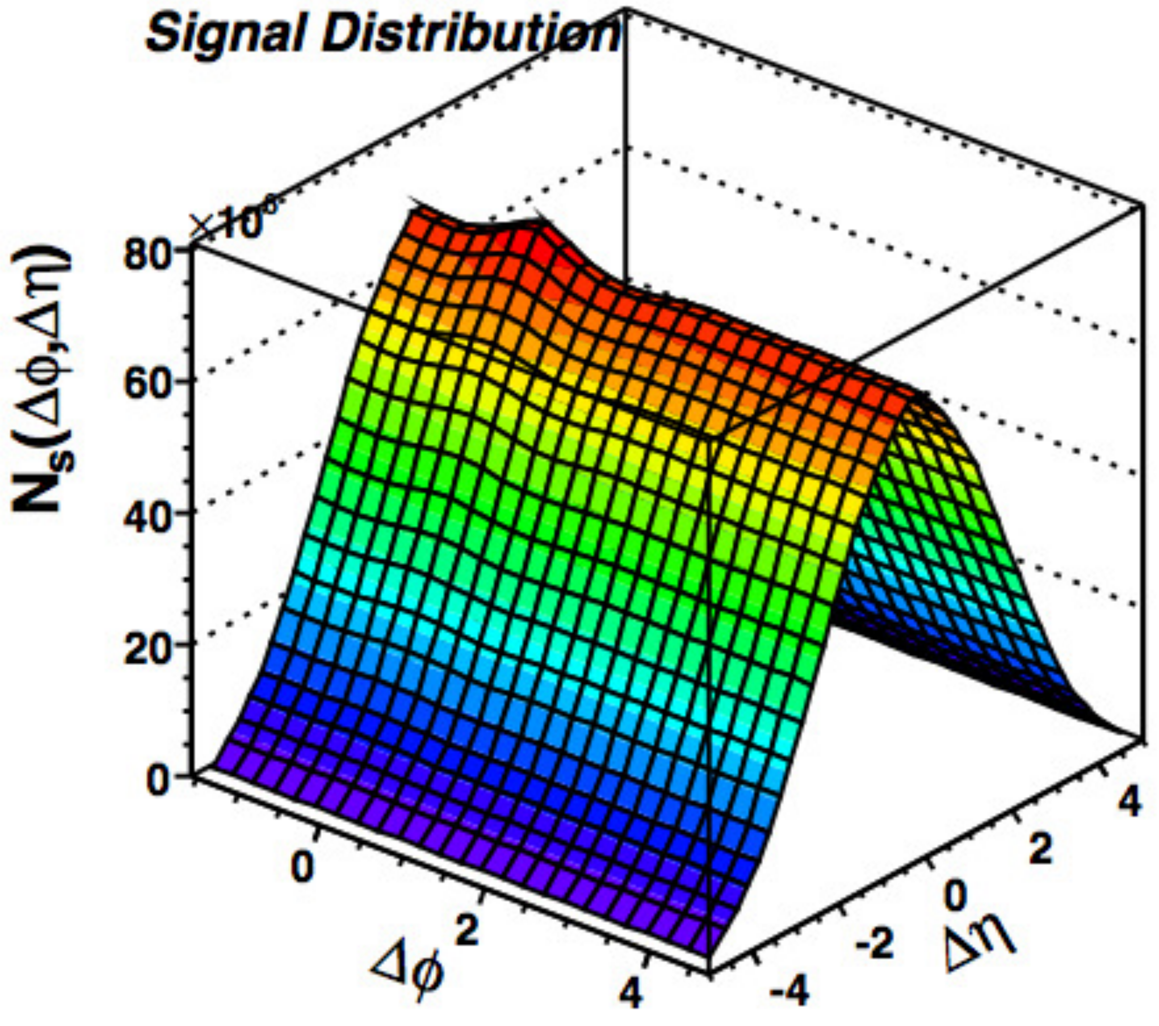


- Observable: azimuthal anisotropy using Fourier decomposition coefficients
- Interpretation: Collective flow from hydrodynamic evolution of QGP → strongly coupled fluid

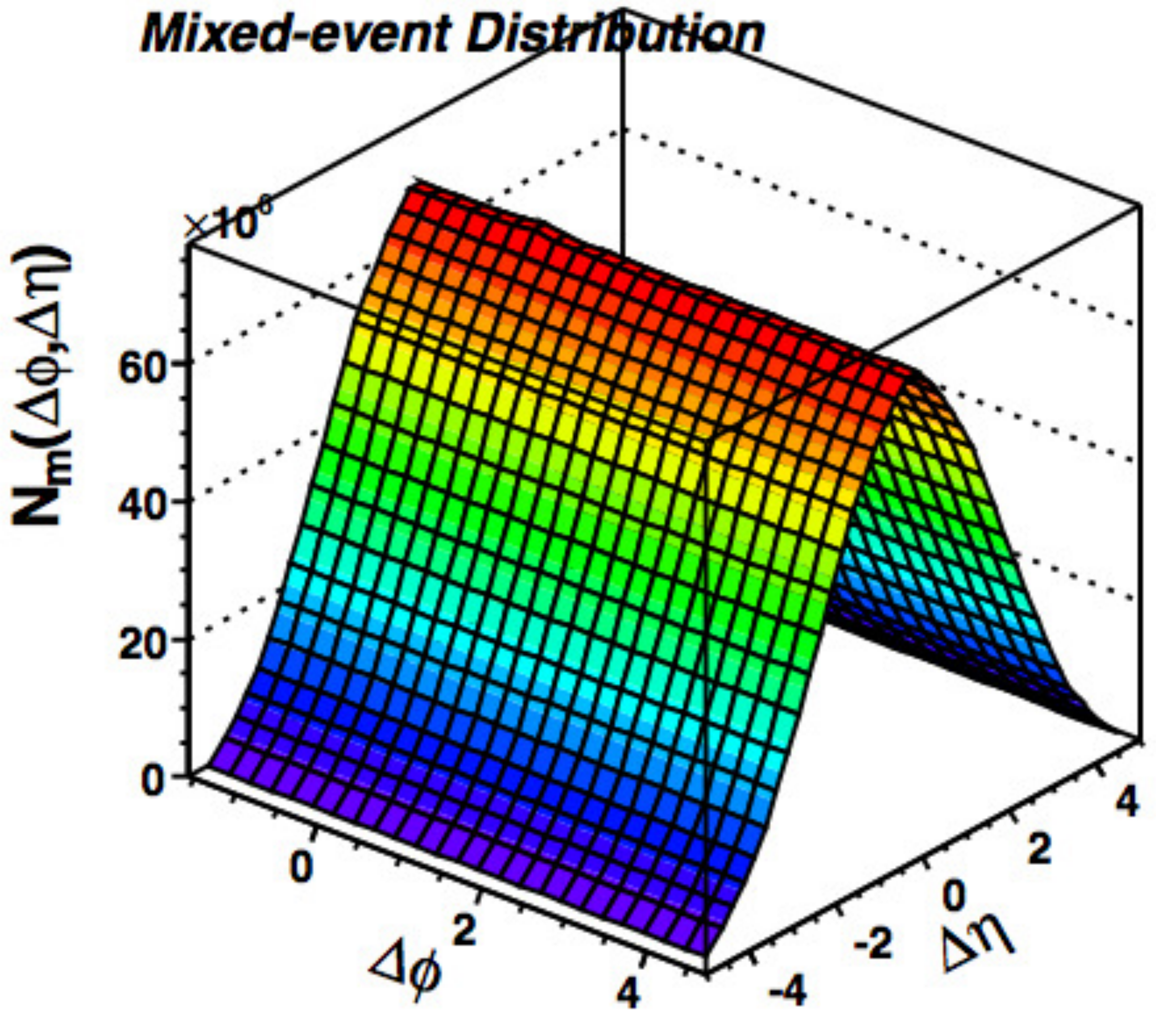
Construct two particle angular correlation

Construct two-particle $\Delta\phi,\ \Delta\eta$ correlation with inclusively selected particles



$$S(\Delta\phi, \Delta\eta) = \frac{d^2N_{\text{pair}}}{d\Delta\phi d\Delta\eta}$$

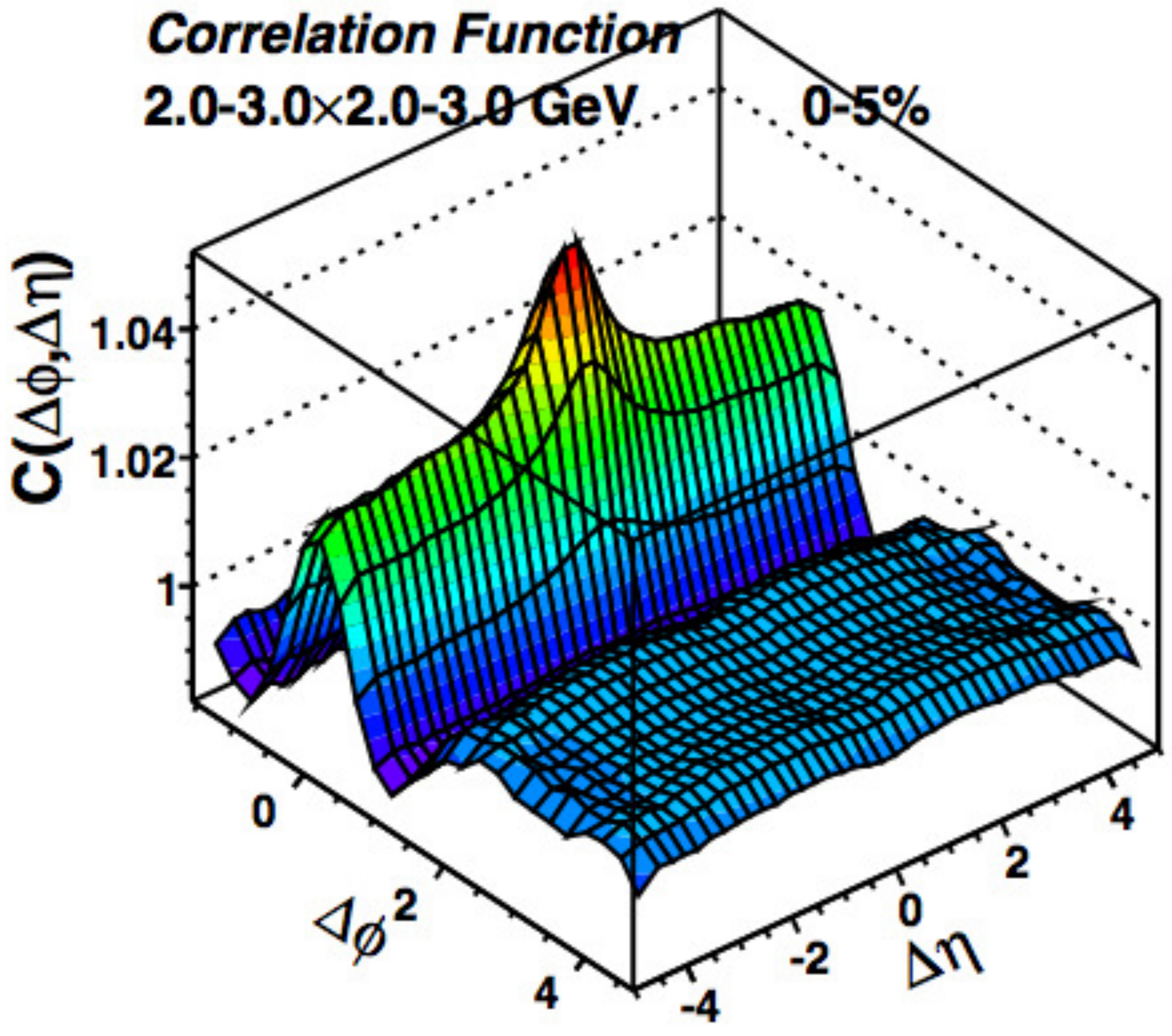
Particle pairs from the same event



$$B(\Delta\phi, \Delta\eta) = \frac{d^2N^{\text{mixed}}_{\text{pair}}}{d\Delta\phi d\Delta\eta}$$

Particle pairs from the different event,

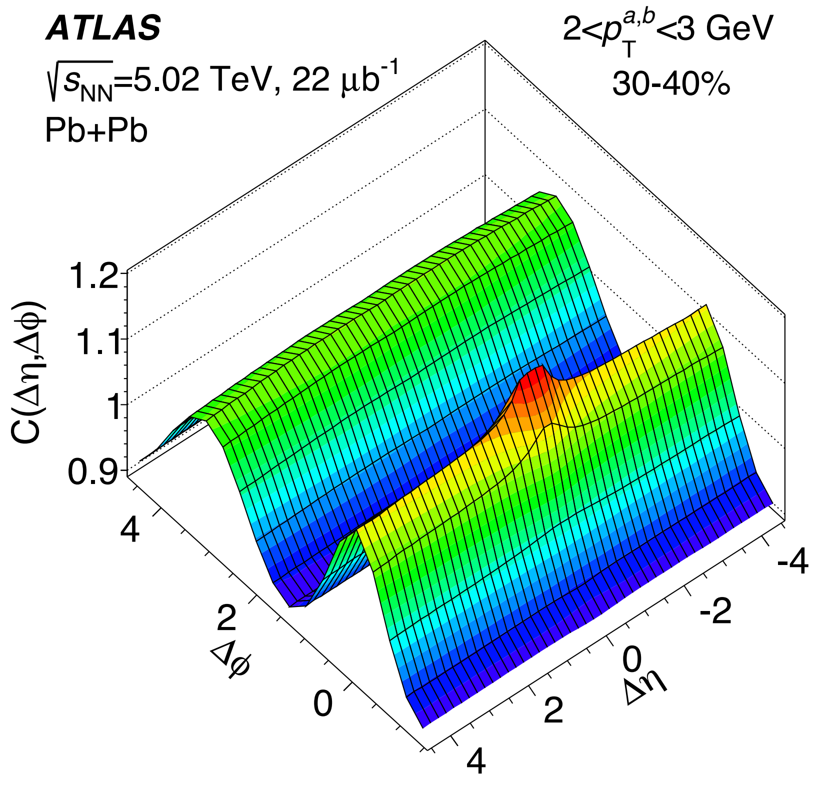
$B(\Delta\phi, \Delta\eta)$ **~ detector acceptance for particle pair**



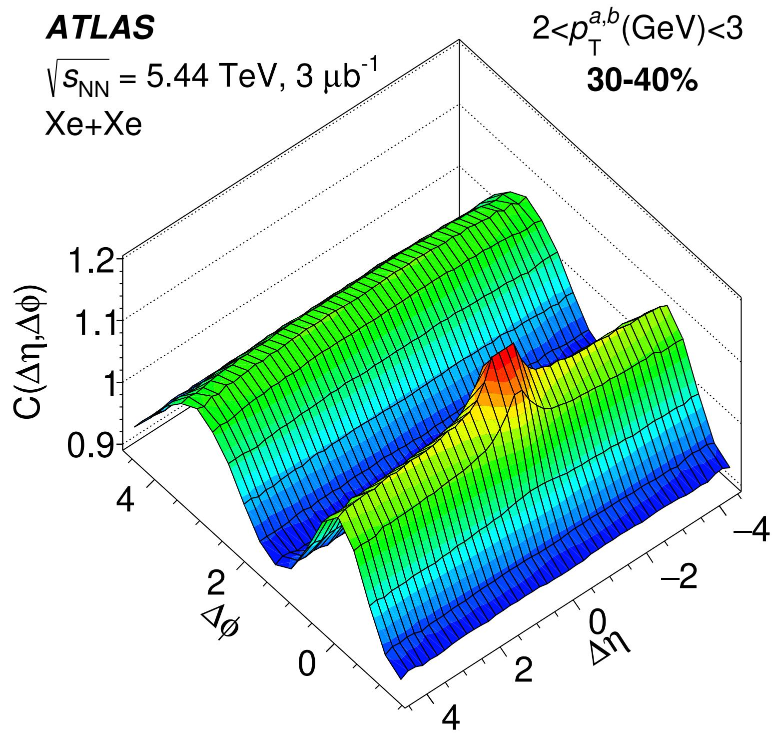
$$C(\Delta\phi, \Delta\eta) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)}$$

$\eta = -\ln\tan(\theta/2)$

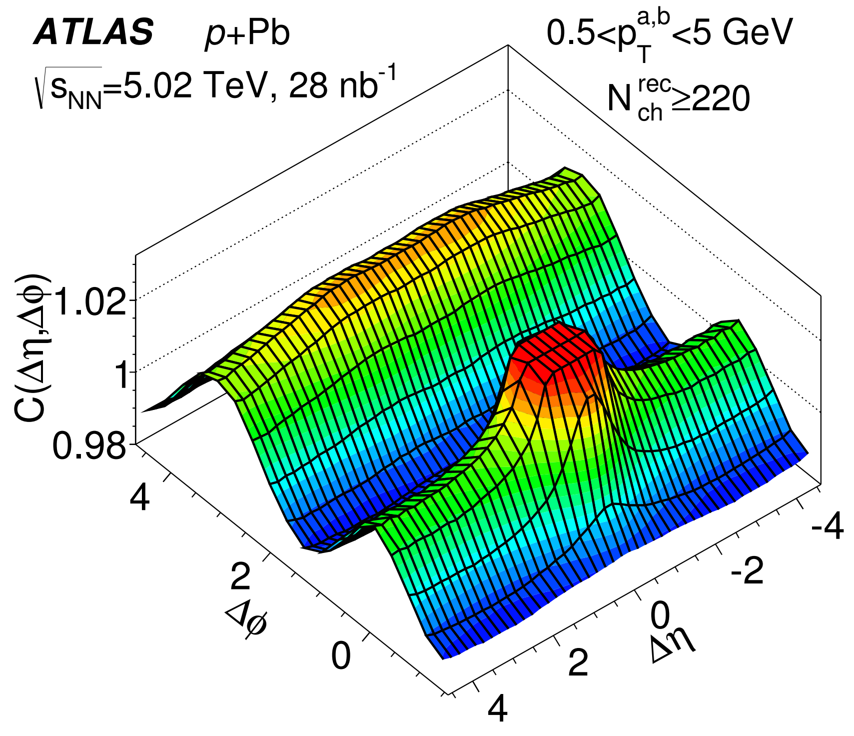
Two-particle correlations from different collisions



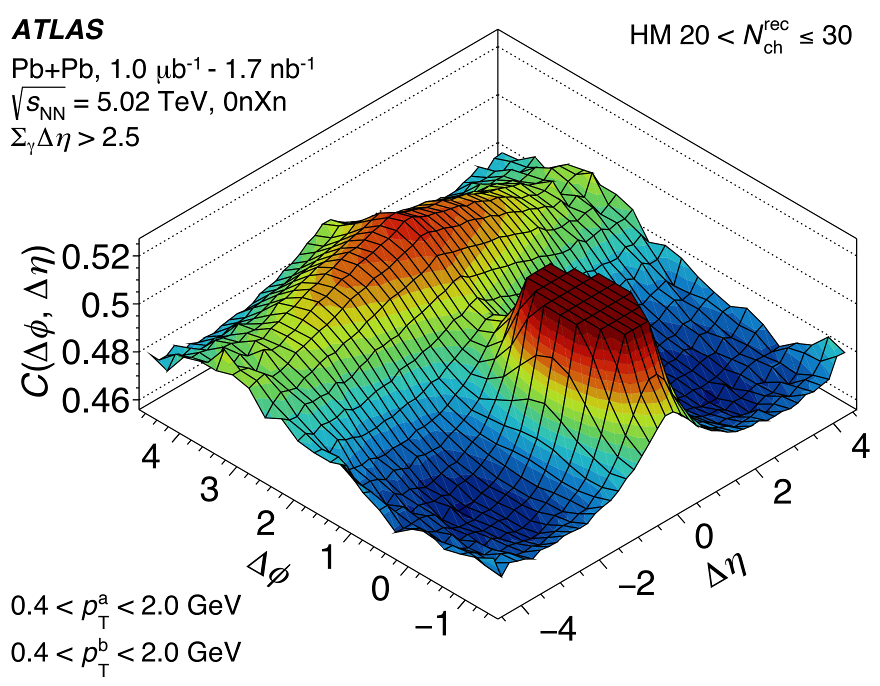
Pb+Pb



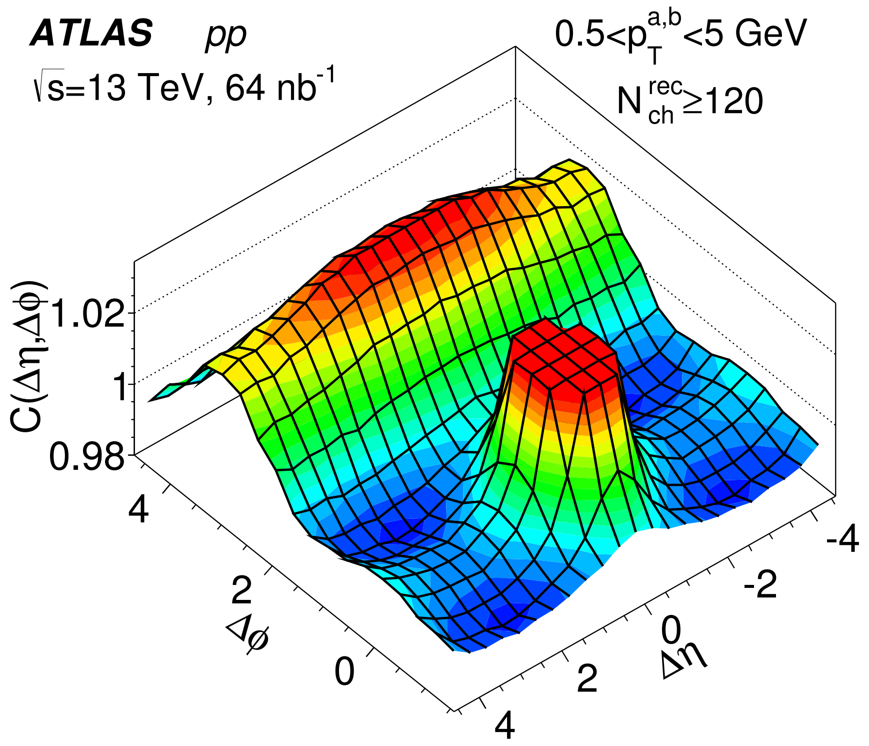
Xe+Xe



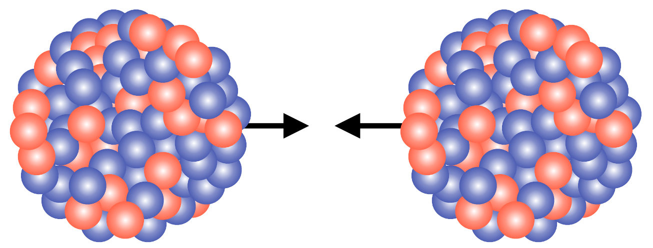
p+Pb

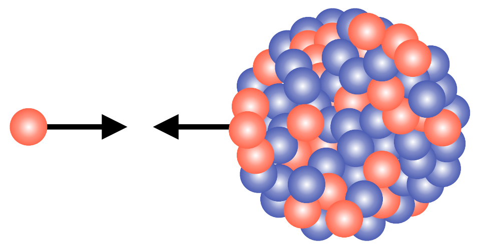


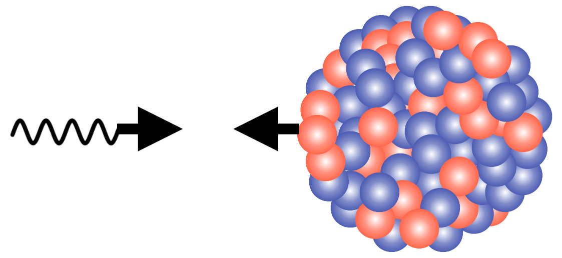
γ+Pb

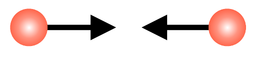


p+p

**


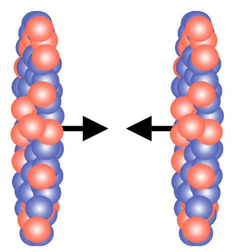






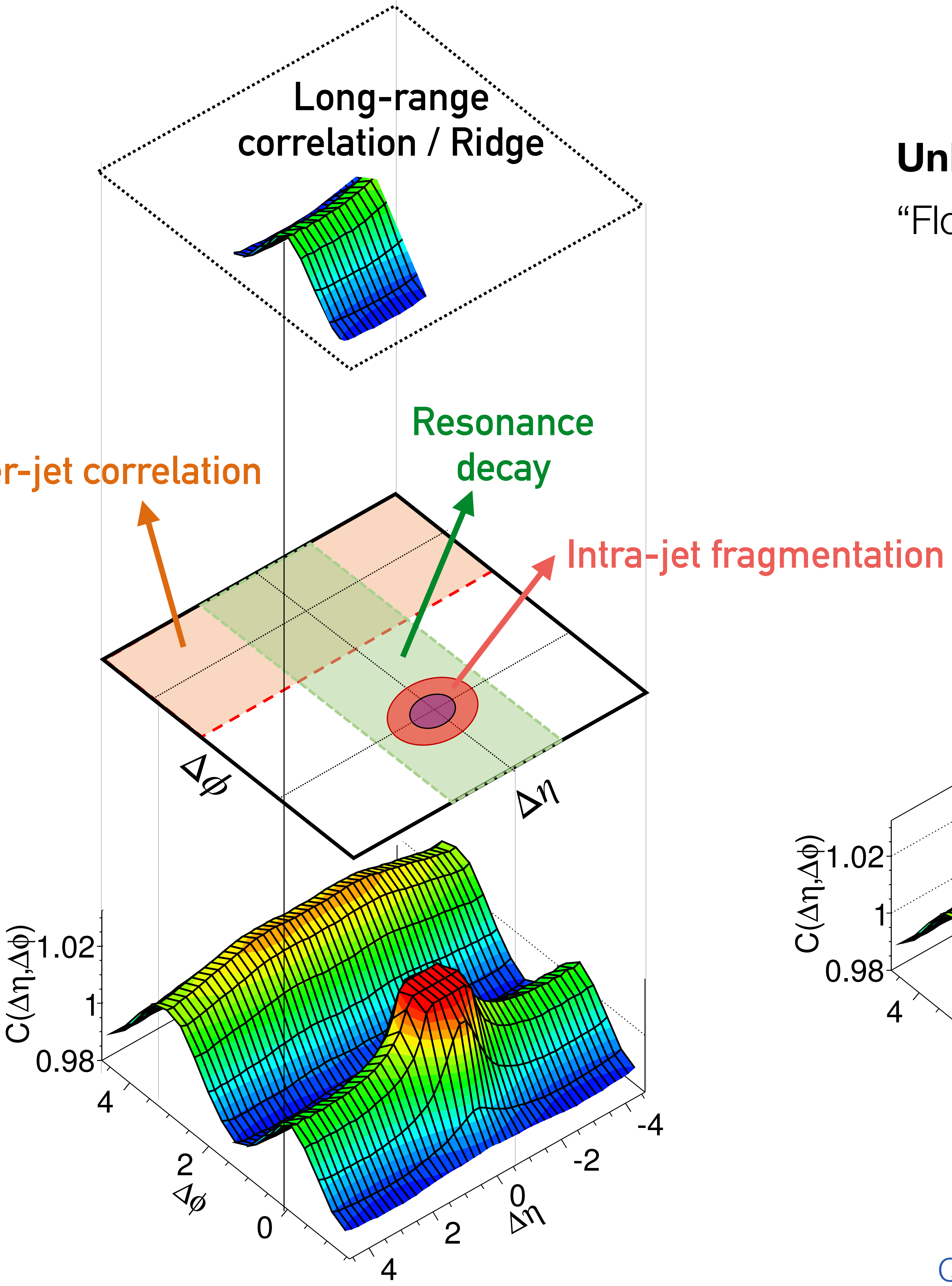
Large system

Small system



** Ignoring Lorentz contraction for demonstration purpose

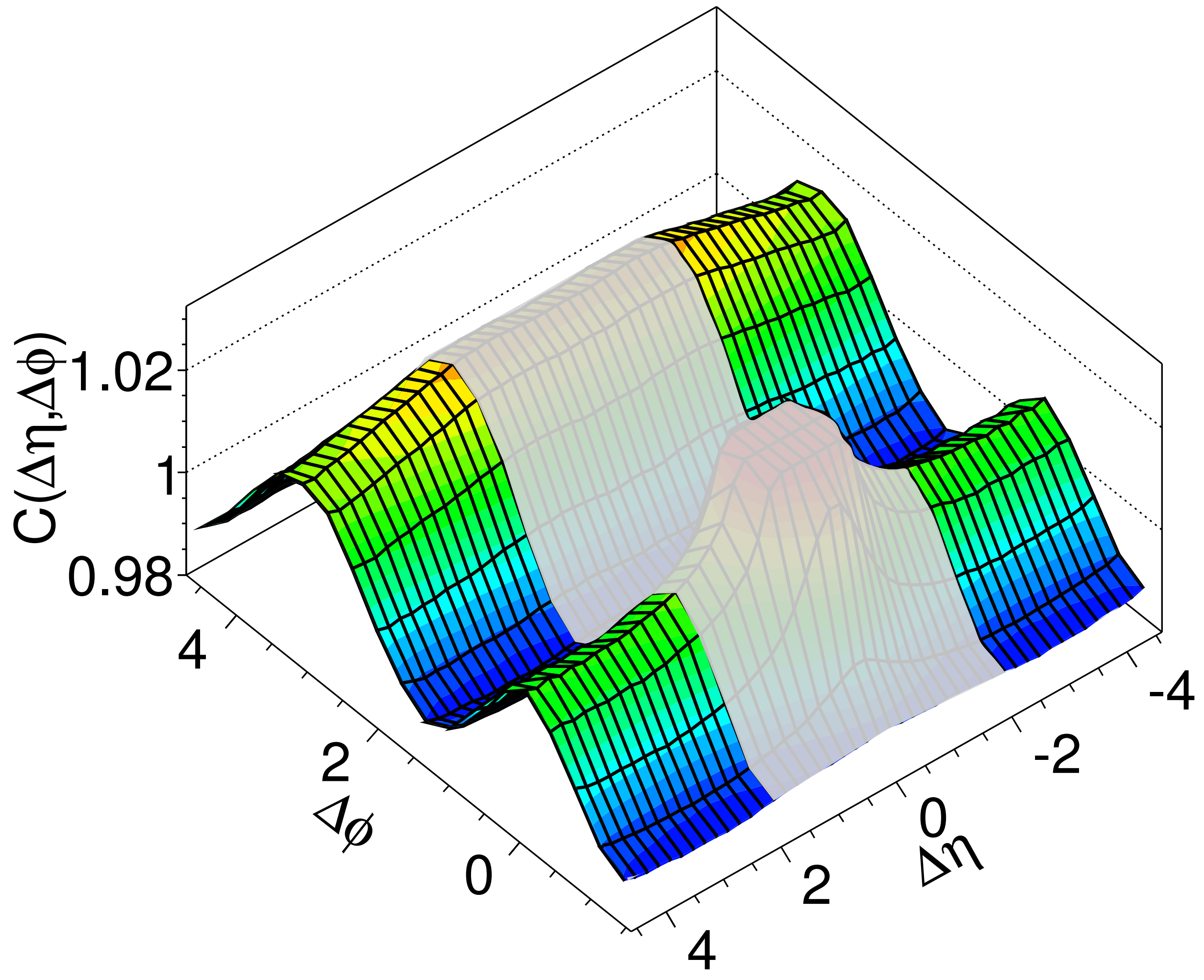
Removing known angular correlation



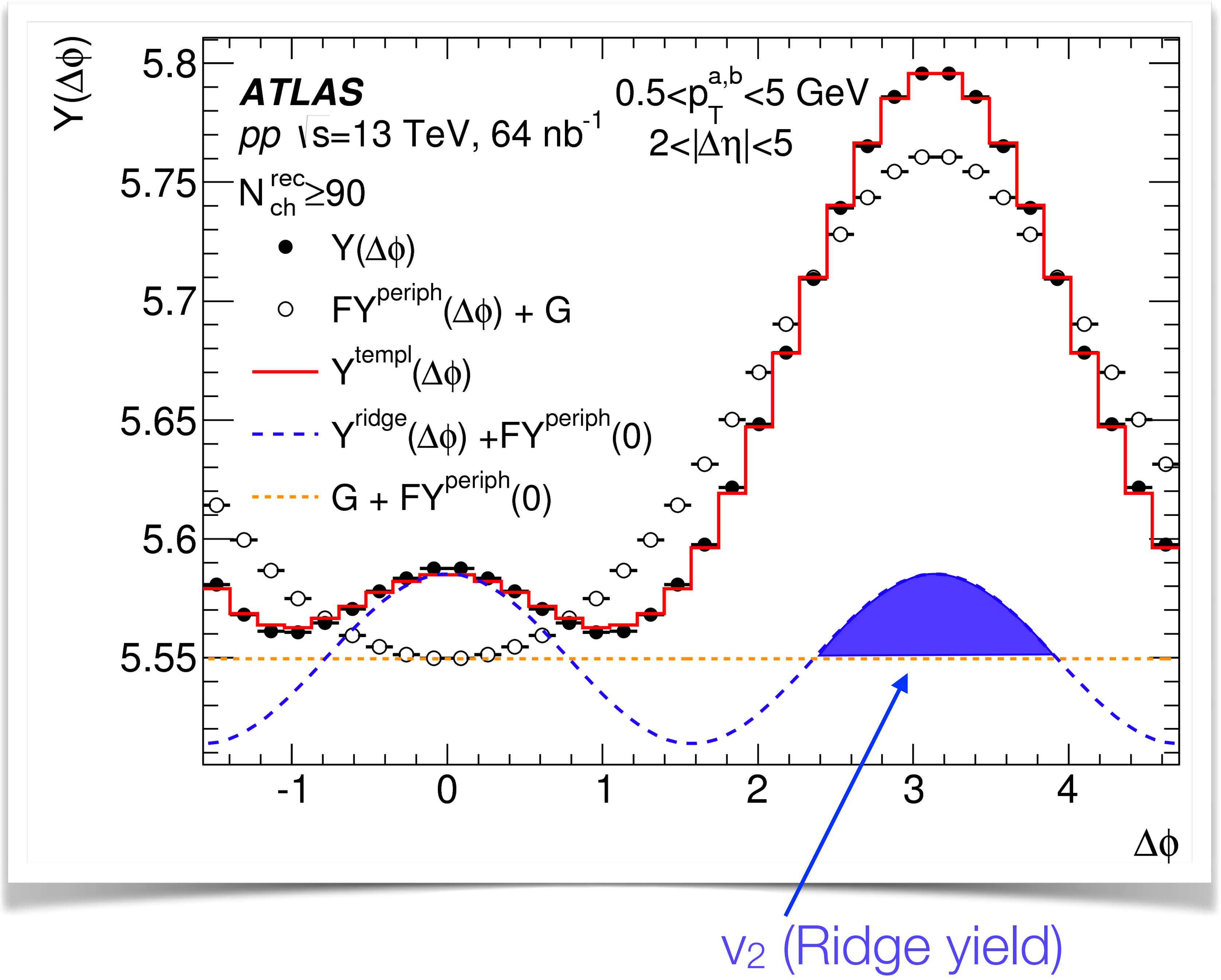
Unknown = Measured - Known

“Flow” = Measured - “non-flow”

①. $|\Delta\eta|$ **gap:** $|\Delta\eta| > 2$



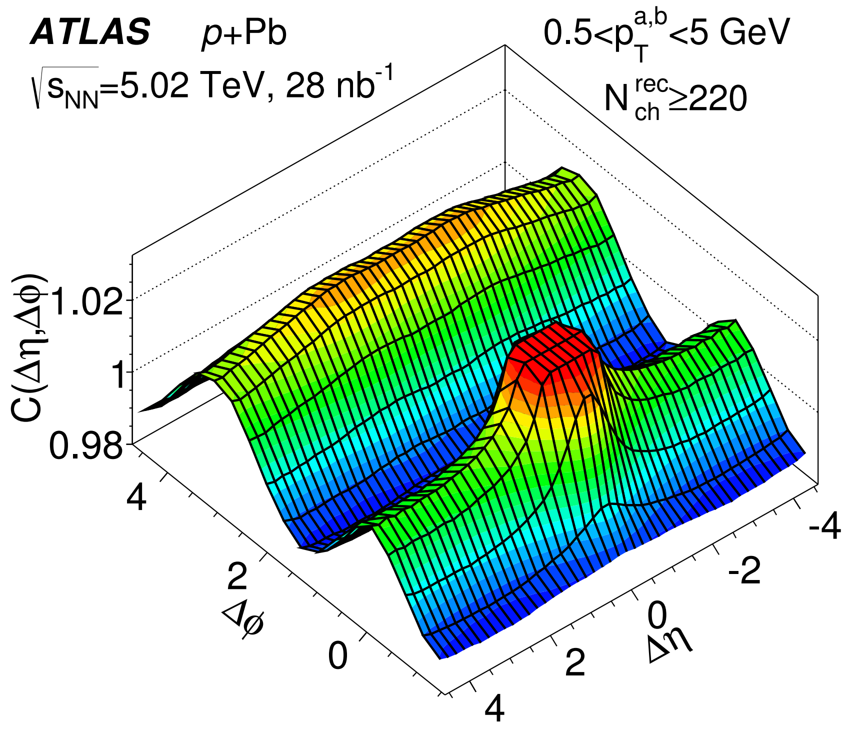
②. **inter-jet correlation subtraction**

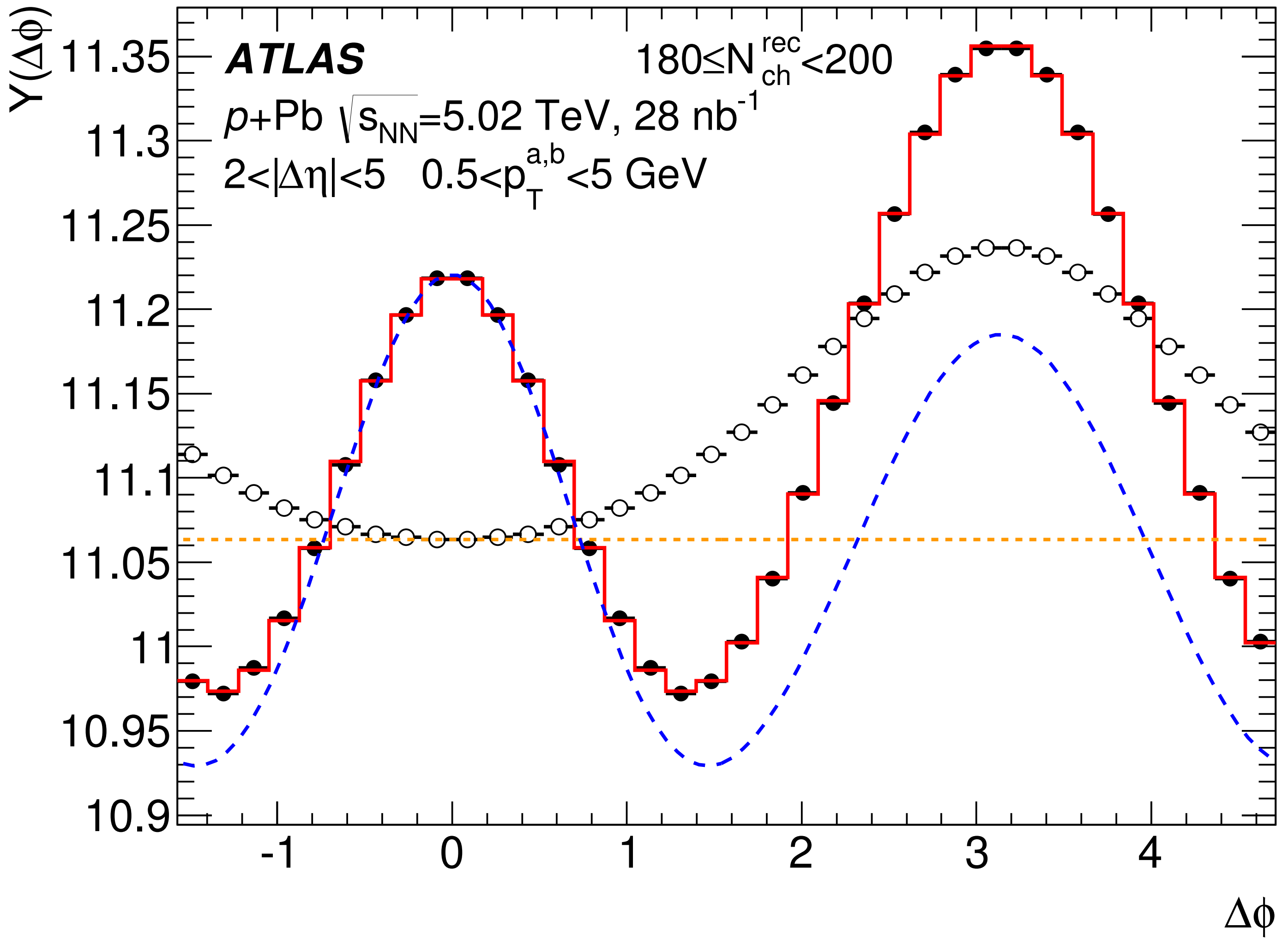


- With $|\Delta\eta| > 2$, the only known source is inter-jet correlation at $\Delta\phi \sim \pi$
- Removed using inter-jet correlation template, often from low multiplicity collisions
- Fourier decomposition, extracted v_n magnitude depends on inter-jet correlation modeling, but sign of v_n is almost model-independent

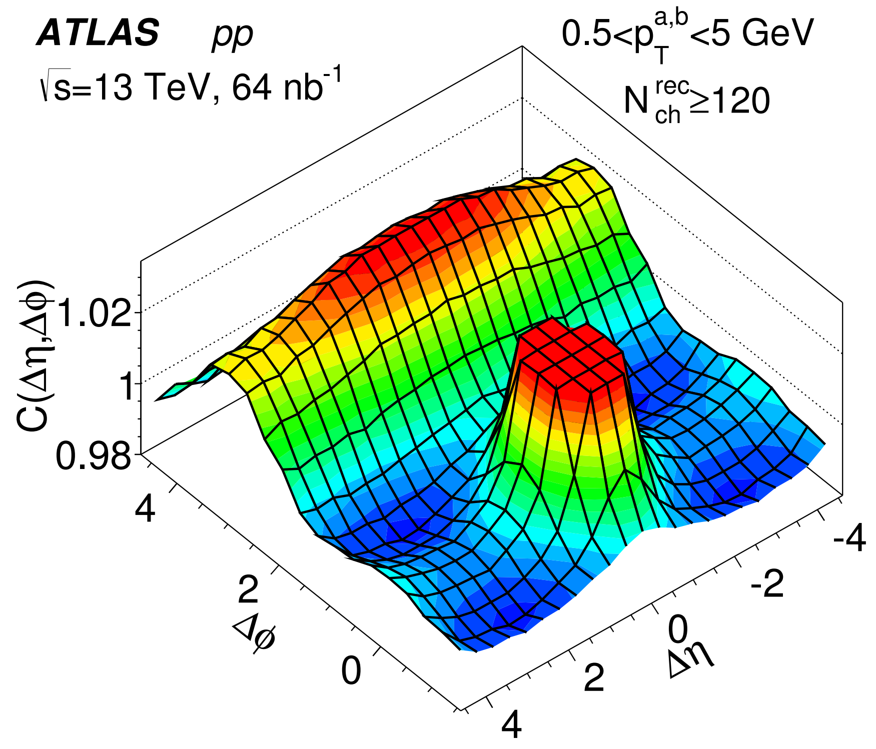
1D long-range correlation in different systems

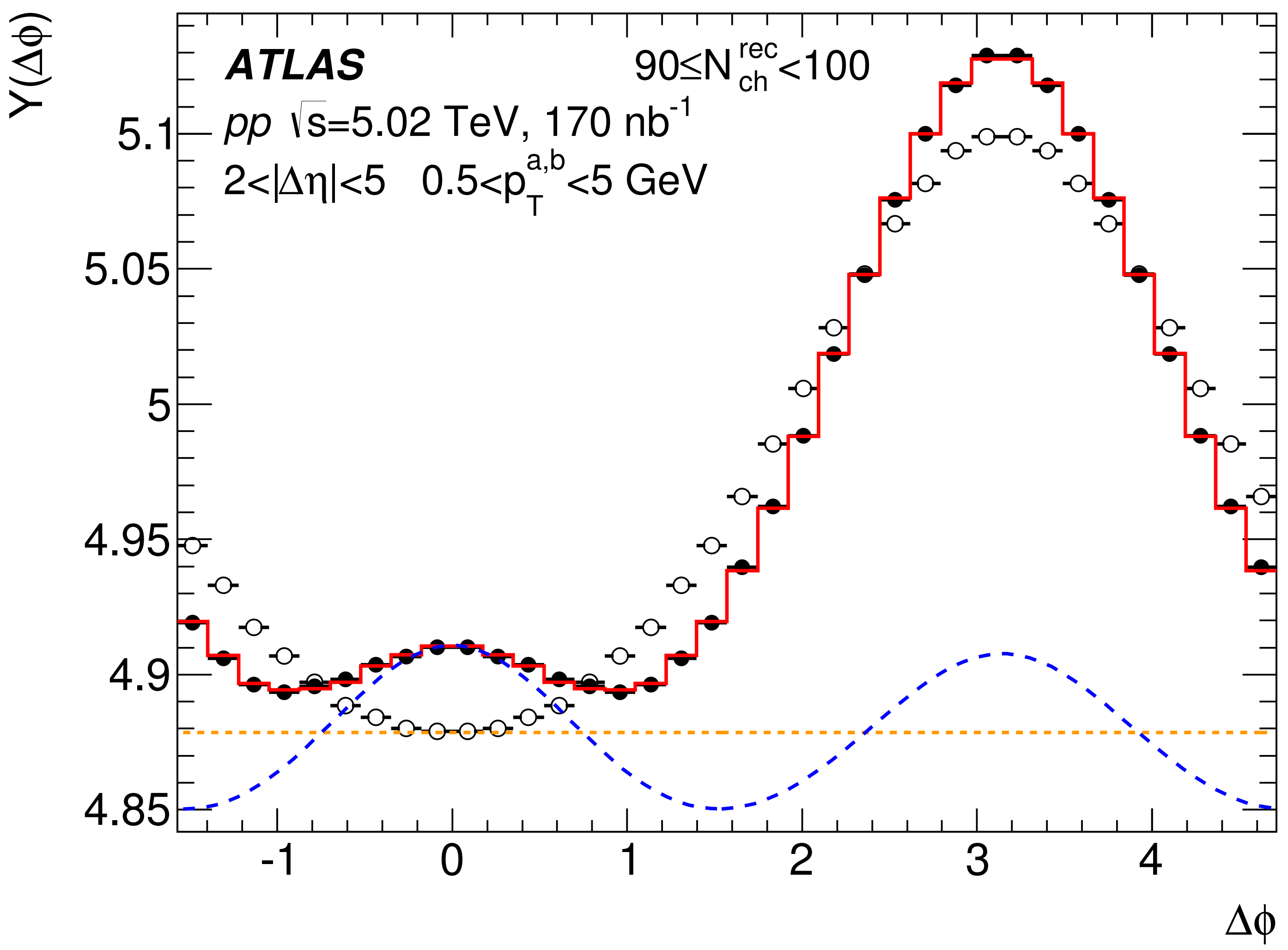
p+Pb



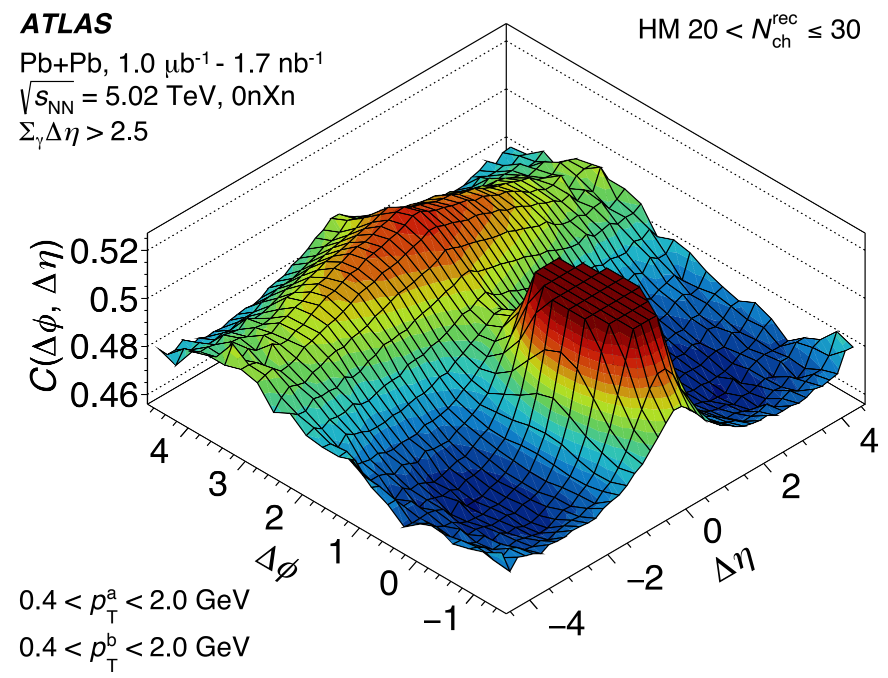


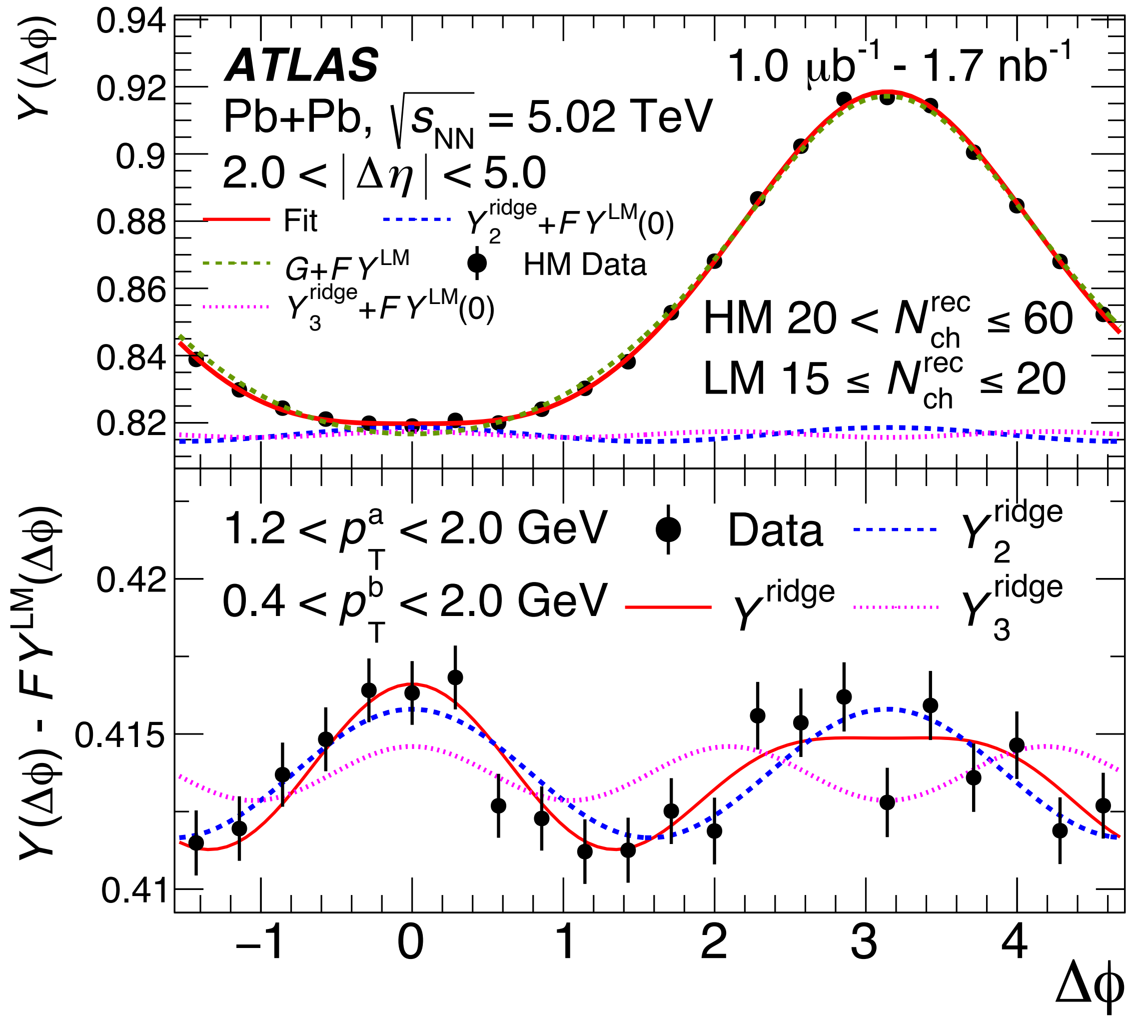
p+p





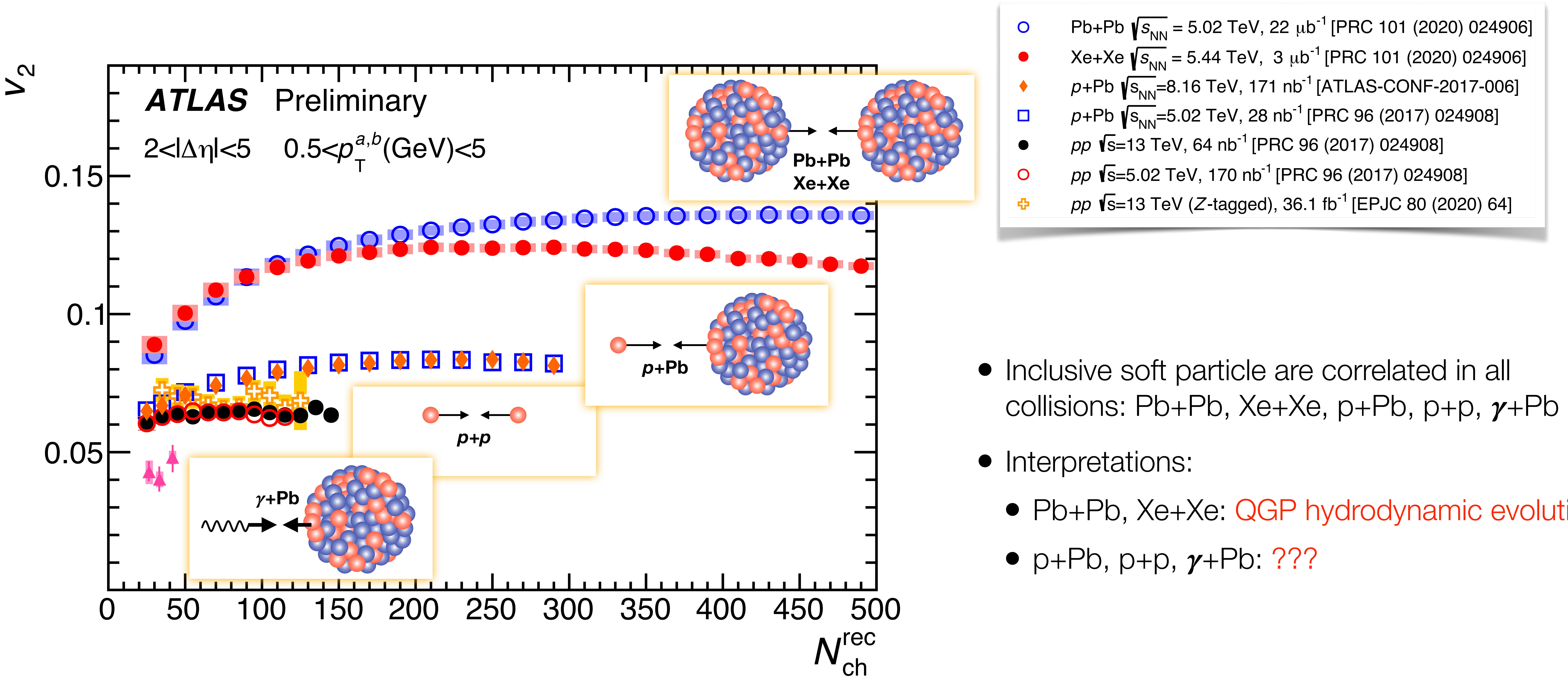
γ+Pb





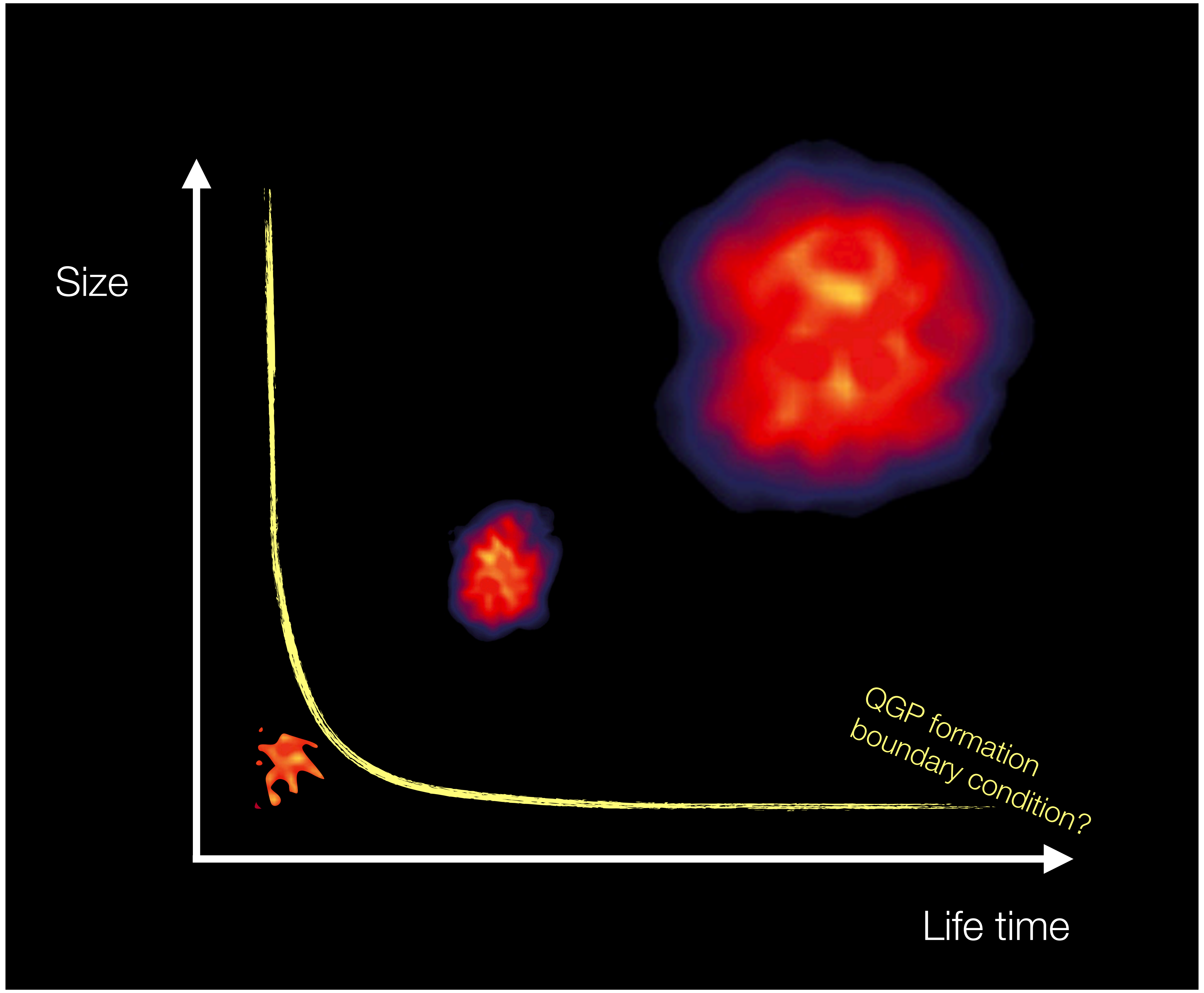
Visible ridge ~ $\frac{N_{\mathrm{pair}} - N_{\mathrm{pair}}^{\mathrm{jet,decay}}}{N_{\mathrm{pair}}} \cdot v_2$

Extracted anisotropies in hadronic collisions



- Inclusive soft particle are correlated in all collisions: Pb+Pb, Xe+Xe, p+Pb, p+p, γ+Pb
- Interpretations:
  - Pb+Pb, Xe+Xe: QGP hydrodynamic evolution
  - p+Pb, p+p, γ+Pb: ???

Physics implication



Credit: MUSIC arXiv:1209.6330

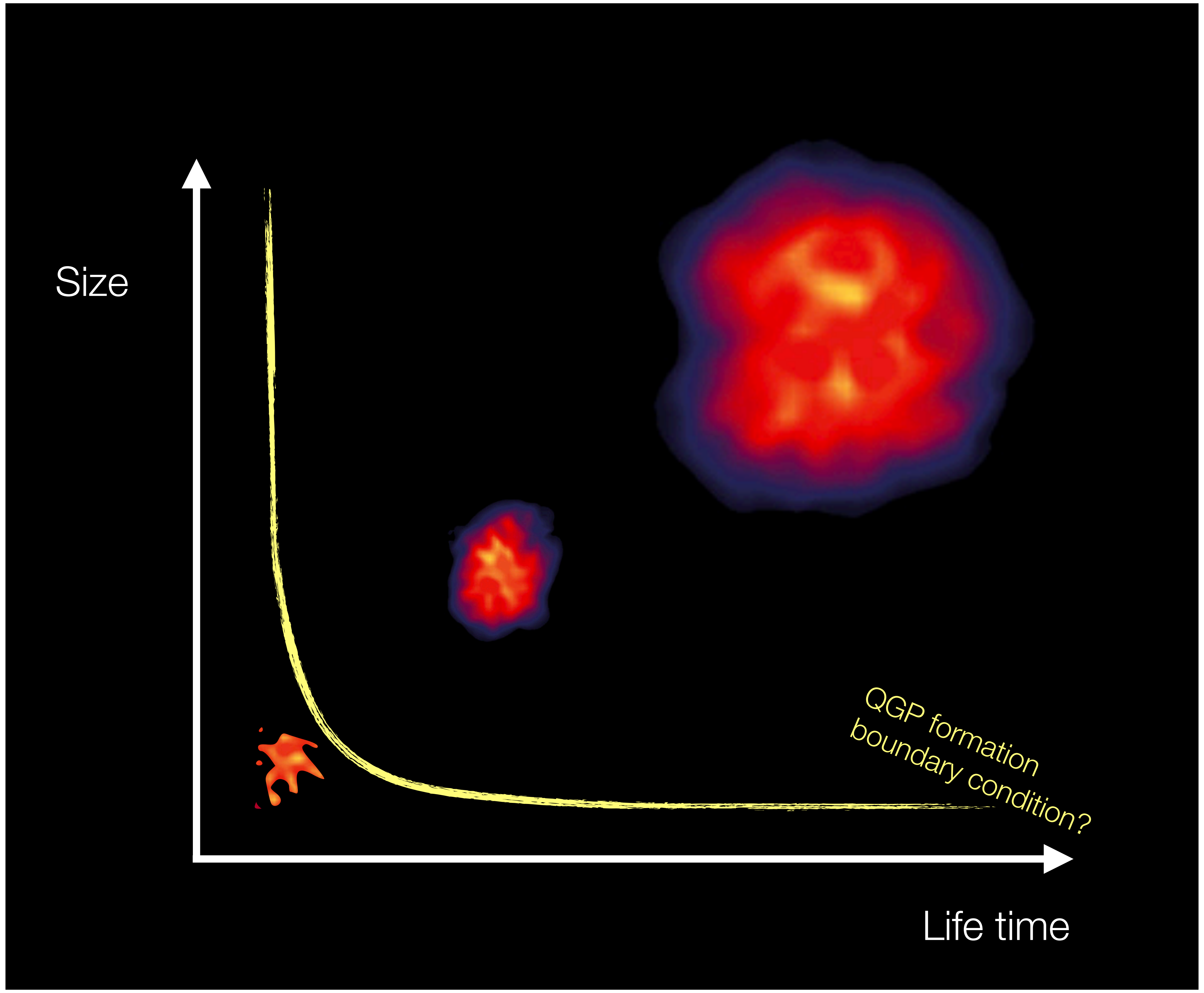
QGP formed in small collisions:

- What are the boundary conditions? Size/energy threshold?
- Implication for hard-QCD measurements?

No QGP formed in small collisions:

- What is the origin of measured correlation?
- Implication for hard-QCD measurements?
- Implication for large system correlation measurement?

Physics implication — cont.



Credit: MUSIC arXiv:1209.6330

QGP formed in small collisions:

- What are the boundary conditions? Size/energy threshold?

  ➡ Long-range azimuthal correlation observed in all examined hadronic collisions

  ➡ Boundary not reached

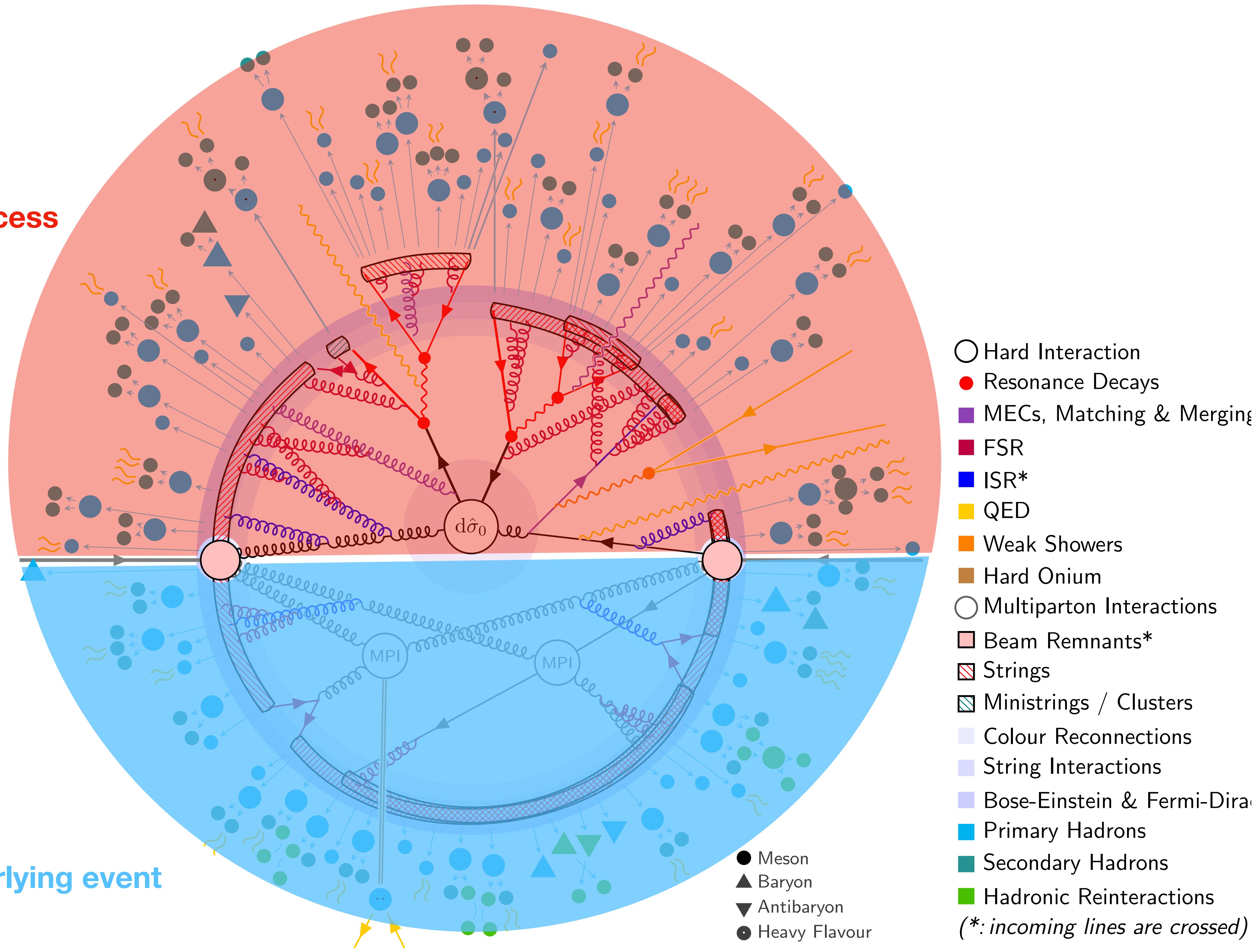
  ➡ A phenomenon without size/energy threshold (present in hadrons themselves)

- Implication for hard-QCD measurements?

p+p collisions in Pythia8

Modeling of hard scattering in p+p collision from Pythia8

Hard process



Soft underlying event

Credit: Pythia8.3 arXiv:2203.11601

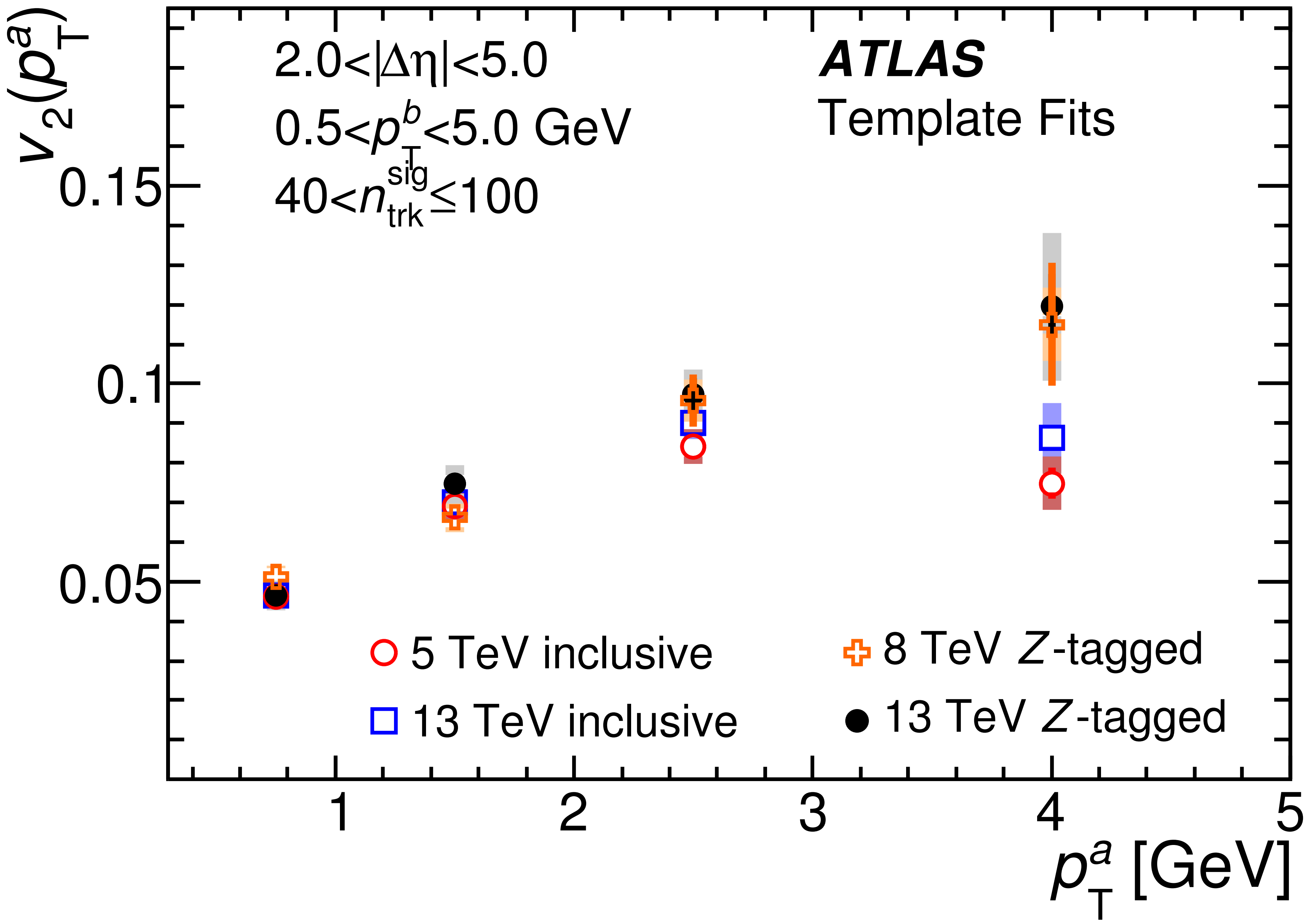
If there is QGP-like matter created in p+p collisions, we have missed it in our modeling (eg. Pythia8)

Potential impact on general QCD measurements:

- Does the anisotropy created by underlying event depend on presence of hard process?
- Does hard process exhibit the same anisotropy?

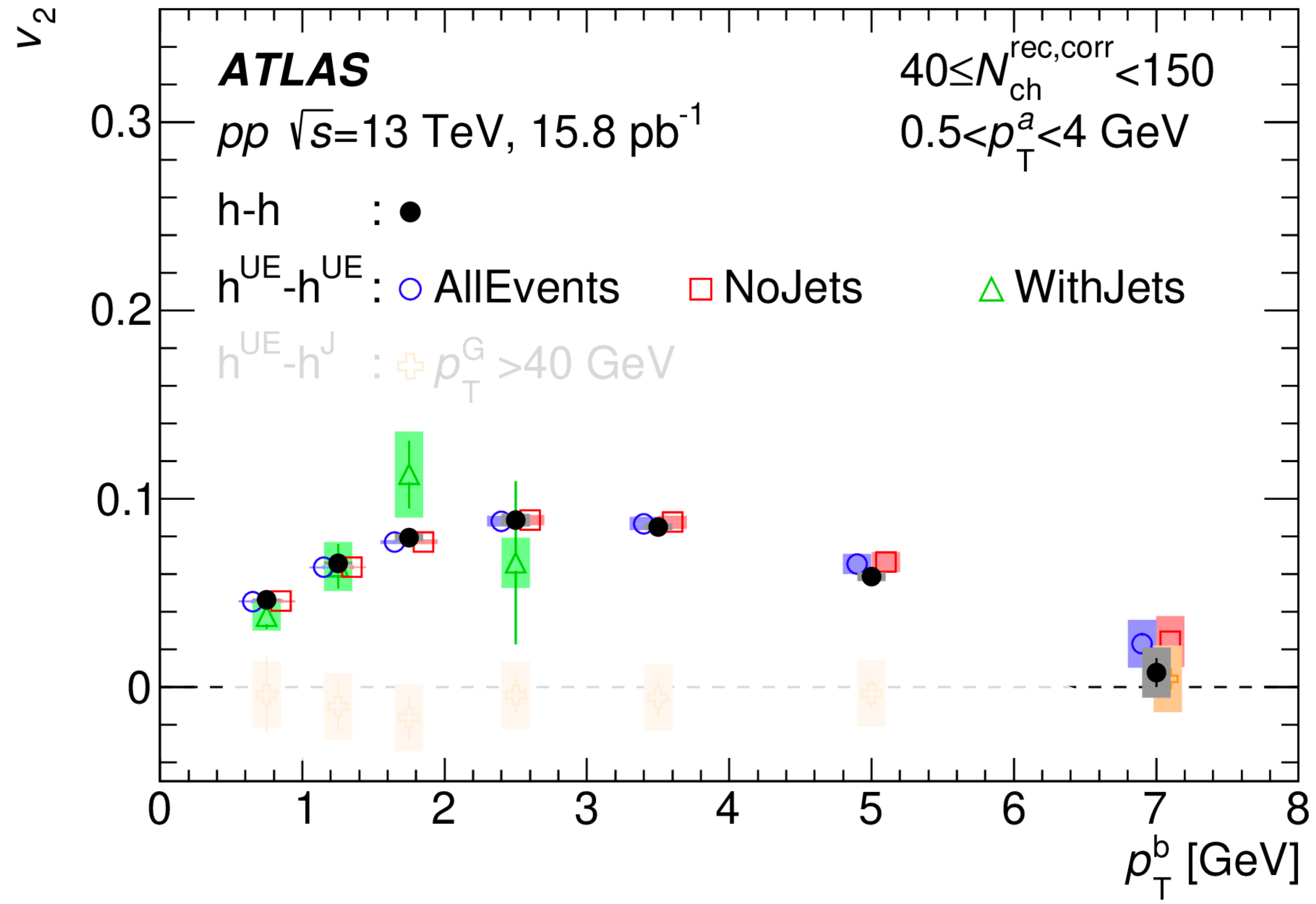
Soft particle anisotropy in Z/jet events

ATLAS, EPJC 80 (2020) 64
ATLAS, arXiv:2303.17357, submitted to PRL



Soft particle v2:

event with *Z* vs. inclusive events



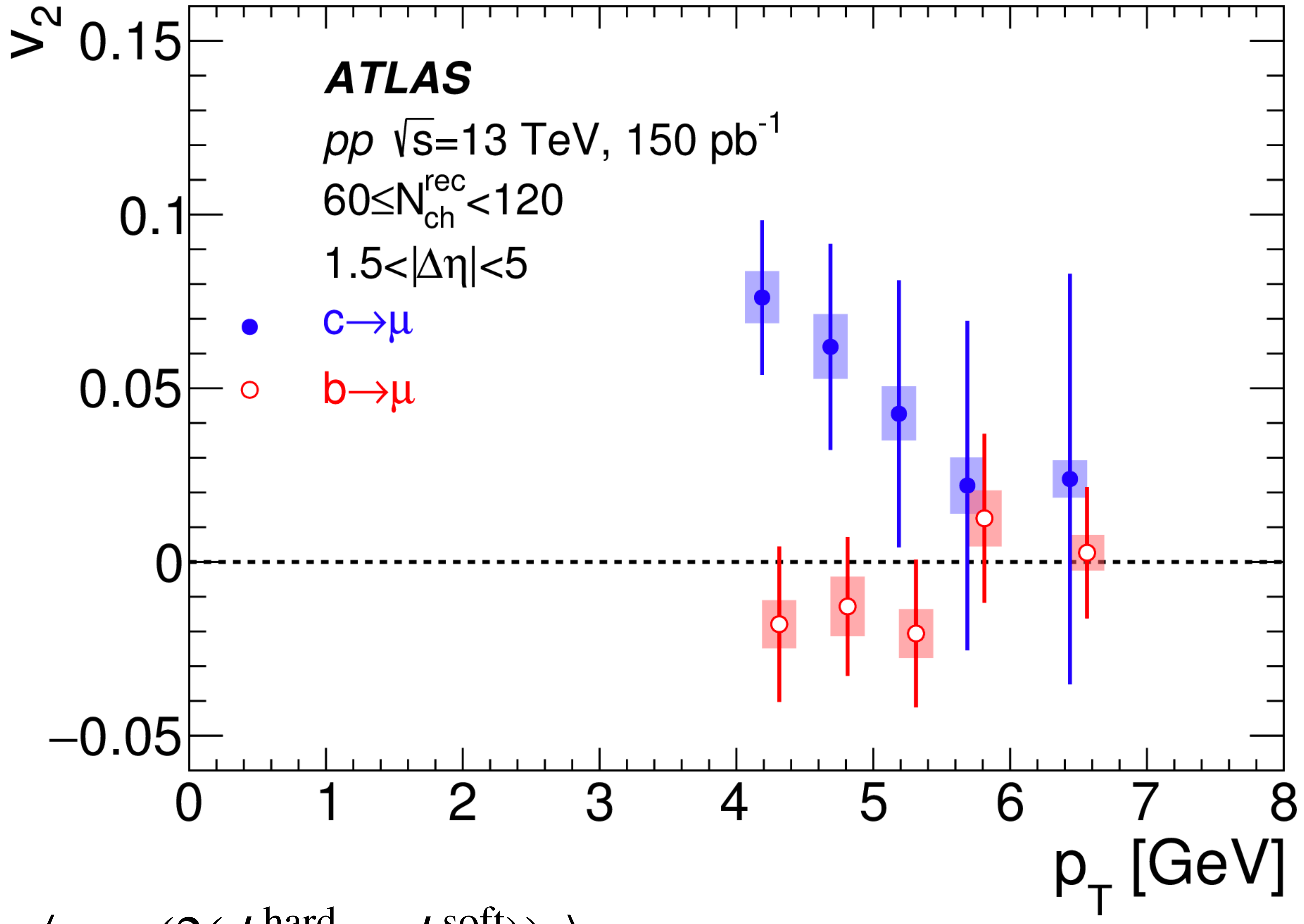
Soft particle v2:

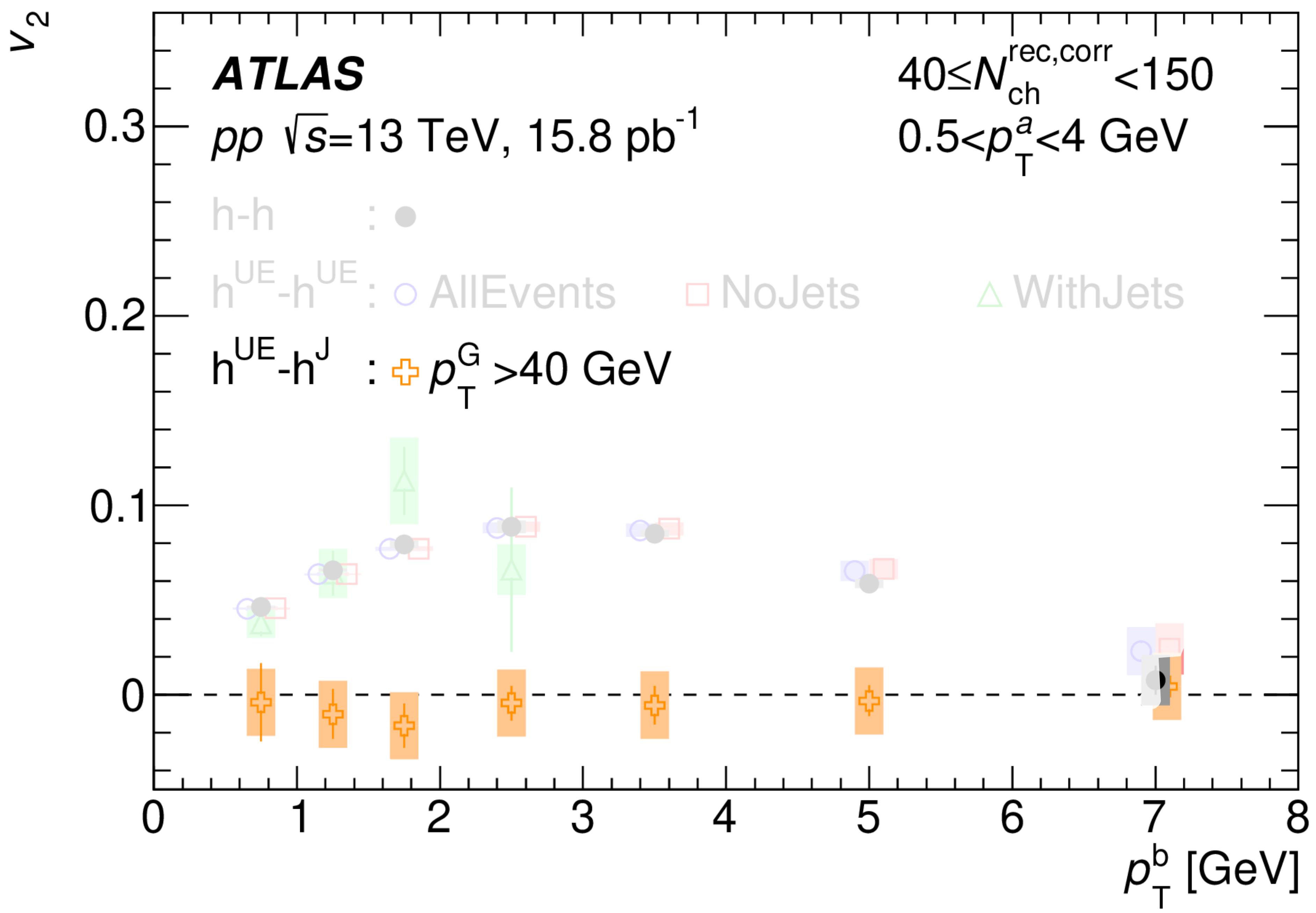
event with *Z* vs. inclusive events

- Does the anisotropy created by underlying event depend on presence of hard process?
  - ➡ Soft particle v_2 shows no obvious dependence on the presence of hard process

Anisotropy of hard process

ATLAS, PRL 124 (2020) 082301
ATLAS, arXiv:2303.17357, submitted to PRL



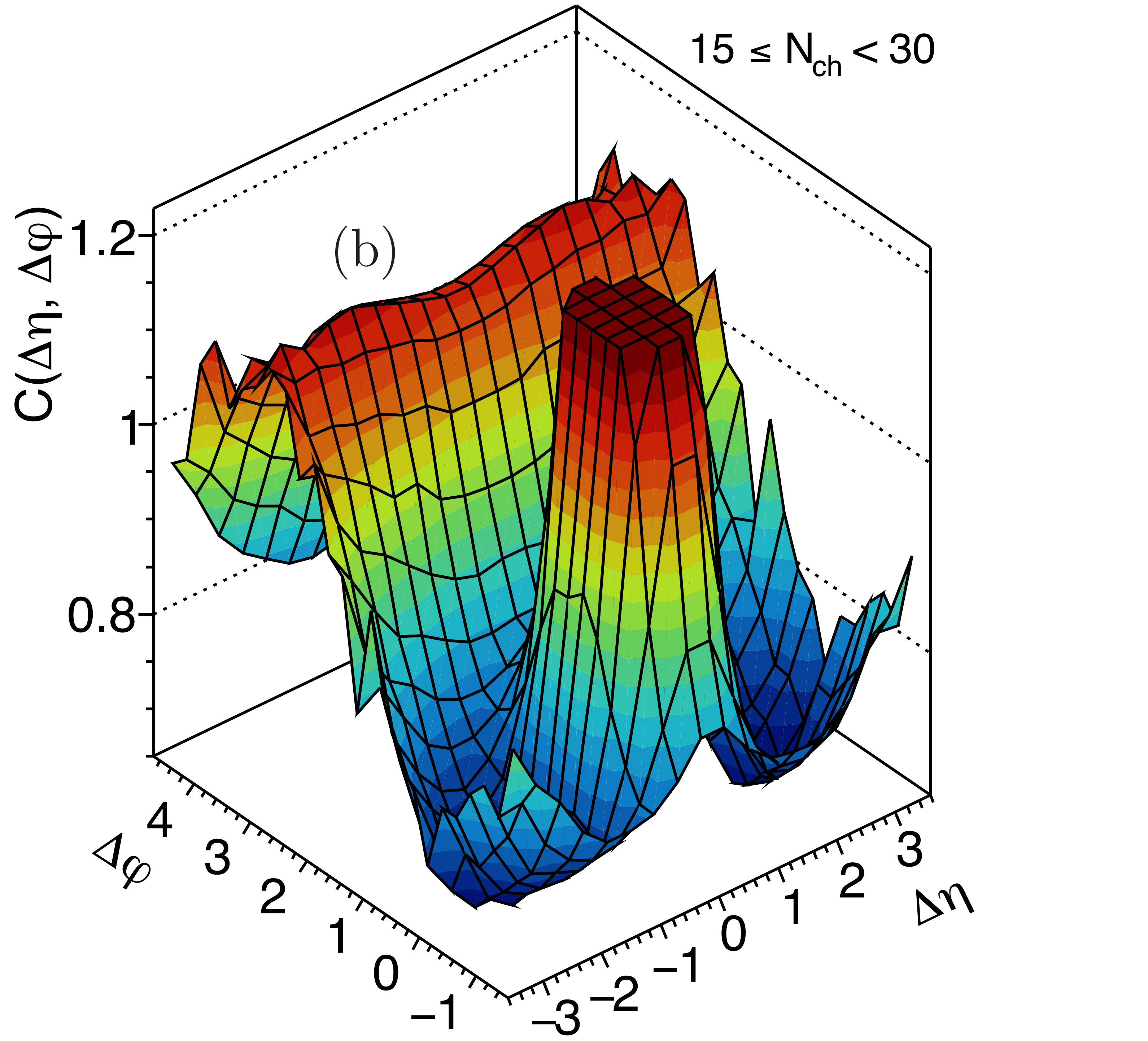


$$v_2 = \frac{\langle\ \cos(2(\phi_1^{\mathrm{hard}} - \phi_2^{\mathrm{soft}}))\ \rangle}{\sqrt{\langle\ \cos(2(\phi_1^{\mathrm{soft}} - \phi_2^{\mathrm{soft}}))\ \rangle}}$$

- Charm-soft correlation, $v_2 > 0$
- Bottom-soft correlation, $v_2 = 0$
- Jet particle-soft correlation, $v_2 = 0$

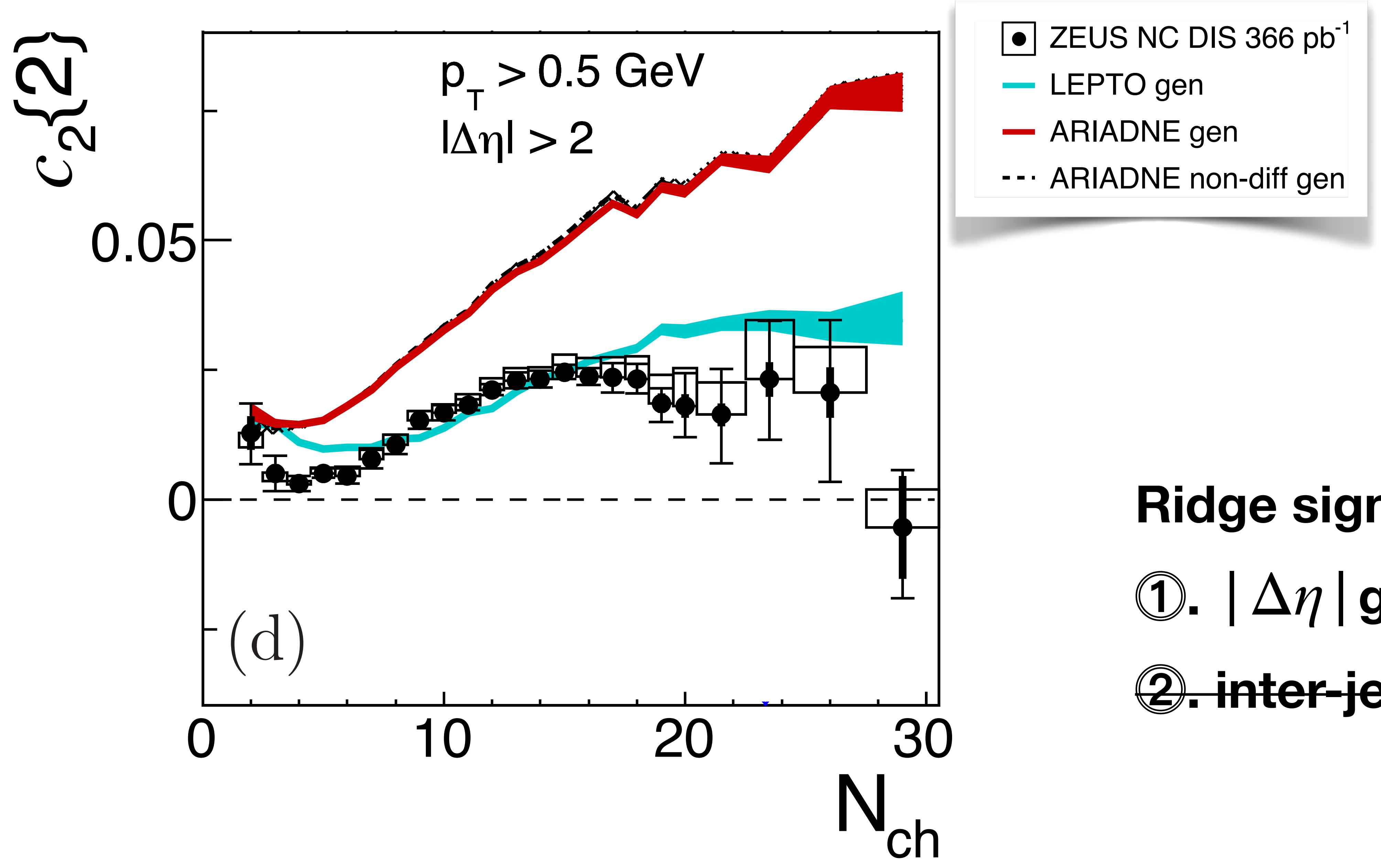
- Does hard process exhibit the same anisotropy?
  - ➡ Charm hadron shows similar anisotropy as inclusive hadrons
  - ➡ Very hard process is not correlated with soft particles

Two-particle correlation in e+p collisions



ZEUS at HERA, e+p, $\sqrt{S} = 318\ \mathrm{GeV}$

ZEUS, arXiv:1912.07431



Ridge signal extraction:

①. $|\Delta\eta|$ **gap:** $|\Delta\eta| > 2$

~~②. **inter-jet correlation subtraction**~~

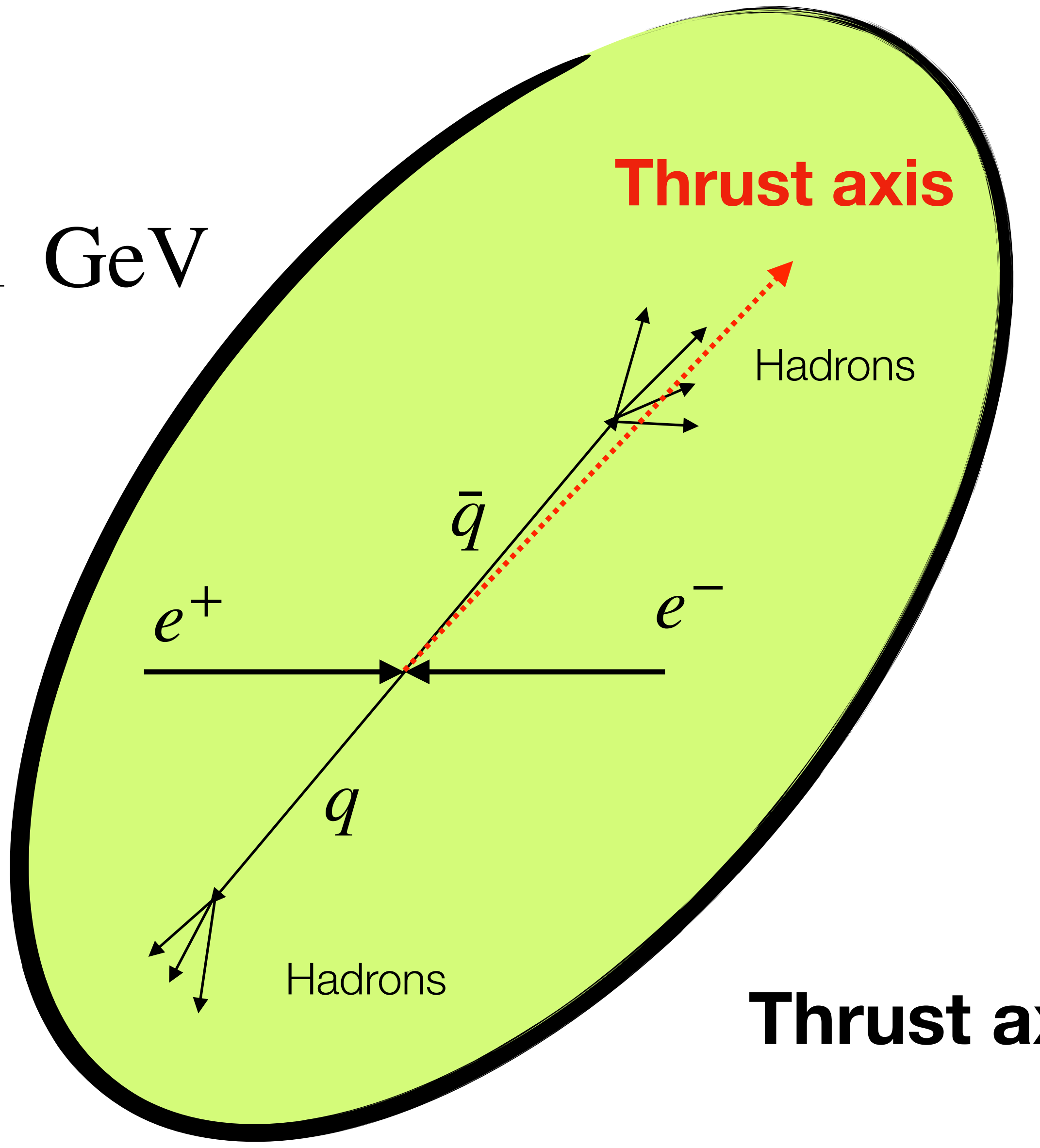
$$c_2\{2\} = \langle \cos(n(\phi_1 - \phi_2)) \rangle \sim v_2^2$$

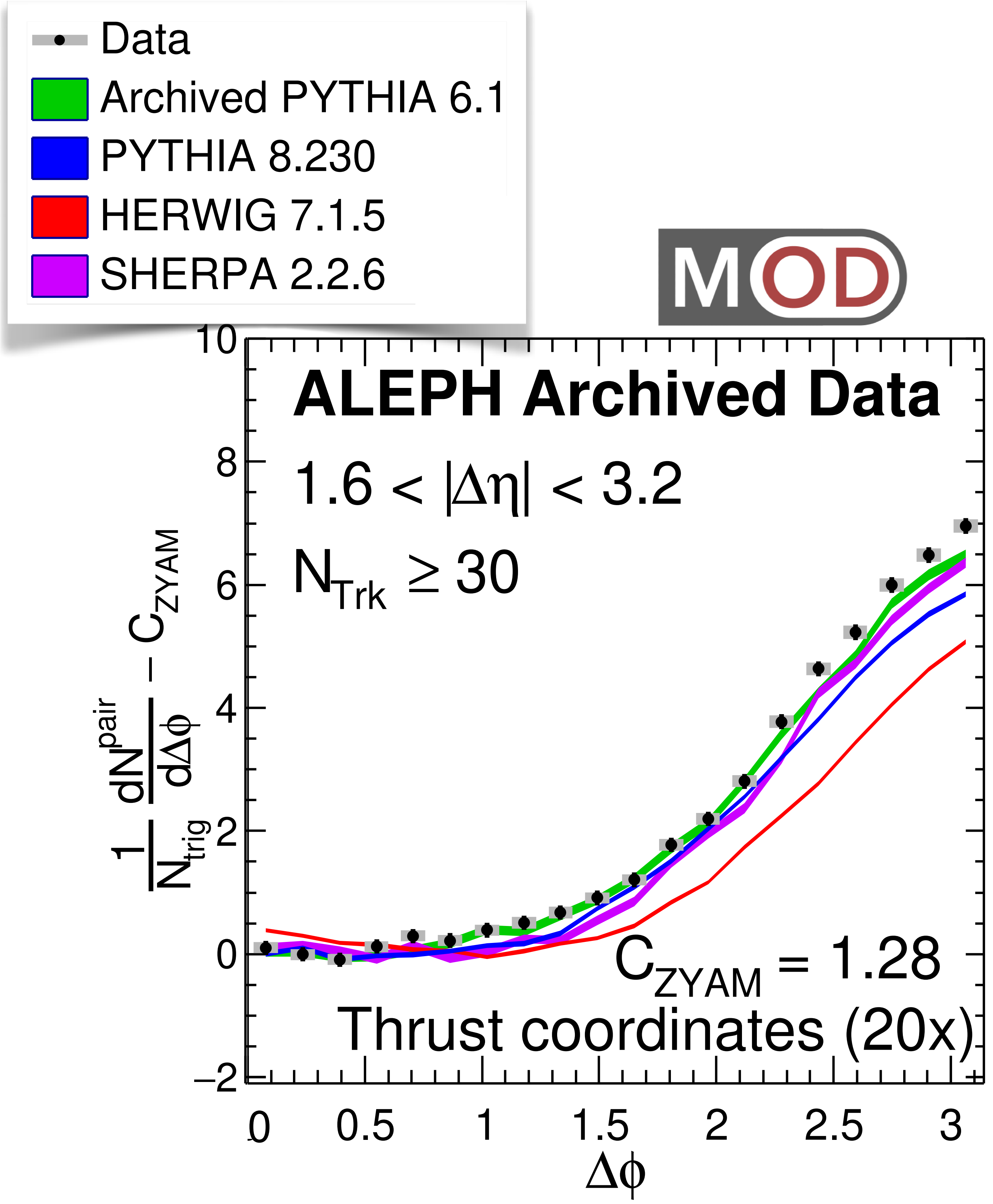
- Measured two-particle correlation consistent with MC.
- No obvious unknown long-range correlation in examined e+p data

Two-particle correlation in e+e- collider

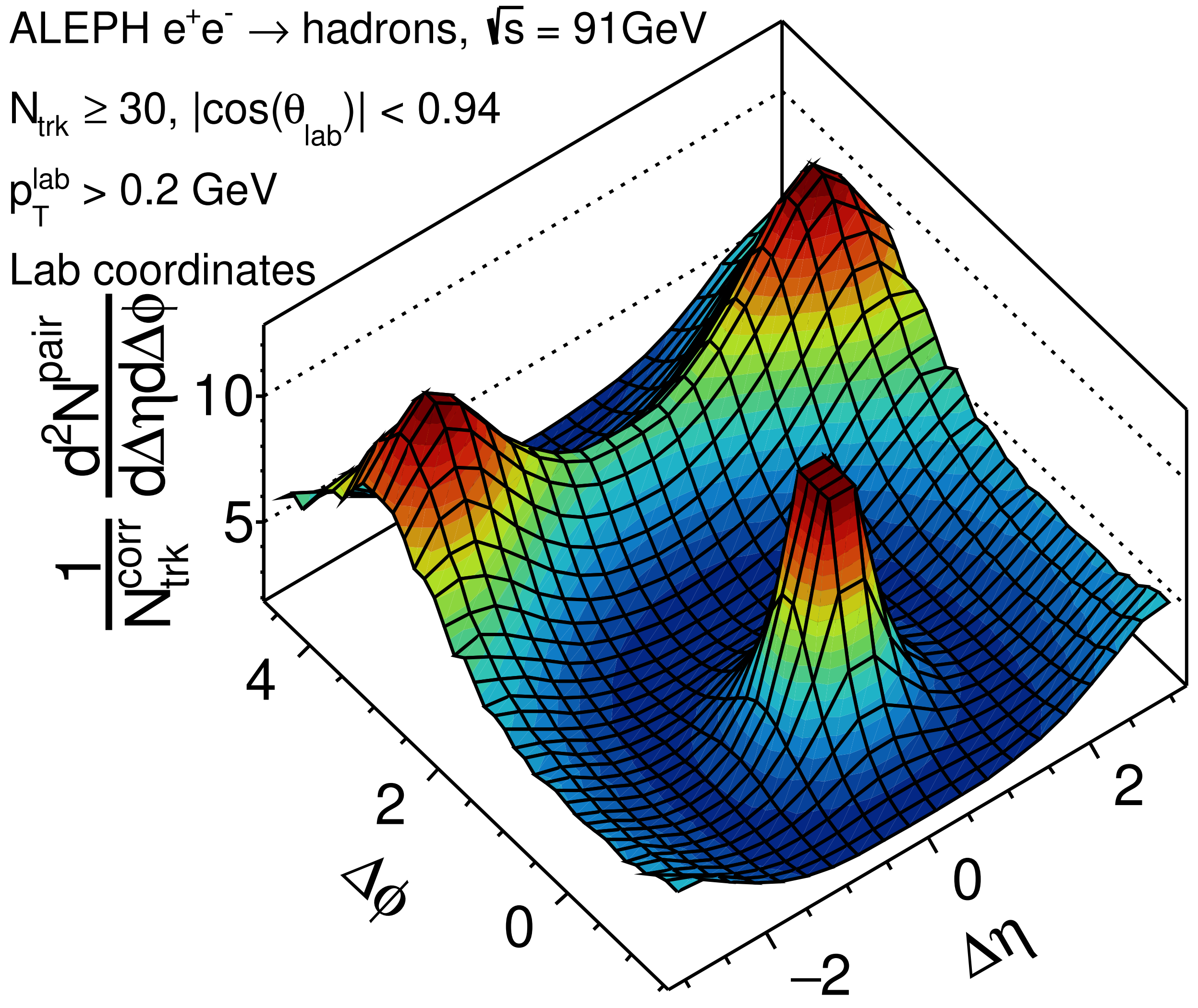
ALEPH at LEP, e+e-, $\sqrt{S} = 91\ \mathrm{GeV}$

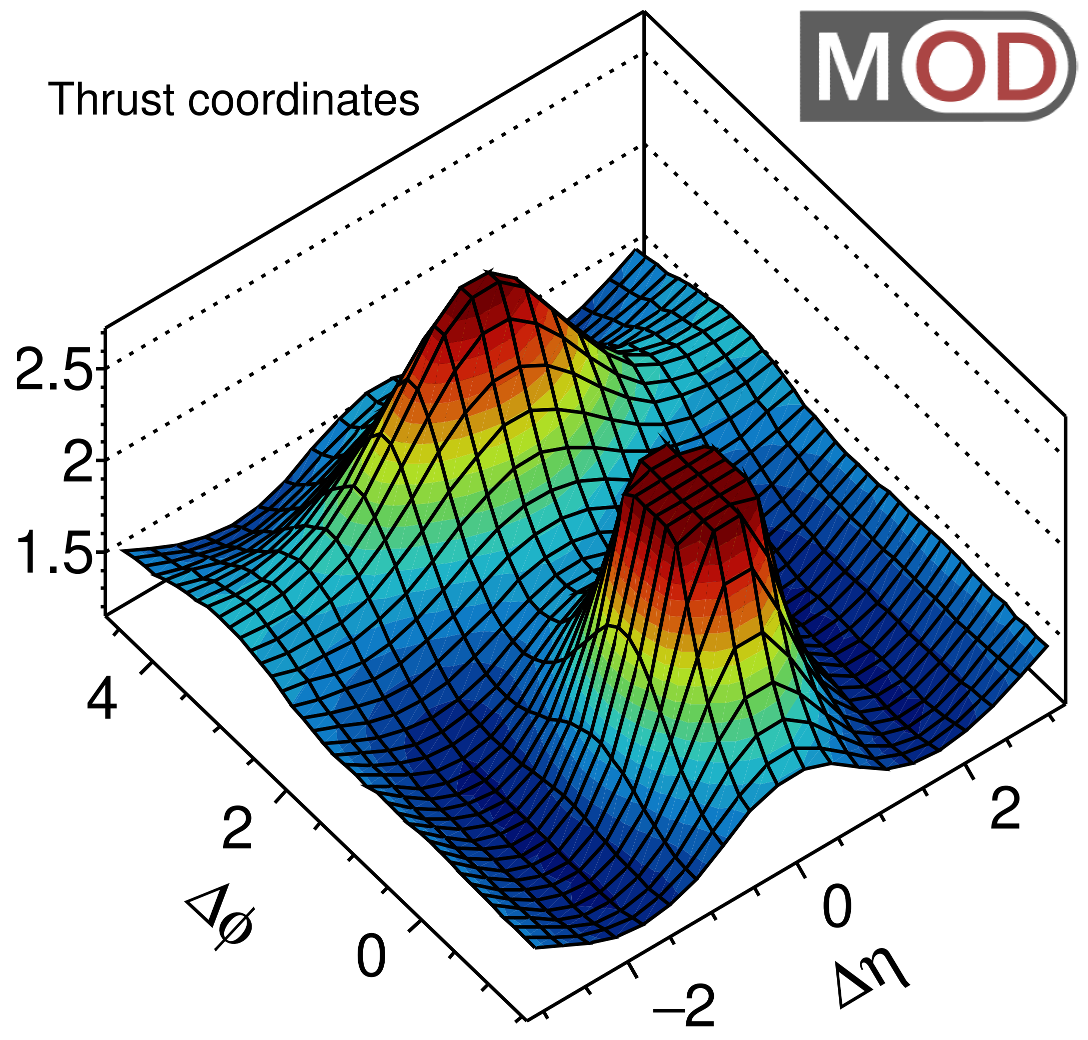
ALEPH + MIT
PRL 123 (2019) 212002





Beam axis **Thrust axis**

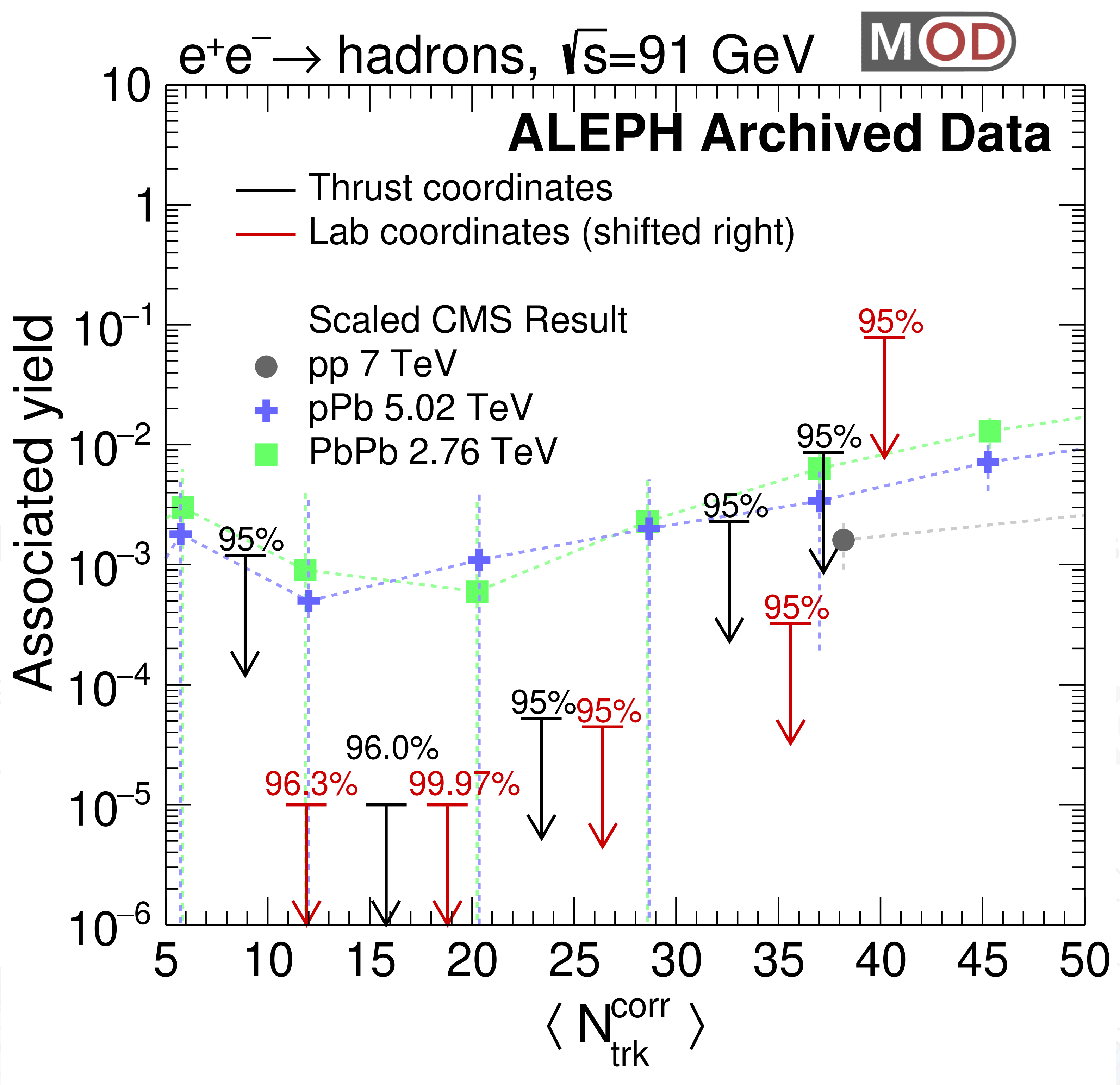


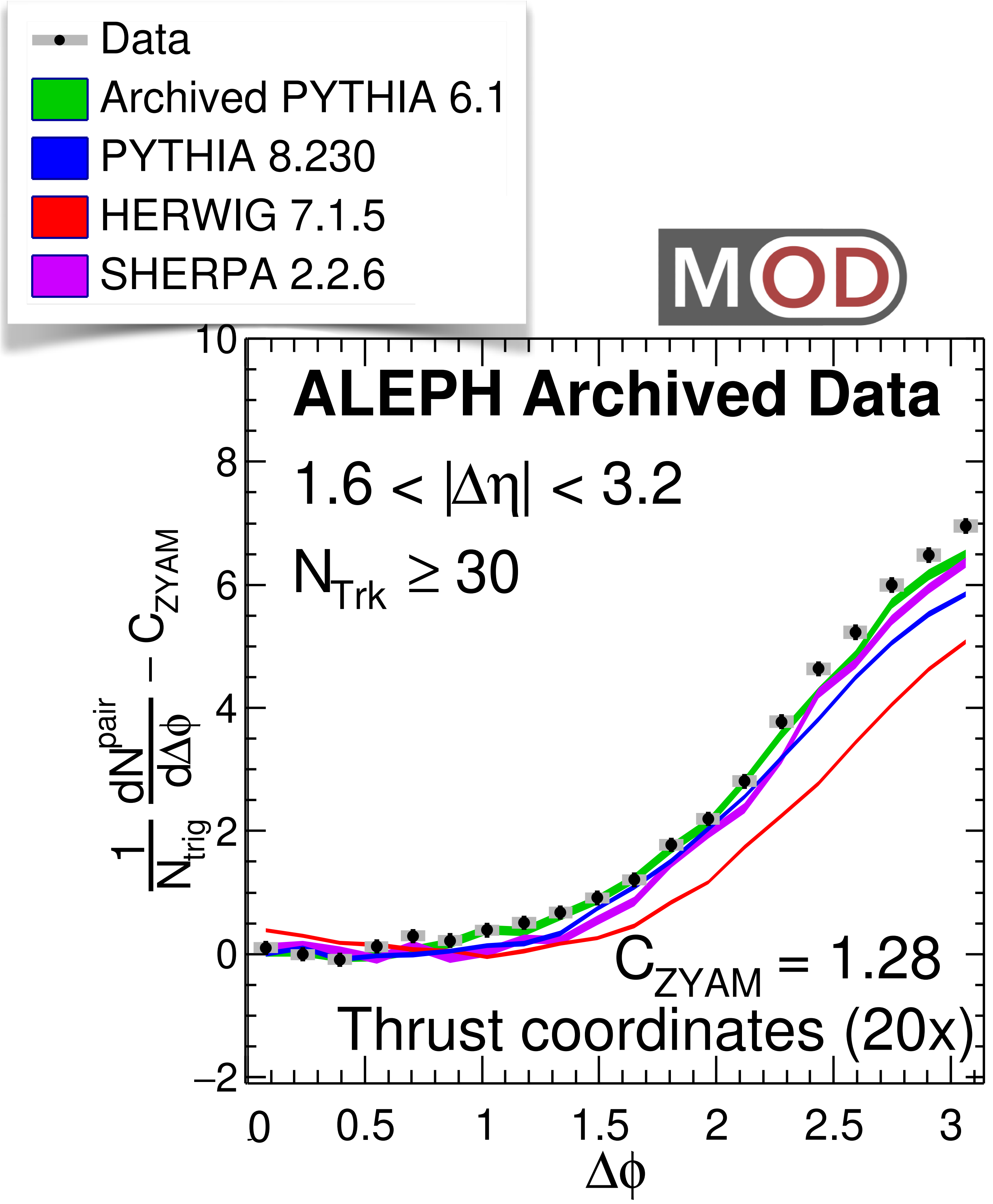


- Thrust axis is more suitable for e+e- collisions: examine collective motion along hadronization expansion

Two-particle correlation in e^+e^- collider

ALEPH + MIT
[PRL 123 (2019) 212002]

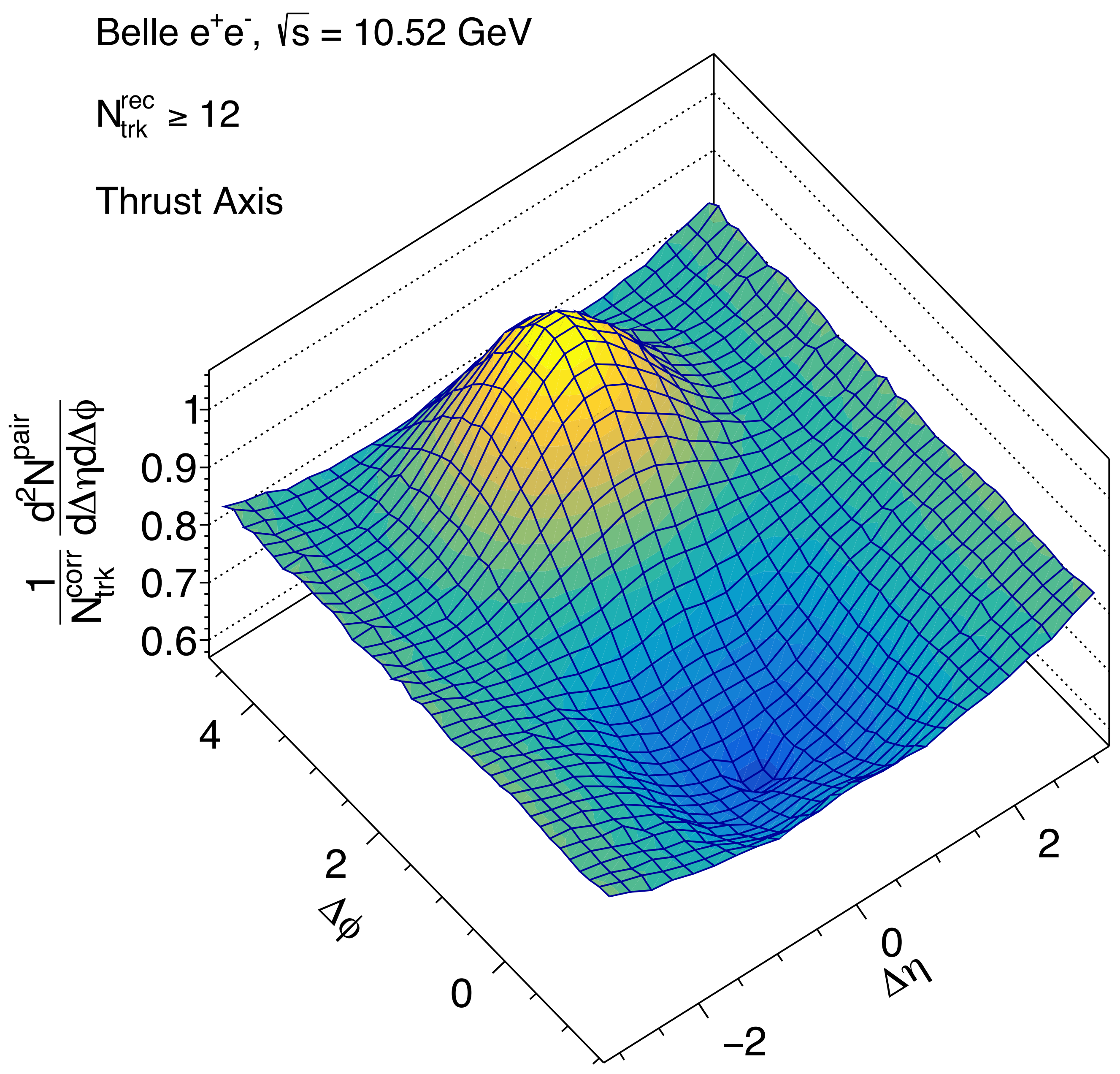


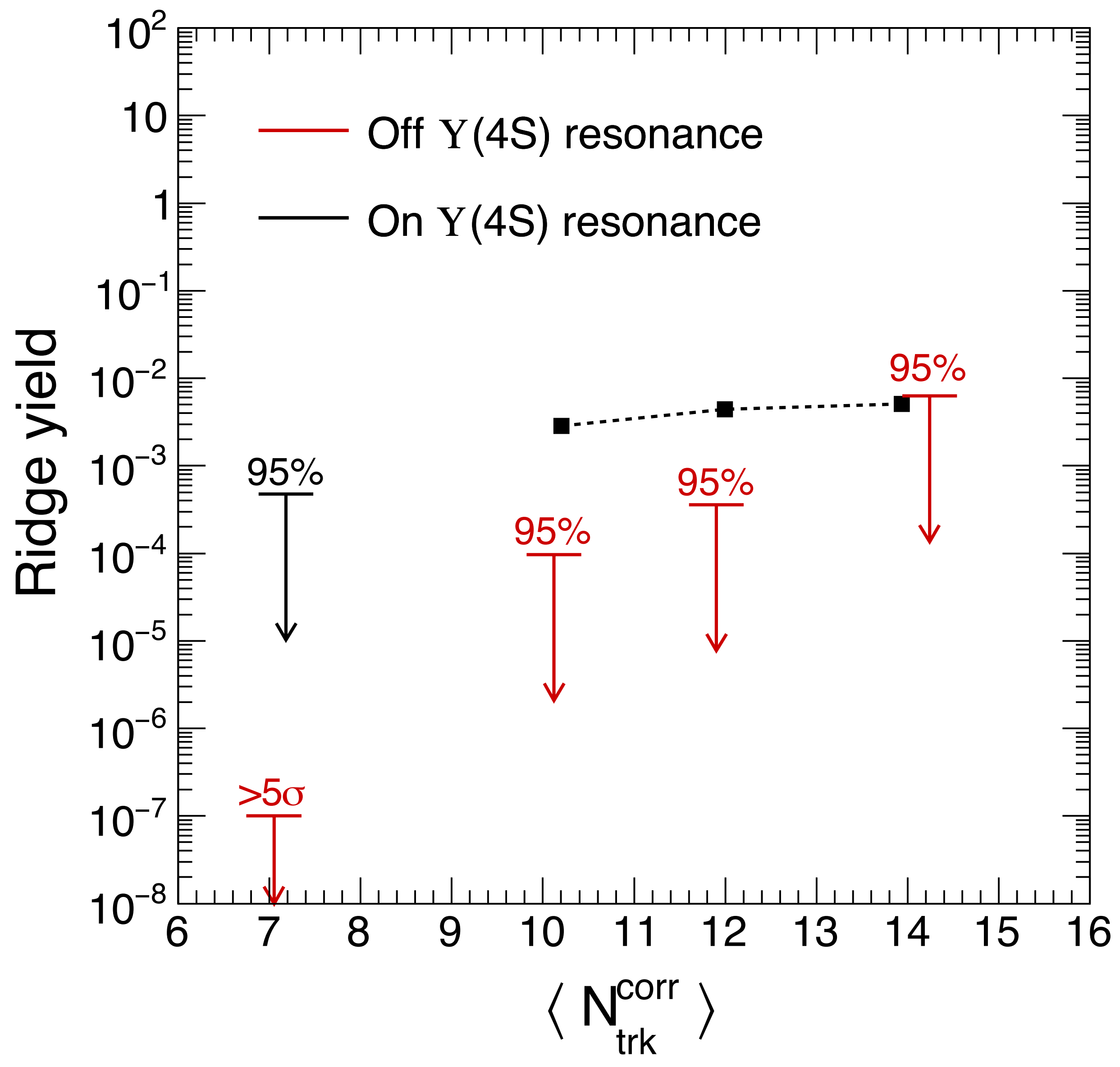


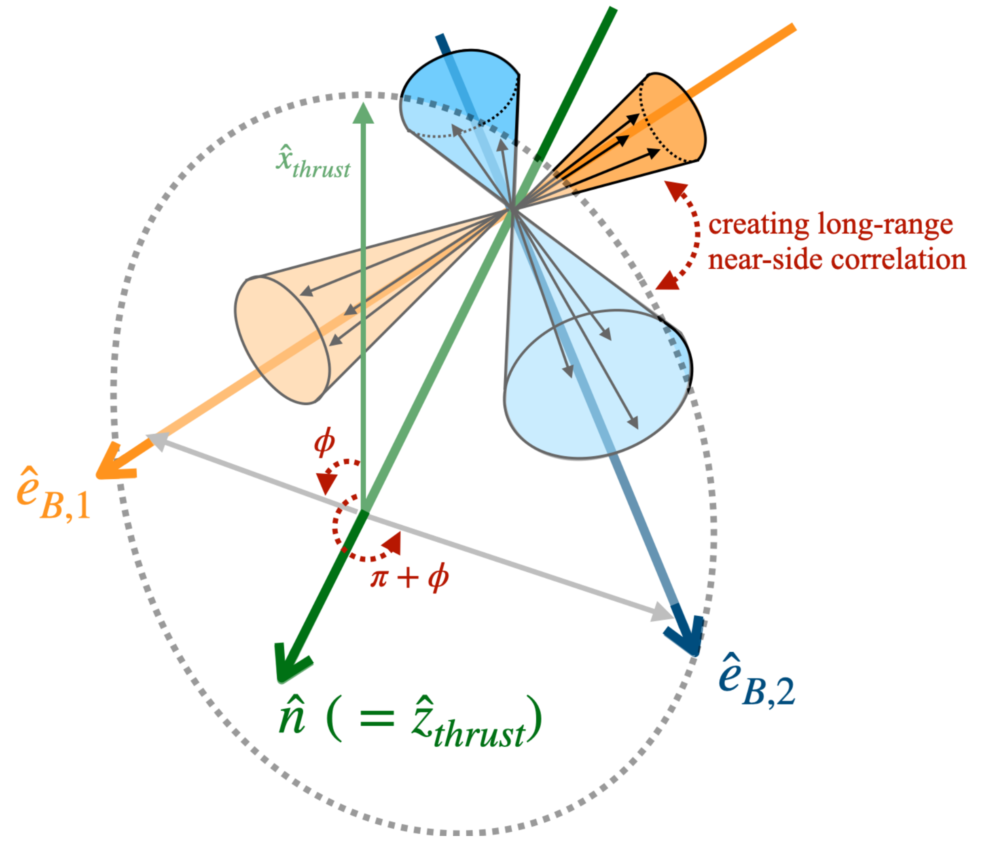
- Thrust axis is more suitable for e+e- collisions: examine collective motion along hadronization expansion

Two-particle correlation in e+e- collider — cont.

Belle + MIT
arXiv:2201.01694 (submitted to PRL)
arXiv:2206.09440







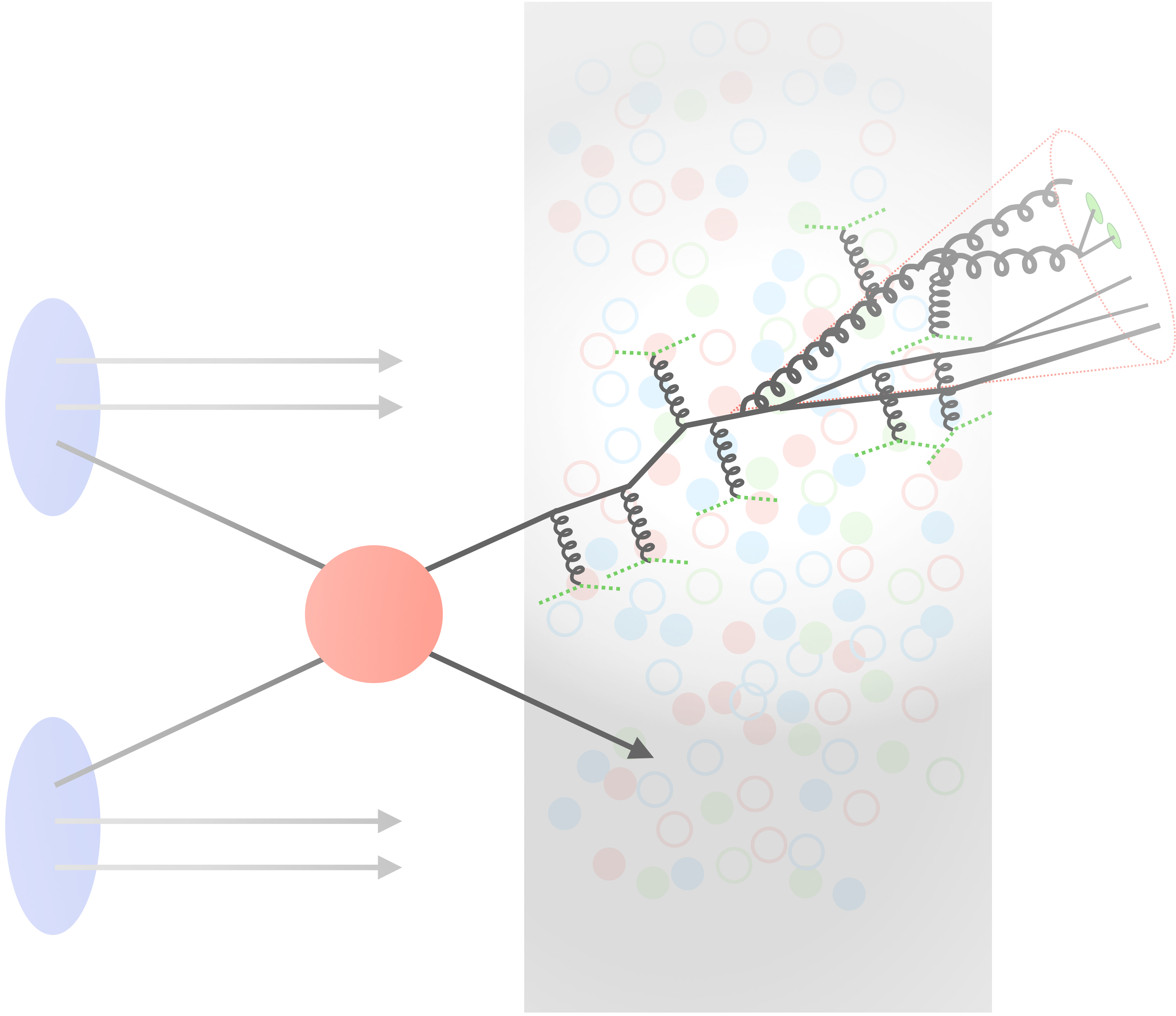
- Two-particle angular correlation is also applied to Belle data ($N_{\rm trk}^{\rm rec} \geq 12$)
- Observed ridge yield attribute to special event topology and thrust axis alignment in two B meson decay systems

Summary on small system two-particle correlation

- Azimuthal anisotropy of inclusive particles is observed in all hadronic collisions
- Azimuthal anisotropy of hard QCD process depends on its hardness:
  - Low p_T charm — similar anisotropy as soft light hadrons
  - Intermediate p_T charm — probing the switch between hard-soft correlation ??
  - Hard jet fragments / bottom — no significant anisotropy

- No significant anisotropy observed in e+p or e^+e^- collisions

Application of **hard** sector methodology



Hard Probes of QGP

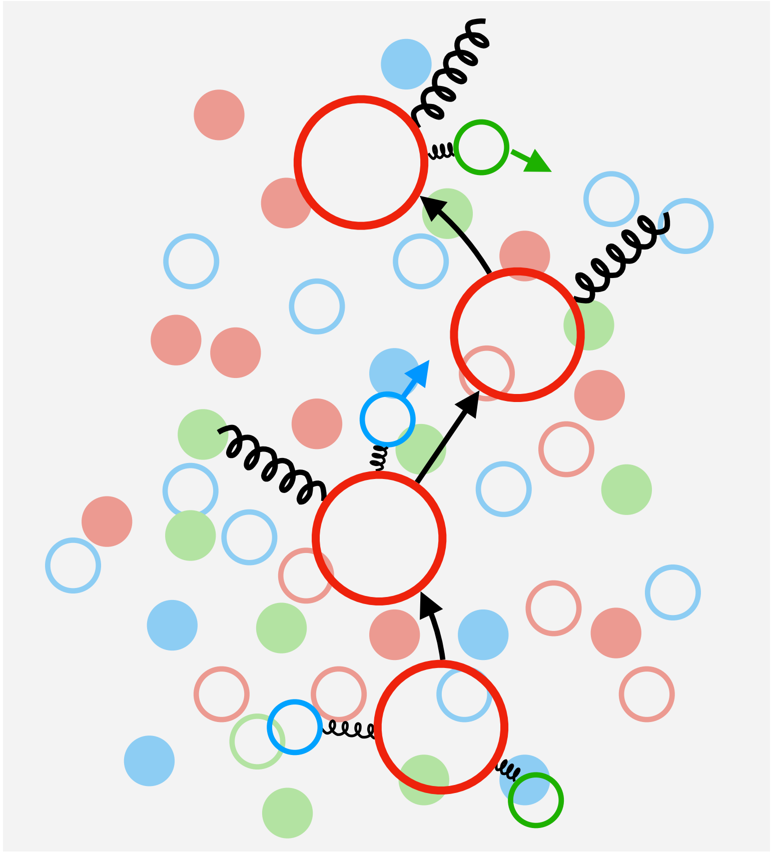
Hard probes:

- Created in the early stages of QGP formation
- Reliable pQCD calculations
- Triggered and detected easily
- Ideal hard probes: energetic jets, heavy flavor hadrons

Nuclear modification factor

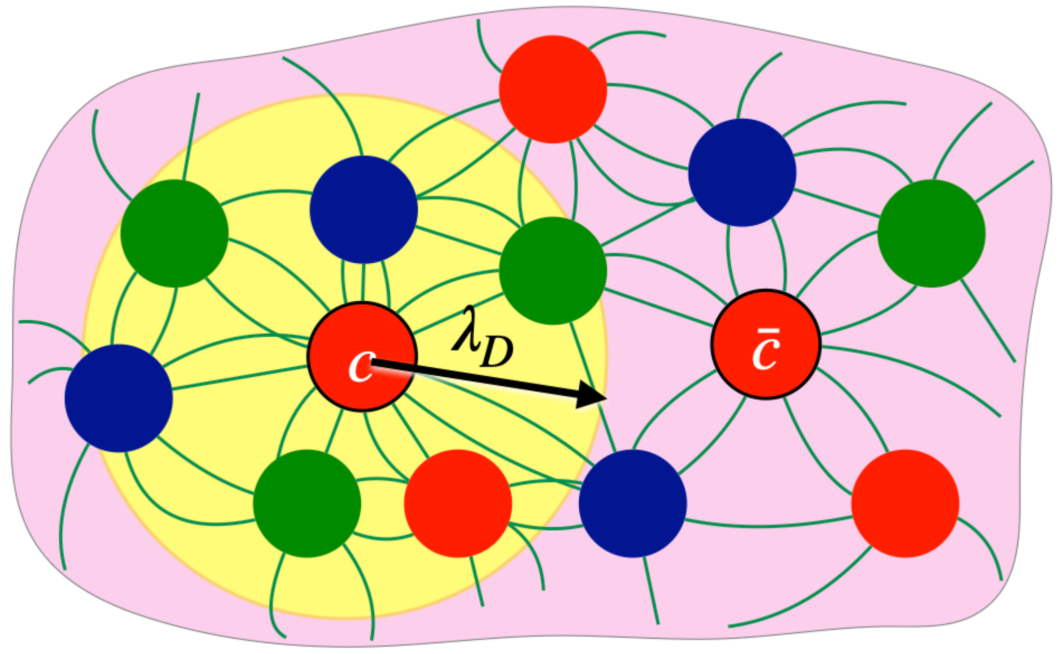
$$R_{AA} = \frac{\text{per-NN yields in A-A}}{\text{yields in } pp}$$

$R_{AA} < 1$ due to presence of QGP

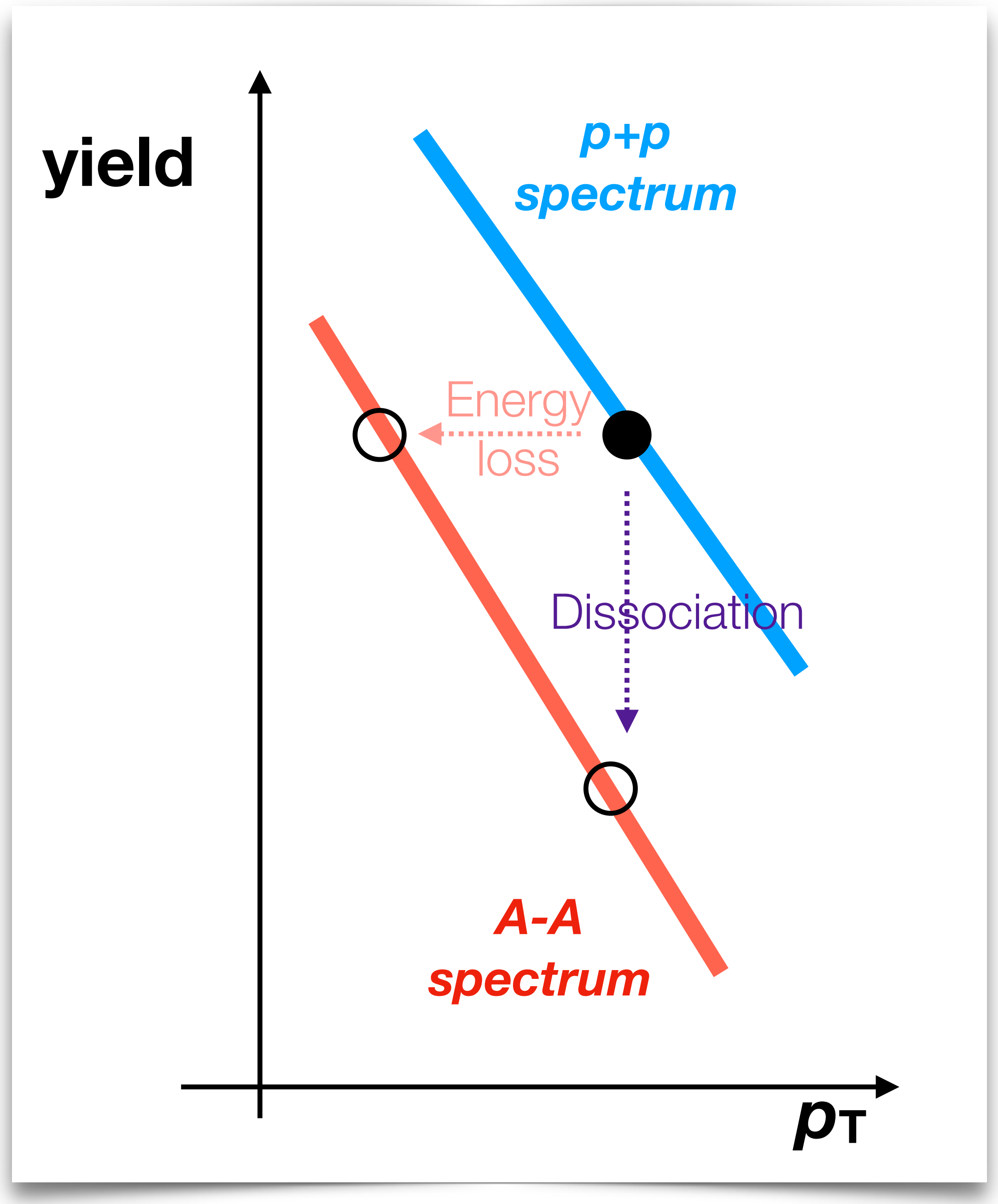


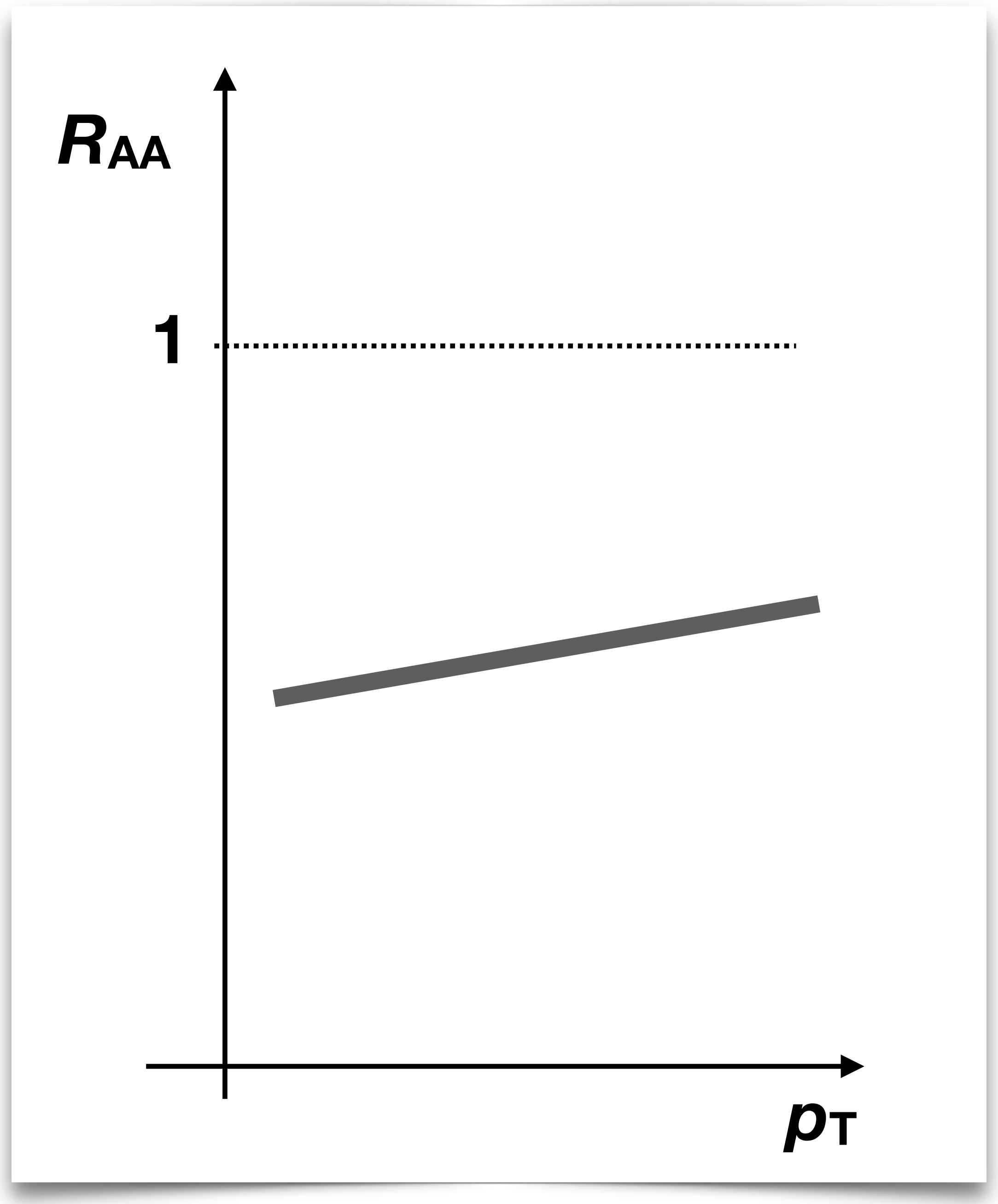
QGP induced energy loss

Transportation



Dissociation due to color screening





Centrality in Pb+Pb collisions at ATLAS

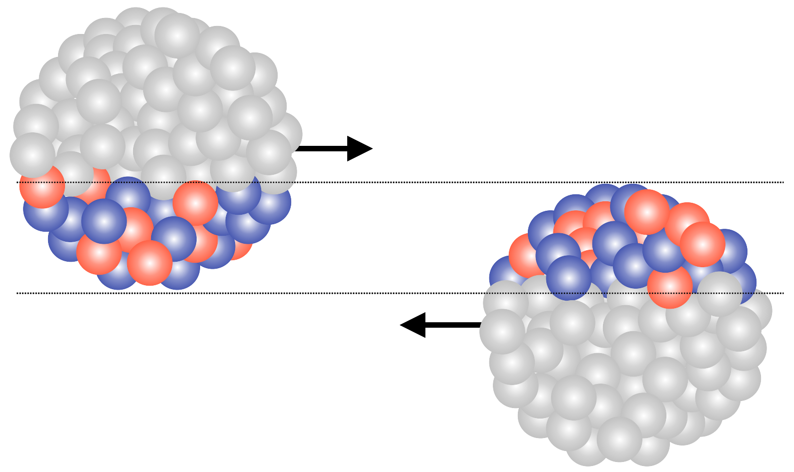
PLB 789 (2019) 167

Energy deposition in FCal in MinBias Pb+Pb collisions

Map to collisions geometry via MC Glauber

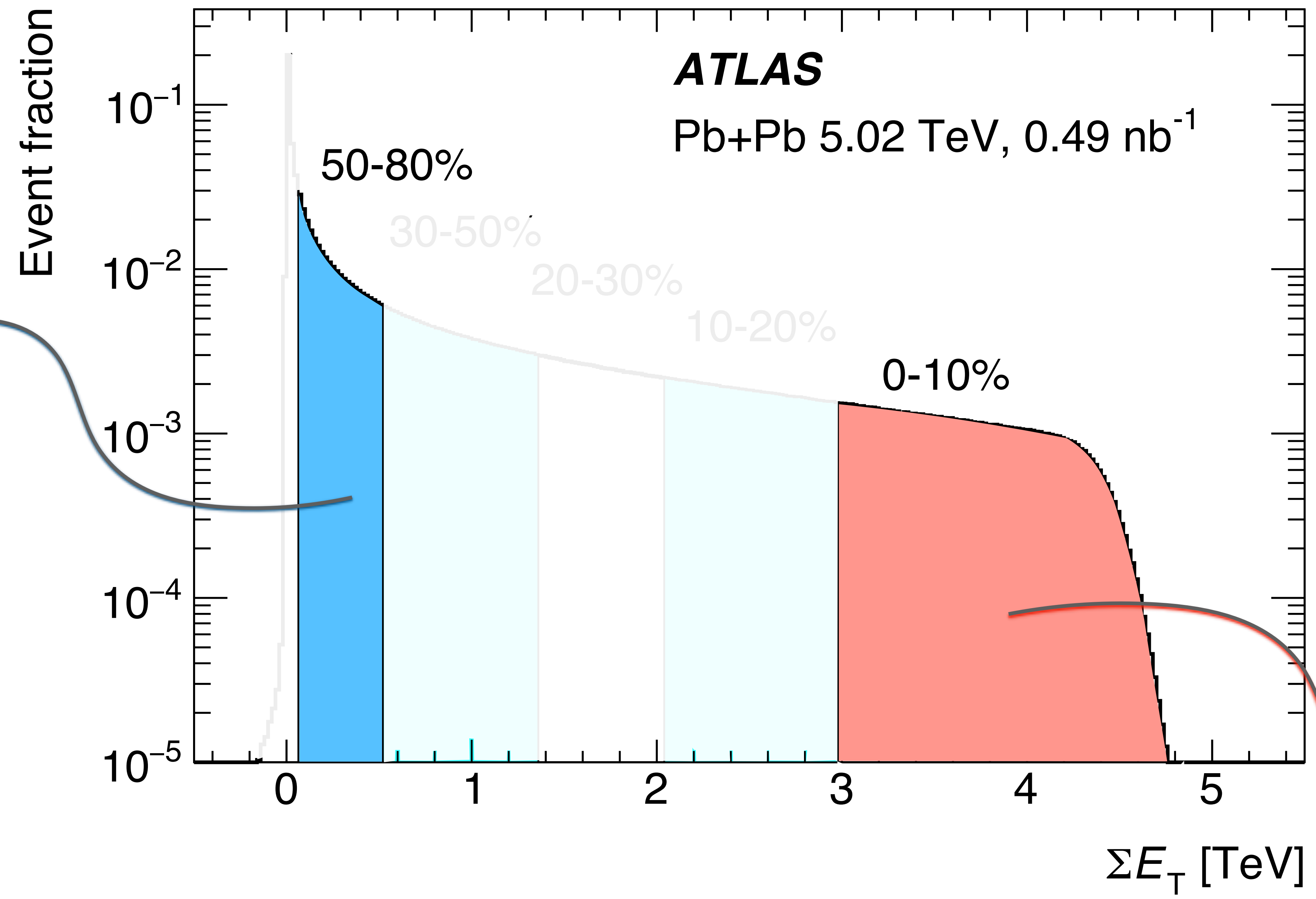
Number of participanting nucleon ~ 34

Number of binary collisions ~ 50



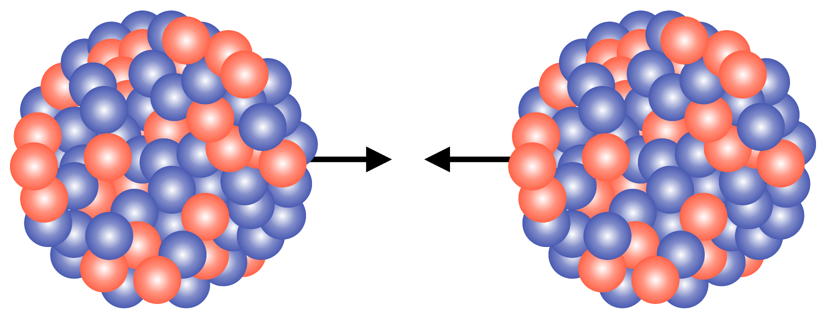
Peripheral collisions

Centrality 50-80%



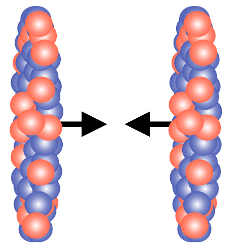
Number of participanting nucleon ~ 358

Number of binary collisions ~ 1600



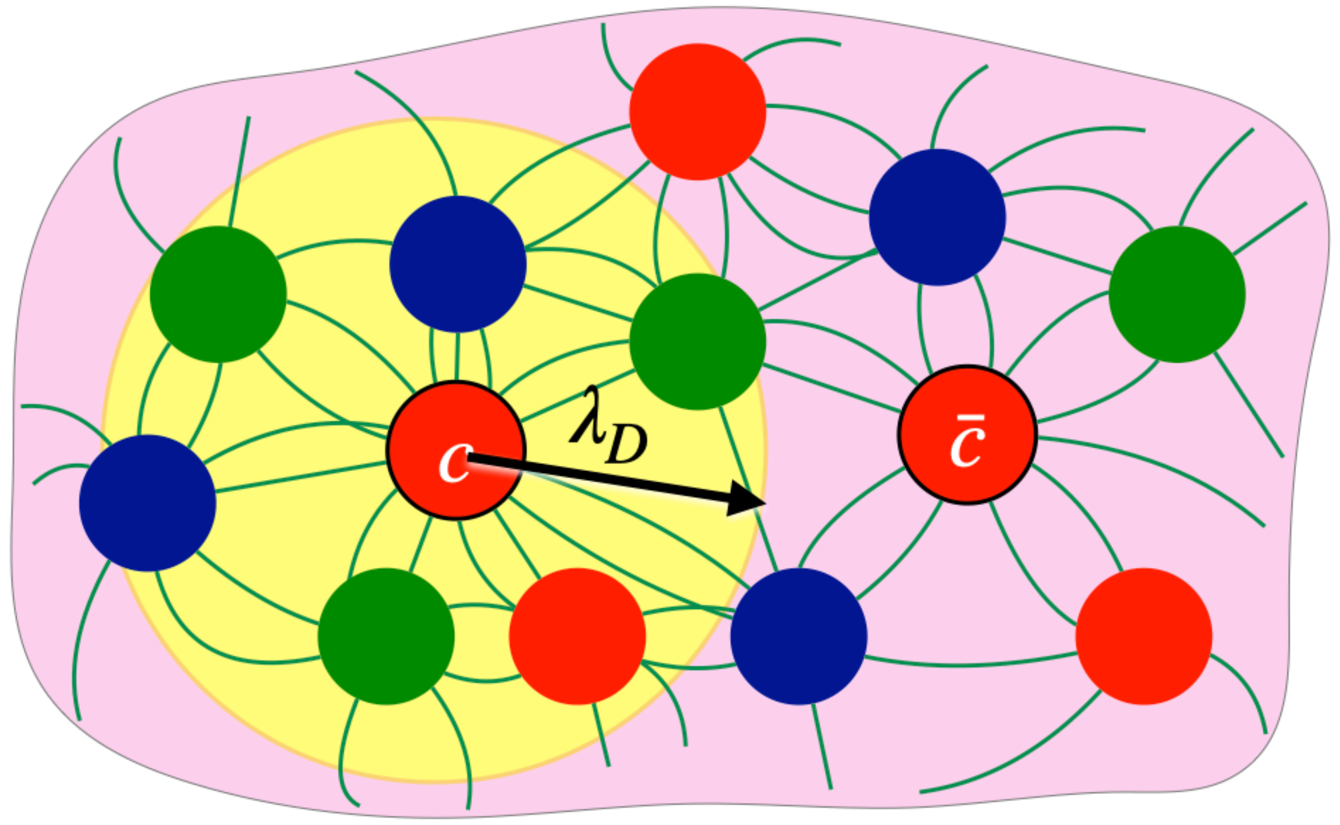
Central collisions

Centrality 0-10%

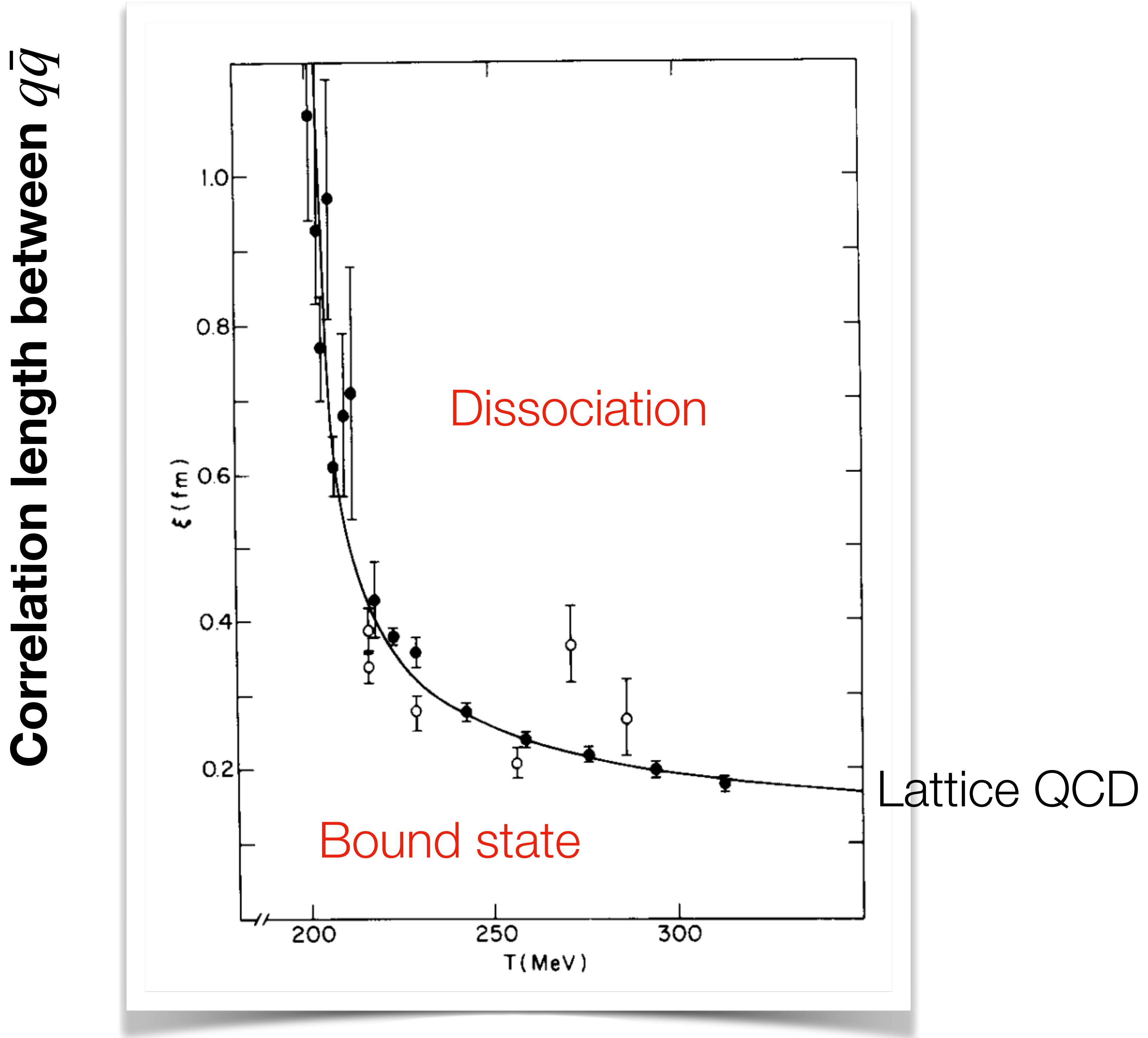


** Ignoring Lorentz contraction for demonstration purpose

Color screening



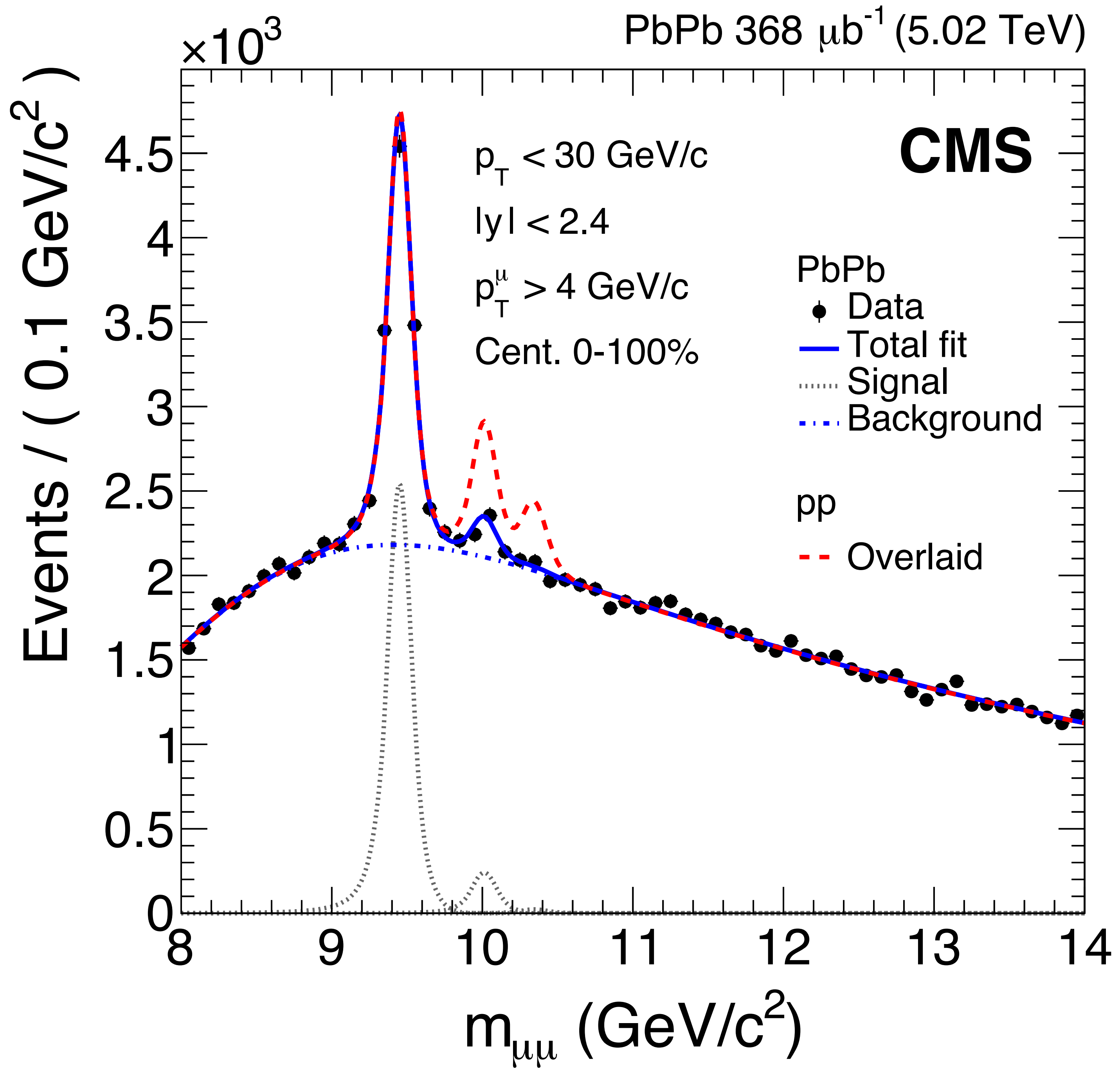
PLB 178 (1986) 416

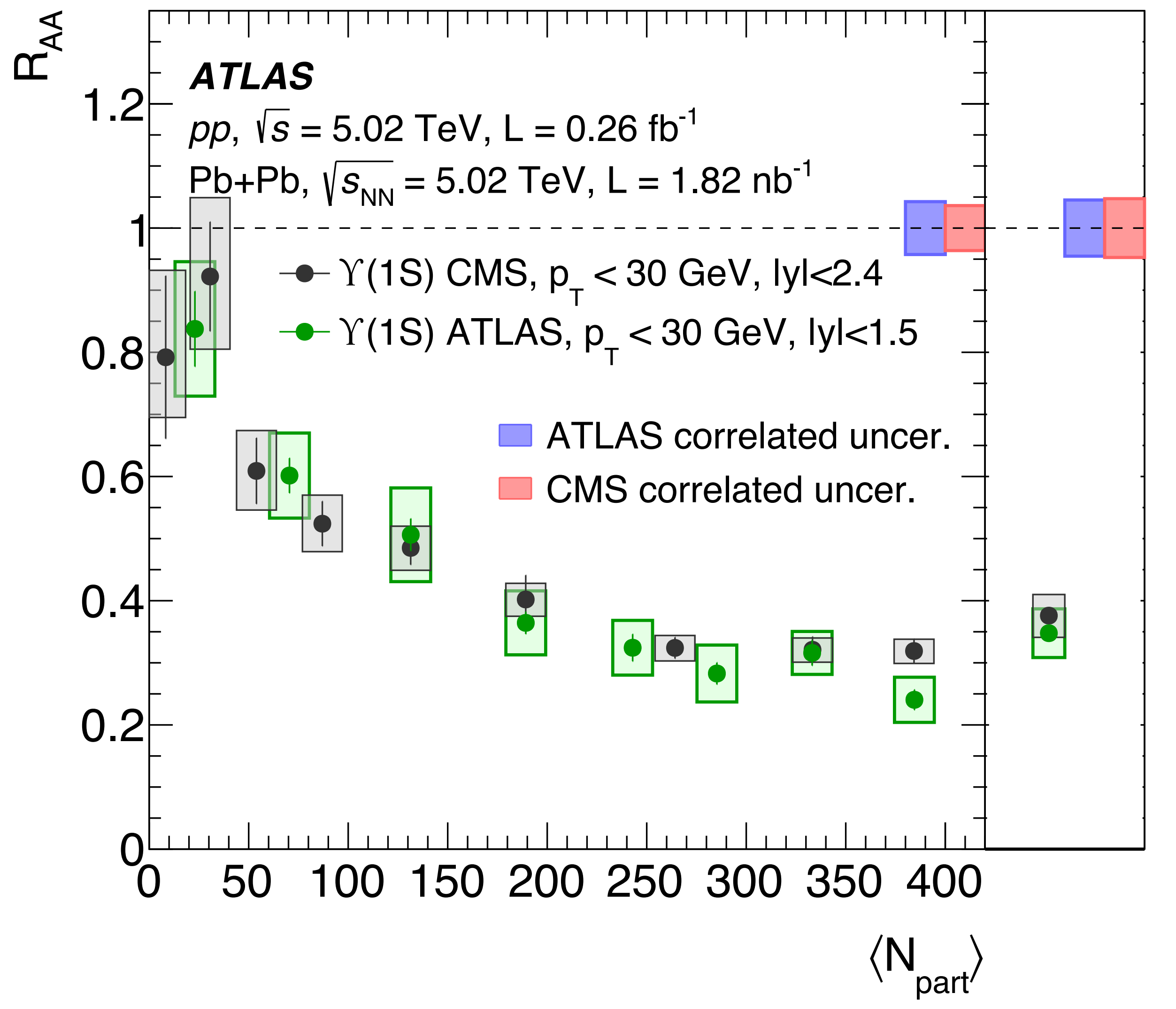


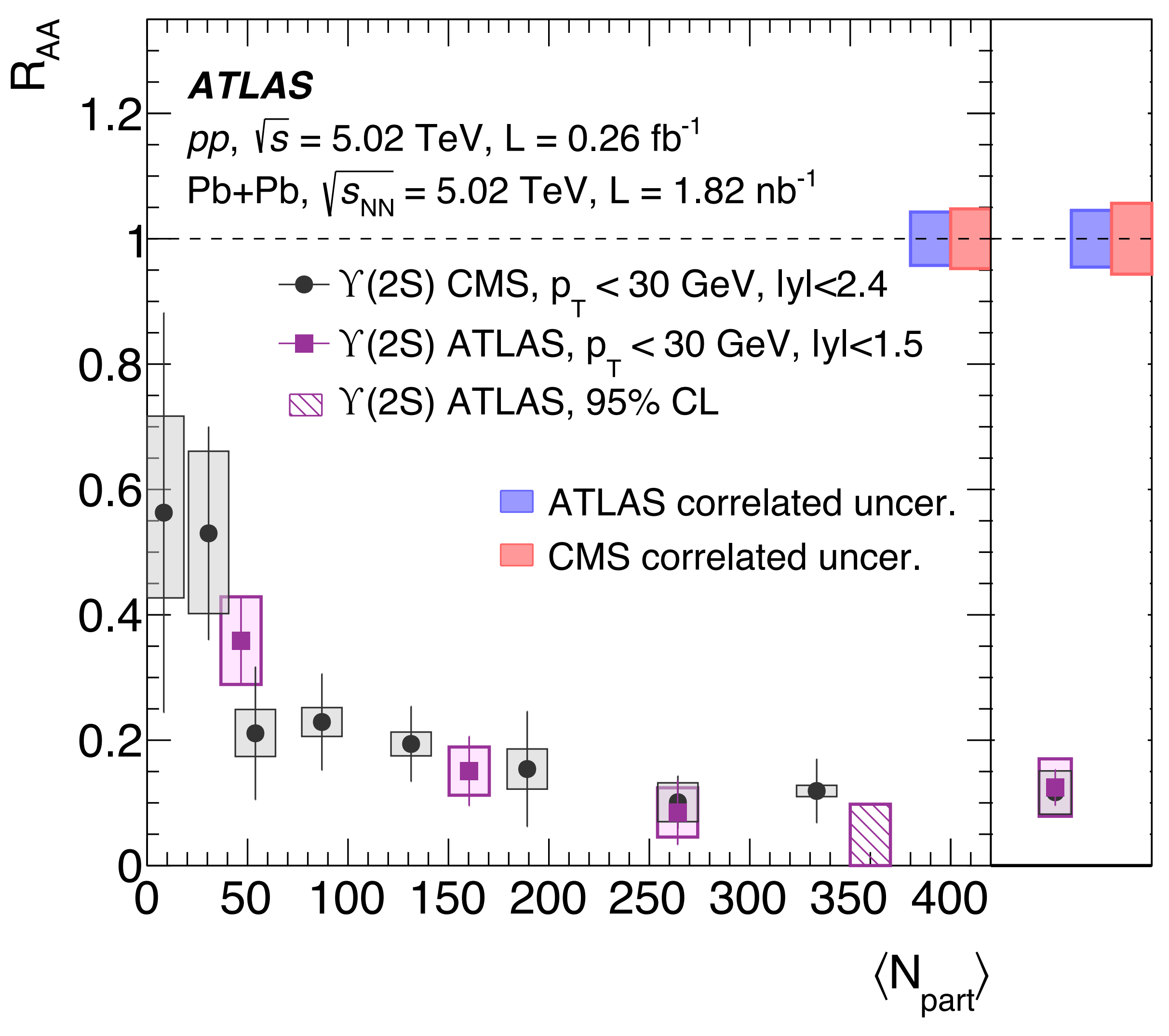
- Simple quarkonium potential in vacuum: $V(r) = -\dfrac{\alpha}{r} + kr$
- Simple static potential with screening: $V(r) = -\dfrac{\alpha}{r} e^{-r/\lambda_D}$
- Color screening effect depends on resonance size

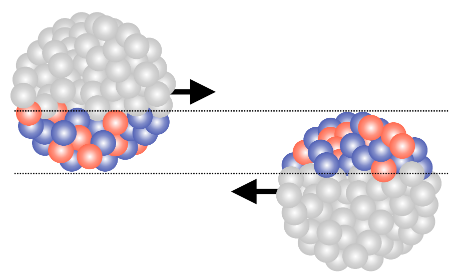
Color screening in experiments

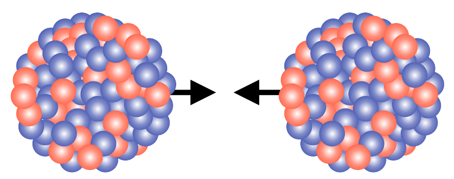
CMS, PRL 120 (2018) 142301
ATLAS, PRC 107 (2023) 054912



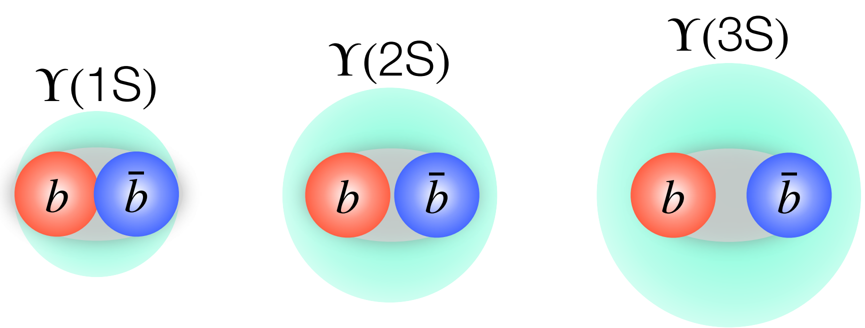






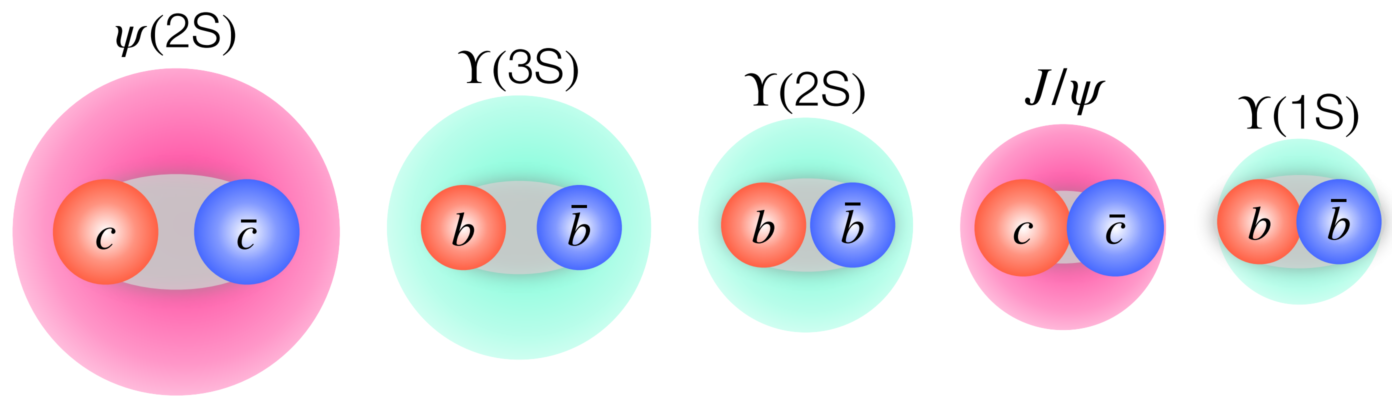


Sequential melting of Upsilon(nS)



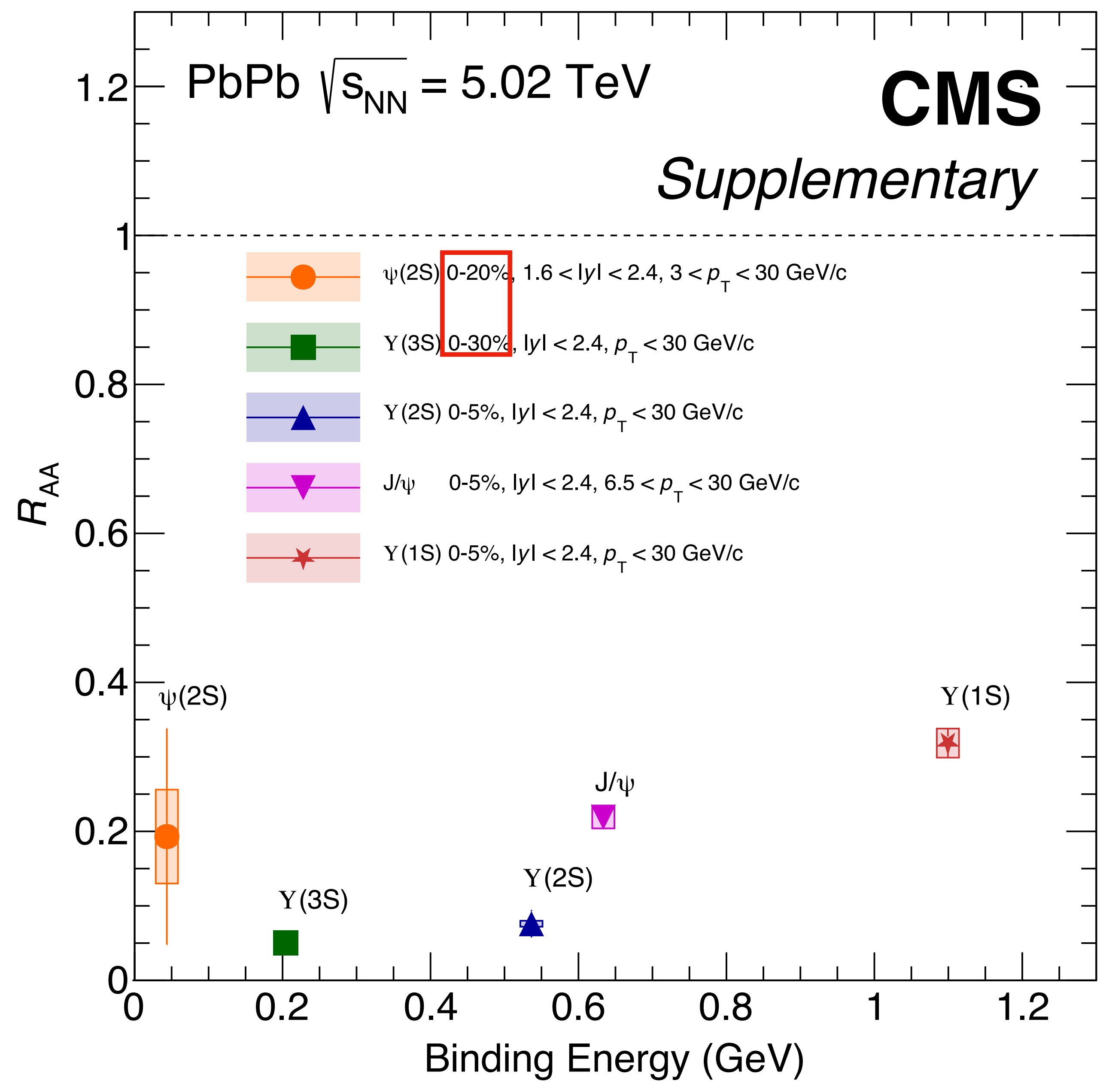
Quarkonium binding energy vs. R_{AA}

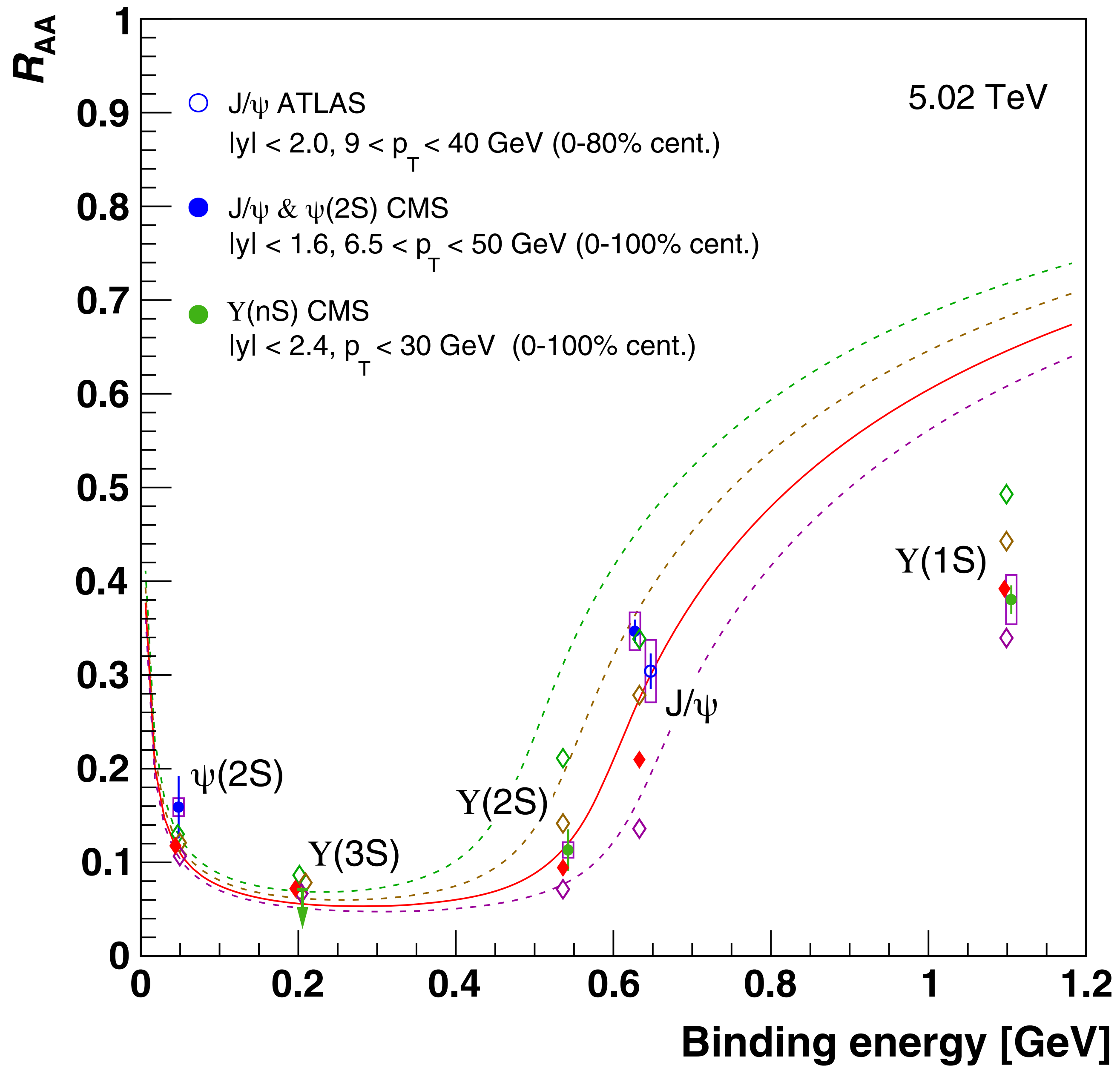
CMS, arXiv:2303.17026, submitted to PRL
EPJC 78 (2018) 731

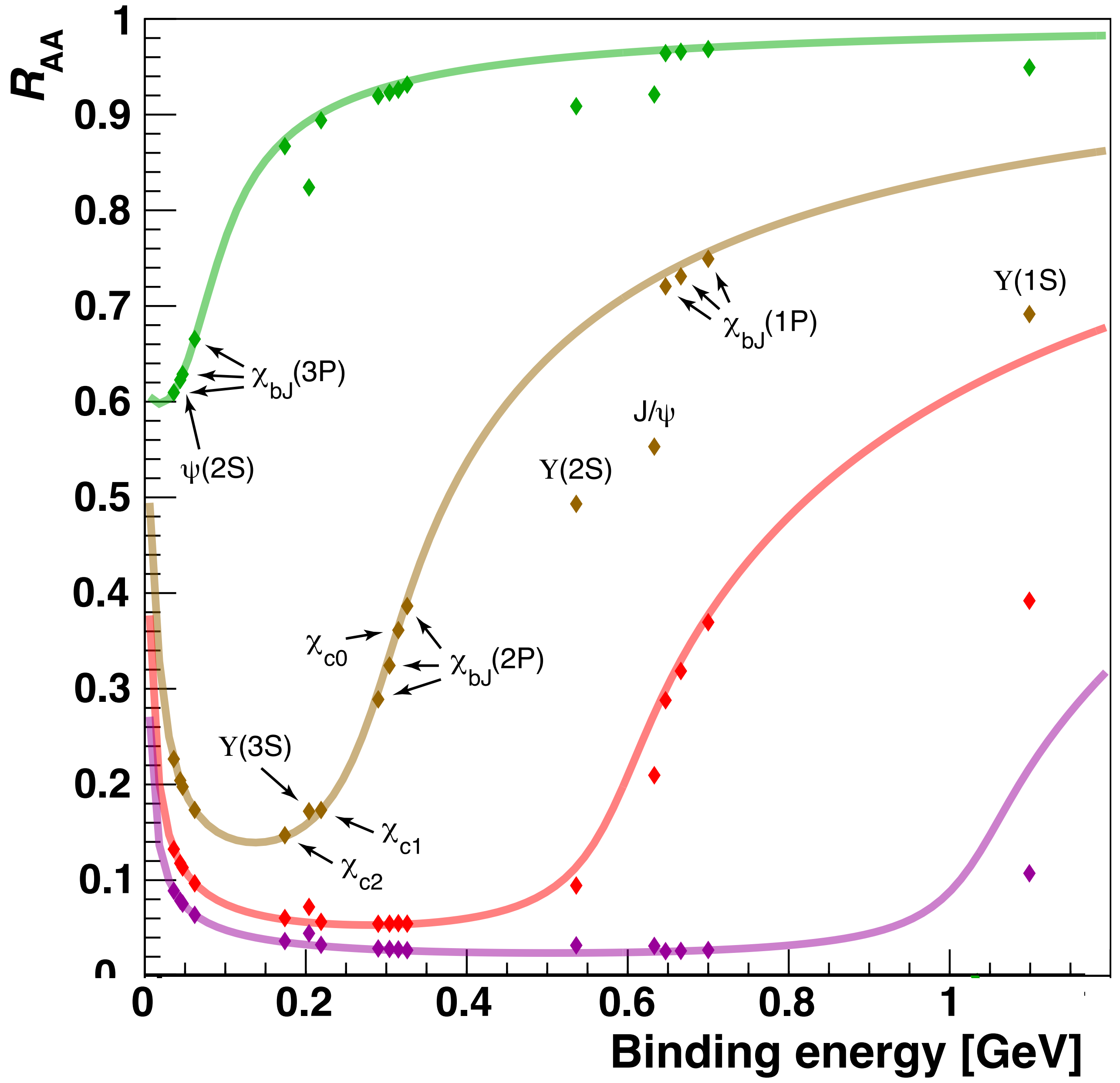


$$f_{\mathrm{pp}}^{\psi/\Upsilon}(E_{\mathrm{b}}) \equiv \left(\frac{\sigma^{\mathrm{dir}}(\psi/\Upsilon)}{\sigma(2m_Q)}\right)_{\mathrm{pp}} = \left(\frac{E_{\mathrm{b}}}{E_0}\right)^{\delta}$$

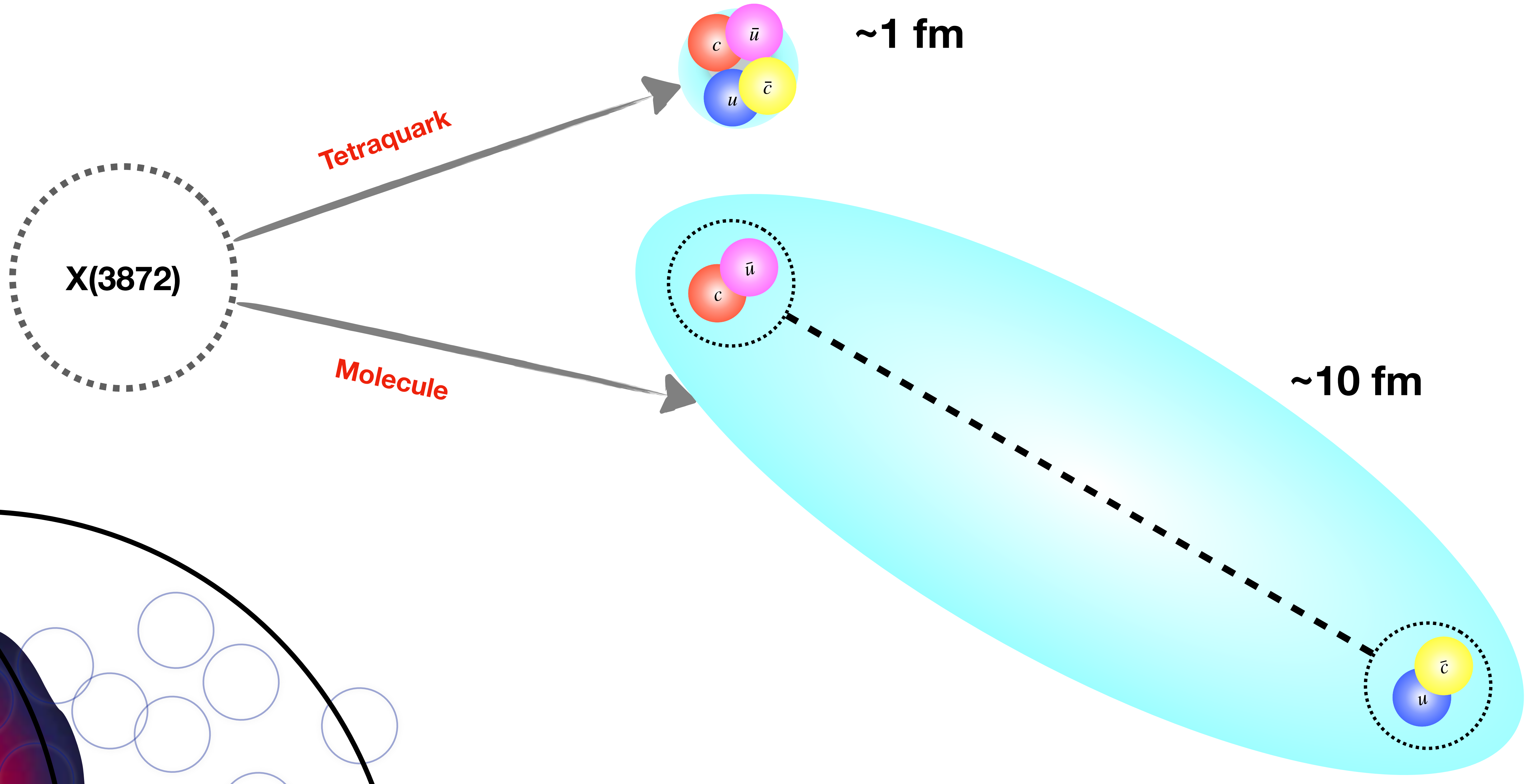
$$f_{\mathrm{PbPb}}^{\psi/\Upsilon}(E_{\mathrm{b}},\epsilon) \equiv \left(\frac{\sigma^{\mathrm{dir}}(\psi/\Upsilon)}{\sigma(2m_Q)}\right)_{\mathrm{PbPb}} = \left(\frac{E_{\mathrm{b}}-\epsilon}{E_0}\right)^{\delta}$$

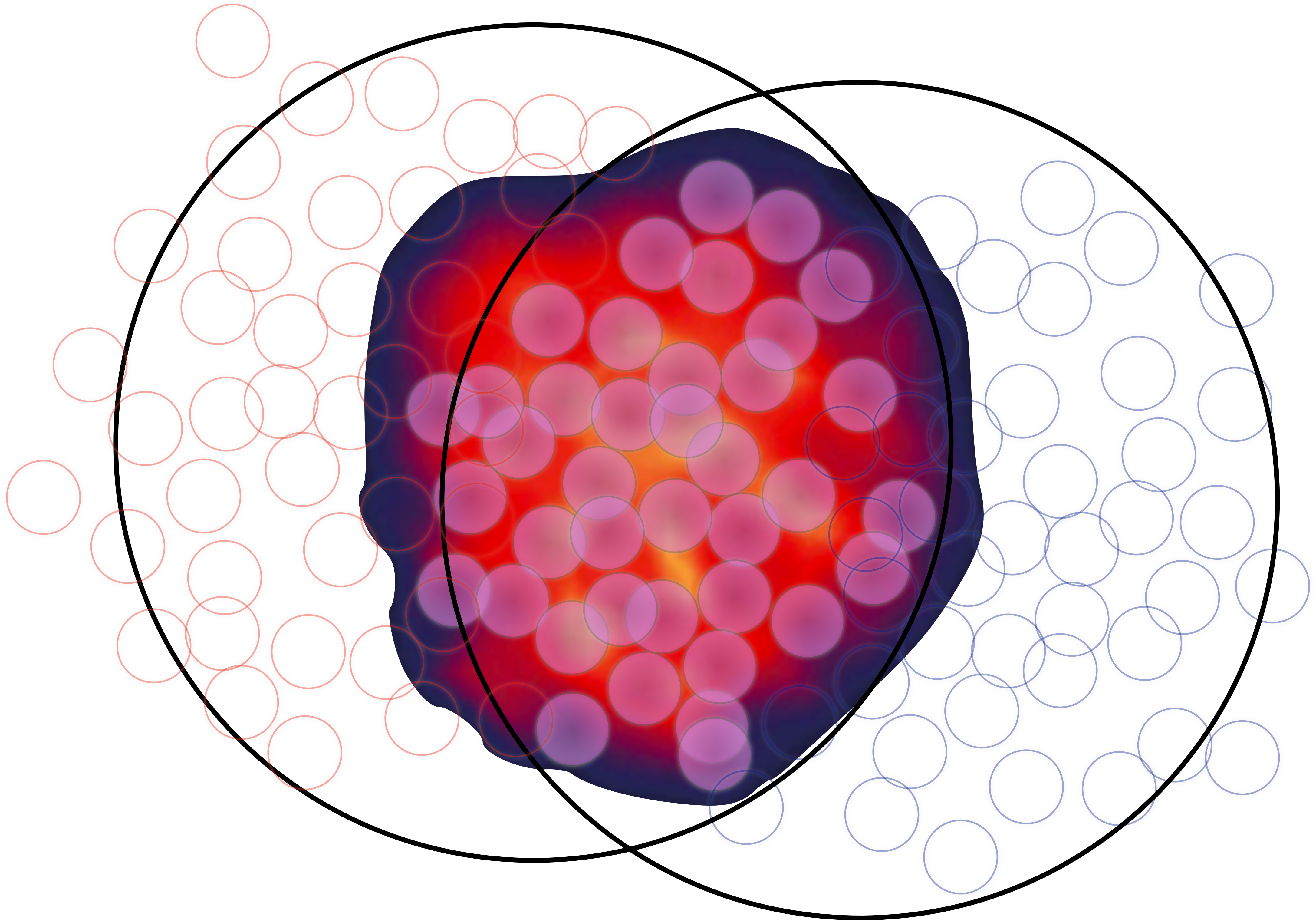






Charmonium-like exotic hadron — X(3872)

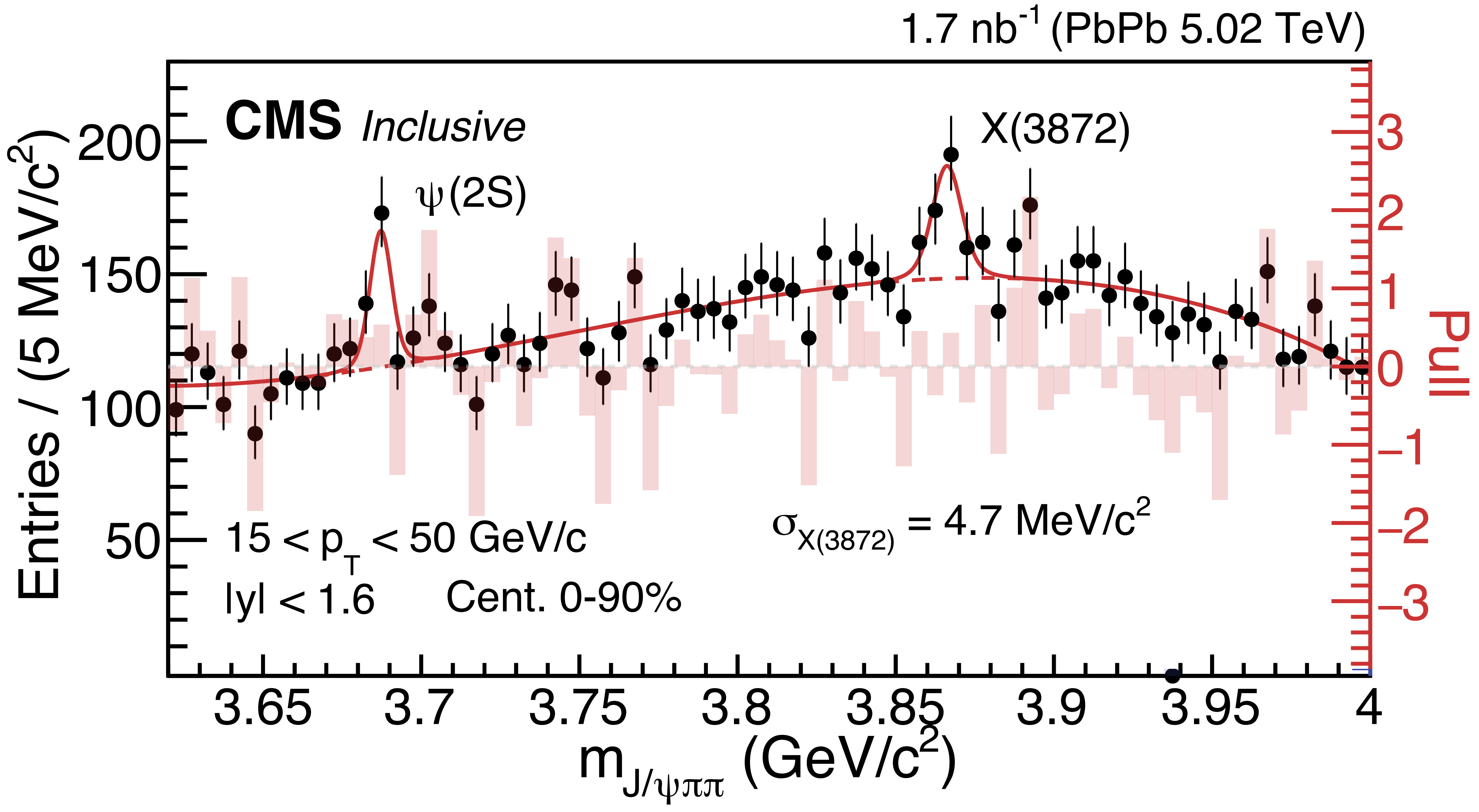


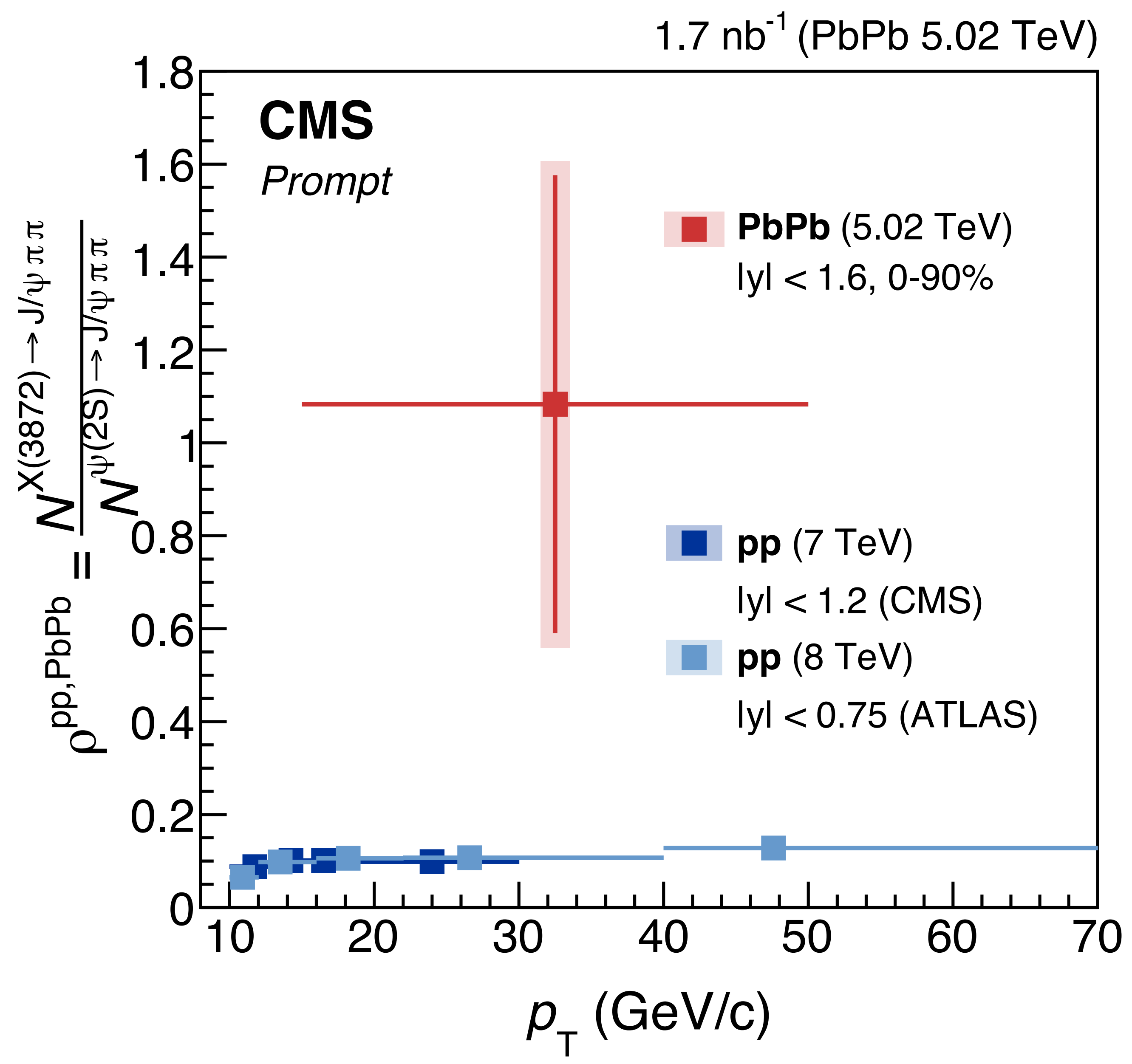


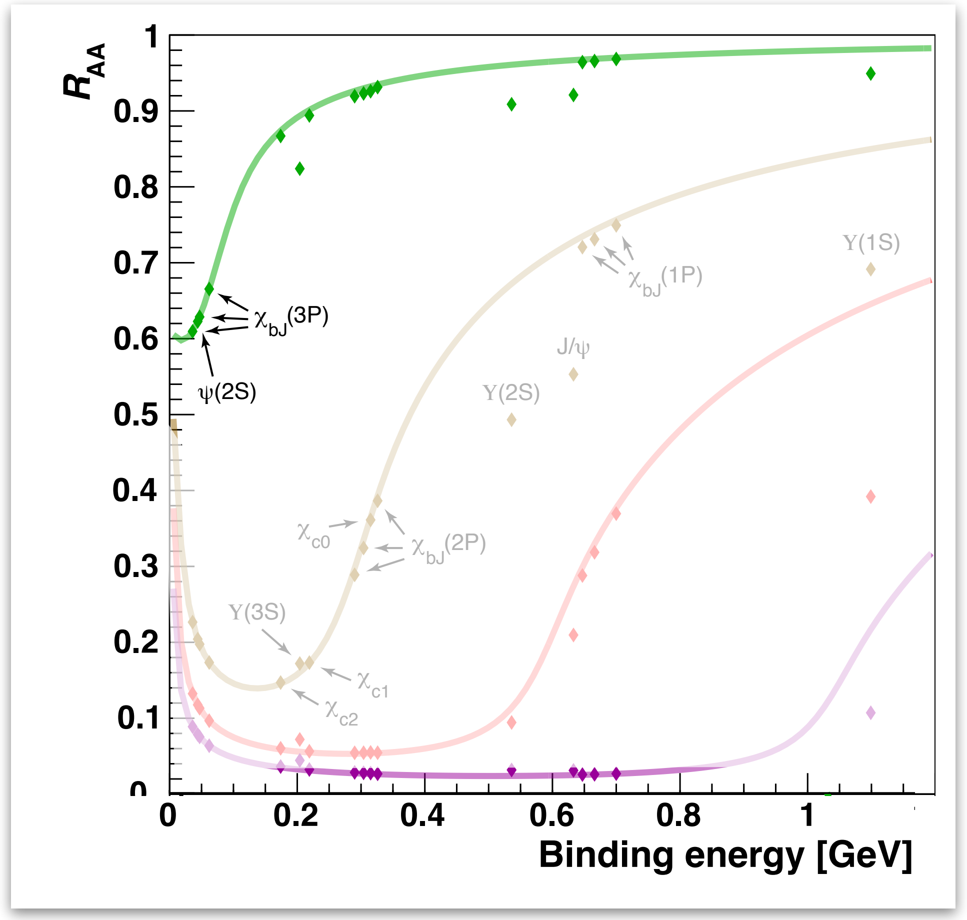
- X(3872), aka $\chi_{c1}(3872)$, is the first and most-studied charmonium-like exotic hadron
- Still with unknown structure and production mechanism:
  - Compact teraquark
  - Di-quark molecule
  - Charmonium-molecule mixture

X(3872) existence in HIC

CMS, PRL 128 (2022) 032001

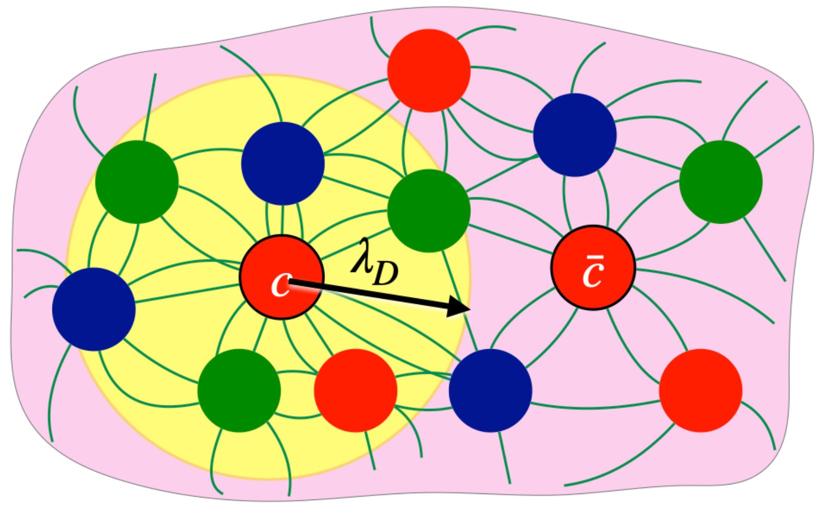




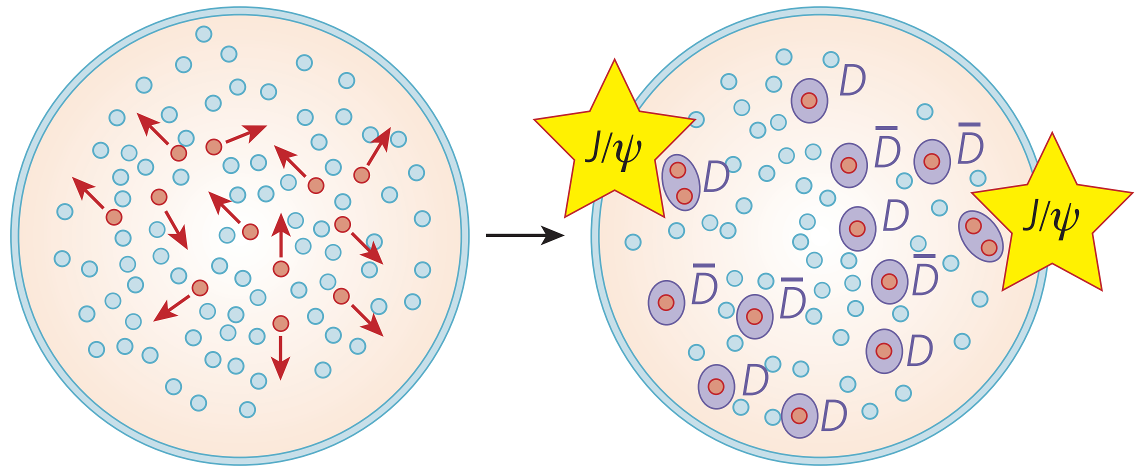


However color screening is not the only factor

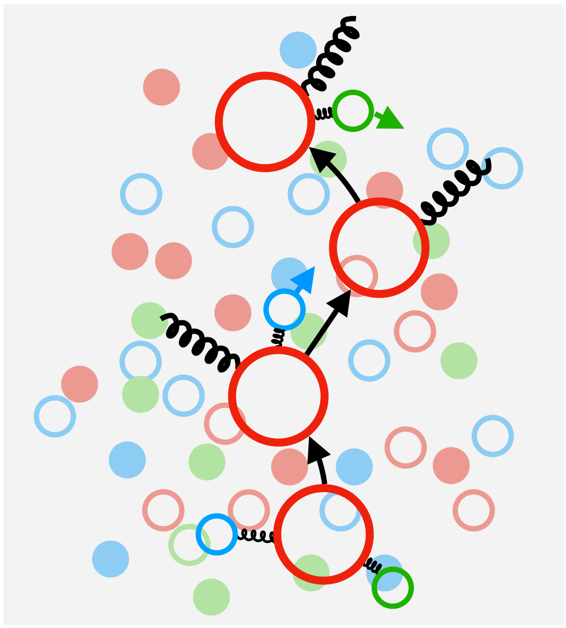
ATLAS, EPJC 78 (2018) 762



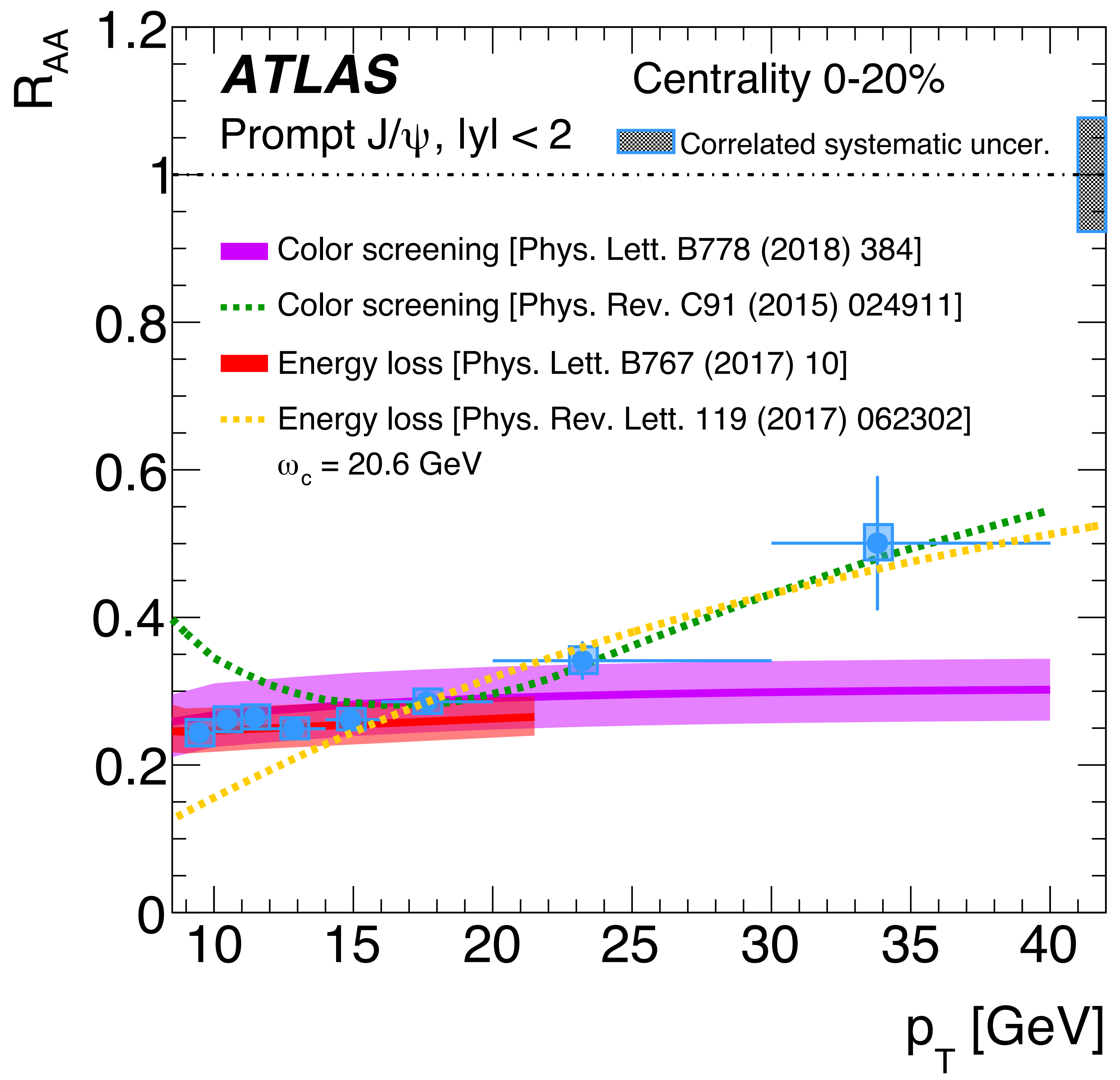
Color screening



Quark recombination



Energy loss



Other effects:

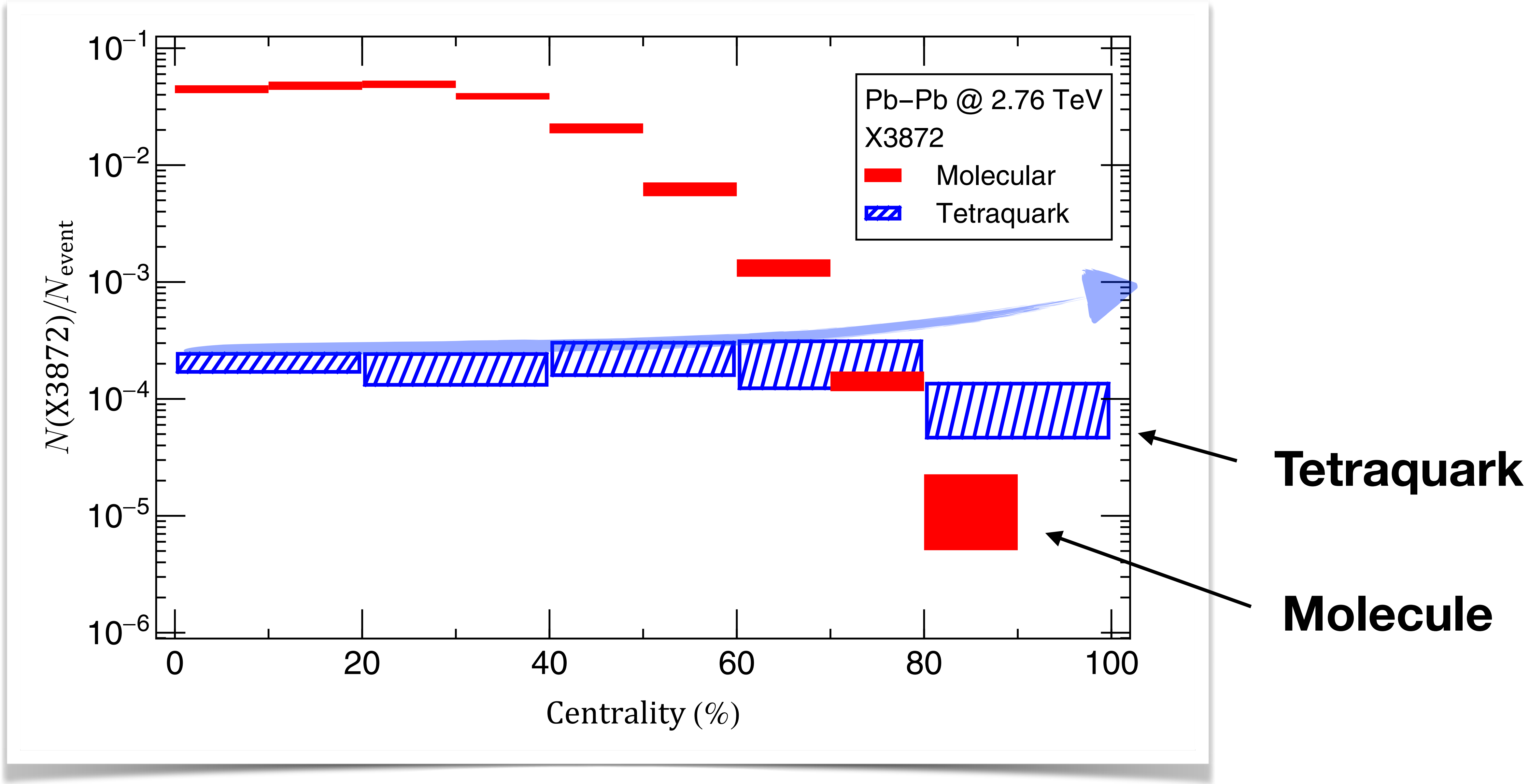
- Feed down contribution
- Quark recombination
- Parton energy loss

X(3872) in HIC — theoretical expectations

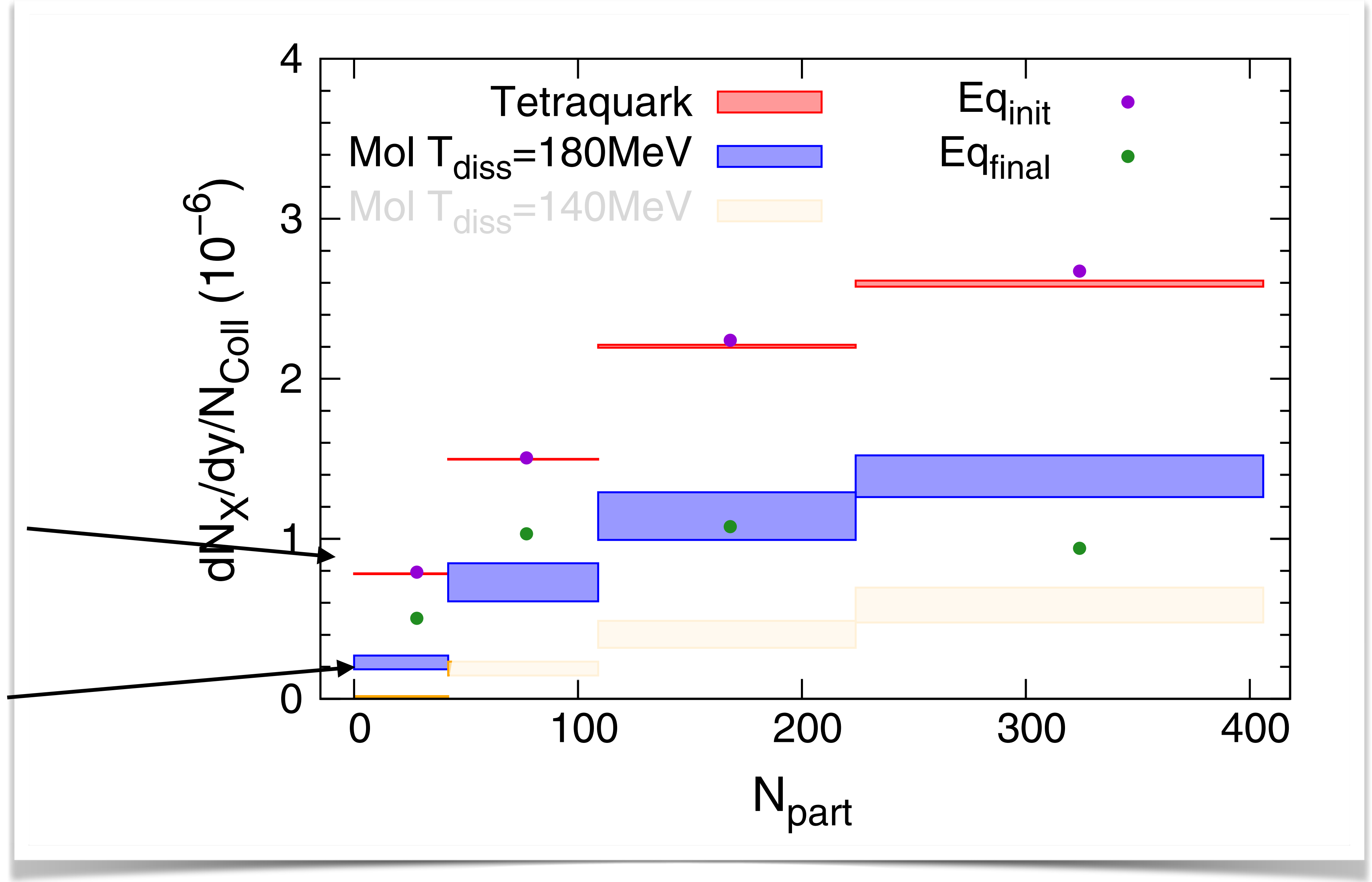
PRL 126(2021) 012301
EPJA 57 (2021) 122

Recombination in AMPT at hadronic stage

Rate controlled by *D* meson rates



Consider transport in medium at hadronic stage



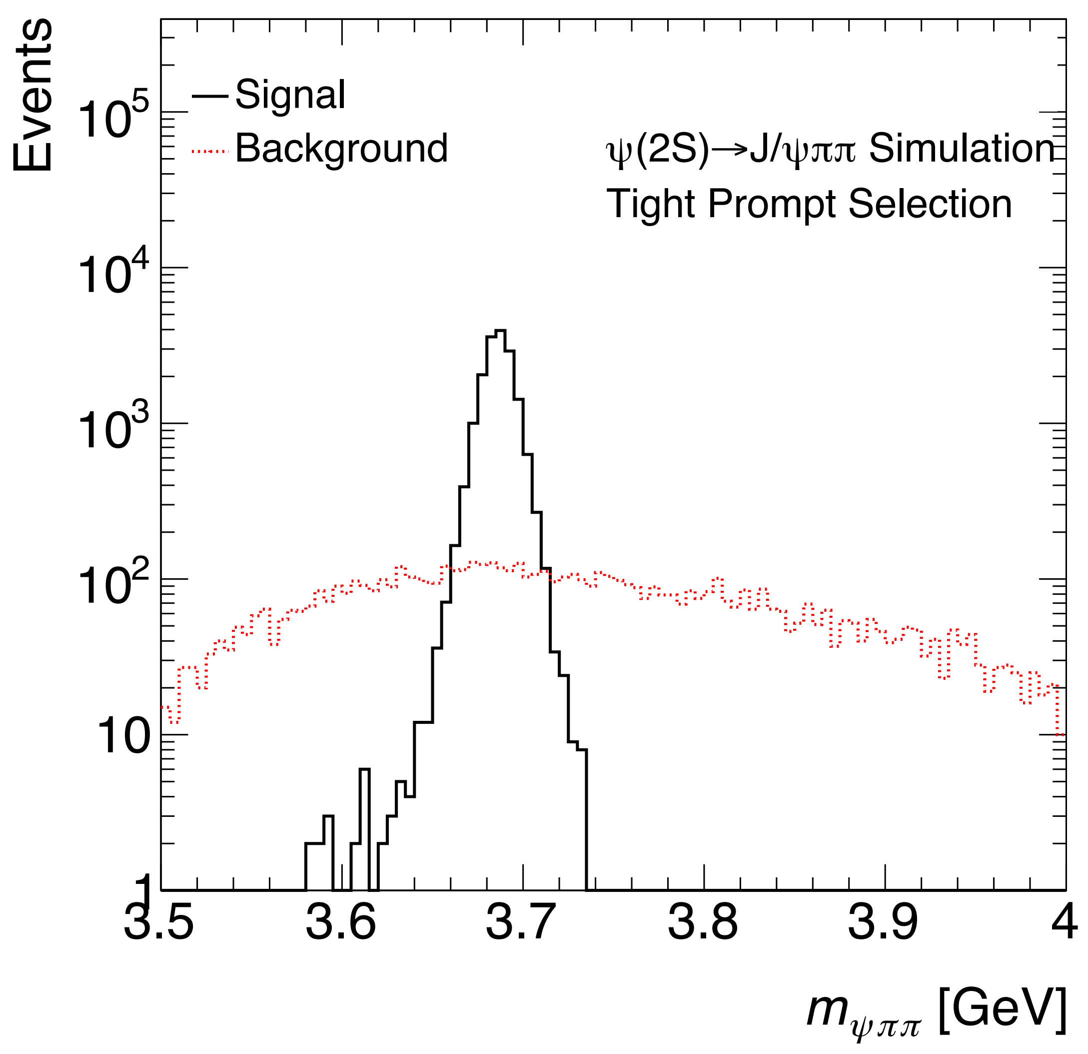
- Centrality dependence of X(3872) production could provide critical input

X(3872) in HIC — experimental challenges

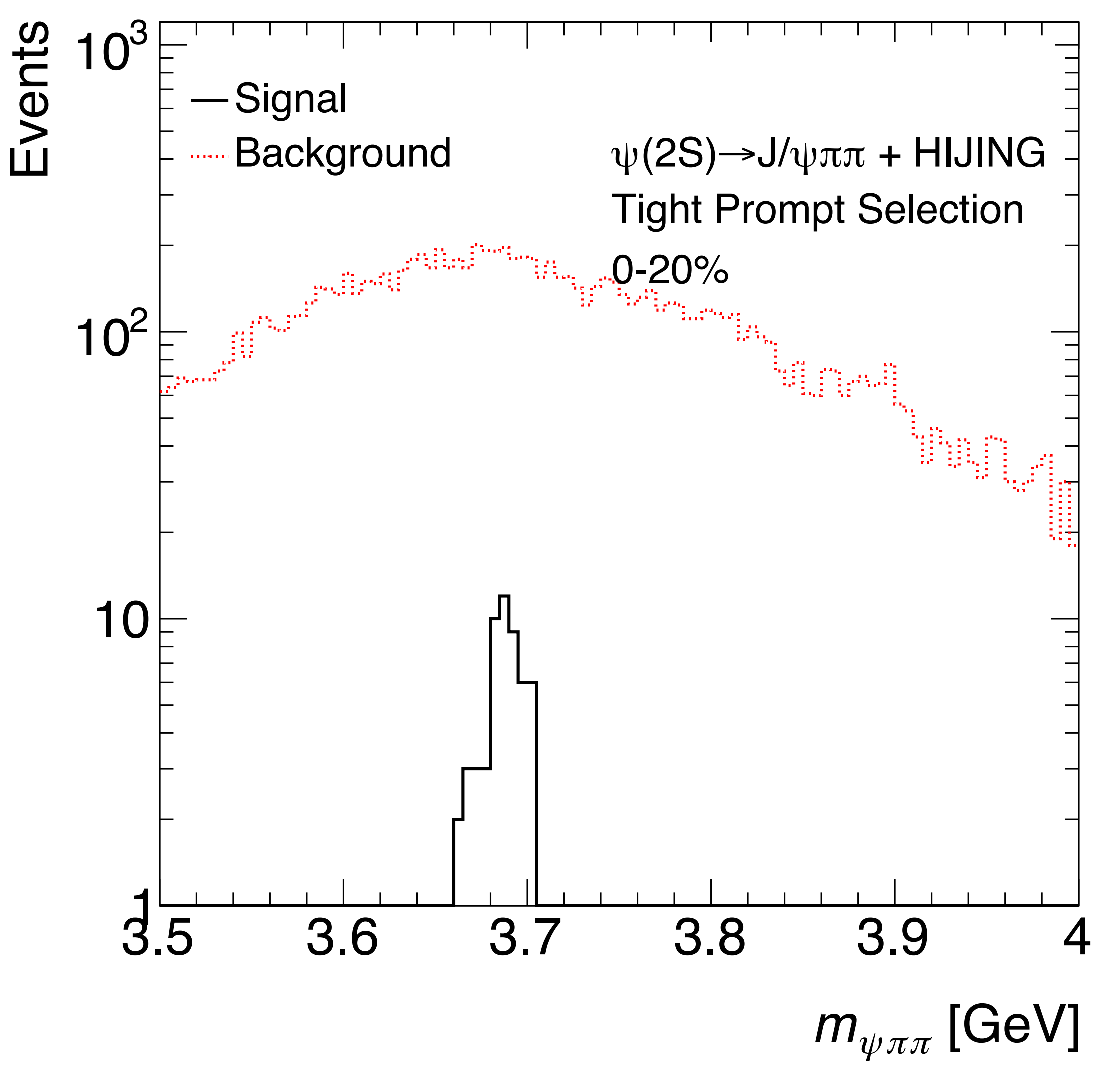
$X(3872) \to J/\psi\pi\pi$ major background:

- Combinatorial from randomly distributed pions produced from the same vertex!

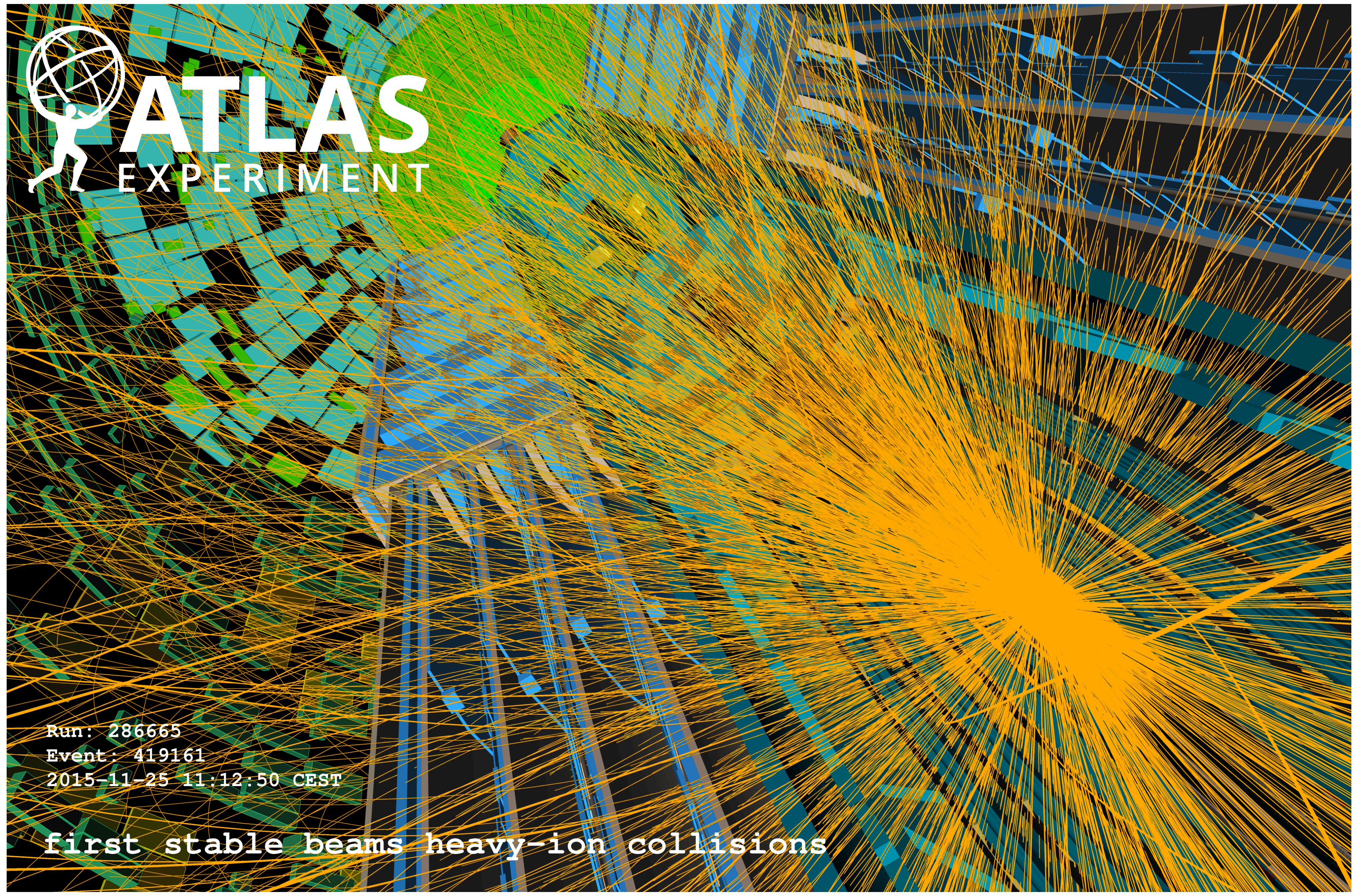
Every true J/ψ can form ~20 $\psi(2S) \to J/\psi\pi\pi$ candidates passing realistic selections



Pythia8



Pythia8 + HIJING (heavy ion event generator)



Summary

Heavy ion physics program is rich and growing

Heavy ion collision/methodology is useful for general high energy physics:

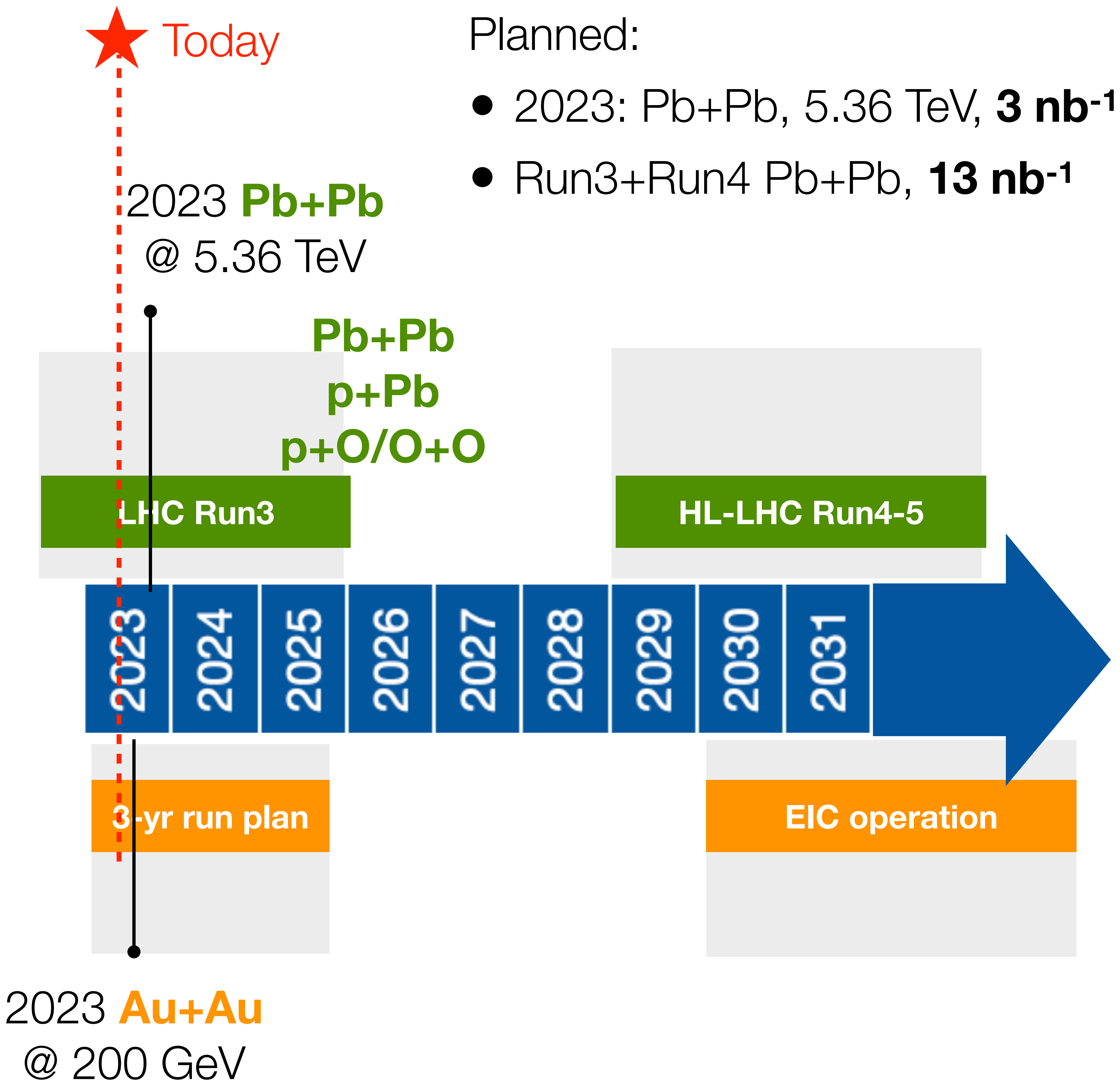
- Long-range azimuthal correlation in hadronic collisions (QGP formation, hadron structure)
- Nature of exotic hadrons
- UPC as photo-nuclear, gamma-gamma interaction sources
- Nuclear structure

Integrated luminosities (ATLAS)

- 2015: Pb+Pb, 5.02 TeV, **0.5 nb^{-1}**
- 2018: Pb+Pb, 5.02 TeV, **1.8 nb^{-1}**

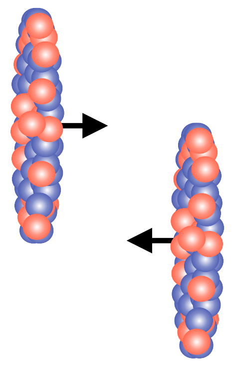
Planned:

- 2023: Pb+Pb, 5.36 TeV, **3 nb^{-1}**
- Run3+Run4 Pb+Pb, **13 nb^{-1}**

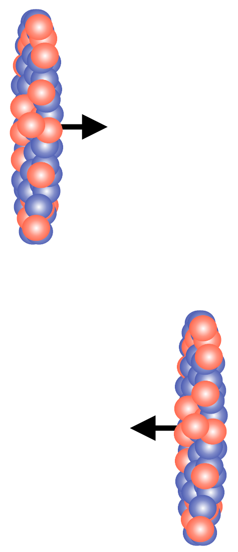


Backup slides

Heavy ion beam as gamma source



- $\gamma\gamma \rightarrow \gamma\gamma$
- $\gamma\gamma \rightarrow \tau\tau$ (τ g-2)
- $\gamma\gamma \rightarrow$ exotica
- Monopole search
- Graviton search

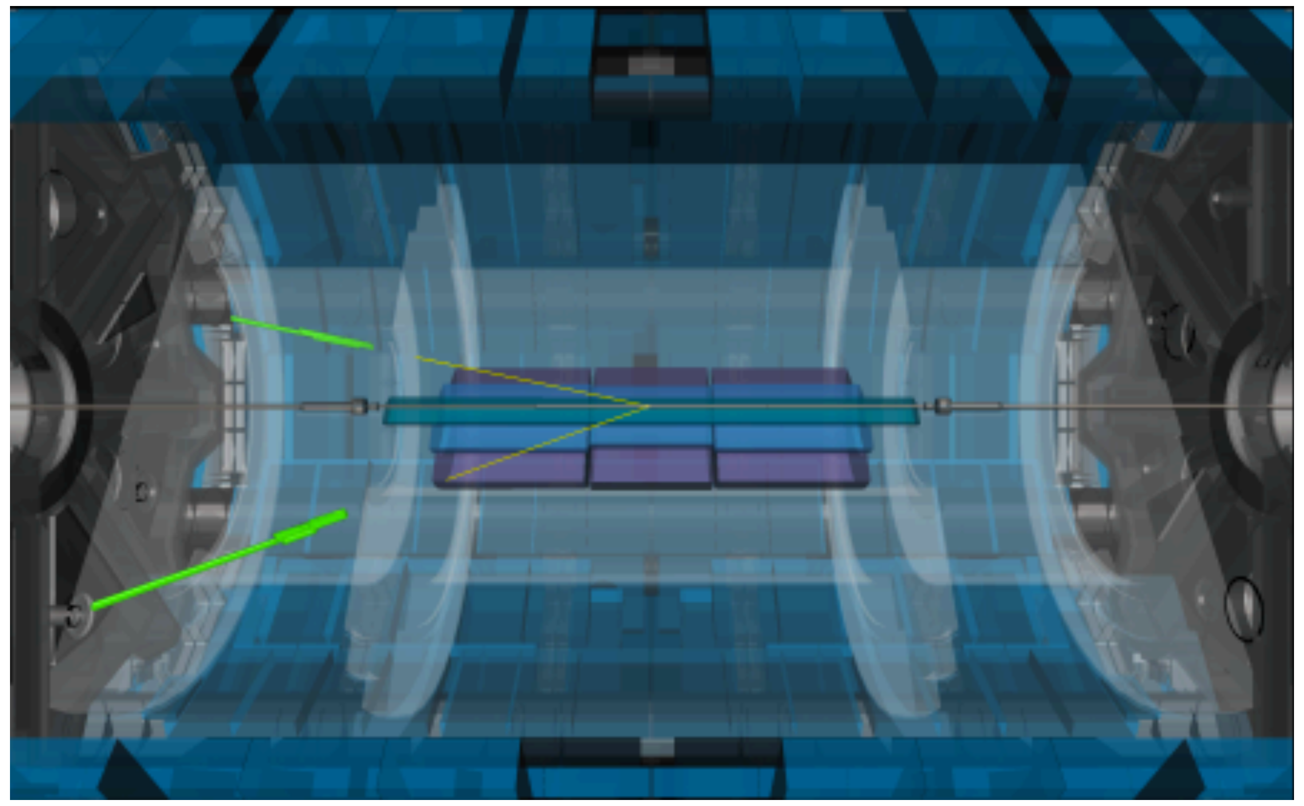


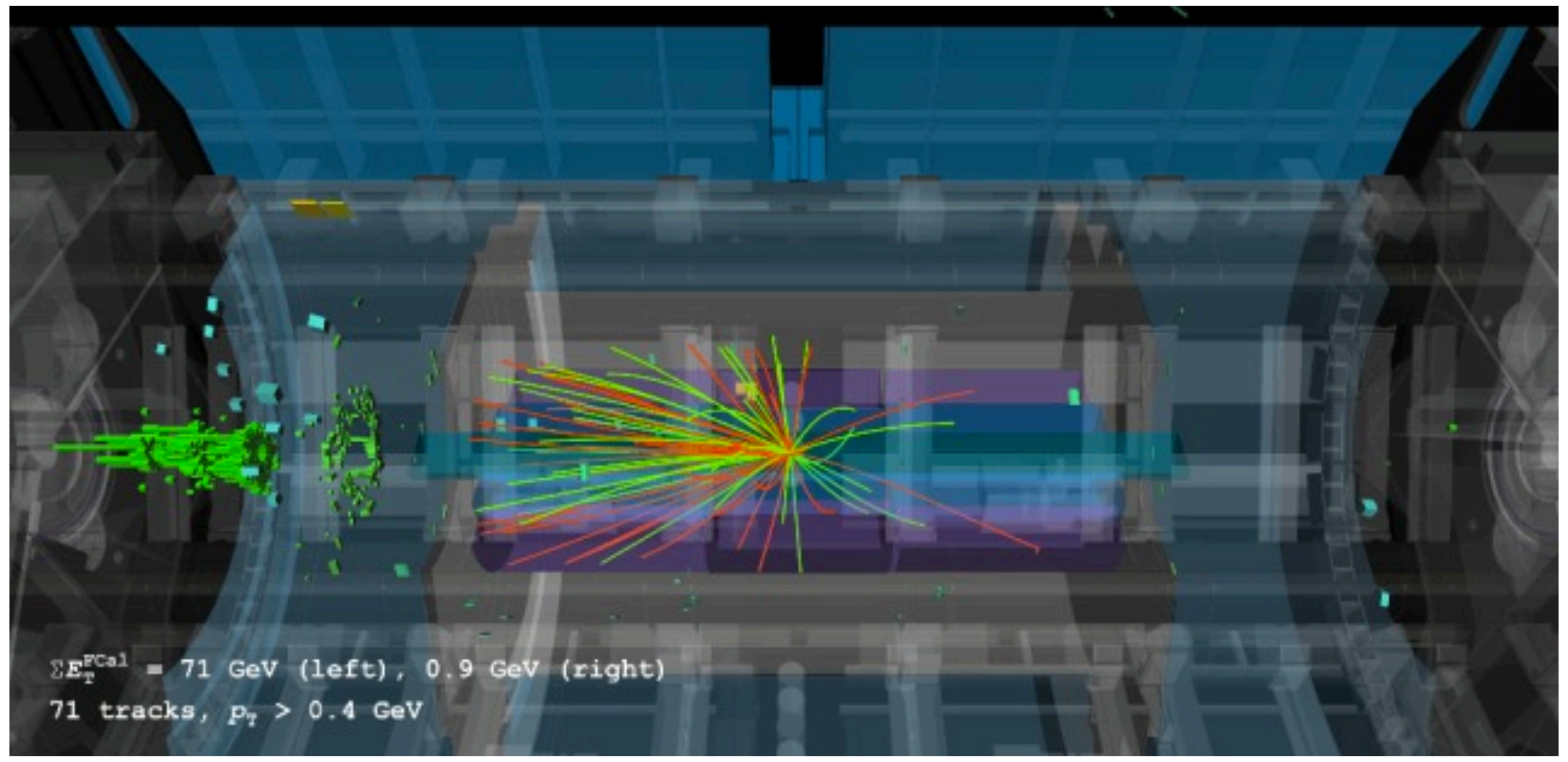
Cons:

- **Large photon flux**
- **Negligible pile-up**

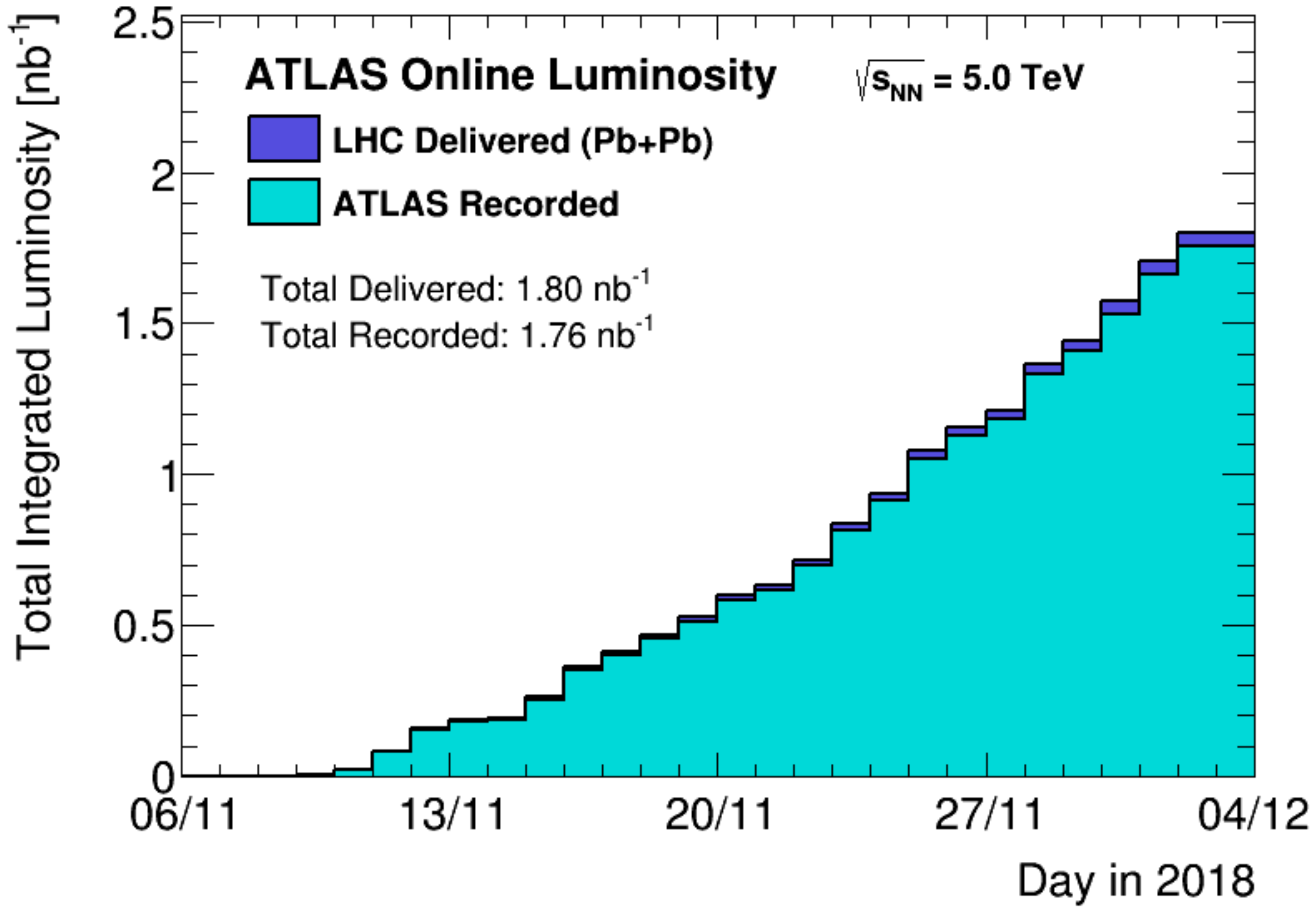
Pros:

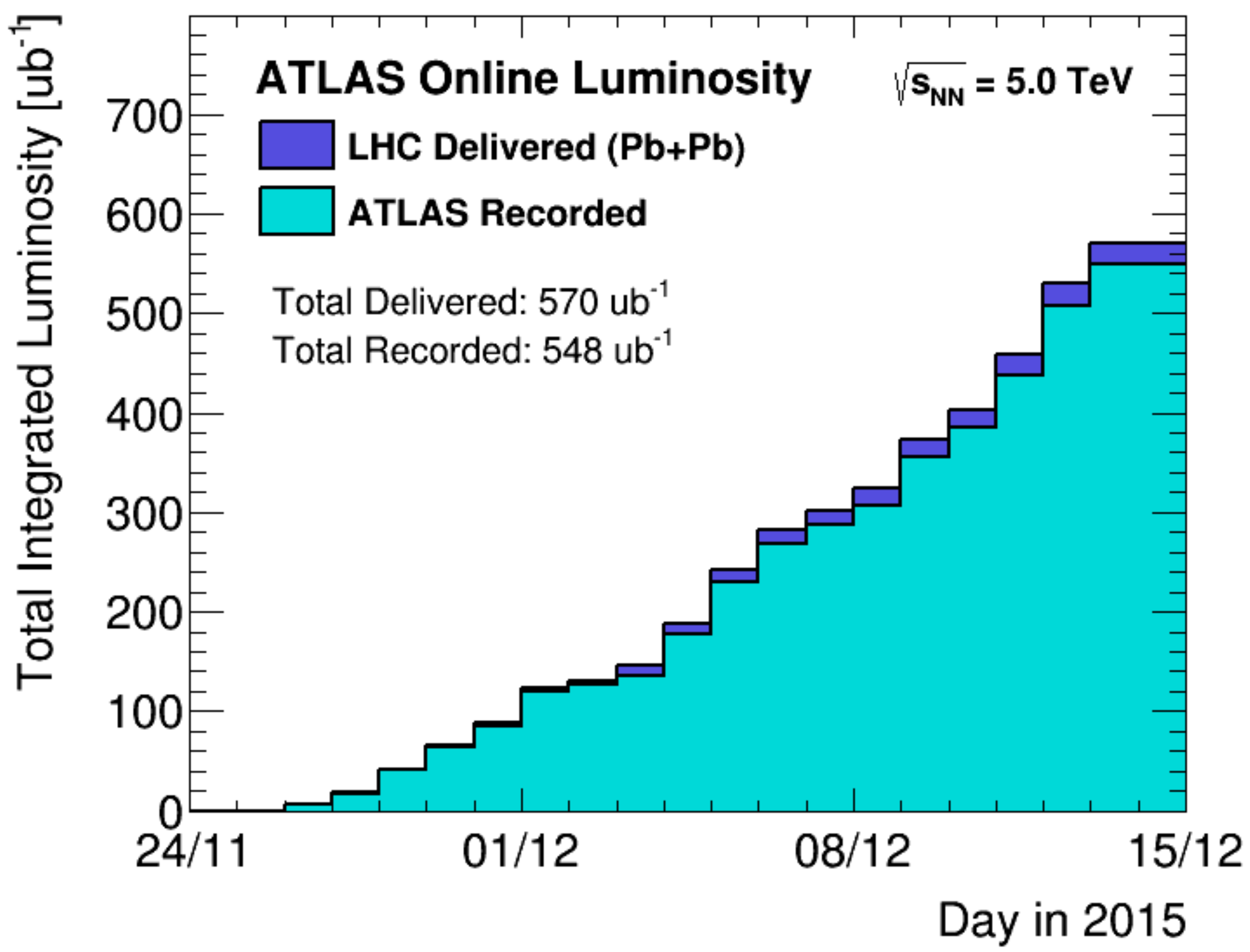
- **low luminosity**
- **No control on photon energy**





Recorded Pb+Pb luminosity at ATLAS





ATLAS detector