U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

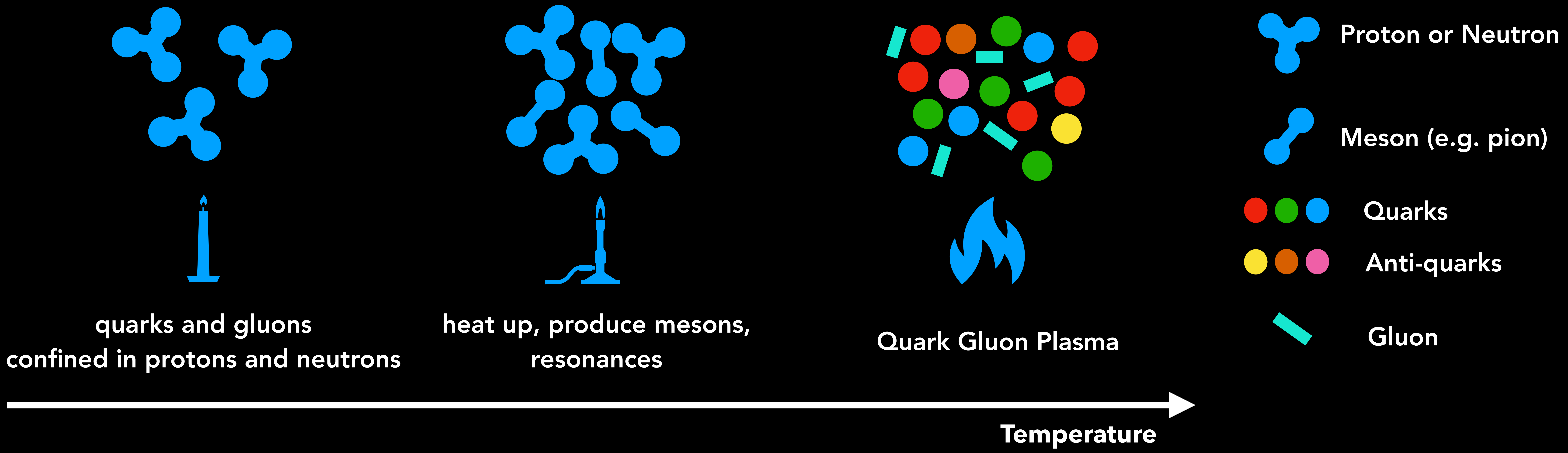
THE SMALLEST FLUID ON EARTH

Björn Schenke, Brookhaven National Laboratory

Theoretical Physics Colloquium
Arizona State University
July 15 2020

It would be intriguing to explore new phenomena by distributing high energy or high nuclear matter density over a relatively large volume. T.D. Lee (1974)

Heat up matter (or the vacuum) ...



“Our basic picture then is that matter at densities higher than nuclear consists of a quark soup.”

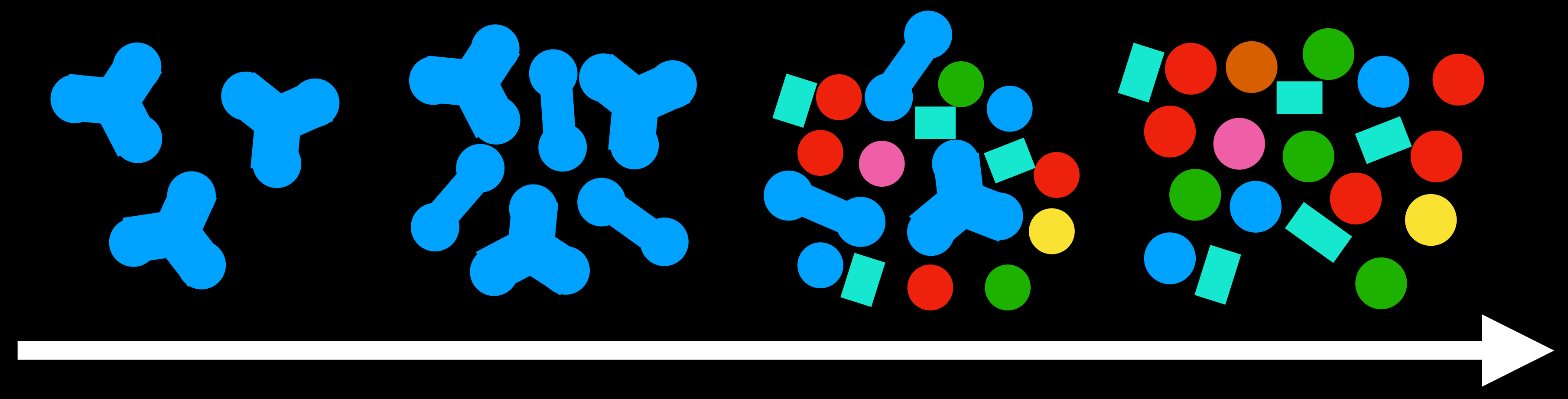
J.C. Collins, M.J. Perry, Phys.Rev.Lett. 34 (1975) 1353; Cabibbo, N. and Parisi, G., Phys. Lett. B 1975, 59, 67-69

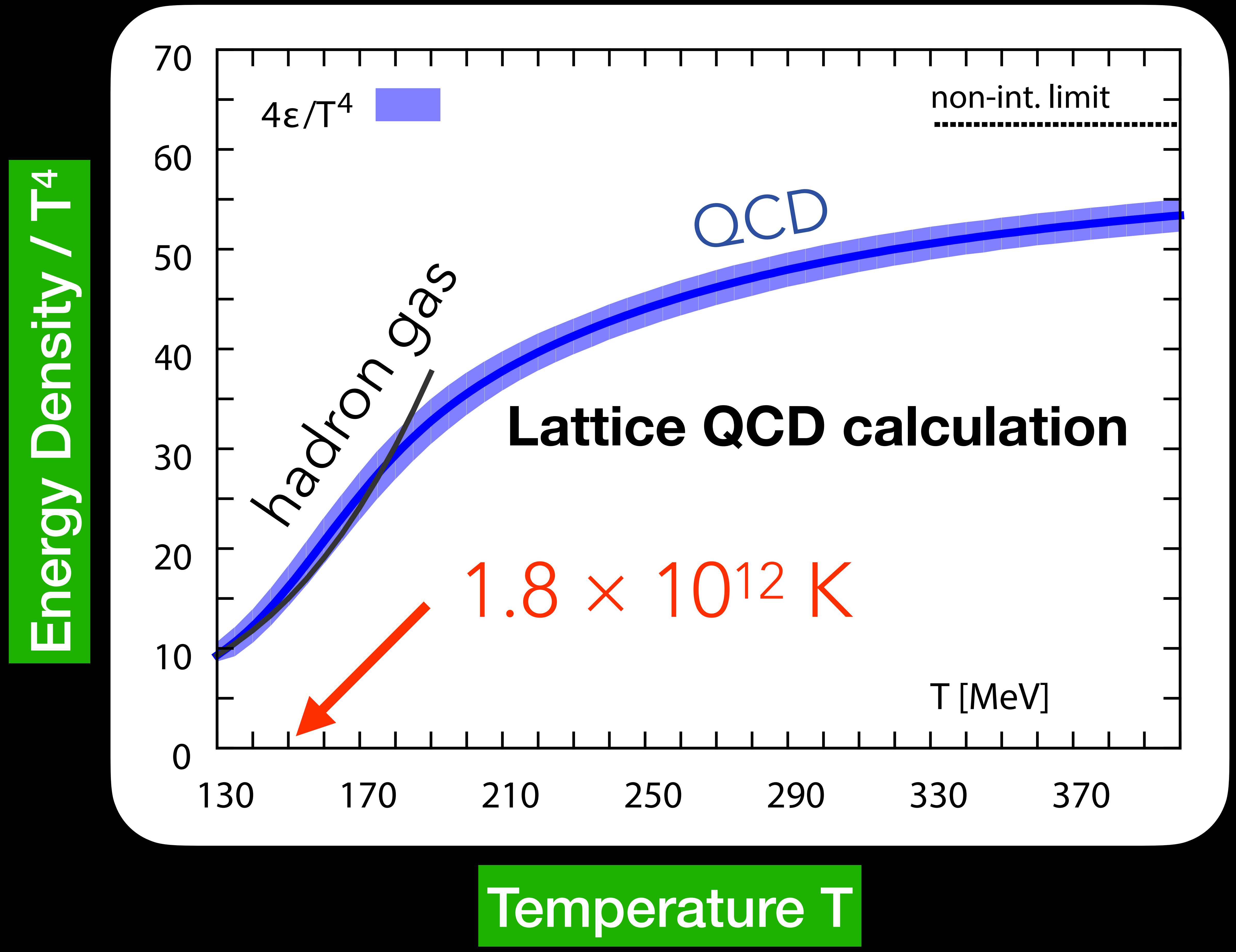
Argument based on asymptotic freedom, a feature of Quantum Chromo Dynamics (QCD)


2004

D. J. Gross and F. Wilczek, Phys. Rev. D 8, 3633 (1973), and 9, 980 (1974)
H. D. Politzer, Phys. Rev. Lett. 90, 1346 (1973)

Quark Gluon Plasma: Quantitative results from QCD





QCD predicts crossover to system of liberated quarks and gluons at temperatures of

$T_c \simeq 156.5 \pm 1.5$ MeV $\simeq 1.8 \times 10^{12}$ K

HotQCD Collaboration: Phys.Lett. B795 (2019) 15-21
(chiral crossover temperature)

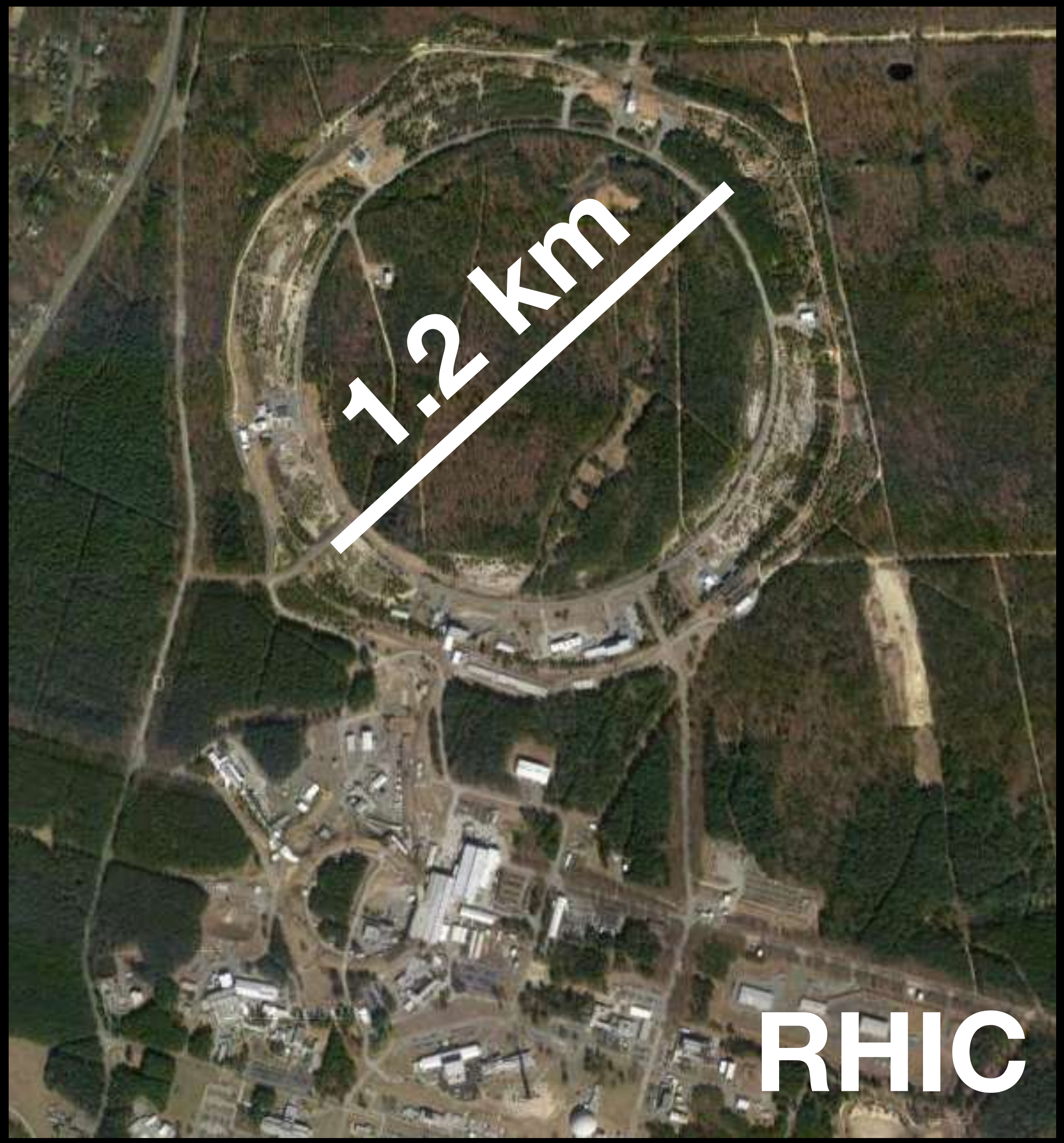
HotQCD Collaboration, Phys.Rev. D90 (2014) 094503
also see: Sz. Borsányi et al, JHEP 1208 (2012) 053

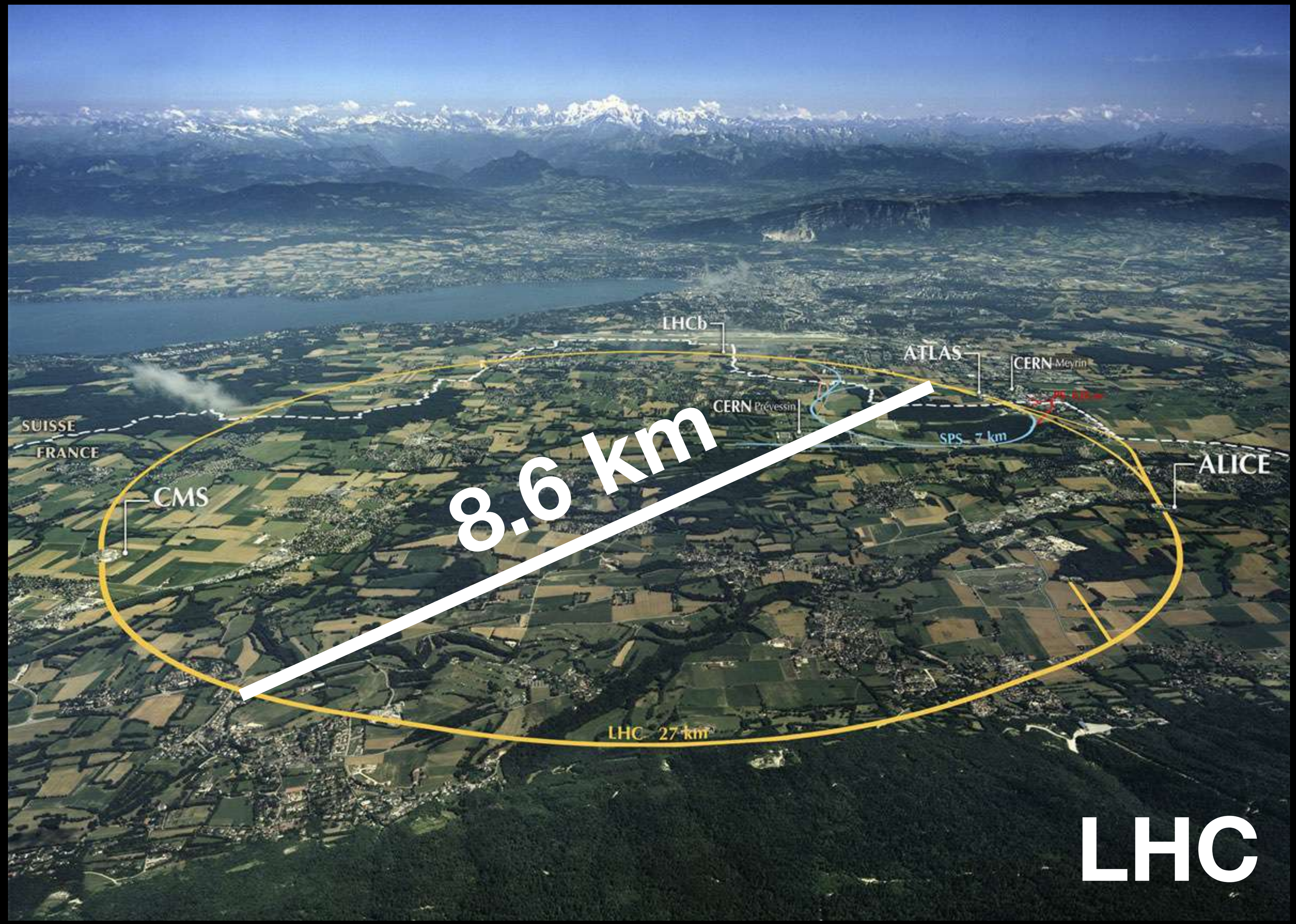
Can we create QGP in a lab? Yes: Heavy Ion Collisions

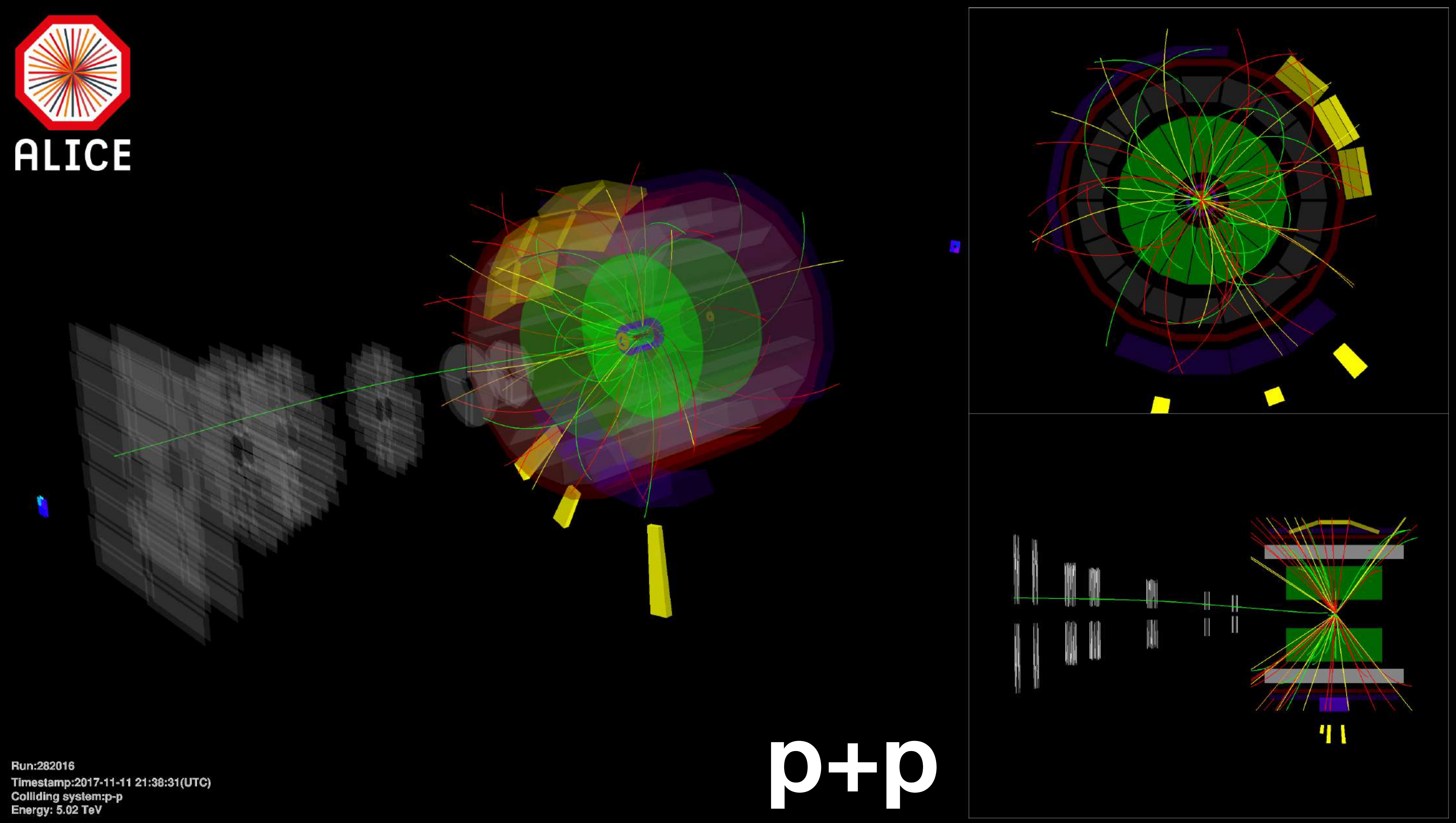
heavy nucleus

heavy nucleus

>99.9999% of the speed of light



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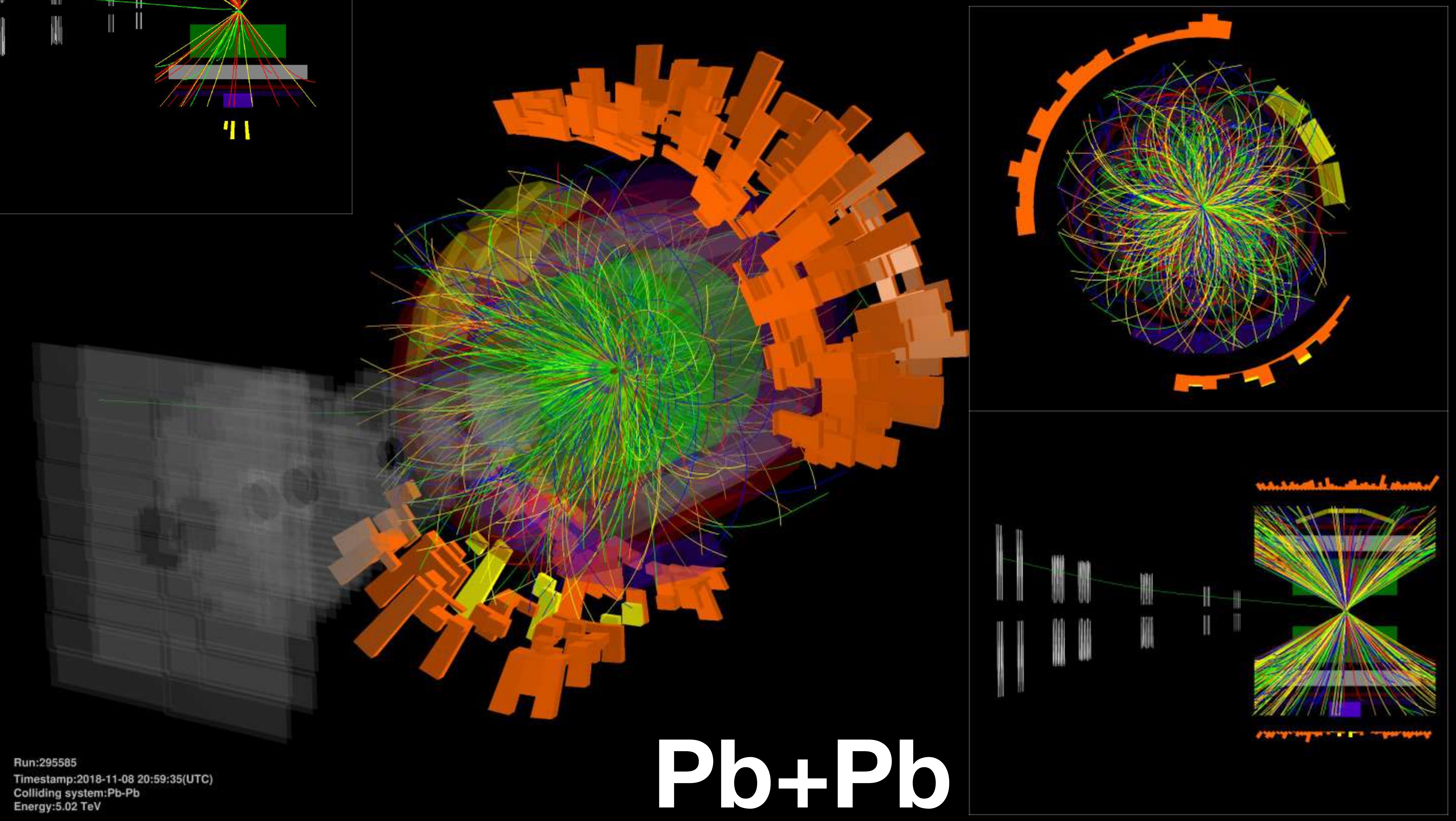
Colliding system:p-p
Energy: 5.02 TeV
p+p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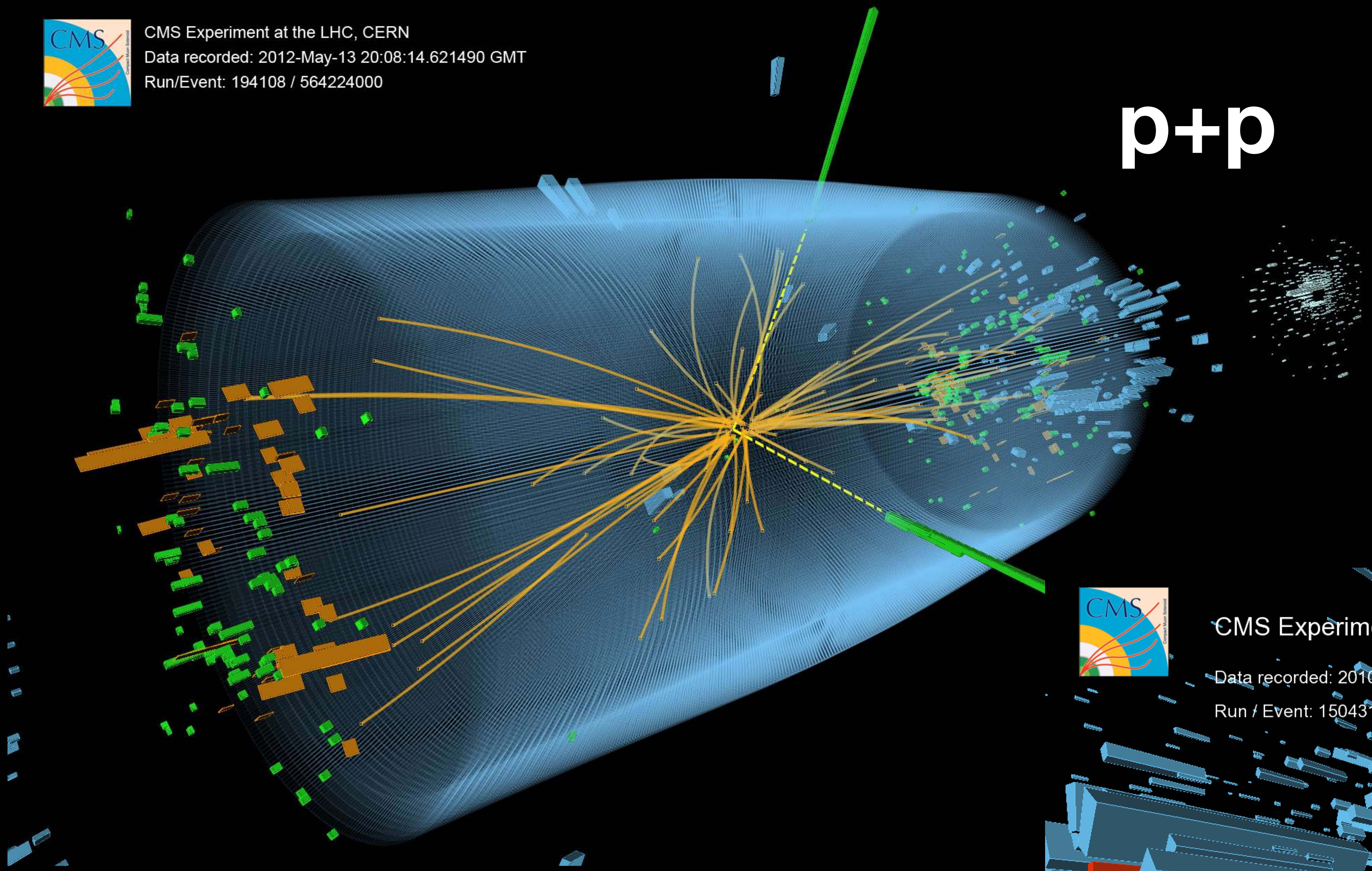
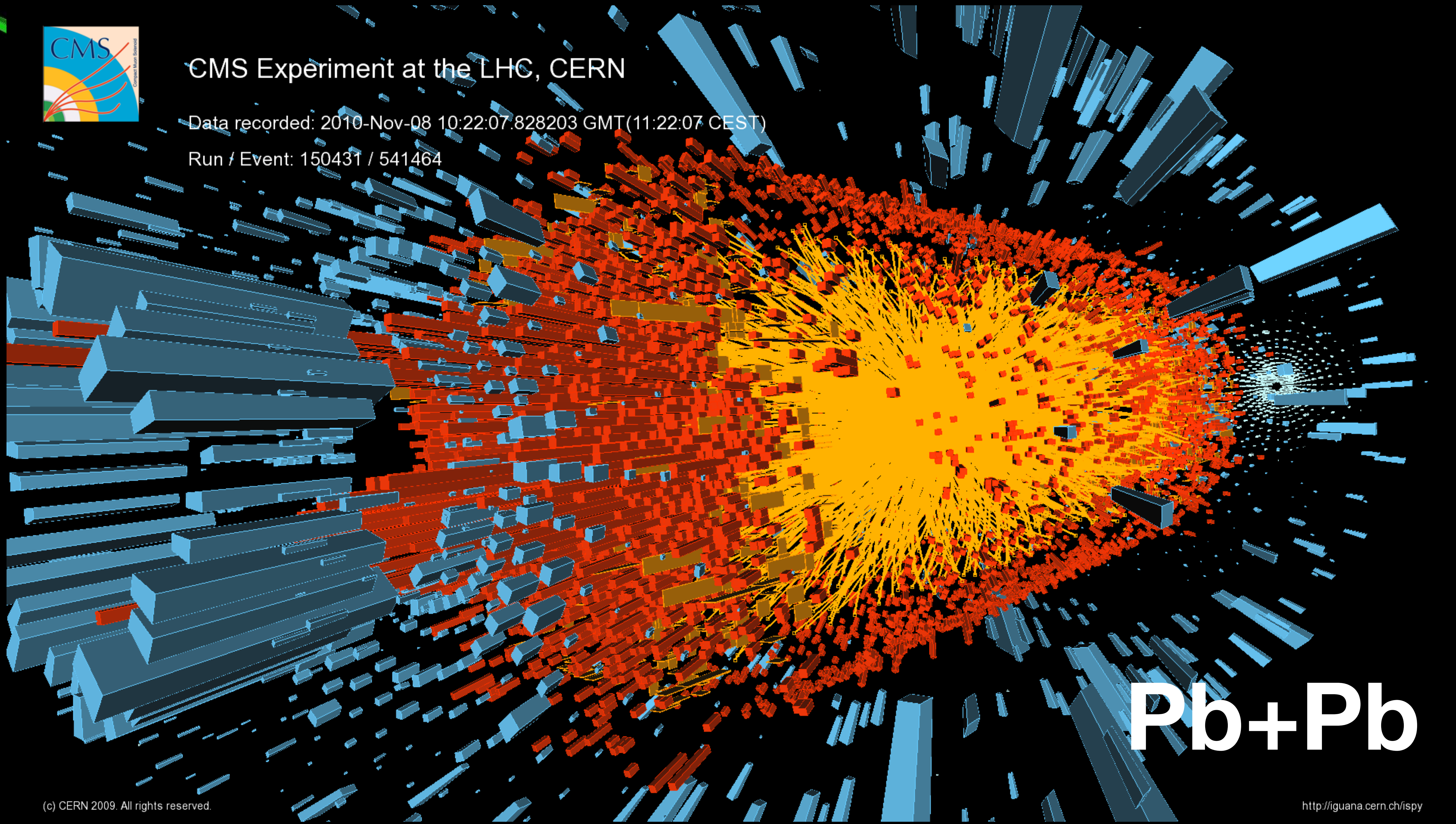
Colliding system:Pb-Pb
Energy:5.02 TeV
Pb+Pb


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

p+p


CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-08 10:22:07.828203 GMT(11:22:07 CEST)
Run / Event: 150431 / 541464
(c) CERN 2009. All rights reserved.
http://iguana.cern.ch/ispy

Pb+Pb

To the extremes...

Hot: $>10^{12}$ K $\gg$ 100,000 times hotter than the sun or a hydrogen bomb (10^7 to 10^8 K)

Small: 10^{-14} m $\ll$ 100,000,000,000 times smaller than a typical water droplet

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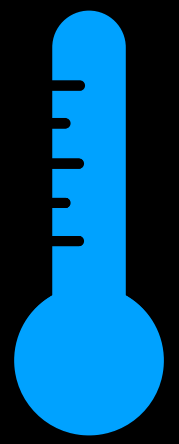
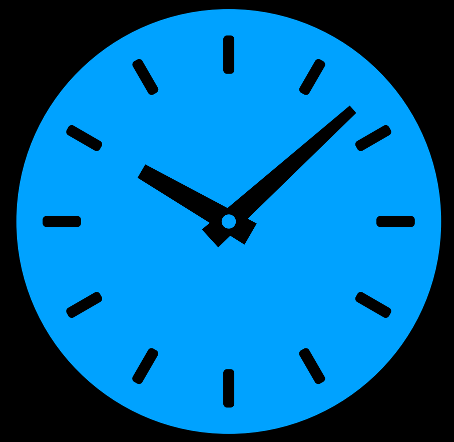
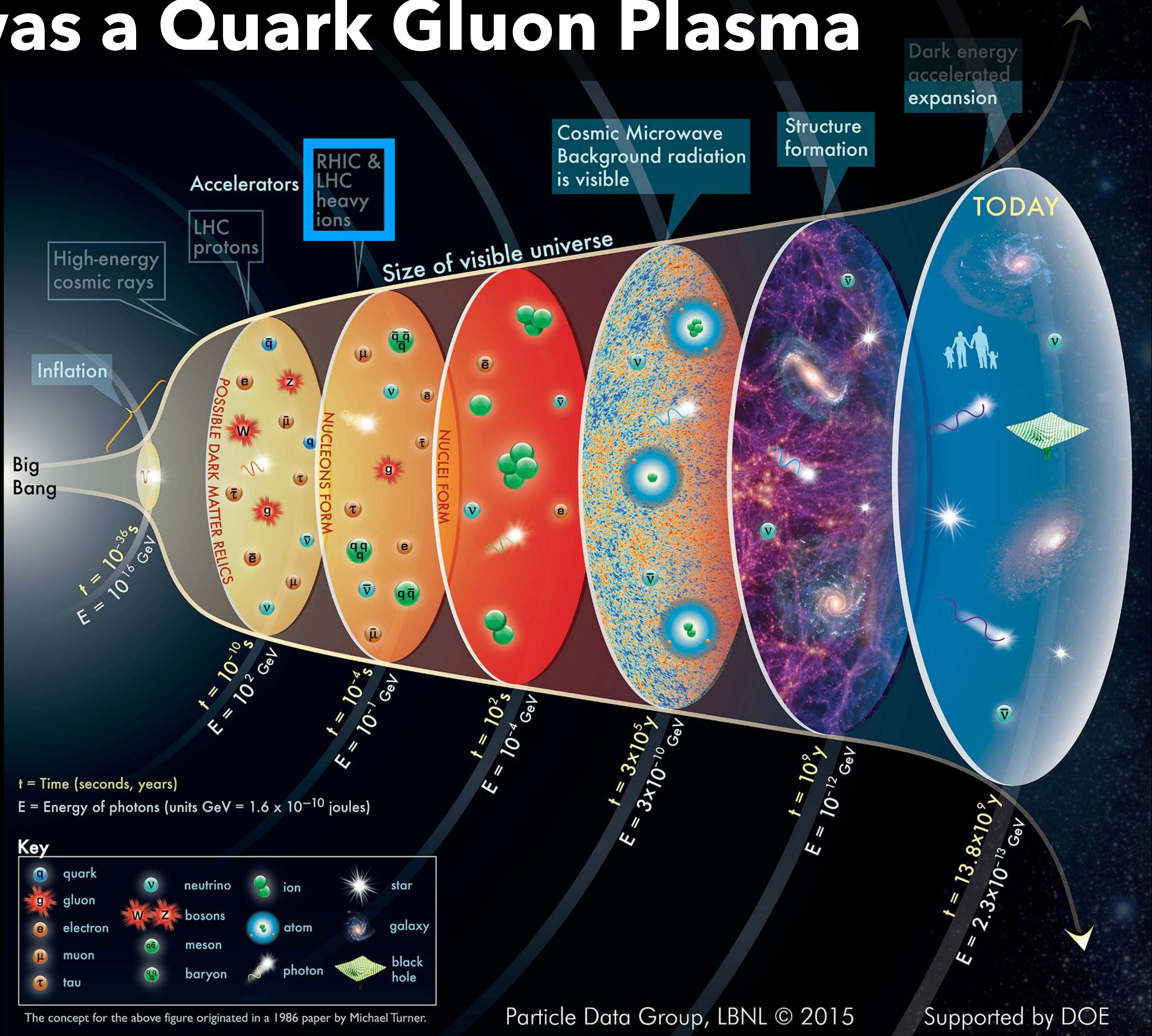
The entire universe was a Quark Gluon Plasma



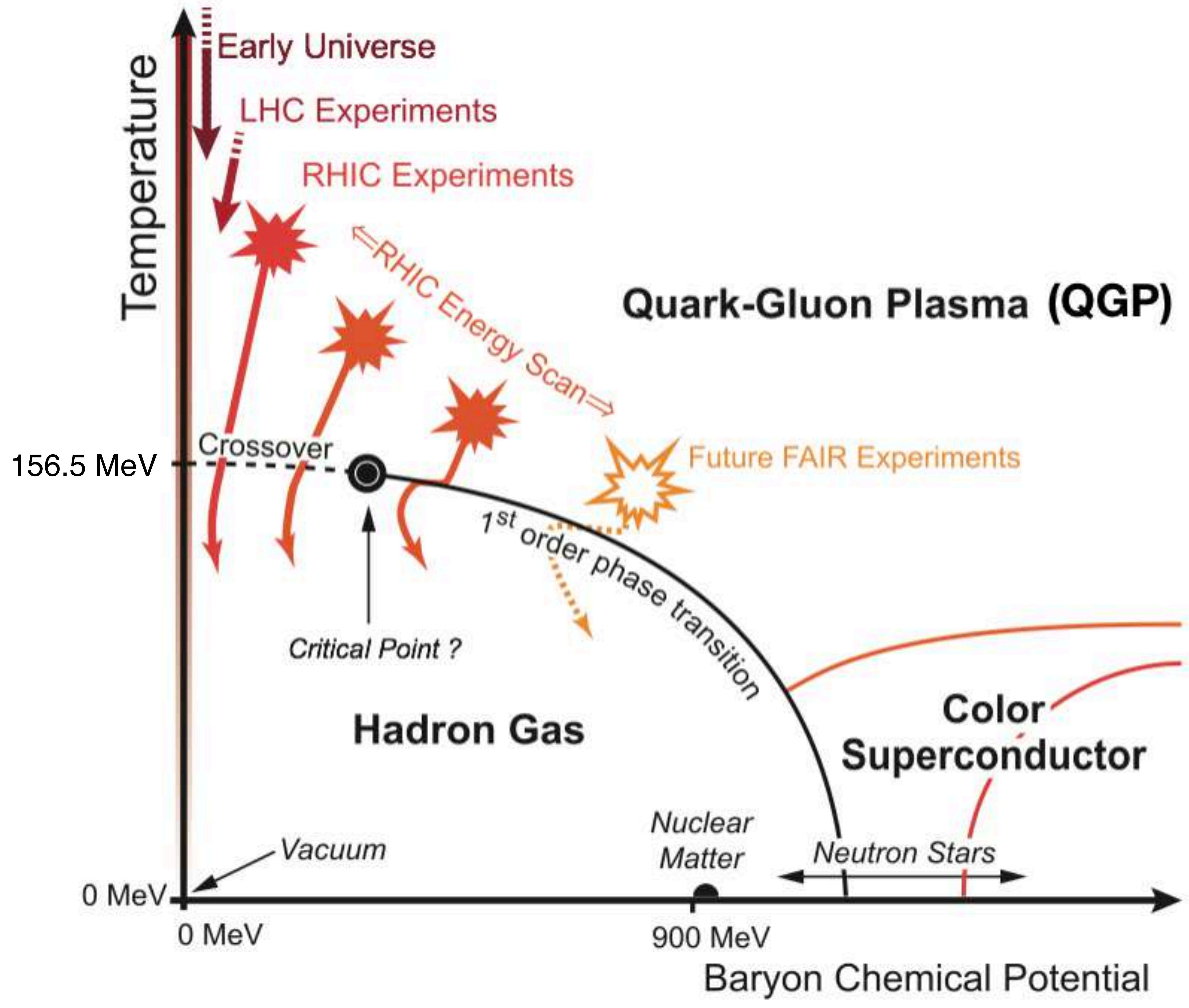
>10^{12} K



~10^{-6} s



Phase diagram of nuclear matter



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Perfect fluid

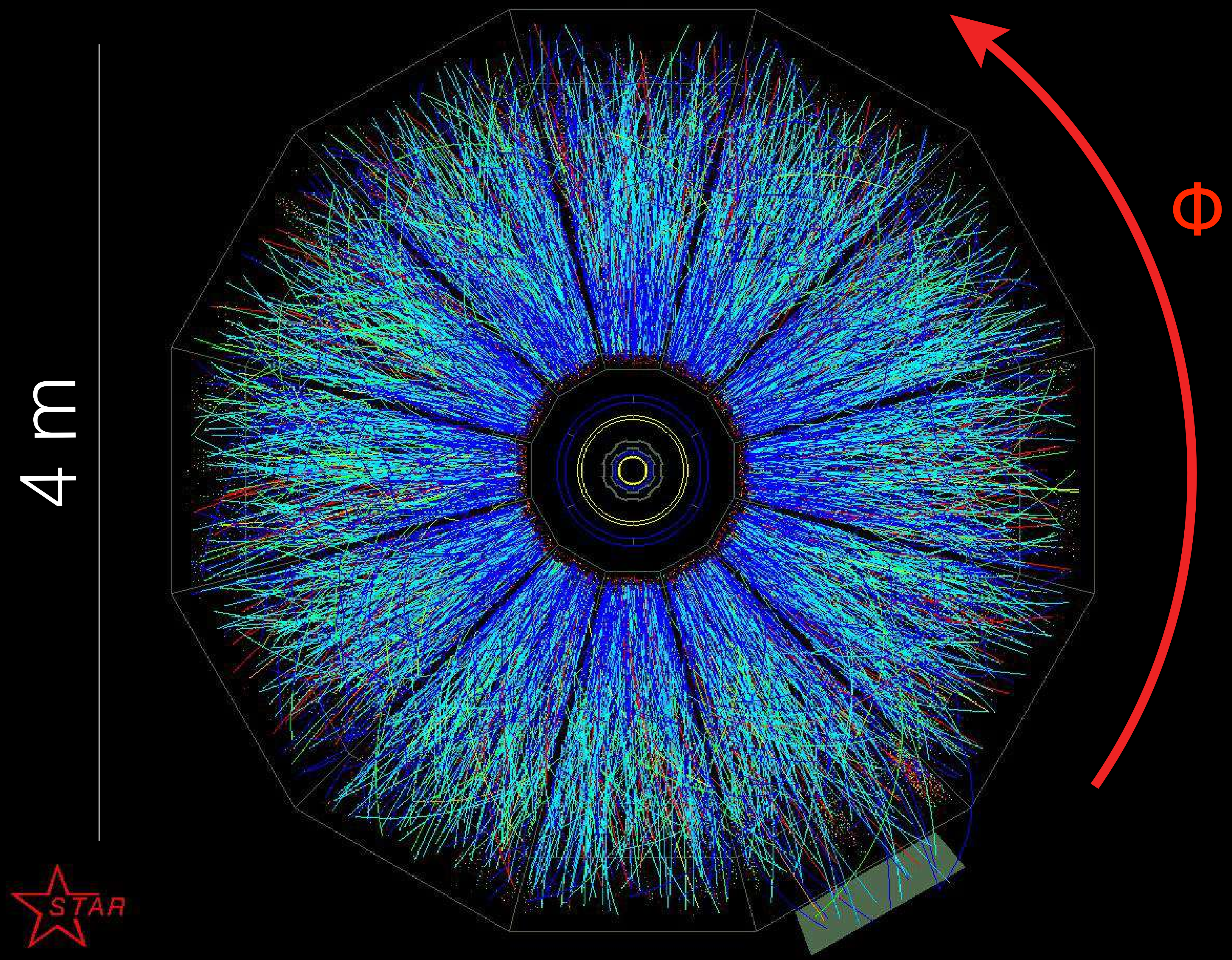
- **Discovery at RHIC:**
  The Quark Gluon Plasma
  behaves like an almost perfect fluid

2006

- **How do we know?**
  Azimuthal anisotropies in particle spectra
  Described only if system described by hydrodynamics with very low viscosity

- Confirmed by results from LHC in 2010

Azimuthal anisotropies in particle spectra



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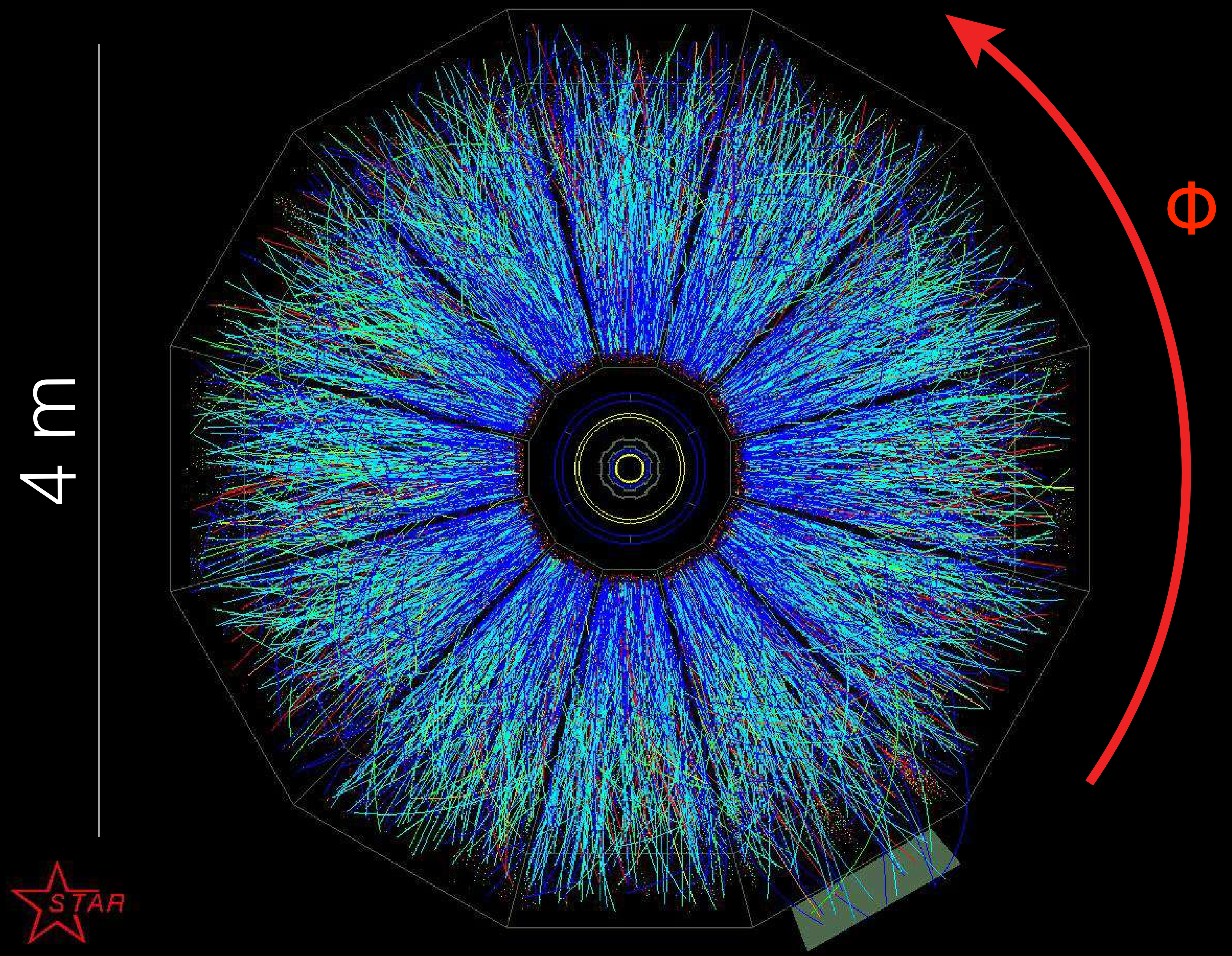
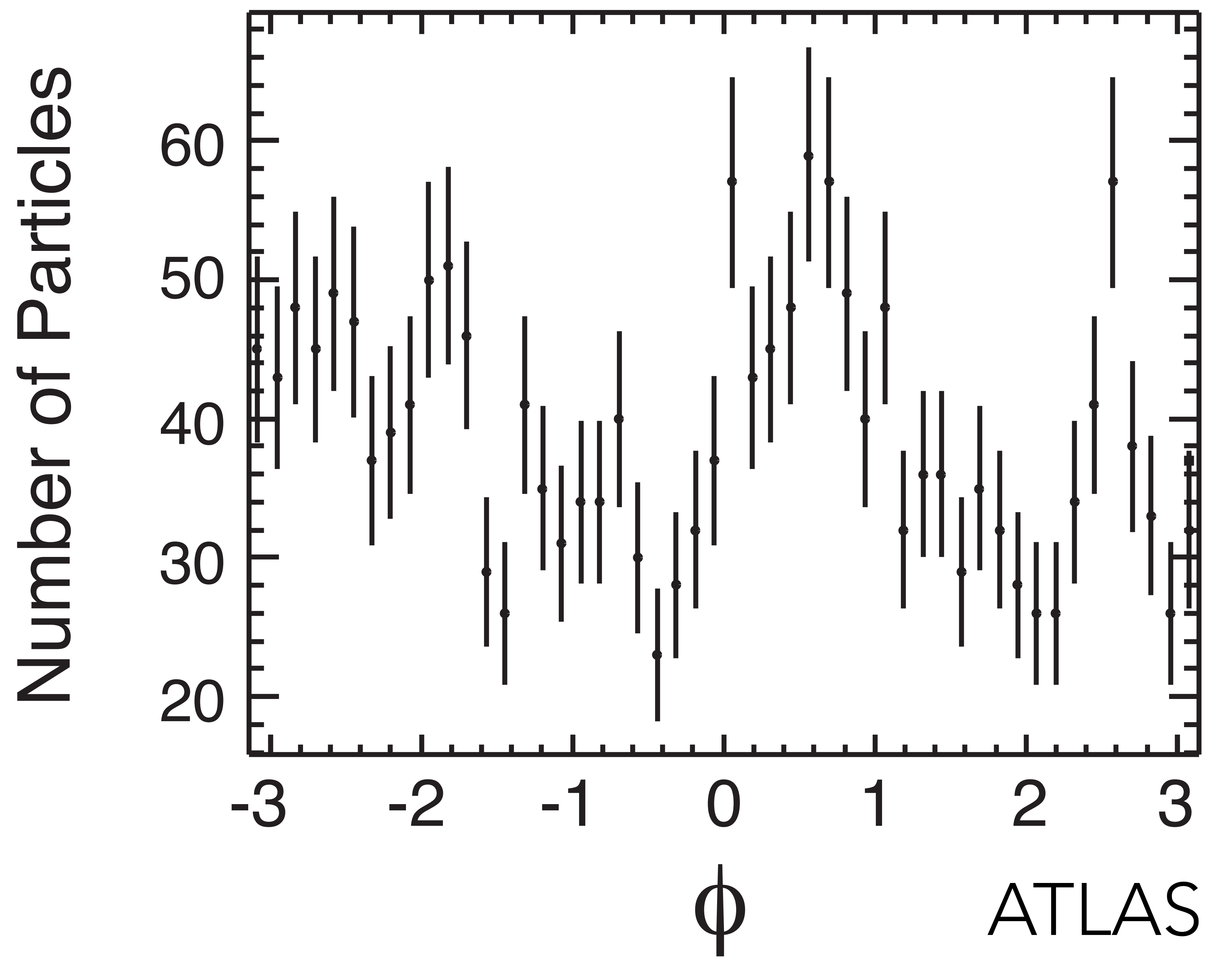
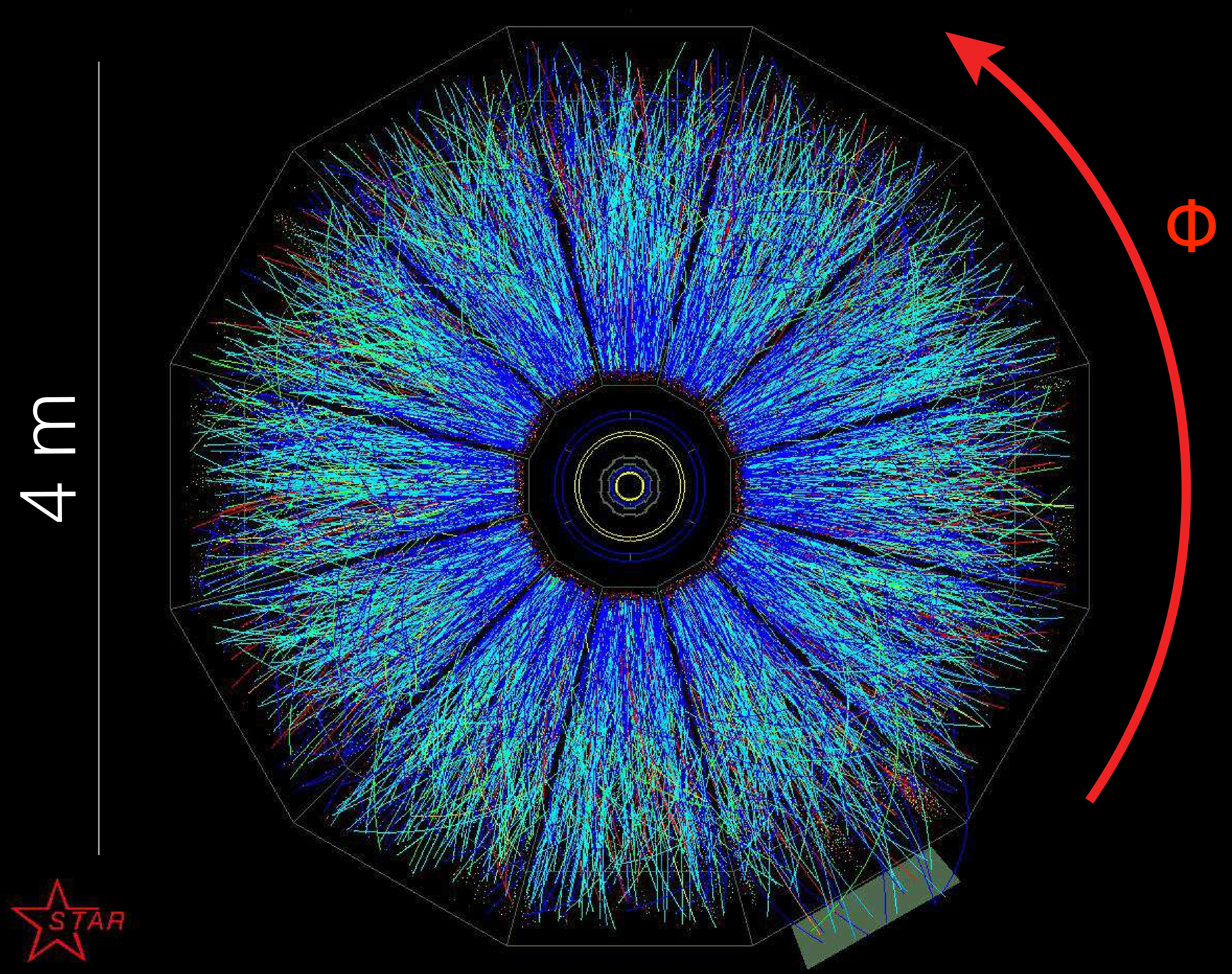
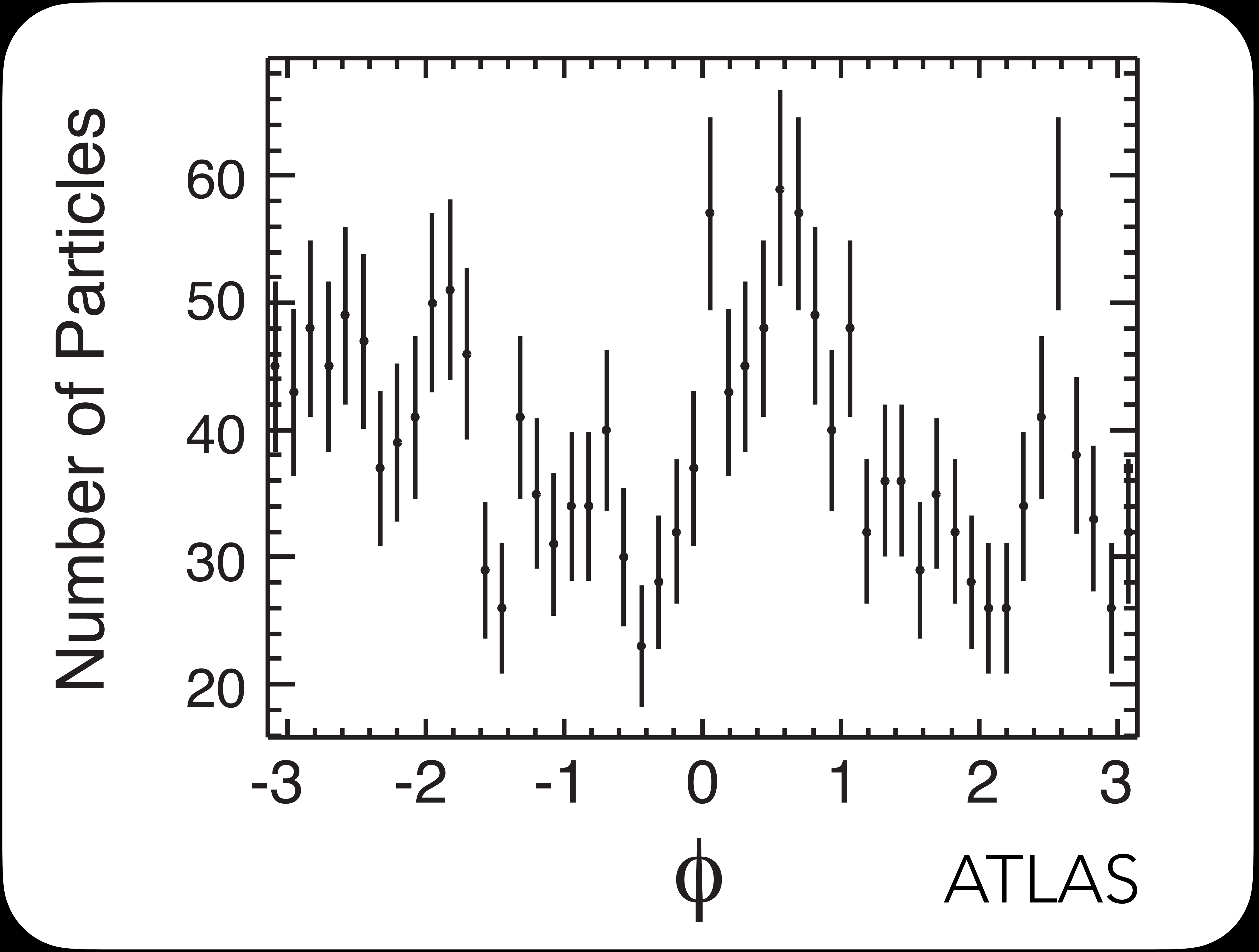
Azimuthal anisotropies in particle spectra





Azimuthal anisotropies in particle spectra





Quantify anisotropy using Fourier expansion: $\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n 2v_n \cos[n(\phi - \psi_n)]\right)$

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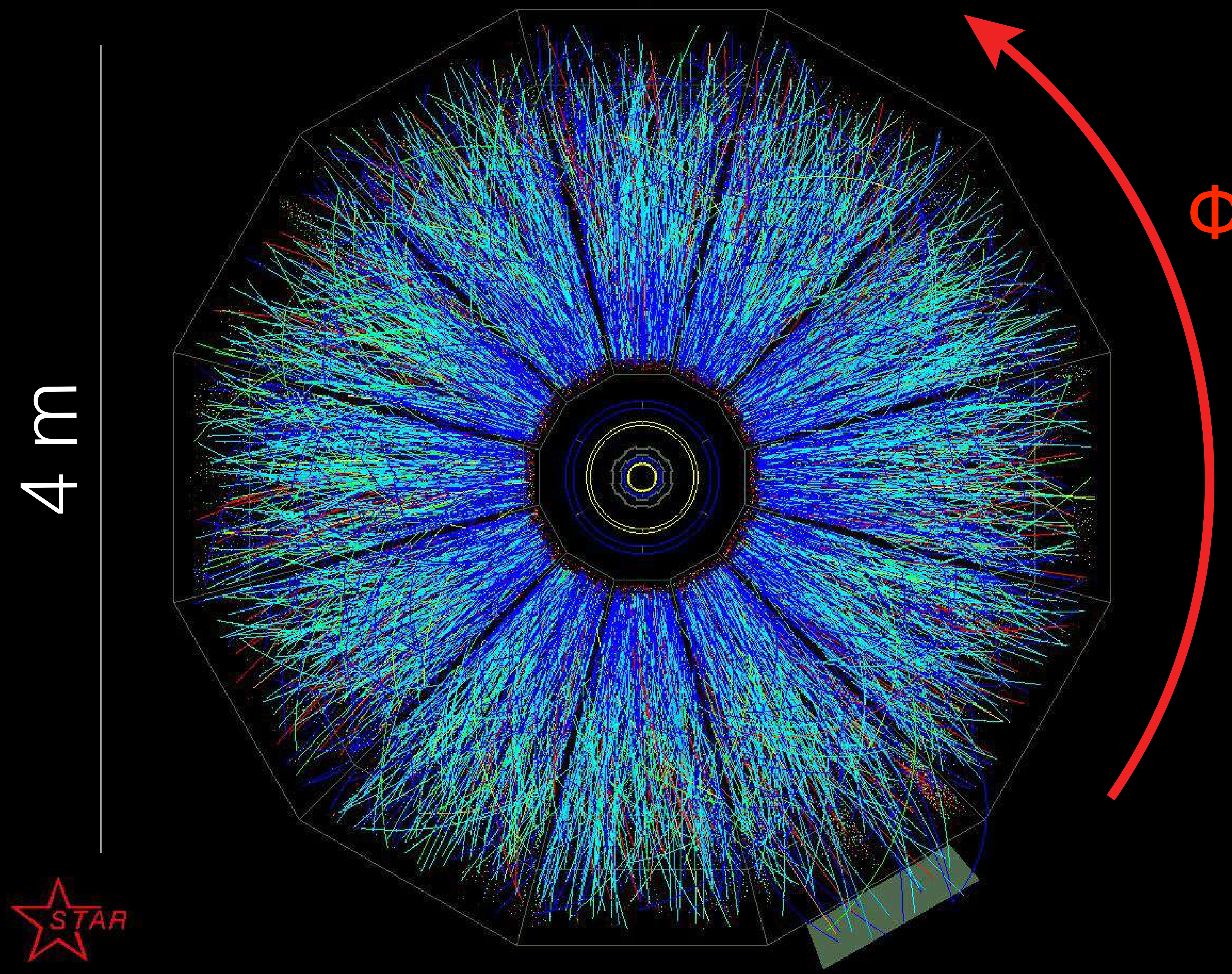
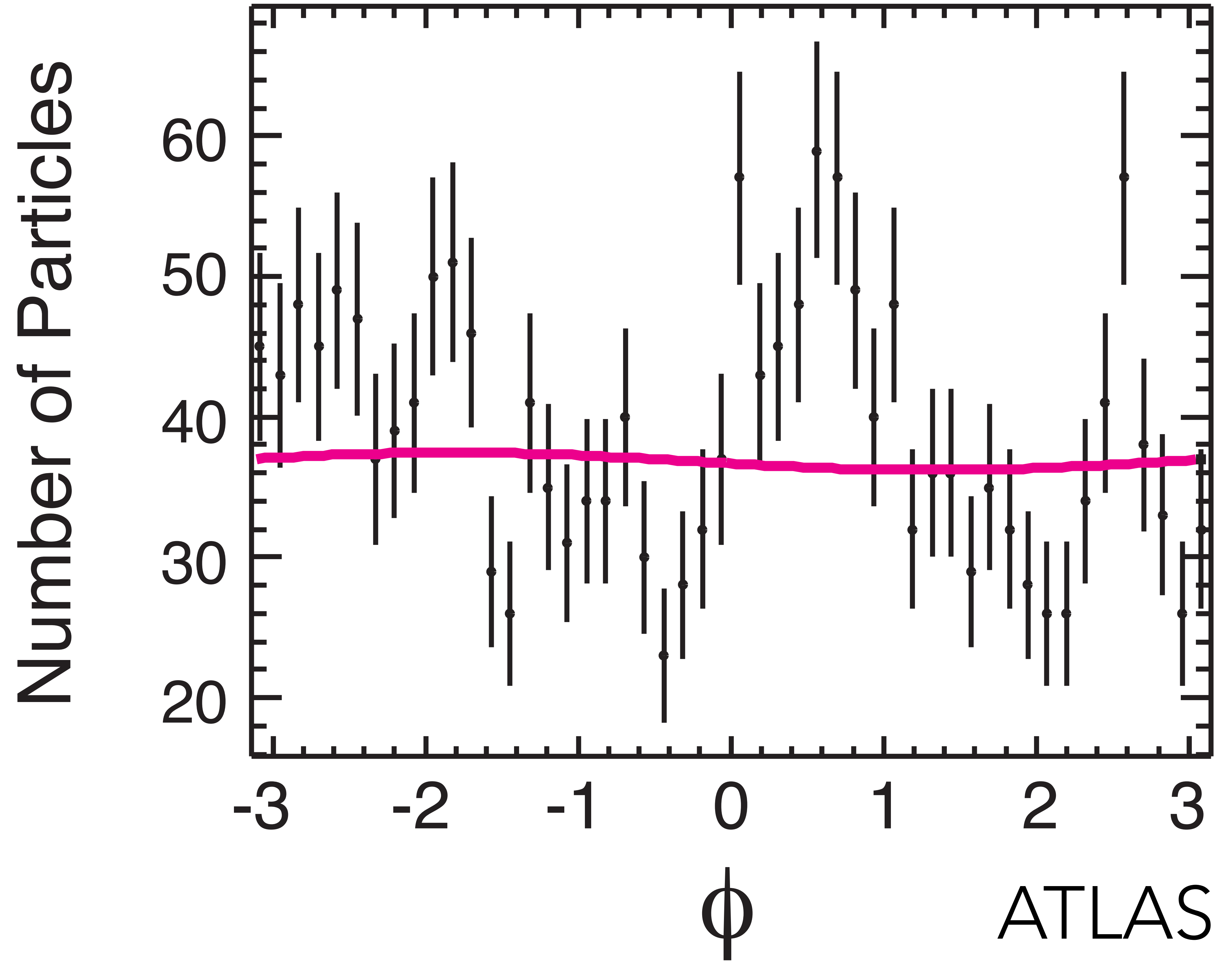
Azimuthal anisotropies in particle spectra

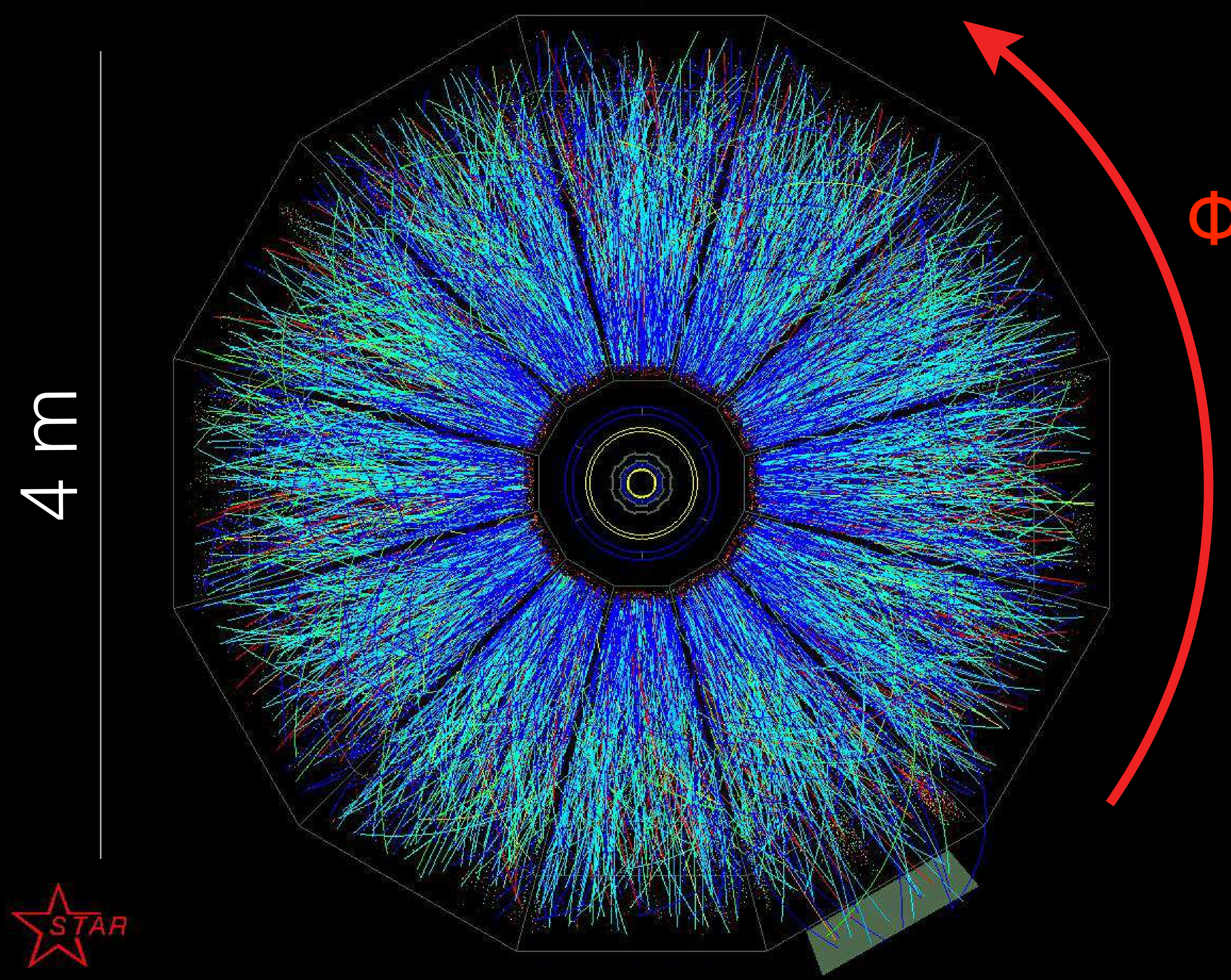


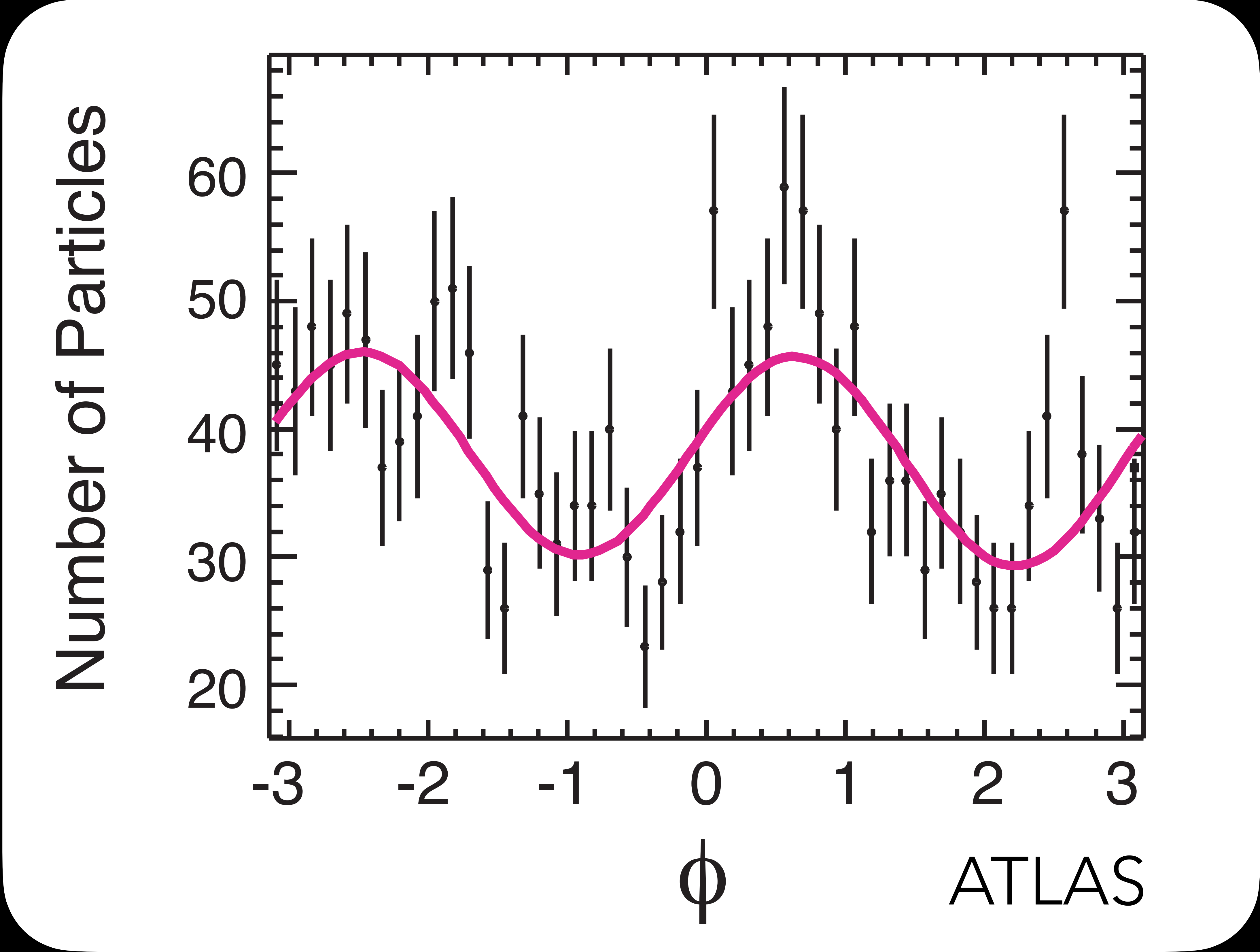


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + v_1 \cos[(\phi - \psi_1)]\right)$$

Azimuthal anisotropies in particle spectra

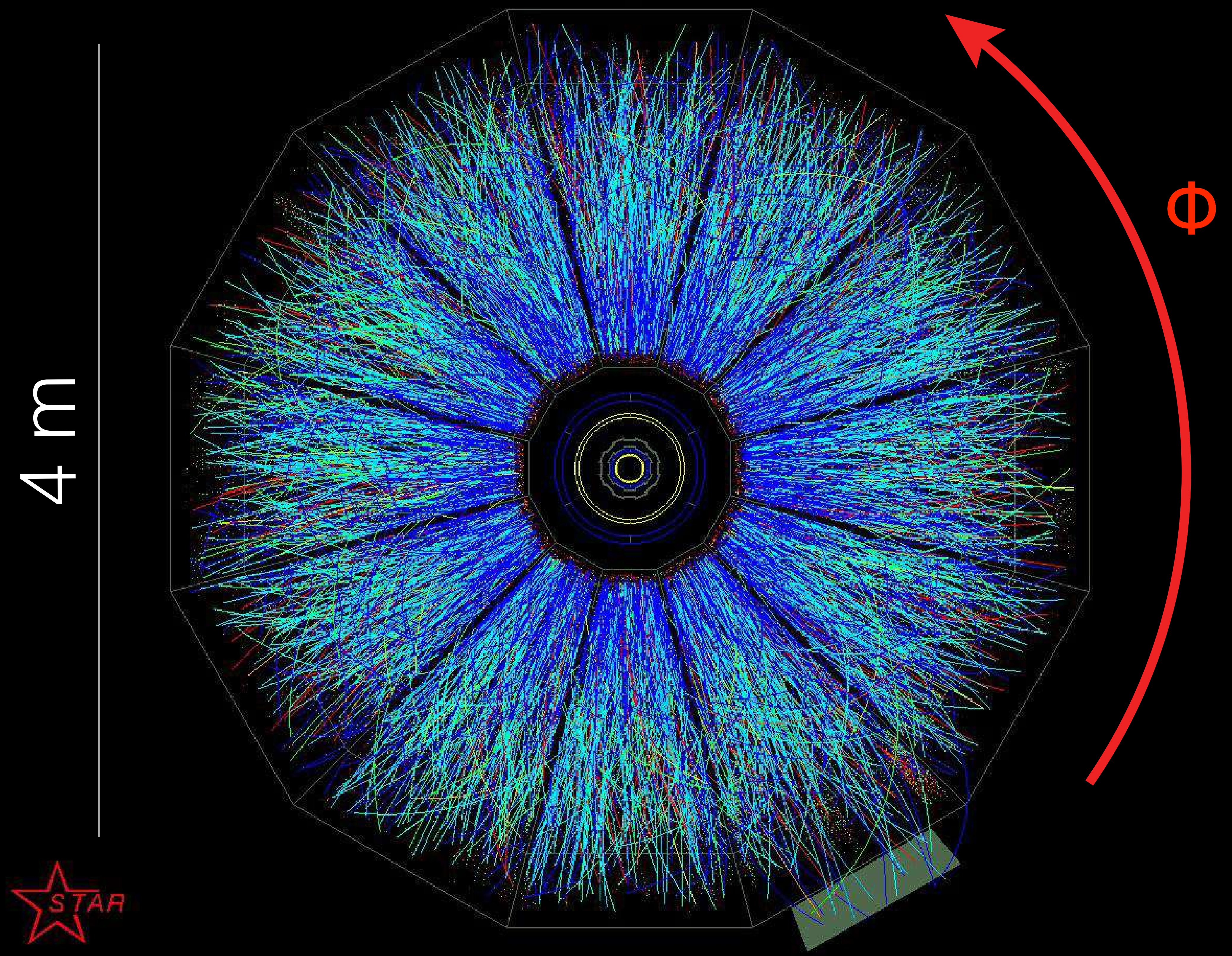


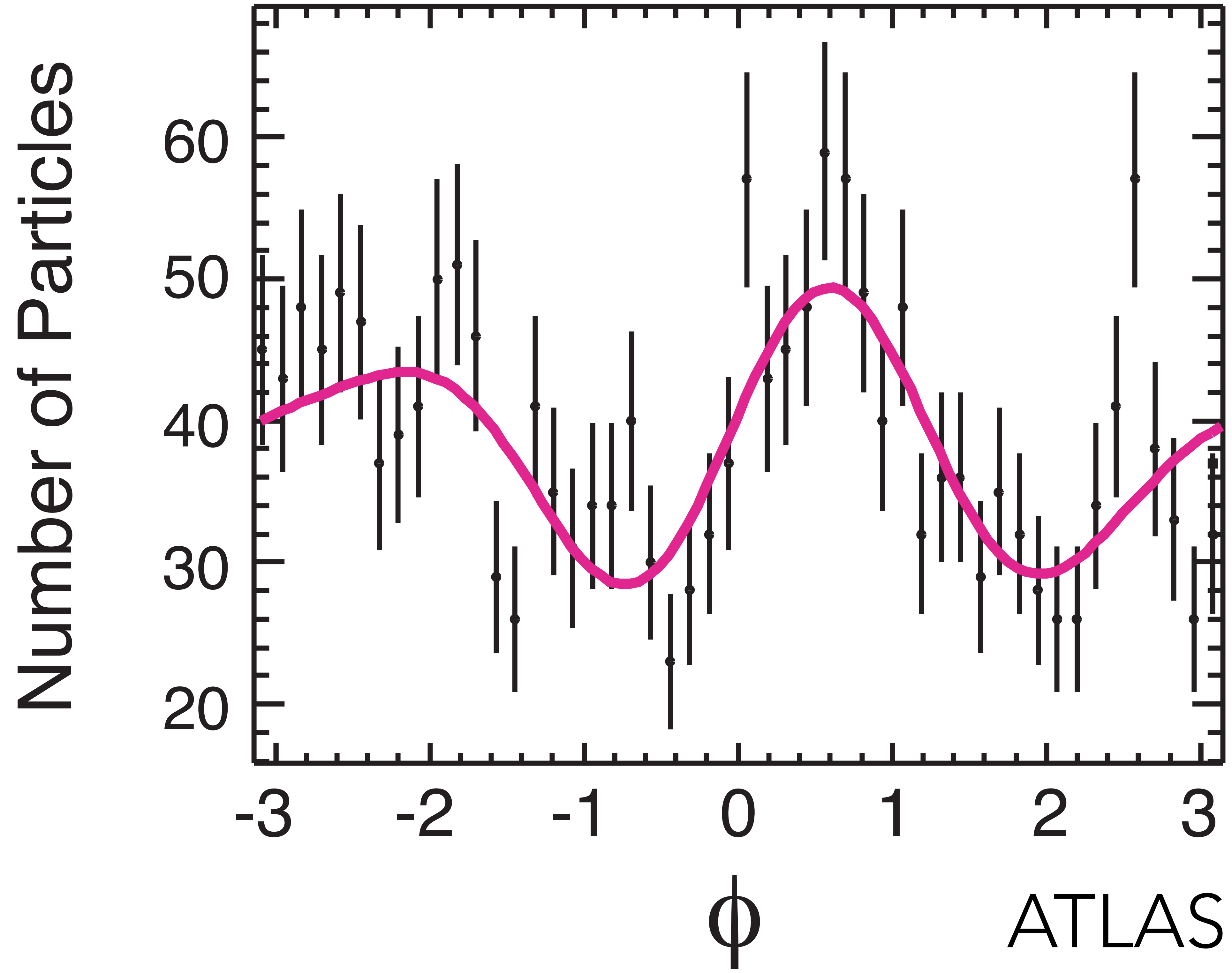


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + v_1 \cos[(\phi - \psi_1)] + v_2 \cos[2(\phi - \psi_2)]\right)$$

Azimuthal anisotropies in particle spectra

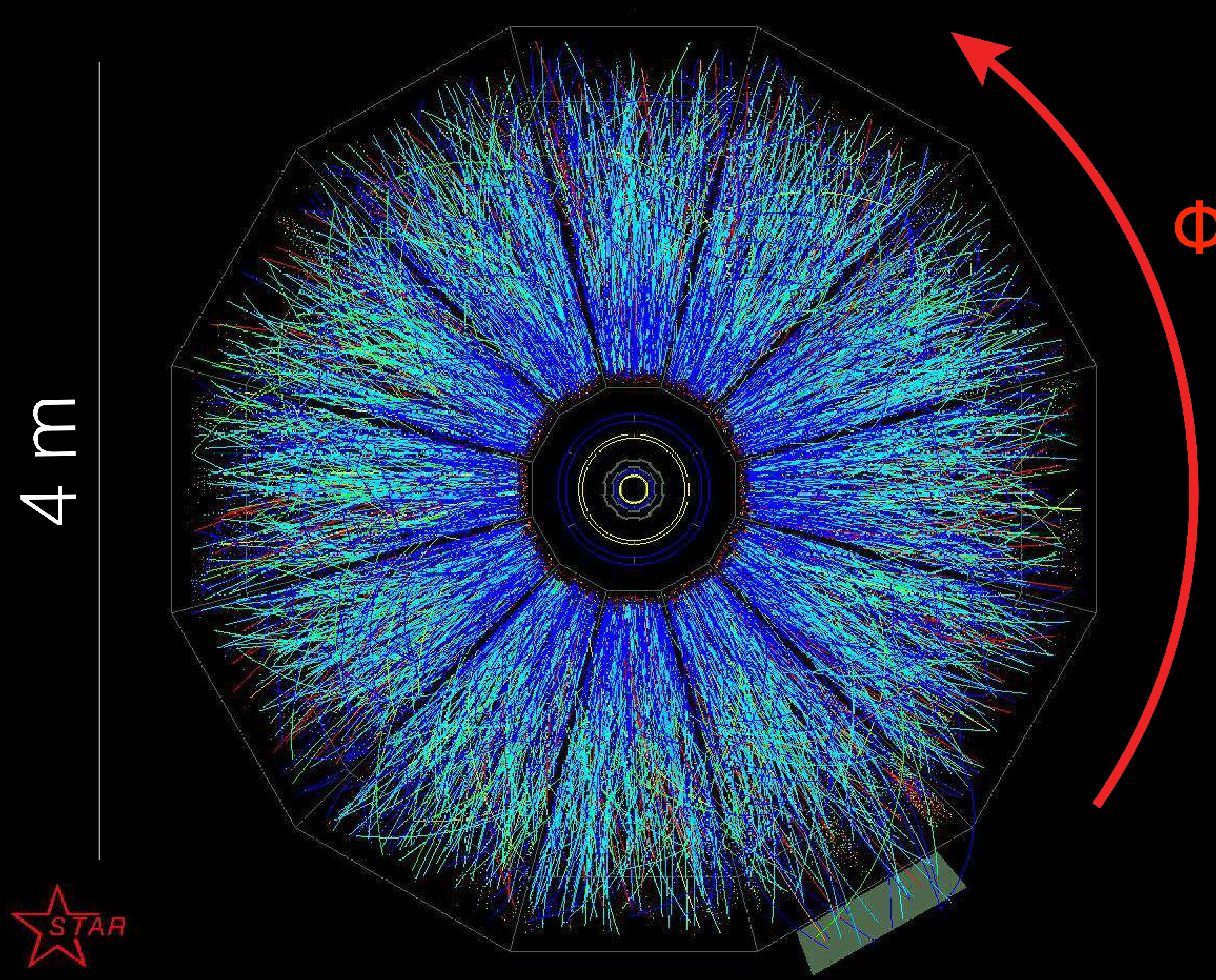


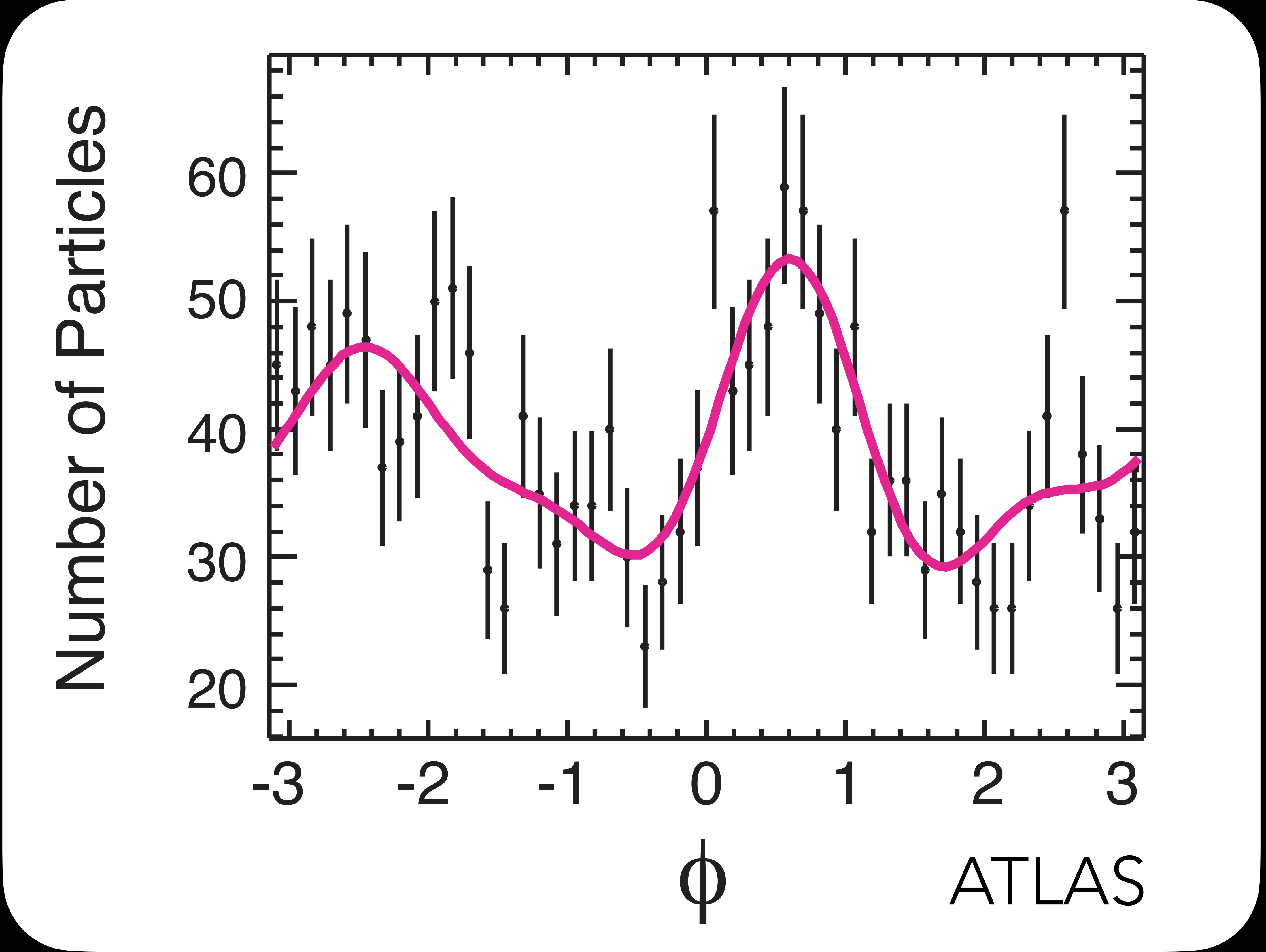


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + v_1 \cos[(\phi - \psi_1)] + v_2 \cos[2(\phi - \psi_2)] + v_3 \cos[3(\phi - \psi_3)]\right)$$

Azimuthal anisotropies in particle spectra





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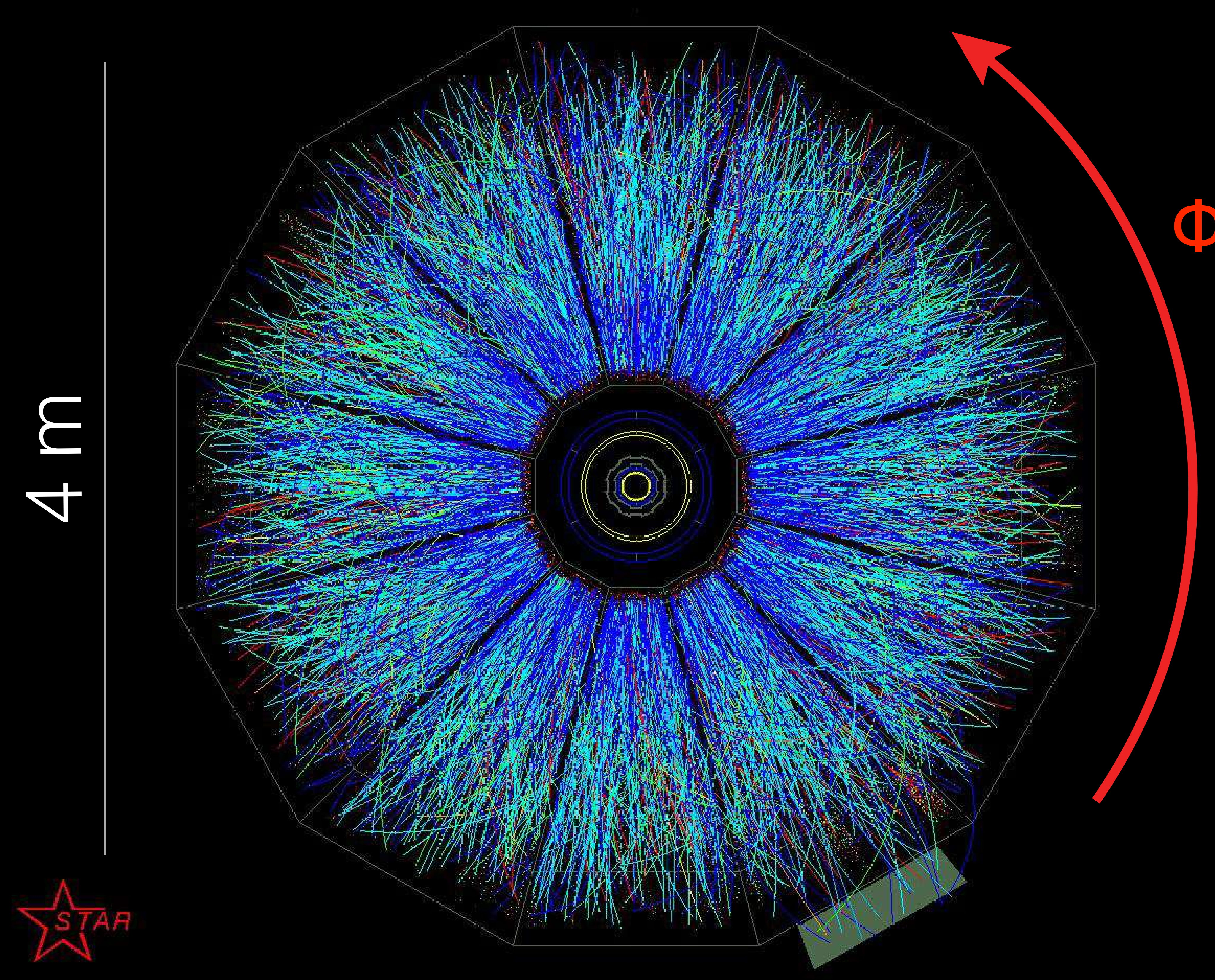
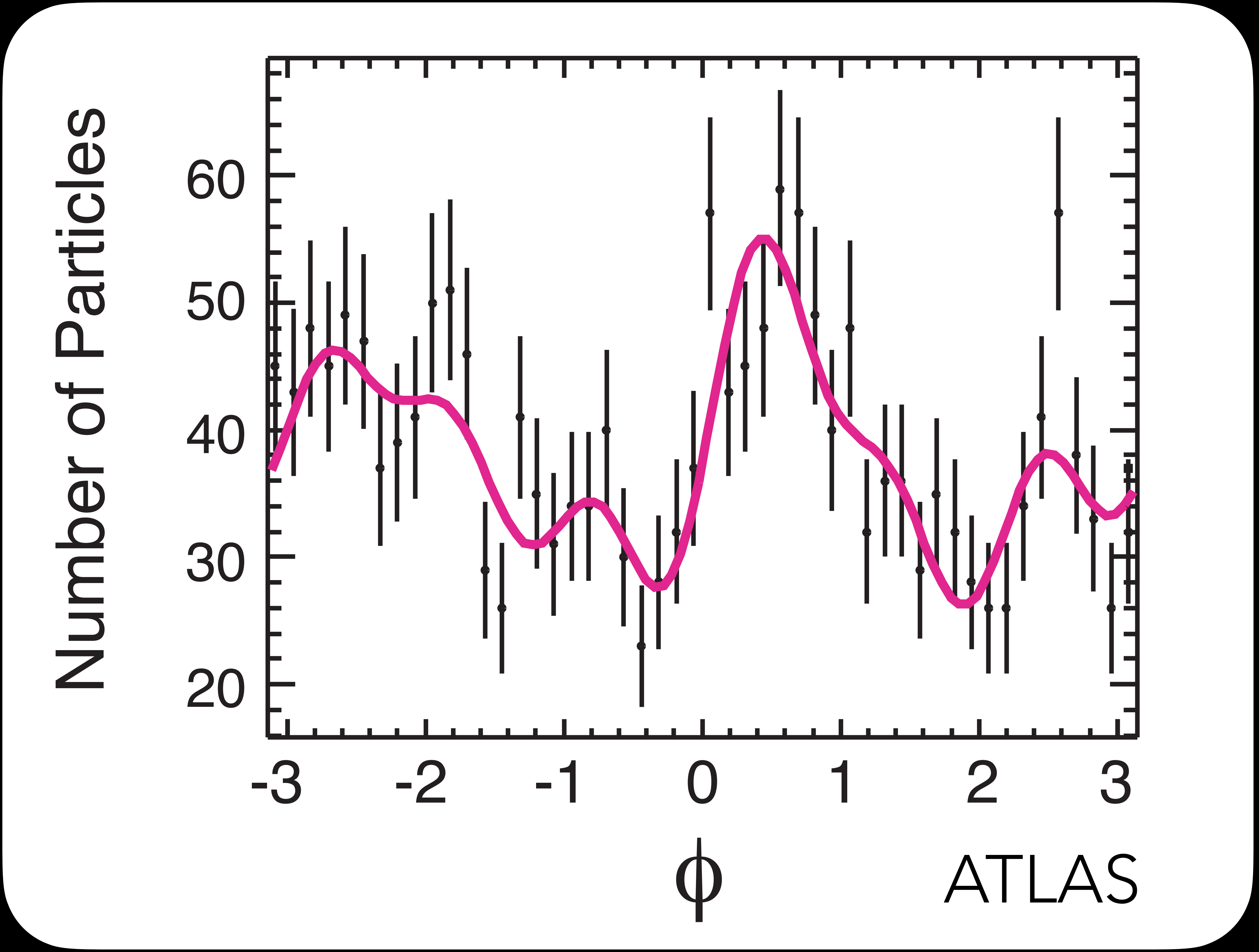
Azimuthal anisotropies in particle spectra





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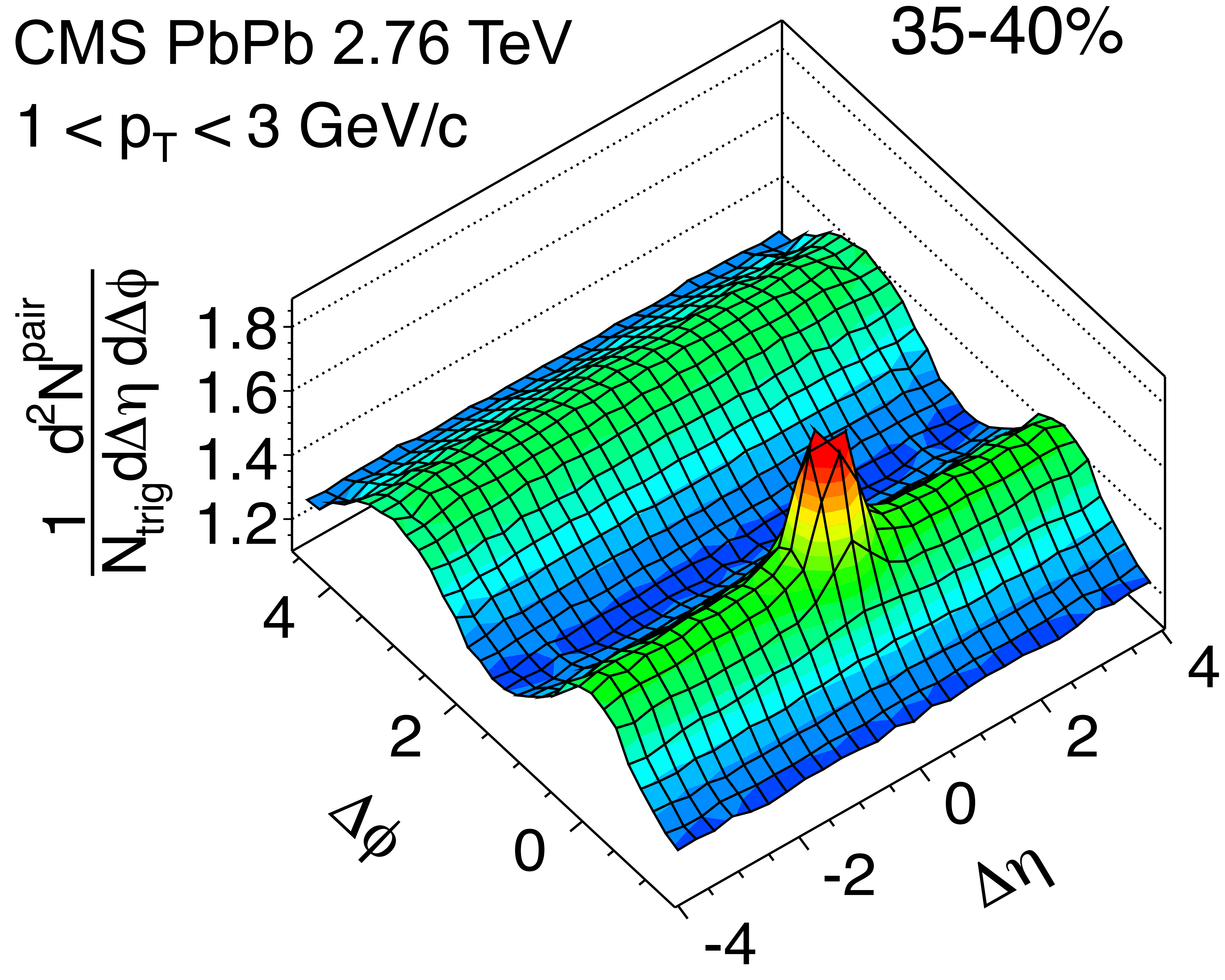
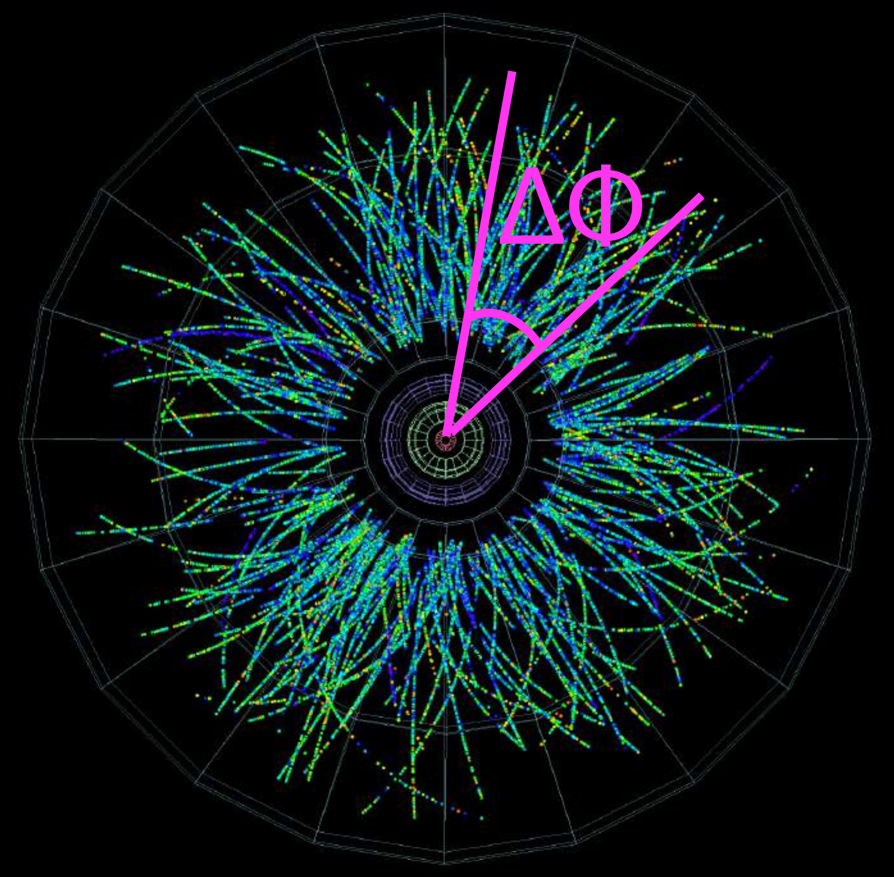
In practice: use multi-particle correlations

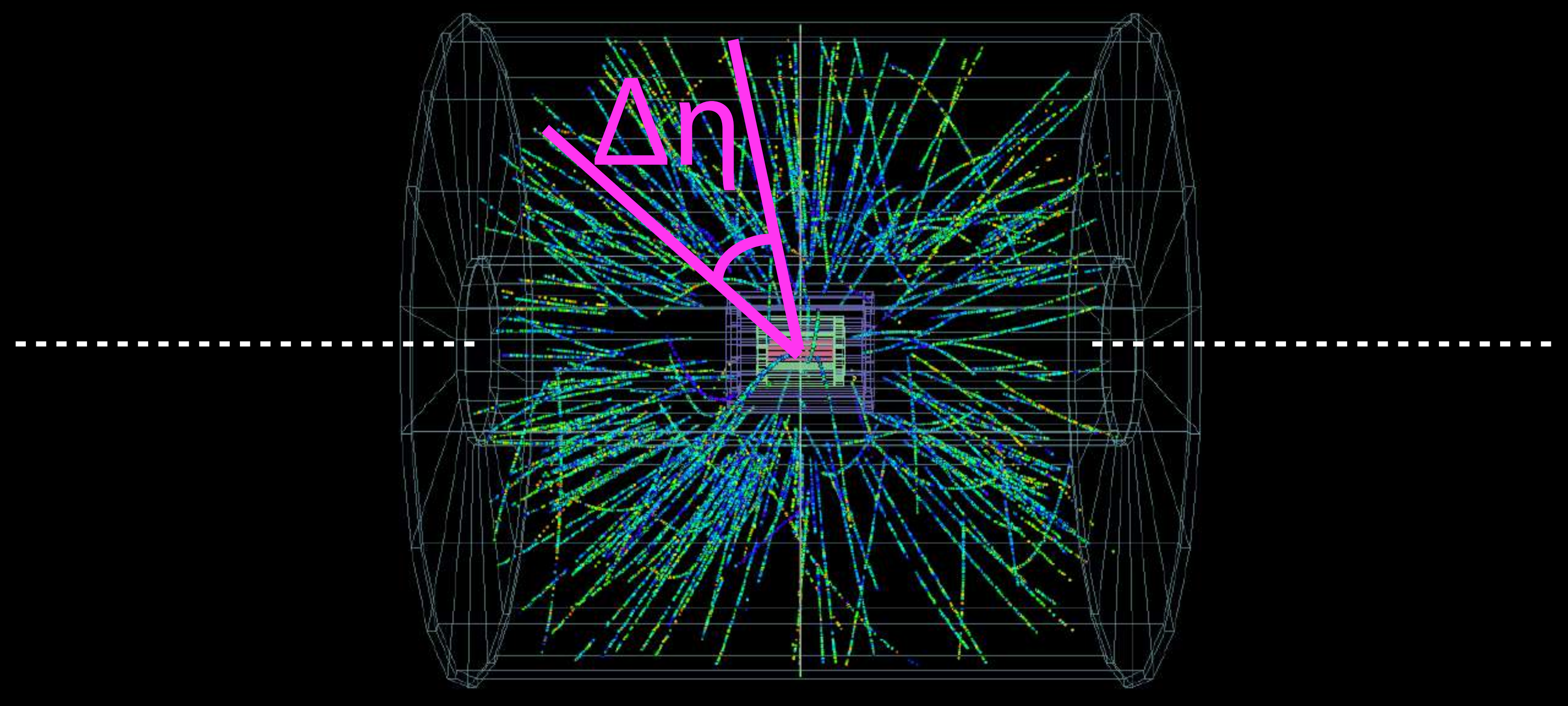
2-particle correlation vs. Δη and Δϕ:



CMS COLL., EUR. PHYS. J. C72 (2012)



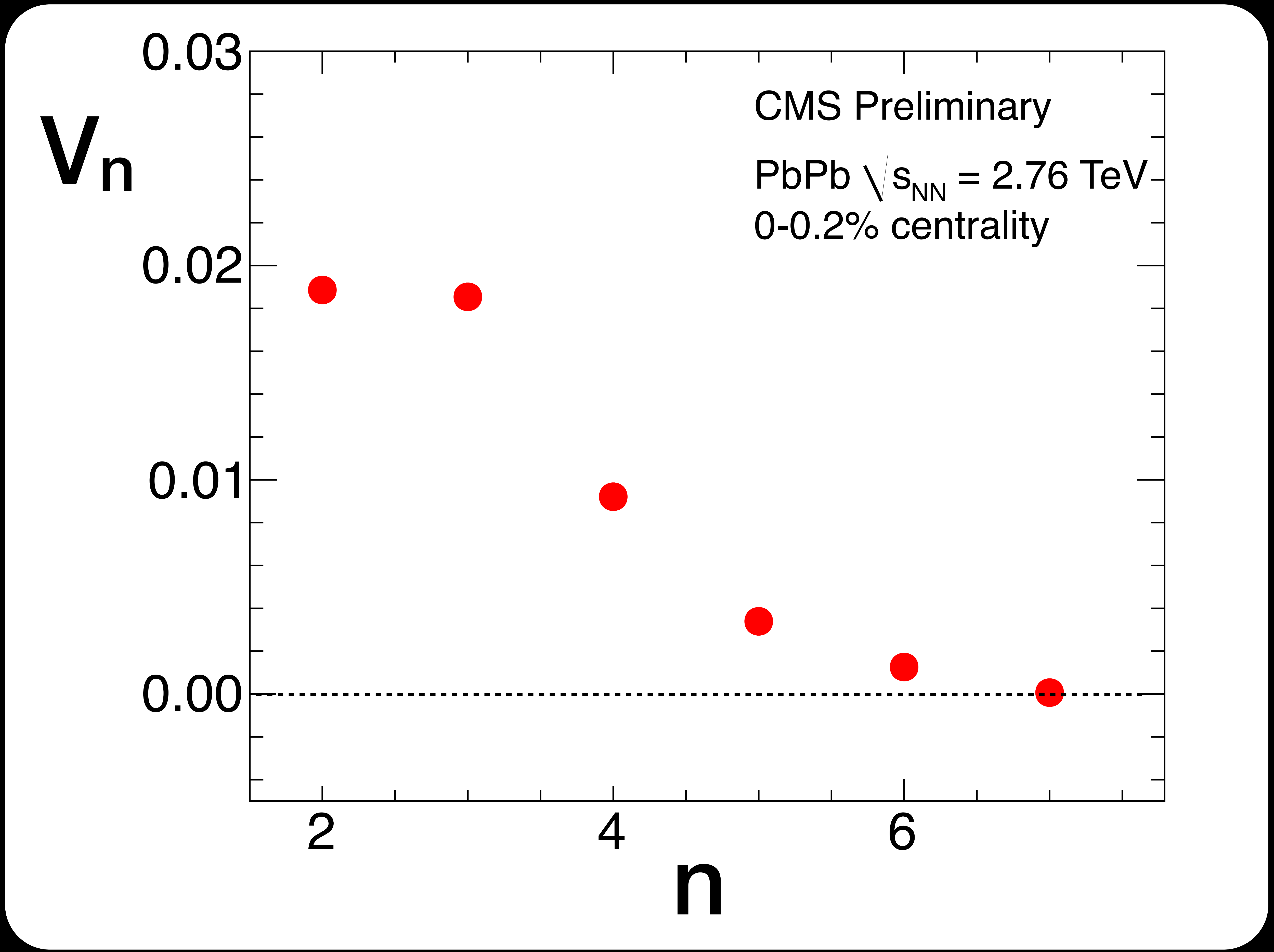
ΔΦ: DIFFERENCE IN AZIMUTHAL ANGLE



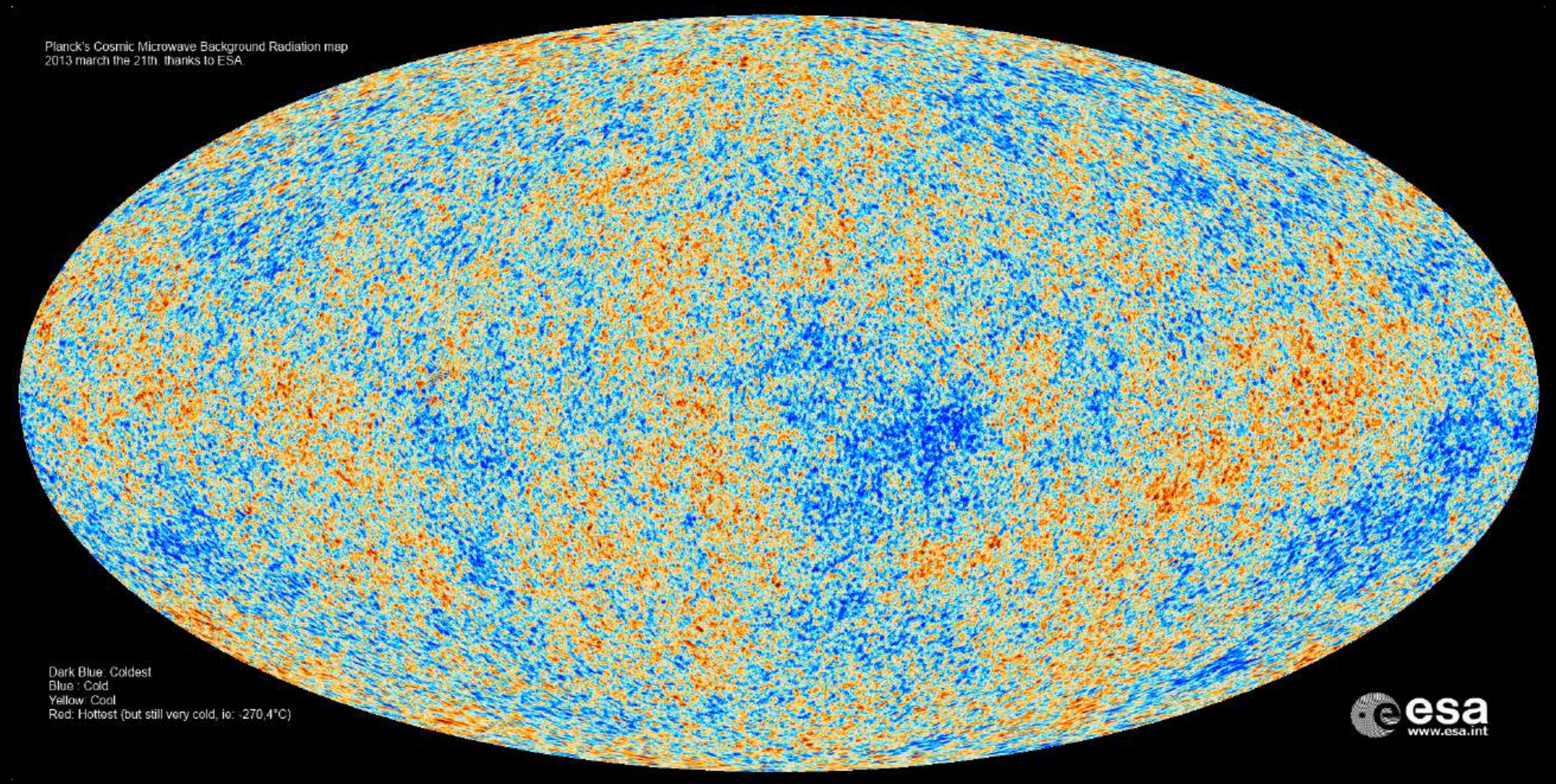
Δη: DIFFERENCE IN PSEUDO-RAPIDITY

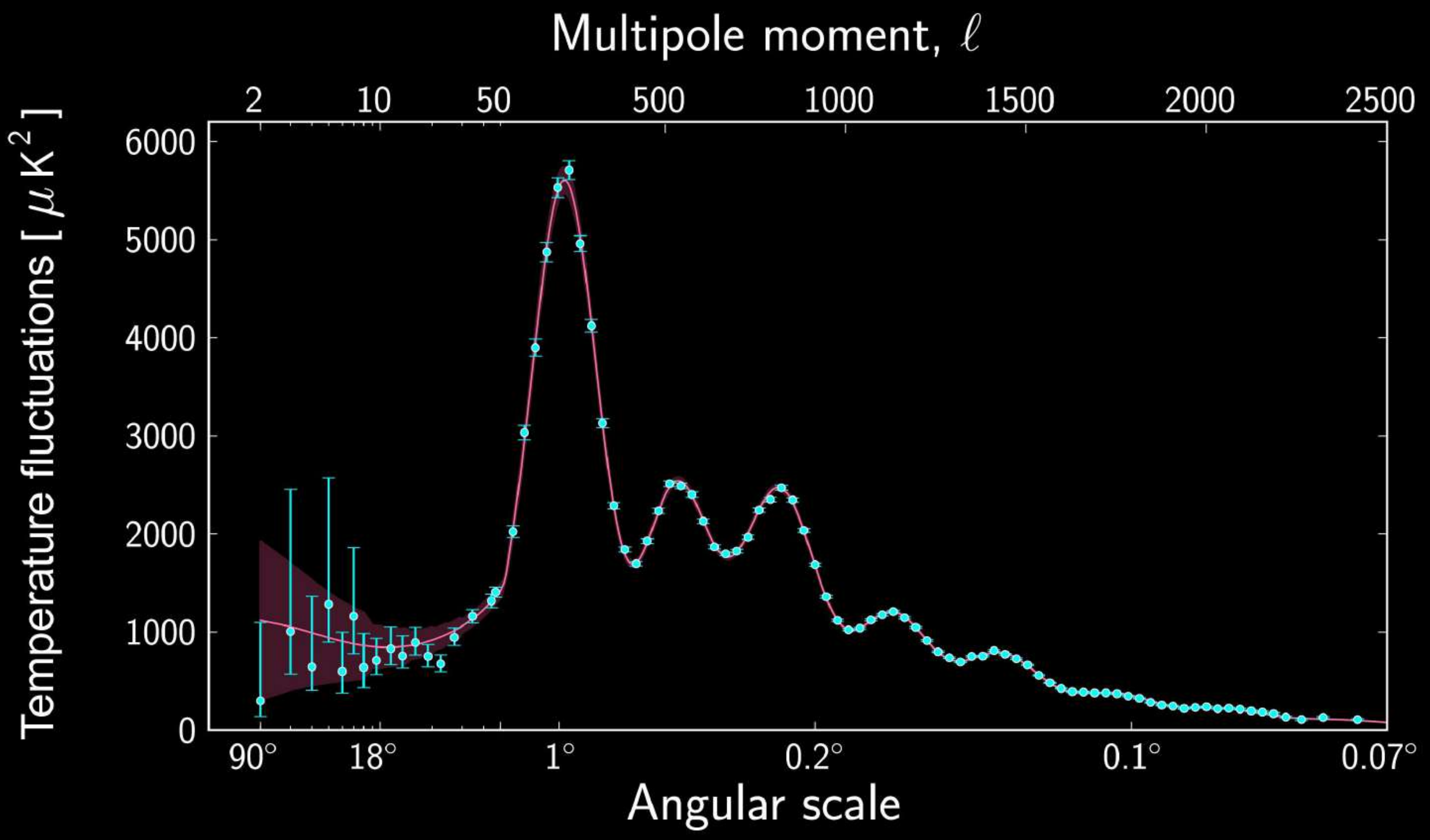
Power spectrum of momentum anisotropies

v_n as a function of n in central Pb+Pb collisions



CMS Collaboration, JHEP 02 (2014) 088

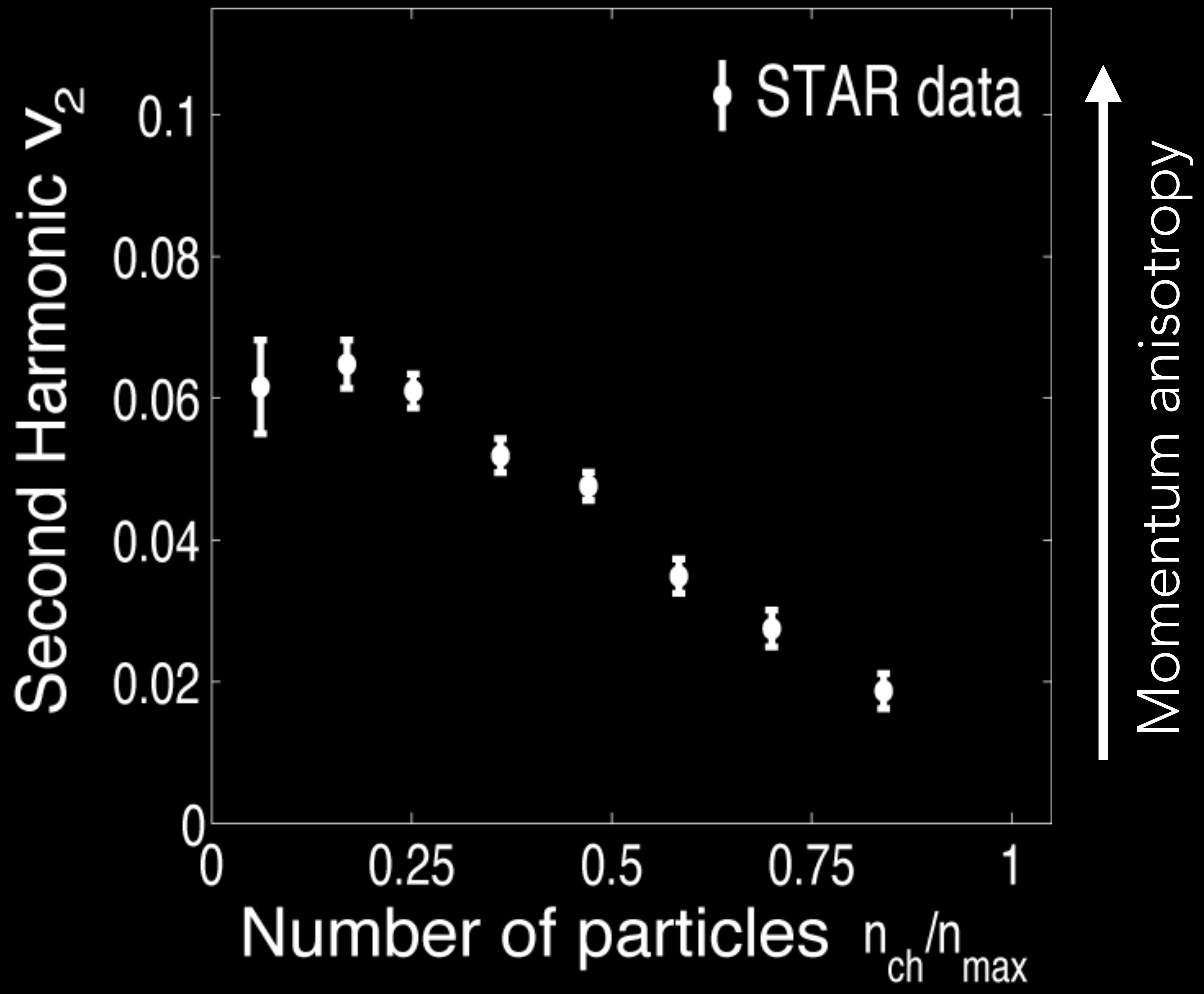




PLANCK Coll. A&A 571, A16 (2014)

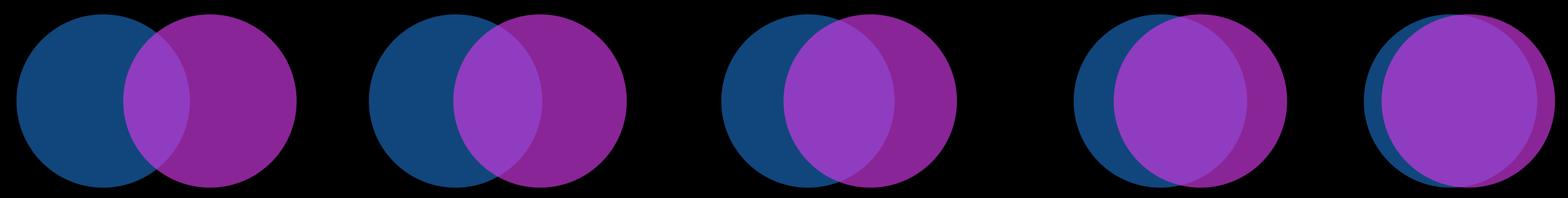
Elliptic flow (v_2) is sensitive to initial shape

STAR Collaboration, Phys.Rev.Lett. 86 (2001) 402-407



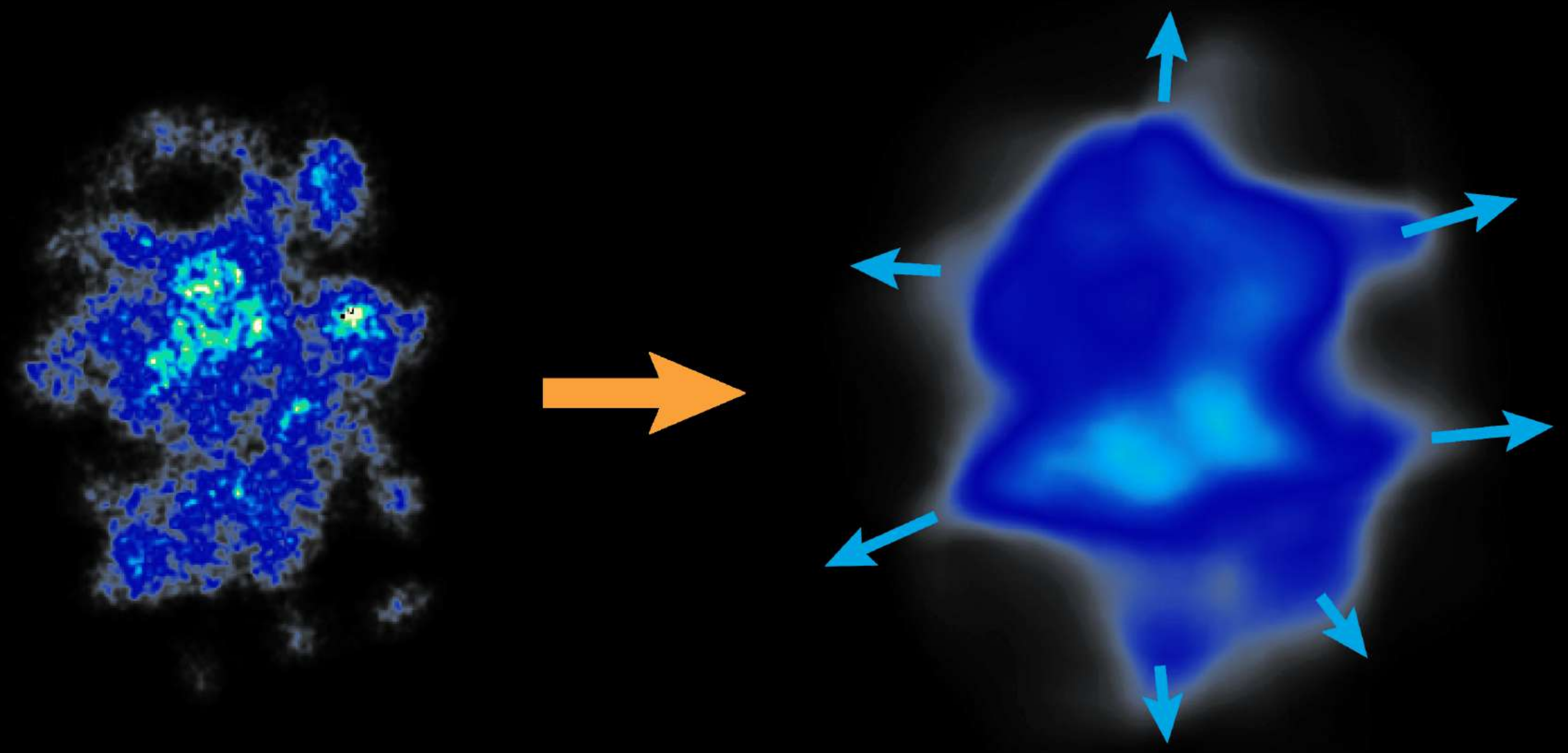
Experimentally found correlation between initial shape and momentum anisotropy

Initial shape:



Interpretation: Strong final state effects

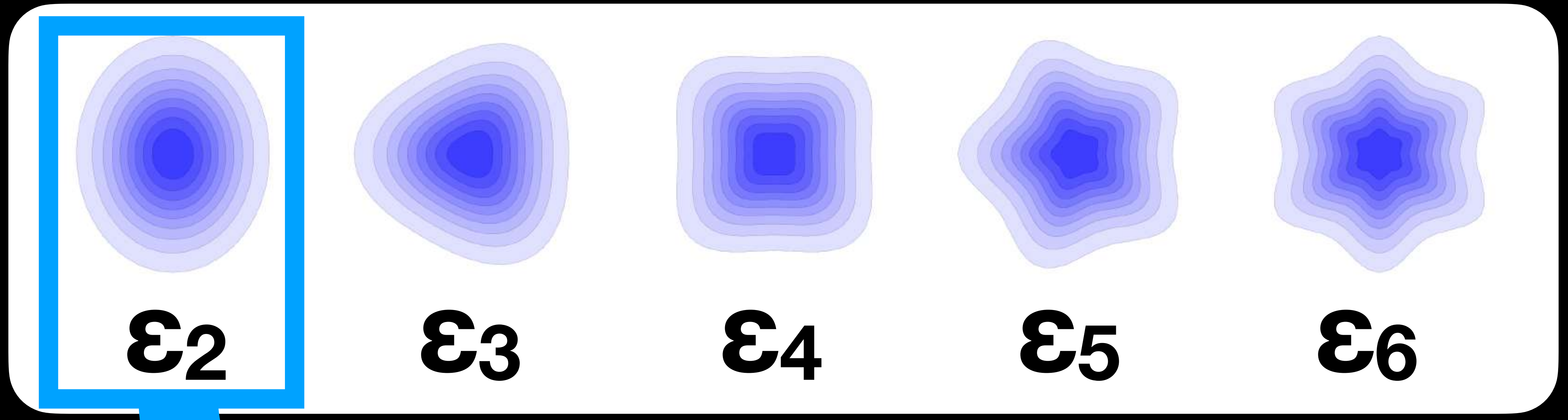
Azimuthal momentum anisotropy generated by medium response to the initial transverse geometry: Pressure gradients drive expansion



Initial energy density distribution

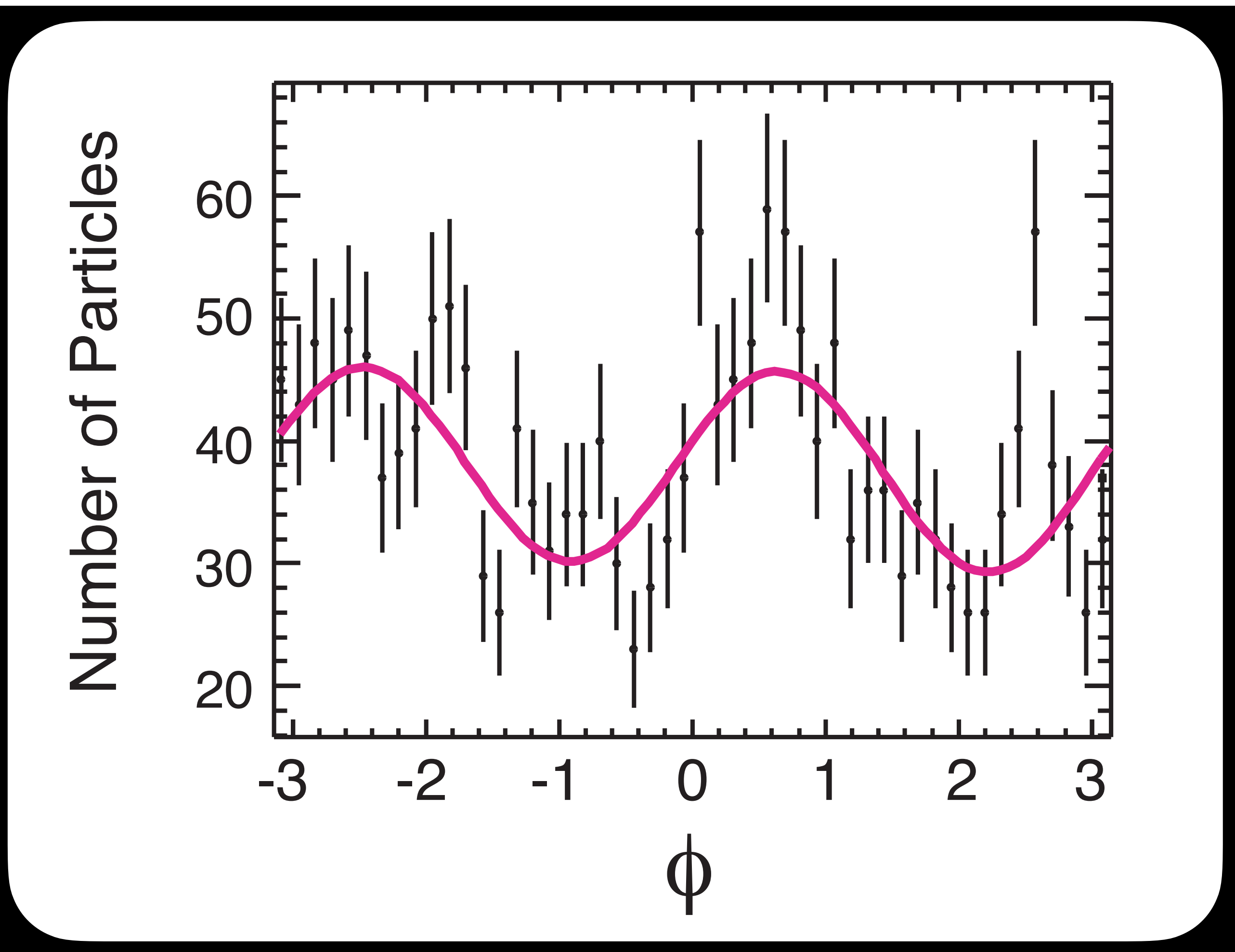
Hydrodynamic expansion

Fourier components of initial geometry



e.g.

$\varepsilon_2 \sim v_2$



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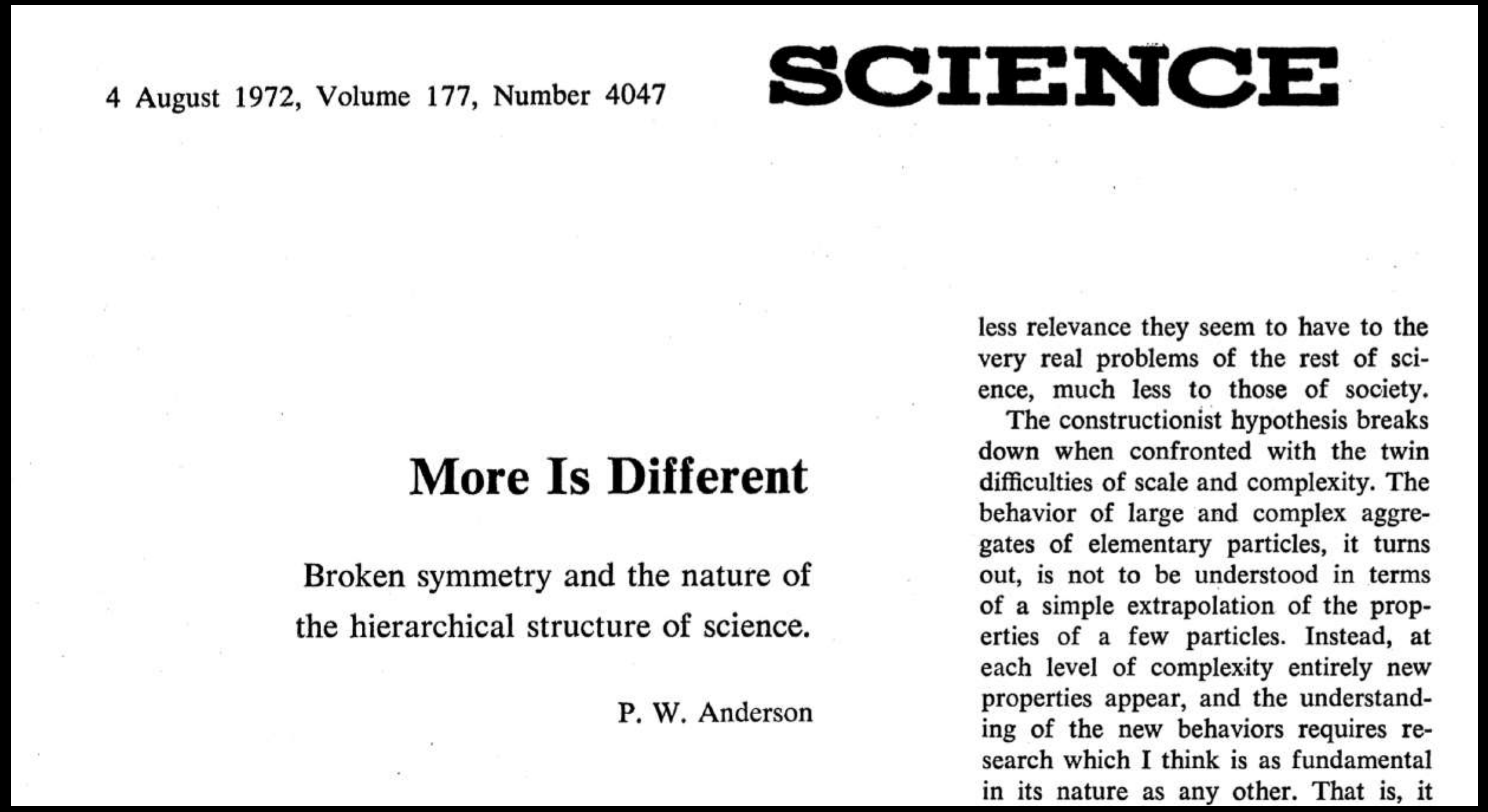
Theory: “More is different”

Complex many-body systems are not well described by simple extrapolation from properties of a few particles

Need effective theories to describe emergent phenomena:

Phase transitions, critical phenomena, hydrodynamic behavior, gluon saturation, plasma instabilities, …


4 August 1972, Volume 177, Number 4047

SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

- **Color Glass Condensate (CGC):** High energy effective theory of QCD
  Includes gluon saturation at small momentum fraction *x* and small transverse momentum $p_T \lesssim Q_s(x)$, with the saturation scale $Q_s \gg \Lambda_{\rm QCD}$
  →Use to compute initial conditions for heavy ion collisions

- **Relativistic Hydrodynamics**
  →Compute the final state evolution of heavy ion collisions

Initial state from an effective theory of QCD

- What is colliding? QCD tells us: mostly gluons
- High energy collisions probe small $x \sim p_T/\sqrt{s}$
  (x is momentum fraction of the parton in nucleus)
- Gluon saturation at $p_T \lesssim Q_s(x)$
  (Q_s is the saturation scale)

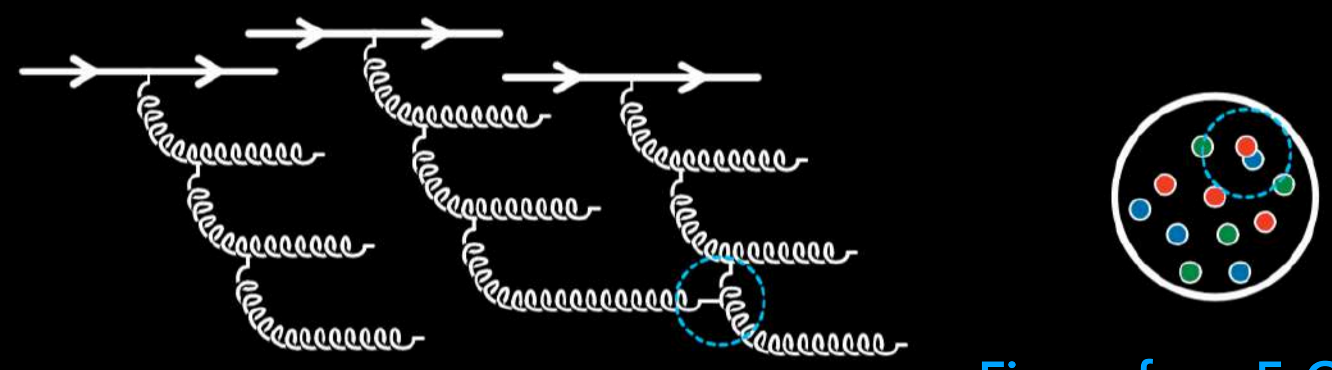
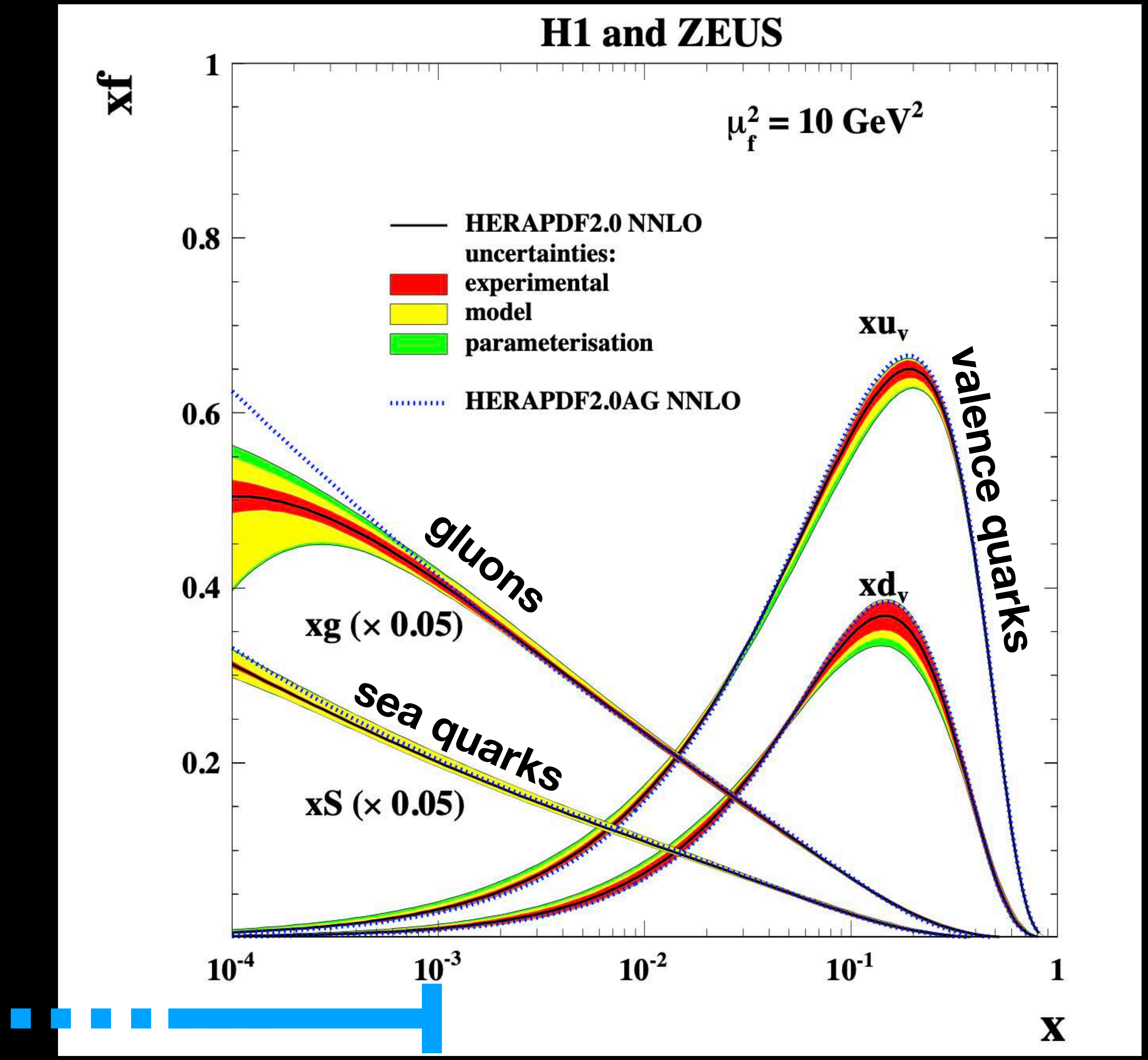


Figure from F. Gelis

- Large occupation numbers →
  Classical description: Yang-Mills equations!
- Leading quantum corrections can be included via small-x evolution (BFKL, BK, JIMWLK)

F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan
Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489

Gluon distribution from experiment:



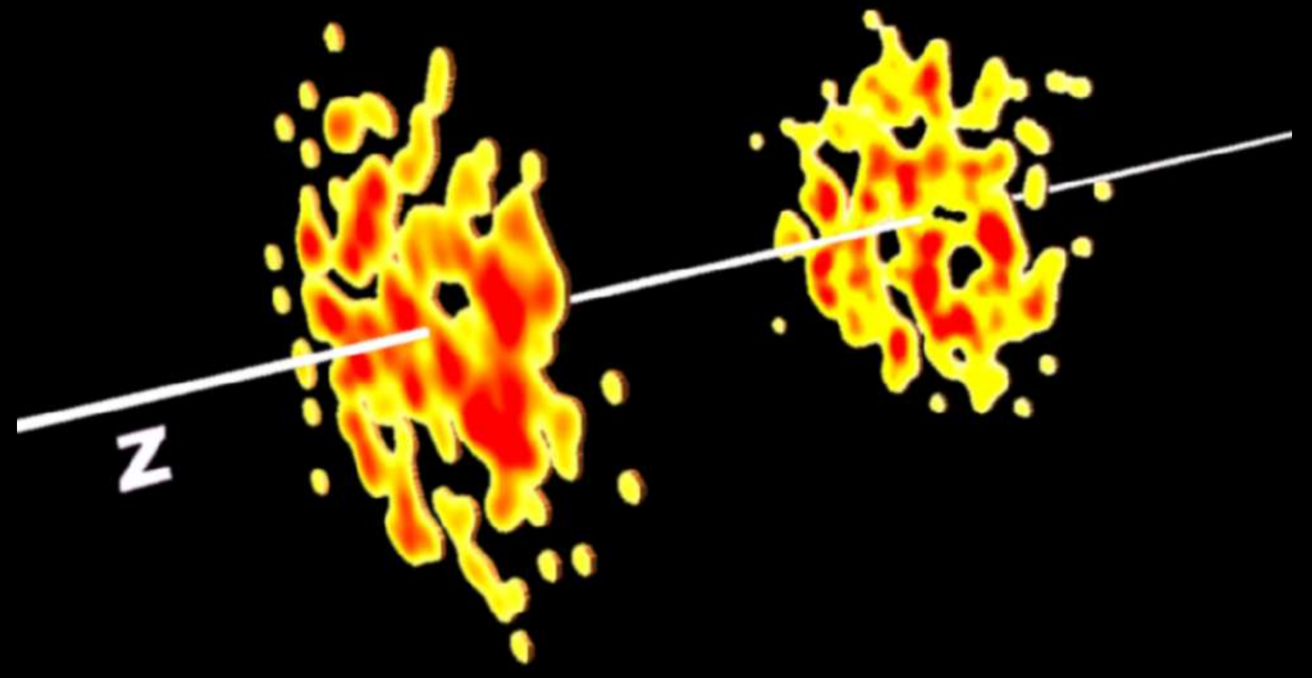
x-range for RHIC and LHC heavy ions (mid-rapidity)

H1 and ZEUS, Eur.Phys.J. C75 (2015) no.12, 580

IP-Glasma: Colliding Color Glass Condensates

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Particle production governed by **Yang Mills equations**



- Determine gluon fields inside fast moving nuclei:
  - Nucleon positions from nuclear wave function
  - Sample color charges in the nucleons
    Their distribution is constrained from e+p scattering data from HERA
    Kowalski, Teaney, Phys.Rev. D68 (2003) 114005
  - Then solve the Yang-Mills equations
    $[D_\mu, F^{\mu\nu}] = J^\nu$, where J^ν is constructed from color charges moving at speed of light
  - Solve for the gluon fields after the collision
    Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)
    Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

$$A^i_{(3)}|_{\tau=0^+} = A^i_{(1)} + A^i_{(2)}$$

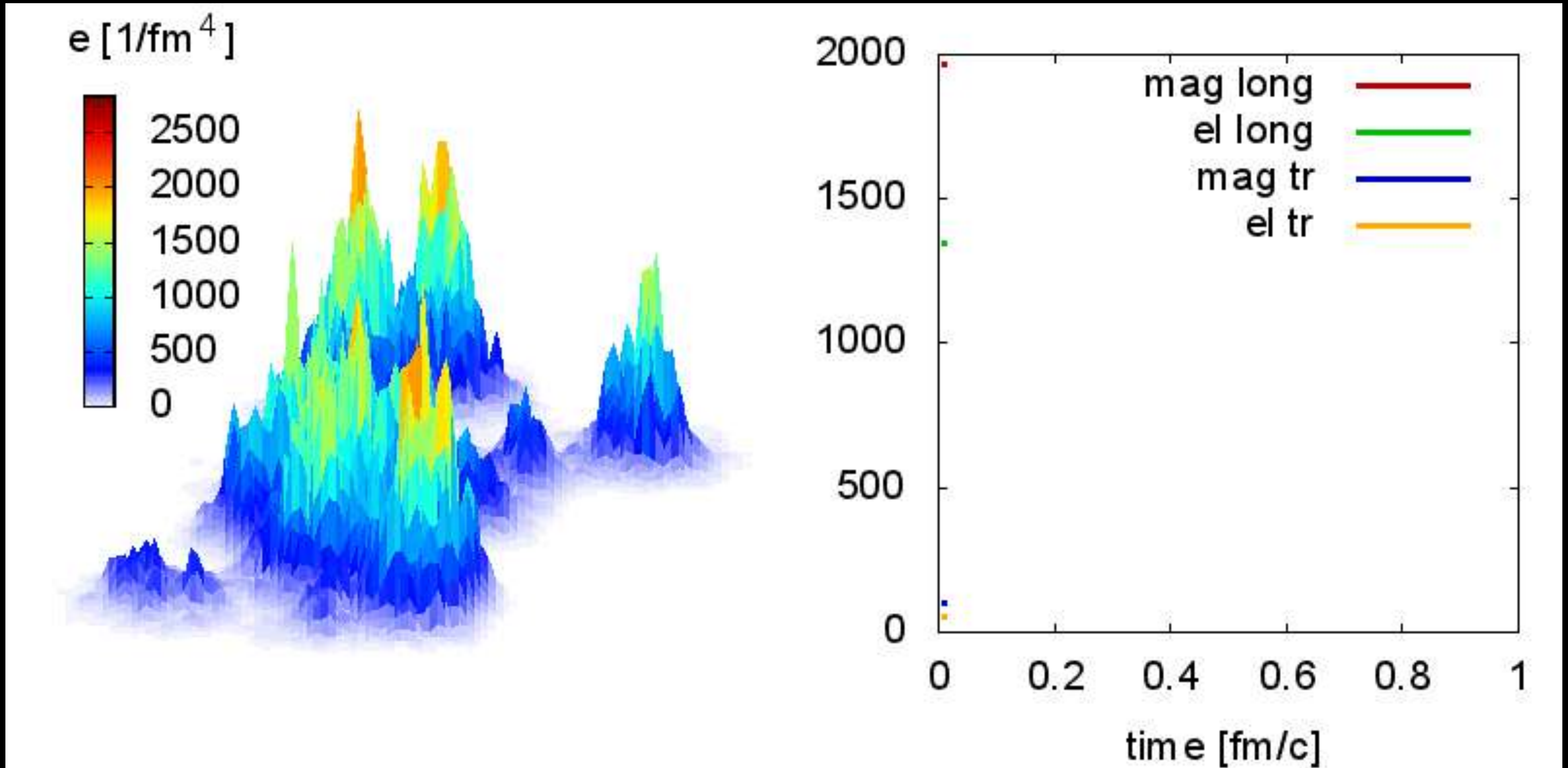
$$A^\eta_{(3)}|_{\tau=0^+} = \frac{ig}{2}[A^i_{(1)}, A^i_{(2)}]$$

From gluon fields to hydrodynamics

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Evolve produced fields in time using Yang Mills equations
- Compute energy-momentum tensor $T^{\mu\nu}(\vec{x})$ of the gluon fields

$$T^{\tau\tau} = \frac{1}{2}(E^\eta)^2 + \frac{1}{2\tau^2}[(E^x)^2 + (E^y)^2] + \frac{1}{2}F_{xy}F_{xy} + \frac{1}{2\tau^2}(F_{x\eta}^2 + F_{y\eta}^2)$$



Relativistic fluid dynamics

- Effective theory for the long wavelength modes, valid for a strongly interacting system

- Basic equations: **energy and momentum conservation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

energy density (ε), pressure (P), flow velocity (u^μ), viscous correction ($\Pi^{\mu\nu}$)

- + constituent equations for $\Pi^{\mu\nu}$ (contains shear viscosity η and bulk viscosity ζ, possibly heat conductivity and higher order transport coefficients)

- Equation of state $P(\varepsilon)$ relates pressure to energy density (from lattice QCD)

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Relativistic hydrodynamic evolution

MUSIC hydrodynamic simulation: Au+Au collision at top RHIC energy

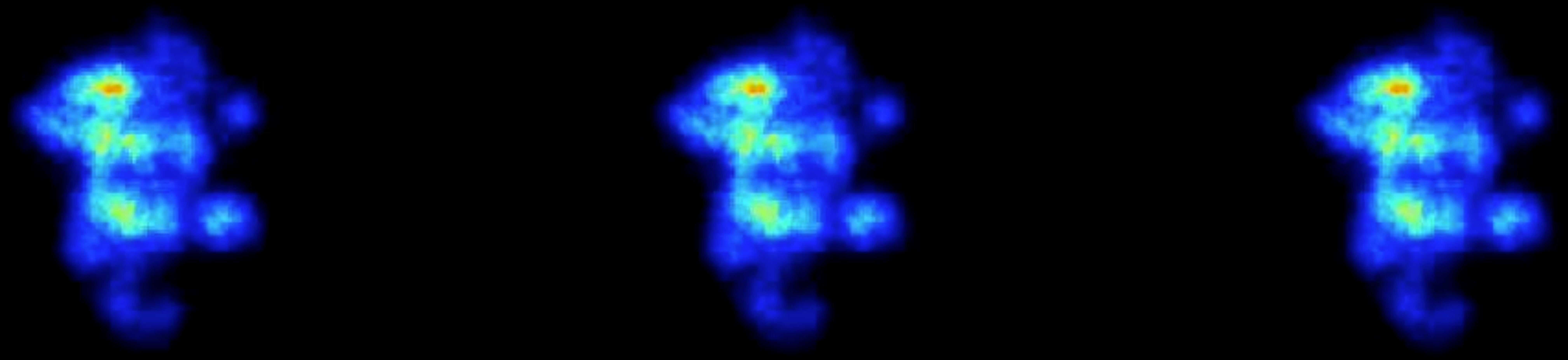
B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

Duration ~10 fm/c ≈ 3 ×10^{-23} s, contours of constant temperature shown

Effect of shear viscosity

C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)

$\eta/s = 0$ $\eta/s = 0.1$ $\eta/s = 0.2$



t = 0.40 fm

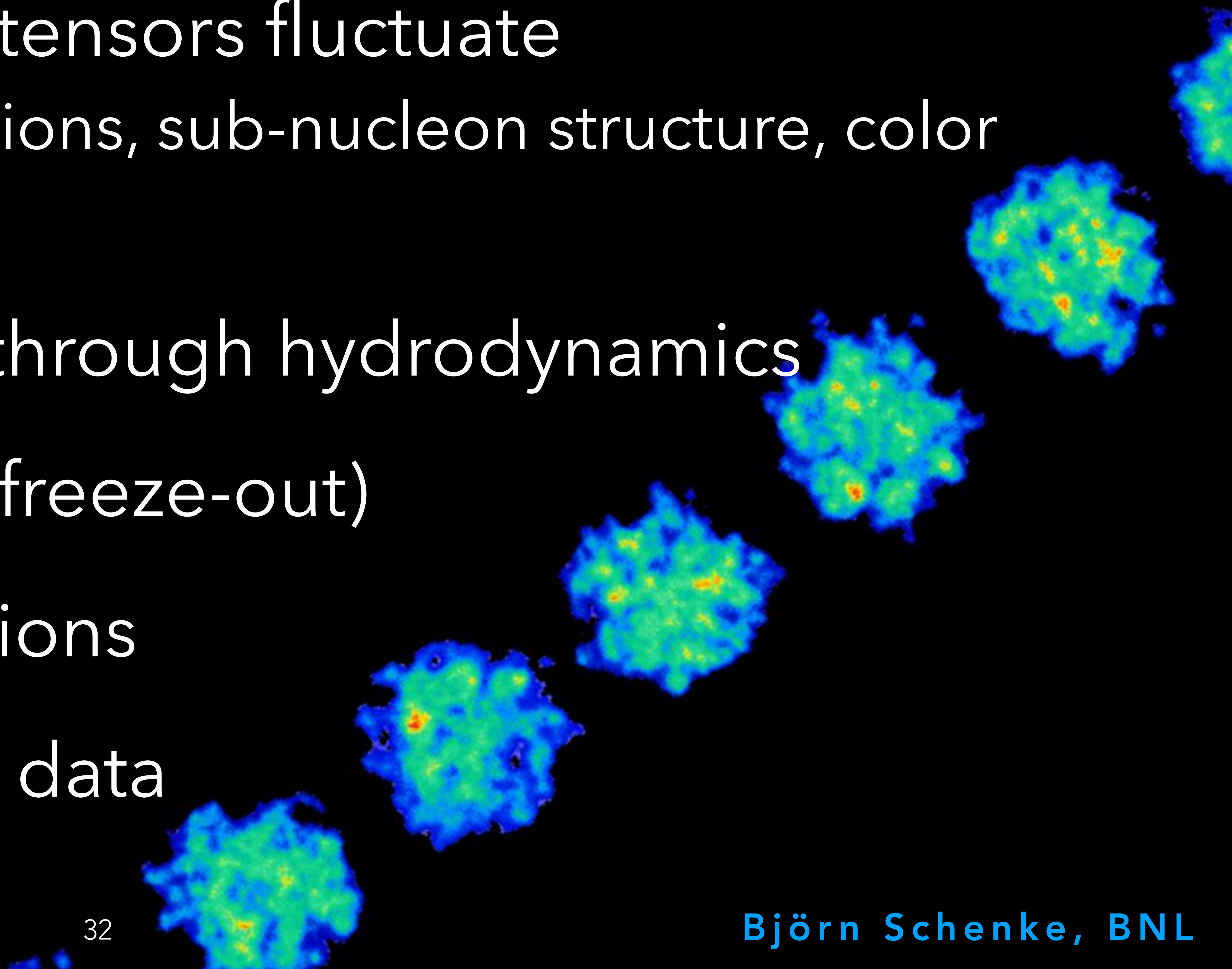
MUSIC hydrodynamic simulation

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

Event-by-event fluid dynamics

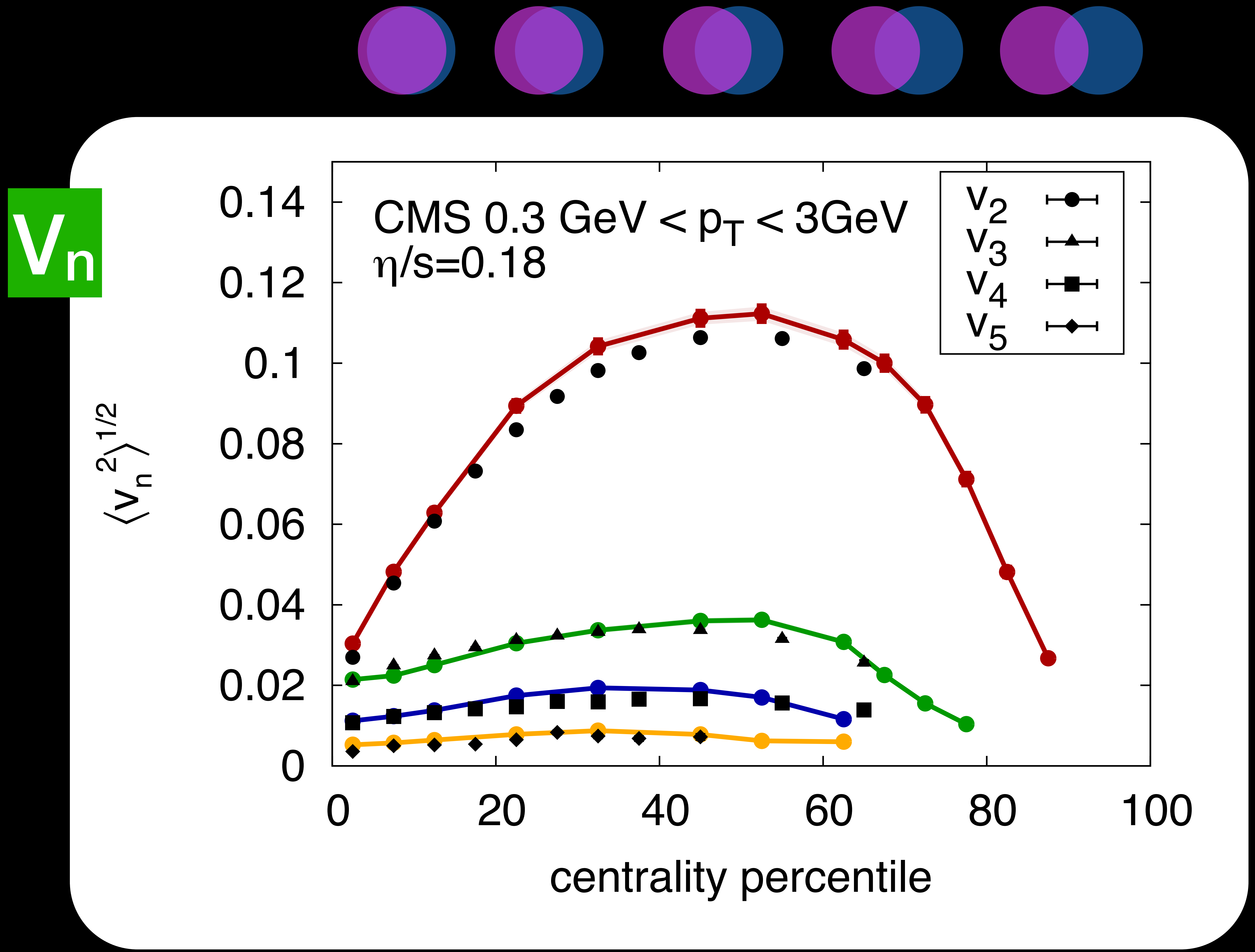
C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)

- Initial energy momentum tensors fluctuate
  (Fluctuations of nucleon positions, sub-nucleon structure, color charges, impact parameter)
- Run many configurations through hydrodynamics
- Convert fluid to particles (freeze-out)
- Compute particle correlations
- Compare to experimental data



Comparing to experimental results: LHC

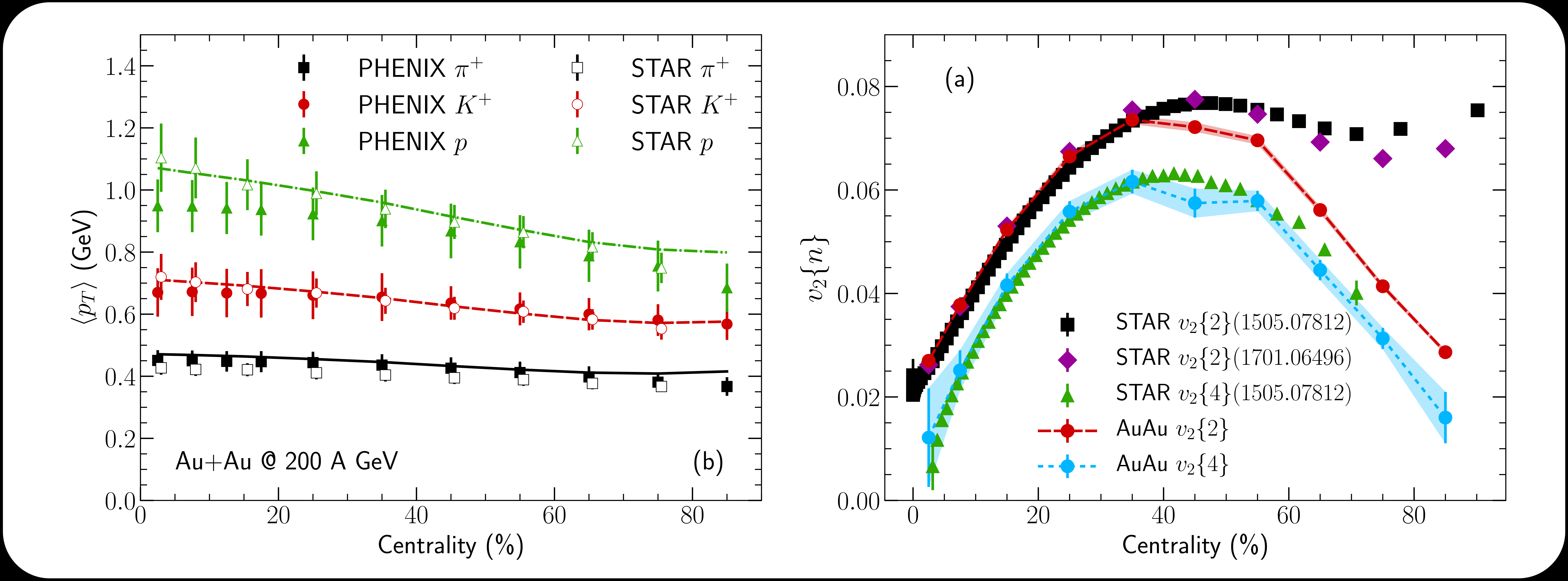
C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301



CMS Collaboration, PRC 87(2013) 014902

Comparing to experimental results: RHIC

B.Schenke, C. Shen, P.Tribedy, Phys.Rev. C99 (2019) no.4, 044908

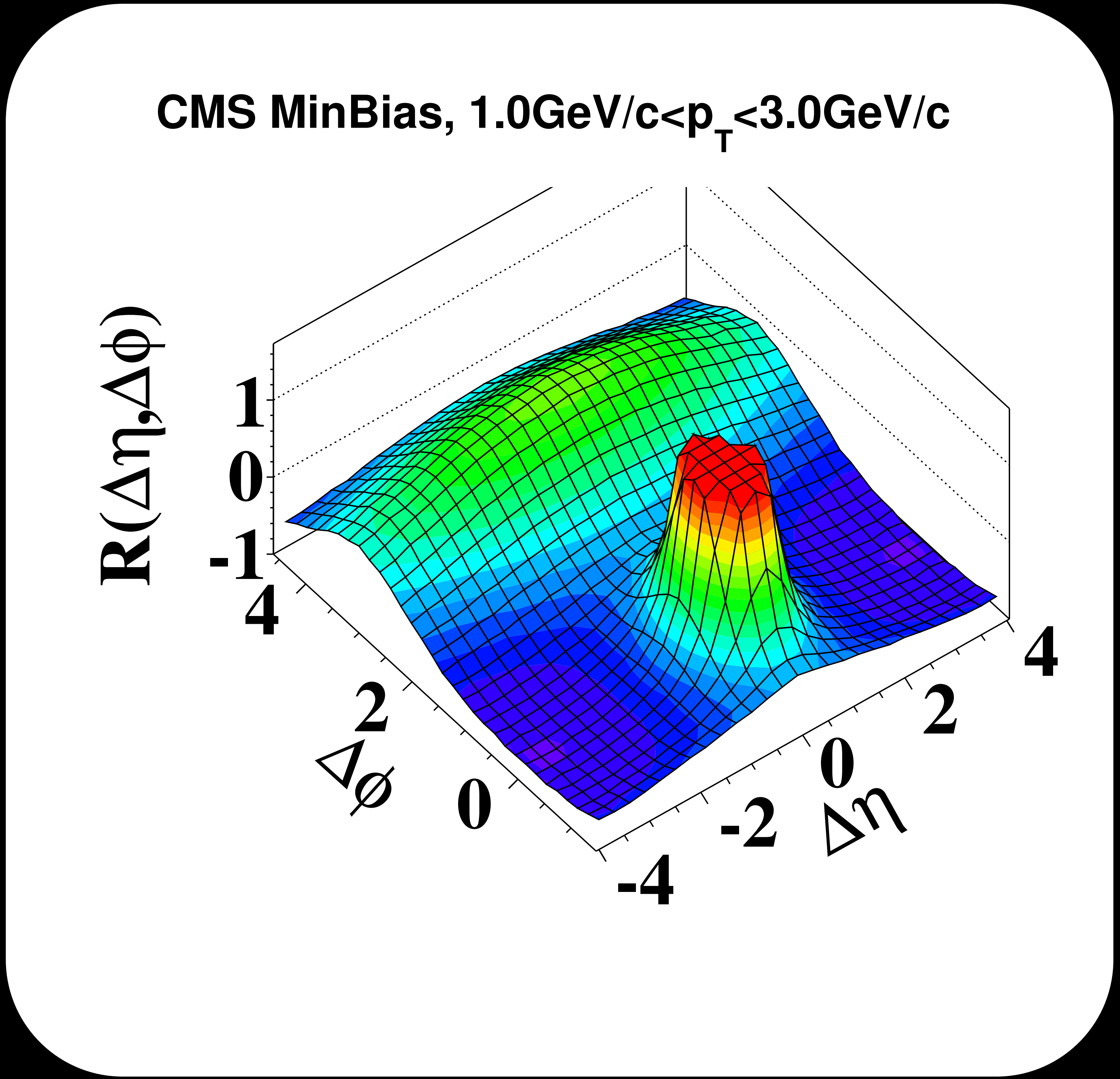


PHENIX Collaboration, Phys. Rev. C69, 034909 (2004), STAR Collaboration, Phys. Rev. C79, 034909 (2009)
STAR Collaboration, Phys. Rev. Lett. 115, 222301 (2015); Phys. Rev. C98, 034918 (2018),

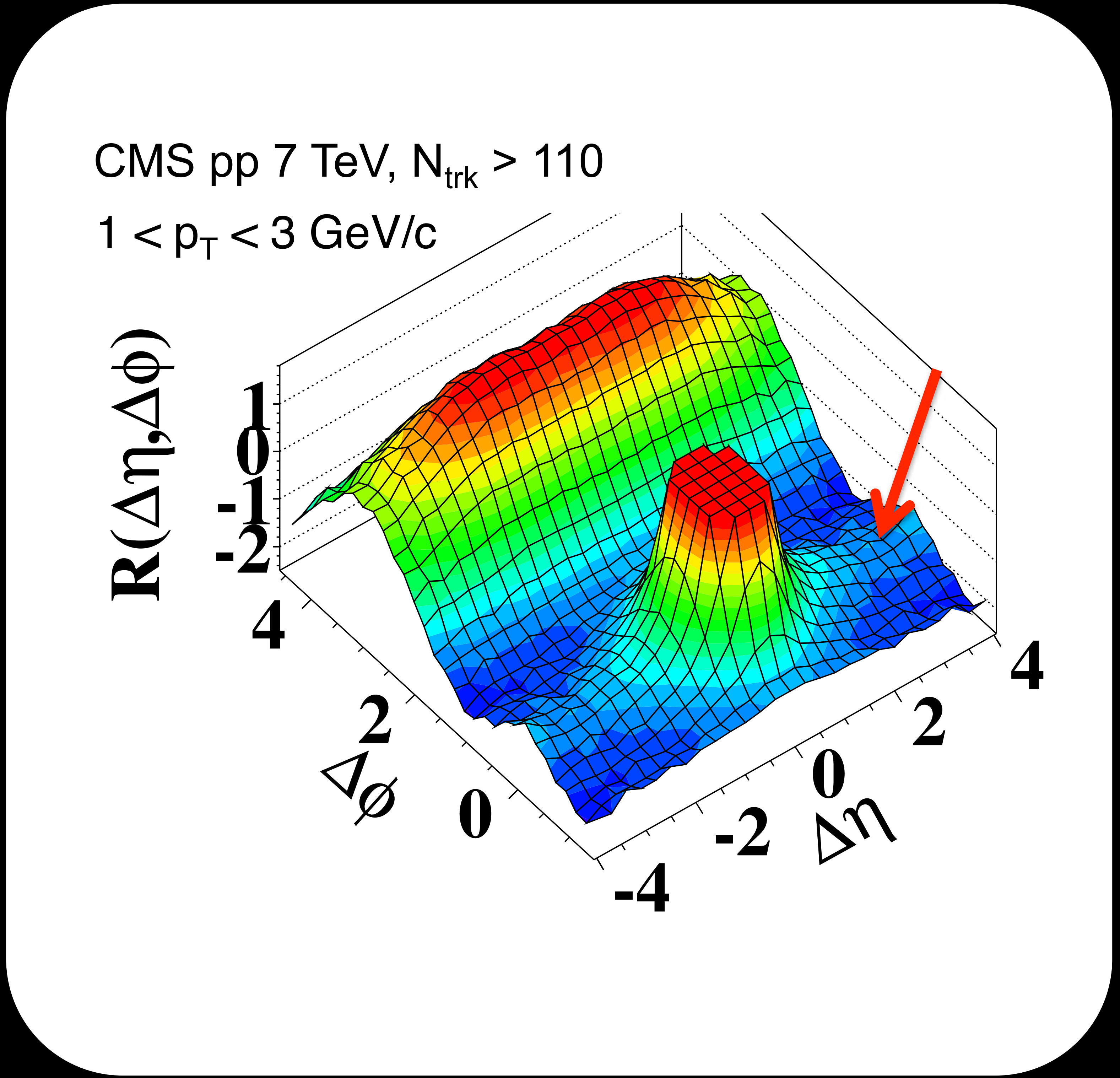
Going smaller ... (~10× smaller)

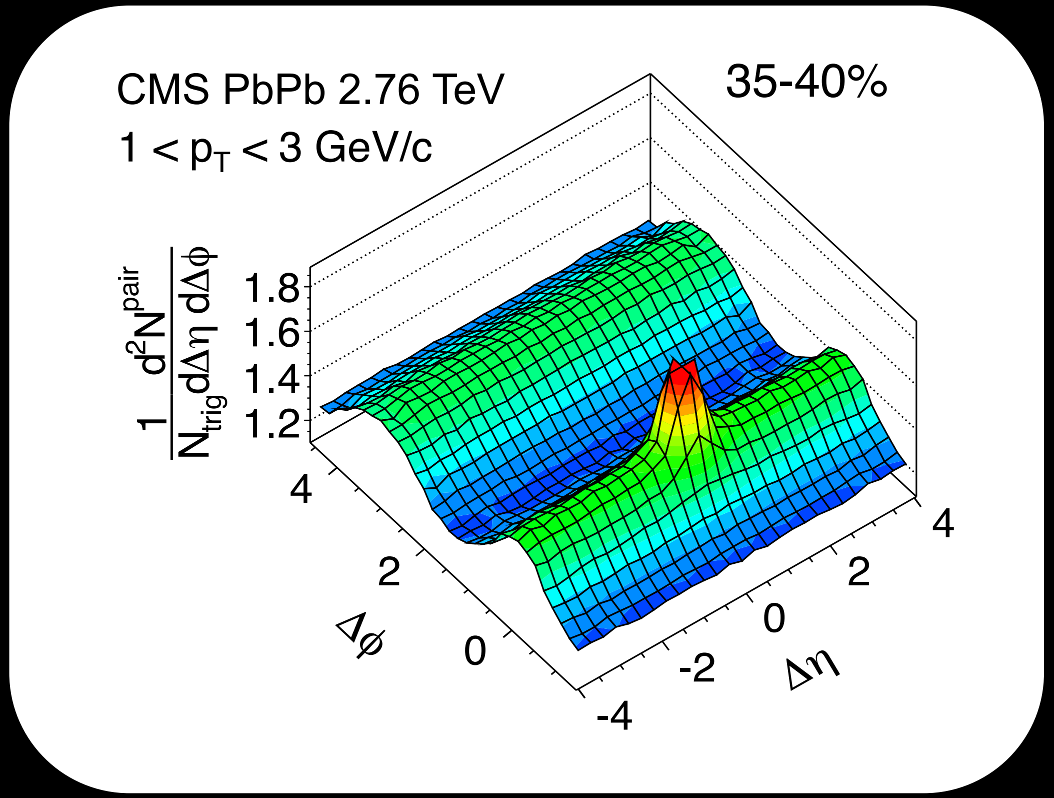
proton →  ← proton

minimum bias p+p



high multiplicity p+p



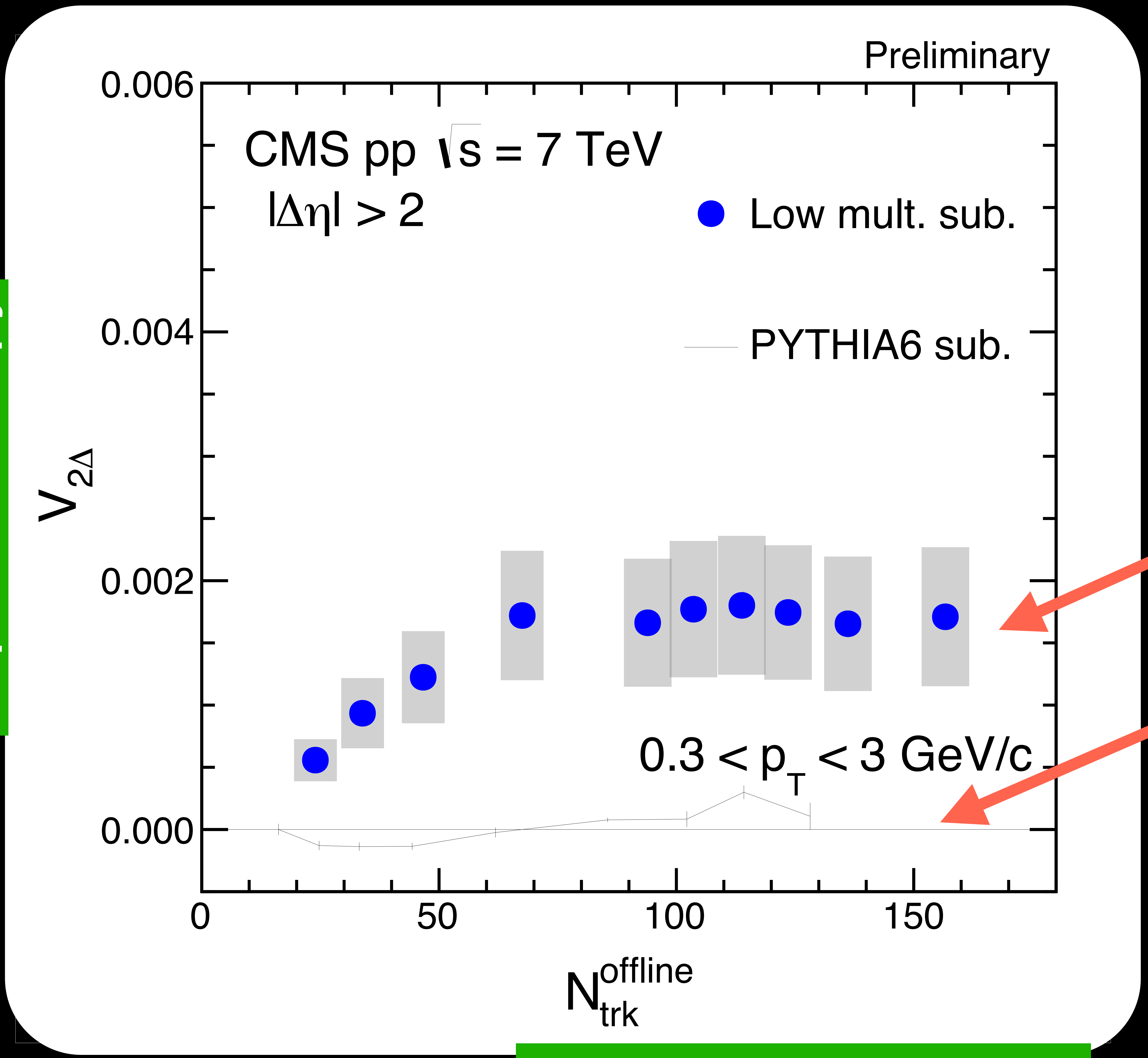


remember PbPb

CMS Collaboration, JHEP09 (2010) 091

Björn Schenke, BNL

Anisotropy in p+p collisions



elliptic anisotropy

# of produced particles

CMS PAS HIN-15-009

Result after correcting for back-to-back jet correlations estimated from low multiplicity events

v_2 in the p+p data

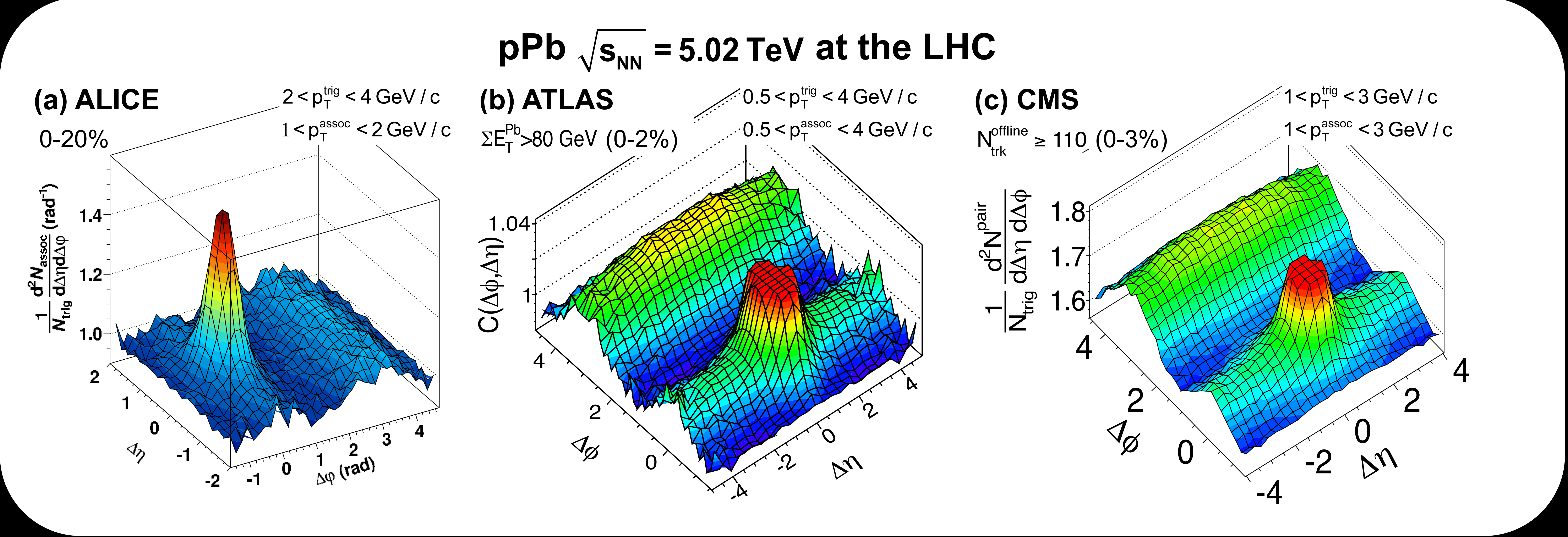
No v_2 in PYTHIA

Our pp standard tools miss this physics entirely!

New extensions to PYTHIA try to include the effect (final state)

see C. Bierlich, G. Gustafson, L. Lönnblad Phys.Lett. B779 (2018) 58-63

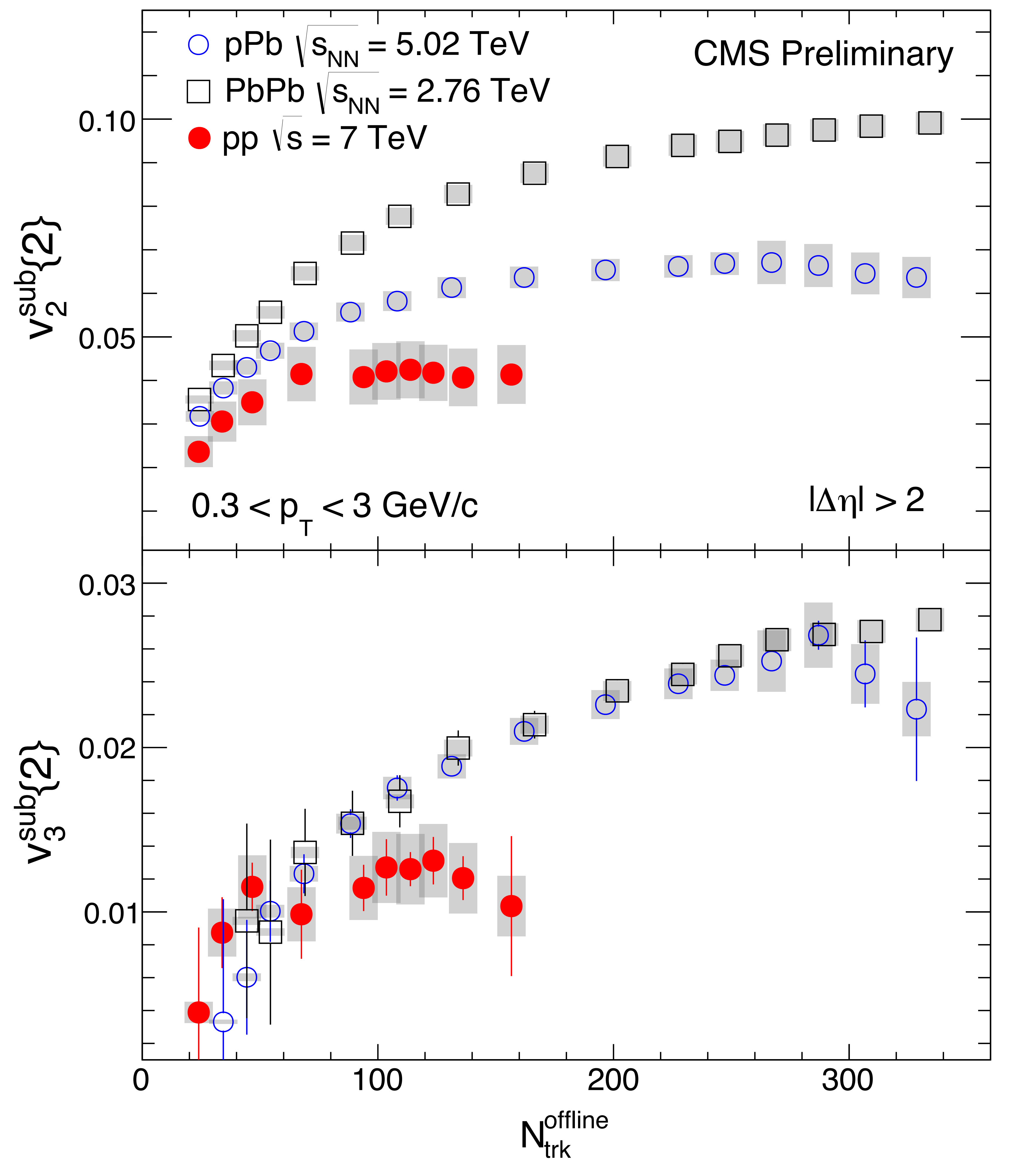
Intermediate size: p+Pb collisions



high multiplicity p+Pb

ALICE Collaboration, Phys. Lett. B 719 (2013) 29
ATLAS Collaboration, Phys. Rev. Lett. 110 (2013) 182302
CMS Collaboration, Phys. Lett. B 718 (2013) 795

v_2 in p+p, p+Pb, Pb+Pb collisions



CMS PAS HIN-15-009

see also:

ALICE Collaboration
Phys. Lett. B719 (2013) 29-41
Phys. Rev. C 90, 054901

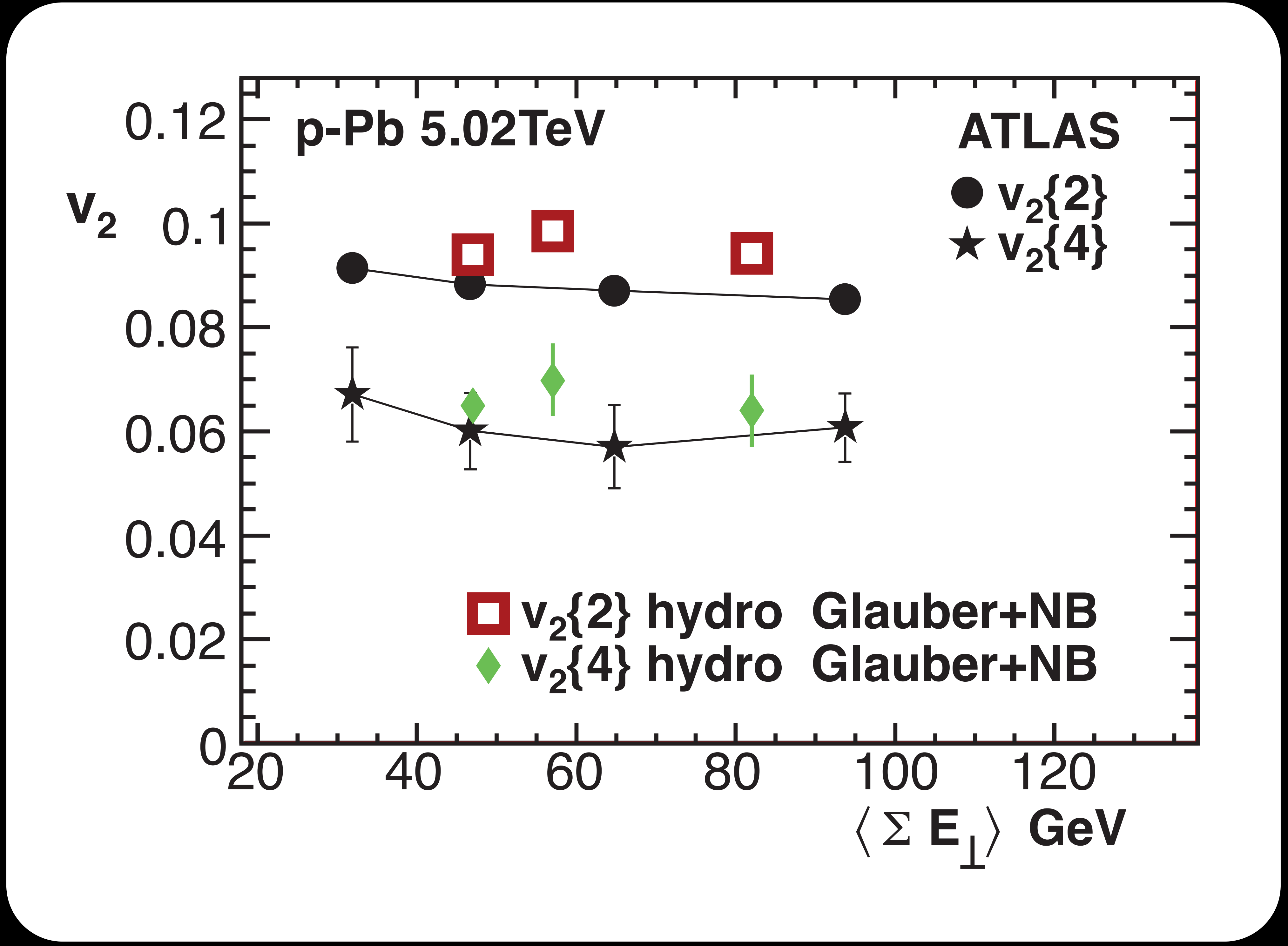
ATLAS Collaboration
Phys. Rev. Lett. 110, 182302 (2013);
Phys. Rev. C 90.044906 (2014)

CMS Collaboration
Phys.Rev.Lett. 115, 012301 (2015)

Hydrodynamics in small systems

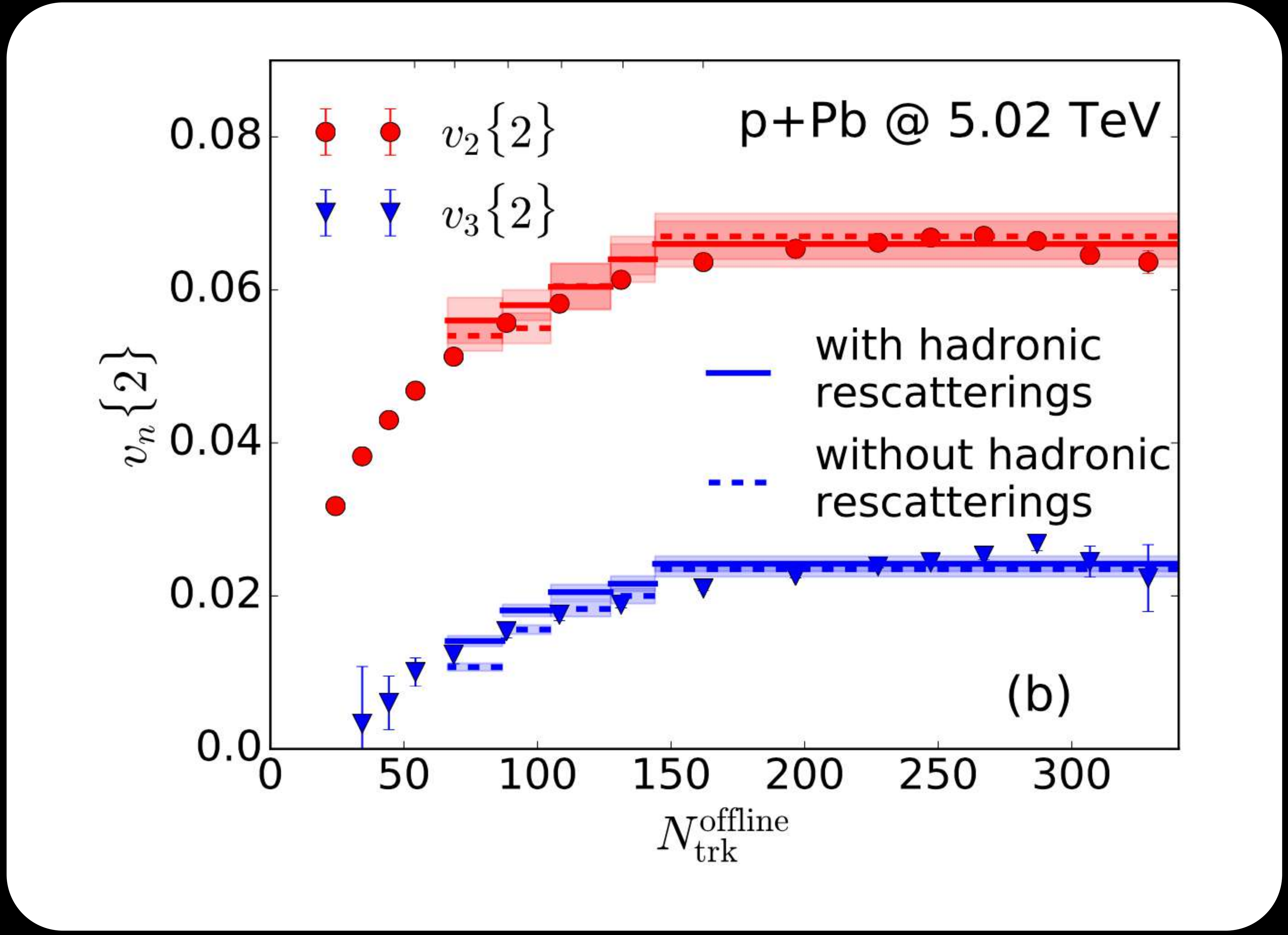
Simple fluctuating initial state + hydrodynamics describes the data

ATLAS Coll. PLB725 (2013) 60-78



Bozek, Broniowski, PRC88 (2013) 014903

CMS Coll. PLB724, 213–240 (2013)

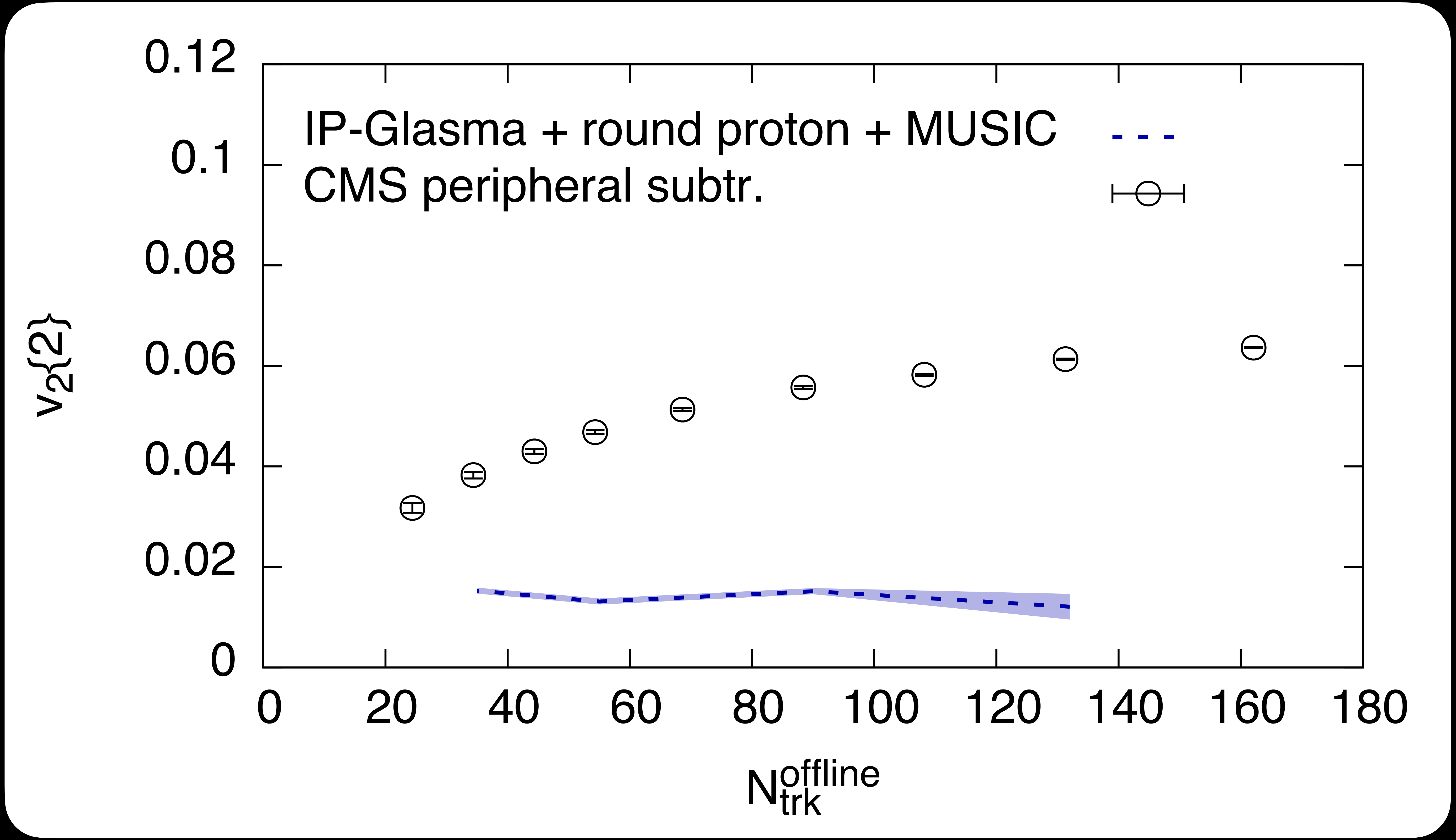


Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; …

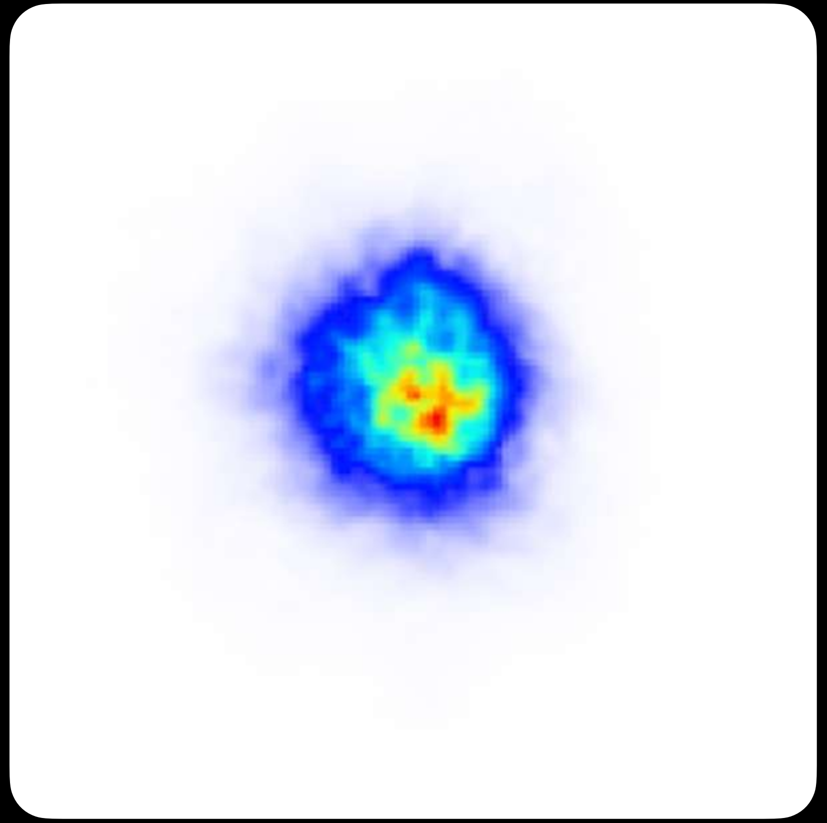
p+Pb v_2 IP-Glasma + MUSIC

Did not work

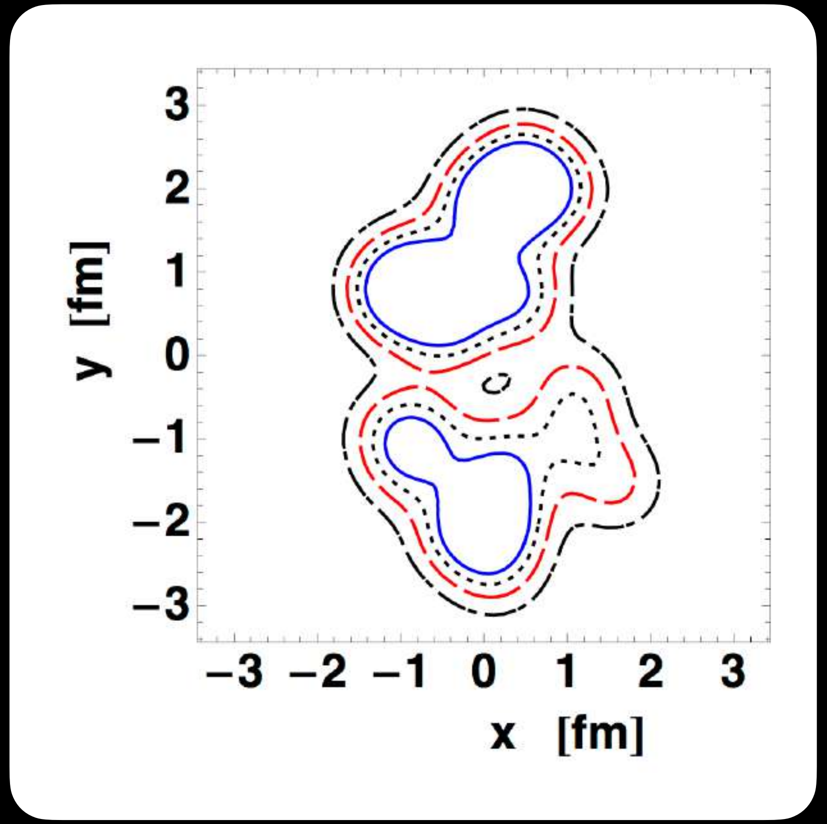


B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)
Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

IP-Glasma



other initial state

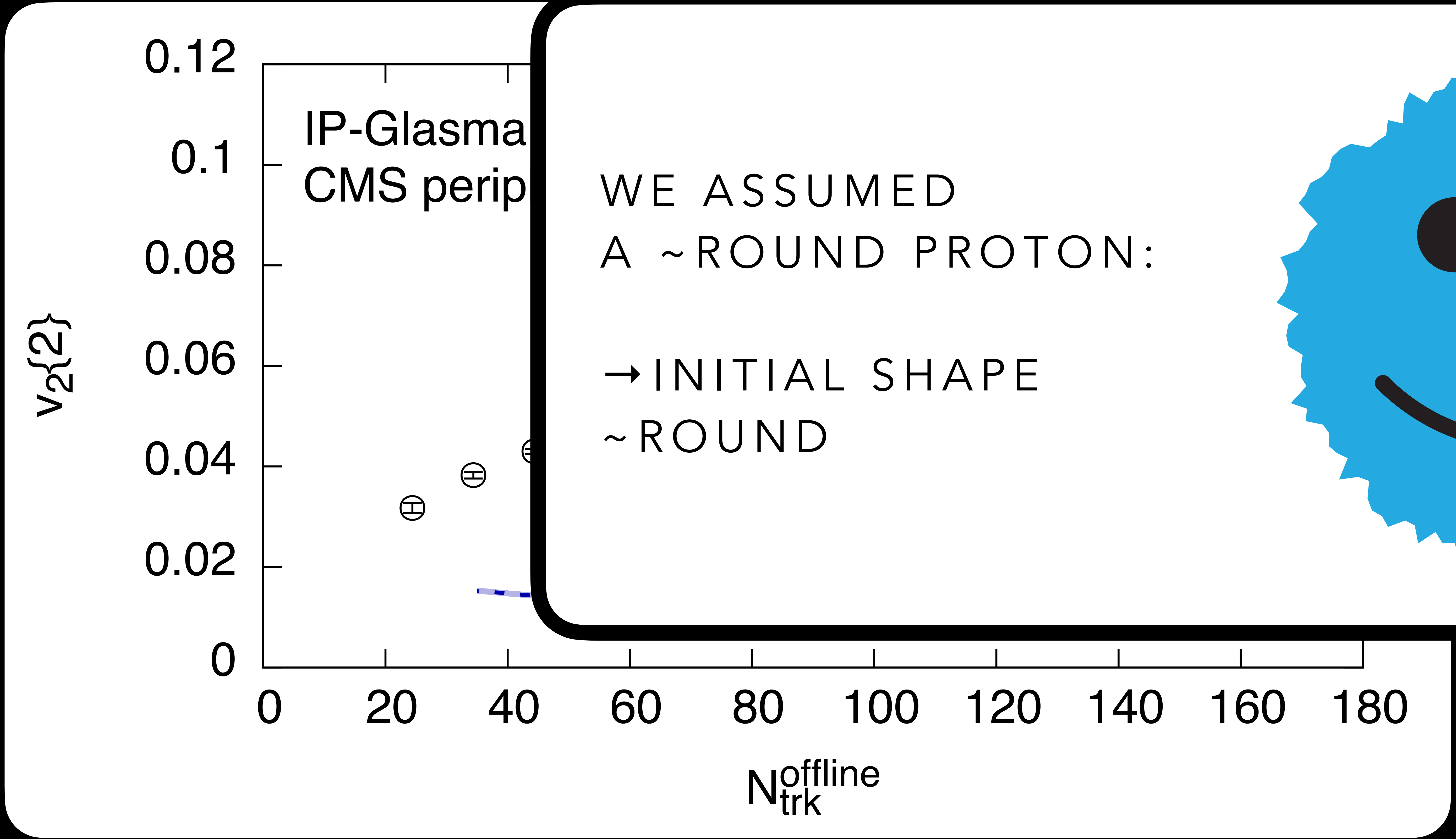


P. Bozek, Phys.Rev. C85 (2012) 014911

p+Pb v_2 IP-Glasma + MUSIC

Did not work

Initial state was missing physics

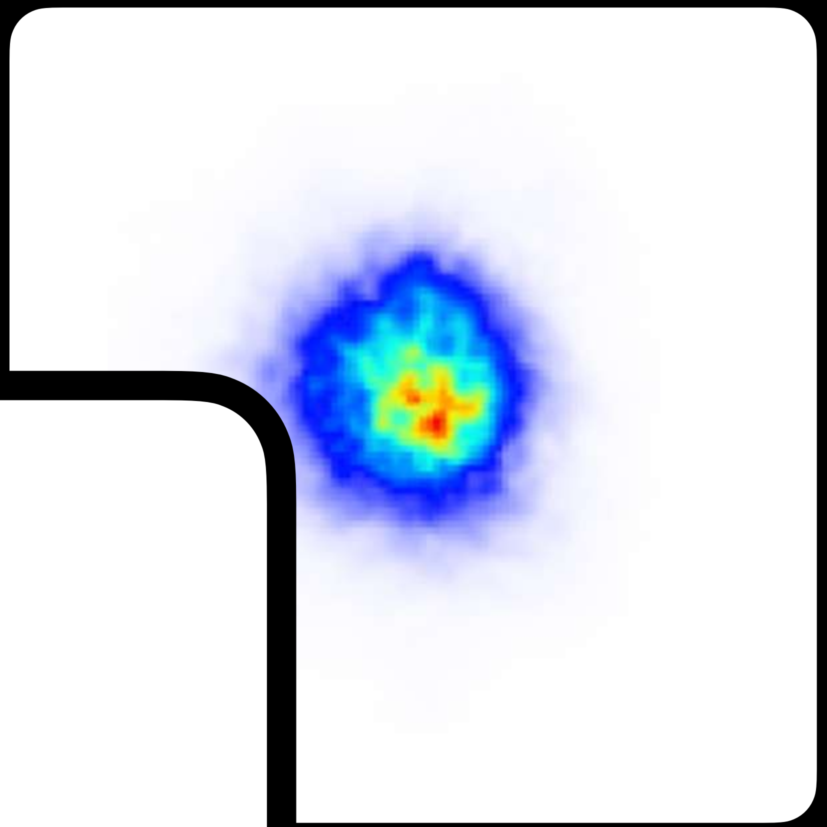


WE ASSUMED
A ~ROUND PROTON:

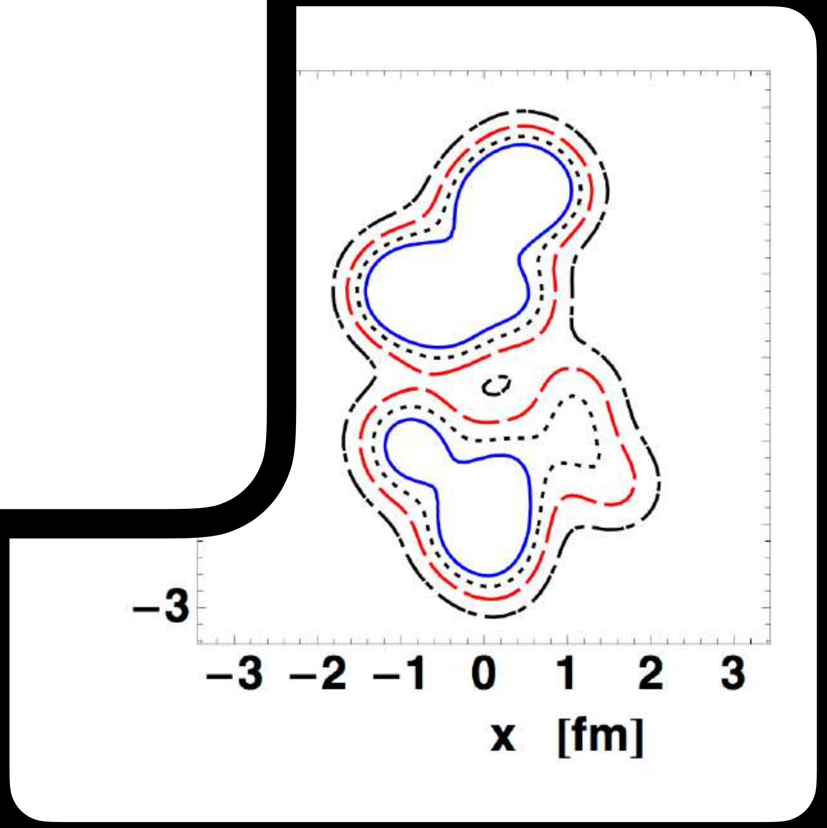
→INITIAL SHAPE
~ROUND

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)
Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

IP-Glasma



nitial state



P. Bozek, Phys.Rev. C85 (2012) 014911

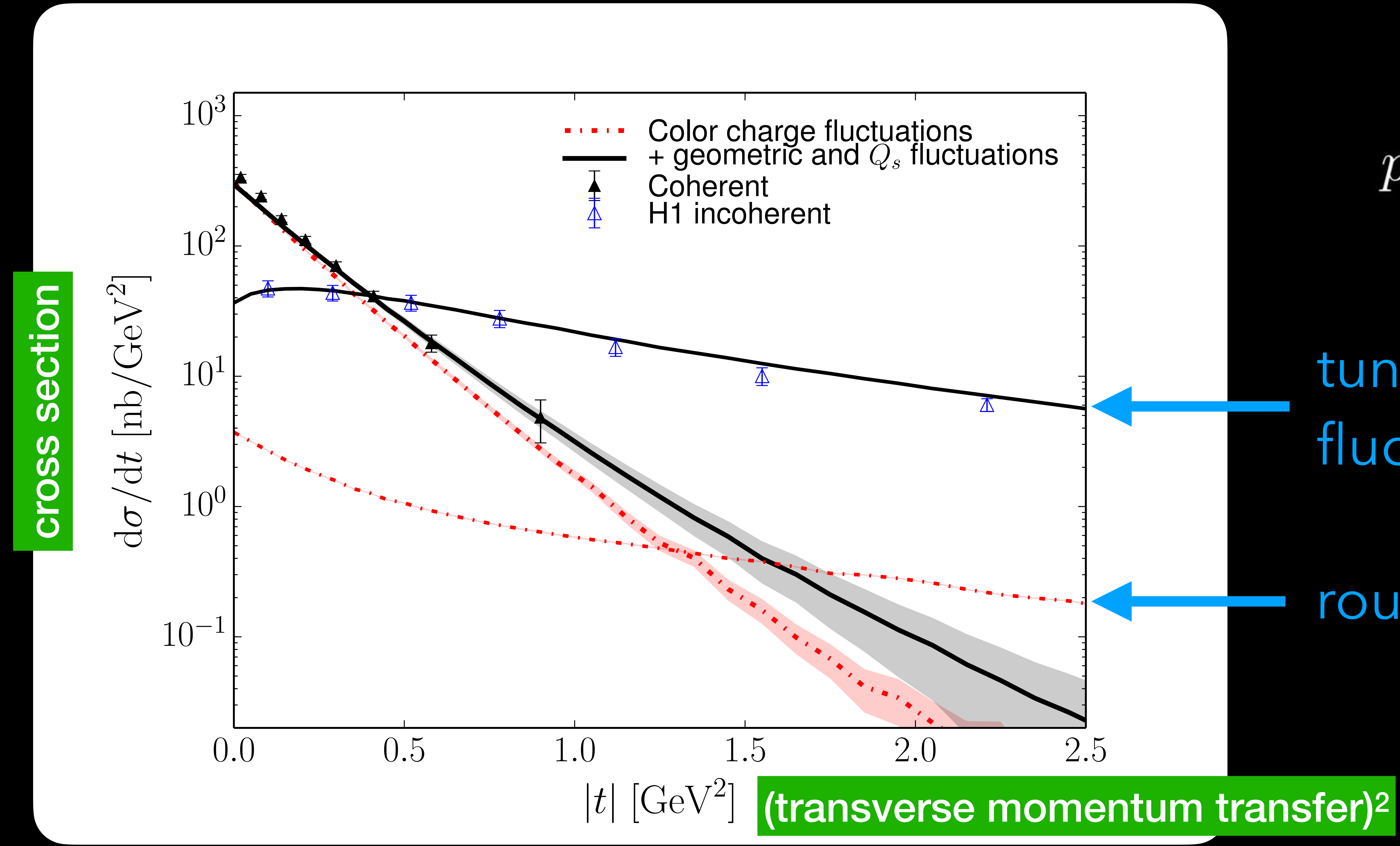
Include proton shape fluctuations - and constrain them

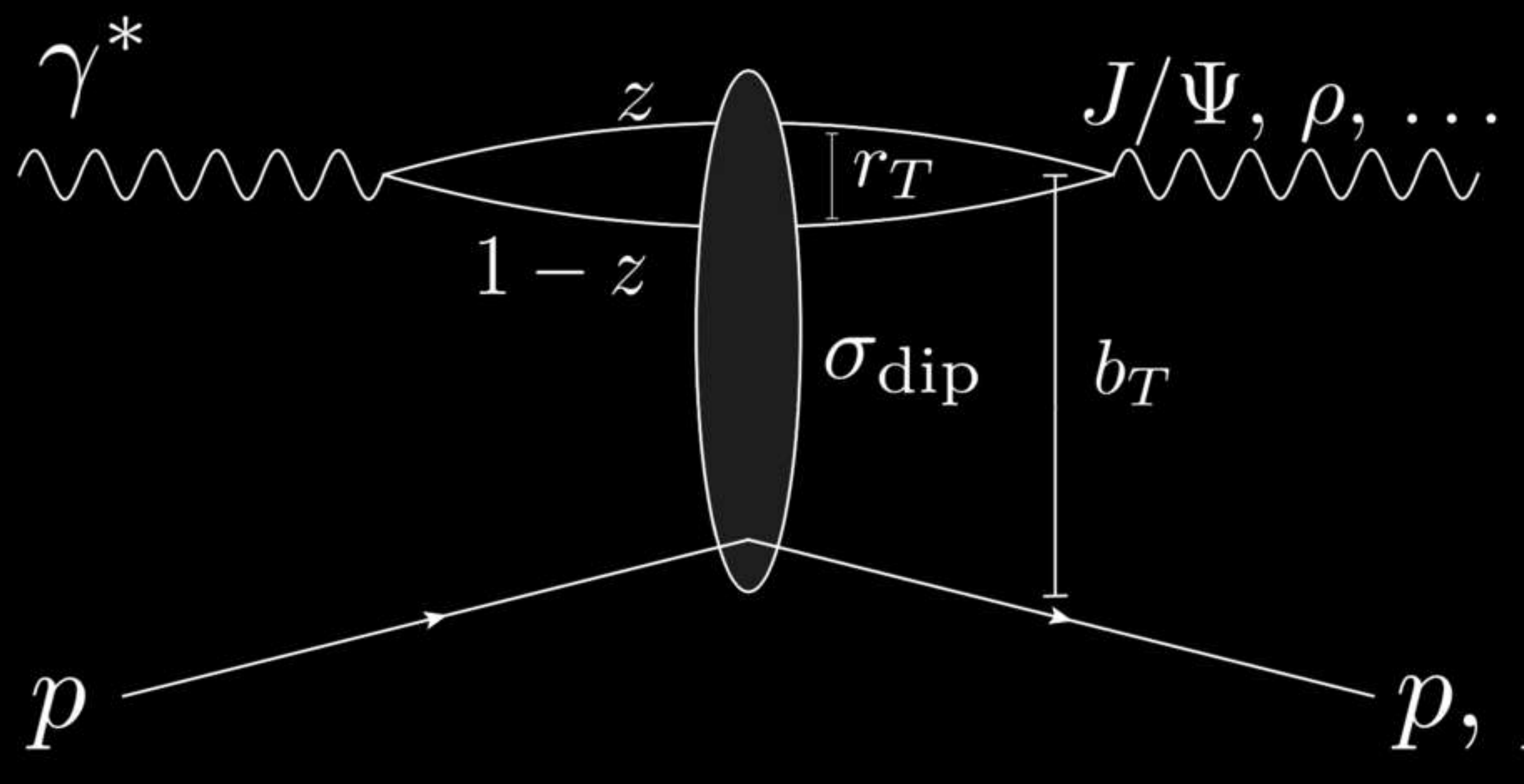
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

also see S. Schlichting, B. Schenke, Phys.Lett. B739 (2014) 313-319

Exclusive diffractive J/Ψ production:

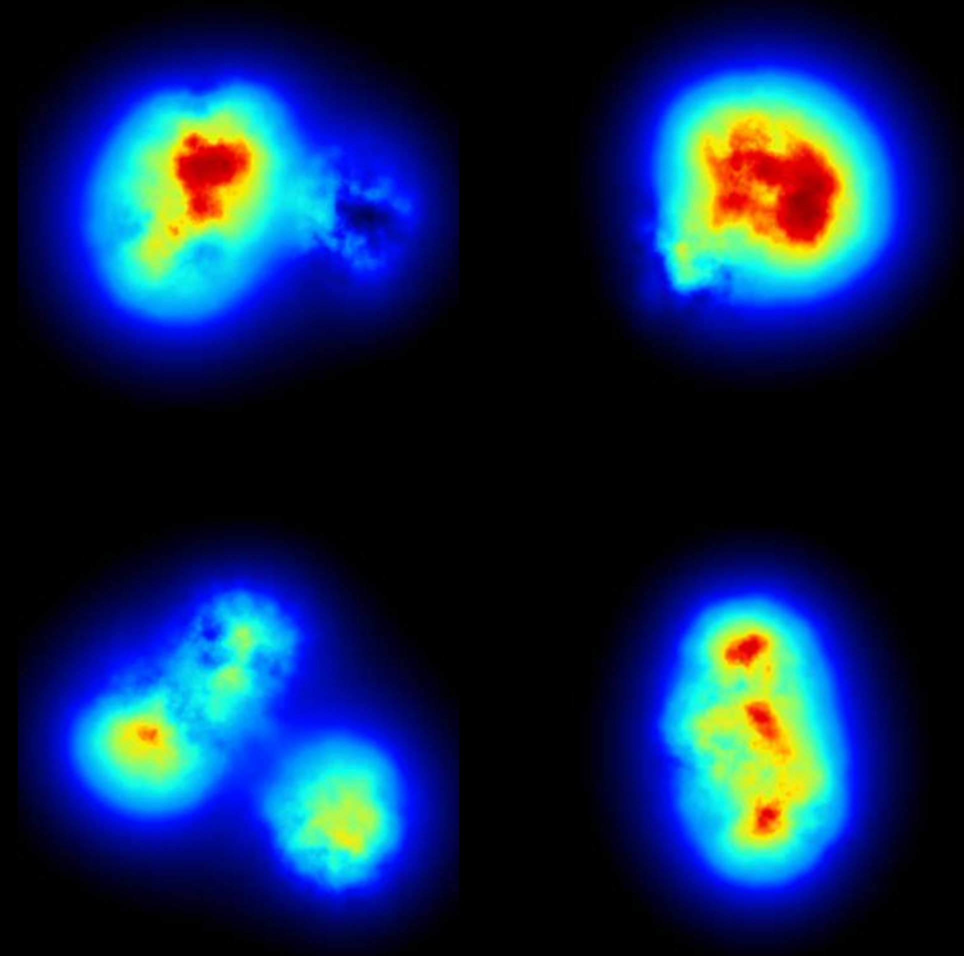
Incoherent x-sec sensitive to fluctuations





tuned shape fluctuations

round proton



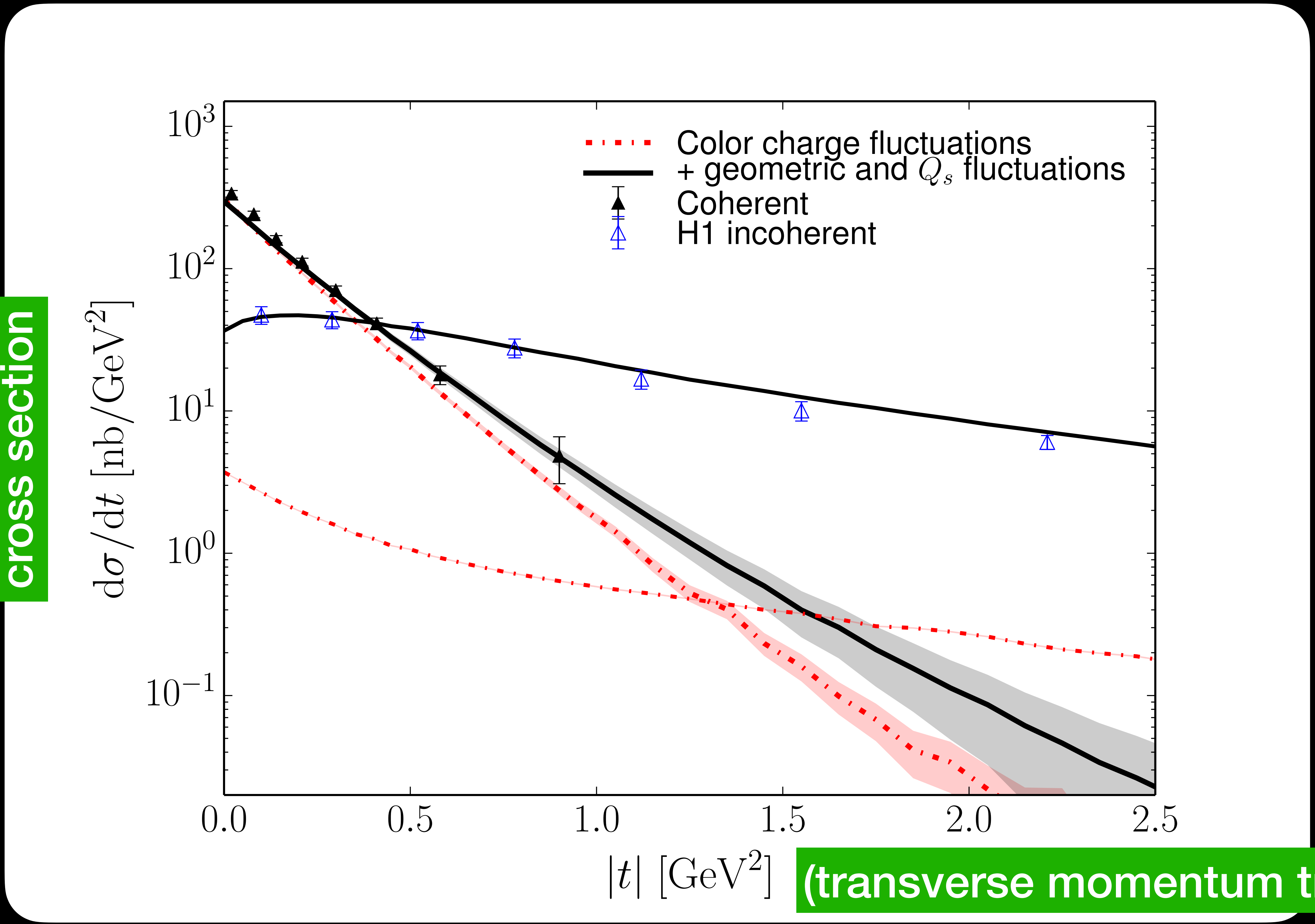
H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

Need proton shape fluctuations - and constrain them

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042
also see S. Schlichting, B. Schenke, Phys.Lett. B739 (2014) 313-319

Exclusive diffractive J/Ψ production:

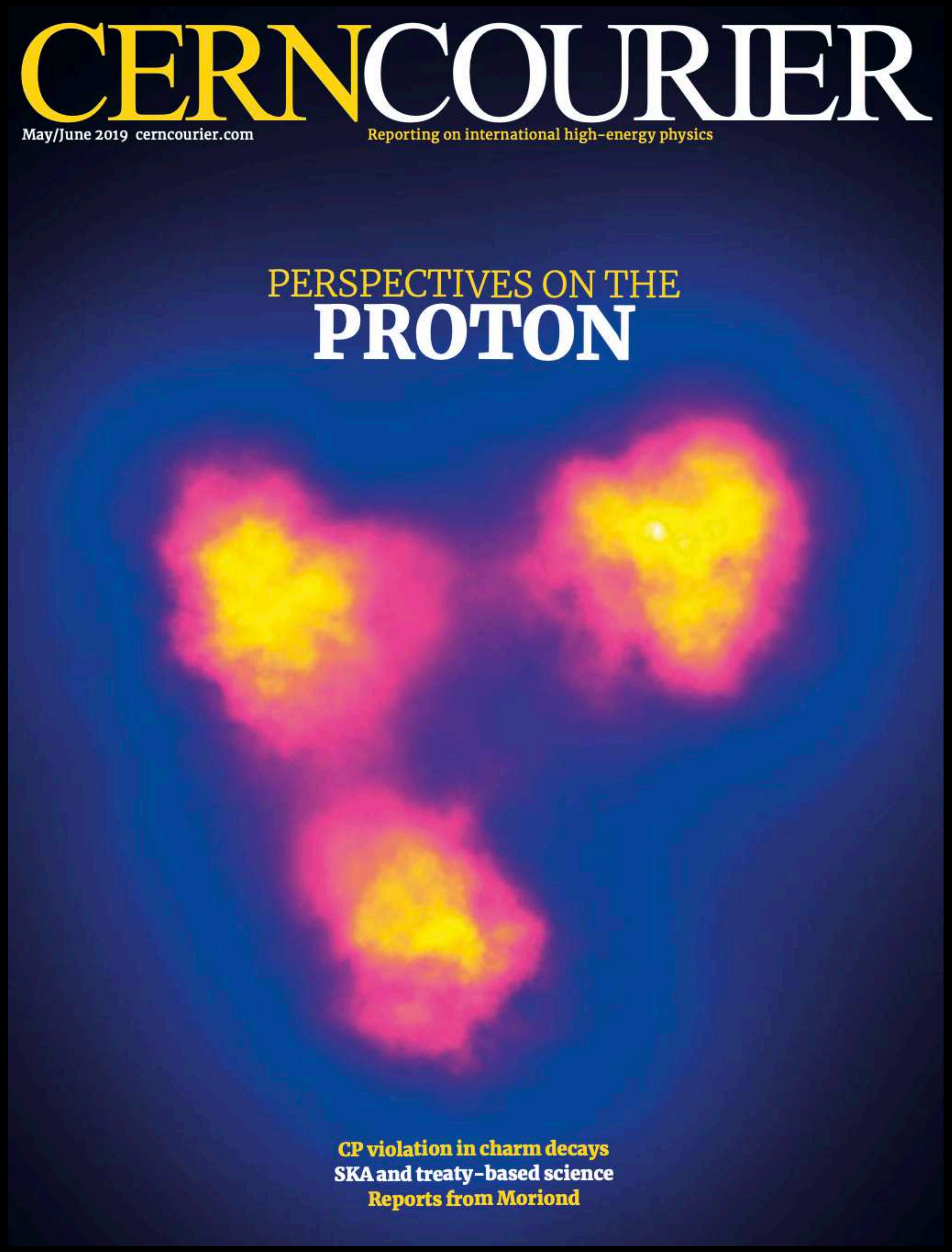
Incoherent x-sec sensitive to fluctuations



cross section

(transverse momentum transfer)^2

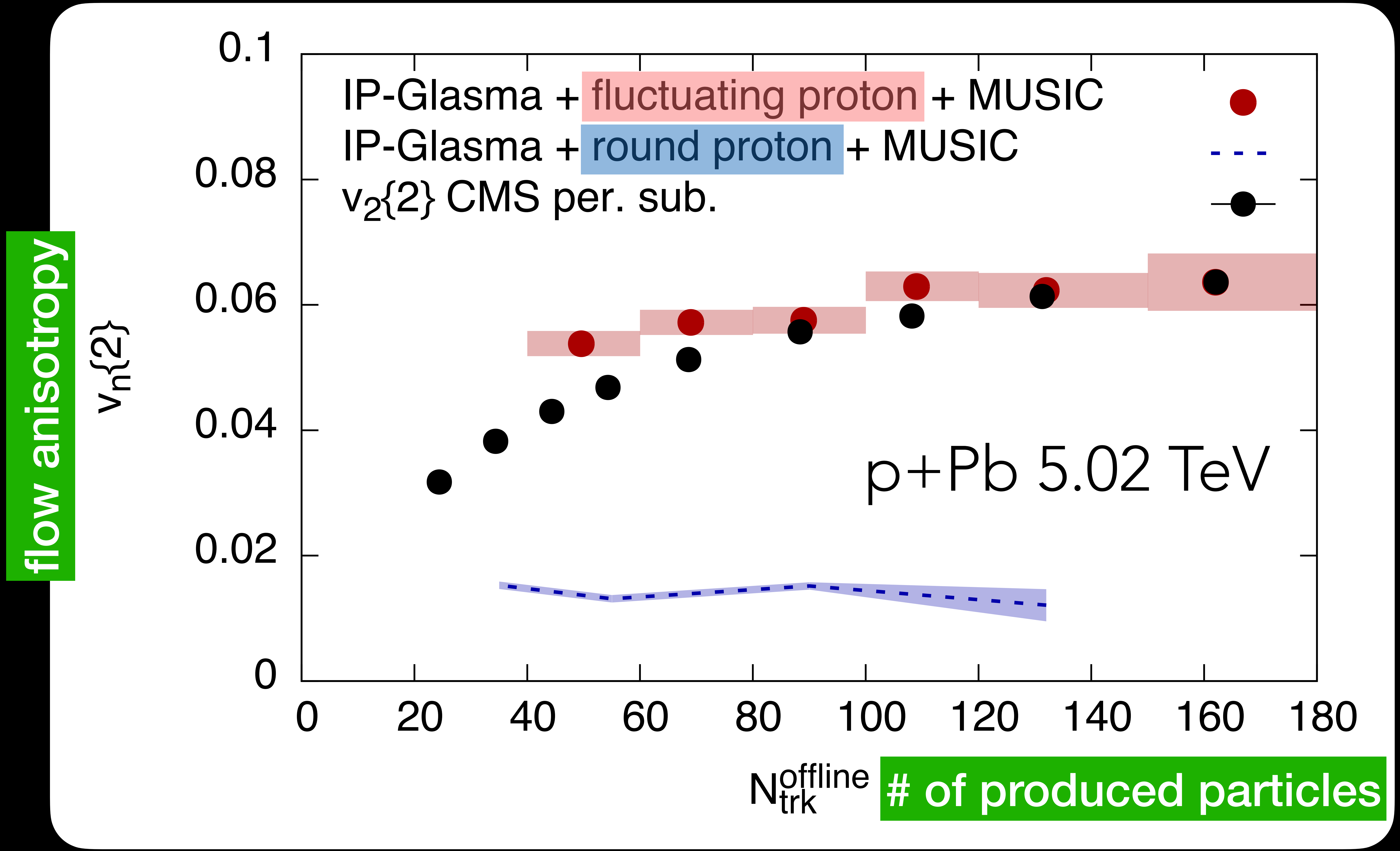
H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466



also see H. Mäntysaari, arXiv:2001.10705 submitted to Reports on Progress in Physics

Effect of proton structure in p+A collisions

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys.Lett. B772 (2017) 681-686

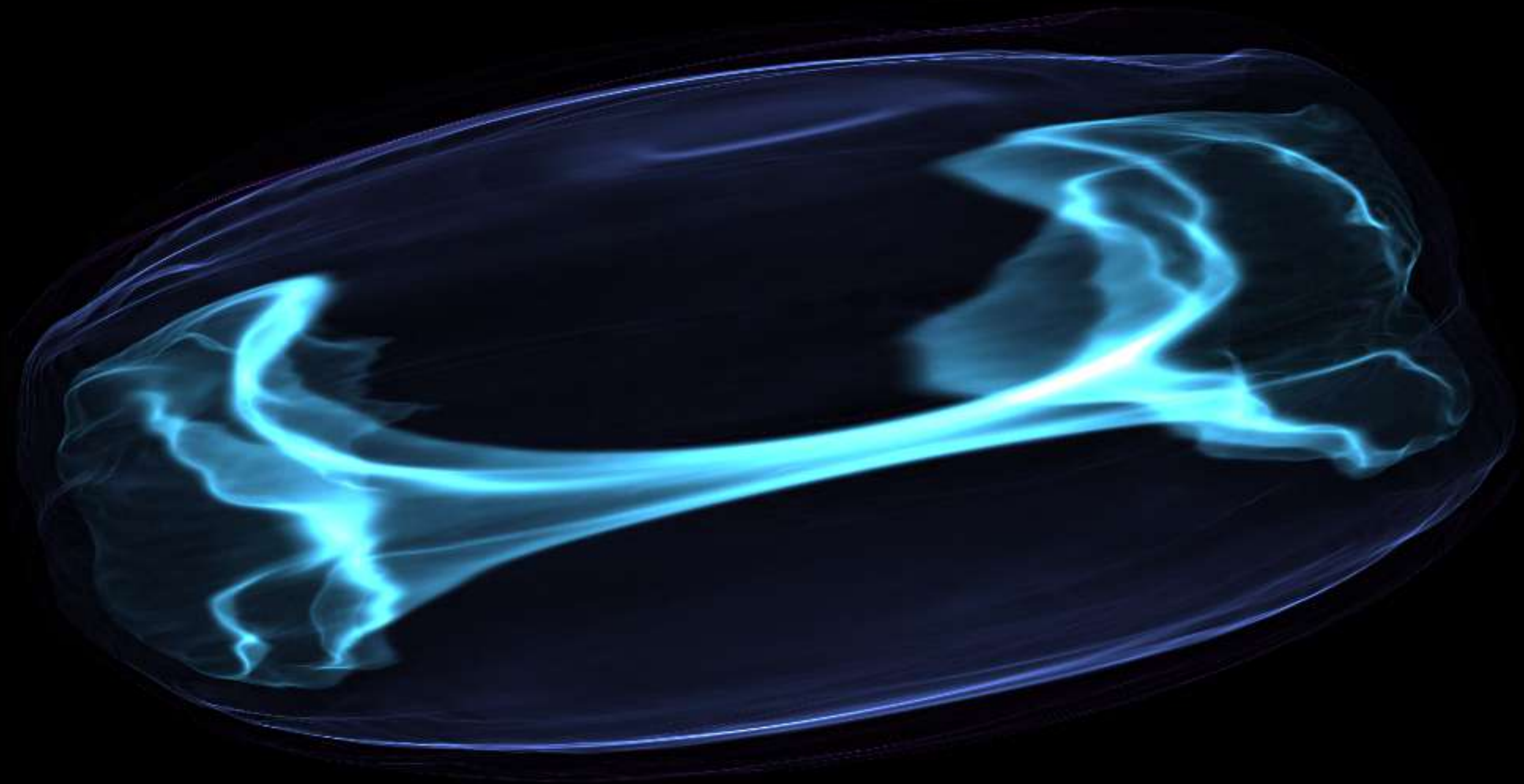


Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

A smaller fluid…

MUSIC hydrodynamic simulation: top RHIC energy

p+Au collision



Au+Au collision

duration ~3 fm/c, contours of constant temperature shown

Success?

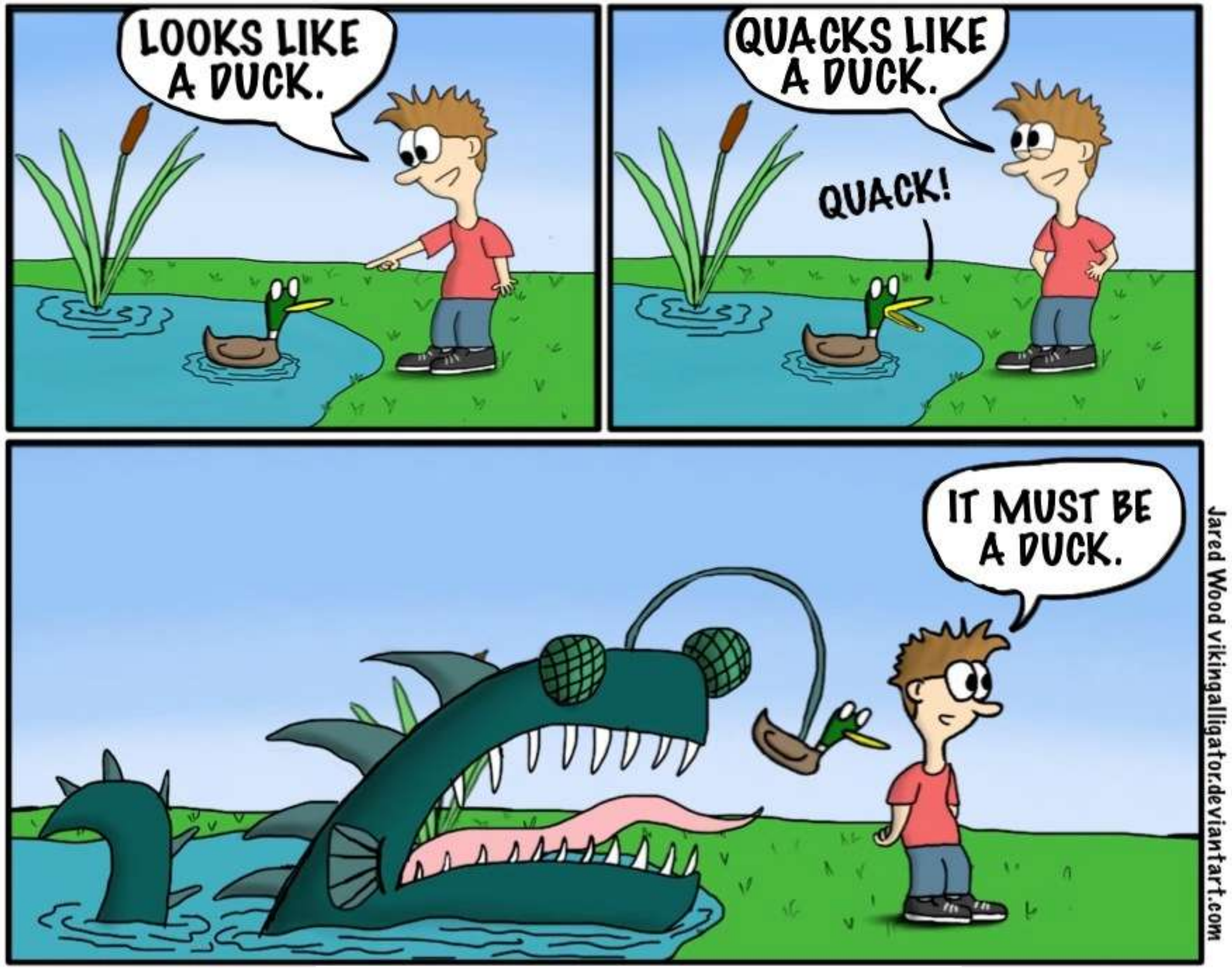
✓ Fluctuating proton + IP-Glasma + MUSIC hydro can describe observations in p+A collisions well

We are sensitive to the shape of the proton and its fluctuations:
Study of v_n distributions in p+A collisions almost like snapping pictures of individual proton shape configurations

✗ Main caveat is the applicability of hydrodynamics:
Non-equilibrium corrections can be large in small systems

- Does not mean what we see is not a final state effect
- For progress in understanding the success of hydrodynamics in describing systems far from equilibrium see
  W. Florkowski, M. P. Heller, M. Spalinski, Rept.Prog.Phys. 81 (2018) no.4, 046001

Initial state momentum correlations

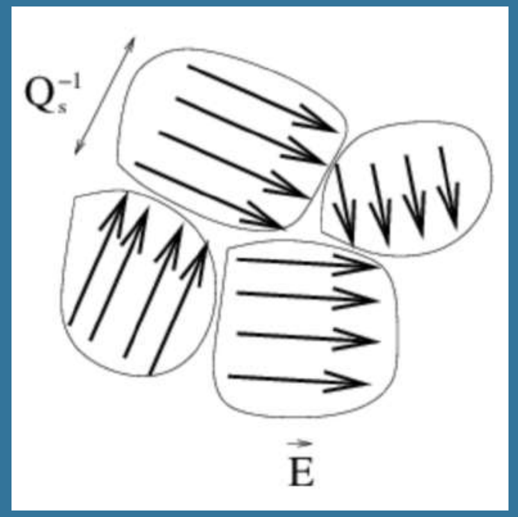
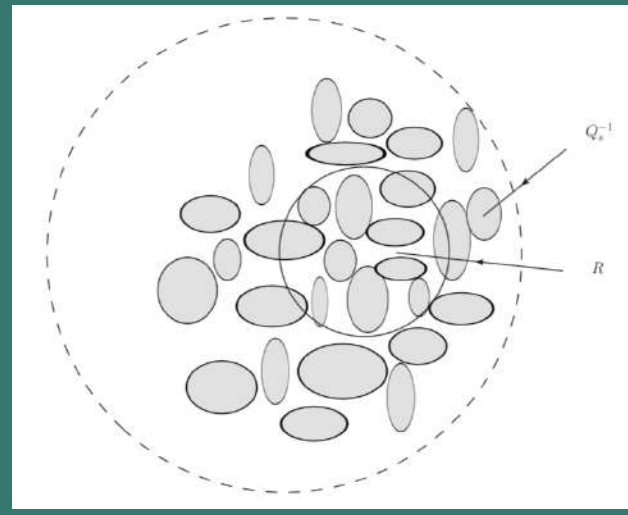


Björn Schenke, BNL

Initial state correlations

Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009); Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010); Dusling, Venugopalan PRD 87 (2013); A. Dumitru, A.V. Giannini, Nucl.Phys.A933 (2014) 212; V. Skokov. Phys.Rev.D91 (2015) 054014; T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061; Kovner, Skokov, Phys.Rev. D98 (2018) no.1, 014004; ...

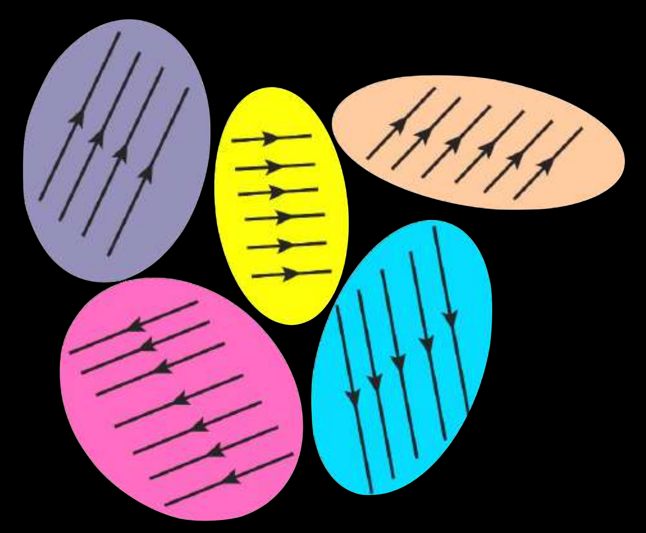
Sources of correlations in the CGC:

Classical	Quantum
Local anisotropy  $1/Q_s$	Bose enhancement in incoming wave function
Density gradients $\frac{dQ_s}{db}/Q_s$	Gluonic HBT 

Incoming gluons need to be close in the transverse plane to feel the same local structure of the target.

Both come with similar contribution for enhancement of anti-aligned momenta of same magnitude

Initial state picture generates anisotropy



Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009)
Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010);
A. Dumitru, K. Dusling, F. Gelis, J. Jalilian-Marian, T. Lappi, R. Venugopalan, PLB697 (2011) 21-25
Dusling, Venugopalan PRD 87 (2013) 5, 051502; PRD 87 (2013) 5, 054014; PRD 87 (2013) 9, 094034
M. Mace, V. Skokov, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 121, 052301 (2018)

Can we distinguish initial from final state effects?

Study different collision systems: Allows to control initial geometry

NEW: Study the correlation between v_2 and $\langle p_T \rangle$

RHIC system scan

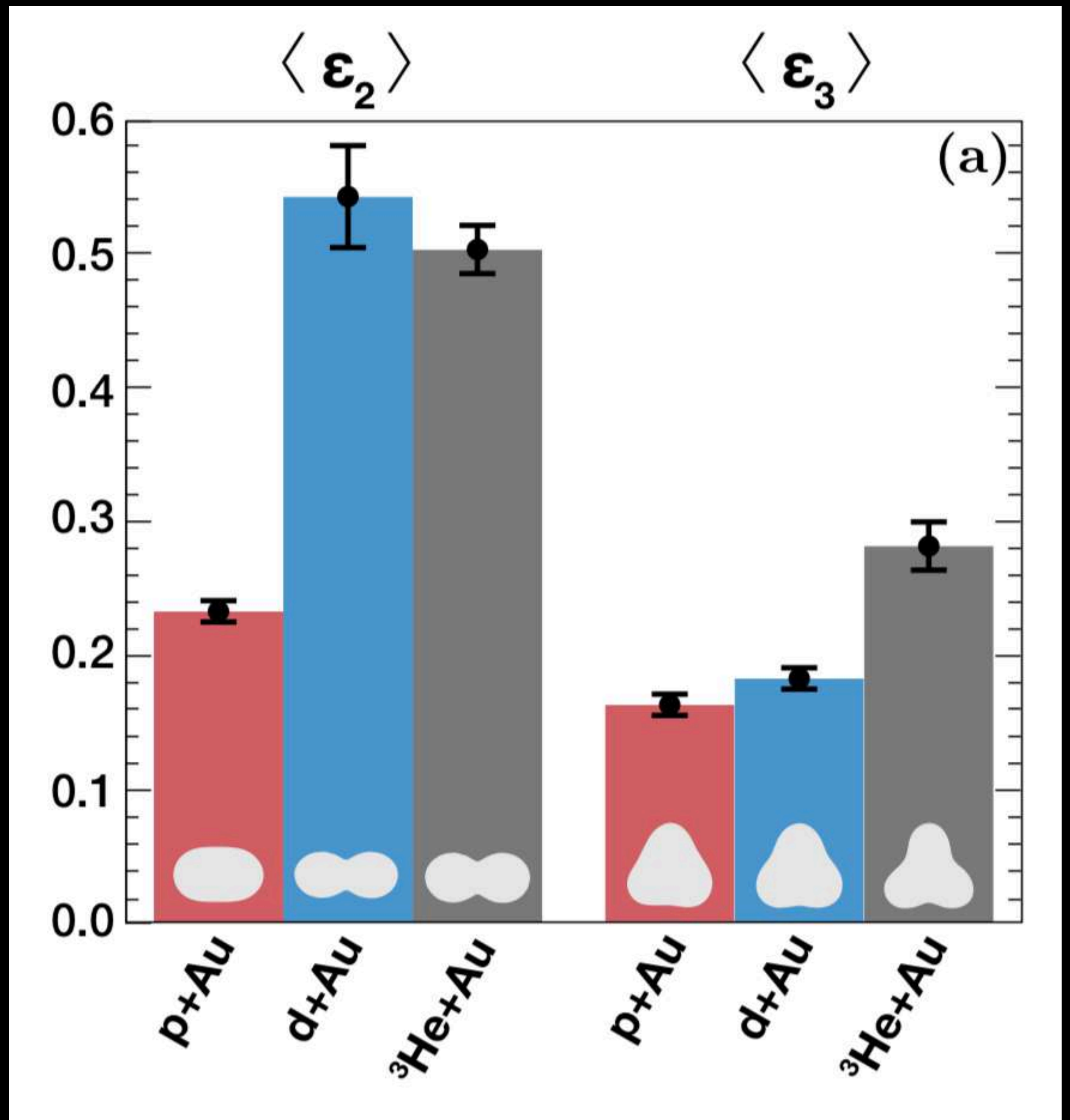
PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220

If final state interactions dominate:

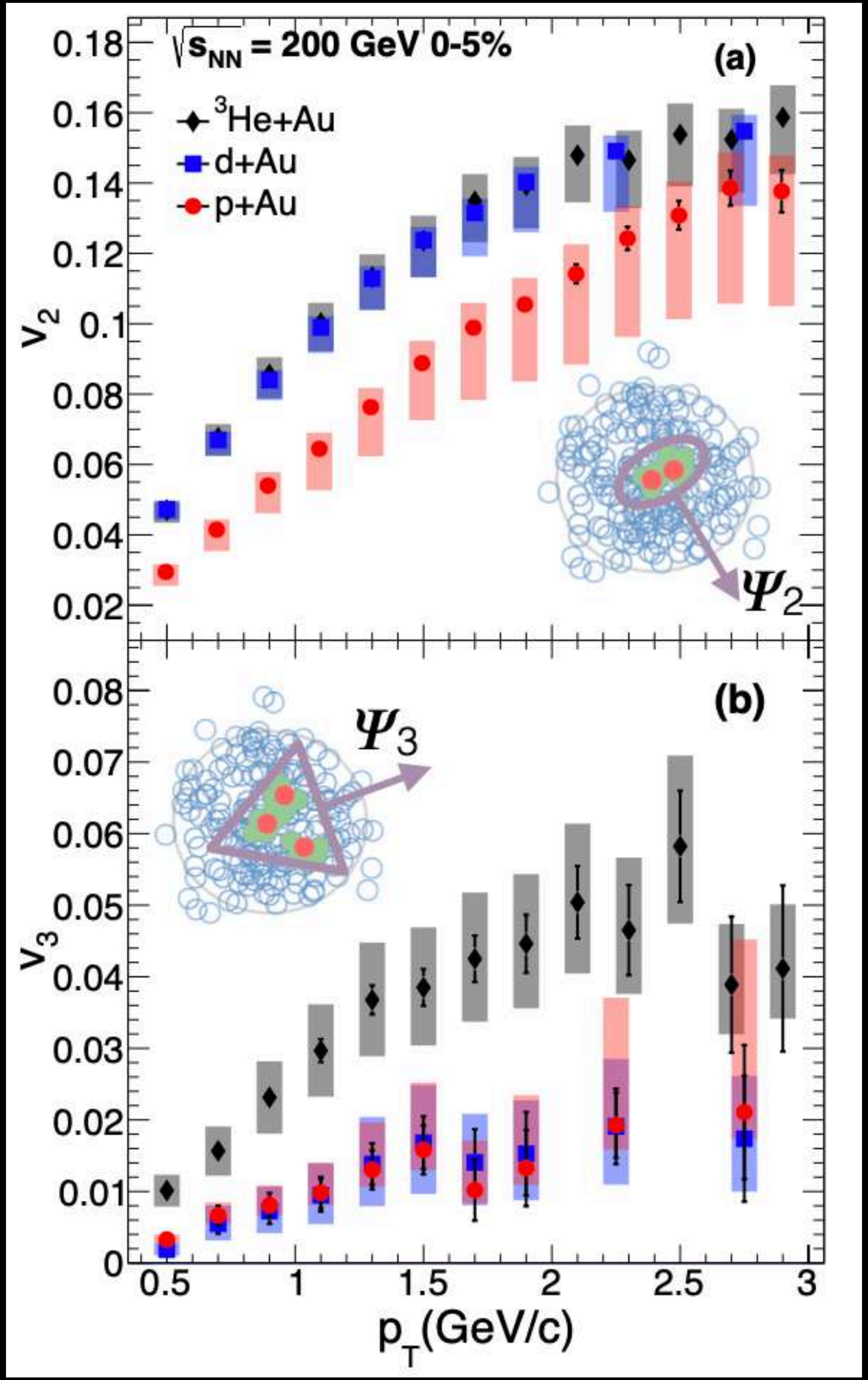
measured anisotropy ∝ spatial anisotropy

So engineer the geometry using different projectiles: p, d, ^{3}He

Simple model expectation: (using nucleon degrees of freedom)



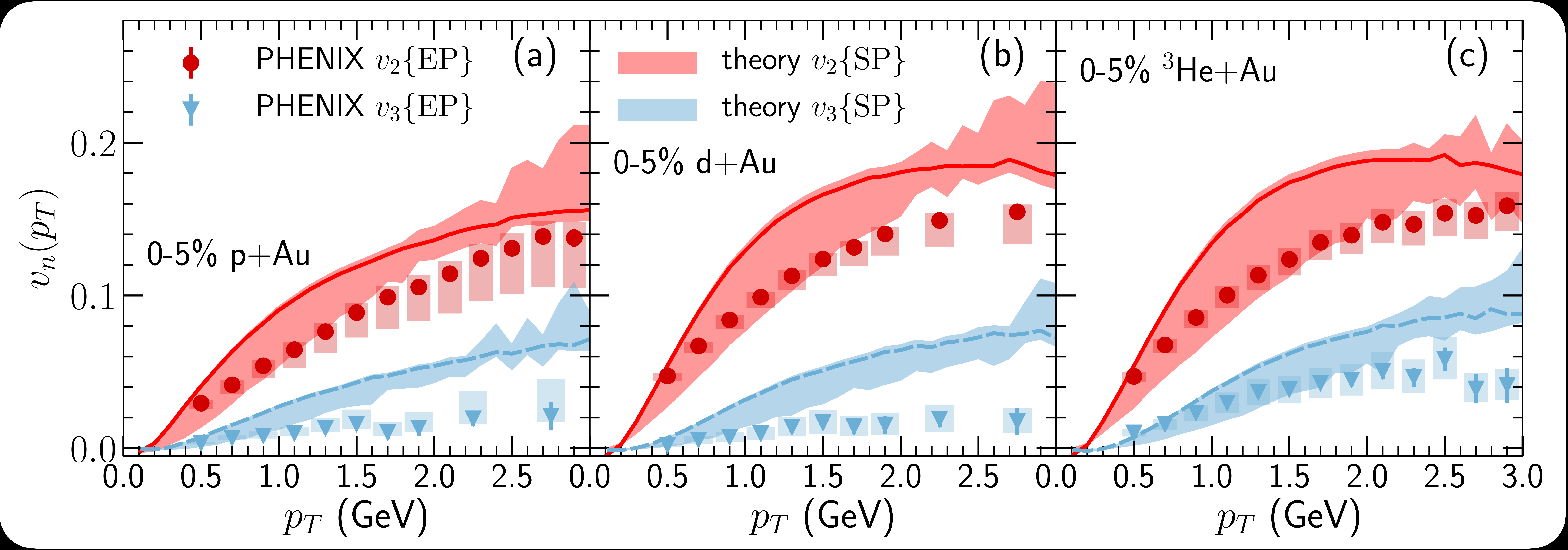
Results confirm expectation:



Björn Schenke, BNL

RHIC system scan: IP-Glasma+Music+UrQMD

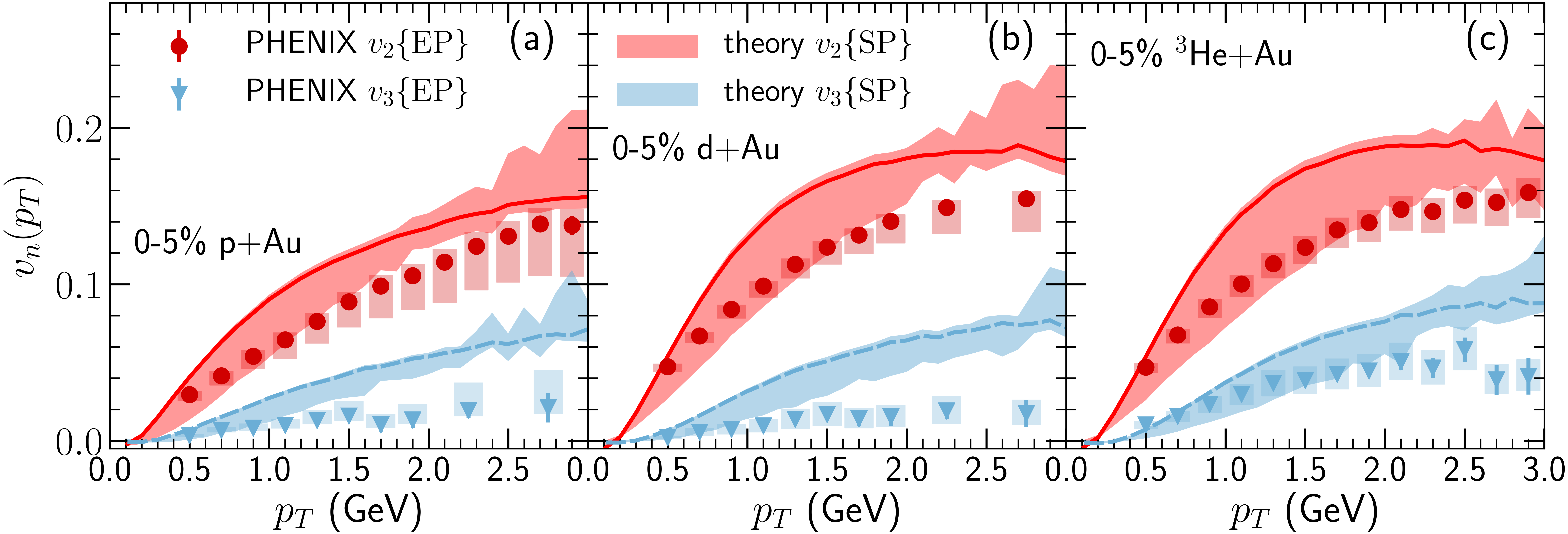
B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322; Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019)



- v_2 (solid) and v_3 (dashed) - parameters constrained by AuAu data
- Bands: systematic uncertainty (different matching of EoS and removal of 2nd order transp. coefficients)

RHIC system scan: IP-Glasma+Music+UrQMD

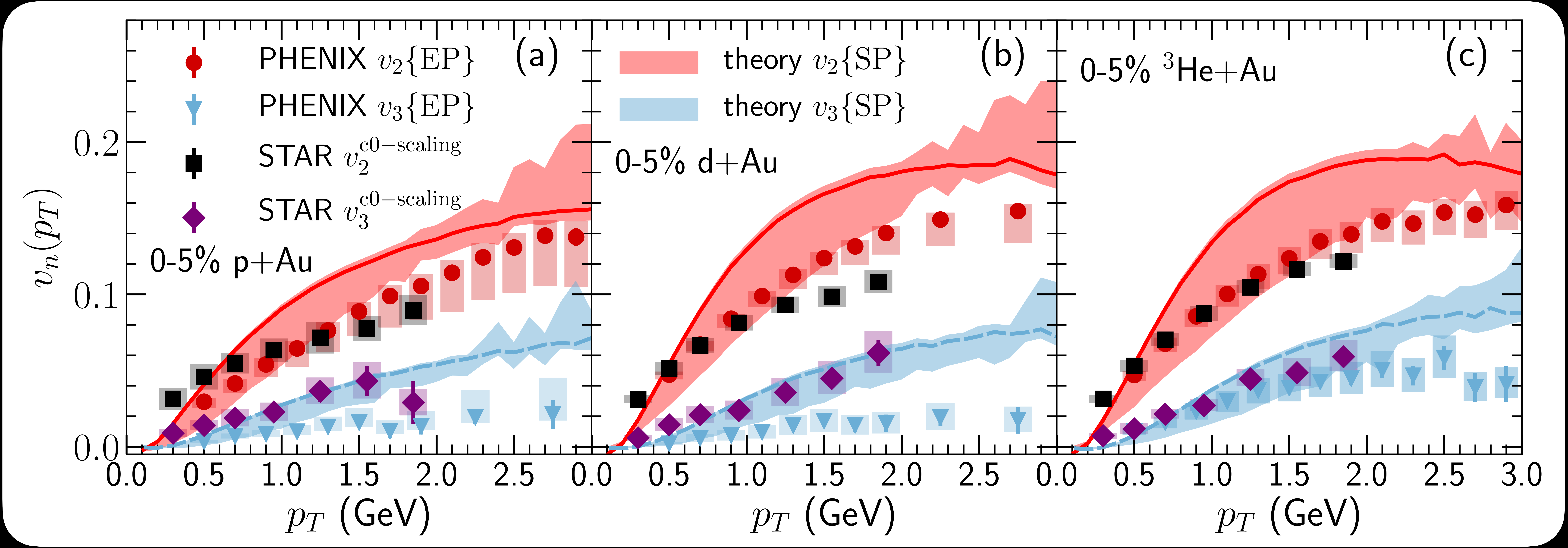
B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322; Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019)



- Computed v_3 similar between systems: Initial shapes are more similar, because of sub-nucleon degrees of freedom

RHIC system scan

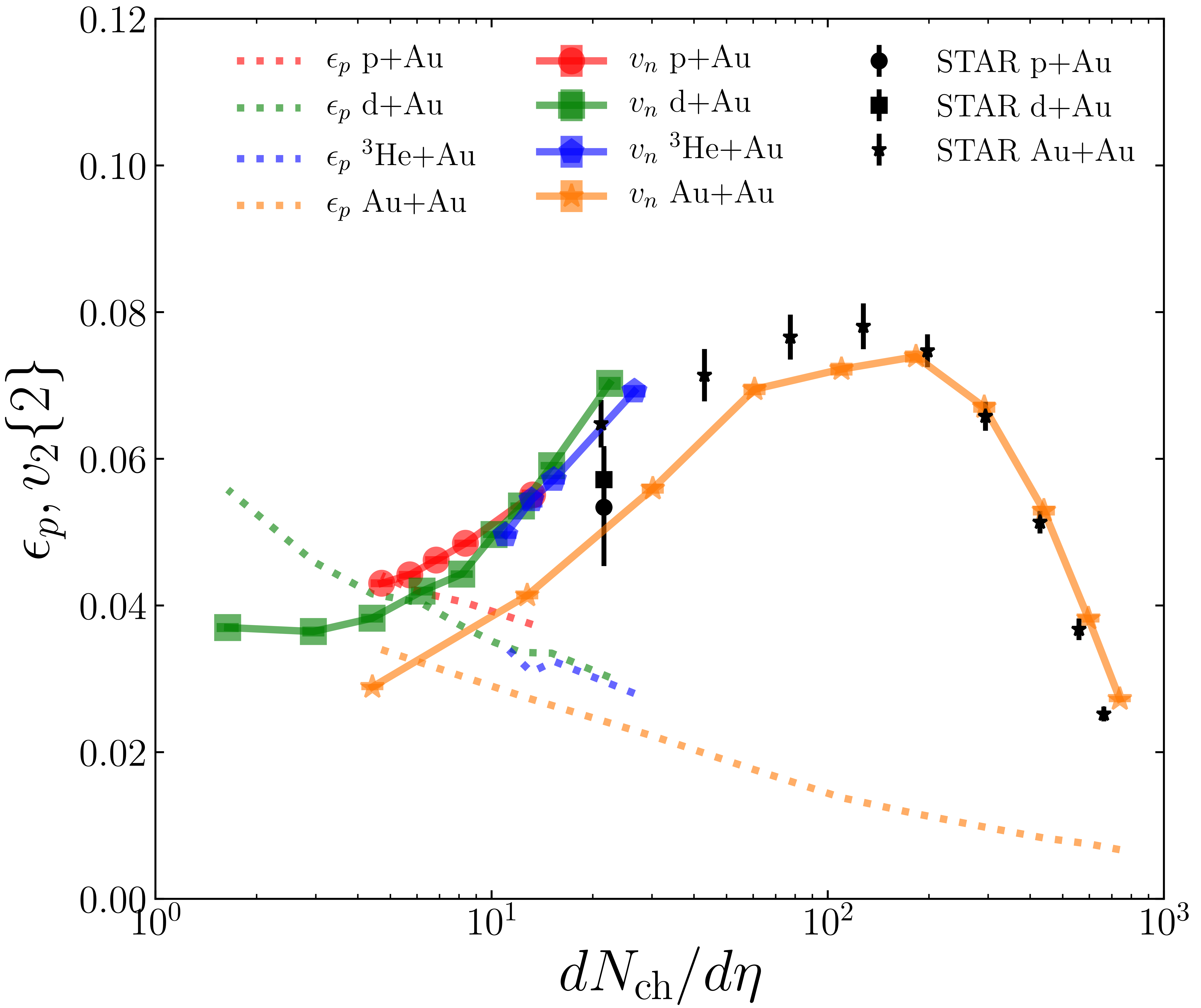
B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322
Experimental Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019)
STAR, New at QUARK MATTER 2019



- STAR Collaboration presented results at Quark Matter 2019 for v_3
  Discrepancy needs to be resolved

Analysis: Effect of initial state momentum anisotropy

B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322



- Initial state momentum anisotropy

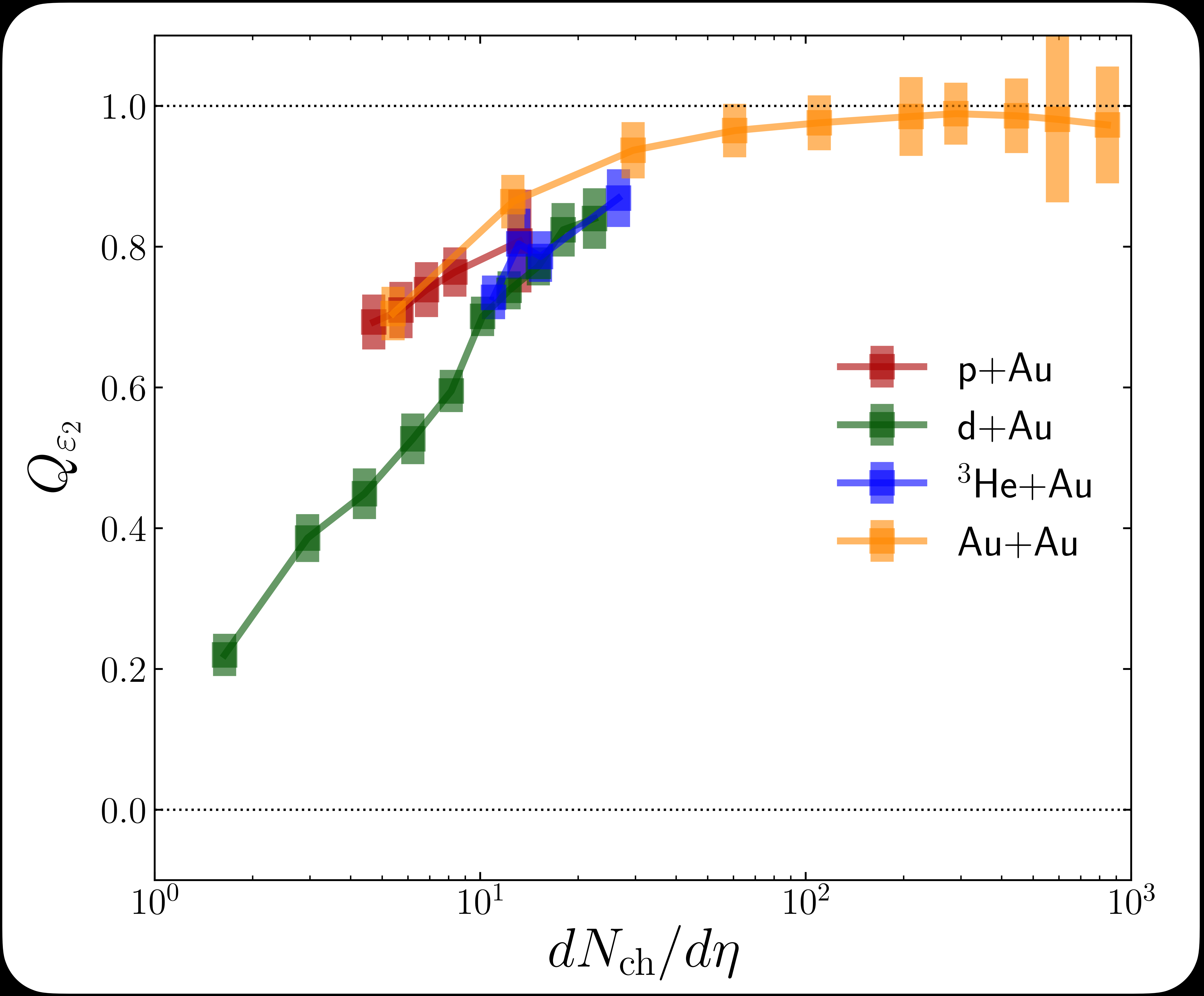
$$\vec{\mathcal{E}}_p = \varepsilon_p e^{2i\psi_2^p} = \frac{\langle T^{xx} - T^{yy}\rangle + i\langle 2T^{xy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$

- ε_p decreases with multiplicity
- Opposite to $v_2\{2\}$
- System ordering opposite to data at $dN_{ch}/d\eta \approx 20$ ($v_2^{dAu} > v_2^{AuAu}$ in calculation)

STAR Collaboration, Phys. Rev. Lett. 122 (2019) 172301

Analysis: Correlation with the initial geometry

B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322



← Q_{ε_2} = 1: v_2 geometry driven

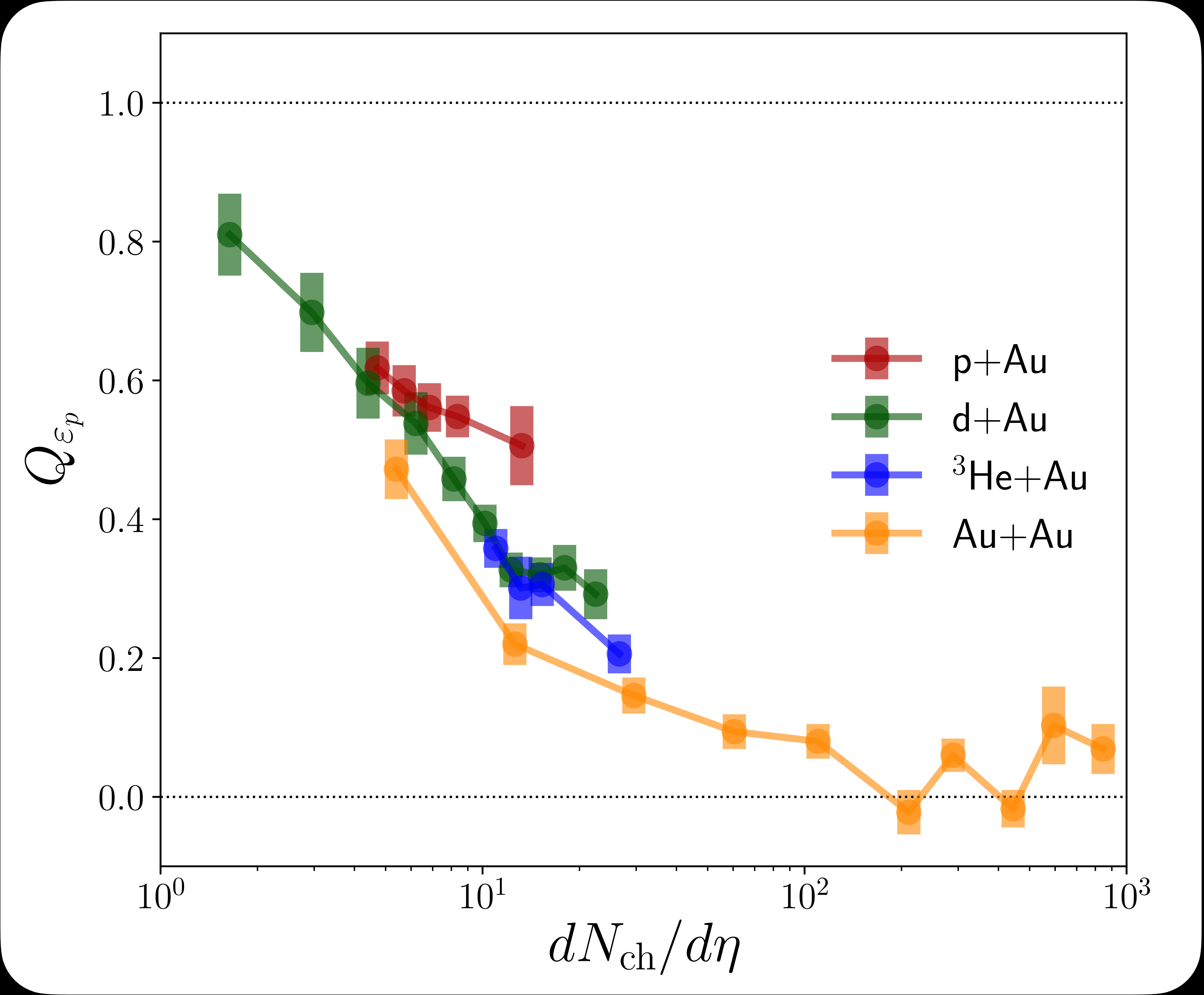
- Pearson coefficient

$$Q_{\varepsilon_2} = \frac{\mathrm{Re}\langle \vec{\mathcal{E}}_2 \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathcal{E}}_2|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

- Correlation of v_2 vector with the geometry (ε_2) vector decreases towards low multiplicity

Analysis: Correlation with initial momentum anisotropy

B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322



← Q_{ε_p} = 1: only initial anisotropy

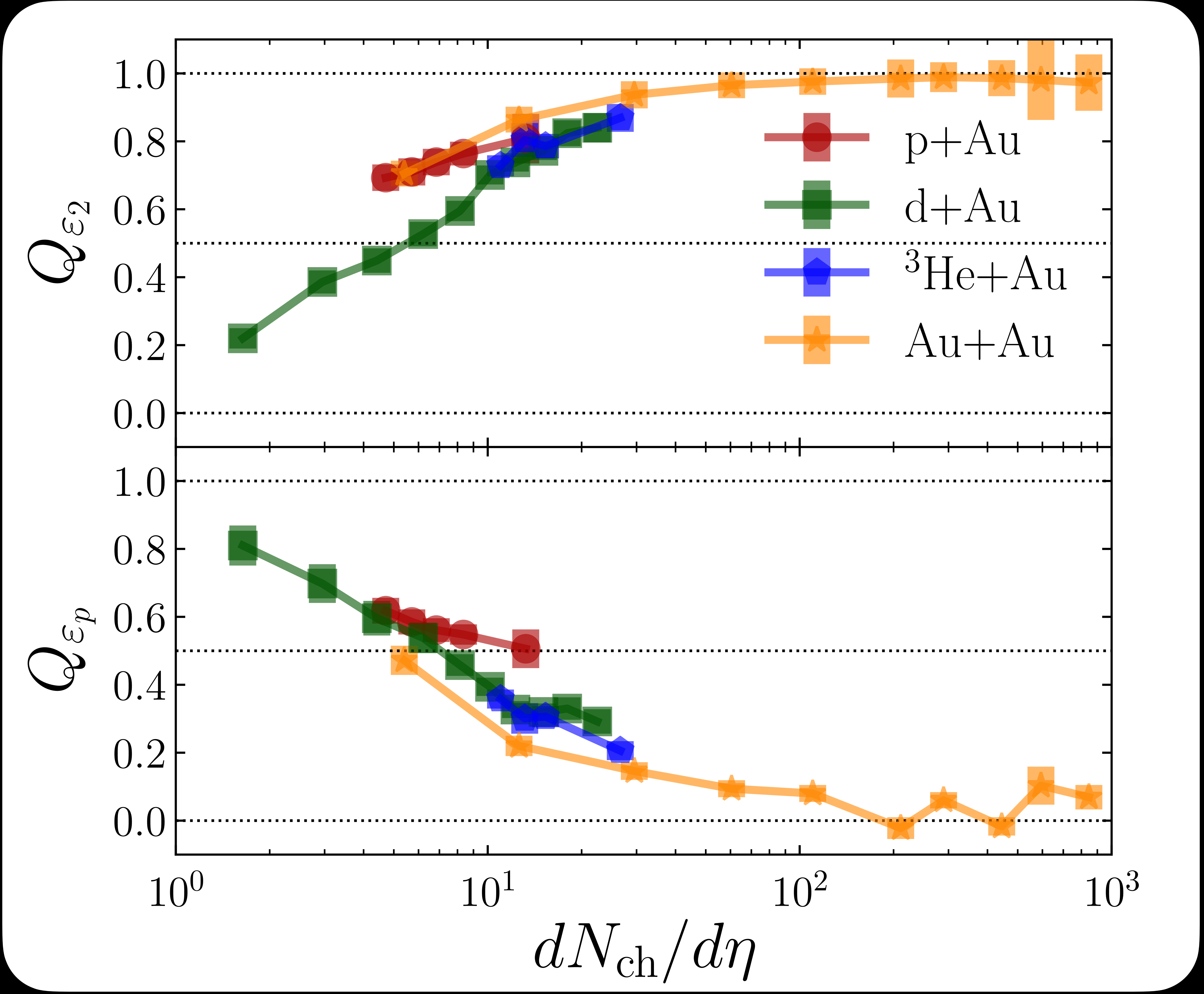
- Pearson coefficient

$$Q_{\varepsilon_p} = \frac{\mathrm{Re}\langle \overrightarrow{\mathscr{E}}_p \cdot \overrightarrow{V}_2^* \rangle}{\sqrt{\langle |\overrightarrow{\mathscr{E}}_p|^2 \rangle \langle |\overrightarrow{V}_2|^2 \rangle}}$$

- Correlation of v_2 with the initial momentum anisotropy ε_p increases towards low multiplicity for all systems

Analysis: What drives the elliptic anisotropy?

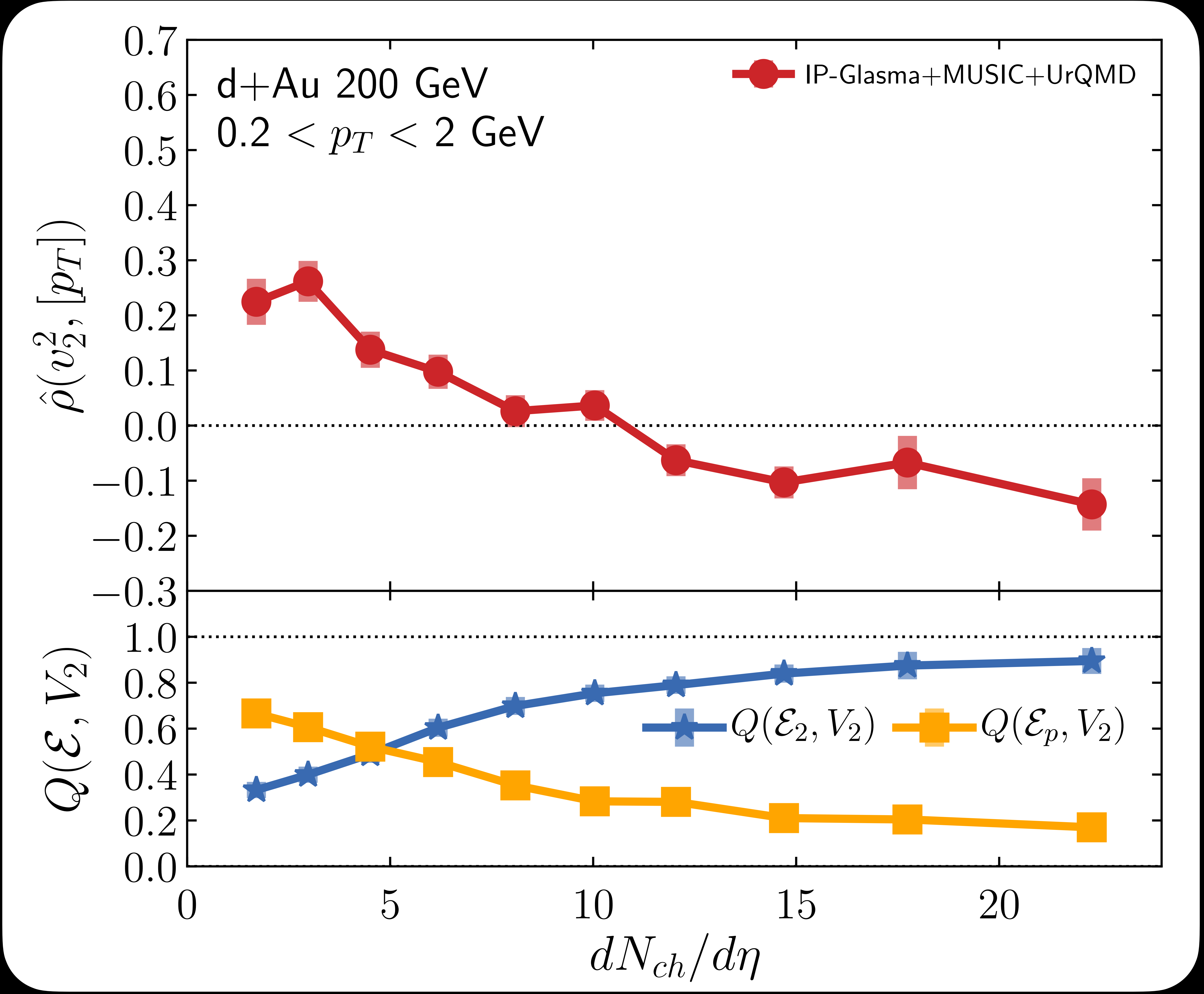
B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322



- Below $dN_{\rm ch}/d\eta \approx 10$ the initial momentum anisotropy contributes strongly to the final charged hadron elliptic anisotropy
- Only above $dN_{\rm ch}/d\eta \approx 100$ (only AuAu here) everything is geometry driven
- But how do we measure this?

Observable to distinguish initial from final state effects

G. Giacalone, B. Schenke, C. Shen, e-Print: arXiv:2006.15721

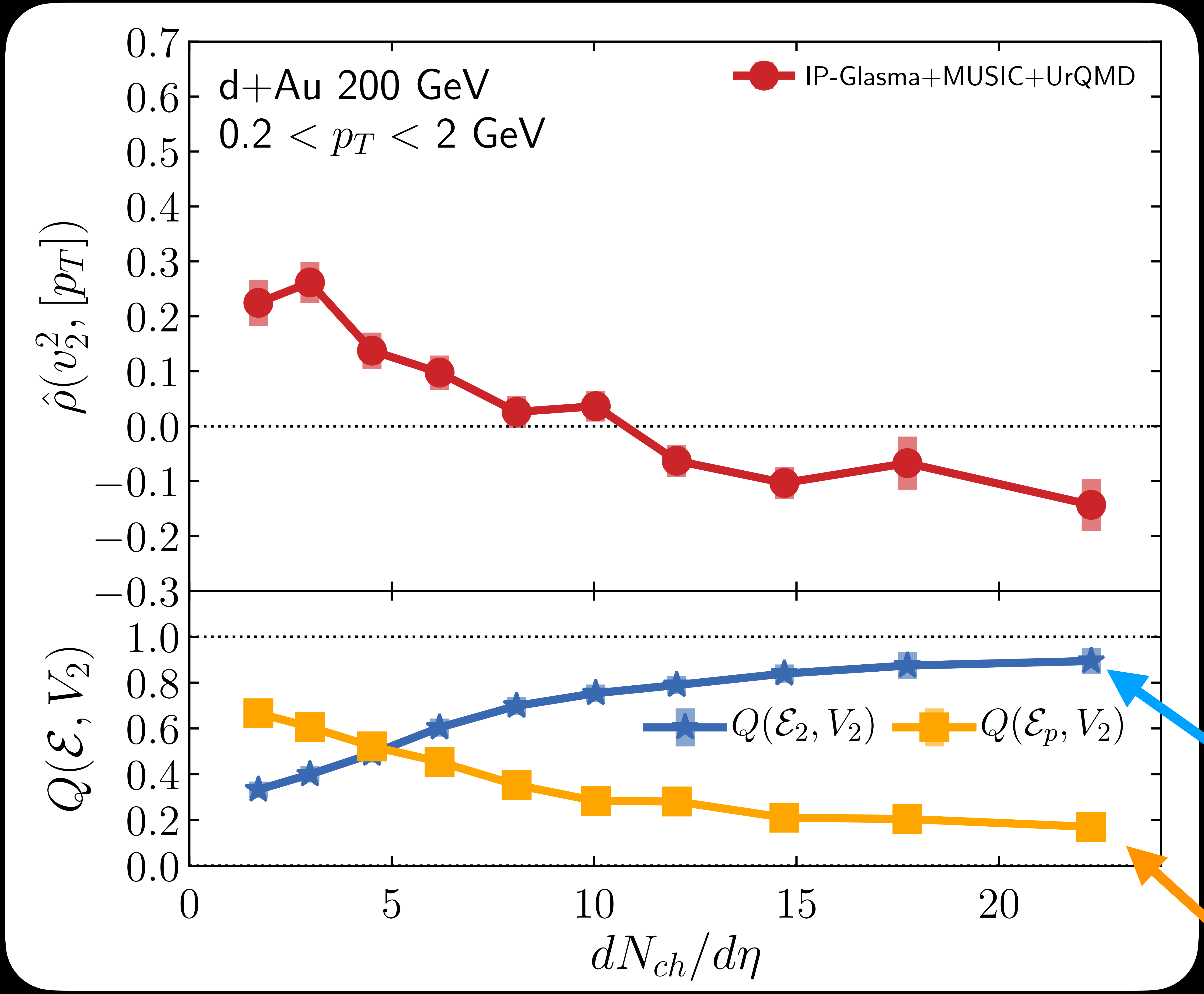


Correlation of v_2^2 and $[p_T]$ at fixed multiplicity:

$$\hat{\rho}(v_2^2, [p_T]) = \frac{\langle \hat{\delta} v_2^2 \, \hat{\delta}[p_T] \rangle}{\sqrt{\langle (\hat{\delta} v_2^2)^2 \rangle \langle (\hat{\delta}[p_T])^2 \rangle}}$$

Observable to distinguish initial from final state effects

G. Giacalone, B. Schenke, C. Shen, e-Print: arXiv:2006.15721



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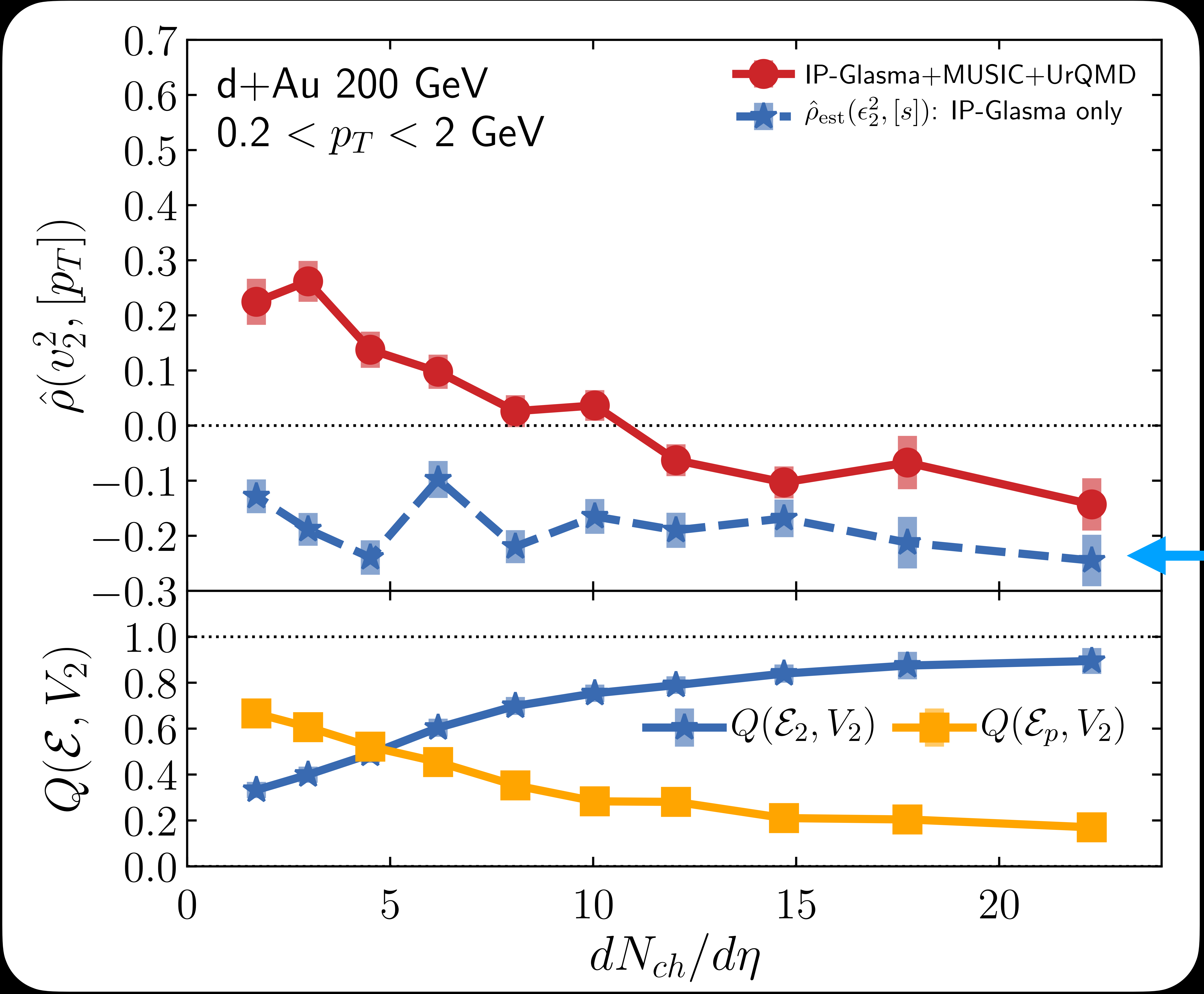
Correlation of v_2 with the geometry

Correlation of v_2 with the initial anisotropy

Observable to distinguish initial from final state effects

G. Giacalone, B. Schenke, C. Shen, e-Print: arXiv:2006.15721



Correlation of v_2^2 and $[p_T]$ at fixed multiplicity:

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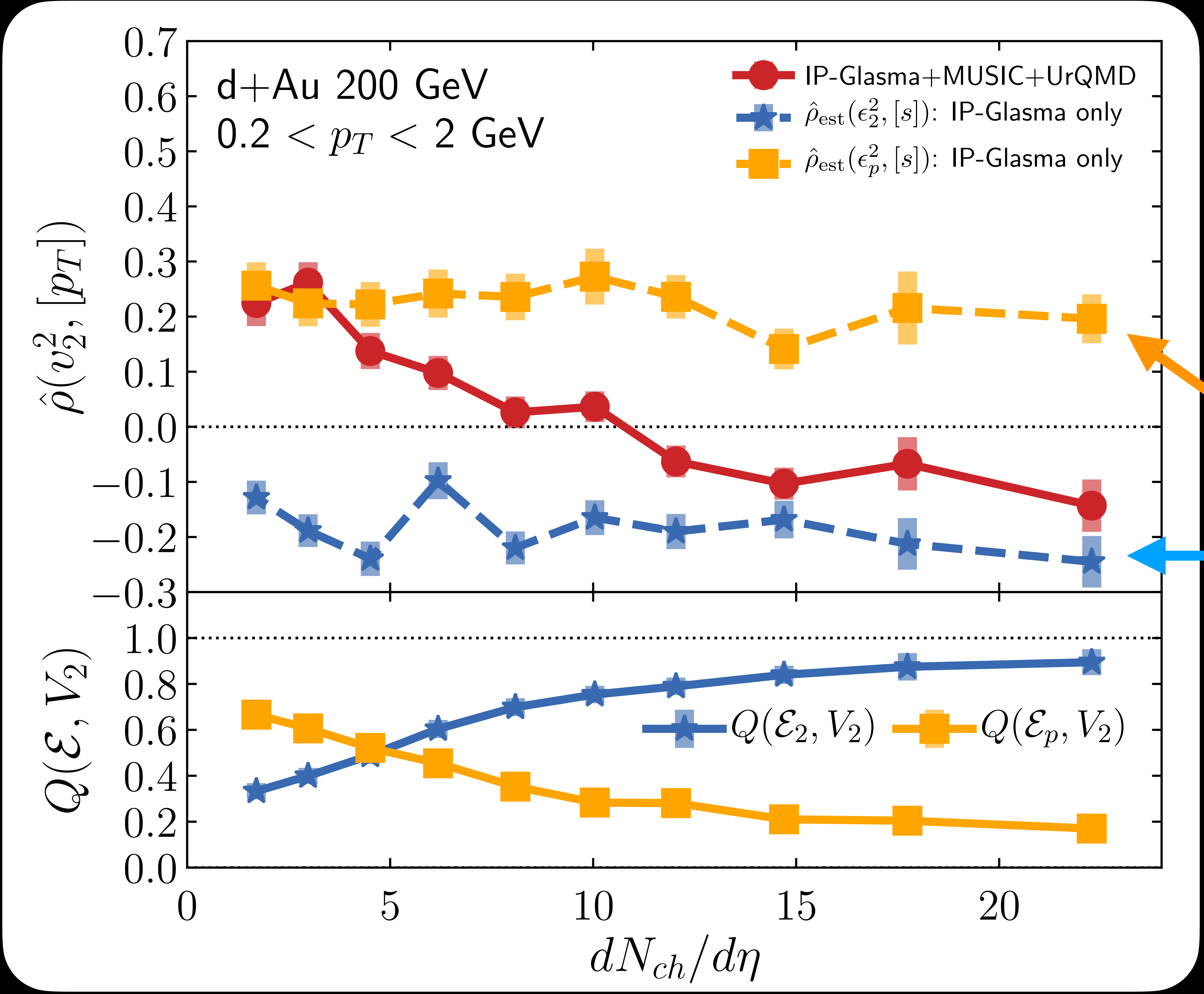
Expectation if final state dominates

Observable to distinguish initial from final state effects

G. Giacalone, B. Schenke, C. Shen, e-Print: arXiv:2006.15721



Correlation of v_2^2 and $[p_T]$ at fixed multiplicity:

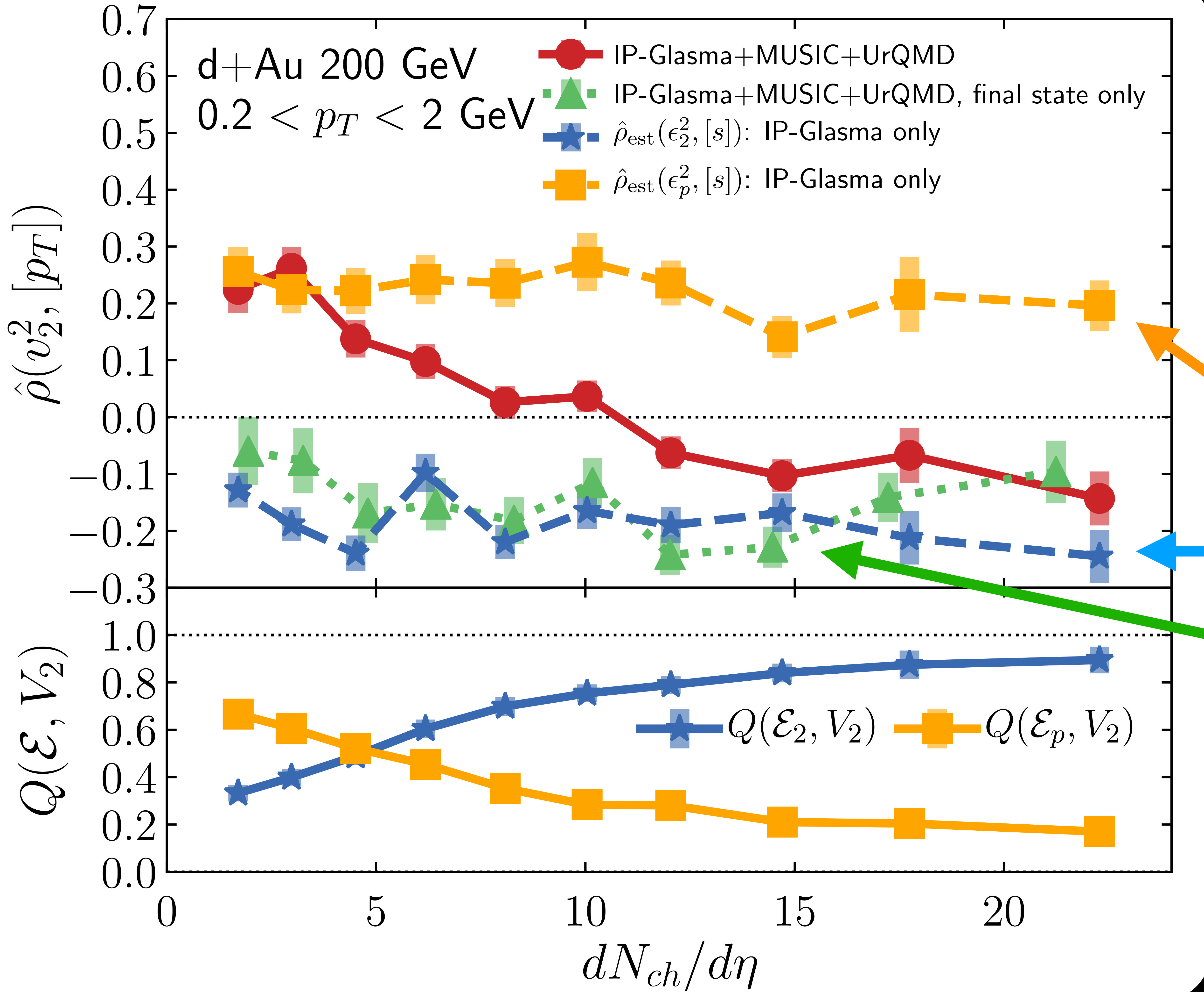
$$\hat{\rho}(v_2^2, [p_T]) = \frac{\langle \hat{\delta} v_2^2 \, \hat{\delta}[p_T] \rangle}{\sqrt{\langle (\hat{\delta} v_2^2)^2 \rangle \langle (\hat{\delta}[p_T])^2 \rangle}}$$

Expectation if initial state dominates

Expectation if final state dominates

Observable to distinguish initial from final state effects

G. Giacalone, B. Schenke, C. Shen, e-Print: arXiv:2006.15721



Correlation of v_2^2 and $[p_T]$ at fixed multiplicity:

$$\hat{\rho}(v_2^2, [p_T]) = \frac{\langle \hat{\delta} v_2^2 \, \hat{\delta}[p_T] \rangle}{\sqrt{\langle (\hat{\delta} v_2^2)^2 \rangle \langle (\hat{\delta}[p_T])^2 \rangle}}$$

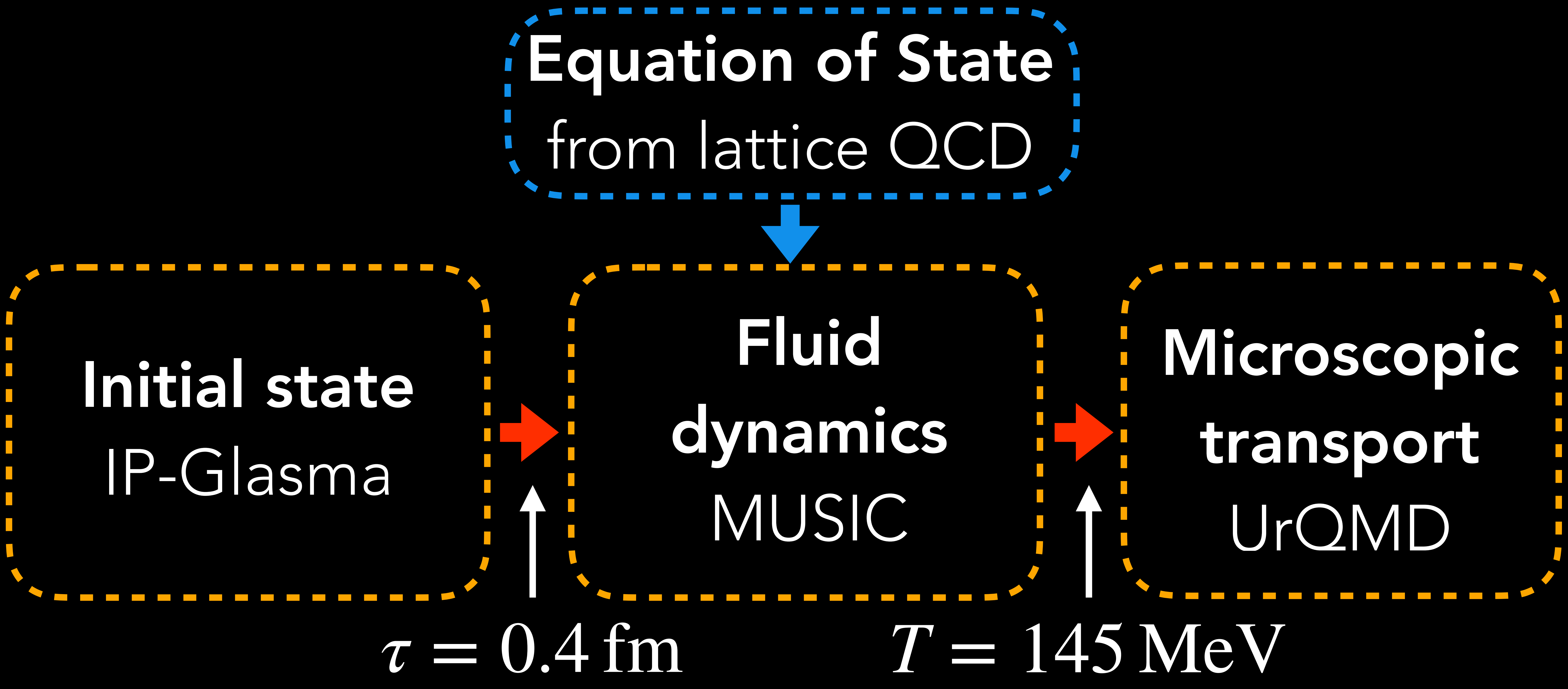
Expectation if initial state dominates

Expectation if final state dominates

Result with initial momentum anisotropy turned off

Running the gamut of high energy nuclear collisions

B. Schenke, C. Shen, P. Tribedy, arXiv:2005.14682



- Exactly match $T^{\mu\nu}$ when switching
- Can add intermediate off-equilibrium evolution before hydro

A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, D. Teaney, Phys.Rev.Lett. 122 (2019) 122302

B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. 108, 252301 (2012)
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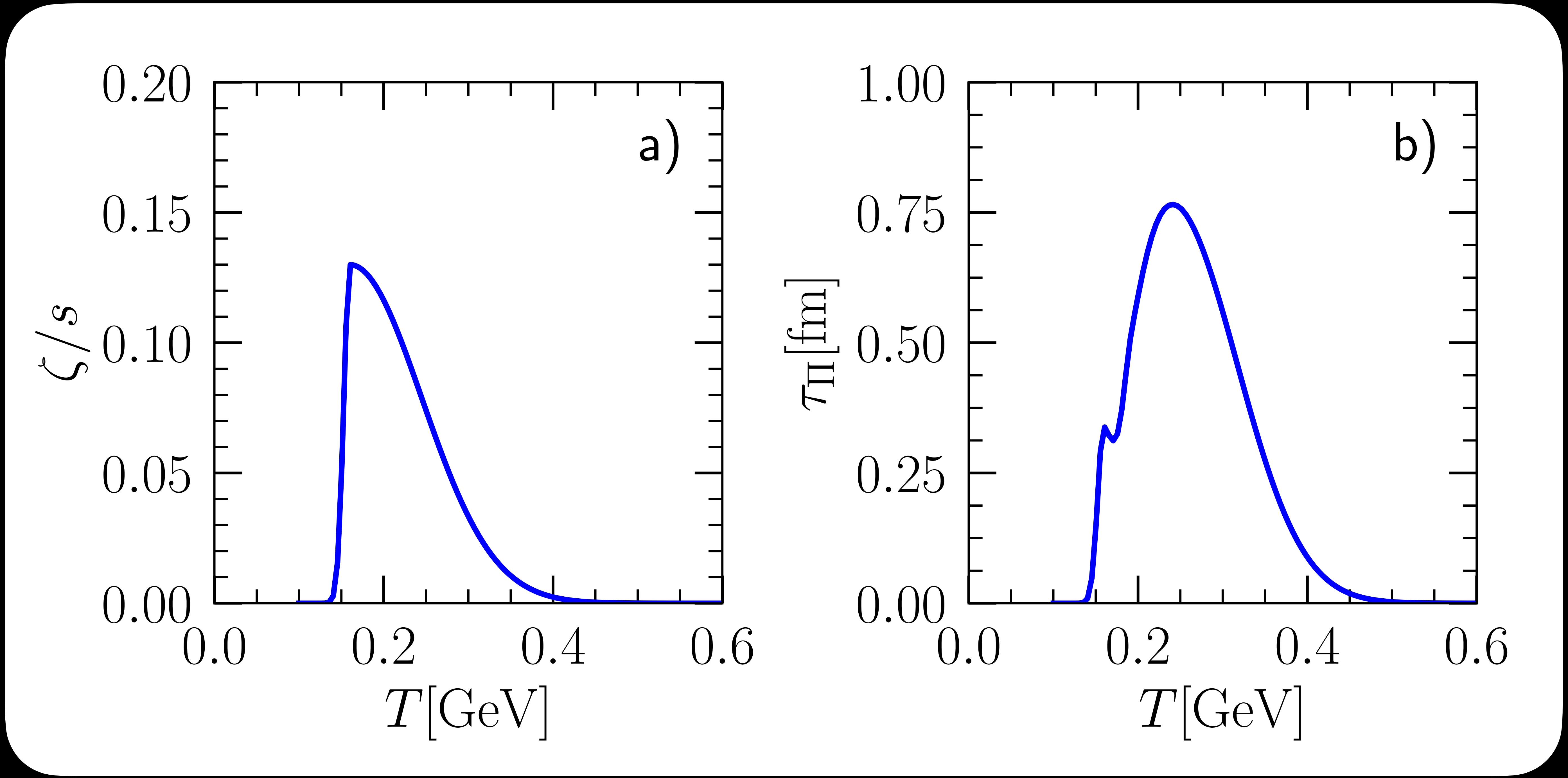
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998); M. Bleicher et al., J. Phys. G25, 1859 (1999)
H. Elfner (nee Petersen), M. Bleicher, S. Bass, H. Stöcker, e-Print: arXiv:0805.0567
A. Bazavov et al, Phys. Rev. D 95, 054504 (2017); A. Monnai, B. Schenke, C. Shen, Phys.Rev. C100 (2019) 024907

Comprehensive description of many collision systems

B. Schenke, C. Shen, P. Tribedy, arXiv:2005.14682

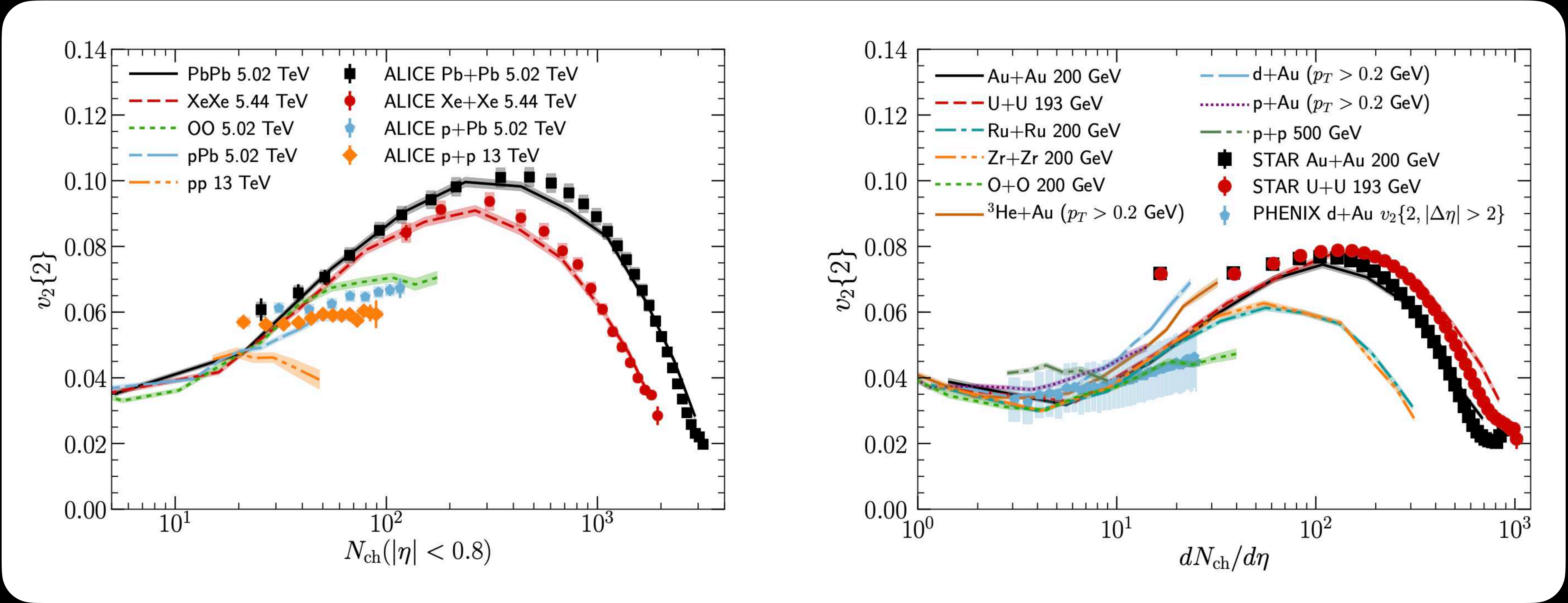
- Use constant η/s=0.12 and temperature dependent ζ/s



Same parameters for all systems and collision energies

Comprehensive description of many collision systems

B. Schenke, C. Shen, P. Tribedy, arXiv:2005.14682



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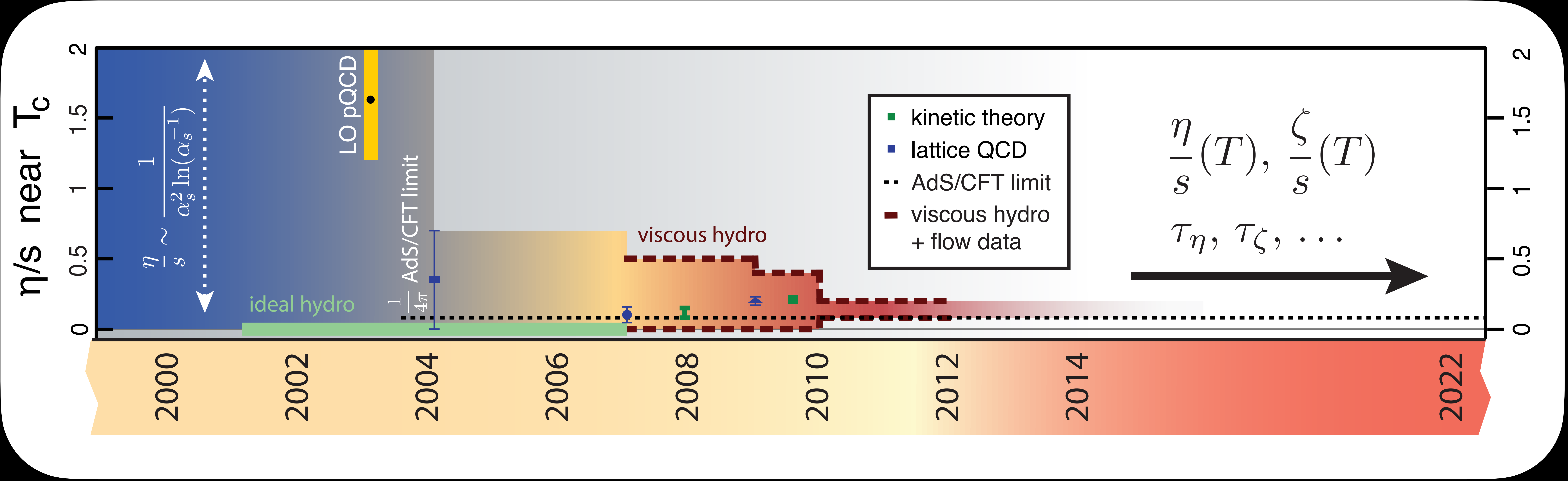
STAR Collaboration, Phys. Rev. Lett. 122 (2019) 172301
L. Adamczyk et al. (STAR), Phys. Rev. Lett. 115, 222301 (2015)
C. Aidala et al. (PHENIX), Phys. Rev. Lett. 120, 062302 (2018)

Improved understanding of QCD shear viscosity

Event-by-event viscous hydrodynamic simulations with
QCD based initial states can help constrain transport properties



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H. B. Meyer, Phys.Rev. D76 (2007) 101701;
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H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033
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Phys.Rev.Lett. 106 (2011) 192301

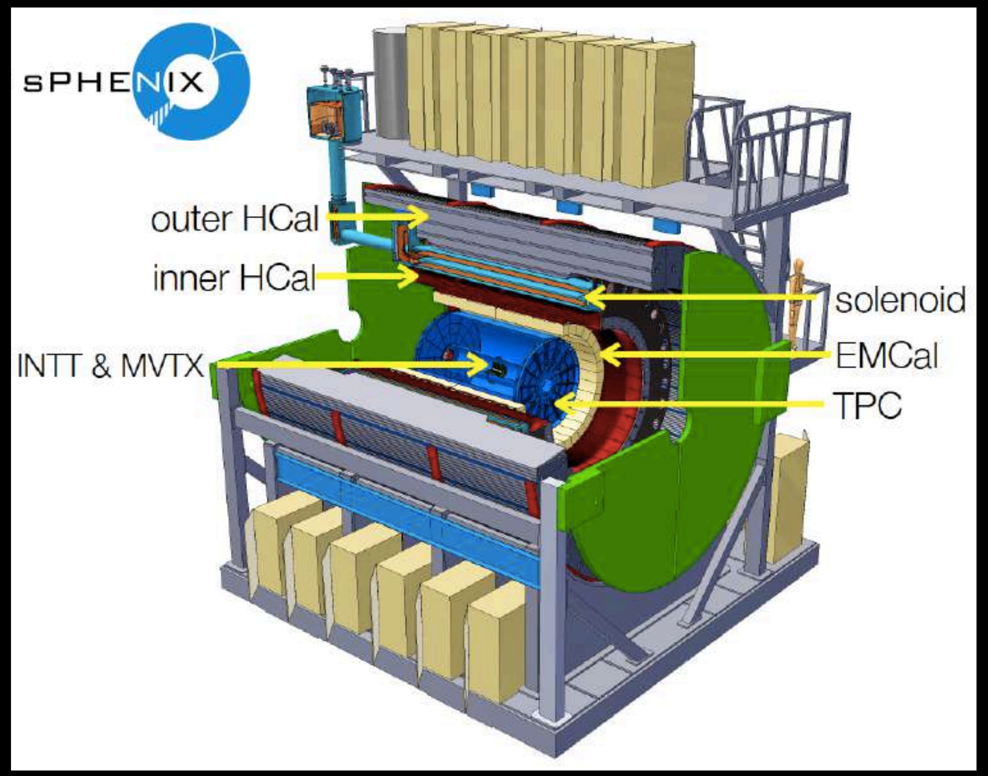
Björn Schenke, BNL

Outlook: More happening at RHIC

- RHIC's fluid also shown to be the most vortical
- Search for the Chiral Magnetic Effect (CME) to observe the chiral anomaly of QCD - most recently with isobars
- RHIC Beam Energy Scan II will probe higher net baryon density regions of the phase diagram - search for the critical point of QCD using event-by-event fluctuations
- sPHENIX is planned to study fully resolved jets, Upsilon states, and heavy quarks as QGP structure probes

Phenomenology for all of these aspects
needs a framework as the one described in this talk + extensions

STAR Collaboration
Nature 548, 62-65 (2017)



Björn Schenke, BNL

Outlook: Electron Ion Collider ~2030

Calculations depend on description of incoming nuclei:
Spatial and momentum distributions of color charges / gluon fields

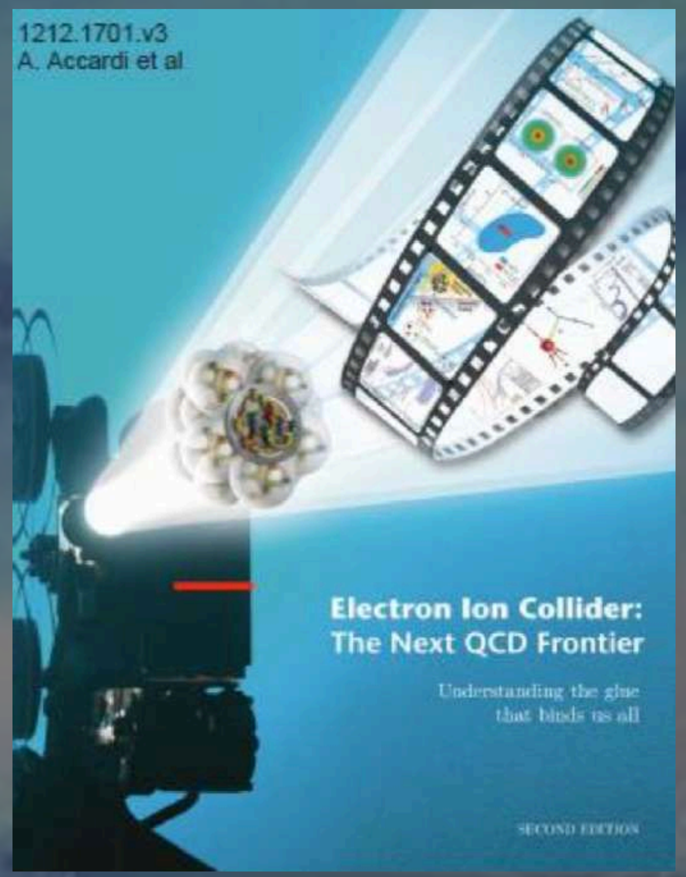
Future Electron Ion Collider will help:

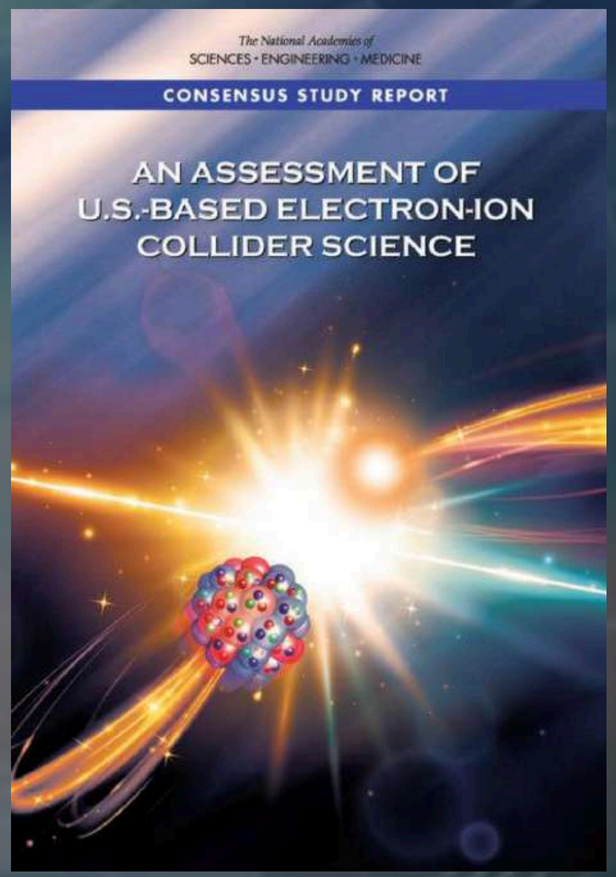
- Tomography of nucleon/nucleus and study of gluon saturation

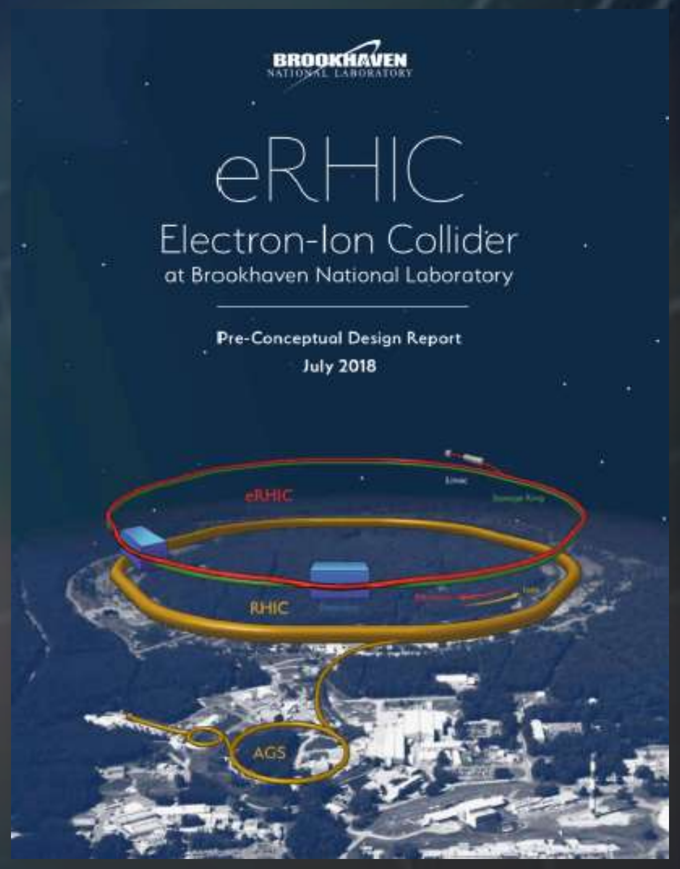
Important inputs for heavy ion physics

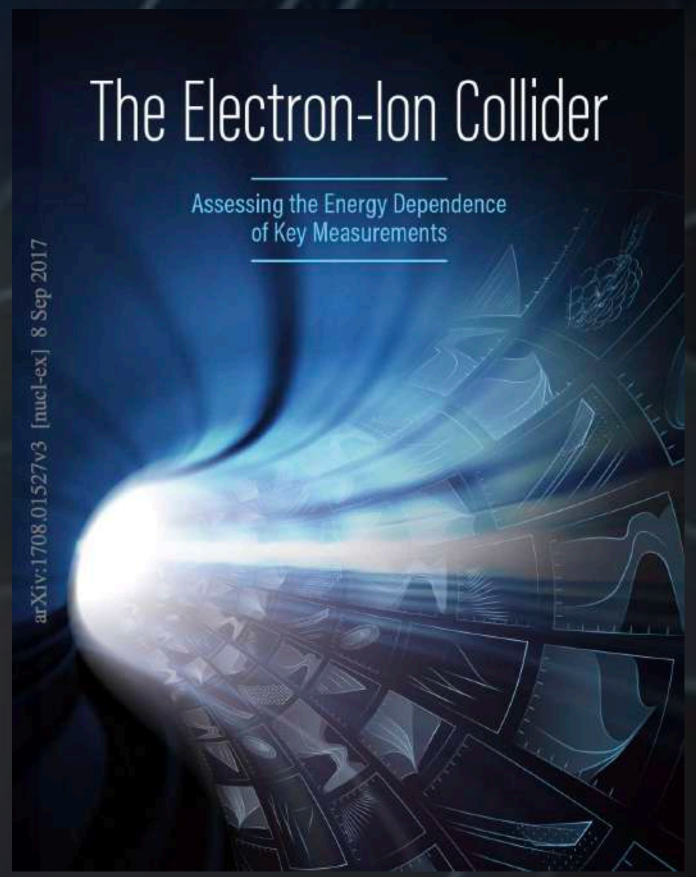
Will also focus on the

- Origin of proton spin
- Origin of proton mass









Outlook: Electron Ion Collider ~2030

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Department of Energy

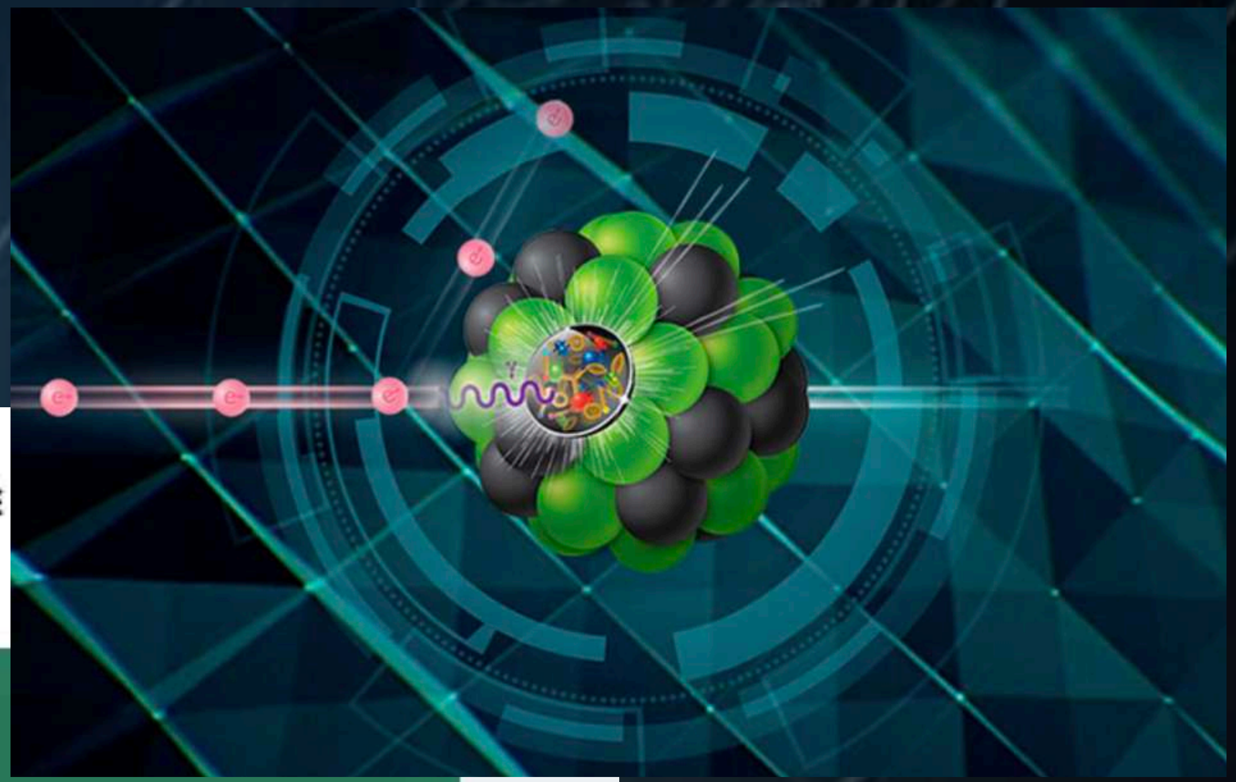
U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

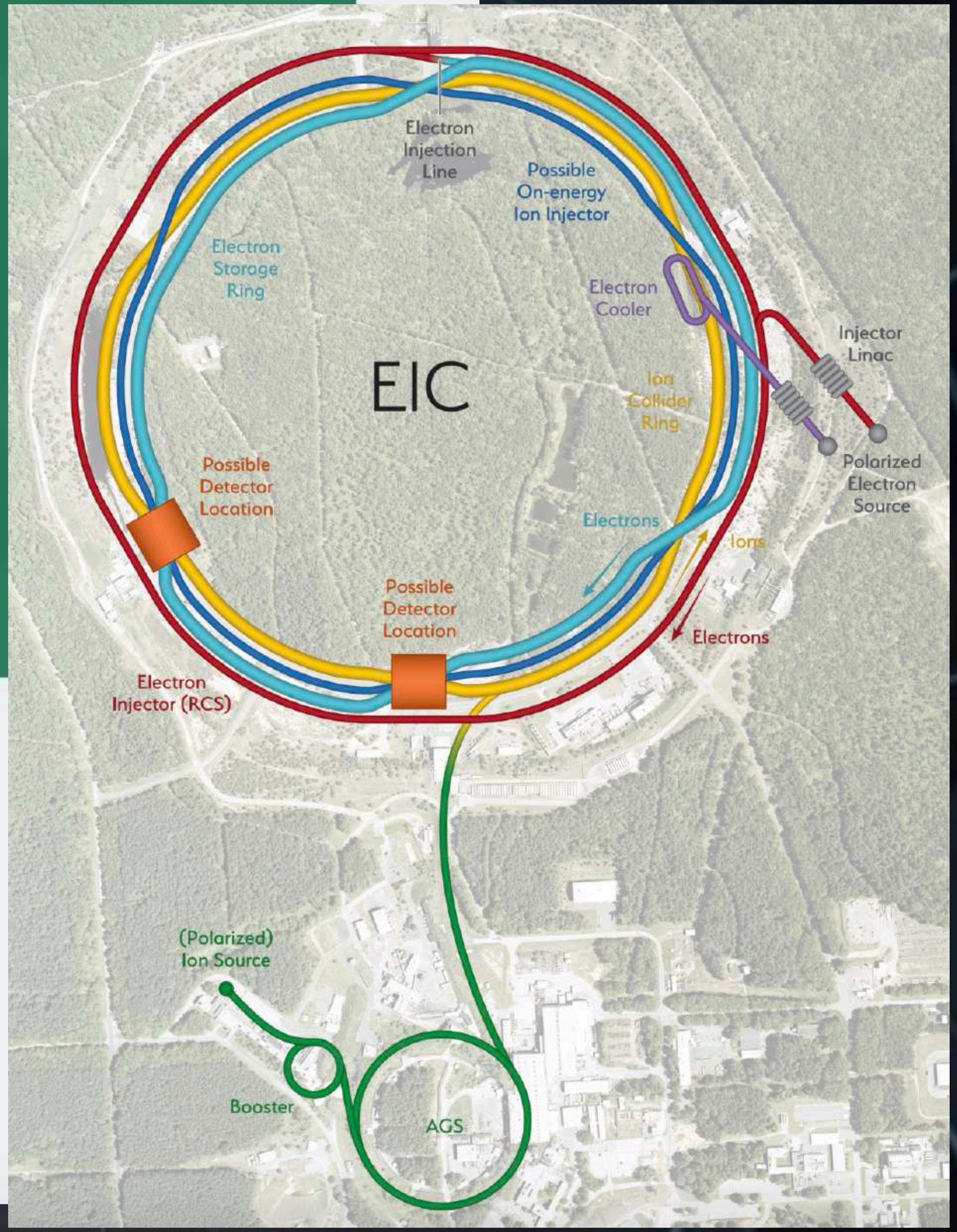
JANUARY 9, 2020

Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.





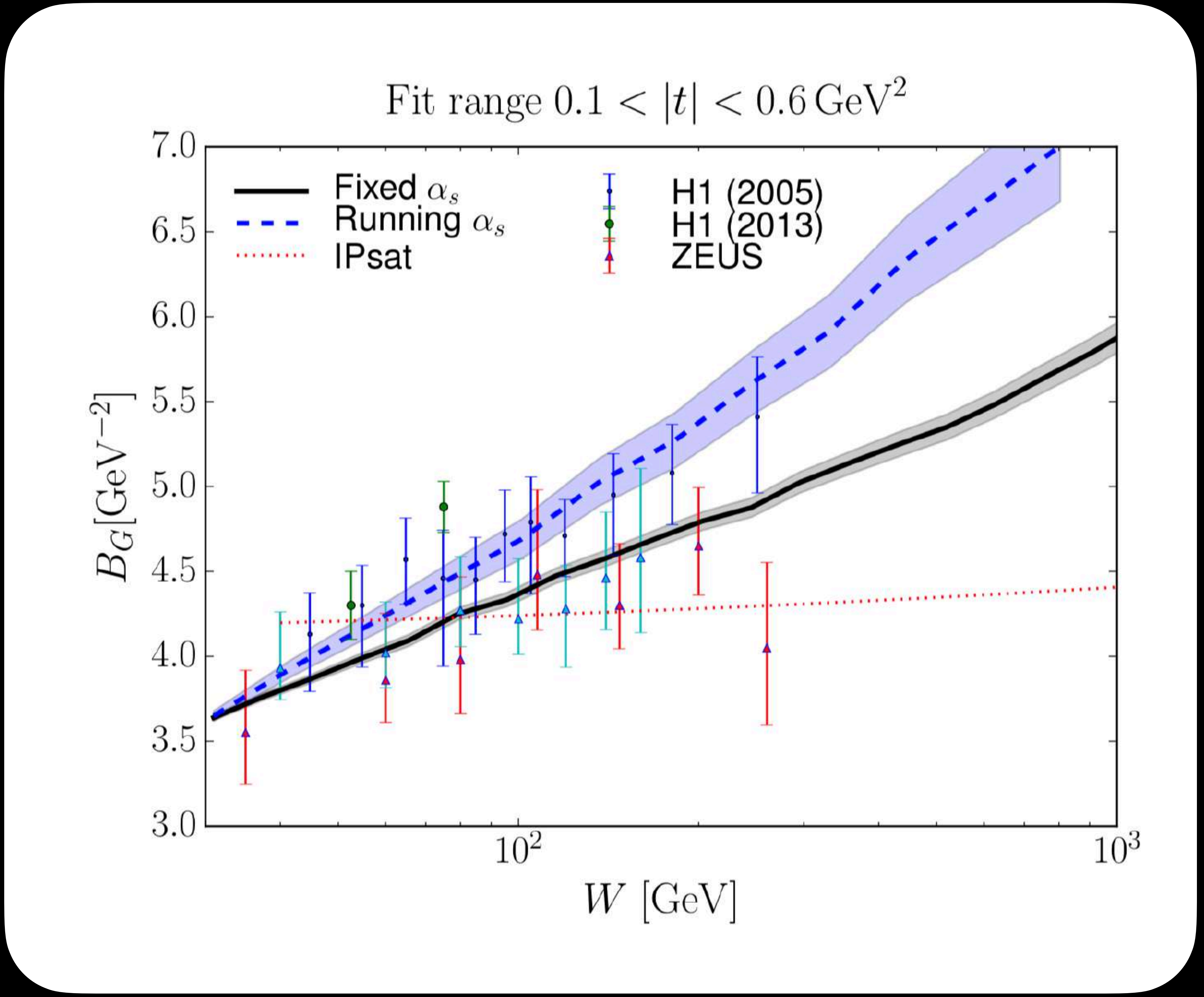
Björn Schenke, BNL

Outlook: Electron Ion Collider

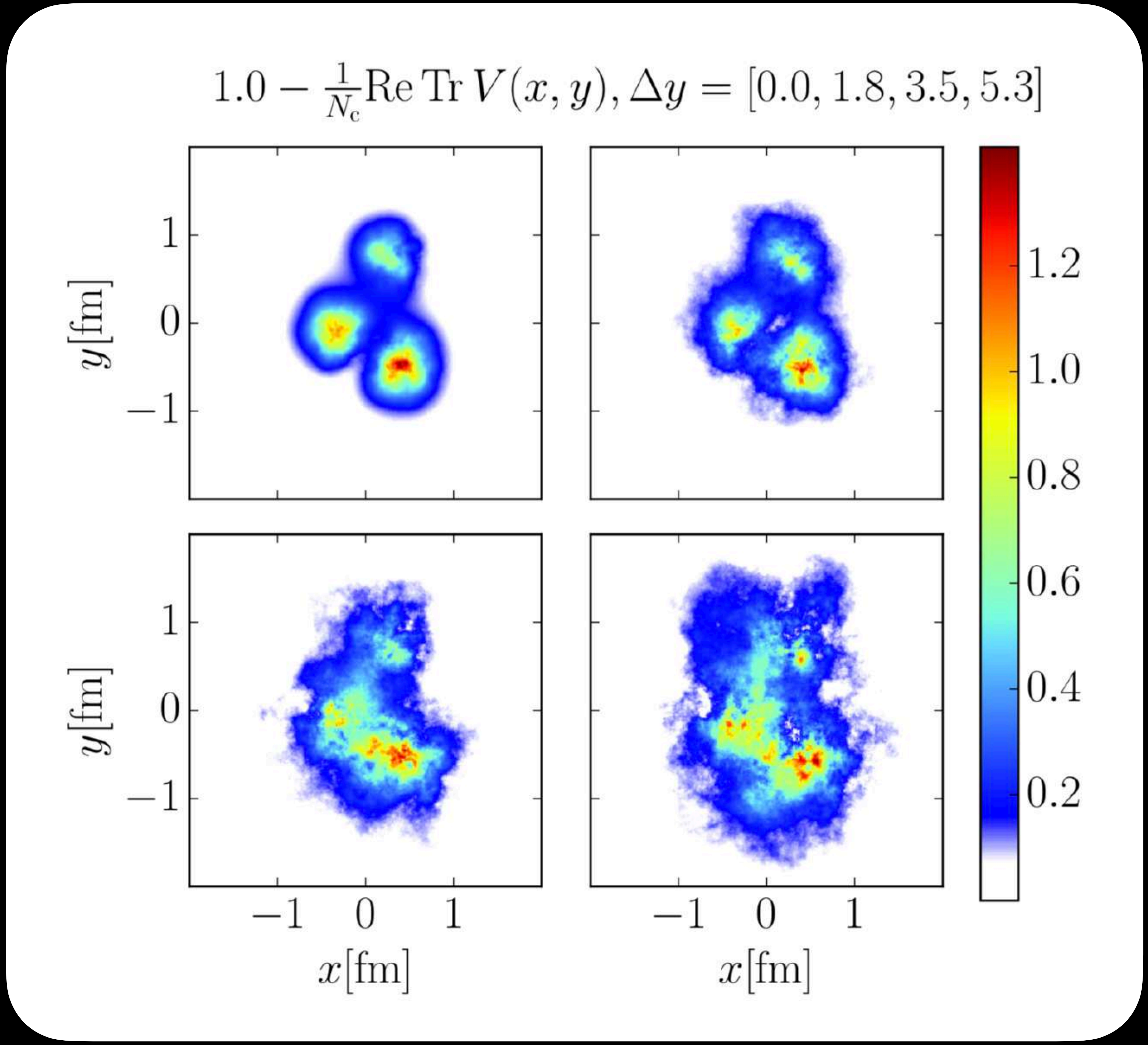
H. Mäntysaari, B. Schenke, Phys.Rev. D98 (2018) no.3, 034013

Proton size and shape at high energy: Study coherent and incoherent diffraction

Small-*x* evolution from numerical solution of JIMWLK equations:



Proton grows with energy



Protons stay lumpy at high energy

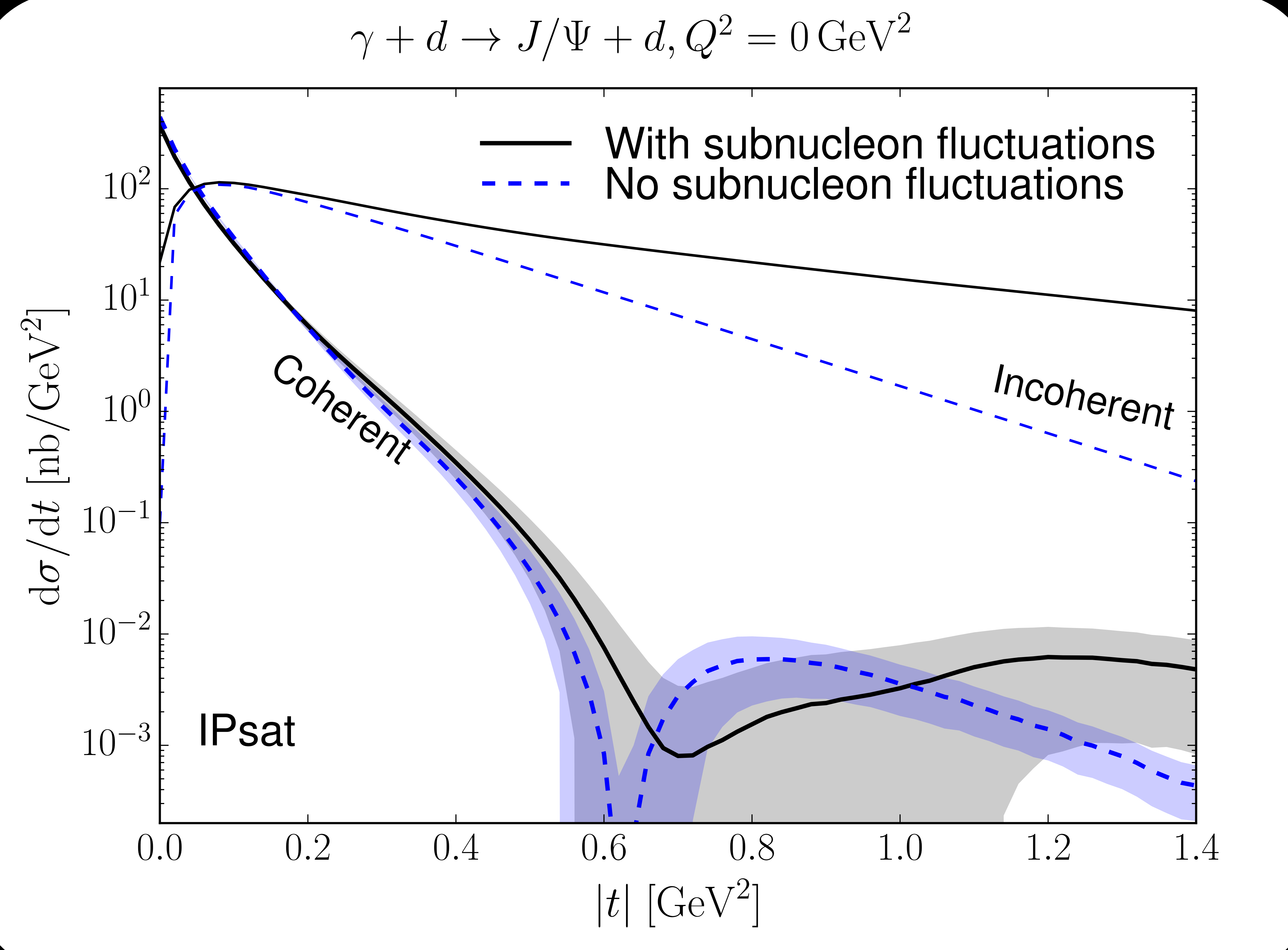
H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

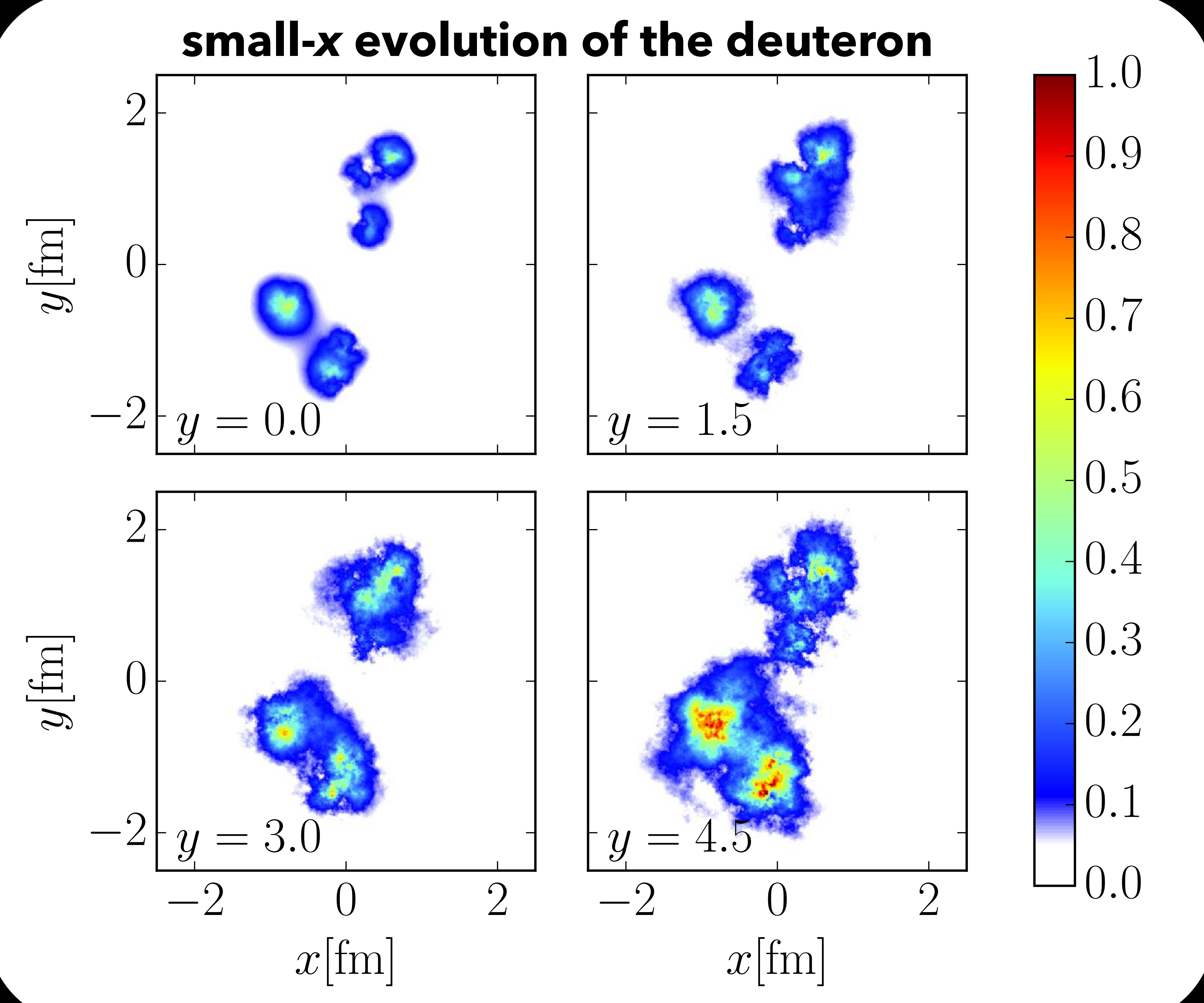
ZEUS collaboration, Eur. Phys. J. C24 (2002) 345

Diffractive vector meson production off light ions

H. Mäntysaari, B. Schenke, Phys.Rev. C101 (2020) 015203

Constrain the shape and fluctuations of the small-x gluon distribution in light ions like d and ^{3}He - better constrain initial state for RHIC system scan





Summary: Rule of 3 (What you will likely remember)

1 The guy's slides had a black background

2 There was a cool video

3 The Electron Ion Collider (EIC) is coming to Brookhaven

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Heavy ion data described quantitatively by framework built from effective theories

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Final state effects and sub-nucleon fluctuations are needed to describe small systems: p+A collisions create the smallest fluid on earth, but other effects are present

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The Electron Ion Collider (EIC) is coming to Brookhaven

Thank you!

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- Computations done at the National Energy Research Scientific Computing Center supported by the Office of Science of the U.S. DOE

- Thanks to my collaborators
  Charles Gale, Sangyong Jeon, Heikki Mäntysaari, Sören Schlichting, Chun Shen, Prithwish Tribedy, Raju Venugopalan

https://quark.phy.bnl.gov/~bschenke

DIY: All components publicly available

IP-Glasma Initial State:
https://github.com/schenke/ipglasma

Music Hydrodynamics:
http://www.physics.mcgill.ca/music

Equation of State:
https://sites.google.com/view/qcdneos

Particle Sampler:
https://github.com/chunshen1987/iSS

UrQMD Afterburner:
https://github.com/jbernhard/urqmd-afterburner