High-Energy Heavy-Ion Collision Physics

Part 2: Selected experimental results

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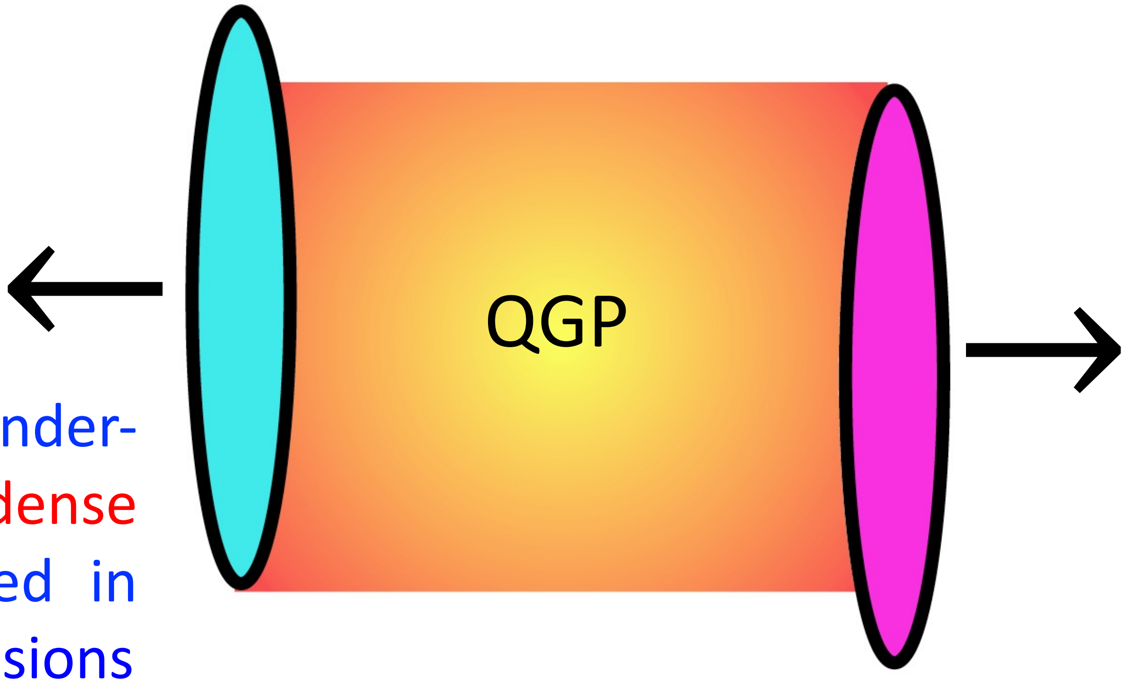
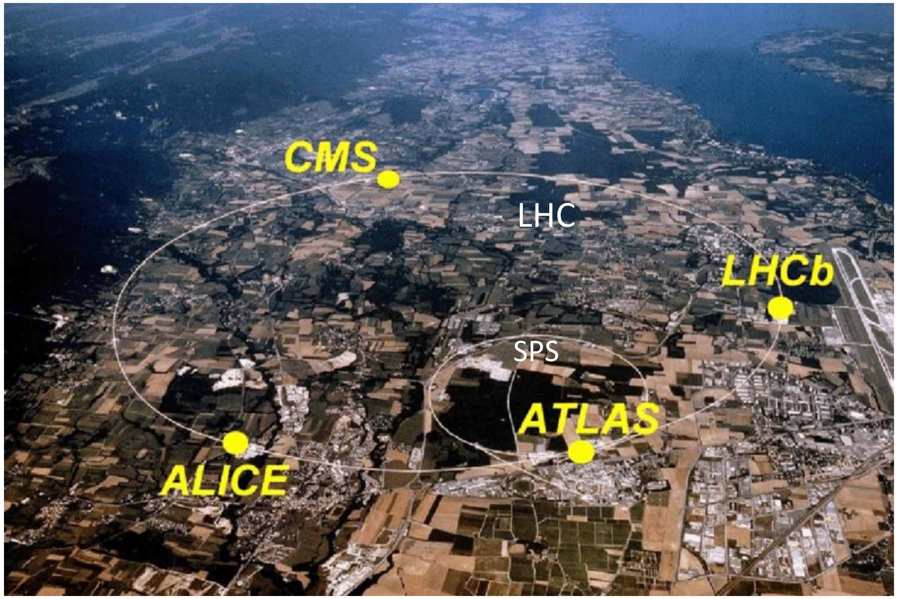


- The main goal is to understand the dynamics of dense and hot medium created in relativistic heavy-ion collisions

- Based on the calculations of the QCD lattice model, it is expected that in nuclear collisions at high energy, there are sufficient conditions to create QGP

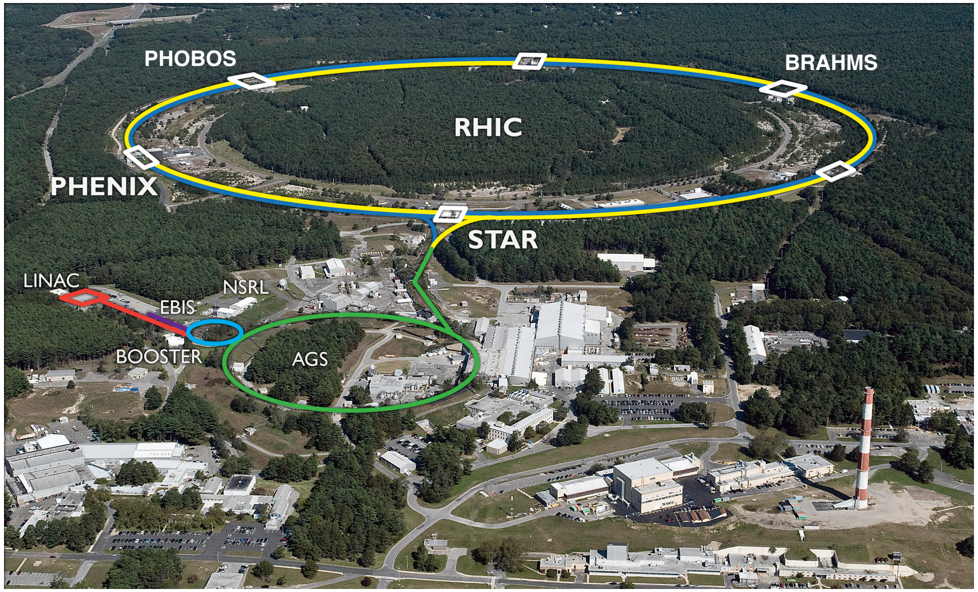
Heavy-Ion Colliders

LHC @ CERN



Species	$\sqrt{s_{NN}}$ (TeV)
Pb+Pb	2.76, 5.02, 5.36
Xe+Xe	5.44
p+Pb	5.02, 8.16
p+p	2.76, 5.02, 8, 13

RHIC @ BNL



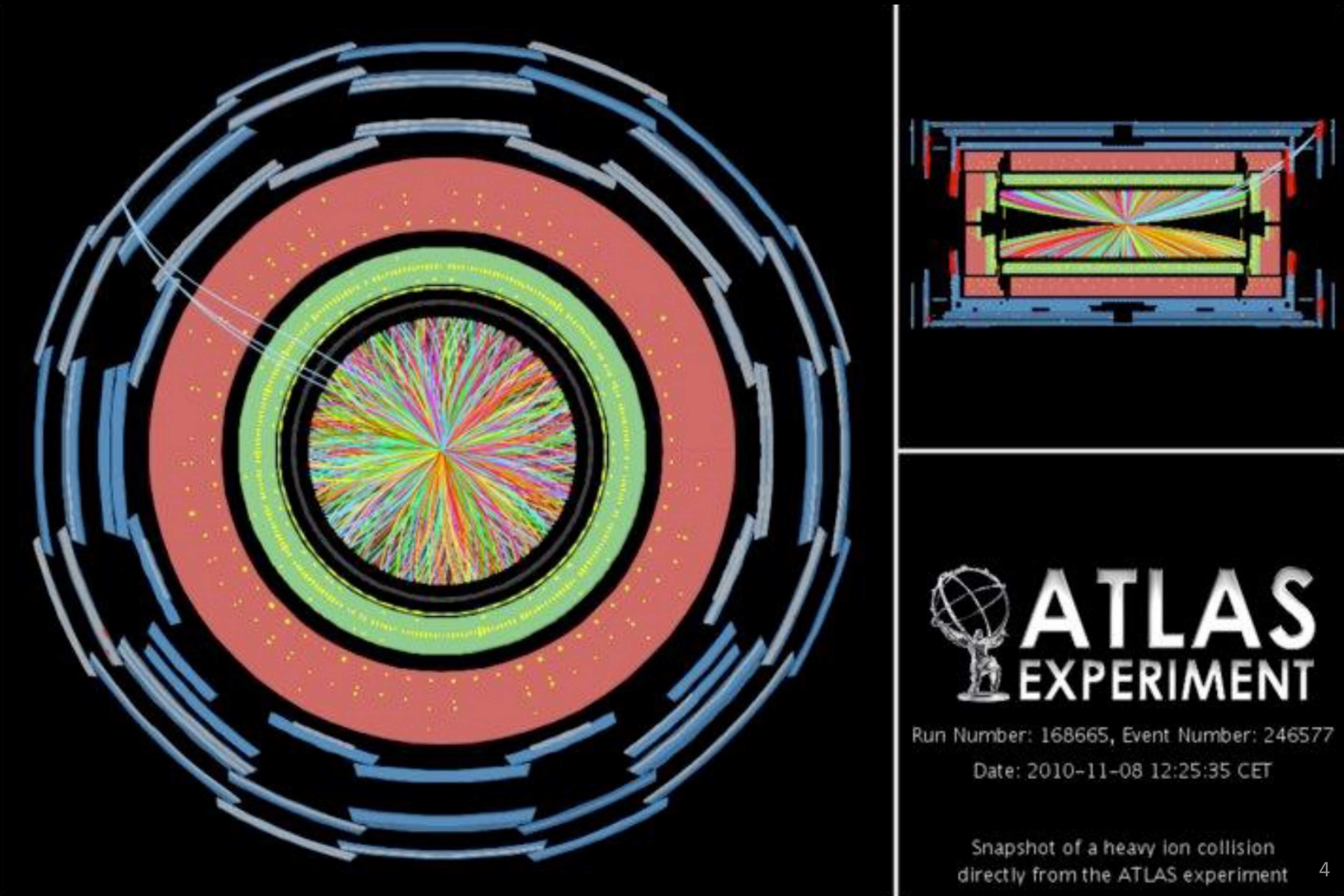
Species	$\sqrt{s_{NN}}$ (GeV)
Au+Au	7.7-200 (BES)
p+p	up to 500

Other collisions at RHIC:

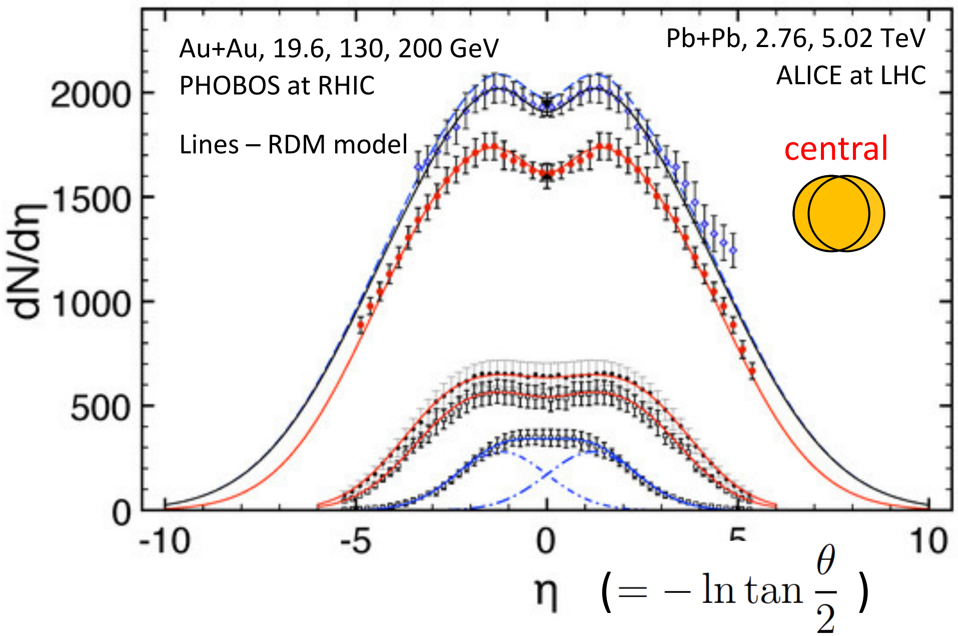
p+Al, p+Au, d+Au, ^{3}He+Au, O+O, Cu+Cu, Cu+Au, Zr+Zr, Ru+Ru, U+U

Soft Particle Production in Heavy-Ion Collisions

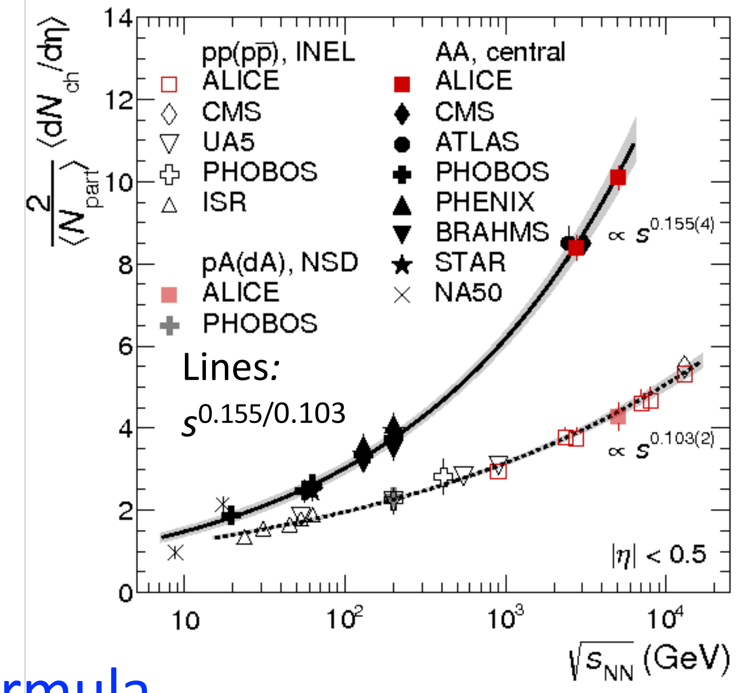
A Heavy-Ion Collision in ATLAS Experiment



Particle Production in Heavy-Ion Collisions

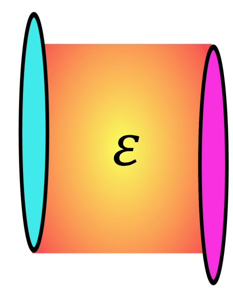


arXiv:1512.06104v2



- Collision energy in QGP, Bjorken formula

$$\varepsilon = \frac{dE_t}{dy}\frac{1}{A\tau} \approx \frac{3}{2}(<m_t>\frac{dN}{dy})\frac{1}{A\tau} \approx \begin{cases} \sim 5\ \text{GeV/fm}^3 \text{ - RHIC} \\ \sim 20\ \text{GeV/fm}^3 \text{ - LHC} \end{cases}$$



E_t is the total transverse energy

A overlap area of two colliding ions

τ is the thermalization time

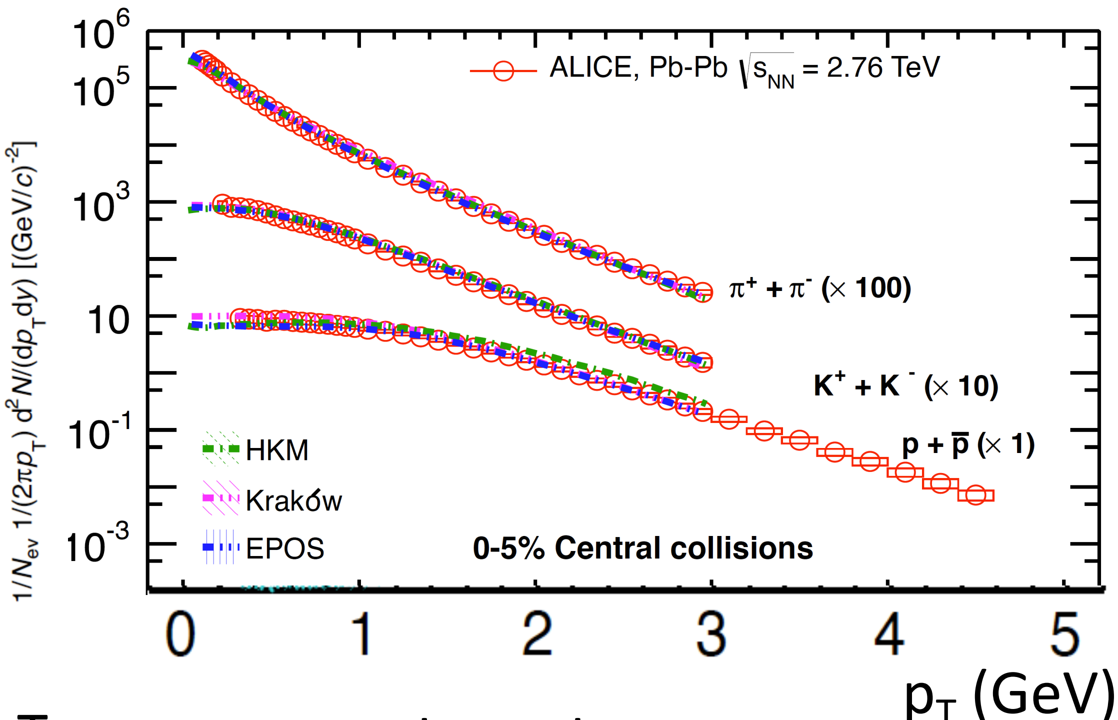
$$y = \frac{1}{2}\ln\frac{(E + p_{\parallel})}{(E - p_{\parallel})}$$

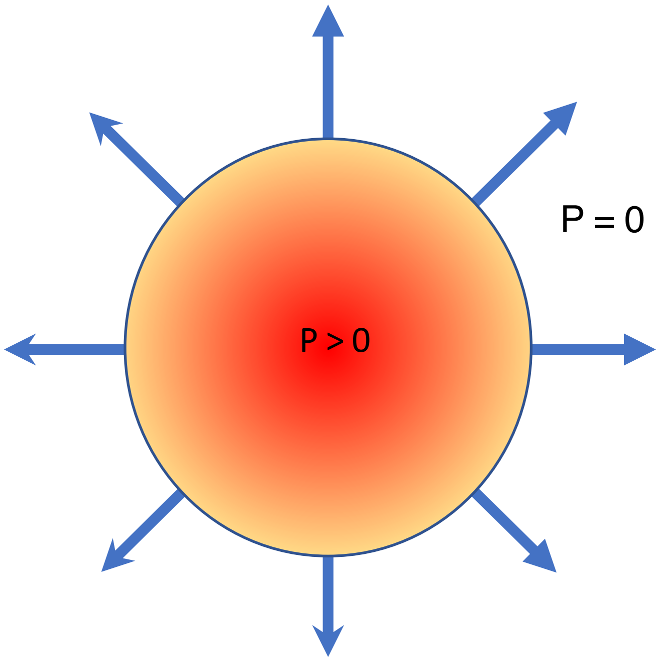
$\varepsilon \gg \varepsilon_c \sim 1$ GeV/fm^3

Signature for dense medium (QGP)

Radial Flow - p_T-Spectra of Identified Particles

Carry information about the dynamics of interactions in QGP





Two component spectrum:

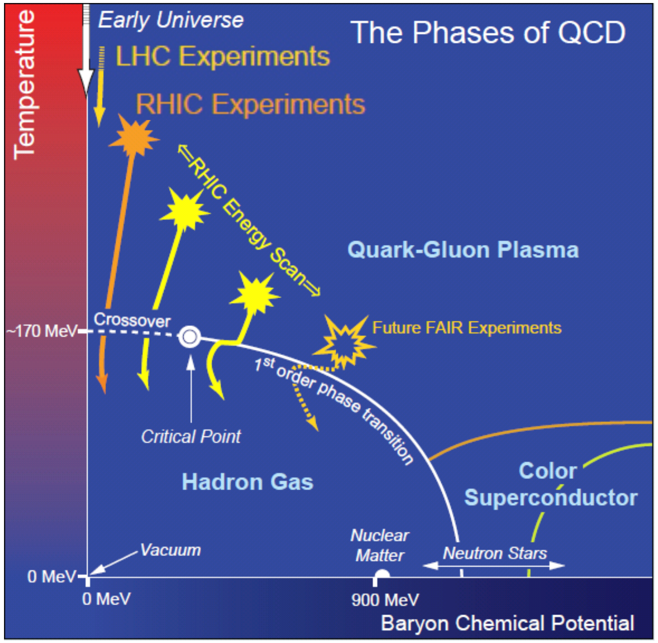
- Soft part ($p_T \lesssim 2$ GeV) - spectra are exponential and become flatter with increasing particle mass.

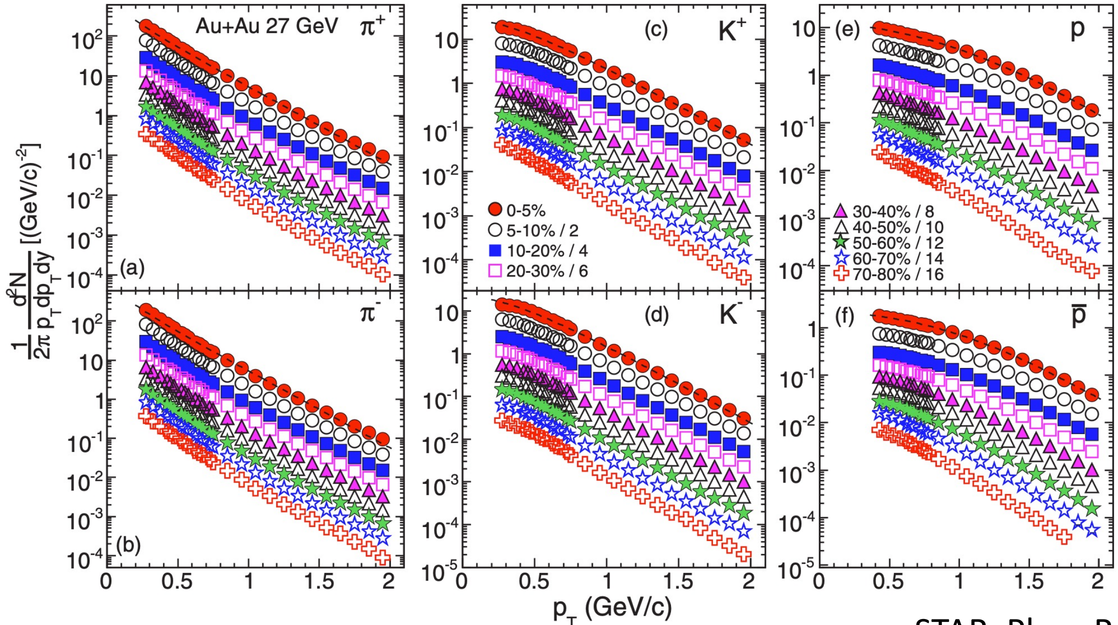
$$T_{eff} \approx T_{fo} + \frac{m_h < \beta_T >^2}{2}$$

Blast Wave Fit: $\beta \approx 0.7c$

Signature of collective radial flow

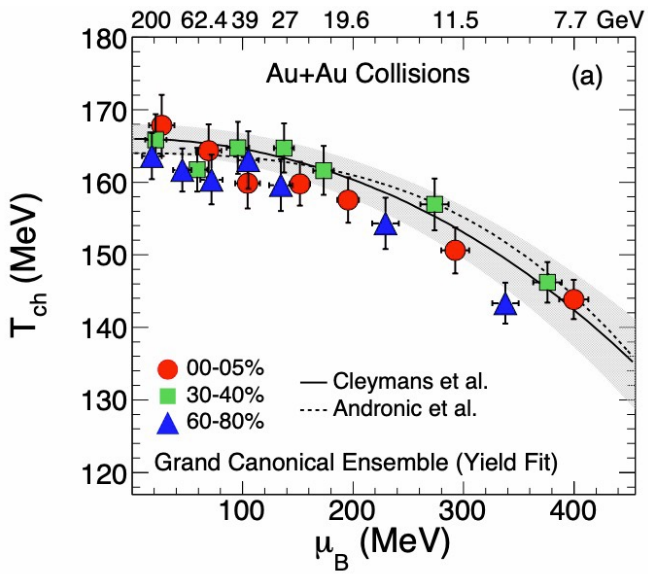
Probing QCD Phase Diagram with HI Collisions





STAR, Phys. Rev. C 96 (2017) 44904

- Changing beam energy leads to changes in the tempe-rature and μ_B of the system
- Grand Canonical Ensemble model (THERMUS) used to measure the temperature and μ_B of the system, using the RHIC BES data

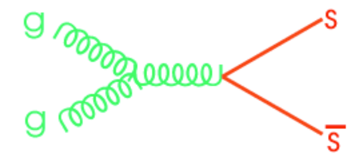


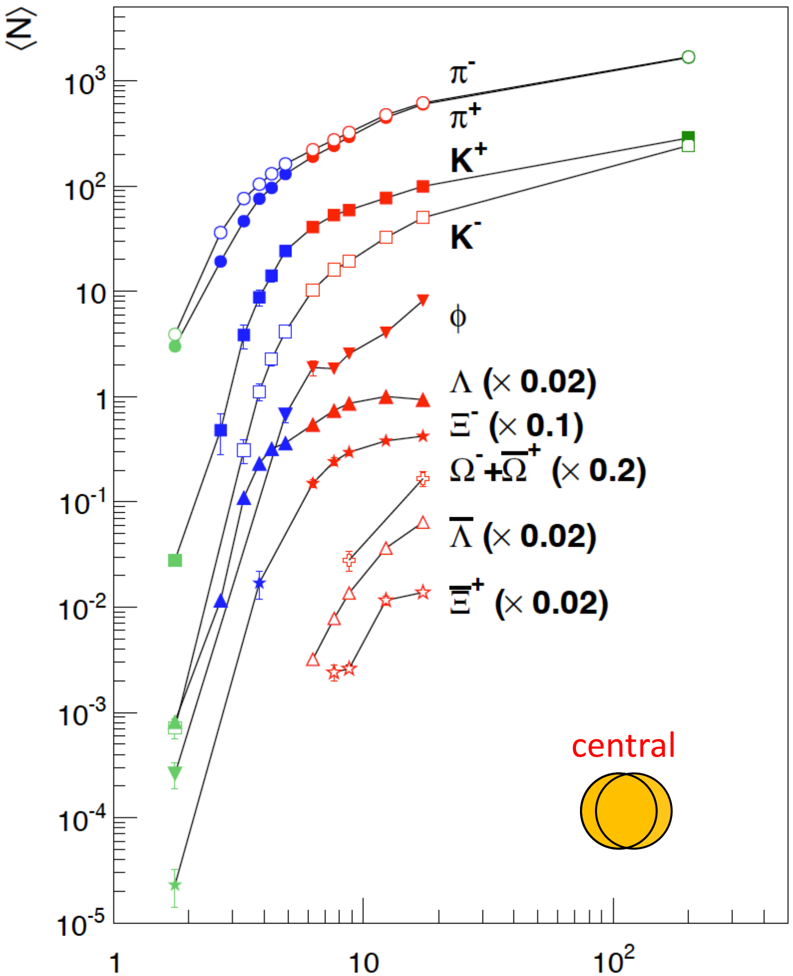
Strangeness Enhancement - QGP Signature

Strangeness is newly produced (no s-Quarks in nucleons)

J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982) – predictions

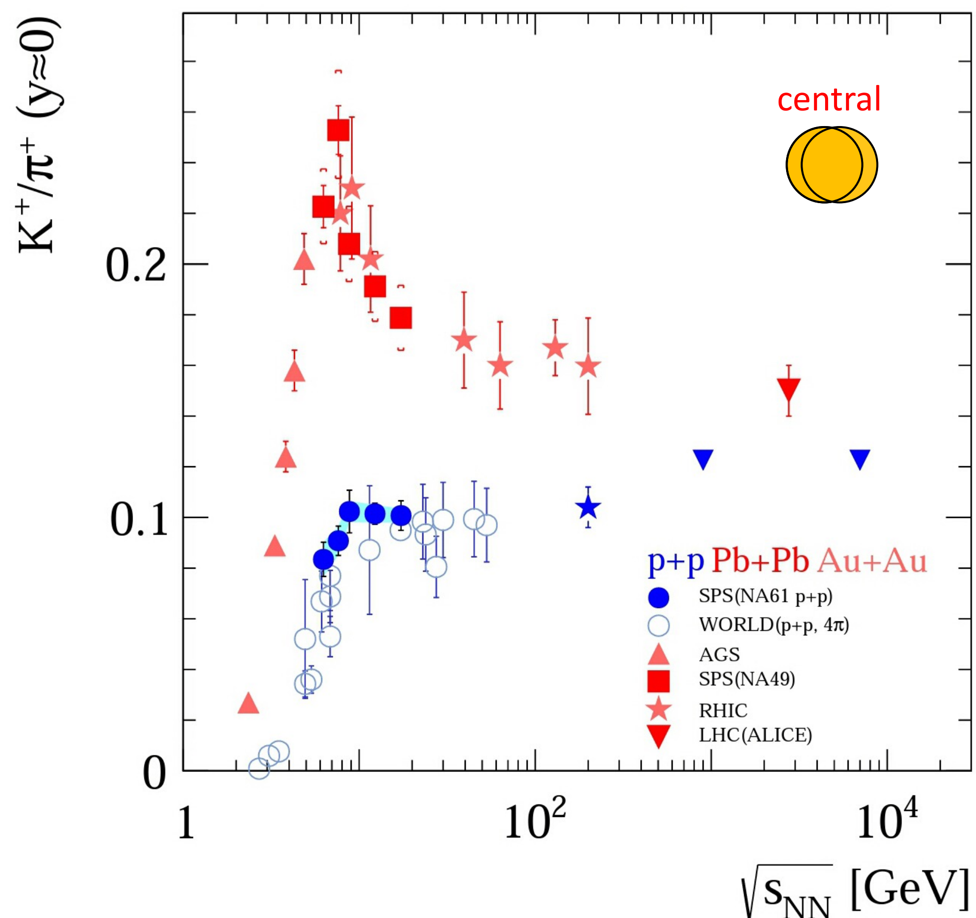
- Energy needed to produce $s\bar{s}$ pair ≈ 200 MeV (>2m$_s$)





JPG31, S57 (2005)

"Horn" – onset of deconfinement

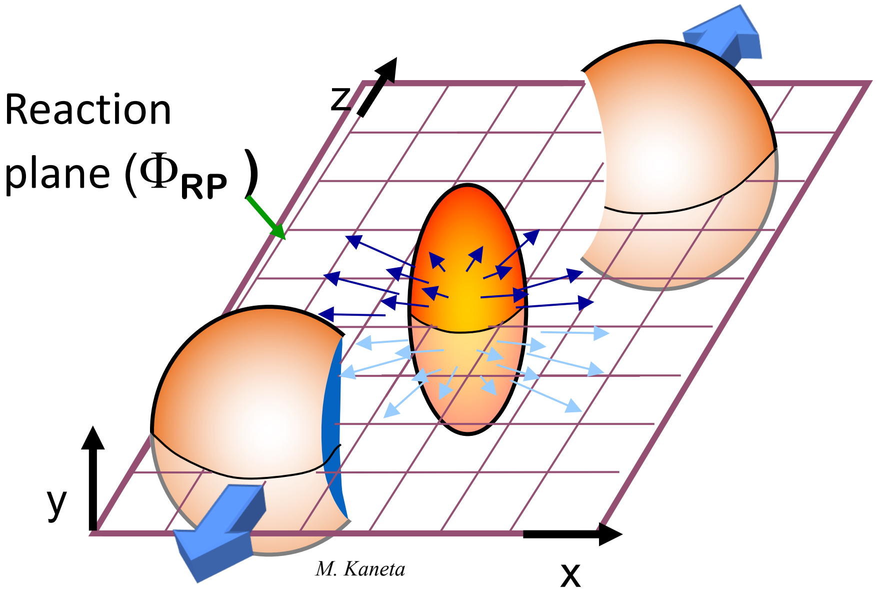


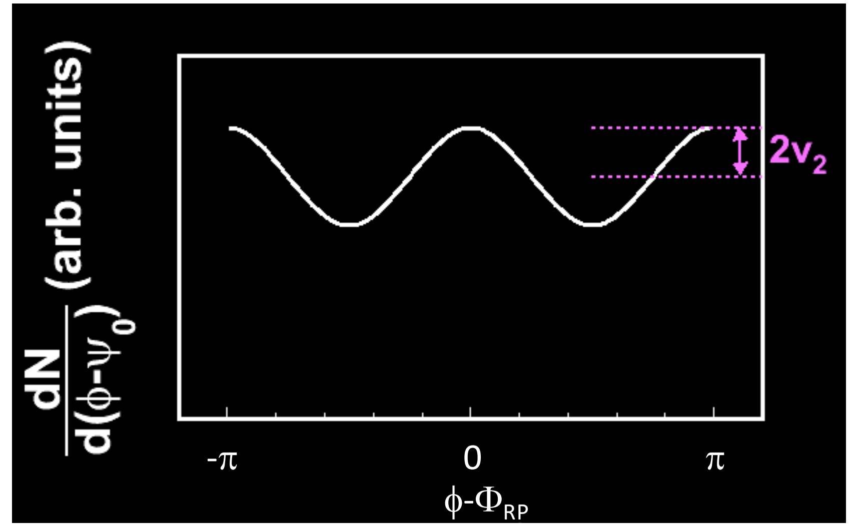
NA61 arXiv:1510.08239

Azimuthal Anisotropy (Collectivity)

Azimuthal Anisotropy of Produced Particles

Signature of strongly interacting QGP

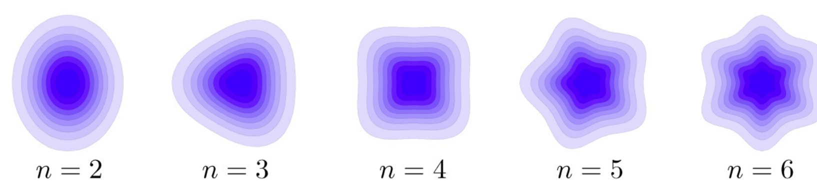




- Anisotropy is "driven" by asymmetry in initial geometry
- Pressure gradients lead to azimuthal anisotropy (collectivity)

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Phi_n)]$$

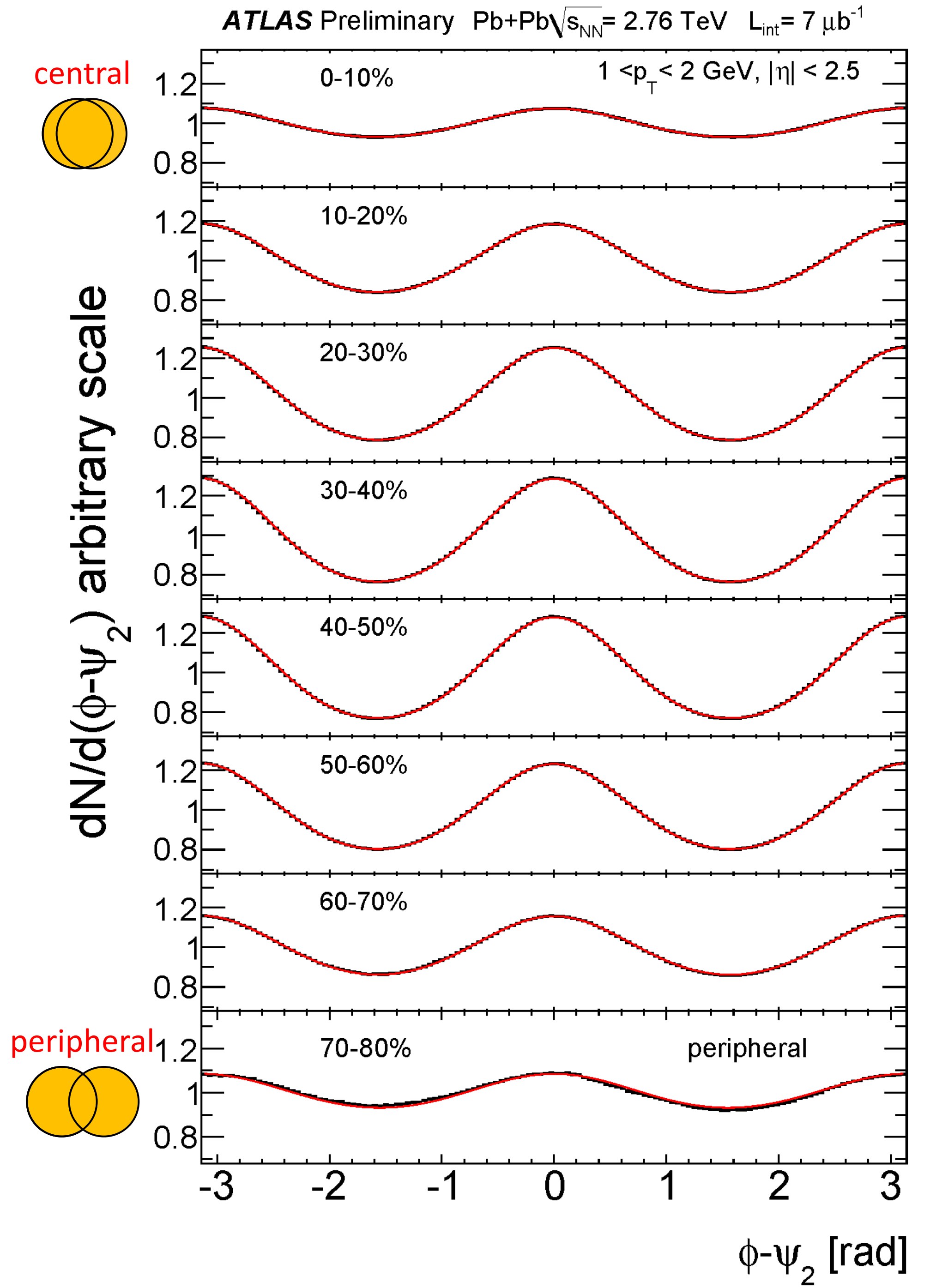
$$v_n = < \cos(n(\phi - \psi_{RP})) >$$



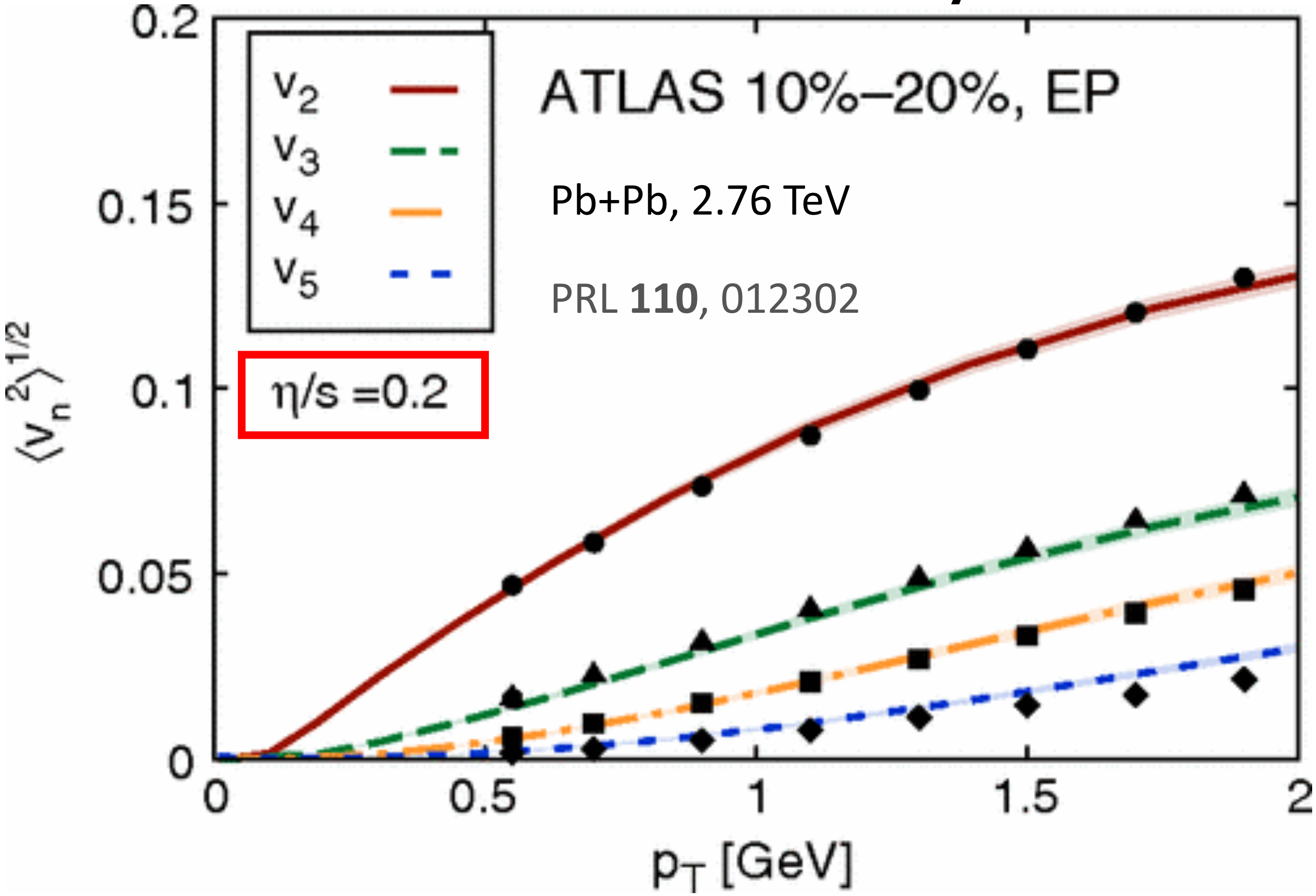
- $\mathbf{v_2}$ – elliptic flow, dominant harmonic

Azimuthal Anisotropy in 5.02 TeV Pb+Pb Collisions

- Φ_{RP} is approximated by event plane obtained from FCal, ψ_2



Flow Harmonics in Heavy-Ion Collisions

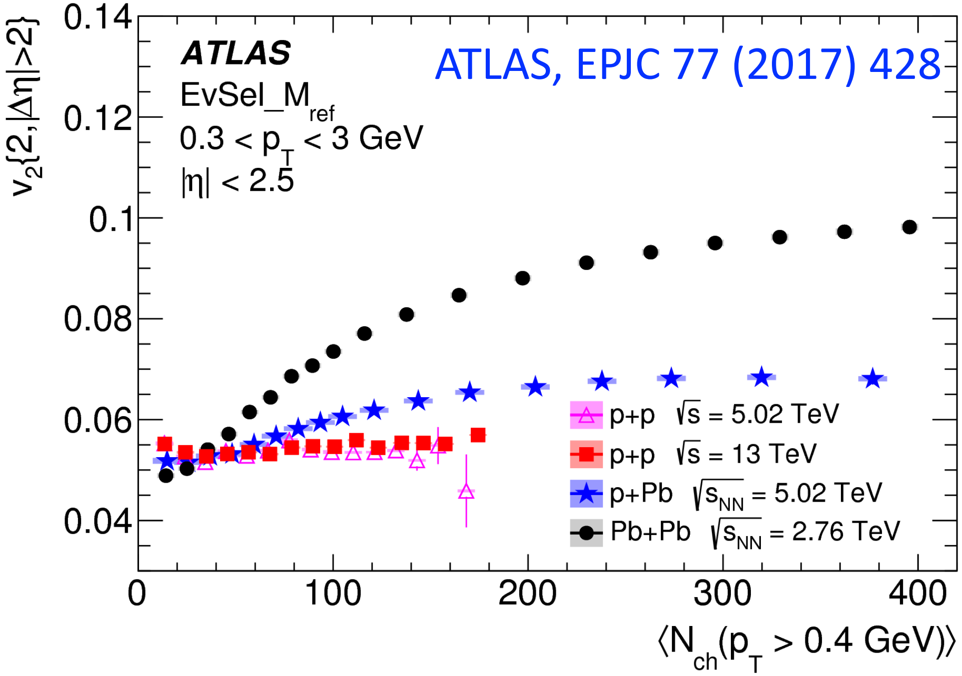


- Large azimuthal flow is observed, v_2 dominates
- Hydrodynamic models well describe v_n harmonics
  - QGP as almost ideal fluid (small viscosity)

RHIC's Major Discovery → QGP *paradigm shift*

Puzzling Collectivity in Small Systems

Significant anisotropy was also observed in pp collisions at the LHC
(first by CMS, JHEP 1009:021, 2010)



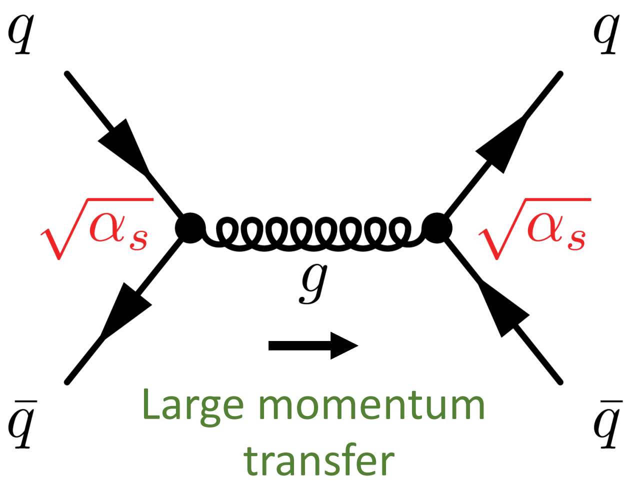
- In *pp* and *p*+Pb collisions similar flow harmonics as in heavy-ion collisions are observed.
- Small system flow results are supported by hydrodynamical models, (e.g. Phys.Rev.C 85(2012) 014911)

However, more studies are needed to address open questions

- Is QGP present in small collision systems?
- …

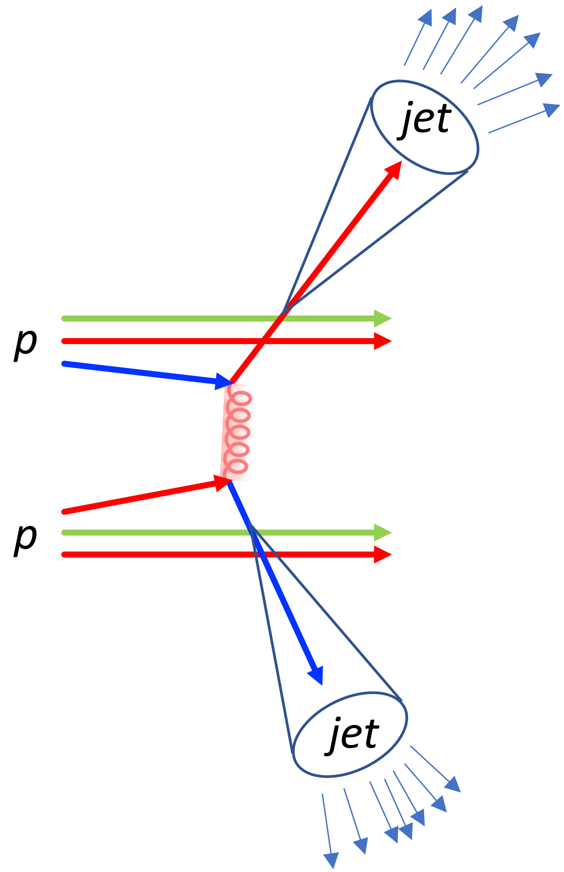
Hard Particle Production in Heavy-Ion Collisions

Hard Particle Production in Heavy-Ion Collisions



- Hard particles ($p_T \gtrsim 2$ GeV) originate from hard parton scatterings, at large Q, before QGP formation

Jet – Collective Spray of Hadrons

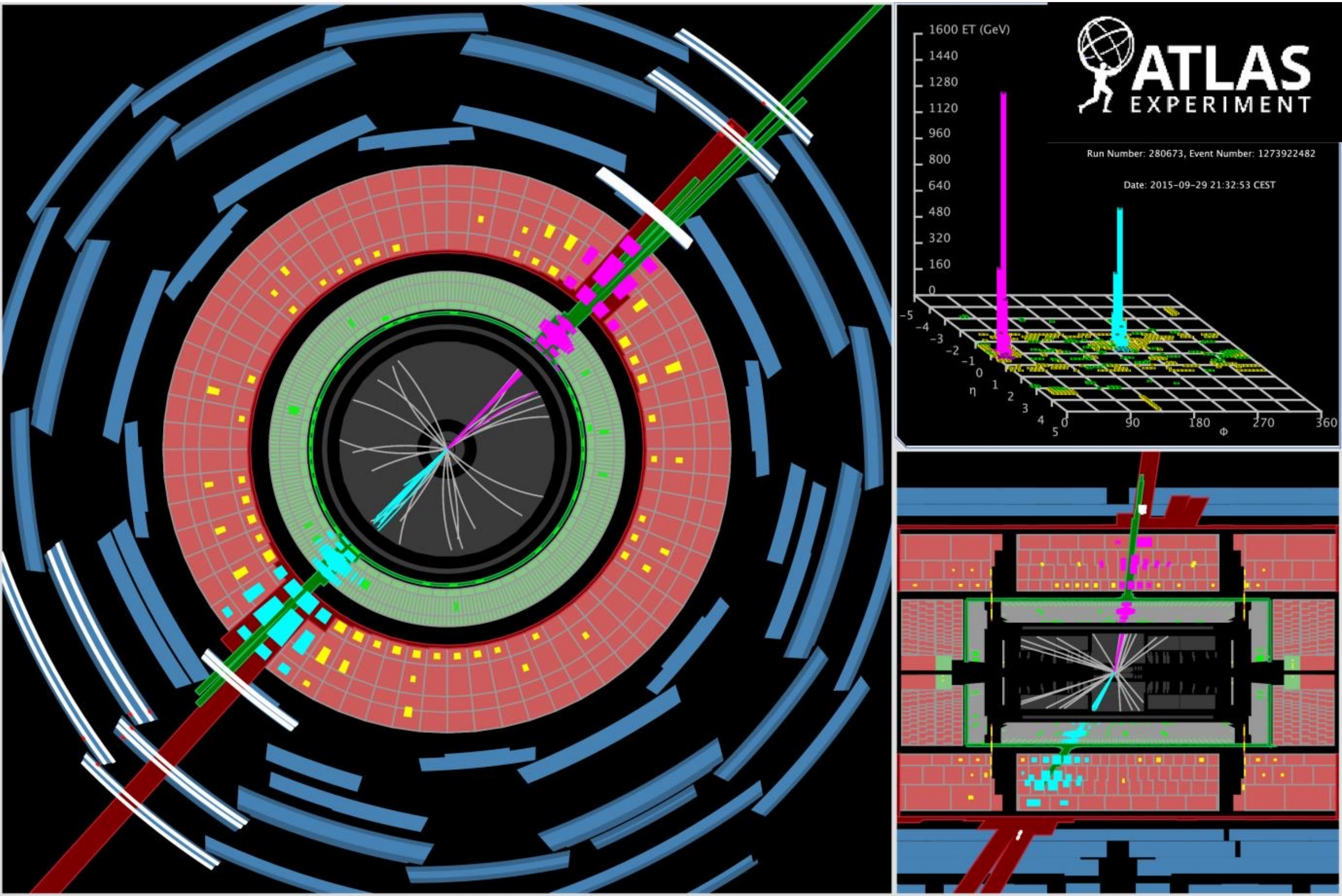


Jet cone,

$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

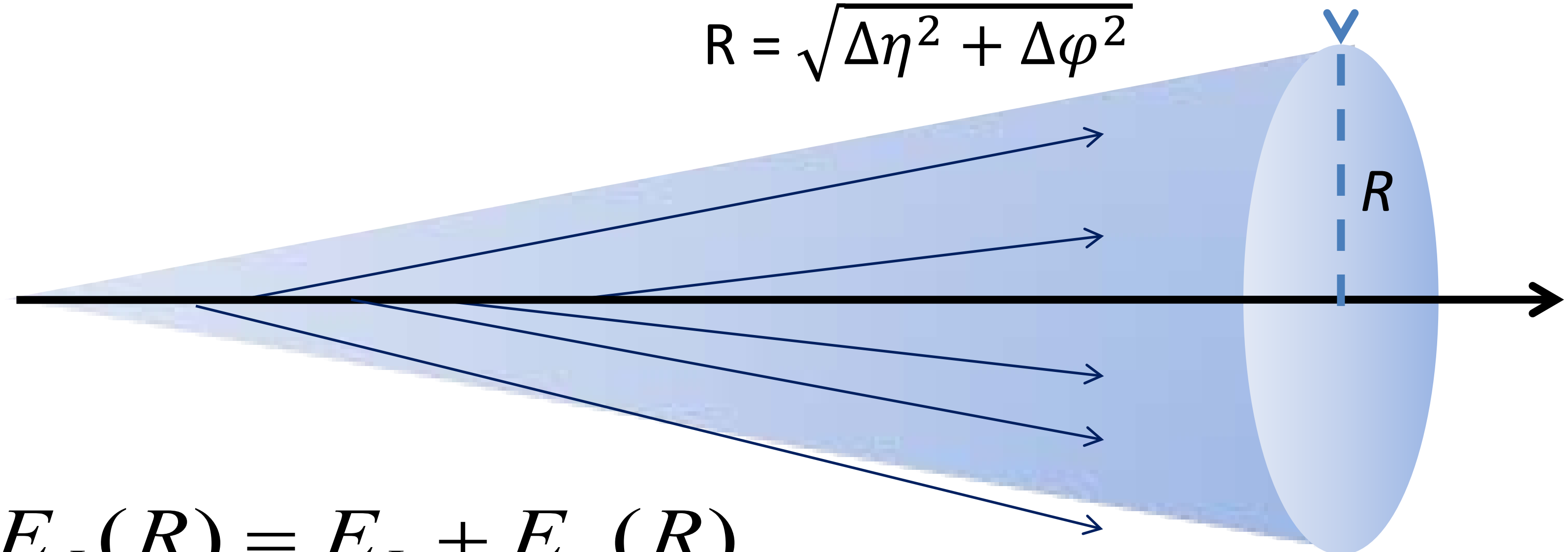
- Jet: a bunch of collimated particles in a narrow R cone generated by hadronization of a common source
- At the LHC, hard processes lead to abundant jet production

2-jet Event (dijet) in the ATLAS Experiment



Jets in Vacuum

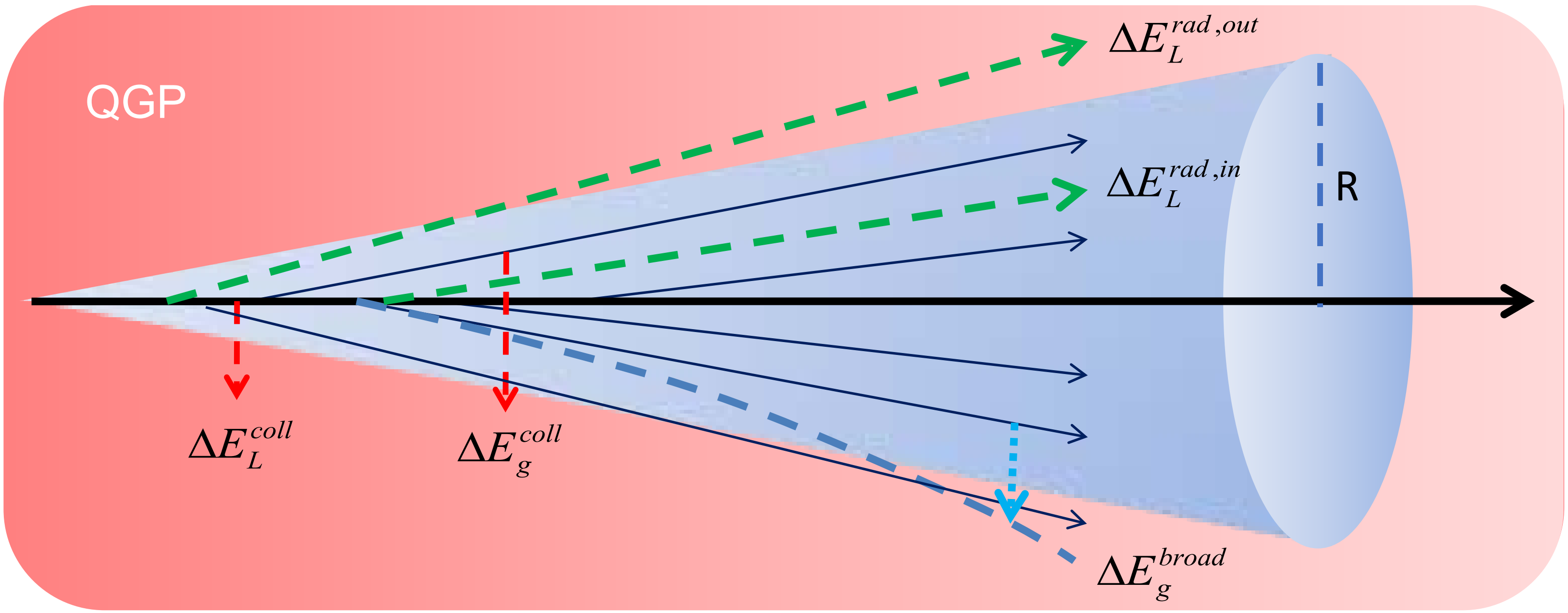
$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$



$$E_J(R) = E_L + E_g(R)$$

For pp collisions, partonic jet shower in developes in vacuum (leading particle and radiated gluons)

Jets in Medium



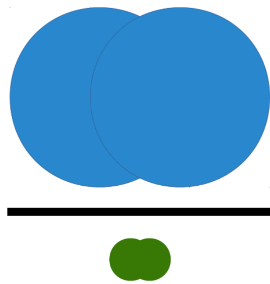
In heavy-ion collisions, additional processes are present due the QGP

- Shower particles interact with the medium and can radiate additional gluons or be scattered out of the jet cone
- Jets loose energy in the medium

X.-N. Wang and M. Gyulassy, PRL 68 (1992) 1480

Measure of Jet Production Modification

- Nuclear-modification factor:

$R_{AA} = \frac{1}{N_{\mathrm{coll}}}$  $= \frac{1}{N_{\mathrm{coll}}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_{\mathrm{T}}}}$

Jet yield in AA

Jet yield in pp (reference)

The number of binary NN interactions (or T_{AA} if cross-sections are compared)

$R_{AA}=1$ → scaling

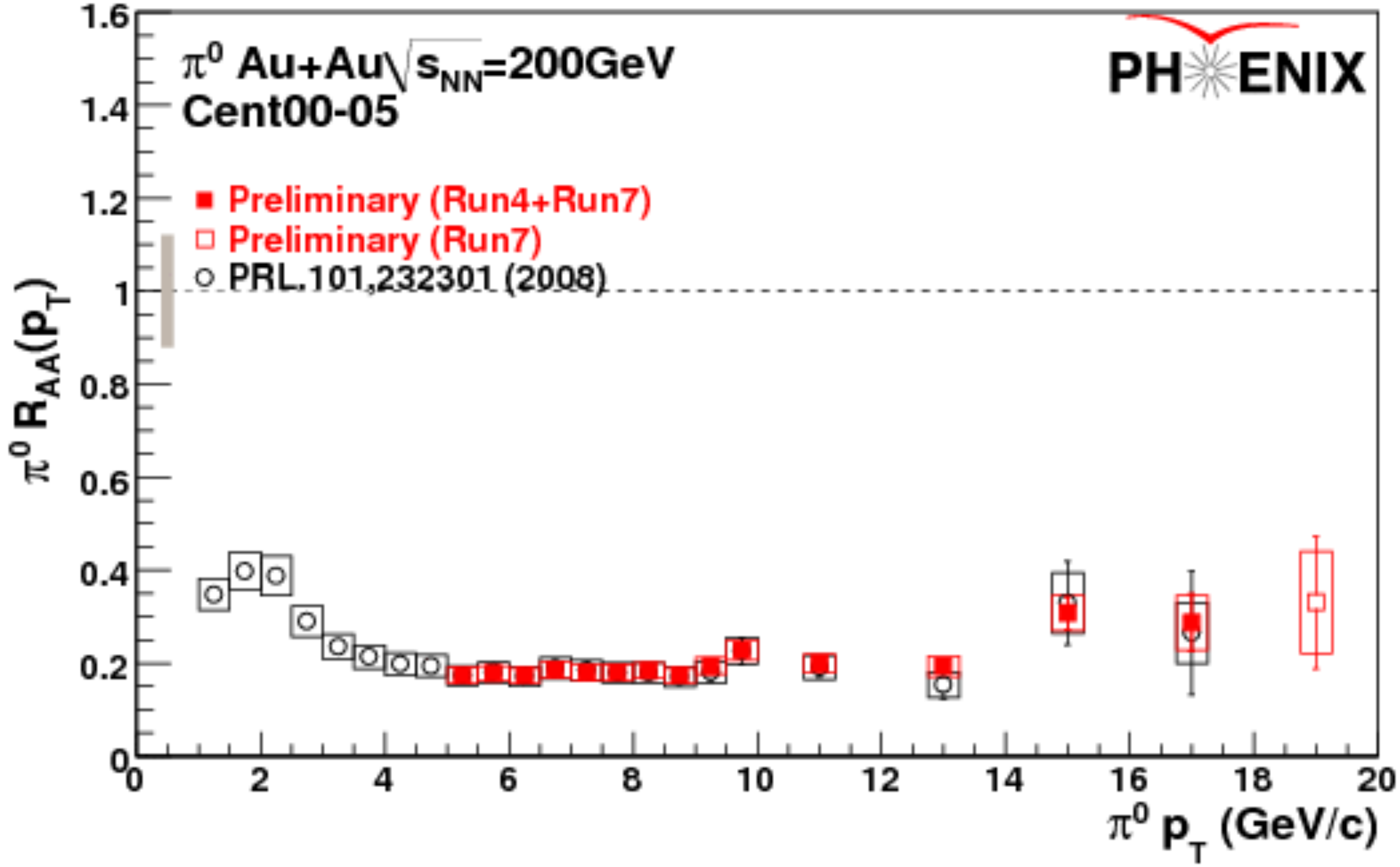
$R_{AA}<1$ → suppression (aka quenching)

$R_{AA}>1$ → enhancement

R_{AA} can be measured for different objects: jets, Z, pions, …

π^0 R_{AA} in 200 GeV Au+Au Collisions (RHIC)

p_T dependence in different centrality intervals:

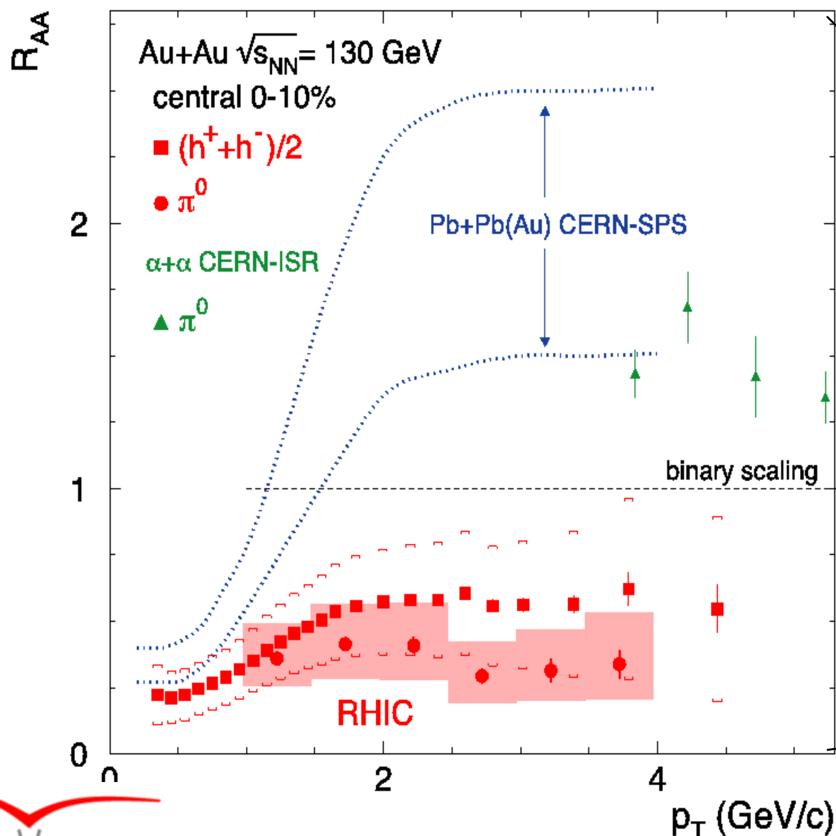


- R_{AA} for π^0 measured up to p_T = 20 GeV (central Au+Au)
- R_{AA} ≈0.2 in central Au+Au up to highest p_T(5 < p_T < 20 GeV) – strong suppression

Historical Remark
Jet Quenching - 23 Years Ago

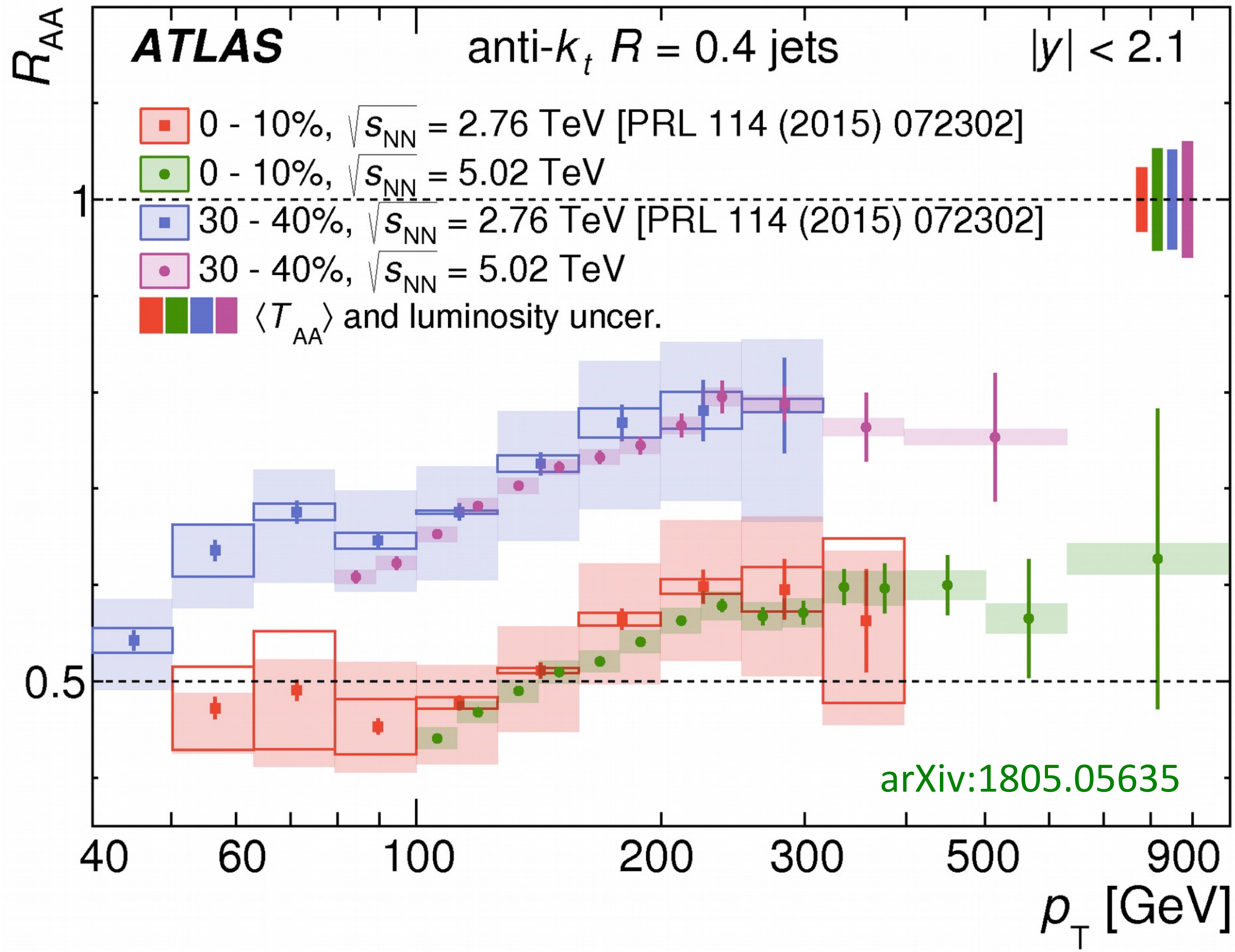
Next RHIC's Major Discovery → QGP *paradigm shift*

Discovery of a strong "jet" suppression → QGP a strongly interacting medium



PHENIX

Jet R_{AA} in Pb+Pb Collisions at the LHC



- Suppression of jet yield is observed in central Pb+Pb collisions
- A weak decrease of suppression with p_T is observed
- Same magnitude of R_{AA} is seen between 2.76 TeV and 5.02 TeV

Outlook

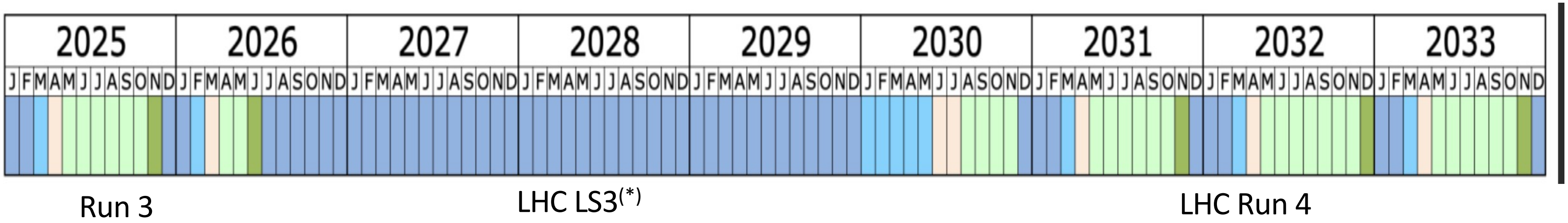
High-Energy Heavy-Ion Collisions

Facility	RHIC	LHC/HL-LHC	SppC / FCC-hh
Timeline	→ 2025	→ 2041 (Runs 3 to 6)	> 2035 / > 2070
Collision system	pp, d-Au, Au-Au	pp, p-Pb and A-A (Pb-Pb, ^{16}O, ^{129}Xe, ^{84}Kr, ^{40}Ar, ...)	FCC: pp, p-A and A-A (Pb-Pb, ^{129}Xe, ^{84}Kr, ^{40}Ar, ...)
$\sqrt{s_{NN}}$ (TeV)	0.2	5.5	~39
Int. rate (kHZ)	~15 (Au-Au)	≳50 (x 3-4 in Run5) for Pb-Pb	~2500 (FCC)
Experiments	sPHENIX, STAR	ALICE, ATLAS, CMS, LHCb phase II of ATLAS and CMS **phase II-b of ALICE and LHCb**	up to four experiments

Luciano Musa (CERN), QM 2023

- General future goals of HI collisions at the LHC
- Future accelerators FCC/SppC will open completely new opportunities for heavy-ion collision physics

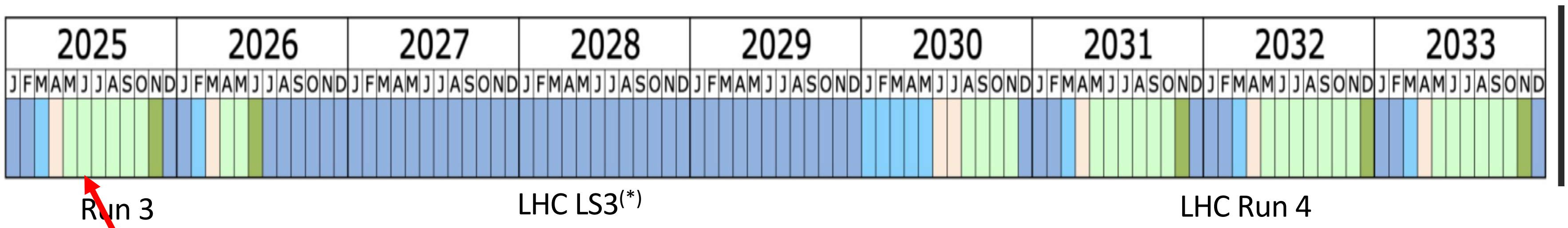
LHC/HL-HLC timeline for Heavy-Ion Run 3/Run 4



See talk M. R. Alemany Fernandez

- Continue with one-month ion runs at the end of the year
- Two more ion runs planned in Run 3
- O-O and p-O collisions last week of June 2025
- In Run 4 three ion runs planned

LHC/HL-HLC timeline for Heavy-Ion Run 3/Run 4



See [talk](#) M. R. Alemany Fernandez

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Summary

- QCD ab initio calculations predict existence of deconfined phase in heavy-ion collisions
  - Phase transition to QGP at T_c ~ 155 MeV
- Dynamical features of the hot and dense medium created in heavy-ion collisions
  - Energy density ~20x critical energy density for QGP formation
  - Significant strangeness enhancement
  - Very strong radial flow, $\beta \approx 0.7$
  - Strong elliptical flow – QGP behaves as nearly ideal fluid
  - Strong suppression of jets and high p_T particles
  - Many others interesting results (heavy-flavour, Z/W, photo-nuclear…)
- Significant azimuthal anisotropy observed in small systems

Significant part of the HI programme at the LHC is ahead
as well as plenty of exciting physics

References: *Quark Matter Conferences websites/proceedings*

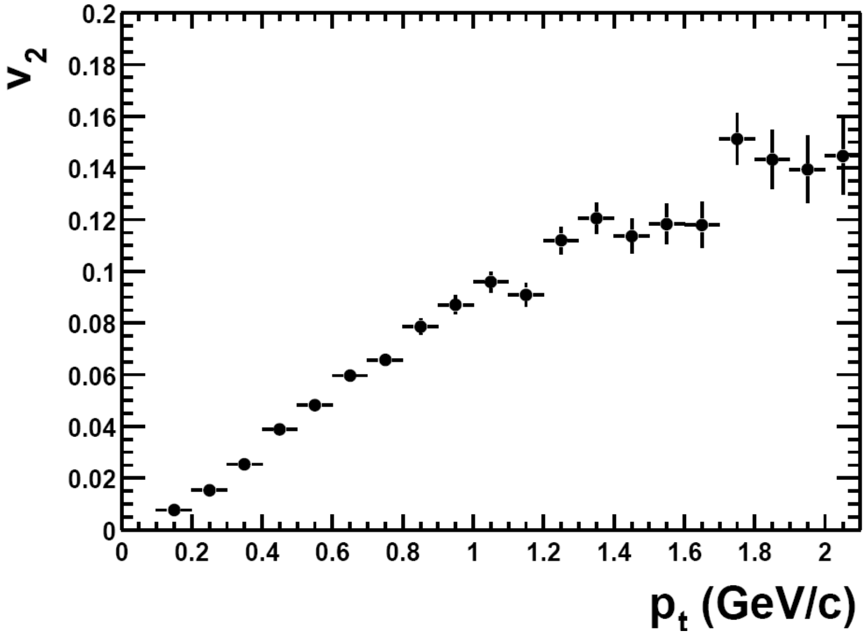
- *e.g. see sessions for students*

Historical Remark
- Large Azimuthal Anisotropy at RHIC

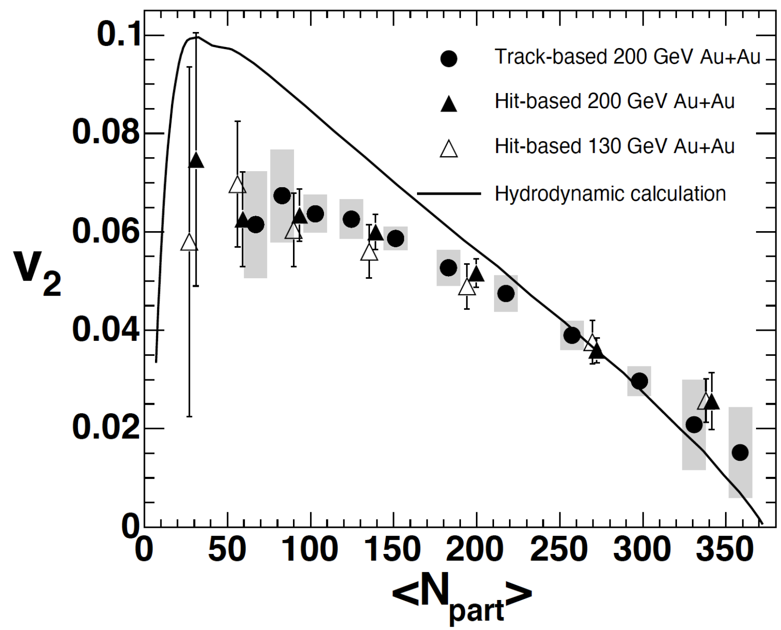
First RHIC's Major Discovery in 2000 ➔ *QGP Paradigm Shift*

Discovery of strong "elliptic" flow consistent with hydrodynamical calculations -> QGP as almost perfect fluid

STAR, Phys.Rev.Lett.86:402-407,2001



PHOBOS, Nucl. Phys. A 757 (2005) 28

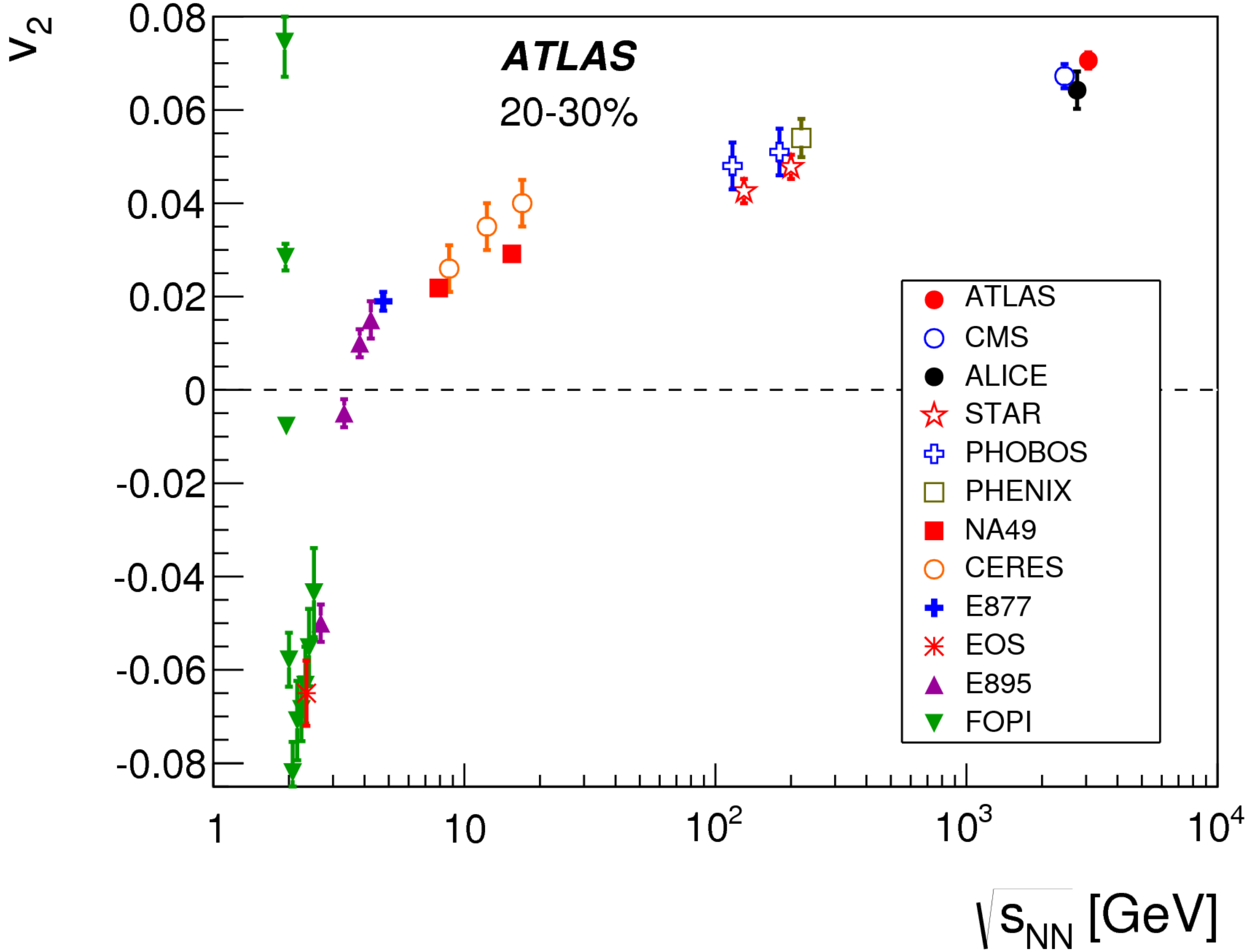


2 Forward Calorimeters (FCal) are used for RP approximation: $3.2<|\eta|<4.9$.

Tracks from Inner Detector are used for flow harmonics determination: $|\eta|<2.5$

$$v_n = < \cos\left(n(\phi - \psi_{RP})\right) >$$

Elliptic Flow, v_2



Strong azimuthal anisotropy in ultra-relativistic HI collisions