High-Energy Heavy-Ion Collision Physics

Part 2: Selected experimental results

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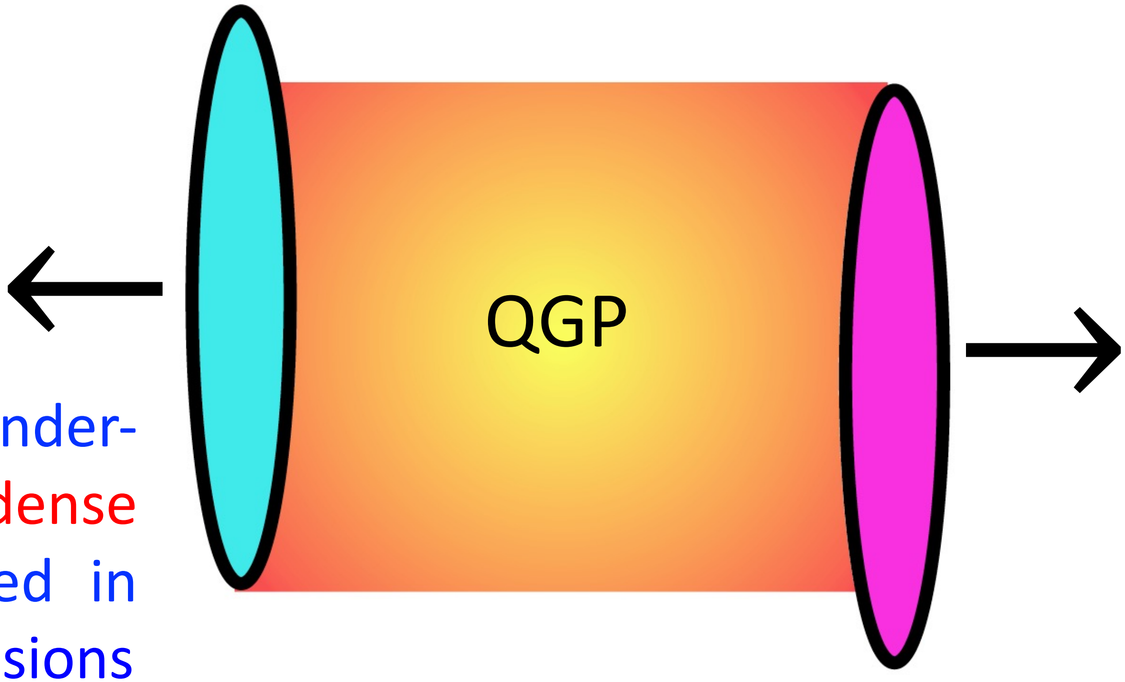
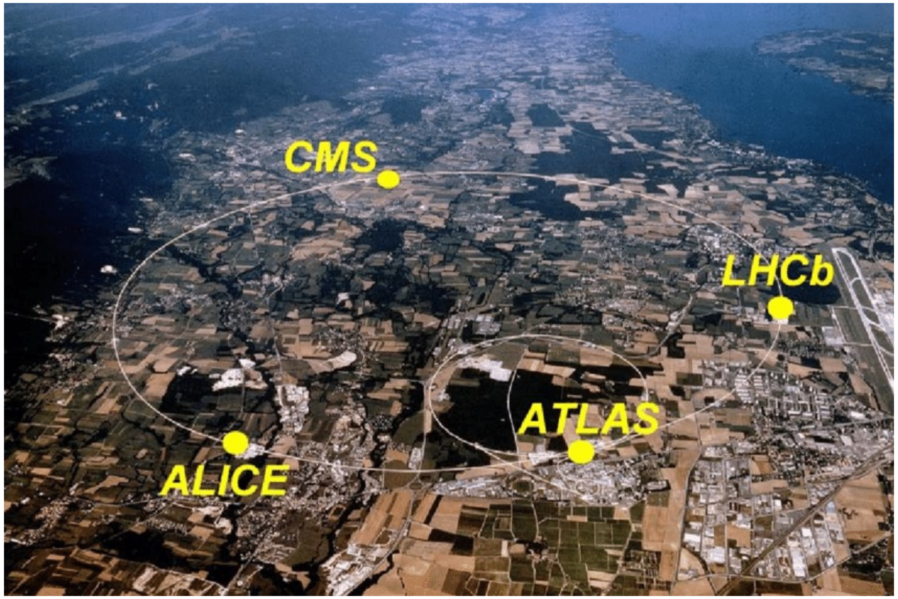


- The main goal is to understand the dynamics of dense and hot medium created in relativistic heavy-ion collisions

- 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

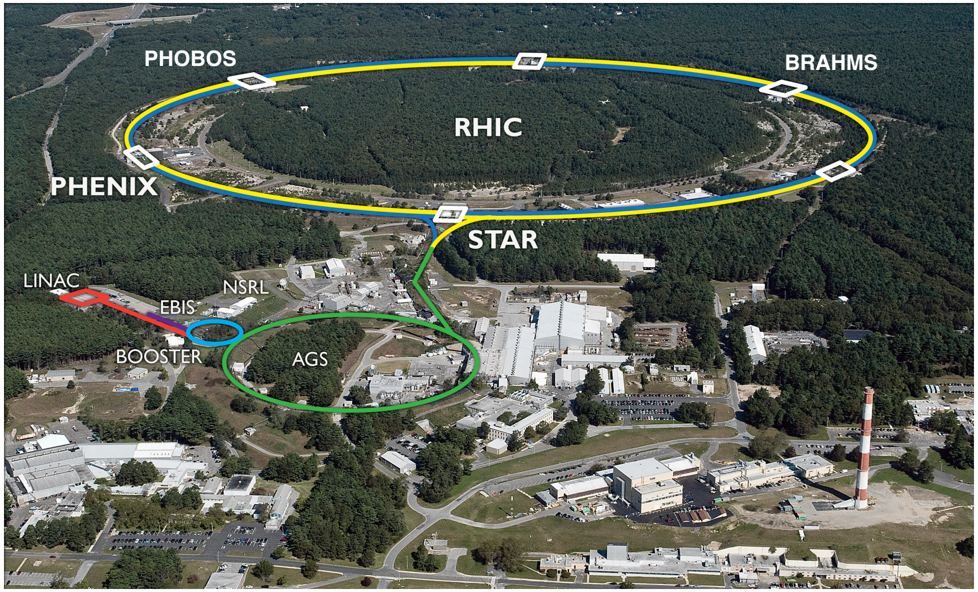
Heavy-Ion Colliders

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

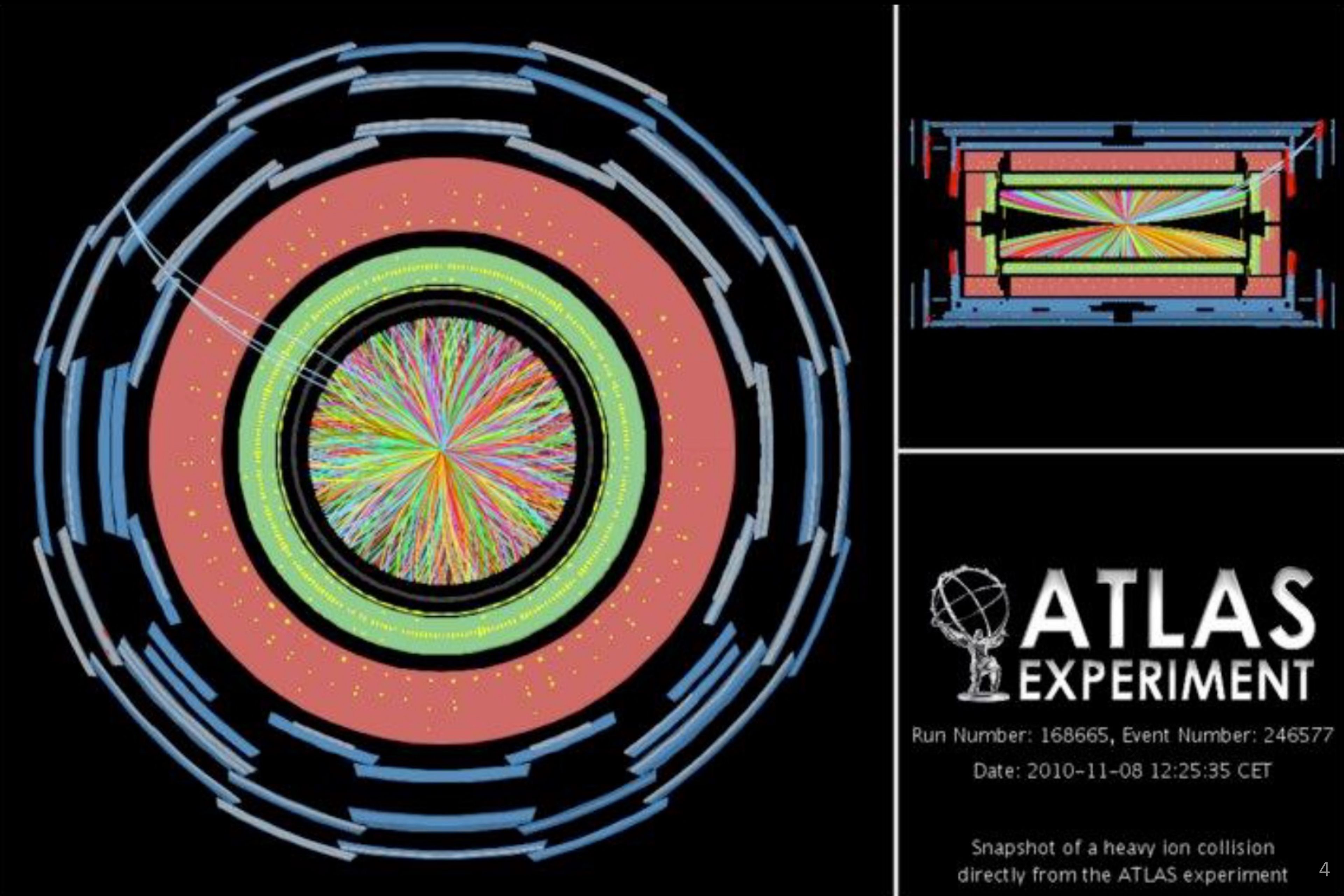


Species	$\sqrt{s_{NN}}$ (GeV)
Au+Au	7.7-200
p+p	up to 500

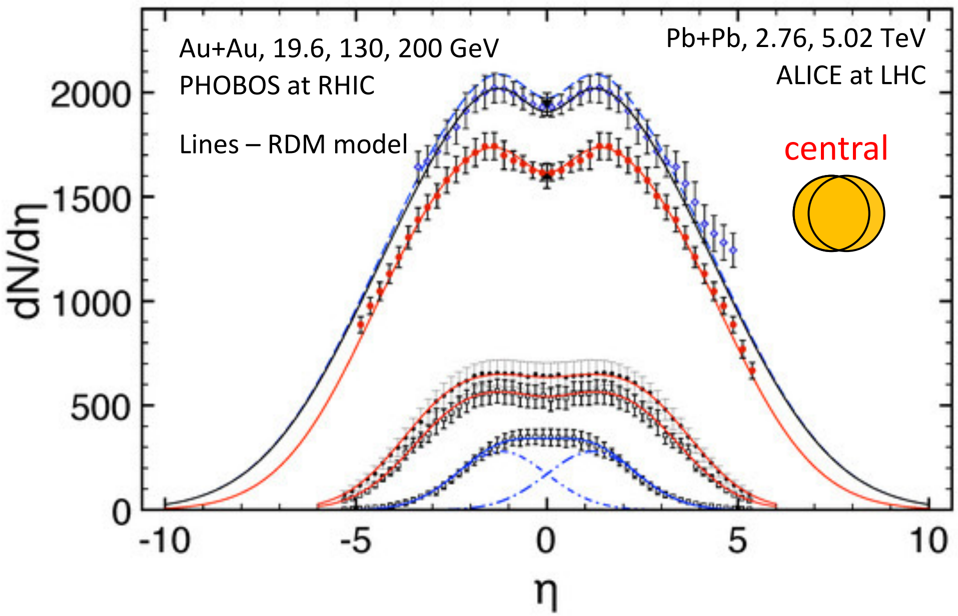
Other collisions at RHIC:
p+Al, p+Au, d+Au, Cu+Cu, Cu+Au, Zr+Zr, Ru+Ru, U+U

Soft Particle Production in Heavy-Ion Collisions

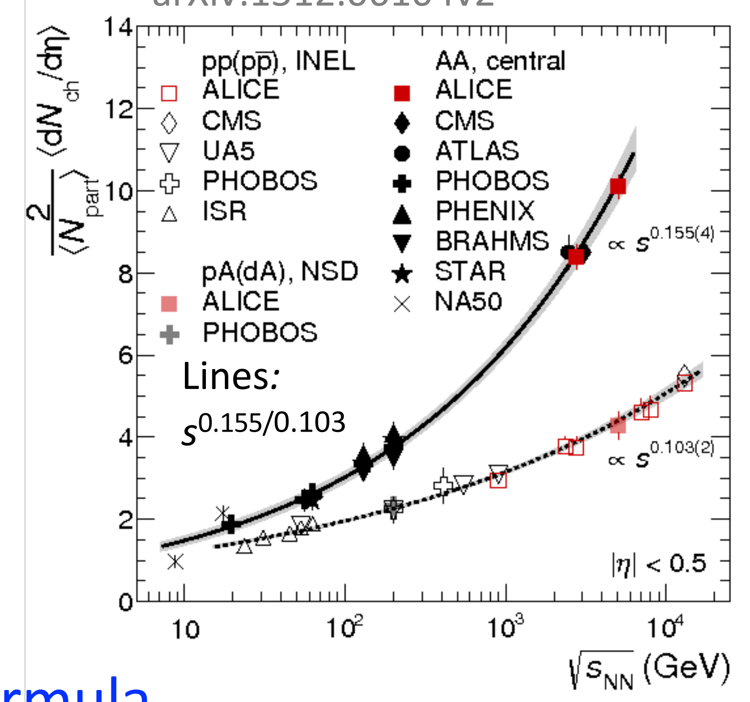
A Heavy-Ion Collision



Particle Production in Heavy-Ion Collisions



arXiv:1512.06104v2

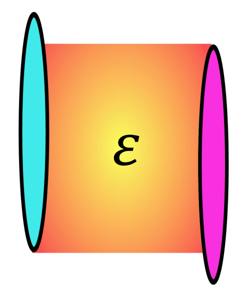


- Collision energy in QGP, Bjorken formula

$$\varepsilon = \frac{dE_t}{dy}\frac{1}{A\tau} \approx \frac{3}{2}(<m_t>\frac{dN}{dy})\frac{1}{A\tau} \approx$$

$\sim$5 GeV/fm^3 - RHIC

$\sim$ 20 GeV/fm^3 - LHC



E_t is the total transverse energy

A overlap area of two colliding ions

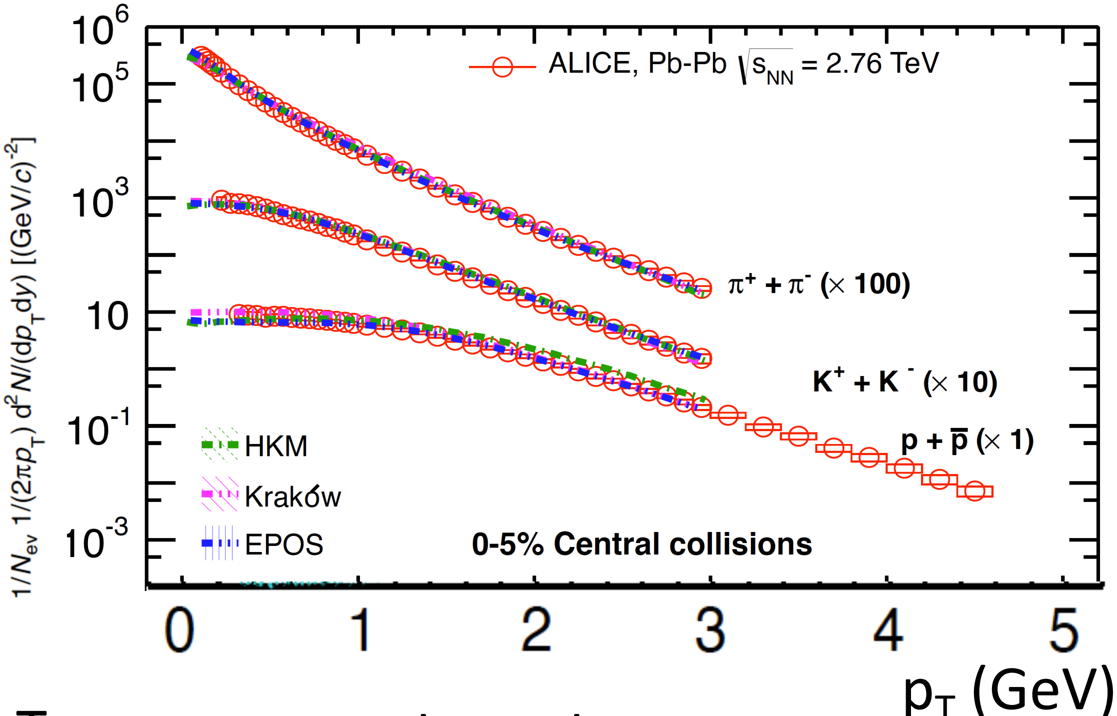
τ is the thermalization time

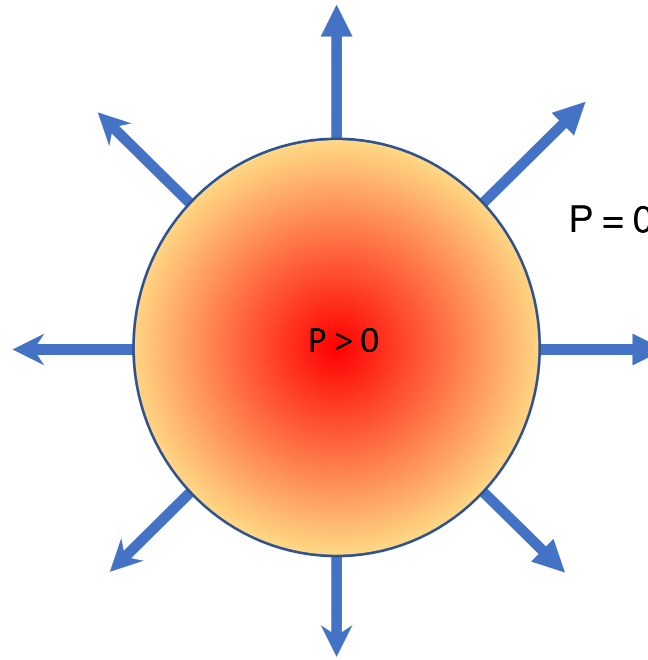
$\varepsilon \gg \varepsilon_c \sim 1$ GeV/fm^3

$$y = \frac{1}{2}\ln\frac{(E+p_{\|})}{(E-p_{\|})} \qquad \eta = -\ln\tan\frac{\theta}{2}$$

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. Signature of collective radial flow

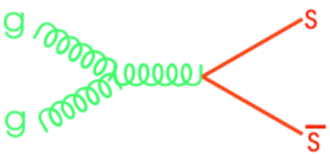
$$T_{eff} \approx T_{fo} + \frac{m_h < \beta_T >^2}{2}$$

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

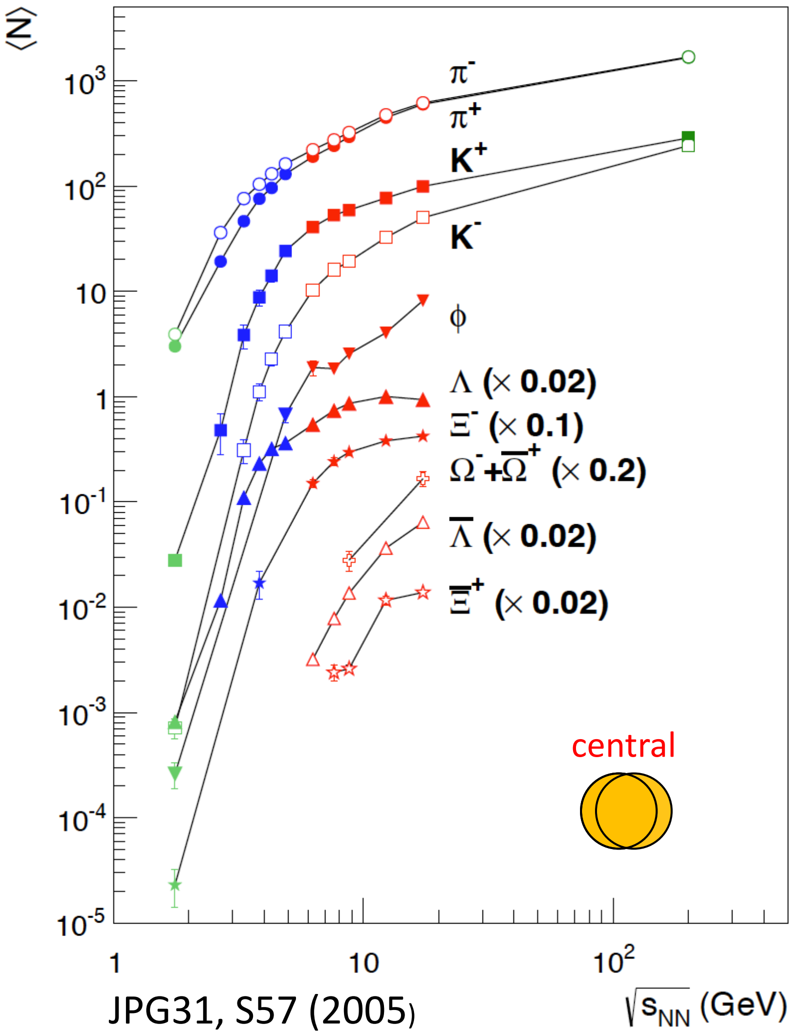
Strangeness Enhancement - QGP Signature

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

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

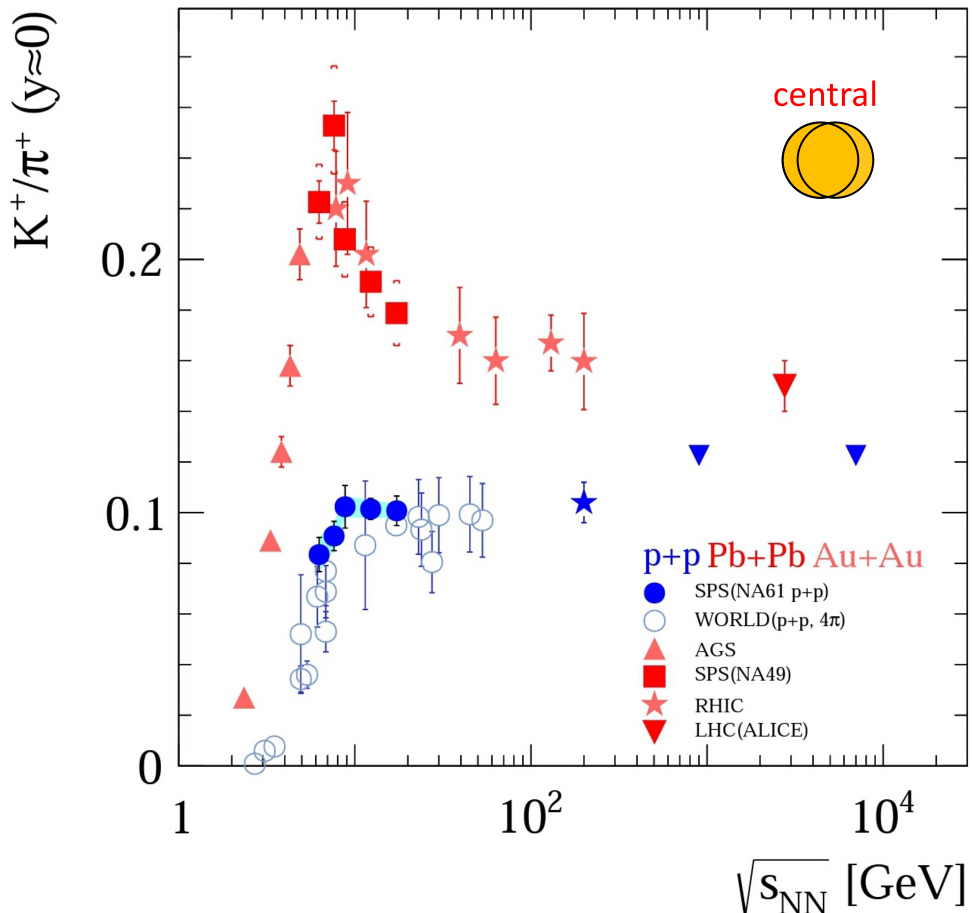


- Energy needed to produce $s\bar{s}$ pair ≈ 200 MeV (>2m$_s$)



JPG31, S57 (2005)

“Horn”

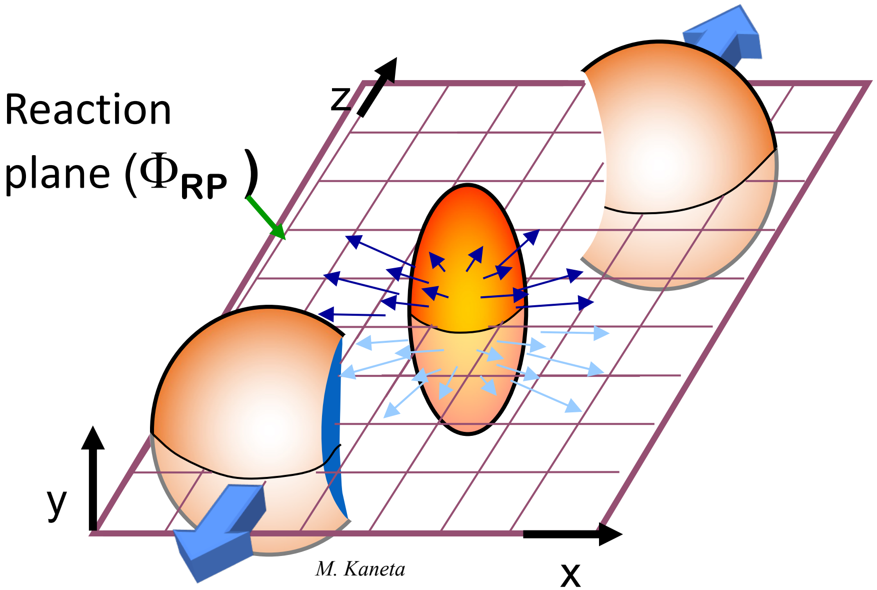


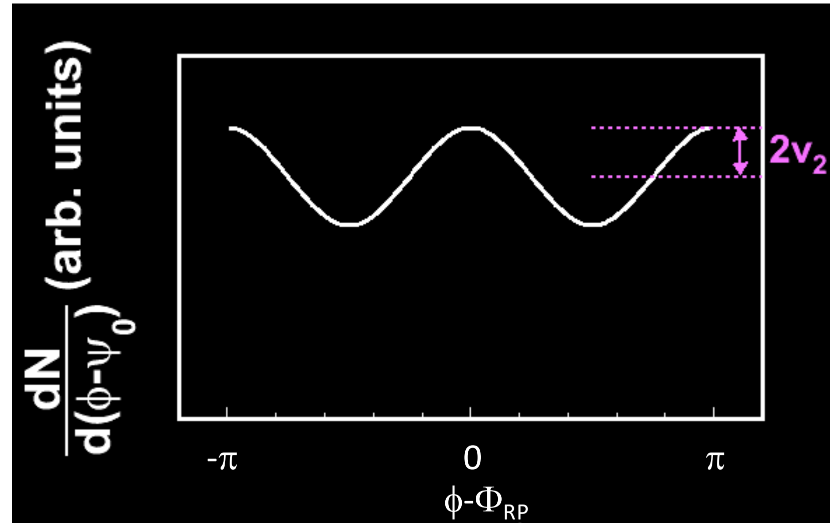
NA61 arXiv:1510.08239

Azimuthal Anisotropy (Collectivity)

Azimuthal Anisotropy of Produced Particles

Signature of strongly interacting QGP

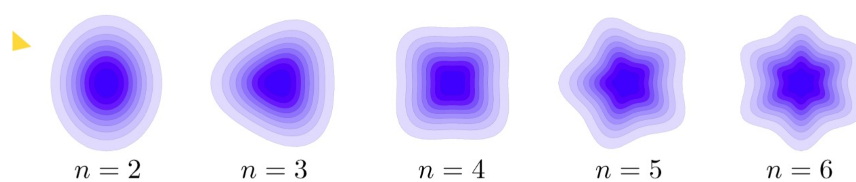




- Anisotropy is “driven” by asymmetry in initial geometry
- Pressure gradients lead to azimuthal anisotropy (collectivity)

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

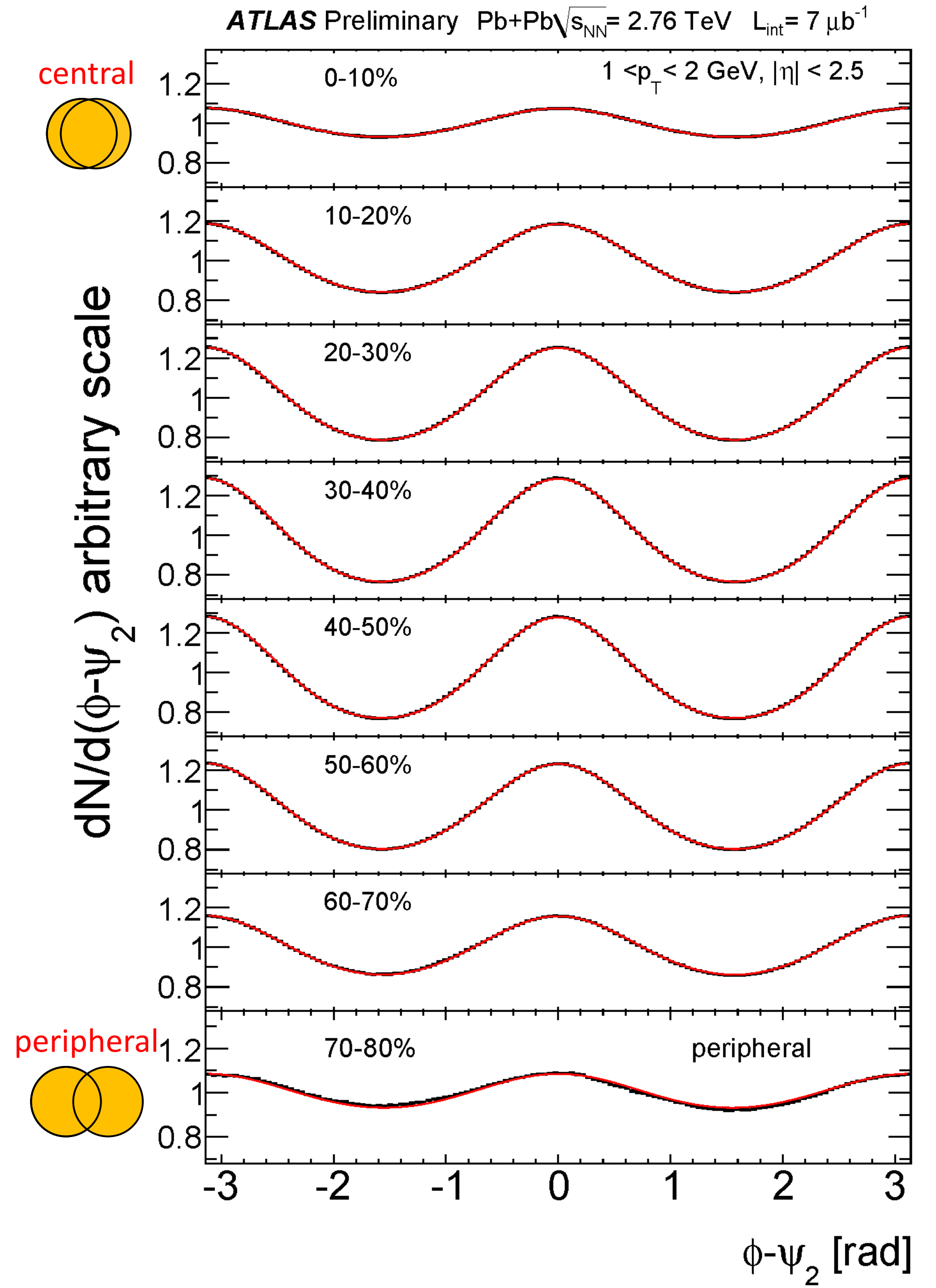
$$v_n = < \cos(n(\phi - \psi_{RP})) >$$



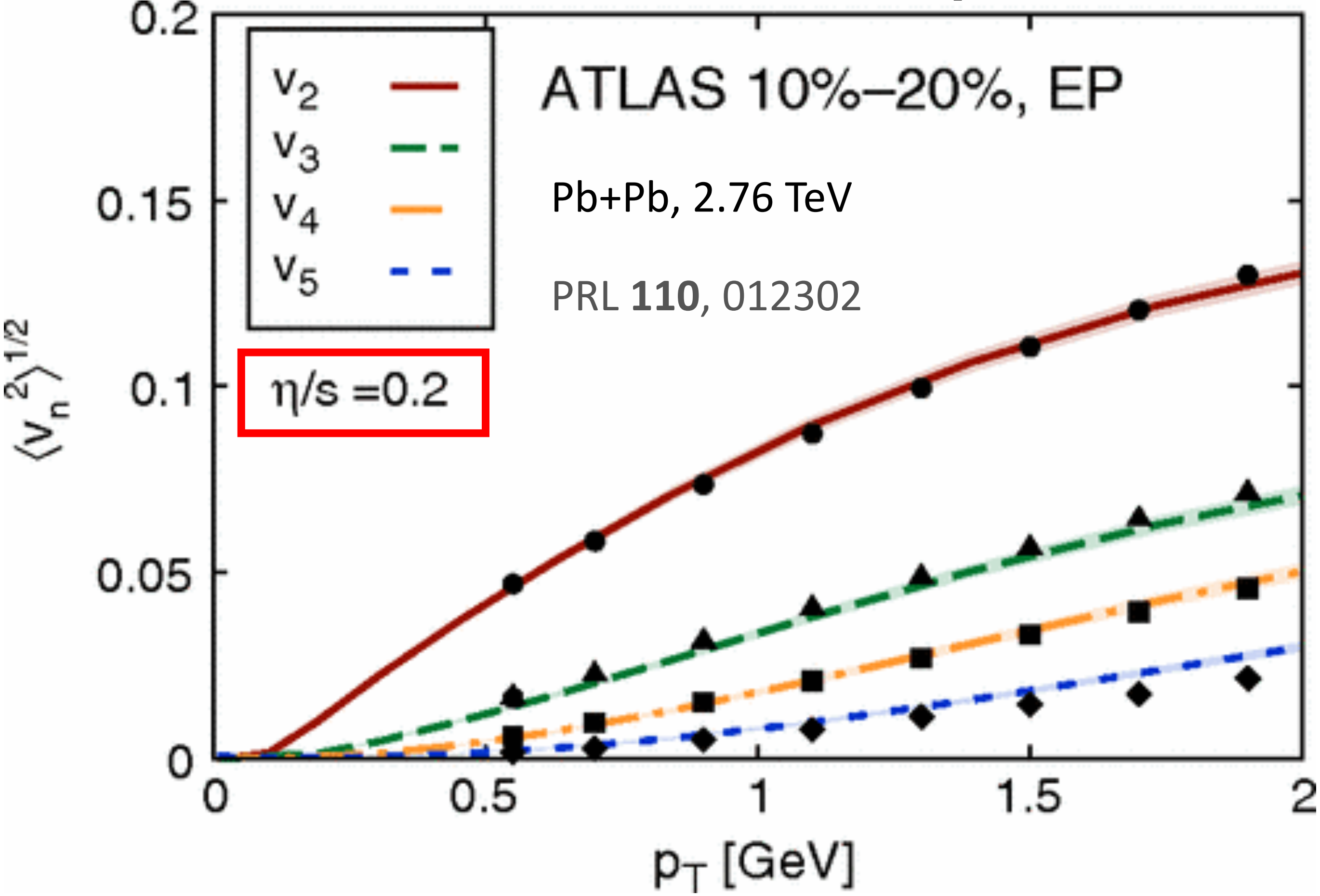
- **v_2** – elliptic flow, dominant harmonic

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

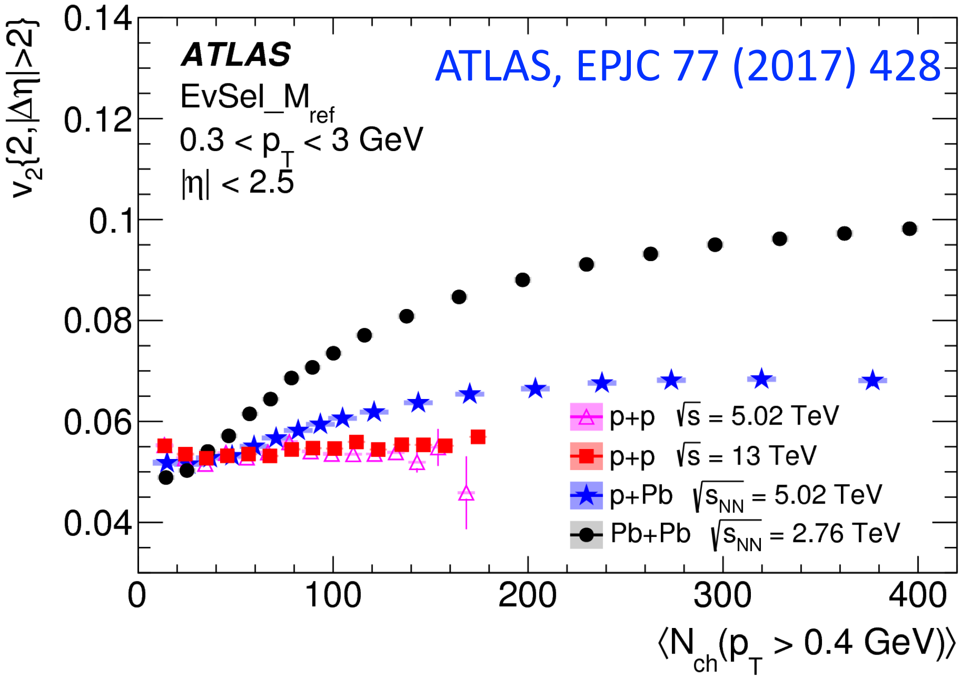


- Large azimuthal flow is observed, v_2 dominates
- Hydrodynamic models well describe v_n harmonics
  - QGP as almost ideal fluid (small viscosity)

RHIC's Major Discovery → QGP *paradigm shift*

Collectivity in Small Systems

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



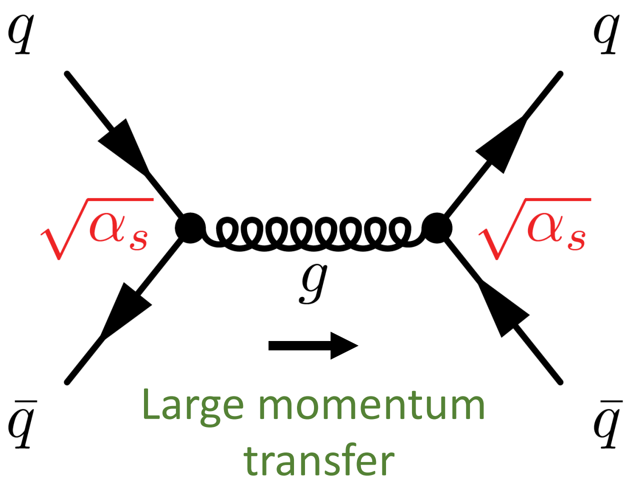
- In *pp* and *p*+Pb collisions similar flow harmonics as in heavy-ion collisions are observed.
- Small system flow results are supported by hydrodynamical models, (e.g. Phys.Rev.C 85(2012) 014911)

However, more studies are needed to address open questions

- Is QGP present in small collision systems?
- …

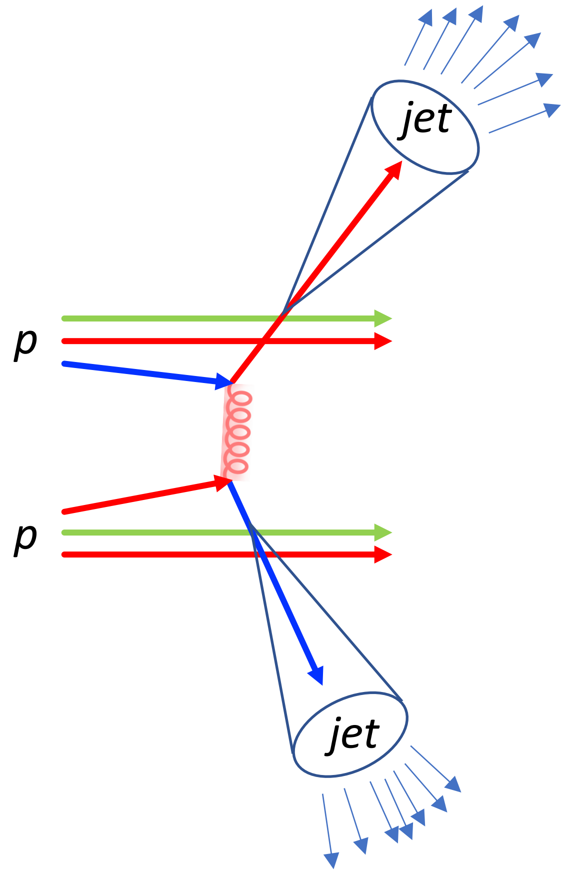
Hard Particle Production in Heavy-Ion Collisions

Hard Particle Production in Heavy-Ion Collisions



- Hard particles ($p_T \gtrsim 2$ GeV) originate from hard parton scatterings, at large Q
- Perturbative QCD works ($\alpha_s \ll 1$)

Jet – Collective Spray of Hadrons

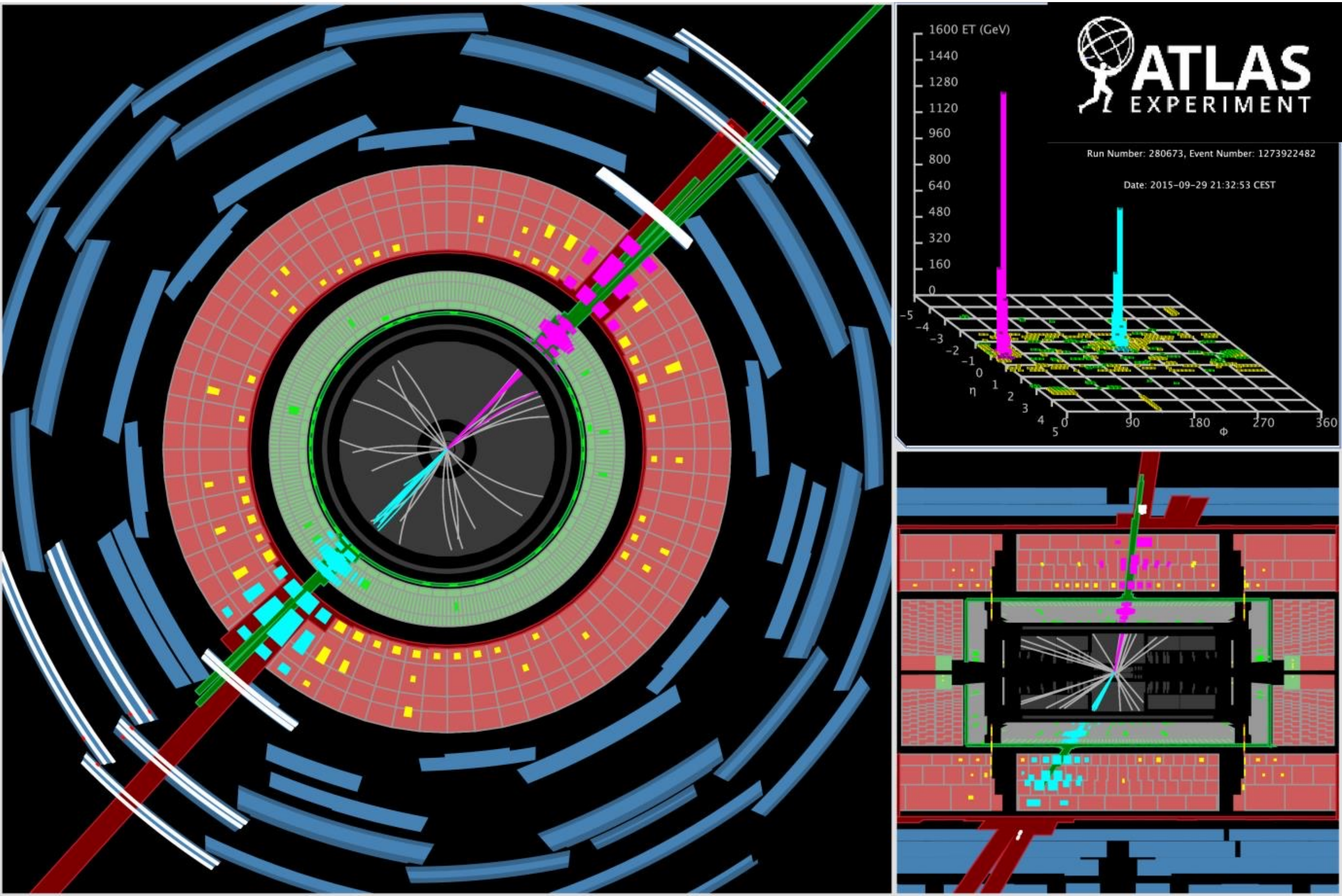


Jet cone,

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

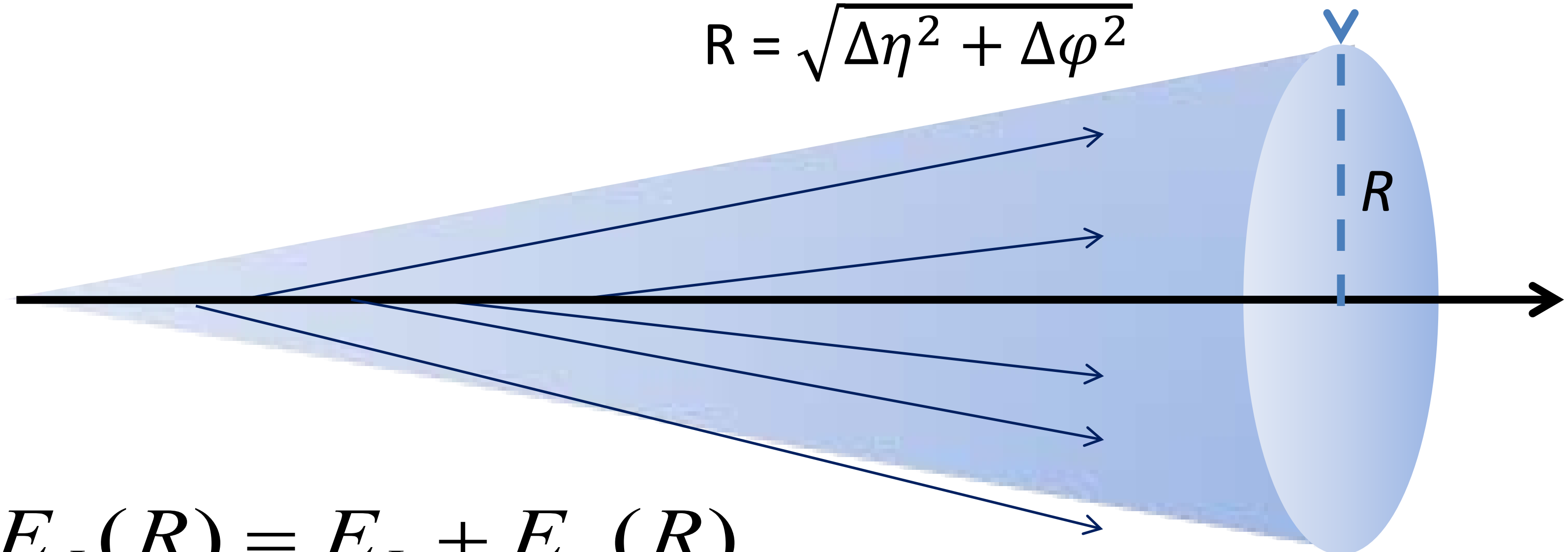
- Jet: a bunch of collimated particles in a narrow R cone generated by hadronization of a common source
- At the LHC, hard processes lead to abundant jet production

2-jet Event (dijet) in the ATLAS Experiment



Jets in Vacuum

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

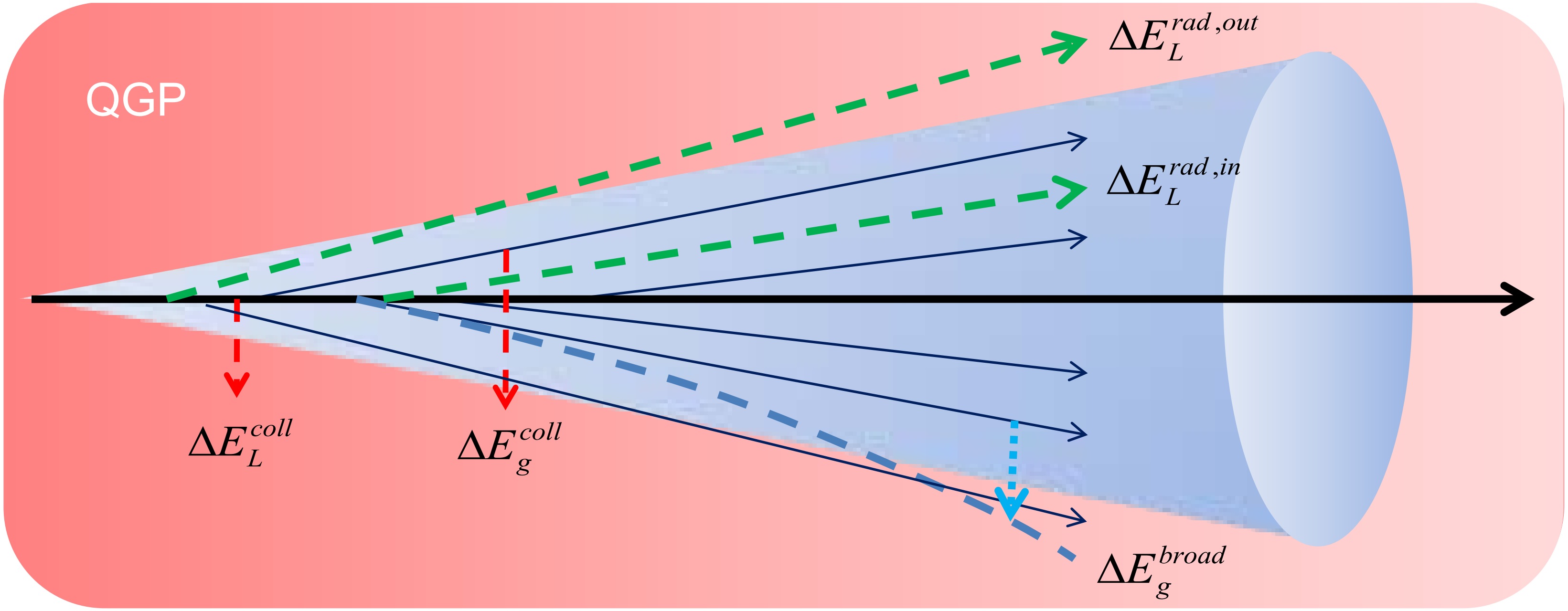


$$E_J(R) = E_L + E_g(R)$$

For pp, partonic jet shower in vacuum is composed of:

<u>Leading Parton</u> and <u>Radiated Gluons</u>

Jets in Medium



For AA, additional processes are present:

Leading Parton:

- E transfer to medium via elastic collisions
- Gluons radiated due to interactions with the medium

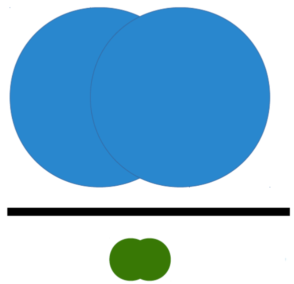
Radiated Gluons:

- E transfer to medium via elastic collisions
- E transfer out of jet cone from multiple scattering

Jets loose energy in the medium X.-N. Wang and M. Gyulassy, PRL 68 (1992) 1480

Measure of Jet Production Modification

- Nuclear-modification factor:



$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{\bullet\bullet}{\bullet\bullet} = \frac{1}{N_{\rm coll}} \frac{\frac{dN_{AA}}{dp_{\rm T}}}{\frac{dN_{pp}}{dp_{\rm T}}}$$

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

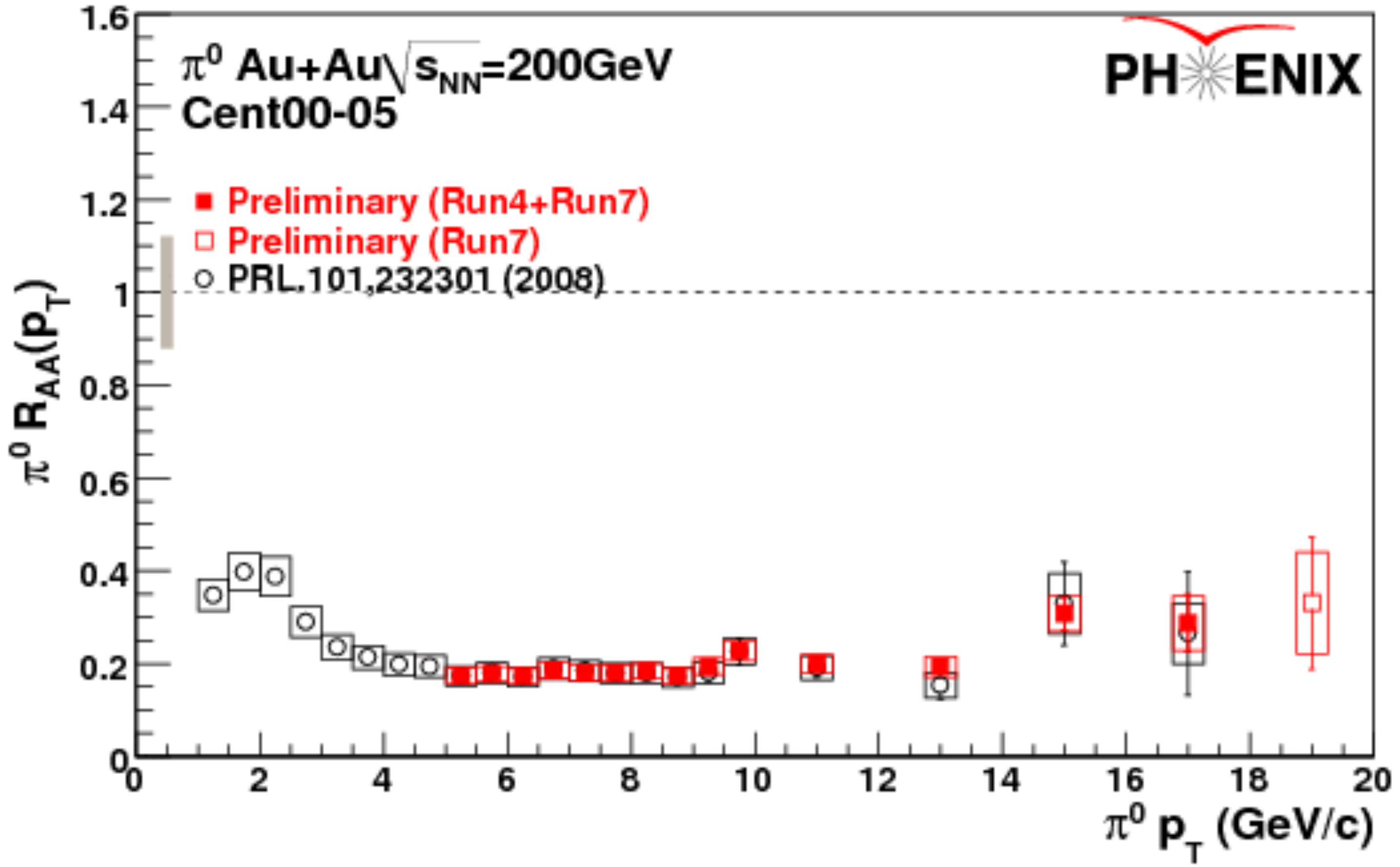
R_{AA}<1 → suppression (aka quenching)

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:

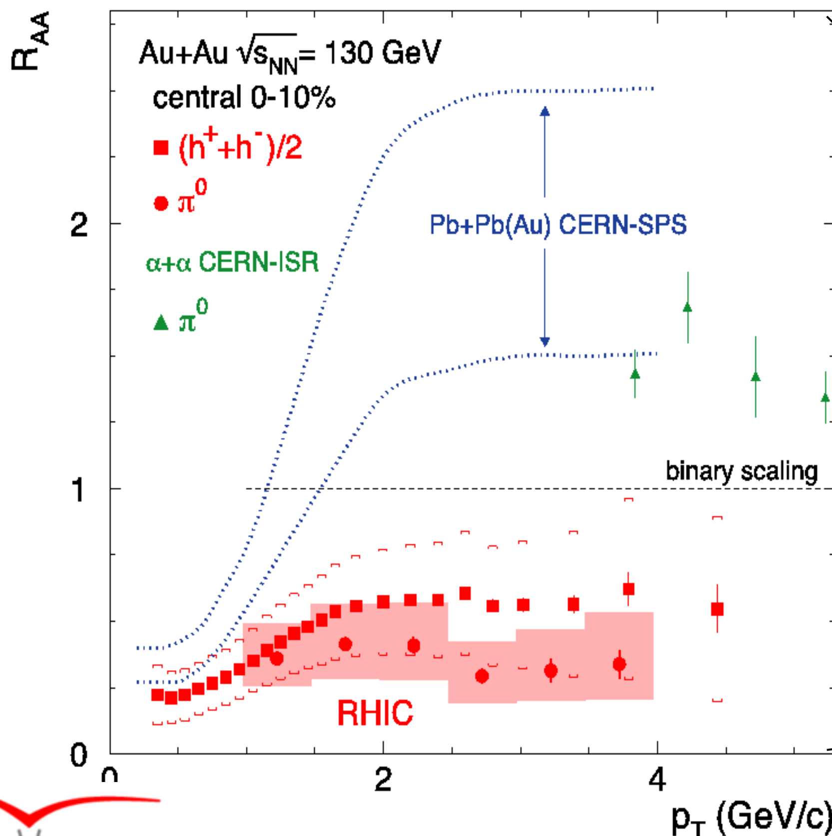


- R_{AA} for π^0 measured up to p_T = 20 GeV (central Au+Au)
- R_{AA} ≈0.2 in central Au+Au up to highest p_T(5 < p_T < 20 GeV) – strong suppression

Historical Remark
Jet Quenching - 21 Years Ago

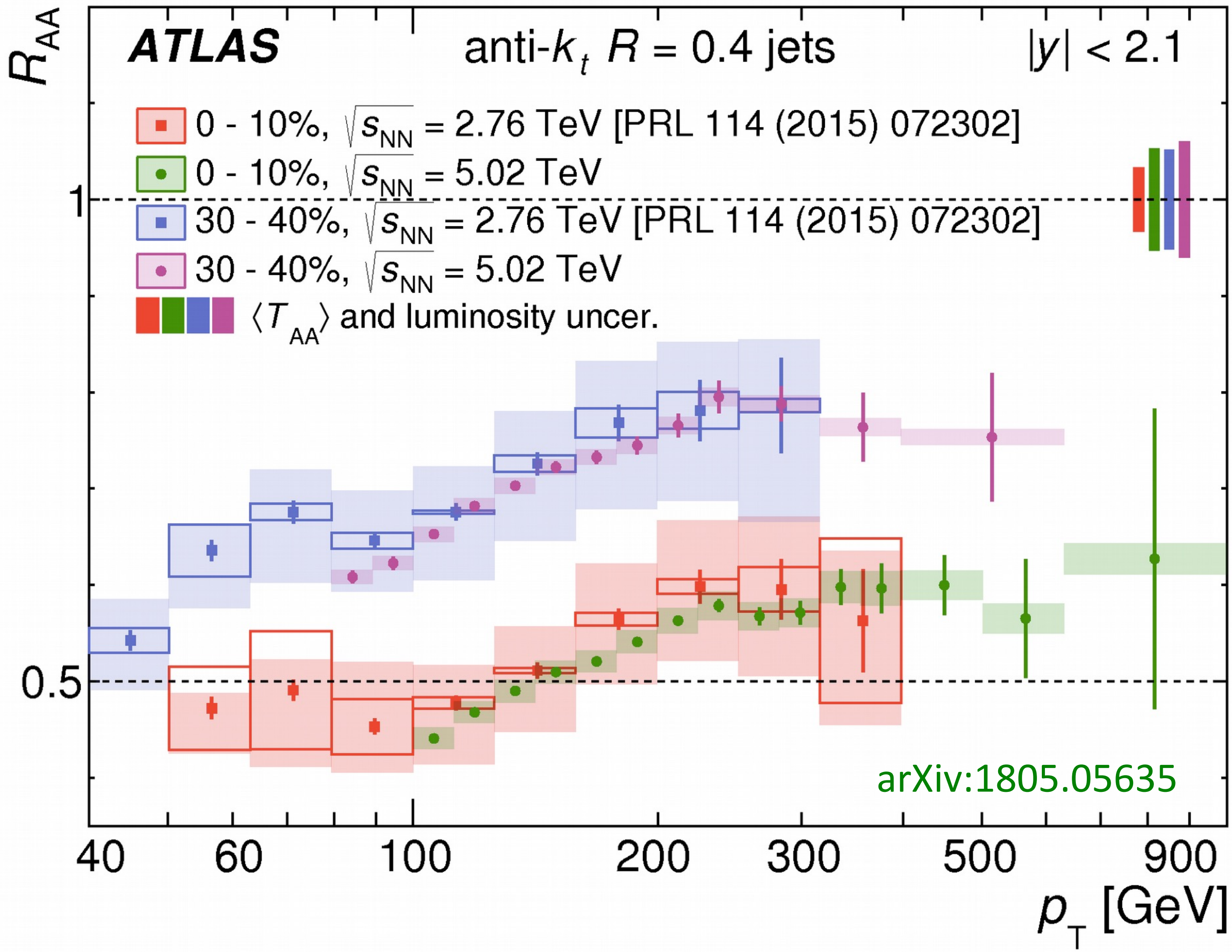
Next RHIC’s Major Discovery → QGP *paradigm shift*

Discovery of a strong “jet” suppression → QGP a strongly interacting medium



PHENIX

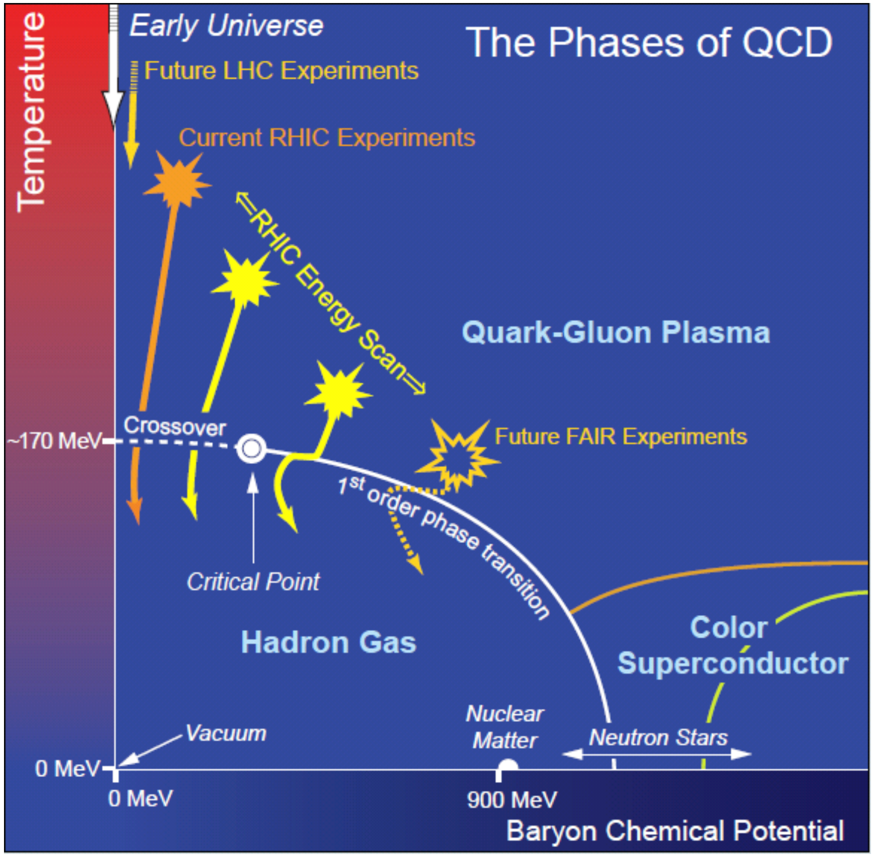
Jet R_{AA} in Pb+Pb Collisions at the LHC



- 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

Future of High-Energy Heavy-Ion Research



High energy HI collisions ($\mu_B \approx 0$):

- Quantify properties of the QGP fluid
- Explore collectivity in small systems
- …

Low energy HI collisions ($\mu_B \gg 0$):

- Onset of deconfinement by energy scan
- Exploration of the phase transition in QCD
  - Search for the Critical Point
- QGP at high μ_B (Neutron Star EoS)
- …

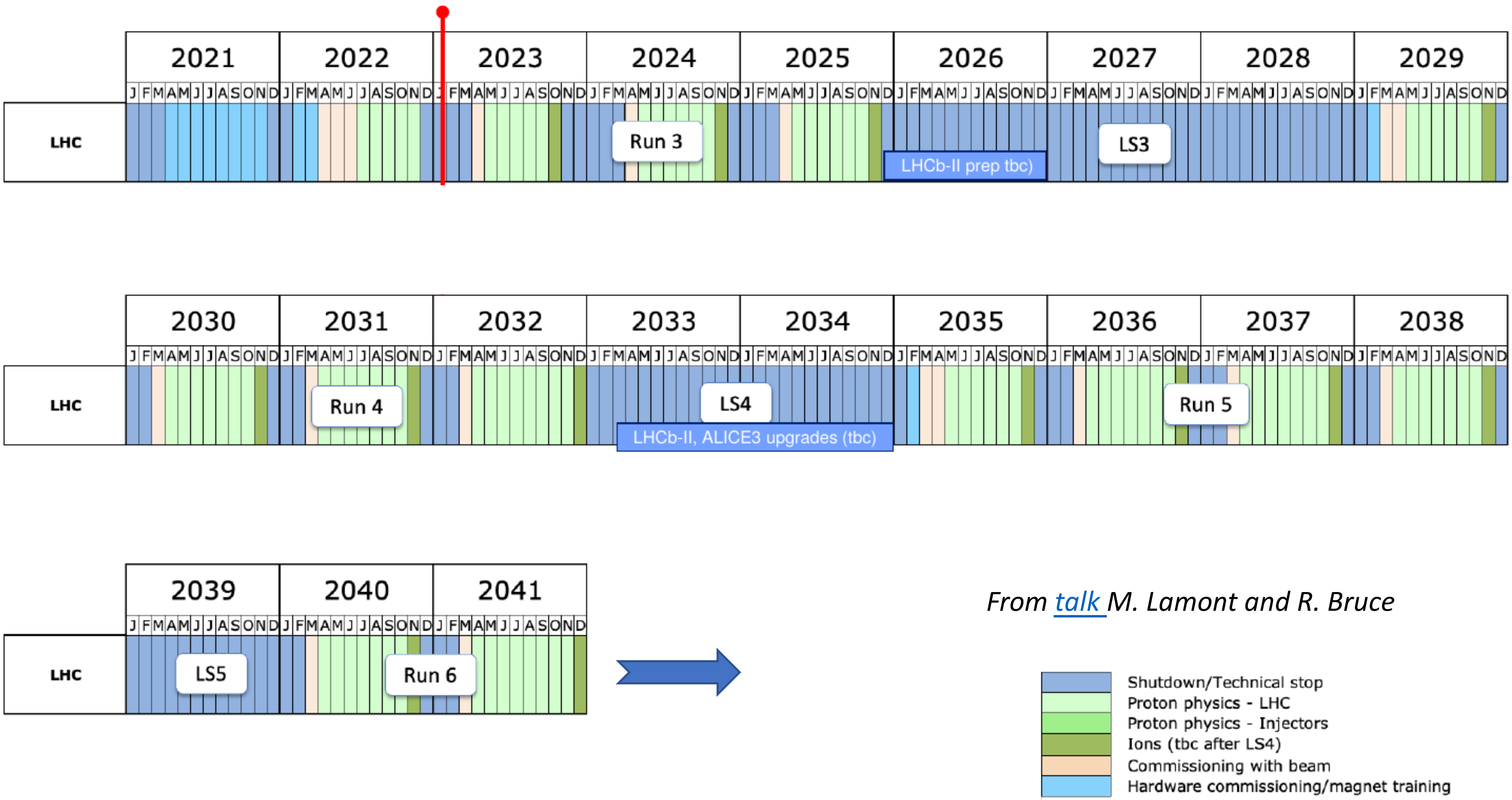
High-Energy Heavy-Ion Collisions

Facility	RHIC	LHC	HE-LHC, FCC / SppC
Experiments	sPHENIX, STAR	ALICE, ATLAS, CMS, LHCb, ?	?
When	2023 – 2025	**2023-2032, >2032**	>2040?, >2045?
$\sqrt{s_{NN}}$ (TeV)	0.2	5.5	10.5, 39
Int. rate (kHz)	~15	~50	~100 (HE-LHC), ~2500 (FCC)

Andrea Dainese, QM 2019

- General future goals of HI collisions at the LHC (arXiv:1812.06772)
- Future accelerators FCC/SppC will open completely new opportunities for heavy-ion collision physics

LHC timeline for Heavy-Ion Runs



From talk M. Lamont and R. Bruce

- In the future, continue with one-month ion runs at the end of the year
- Three ion runs planned in Run 3, after cut of 2022 run
- In Run 4 four ion runs planned

Summary

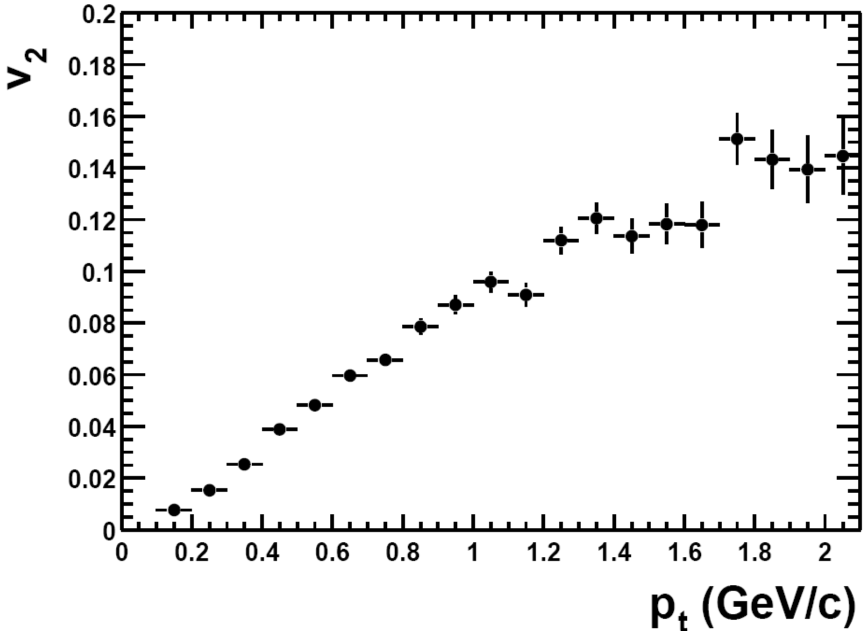
- QCD ab initio calculations predict existence of deconfined phase in heavy-ion collisions
  - Phase transition to QGP at T_c ~ 155 MeV
- Dynamical features of the hot and dense medium created in heavy-ion collisions
  - Energy density ∼20x critical energy density for QGP formation
  - Significant strangeness 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
  - …
- 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

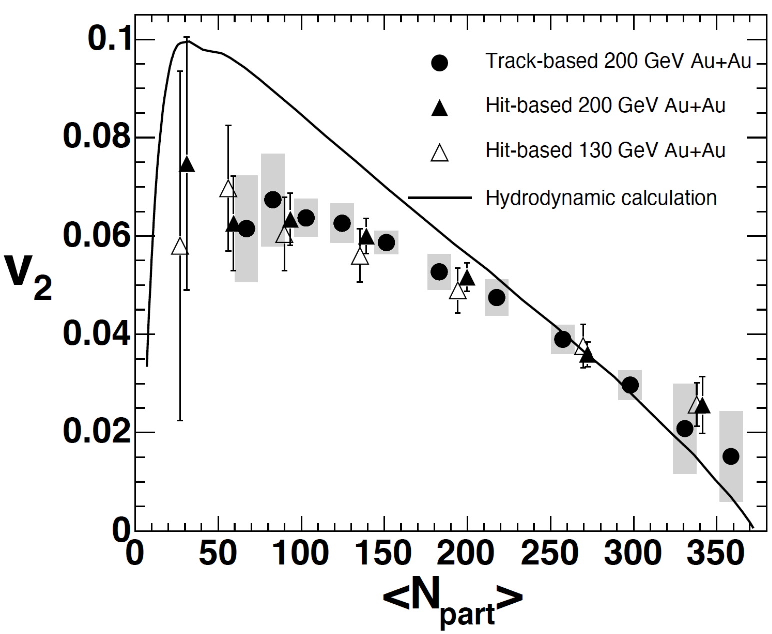
Historical Remark
- Large Azimuthal Anisotropy at RHIC

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

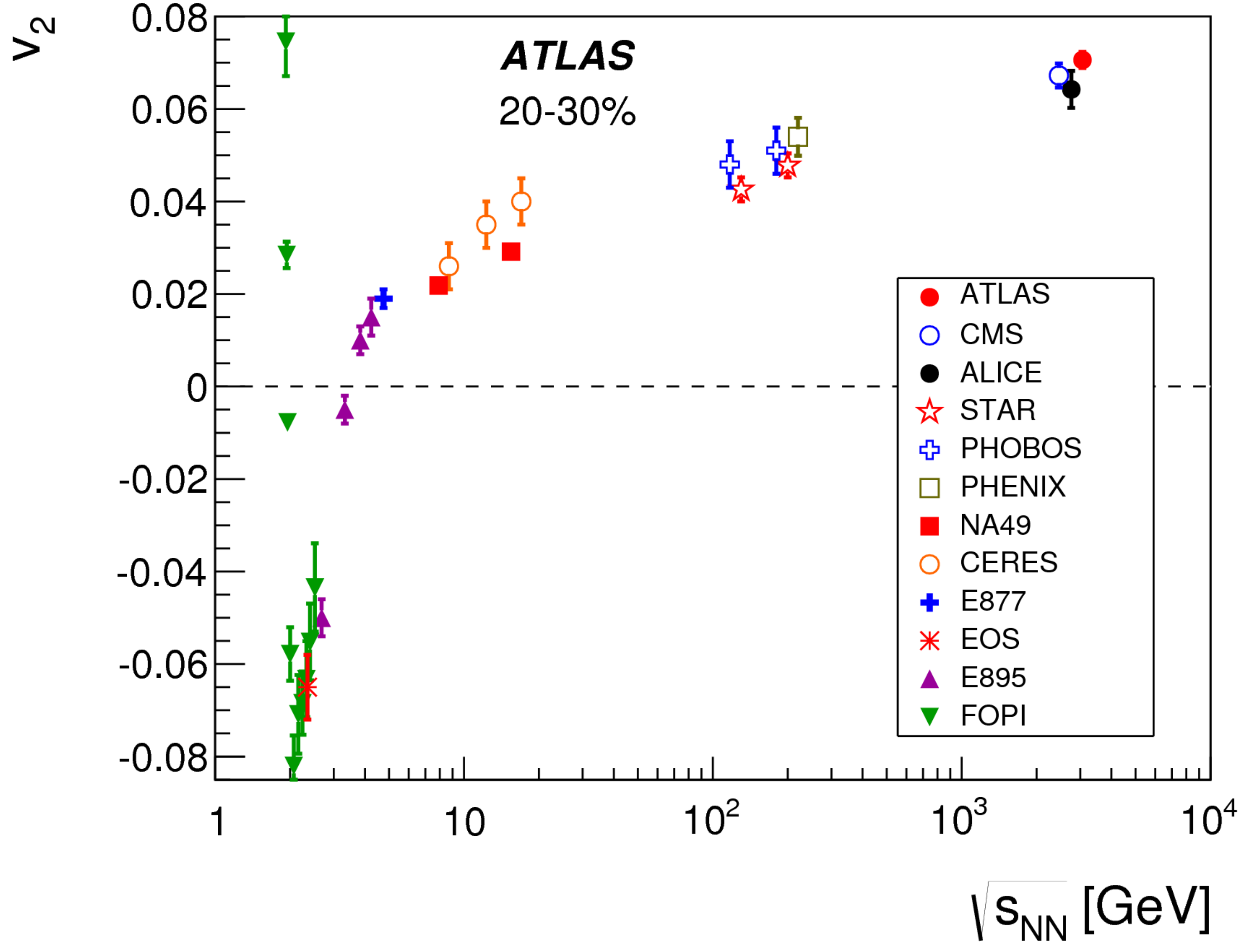


2 Forward Calorimeters (FCal) are used for RP approximation: 3.2<|η|<4.9.

Tracks from Inner Detector are used for flow harmonics determination: |η|<2.5

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

Elliptic Flow, v_2



Strong azimuthal anisotropy in ultra-relativistic HI collisions