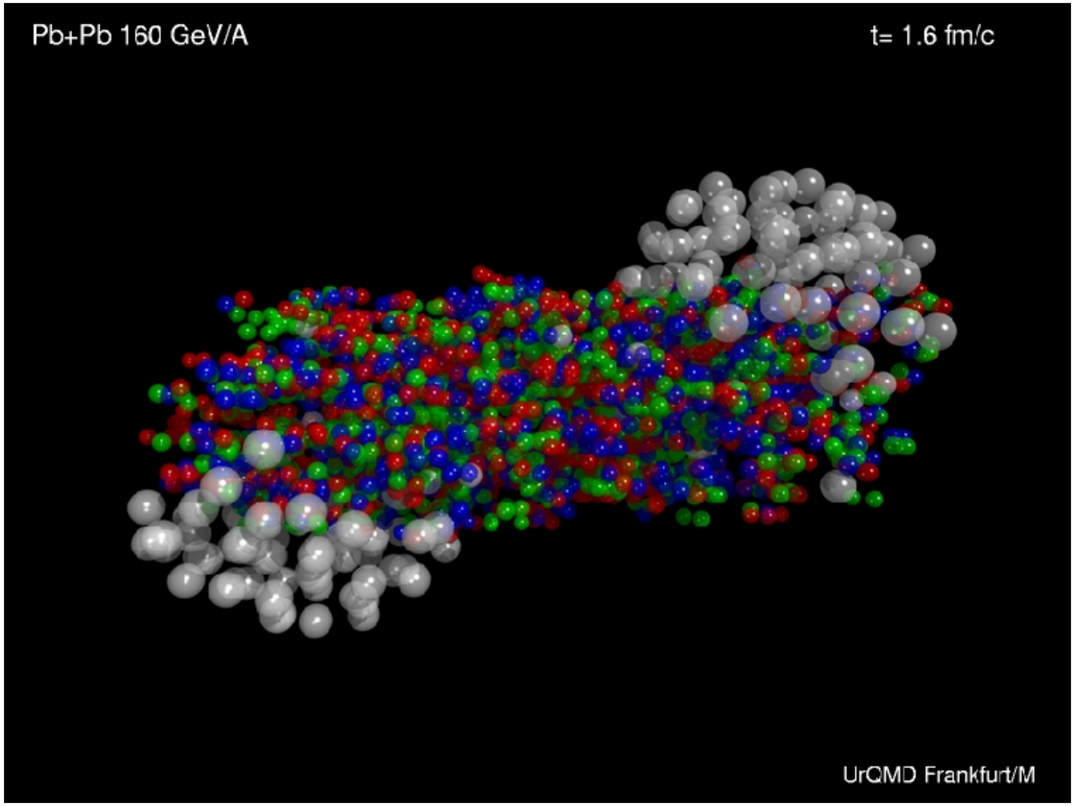
Physics from ALICE

Anthony Timmins for the ALICE Collaboration

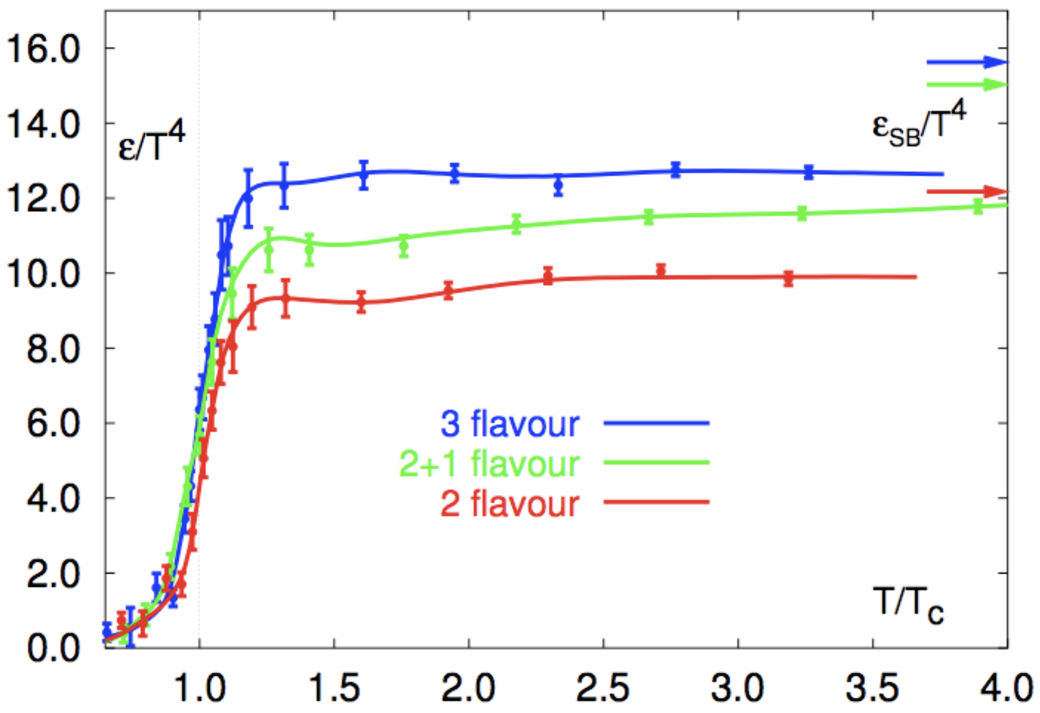
Heavy-Ion collisions and little bangs

- What we do:
  - ✓ Collide Pb-Pb nuclei together and make little bangs..
- ✓ Two facilities:
  - ✓ RHIC, at Brookhaven Lab, New York
  - ✓ LHC at CERN, French-Swiss border
- Why?
  - ✓ Understand how matter behaves at large energy densities
  - ✓ Recreate conditions similar to those just after the big bang



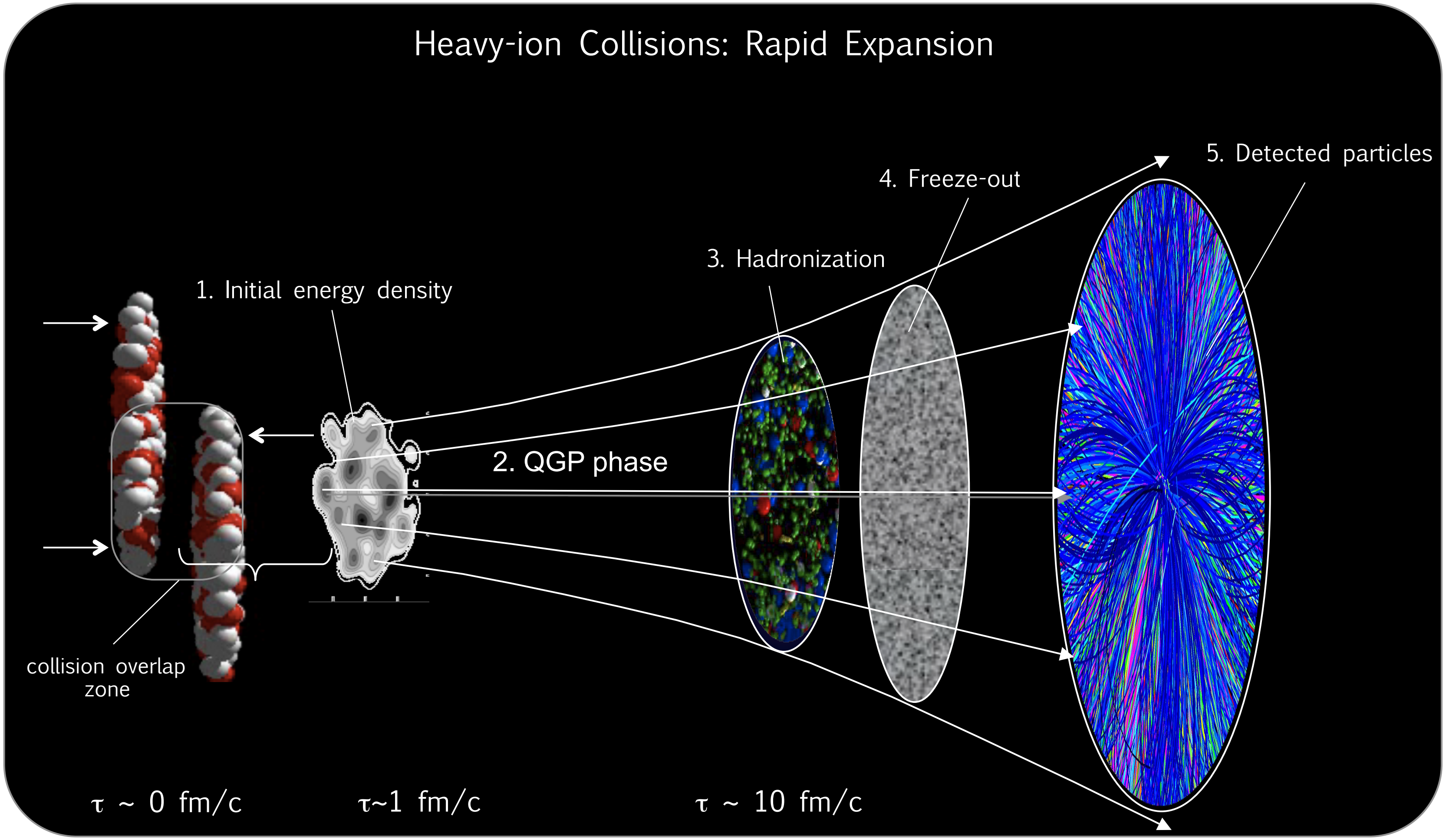
Heavy-Ion collisions and little bangs

- The Quark Gluon Plasma (QGP)
  - ✓ Very hot hadronic matter
  - ✓ Quarks/gluons disassociate
- Lattice QCD
  - ✓ Framework predicting soft QCD interactions
  - ✓ QGP predicted T at 170 MeV
- Heavy–ion collisions deposit large energy in small volume
  - ✓ Does the hadronic matter get hot enough?

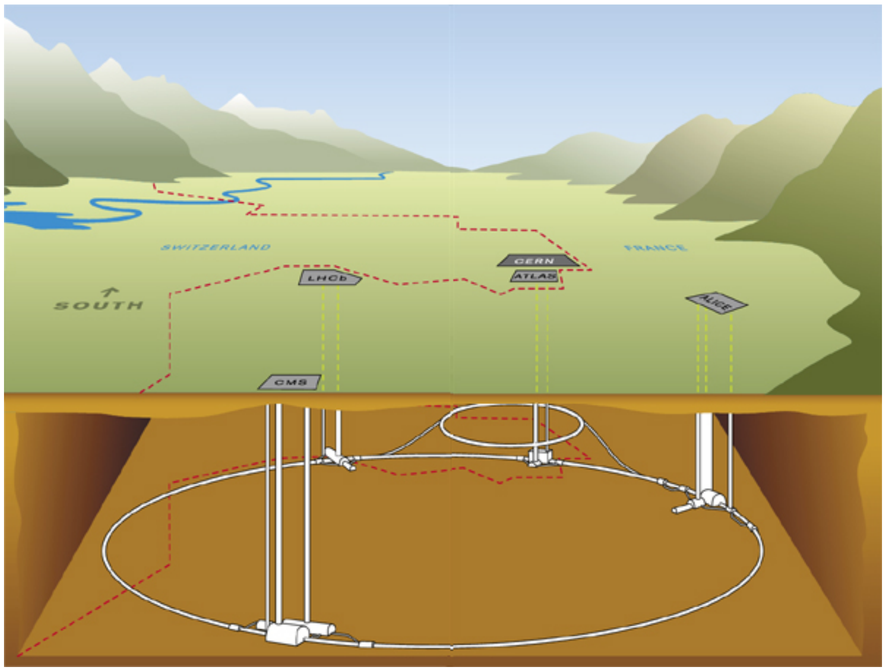


Nucl. Phys. A 698 (2002) 199

Heavy-Ion collisions and little bangs



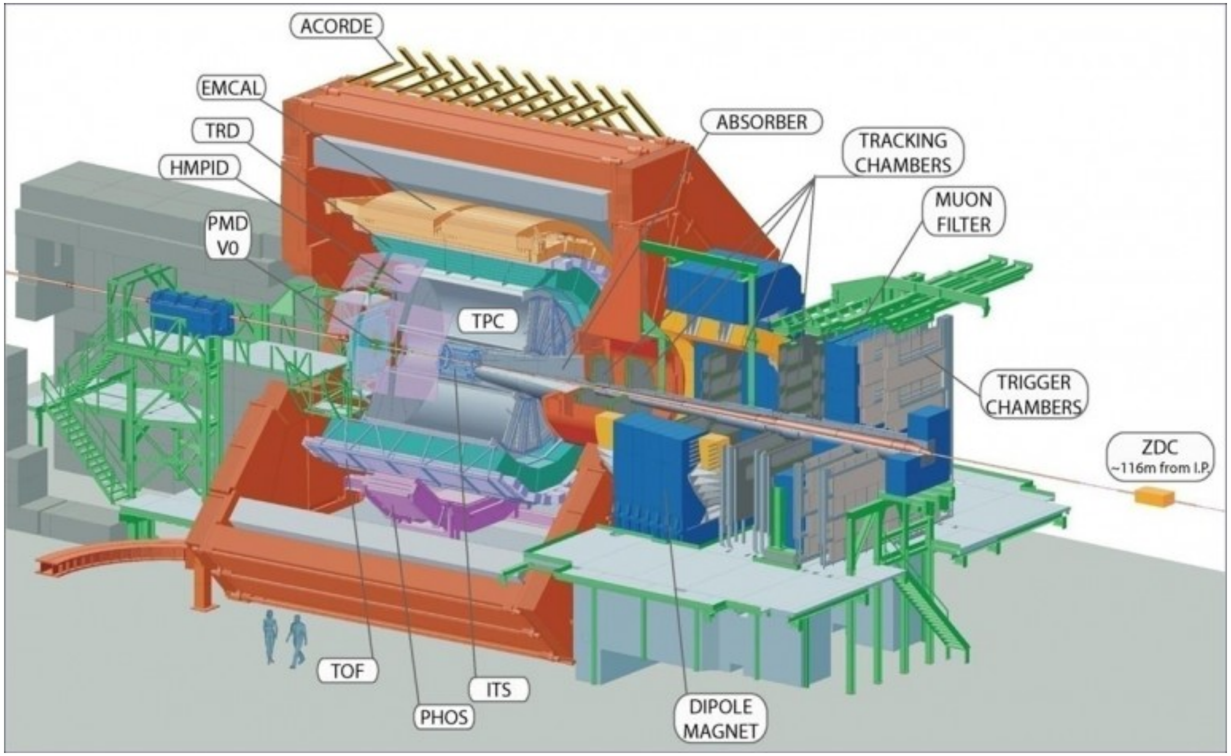
ALICE at the LHC



- Large Hadron Collider (LHC) located at CERN, on Swiss-French border
  - ✓ ALICE on French side next to Jura mountains

ALICE at the LHC

- Many sub detectors
  - ✓ All with important roles
- Time Projection Chamber (TPC)
  - ✓ Main physics detector
  - ✓ Biggest in the world
- Detects charged hadrons created by collision
  - ✓ 90% efficiency
  - ✓ Measures ϕ, η, p_T and energy loss of tracks



LHC heavy-ion running

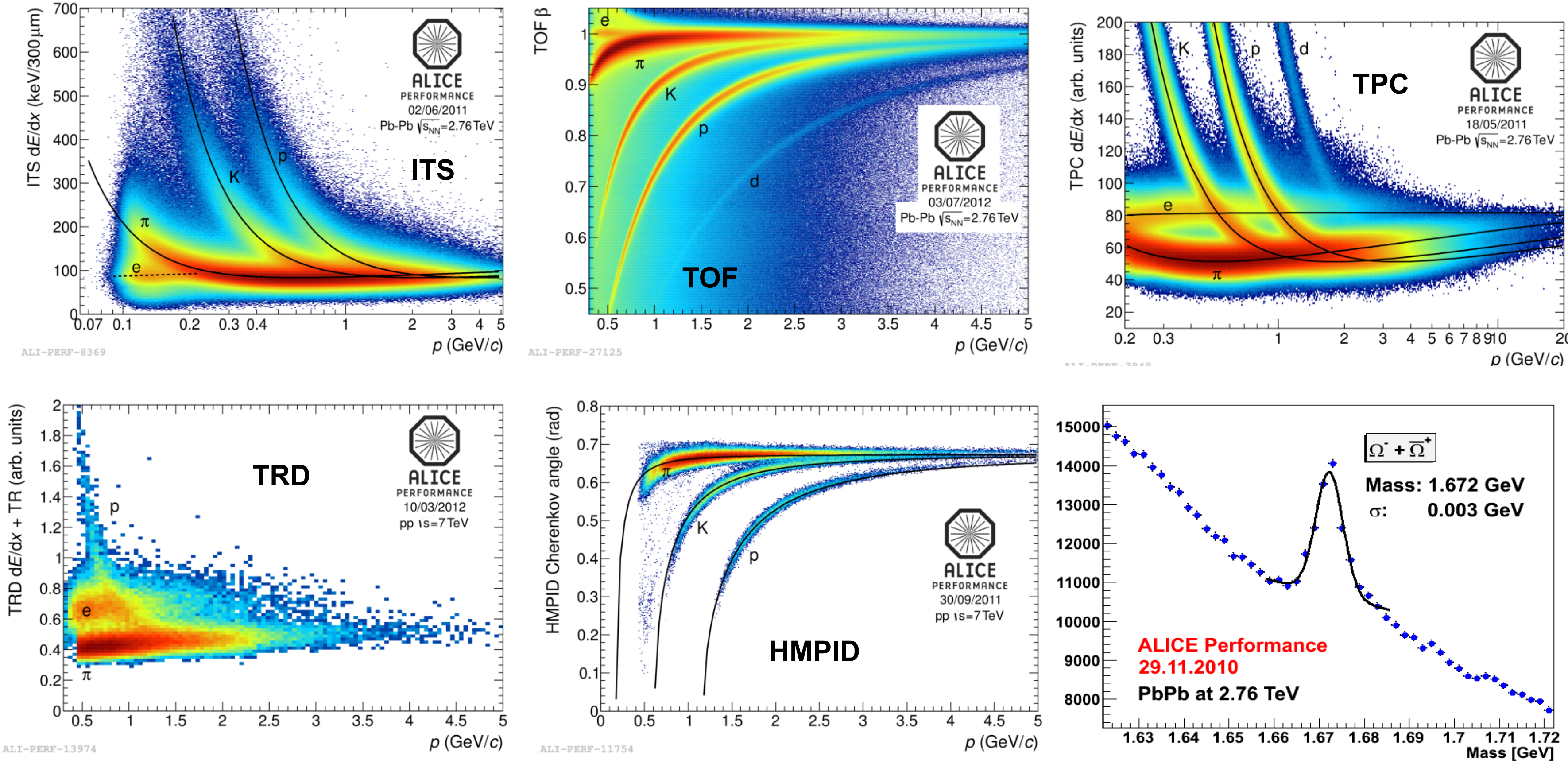
Year	System	Energy $\sqrt{s_{NN}}$ (TeV)	Delivered Integrated luminosity
2010	Pb-Pb	2.76	10 μb^{-1}
2011	Pb-Pb	2.76	0.1 nb^{-1}
2013	p-Pb	5.02	30 nb^{-1}

- Two Pb-Pb runs
  - ✓ In 2010 - commissioning and first data taking
  - ✓ In 2011 – Second run, factor 10 increase in luminosity
- p-Pb occurred this year
  - ✓ LHC delivered target luminosity
- Long shutdown this year (LS1)

Selected physics results

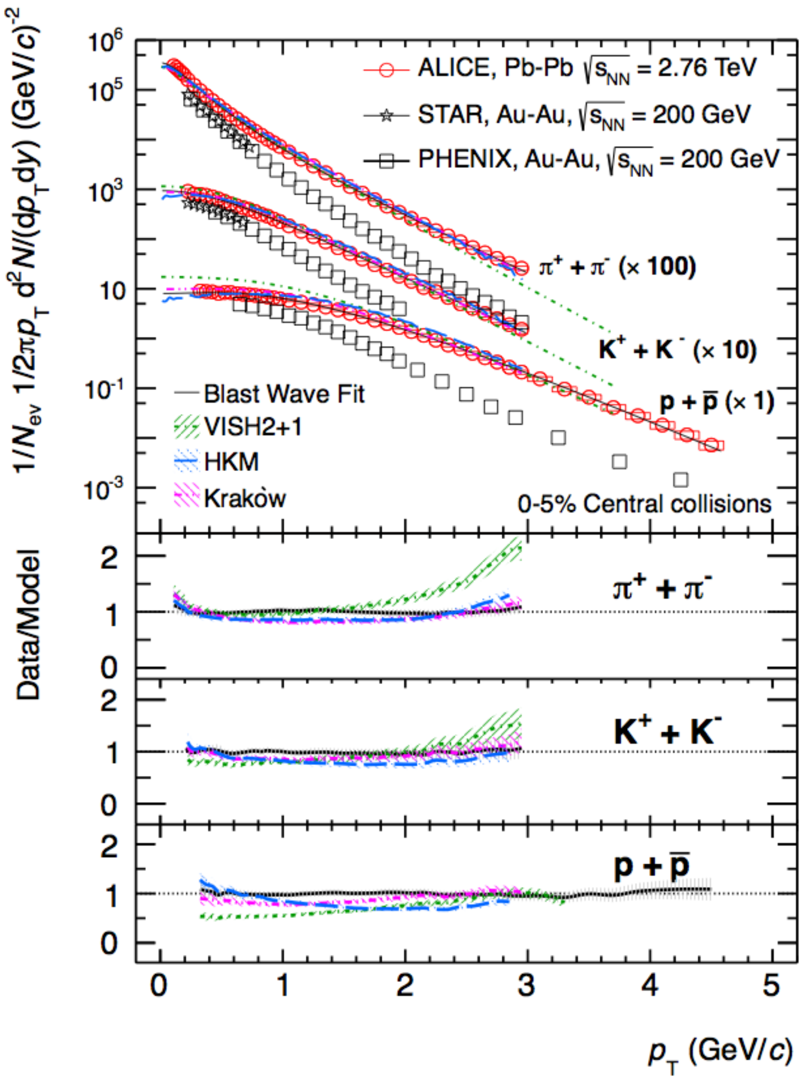
1. **Identified particle production**
   - ✓ Insights into chemical freeze out temperatures and radial flow
2. **Angular correlations and flow**
   - ✓ Give information on initial stages of the collisions
   - ✓ Help establish early equation of state, searches for chiral magnetic effect
3. **Hard Probes**
   - ✓ Rare processes: Jets and heavy flavor production
   - ✓ How are they altered in the presence of a medium?
4. **New measurements from recent p-Pb run**

Identified particle production



- ALICE optimized for particle identification

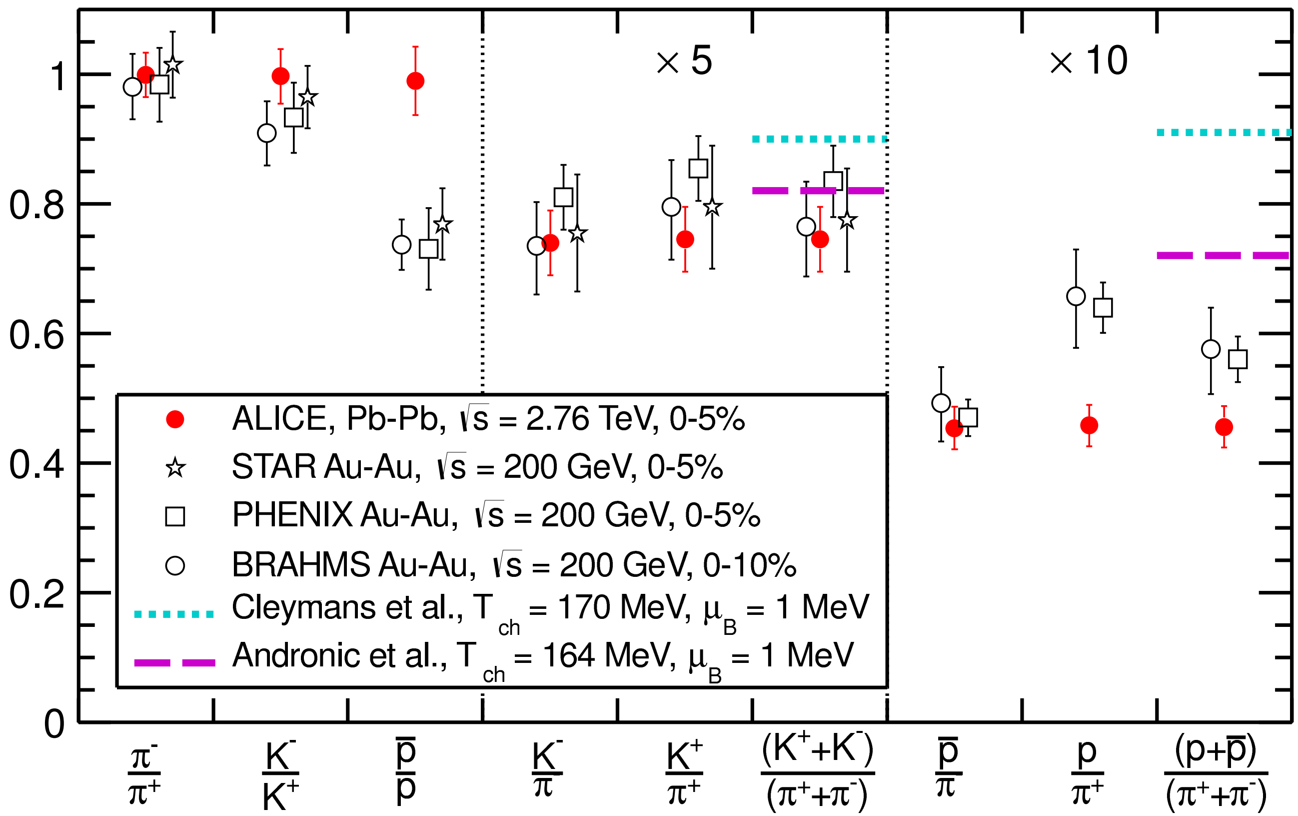
Identified particle production



- Spectra becomes harder for particles with higher mass
- Indicative of common radial flow velocity
  - ✓ Higher mass, higher p_T
- Blast-wave model can obtain flow velocity
  - ✓ $<\beta_T>$ = 0.65c
  - ✓ 10% higher than RHIC

Phys. Rev. Lett. 109 (2012) 252301

Identified particle production

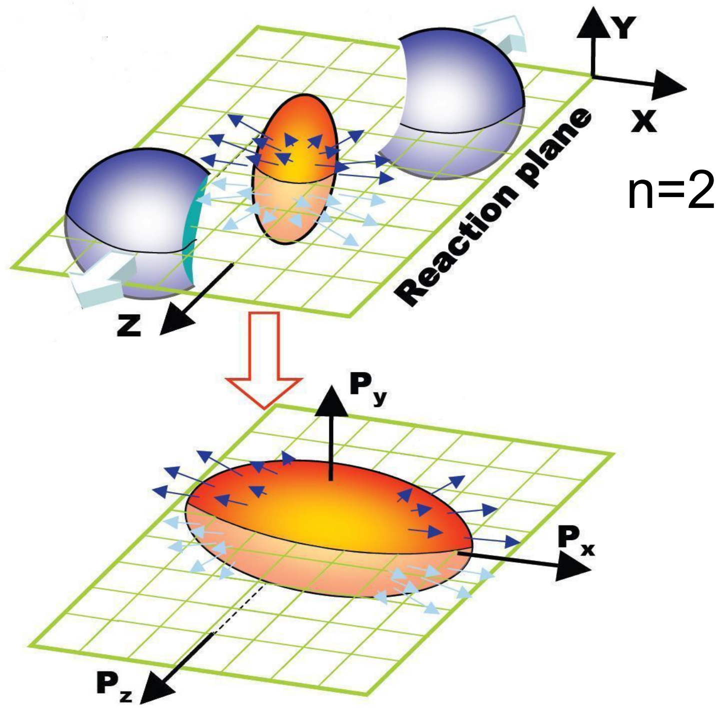


- Measure integrated particle yields
- Fit ratios with thermal model
- Obtain chemical freeze-out temperature
- T_{ch} ~ 170 MeV

Phys. Rev. Lett. 109 (2012) 252301

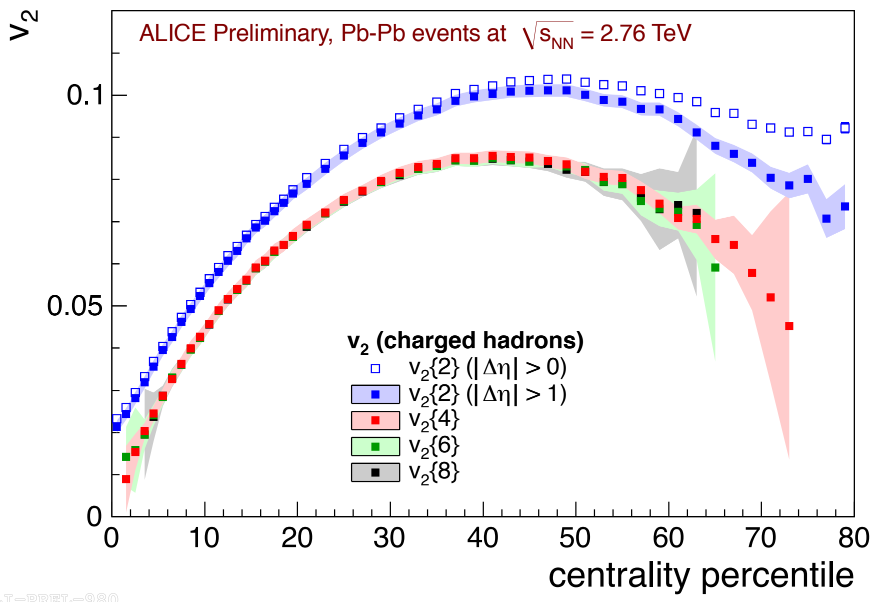
Angular correlations and flow

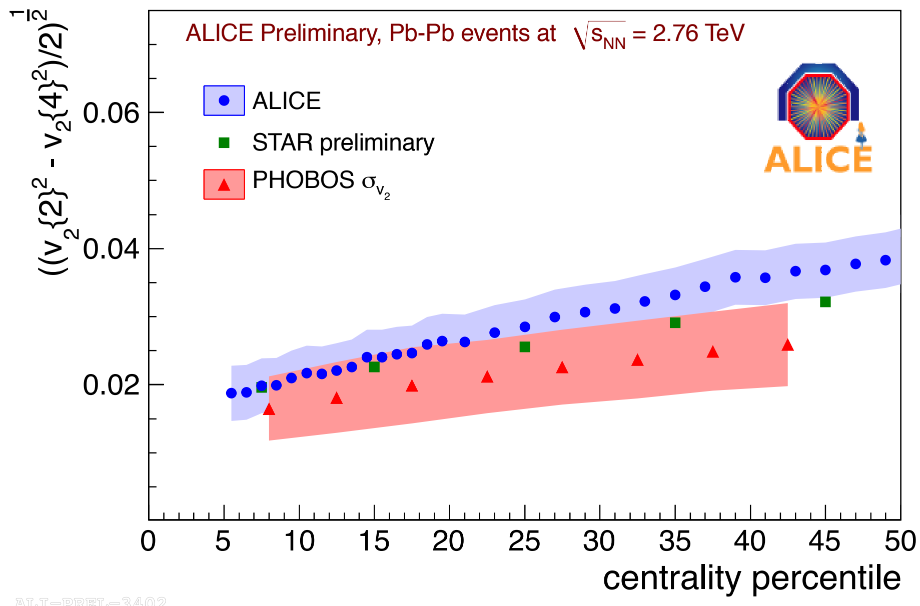
- Anisotropic initial conditions induce angular correlations
- Pressure gradients
  - ✓ Spatial anisotropies ➔ momentum anisotropies
- Φ distribution expressed as a Fourier series
- v_n represents the magnitude of flow
- v_n α eccentricity$_n$



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} \mathrm{v}_n cos(n(\varphi - \psi_r))$$

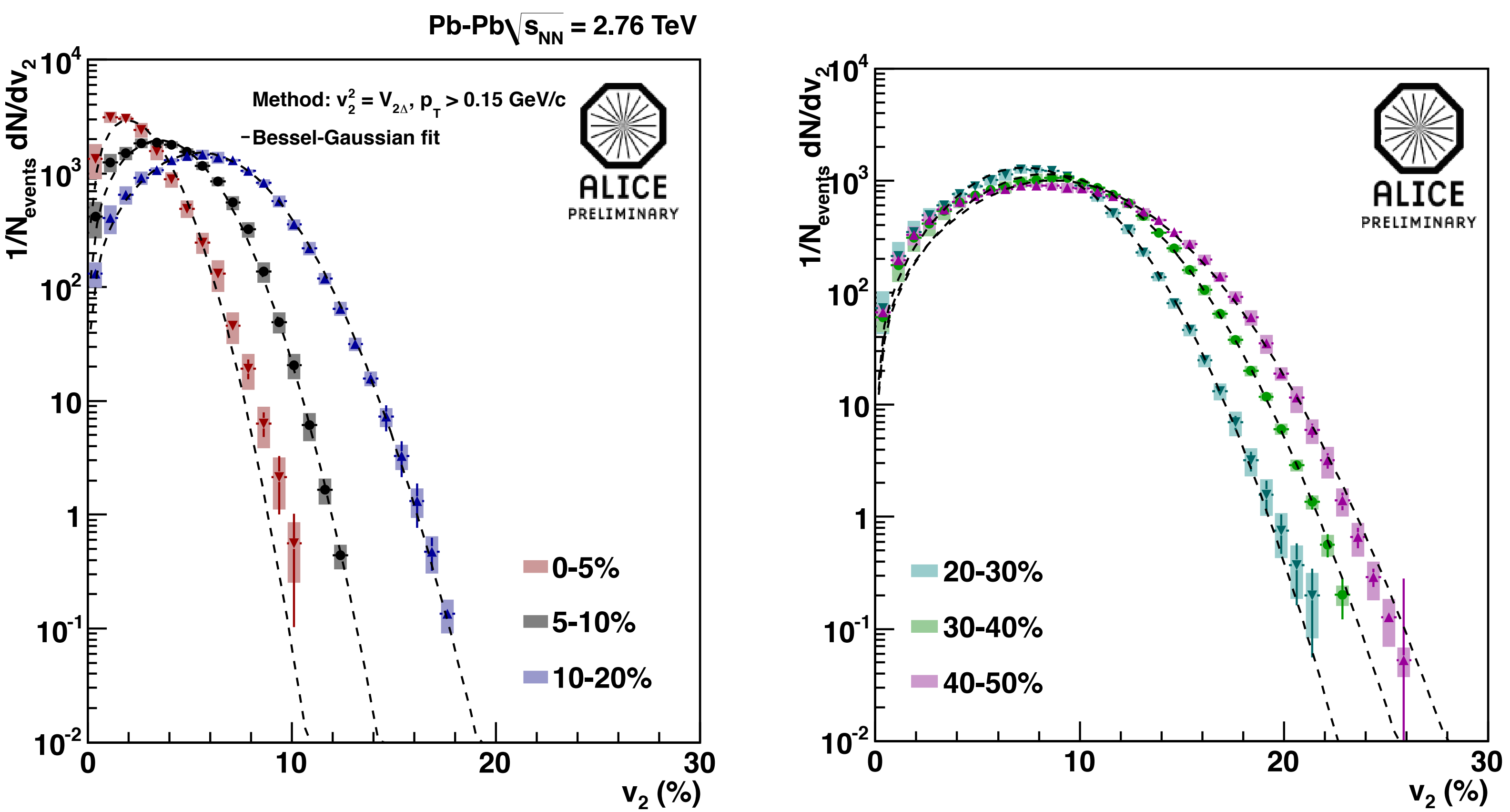
Angular correlations and flow





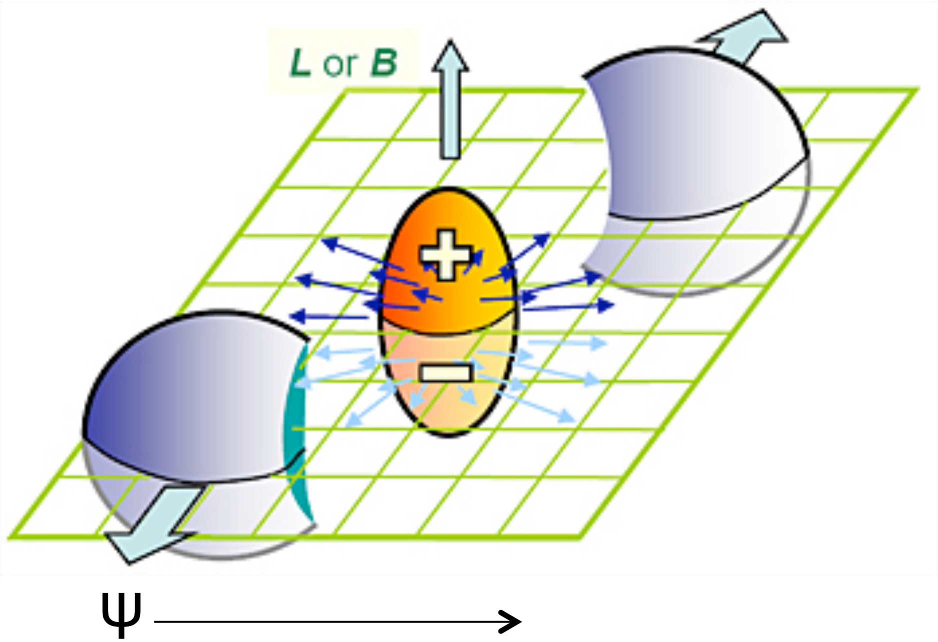
- Elliptic flow (n=2) typically strongest:
  - ✓ $v_2\{2\}$ and $v_2\{4\}$ obtained from 2 and 4 particle correlations
  - ✓ Strength of flow fluctuations σ_{v2} can also be determined
- Can compare to predictions from hydrodynamic models
  - ✓ Handle on initial equation of state

Angular correlations and flow



- Measurements of v_2 distributions
  - ✓ Requires measurements of single event v_2 ➔ works best at LHC
  - ✓ Expected to reflect eccentricity fluctuations of initial state

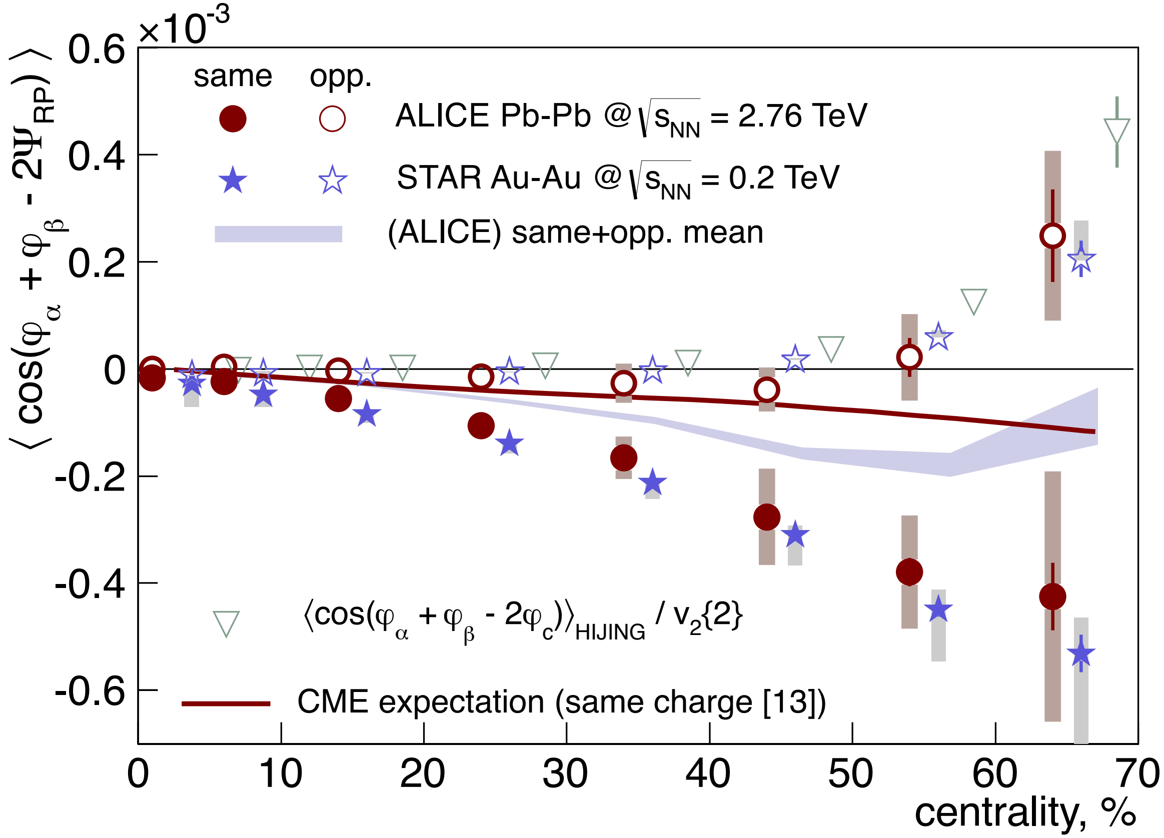
Angular correlations and flow



- Chiral magnetic effect (CME)
  - ✓ Hypothesis: domains exist that "violates" parity for strong force
  - ✓ Domains manifest themselves as a separation of charge
- B-field pushes + & - particles in opposite direction
  - ✓ Perpendicular to reaction plane
- Correlator: $\langle\cos(\varphi_1 + \varphi_2 - 2\psi)\rangle$
  - ✓ < 0 for same-sign charges if CME occurs

D. Kharzeev, Phys. Lett. B633 (2006) 260
D. Kharzeev and A. Zhitnitsky, Nucl. Phys. A797 2007) 67
D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A803 (2008) 227
K. Fukushima, D. E. Kharzeev and H. J. Warringa, Phys. Rev. D78 (2008) 074033

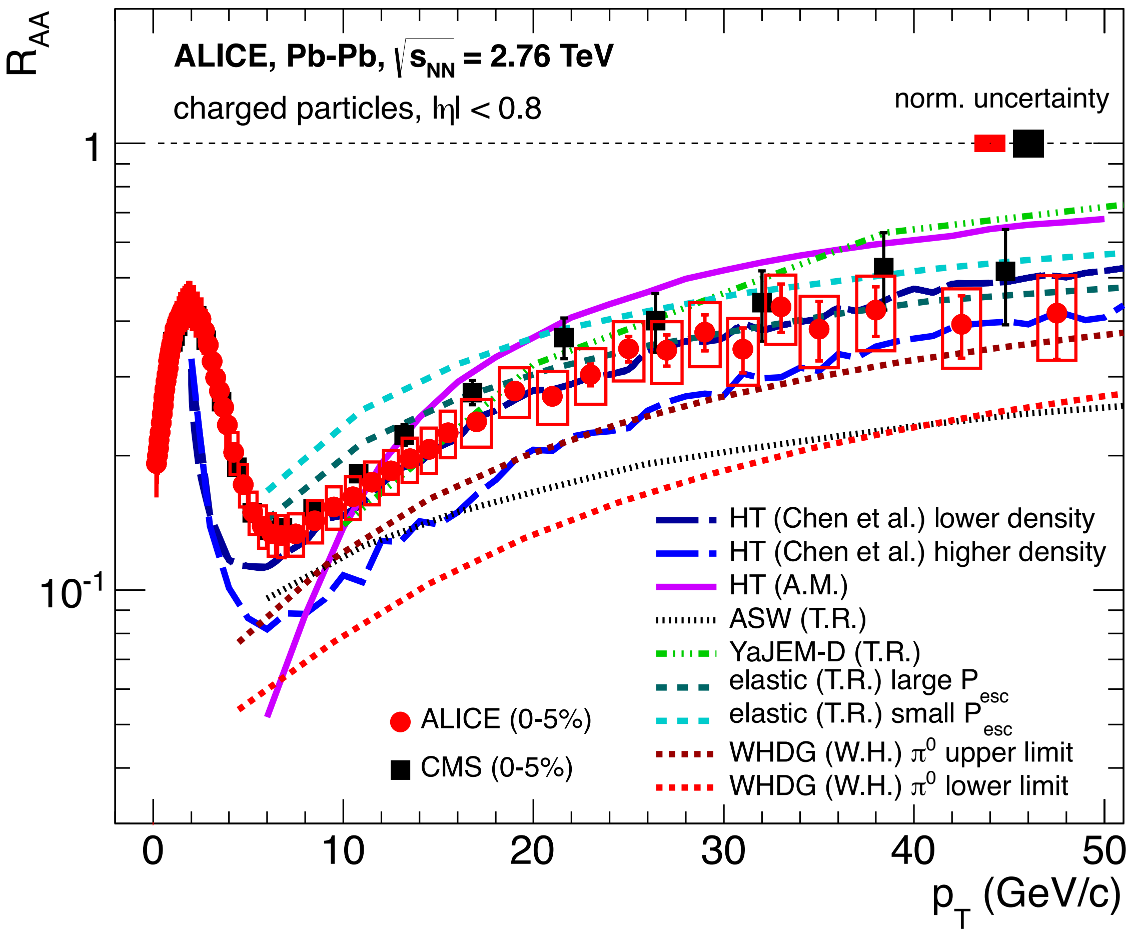
Angular correlations and flow



Phys. Rev. Lett. 110 (2013) 012301

- $<\cos(\varphi_1 + \varphi_2 - 2\psi)>$ indeed below 0 for same charges
- $<\cos(\varphi_1 + \varphi_2 - 2\psi)>$ ~ 0 for opposite charges
- Results at LHC similar to those at RHIC

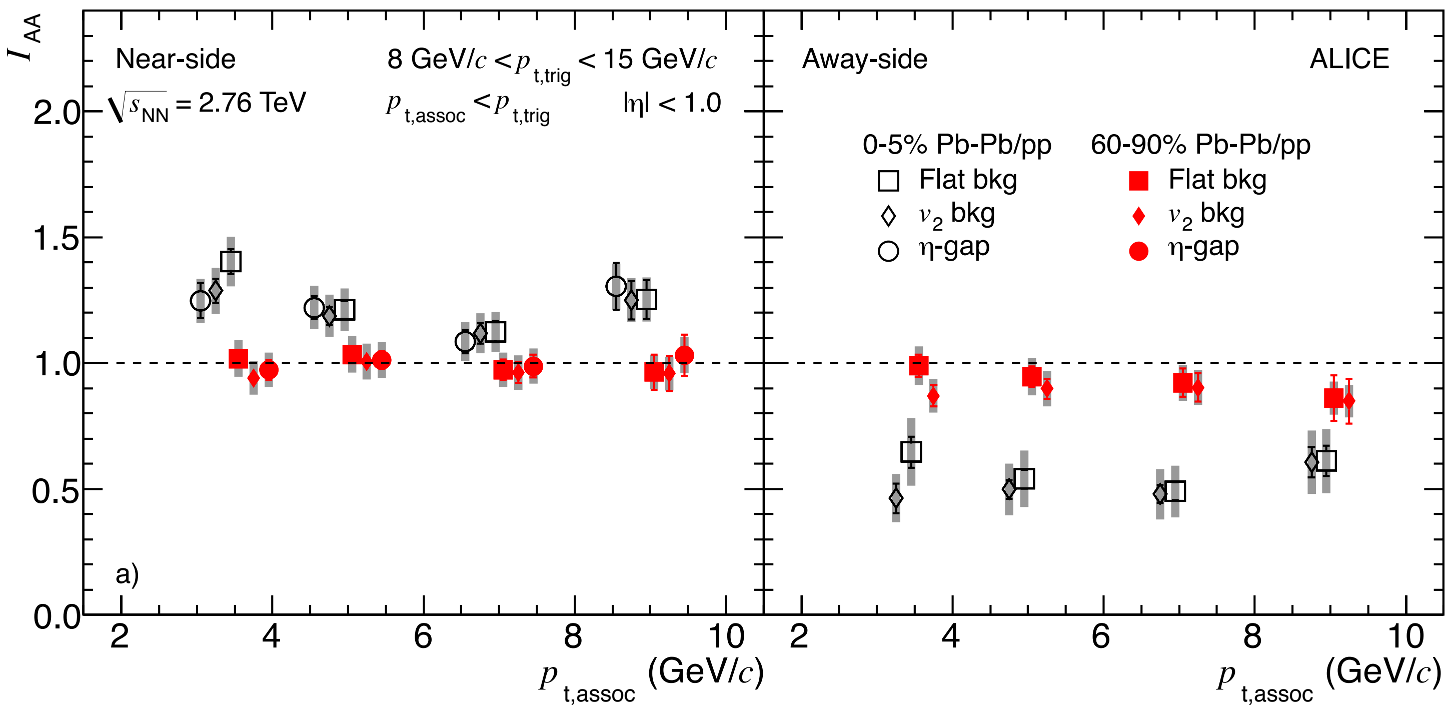
Hard Probes



Phys. Lett. B. 720 (2013) 52-62

- R_{AA}: Yield in heavy-ion collisions per <# of nucleon collisions>/ Yield in p-p collisions
- Expectation ~1 for hard processes i.e at high p_T
- Suppression observed
  - ✓ Indicative of medium induced jet quenching
  - ✓ Rises for p_T > 10 GeV/c
  - ✓ Not observed at RHIC

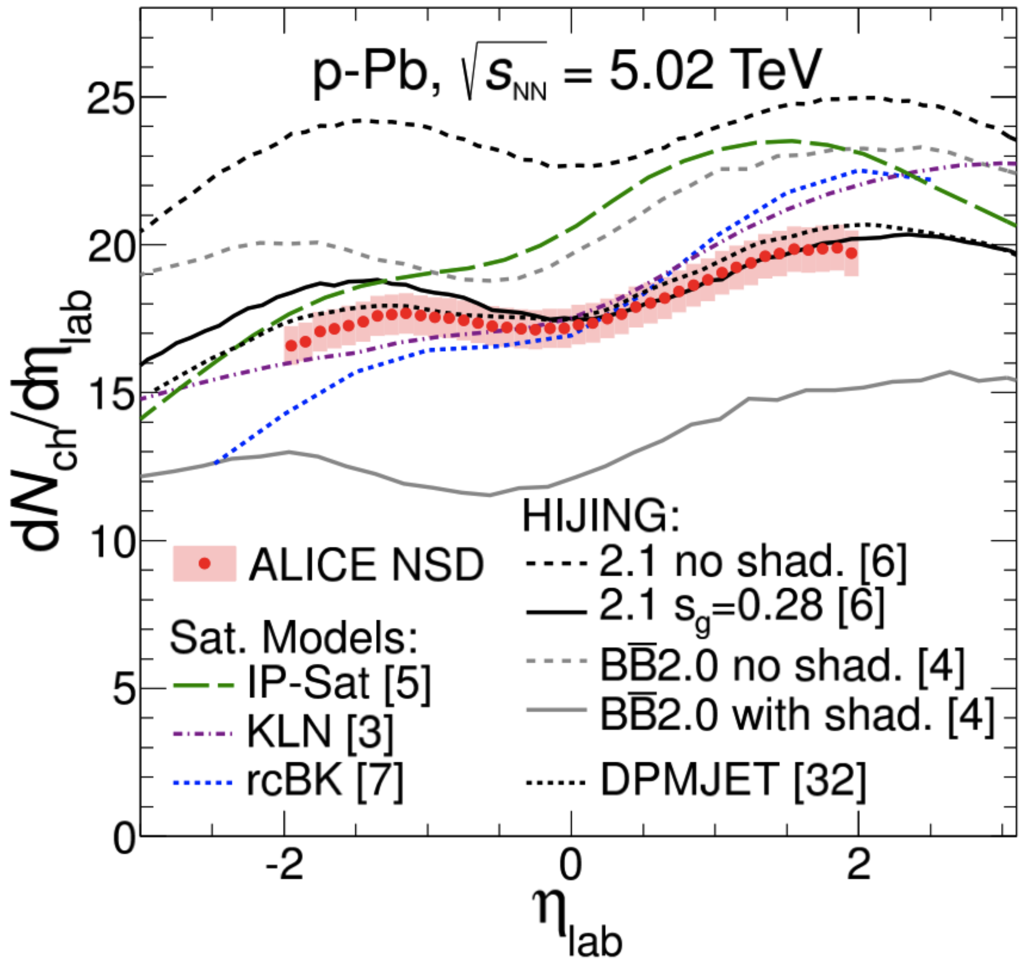
Hard Probes



Phys. Rev. Lett. 108, 092301 (2012)

- I_{AA}: Jet yield in heavy-ion collisions/Jet yield in p-p collisions
  - ✓ Obtained from 2 particle correlations
- Slight enhancement on near-side, suppression for away side jets

Something new ➔ p-Pb collisions

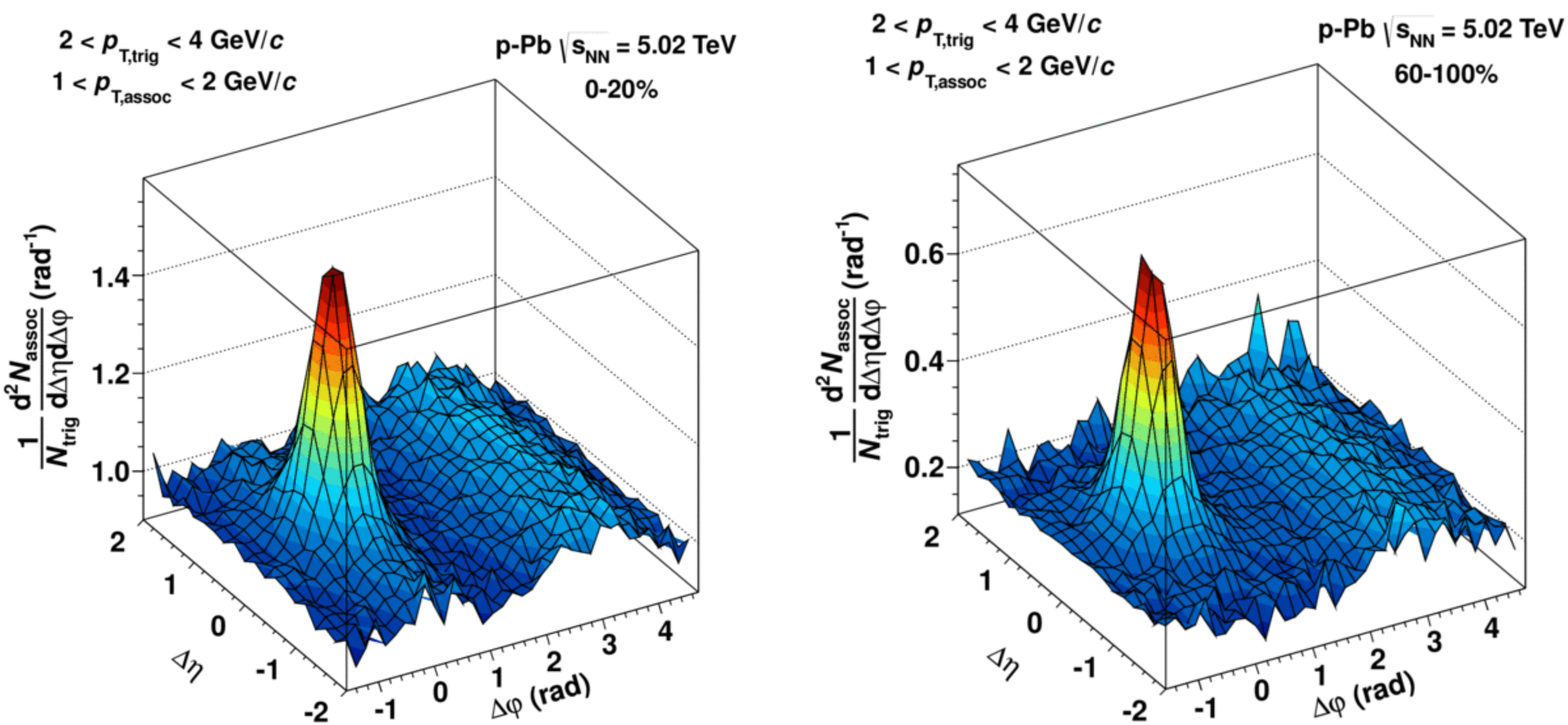


Phys. Rev. Lett. 110 (2013) 032301

- Expectation: No QGP formation
  - ✓ Understand initial state nuclear effects
- dN/dη: Integrated charged hadron yield
  - ✓ Asymmetric
  - ✓ More production in Pb direction
- Comparisons made to various model
  - ✓ Saturation
  - ✓ HIJING: Jets+string breaking

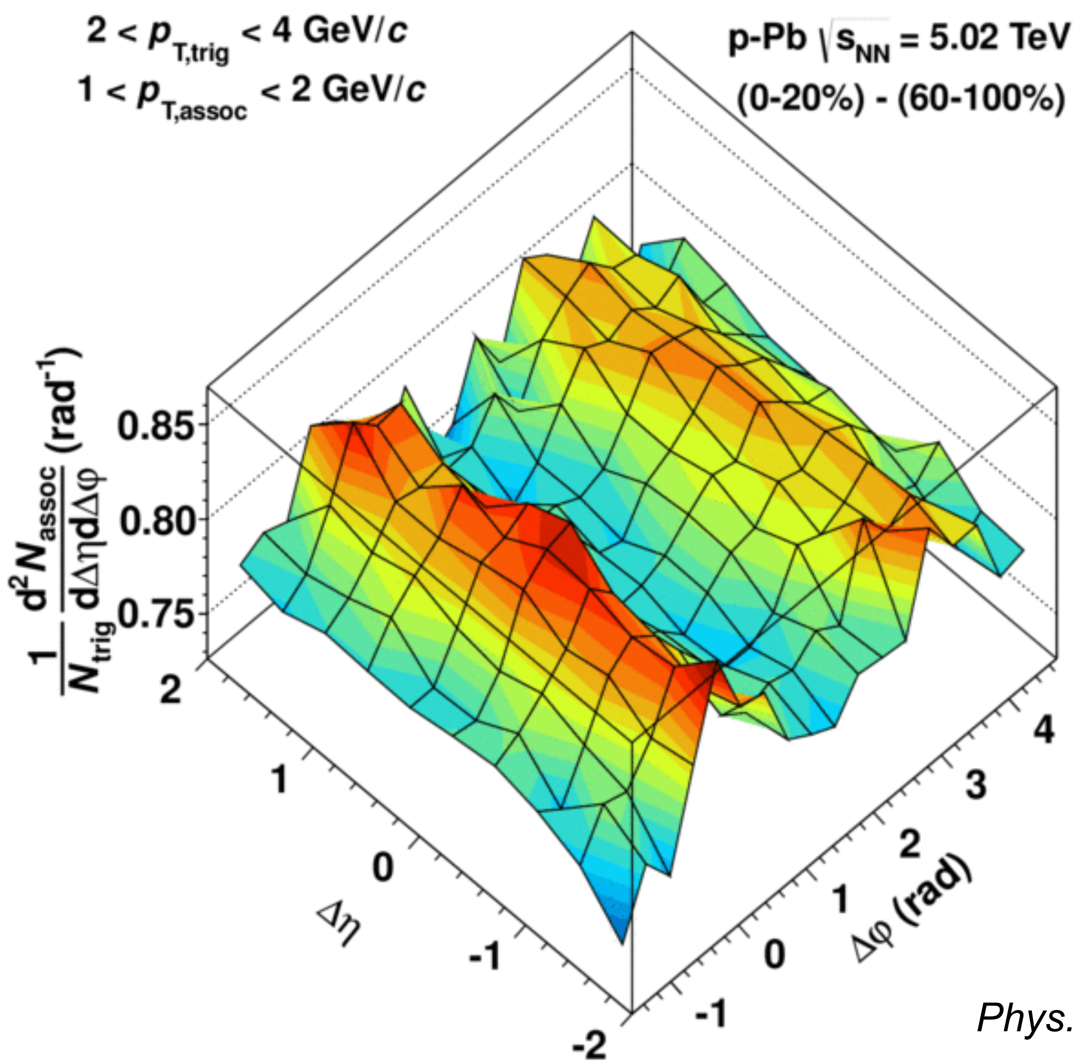
p-Pb collisions

Phys. Lett. B 719 (2013) 29-41



- Two particle correlation function extracted as a function of Δφ and Δη
- Central collisions (highest multiplicities) appear to have nearside ridge

p-Pb collisions



- Subtracting peripheral collisions (low multiplicity) from central reveals double ridge
- cos(2Δφ) structure consistent with elliptic flow in p-Pb collisions!
- ALICE currently looking into 4 particle correlations…

Phys. Lett. B 719 (2013) 29-41

Summary

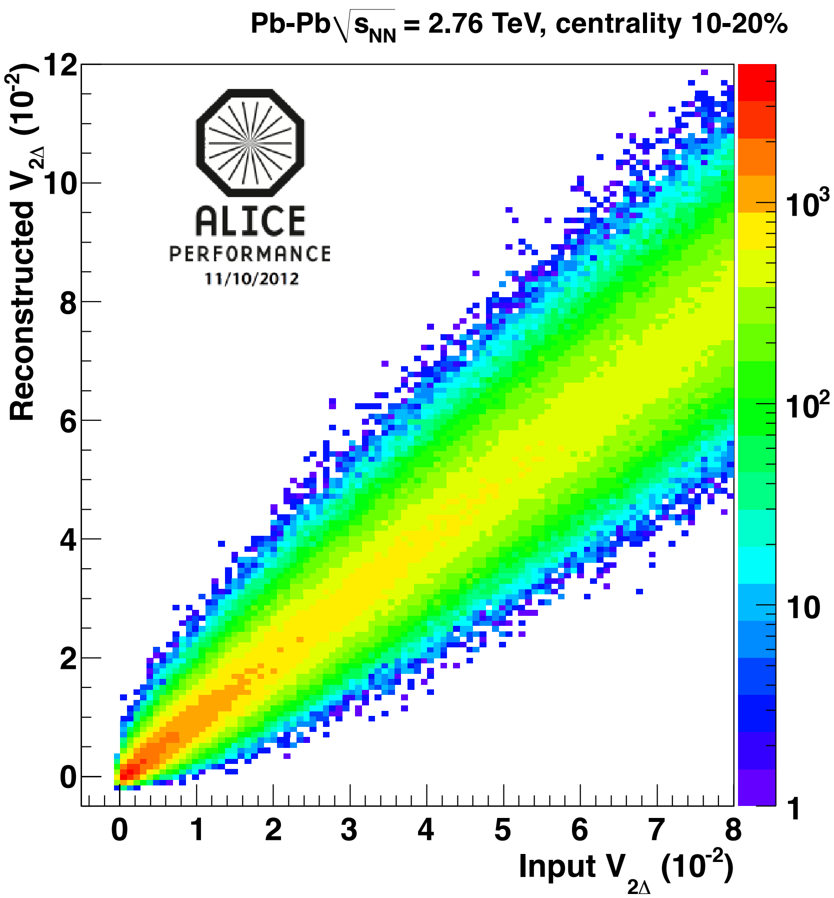
1. Identified particle production of light flavors
   - ✓ Radial flow 0.65c, 10% higher than RHIC
   - ✓ Chemical freeze-out temperatures close to expectations for QGP formation

2. Angular correlations and flow
   - ✓ Very comprehensive set of flow measurements, strong constraints on initial conditions
   - ✓ Evidence for strong parity violation at the LHC

3. Hard Probes
   - ✓ High p_T production suppressed in heavy-ion collisions
   - ✓ R_{AA} rises for p_T > 10 GeV/c

4. Appearance of elliptic flow in p-Pb collisions?

Backup: unfolding procedure

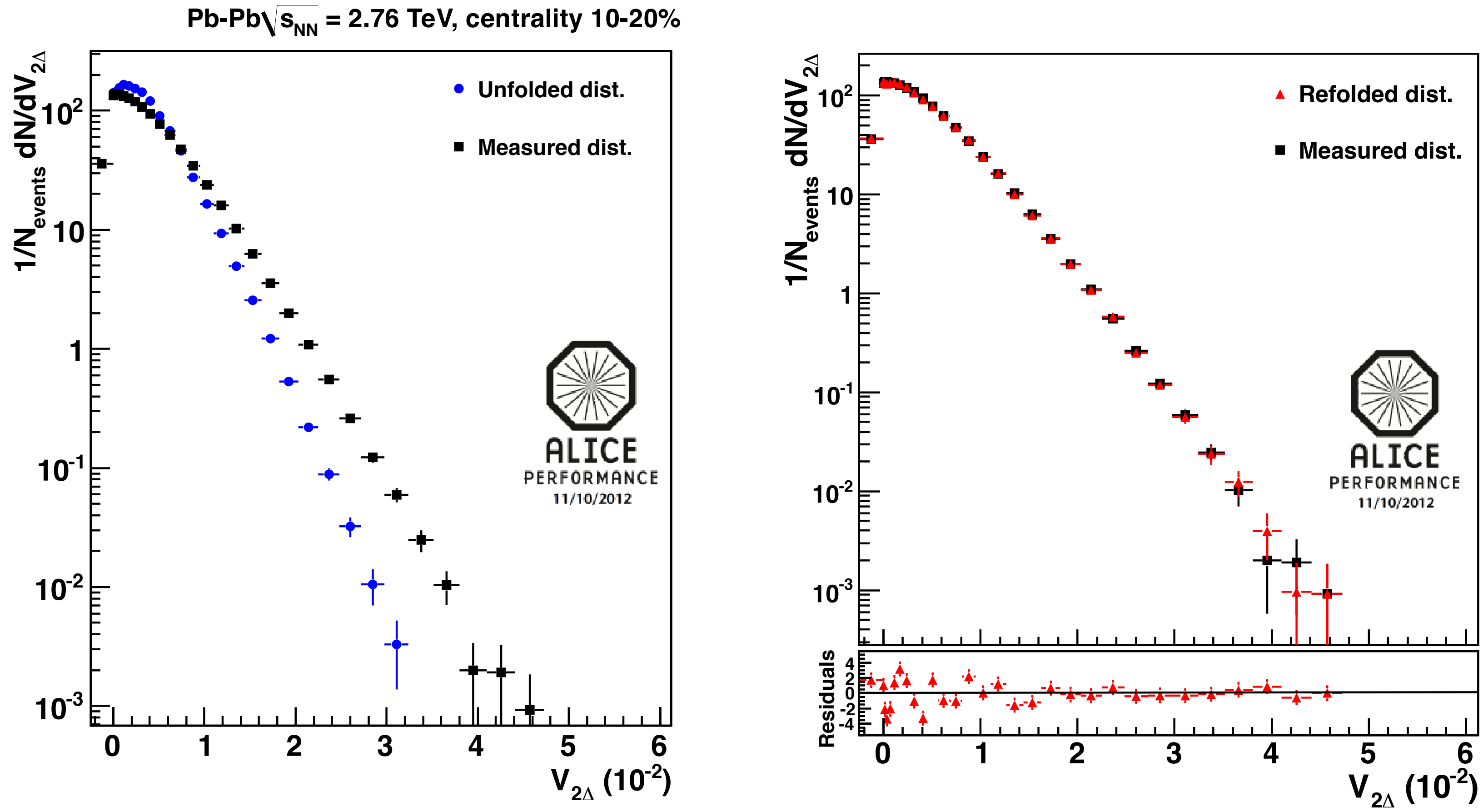


- Measured $V_{2\Delta}$ distribution = true $V_{2\Delta}$ distribution + stat. smearing + non flow
  - ✓ Use Bayes algorithm (NIM A 362 (1995) 487) with 18 iterations to unfold
- Stat. smearing determined via sampling:

$$\frac{dN}{d\varphi} \propto 1 + 2\mathrm{v}_2(input)cos(2(\varphi - \psi_2))$$

- …extracting $V_{2\Delta}$(reco) from sample, then comparing to $V_{2\Delta}$(input)
- φ distribution flat, no need for full detector simulation

Backup: example of unfolding



- Narrows $V_{2\Delta}$ distribution, refolded consistent with measured
- Calculate v_2 distribution via unfolded $\sqrt{V_{2\Delta}}$