Heavy Ions under Extreme Conditions – Recent Highlights from the ALICE-Experiment at the LHC

Final Colloquium
International Research Training Group, GRK 881

Bielefeld 13.09.2012

ALICE

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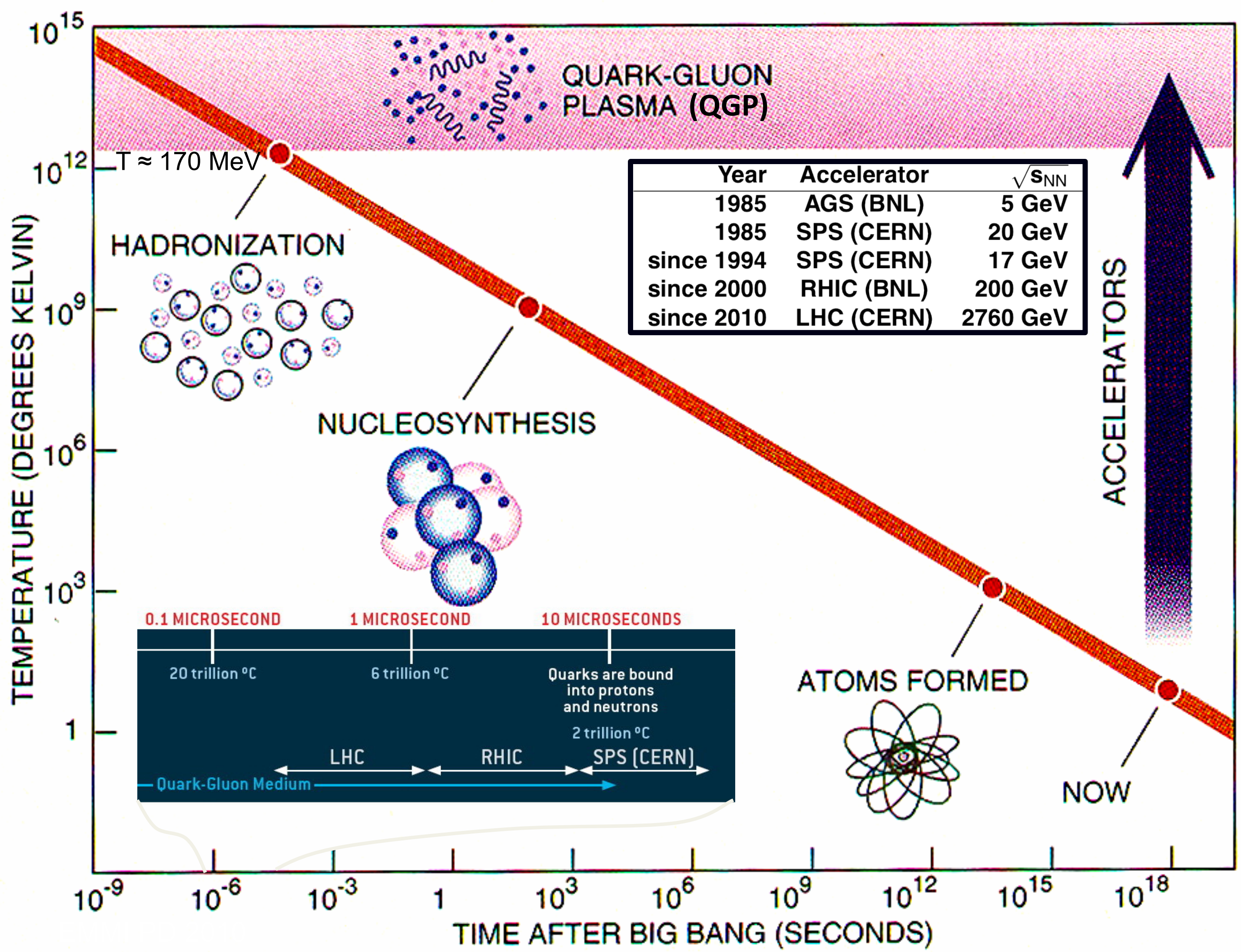
EMMI

13.7 Billion Years ago: Extreme Matter, the Quark-Gluon Plasma



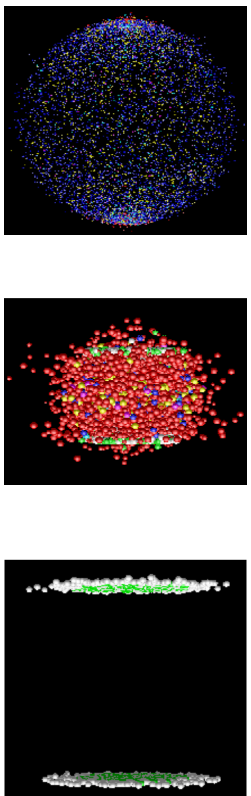
Year	Accelerator	$\sqrt{s_{NN}}$
1985	AGS (BNL)	5 GeV
1985	SPS (CERN)	20 GeV
since 1994	SPS (CERN)	17 GeV
since 2000	RHIC (BNL)	200 GeV
since 2010	LHC (CERN)	2760 GeV

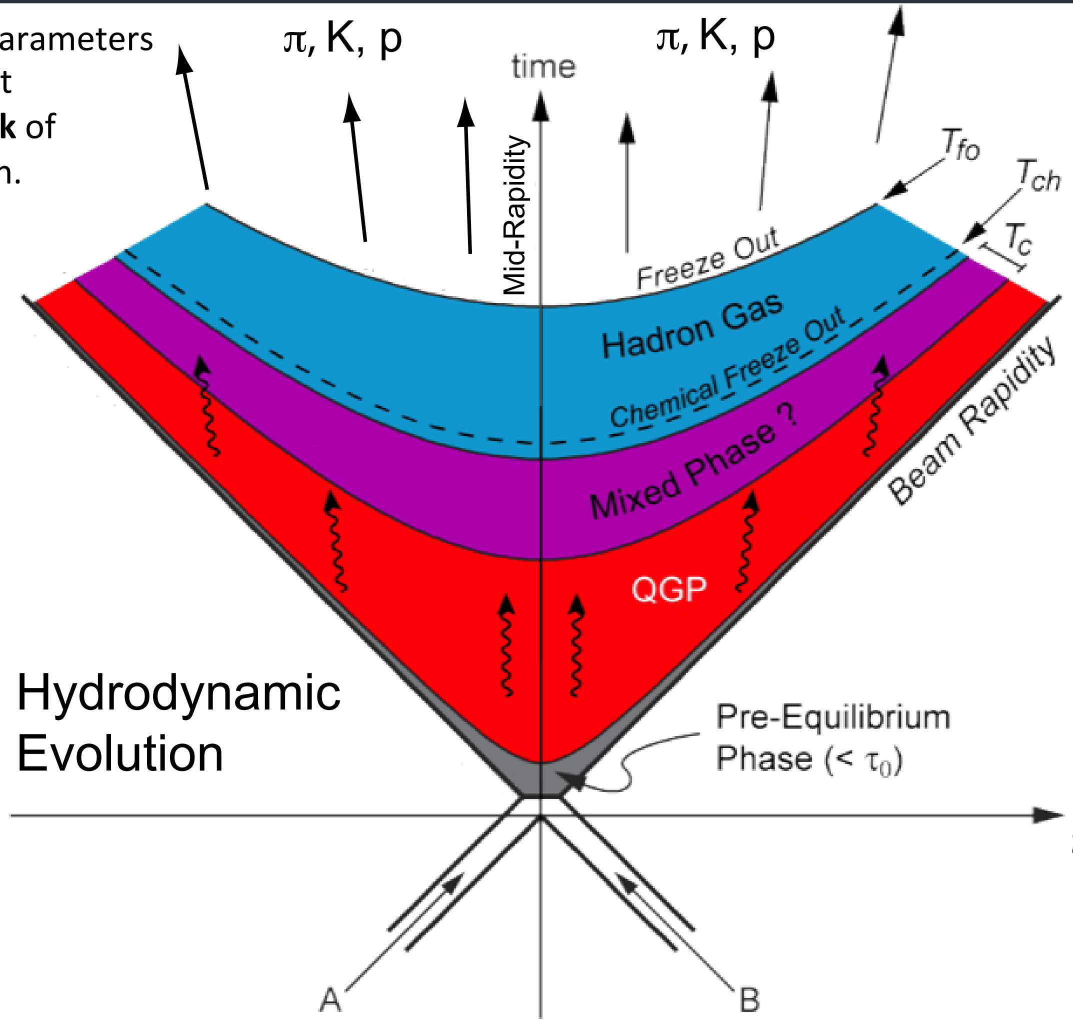
Quarks and gluons are not confined into hadrons but can move freely

Recreated in the laboratory by colliding heavy ions (e.g. Au, Pb)

Time Line of a Heavy-Ion Collision

Thermodynamic parameters (T,μ_B) at freeze-out determine the **bulk** of particle production.

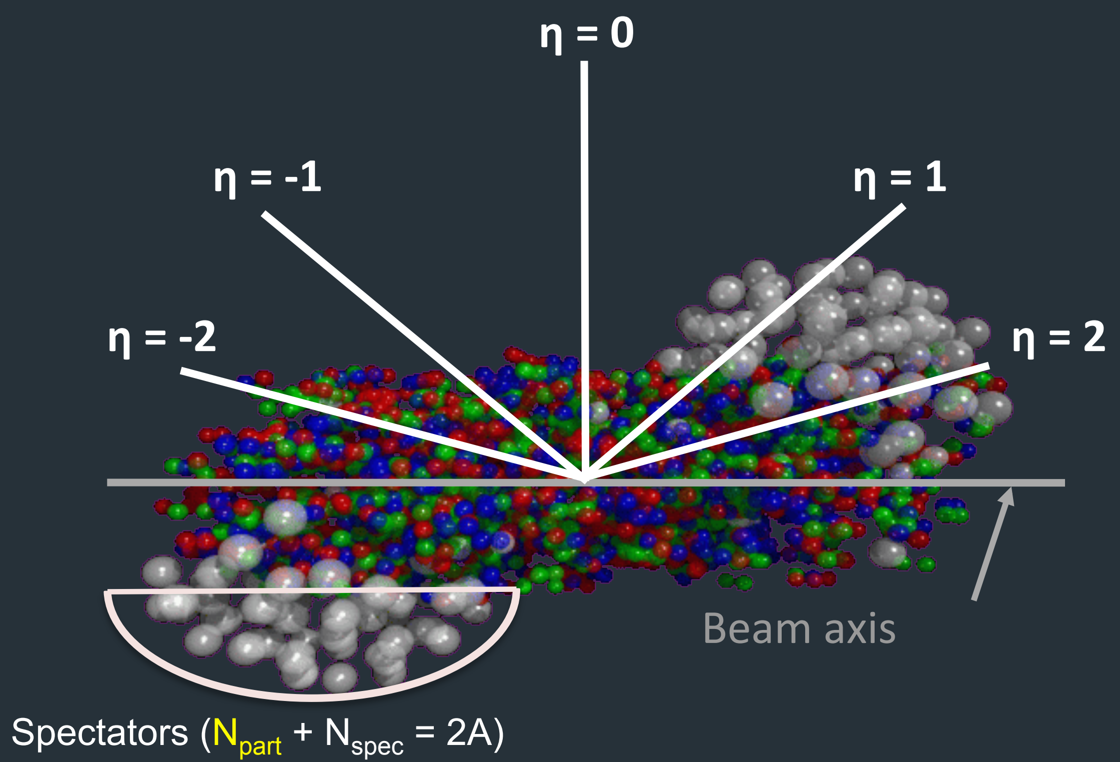




expansion, cool down

time scale: O(fm/c) ~ O(10^{-23} s)

Important Variables



- Transverse momentum

$$p_T = p \sin \vartheta$$

- Pseudo-rapidity

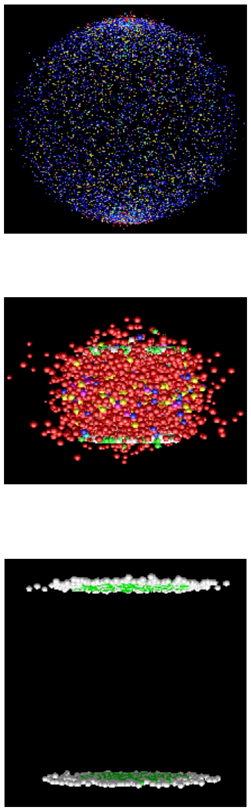
$$\eta = \frac{1}{2} \ln \frac{p + p_L}{p - p_L}$$

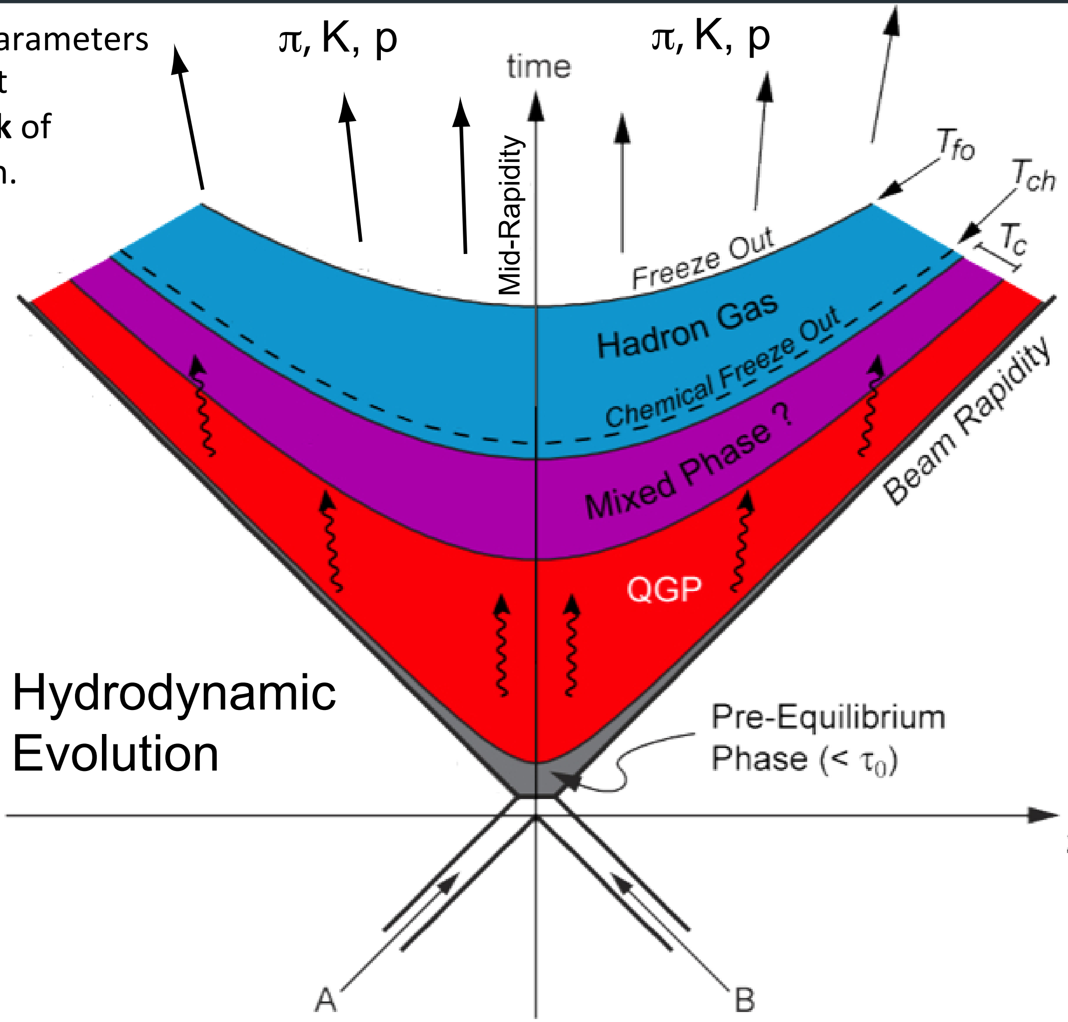
p_T invariant under Lorentz-transformation, measure for momentum transfer Q^2

η (measure for p_L) additive

Time Line of a Heavy-Ion Collision

Thermodynamic parameters (T,μ_B) at freeze-out determine the **bulk** of particle production.



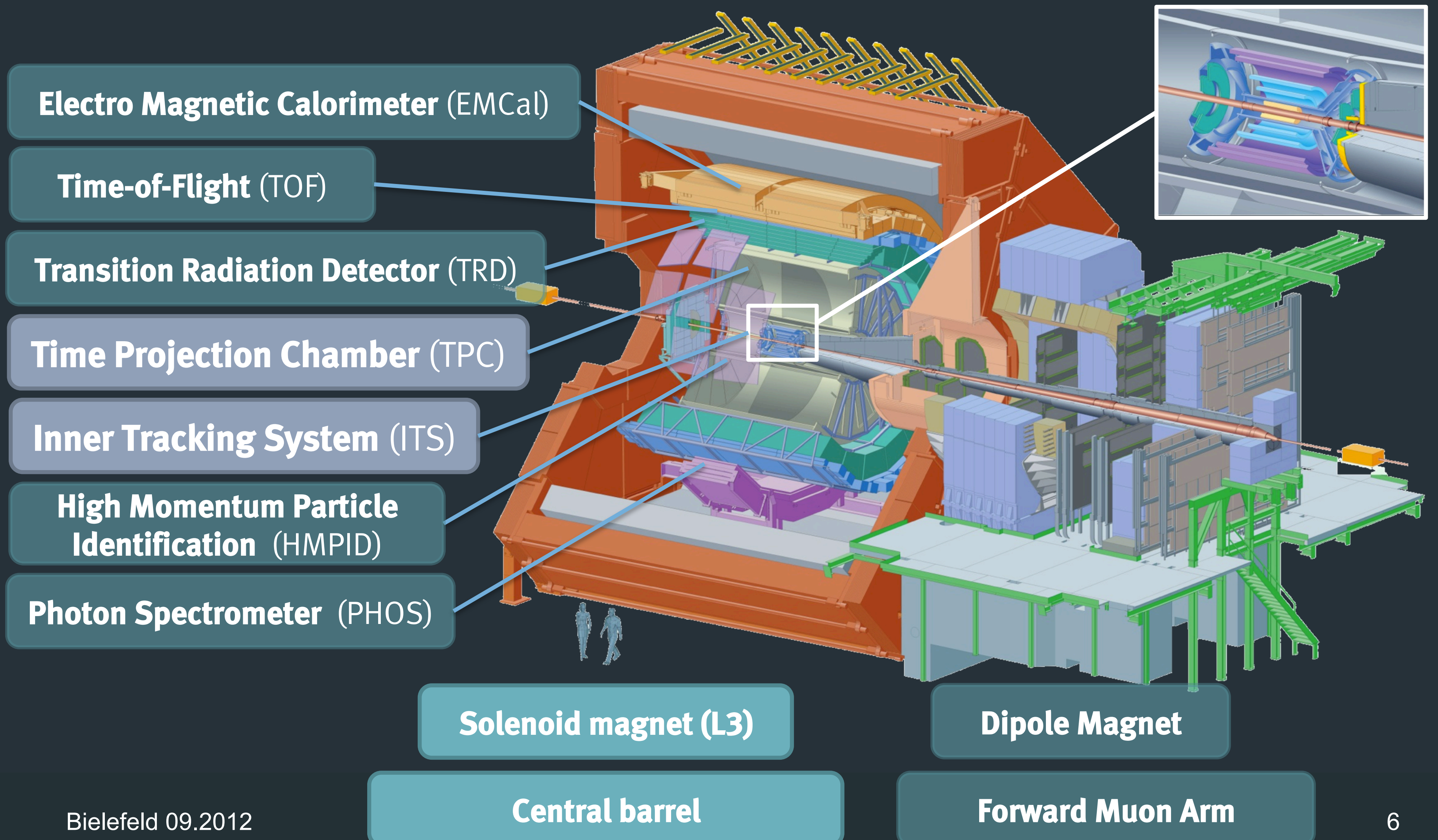


Particle production:

soft/low p_T
medium dominated, collective behavior

hard/high p_T,
large Q^2 parton scattering/jets
(N_{coll} scaling)

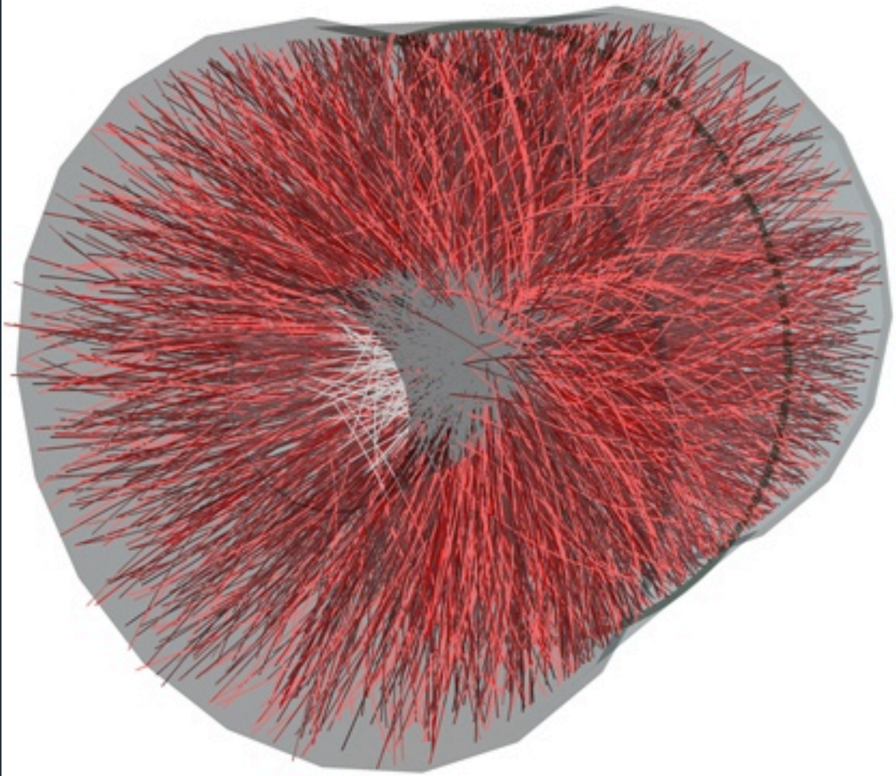
ALICE @ LHC



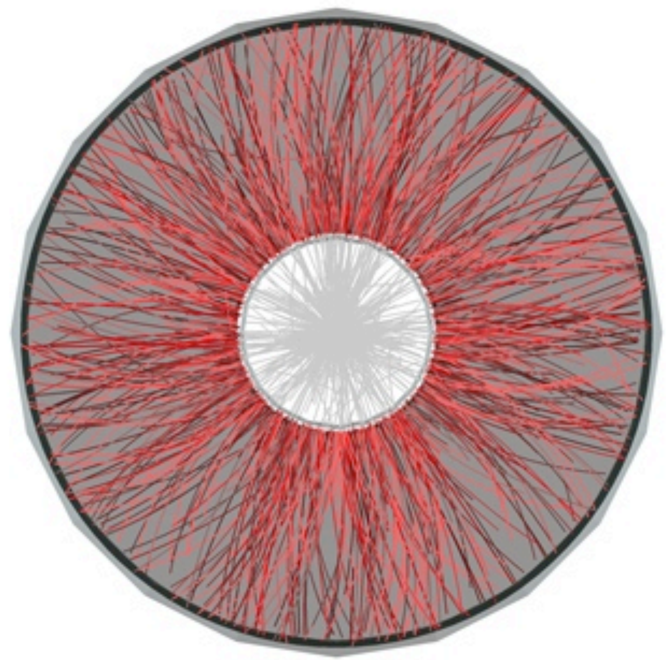
Electro Magnetic Calorimeter (EMCal)
Time-of-Flight (TOF)
Transition Radiation Detector (TRD)
Time Projection Chamber (TPC)
Inner Tracking System (ITS)
High Momentum Particle Identification (HMPID)
Photon Spectrometer (PHOS)
Solenoid magnet (L3)
Dipole Magnet
Central barrel
Forward Muon Arm

Pb-Pb Collision at $\sqrt{s_{NN}} = 2.76$ TeV

3D view of TPC and ITS tracks



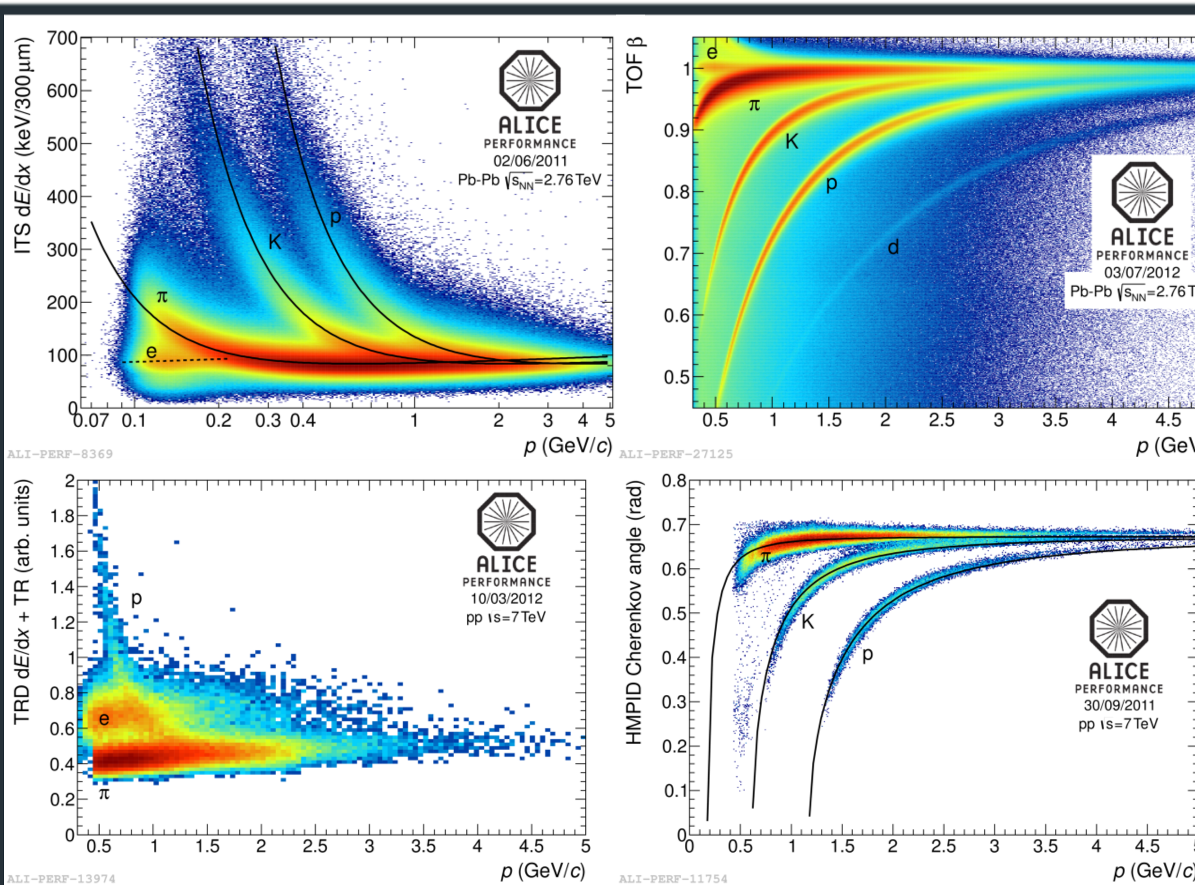
Beam view (η slice)

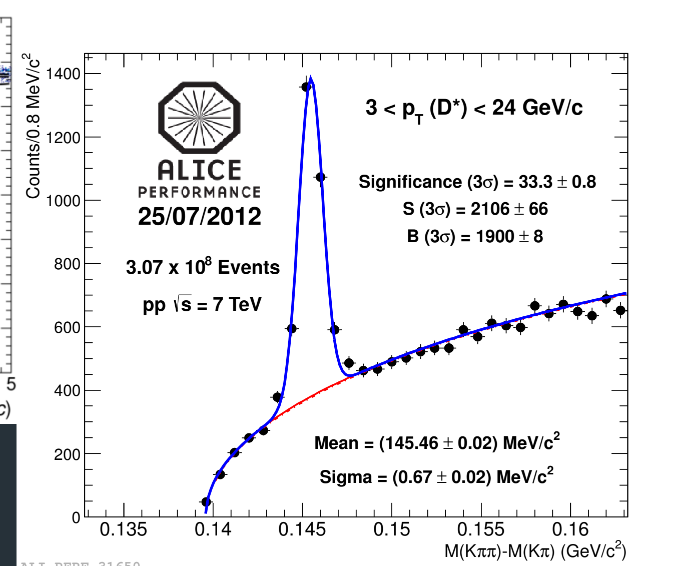


$$\frac{p_T}{\mathrm{GeV}/c} = 0.3 \cdot \frac{B}{\mathrm{T}} \cdot \frac{r}{\mathrm{m}}$$

Precision measurement of charged particles with high and uniform efficiency down to ≈ 100 MeV/c.

Particle Identification

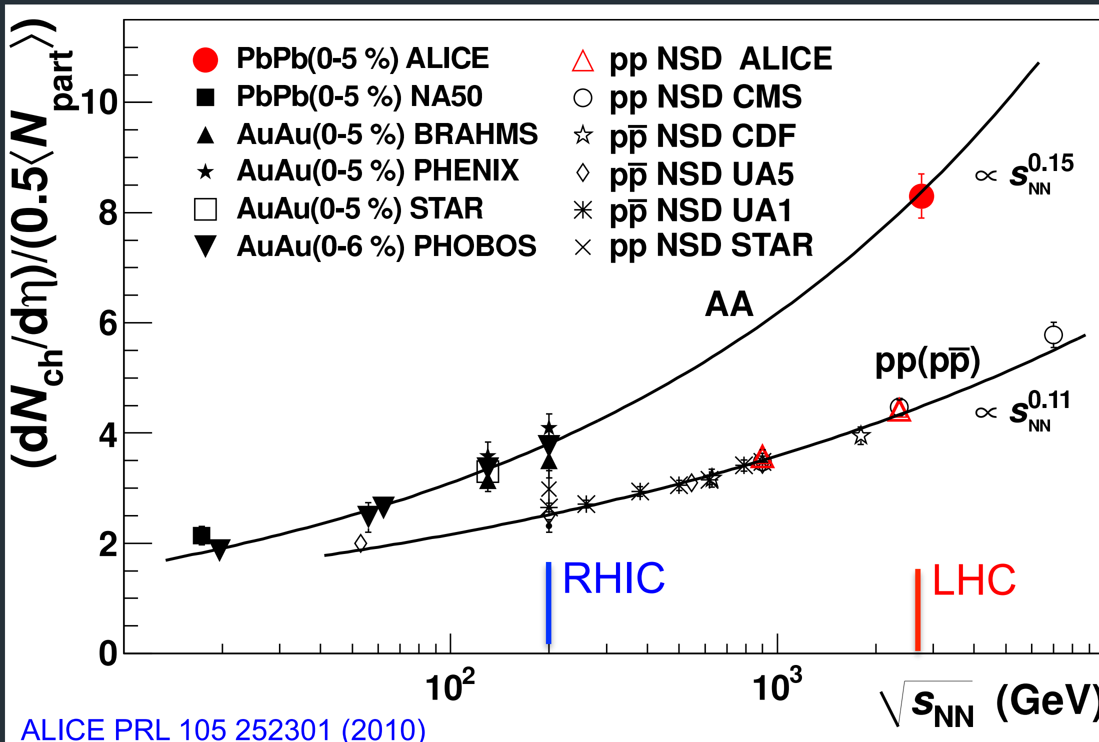




ALICE employs basically all known techniques for separation of stable particles, short and long lived decay reconstruction.

GLOBAL, SOFT OBSERVABLES

Energy Density



Initial energy density sufficient at RHIC.
About 3 × larger at LHC.

- Energy density*
  - Deposited energy
    - Produced particles
  - Volume
    - After formation time of the fireball

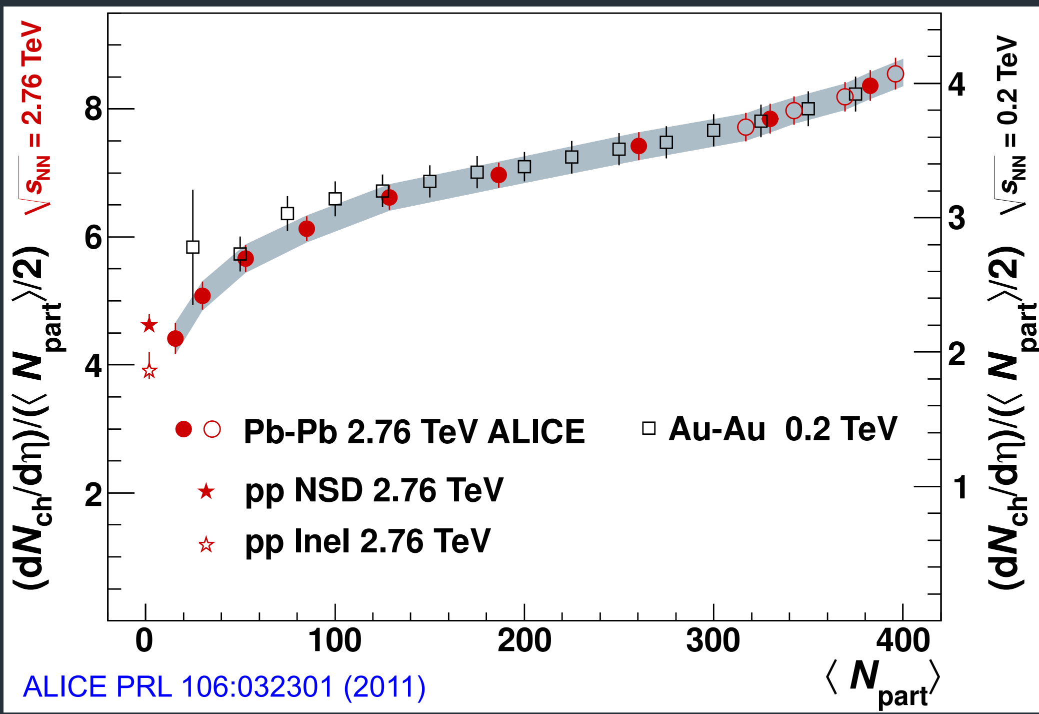
$$\varepsilon_{Bj} = \frac{\langle E_T \rangle}{\tau_0 A} \cdot \frac{dN}{d\eta}\bigg|_{\eta=0}$$

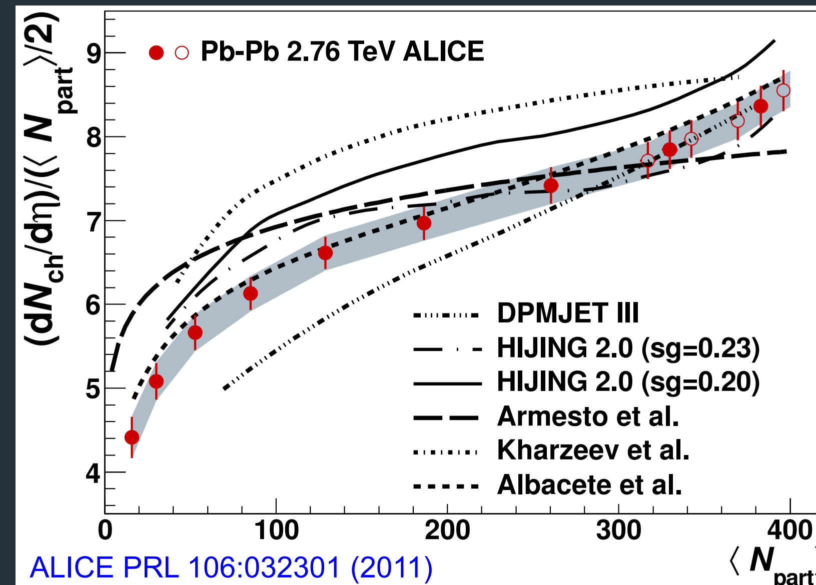
*Bjorken PRD 27, 140 (1983)

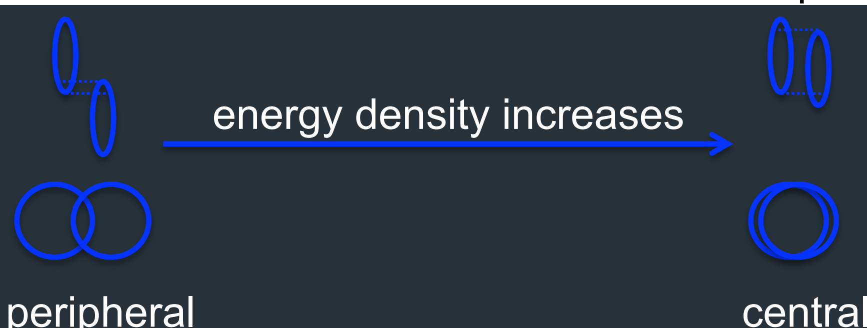
- RHIC dN/dη ≈ 600
  - $\varepsilon > 5\ \mathrm{GeV/fm^3}$
  - $30 \times \varepsilon_0$ bzw. $5 \times \varepsilon_c$
- LHC dN/dη ≈ 1600
  - Rough estimate:

$$\frac{T_0^{LHC}}{T_0^{RHIC}} = \sqrt[4]{\frac{1600}{600}} \approx 1.3$$

Centrality Dependence of Particle Production



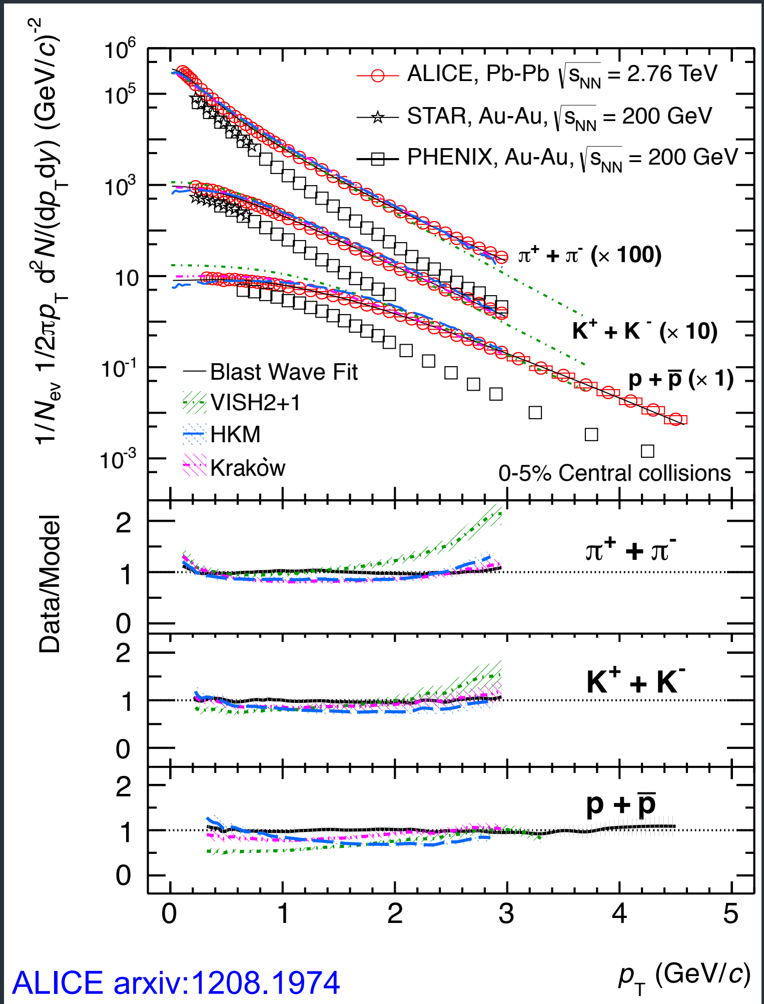




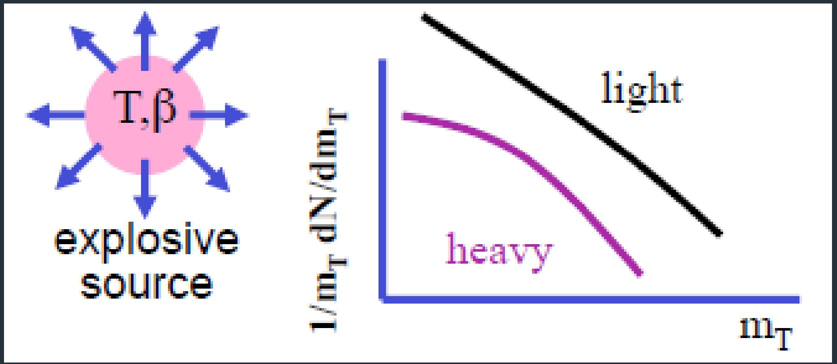
Remarkable shape similarity of RHIC and LHC data.

Most models fail to reproduce the shape. Weak increase favors moderation of gluon density.

Collective Behavior 1
Radial Flow and Kinetic Freeze-Out



ALICE arxiv:1208.1974

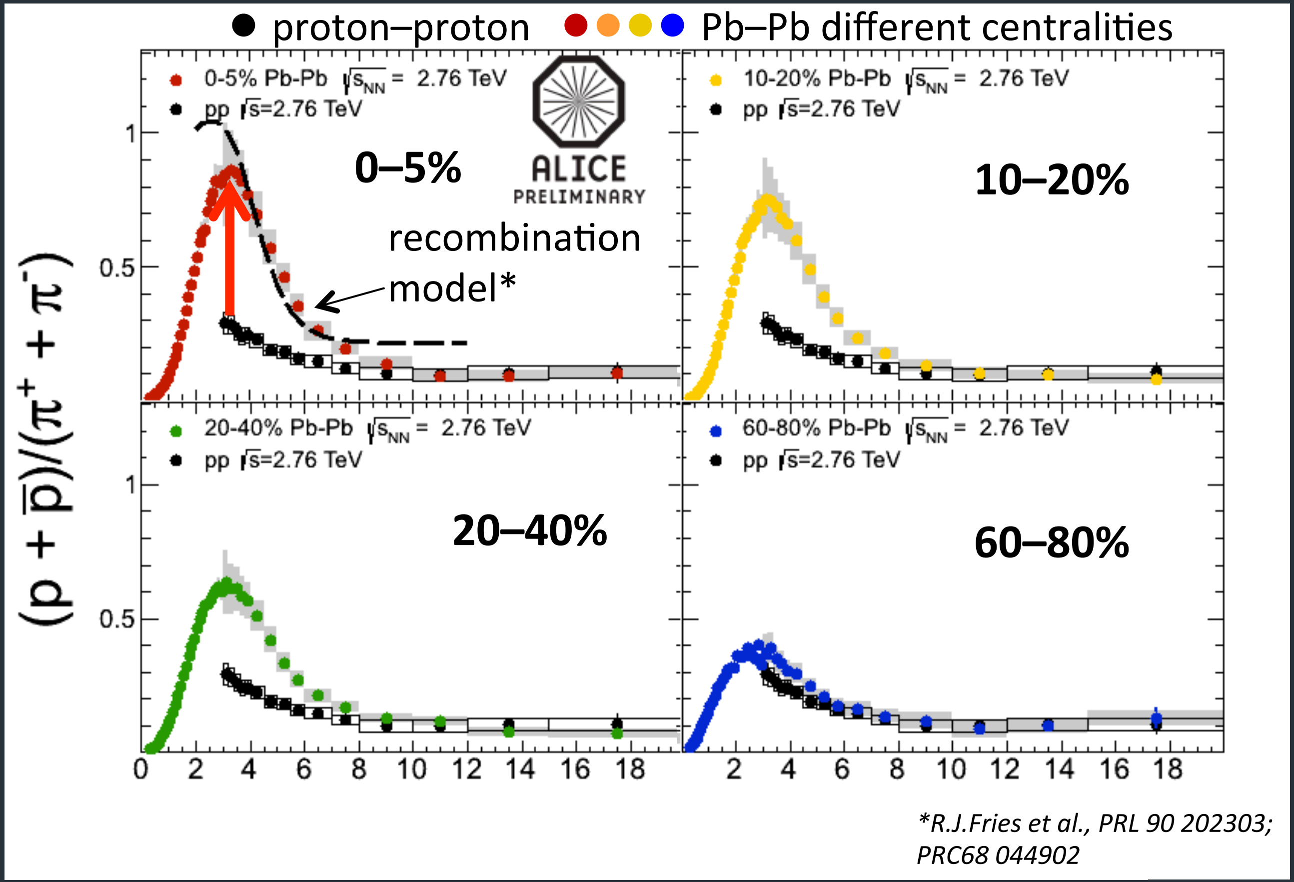


Combined Blast-Wave Fit:
More violent transverse expansion $\beta_T \approx 0.65 \pm 0.02$
Kinetic freeze-out: $T_{kin,fo} = 96 \pm 10$ MeV

Detailed model comparison:
Additional processes needed after chemical freeze-out to correctly describe protons

Strong collectivity in transverse direction

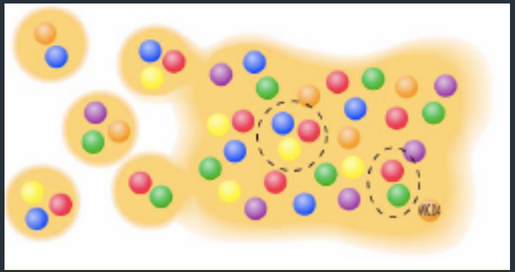
p/π ratio vs. p_T



„Anomalous" baryon/meson ratio extends farther than expected from radial flow. Recombination of quarks?

$p_T(qqq) \approx 3 \cdot p_T(q)$

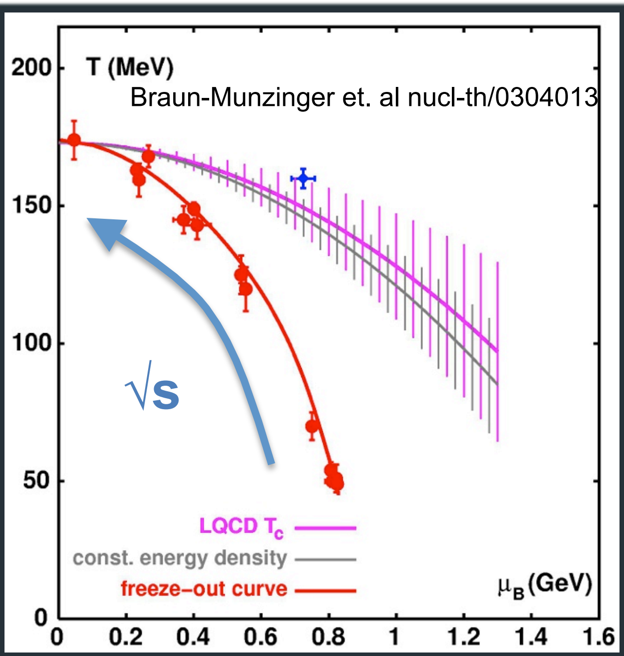
$p_T(q\bar{q}) \approx 2 \cdot p_T(q)$

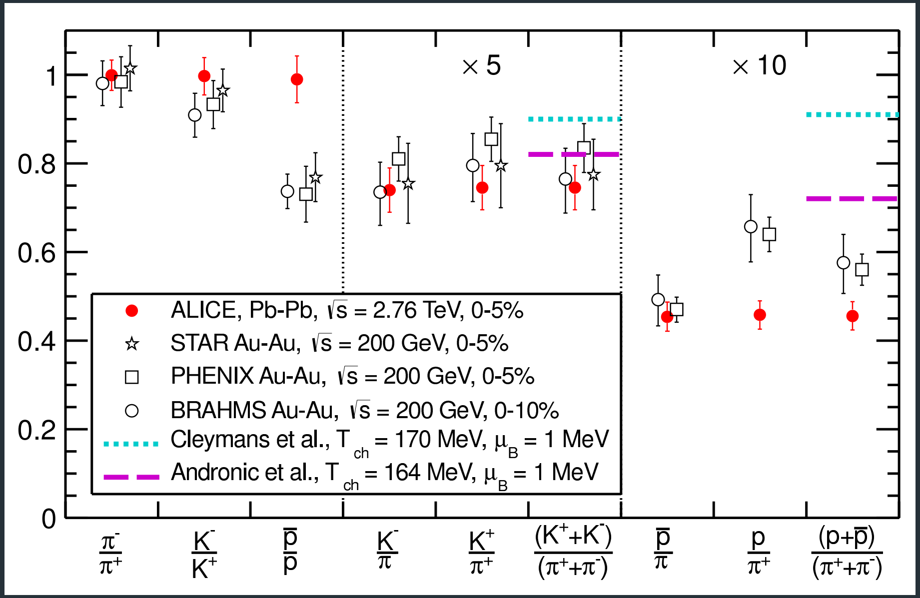


p/π ratio at $p_T \approx 3$ GeV/*c* in 0–5% central Pb–Pb collisions 3 × higher than in pp. Above ~ 10 GeV/*c* back to the "normal" pp value.

Chemical Freeze-Out

- Chemical equilibrium
  - Statistical discription via partition function Z(T,μ,V): occupation numbers
- Experimentally
  - Particle ratios fixed at chemical freeze out
  - Sets minimal temperature in reaction



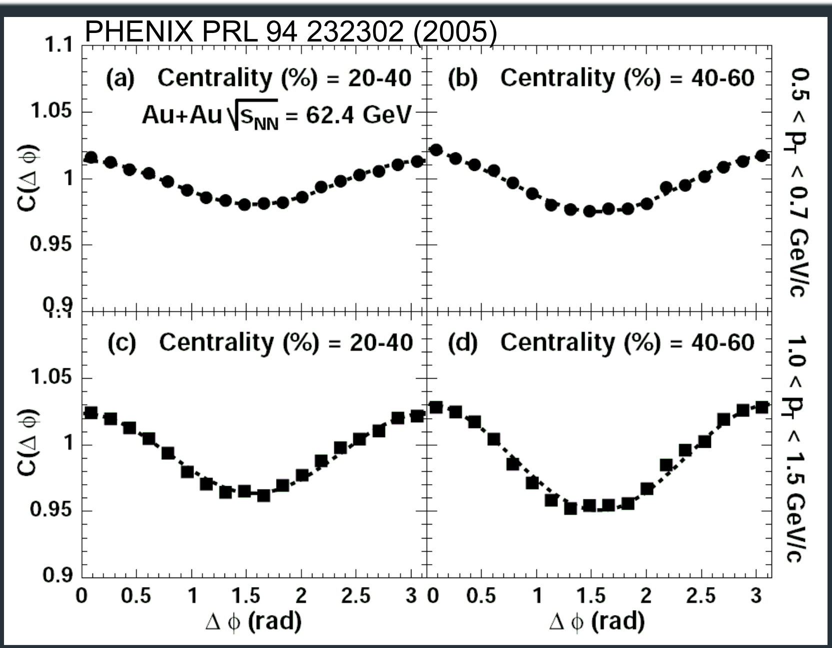


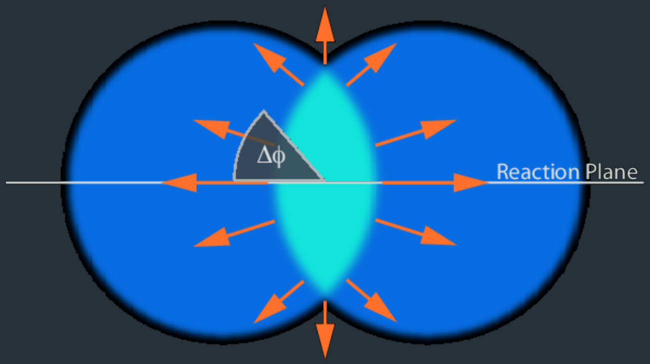
RHIC: Chemical freeze out close to phase boundary $T_c \approx 170$ MeV

ALICE/LHC: higher precision data, protons over predicted in thermal model.
Fit yields only poor agreement and T ≈ 154 MeV

Possible explanation:
Hadronic re-interactions.

Collective Behavior 2
Elliptic Flow





- Non-central collisions
  - Elliptic reaction zone
  - Pressure gradient

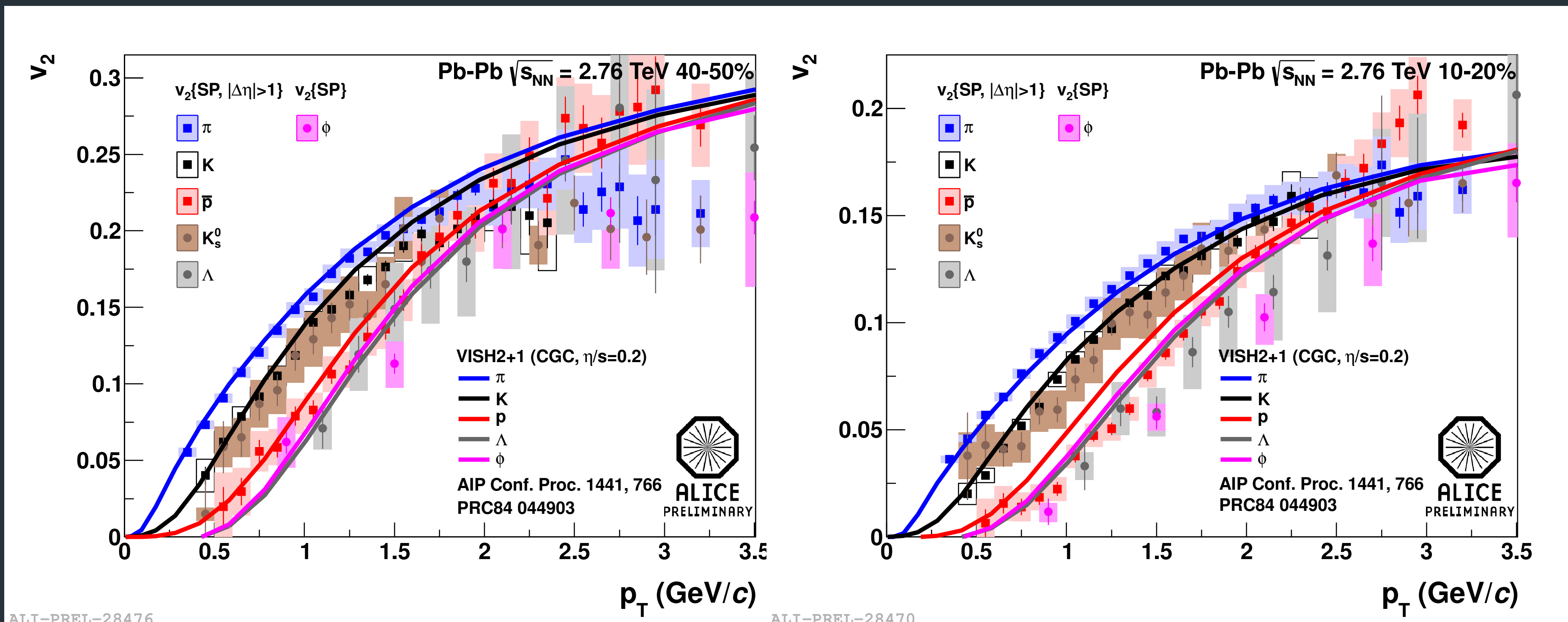
$$\frac{dP}{dx}(0°) > \frac{dP}{dx}(90°)$$

- Collective flow of particles
  - Spatial anisotropy ⇒ momentum anisotropy
- Characterized by harmonic series

$$C \propto 1 + \sum v_n \cos(n \cdot \Delta\phi_n)$$

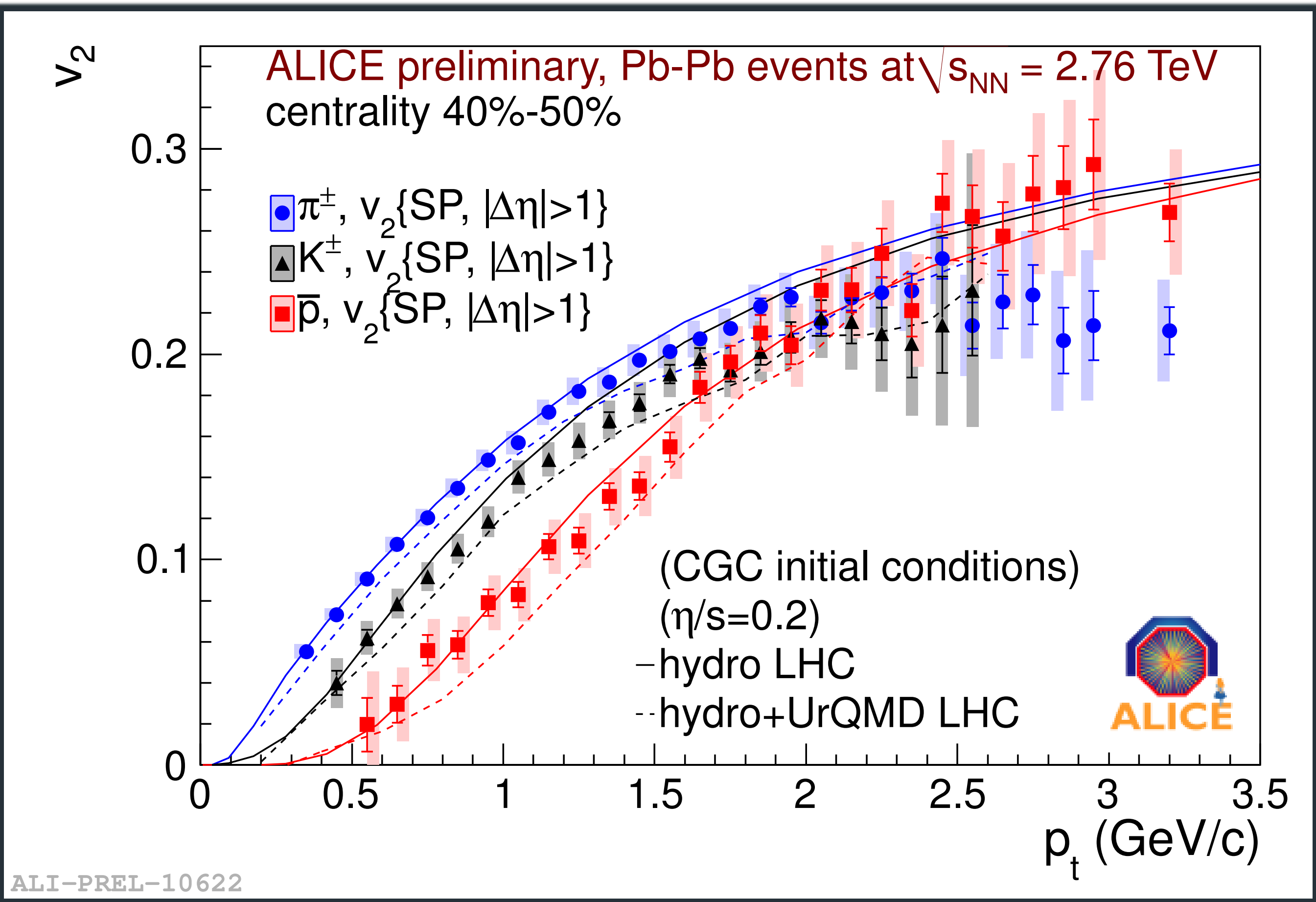
  - v_2: elliptic flow
- Test collectivity
- Test of equation of state and initial conditions via hydrodynamic calculations

Elliptic Flow of Identified Particles



Confirmation of RHIC discovery: (Almost) perfect liquid created
Described by hydro dynamical calculation with close to minimal viscosity.
Some tension in more central collisions

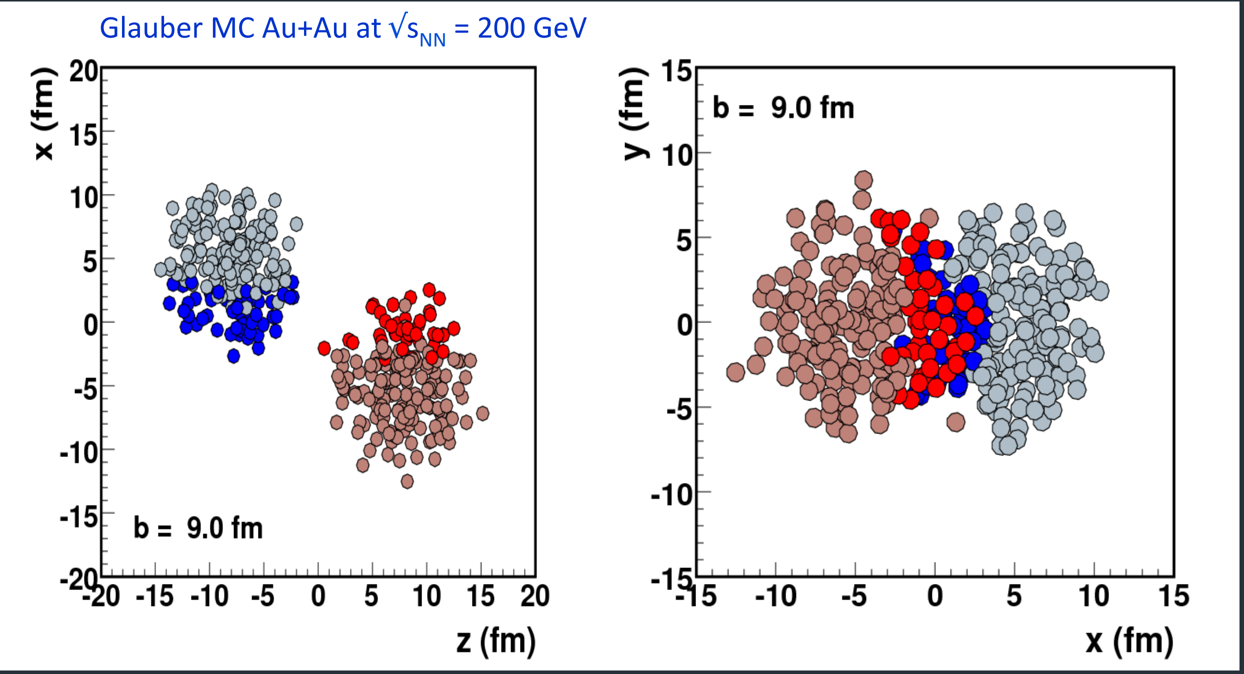
Elliptic Flow of Identified Particles



Confirmation of RHIC discovery: (Almost) perfect liquid created
Described by hydro dynamical calculation with close to minimal viscosity.
Some freedom in η/s vs. hadronic re-interaction (vs. initlal conditions).

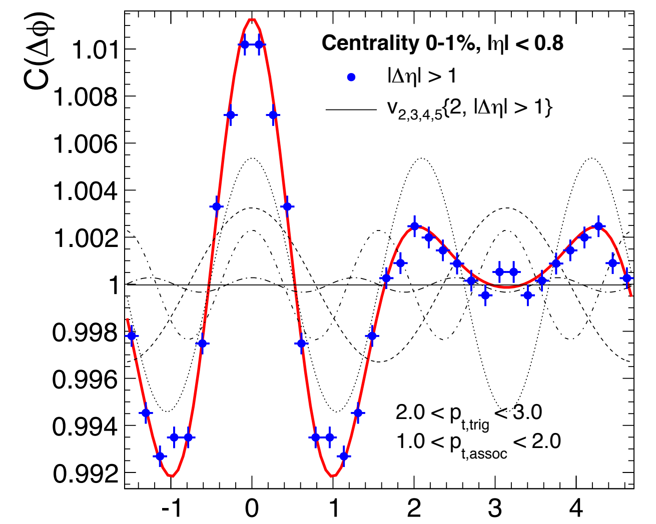
Higher Harmonics

- Long standing paradigm:
  - No odd flow coefficients at mid-rapidity due to symmetry of the colliding system ($v_n = 0$, for n = 1,3,5…) $v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$

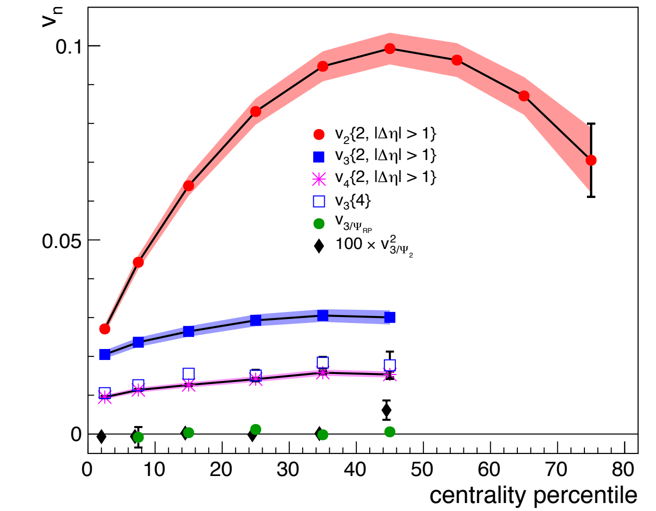


But odd harmonics could be caused by event by event fluctuation of participants. New, independent symmetry plane?

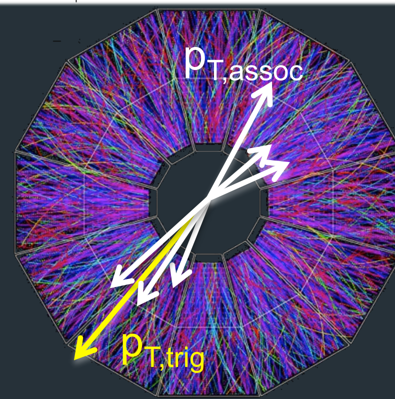
Higher Harmonics
Two Particle Correlations



ALICE Phys.Rev.Lett., 107:032301



- Associate particles in $\Delta\phi$ with trigger particle

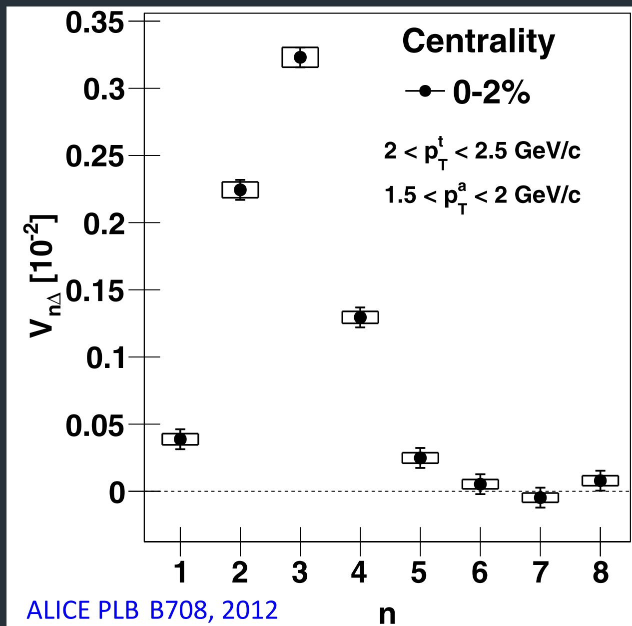


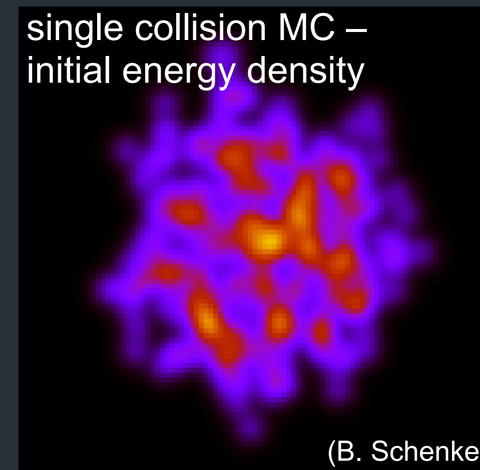
- Clear odd harmonic structure in very central events: Initially described as “Mach Cone”
- Significant triangular anisotropy, only little change with centrality
- No correlation of odd harmonics with the event reaction plane
- Not shown: For $p_{T,a} < 4$ GeV/c, p_T dependence factorizes:

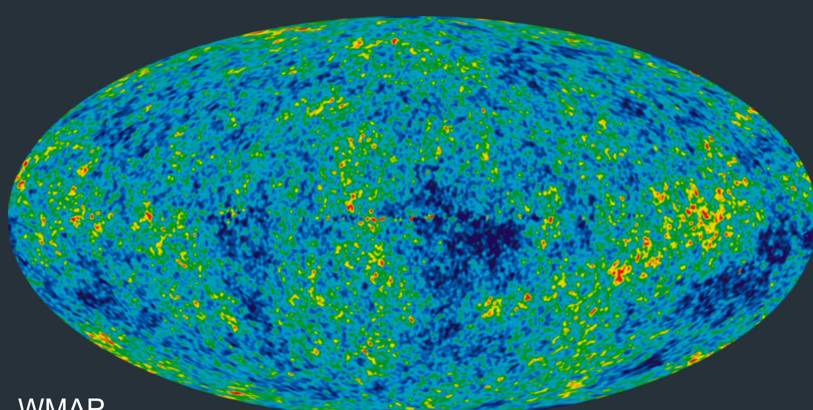
$$v_{n\Delta} = \langle v_n\{2\}(p_T^t) v_n\{2\}(p_T^a) \rangle$$

Momentum anisotropy at low p_T induced by initial spatial anisotropies for all harmonics.

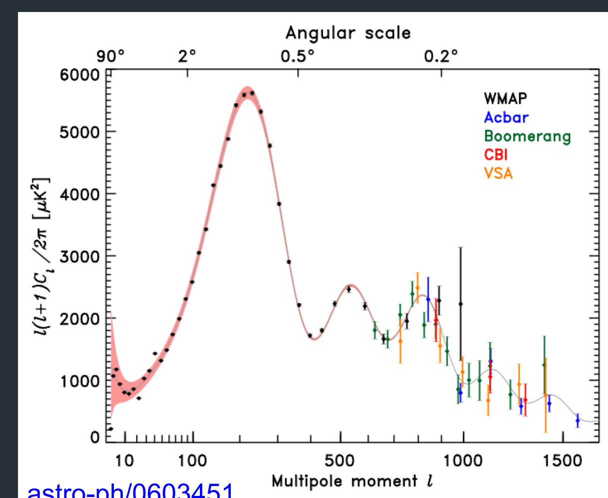
An Intriguing Analogy…



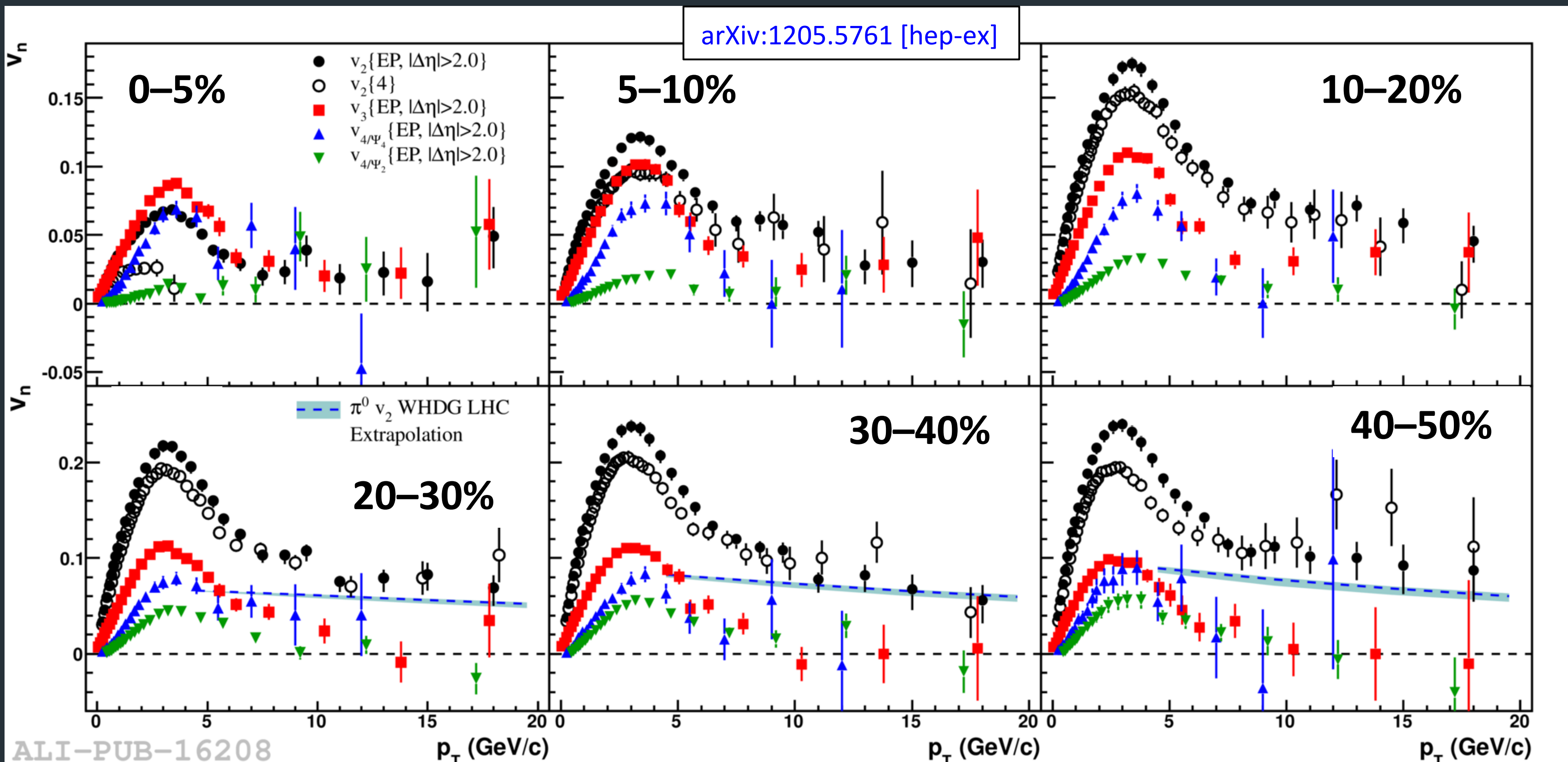




WMAP



v_n at High p_T



Non-zero v_2 at large transverse momentum: Path length dependence of parton momentum <u>loss</u>, v_3 and v_4 diminish above 10 GeV/c – impact of fluctuations vanishes, no more sizeable momentum <u>gain</u> due to expansion.

HARD PROBES

Recap: Hard Probes

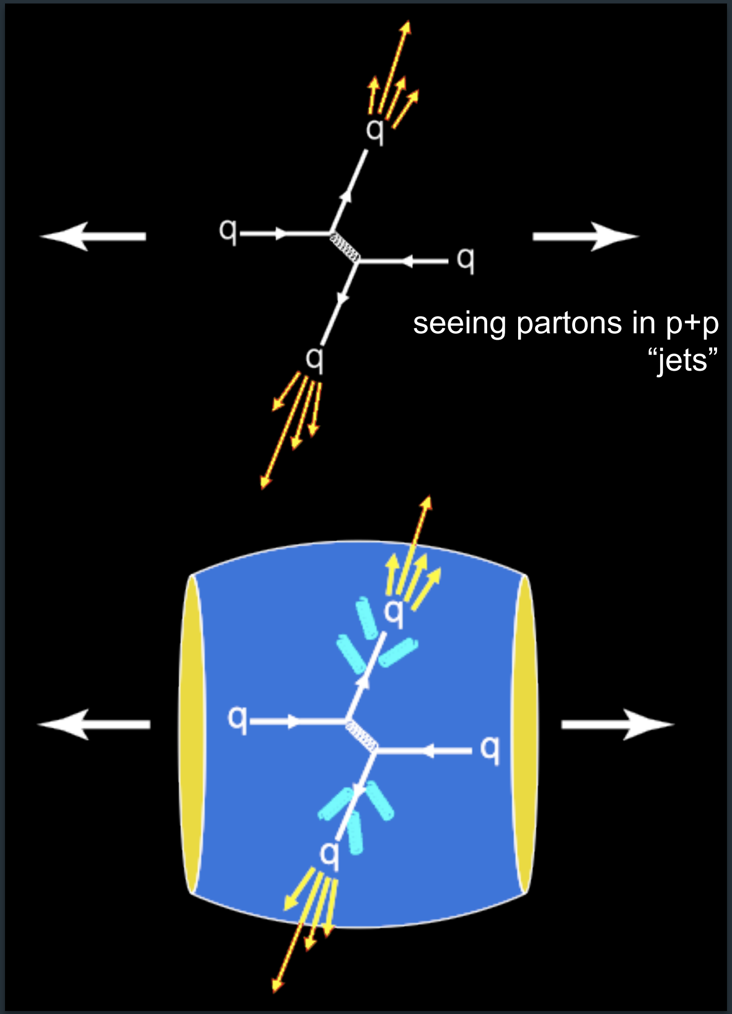
- Hard probes
  - $t \sim 1/Q \ll 1$ fm/c (rare)
  - Hard scale set by momentum or mass (**high p_T** or **heavy flavour**)
- Parton scattering with large Q^2
  - Partons fragment into "jets" of observable hadrons
    - Strong back-to-back correlation
  - Main source of particle production at high p_T

$$\frac{d^2\sigma_h}{dp_T dy} = \int \mathbf{PDF} \times \mathbf{pQCD} \times \mathbf{FF}(q, g \rightarrow h)$$

  - In A+A: High p_T partons interact with QCD medium prior to fragmentation (***"jet tomography"***)

$$\Delta E \propto \alpha_s C_R \langle \hat{q} \rangle L^2 f(E, m_q)^*$$

Scattered parton properties (including medium effects) reflected in high p_T particles/jets.



*E.g. Baier et. al NPB 484: 265 (1997)

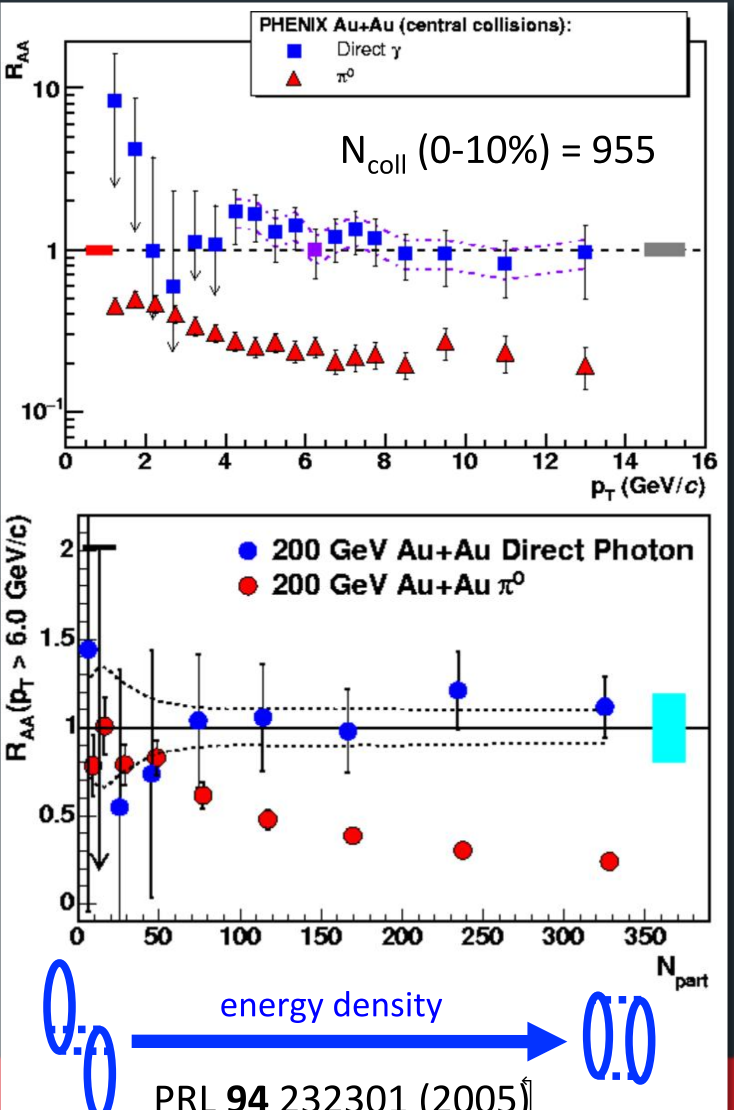
Hard Probes @ RHIC
The Nuclear Modification Factor

- Compare spectra in p+p and A+A ("transmission coefficient")
  - T_{AA} accounts for increased parton flux in A+A

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{T_{AA}\,d^2\sigma_{pp}\,dydp_T} \qquad T_{AA} = N_{coll}/\sigma_{NN}$$

- Observation:
  - Strong suppression for hadrons/jet leading particles
  - No suppression of photons
    - Also produced in hard scattering but electromagnetic probe
    - Proof that hard scattering occurs at the expected rate

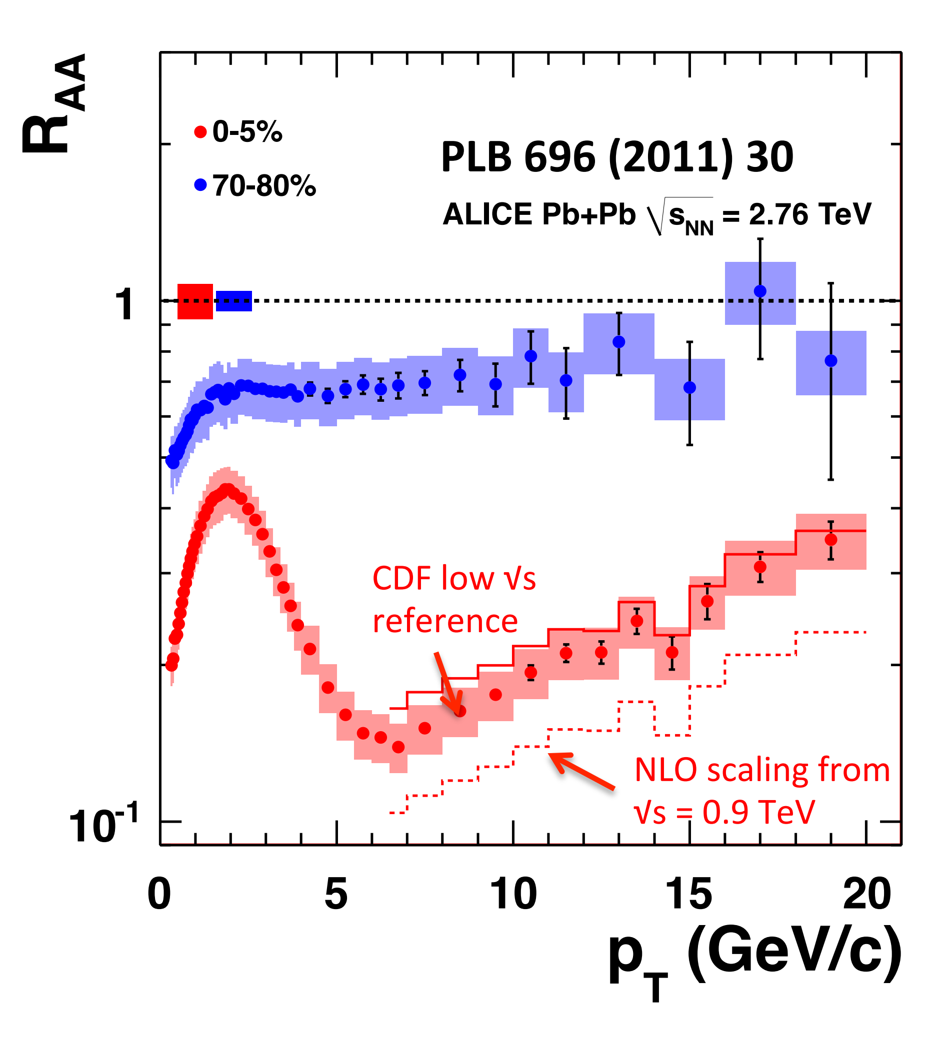
Strong final state effect in central Au+Au



PRL **94** 232301 (2005)

First Nuclear Modification Factor @ LHC

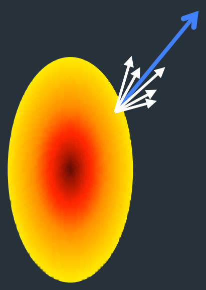
- Peripheral (70-80%)
  - Little suppression
  - Suggesting weak parton energy loss
- Central (0-5%)
  - Pronounced peak at 0-5 GeV
  - Reflects change of shape in central Pb+Pb (exponential/thermal)



Significant suppression in central events (up to factor of 7). Significant increase at large p_T

Opaque Medium?

- Worst case, black/white picture
  - Jets are completely absorbed or unmodified
  - R_{AA} would have **no** sensitivity on L-dependence
  - „Surface limit“

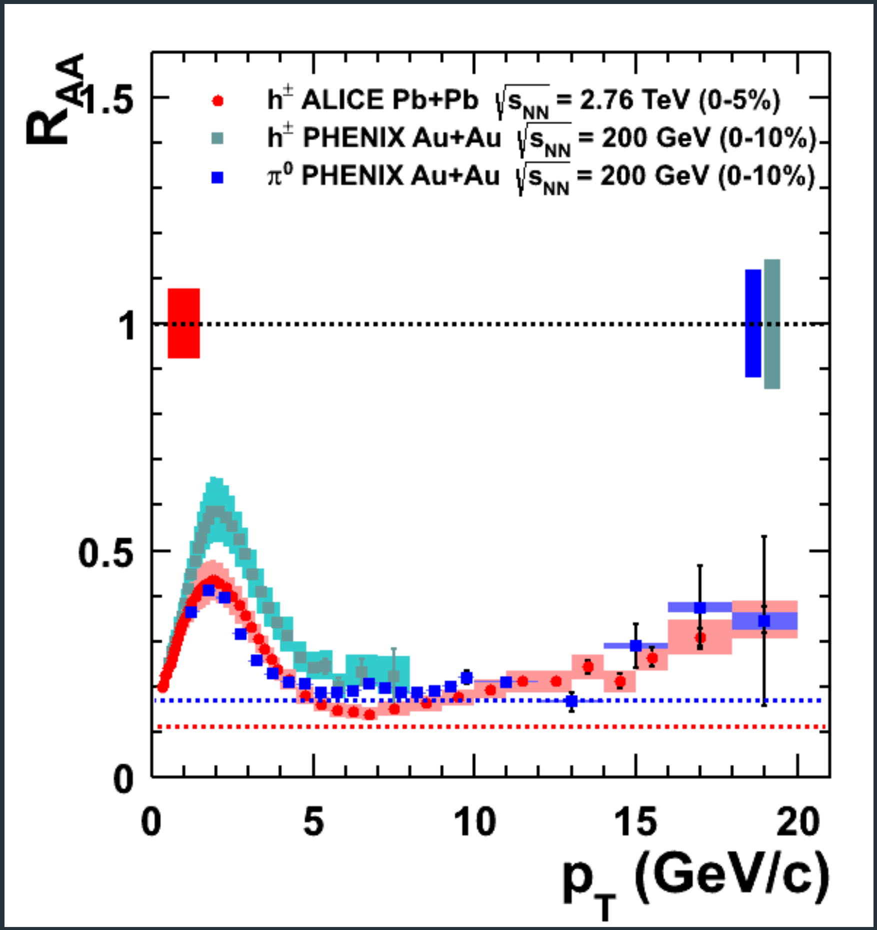


$$R_{AA} \approx \frac{N_{part}}{2 \cdot N_{coll}}$$

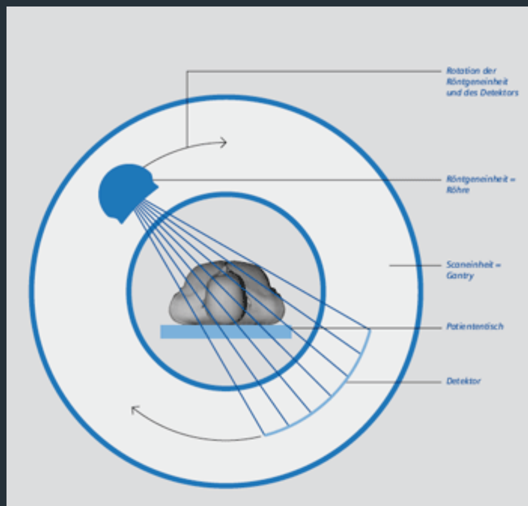
- R_{AA} provides only indirect access to parton p_T

$$\frac{d^2\sigma}{dp_T dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(q, g \rightarrow h)$$

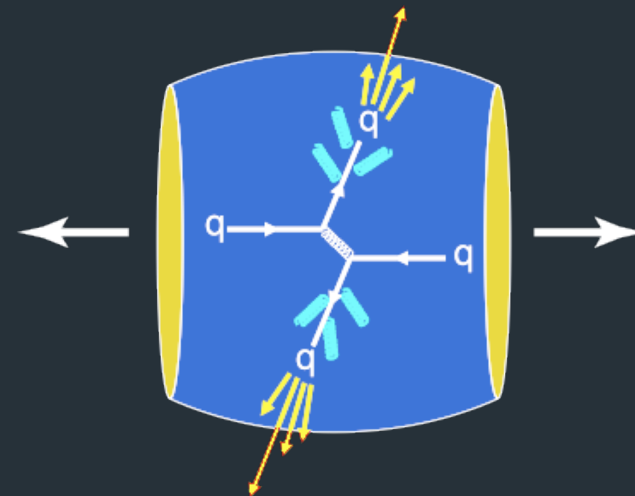
Need broader kinematic reach or reconstructed jets for tighter constraints.



Beyond Discovery: Imaging



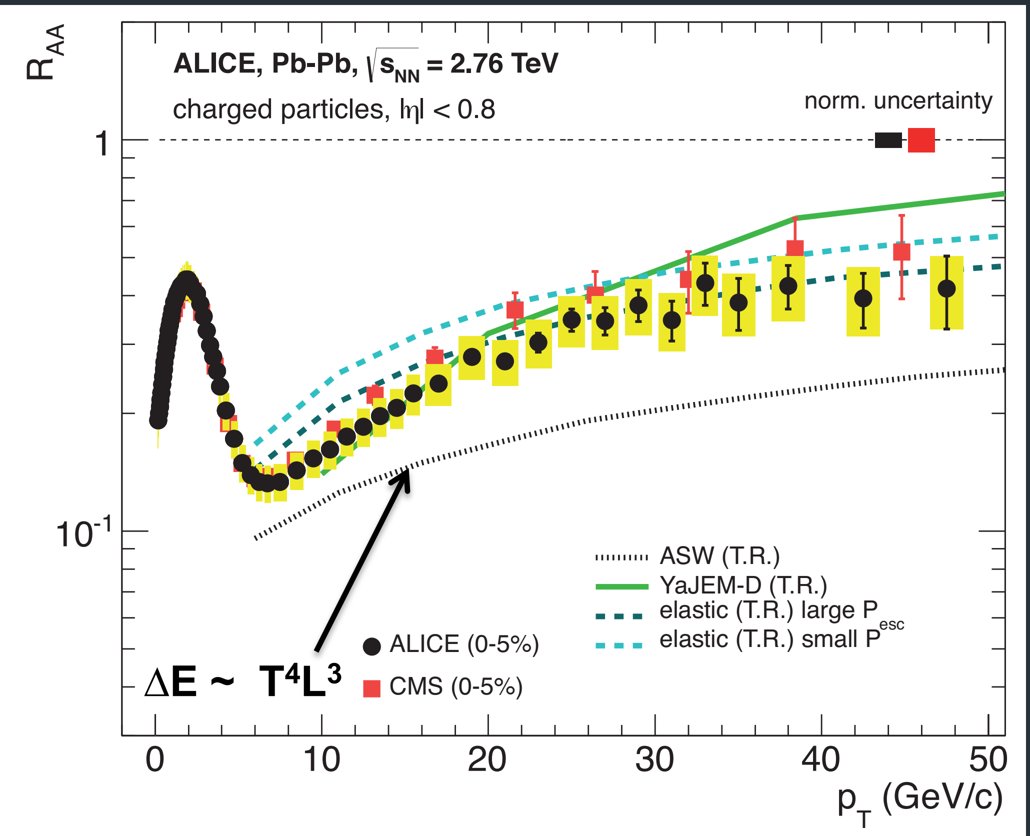
vs.



Some qualitative differences

- Medium interaction processes not exactly known
  - Elastic: Δ**E ~ L**, gluon-bremsstrahlung: Δ**E ~ L²**, AdS/CFT: Δ**E ~ L³**
- Medium expands with v > 0.5 c
- Origin (and momentum) of probe only known on average

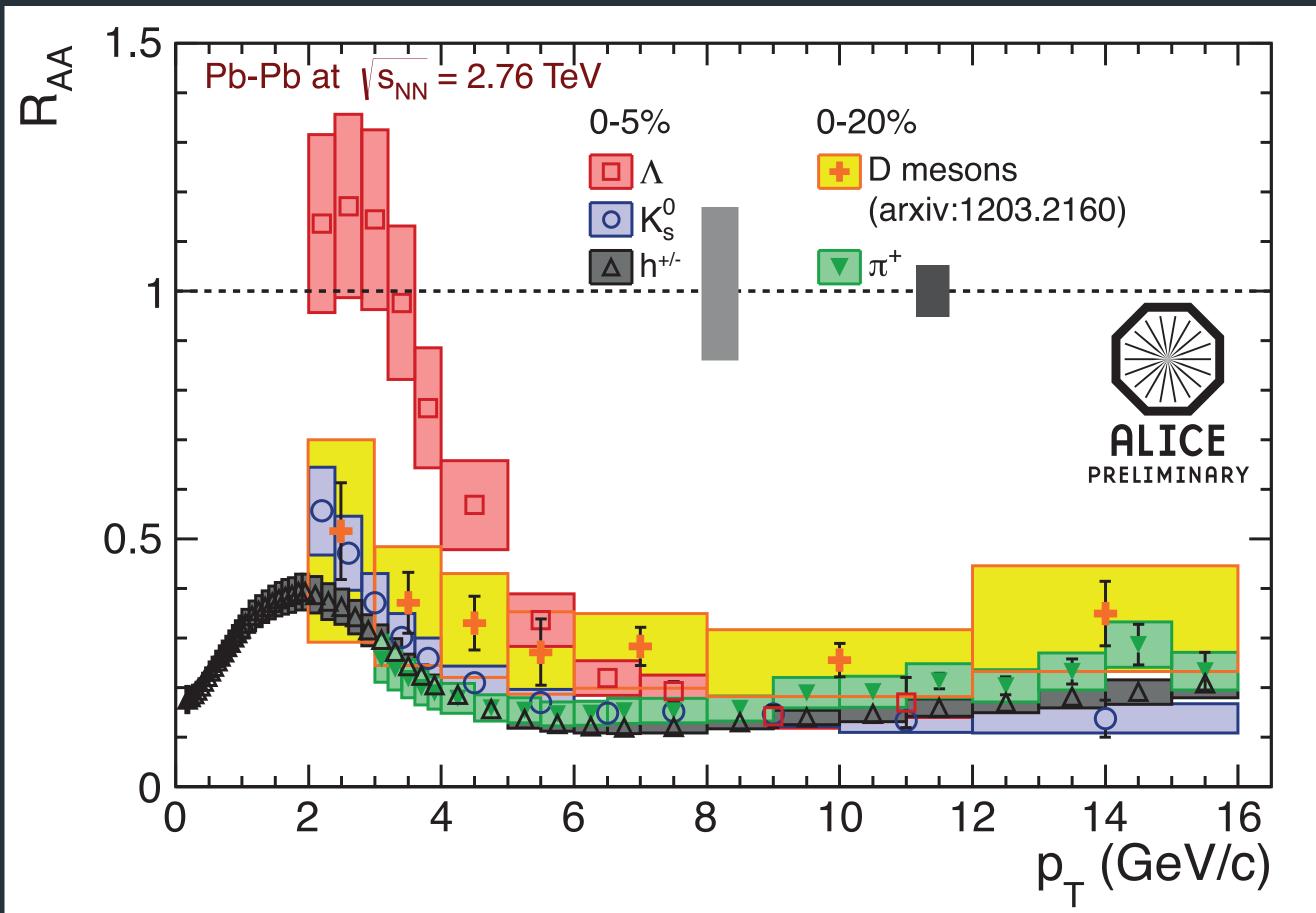
The Kinematic Lever Arm



- Models tuned to RHIC data
  - Identical expansion model Renk PRC85 044903 (2012)
  - LHC-extrapolation: Test of T-dependence
- Flattening of R_{AA}
  - Generic property of all models
- LHC data favor
  - $\Delta E \sim T^3L^n$ **(n ≤ 2)**

Further constraint of energy loss scenarios.

Identified Particles



Influence of partonic color charge and mass

$\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b$

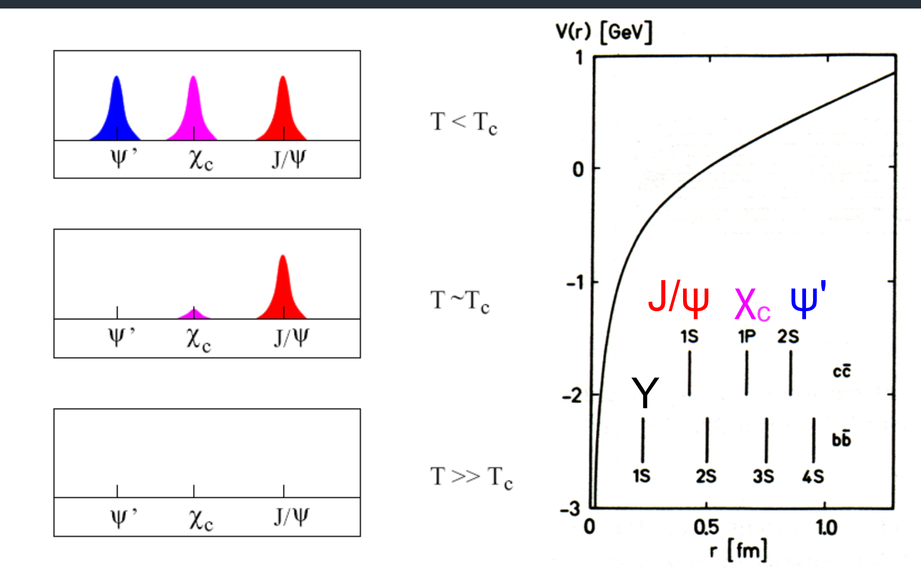
Clear suppression of heavy charm quarks (D-Mesons)

R_{AA} similar for all hadrons above 8 GeV/c.
Some room for mass hierarchy left.

Charmonia

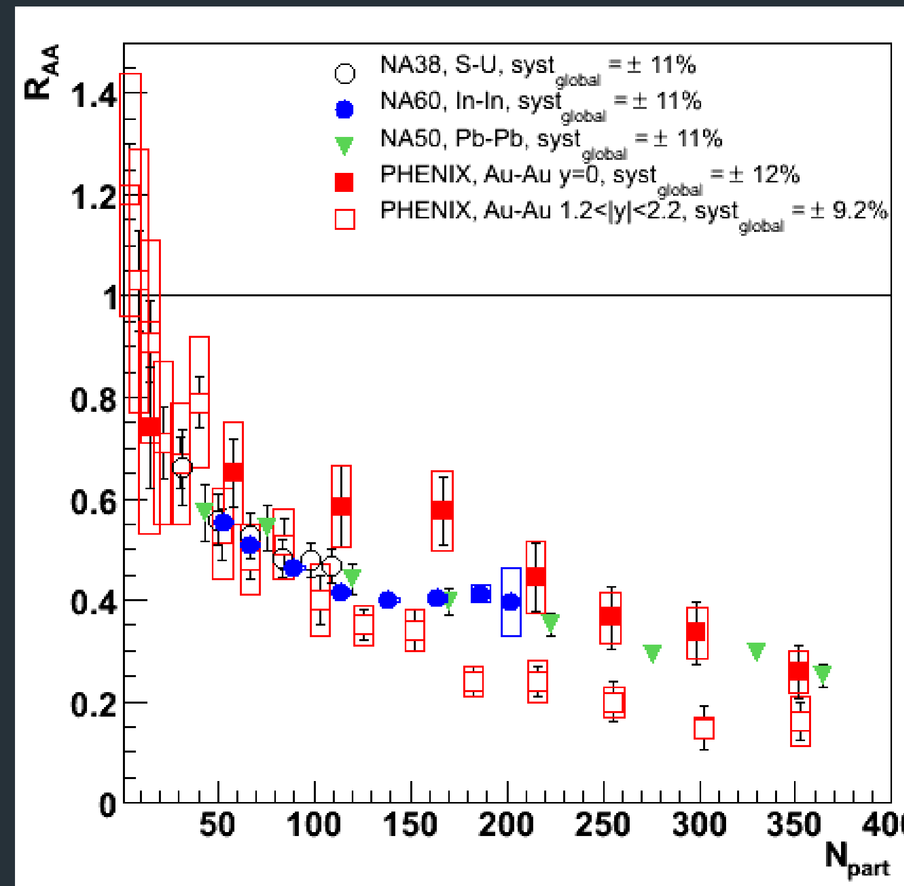
$c\bar{c}$ formed in early hard scatterings

Basic idea (Matsui, Satz PLB 178, 416 (1986)):
color screening modifies strong potential
sequential melting of charmonium states:
Effective thermometer



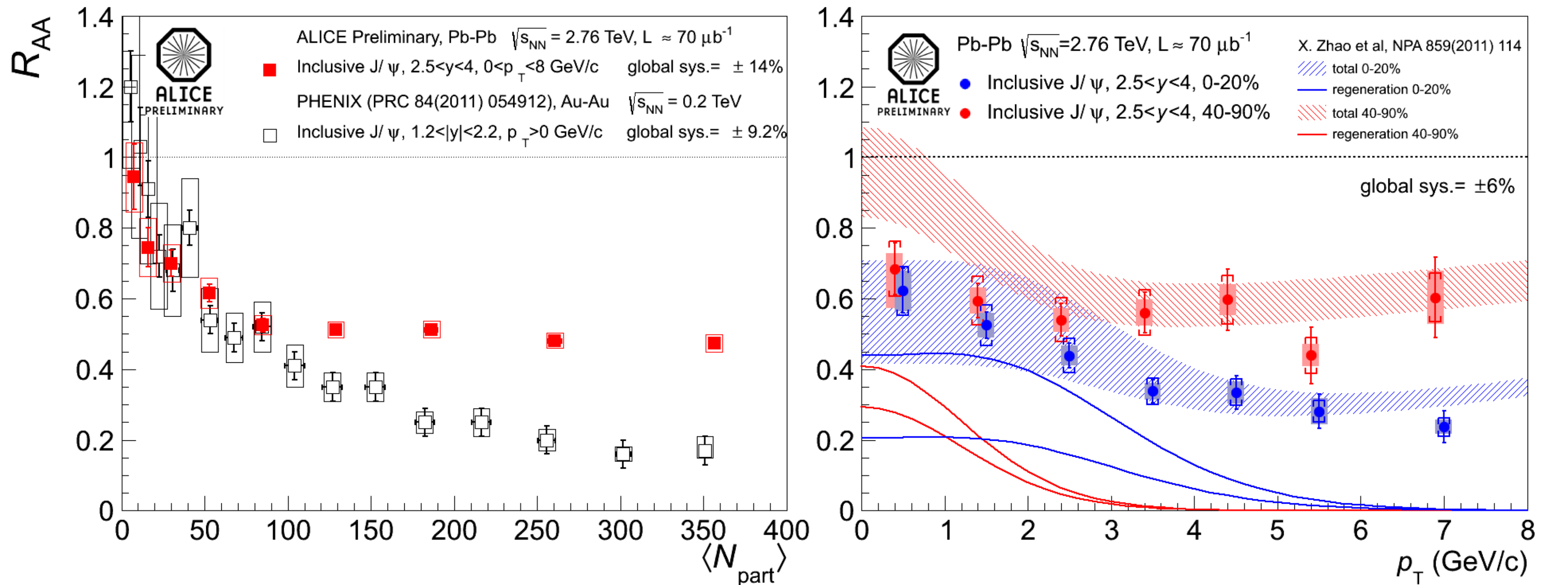
… but more effects need to be taken into account:
cold nuclear matter, recombination

Pre –LHC: Integrated R_{AA}



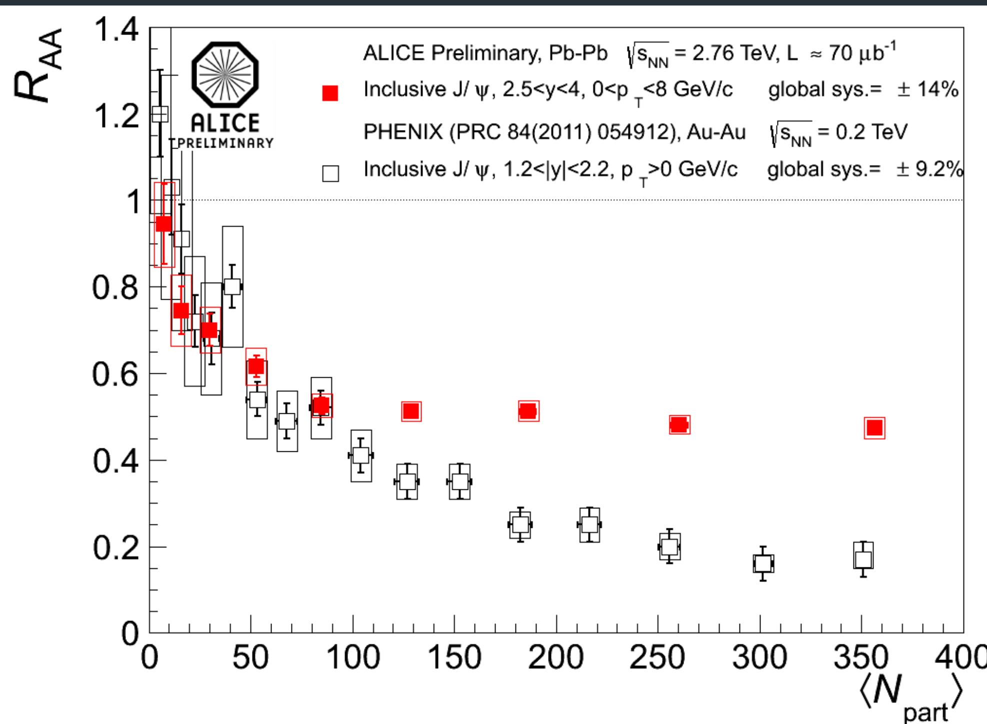
J/ψ suppression at RHIC and SPS.
Similar magnitude at mid-rapidity.

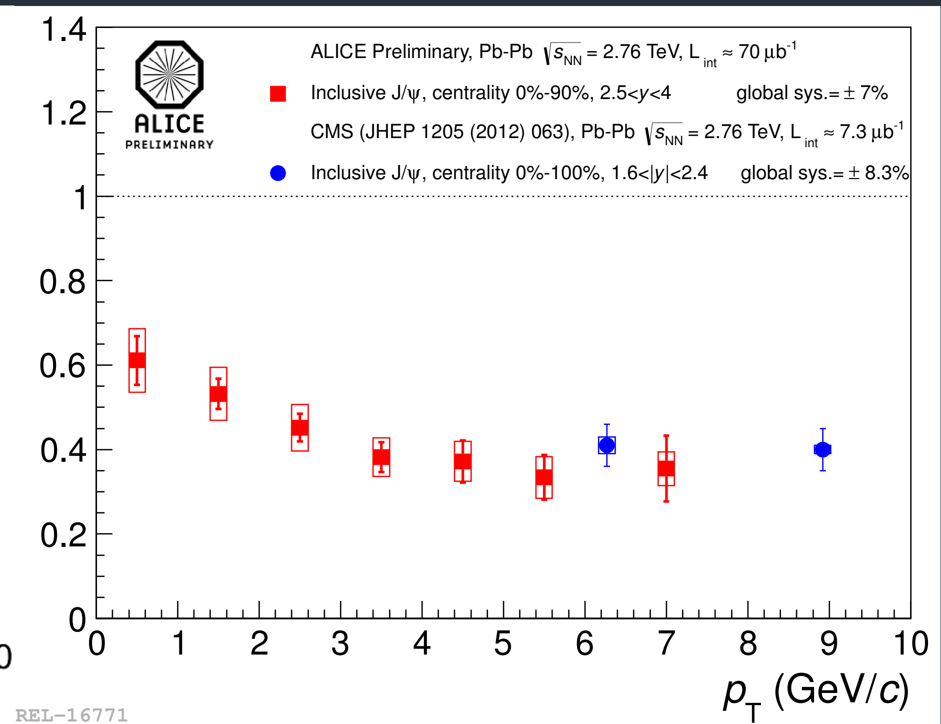
J/ψ at LHC



Rather flat centrality dependence
R_{AA} higher than at RHIC: Clear sign of recombination.
Recombination effects are separable in p_T.

J/ψ at LHC



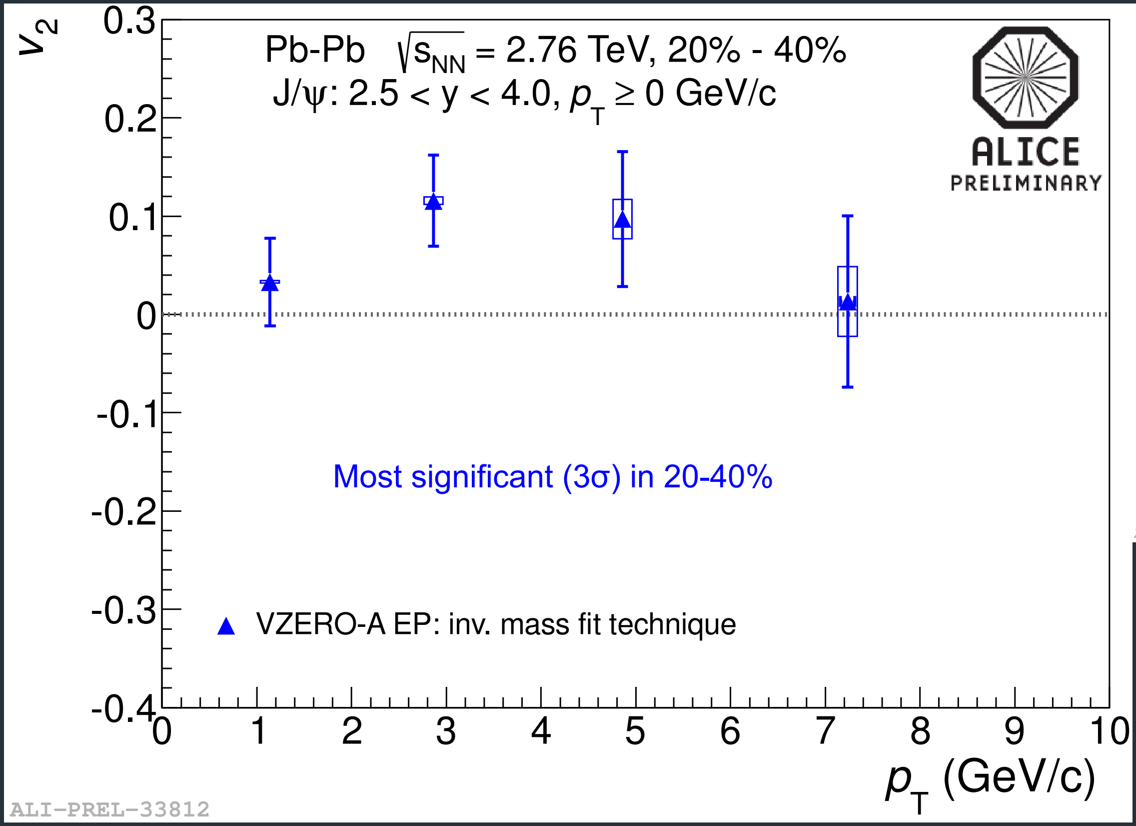


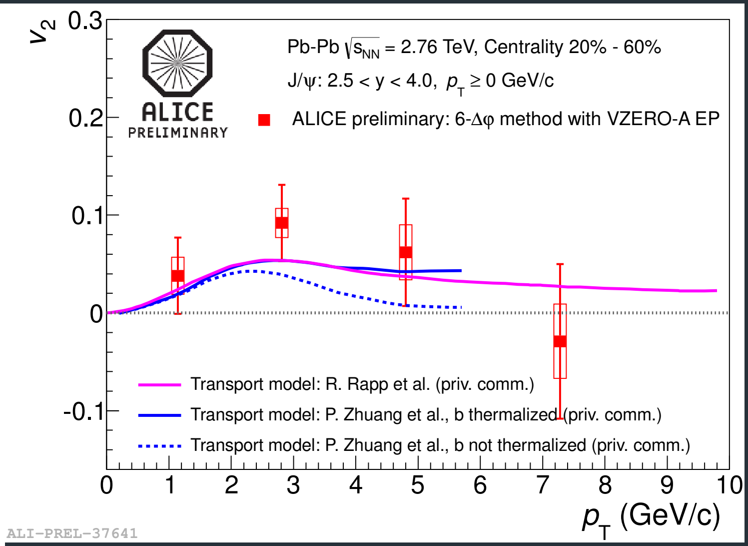
Rather flat centrality dependence

R_{AA} higher than at RHIC: Clear sign of recombination.

Recombination effects are separable in p_T. Higher p_T trend confirmed/extended by CMS.

J/ψ Elliptic Flow

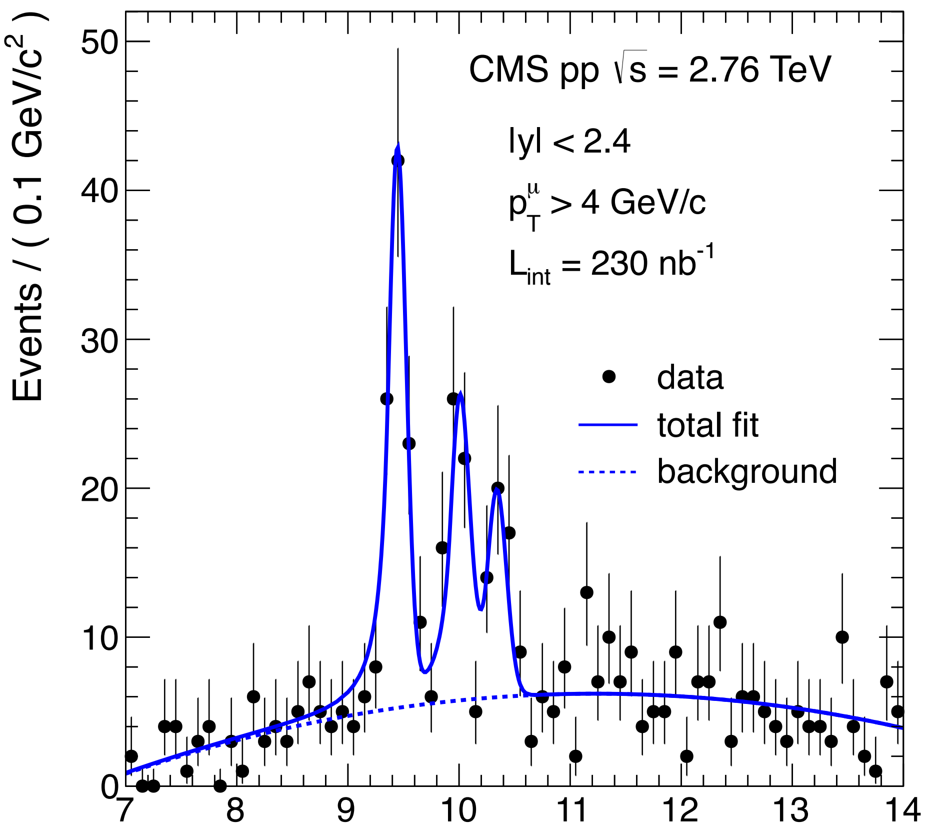


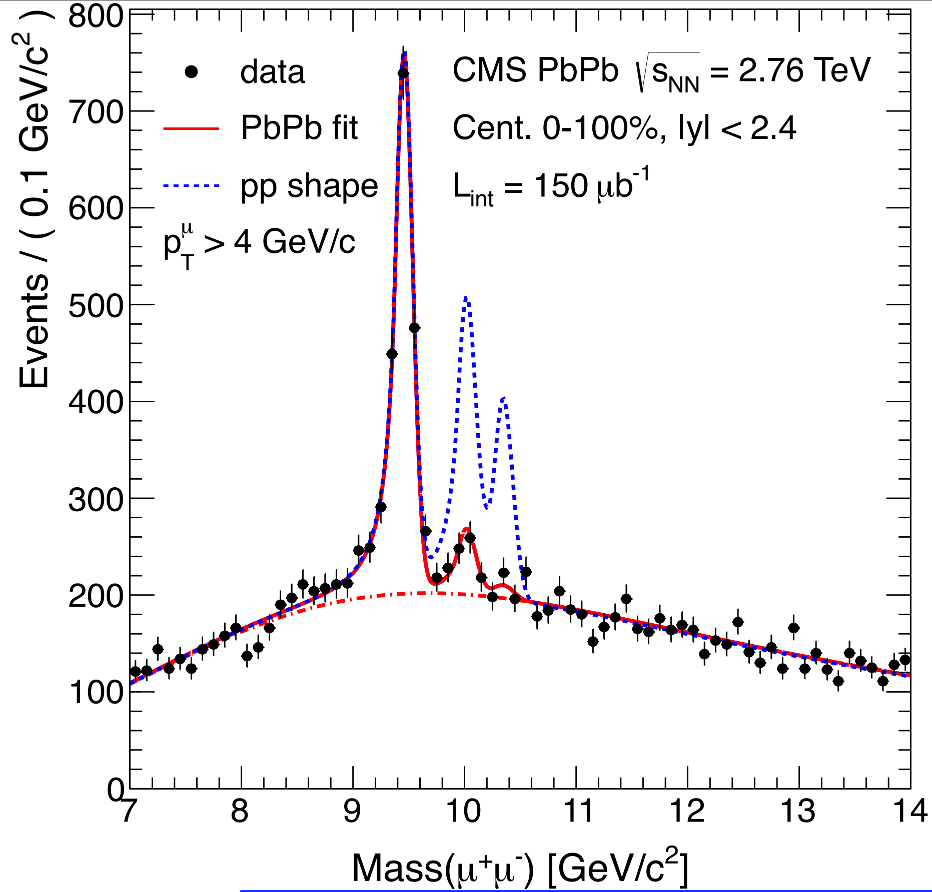


Models with large recombination (50%) and thermalized charm can account for magnitude.

First indication of J/ψ flow.
Hint for partially thermalized charm quarks.

Bottomium @ LHC





CMS: arXiv:1208.2826

CMS observes sequential suppression of bottomium states.

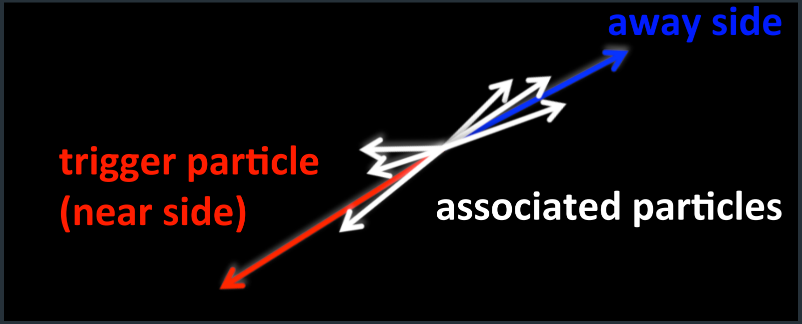
$$
\begin{aligned}
R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.})\\
R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.})\\
R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04\,(\text{stat.}) \pm 0.01\,(\text{syst.})\\
&< 0.10 \quad (95\%\ \text{C.L.}).
\end{aligned}
$$

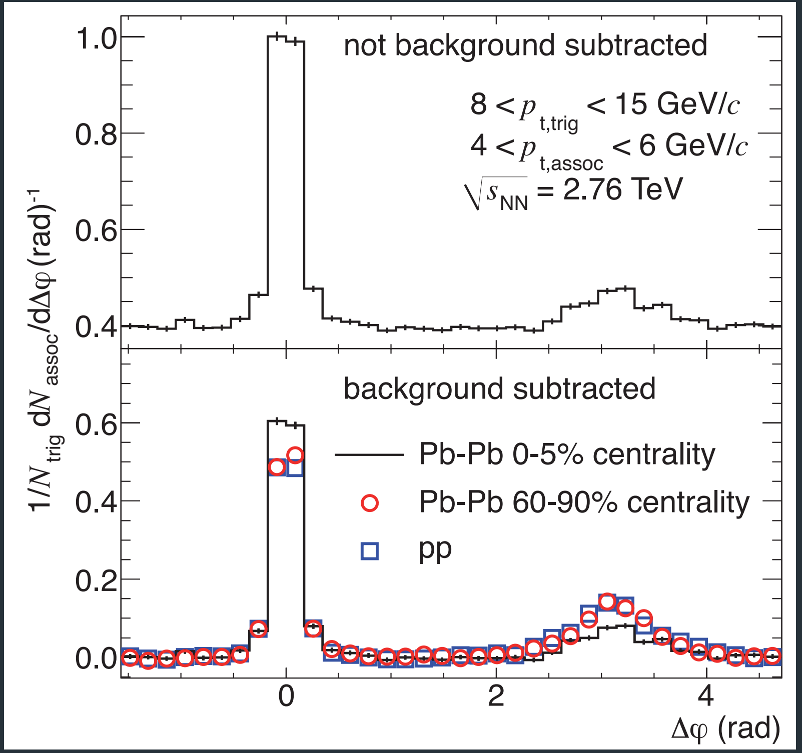
Two Particle Correlations: Jet Particle Yield

- Simple and clean way to access di-jet fragmentation
  - But no direct access to parton energy
- Non-jet component (baseline) needs to be removed
  - No known assumption-free methods
- Measure in high p_T a region where the signal dominates over pedestal and v_2 modulation (8 GeV/c < $p_{T,trig}$ < 15 GeV/c)
- Near and away-side jet yields from per-trigger yields
  - Compare Pb-Pb and pp
  - More associated yield on the near side, less on the away side
  - Quantify

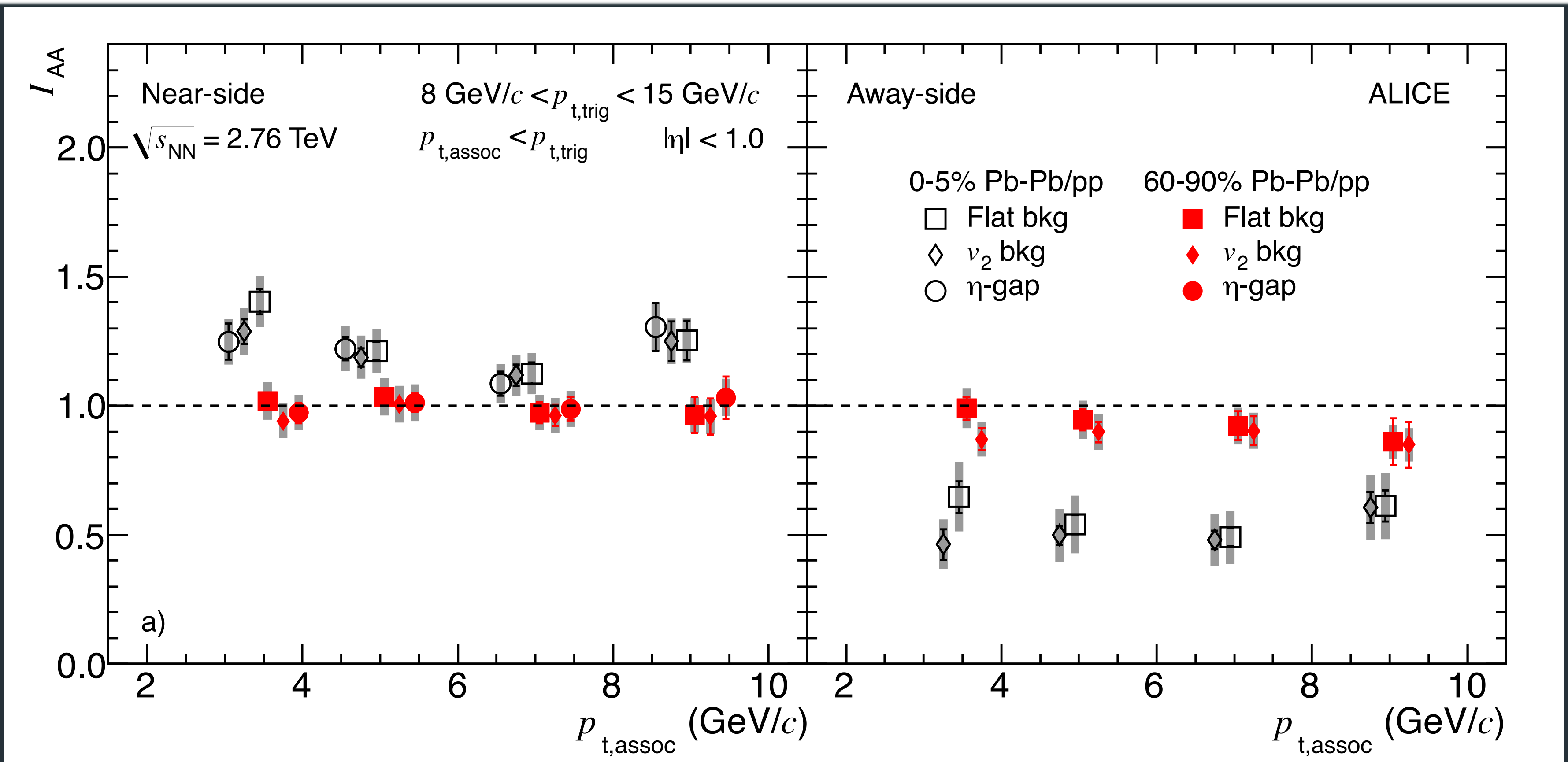
$$I_{AA} = \frac{Y^{AA}}{Y^{pp}}$$

Clear back-to-back jet structure above background allows to extract per jet yield.
Background subtraction essential.





Modification of Jet Particle Yield

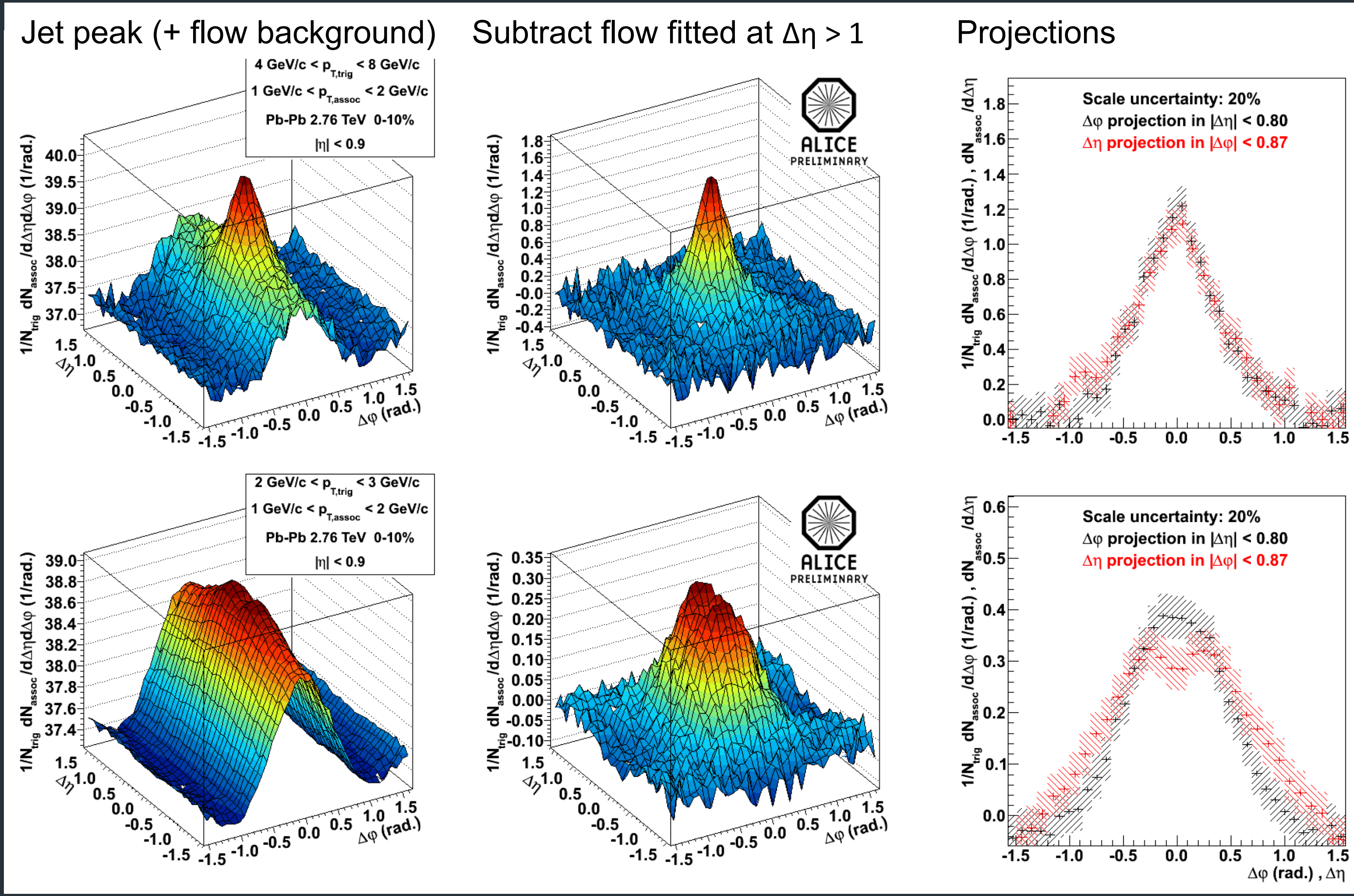


Peripheral: Consistent with unity for near and away side

Central: **First observation of enhanced near-side: $I_{AA} \approx 1.2$, probing different parton p_T/flavor in pp and Pb-Pb?**
Away-side suppressed: $I_{AA} \approx 0.6$, expected from in-medium energy loss.

Near-Side Jet Shape 1

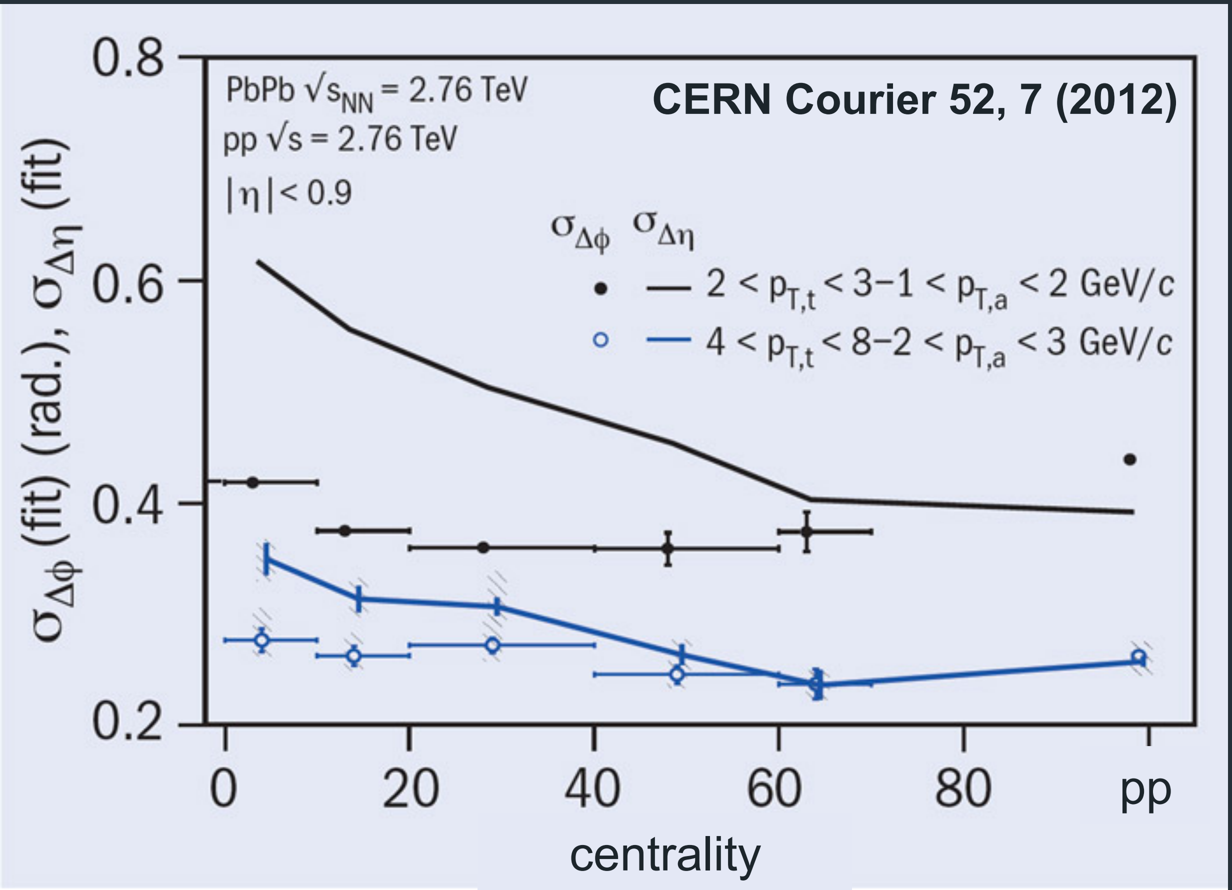
ΔηΔϕ Correlation



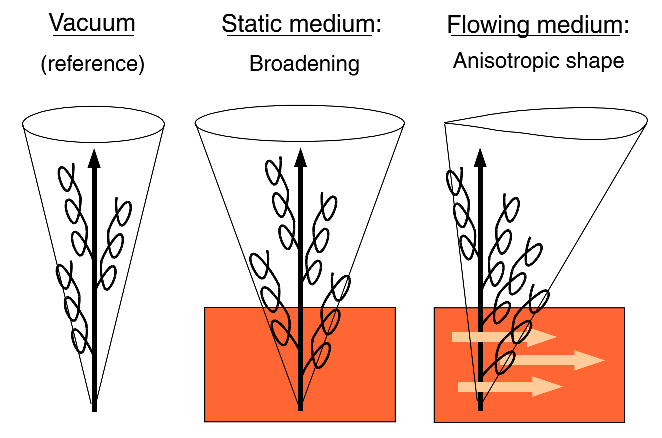
Higher p_T trigger: Same width in Δη and Δφ

Lower p_T trigger: Δη correlation broader than Δφ

Near-Side Jet Shape 2



Longitudinal flow deforms jet shape



Armesto et al., PRL 242301 (2004)

Significant increase of longitudinal width towards central collisions (eccentricity 20%).
Direct impact of flowing medium on jet shape.

Accessing Hard Probes

Bottom-Up: Particles
> Spectra at high p_T
> Leading particles
> Identified π, K, p, η
> Particle correlations

Top-Down: Reconstructed jets
> Spectrum
> Angular distribution
> Jet fragmentation

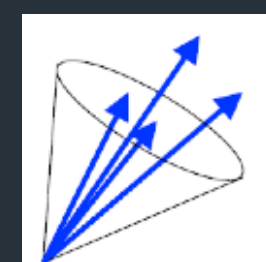
± Underlying Event

single particles

detailed fragmentation

jet like properties

fully reconstructed jets



Jet-like properties:
> Spectral shape, back-to-back correlation

A+A: large background level, fluctuations
soft ⊗ hard

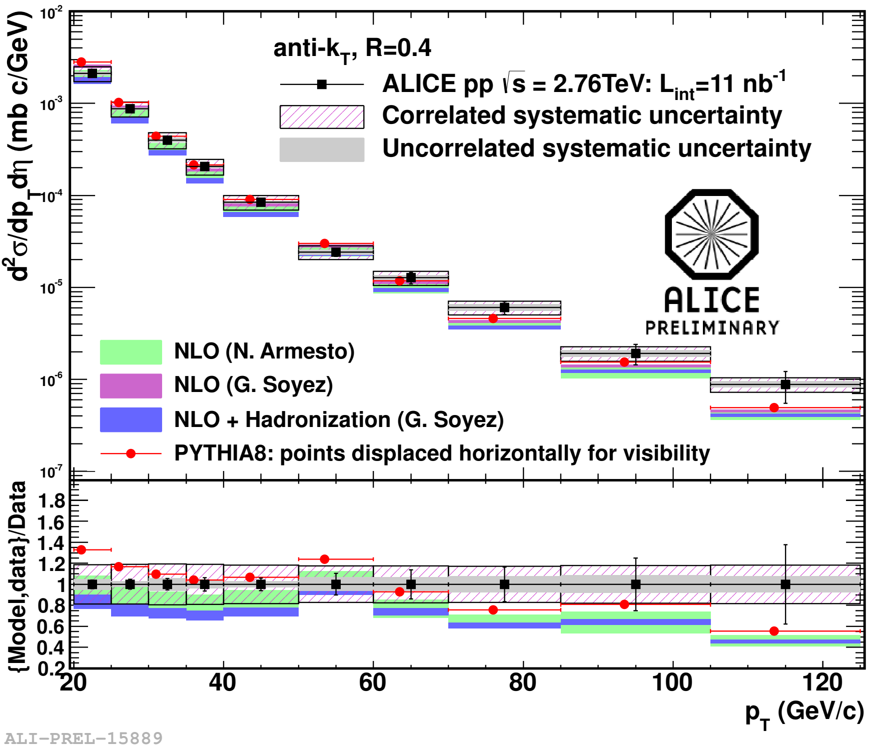
Experimentally clearly defined.
Bias: hard fragmentation, surface.

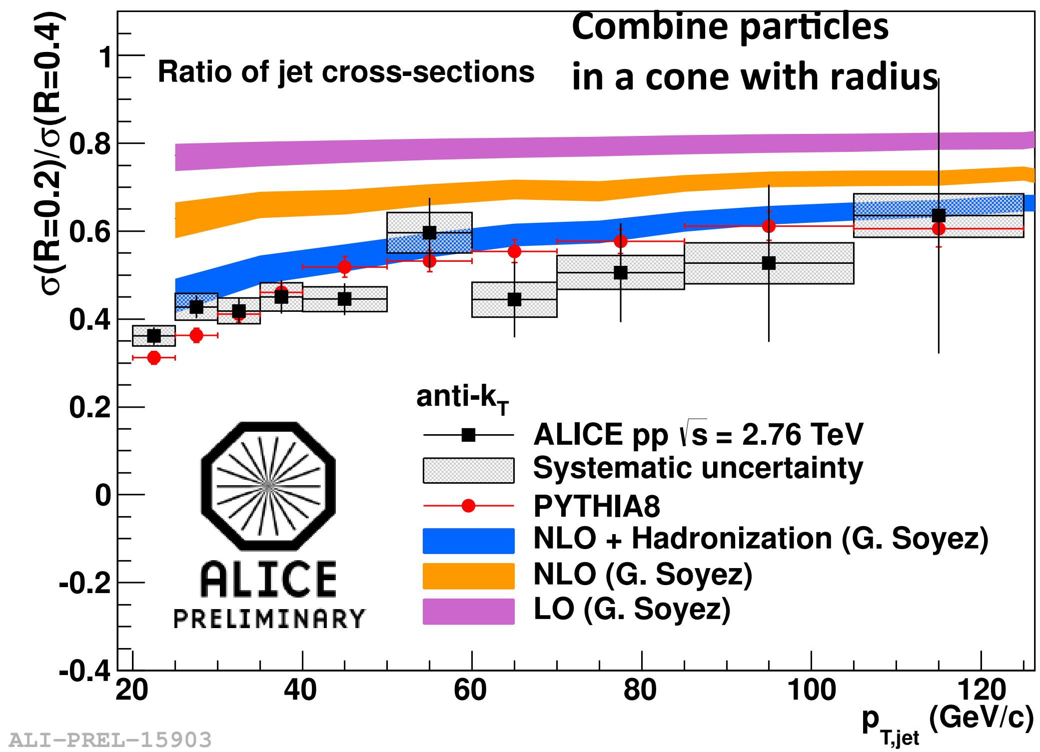
Related to theoretically well defined parton properties.

Jets in pp

Fully reconstructed jets in pp
Tracking + EMCal

Varying jet size via distance parameter
$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ tests jet shapes

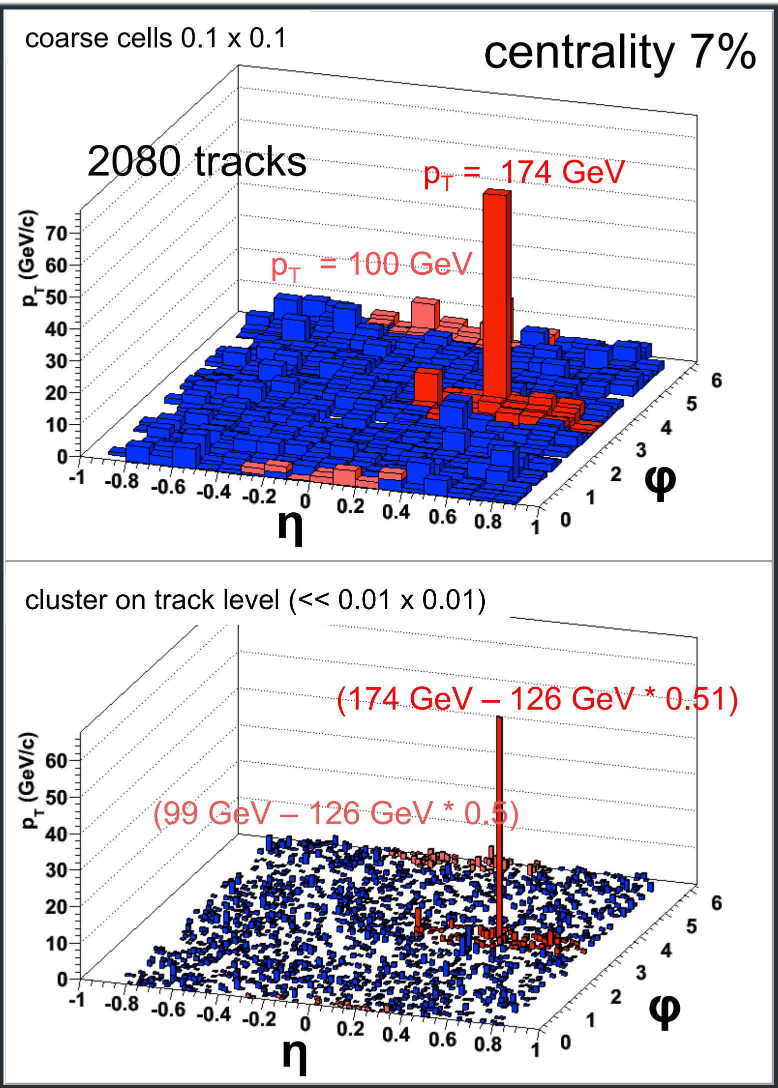




Good agreement between date and NLO/Generators.
Basis for Heavy Ion Reference.

Jet Finding in Pb-Pb

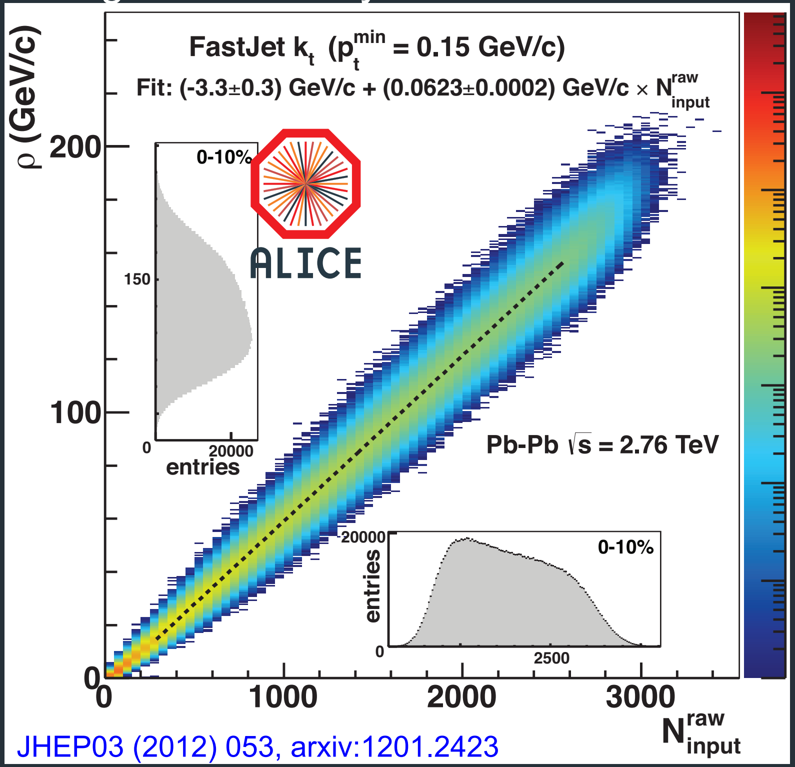
- Focus on sequential recombination
  - FastJet (Phys. Lett. B **641** (2006) 57)
  - k_T: background density
  - anti-k_T: stable area, signal jets
- Here: Clustering on **particle level**
  - ALICE TPC: high precision, uniform ηφ-efficiency
- Low momentum cut off **(150 MeV)**
- Stronger affected by background but essential for understanding of energy dissipation



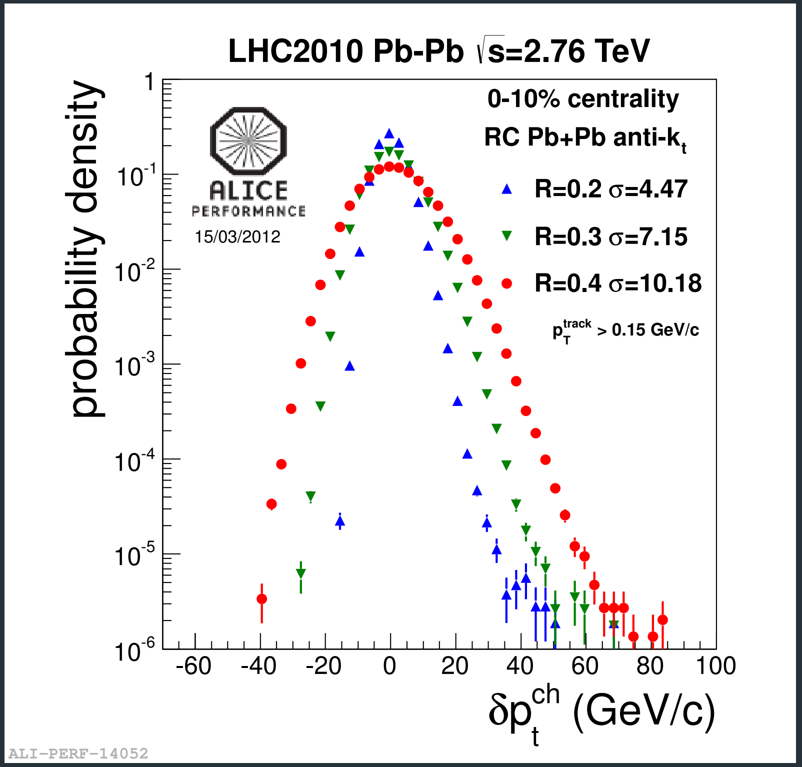
Minimize bias on hard fragmentation and unquenched jets.
Resolve the detailed structure of jets and jet background sources.

Impact of Background and its Fluctuations

Event wise median of background density



Background fluctuations, regional deviations from median



Induced by: Statistical fluctuations, flow, (mini) jet overlap

For R = 0.4 and central event, typical background ≈ 70 GeV/c.
Typical fluctuations σ ≈ 11 GeV/c.

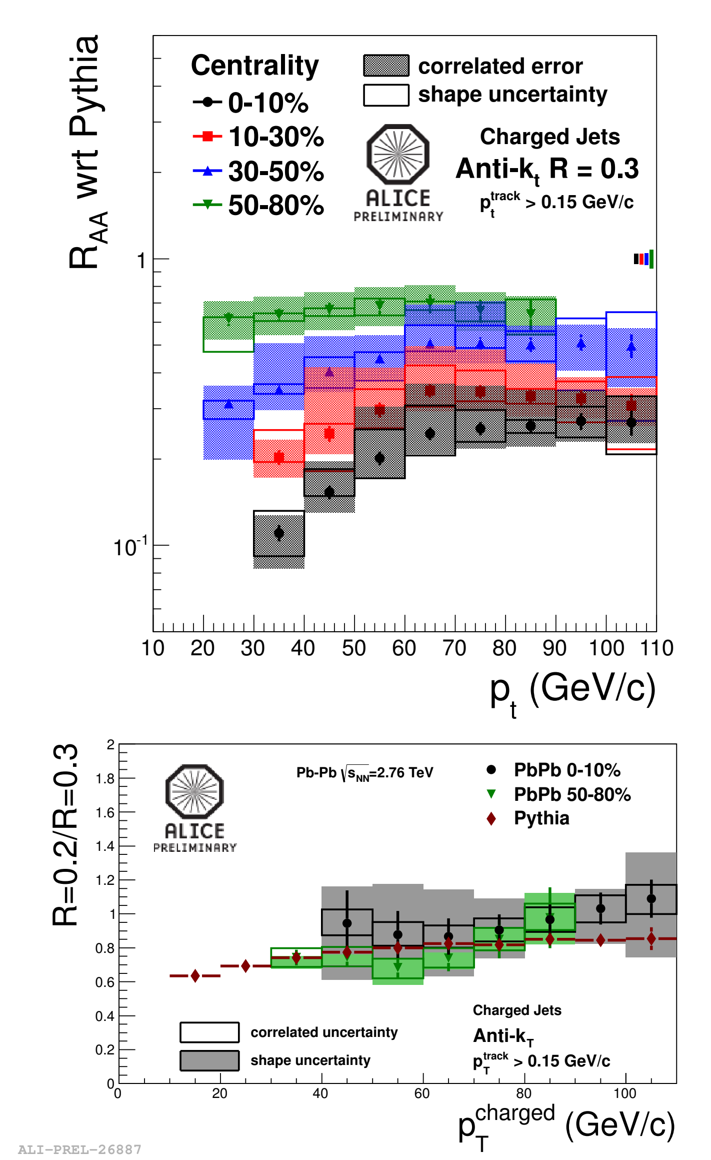
ALICE Jet-R_{AA}

- First jet-R_{AA} with charged particles
  - pp reference based on simulation
  - R_{AA} < 0.4 in central collisions

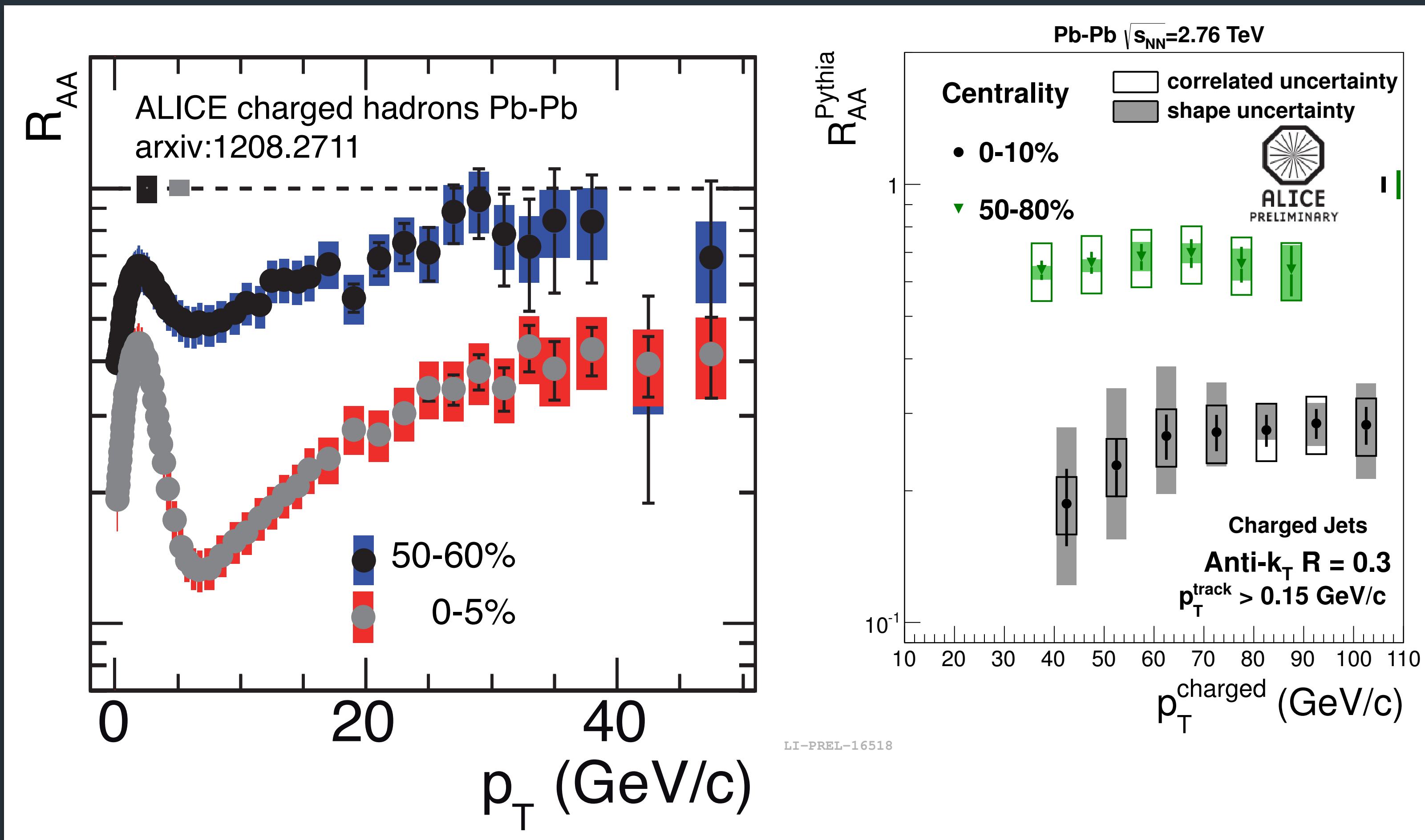
- No significant redistribution of energy from R = 0.2 to R = 0.3 observed

- Next steps:
  - Momentum distribution in jets
  - Lost energy outside of jet cone, larger radii

pp jet-energy not recovered, despite low p_T cut. Points towards a change in angular distribution of jet particles.

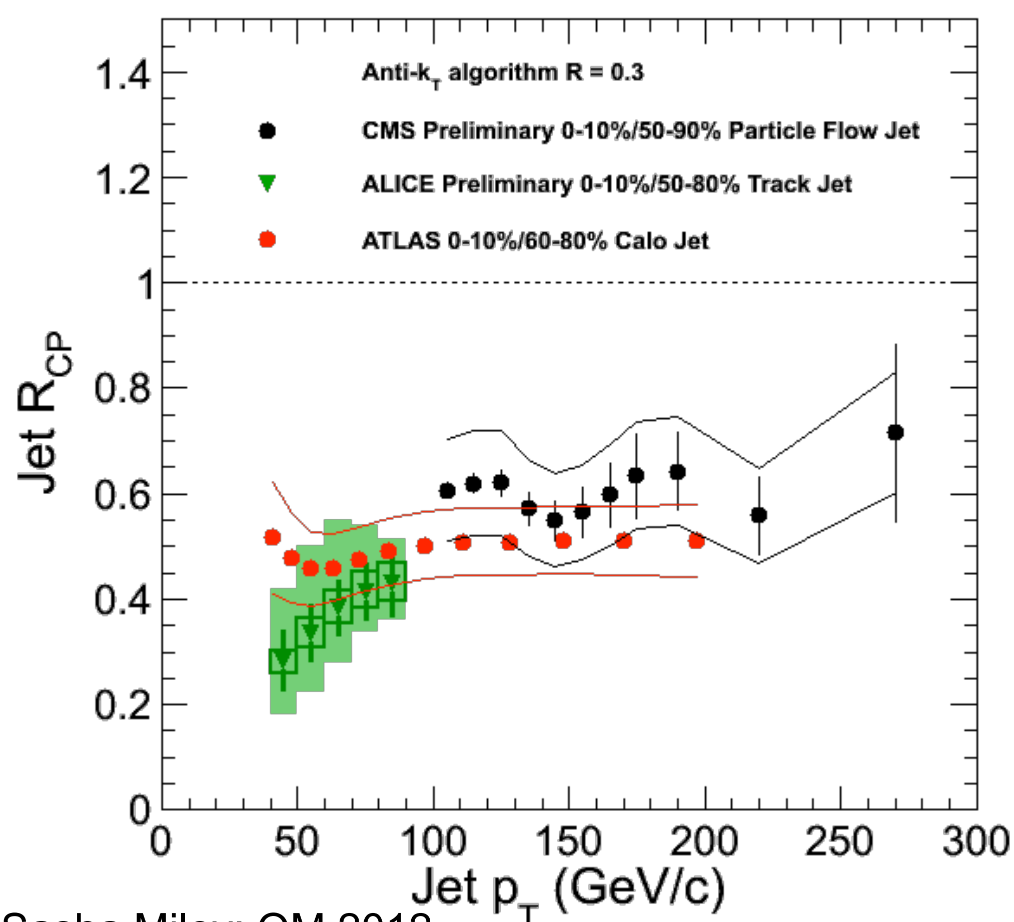


Hadron vs. Jet R_{AA}



Comparable suppression pattern and magnitude for hadrons and charged particle jets.

R_{CP} LHC-Comparison



Sasha Milov: QM 2012

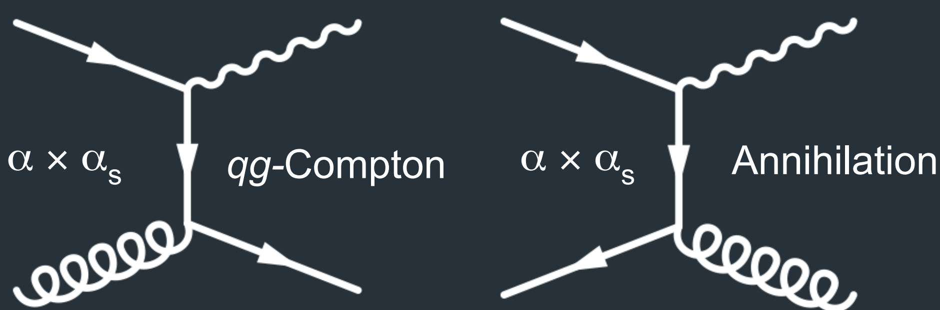
- N.B. different
  - Jet constituent objects
  - Momentum cut-offs
  - Treatment/suppression of UE background fluctuations

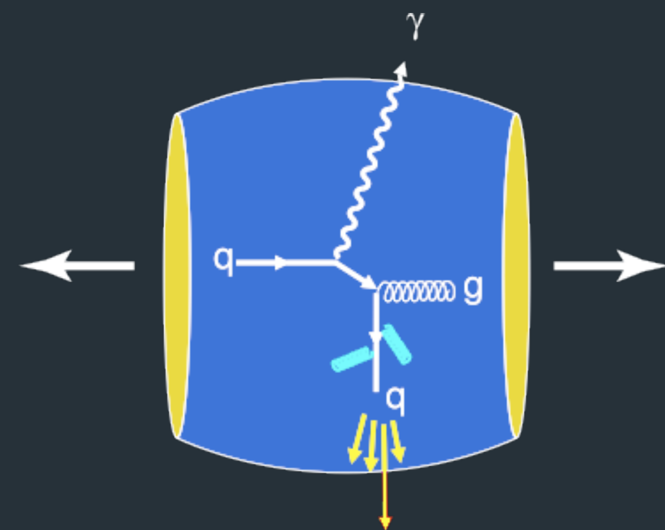
Similar message from all LHC experiments: Jets are strongly suppressed over a broad p_T range.
Details will provide new insight.

Control Measurement: Direct Photons

- Direct: Not originating from hadronic decays (mainly $\pi^0 \to \gamma\gamma$)
  - At high p_T also produced in hard parton scatterings
  - Not affected by strong interaction

LO

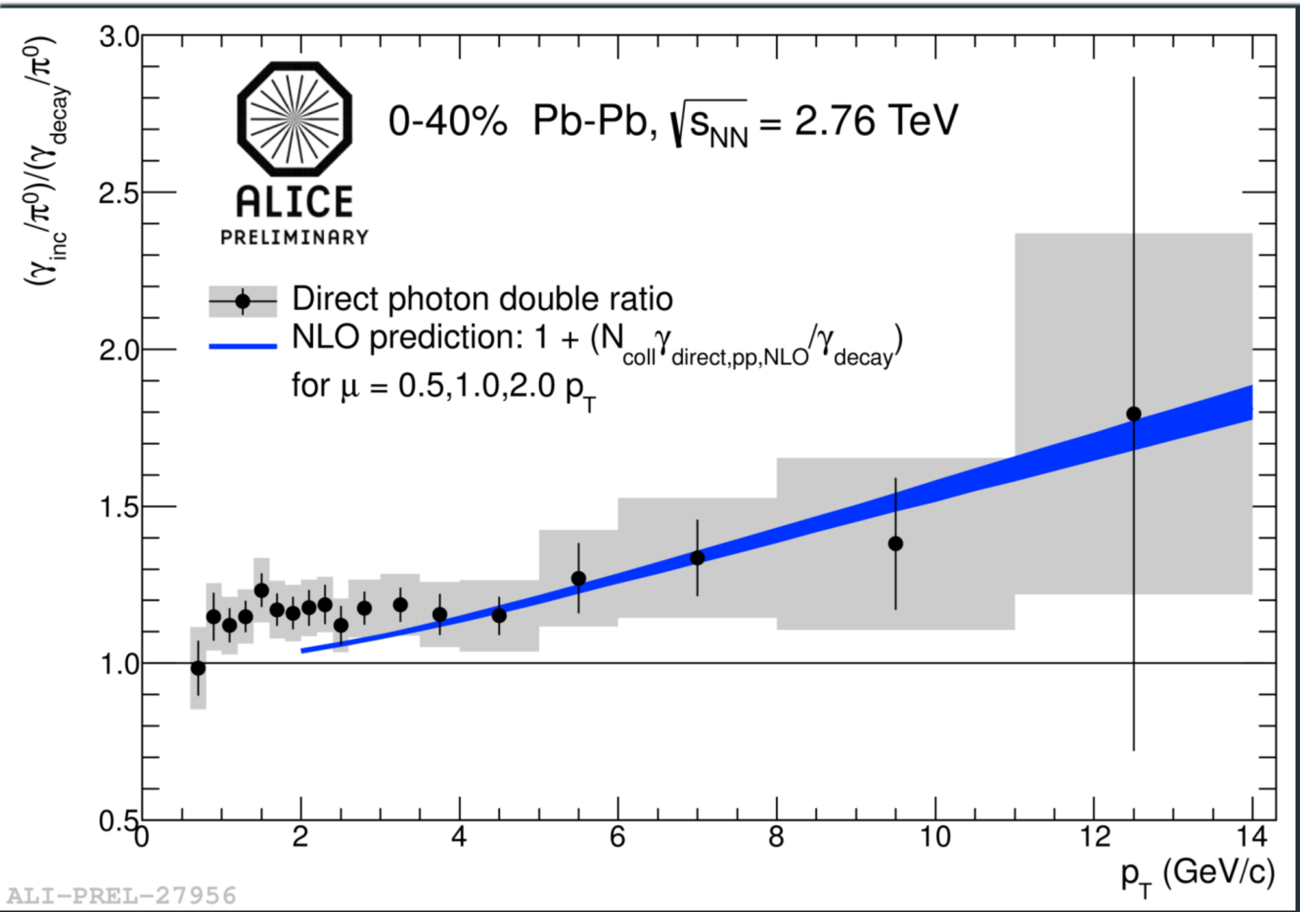




$$\frac{d^2\sigma}{dp_T dy} = \int \mathbf{PDF} \times \mathbf{pQCD} \times \delta$$

- Direct control of N_{coll} scaling in A+A
  - In LO no fragmentation component

Direct Photons

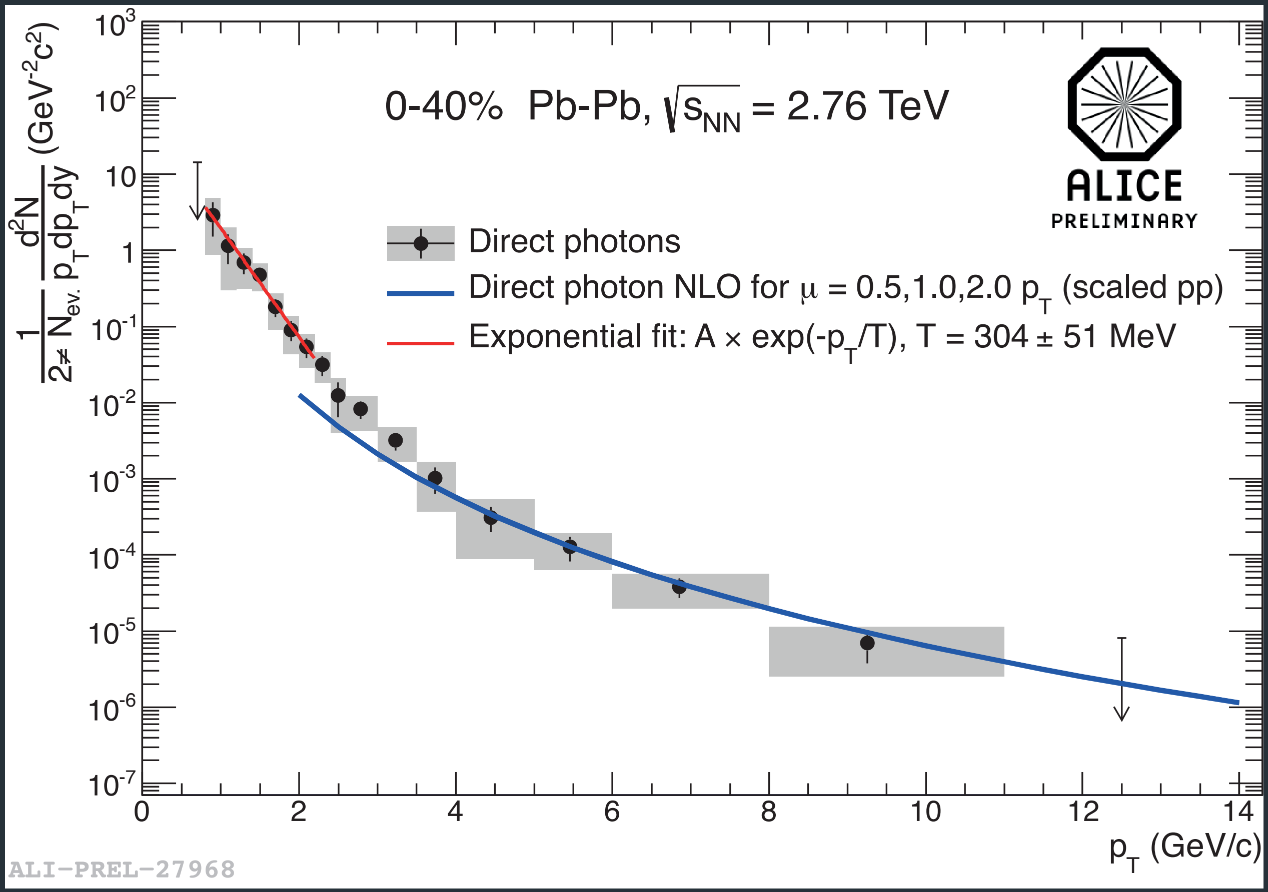


Comparison of all photons to photon decay expectation (mainly $\pi^0 \rightarrow \gamma\gamma$).

Hadron suppression helps S/N.

p_T > 4 GeV/c follows scaled NLO expectation:
Color neutral probes are not suppressed, similar results for p_T > 20 GeV from CMS/ATLAS
Hard scattering occurs at expected rate. ALICE measures 20% excess at low p_T.

Direct Photon Spectra



Exponential fit for p_T < 2.2 GeV/c
inv. slope T_{LHC} = 304 ± 51 MeV

PHENIX: T_{RHIC} = 221 ± 27 MeV*
0-20% Au-Au at $\sqrt{s_{NN}}$ = 200 GeV

*PHENIX PRL 104:132301 (2010)

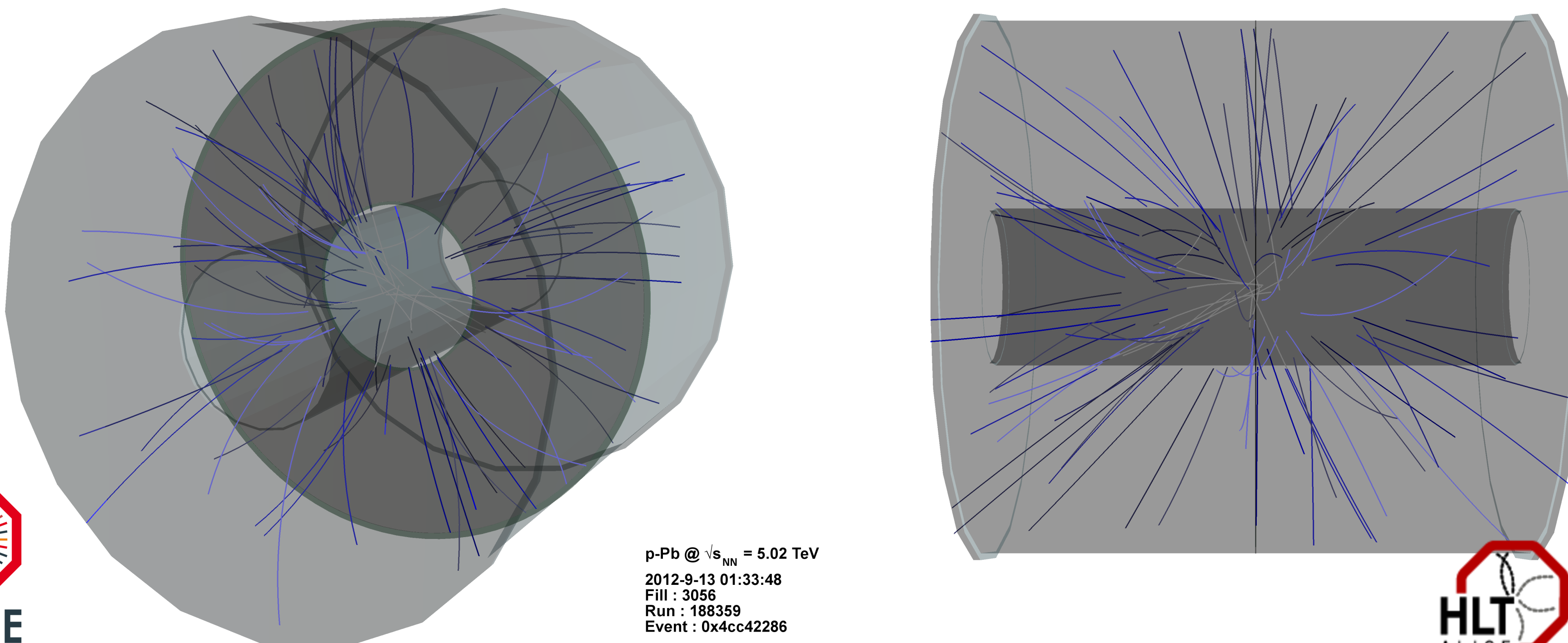
First indication of thermal radiation at LHC.
Average slope ≈ 40% higher than at RHIC.

Conclusions

- A new era for QGP study just started at LHC
  - Factor 3 more initial energy density
  - Photons point to more than 300 MeV initial temperature
  - Hint for onset of charm thermalization
  - Medium modification of jet shapes
  - Suppression of reconstructed jets

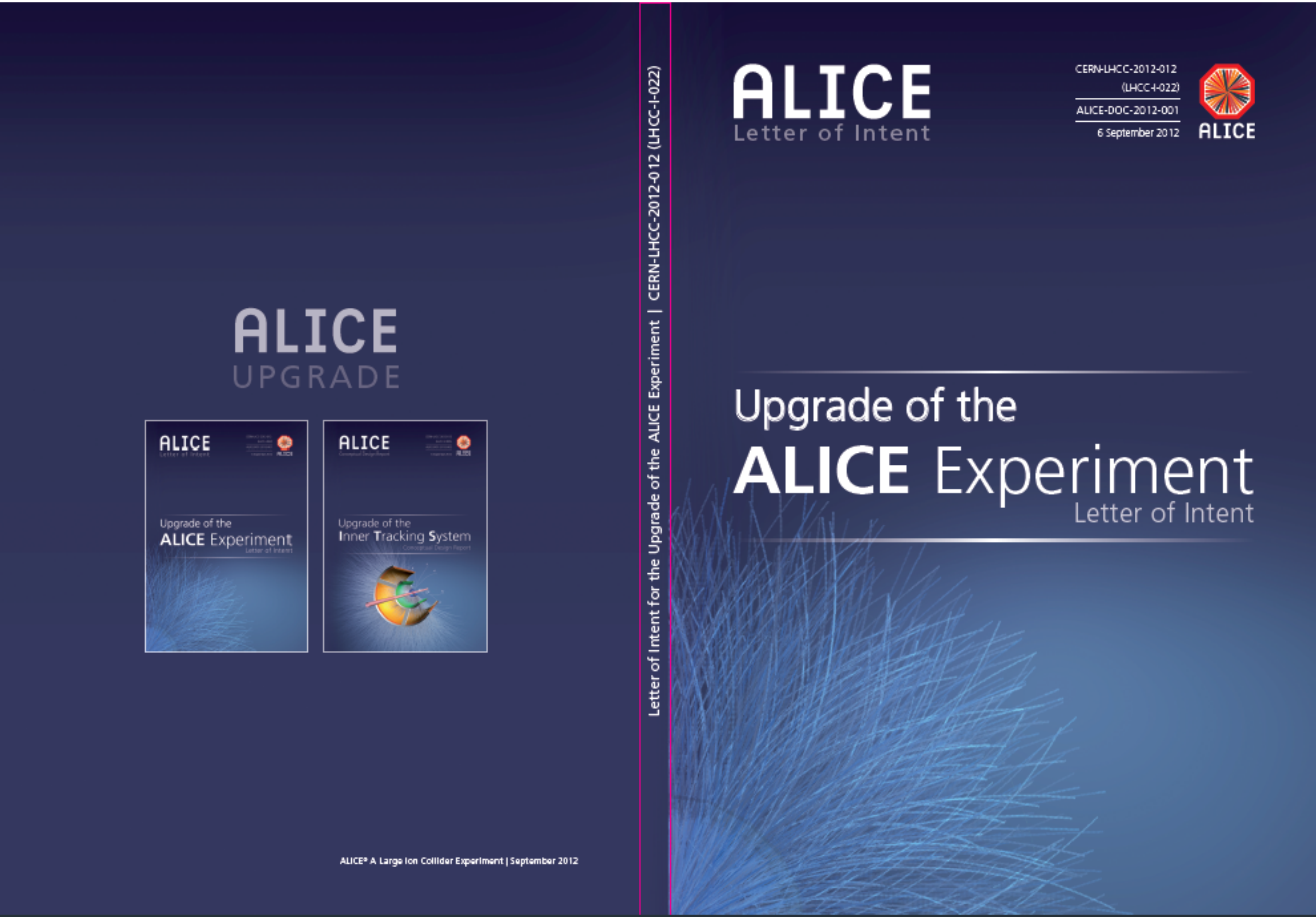
- Going from discovery to precision:
  - Experimental complementarity
    - ALICE and CMS/ATLAS @ LHC
    - Continuing RHIC program
  - Reference measurements (p+A pilot run yesterday!)
  - Hand-in-hand with theoretical progress
    - Away from idealized/averaged descriptions, adding hadron transport, event-by-event fluctuations of initial conditions, CGG, Glasma etc.

First p-Pb Collisions from Last Night!



ALICE
A JOURNEY OF DISCOVERY

HLT
ALICE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UPGRADE
ALICE
Upgrade of the
ALICE Experiment
ALICE
Upgrade of the
Inner Tracking System
ALICE® A Large Ion Collider Experiment | September 2012
Letter of Intent for the Upgrade of the ALICE Experiment | CERN-LHCC-2012-012 (LHCC-I-022)
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Letter of Intent
CERN-LHCC-2012-012
(LHCC-I-022)
ALICE-DOC-2012-001
6 September 2012
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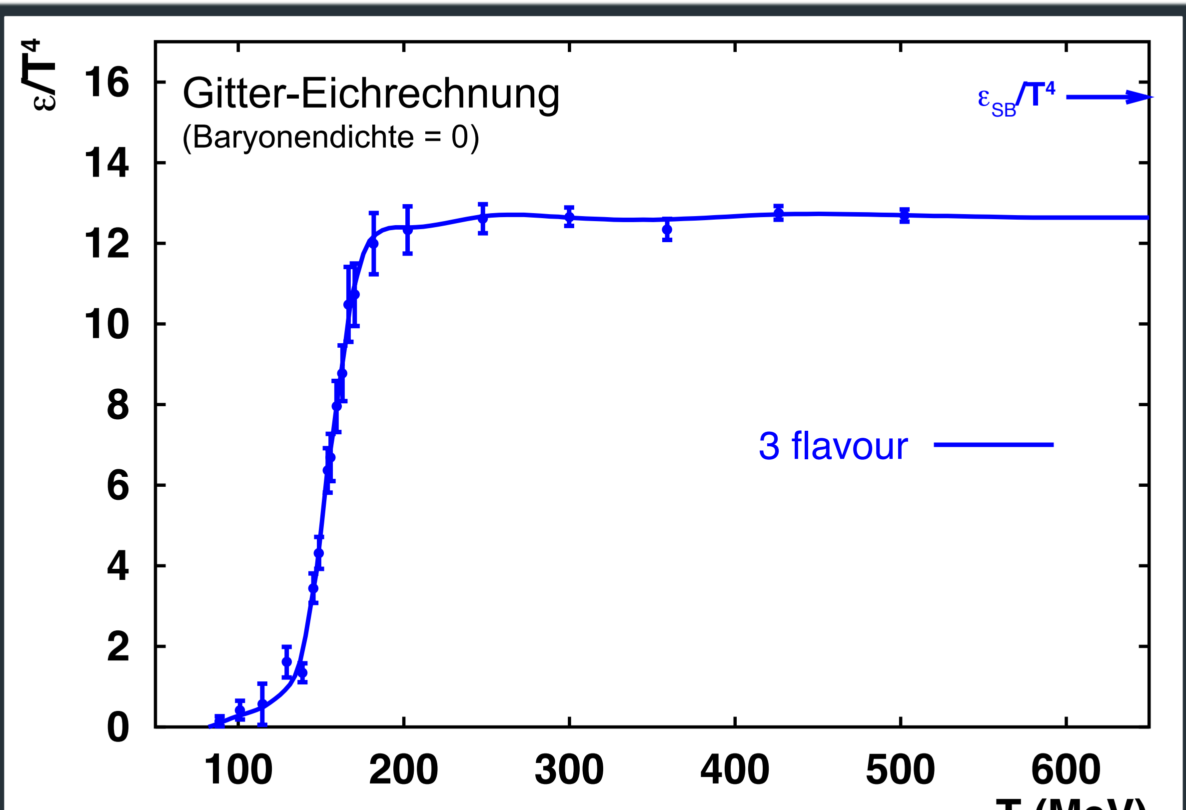
Upgrade of the
ALICE Experiment
Letter of Intent

Phasenübergang zum Quark-Gluon-Plasma



Karsch hep-lat/0305025

Phasenübergang zum Quark-Gluon-Plasma (QGP) bei $T_C \approx 160$ MeV ($2\cdot10^{12}$ K) erwartet.

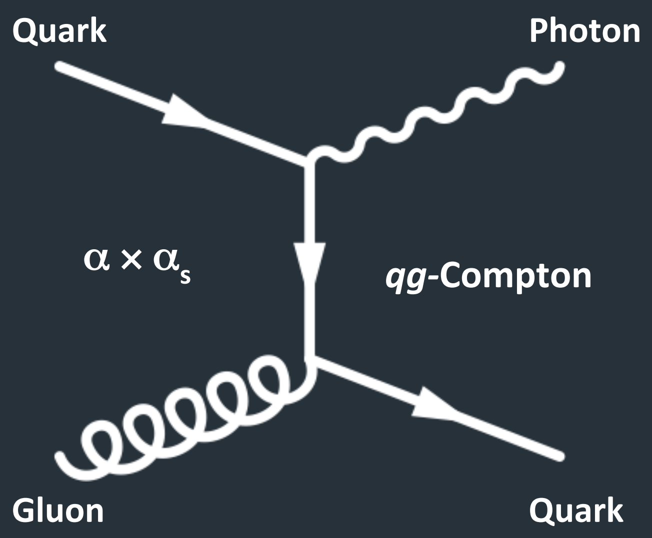
Übergang von einem Hadronengas zu einem Plasma freier Quarks und Gluonen.

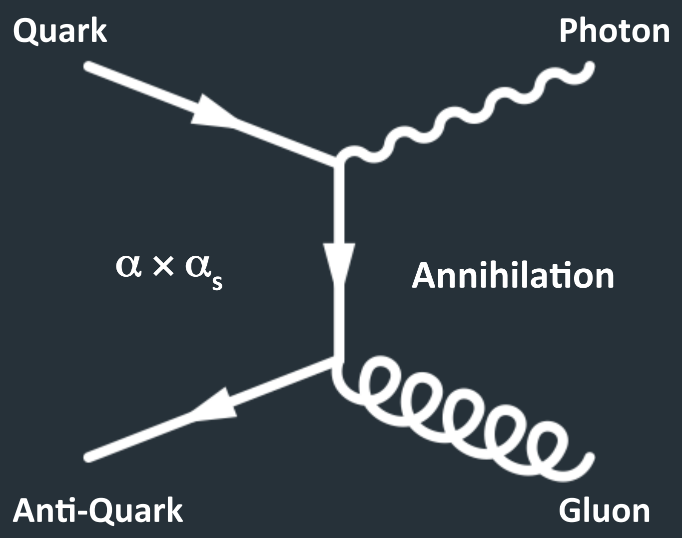
Abschätzungen

- Übergangstemperatur
  - Bag-Modell: $T_c \approx 150$ MeV
  - LQCD: $T_c \approx 160$ MeV
  - $\varepsilon \approx 0.8 - 1.3$ GeV/fm^3
- Kritische Baryonendichte
  - Bag-Modell: $\rho_c \approx 0.8/\text{fm}^3$ ($\rho_0 = 0.14/\text{fm}^3$)

Temperatur des QGP

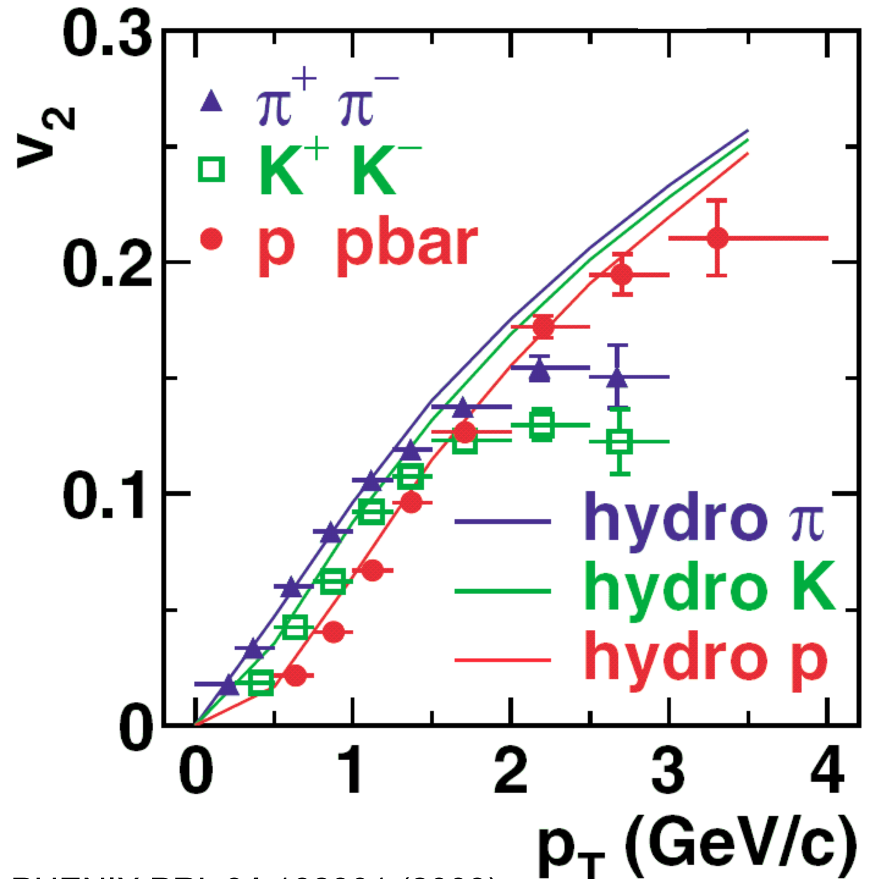
- Quarks und Gluonen nicht direkt beobachtbar
- Thermalisierte Quarks und Gluonen reagieren im QGP und können Photonen bilden





Photonen verlassen QGP ungestört und liefern direkte Information über Temperatur der Quarks und Gluonen.

RHIC: Kollektives Verhalten

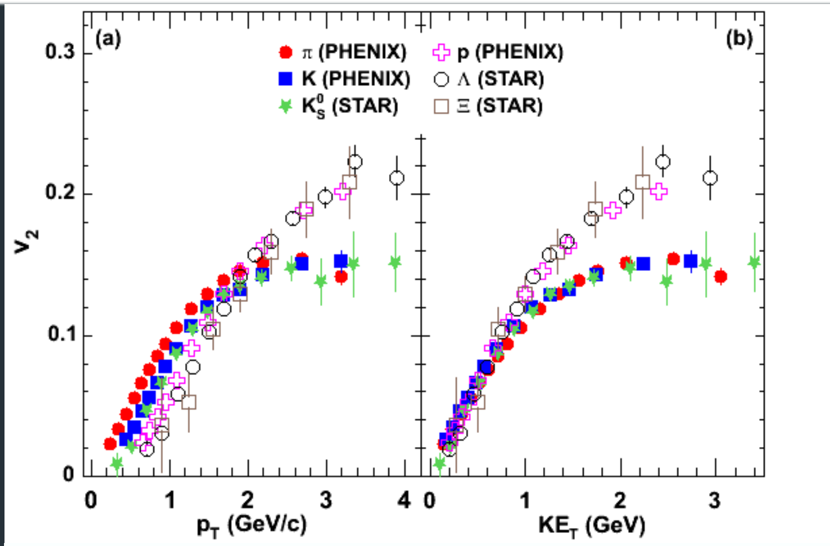


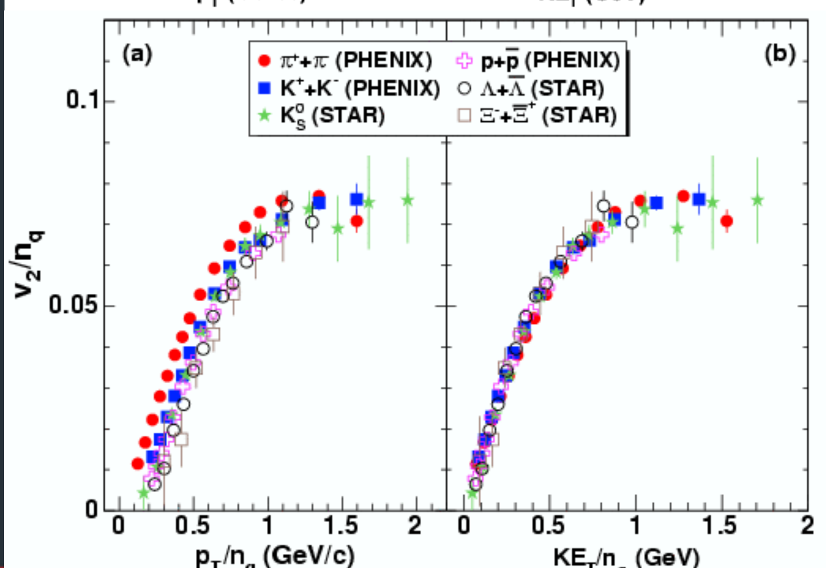
PHENIX PRL **91** 182301 (2003)

- RHIC: Erstmals im Bereich idealer relativistischer Hydrodynamik
  - "Perfekte Flüssigkeit", kein ideales Gas
  - Niedrigstes gemessenes Verhältnis Viskosität/Entropie
  - Thermalisierungzeit $\tau \approx 0.6$ fm/c
- LHC: Bestätigung der Energieabhängigkeit
  - **ALICE PRL 105 252302 (2010)**

Starke Kollektivität im produzierten Medium. Frühe Thermalisierung.

RHIC :Scaling Law for Elliptic Flow



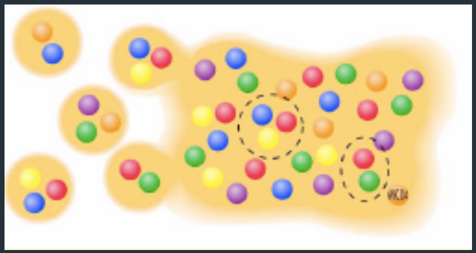


PRL 98 162301 (2007)

- Use transverse kinetic energy to account for mass effect

$$p_T \Rightarrow KE_T = m_T - m$$

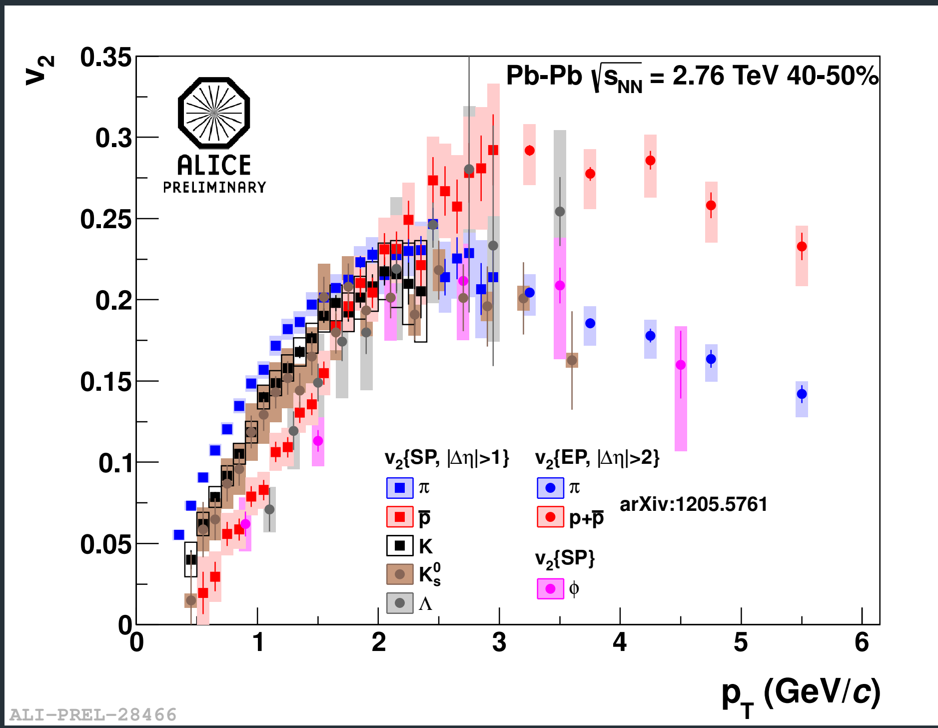
  - Two separate curves for baryons and mesons
- Quark number scaling

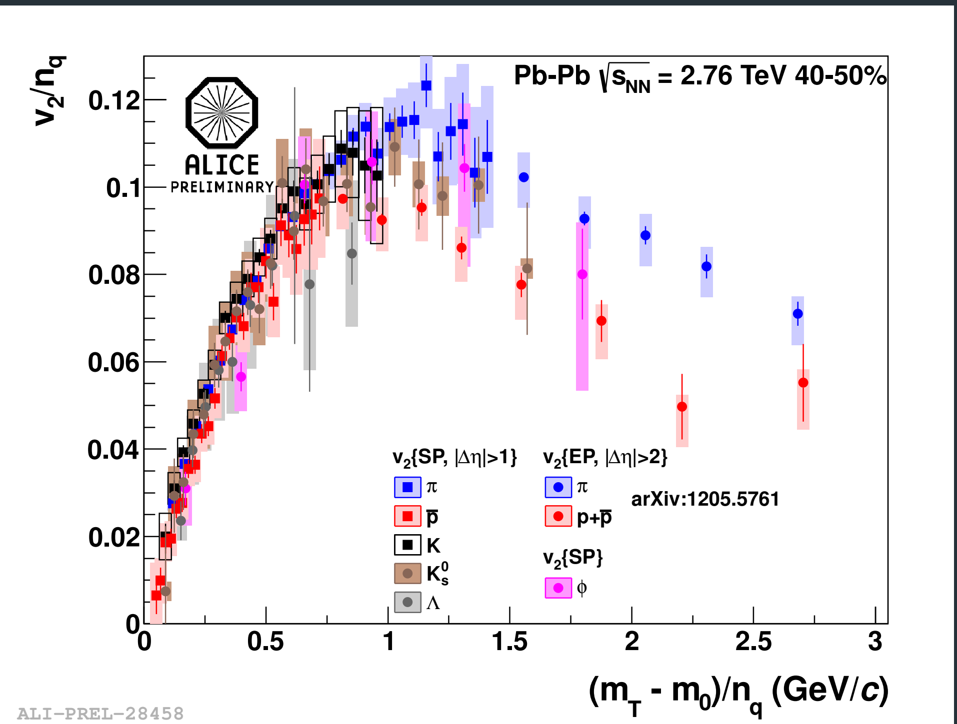


$$v_2^{\text{hadron}}(p_T^{\text{hadron}}) \approx n \cdot v_2^{\text{quark}}(p_T^{\text{quark}})$$
$$p_T^{\text{hadron}} \approx n \cdot p_T^{\text{quark}}$$

The constituent quarks themselves seem to flow! The hadrons only inherit the momentum anisotropy of the quarks

Quark Number Scaling still valid?





Basic idea:

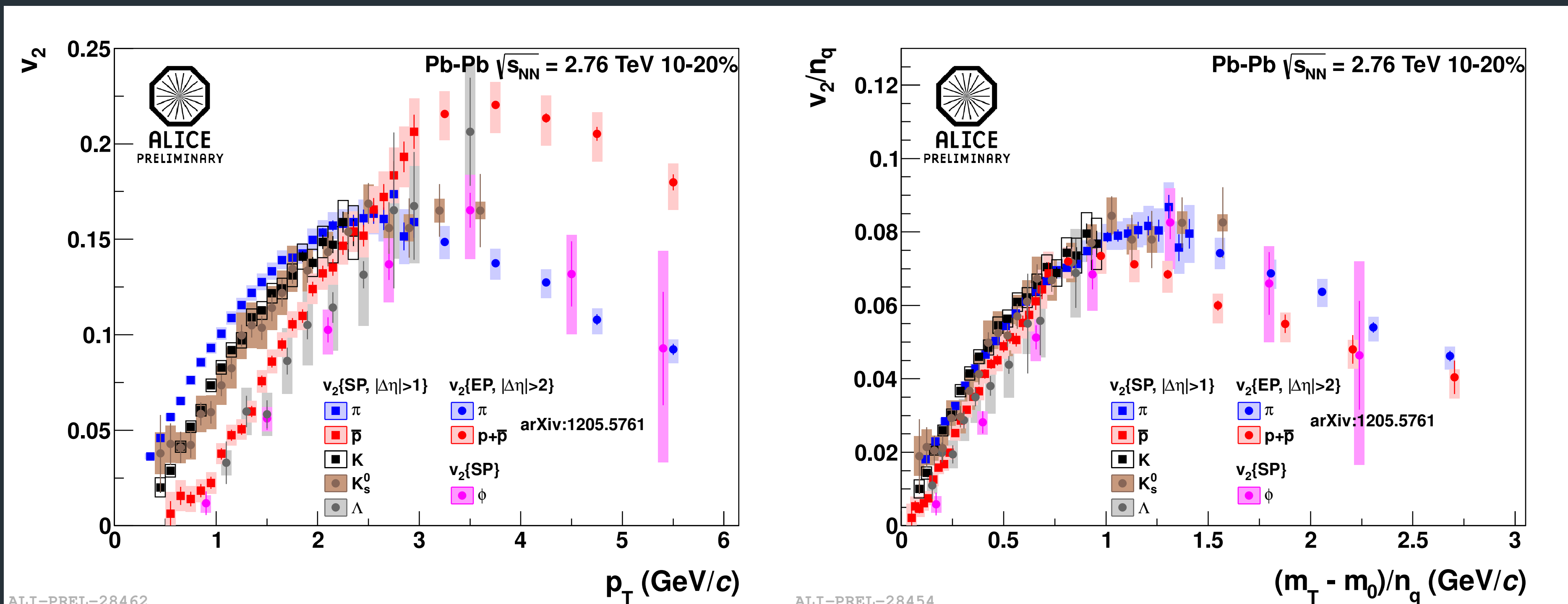
$$v_2^{hadron}(p_T^{hadron}) \approx n \cdot v_2^{quark}(p_T^{quark})$$

$$p_T^{hadron} \approx n \cdot p_T^{quark}$$

And account for mass effect:

$$p_T \rightarrow (m_T - m_0)$$

Quark Number Scaling 10-20%

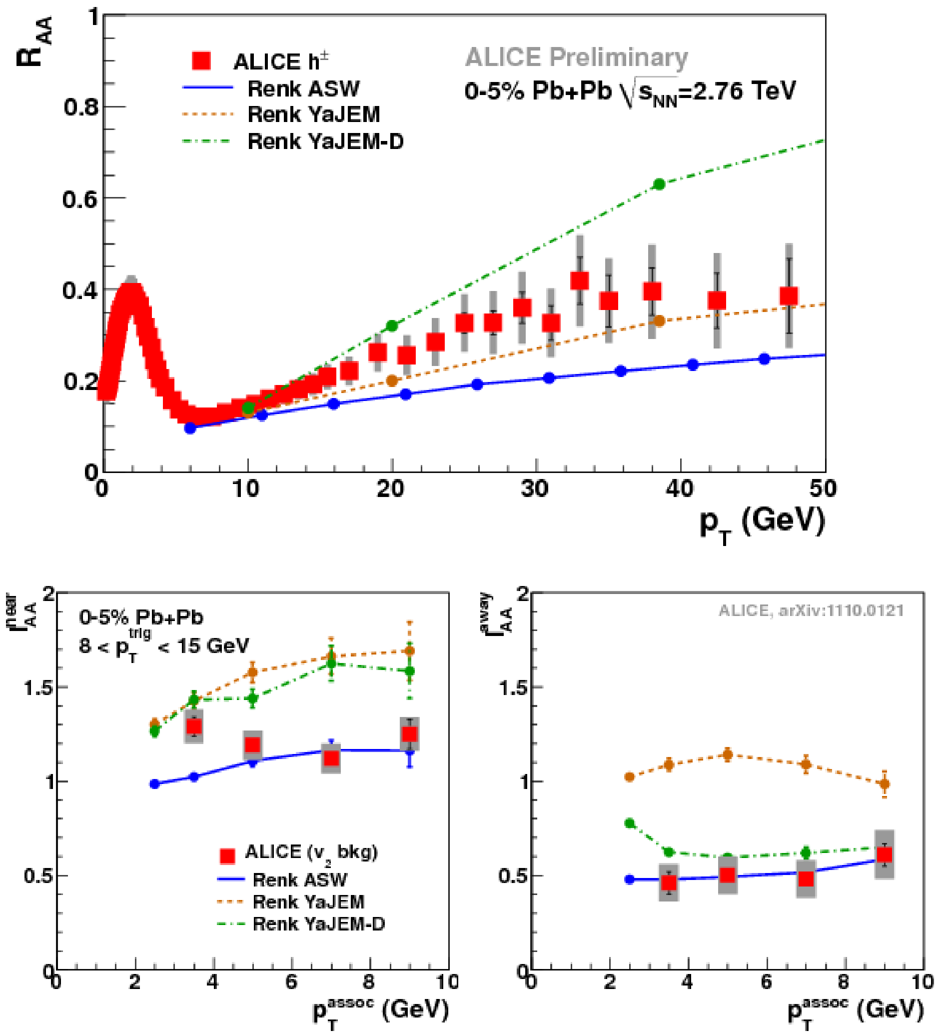


Protons and pions stay separate above 1 GeV
20% difference for below 1 GeV.
Poorer scaling than at RHIC

Theory Comparison R_{AA} and I_{AA}

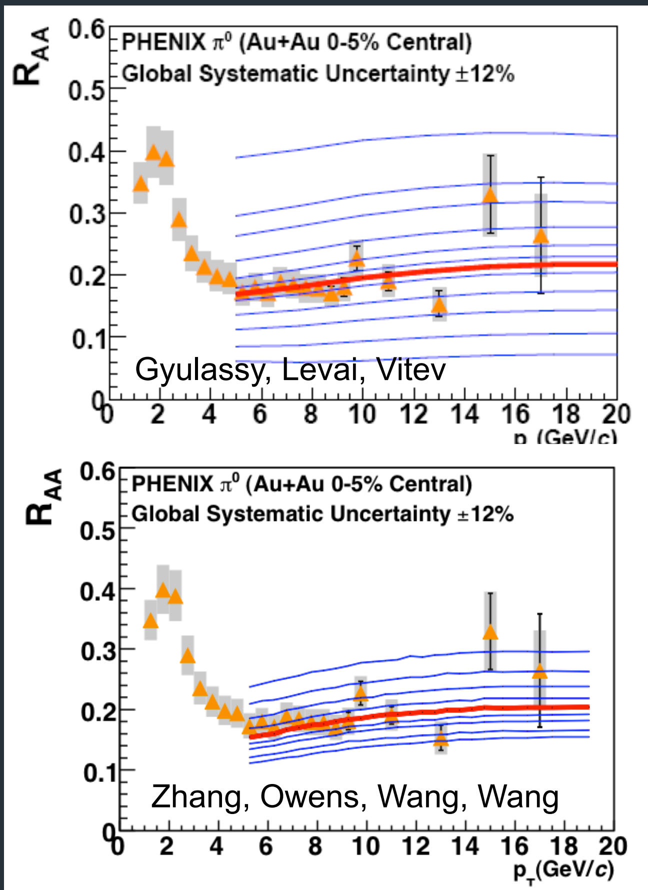
Need simultaneous comparison to several measurements to constrain geometry and E-loss

Here: R_{AA} and I_{AA}



Three models:
ASW: radiative energy loss
YaJEM: medium-induced virtuality
YaJEM-D: YaJEM with L-dependent virtuality cut-off (induces L^2)

Extraktion von Modellparametern mit Präzisionsdaten



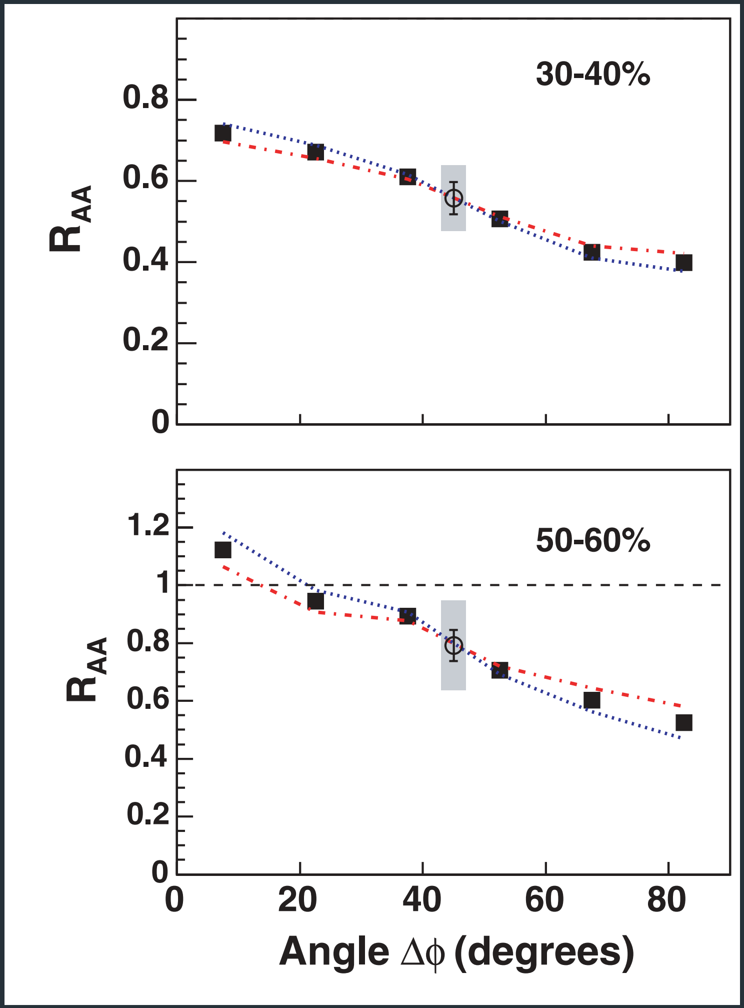
PHENIX PRL 101 232301 (2008)
& PR C 77 064907 (2008)

- **Fit benötigt Unterscheidung verschiedener Unsicherheiten**
  - **Typ A: Point-by-Point unkorreliert**
  - **Typ B: Korreliert (in p_T)**
  - **Type C: Normierung (konstanter Faktor)**
- **Least-Squares-Fit (1σ-Bereiche)**

PQM	$\hat{q} = 13.2^{+2.1}_{-3.1}$ GeV^2/fm	GLV	$dN^g/dy = 1400^{+270}_{-150}$
WHDG	$dN^g/dy = 1400^{+200}_{-540}$	ZOWW	$\epsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm^3

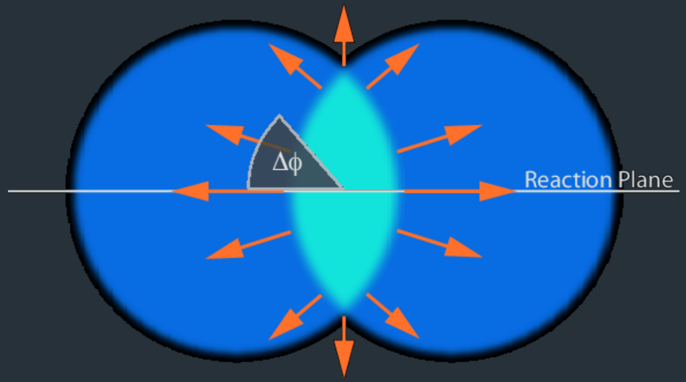
Aber: Theoretische Unsicherheiten nicht berücksichtigt.
Abhängigkeit von nur **einem** Parameter.

Δϕ-Tomographie



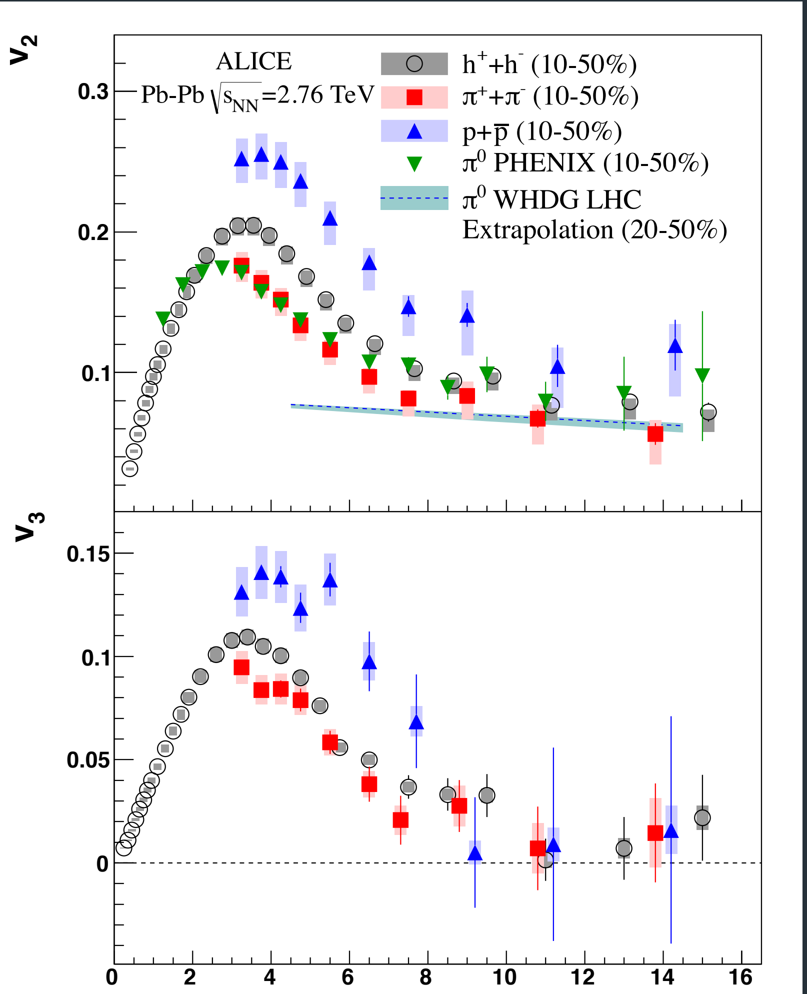
PHENIX: PR C76 034904 (2007)

- R_{AA} bzgl. der Reaktionsebene
- Geringere Unterdrückung in Richtung des dünneren Mediums



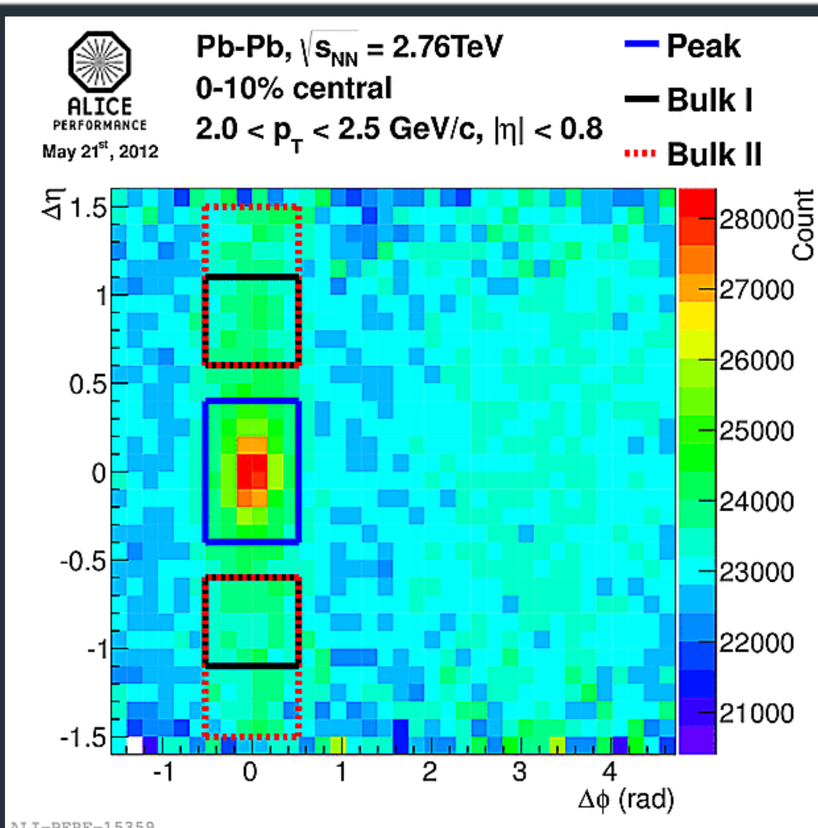
Starke Abhängigkeit des Jet-Quenchings von der Weglänge. Zusätzliche Randbedingung bevorzugt $\Delta E \sim L^n$ ($n > 1$).

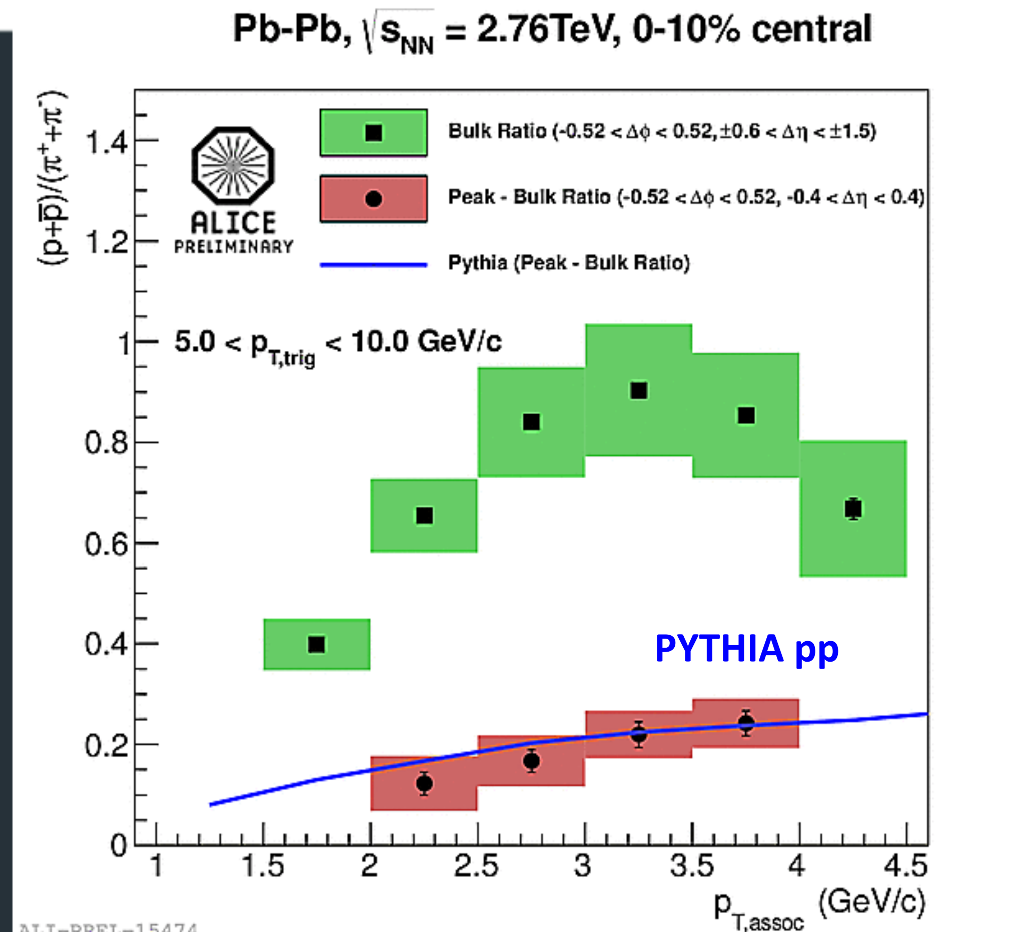
Identified Particle v_2 and v_3



ALICE arXiv:1205.5761

PID in Jets





Near-side peak (after bulk subtraction): p/π ratio compatible with that of pp (PYTHIA)
Bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement
Jet particle ratios not modified in medium? Could this still be surface bias?