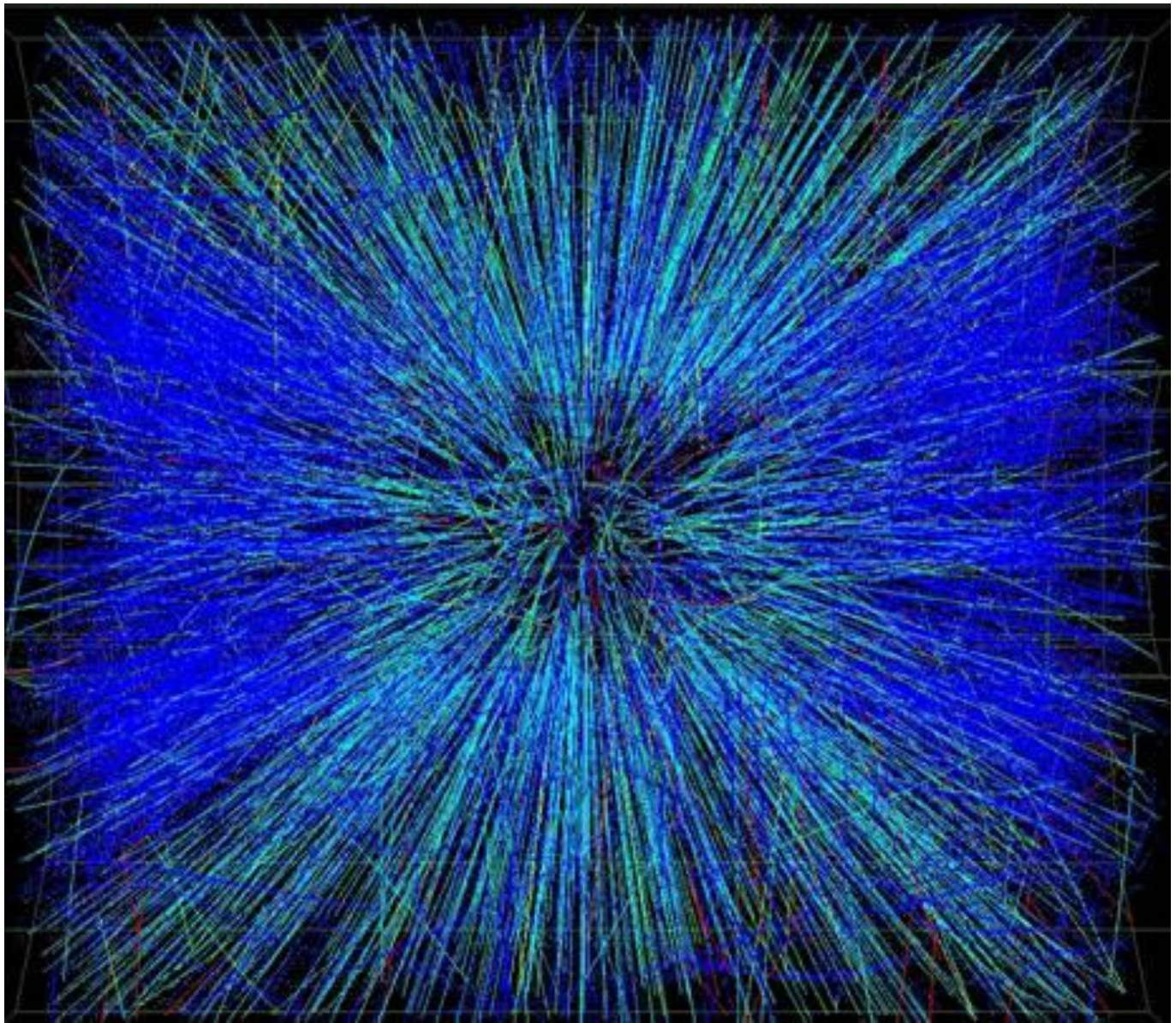
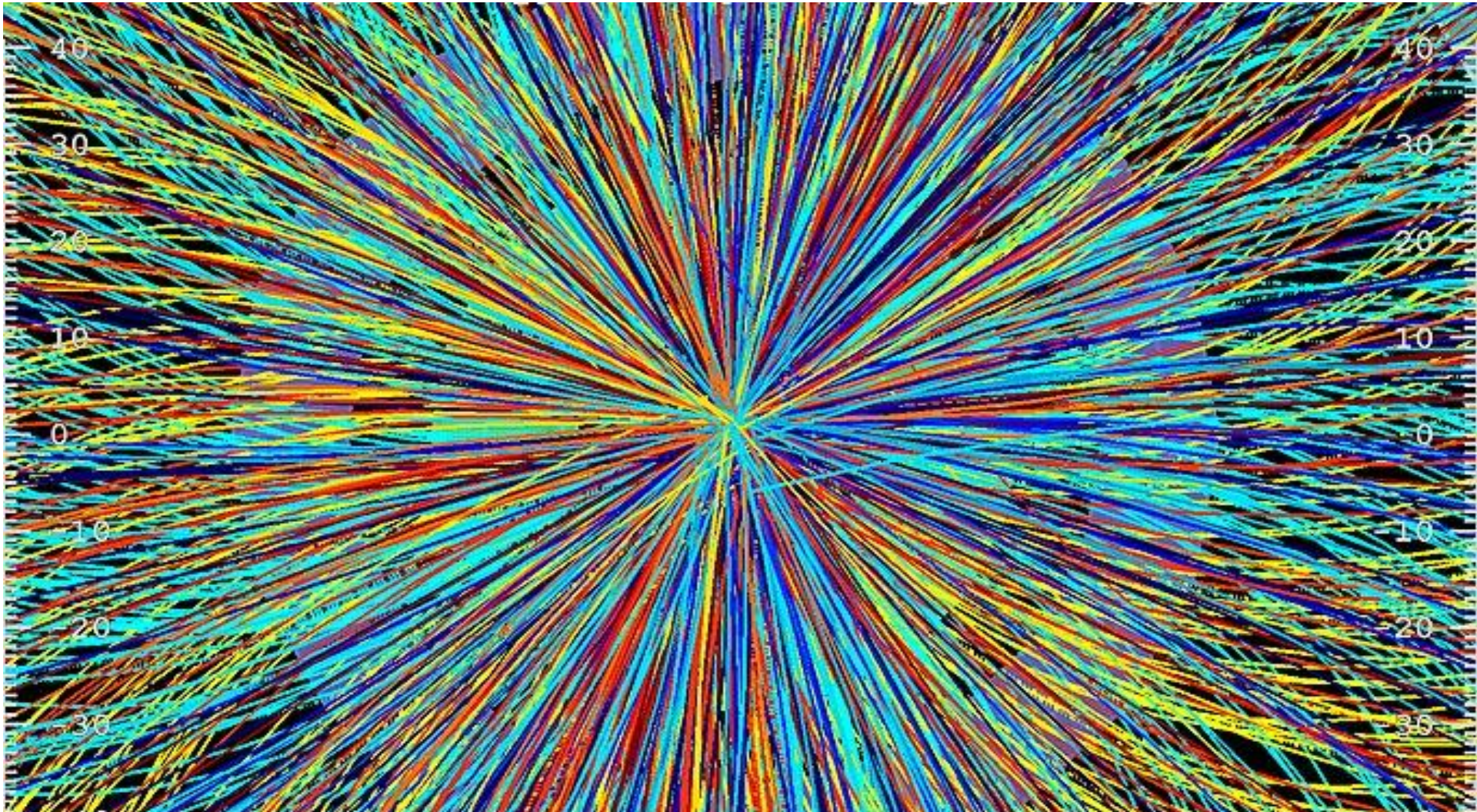
Overview of Heavy-Ion Results from RHIC



Overview of Heavy-Ion Results from RHIC to LHC

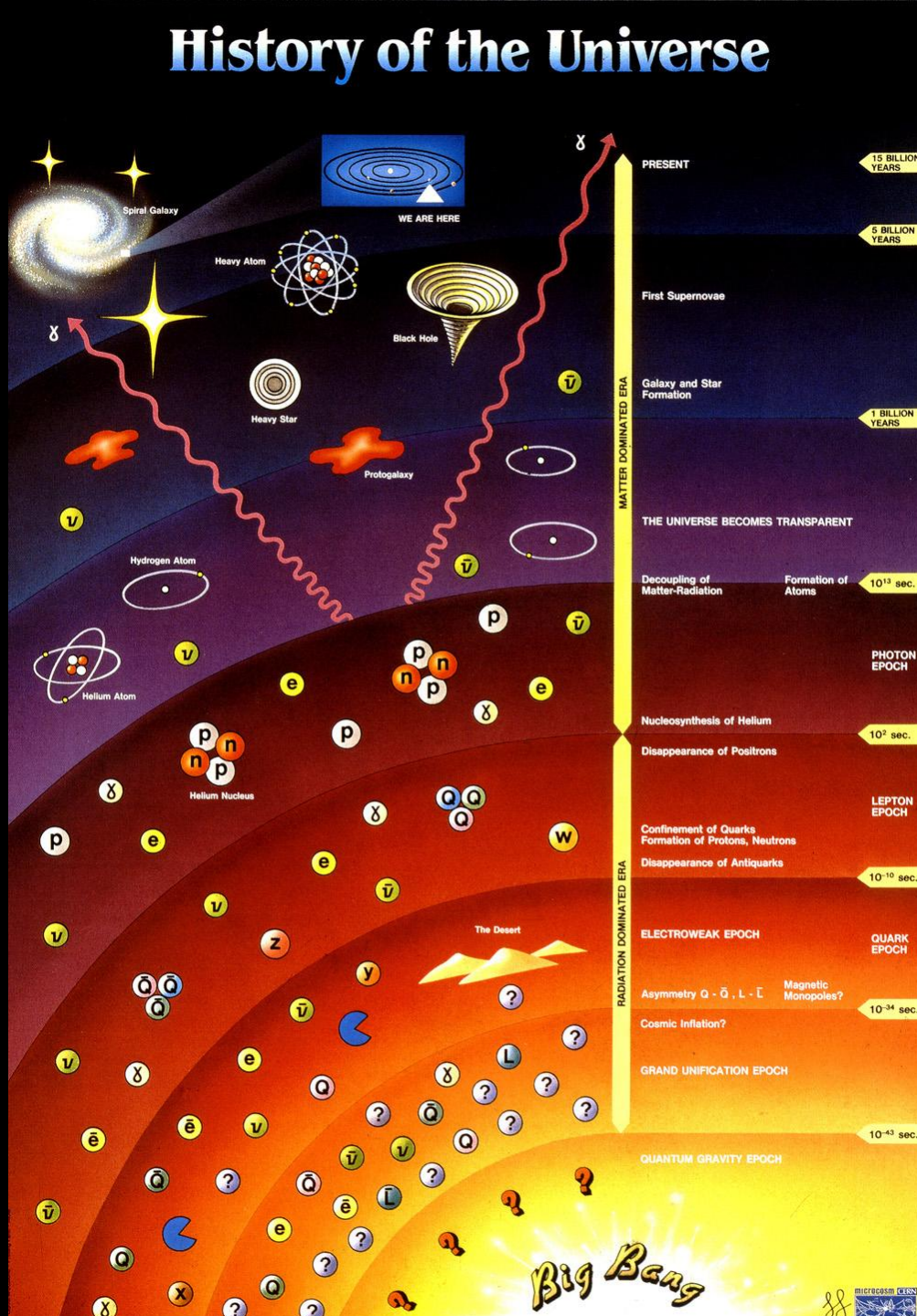


Fundamental questions of Standard Model

- phase transitions with quantum fields
- symmetries of nature
- origin of masses in the Universe

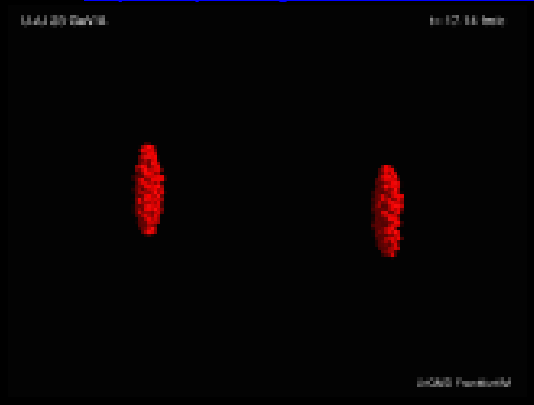
QCD prediction of deconfinement and chiral symmetry restoration in Quark Gluon Plasma

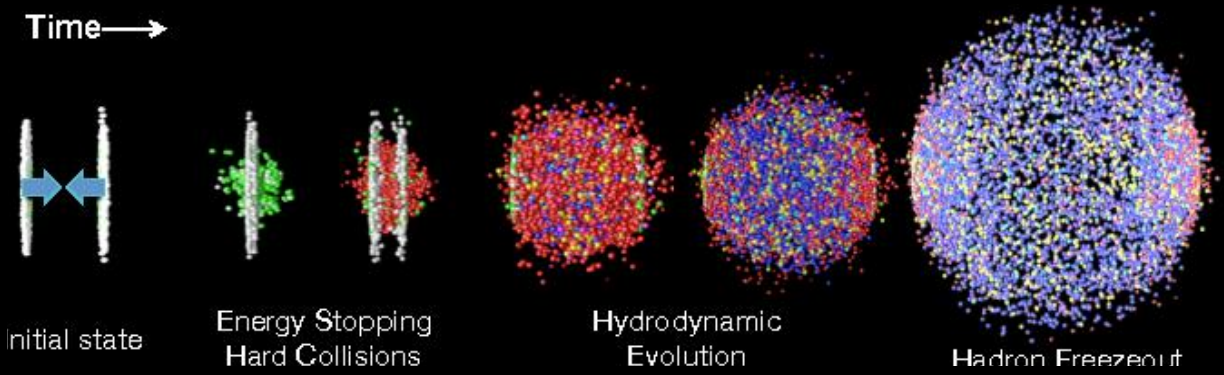
primordial matter of the Universe



Heavy-ion collisions

http://urqmd.org/~weber/CERNmovies



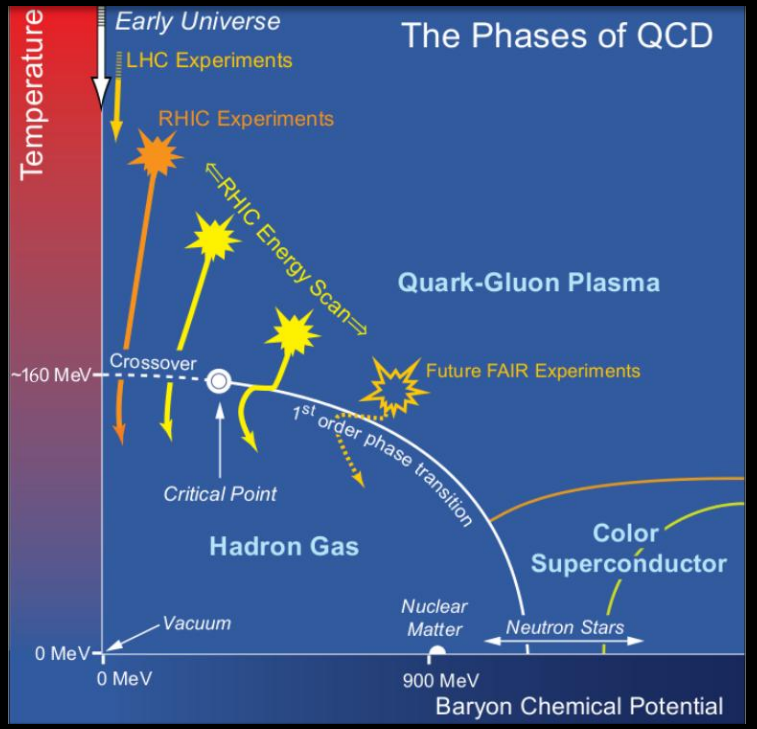


Macroscopic piece of QCD matter characterized by high density and collective phenomena

Heavy Ion Collisions is the tool to provide the necessary conditions for the phase transition: they occur in macroscopic volumes

QCD Thermodynamics

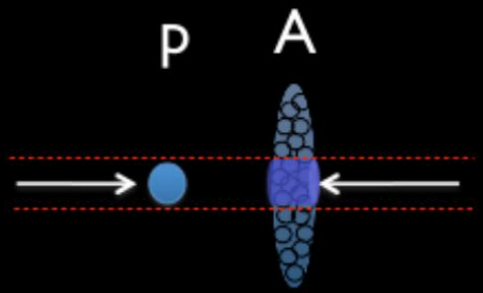
Study high energy density QCD (strong, non-perturbative QCD)

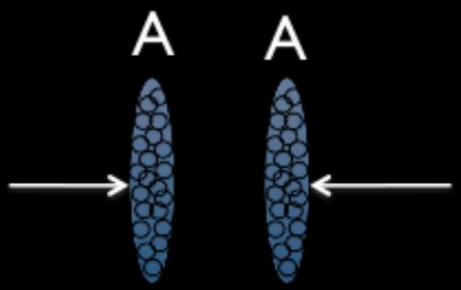


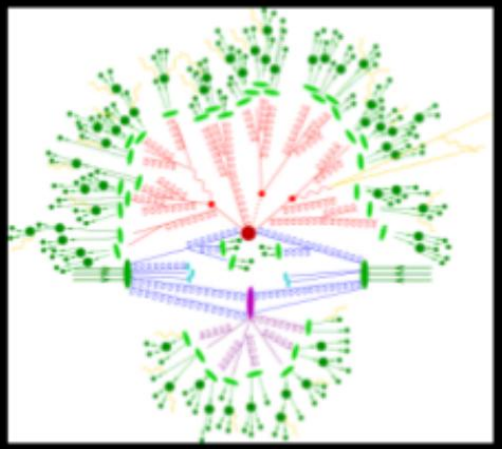
from CERN-THESIS-2011-2411

Strategy of Heavy-Ion Physics

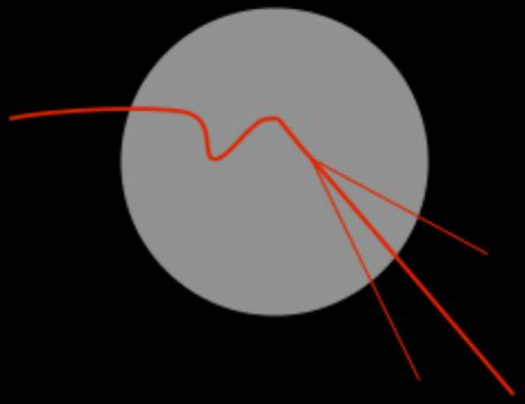
measure all these systems



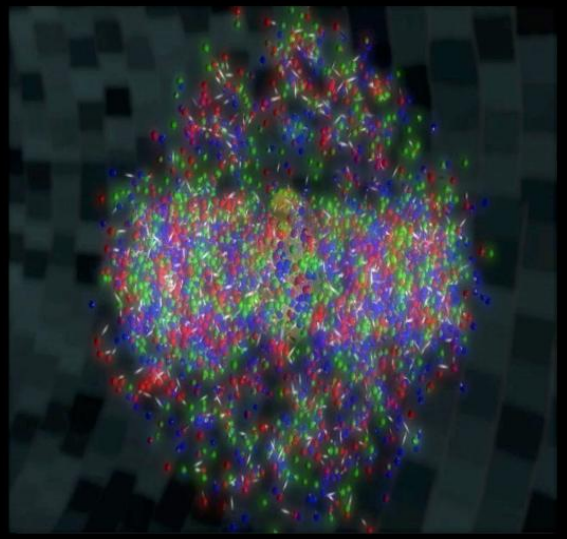




Local structure of QCD vacuum



Local QCD
+
initial state/cold nuclear matter



Local QCD
+
initial state/cold nuclear matter
+
Quark-Gluon Plasma

from G. Roland (IS 2013) modified by C. Loizides (QM 2014)

QCD studies

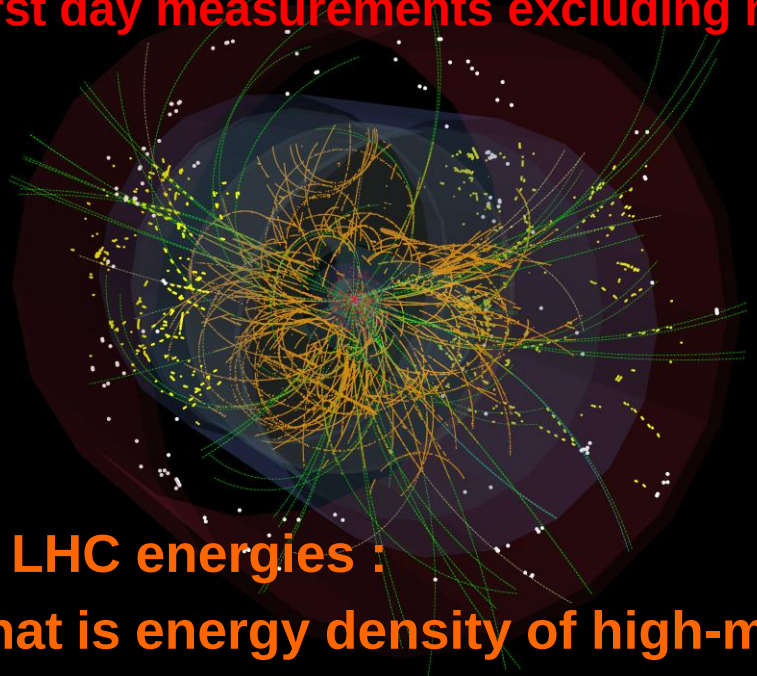
Material from paper published on the occasion of the 10th anniversary of
"Quark Confinement and the Hadron Spectrum" CONFX

QCD: where we stand, open questions, future directions
By N. Brambilla,… Y. Foka,… S. Gardner,… conveners of sessions

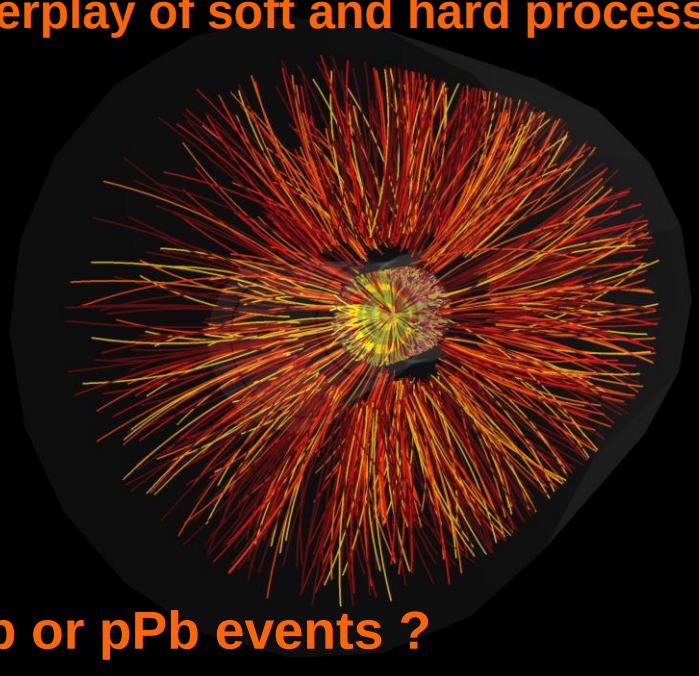
EPJC 74 (2014) 2981
http://arxiv.org/pdf/1404.3723.pdf

QM 2014 at Darmstadt updates: http://qm2014.gsi.de

First day measurements excluding models



Interplay of soft and hard process



At LHC energies :

what is energy density of high-multiplicity pp or pPb events ?

Starting 70'- to early 80's at Bevalac/Berkely
field started by a few dozen physicists
> 2500 physicists active worldwide today

energy increase by factor 10^4 in ~ 30 years

SPS: 1986 - 2002(4); NA61: >2009
O, S, Pb
$\sqrt{s_{NN}}$ = 6.5 - 20 GeV/A, 3.9 - 17 GeV/A
Users: ~ 600

LHC: 2010 -
Pb, $\sqrt{s_{NN}}$ = 2.76, 5.5 TeV/A
Users: ~ 1000

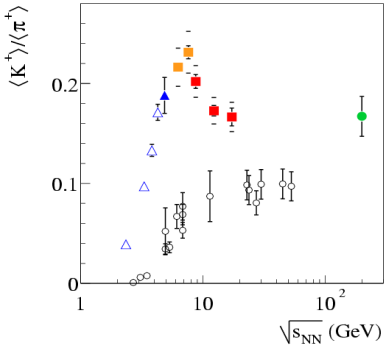
AGS: 1986 - 1996(8)
Si, Au
$\sqrt{s_{NN}}$ = 2.5 - 5.5 GeV/A
Users: ~ 400

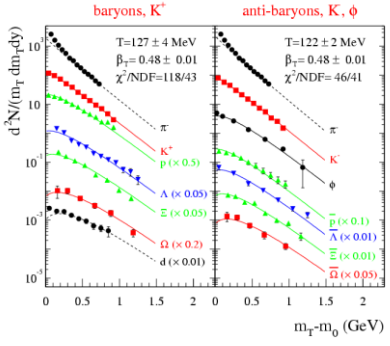
RHIC: 2000 -
d, Cu, Au,
$\sqrt{s_{NN}}$ = 7.7-200 GeV/A
Users: ~ 1000

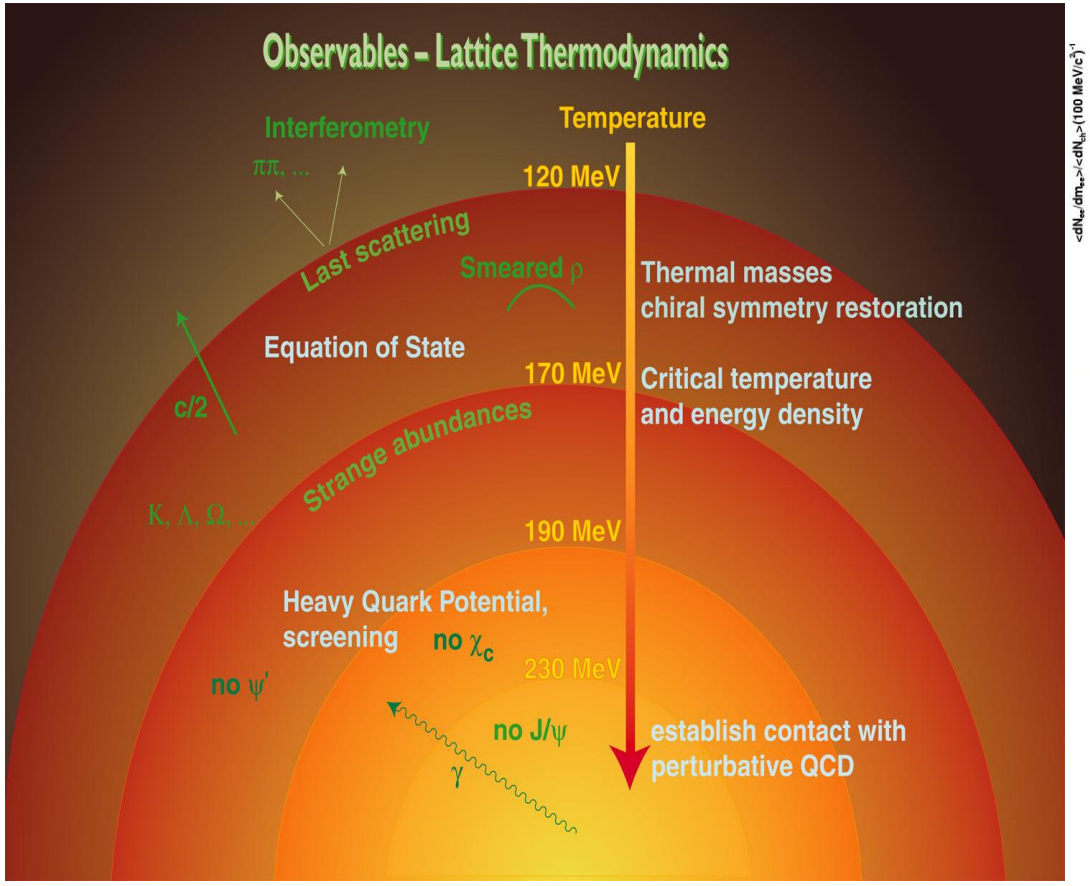
First evidence of a deconfined state of matter based on the results of different fixed target experiments at the CERN SPS

….. compelling evidence for a new state of matter,
featuring many of the characteristics expected for a Quark-Gluon Plasma

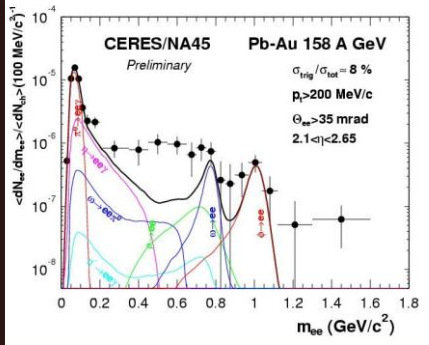
strangeness enhancement, thermalization



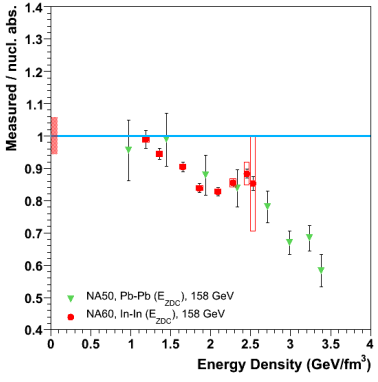




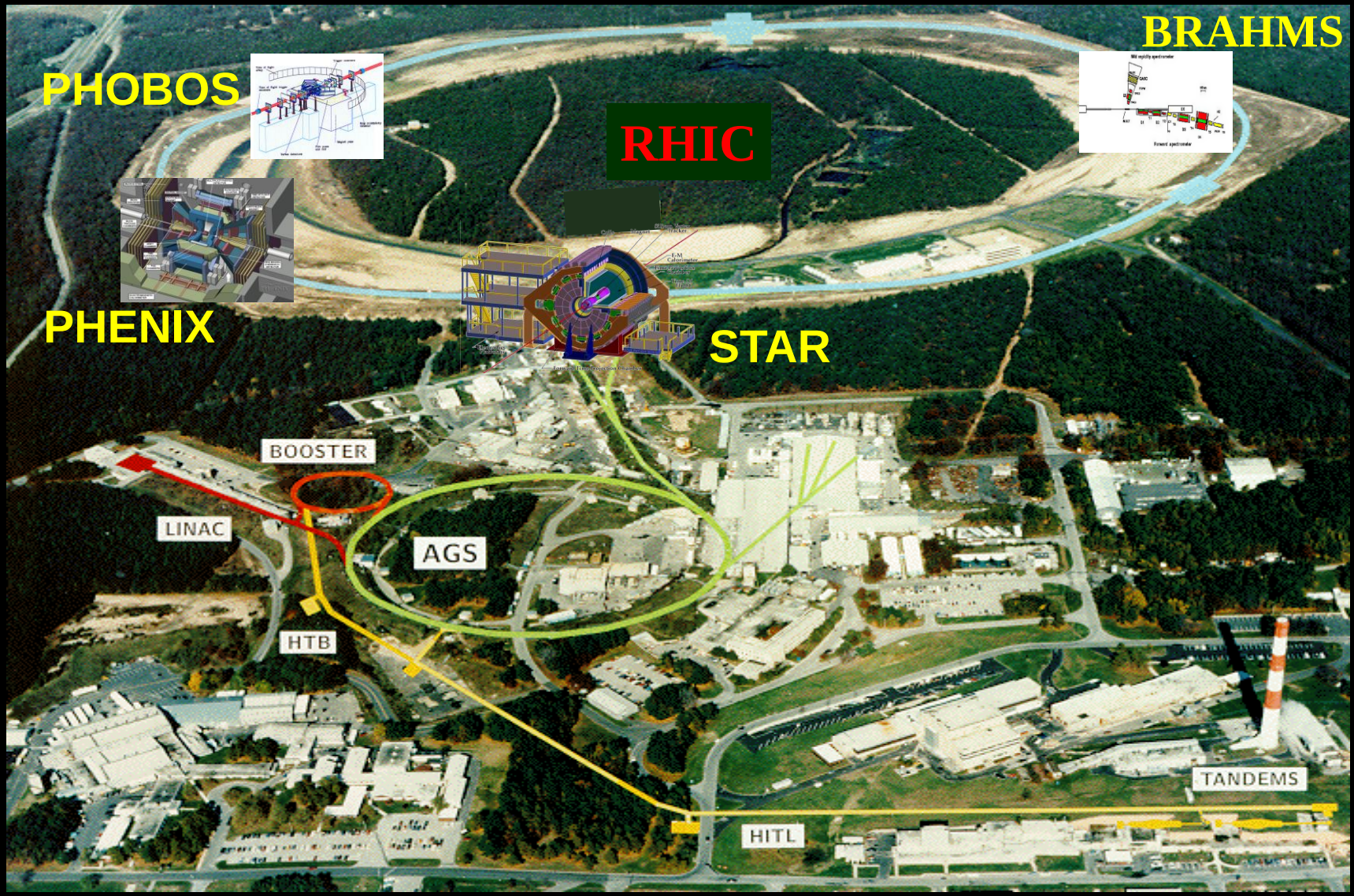
rho melting, chiral symmetry restoration



J/Psi suppression, deconfinement



4 dedicated HI experiments at RHIC, took over



starting summer 2000 with Au+Au collisions at 130 GeV and reaching 200 GeV a year later

Highlights at RHIC

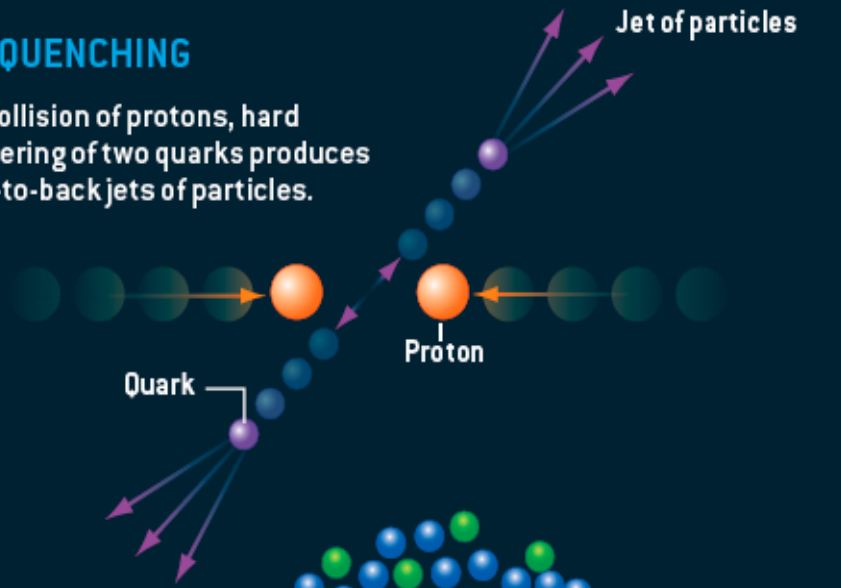
Hot, strongly interacting, nearly perfect liquid

EVIDENCE FOR A DENSE LIQUID

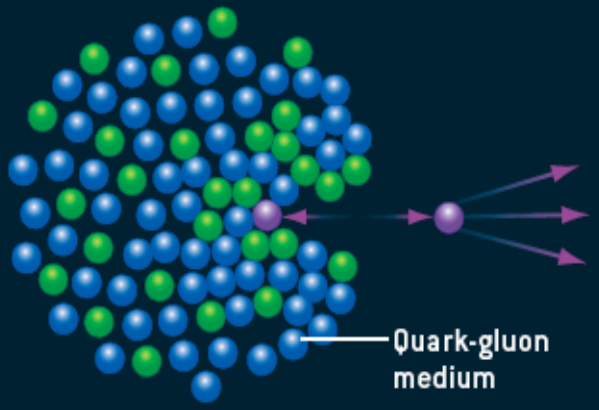
Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

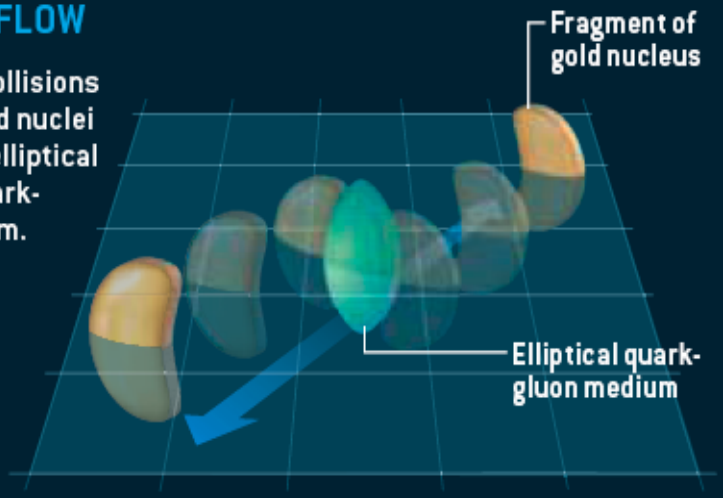


In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

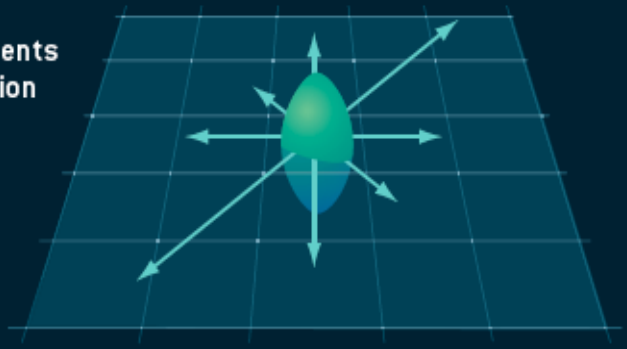


ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

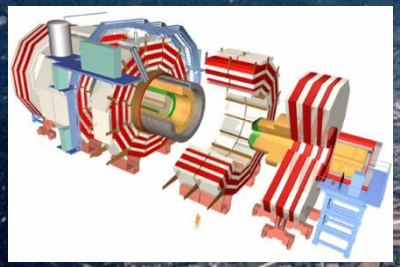


The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

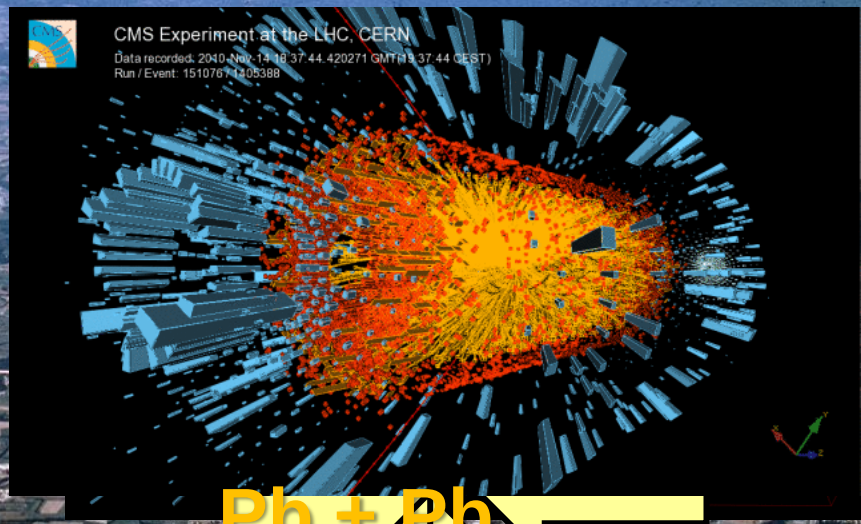


Collider of Large Hadrons

Design Energy:
14 TeV (pp)
1150 TeV (PbPb)



CMS

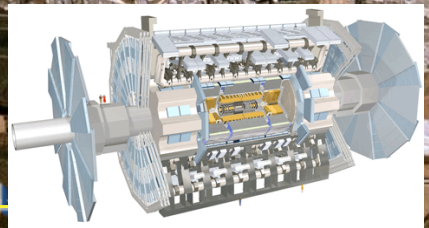


Pb + Pb

LHCb

ALICE

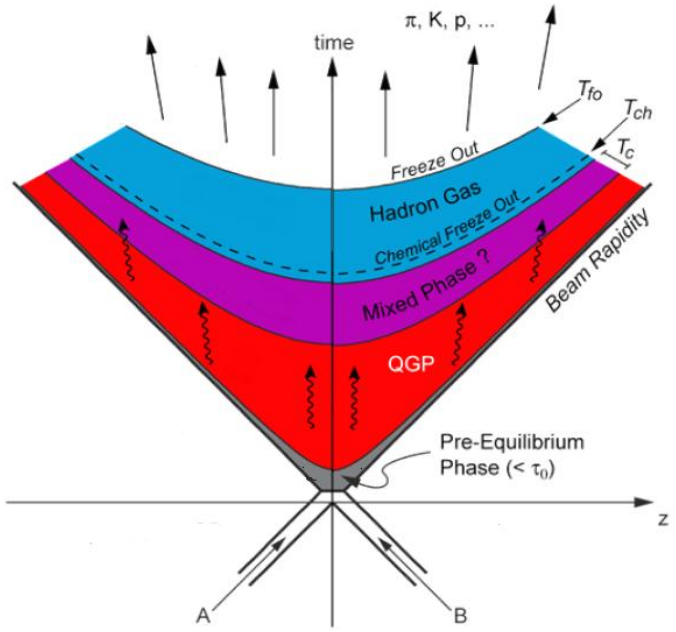
ATLAS



4 all participate in HI program (L

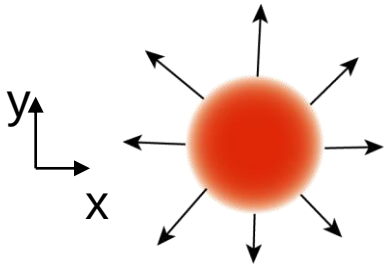
Collective expansion

Most direct evidence of strongly interacting, macroscopic (i.e. large compared to mean free path) and dense bulk matter system described in terms of hydrodynamics

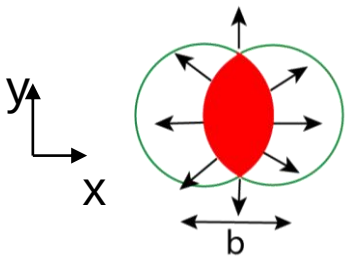


Equation Of State

p_T spectra and azimuthal corerlations (v_n)



In a thermalized system the radial expansion is driven by the pressure gradient from inside to outside resulting in boosted p_T spectra



If the system is asymmetric in spatial coordinates the expansion will lead to anisotropy in momentum space (azimuthal correlations)

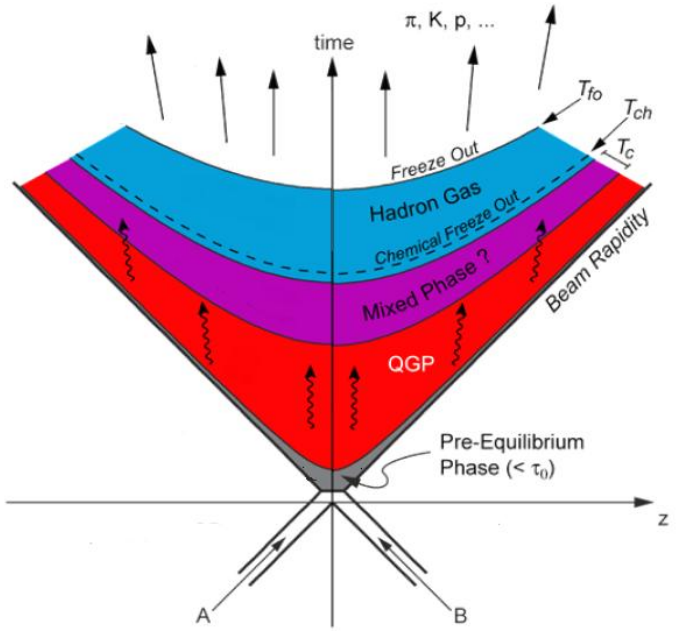
- **dependence of the shape of the p_T distribution on the particle mass**
- **azimuthal anisotropic flow patterns (initial spatial anisotropy)**

The final state anisotropy at low p_T can be calculated using hydrodynamics giving as input

- initial conditions (eccentricity, volume, energy density,..)
- properties of produced matter (viscosity, ...)

Collective expansion

Most direct evidence of strongly interacting, macroscopic (i.e. large compared to mean free path) and dense bulk matter system described in terms of hydrodynamics



Equation Of State

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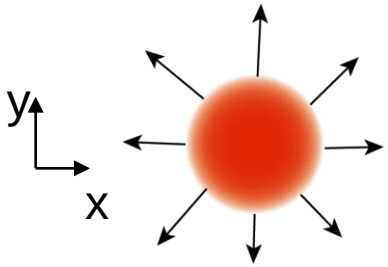

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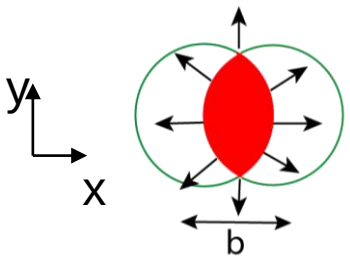
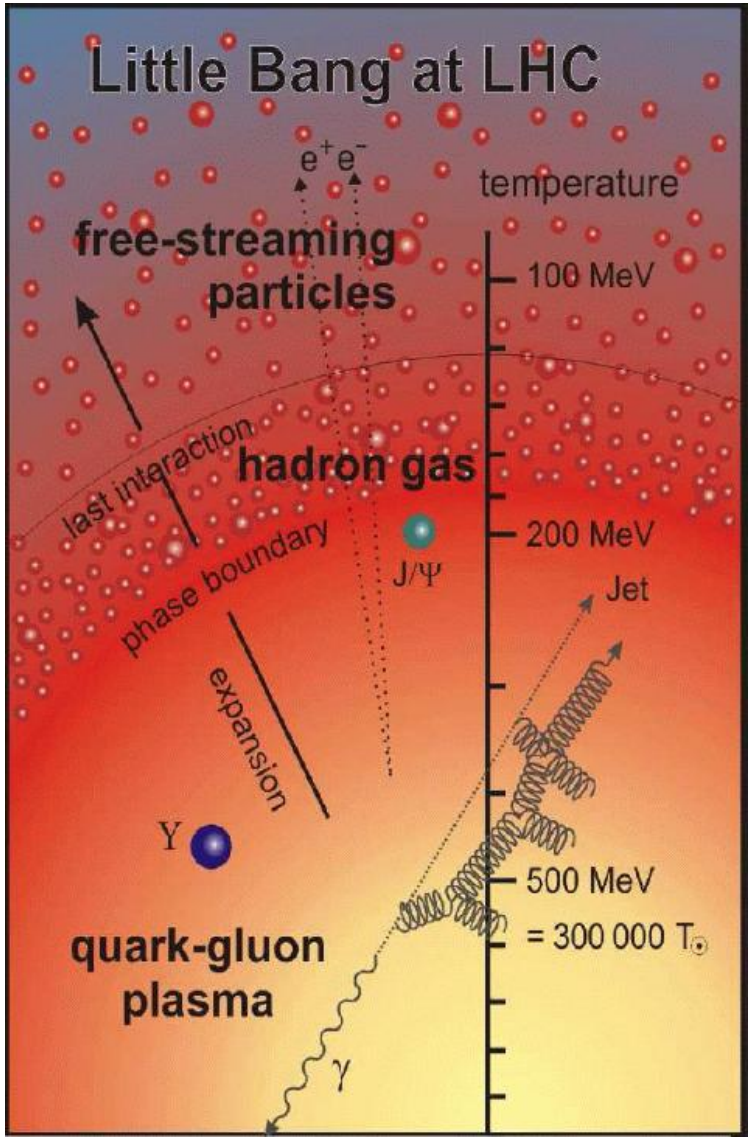


If the system is asymmetric in spatial coordinates the expansion will lead to anisotropy in momentum space (azimuthal correlations)

- **dependence of the shape of the p_T distribution on the particle mass**
- **azimuthal anisotropic flow patterns (initial spatial anisotropy)**

are there final state dense matter effects in high multiplicity pp and pPb events?

Probes of HI Collisions - Outline



soft

hard probes

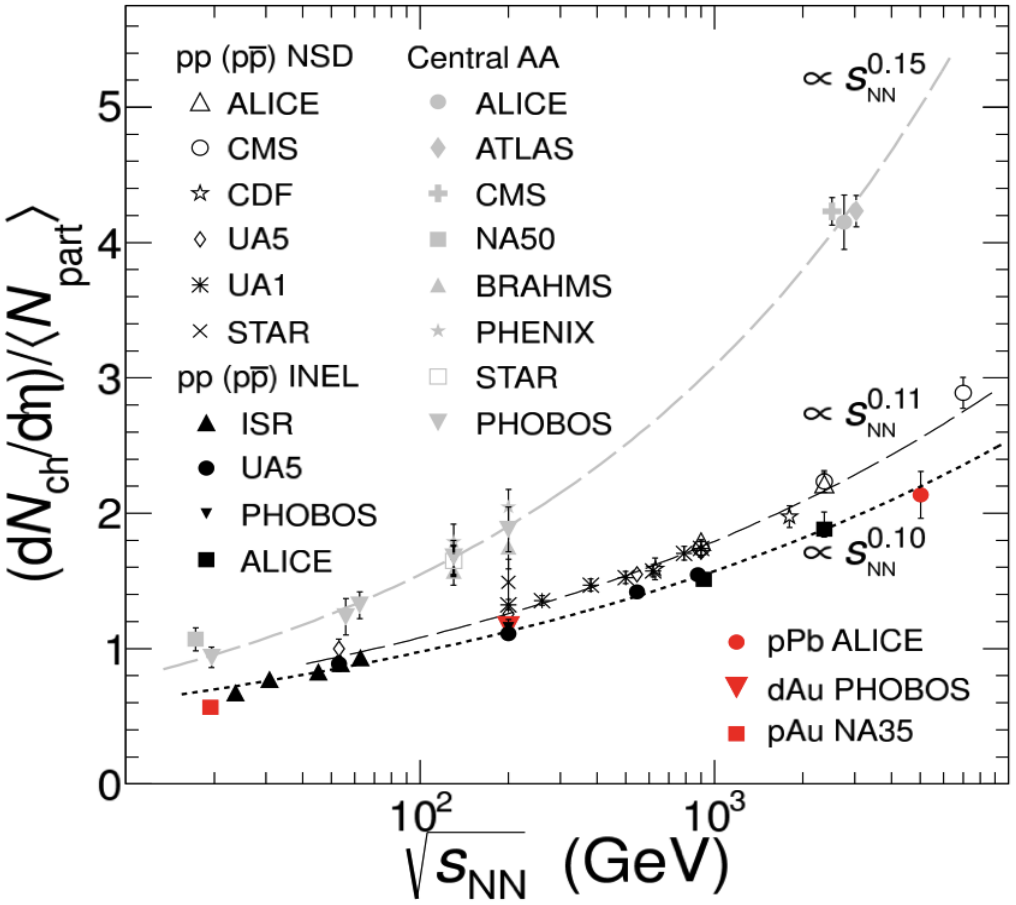
Global bulk event properties

- multiplicities, energy density, temperature
- space-time evolution of the emitting source: HBT
- degrees of freedom as a function of T: hadron spectra and ratios
- early state collective effects
- direct thermal photons

Medium induced effects

- parton energy loss: high p_T spectra
  open charm and open beauty
- deconfinement:
  charmonium and bottonium spectroscopy

$dN_{ch}/d\eta$ energy dependence



p-Pb : ~ $s_{NN}^{0.10}$
$dN_{ch}/d\eta$: 16.95 ± 0.75

pp : ~ $s_{NN}^{0.11}$
$dN_{ch}/d\eta$: 6.01 ± 0.01 (stat.) + 0.2 – 0.12

Pb-Pb : $s_{NN}^{0.15}$ (most central)
$dN_{ch}/d\eta$: 1584 ± 4 (stat.) ± 76 (syst.)

Pb-Pb : using $dN_{ch}/d\eta$

and geometry model

based on Bjorken formula

ε ~15 GeV/fm^3 T = 300 MeV

Bjorken estimate for a thermalized system

$$\epsilon(t) = \frac{E}{V} \gg \frac{1}{t_0 A}\frac{dN}{dy} < m_t > \gg \frac{1}{t_0 A}\frac{dE_T}{dy} \gg k_B T^4$$

arXiv:1210.3615 [nucl-ex], Phys Rev Lett 110, 032301 (2013)

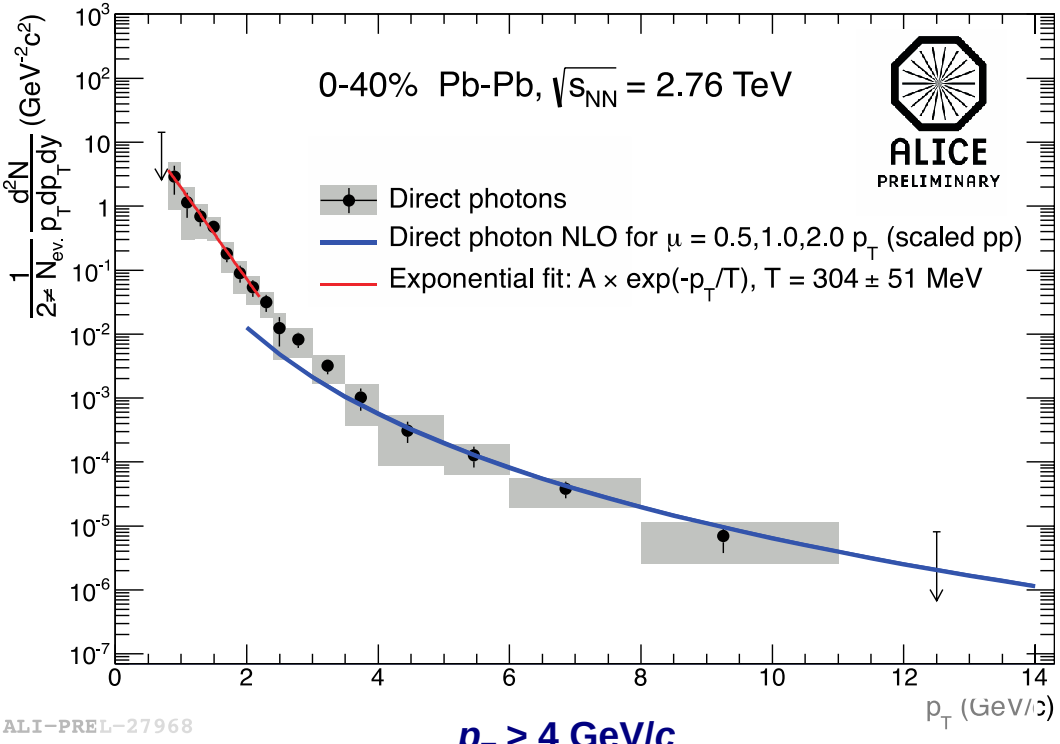
3 x RHIC

Well above critical conditions!

of ~ 160 MeV

Direct photon spectra

Direct photon p_T spectrum compared to scaled NLO



p_T > 4 GeV/*c*
agreement with N_{coll} scaled NLO pQCD

p_T < 2 GeV/*c*
~20% excess of direct photons

Exponential fit for p_T < 2.2 GeV/*c*

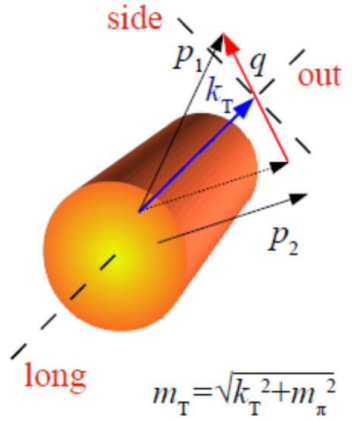
ALICE inverse slope:
T = 304 ± 51 MeV
in 0-40% central Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV

PHENIX:
T = 221 ± 19 ± 19 MeV
in 0-20% central AuAu
$\sqrt{s_{NN}}$ = 200 GeV
PHENIX, PRL 104, 132301 (2010)

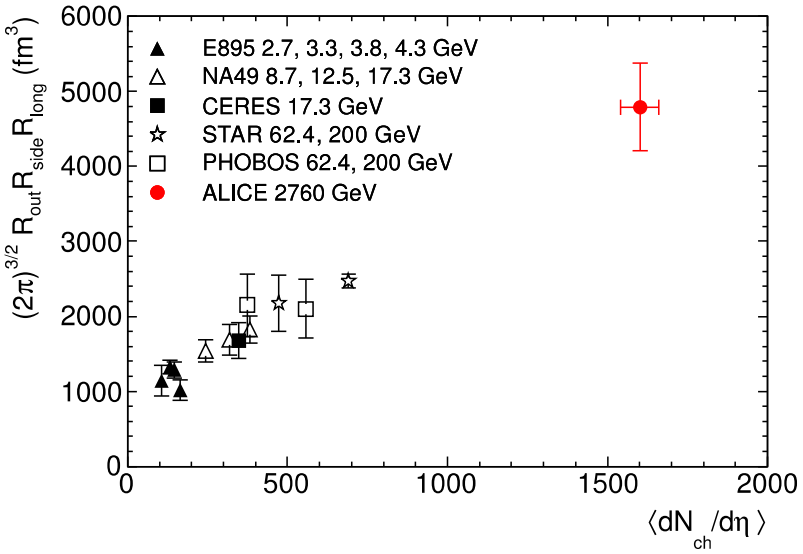
Ongoing studies:
blue shifted T due to flow effects

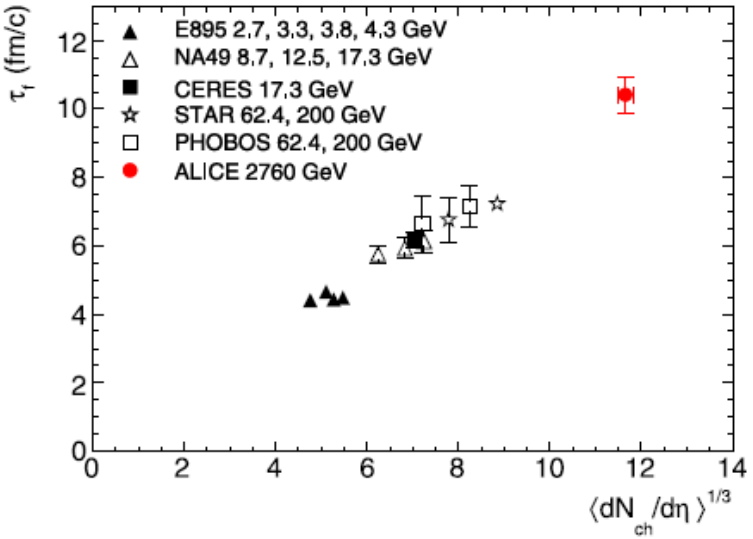
arXiv:1210.5958 [nucl-ex]

The source



Volume and Lifetime





Source size for hadron emission is determined by two-pion correlations methods: Hanbury-Brown Twiss (HBT) or femtoscopy

Volume at freeze out: ~ 5000 fm^3

x2 of RHIC

Initial volume ~ 800 fm^3

Lifetime from collision to freeze out

~ 10 fm/c

30% longer

QGP fireball at LHC

hotter, bigger and longer-lived

than at RHIC

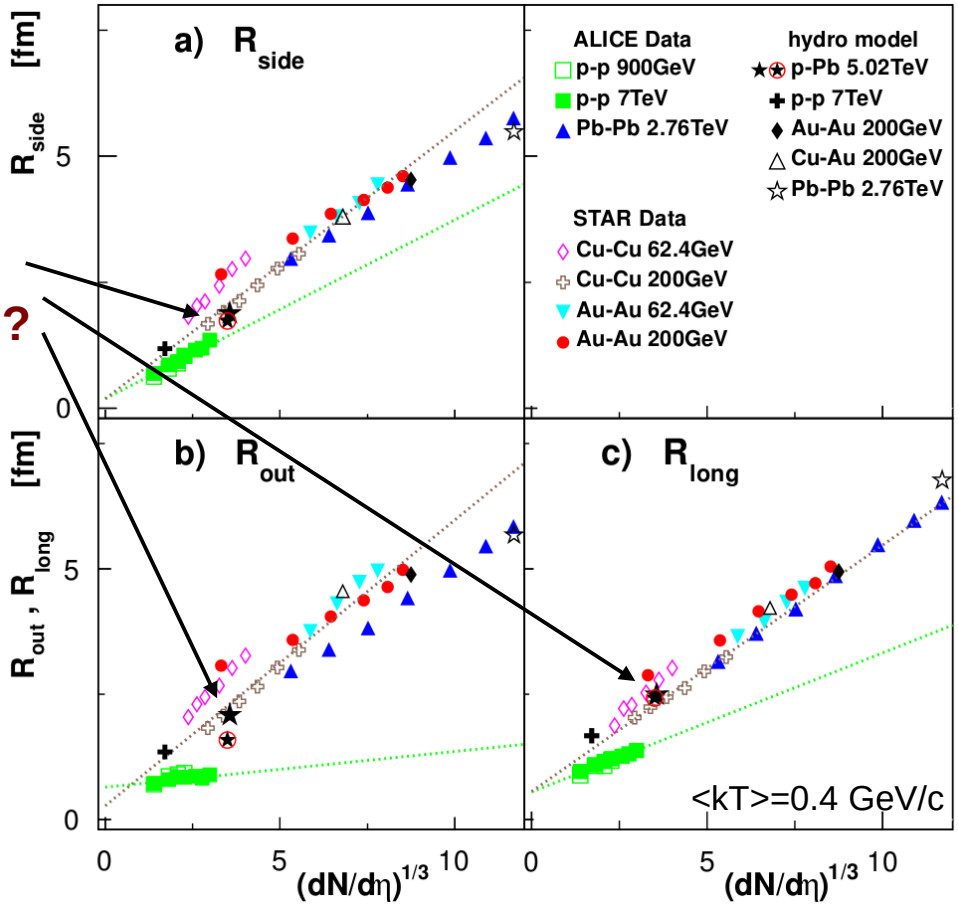
PLB 696, 328 (2011)

Radii scaling

Femtoscopic radii scale approximately with cube root of multiplicity

- Scaling for pp is clearly different from heavy ions.
- Radii from p-Pb collisions agree with pp for low multiplicities and start to diverge at higher multiplicities.

Hydro predictions for p-Pb consistent with Pb-Pb scaling?



Phys. Lett. B720 (2013) 250
arXiv:1301.3314 [nucl-th]

central p-Pb collisions undergo collective expansion similarly to peripheral A-A collisions

HBT radii

N_{ch} & m_T dependence of radii in AA: hallmark of expansion

pp 20 GeV – 1.8 TeV

HBT:
R_O, R_S, R_L vs m_T

pp 200 GeV

HBT:
R & cτ vs dN_{ch}/dy

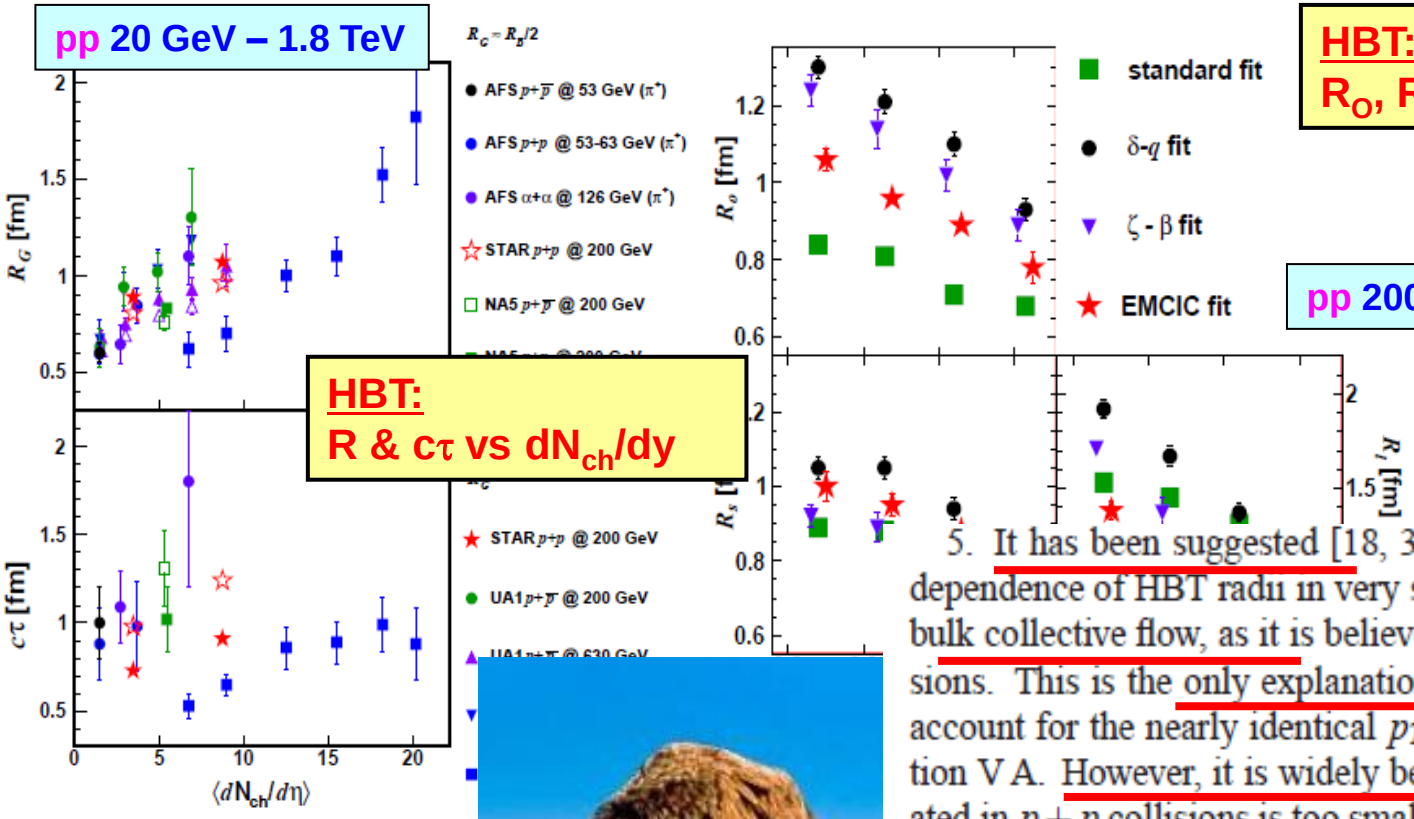


FIG. 12: (Color online) The multiplicity depe
timescale parameters to 2-dimensional correla
sured by STAR, E735 [36], UA1 [63], AFS [64
legend on the right indicates that the first 7 set
from fits to Eq. 7, in which case the parameter
upper panel; the last 5 sets of datapoints come
which R_G is plotted. As discussed in Section II
STAR and UA1, $R_G \approx R_B/2$. The UA1 Colla
their fits.

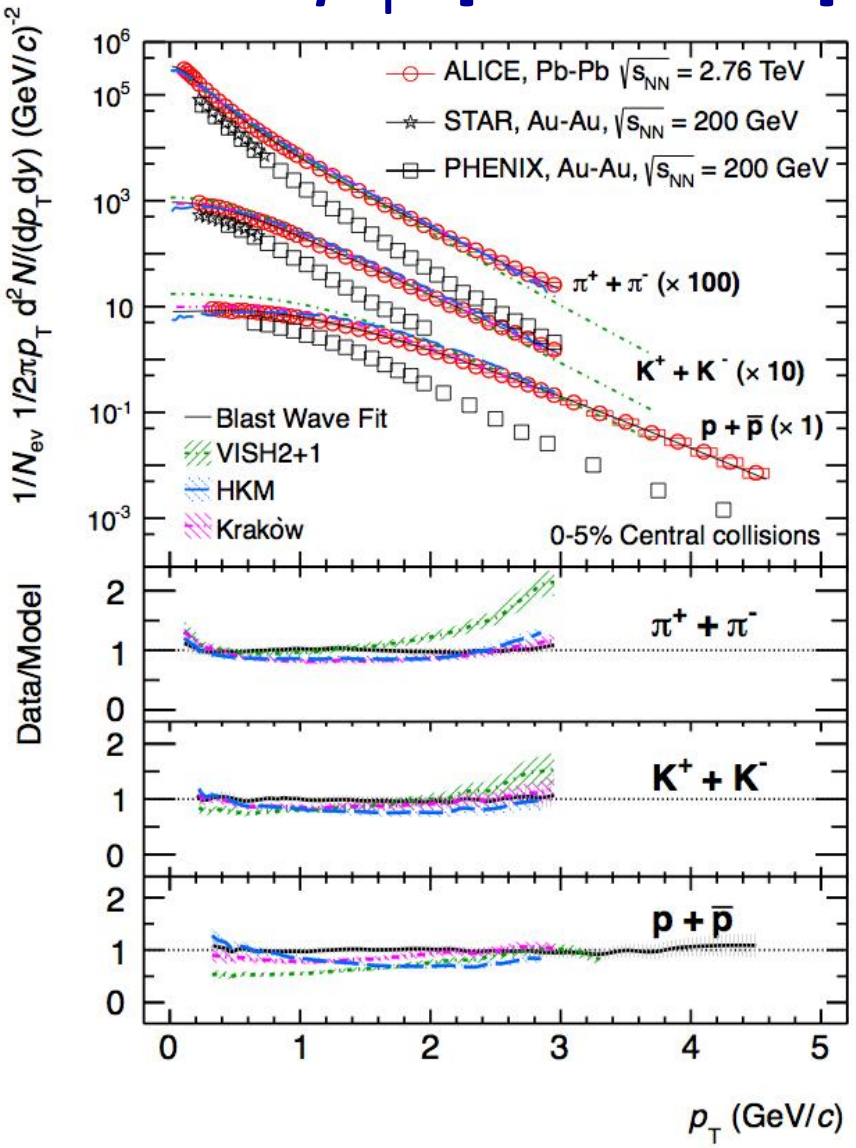
5. It has been suggested [18, 30, 31, 36, 78] that the p_T-dependence of HBT radii in very small systems might reflect bulk collective flow, as it is believed to do in heavy ion collisions. This is the only explanation that would automatically account for the nearly identical p_T-scaling discussed in Section V A. However, it is widely believed that the system created in $p+p$ collisions is too small to generate bulk flow.

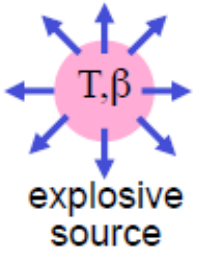
The remarkable similarity between the femtoscopic systematics in heavy ion and hadron collisions may well be coincidental. Given the importance of the m_T-dependence of HBT radii in heavy ion collisions, and the unclear origin of this dependence in hadron collisions, further theoretical investigation is clearly called for. Additional comparative studies of other soft-sector observables (e.g. spectra) may shed further light onto this coincidence.

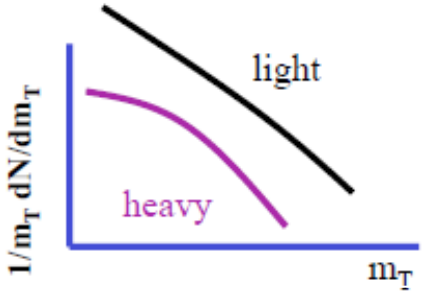
STAR http://arxiv.org/abs/1004.0925

Slide from Jurgen Schukraft

Low-p_T particle production in Pb-Pb







Low-p_T spectra : superposition of thermal motion with collective radial expansion

Strong collectivity in transverse direction, spectra harder than at RHIC

"Blast-Wave" fit to p_T spectra [1]:

→ Radial flow velocity $\langle\beta\rangle \approx 0.65$

10 % larger than at RHIC

→Kinetic freezout temp. $T_K \approx 95$ MeV

same as RHIC within errors

To correctly describe protons additional processes needed after chemical freeze-out

arXiv:1208.1974 [hep-ex]
[1] E. Schnedermann, et al.; Phys. Rev. C48, 2462 (1993)

Low-p_T particle production in p-Pb

Blast-Wave

hydro-motivated

fit thermal sources expanding with common velocity

Krakow

3+1 viscous hydro

DPMJET

pQCD based

EPOS LHC

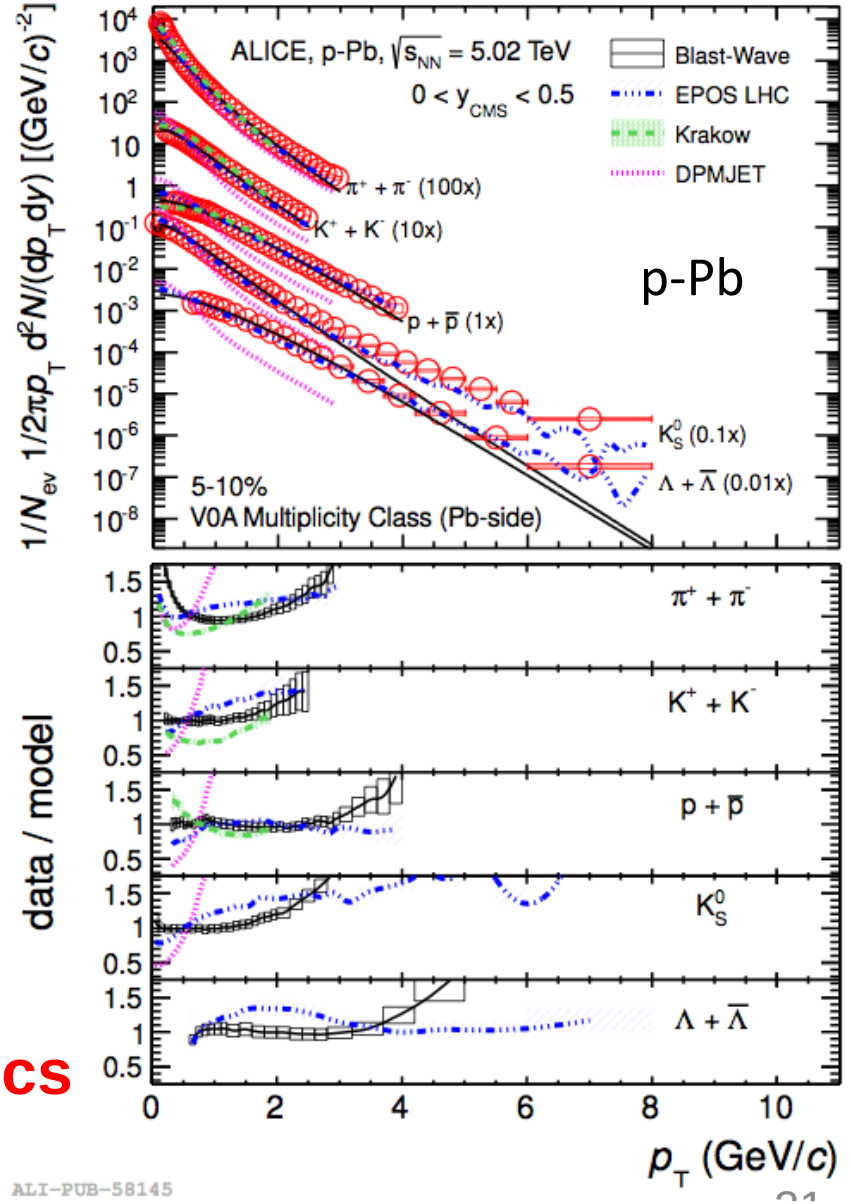
full event generator

with hydro evolution

Based on Gribov-Regge theory

Initial hard and soft scatterings create flux tubes that either escape the medium and hadronize as jets or contribute to the bulk matter described by hydrodynamics

Models including hydrodynamics describe the data better



ALI-PUB-58145

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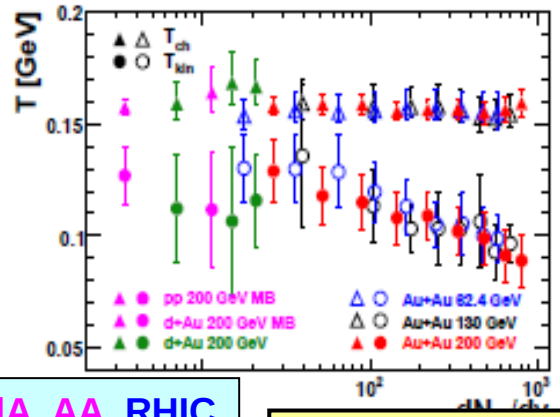
Momentum Spectra

STAR http://arxiv.org/abs/0808.2041



pp, dA, AA RHIC

Radial Flow fit (BW):
T & <β> vs dN_{ch}/dy

FIG. 36: (color online) Chem
peratures as a function of
Errors shown are the total
tainties. The 200 GeV *pp* and Au+Au data are taken from
Ref. [17].

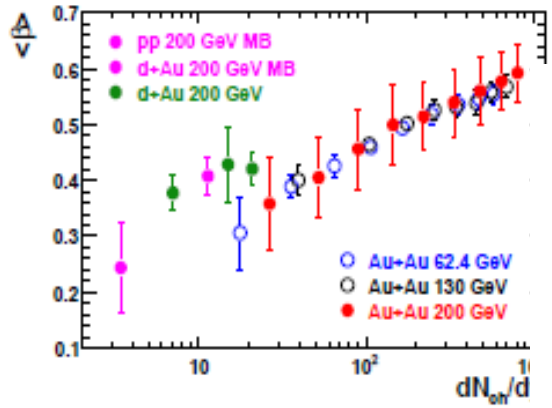


FIG. 37: (color online) Average transverse radial flow v
ity extracted from blast-wave model fit to *pp* and d+A
200 GeV, and to Au+Au collisions at 62.4 GeV, 130
and 200 GeV as a function of the charged hadron multipl
Errors shown are the total statistical and systematic u
tainties. The 200 GeV *pp* and Au+Au data are taken
Ref. [17].

The interpretation of the fit parameters is difficult in the context of a $p+p$ collision where the system is not expected to thermalize and the volume is small. It is important to note that in a pure thermal model, all emitted particles would be expected to reflect the same temperature. Non-thermal effects such as flow would modify this result. In $p+p$ collisions, the particle spectra clearly show different slopes and those slopes are not in agreement with the T parameter that results from the statistical model fit to the particle ratios. As no flow is thought to be present in the $p+p$ system and the results of Section IV B support that conclusion, this result is a further indication of contributions to the particle spectra from non-thermal processes like mini-jets.

pp 200 GeV

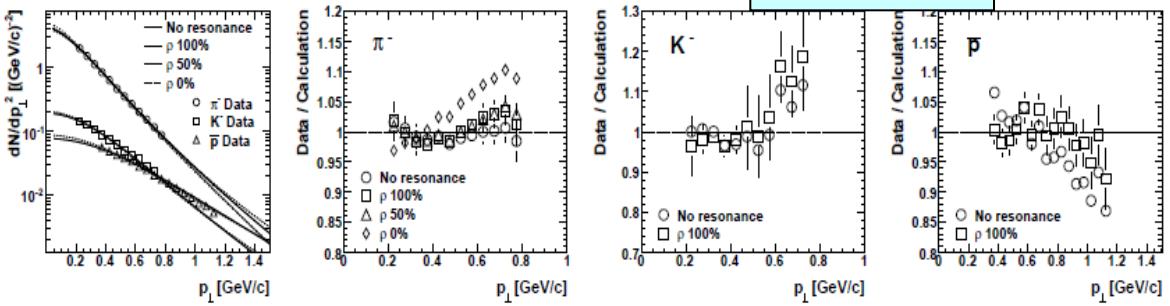
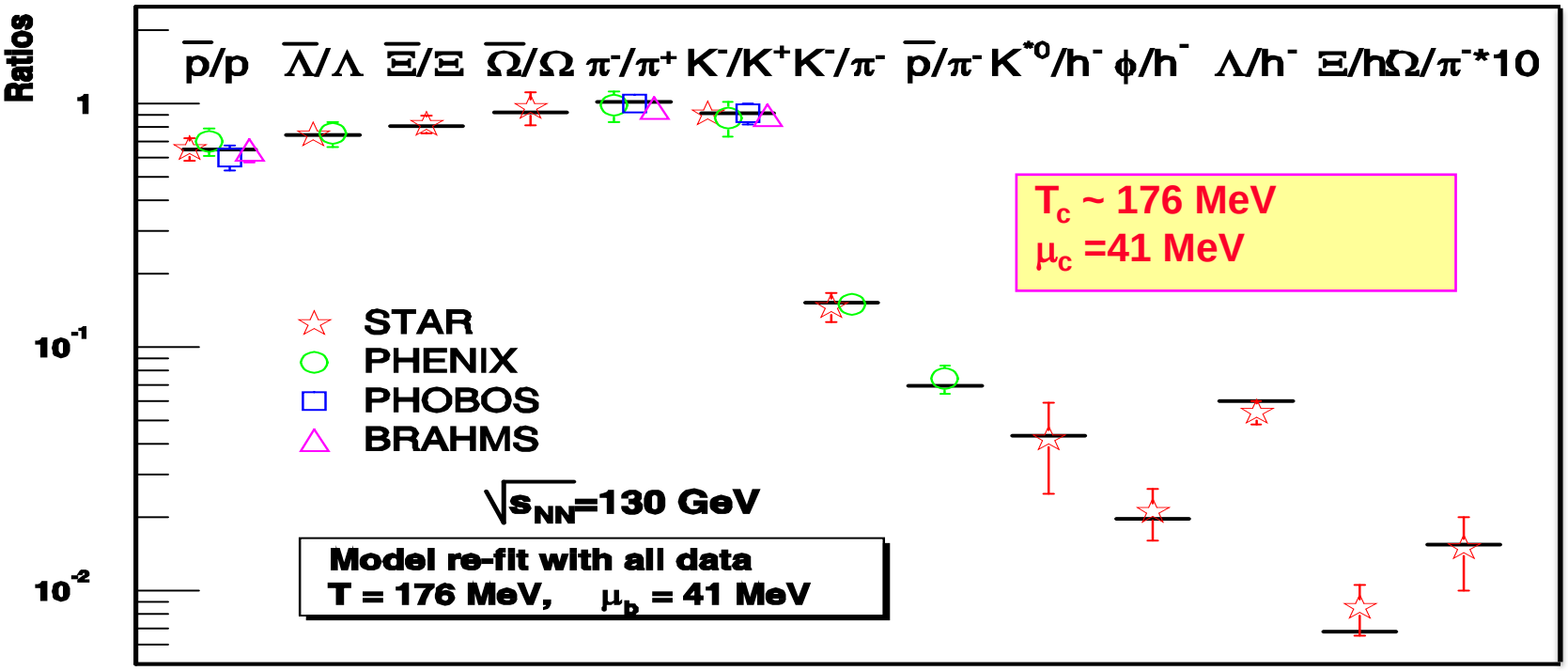


FIG. 45: Left panel: Fit of the calculated spectra (curves) to the measured ones (data points) in *pp* collisions at 200 GeV [17]. Four calculated spectra are shown for π^- (upper curves): including resonances with three different ρ contributions and excluding
curves) and $\bar{p}$ (lower curves): including resonances with
spectrum to calculations. Two calculations are shown for
re the quadratic sum of the statistical and point-to-point
a

Radial Flow fit (BW):
Data/Fit (π,K,p)

Slide from Jurgen Schukraft

Thermal Model from RHIC to LHC



Within the framework of thermal models

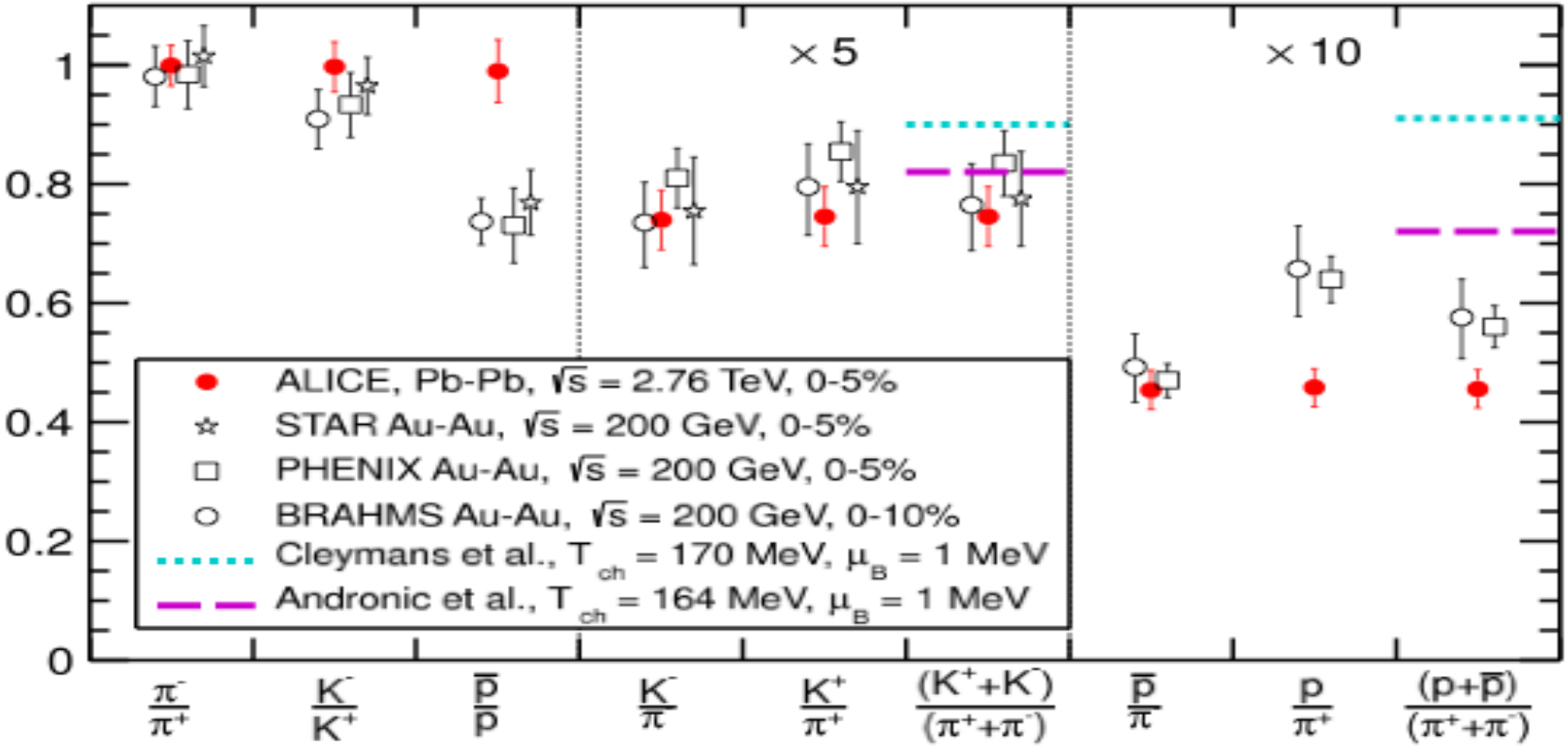
baryochemical potential

μ_β = 41 MeV

chemical freezout temperature

T ~ 176 MeV

Thermal Model from RHIC to LHC



Within the framework of thermal models

baryochemical potential

μ_β = 1 MeV

chemical freezout temperature

T ~ 164 MeV

PRL 109 (2012) 252301

At LHC

p/π ratio significantly (~1.5x) lower than expectations from RHIC extrapolations

hadronic re-interactions ?

F.Becattini et al. 1201.6349

J.Steinheimer et al. 1203.5302

baryon-antibaryon annihilation ?

Particle production

No quantitative interpretation which smoothly describes small & large

despite evident relevance for understanding HOW we reach thermal ratios..

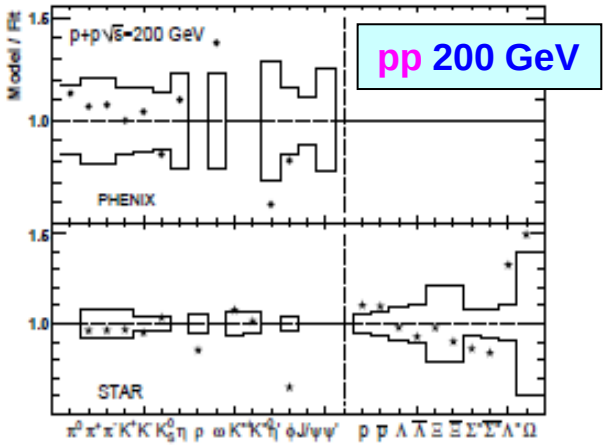


FIG. 18: Ratio of integrated yields predicted by the statistical model [40] to those of the constrained Tsallis fits for various particles. Results for fits to PHENIX data are shown in the upper panel and STAR data in the lower panel. The band reflects the uncertainty of the Tsallis fit results and includes

Particle production:
Data /Thermal Model

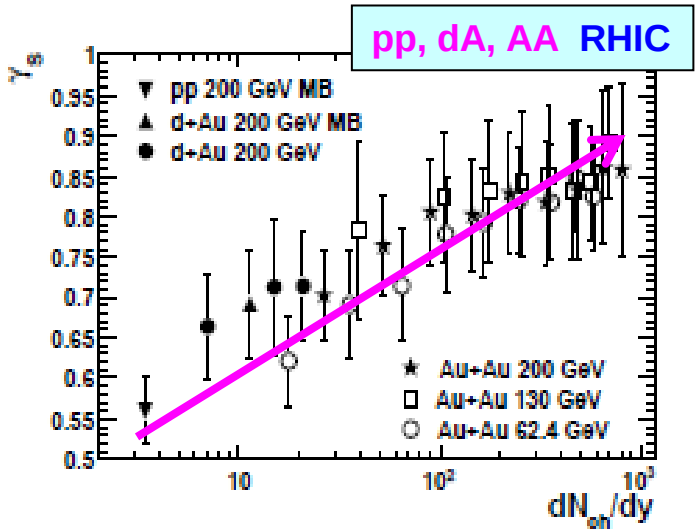


FIG. 35: Strangeness suppression factor extracted from chemical equilibrium model fit to pp and d+Au data at 200 GeV, and Au+Au data at 62.4 GeV, 130 GeV, and 200 GeV. Errors shown are t
ties. The 200 G
Ref. [17].

Particle production:
γ_s vs dN_{ch}/dy

Although statistical models are not commonly used to describe $p+p$ data the agreement of the statistical model calculation with the STAR results was found to be accurate for most particles except for the ρ, ϕ, and Λ^* [40]. Leaving aside baryons, for which the calcula-

nificantly suppressed in these collisions. The strangeness suppression factor in medium-central to central Au+Au collisions is not much below unity; the strangeness and light flavor are nearly equilibrated, which may suggest a fundamental change from peripheral to central collisions.

Phenix http://arxiv.org/abs/1005.3674

STAR http://arxiv.org/abs/0808.2041

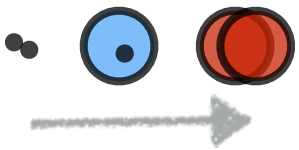
STAR http://arxiv.org/abs/nucl-ex/0607033

Particle ratios at LHC

Overview of particle production

Particle ratios evolve as a function of the system size

from small (pp), intermediate (p-Pb) to large (Pb-Pb) collision systems

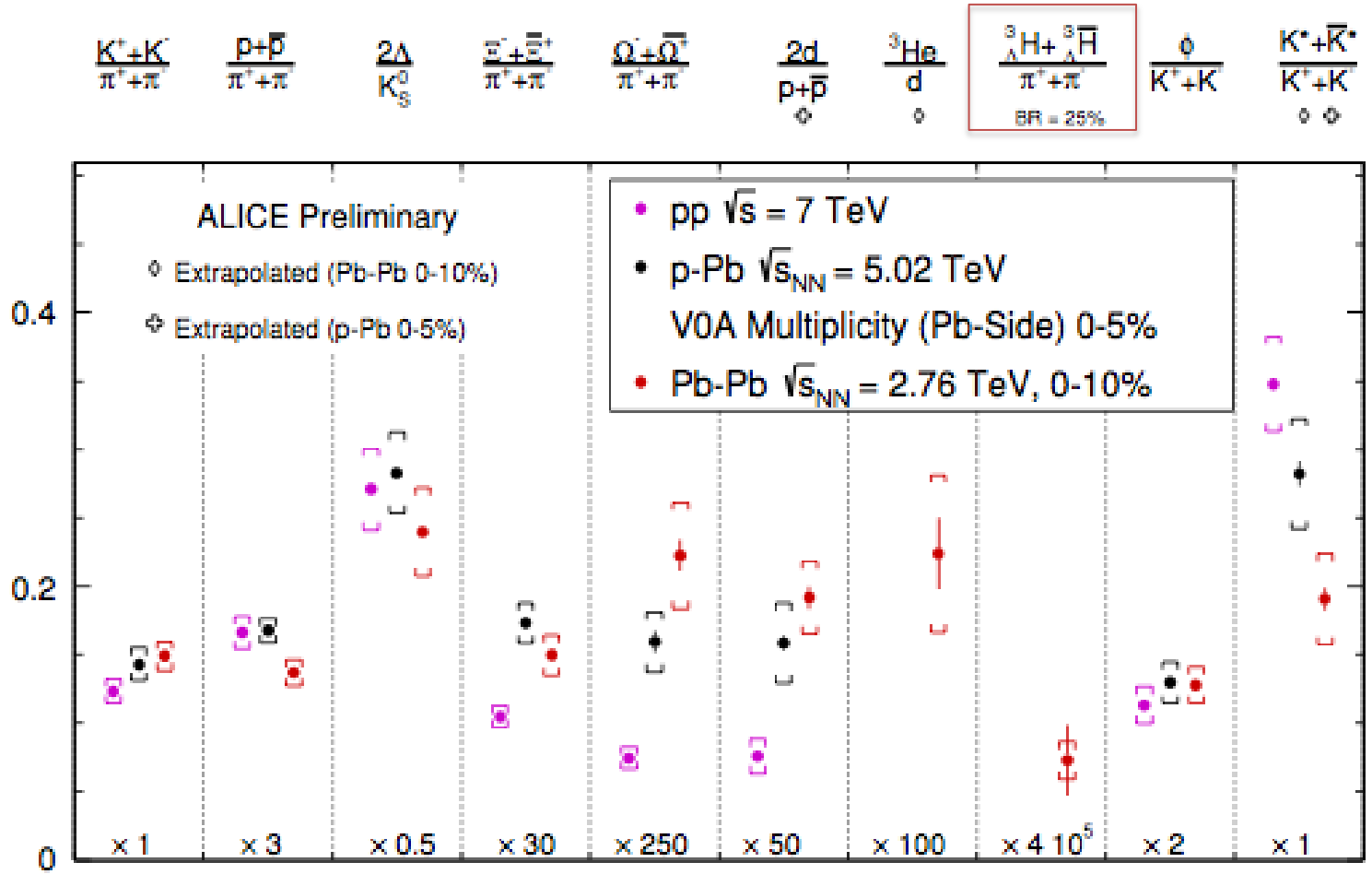


strangeness enhancement

deuteron enhancement

baryon suppression

K* suppression



Baryon-to-meson in p-Pb and Pb-Pb

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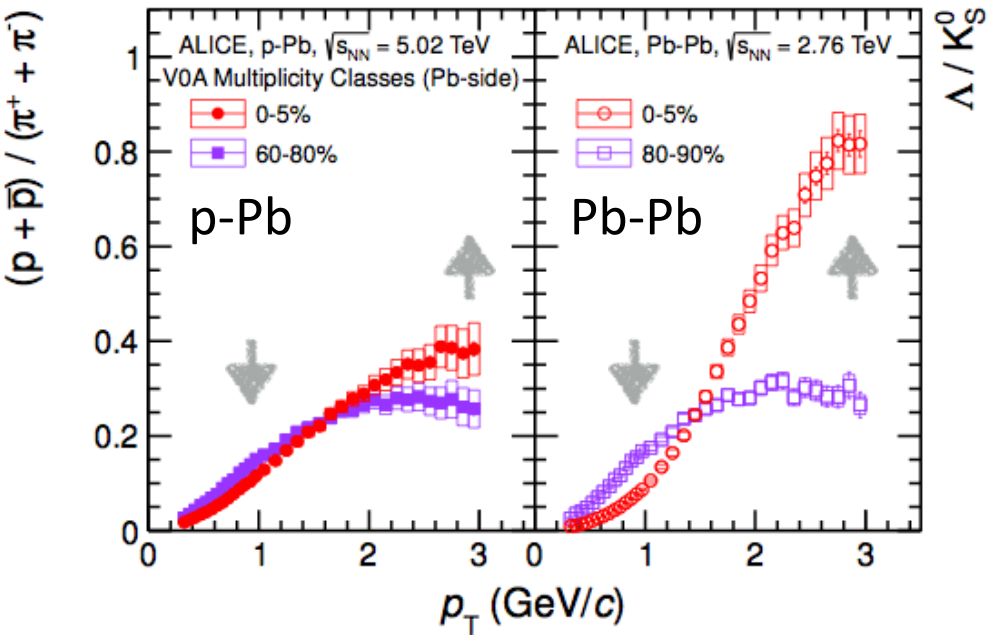
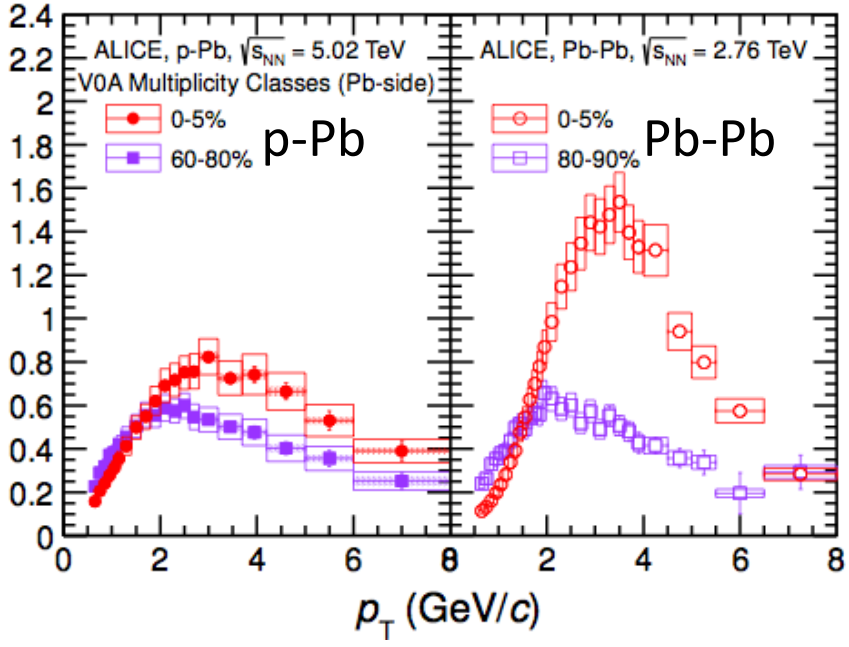


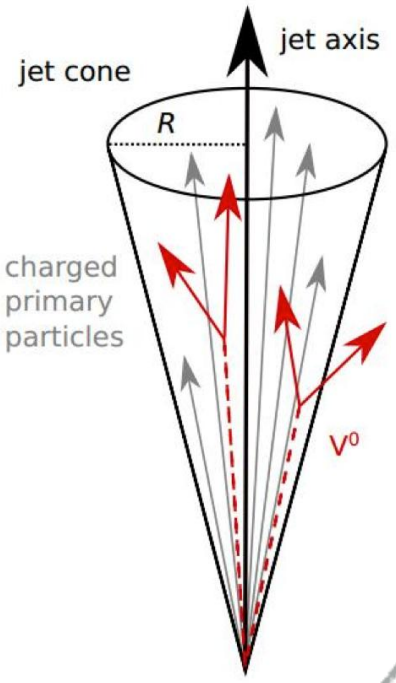


Baryon-to-meson enhancement first observed at RHIC at intermediate pt

Significant centrality/multiplicity dependence of the ratios
enhancement at intermediate-p_T with increasing multiplicity
corresponding depletion in the low-p_T region

Reminiscent of A-A observations
commonly understood in terms of **collective flow**

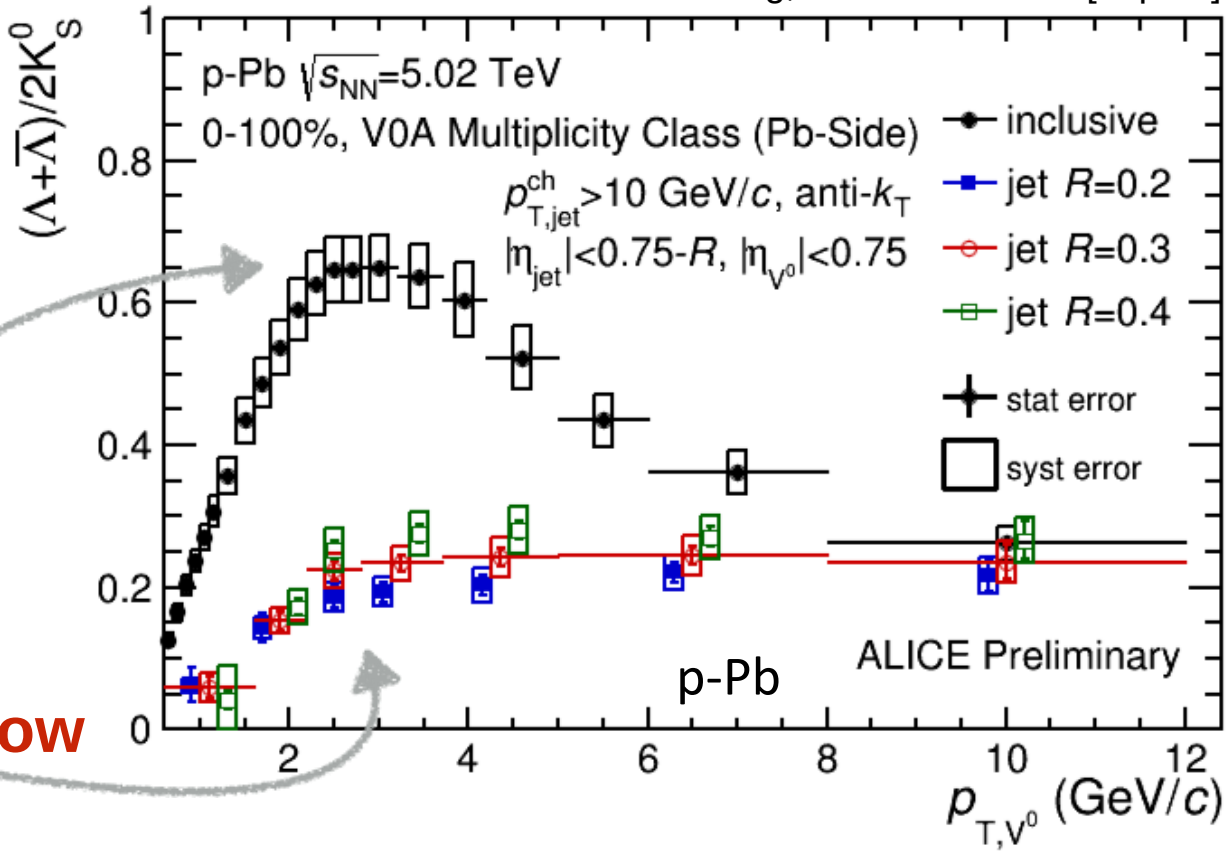
What is the origin of extra baryons ?



inclusive particles

Λ/K^0_S production ratio in p-Pb measured in charged jets

Zhang, arXiv:1408.2672 [hep-ex]



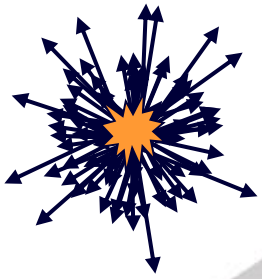
jets do not show enhancement

the extra baryons are not coming from jets

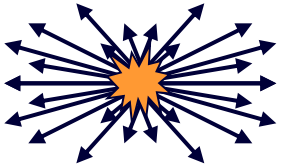
Elliptic flow

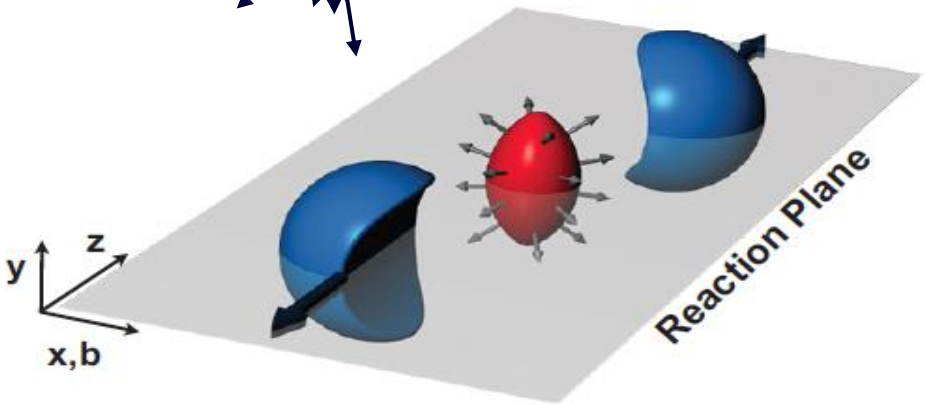
In non-central collisions, pressure gradient transforms the initial spatial anisotropy into the observed momentum-space anisotropy

Superposition of independent pp collisions:
momenta pointed at random relative to reaction plane



Evolution as a **bulk system:**
Pressure gradients (larger in-plane) push bulk "out" → "flow"





Azimuthal distribution described by a Fourier expansion

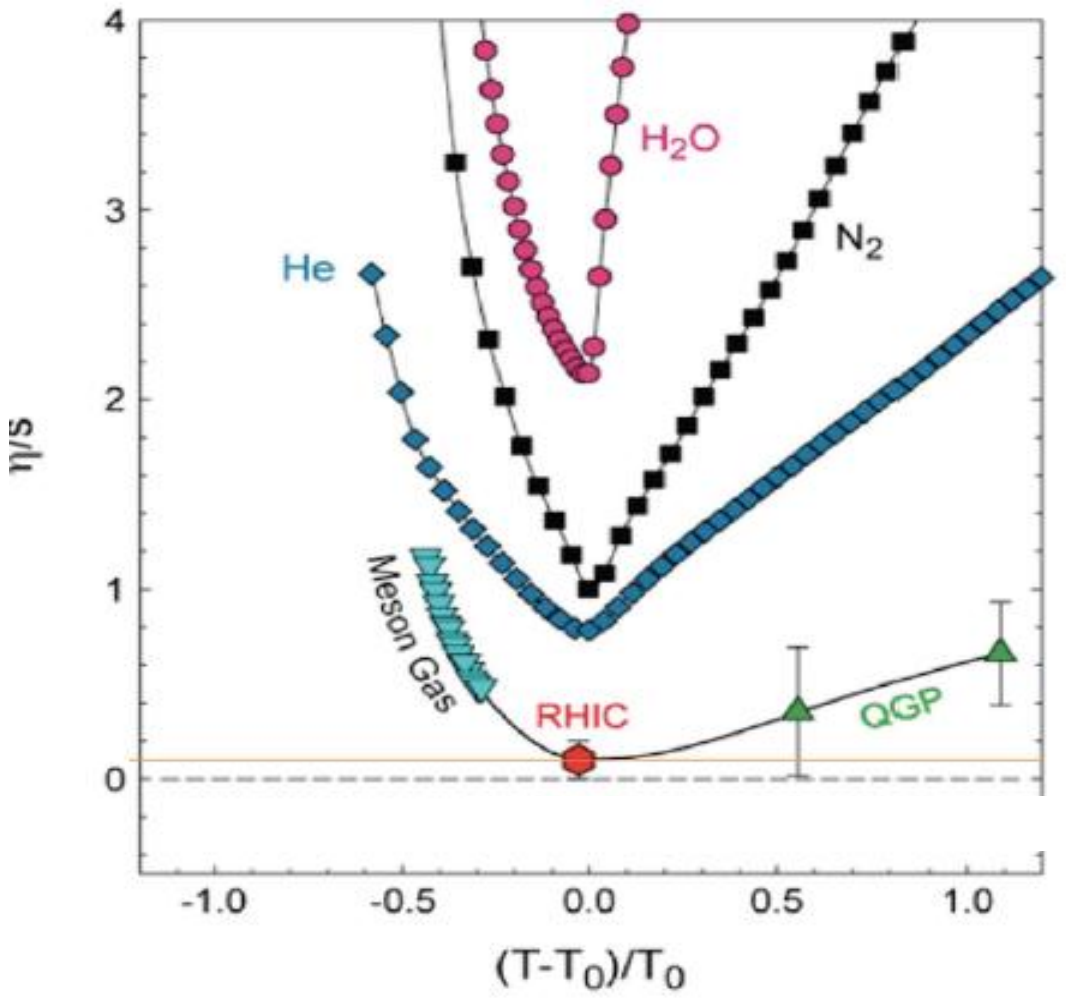
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

$$v_n\left(p_t, y\right) = \left\langle \cos\left[n\left(\phi - \Psi_n\right)\right] \right\rangle$$ measured with two and multi-particle correlations

v_2 : elliptic flow (v_1 : directed flow v_0 : radial flow)

S. Voloshin and Y. Zhang, Z. Phys. C70, 665 (1996)

Elliptic flow



Perfect liquid at RHIC

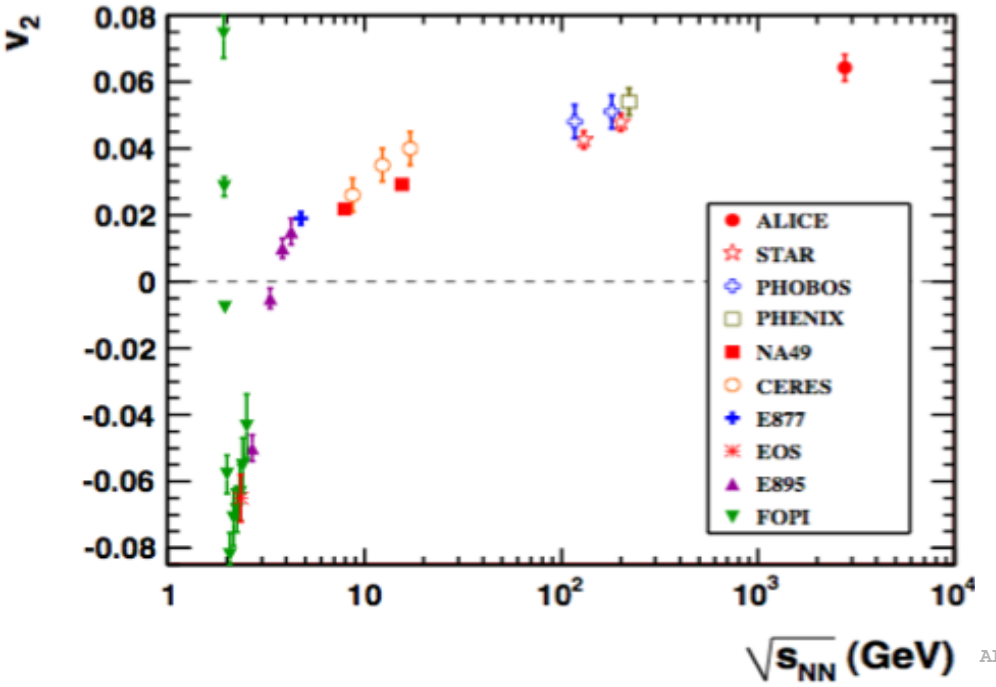
Lower viscosity than water !!

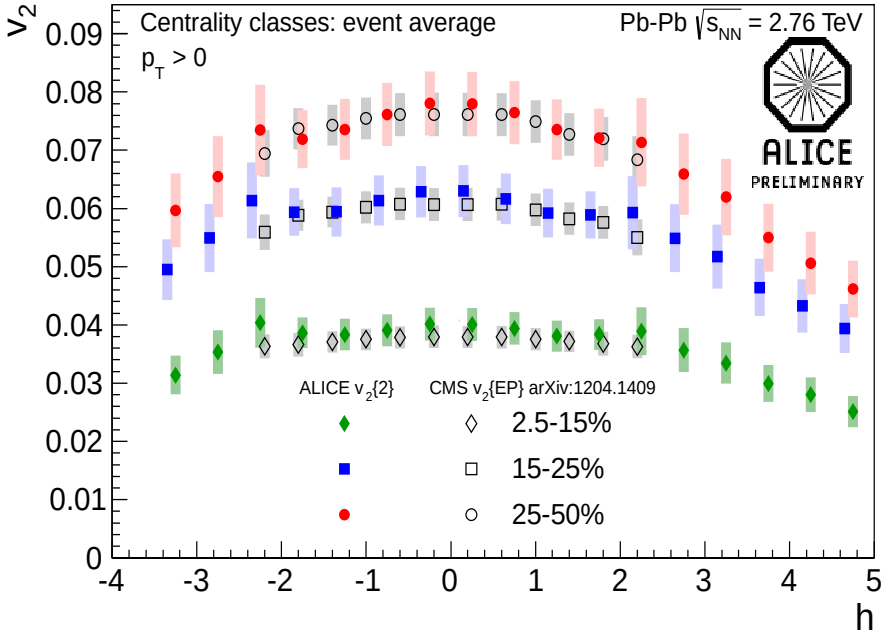
Precision measurements show a hint of temperature dependence slightly increasing from RHIC to LHC

Connection to viscosity η/s

➔ **RHIC and LHC values close to the lower theoretical values of 1/4π** (given by AdS/CFT)

Elliptic flow





First LHC results confirmed hydrodynamic predictions

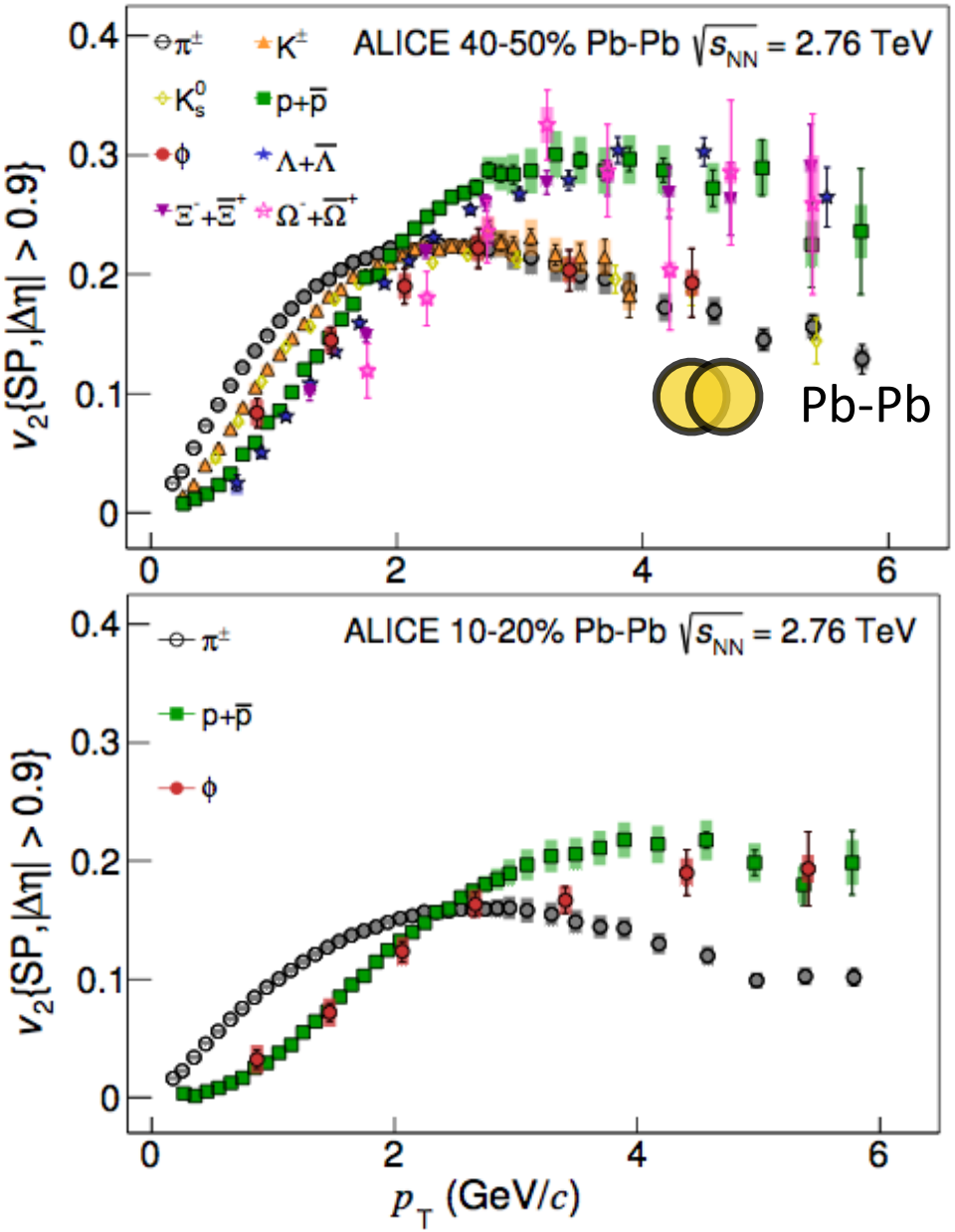
- Medium at LHC: an almost perfect strongly interacting liquid with minimal viscocity, like at RHIC

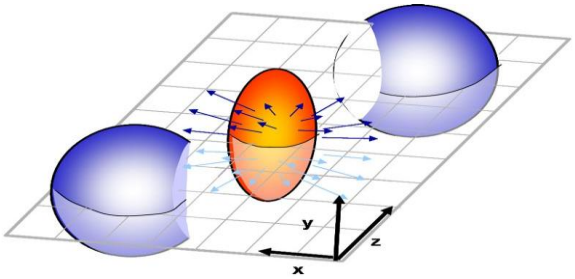
Extended v2 measurements at wide η and p_T range

- in agreement with hydrodynamics: increase from RHIC to LHC
  - 20-30% at mid-rapidity
  - 30% at forward rapidity

v_2 of identified particles in Pb-Pb

arXiv:1405.4632 [nucl-ex]





v_2 of identified particles further constrains properties of the deconfined phase: viscosity over entropy-density (η/s) of hot dense medium

v_2 measured for
$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, φ, Λ, Ξ, Ω

φ, meson with mass similar to proton ; clarify if mass ordering effects are due to mass or quark content

ϕ meson behaves like a proton

mass drives v_2 and spectra, not number of constituent quarks as was observed at RHIC

v_2 of identified particles in p-Pb

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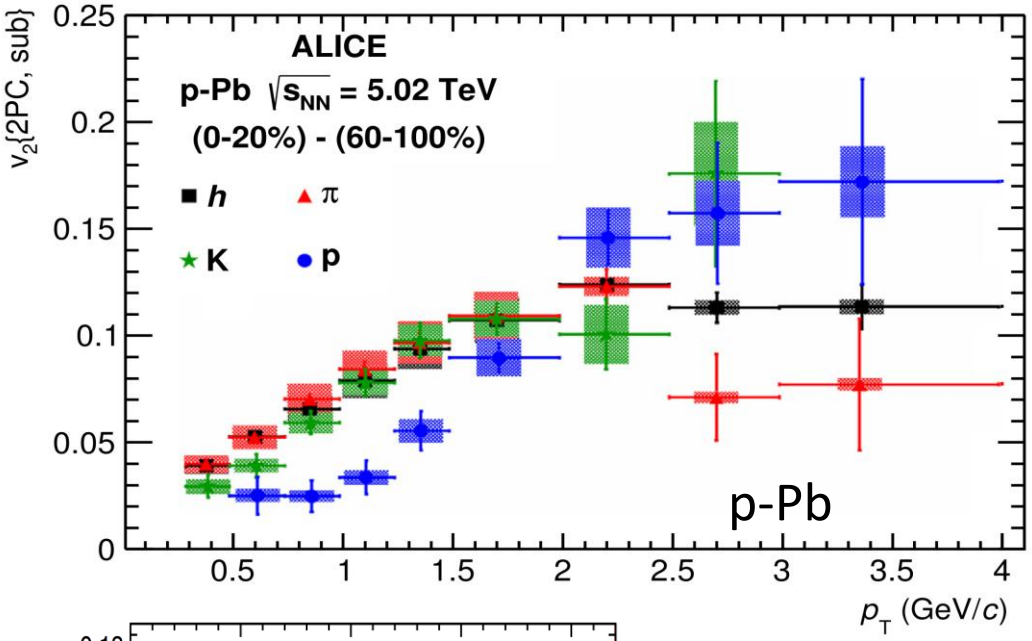
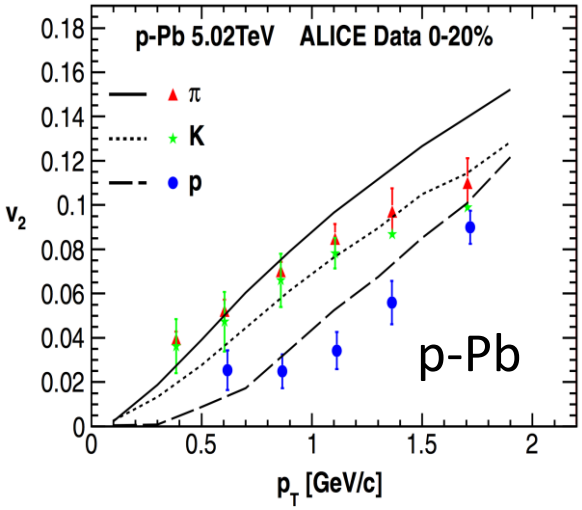


mass ordering observed at low p_T
lower v_2 for heavier particles
crossing at higher p_T

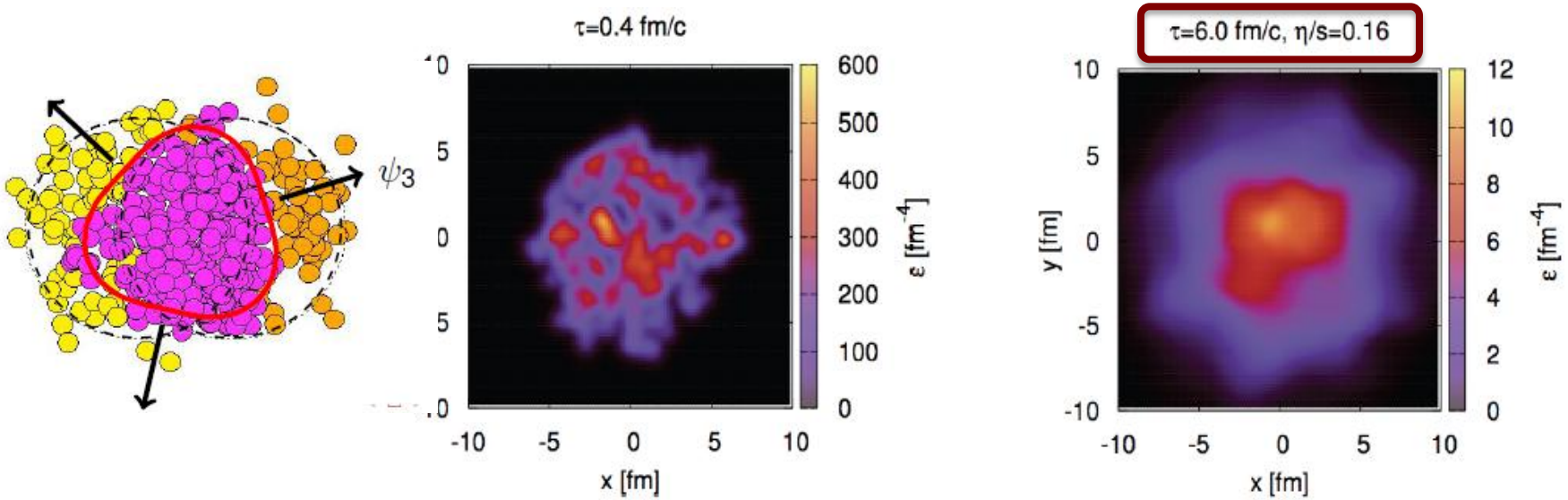


consistent with expectations
from collective hydrodynamic expansion
Bozek et al., PRL 111 (2013) 172303

Higher harmonics and initial state

Measurable complex flow patterns with v_n up to 6th order

- **Initial geometry not described by the ideal almond shape**
  - Fluctuations of initial energy/pressure distributions lead to "irregular" shapes fluctuating event-by-event
  - Higher (odd) harmonics each one having its own symmetry plane
- **Higher harmonics more sensitive to the value of shear viscosity**



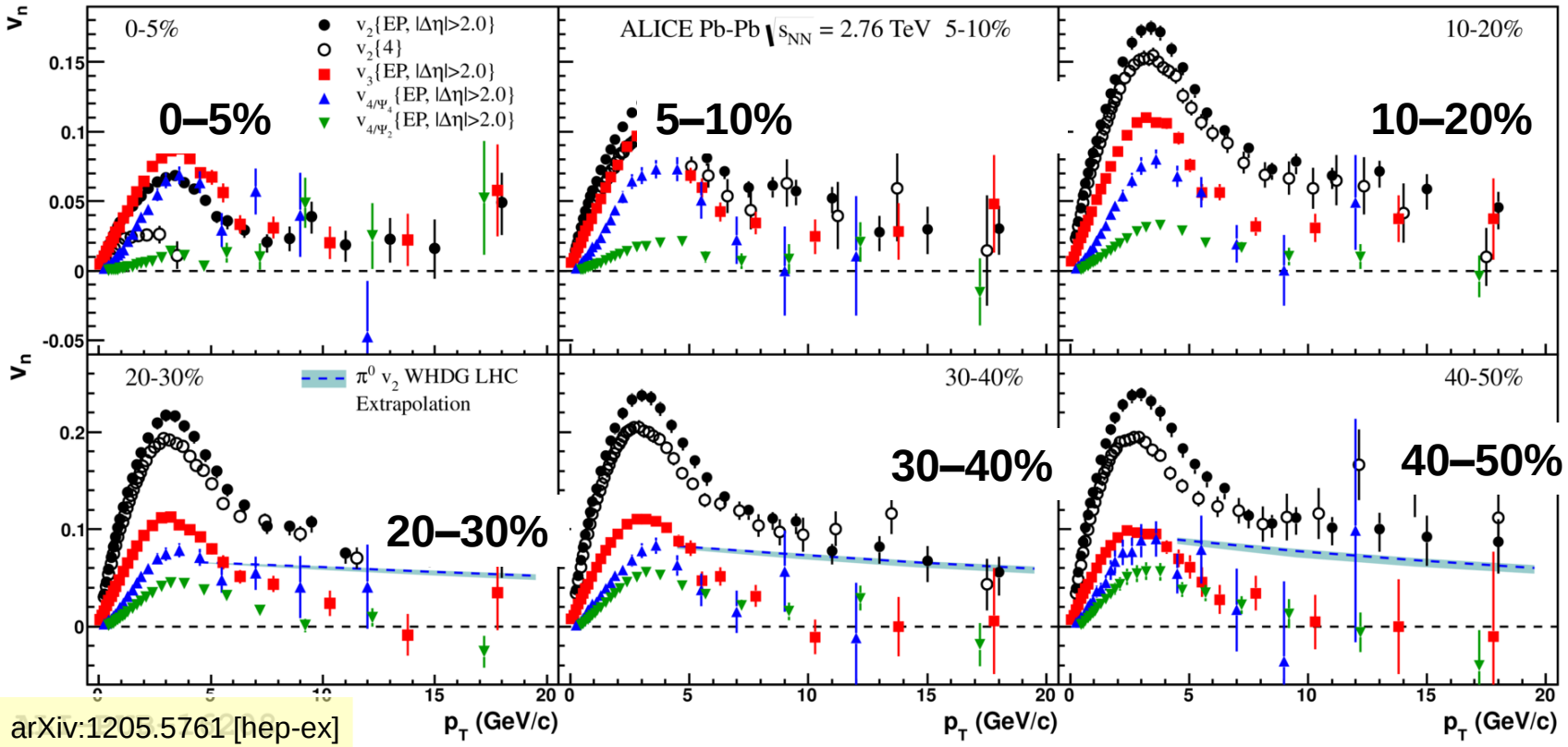
Hydro simulation of initial state (ideal and viscous hydro): fluctuations of initial state are damped by viscosity

Understood to arise

- **from event-by-event fluctuations of the initial geometry**
- **or/and CGC initial state**

Extending v_n measurements in p_T

v_n measurements up to 20 GeV/*c*



arXiv:1205.5761 [hep-ex]

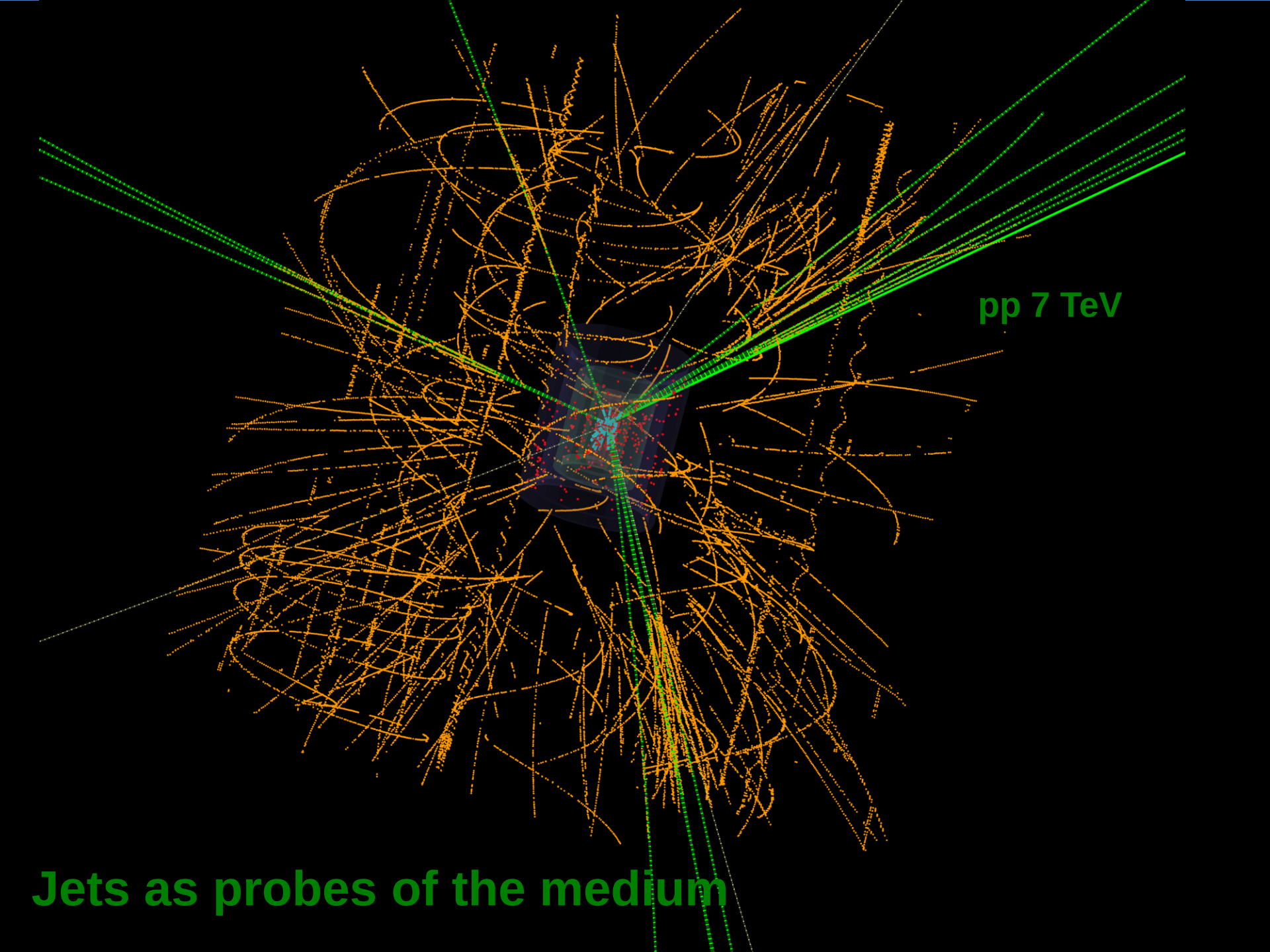
v_2 non-zero up to high p_T : where dominated by jet quenching

- **v_2 at low- p_T :** degree of thermalization
- **v_2 at high p_T :** path - length dependence of energy loss

Higher harmonics provide important constraints on the physics and origin of the flow fluctuations.

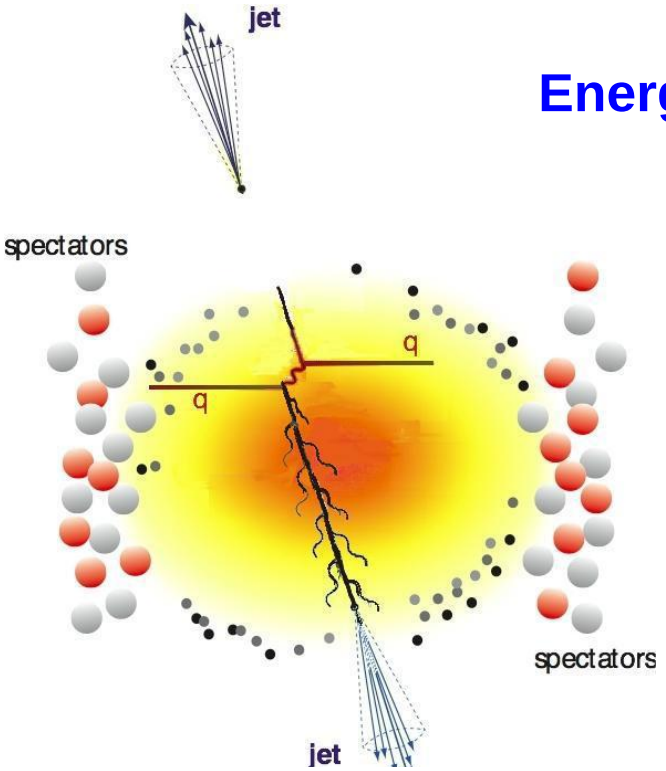
Effects of v_2 and v_3 interplay on Ridge and higher harmonics

Talk by Evgeny Zabrodin



Jets as probes of the medium

Jet quenching and R_{AA}

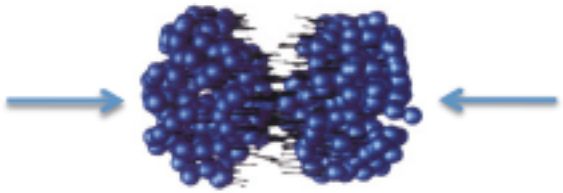


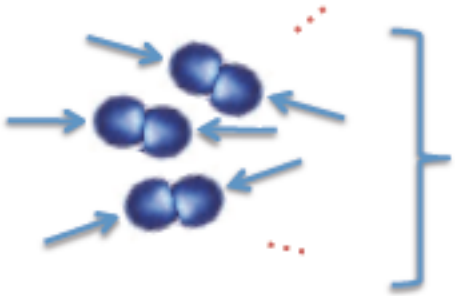
Energy loss quantified by R_{AA}

$$R_{AA} = \frac{d^2N^{AA}/dp_T dh}{\langle N_{coll}\rangle d^2N^{pp}/dp_T dh}$$

$$\langle N_{coll}\rangle = \langle T_{AA}\rangle \times \sigma_{pp}^{INEL}$$

Nuclear overlap function $\langle T_{AA}\rangle$ from Glauber related to the number of binary collisions Ncoll

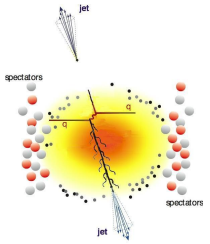


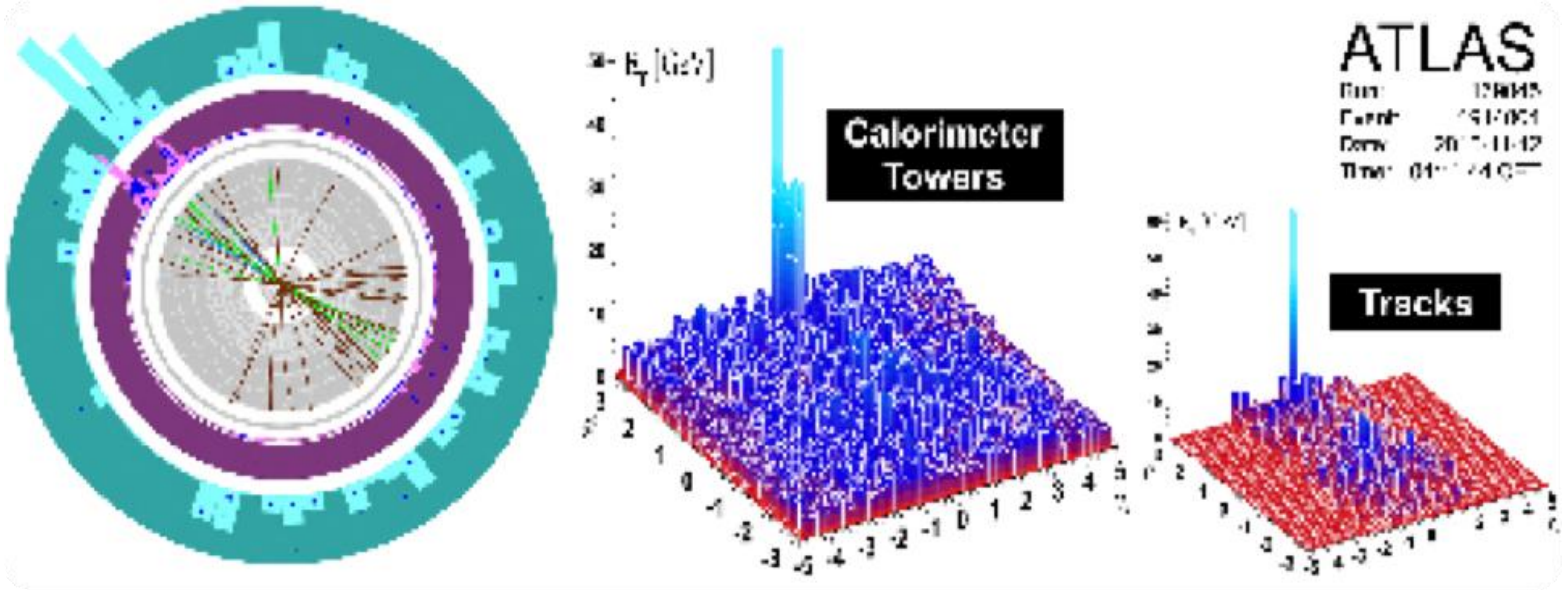


Medium effect → $R_{AA} < 1$

No medium effect → $R_{AA} \approx 1$

Jet quenching





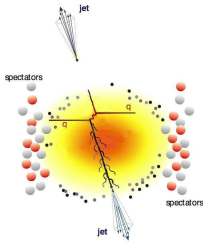
Discovered at RHIC as a suppression of high-pt leading jet fragments

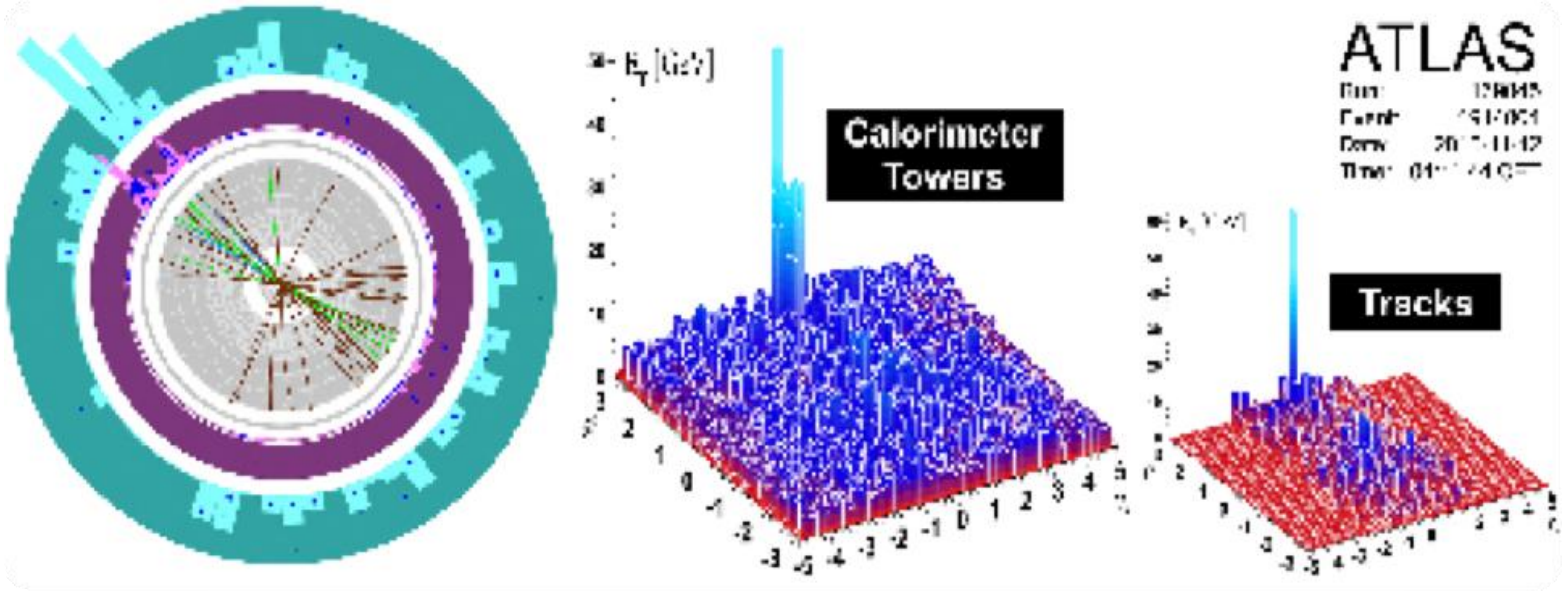
At LHC energy jets stand out:unbalanced jets, mono-jets…

While the amount of energy lost can be of order of tens of GeV

- The two jets remain essentially back-to-back (with little or no angular broadening relative to pp)
- The radiated energy ΔE is found in very low pt particles (< 2 GeV)
  and large angles relative to the jet direction.
- The parton leaves the matter and undergoes normal vacuum fragmentation
  looking like a normal pp jet but with reduced energy
- The amount of lost energy was found to depend on the path length traversed in the medium.

Jet quenching



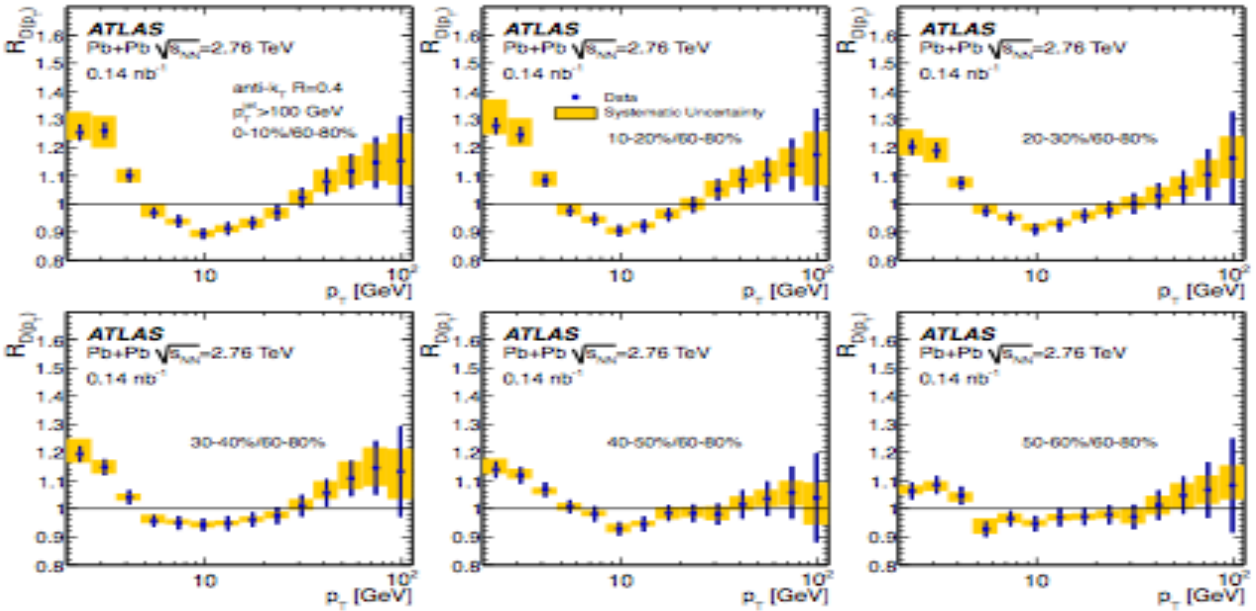


Jet fragmentation

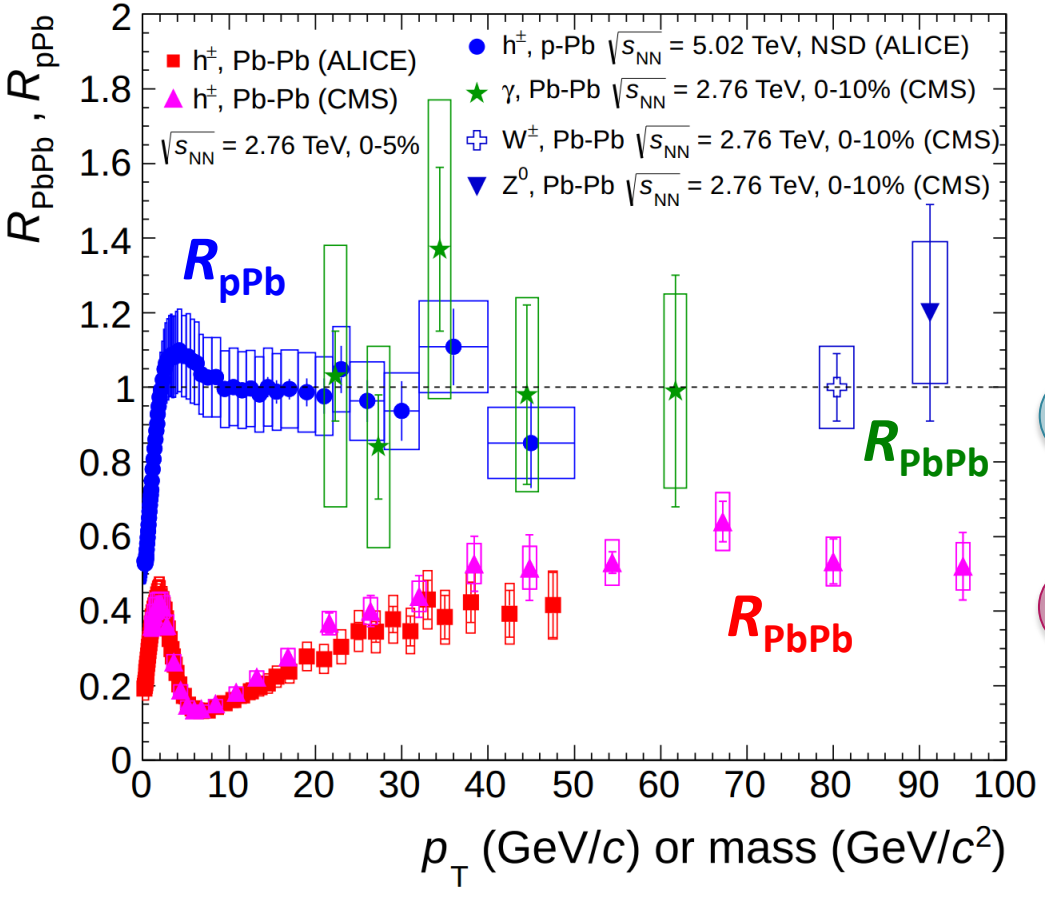
To first order

the jets still look

like vacuum jets



R_{AA} of charged particles



γ, W, Z unaffected

pPb control experiment for PbPb

p_T < 2 GeV/c : suppression

2 < p_T < 4 GeV/c : rise to 1.1 (Cronin effect)

R_{pPb} ~1 p_T > 6 GeV/c

- **Absence of nuclear modification**

R_{PbPb} strong suppression

- Increases with centrality
- **NOT initial state effect**
- Final state effect

Confirmed by jets R_{AA}

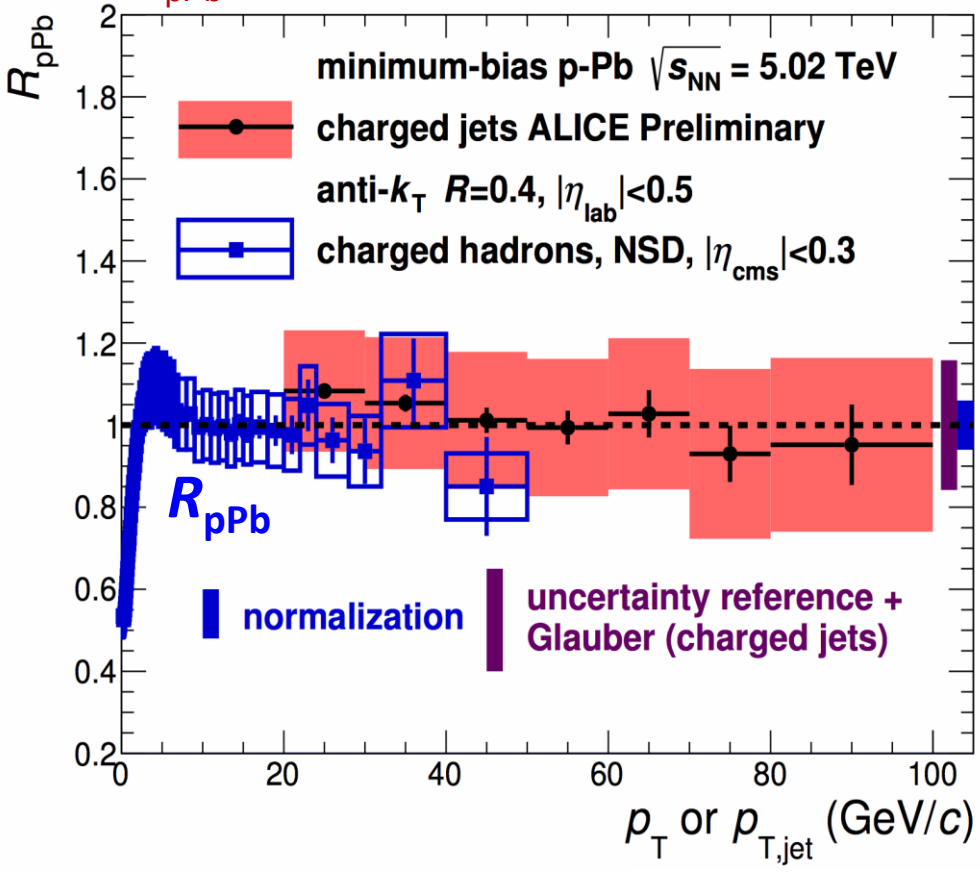
Strong suppression in central Pb-Pb fingerprint of

hot QCD matter !!

arXiv:1210.4520 [nucl-ex] PLB 696, 30 (2011)

R_{AA} of charged particles

R_{pPb} of charged particles and jets



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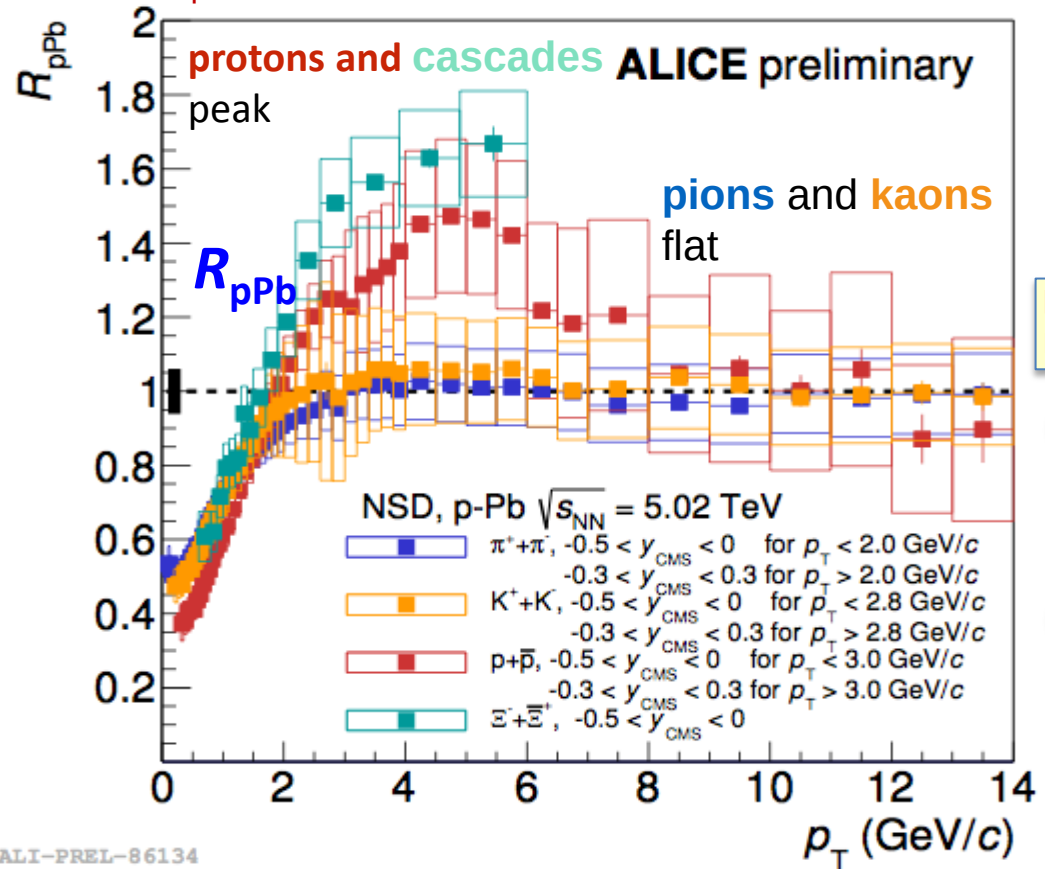
hot QCD matter !!

arXiv:1210.4520 [nucl-ex] PLB 696, 30 (2011)

R_{AA} of charged particles

R_{pPb} of identified charged particles



γ, W, Z unaffected

pPb control experiment for PbPb

p_T < 2 GeV/c : suppression

particle species dependence suggests final state effects:
recombination, collective flow, …

R_{pPb} ~1 p_T > 6 GeV/c
- **Absence of nuclear modification**

R_{PbPb} strong suppression
- Increases with centrality
- **NOT initial state effect**
- Final state effect

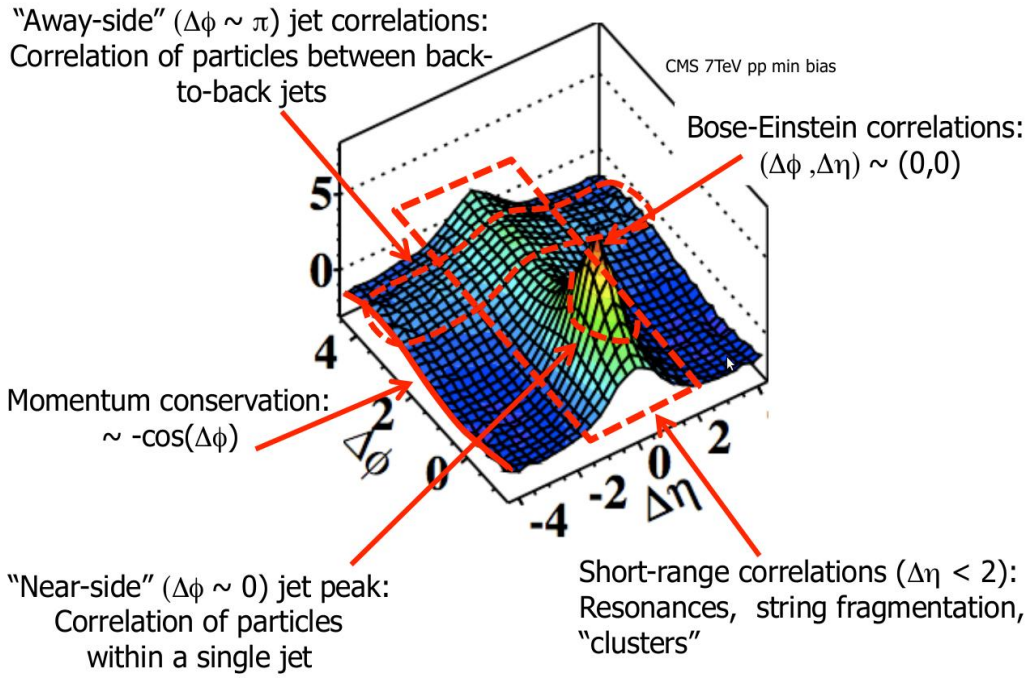
Confirmed by jets R_{AA}

Strong suppression in central Pb-Pb fingerprint of

hot QCD matter !!

arXiv:1210.4520 [nucl-ex] PLB 696, 30 (2011)

Interplay of flow and jets via correlations



Particle composition not modified by medium

p/π enhancement in PbPb is result of bulk processes and not jet fragmentation

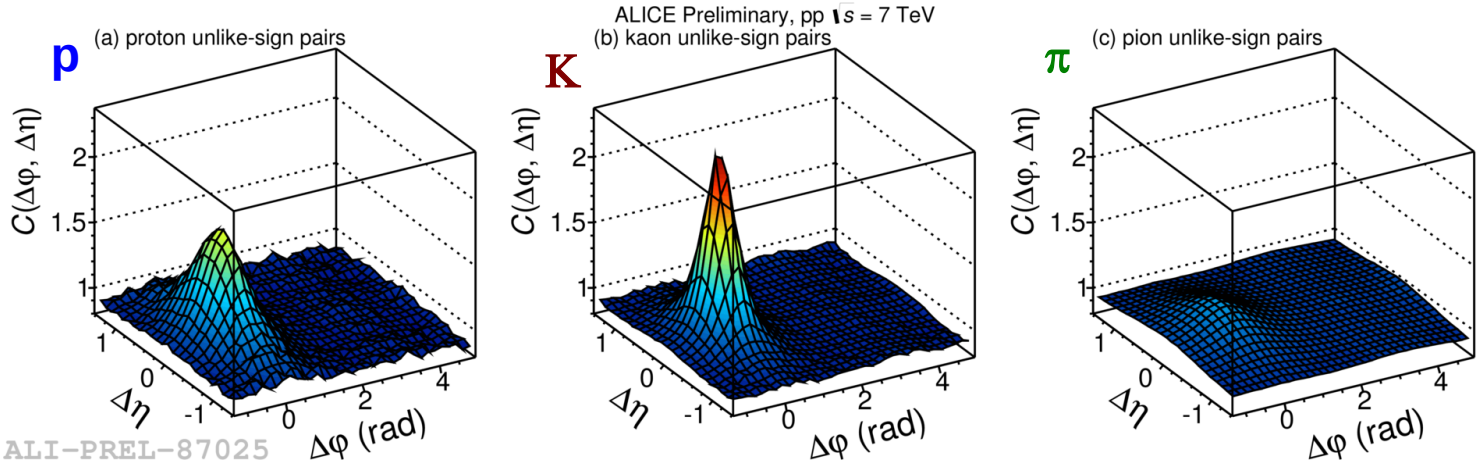
Peak evolution

jet shape affected by longitudinal flowing medium

Non-femtoscopic background in pPb

affected by jets

MC comparisons and effects of conservation laws extensively studied in **pp** using identified particles



Discoveries

The first LHC Discovery (pp, Sept 2010)

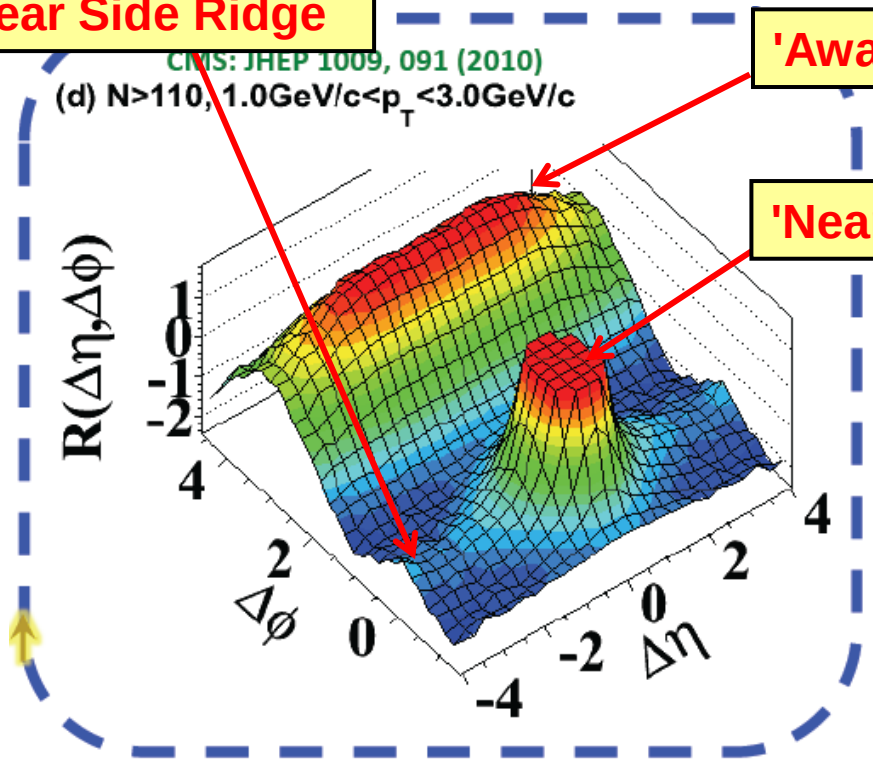
- long range rapidity 'ridge' in 2-particle correlations
  - visible in the highest multiplicity pp collisions
  - most unexpected LHC discovery

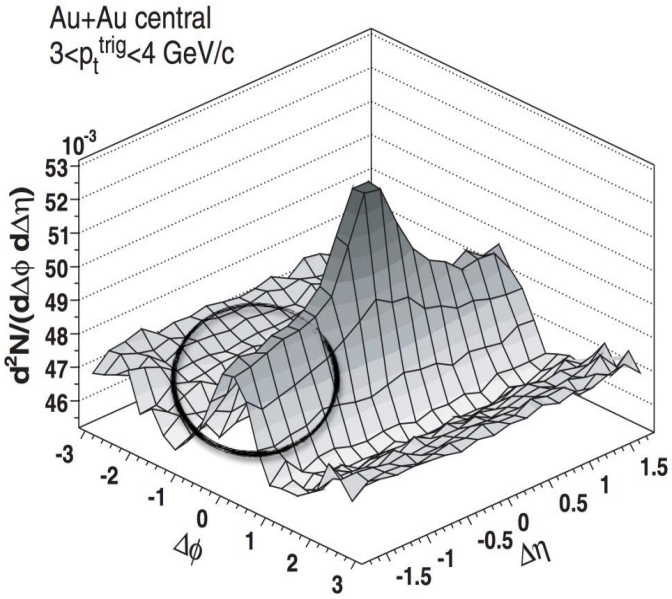
First seen at RHIC
long range correlation
in Au-Au collisions
interpreted as consequence
of hydrodynamic flow

'Near Side Ridge'

'Away Side JET'

'Near Side JET'





Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider

Scientific American, February (2011)

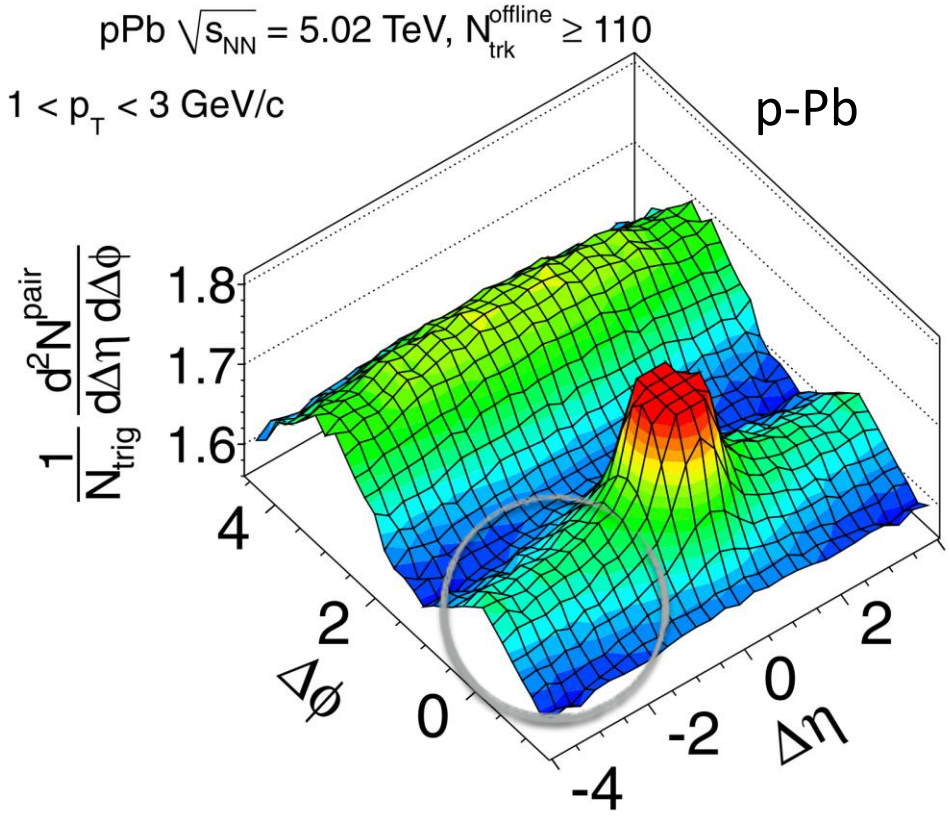
Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

If we are here today it is because we didn't succeed to kill it.

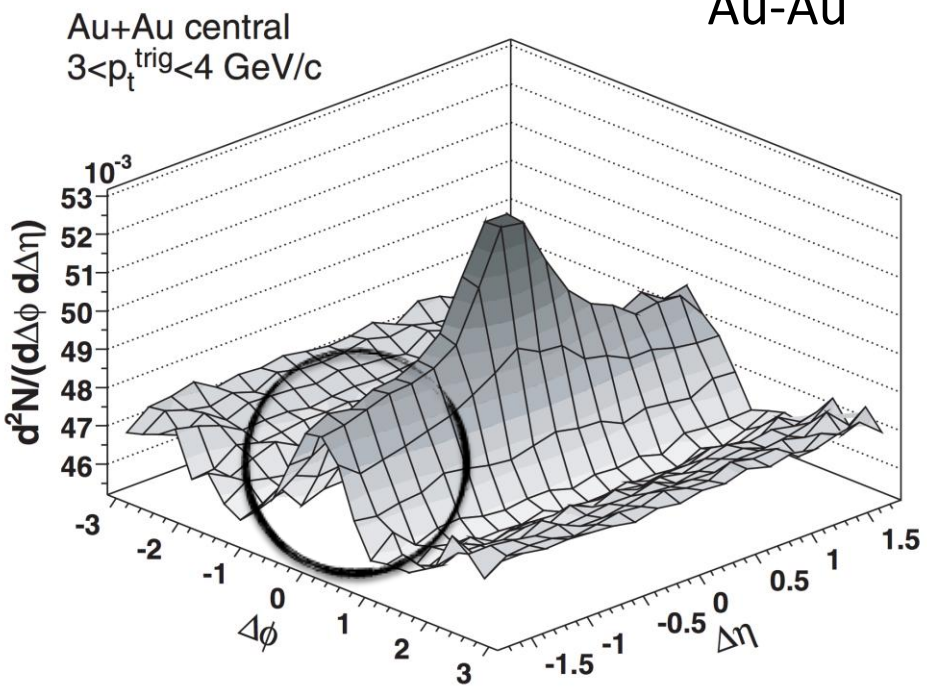
We have therefore submitted the paper to expose our findings to the scrutiny of the scientific community at large.

The 'Ridge' in p-Pb

long-range ($2 < |\Delta\eta| < 4$), **near-side** ($\Delta\varphi \approx 0$)
resembles the ridge-like correlation
first seen in Au-Au collisions at RHIC
interpreted as consequence of hydrodynamic flow



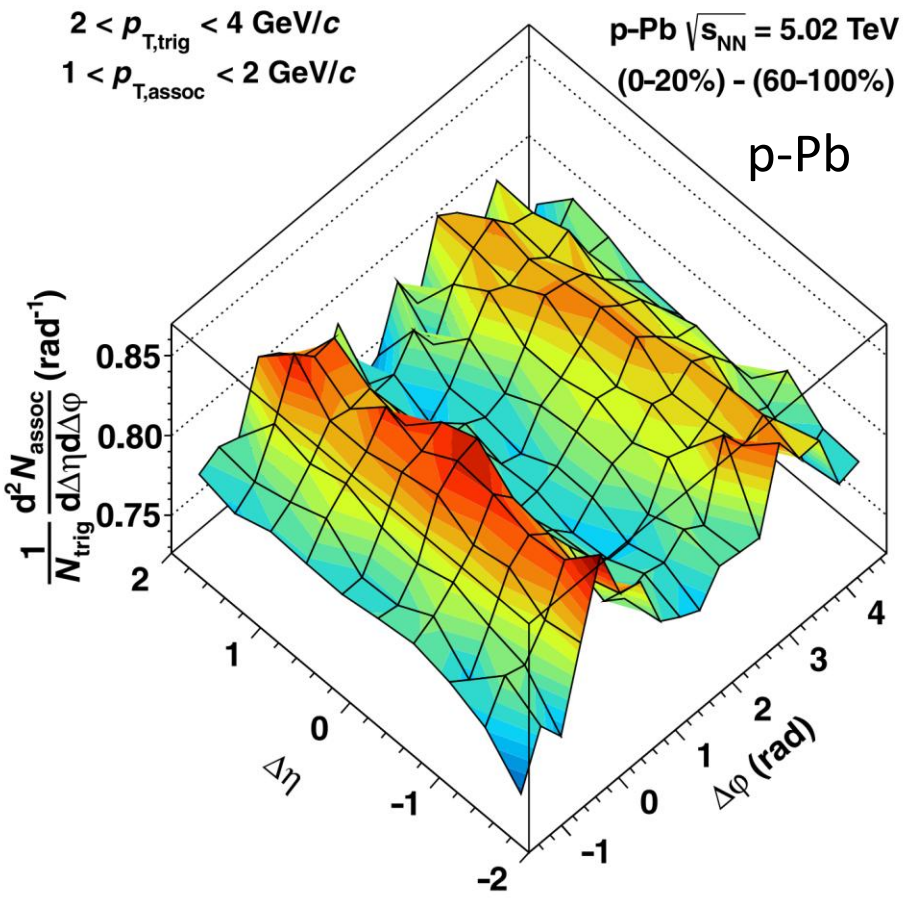
CMS, PLB 718 (2013) 795



STAR, PRC 80 (2010) 064912

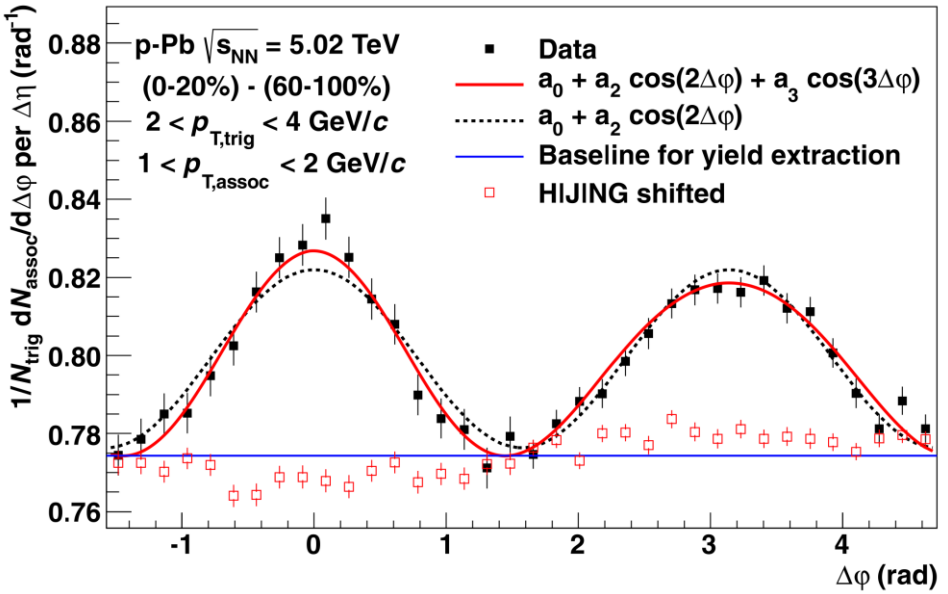
The double 'Ridge' in p-Pb

the ridge in p-Pb events triggered further investigations
removing jet contribution
a double ridge structure was revealed



this looks like flow

Fourier decomposition of Δφ: v_2, v_3, ...



ALICE, PLB 719 (2013) 29

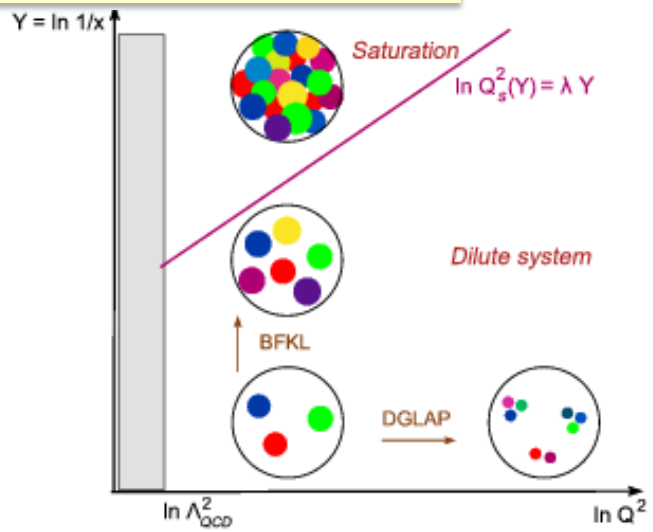
Origin of the pp 'Ridge'

- Spawned a large number of different explanations

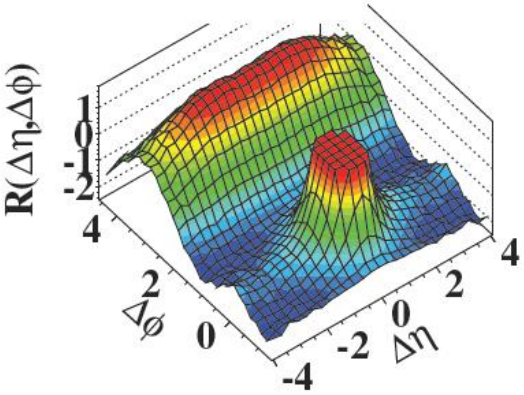
see talk of

Raju Venugopalan on Friday

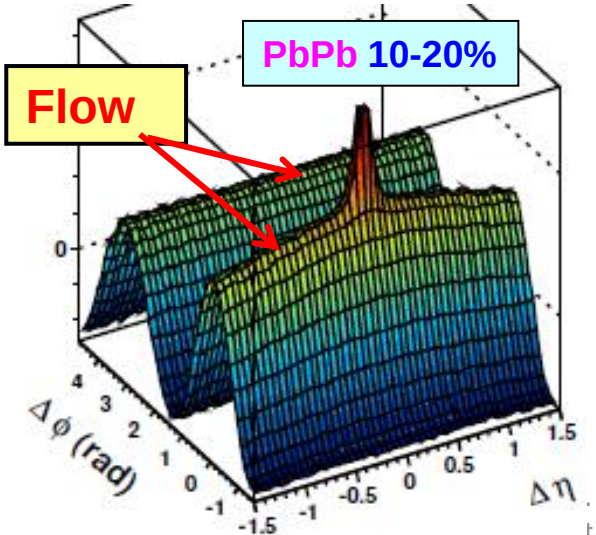
- Color Glass Condensate CGC: 'first principles' theory
  - classsical FT in high density limit (small x, small Q^2)
  - 'new state of cold & dense parton matter'
  - some success describing aspects of ep, pp, eA: geometric scaling, low-x, particle production, ..
    - however, no 'smoking gun' so far…



- Collective flow (Hydro) ?
  - vaguely similar correlations in nucleus-nucleus

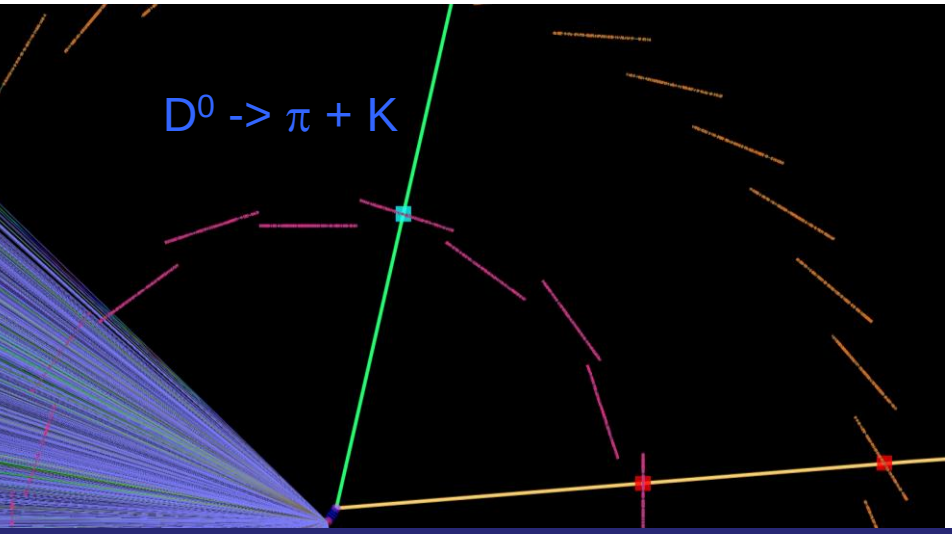


Talk by Evgeny Zabrodin



Heavy flavours

Abundantly produced at LHC



Measured in various decay channels

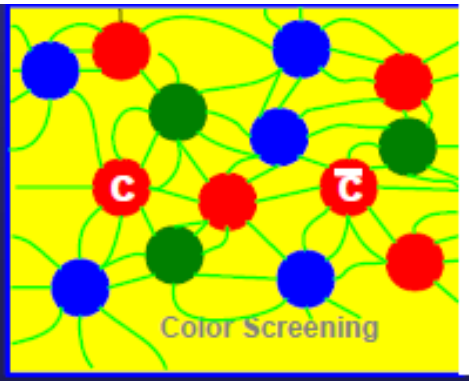
- Charmed mesons hadronic decays
- Heavy-flavour decay electrons
- Heavy-flavour decay muons

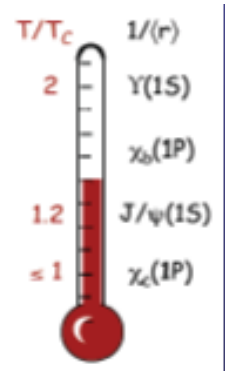
and wide kinematic range

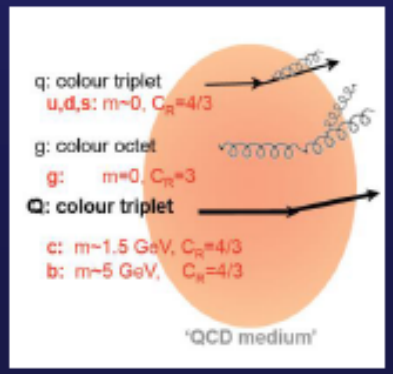
Quarkonia

talk by J.C. Castellanos

Sensitive to the temperature of QGP





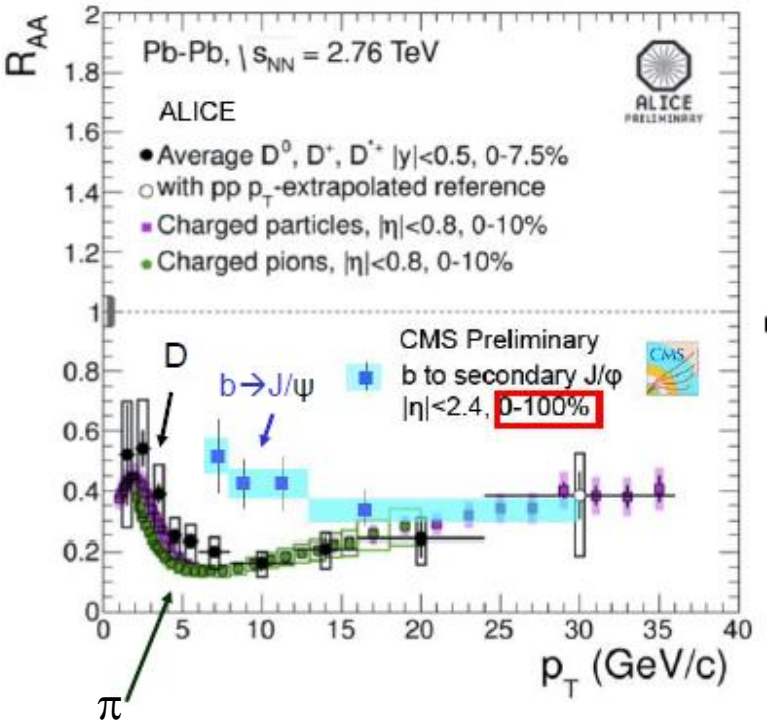


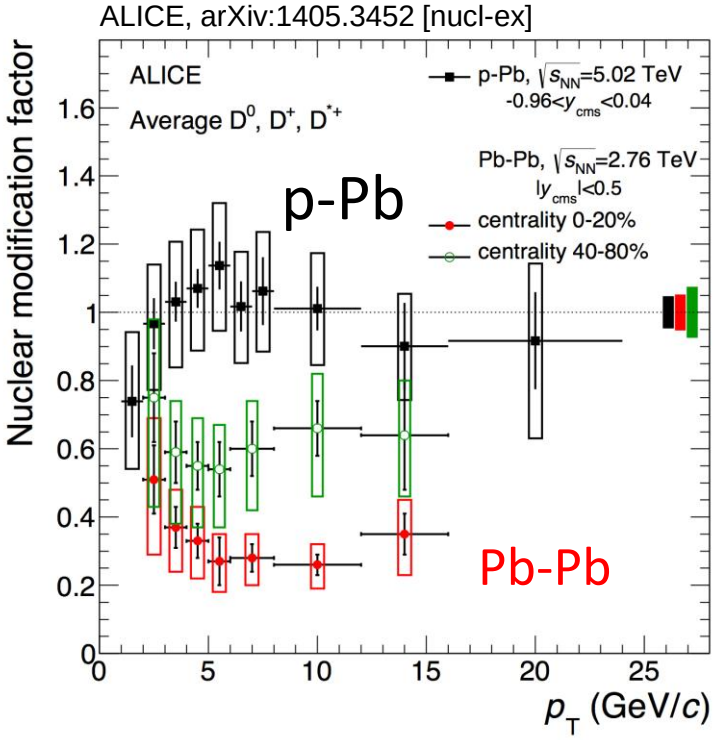
Probe the opacity of QGP

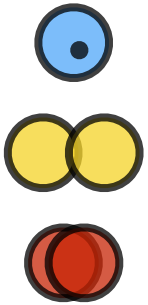
Open heavy quarks

talk by A. Alici

Charm R_{AA} in Pb-Pb and p-Pb





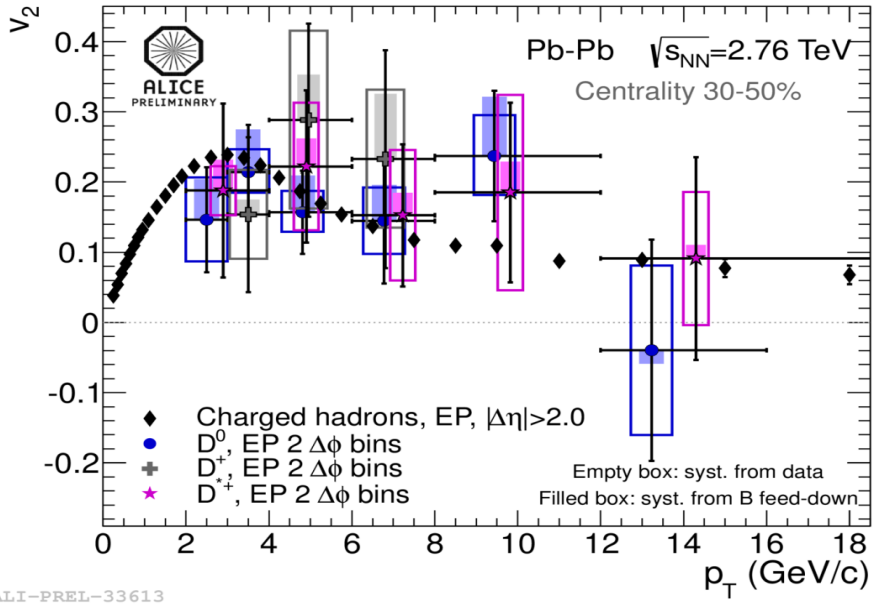


Strong suppression of prompt D mesons in central collisions
Comparison with results for p-Pb collisions shows that the effect is due to strong final-state effects, hot partonic matter

- Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
- $R_{AA}^{beauty} > R_{AA}^{light}$ at low p_T, effect vanishing at very high p_T
- R_{AA}^{charm} vs. R_{AA}^{light} comparison more delicate

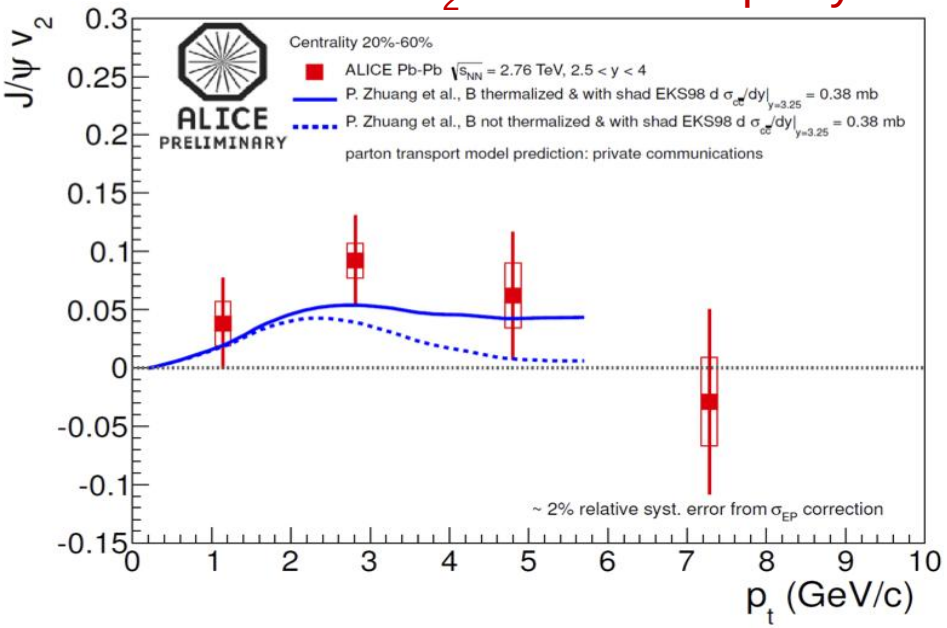
v_2 of D and J/ψ

D-mesons v_2 at midrapidity

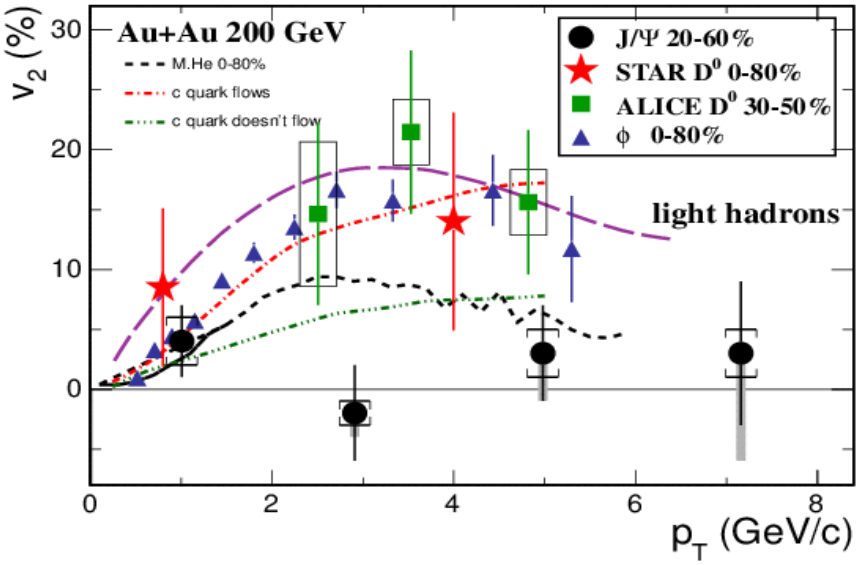


ALI-PREL-33613

J/Ψ v_2 at forward rapidity



v_2 of D and light hadrons compatible



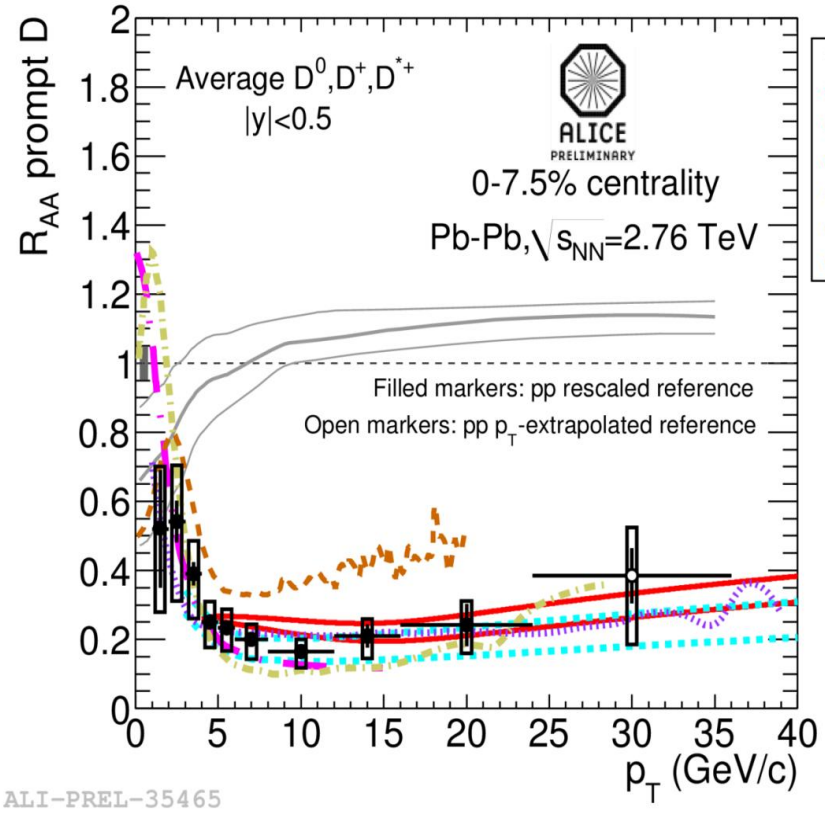
Hint of non-zero J/ψ v_2 at forward rapidity

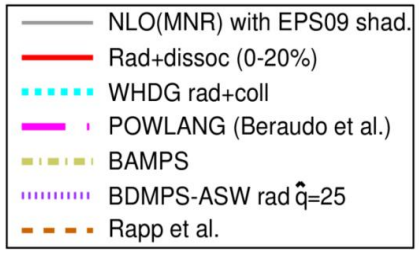
Indication of charm thermalisation

R_{AA} and v_2 of D compared to models

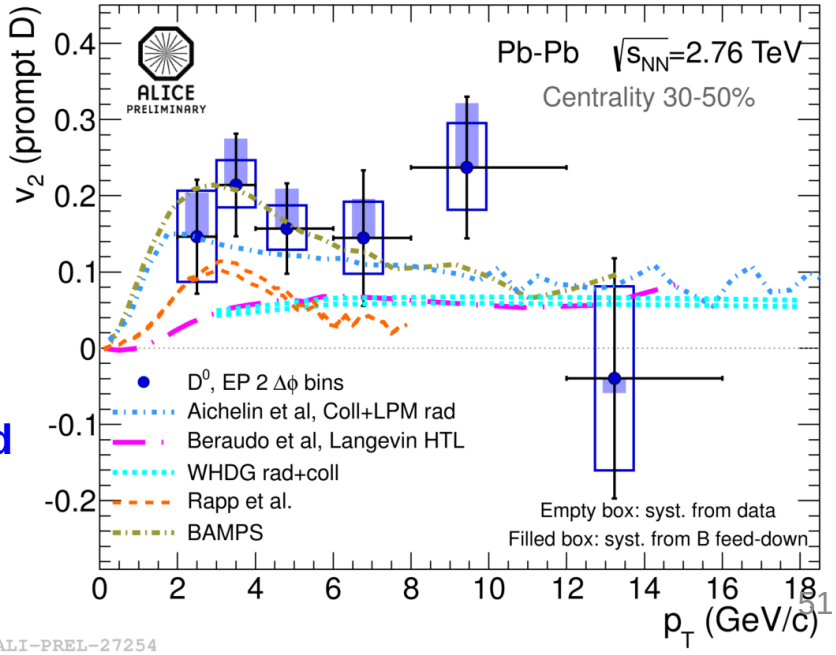
R_{AA} and v_2 sensitive to medium transport properties
- degree of thermalisation
- path-length dependence of energy loss

Goal: transport coefficients



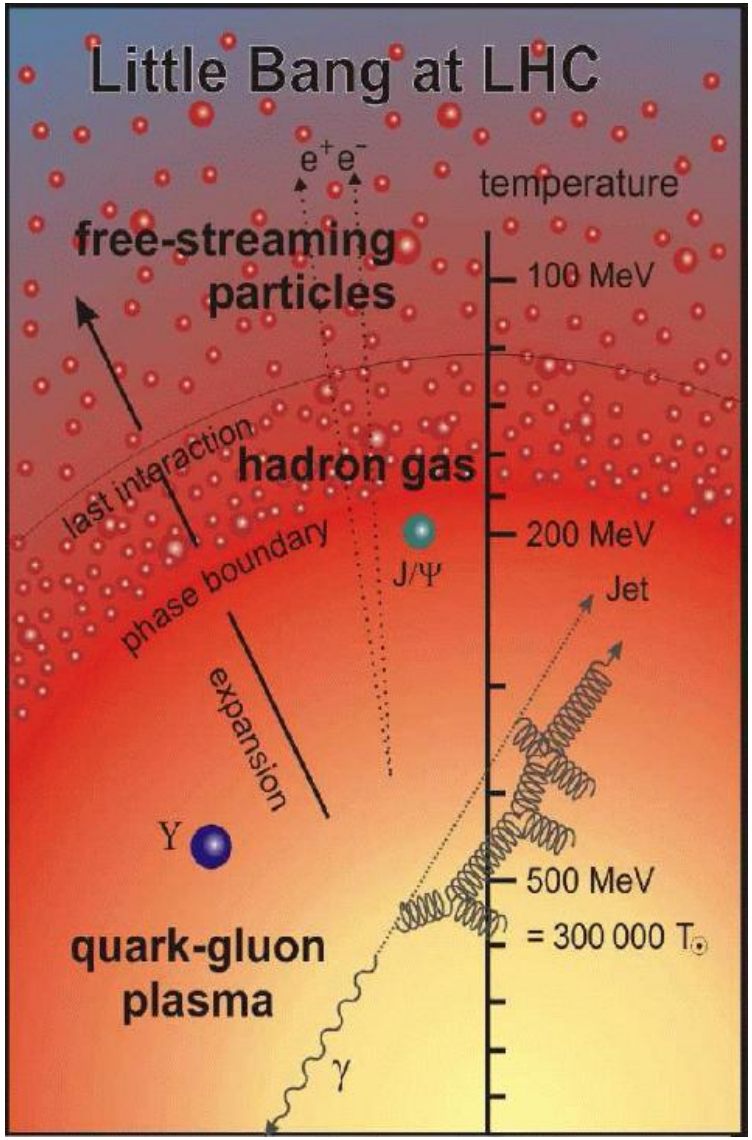


Simultaneous description of R_{AA} and v_2



Heavy-flavor suppression cannot be explained with only nuclear shadowing for p_T > 4 GeV/*c*.

Probes of HI Collisions - Summary



soft

hard probes

Global bulk event properties

- multiplicities, energy density, temperature
- space-time evolution of the emitting source: HBT
- degrees of freedom as a function of T: hadron spectra and ratios
- early state collective effects
- direct thermal photos

Medium induced effects

- parton energy loss: high p_T spectra, open charm and open beauty
- deconfinement: charmonium and bottonium spectroscopy

Era of precision measurements
Towards Standard Model of Little Bang

Evolution of QGP studies

From "To Be or Not To Be" questions…

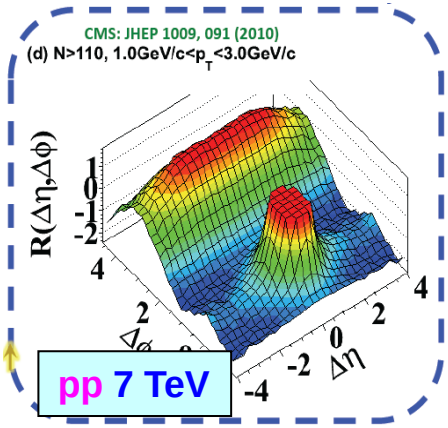
- **1970:** QCD, asymptotic freedom, shock flow, Bevalac, Dubna
  - first characterisation of the collision; fireball model, coalescence, …
- **1980:** Quark Gluon Plasma, Bevalac, AGS SPS
  - collective flow, HBT, thermal model, ….
- **1990:** AGS, SPS
  - J/Ψ suppression, strangeness enhancement, …
- **2000:** SPS, RHIC, the perfect liquid (paradigm change)
  - large collective flow, high-p_t suppression, …
- **2010:** SPS, RHIC, LHC
  - higher harmonics, jet suppression, heavy flavor, …

Narrowing down on QGP
World-wide effort
Growing community

…to a standard model for the QGP evolution!

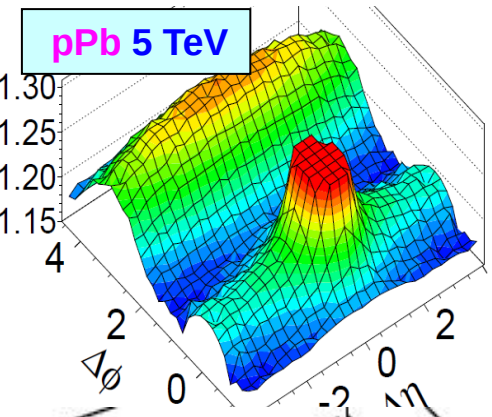
Everything falling in place….

.. and then came the 'Ridges'

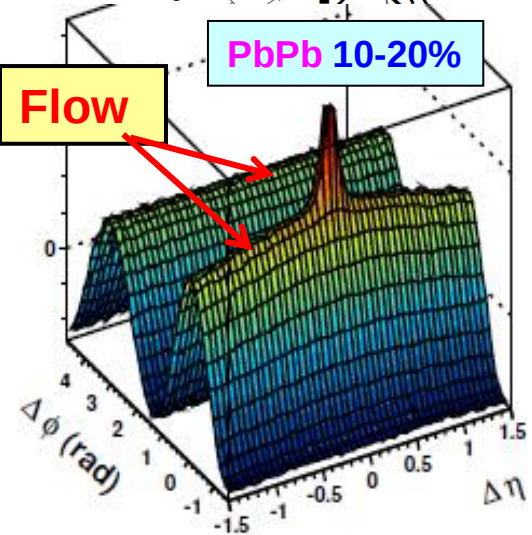


pp 7 TeV

pPb 5 TeV



PbPb 10-20%



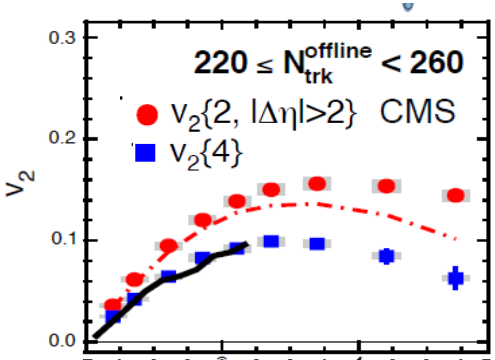
Flow

.. With ALL the bells & whistles of hydro flow…

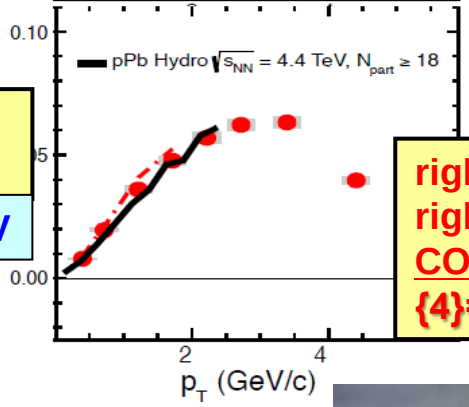
measured

to be fully collective

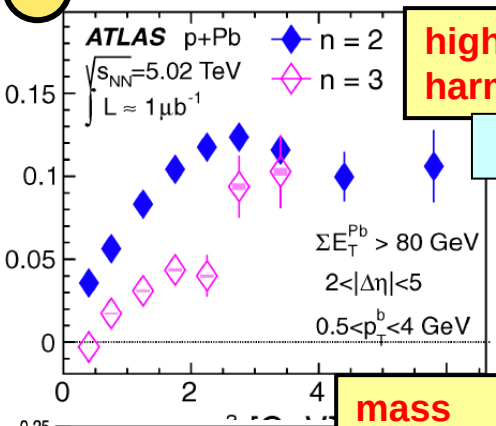
Slide from Jurgen Schukraft



pPb 5 TeV

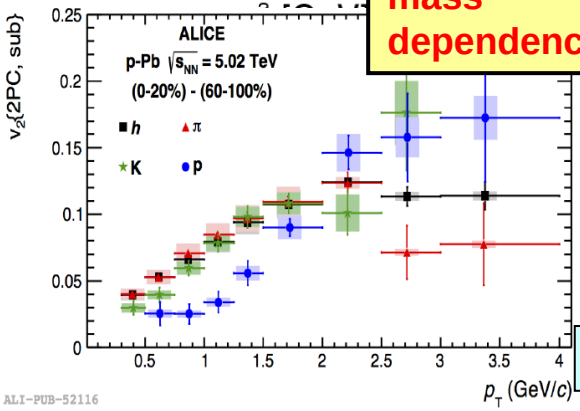


right size
right shape
COLLECTIVE
{4}={6}={8}= ∞



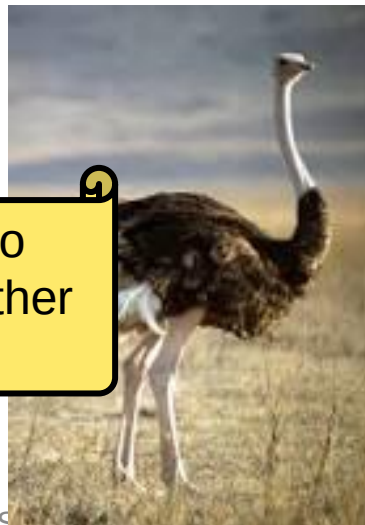
higher harmonics

pPb 5 TeV



mass dependence

.. and we could no longer look the other way…

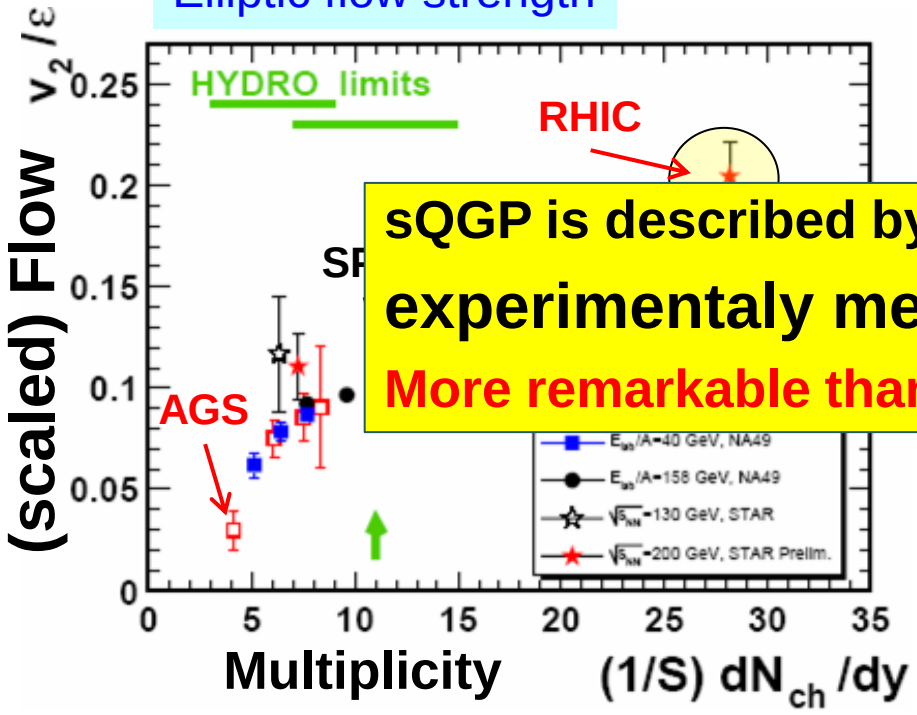


pPb 5 TeV

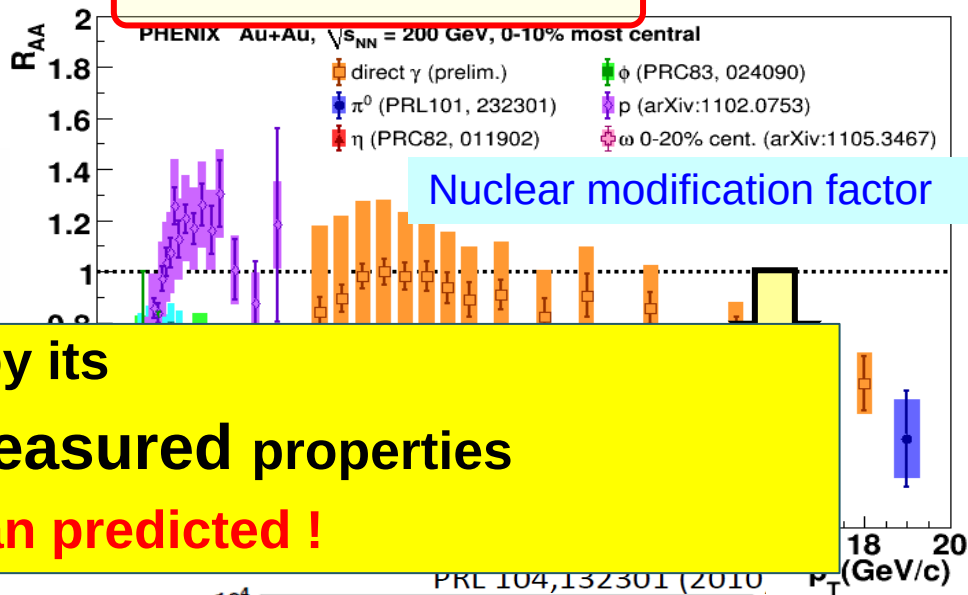
Main Results from RHIC

- **strong elliptic flow**
  - ~ maximum possible i.e. 'ideal liquid' ($\eta/s \approx 0$)
  - mostly produced in the early phase (partonic?)

Elliptic flow strength



- **high p_T suppression 'jet-quenching'**
  - very strongly interacting (large energy loss)

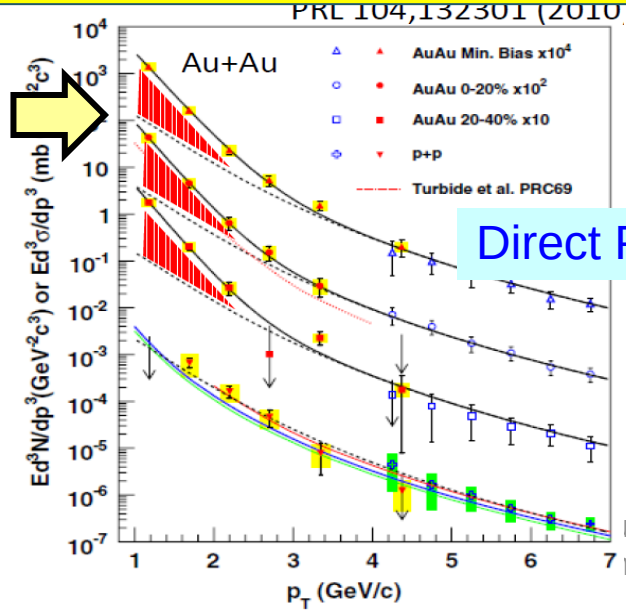


Nuclear modification factor

sQGP is described by its

experimentaly measured properties

More remarkable than predicted !



Direct Photons

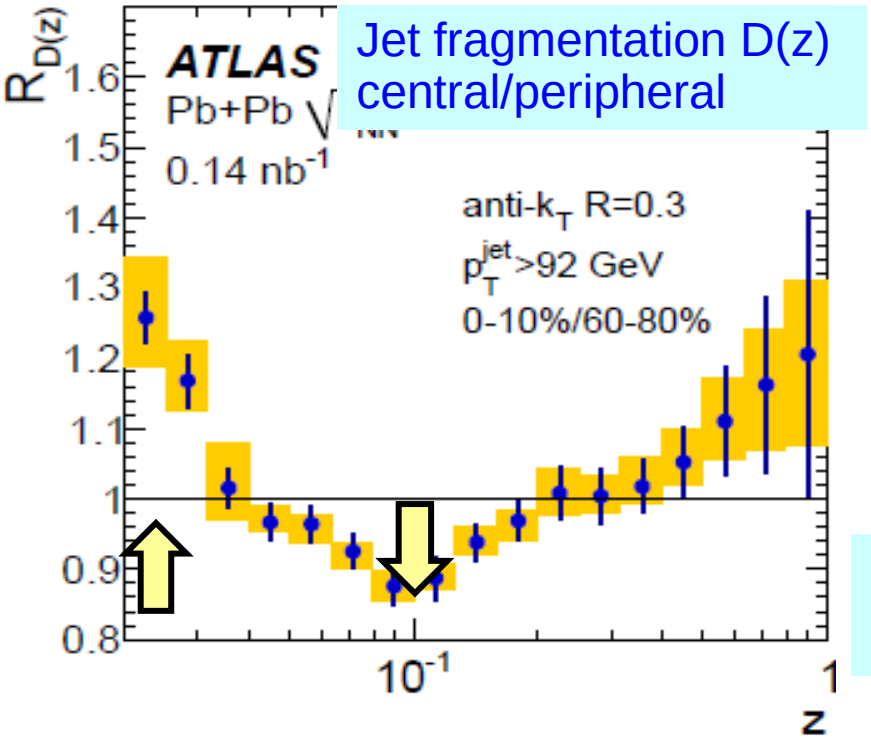
- **direct 'thermal' photons => 'hot matter'**
  - data: inverse slope T ~ 220 ± 20 MeV
    model dependent T_0: 300 - 600 MeV

incil J.
ukraft

Slide from Jurgen Schukraft

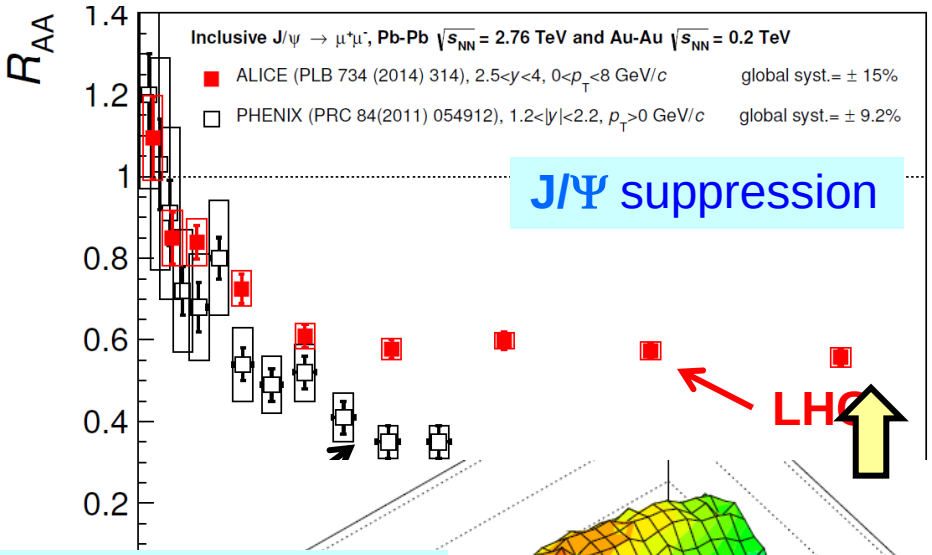
Main Results from LHC

- **in-medium jet fragmentation**
  - insight into dynamics of jet quenching
  - multiple soft gluon radiation at large angles



Jet fragmentation D(z)
central/peripheral

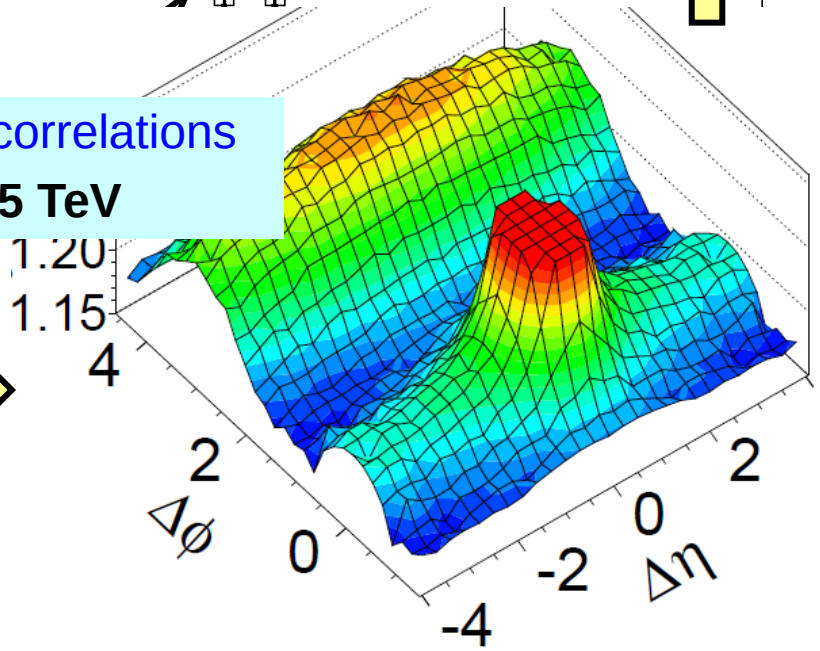
- **J/Ψ coalescence & seq. ϒ melting**
  - SPS/RHIC J/Ψ puzzle solved
  - qualitative confirmation of deconfinement



J/Ψ suppression

LHC

2-Particle correlations
CMS pPb 5 TeV



- **the ever surprising ideal liquid**
  - collective hydro flow in small systems (pp, pA)

Slide from Jurgen Schukraft

Heavy-Ion Physics Paradigm

interplay of theory and experiment

- large & dense systems = Heavy Ion Physics
- small & dilute systems = Comparison Data

Have we discovered
- collective hydrodynamic flow in small systems
- yet another "new state of matter",
  (like a dense gluon matter….)

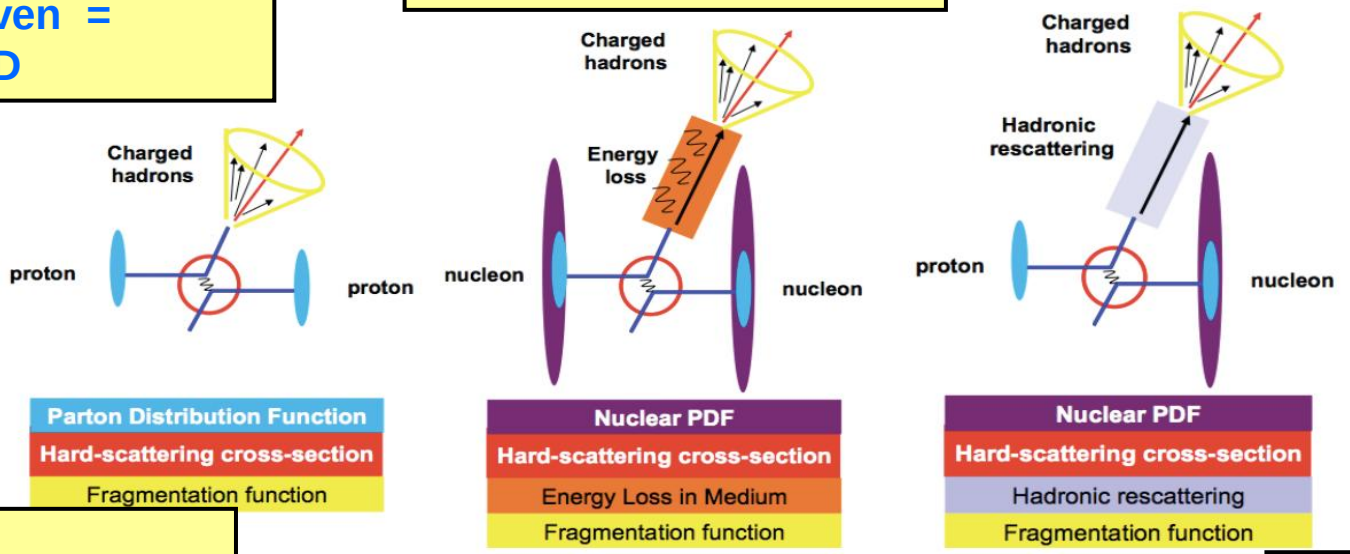
Evidence that energy density of very high multiplicity pp events comparable to heavy-ions.

Macroscopic: system size compared to mean free path.

pp:
God Given = (n)pQCD

AA:
'Hot Matter' modifications ("R_{AA}")

pA:
CNM modifications



MB pp/e^+e^-
The modifications start here !

"Heavy-Ion" Physics ??

'central' pp/pA:
Hot Matter ?

Future directions

Complete high T extreme

Heavy and high-pt probes

Locate the critical point

Beam energy scan

at RHIC and SPS

see talks of

P. Sorensen, T. Czopowicz

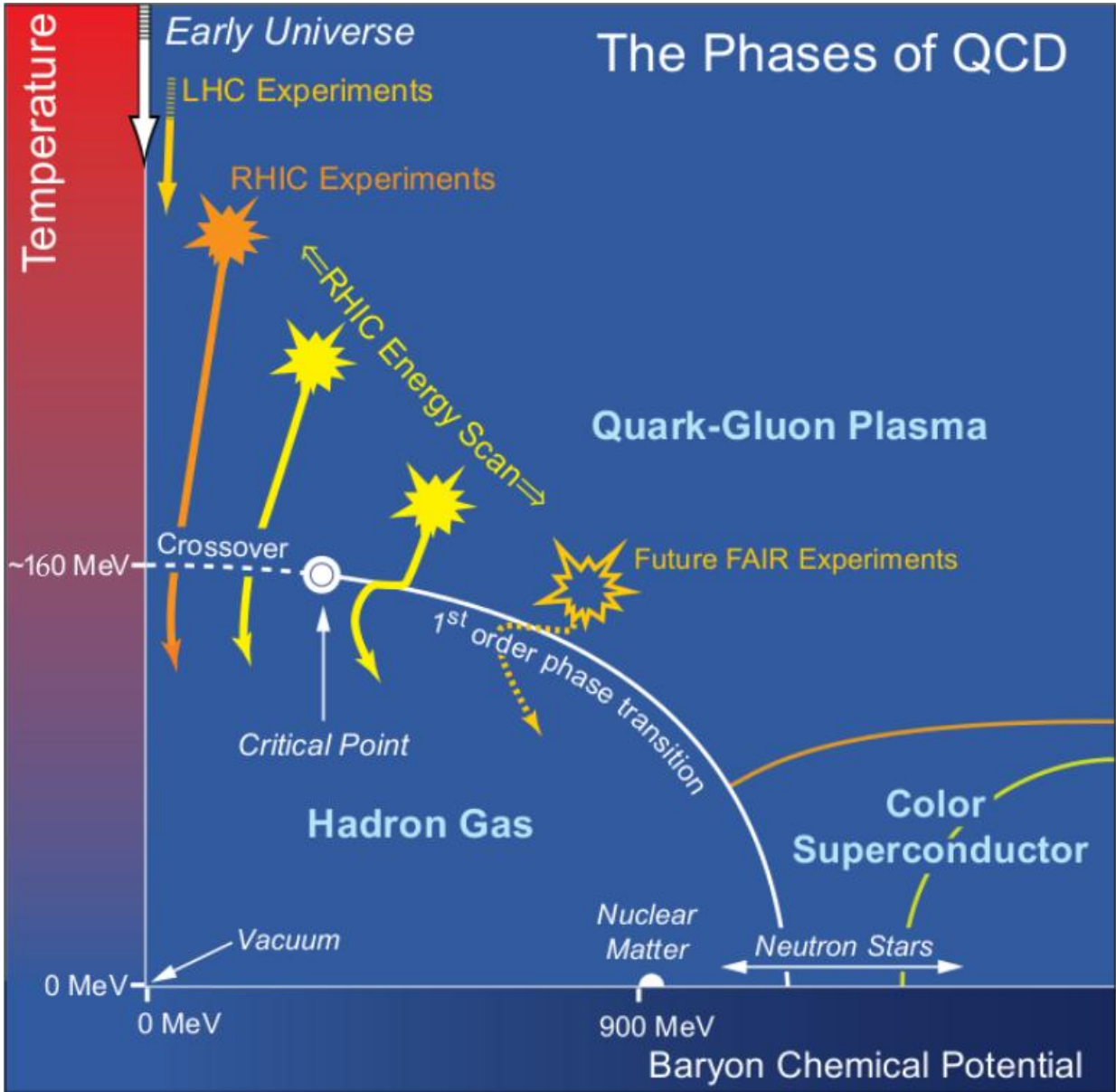
Complete mapping out

Explore the other extreme

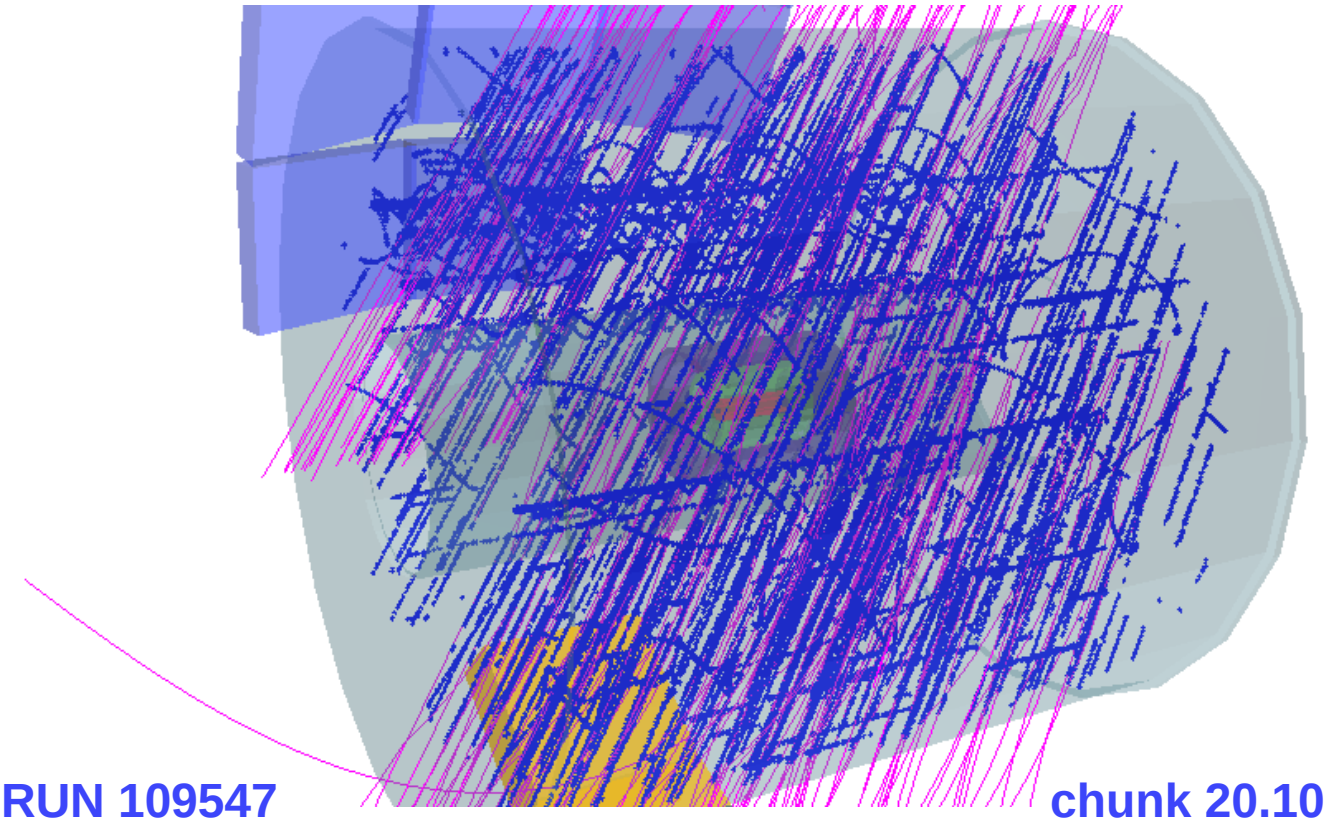
of the phase diagram

at low T and large density

at FAIR/GSI



…..a lot to do in the agenda
….. and ready for surprises…..



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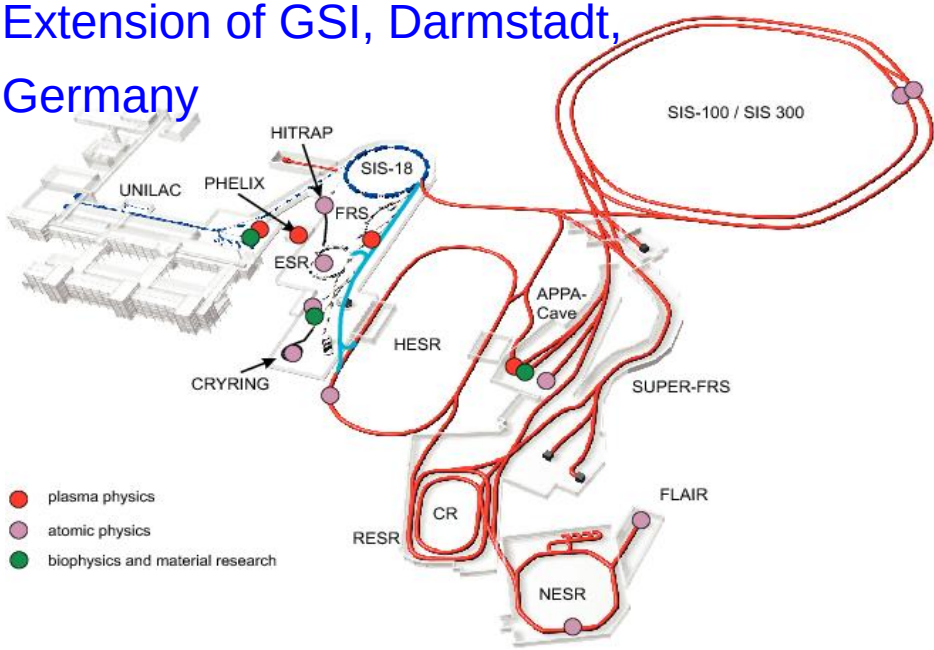
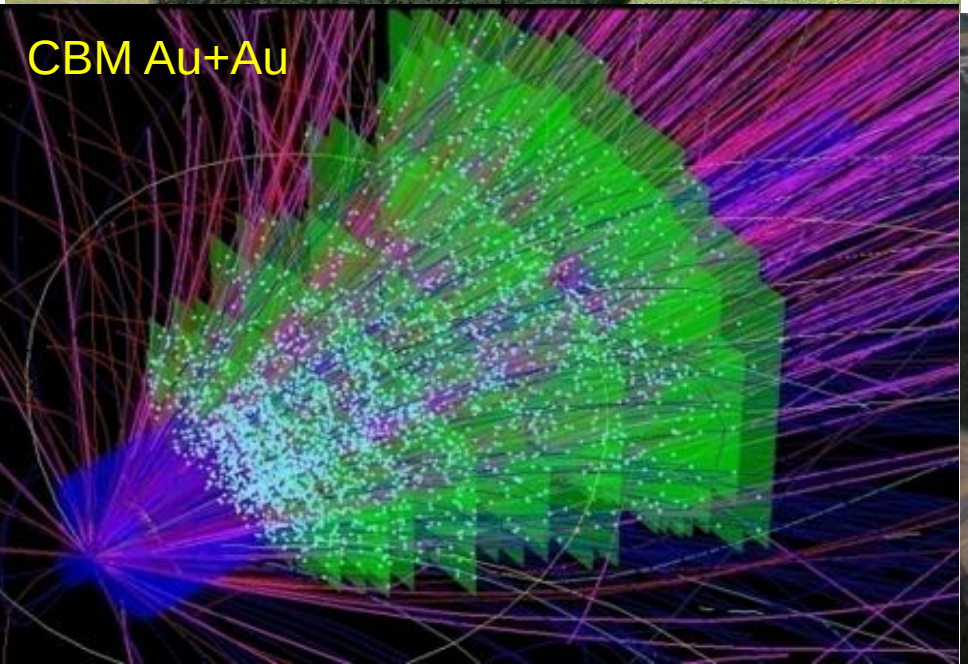
Thank you !!

BACKUP

FAIR

Extension of GSI, Darmstadt, Germany





Hadron (carbon ion) therapy

Pioneered at GSI

Implemented in hospitals

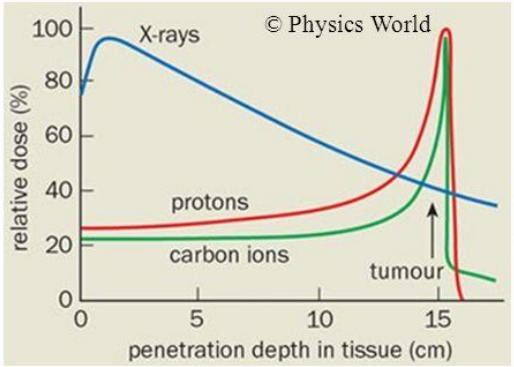
(i.e. Heidelberg…)

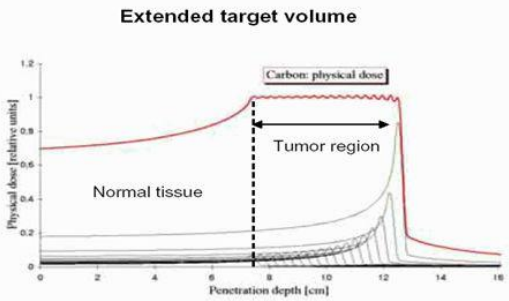
Part of FAIR program

GSI Darmstadt: scanned carbon beam

Clinically relevant properties of heavy-ion beams

- Inverted depth-dose profile (Bragg curve)

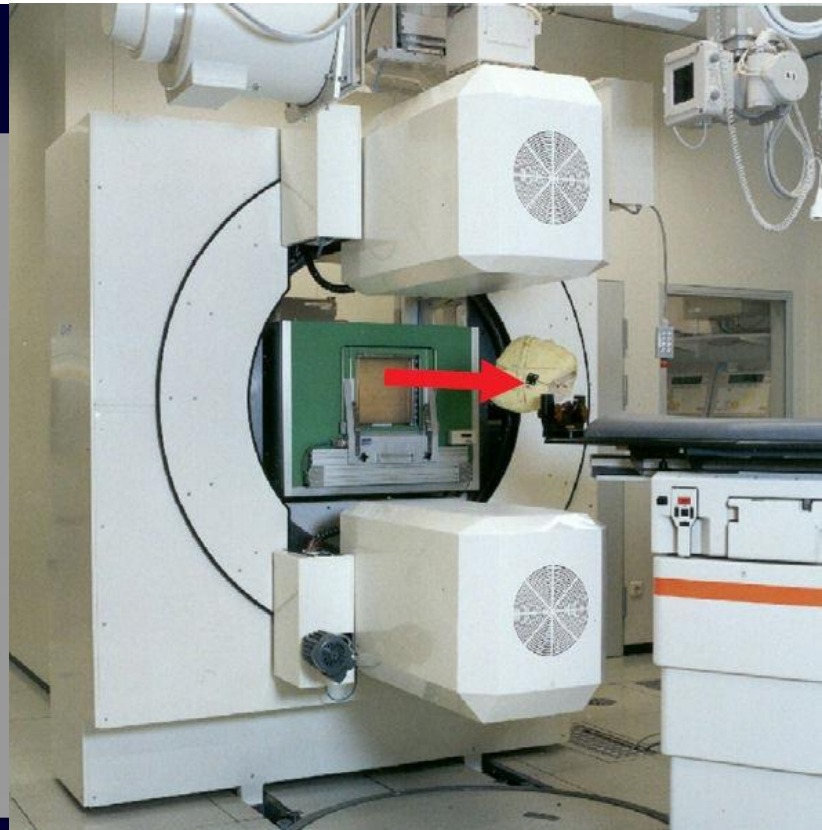




Typically 30 energy steps needed
for a ripple < 5%

D Shardt (GSI)

GSI



Probing the medium with heavy flavours

Energy loss

Hierarchy of suppression:

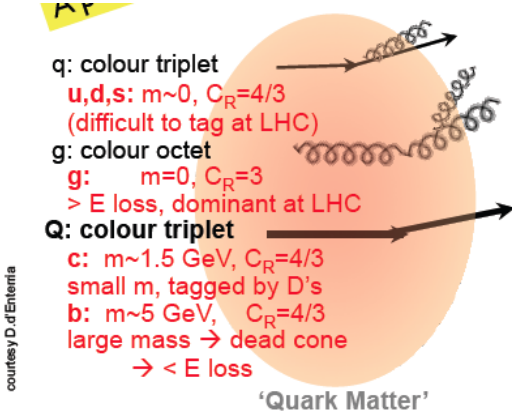
$$\Delta E_{quark} < \Delta E_{gluon}$$
$$\Delta E_b < \Delta E_c < \Delta E_{light\ q}$$

which should imply

$$R_{AA}{}^{B} > R_{AA}{}^{D} > R_{AA}{}^{\pi}$$

Depends on:

- Colour coupling factor C_R (g>q)
- Parton mass



Azimuthal anisotropy

Does heavy flavour "flow" with medium?

If heavy-quarks interact with the medium,
heavy-flavoured hadrons should inherit the medium azimuthal anisotropies:

- ***v_2* at low- *p_T* :** degree of thermalization
- ***v_2* at high *p_T* :** path - length dependence of energy loss

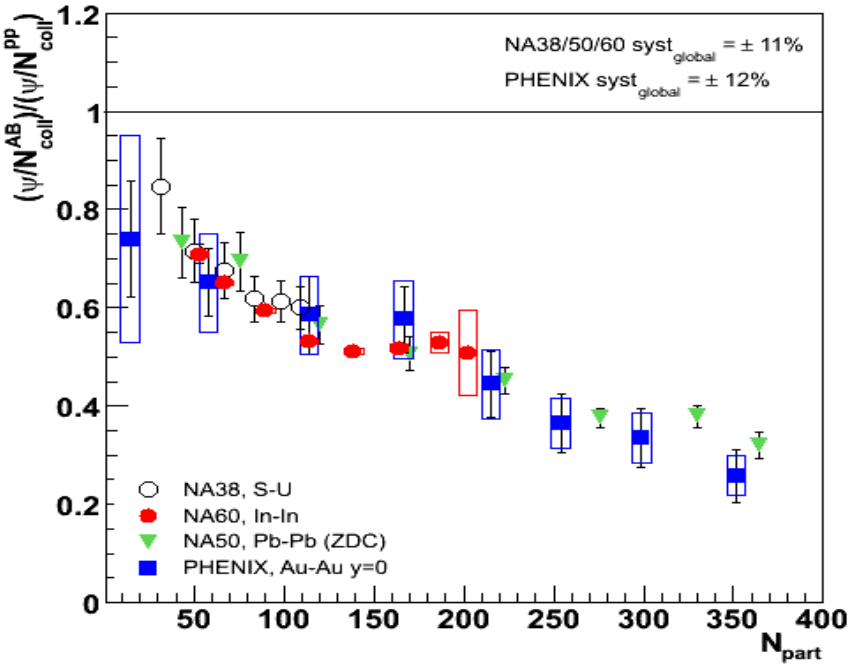
Deconfinement

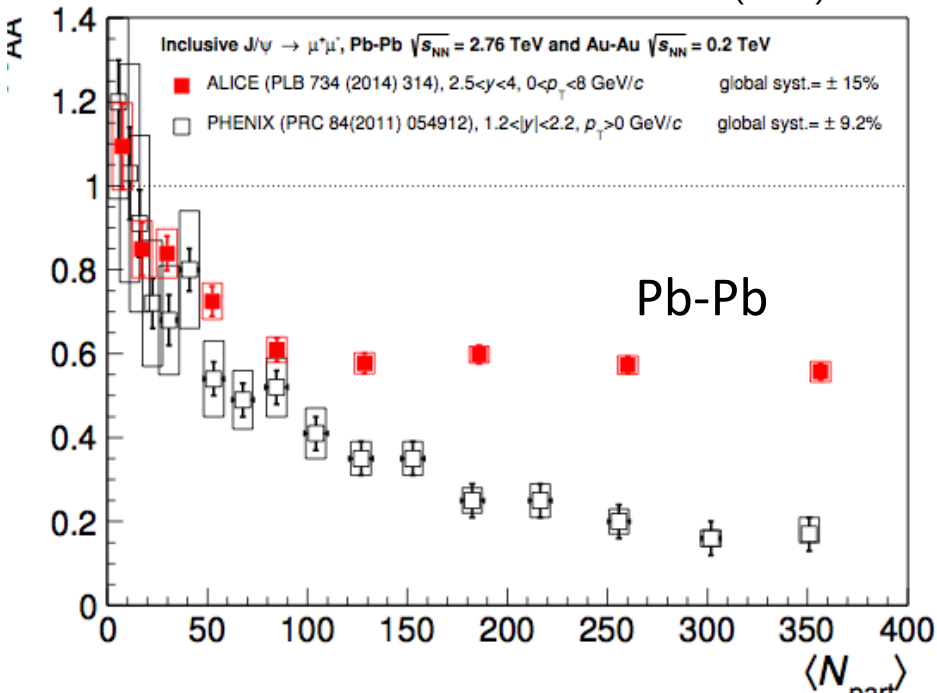
Pattern of sequential melting of quarkonia bound states due to colour screening in a deconfined plasma of quarks and gluons: **J/ψ suppression**
(Matsui and Satz, 1986)

At LHC an enhancement maybe expected via (re)combination of cc pairs

Inclusive J/ψ production in Pb-Pb

PLB 734 (2014) 314





ALI-DER-65

- J/Ψ suppression observed at SPS
- J/Ψ suppression at RHIC almost identical to SPS
- Hint that part of J/Ψ originate from recombination?

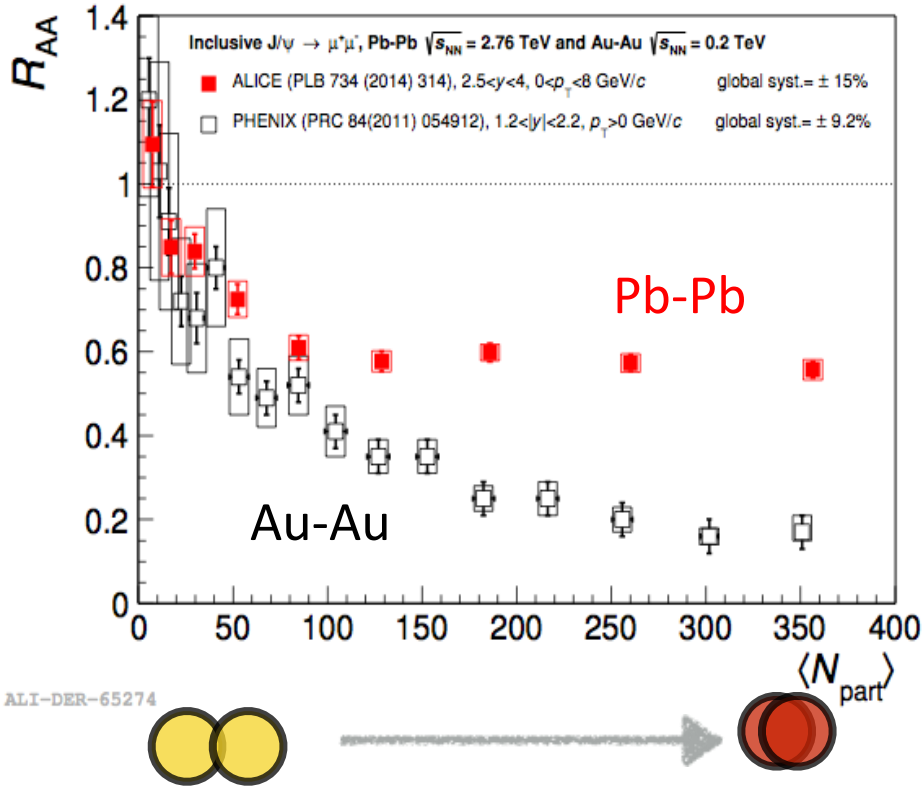
systematically lower suppression

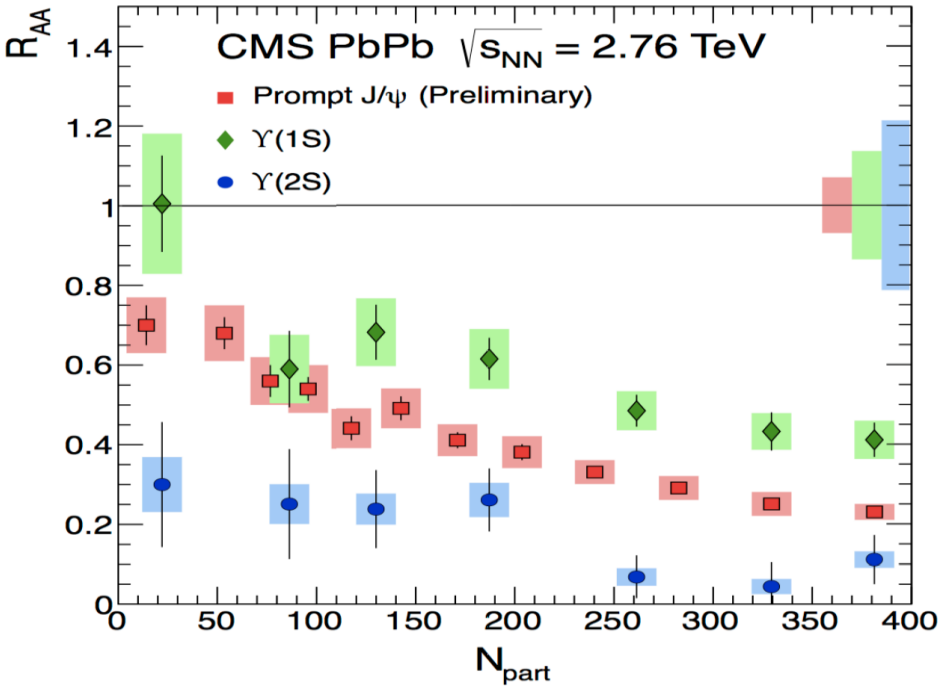
RHIC: suppression dominates
LHC: suppression + recombination

recombination scenarion supported by observations of:

- **enhancement at low-p_T**
- non-zero v_2

Quarkonia melting





systematically lower suppression

RHIC: suppression dominates
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recombination scenarion supported by observations of:

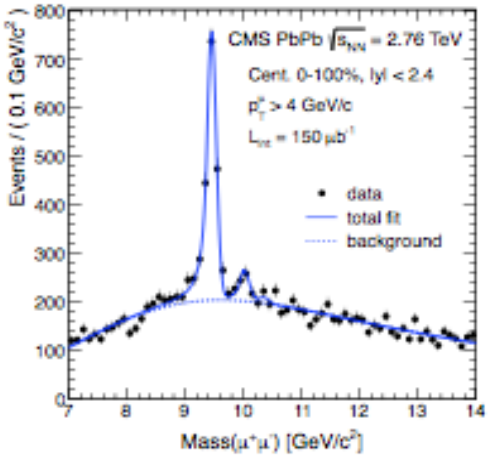
- **enhancement at low-p_T**
- **non-zero v_2**

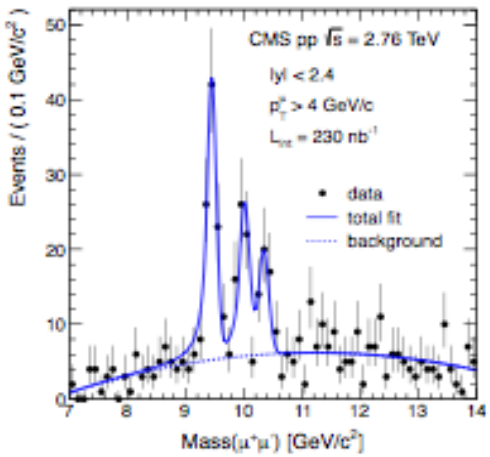
Sequential melting observed:

Upsilon 1s state

is more tightly bound than 2s

Quarkonia: melting of Upsilon





Sequential melting observed:

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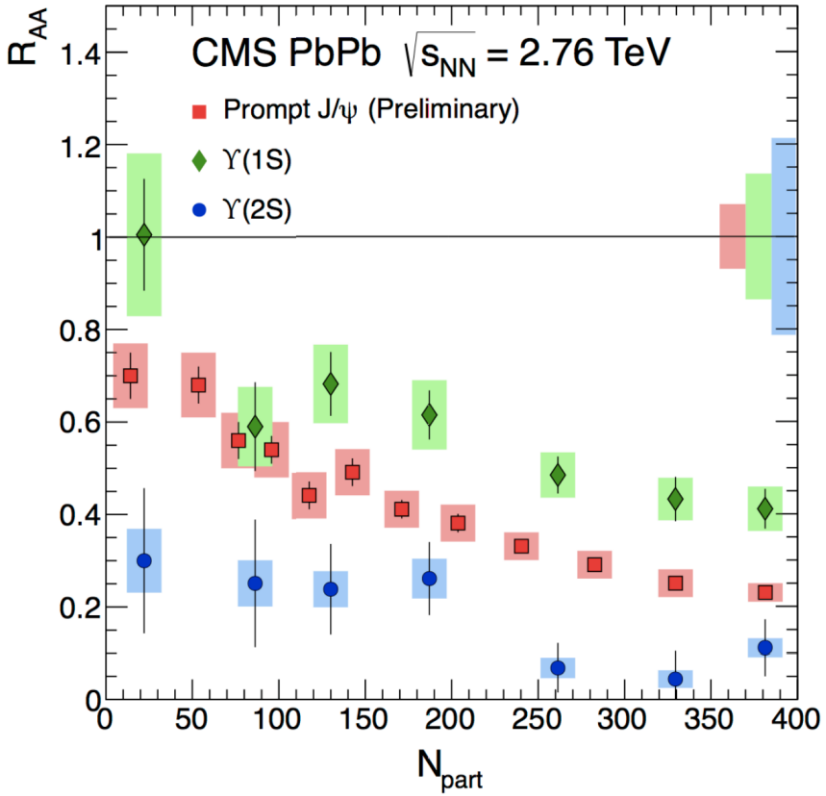
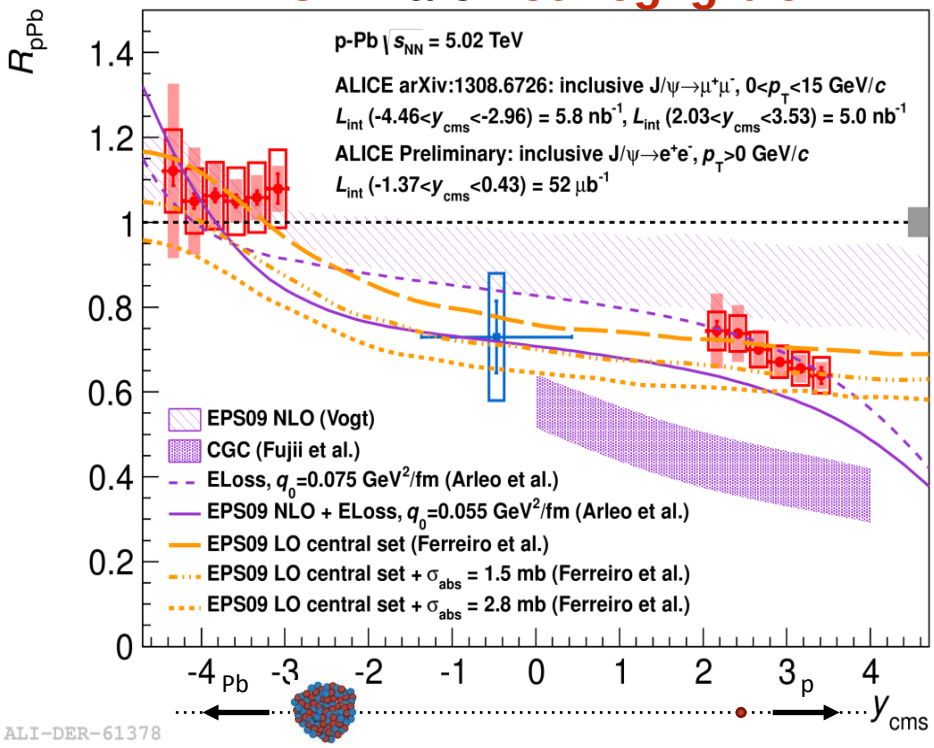
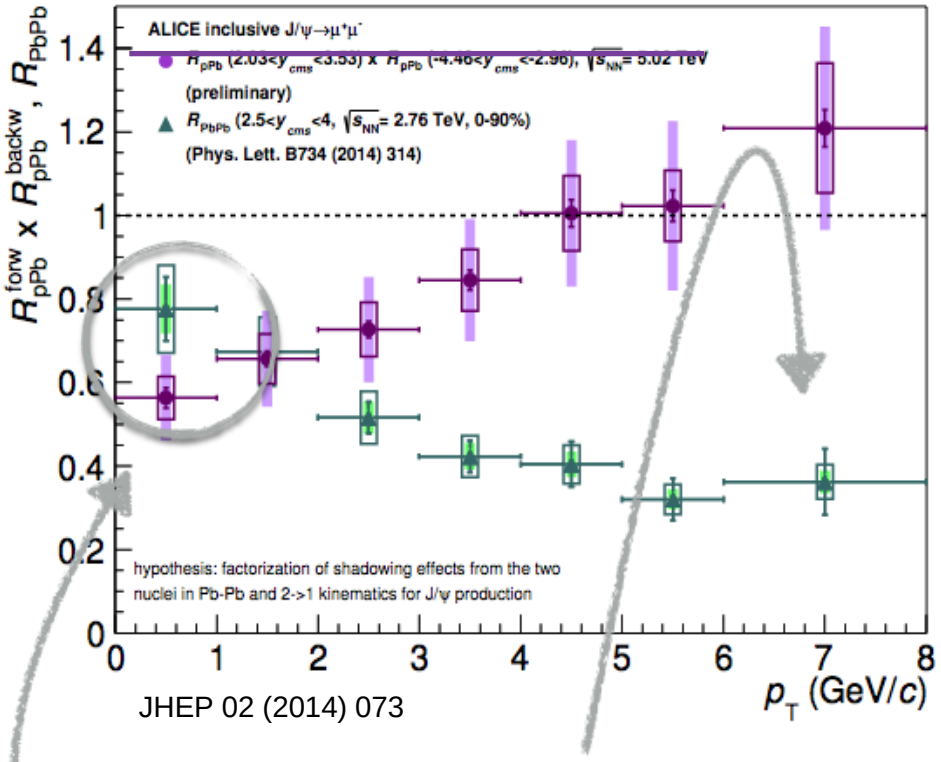


Quarkonia: CNM effects from p-Pb to Pb-Pb

CNM are **not negligible**





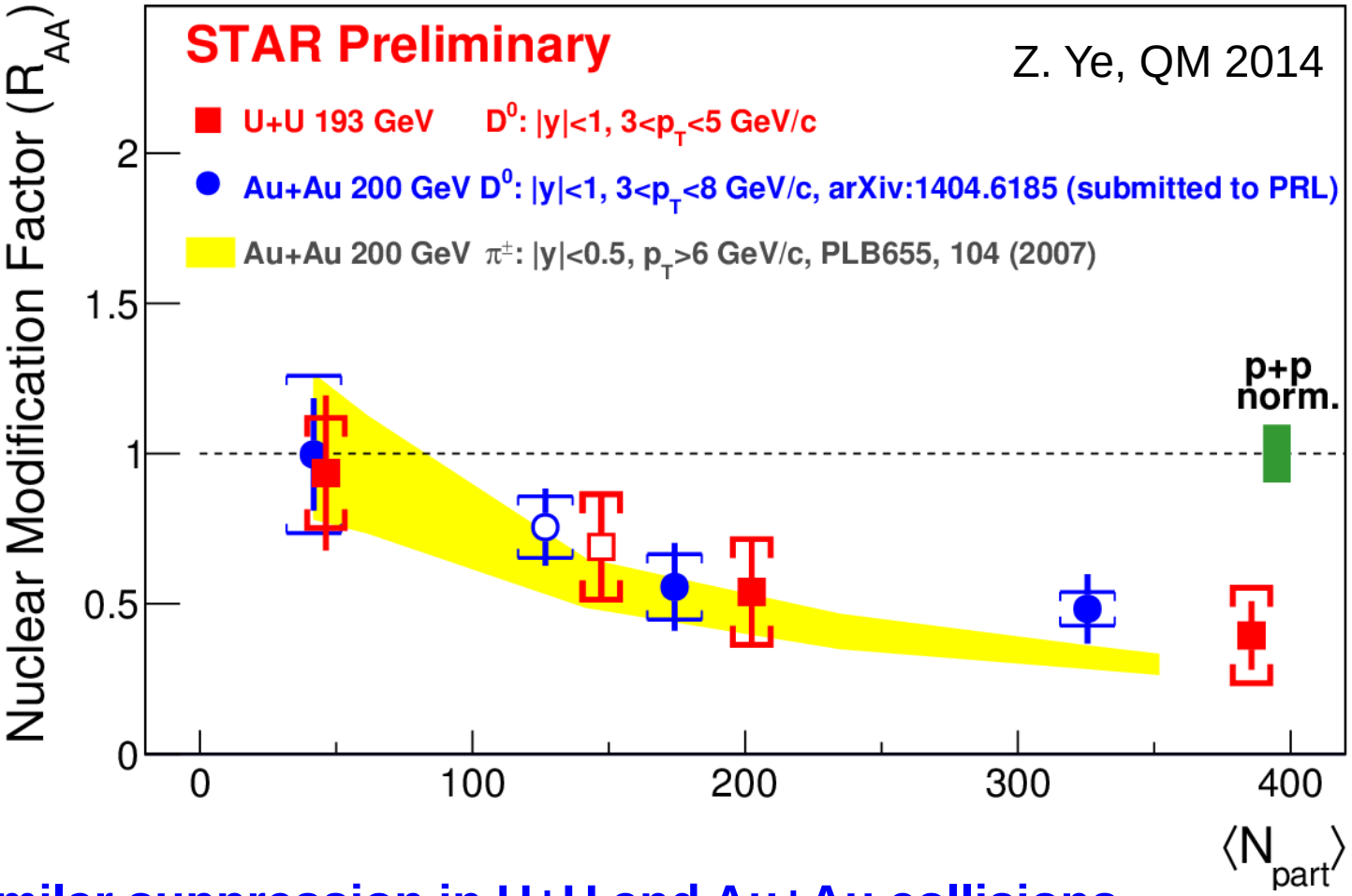
J/ψ production is modified also in pPb because of Cold Nuclear Matter effects:
R_{pA} decreases towards forward (and central) *y*.

Reasonable agreement with nuclear shadowing and/or partonic energy-loss (shadowing depends on y)
Saturation (CGC) models overestimate suppression

strong suppression at high-p_T
CNM effects not enough
evidence for hot matter effects

enhancement at low-p_T suggests recombination

Charm high p_T suppression at RHIC

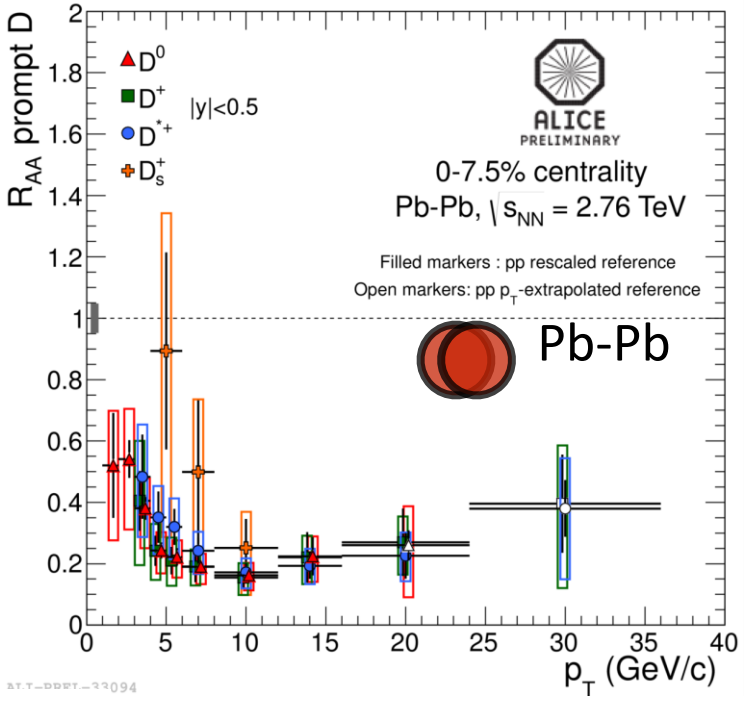


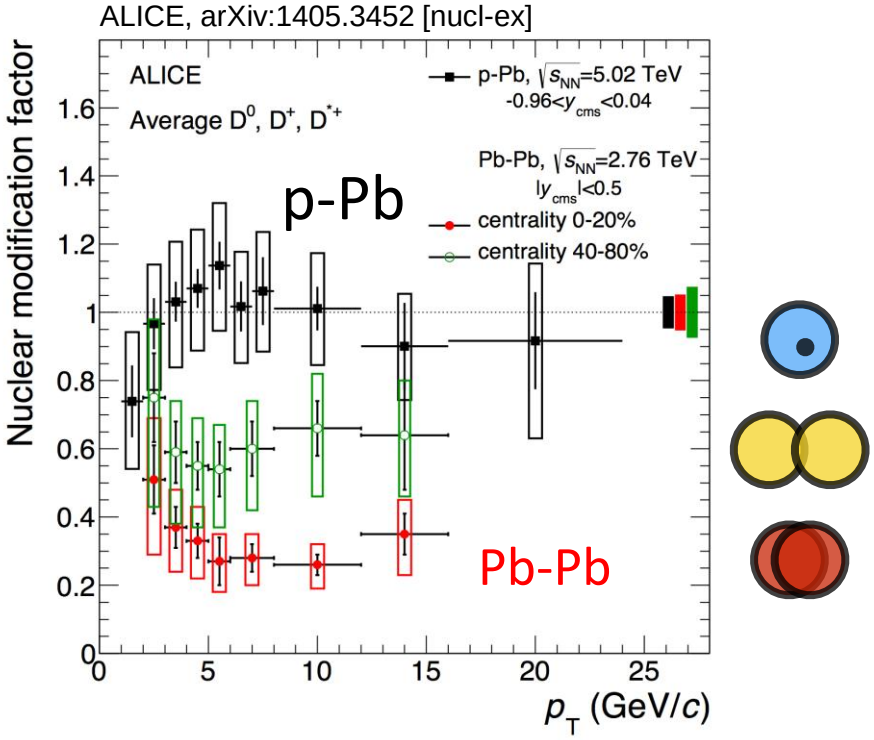
D^0: Similar suppression in U+U and Au+Au collisions

Similar trend vs system size as for pions

D^0 suppression suggests strong charm-medium interaction

Charm R_{AA} in Pb-Pb and p-Pb



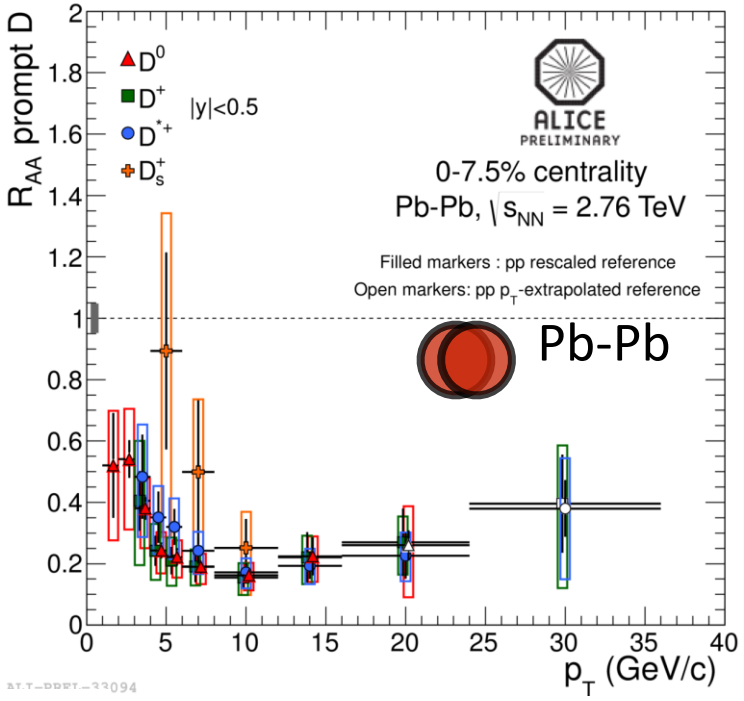


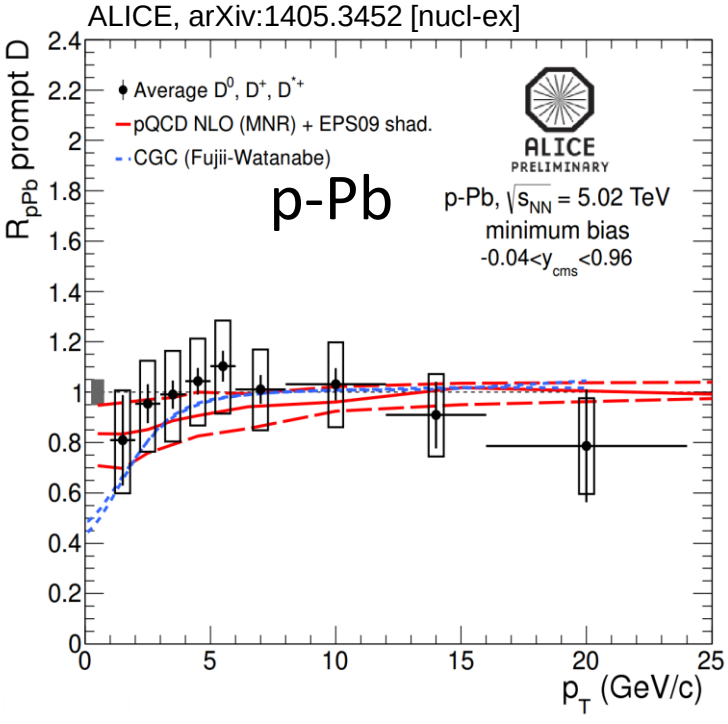
D^0, D^+ and D^{*+} R_{AA} agree within uncertainties
First measuremetns of Ds

Strong suppression of prompt D mesons in central collisions

Comparison with results for p-Pb collisions shows that the effect is due to strong final-state effects, hot partonic matter

Charm R_{AA} in Pb-Pb and p-Pb





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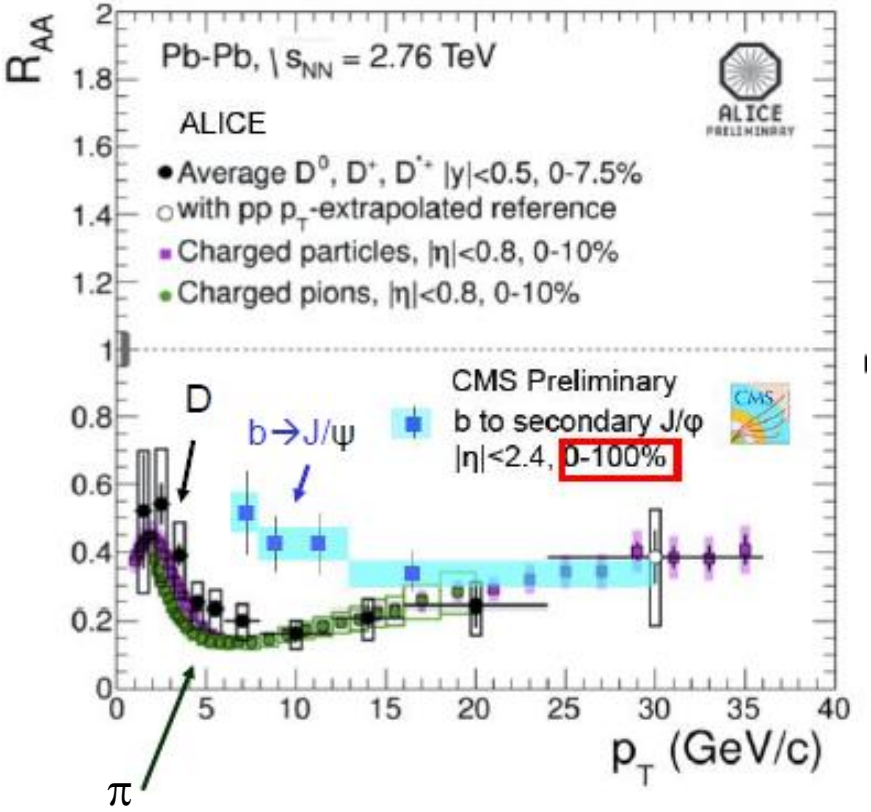
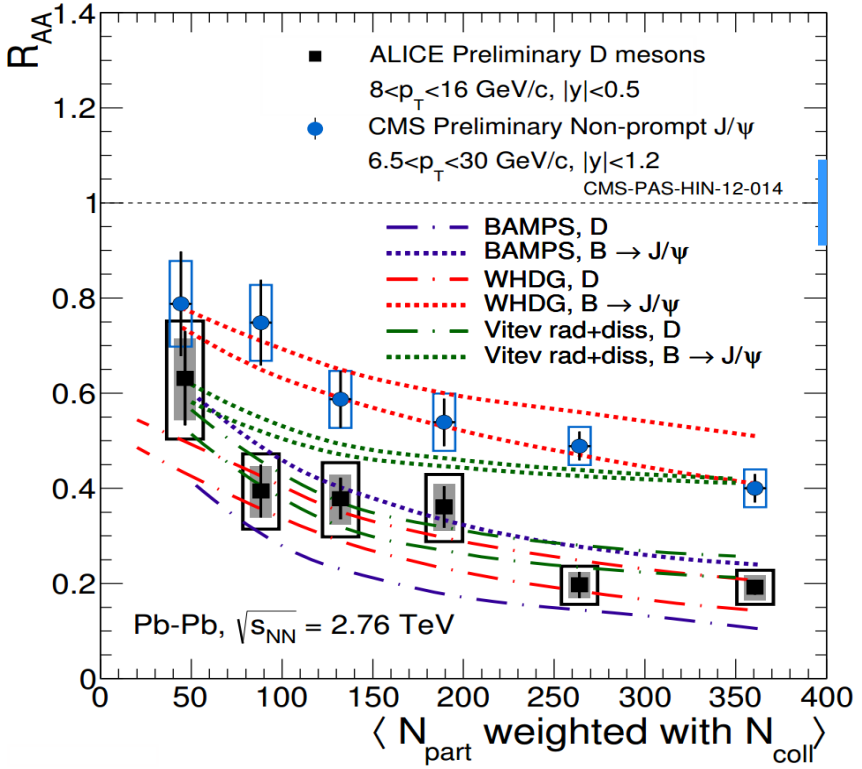
R_{AA} and hierarchy of suppression in Pb-Pb

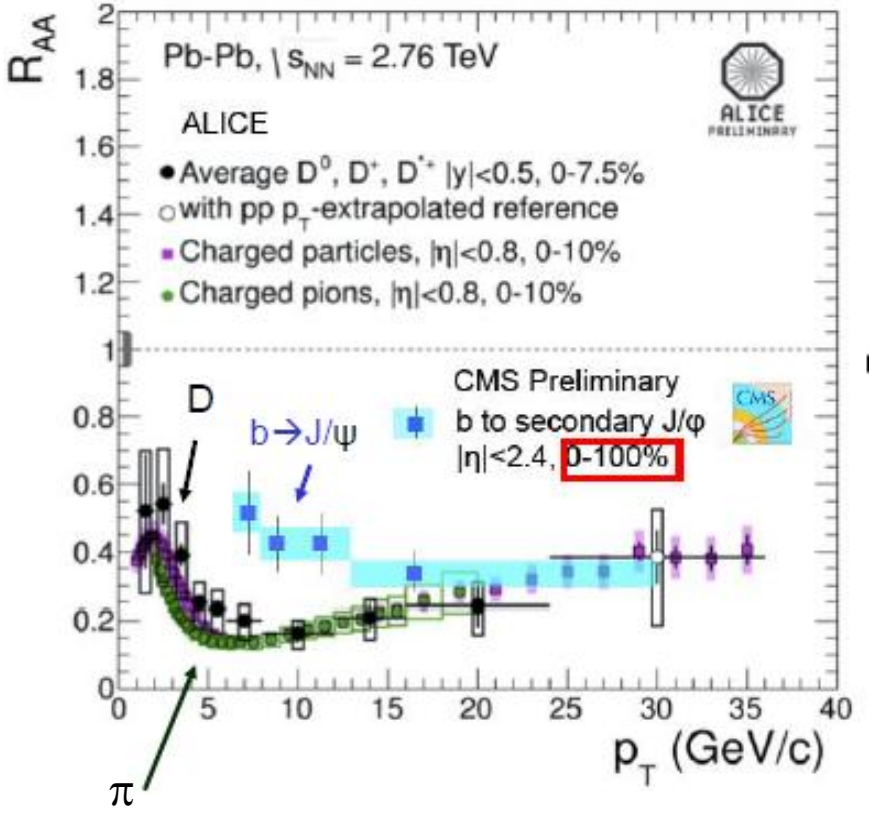


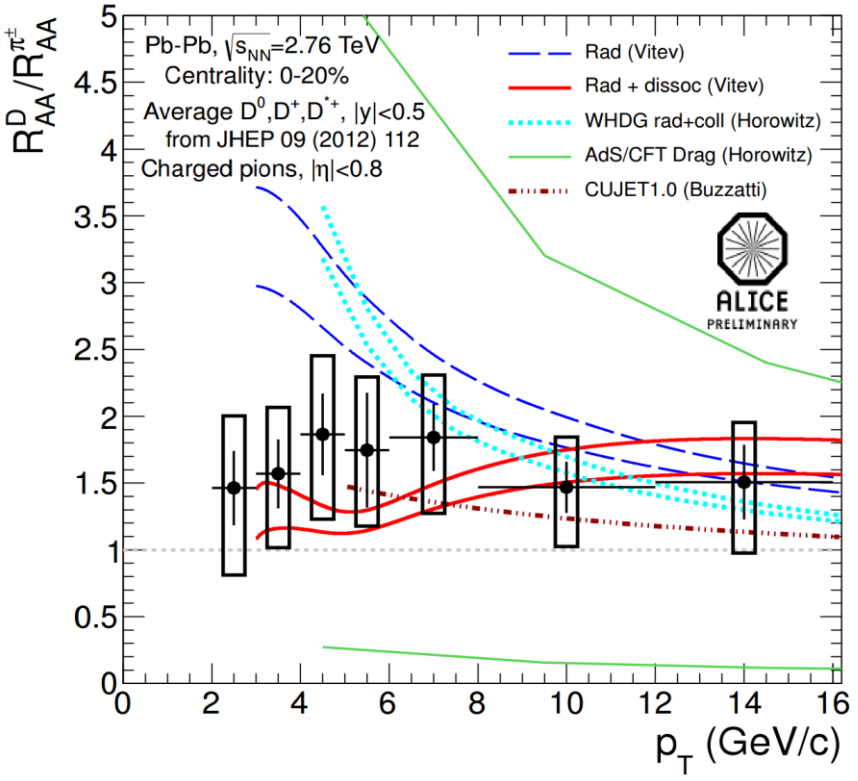


p_T < 2 GeV/*c* effects of mass (flow, hydro)

- Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
- $R_{AA}^{beauty} > R_{AA}^{light}$ at low p_T, effect vanishing at very high p_T
- R_{AA}^{charm} vs. R_{AA}^{light} comparison more delicate

R_{AA} and hierarchy of suppression in Pb-Pb





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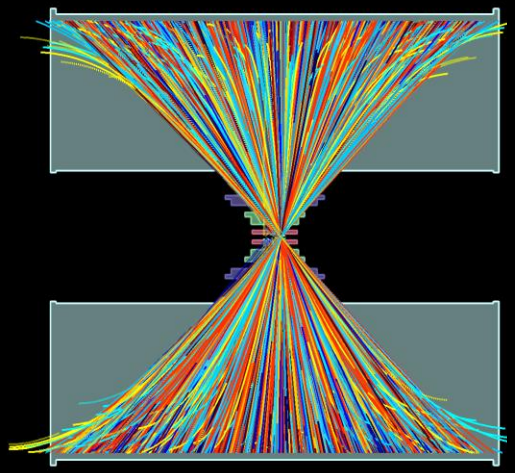
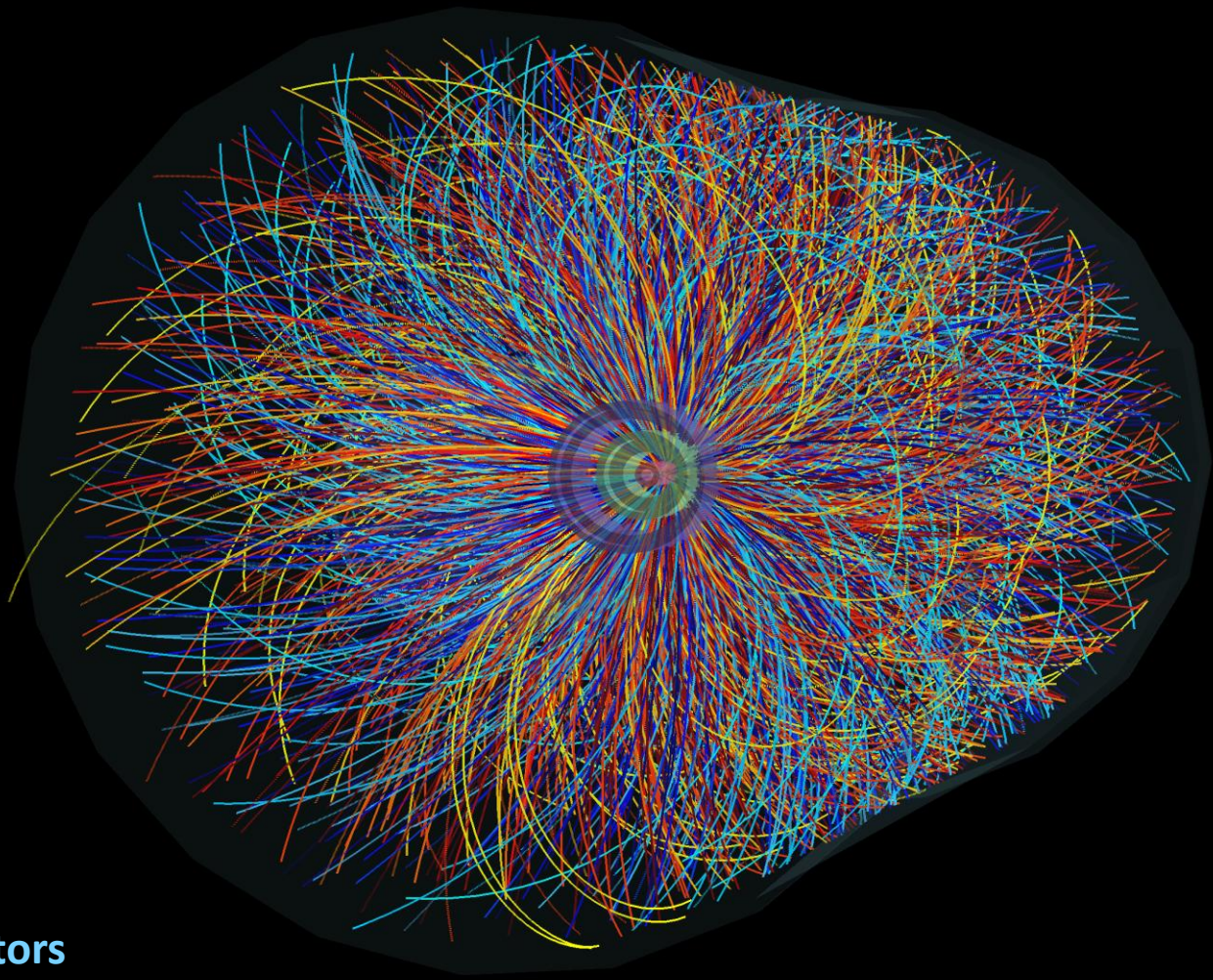
Pb-Pb collisions in ALICE

Increased precision to study strongly interacting matter under extreme conditions

in events of extreme particle multiplicity





Fully characterize the events

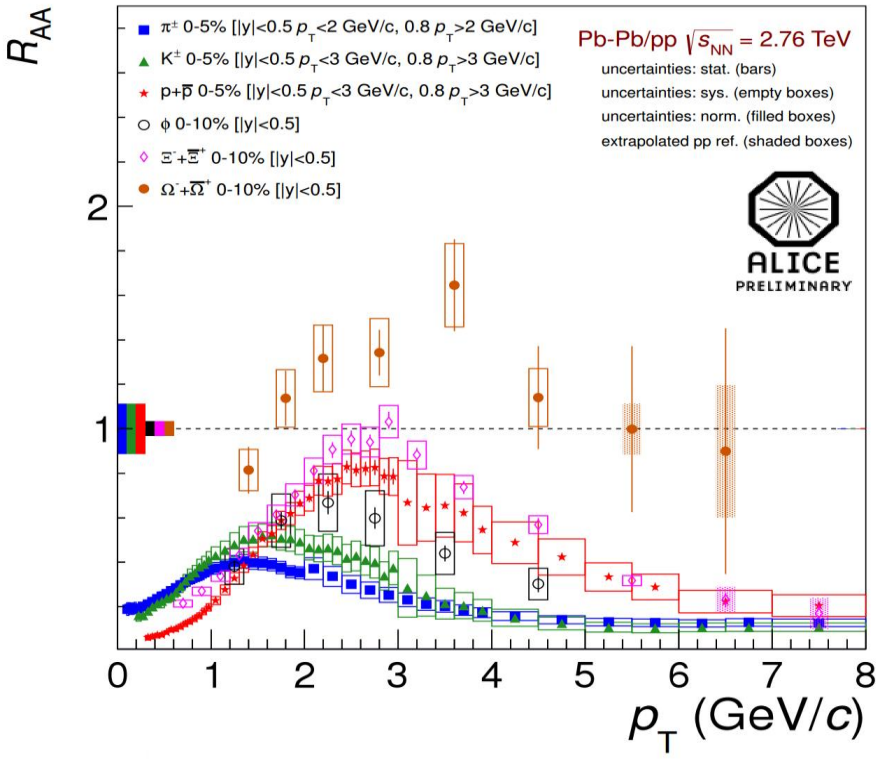
Challenge for the experiments

state-of the art detectors

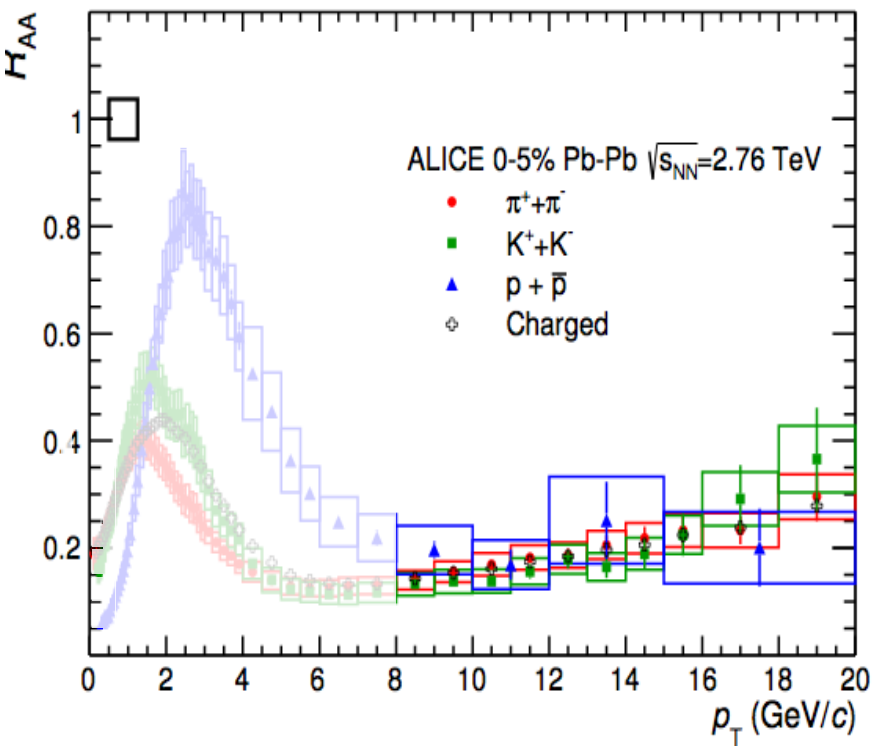
sophisticated reconstruction and analysis methods

R_{AA} of charged and identified particles

R_{AA} of identified particles low p_T



R_{AA} of identified particles high p_T



p_T < 8 GeV/c : hierarchy of suppression

the higher the mass, the less suppression; mesons cluster while protons less suppressed

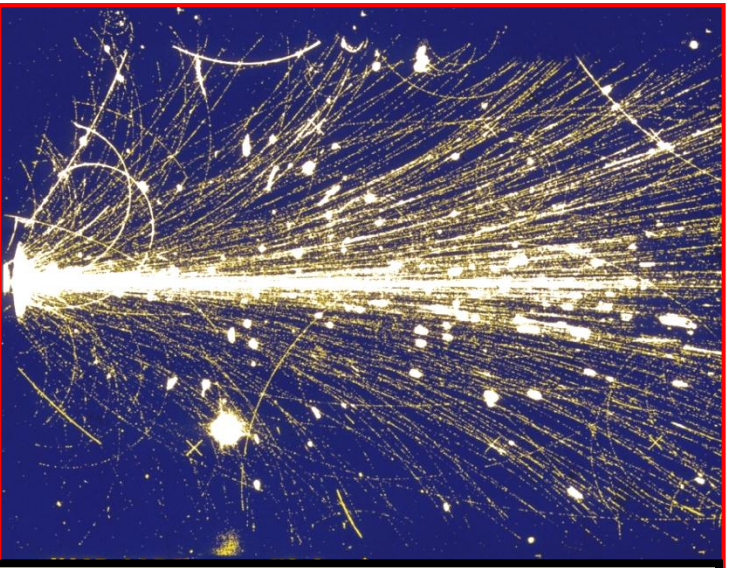
indication of strong radial flow

p_T > 8 GeV/c : R_{AA} similar for all hadrons

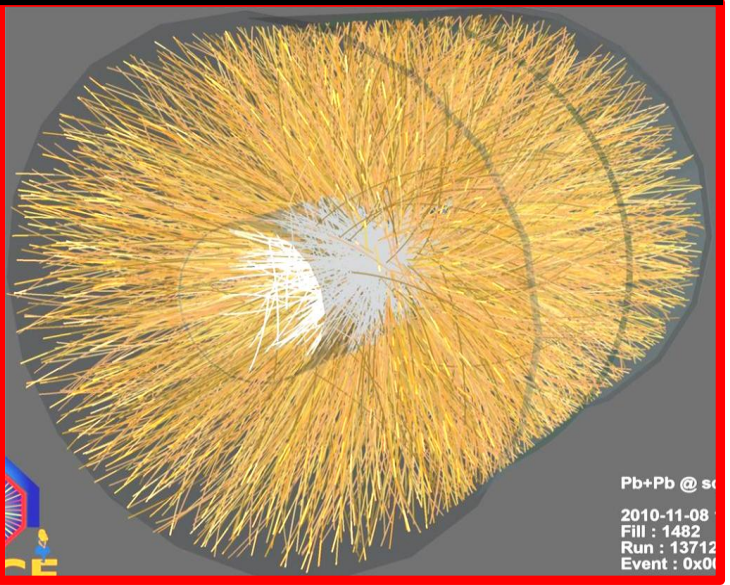
indication that all species are affected by the medium the same way

…coming soon…

1986: NA35 at CERN SPS



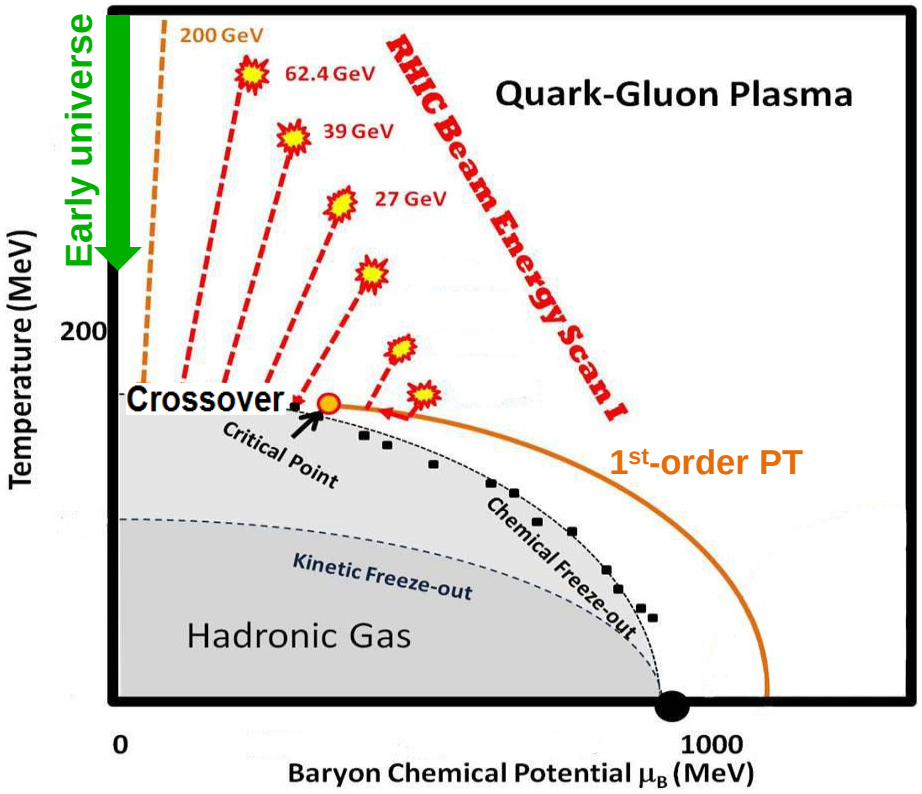
2010: ALICE at CERN LHC



Toward the Limits of Matter:
Ultra-relativistic nuclear collisions at CERN

by
Jurgen Schukraft and Reinhard Stock

Mapping the QCD phase diagram



Beam Energy Scan topics:

Are there signs of EOS softening (possible 1st-order Phase Transition)?

Do we observe a turn-off of QGP signatures? ?

…or Critical Point *?*

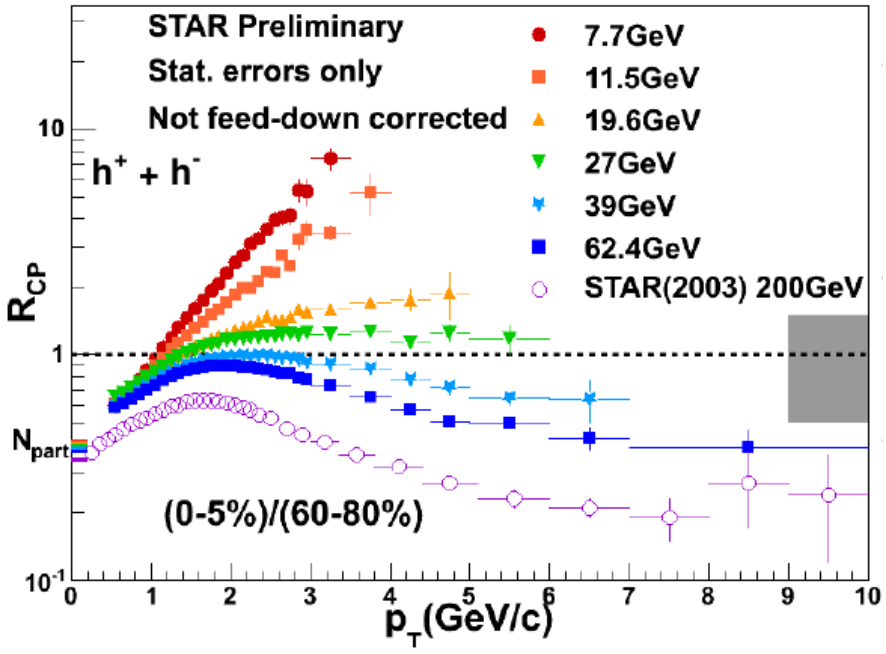
…or Chiral Effect?

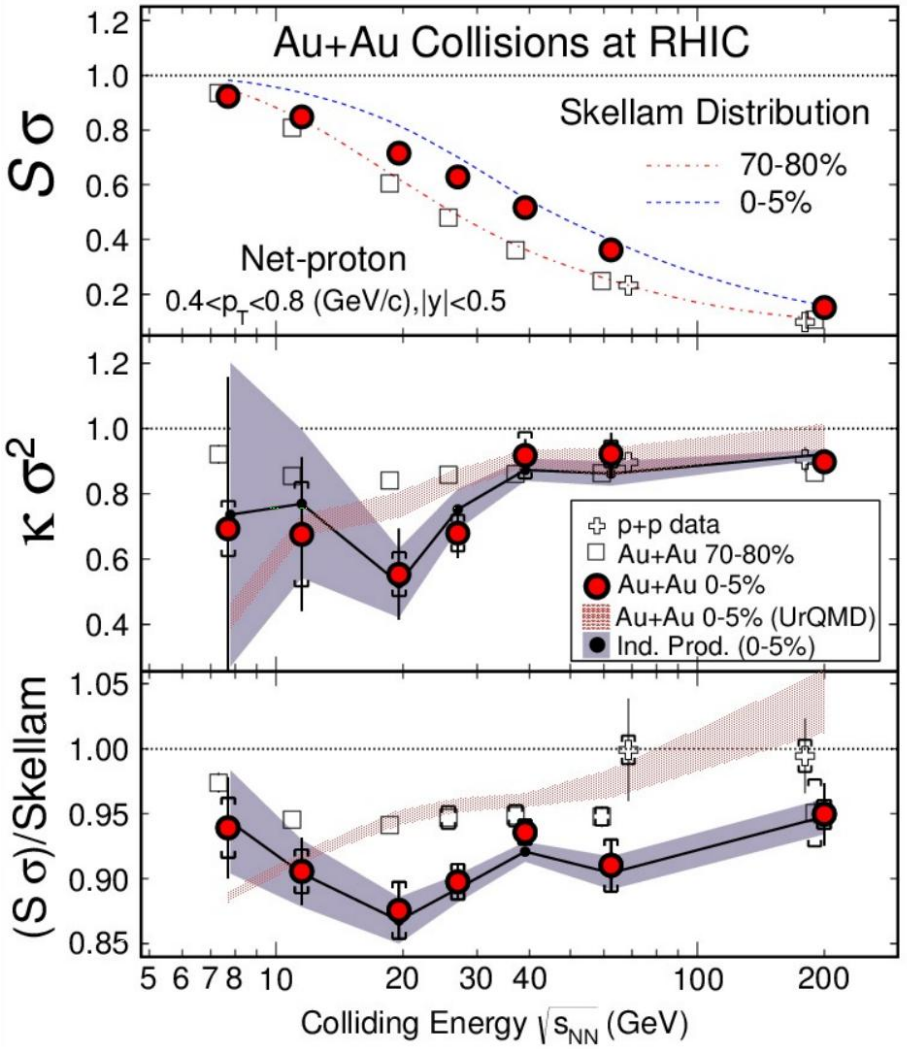
RHIC BES History

2007: STAR Beam Energy Scan (BES) Focus Group formed
2008: Test run at $\sqrt{s_{NN}}$ = 9.2 GeV [PRC **81**, 024911 (2010)]
2009: Proposal for BES Phase-I [STAR Note SN0493 & arXiv:1007.2613]
2010: BES-I data-taking began (39, 11.5 & 7.7 GeV)
2011: Two further energies (27 & 19.6 GeV)
2012: Test at 5 GeV
2014: Final BES-I energy (14.5 GeV) & BES-II proposal

BES I Results

Jet quenching at RHIC



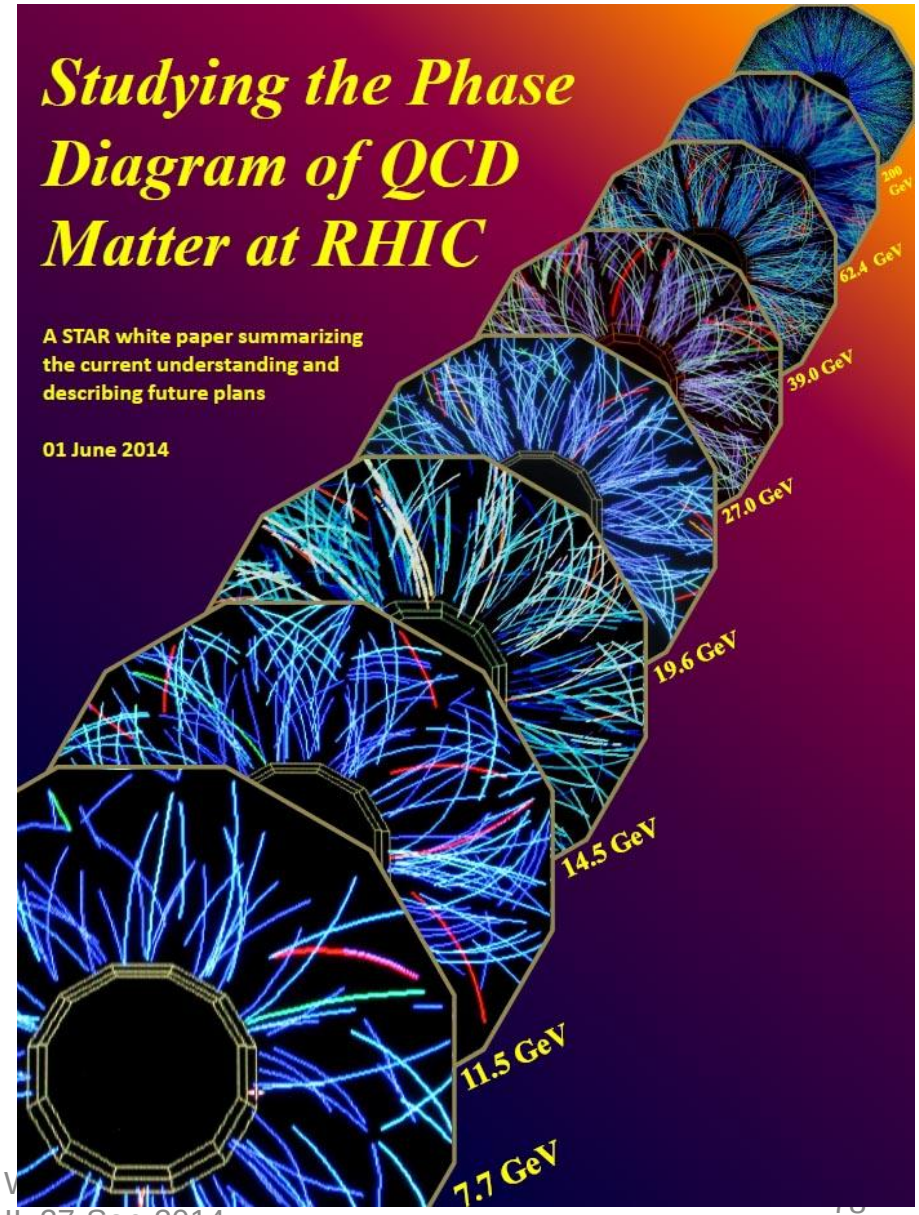


Light hadrons suppressed at high p_T

at 39 - 200 GeV

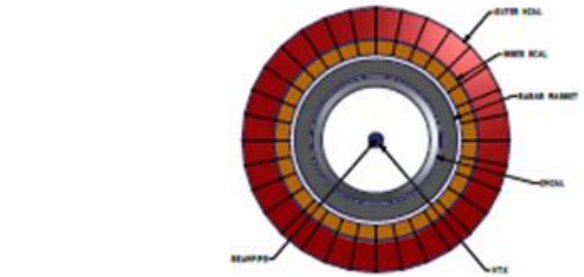
Several Measurements giving hints

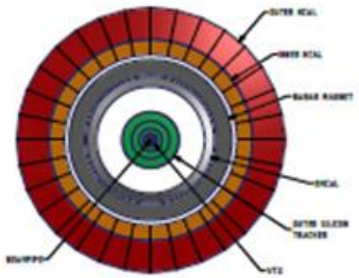
Plans for BES II

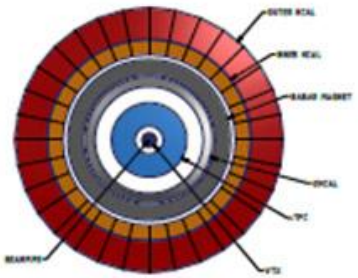


Beam Energy Scan II (2018–2019)

PHENIX Collaboration White Paper



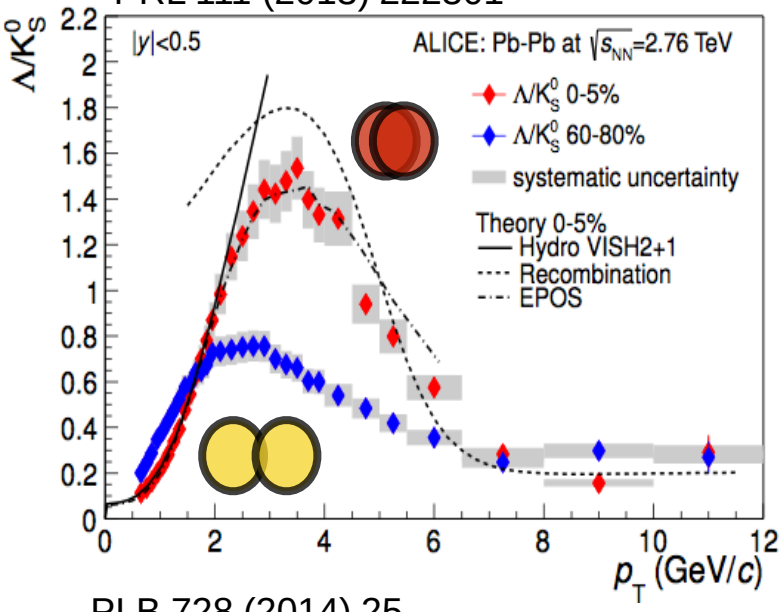




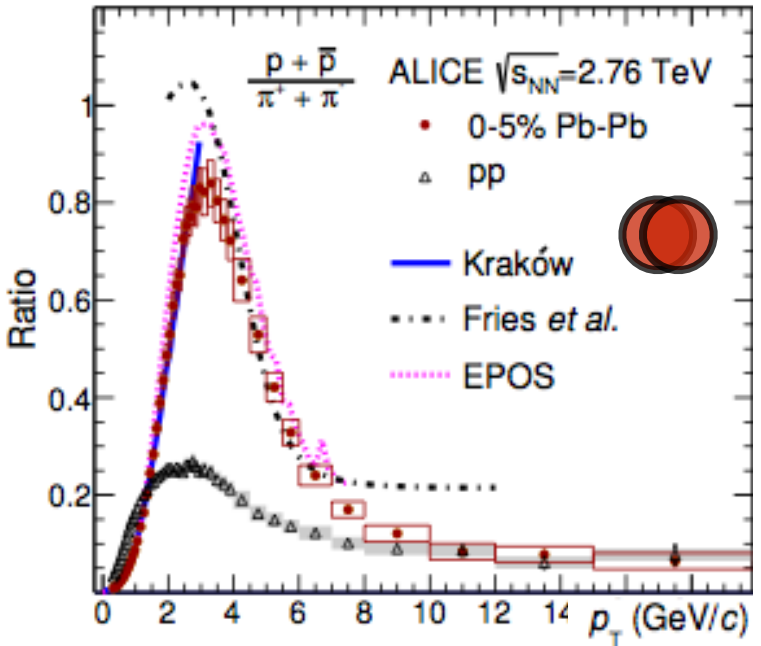
Version 1: March 1, 2014

Intermediate p_T: baryon-to-meson in Pb-Pb

PRL 111 (2013) 222301



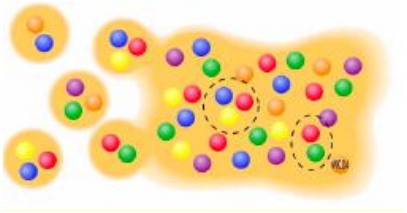
PLB 728 (2014) 25



Λ/K^0_S and p/π ratios are
enhanced in central A-A wrt. pp
as observed at RHIC

the maximum increases and shifts to higher p_T

Flow or recombination of quarks ?



Mesons (π, K^0_S) $p_T(q\bar{q}) \approx 2 \times p_T(q)$

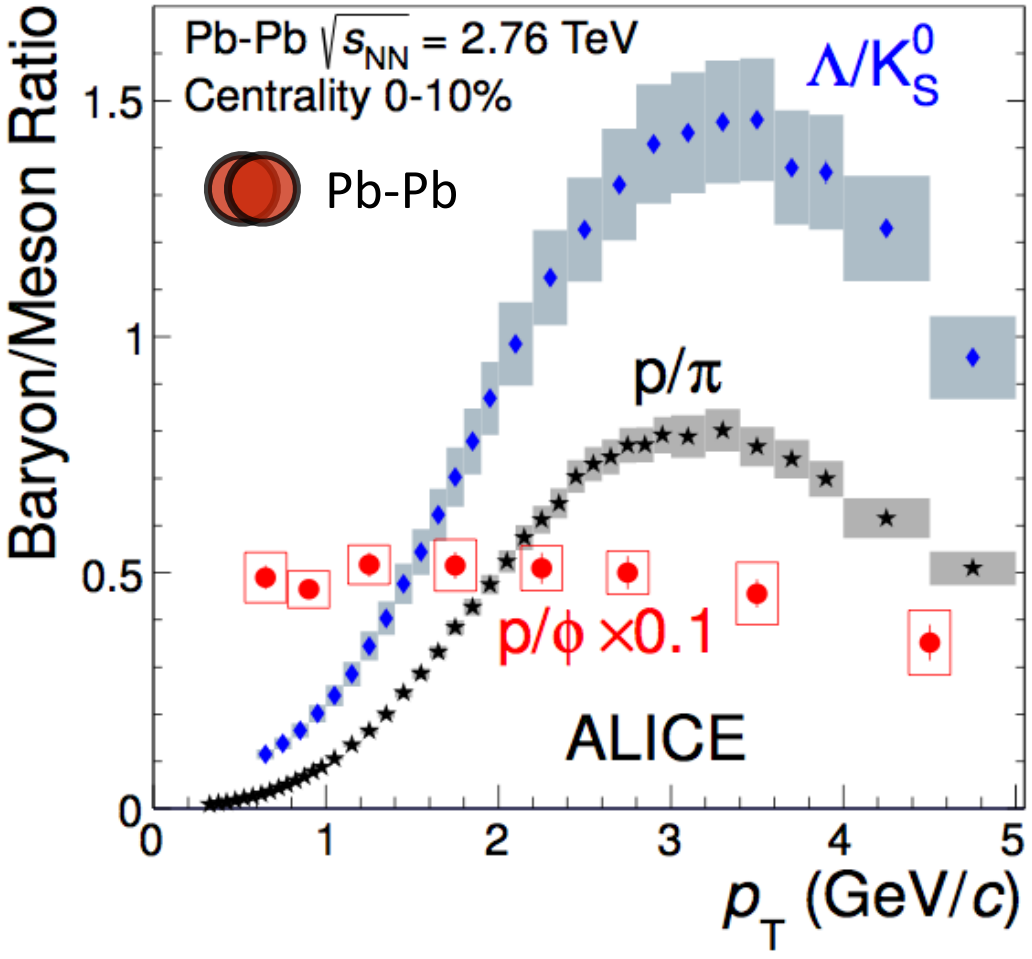
Baryons (p,Λ) $p_T(qq) \approx 2 \times p_T(q)$

hydro model works fine for p_T < 2 GeV
but **deviates at higher p_T**
Song, PLB 658 (2008) 279

recombination approximately reproduces shape
but **overestimates effect**
Fries, Ann.Rev.Nucl.Part.Sci. 58 (2008) 177

EPOS provides **good description** of data
Werner, PRL 109 (2012) 102301

Baryon-to-meson in Pb-Pb



p/ϕ ratio in Pb-Pb

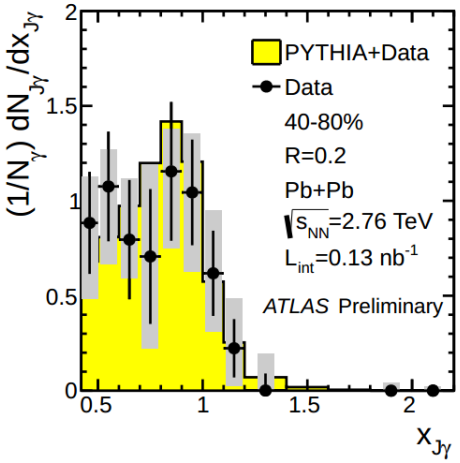
test baryon enhancement:

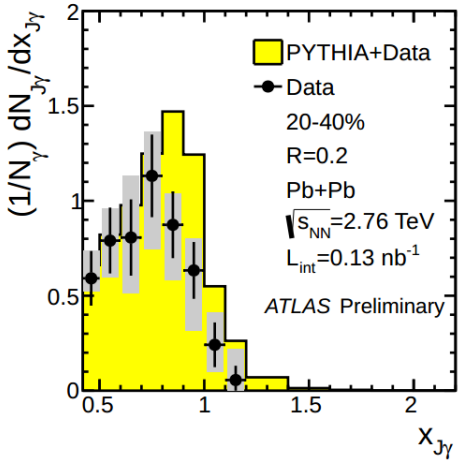
p:	938 MeV/c^2	*qqq*
φ:	1018 MeV/c^2	*qq*

spectral shapes are
very similar if particles have similar mass

p/φ ratio is constant

the data indicate that
mass is the main parameter driving particle spectra
as foreseen by hydro


PYTHIA+Data
Data
40-80%
R=0.2
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_\gamma)\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$


PYTHIA+Data
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R=0.2
Pb+Pb
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ATLAS Preliminary
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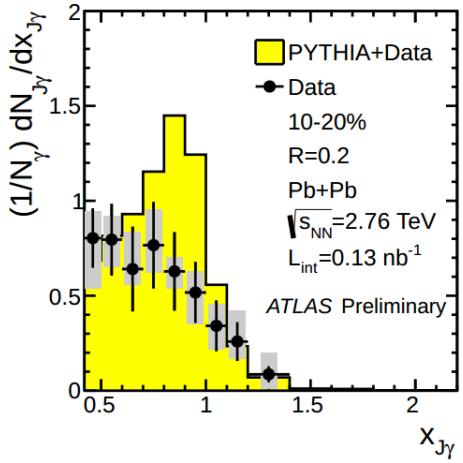
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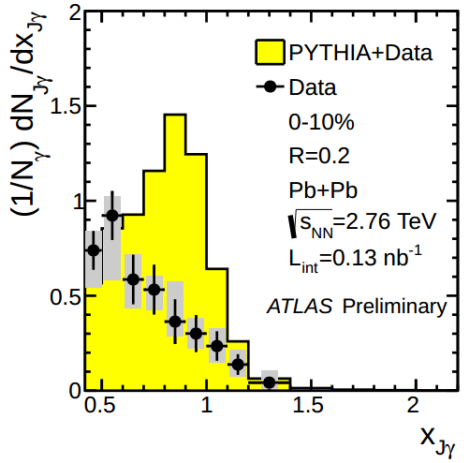
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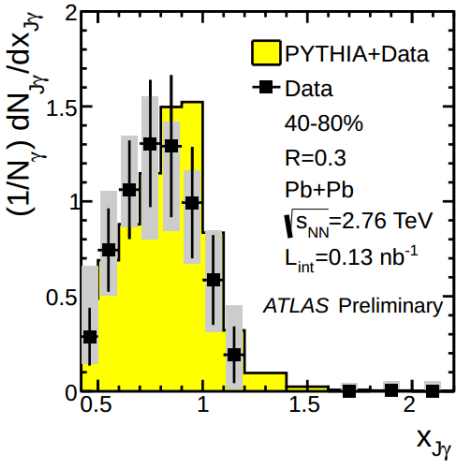
PYTHIA+Data
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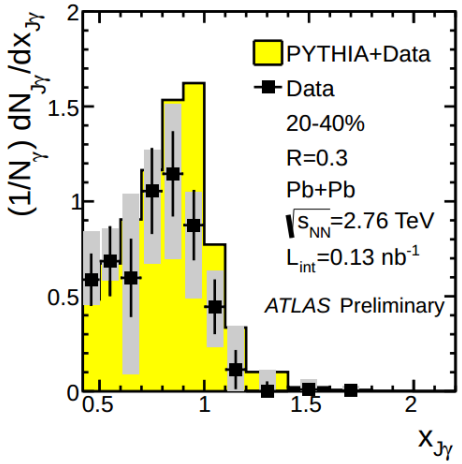
PYTHIA+Data
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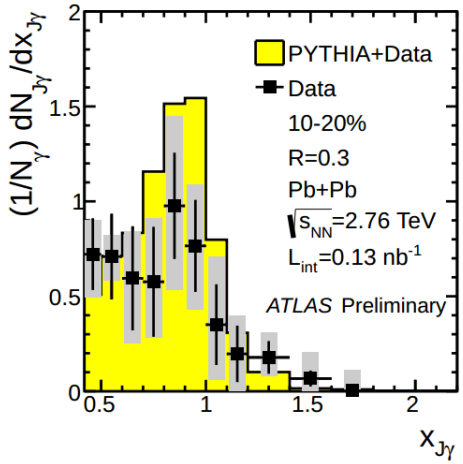
PYTHIA+Data
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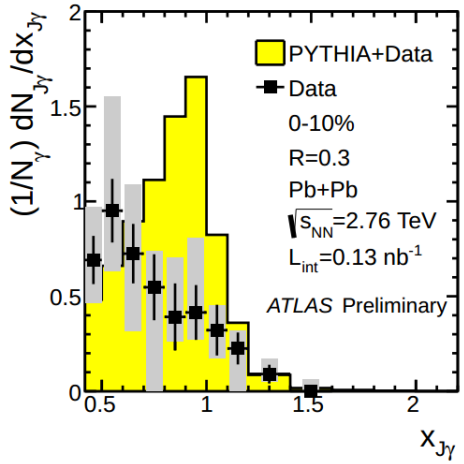
PYTHIA+Data
Data
0-10%
R=0.3
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
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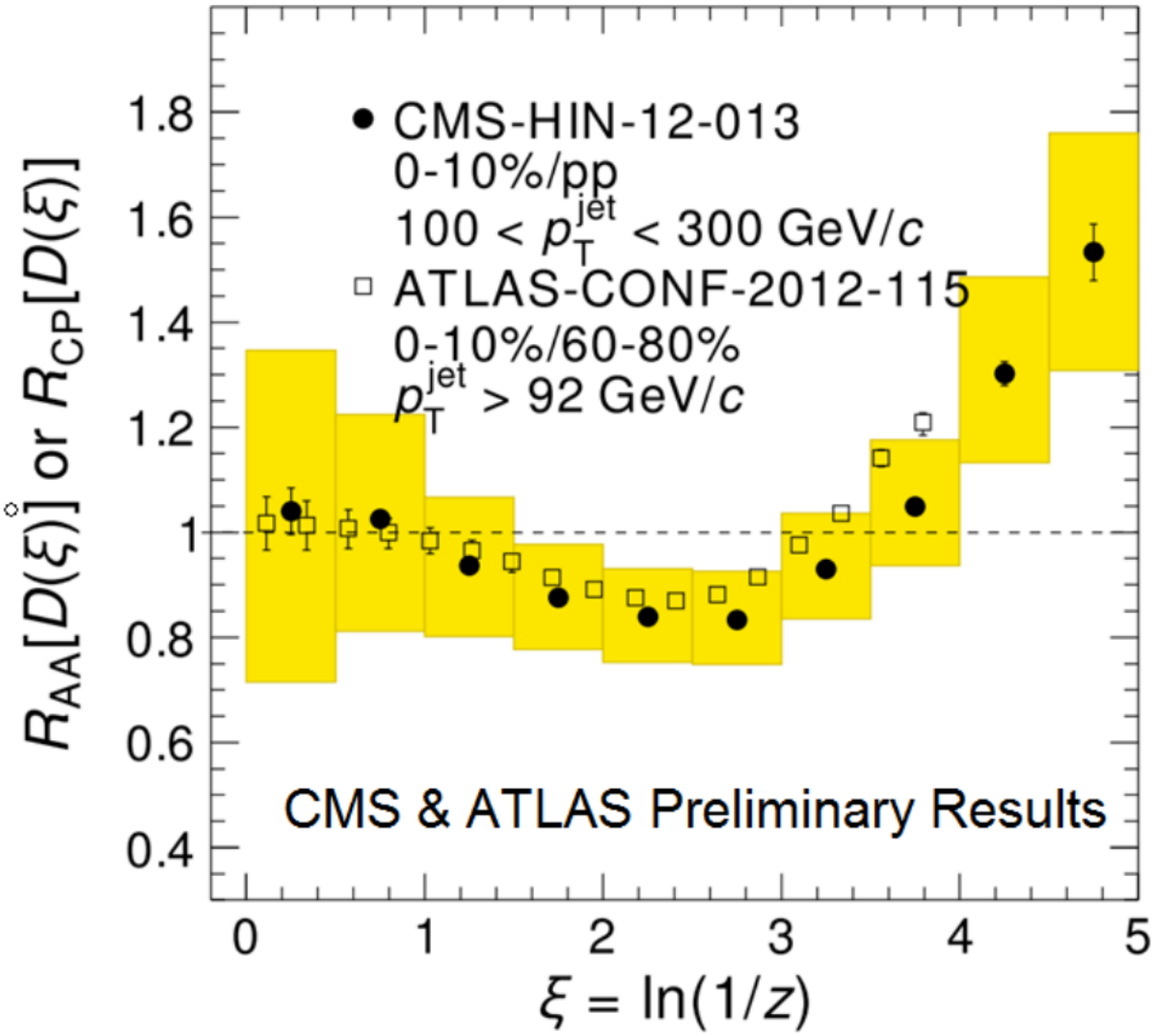
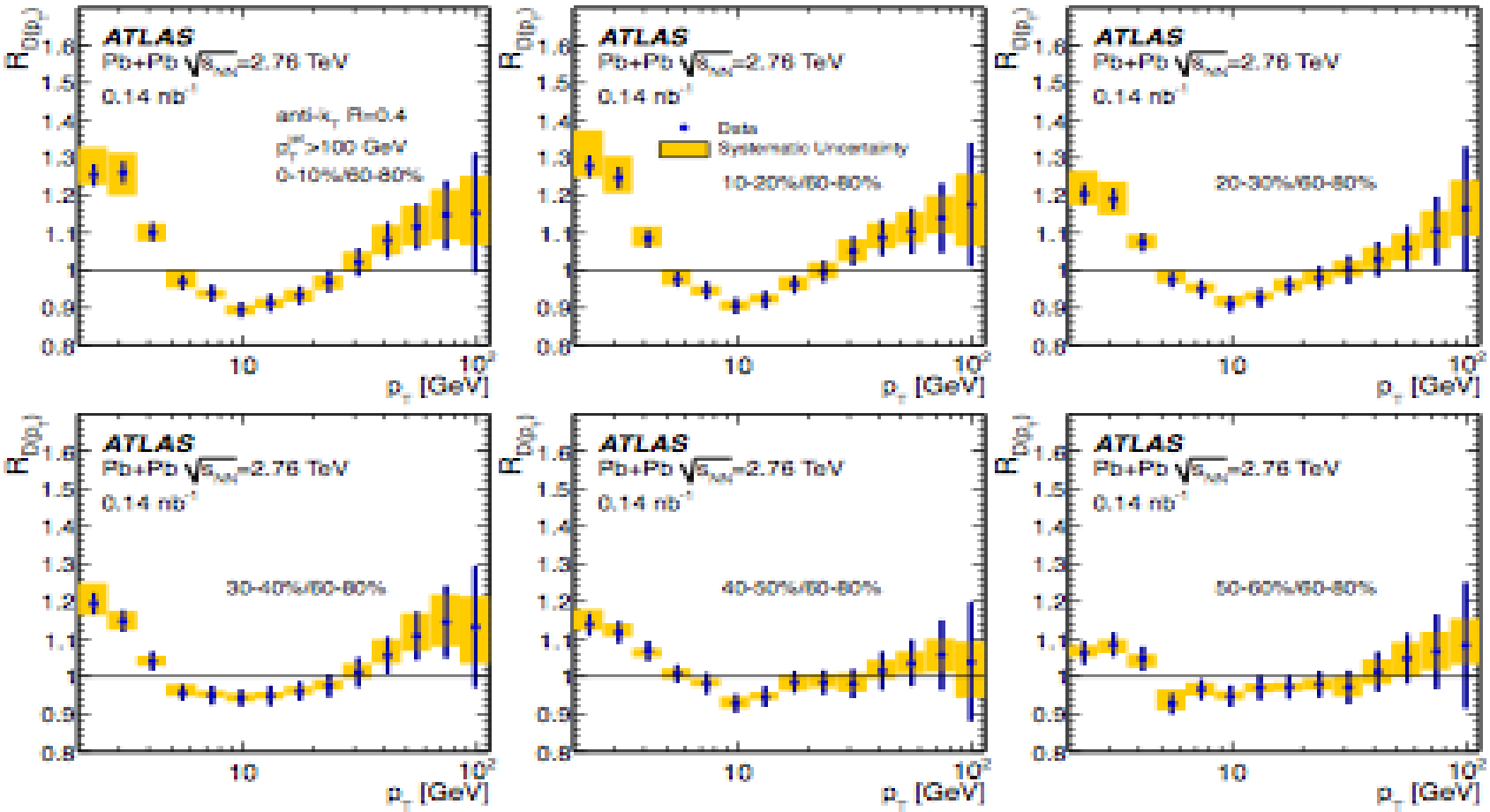
$x_{J\gamma}$


CMS-HIN-12-013
0-10%/pp
100 < p_T^{jet} < 300 GeV/c
ATLAS-CONF-2012-115
0-10%/60-80%
p_T^{jet} > 92 GeV/c
CMS & ATLAS Preliminary Results
$R_{AA}[D(\xi)]$ or $R_{CP}[D(\xi)]$
$\xi = \ln(1/z)$
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0
1
2
3
4
5

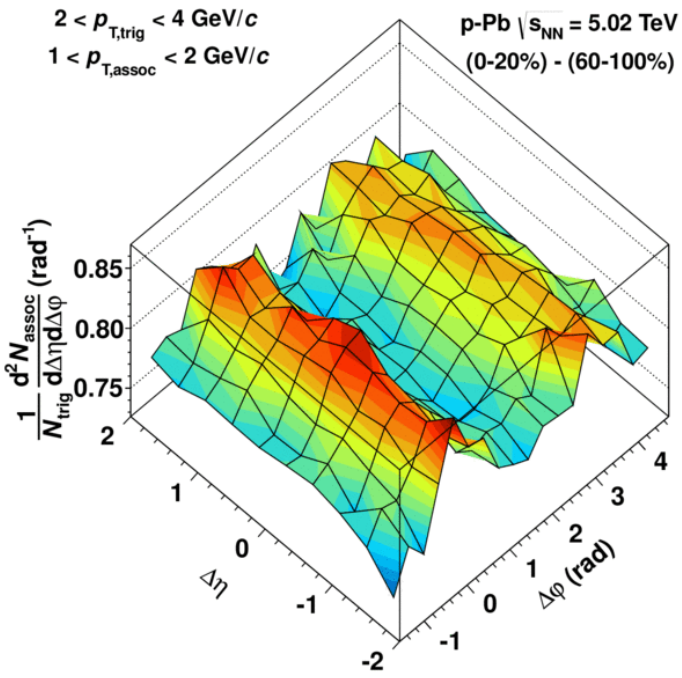
Jet Quenching (jet fragmentation)



- To first order the jets still look like vacuum jets
- Detailed measurements do show small deviations
- Not well understood in models yet

The double ridge

Excess in the correlation yield between the two multiplicity event classes



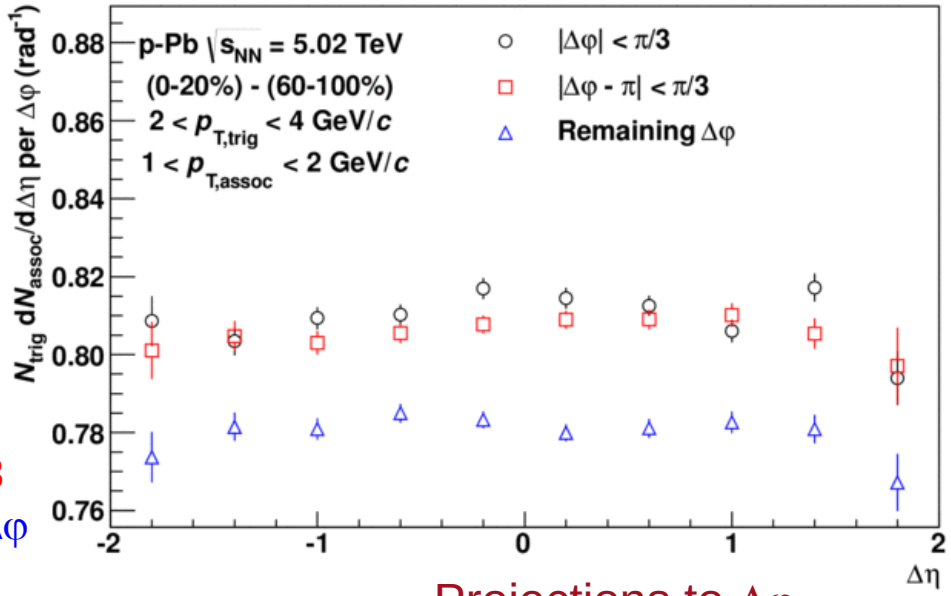
Two ridges:
Magnitude the same and fairly flat in $\Delta\eta$

Fit allows to extract v_n coefficient

$$v_n = \sqrt{a_n / b}$$

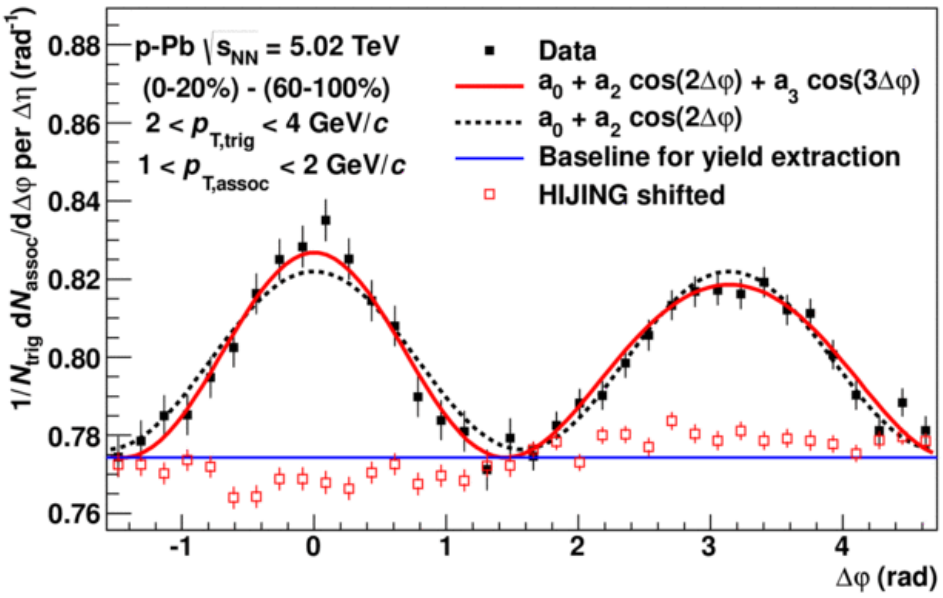
PLB719 (2013) 29

Projections to $\Delta\eta$



|Δφ| < π/3
|Δφ - π| < π/3
Remaining Δφ

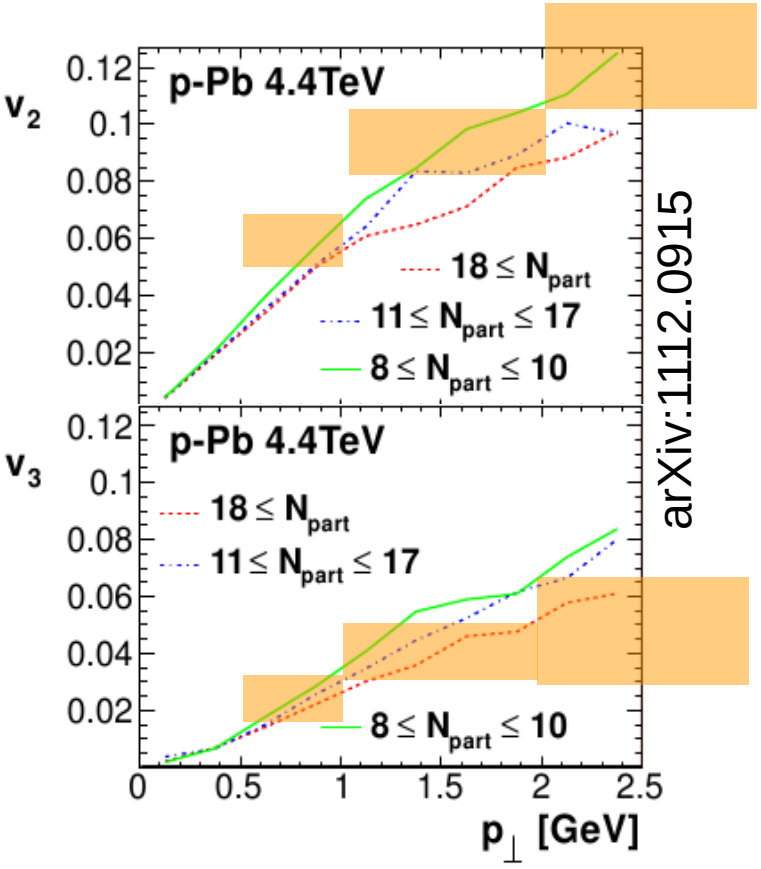
Projections to $\Delta\varphi$



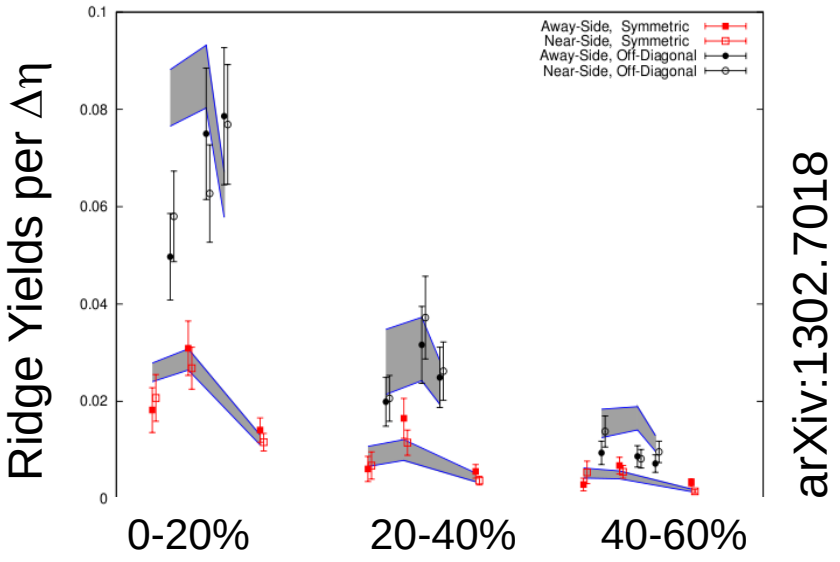
Comparison to models

3+1 viscous hydro in p-Pb collisions

Boxes: ALICE data for 0-20%



Color glass condensate



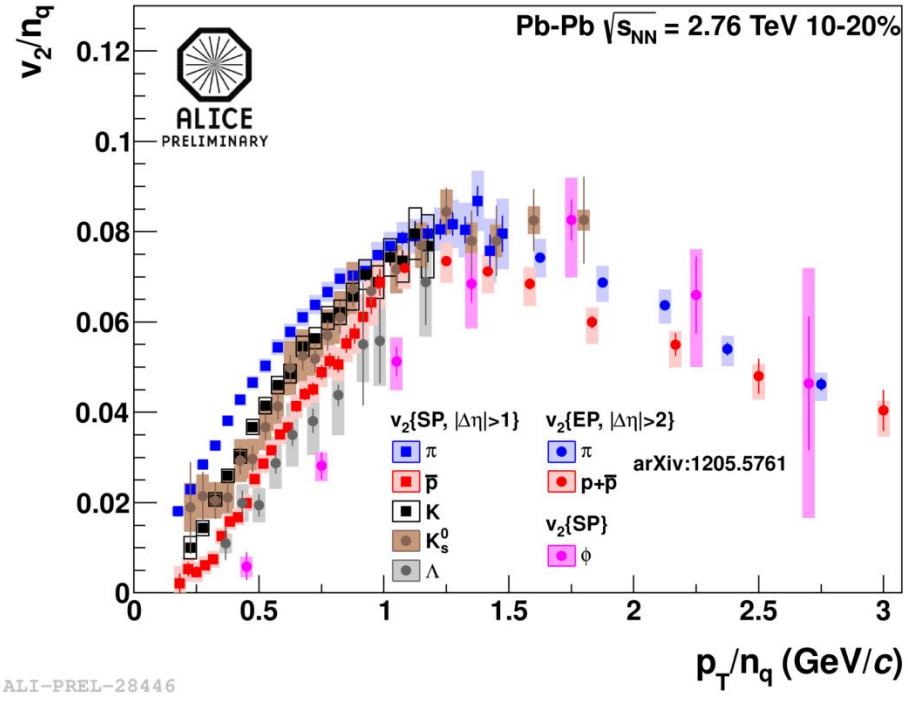
Near and away side yields:

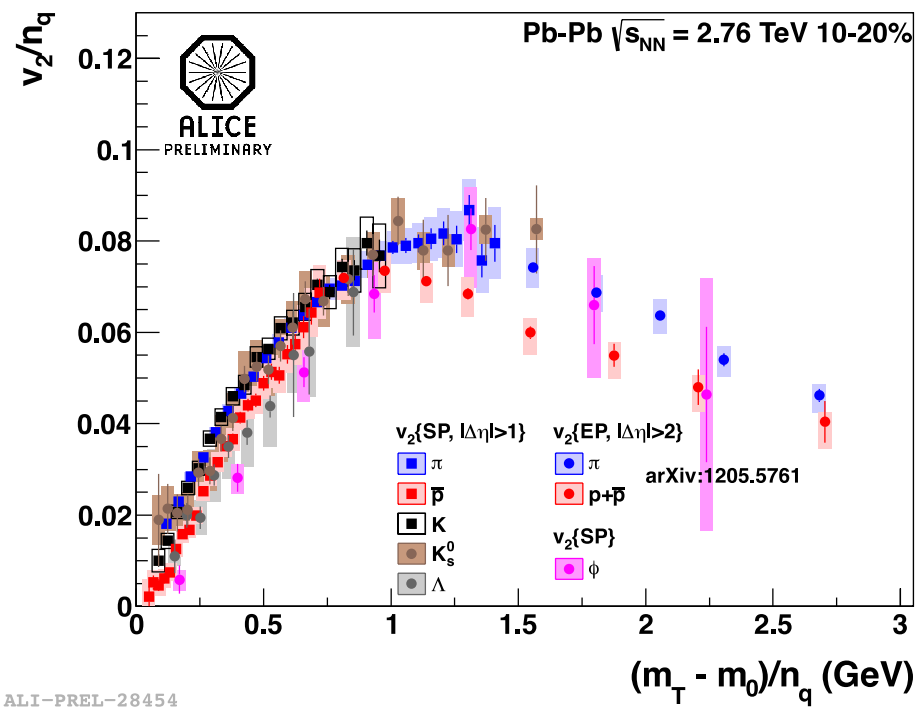
- **vary over a large range**
- **agree for each p_T and event class**

Common underlying processes?

Quark scaling

v_2 scaled with n of constituent quarks versus scaled p_T and kinetic energy



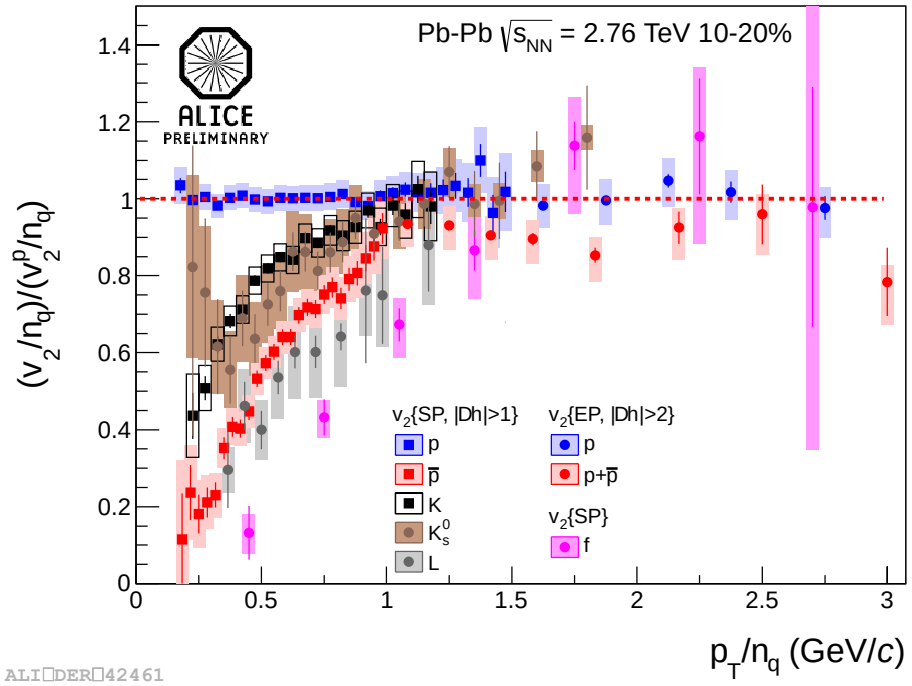


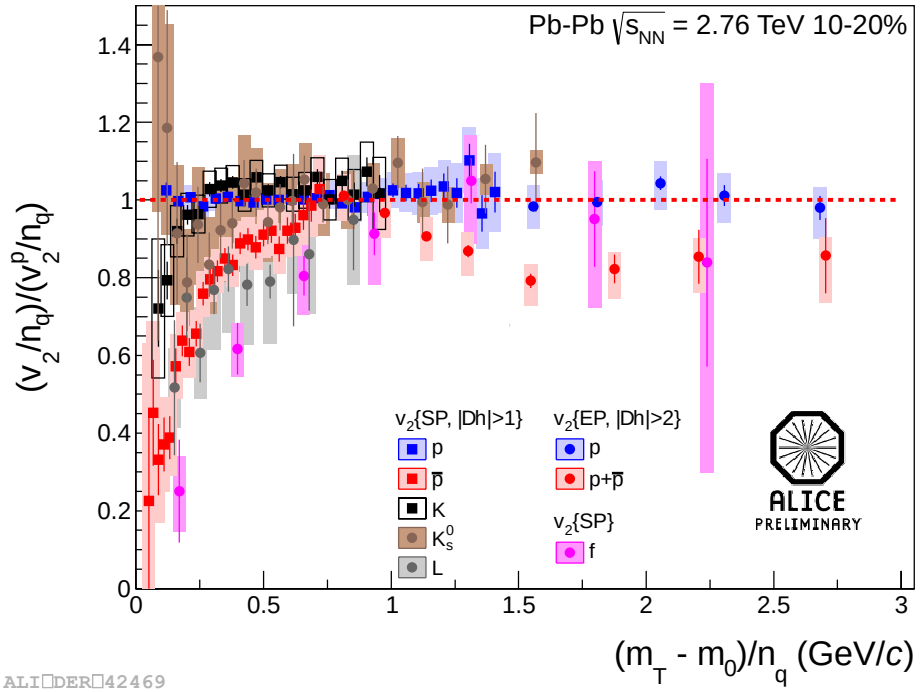
Quark scaling at RHIC: sign that hadron formation is dominated by quark coalescence at the end of the partonic evolution

*Results already published in the central η region:
v_2 → Phys. Rev. Lett. 105, 252302 (2010),
v_3 → Phys. Rev. Lett. 107, 032301 (2011)

Quark scaling

v_2 scaled with n of constituent quarks versus scaled p_T and kinetic energy

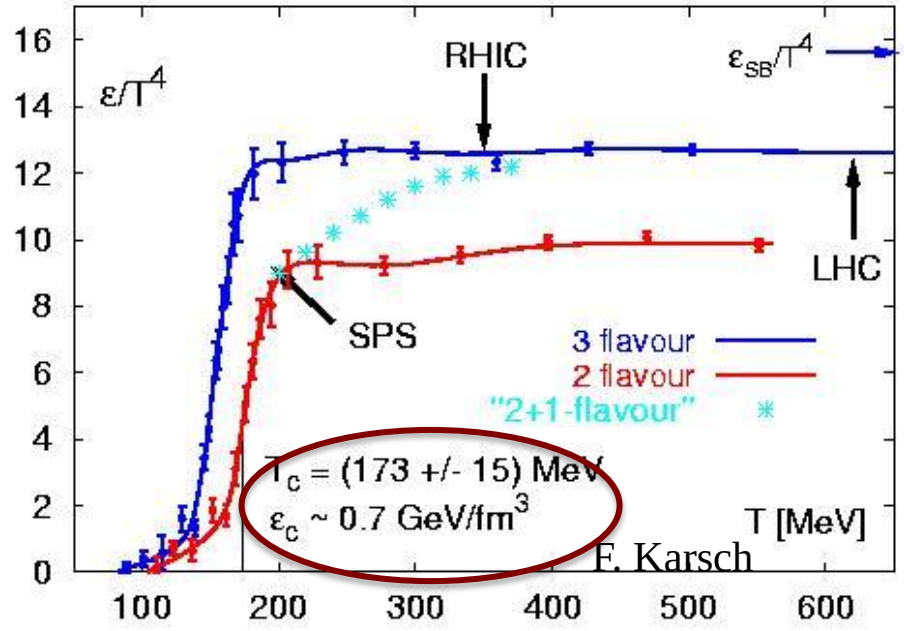




divided by polynomial fit to pion v_2

*Results already published in the central η region:
v_2 → Phys. Rev. Lett. 105, 252302 (2010),
v_3 → Phys. Rev. Lett. 107, 032301 (2011)

QCD Phase Transition



QCD on the Lattice

Critical conditions:

Phase Transition to **Guark-Qluon Plasma**

- Deconfinement
- Chiral Symmetry Restoration

Mass

- Elementary particles: Higgs
- Complex systems: QGP

LHC: $\mu_B = 0$, where Lattice is exact

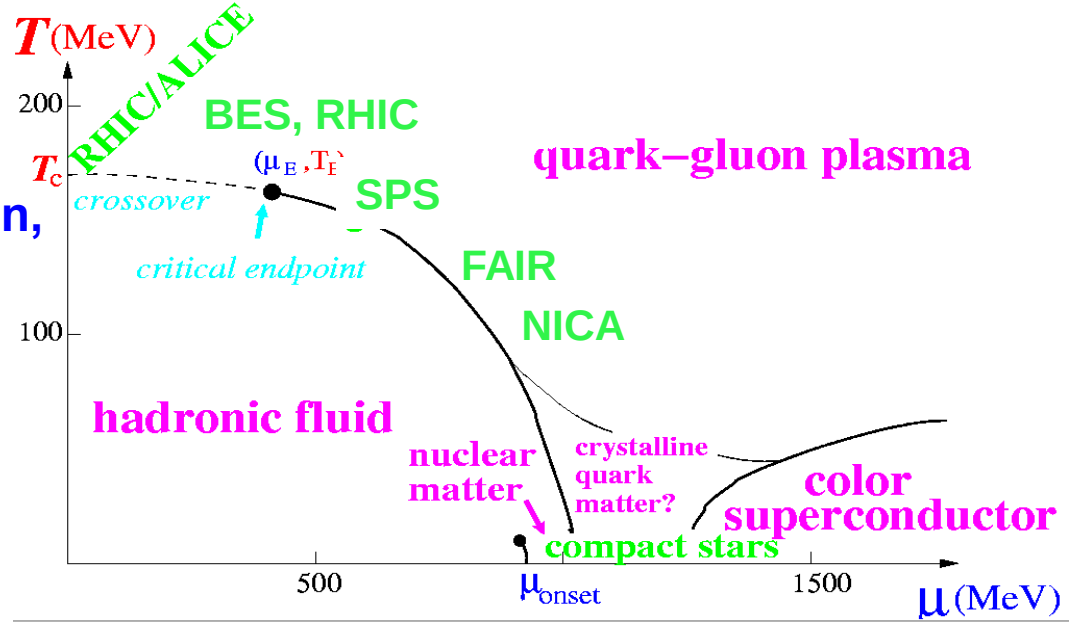
Standard Model Physics (QCD)

But QCD Lagrangian cannot describe "real life" particles

"Soft" physics: experimentally driven, interplay of experiment and theory

Macro- and microscopic properties

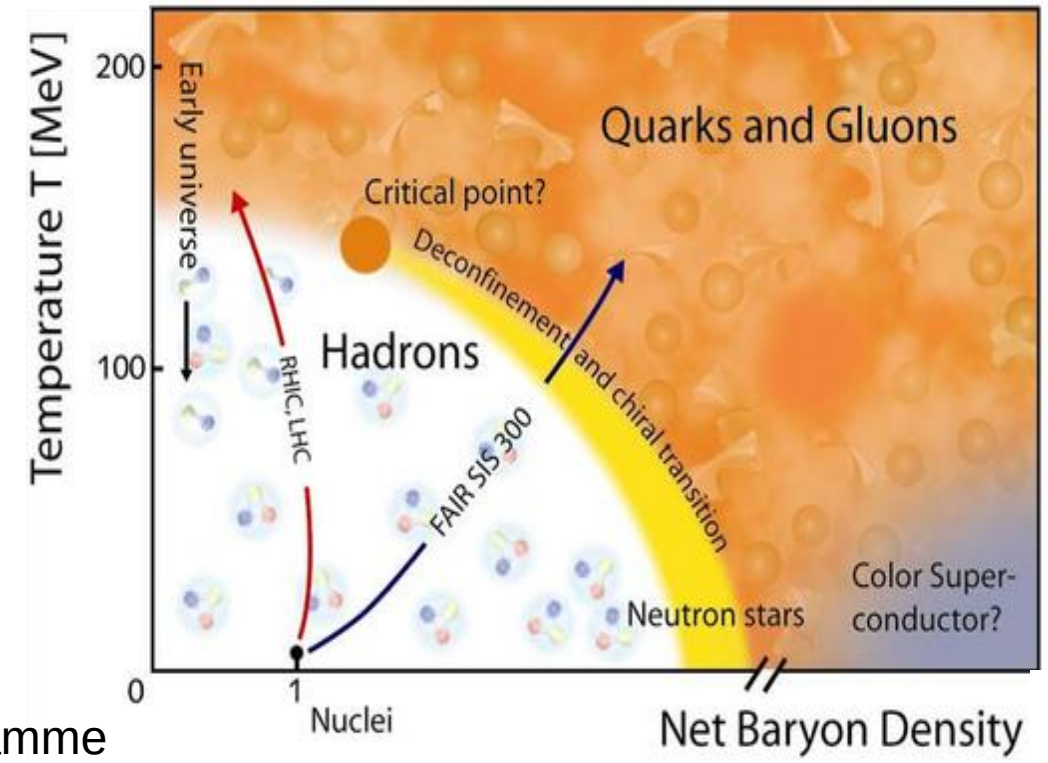
- Transition Temperature
- Critical Point ?
- Equation of State (p,T)
- Transport Coefficients, Viscosity



Heavy-ion Physics

study QCD matter under extreme conditions
high temperature and energy-density

expected to undergo a **phase-transition**
normal hadronic matter to
deconfined quarks and gluons (QGP)



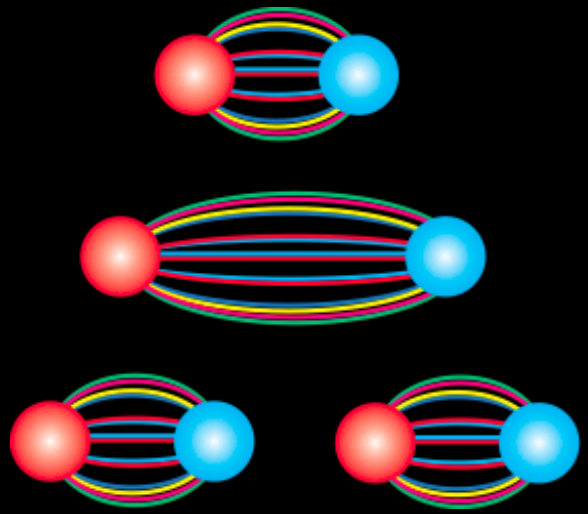
Study the phase diagram and
the properties of hot QCD matter

A rich ultra relativistic heavy-ion programme

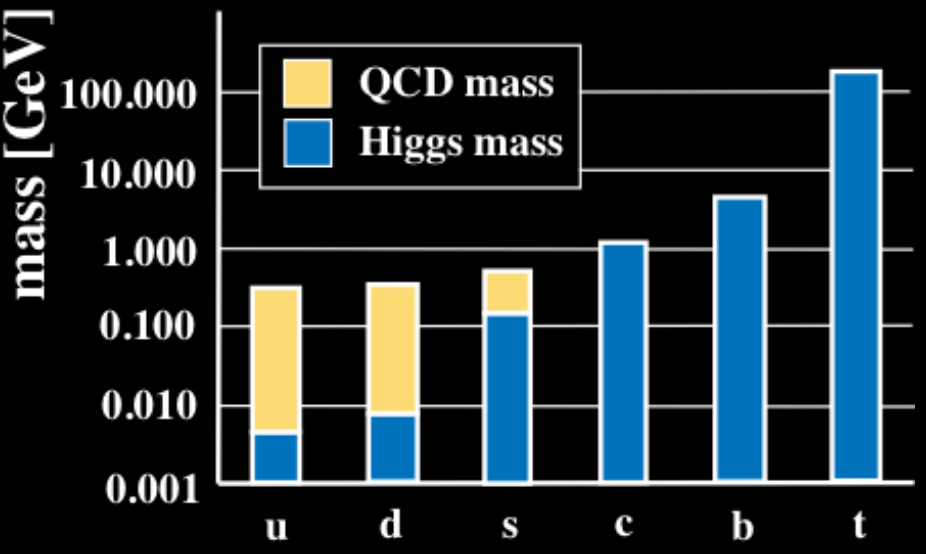
past:		GSI	SIS		~2 GeV
			BNL	AGS	~5 GeV
			CERN	SPS	~20 GeV
present:	BNL	RHIC	~200 GeV		
			CERN	LHC	~5 TeV
future:	GSI	FAIR	~45 GeV		

Studying the macroscopic quantities of the QGP we expect to better understand the underlying theory of strong interactions (QCD) in the non-perturbative regime

mechanism of confinement

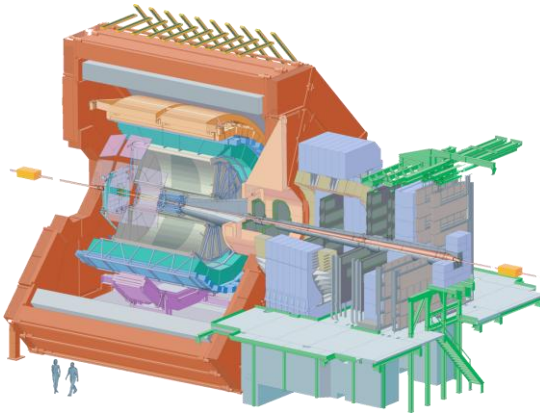


mass generation in the strong interaction



Change name: “Heavy-Ion Physics”

What is ALICE looking for through the Looking Glass



A macroscopic piece of QCD matter (the QGP) characterized by high density and collective phenomena

Heavy-Ion Collisions is the tool

that we expect will provide the necessary conditions for the QCD phase transition to QGP to happen

to study “high energy density QCD” and the properties of the QGP

At LHC energies valid question :

energy density of high-multiplicity pp or pPb events ?

http://info.web.cern.ch/info/Press/PressReleases/Releases2000/PR01.00EQuarkGluonMatter.html

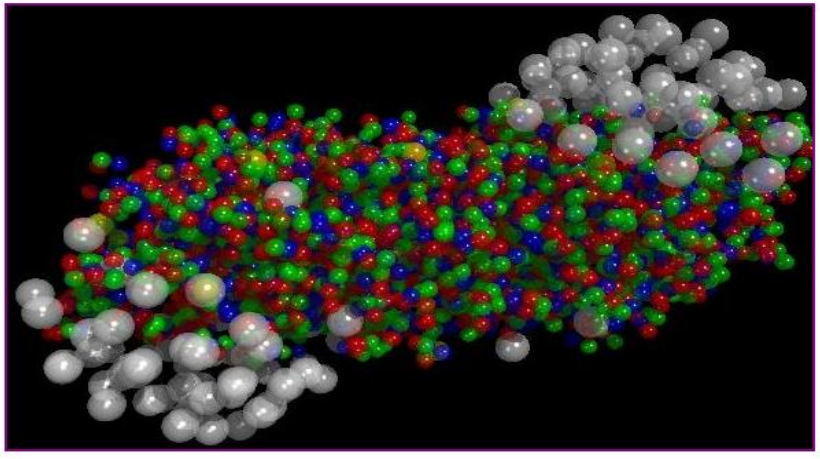
This lead to a Press Release

….. compelling evidence for a new state of matter,
featuring many of the characteristics expected for a Quark-Gluon Plasma

PRESS RELEASE

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Professor Luciano Maiani, CERN Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundemental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*

The aim of CERN's Heavy Ion programme was to collide lead ions so as to create immensely high energy densities which would break down the forces which confined

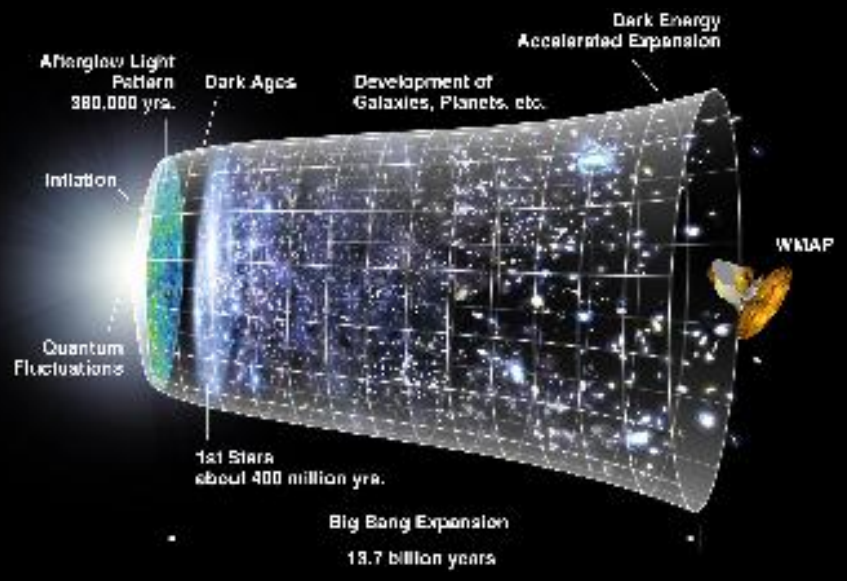
start ASecolint Microsoft Outlook We... New State of Matter ... Local Disk (C:) 4:33 PM

Big and Little Bang

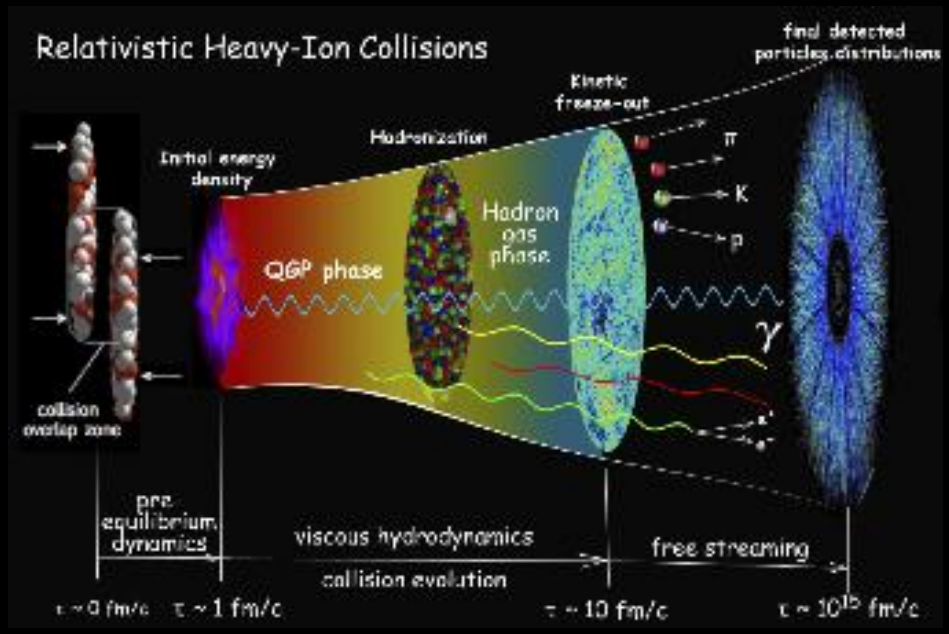
How do we study these “collisions”

Proposed signatures and methods

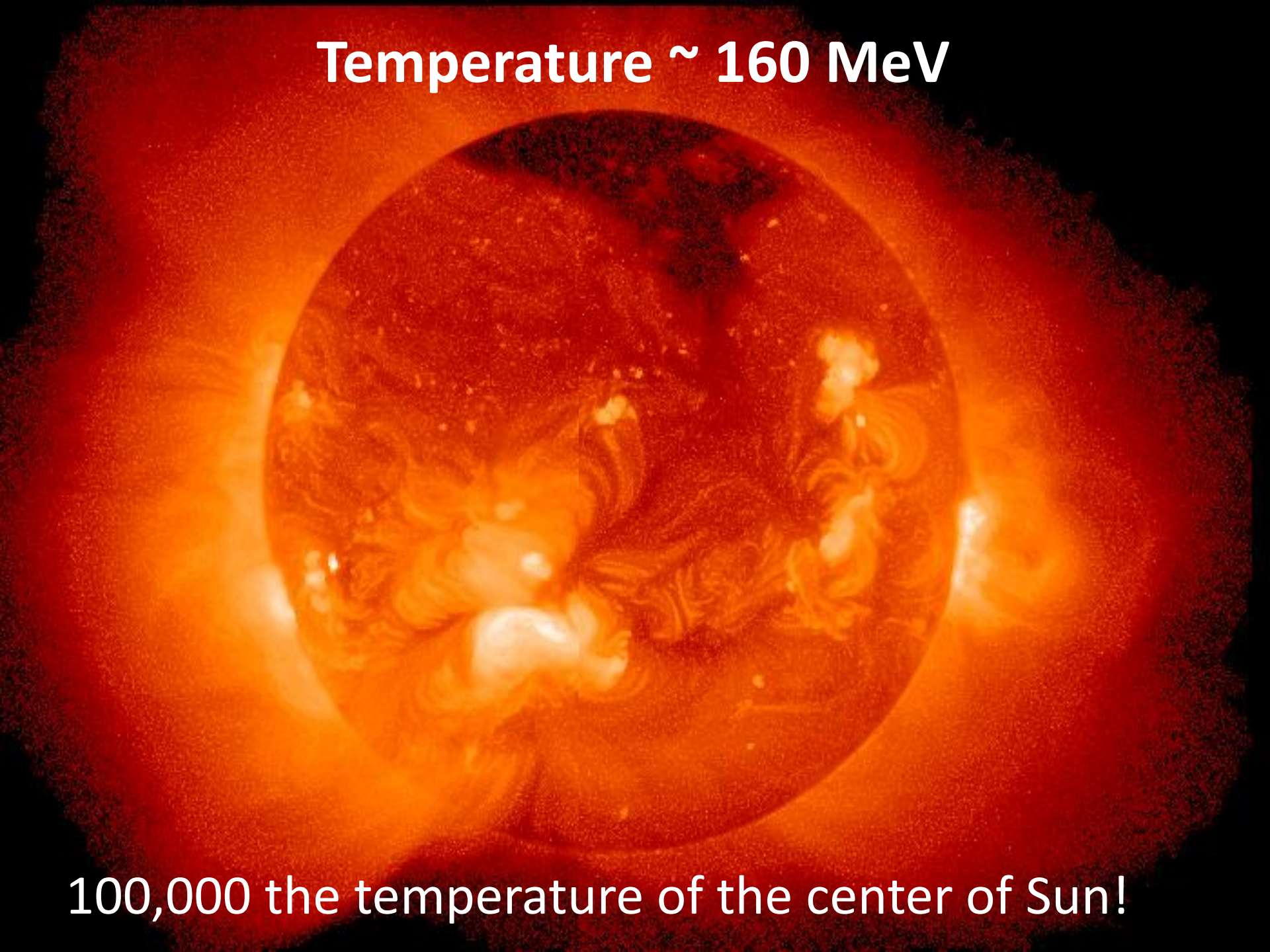
to study the properties of the expanding hot and dense QCD matter



our Universe



a heavy-ion collision


Temperature ~ 160 MeV
100,000 the temperature of the center of Sun!