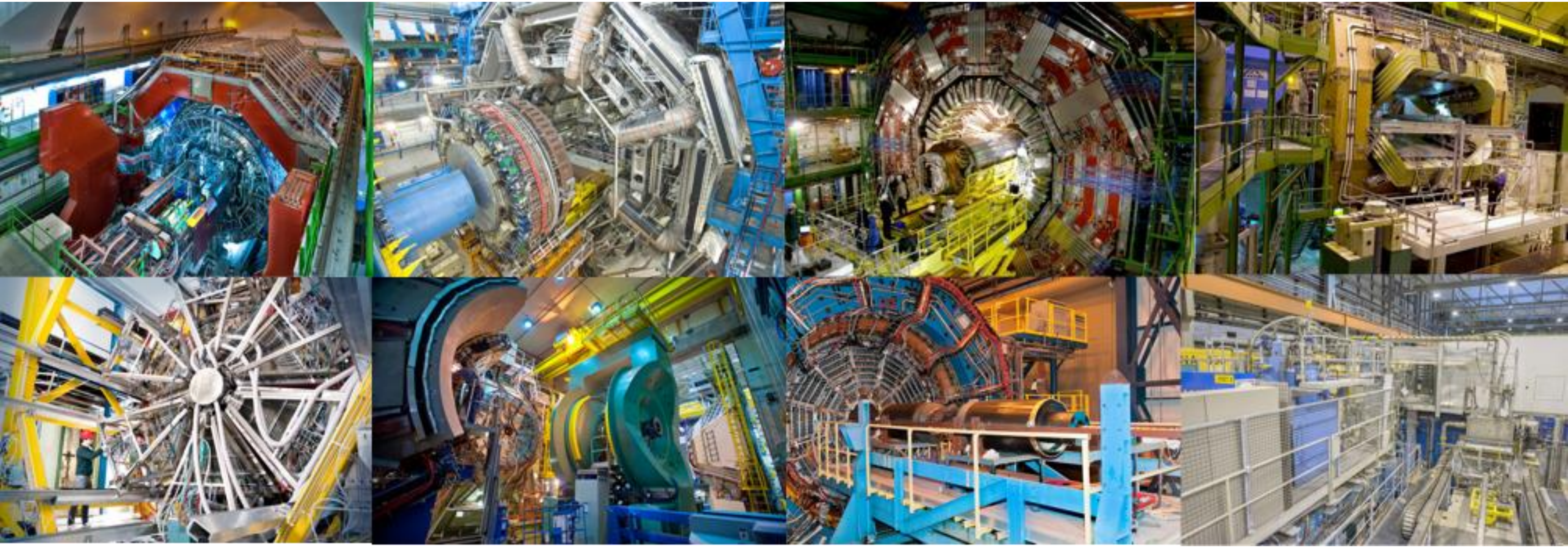
The physics of heavy-ion collisions



Alexander Kalweit, *CERN*

Overview

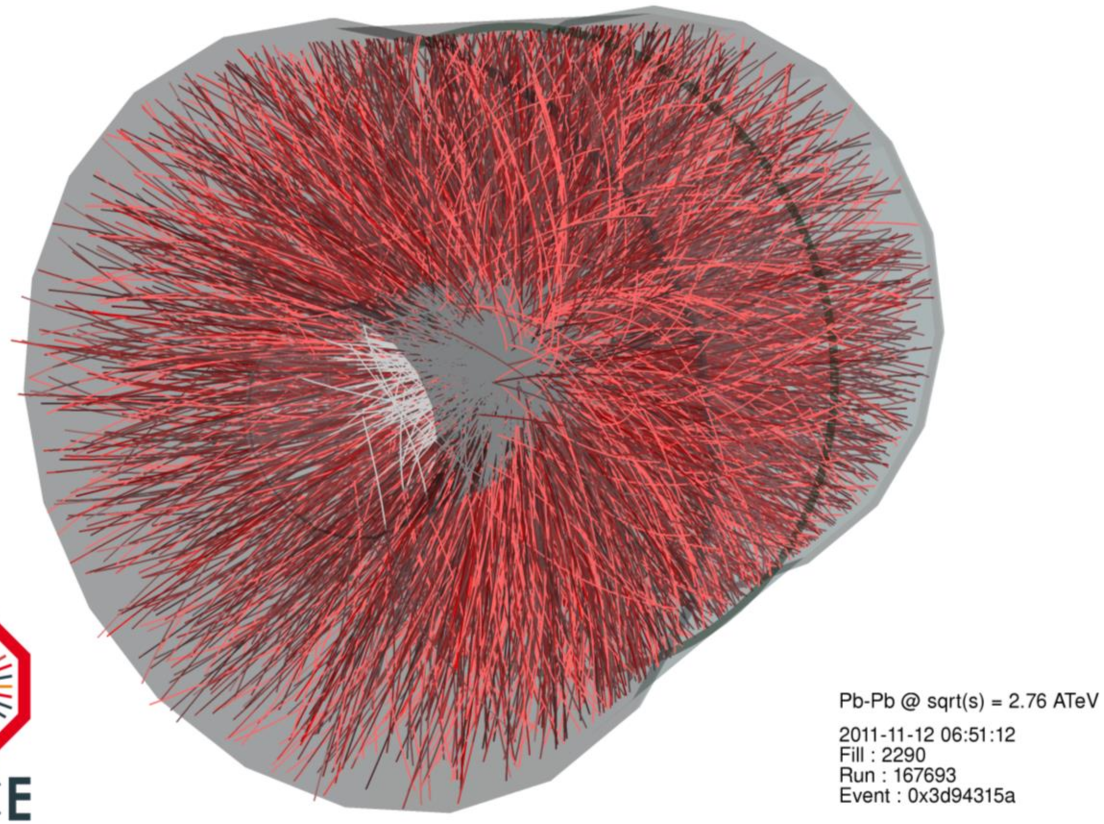
- Three lectures (one hour each):
  - Friday, 10:30h-11:30h (Prevessin)
  - Saturday, 11:30h-12:30h (Meyrin)
  - Monday, 10:30h-11:30h (Prevessin)

- Specialized discussion sessions with **heavy-ion experts** in the afternoons on Friday and Monday.

- Feel free to contact me for any questions regarding the lecture: Alexander.Philipp.Kalweit@cern.ch

- Many slides, figures, and input taken from:

  Jan Fiete Grosse-Oetringhaus, Constantin Loizides, Federico Antinori, Roman Lietava



ALICE
A JOURNEY OF DISCOVERY

Outline and discussion leaders

- Introduction
- The QCD phase transition
- QGP thermodynamics and soft probes (Francesca)
  - Particle chemistry
  - QCD critical point and onset of de-confinement
  - (anti-)(hyper-)nuclei
  - Radial and elliptic flow
  - Small systems
- Hard scatterings (Leticia, Marta)
  - Nuclear modification factor
  - Jets
- Heavy flavor in heavy-ions
  - Open charm and beauty
  - Quarkonia

Francesca Bellini

Leticia Cunqueiro

Marta Verweij

Summary lecture 2

- Now we know the temperature of the system at the final decoupling.
- Today: elliptic flow and why the QGP is an *ideal liquid*.

Particle detection
($t \approx 10^{15}$fm/c)

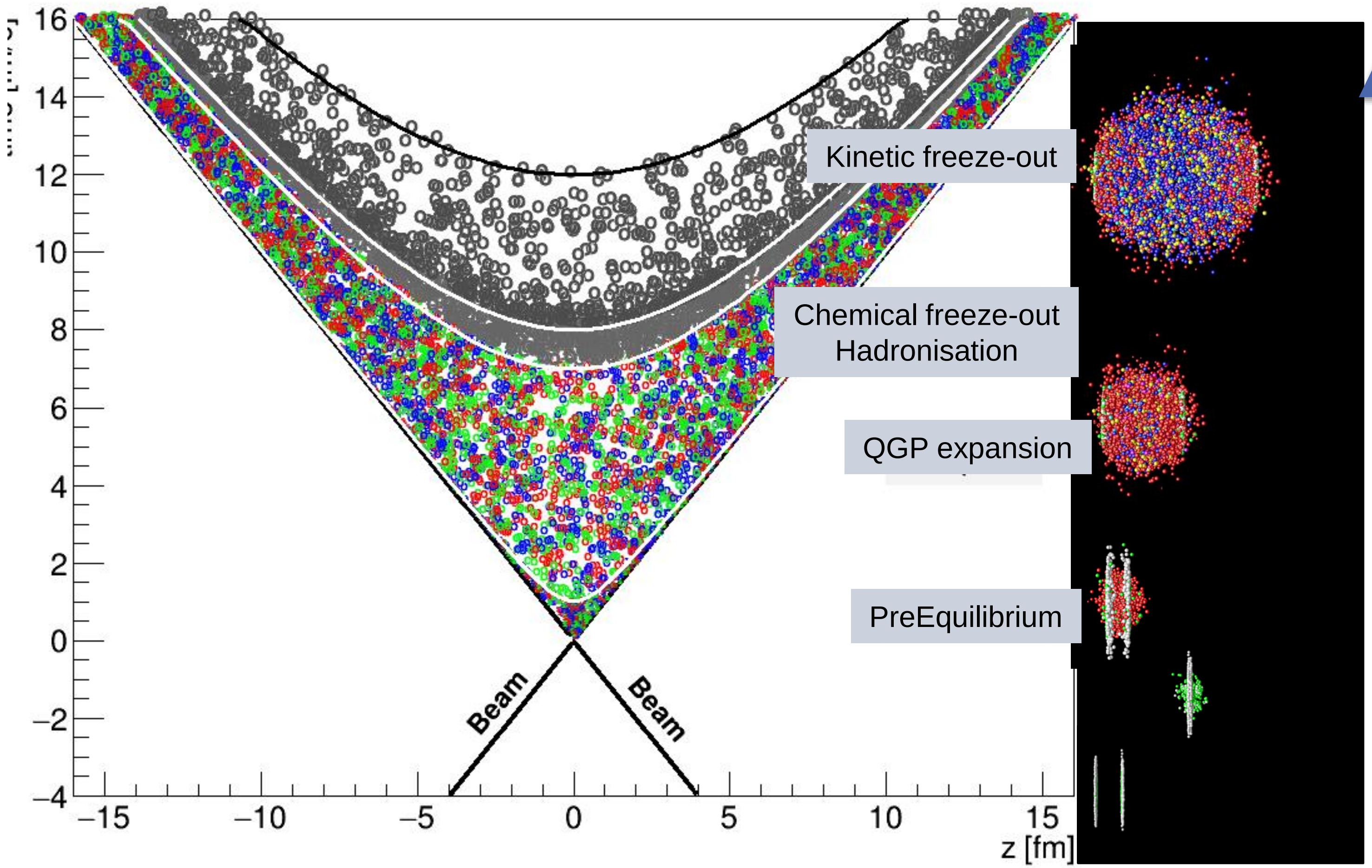
Kinetic freeze-out
(t=10fm/c)

Chemical freeze-out
156 MeV

Hydrodynamic
evolution (t~0.5fm/c)

Pre-equilibrium

Collision (t=0fm/c)



T ~ 90 MeV

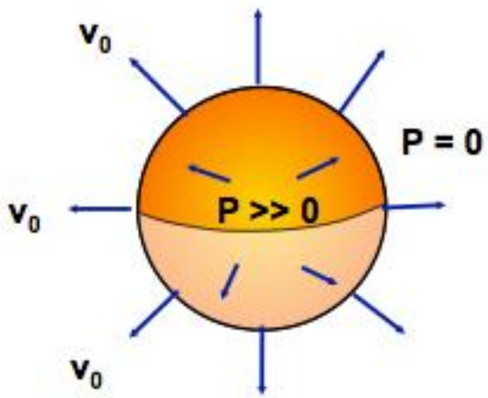
System cools down by (isentropic) expansion

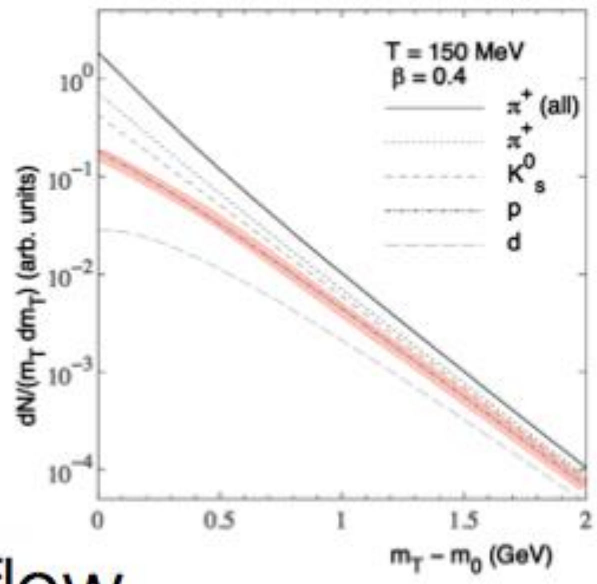
T > 300 MeV

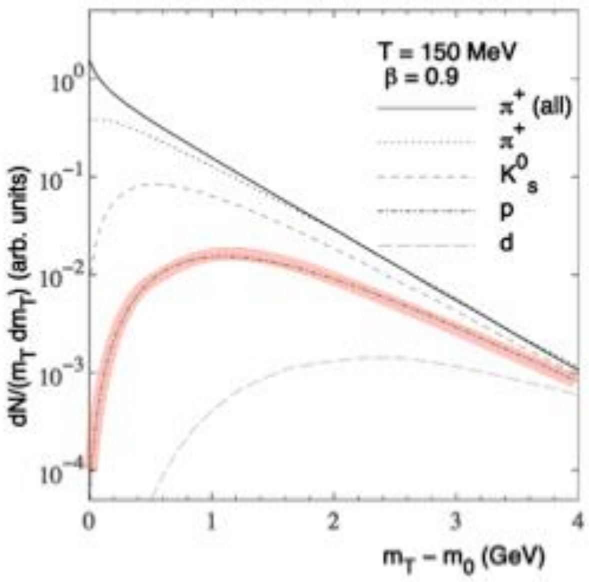
QGP thermodynamics and soft probes

Radial and elliptic flow

Isotropic radial flow

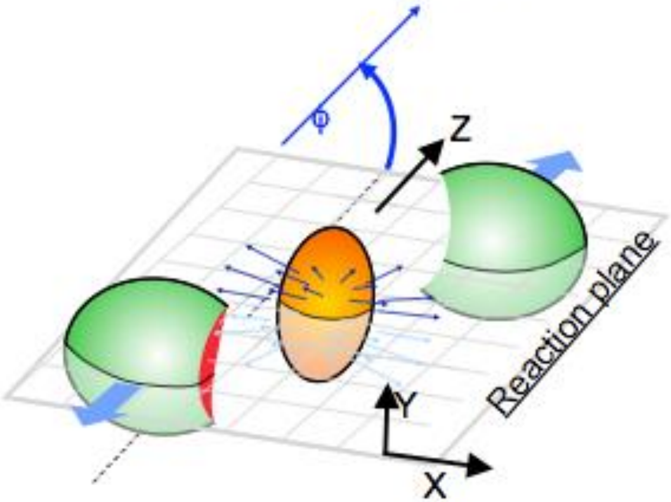




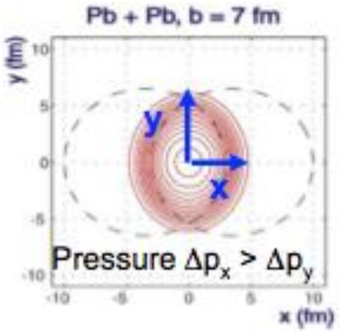


Anisotropic (elliptic) flow

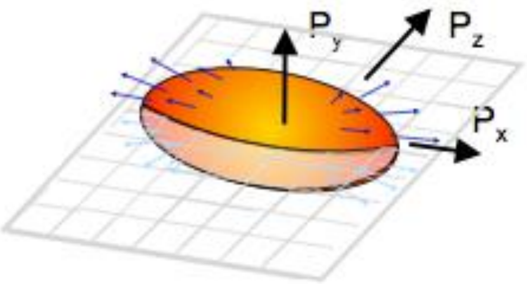
Spatial deformation



Azimuthal (φ) pressure gradients

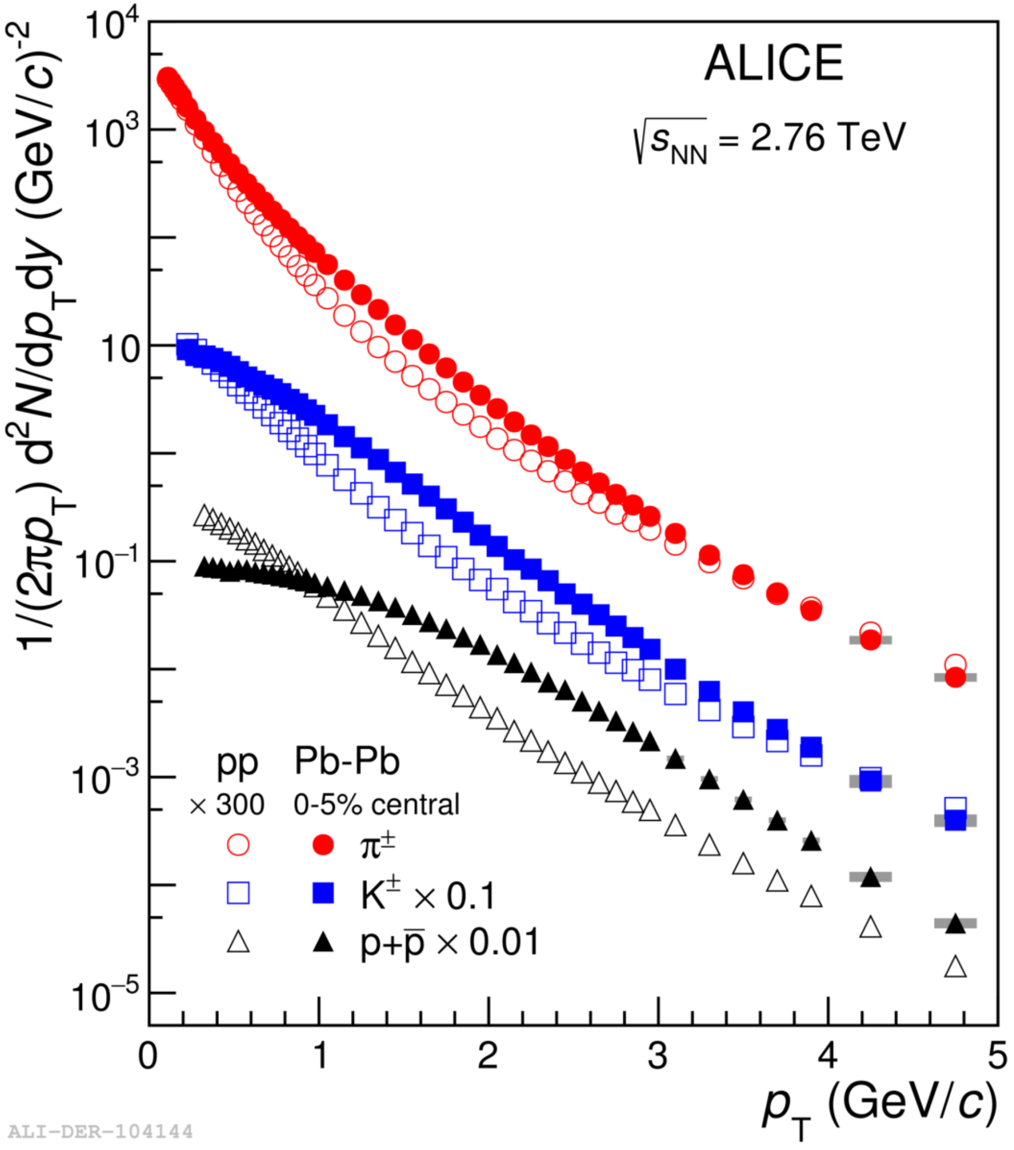


Anisotropic particle density



$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

Radial flow



Common radial hydrodynamic expansion leads to a modification of the spectral shape: mass dependent *boost.*

→ p_T-spectra harden with centrality.

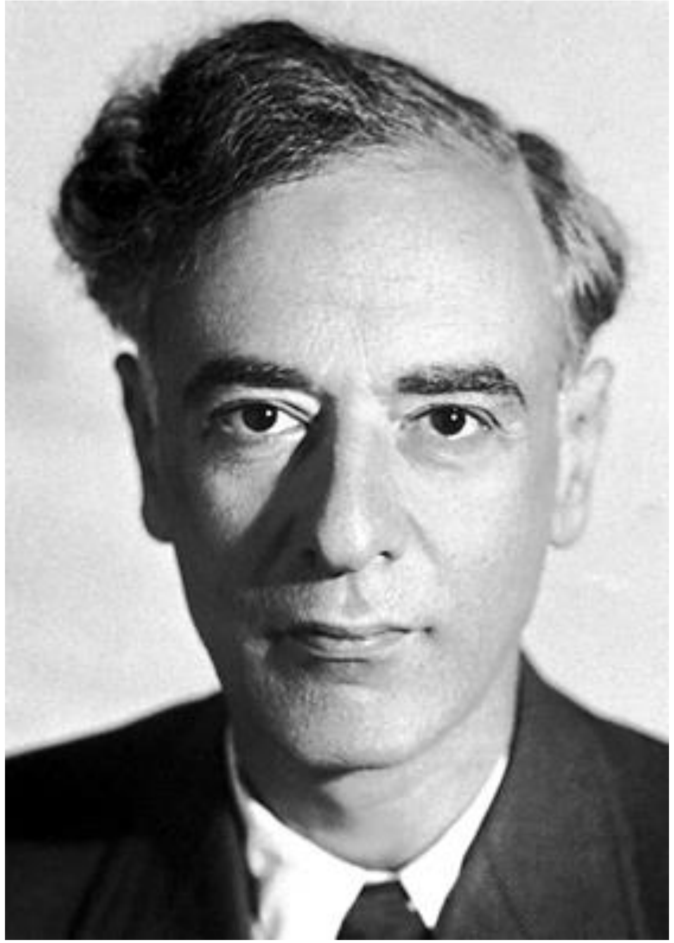
→ More pronounced for heavier particles(e.g.: $p > K > \pi$) as *velocities* become equalized in the flow field (p = βγ·m).

→ Hydrodynamic models show a good agreement with the data.

→ Kinetic freeze-out temperature from Blast-Wave model: ~90 MeV

Relativistic Hydrodynamics

- General framework of relativistic hydrodynamics was first developed by Landau and is textbook knowledge since then.
- Only requirement for applicability: *local thermodynamic equilibrium*.
- **Perfect fluid: no dissipation**
  - Conservation of energy and momentum: $\partial_\mu T^{\mu\nu} = 0$
  - Conservation of baryon number current: $\partial_\mu j^\mu_B(x) = 0$
    → gives five independent equations
- Six thermodynamic variables: the energy density *ε(x)*, the momentum density *P(x)*, the baryon number density $n_B(x)$, and the fluid velocity *v(x)*.
- Equation-of-state: functional relation of *ε, P,* and n_B (taken from Lattice QCD).
- In reality: dissipative corrections play an important role:
  → **shear viscosity *η*** and bulk viscosity ζ (so called *transport coefficiencts*)enter in correction terms on the right hand side of the equations above.



Lew Landau (1908-1986)

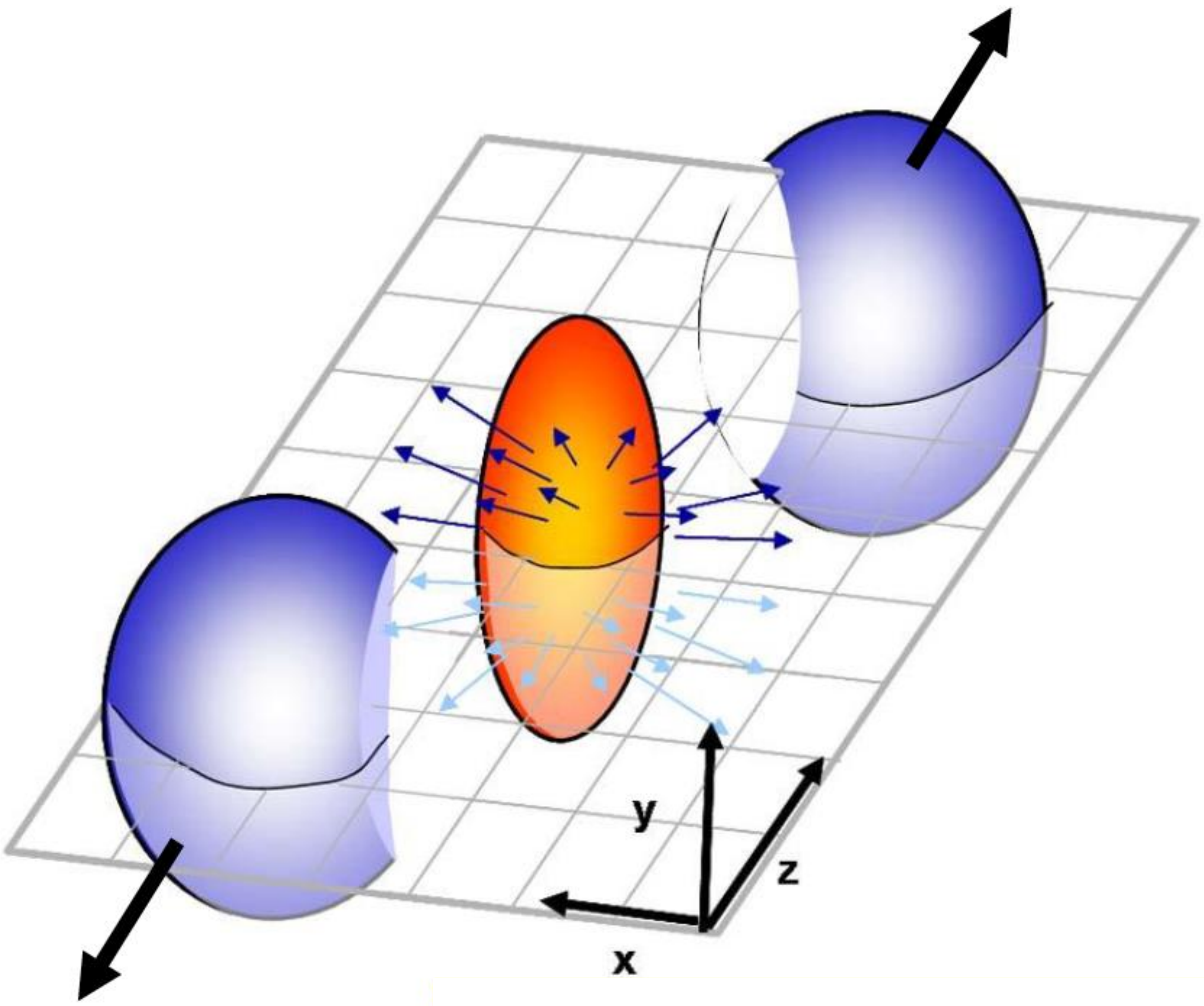
Elliptic flow v_2

- Not only the observed particle spectrum in p_T, but also in φ is the result of the fireball expansion.
- If the system is asymmetric in spatial coordinates, scattering converts it to **anisotropy in momentum space:**

$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left\{1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos[n(\varphi - \psi_n)]\right\}$$

Radial flow v_1 – direct flow, **v_2- elliptic flow**

- If nuclei overlap was a smooth almond shape, odd harmonics (v_3,..) would be zero.



Centrality dependence of v_2

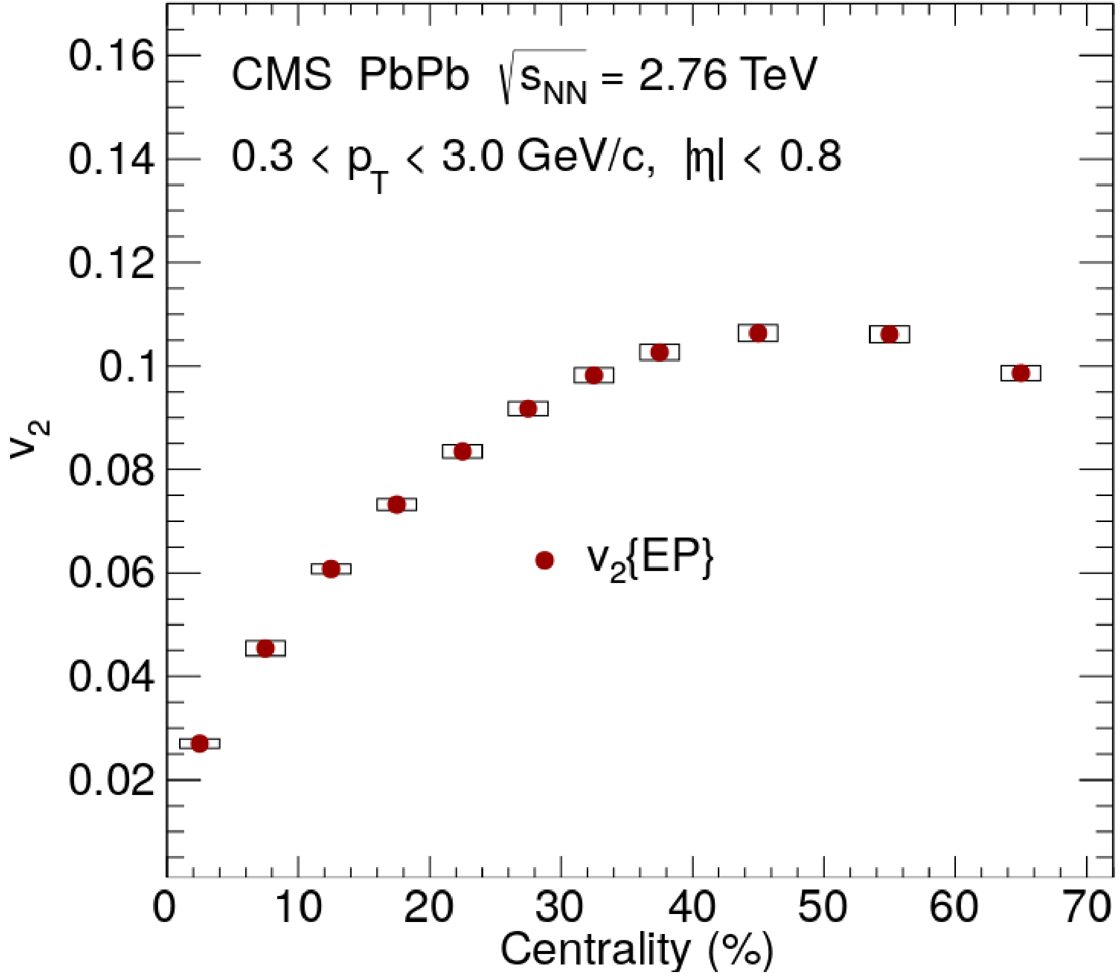
- v_2 exhibits a strong centrality dependence

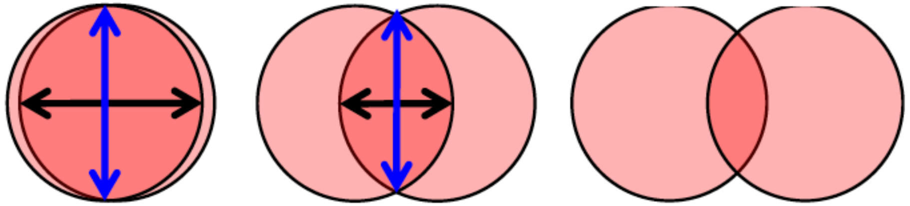
- v_2 largest for 40-50%

- Spatial anisotropy very small in central collisions

- Largest anisotropy in mid-central collisions

- Small overlap region in peripheral collisions

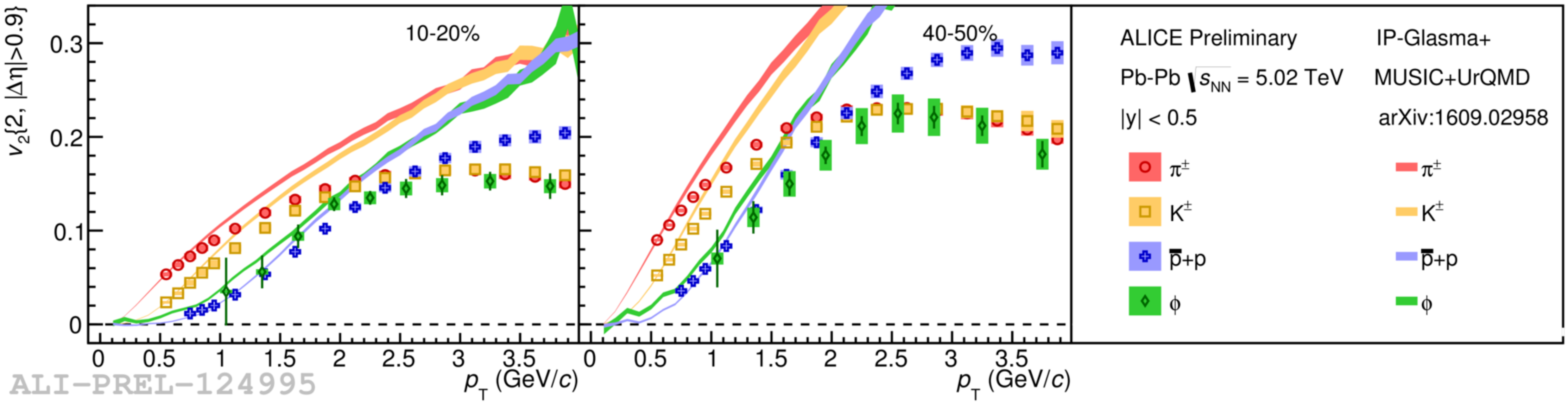




CMS, PRC 87(2013) 014902

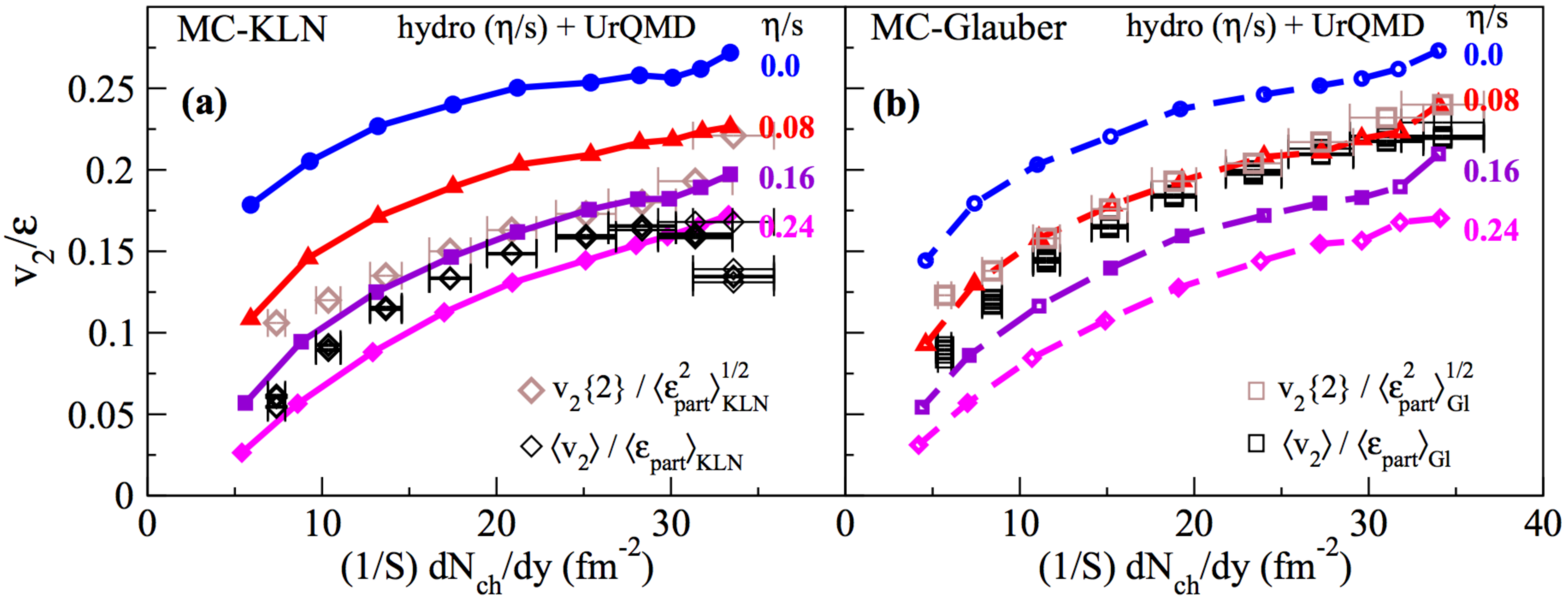
Mass ordering of v_2 vs. transverse momentum

Transverse momentum dependence of elliptic flow shows the same mass ordering (p = βγ·m) as radial flow and as expected from hydrodynamics.
→ interplay of radial and elliptic flow.



Sensitivity of v_2 to shear viscosity

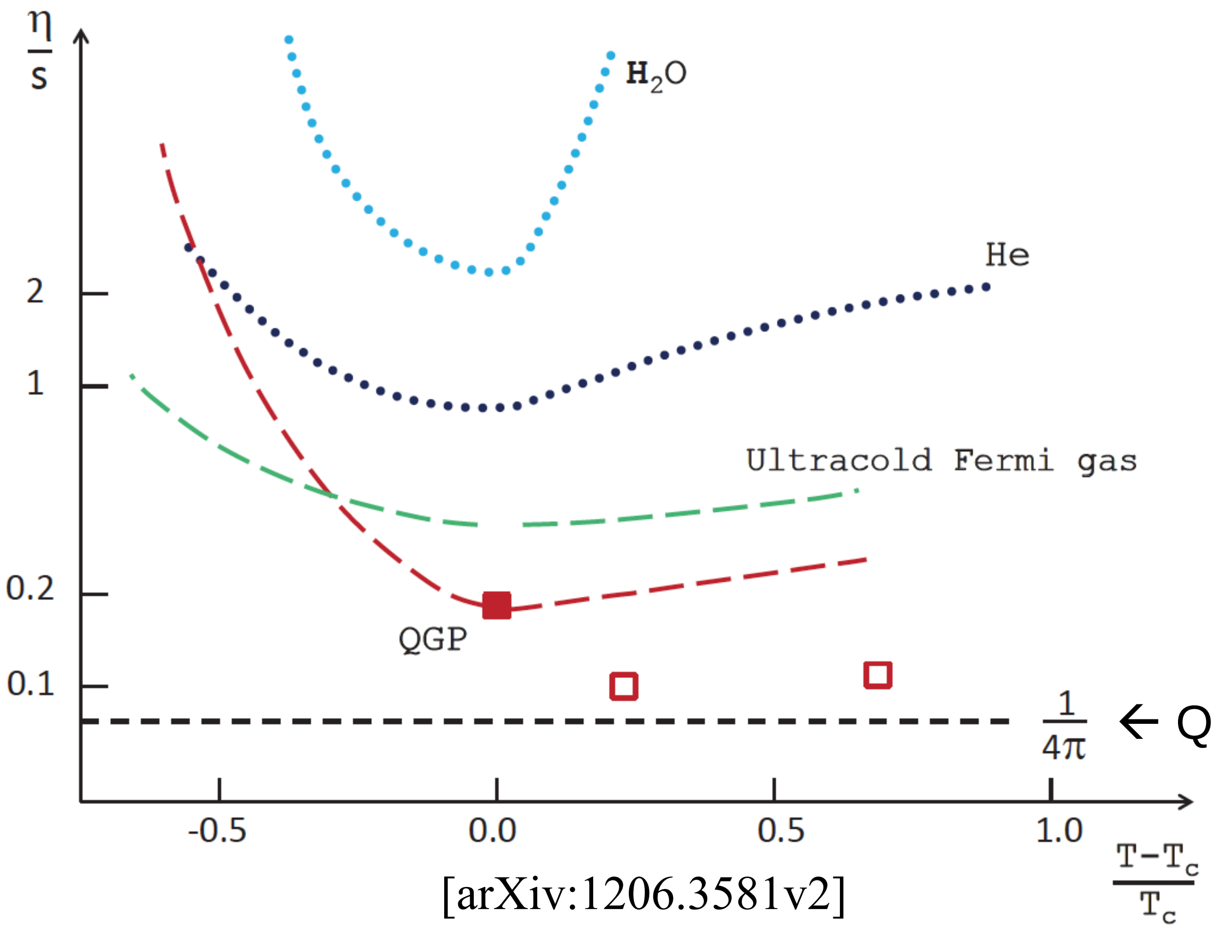
[Phys.Rev.Lett. 106 (2011) 192301]



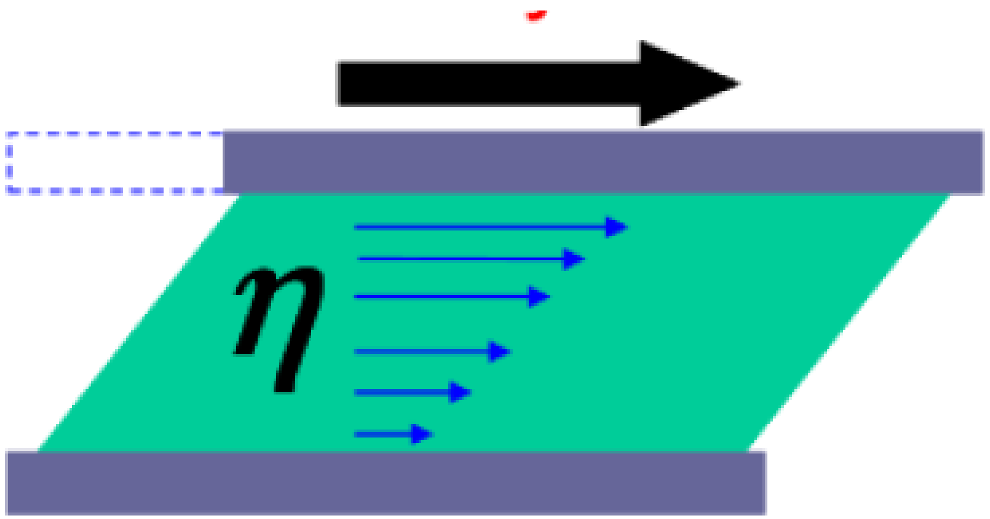
- The larger the shear viscosity per entropy density ratio *η/s* of the QGP, the more v_2 is reduced.
- Dissipative losses hamper the buildup of flow => measuring the magnitude of v_2 and comparing it to models, we can determine how *ideal* the QGP liquid is.

Ideal fluids

→ Why are ideal fluids (η/s very small) fascinating? Look at superfluid Helium as an example: https://www.youtube.com/watch?v=2Z6UJbwxBZI

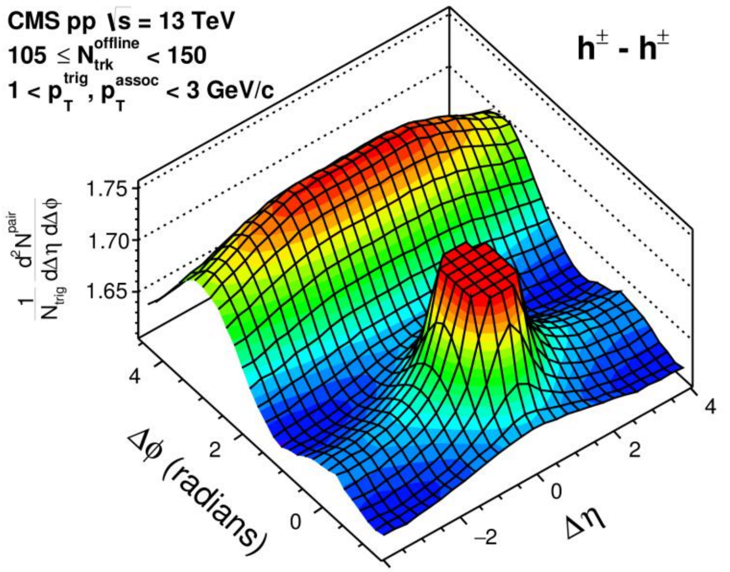


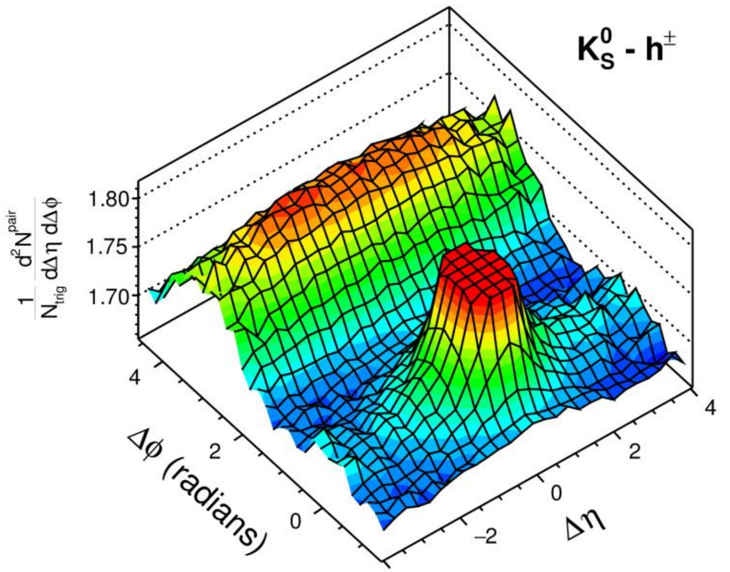
[arXiv:1206.3581v2]



← Quantum limit derived from string theory via AdS-CFT

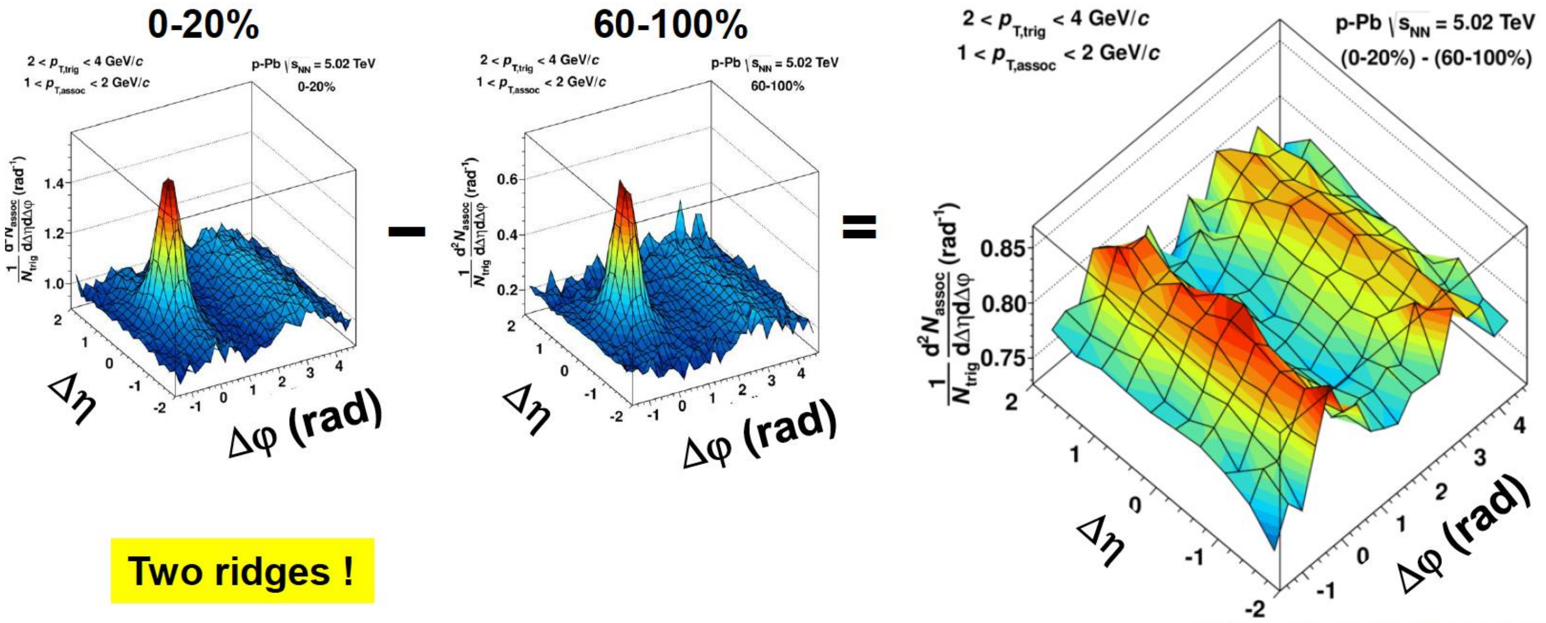
Double ridges (1)





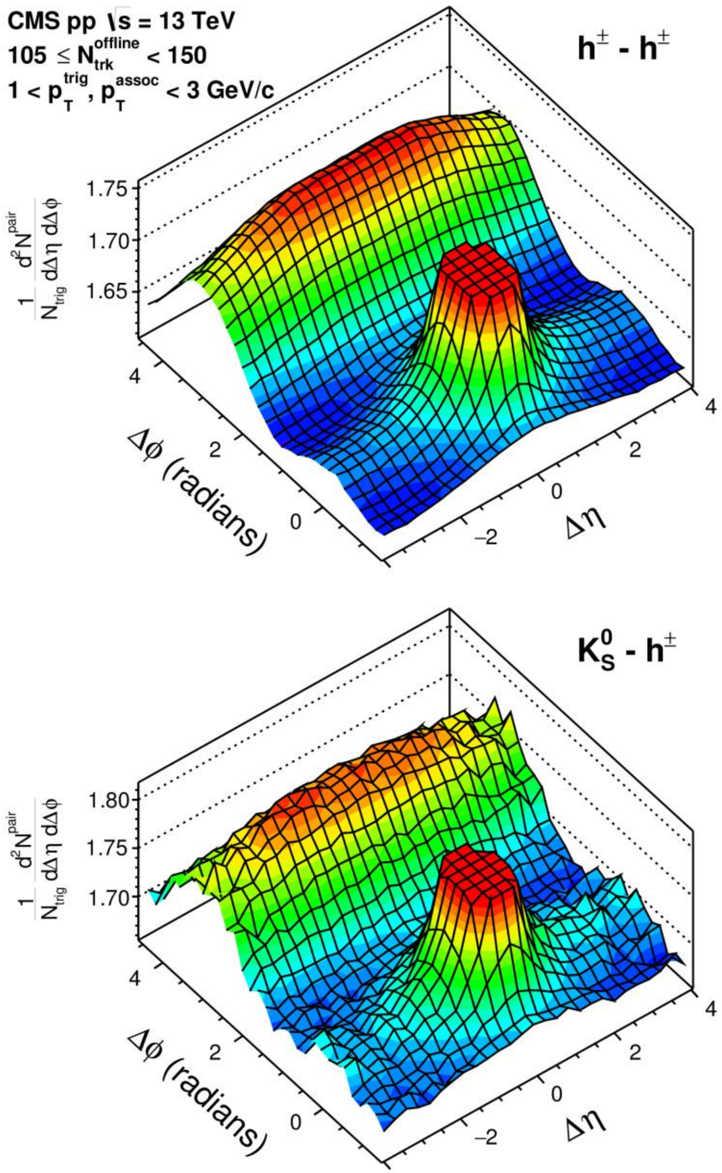
[Phys. Lett. B 765 (2017) 193]

- Subtraction procedure to “isolate” ridge contribution from jet correlations:
  - No ridge seen in 60-100% and similar to pp.
  - As a result one finds two symmetric ridges as expected from elliptic flow (“hydro-like”).

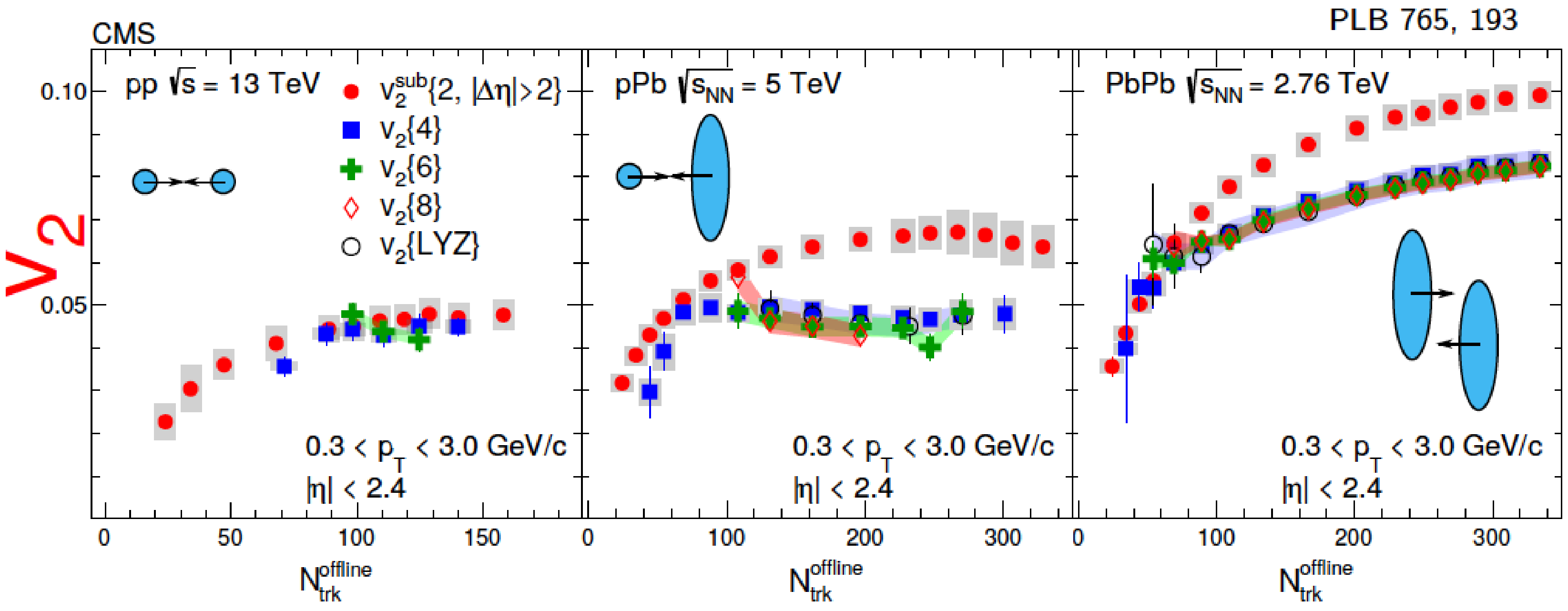


ALICE, PLB719 (2013) 29

Double ridges (2)



- Long-range azimuthal correlations (as originating from elliptic flow) are also observed in small systems: double ridges.

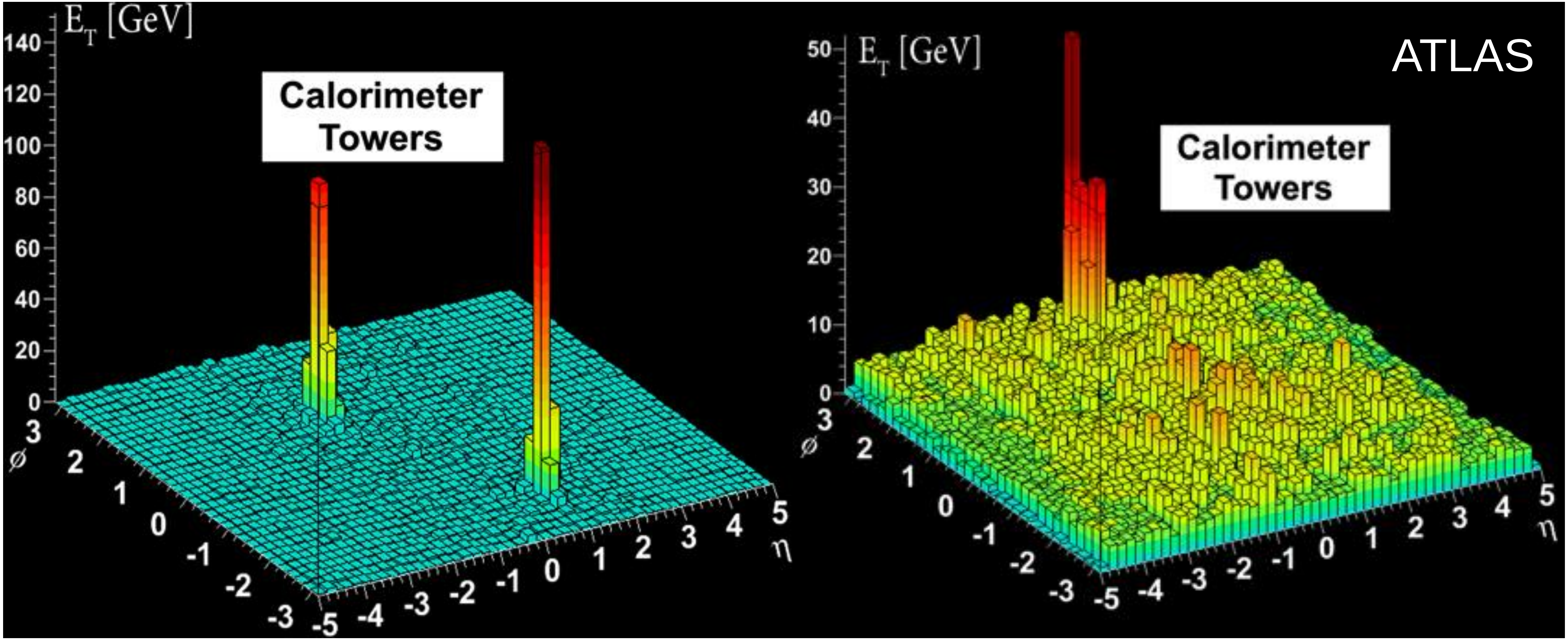


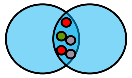
- Similar observations hold true for many other typical *kinetic* heavy-ion observables measured in high multiplicity pp and pPb collsions → clear indication for collectivity in small systems.

[Phys. Lett. B 765 (2017) 193]

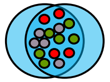
Hard scatterings and jets

Jet-medium interactions (1)



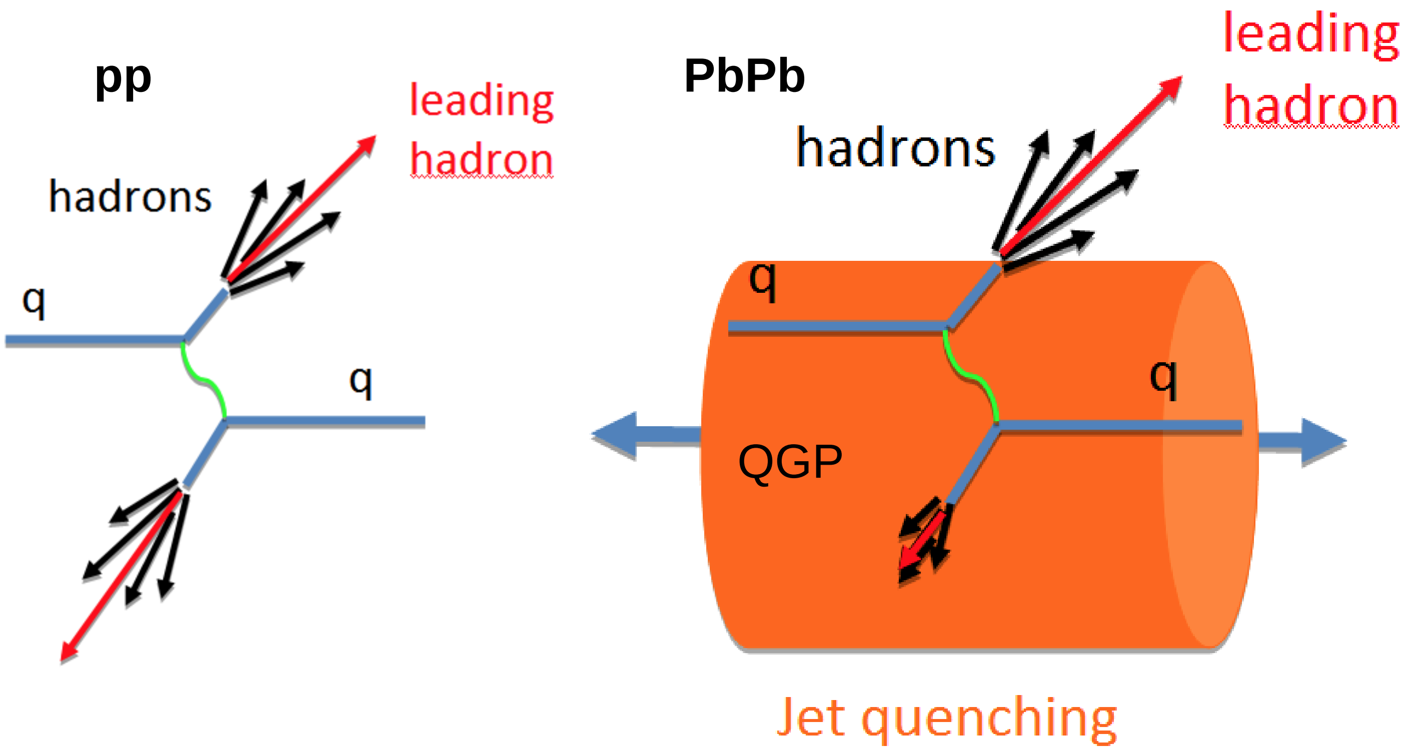
Peripheral Pb-Pb 

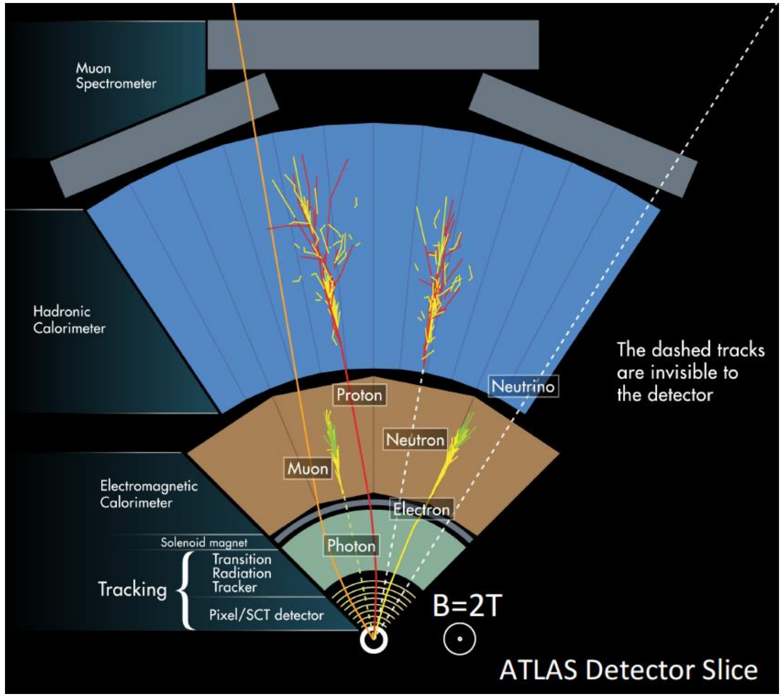
[PRL105:252303,2010]

Central Pb-Pb 

Jet-medium interactions (2)

- One jet disappears (or loses a substantial amount of its energy) in the QGP → ”jet quenching”





→ N.B.: To stop a highly energetic jet (e.g. 100 GeV), it needs a 10fm droplet of QGP or ~1.5m of hadronic calorimeter.

Drawing: M. Knichel

Dijet asymmetry

[PRC 84 (2011) 024906]

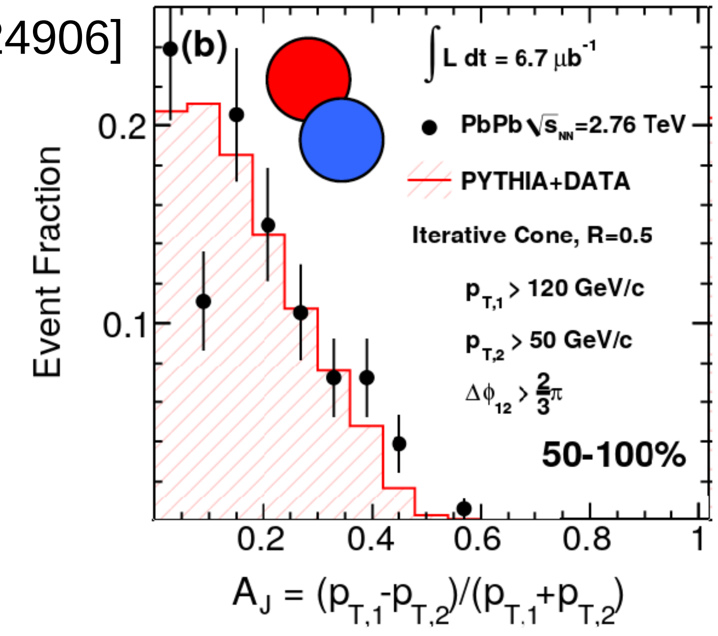
- How often do jets lose a large amount of energy?
  → quantified by the dijet asymmetry
- Two highest energy jets with $\Delta\varphi > 2\pi/3$:

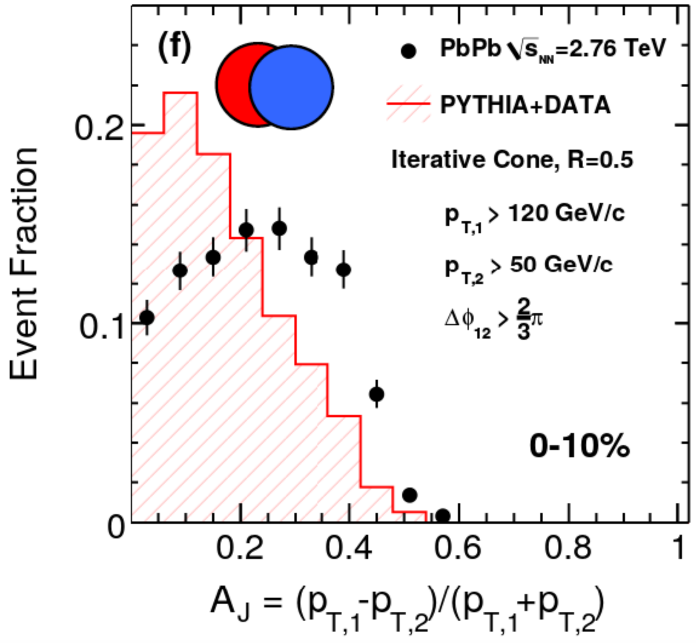
$$A_J = \frac{|p_{T1} - p_{T2}|}{p_{T1} + p_{T2}}$$

$p_{T1} = p_{T2} \rightarrow A_J = 0$

1/3 $p_{T1} = p_{T2} \rightarrow A_J = 0.5$

- Peripheral collisions: distribution as in Pythia (as in pp)
- Central collisions:
  - Symmetric configuration is significantly depleted
  - Enhancement of asymmetric configurations





Nuclear modification factor R_{AA}

- Hard process occur in *initial* nucleon-nucleon (NN) collisions. The momentum transfers in the later evolution of the system are smaller.

- Heavy-ion collision: many NN collisions

- Without *nuclear effects* (interaction with the QCD medium), a heavy-ion collision would just be a superposition of independent NN collisions with incoherent fragmentation.

- The number of independent NN collisions $\langle N_{coll} \rangle$ can be calculated for a given impact parameter/centrality in the Glauber model.

Spectrum in AA collisions

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

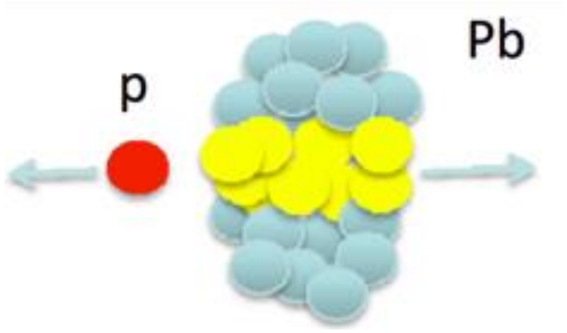
Spectrum in pp collisions

R_{AA} = 1 → no modification
R_{AA} != 1 → medium effects

The most simple example: R_{pA}

Phys. Rev. Lett. 110 (2013) 082302

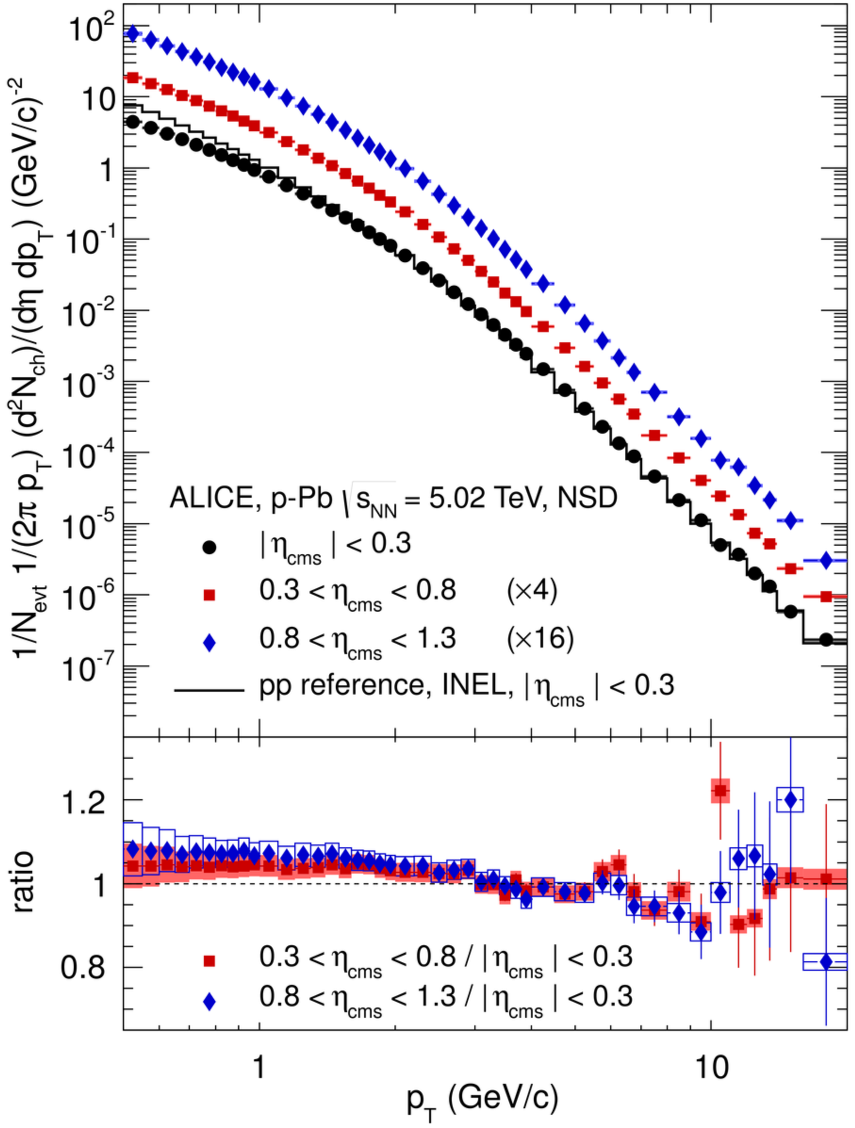
- In a pA collision, the proton hits on average 6.9 nucleons of the Pb nucleus:



$$R_{pA} = \frac{dN_{pA} / dp_T}{\langle N_{coll} \rangle dN_{pp} / dp_T}$$

→ $\langle N_{coll} \rangle = 6.9 \pm 0.6$

- We distinguish number of collisions N_{coll} and number of participants N_{part}:
  - A nucleon can *collide* several times with nucleons of the target nucleus (Glauber assumes that it stays intact after each collision).
  - Each nucleon with experiences at least one collision, is called a participant (N_{part}).
    => $N_{part} = N_{coll} + 1$ in pPb



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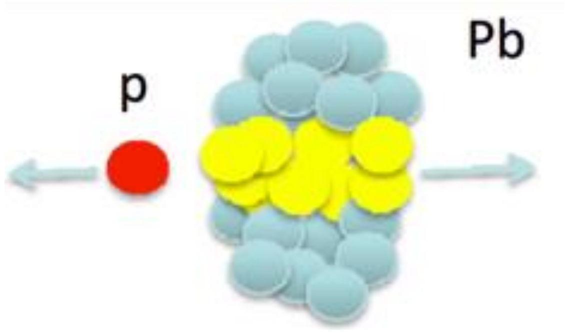

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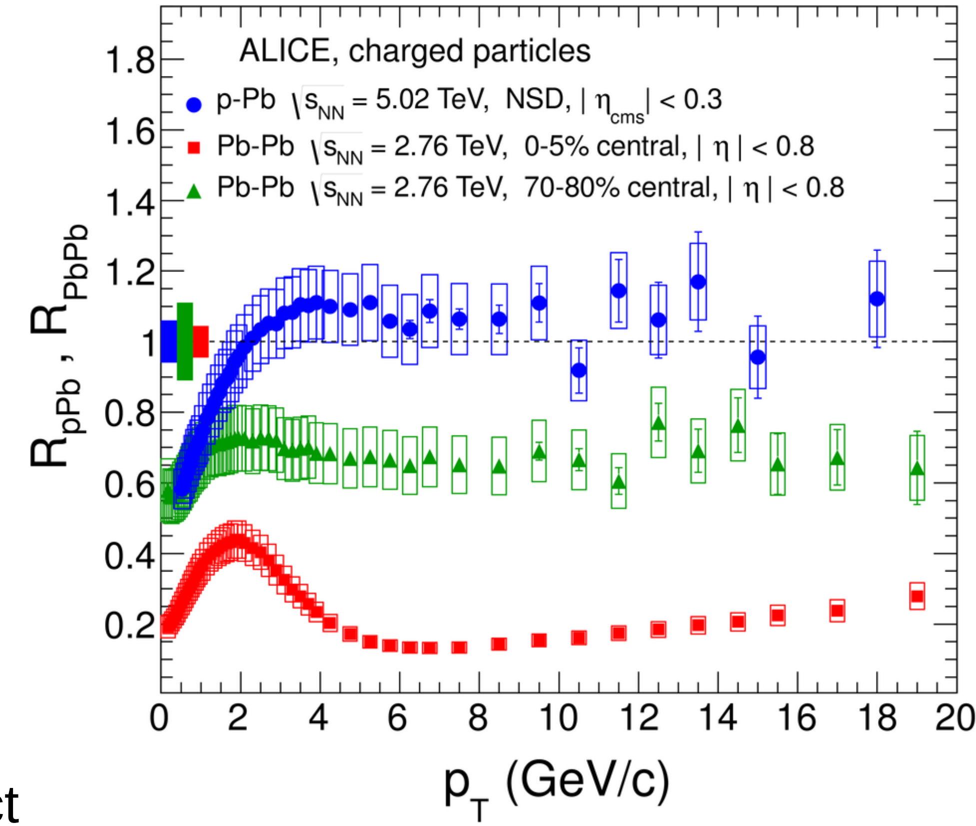
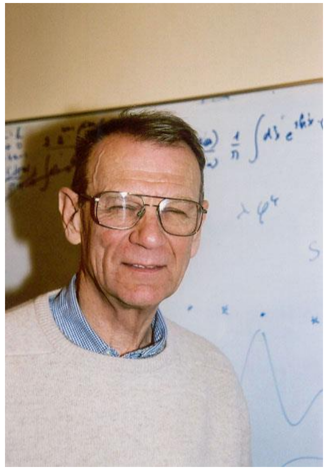


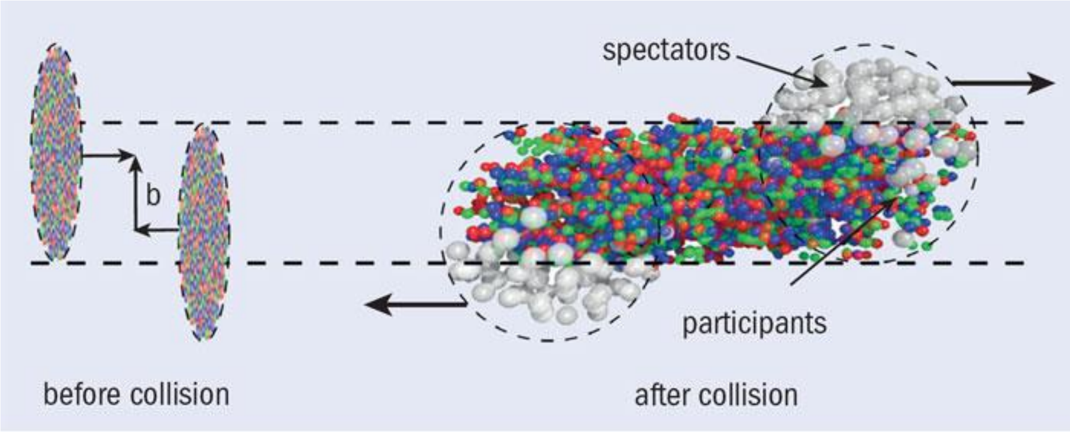
How to determine N_{coll} and N_{part}?

- "Billard ball" Monte-Carlo, named after Roy Glauber, but orginally introduced to heavy-ion physics by Bialas, Blezynski, and Czyz (Nucl. Phys. B111(1976)461).
- Assumptions:
  - Nucleons travel on straight lines
  - Collisions do not alter their trajectory (nor anything else, they remain intact) assuming their energy is large enough
  - No quantum-mechanical interference
  - Interaction probability for two nucleons is given by the nucleon-nucleon (pp) cross-section.
- Strong dependence on *impact parameter b*

R. Glauber

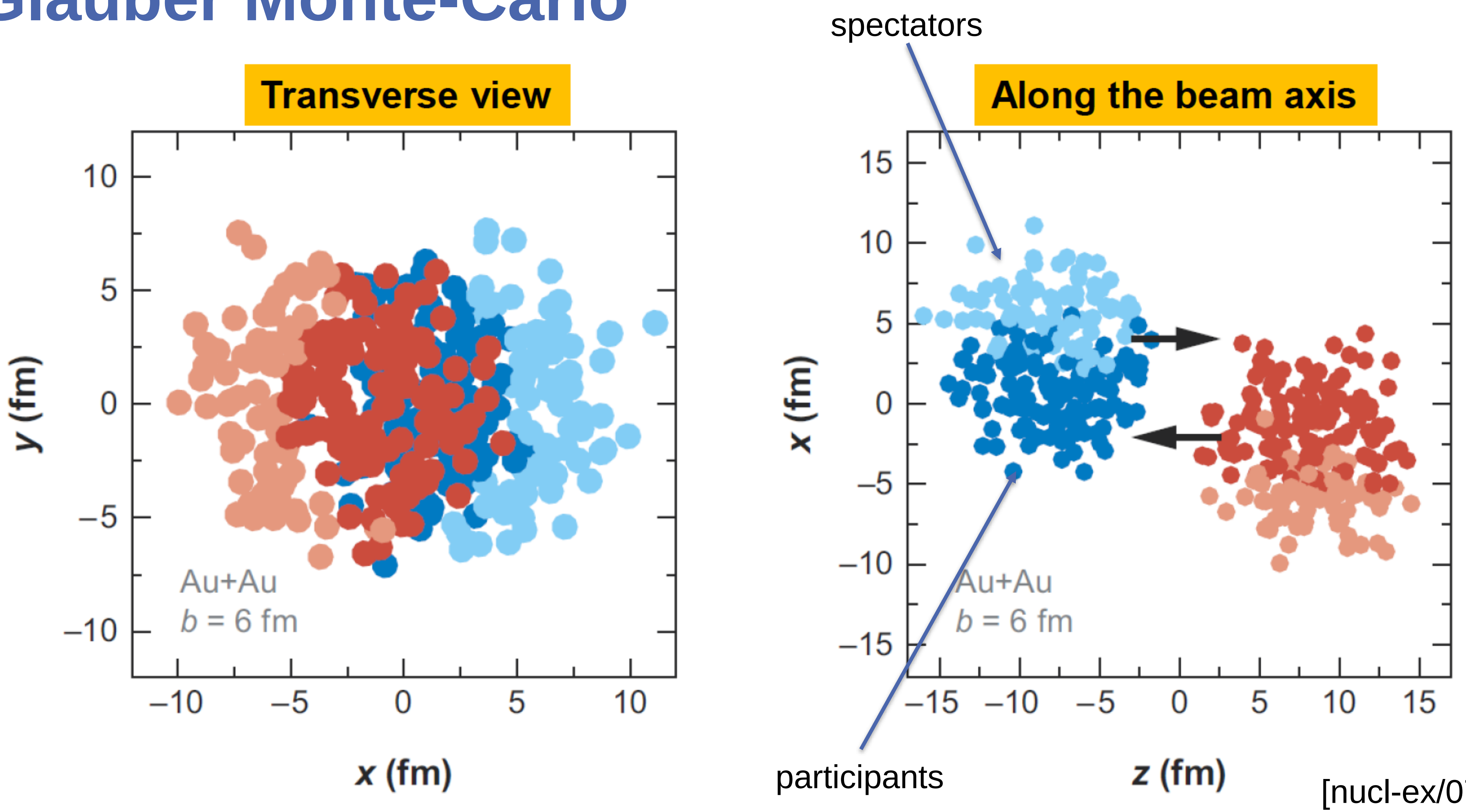


A. Bialas



http://cerncourier.com/cws/article/cern/53089

Glauber Monte-Carlo



[nucl-ex/0701025]

[nucl-ex/0701025]

Input to Glauber MC (1)

- Distributions of nucleons in nuclei:
  - well measured by electron-ion scattering experiments
  - Paramterised as Woods-Saxon disitrubtion

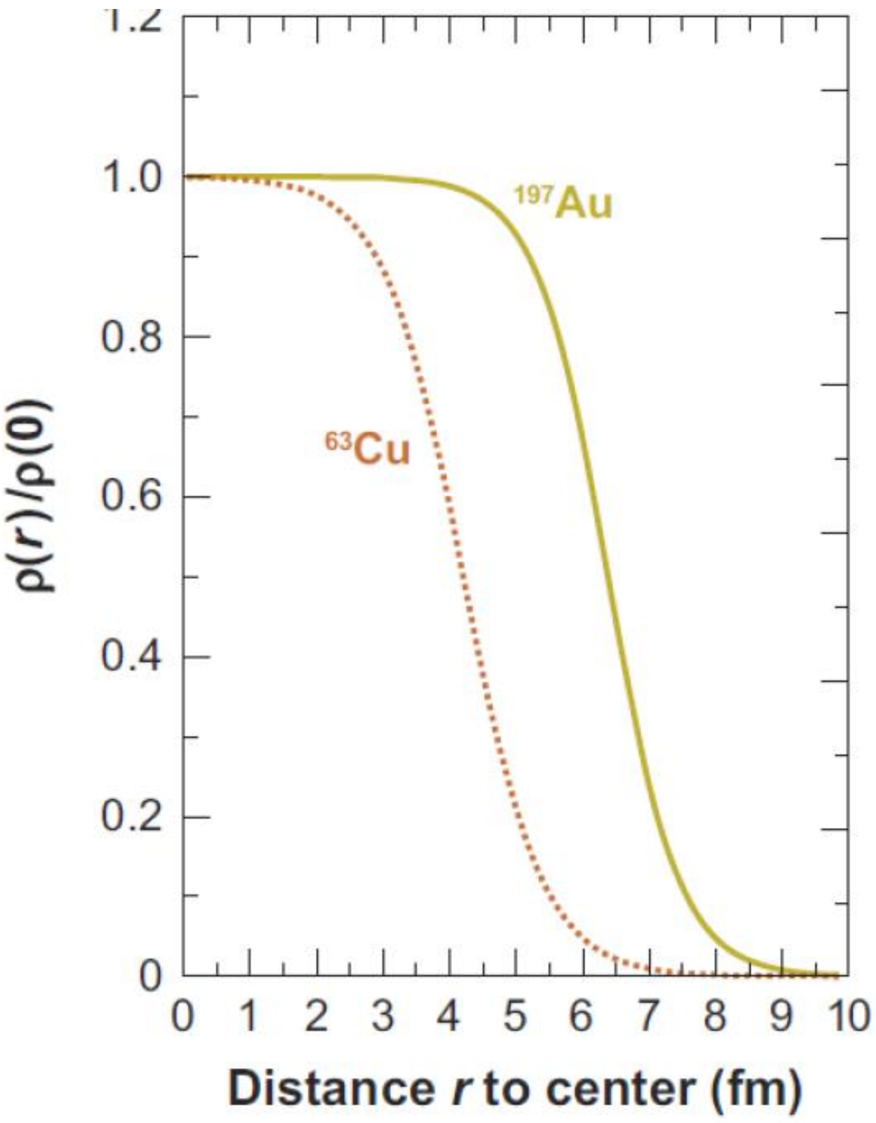
$$\rho(r) = \rho_0 \frac{1}{1 + \exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Density in the center

Skin depth a

- Nucleon-nucleon cross-section
  - Measured in pp collisions or from extrapolations



Input to Glauber MC (2)

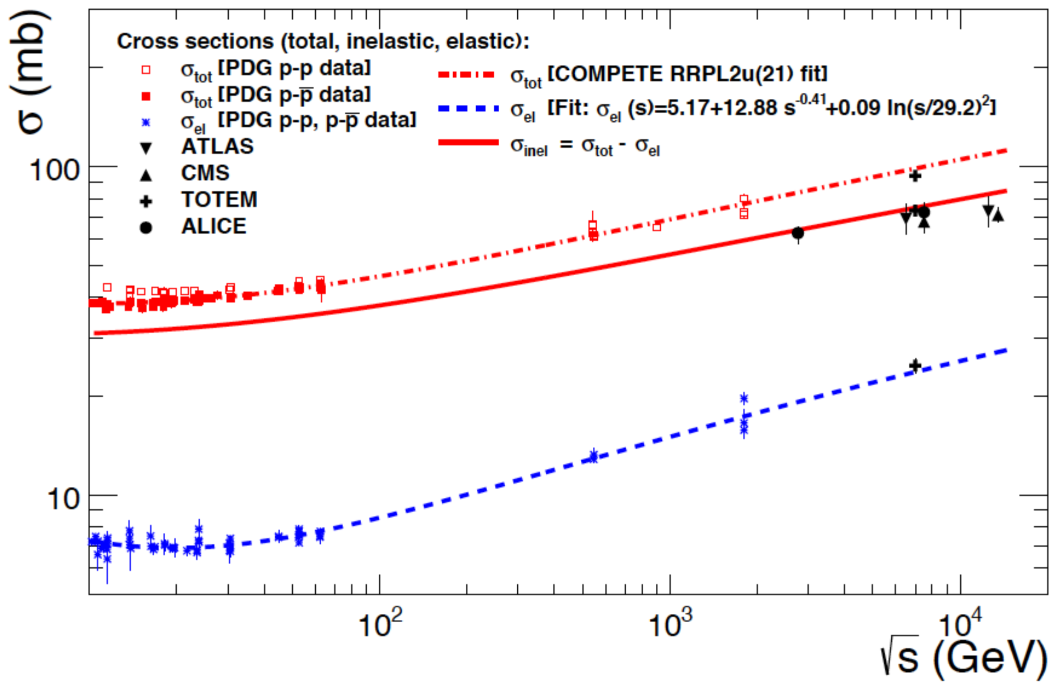
- Distributions of nucleons in nuclei:
  - well measured by electron-ion scattering experiments
  - Paramterised as Woods-Saxon disitrubtion

$$\rho(r) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Skin depth a

Density in the center



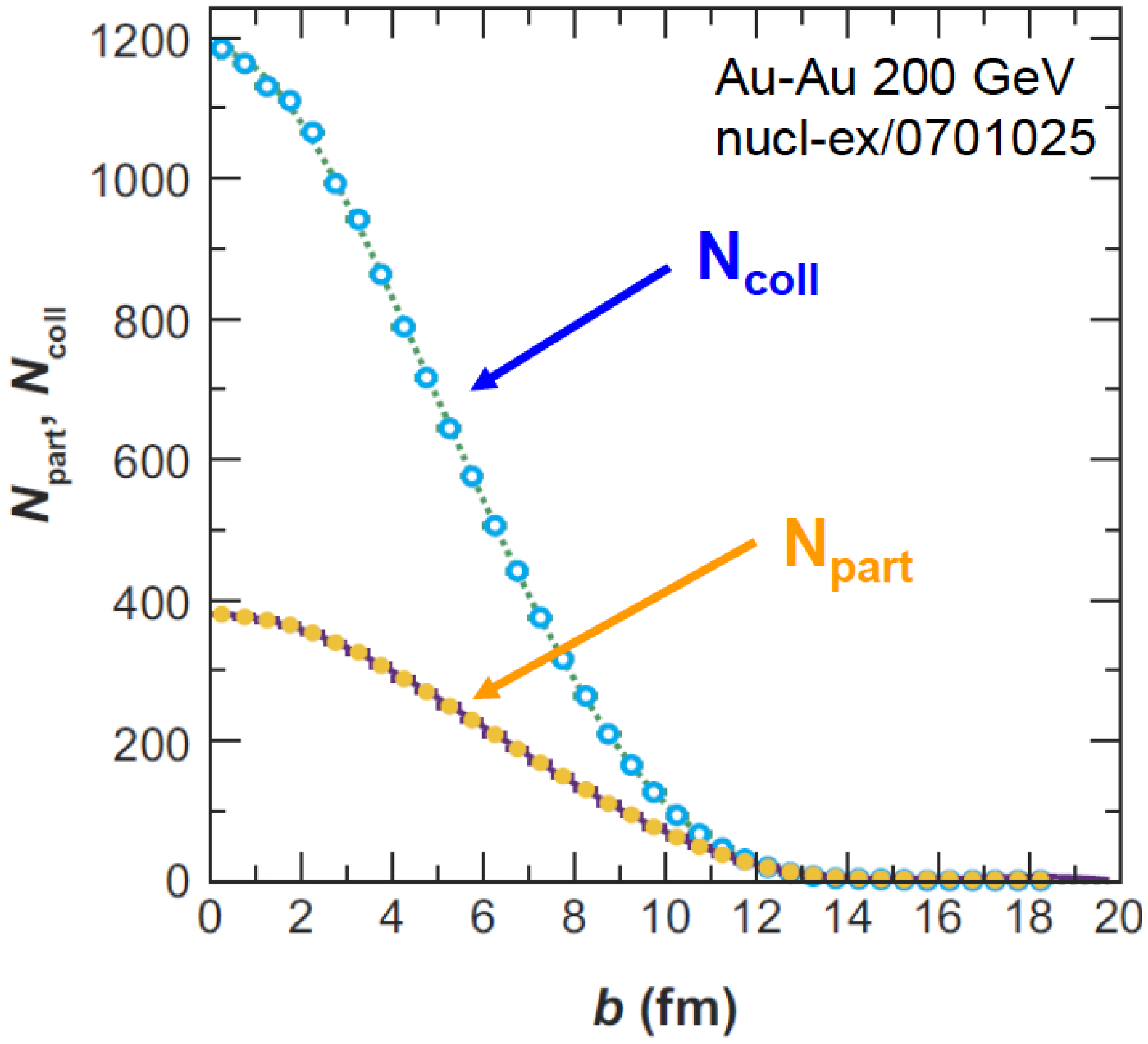
[arXiv:1603.07375v3]

- Nucleon-nucleon cross-section
  - Measured in pp collisions or from extrapolations

Glauber MC output

Typical values:

- 10% most central collisions at RHIC (Au-Au, 200 GeV)
  - N_{coll} ~1200
  - N_{part} ~380
- 5% most central collisions at LHC (Pb-Pb 2.76 TeV)
  - N_{coll} ~1680
  - N_{part} ~382
- Difference mainly from cross-section increase and slightly larger nucleus

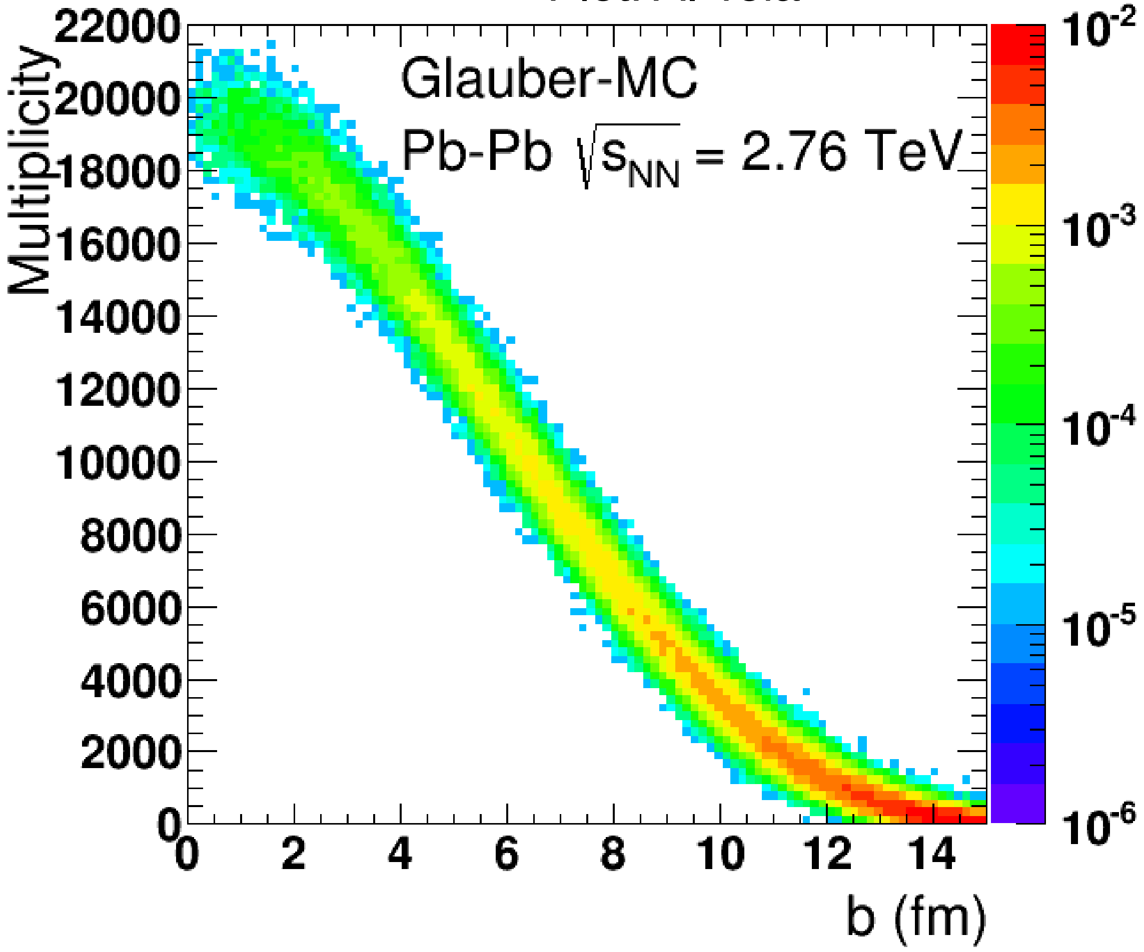


Centrality and Glauber model

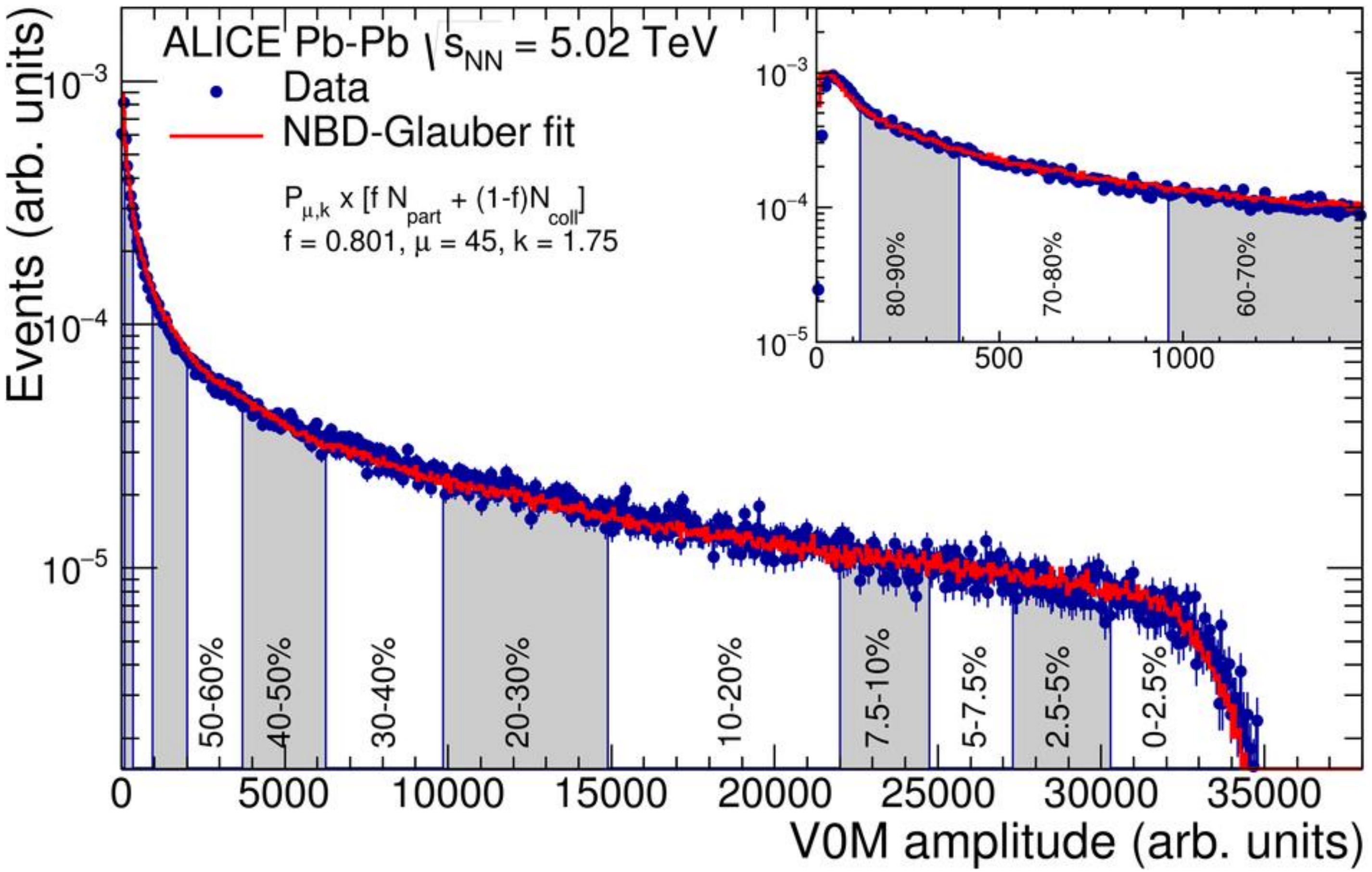
- Multiplicity is inversely proportional to the impact parameter
  => Knowing the multiplicity of the event, we roughly know the impact parameter (and thus also N_{coll} and N_{part}). We *fit* the multiplicity distribution with the Glauber model (see next slide).

- Multiplicity is strongly correlated in different phase space regions in heavy-ion collisions (e.g. forward and mid-rapditity).

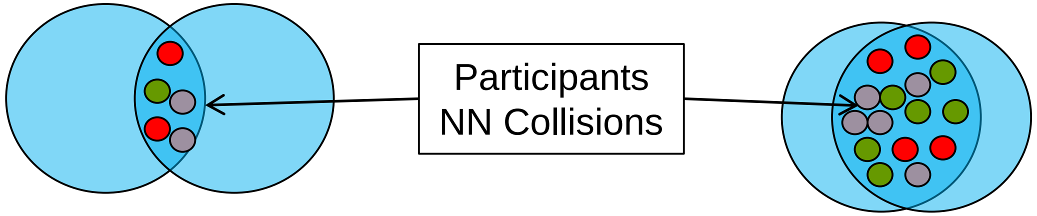
Plot: A. Toia



Geometry of heavy ion collisions



~ # charged particles



Centrality Variables:

- N_{coll}: Number of nucleon-nucleon collisions
- N_{part}: Number of participating nucleons

- Percentile of hadronic cross-section:

0-5% => central (“many particles”)
80-90% => peripheral (“few particles”)

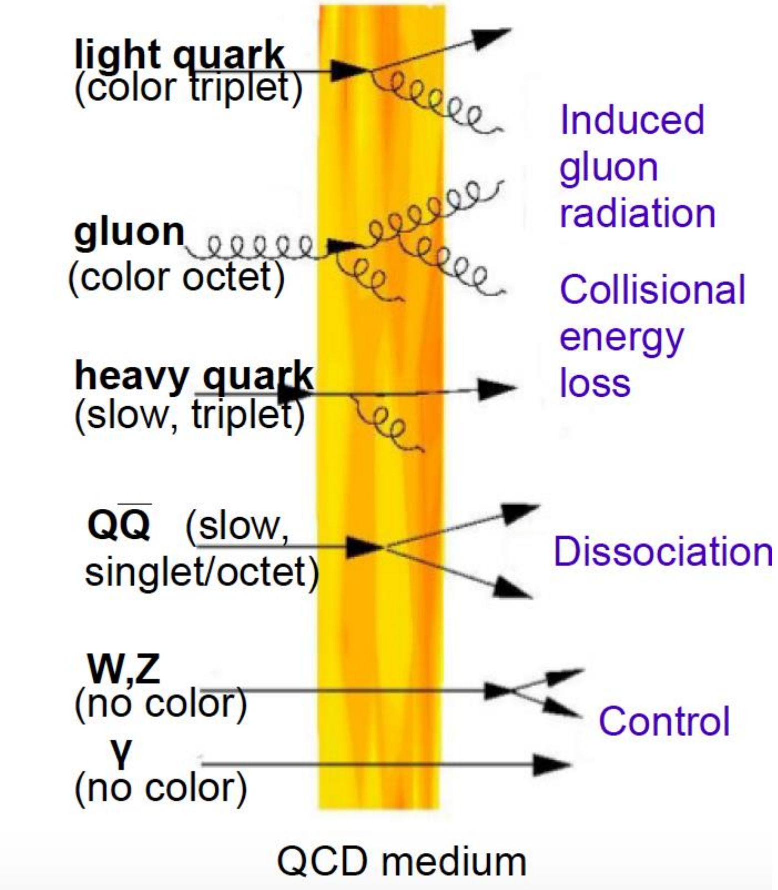
→ We can determine (a posteriori) the geometry of heavy ion collisions. More details on the ***Glauber model*** when discuss hard probes..

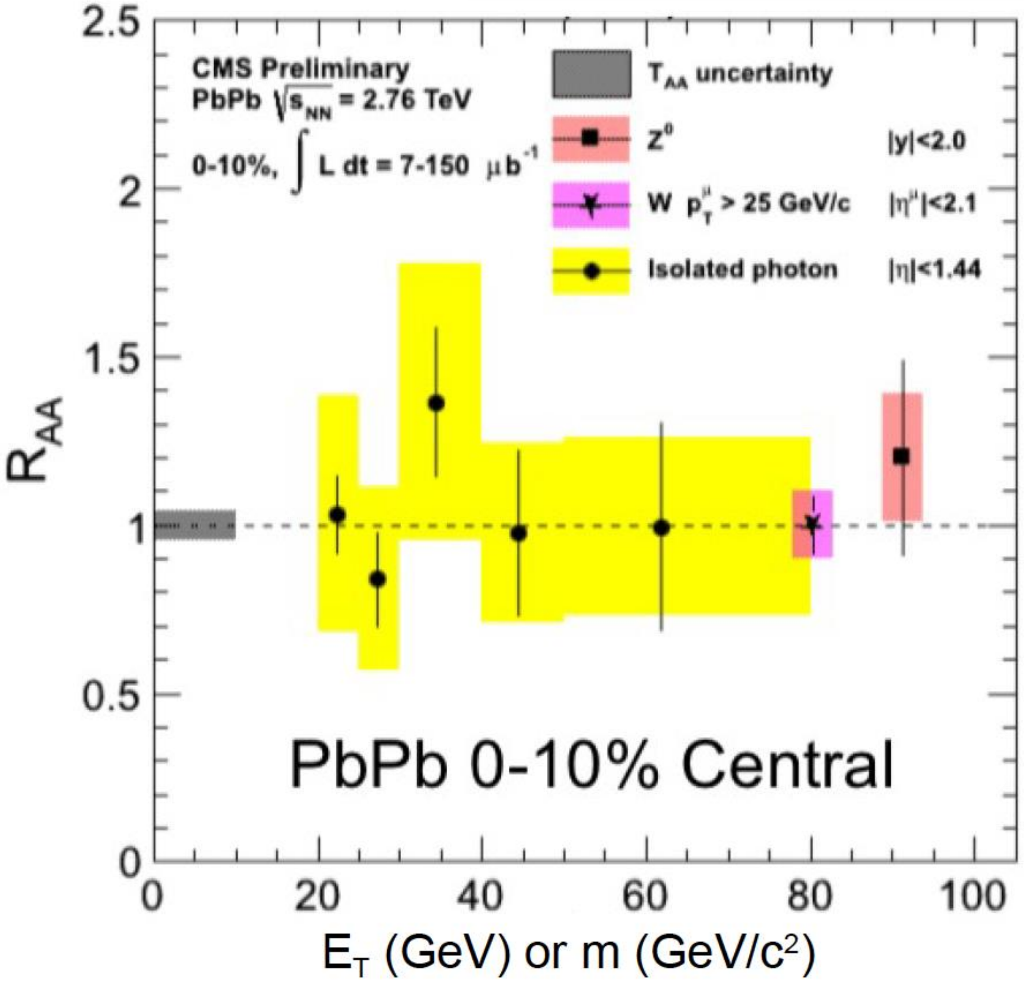
Does the Glauber model work?

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$$

→ Yes, we can test it with electroweak control probes.

→ No medium modification observed (despite multiplying by N_{coll}~1680!).



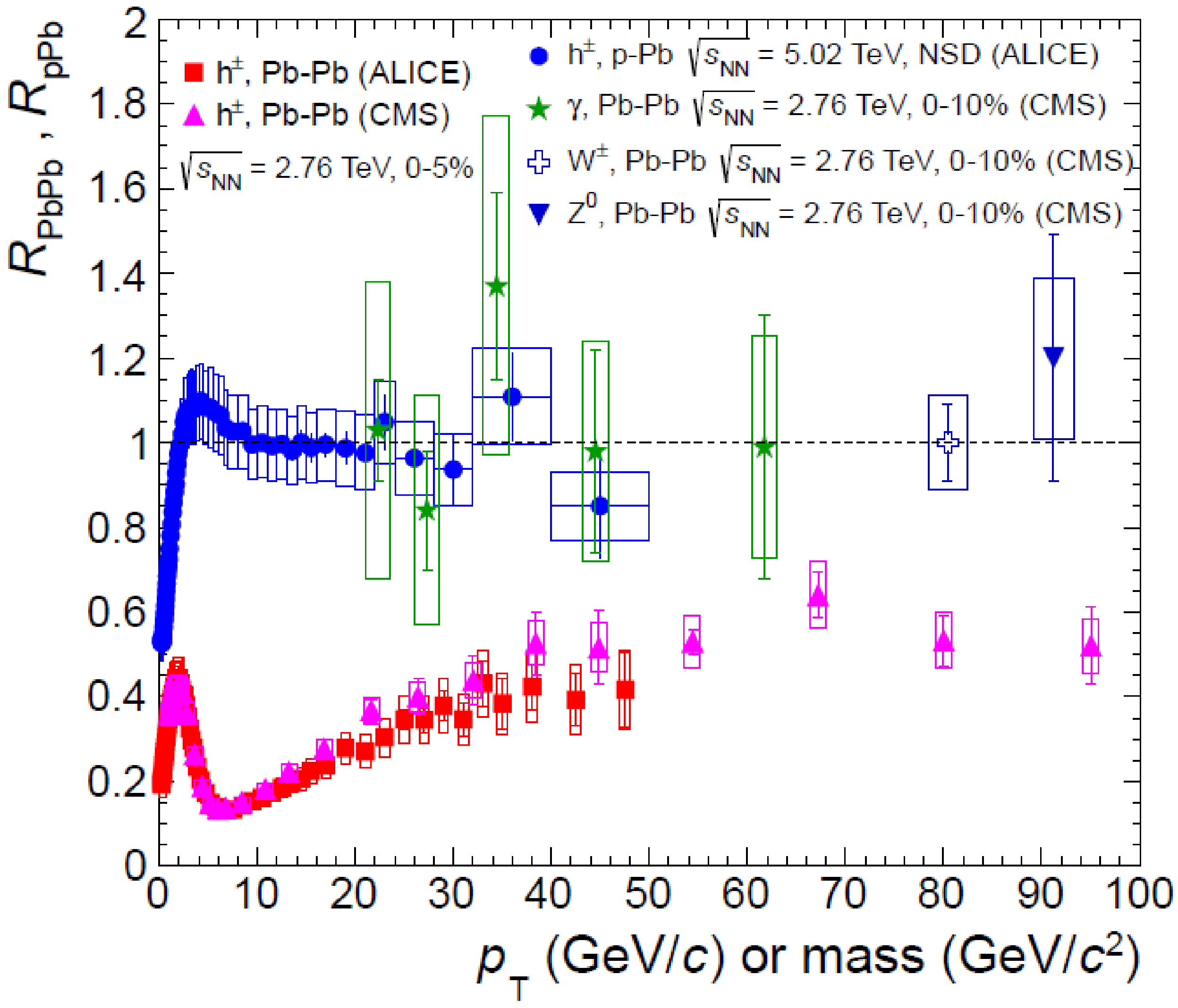


R_{AA} for charged hadrons (1)

- N_{coll} scaling works well above p_T > 4 GeV/*c* for electroweak probes and also in pPb.
  => There are no *cold nuclear matter effects* and N_{coll}-scaling is a reasonable assumption for AA.

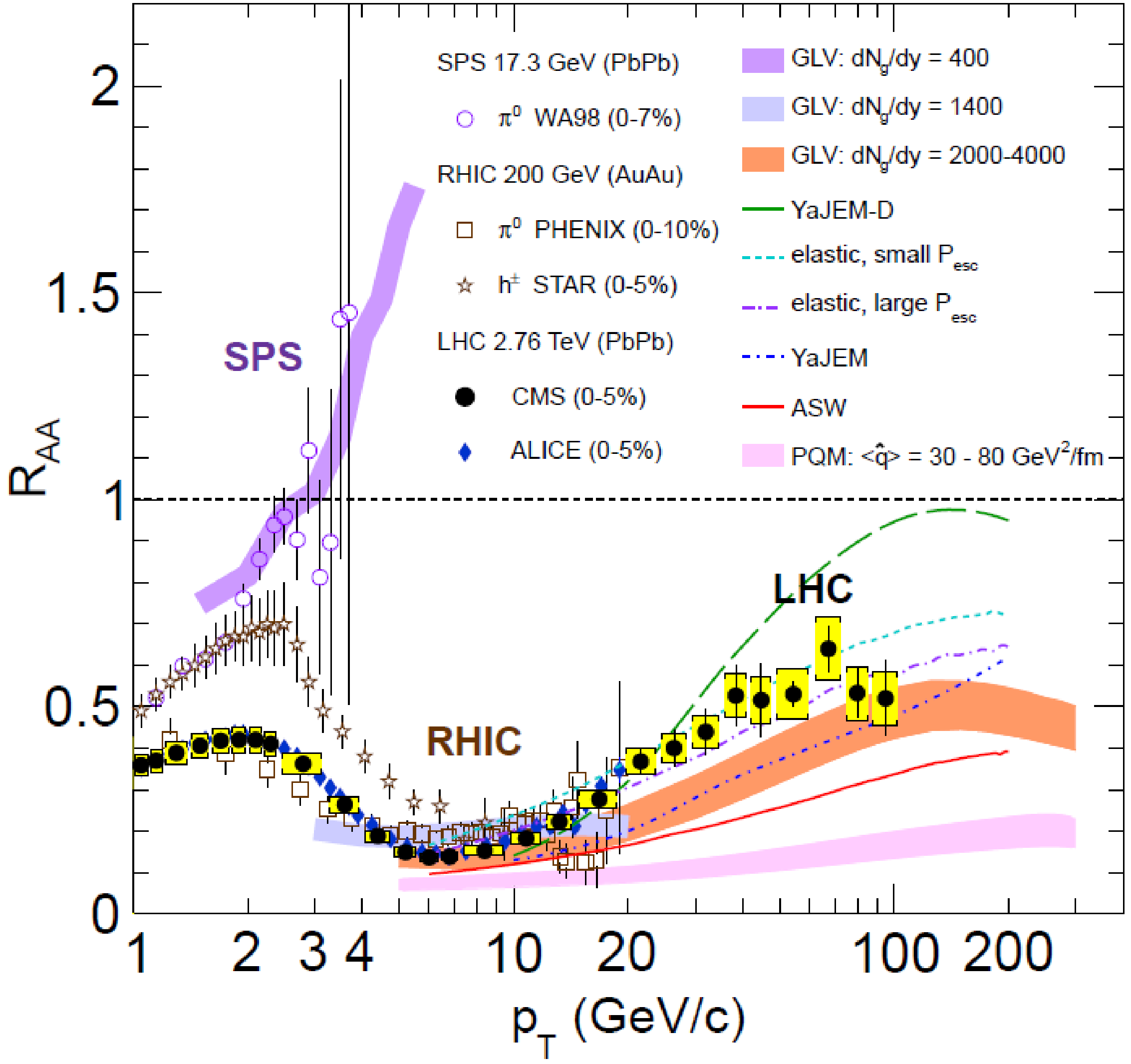
- There is a significant suppression of high p_T-particles observed in AA collisions which is a true medium effect.
  => High p_T particle production in AA collision is not a simple superposition of incoherent nucleon-nucleon collisions.

- How does the medium achieve this suppression?

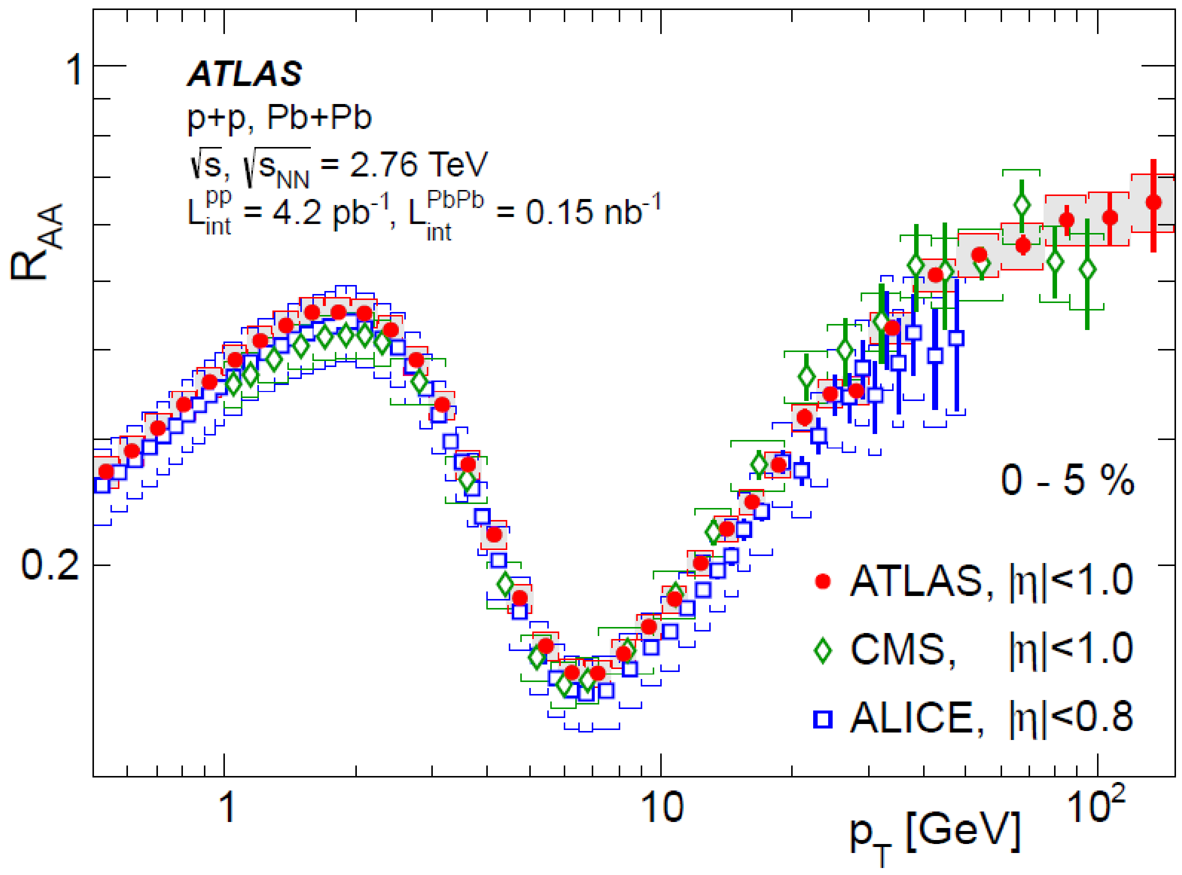


R_{AA} for charged hadrons (2)

CMS Collaboration, Eur. Phys. J. C (2012) 72:1945



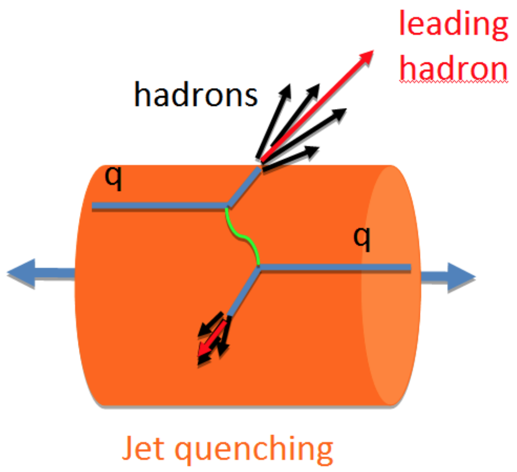
ATLAS Collaboration, JHEP09(2015)050



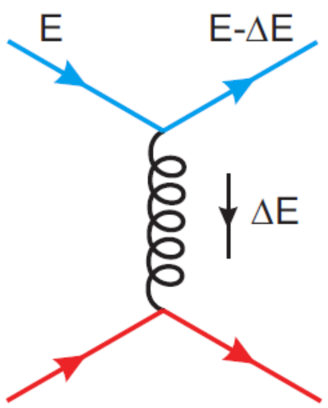
→ No high p_T particle suppression at SPS energies.
→ All LHC experiments in agreement.

Energy loss in the QGP

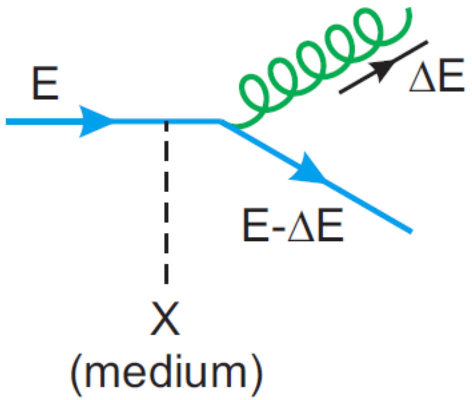
- The QGP is a high density source of color sources (quarks and gluons) which are felt by the traversing quark or gluon.
- It experiences
  - Collisional energy loss: elastic scatterings, dominant at low momentum
  - Radiative energy loss: inelastic scatterings, **gluon bremsstrahlung**, dominates at high momentum
- Total energy loss is a sum of the two processes.



[Lect. Notes Phys. 785,285 (2010)]



(Collisional energy loss)



(radiative energy loss)

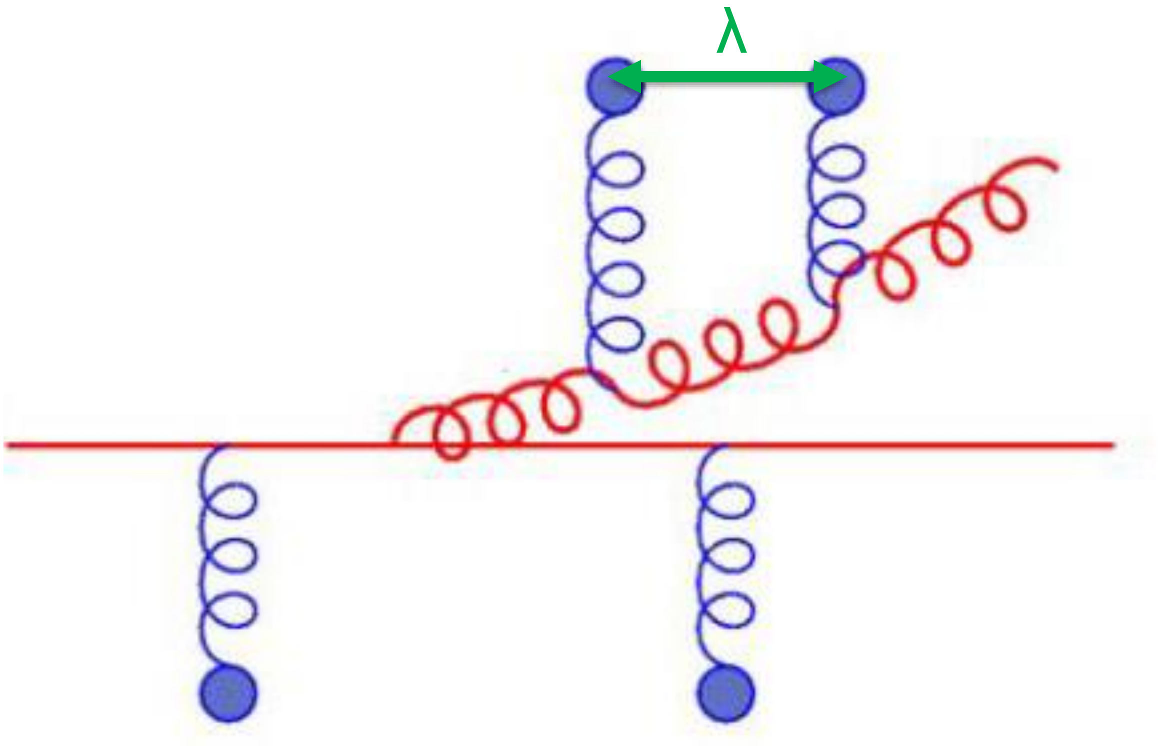
Radiative energy loss

NPB 483 (1997) 291

- BDPMS formalism
  - Baier, Dokshitzer, Mueller, Peigne, Schiff
  - Infinte energy limit
  - Static medium

$$\Delta E \propto \alpha_S \cdot C_R \cdot \hat{q} \cdot L^2$$

- Energy loss proportional to:
  - Path length through medium **squared**
  - Casimir factor
    - CR = 4/3 (quarks)
    - CR = 3 (gluons)
  - Medium properties are encoded in the parameter “q-hat” which corresponds to the average squared transverse momentum transfer per mean free path.



→ For the **characterization of the QGP medium**, q-hat has a similar significance as e.g. the shear viscosity.

$$\hat{q} = \frac{\langle q_T^2 \rangle}{\lambda}$$

← average momentum transfer

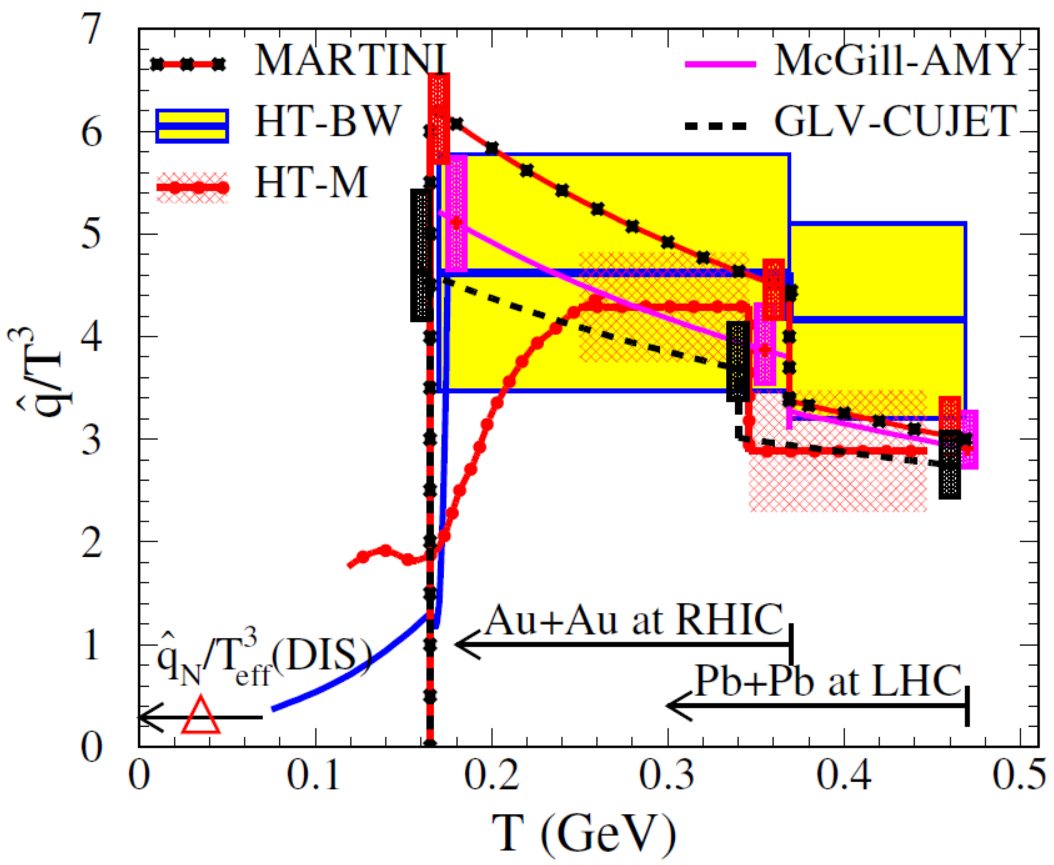
← mean free path

Determination of q-hat

- From the theory side, the JET collaboration extracted q-hat using combined CMS and ALICE LHC R_{AA} data assuming no fluctuations of initial conditions and coupling the same hydro to all energy loss models.

- 5 different models with different approaches:
  - higher twist (HT-BW, HT-M)
  - hard thermal loop (MARTINI, McGill-AMY)
  - opacity expansion (GLV-CUJET)

quark with E = 10 GeV

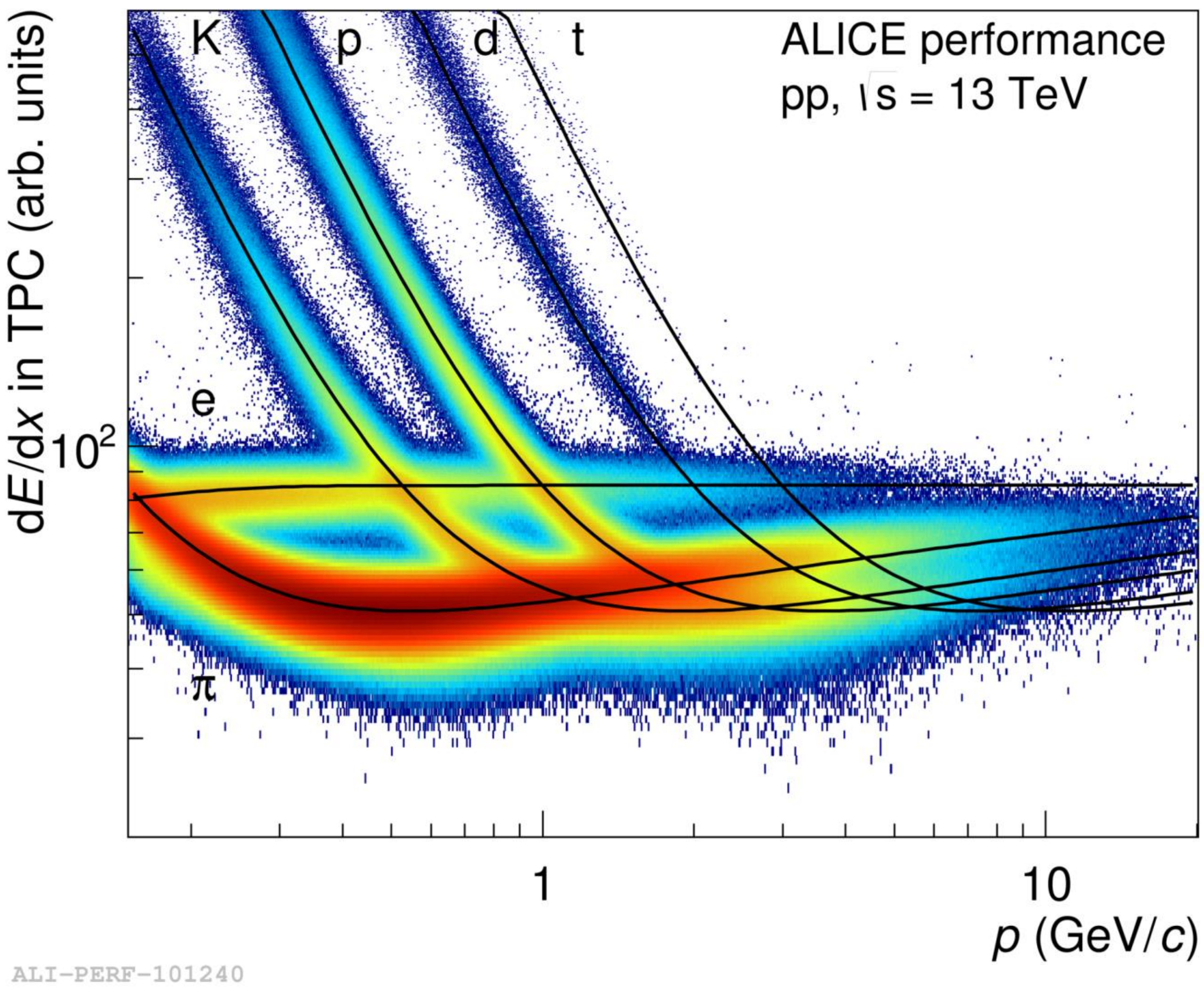


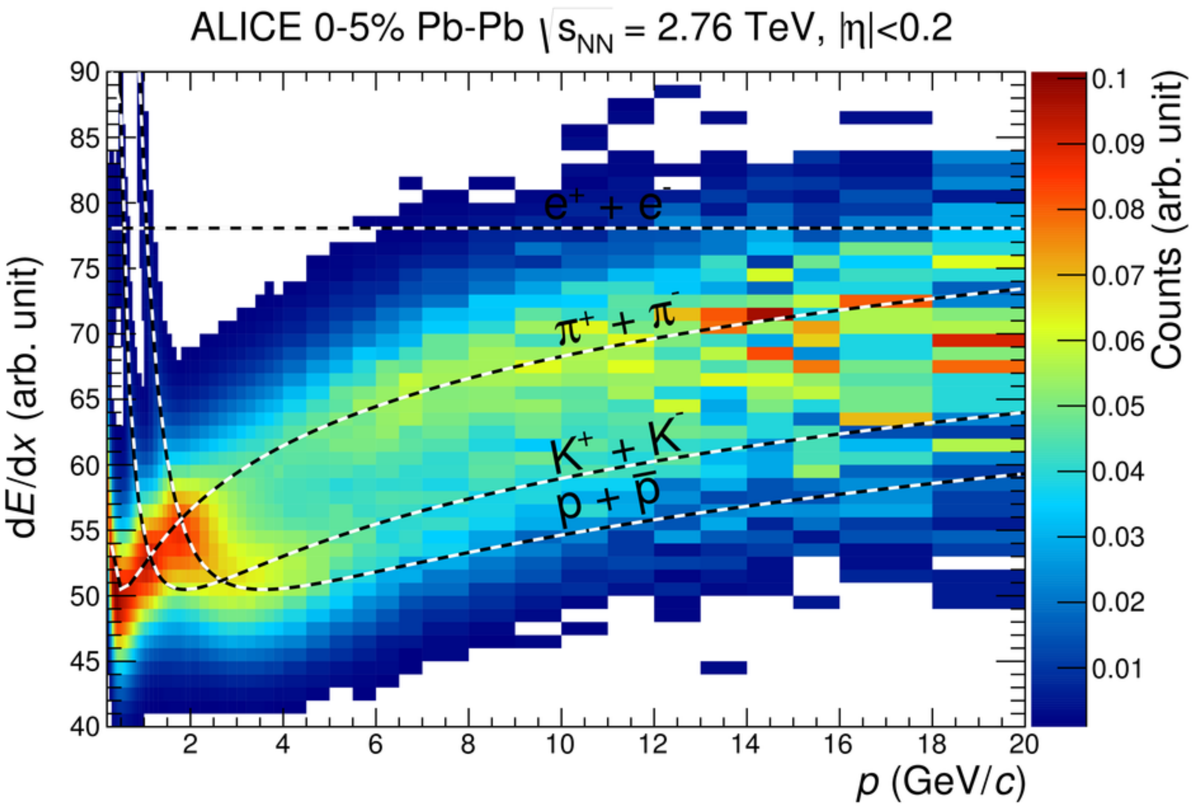
$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC.} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \begin{matrix} \text{T=370 MeV} \\ \text{T=470 MeV} \end{matrix}$$

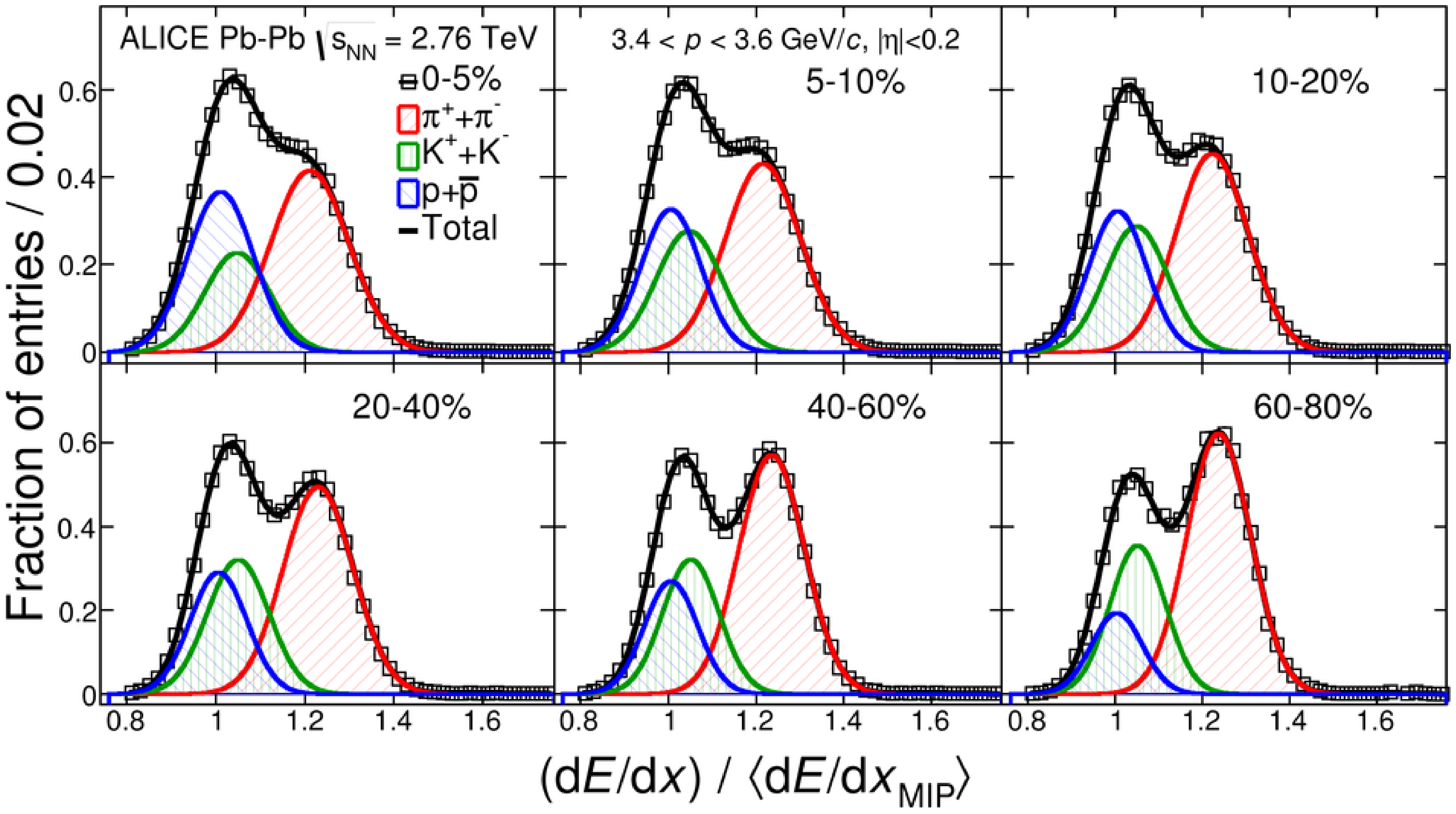
For comparison: in cold nuclear matter q = 0.02 GeV²/fm **(at t_0 = 0.6 fm)**

PID via dE/dx on the relativistic rise (1)

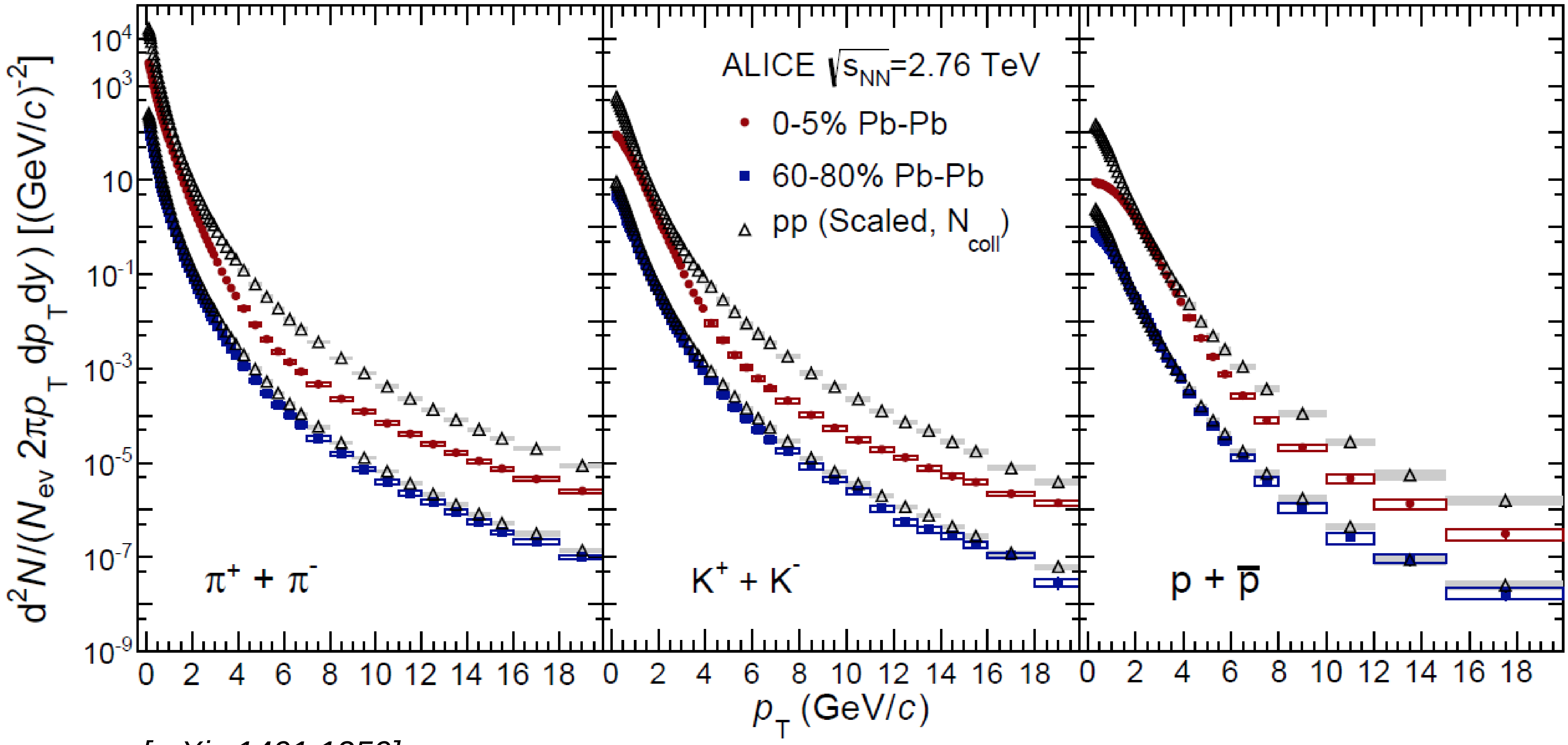




PID via dE/dx on the relativistic rise (2)



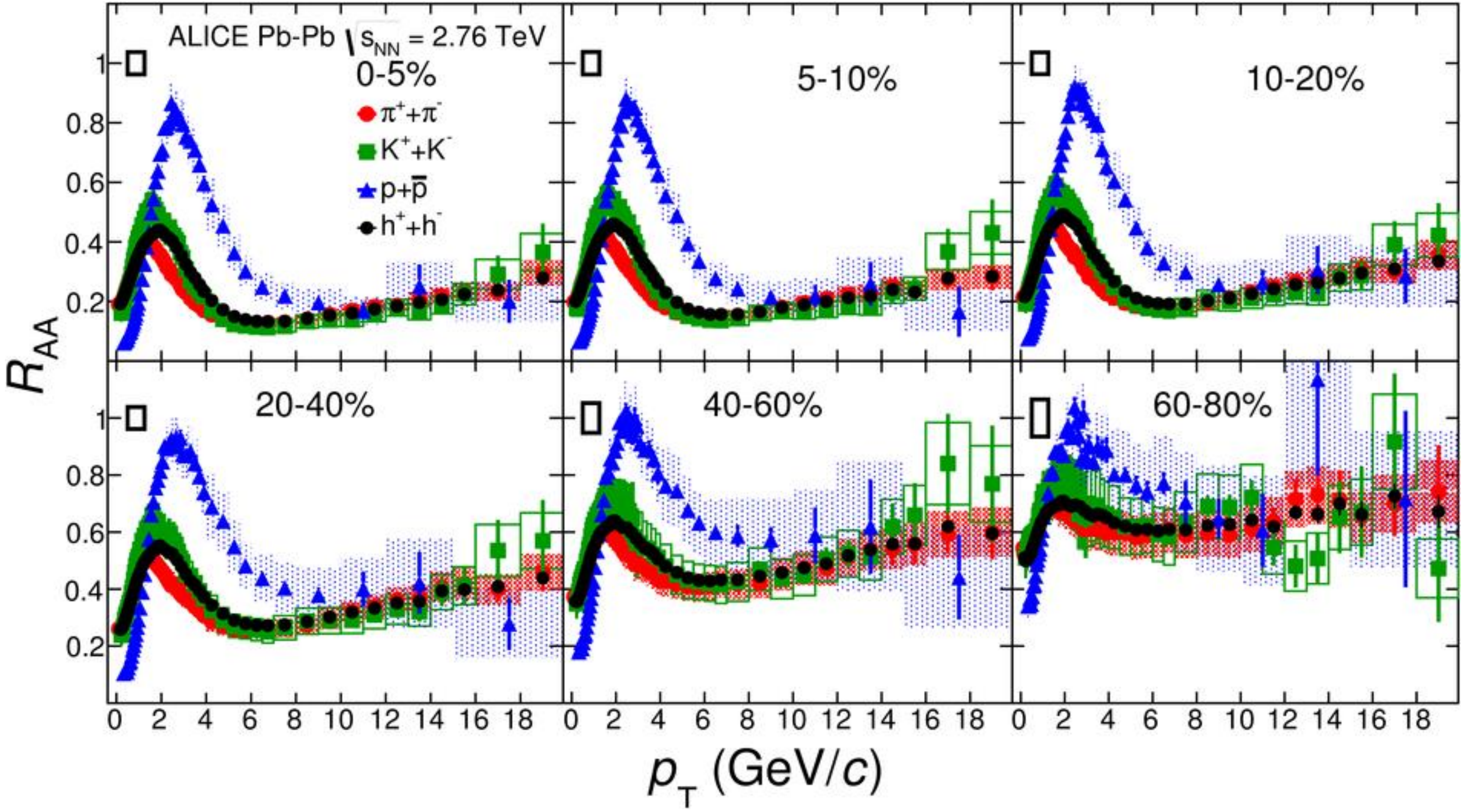
R_{AA} for identified particles (1)



[arXiv:1401.1250]

R_{AA} for identified particles (2)

R_{AA} independent of hadron species (light quarks) for momenta above ~8 GeV/*c*.

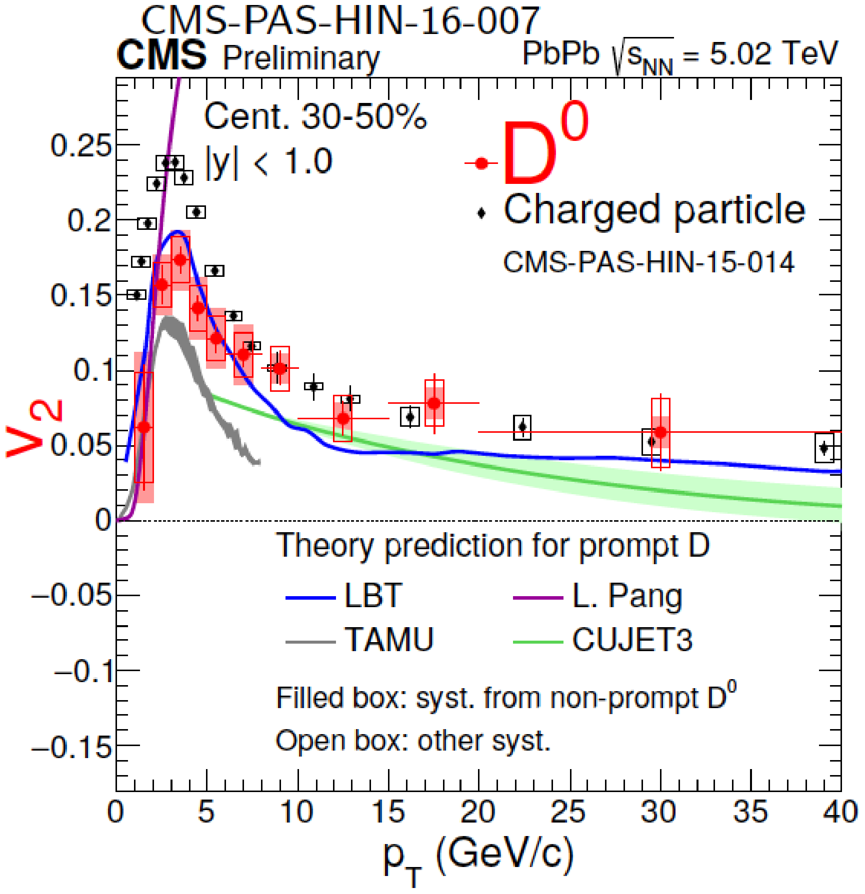


Quarkonia and heavy flavour

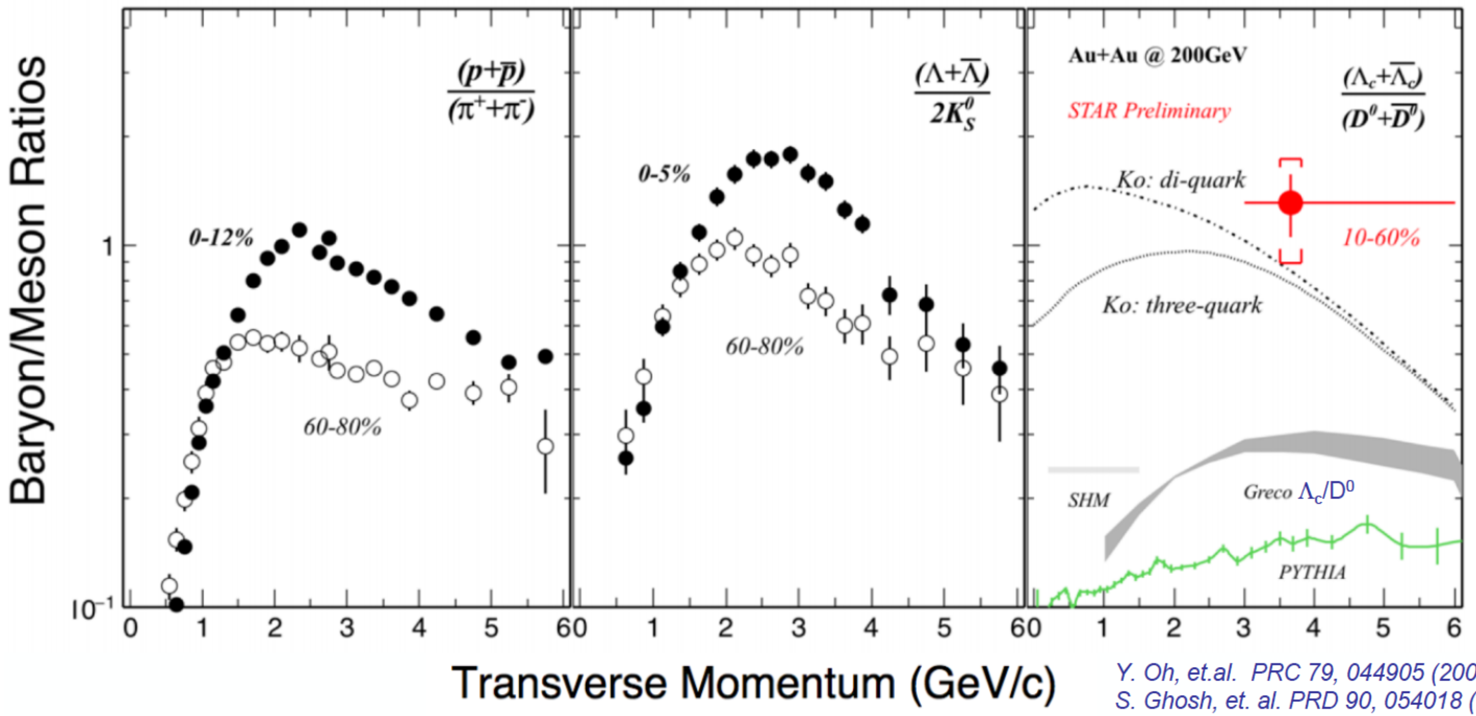
Heavy flavor (1)

- Heavy quark flavors (*c*,*b*) are dominantly produced in initial hard scatterings (calculable in pQCD) and then interact with the medium.
- There is strong evidence that **charm quarks *thermalize*** in the medium.

(A.) Elliptic flow of D mesons:



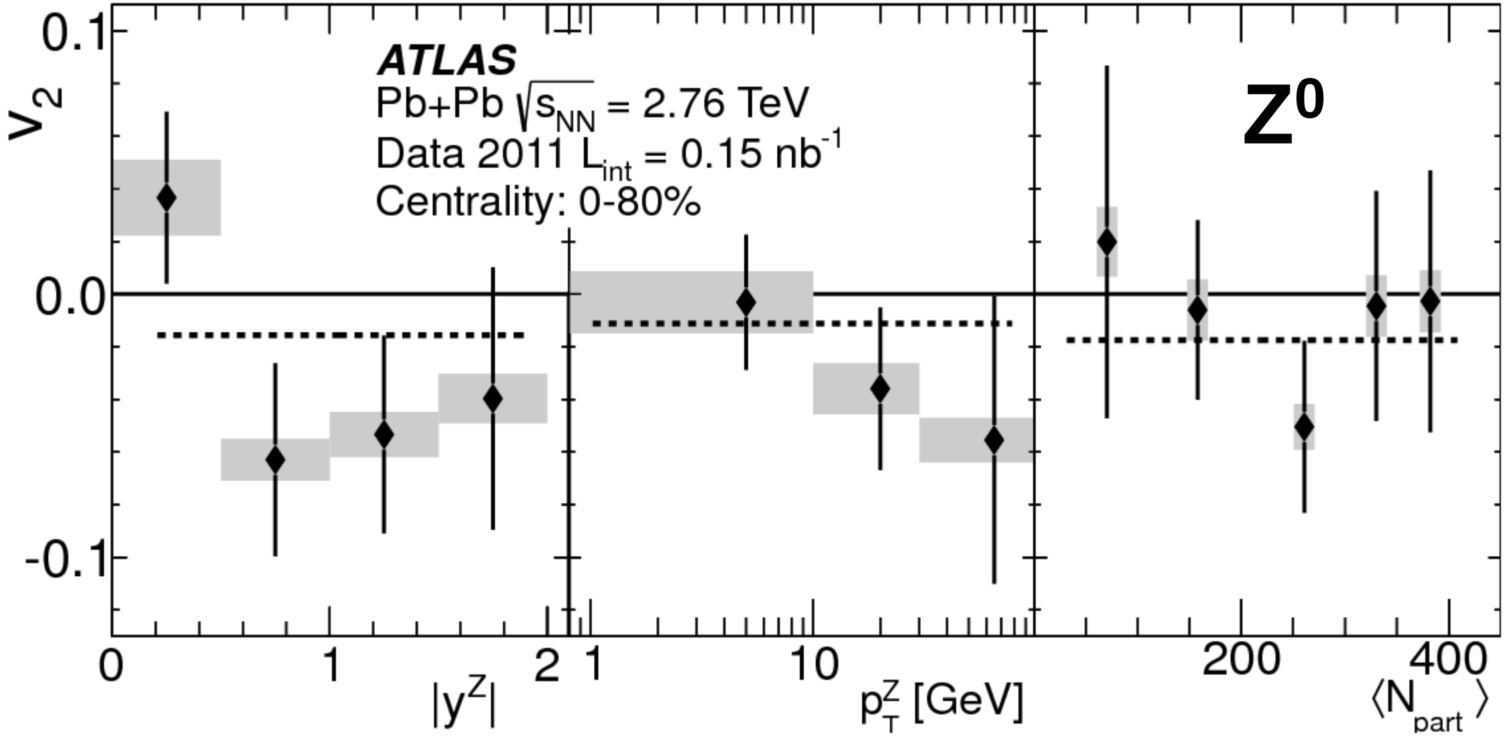
(B.) Baryon-to-meson enhancement seen in Λ_C:



Y. Oh, et.al. PRC 79, 044905 (2009)
S. Ghosh, et. al. PRD 90, 054018 (2014)

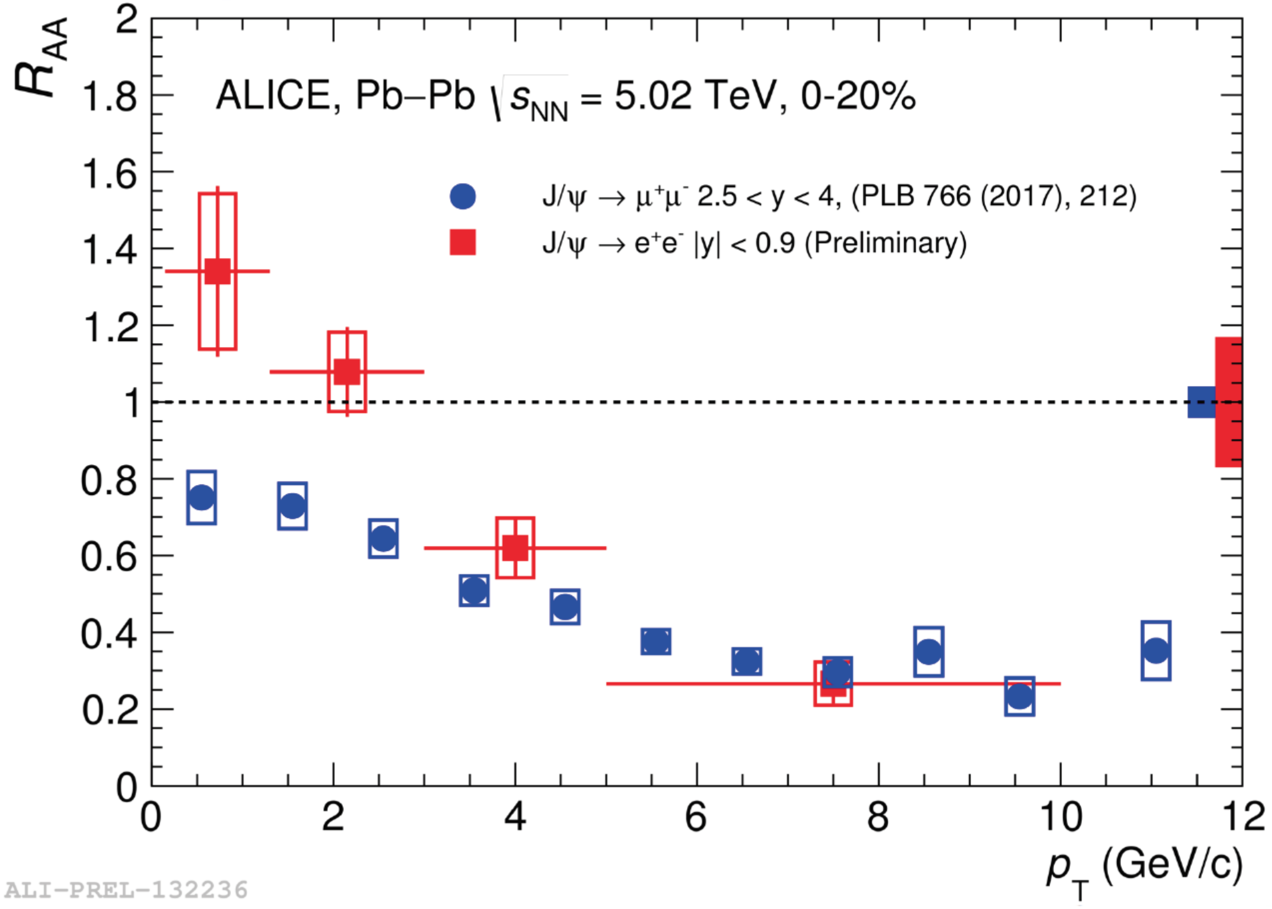
Heavy flavor (2)

- Heavy quark flavors (*c*,*b*) are dominantly produced in initial hard scatterings (calculable in pQCD) and then interact with the medium.
- There is strong evidence that **charm quarks *thermalize*** in the medium.
- N.B.: **electroweak probes do not show any interaction with the medium**.



[PRL 110, 022301 (2013)]

J/ψ recombination



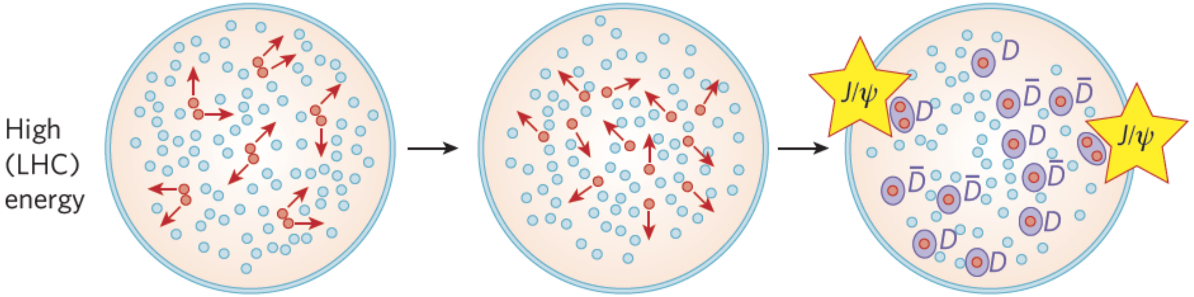
→ As $c\bar{c}$ bound state, the J/ψ is expected not to be bound in the QGP phase (*Matsui/Satz*, 1986), but it can re-generate at the phase boundary.

→ 5.02 TeV Pb-Pb data strongly confirms J/ψ recombination picture:

- R_{AA}(LHC) > R_{AA}(RHIC)
- R_{AA} midrapidity > R_{AA} forward rap.

→ Signature of de-confinement.

[P. Braun-Munzinger, J. Stachel, Nature doi:10.1038/nature06080]

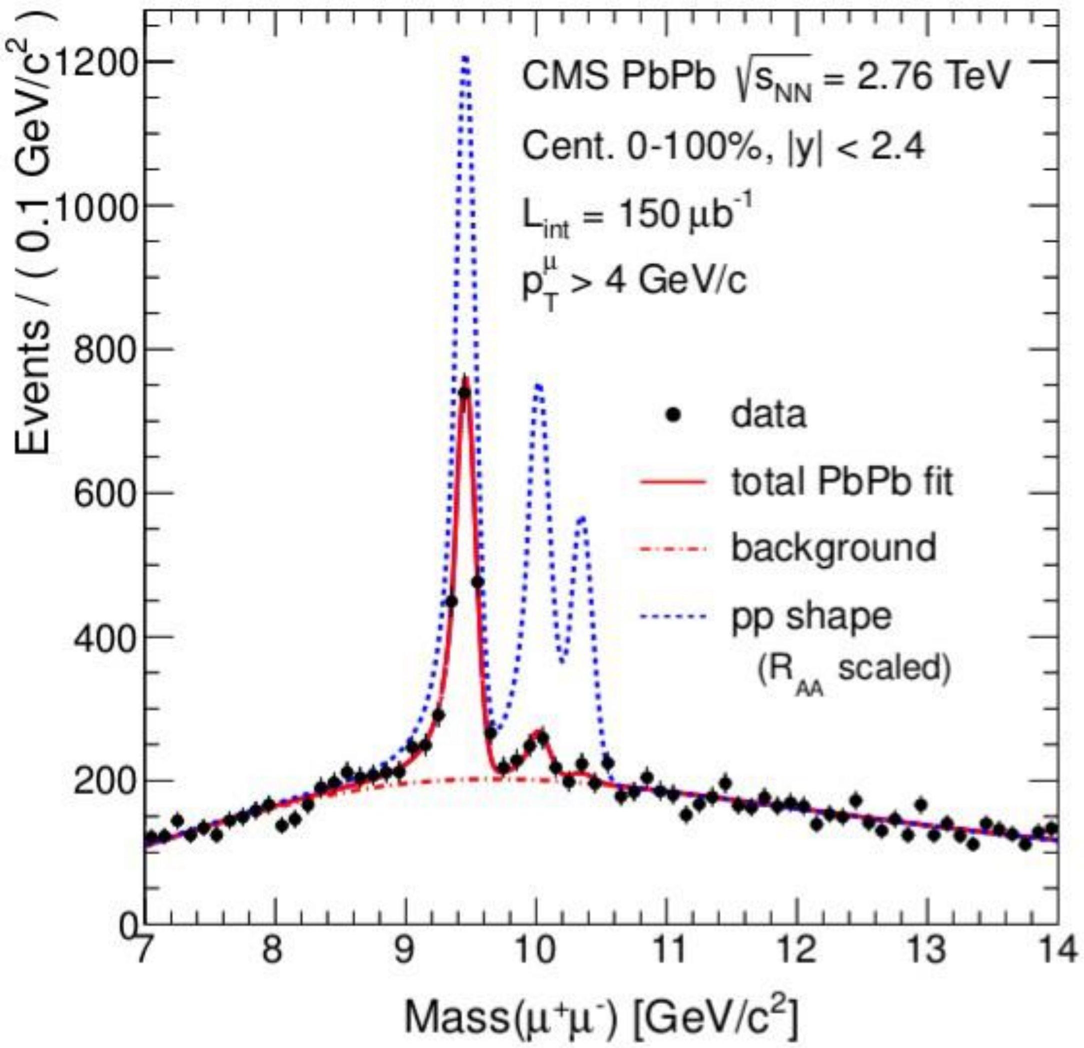


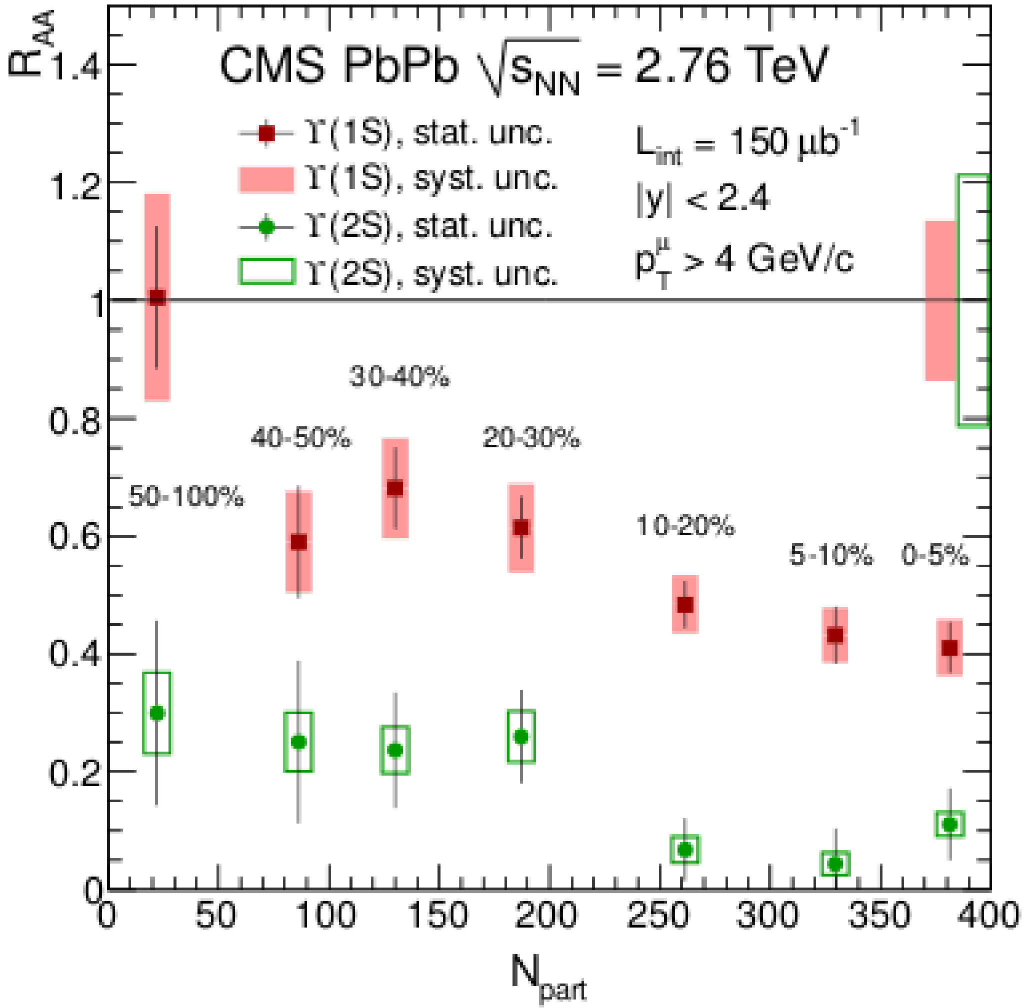
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \cdot dN_{pp}/dp_T}$$

$R_{AA} < 1$ → suppression w.r.t pp coll.
$R_{AA} > 1$ → enhancement w.r.t to pp coll.

Suppression of Upsilon states

[PRL 109 (2012) 222301]

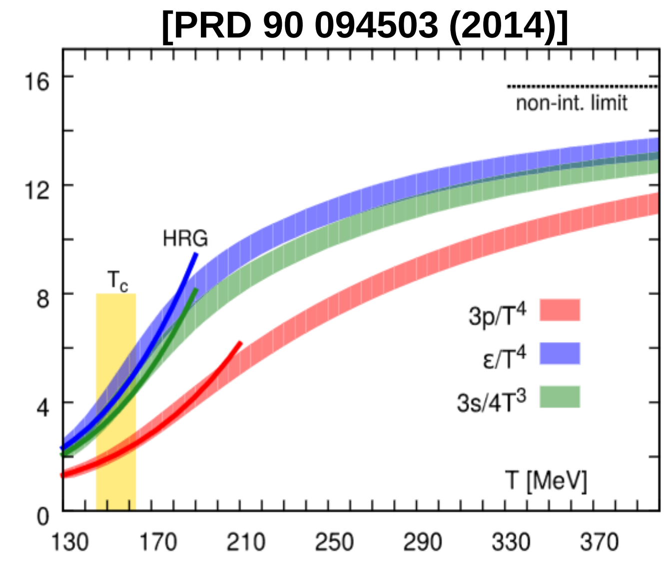


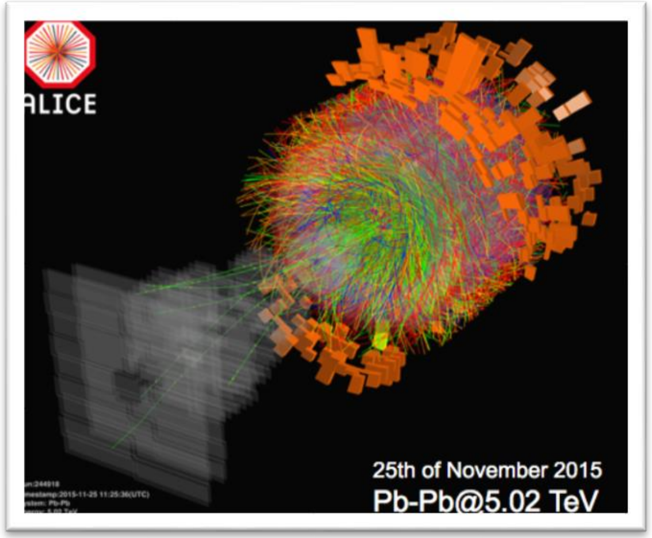


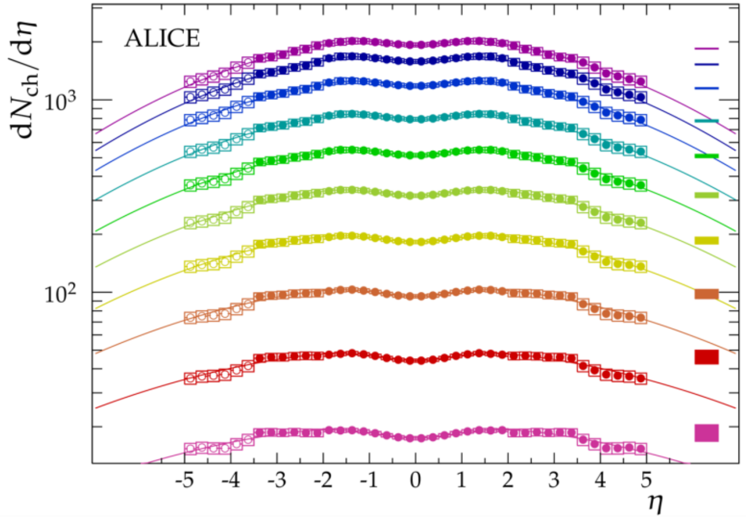
No re-generation for the much more rare b-quarks!

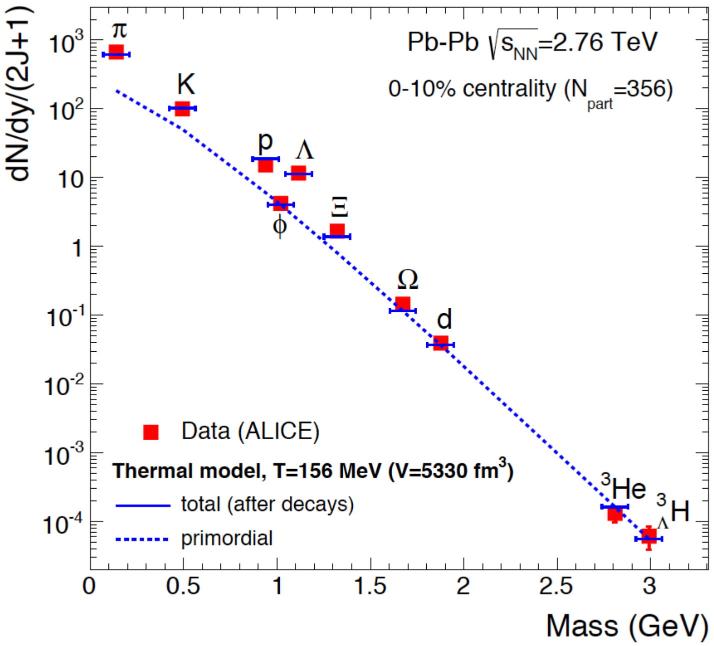
Suppression of Y(1S) ground, and excited Y(2S) and Y(3S) states.

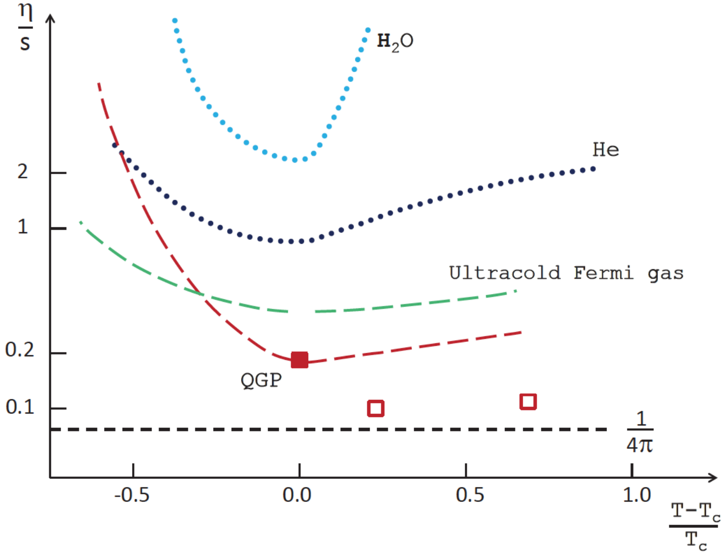
Summary

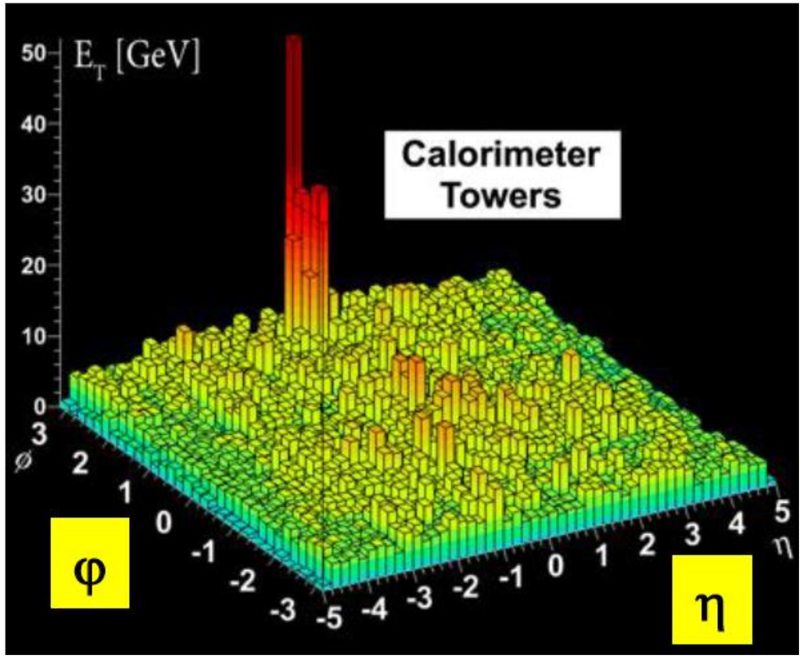

[PRD 90 094503 (2014)]
non-int. limit
HRG
T_c
$3p/T^4$
ε/T^4
$3s/4T^3$
T [MeV]
16
12
8
4
0
130
170
210
250
290
330
370


ALICE
25th of November 2015
Pb-Pb@5.02 TeV


ALICE
$dN_{ch}/d\eta$
10^3
10^2
η
-5 -4 -3 -2 -1 0 1 2 3 4 5


Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
0-10% centrality (N_{part}=356)
dN/dy/(2J+1)
π
K
p
Λ
ϕ
Ξ
Ω
d
^{3}He
$^3_\Lambda$H
Data (ALICE)
Thermal model, T=156 MeV (V=5330 fm^3)
total (after decays)
primordial
Mass (GeV)


$\frac{\eta}{s}$
H_2O
He
Ultracold Fermi gas
QGP
$\frac{1}{4\pi}$
$\frac{T-T_c}{T_c}$
2
1
0.2
0.1
-0.5
0.0
0.5
1.0


E_T [GeV]
Calorimeter Towers
φ
η

Further reading

- Lectures
  - J. Stachel, K. Reygers (2011)
    http://www.physi.uni-heidelberg.de/~reygers/lectures/2011/qgp/qgp_lecture_ss2011.html
  - P. Braun-Munzinger, A. Andronic, T. Galatyuk (2012)
    http://web-docs.gsi.de/~andronic/intro_rhic2012/
  - Quark Matter Student Day (2014)
    https://indico.cern.ch/event/219436/timetable/#20140518.detailed
- Books
  - C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994
    http://books.google.de/books?id=Fnxvrdj2NOQC&printsec=frontcover
  - L. P. Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994 (**free as pdf**)
    http://www.csernai.no/Csernai-textbook.pdf
  - E. Shuryak, The QCD vacuum, hadrons, and superdensematter, World Scientific, 2004
    http://books.google.de/books?id=rbcQMK6a6ekC&printsec=frontcover
  - Yagi, Hatsuda, Miake, Quark-Gluon Plasma, Cambridge University Press, 2005
    http://books.google.de/books?id=C2bpxwUXJngC&printsec=frontcover
  - R. Vogt, UltrarelativisticHeavy-ion Collisions, Elsevier, 2007
    http://books.google.de/books?id=F1P8WMESgkMC&printsec=frontcover
  - W. Florkowski, Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, World Scientific, 2010
    http://books.google.de/books?id=4gIp05n9lz4C&printsec=frontcover