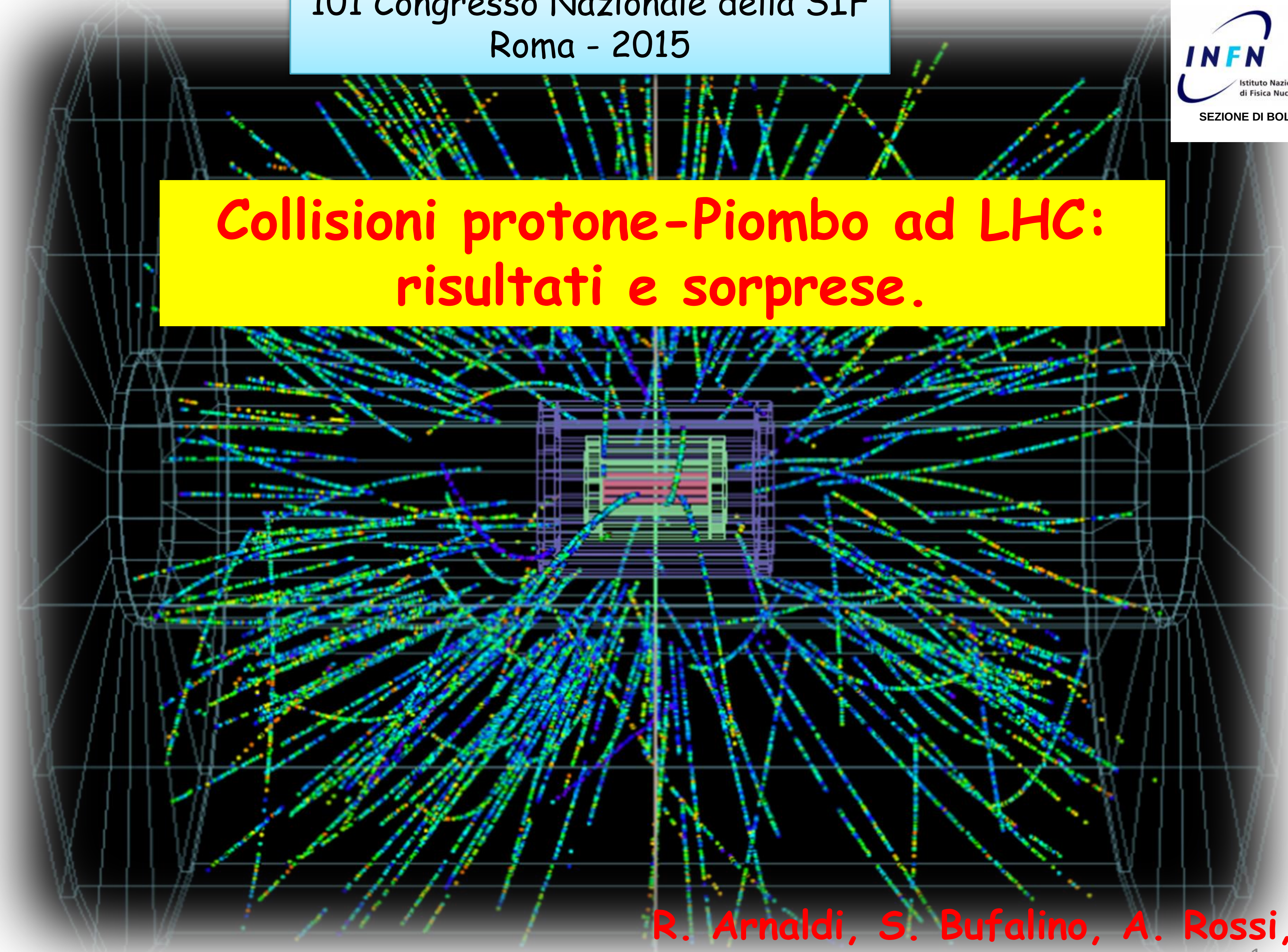
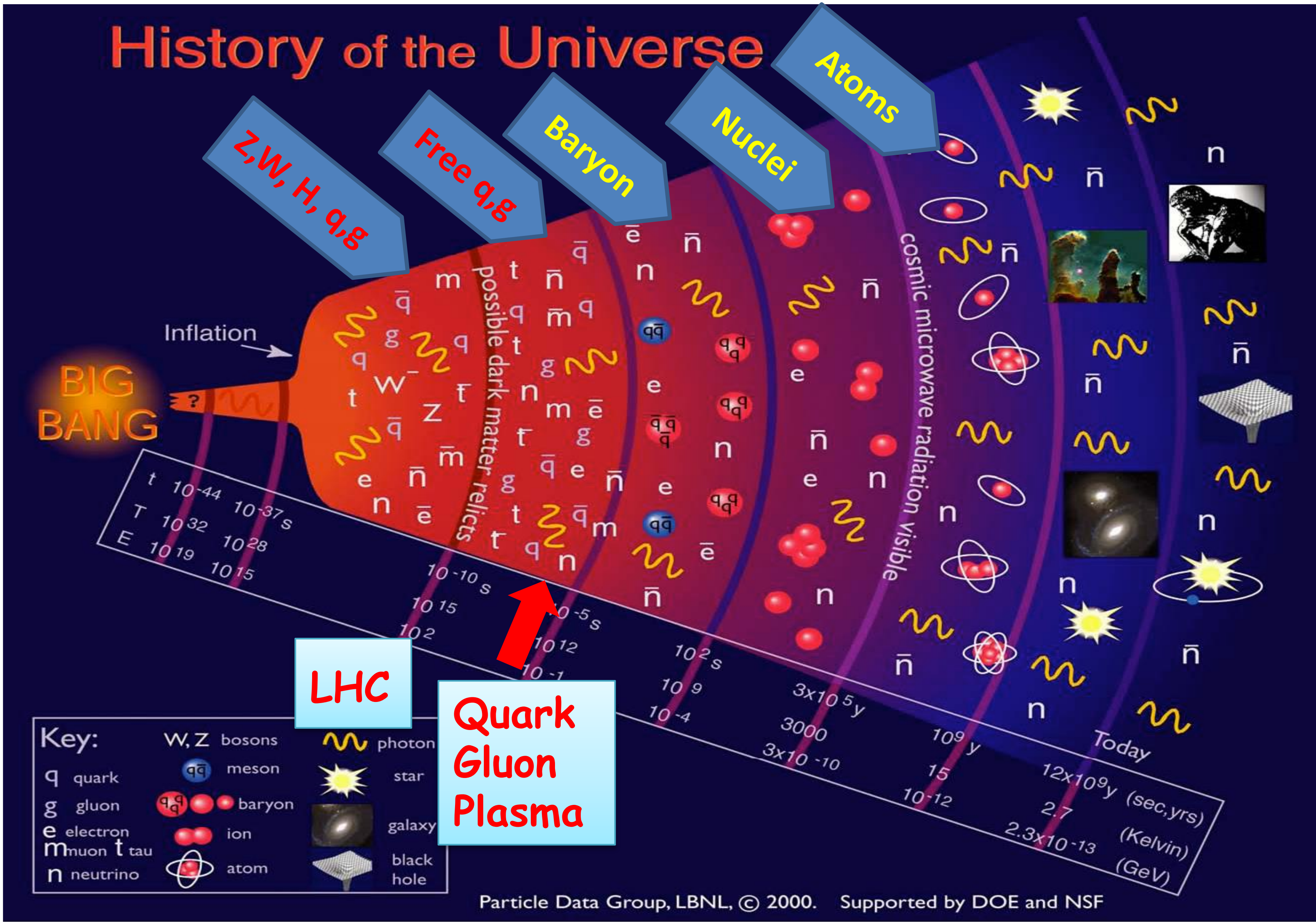
101 Congresso Nazionale della SIF
Roma - 2015

R. Nania
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI BOLOGNA

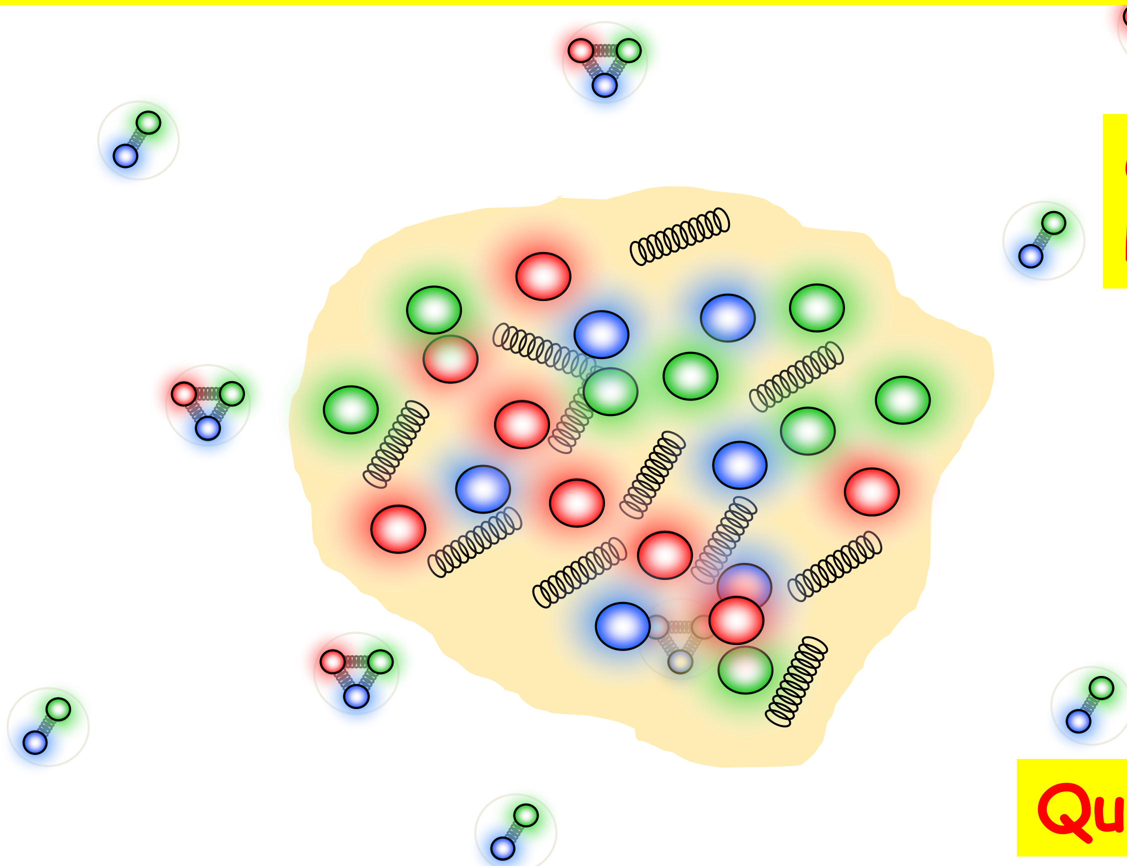
Collisioni protone-Piombo ad LHC: risultati e sorprese.



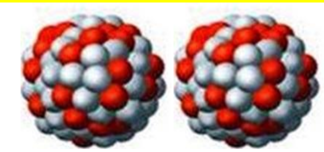
R. Arnaldi, S. Bufalino, A. Rossi,
E. Scapparone, P. Di Nezza


History of the Universe
Z,W, H, q,g
Free q,g
Baryon
Nuclei
Atoms
BIG BANG
Inflation
possible dark matter relicts
cosmic microwave radiation visible
LHC
Quark Gluon Plasma
Today
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Quarks and gluons are usually confined inside hadrons,
But what happens if they collapse in a wide space region as during the Big-Bang ?



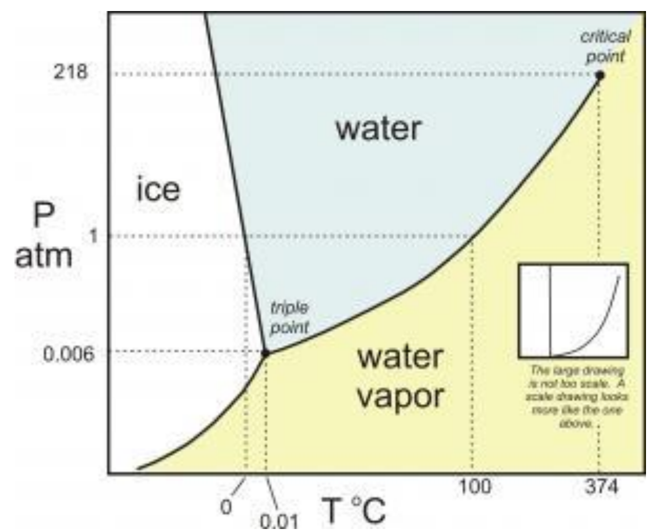
Create QGP with Pb-Pb collisions



Quark Gluon Plasma

Require
- Energy density >> 1 GeV/fm^3
- Lasting for > 1 fm/c
- In a volume much larger than a hadron , ≈10 fm^3

Temperature decreases

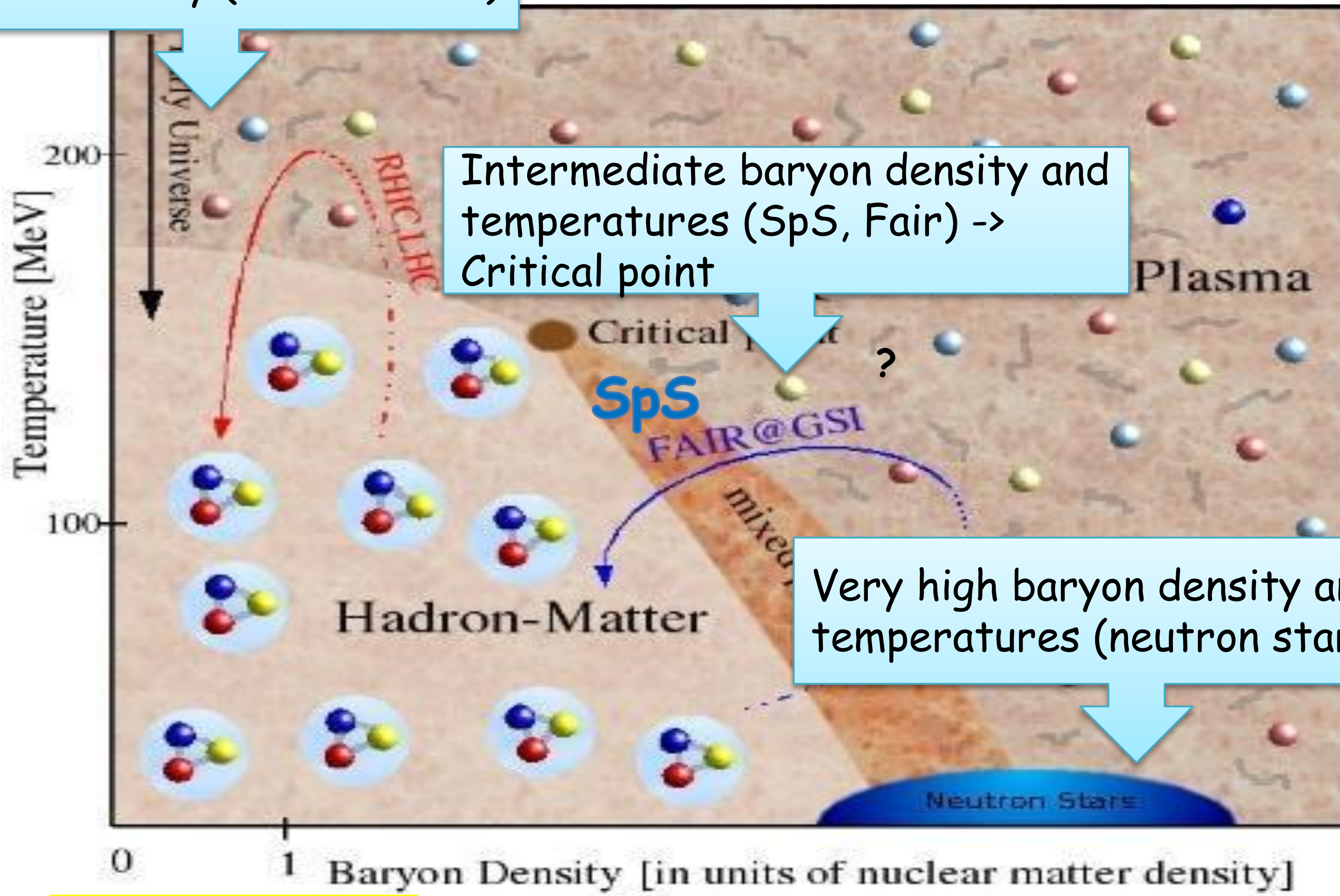


Where to look for QGP : The Phase Diagram

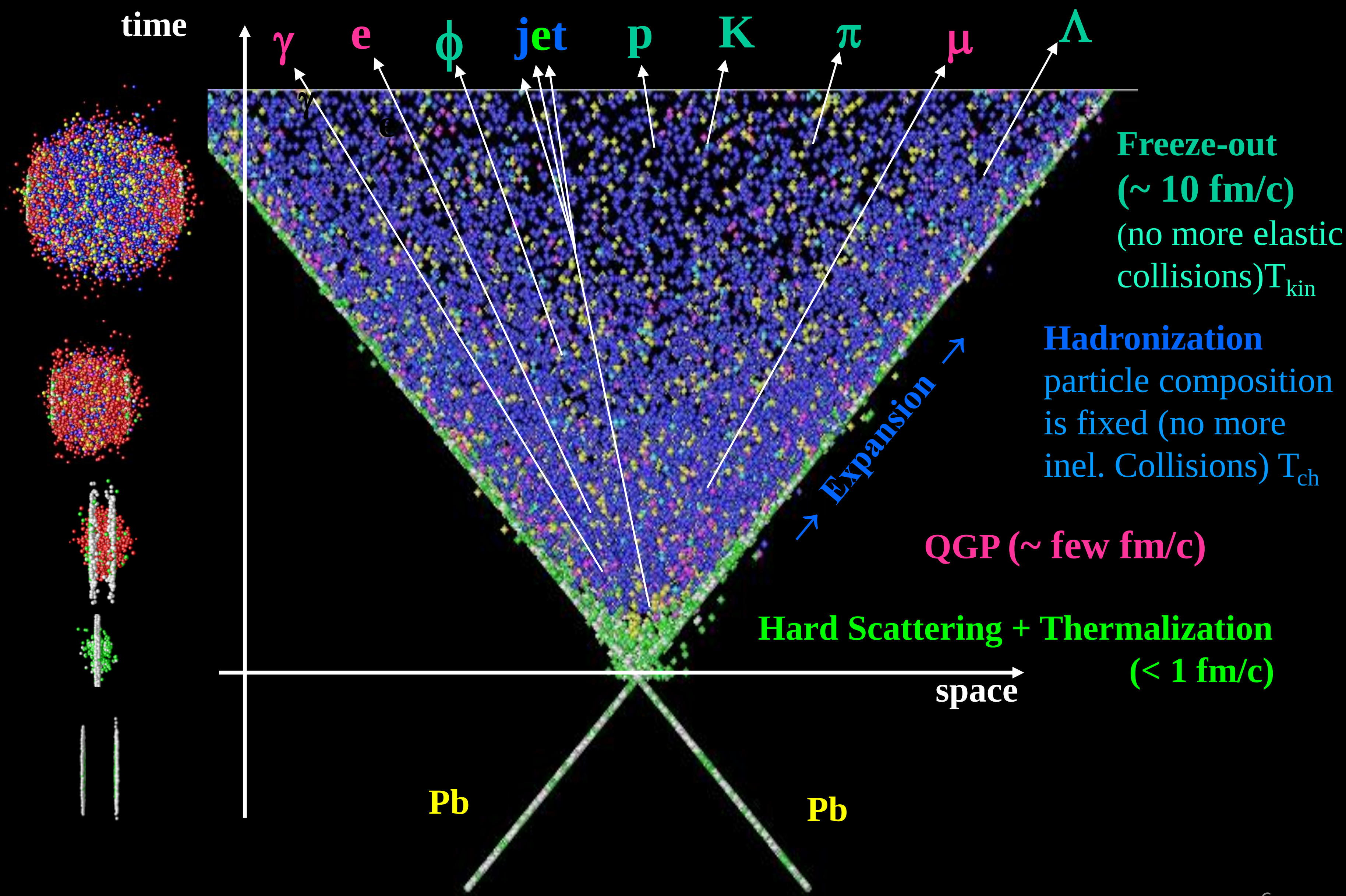
High temperature and low baryon density (RHIC + LHC)

Intermediate baryon density and temperatures (SpS, Fair) -> Critical point

Very high baryon density and low temperatures (neutron stars)

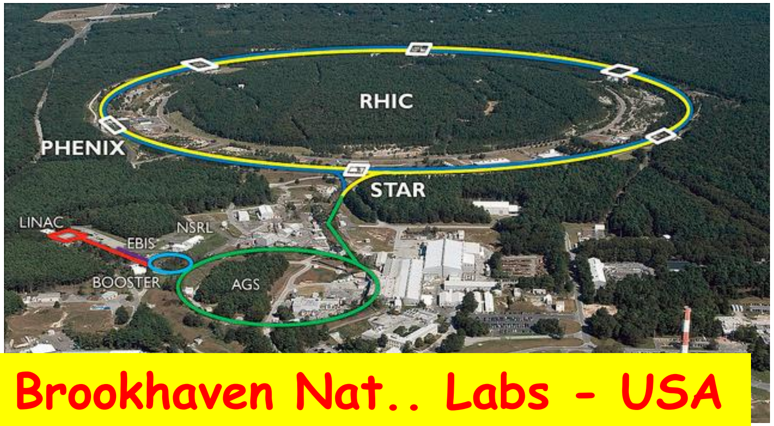


$n_{baryon} \approx n_{anti\text{-}baryon}$



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

Present Ion Colliders



Brookhaven Nat.. Labs - USA

RHIC Collider

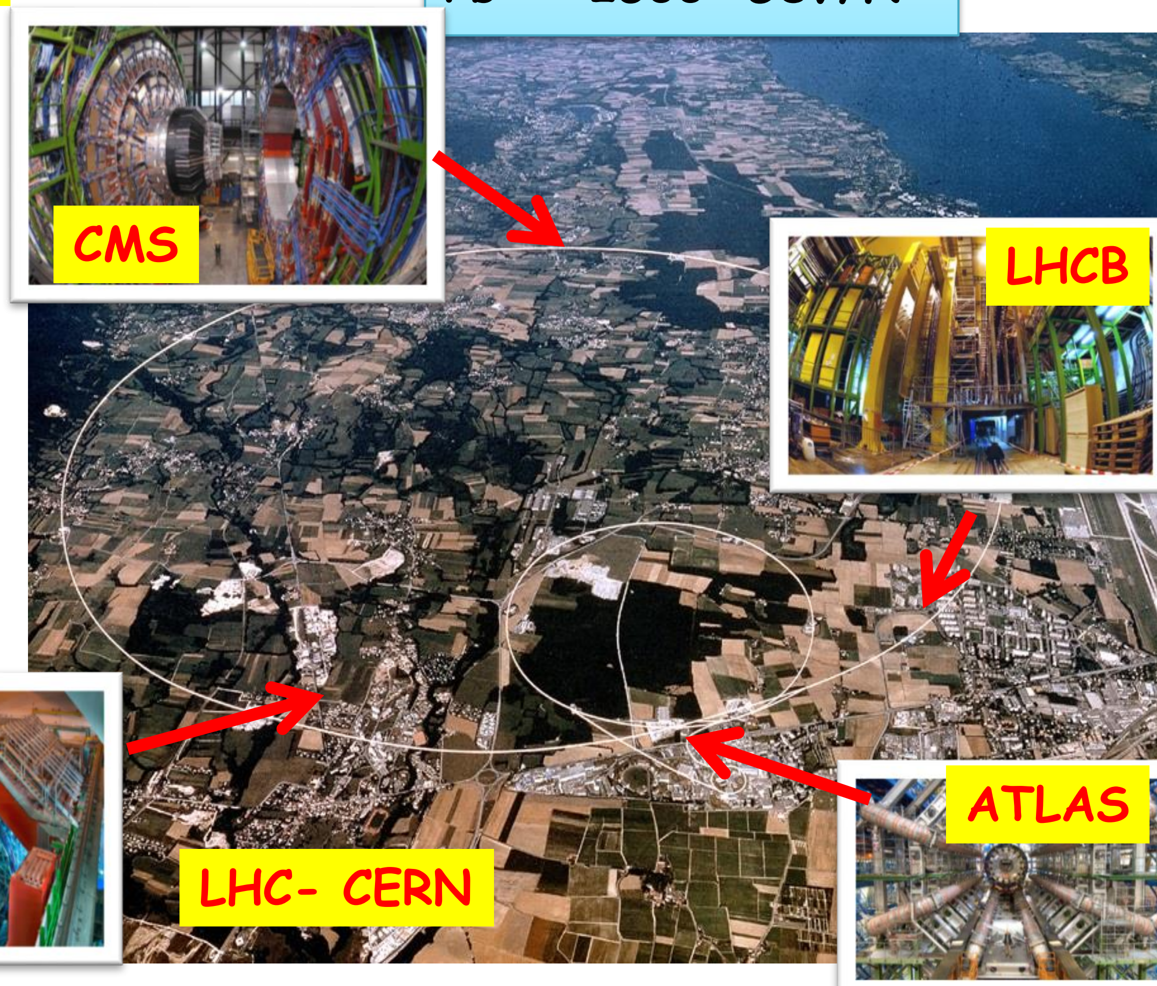
Protons → 250 GeV

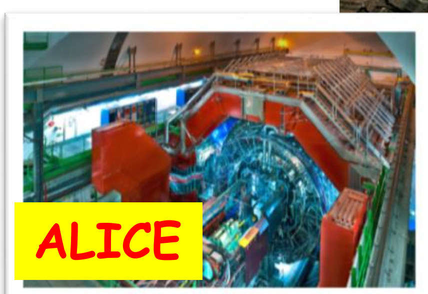
Au → 100 GeV/N

LHC Collider

Protons → 7000 GeV

Pb → 2500 GeV/N





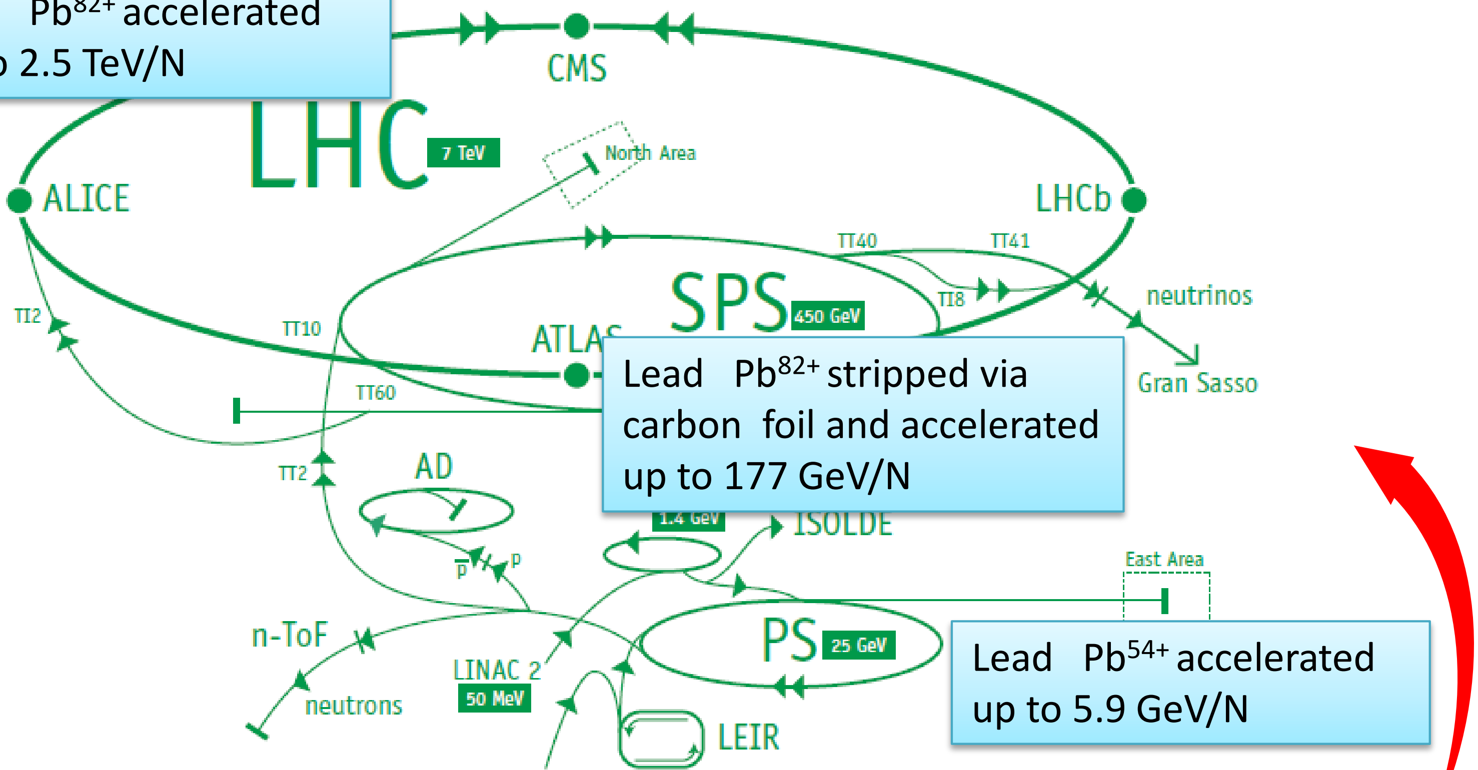
How Lead beam is obtained at LHC

Lead Pb^{82+} accelerated up to 2.5 TeV/N

Lead Pb^{82+} stripped via carbon foil and accelerated up to 177 GeV/N

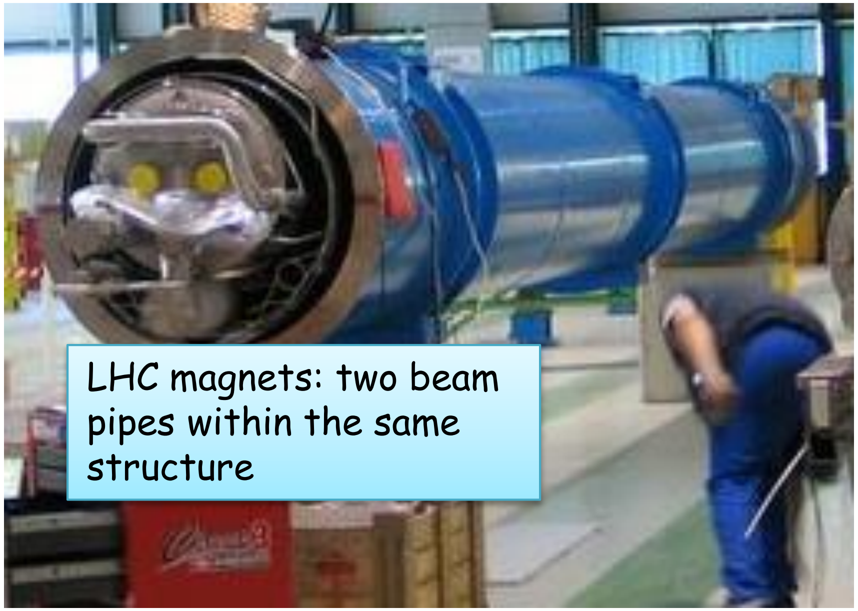
Lead Pb^{54+} accelerated up to 5.9 GeV/N

Lead Pb^{54+} stripped via carbon foil and accelerated up to 70 MeV/N



Lead vapour is ionized via electron beam

Lead and proton beam inside LHC



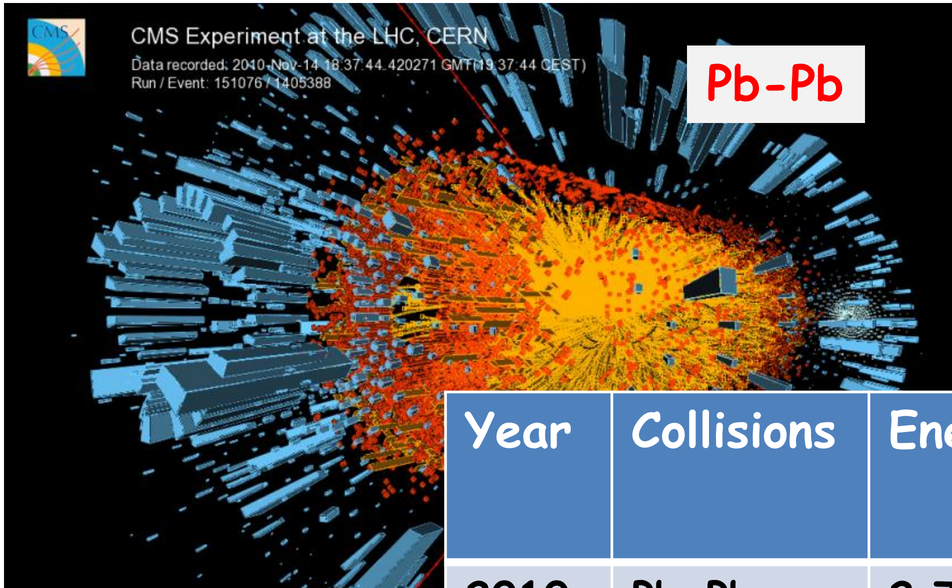
LHC magnets: two beam pipes within the same structure

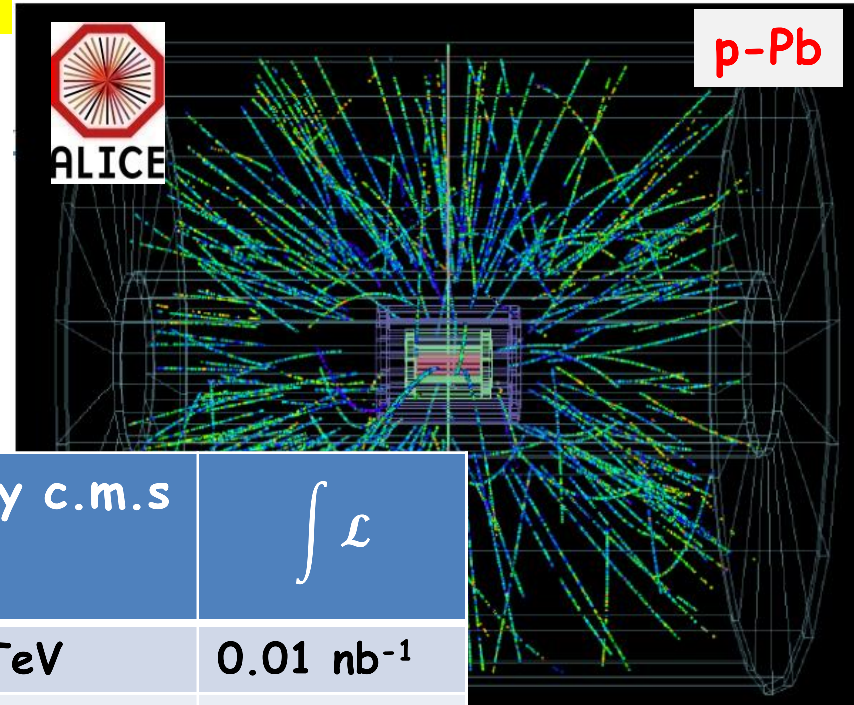
Lead ions are 208 times heavier and have 82 times more positive charge than protons, but in the same magnets.

Use the two separate radiofrequency systems and their carefull tuning of the two beam orbits to reliaby collide the two beam in the four interaction regions.

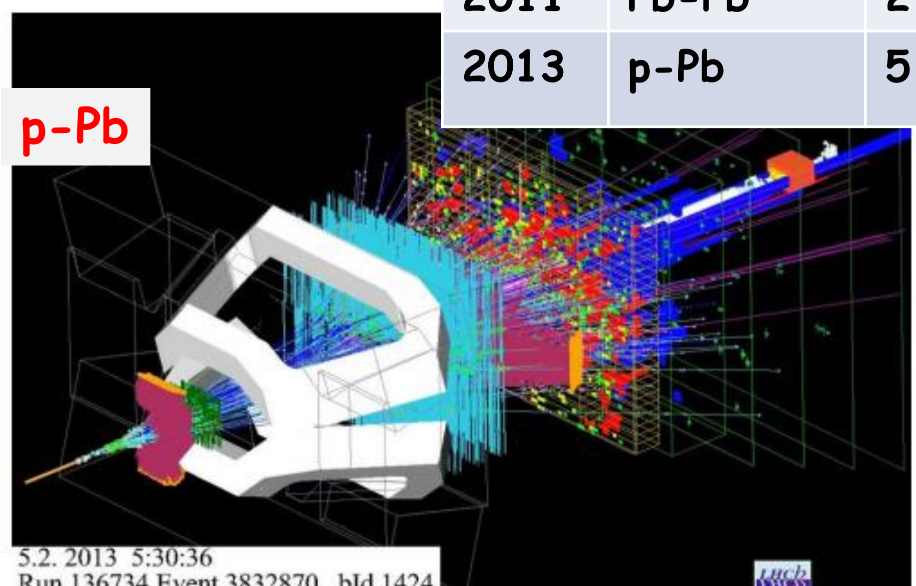
Collisions with asymmetric and different beams :
PB =1.58 TeV , p =4,0 TeV $\rightarrow$ **5.02 TeV/N c.m.s.**
LHC world premiere !

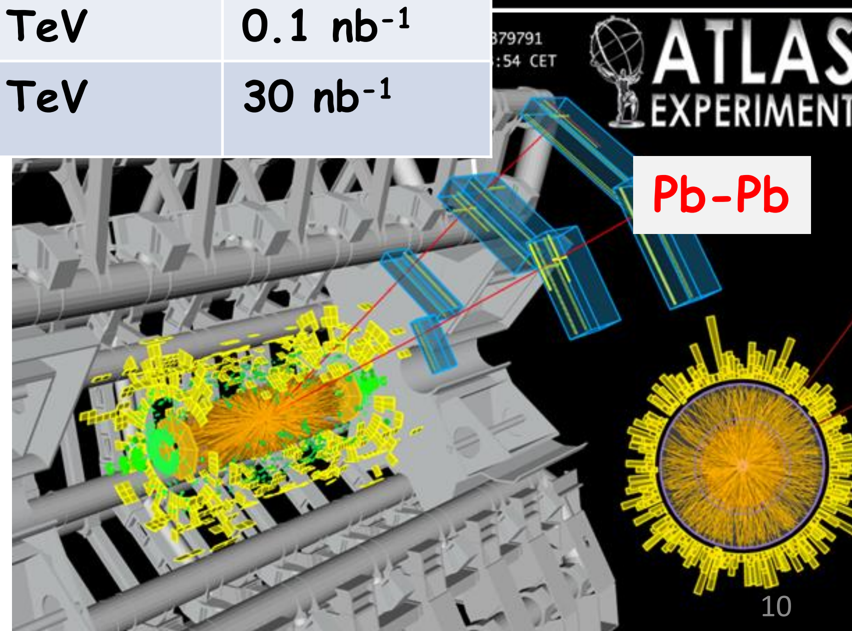
All 4 LHC experiments involved



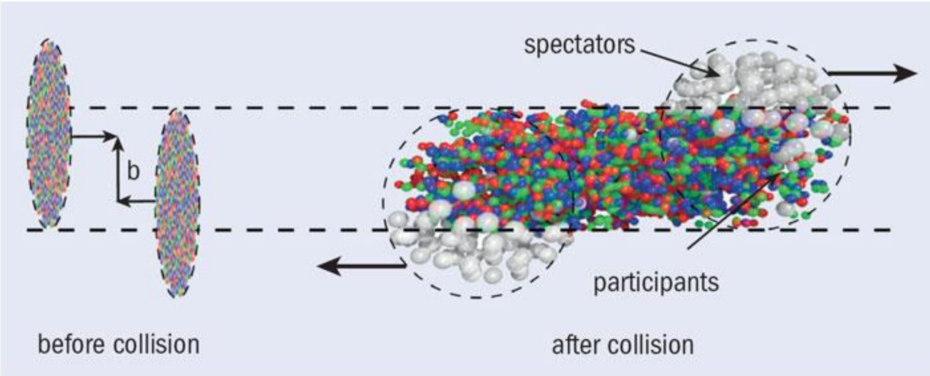


Year	Collisions	Energy c.m.s	$\int \mathcal{L}$
2010	Pb-Pb	2.76 TeV	0.01 nb^{-1}
2011	Pb-Pb	2.76 TeV	0.1 nb^{-1}
2013	p-Pb	5.02 TeV	30 nb^{-1}





Centrality definition

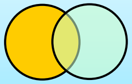


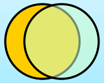
N_{part} : Number of nucleons participating to the collision

N_{coll} : Number of binary collisions between nucleons

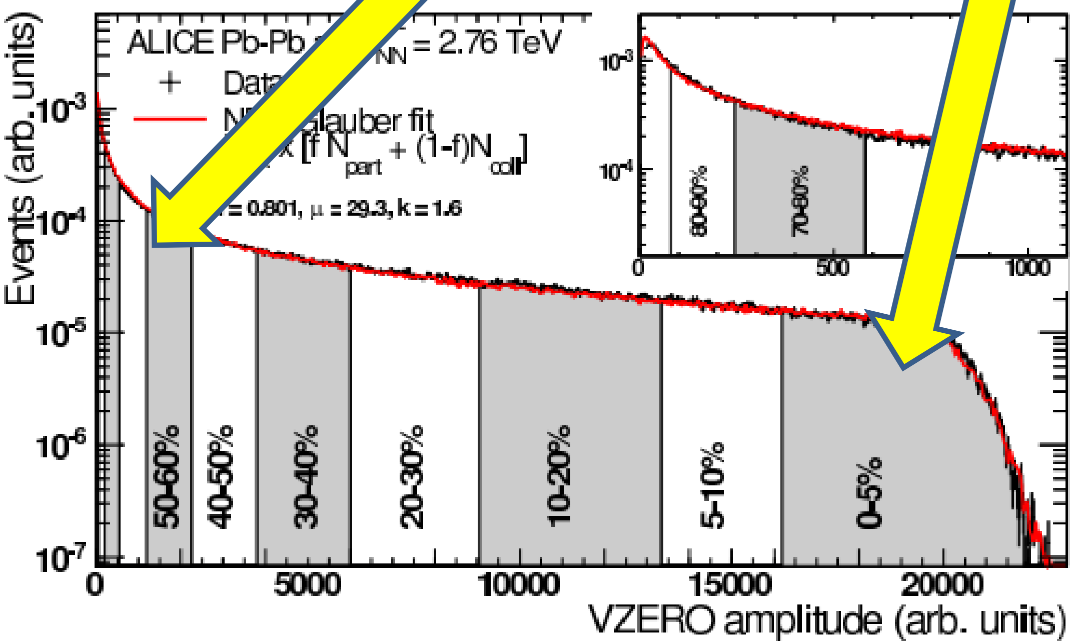
Example LHC:
Centrality 0-1%
Npar = 403
Ncoll = 1681

Centrality = fraction of σ_{PbPb}

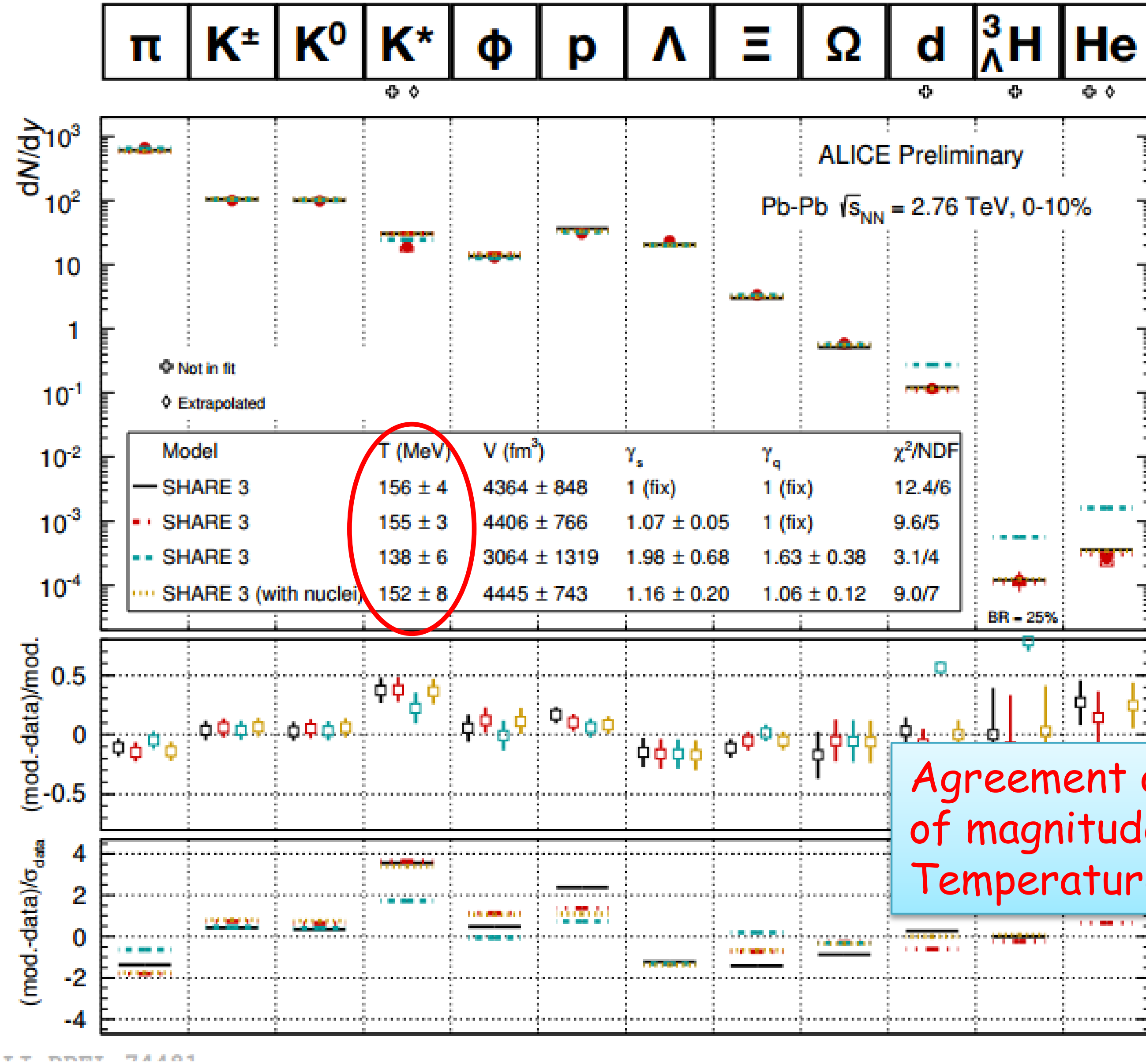

60-80%


0-5%

PhysRevC.88.044909 (201

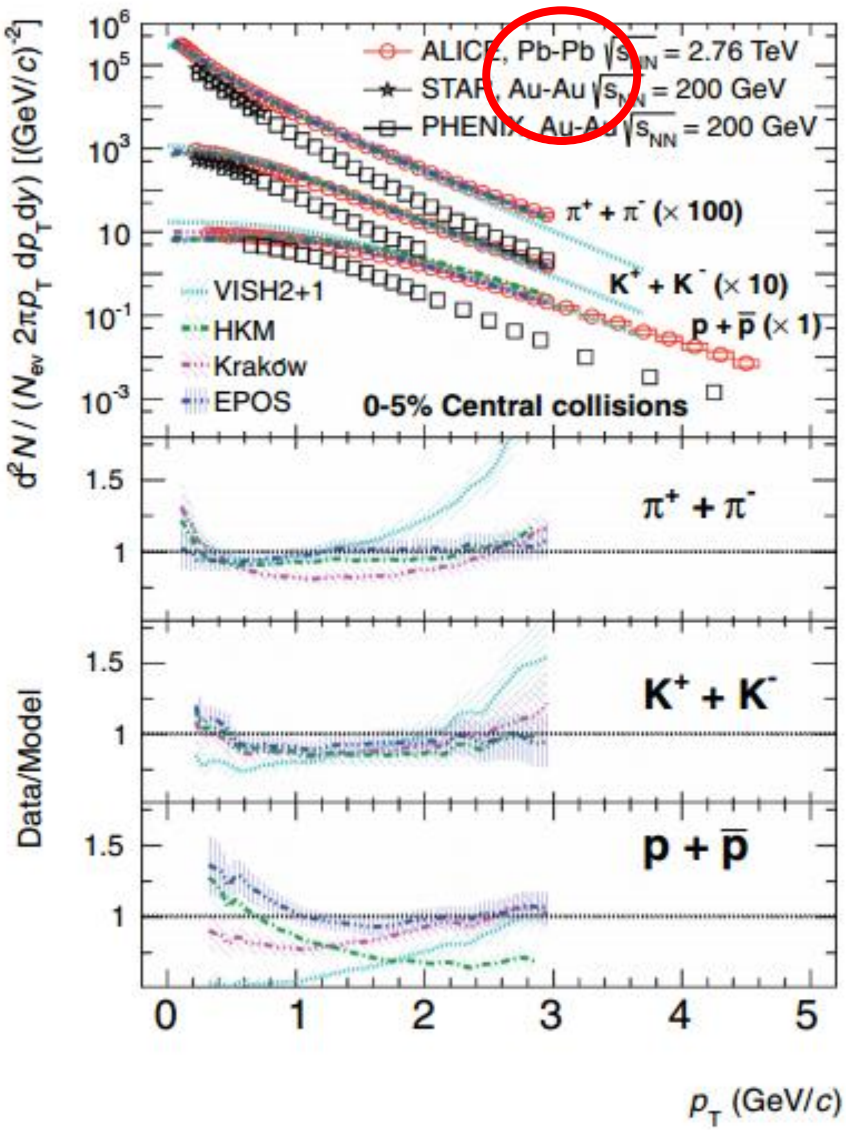


How to characterize the hot medium I: Hadrochemistry based on thermal model



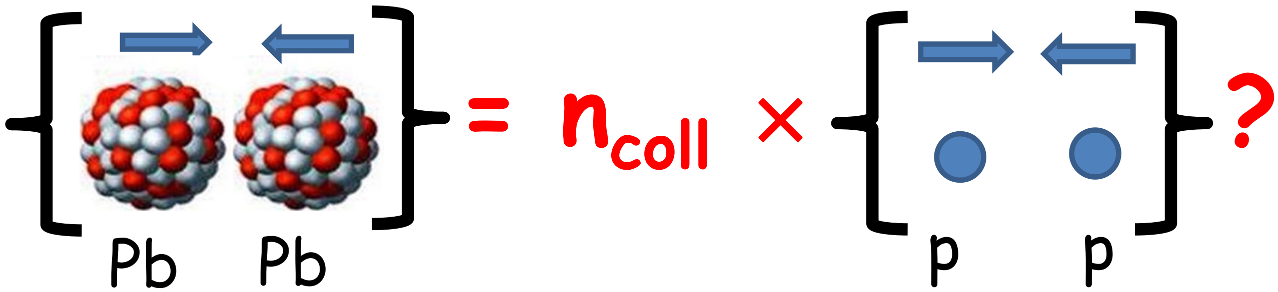
Agreement over 7 orders of magnitude !
Temperature ≈ 150 MeV

How to characterize the hot medium II : Particle production



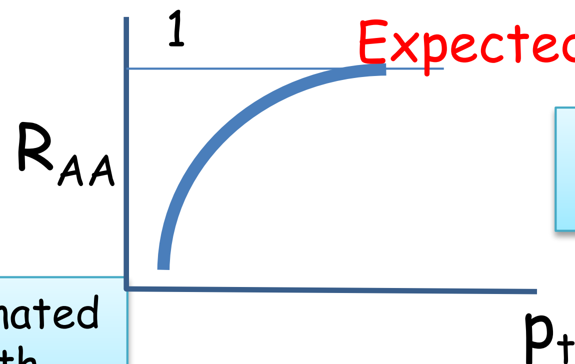
Relativistic hydrodynamical models describe reasonably well particle production validating the assumption of a matter which has reached thermal equilibrium after the collisions

How to characterize the hot medium III : Nuclear Modification Factor



$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{COLL} \rangle_{AA} \, \text{Yield}_{pp}(p_T)}$$

Indicates if in HI collisions the yield of particles, compared with pp yield , scales with the number of collisions or not



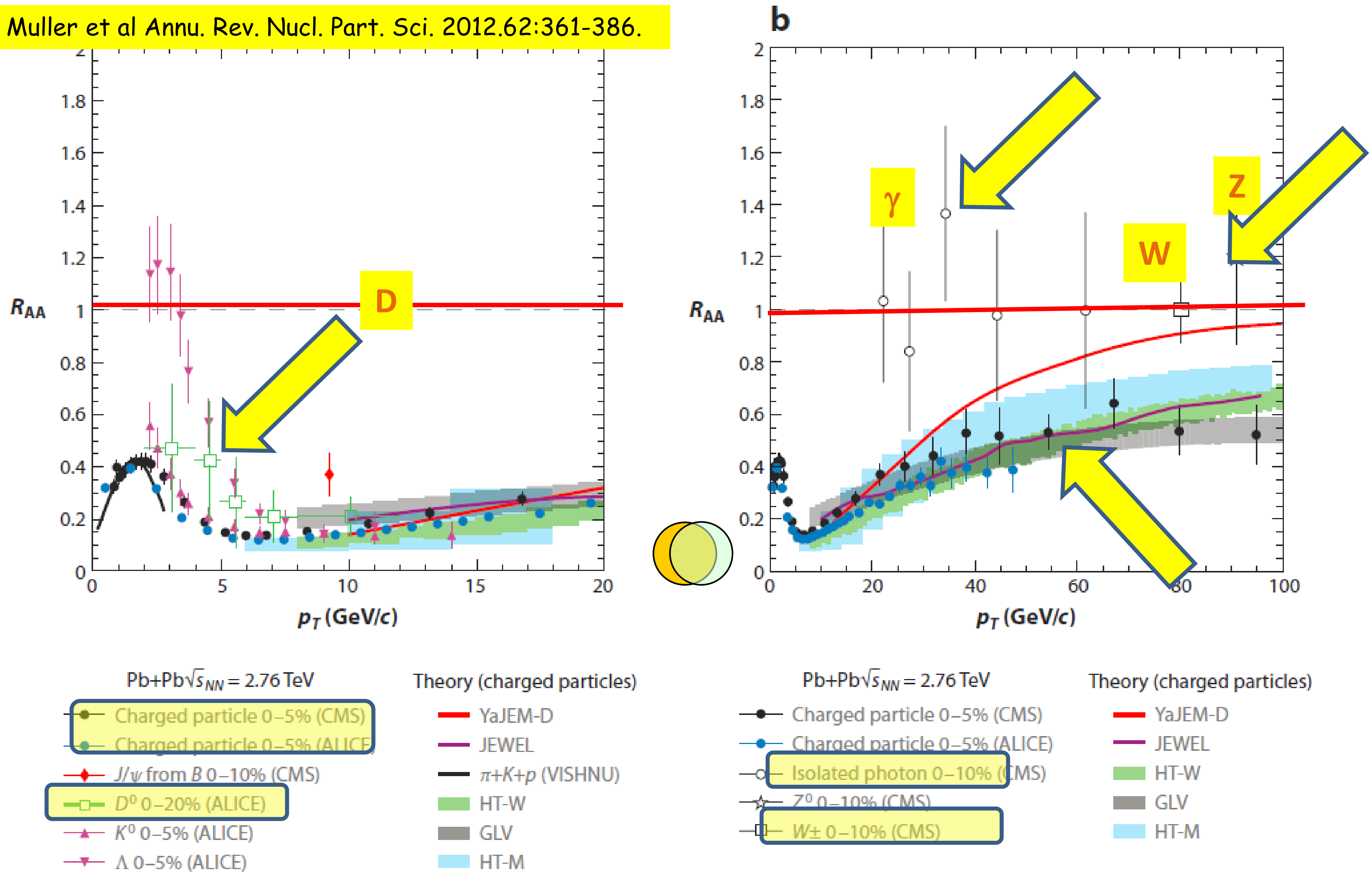
Expected if nothing happens

R_{AA} =1 simple scaling Expected at high p_t

At low p_t R_{AA} <1 dominated by soft interactions with the medium

Nuclear modification factor R_{AA}: a compilation

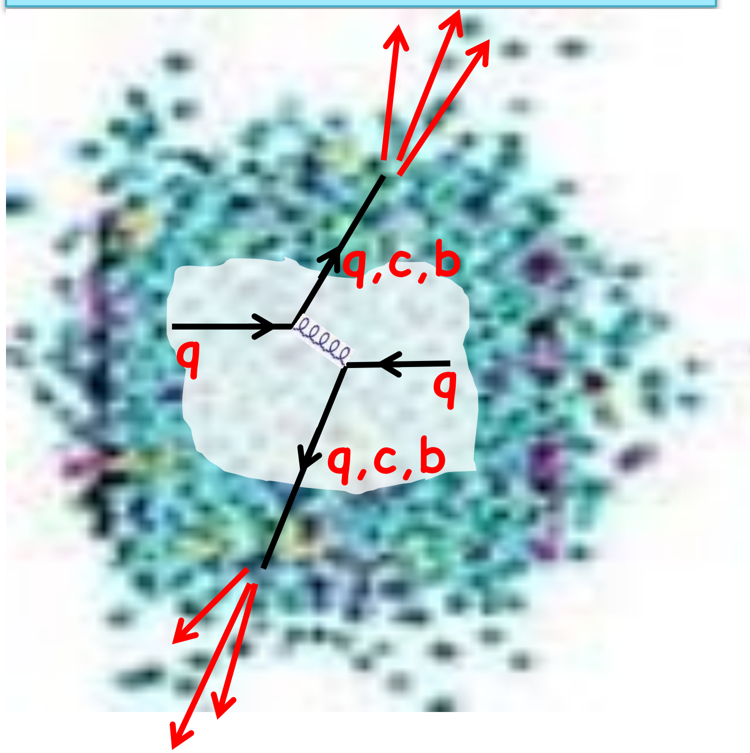
Muller et al Annu. Rev. Nucl. Part. Sci. 2012.62:361-386.



Hadron traversing a hot and dense medium loose substantial energy via gluon radiation and elastic scattering

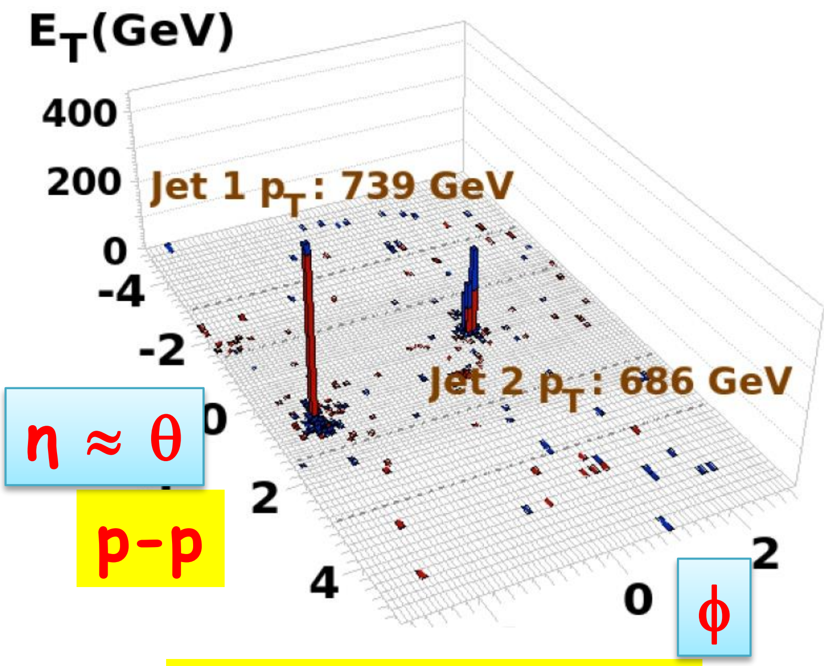
How to characterize the hot medium IV from inside via hard probes

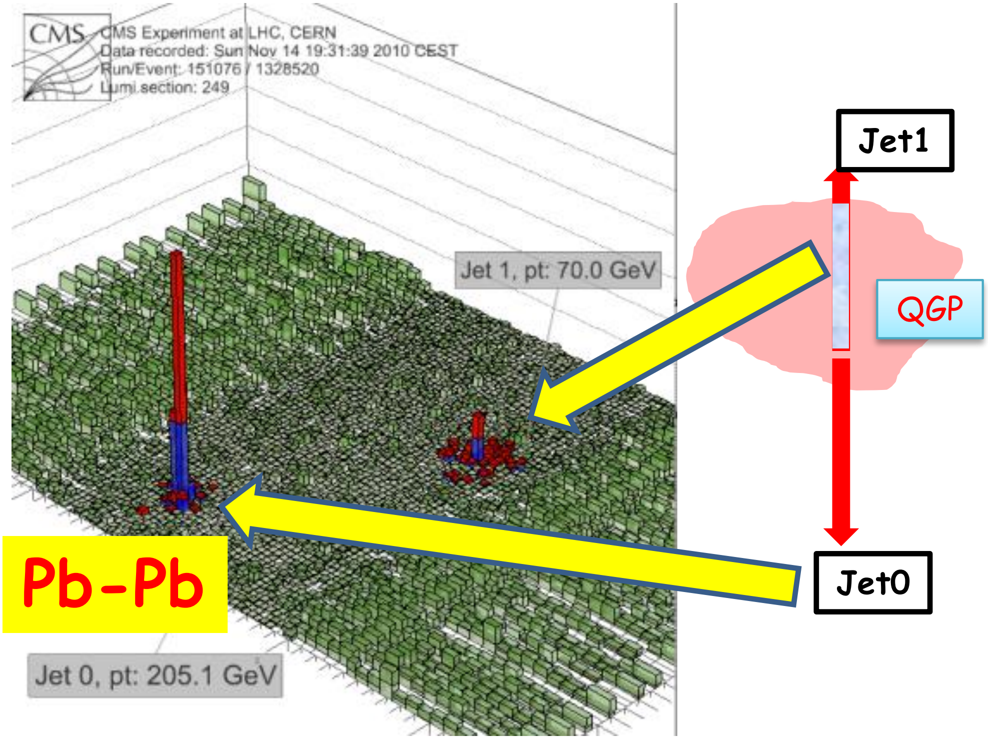
C: Hot medium tomography using hard probes produced in the collision



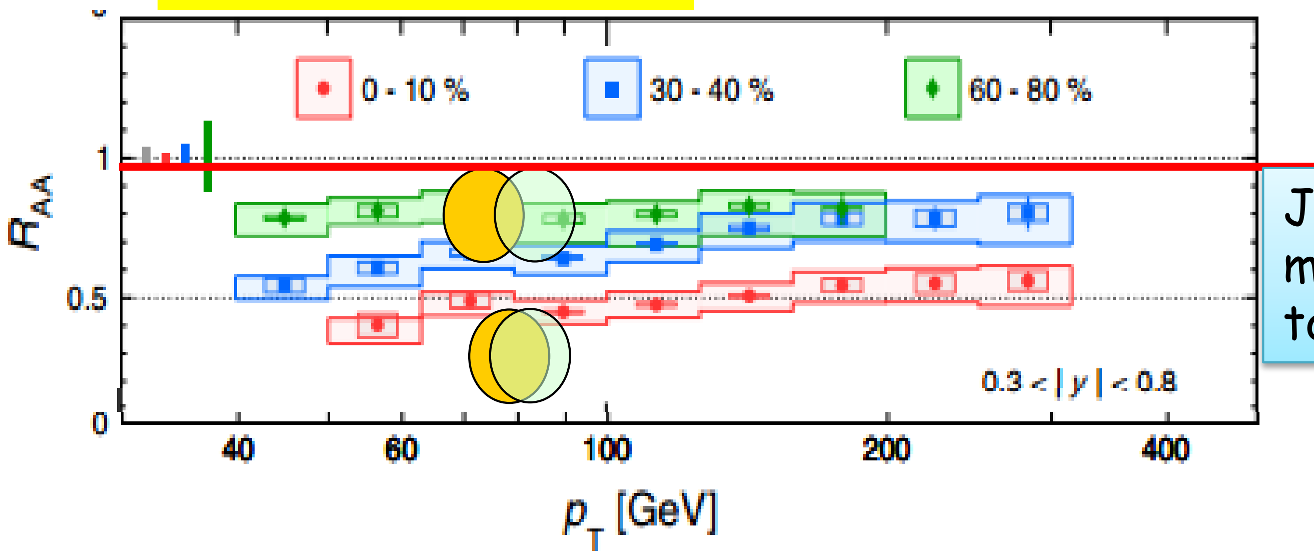
Heavy Flavours ,Jets , high p_t particles: we can calculate how many are produced

Jet quenching in PbPb





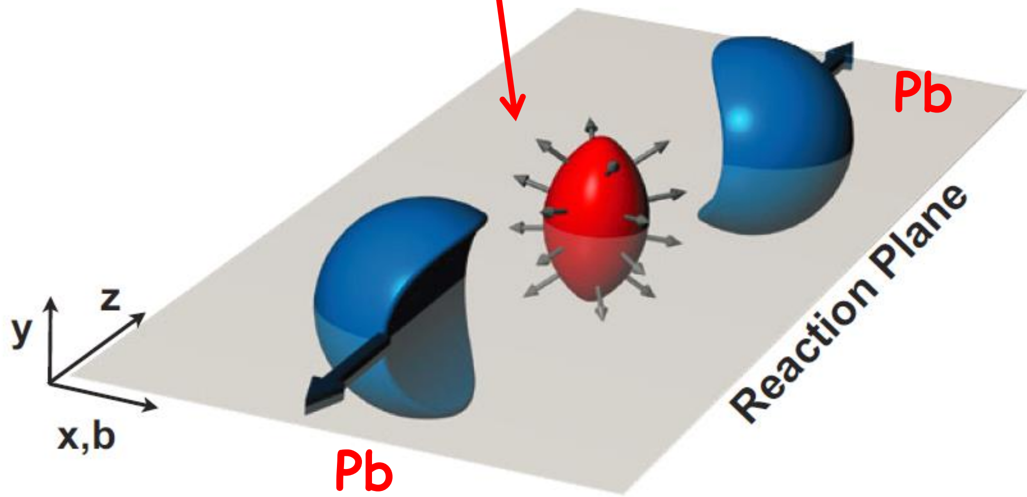
ATLAS PRL 114, 072302 (2015)

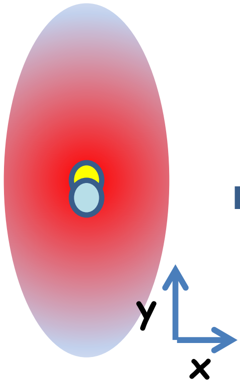


Jets traversing the hot medium are quenched up to several hundred GeV

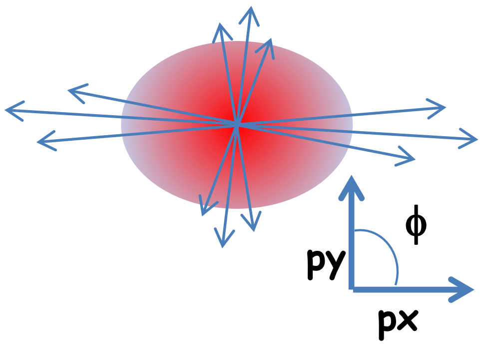
How to characterize the hot medium V: Elliptic flow v2

Hot medium with thermal equilibrium reached in very short time, mantaining the shape.

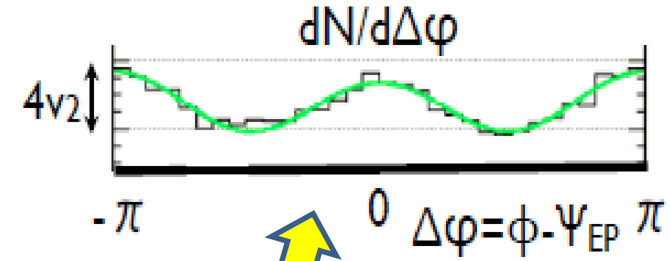


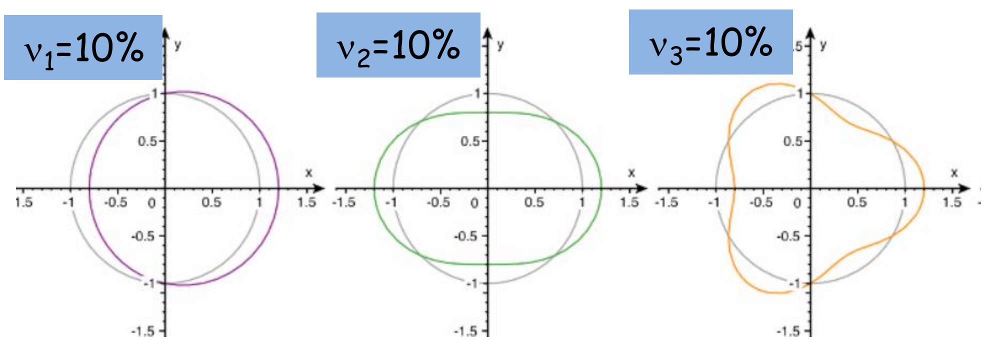


Momentum space



$$\frac{d^2N}{dp_t d\phi} = \frac{dN}{dp_t}\left[1 + 2\upsilon_2 \cos(2\phi) + 2\upsilon_4 \cos(4\phi) + ...\right]$$

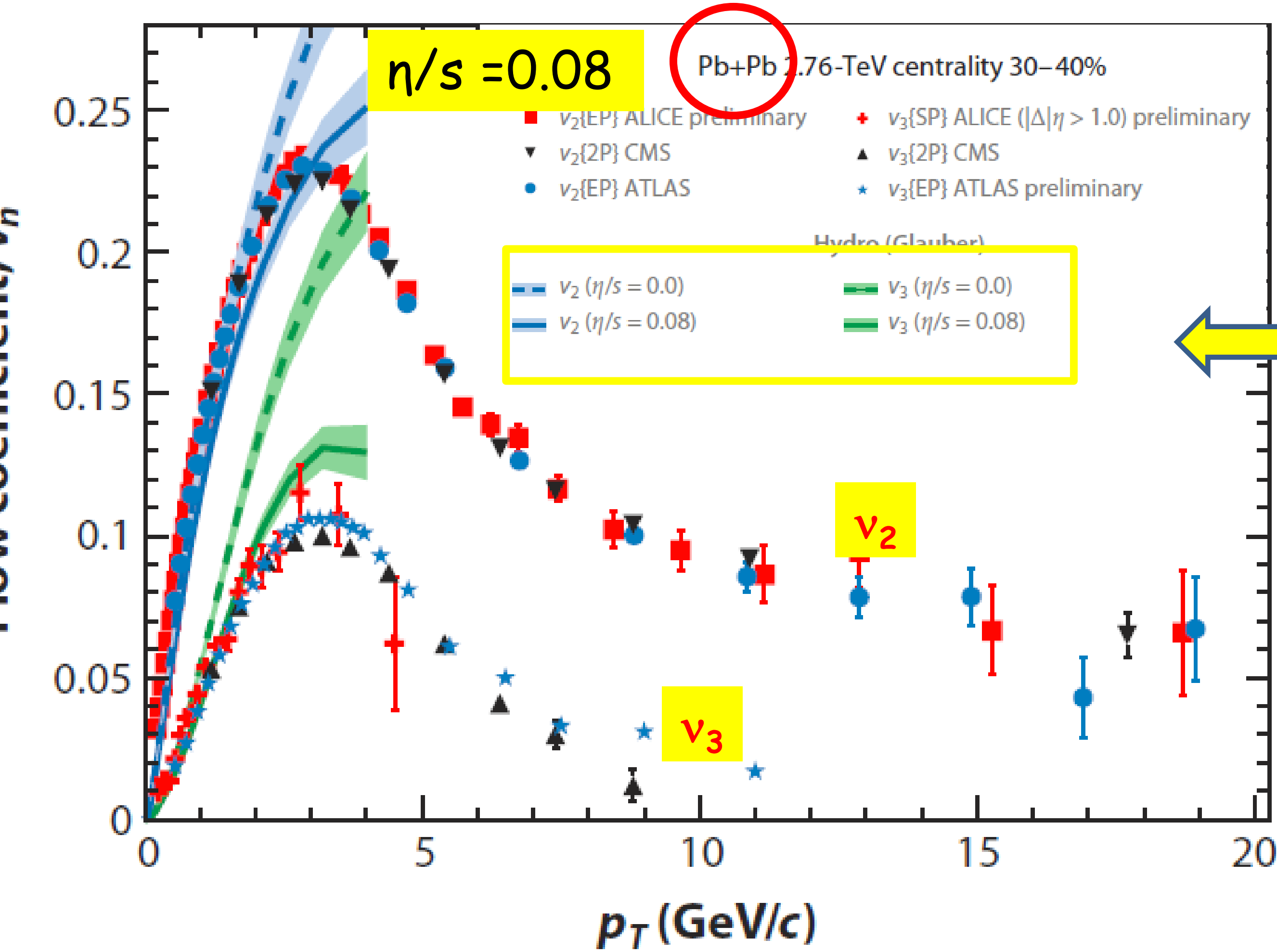




Magnitude depends on the viscosity/entropy (η/s) ratio of the medium and on the p_t of the particles considered

Muller et al Annu. Rev. Nucl. Part. Sci. 2012.62:361-386.

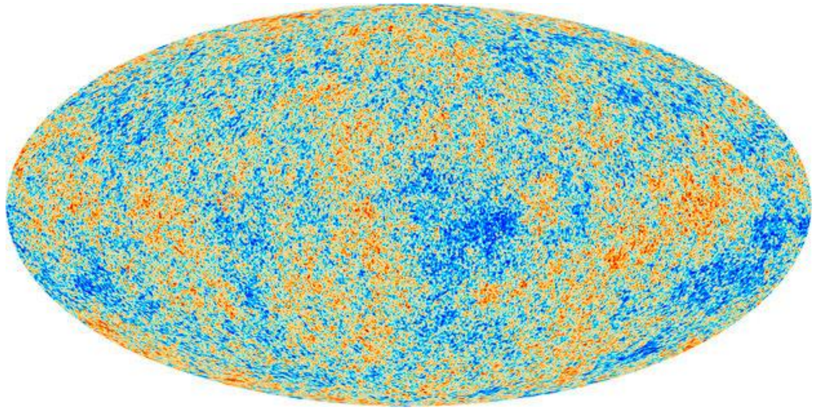
Elliptic flow v_2

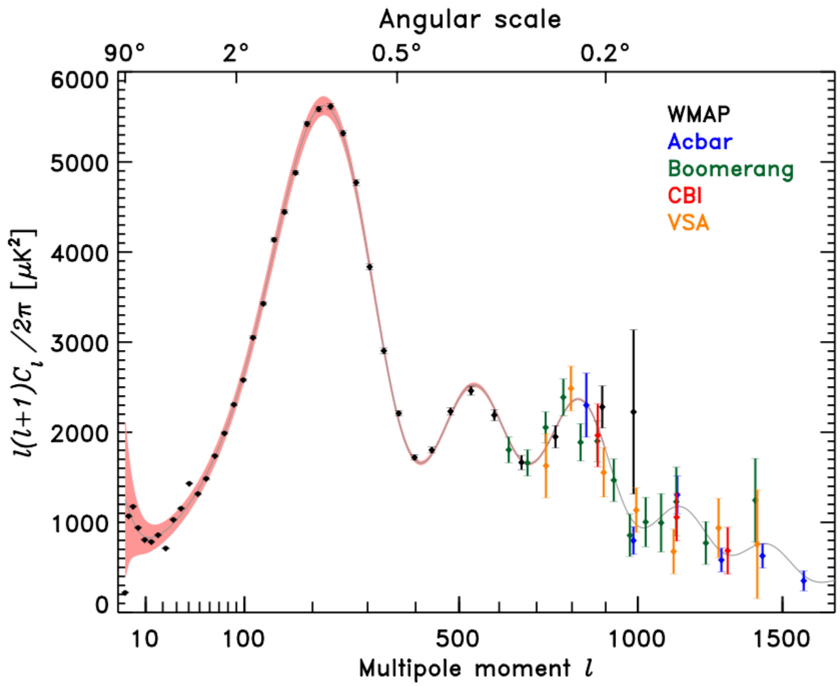


Hydrodynamical models points toward low viscosity/entropy (≈ perfect liquid) for the produced medium http://en.wikipedia.org/wiki/Pitch_drop_experiment

Date	Event	Duration (months)	Duration (years)
1927	Hot pitch poured	-	-
October 1930	Stem cut	0	0.0
December 1938	1st drop fell	98	8.1
February 1947	2nd drop fell	99	8.2
April 1954	3rd drop fell	86	7.2
May 1962	4th drop fell	97	8.1
August 1970	5th drop fell	99	8.3
April 1979	6th drop fell	104	8.7
July 1988	7th drop fell	111	9.2
November 2000	8th drop fell	148	12.3
17 April 2014	9th drop touched 8th drop	(156)	(13.4)
24 April 2014	9th drop separated from funnel during beaker change	156	13.4

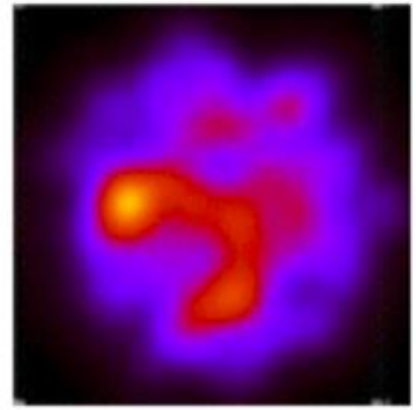
PLANCK Cosmic Microwave Background

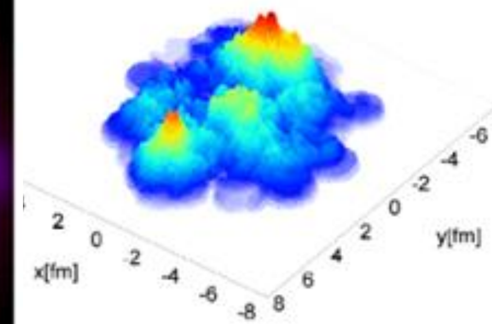


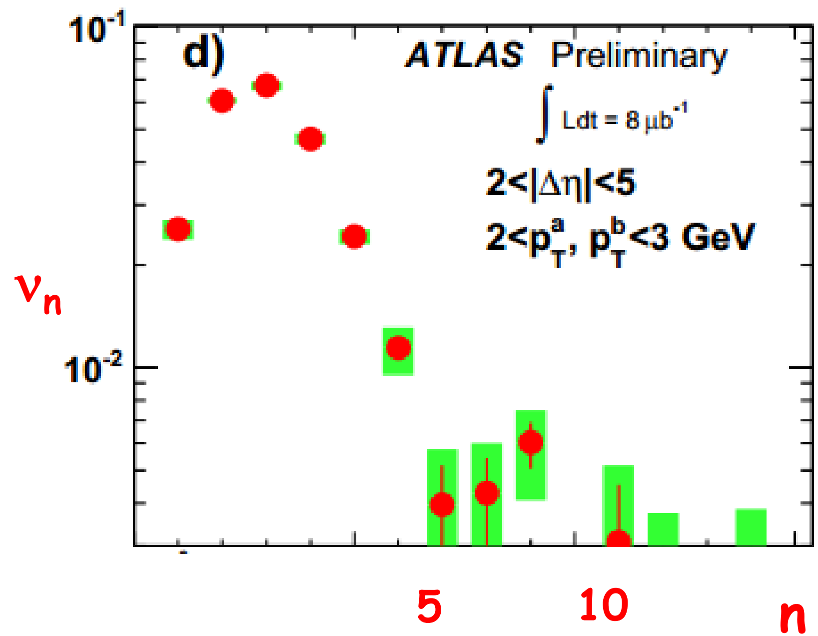


Understanding universe structure

HI collisions QGP







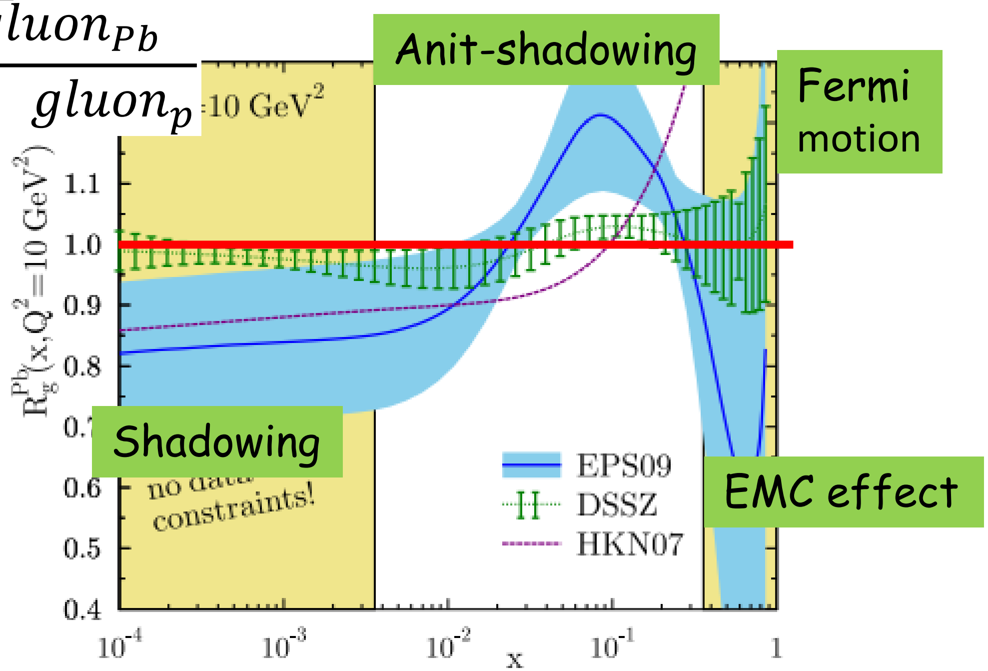
Understanding initial QGP conditions and transport theory

But are we observing effects related to the creation of a hot, dense new QGP state or these are reflections of the presence of a Heavy Ion projectile ?

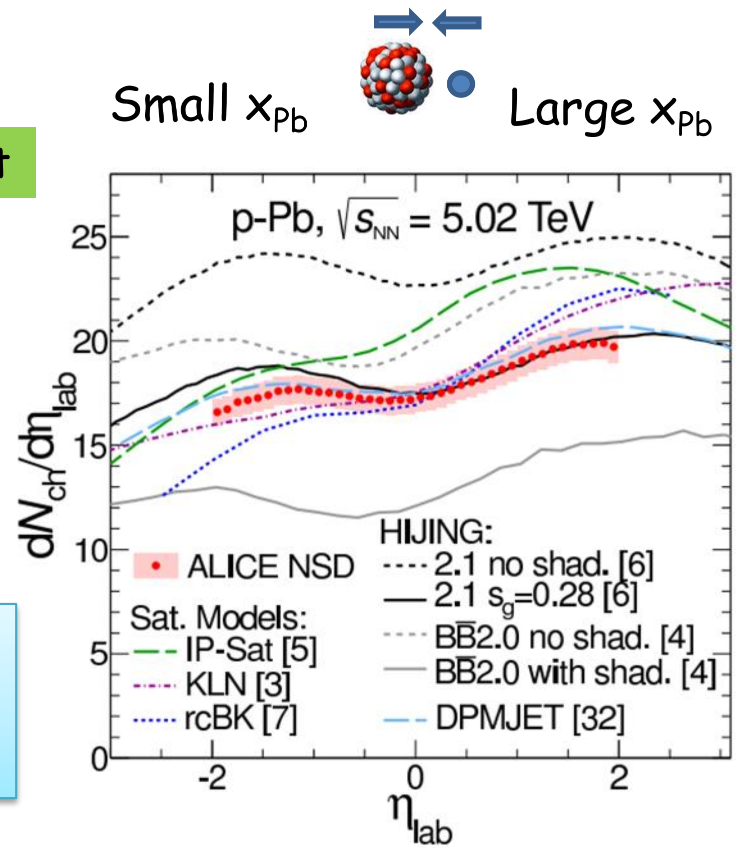
It is mandatory to check the magnitude of <u>Cold Nuclear Matter Effects (CNM</u>) using p-Pb collisions.

Uncertainties in the Parton Distribution Functions (PDF) for Nuclei: nPDF

$$\frac{1}{A}\frac{gluon_{Pb}}{gluon_p}$$



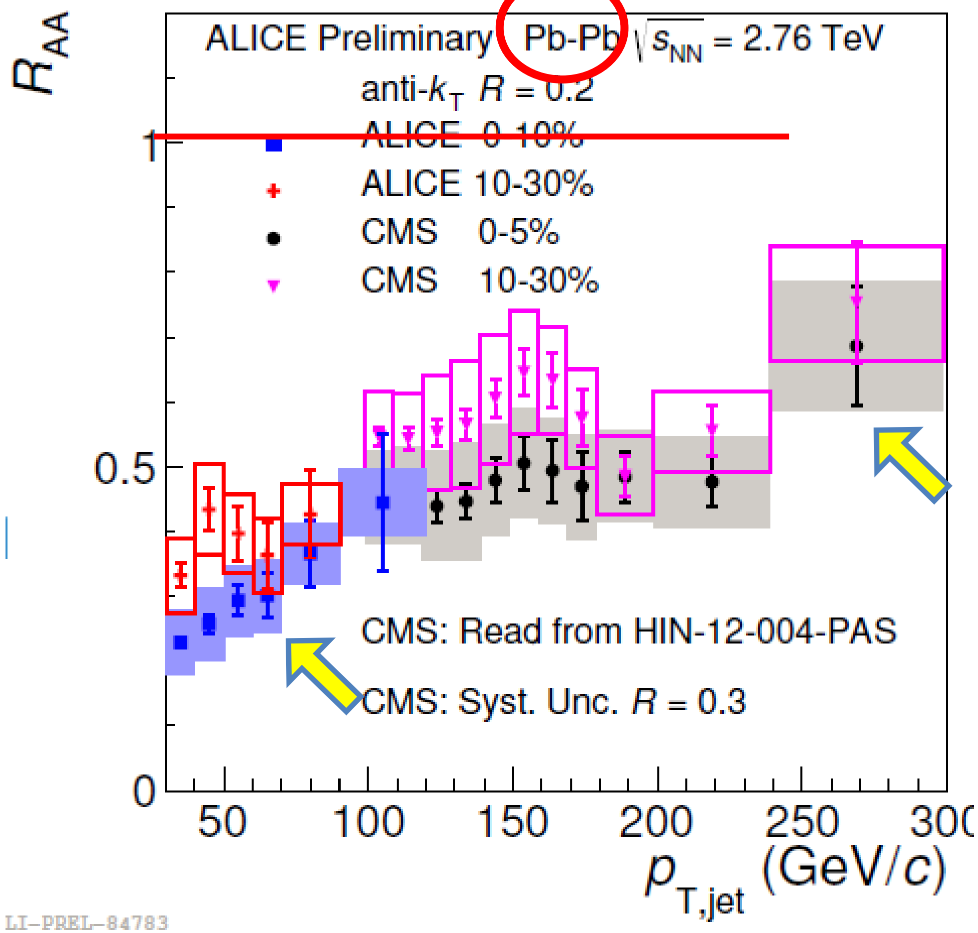
H. Paukkunen arXiv:1401.2345v2

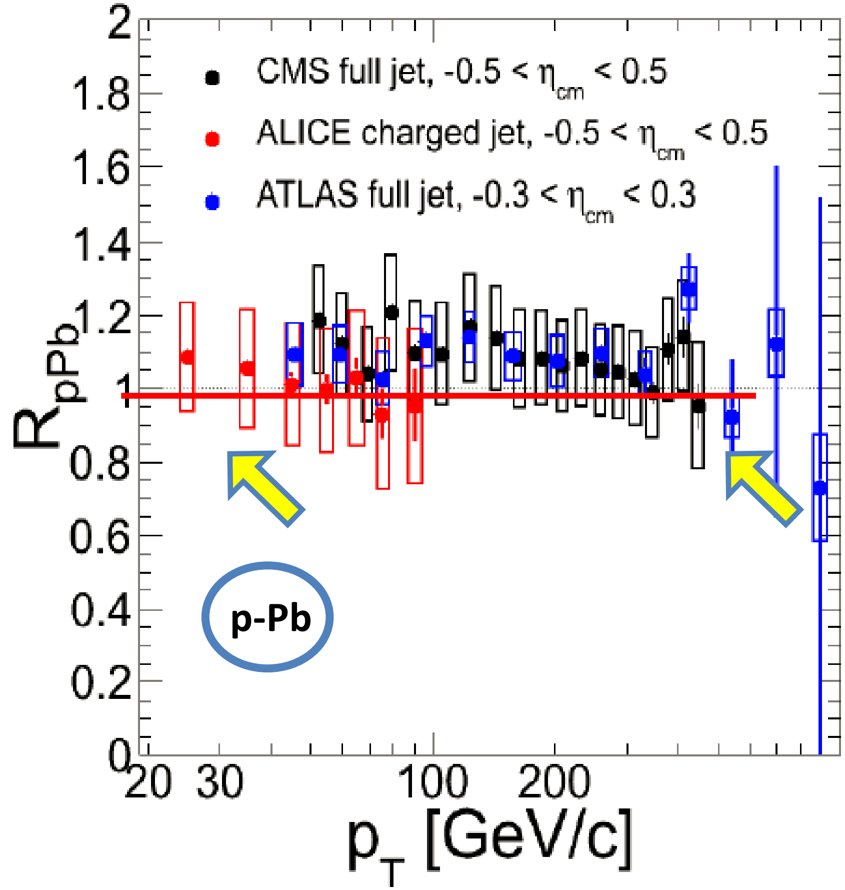


Even first results from p-Pb gives important informations on nPDF and shadowing models

$R_{AA/pA}$ with jets

Y.Lee QM2014





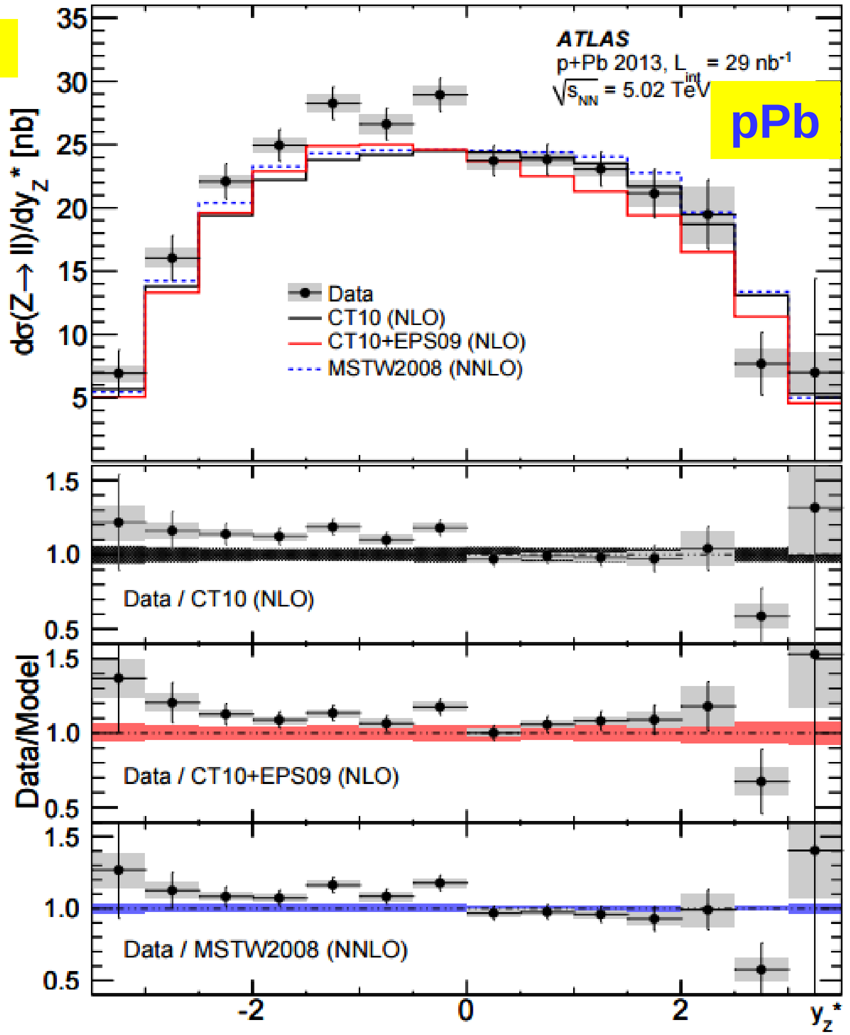
In Pb-Pb R_{AA} jet suppression extends down to 30 GeV and up to 300 GeV

In p-Pb no CNM effects from 25 up to 800 GeV

R_{pA} with Z Boson

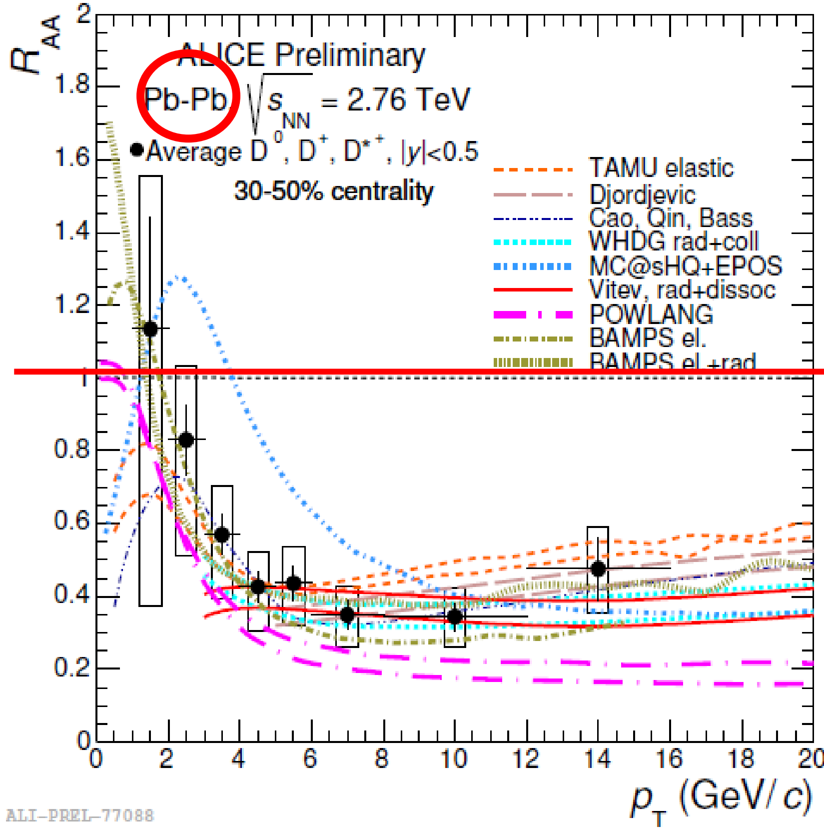
ATLAS: arXiv:1507.06232

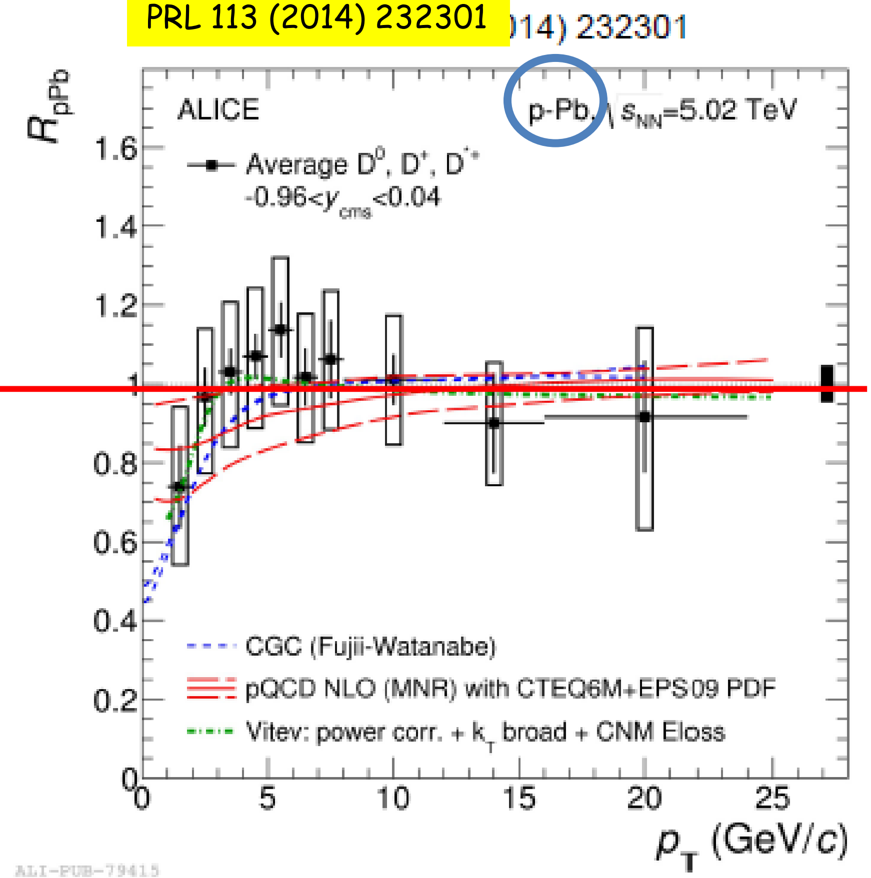
W production
CMS: arXiv:1503.05825



Z production proportional to n_{coll} : no suppression
Rapidity asimmetry -> sensitivity to nPDF

Heavy Flavour/D meson R_{AA} and R_{pPB}

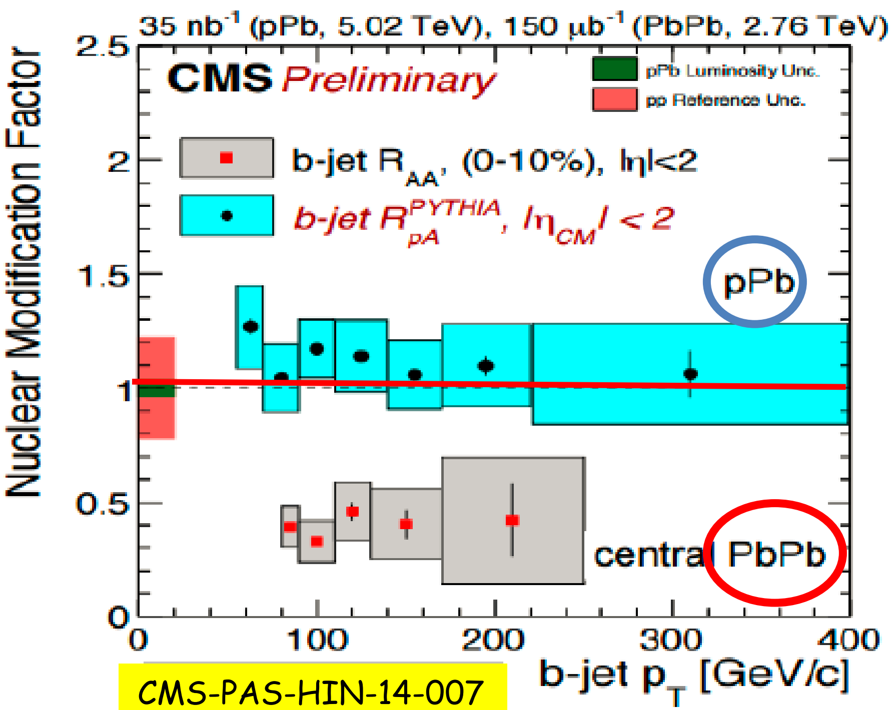




Cold Nuclear Matter effects cannot explain D meson suppression in Pb-Pb

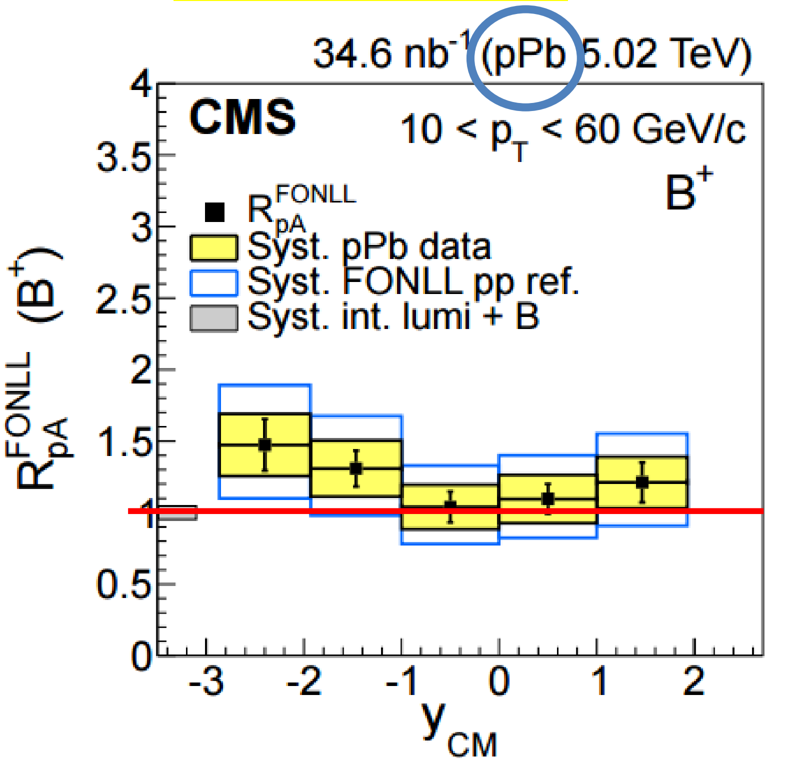
Heavy Flavour/Beauty R_{AA} and R_{pPB}

PRL 113 (2014) 132301



CMS-PAS-HIN-14-007

CMS-arXiv:1508.06678



Cold Nuclear Matter effects cannot explain Beauty hadron suppression in Pb-Pb

Conclusion I

At high p_t CNM effects in p-Pb collisions are not present in jets, hadrons, HF.

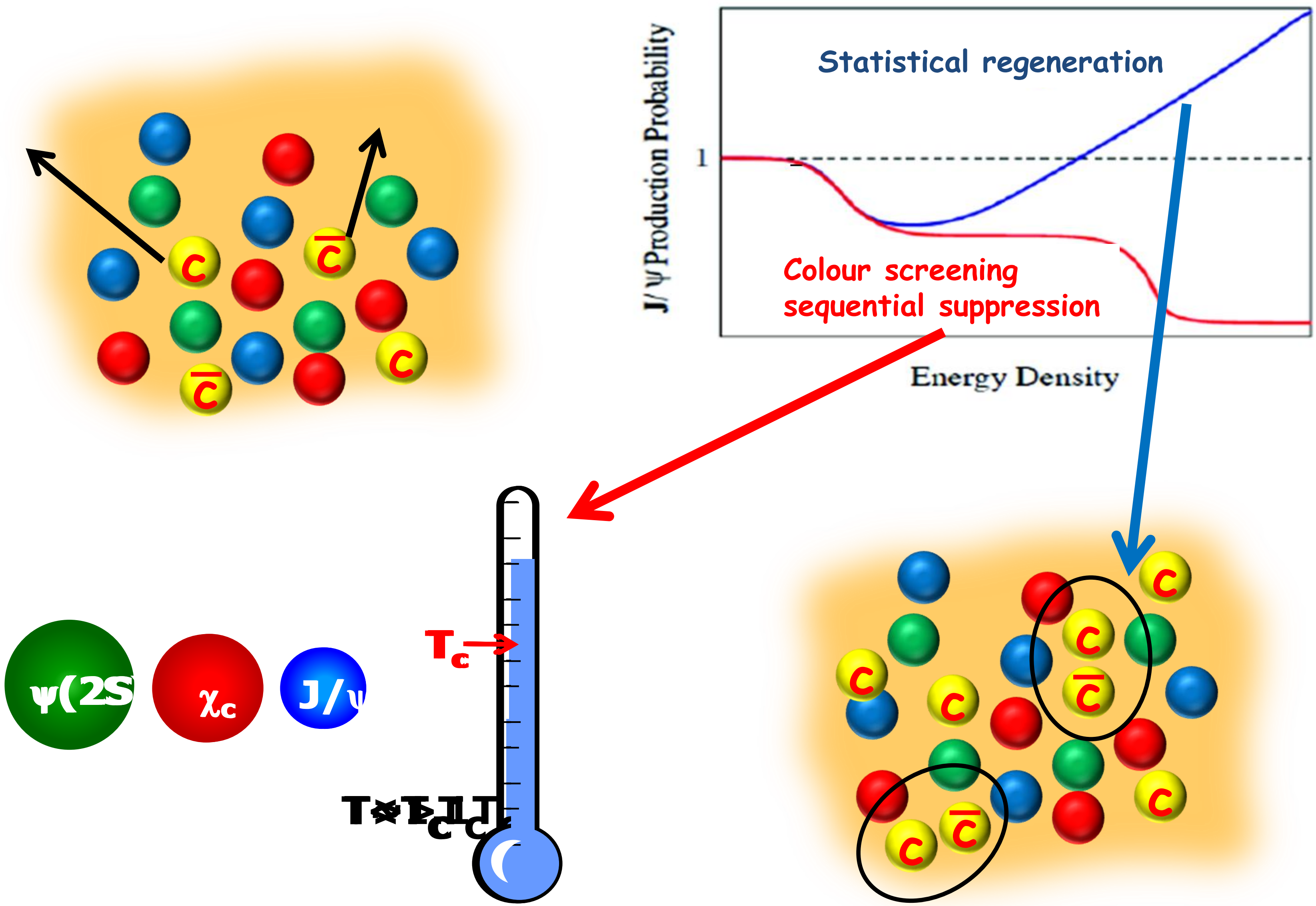
W/Z production are in agreement with pQCD scaled by the number of collisions.

↓

What measured in Pb-Pb collisions at high p_t reveals the presence of a hot, dense QGP medium with low viscosity.

p-Pb data allow important informations on the nPDF

Production of quarkonia ($c\bar{c}$) ($b\bar{b}$) in Pb-Pb

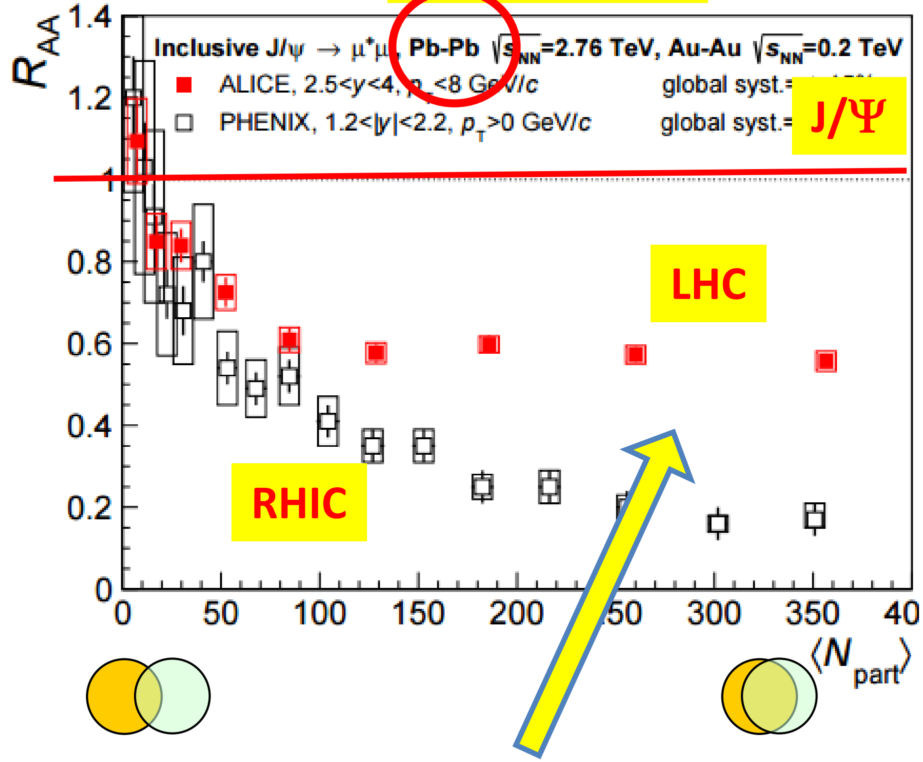


Low pt enhanced
Expected mainly for charm

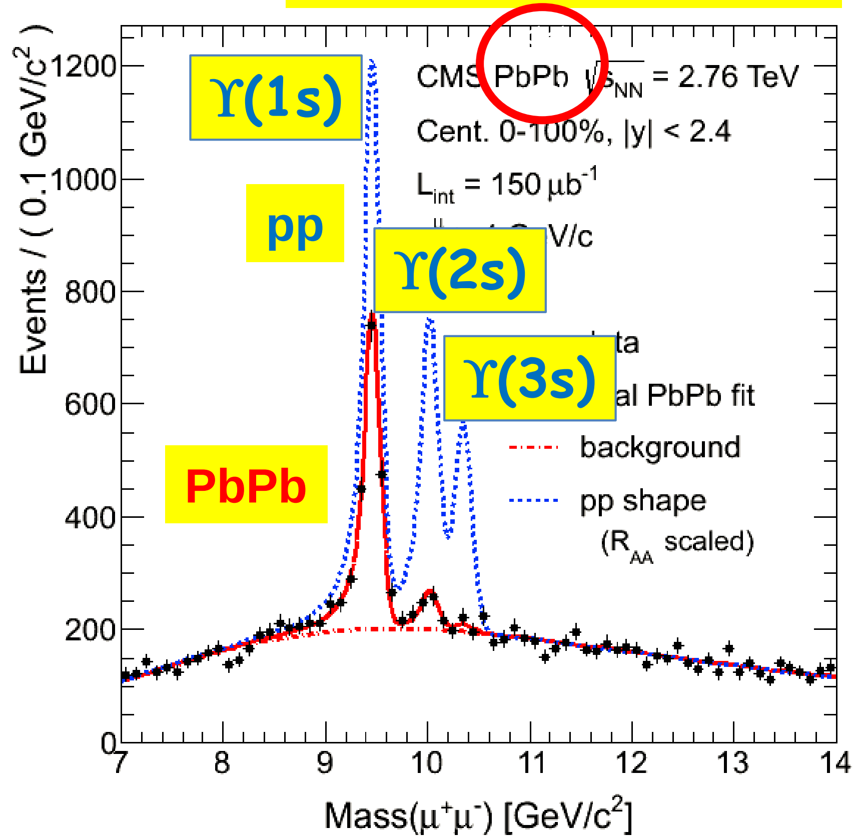
Matsui T, Satz H (1986)
PHYSICS LETTERS B 178(4): 416-422.

Production of quarkonia in Pb-Pb

arXiv:1506.08804



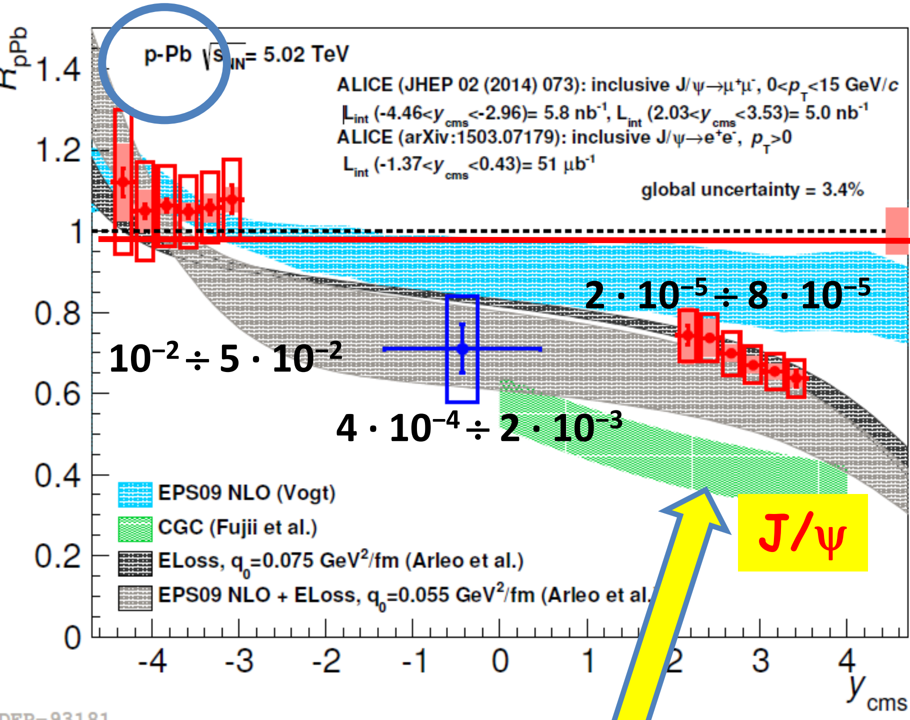
Phys. Rev. Lett. 107(2011) 052302

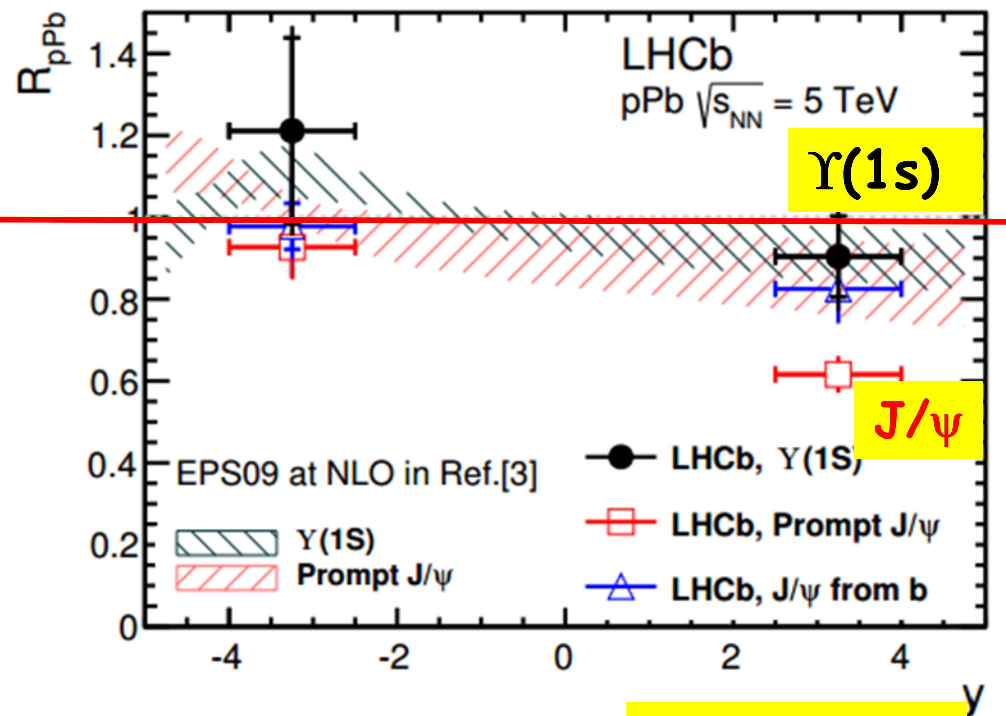


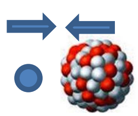
At LHC higher production than RHIC: statistical regeneration at work ?

Sequential suppression observed in Pb-Pb

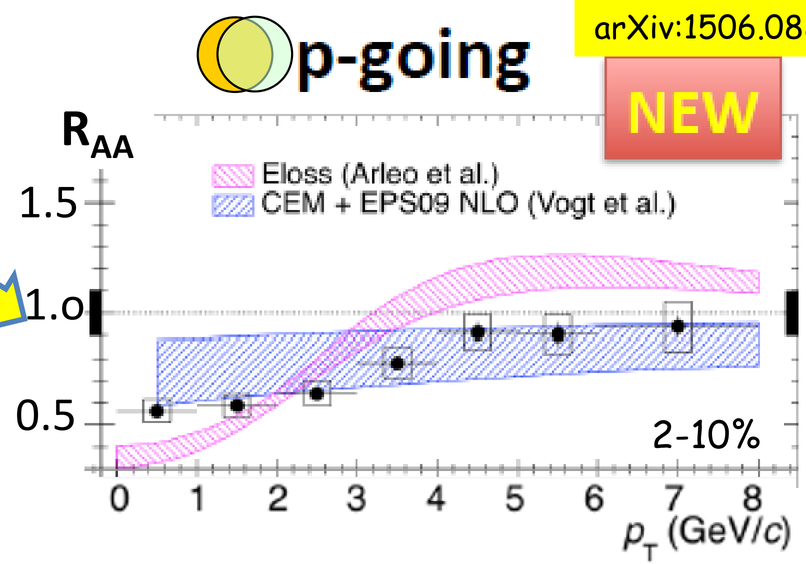
Production of quarkonia in p-Pb







arXiv:1506.08808v1



- CNM suppression for J/ψ only at low pt
- Lower effect for Υ(1s)
- Effect in the nPDFs shadowing region
- Other possibilities : comover

Conclusion II

At high p_t CNM effects in p-Pb collisions are not present in quarkonia

However at lower p_t effect not negligible.

↓

Contribution of regeneration in Pb-Pb very important expecially for J/ψ

Quarkonia suppression in medium is observed

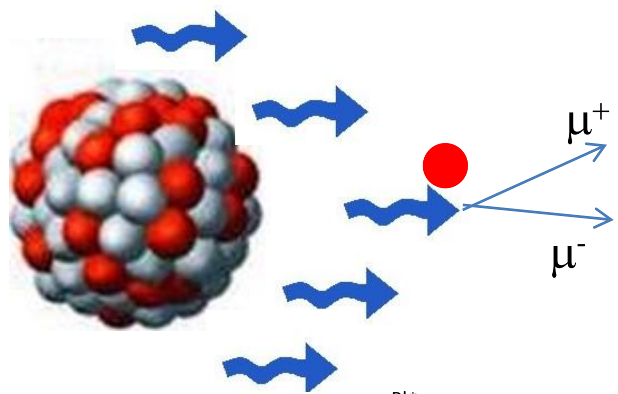
Shadowing in nPDFs is a possible explanation for suppression at low p_t in p-Pb

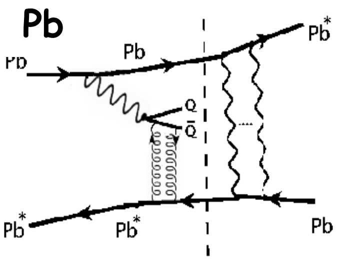
LHC as the highest energy γp , γPb, γγ collider !

J/ψ production in untraperipheral collisions

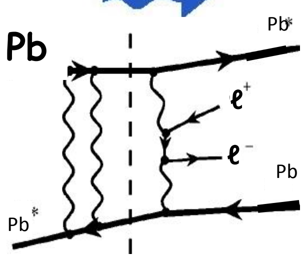
Vantaggi 3×1 !

With nuclei very high flux of γ ($\propto Z^2$)

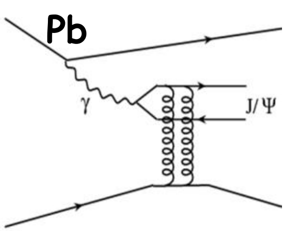




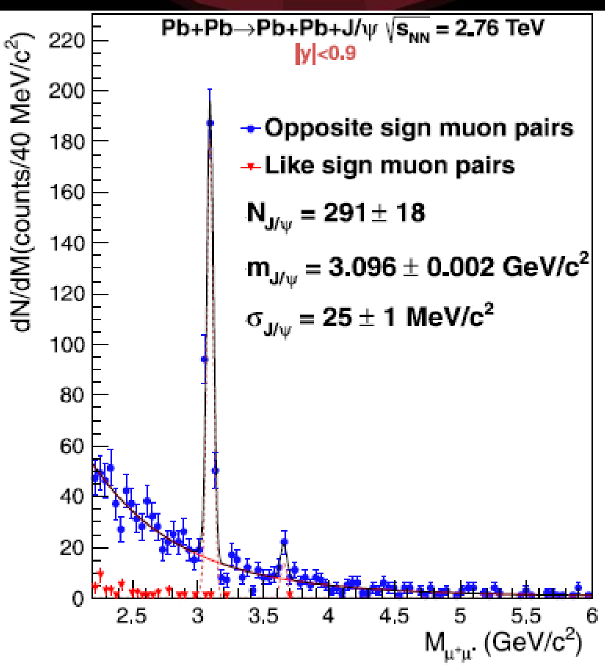
$\gamma A \rightarrow J/\psi$



$\gamma\,\gamma \rightarrow J/\psi$

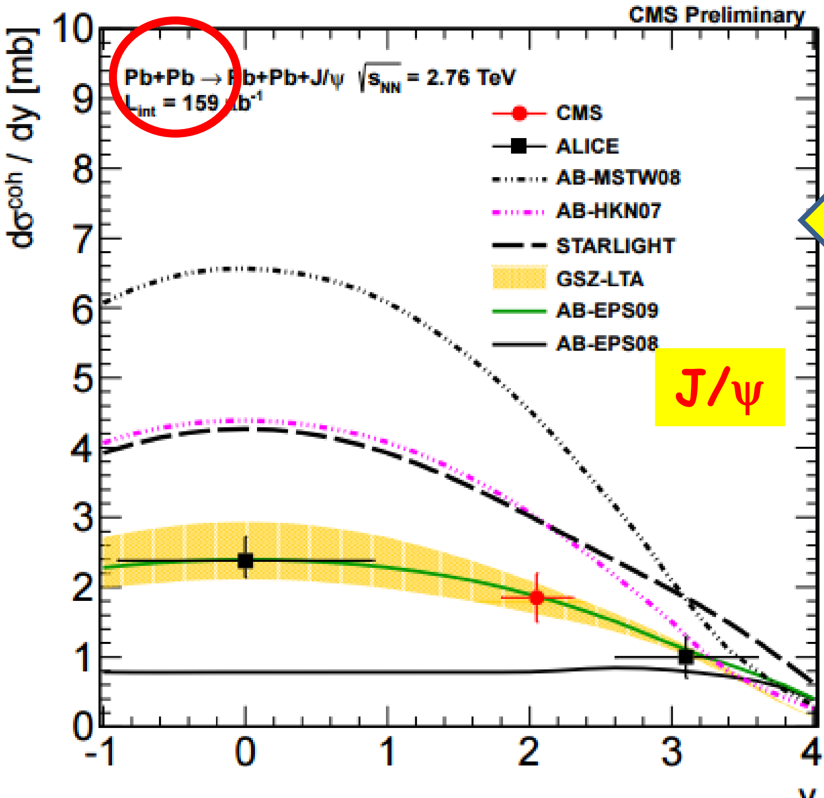


$\gamma\, p \rightarrow J/\psi$



Cross section sensitive to $g_{Pb}{}^2$ at low-x

J/ψ production in UPC



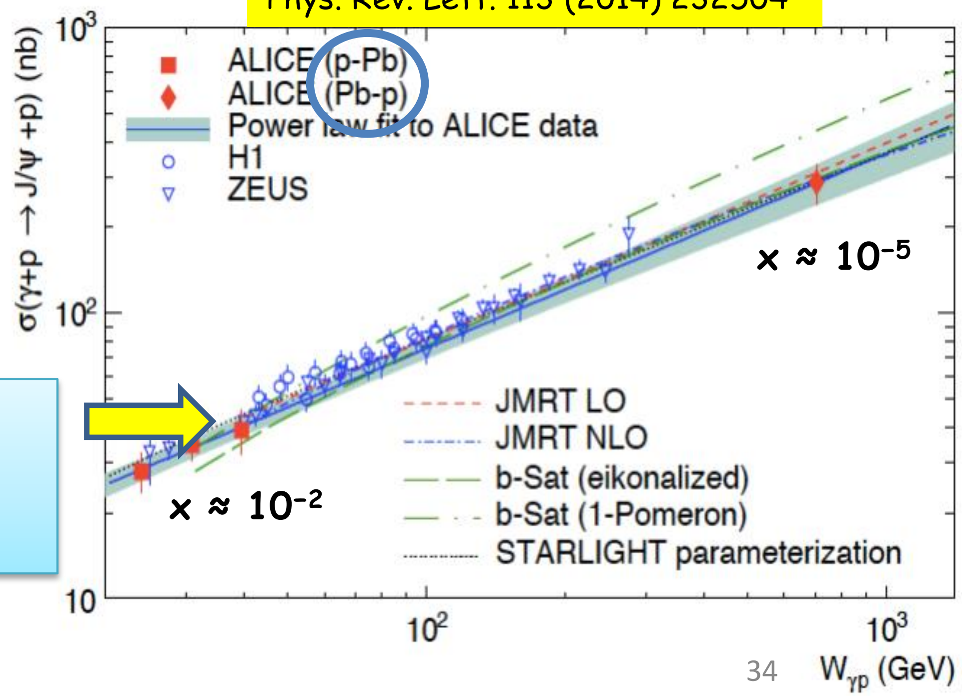
ALICE: EPJ C73, 2617 (2013), PLB 718 (2013) 1273-1283
CMS: HIN-12-009

Preference of LO-pQCD models with moderate gluons shadowing and nuclear modifications for gluon nPDFs

Strikman: " ..provide the first direct experimental evidence for the strong nuclear gluon shadowing in lead" !

Data in line with and extend HERA measurements : no change in PDF with energy

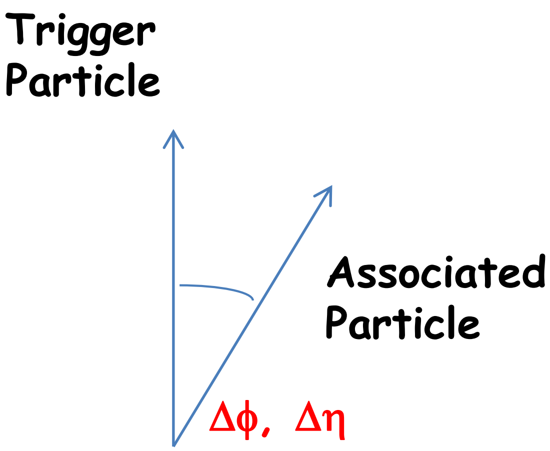
Phys. Rev. Lett. 113 (2014) 232504

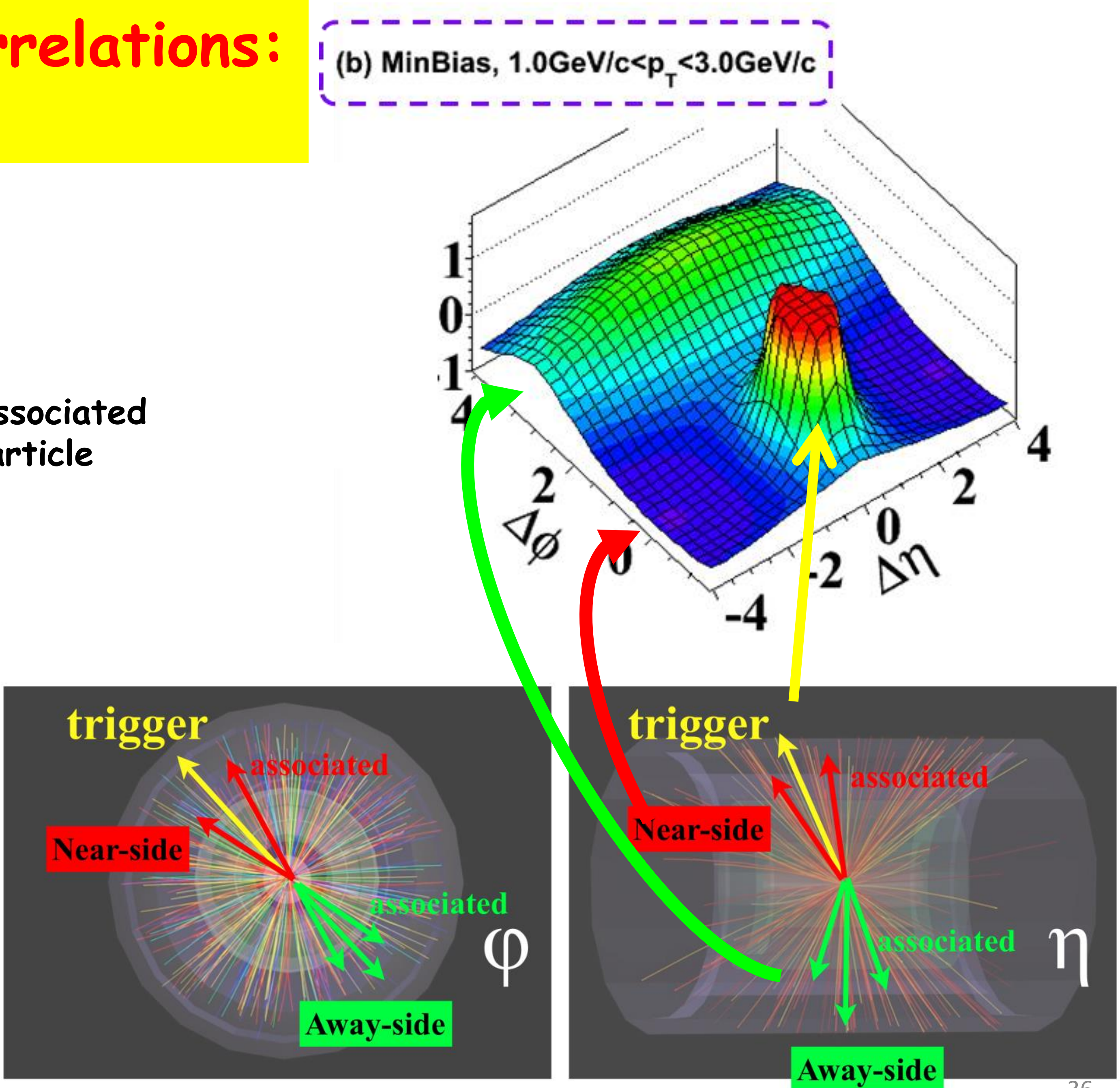


Conclusion III

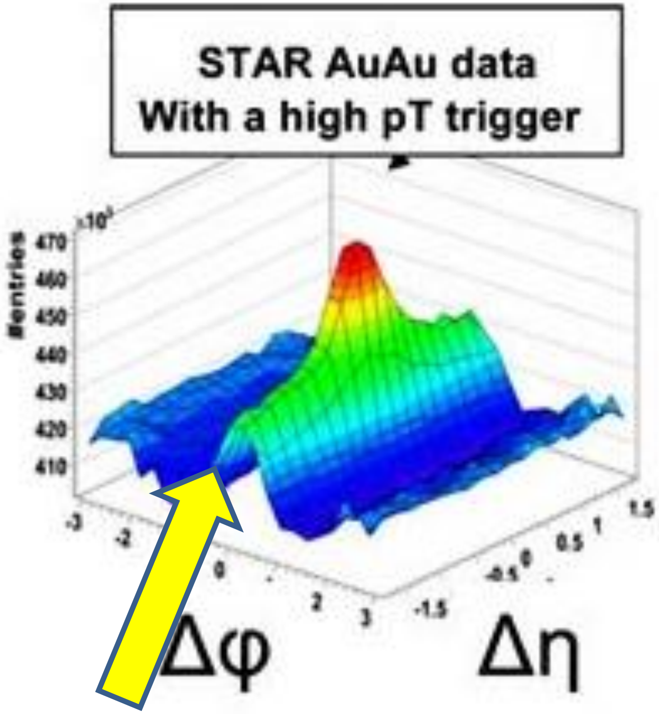
LHC as γp , γPb, $\gamma\gamma$ collider reach of important data for comparisons with different nPDF and gluon pPDF.

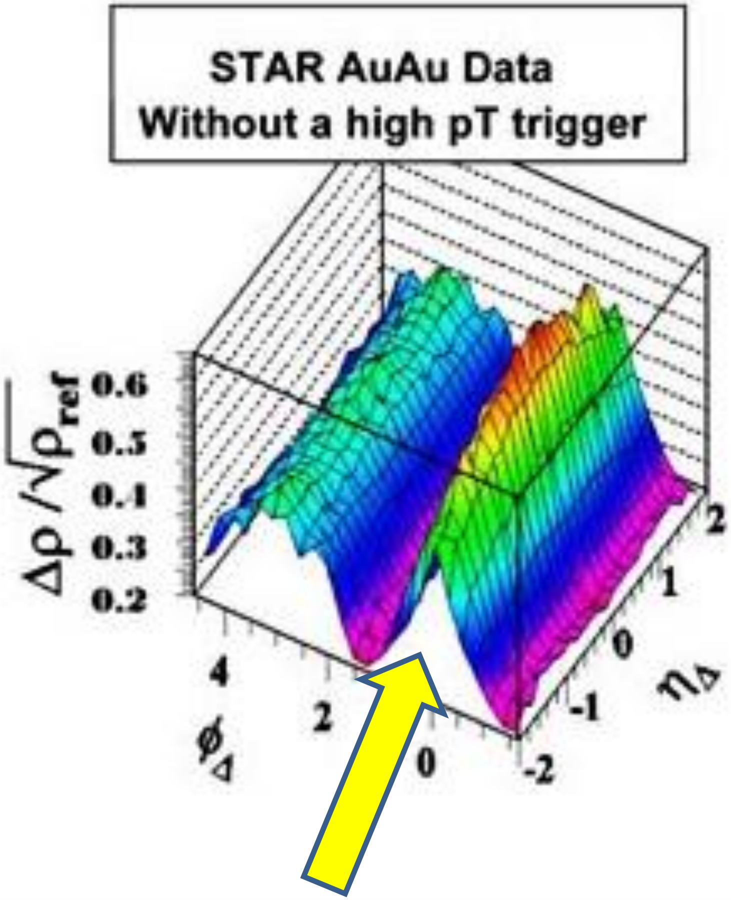
Flow and correlations: The ridge





The "ridge " as measured at RHIC

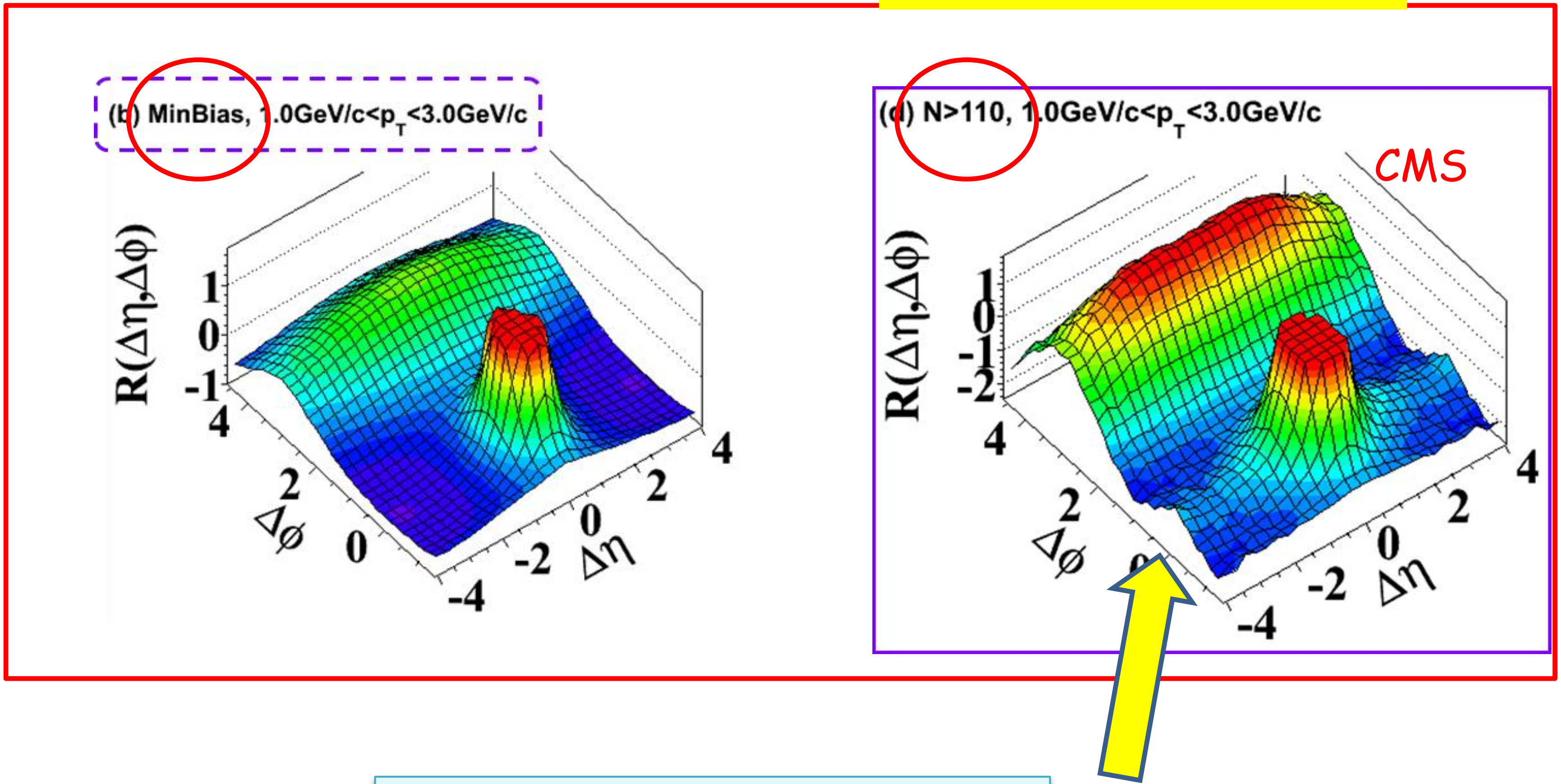




Interpreted as a collective behavior in the dense hot medium

Unexpected observation of a "ridge " in pp

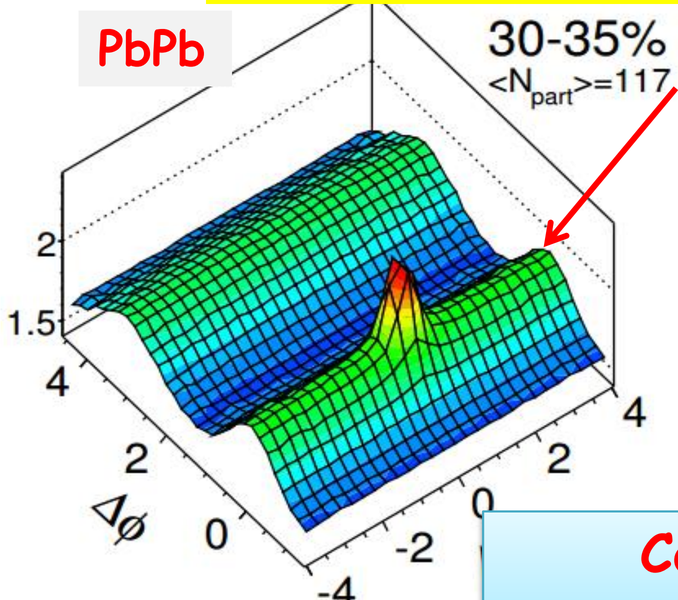
CMS JHEP1009:091 (2010)



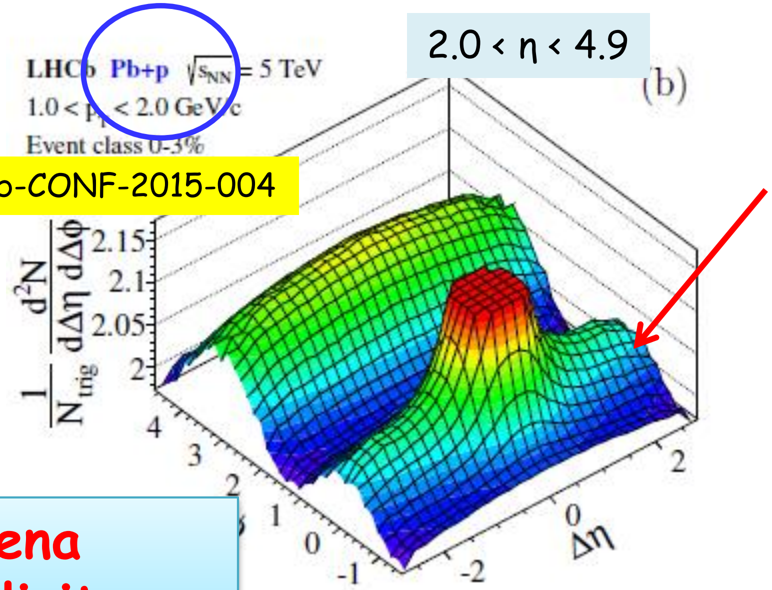
Collective phenomena connected to multiplicity ?

The near side ridge in Pb-Pb and p-Pb

PbPb

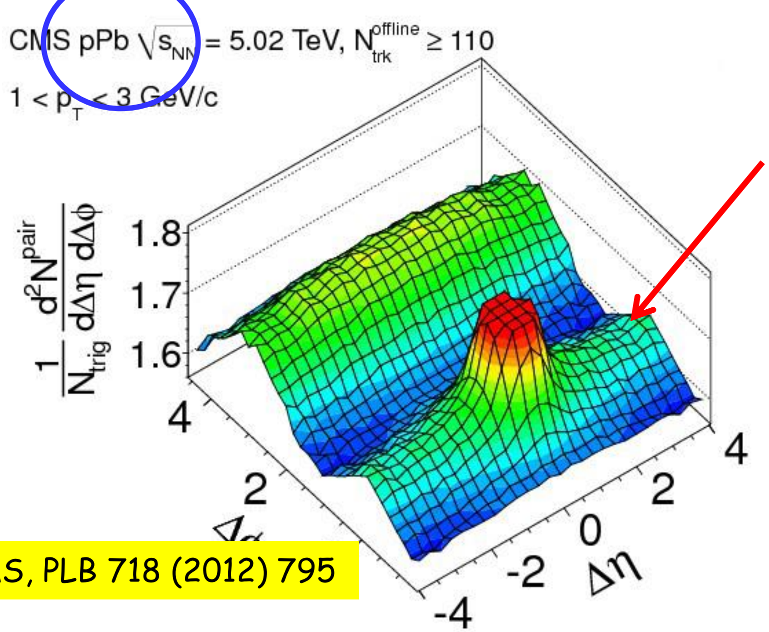


CMS, JHEP 1009 (2010) 91

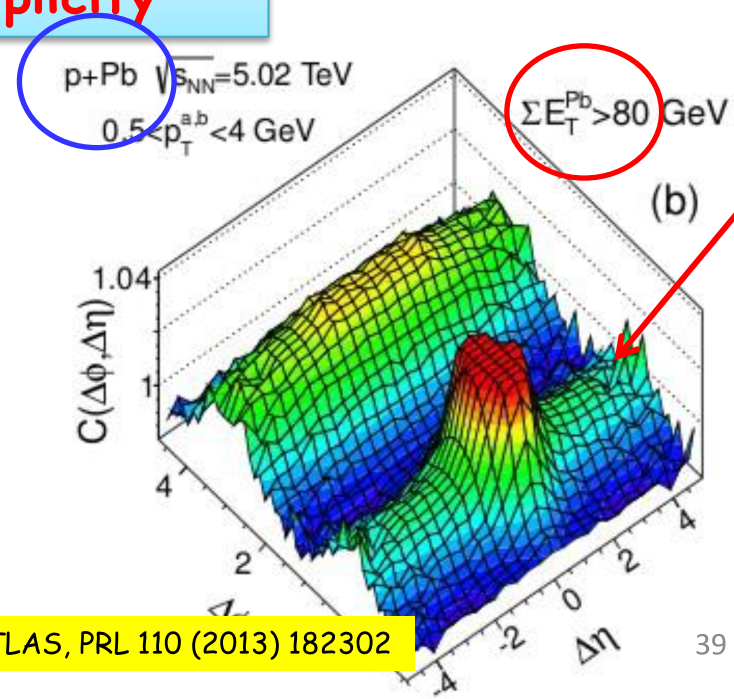


LHCb-CONF-2015-004

Collective phenomena connected to multiplicity



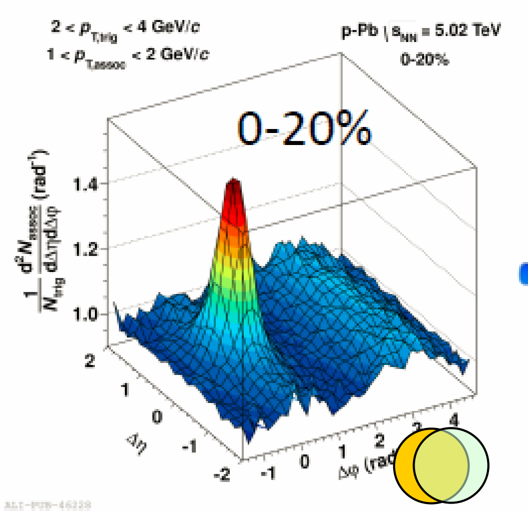
CMS, PLB 718 (2012) 795

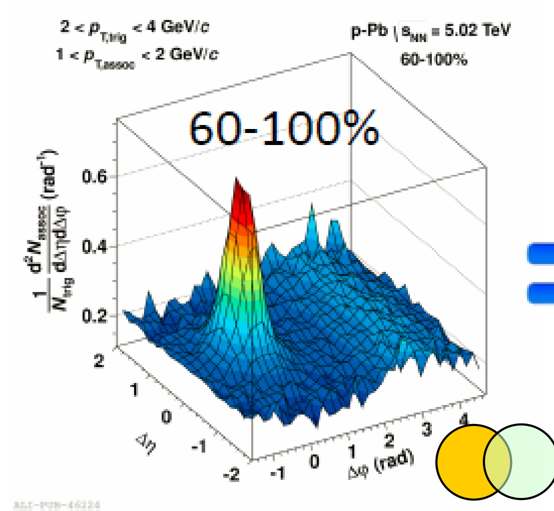


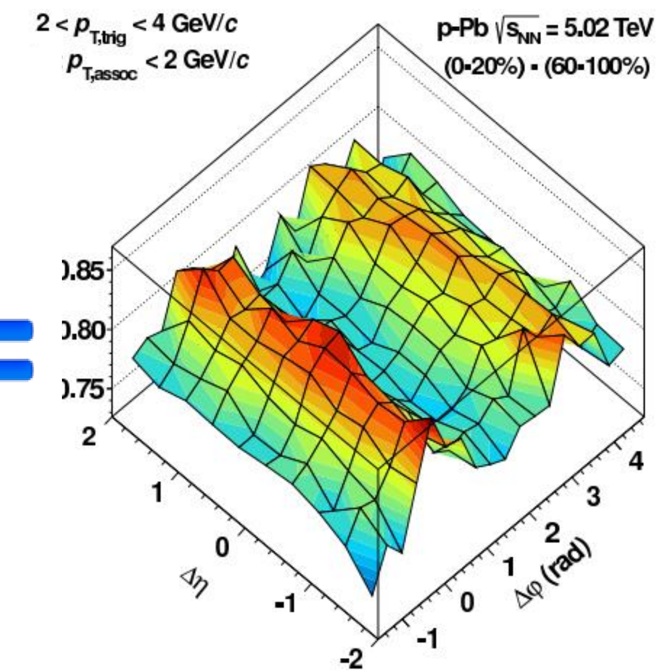
ATLAS, PRL 110 (2013) 182302

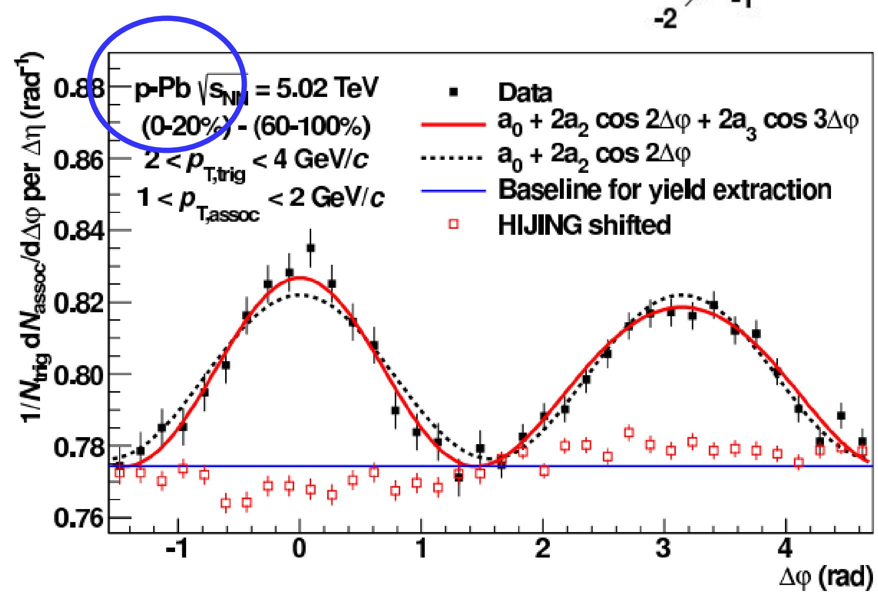
The unexpected "double ridge " in p-Pb

ALICE PLB 719:29 (2013)







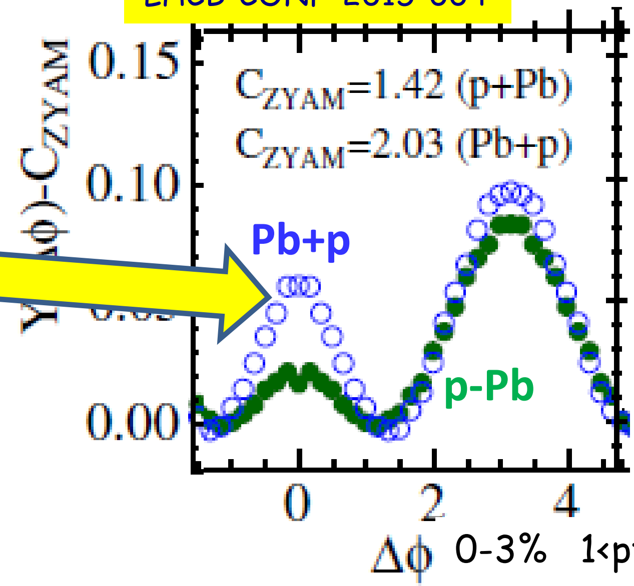


Collective phenomena related to multiplicity

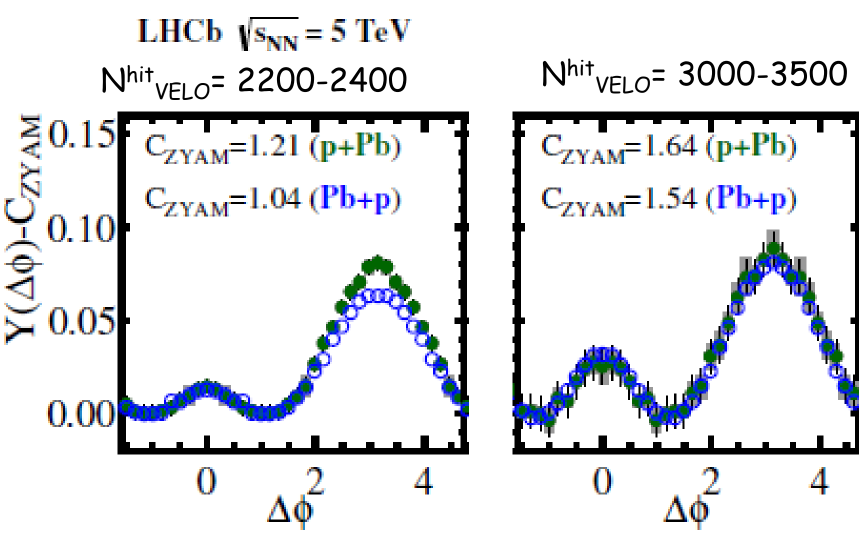
Where is the ridge in p-Pb ?

LHCB-CONF-2015-004

Ridge more pronounced in the Pb outgoing region



0-3% 1<pt<2 Gev/c

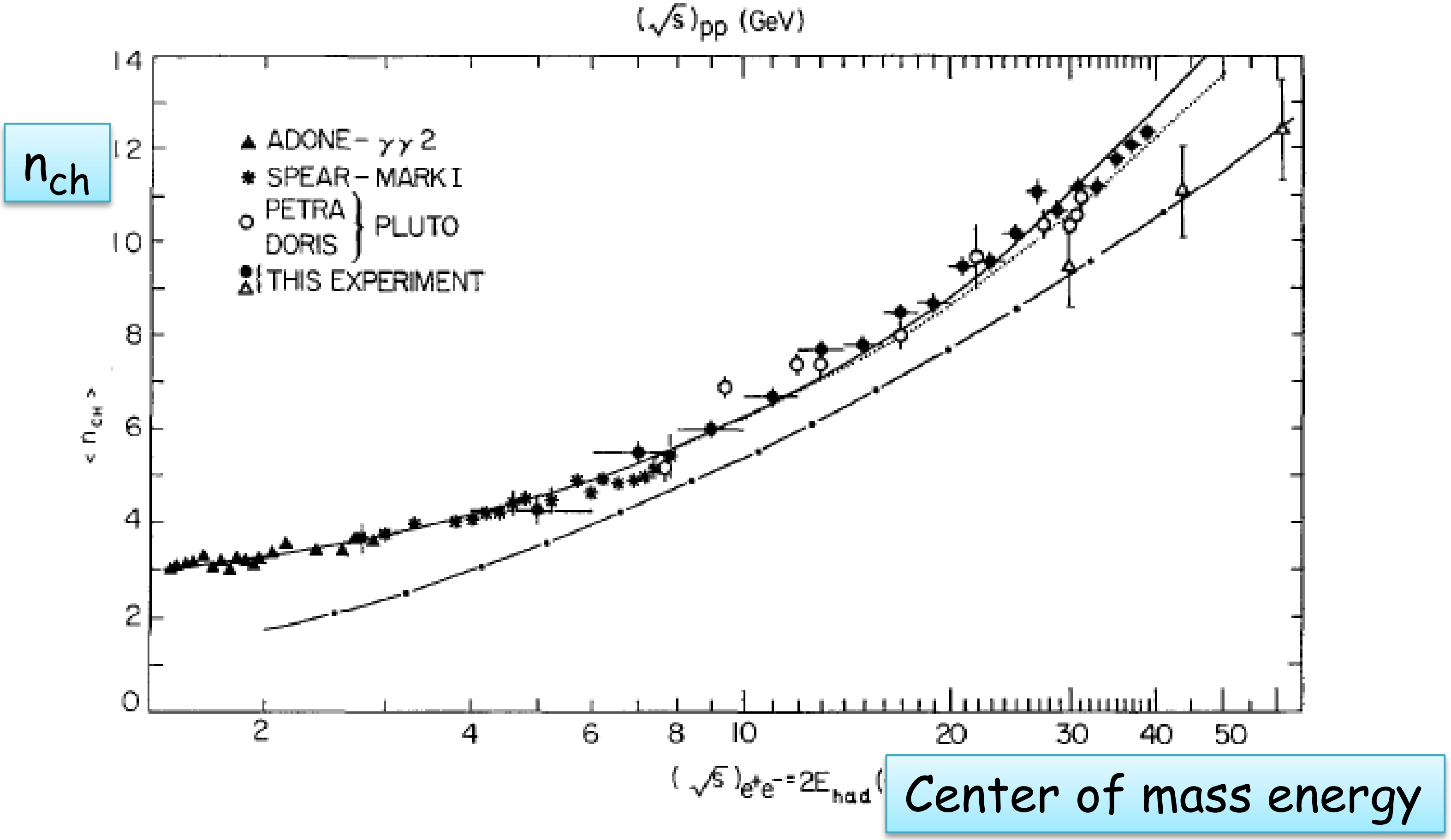


Compare ridges not looking at Pb or p side but with the same activity in the detector
i.e. take the same multiplicity in Pb or p side

"The ridge appear to be independent of the beam (p) or the target (Pb) fragmentation, but only depends on the activity in the respective direction".

Idea of using effective activity/energy to compare different collisions: an old idea

M. Basile et al :
Universality Features in (pp), (e+e -) and Deep-Inelastic.Scattering Processes.
Nuovo Cim. 79 A (1984) 1

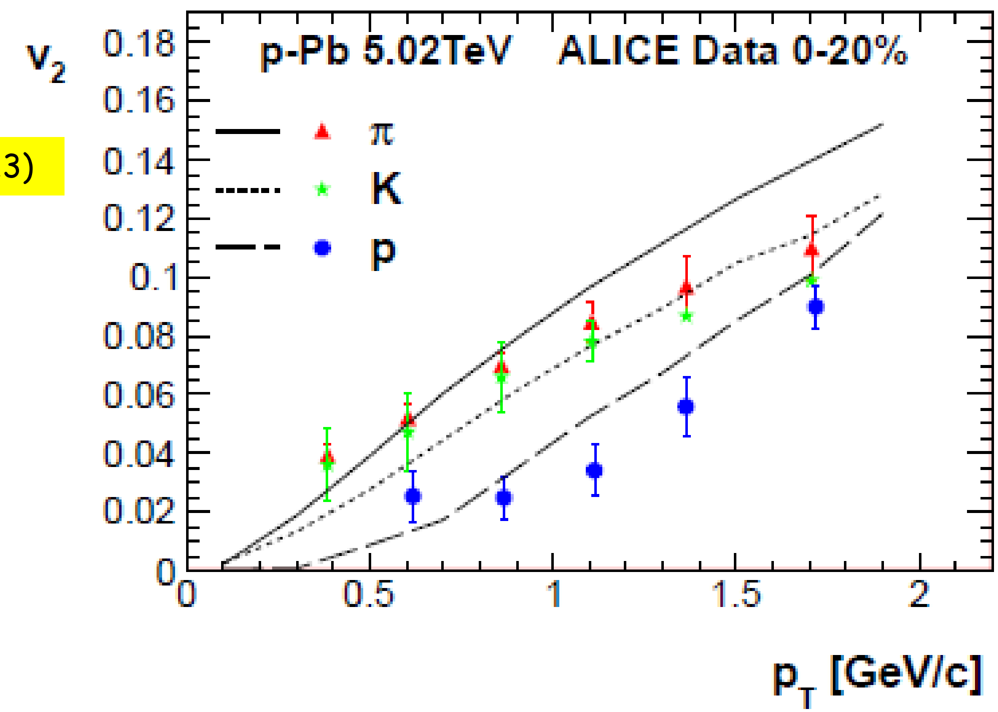


The ridge in theory
Hydrodynamical models

Analogy with Pb-Pb suggests a formation of mini-QGP with later hydrodynamic expansion

OK for PID flow
BUT is there enough time to thermalize the system ?

PRL 111 – 172303 (2013)



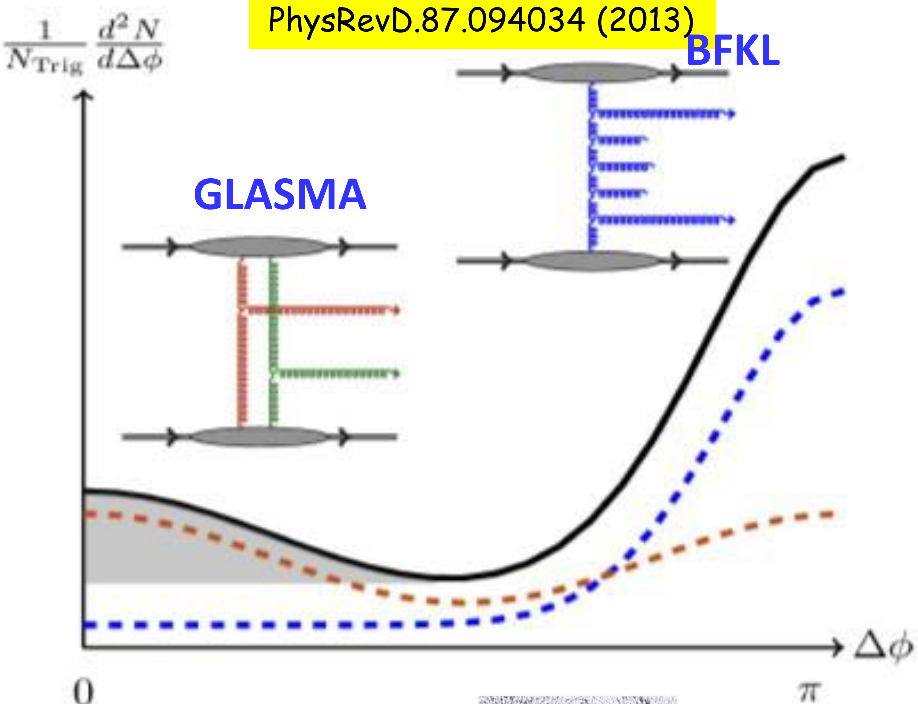
The ridge in theory
GLASMA + BFKL models

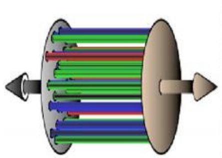
Colour reconnection and gluon saturation in the framework of a colour-glass condensate

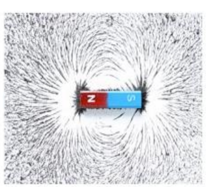
Ok for double ridge

BUT not clear if it can explain mass hierarchy behavior observed in flow(s)

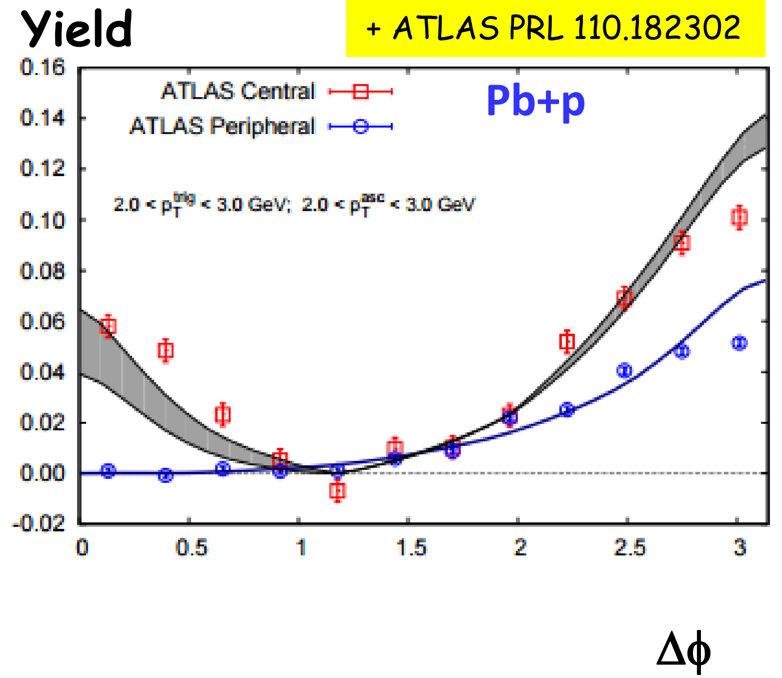
PhysRevD.87.094034 (2013)





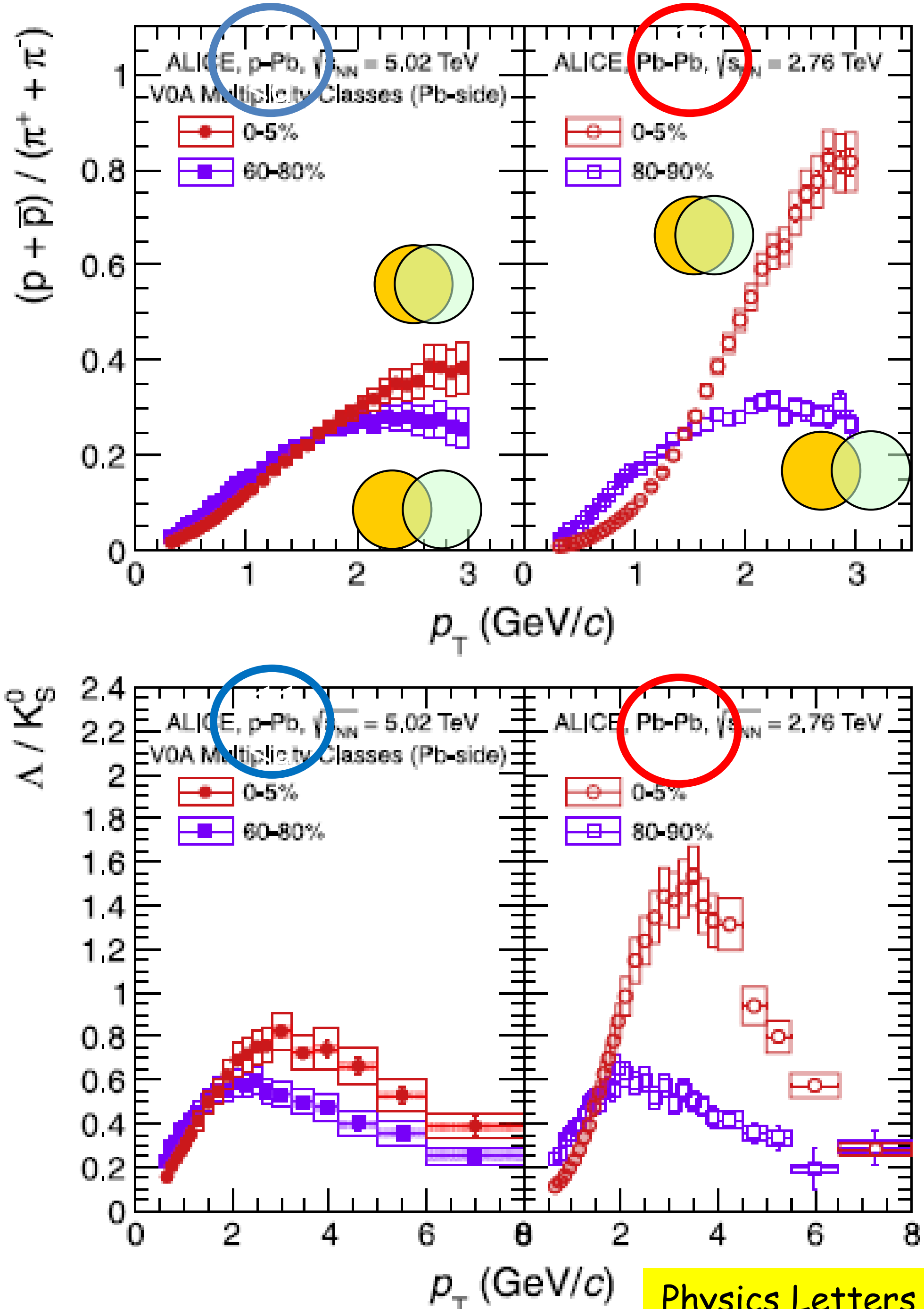


+ ATLAS PRL 110.182302



But is "the ridge " the only measurement where collective phenomena appear in high multiplicity events ?

Several other analysis show similar behavoir between high multiplicity p-Pb events and Pb-Pb collisions



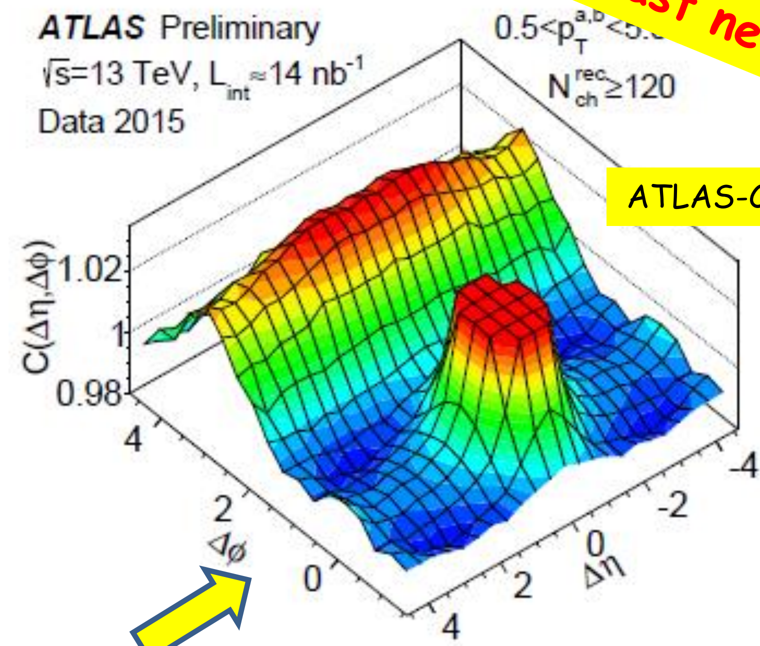
Baryon (proton and Λ) to meson ratio

- Baryon/meson ratio in p-Pb events at high/low multiplicity show a behavior similar to Pb-Pb collisions

Physics Letters B 728 (2014) 25-38

Conclusion IV

pp



Last news !

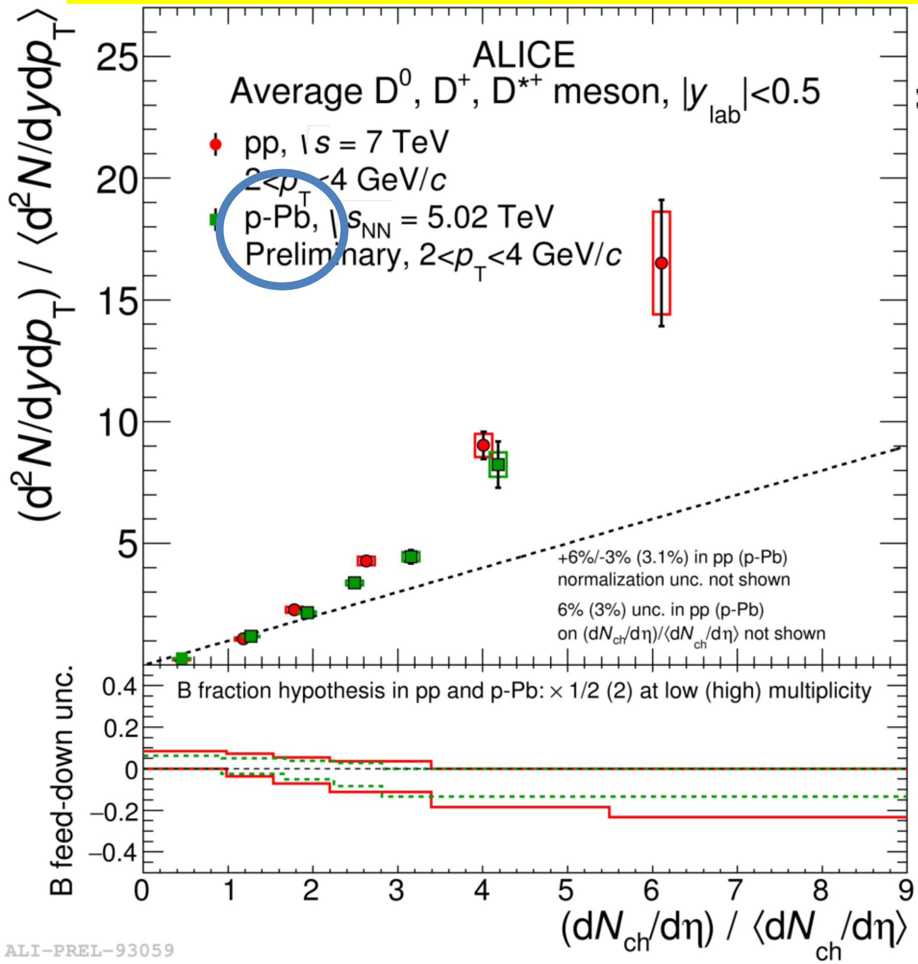
ATLAS-CONF-2015-027

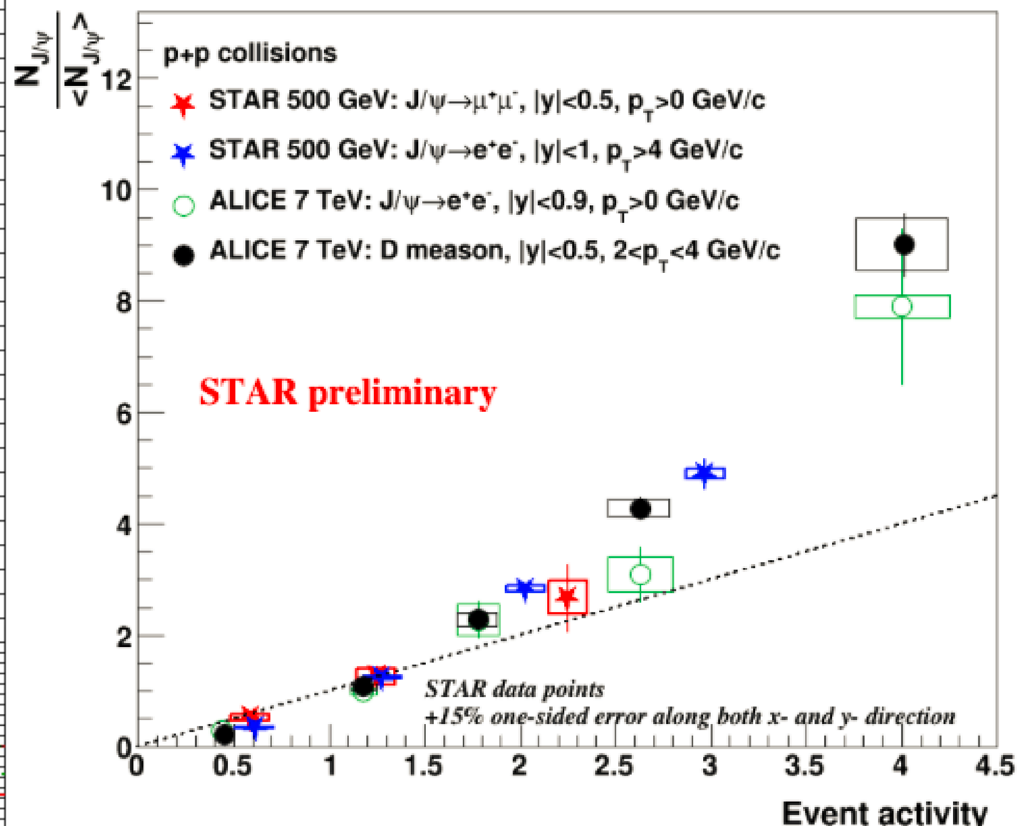
Multiplicity/activity is an important parameter in the comparison of different processes, allowing the appearence of similarities and common features among systems of different sizes.

↓

It suggests a new approach in understanding QCD using different collisions as inputs and gives constraints on the dynamics of the collisions.

HF production vs event multiplicity/activity

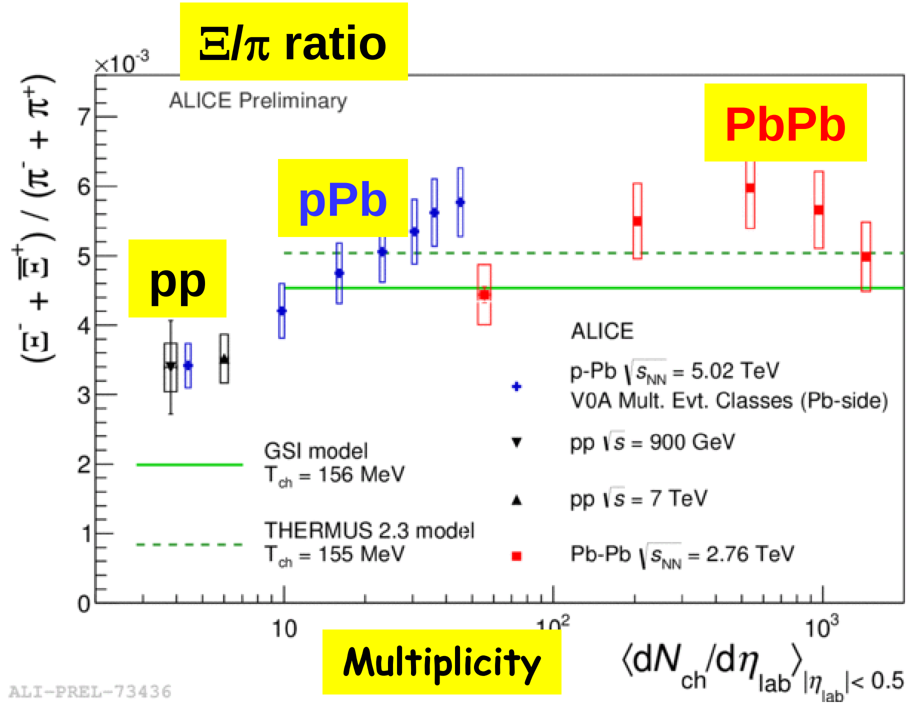


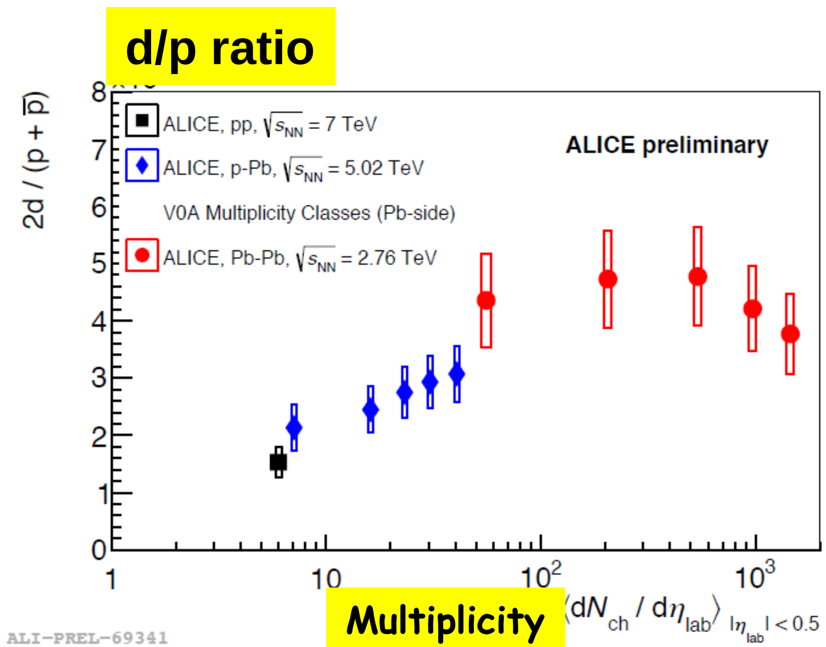


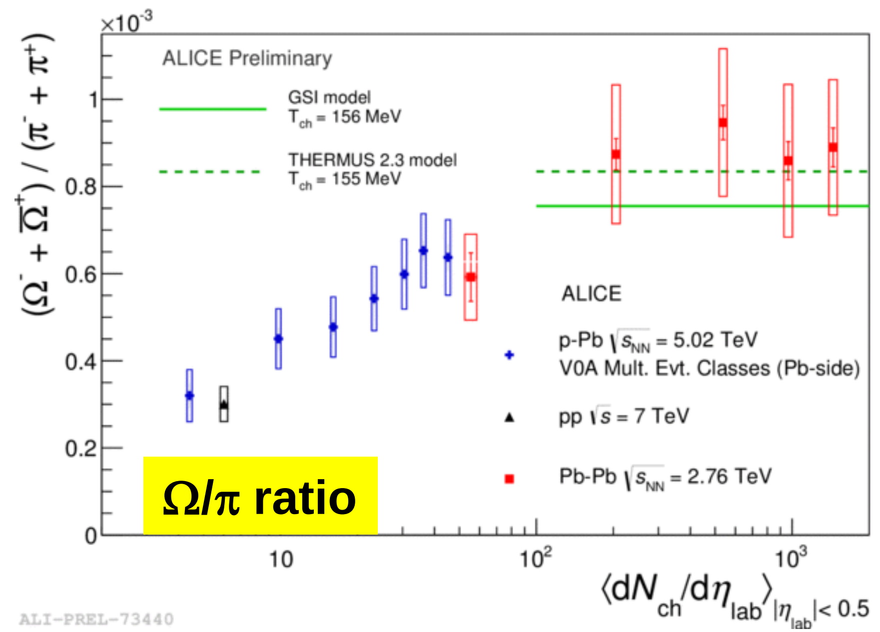
Charm production show and increase with multiplicity faster than linear : presence of MPI or other QCD processes related to the high multiplicity enviroment.

Particle ratio vs event multiplicity/activity

- Continuos evolution across different system size
- Multiplicity as a system temperature monitor ?
- Need different variables (energy density …)?







Conclusion V

Analysis as function of multiplicity/activity across several type of collisions and system sizes are fundamental to better understand QCD processes and particle formation.

A new challenge for RUN II.

Final remarks

Cold Nuclear Matter effects cannot explain results from lead-Lead collisions → LHC has produced a hot dense medium (QGP) with low viscosity

Importance of shadowing effects in the nuclear Parton Distribution Functions

Strong similarities among lead-lead collisions and high multiplicity events in pp and proton-Lead collisions → Evidence for similar collective effects and QCD dynamics

Proton-Lead collisions has opened a window on new interesting QCD studies crossing different collisions systems using the multuplicity/activity variables.