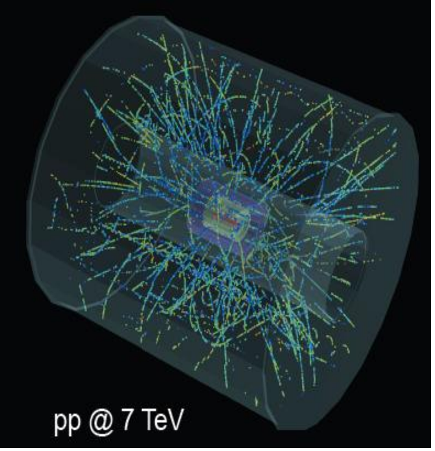
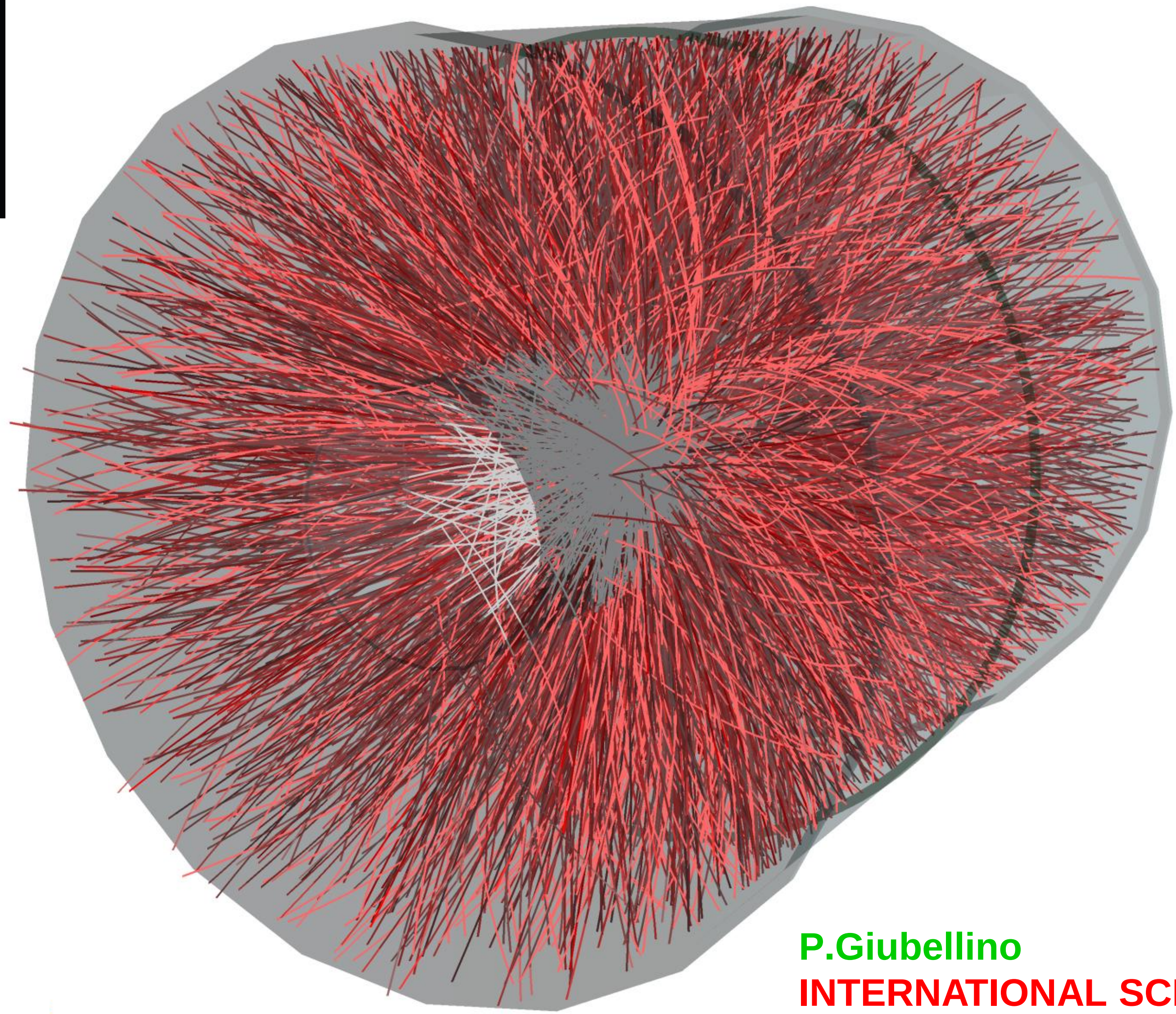
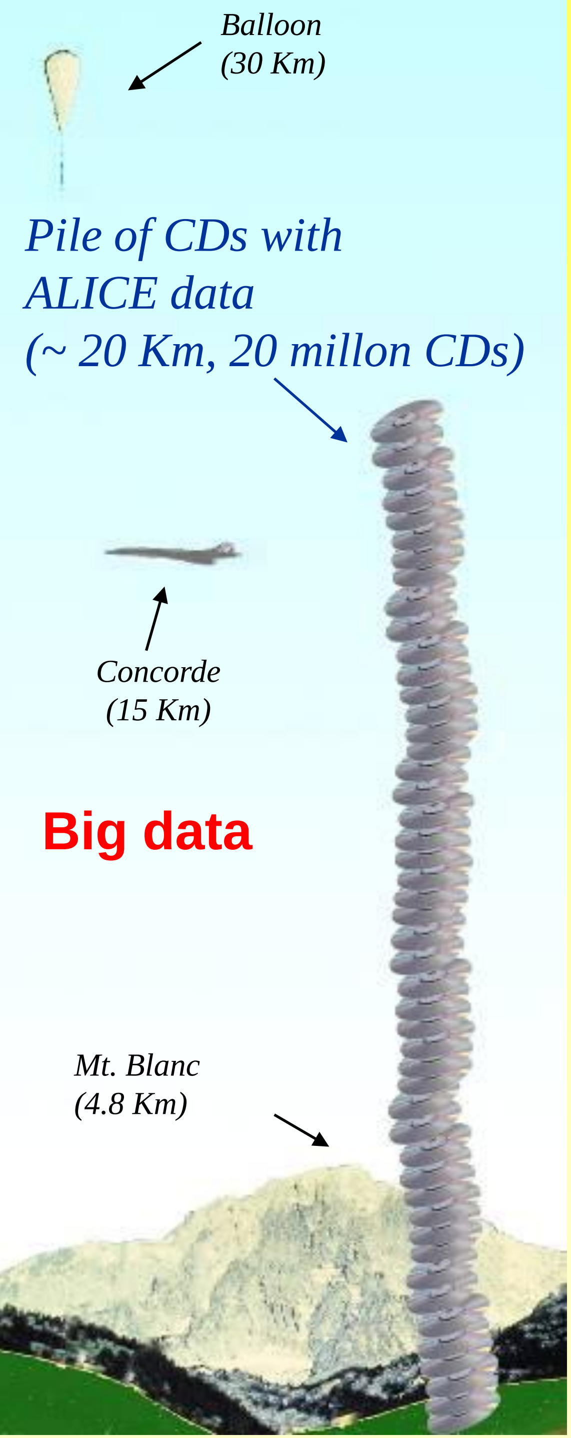


Highlights from ALICE

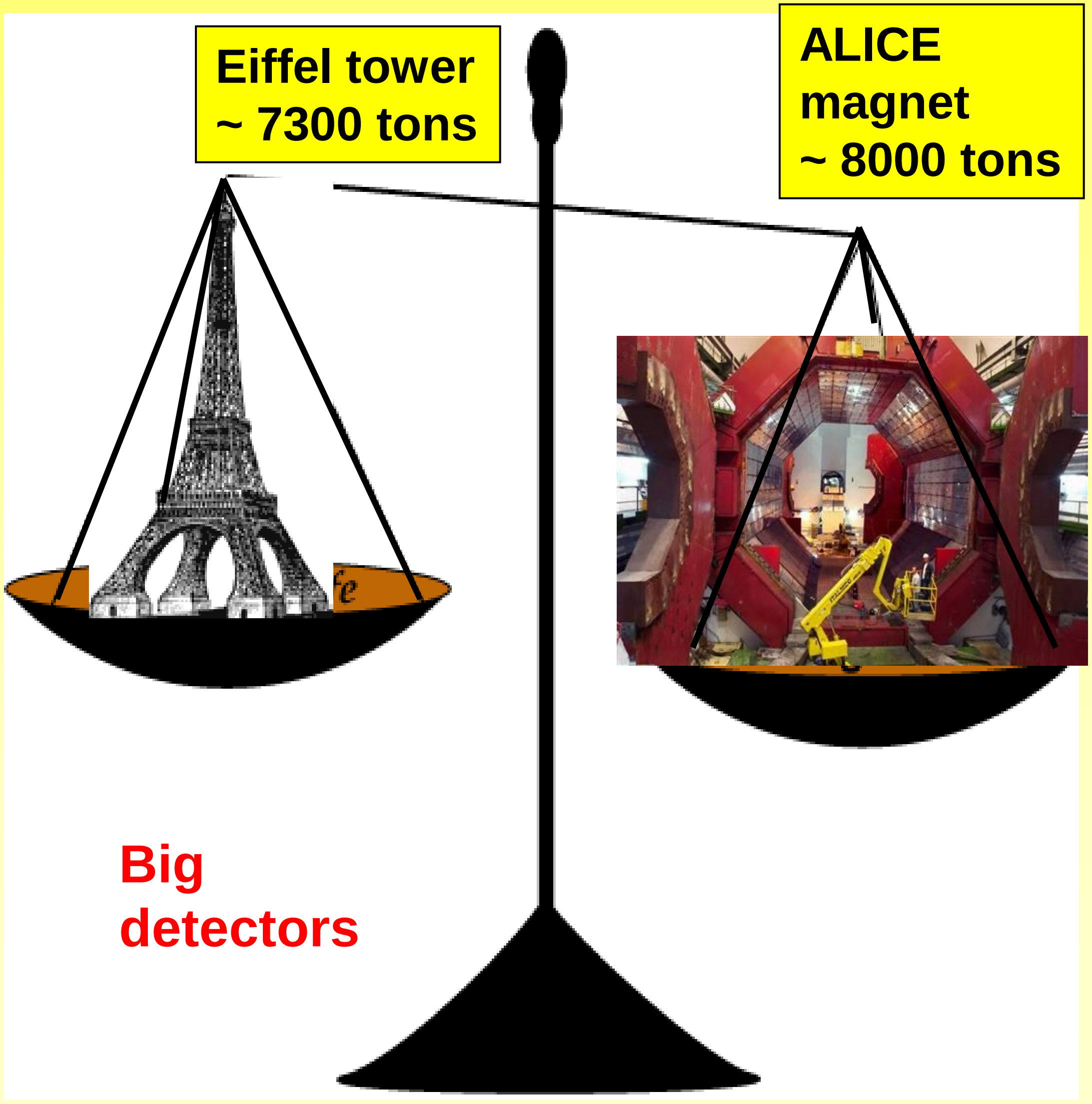


P.Giubellino
INTERNATIONAL SCHOOL
OF SUBNUCLEAR PHYSICS
Erice 2015

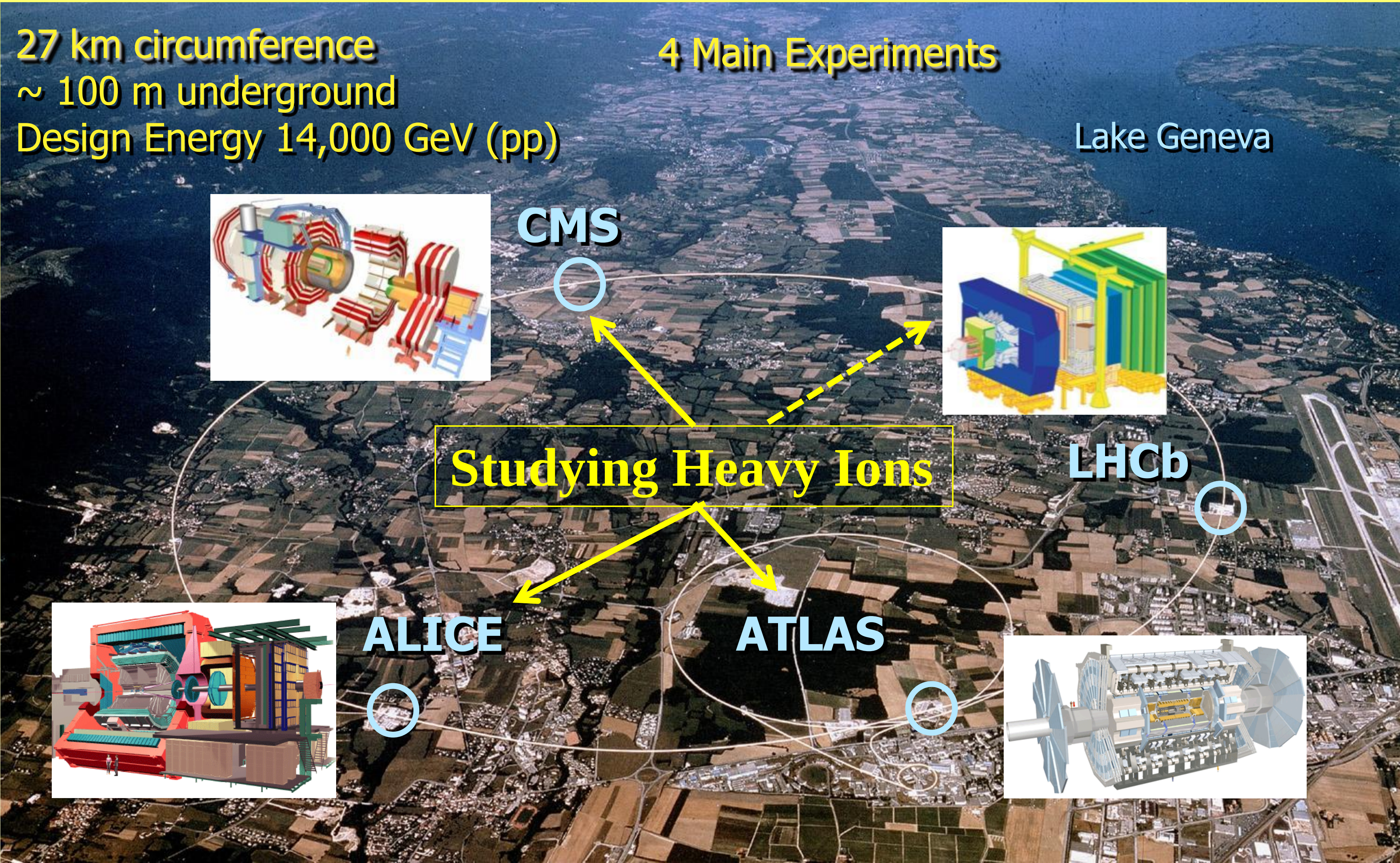
Nuclear Physics has changed…



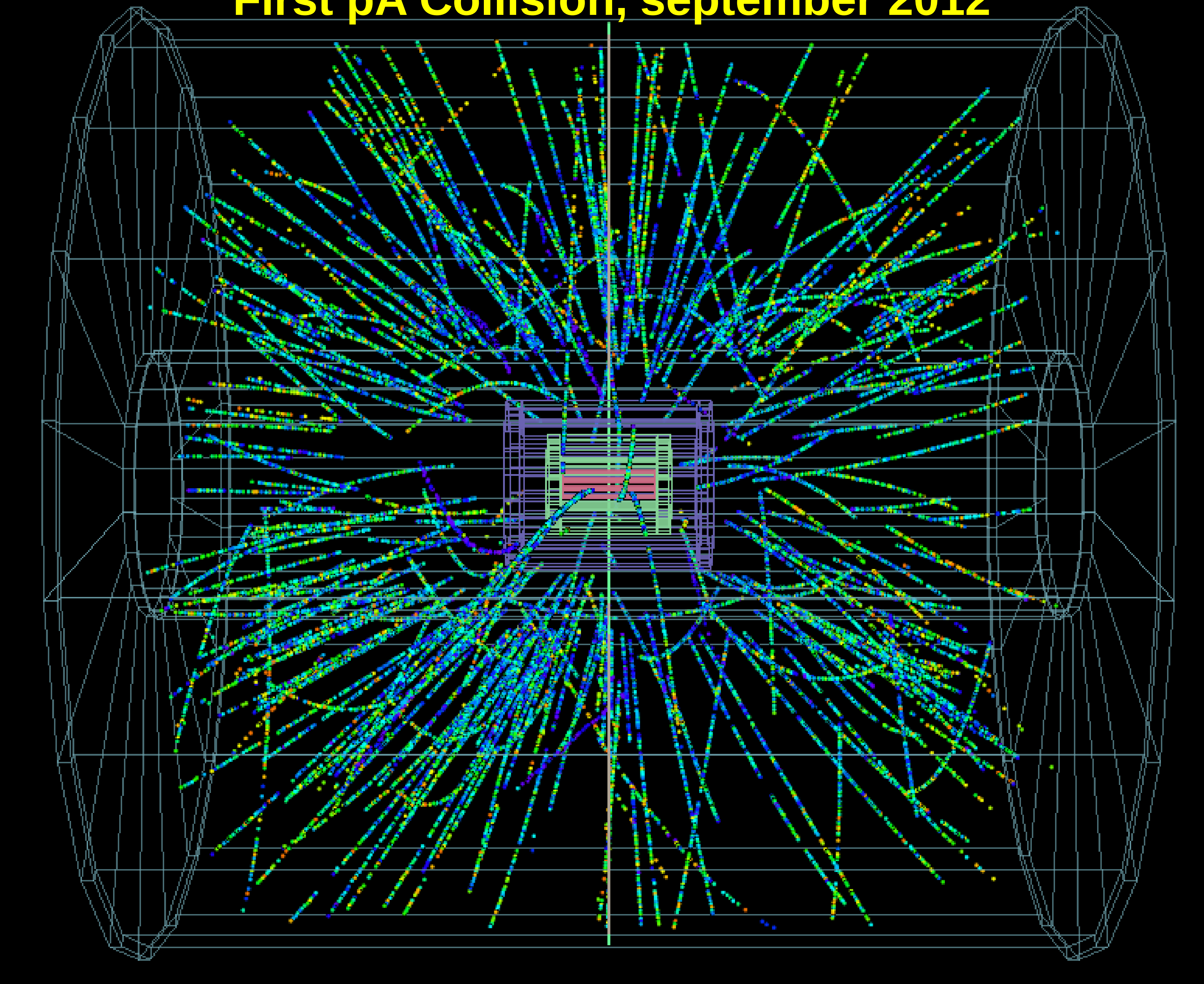
Nuclear Energy Physics experiments are nowadays world-wide high-tech projects of extreme complexity, which develop over decades!



Using the World's most powerful accelerator: the Large Hadron Collider LHC



First pA Collision, september 2012



ALICE

THE ALICE COLLABORATION

History of the ALICE Experiment:

1990-1996 Design

1992-2002 R&D

2000-2010 Construction

2002-2007 Installation

2008-2009 Commissioning

2009-> Data Taking!

4 TP addenda along the way:

- 1996 Muon spectrometer
- 1999 TRD
- 2006 EMCAL
- 2007 DCAL

2012 LoI for the Upgrade

2012-2015 R&D

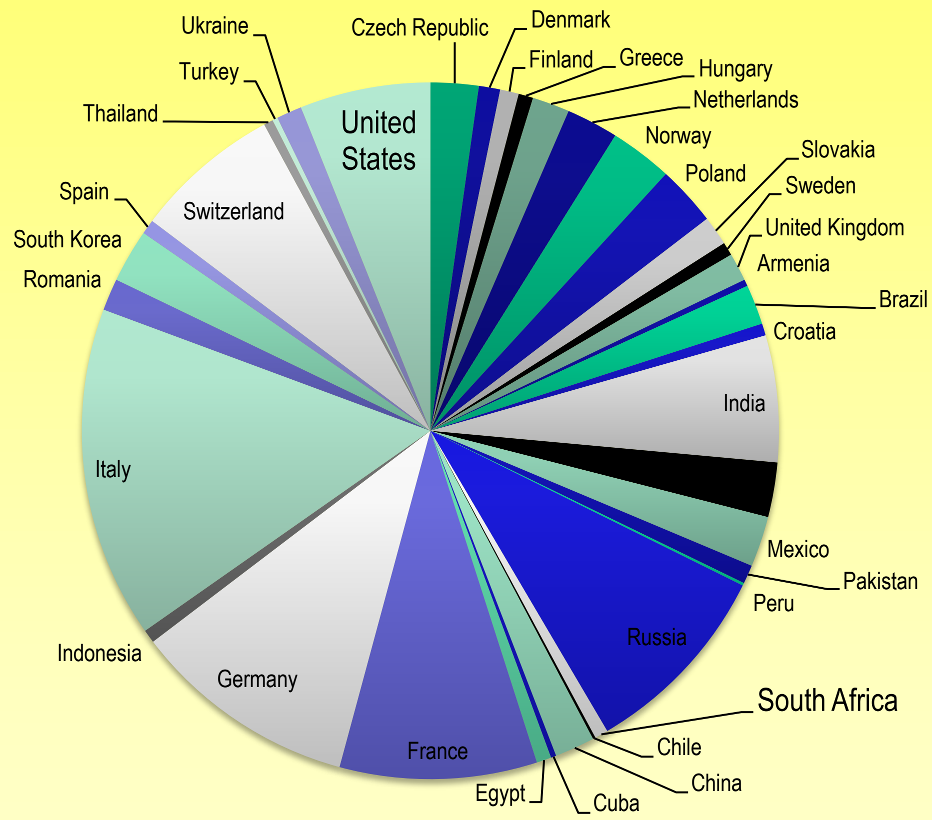
2015-2017 Procurement/Fabrication

2017-2018 Integration, pre-commissioning

2018-2019 Installation, commissioning

2019-2020 Full deployment of DAQ/HLT

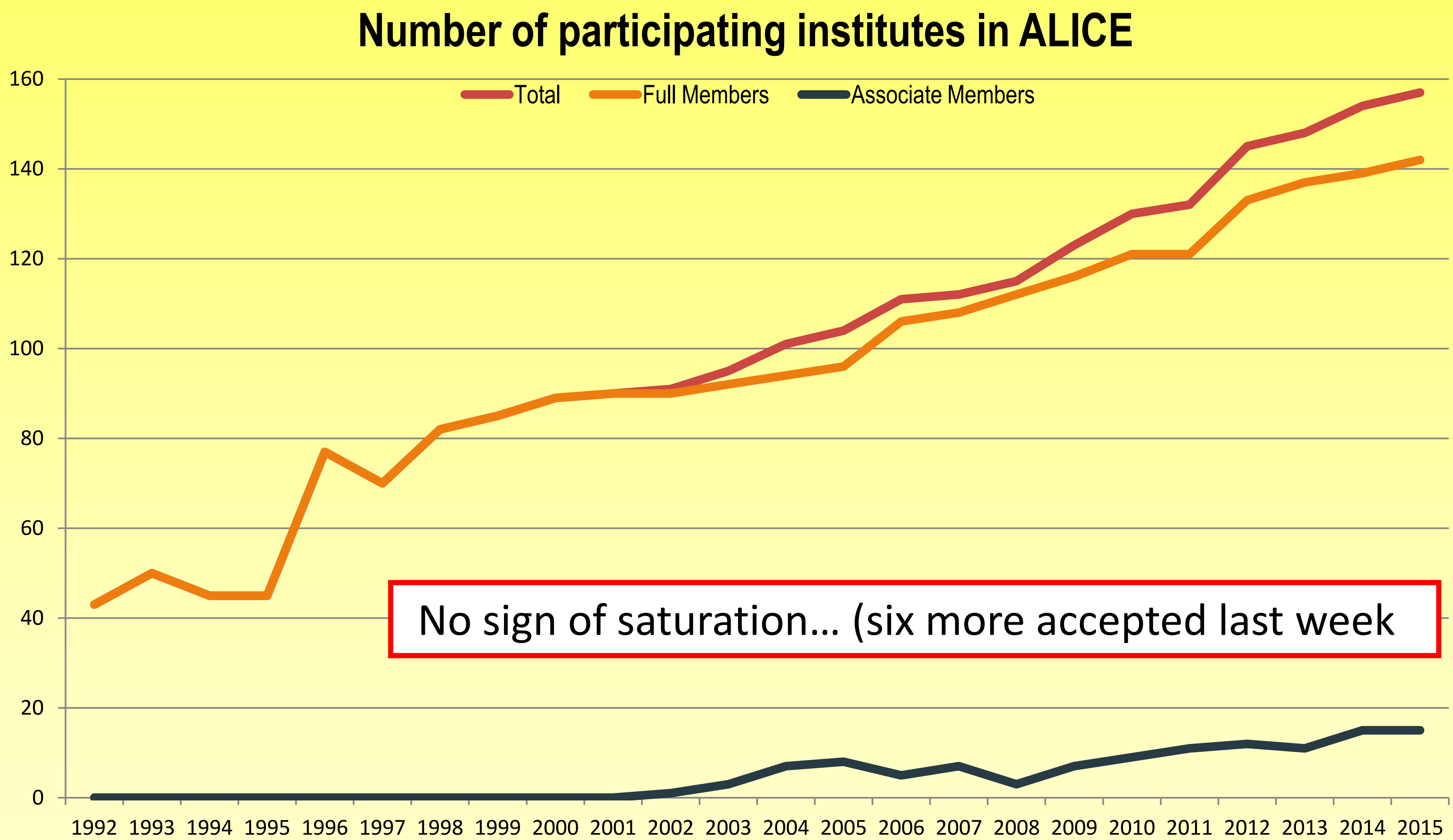
More than 1500 Collaborators



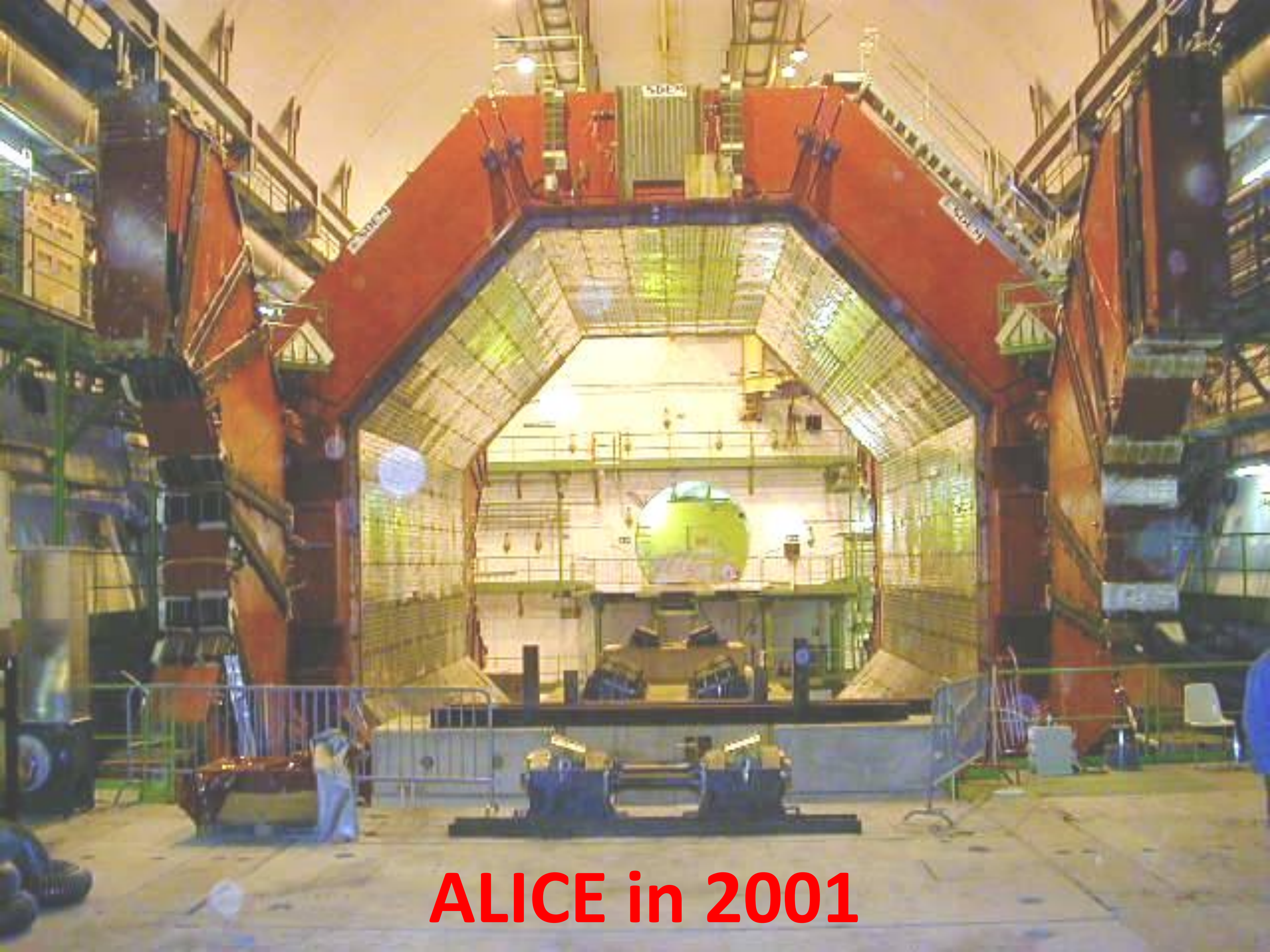
37 Countries

157 Institutes

and keeps growing



A scientific and technological program with great prospects!



ALICE in 2001

The preparation required a decade of R&D for the experiments, to meet the LHC Challenges

For ALICE:

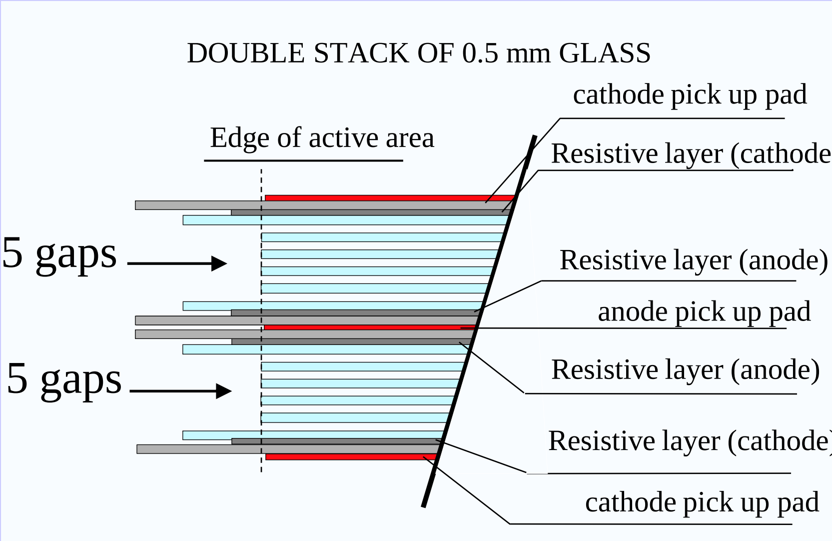
In detector Hardware and VLSI Electronics

- Inner Tracking System (ITS)
  - Silicon Pixels (RD19)
  - Silicon Drift (INFN/SDI)
  - Silicon Strips (double sided)
  - low mass, high density interconnects
  - low mass support/cooling
- TRD
  - bi-dimensional (time-space) read-out, on-chip
  - trigger (TRAP chip)
- TPC
  - gas mixtures (RD32)
  - advanced digital electronics
  - low mass field cage
- EM calorimeter
  - new scint. crystals (RD18)
- PID
  - Multigap RPC's (LAA)
  - solid photocathode RICH (RD26)

In DAQ & Computing:

How to digest 2 (now 4..) Gygabytes/s of data…

- scalable architectures with consumer electronics commercial components (COTS)
- high perf. storage media
- GRID computing

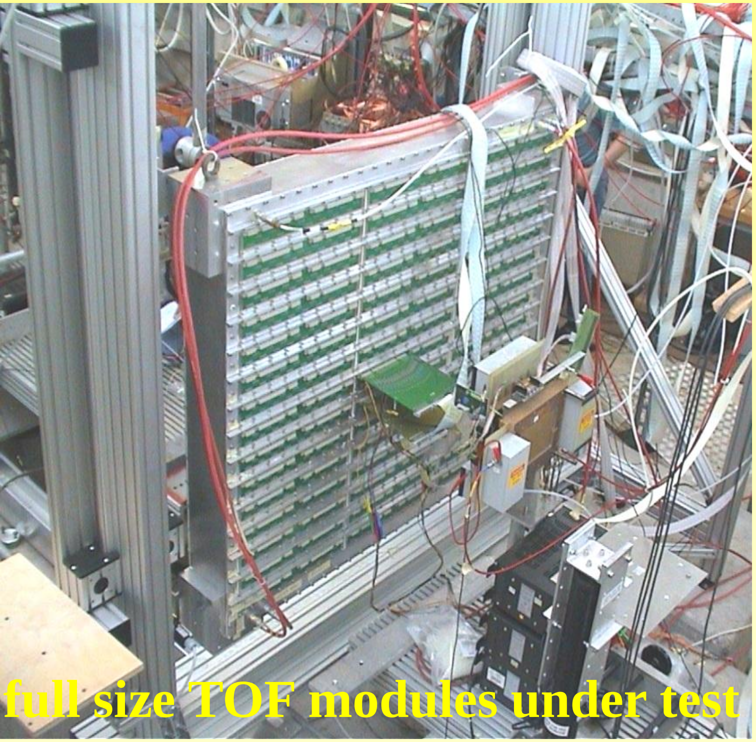


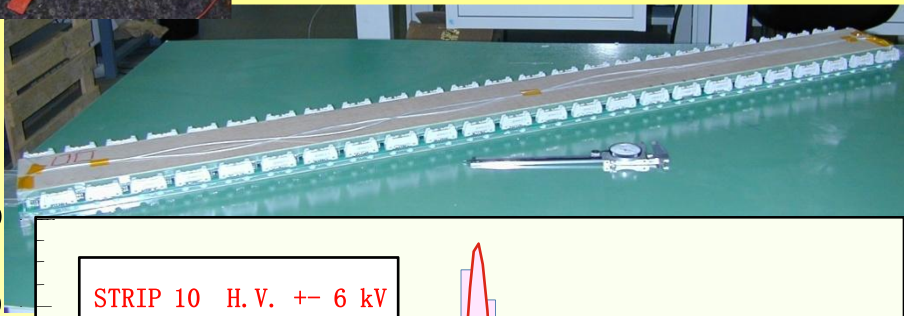
Multigap Resistive Plate Chambers

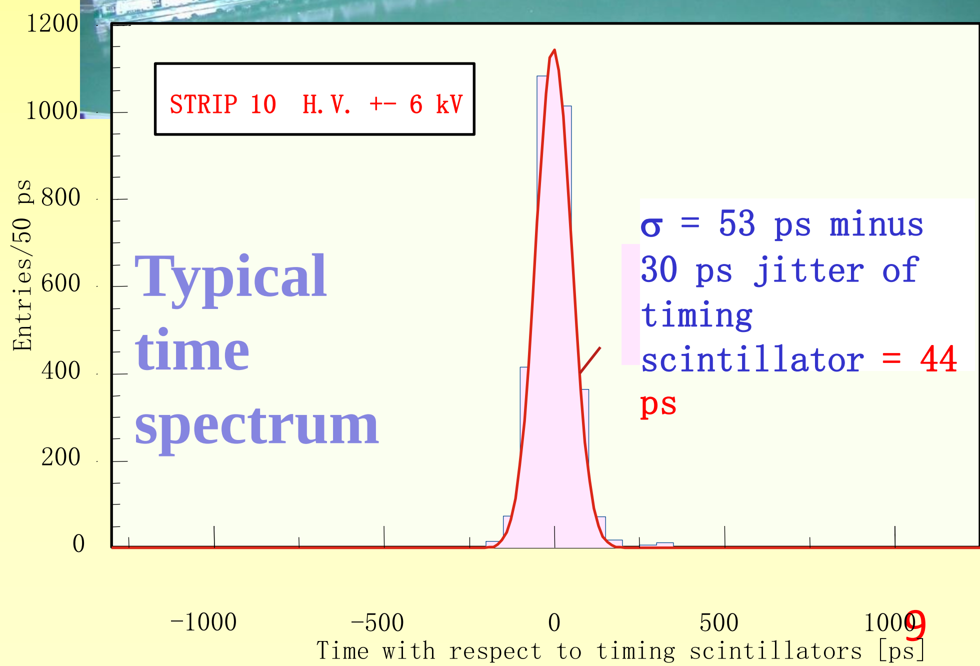
Example:Time Of Flight Breakthrough after > 5 years of R&D

for π, K, p PID
π, K for p <2 GeV/c
p for p <4 GeV/c

- 0.9 < η < 0.9 full ϕ → 150 kchann. over ~150 m²

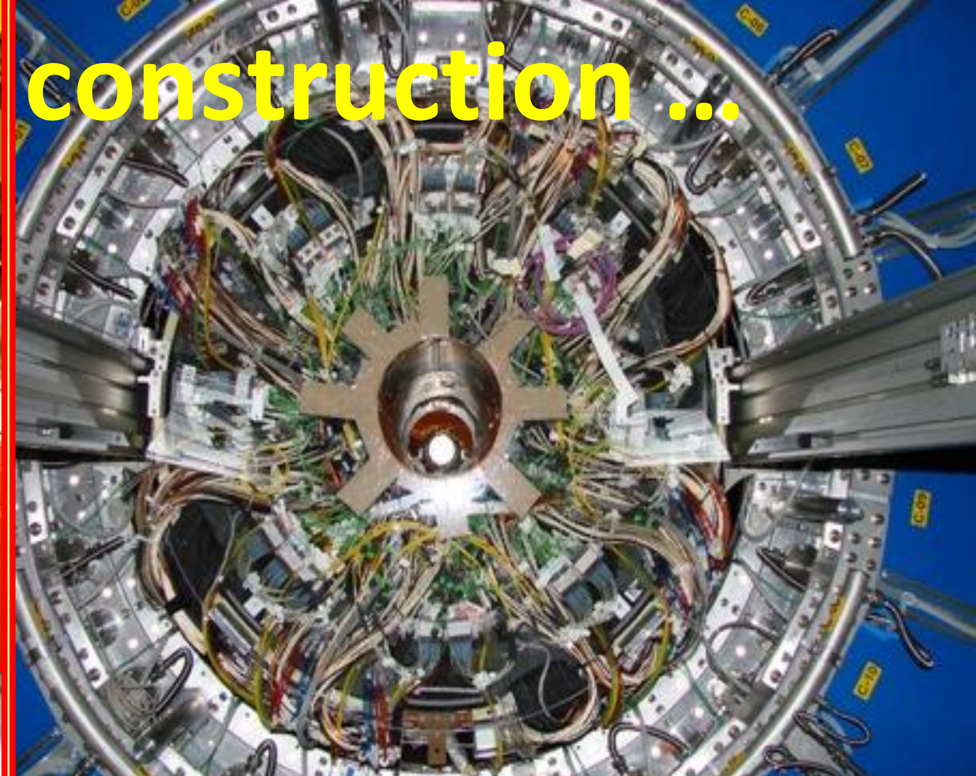


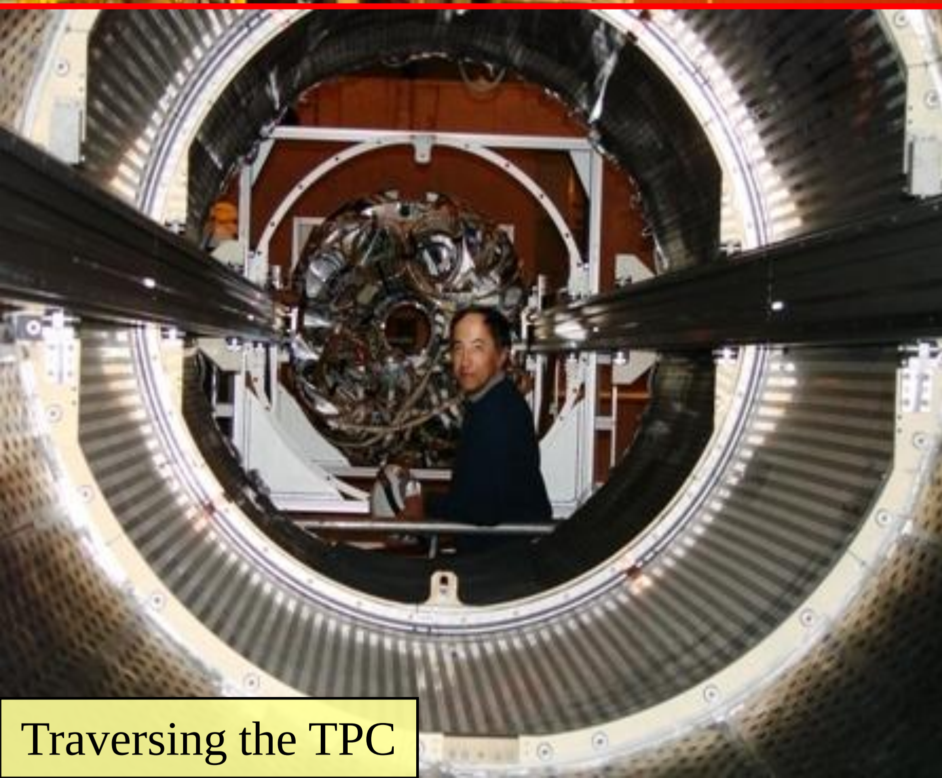


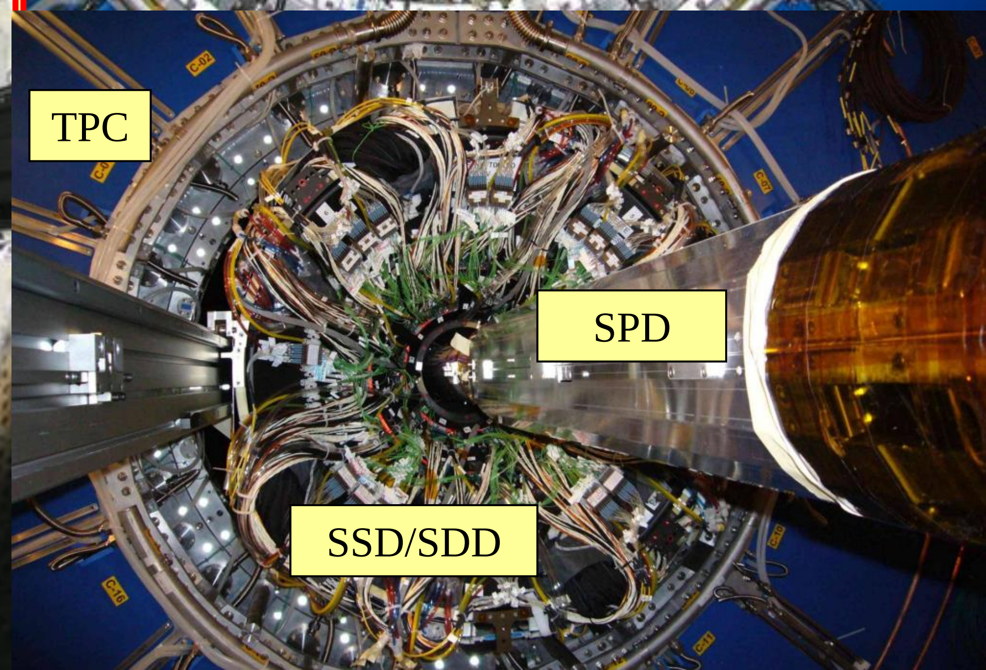


Prof. A. Zichichi's group

… in construction …

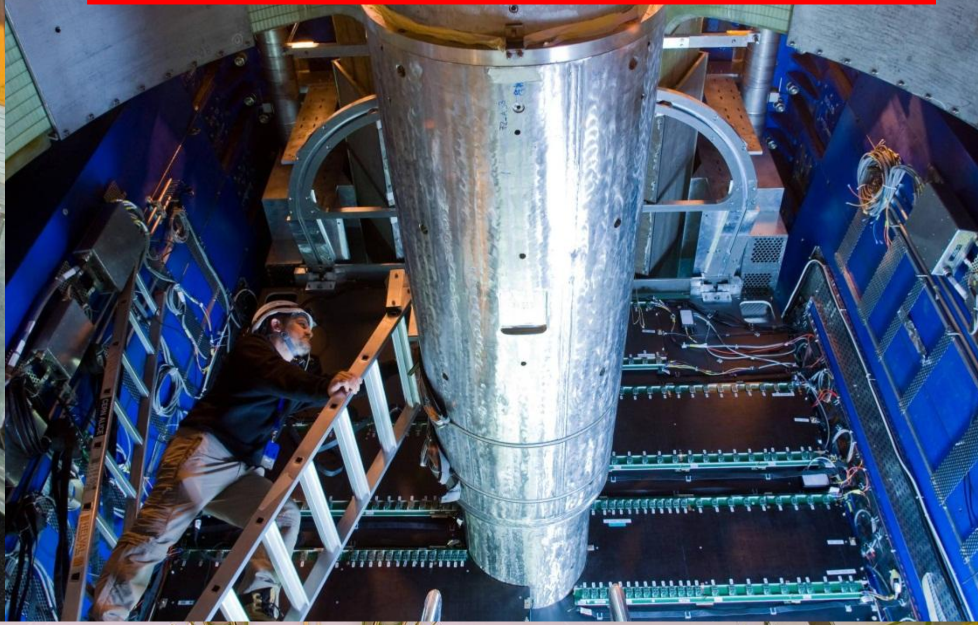






Insertion of final TOF super module

Installation of final muon chamber

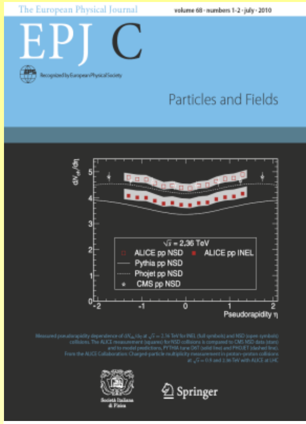


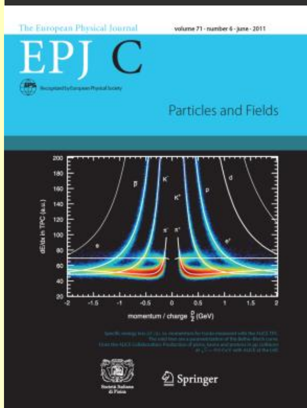
ALICE in 2008

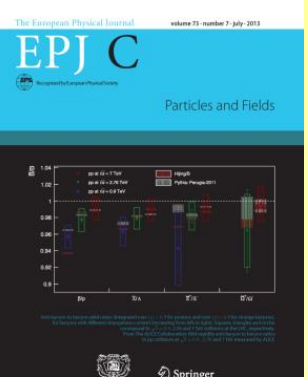
Formal end of ALICE installation July 2008

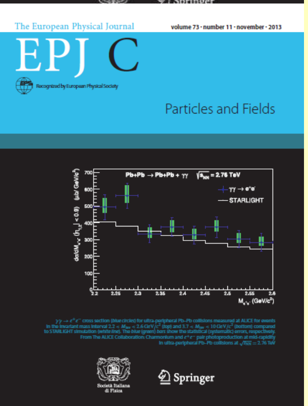
A program of major impact

- A very large community of physicists involved
  - over one and a half thousands just in ALICE, hundreds in the other LHC experiments
- A huge scientific output
  - **119 ALICE papers on arXiv**
  - **High impact papers (**average of 89 citations per paper) **:** the top cited paper at the LHC after the Higgs discovery ones is the ALICE paper on flow in HI collisions, and out of the 10 top cited physics papers at the LHC 3 are from ALICE and one from ATLAS-Heavy Ion program (source: ISI).
  - **Several hundred** presentations at international conferences *each year*







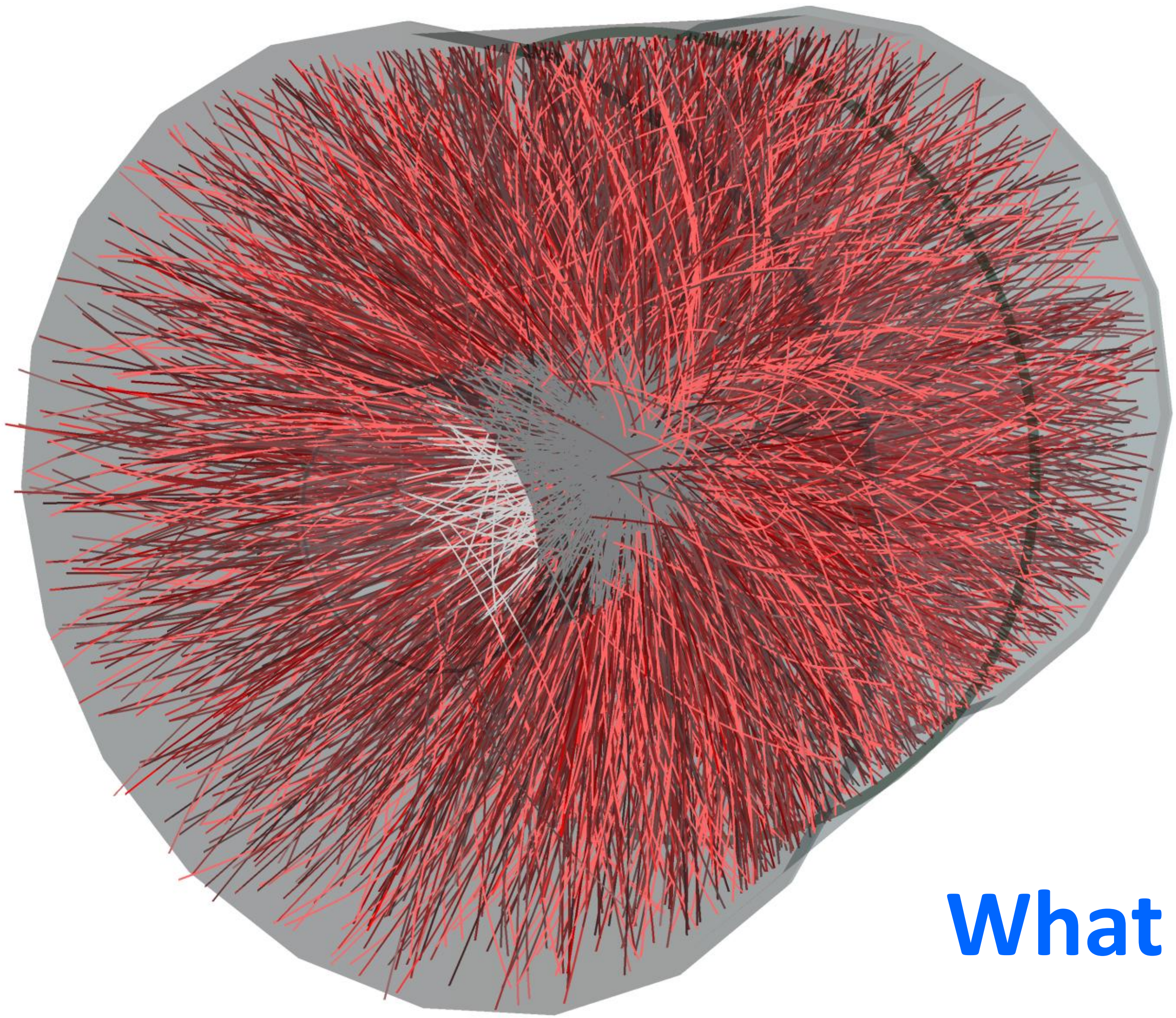


Most cited physics papers at the LHC (source: ISI)

Use the checkboxes to remove individual items from this Citation Report
or restrict to items published between 2010 and 2015 Go

	2011	2012	2013	2014	2015	Total	Average Citations per Year
	2036	5815	7751	8592	1070	25396	4232.67
1. **Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC** By: Aad, G.; Abajyan, T.; Abbott, B.; et al. Group Author(s): ATLAS Collaboration PHYSICS LETTERS B Volume: 716 Issue: 1 Pages: 1-29 Published: SEP 17 2012	0	137	1039	991	114	2281	570.25
2. **Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC** By: Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; et al. Group Author(s): CMS Collaboration PHYSICS LETTERS B Volume: 716 Issue: 1 Pages: 30-61 Published: SEP 17 2012	0	123	989	918	112	2142	535.50
3. **Combined results of searches for the standard model Higgs boson in pp collisions at root s=7 TeV** By: Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; et al. Group Author(s): CMS Collaboration PHYSICS LETTERS B Volume: 710 Issue: 1 Pages: 26-48 Published: MAR 29 2012	0	221	98	48	7	374	93.50
4. **Combined search for the Standard Model Higgs boson using up to 4.9 fb(-1) of pp collision data at root s=7 TeV with the ATLAS detector at the LHC** By: Aad, G.; Abbott, B.; Abdallah, J.; et al. Group Author(s): ATLAS Collaboration PHYSICS LETTERS B Volume: 710 Issue: 1 Pages: 49-66 Published: MAR 29 2012	0	223	78	29	6	336	84.00
5. **Elliptic Flow of Charged Particles in Pb-Pb Collisions at root s(NN)=2.76 TeV** By: Aamodt, K.; Abelev, B.; Abrahantes Quintana, A.; et al. Group Author(s): ALICE Collaboration PHYSICAL REVIEW LETTERS Volume: 105 Issue: 25 Article Number: 252302 Published: DEC 13 2010	48	82	78	66	5	279	46.50
6. **Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at root s(NN)=2.76 TeV with the ATLAS Detector at the LHC** By: Aad, G.; Abbott, B.; Abdallah, J.; et al. Group Author(s): ATLAS Collaboration PHYSICAL REVIEW LETTERS Volume: 105 Issue: 25 Article Number: 252303 Published: DEC 13 2010	44	80	86	60	7	277	46.17
7. **Suppression of charged particle production at large transverse momentum in central Pb-Pb collisions at root s(NN)=2.76 TeV** By: Aamodt, K.; Abrahantes Quintana, A.; Adamova, D.; et al. Group Author(s): ALICE Collaboration PHYSICS LETTERS B Volume: 696 Issue: 1-2 Pages: 30-39 Published: JAN 24 2011	65	80	71	47	6	269	53.80
8. **Higher Harmonic Anisotropic Flow Measurements of Charged Particles in Pb-Pb Collisions at root s(NN)=2.76 TeV** By: Aamodt, K.; Abelev, B.; Abrahantes Quintana, A.; et al. Group Author(s): ALICE Collaboration PHYSICAL REVIEW LETTERS Volume: 107 Issue: 3 Article Number: 032301 Published: JUL 11 2011	11	78	84	75	5	253	50.60
9. **Transverse-Momentum and Pseudorapidity Distributions of Charged Hadrons in pp Collisions at root s=7 TeV** By: Khachatryan, V.; Sirunyan, A. M.; Tumasyan, A.; et al. Group Author(s): CMS Collaboration PHYSICAL REVIEW LETTERS Volume: 105 Issue: 2 Article Number: 022002 Published: JUL 6 2010	69	54	48	33	5	221	36.83
10. **First Evidence for the Decay B-s(0) -> mu(+) mu(-)** By: Aaij, R.; Abellan Beteta, C.; Adametz, A.; et al. Group Author(s): LHCb Collaboration PHYSICAL REVIEW LETTERS Volume: 110 Issue: 2 Article Number: 021801 Published: JAN 7 2013	0	0	119	59	6	184	61.33

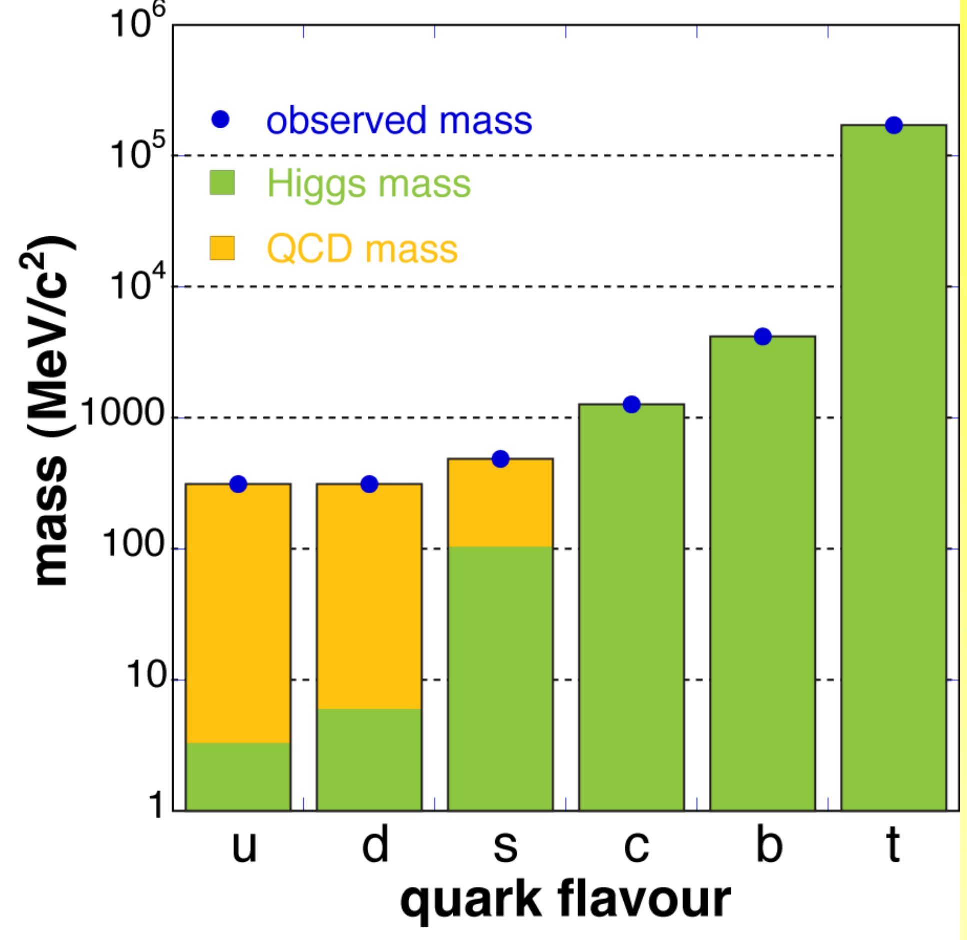
A worldwide effort to study the world's most energetic and most complicated collisions



What for?

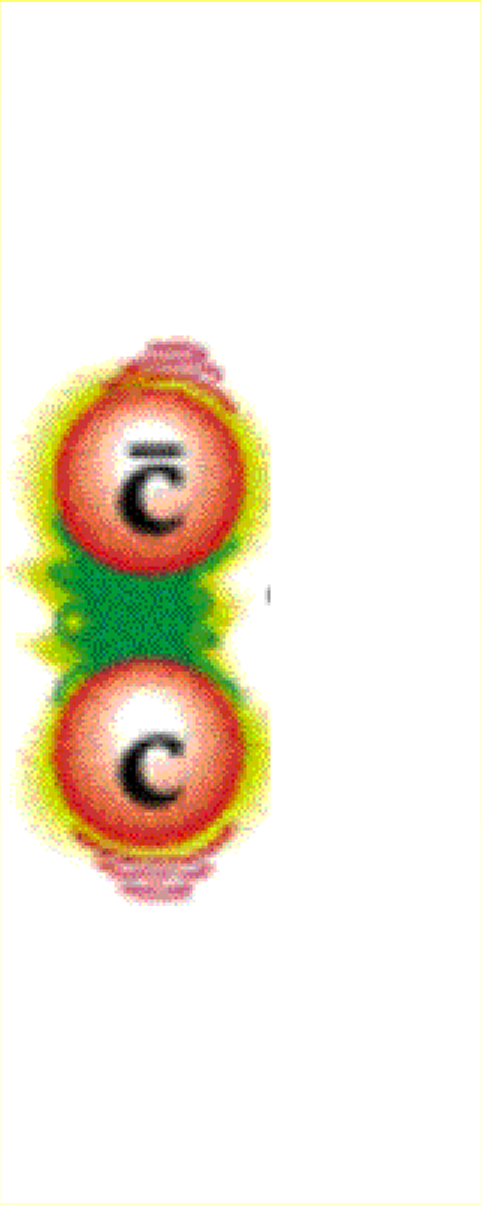
Origin of hadron masses

- **most of the mass of the hadrons is a dynamical effect of quark confinement**



- ***Higgs boson gives mass to quarks, but interactions among confined quarks & gluons ⇒ ~99% of all mass of visible matter!***
- Can be studied by bringing the system of strongly interacting matter to very high temperature or baryon density => "Partial Restoration of Chiral Symmetry"

The Strong force and confinement



- The force between quarks increases with distance (unlike the electrical force)
- More and more energy is stored in the color field as quarks are pulled apart
- At some point it becomes energetically convenient to Convert part of the energy into a quark-antiquark pair
- We get two hadrons instead of one, and we are never able to obtain a free quark

A long way...

- Hagedorn 1965: mass spectrum of hadronic states $\rho(m) \propto m^a \exp(m/B)$
  => Critical temperature T_c=B
- QCD 1973: asymptotic freedom
  - D.J.Gross and F.Wilczek, H.D. Politzer
- 1975: asy... q... and gluons

Prize motivation: "for the discovery of asymptotic freedom in the theory of the strong interaction"

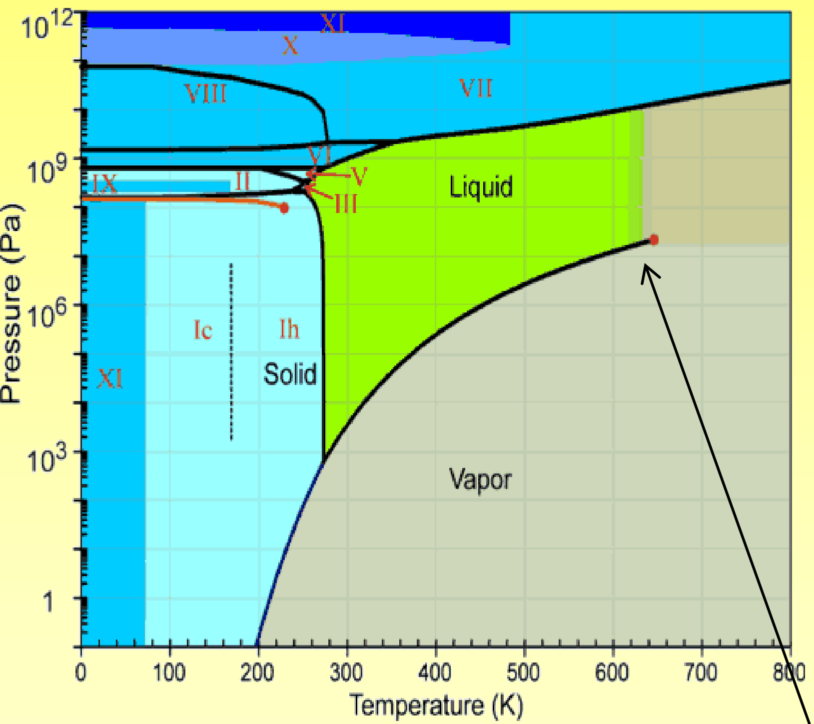
Nobel Prize in Physics 2004

David J. Gross | H. David Politzer | Frank Wilczek

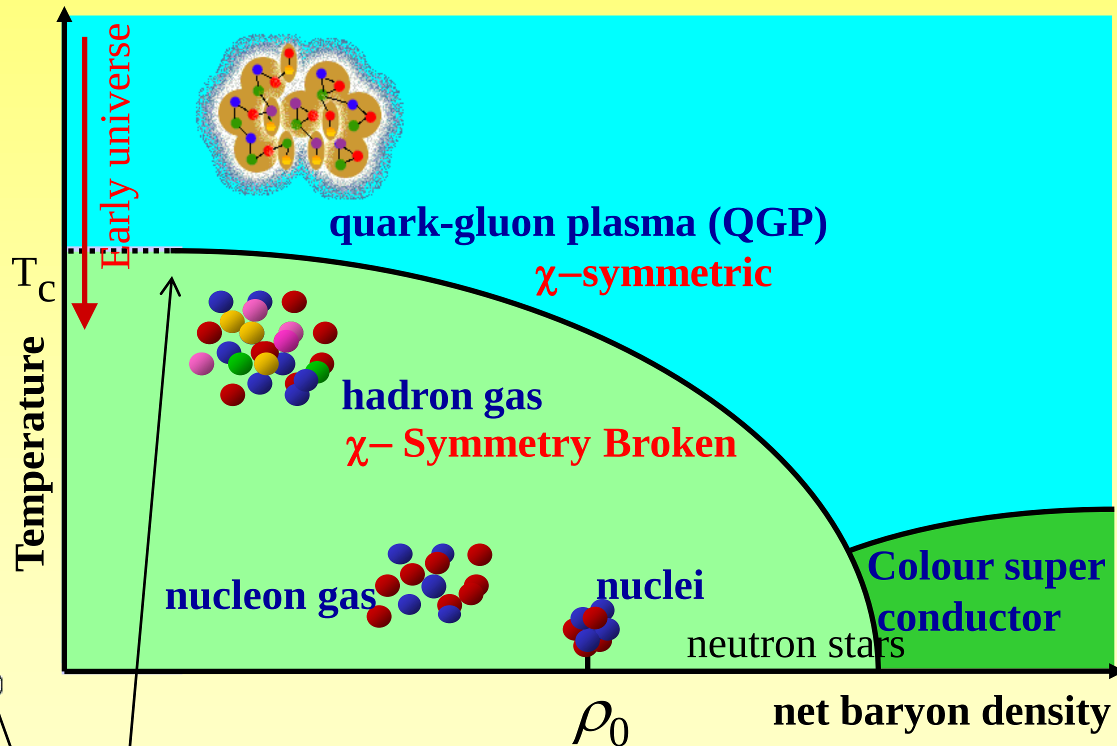
The QCD phase diagram

T.D. Lee (1975) “it would be interesting to explore new phenomena by distributing a high amount of energy or high nuclear density over a relatively large volume “ **How?** ⇒ Colliding nuclei at very high energy

Complex picture, with many features



Phase diagram for H_2O



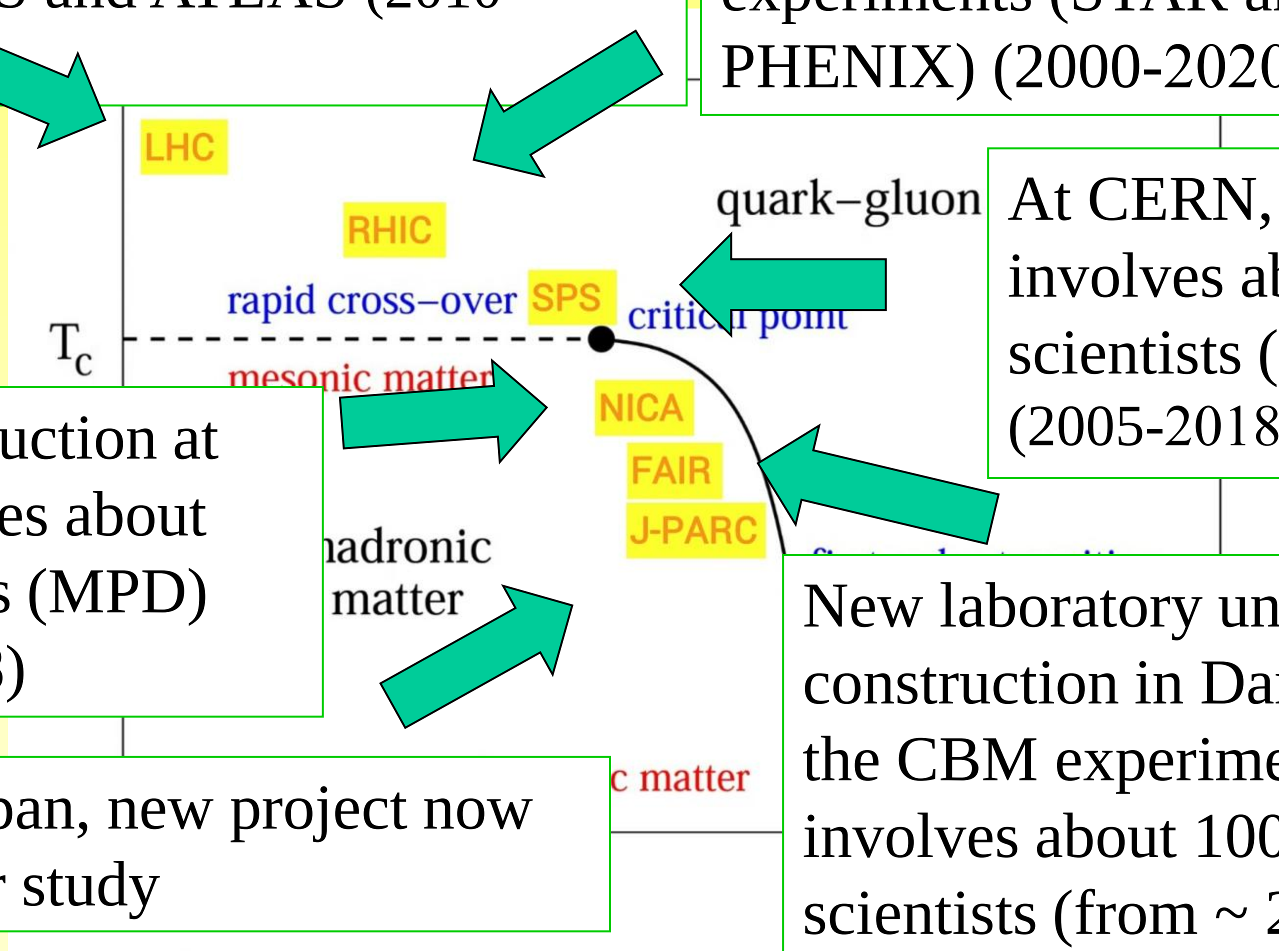
Critical endpoint

Study how collective phenomena and macroscopic properties of strongly interacting matter emerge from fundamental interactions

The exploration of the phase diagram of strongly interacting matter: a world wide enterprise

At CERN, involves about 1500 scientists in three large experiments ALICE, CMS and ATLAS (2010-2028…)

At BNL, involves about 1000 scientists in two large experiments (STAR and PHENIX) (2000-2020…)



At CERN, involves about 300 scientists (SHINE) (2005-2018…)

Under construction at JINR, involves about 500 scientists (MPD) (from ~ 2018)

New laboratory under construction in Darmstadt. the CBM experiment involves about 1000 scientists (from ~ 2020)

In Japan, new project now under study

Why HI Collisions?

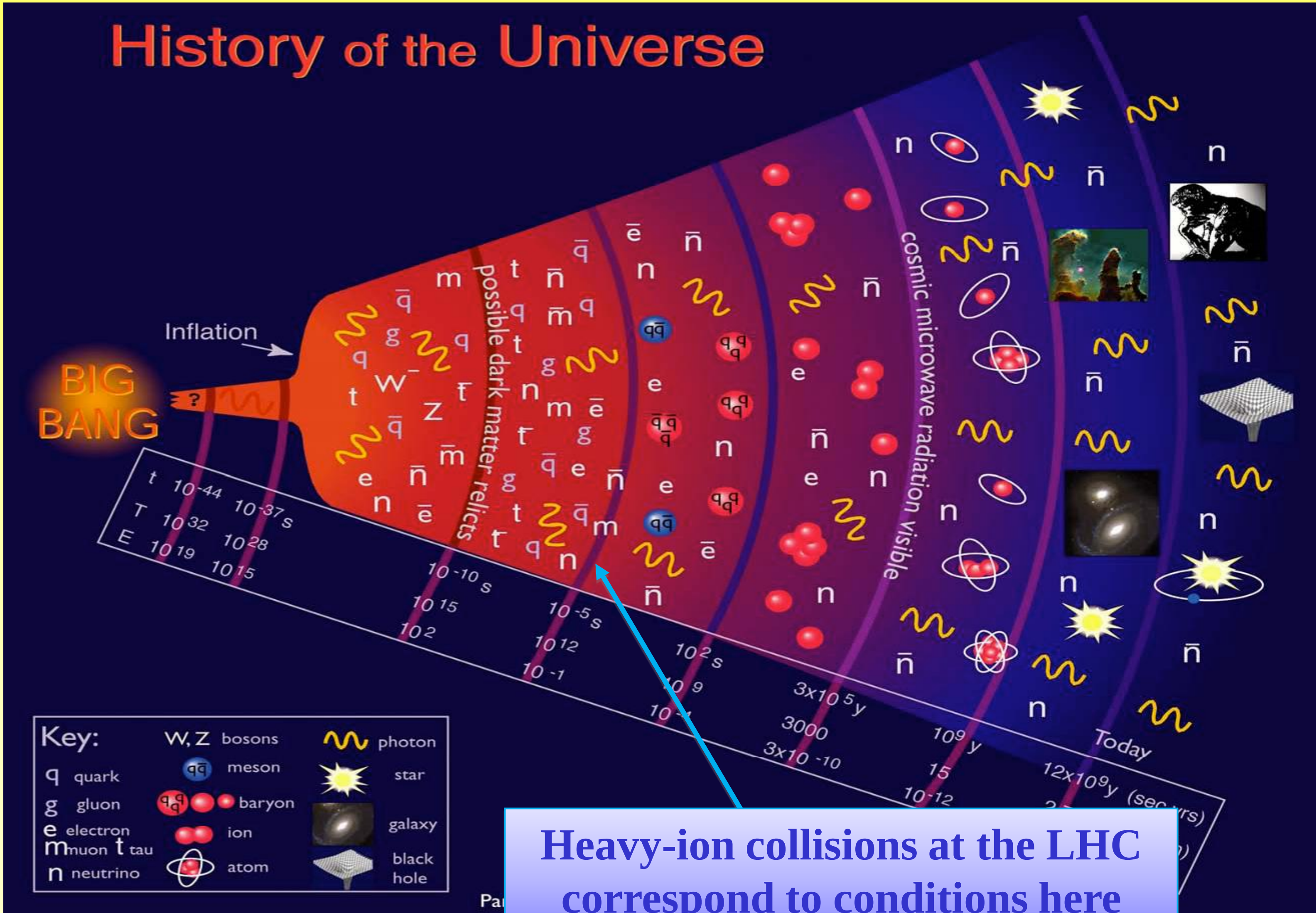
- What are the fundamental properties of strongly interacting matter as a function of temperature and density?
- What are the microscopic mechanisms responsible for them?
  - What are the microscopic degrees of freedom and excitations of matter at ultra---high temperature and density?
  - Which are its transport properties and equation of state?

- How did its properties influence the evolution of the early universe?
- How is mass modified by the medium it moves in?
- How do hadrons acquire mass?
- What is the structure of nuclei when observed at the smallest scales, i.e. with the highest resolution?

•**Heavy--Ion collisions:**
Laboratory studies of the bulk properties of non--Abelian matter

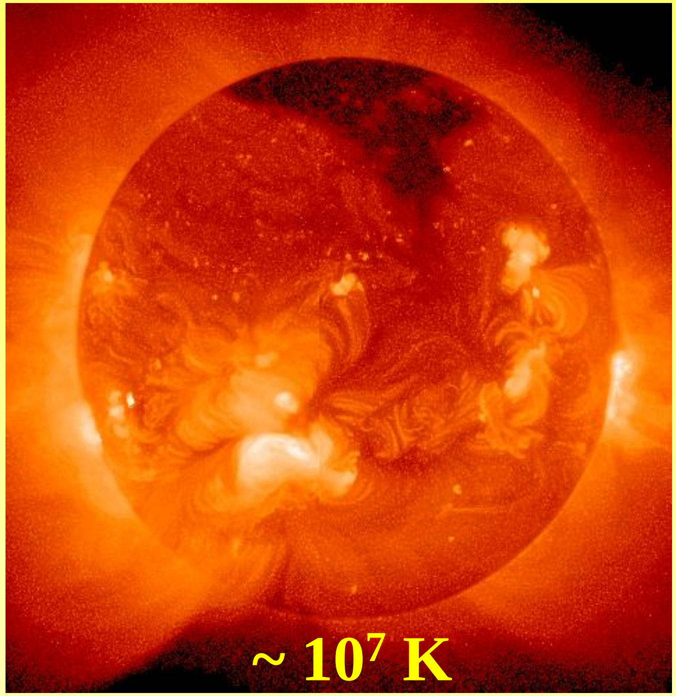
•...with deep connections to other fields in physics:
String Theory, Cosmology, Condensed Matter Physics, Ultra---Cold Quantum Gases

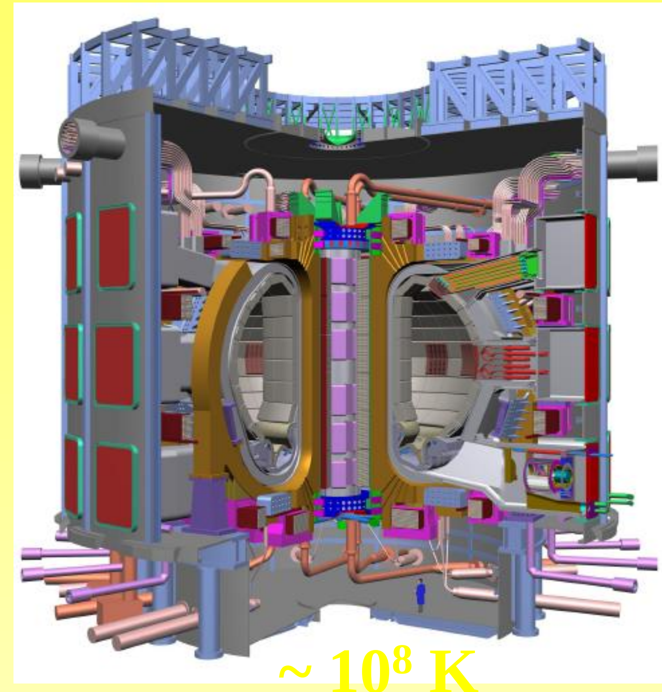
Brief History of Our Universe

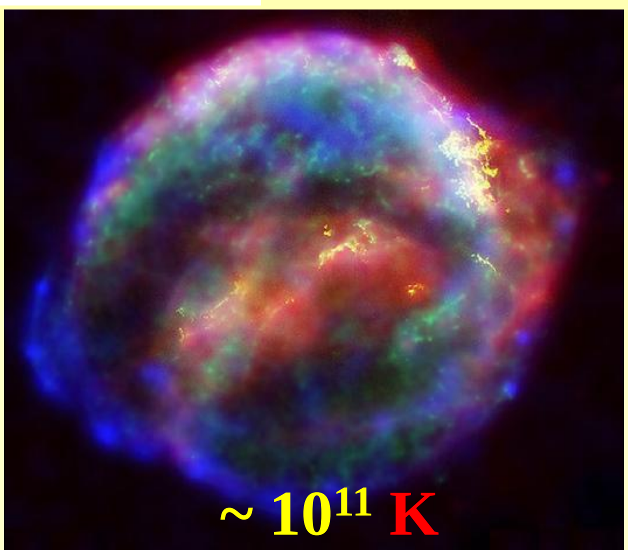


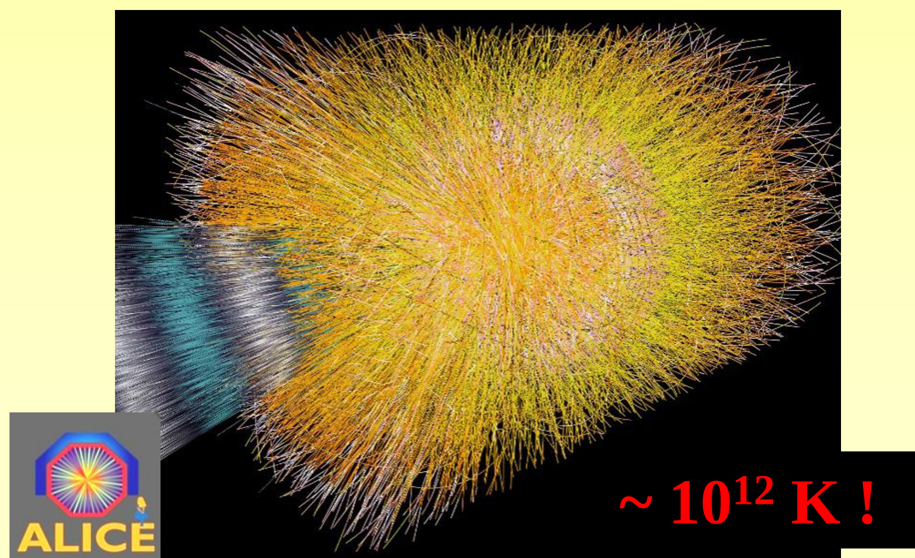
Many critical features of our universe were established in these very early moments. ***WHEN MATTER FIRST STARTED TO HAVE STRUCTURE***

Temperature ~ 170 MeV (~ 10^{12} K) : How hot is it? 100,000 times the temperature at the center of the Sun!





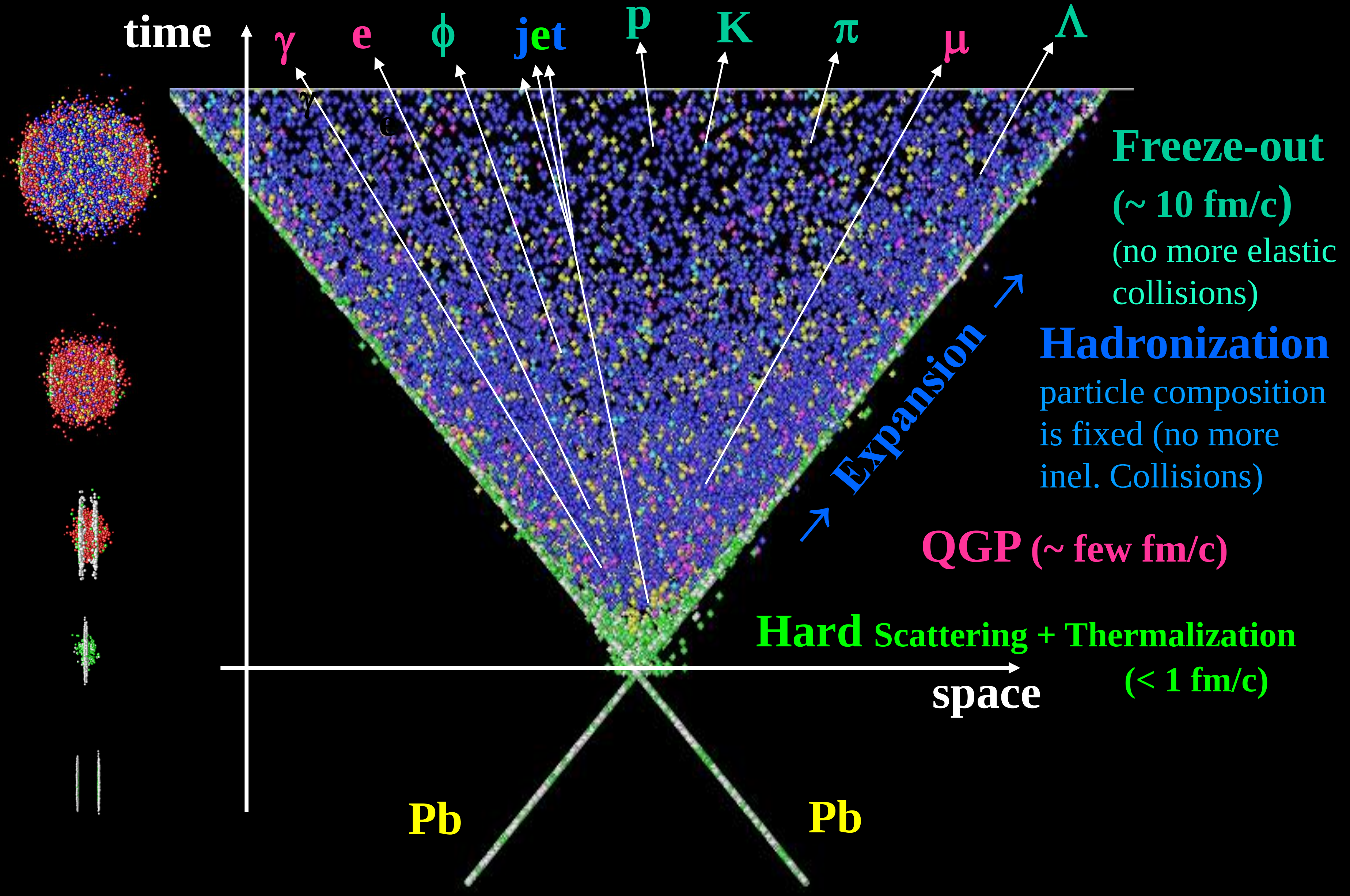




Why Heavy Ions @ LHC?

- It is a ***different matter*** as compared to RHIC (and even more to SpS)
  - Larger temperature, volume, energy density and lifetime
    - Study QGP properties vs T …
  - small net-baryon density at mid-rapidity ($\mu_B \approx 0$), corresponding to the conditions in the early universe
  - large cross section for '**hard probes**' : high p_T, jets, heavy quarks,…
  - First principle methods (pQCD, Lattice Gauge Theory) more directly applicable
  - new generation, large acceptance state-of-the-art detectors
    - Atlas, CMS, ALICE, [LHCb, for pA]
- A comprehensive program, ***complementary*** to the one at RHIC (and later FAIR)

Difficult! Space-time Evolution of the Collisions



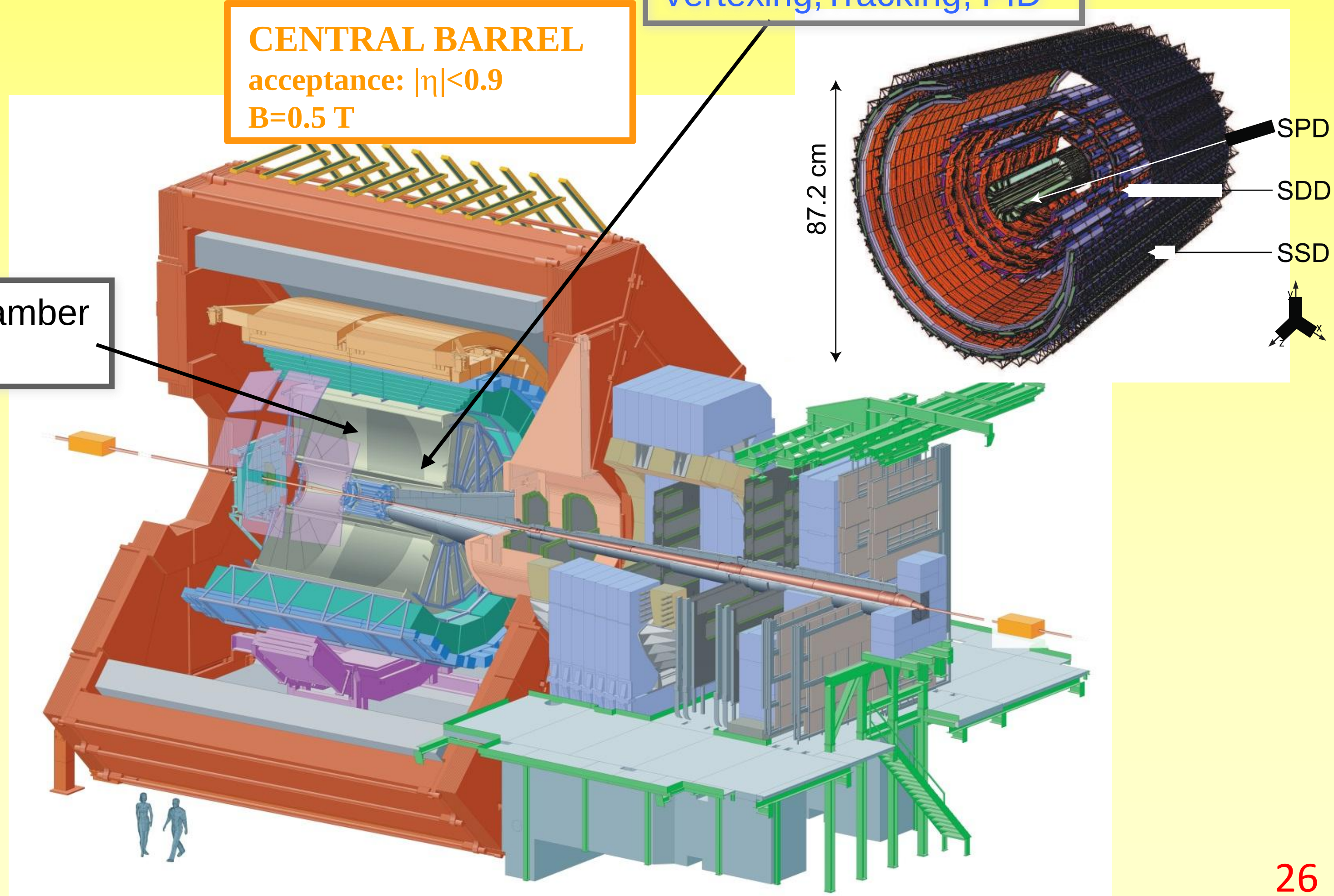
The Experiments

- ALICE
  - Experiment designed for Heavy Ion collision
    - only dedicated experiment at LHC, must be comprehensive and able to cover all relevant observables
    - **VERY robust tracking** for p_T from **0.1 GeV/*c*** to **100 GeV/*c***
      - high-granularity 3D detectors with many space points per track (**560 million** pixels in the TPC alone, giving 180 space points/track)
      - **very low material budget** (**< 10%X_0** in r < 2.5 m)
    - **PID** over a very large p_T range
      - use of essentially all known technologies: TOF, dE/dx, RICH, TRD, topology, EM calor.
    - Hadrons, leptons and photons + Excellent vertexing
- ATLAS and CMS
  - General-purpose detectors, optimized for hard processes
    - Excellent Calorimetry = > Jets
    - Excellent dilepton measurements, especially at high pT
    - Very large acceptance tracking
- Now Joined by LHCb for pPb
  - Excellent dilepton measurement and PID in forward direction

Each required 20 years of work by a worldwide collaboration...

ALICE detector specificities

Excellent track and vertex reconstruction capabilities (TPC, ITS) in a high multiplicity environment over a wide transverse momentum range



ALICE detector specificities

Particle identification over a wide momentum range

Inner Tracking System
Vertexing,Tracking, PID

CENTRAL BARREL
acceptance: |η|<0.9
B=0.5 T

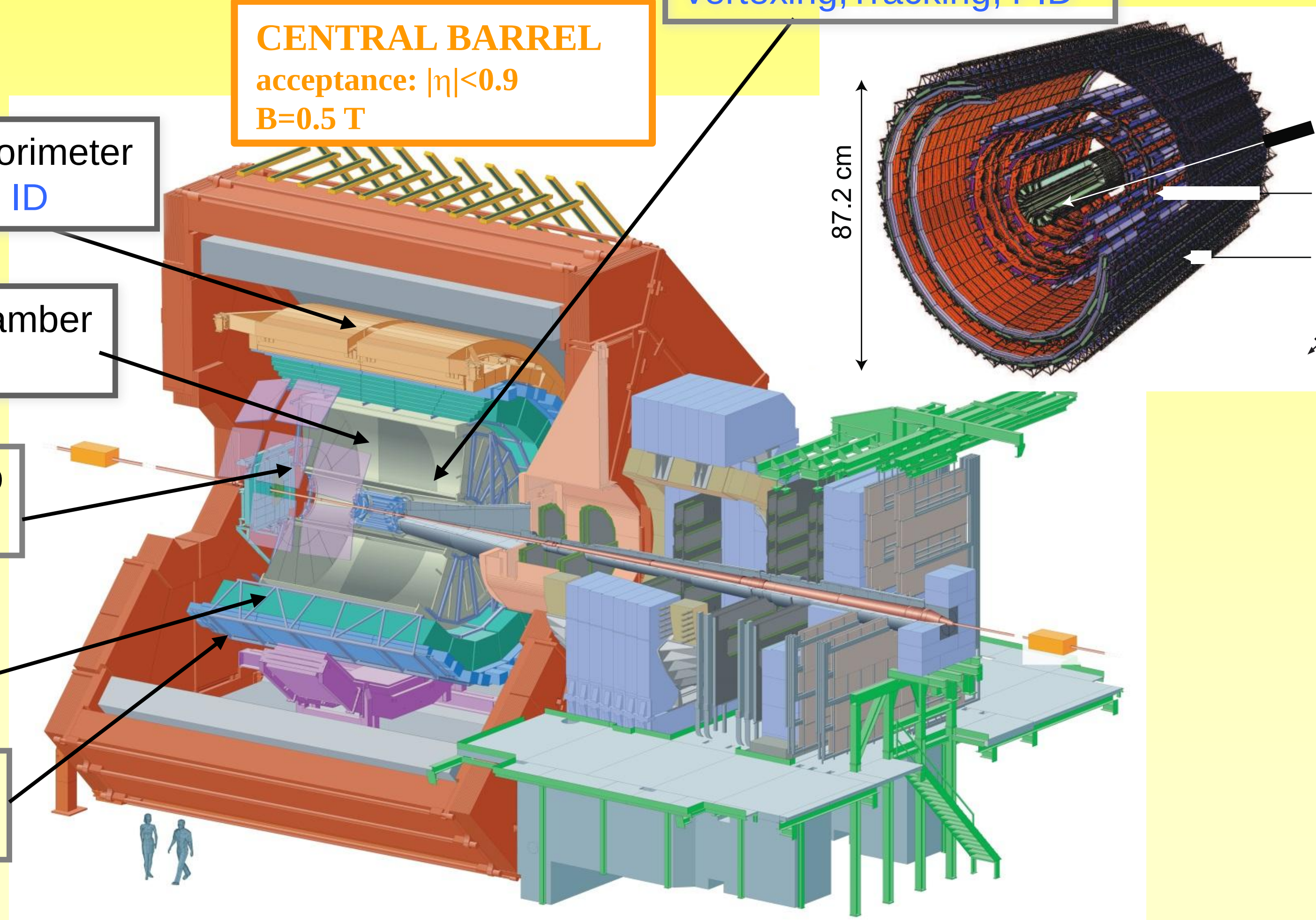
Eletro**M**agnetic **CAL**orimeter
Calorimeter, electron ID

Time **P**rojection **C**hamber
Tracking, PID

High **M**omentum **PID**
PID

Transition **R**adiation **D**etector
PID

Time **O**f **F**light
PID



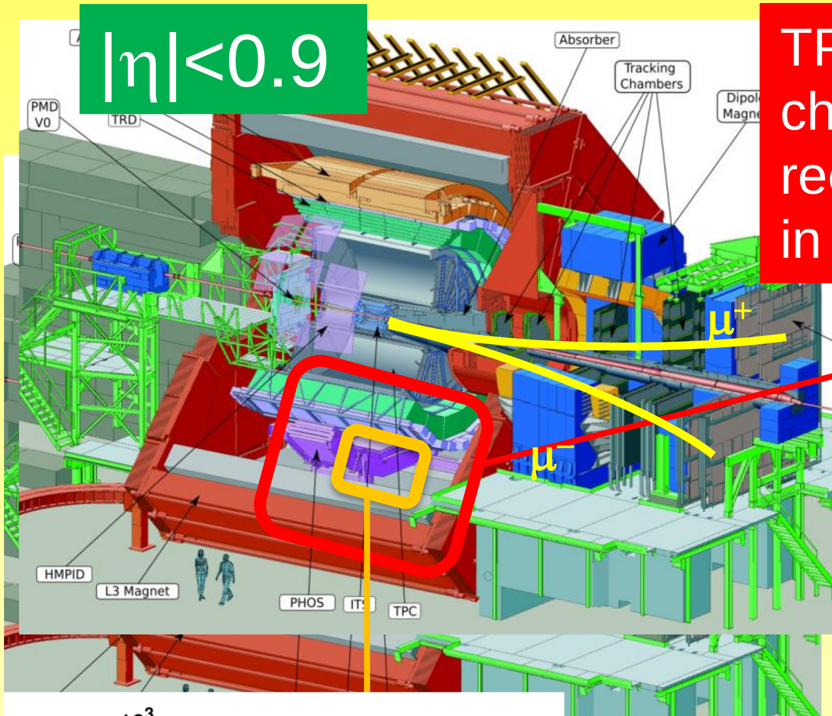
ALICE performance: tracking/vertexing

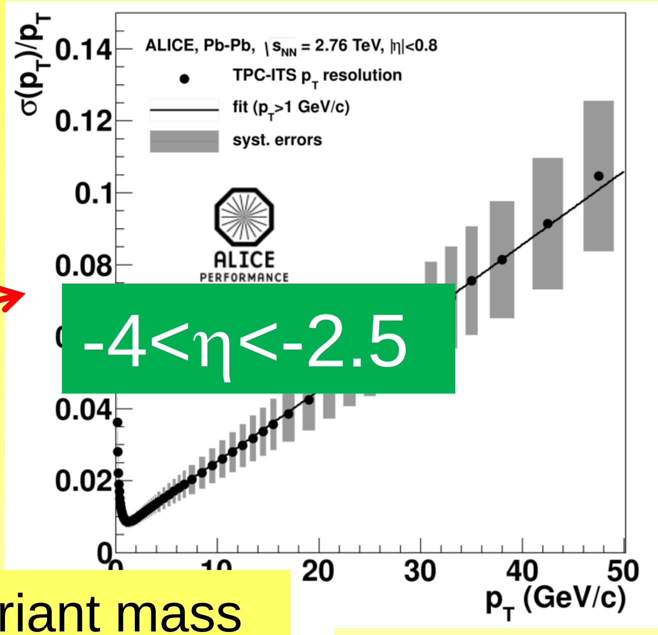
|η|<0.9

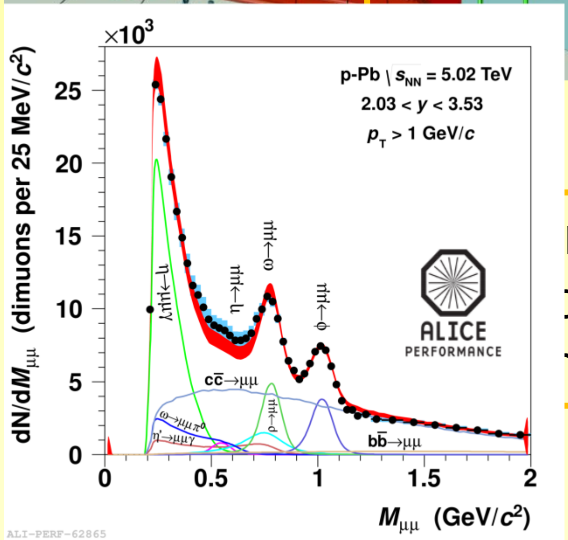
TPC+ITS: charged track reconstruction in |η| < 0.9

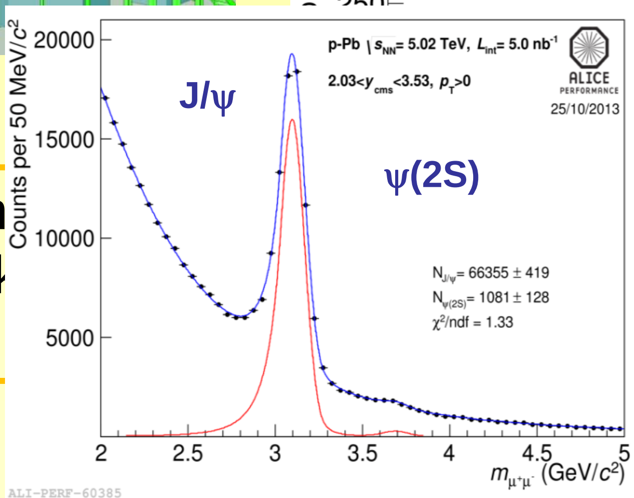
-4<η<-2.5

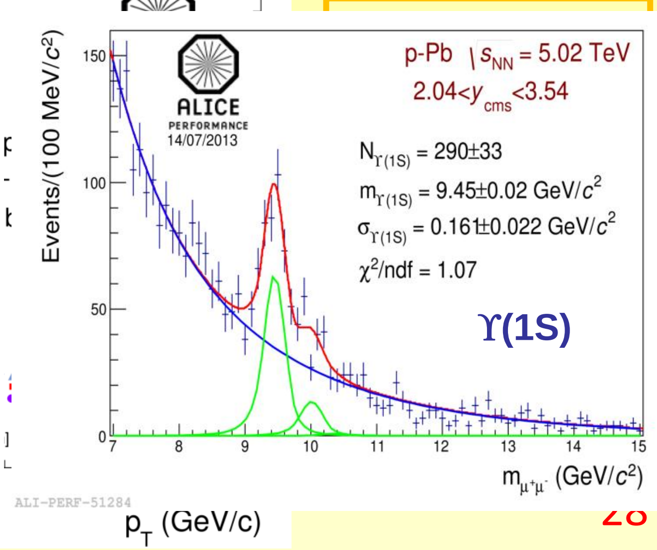
Di-muon invariant mass



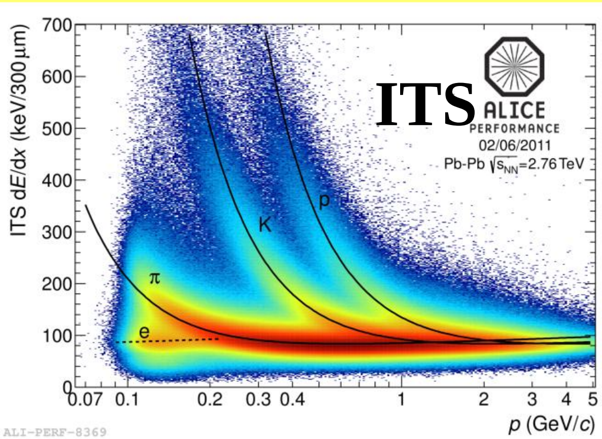


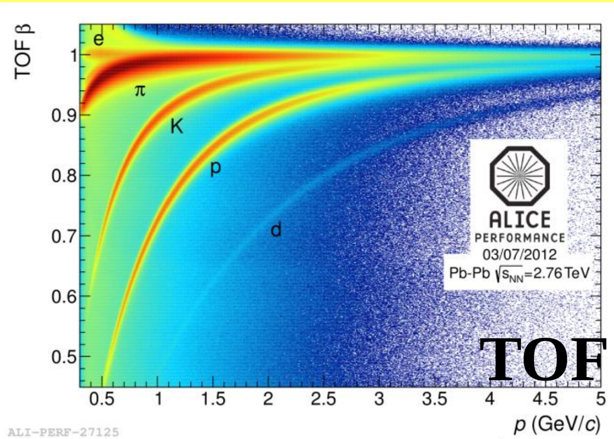


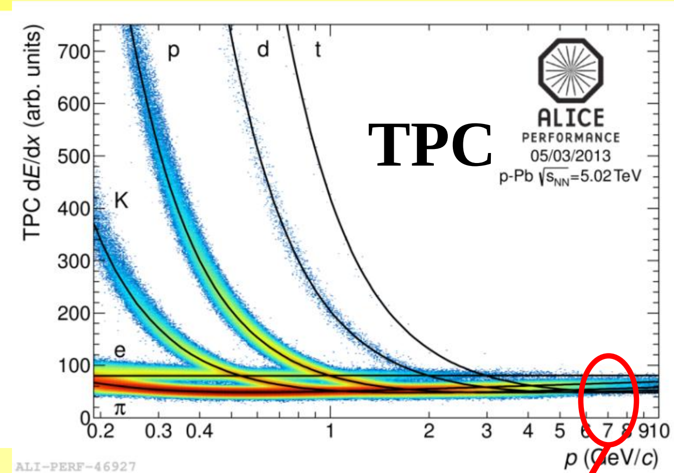


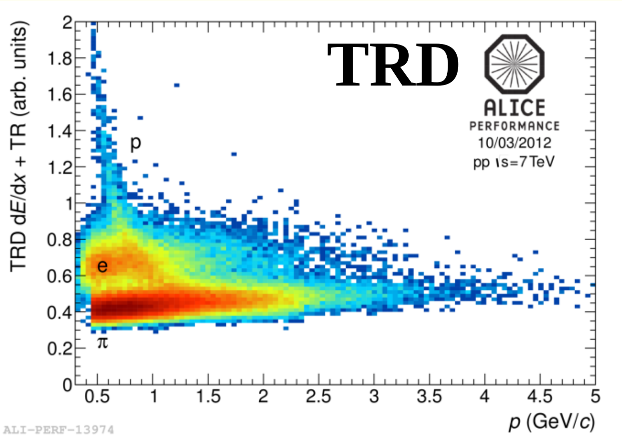


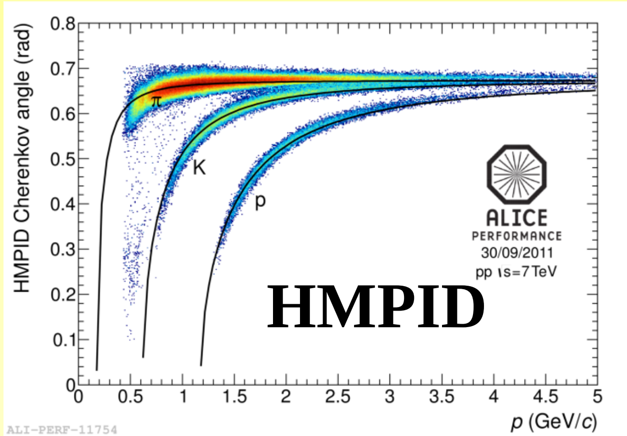
ALICE performance: PID

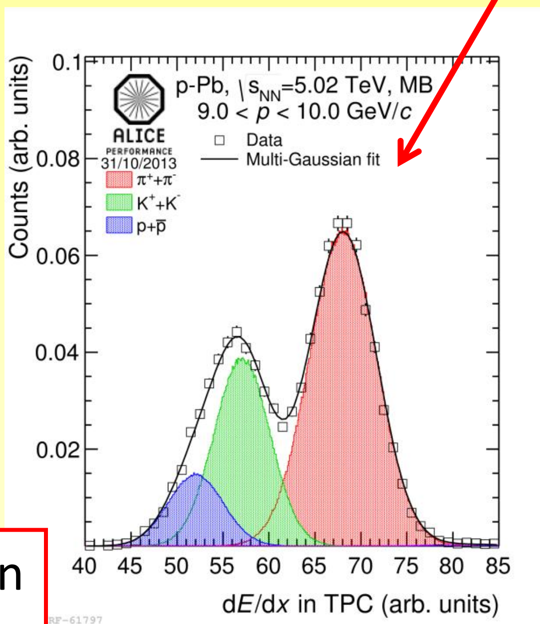












- ALICE uses practically all known techniques

Statistical separation in relativistic rise region

The ALICE program

Core Business: PbPb

- **Study the properties of strongly interacting matter under extreme conditions of temperature and density.**
  - Understand confinement, producing and studying in the lab a deconfined plasma of quark and gluons (QGP)
  - Understand evolution of matter from the hot and dense deconfined phase towards ordinary hadrons (analogous to the early Universe evolution)

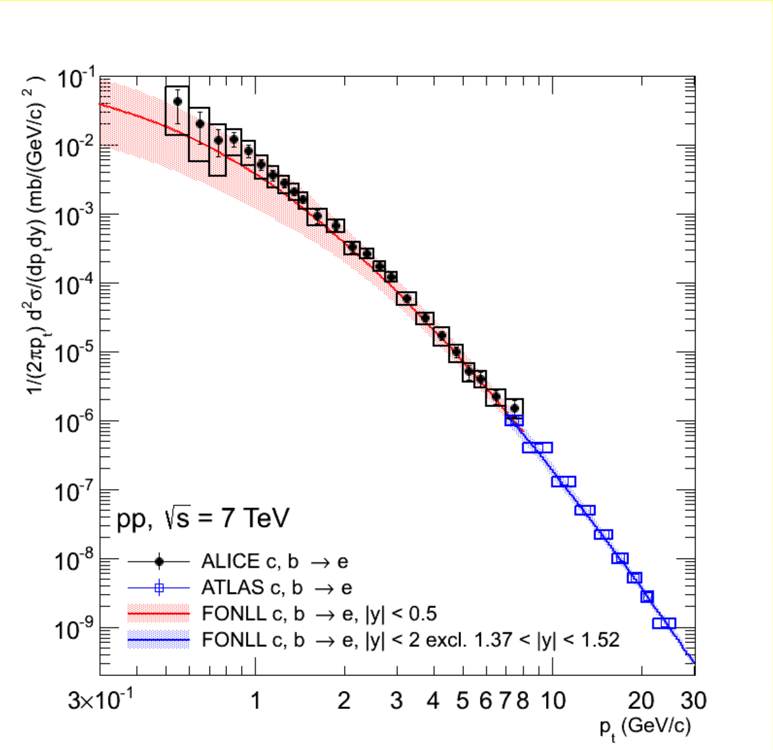
pp

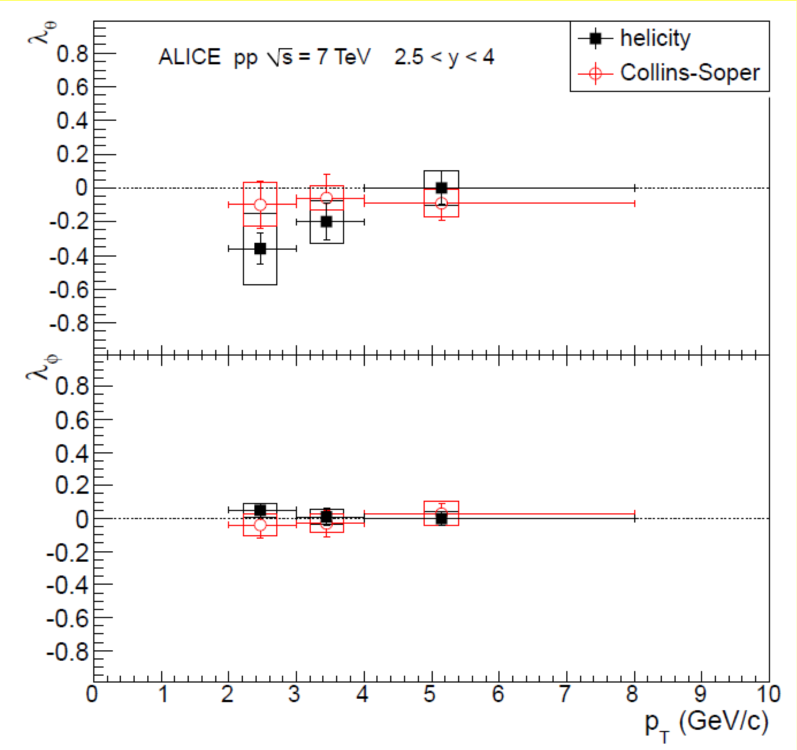
- collect 'comparison data' for heavy ion program
  - many observables measured 'relative' to pp
- comprehensive study of MB@LHC
  - tuning of Monte Carlo (background to BSM)
- soft & semi-hard QCD
  - very complementary to other LHC experiments
  - address specific issues of QCD
- very high multiplicity pp events
  - dN_{ch}/dh comparable to the one in HI => mini-plasma ?

pA

- Control experiment for PbPb
  - pp and pPb measurement are used as reference for the Pb-Pb ones.
- Important measurements in their own right
  - Probe nucleus structure in a QCD regime of very small-x (gluon saturation, shadowing,…)

A taste of pp results



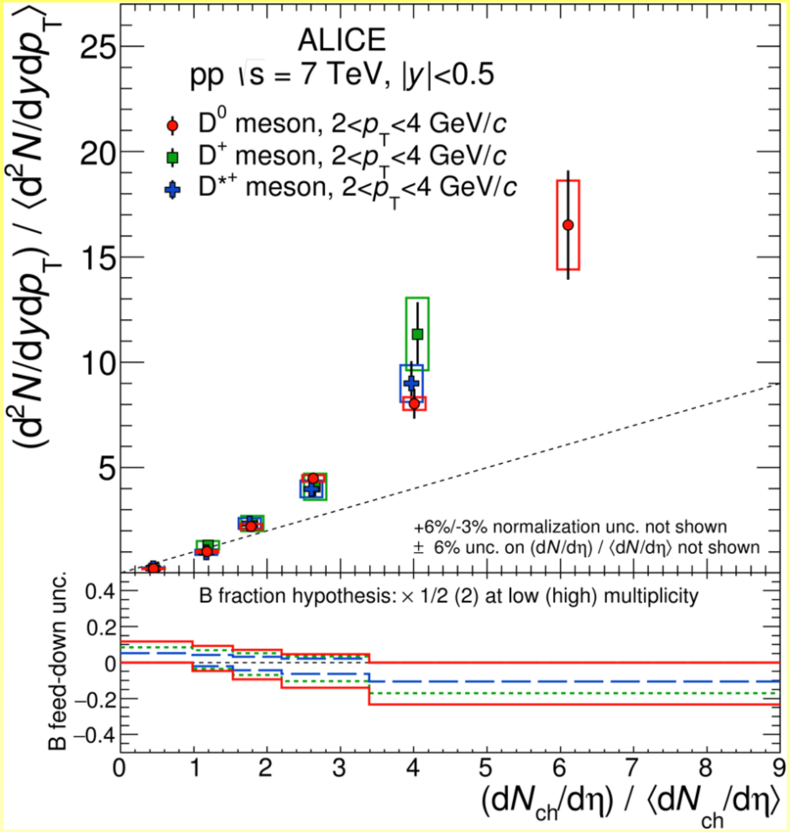


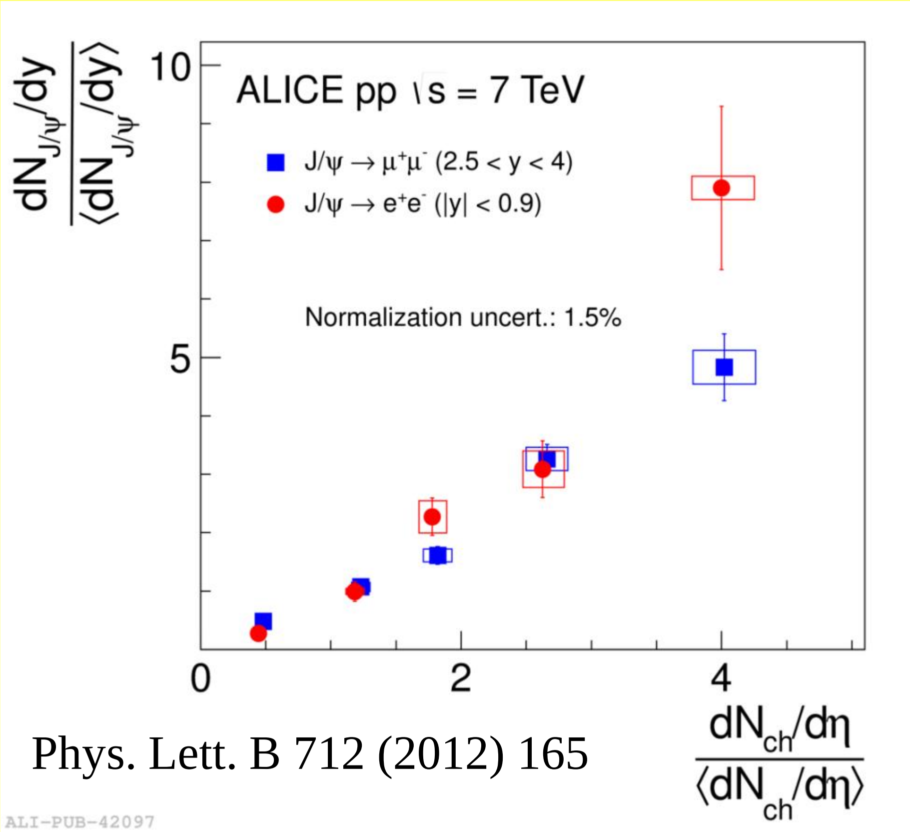
Electrons from Heavy Flavors
=> Complementarity with ATLAS

First measurement of J/ψ polarization at LHC

Phys.Rev.Lett. 108 (2012) 082001

High-multiplicity pp collisions



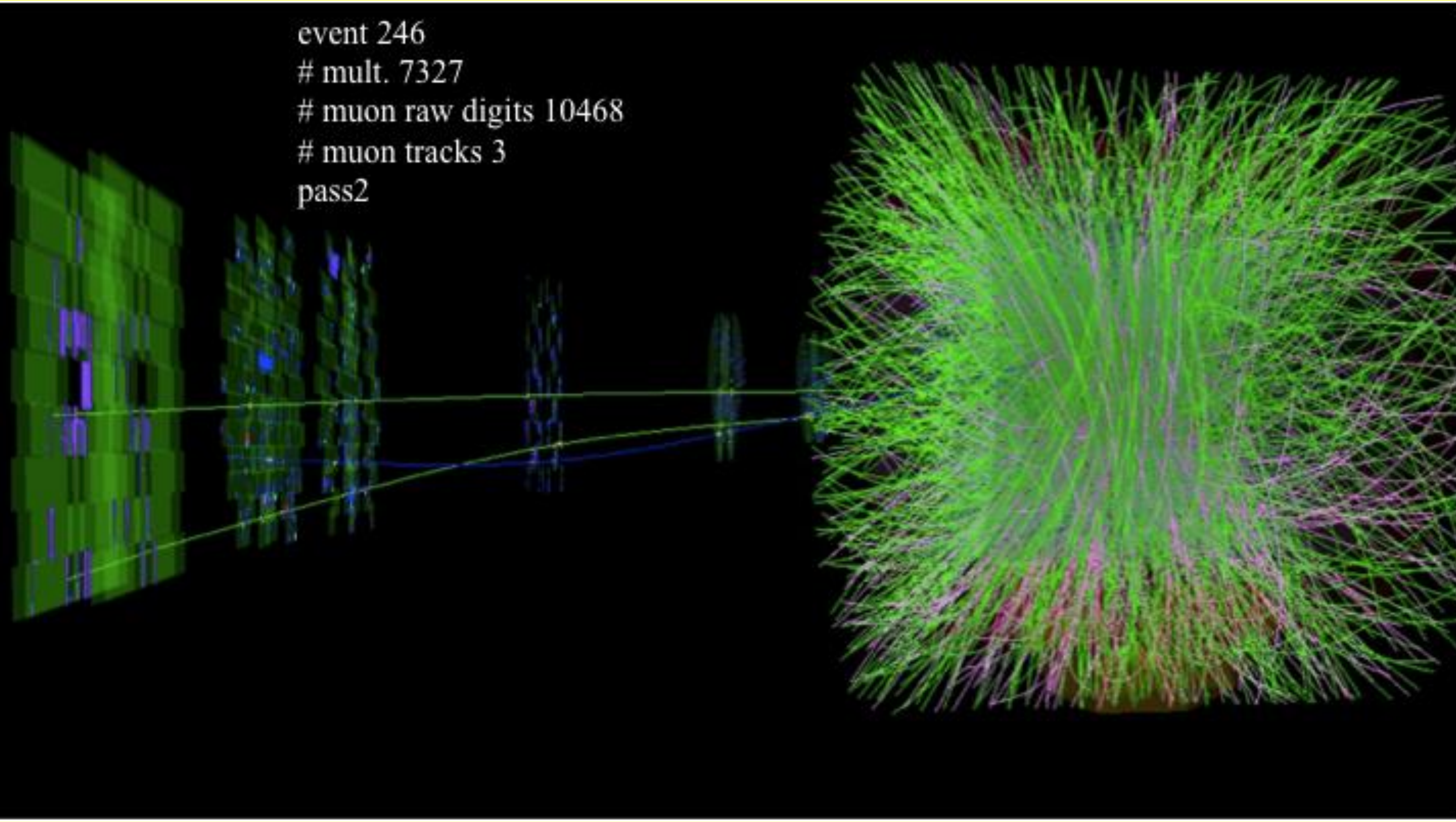


Phys. Lett. B 712 (2012) 165

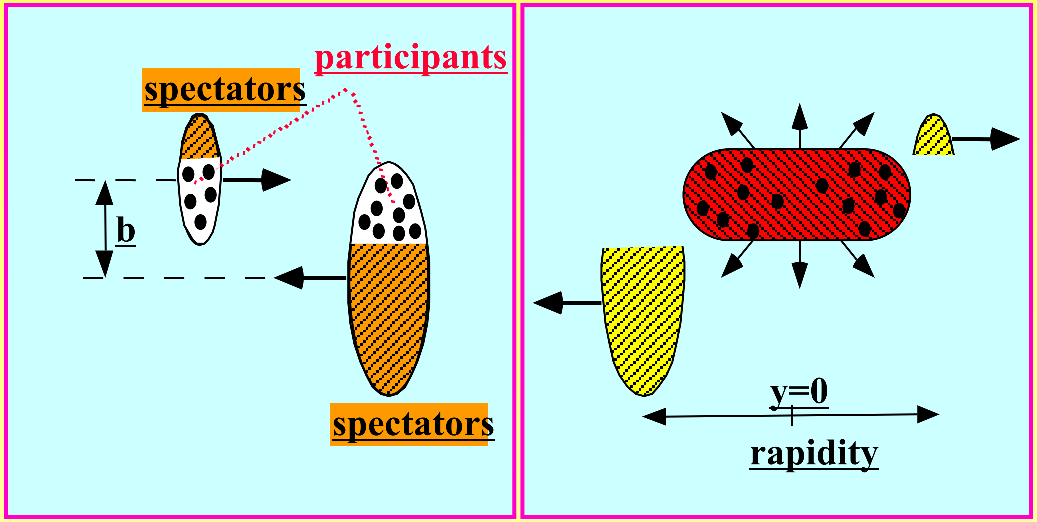
Multiplicity dependence of open-charm and J/psi yield

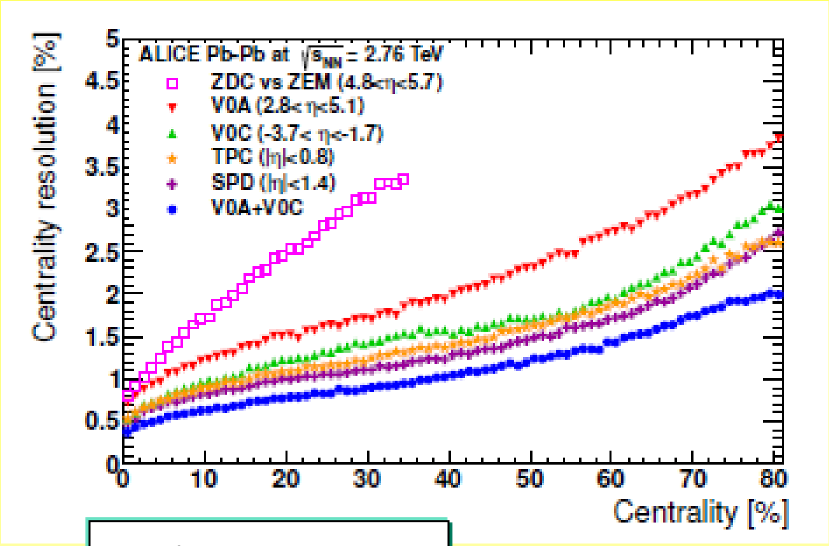
- Increase of D-meson yield with multiplicity beyond naïve assumptions
- Factor of 15 increase for the highest multiplicities!
- Multi Parton Interactions?
- Do we understand pp? Core program for 2015 pp data taking

Heavy-Ions!

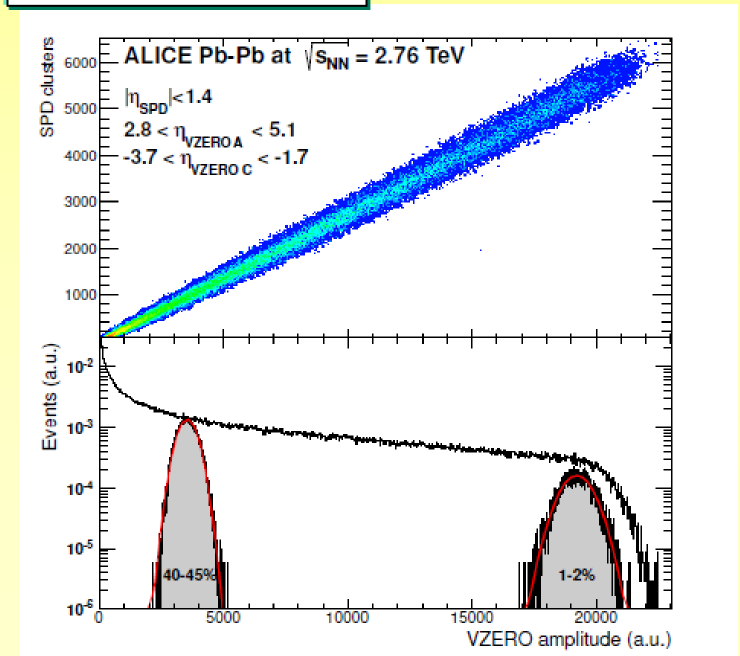

event 246
mult. 7327
muon raw digits 10468
muon tracks 3
pass2

Initial Conditions





arXiv:1301.4361



Centrality Determination

- Essential in all HI analysis, in ALICE based on correlation between:
  - clusters measured in central rapidity region
  - amplitudes of the signals in the
    forward region detectors:
    - VZERO scintillators $2.8 < \eta < 5.1$
    - $-3.7 < \eta < -1.7$

    ZERO Degree Calorimeters
- With the full VZERO detector the resolution ranges from 0.5% in central collisions to 2% for peripheral

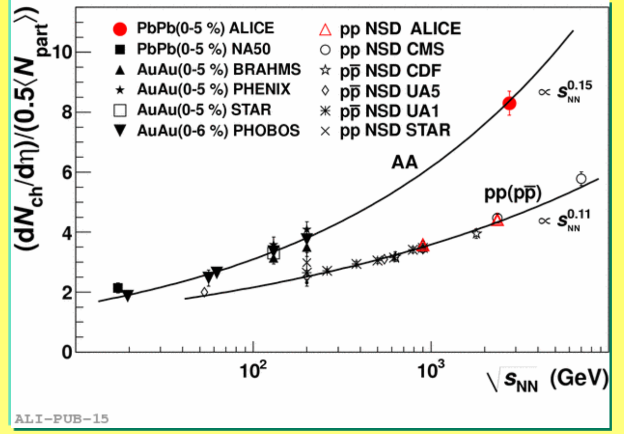
Global properties

- Fr
  de

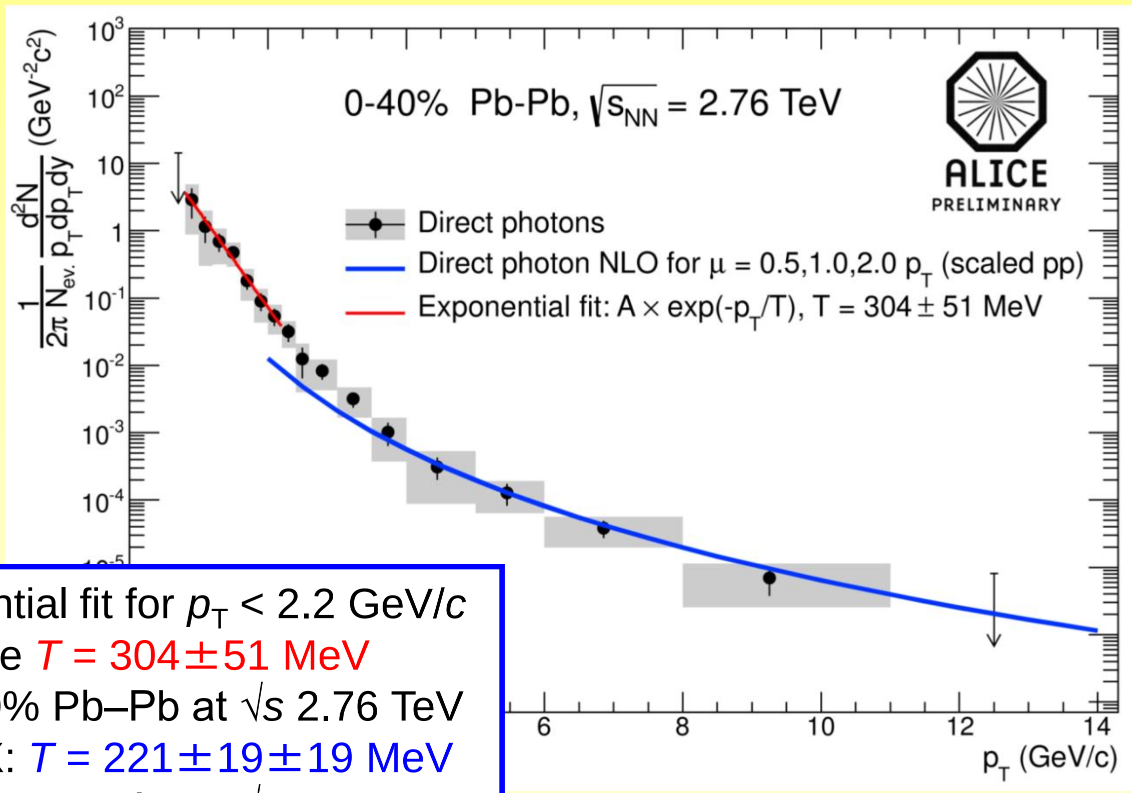
Matter under extreme conditions:

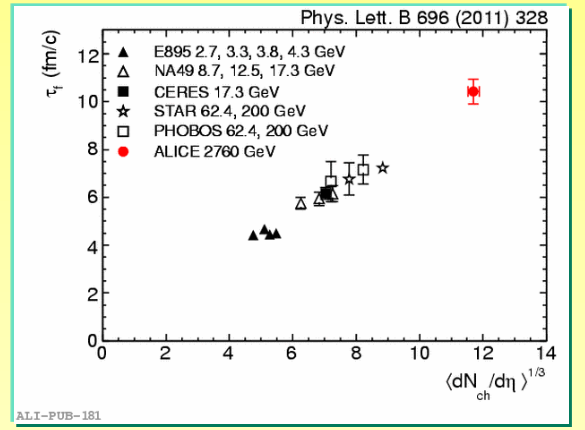
~ 50 times the density of neutron star core
(40 billion tons/cm3)
50 protons packed into the volume of one p
Highest temperature ever measured
More than enough for deconfinement

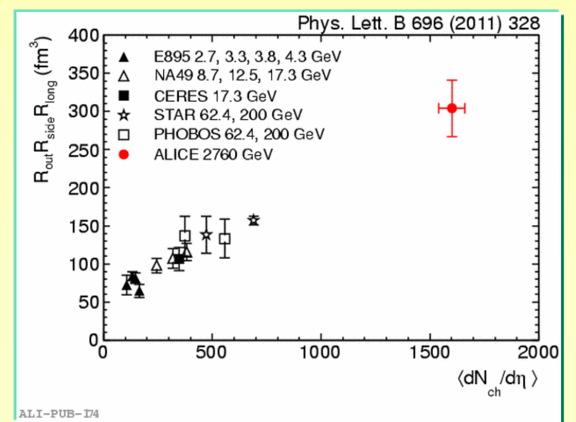
- T



$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$







Exponential fit for p_T < 2.2 GeV/c
inv. slope T = 304±51 MeV
for 0–40% Pb–Pb at √s 2.76 TeV
PHENIX: T = 221±19±19 MeV
for 0–20% Au–Au at √s 200 GeV

Measuring Volume & Lifetime

- Identical particle interferometry (Bose Einstein Correlations, HBT)
  - Quantum mechanical interference => Bose-Einstein / Fermi-Dirac statistics enhanced(bosons)/suppressed(fermions) occupation of quantum states
    - Bose Einstein Condensate at zero temperature (all particles in same state)
    - used to measure star diameter ($\gamma\gamma$) Hanbury-Brown & Twiss (ca 1953)
    - used in high energy physics ($\pi\pi$) Goldhaber (ca 1959)
- measure extend of dynamical (evolving) source

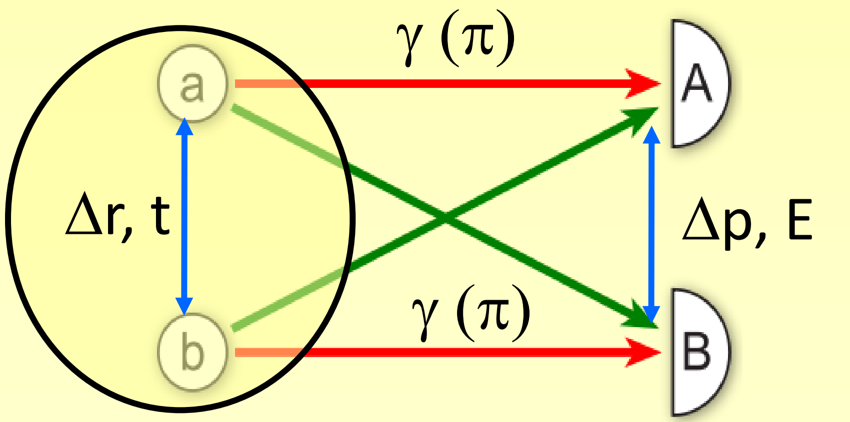
Source distribution **space & time**

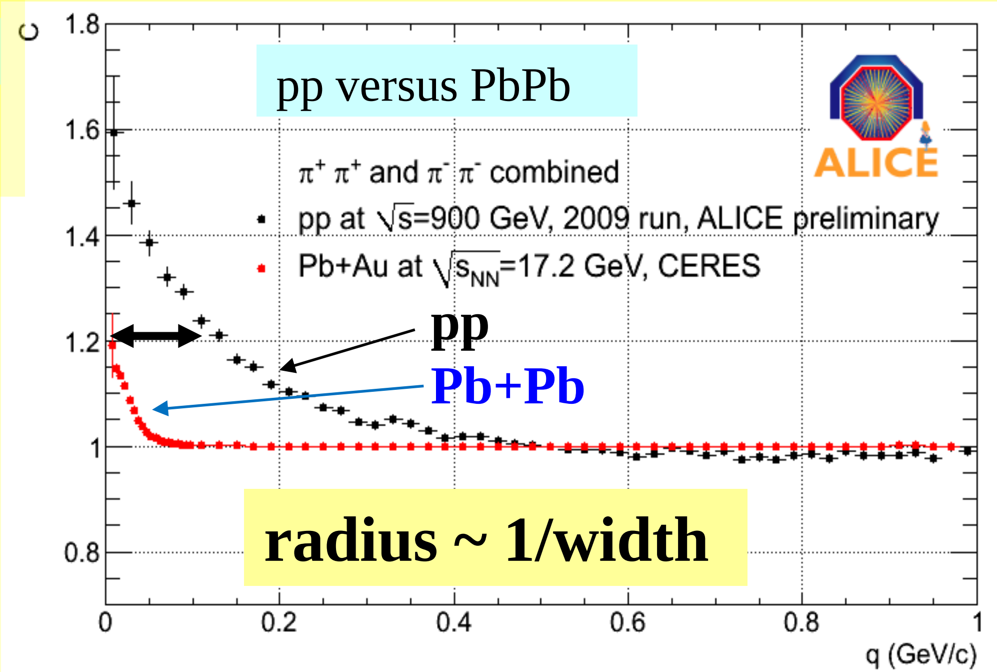
⇓

<u>Fourier Transform</u>

⇓

Particle correlations in **momentum & energy**

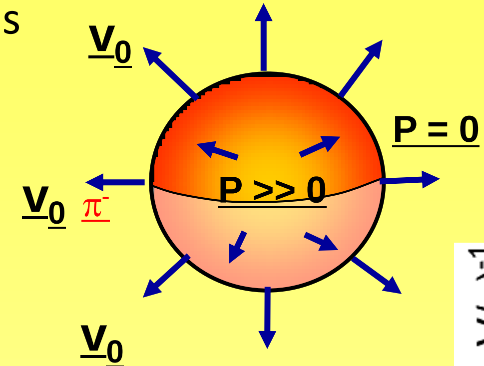




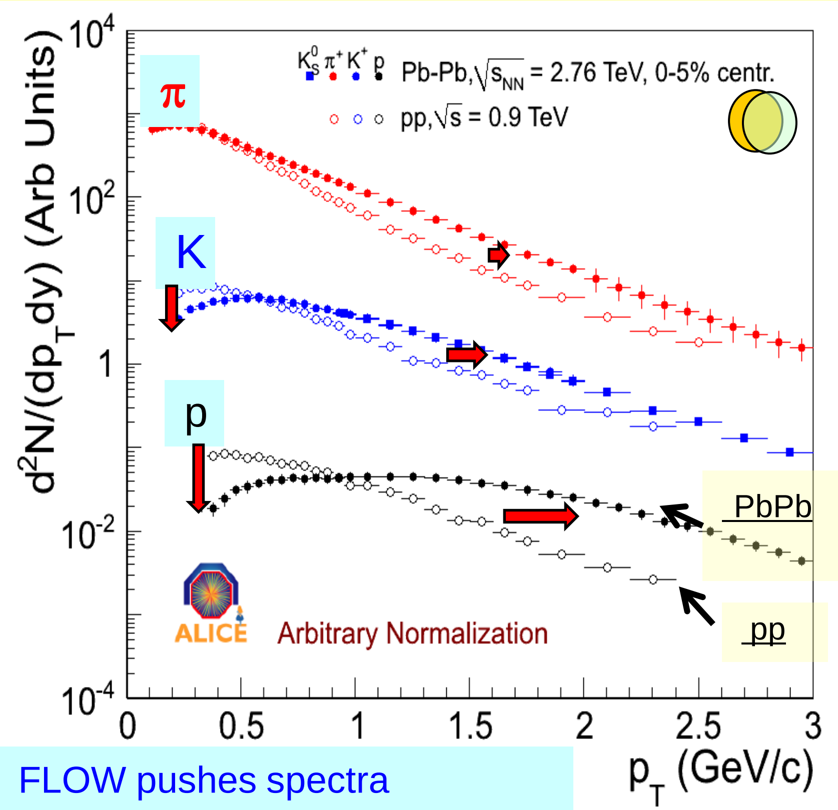
Radial Flow

- pressure **P** in center drives expansion
- flow velocity $\beta = v_0/c$ depends on **f(P, τ, EoS,)**
- momentum $p = \gamma\, m\, v_0$ => particles of different mass have characteristic & different momentum

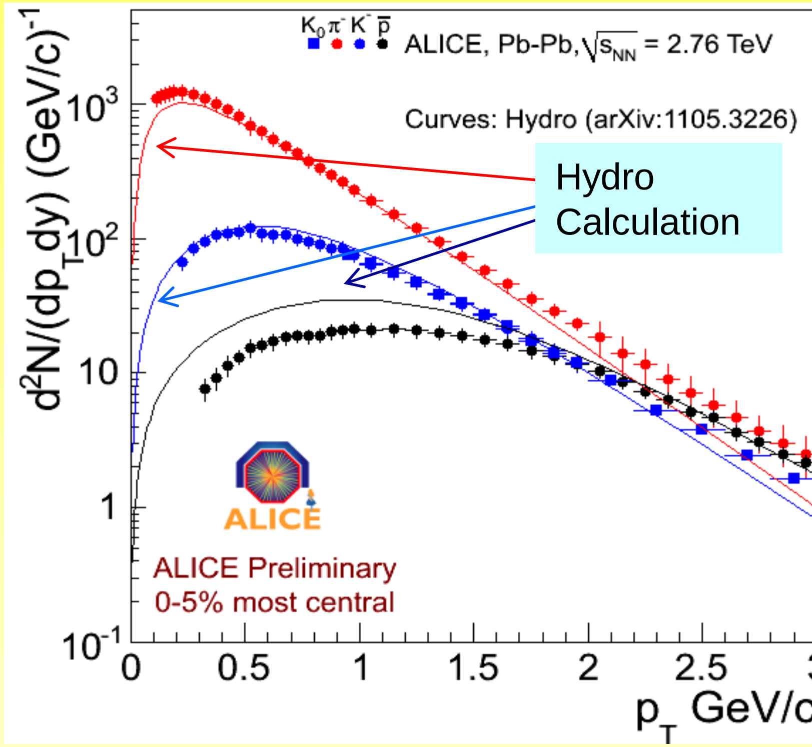
isotropic **radial** flow



Particle Flow: hydro properties of the plasma



FLOW pushes spectra depending on mass



IDENTIFIED PARTICLE SPECTRA @LHC: significant changes in slope compared to RHIC

Most dramatically for protons

Very strong radial flow, $\beta \approx 0.66$

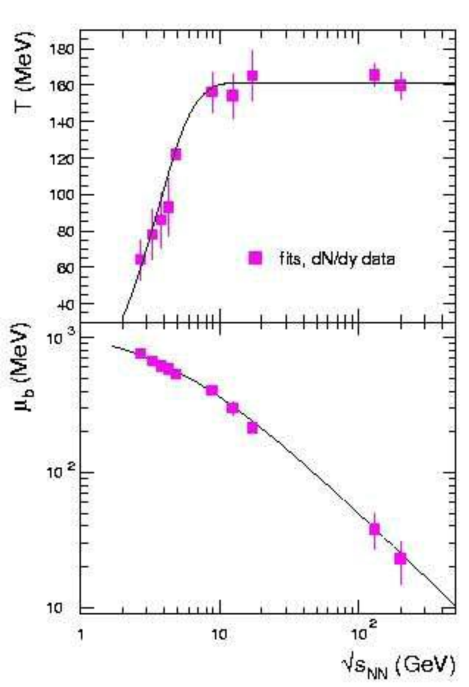
(2/3 of c!) even larger than predicted by most recent hydro

Particle Production: Hadrochemistry

- Many particle types produced: π(u<u>**d**</u>),p(uud), K(u<u>s</u>), Λ(uds),Ξ(uss),Ω(sss),….
  - production ratios can not be calculated with QCD (non-pertubative)
    - phenomenological models ('event generators') use many adjustable parameters
- Statistical ('thermal') models:

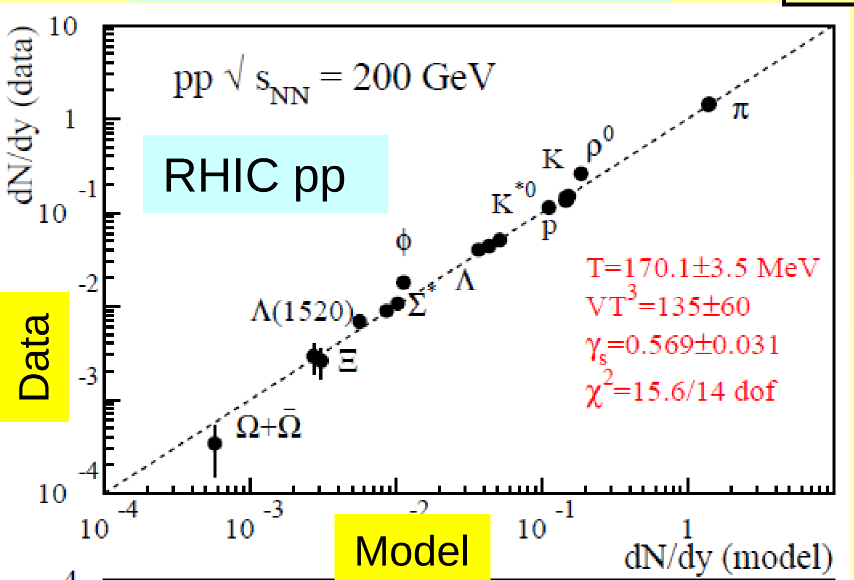
particle with mass *m* produced in 'heat bath T' according to phase space

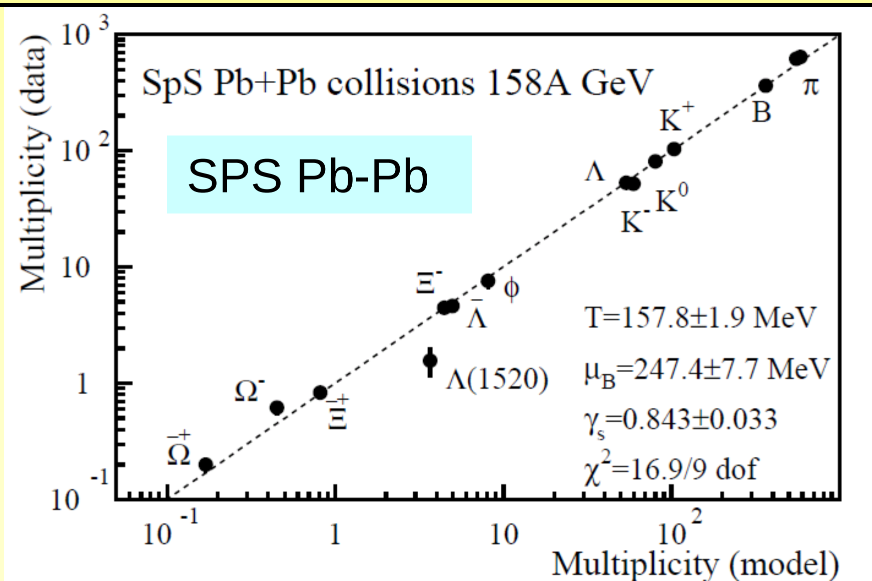
- $P(m) \sim e^{-(m/T)}$; fit depends on
  - T Temperature
  - μ_b Baryo-chemical potential (baryon conservation)
  - γ_s Strangeness suppression



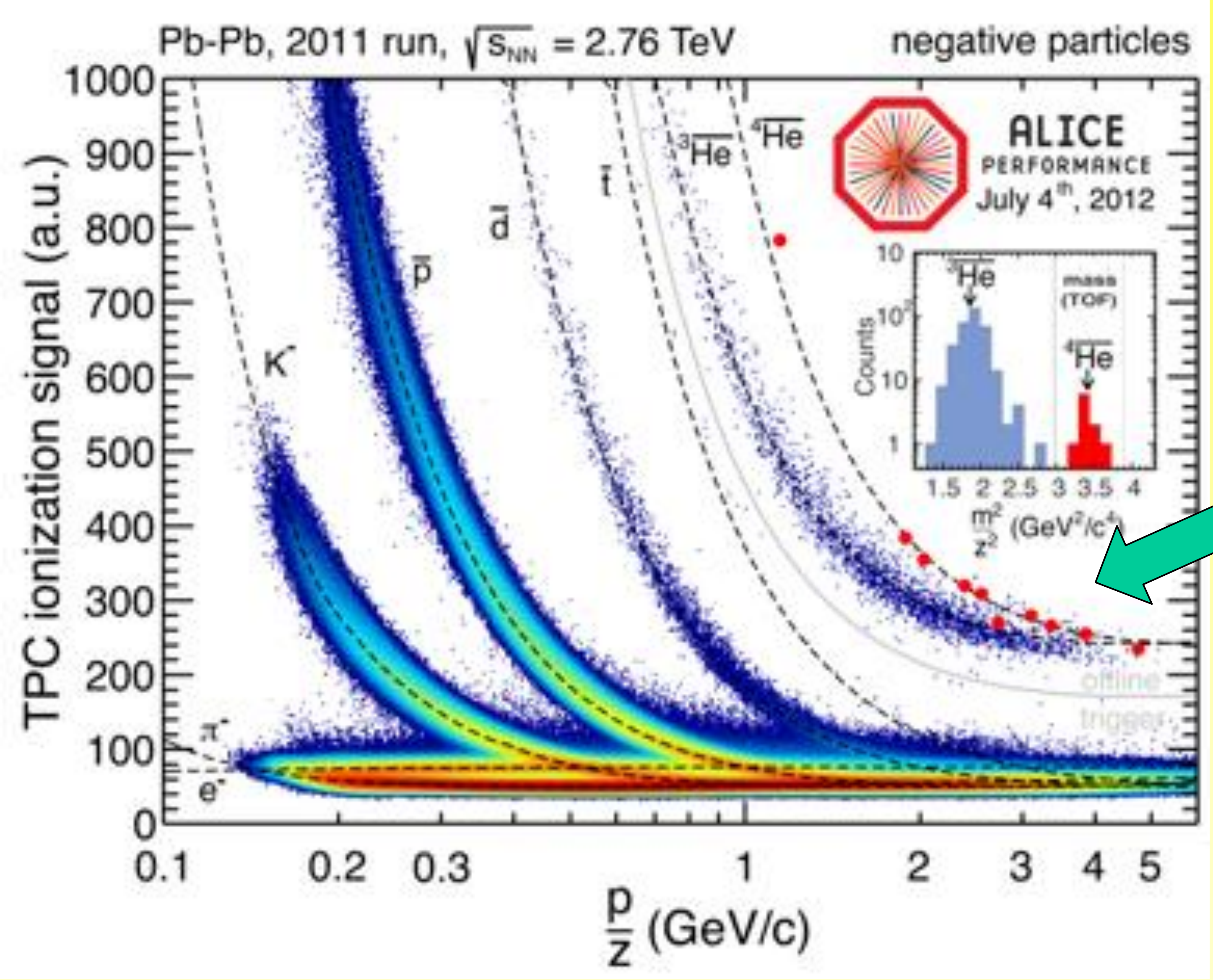
T_{ch}: 160-170 MeV γ_s : 0.9-1 (AA), 0.5-0.6 (pp)
strangeness enhancement = QGP signal ?

particles created per collision





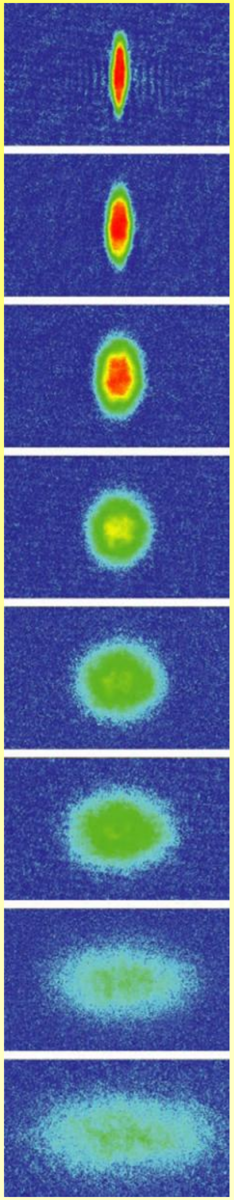
An antimatter factory



Anti-^{4}He is the heaviest anti-nucleus ever observed

Azimuthal Asymmetry

SCIENCE Vol: 298 2179 (2002) ^{7}Li



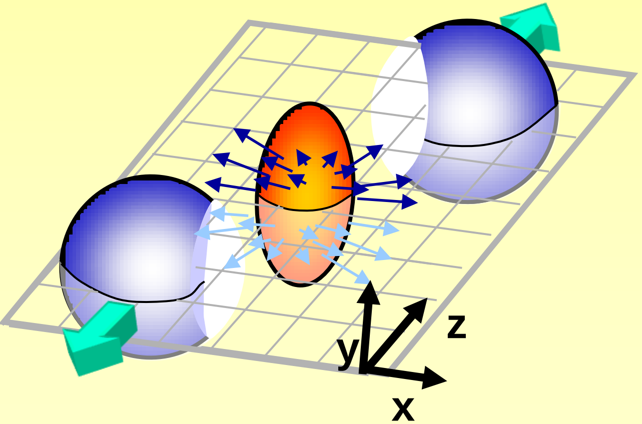
Ultra-cold ^{7}Li 10^{-12} eV , 2 ms of expansion

- Fourier expansion of azimuthal distribution:

$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T dy} \left(1 + 2v_1 \cos(\varphi) + 2v_2 \cos(2\varphi) + \ldots\right)$$

$v_1 = \langle \cos\varphi \rangle$ "directed flow"

$v_2 = \langle \cos 2\varphi \rangle$ "elliptic flow"



Flow: Correlation between coordinate and momentum space => azimuthal asymmetry of interaction region transported to the final state

$\rightarrow$ measure the strength of collective phenomena

Large mean free path

particles stream out isotropically, no memory of the asymmetry

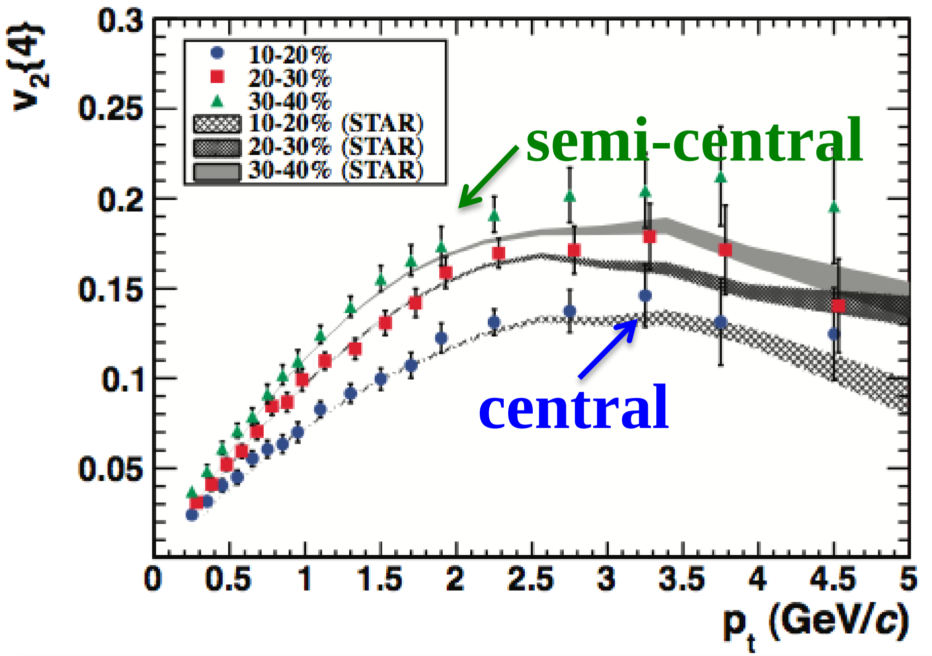
extreme: ideal gas (infinite mean free path)

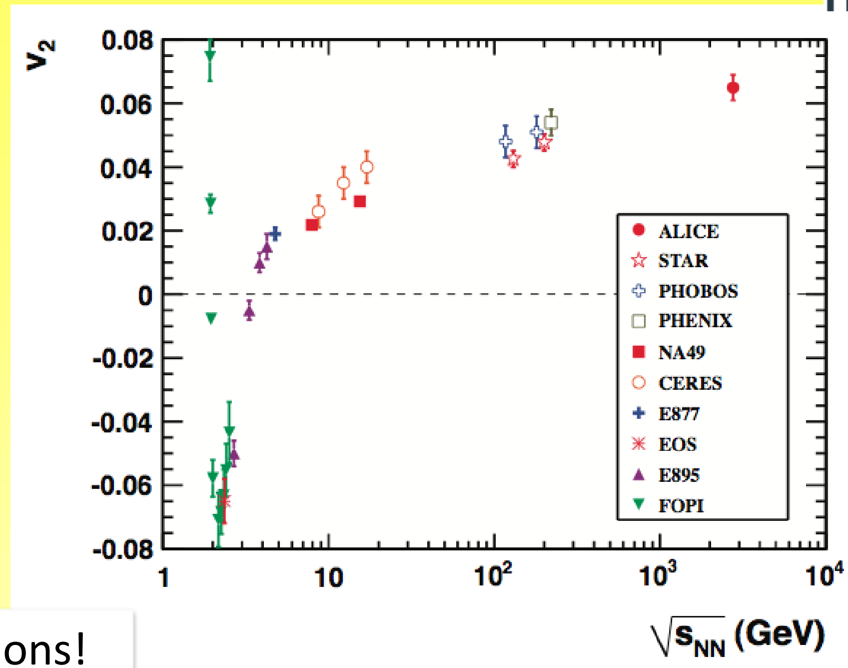
Small mean free path

larger density gradient -> larger pressure gradient -> larger momentum

extreme: ideal liquid (zero mean free path, hydrodynamic limit)

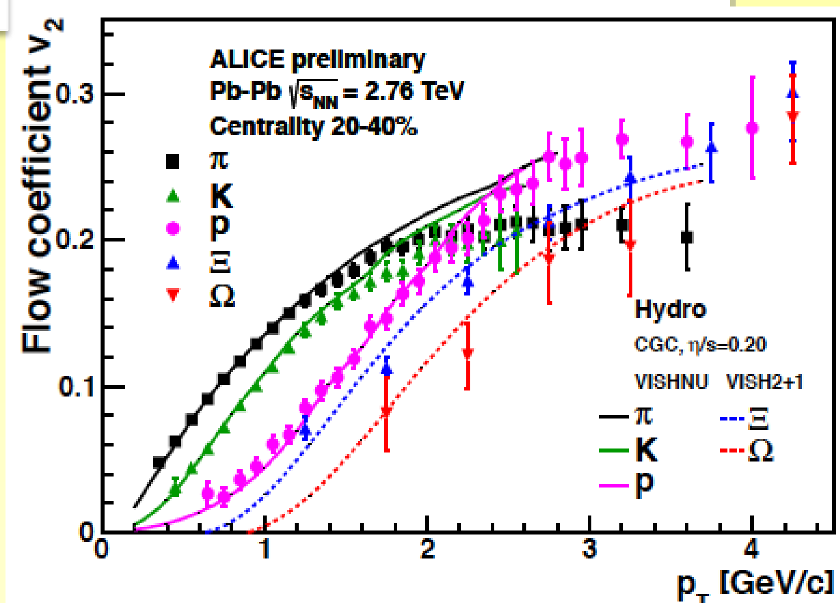
v_2 Measurements at the LHC





PRL 105, 252302 (2010), already over 300 citations!

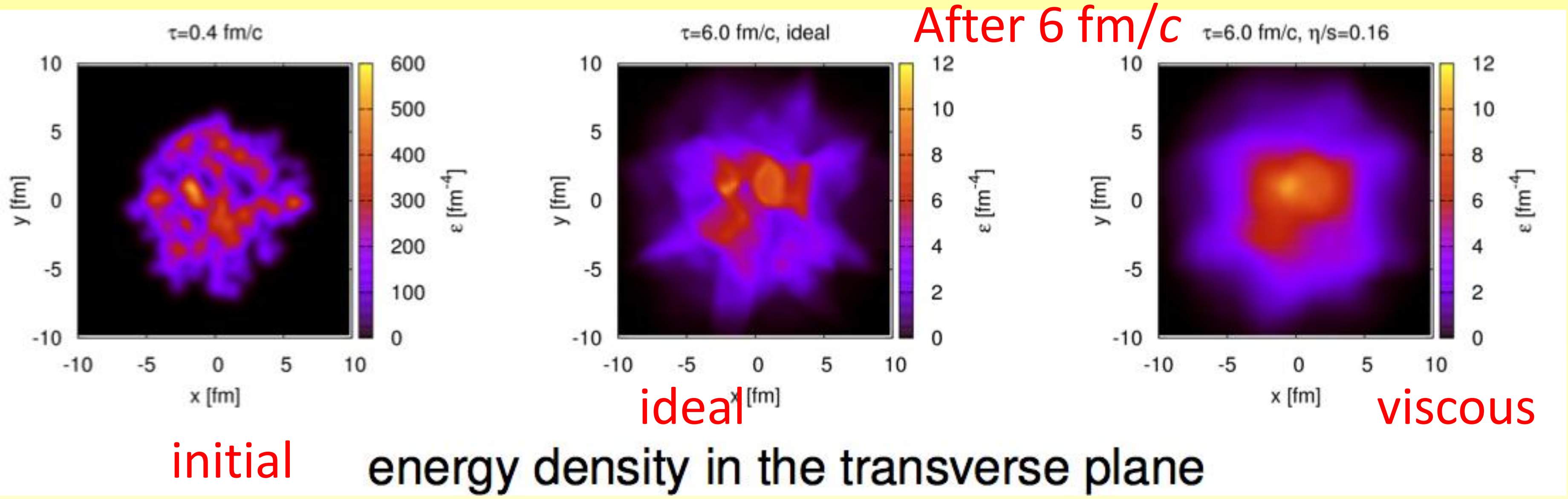
- **Collective behavior observed in Pb-Pb collisions at LHC (+30% vs. v_2^{RHIC}) => ideal fluid behavior (extremely low ratio of sheer viscosity to entropy density $\eta/s \approx 0$), very similar p_T dependence and values to RHIC**
- **Testing hydrodynamical evolution**



Flow as a tool

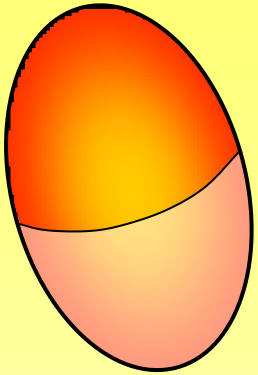
- Understand initial conditions and fluctuations; measure the transport properties (e.g. η/s) of the medium

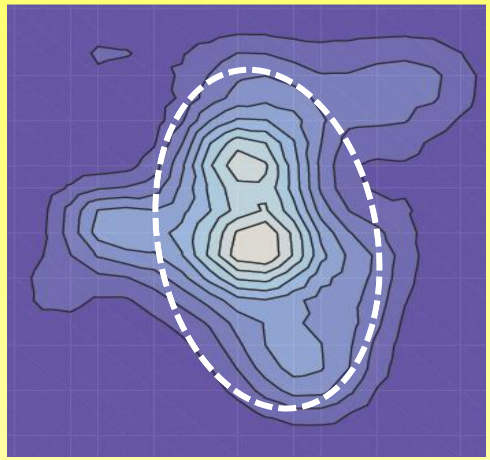
- Observables (for different event classes):
  - Higher harmonics
  - Event by Event fluctuations
  - Studies as a function of EbyE flow
  - Event plane correlations

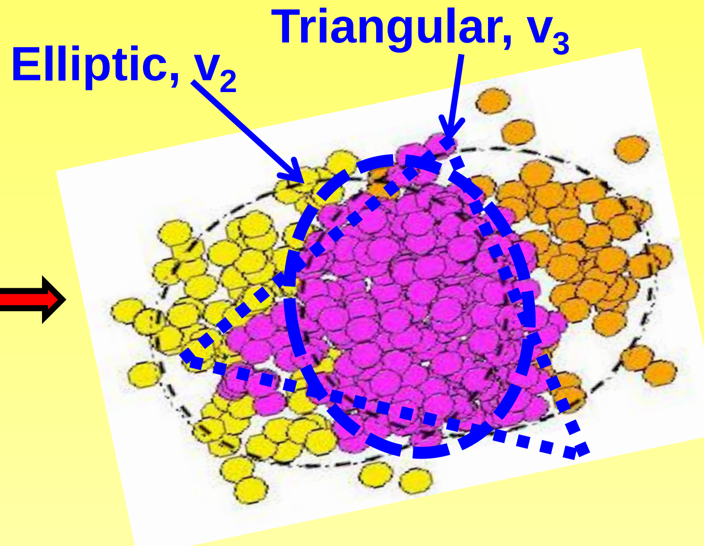


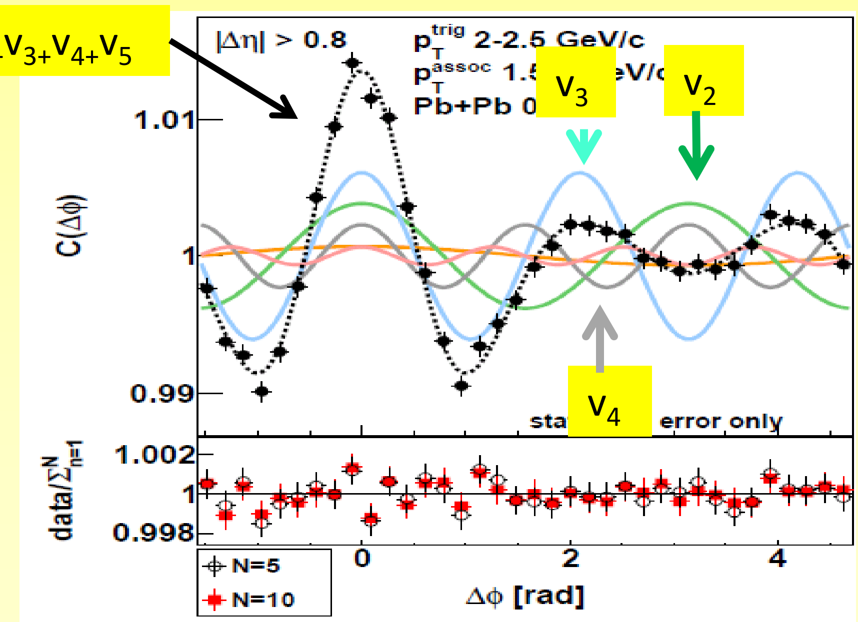
Flow patterns

Fourier series: $dN/d\phi = 1 + 2\,v_1 \cos(\phi) + 2\,v_2 \cos(2\phi) + 2\,v_3 \cos(3\phi) + \ldots$





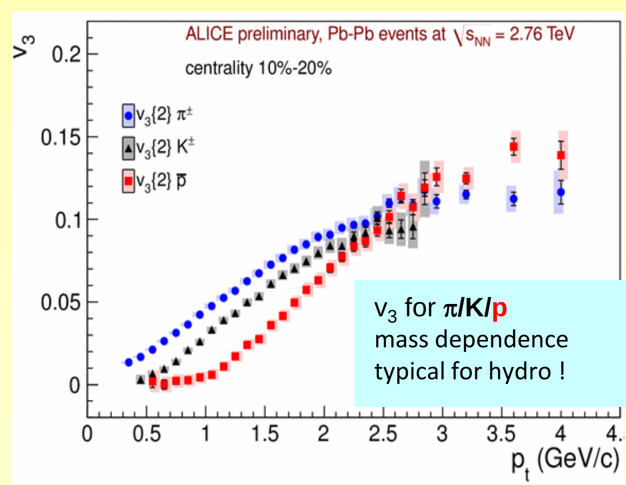




Two Particle Correlation projection on ϕ

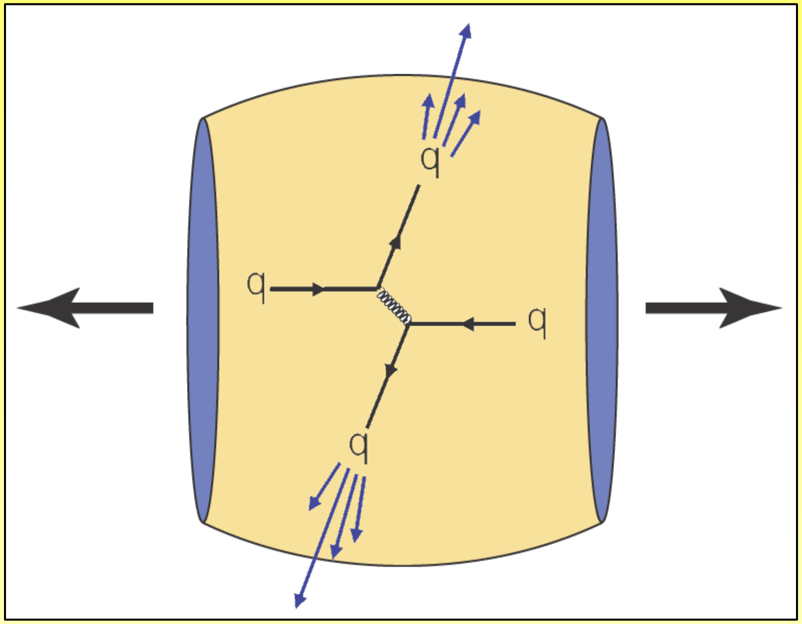
all characteristics as expected from hydro:

- strength, mass/centrality/momentum dependence



Hard Processes to Probe the Medium (Rutherford experiment...)

- initial parton-parton scattering with large momentum transfer
  - calculable in pQCD
- particle jets follow direction of partons



➢ nucleus-nucleus collisions
  - hard initial scattering
  - scattered partons probe traversed hot and dense medium
  - 'jet tomography'

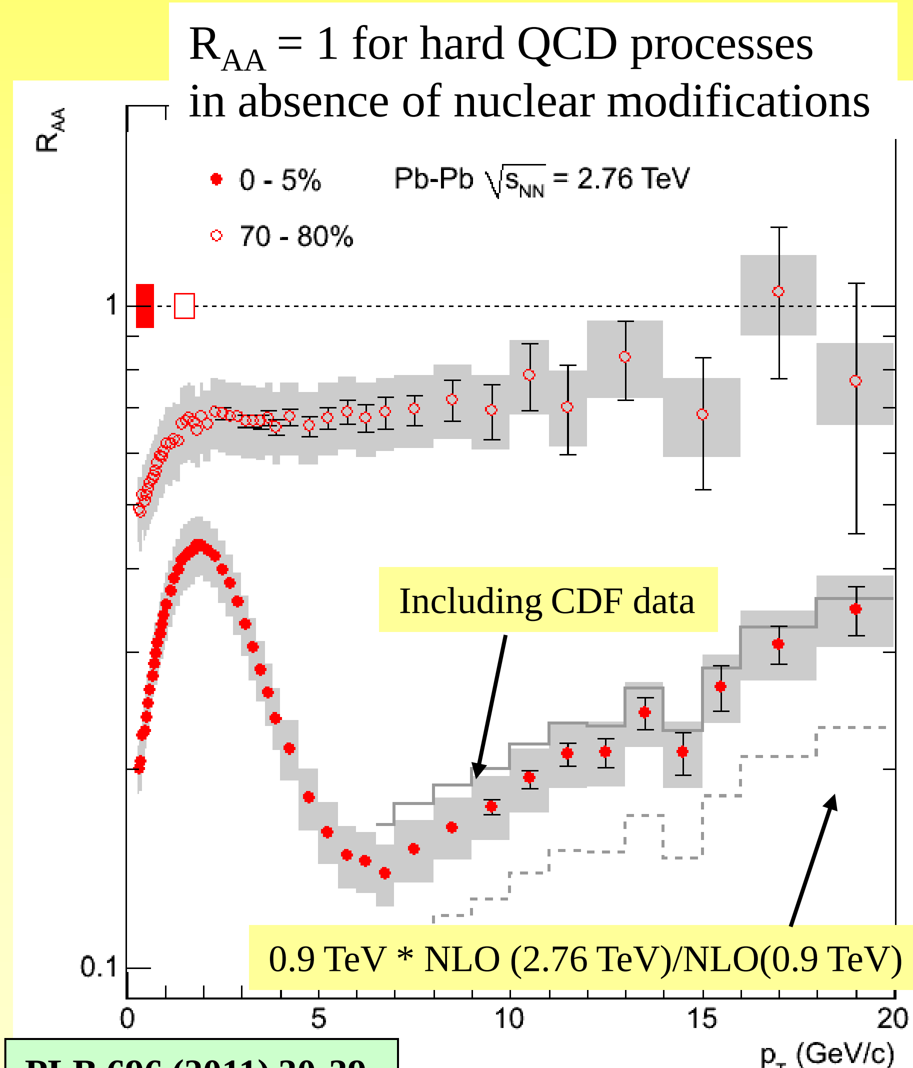
Medium modification quantified via nuclear modification factor R_{AA}

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

Suppression of High-p_T Hadrons

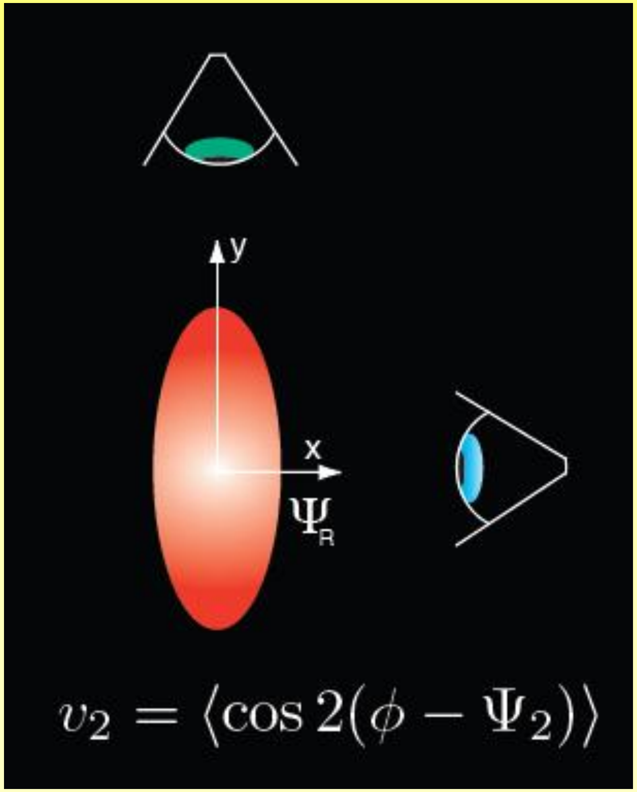
$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

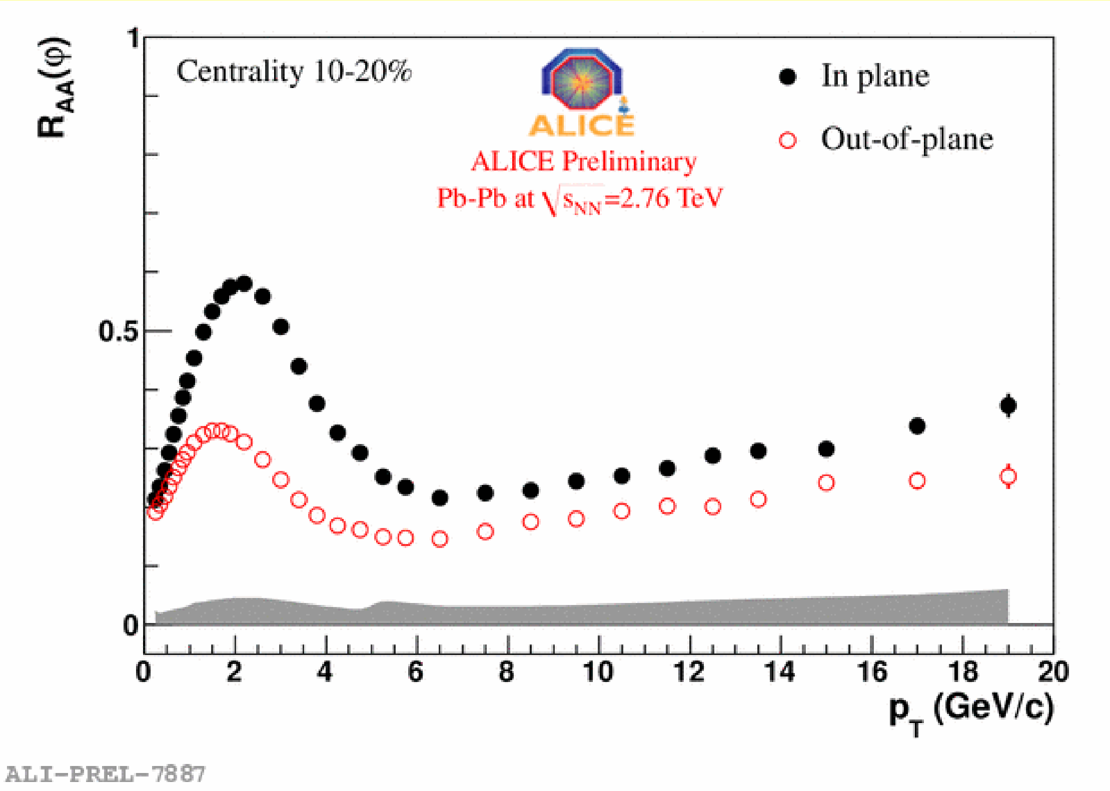
- Strong Suppression even larger than @ RHIC
- Nuclear modification factor $R_{AA}(p_T)$ for charged particles produced in 0-5% centrality range
  - minimum (~ 0.14) for p_T ~ 6-7 GeV/c
  - then slow increase at high p_T
- essential quantitative constraint for parton energy loss models!



PLB 696 (2011) 30-39

Sensitive to path length

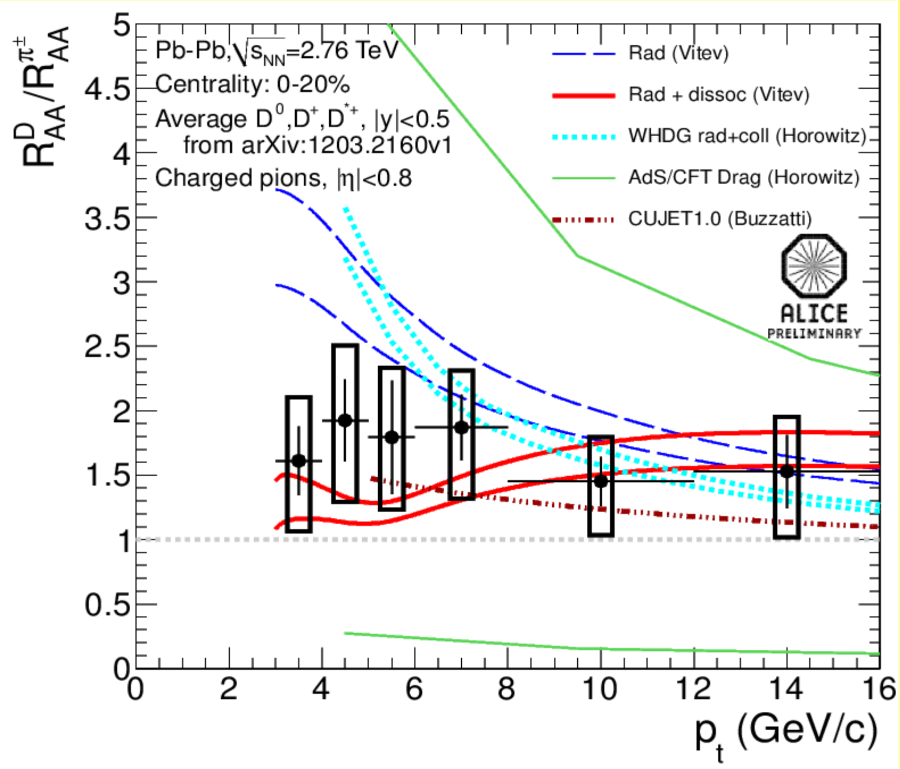




- Significant effect even at high p_T

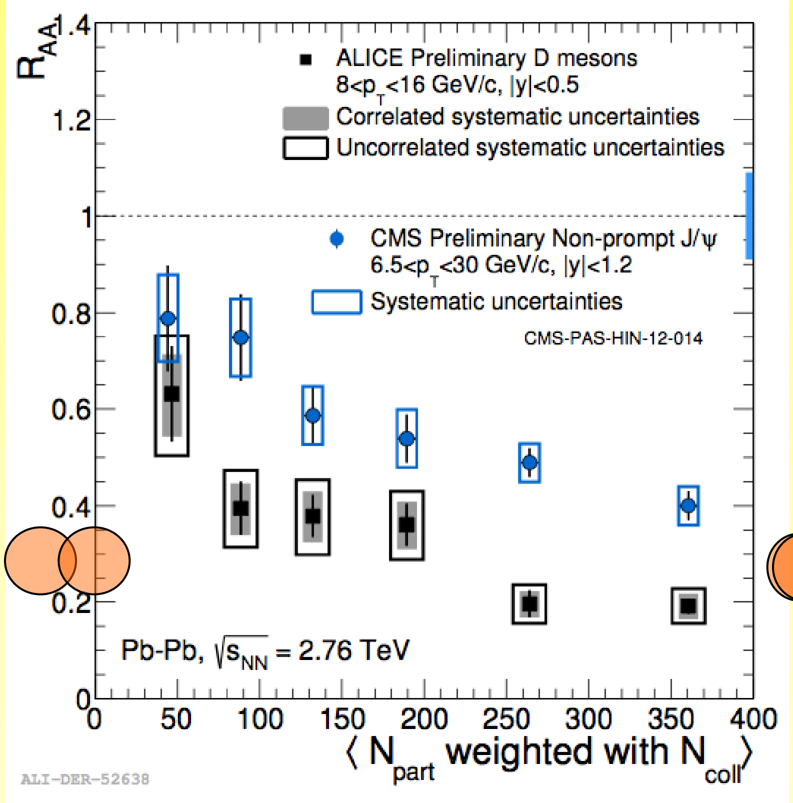
Mass dependence of parton energy loss

- Expectation from radiative energy loss: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Could be reflected in an hierarchy of R_{AA}: $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$
- **Charmed mesons (ALICE)** vs. **Pions**



hints for the expected hierarchy in charm/pion R_{AA} ratio

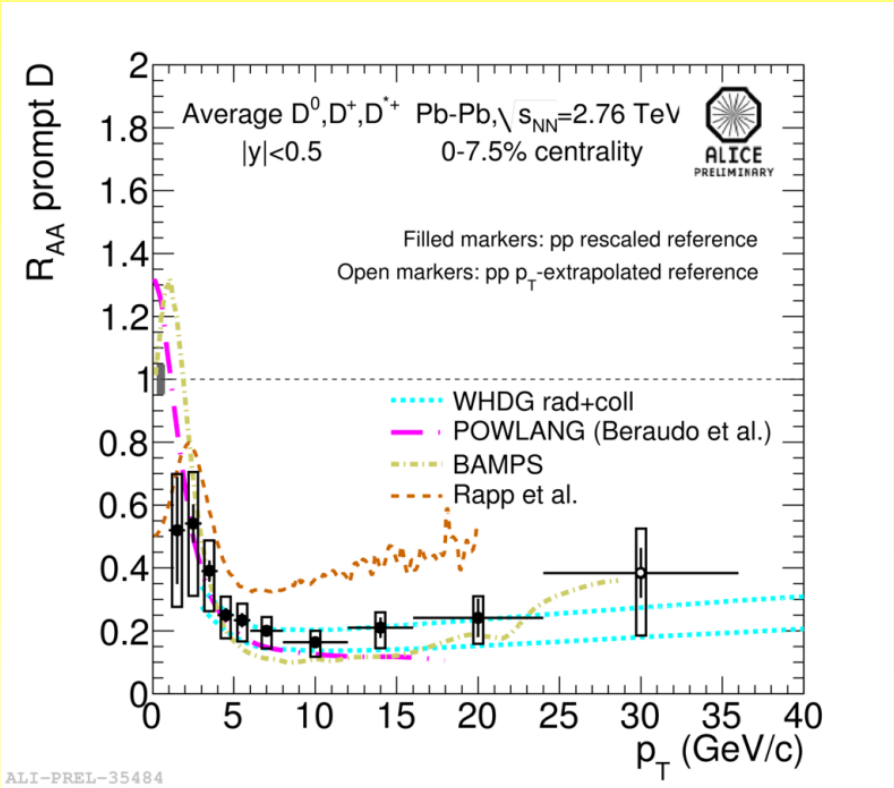
- **Charmed mesons (ALICE)** vs. **J/ψ from beauty decays (CMS)**



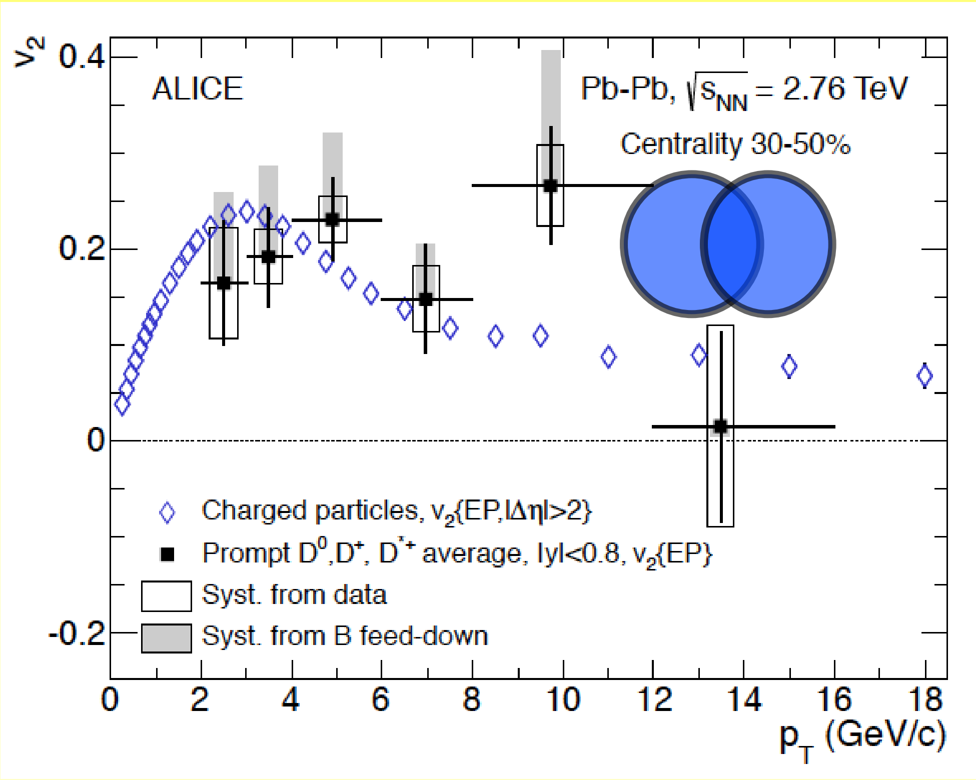
→ **First indication** of a dependence on heavy quark mass: $R_{AA}^B > R_{AA}^D$

D Meson Elliptic Flow

- v_2 is sensitive to the Eq. of state and shear viscosity of the medium.



D meson strongly interacting with the medium.
Does that mean **it flows too?**



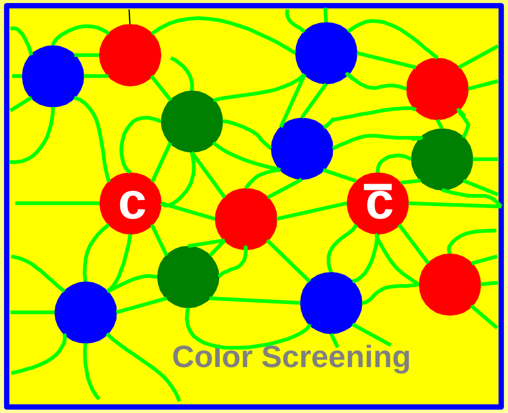
Prompt D^0, D^+, D^{*+} average.
D meson v_2 suggests collective expansion.

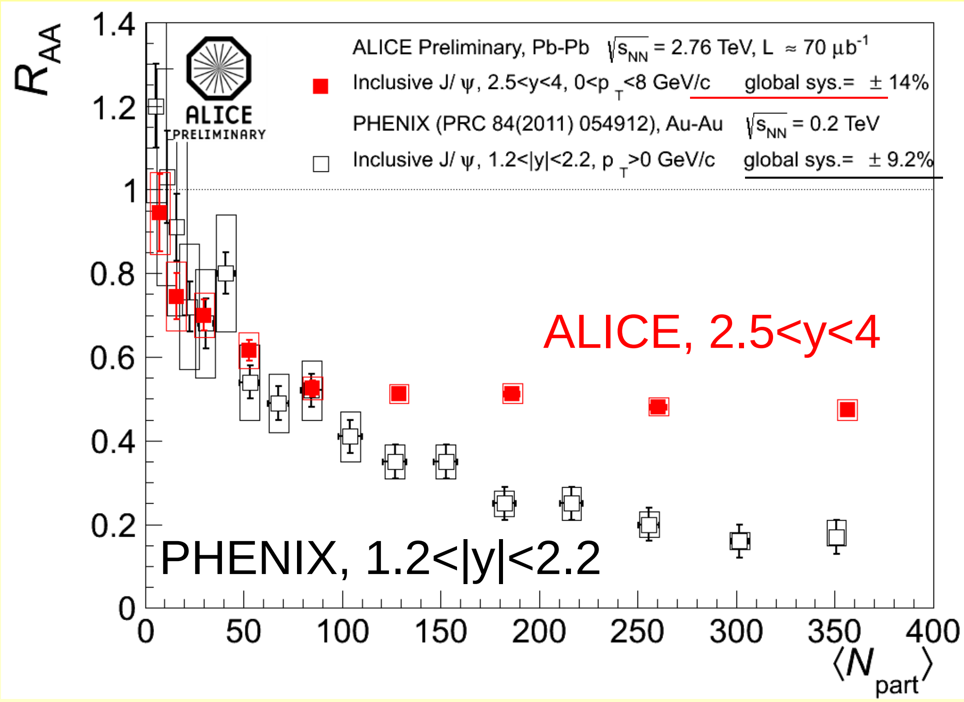
J/ψ "suppression" at the LHC

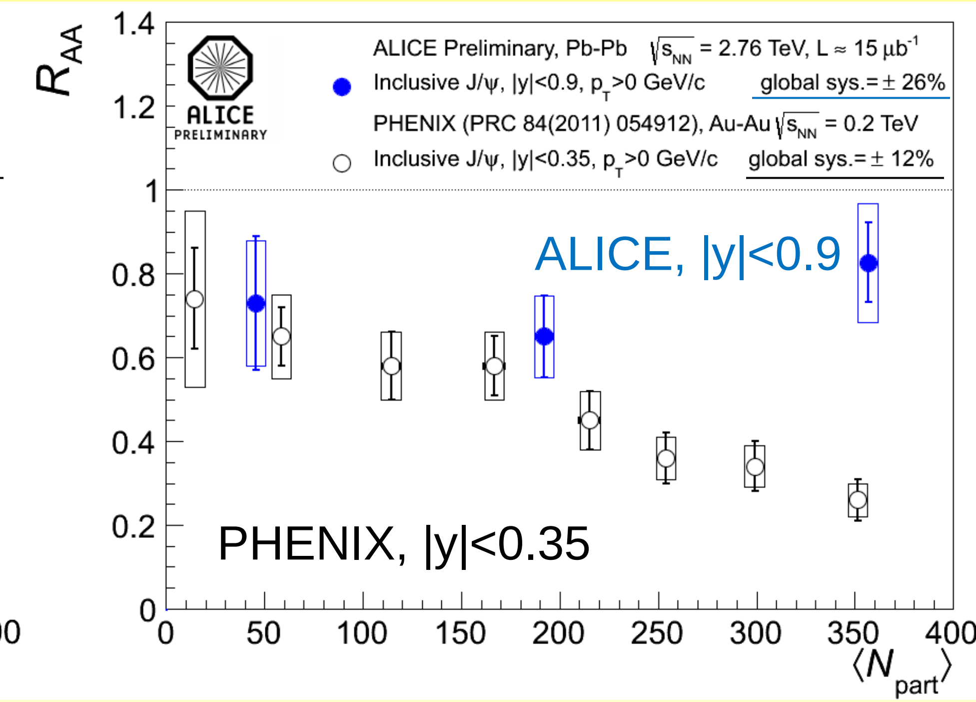
Predicted as a signature of deconfinement, due to the temperature (color charge density density) dependent screening of the color charge in a Quark-Gluon Plasma

Observed at lower energy experiments (SPS, RHIC)

ALICE measures a suppression of the J/ψ yield (R_{AA}<1), at both central and forward y, BUT SMALLER than at RHIC



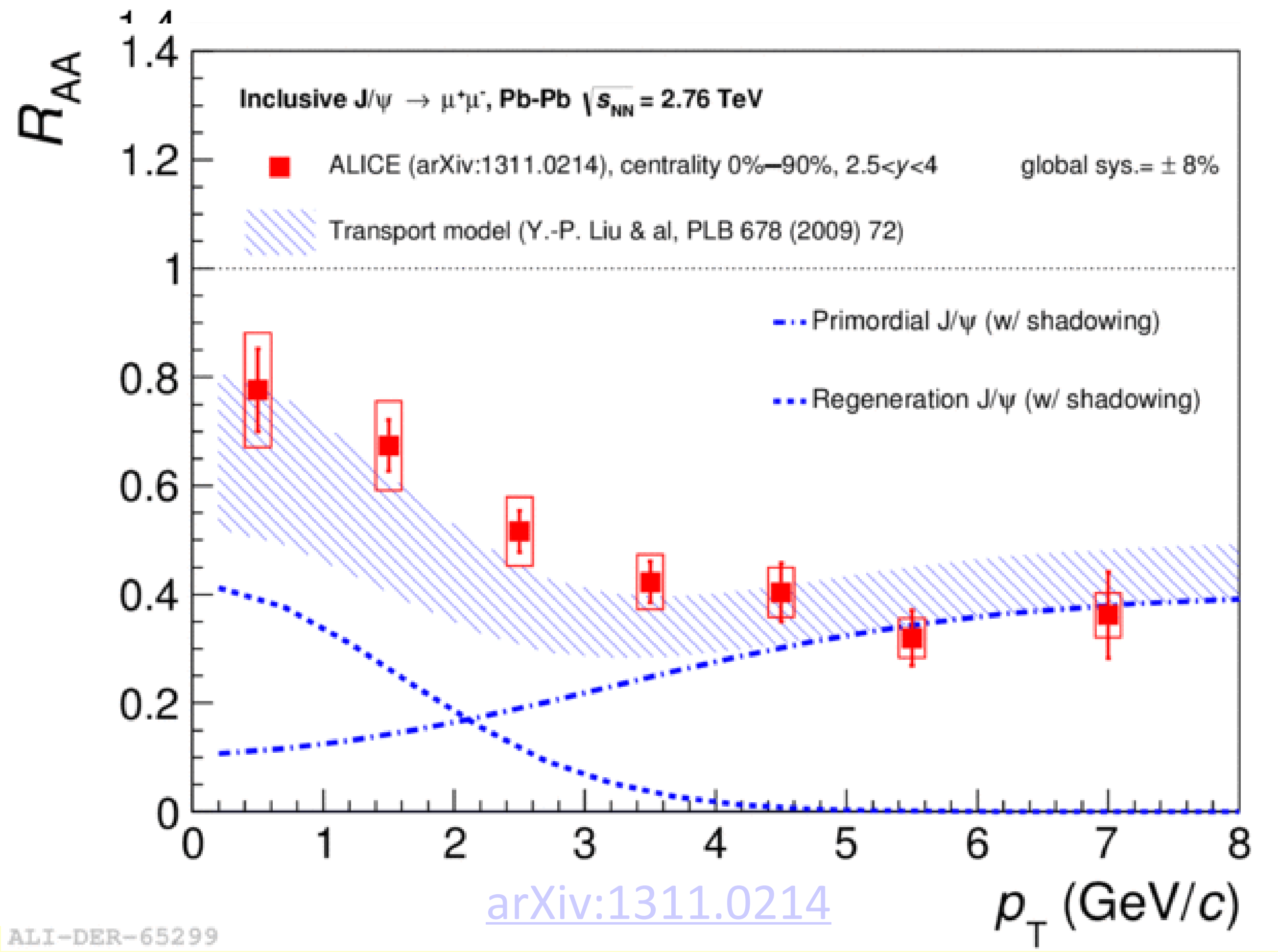




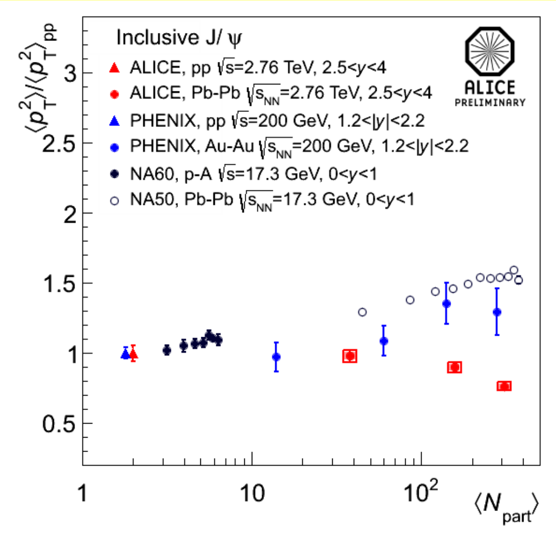
J/ψ production in Pb-Pb

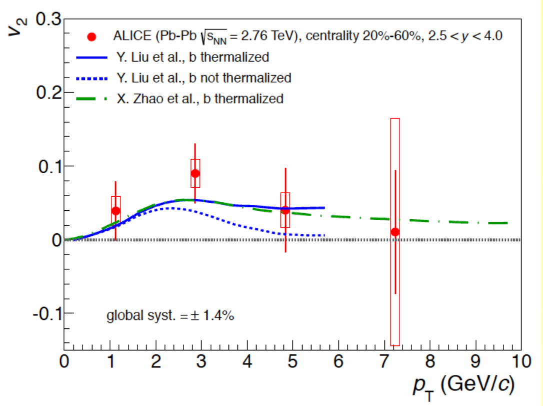
now with full RUN1 statistics:

studied vs centrality, rapidity and transverse momentum



arXiv:1311.0214



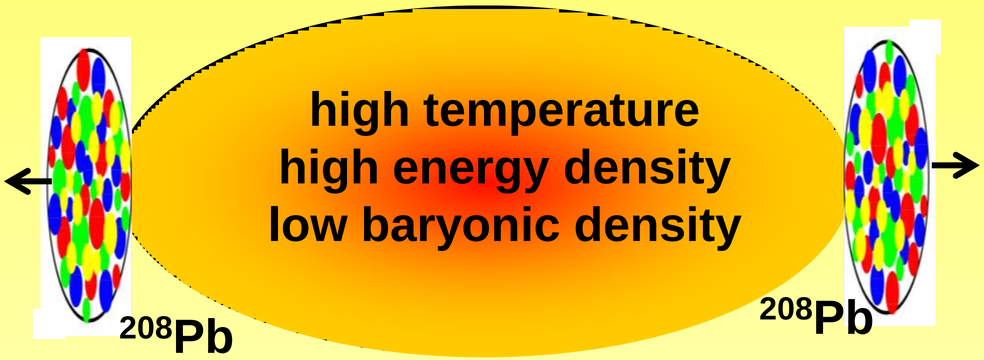


With a hint of flow..

As expected in a scenario with cc recombination, especially at low p_T

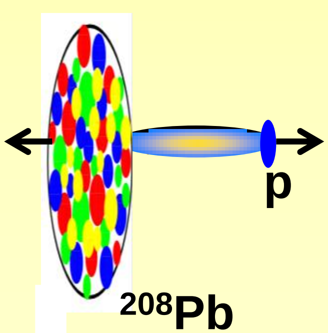
The role of proton-nucleus collisions

- In high-energy nucleus-nucleus collisions, large energy density (ε >> 1 GeV/fm^3) over large volume (>> 1000 fm^3)



Photon spectrum → T ~ 300 MeV
Transverse energy → ε ~ 15 GeV/fm^3
Volume ~ 3 x Pb nucleus

- In high-energy proton-nucleus collisions, large energy densities (?) in a small volume



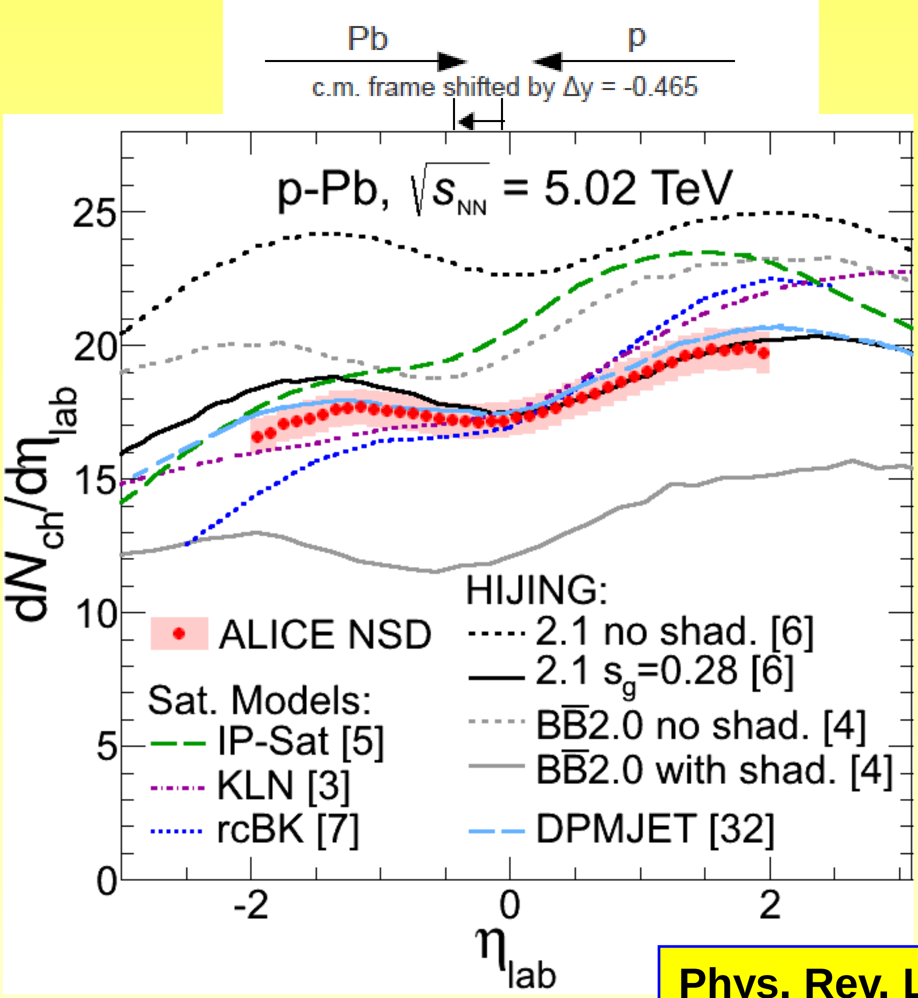
Control experiment: calibrate the initial-modification of hard probes (jets, heavy quarks, quarkonia)
→ single-out final-state effects (hot medium) in Pb-Pb

Explore new territory in QCD: high gluon density in the initial state; potentially, high energy density in the final state, but in a small volume

Pseudorapidity density in pPb at 5.02 TeV

- Measurement based on tracklets (SPD)
- Non-single-diffractive event selection

Norm. uncertainty: 3.1%

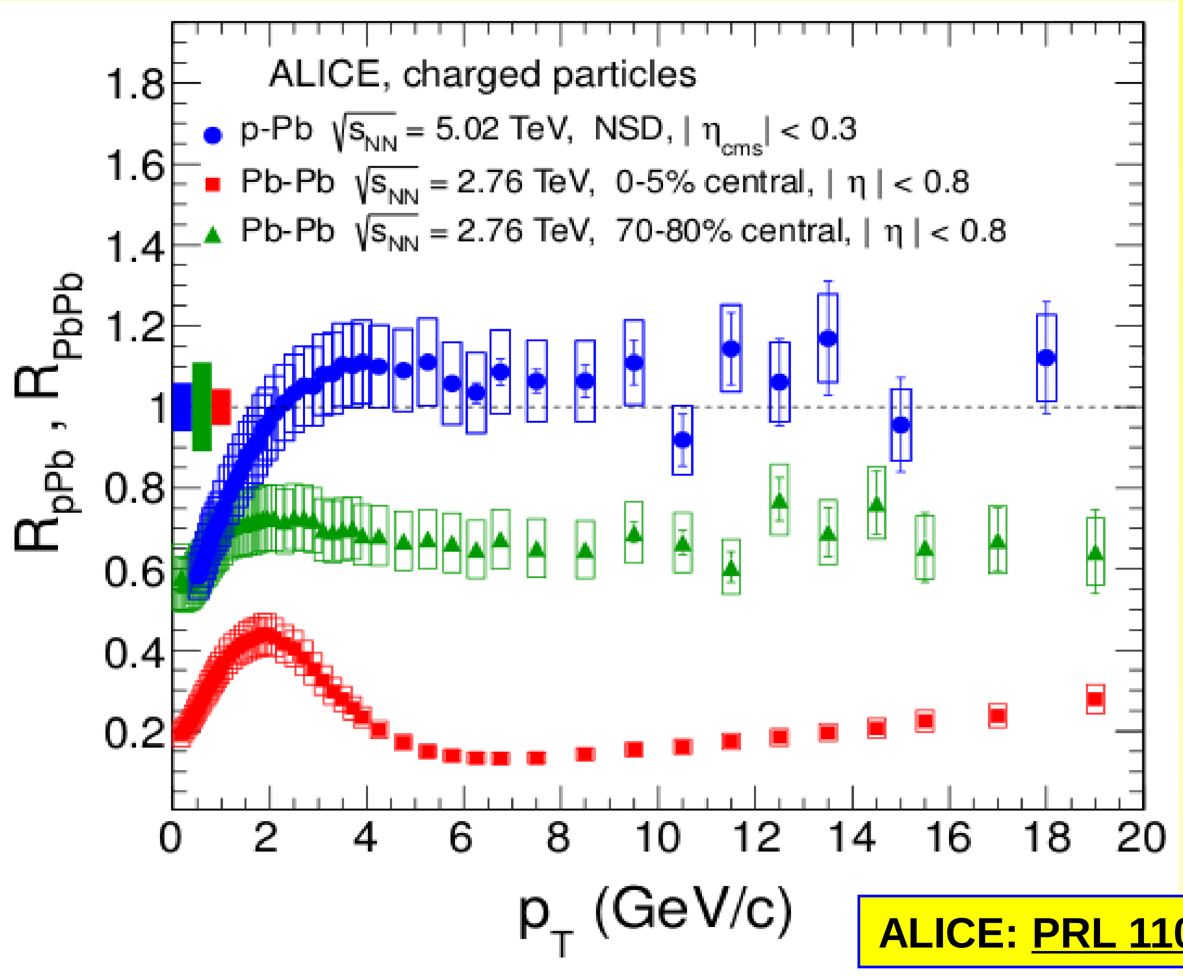


Phys. Rev. Lett. 110, 032301 (2013)

Data favors models that incorporate shadowing

Saturation models predicted steeper η-dependence which is not observed in the data.

The control experiment: p-Pb collisions



ALICE: PRL 110, 082302 (2013)

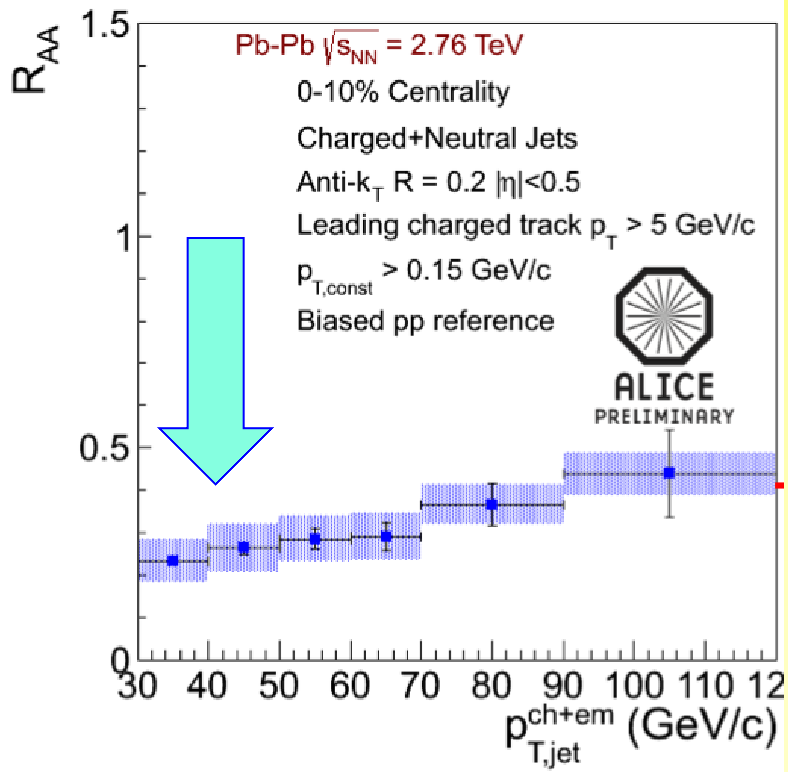
High-p_T charged particles exhibit binary scaling. Initial state effects are small.

The high-p_T suppression observed in PbPb is dominated by hot matter effects.

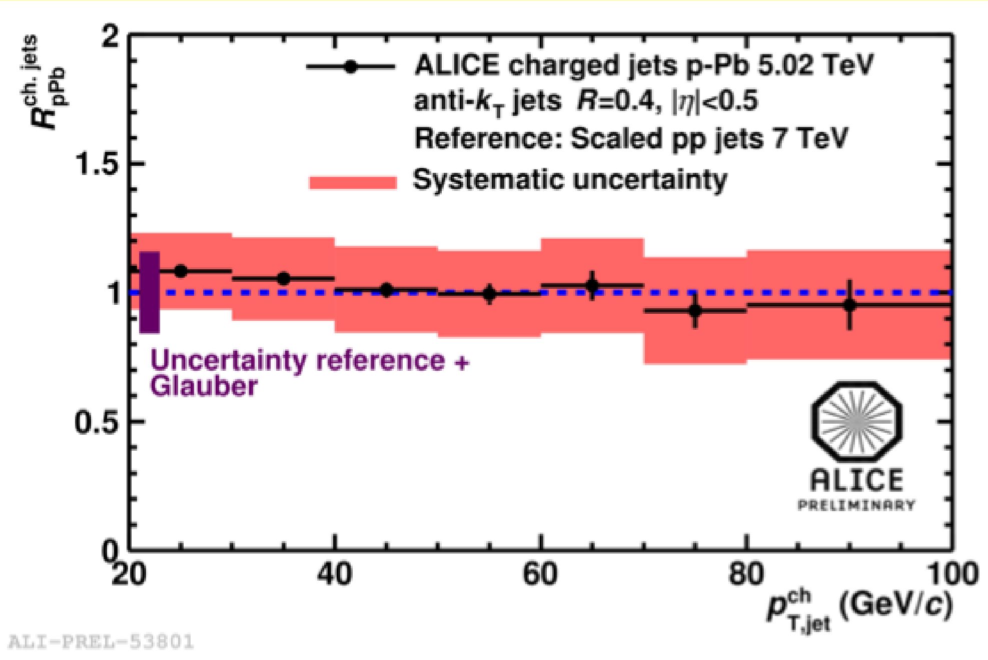
p-Pb at LHC as a control experiment: Jets

- Also for jets, no evident nuclear modification in p-Pb (R_{pPb}~1)

Pb-Pb (central)



p-Pb (minimum bias)



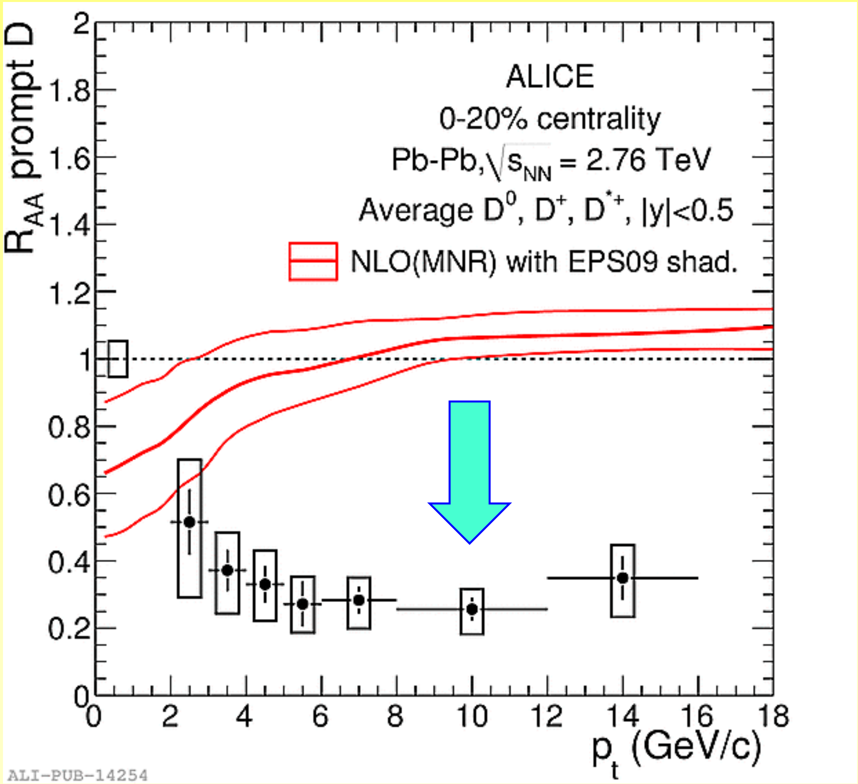
Large high-p_T suppression in Pb-Pb (x3-4) is a medium effect → probes the properties of QCD interactions over extended volumes

p-Pb at LHC as a control experiment: D

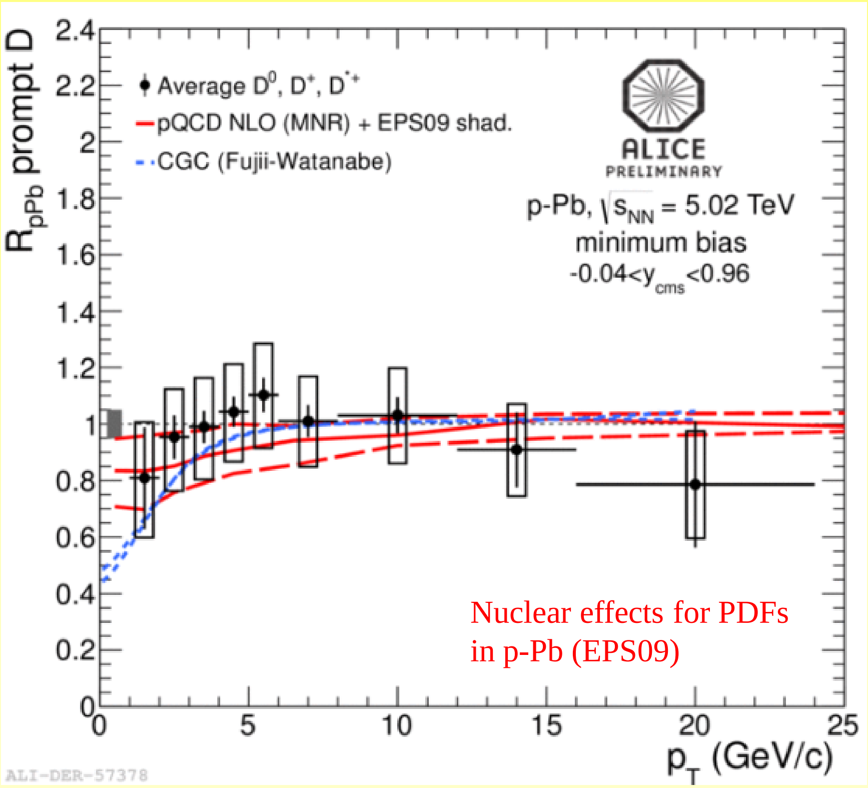
- Measurements for main hard probes in minimum-bias p-Pb indicate that the effects seen in Pb-Pb are dominated by the hot medium

$$R_{pA(AA)}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pA(AA)}/dp_T}{dN_{pp}/dp_T}$$

Pb-Pb (central)



p-Pb (minimum bias)



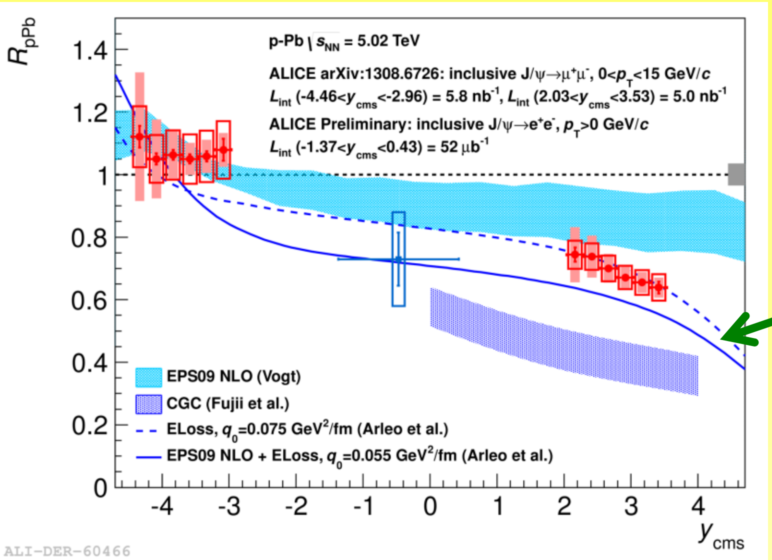
Open Charm: No significant nuclear modification in p-Pb (R_{pPb}~1)

- Consistent with modest effect expected from PDF shadowing

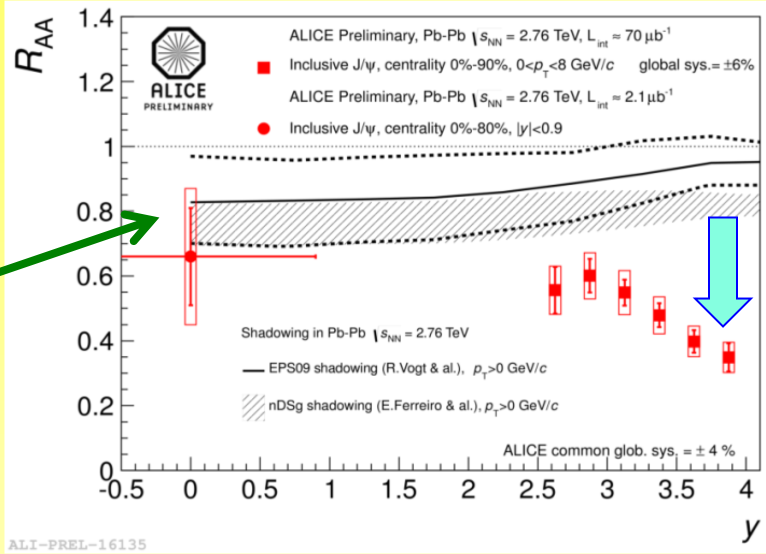
p-Pb at LHC as a control experiment: J/ψ

ALICE

p-Pb (minimum bias)



Pb-Pb (central)



Nuclear modification in **p-Pb** described by expected PDF shadowing

Measurements constrain nuclear modification of PDF at small and very small x

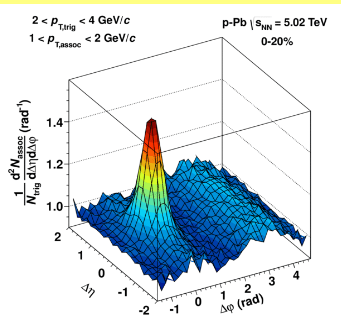
Additional suppression in Pb-Pb, more pronounced at forward rapidity, is a medium effect → colour-screening "melts" c-cbar bound states

Reduced suppression in Pb-Pb at central rapidity, wrt forward, and wrt to RHIC measurement → described by scenario of J/ψ regeneration in deconfined medium

Intriguing findings in high-multiplicity p-Pb

From p-Pb pilot run:

0-20%



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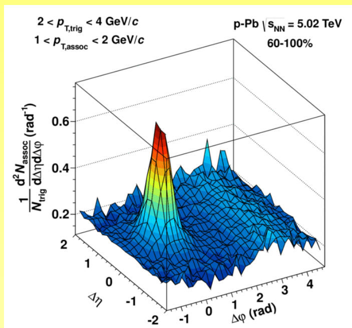
60-100%



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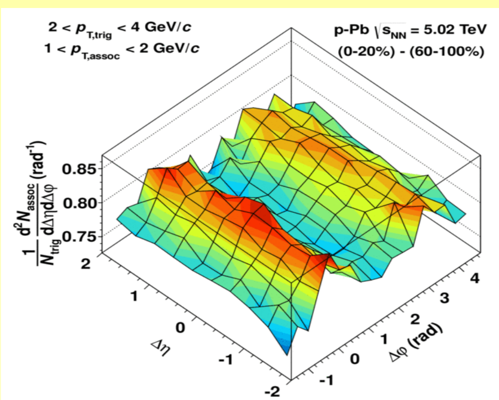


Structure emerging when subtracting low mult correlations from high-mult. Origin still unknown …

Possible interpretations:

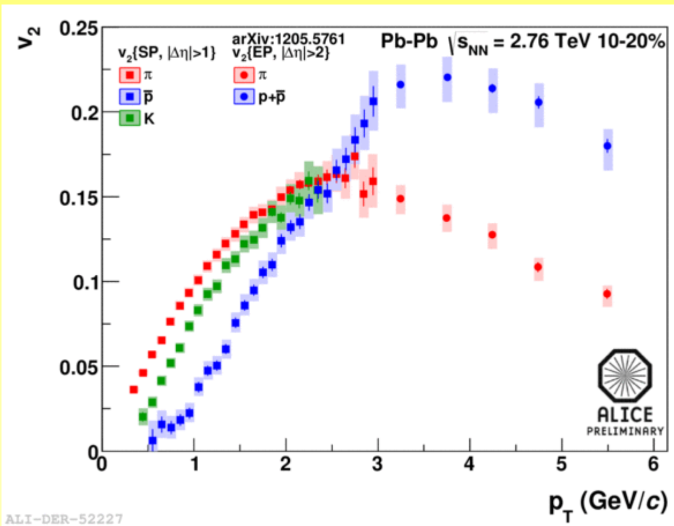
- Hydrodynamic flow in the final state: a “medium”
- Colour reconnection: a “pure QCD effect”
  - could be interesting to understand QGP formation in Pb-Pb
- Multi-gluon processes from saturated initial-state (Colour Glass Condensate)

→ Use ALICE PID capabilities to test these possibilities

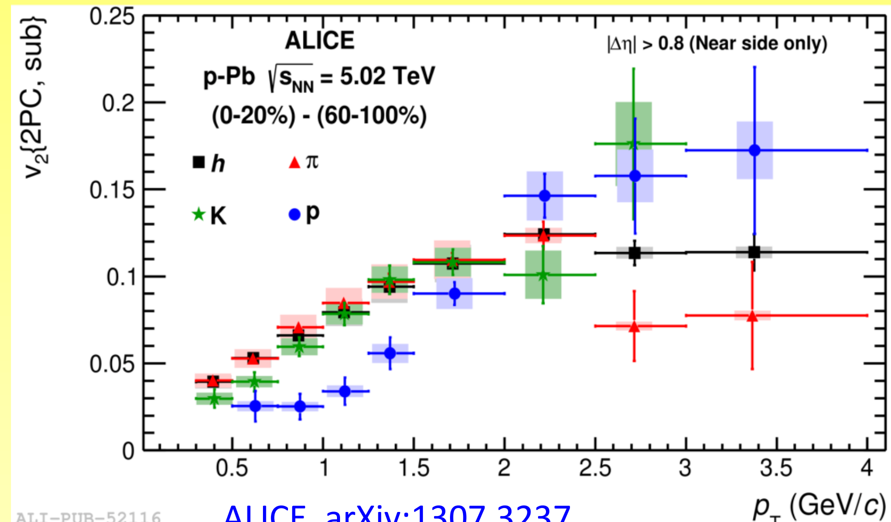
Intriguing findings in high-multiplicity p-Pb

Quantify the azimuthal modulation in terms of second order Fourier harmonics:

Pb-Pb



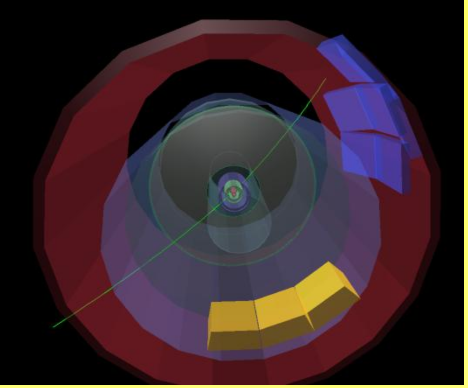
p-Pb, high-multiplicity



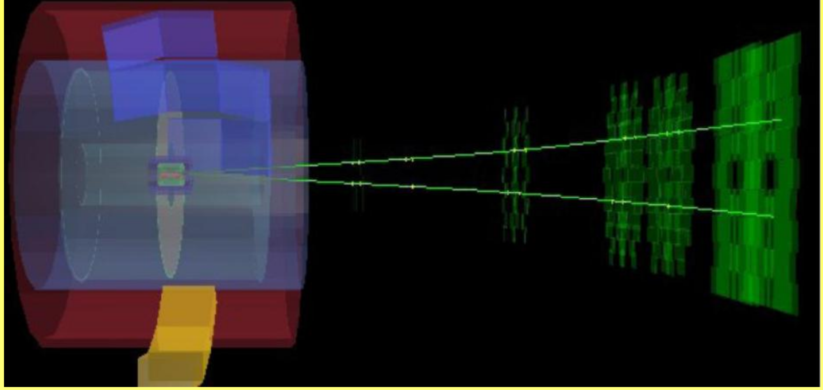
ALICE, arXiv:1307.3237

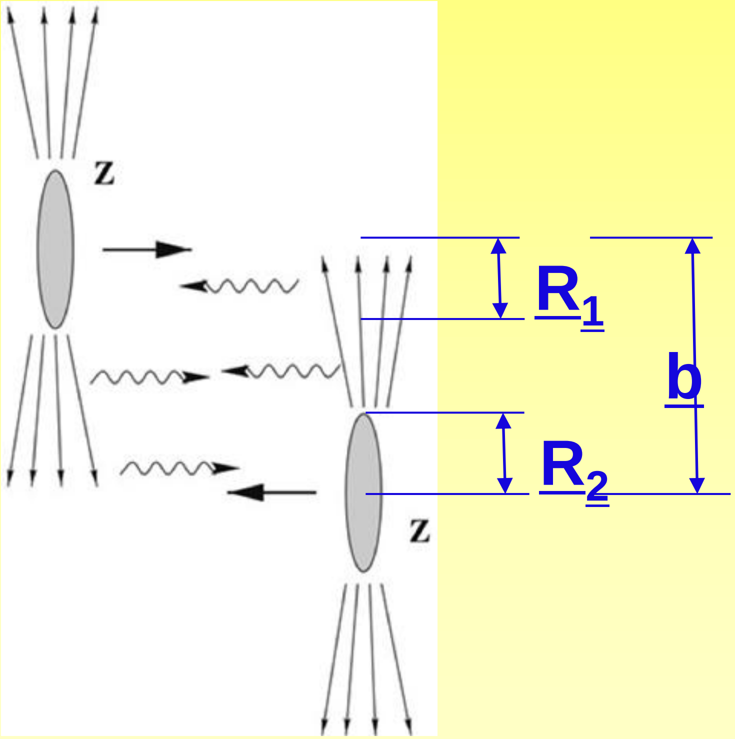
- Pb-Pb: mass ordering, interpreted in terms of collective radial and elliptic flow
- Clear indication for mass ordering also in p-Pb
- further support for flow picture?

Many other measurements done (e.g. baryon/meson ratios) or in progress to provide strong experimental constraints for understanding of this unexplored area of QCD



LHC as γPb and γp collider





Ultra-peripheral (UPC) collisions:

$b > R_1+R_2$

→ hadronic interactions strongly suppressed

High photon flux

→ well described in Weizsäcker-Williams approximation (quasi-real photons)

→ flux proportional to Z^2

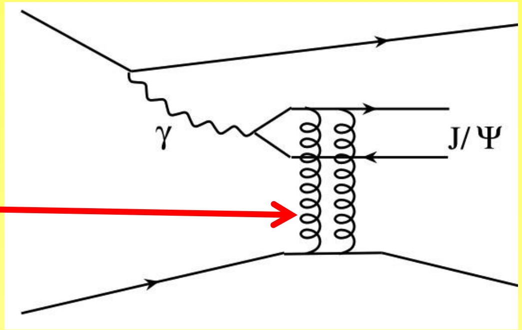
→ high cross section for γ-induced reactions

Pb-Pb and p-Pb UPC at LHC can be used to study γ-Pb, γp and γγ interactions at higher center-of-mass energies than ever before

J/ψ photoproduction in UPC

- LO pQCD: coherent J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**:

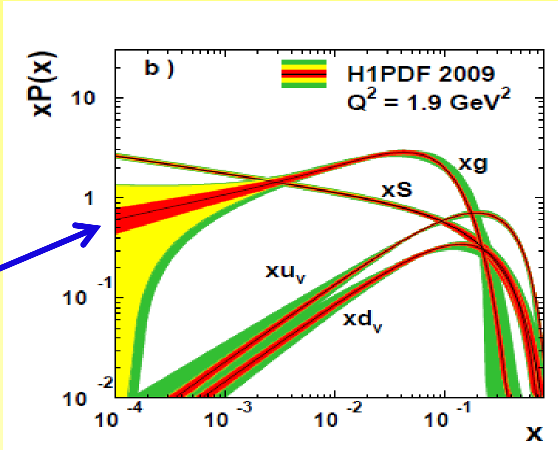
$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{\rm em}Q^8}\left[xG_A(x,Q^2)\right]^2$$



- Mass of J/ψ serves as a hard scale: $Q^2 \sim \frac{M^2_{J/\psi}}{4} \sim 2.5\ {\rm GeV}^2$

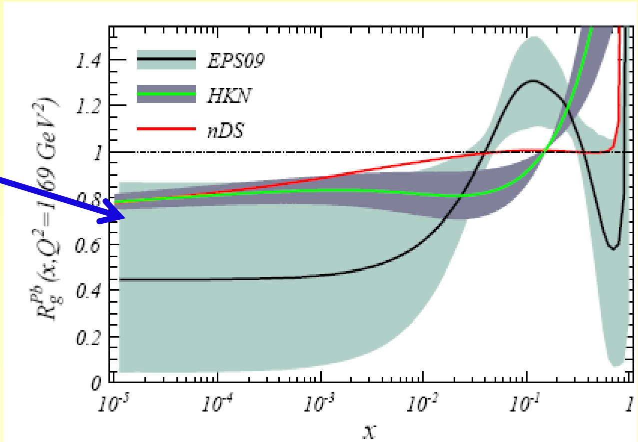
- Bjorken x ~ 10^{-2} – 10^{-5} accessible at LHC: $x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}}$

- J/ψ photoproduction in p-Pb UPC (proton target) allows one to probe poorly known **gluon distribution in the proton at low x** and search for **saturation effects**

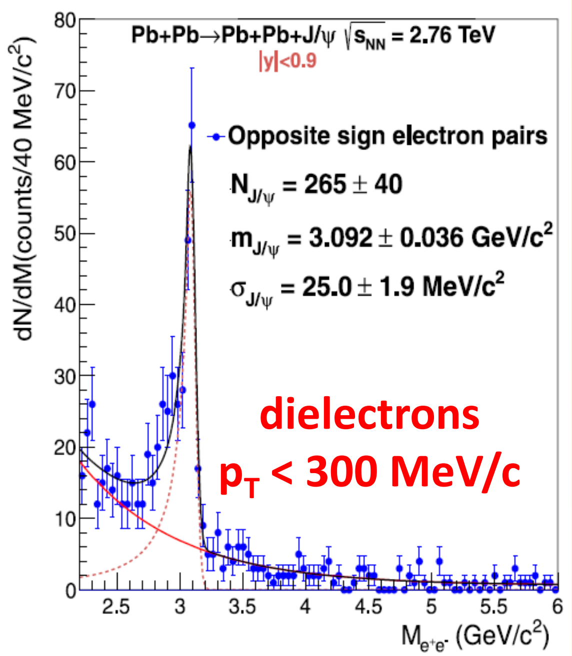


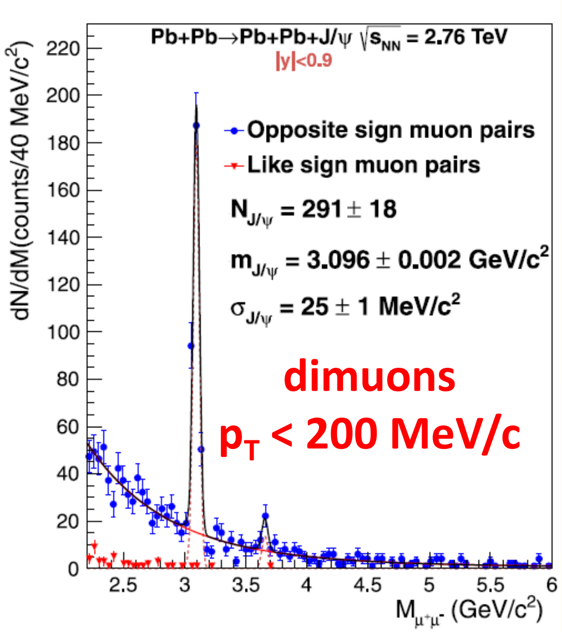
- J/ψ photoproduction in Pb-Pb UPC (lead target) provides information on **gluon shadowing in nuclei at low x** which is essentially unconstrained by existing data

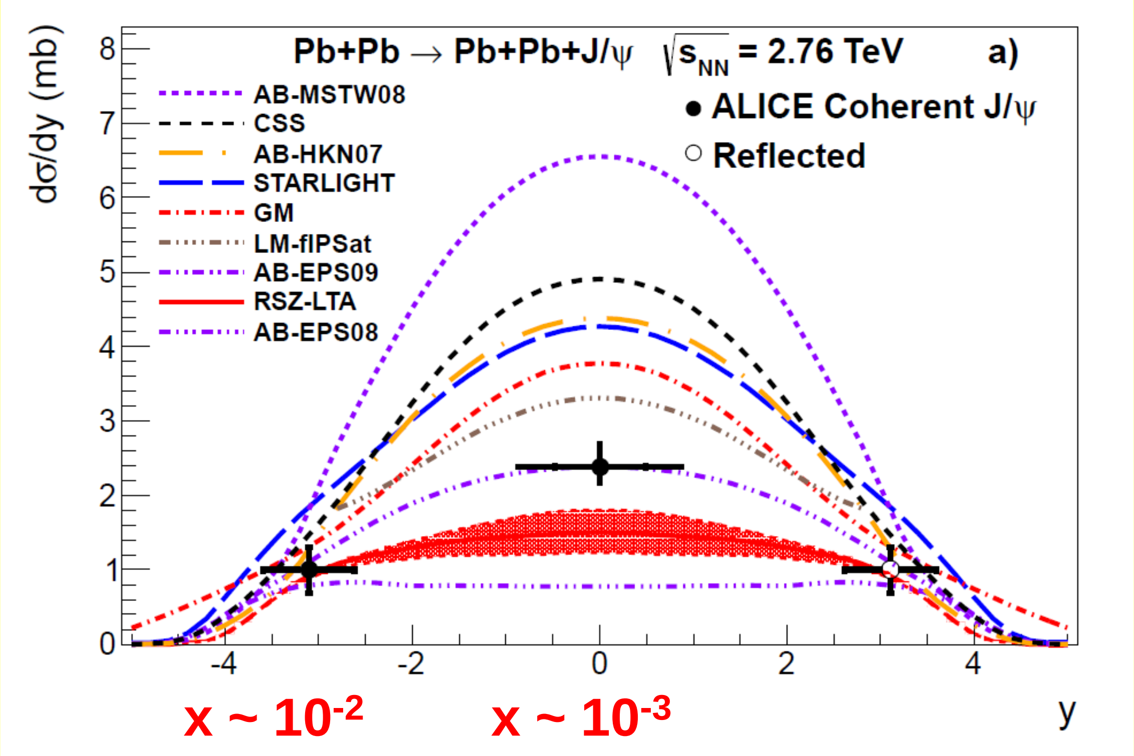
$$R_g^A(x,Q^2) = \frac{G_A(x,Q^2)}{AG_p(x,Q^2)}$$ – gluon shadowing factor



Coherent J/ψ production







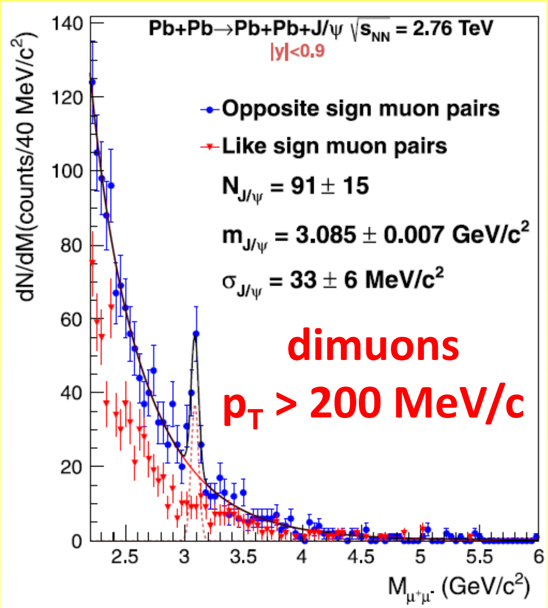
Good agreement with models which include nuclear gluon shadowing.

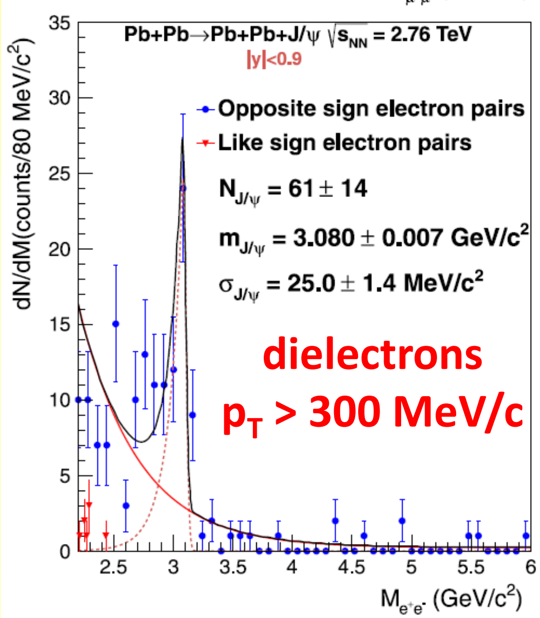
Best agreement with EPS09 shadowing

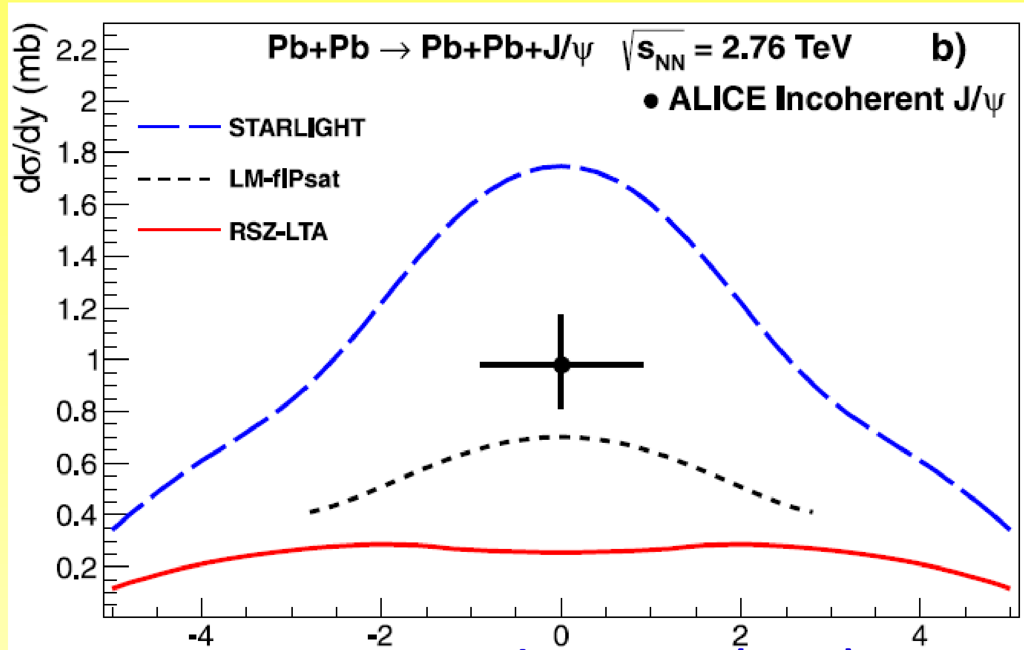
(shadowing factor ~0.6 at $x \sim 10^{-3}$, $Q^2 = 2.4\ GeV^2$)

Eur. Phys. J. C73 (2013) 2617

Incoherent J/ψ at central rapidity







Eur. Phys. J. C73 (2013) 2617

- Coherent : scattered on whole nucleus, Incoherent: on individual nucleon
- Almost one order of magnitude difference in the predicted cross sections

- ALICE sets strong constraints

J/ψ photoproduction in pPb

Data collected in

p-Pb: p towar

Pb-p: Pb towa

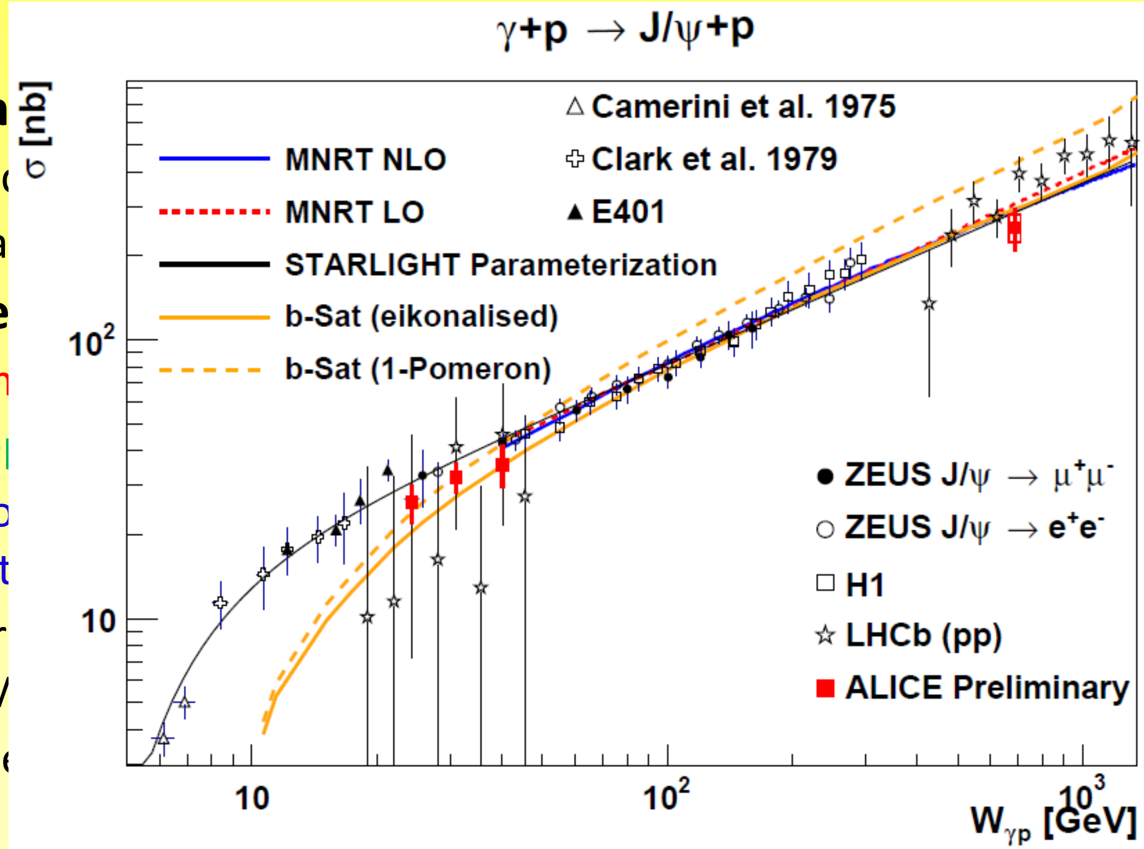
Three UPC trigge

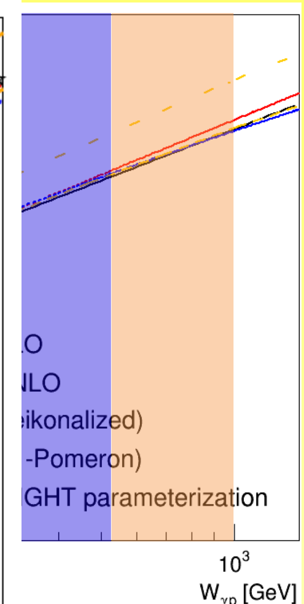
First results from forward muons

- Forward: both n
- Central: both le
- Semi-forward: o arm, second in t

→ wide gamma-pr up to W ~ 1 TeV

→ wide x coverage





- Access to gluon distribution in proton target at low x
- Advantage of p-Pb:
  - Large photon flux from Pb, The photon source is known, so $W^2_{\gamma p} = 2E_p M_{J/\psi} \exp(-y)$
  - Hadronic contribution can be strongly suppressed by ensuring Pb nuclei are intact (no signal in ZDC)
  - Contamination from central exclusive χ_c production negligible

More results to come from barrel/barrel and barrel/muon

The future

- So far:

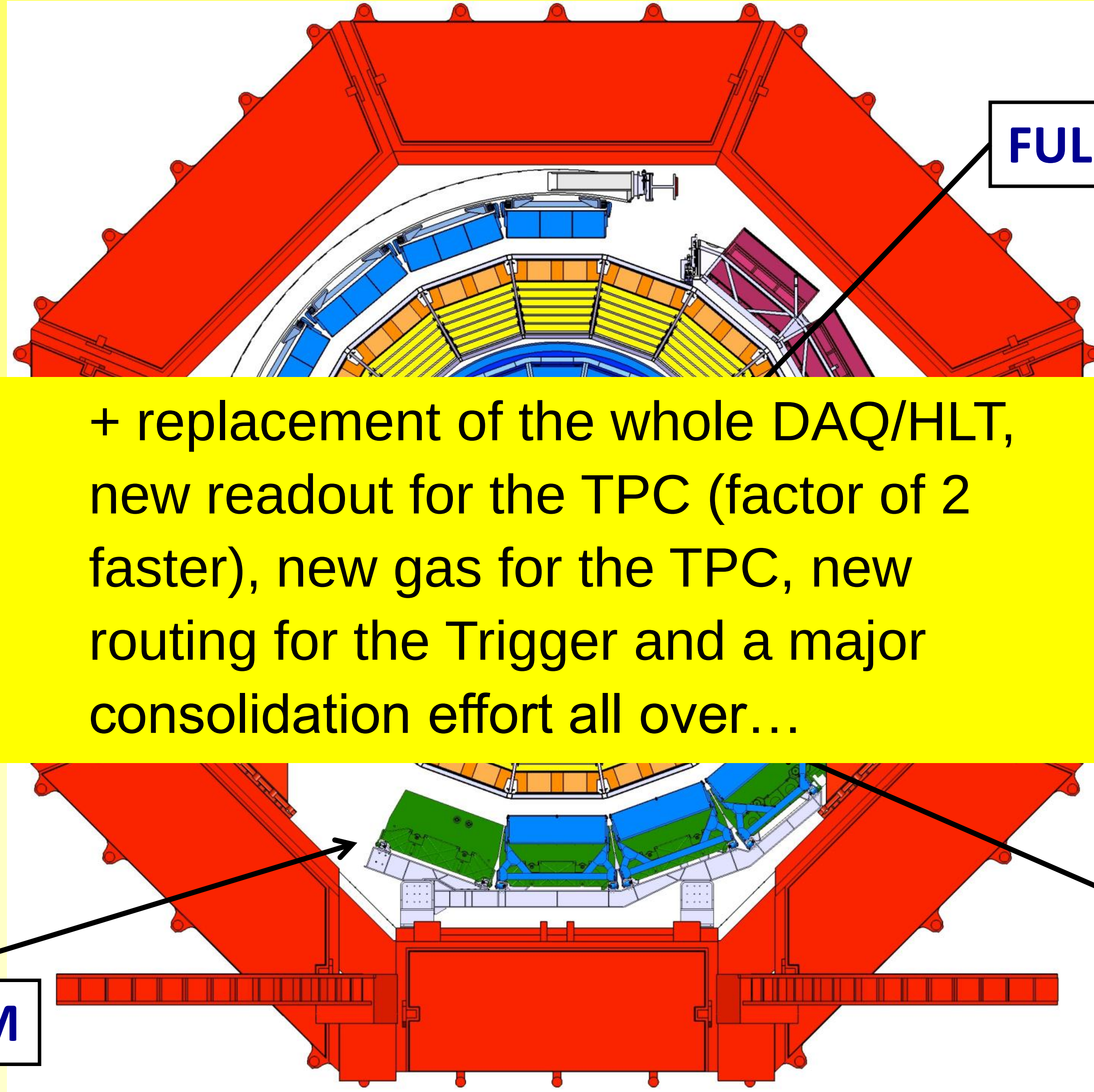
year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 0.01 nb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

- The future:
  - **RUN2 (2015, 2016, 2017)** : will allow to approach the **1 nb^{-1}** for PbPb collisions, with improved detectors and double energy
  - **RUN3 + RUN4 (2020, 21, 22 and 26, 27, 28): 10 nb^{-1}** with major detector improvements (plus a dedicated low-field run and pPb)
- So: three phases, each jumping one order of magnitude in statistics and progressively improving the detectors

ALICE for RUN2: a busy LS1

New installations

- 5 TRD modules
- 8 DCal modules (approved in 2010, US led project)
- Add 1 PHOS module

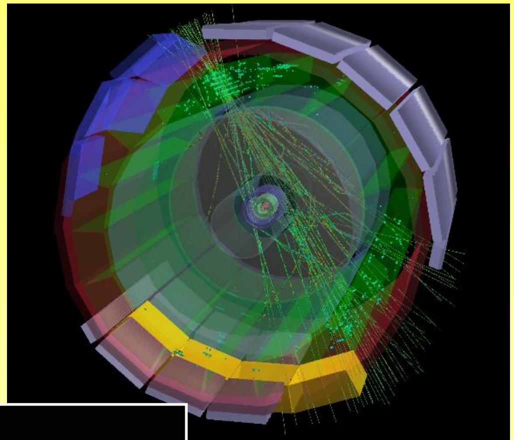


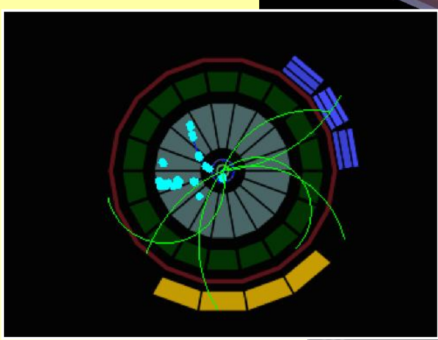
+ replacement of the whole DAQ/HLT, new readout for the TPC (factor of 2 faster), new gas for the TPC, new routing for the Trigger and a major consolidation effort all over…

LHC Restart

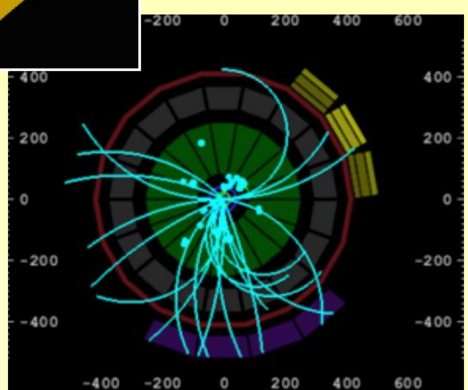
Commissioning Phases

Cosmics with B=-/0/+





Quiet Beams at 900 GeV

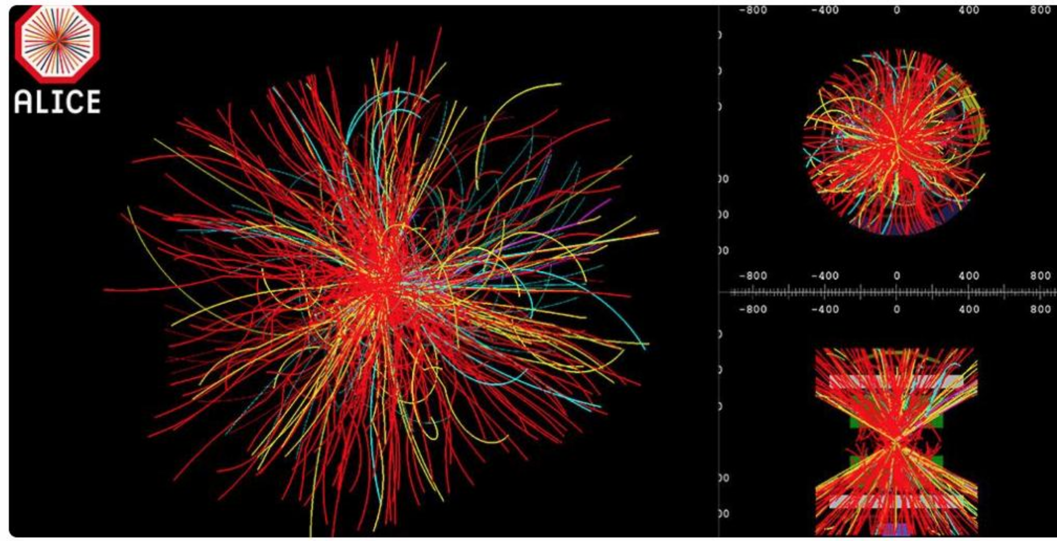


Quiet Beams at 13 TeV

13 TeV LHC Era

The Economist
@TheEconomist

Scientists at CERN announce a milestone turning knobs at the #LHC: this one goes to #13TeV econ.st/1dkYzqJ



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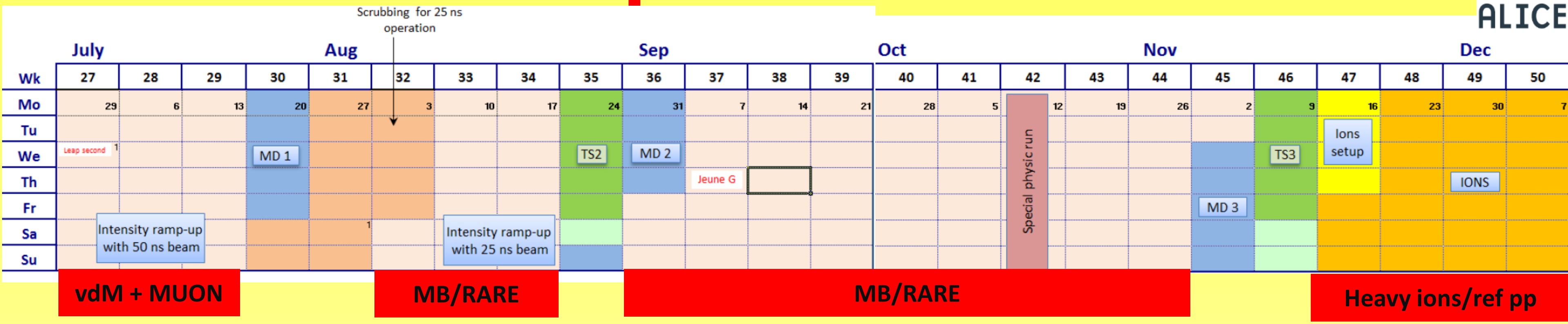
149 RETWEETS 136 FAVORITES

ALICE In production data taking for low pile-up diffractive measurement

ALICE plans for 2015



- **pp@13TeV, 50ns ramp up**:
  - Target rate ~ 600kHz, μ ~ 1
  - Muon triggers: 3 pb^{-1}
- **pp@13TeV, 25ns filling schemes**:
  - Target rate ~ 300kHz, μ ~ 0.01
  - Minimum bias: 600M
  - High multiplicity (10^{-3} rejection): 100M V0-based + 100M SPD-based
- **Pb-Pb@5.02 TeV.** Expected statistics:
  - Minimum bias: 250M
  - CENTRAL 0-10%: 70M
  - Central barrel rare triggers (EMCAL + UPC): 0.1 nb^{-1}
  - Muon triggers: 0.4 nb^{-1}
- **pp@5.02 TeV (~4 days).** Expected statistics:
  - Minimum bias (70% time share): 50M in cluster ALL (100M in cluster FAST)
  - Central barrel rare triggers (30% time share): 0.1 pb^{-1}
  - Muon triggers: 0.3 pb^{-1}

Long term future of the LHC HI Program

- All experiments are building on the success of RUN1 and learning from the results
- June 29th 2012 Town meeting of the whole HI community (at CERN)
  - Very important meeting, resulting in a common document of the Community submitted to the Cracow one, and indicating clearly the extension of the LHC HI program, including the ALICE upgrade, as its first priority. Remarkable coherence of ALICE, ATLAS and CMS
    - "***The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC.***"
- All 3 experiments would benefit from the PbPb luminosity upgrade, and in their upgrades would strengthen their complementarity
- NUPECC also submitted a document to Cracow European Strategy Meeting,
  - Stresses the commitment of the Nuclear Physics Community to the ALICE long term programs, "**top priority for European Nuclear Physics**"
- Cracow European Strategy Meeting
  - Heavy Ion Physics an integral part of the future LHC program till at least the mid 2020s

Experimental Strategy

Upgrade ALICE rate capability and precision for the last 3 years of the approved program and extend it for about three more, after LS3

- The relevant observables are at low-transverse momentum (complementary/orthogonal to the general-purpose detectors)
  - not triggerable => need to examine full statistics
  - need to preserve ALICE uniqueness, superb tracking and PID, and enhance its secondary vertex capability and tracking at low-p_T
- Gain a factor of **100** in statistics over approved program: x 10 integrated luminosity, **$1 nb^{-1}$ => $10 nb^{-1}$**, x 10 via **pipelined readout** to inspect all collisions, inspect $O(10^{10})$ central collisions instead of $O(10^8)$
  - run ALICE at 50kHz Pb-Pb (i.e. $L = 6x10^{27} cm^{-1}s^{-1}$), with minimum bias (pipeline) readout (max readout with present ALICE set-up ~500Hz)
  - ➢ High-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ/HLT, Muons and Trigger detectors
- Improve vertexing and tracking at low p_t:
  - ➢ New, smaller radius beam pipe
  - ➢ New inner tracker (ITS) with improved material, precision and rate capability

ALICE Upgrade Physics Reach

p_T coverage (p_T^{min}) and statistical error for current ALICE with approved programme and upgraded ALICE with extended programme. Error in both cases at p_T^{min} of "approved".

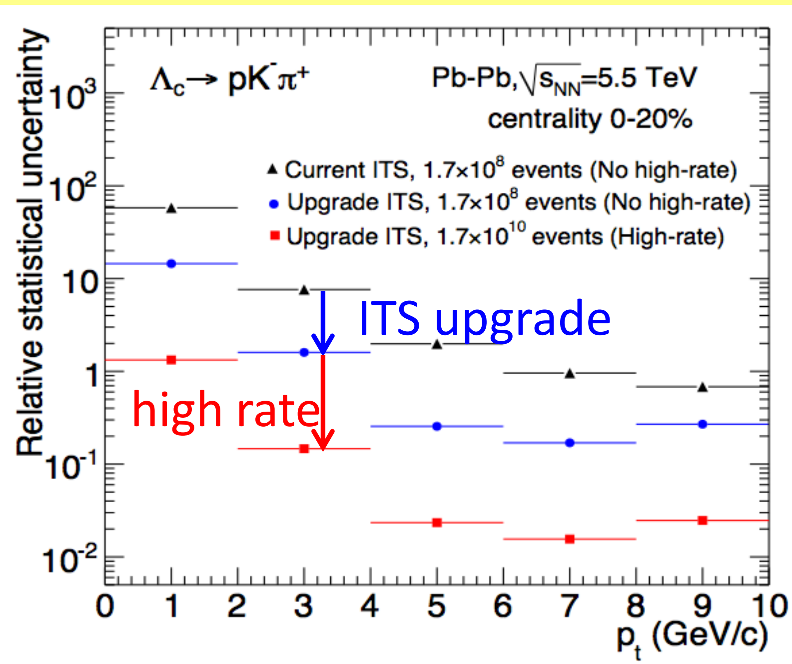
Topic	Observable	Approved (1/nb delivered, 0.1/nb m.b.)	Upgrade (10/nb delivered, 10/nb m.b.)
Heavy flavour	D meson R_{AA}	p_T>1, 10%	p_T>0, 0.3%
	D from B R_{AA}	p_T>3, 30%	p_T>2, 1%
	D meson elliptic flow (for v_2=0.2)	p_T>1, 50%	p_T>0, 2.5%
	D from B elliptic flow (for v_2=0.1)	not accessible	p_T>2, 20%
	Charm baryon/meson ratio (Λ_c/D)	not accessible	p_T>2, 15%
	D_s R_{AA}	p_T>4, 15%	p_T>1, 1%
Charmonia	J/ψ R_{AA} (forward y)	p_T>0, 1%	p_T>0, 0.3%
	J/ψ R_{AA} (central y)	p_T>0, 5%	p_T>0, 0.5%
	J/ψ elliptic flow (forward y, for v_2 =0.1)	p_T>0, 15%	p_T>0, 5%
	ψ'	p_T>0, 30%	p_T>0, 10%
Dielectrons	Temperature IMR	not accessible	10% on T
	Elliptic flow IMR (for v_2=0.1)	not accessible	10%
	Low-mass vector spectral function	not accessible	p_T>0.3, 20%
Heavy nuclei	hyper(anti)nuclei, H-dibaryon	35% ($^4_\Lambda$H)	3.5% ($^4_\Lambda$H)

Examples of performance studies

$\Lambda_c \rightarrow pK\pi$

- Λ_c $c\tau$=60 μm, to be compared with D^+ $c\tau$=300 μm

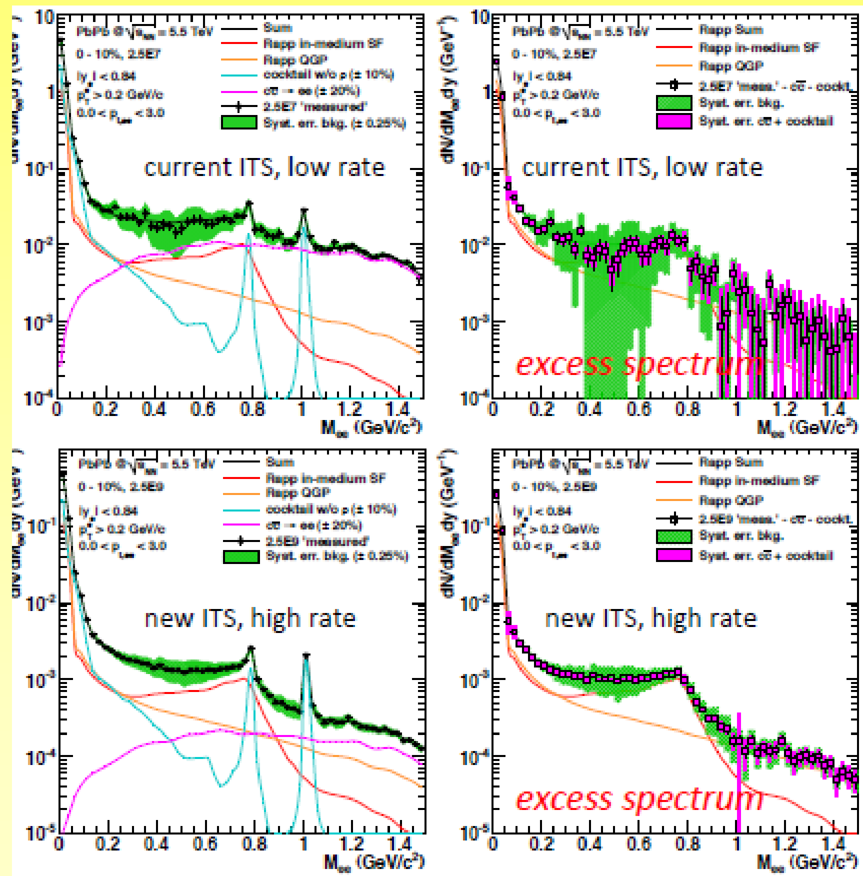
→ practically impossible in Pb-Pb with current ITS



With new ITS and high-rate, measurement down to 2 GeV/*c*

low-mass e^+e^-

- e-PID in TPC and TOF



- Dalitz rejection, conversion and charm suppression
  - New ITS improves major sources of systematic uncertainties

The LS2 ALICE upgrades

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

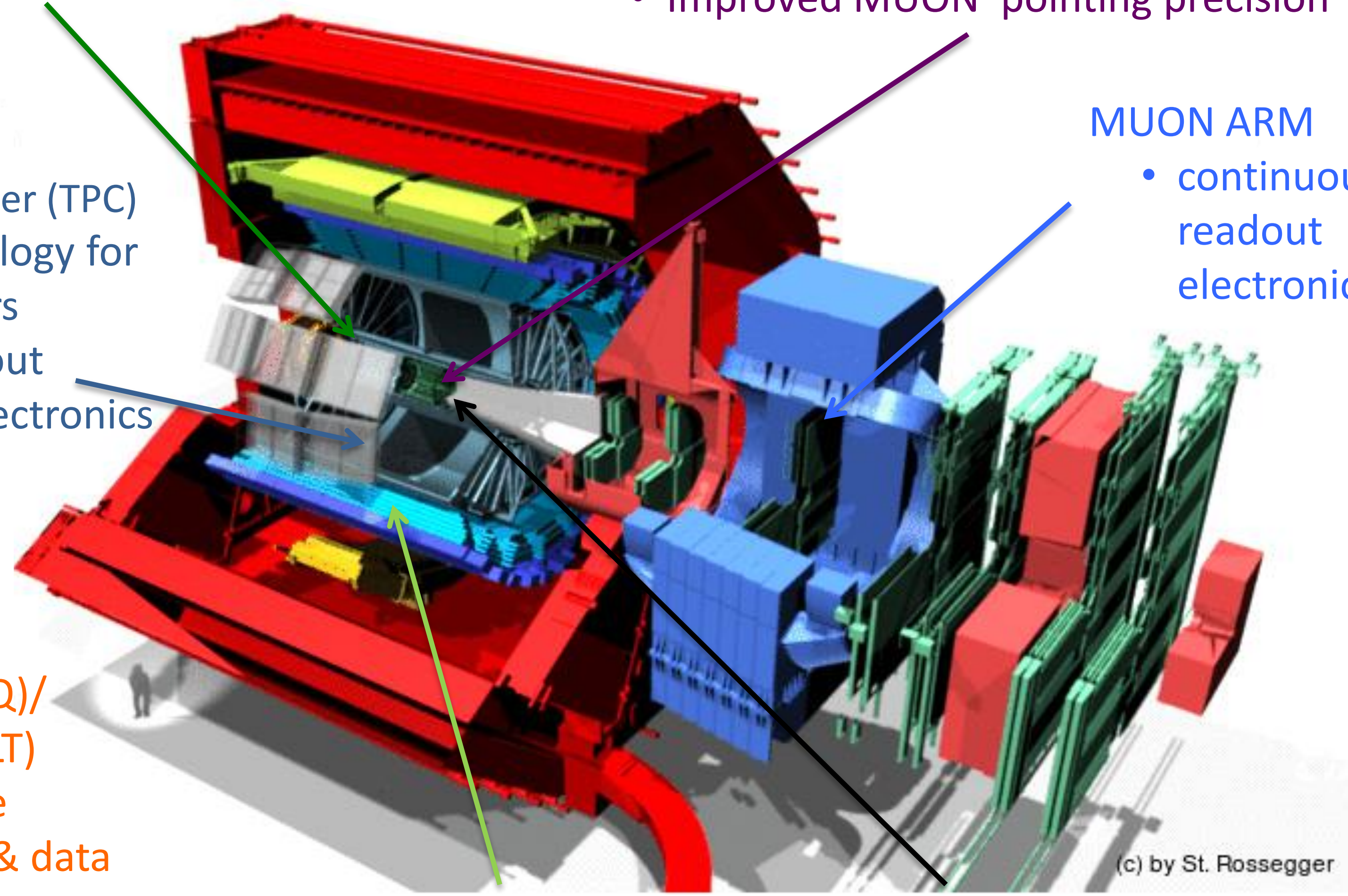
Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

New Central Trigger Processor

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate



TOF, TRD
- Faster readout

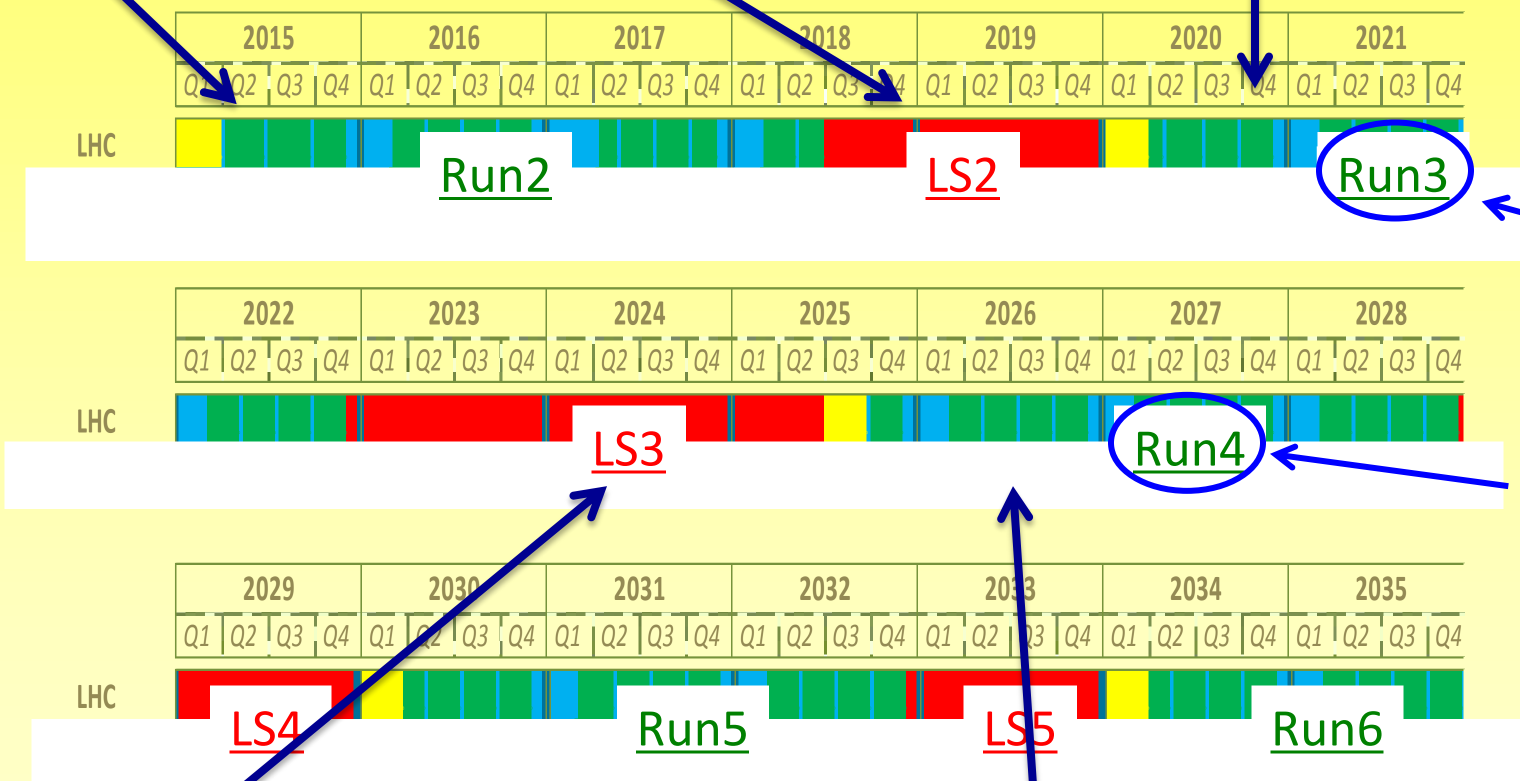
New Trigger Detectors (FIT)

Long Term Schedule

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS „“minor“ upgrade

NOW

Heavy Ion Luminosity from 10^{27} to 7 $x10^{27}$



Upgraded ALICE Runs: 2020 to 2028

PHASE II Upgrade
ATLAS, CMS major upgrade

HL-LHC, pp luminosity from 10^{34} (peak) to 5 $x10^{34}$ (levelled)

Conclusions

- **A rich harvest of Physics results, promising to continue even richer!**
  - **A continuous flow of new results**
    - global features defined
    - QGP strongly interacting liquid even at higher T, access to transport coefficients
    - energy loss of partons in QGP: wealth of data from leading particles and reconstructed jets, including heavy quarks
    - Heavy quarks also appear to thermalize!
    - rich results on charmonium, well on the way towards proof of deconfinement
  - **Intriguing, unexpected results from the pA run**
    - How small a QGP serving to observe collective behaviour?
- **An exciting plan for the years to come**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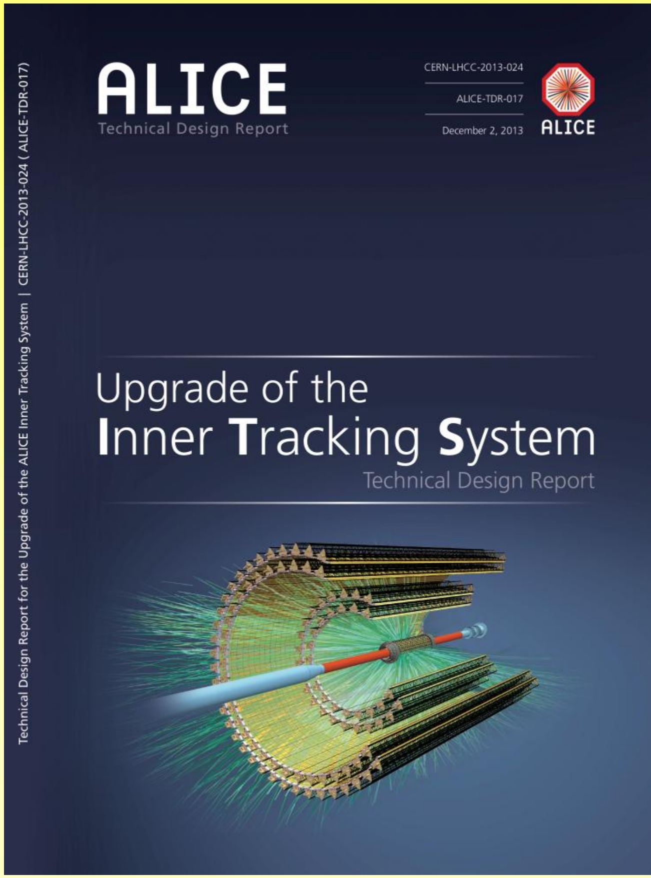
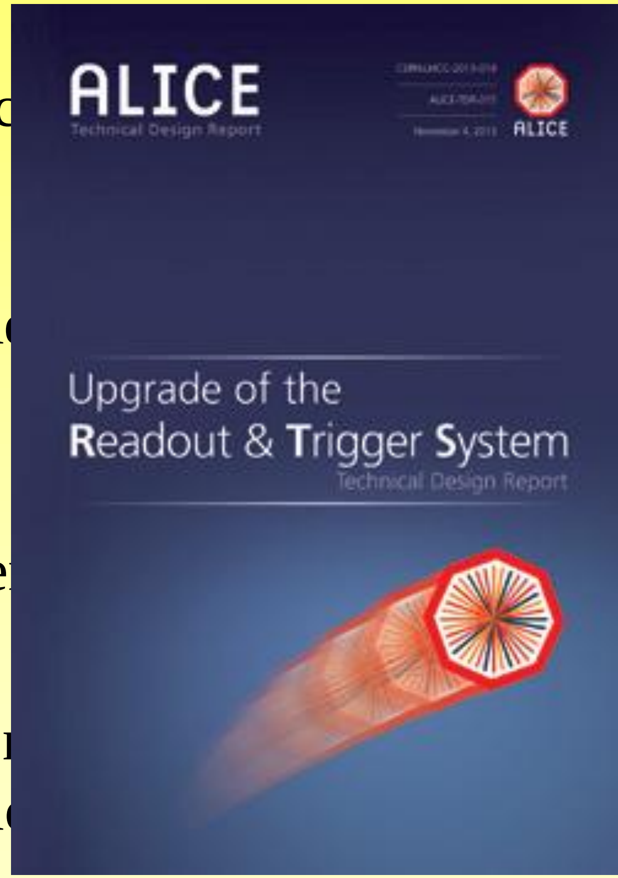
The ALICE Upgrade

- **Five Pillars (each in a Technical Design Report):**



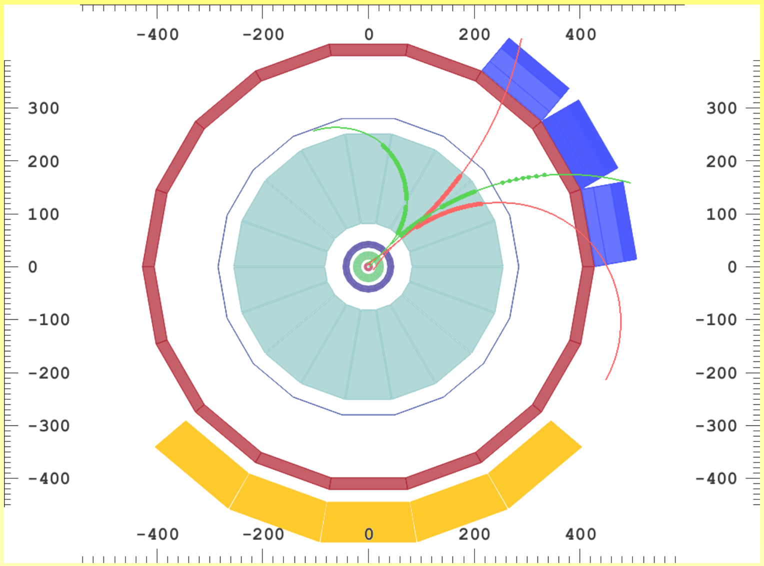


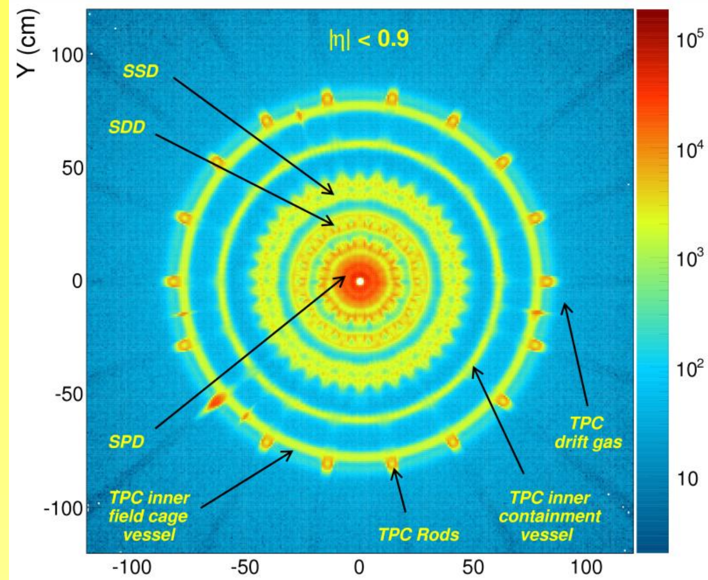
- New Silicon Tracker in front of Muon Absorber

TDR in Late 2014

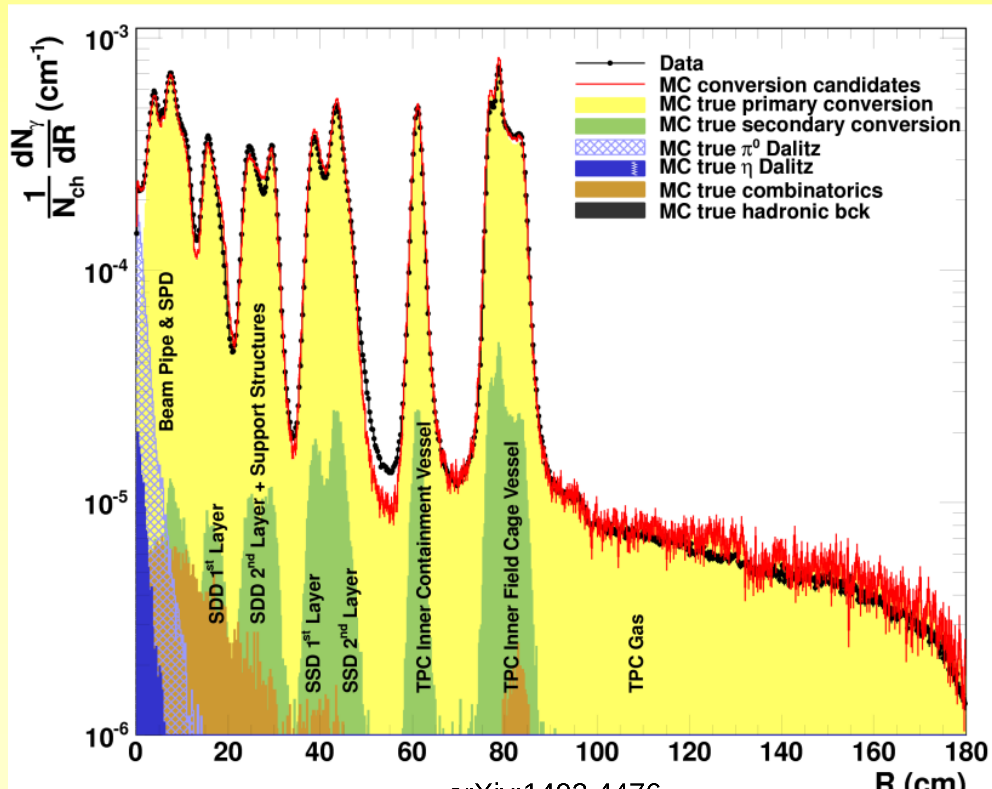
ALICE performance studies: Material

$\pi^0 \rightarrow 2\gamma$ converts to $2(e^- + e^+)$





arXiv:1402.4476

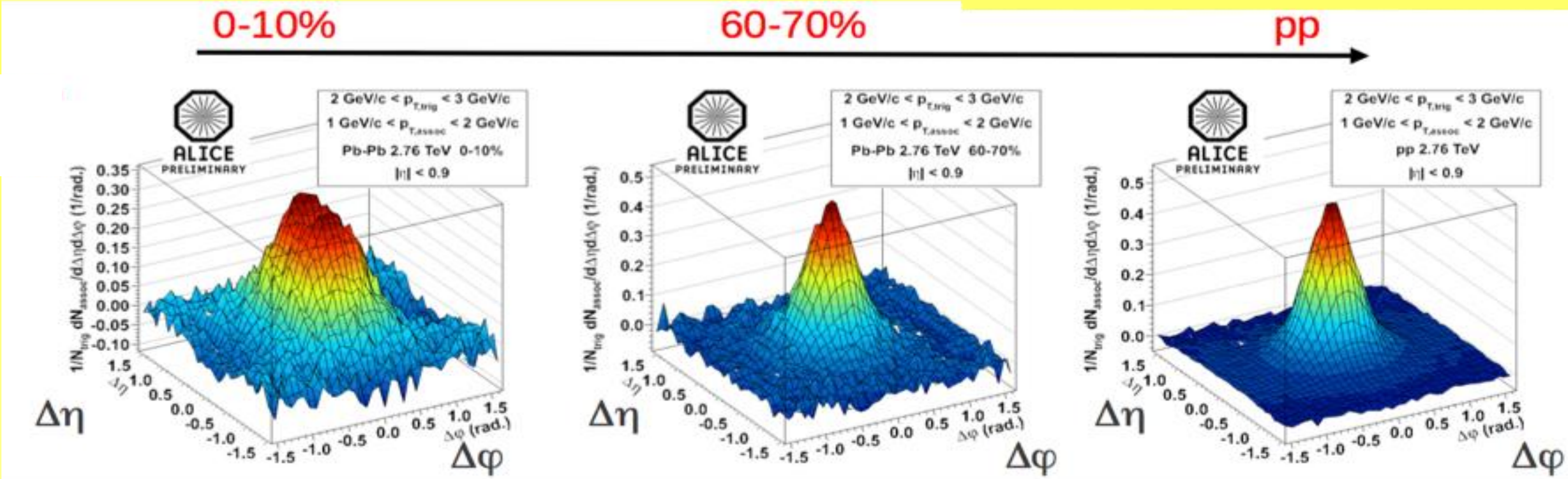


arXiv:1402.4476

The integrated detector material for $R < 180$ cm and $|\eta| < 0.9$ amounts to a radiation thickness of $11.4 \pm 0.5\%$ X_0 and results in a conversion probability of about 8.5%.

The precision of this measurement (currently 4.5%) directly contributes to the error in all photon analyses.

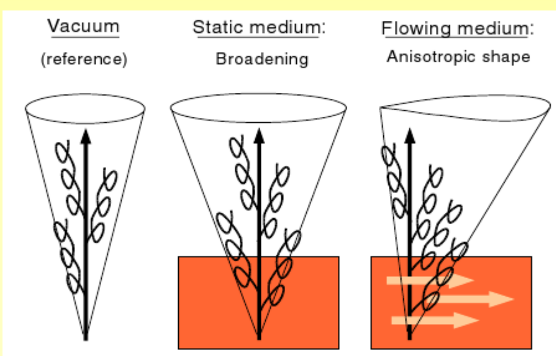
Detailed studies: Jet peak shape deformation

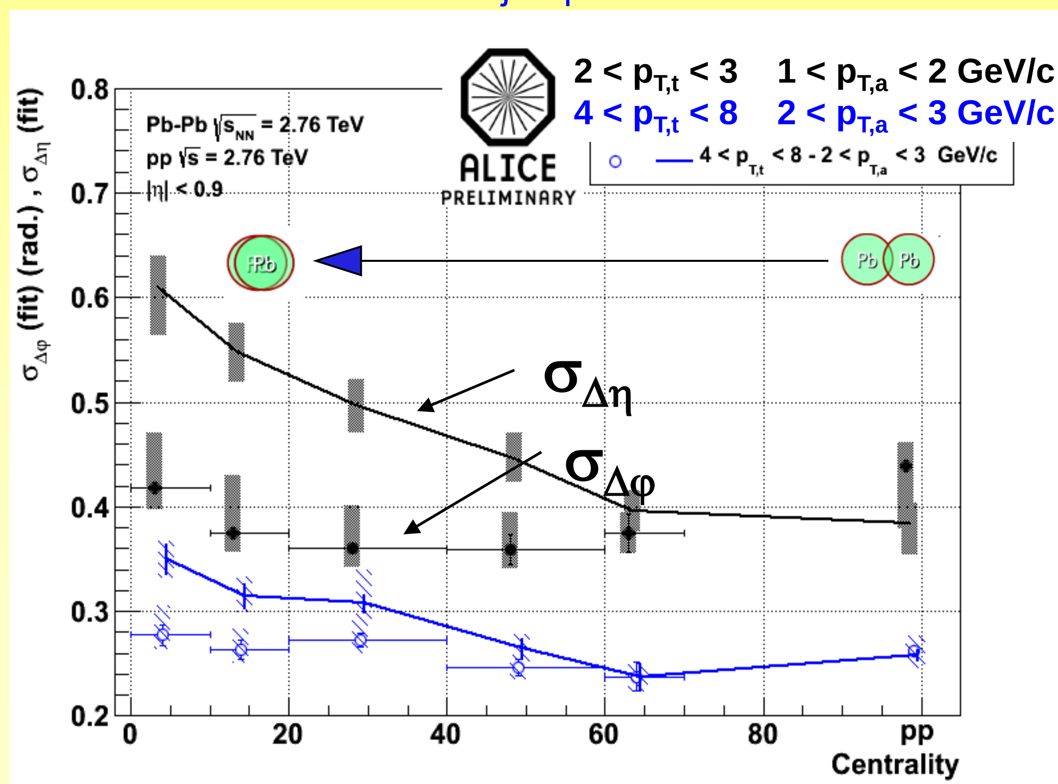


Long-range $\Delta\eta$ correlations subtracted Near-side "jet" peak

conical jet shape deformed
by longitudinal flow ?

N. Armesto et al., PRL 93,242301 (2004)





$\sigma_{\Delta\varphi}$ constant whereas $\sigma_{\Delta\eta}$ increases with centrality.

$\sigma_{\Delta\eta} > \sigma_{\Delta\varphi}$ predicted by models including longitudinal flow.

ALICE Upgrade: Objectives

(a subset!! The upgrade opens many more opportunities!)

- **Detailed characterization of the Quark-Gluon-Plasma**

- **Measurement of heavy-flavour transport parameters**
  - Diffusion coefficient (QGP eq. of state, η/s) → HF azimuthal anisotropy and R_{AA}
  - In-medium thermalization and hadronization → HF baryons and mesosn
  - Mass dependence of energy loss → HF R_{AA}
- **Measurement of low-mass and low-p_t di-electrons**
  - Chiral symmetry restoration → ρ spectral function
  - γ production from QGP (temp.) → low-mass dilepton continuum
  - Space-time evolution of the QGP → radial and elliptic flow of emitted radiation
- **J/ψ , ψ', and χ_c states down to zero p_t**
  - statistical hadronization vs. dissociation/recombination scenario
  - transition between low and high transverse momenta
  - density dependence – central vs. forward production
- **Light nuclear states**
  - mass-4 and -5 (anti-)hypernuclei
  - search for H-dibaryon, Λn bound states, etc.

➡ requires high statistics and precision measurements

Puzzles in QCD: ii) hadron masses

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b beauty	4.3	−1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- A proton is thought to be made of two u and one d quarks
- The sum of their masses is around 12 MeV
- ... but the proton mass is 938 MeV!
- **how is the extra mass generated?**

QCD

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	<1×10⁻⁸	0
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W⁻	80.4	–1
W⁺	80.4	+1
Z⁰	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

- **strong interaction**:
  - binds quarks into hadrons
  - binds nucleons into nuclei
- **described by QCD:**
  - interaction between particles carrying colour charge (quarks, gluons)
  - mediated by strong force carriers (gluons)
- **very successful theory**
  - jet production
  - particle production at high p_T
  - heavy flavour production
  - ...
- ... but with some **outstanding puzzles**

Two puzzles in QCD: i) confinement

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

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Flavor		Mass GeV/c^2	Electric charge
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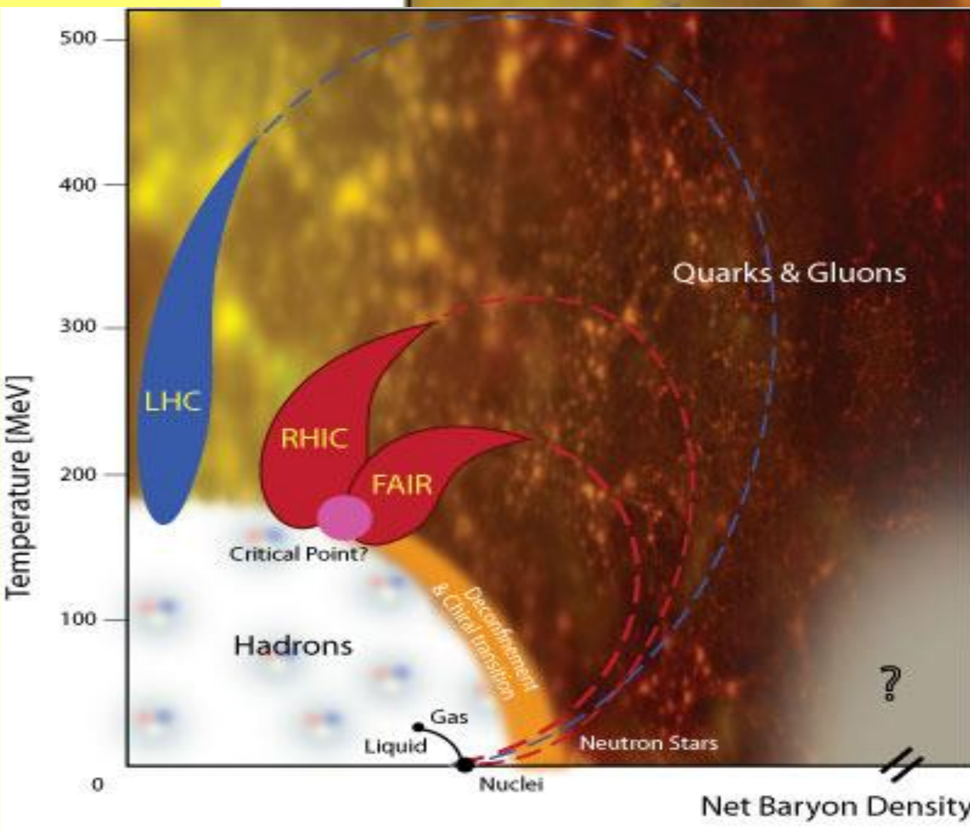
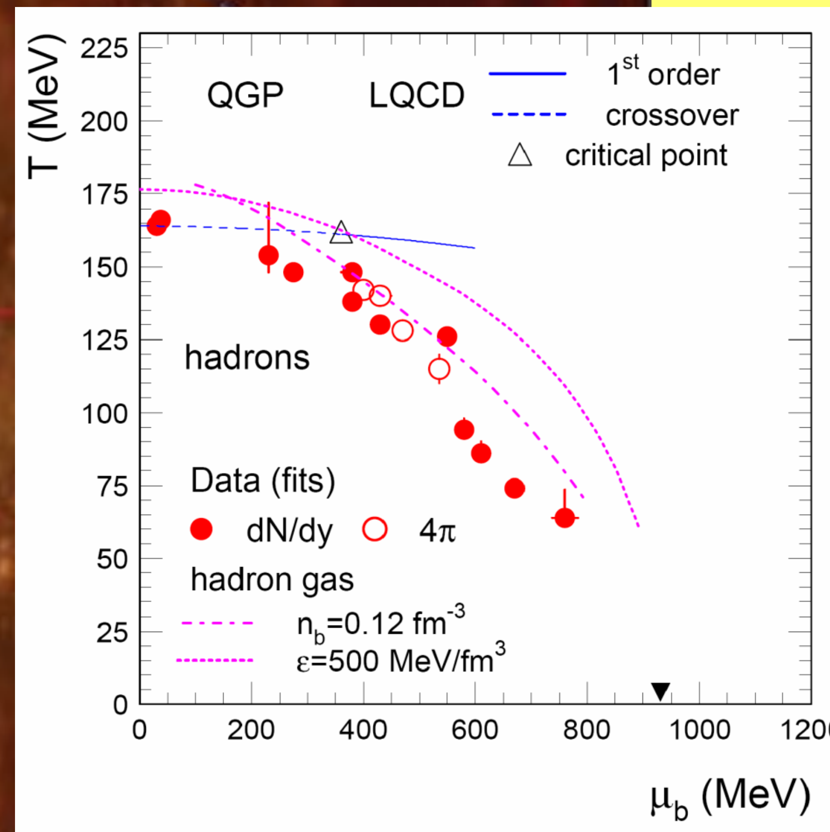
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons.
- It looks like one half of the fundamental fermions are not directly observable…

  <u>how does this come about?</u>

Exploring the QCD Phase Diagram





- Being populated with experimental points…

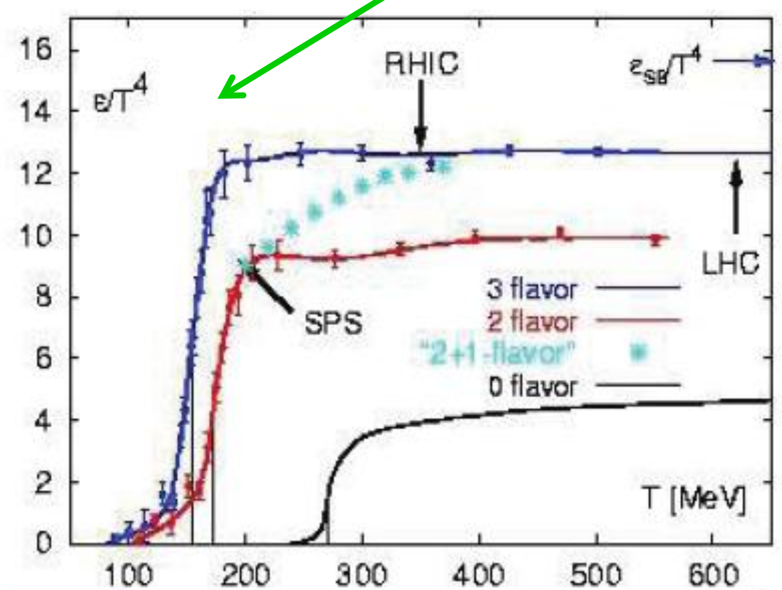
Lattice QCD

- rigorous way of doing calculations in non-perturbative regime of QCD discretization on a space-time lattice

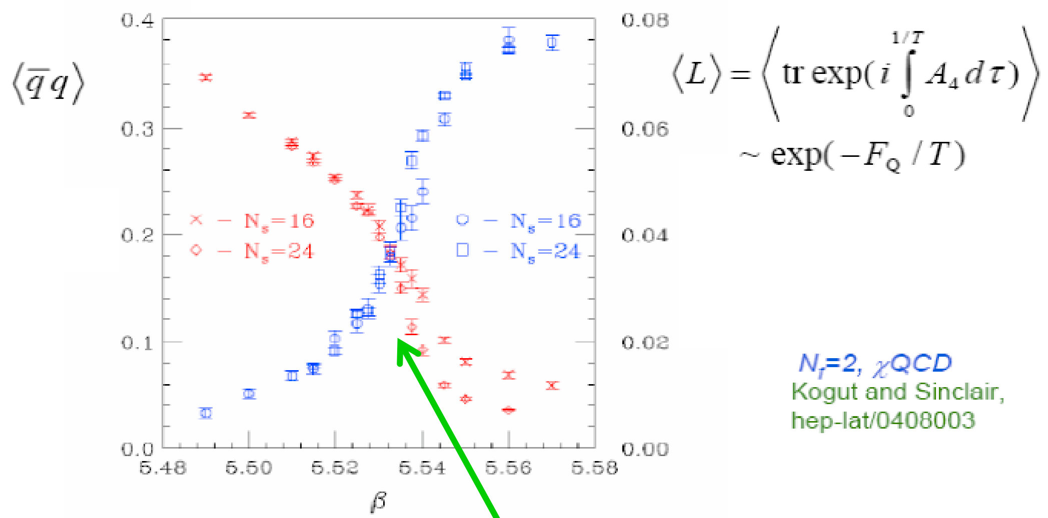
For the (2 + 1) flavor case (but zero baryon density): the phase transition to the QGP and its parameters are quantitative predictions of QCD.

Tc = 173 ± 12 MeV **ε_c = 700 ± 200 MeV/fm3**

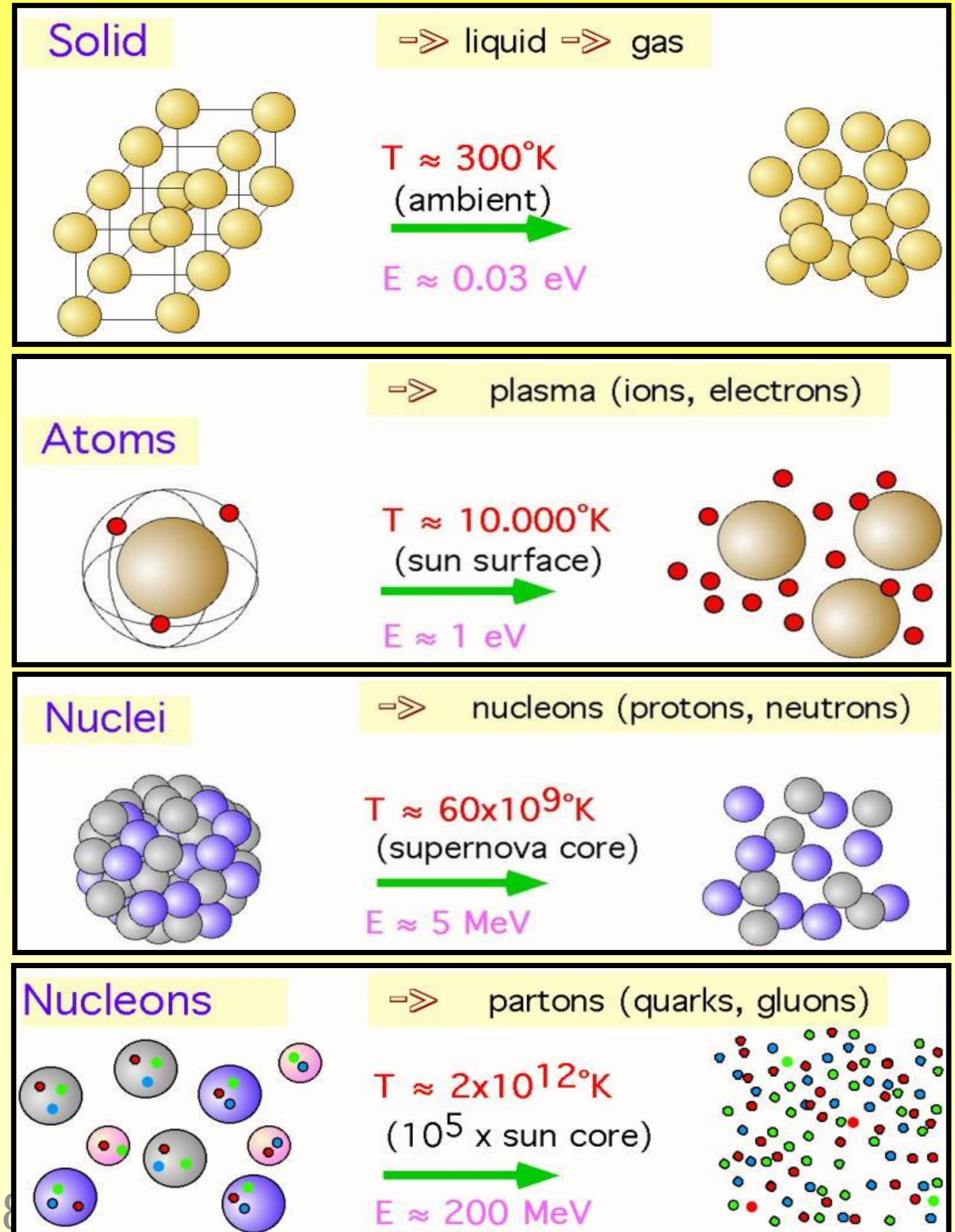
Energy density increases sharply around T_c by the latent heat of deconfinement



Lattice QCD calculations for μ_B= 0
Karsch et al, hep-lat/0305025



Moreover, Lattice QCD predicts a rapid transition, with correlated deconfinement and chiral restauration



Melting Matter

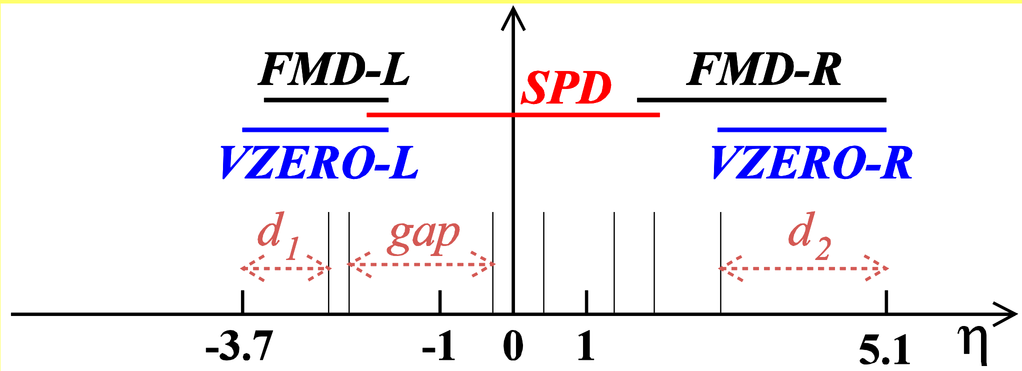
If the force grows with distance, at small distances it is small (*asymptotic freedom*)

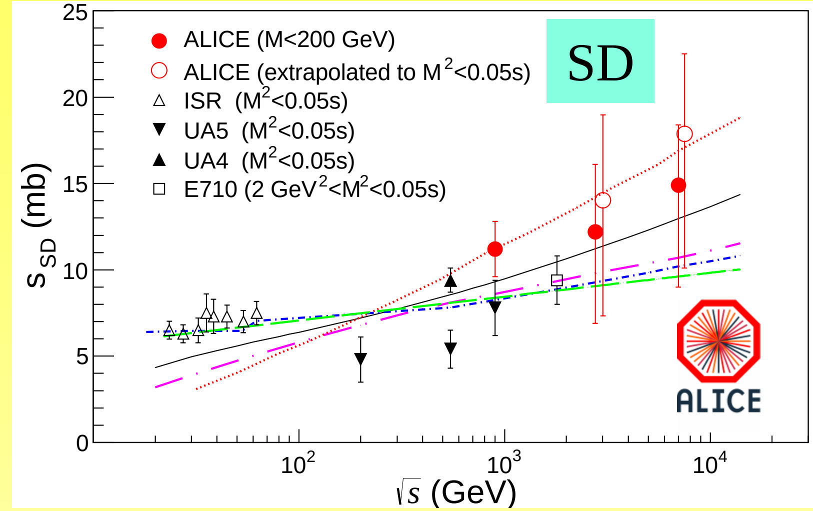
Idea: obtain deconfinament using collisions of Nuclei => compresssion and heating

Afterwards the system espands and cools, and ordinary hadrons reconstitute after a short time (about 10^{-23}s, or a few fm/c) … just as they did in the evolution of primordial Universe, some 11 millionth of a second after the Big Bang!

pp single- and double- diffractive and inelastic cross-sections

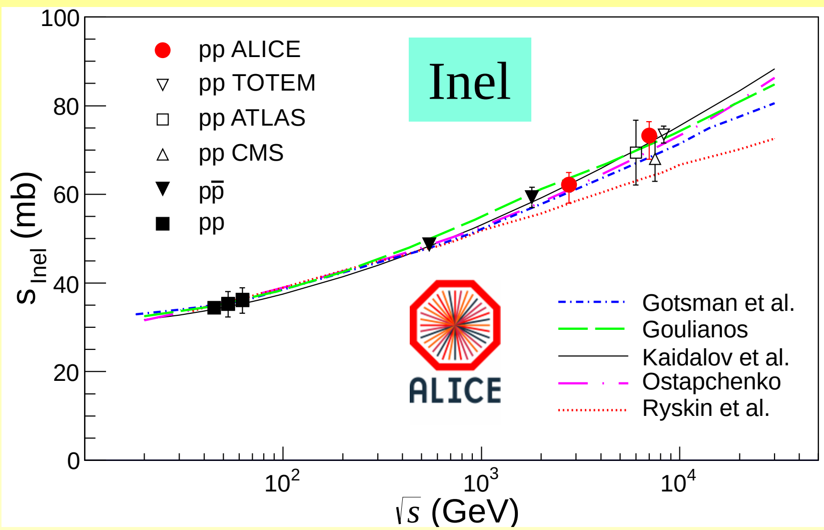
vdM scan (final here) + MC generators tuned to measured ratio of 1-arm to 2-arm trigger.

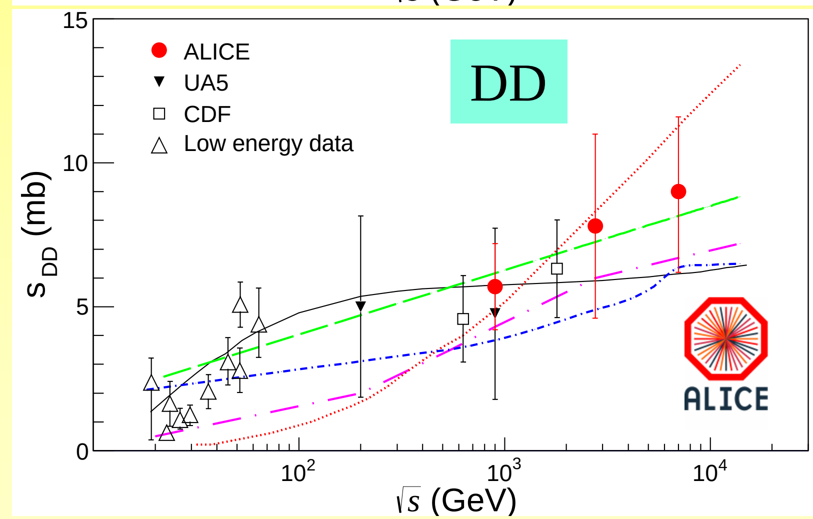




Left-side 1-arm trigger : no signal with η > +1

Right-side 1-arm trigger: no signal with η < –1





σ_{Inel} at $\sqrt{s} = 7$ TeV

ALICE : $73.2\ ^{+2.0}_{-4.6}{}^{\text{model}} \pm 2.6^{\text{lumi}}$

ATLAS : $69.4 \pm 2.4^{\text{exp.}} \pm 6.9^{\text{extrap.}}$

CMS : $68.0 \pm 2.0^{\text{syst.}} \pm 2.4^{\text{lumi}} \pm 4^{\text{extrap.}}$

TOTEM: $73.5 \pm 0.6^{\text{stat.}}\ ^{+1.8}_{-1.3}{}^{\text{syst.}}$

Gotsman et al., arXiv:1010.5323, EPJ. C74, 1553 (2011)

Kaidalov et al., arXiv:0909.5156, EPJ. C67, 397 (2010)

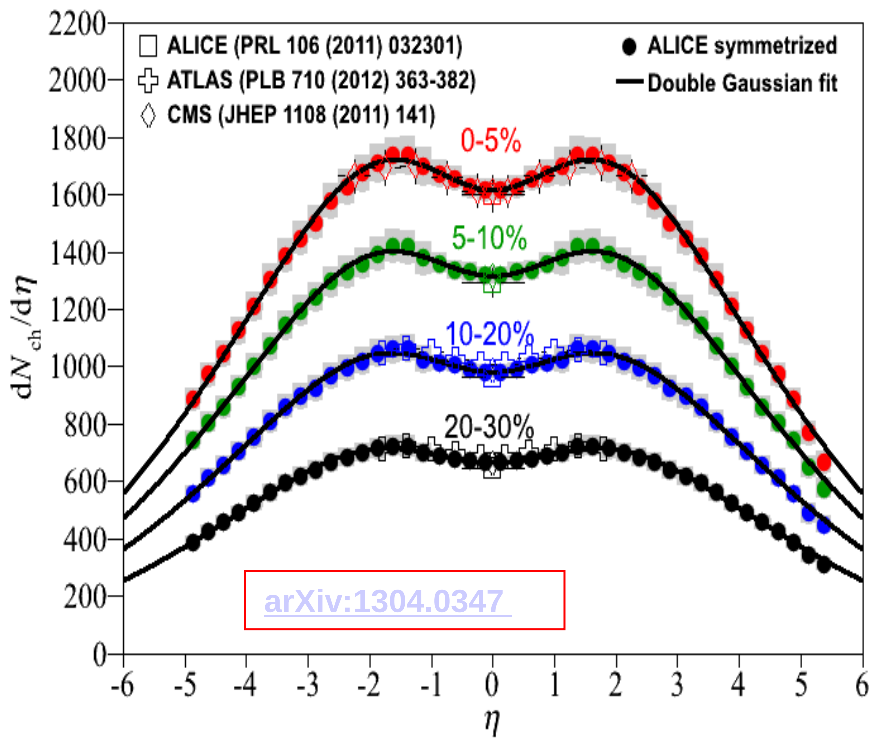
Ostapchenko, arXiv:1010.1869, PR D83 114018 (2011)

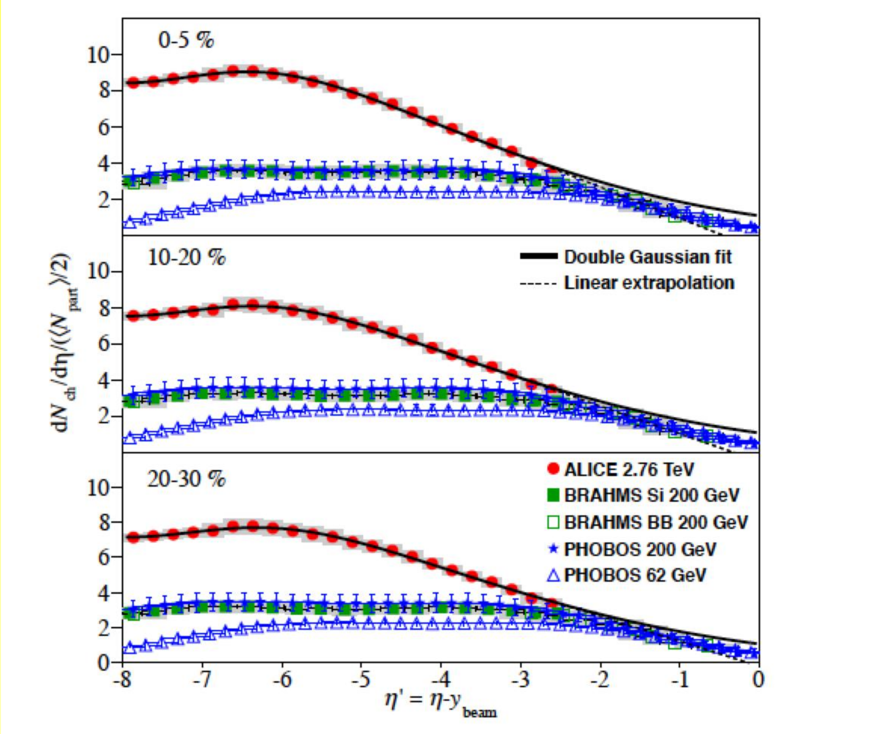
Ryskin et al., EPJ. C60 249 (2009), C71 1617 (2011)

K. Goulianos, arXiv:0203141; 1105.4916, PL B358, 379 (1995)

Model predictions: SD ➔ $M^2 < 0.05s$ DD ➔ $\Delta\eta > 3$

$dN_{ch}/d\eta$ versus η



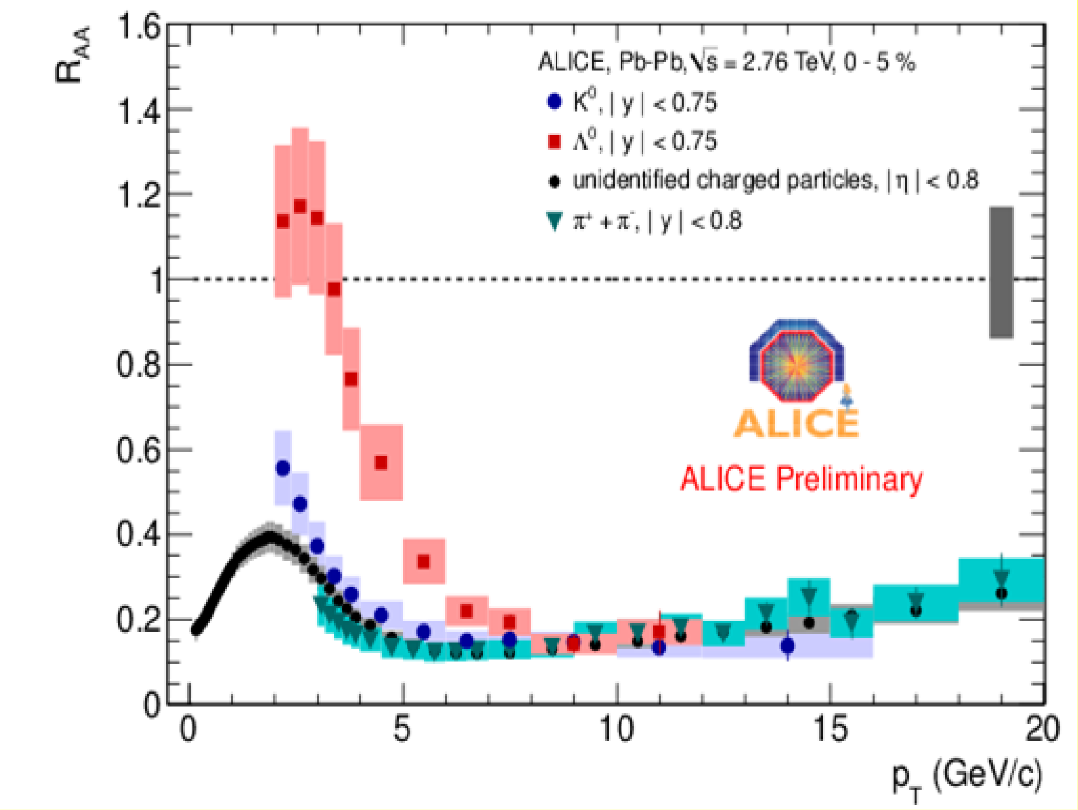


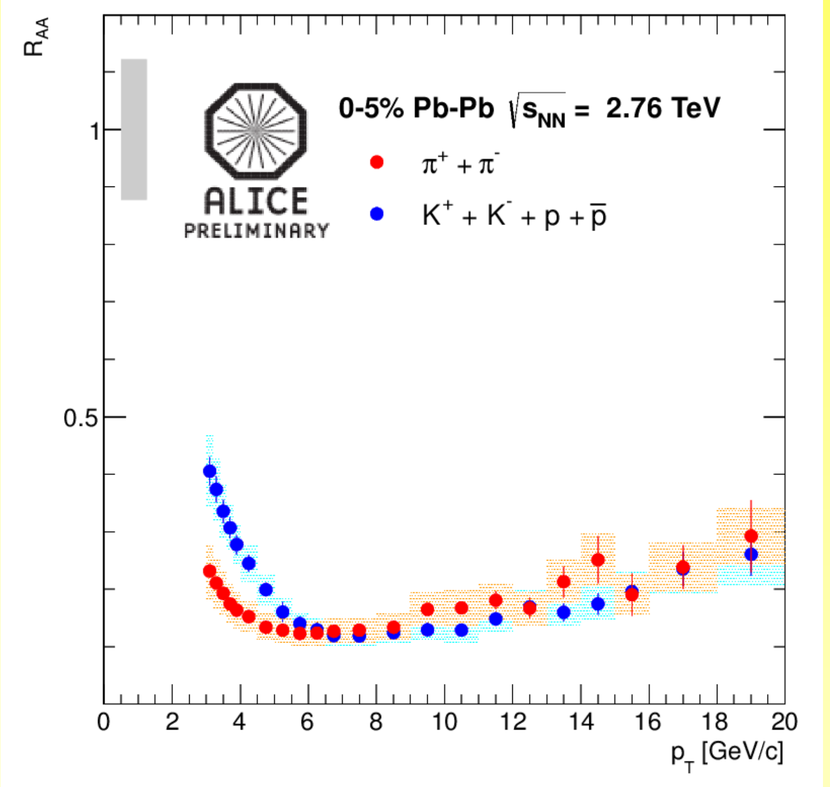
- **17165 ± 722 charged particles produced in 5% most central coll**
- **$\varepsilon \geq 16$ GeV/fm³**
- **x 100 above nuclear density**
- **x 30 above nucleon density**
- **x 20 above lattice-QCD prediction for quark-gluon plasma formation**

- **Longitudinal Scaling?**
  - Is particle production in the fragmentation region invariant with beam energy? (Benecke et al., Phys Rev, v188, n5, 1969)
  - Extrapolation of $dN_{ch}/d\eta$ vs η-y_{beam} coincides with lower energy data
  - Measurements consistent with longitudinal scaling

Matter under extreme conditions: ~ 50 times the density of neutron star core(40 billion tons/cm3)

Understanding R_{AA}





- Nuclear modification factor RAA studied for several identified particles
- Λ R_{AA}: interplay of suppression and baryon enhancement

Jet quenching

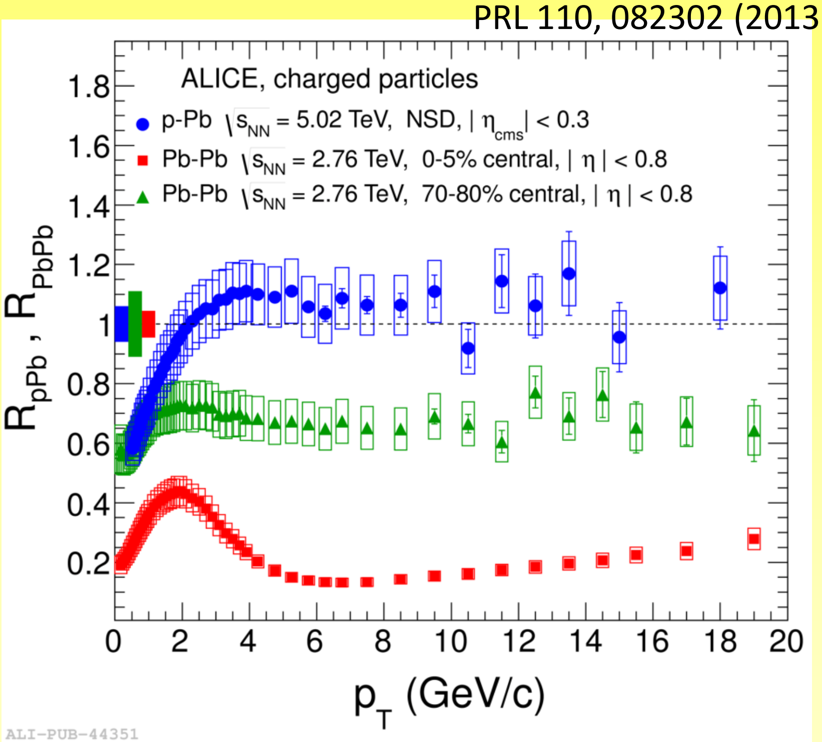
- partons lose energy **ΔE** when traversing a medium
  - **Jet(E) → Jet (E' = E-ΔE) + soft particles(ΔE)**
  - QCD energy loss **ΔE** expected to depend on:
    - **q** : 'opacity ' = property of medium ('radiation length of QGP')
    - **L**: size of medium (**~ L** (elastic) ~ L^2(radiative), L^3(AdS/CFT))
    - c_q: parton type (gluon > quark)
    - **f(*m*)** : quark mass (light q > heavy Q)
    - **f(*E*)** : jet energy (ΔE = constant or ~ ln(E))

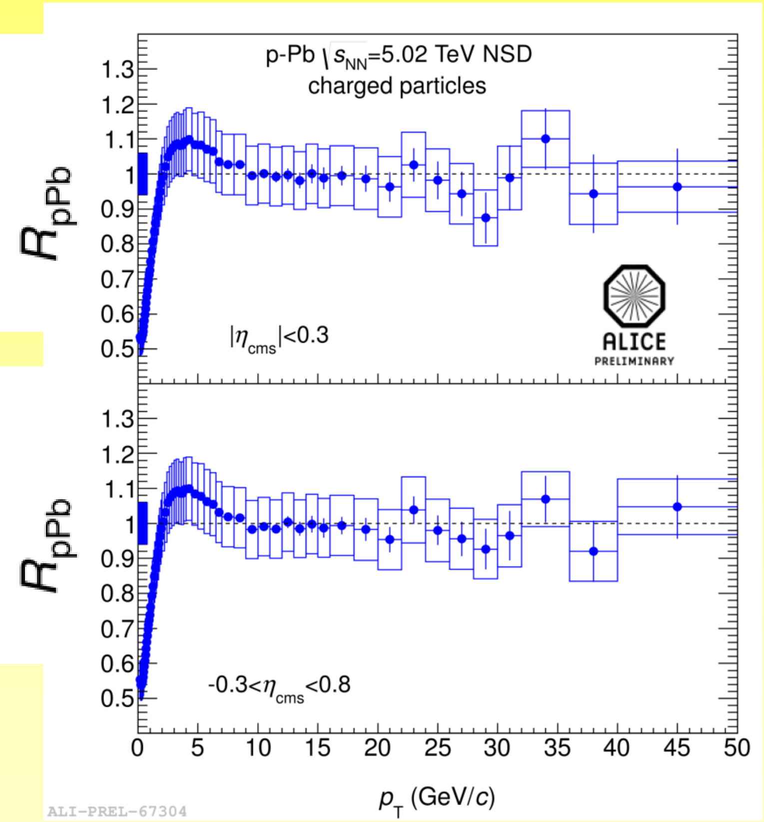
jet quenching measures
'stopping power' of QGP
$\Delta E \sim f(m) \times c_q \times q \times L^n \times f(E)$

- At LHC all aspects of quenching can be addressed, thanks to the large cross section and the quality of the detectors

The nuclear modification factor in p-Pb: latest news

PRL 110, 082302 (2013)



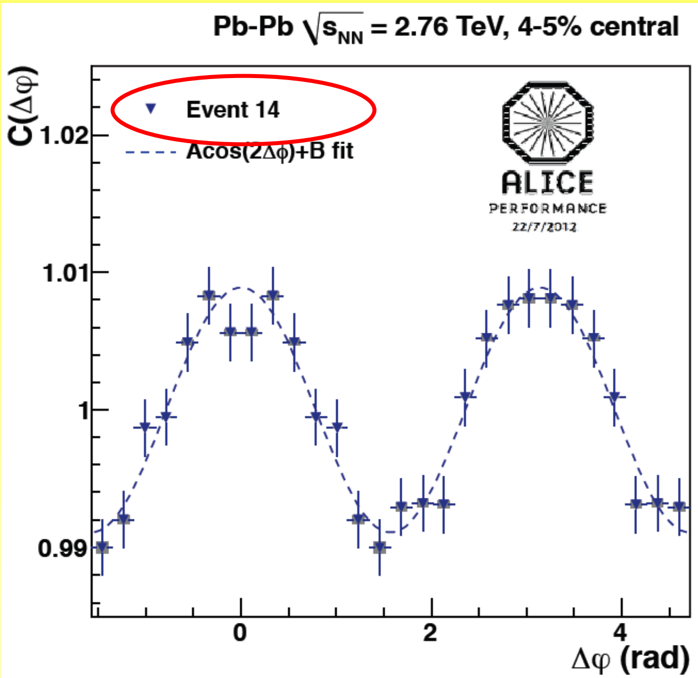


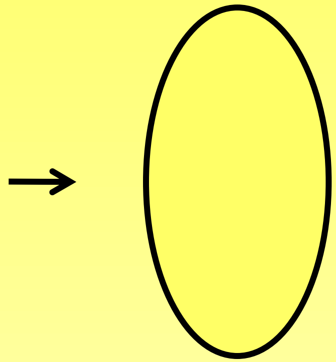
The new ALICE preliminary results are consistent with no modications up to p_T = 50 GeV/c.

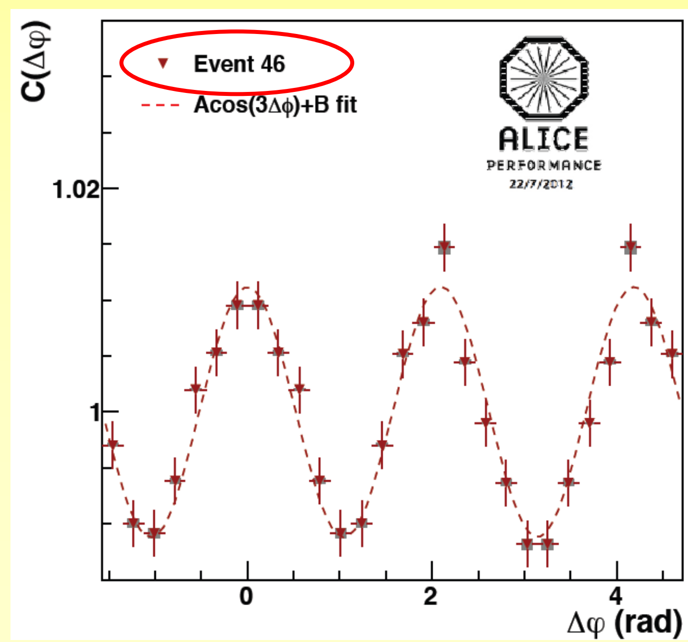
HI@LHC after LS2 (~2019)

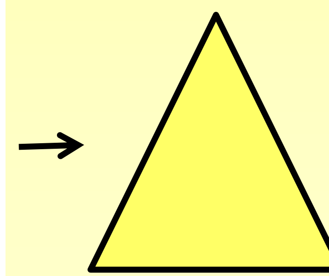
- **ALICE Upgrade**
  - Major upgrade of the experiment:
    - Capability to handle continuous readout of all collisions at 50 kHz of PbPb collisions => 100 times increase in statistics for low-p_T observables => needs new readout for all dets, new DAQ, new HLT
    - Improved secondary vertex capability and tracking at low-p_T => all new Inner Tracker
  - Endorsed by LHCC sept 6th 2012
  - Approved by Research Board Nov 28th 2012
- **Erice final document on the European Strategy for Particle Physics**
  - Heavy Ions are an integral part of **the top priority of the plan**: "*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics* ***and the quark-gluon plasma."***

Individual events….

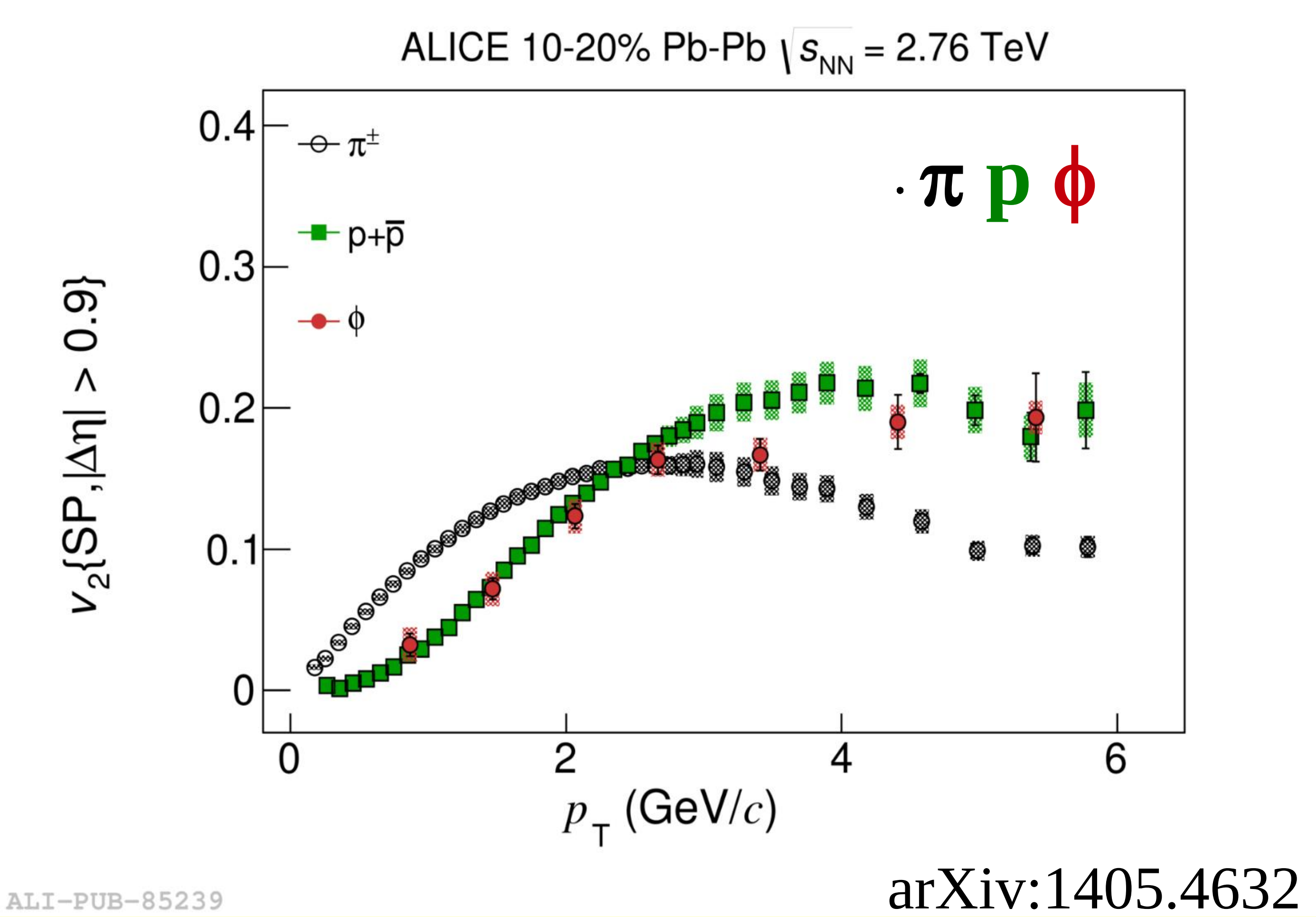






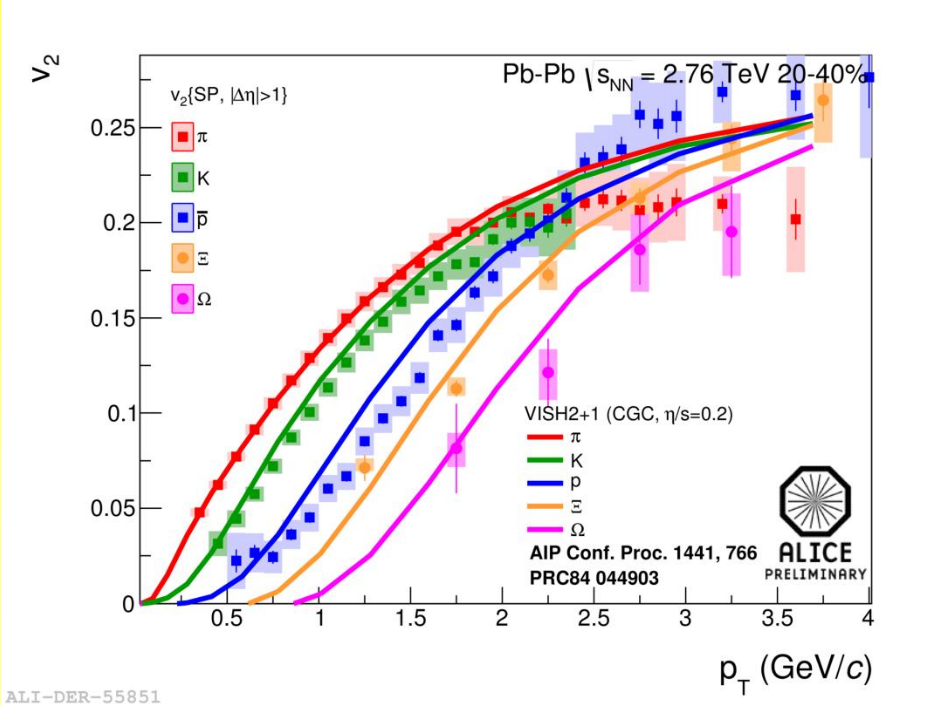


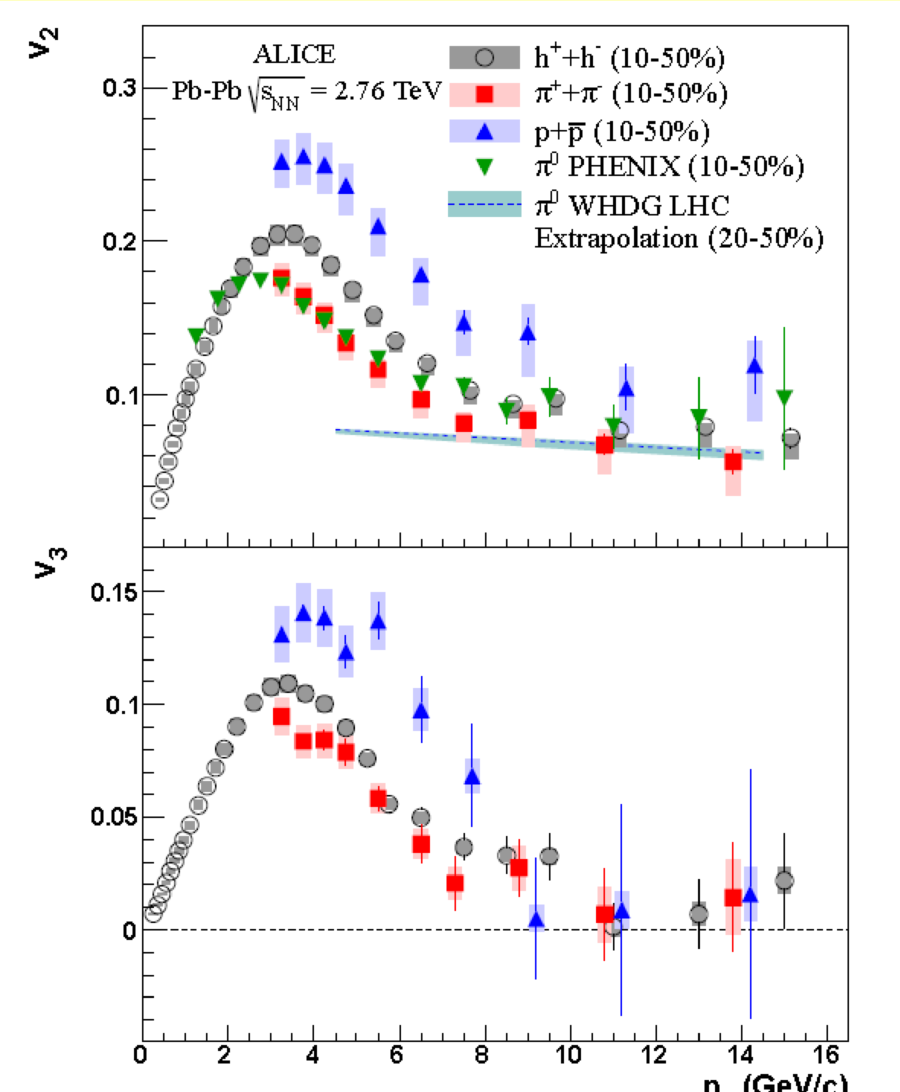
The ϕ again...



- Mass ordering → attributed to common radial expansion velocity
- ϕ meson behaves like a baryon
- Mass drives the $v2$ and spectra and not number of quark constituents

Flow of identified particles

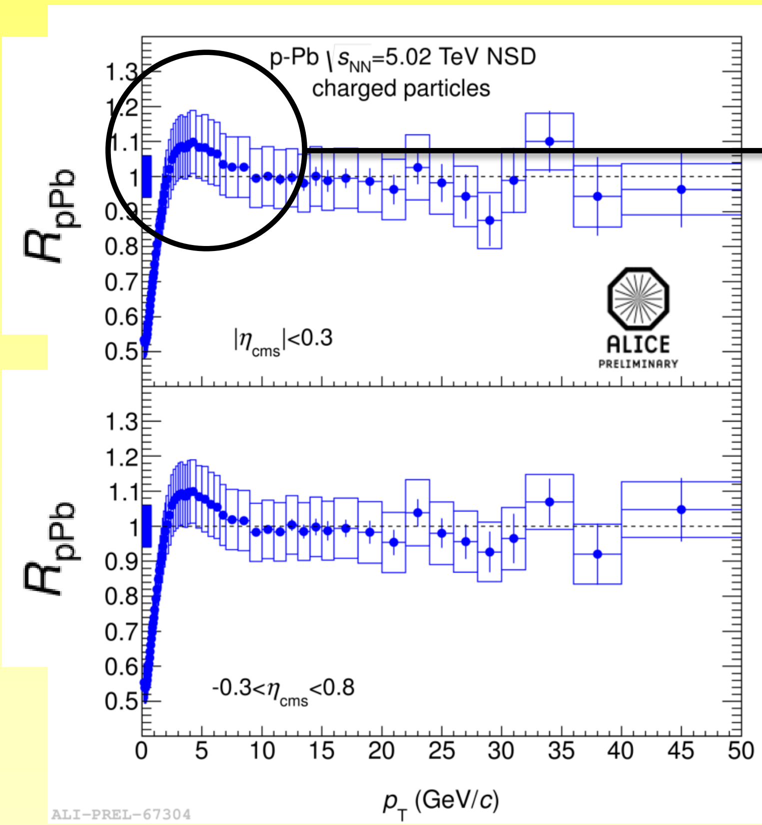


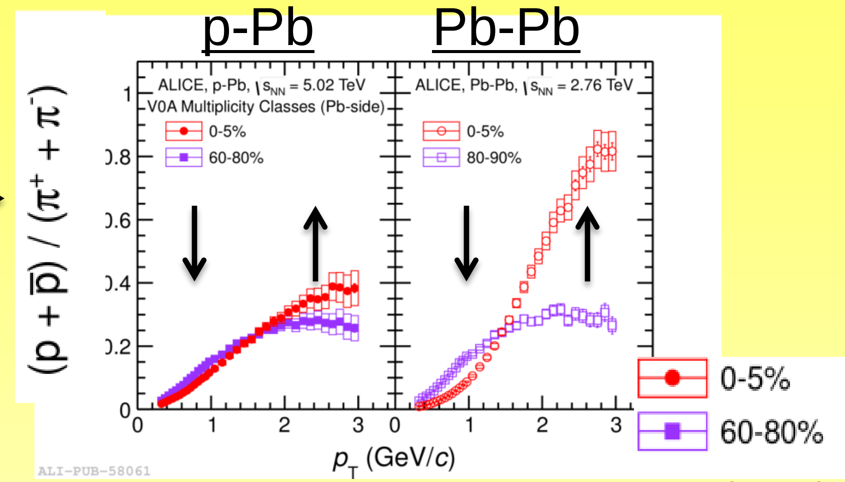


ALICE, PLB 719 (2013) 18

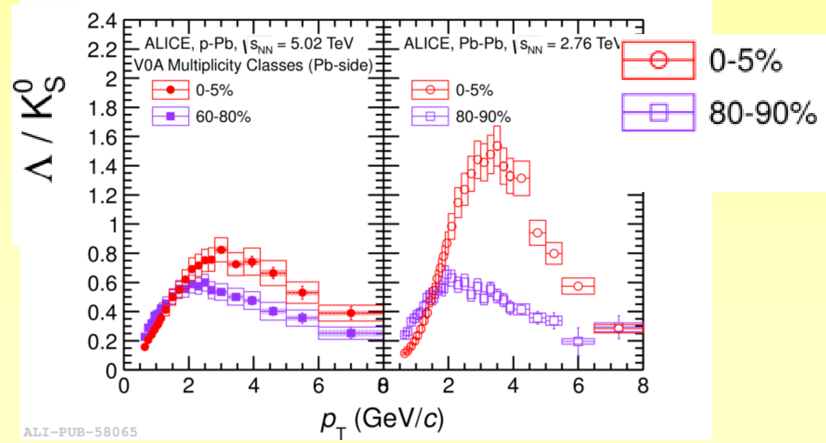
- Identified particle elliptic flow
  - Mass ordering at low p_T described by hydrodynamics
  - Particle species dependence persists up to $p_T \approx 8$ GeV/c

Using particle identification to understand the structure



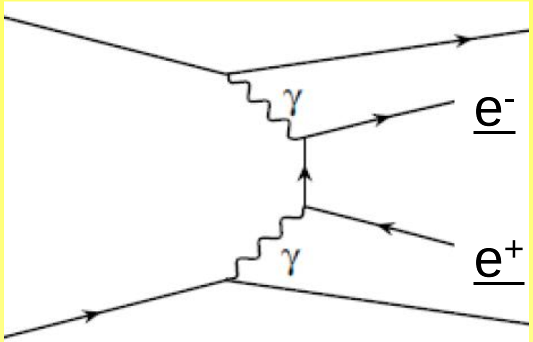


PLB 728 (2014)



Collectivity in small systems?

$\gamma\gamma \to e^+e^-$ in central barrel



Huge cross section: O(100) kb

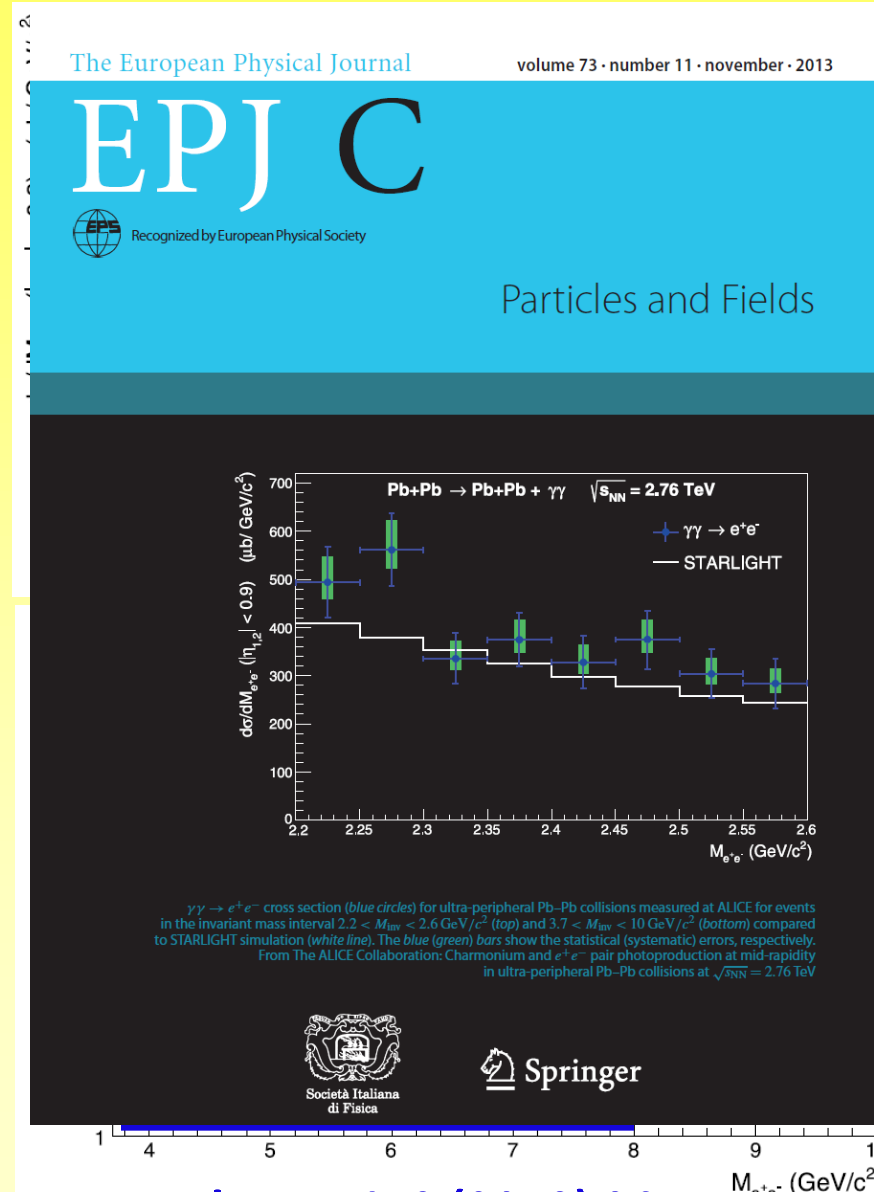
STARLIGHT, PRC60 (1999) 014903:

(LO prediction, $|\eta|<0.9$):

- 2.2 GeV/c^2 < M_{inv} < 2.6 GeV/c^2: $\sigma_{\gamma\gamma}$=128 μb
- 3.7 GeV/c^2 < M_{inv} < 10 GeV/c^2 : $\sigma_{\gamma\gamma}$=77 μb

ALICE:

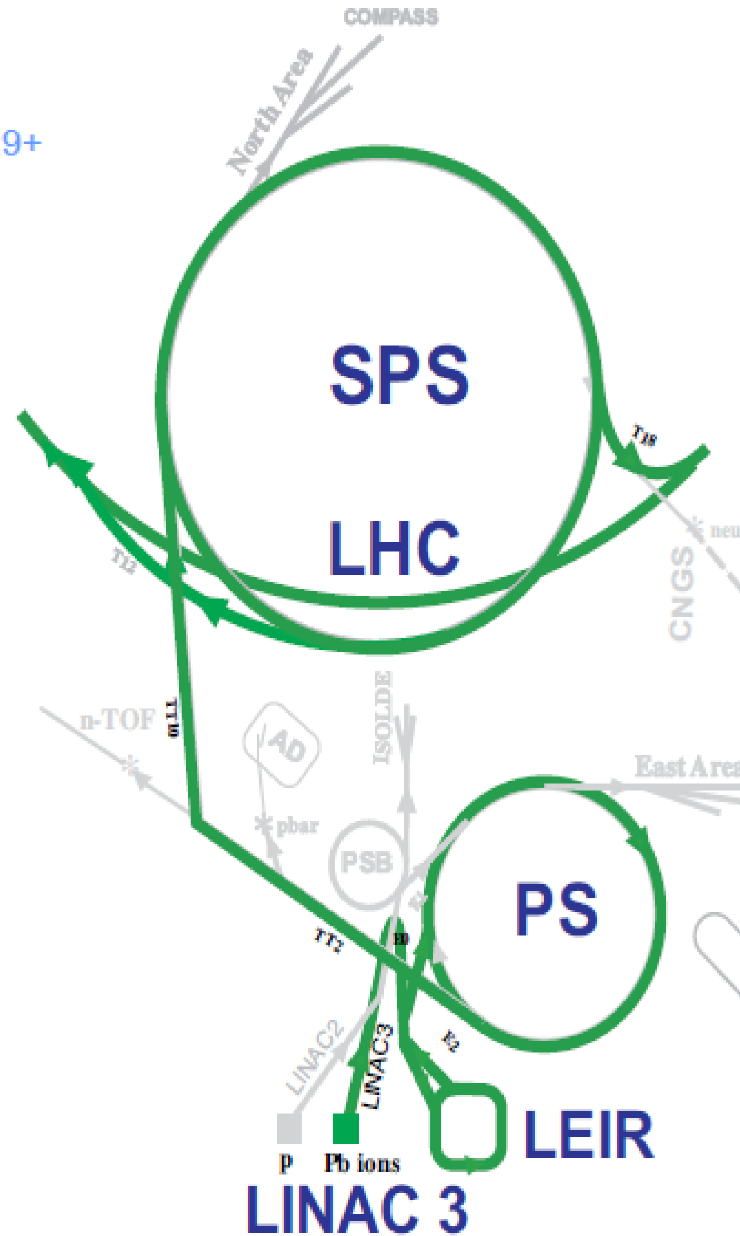
- Data slightly above LO prediction
- 12% and 16% precision in two mass ranges
- ALICE data sets stringent limits on the contribution from high order terms



Eur. Phys. J. C73 (2013) 2617

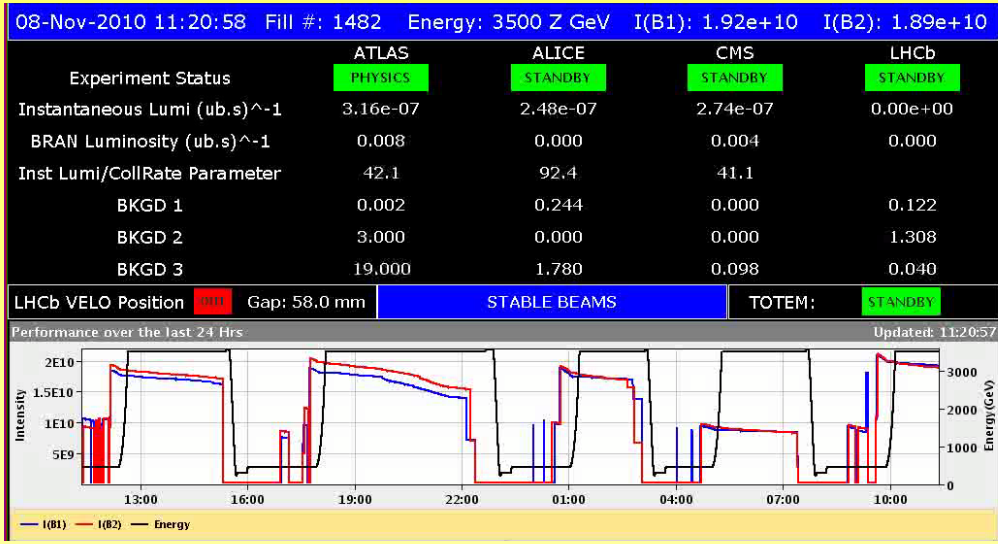
Lead ion injector chain

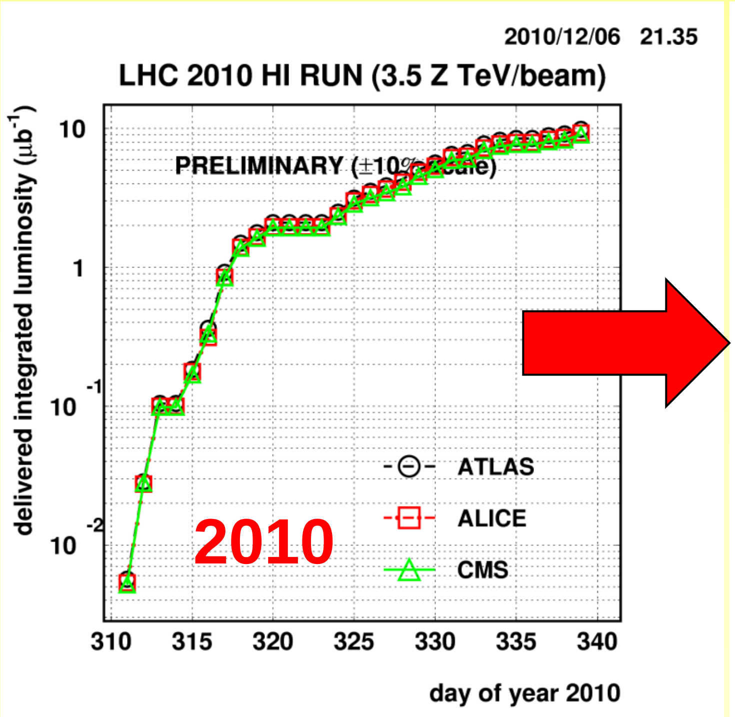
- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme

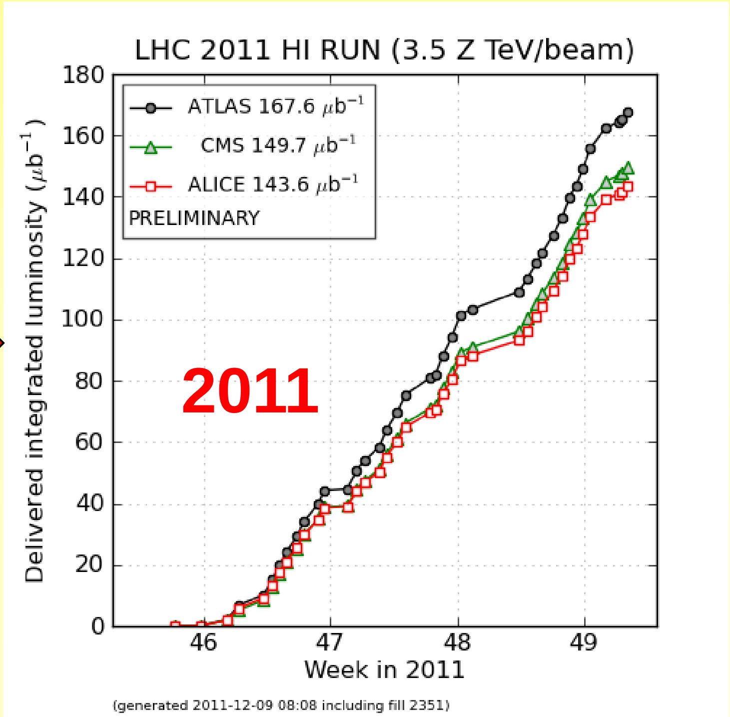


The LHC as a Heavy-Ion Collider

- **8 November 2010: the beginning of a new era for Heavy Ion Physics: a jump of more than an order of magnitude in energy since the previous record (RHIC @BNL)**
- **Three day to switch from protons to Pb Ions**



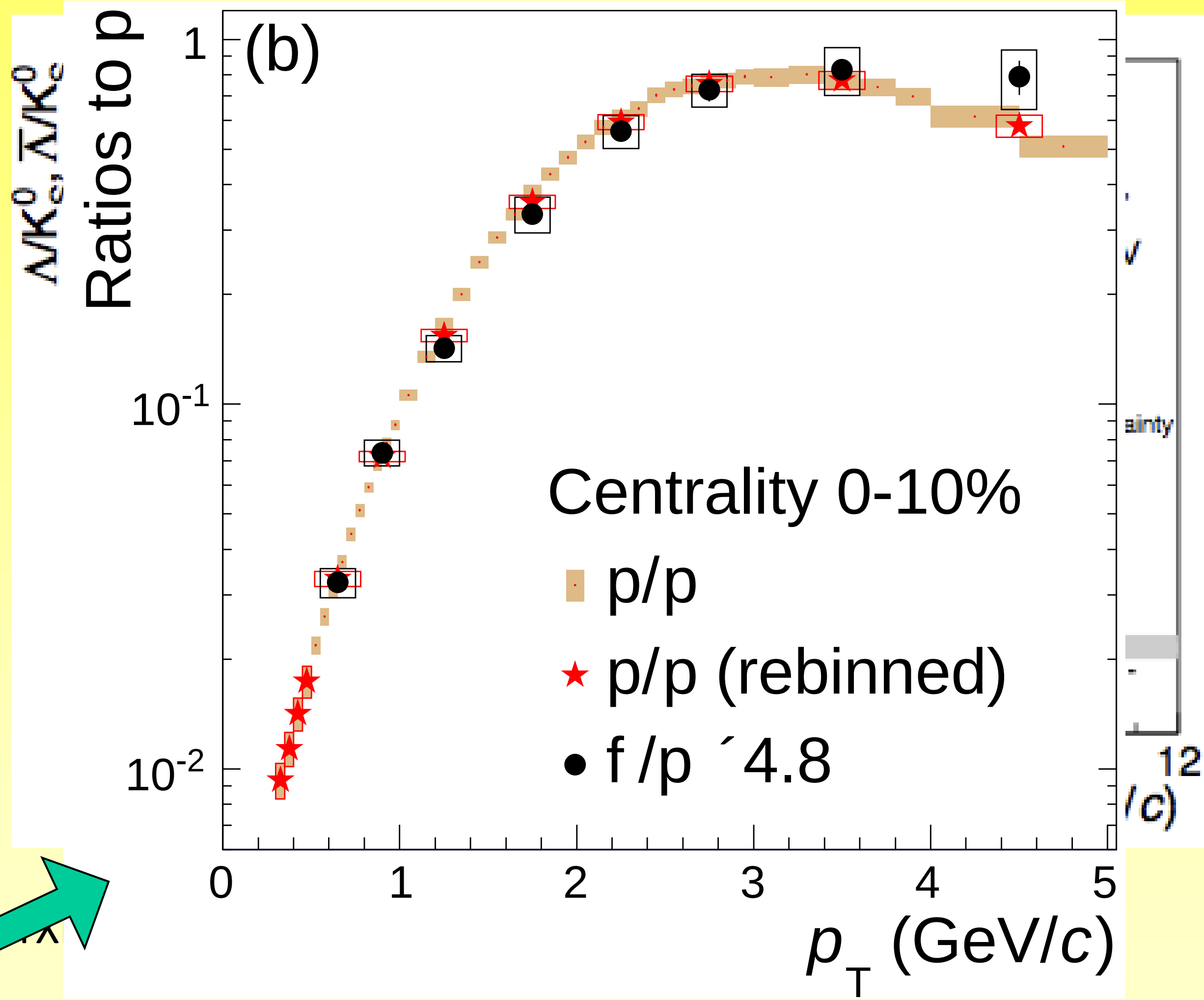




- **2011: > 10 times larger integrated luminosity + tests for pA**
- **2012: first pA collisions**
- **2013: pA run**

Baryon/meson ratio a.k.a. baryon anomaly

- Large baryon/meson enhancement at intermediate p_T
- x2 higher in central wrt periph
- Similar peak at RHIC and LHC but shifted by ~1 GeV
- Described by flow
- Vanishes at ~8 GeV
  - Flow dies out
  - In-vacuum fragmentation

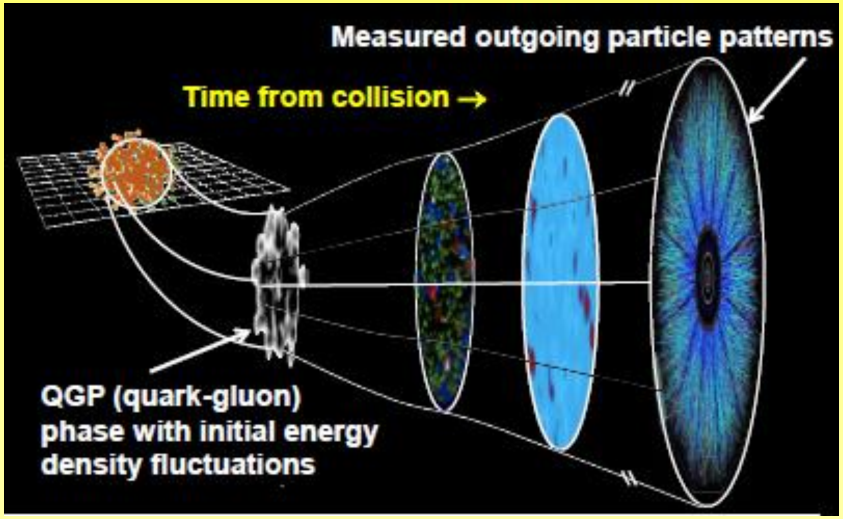


→low-p_T p/π and φ/π ratios have same shapes

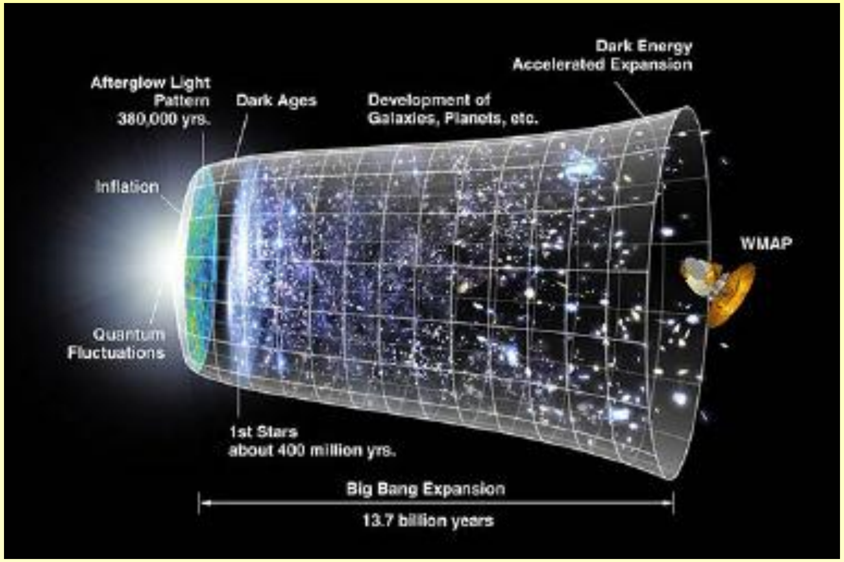
→ baryon anomaly due to particle mass at low p_T

The extremely low viscosity translates early state features into final state ones => a powerful tool!

- From the detailed study of the particles produced in the collisions, infer properties and behavior of the matter produced , and how it evolved during first ~10^{-23} sec. of existence, including the impact of quantum fluctuations



- Analogy to Cosmic Microwave Background Explorations: pattern recognition on present-day background allows inference of structures in universe a few hundred thousand years after Big Bang, which can be attributed to quantum fluctuations in inaccessible inflationary period just after Big Bang.



- from S. Vigdor, BNL, @QM2012