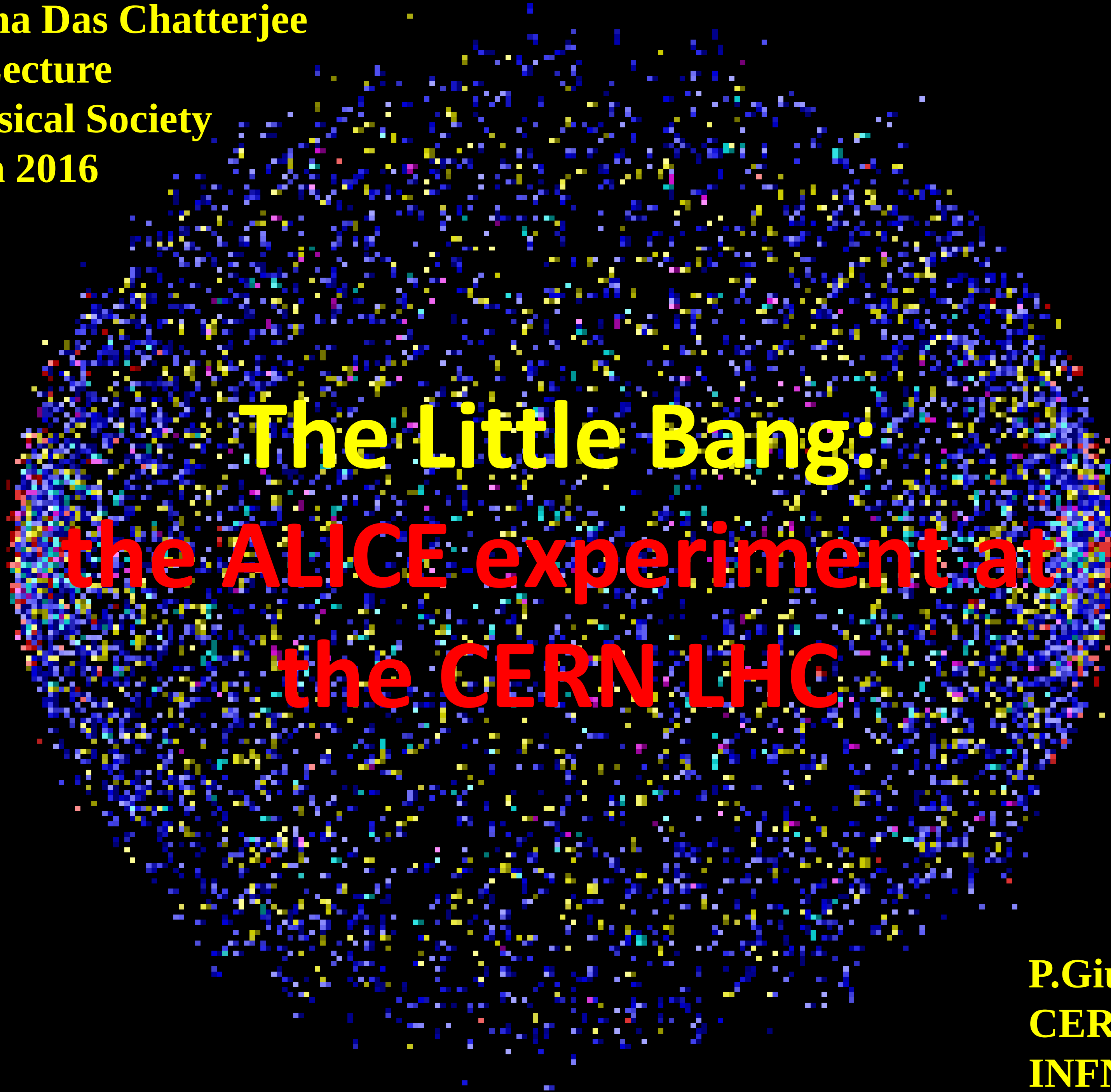
Prof. Shyama Das Chatterjee
Memorial Lecture
Indian Physical Society
January 4th 2016

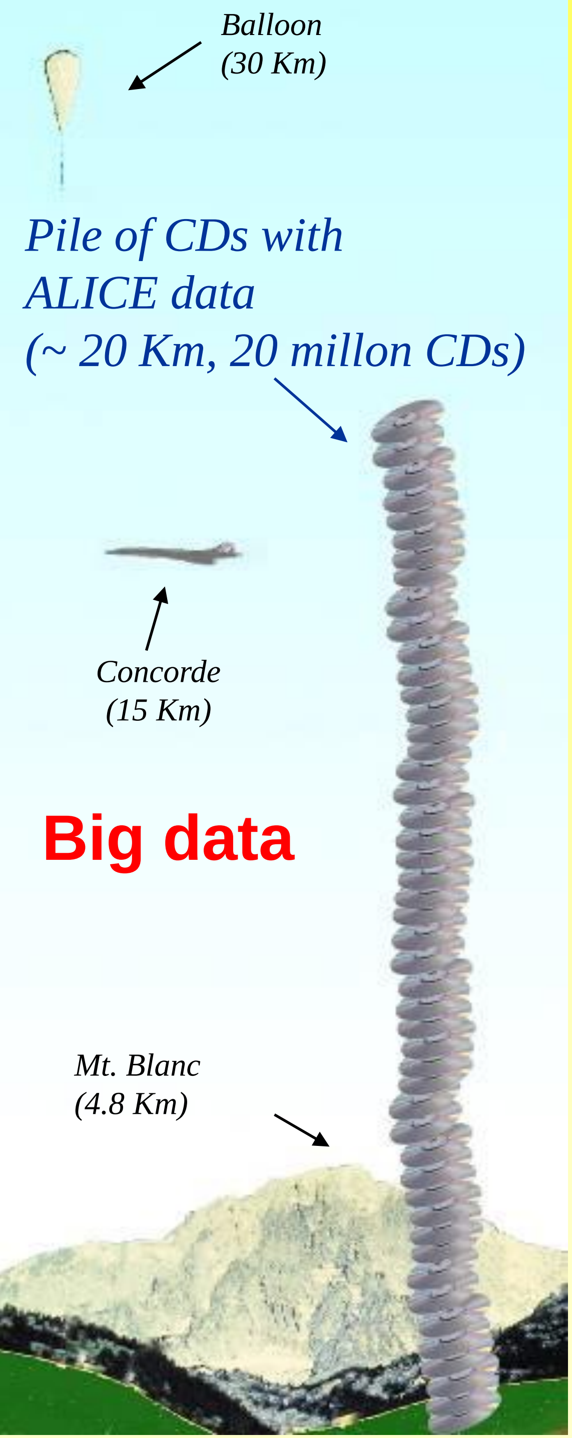


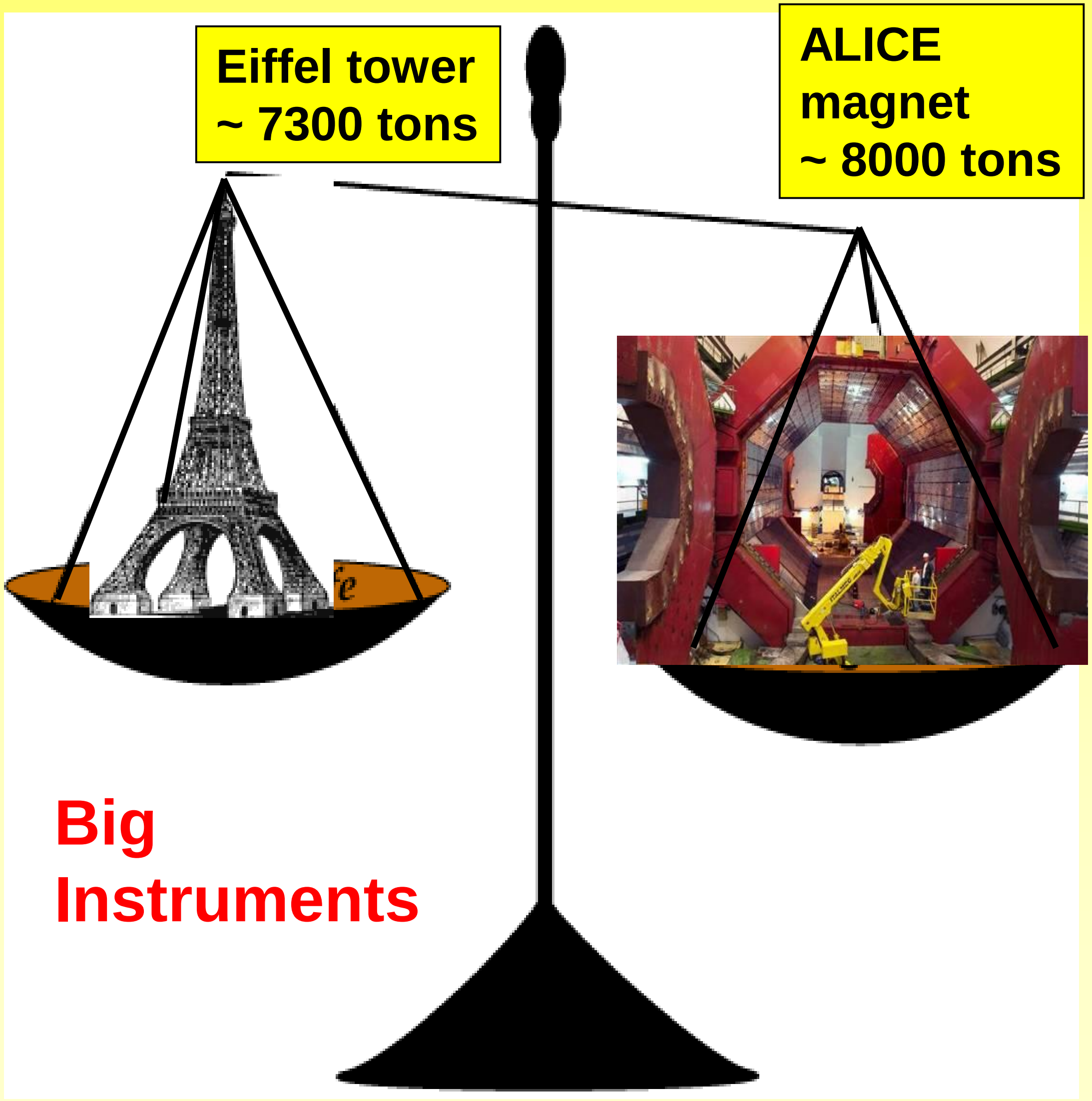
The Little Bang: the ALICE experiment at the CERN LHC

P.Giubellino
CERN and
INFN Torino

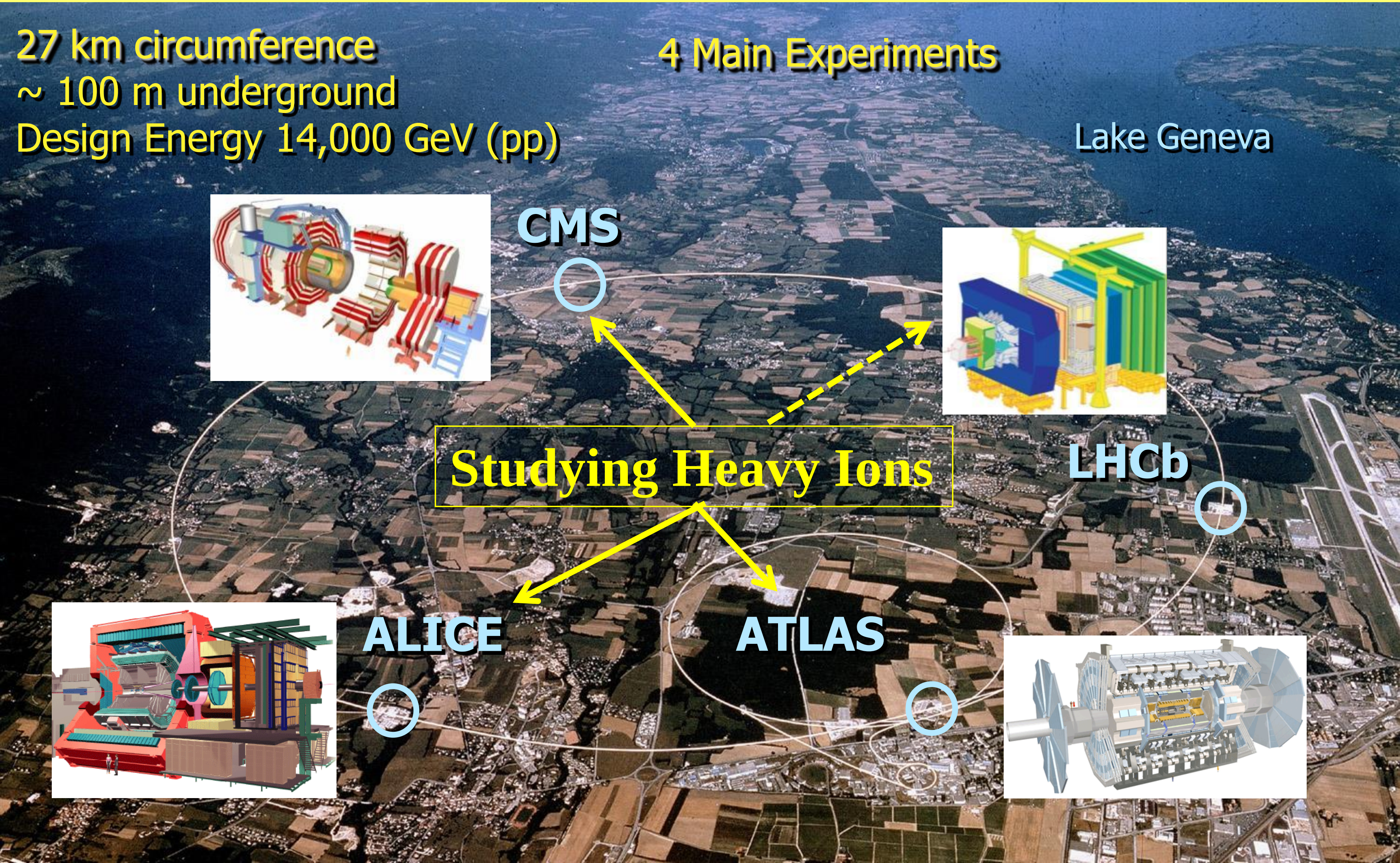
Physics has changed…

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

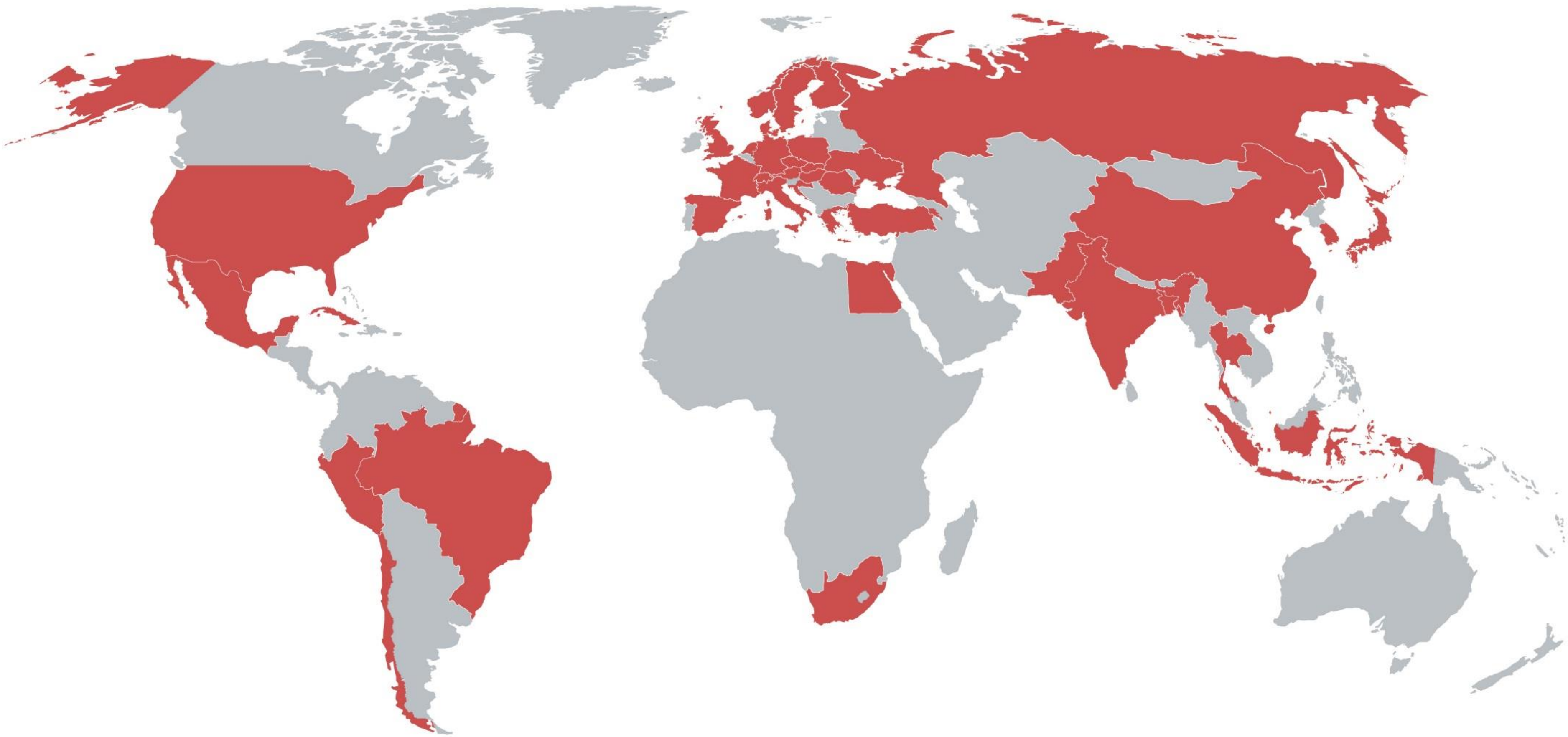




Using the World's most powerful accelerator: the Large Hadron Collider LHC



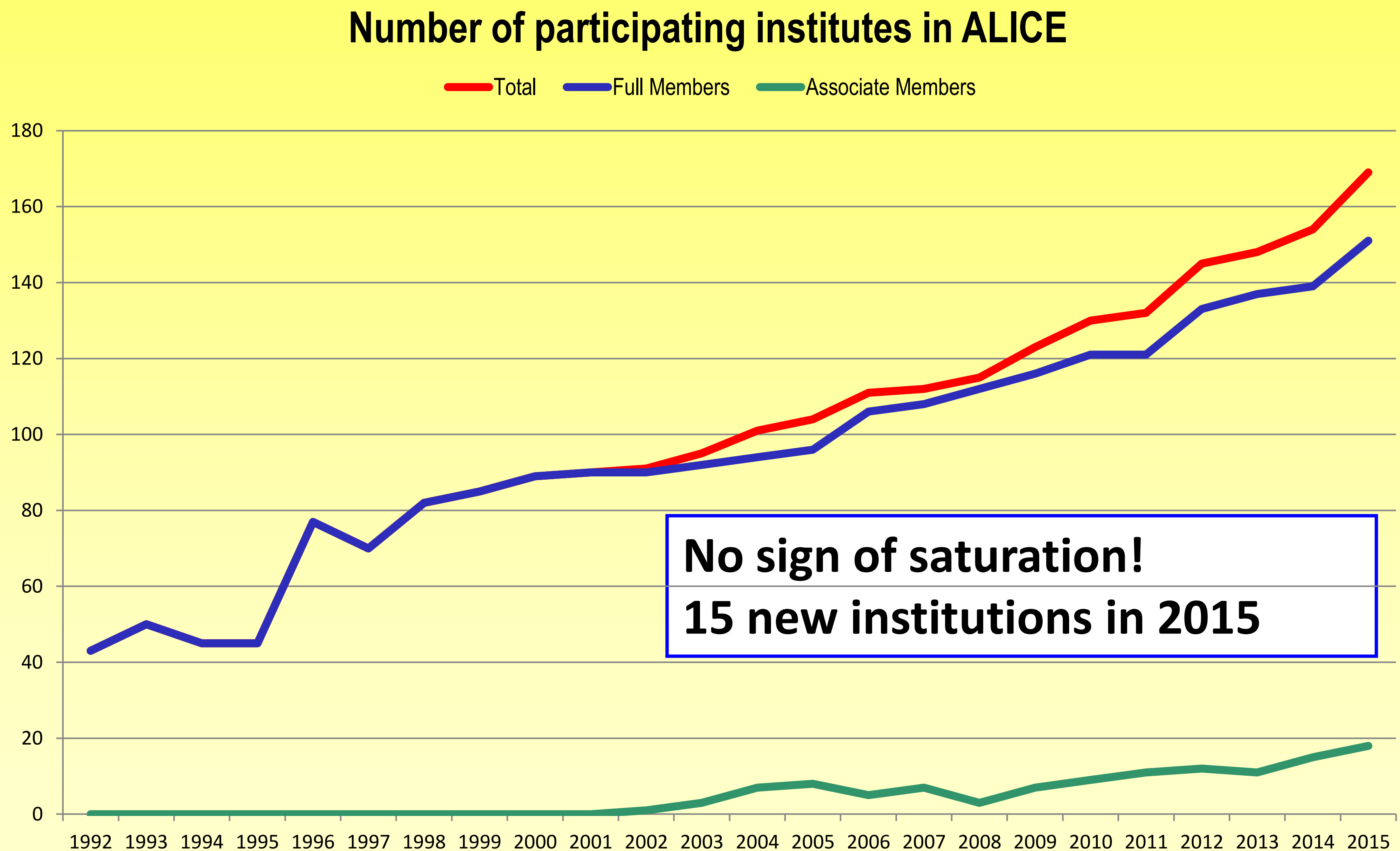
ALICE: a world-wide effort



1660 SCIENTISTS - 42 COUNTRIES – 169 INSTITUTES

ALICE Continues to grow!

Now over 1600 members from 169 Institutions in 42 countries



A scientific and technological program with great prospects!

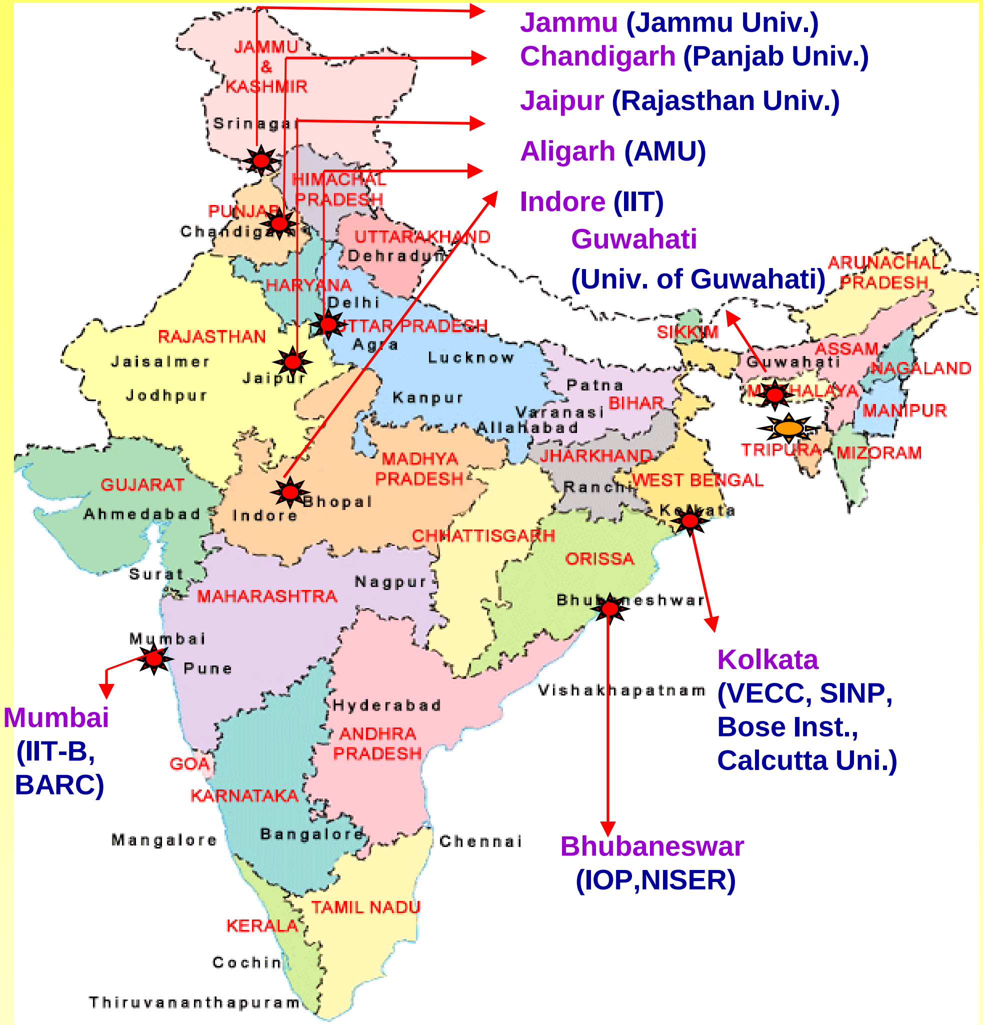
A TRUE "GLOCAL" SYSTEM

- The detectors are designed and built "at home", in the individual participating institutions, **which bring in their know-how, scientific and technical skills, the local industry…** but with a continuous exchange with the others, which makes it possible for all the individual elements to fit together.
- The groups who have developed a specific element follow it up in the test, commissioning and integration in the experiment, and later in its operation at CERN
- The data collected are spread worldwide for processing and final analysis, which is carried again in the home institutions, although the analysis groups meet typically on a weekly basis (via internet)
- All decisions on the technical choices, on operations and on the analysis are taken collectively by the collaboration

Even the “simplest” element requires

wo

With INDIA as a Major player!



INDIAN Participation in ALICE now:

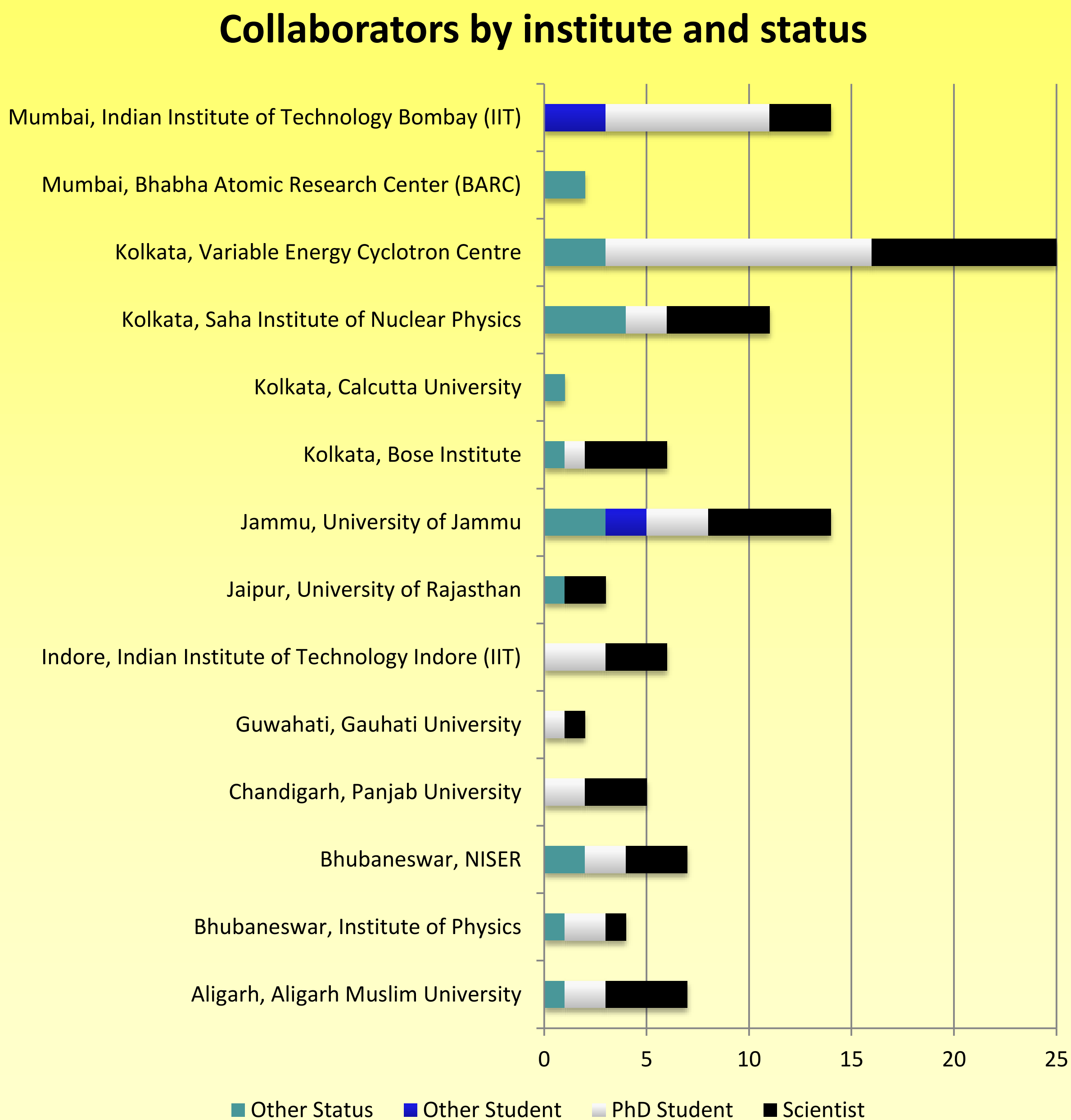
1. Kolkata: VECC
2. Kolkata: SINP
3. Kolkata: Bose Institute
4. Kolkata: University of Calcutta
5. Aligarh: Aligarh Muslim University
6. Bhubaneswar: Institute of Physics
7. Bhubaneswar: NISER
8. Chandigarh: Panjab University
9. Guwahati: University of Guwahati
10. Indore: IIT
11. Jaipur: Rajasthan University
12. Jammu: University of Jammu
13. Mumbai: IIT, Bombay
14. Mumbai: BARC

Indian scientists are involved since the beginning of ALICE
Largest non-European participation

Funded by:

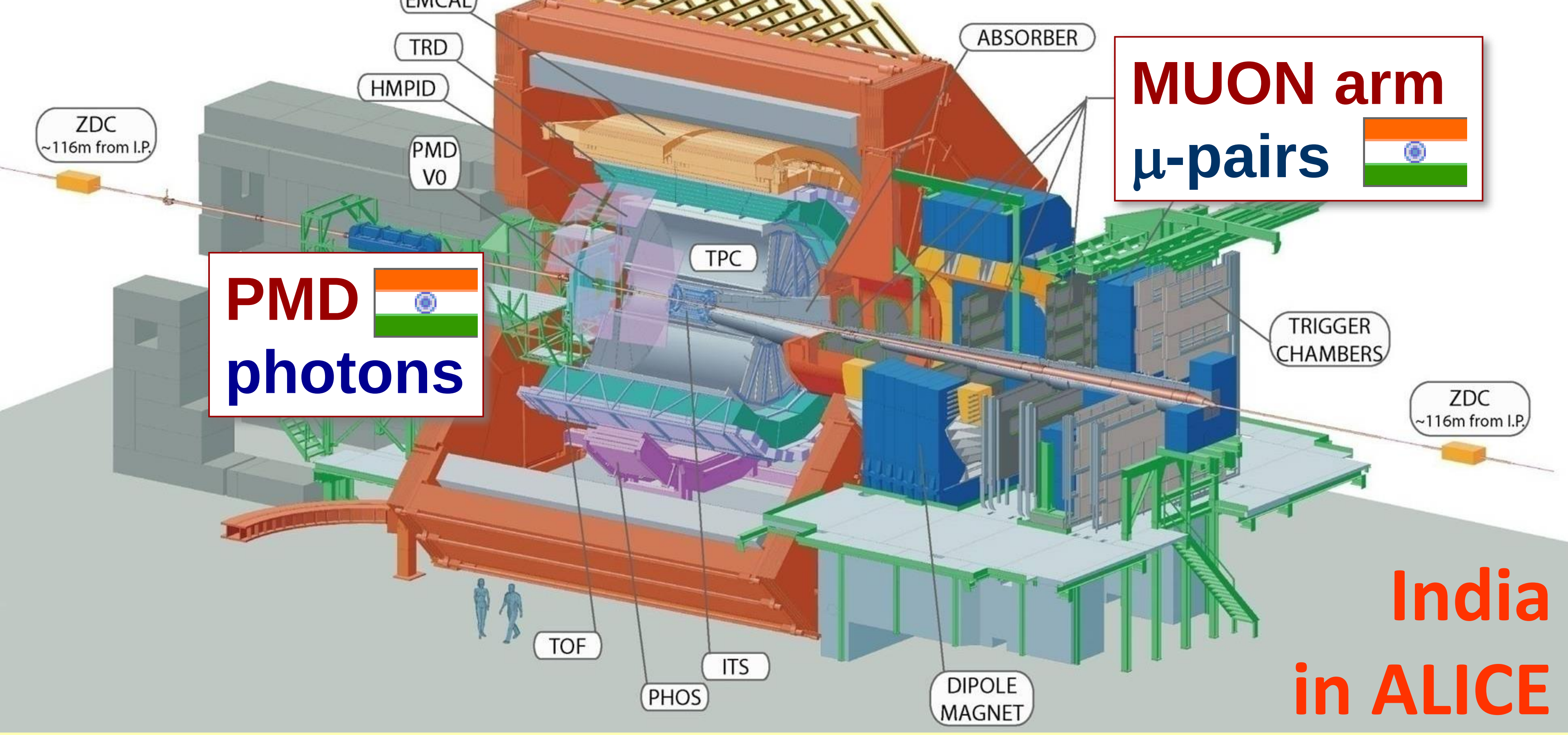
- Department of Atomic Energy and
- Department of Science and Technology

ALICE MEMBERS FROM INDIA



14 INSTITUTES,

108 COLLABORATORS



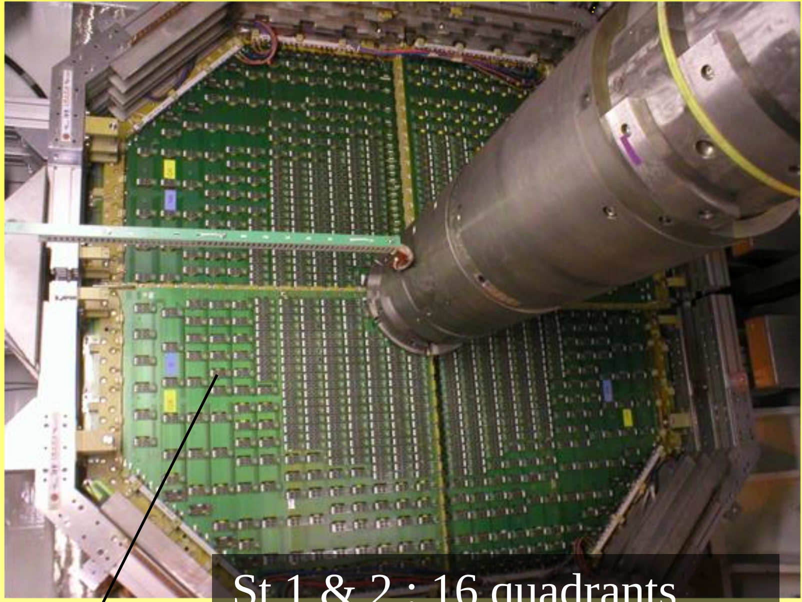
- **at the core of the technology:**
  - ⇨ **Front-end electronics VLSI** **full-custom design and manifacturing: the MANAS chip (for PMD and MS)**
  - ⇨**high tech PMD:**
    - ✪ **100% Indian Project**
  - ⇨ **Muon Spectrometer:**
  - ⇨ **worlwide collaboration, with India as major player**
  - **-> Sation 2 construction**
  - **-> High Level Trigger Development**
  - ⇨ **Now Launching Upgrades: FoCal**

- **at the core of the Physics:**
  - ⇨ **PMD:**
    - ✪ **on the track of flow**
    - ✪ **chase surprises (DCC)**
  - ⇨**Luminosity project (cross sections)**
  - ⇨**Muon Spectrometer:**
    - ✪ **solving the Quarkonia puzzle**

PMD installation in progress at point-2 June 2009

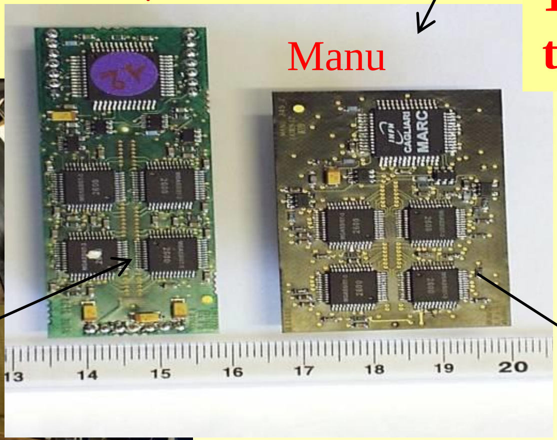
Muon Tracking Chambers

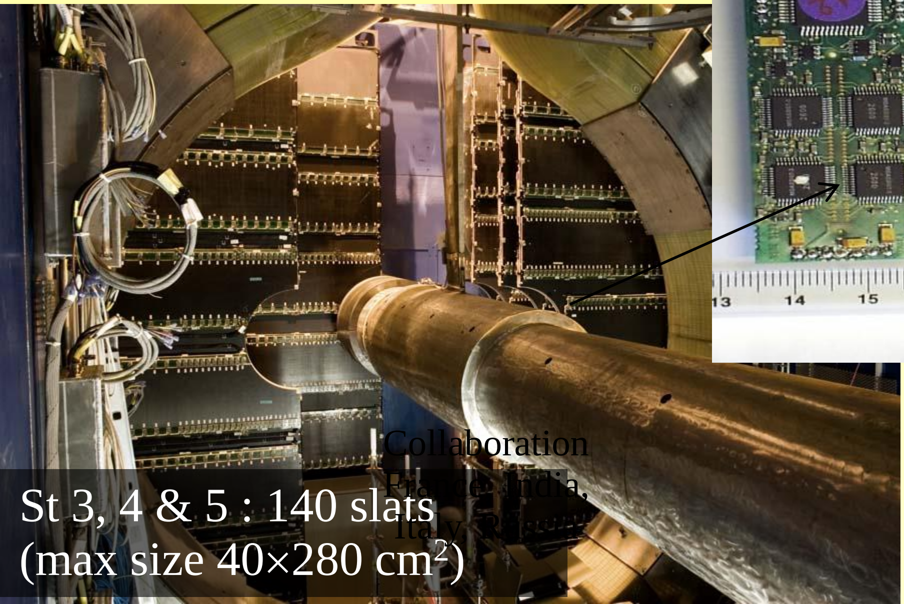
- 5 stations of two Cathode Pad Chambers ~ **100 m^2**
- **1.1×10^6 channels** , occupancy < 5% (in Pb+Pb)
  → Read out at 1 kHz
- Chamber thickness ~ 3% X0
- Beam test results for the spatial resolution : 50 μm for a required resolution < 100 μm



St 1 & 2 : 16 quadrants

Manas electronics chip:
16-channel Amplifier, shaper, track-and-hold



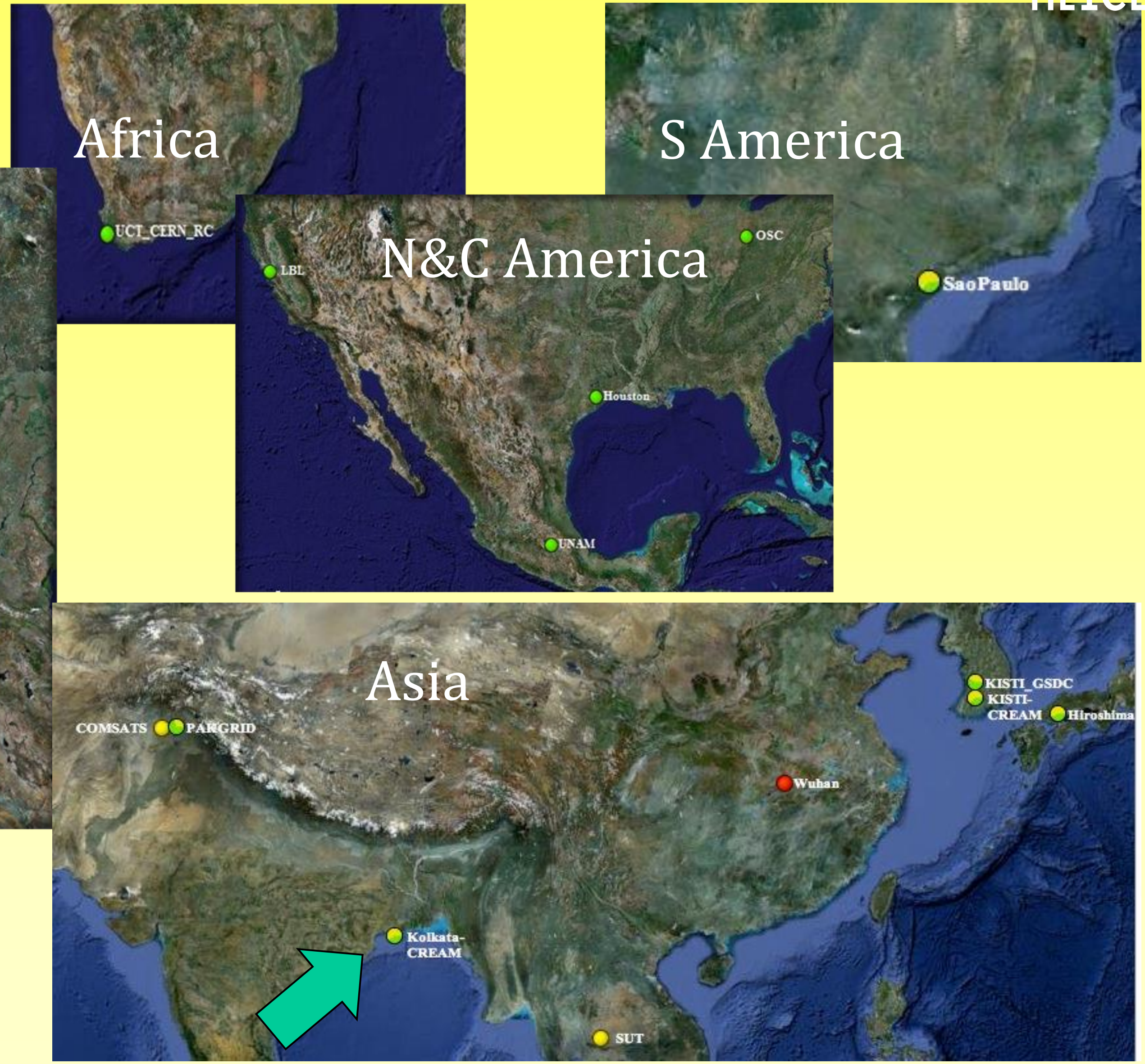


St 3, 4 & 5 : 140 slats (max size 40×280 cm^2)

Collaboration France, India, Italy, …

Storing, processing and analysis of the ALICE data

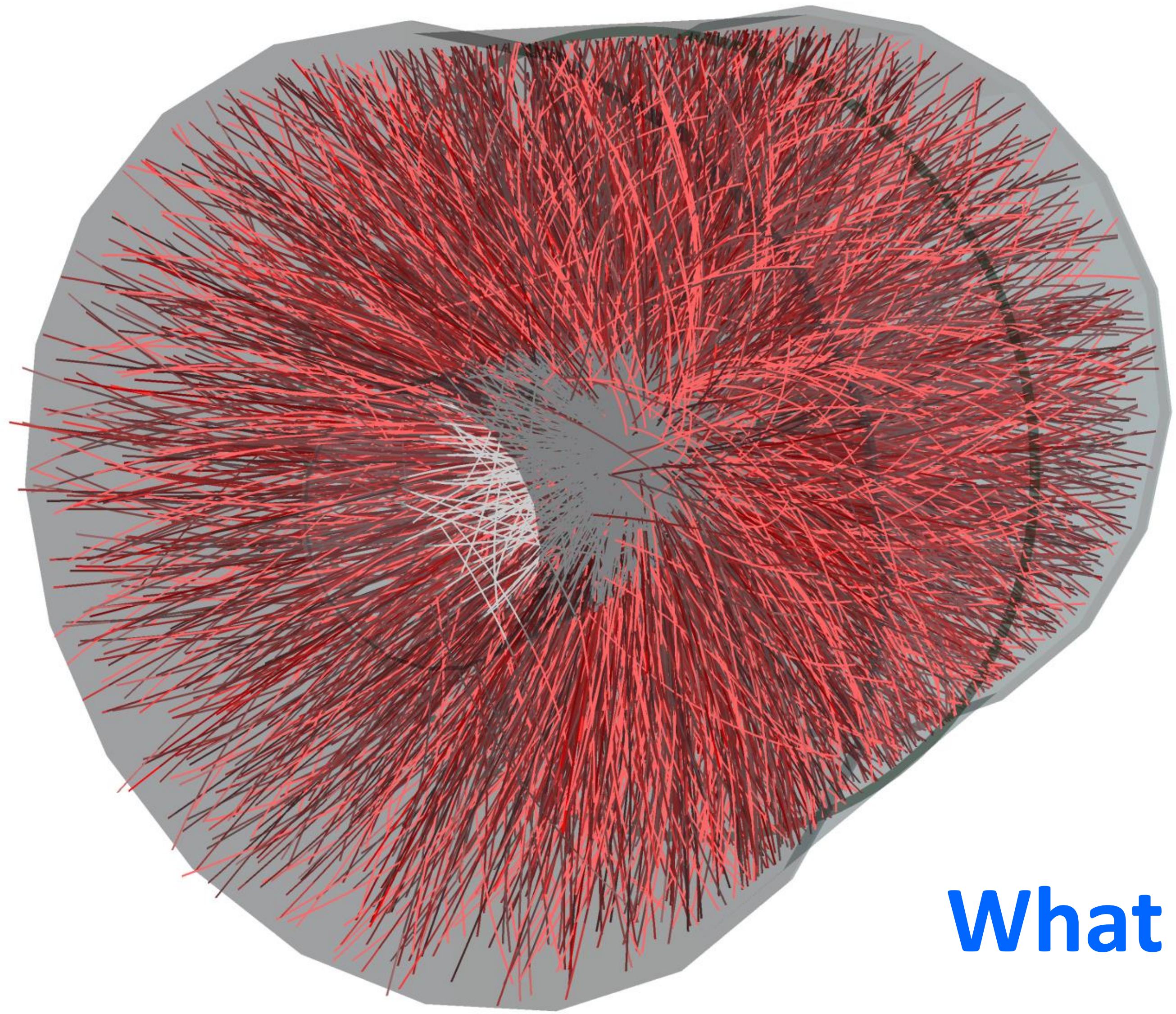
Collaborating computing
Centers in the WLCG Grid



Currently over 60k
jobs run in parallel….

Tier2 at VECC Kolkata: ~2000 Cores and 0.4 Pbytes

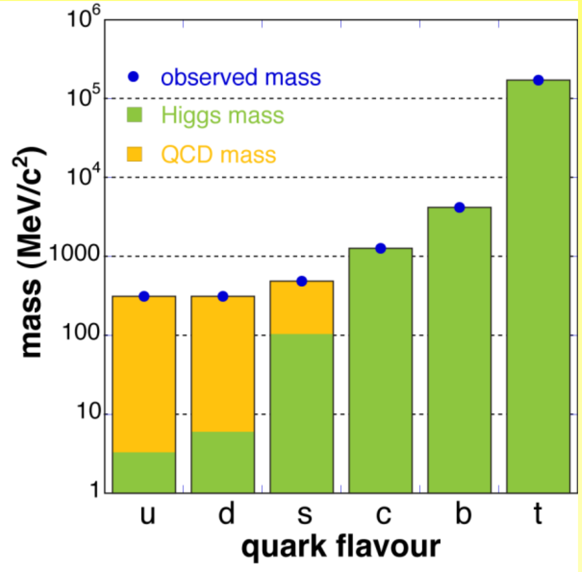
A worldwide effort to study the world's most energetic and most complicated collisions



What for?

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?



Most of the observed mass of light quarks is generated by the spontaneous breaking of chiral symmetry

•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

A long way...

- Hagedorn 1965: mass spectrum of hadronic states
  => Critical temperature T_c=B

$$\rho(m) \propto m^{\alpha} \exp\left(m/B\right)$$

- QCD 1973: asymptotic freedom
  - D.J.Gross and F.Wilczek, H.D. Politzer
- 1975: asymptotic QCD and deconfined quarks and gluons
  - N. Cabibbo and G. Parisi, J. Collins and M. Perry

Interpretation of the Hagedorn temperature as a phase transition rather than a limitingT:

"We suggest … a different phase of the vacuum in which quarks are not confined"

Volume 59B, number 1 PHYSICS L

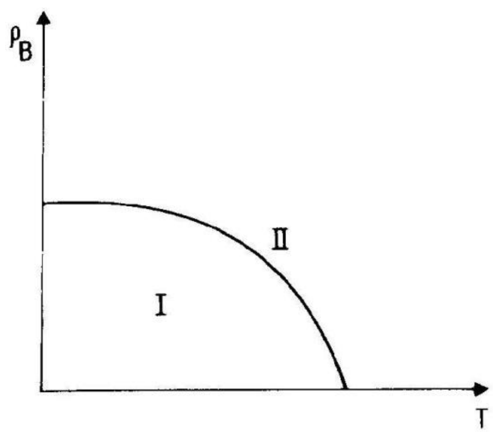


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

First schematic phase diagram (Cabibbo and Parisi, 1975)

A long way...

Hagedorn 1965: mass spectrum of hadronic states

$\rho(m) \propto m^{\alpha} \exp(m/B)$

=> Critical temperature T_c=B

QCD 1973: asymptotic freedom

- D.J.Gross and F.Wilczek, H.D. Politzer

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

1975: asymptotic QCD and deconfined quarks and gluons

- N. Cabibbo and G. Parisi, J. Collins and M. Perry

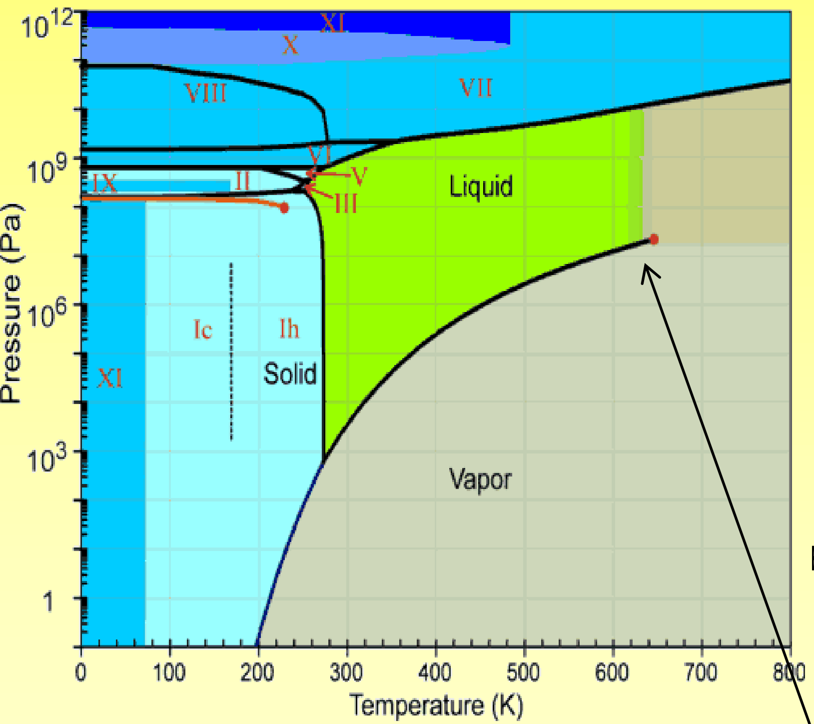
Nobel Prize in Physics 2004

David J. Gross H. David Politzer Frank Wilczek

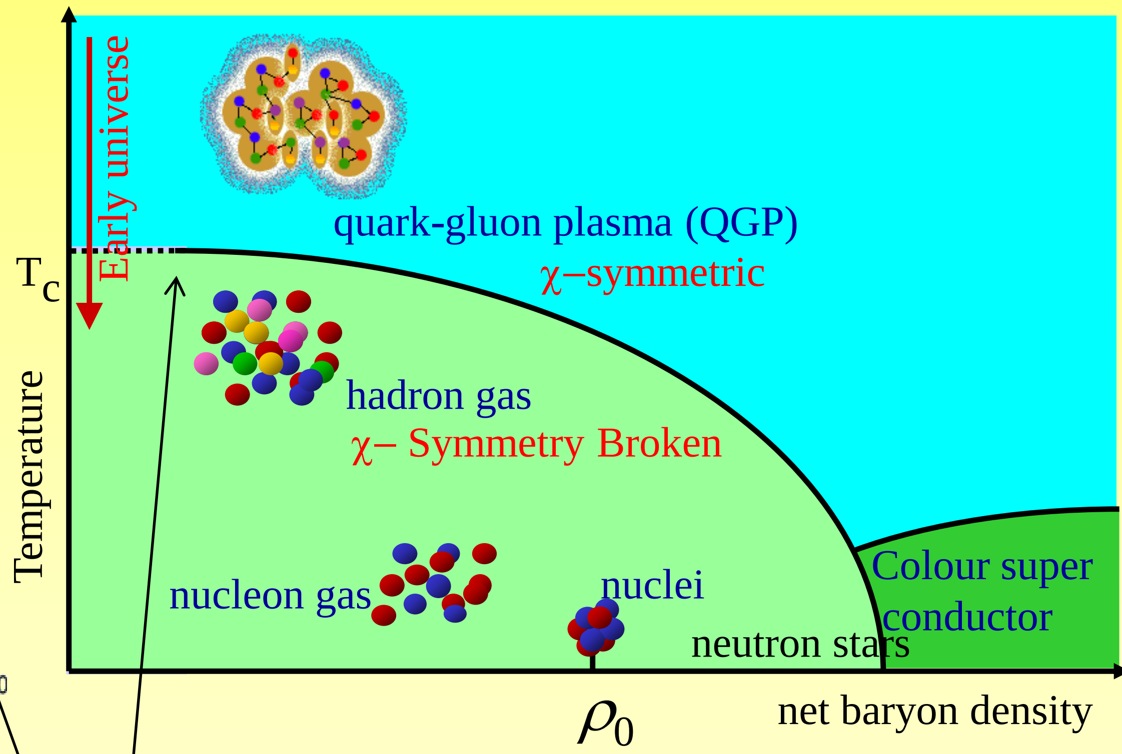
The phase diagram of strong interactiong matter

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



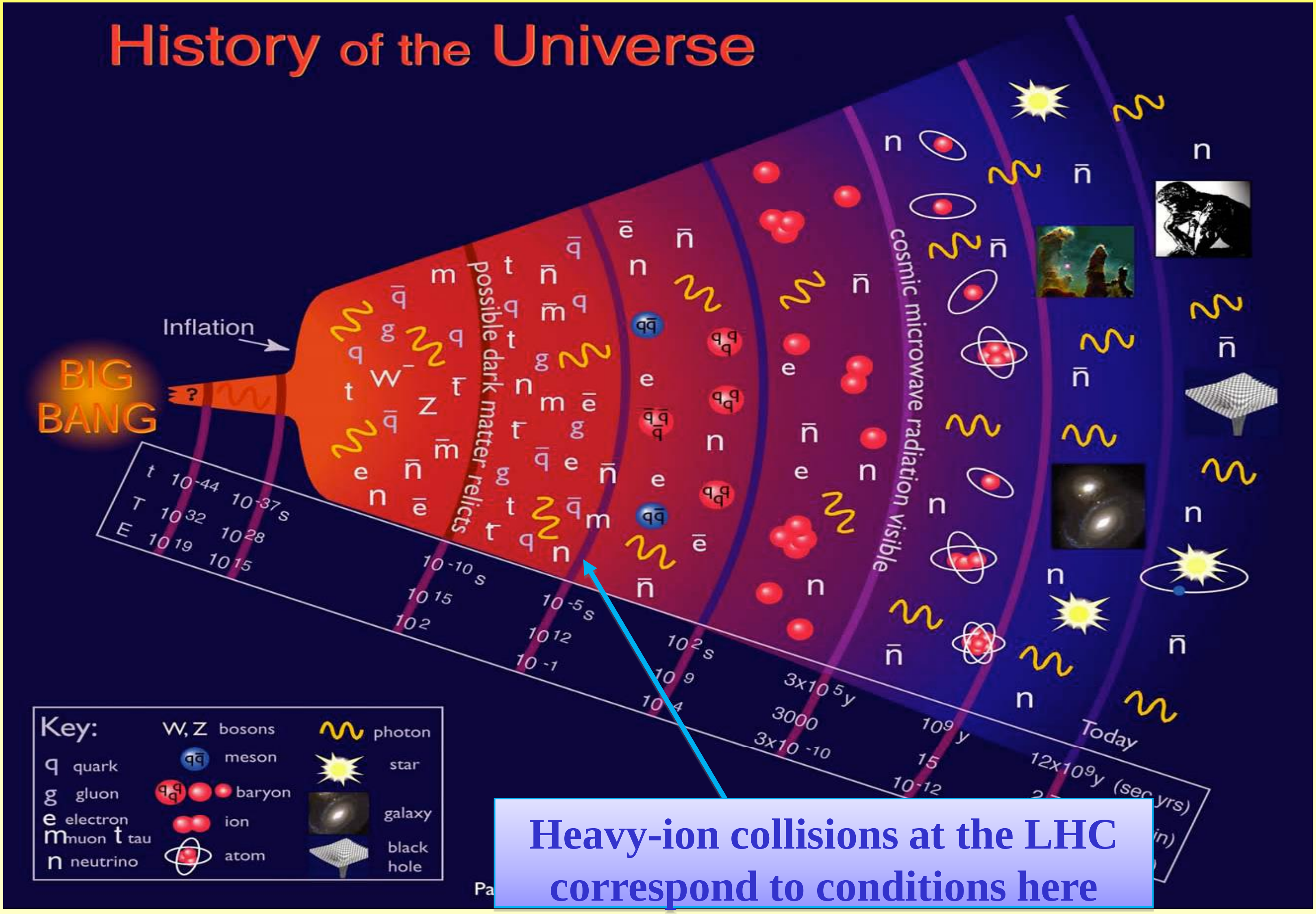
Phase diagram for H_2O



Critical endpoint

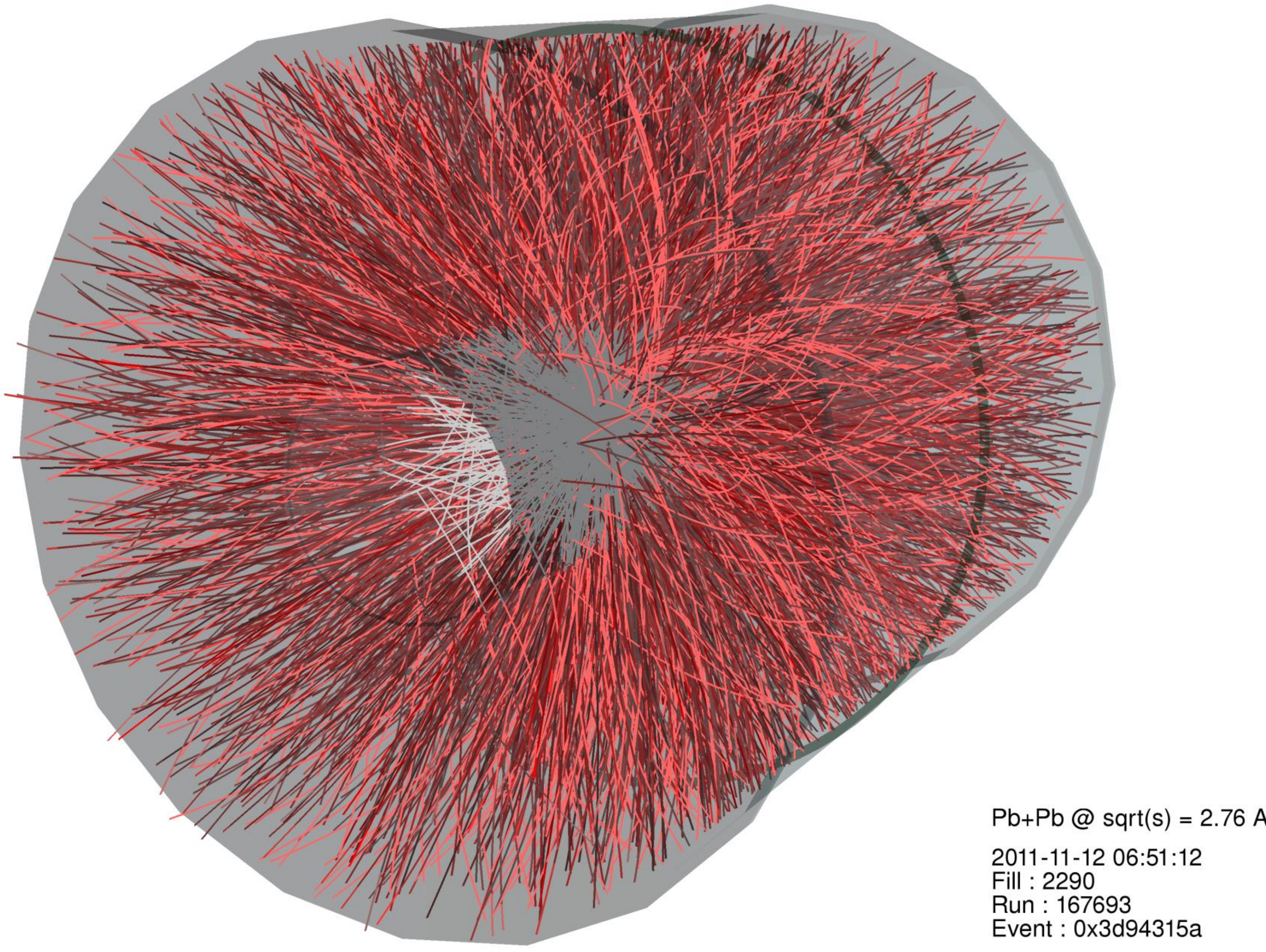
Study how collective phenomena and macroscopic properties of strongly interacting matter emerge from fundamental interactions

Brief History of Our Universe



Many critical features of our universe were established in these very early moments.

Few millionth of a second from the Big Bang

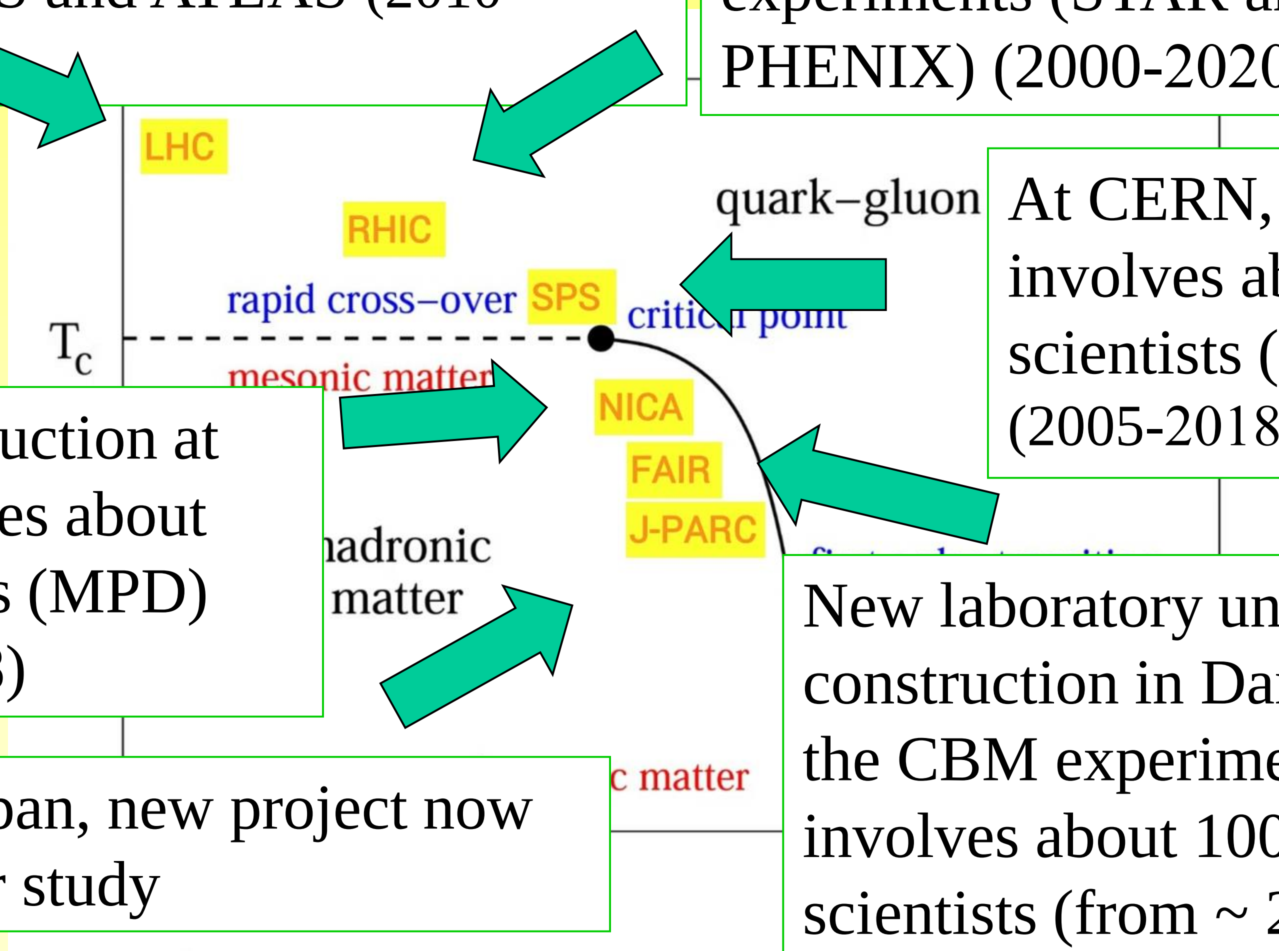


ALICE

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

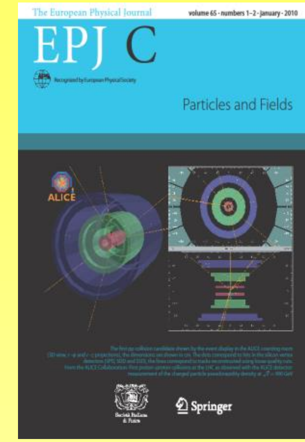
Why Heavy Ions @ LHC?

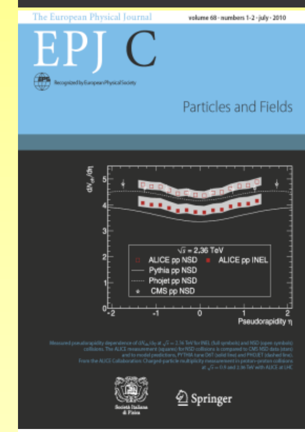
- It is a ***different matter*** as compared to RHIC (and even more to SpS)
  - Larger temperature, volume, energy density and lifetime
    - Study QGP properties vs T …
  - small net-baryon density at mid-rapidity ($\mu_B \approx 0$), corresponding to the conditions in the early universe
  - large cross 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)

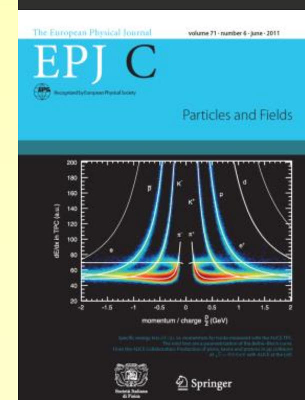
A program of major impact

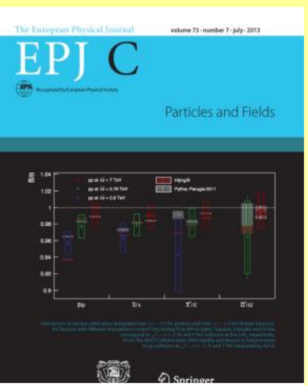
- A very large community of physicists involved
  - over one and a half thousands just in ALICE, hundreds in the other LHC experiments

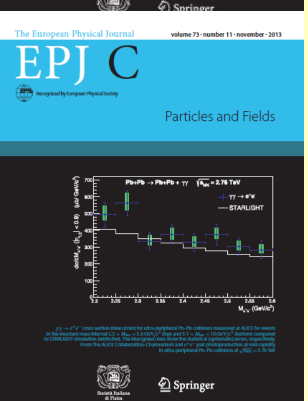
- A huge scientific output
  - **147 ALICE papers on arXiv**
  - **High impact papers (***average of ~80 citations per paper***) :** the top cited paper at the LHC after the Higgs discovery ones is the ALICE paper on flow in HI collisions, and out of the 10 top cited physics papers at the LHC 3 are from ALICE and one from ATLAS-Heavy Ion program (source: ISI).
  - **Several hundred** presentations at international conferences *each year*











LHC physics publications by number of citations

Use the checkboxes to remove individual items from this Citation Report

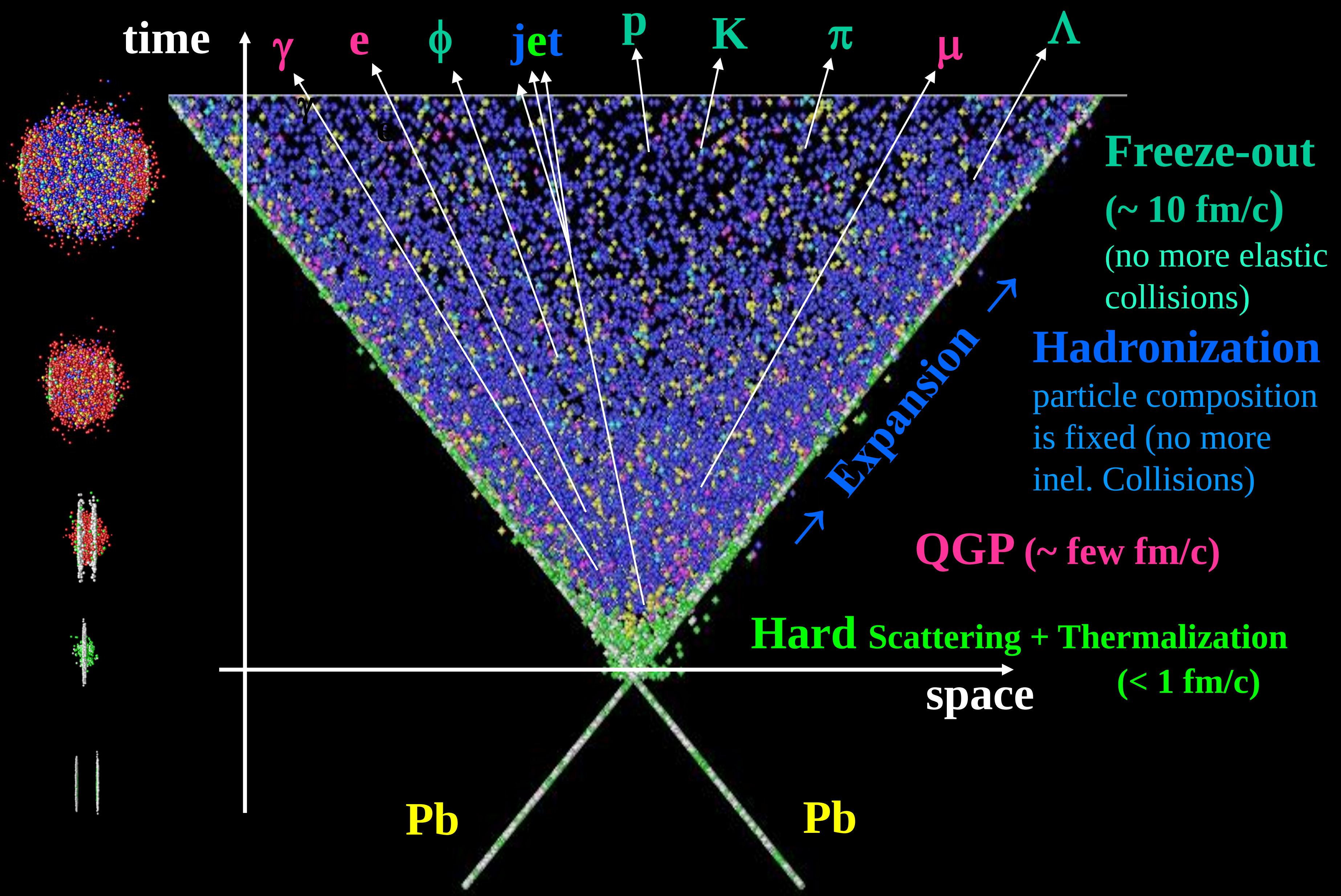
or restrict to items published between 2010 and 2015 Go

	Publication	2011	2012	2013	2014	2015	Total	Average Citations per Year
		2037	5827	7773	8780	5522	30071	5011.83
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	138	1042	1007	549	2736	684.00
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	124	992	934	535	2585	646.25
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	49	25	393	98.25
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	79	29	21	352	88.00
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	67	27	302	50.33
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	61	30	301	50.17
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	66	80	71	48	27	292	58.40
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	77	37	287	57.40
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	30	246	41.00
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	18	196	65.33

11.	**Measurements of Higgs boson production and couplings in diboson final states 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: 726 Issue: 1-3 Pages: 88-119 Published: OCT 2013	0	0	18	127	50	195	65.00
12.	**Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at root s(NN)=2.76 TeV** By: Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; et al. Group Author(s): CMS Collaboration EUROPEAN PHYSICAL JOURNAL C Volume: 72 Issue: 5 Article Number: 2012 Published: MAY 2012	0	4	33	71	76	184	46.00
13.	**Long-range angular correlations on the near and away side in p-Pb collisions at root S-NN=5.02 TeV** By: Abelev, Betty; Adam, Jaroslav; Adamova, Dagmar; et al. Group Author(s): ALICE Collaboration PHYSICS LETTERS B Volume: 719 Issue: 1-3 Pages: 29-41 Published: FEB 12 2013	0	0	33	102	46	181	60.33
14.	**Search for Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy** By: Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; et al. Group Author(s): CMS Collaboration PHYSICAL REVIEW LETTERS Volume: 107 Issue: 22 Article Number: 221804 Published: NOV 21 2011	0	118	41	9	6	174	34.80
15.	**Observation of long-range, near-side angular correlations in pPb collisions at the LHC** By: Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; et al. Group Author(s): CMS Collaboration PHYSICS LETTERS B Volume: 718 Issue: 3 Pages: 795-814 Published: JAN 8 2013						62	54.00
16.	**Search for the Standard Model Higgs Boson in the Diphoton Dec... root s=7 TeV with ATLAS** By: Aad, G.; Abbott, B.; Abdallah, J.; et al. Group Author(s): ATLAS Collabo... PHYSICAL REVIEW LETT...	0	82	48	25	0	155	38.75
17.	**Study of the Mass and S... Decays to Z Boson Pairs** By: Chatrchyan, S.; Khachat... Group Author(s): CMS Collab... PHYSICAL REVIEW LETTER... Issue: 8 Article Number: 081803 Published: FEB 21 2013	0	0	44	78	31	153	51.00
18.	**Charged-Particle Multiplicity Density at Midrapidity in Central 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: 252301 Published: DEC 13 2010	49	38	28	27	11	153	25.50
19.	**Evidence for the spin-0 nature of the Higgs boson using ATLAS data** By: Aad, G.; Abajyan, T.; Abbott, B.; et al. Group Author(s): ATLAS Collaboration PHYSICS LETTERS B Volume: 726 Issue: 1-3 Pages: 120-144 Published: OCT 2013	0	0	7	95	47	149	49.67
20.	**Charged-particle multiplicity measurement in proton-proton collisions at root s=0.9 and 2.36 TeV with ALICE at LHC** By: Aamodt, K.; Abel, N.; Abeysekara, U.; et al. Group Author(s): ALICE Collaboration EUROPEAN PHYSICAL JOURNAL C Volume: 68 Issue: 1-2 Pages: 89-108 Published: JUL 2010	50	32	34	12	5	146	24.33

30% of the top cited scientific production at the LHC is from ALICE

Space-time Evolution of the Collisions



Experiments at the LHC…

- 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, Ecal, topology
    - Hadrons, leptons and photons + Excellent vertexing
- ATLAS and CMS
  - General-purpose detectors, optimized for rare processes
    - Excellent Calorimetry = > Jets
    - Excellent dilepton measuremens, especially at high pT
    - Very large acceptance in rapidity
- Now Joined by LHCb

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

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 ?

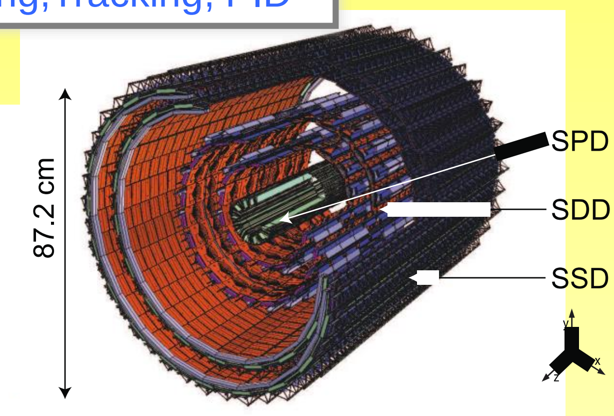
pA

- 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,…)

ALICE Detector Specifics

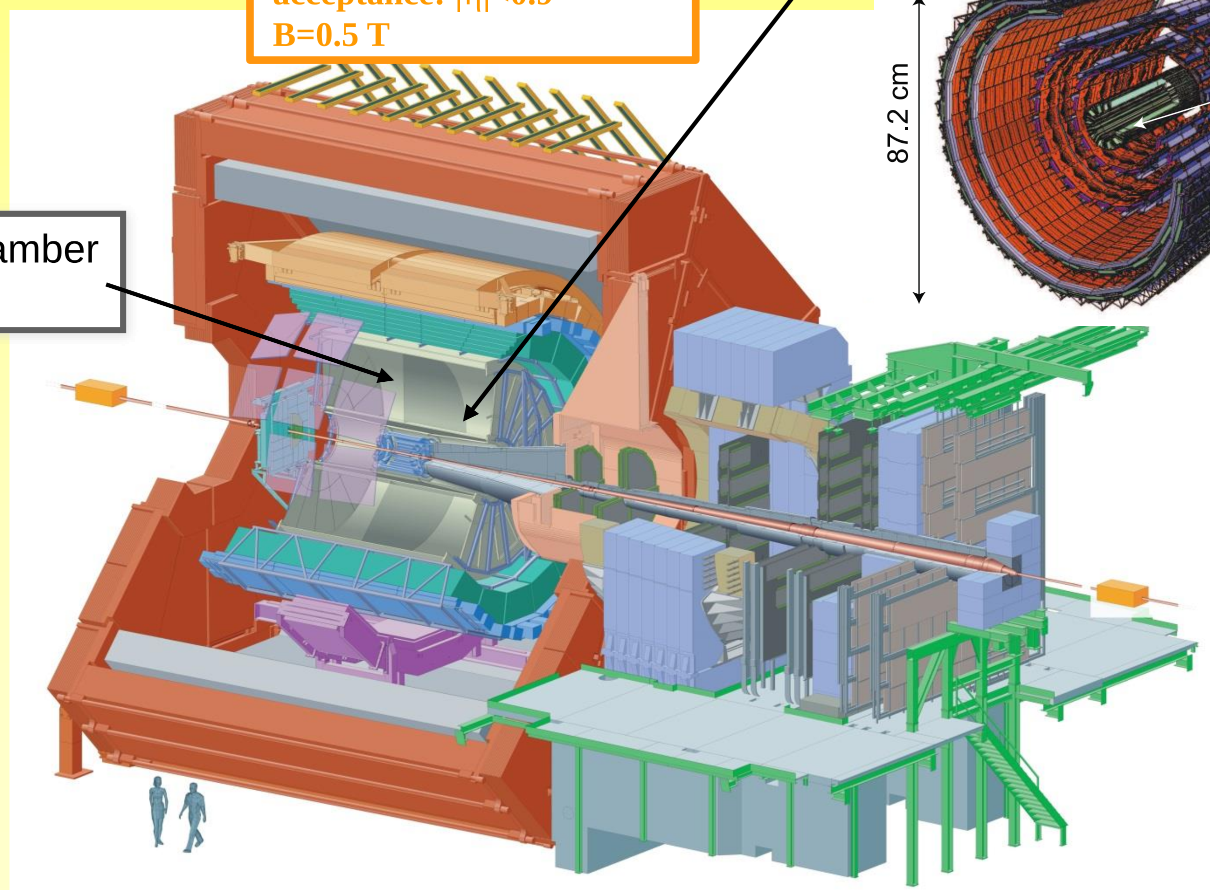
Excellent track and vertex reconstruction capabilities (TPC, ITS) in a high multiplicity environment over a wide transverse momentum range

Inner Tracking System
Vertexing, Tracking, PID



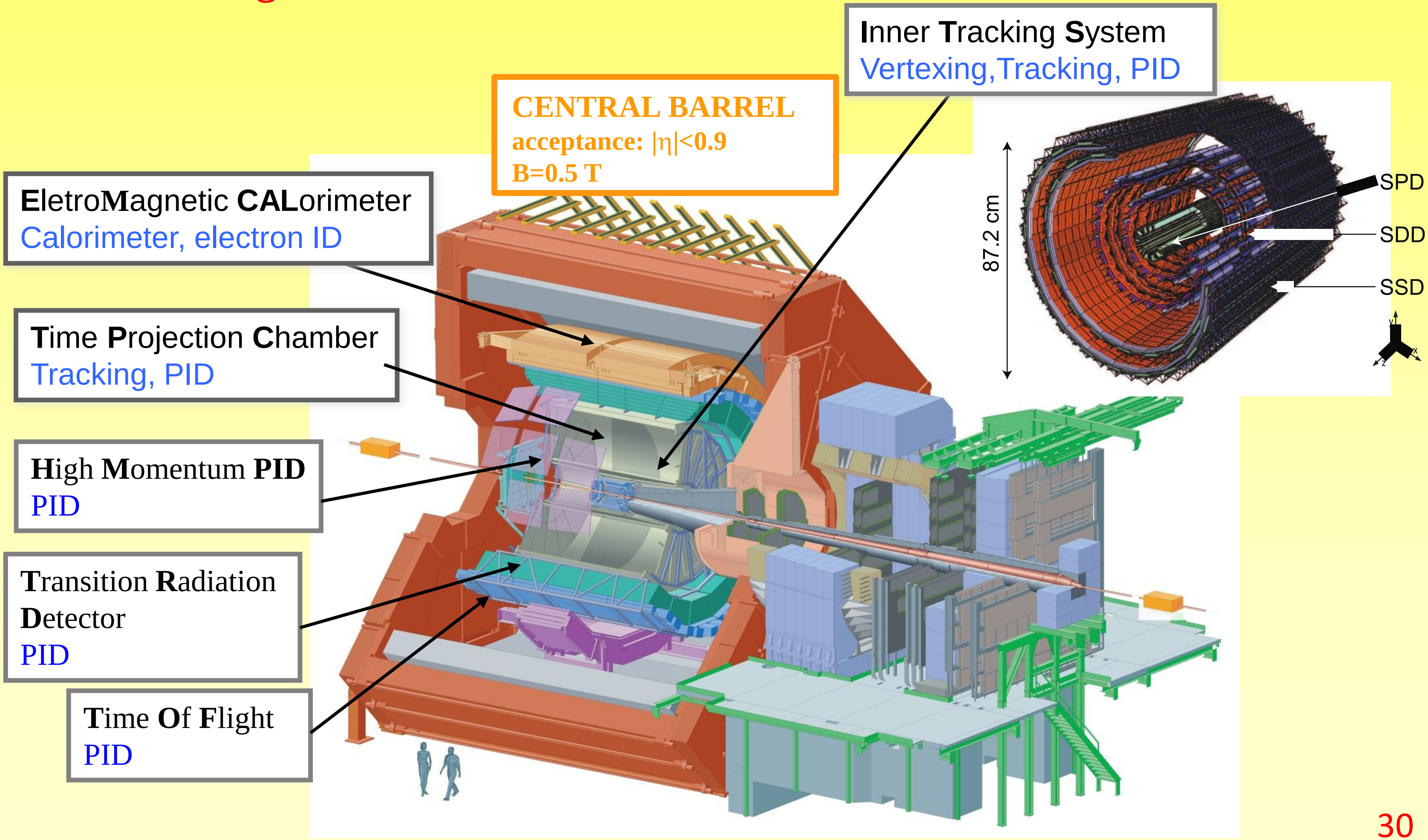
CENTRAL BARREL
acceptance: |η|<0.9
B=0.5 T

Time Projection Chamber
Tracking, PID

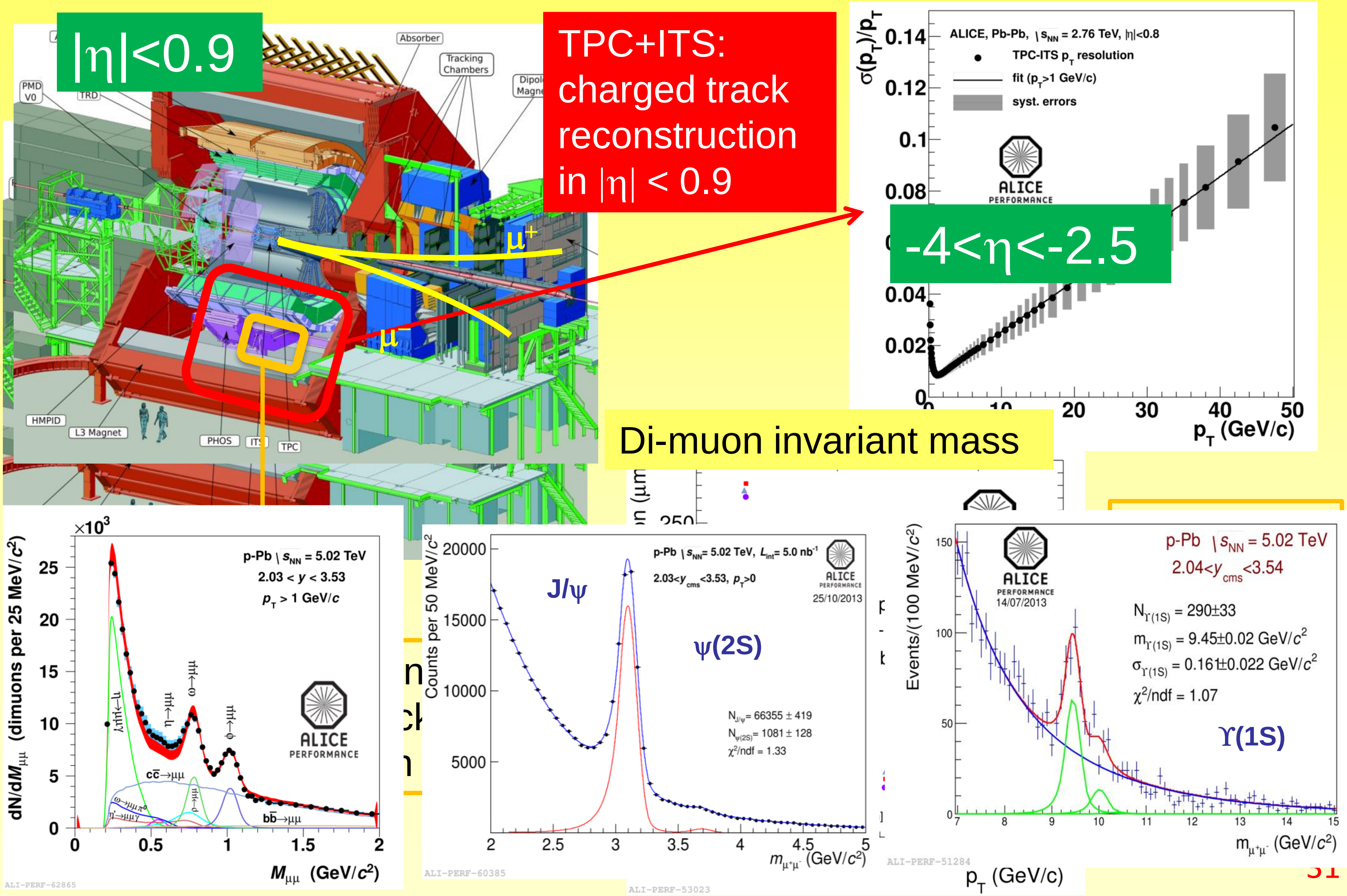


ALICE Detector Specifics

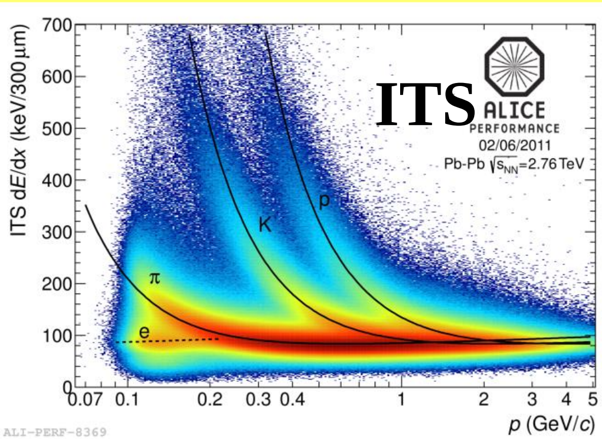
Particle identification over a wide momentum range

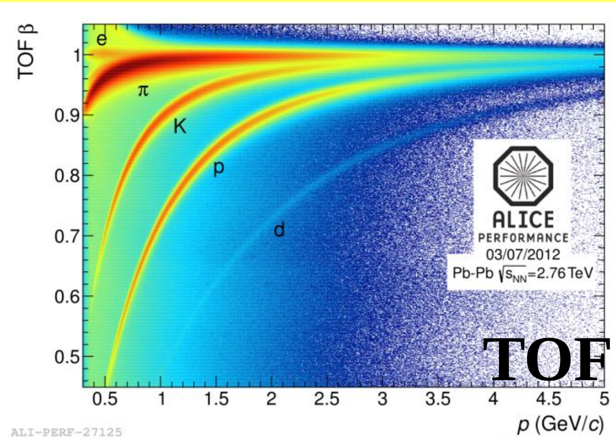


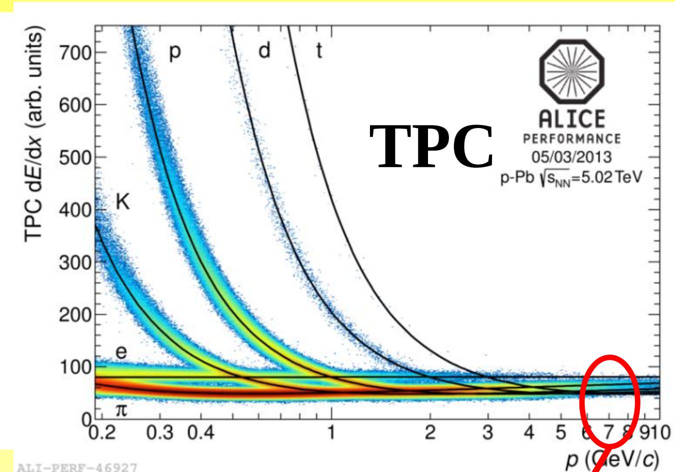
ALICE performance: tracking/vertexing

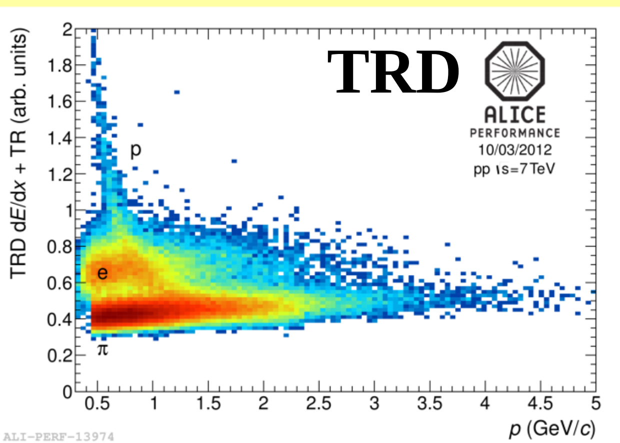


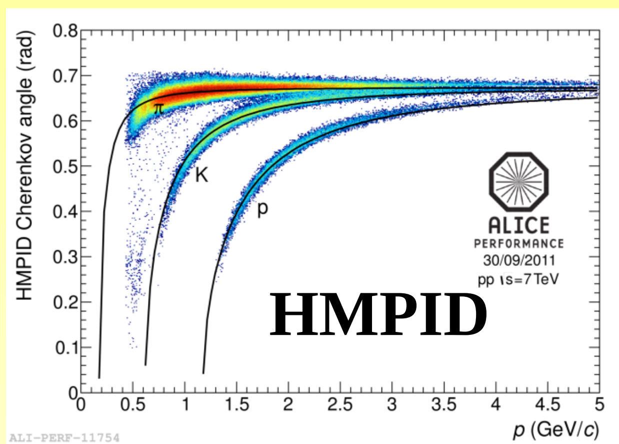
ALICE performance: PID

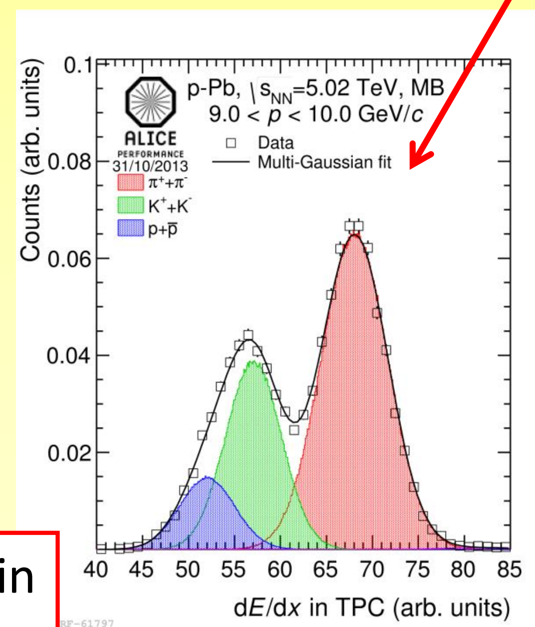








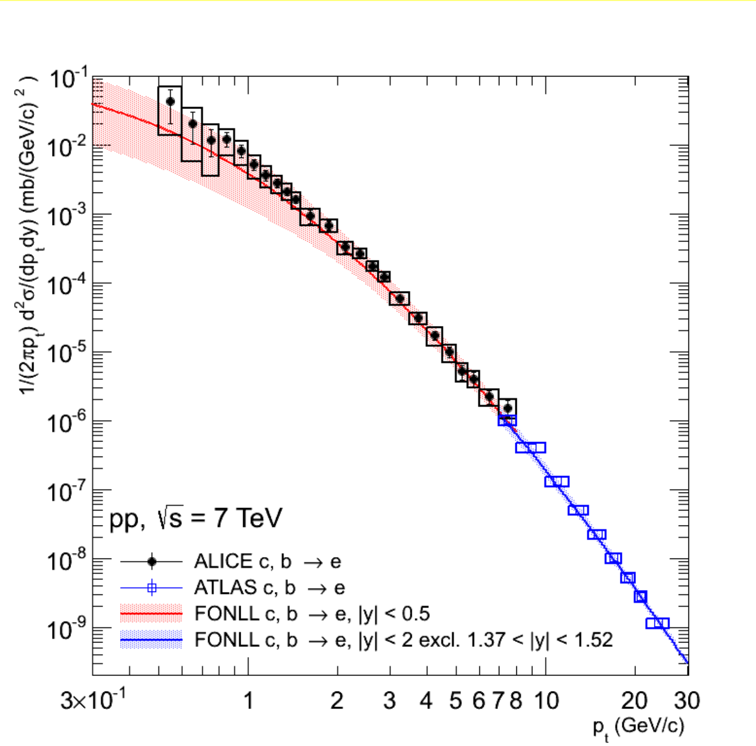




- ALICE uses practically all known techniques

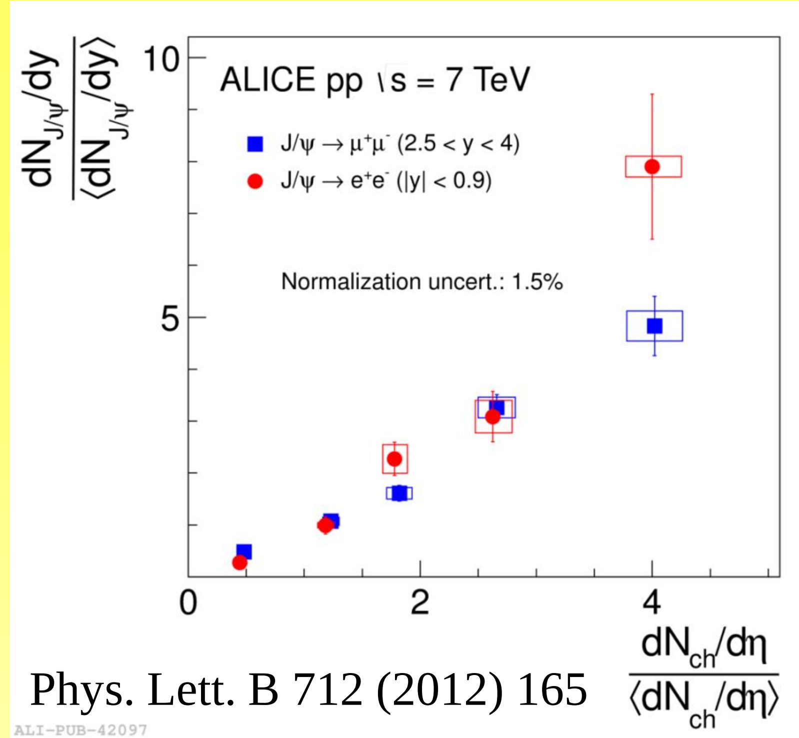
Statistical separation in relativistic rise region

A taste of pp results

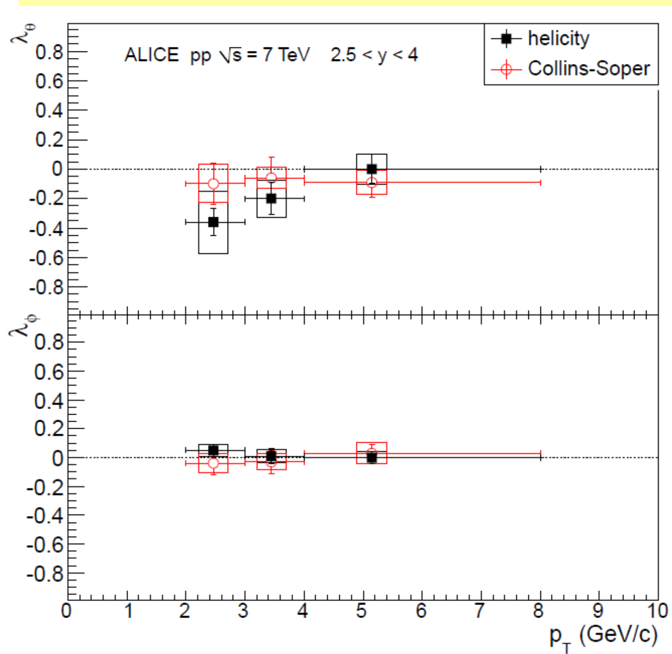


Electrons from Heavy Flavors => Complementarity with ATLAS

Mult. dep. of J/psi yield



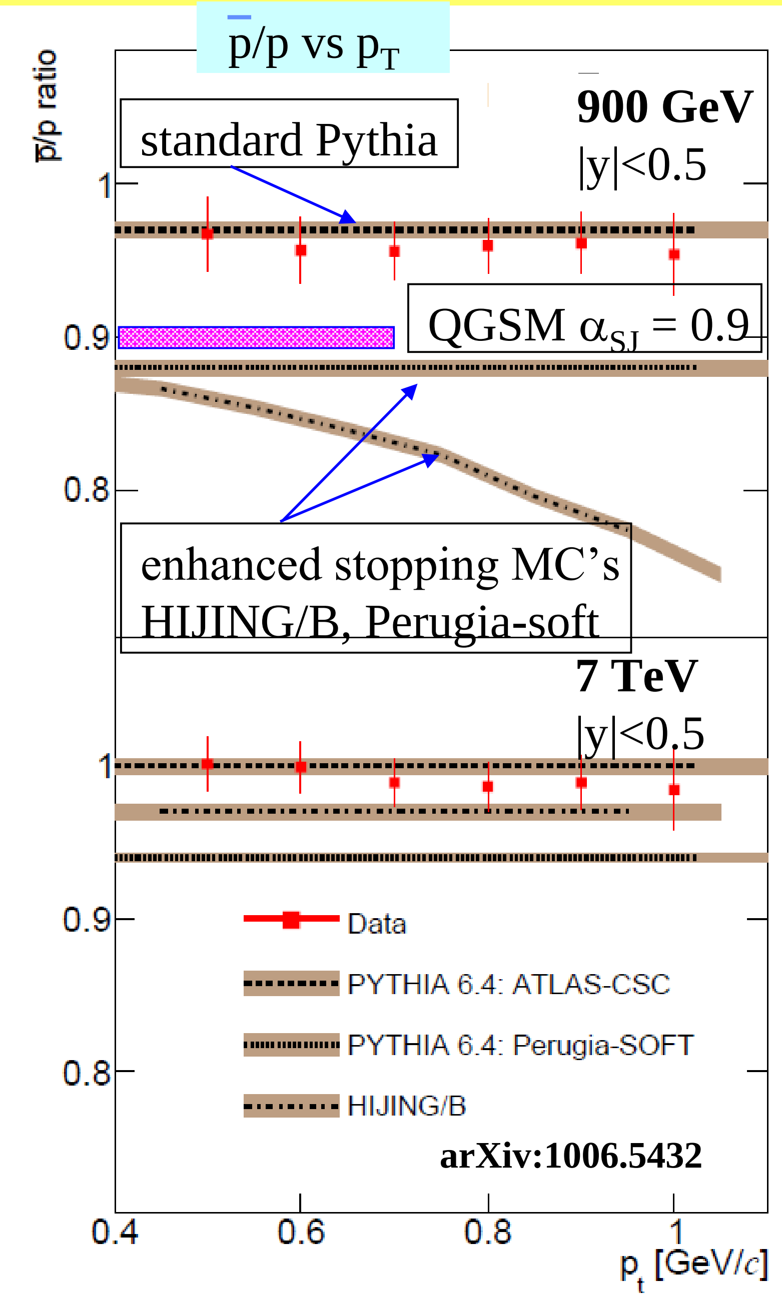
Phys. Lett. B 712 (2012) 165

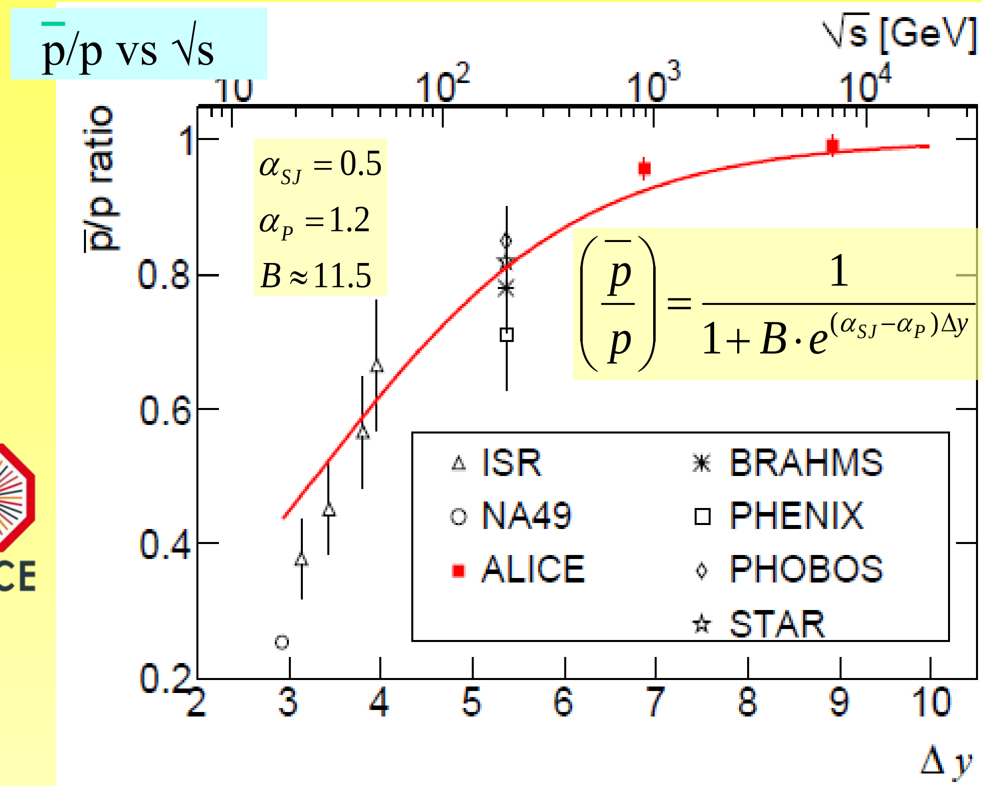


First measurement of J/ψ polarization at LHC

Phys.Rev.Lett. 108 (2012) 082001

p/p ratio: measure of Baryon stopping





Challenging to measure to 1% (need excellent control over material, transport codes)

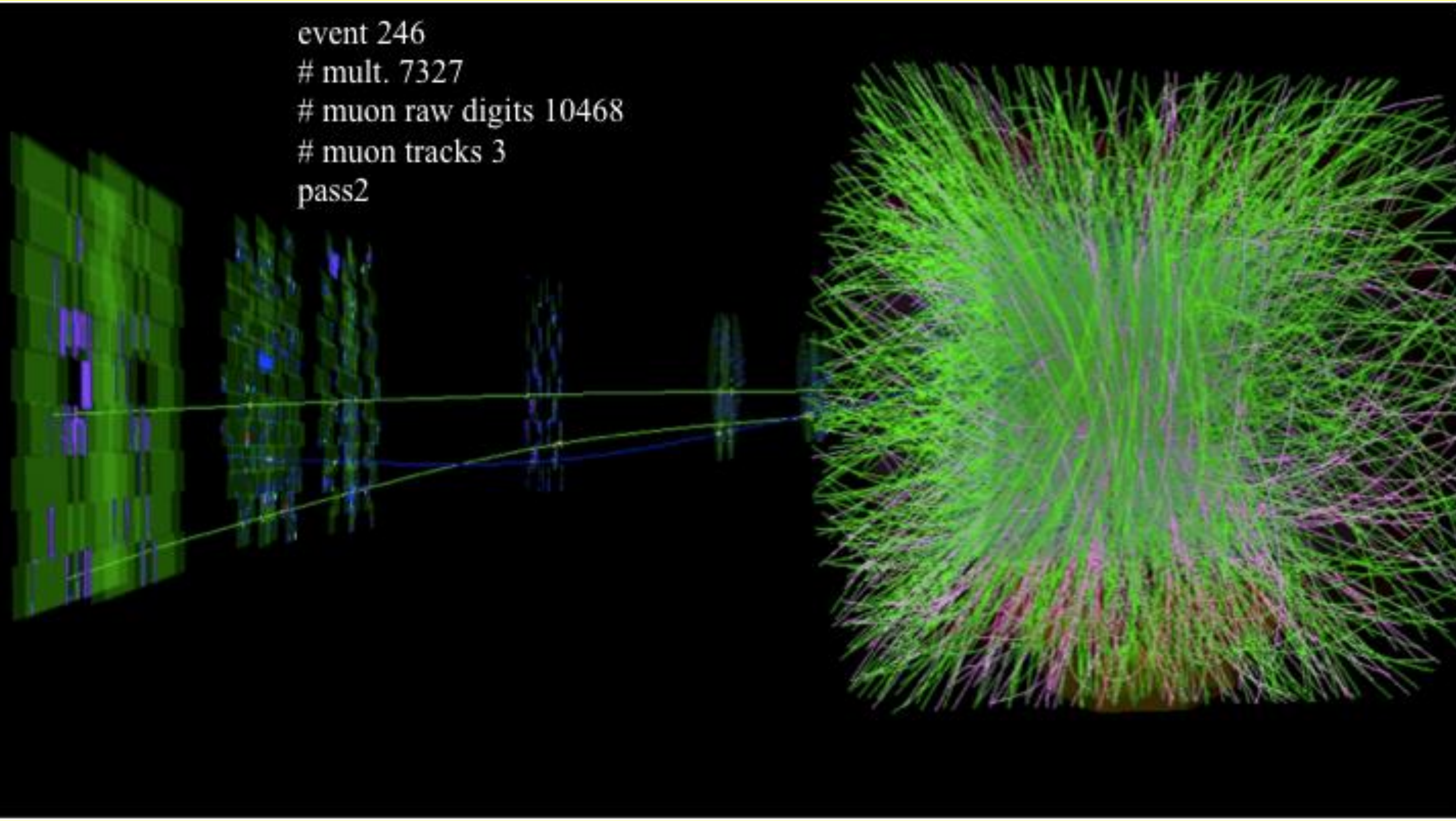
- data well described by PYTHIA tunes

-little room for **any** additional diagrams which transport baryon number over large rapidity gaps

0.9 TeV: p̄/p = **0.957** ±0.006(stat) ±0.014(syst)

7 TeV: p̄/p = **0.990** ±0.006(stat) ±0.014(syst)

Heavy-Ions!


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

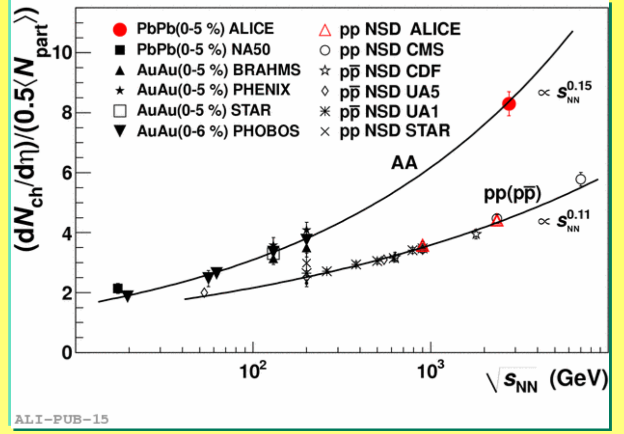
Global properties

- Fr
  de

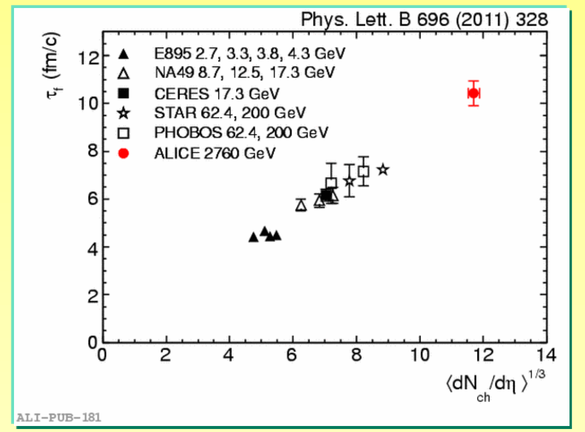
- T

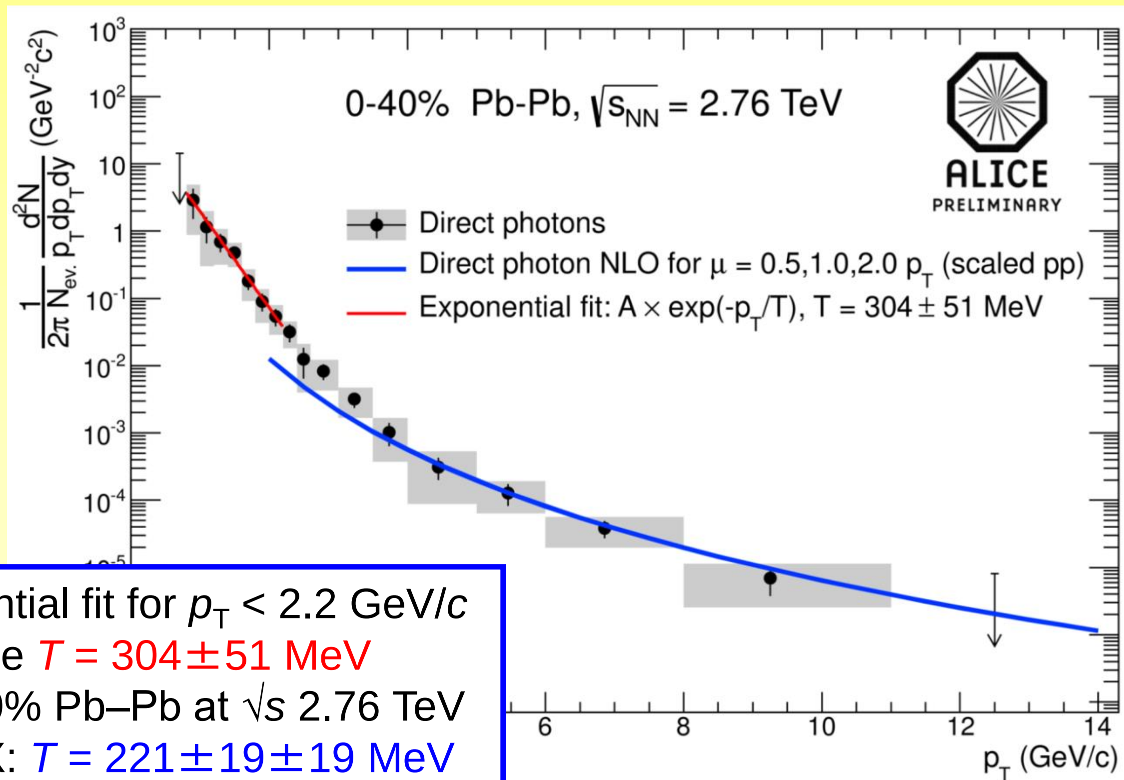
Matter under extreme conditions:

~ 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

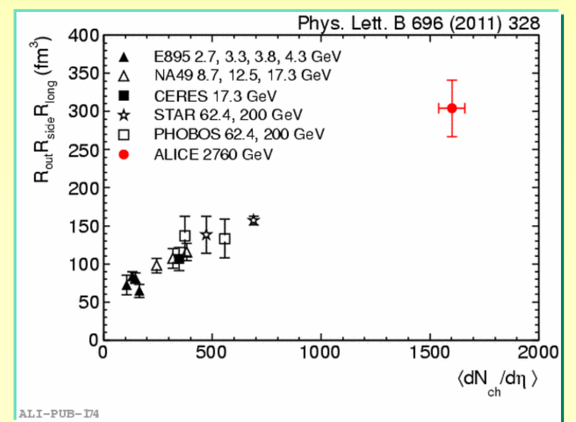


$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$





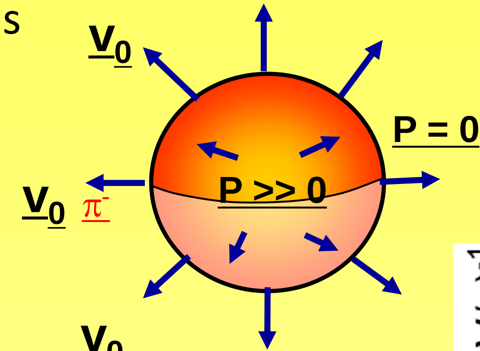
Exponential fit for p_T < 2.2 GeV/c
inv. slope T = 304±51 MeV
for 0–40% Pb–Pb at √s 2.76 TeV
PHENIX: T = 221±19±19 MeV
for 0–20% Au–Au at √s 200 GeV



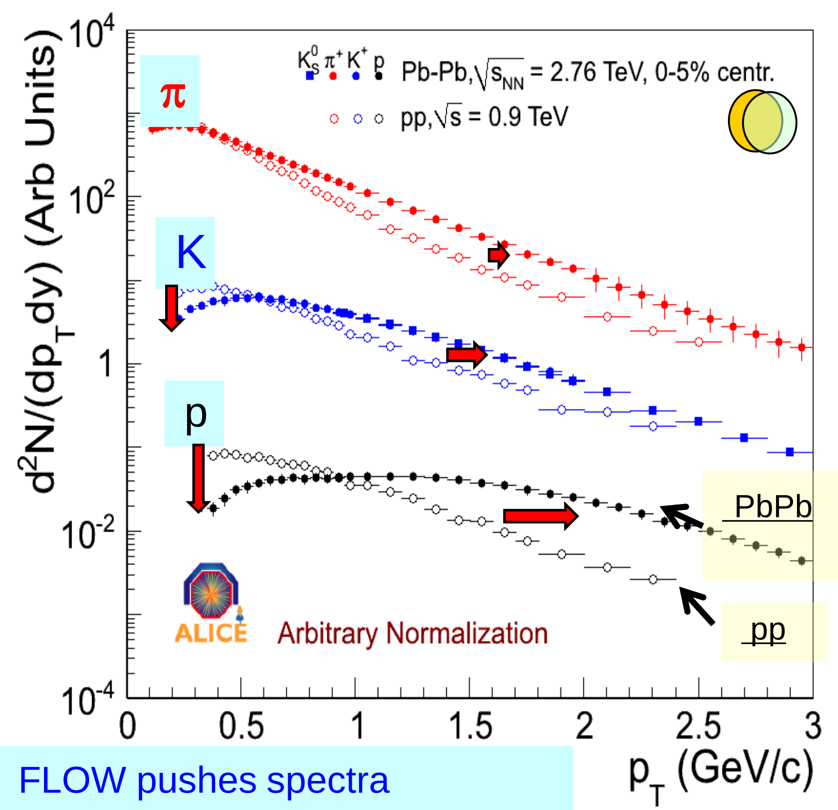
Radial Flow

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

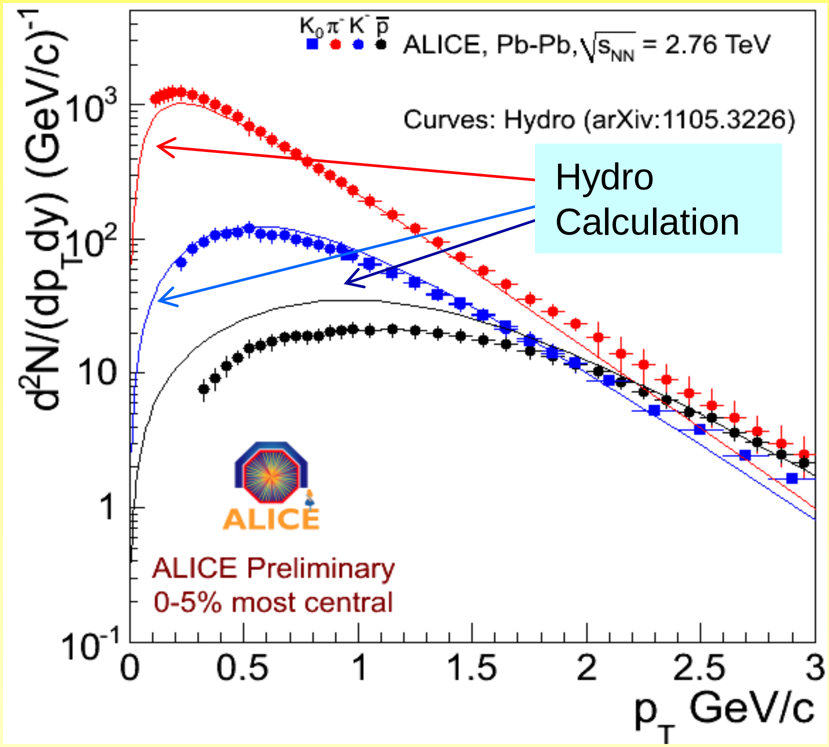
isotropic radial flow



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, $\beta \approx 0.66$

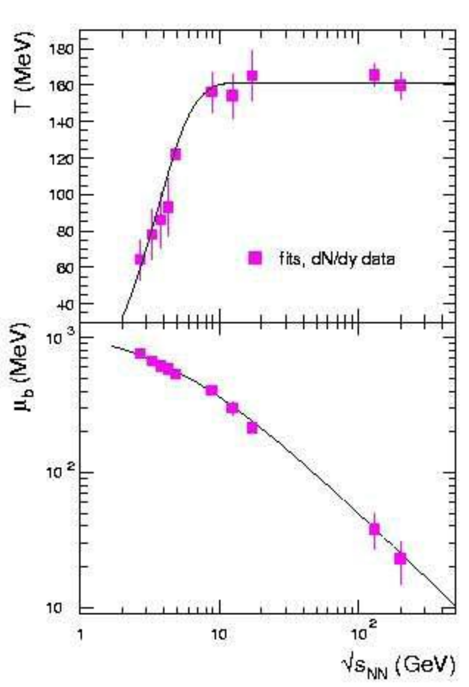
(2/3 of c!) even larger than predicted by most recent hydro

Particle Production: Hadrochemistry

- Many particle types produced: $\pi(u\underline{d})$,p(uud), K(u$\underline{s}$), 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:

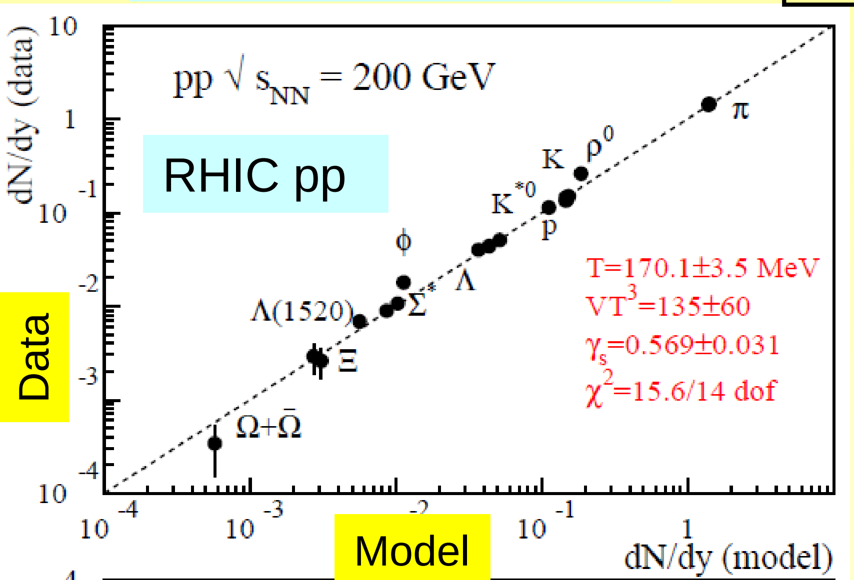
particle with mass *m* produced in 'heat bath T' according to phase space

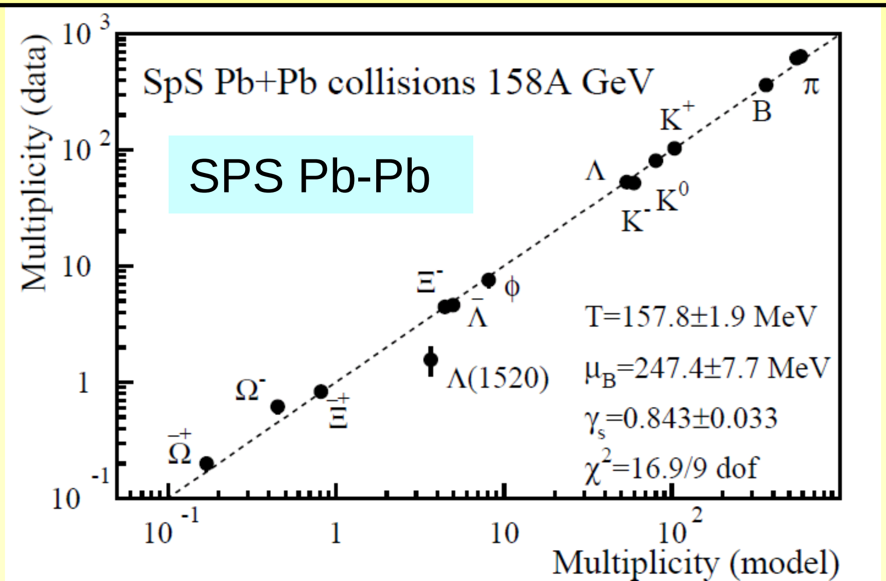
- P(m) ~ $e^{-(m/T)}$; fit depends on
  - T Temperature
  - μ_b Baryo-chemical potential (baryon conservation)
  - γ_s Strangeness suppression



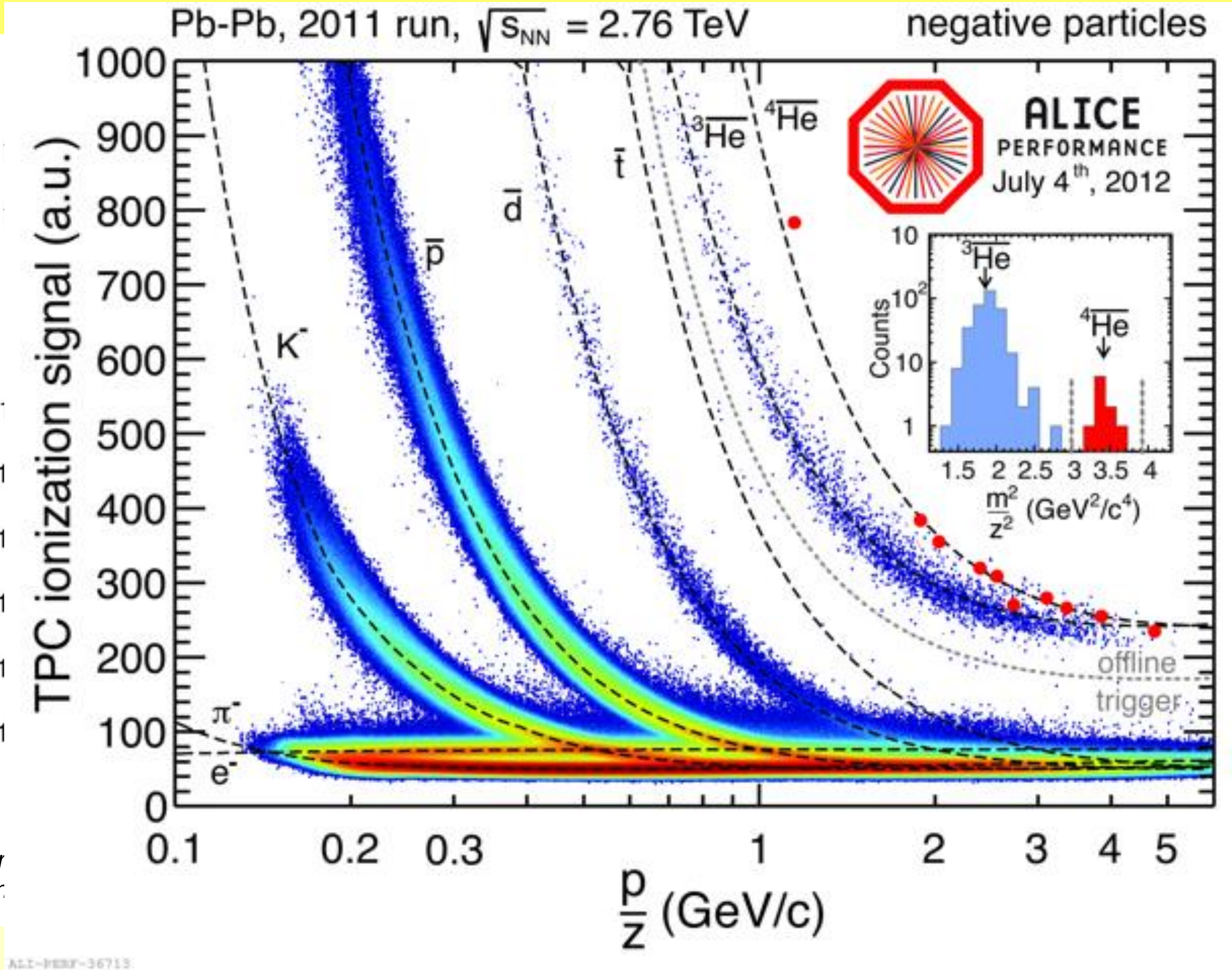
T_{ch}: 160-170 MeV γ_s : 0.9-1 (AA), 0.5-0.6 (pp)
strangeness enhancement = QGP signal ?

particles created per collision





(Anti-)nuclei and hyper-nuclei



dN/dy

Ther
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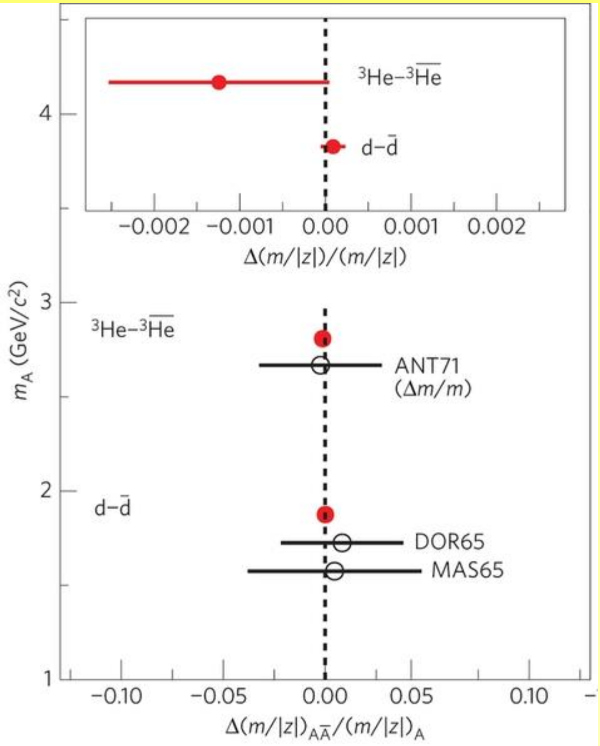
r-)nuclei
nal model

tive to the
ge mass).

consistent
T_{ch} ≈ 156
tension
σ) and
σ).

Just published.... (on Nature Physics)

- **NUCLEAR MATTER AND ANTIMATTER THE SAME MASS**
  - Precision measurement, on part in 10000
  - Confirms one of the fundamental symmetries in nature, the so-called “CPT” (Charge, Parity, Time)
  - **See the short produced by Nature Find it on YouTube searching for: ALICE Collaboration Nature**
  - https://www.youtube.com/watch?v=uooIcCJJttU



- **With an excellent instrument one can have unexpected results**

Azimuthal Asymmetry

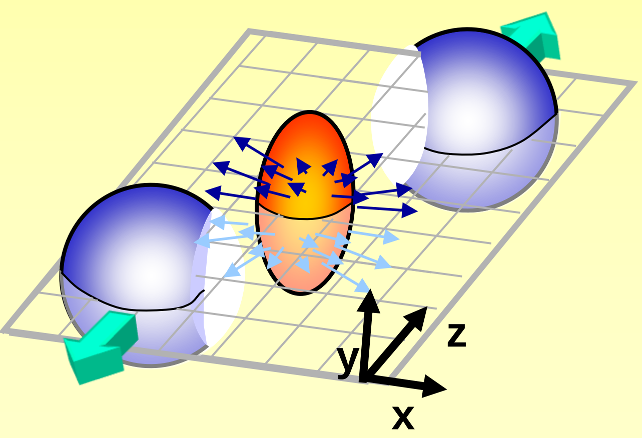
SCIENCE Vol: 298 2179 (2002) ^{7}Li

- Fourier expansion of azimuthal distribution:

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

$$v_1 = \langle \cos\varphi \rangle \quad \text{"directed flow"}$$

$$v_2 = \langle \cos 2\varphi \rangle \quad \text{"elliptic flow"}$$



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

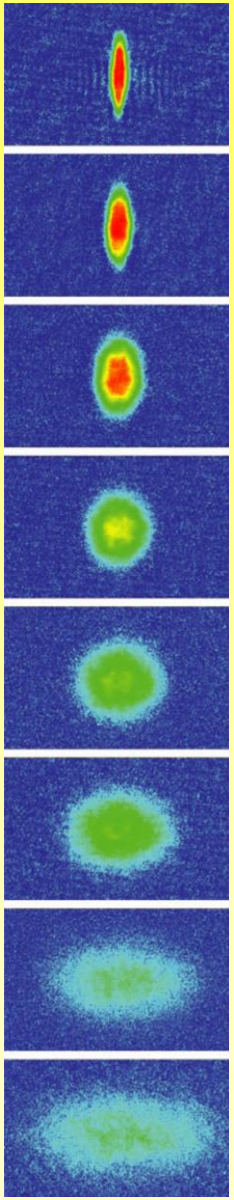
particles stream out isotropically, no memory of the asymmetry

extreme: ideal gas (infinite mean free path)

Small mean free path

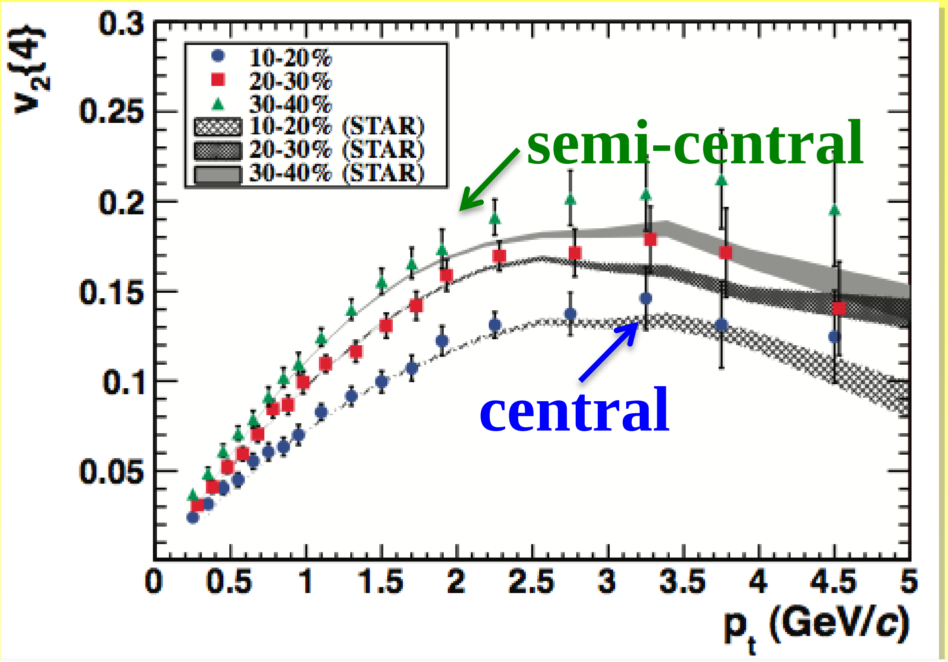
larger density gradient -> larger pressure gradient -> larger momentum

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

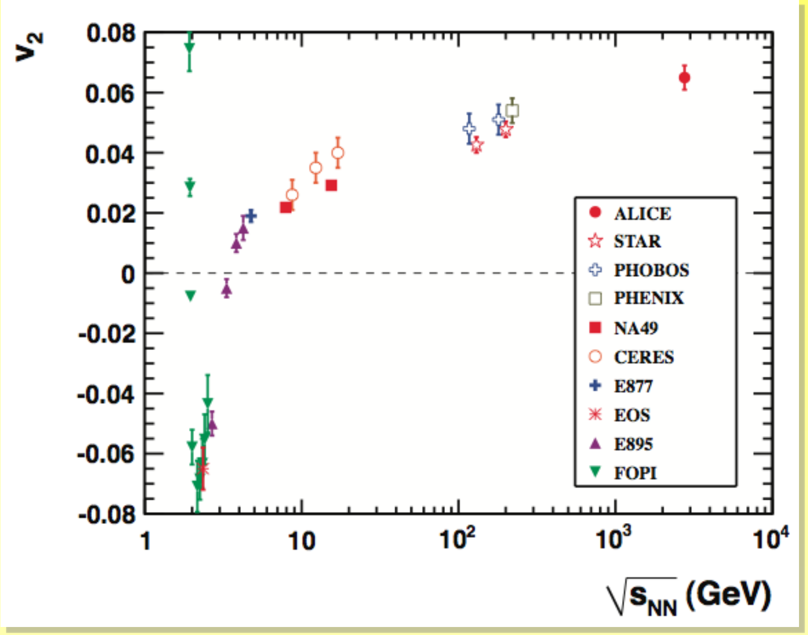


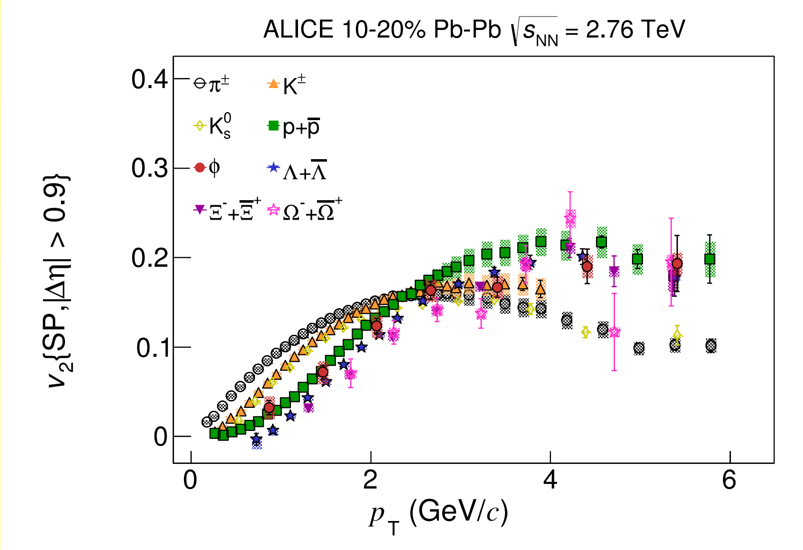
Ultra-cold ^{7}Li 10^{-12} eV , 2 ms of expansion

v_2 Measurements at ALICE



PRL 105, 252302 (2010), already over 500 citations!



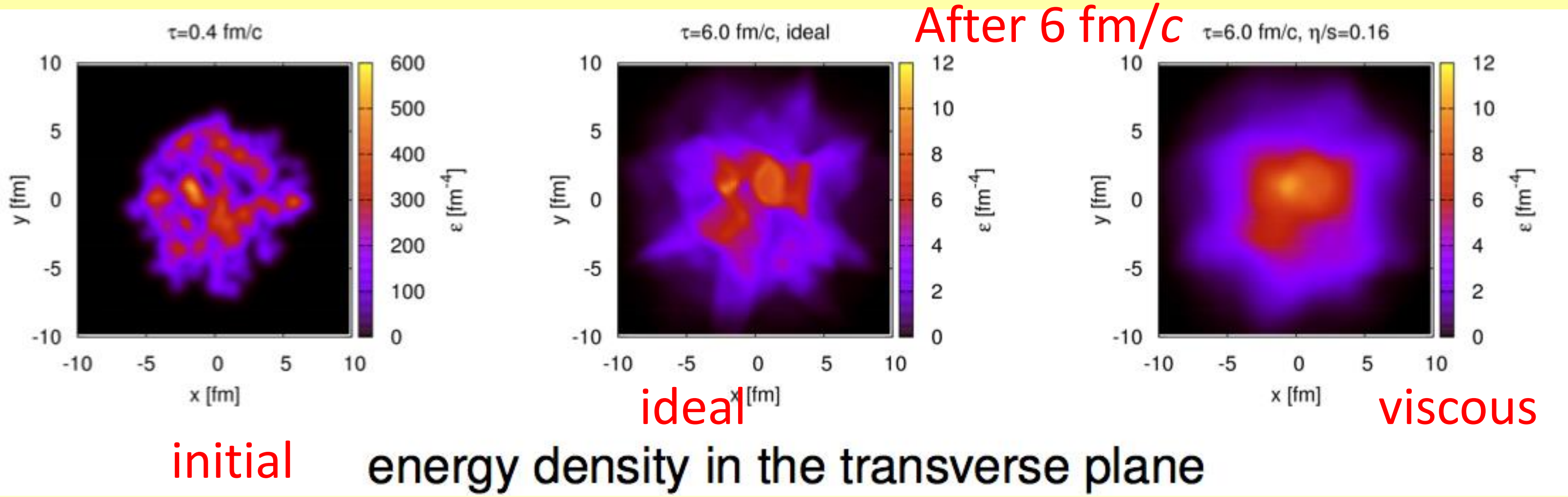


- **Collective behavior observed in Pb-Pb collisions at LHC (+30% vs. v_2^{RHIC}) => ideal fluid behavior (extremely low ratio of sheer viscosity to entropy density $\eta/s \approx 0$), very similar p_T depe. and values to RHIC**
- **Testing hydrodynamical evolution**

Flow as a tool

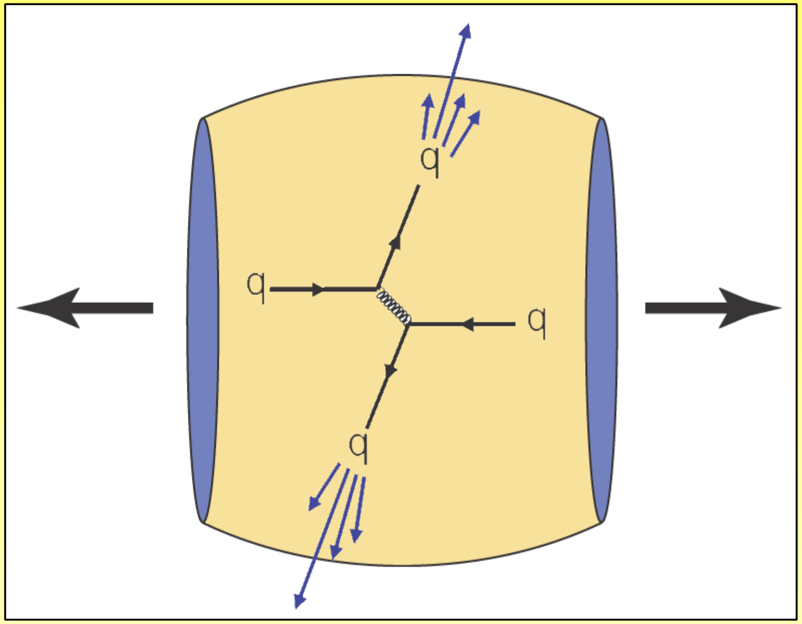
- Understand initial conditions and fluctuations; measure the transport properties (e.g. η/s) of the medium

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



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}

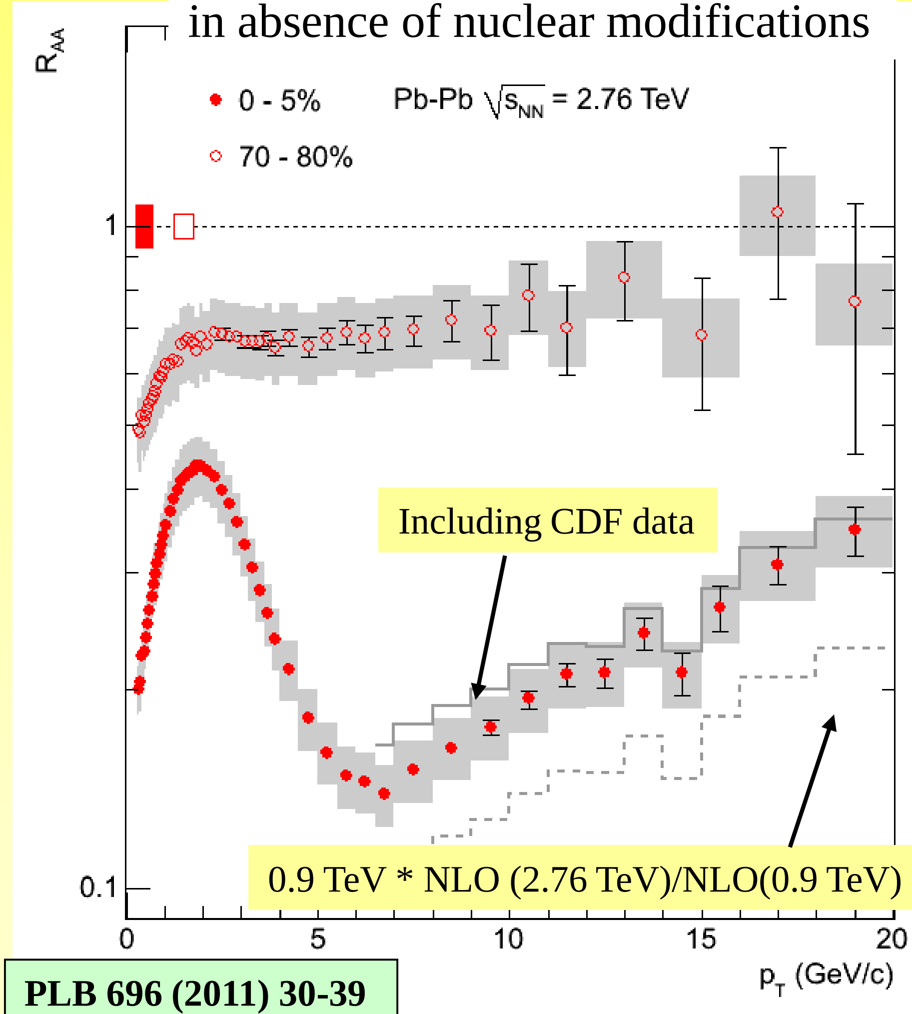
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

Suppression of High-p_T Hadrons

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

$R_{AA} = 1$ for hard QCD processes in absence of nuclear modifications

- 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!

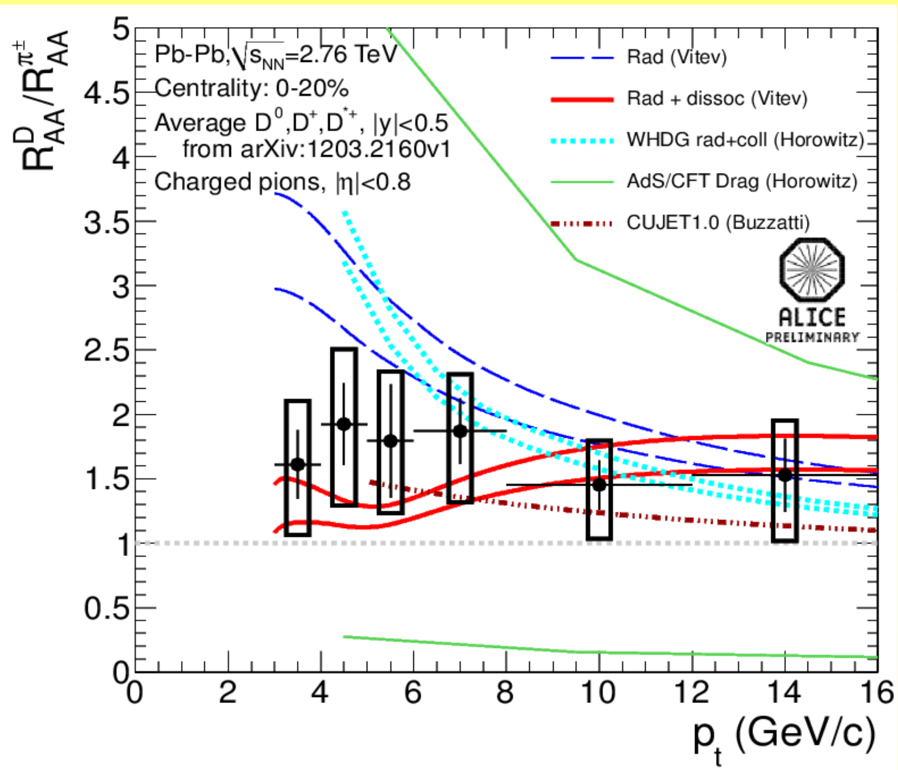


PLB 696 (2011) 30-39

Mass dependence of parton energy loss

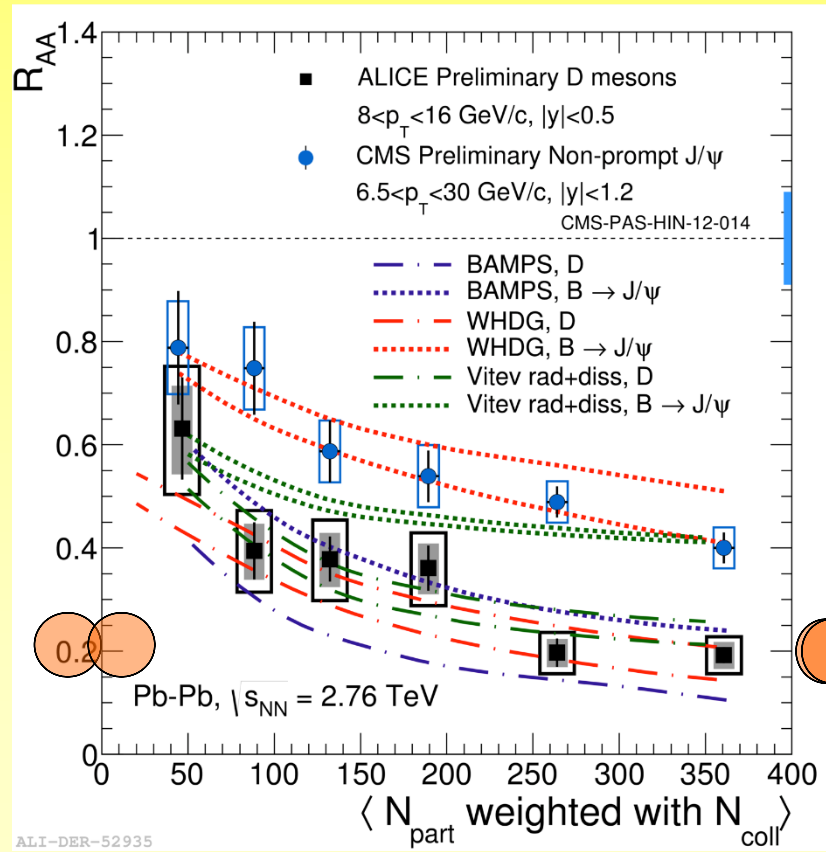
- Expectation from radiative energy loss: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Could be reflected in an hierarchy of R_{AA}: $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$

- **Charmed mesons (ALICE)** vs. **Pions**



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

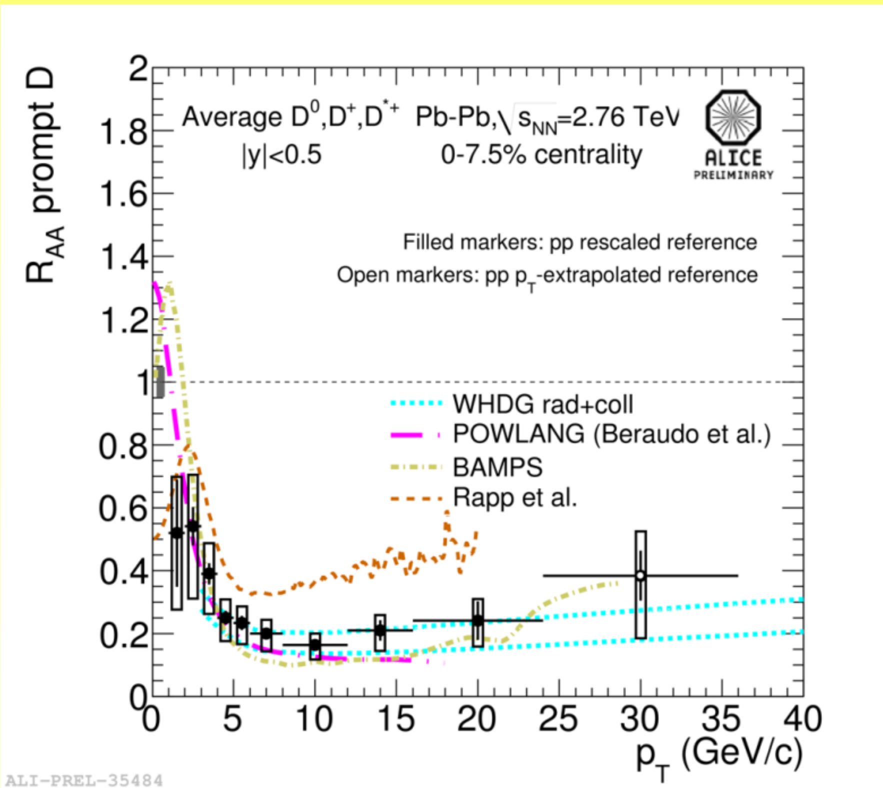
- **Charmed mesons (ALICE)** vs. **J/ψ from beauty decays (CMS)**

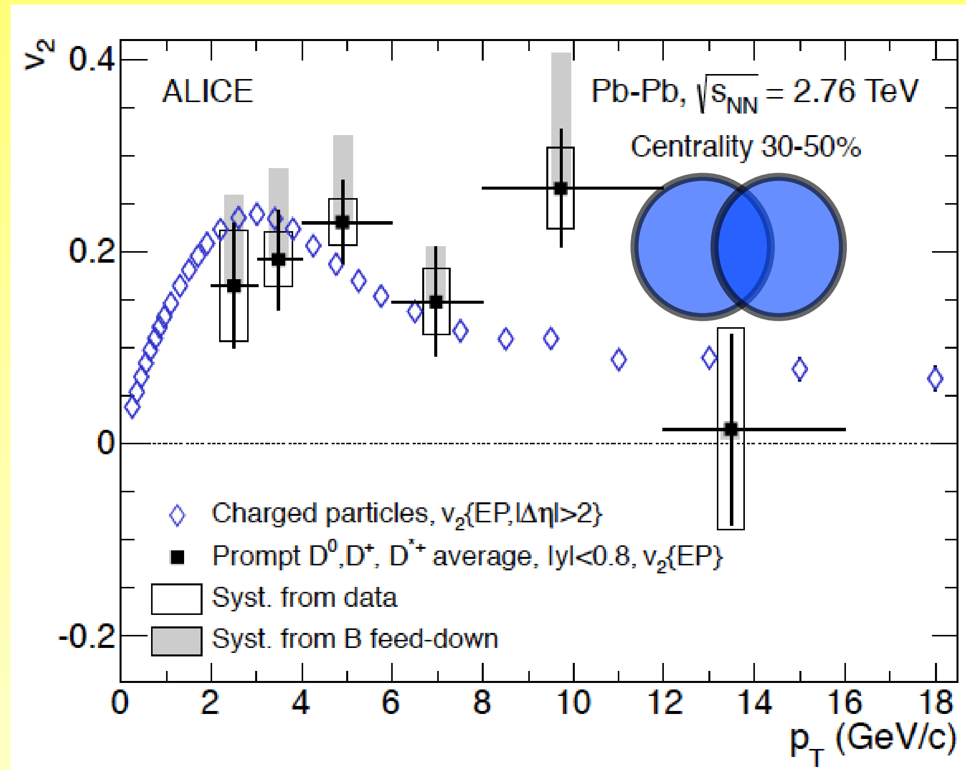


→ **First indication** of a dependence on heavy quark mass: $R_{AA}^B > R_{AA}^D$

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.

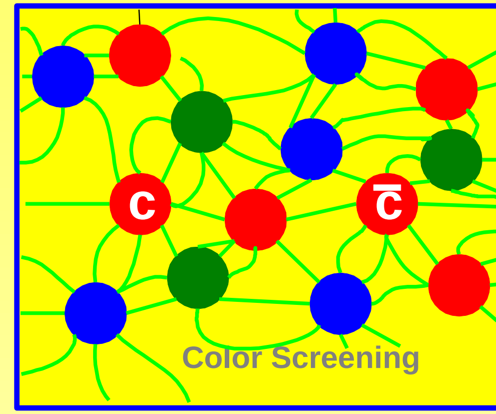
Does that mean **it flows too?**

Prompt D^0, D^+, D^{*+} average.

D meson v_2 suggests collective expansion.

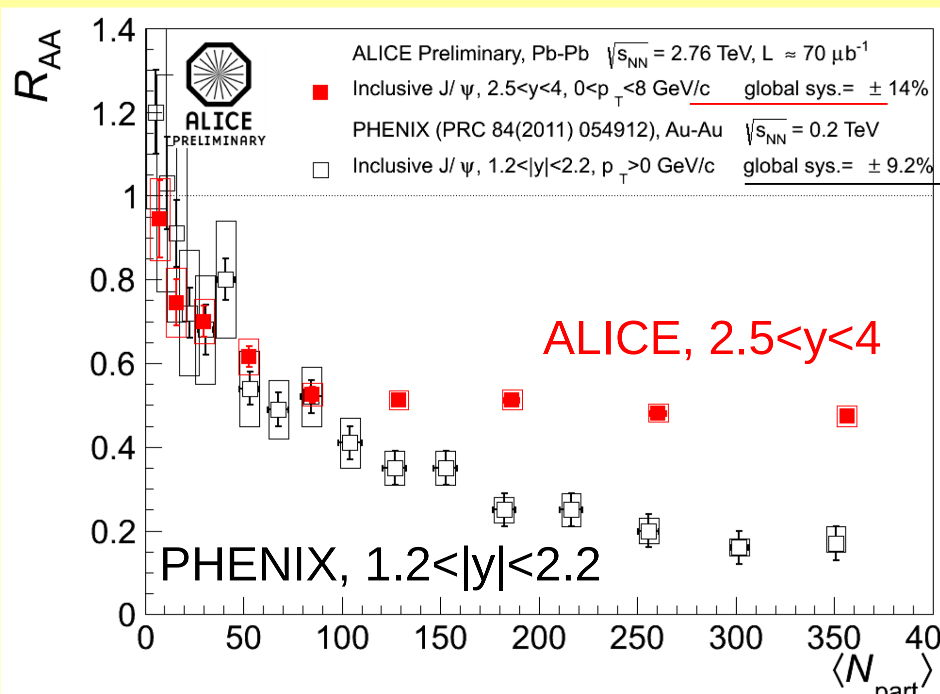
J/ψ "suppression" at the LHC

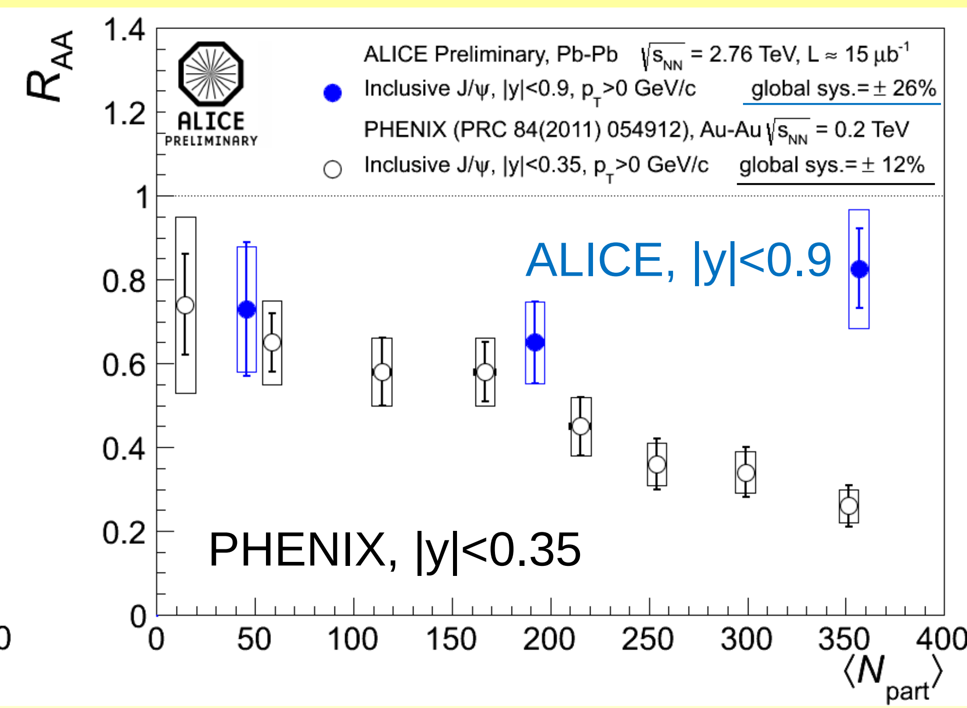
Predicted as a signature of deconfinement, due to the temperature (color charge density density) dependent screening of the color charge in a Quark-Gluon Plasma



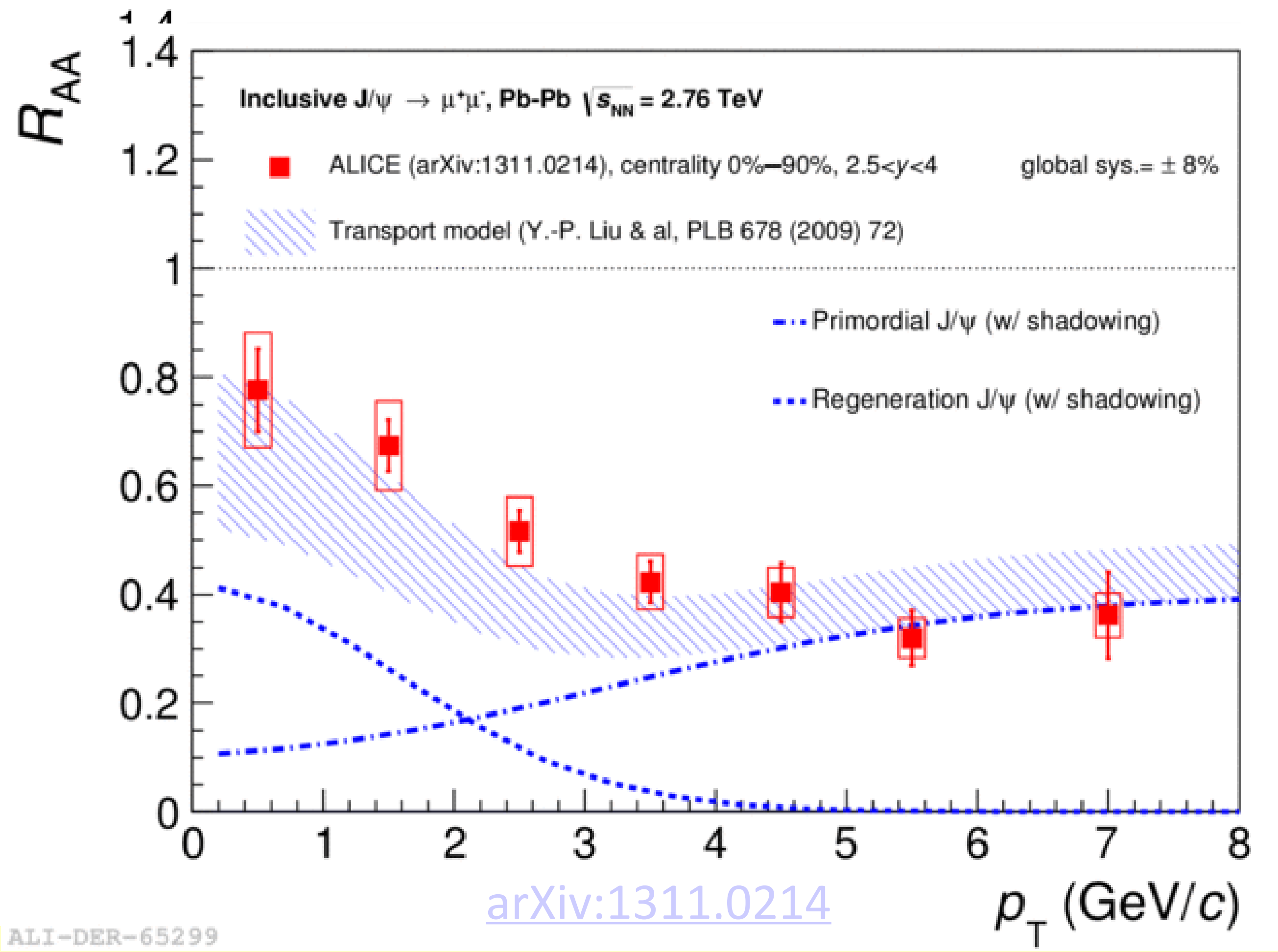
Observed at lower energy experiments (SPS, RHIC)

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

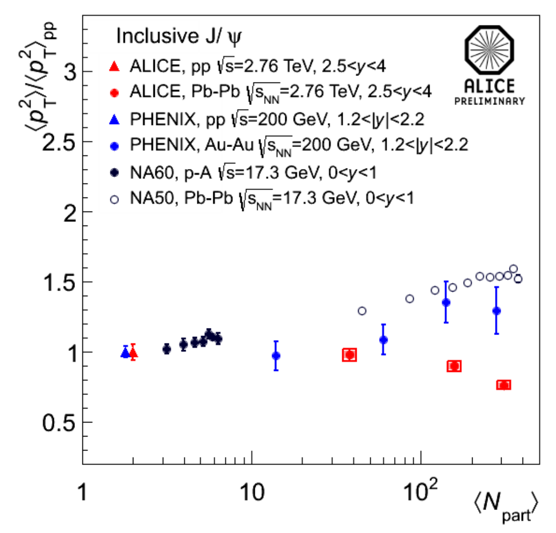


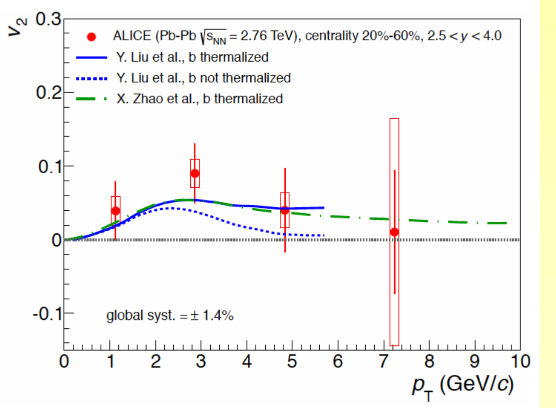


J/ψ production in Pb-Pb



arXiv:1311.0214

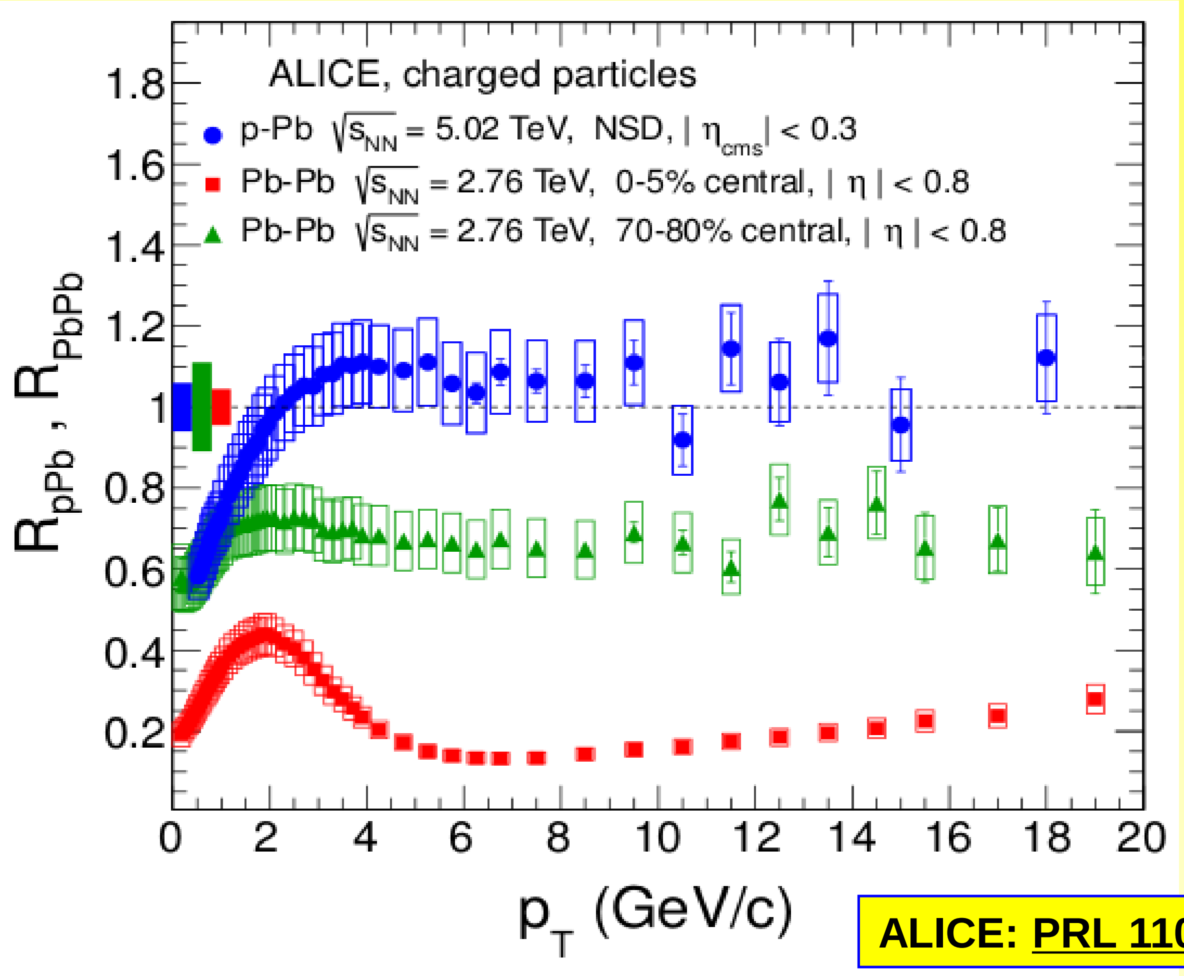




With a hint of flow..

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

The control experiment: p-Pb collisions



ALICE: PRL 110, 082302 (2013)

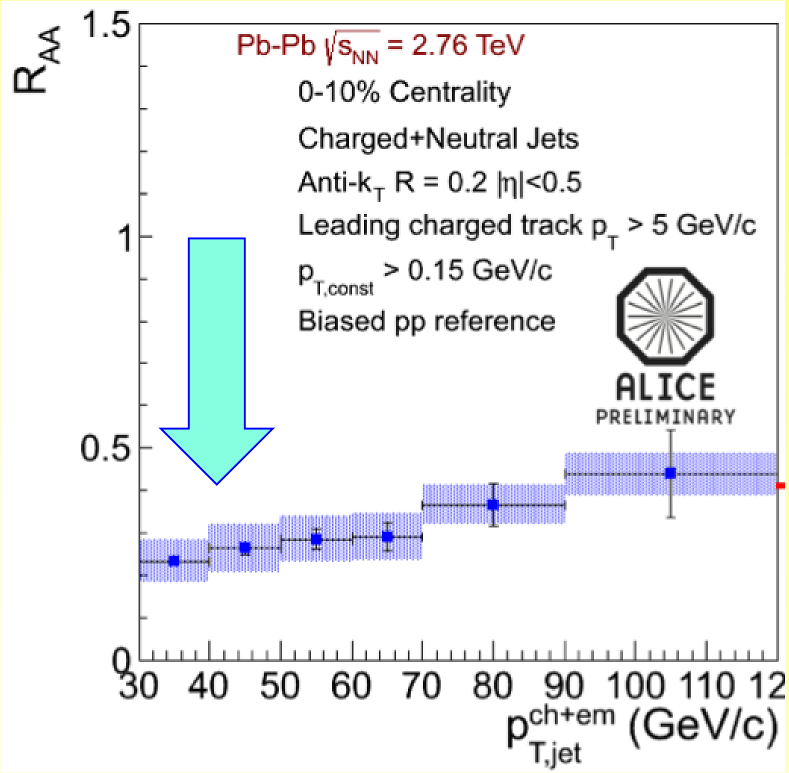
High-p_T charged particles exhibit binary scaling. Initial state effects are small.

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

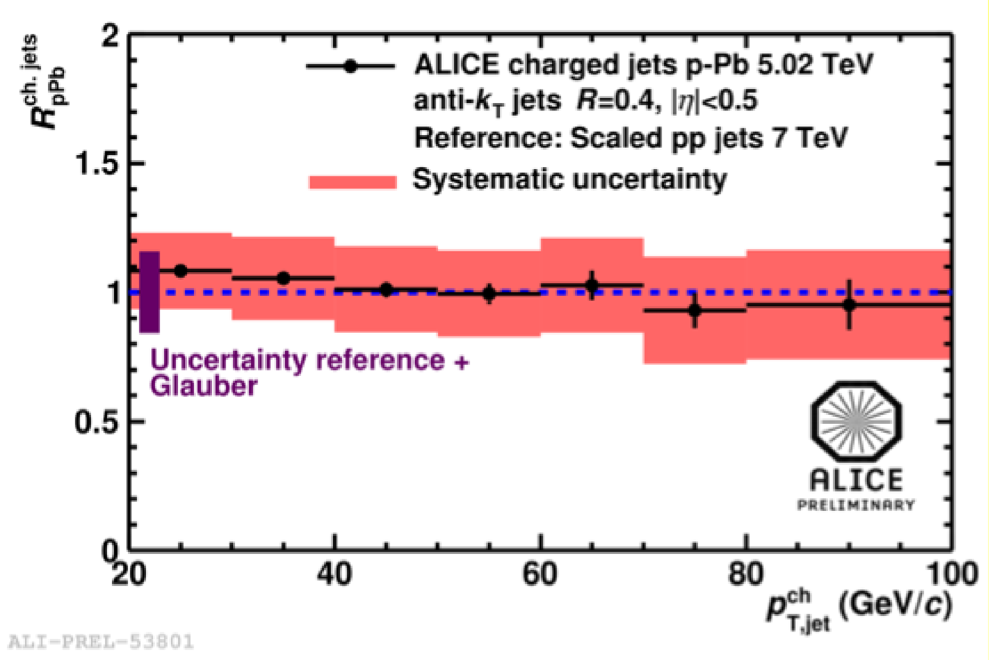
p-Pb at LHC as a control experiment: Jets

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

Pb-Pb (central)



p-Pb (minimum bias)



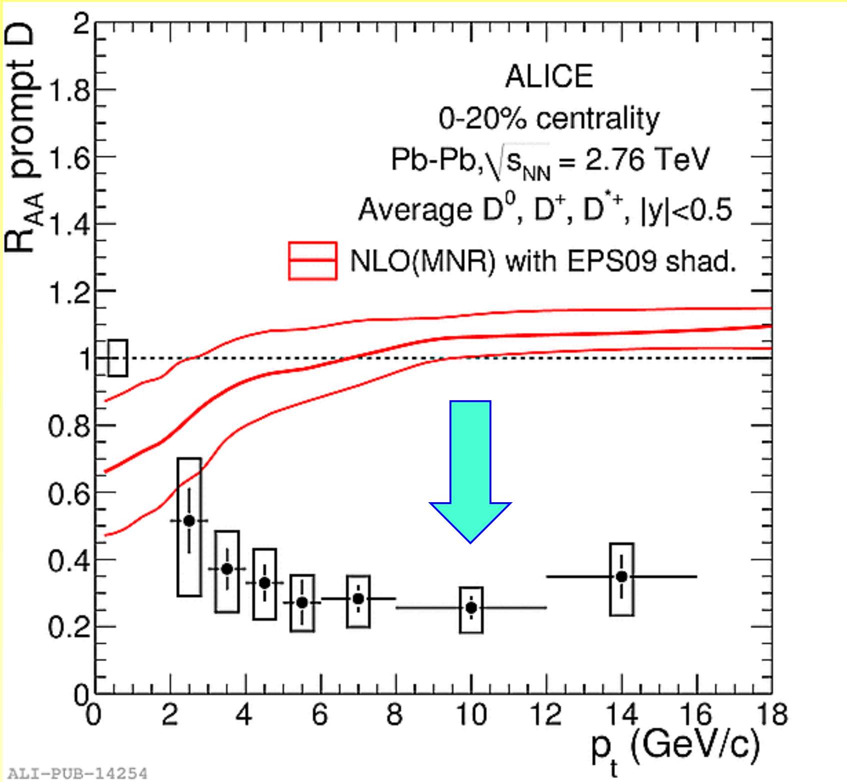
Large high-p_T suppression in Pb-Pb (x3-4) is a medium effect → probes the properties of QCD interactions over extended volumes

p-Pb at LHC as a control experiment: D

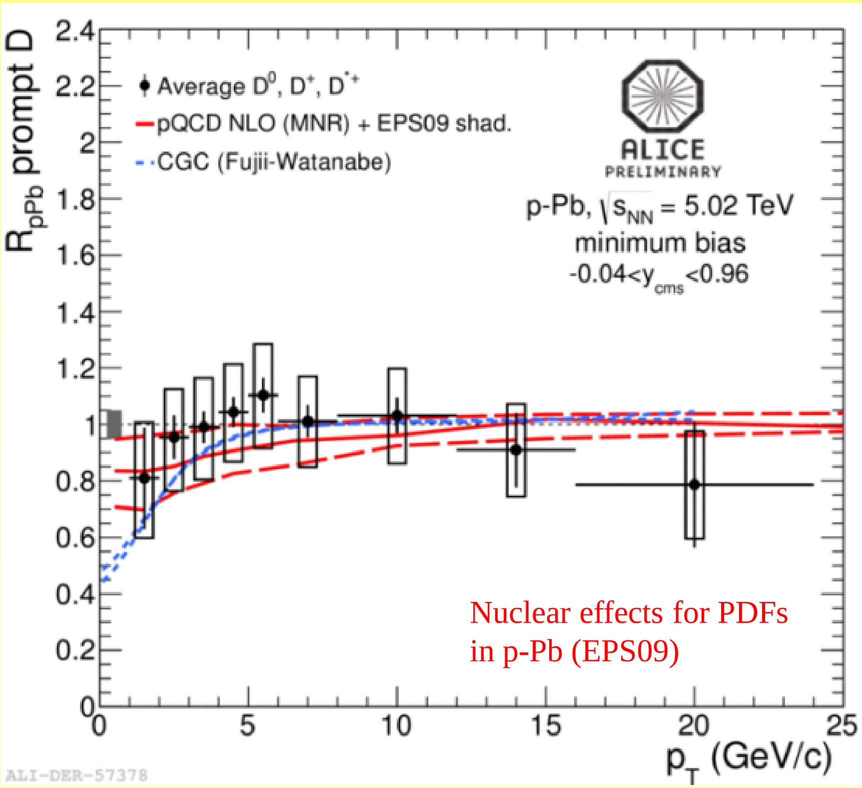
- Measurements for main hard probes in minimum-bias p-Pb indicate that the effects seen in Pb-Pb are dominated by the hot medium

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

Pb-Pb (central)



p-Pb (minimum bias)



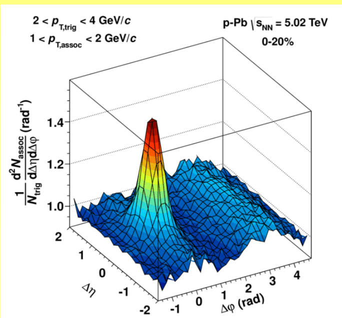
Open Charm: No significant nuclear modification in p-Pb (R_{pPb}~1)

- Consistent with modest effect expected from PDF shadowing

Intriguing findings in high-multiplicity p-Pb

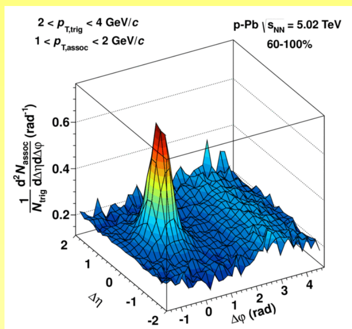
From p-Pb pilot run:

0-20%



−

60-100%



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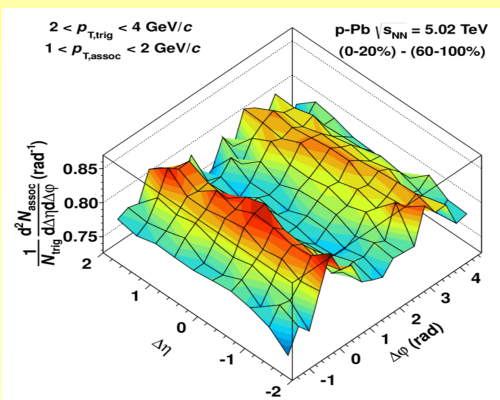


Structure emerging when subtracting low mult correlations from high-mult. Origin still unknown …

Possible interpretations:

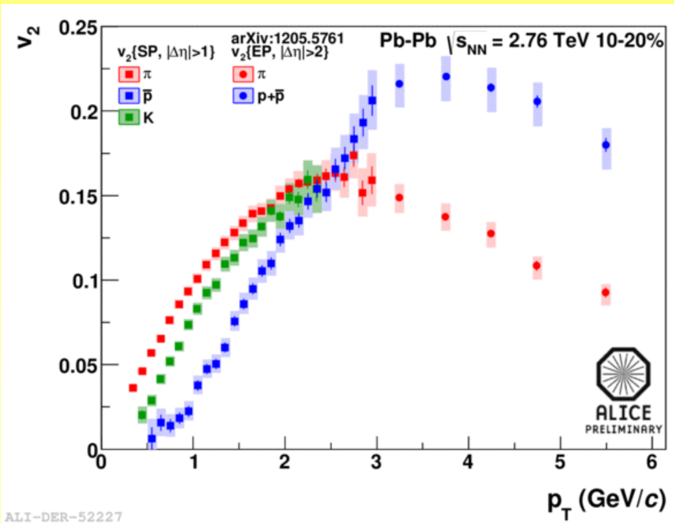
- Hydrodynamic flow in the final state: a "medium"
- Colour reconnection: a "pure QCD effect"
  - could be interesting to understand QGP formation in Pb-Pb
- Multi-gluon processes from saturated initial-state (Colour Glass Condensate)

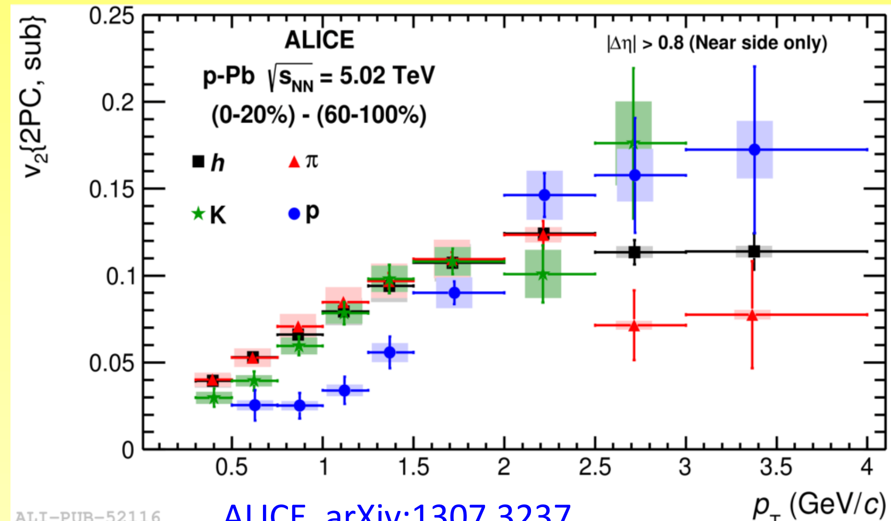
→ Use ALICE PID capabilities to test these possibilities

Intriguing findings in high-multiplicity p-Pb

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

Pb-Pb | **p-Pb, high-multiplicity**

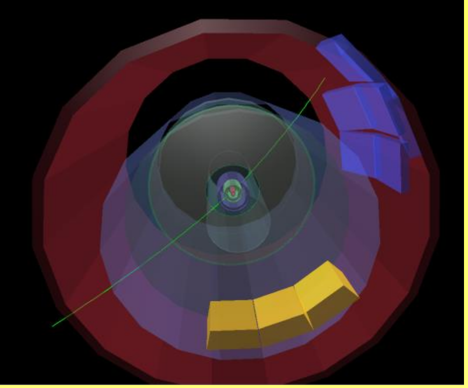




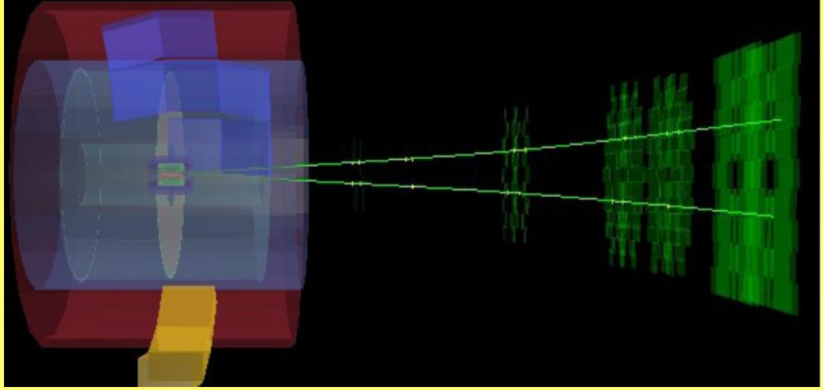
ALICE, arXiv:1307.3237

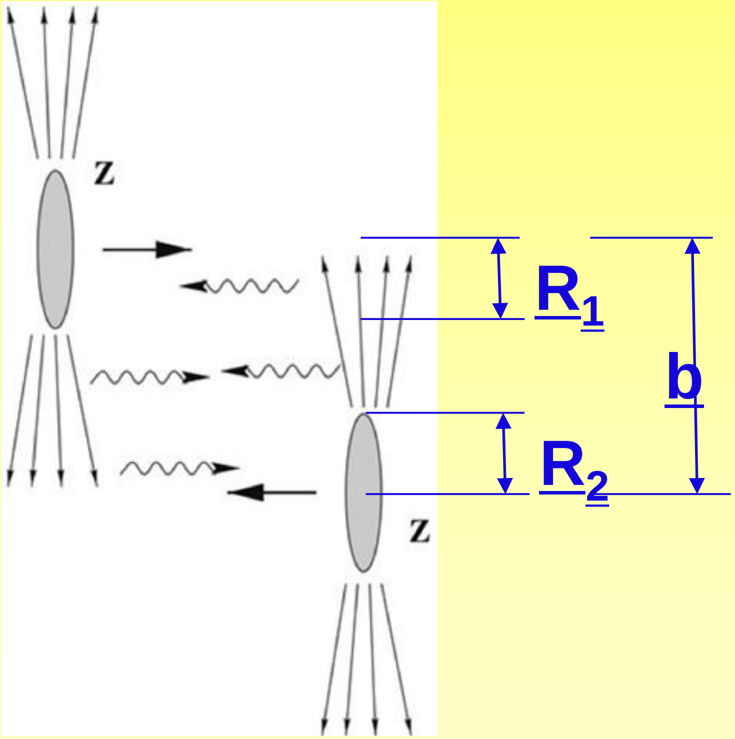
- Pb-Pb: mass ordering, interpreted in terms of collective radial and elliptic flow
- Clear indication for mass ordering also in p-Pb
- further support for flow picture?

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: $b > R_1+R_2$

$\rightarrow$ hadronic interactions strongly suppressed

High photon flux

$\rightarrow$ well described in Weizsäcker-Williams approximation (quasi-real photons)

$\rightarrow$ flux proportional to Z^2

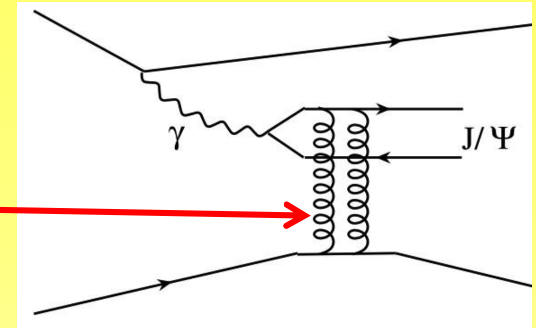
$\rightarrow$ high cross section for γ-induced reactions

Pb-Pb and p-Pb UPC at LHC can be used to study γ-Pb, γp and $\gamma\gamma$ 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**:

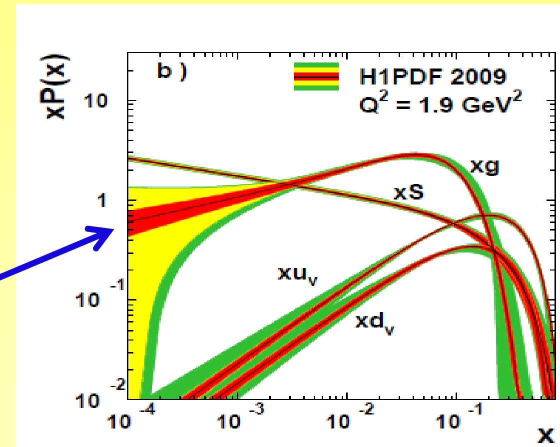
$$\left.\frac{d\sigma_{\gamma A \to J/\psi A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s^2(Q^2)}{48 \alpha_{\mathrm{em}} Q^8} \left[xG_A(x, Q^2) \right]^2$$



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

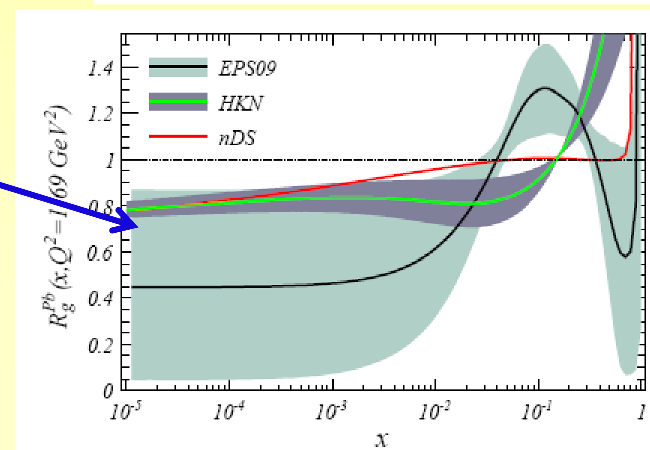
- Bjorken x ~ $10^{-2} - 10^{-5}$ accessible at LHC: $x = \frac{M_{J/\psi}^2}{W_{\gamma p}^2}$

- 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**

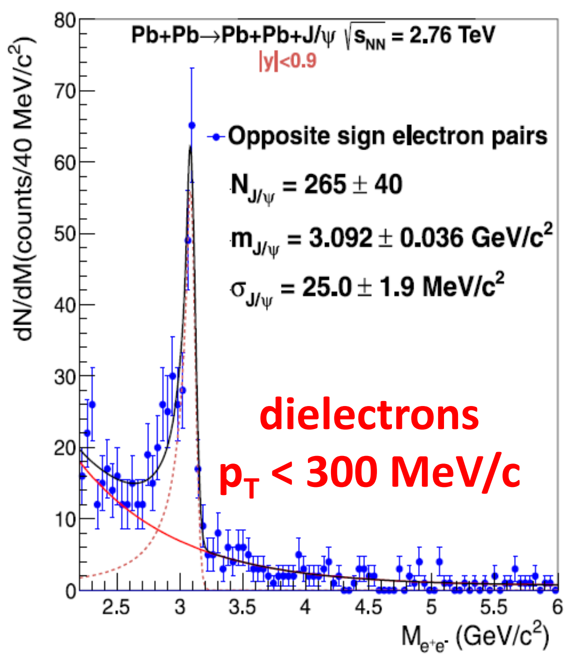


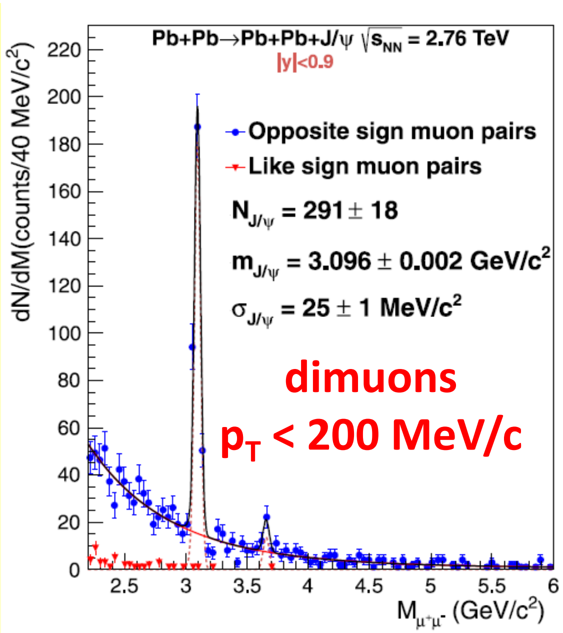
- J/ψ photoproduction in Pb-Pb UPC (lead target) provides information on **gluon shadowing in nuclei at low x** which is essentially unconstrained by existing data

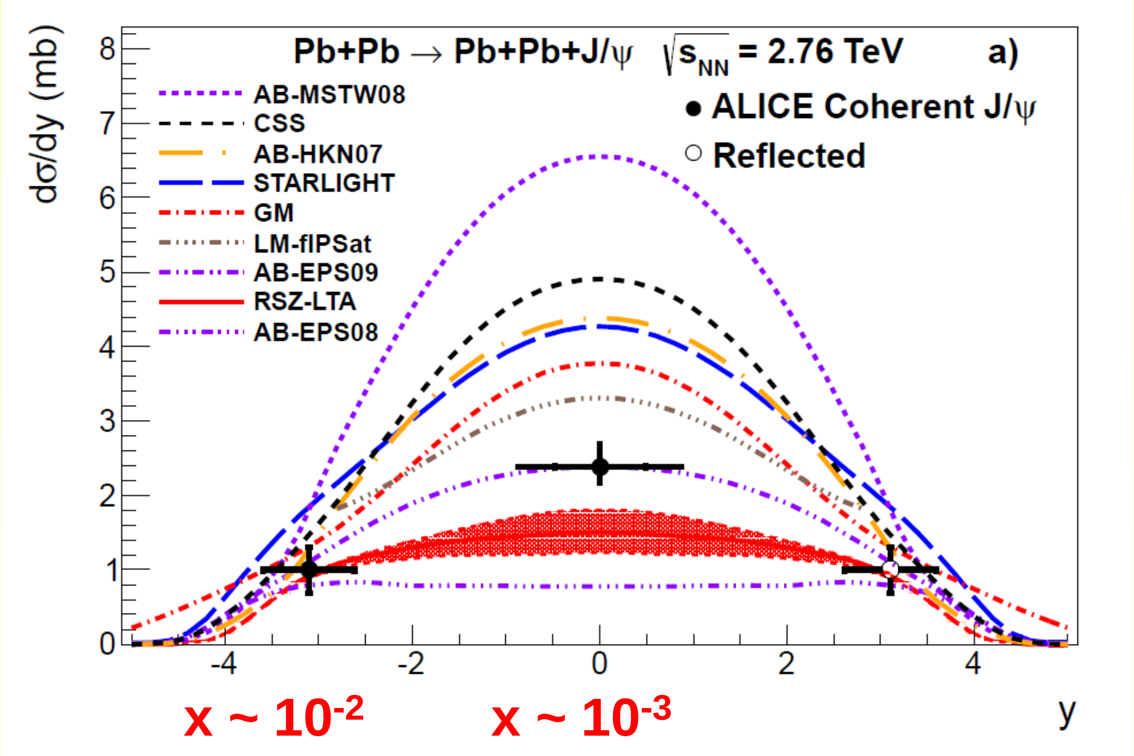
$$R_g^A(x, Q^2) = \frac{G_A(x, Q^2)}{A G_p(x, Q^2)}$$ – gluon shadowing factor



Coherent J/ψ production







Good agreement with models which include nuclear gluon shadowing.

Best agreement with EPS09 shadowing

(shadowing factor ~0.6 at x ~ 10^{-3}, Q^2 = 2.4 GeV²)

Eur. Phys. J. C73 (2013) 2617

J/ψ photoproduction in pPb

Data collected in

p-Pb: p towar

Pb-p: Pb towa

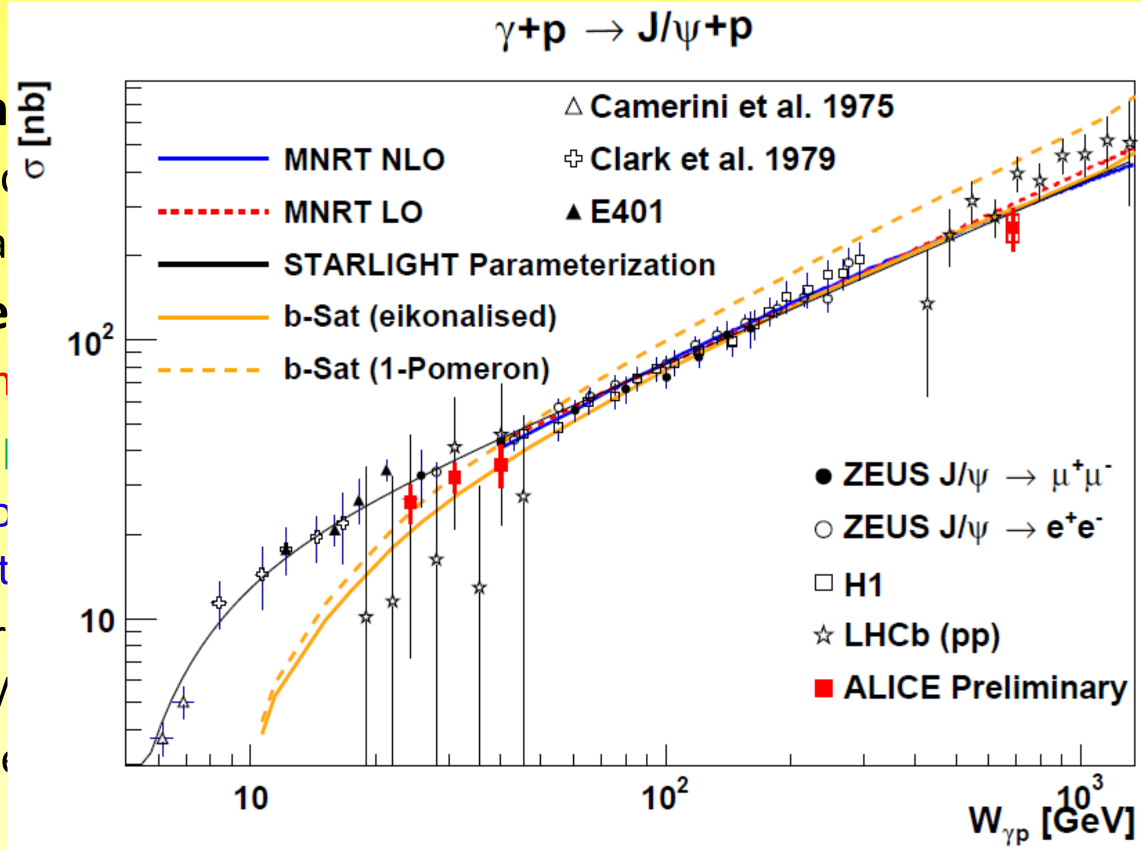
Three UPC trigge

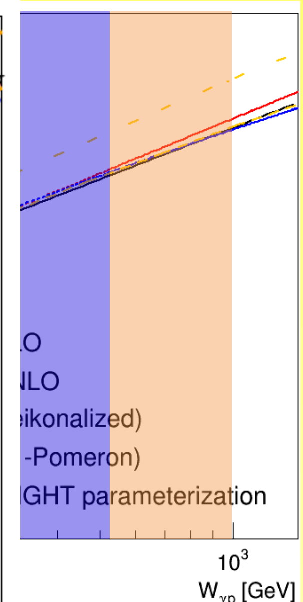
First results from forward muons

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

→ wide gamma-pr up to W ~ 1 TeV

→ wide x coverage

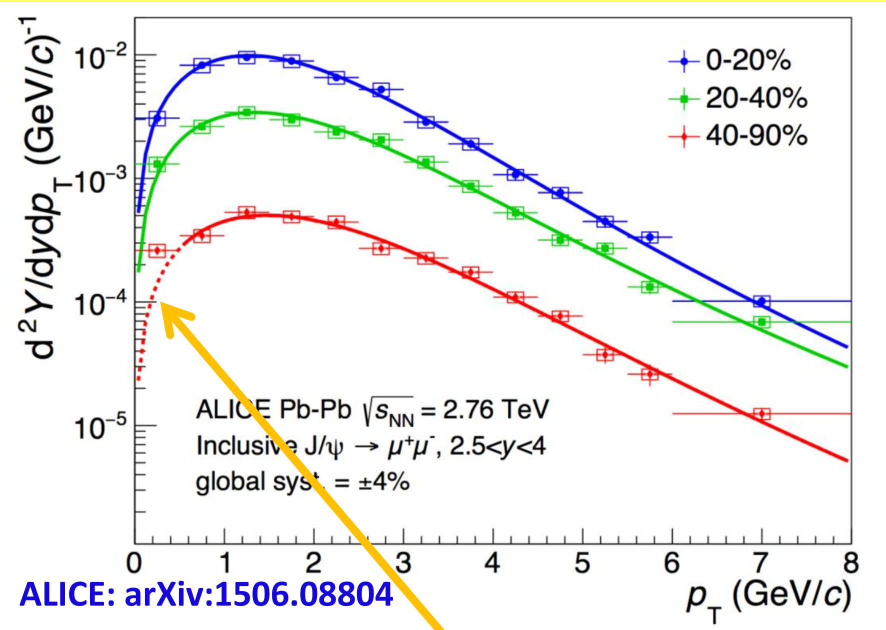




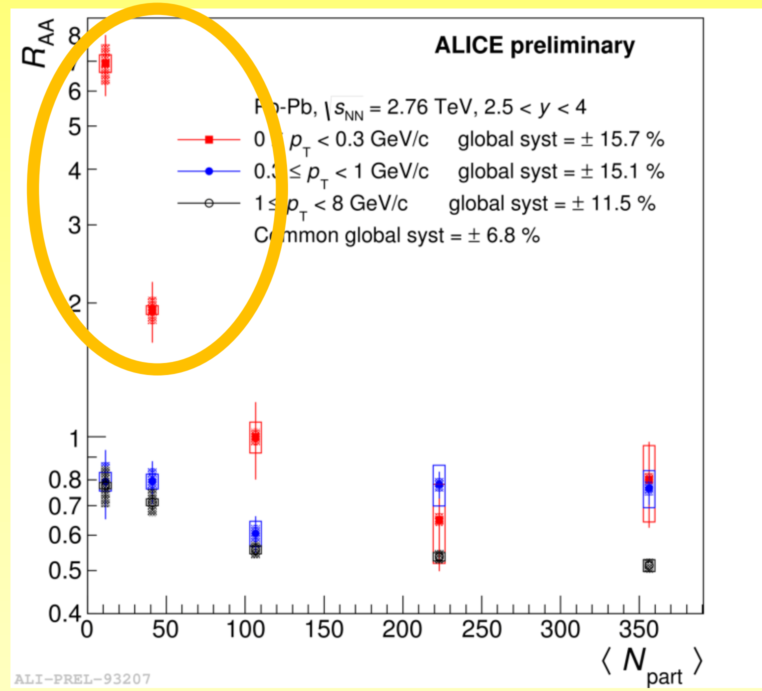
- Access to gluon distribution in proton target at low x
- Advantage of p-Pb:
  - Large photon flux from Pb, The photon source is known, so $W^2_{\gamma p} = 2E_p M_{J/\psi}\ \exp(-y)$
  - Hadronic contribution can be strongly suppressed by ensuring Pb nuclei are intact (no signal in ZDC)
  - Contamination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

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

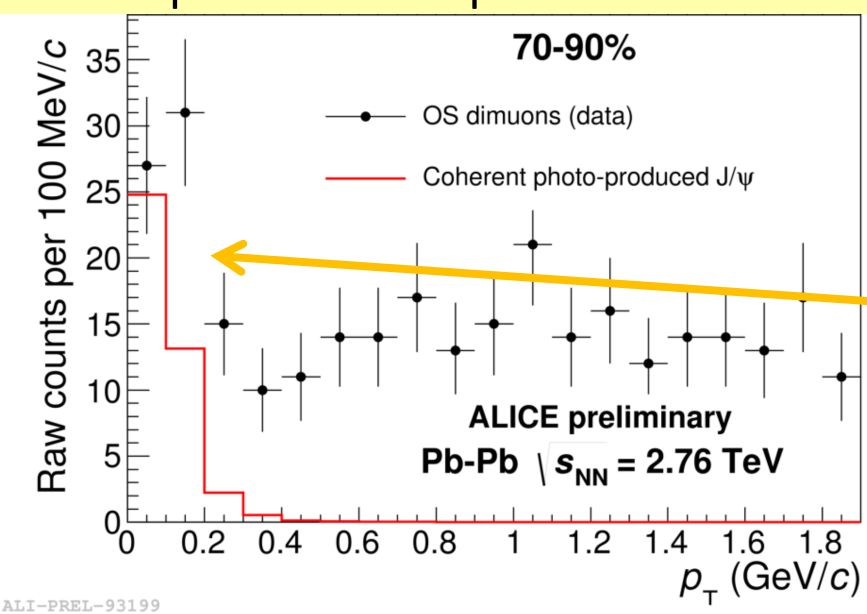
Excess of very low-p_T J/ψ in peripheral Pb-Pb



Enhancement of J/ψ R_{AA} in most peripheral collisions for p_T < 0.3 GeV/c



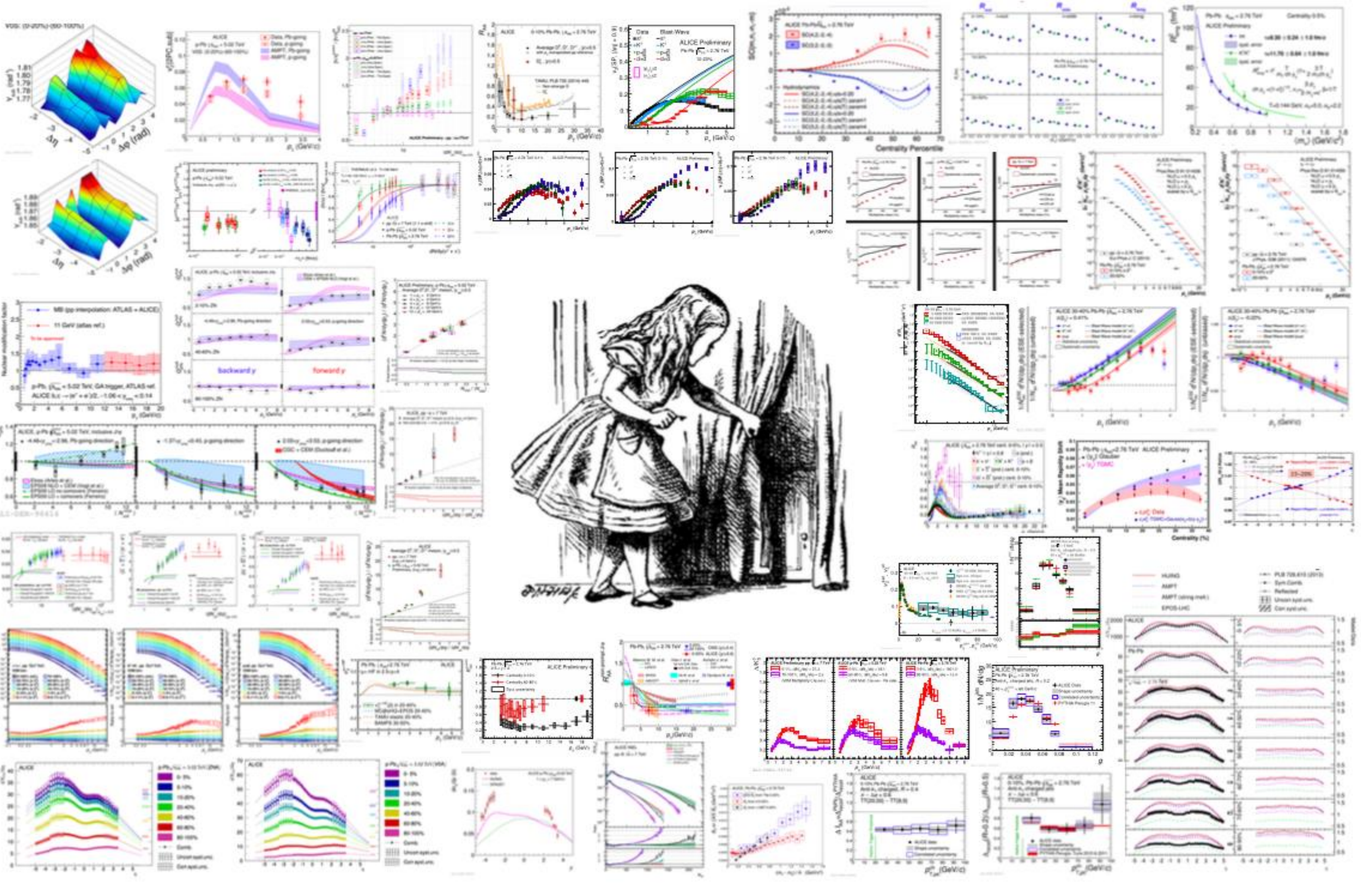
Excess at low p_T in peripheral Pb-Pb collisions with respect to hadronic production expectations



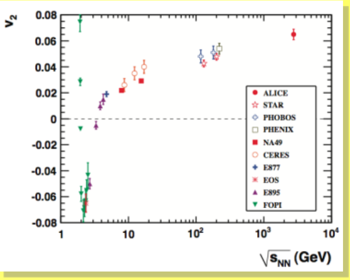
P_T spectrum consistent with photoproduction

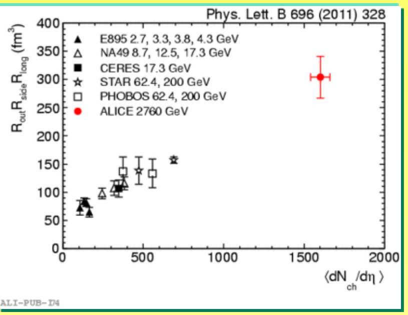
Process is not included in any model, but extrapolation from UPC measurement matches reasonably the observed cross section ~ 50 μb

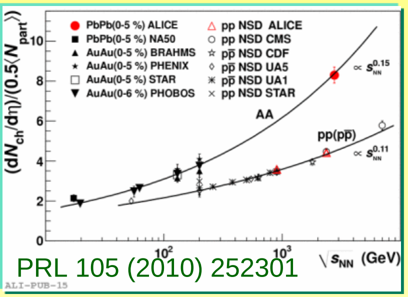
And many, many more…:ALICE @ Quark Matter 2015

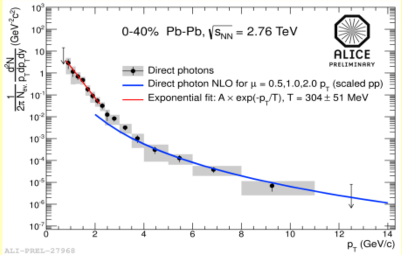


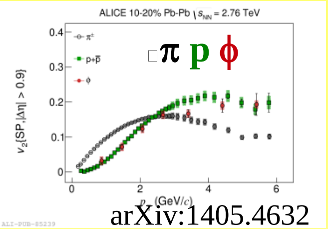
Main RUN1 ALICE results

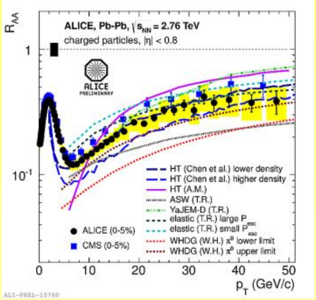


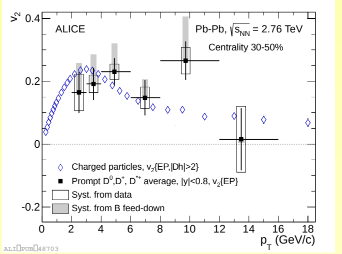








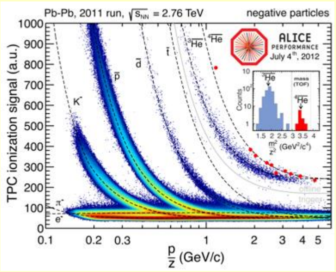


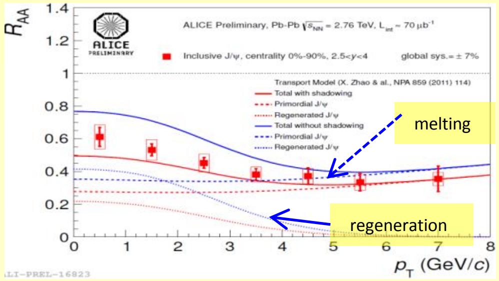


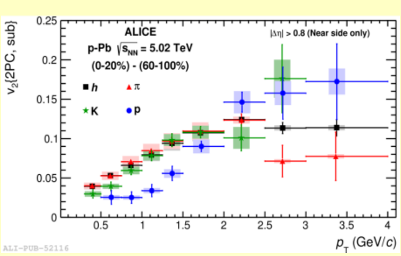
- global features defined
- QGP strongly interacting liquid even at higher T, access to transport coefficients
- energy loss of partons in QGP: wealth of data from leading particles and reconstructed jets, including heavy quarks
- Heavy quarks also appear to thermalize!
- rich results on charmonium, with evidence of regeneration
- Access to low-x PDF from UPC

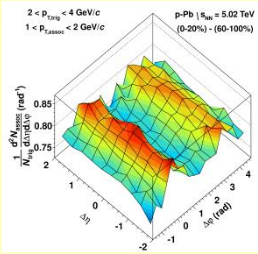
Intriguing, unexpected results from the pA run

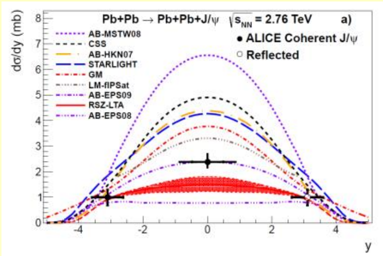
- How small a system to observe collective behaviour?











The ALICE program

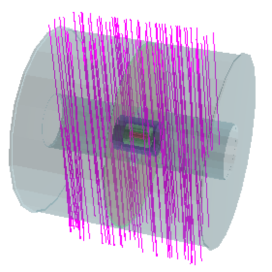
- The past:

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}

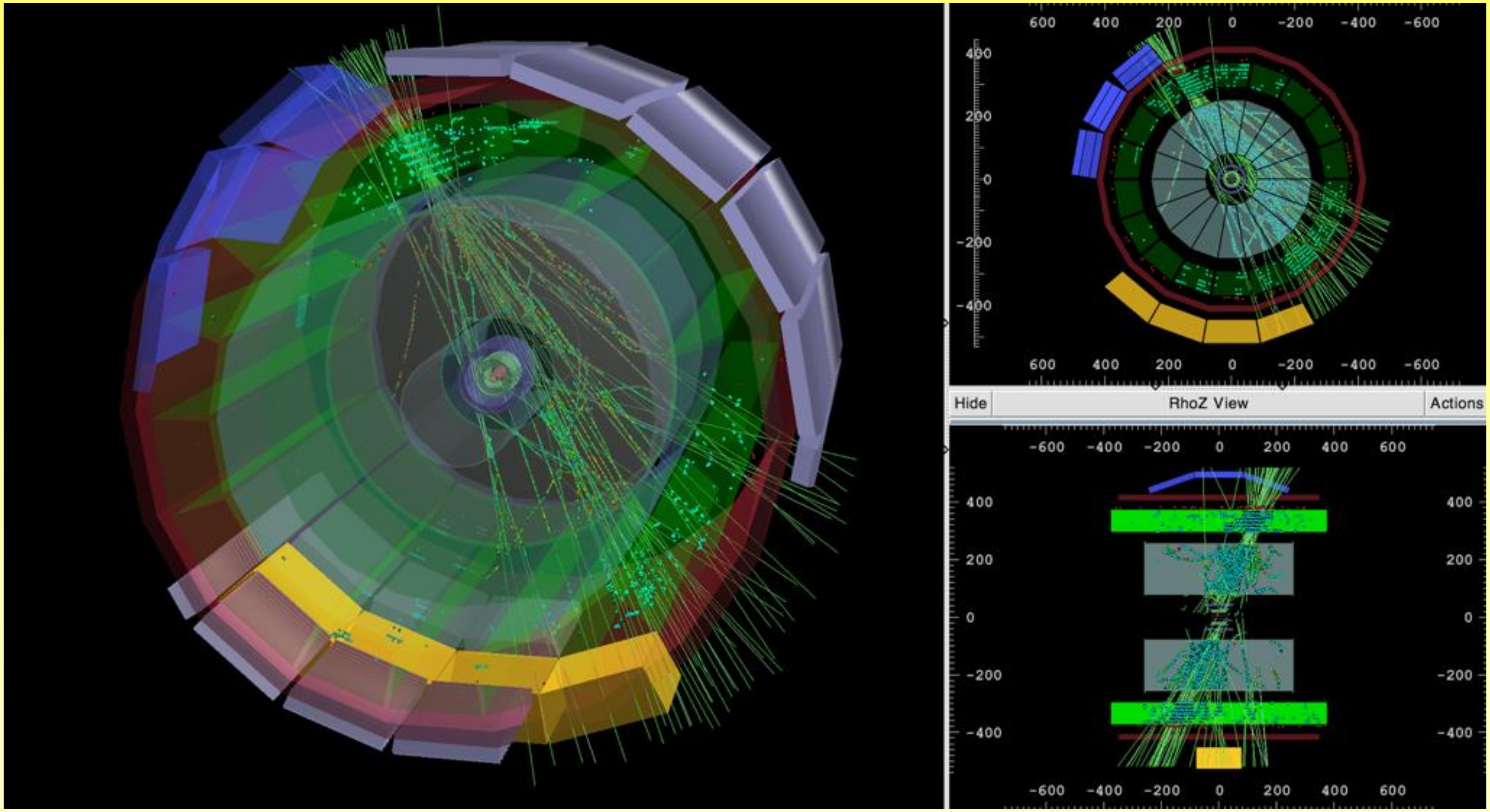
- The present:
  - **RUN2 (2015, 2016, 2018)** : will allow to approach the **1 nb^{-1}** for Pb-Pb collisions, with improved detectors and double energy (2015 and 2018), and a p-Pb run with 10* statistics (this year)

- The Future:
  - **RUN3 + RUN4 (2021, 22, 23 and 27, 28, 29): 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

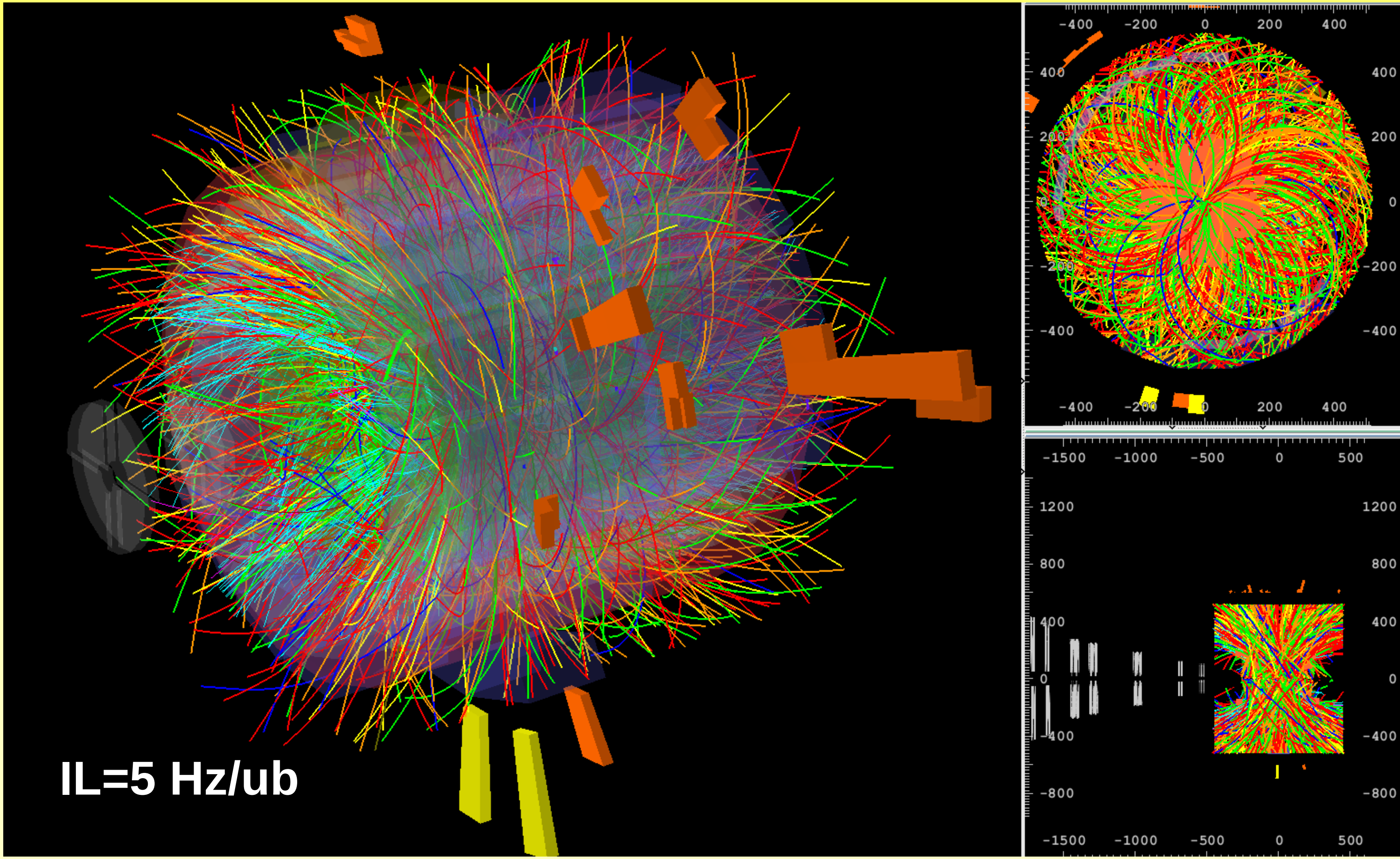


ALICE RUN2 restart: Cosmics...



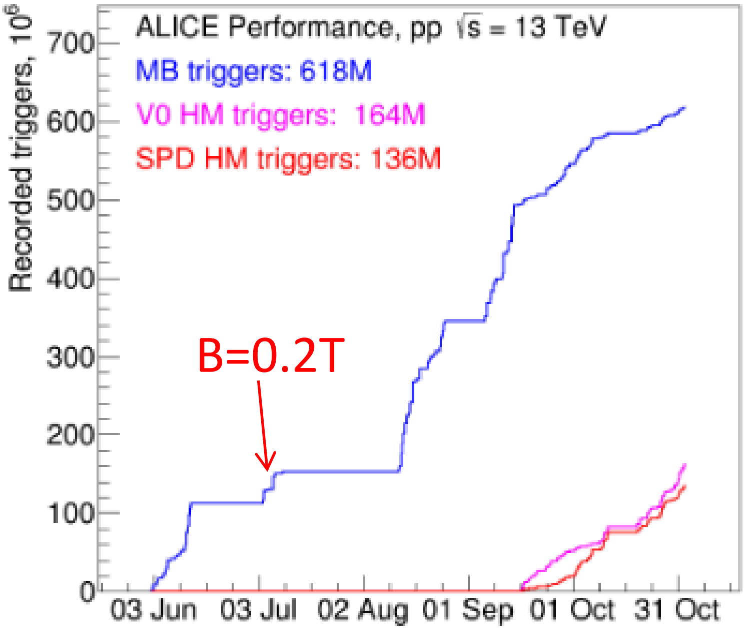
- Data for both alibration and Physics. Statistics >> RUN1
  - RUN1 results on Muon Bundles: arXiv:1507.07577

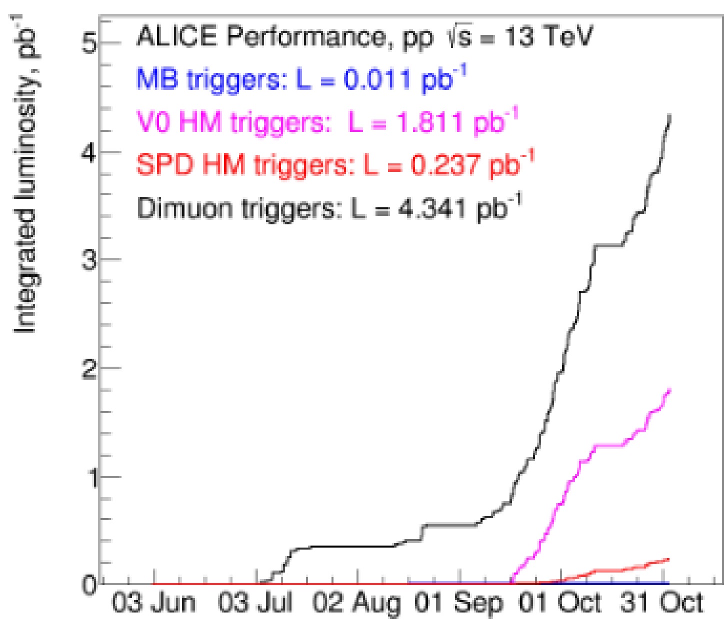
RUN2 2015: pp at 13 TeV



NOTE: Beam induced background x10 better than 2012: took data from the beginning of each fill

ALICE pp run at 13 TeV

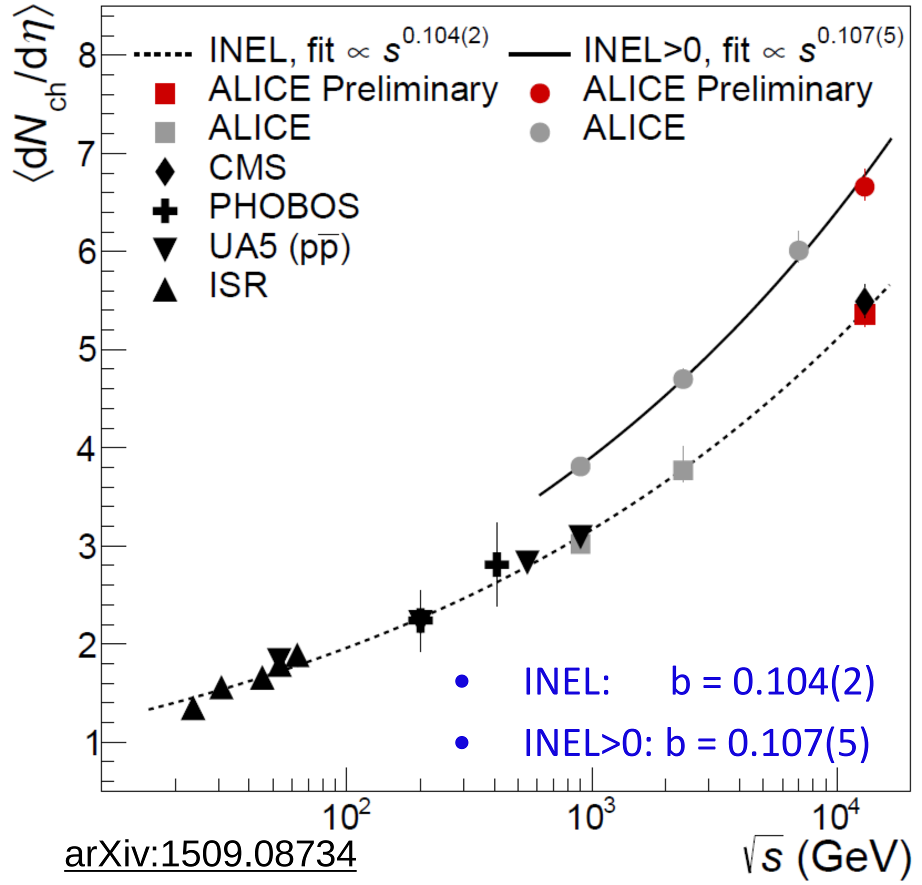


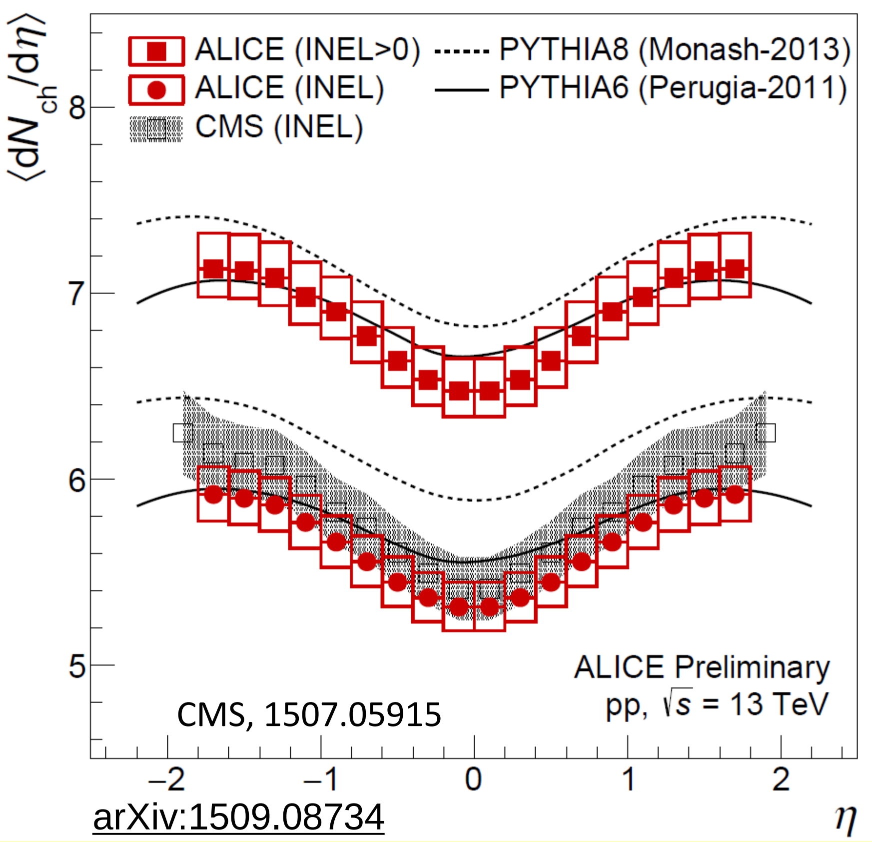


- LHC restart (Isolated bunches): diffractive data taking with global OR triggers (V0 | AD | ZDC |SPD). Planned 100M, collected 165 M
- 50ns: muon data taking
- 90m run: diffractive data taking, collected ~250 nb-1
- 25ns: data taking at rates up to 5 Hz/ub with rare triggers and minimum bias data taking at low μ

MB: planned 600M, collected 616M
muon triggers: planned 4pb^{-1} coll. 4.3 pb^{-1}
high mult triggers: planned 2pb^{-1} coll 1.8 pb^{-1}

Charged-particle density at 13 TeV





INEL: ⟨dN/dη⟩ in |η|<0.5

INEL>0: ⟨dN/dη⟩ in |η|<1.0

Energy dependence fitted with power-low function as^{b}

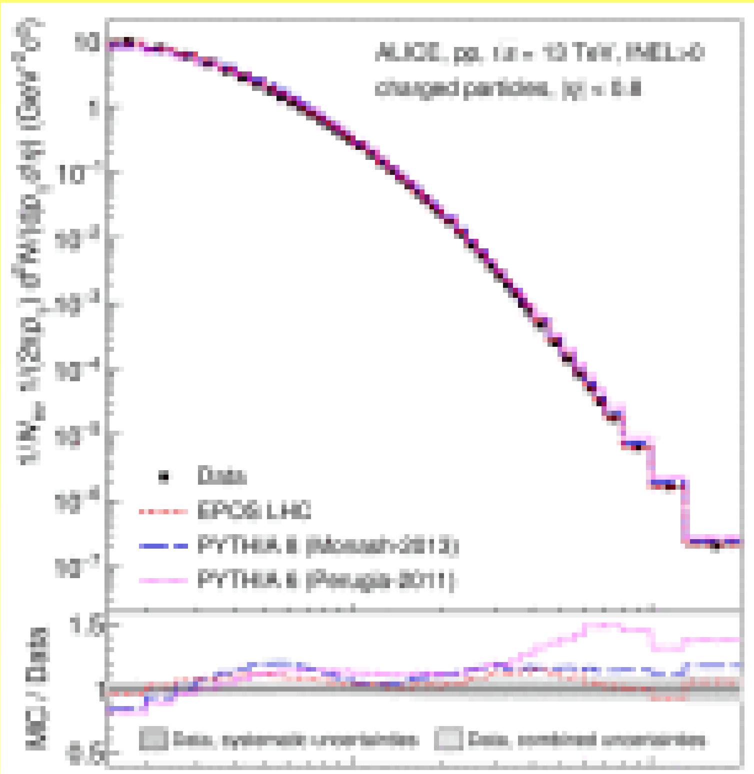
Energy dependence in fair agreement with expectations from low energy extrapolations

dN/dη measured for two normalisation classes:

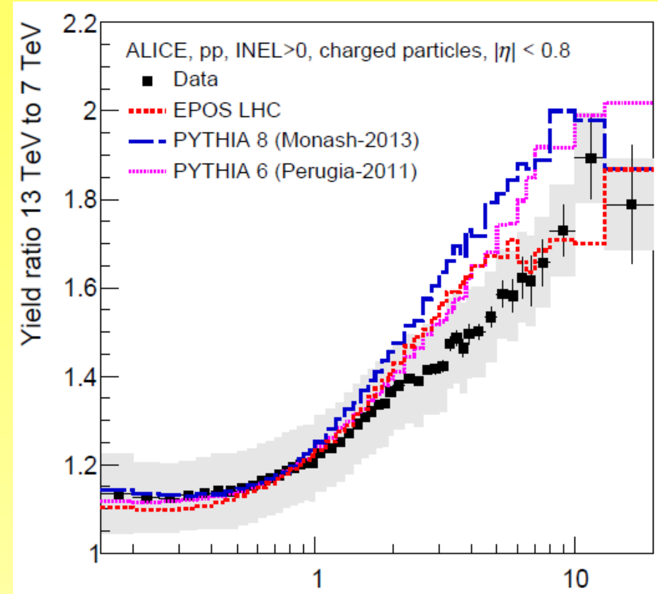
INEL: inelastic events

INEL>0: events having at least one charged particle in |η|<1

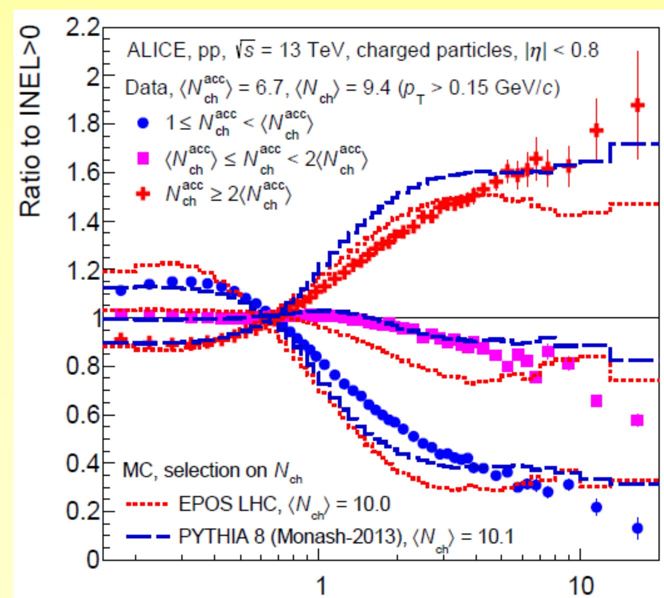
P_T distributions at 13 TeV



arXiv:1509.08734



arXiv:1509.08734

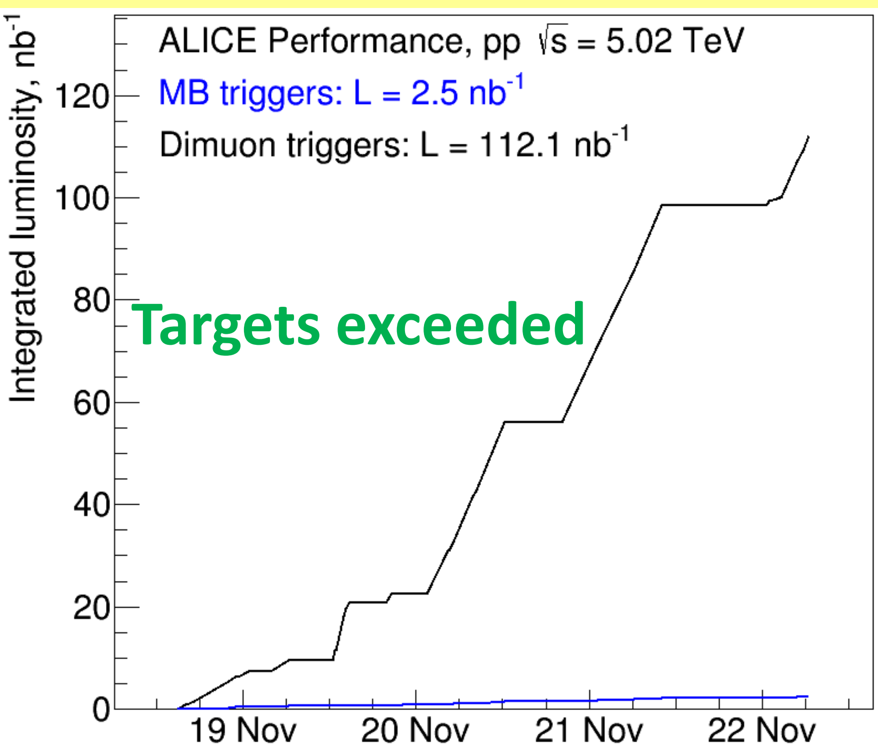


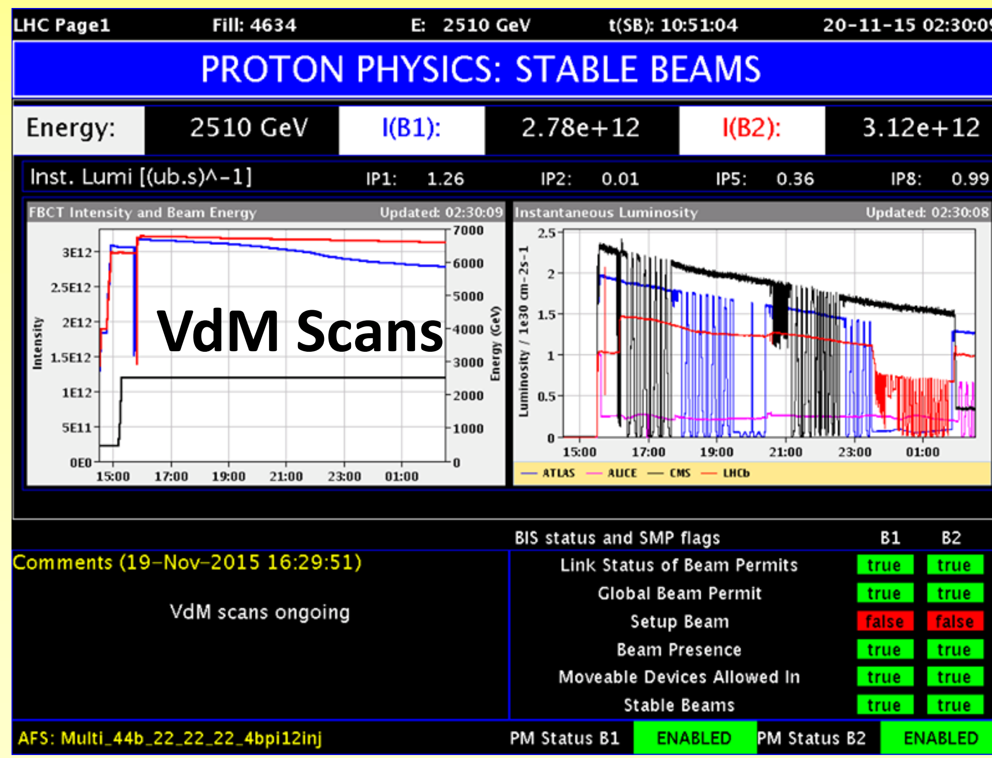
arXiv:1509.08734

- Spectrum significantly harder than at 7 TeV
- shapes depend strongly on charged-particle multiplicity
- in fair agreement with event generators.

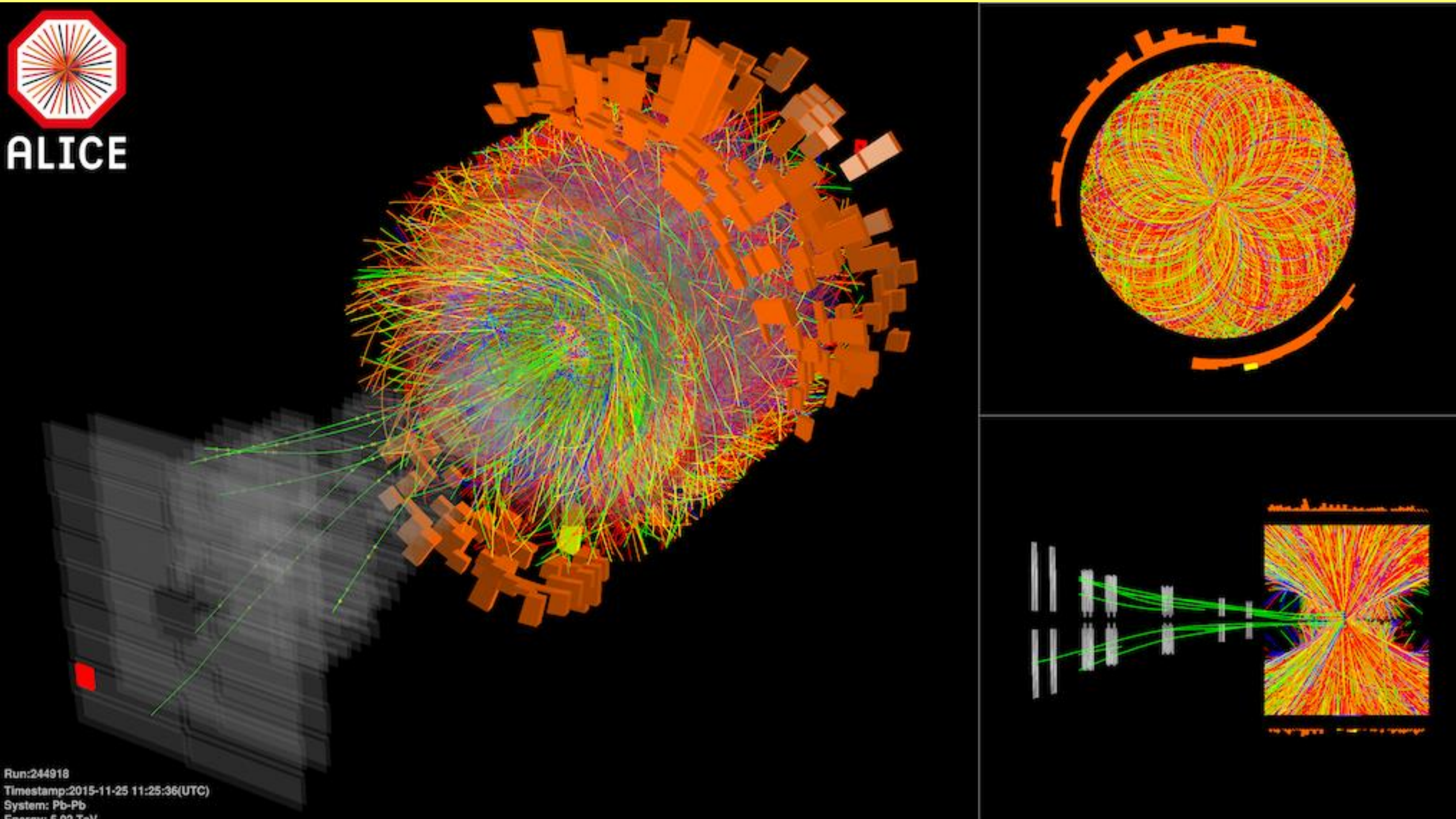
pp Reference Run at 5.02 TeV

- **Precious reference data for PbPb 2015 and pPb 2013**
- **Complex operations: short setup time, little contingency**
  - **LHC moved from ion to proton cycles several times.**
  - **vdM + PHYSICS scan**
  - **High ALICE data taking and operational efficiency**

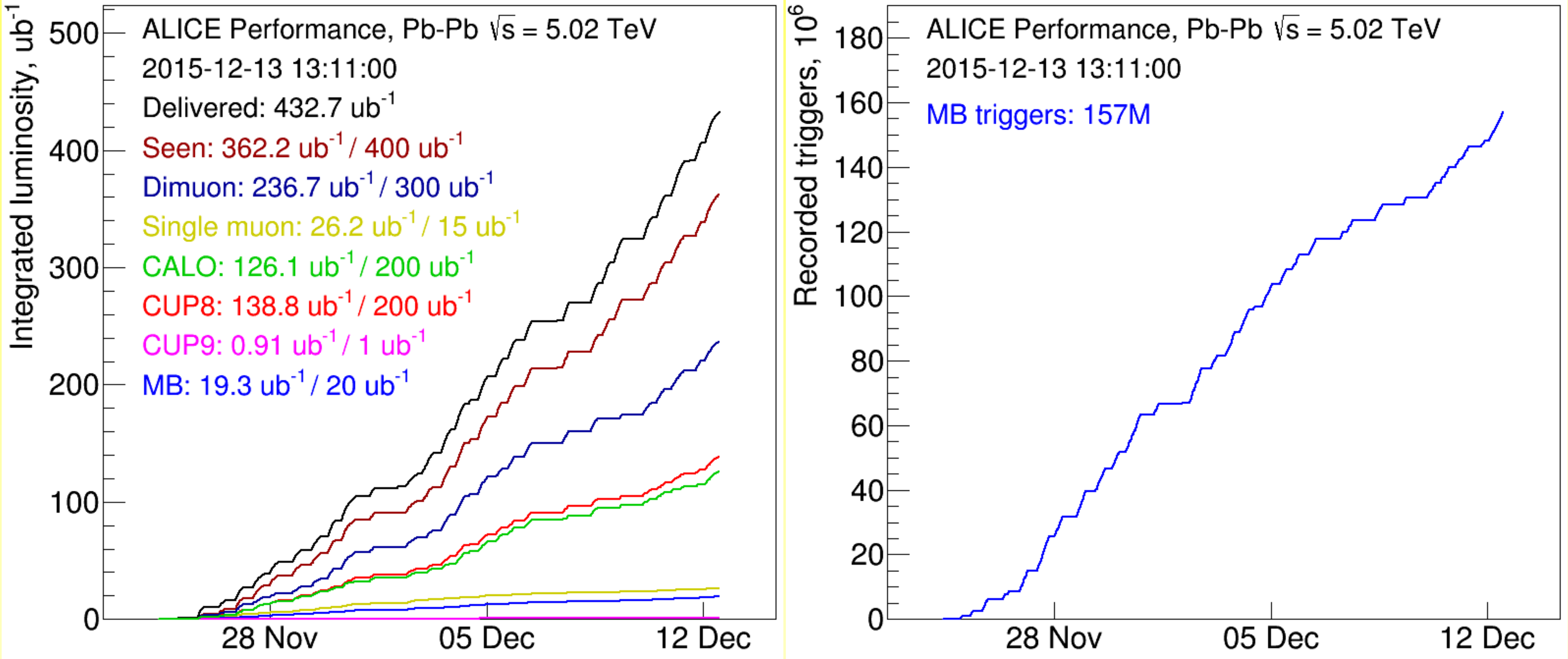




PbPb! PeV Collisions

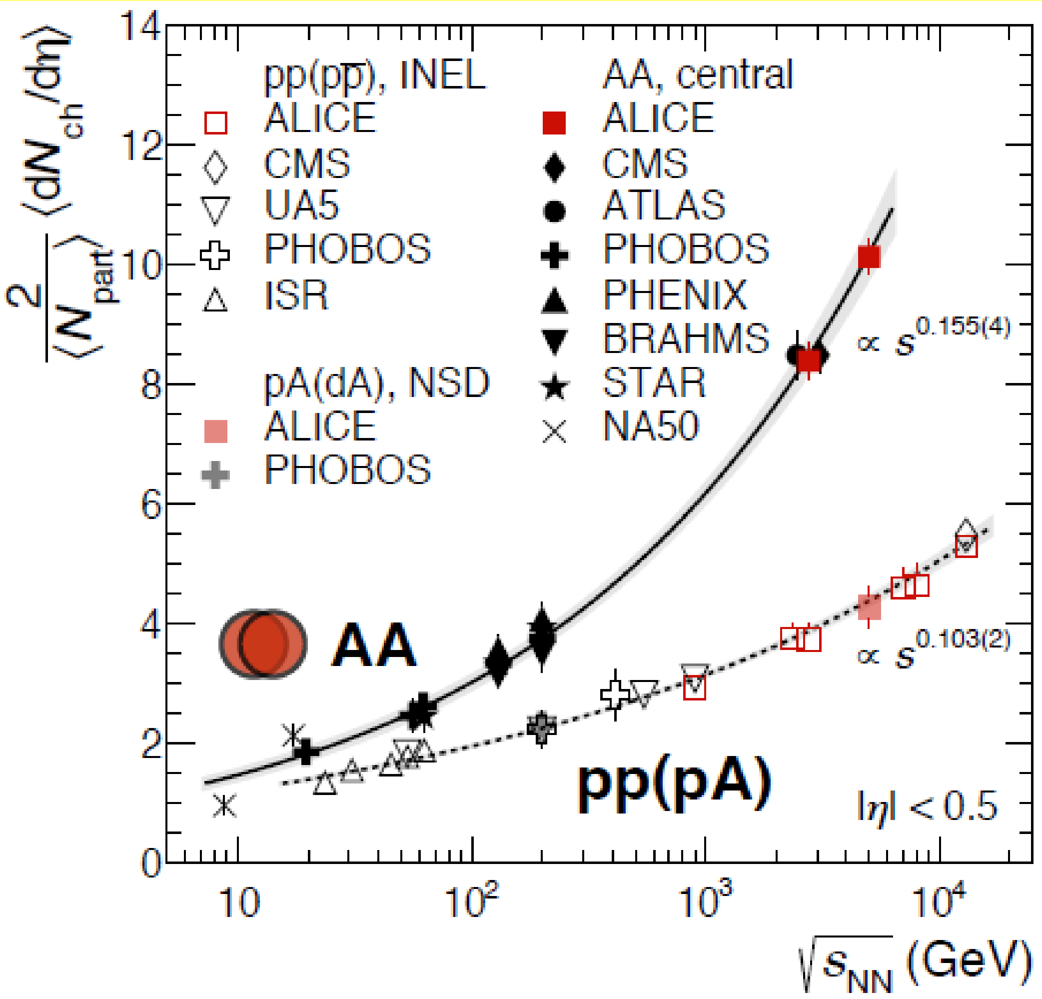


PbPb Run at 5.02 TeV



- Statistics reasonably close to our goals (especially for MB)
- Should insist for the future not to take the pp reference run out of the HI time

Charged particles in Pb-Pb@5.02 TeV



- **charged-particle multiplicity density**
  - at mid-rapidity, |η| < 0.5 reaches a value of 1943 ± 56 in most central collisions
- **much stronger √s dependence than pp**
  - 2.4x larger charged-particle multiplicity than p-Pb at same energy scaled by the average number of participating nucleon pairs ⟨*N*part⟩/2

- Submitted dec 18th : *CERN-PH-EP-2015-324*

ALICE Upgrade for RUN3 and RUN4 (after LS2)

- Focus on rare probes, study their coupling with QGP medium and their (medium-modified) hadronization process
- **low-transverse momentum observables** (complementary to the general-purpose detectors)
  - not triggerable => need to examine full statistics.
  - Target:
    - Pb-Pb recorded luminosity $\geq$ 10 nb^{-1} ➡ 8 x 10^{10} events
    - pp (@5.5 Tev) recorded luminosity $\geq$ 6 pb^{-1} ➡ 1.4 x 10^{11} events
- Gain a factor **100** over the statistics of the approved programme

- **Operate ALICE *at high rate* while preserving its uniqueness, superb tracking and PID, and enhance its vertexing capability and tracking at low-p_T**

Physics goals of the ALICE upgrade

Precise measurement of heavy-flavour hadron production (spectrum, elliptic flow) in a wide momentum range, down to very low p_T

Jet quenching and fragmentation: PID of jet particle content, heavy flavour tagging

Measurement of low-mass and low-p_T di-leptons (from ρ,ω,.. decay, in-medium $q\bar{q} \to l^+ l^-$, direct photons) ➡ **electromagnetic radiation from QGP**

J/ψ, ψ' states down to zero p_T in wide rapidity range

Heavy nuclear states

The LS2 ALICE upgrades

ALICE

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

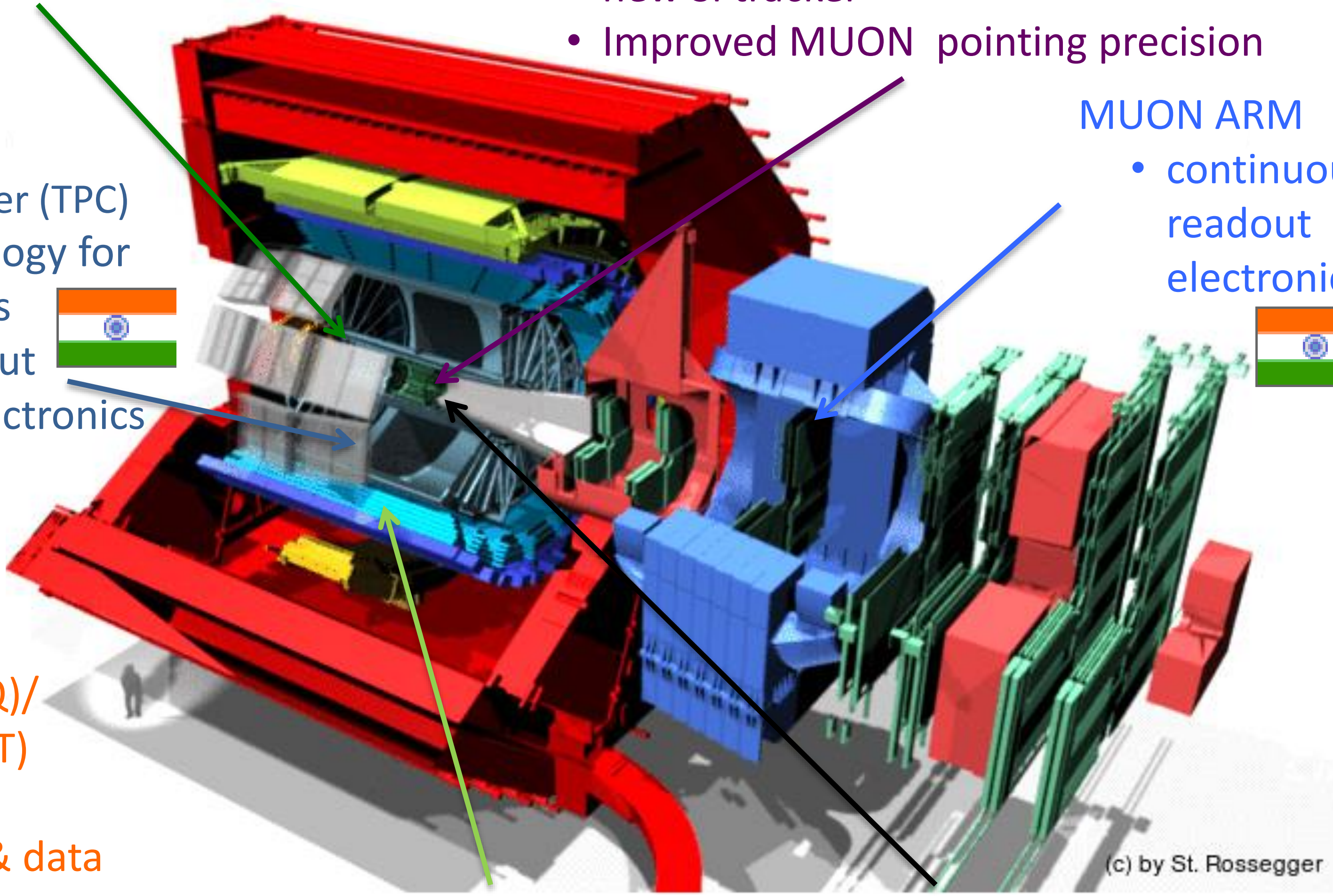
Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

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, ZDC
- Faster readout

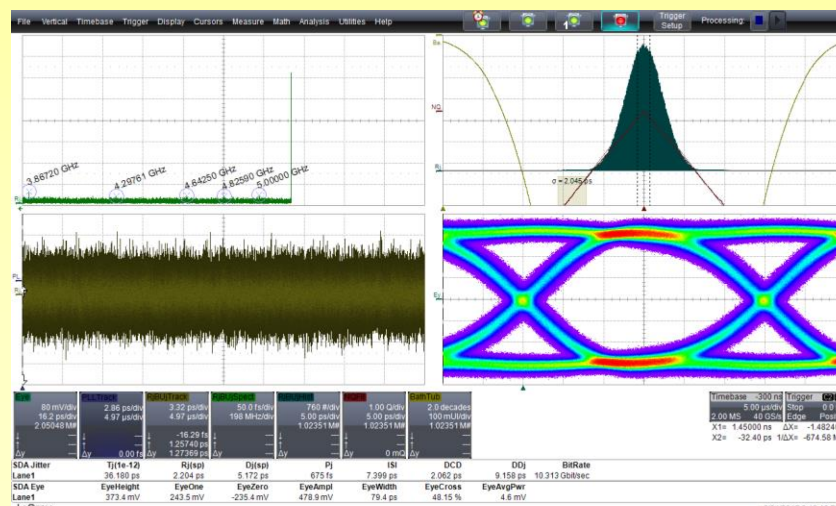
New Trigger Detectors (FIT)

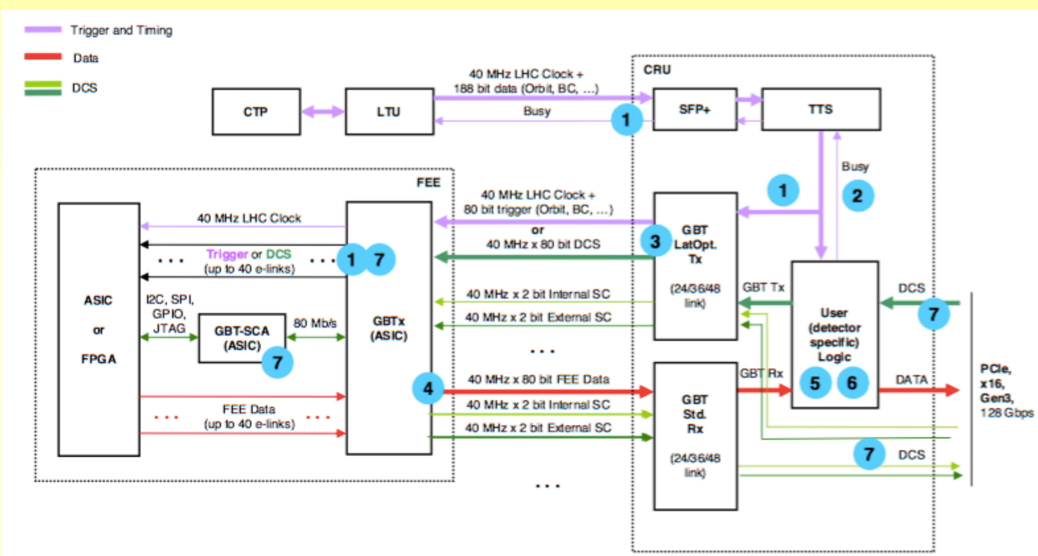
The ALICE Upgrade: status

- **Five Pillars (each in a Technical Design Report), all approved by LHCC, UCG and RB, the latest this past September:**
  - Completely new Silicon Inner Tracking System
  - New or upgraded readout for all detectors to cope with the higher rate, new CTP and Trigger Detectors
  - New readout chambers for the Time Projection Chamber
  - New Silicon Tracker in front of Muon Absorber
  - New Data Acquisition System and High Level Trigger to handle the continuous readout, new Offline

The CRU: Common Readout Unit

- Will be used for the readout of all main ALICE detectors
  - Key element of the overall project
- CRU (PCI based), prototype tested, pre-series production to be started
- Detector specific firmware specifications defined

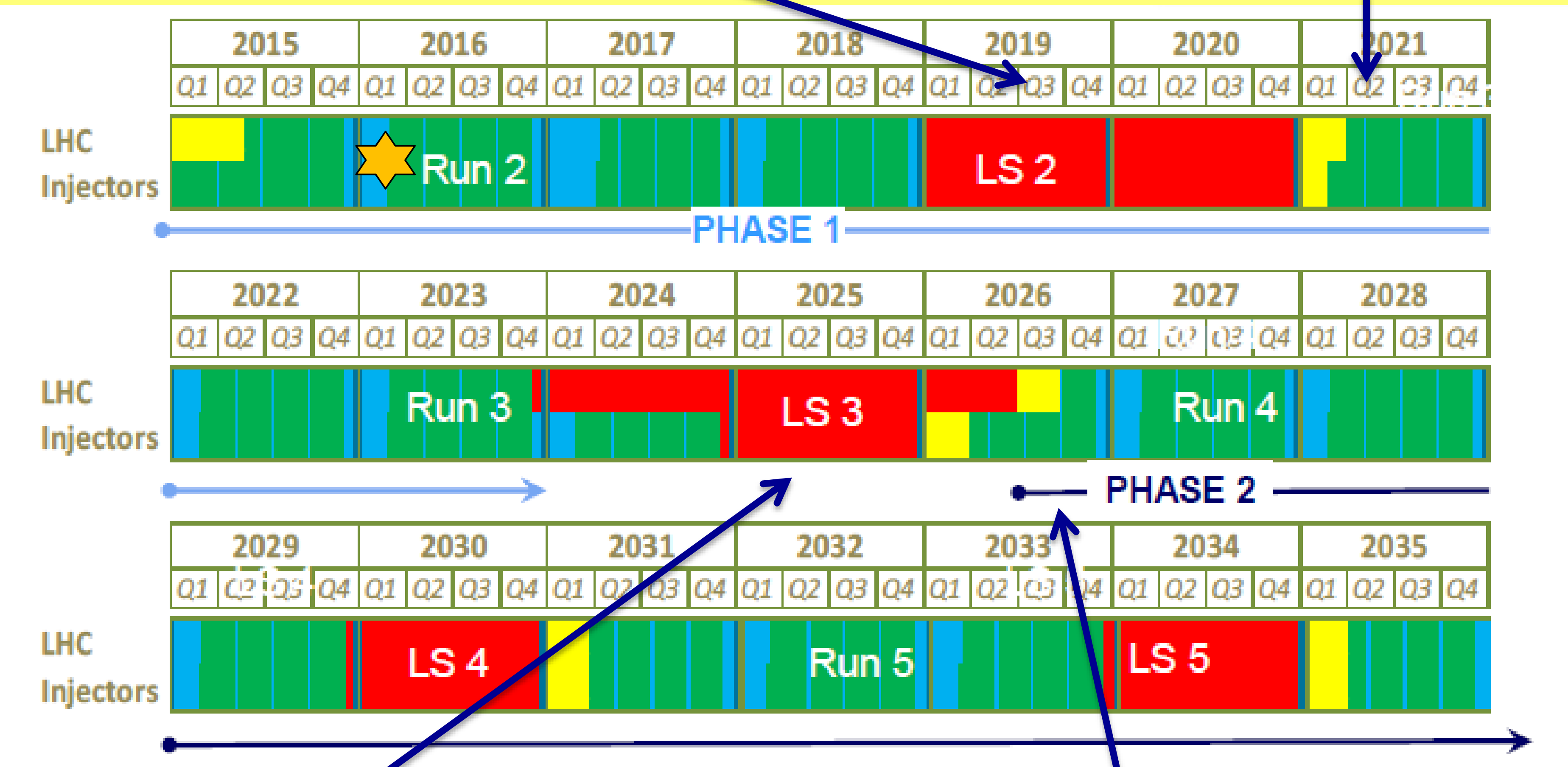




LHC Schedule

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS ‚minor' upgrade

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



PHASE II Upgrade
ATLAS, CMS major upgrade

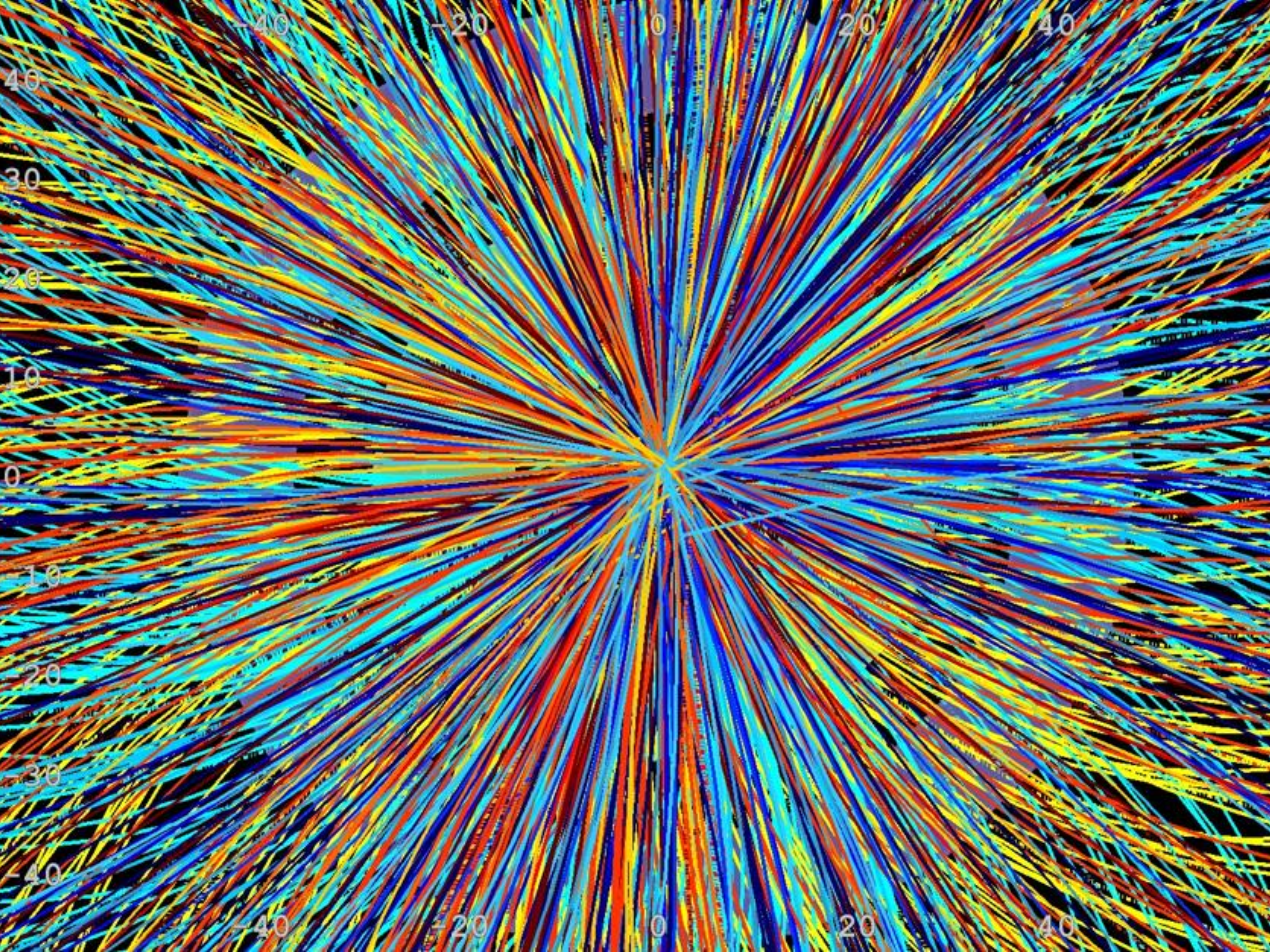
HL-LHC, pp luminosity from 10^{34} (peak) to 5 x10^{34} (levelled)

SUMMARY

- **RUN1 has started well for ALICE, the LS1 work is paying off**
- **Excellent data sets in pp at both 13 TeV and 5.02 TeV, and PbPb at 5.02 TeV per nucleon.**
  - **First results from RUN2 already coming**
- **In the meantime**
  - **The rich harvest of RUN1 Physics results continues**
  - **The upgrade for LS2 progresses steadily**

The future is bright for ALICE

The adventure continues !!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spares

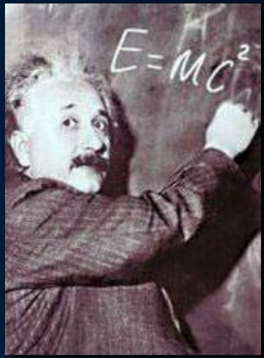
What is CERN?

- CERN: the world's largest particle physics centre funded in 1954. Over 60 years of successes
- 21 Member States, plus associate and observer members (latest: Pakistan)
- “Science for Peace”: only scientific organization to be granted Observer Status at the United Nations (since 2012)

- Particle physics is about:
  - Elementary particles of which all matter in the universe is made of
  - Fundamental forces which hold matter together
- Particles physics requires:
  - Special tools to create new particles: the accelerators
  - Special instruments to study new particles: the experiments
  - Particle accelerators and experiments are designed and built in cooperation's with Universities and HEP institutes from all over the world

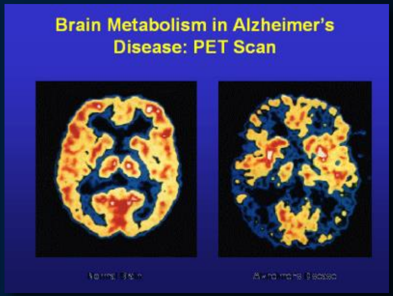
Innovation Education
CERN
uniting people
Research

The Mission of CERN



- **Push back** the frontiers of knowledge

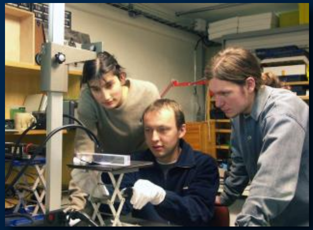
  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?



- **Develop** new technologies for accelerators and detectors

  Information technology - the Web and the GRID

  Medicine - diagnosis and therapy



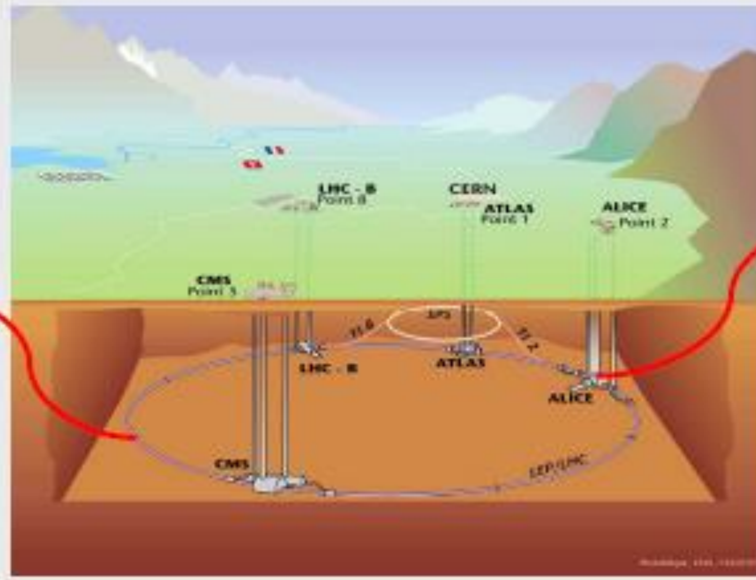
- **Train** scientists and engineers of tomorrow

- **Unite** people from different countries and cultures

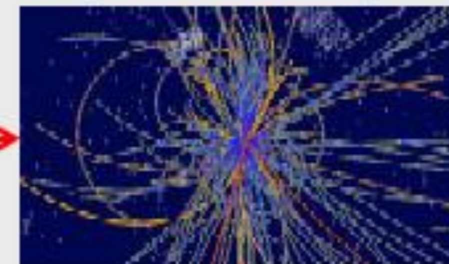
CERN technologies

- 3 key technologies:

Accelerating particle beams



Detecting particles



Large-scale computing (Grid)

Examples of technologies developed at CERN

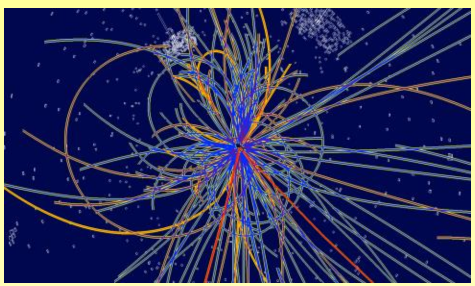
WWW, of course! But there are many more....

Tim Berners-Lee, CERN March 1989, May 1990

Frank Beck and Bent Stumpe, engineers from CERN, developed a transparent touch screen in the early 1970s. it was manufactured by CERN and put to use in 1973

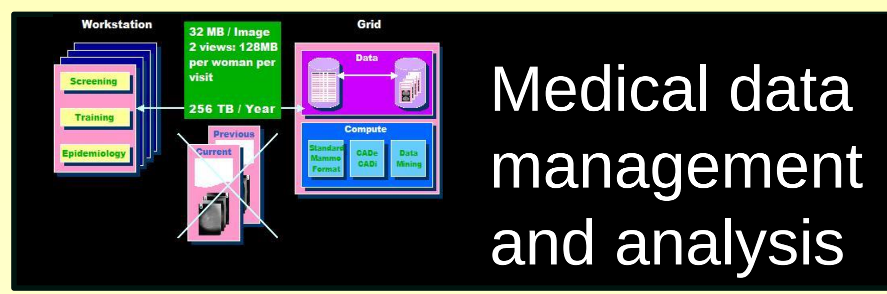
Medical applications: few examples

Particle accelerators



Particle detectors

Distributed computing



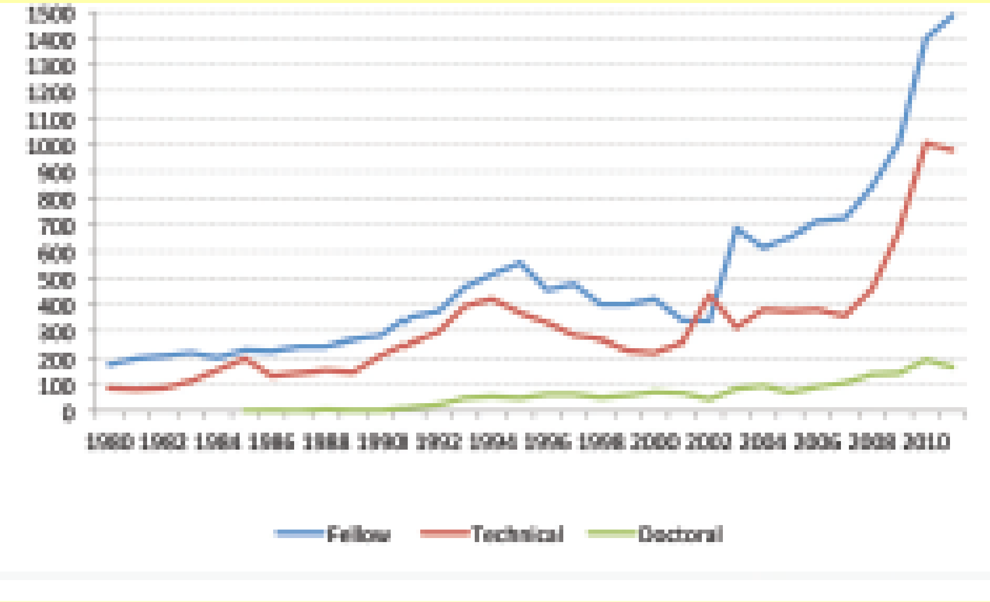
Knowledge Transfer through People

Every year hundreds of students come to CERN to contribute to our research programs

An opportunity for young people to learn in a multicultural environment

Not only for physicists! Also engineers, computer scientists, administrative students…

A great opportunity for students from all over the world (now including Indonesia!)



The European Strategy

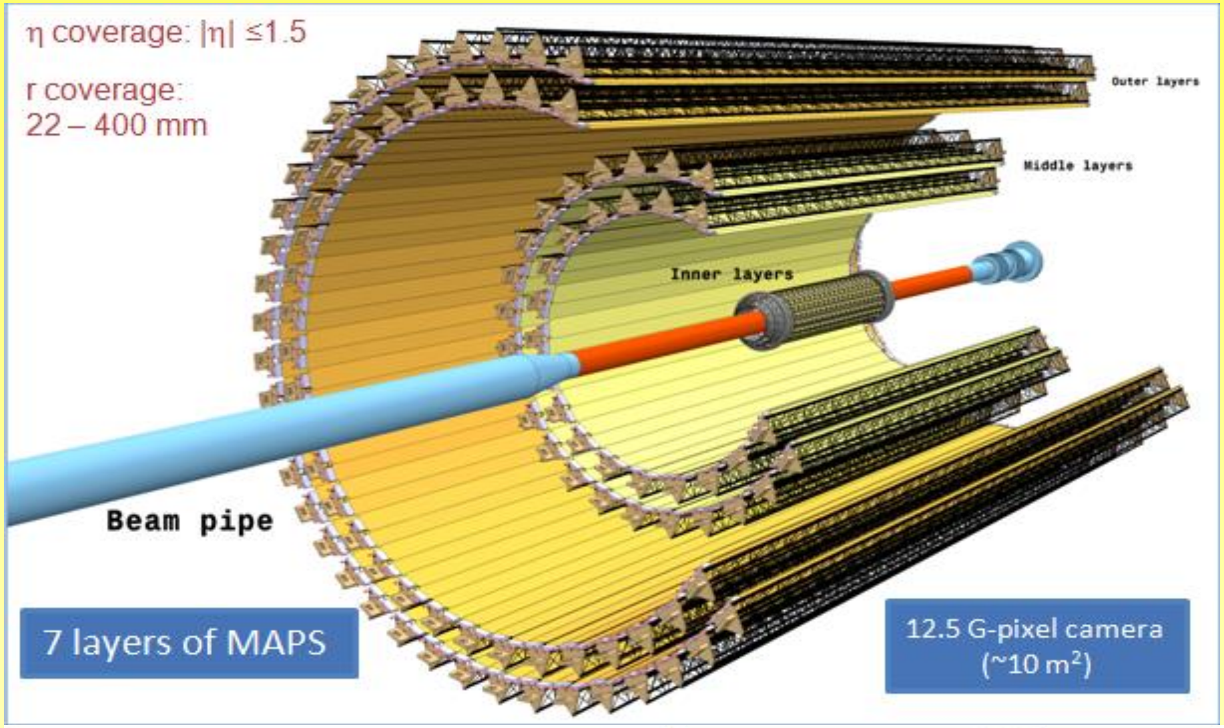
– 2012 Cracow European Strategy Meeting

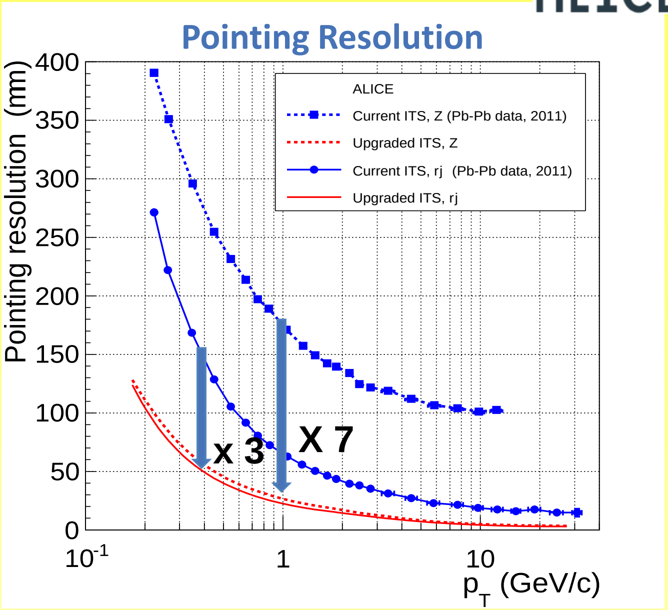
- Heavy Ion Physics an integral part of the future LHC program till at least the mid 2020s

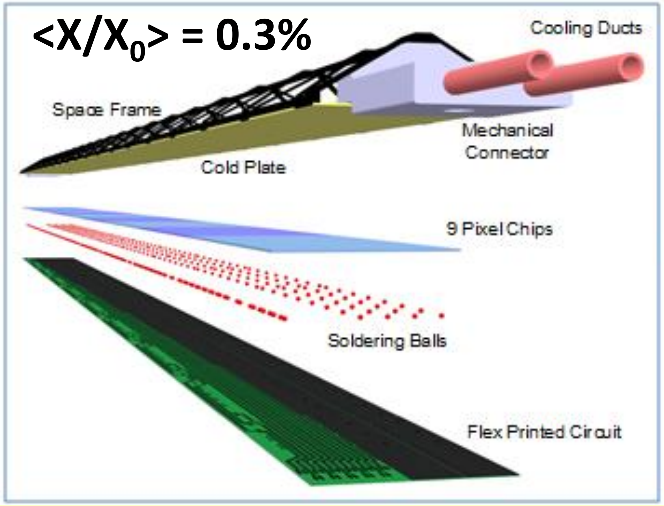
– Erice final document on the European Strategy for Particle Physics

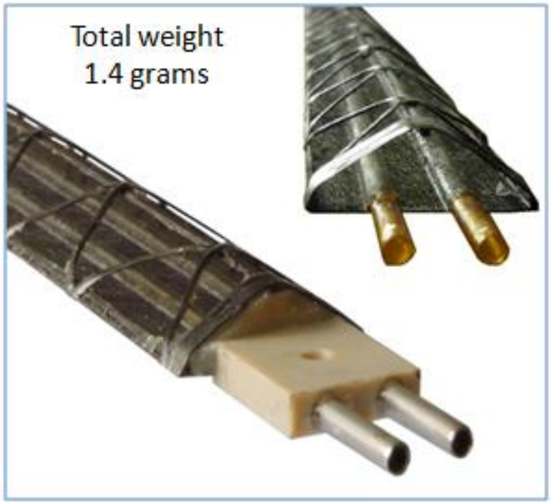
- Heavy Ions are an integral part of the top priority of the plan: *"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics **and the quark-gluon plasma."***

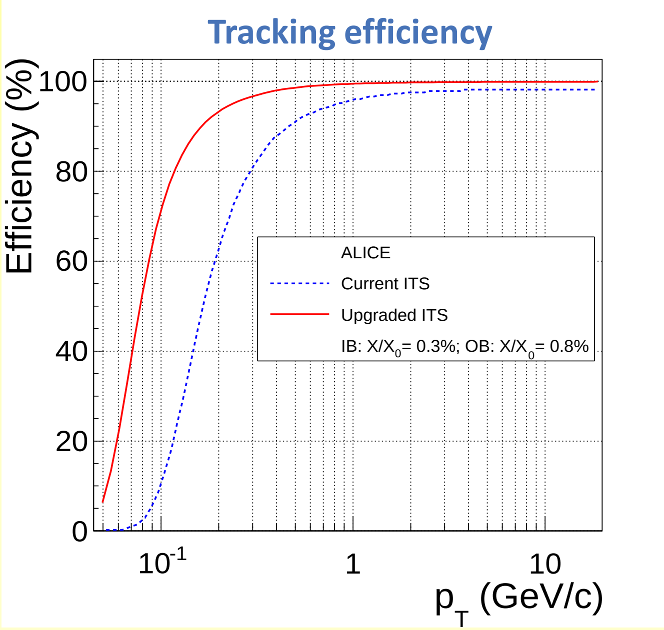
LS2 upgrade: new Inner Tracking System



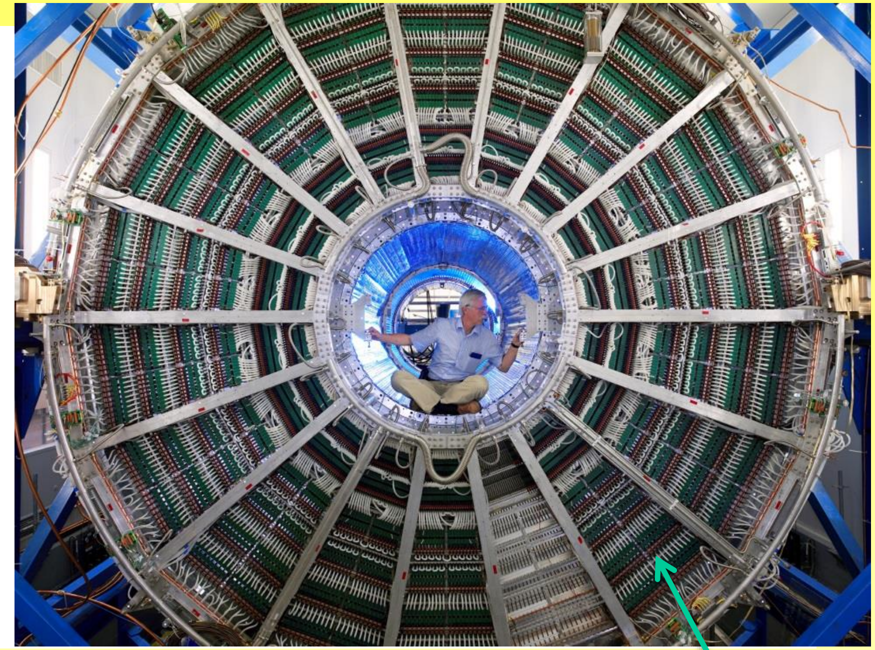








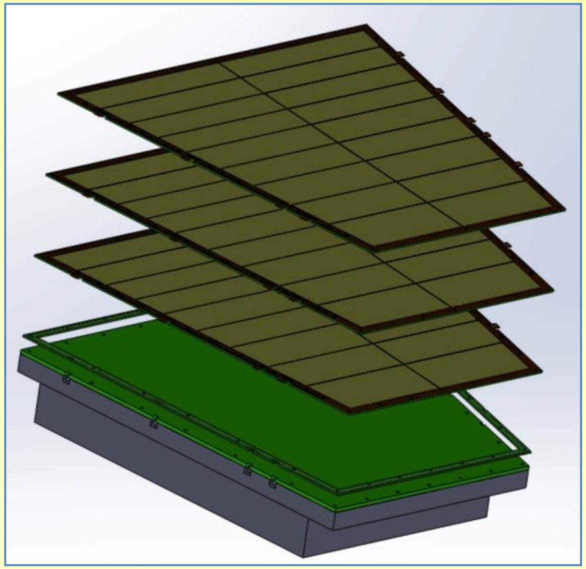
TPC Upgrade with GEMs



World Largest TPC
ALICE key tracking and PID instrument
500 million pixels

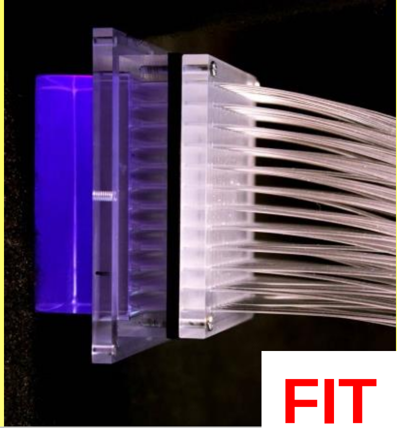
Replacement of wire-chambers with GEM-chambers
- 100 m^2 single-mask foils
- Limit Ion-Back-Flow into drift volume
- Maintain excellent dE/dx resolution

New readout electronics
Keep all other subsystems



Replace wire chambers with quadruple-GEM or 2 GEMs + Micro Megas
(full scale prototypes tested in beam in late 2014)

Upgrade of the ALICE Readout and Trigger System



FIT

- **New Forward Trigger Detector (FIT)**
- **New Central Trigger Processor (CTP)**
- **Electronics upgrade for 100 kHz Pb-Pb interaction rate of**
  - Time Of Flight Detector (TOF)
  - Transition Radiation Detector (TRD)
  - Muon System
  - TOF
  - ZDC

Common TDR,

Including also the

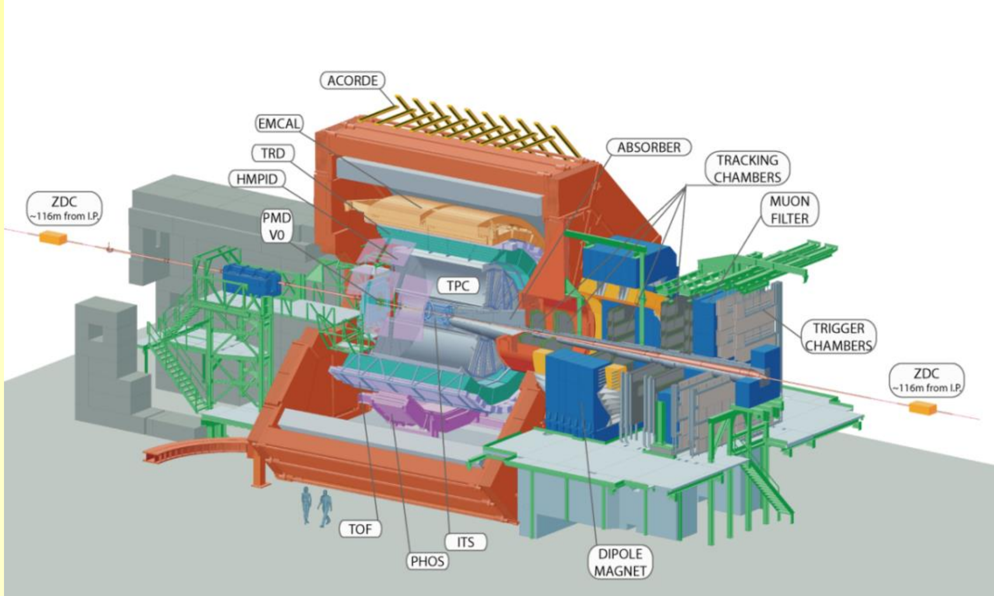
Common Readout Unit (CRU)

and the FRONTEND for TPC

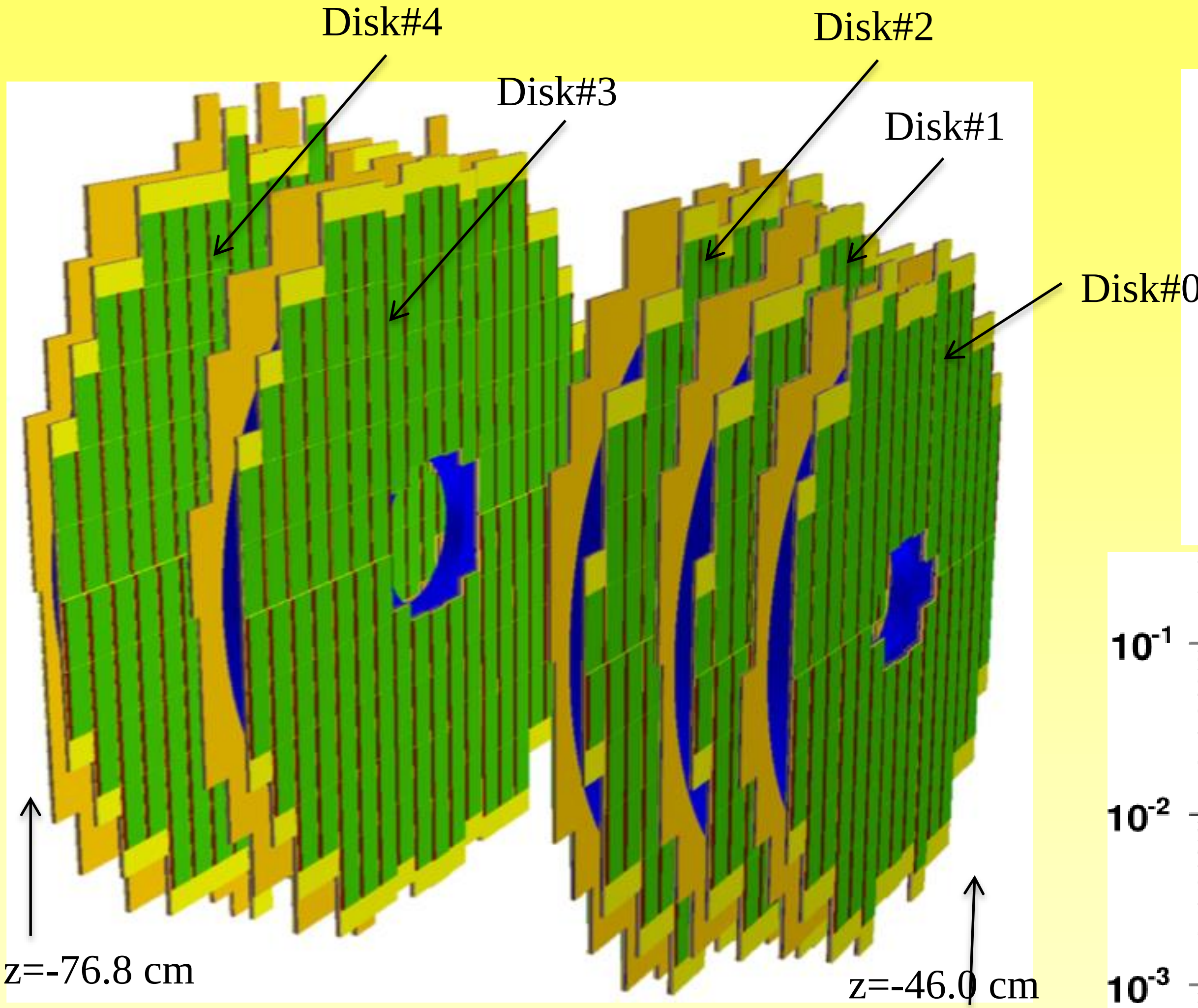
and Muons (SAMPA chip)

Endorsed by LHCC

Approved by UCG

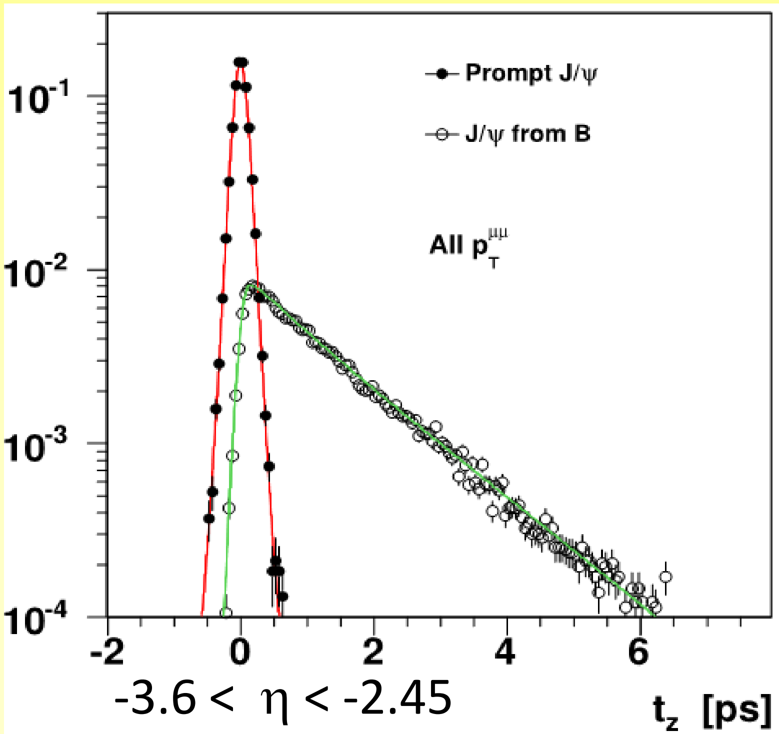


Muon Forward Tracker



Secondary vertexing for the muon spectrometer

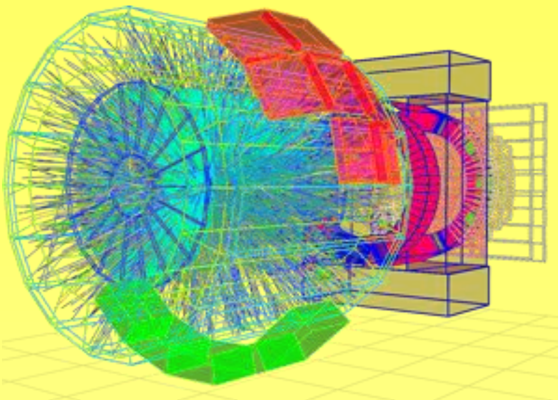
- $c \rightarrow \mu$
- $b \rightarrow J/\psi$
- low mass di-muons
- $\psi(2S)$
- ...



$-3.6 < \eta < -2.45$

- **10 Half-disks** of 2 detection planes each
- 896 **silicon pixel sensors** (0.4 m^2) in 280 ladders
- **Common pixel chip development with ITS**

A flood of data…



50 kHz

1 TByte/s
into PC farm

Reconstruction
+
Compression

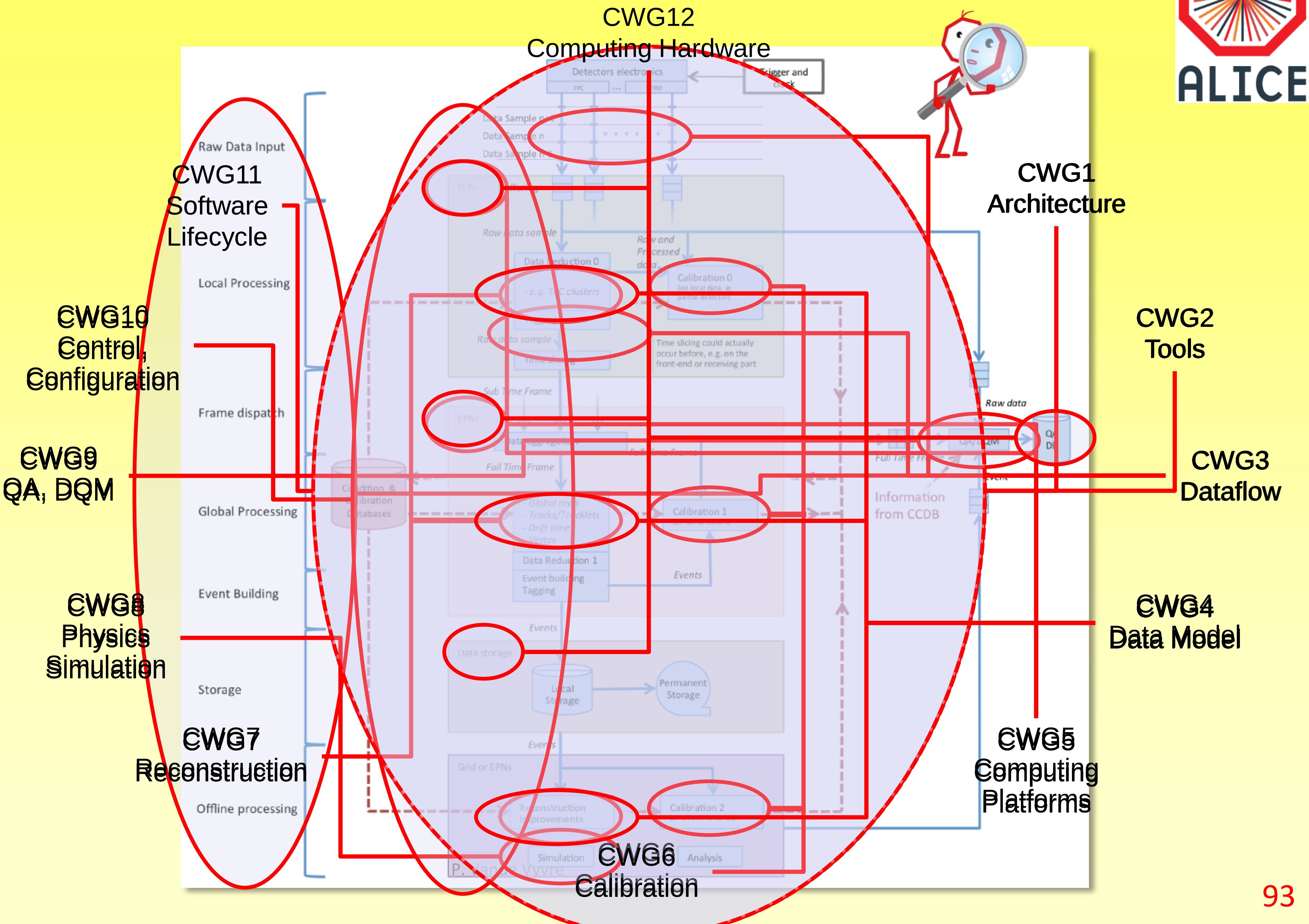
O^2 (Online Offline) System

Storage

75 GB/s

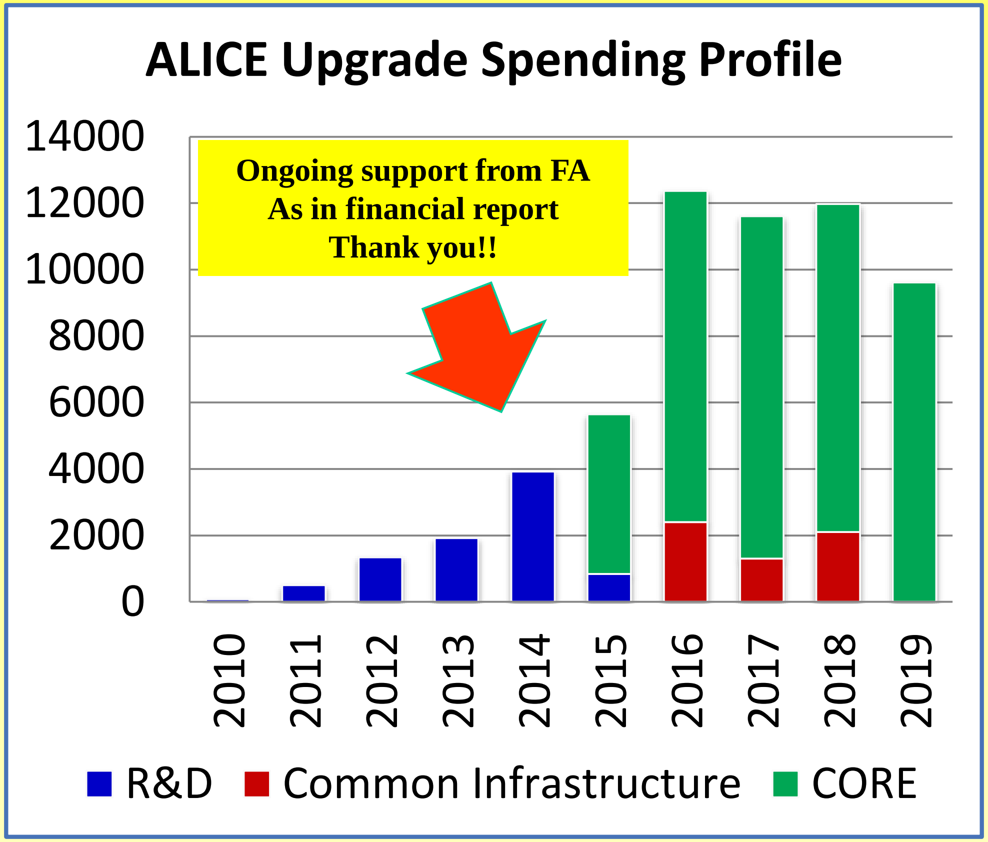
← PEAK OUTPUT
(20 GB/s average)

O^2 Computing Working Groups



Upgrades: CORE investment estimates & timelines

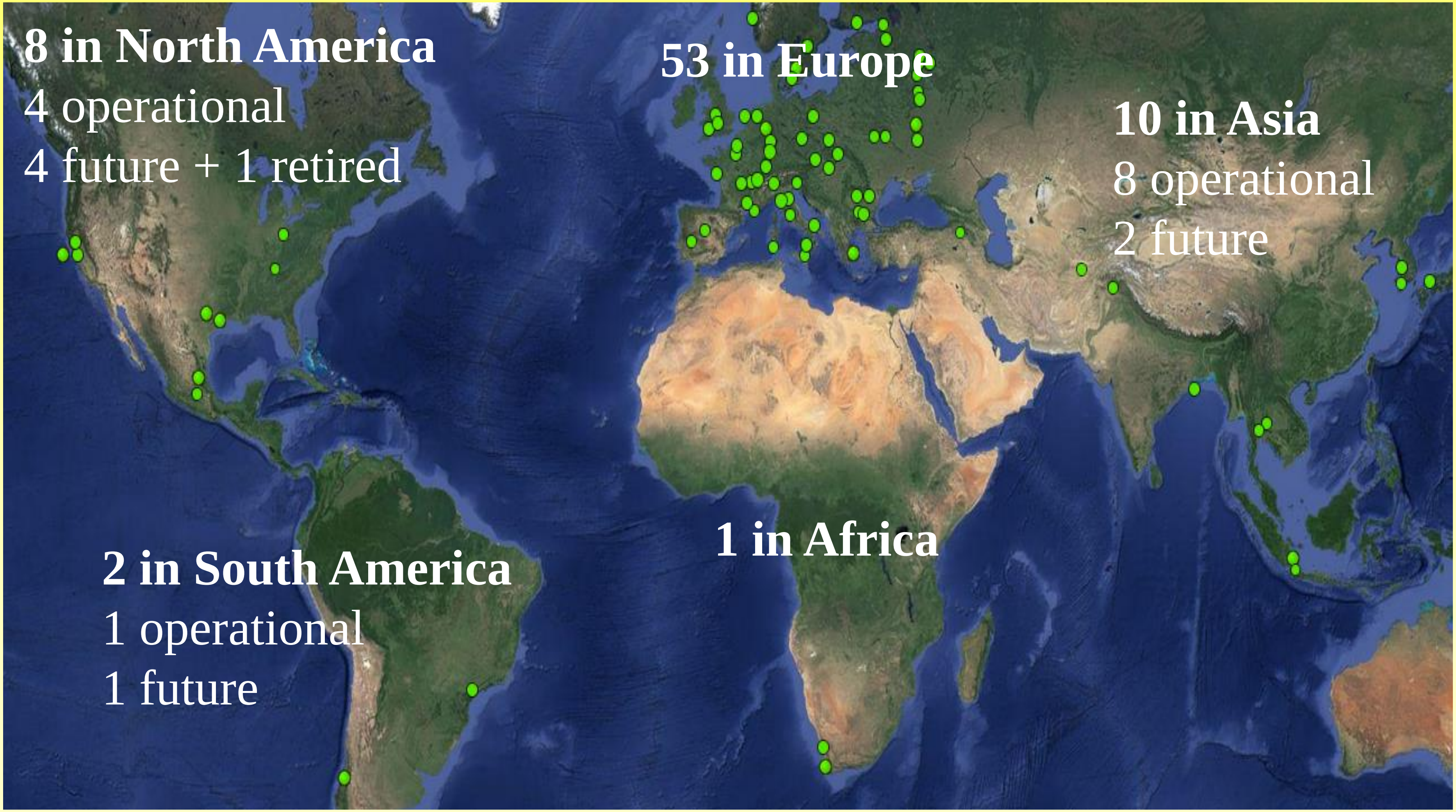
ALICE upgrade subsystem	CORE cost (MSF)
1. ITS	13.6
2. TPC	10.5
3. MFT	3.3
4. Other projects (Muon, TRD, TOF, etc..)	6.6
5. O2 (online/offline)	10.5
6. Common infrastructure	5.8
Total (MSF)	50.3
R&D costs MSF	8.6
GRAND TOTAL including R&D	58.9



- Current best estimate, based on Cost Review Documents. Slight increase as compared to early estimates (was 57 M)
- Sharing within the projects fixed on the basis of responsibilities, as detailed in the UCG documents
- Strong commitment from the collaboration: the know-how and human resources necessary to carry each of the upgrade projects exist. All projects backed by the commitment of large consortia of strong groups. The indications from the funding agencies in response to the group's funding requests are encouraging, and give us confidence that the necessary funds will be available. Many Funding Agencies have already approved the funds, and several have already signed the MoU for the ITS

STORING, PROCESSING AND ANALYSIS OF THE DATA:

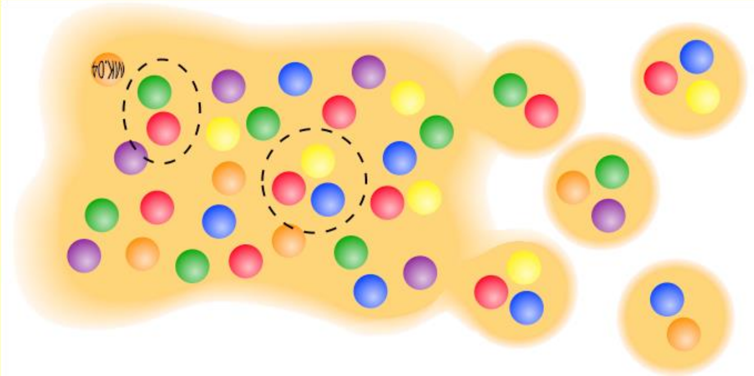
The ALICE GRID



- Currently over 60k jobs run in parallel....

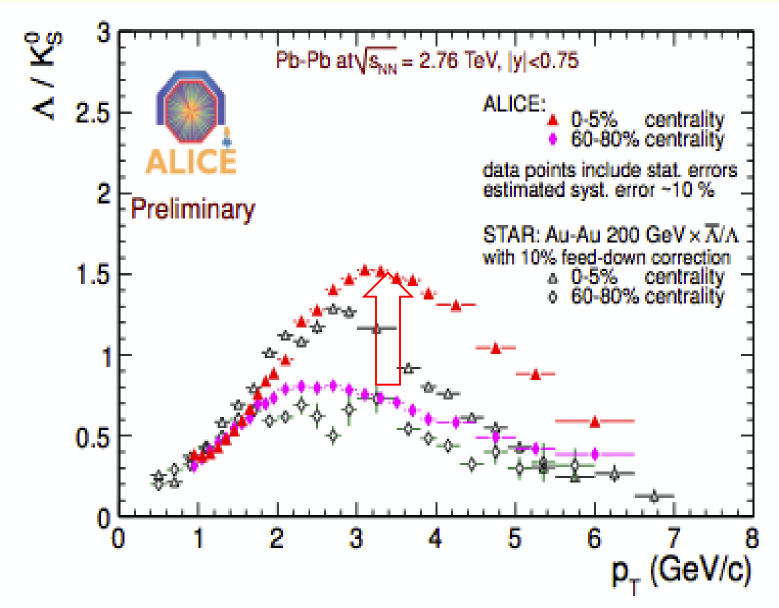
HF thermalization and in-medium hadronization: Λ_c and D_s as probes

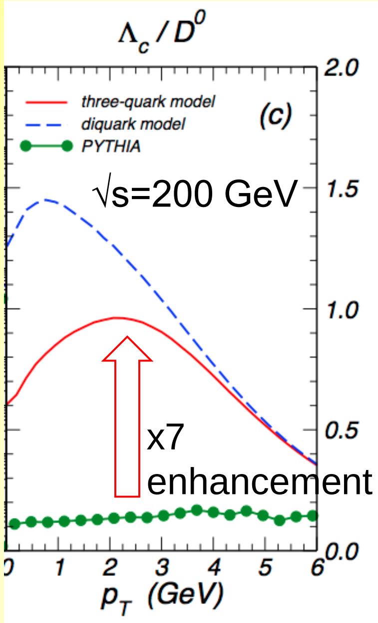
- Baryon/meson enhancement and strangeness enhancement → indication of light-quark hadronization from partonic system



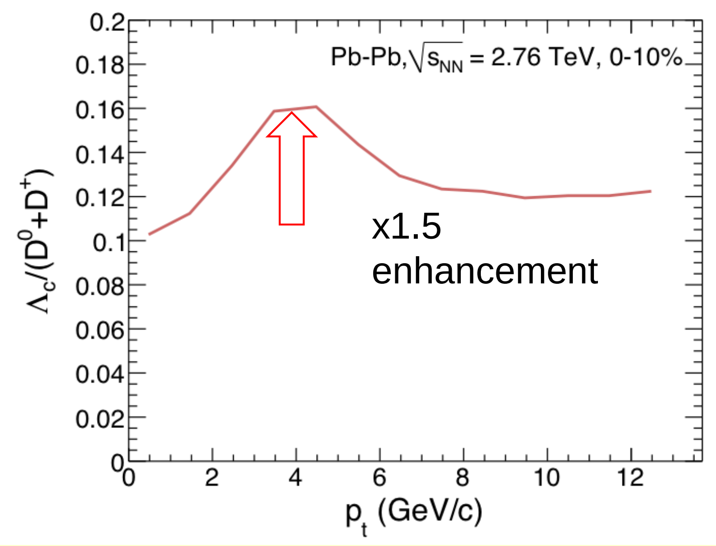
➡ Charm baryons (Λ_c)

- Λ_c/D enhancement predicted by coalescence models. Size of effect depends strongly on details of c quark thermalization





C.M.Ko et al. PRC79

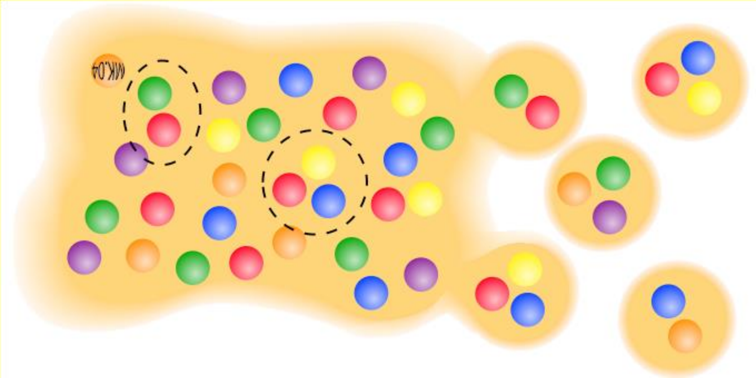


R. Rapp et al. PRC86

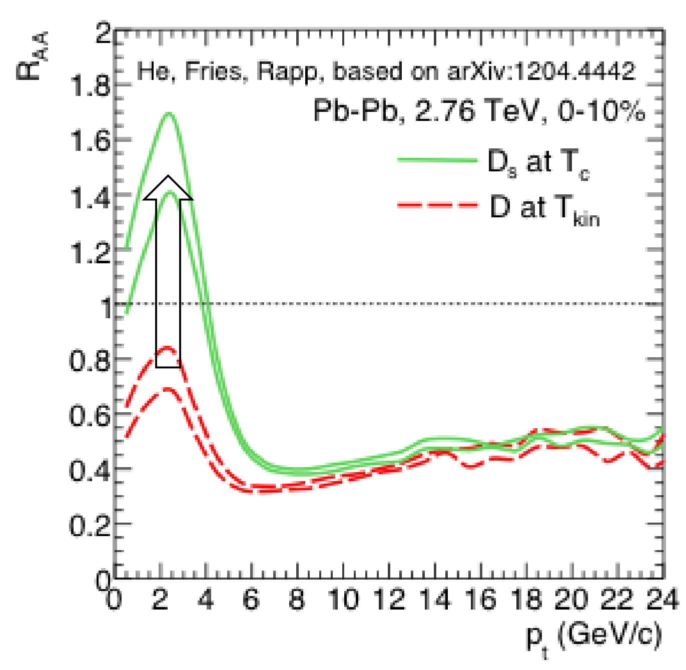
HF thermalization and in-medium hadronization: Λ_c and D_s as probes

- Baryon/meson enhancement and strangeness enhancement → indication of light-quark hadronization from partonic system

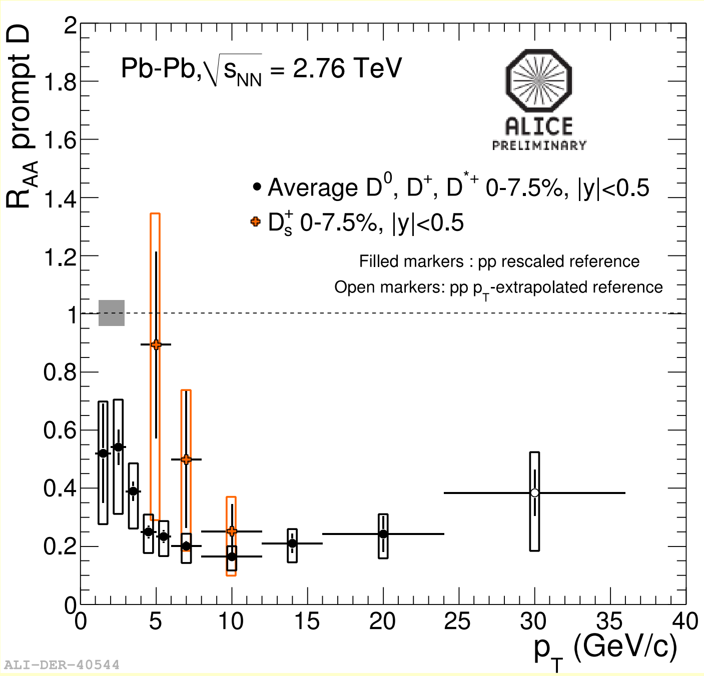
➡ Charm-strange mesons (D_s)



Factor 2 enhancement for D_s/D predicted by coalescence

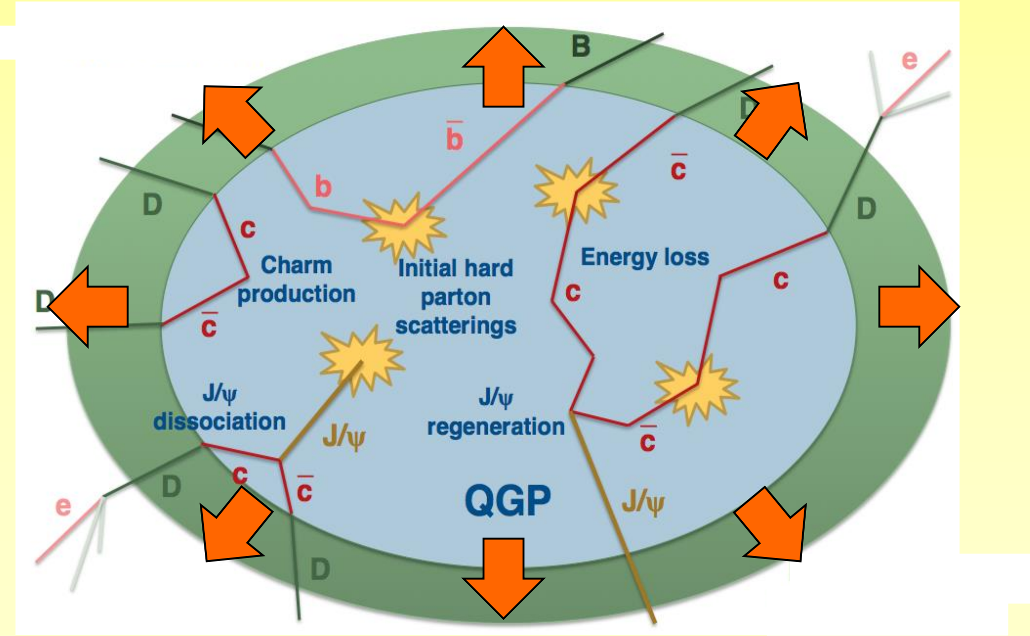


Our first measurement is intriguing, but not conclusive

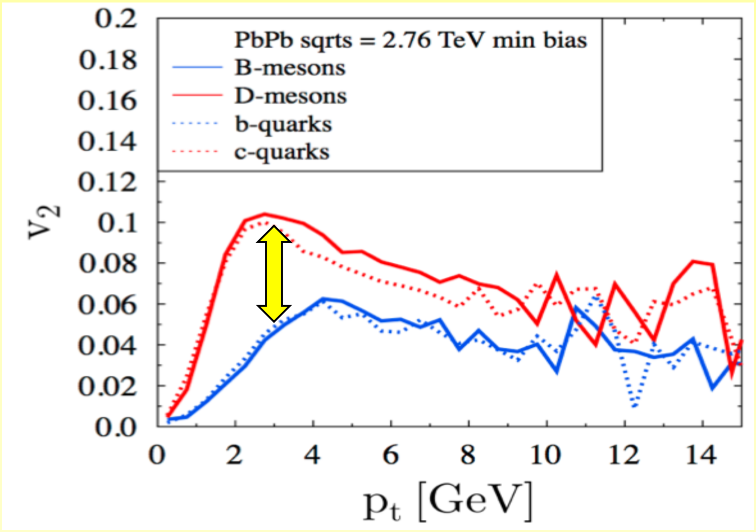


Heavy flavour v_2

- Uniqueness of heavy quarks: cannot be "destroyed/created" in the medium → transported through the full system evolution
- Due to their large mass, c and b quarks should "feel" less the collective expansion
  - → need frequent interactions with large coupling to build their v_2 → $v_2^b < v_2^c < v_2^q$
- HF v_2 sensitive to medium viscosity and equation of state

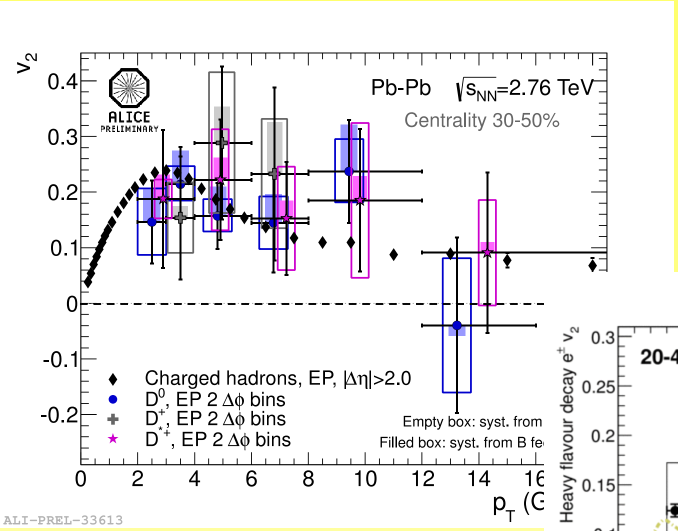


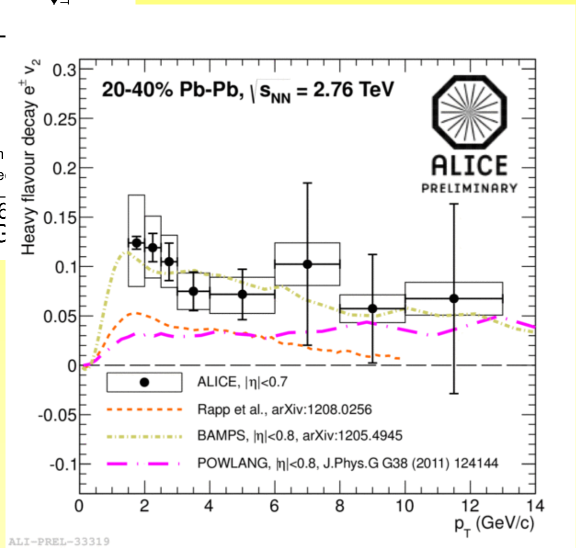
See also J. Uphoff et al., R. Rapp et al., A. Beraudo et al.



J. Aichelin et al. in arXiv:1201:4192

Heavy flavour v_2: present and future





- ALICE preliminary results with full 2011 sample (10^7 events in 30-50%)
- Indication of non-zero v_2
- But uncertainties are substantial
  - Reduction by x0.6 expected with 2015-16 data

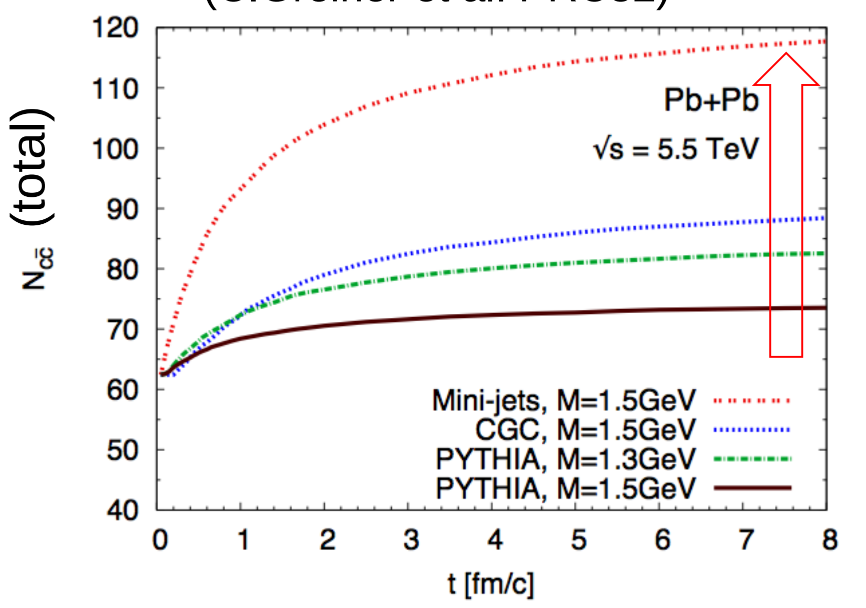
→ **Need precise measurement of v_2 of D and B mesons to answer these questions:**

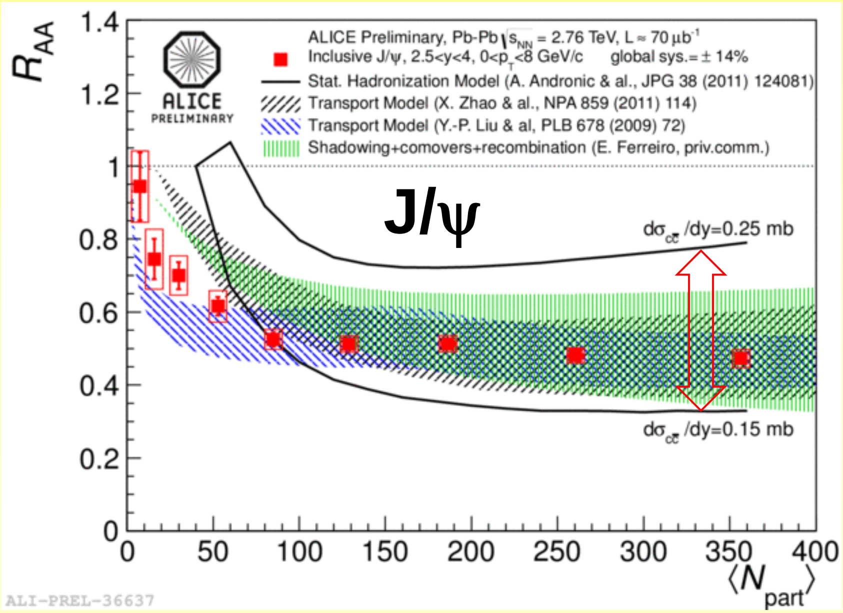
- is v_2 of charm the same as of pions?
- is v_2 of beauty smaller than of charm?
- comparison with models → HQ transport coefficient of QGP

Measuring the total charm production

- Reaching $p_T \rightarrow 0$ in central Pb-Pb provides:
  - Handle on the possibility to detect thermal charm production
    - May increase low-p_T yields by up to 50-100%
    - Sensitive to initial temperature of the QGP
  - Natural normalization for total charmonium production
    - Total charm yield: main uncertainty in J/ψ regeneration models

(C.Greiner et al. PRC82)



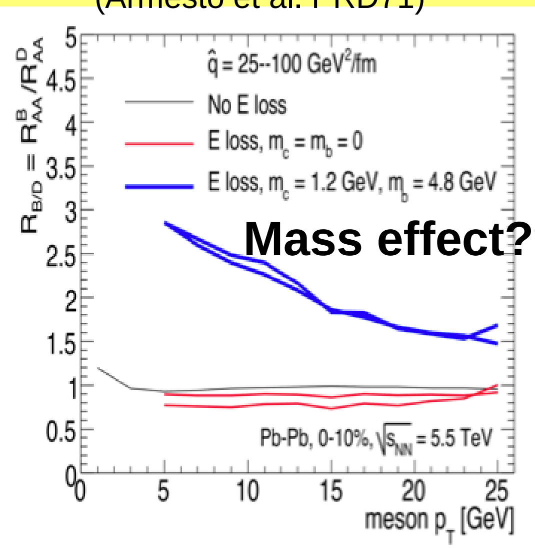


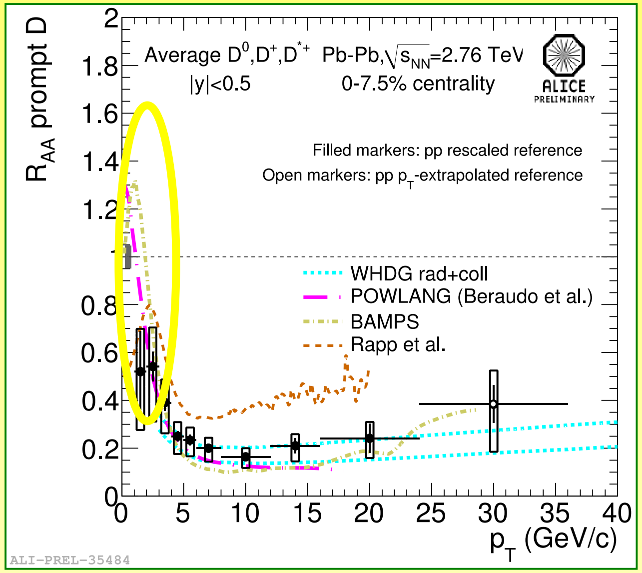
(see also C.M.Ko et al. PRC77)

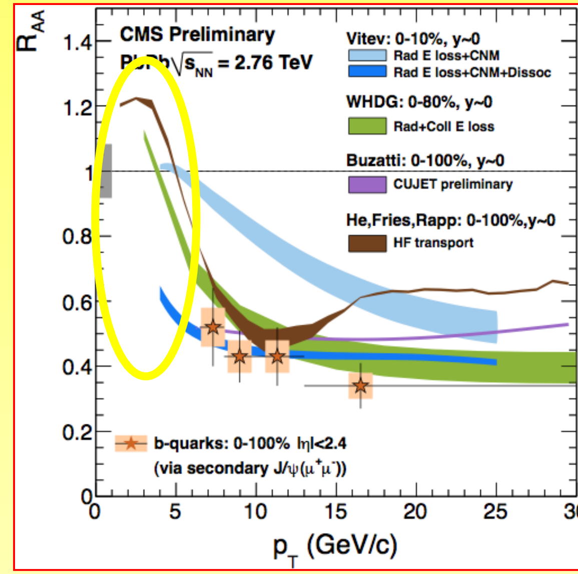
Heavy-flavour quenching

- Goal: measure D and B separately down to low p_T

B/D R_{AA}
(Armesto et al. PRD71)



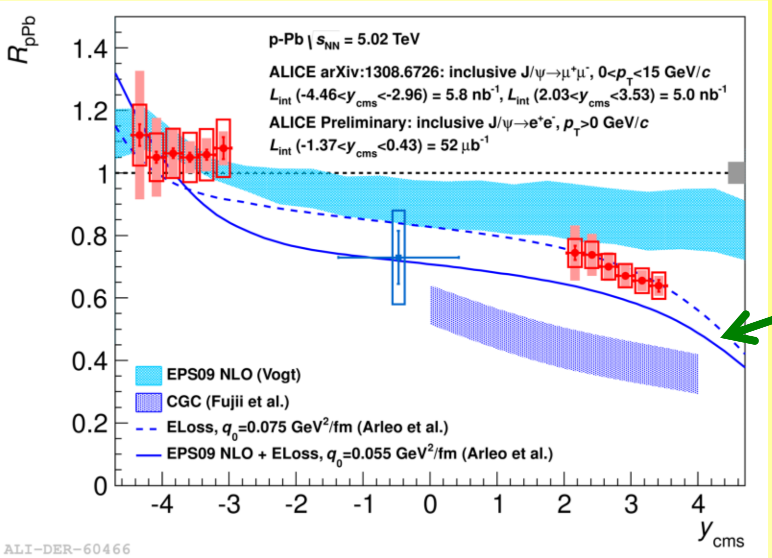




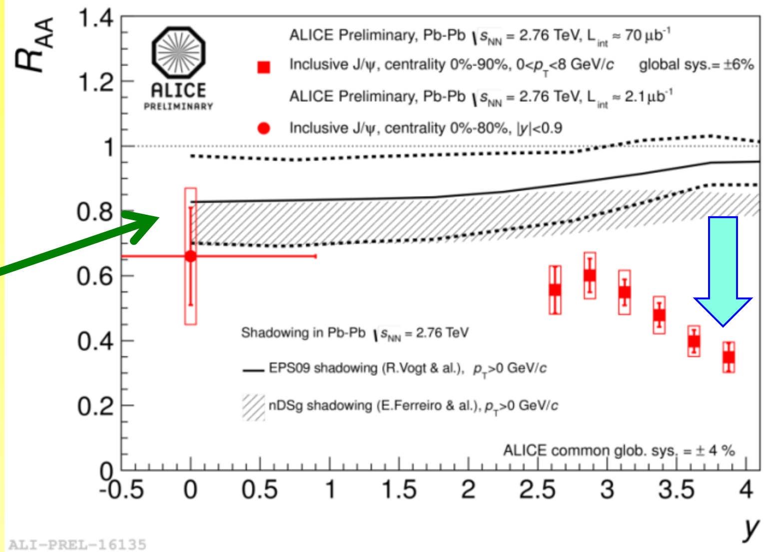
- Latest ALICE (charm) and CMS (beauty) data from QM2012: not conclusive in comparison with models at low p_T
- Overcome current ALICE limits:
  - charm difficult for $p_T \rightarrow 0$ (background is too large)
  - indirect B measurement via electrons (loose correlation p_T^B vs p_T^e)
- **Build on ALICE uniqueness at low p_T: PID, low material and B field**

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

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

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

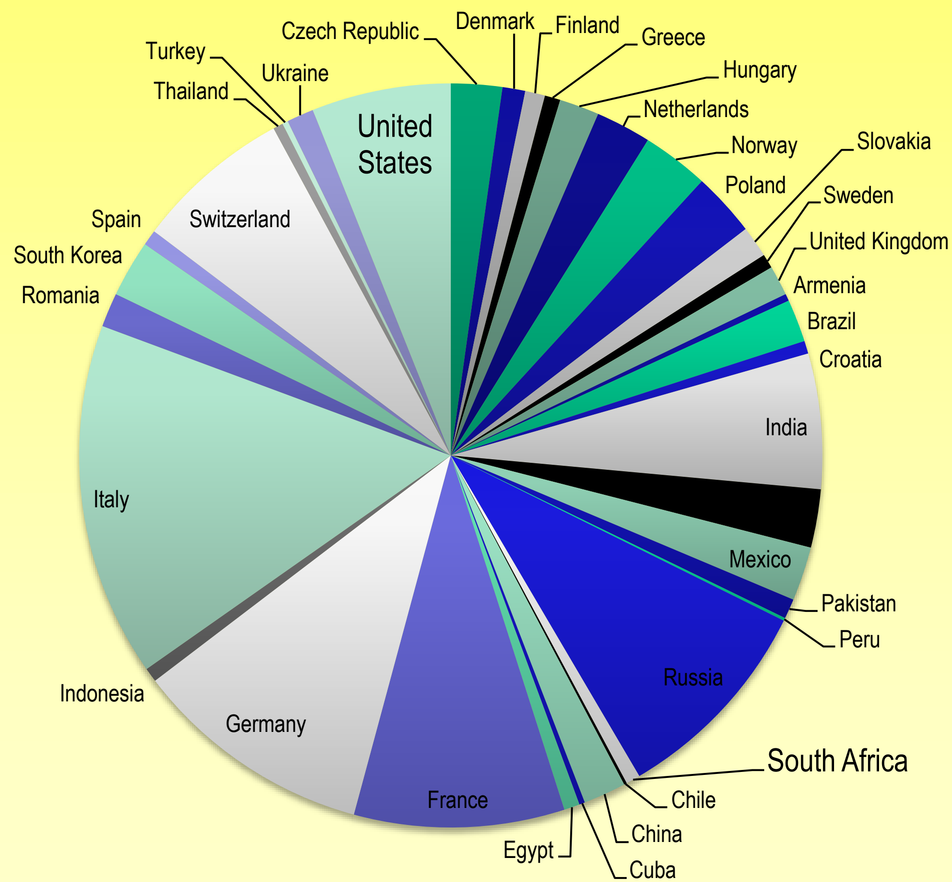
2015-2017 Procurement/Fabrication

2017-2018 Integration, pre-commissioning

2018-2019 Installation, commissioning

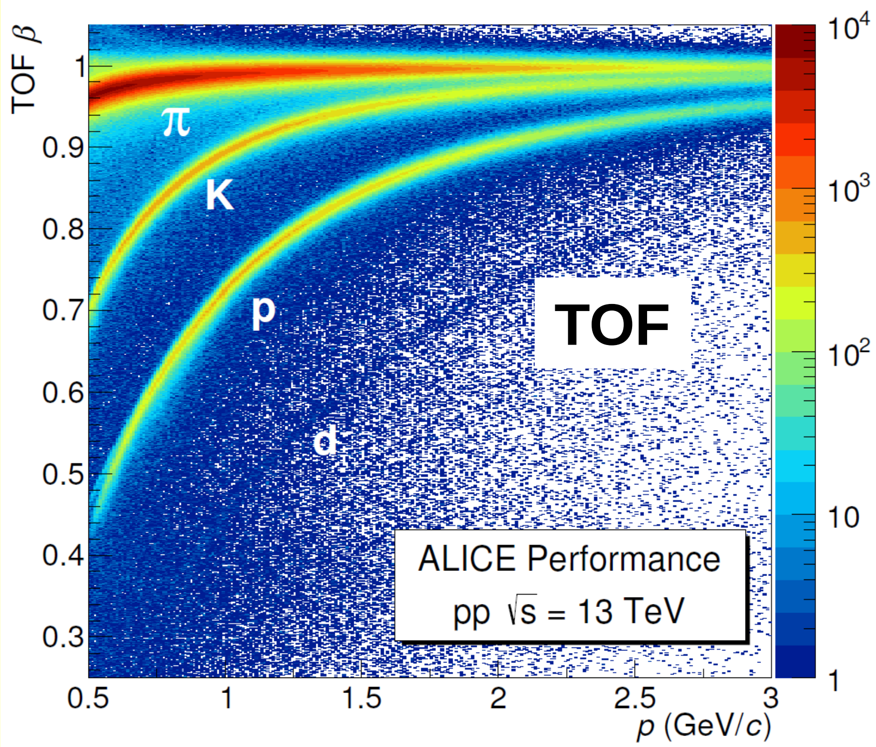
2019-2020 Full deployment of DAQ/HLT

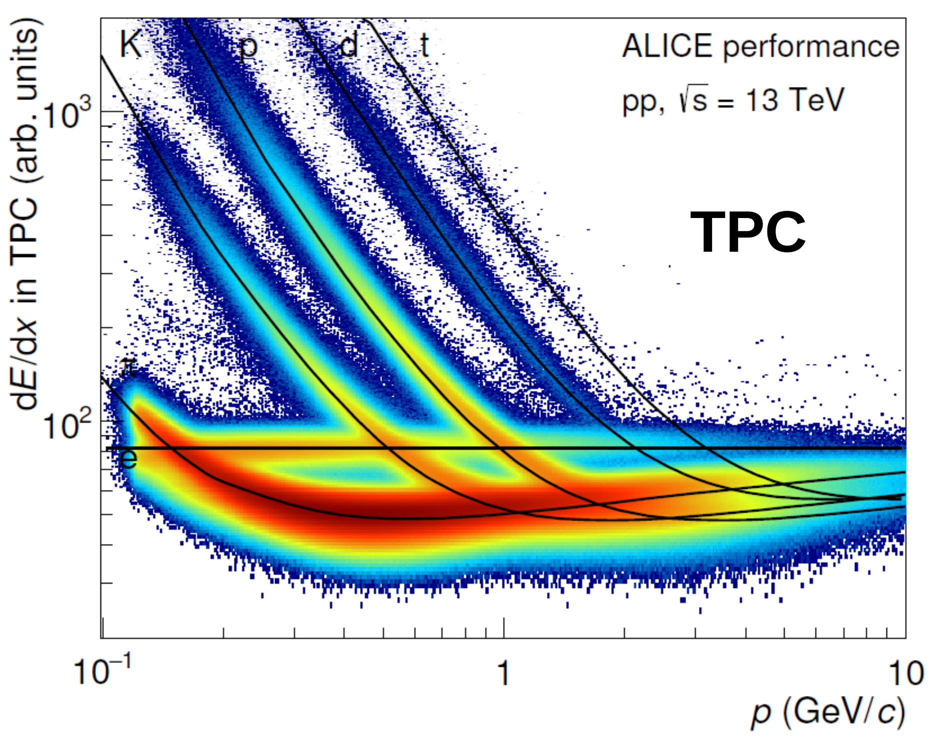
More than 1500 Collaborators



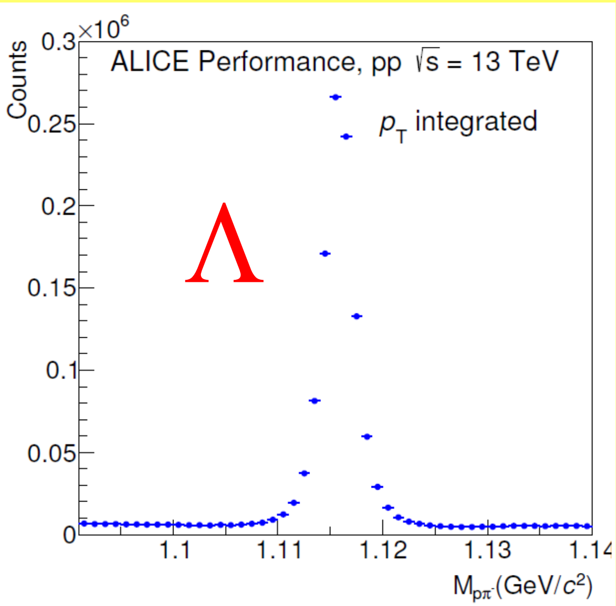
ALICE Detector Performance

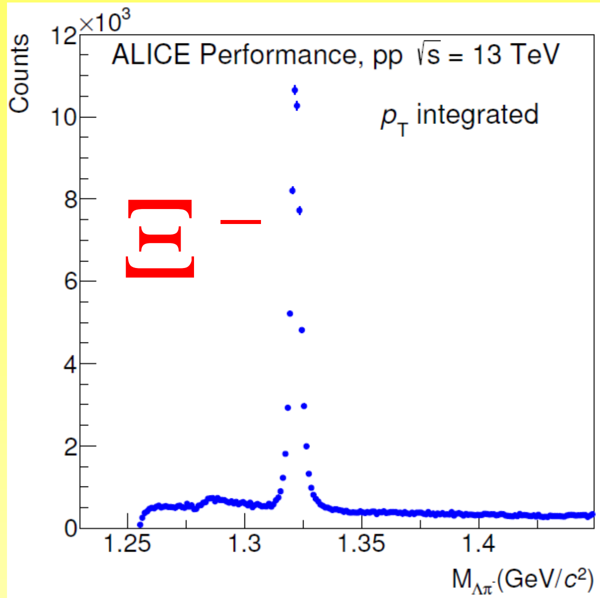
- **New detectors (DCAL, AD, CPV) and new triggers (TRD sub-L0, CALO L0 and L1g,jet)**
- **Good detector stability and running efficiency**
- **TPC gas mixture changed from $NeCO_2$ (90:10) to $ArCO_2$ (90:10)**
- **TPC stable response at high fluxes (up to 800 kHz,** 14 Hz/μb)
- **Muon Chambers tested up to RUN3 rates (2.5 MHz,** 42Hz/μb)

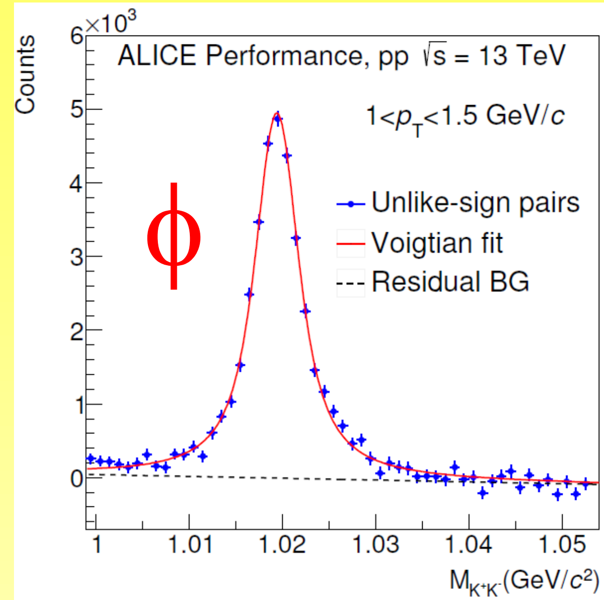


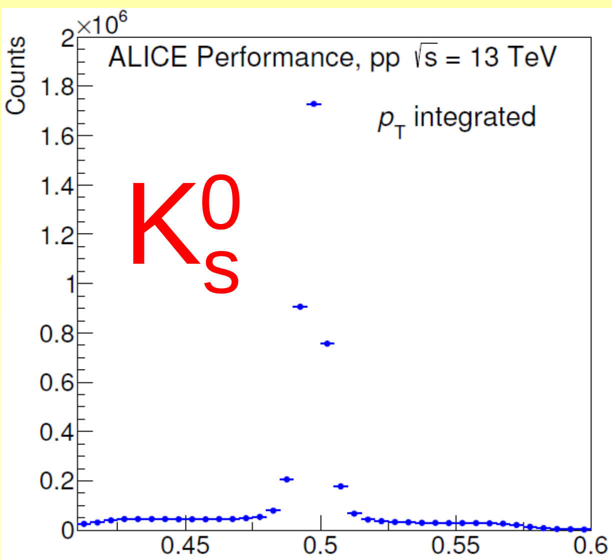


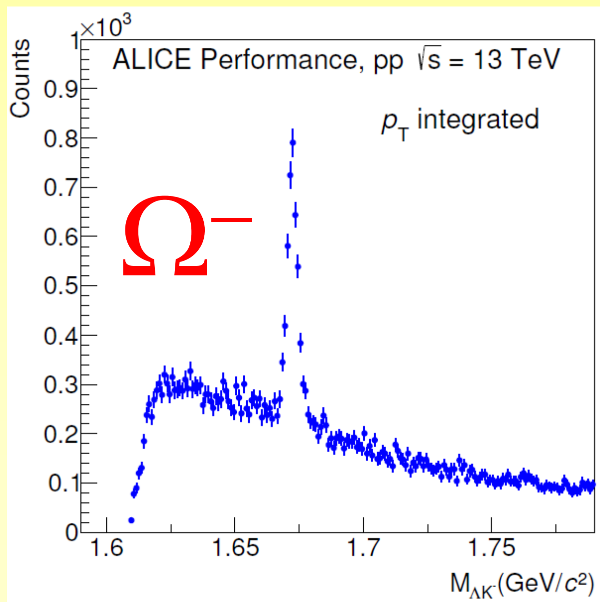
The Particle Zoo: strangeness...

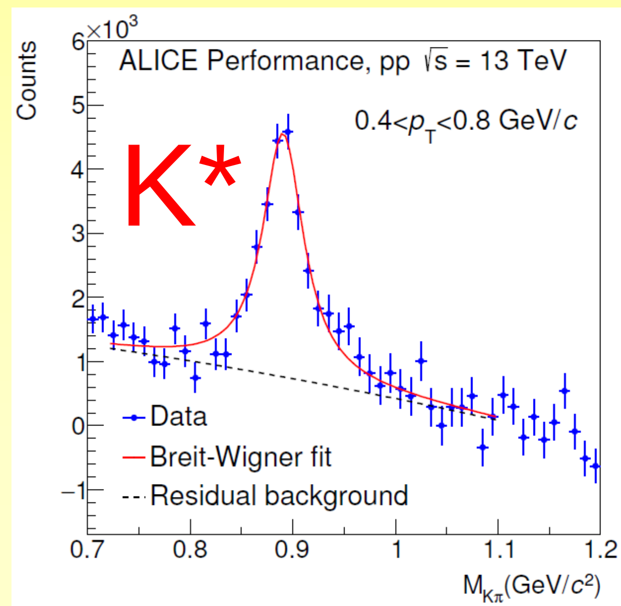






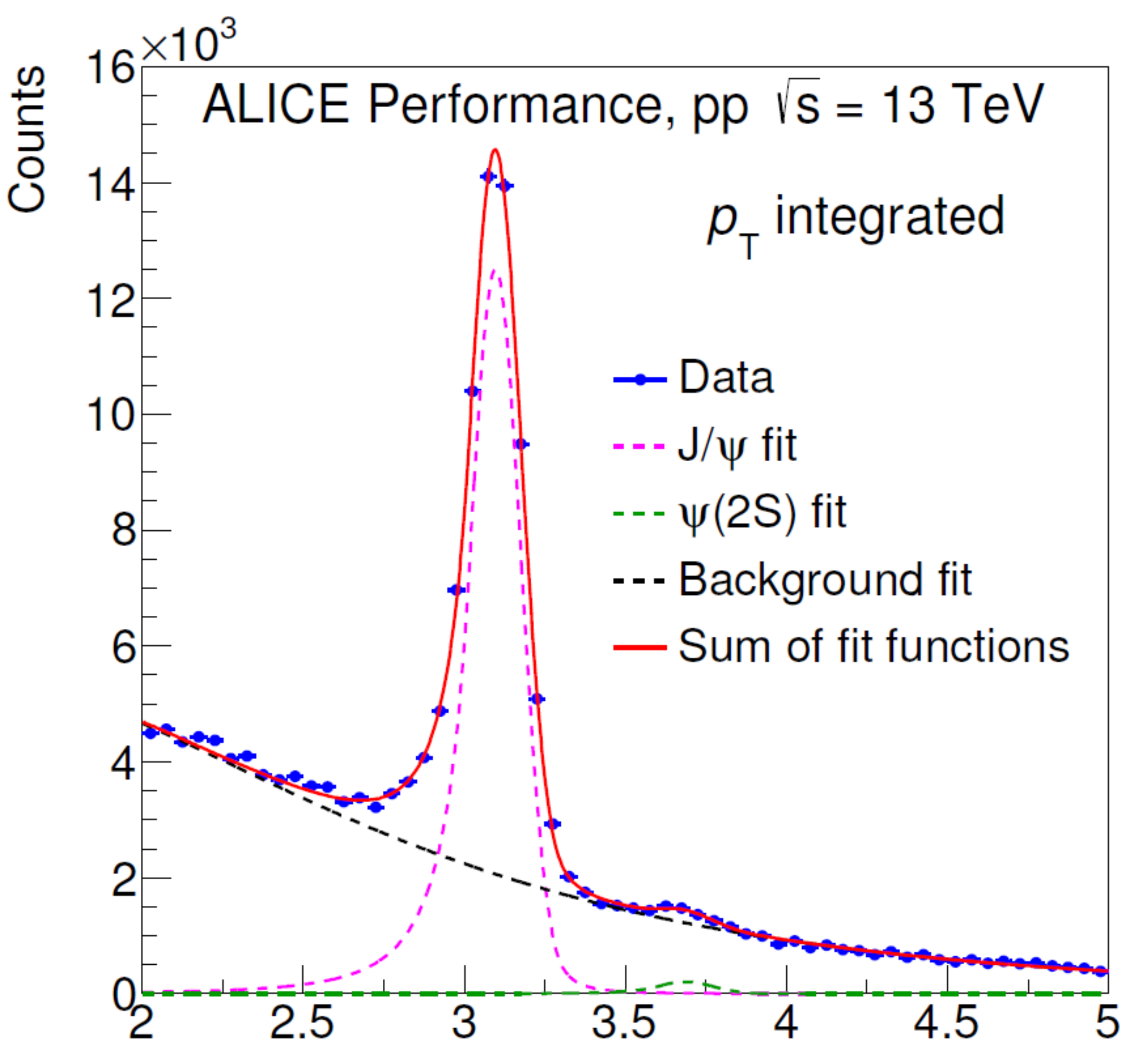






ALICE-PUBLIC-2015-004

… and charm



ALICE-PUBLIC-2015-004

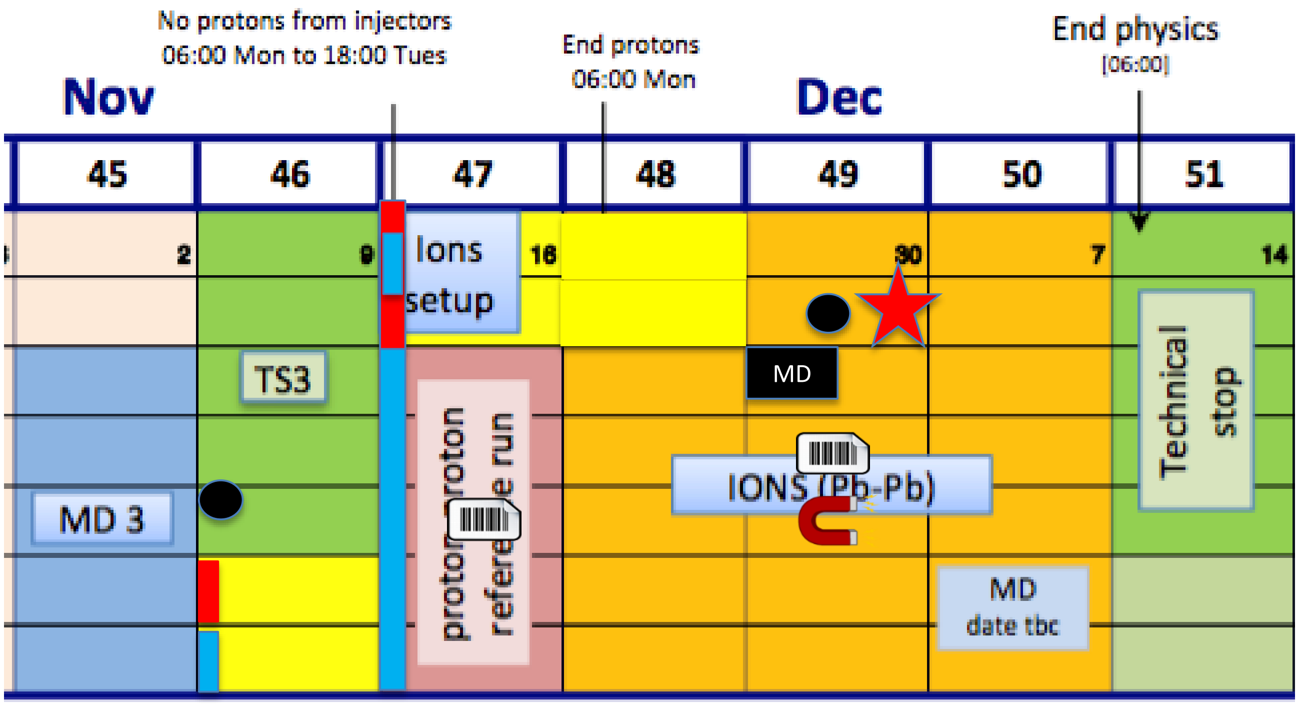
HI 2015: Tight Schedule

A Large Ion Collider Experiment

ALICE

Proton Cycle 2.51 TeV

Ion Cycle 6.37Z Tev



Machine development

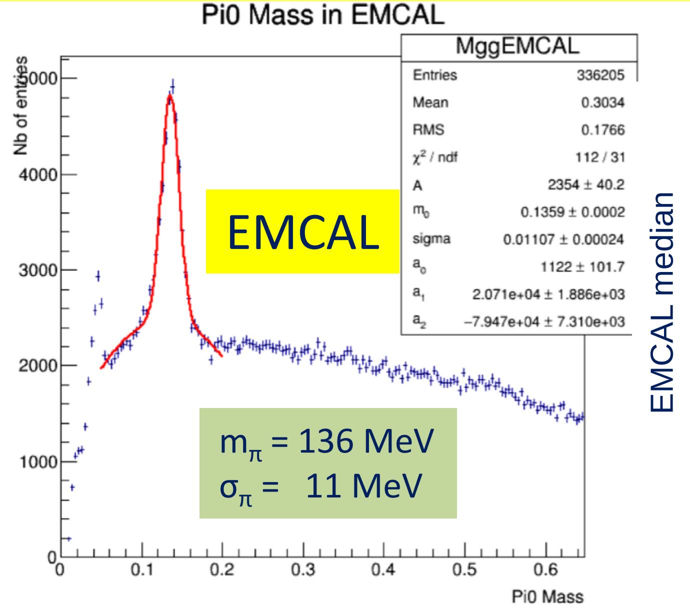
ALICE polarity flip

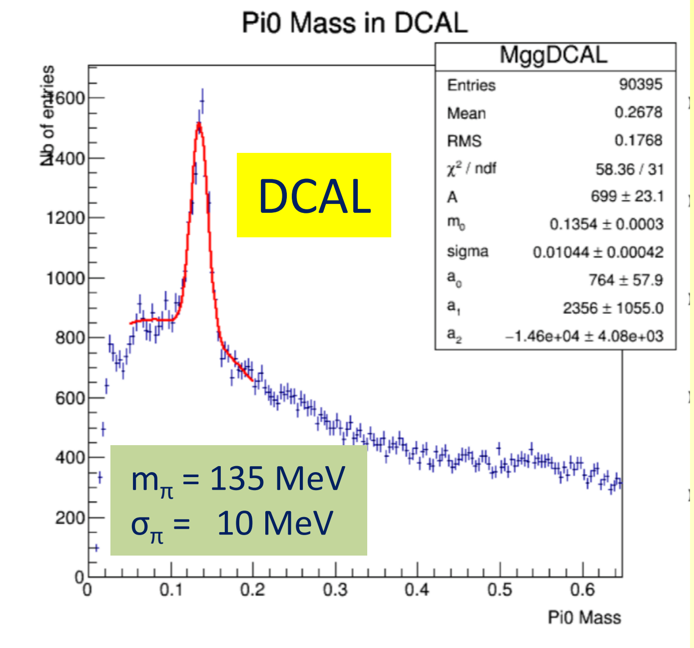
Special physics runs (indicative - schedule to be established)

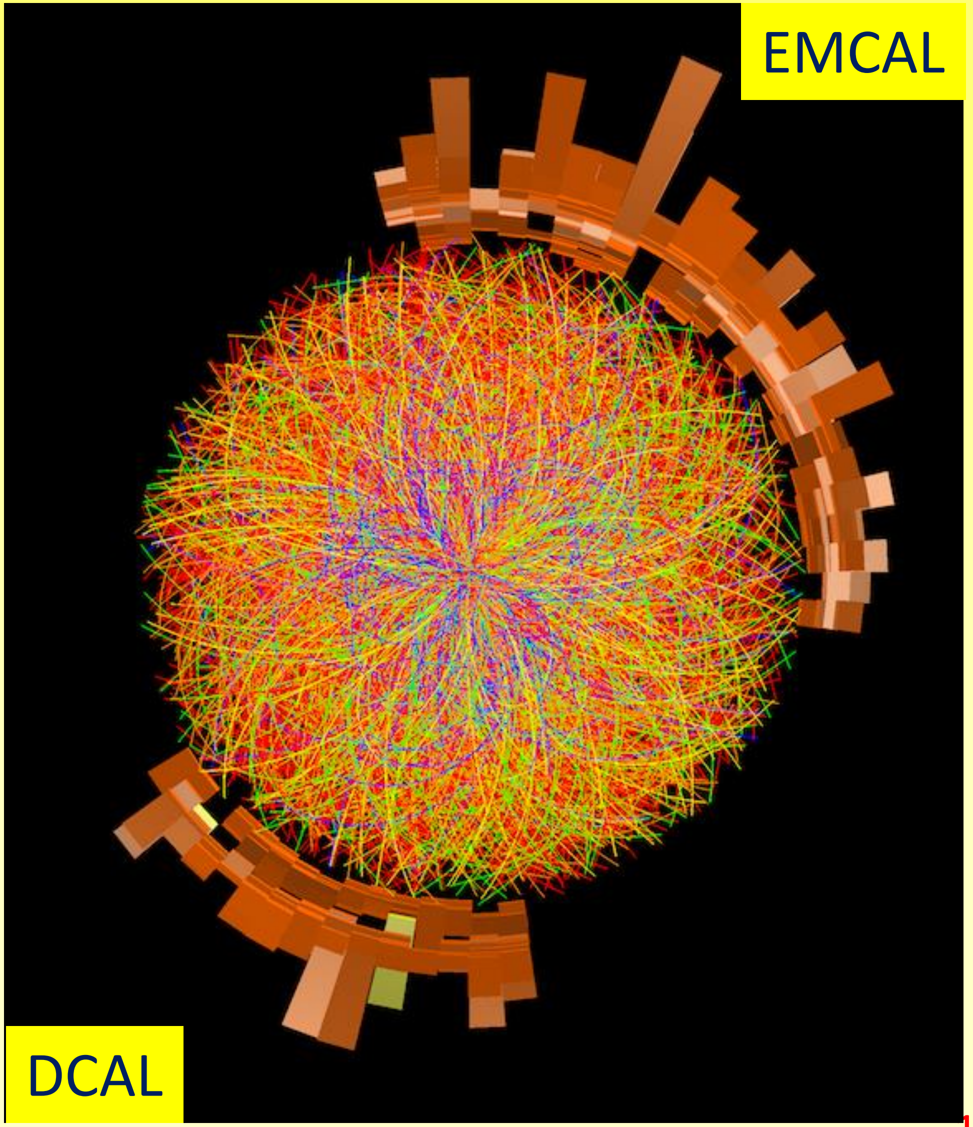
Pb oven re-fill

vdM scan

Detector Performance: EMCAL/DCAL

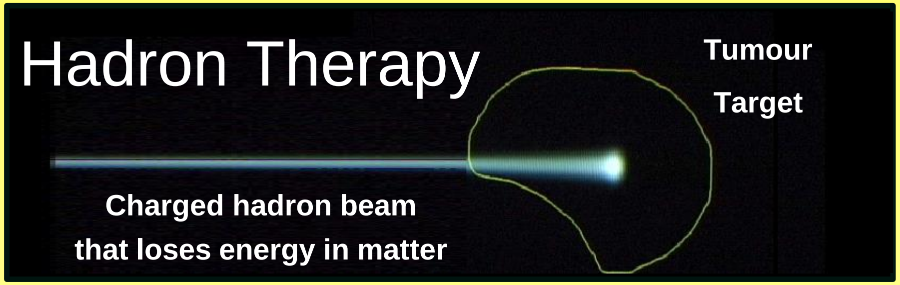






Medical applications: few examples

Particle accelerators

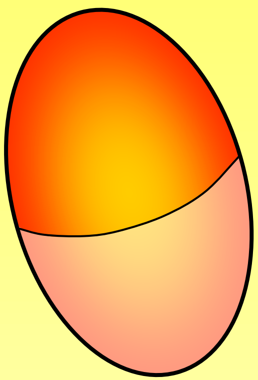


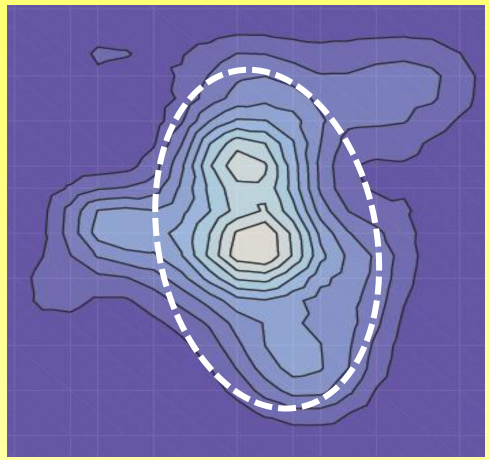
There are today 17000 accelerators in the world of which just 100 used for particle physics research, the others are used for:

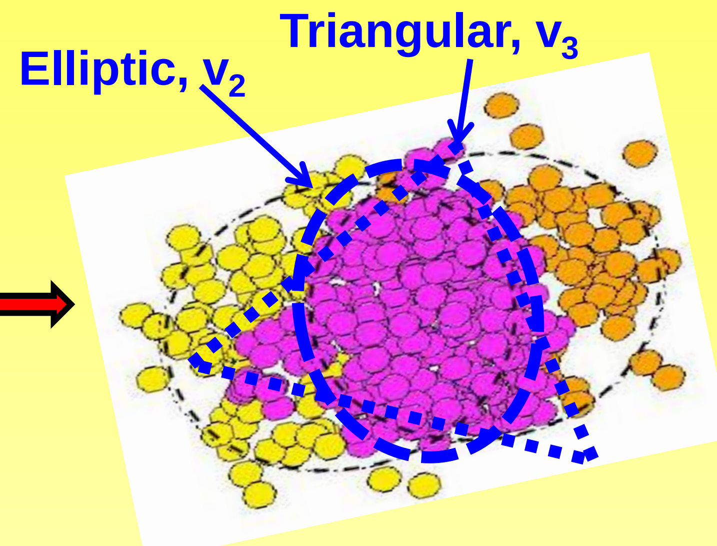
- **Cancer therapy**
- **semiconductor industry**
- **electron beam welding and cutting**
- **sterilization – food, medical**
- **radioisotope production**
- **non-destructive testing**
- **incineration of nuclear waste**
- **source of neutrons**
- **source of synchrotron radiation**
- **biology**
- **solid state physics**

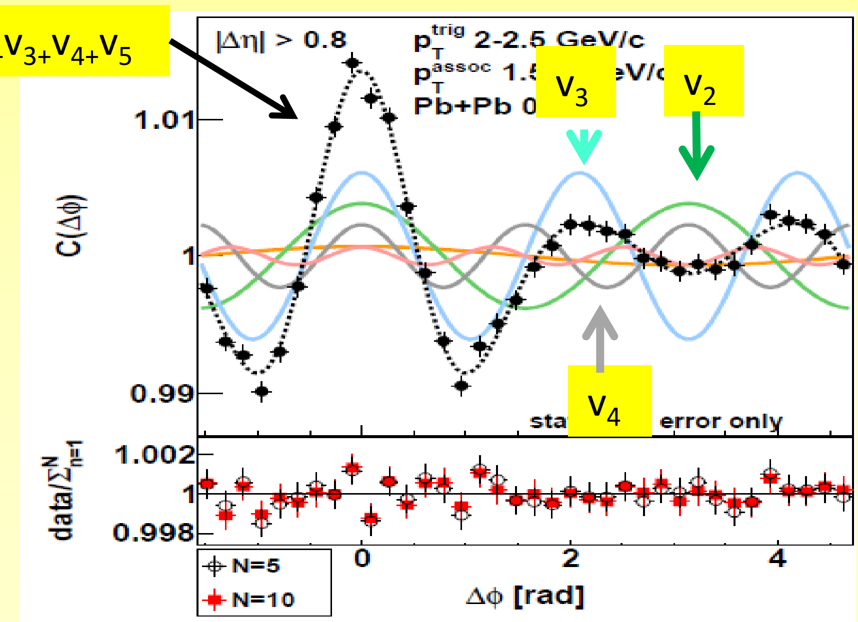
Flow patterns

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





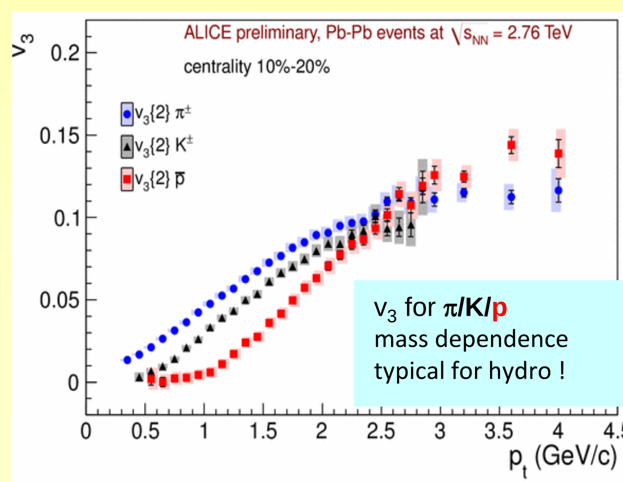




Two Particle Correlation projection on ϕ

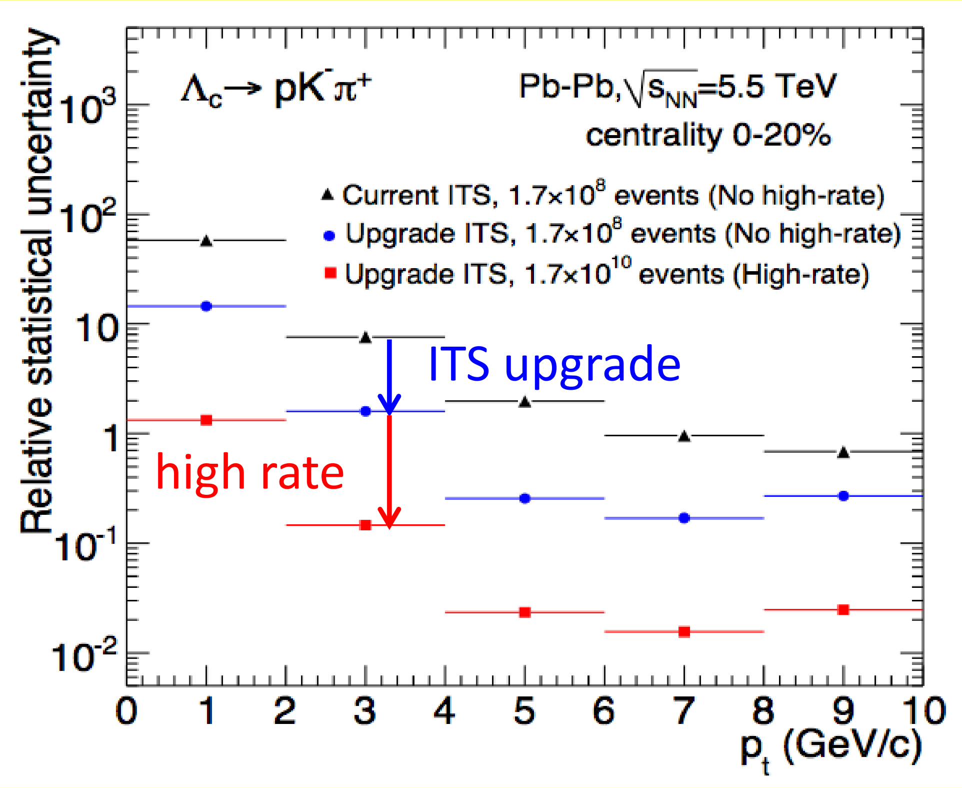
all characteristics as expected from hydro:

- strength, mass/centrality/momentum dependence



Example of performance studies: $\Lambda_c \rightarrow pK\pi$

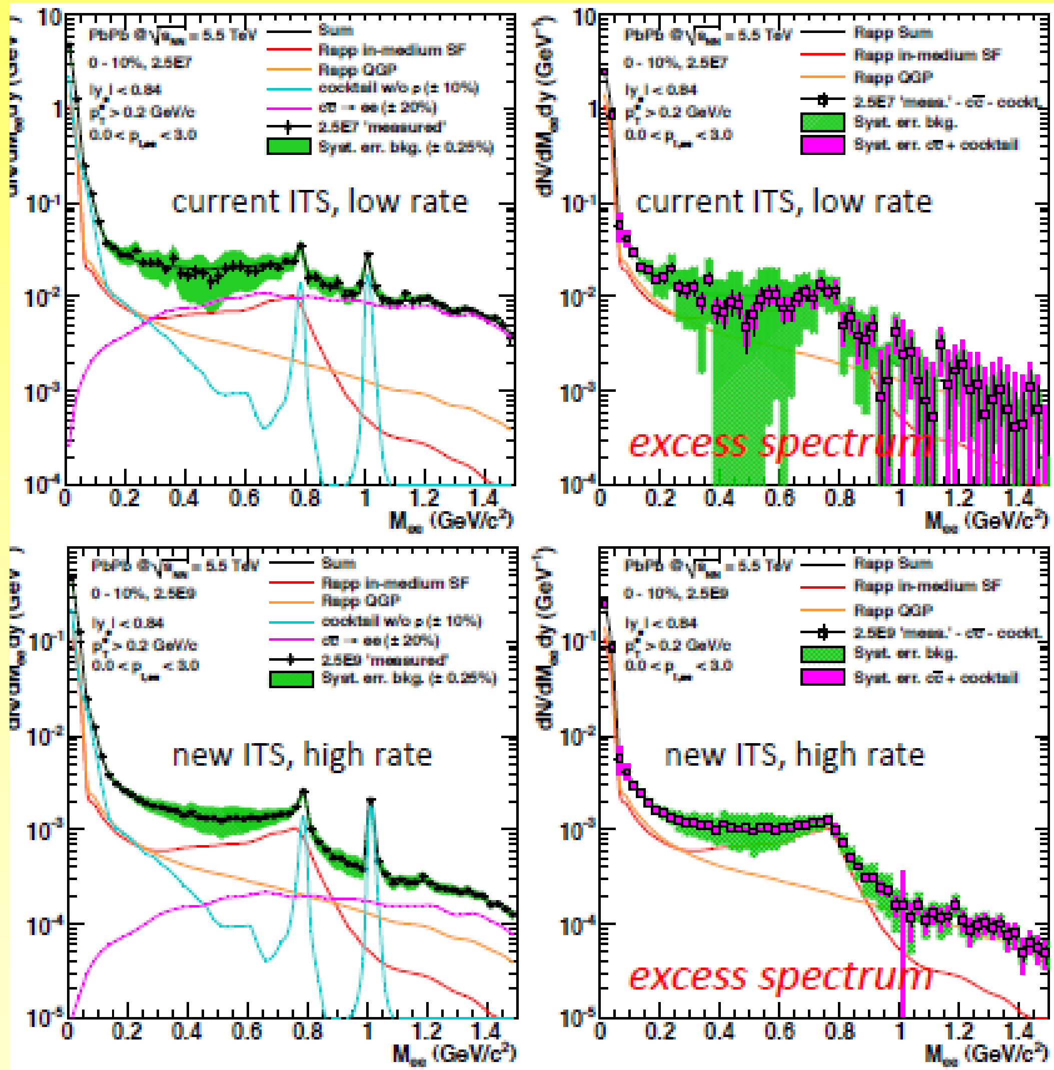
- Λ_c $c\tau$=60 μm, to be compared with D^+ $c\tau$=300 μm
  → practically impossible in Pb-Pb with current ITS



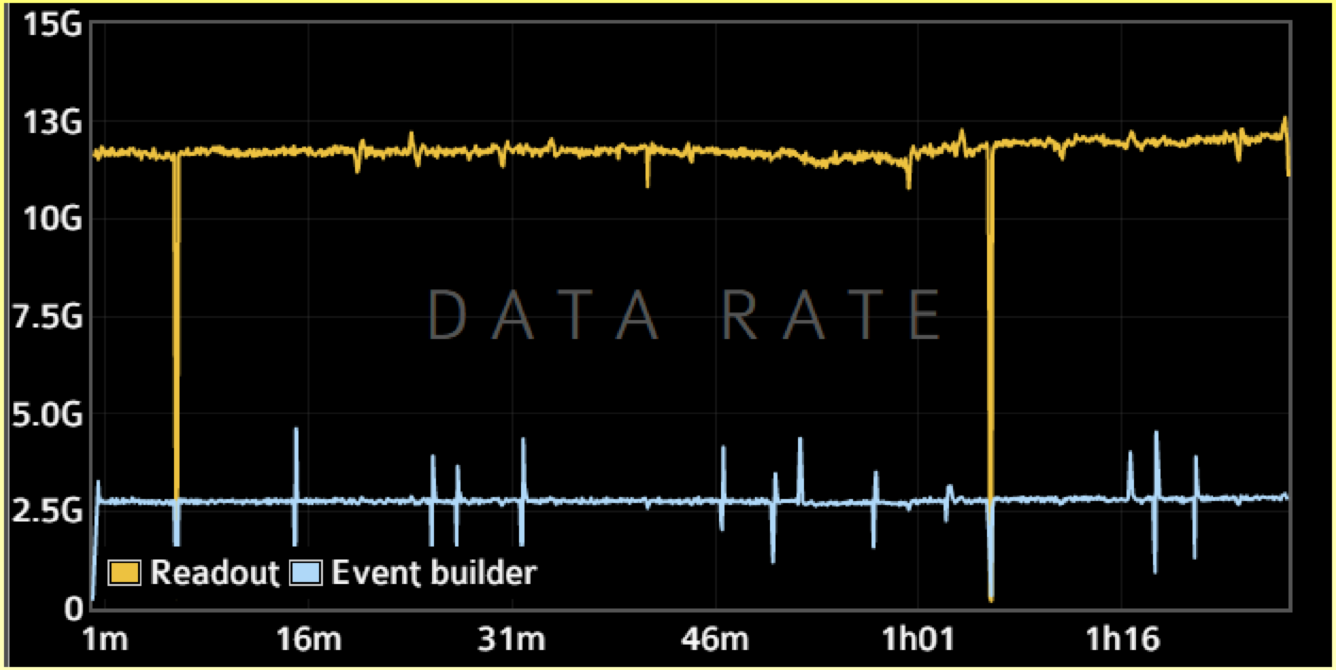
With new ITS and high-rate, measurement down to 2 GeV/*c*

Example of performance studies: low-mass e^+e^-

- e-PID in TPC and TOF
  - Needs high-rate readout
- Dalitz rejection, conversion and charm suppression
  - New ITS improves major sources of systematic uncertainties



Run 2 pp data taking: Online systems



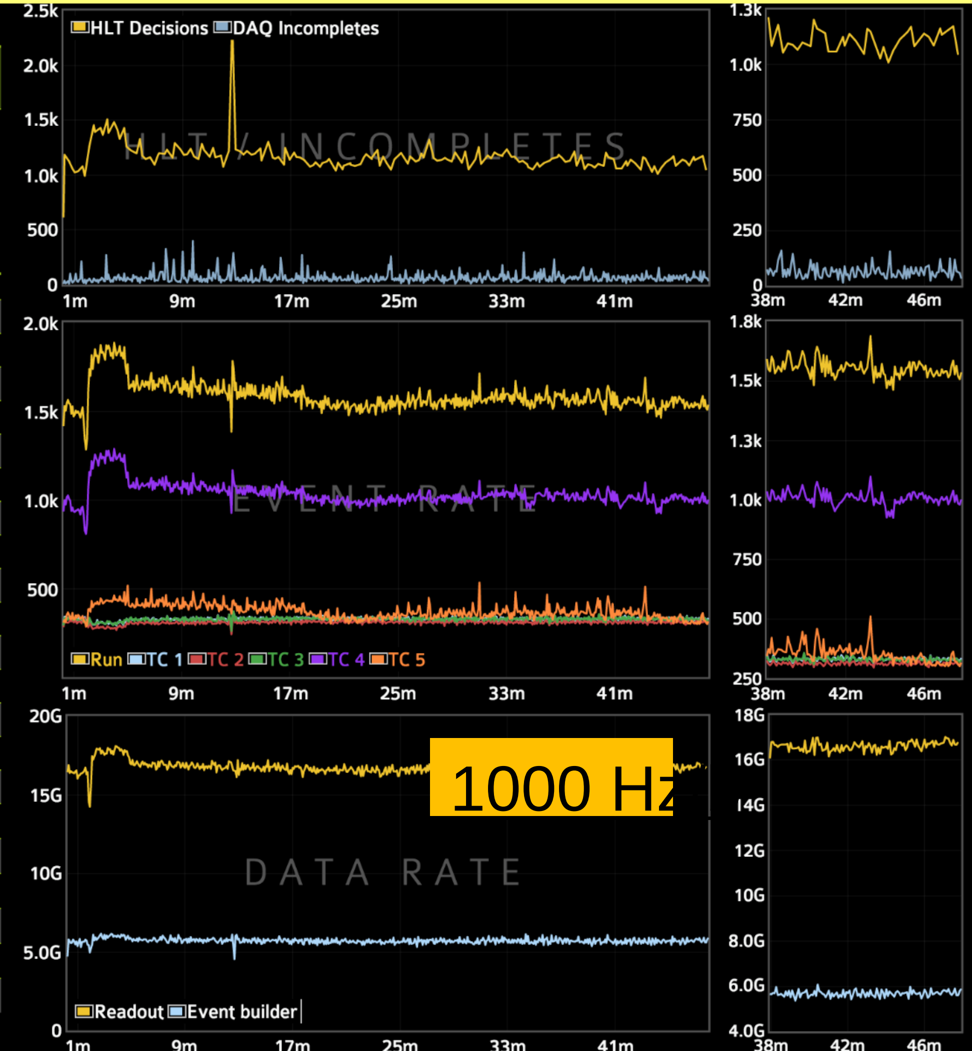
- Data taking at up to 12.5 GB/s
- Data compression by a factor 5
- Data recorded at up to 2.5 GB/s

PbPb data taking

1000 Hz/b → 16 GB/s readout, 6 GB/s on disk after HLT compression

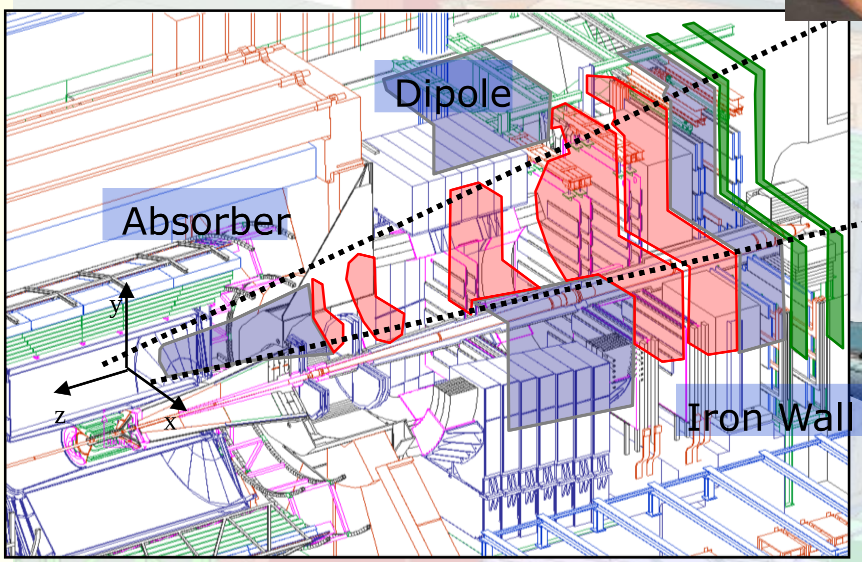
Run	Beam	Partition	Run type	HLT	Rec	Duration	Events
245683	Y	PHYSICS_1	PHYSICS	C	Y	00:48:05	4.5M
		CTP Config: PbPb2015 (v39)					

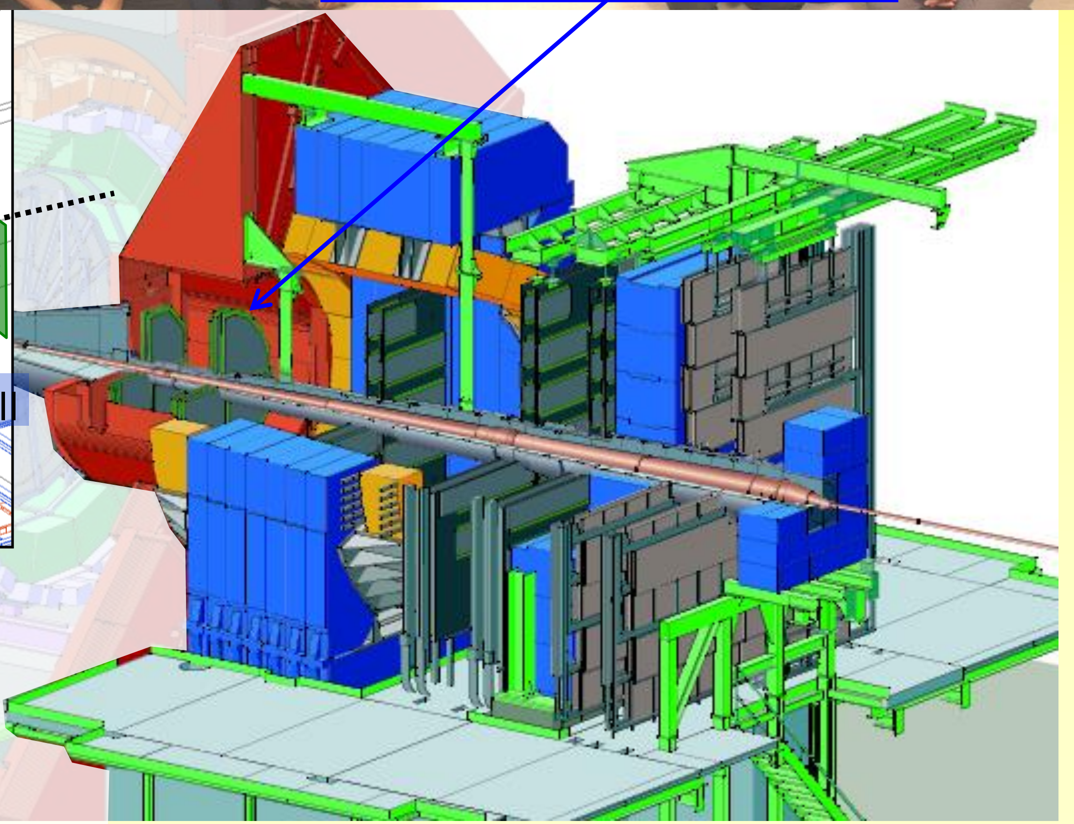
Calib	Bsy	Bck	Name	RUN	TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8
	-	-	-	4.5M	940k	884k	938k	3m	1.1m	-	-	-
	-	-	ACO	-	-	-	-	-	-	-	-	-
21:23 PED	-	○	AD0	✓	✓	✓	✓	✓	✓	-	-	-
21:45 PED	-	○	CPV	✓	✓	✓	✓	-	-	-	-	-
	-	○	EMC	✓	✓	✓	✓	-	-	-	-	-
	-	○	FMD	✓	✓	✓	✓	-	-	-	-	-
21:24 CAL	-	○	HMP	✓	✓	✓	✓	-	-	-	-	-
16:33 CAL	-	○	MTR	✓	-	-	-	✓	○	-	-	-
21:52 PED	-	○	MCH	✓	-	-	-	✓	-	-	-	-
	-	○	PHS	✓	✓	✓	✓	-	-	-	-	-
21:44 PED	-	-	PMD	-	-	-	-	-	-	-	-	-
21:51 INJ	-	○	SDD	✓	✓	✓	✓	-	-	-	-	-
	-	○	SPD	✓	✓	✓	✓	✓	✓	-	-	-
21:26 PED	-	○	SSD	✓	✓	✓	✓	-	-	-	-	-
	-	○	T00	✓	✓	✓	✓	✓	✓	-	-	-
21:23 NOI	-	○	TOF	✓	✓	✓	✓	-	✓	-	-	-
19:19 LAS	-	○	TPC	✓	✓	✓	✓	-	-	-	-	-
	-	○	TRD	✓	✓	✓	-	-	-	-	-	-
	-	○	TRI	✓	✓	✓	✓	✓	✓	-	-	-
	-	-	TST	-	-	-	-	-	-	-	-	-
	-	○	V00	✓	✓	✓	✓	✓	✓	-	-	-
21:27 SPE	-	○	ZDC	✓	✓	✓	✓	✓	✓	-	-	-
	-	○	HLT									



The ALICE muon Spectrometer

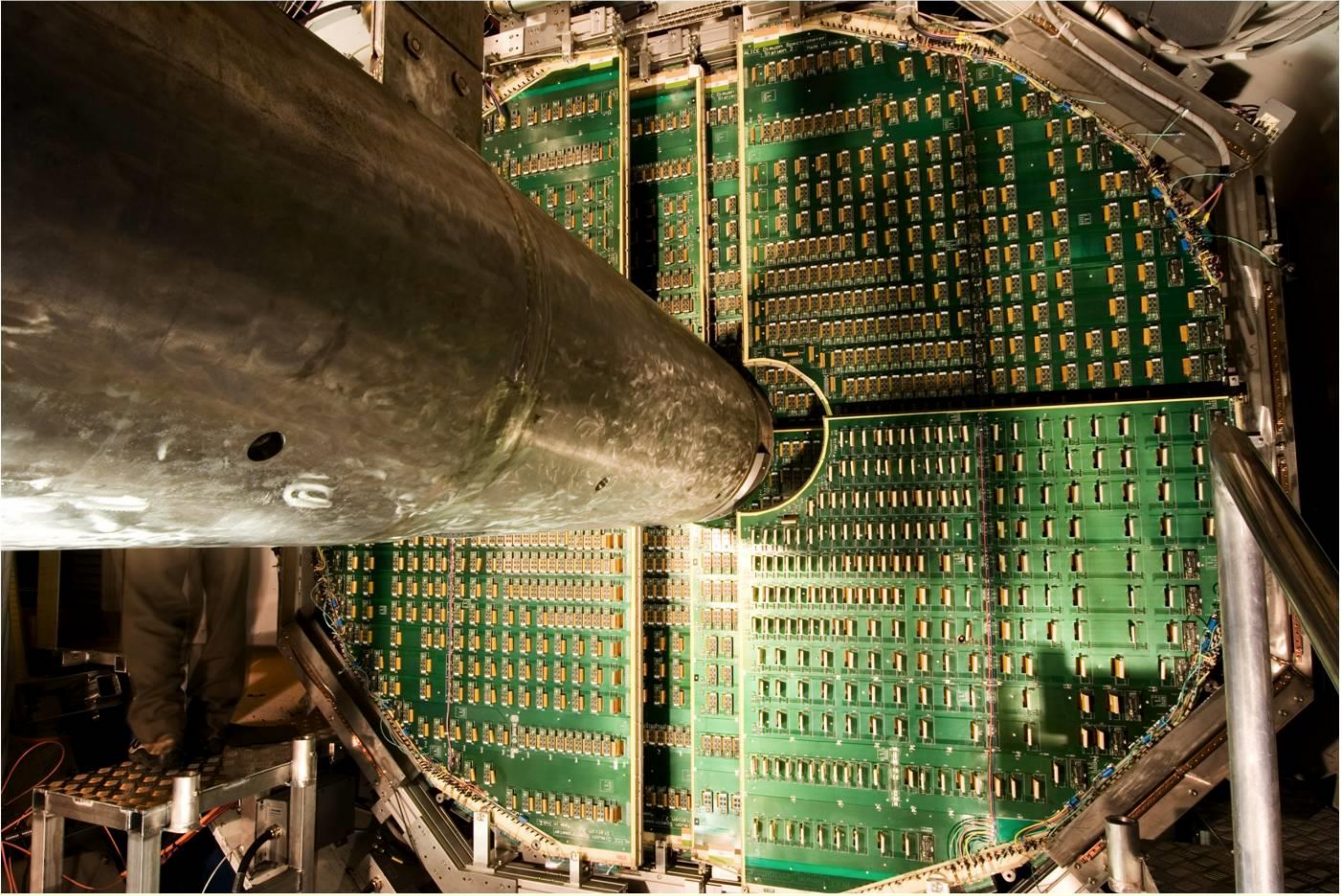
dedicated to the (di-)muons measurement (2.5<η<4)





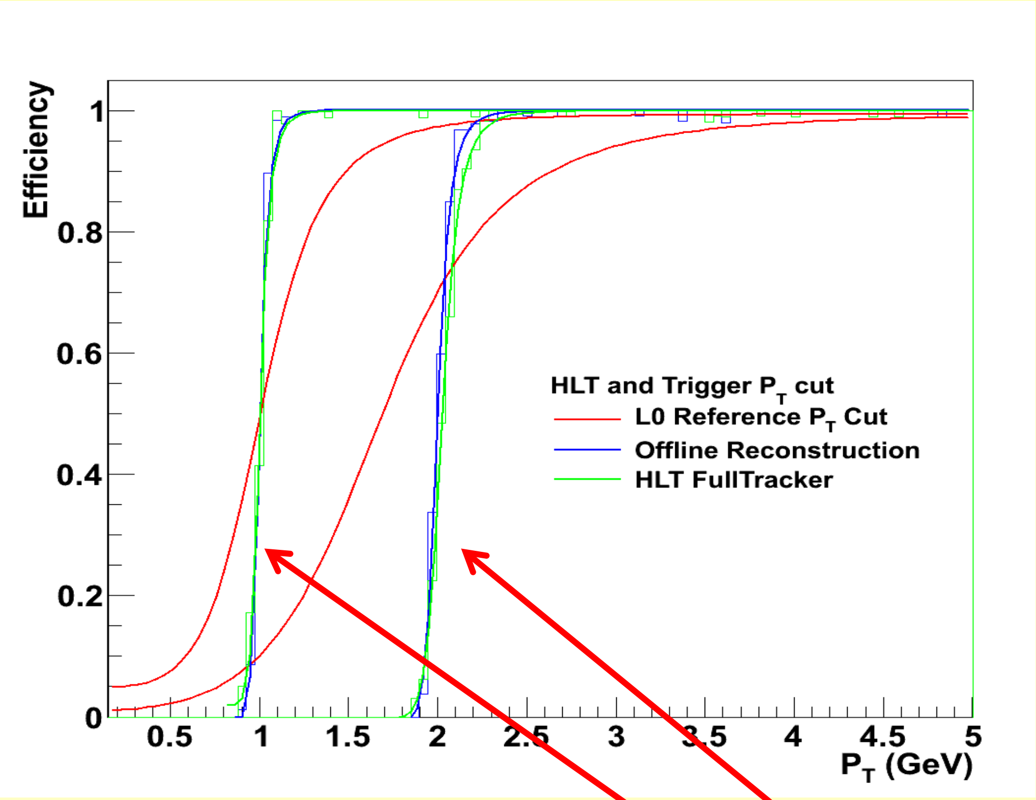
2 stations of Trigger Chambers

5 stations of Tracking Chambers
1 & 2 : quadrant type
3, 4 & 5 : slats type



Station2, 100% Made in India, as Appeared on the CERN Courier

Muon HLT:
P_T Cut Efficiency

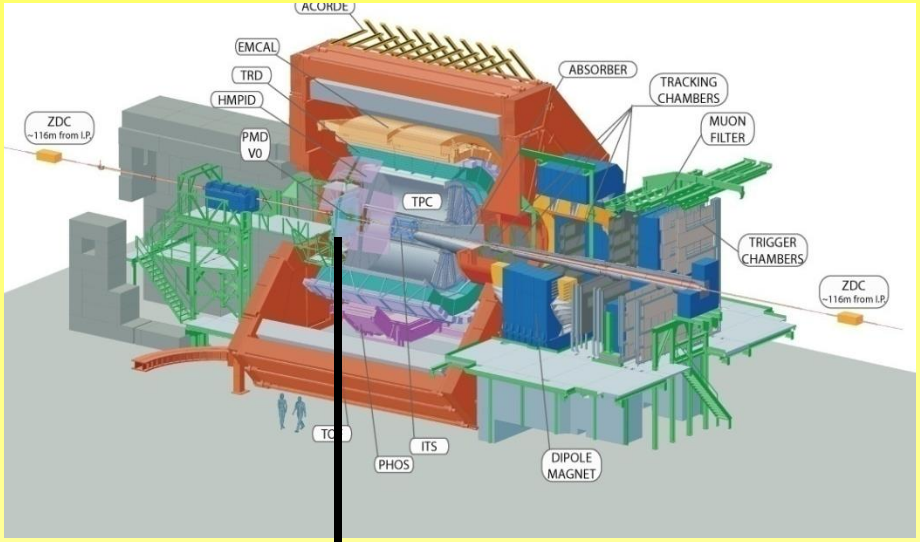


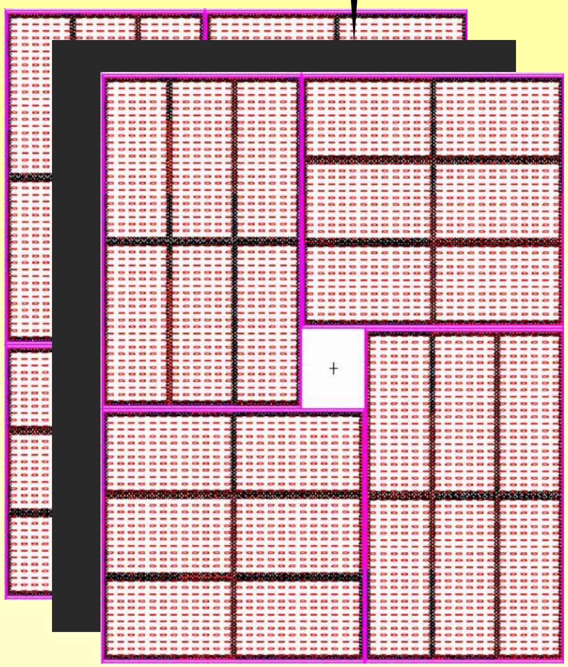
Main motivation of Dimuon HLT

For the Muon Spectrometer, HLT algorithms are supposed to improve the p_T cuts (1 GeV or 2 GeV at most, depending on beam luminosity) as defined by Muon Trigger Station (L0 Trigger), which are important remove the combinatorial background of low momentum particles to clear the J/Ψ and Υ signals. A typical processing rate of 1 kHz is the design requirement of muon HLT for heavy ion Pb-Pb collisions.

The HLT performance approaches the offline one

PMD : Physics Goals





$\underline{\eta}$: 2.3 to 3.9
Z dist. : 361.5 cm from IP

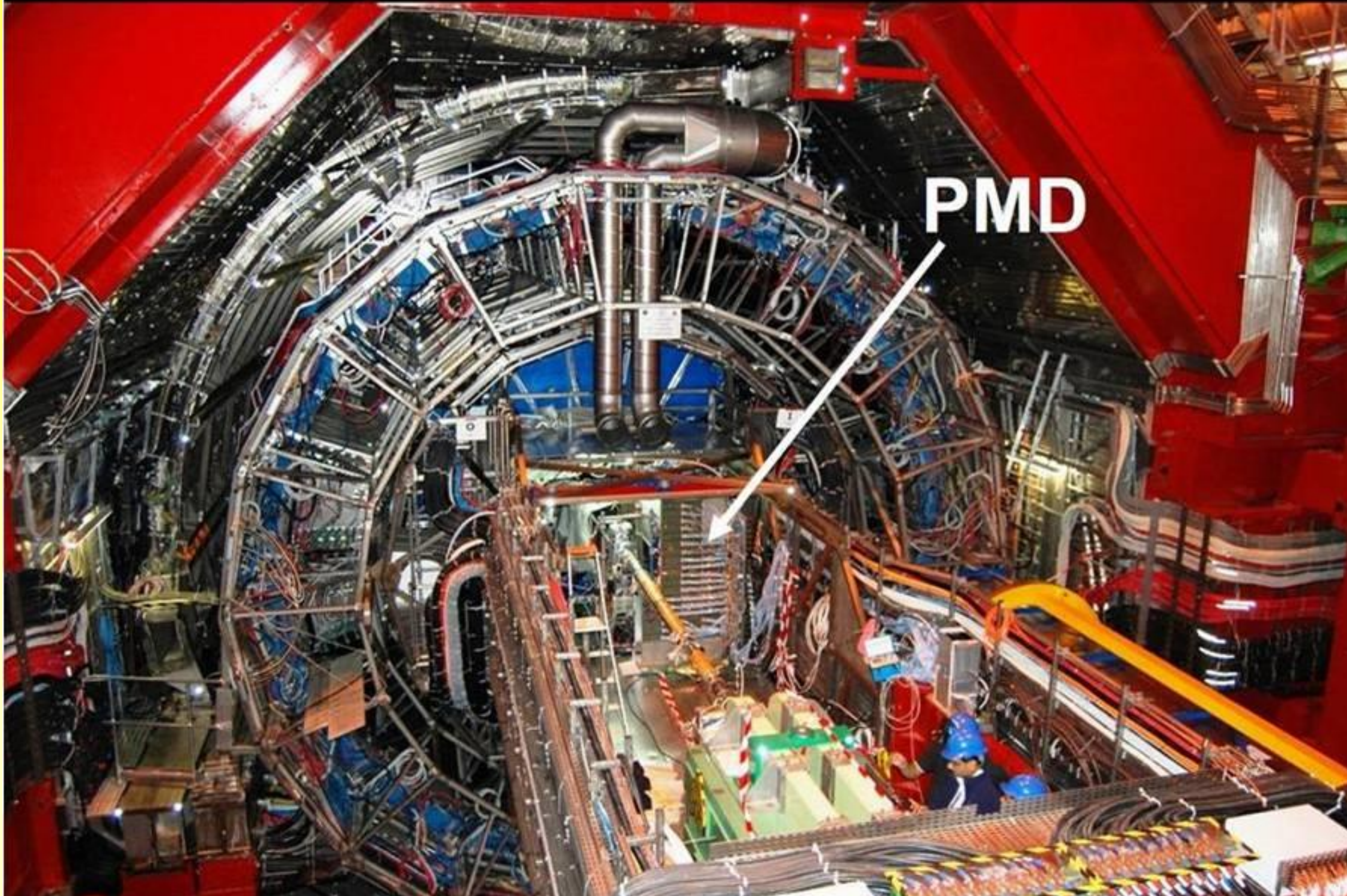
Measurement of photon multiplicity and its spatial distribution in the forward region on an event-by-event basis

- **Rapidity & Multiplicity distributions of photons**
- **Determination of reaction plane and probes of thermalization via study of azimuthal anisotropy**
- **Multiplicity Fluctuations**
- **Signal of chiral symmetry restoration (DCC) through the measurement of charged particle (FMD) and photon multiplicities in a common phase space**

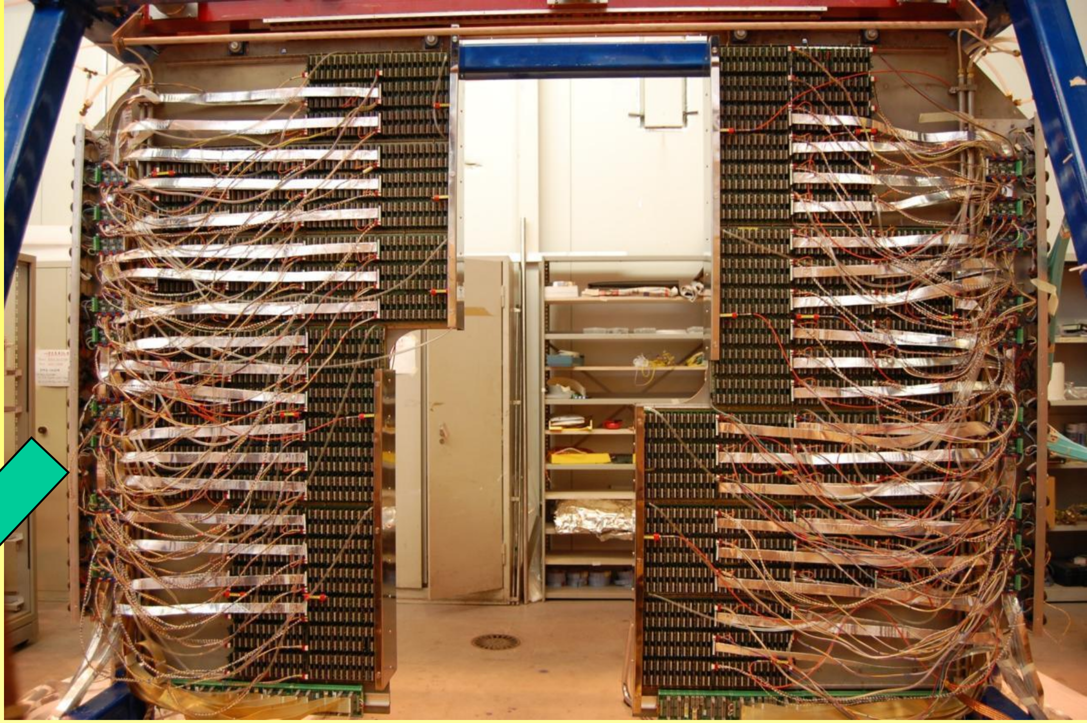
PMD Construction

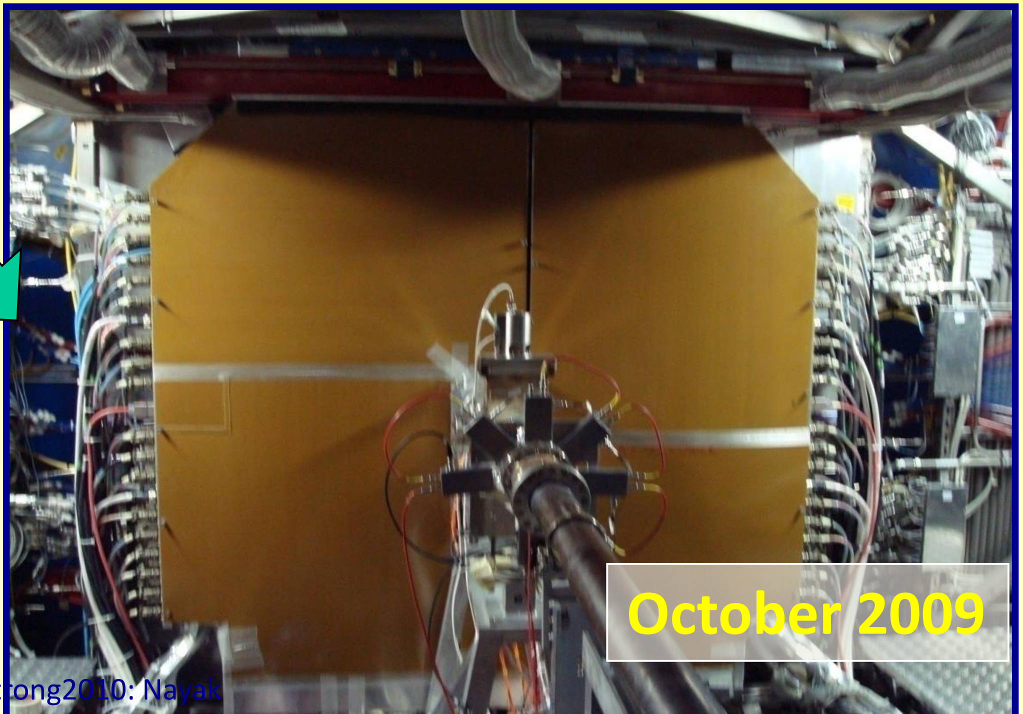
~221K honeycomb gas cells, arranged in 48 modules, readout by **MANAS** chips.

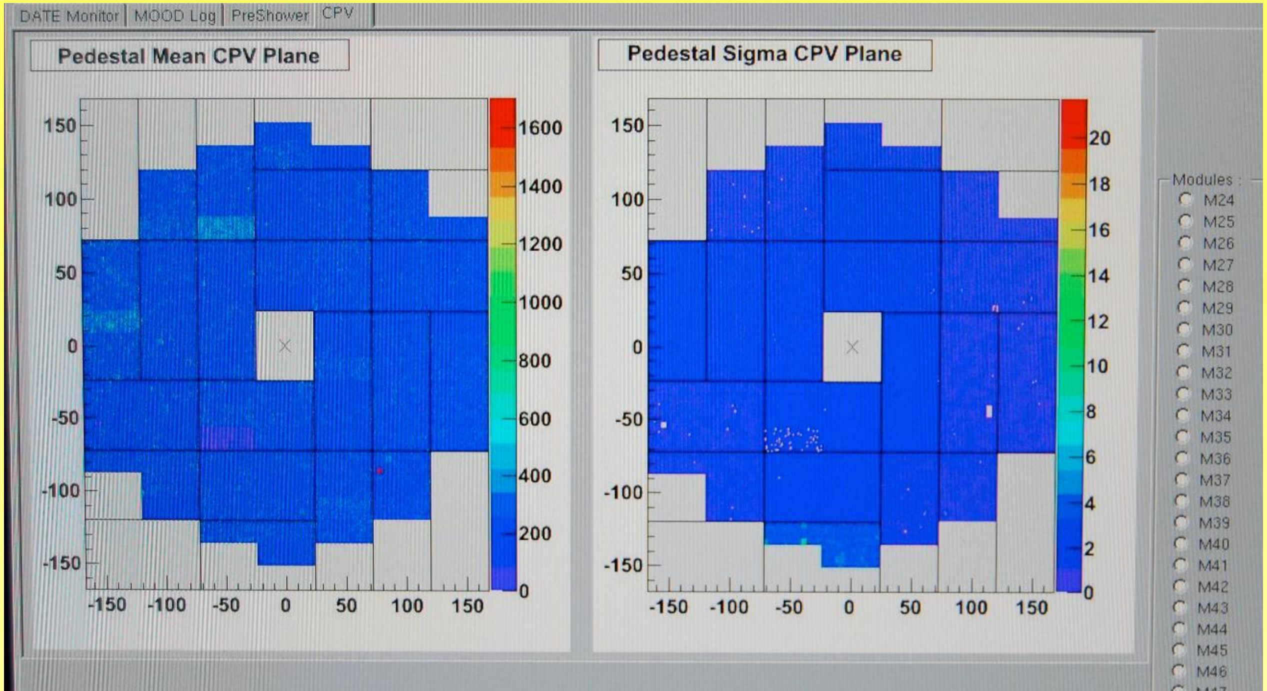
ALICE Setup – View from A-Side showing PMD



PMD installation in the ALICE Cavern

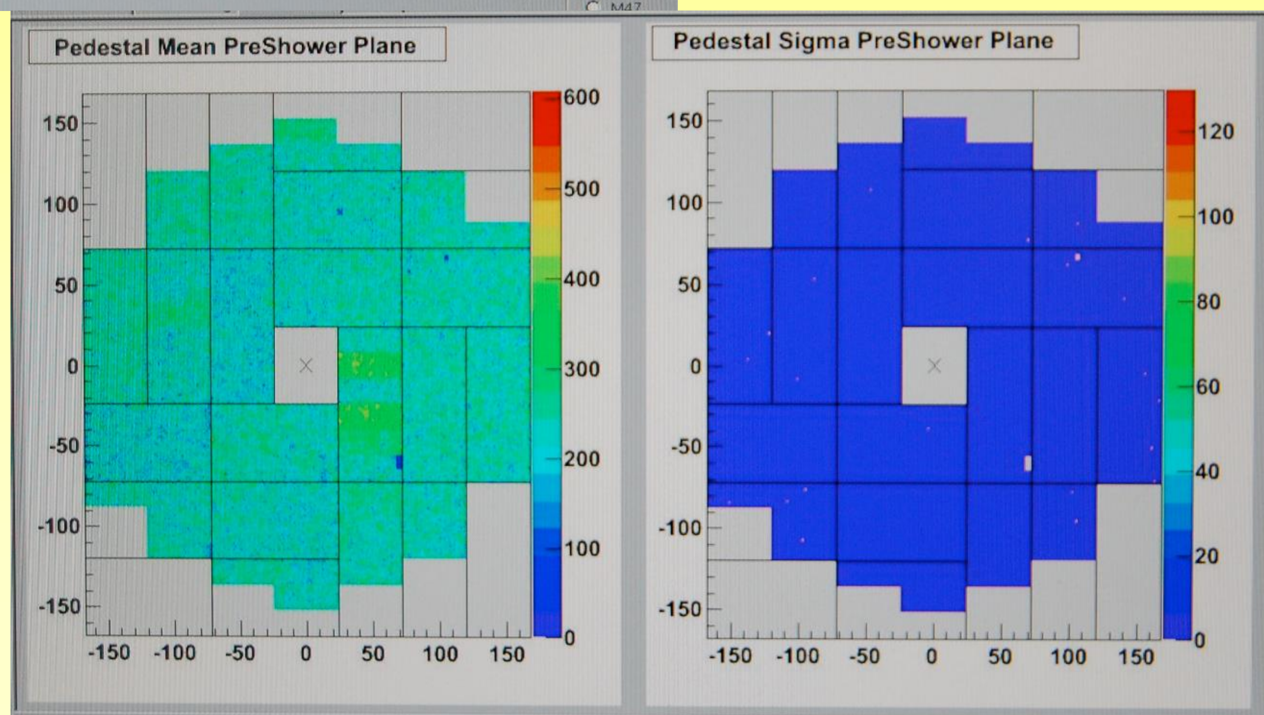






Pedestals – CPV Plane

Pedestals – Preshower Plane



PMD Fully Operational with:

- 97% of CPV Plane
- 100% of Preshower Plane

Modules, HV, LV, DCS, DAQ are fully working

But need to eventually analyze the data!

The ALICE Grid

The ALICE Grid framework AliEn

- ✓ Single interface to distributed computing for all ALICE physicists
- ✓ File catalogue, job submission and control, software management, user analysis

~80 participating sites

- ✓ 1 T0 - CERN/Switzerland
- ✓ 7 T1s - France, Germany, Italy, The Netherlands, Nordic DataGrid Facility, **Korea**, UK + (soon) Mexico
- ✓ 62 T2s spread over 4 continents

~30,000 (out of ~150,000 WLCG) cores and over 10 PB of disk and tape

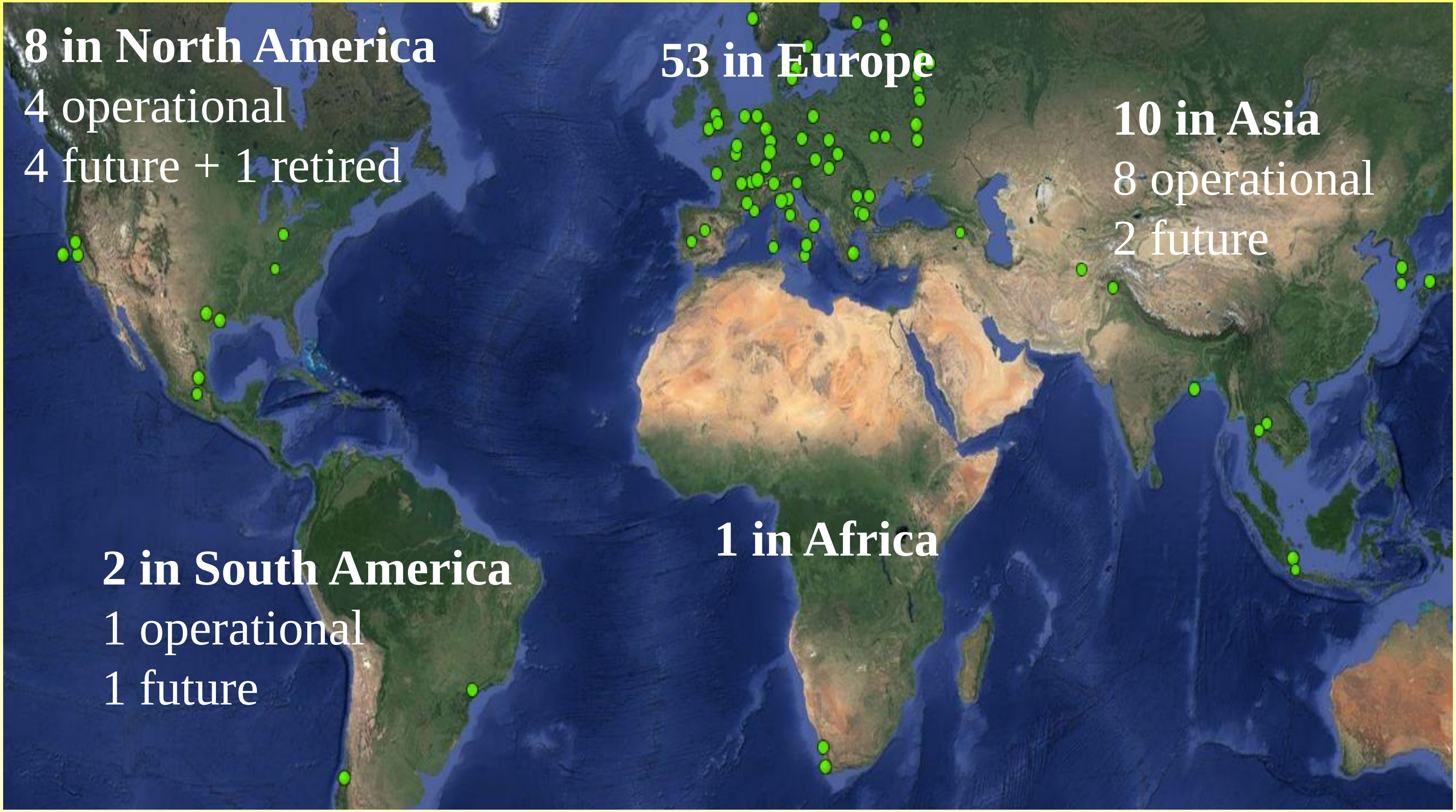
Resources are "pooled" together

- ✓ No localization of roles / functions
- ✓ National resources must integrate seamlessly into the global grid to be accounted for
- ✓ FAs are encouraged to contribute at least proportionally to the number of PhDs (M&O-A share)

India is again playing its part…

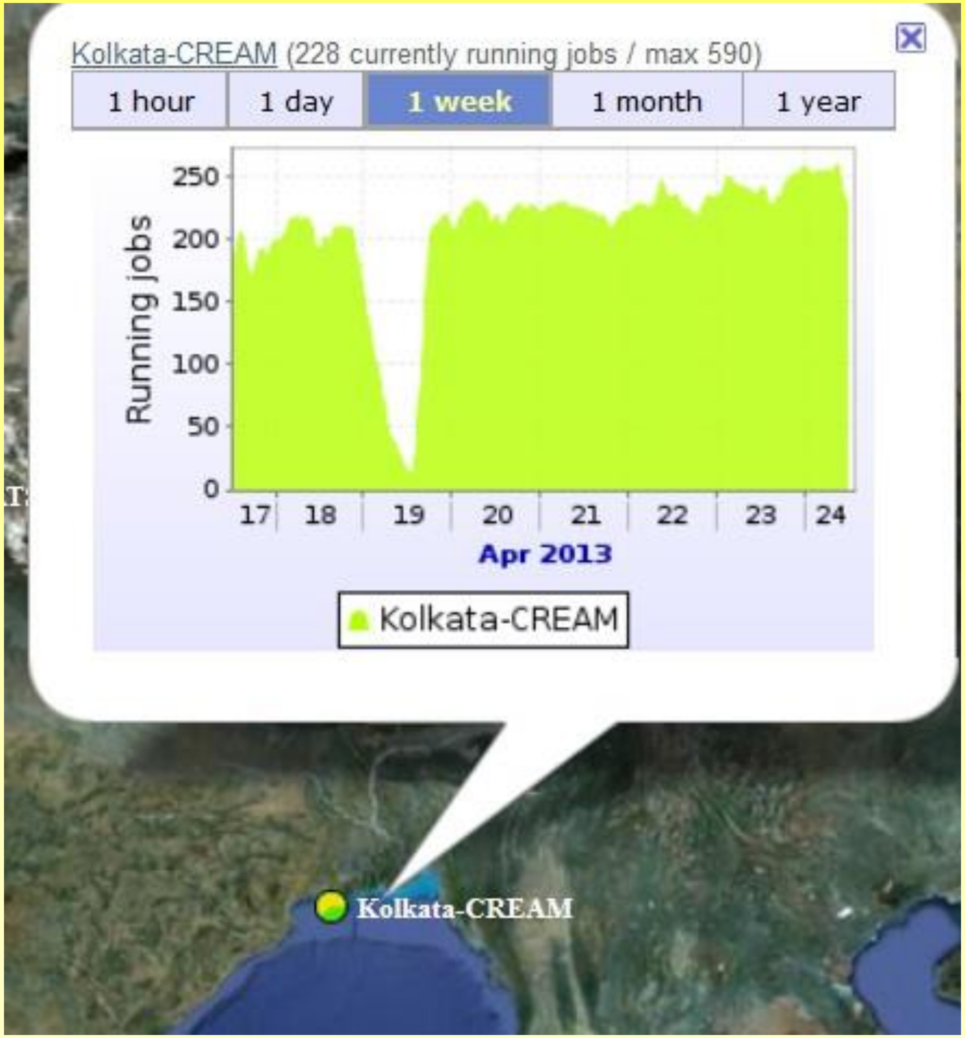
STORING, PROCESSING AND ANALYSIS OF THE DATA:

The ALICE GRID



- Currently over 60k jobs run in parallel….

The Kolkata T2 centre



- In operation since 2009
- Today provides ~600 CPU cores and 200TB of disk storage
- Very good network connectivity with the rest of the Grid sites
- Excellent local support and site stability

Now expand with the creation of 2 new T2 centers

KOLKATA TIER-2 GRID CENTRE

Kolkata Tier-2 Resources:

- *476 Cores Computing,*
- *230TB Storage,*
- *1Gbps Network speed,*
- *A Tier-3 cluster comprises150 core and 37TB storage*

Implemented efficient cooling solution which reduced power consumption and increased overall performance of entire Kolkata Tier-2.