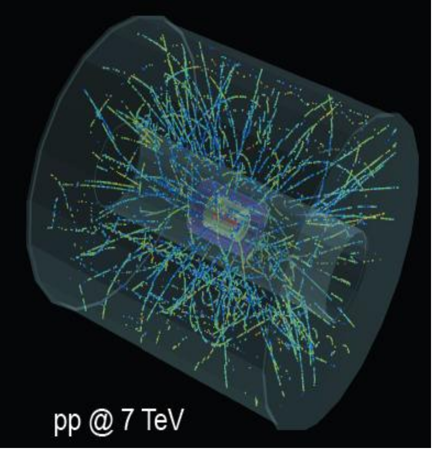
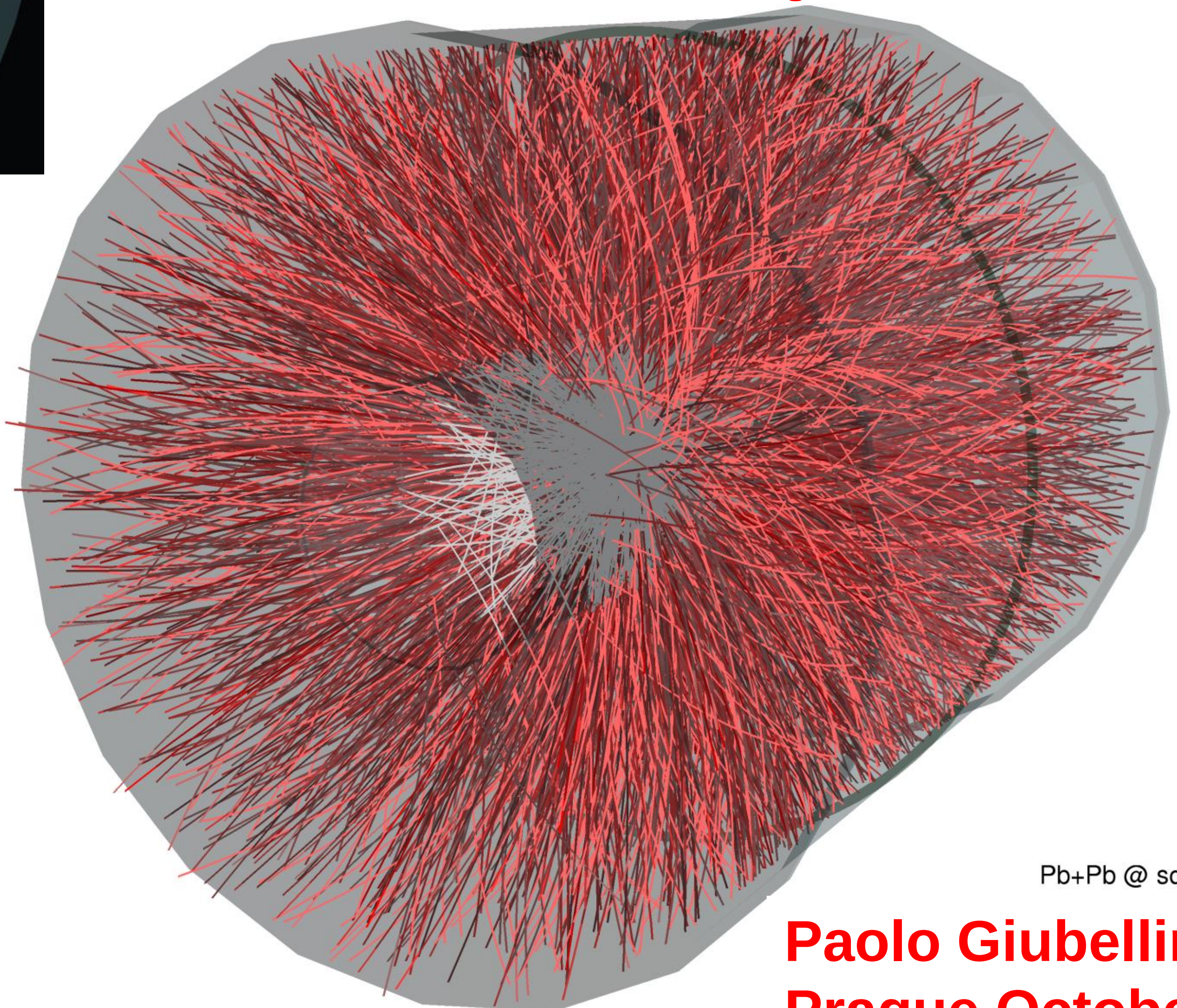


Highlights and prospects of the ALICE experiment

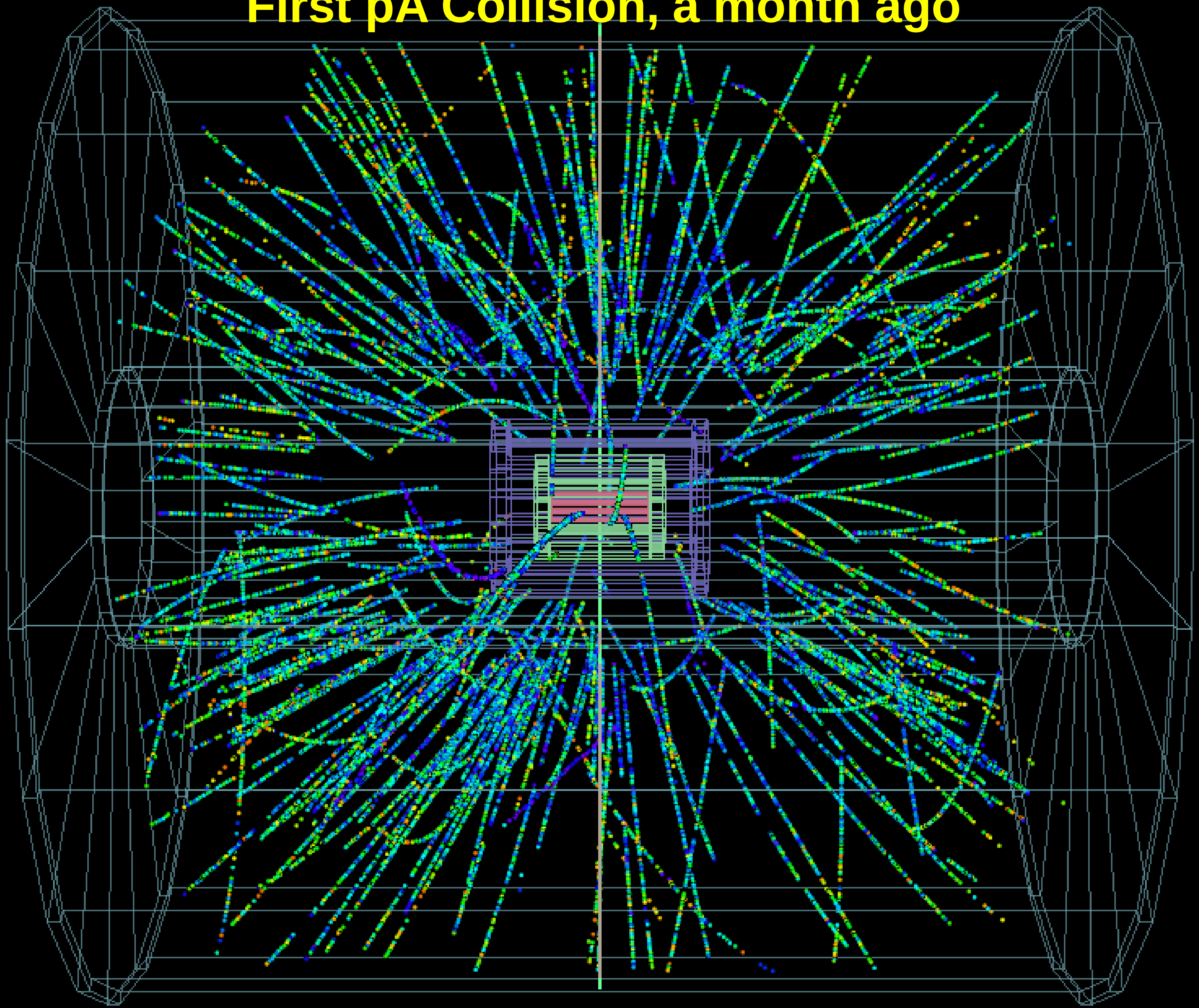


ALICE

Paolo Giubellino

Prague October 2012

First pA Collision, a month ago



QCD

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

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b beauty	4.3	−1/3

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

Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

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

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

Two puzzles in QCD: i) confinement

FERMIONS

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

Leptons spin = 1/2

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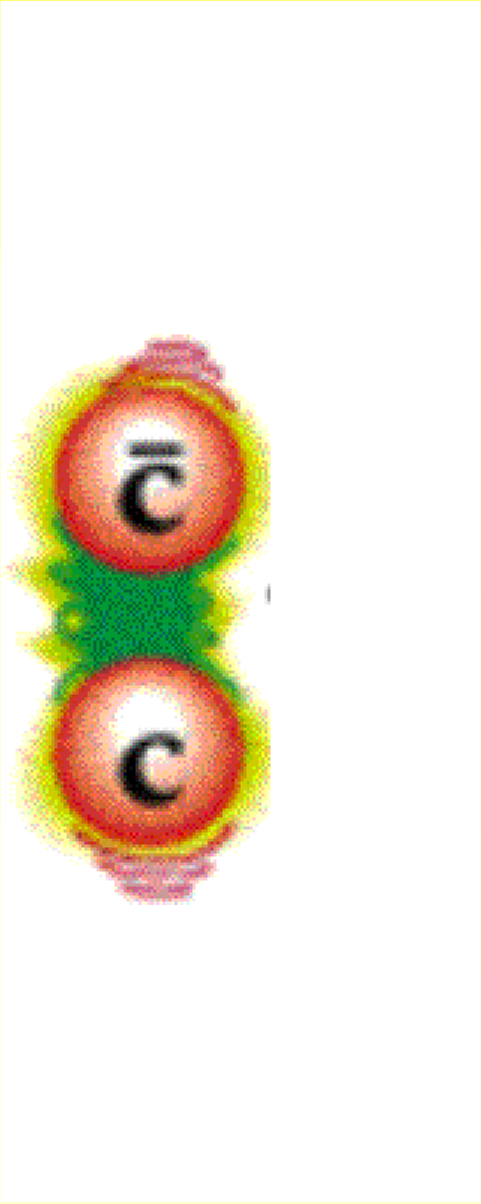
- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons.
- It looks like one half of the fundamental fermions are not directly observable…

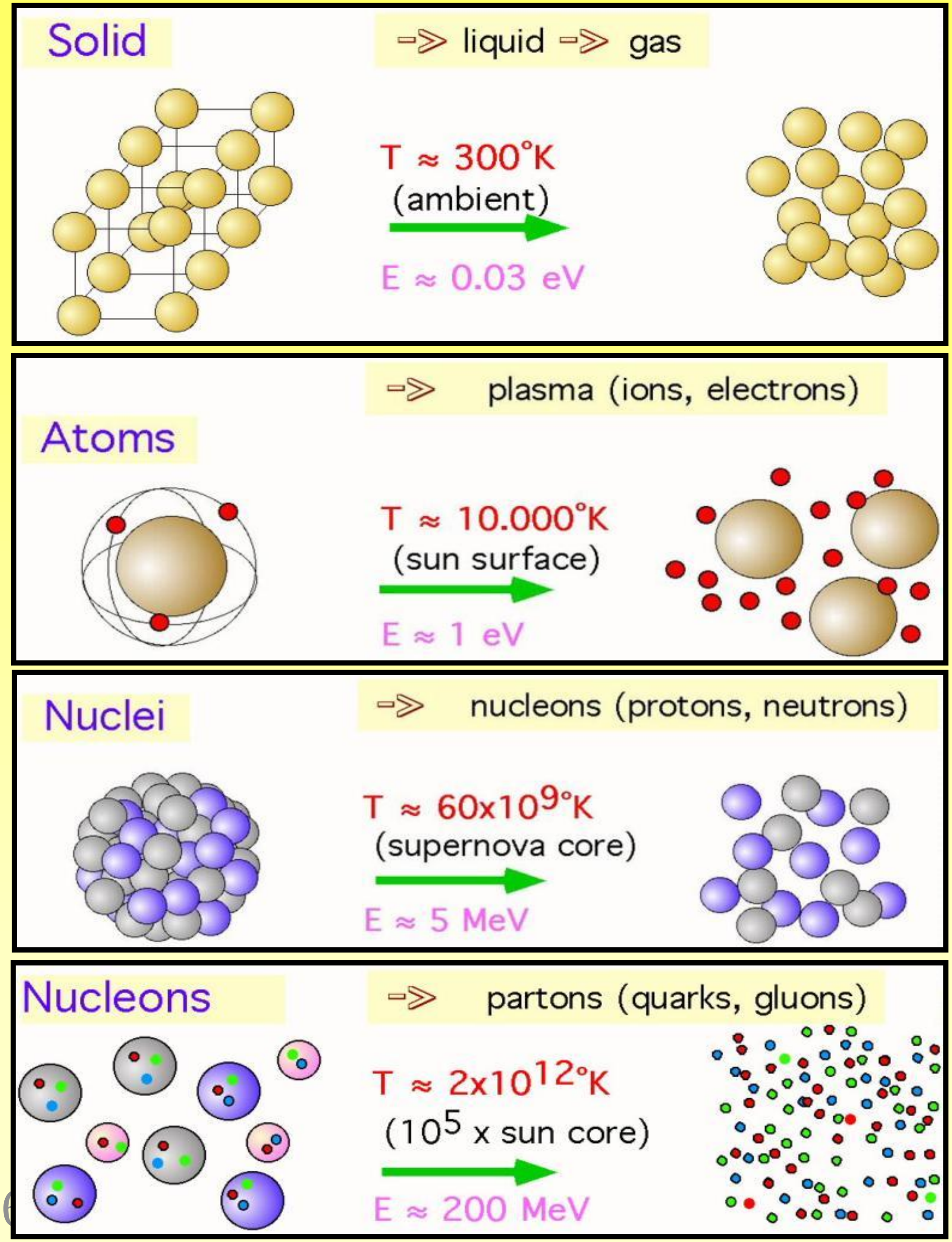
  how does this come about?

The Strong force and confinement



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

Melting Matter

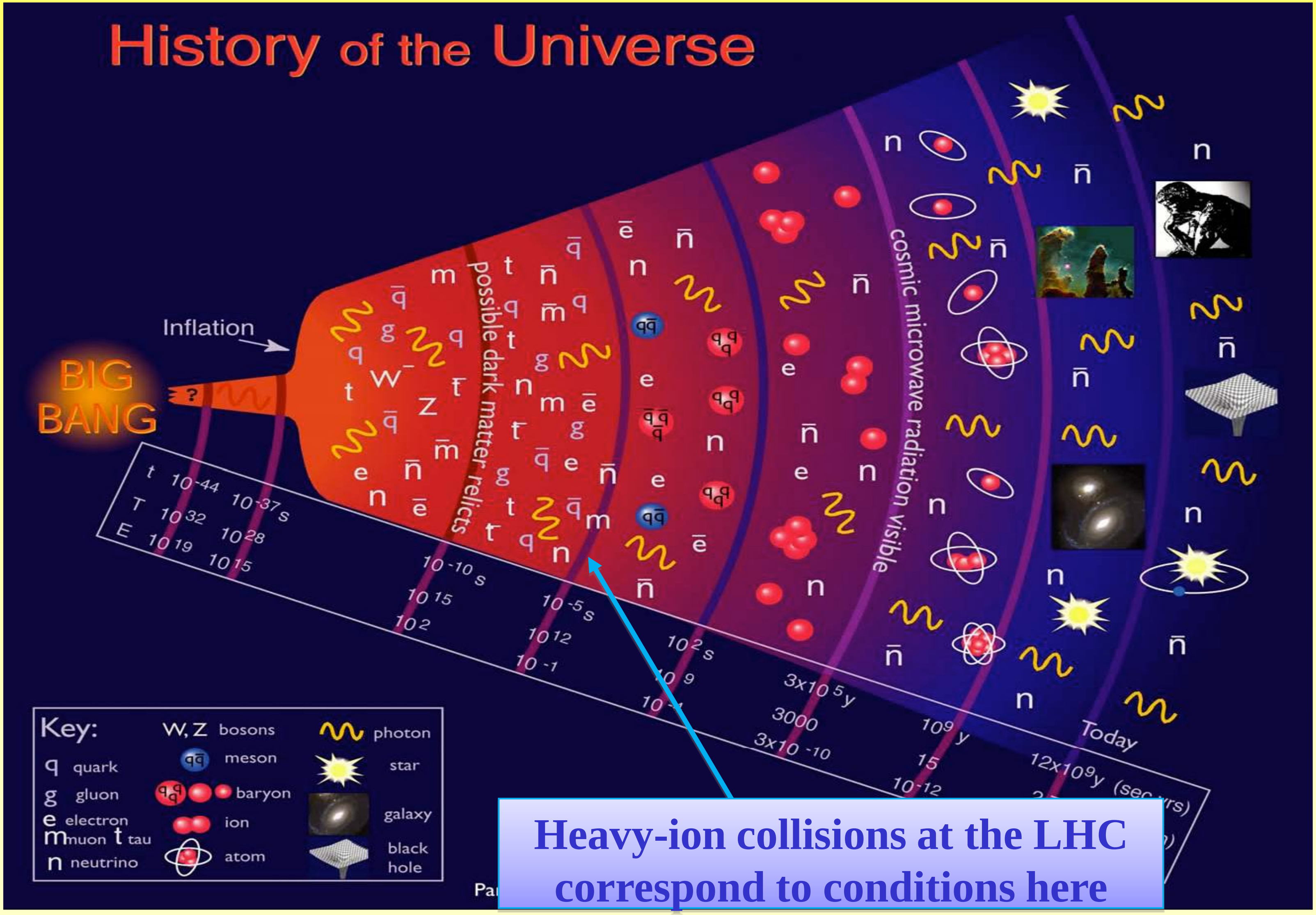


If the force grows with distance, at small distances it is small (*asymptotic freedom*)

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

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

Brief History of Our Universe



Heavy-ion collisions at the LHC correspond to conditions here

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

Puzzles in QCD: ii) hadron masses

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

Leptons spin = 1/2

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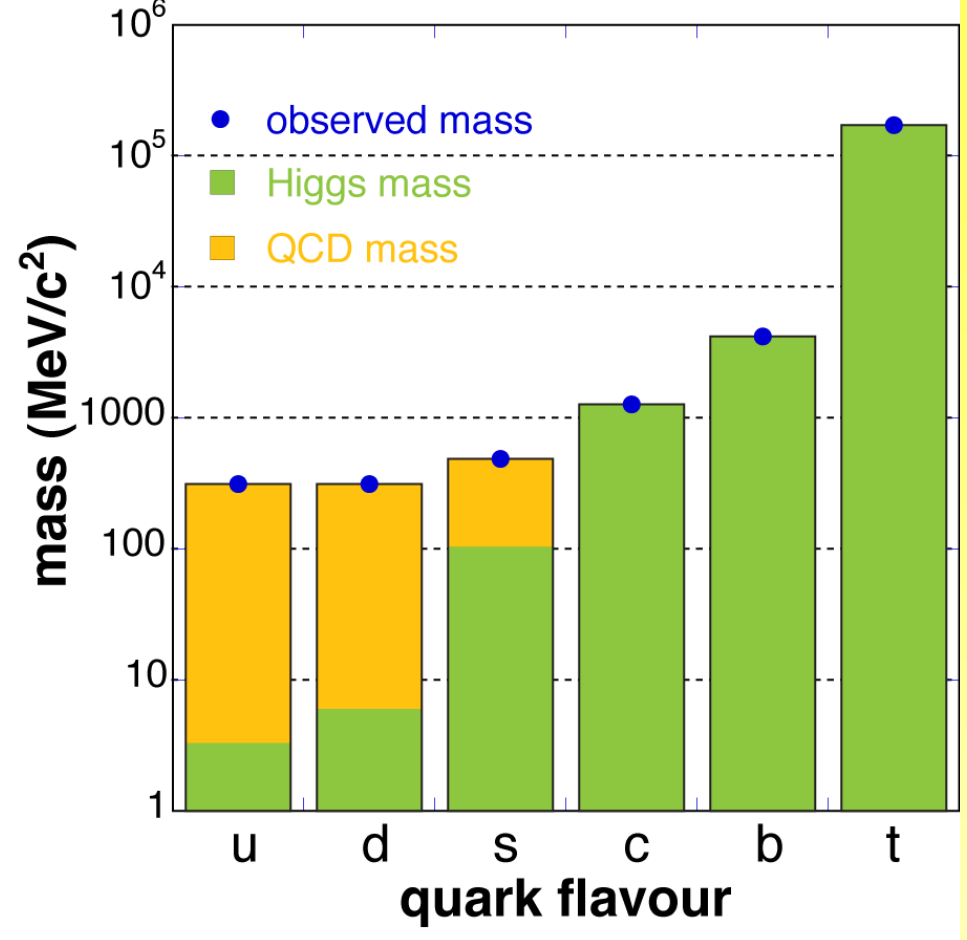
Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

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

Origin of hadron masses

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



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

Early Ideas

- 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
- 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"

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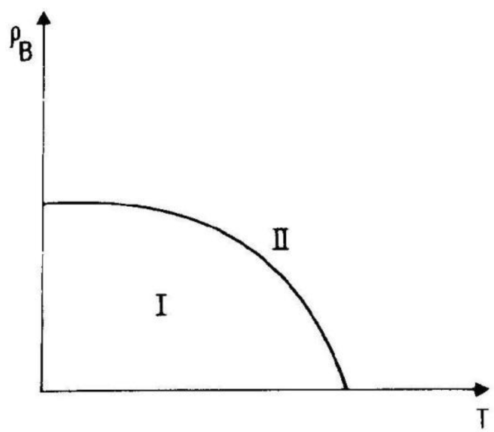


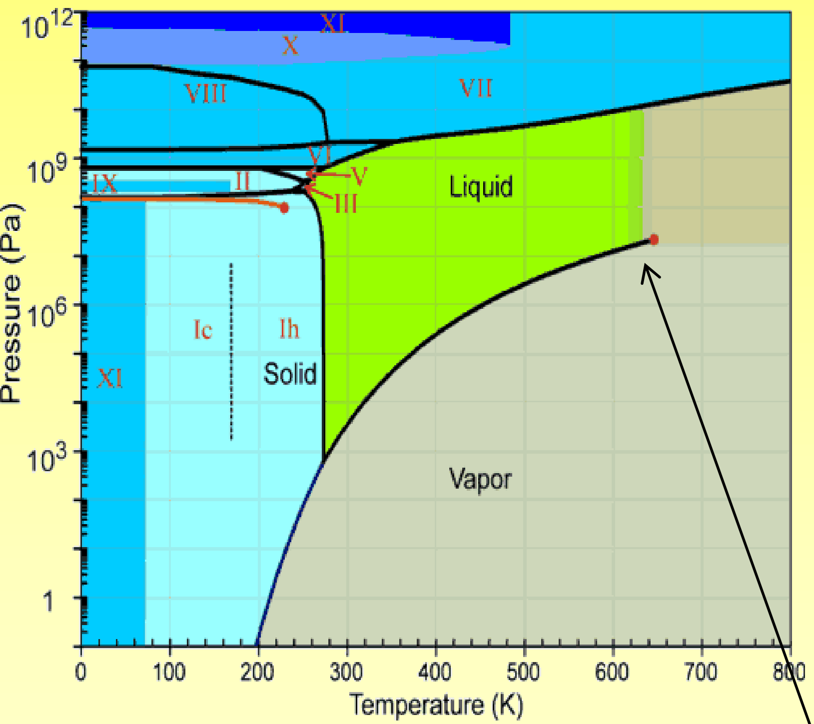
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

First schematic phase diagram (Cabibbo and Parisi, 1975)

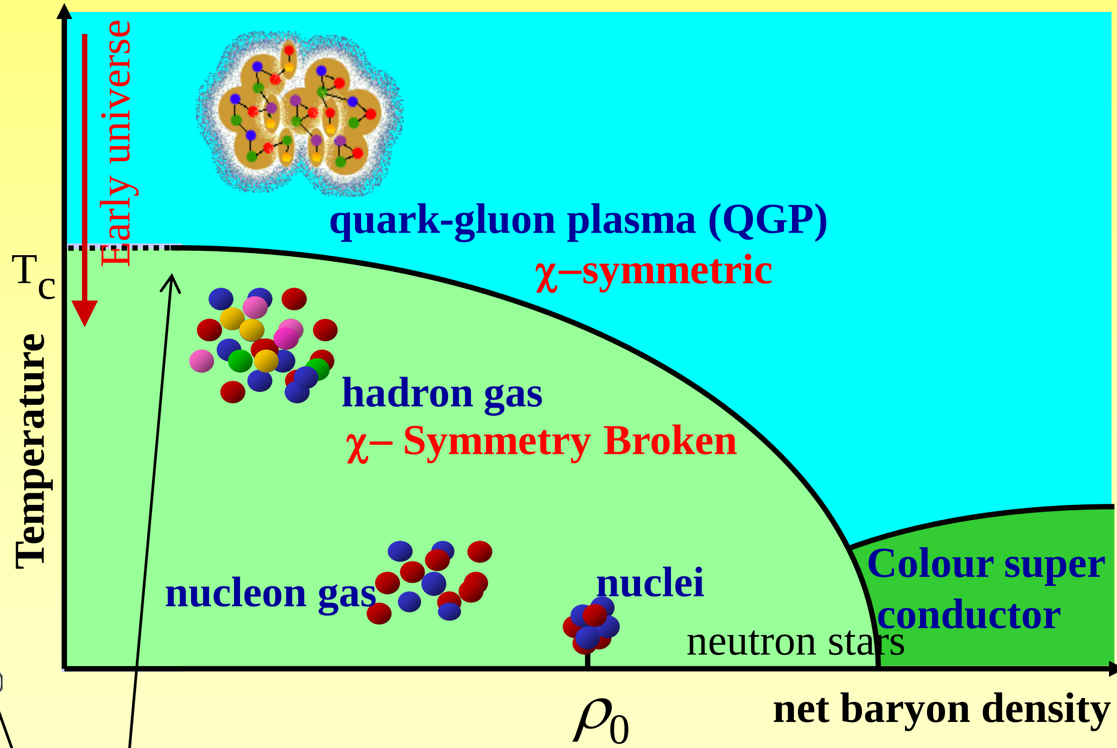
The QCD phase diagram

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

Complex picture, with many features



Phase diagram for H_2O

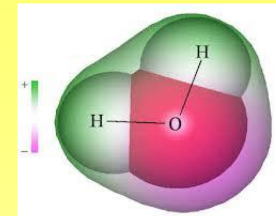


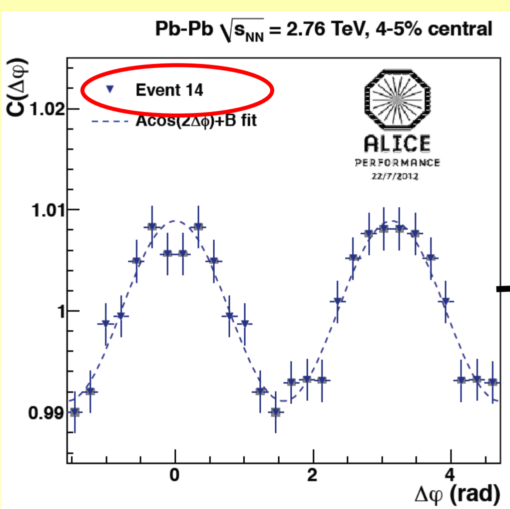
Critical endpoint

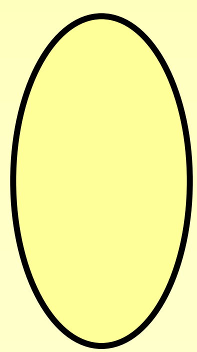
Study how collective phenomena and macroscopic properties of strongly interacting matter emerge from fundamental interactions

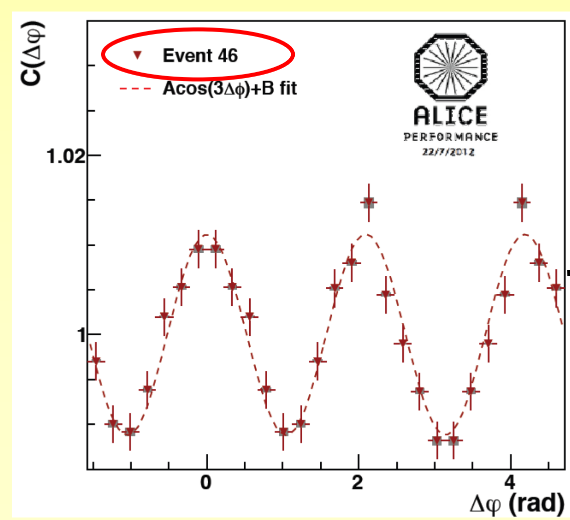
Heavy Ion Collisions

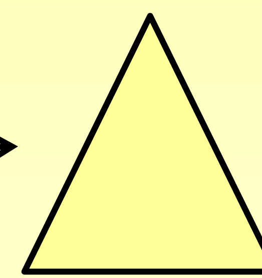
- Tool to tudy properties of **large, macroscopic** systems of strongly interacting matter (mean free path >> system size)
  - which are shaped by, but usually can not be derived from, its basic constituents and their interactions
  - H2O + QED: constituents and forces of 'water', but looking at a single (or a few) H20 molecules, we don't learn anything about the properties of 'water', its phases (ice, water, steam), …
  - we need a 'bucket' full and experiment with it
- Is it possible? **Yes!**
  - At LHC we can even measure the shape of each 'event'
    - by looking at the 'waves' generated in the liquid by the collision











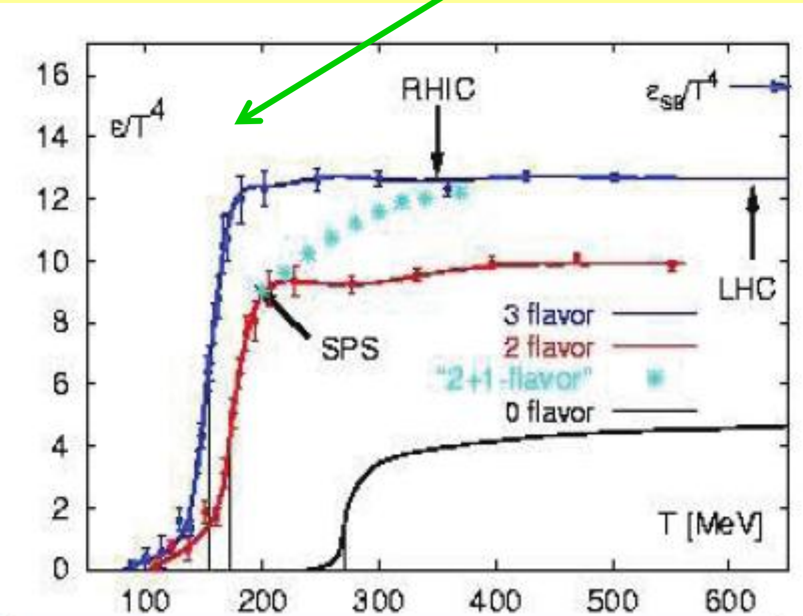
Lattice QCD

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

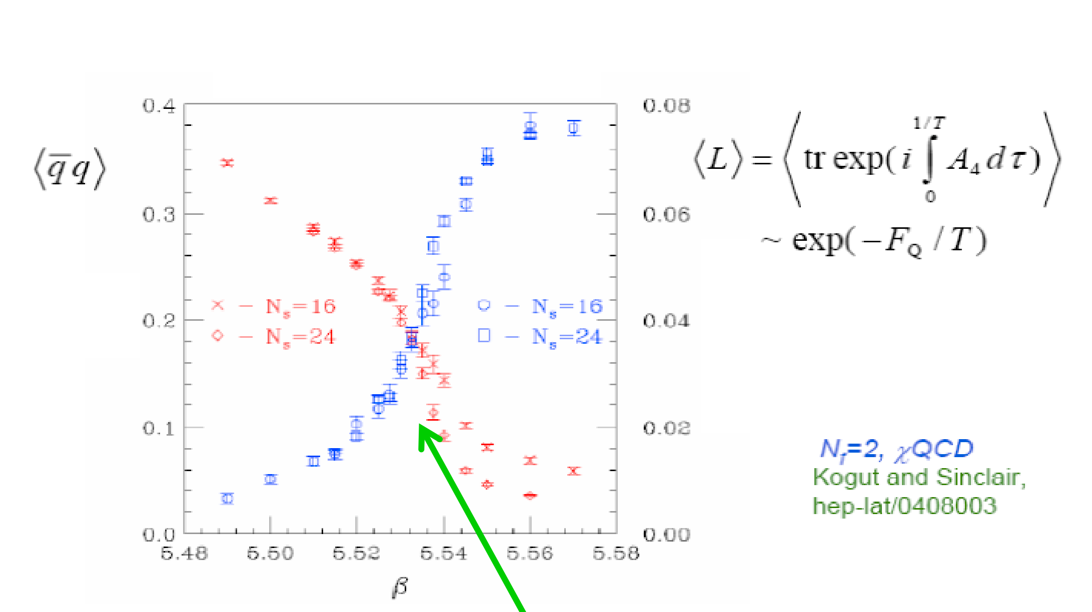
For the (2 + 1) flavor case (but zero baryon density): the phase transition to the QGP and its parameters are quantitative predictions of QCD.

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

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

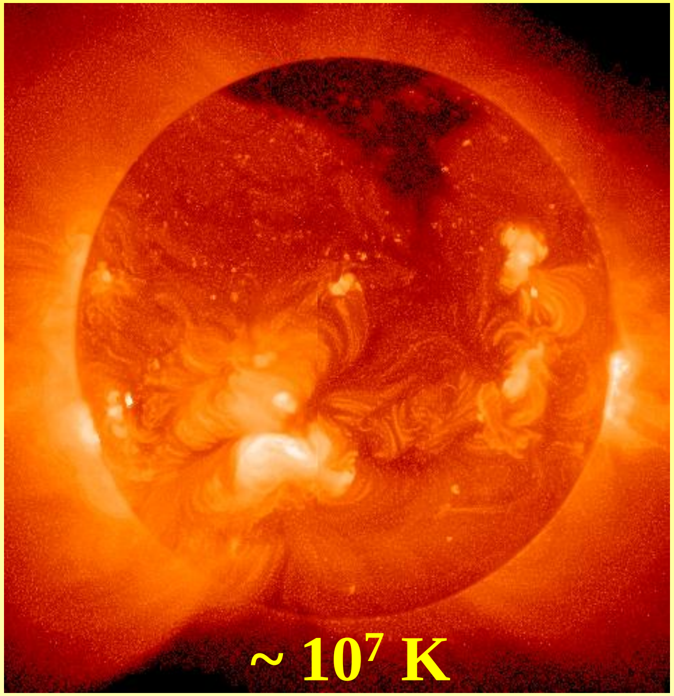


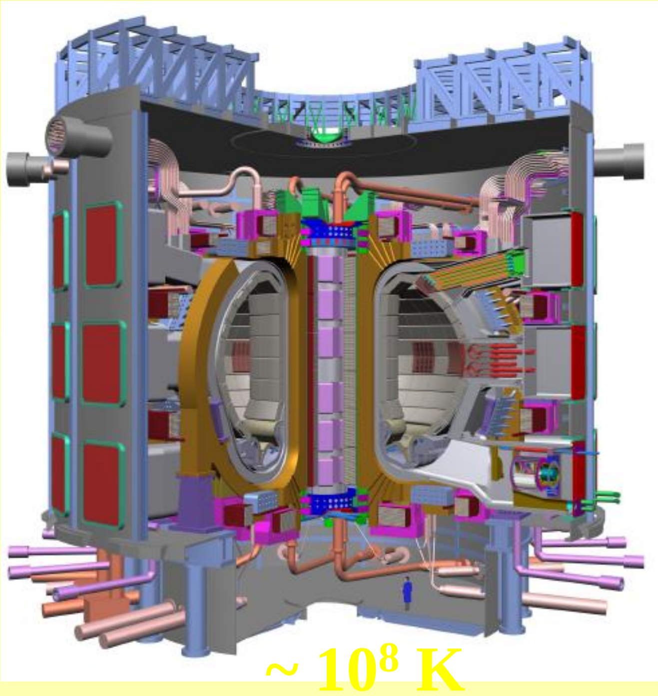
Lattice QCD calculations for μ_B= 0
Karsch et al, hep-lat/0305025

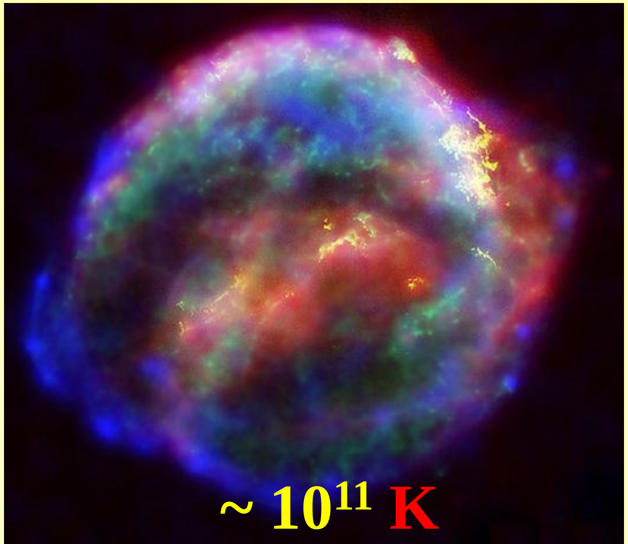


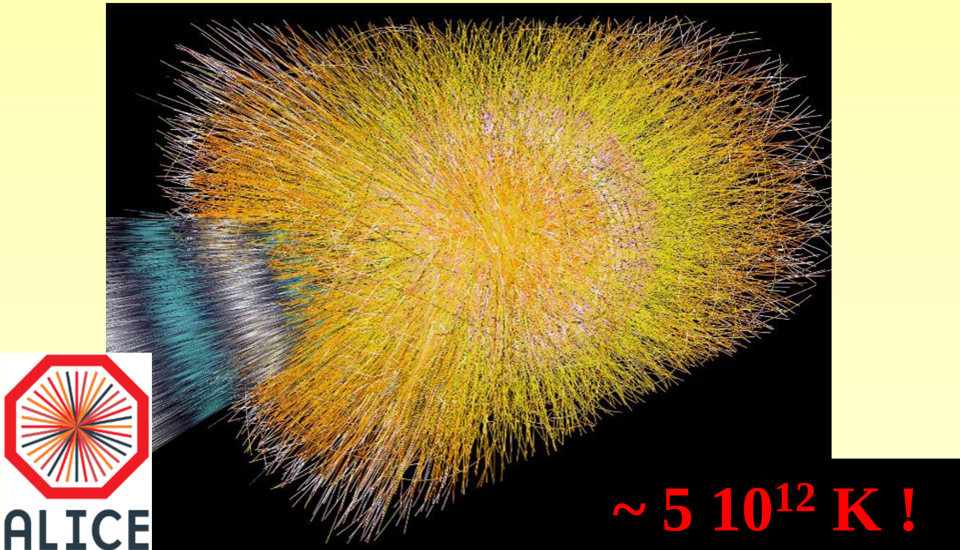
Moreover, Lattice QCD predicts a rapid transition, with correlated deconfinement and chiral restauration

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



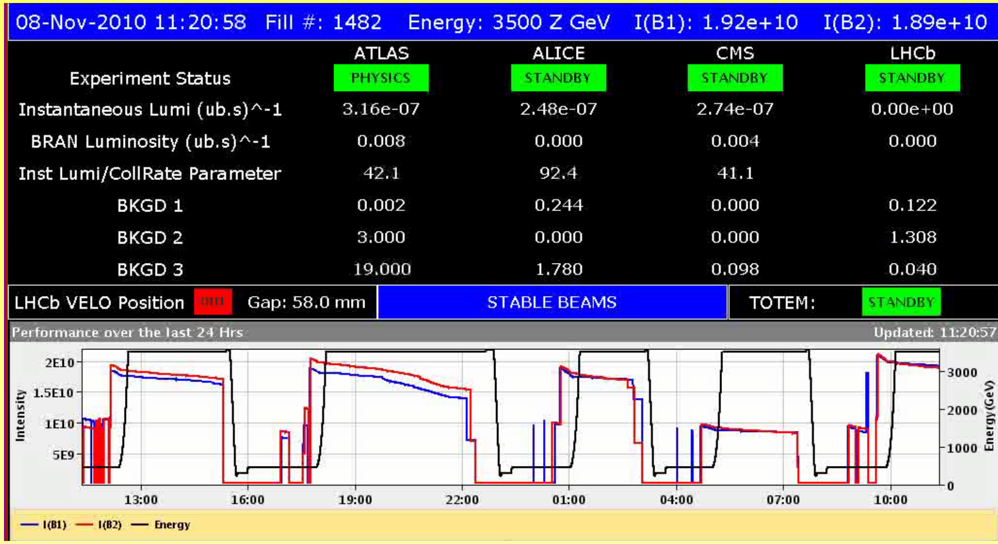


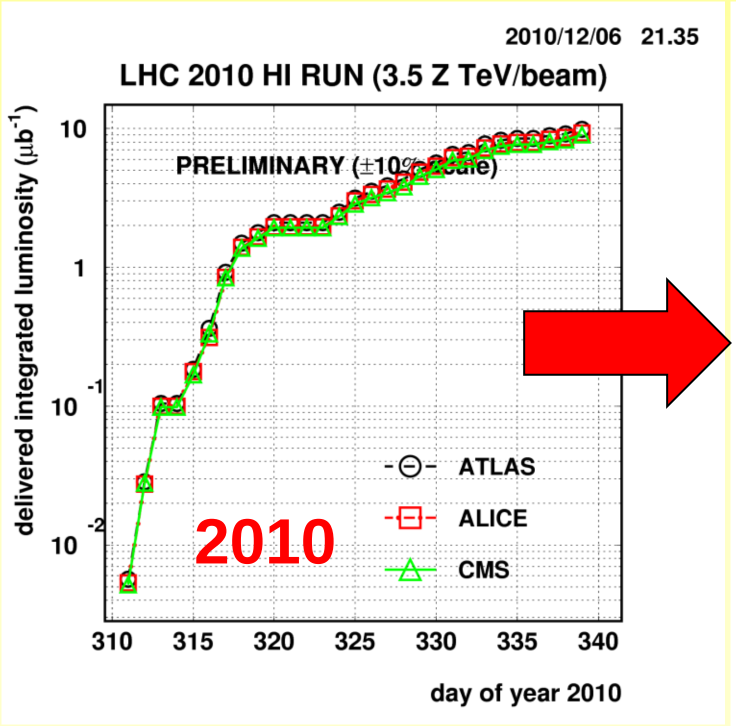


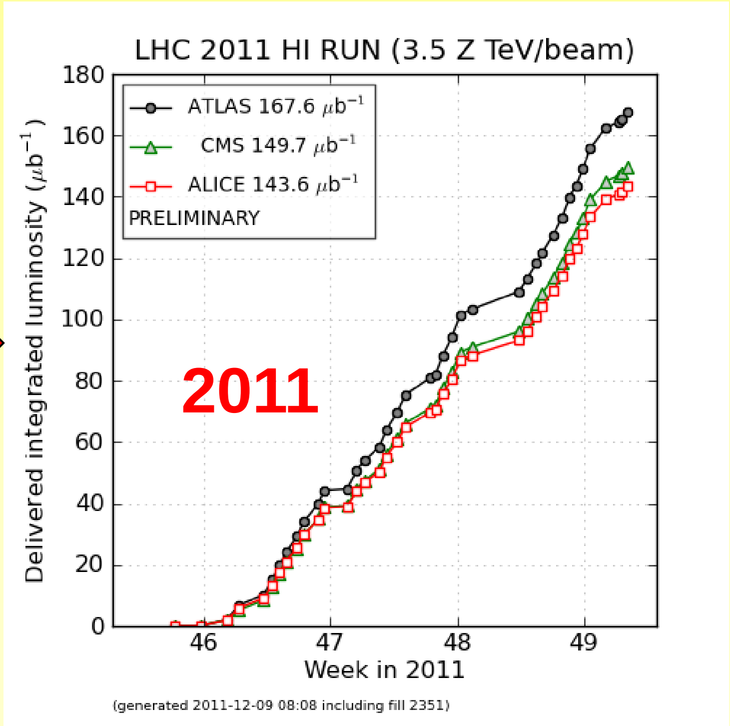


The LHC as a Heavy-Ion Collider

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





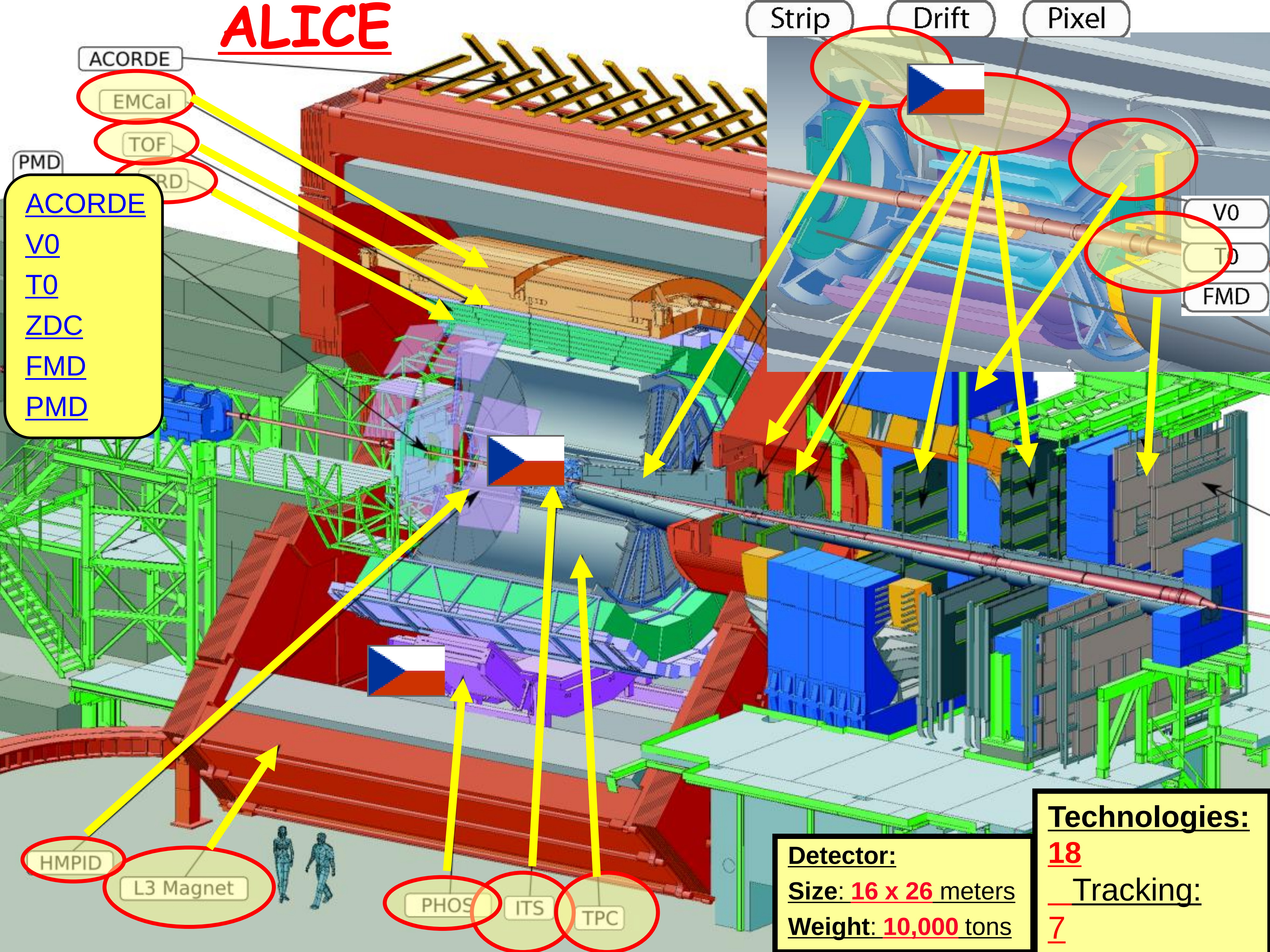


- **2011: > 10 times larger integrated luminosity + tests for pA**
- **2012: first pA collisions**
- **2013: pA run**

Heavy Ions 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, topology
    - Hadrons, leptons and photons + Excellent vertexing
- ATLAS and CMS
  - General-purpose detectors, optimized for hard processes
    - Excellent Calorimetry = > Jets
    - Excellent dilepton measuremens, especially at high p_T

ALICE



ACORDE
V0
T0
ZDC
FMD
PMD

Detector:

Size: 16 x 26 meters

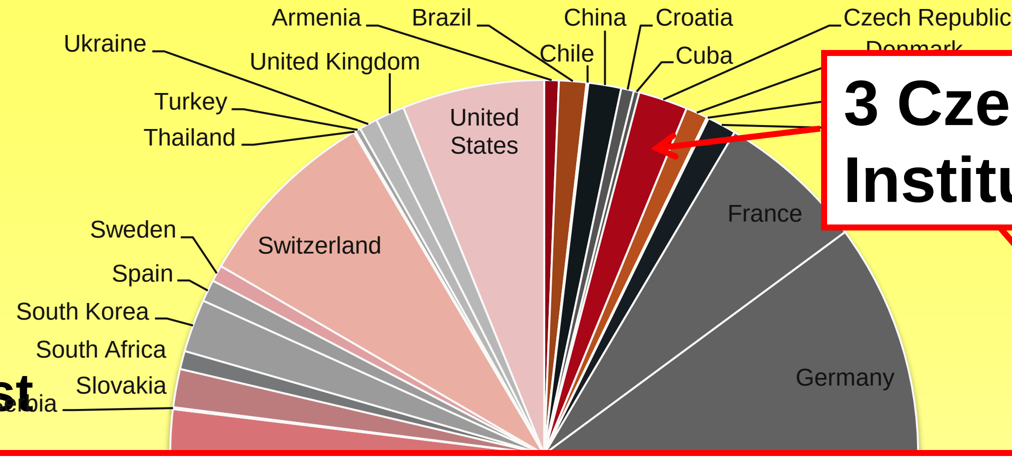
Weight: 10,000 tons

Technologies: 18

Tracking: 7

The ALICE Collaboration

~ 1300 **Members** from **both NP and HEP communities**
35 **Countries**
132 **Institutes**
~ 160 MCHF capital cost
(+ 'free' magnet)



3 Czech Institutions

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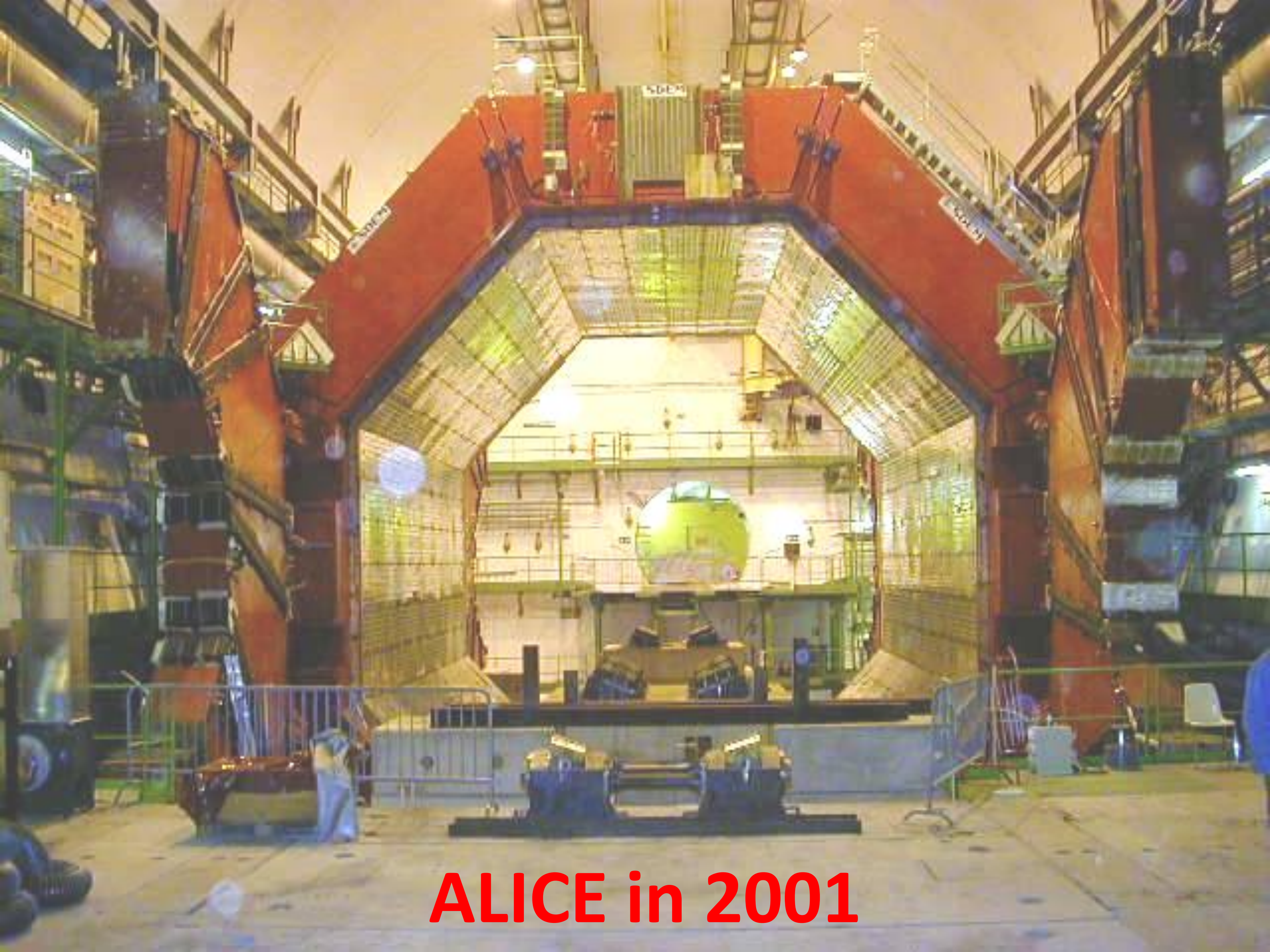
28 ALICE members from three Institutes:

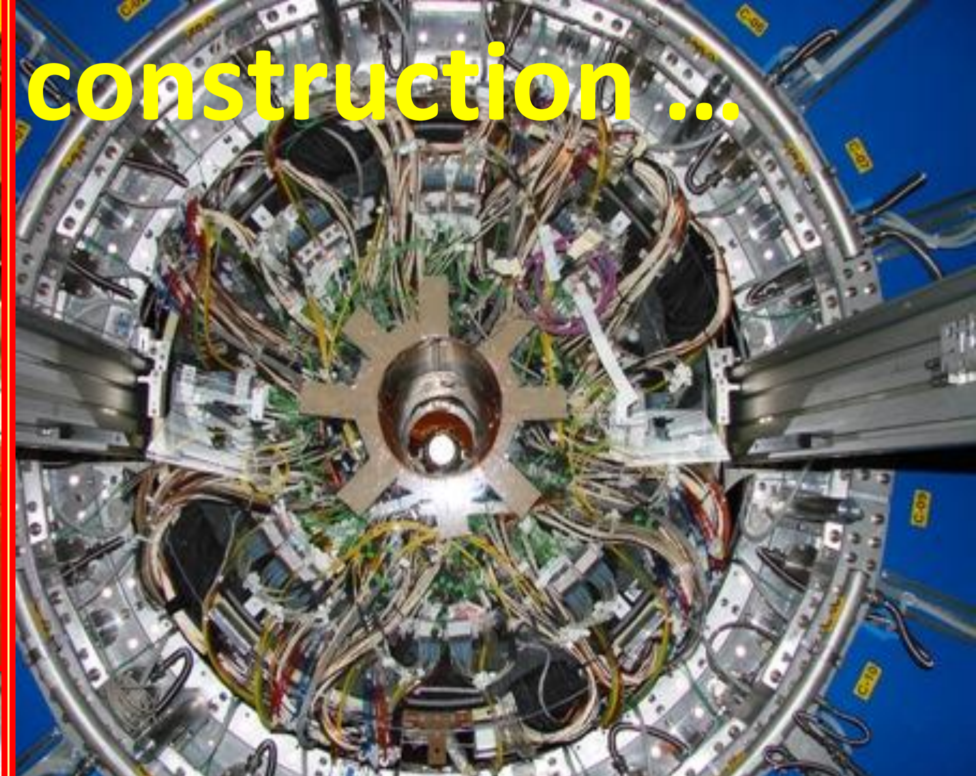
- ✓ Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Prague
- ✓ Institute of Physics, Academy of Sciences of the Czech Republic, Prague
- ✓ Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Rez

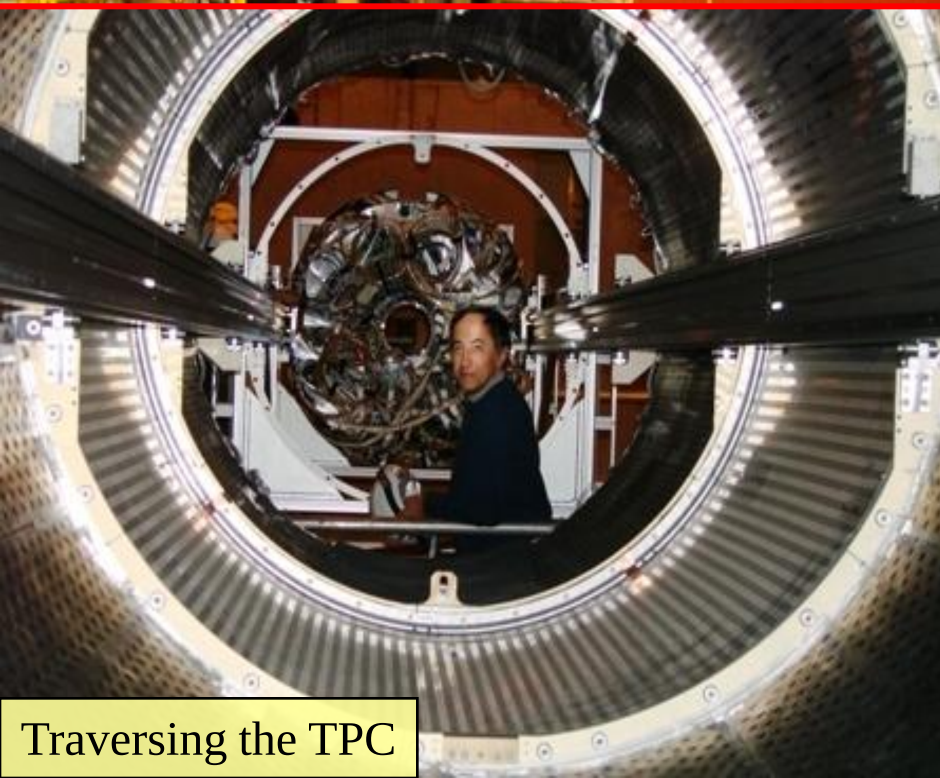
Among the ALICE founders

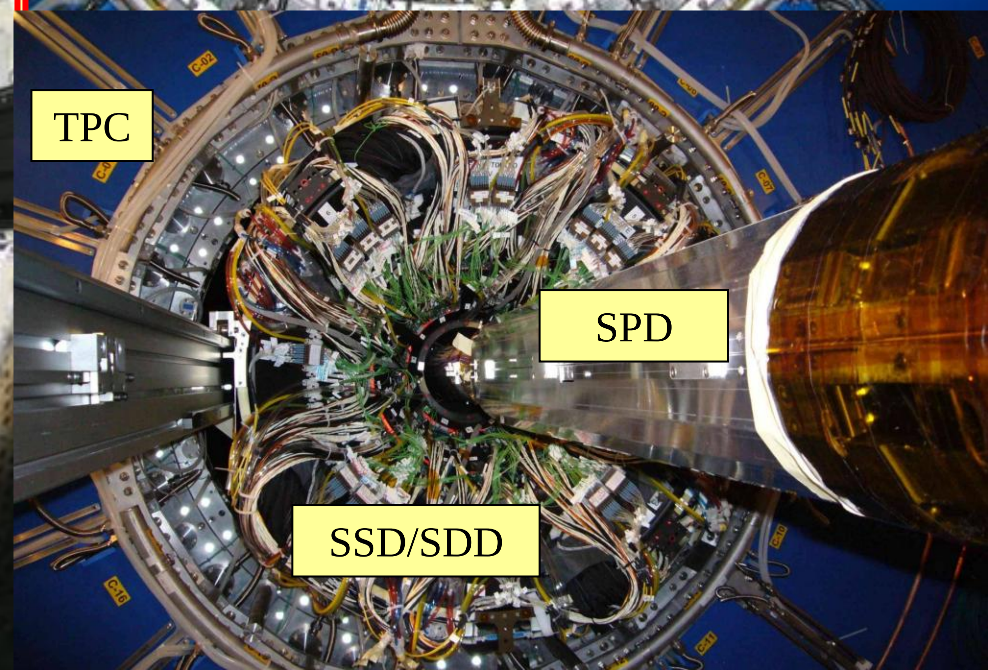


ALICE in 2001

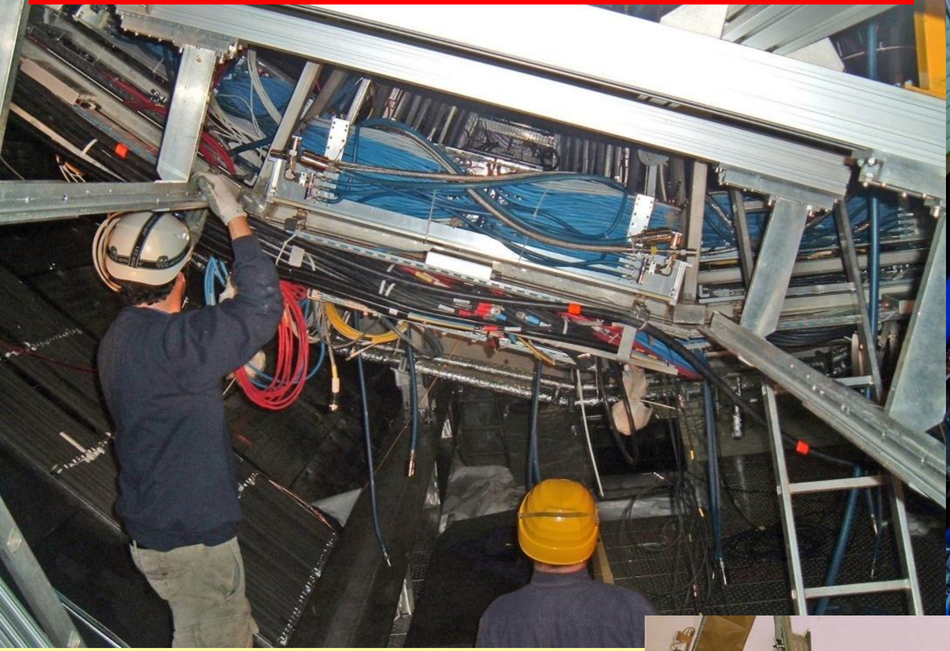
… in construction …



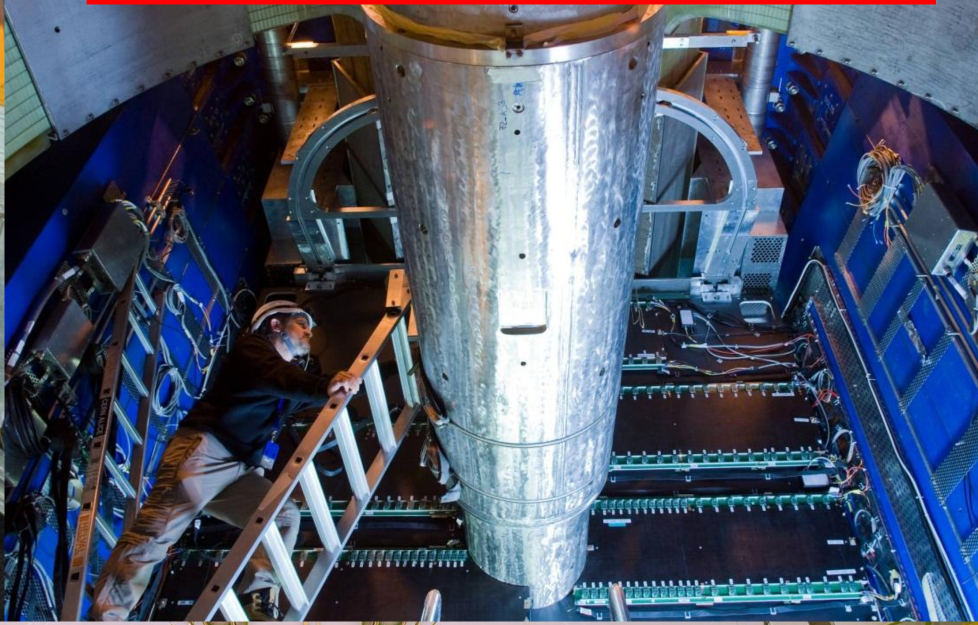




Insertion of final TOF super module



Installation of final muon chamber



ALICE in 2008

Formal end of ALICE installation July 2008

The CZECH REPUBLIC in ALICE: the PHOS GROUP

ALICE

PHOS (PHOton Spectrometer) is a high resolution electromagnetic calorimeter consisting of 17920 detection channels based on leadtungstate crystals (PWO).

- Energy range: ~ 0.5-10 GeV
- Very high granularity (~same cell size as CMS EMcal at ~ 3 times larger distance)
- PHOS provides unique coverage of the following physics topics:
  - study initial phase of the collision of heavy nuclei via direct single photons and diphotons,
  - Jet-quenching as a probe of deconfinement, studied via high pT_and π^0,
  - signals of chiral-symmetry restoration.

Czech group

- Studies of optical and detection properties of the PWO crystals
- Cooperation with the Czech factories TENEZ Chotebor and DUO Opocno on production of special mechanical components for PHOS (e.g. CRADLE)
- Participation in assembling of the individual PHOS modules


Works at the set-up


PHOS module


PHOS CRADLE delivered to CERN

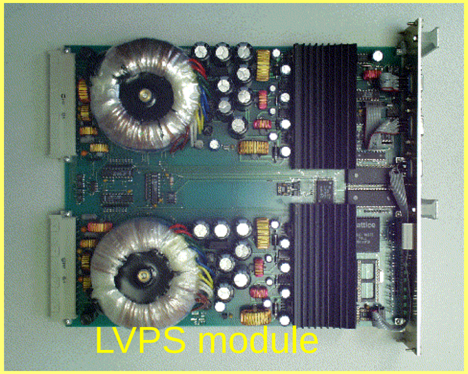
The CZECH REPUBLIC in ALICE: the SDD GROUP

SDD (Silicon Drift Detectors)

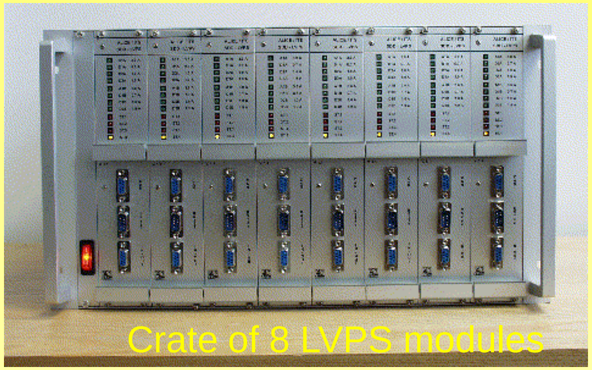
- position sensitive
- based on the measurement of the drift time of the electron cloud produced by the passage of a particle from its crossing point to collection anodes under the effect of a built-in electrostatic field

Czech group

- Since 1994 collaboration with INFN (Torino, Trieste)
- Development of SDD prototypes
- Participation in SDD testing: in laboratory and at CERN SPS beams
- Studies of the SDD performance with the inclined tracks
- Studies of SDD radiation hardness
- **Development of the Low Voltage Power Supply system: Developed at NPI ASCR and FNSPE CTU Manufactured by Czech company AREMPRO, Prague**
- **Development and implementation of SDD Detector Control system, at FNSPE CTU**



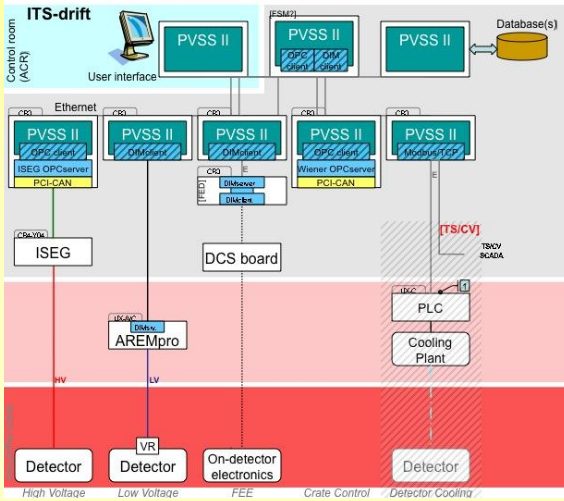
LVPS module



Crate of 8 LVPS modules

Installed LVPS system at P2

Jiří Král, graduate student of FNSPE CTU, testing the SDD DCS in ALICE



Scheme of SDD Detector Control System

Up to 4 Gbytes/s of data… how to handle them? The ALICE Grid

24

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) US
- ✓ 62 T2s spread over 4 continents

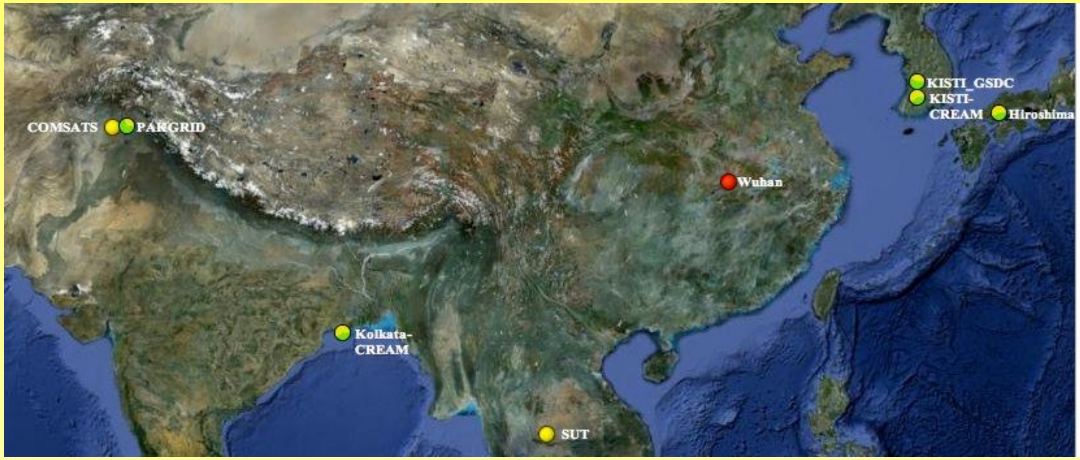
~30,000 (out of ~150,000 WLCG) cores and over 10 PB of disk and tape

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)

STORING, PROCESSING AND ANALYSIS OF THE DATA

Collaboration computing centers in WLCG Grid



Czech Republic:

- 1.9% of the total 2012 M&O-A budget
- 4.2% of total TIER2 for ALICE, Jan – Oct 2012
- 5.1% of total TIER2 for ALICE, Oct 2011 – Jul 2012

(http://accounting.egi.eu/tier2.php)

HEP/ALICE COMPUTING IN PRAGUE

The farm GOLIAS

A national computing center for processing data from various HEP experiments

- Located in the Institute of Physics in Prague
- Officially started in 2004, basic infrastructure already in 2002

Certified as a Tier2 center of LHC Computing Grid (praguelcg2), Collaboration with several Grid projects.

HEP/ALICE COMPUTING IN PRAGUE

The farm GOLIAS

April 2008, WLCG MoU signed for Golias (ALICE+ATLAS)

Excellent network connectivity: Multiple dedicated 1-10Gb/s connections to collaborating institutes

Provides computing services for ATLAS + ALICE, D0, Solid state physics, Auger, Star …

CURRENT NUMBERS

1 batch system (torque + maui)

2 main WLCG VOs: ALICE, ATLAS

- FNAL's D0 (dzero) user group
- Other EGEE VOs: Auger, Star

~ 3860 published cores in the Grid

> 1.5 PB on new disk servers (DPM, XRootD or NFSv3)

The use of virtualization at the site is quite extensive, most of the services are running on virtual machines

- **The WLCG services include:**
  - Grid UI, MonBox, ALICE VOBOX, CREAM-CE

Disk XRootD Storage Element ALICE::Prague::SE

538.7 TB of disk space in total

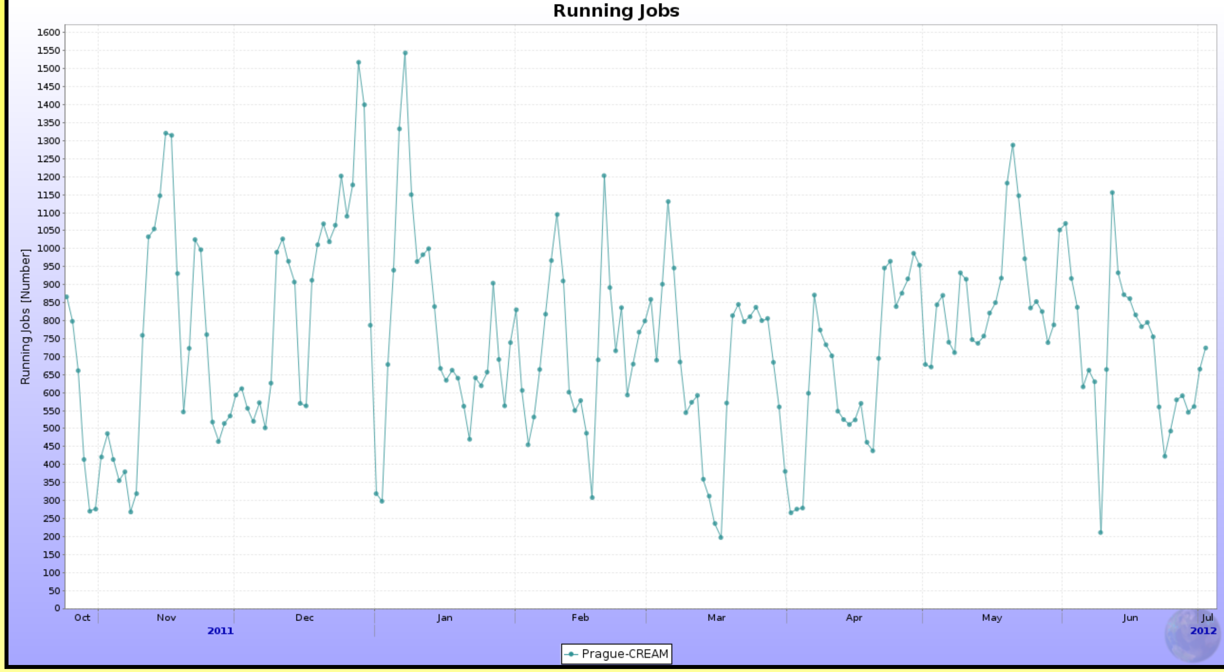
Redirector + 3 clients @ Golias, 4 clients @ NPI Rez

distributed SE/storage cluster for ALICE

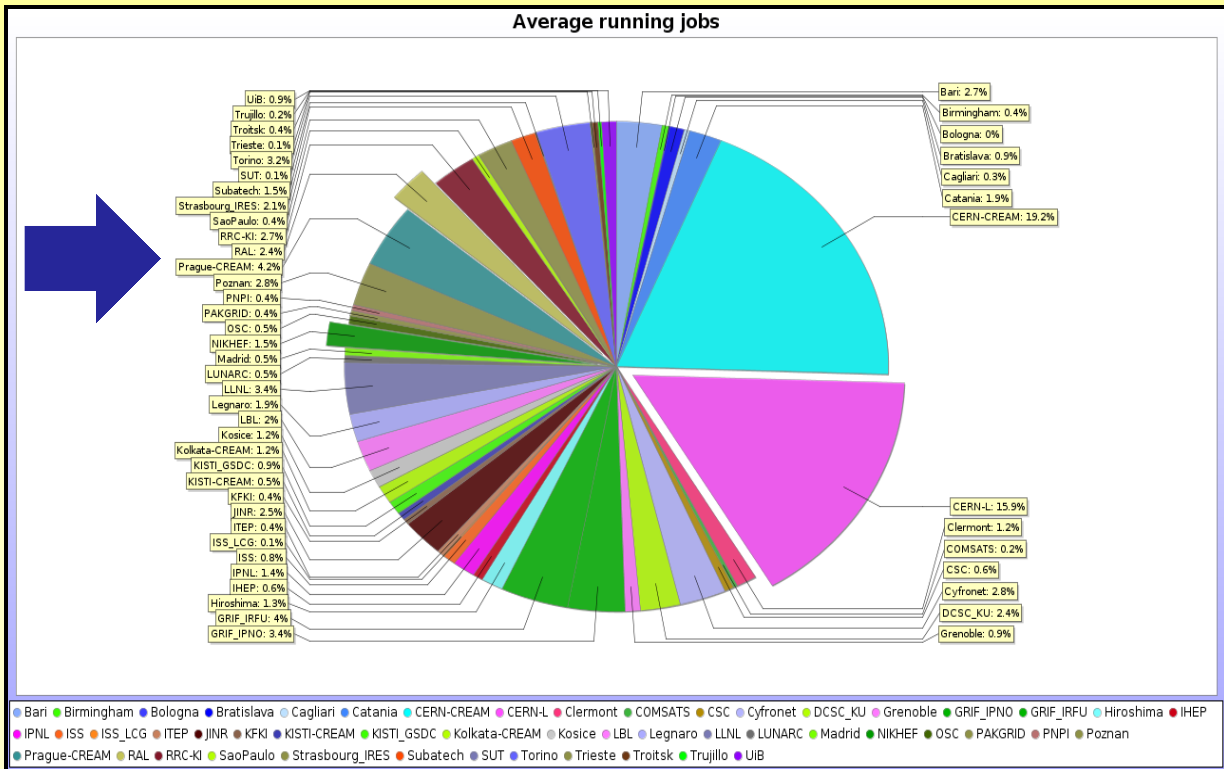
NETWORK TRAFFIC ON PRAGUE ALICE STORAGE CLUSTER, 23.10.2011 – 02.07.2012

Total data read 1.629 PB, max. IN 510 MB/s, max. OUT 850 MB/s

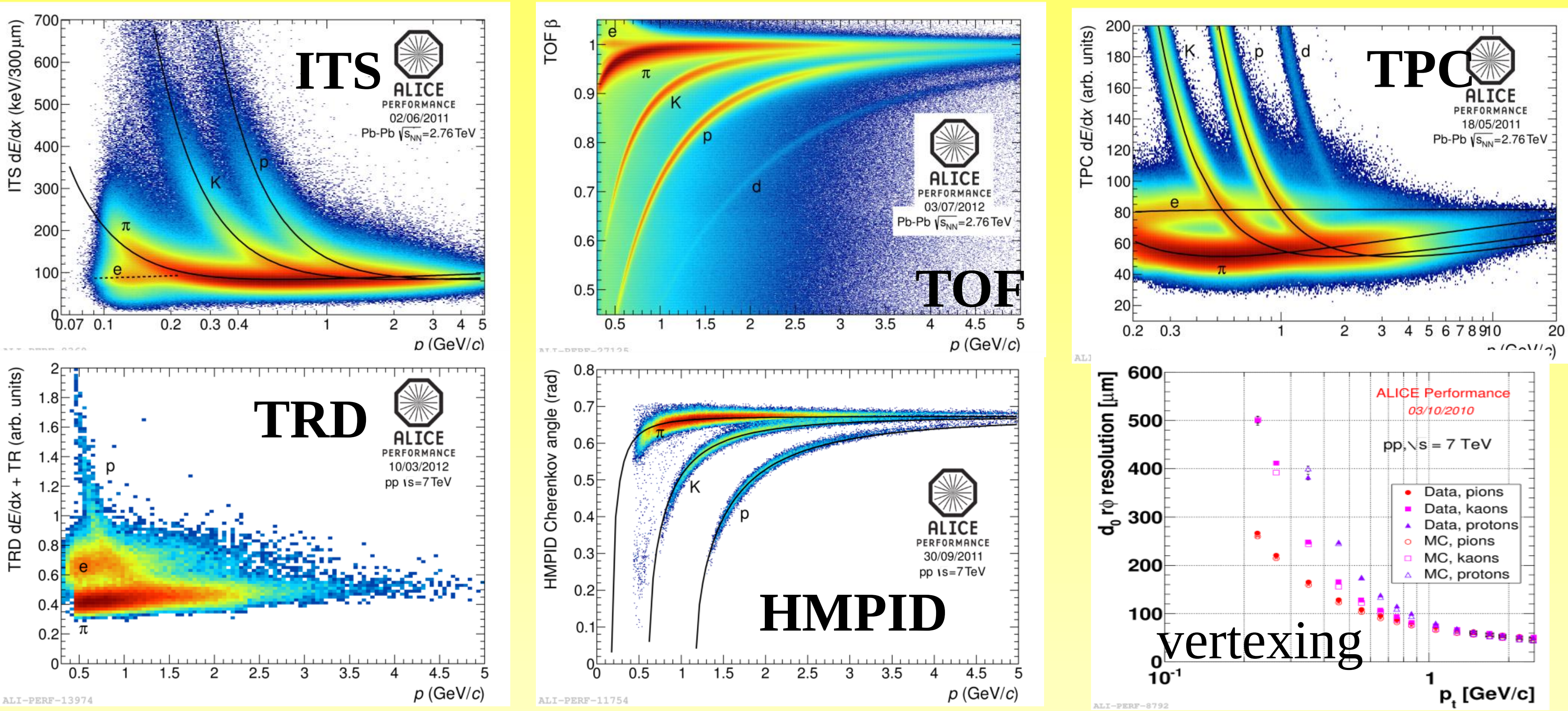
RUNNING ALICE JOBS IN PRAGUE, 23.10.2011-02.07.2012: avg. 743, max. 1544



CZECH CONTRIBUTION TO ALICE JOB PROCESSING, in 23.10.2011 – 02.07.2012: 4.2%



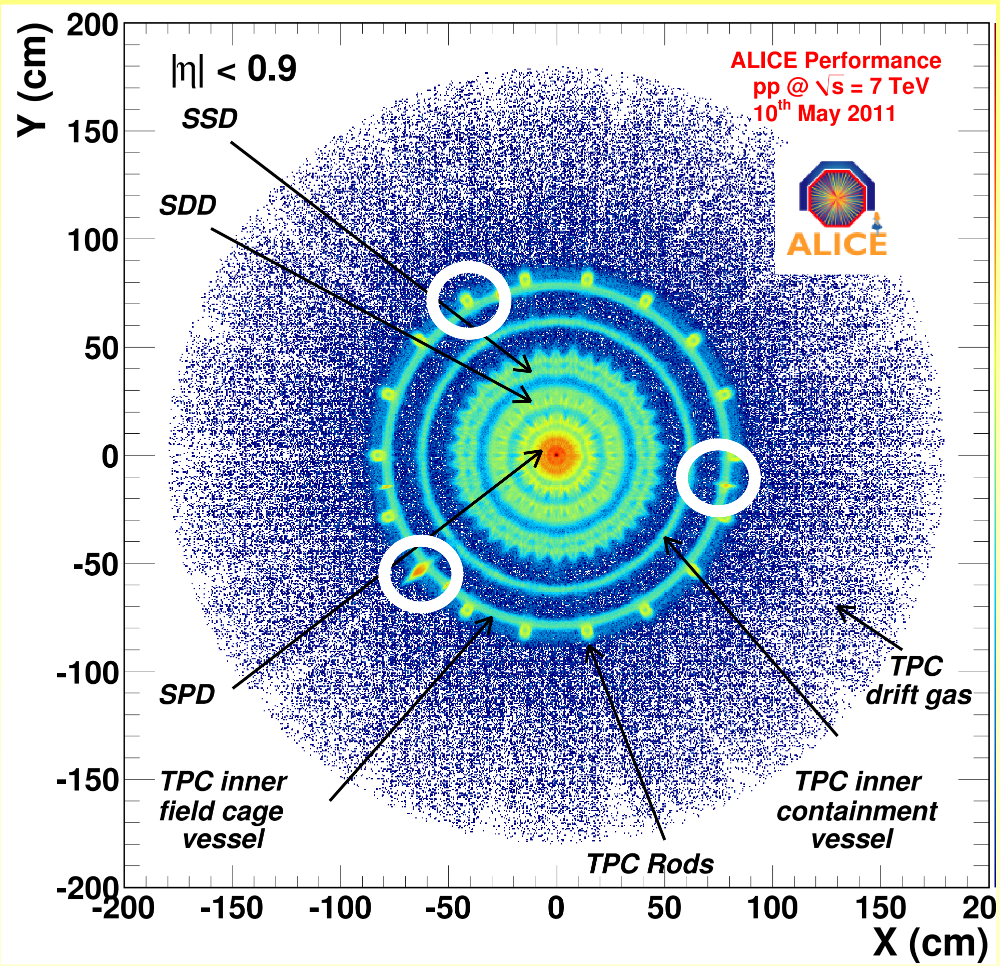
ALICE performance

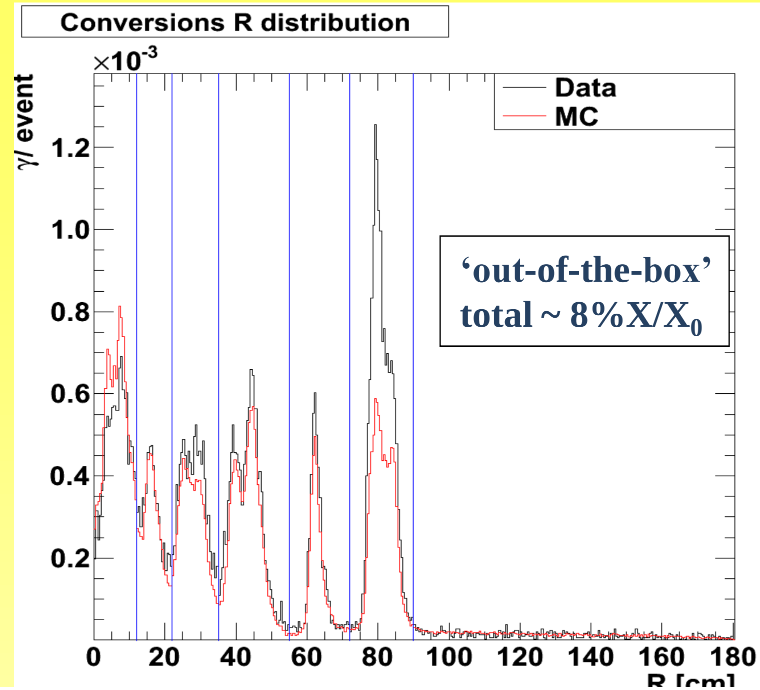


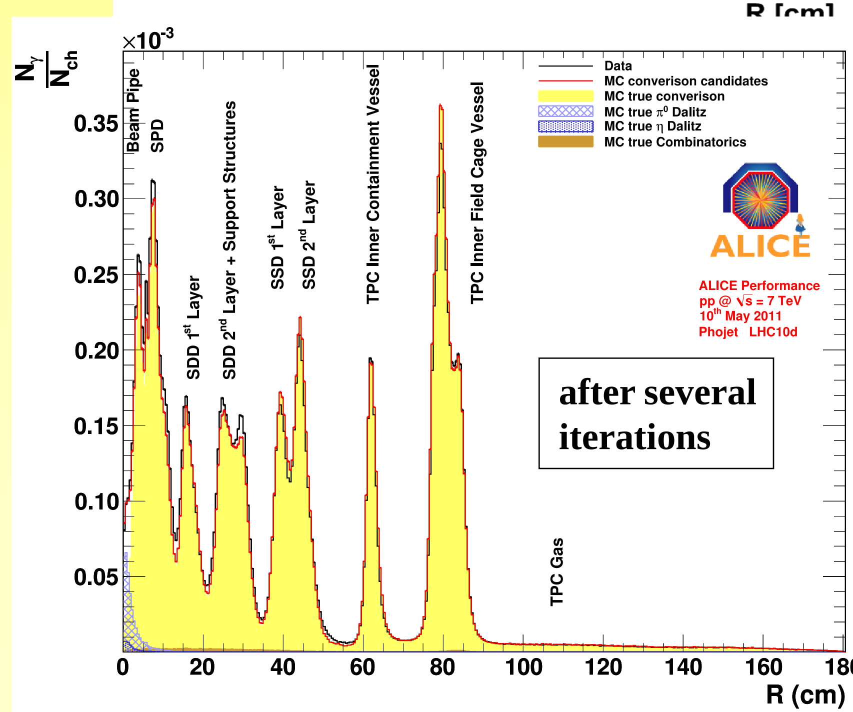
- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of X_0
- excellent vertexing capability
- efficient low-momentum tracking – down to ~ 100 MeV/c

Material

γ-ray image of ALICE
photon conversion vertices







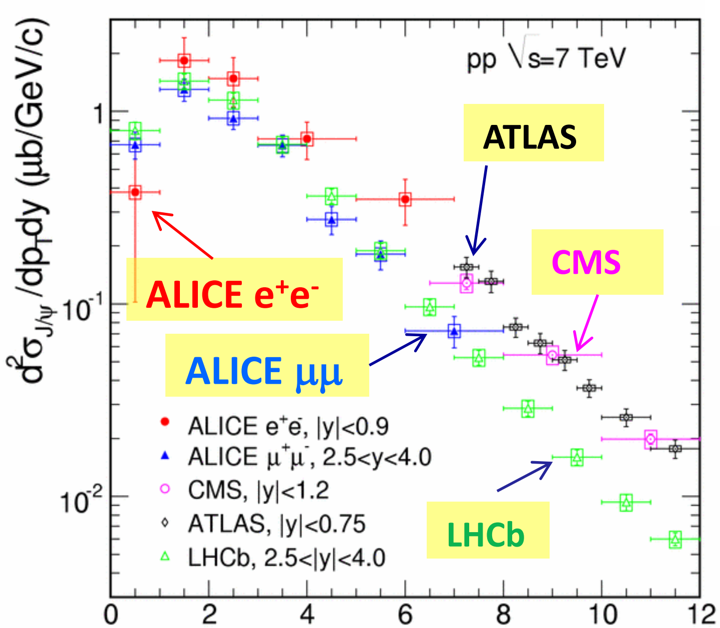
The ALICE program

- **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
    - $dN_{ch}/d\eta$ comparable to the one in HI => mini-plasma ?
- **pA**

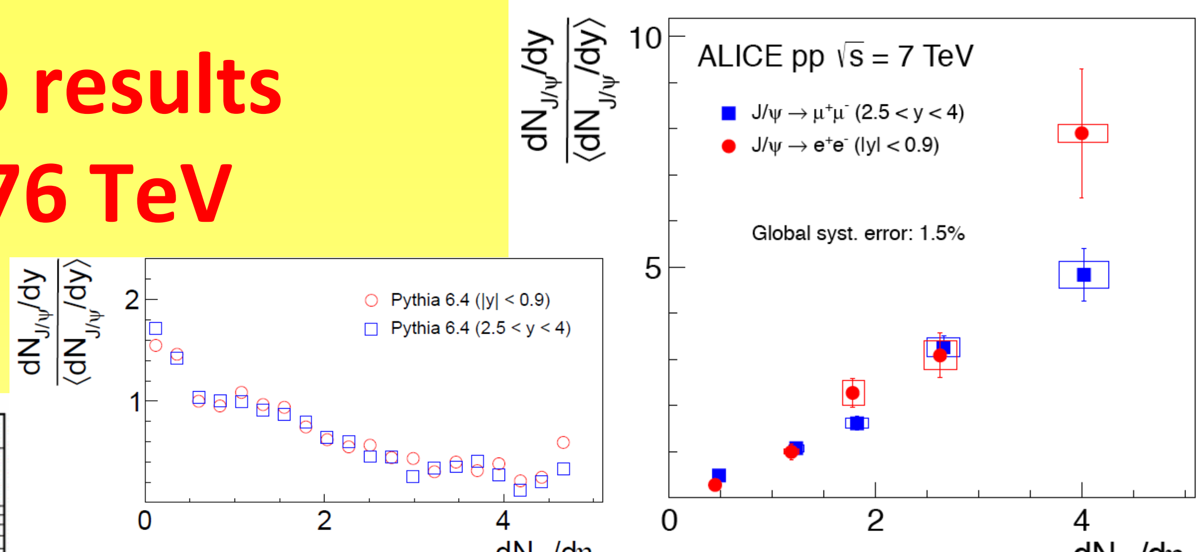
essential for the interpretation of PbPb data (shadowing, cold nuclear matter effects)

=> November 2012!

A taste of pp results at 7 and 2.76 TeV

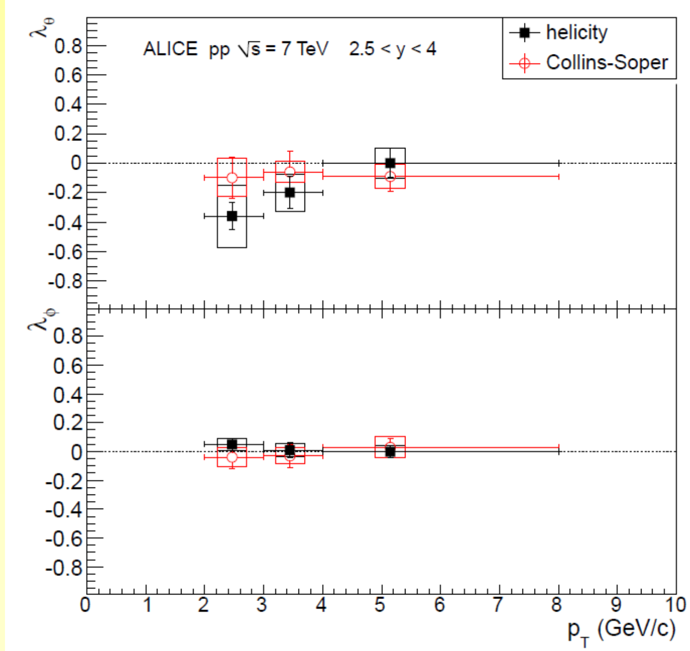


J/ψ 4 LHC experiments



Phys. Lett. 712 (2012) 165-175

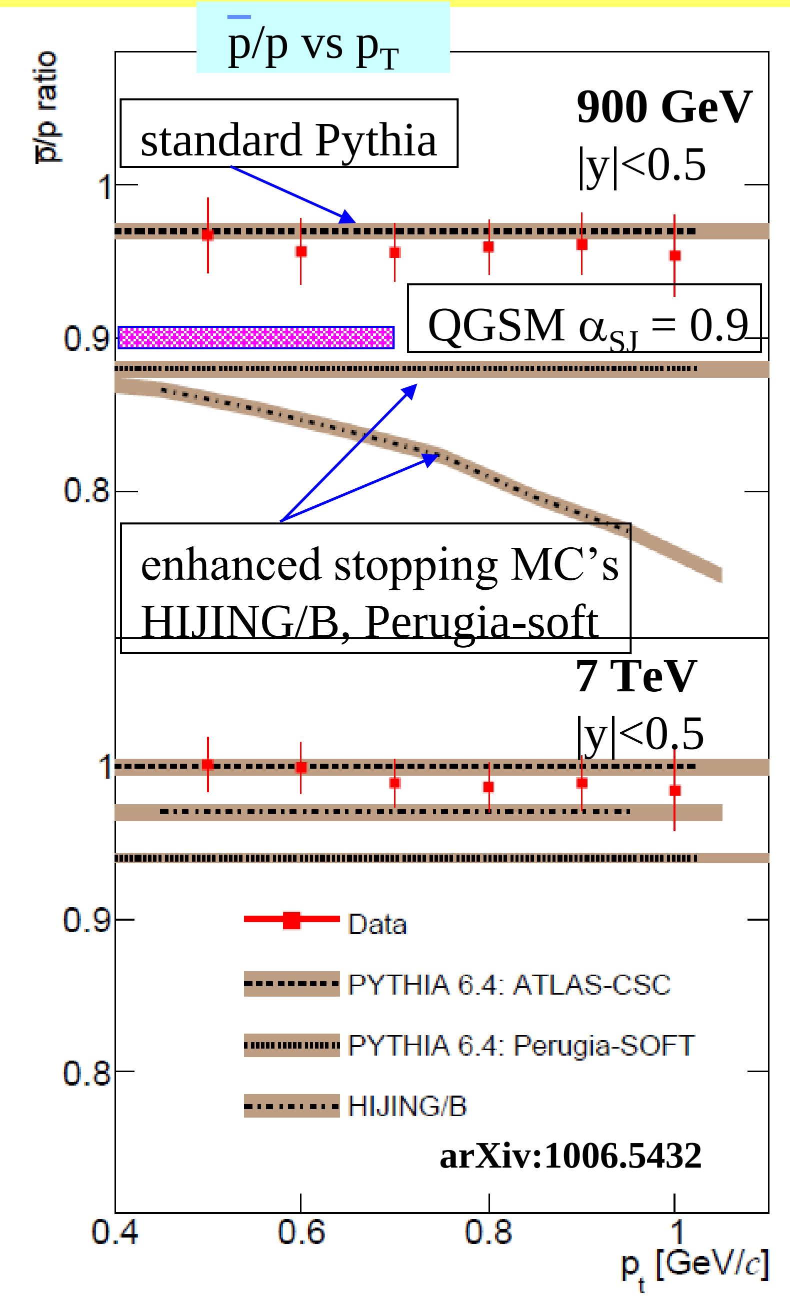
J/ψ yield as a function of charged-multiplicity in pp collisions at √s=7 TeV

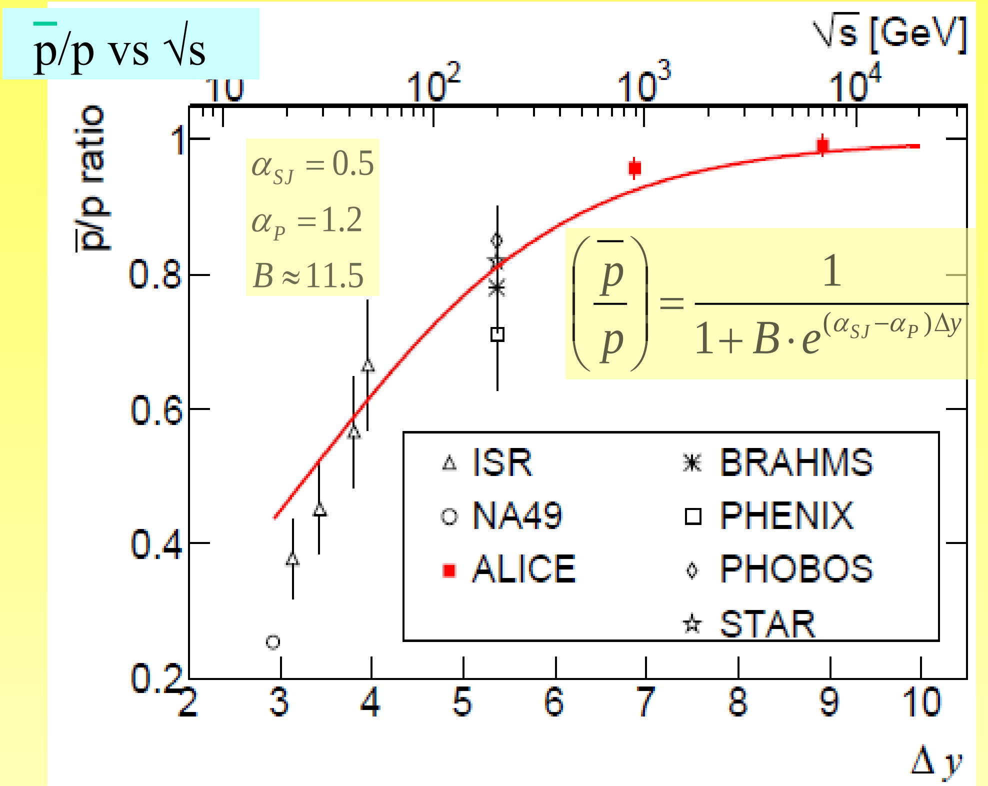


First measurement of J/ψ polarization at LHC

Phys.Rev.Lett. 108 (2012) 082001

p̄/p ratio: measure of Baryon stopping





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

- data well described by PYTHIA tunes

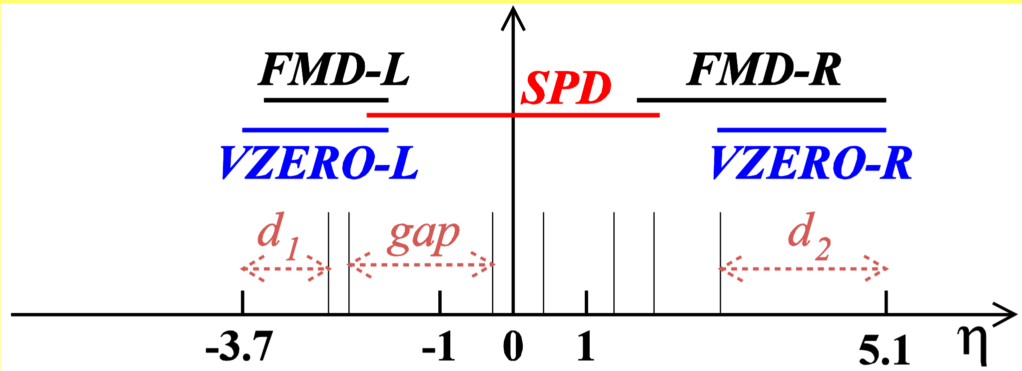
-little room for **any** additional diagrams which transport baryon number over large rapidity gaps

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

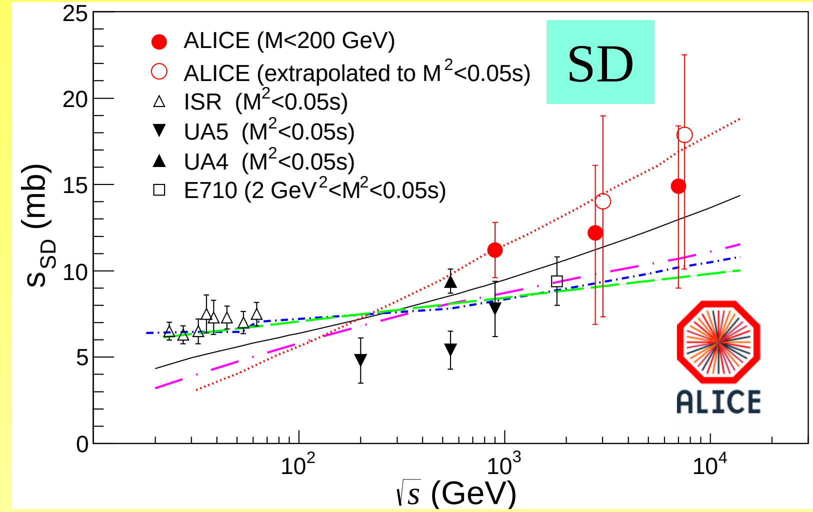
7 TeV: p̄/p = **0.990** ± 0.006(stat) ± 0.014(syst)

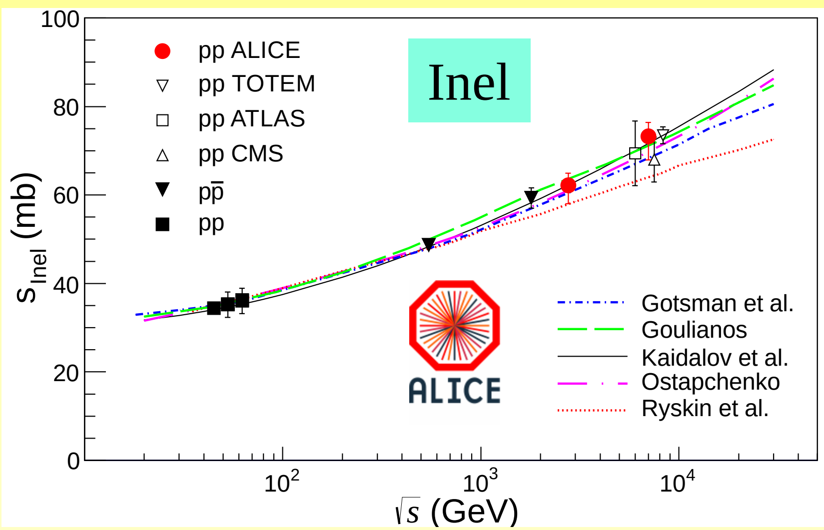
pp single- and double- diffractive and inelastic cross-sections

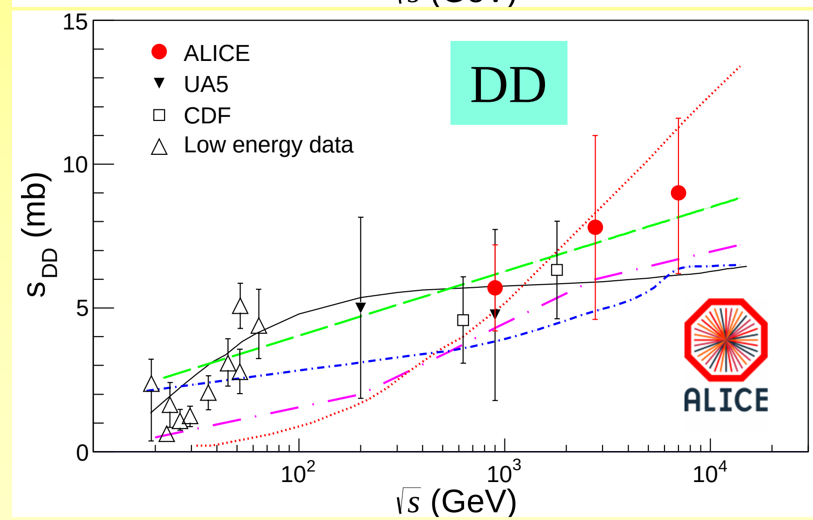
vdM scan (final here) + MC generators tuned to measured ratio of 1-arm to 2-arm trigger.



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





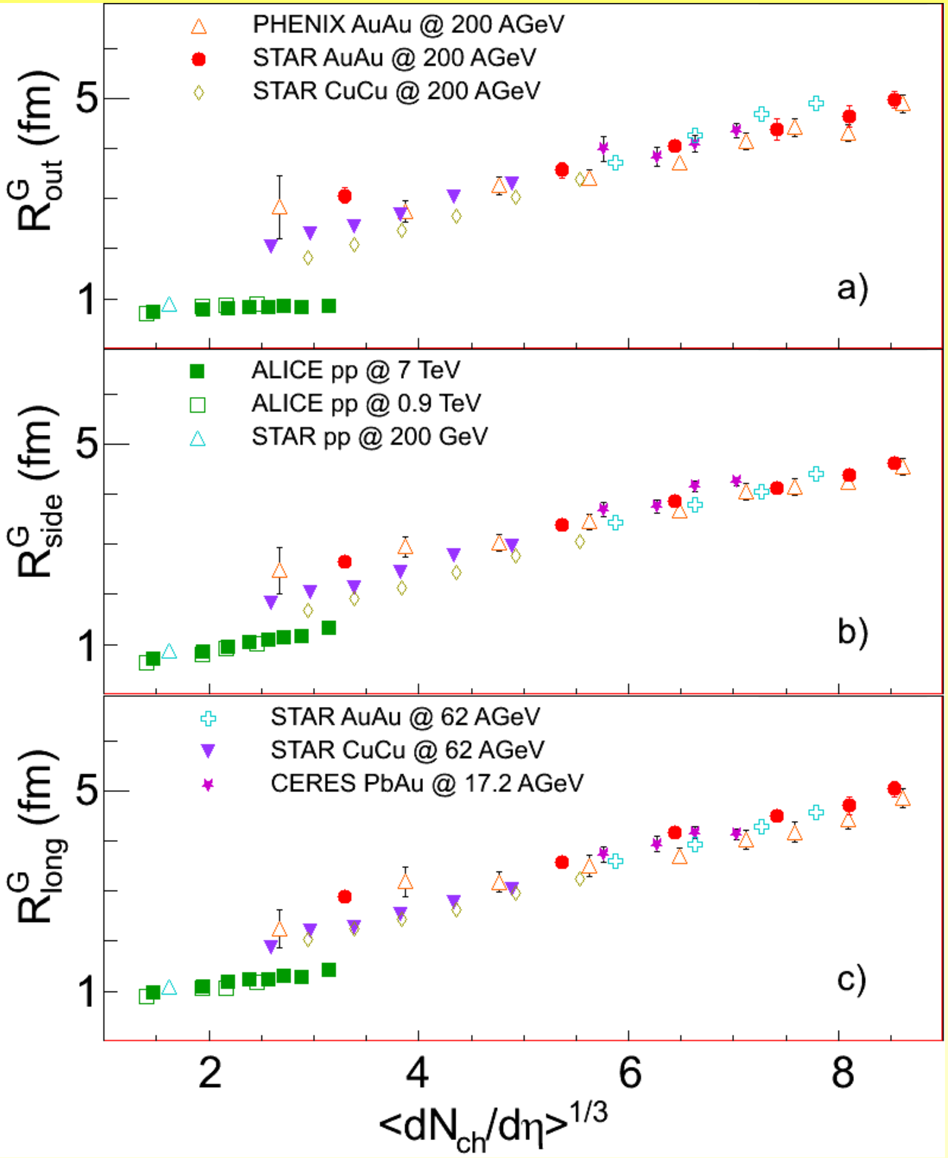


σ_{Inel} at $\sqrt{s}$ = 7 TeV

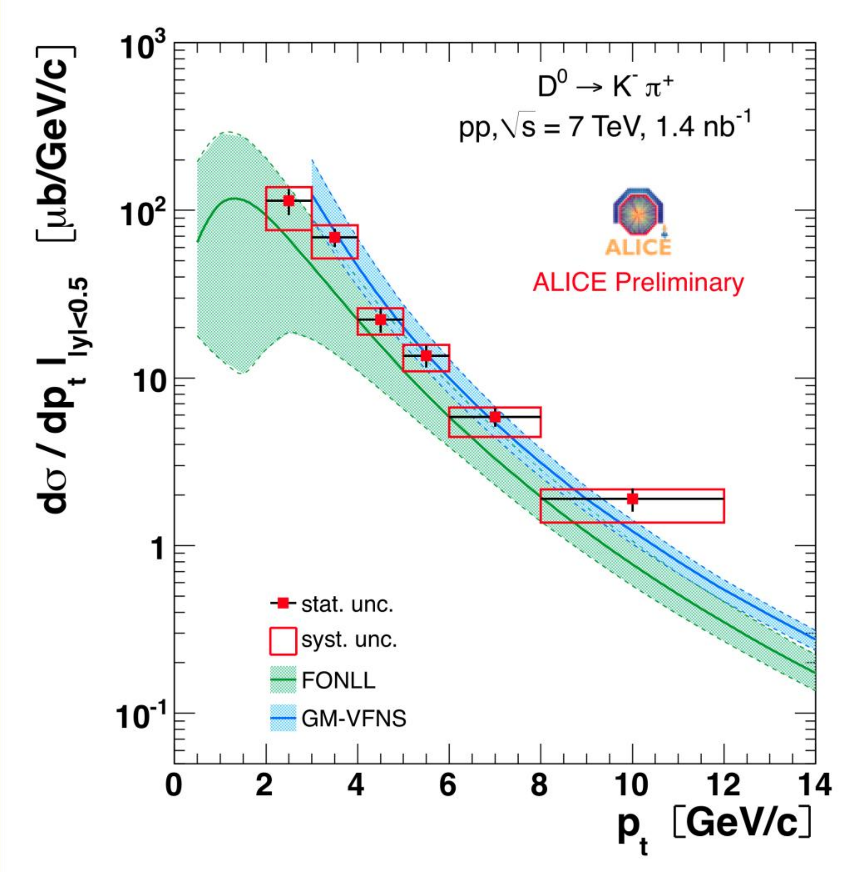
ALICE : $73.2\ ^{+2.0}_{-4.6}$ model $\pm\ 2.6^{lumi}$
ATLAS : $69.4 \pm 2.4^{exp.} \pm 6.9^{extrap.}$
CMS : $68.0 \pm 2.0^{syst.} \pm 2.4^{lumi} \pm 4^{extrap.}$
TOTEM: $73.5 \pm 0.6^{stat.}\ ^{+1.8}_{-1.3}$ syst.

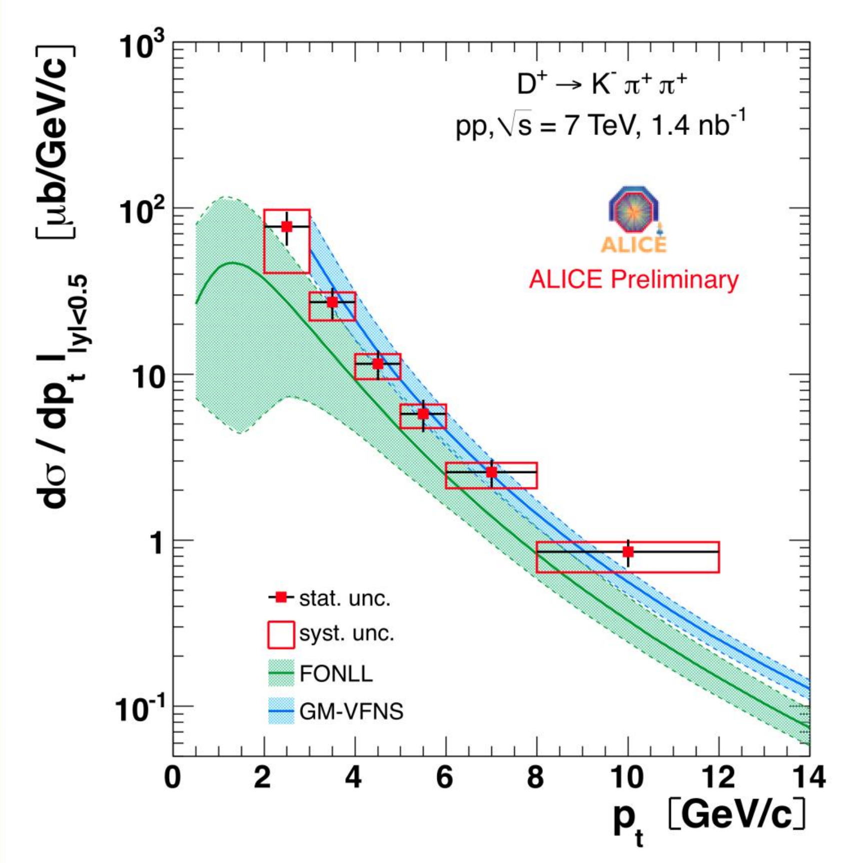
Gotsman et al., arXiv:1010.5323, EPJ. C74, 1553 (2011)
Kaidalov et al., arXiv:0909.5156, EPJ. C67, 397 (2010)
Ostapchenko, arXiv:1010.1869, PR D83 114018 (2011)
Ryskin et al., EPJ. C60 249 (2009), C71 1617 (2011)
K. Goulianos, arXiv:0203141; 1105.4916, PL B358, 379 (1995)
Model predictions: SD ➔ $M^2 < 0.05s$ DD ➔ Δη > 3

High multiplicity in pp: HBT



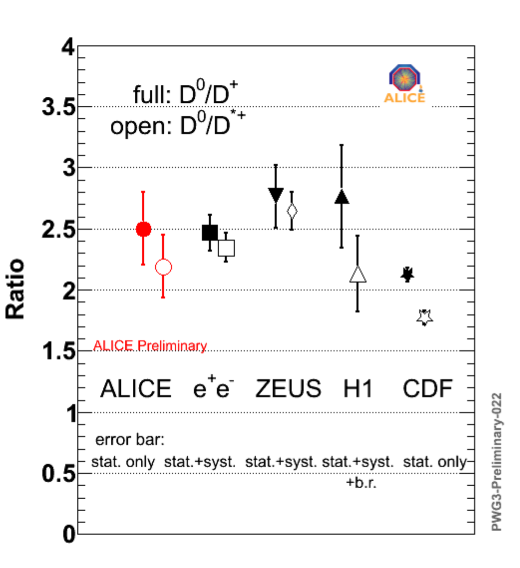
- Multiplicity reach at 7 TeV comparable to peripheral heavy-ion collisions at RHIC
- Scaling law of radii vs. observed multiplicity proposed to explain RHIC measurements
- We test this scaling directly and find that:
  - The pp measurement does not follow the “universal” scaling
  - But the radii do scale linearly with multiplicity, although with different slope and offset
  - initial geometry does play a role in the final size



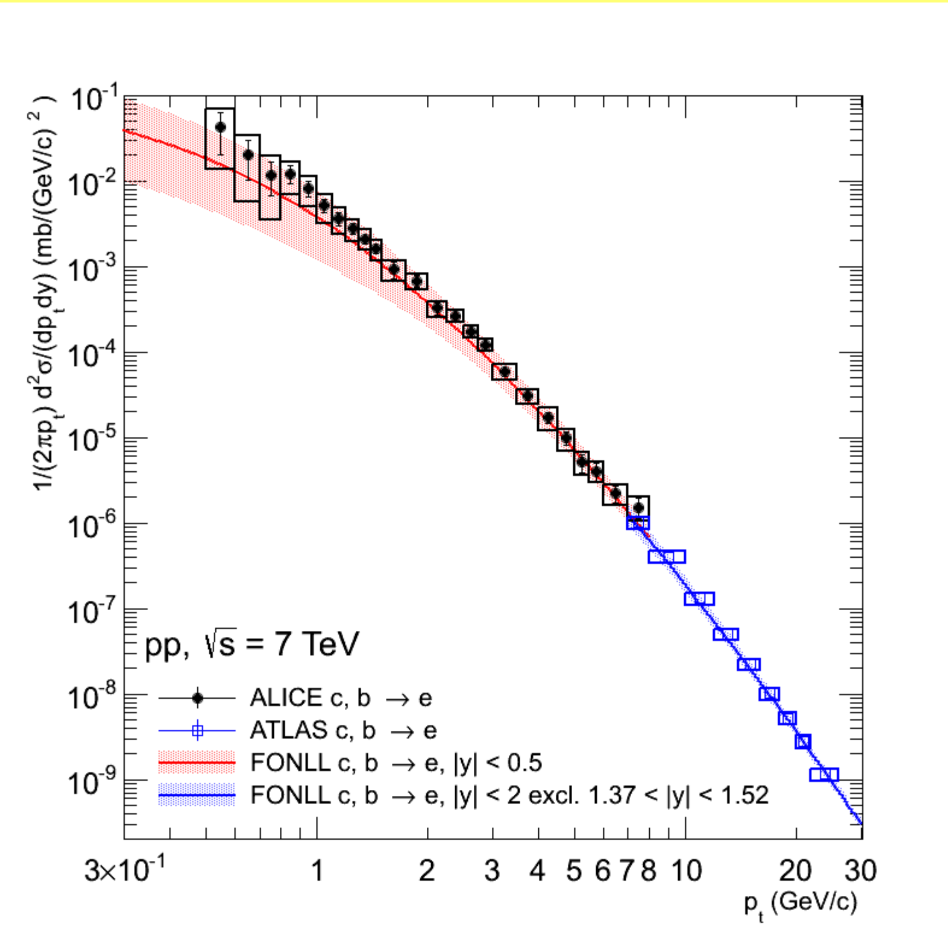


D^0 and D^+ $d\sigma/dp_t$, $|y|<0.5$, pp 7 TeV

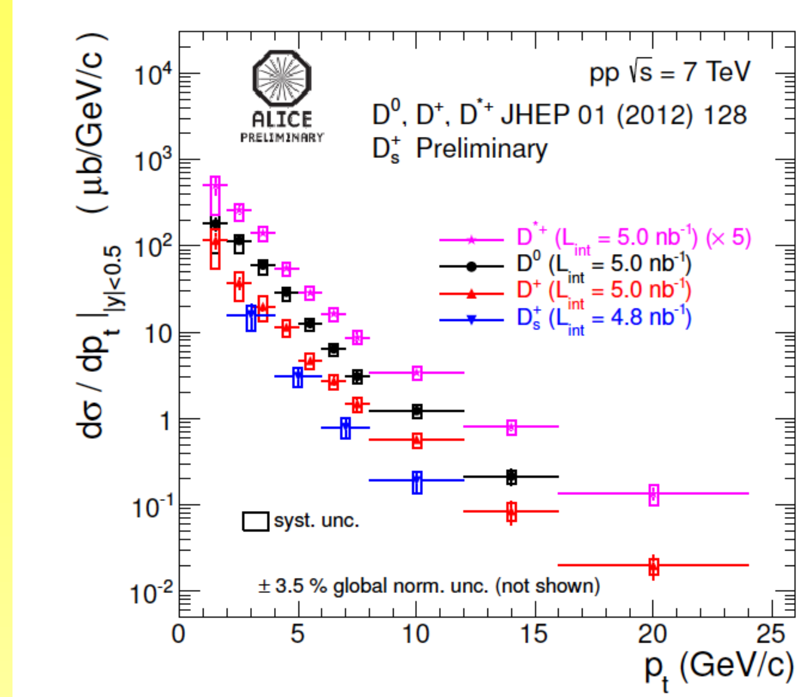
- $2 < p_t < 10$ GeV/c, with 1.4 nb^{-1} (~20% of 2010 statistics)
- y acceptance is p_t-dep (0.5→0.8), data scaled to $|y|<0.5$
- pQCD pred. (FONLL and GM-VFNS) compatible with data
- Most of the Cross-section (and of the theoretical uncertainty) at low p_T



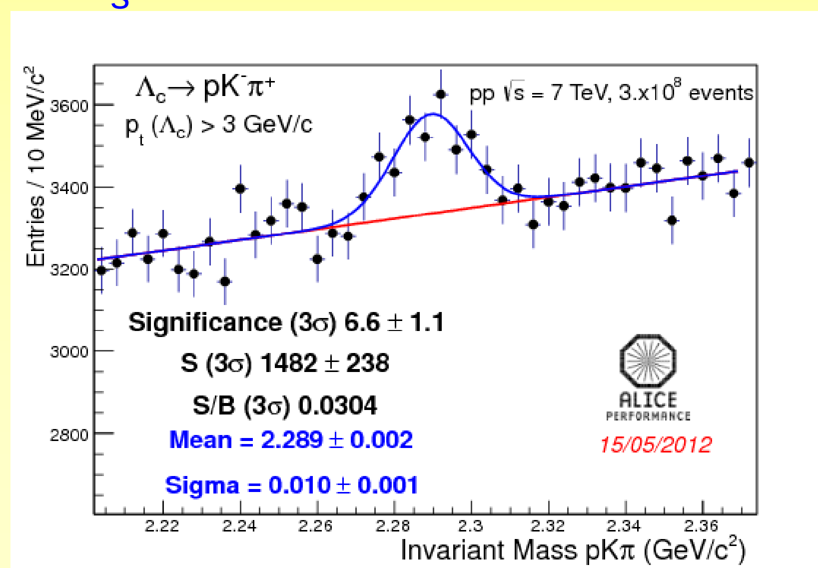
Some latest pp results



Electrons from Heavy Flavors
=> Complementarity with ATLAS

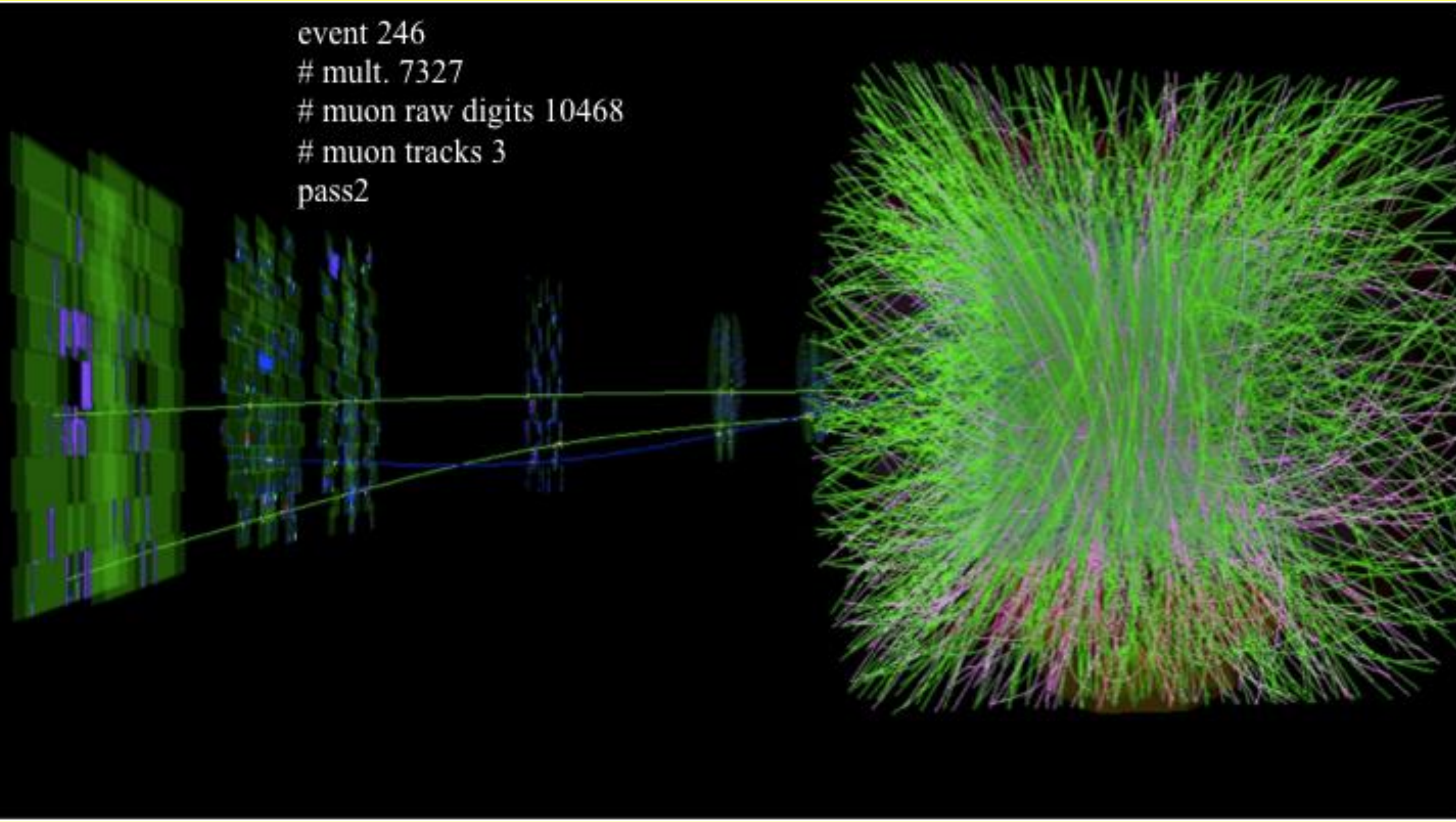


$D_s \rightarrow K\pi\pi$ production cross section



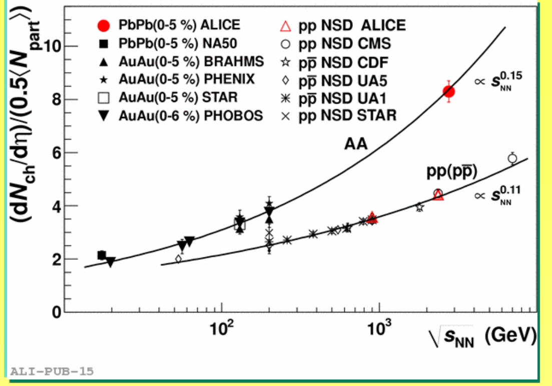
- $\Lambda_c \rightarrow pK\pi$ signal

Heavy-Ions!

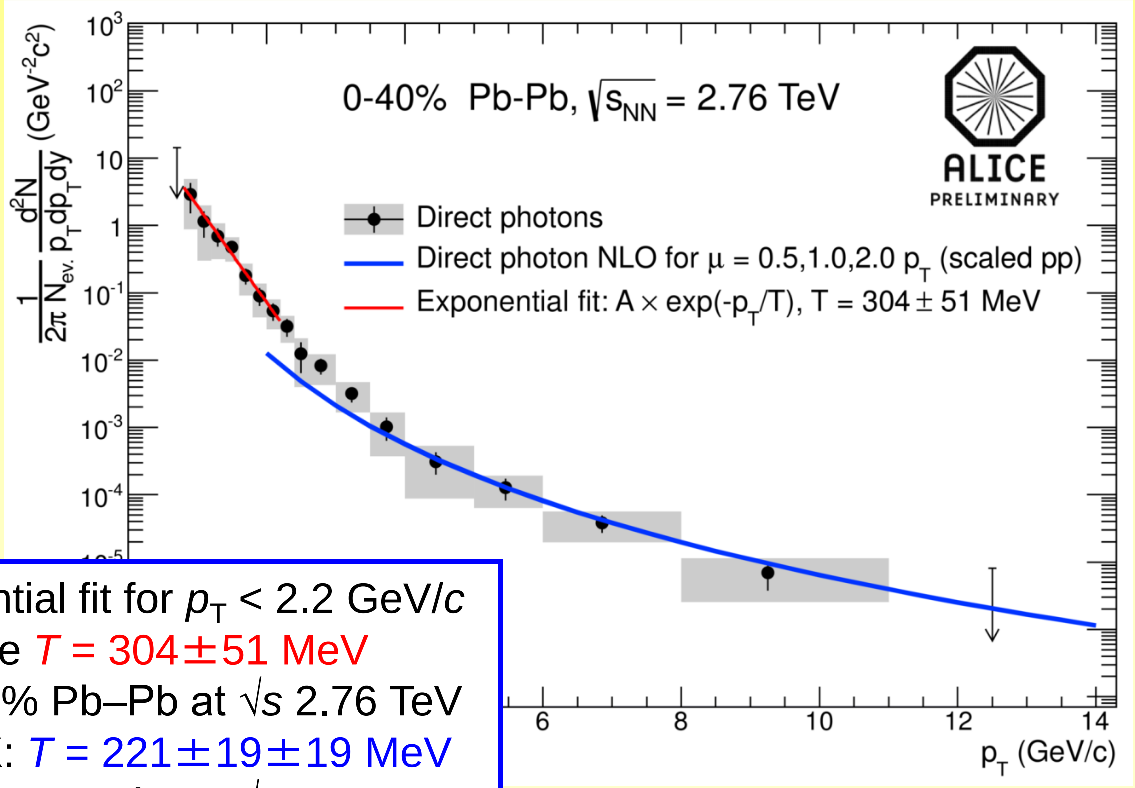

event 246
mult. 7327
muon raw digits 10468
muon tracks 3
pass2

Global properties

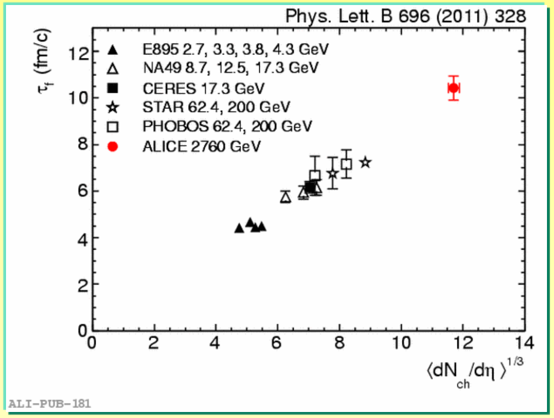
- From the very first 2010 analysis, fireball at LHC denser, larger and longer lived than at RHIC
  - **Energy density ≈ 3 x RHIC** (p_T is larger)
  - **Volume ≈ 2 x RHIC (≈ 300 fm³)**
  - **Lifetime ≈ +20% (≈ 10 fm/c)**
- **Now, measure T from photon spectrum**

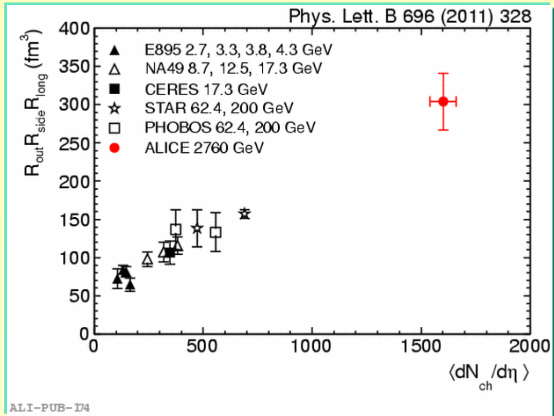


$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$



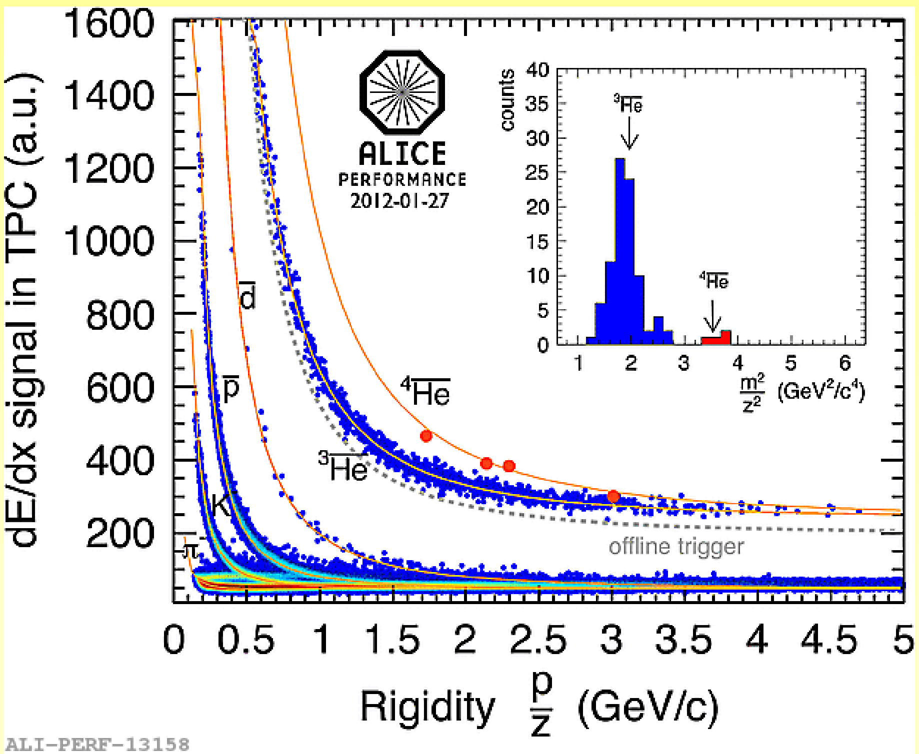
Exponential fit for p_T < 2.2 GeV/c
inv. slope T = 304±51 MeV
for 0–40% Pb–Pb at √s 2.76 TeV
PHENIX: T = 221±19±19 MeV
for 0–20% Au–Au at √s 200 GeV

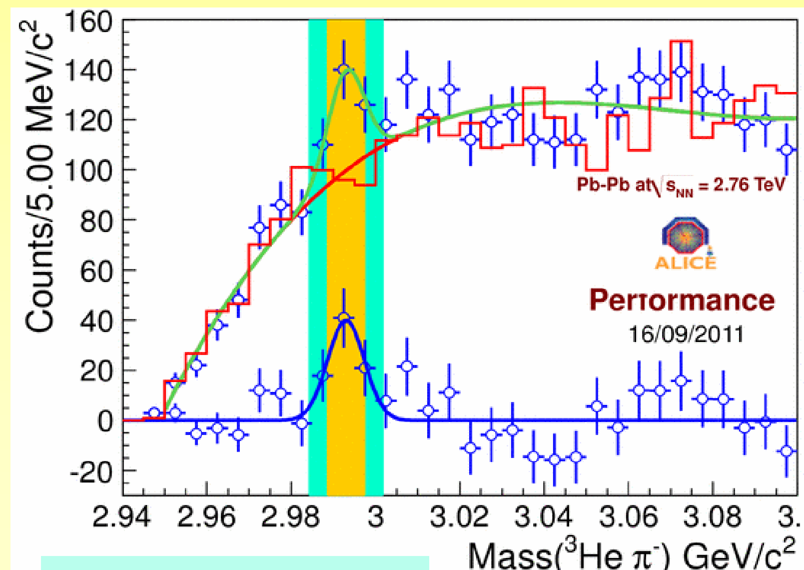




Nucleo-synthesis at LHC

- Light Nuclei & anti-Nuclei
  - **Anti-^{4}He** is the heaviest anti-nucleus ever observed
  - **Hypertriton:** one proton replaced by Λ particle



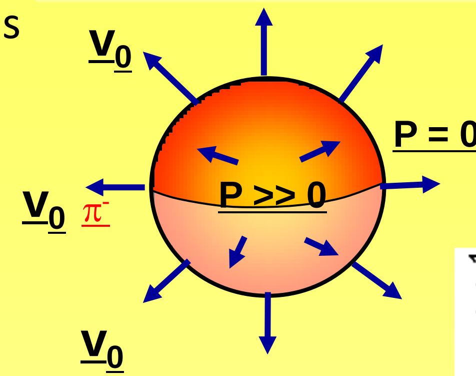


$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$

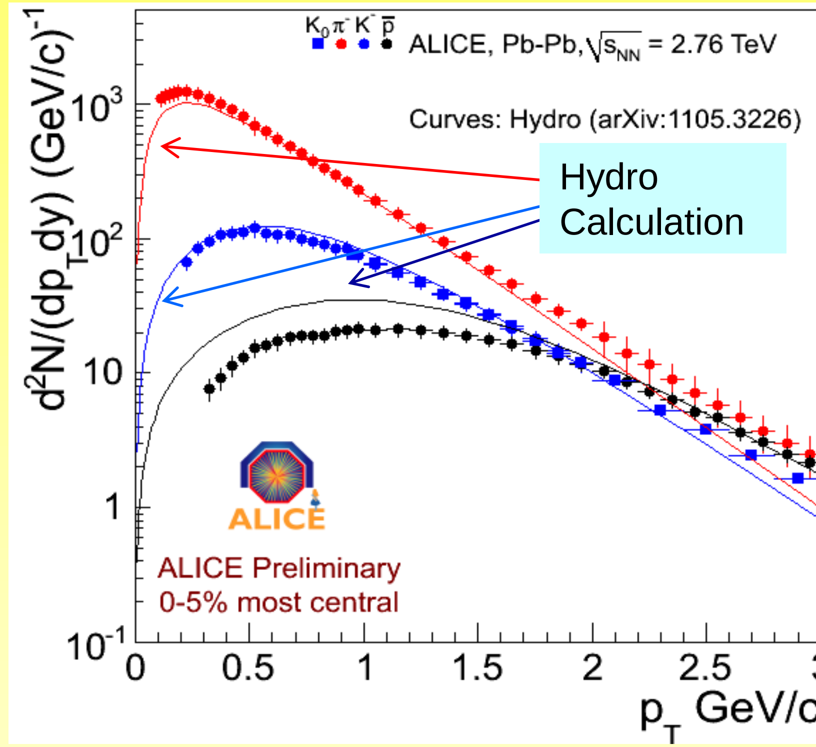
Radial Flow

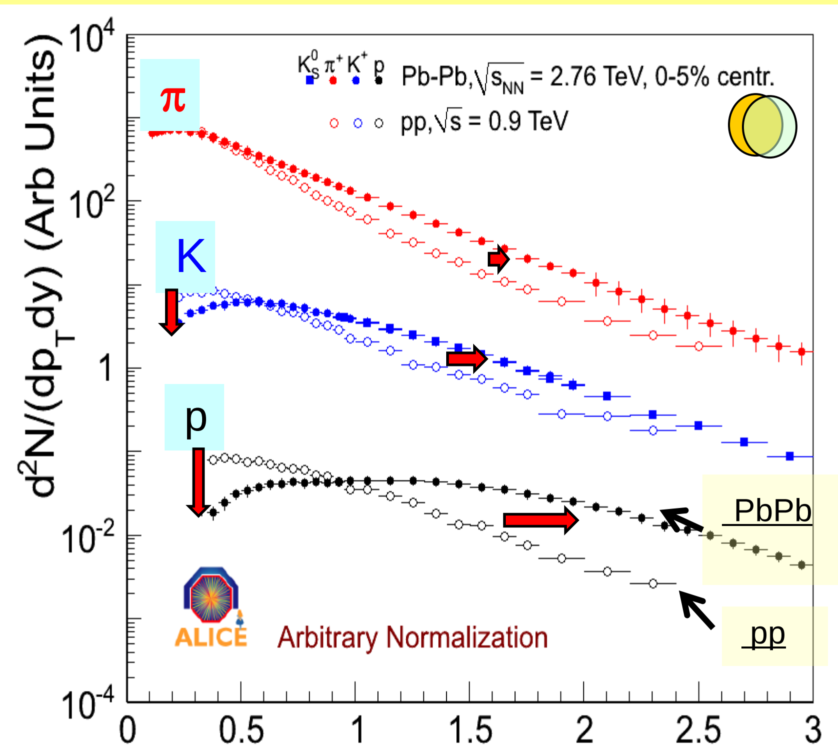
- pressure **P** in center drives expansion
- flow velocity $\beta = v_0/c$ depends on $f(P, \tau, EoS,)$
- momentum $p = \gamma\, m\, v_0$ => particles of different mass have characteristic & different momentum

isotropic radial flow



Particle Flow: hydro properties of the plasma





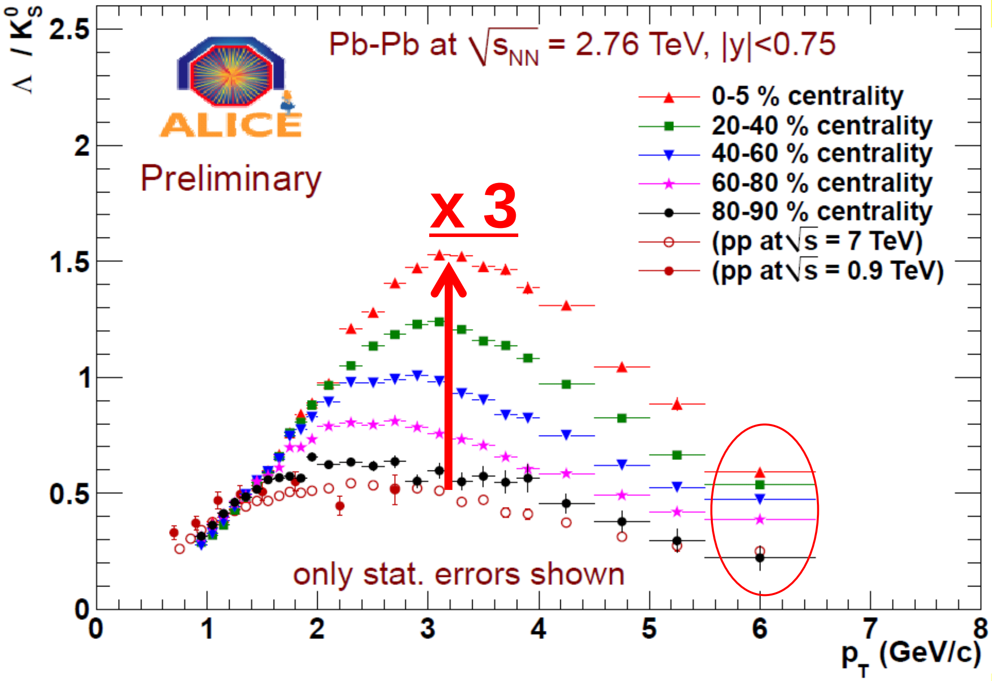
FLOW pushes spectra depending on mass

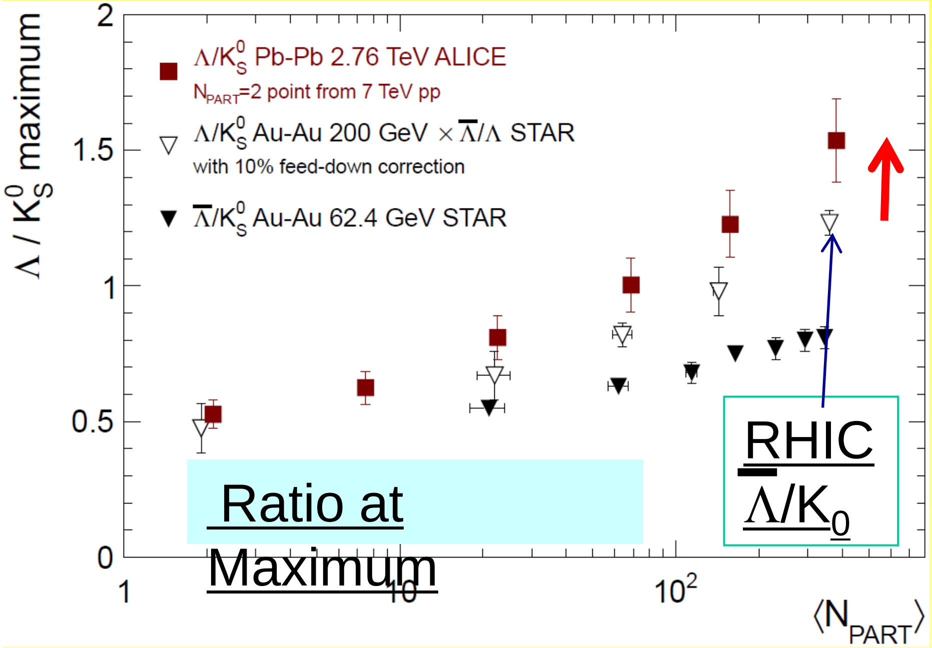
IDENTIFIED PARTICLE SPECTRA @LHC: significant changes in slope compared to RHIC
Most dramatically for protons

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

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

'Baryon anomaly': Λ/K^0





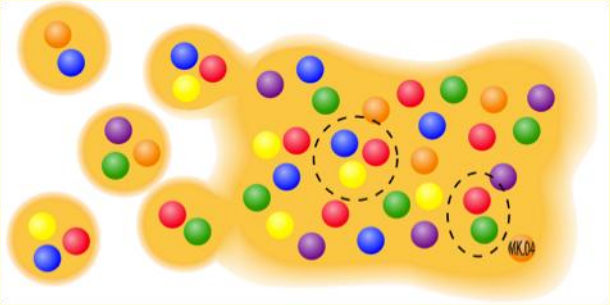
Baryon/Meson ratio still strongly enhanced

x 3 compared to pp at 3 GeV

- Enhancement slightly larger than at RHIC
- Still present at 6 GeV/c
- Maximum shift very little in p_T compared to RHIC

despite large change in underlying spectra !

Recombination + Radial flow?



Azimuthal Asymmetry

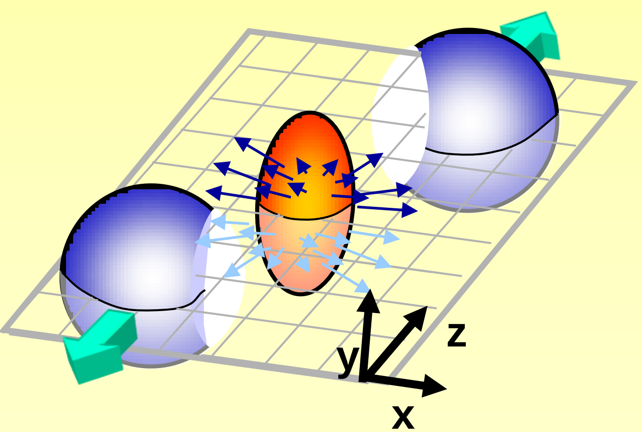
SCIENCE Vol: 298 2179 (2002) ^{7}Li

- 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

→ measure the strength of collective phenomena

Large mean free path

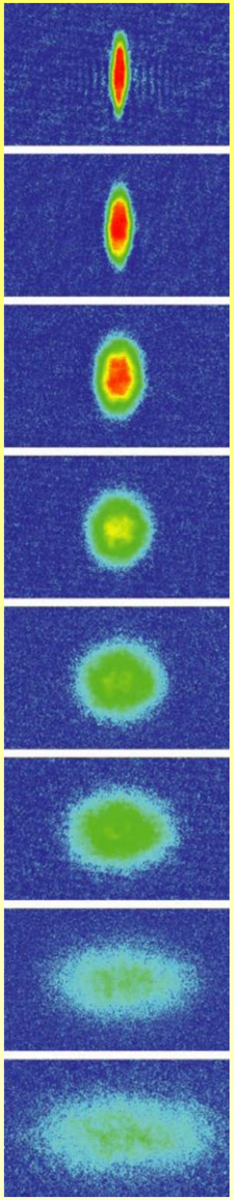
particles stream out isotropically, no memory of the asymmetry

extreme: ideal gas (infinite mean free path)

Small mean free path

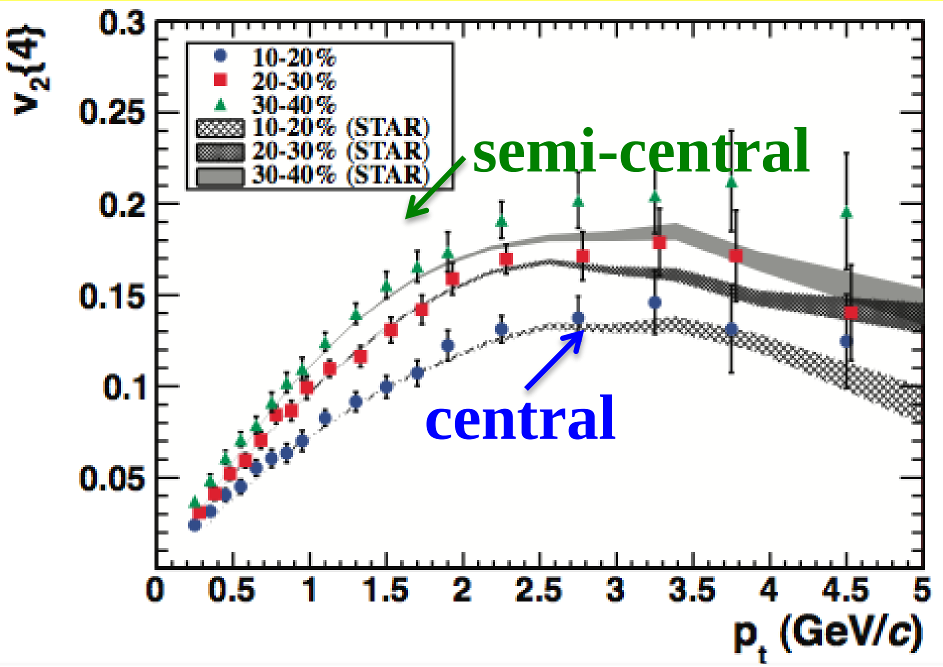
larger density gradient -> larger pressure gradient -> larger momentum

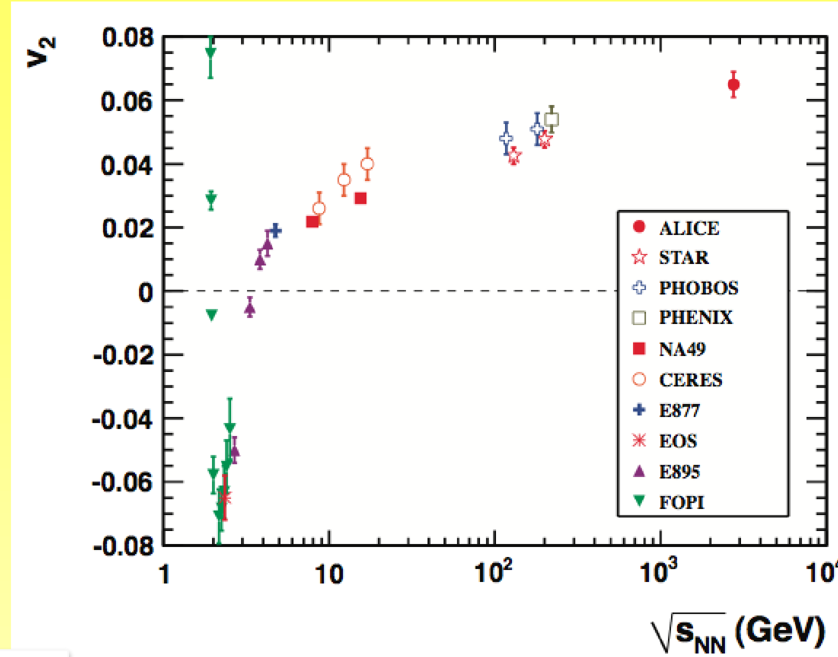
extreme: ideal liquid (zero mean free path, hydrodynamic limit)



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

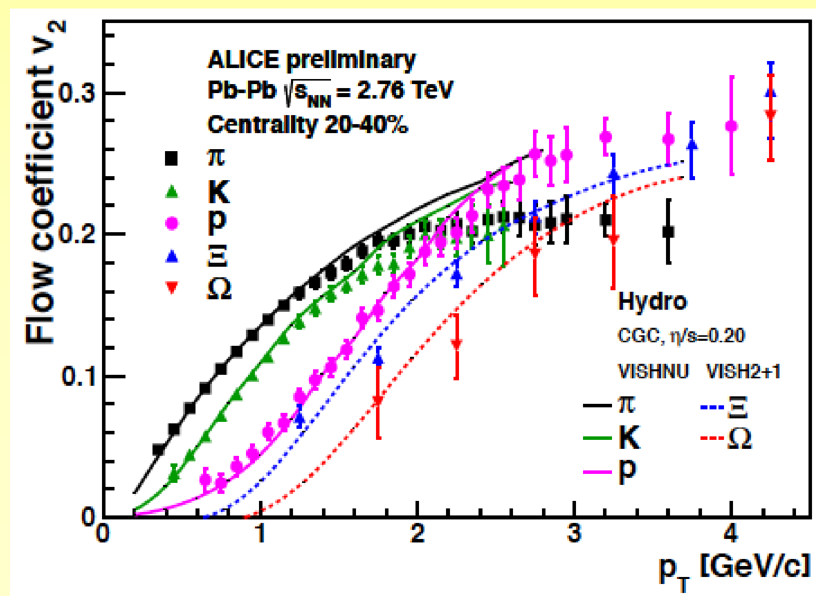
v_2 Measurements at the LHC





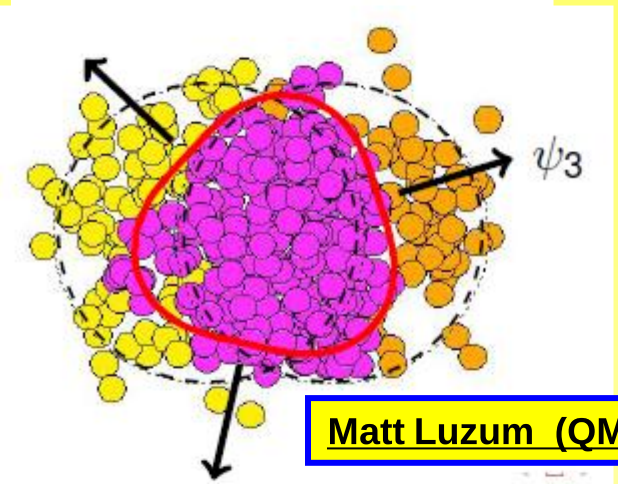
PRL 105, 252302 (2010), already over 200 citations!

- **Collective behavior observed in Pb-Pb collisions at LHC** (+30% vs. v_2^{RHIC}) **=> ideal fluid behavior (extremely low viscosity $\eta \approx 0$)**
- **Testing hydrodynamical evolution**
- **Precision measurement for viscosity/entropy ratio**

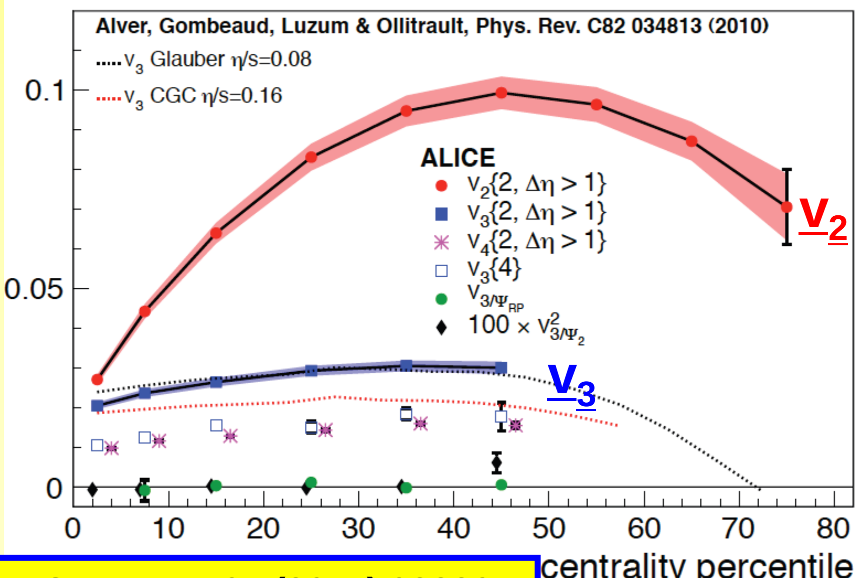


Fluctuations → v_3

- "ideal" shape of participants' overlap is ~ elliptic
  - in particular: no odd harmonics expected
  - participants' plane coincides with event plane
- but fluctuations in initial conditions:
  - participants plane ≠ event plane
  - → v_3 ("triangular") harmonic appears [B Alver & G Roland, PRC81 (2010) 054905]
- and indeed, $v3 \neq 0$!
- v_3 has weaker centrality dependence than v_2
- when calculated wrt participants plane, v_3 vanishes
  - as expected, if due to fluctuations…
- progress in precision measurements of η/s
  - fluctuations discriminate & constrain models
  - have large sensitivity to viscosity



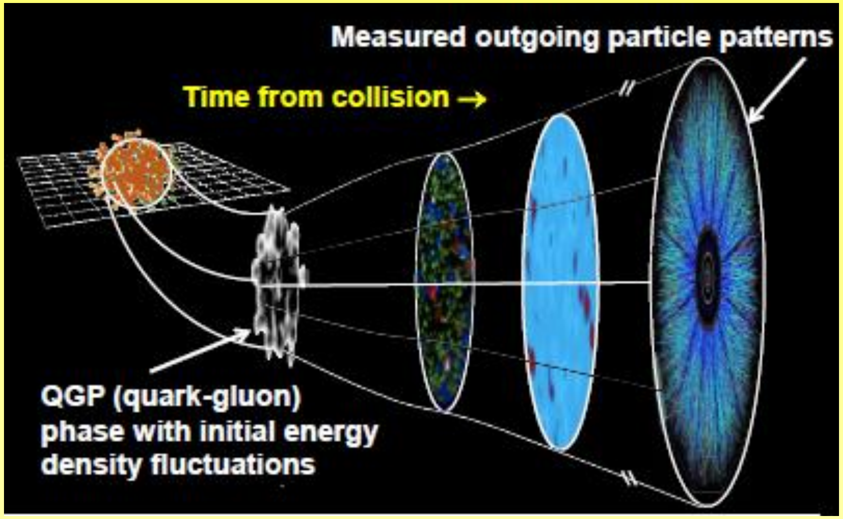
Matt Luzum (QM 2011)



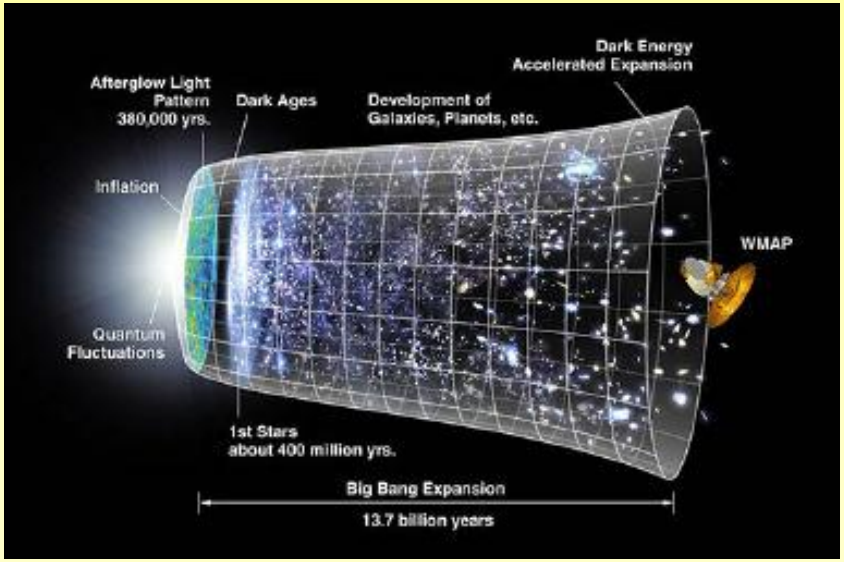
ALICE: PRL 107 (2011) 032301

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

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



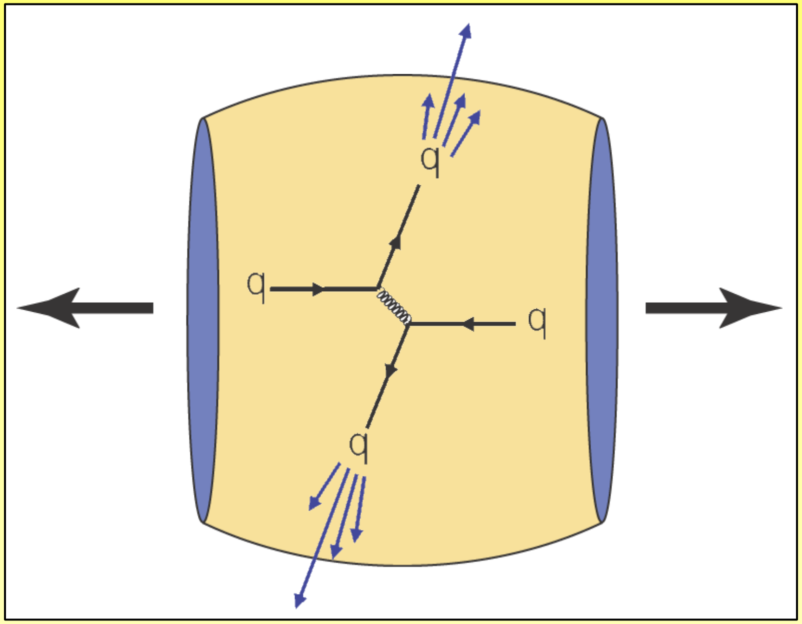
- Analogy to Cosmic Microwave Background Explorations: pattern recognition on present-day background allows inference of structures in universe a few hundred thousand years after Big Bang, which can be attributed to quantum fluctuations in inaccessible inflationary period just after Big Bang.



- from S. Vigdor, BNL, @QM2012

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'

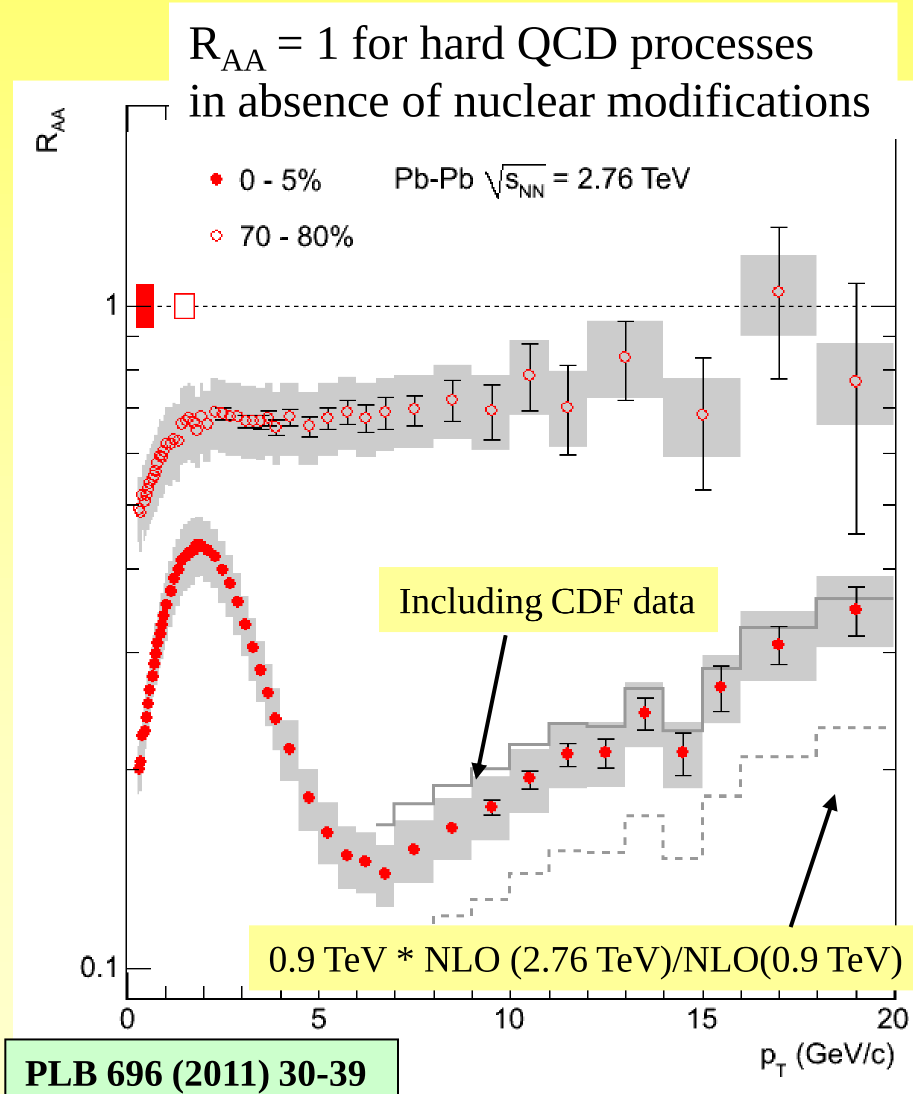
Medium modification quantified vi nuclear modification factor R_{AA}

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

Suppression of High-p_T Hadrons

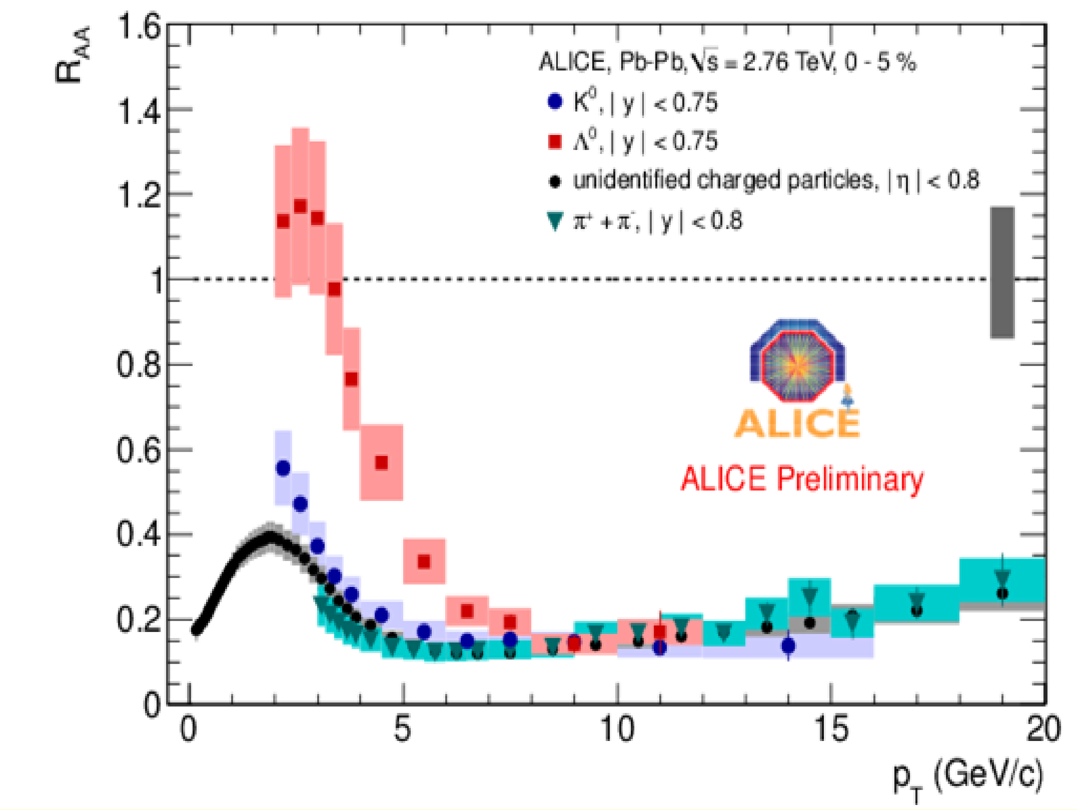
$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

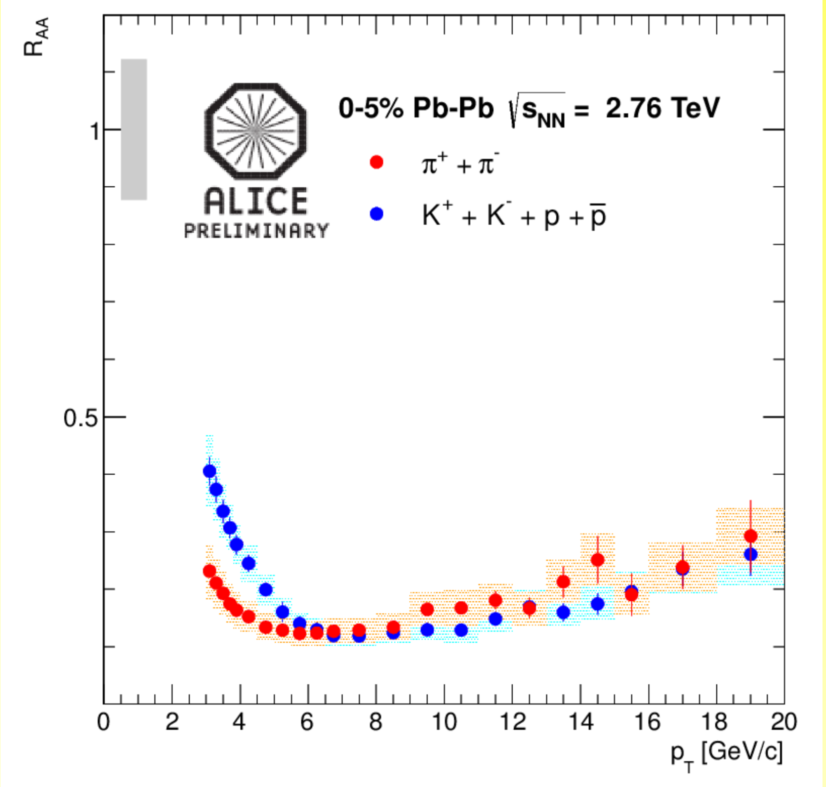
- Strong Suppression even larger than @ RHIC
- Nuclear modification factor $R_{AA}(p_T)$ for charged particles produced in 0-5% centrality range
  - minimum (~ 0.14) for p_T ~ 6-7 GeV/c
  - then slow increase at high p_T
- essential quantitative constraint for parton energy loss models!



PLB 696 (2011) 30-39

Understanding R_{AA}



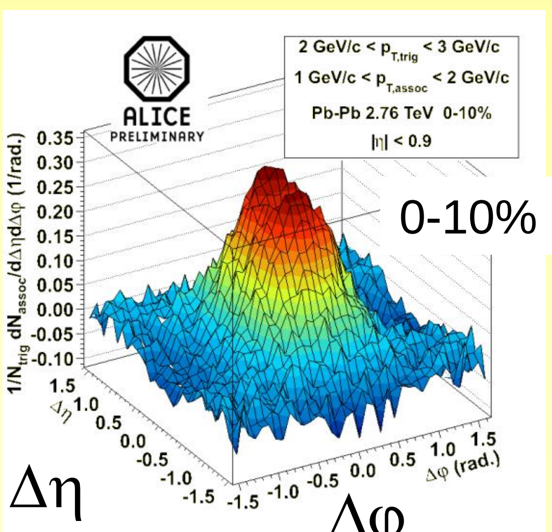


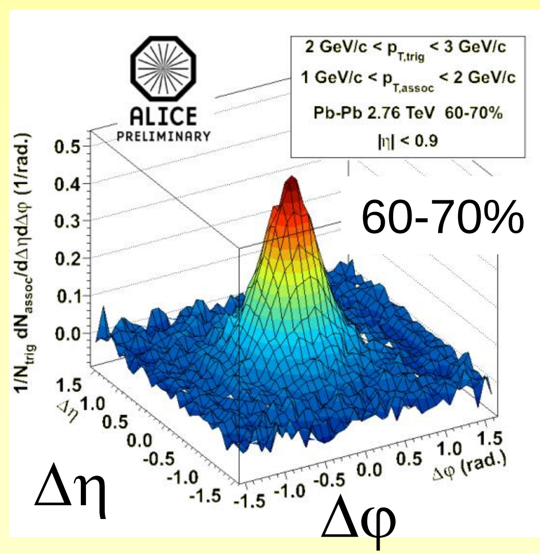
- Nuclear modification factor RAA studied for several identified particles
- Λ R_{AA}: interplay of suppression and baryon enhancement

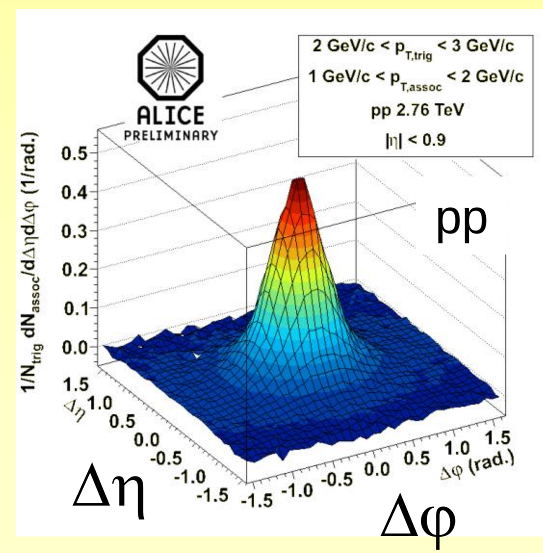
Jet-like near-side peak shapes using di-hadron correlations in $(\Delta\varphi,\Delta\eta)$

- Strong quenching in central HI collisions at LHC
  - Quenched energy reappears at low p_T, also outside the jet cone
- Study the low p_T region with two-particle correlations where the energy reappears
- Subtract $\Delta\eta$-independent effects (e.g. flow) by η-gap method
- Modification of the near-side jet peak in central collisions

$2 < p_{T,trig} < 3$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c

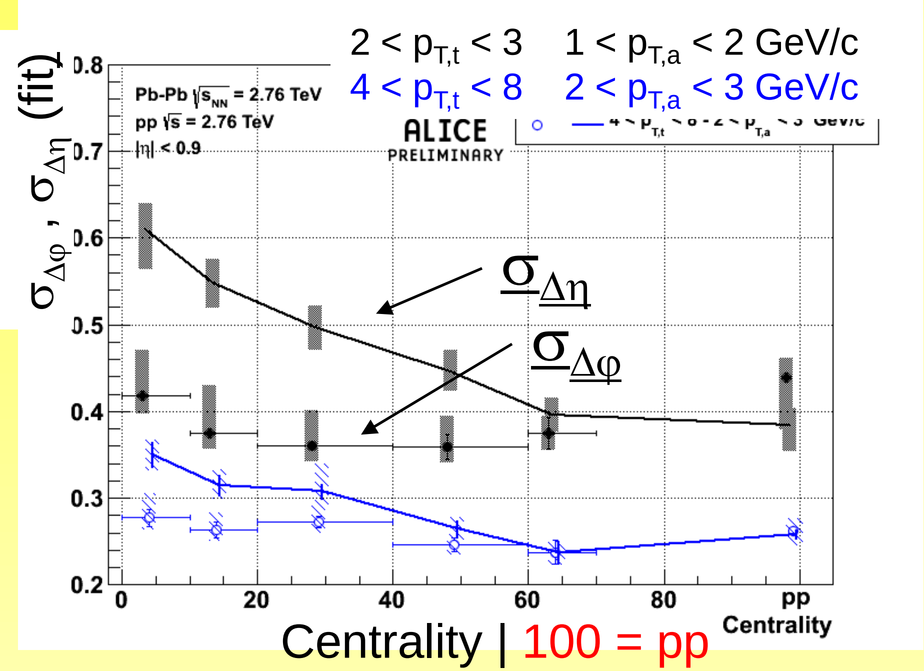


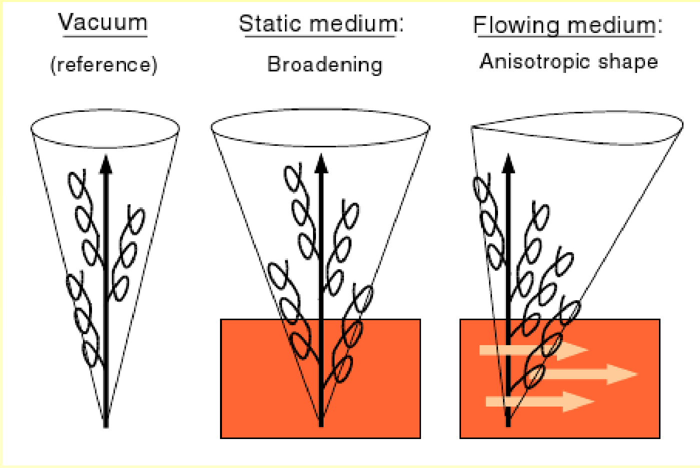




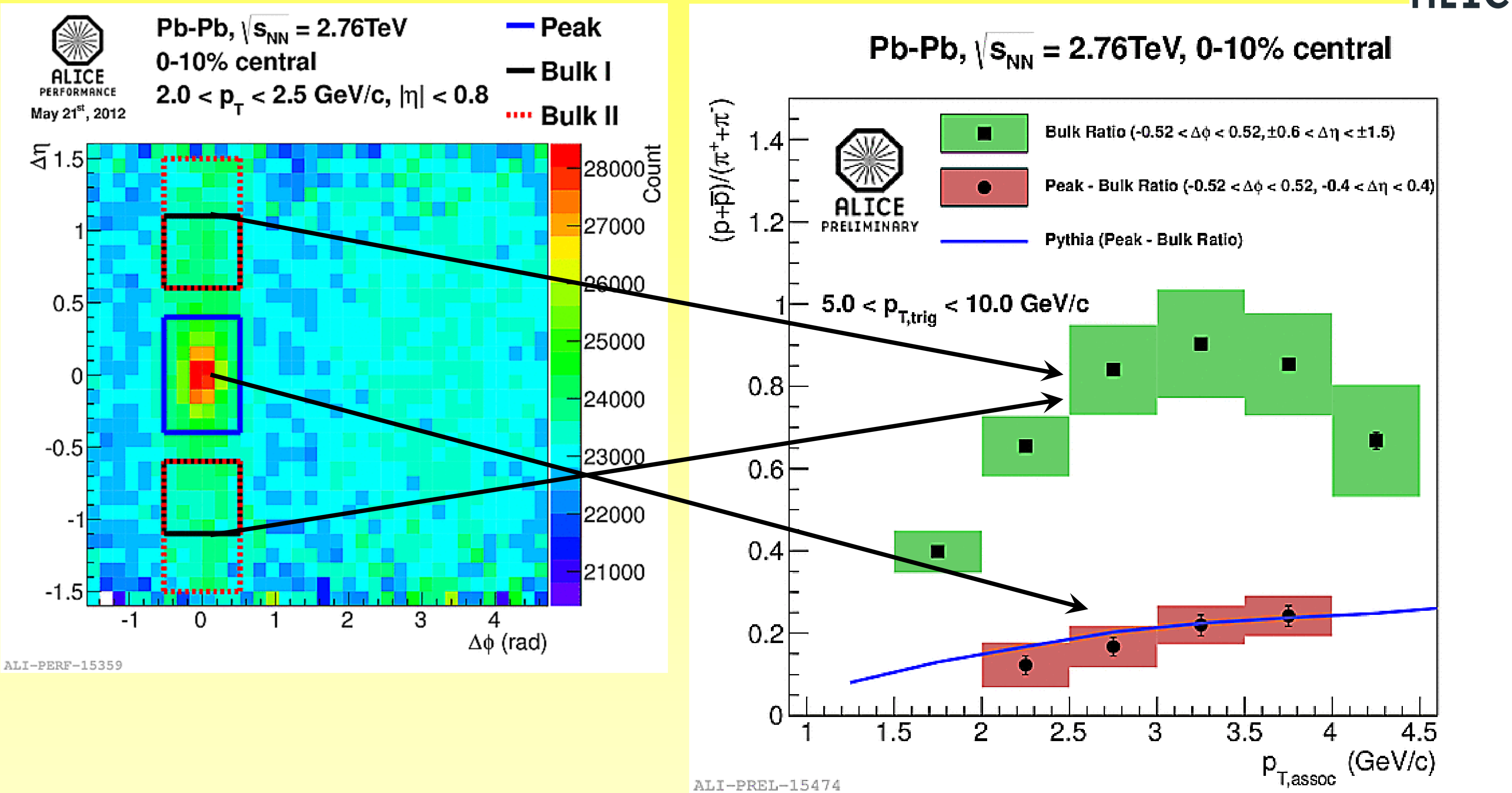
Near-Side Jet Peak

- Significant increase of $\sigma_{\Delta\eta}$ towards central events
  - $\sigma_{\Delta\varphi}$ independent of centrality within uncertainties
  - $\sigma_{\Delta\eta} > \sigma_{\Delta\varphi}$ (eccentricity ~ 0.2)
- Observation consistent with
  - suggestion that longitudinal flow deforms the conical jet shape (Armesto, Salgado, Wiedemann, PRL 93,242301 (2004))
  - AMPT (A MultiPhase Transport Code) MC which describes collective effects (e.g. v_2, v_3, v_4) in HI collisions at LHC using partonic and hadronic rescattering (PRC72 06490 (2005))
- Interplay of flow with the jet?





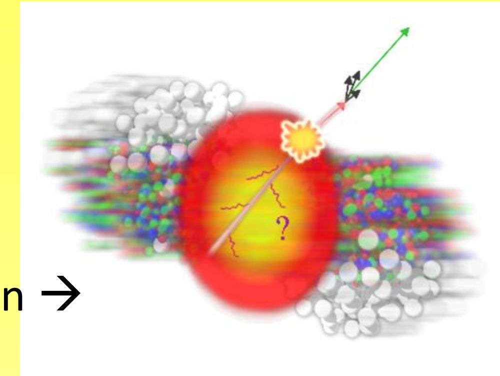
PID in jet structures

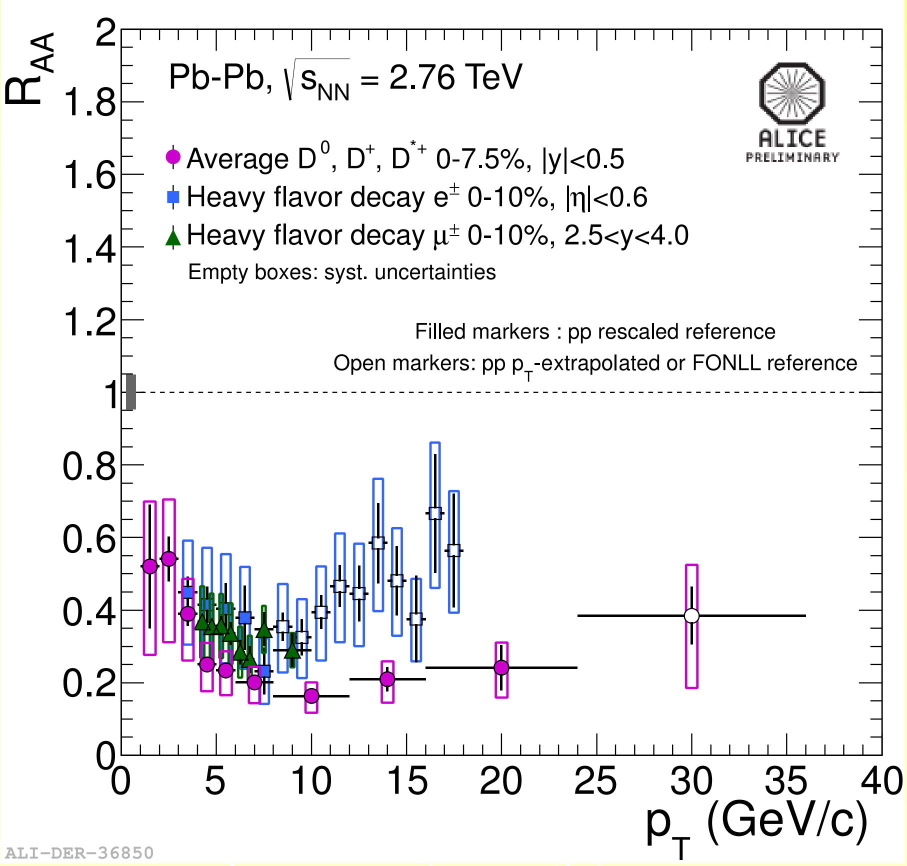


near-side peak (after bulk subtraction): p/π ratio compatible with that of pp (PYTHIA)
bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement
jet particle ratios not modified in medium ? still might be surface bias…

Heavy-flavour suppression at high p_T

- Study Heavy Quark Energy Loss in the medium
- Why Heavy Quarks?
  - Unique handle on Mass and Colour Charge dep. of energy loss
  - HQ preserve their identity (flavour) from production to detection → full information on medium evolution





$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN^D_{AA}/dp_t}{dN^D_{pp}/dp_t}$$

- D mesons (D^0,D^+,D^*) extended at low and high p_T
  - Charm suppression up factor 5!
  - Strong suppression even at 30 GeV/c
- HF-decay electrons up to 18 GeV/c
  - C - B separation ongoing
- HF-decay muons at forward rapidity
  - Similar suppression as at central rapidity

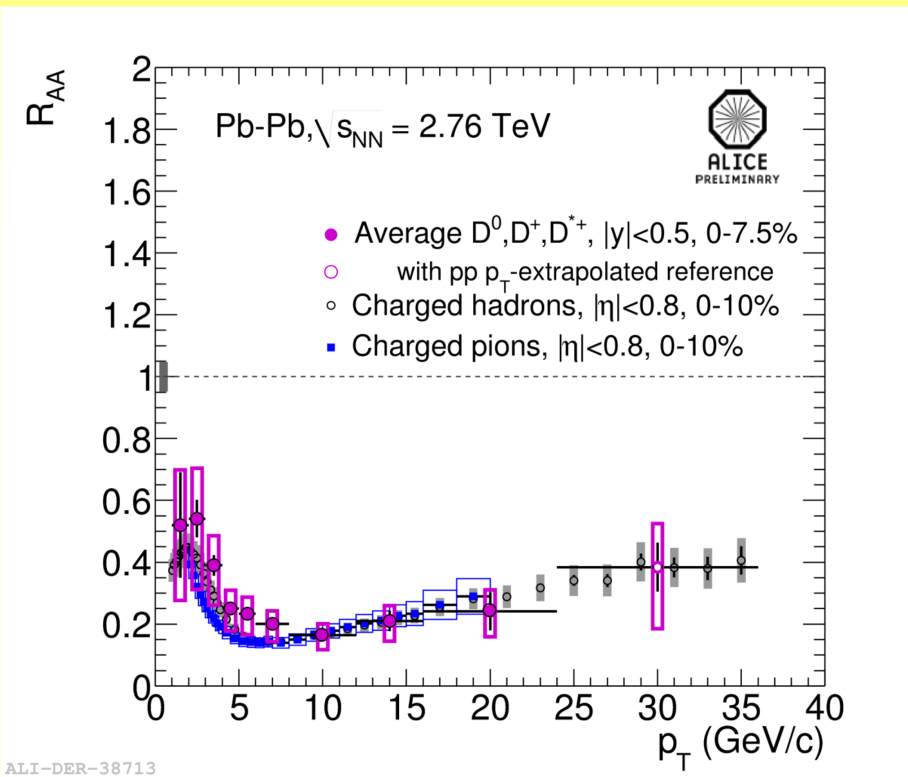
First measurement of R^{D}_{AA}/R^{π}_{AA}

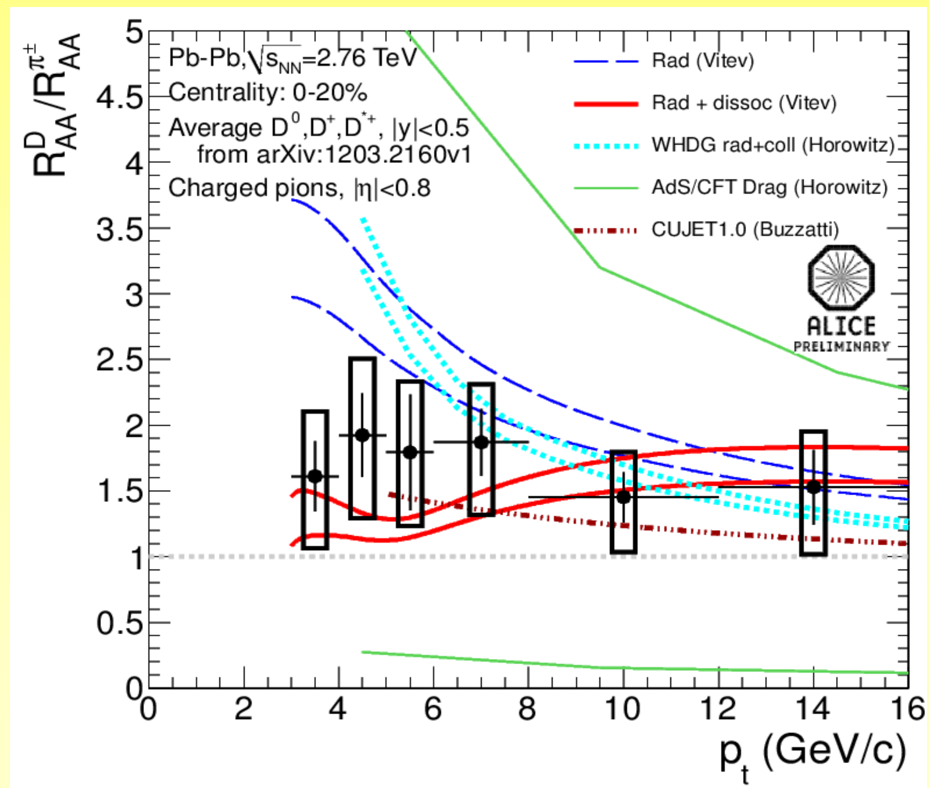
Expectation:

$\Delta E_{gluon} > \Delta E_{quark}$ (Casimir factor)

$\Delta E_{light\ quark} > \Delta E_{massive\ quark}$ ('dead cone')

$R^{D}_{AA}/R^{\pi}_{AA} > 1$ (?)

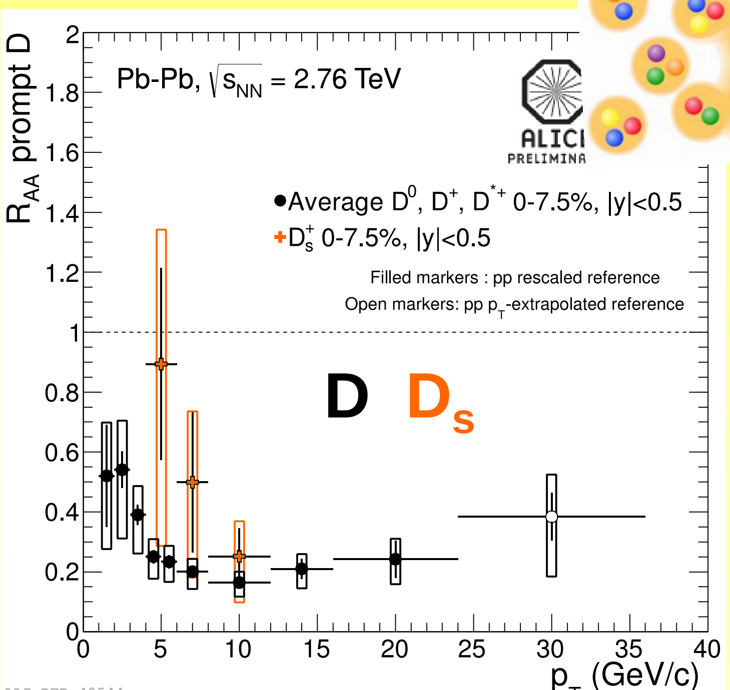


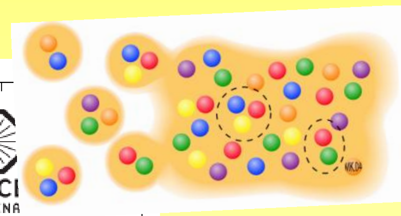


First indication of color-charge effects ?

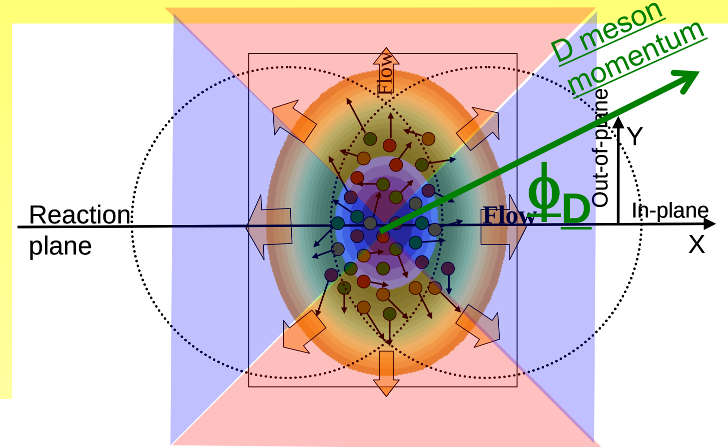
Heavy-flavour suppression: further steps

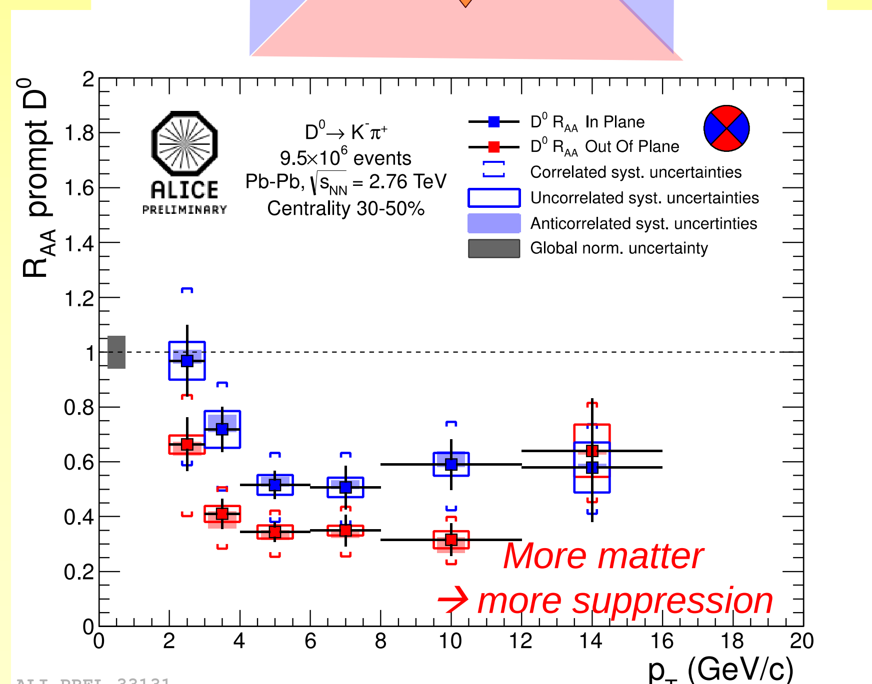
- First measurement of $D_s(c\bar{s})$ in heavy ions
  - D_s enhancement expected, if *c* quarks recombine in the QGP (high strangeness content)





- D meson suppression in different azimuthal directions

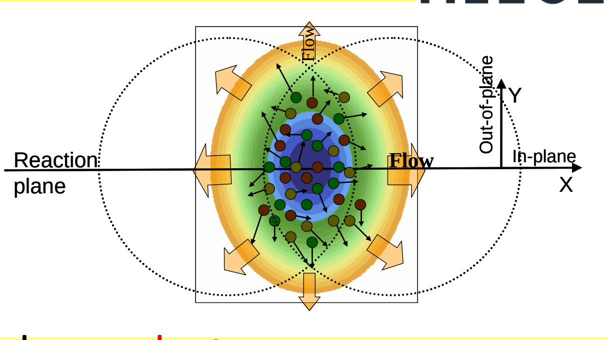




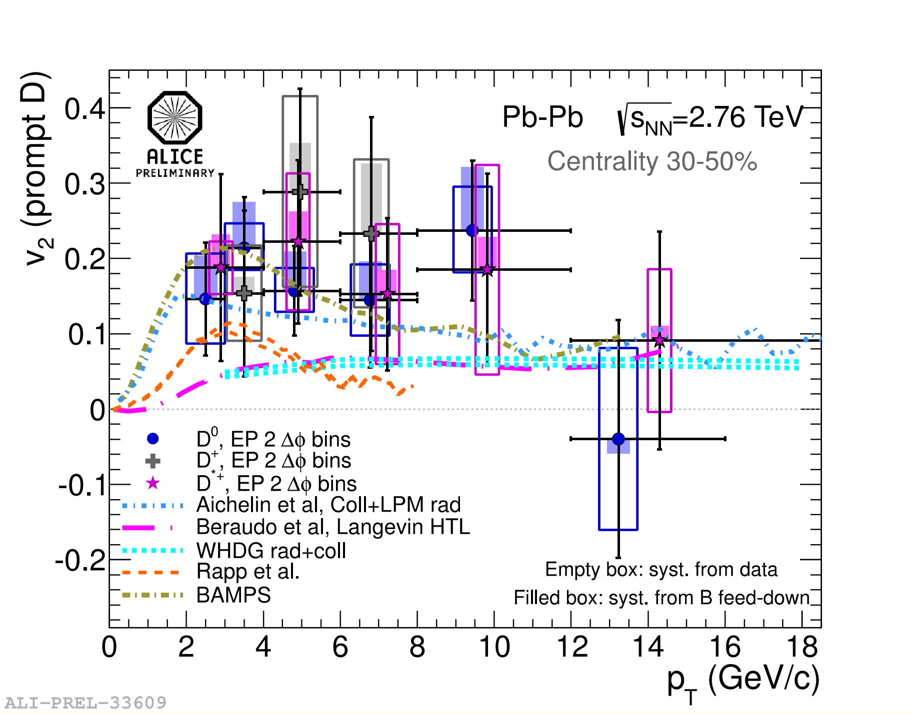
  - Data very intriguing, but not conclusive (→next runs, upgrades)

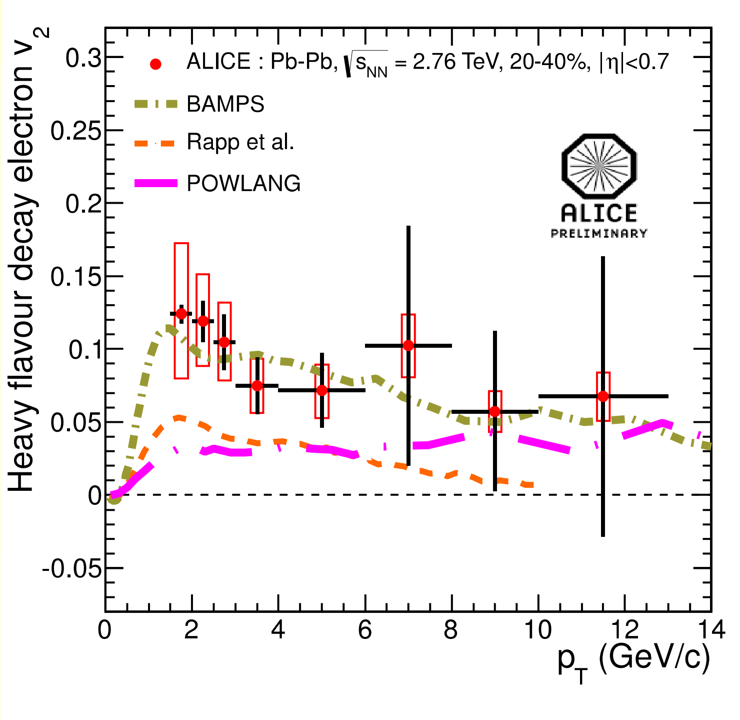
Heavy-flavour azimuthal anisotropy v_2

- Non-central collisions, expansion under azimuth-dep. pressure gradient results in azimuth-dep. momentum distributions
- 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



- Anisotropy (v_2>0) observed at low p_T for D's (D^0,D^+,D^*) and HF-decay electrons:

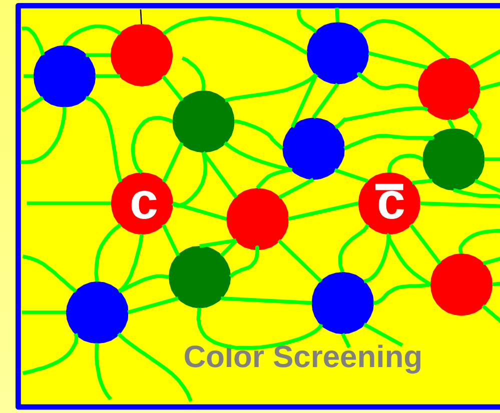




- Described qualitatively by models with heavy-quark transport in expanding QGP

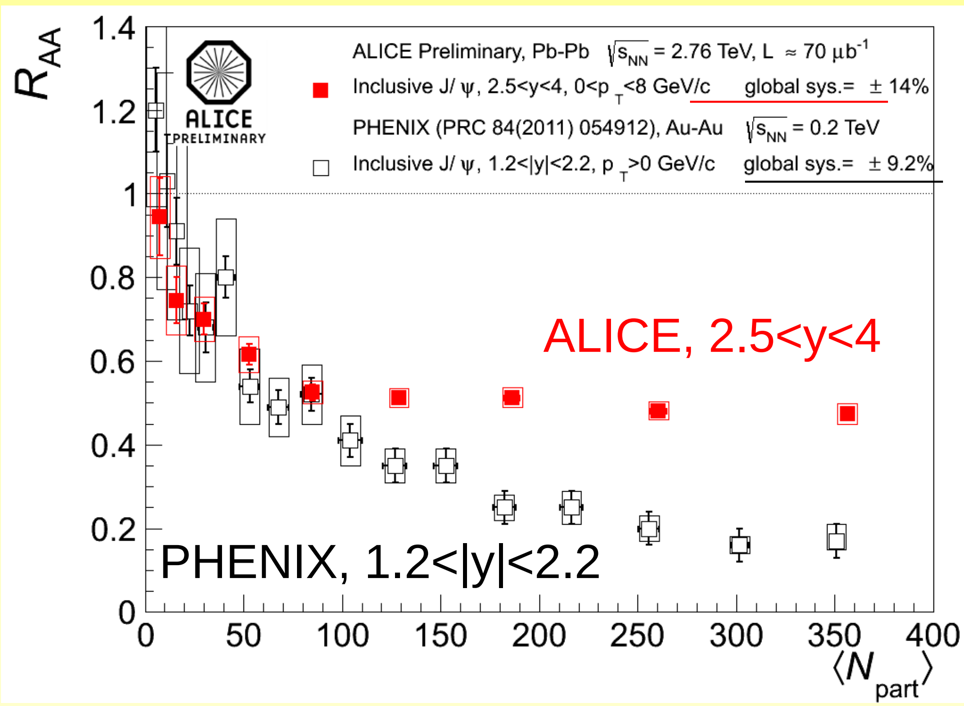
J/ψ "suppression" at the LHC

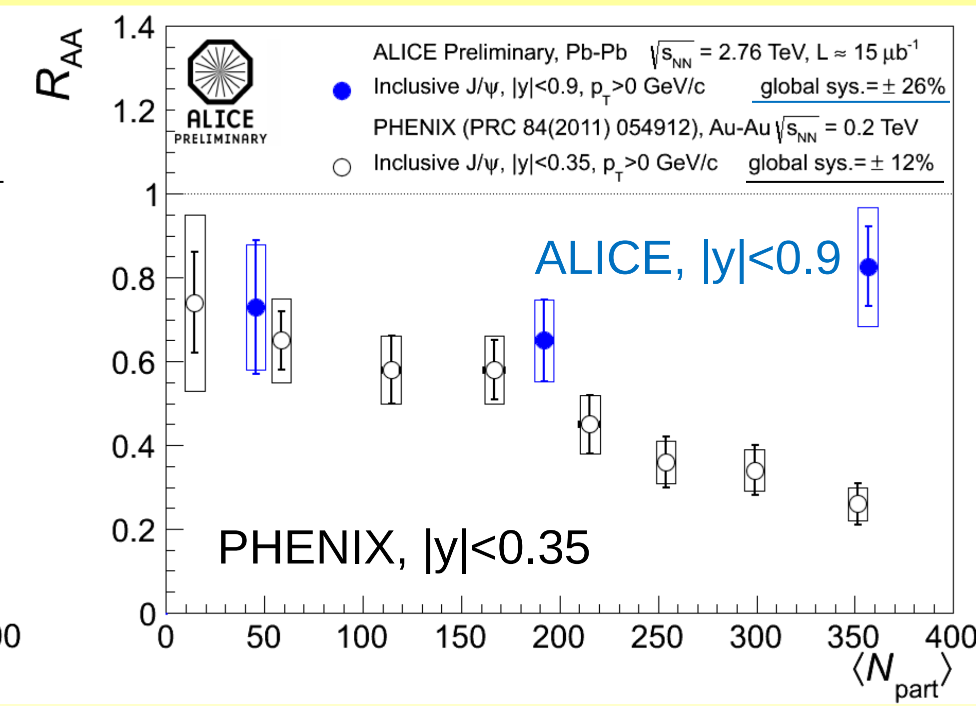
Predicted as a signature of deconfinement, due to the temperature (color charge density density) dependent screening of the color charge in a Quark-Gluon Plasma



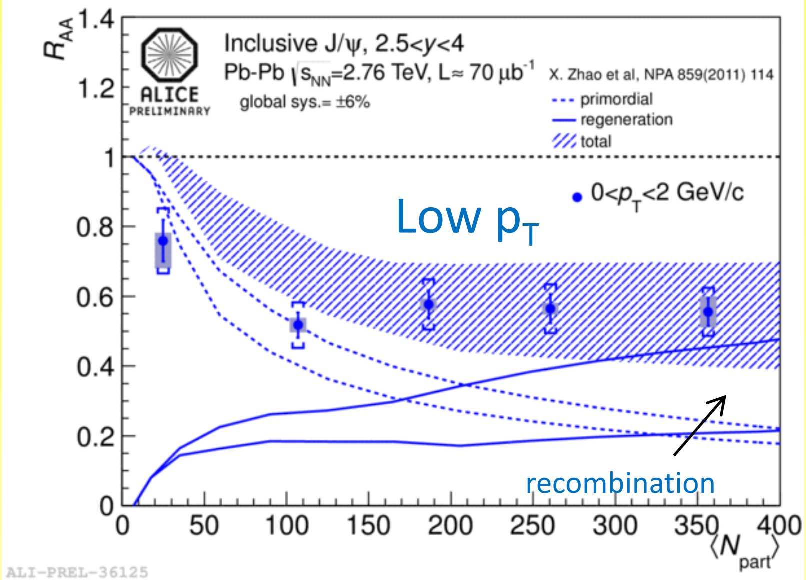
Observed at lower energy experiments (SPS, RHIC)

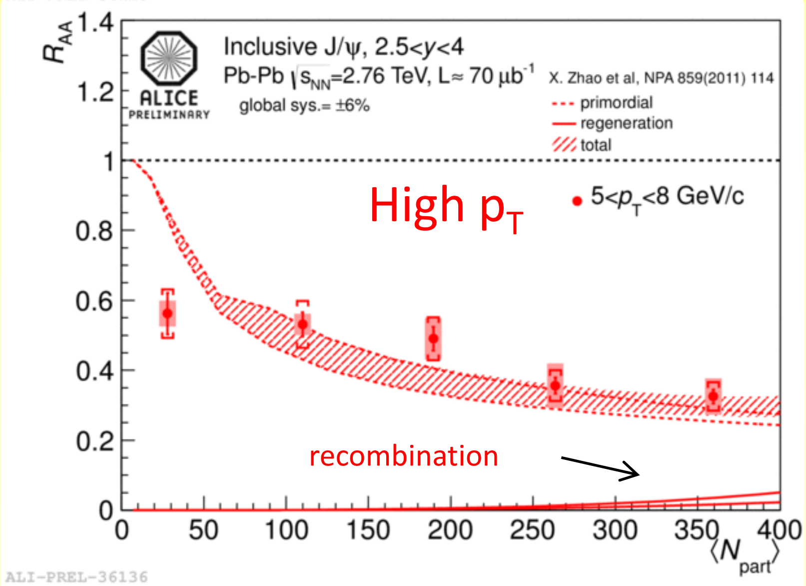
ALICE measures a suppression of the J/ψ yield (R_{AA}<1), at both central and forward y, BUT SMALLER than at RHIC





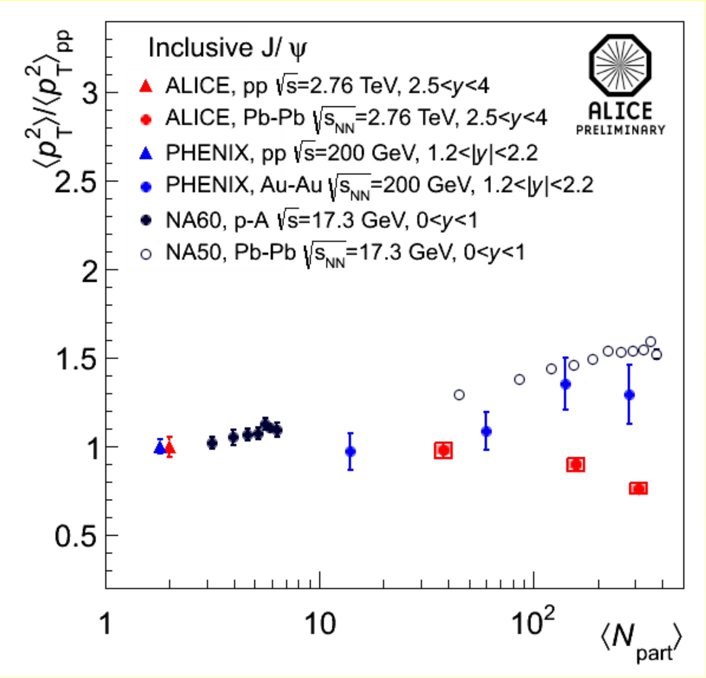
New regime at LHC energy ?





We find a smaller suppression at low transverse momentum (only accessible by ALICE)

J/ψ are suppressed in the QGP, as at lower energies, BUT are (re)generated from the large number of freely roaming charm quarks in the QGP (only important at low p_T !) ?

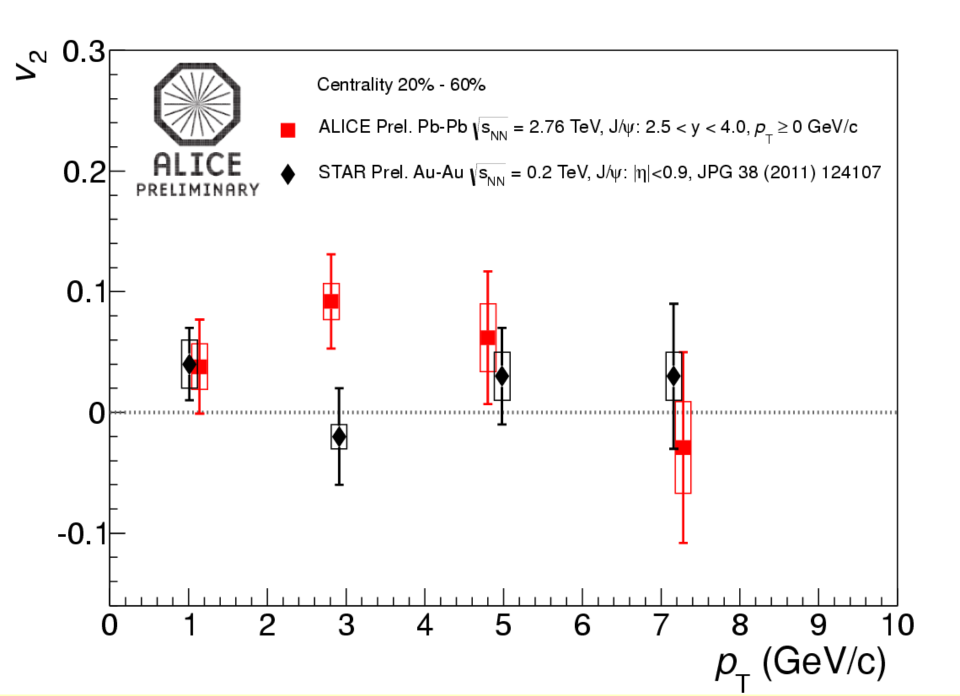


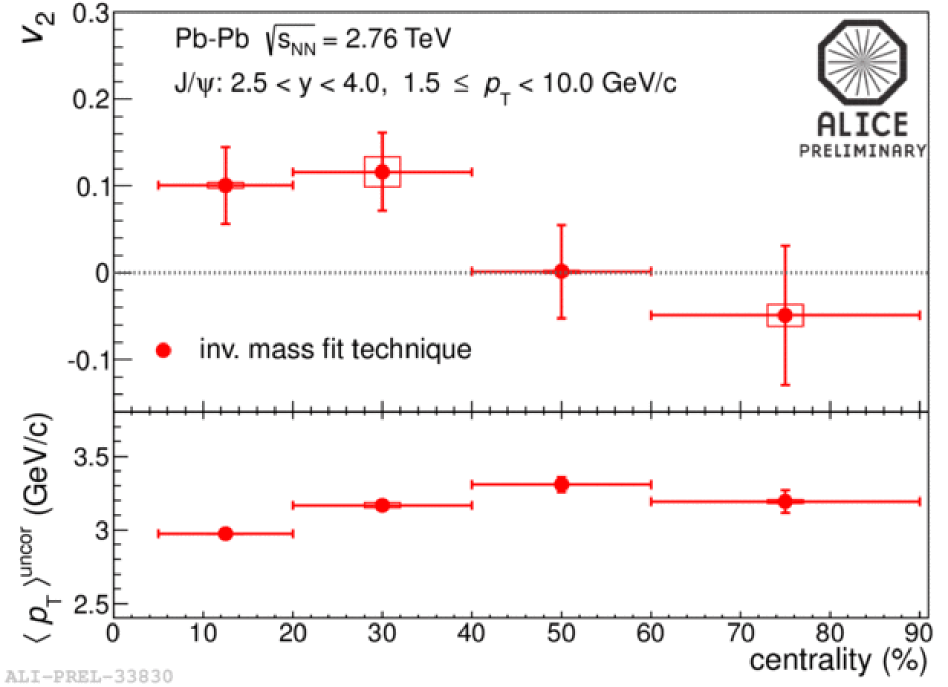
Low p_T enhancement of J/ψ only visible at LHC

Flowing with the charm

Open charm hadrons exhibit a significant elliptic flow

J/ψ from (re)combination of charm quarks should exhibit a non-zero v_2 too





Hint for a finite J/ψ v_2 observed for the first time at LHC energy
(final observation probably needs upgrade luminosity)

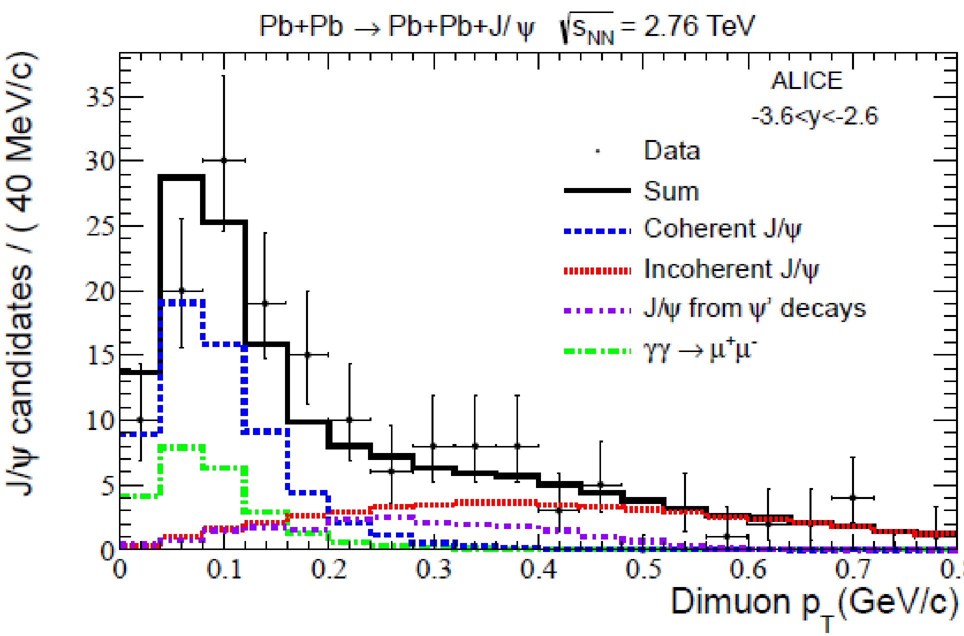
Picture emerging at the LHC: J/ψ melting in the QGP stage, followed by subsequent regeneration in QGP or at freeze-out

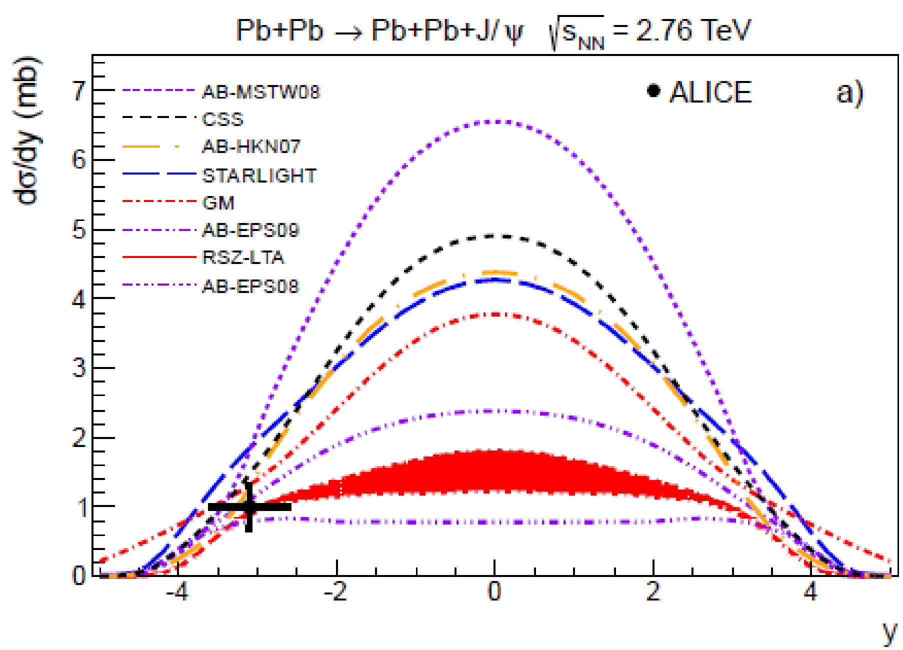
From hadronic to e.m. production

First measurement at the LHC of J/ψ photoproduction in ultra-peripheral Pb-Pb-collisions

Probes nuclear gluon distribution, poorly known at low Bjorken-x

CERN-PH-EP-2012-270: out this morning

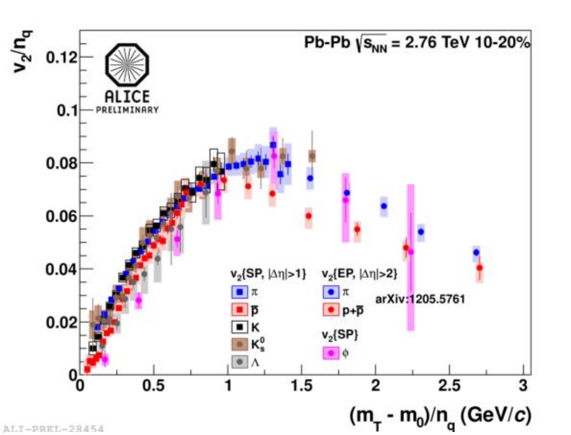


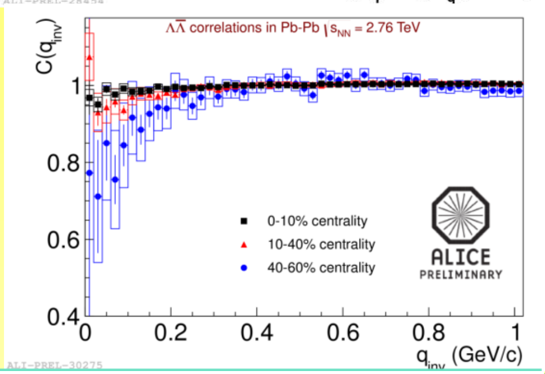


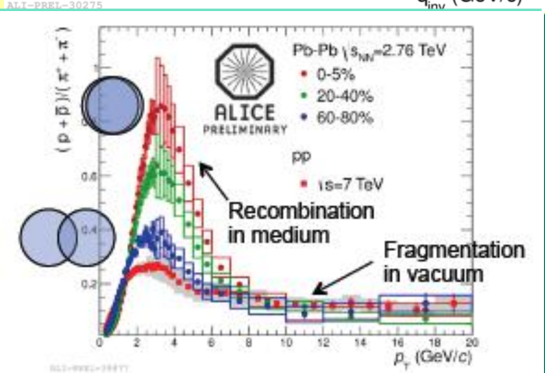
Low p_T enhancement due to coherent production (photon couples to all nucleons), target nucleus does not break-up

Best agreement found with models which include nuclear gluon shadowing consistent with the recent EPS09 parameterization

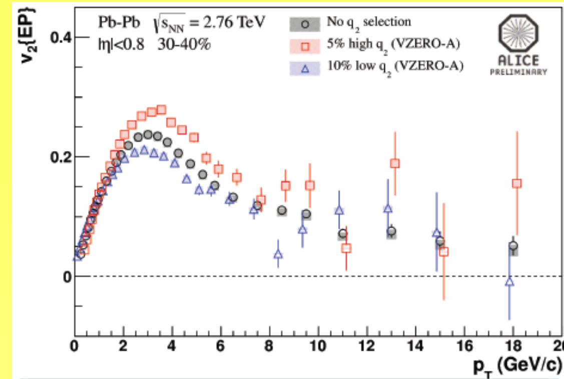
ALICE

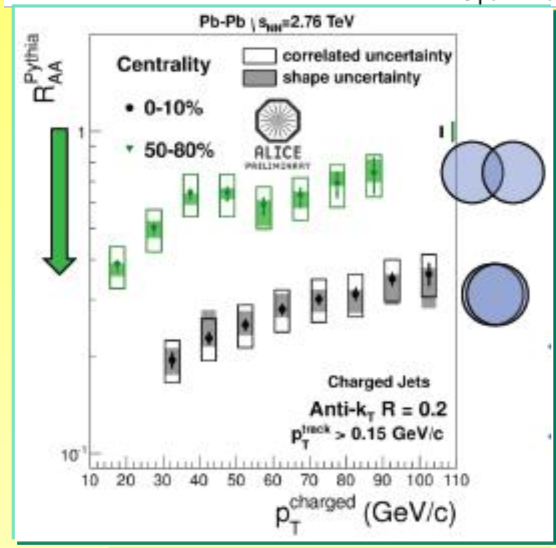

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV 10-20%
ALICE PRELIMINARY
v_2/n_q
$(m_T - m_0)/n_q$ (GeV/c)
arXiv:1205.5761
ALI-PREL-28454

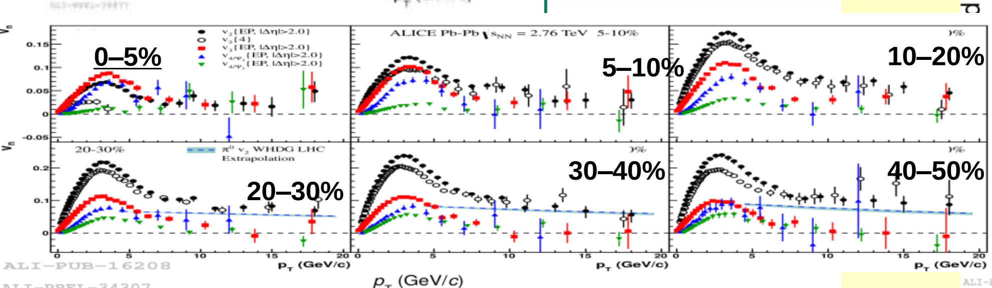

$\Lambda\bar{\Lambda}$ correlations in Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$C(q_{inv})$
0-10% centrality
10-40% centrality
40-60% centrality
ALICE PRELIMINARY
q_{inv} (GeV/c)
ALI-PREL-30275

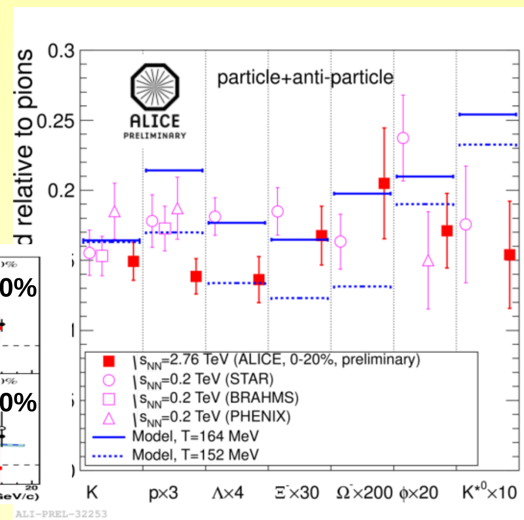

Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
0-5%
20-40%
60-80%
ALICE PRELIMINARY
pp
$\sqrt{s}$=7 TeV
Recombination in medium
Fragmentation in vacuum
p_T (GeV/c)

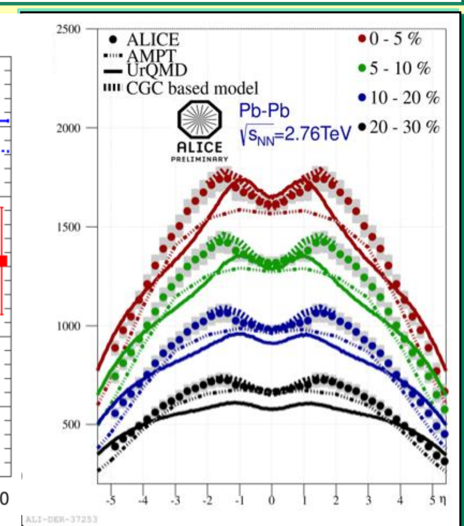
And More...


Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$|\eta|$<0.8 30-40%
No q_2 selection
5% high q_2 (VZERO-A)
10% low q_2 (VZERO-A)
ALICE PRELIMINARY
$v_2\{EP\}$
p_T (GeV/c)


Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
R_{AA}^{Pythia}
Centrality
0-10%
50-80%
correlated uncertainty
shape uncertainty
ALICE PRELIMINARY
Charged Jets
Anti-k_T R = 0.2
p_T^{track} > 0.15 GeV/c
$p_T^{charged}$ (GeV/c)

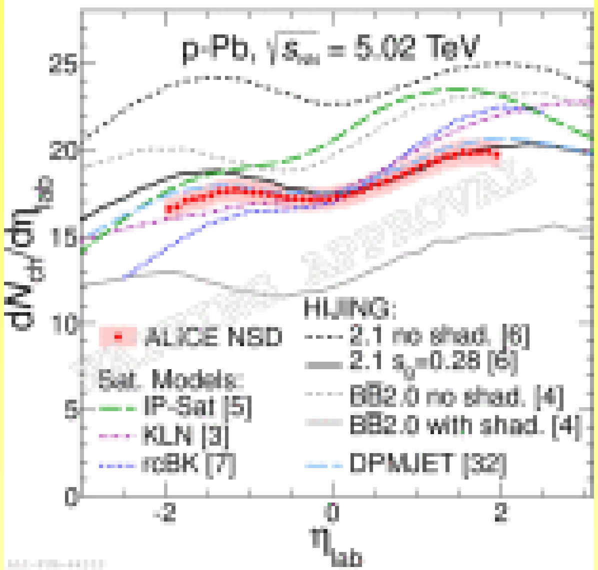

0–5%
5–10%
10–20%
20–30%
30–40%
40–50%
ALICE Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV 5-10%
p_T (GeV/c)
ALI-PUB-16208

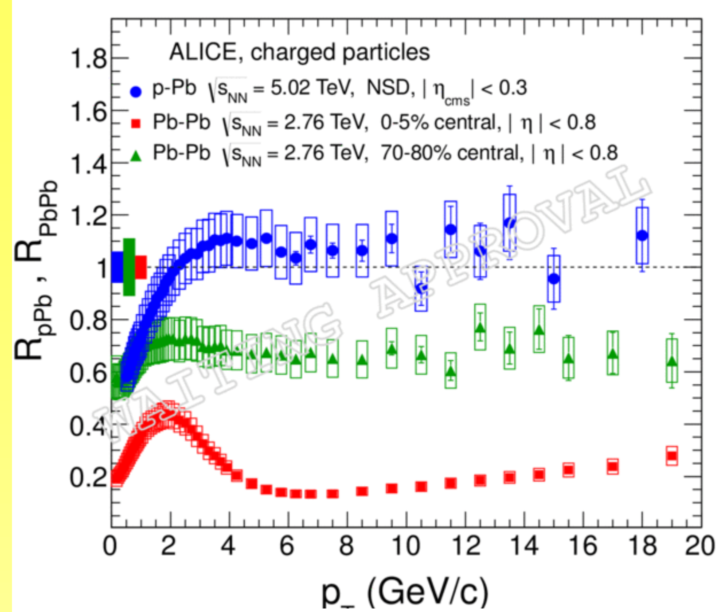

relative to pions
particle+anti-particle
ALICE PRELIMINARY
$\sqrt{s_{NN}}$=2.76 TeV (ALICE, 0-20%, preliminary)
$\sqrt{s_{NN}}$=0.2 TeV (STAR)
$\sqrt{s_{NN}}$=0.2 TeV (BRAHMS)
$\sqrt{s_{NN}}$=0.2 TeV (PHENIX)
Model, T=164 MeV
Model, T=152 MeV
K
p×3
Λ×4
Ξ×30
Ω×200
φ×20
K*0×10
ALI-PREL-32253


ALICE
AMPT
UrQMD
CGC based model
0 - 5 %
5 - 10 %
10 - 20 %
20 - 30 %
Pb-Pb
$\sqrt{s_{NN}}$=2.76TeV
ALICE PRELIMINARY
η

First glance at pA !

- crucial control experiment, already constraining models!

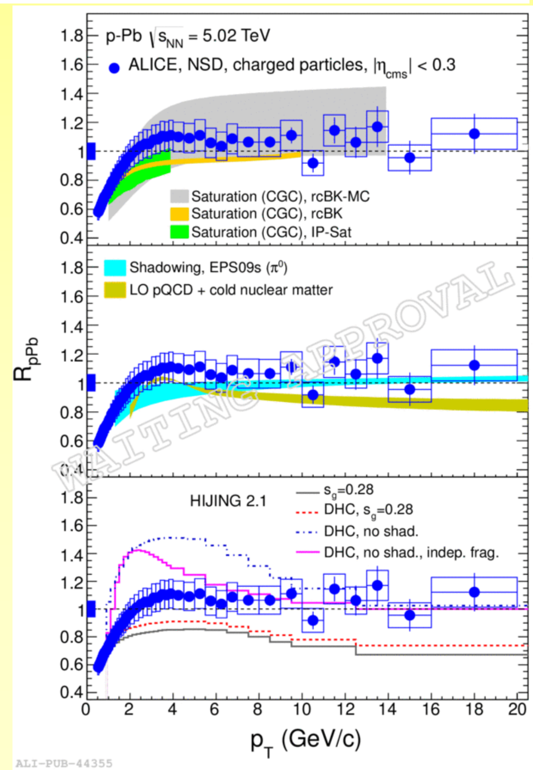




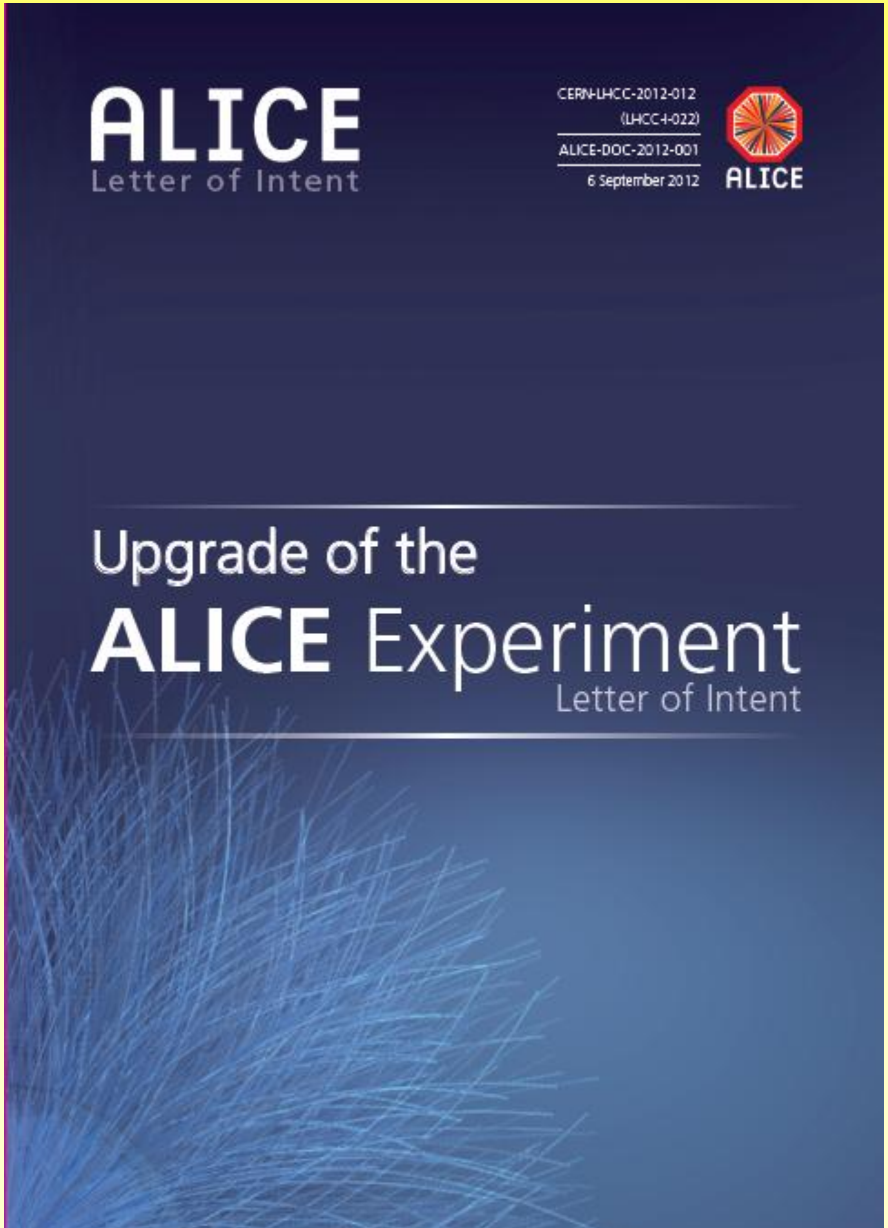
http://arxiv.org/abs/1210.4520

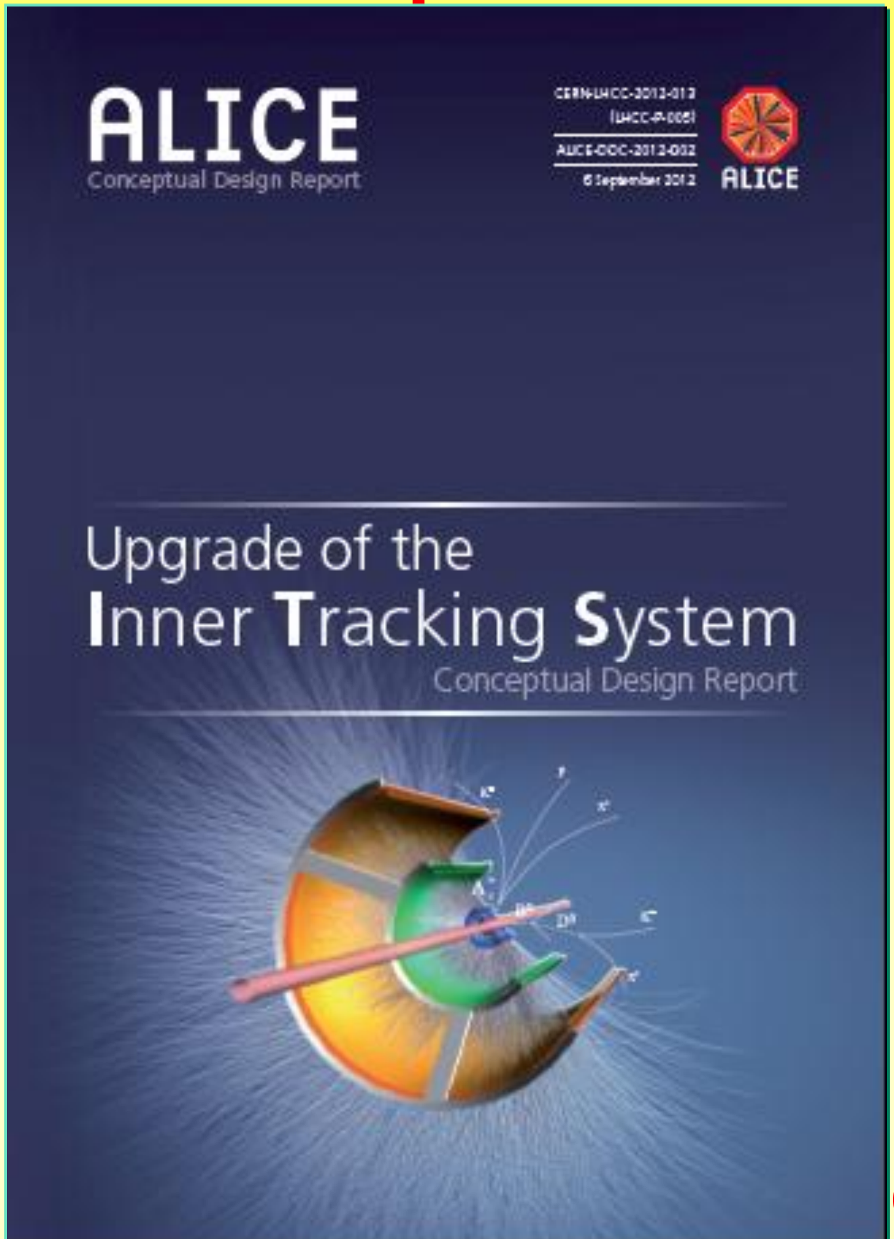
http://arxiv.org/abs/1210.3615

	$dN_{ch}/d\eta_{lab}$			$\frac{dN_{ch}/d\eta_{lab}\vert_{\eta_{lab}=2.0}}{dN_{ch}/d\eta_{lab}\vert_{\eta_{lab}=-2.0}}$
	−2.0	0.0	2.0	
ALICE	16.65 ±0.65	17.24 ±0.66	19.81 ±0.78	1.19 ±0.05
Saturation Models				
IP-Sat [5]	17.55	20.55	23.11	1.32
KLN [3]	15.96	17.51	22.02	1.38
rcBK [7]	14.27	16.94	22.51	1.58
HIJING				
2.1 no shad. [6]	23.58	22.67	24.96	1.06
2.1 s_g = 0.28 [6]	18.30	17.49	20.21	1.10
B$\bar{B}$2.0 no shad. [4]	20.03	19.68	23.24	1.16
B$\bar{B}$2.0 with shad. [4]	12.97	12.09	15.16	1.17
DPMJET [32]	17.50	17.61	20.67	1.18



The future… LoI and ITS CDR for the Upgrades, Submitted to the LHCC sept 6th





ALICE Upgrade: target LS2 (2018)

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

- Primary scope:
  - precision studies of charm and beauty mesons and baryons and charmonia
  - low mass lepton pairs and thermal photons
  - gamma-jet and jet-jet with particle identification from low momentum up to 30 GeV.
  - heavy nuclear states

➢ low-transverse momentum observables (complementary/orthogonal to the general-purpose detectors)

- not triggerable => need to examine full statistics.

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

ALICE Upgrade: Physics Motivation

Main physics topics that are uniquely accessible (among others) with the upgraded ALICE detector:

- **Measurement of heavy-flavour transport parameters**
  - Diffusion coefficient (QGP equation of state, η/s) → HF azimuthal anisotropy and R_{AA}
  - In-medium thermalization and hadronization → HF baryons
  - Mass dependence of energy loss → HF R_{AA}

- **Measurement of low-mass and low-p_t di-electrons**
  - Chiral symmetry restoration → ρ spectral function
  - γ production from QGP (temp.) → low-mass dilepton continuum
  - Space-time evolution of the QGP → radial and elliptic flow of emitted radiation

- **J/ψ , ψ', and χ_c states down to zero p_t**
  - statistical hadronization vs. dissociation/recombination scenario
  - transition between low and high transverse momenta
  - density dependence – central vs. forward production

66

Additional measurements

- Jets
  - Heavy-flavour tagged jets
    - gluon vs. quark induced jets and charm fragmentation
  - Particle identified fragmentation functions
    - influence of medium on fragmentations
  - γ – jet correlations
    - radiated energy recovery at very low momenta
- Heavy nuclear states
  - mass-4 and -5 (anti-)hypernuclei
  - search for H-dibaryon, Λn bound state, etc.

ALICE Upgrade Physics Reach

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

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

Experimental Strategy

- run ALICE at 50kHz Pb-Pb (i.e. $L = 6x10^{27}$ $cm^{-1}s^{-1}$), with minimum bias (pipeline) readout (max readout with present ALICE set-up ~500Hz)
  - Gain a factor of 100 in statistics over current program: x 10 integrated luminosity, $1nb^{-1}$ => 10 nb^{-1}, x 10 via pipelined readout allowing inspection of all collisions, namely inspect O(10^{10}) central collisions instead of O(10^8)
- improve vertexing, and tracking at low p_t
- This entails :
  - New, smaller radius beam pipe
  - New inner tracker (ITS) (scope and rate upgrade)
  - High-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ/HLT, Muons and Trigger detectors
- Furthermore, three major proposals are under consideration by the collaboration to extend the scope of ALICE (collaboration decision in September):
  VHMPID, MFT, and FoCal
  - new high momentum PID capabilities
  - b-tagging for J/ψ, low-mass di-muons
  - low-x physics with identified γ/π^o

Timeline for UPGRADES

- 2012 Sept LoI
- 2012 Sept Decision on Overall Scope
- 2012-2013 Complete R&D
- 2014-2016 Procurement/Fabrication
- 2016-2017 Integration, pre-commissioning
- 2017-2018 Installation, commissioning
- 2019-2020 Full deployment of DAQ/HLT

- **Installation**: need 18 months. Two alternatives
  - 18 months long LS2 (as requested by LHCb)
  - Removal of TPC and ITS in the winter shutdown 2016/2017 and reinstallation in 2018. Would need to move the HI run of 2017 to 2016 (2 months of HI instead of 1)

Upgrades, a busy summer

- WG with ATLAS and CMS
  - to assess relative capabilities
- Town meeting of the whole HI community (at CERN June 29th)
  - Very important meeting, resulting in a common document of the Community submitted to the Cracow one, and indicating clearly the extension of the LHC HI program, including the ALICE upgrade, as its first priority. Remarkable coherence of ALICE, ATLAS and CMS
    - "***The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC.***"
- NUPECC also submitted a document to Cracow,
  - Stresses the commitment of the Nuclear Physics Community to the ALICE long term programs, "top priority for European Nuclear Physics"
- Cracow European Strategy Meeting
  - Heavy Ion Physics an integral part of the LHC program till at least the mid 2020s

Upgrades: STATUS

- **LHCC** => On September 27, the after the third round of discussions with ALICE, the LHCC has endorsed our Upgrade LoI and ITS CDR. Minutes are not out yet, but there is a statement which we can quote issued by the LHCC chair:
  - *"There is an interest amongst the collider experiments (ALICE, ATLAS and CMS) for a continued heavy ion programme that gives access to rare final states. This programme will extend well into the 20ies assuming the current HI running mode of one month per year.*
    The physics programmes of the two general purpose detectors and ALICE are complementary: while the former may focus on selected hard probes ALICE will be optimized for particle identification at low transverse momenta. The experiments are hence sensitive to different "messenger" signals and phases of the evolution of the quark gluon plasma.
    This increase in sensitivity for ALICE entails an upgrade of the rate capability of the TPC, a high resolution ITS, and a major upgrade of the online system and the read-out electronics.
    The LHCC commends this joint approach to heavy ion physics and endorses the upgrade plans of the ALICE collaboration. The committee is looking forward to the seeing the detailed technical solutions presented in the respective TDRs.."

- **ALICE looking forward to a long-term future!**

Upgrades, next

- **What Happens Next?**
- **RRB 29 Oct -1 Nov**
  - Extension of the construction MoU
  - General Endorsement of the Upgrade
  - Agreement on the amount and sharing of the Common Fund
- **TDRs** to be prepared in O(1 year)
  - Will define the construction design
  - Will contain the specific commitments of the Institutions to the projects
  - Followed by MoU addendum (or addenda)
- **R&D**
  - Will have to continue vigorously throughout the process, with substantial funding, agreed within each project.

- Decisions on MFT, VHMPID, FOCAL

ALICE upgrade in the Czech Republic

Czech groups are participating in two of the ALICE upgrade projects

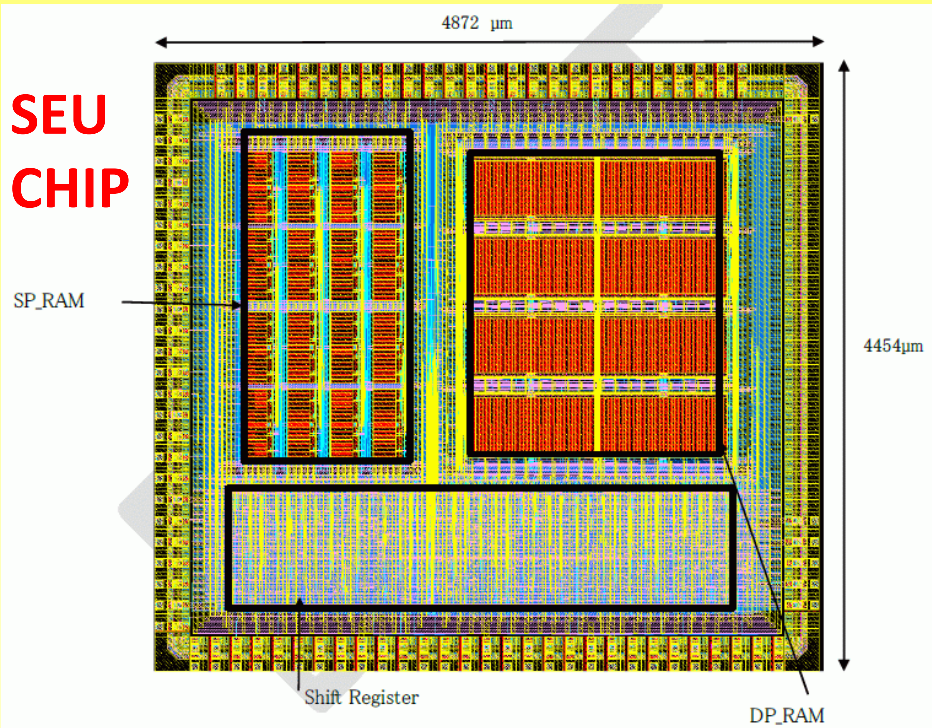
- ITS upgrade
- Forward calorimeter project FOCAL

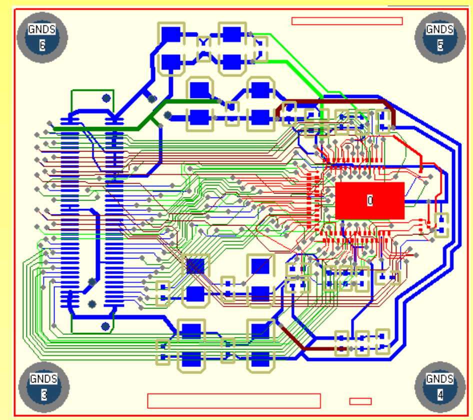
•NPI AS CR is participating in **ITS upgrade** in hardware development (readout chip tests…) and radiation hardness tests

•FNSPE CTU and IP AS CR groups Is actively involved in the **FOCAL project**. At CTU is being developed a calorimeter prototype with optical readout, group also works on development of the pad detector for Si-W design of the calorimeter, mechanical structures and services for calorimeter etc. Simulations for calorimeter design are coordinated from CTU and they run on the CTU computer farm.

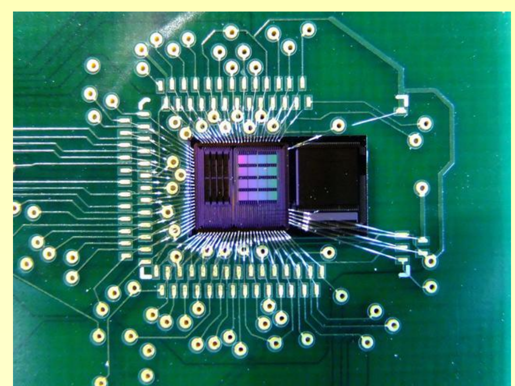
Contribution to ITS upgrade project of NPI CAS Řež and IEP SAS Košice Radiation Hardness - Single Upset Event

NPI CAS: V.Kushpil, S.Kushpil, V.Mikhaylov, J. Ferencei, IEP SAS: J.Špalek





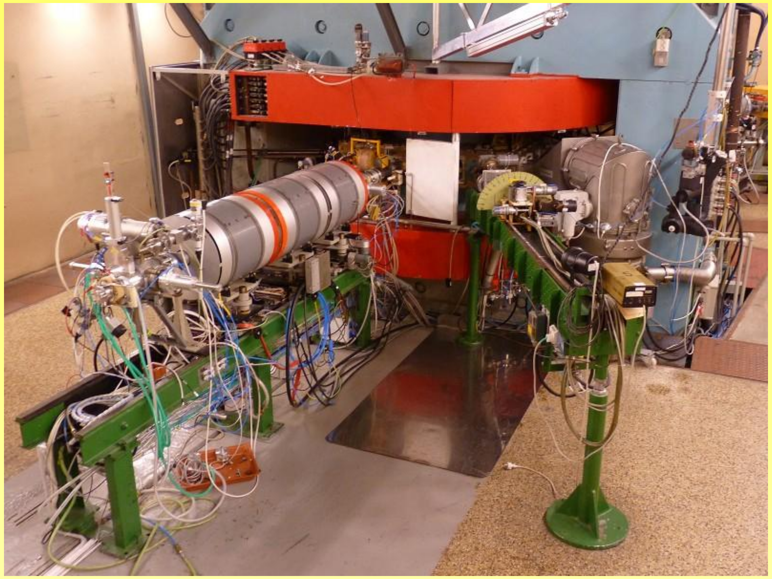
Custom SEU chip board by V.Kushpil



Contribution of NPI group: measurement of the SEU sensitivity / cross section for:

- single port RAMs (16 x 1024x16bits)
- dual port RAMs (8 x 2048x16bits)
- 16 bit 32K stages shift register

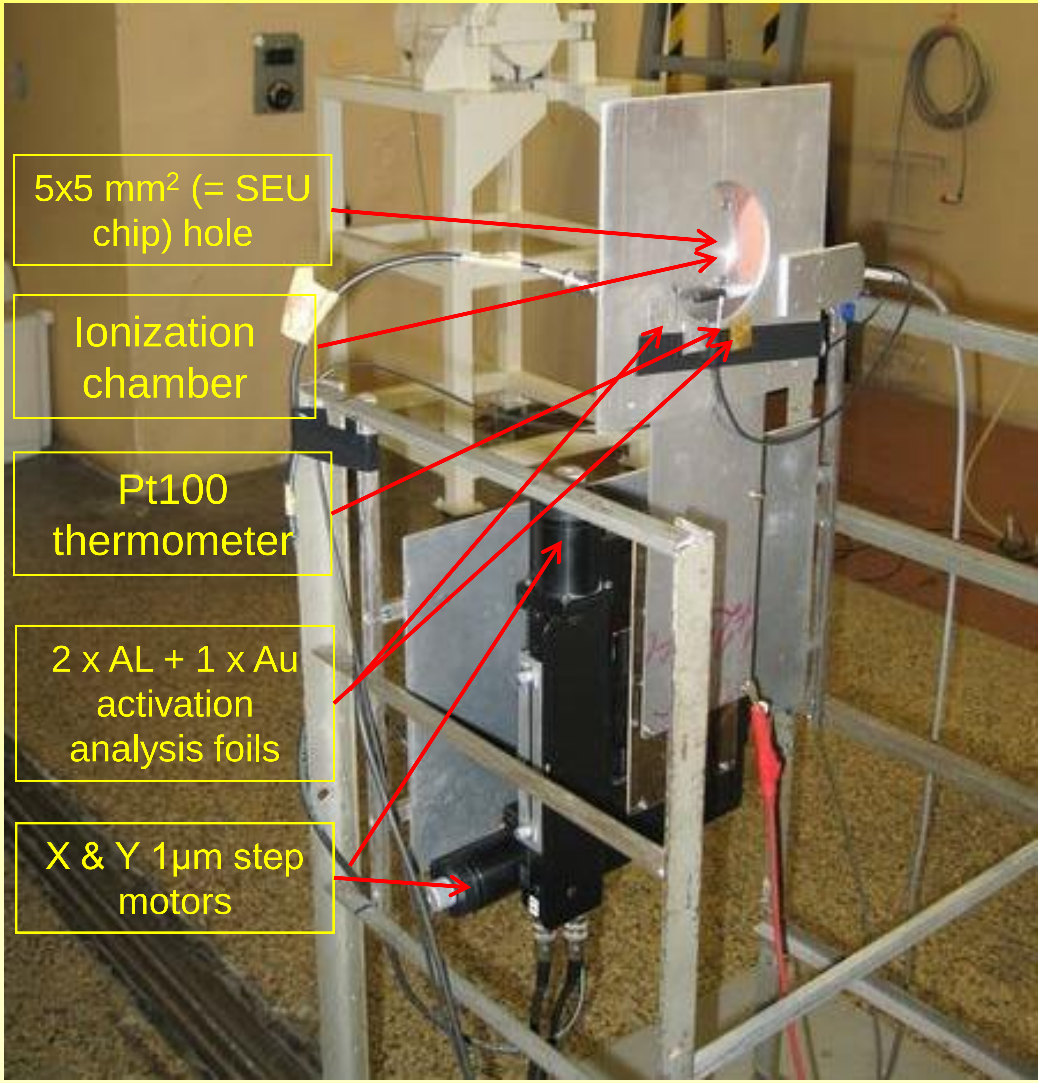
CYCLOTRON U-120M AT NPI ASCR AS A TEST BED INSTRUMENT



Immediate plans:

- determine SEU proton energy dependence as a function of accumulated doses
- verify SEU proton angular dependence
- especially look for multiple bit errors
- the same above also for neutrons

MEASUREMENT SETUP IN CYCLOTRON



Conclusion

- **It is an exciting time for ALICE**
  - Scientific results are pouring in
  - More are coming, and the pA run is about to start
  - An even wider horizon opens with the upgrades
  - The Collaboration is lively and growing
- **The Czech participation in ALICE is great**
  - Substantial contribution to the detector
  - Important contribution to computing
  - Strong presence in Physics
  - **Major role in the Upgrade program**
- **A bright future ahead for ALICE and the Czech Republic**

-40
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0
20
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SPARES

Highlights

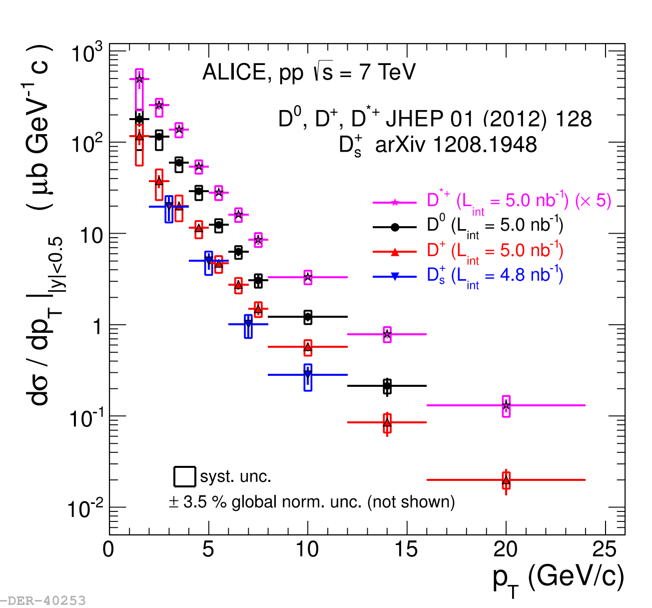
– Study of the interplay between hard and soft processes with di-hadron correlations
  - Observe jet shape modifications in central Pb-Pb collisions but no modification of the p/π ratio.
– Measure of the elliptic flow of D-mesons
  - Sign of thermalization at low-*p*T ?
– J/ψ suppression measurements
  - Color screening and charm recombination could explain the experimental data on centrality, rapidity and transverse momentum dependence of J/ψ suppression.

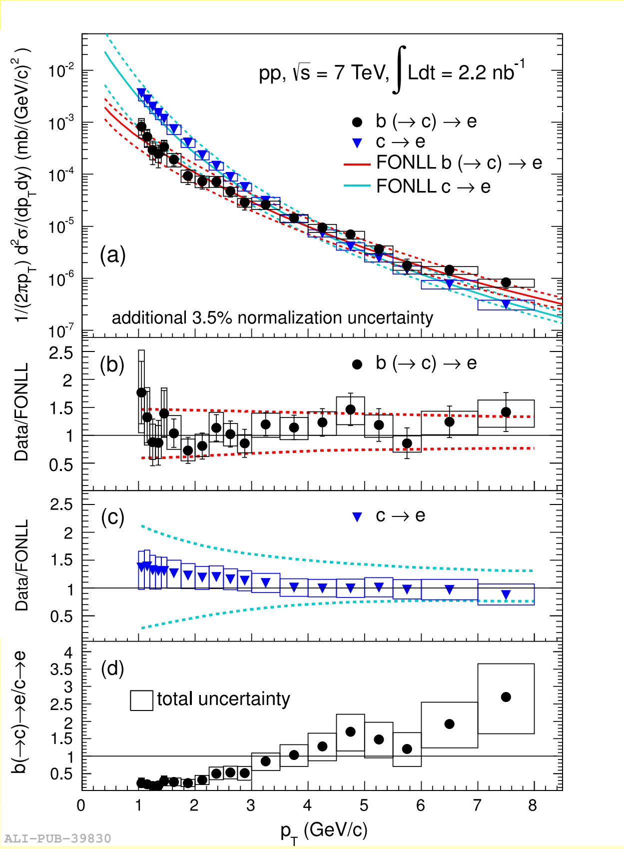
Heavy flavour in pp

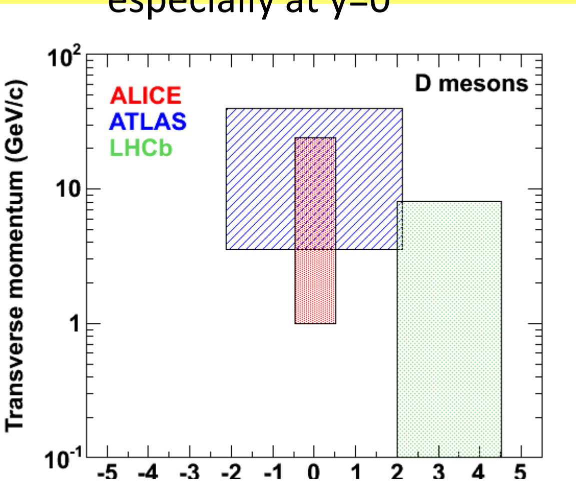
- Latest new results on HF in pp:
  - D_s production for p_T>2 GeV/c (arXiv:1208.1948)
  - B-decay electron production for p_T>1 GeV/c (arXiv:1208.1902)

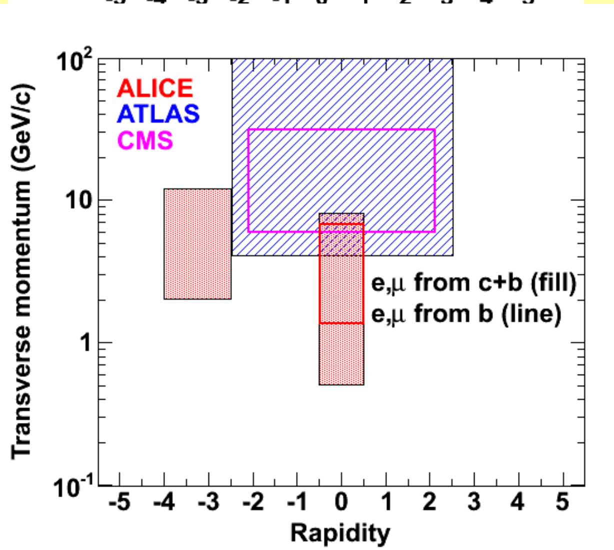
✓ Complementary coverages

✓ ALICE's special: low-p_t, especially at y=0









Not shown:
B hadrons (ATLAS, CMS, LHCb)
b-jets (ATLAS, CMS)

QCD

FERMIONS

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

Leptons spin = 1/2			
Flavor		Mass GeV/c²	Electric charge
ν_e	electron neutrino	<1×10⁻⁸	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2			
Flavor		Approx. Mass GeV/c²	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	beauty	4.3	–1/3

BOSONS

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

Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W⁻	80.4	–1
W⁺	80.4	+1
Z⁰	91.187	0

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

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

Two puzzles in QCD: i) confinement

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

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

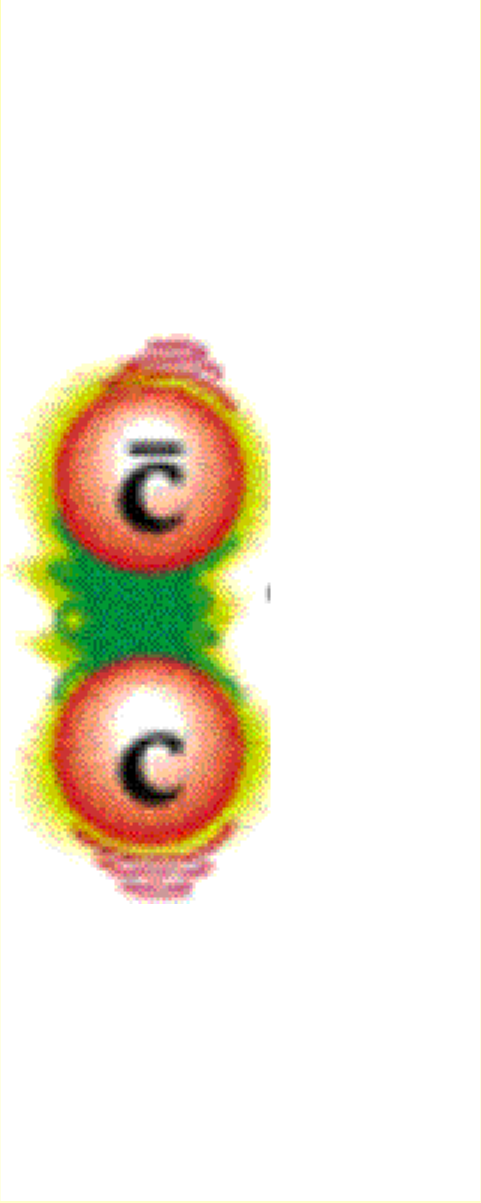
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

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

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

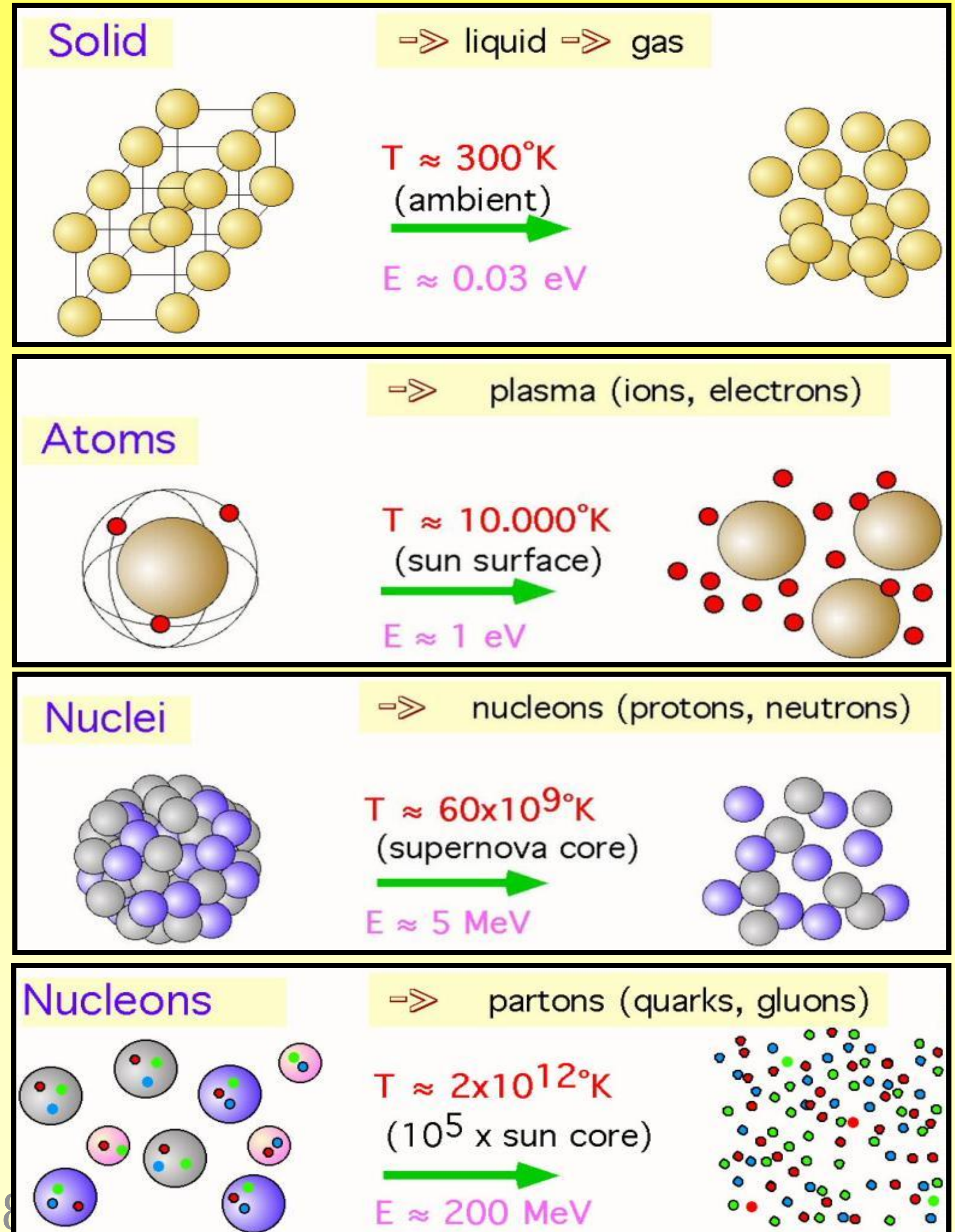
<u>how does this come about?</u>

The Strong force and confinement



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

Melting Matter



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

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

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

Puzzles in QCD: ii) hadron masses

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

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
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τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
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BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

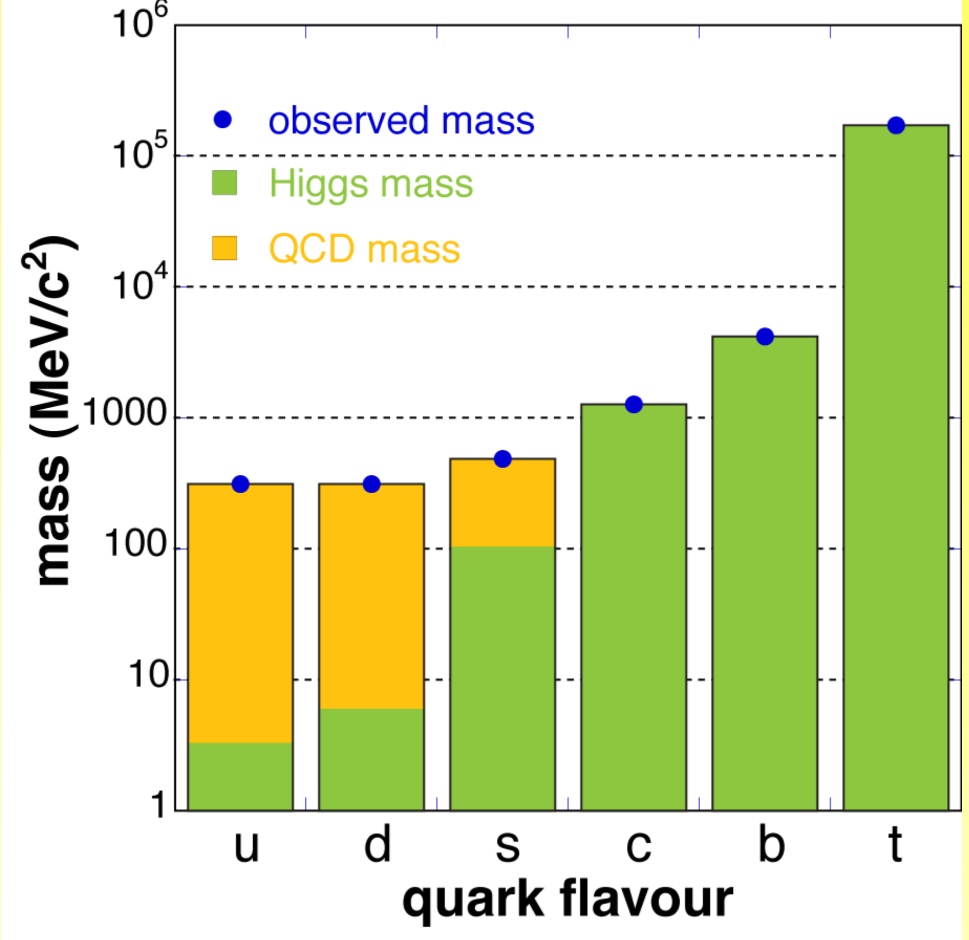
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

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

Origin of hadron masses



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

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

Heavy Ion Collisions

- Tool to tudy properties of **large, macroscopic** systems of strongly interacting matter (mean free path >> system size)
  - which are shaped by, but usually can not be derived from, its basic constituents and their interactions
  - H2O + QED: constituents and forces of 'water', but looking at a single (or a few) H20 molecules, we don't learn anything about the properties of 'water', its phases (ice, water, steam), …
  - we need a 'bucket' full and experiment with it
- Is it possible? **Yes!**
  - At LHC we can even measure the shape of each 'event'
    - by looking at the 'waves' generated in the liquid by the collision