Statistical Methods in Particle Physics

Lecture 5

November 12, 2012

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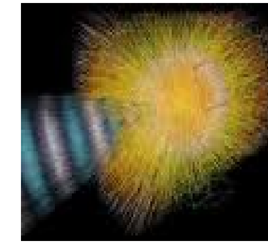
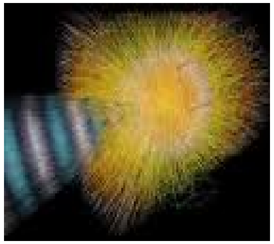
Winter Semester 2012 / 13



Source

Lecture in the program for the GSI summer students
http://hgs-hire.de/program/events/summer-program/2012/index.shtml

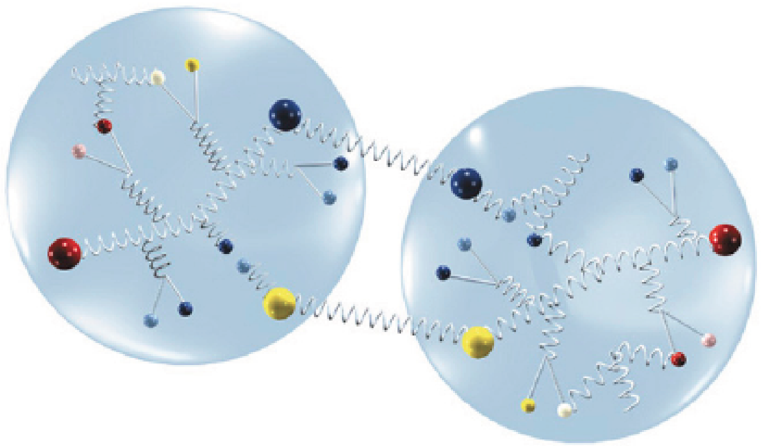
Outline

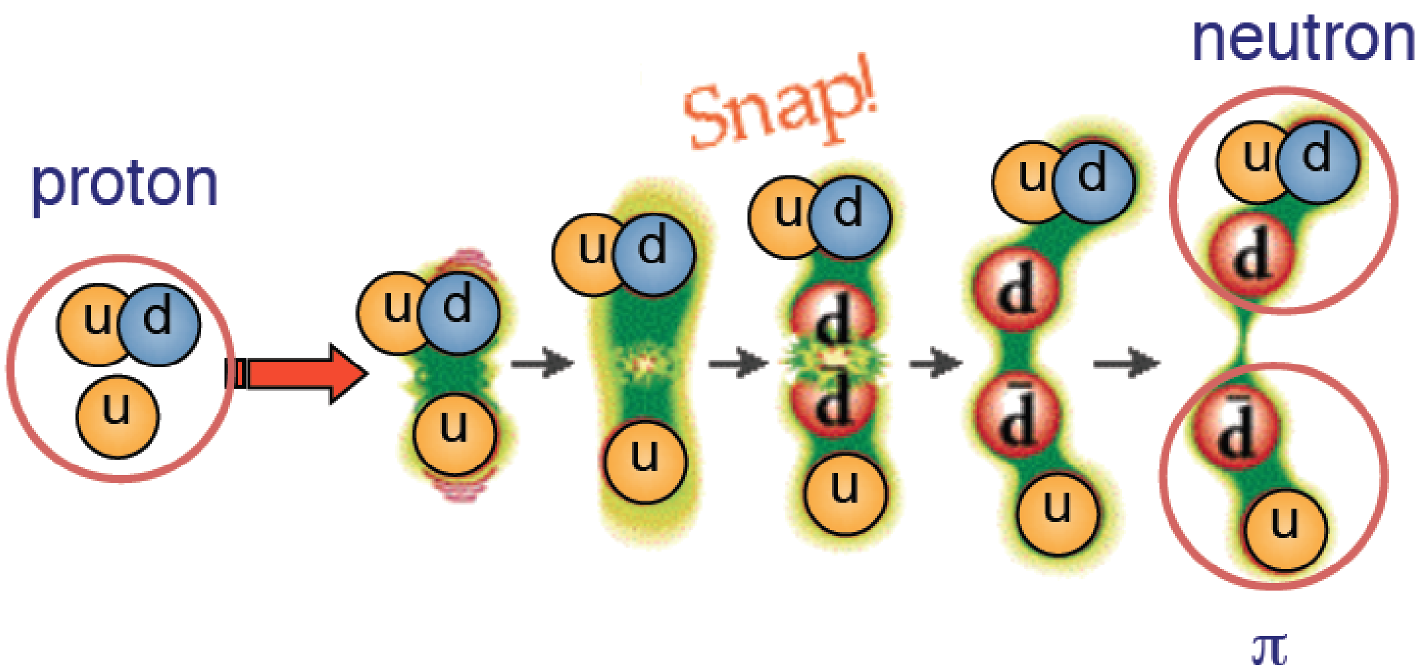


- The Quark-Gluon Plasma
- A few words about the LHC
- Heavy-ion collisions at the LHC
- ALICE:
  - The spectrometer
  - Vertexing and particle identification
  - Nuclear modification factor
    - From charged particles to heavy flavors
  - The highest temperature reached on hearth
- Outlook

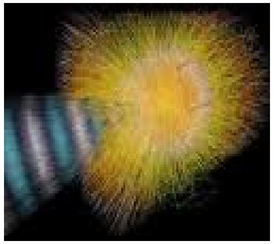
Confinement

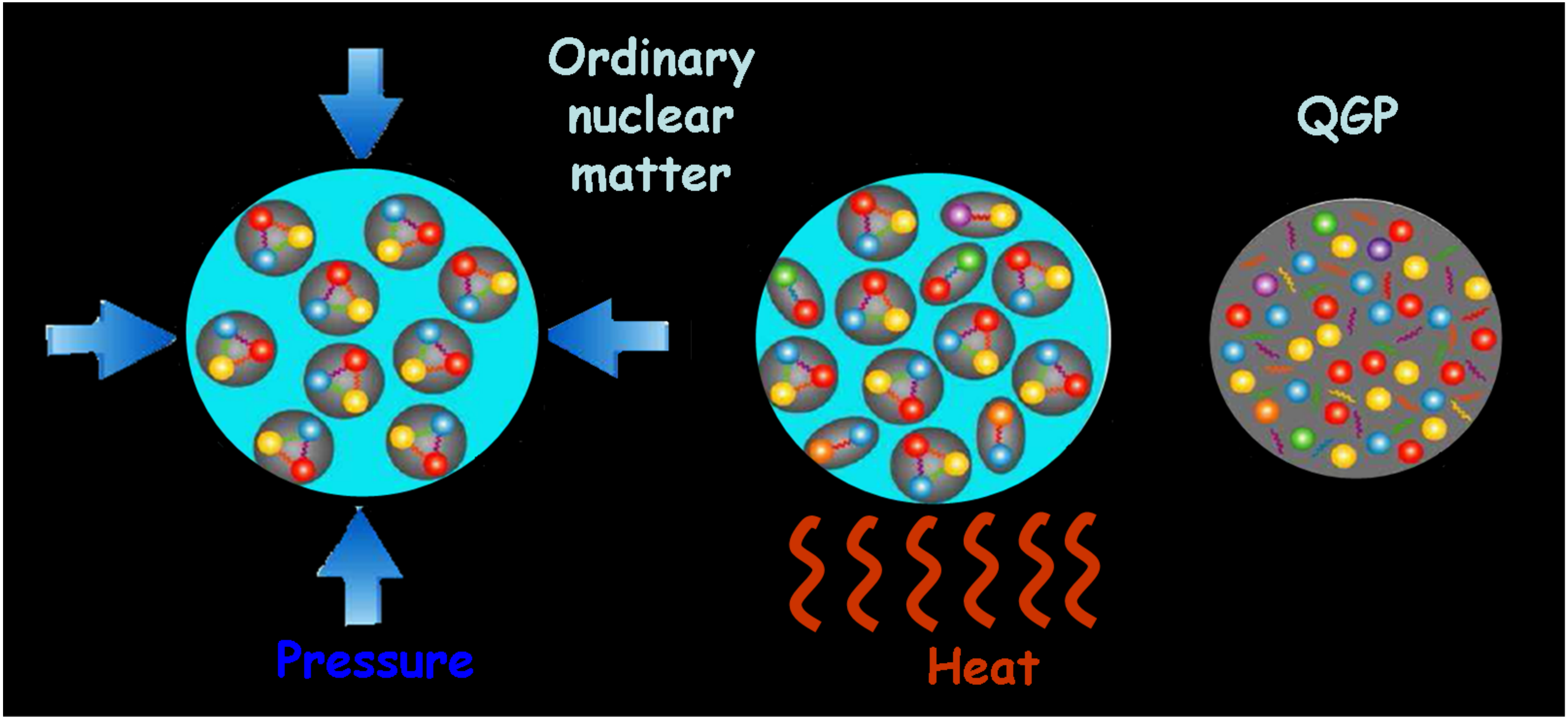
All matter we know, is confined:



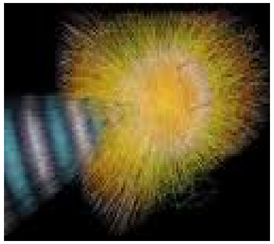


Quark-Gluon Plasma



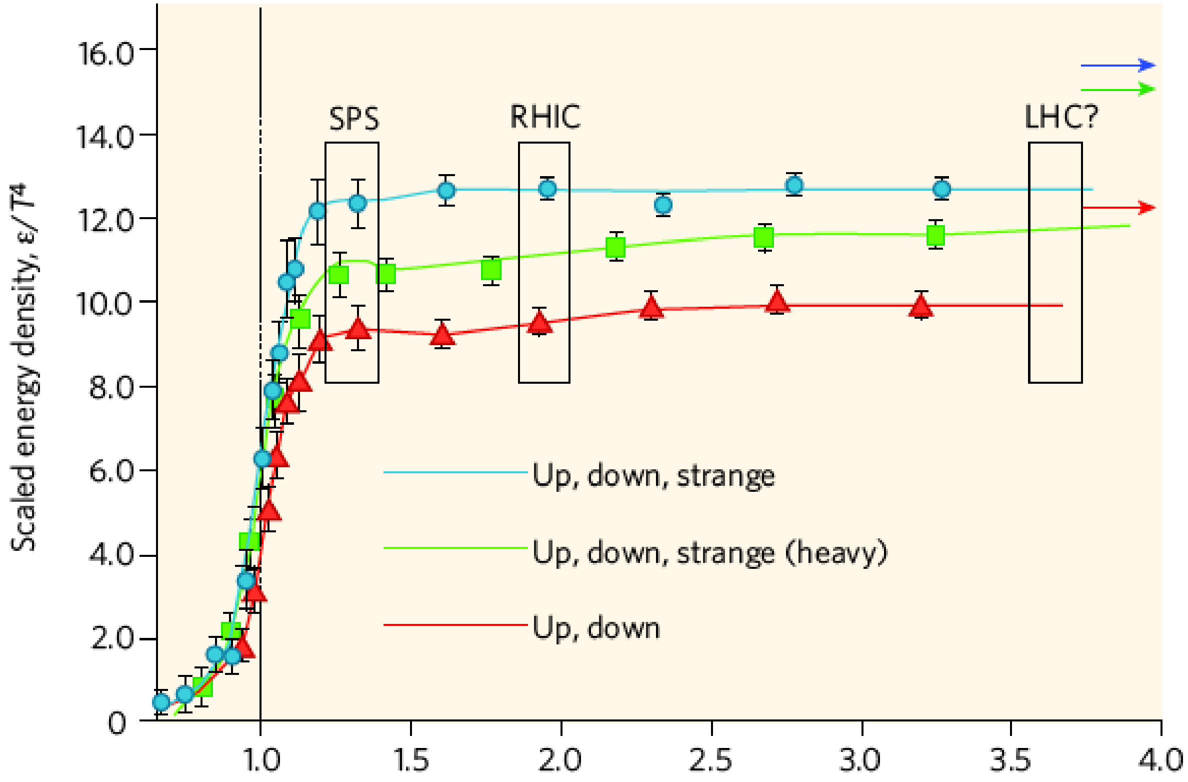


Lattice QCD calculation



Non-perturbative problems treated by discretization on a space-time lattice

Energy density

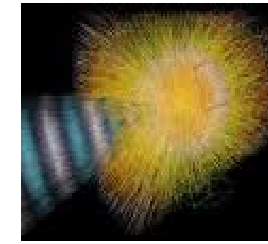


No details here!
Not the latest prediction!

Temperature / T_C

Hadron gas to QGP
phase transition

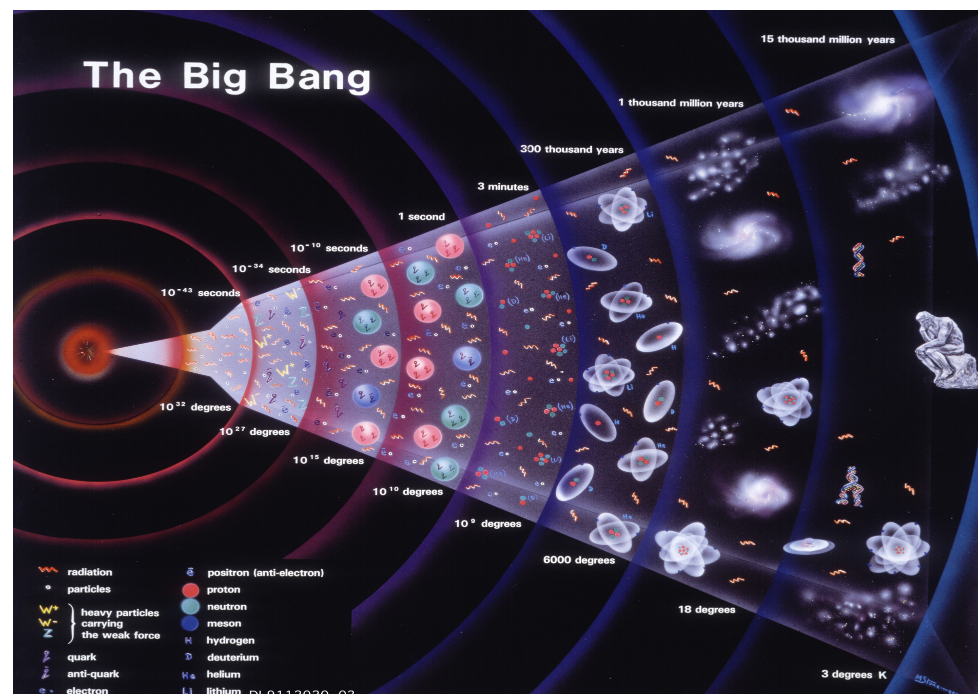
Dense and hot nuclear matter: why?

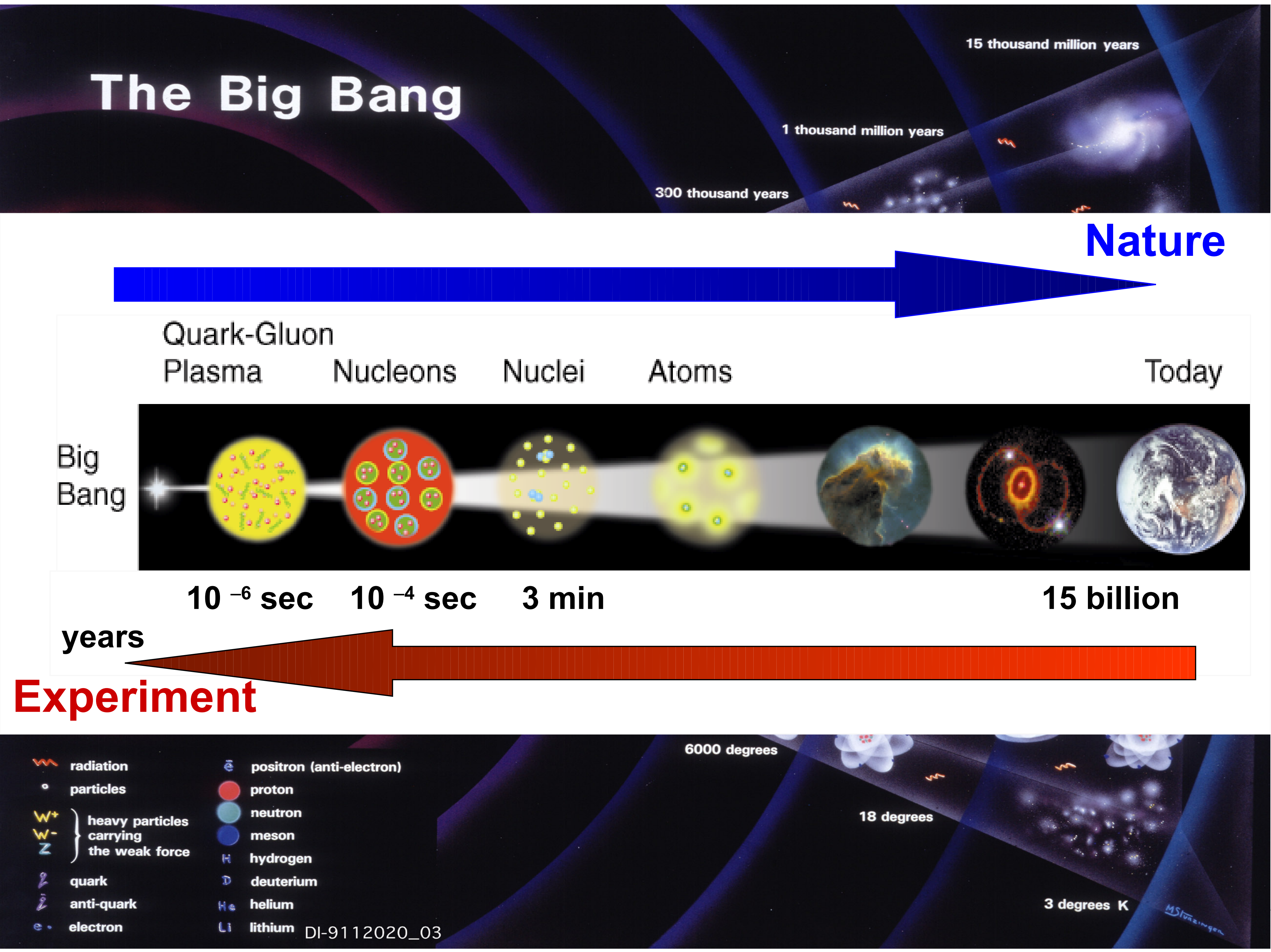


Status of matter in:

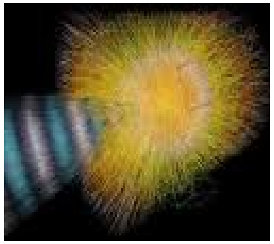
- Neutron stars and core-collapse supernovae

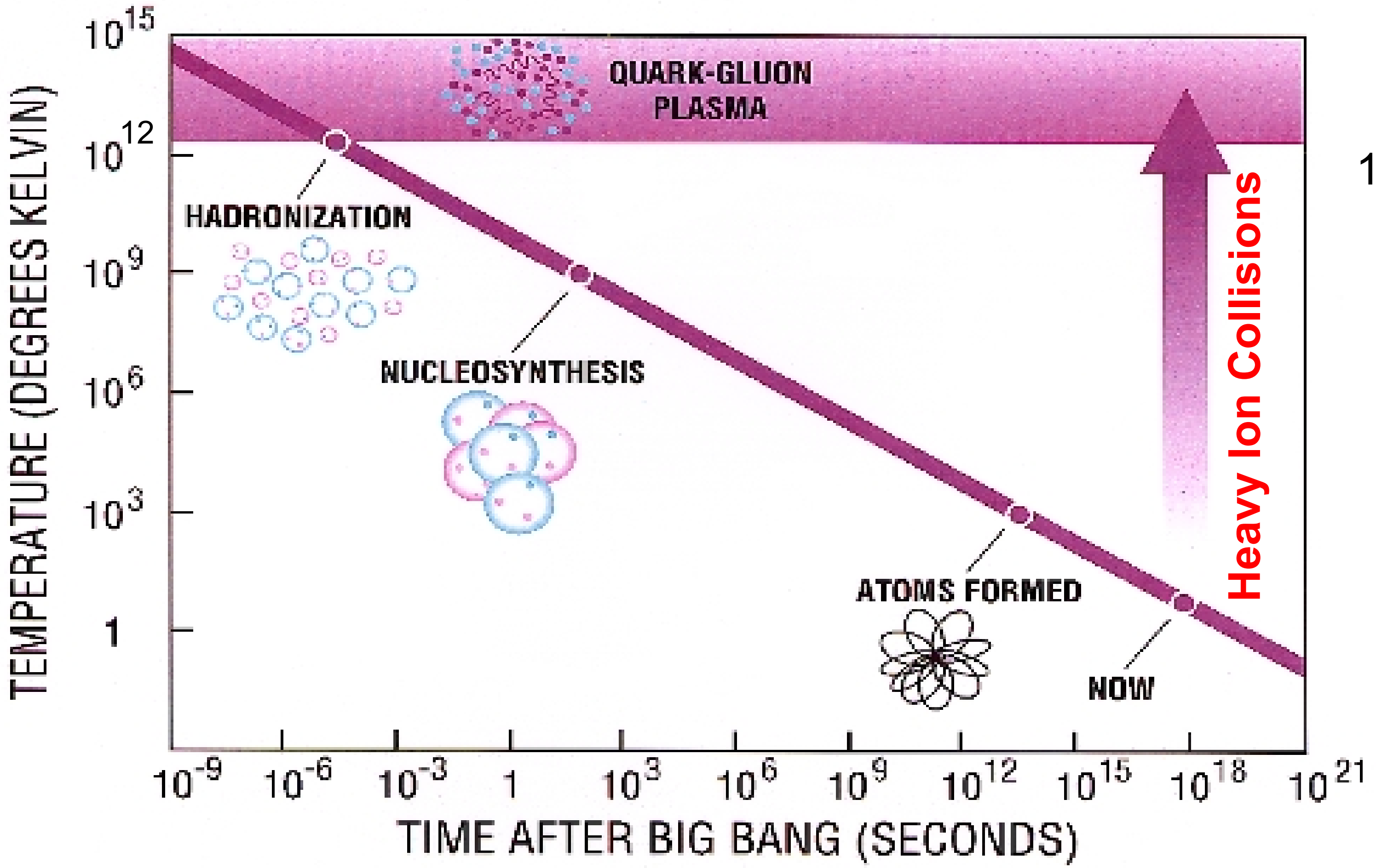
- First instants of our universe (10^{-6} seconds)




The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
Nature
Quark-Gluon Plasma
Nucleons
Nuclei
Atoms
Today
Big Bang
10 $^{-6}$ sec
10 $^{-4}$ sec
3 min
15 billion years
Experiment
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
DI-9112020_03

Temperature Evolution of the Universe

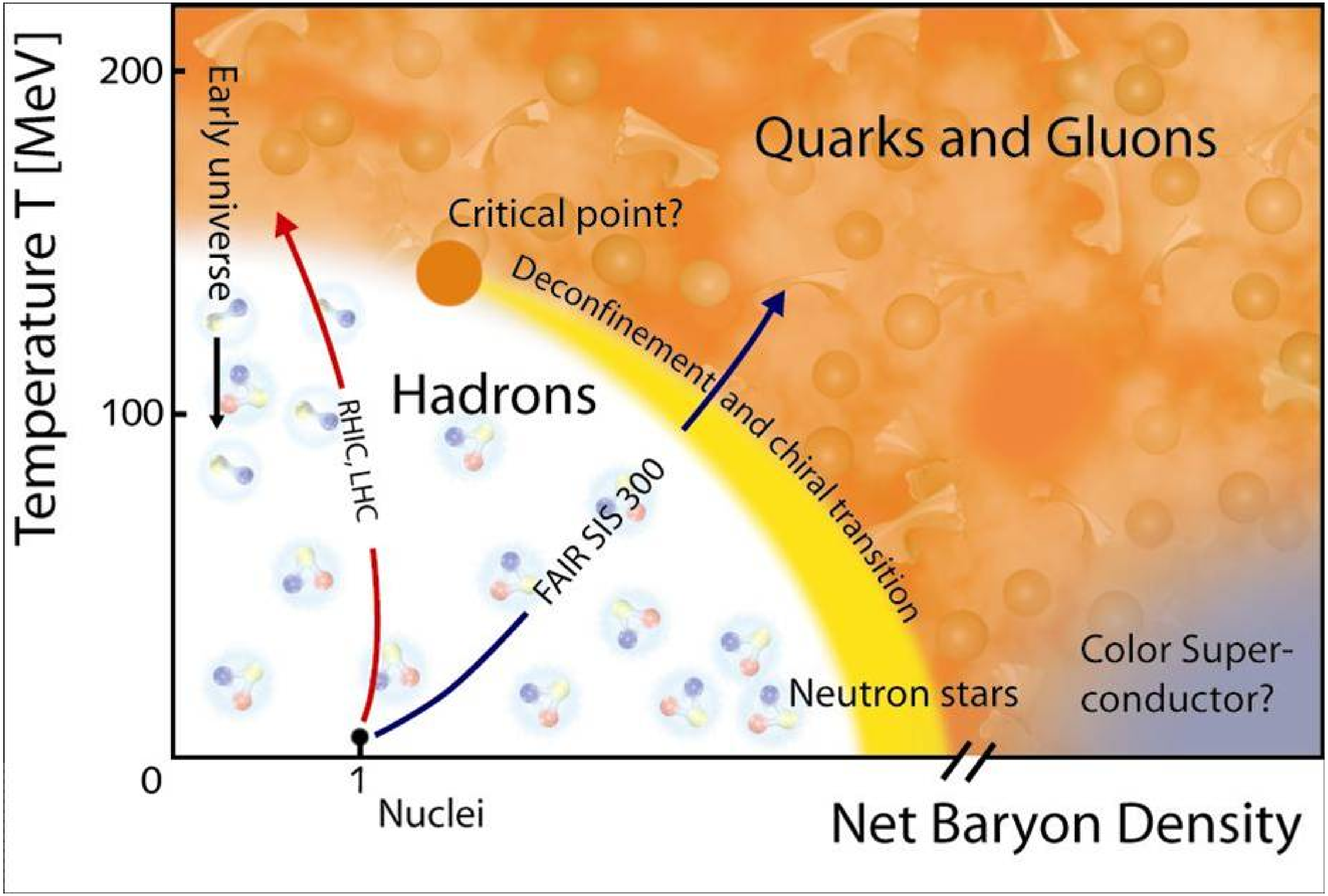




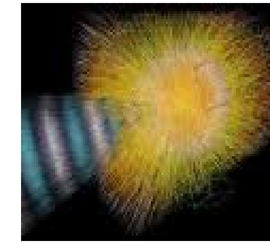
160 MeV

1 MeV ≈ 10 billion degrees = 10^{10} degrees

Phase diagram

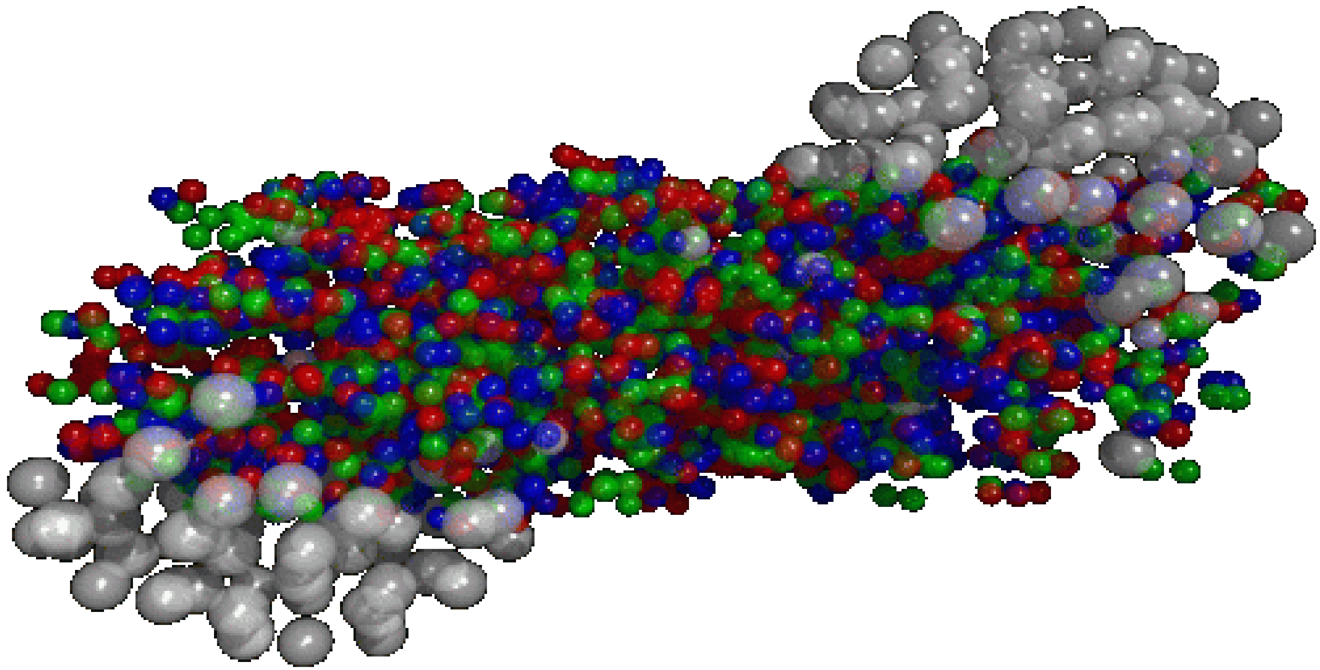


QGP in the laboratory



Produced in the collisions of **heavy ions** at **high energies**

A



A

(Au, Pb ...)

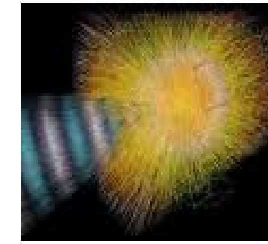
$\sqrt{s_{NN}}$ from few GeV at the SPS

up to 200 GeV at RHIC

up to 2.76 TeV at LHC

UrQMD

The Large Hadron Collider (LHC)



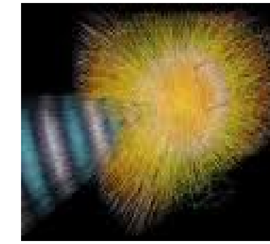
At CERN, Geneva, Switzerland

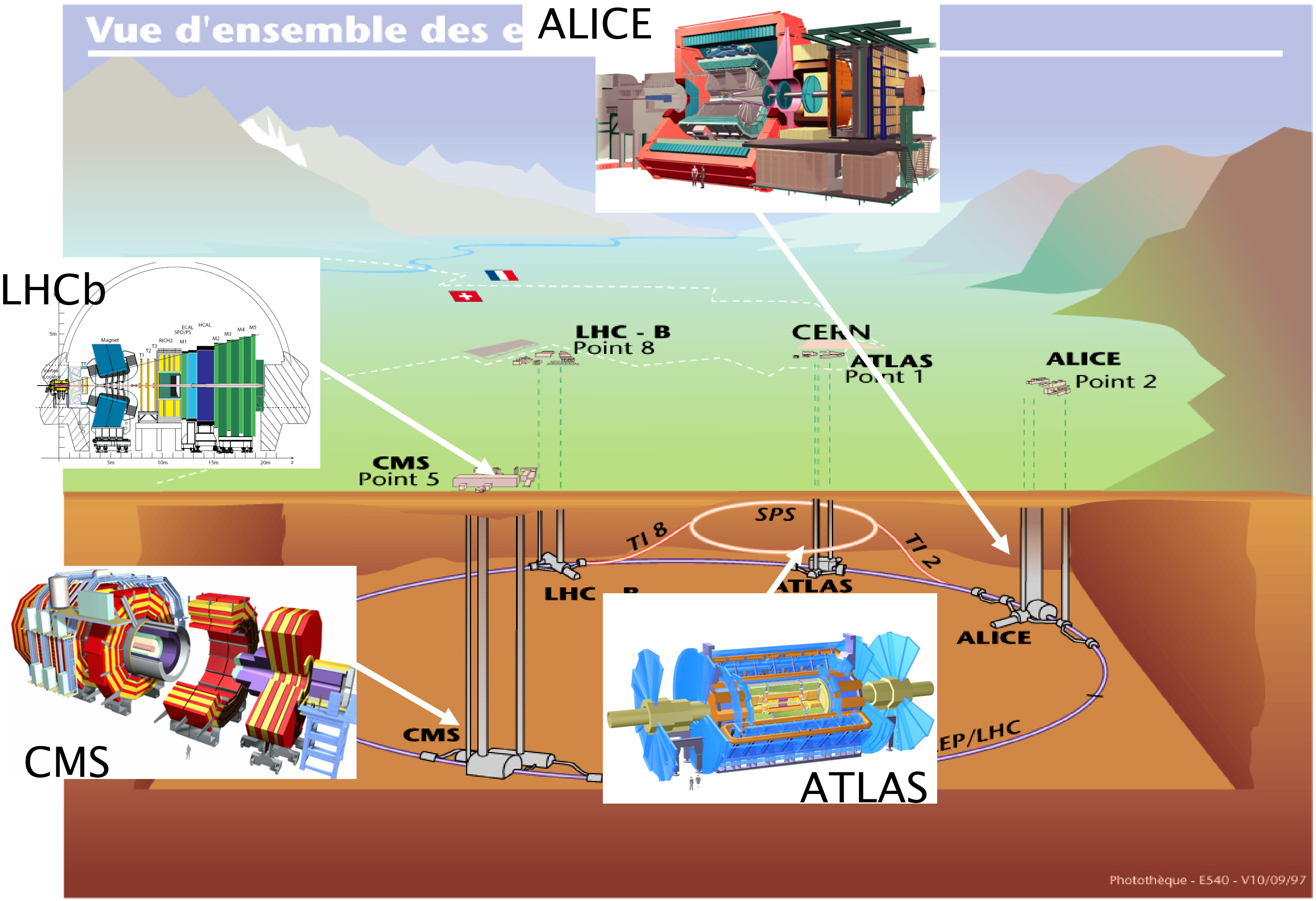
- 27 km length
- 4 main experiments

Colliding systems:

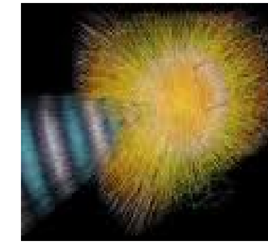
- **proton-proton**
  up to $\sqrt{s}$**=14 TeV**
  2010-2011: 7 TeV + 2.76 TeV
- **Pb-Pb**
  up to $\sqrt{s_{NN}}$**=5.5 TeV**
  2010-2011: 2.76 TeV

Experiments at LHC

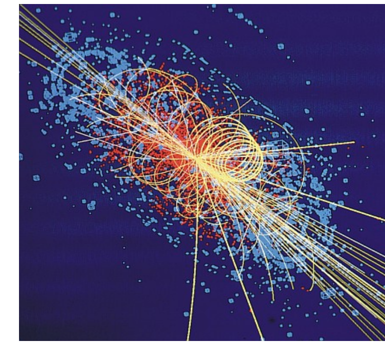




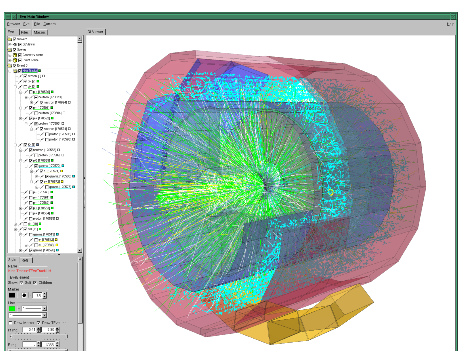
Physics at LHC



From proton-proton …



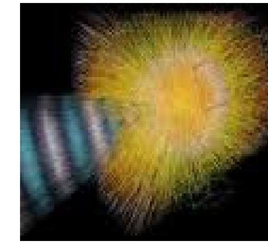
- Generation of mass (Higgs)
- New elementary particles (supersymmetric)
- Matter dominance over antimatter (CP violation)
- Gravity unification (extra dimensions, black holes)
- Overall QCD aspects (multiplicities, charm, beauty …)



... to lead-lead collisions

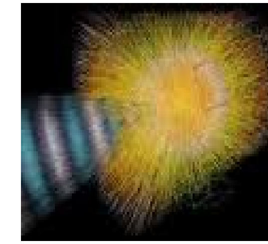
- Study matter within the first microseconds of the Universe life (ALICE, but also CMS, ATLAS)

LHC in Numbers



- 27 km long, 8 sectors
- **1232 dipole** magnets (15m, 30 tonnes each) to bend the beams
- Cooled with **120 tonnes of He at 1.9 K**
- pp: 2808 bunches/ring, each 1.15×10^{11} protons (8 min filling time)
  Design luminosity: **10^{34} $cm^{-2}s^{-1}$**
- PbPb: 592 bunches/ring, each 7×10^{7} Pb ions
  Design luminosity: 10^{27} $cm^{-2}s^{-1}$
- Transverse r.m.s beam size: **16 μm**, r.m.s. bunch length: 7.5 cm
- Beam kinetic energy: 362 MJ per beam (1 MJ melts 2 kg copper)
- Total stored electromagnetic energy: **8.5 GJ** (dipole magnets only)

LHC runs



November 23, 2009

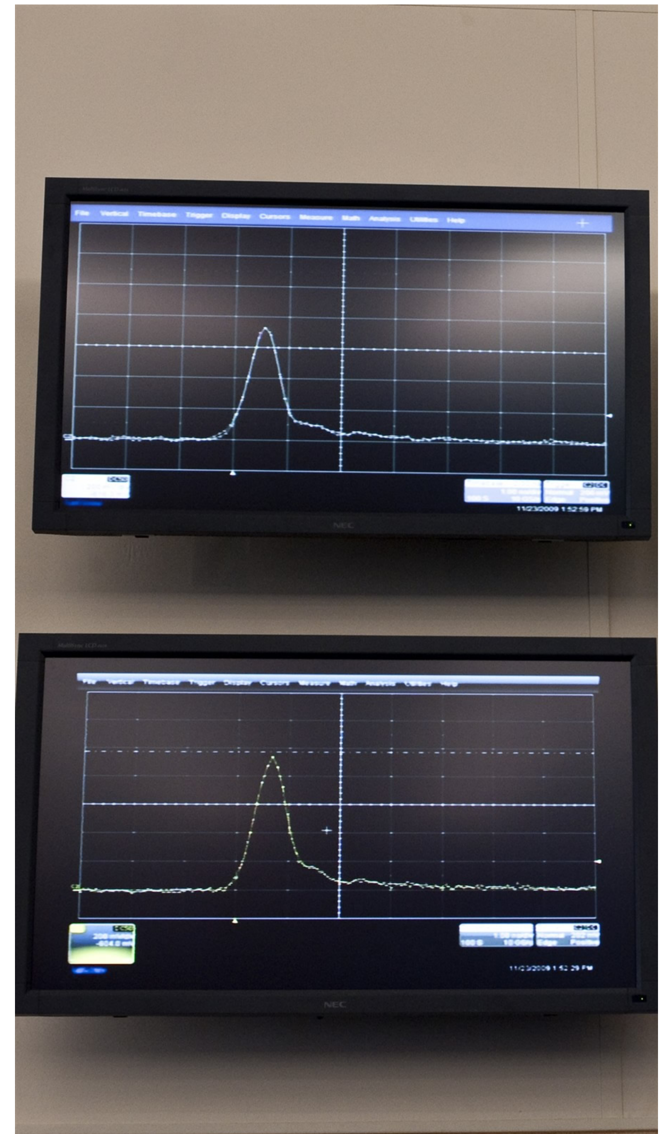
2 beams (at injection energy of 450 GeV) circulated simultaneously for the first time!

1 pilot bunch, low intensity

First collisions at $\sqrt{s}$ = 900 GeV in all experiments!!

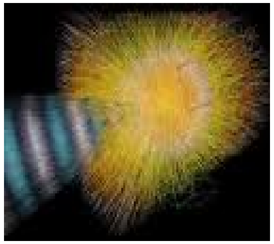
December 13, 2009

collisions at 2.36 TeV !!



Screen shots of LHC beam monitor

LHC runs



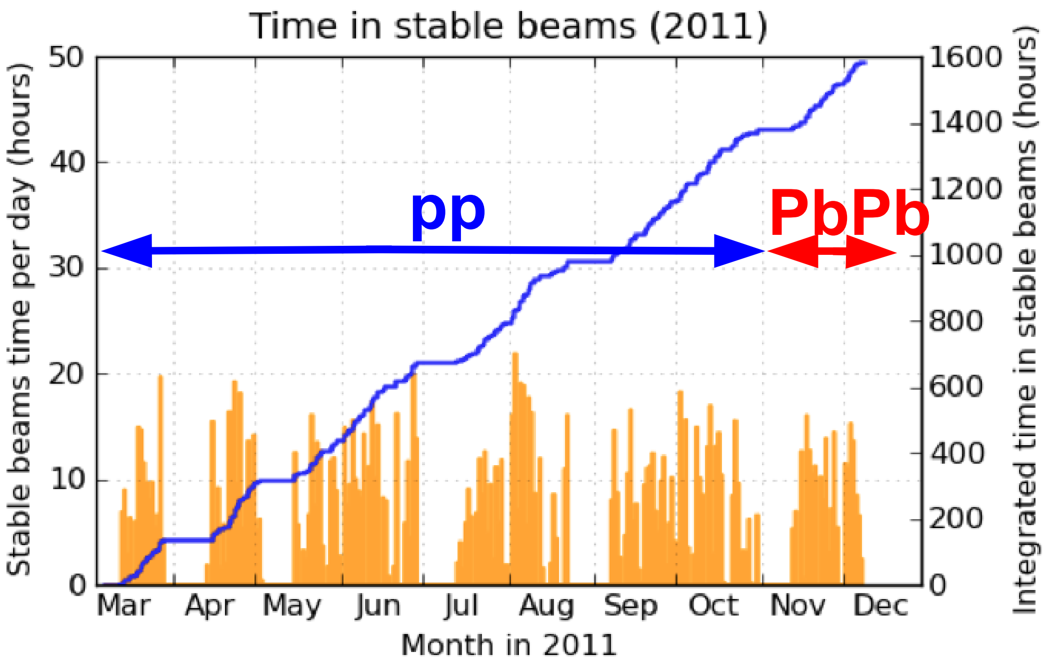
- Proton-proton
  - 0.9 TeV: Nov 2009, Mar 2010
  - 2.76 TeV: Mar 2011
  - 7 TeV: 2010, 2011
  - 8 TeV: 2012 (now!)

- Pb-Pb
  - 2.76 TeV: 2010, 2011

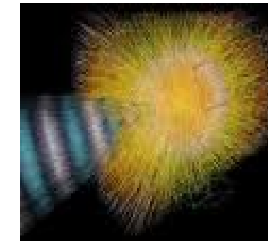
- p-Pb
  - Beginning of 2013

In 2010 and 2011:

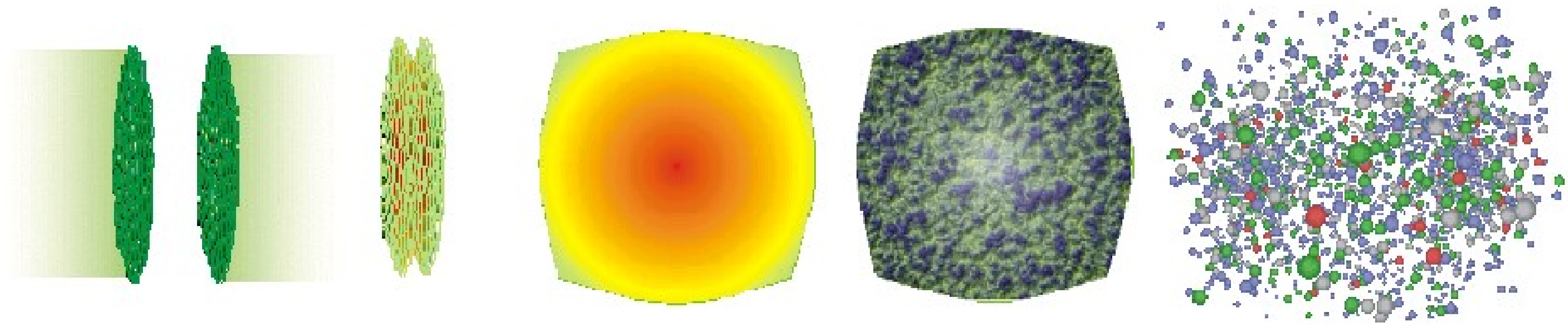
- March – October: pp collisions (~ 1400 hours of stable beams)
- November – December: 4 weeks of PbPb collisions (~ 200 hours)



Ultra-relativistic heavy-ion collisions



High energy heavy ions collide …



Under extreme conditions of temperature and density, they produce a state of matter called

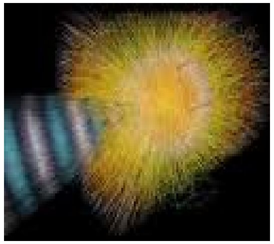
QUARK-GLUON PLASMA

where quark and gluons are deconfined,

followed by chemical freeze-out,

and kinetic freeze-out

Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



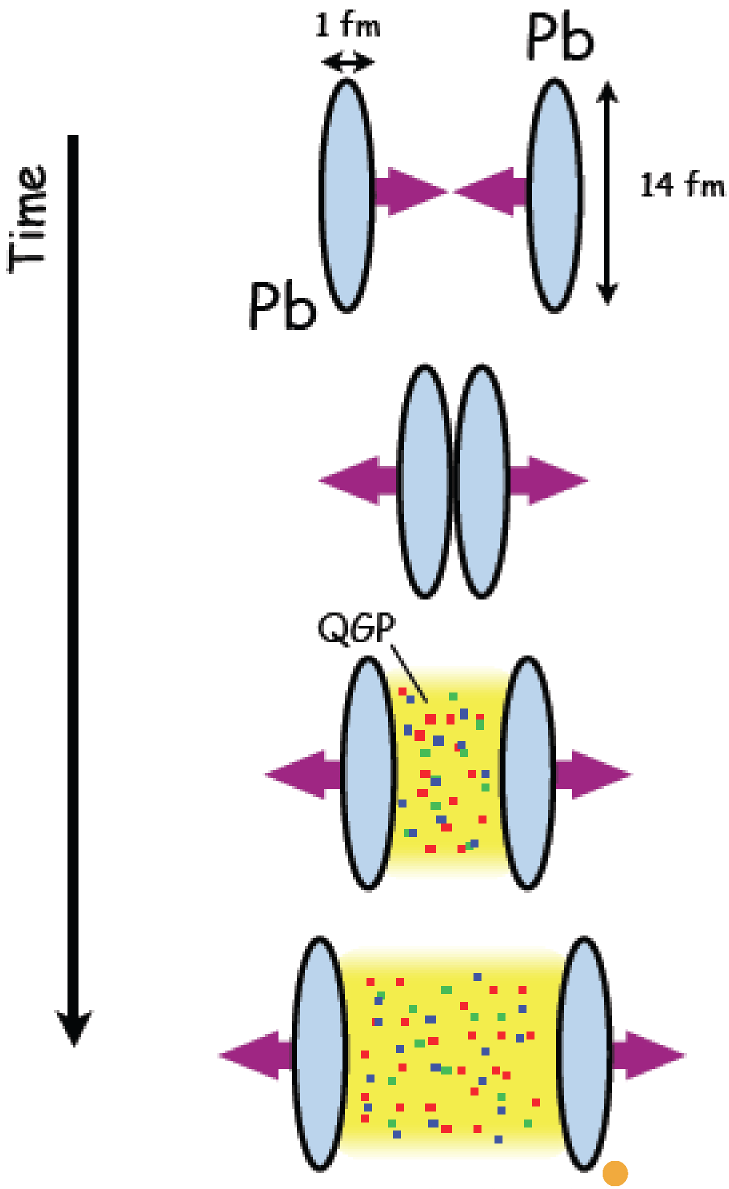
Compress a very large amount of energy in a very small volume

→ “fireball” of hot matter

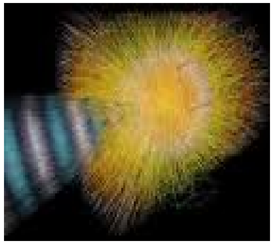
- Temperature O(10^{12} K)
    - ~10^5 x T at the center of the sun
    - ~T of the early universe (μs after Big Bang)

- At LHC: very high temperature
  low baryochemical potential
  (~pressure in the water phase diagram)

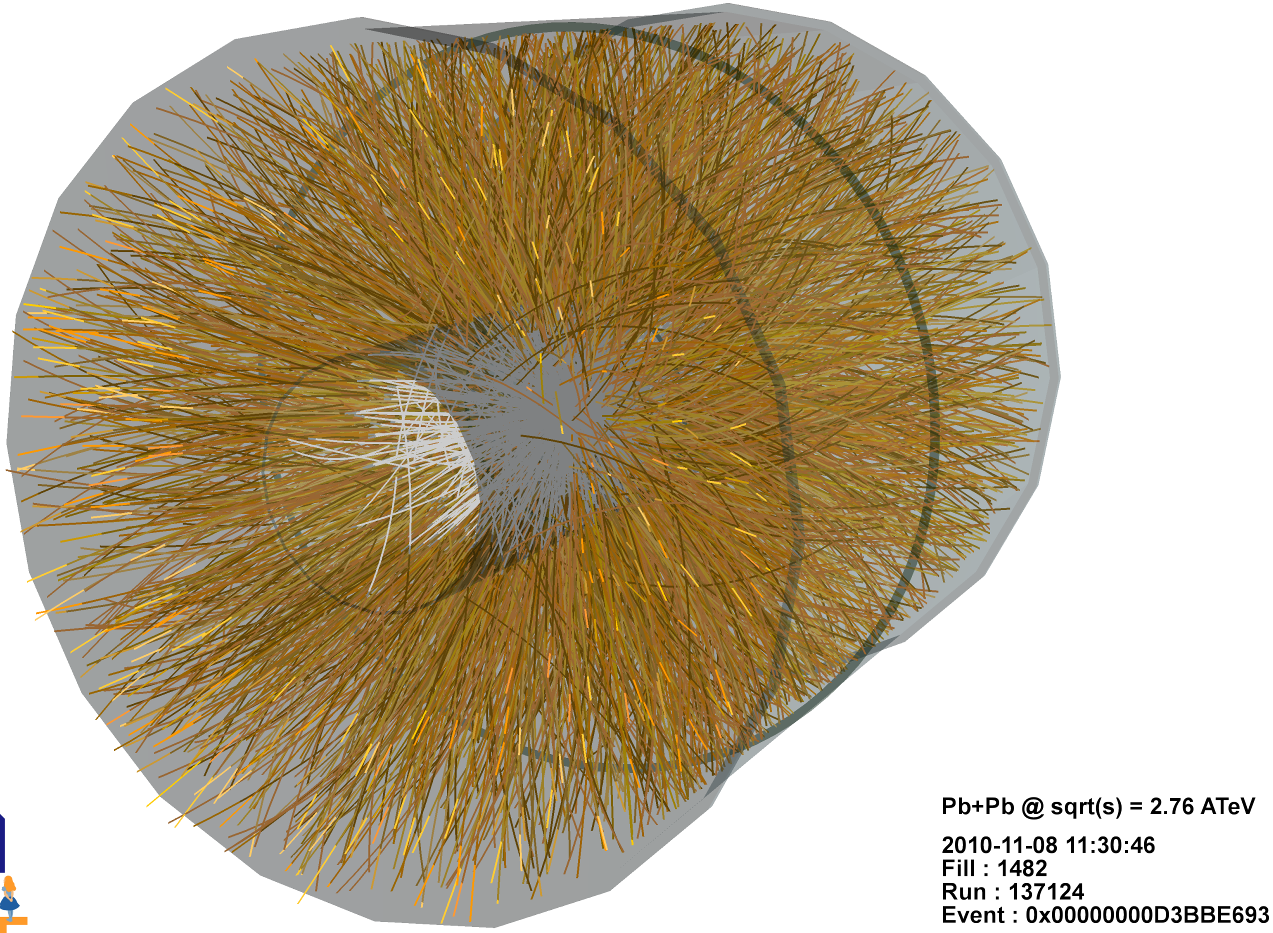
- At FAIR: lower temperature
  high baryochemical potential



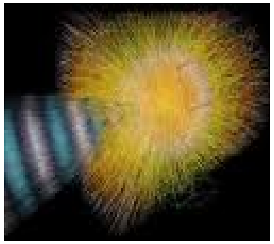
Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



Pb ions accelerated to ~290 TeV → collision: 575 TeV !!!



Comparison SPS-RHIC-LHC



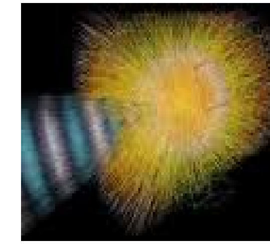
PbPb central collisions

	SPS	RHIC	LHC
E_{cm} [GeV]	17	200	5500
dN_{ch}/dy	500	700	3000 - 8000
E [Gev/fm^3]$_{t_0=1fm/c}$	≈2.5	≈3.5	15 - 40
t_{QGP} [fm/c]	<1	≈1	≈4.5-12

Fireball initial temperature ≈220 MeV ≈4-700 MeV

Significant increase in relevant parameters (ε, V, τ)
Factor 10 from SPS to LHC

ALICE

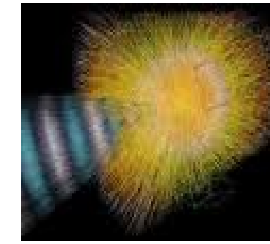


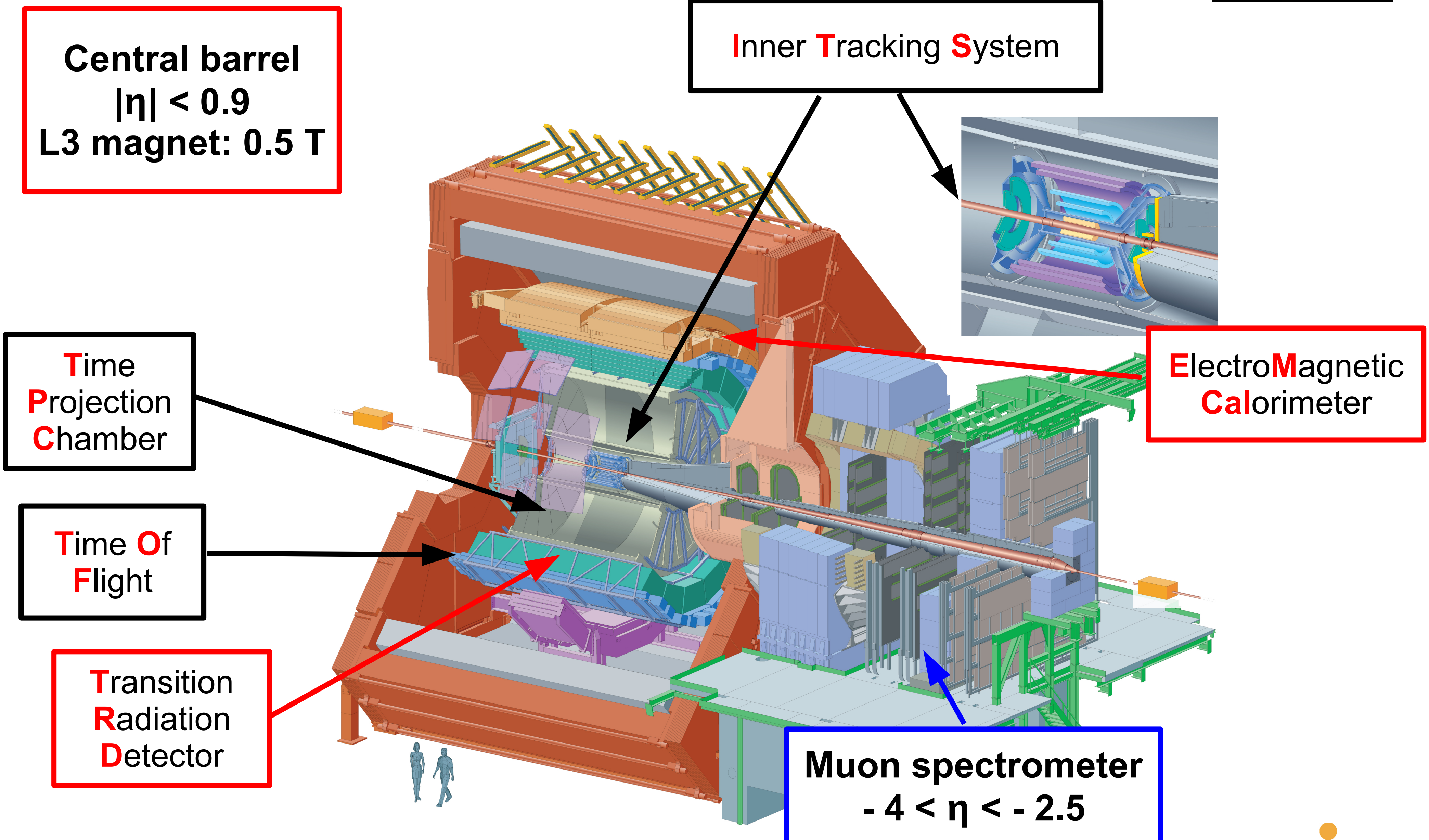
A Large Ion Collider Experiment

Dedicated experiment to study heavy-ion collisions

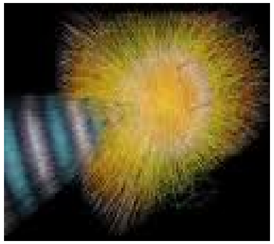
35 countries, 120 institutes, 1300 members

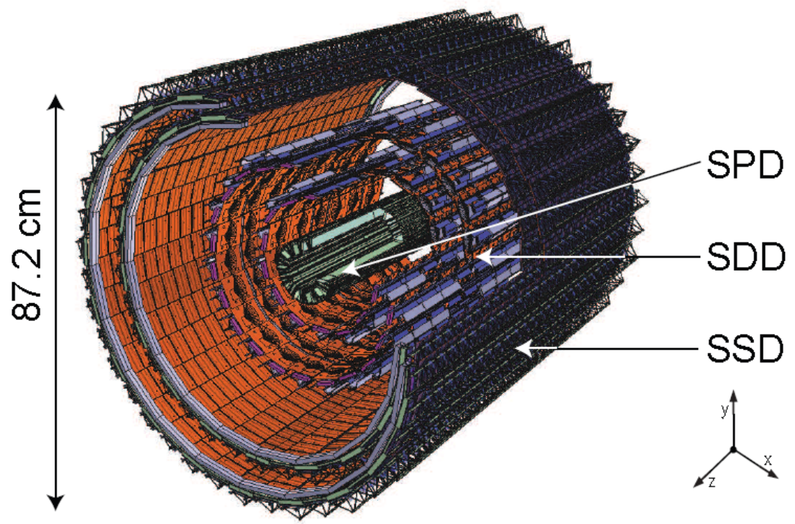
The ALICE Spectrometer

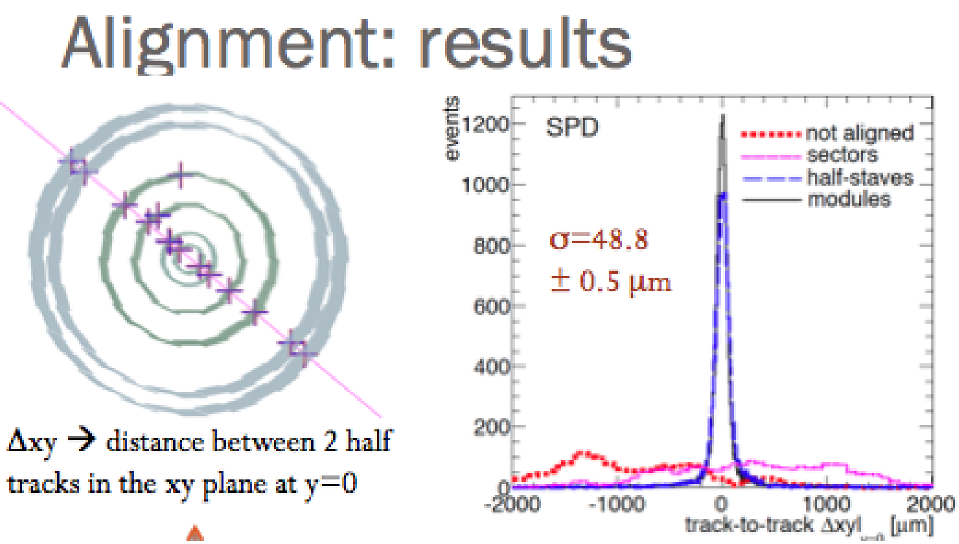




The Inner Tracking System





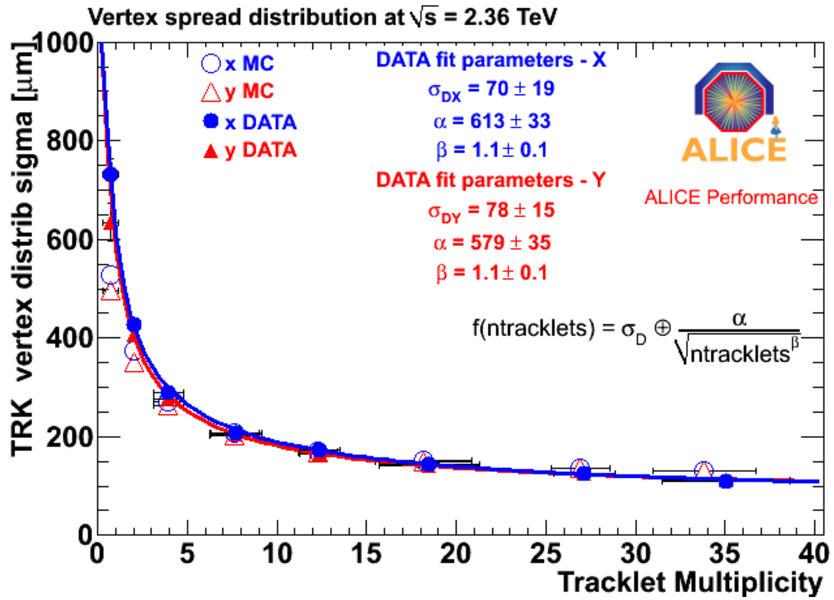


2010 JINST **5** P03003

Silicon vertex detector

3 technologies:

- 10 million pixels
- 133 k drift detector channels
- 2.6 million microstrips



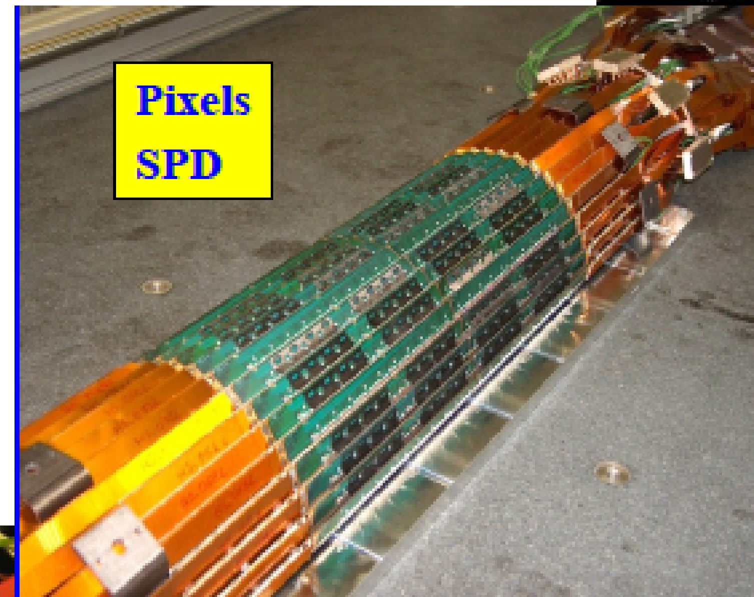
Excellent tracking and vertexing!

ITS

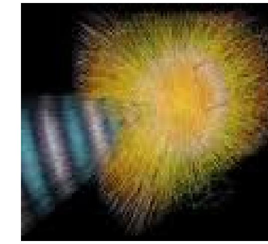
Inner Tracking System

~10 m^2 Si detectors, 6 layers

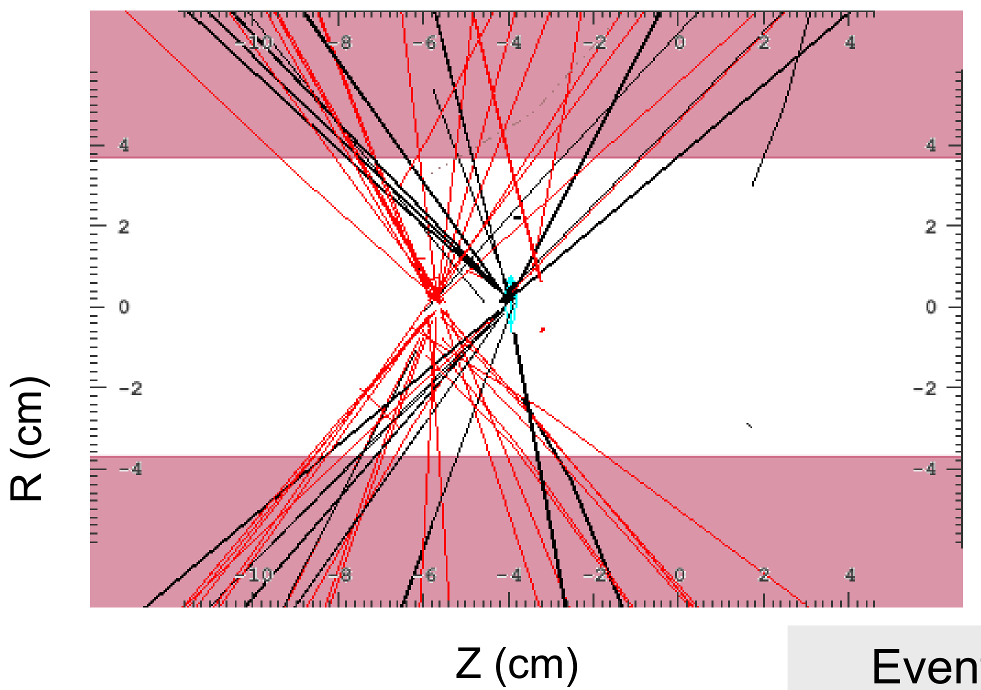
Pixels, Drift, double sided Strips

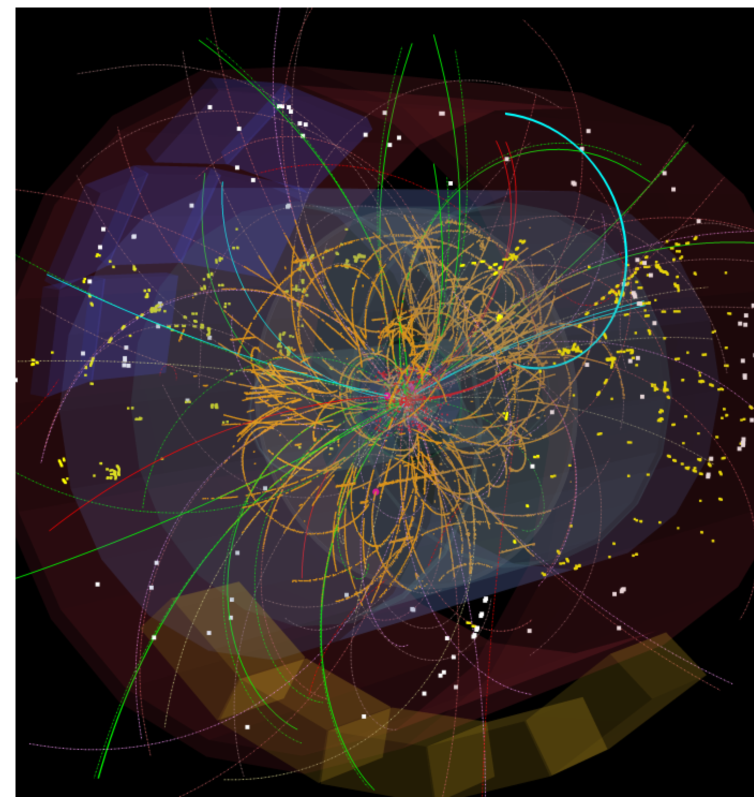


ALICE Specialties



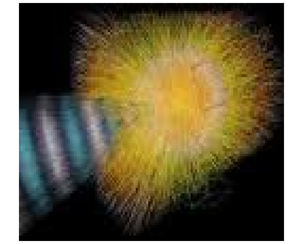
- Very low momentum cutoff (~0.1 GeV/c)
- p_T reach up to 100 GeV/c
- Excellent particle identification
- Efficient minimum bias trigger
- **Excellent vertex capabilities**





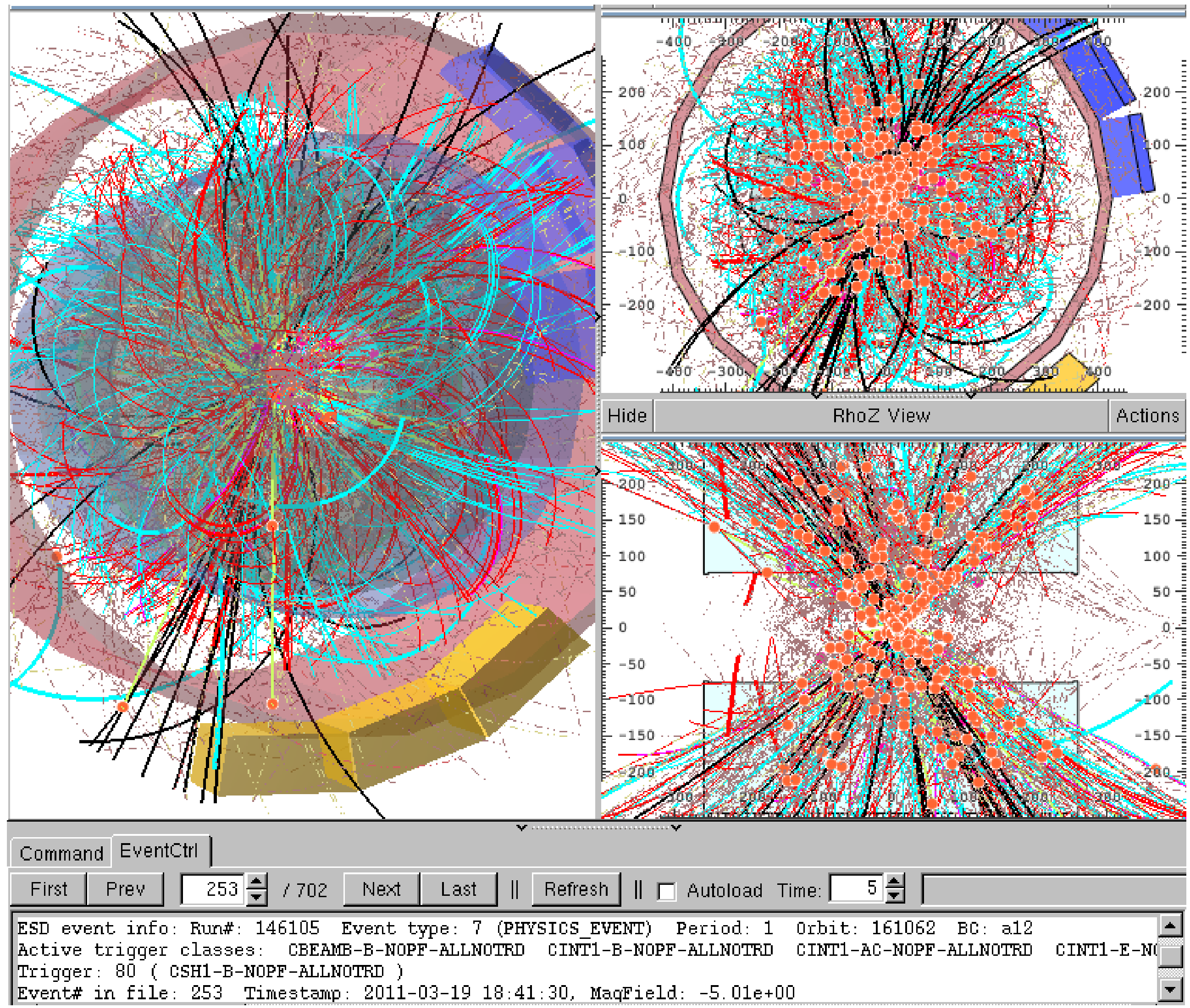
Event display of a pile-up event at 900 GeV

Pile-up in pp

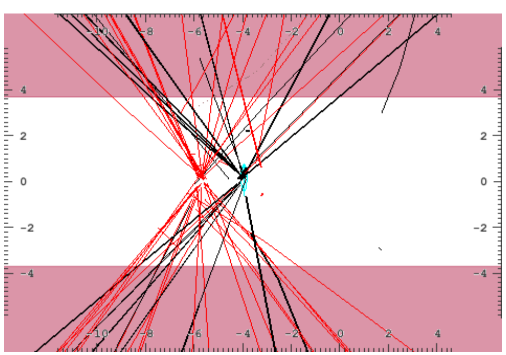


Events become a real "mess".

We need to learn to handle this in reconstruction and in analysis !!! (e.g. normalization to cross sections)

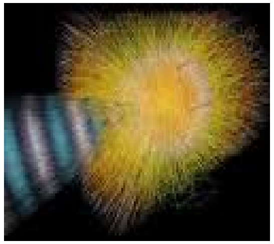


R (cm)

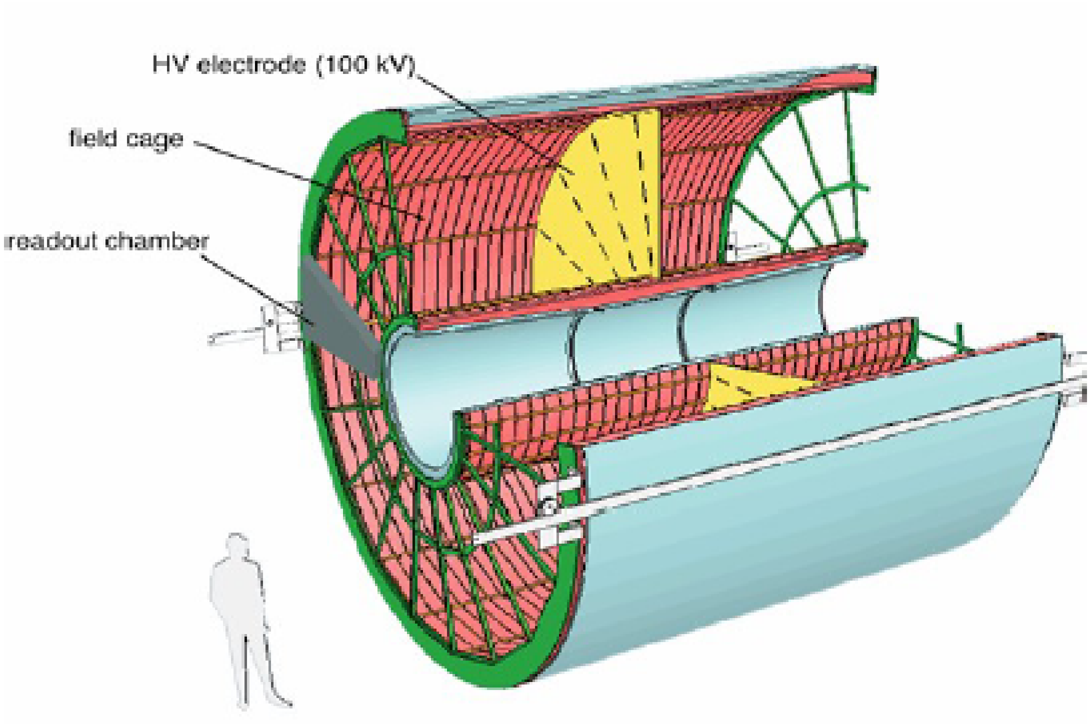


Z (cm)

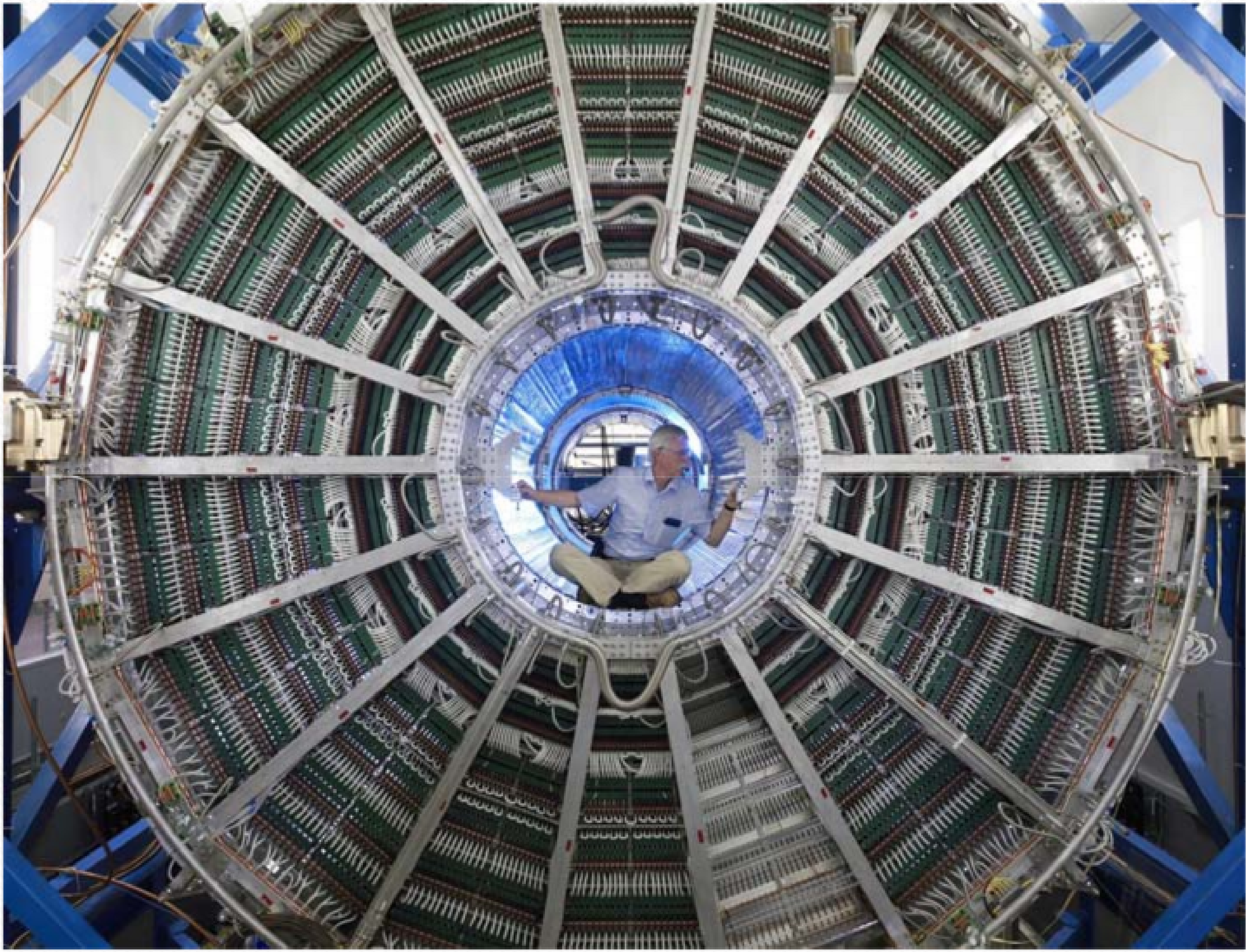
Time Projection Chamber



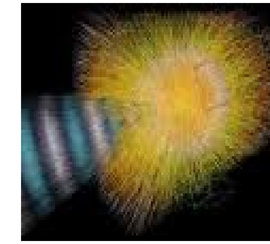
- Optimized for dN/dη ≈ 8000
  - l = 5 m, Ø = 5.6m, 88 m3, 570 k channels,
  - up to 80 Mbytes/event (after 0 suppression)
- Features:
  - lightweight: 3% X_0 total material for perpendicular tracks
  - Drift gas:Ne (86) / CO_2 (9.5) / N_2(4.5) + ~1ppm O_2
  - novel digital electronics (ALTRO)
  - highly integrated, digital shaping; tail cancellation;0-suppression; Baseline restoration
  - Powerful laser calibration system



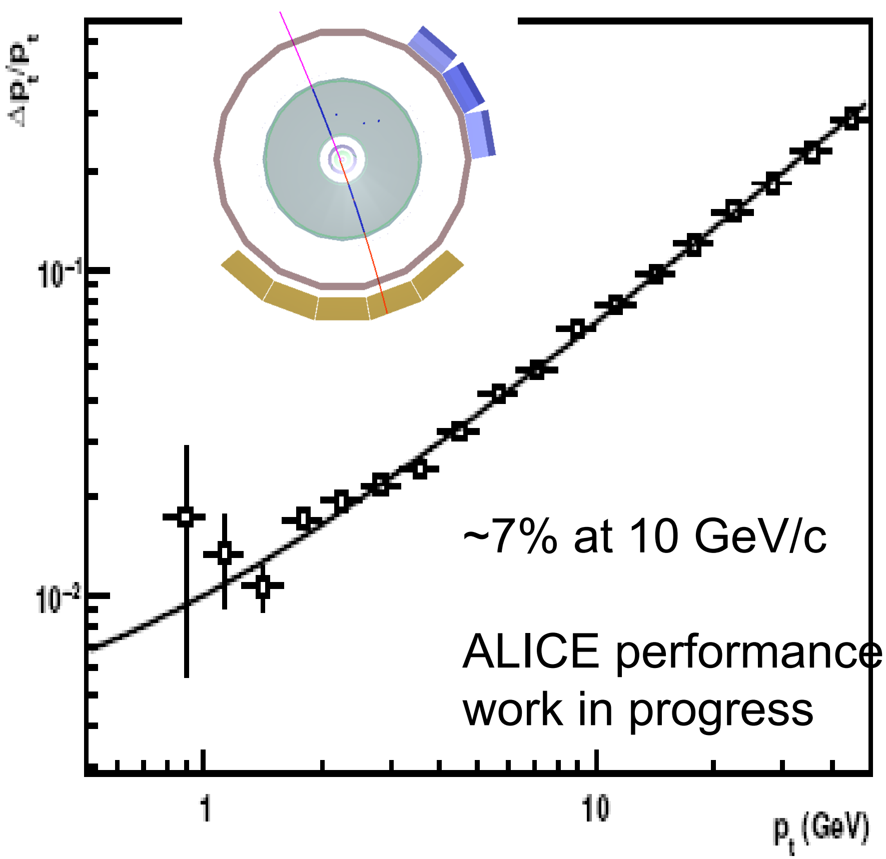
ALICE – TPC

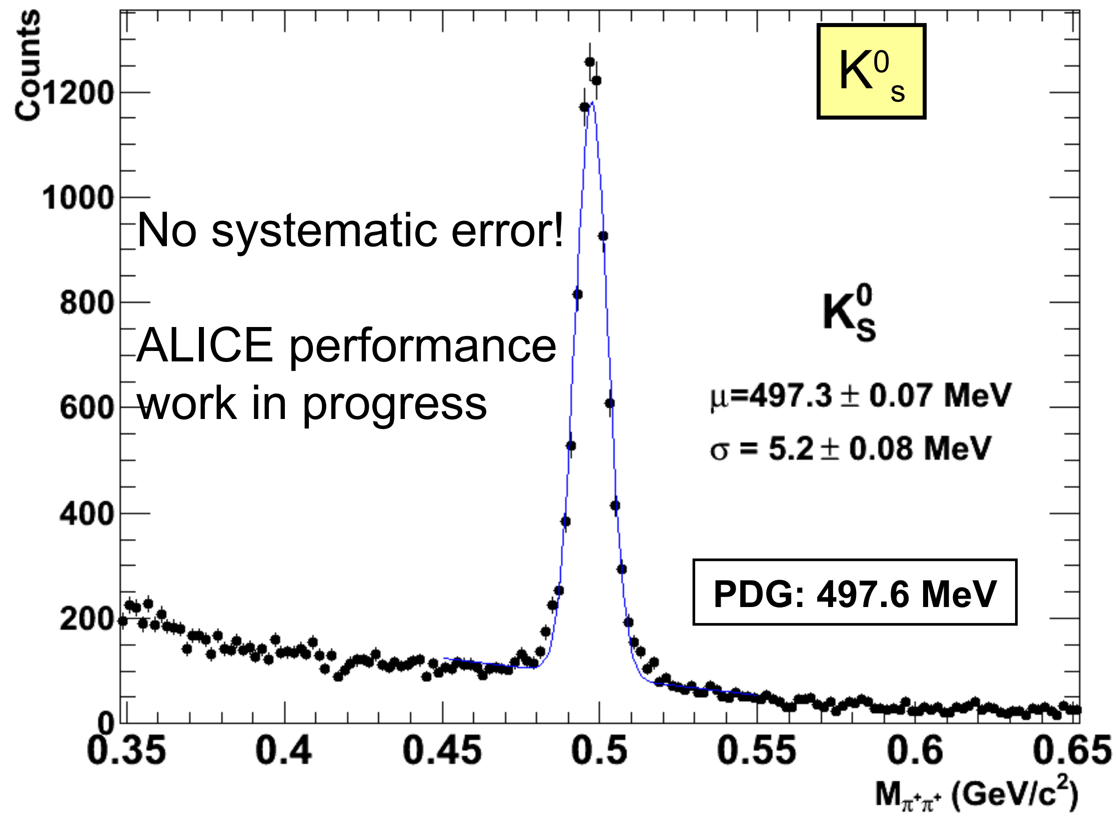


The Time Projection Chamber
Track Momentum Resolution



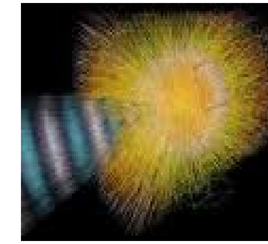
From matching of two segments of cosmic tracks



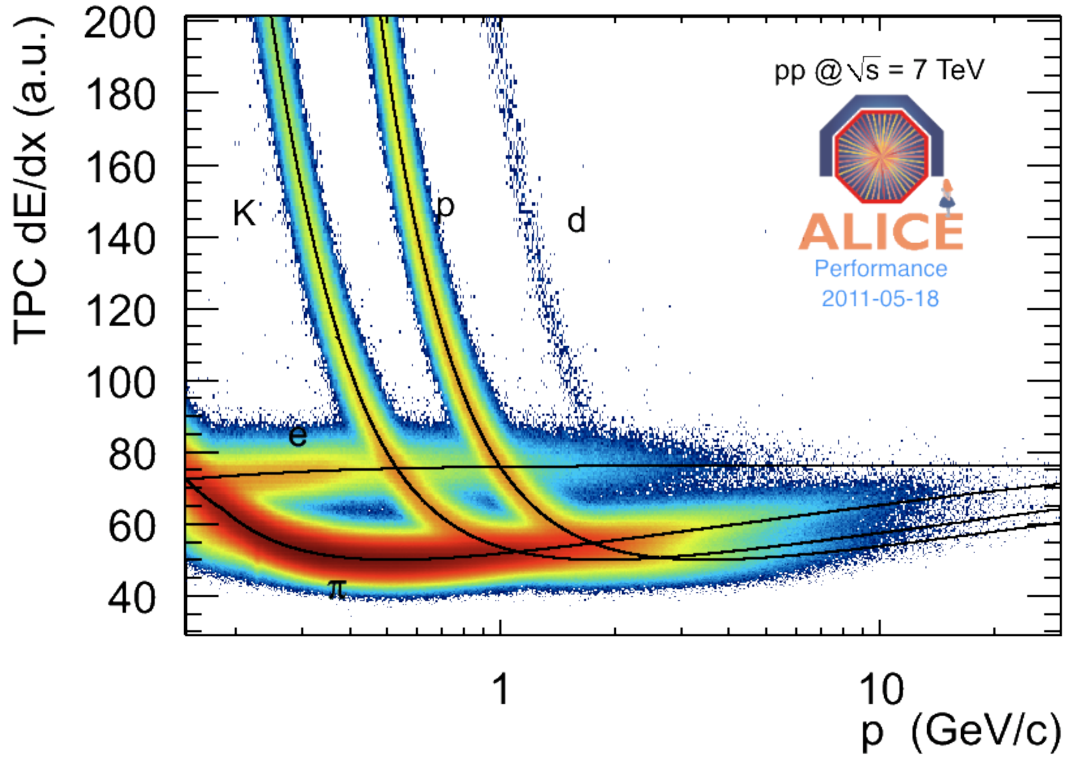


- **p_T resolution 7% at 10 GeV/c (aim 5%)**
- **... and below 1% at p_T<1 GeV/c – confirmed by K^0_s measurements**

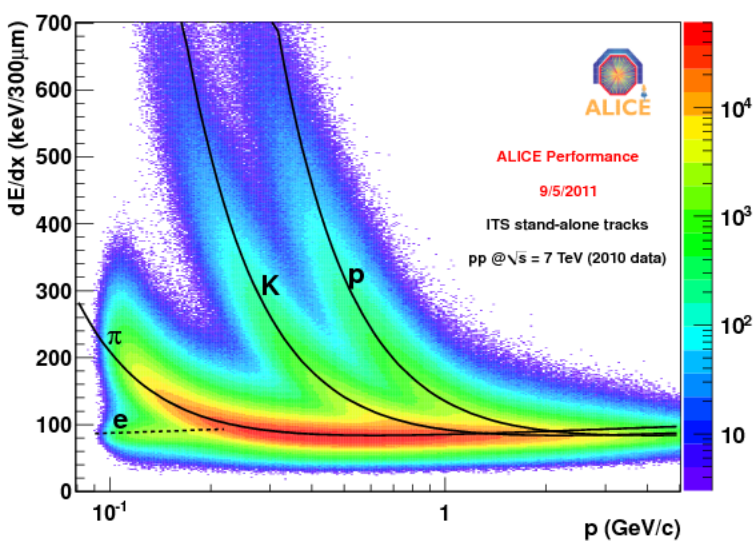
Particle identification



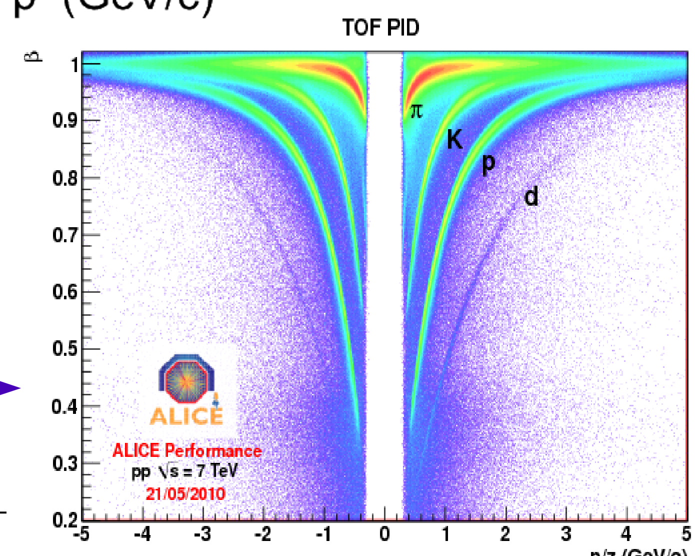
Time Projection Chamber



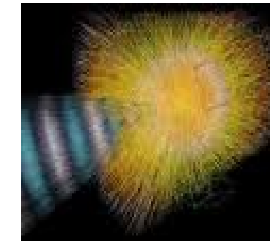
Inner Tracking System

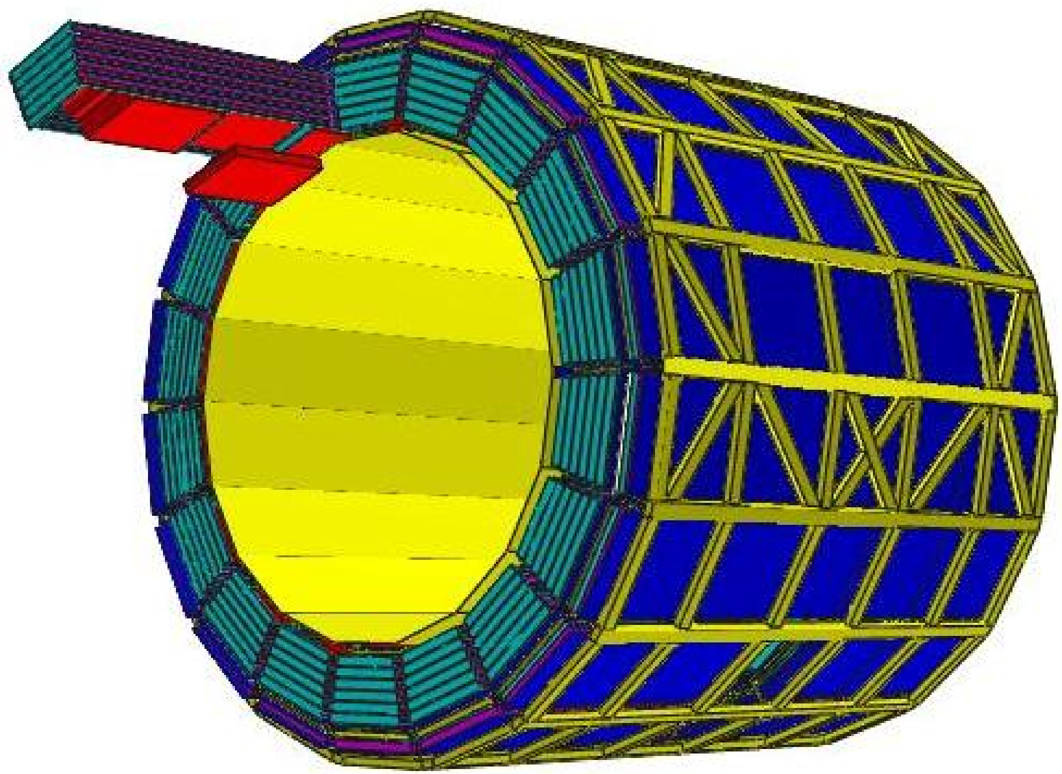


Time of Flight



Transition Radiation Detector

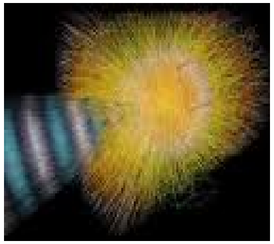


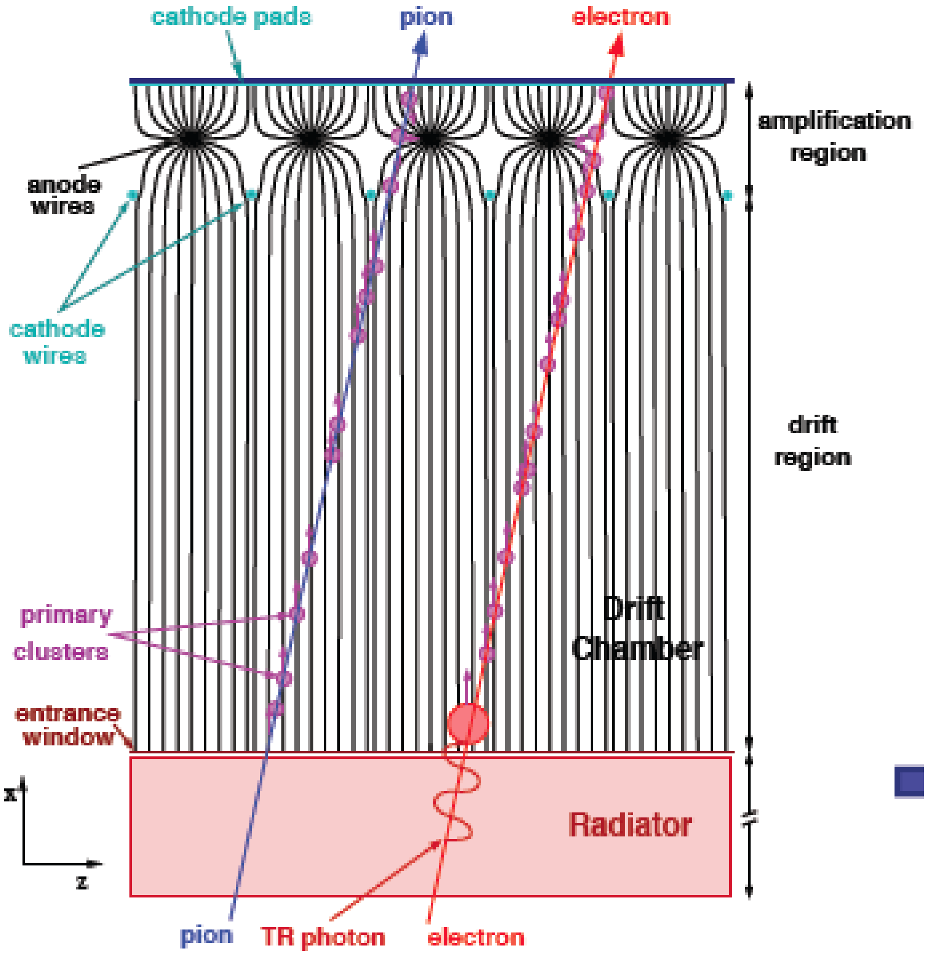


- For electron/pion separation
- For trigger on electrons at medium/high p_T

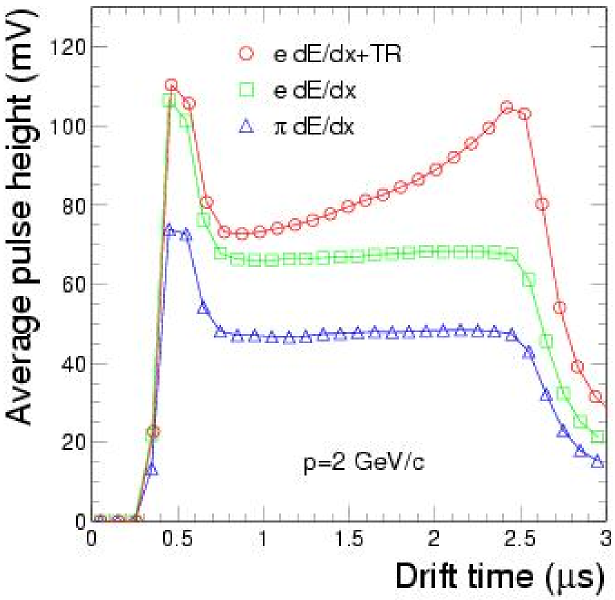
TRD in Numbers	
Supermodules	18
Stacks	5
Layers	6
Readout pads	1.2x106

Transition Radiation Detector



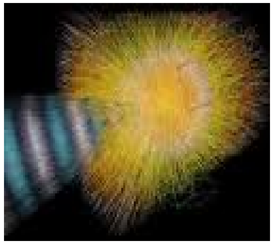


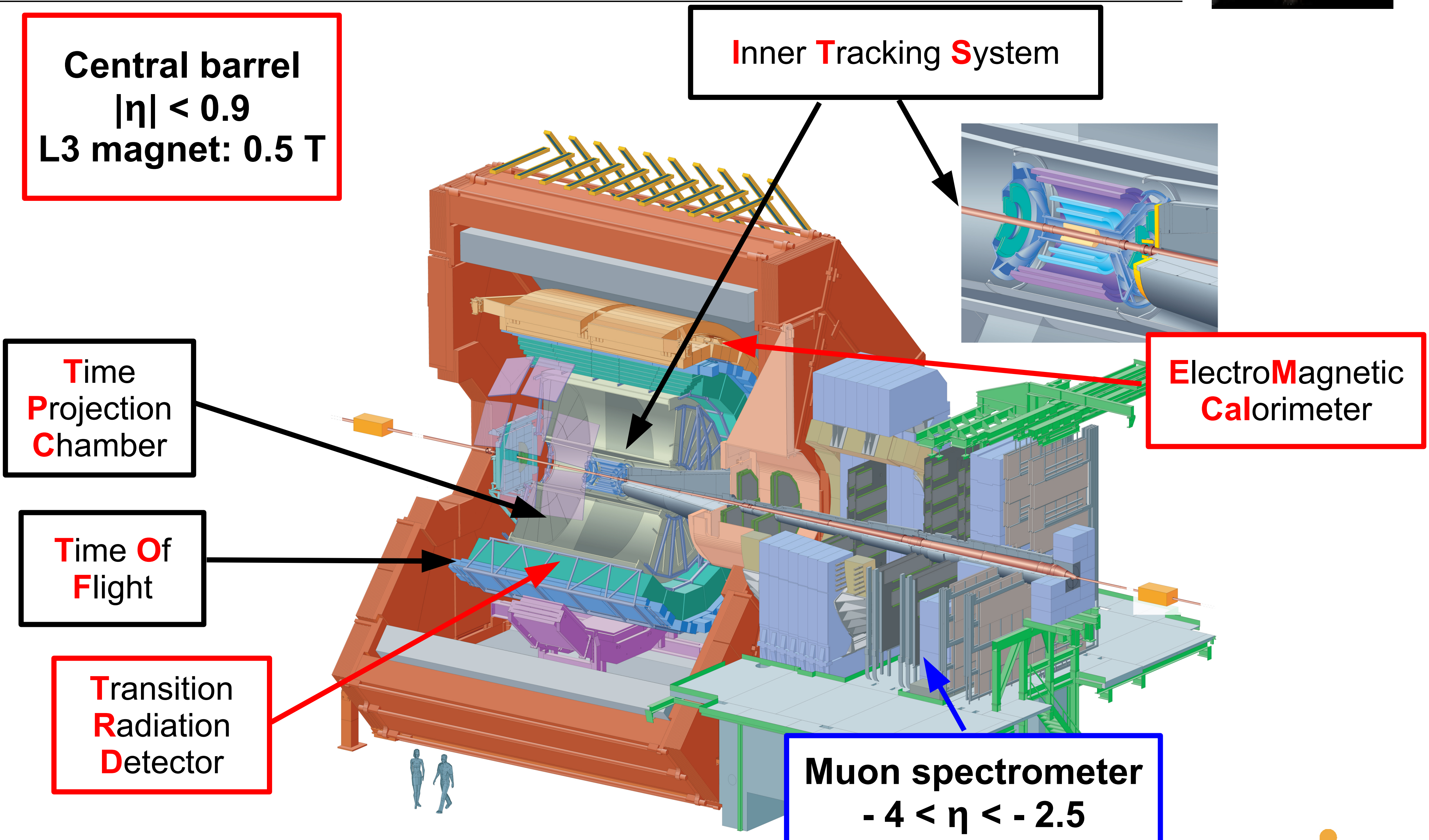
- For electron/pion separation
- For trigger on electrons at medium/high p_T



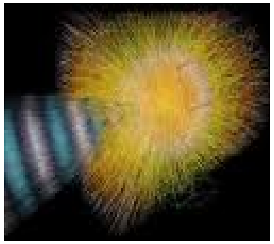
Transition Radiation Detector

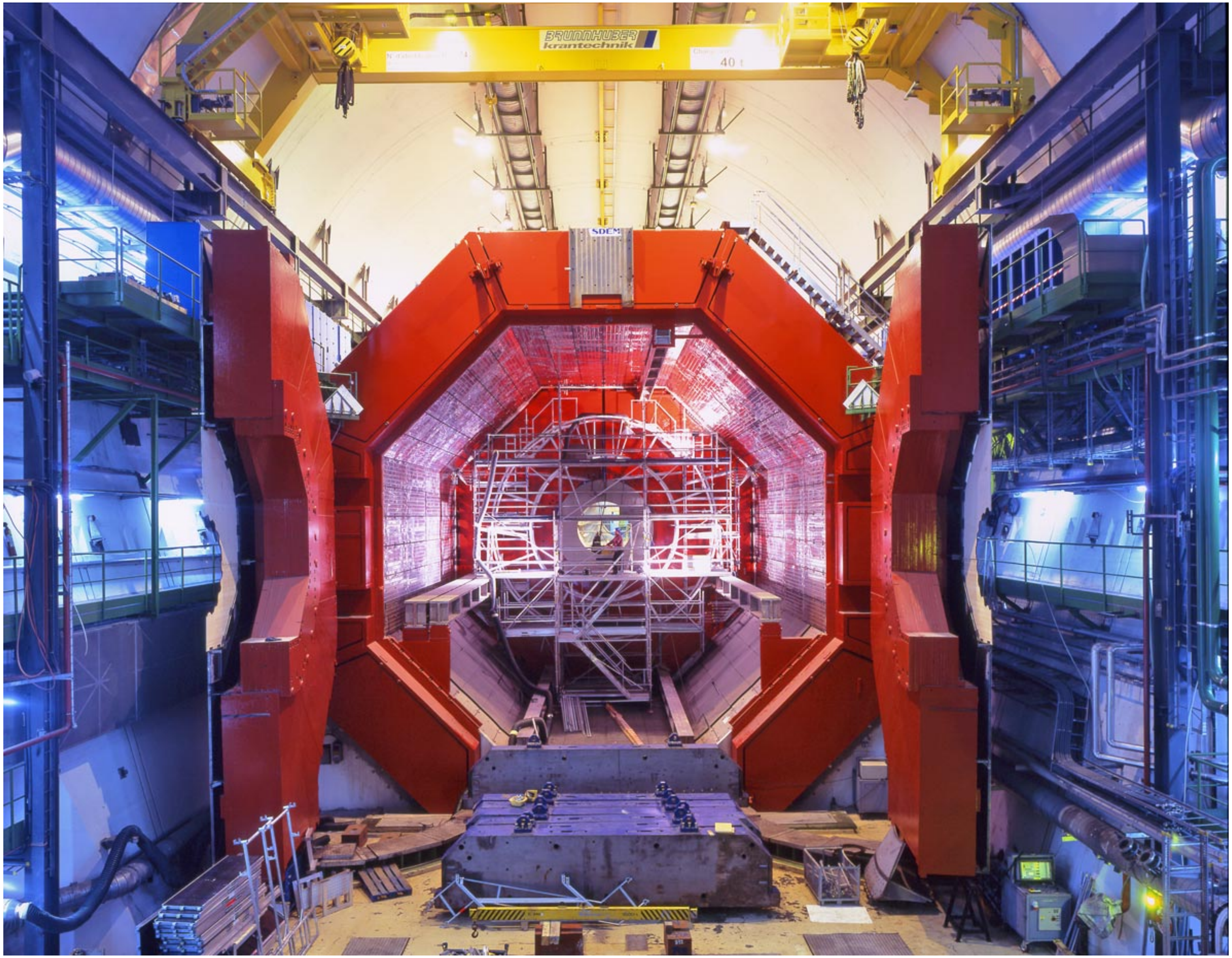
The ALICE Spectrometer





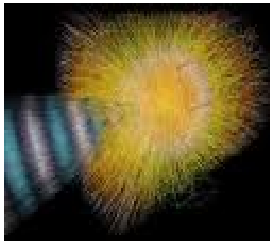
ALICE

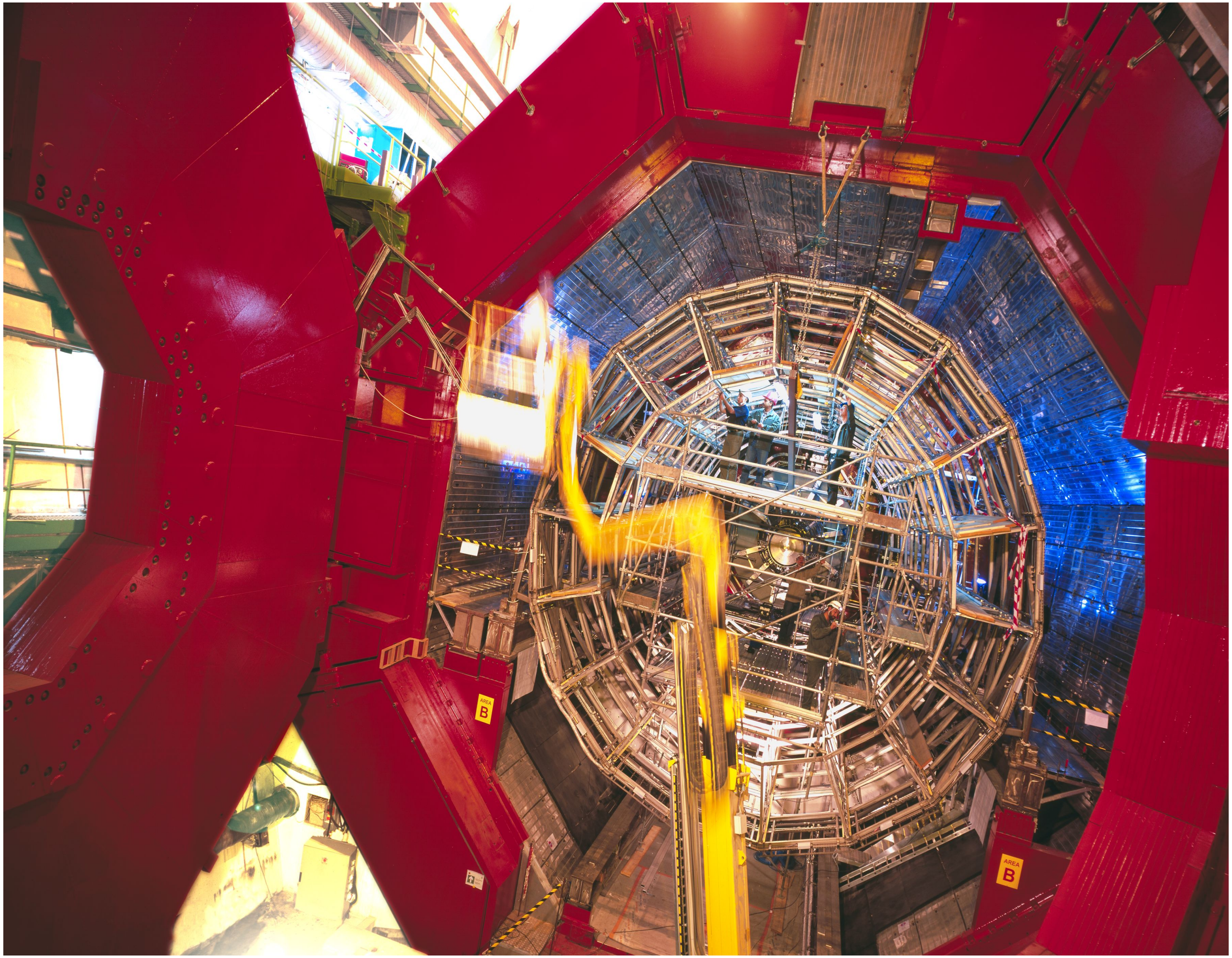




2005

ALICE





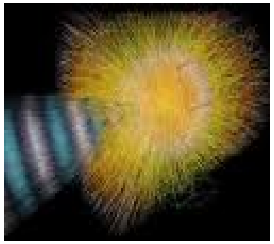
2006

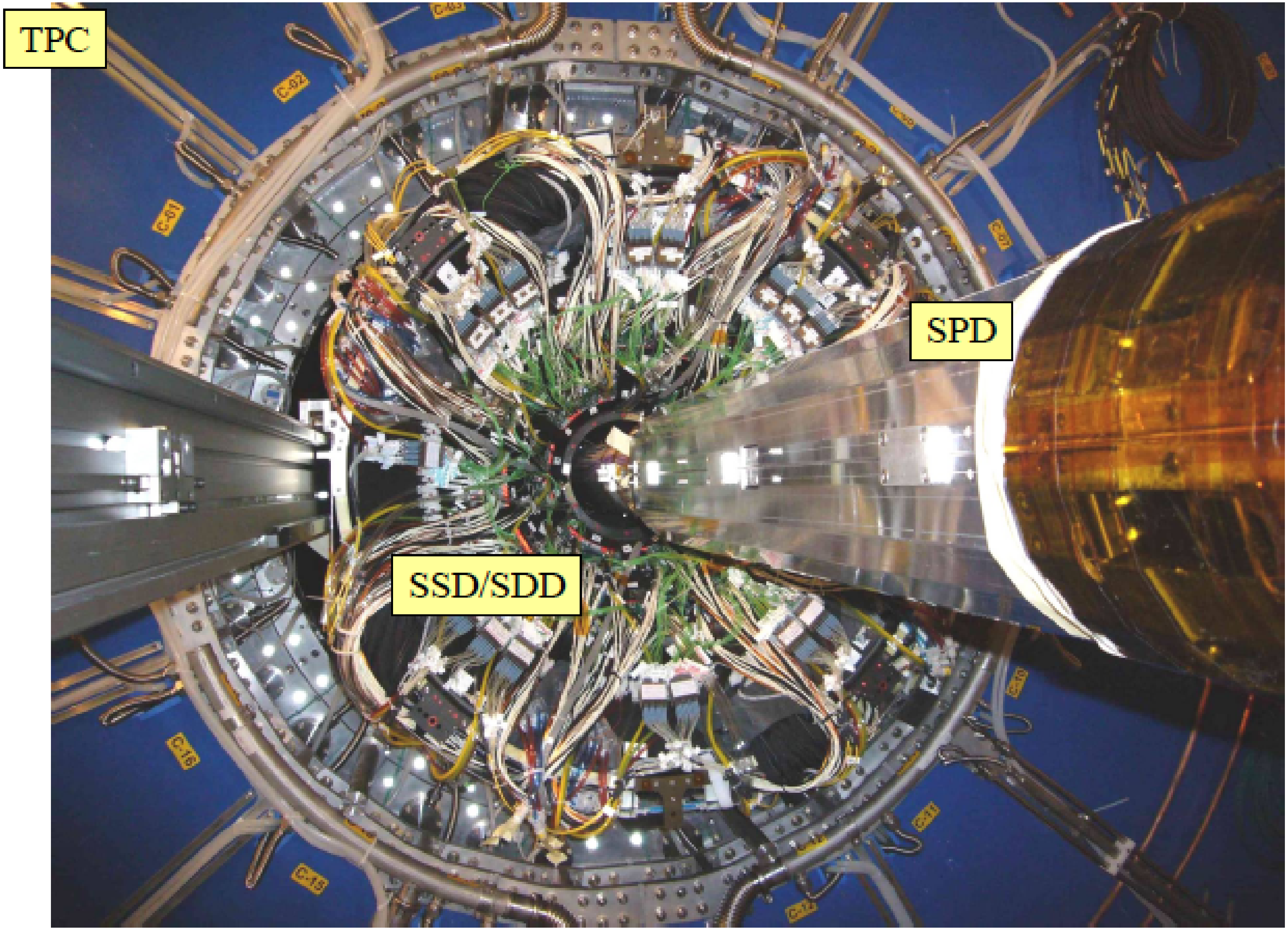
ALICE – TPC

ALICE – TPC

2007

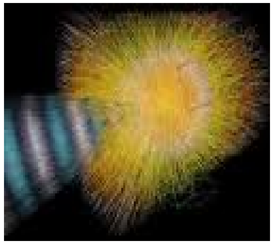
ALICE – TPC and ITS

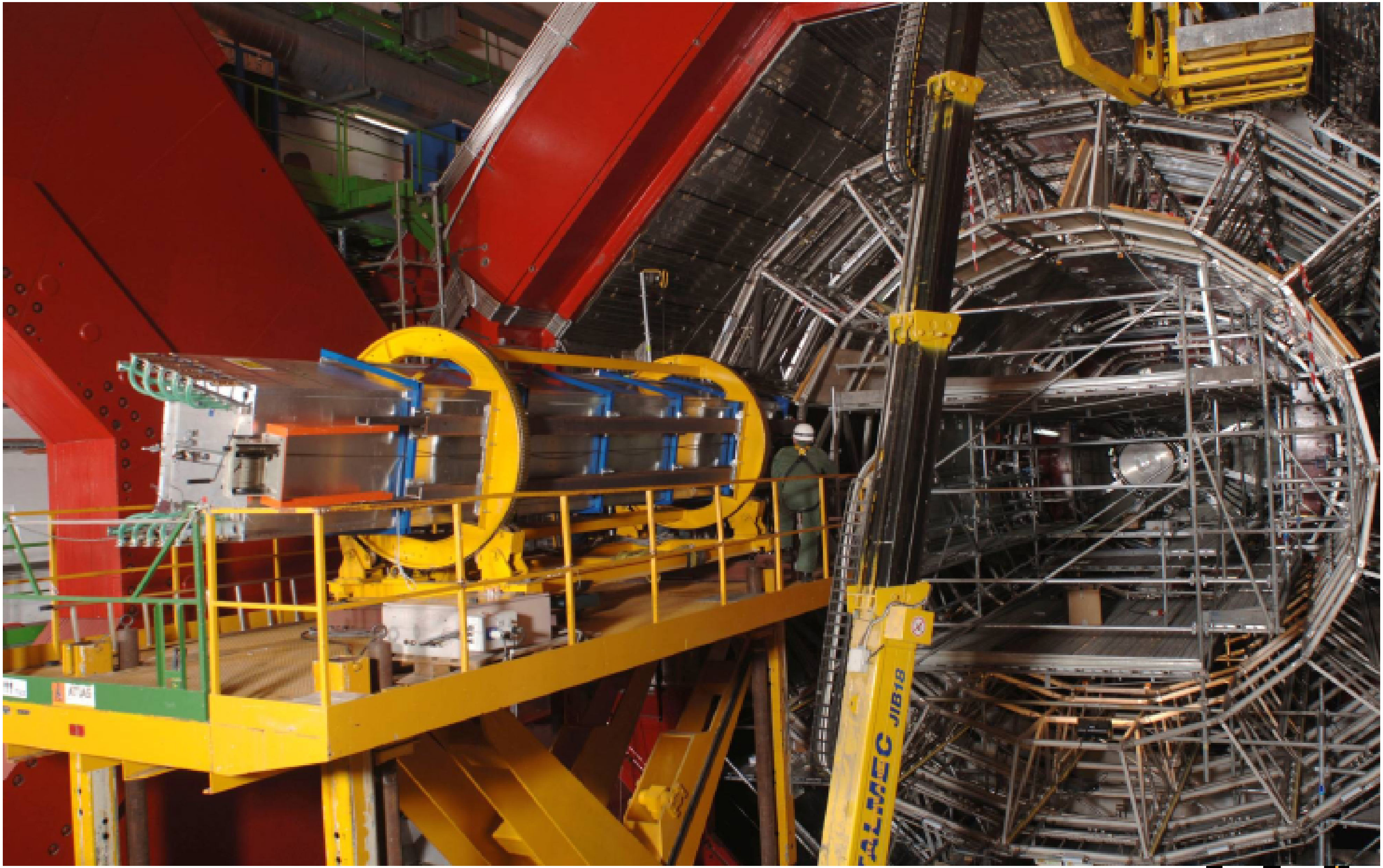




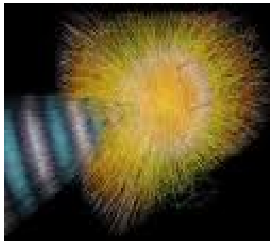
2007

ALICE – TRD



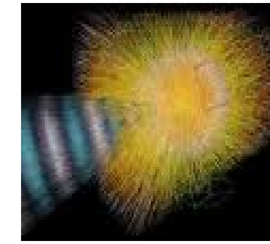


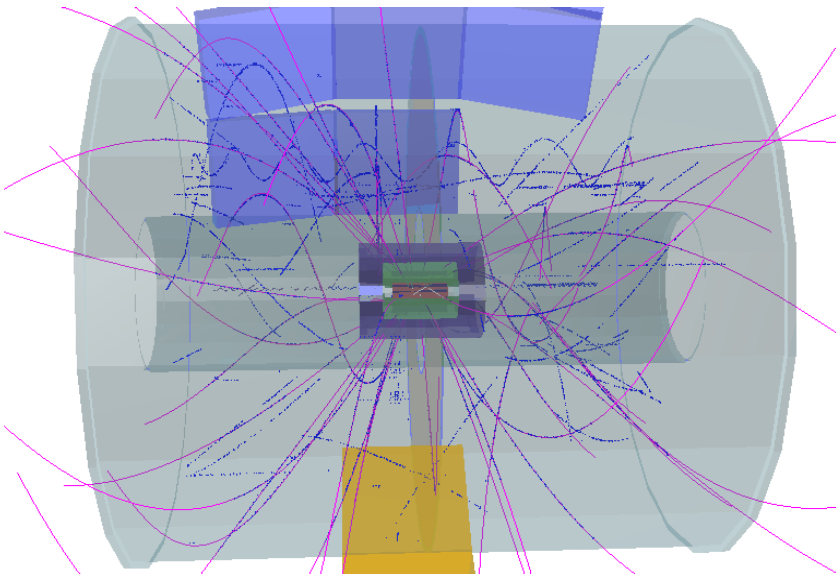
ALICE



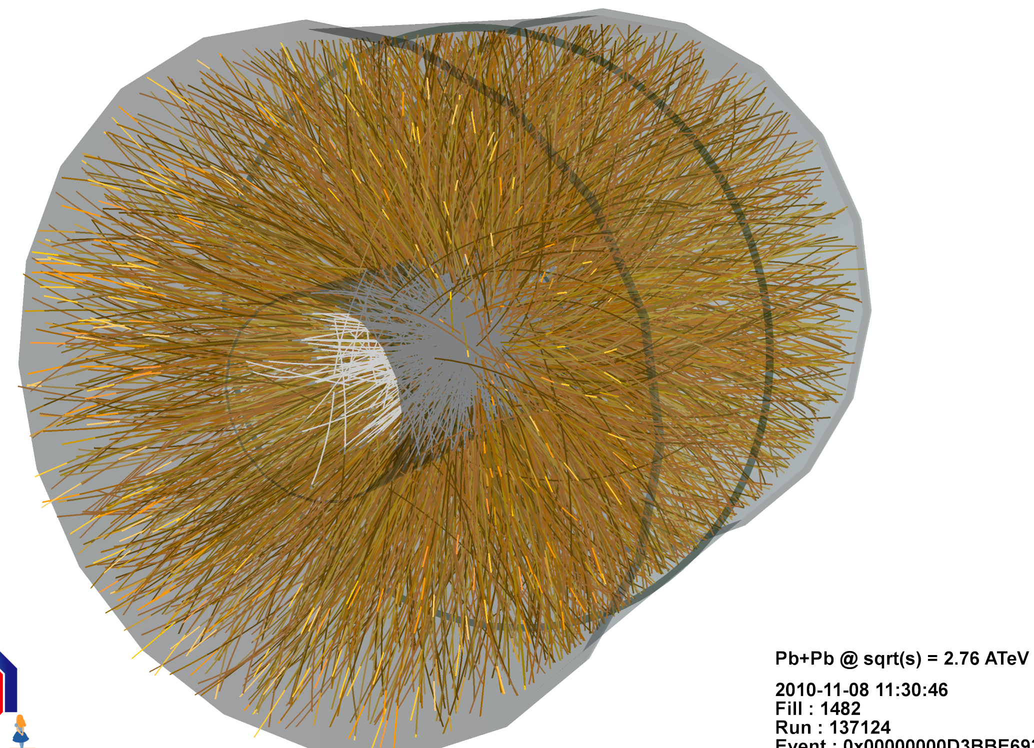
2008

From proton-proton ...

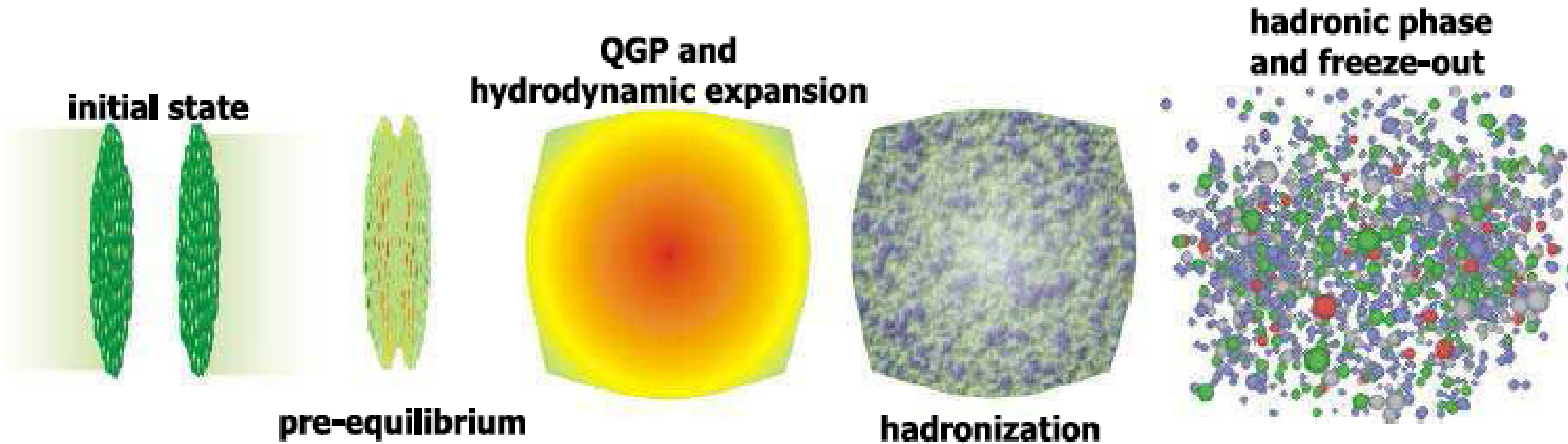




… to Pb-Pb collisions !!!



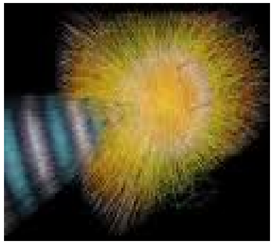
Stages of a high-energy nucleus-nucleus collision



1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\rm cm}c$)
2. thermalization: equilibrium is established ($t \lesssim 1$ fm/c)
3. expansion and cooling ($t <$ 10-15 fm/c)
4. hadronization (quarks and gluons form hadrons)
5. chemical freeze-out: inelastic collisions cease; yields are frozen
6. kinetic freeze-out: elastic collisions cease; spectra are frozen ($t+ =$ 3-5 fm/c)

we measure at stages 5. and 6. want to know properties of 2.+3.

Hundreds of physics observables

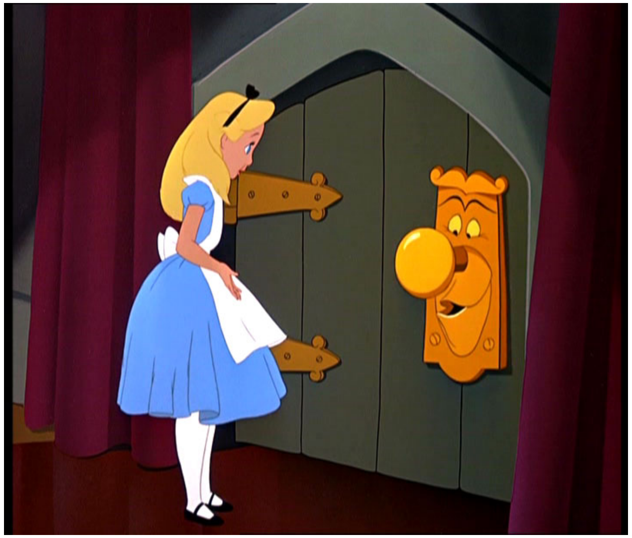


ALICE steps into wonderland

- Particle multiplicities
- Transverse momentum spectra
- Identified particle spectra (π, K, p)
- π^0 production
- Strangeness (K^0_S, Λ, Σ, Ω …)
- Two-pion Bose Einstein correlations
- Photons (calorimetry and conversions)
- Dielectrons (ω, ρ, φ …)

- Deuteron, tritium, He
- Hypernuclei

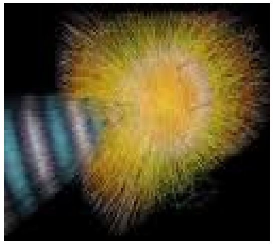
- Jets
- … etc ...



Open and hidden heavy flavors

- J/ψ production
- Charm hadron production
  - D, D*, D_s, Λ_c
- Single electron/muon spectra
- $B \rightarrow J/\psi$
- … etc ...

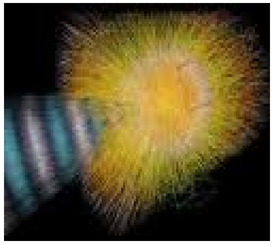
Today we look at



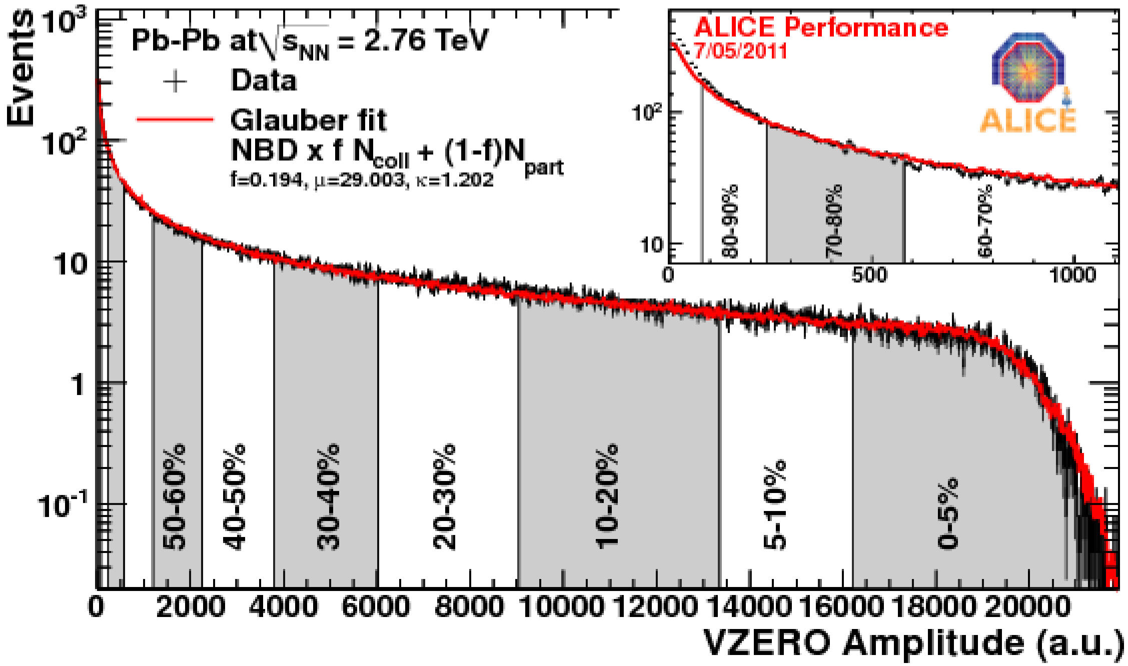
- Energy loss in the medium
  - Charged particles
  - Open heavy flavours (charm, D mesons)
  - J/ψ

- Direct photons, thermal radiation

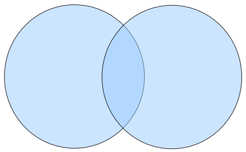
Reminder: centrality

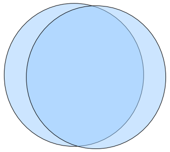


Collision centrality from multiplicity distributions (e.g. VZERO scintillator hodoscopes) + Glauber fit:



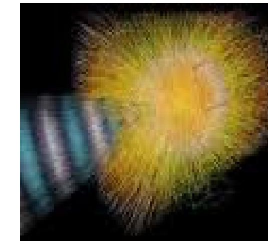
peripheral





central

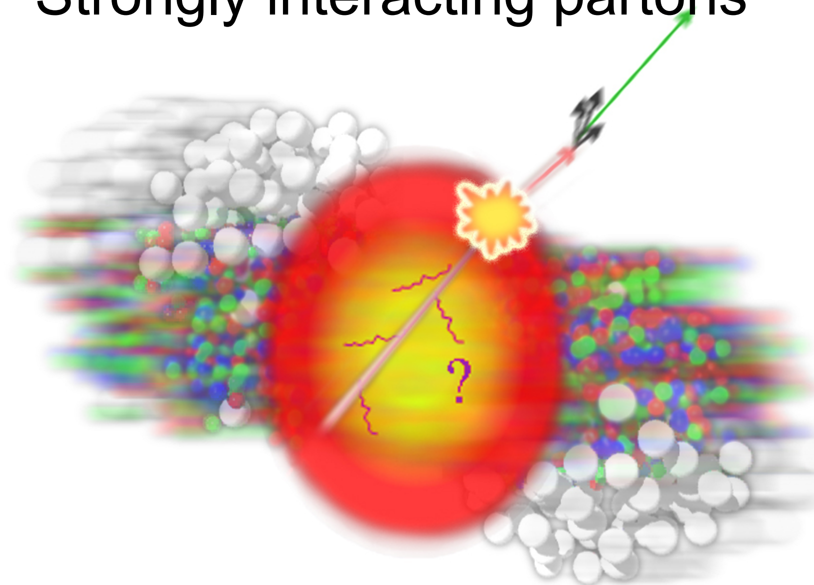
Energy loss



Understand internal structure from the absorption and attenuation of radiation

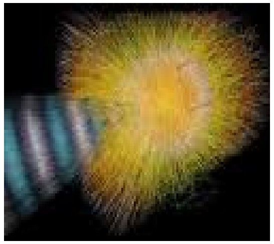
Probes for the QGP?

Strongly interacting partons



Interaction of gluons, light and heavy quarks inside the medium
→ energy loss, suppression

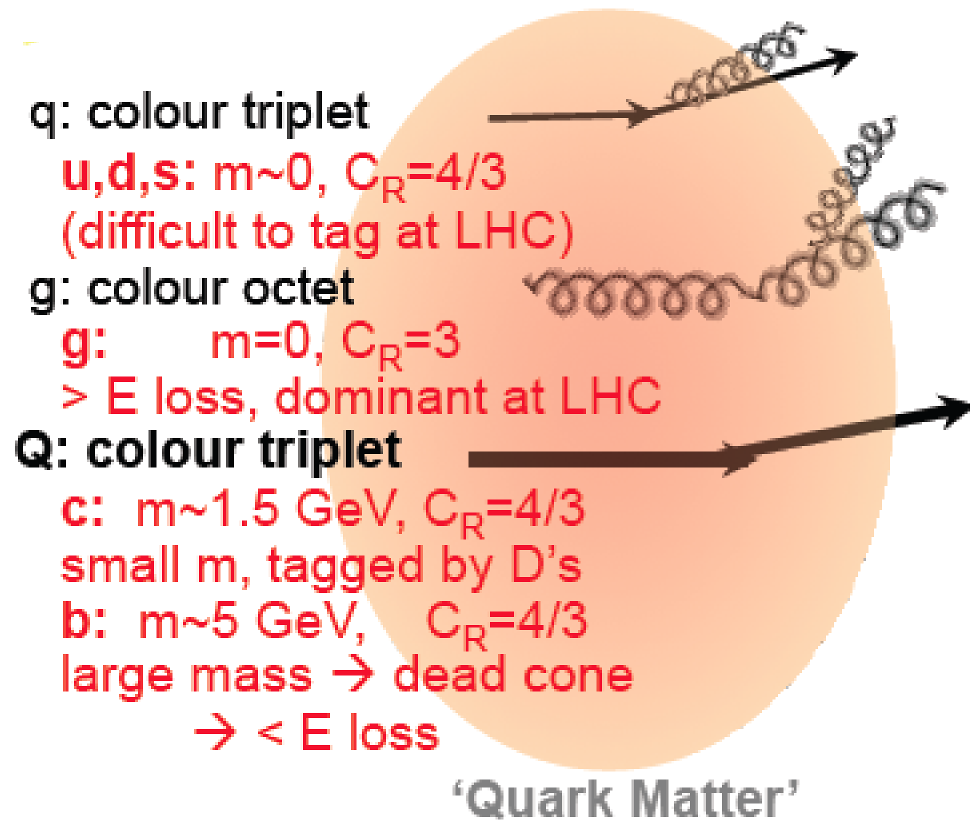
In-medium parton energy loss



- Energy loss by:
  - Medium-induced gluon radiation
  - Collisions with medium partons
- Depends on:
  - Colour coupling factor C_R (g>q)
  - Parton mass
- Predicted energy loss:

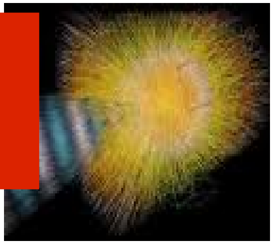
$$\Delta E_{gluon} > \Delta E_{q \approx c} > \Delta E_b$$

"suppression": $\pi > D > B$

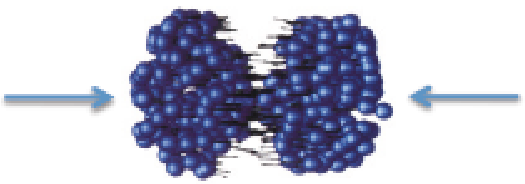


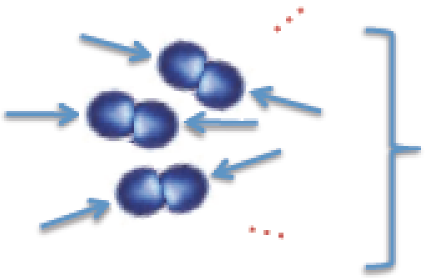
courtesy D.d'Enterria

Nuclear modification factor



Is Pb-Pb different from N * (nucleon – nucleon) ?





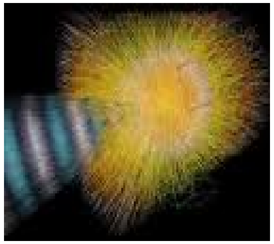
$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{coll}}$$

Scaling by number of binary collisions (Glauber)

No medium effect → $R_{AA} \approx 1$

Medium effect → medium “slows” down particles → $R_{AA} < 1$

Nuclear modification factor



$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{coll}}$$

pp reference:

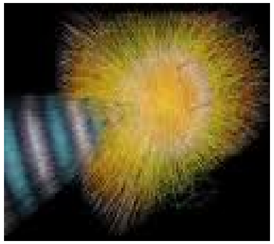
- Proton-proton data sample recorded at $\sqrt{s}$ = 2.76 TeV
- If statistically limited → scaled from results at $\sqrt{s}$ = 7 TeV (NLO, FONLL,...)

Results about:

- **Charged particles**
- **Identified particles: pions, K^0_S, Λ**
- **Heavy-flavour hadrons**
- **Quarkonia**

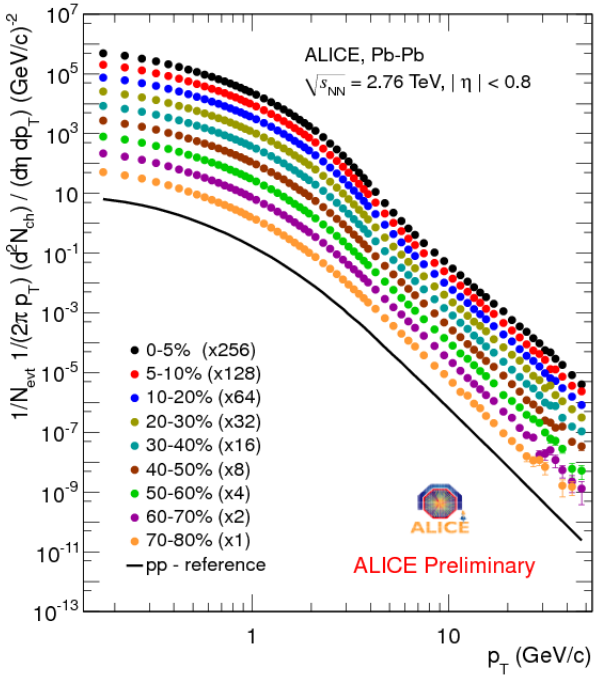
Exclusive !!
Reconstructed charm mesons
Separation charm / beauty

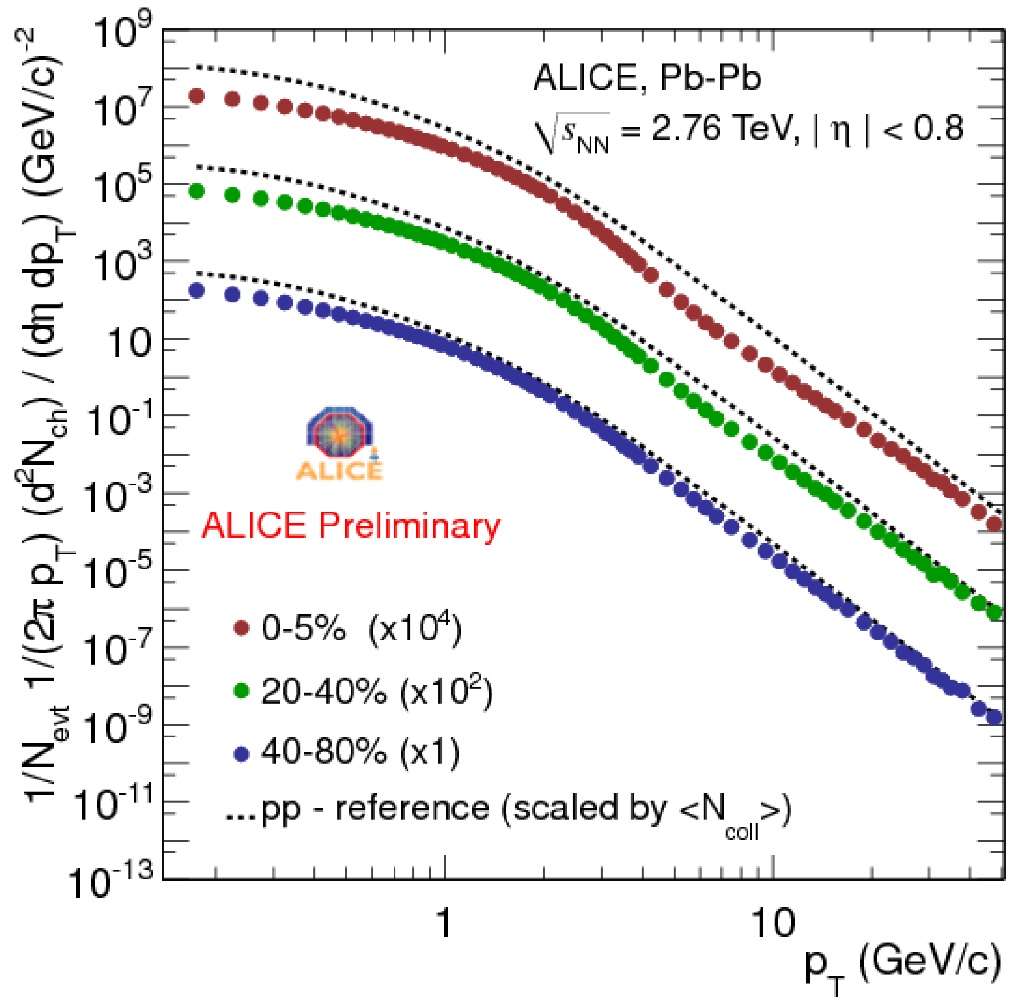
Charged particle spectra



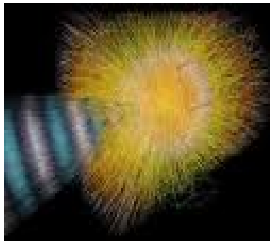
Clear modification of the p_t spectrum shape !

Effect stronger with increasing centrality !

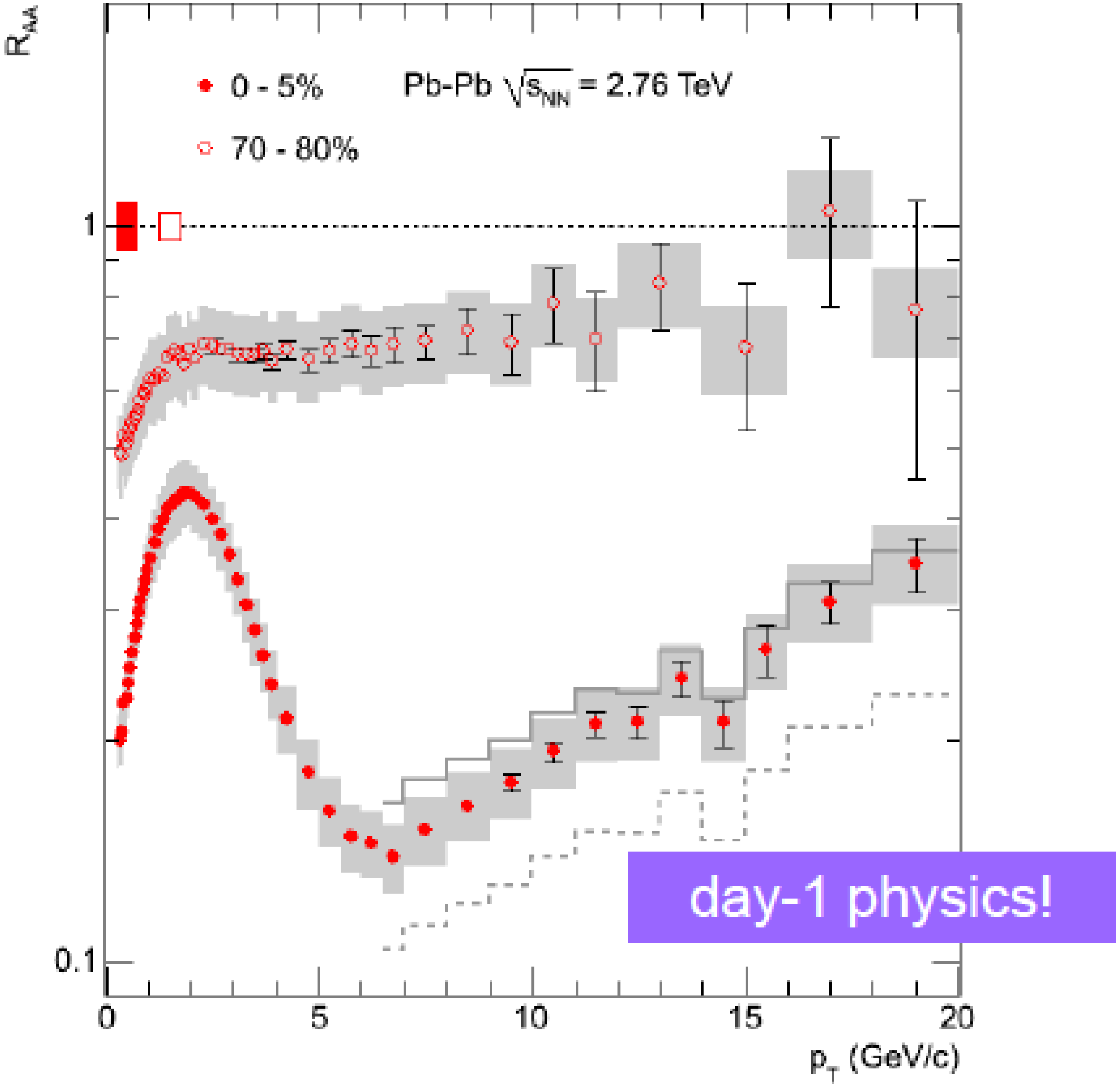




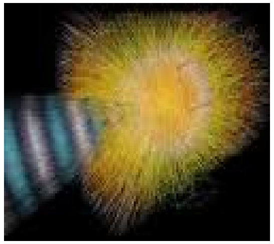
Charged particle R_{AA} – day 1

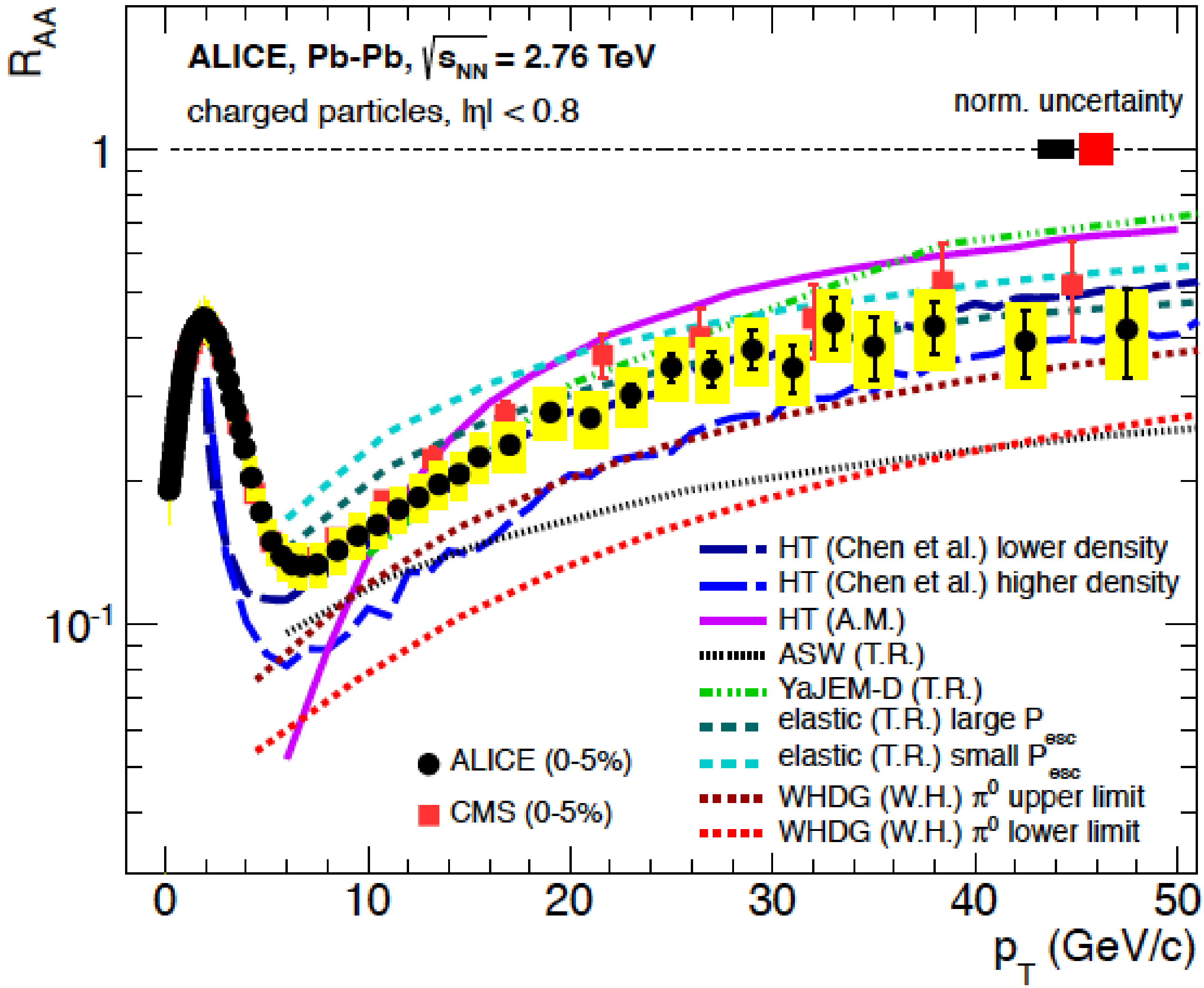


ALICE Collaboration, Phys. Lett. B696 (2011)



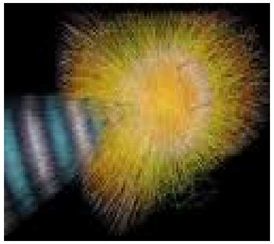
Charged particle R_{AA} (published)





arXiv:1208.2711v1 [hep-ex]

Charged particle R_{AA}

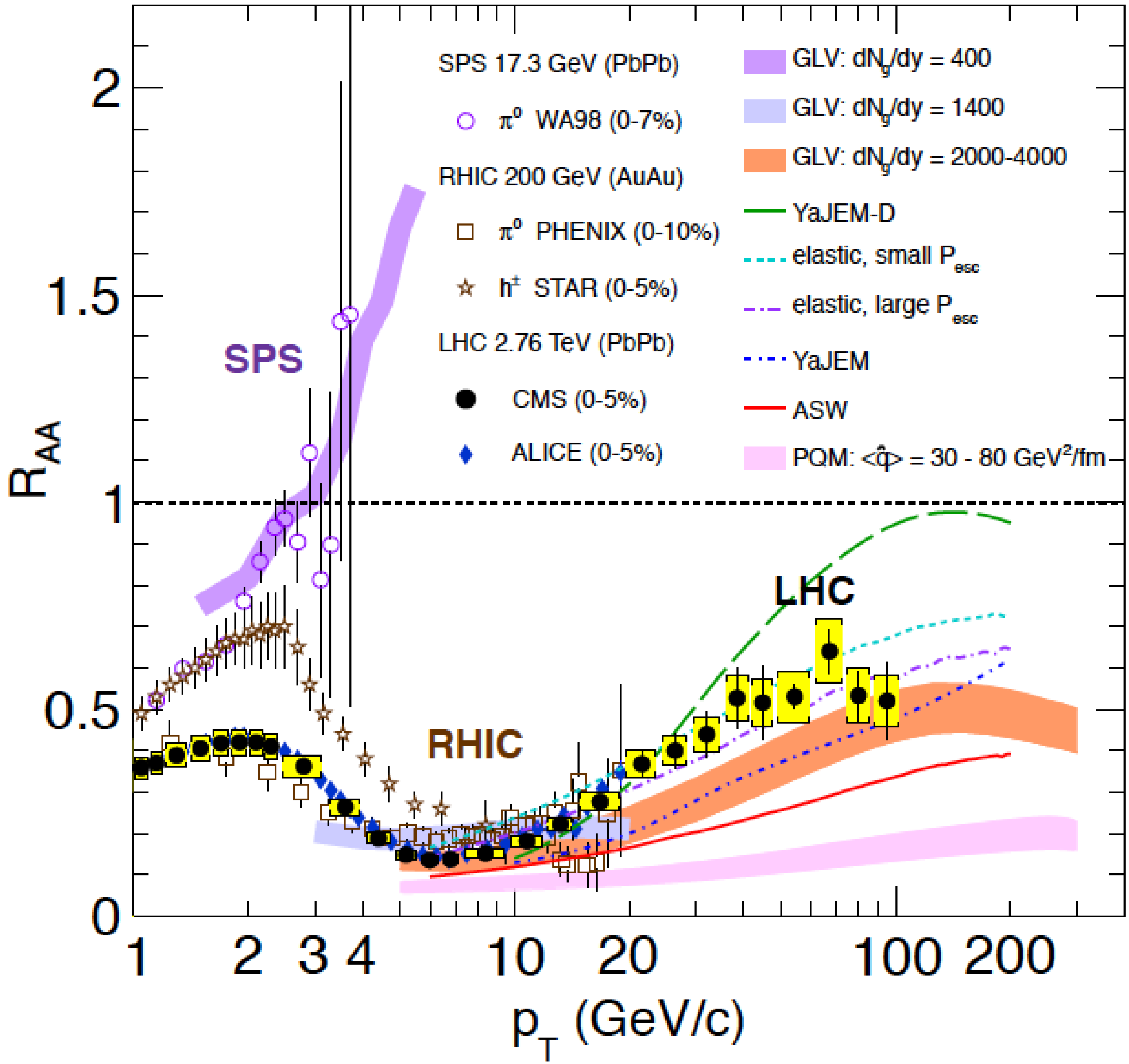


0-5% most central coll.

- Minimum at p_t ~ 6-7 GeV/c
- Then a slow increase for higher pt
- Still a significant suppression at 100 GeV/c !!

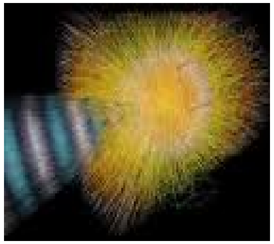
Medium so dense that pQCD still not restored around 100 GeV/c !!

Models!

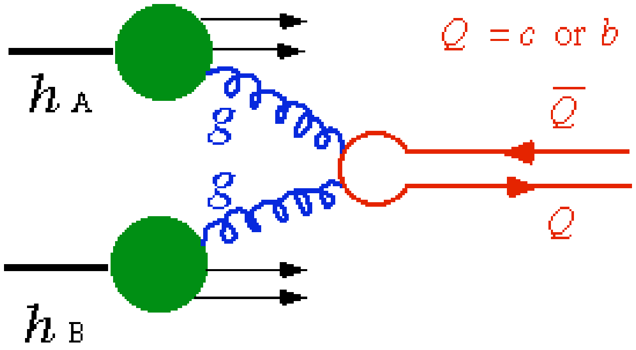


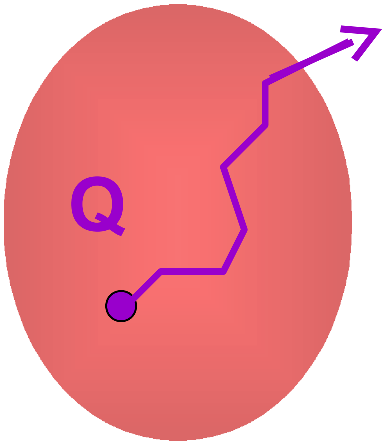
arXiv: 1202.2554v1 [nucl-ex]

Heavy flavours: probes of the medium



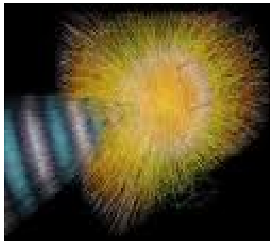
- Heavy flavors are produced mostly by gluon-gluon fusion ...
- … in the **INITIAL** partonic collisions → present from the **early time** of the medium, in the **HIGHEST DENSITY** phase
- Travel and interact in the medium → **FULL collision history**





Large production cross sections at LHC energies !!

Heavy flavours: probes of the medium



LARGE YIELDS compared to RHIC!

Large production cross sections at LHC energies !!

$\sigma^{c\bar{c}}_{LHC} \approx 25 \cdot \sigma^{c\bar{c}}_{RHIC}$

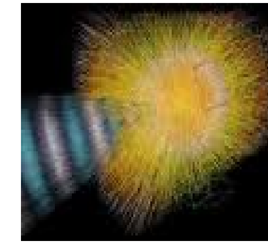
$\sigma^{b\bar{b}}_{LHC} \approx 100 \cdot \sigma^{b\bar{b}}_{RHIC}$

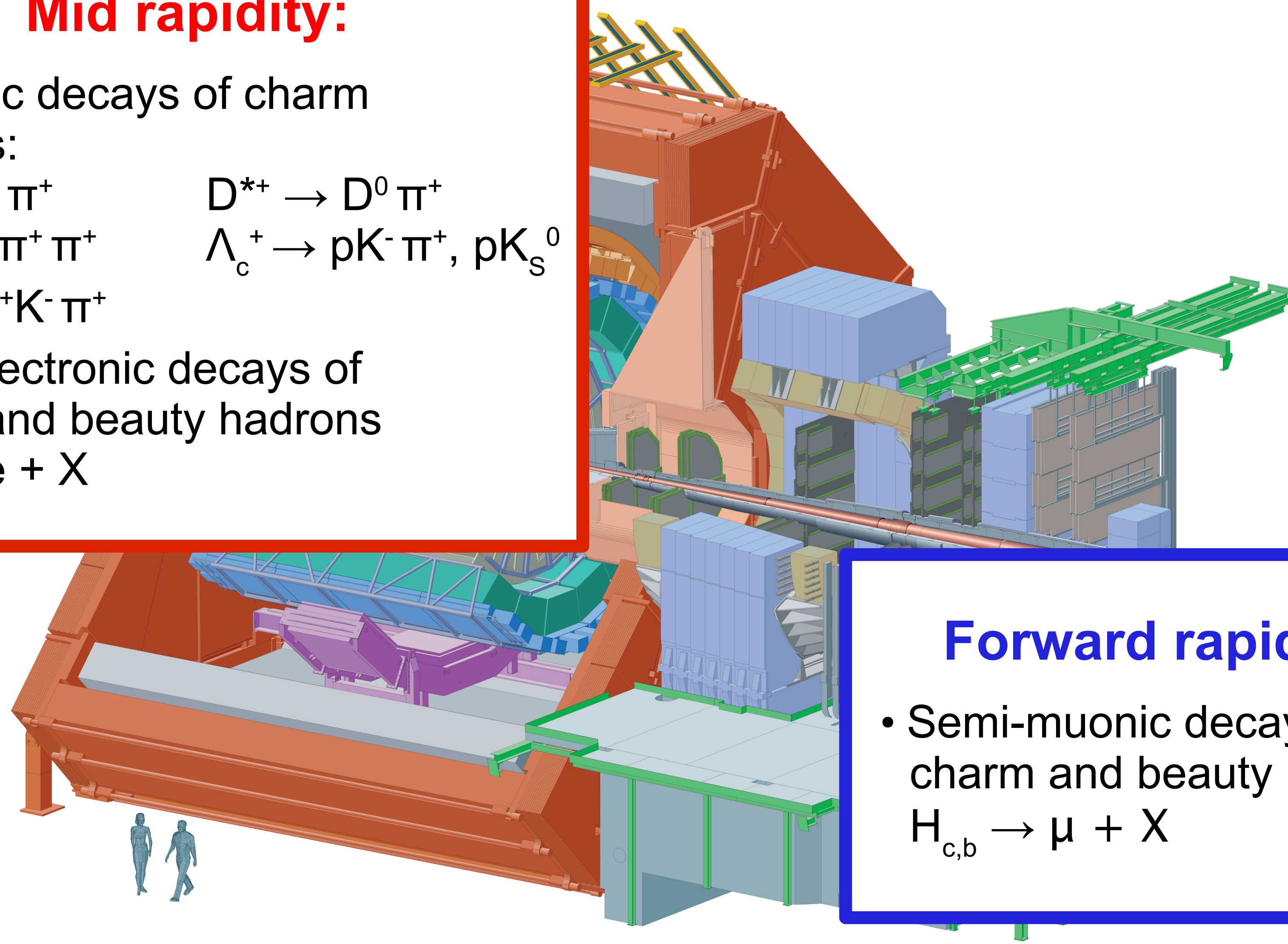
Remember: some energy loss models predict:

$\Delta E_{gluon} > \Delta E_{q \approx c} > \Delta E_{b}$

"suppression": π > D > B

The heavy-flavour program





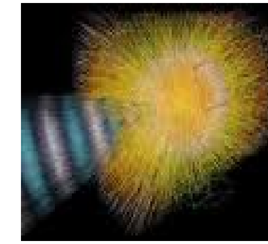
Mid rapidity:

- Hadronic decays of charm hadrons:
  $D^0 \to K^- \pi^+$ $\quad$ $D^{*+} \to D^0 \pi^+$
  $D^+ \to K^- \pi^+ \pi^+$ $\quad$ $\Lambda_c^+ \to pK^- \pi^+,\ pK_S^0$
  $D_s^+ \to K^+ K^- \pi^+$
- Semi-electronic decays of charm and beauty hadrons
  $H_{c,b} \to e + X$

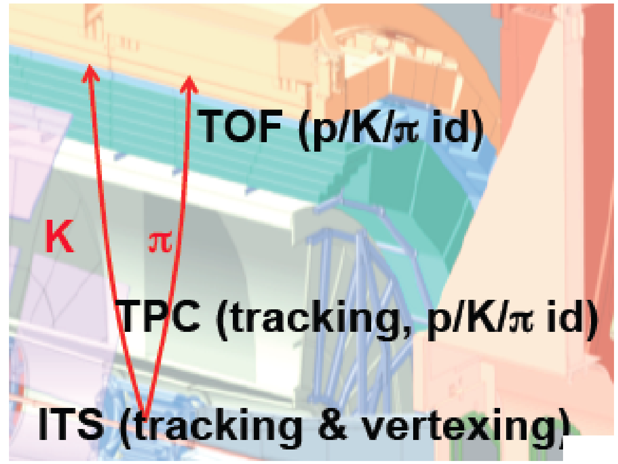
Forward rapidity:

- Semi-muonic decays of charm and beauty hadrons
  $H_{c,b} \to \mu + X$

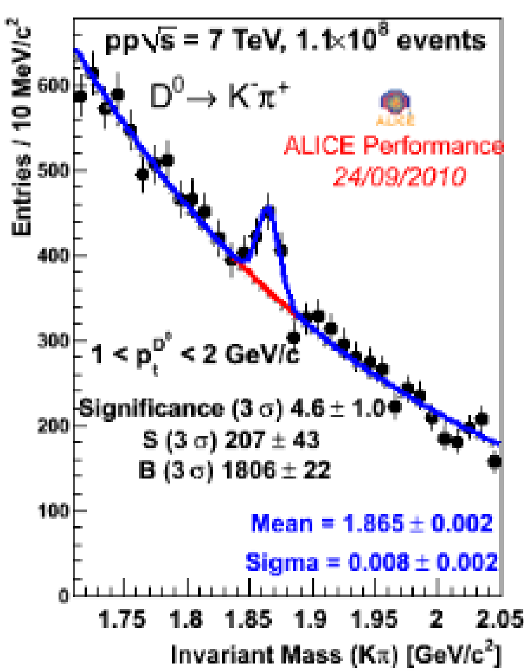
Hadronic decays of charm hadrons



- $D^0 \rightarrow K\pi$
- $D^\pm \rightarrow K\pi\pi$
- $D_s \rightarrow KK\pi$

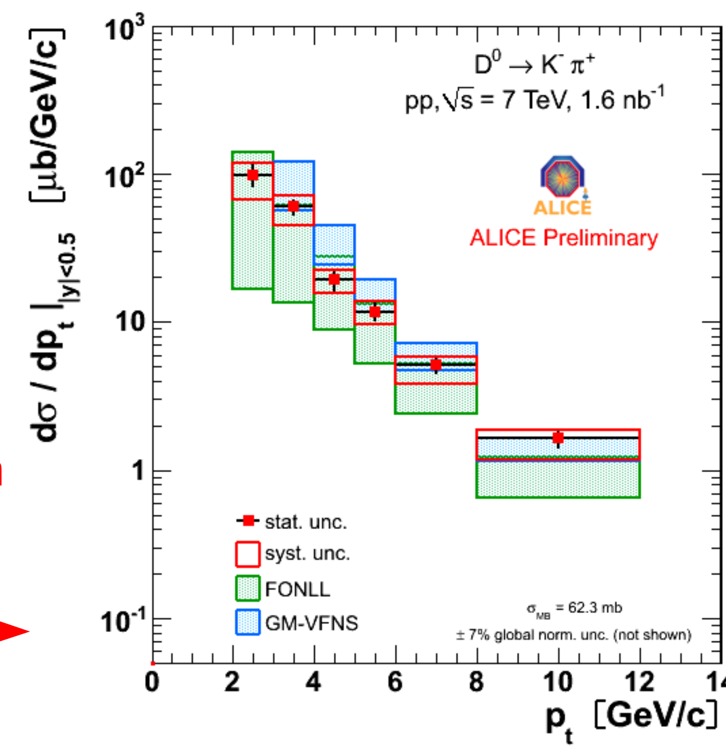


- $D^0 \rightarrow K\pi\pi\pi$
- $D^* \rightarrow D^0\pi$
- $\Lambda_c \rightarrow pK\pi$

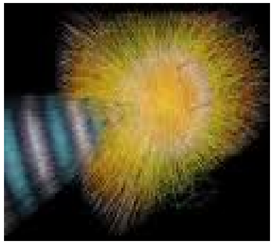


Invariant mass

Differential production cross section

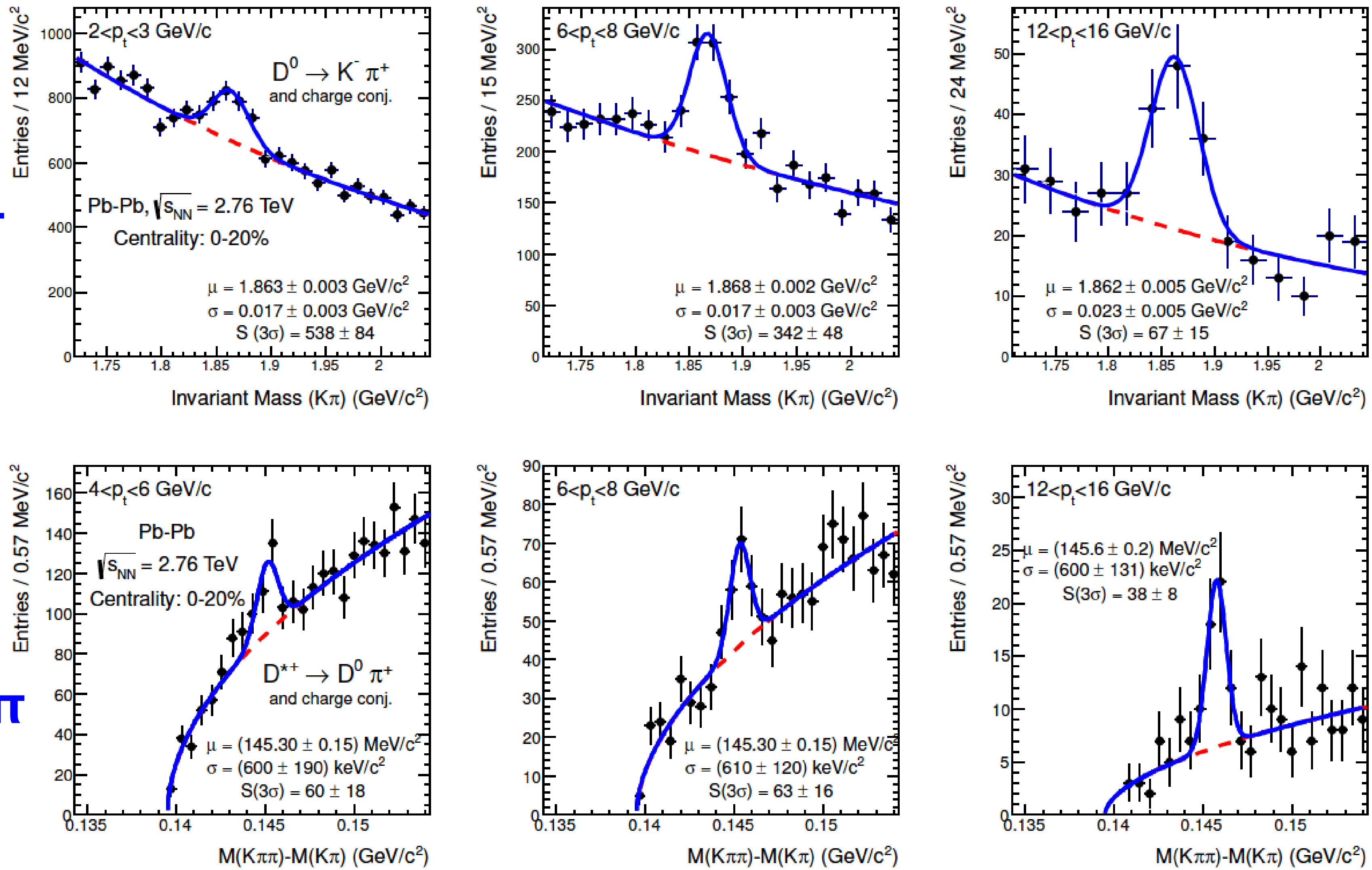


D mesons in PbPb



$D^0 \rightarrow K\pi$

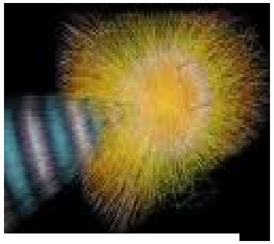
$D^* \rightarrow D^0\pi$

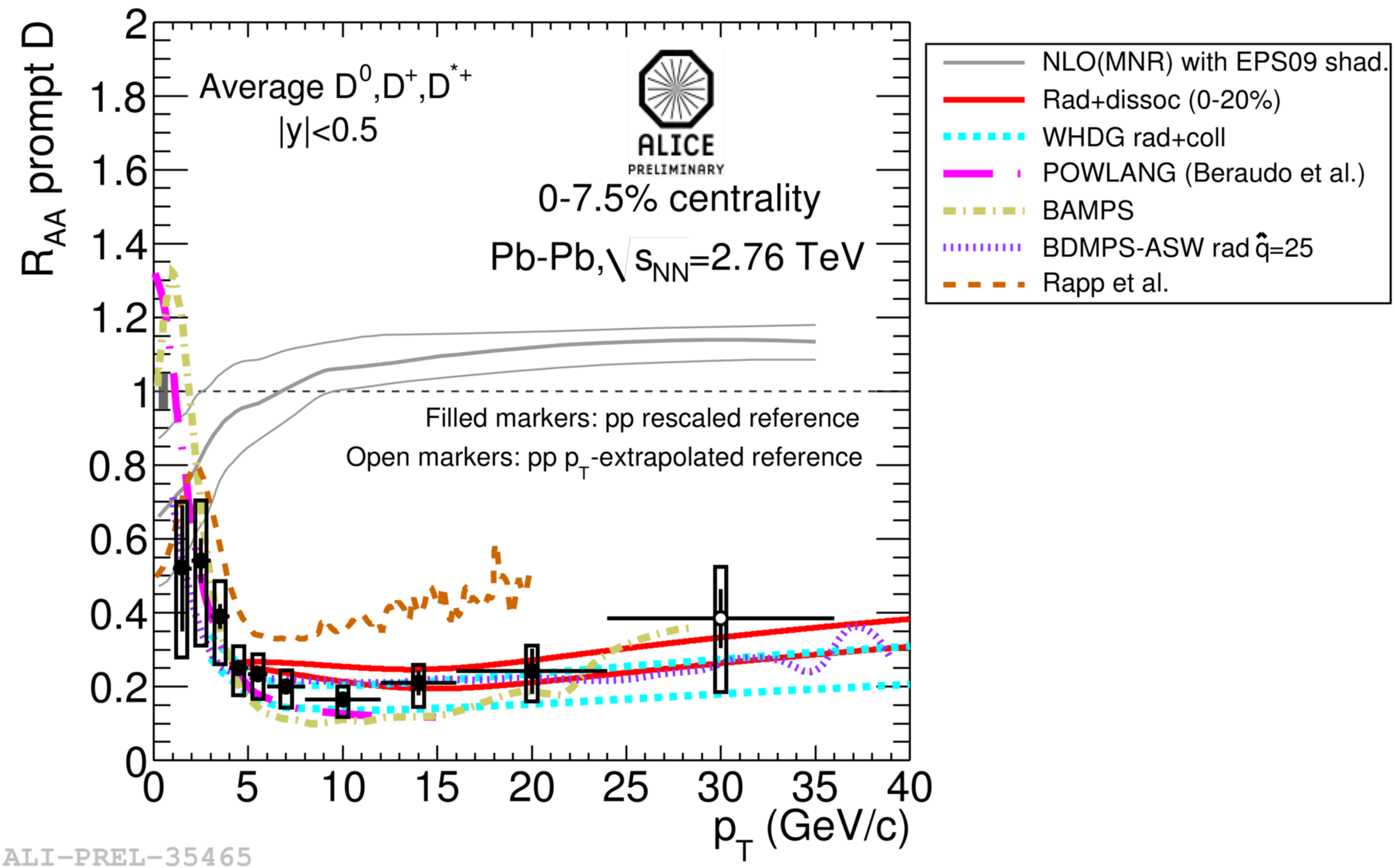


arXiv:1203.2160

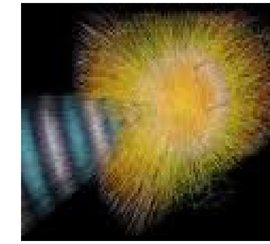
Also $D^+ \rightarrow K\pi\pi$

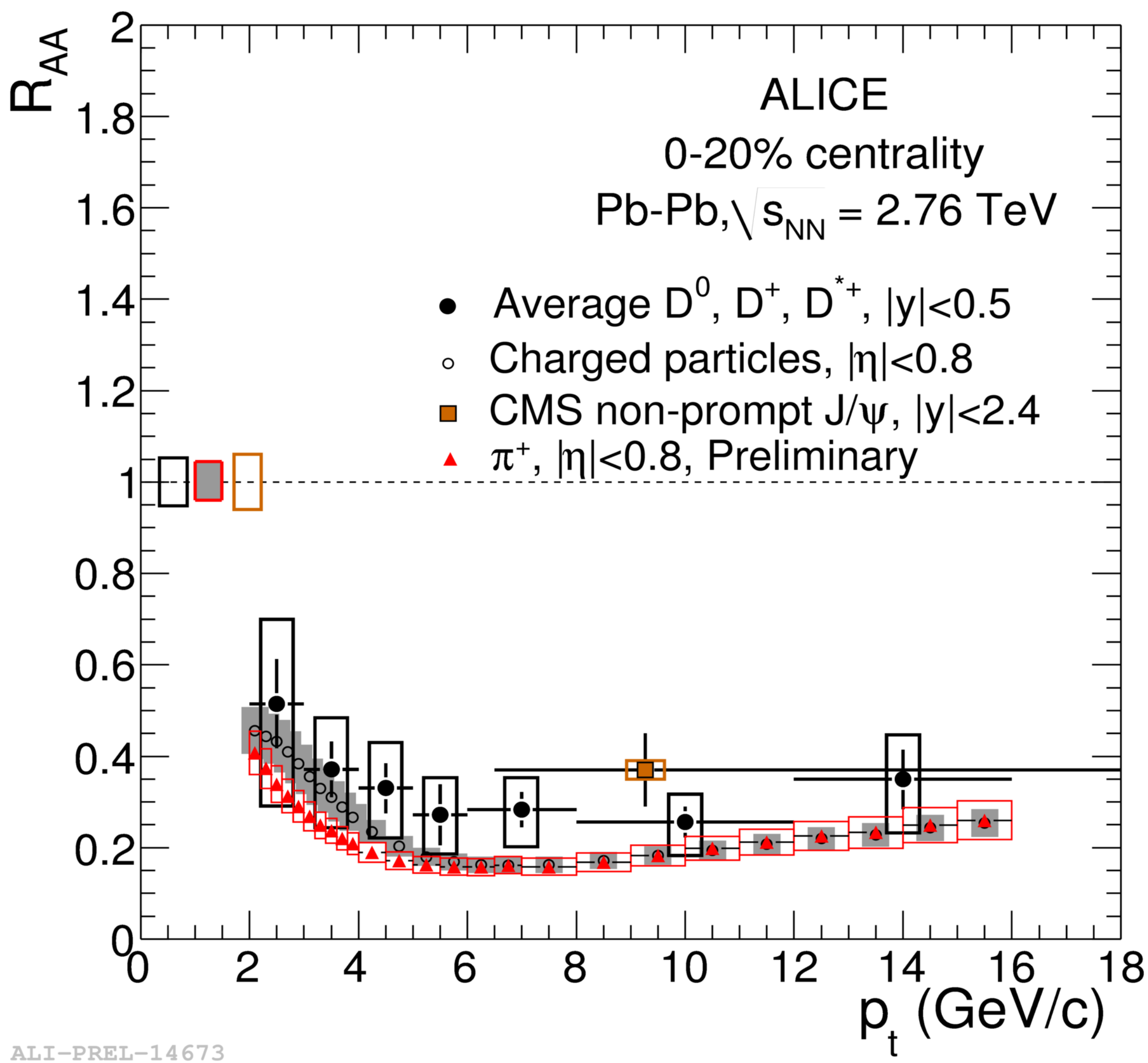
Charm meson R_{AA}





Pions, charm and beauty



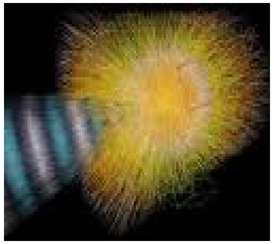


- Charged particles
- Pions
- D mesons (charm)
- B → J/ψ (beauty) CMS

arXiv:1201.5069

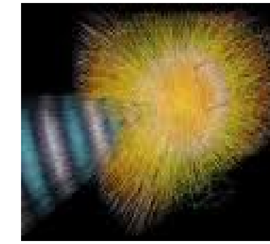
- *No evidence of mass effects yet*
- *Better precision needed*
- *Work for models!*

R_{AA}: working on the puzzle



- Understanding the mechanisms of energy loss of different particles in the medium will help tremendously to learn more about the medium itself!!
- ALICE at LHC do and will provide high precision measurements for many different particle species (light, strange, charm and beauty)
- ALICE vertexing capabilities allow to separate charm and beauty → NEW !!!
- Lots of exciting results ahead!!

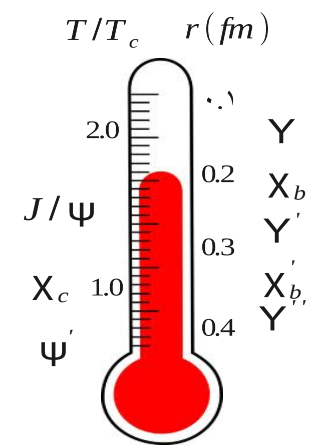
Quarkonium

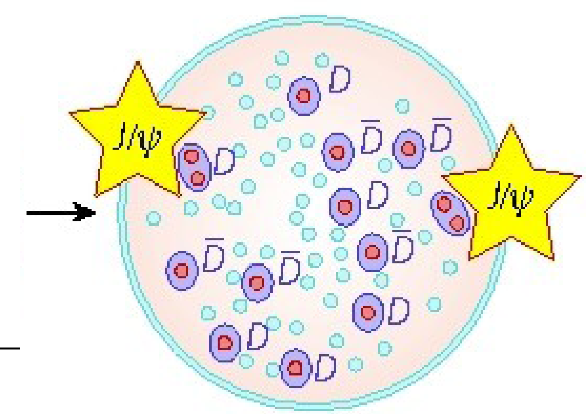


$Q\bar{Q}$ **states** $\left\{ \begin{array}{ll} c\bar{c} & J/\psi,\ \psi',\ \chi_c \\ b\bar{b} & \Upsilon(1S),\ \Upsilon(2S),\ \Upsilon(3S),\ \chi_b \end{array} \right.$

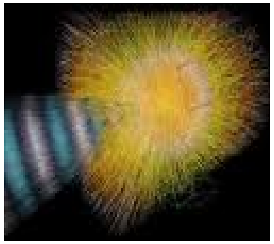
Probes of the medium by excellence!

- Quarkonium state survival depends on the medium temperature (color-screening, in-medium dissociation)
- Test of hadronization models: production or regeneration component from deconfined charm quarks in the medium





J/ψ in ALICE

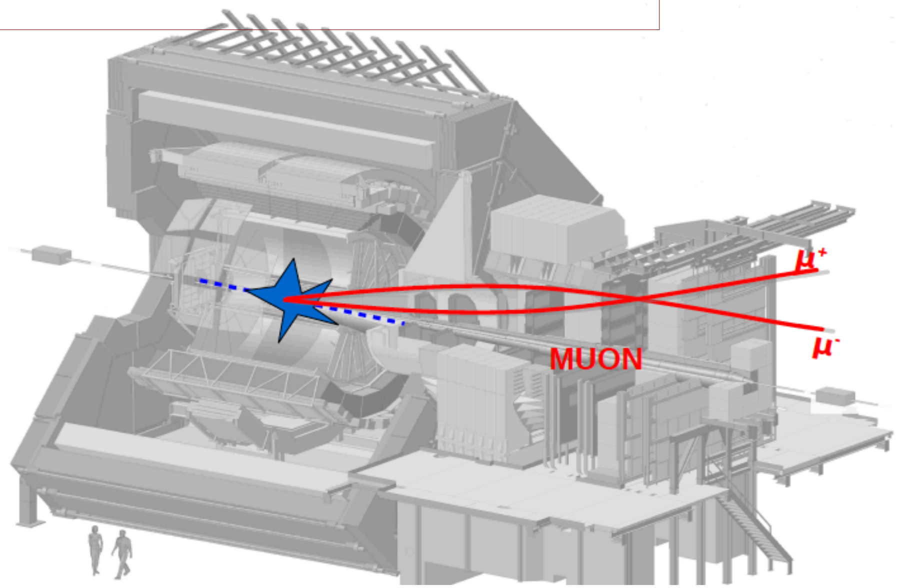


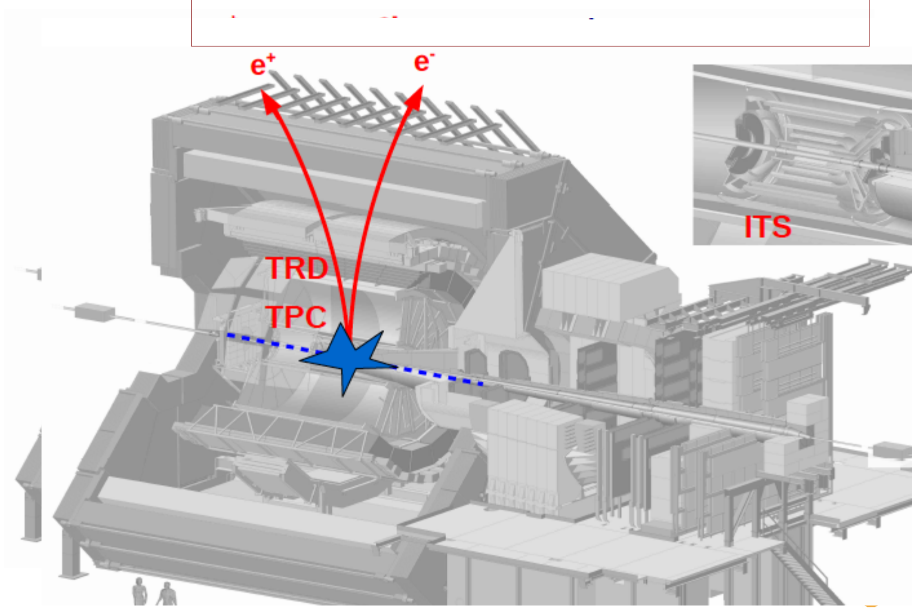
Title:: 4 Mar 2012
Creator:ROOT Version 5.30/06
CreationDate:Sun Mar 4 23:14:52 2012

J/ψ

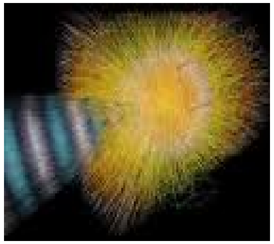
$\mu^+\mu^-$ e^+e^-

Title:: canvas
Creator:ROOT Version 5.30/03
CreationDate:Mon Jan 30 18:23:24 2012





J/ψ production at forward rapidity

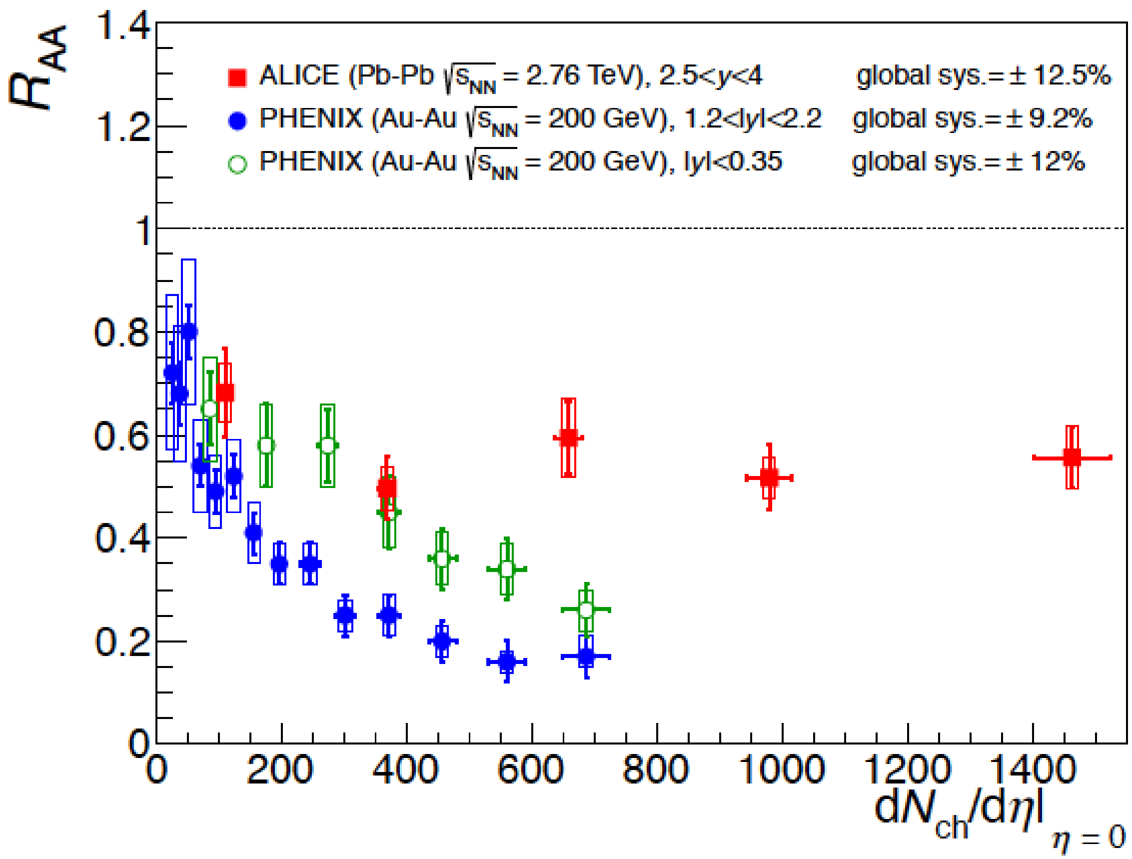


Inclusive production, p_t>0

Comparison with PHENIX results (RHIC)

As a function of number of participants (≈ centrality). At LHC:

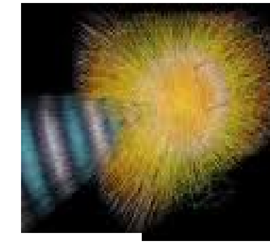
- Flat trend
- R_{AA} larger by factor 3 !!



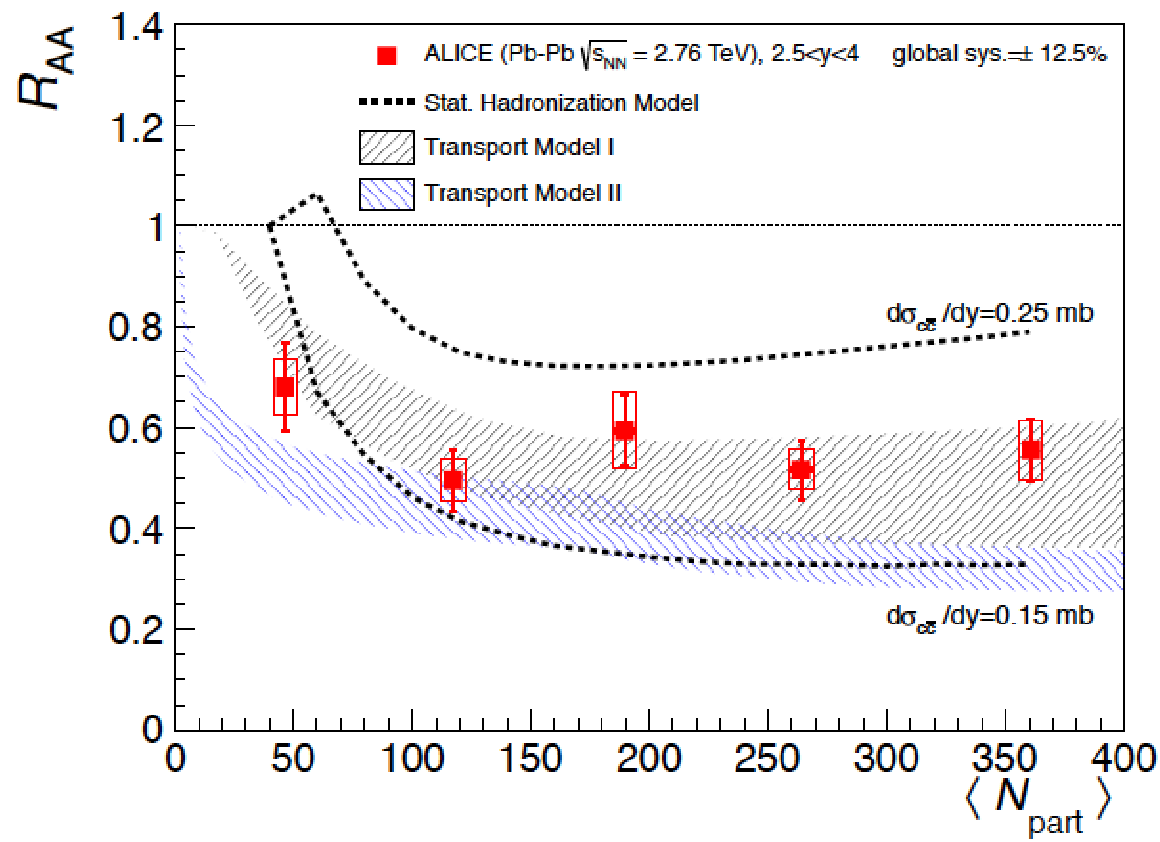
Energy density !

arXiv:1202.1383v1

J/ψ production: models



(Re-)generation of J/ψ from deconfined charm quarks in the medium



Still missing ingredients to estimate quantitatively the final state effects:

- Cold Nuclear Matter effects: nuclear absorption likely to be negligible
- Shadowing

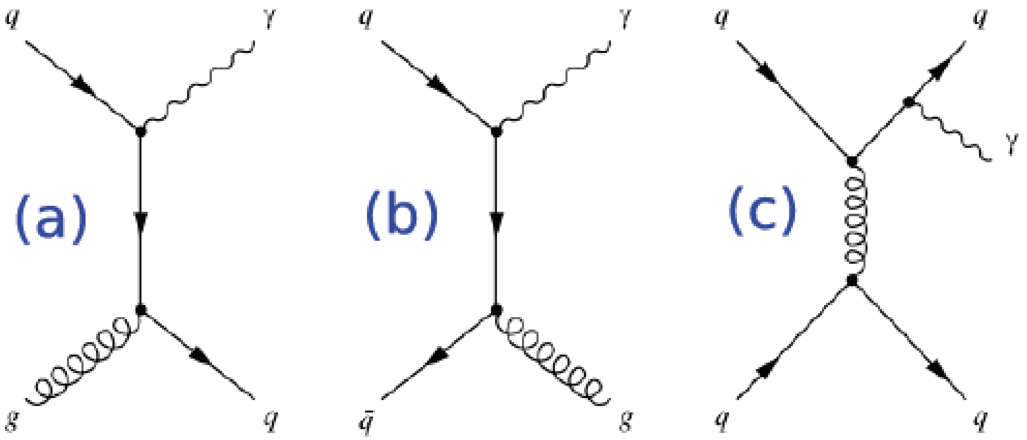
} **pA (2012)**

- Charm production cross section
- Beauty feed-down (order of ~ 10%)

Direct photons

Definition: photons that are not produced by particle decays

Calculable with perturbative QCD in proton-proton collisions

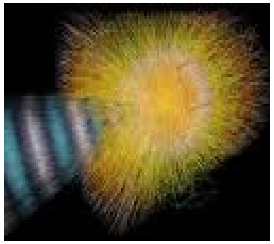


(a) Quark-gluon Compton scattering

(b) Quark-Anti-quark annihilation

(c) Fragmentation photons (bremsstrahlung)

Direct photons in Pb-Pb



An additional source of direct photons in Pb-Pb collisions is

THERMAL PHOTONS:

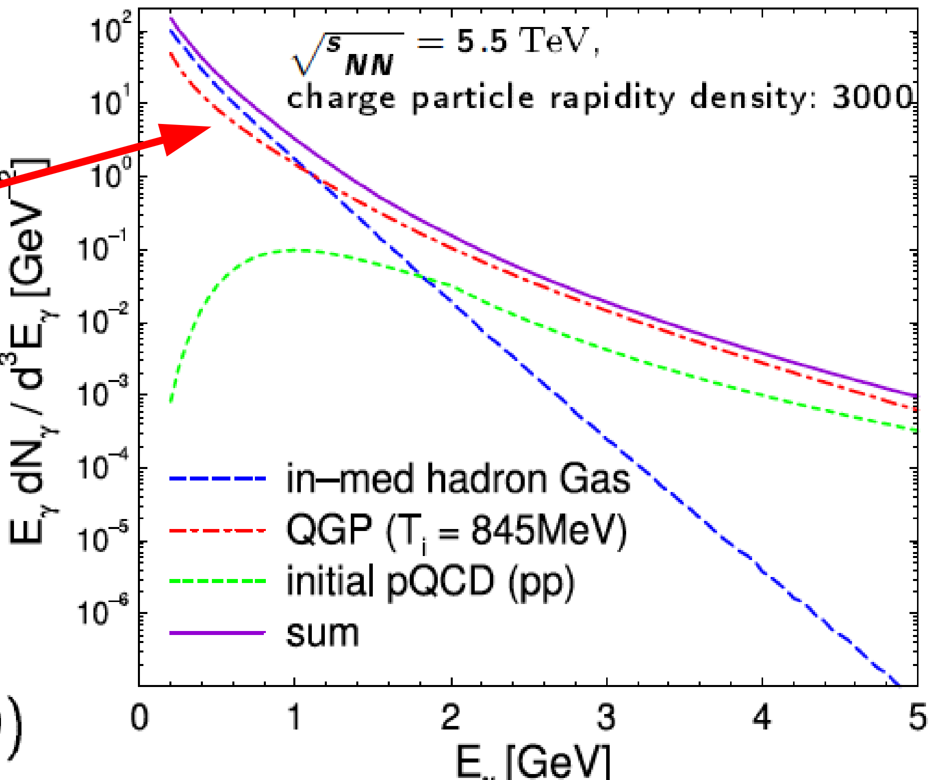
Scattering of thermalized particles:

- QGP: $q\bar{q} \rightarrow g\gamma, qg \rightarrow q\gamma\,(+\mathrm{NLO})$
- HHG (hot hadronic gas): hadronic interactions (e.g. $\pi^+\pi^- \rightarrow \gamma\rho_0$)

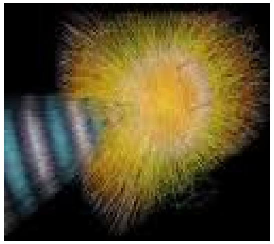
2006 J. Phys. G: Nucl. Part. Phys. 32 1295

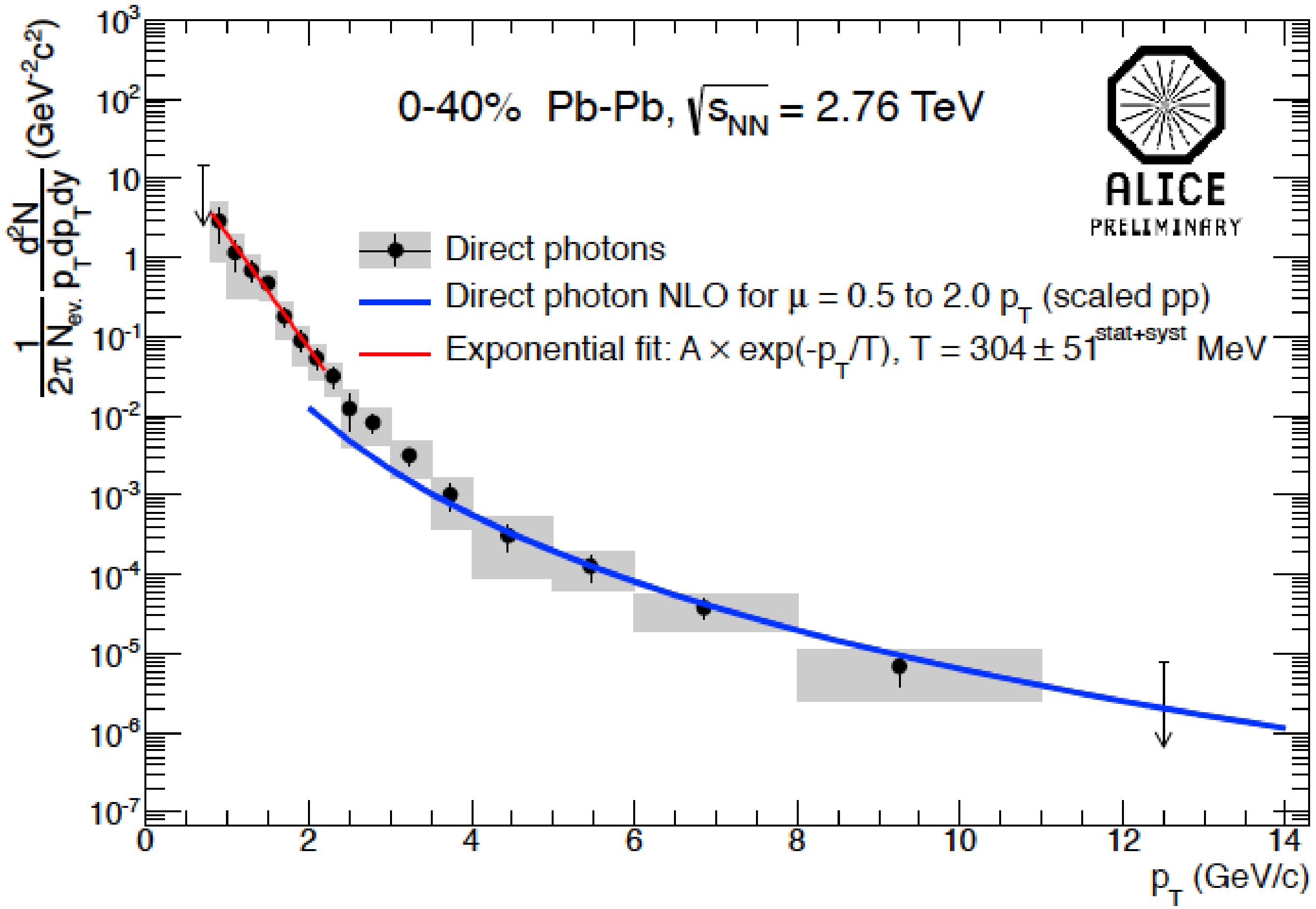
Exponentially decreasing

Dominant at low p_T



Direct photons: results





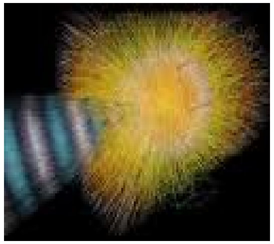
Excess at low p_T interpreted as thermal signal

At low p_T (<2.2 GeV/c) spectrum fitted with an exponential →

Slope parameter: $T_{ALICE} = 304 \pm 51^{stat+syst}$ MeV (0-40%)

$T_{PHENIX} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV (0-20%)

Hottest temperature: in the news



http://qm2012.bnl.gov/pressCoverage.asp

http://blogs.nature.com/news/2012/08/hot-stuff-cern-physicists-create-record-breaking-subatomic-soup.html

NATURE NEWS BLOG

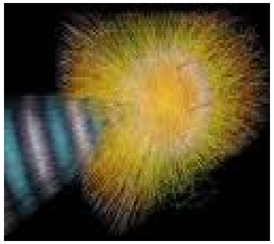
Hot stuff: CERN physicists create record-breaking subatomic soup

13 Aug 2012 | 23:58 BST | Posted by Eric Hand | Category: Physics & Mathematics

38% hotter than RICH

ALICE physicists, presenting on Monday at Quark Matter 2012 in Washington DC, say that they have achieved a quark–gluon plasma 38% hotter than a record 4-trillion-degree plasma achieved in 2010 by a similar experiment at Brookhaven National Laboratory in New York, which had been anointed the Guinness record holder.

Hottest temperature: in the news



http://www.space.com/17084-quark-gluon-plasma-big-bang-conditions.html

Hottest Particle Soup May Reveal Secrets of Primordial Universe

Clara Moskowitz, LiveScience Senior Writer

Date: 13 August 2012 Time: 04:59 PM ET

In Cooperation with LiveScience.

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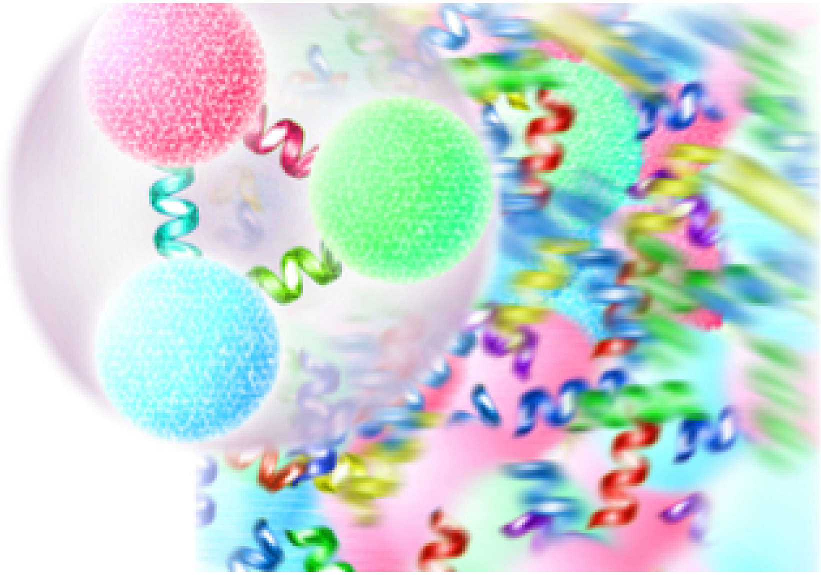
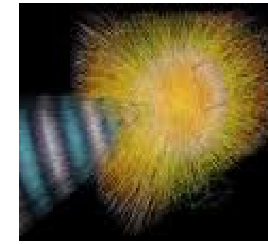


A soup of ultra-hot elementary particles could be the key to understanding what the universe was like just after its formation, scientists say.

Over the past few years, physicists have created this soup inside two of the world's most powerful particle accelerators — the Large Hadron Collider (LHC) in Switzerland and the Relativistic Heavy Ion Collider (RHIC) in New York — by smashing

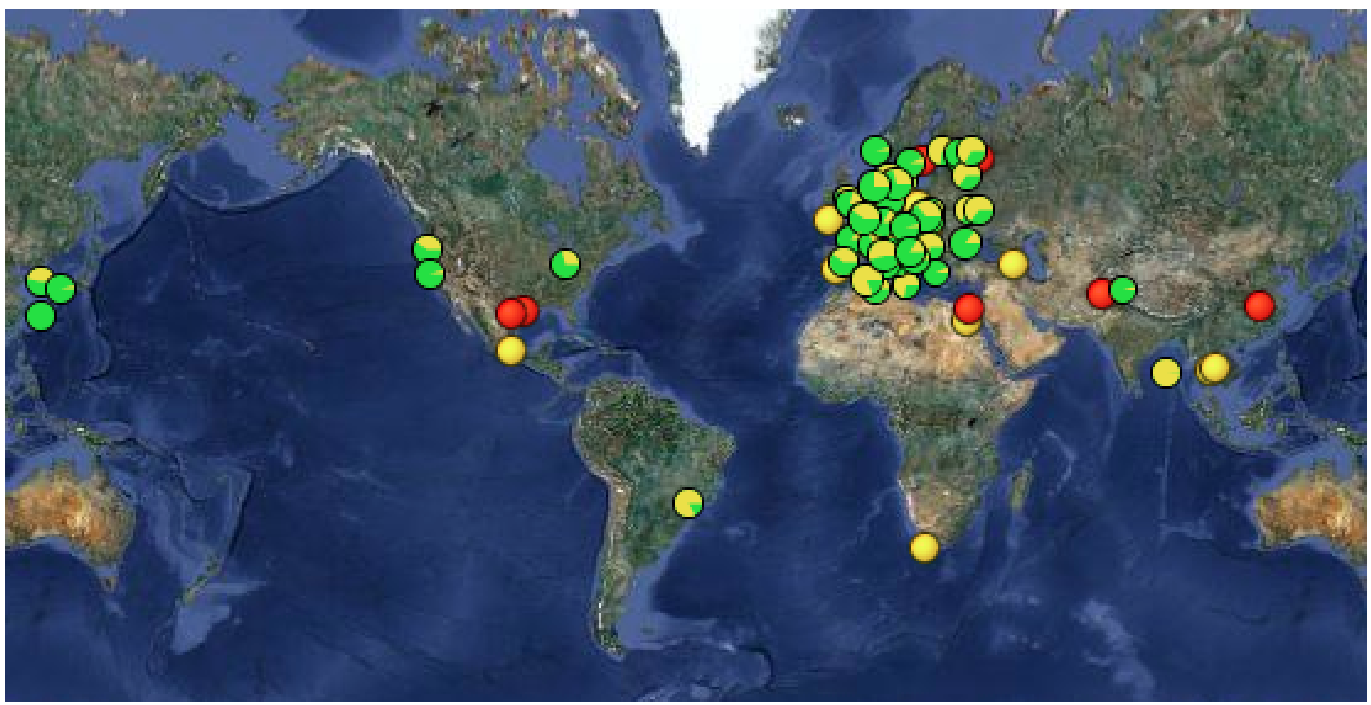
ALICE on the computing GRID



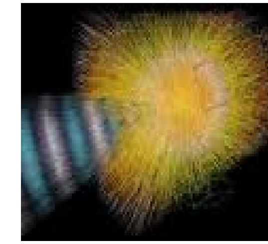
A Large Ion Collider Experiment

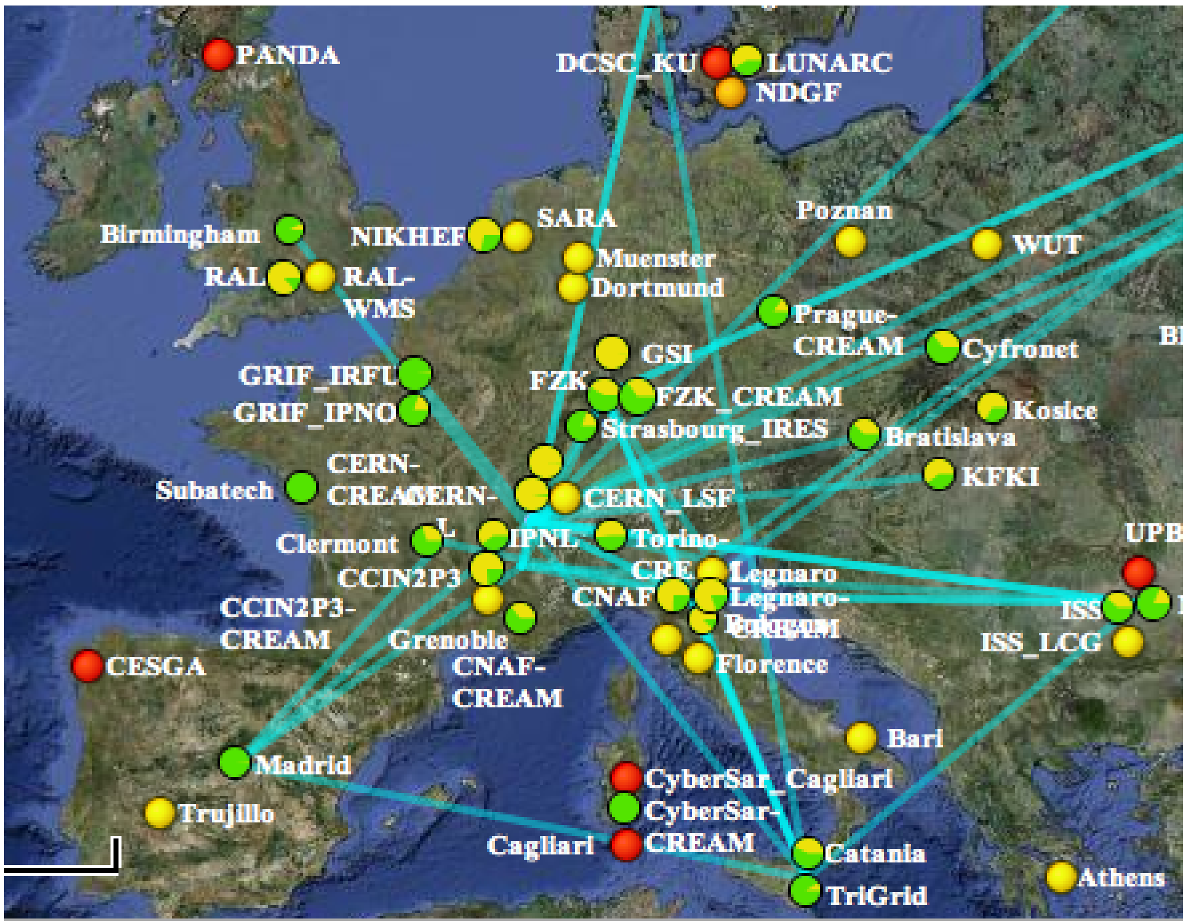
35 countries, 120 institutes, 1300 members

72 active computing sites



GSI TIER 2/3 in GRID





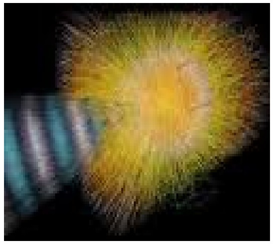
- GSI: very important TIER2 center, central role in ALICE
  20% of all TIER2s of ALICE
- Data analysis, detector calibration, MC production, MC and real data storage
- Excellent support to whole Germany

TIER2 continuously expands

Relative growth +30%/y !

GSI GRID group

GSI Computing Wonderland



Extremely fast feedback at ALICE startup:

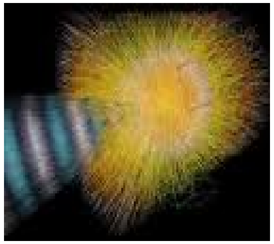
thanks to excellent computing at GSI

High Performance Cluster

- **1500+6500 cores**
- **~ 2.2+1.5 PB file system (lustre)**
- **200 Gbit/sec I/O bandwidth**

- **Built and tuned over the last years**
- **GSI IT - ALICE special collaboration**

Yet More Wonderland

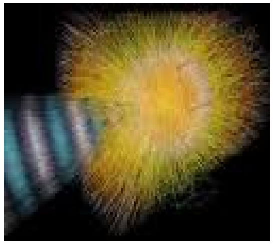


LHC approximate schedule:

- 2013 p-Pb collisions
- 2013-4 shutdown to bring the machine to operate safely at the design energy
- **2015 pp at 14 TeV**
  PbPb at 5.5 TeV

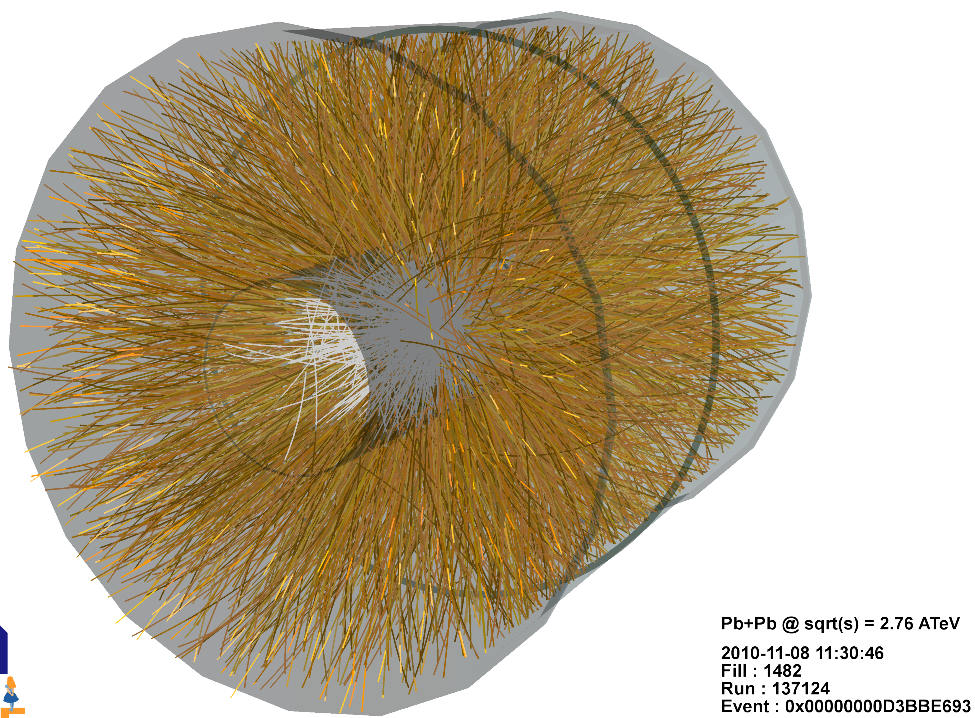
Highest every reached energies !!!

This Physics ...



… is hot and dense! (many open questions and mysteries)

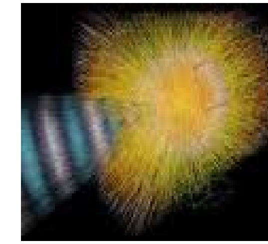
And these are extremely exciting times!!!



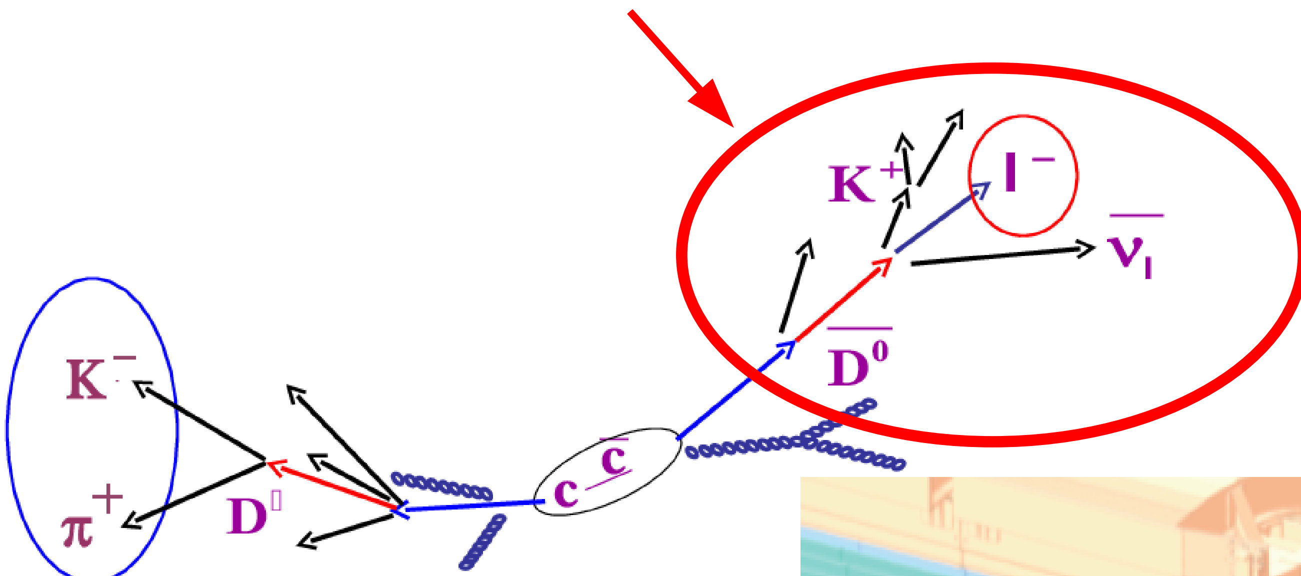
ALICE

SPARES

Semileptonic decays



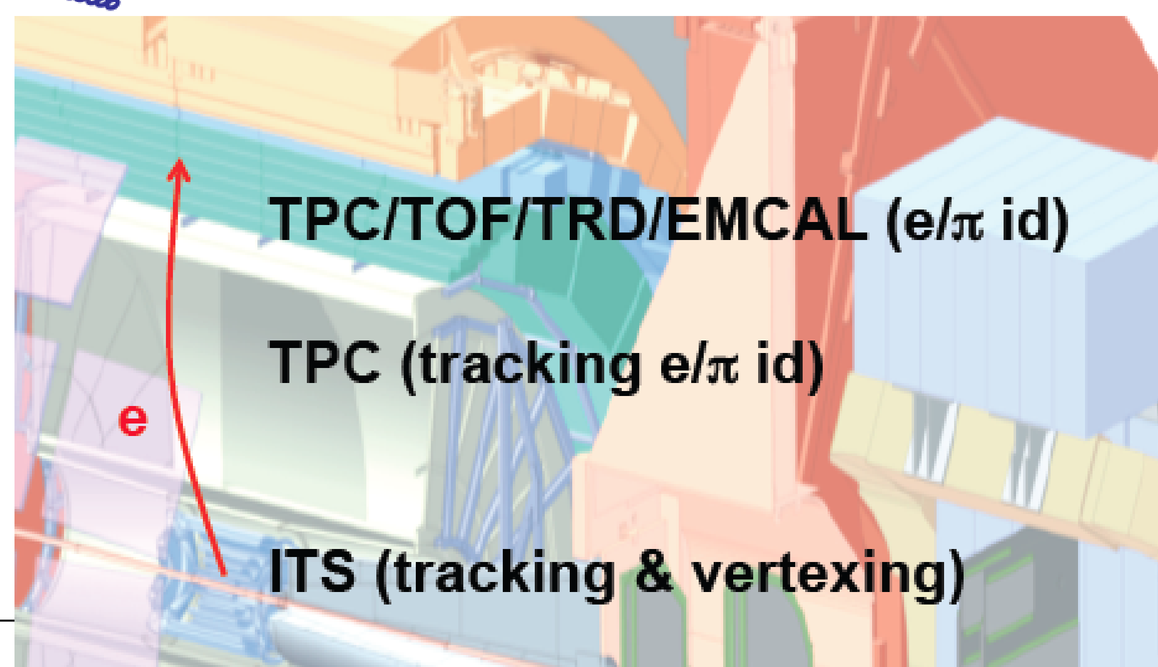
Semileptonic decays of open charm and open beauty hadrons:



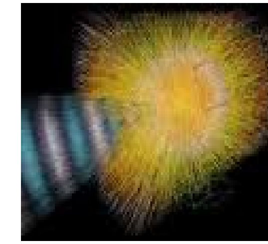
Branching Ratios:

$c \rightarrow e + X$	$\mathcal{O}$ (9.6%)
$b \rightarrow e + X$	$\mathcal{O}$ (11%)
$b \rightarrow c \rightarrow e + X$	$\mathcal{O}$ (10%)

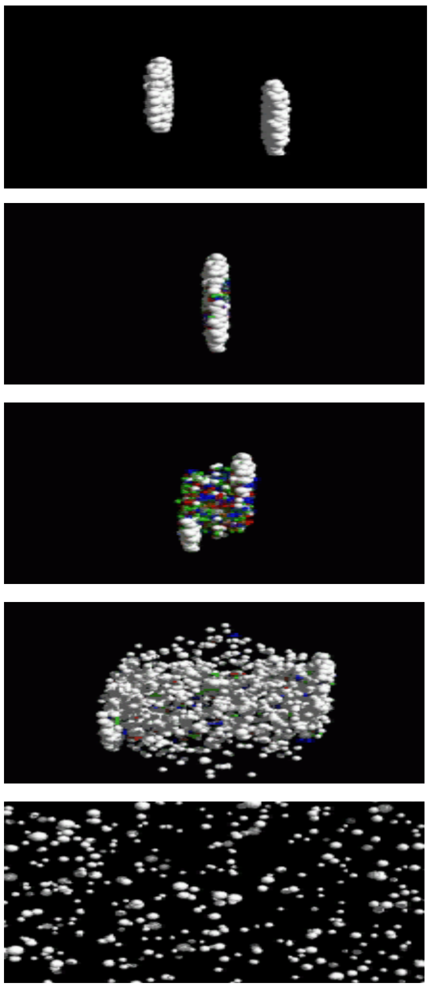
- **Electrons** at mid-rapidity
- **Muons** at forward rapidity



Phases of heavy ion collisions

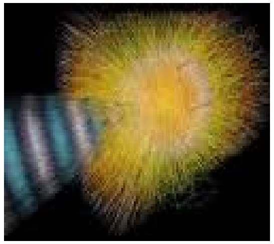


UrQMD 160 GeV Au+Au



- Before collision
- Compression and heating
- Thermalization: equilibrium is established (t < 1 fm/c)
- Expansion and cooling (t < 10-15 fm/c)
- Chemical freeze-out: inelastic collisions cease (number of particles frozen)
- Kinetic freeze-out: elastic collisions cease (particle momenta, spectra frozen)

Charged Particle Multiplicity

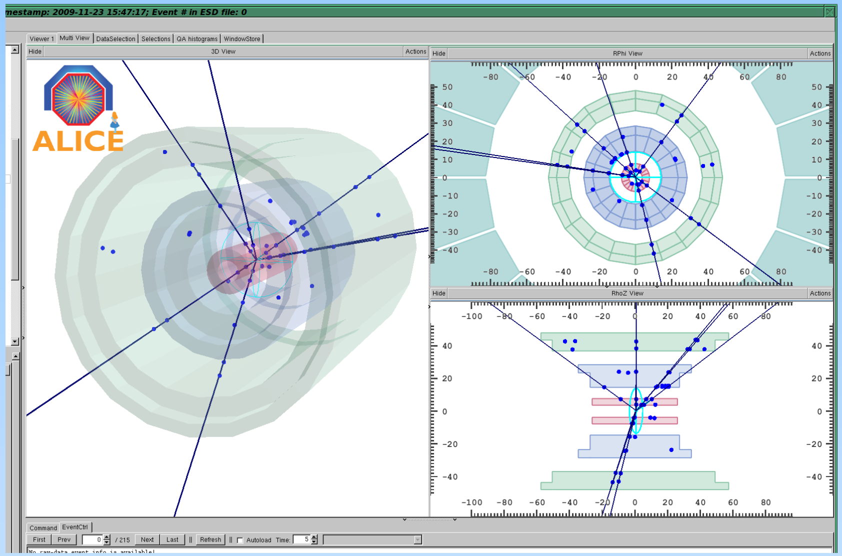


MOTIVATION

- Measure the global characteristics of hadron collisions
- Interactions dominated by soft processes

  - Study QCD in non-perturbative regime
  - Constrain phenomenological models
  - Give input to event generators
  - Understand background to hard and rare processes

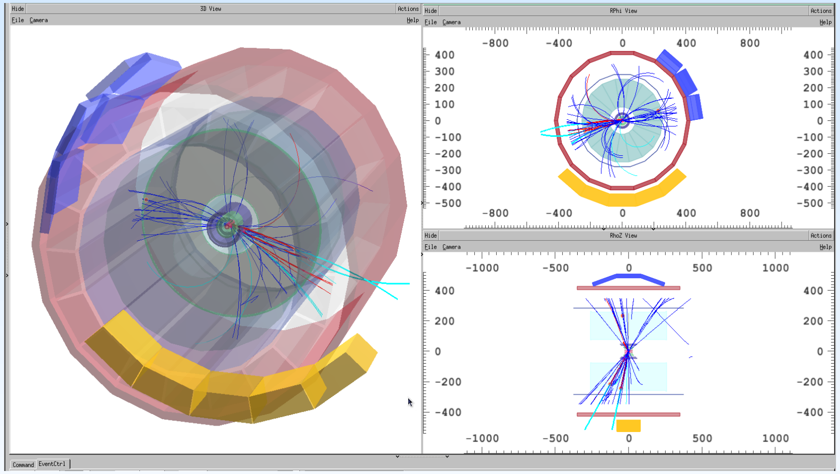
At LHC: scan over wide c.m. energy range and reach NOW!!! totally unexplored energy regimes !!



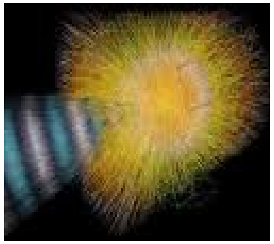
- **Multiplicity Measurement**

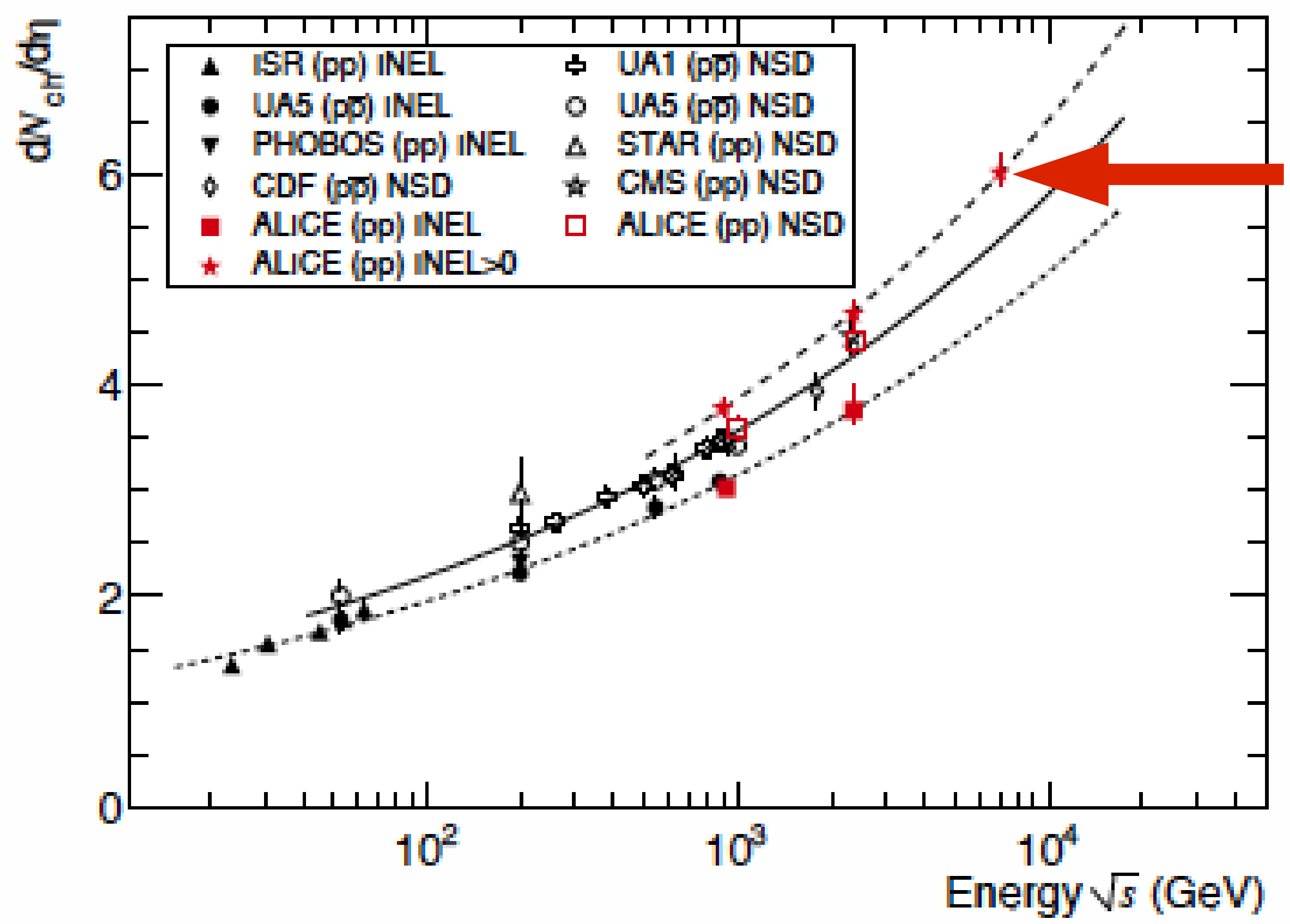
- **Transverse Momentum Distribution**

- **Identified Particle Spectra**



Pseudo-rapidity Density





* *INEL>0:* at least 1 track in |η|<1

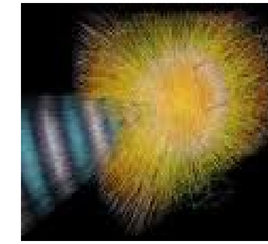
Lines: fit with a power-law dependence on energy

Increase of multiplicity with energy vs models!?

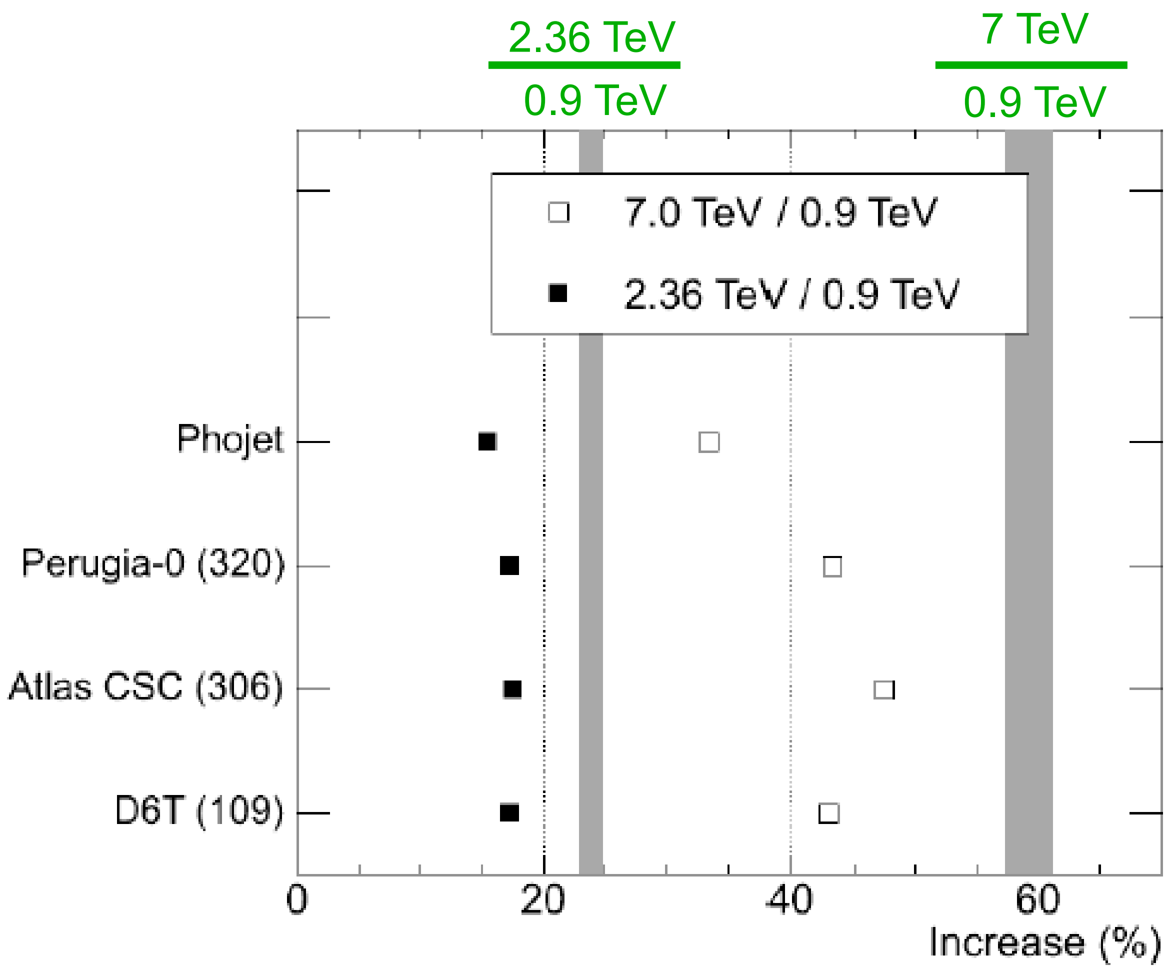
- INEL = non-diffractive + single-diffractive + double-diffractive
- NSD = non-single-diffractive

} in |η|<0.5

Multiplicity Increase with √s



ALICE measurements:



arXiv:1004.3514

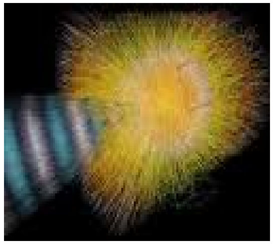
Relative increase of the charged particle pseudorapidity density (INEL>0 events)

compared to various models

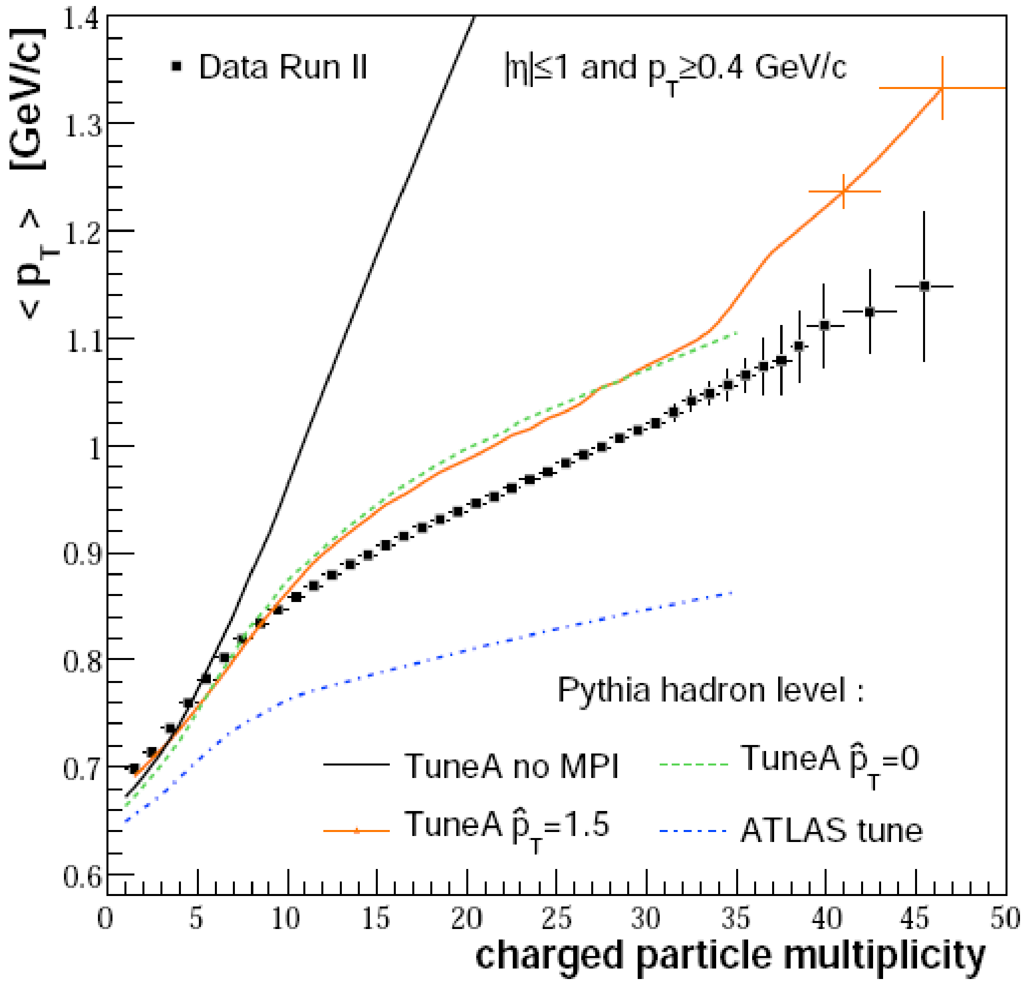
Increase with energy FASTER than in any model considered !!!

59.1% ± 0.4% (stat) $^{+2.1}_{-1.8}$ % (syst)

Transverse Momentum Spectrum



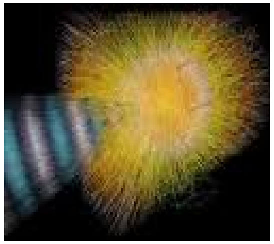
CDF: Phys. Rev. D 79/2009, 112005

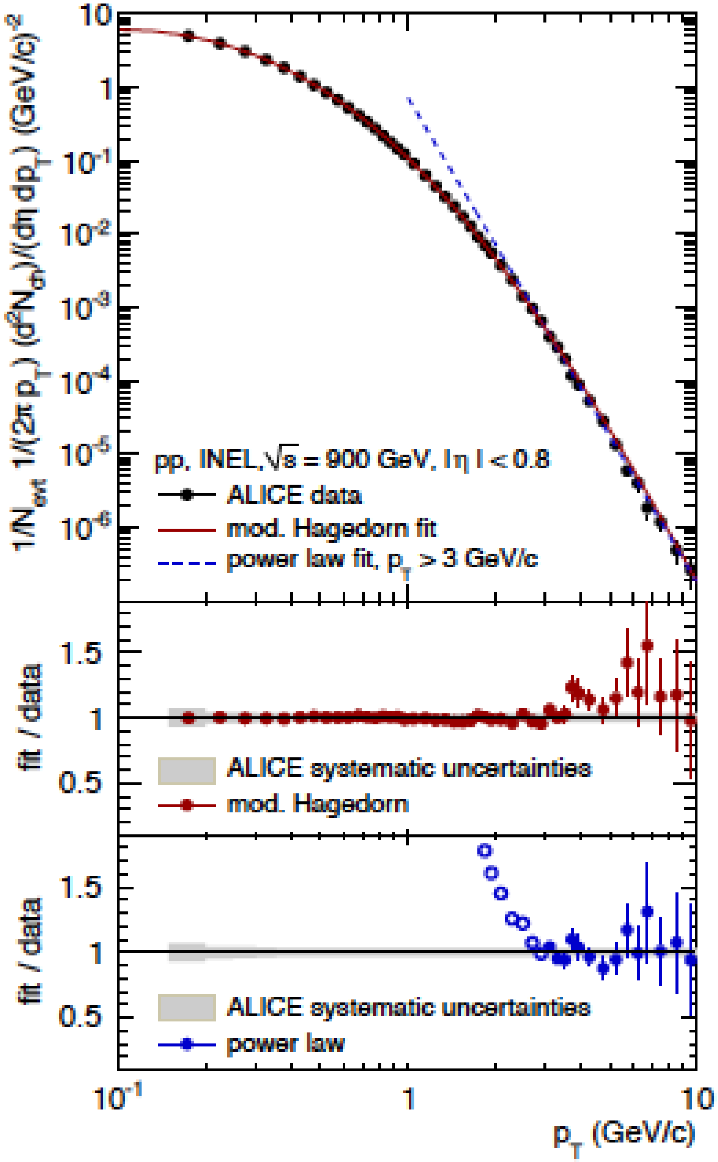


- Bulk (multi)particle production remains a challenge for (non-perturbative) QCD
- Transverse momentum spectra for multiplicity classes and as a function of energy are crucial tests of soft QCD understanding
- pp data as reference for hot and dense QCD matter produced in Pb+Pb
- ...or dense QCD in pp? (collective flow in high-multiplicity events)

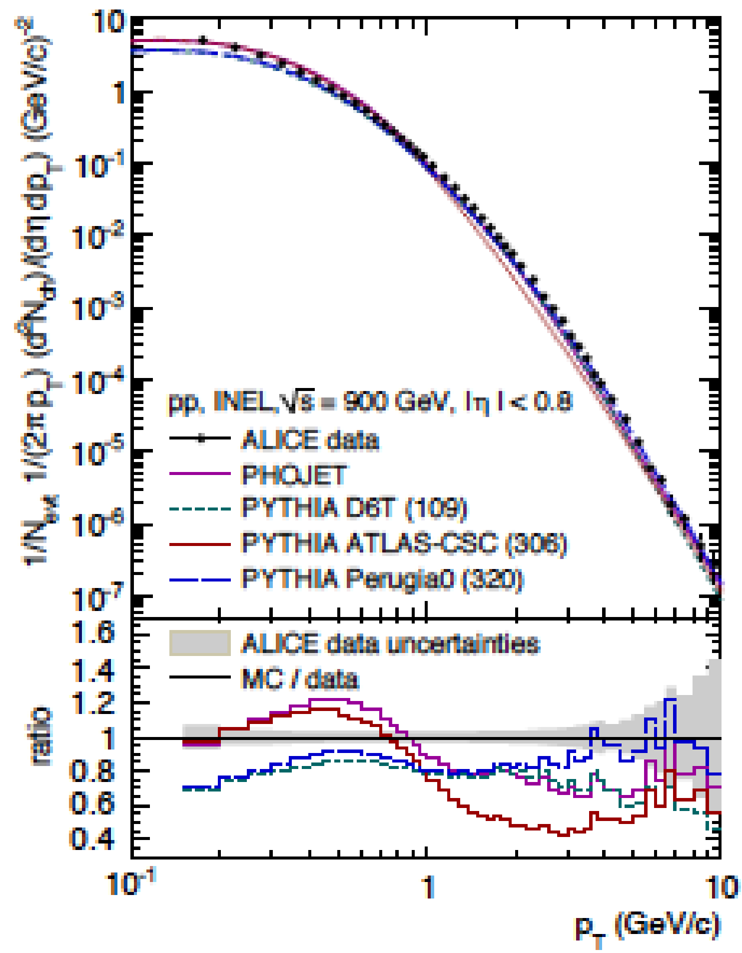
→ Track p_T spectrum !

Transverse Momentum Spectrum

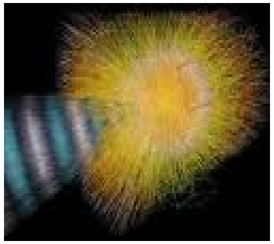




And comparison to models:

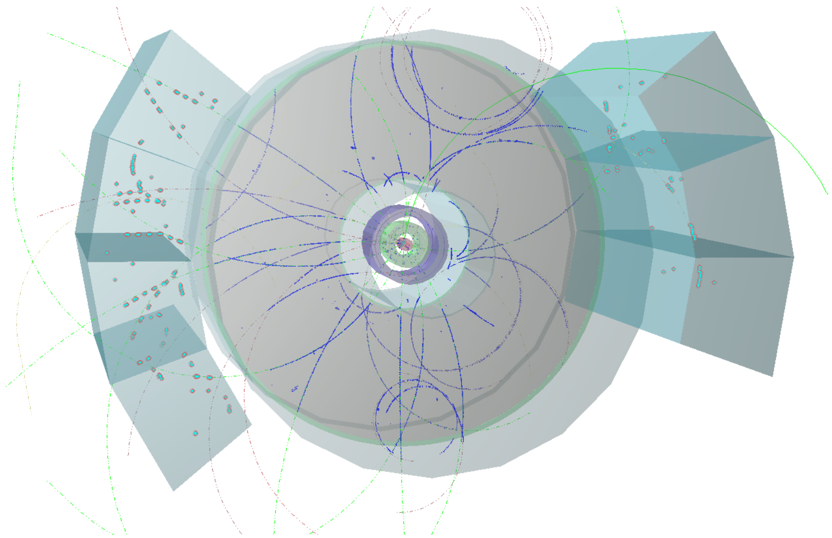


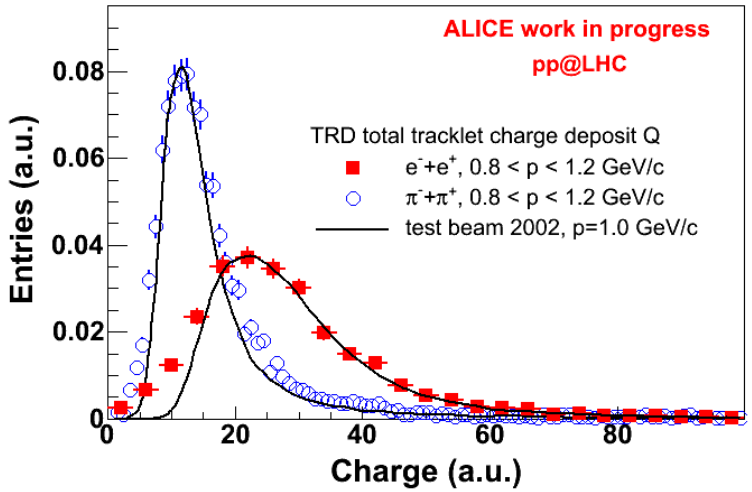
Identified Electrons

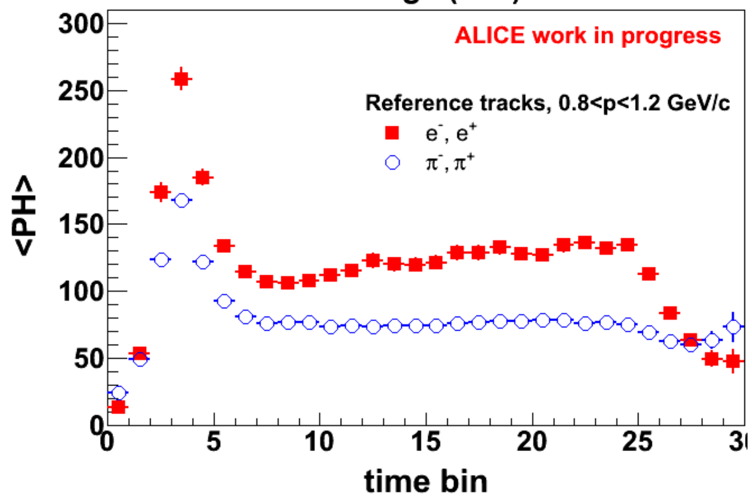


Transition Radiation Detector

- **Electron/pion discrimination**
- **Electron trigger**
  (high pT, particle ID)







From an inclusive electron spectrum (cocktail subtracted) we will measure the charm and beauty production cross sections