ALICE@LHC
A Large Ion Collider Experiment

- A short History of Heavy Ions
- ALICE Experiment
- First Results from the Ion Run

Progress of Accelerators

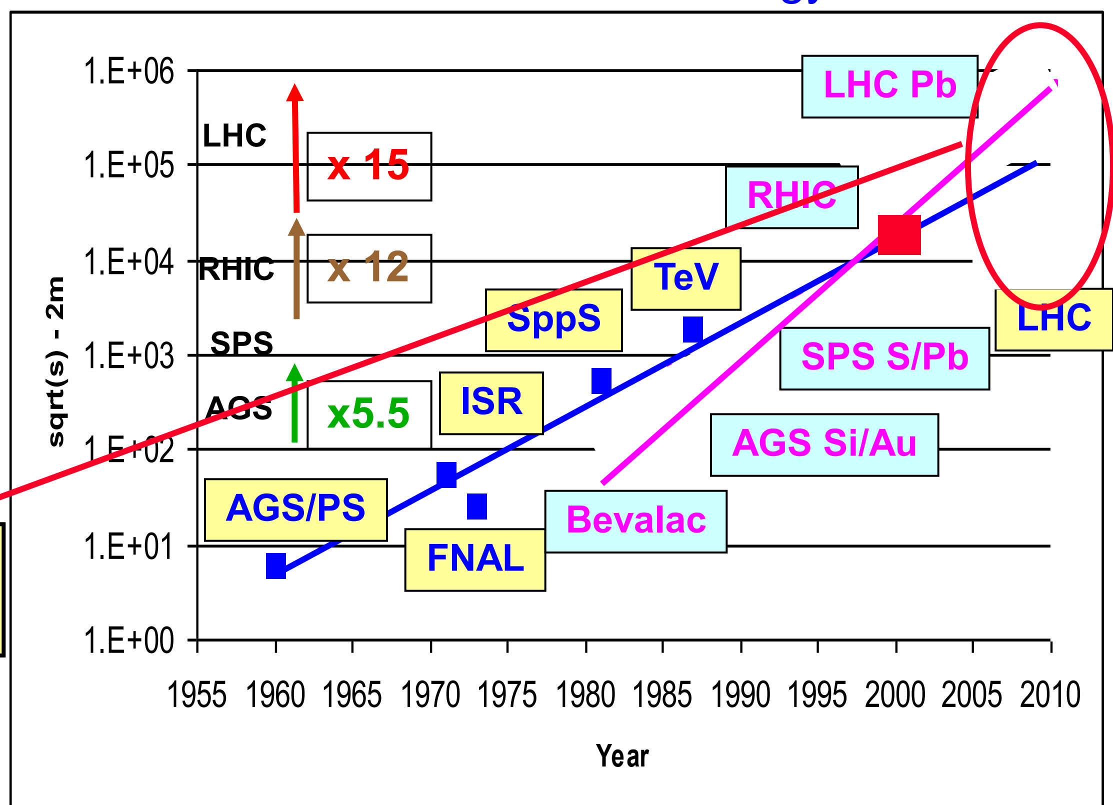
- **Particle Physics: energy doubling time ~ 4 years**
- **Heavy Ion Physics: doubling time ~ 2 years**
  - ⇨ energy increase by factor 10^4 in ~ 30 years
  - ⇨ starting 70'- to early 80's at Bevalac (LBNL Berkeley USA)
    - ✪ field started by a few dozen physicists from a handful of countries
    - ✪ > 2000 physicists active worldwide today

Possible mostly by (re-) using particle physics machines.

Field went from the periphery into a **central activity** of contemporary **Nuclear Physics**
(and now gets even some HEP guys excited !)

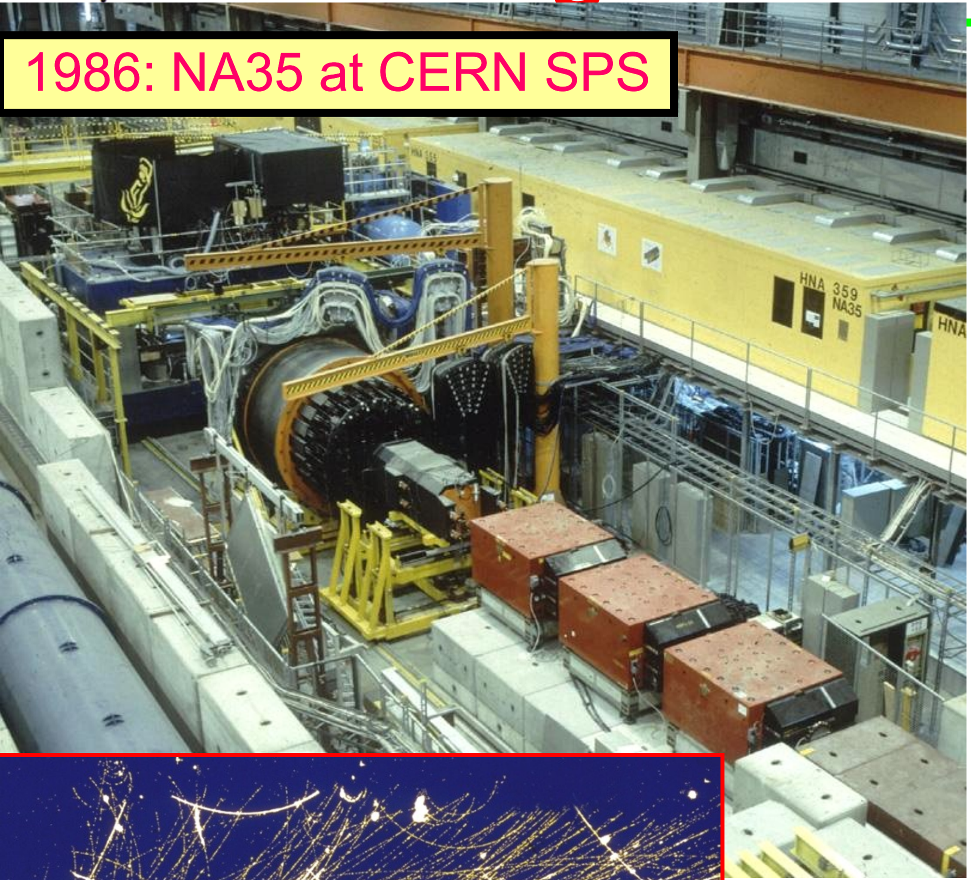
LHC: At the Energy Frontier of both Nuclear and High Energy Physics

Total center-of-mass energy versus time

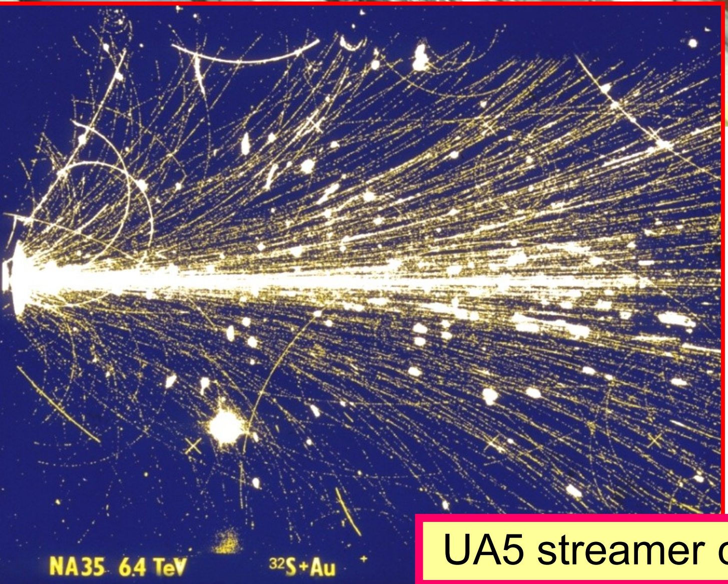


Progress of Experiments

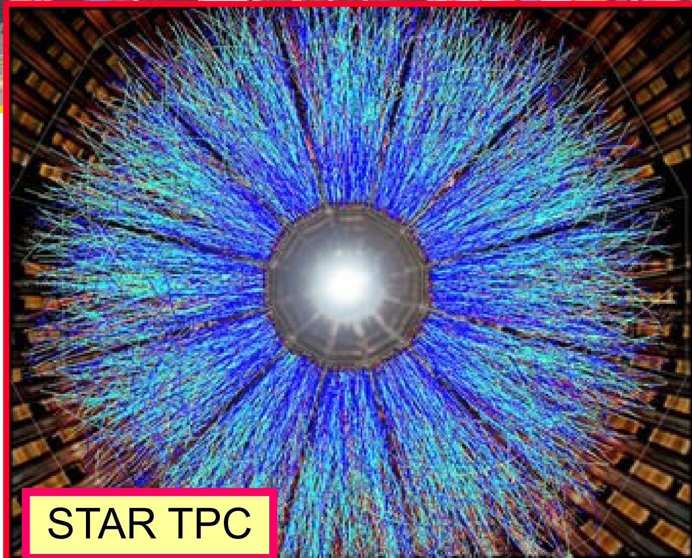
1986: NA35 at CERN SPS



2000: STAR at BNL RHIC



UA5 streamer chamber used in NA35

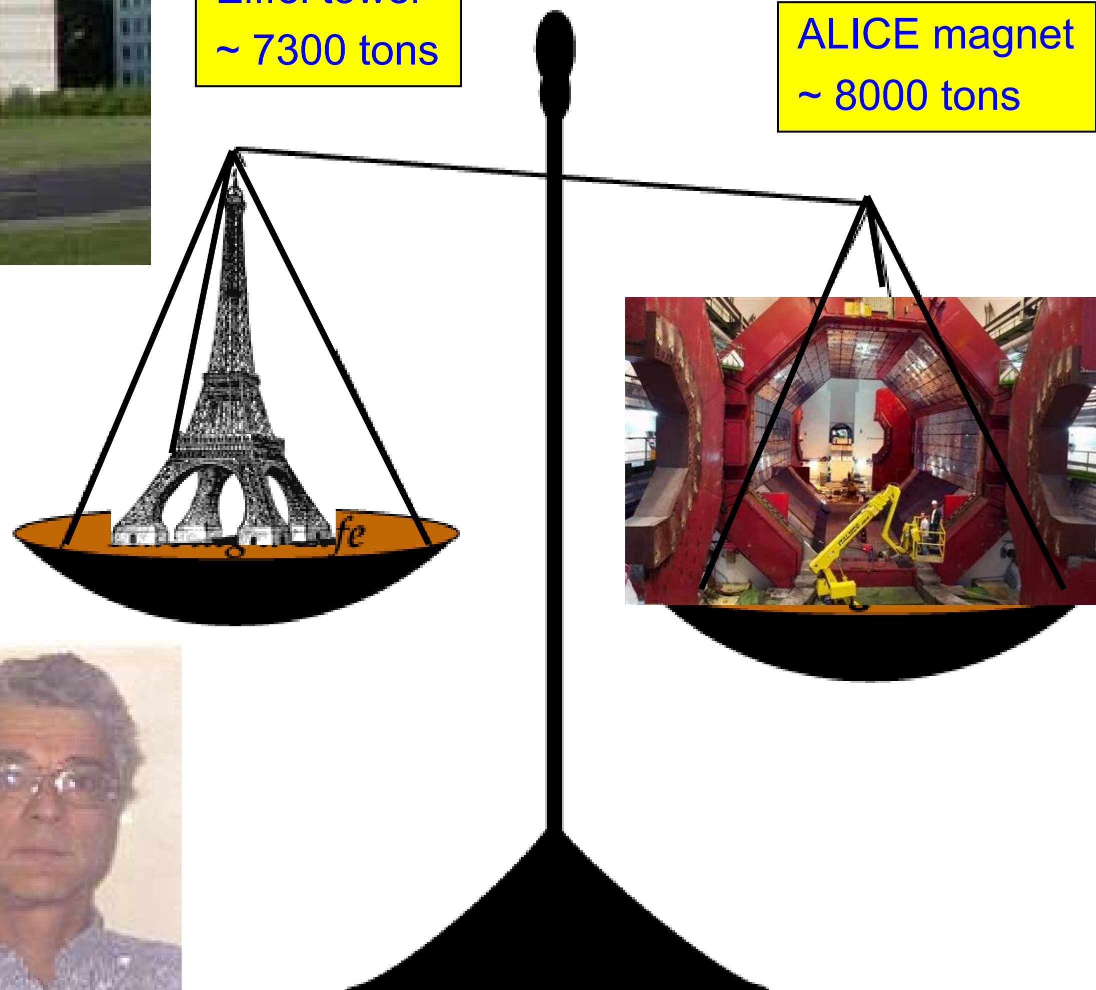


STAR TPC

Experiments at LHC are

- ⇨ **Big**
- ⇨ **Heavy**
- ⇨ **and took a looong time …**

ATLAS superimposed to the 5 floors of building 40

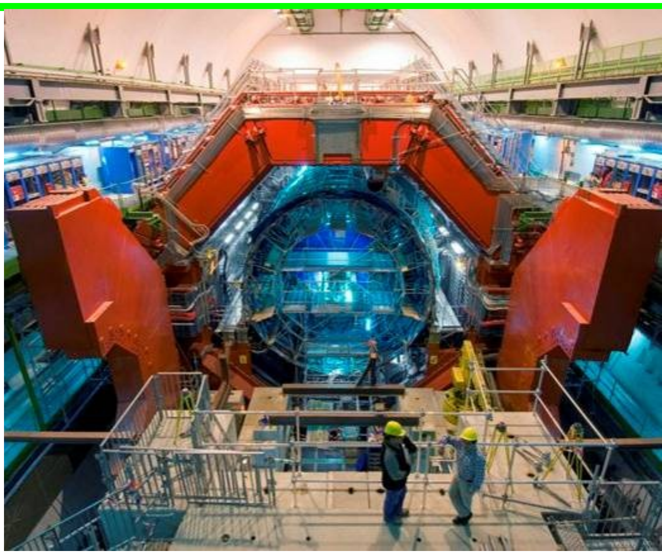


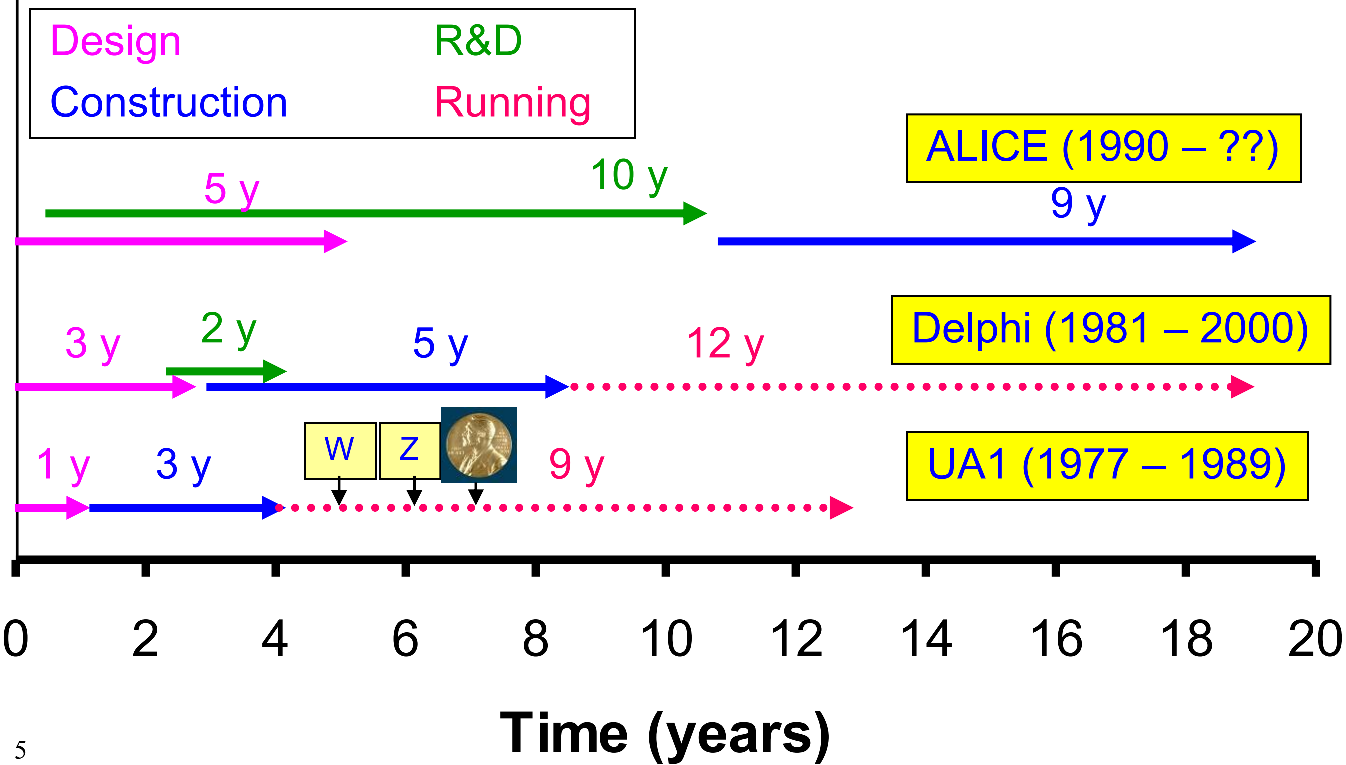
Eiffel tower ~ 7300 tons

ALICE magnet ~ 8000 tons

1990 → 2007

The Life of Collider Experiments





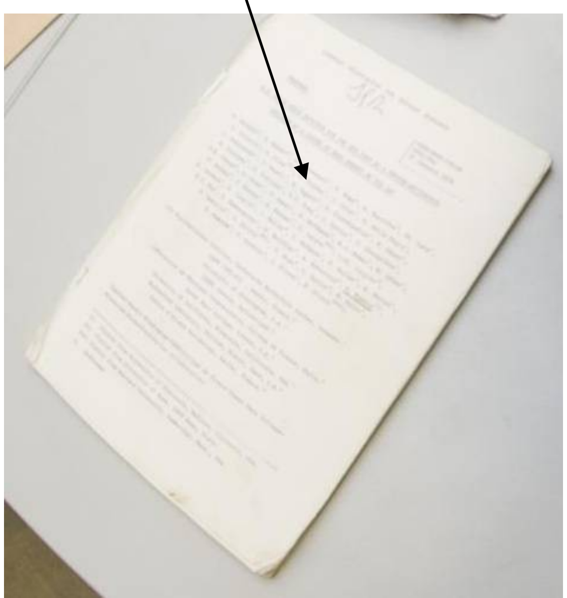
Paper and Committee work..

UA1 proposal (154 p.)
sub. Jan '78, approved June '78

Delphi LoI, TP, 7 Addenda (500 p.)

Alice:
EoI
LoI + 1 Add
TP + 3 Add
12 TDR's + 3 Add
3 Vol PPR

4422 p.



ALICE R&D

1990-2002:Strong, well organized, well funded R&D activity

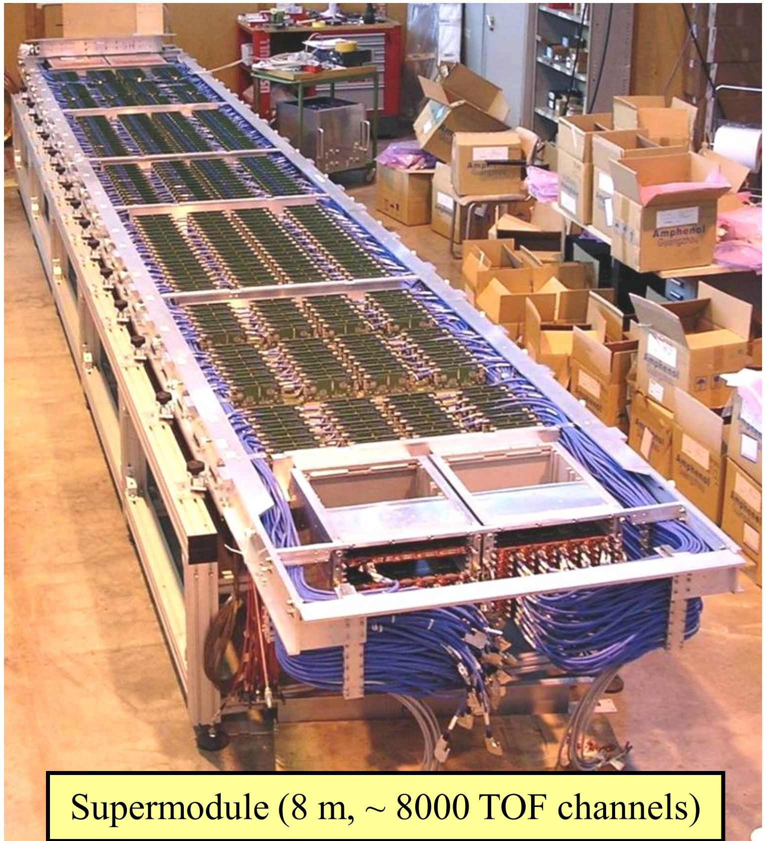
- Inner Tracking System (ITS)
  - ⇨ Silicon Pixels (RD19)
  - ⇨ Silicon Drift (INFN/SDI)
  - ⇨ Silicon Strips (double sided)
  - ⇨ low mass, high density interconnects
  - ⇨ low mass support/cooling
- TPC
  - ⇨ gas mixtures (RD32)
  - ⇨ new r/o plane structures
  - ⇨ advanced digital electronics
  - ⇨ low mass field cage
- em calorimeter
  - ⇨ new scint. crystals (RD18)
- PID
  - ⇨ Pestov Spark counters
  - ⇨ Parallel Plate Chambers
  - ⇨ Multigap RPC's (LAA)
  - ⇨ low cost PM's
  - ⇨ CsI RICH (RD26)
- DAQ & Computing
  - ⇨ scalable architectures with COTS
  - ⇨ high perf. storage media
  - ⇨ GRID computing
- misc
  - ⇨ micro-channel plates
  - ⇨ rad hard quartz fiber calo.
  - ⇨ VLSI electronics

- **R&D made effective use of long (frustrating) wait for LHC**
- **was vital for all experiments to meet LHC challenge !**

Time of Flight Detectors

- aim: state-of-the-art TOF
  - ⇨ requirements: area > 150 m^2, channels ~ 150,000
  - ⇨ 2 orders of magnitude bigger any other existing TOF array !
- challenge
  - ⇨ state of the art time resolution **σ < 100 ps** (~ 3 cm at speed of light !)
  - ⇨ at **< 1/10 of the cost** of existing solutions (~ 150 M$)
- after 5 years of R&D and many dead ends
  - ⇨ eg 'Pestov Spark counters', 'Parallel Plate Chambers'
  - ⇨ new technology (‘**Multigap** Resistive Plate Chambers’)
  - ⇨ **σ ~ 50 ps, ‘cheap’**
  - ⇨ very simple & robust construction/operation

found immediate wide use:
HARP, STAR,PHENIX, HADES/CBM@GSI,..
option for time-stamping at ILC/CLIC
medical application (PET scanner) under development



Supermodule (8 m, ~ 8000 TOF channels)

HI @LHC: Constraints and Solutions

- Extreme particle density : $dN_{ch}/d\eta$ expected ~ 2000 – 4000

  x 500 compared to pp@LHC; x 30 compared to ^{32}S@SPS

⇨ high granularity, 3D detectors

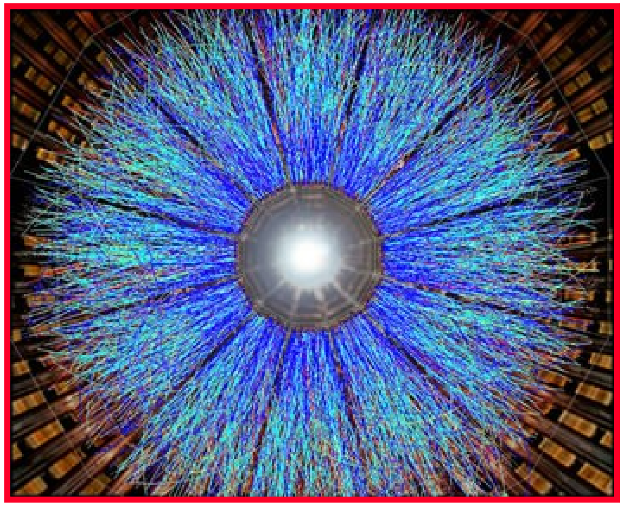
- Silicon **pixels** and **drift** detectors, **TPC** with low diffusion gas mixture (Ne-CO_2)

⇨ conservative & redundant tracking

- up to ~**200 space points** per track

⇨ large distance to vertex

- e.g. emcal at **4.5 m** (typical is 1-2 m !)



- Large dynamic range in momentum p_t:

  from very soft (**0.1 GeV**) to fairly hard (**100 GeV**)

⇨ very thin detector, modest field **0.5 T** (low p_t),

- ALICE: **~ 10%X_0** in r < 2.5 m (typical is 50-100%X_0) (10%X_0 ≈ 1.5 mm of Cu)

⇨ large lever arm + good hit resolution (large p_t)

- B= **0.5T**, tracking **L ~ 3.5m**, **BL^2** ~ like CMS !

HI @LHC: Constraints and Solutions

- **Both partons & hadrons matter:**

fragmentation (i.e. hadrons) is part of the signal, not of the problem

⇨ partons (heavy quarks): secondary **vertices**, lepton ID

⇨ hadrons: use of essentially all known **PID** technologies

✪ dE/dx, Cherenkov & transition rad., TOF, calorimeters, muon filter, topological

- **Modest Luminosity and interaction rates; short runs**

10 kHZ (Pb-Pb), (< 1/10000 of pp@10^{34}) ~ 1 month/year

⇨ allows slow detectors (TPC, SDD), moderate radiation hardness

✪ moderate trigger selectivity, no pipelines (mostly 'track & hold' electronics)

⇨ large event size (~ 100 MB) + short runs => high throughput DAQ (> 1GB/s)

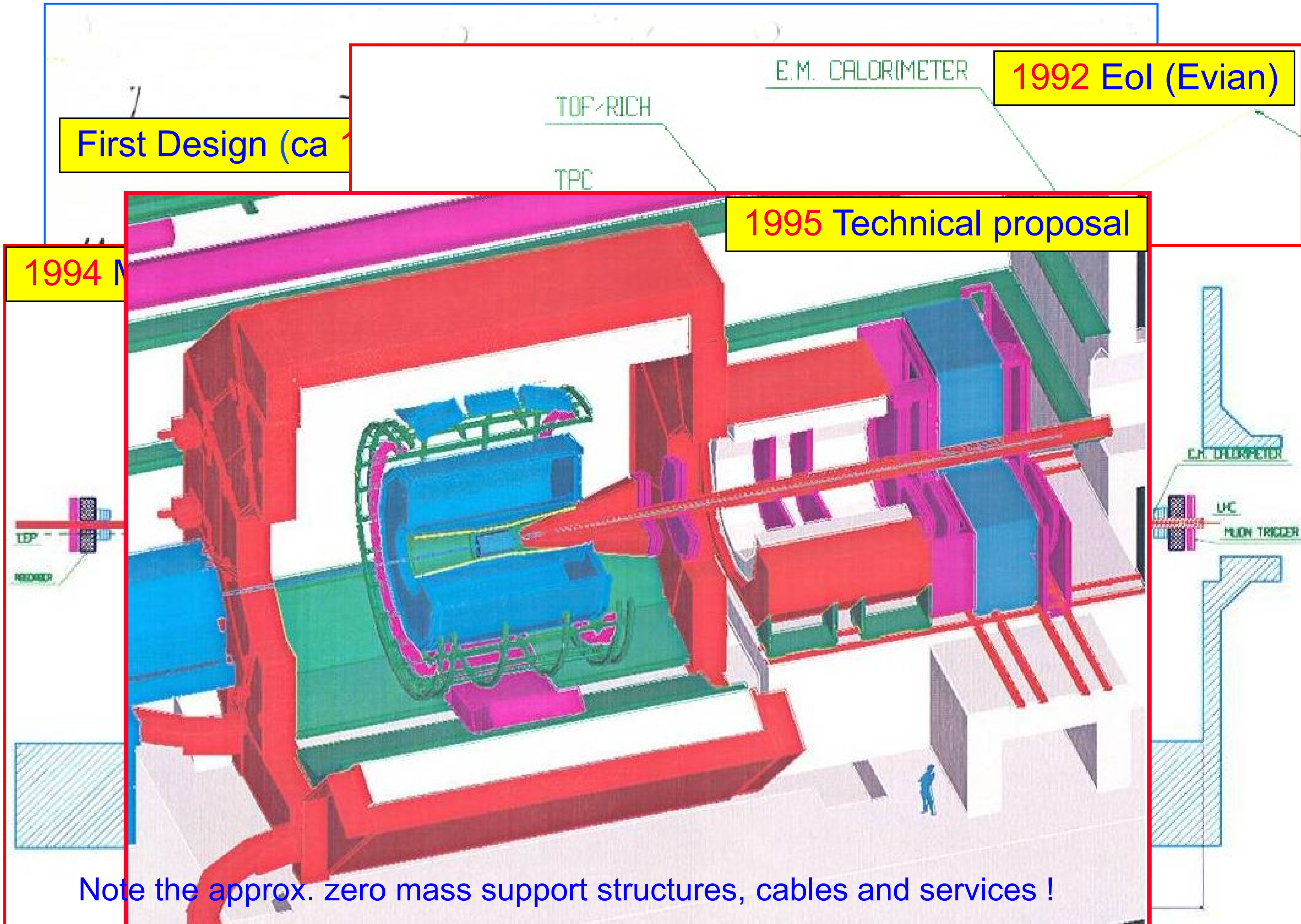
- **Single dedicated heavy ion experiment**

combine capabilities of a handful of more specialized HI expts at AGS/SPS/RHIC

✪ 18 detector technologies, several smaller 'special purpose' detectors (HMPID, PHOS, PMD, FMD, ZDC..)

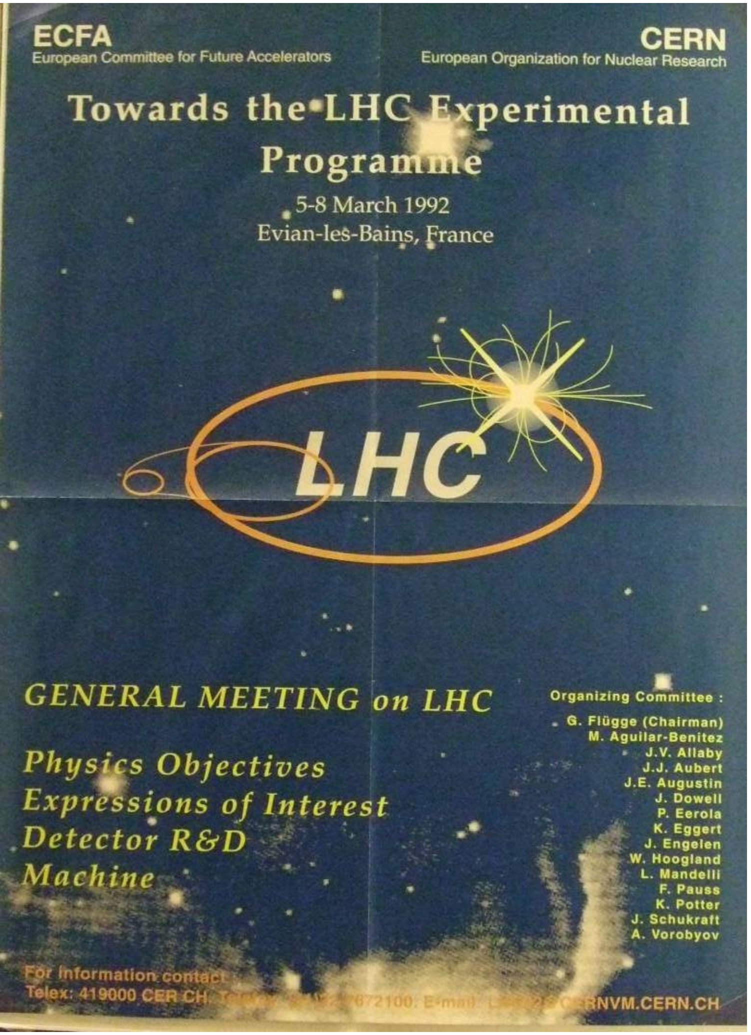
✪ central barrel + forward muon arm

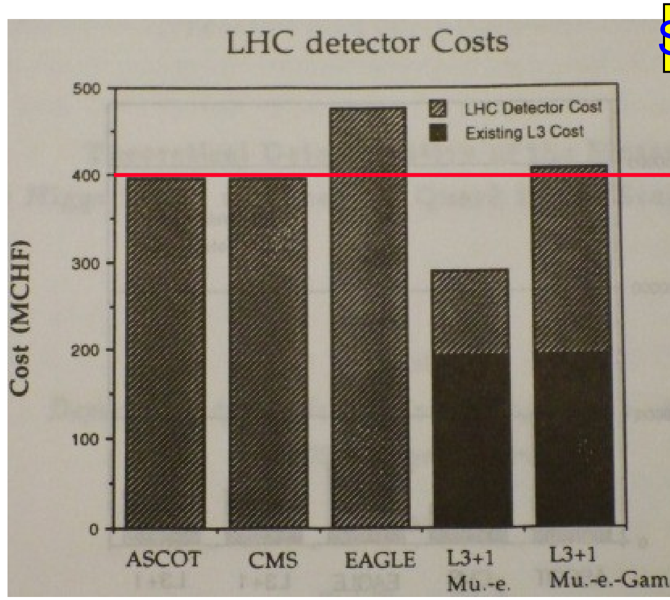
Early ALICE Designs



Note the approx. zero mass support structures, cables and services !

Evian Workshop 1992





Summary by C. Rubbia:

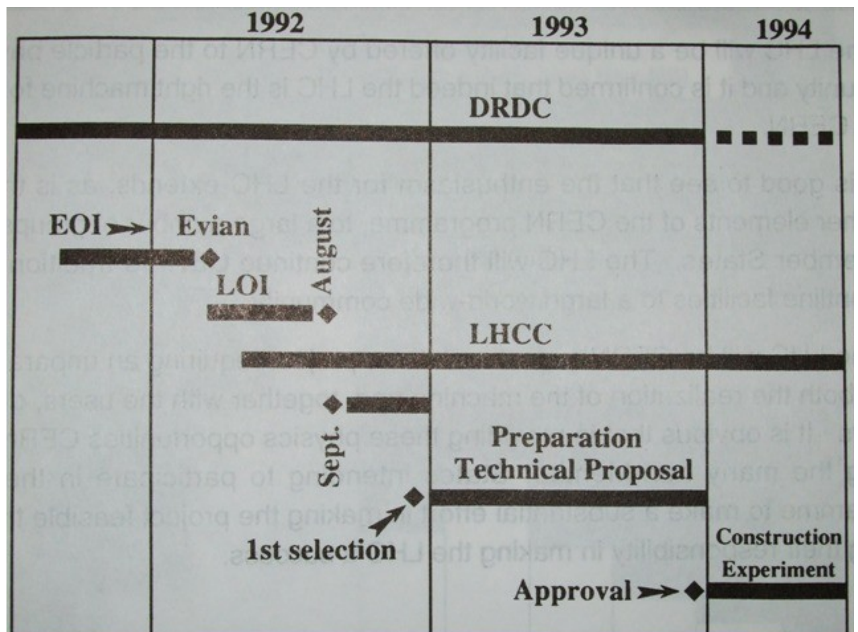
Ascot = 395 M

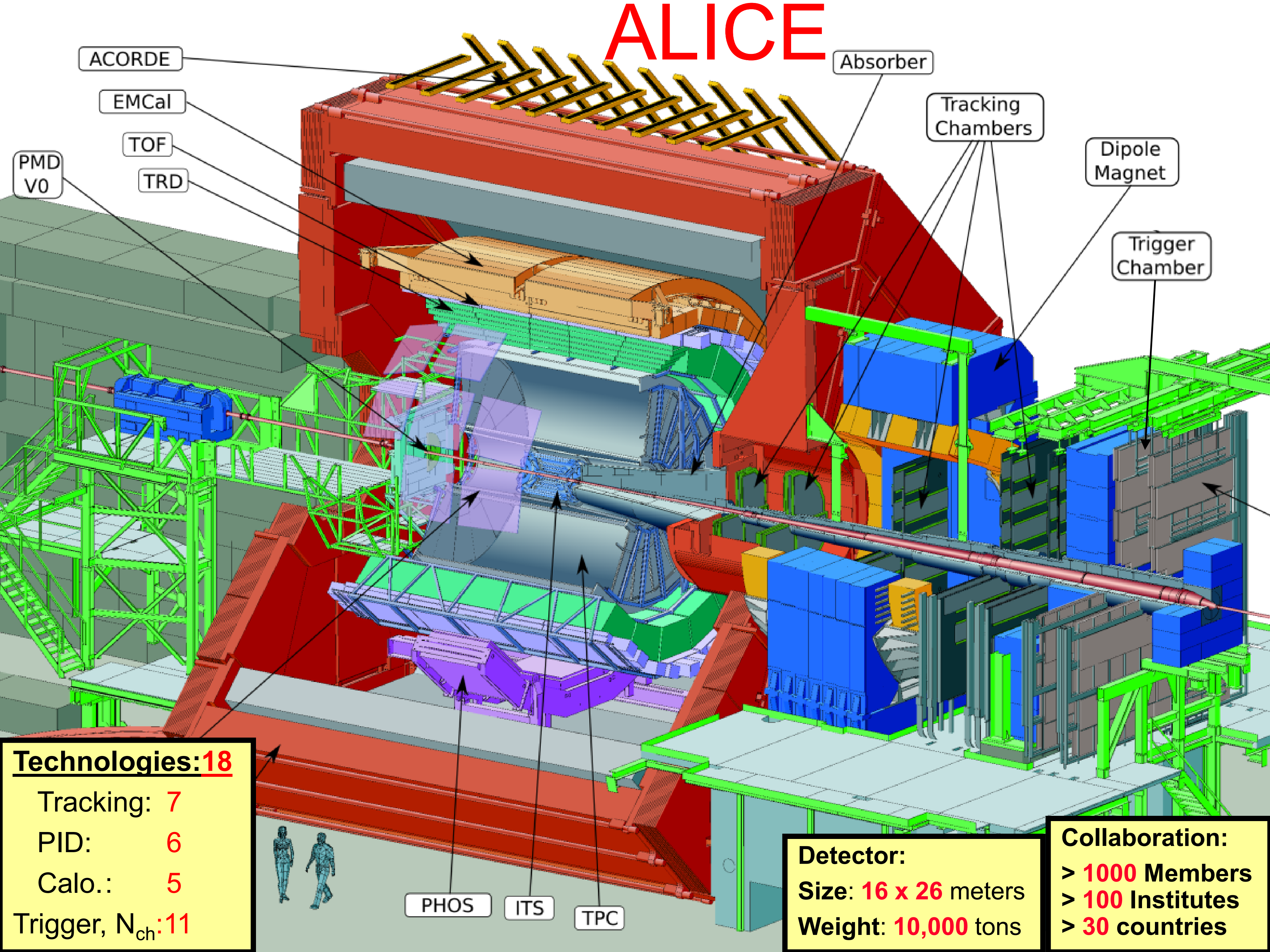
CMS = 395 M

ALICE = 395M

Construction: '94

1st beam: '98



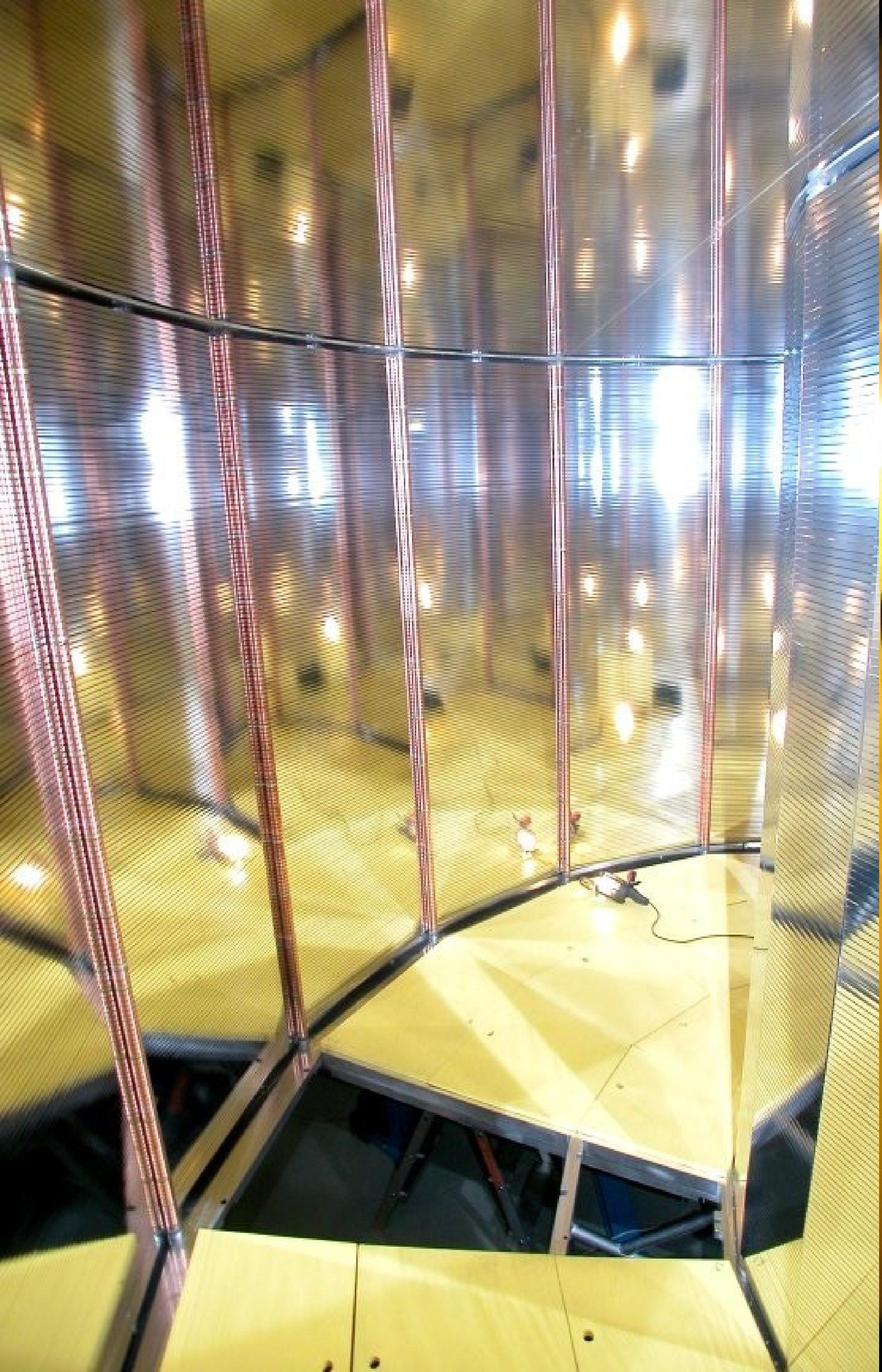


ALICE
ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Trigger Chamber
PHOS
ITS
TPC
Technologies: 18
Tracking: 7
PID: 6
Calo.: 5
Trigger, N$_{ch}$: 11
Detector:
Size: 16 x 26 meters
Weight: 10,000 tons
Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

Time Projection Chamber TPC

~ 5 m length, 5.6 m diamter, 90 m^3

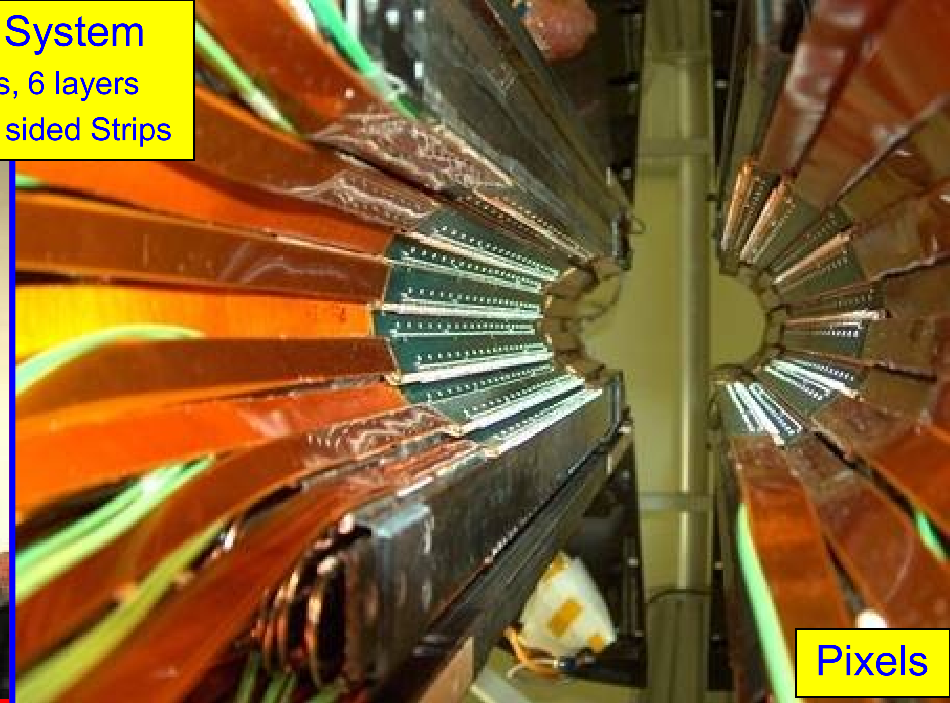
500 x 10^6 3D space points

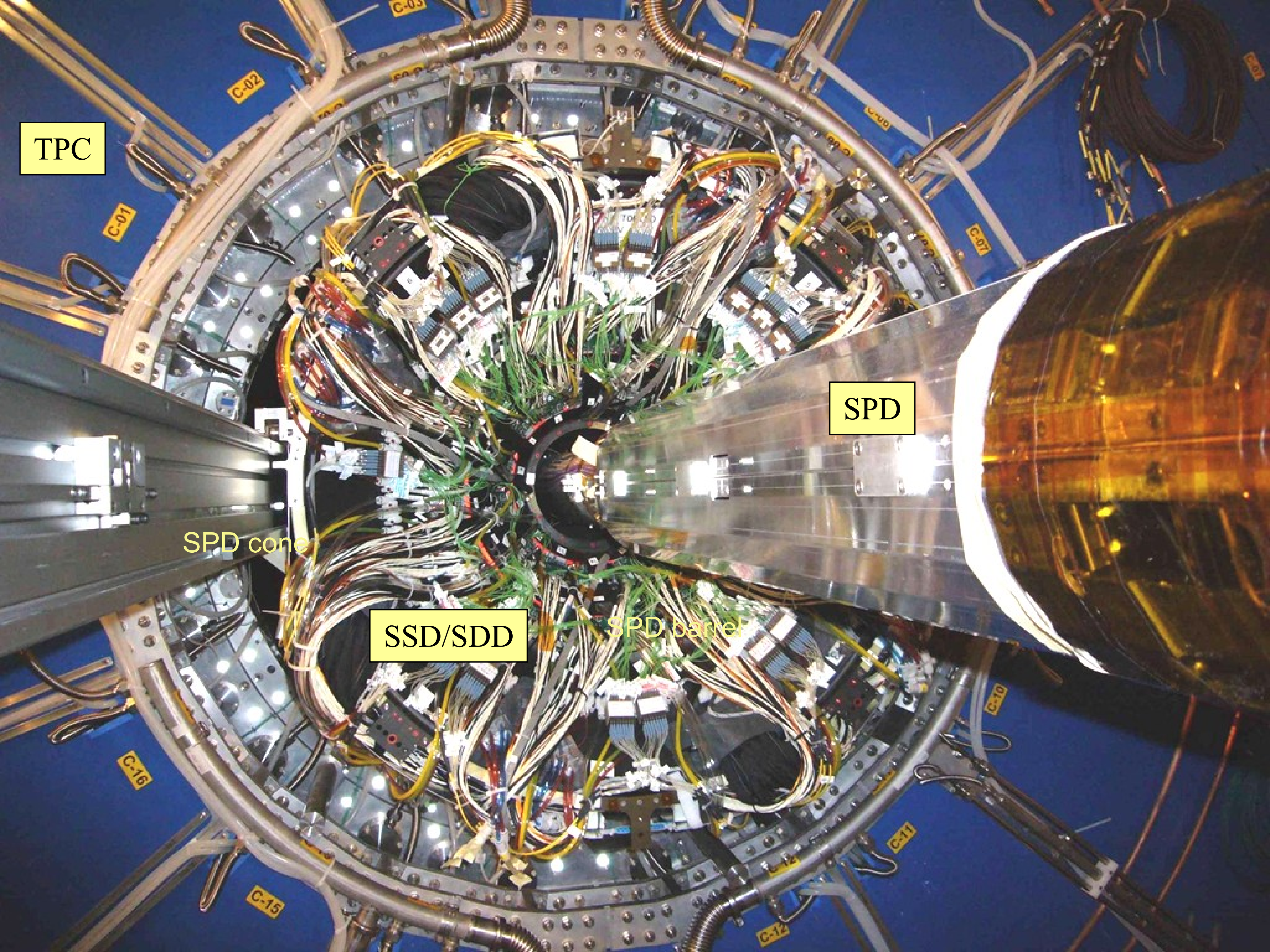



Inner Tracking System

~ 10 m^2 Si detectors, 6 layers

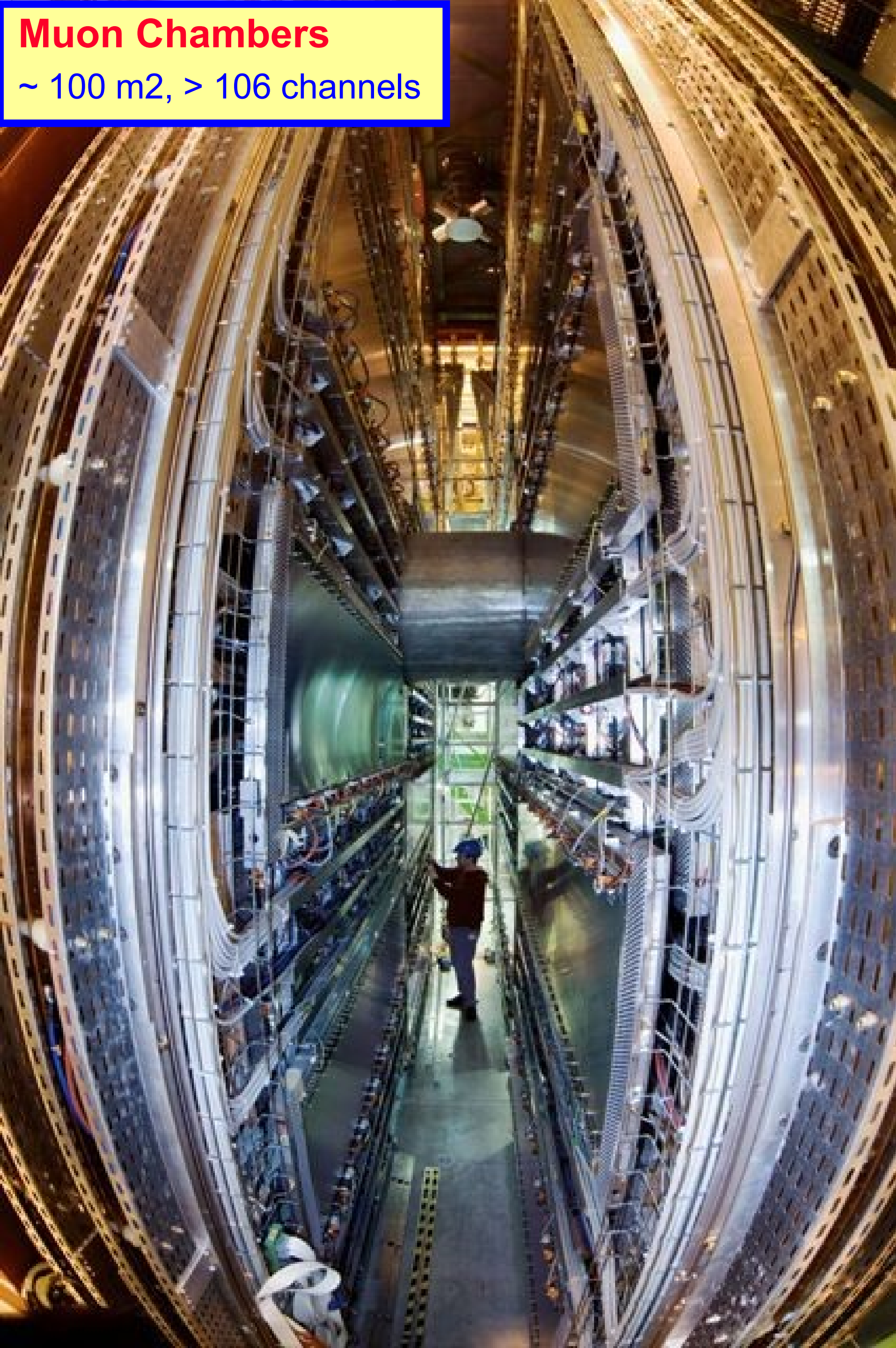
Pixels, Drift, double sided Strips




TPC
SPD
SPD cone
SSD/SDD
SPD barrel

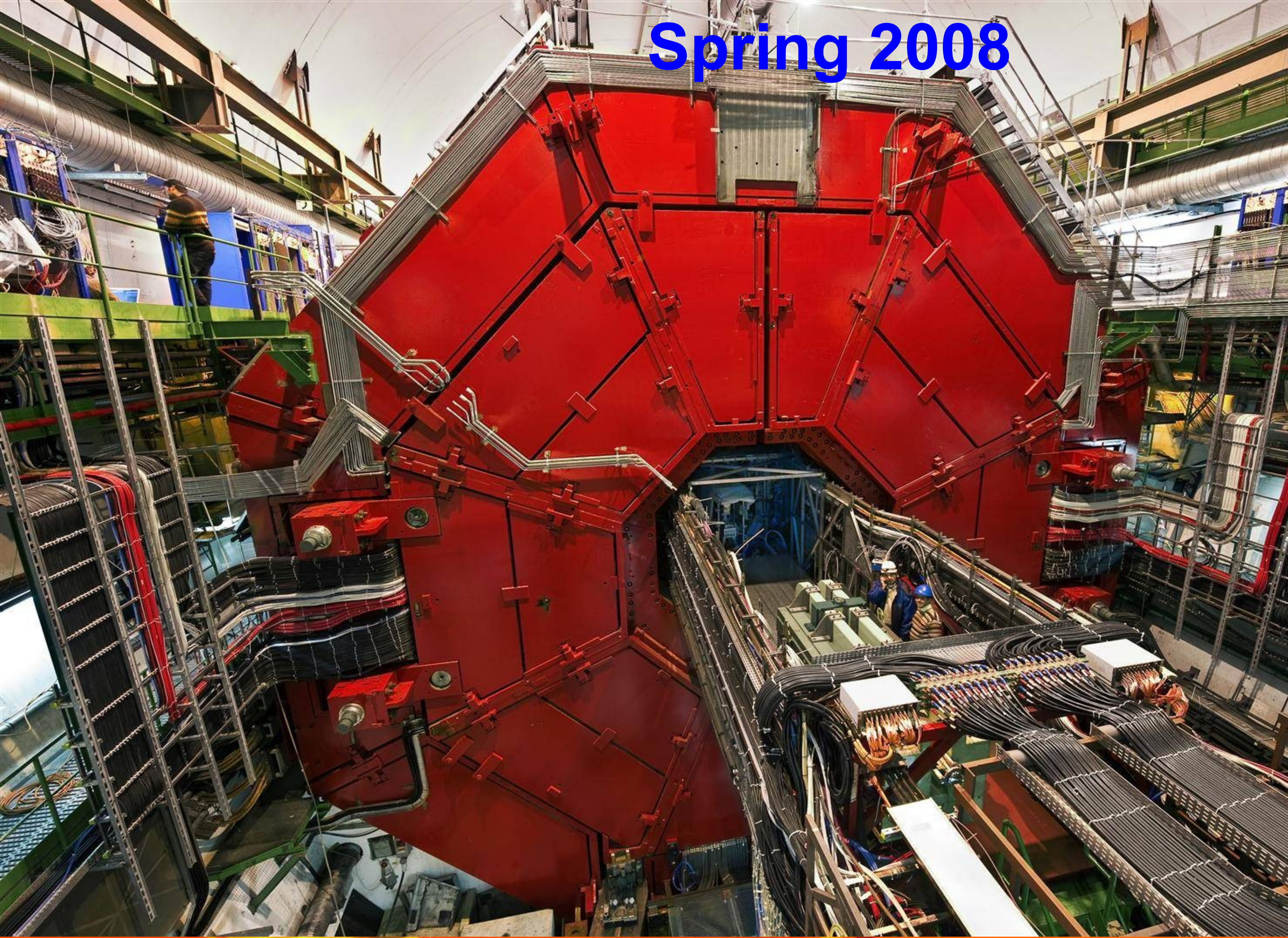
Muon Chambers

~ 100 m2, > 106 channels



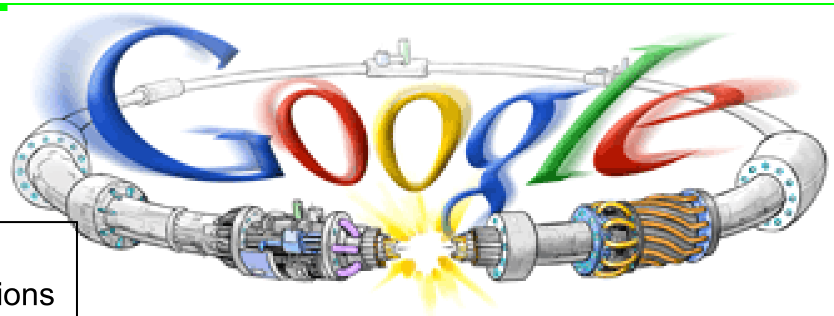
PMD

Spring 2008



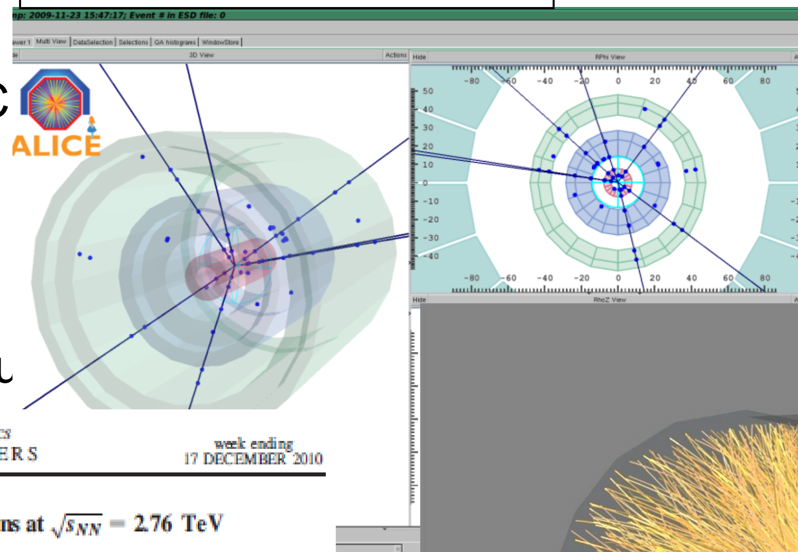
Fast Forward to

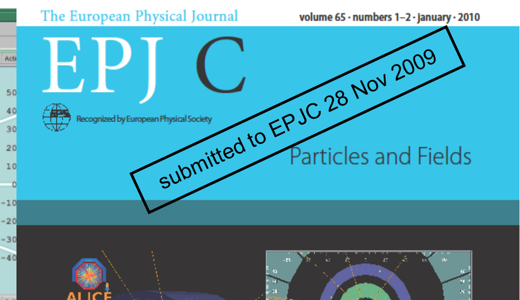
- September 2008:
  - ⇨ LHC starts with a ‘Big Bang’



23rd November, ~16:41
One of the very first LHC collisions
pp at 900 GeV

- November 2009:
  - ⇨ Start of Physics @ LHC





- November 2010:
  - ⇨ First Pb-Pb heavy ion ru

Selected for a Viewpoint in *Physics*
PRL 105, 252302 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

K. Aamodt *et al.**
(ALICE Collaboration)
(Received 18 November 2010; published 13 December 2010)

Physics 3, 105 (2010)
DOI: 10.1103/Physics.3.105

A “Little Bang” arrives at the LHC

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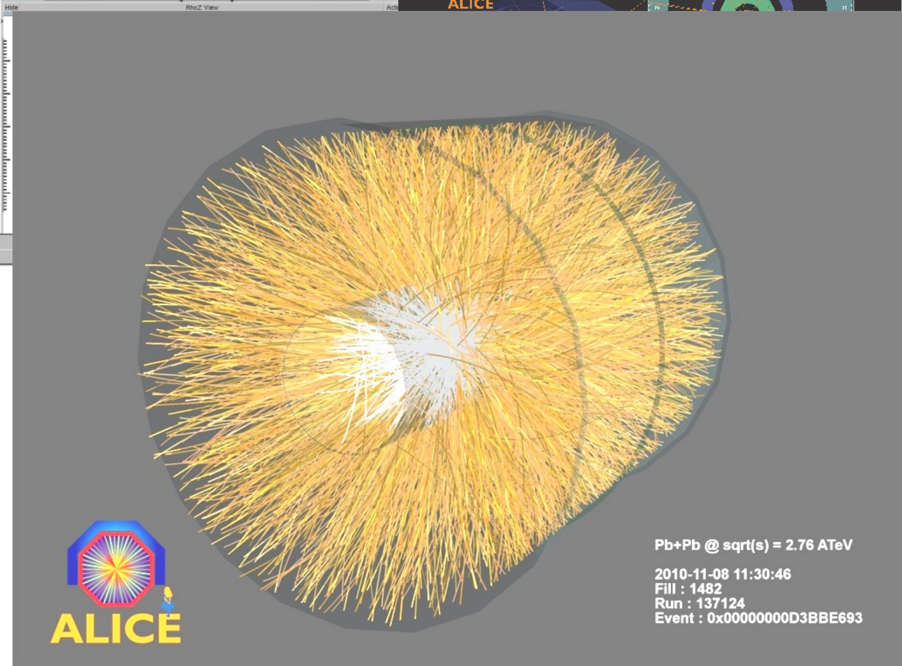
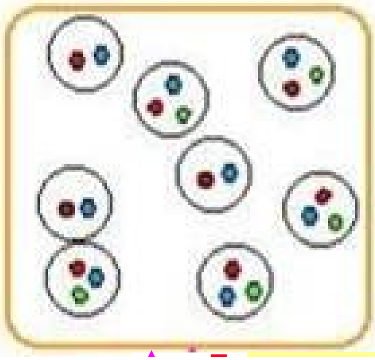
Published December 13, 2010

The first experiments to study the quark-gluon plasma at the LHC reveal that even at the hottest temperatures ever produced at a particle accelerator, this extreme state of matter remains the best example of an ideal liquid.



Heavy Ion Physics at the LHC



Hadronic Matter

ε(nucleus) ≈ 0.15 GeV/fm^3
ε(proton) ≈ 0.3 GeV/fm^3
q's confined
q's large effective mass
m_u,m_d ≈ 1/3 m_p ≈ 300 MeV
m_s ≈ 500 MeV

Phase Transition

composite hadrons 'melt'

Quark Gluon Plasma

ε_c > 1 - 2 GeV/fm^3
ρ_c ≈ 5 - 10 ρ(nucleus)
q's are deconfined
chiral symmetry restored
m_u ≈ m_d ≈ few MeV
m_s ≈ 150 MeV

Matter under extreme conditions

QCD prediction:

increase energy density (T, P)

→

new state of matter

QGP:

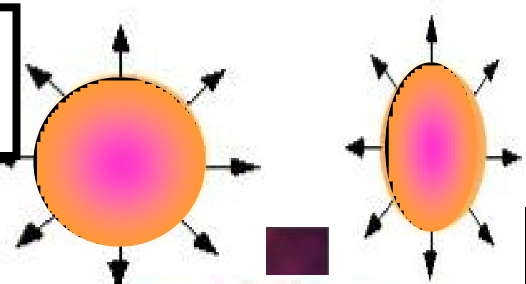
The 'primordial' state of matter
in the early Universe
(at high Temperature & energy density)

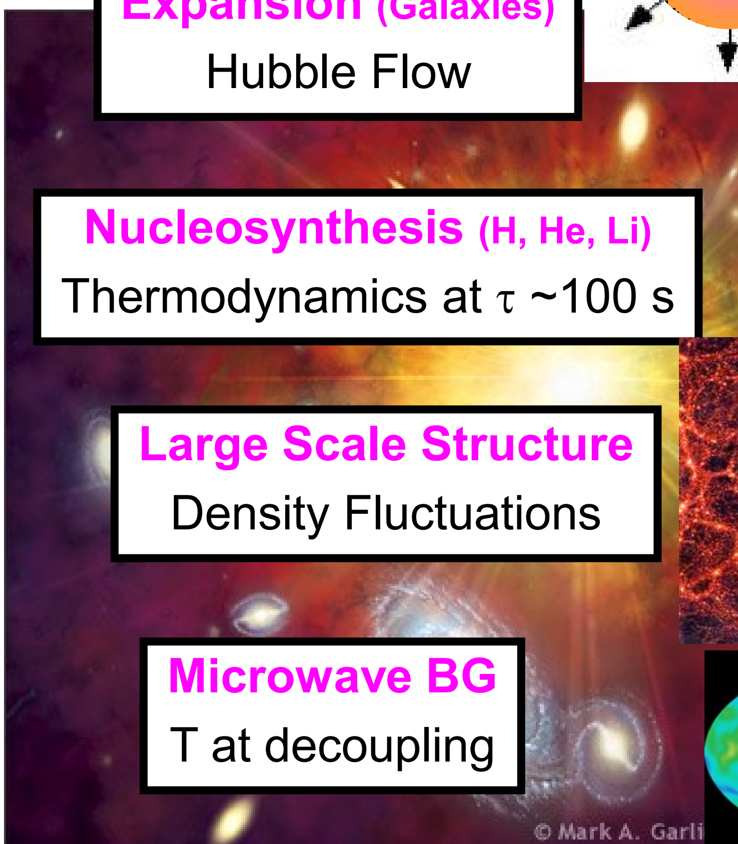
Physics is QCD:

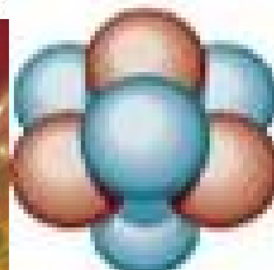
strong interaction sector of the Standard Model
(where its very strong !)

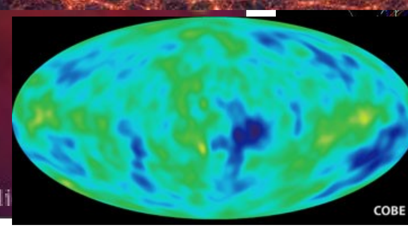
Big Bang

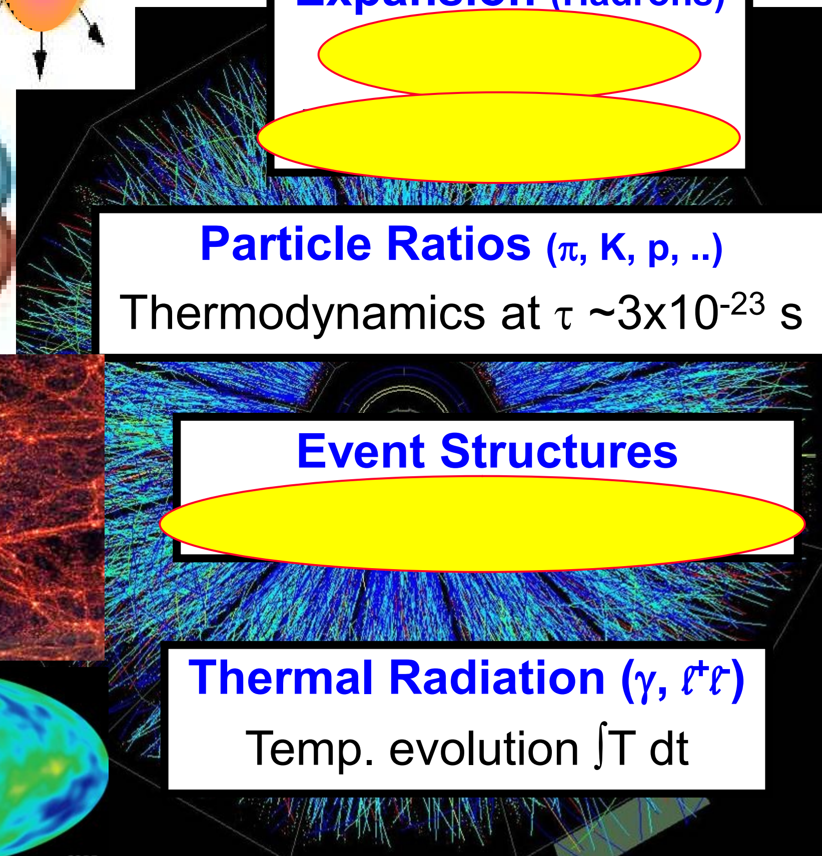
Little Bang

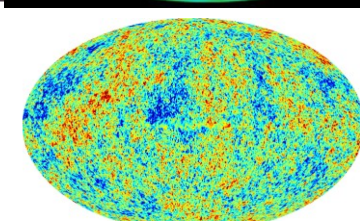












Global Characteristcs

Mass density Ω, Age

Global Characteristics

Expansion (Galaxies)

Hubble Flow

Expansion (Hadrons)

Nucleosynthesis (H, He, Li)

Thermodynamics at τ ~100 s

Particle Ratios (π, K, p, ..)

Thermodynamics at τ ~3x10^{-23} s

Large Scale Structure

Density Fluctuations

Event Structures

Microwave BG

T at decoupling

Thermal Radiation (γ, $\ell^+\ell^-$)

Temp. evolution ∫T dt

Temperature Fluctuations

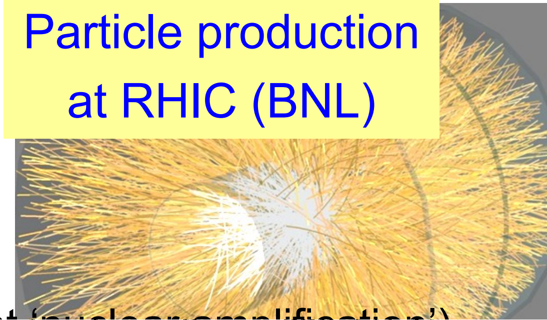
signal from the earliest phase

Colour Screening (J/Ψ, Υ)

Characterizing the Little Bang (1)

- **Particle Production and Energy density ε:**
  - ⇨ Produced Particles: **$dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)**
    - ~ 30,000 particles in total, ~ 400 times pp !
    - somewhat on high side of expectations
    - growth with energy faster in AA than pp (√s dependent 'nuclear amplification')
  - ⇨ **Energy density ε > 3 x RHIC** (fixed τ_0)
  - ⇨ **Temperature + 30%**
    - lower limit, likely τ_0(

Particle production at RHIC (BNL)



Matter under extreme conditions:

ε > 15 GeV/fm^3

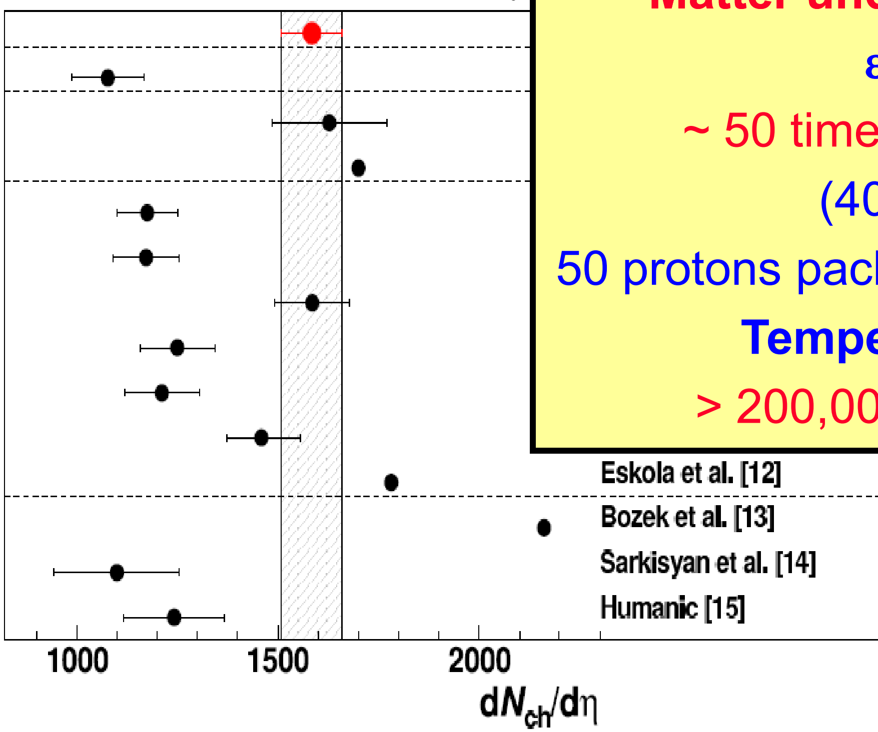
~ 50 times core of a neutron star

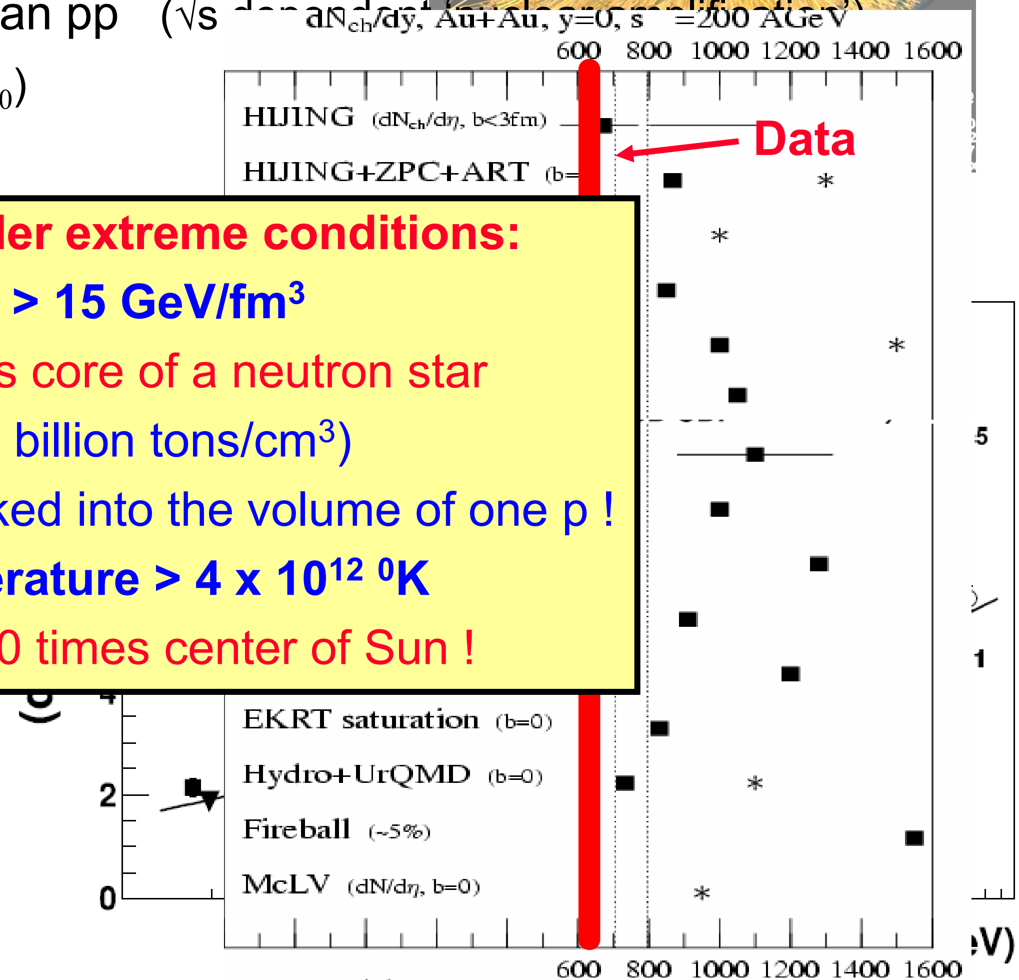
(40 billion tons/cm^3)

50 protons packed into the volume of one p !

Temperature > 4 x 10^{12} ^{0}K

> 200,000 times center of Sun !



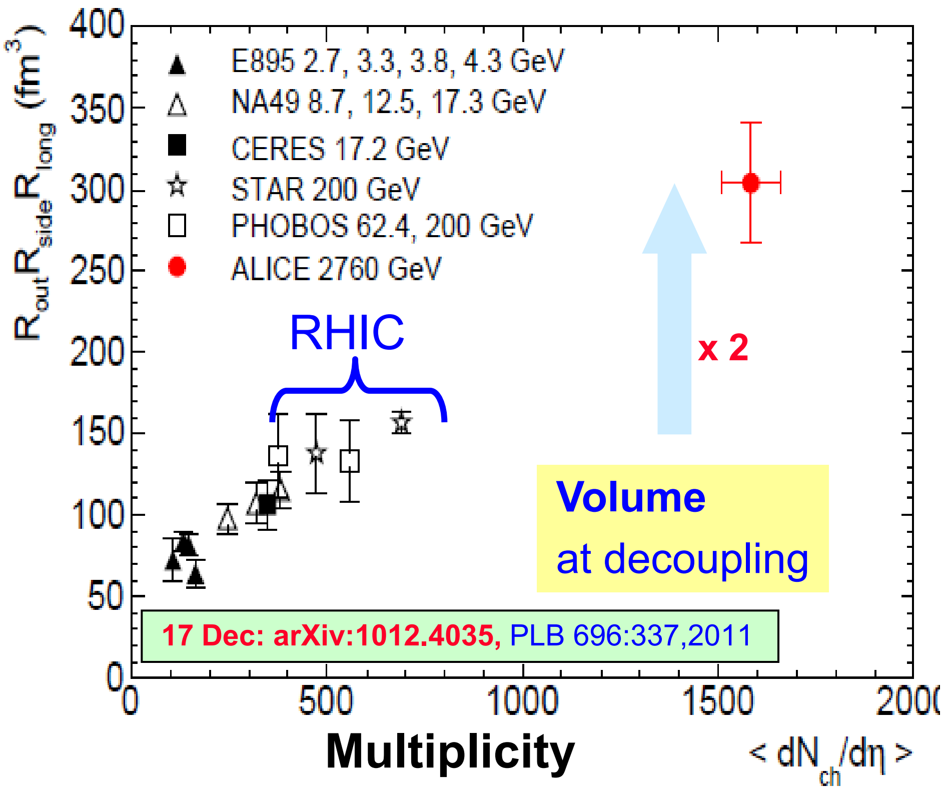


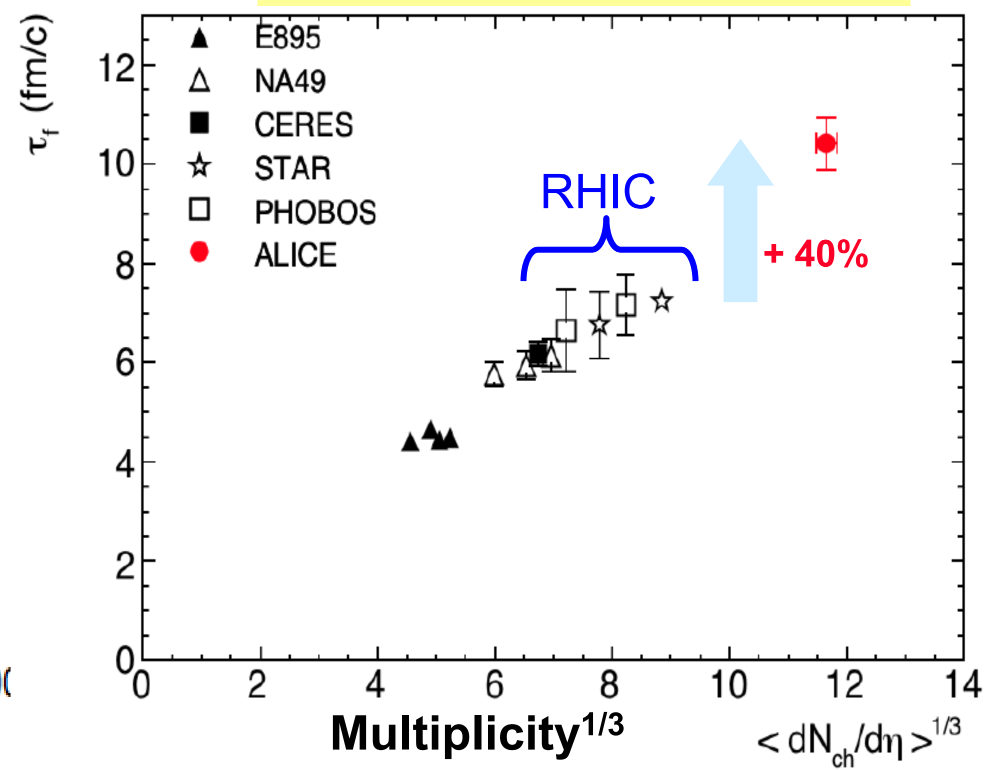
Characterizing the Little Bang (2)

- Volume and Lifetime:
  - ⇨ Identical particle interferometry
    - ✪ Quantum effect, leading to Bose Einstein Condensate at zero temperature
  - ⇨ **Volume ≈ 2 x RHIC** (≈ $(2\pi)^{3/2} x R^3$ ≈ 5000 fm^3)
    - ✪ observable 'comoving' volume !
  - ⇨ **Lifetime ≈ +30-40%** (> 10 fm/c ~ $3x10^{-23}$ s)

'Little Bang' lives some 10^{40} less than current age of Universe..

Lifetime: from collision to 'freeze-out' (hadron decoupling)



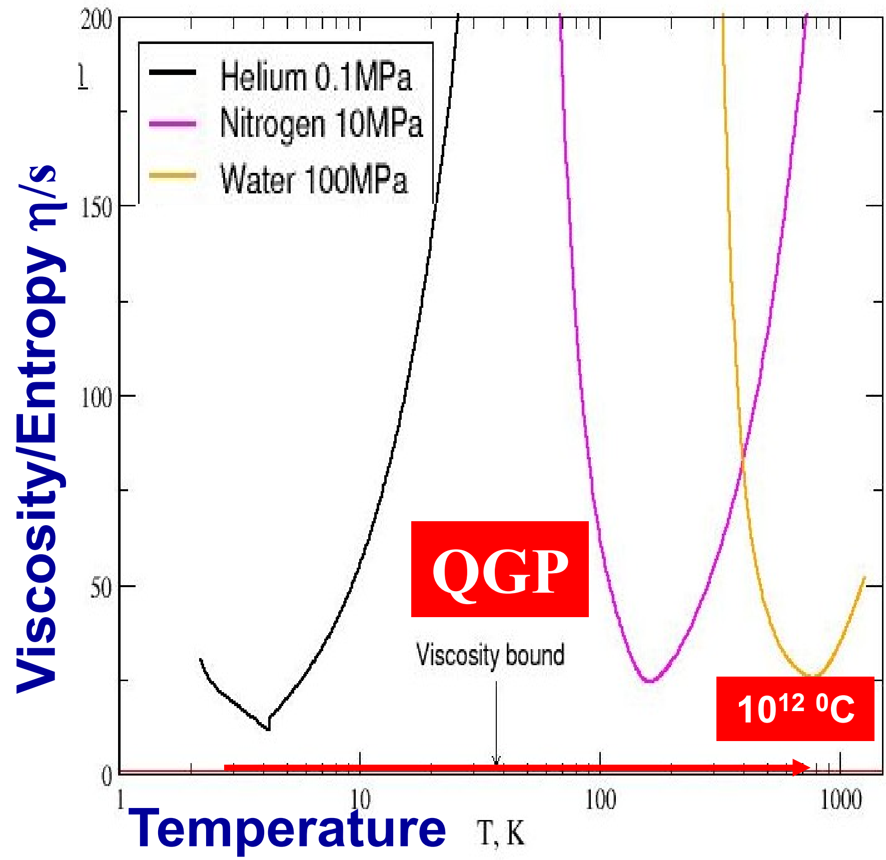


Characterizing the Matter (1)

- RHIC discovery in 2005: The QGP is a (almost) perfect liquid
  - ⇨ **perfect liquid → Viscosity $\eta \approx 0$** ('response to pressure gradients')
    (→ strong interactions in the liquid)
  - ⇨ QGP almost **ideal fluid**, η/S < 0.2 - 0.5
    - ✪ usually use Viscosity/Entropy (η/S dimensionless number)
- unexpected result
  - ⇨ QGP though to behave like a gas (weakly interacting)
  - ⇨ closest Theory prediction $\eta/S > 1/4\pi \approx 0.08$
    - ✪ AdS/CFT:

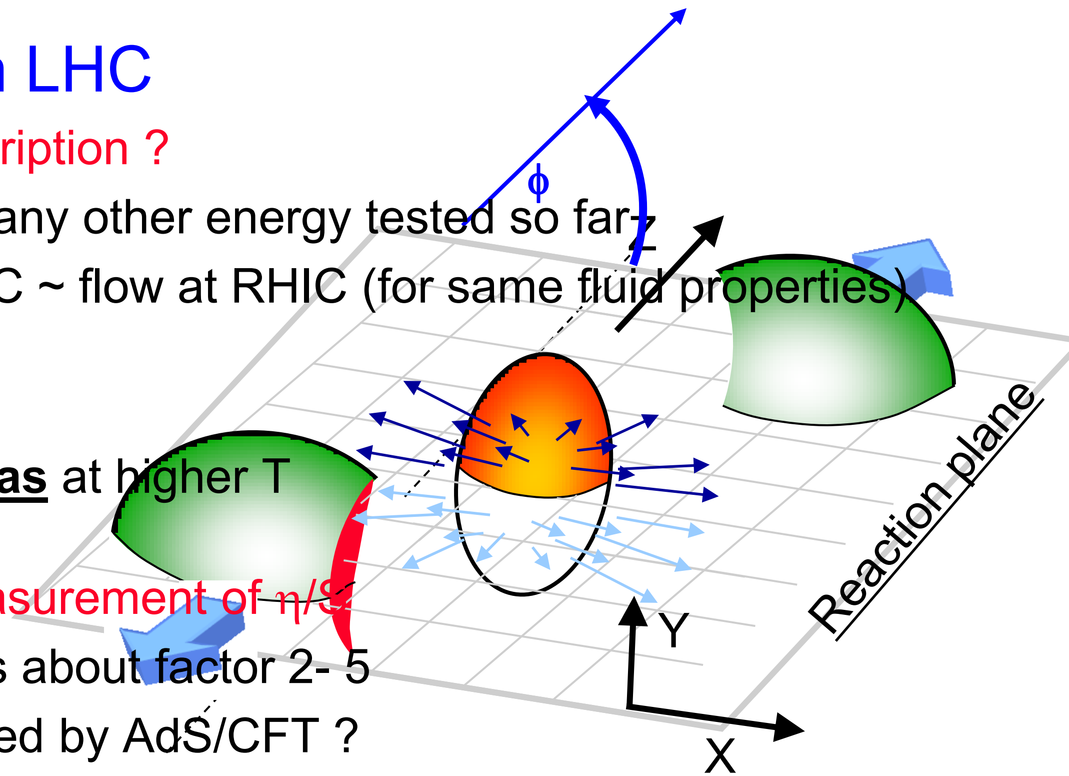
SUSY string theory in 5 dimensions !

BNL Press release, April 18, 2005:
QGP = "Perfect" Liquid
New state of matter more remarkable than predicted – raising many new questions



Does the QGP 'flow' at LHC ?

- 'Elliptic Flow'
  - ⇨ Pressure gradients & the nuclear collision geometry lead to a characteristic **'sideway splash'** of the produced particles
- Hydrodynamics
  - ⇨ predicts flow pattern as function of geometry (initial conditions)& fluid properties (e.g. η/S, speed of sound, EoS, ..)
- Answers anticipated from LHC
  - ⇨ is Hydro actually the correct description ?
    1. ✪ only successful at RHIC, not at any other energy tested so far
       ✪ **testable prediction**: flow at LHC ~ flow at RHIC (for same fluid properties)
  - ⇨ is the matter still a fluid ?
    2. ✪ or does it become more like a **gas** at higher T
  - ⇨ how perfect a fluid: precision measurement of η/S
    3. ✪ current uncertainty from RHIC is about factor 2- 5
       ✪ is it at the quantum limit stipulated by AdS/CFT ?



First Elliptic Flow Measurement at LHC

- Elliptic Flow as function of momentum.

practically no change with energy !

1 ⇨ **1)** Hydro prediction confirmed !

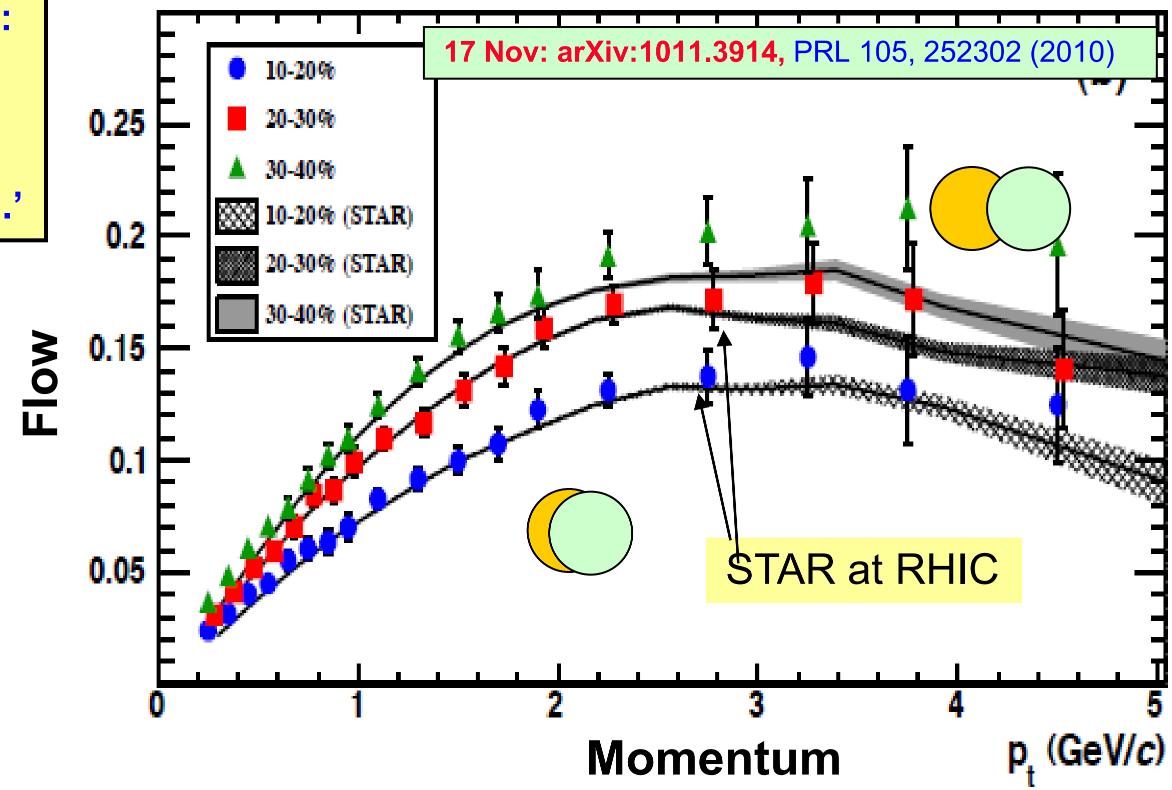
2 ⇨ **2)** QGP still behaves like a liquid even at Temperature of LHC

⇨ some small differences, to be investigated further

- extends towards more distant collisons/higher p_t ?

CERN Press release, November 26, 2010:

'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'



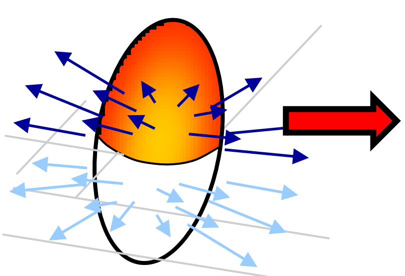
Towards Precision Measurements

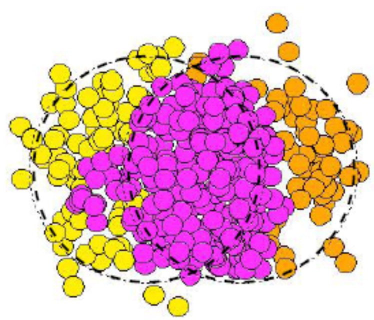
- **Precision: Why ?**
  - current RHIC limit: $\eta/S \sim (2\text{-}5) \times 1/4\pi$
  - 3 $\eta/S < 1/4\pi$ => conjectured limit is wrong
  - $\eta/S > 1/4\pi$ => measure σ
  - $\eta/S \approx 1/4\pi$ => quantum corrections O(10-30%) !
    - **20% in v_2 ~ $1/4\pi$ => need few % precision**

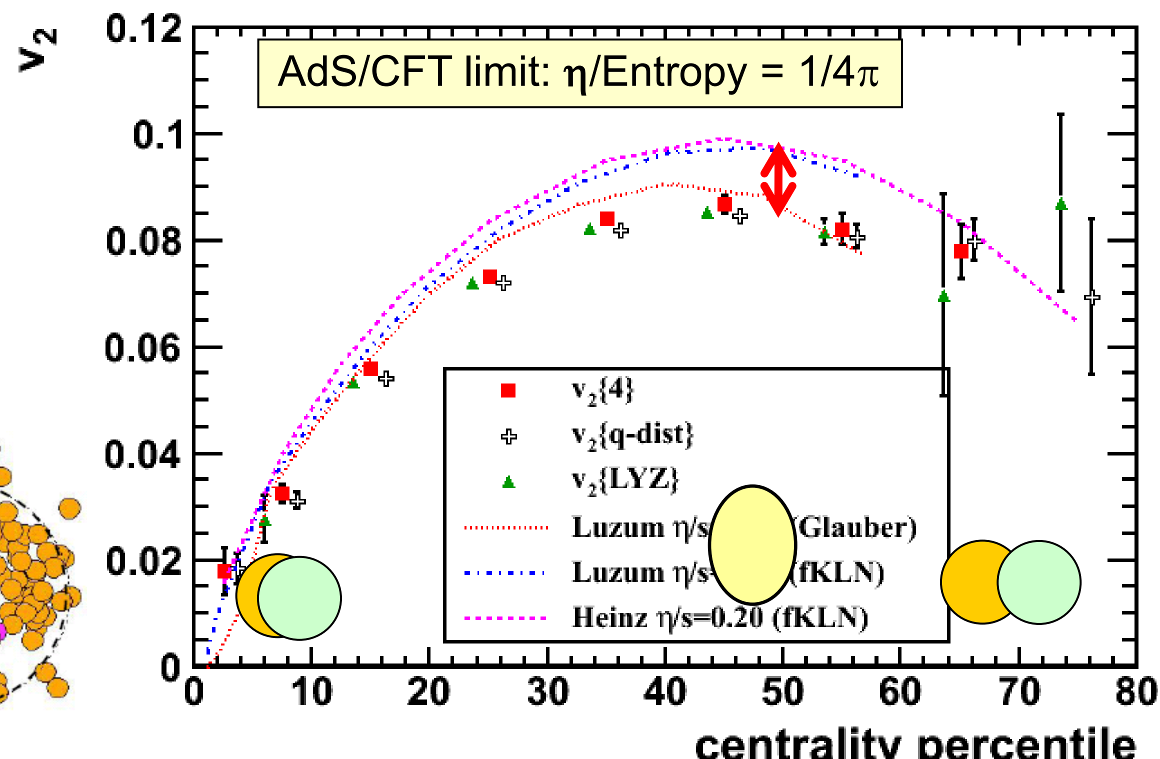
$$\eta = \frac{\sqrt{2mkT}}{\sigma}$$

Precision measurements now underway, it looks like we can get there !

- **Precision: How ?**
  - fix **initial conditions**
    - irregular shapes, fluctuations captured by higher order Fourier Coefficients (v_2,v_3, ..)
  - non flow background, theory improvements, ...

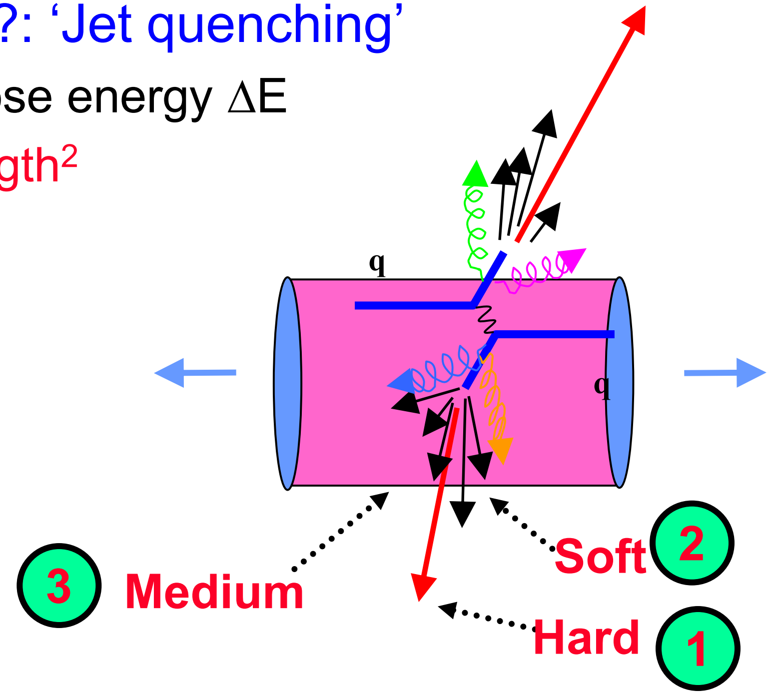






Characterizing the Matter (2)

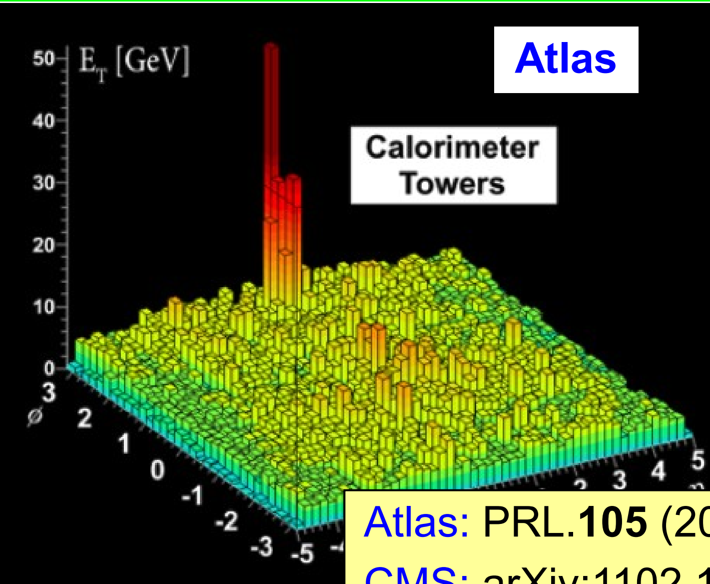
- How strongly interacting is the matter ?: ‘Jet quenching’
  - ⇨ quarks/gluons traveling through QGP loose energy ΔE
    - ✪ some unusual properties, e.g. ΔE ~ Length^2
(not ΔE ~ L, as in normal matter !)

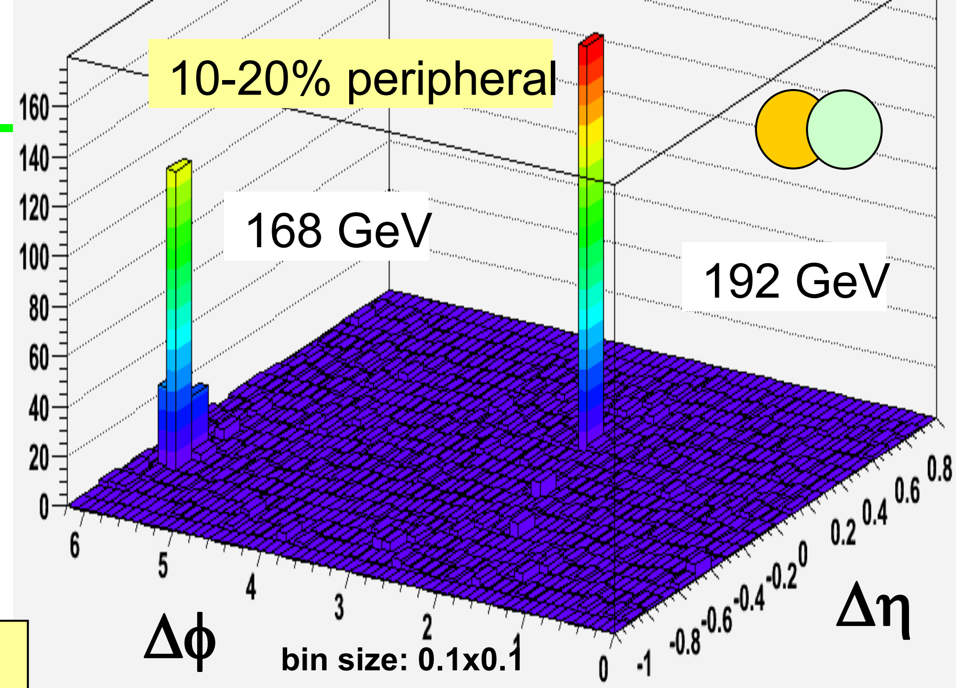


  - ⇨ how much energy is lost ? (measures ‘interaction strength’ of QGP)
    - ✪ look at high momentum (‘hard’) part of jets
  - ⇨ how is it lost ?
    - ✪ many **soft** or few **hard** scatterings
    - ✪ look at low momentum (‘soft’) part
  - ⇨ ‘response of QGP’ ??
    - ✪ shock waves, Mach cones ??
    - ✪ look at average (‘very soft’) particles of the medium


‘Jet’ breaking the sound barrier

Jets

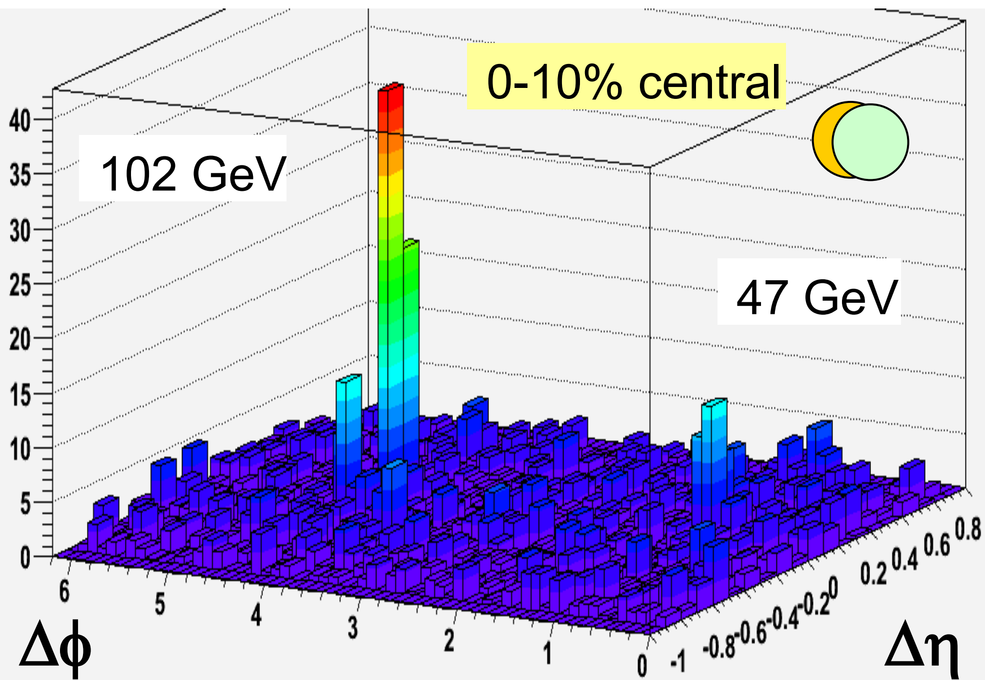


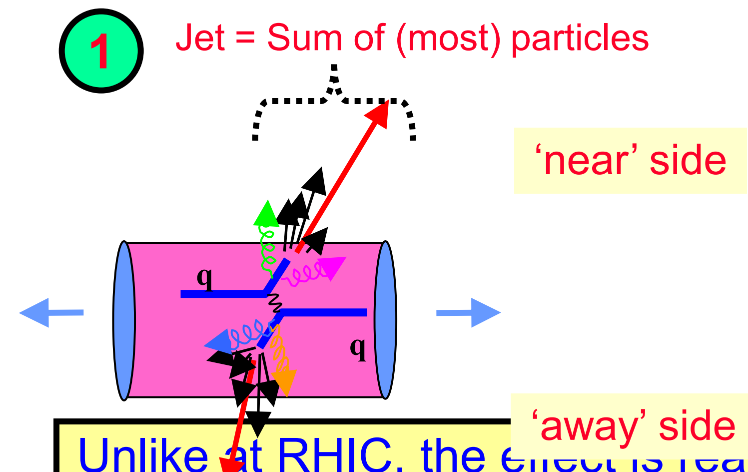


Atlas: PRL.**105** (2010) 252303

CMS: arXiv:1102.1957

Spatial distribution of charged tracks in TPC



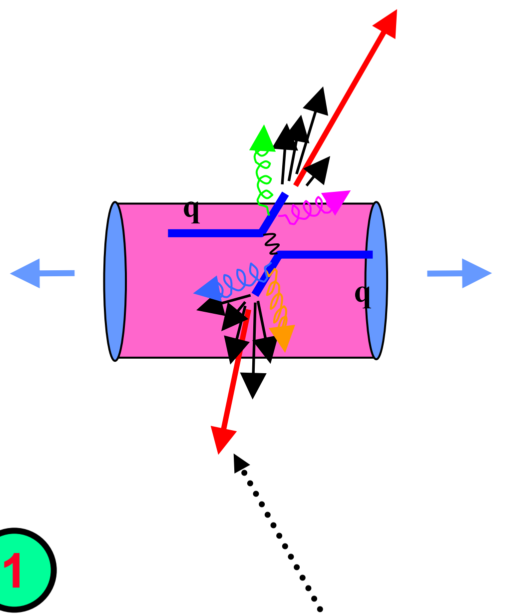


Unlike at RHIC, the effect is readily and directly visible at LHC.

Quantifying energy loss now under way

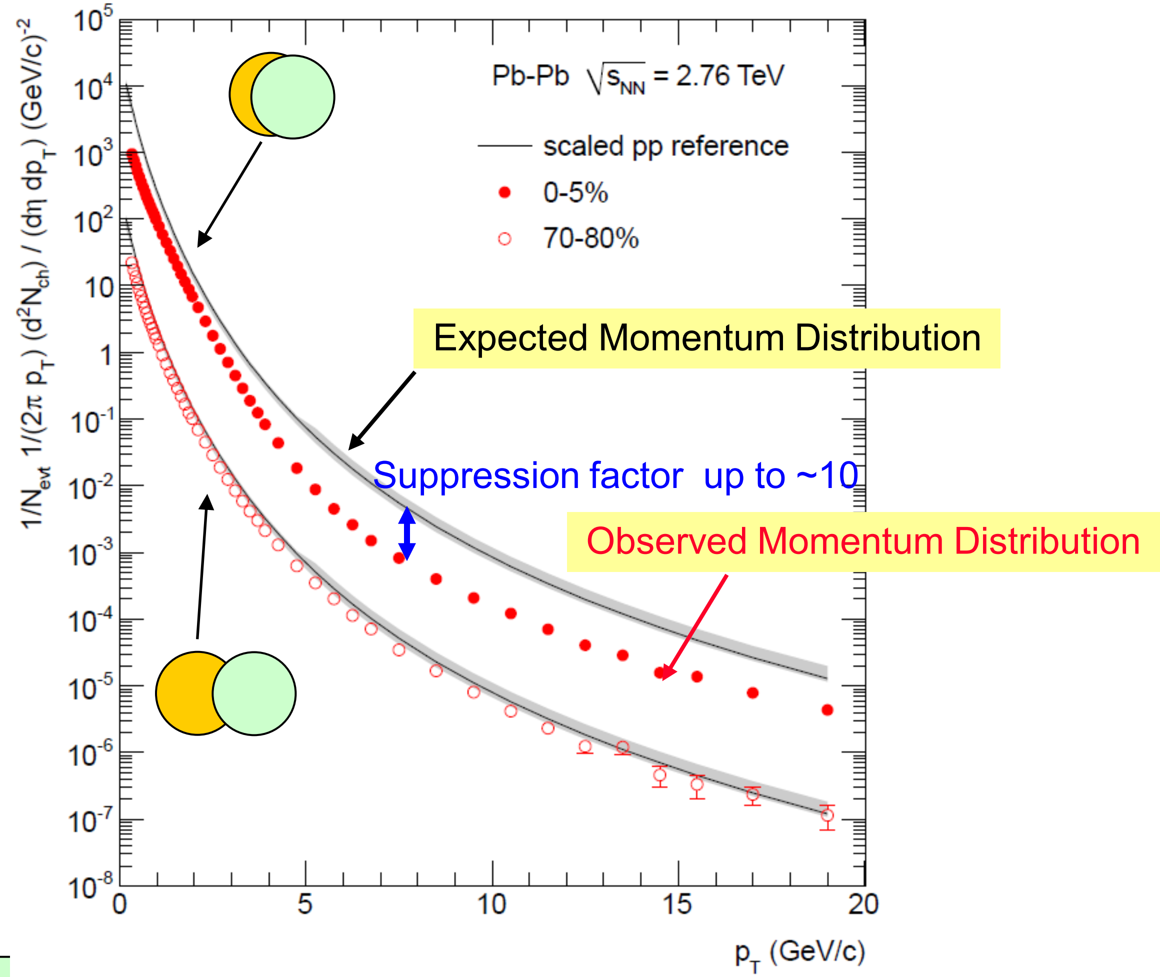
‘Jet Quenching’ seen in single high p_t particles

- Strong suppression of high momentum particles (~ jet fragments)
  - ⇨ on first sight, **seems stronger** than at RHIC
  - ⇨ distinct (and very interesting) **dependence on momentum**



1

Most energetic (‘leading’) jet particle

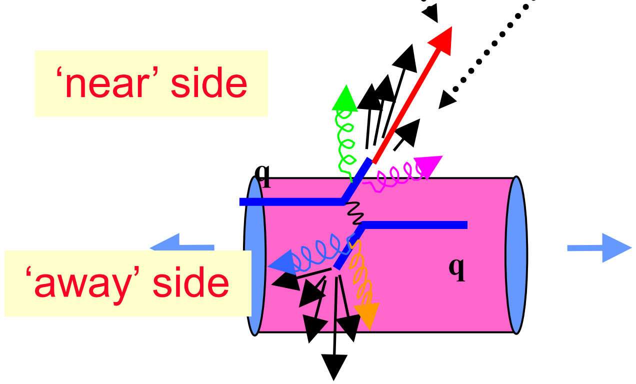


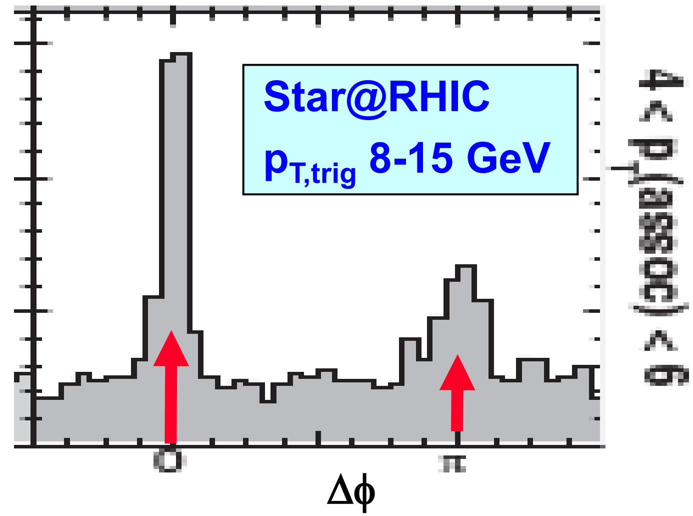
2 Dec: arXiv:1012.1004, PLB 696 (2011) 30-39,

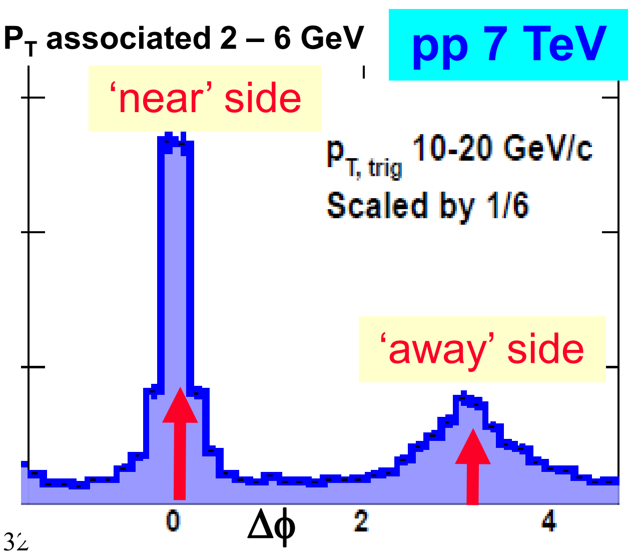
Jet Quenching seen by high p_T Correlations

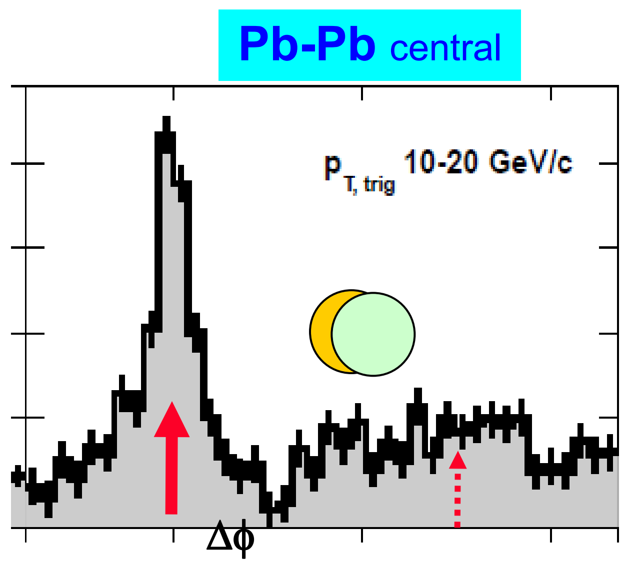
- classic 'jet quenching signal'
  - ⇨ away side correlation in central Pb-Pb disappears
  - ⇨ seems stronger than at RHIC

2 Correlation between 'leading' and soft jet particles



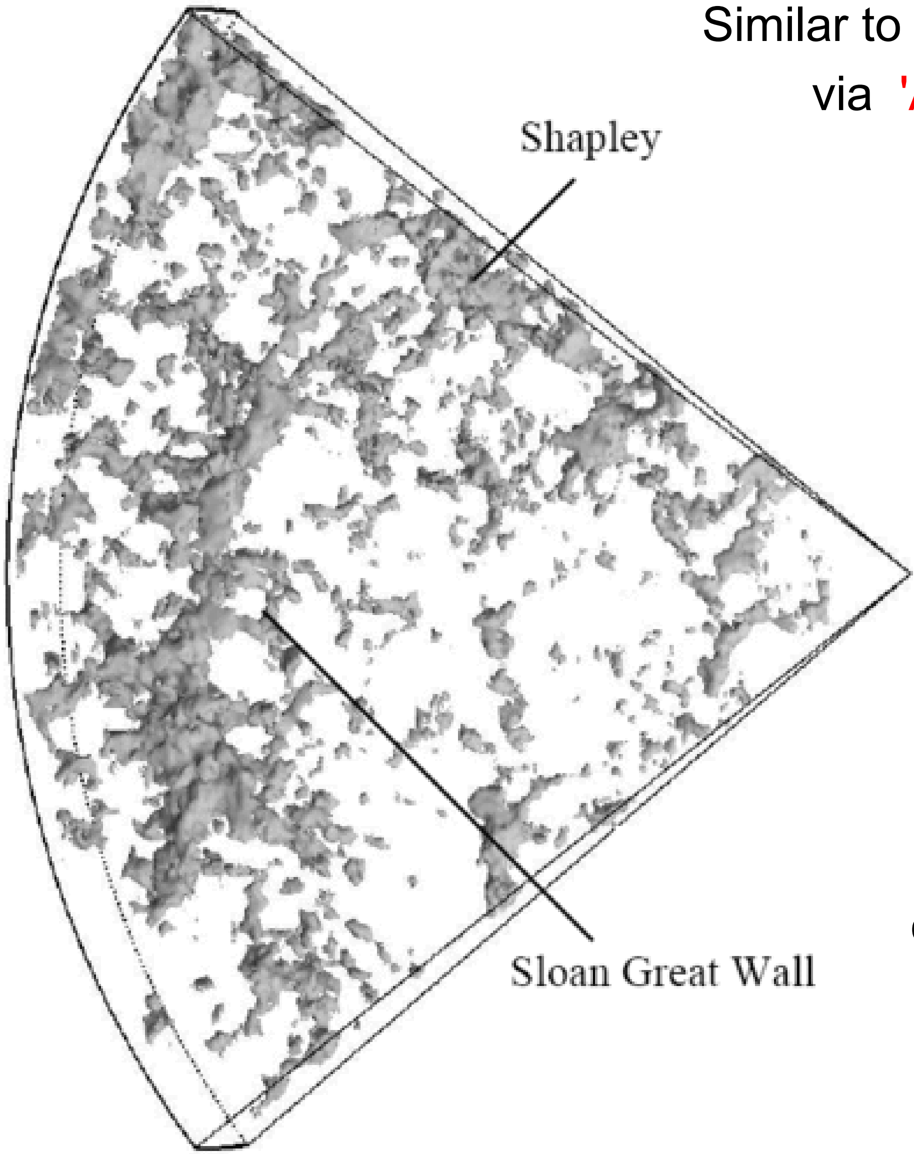


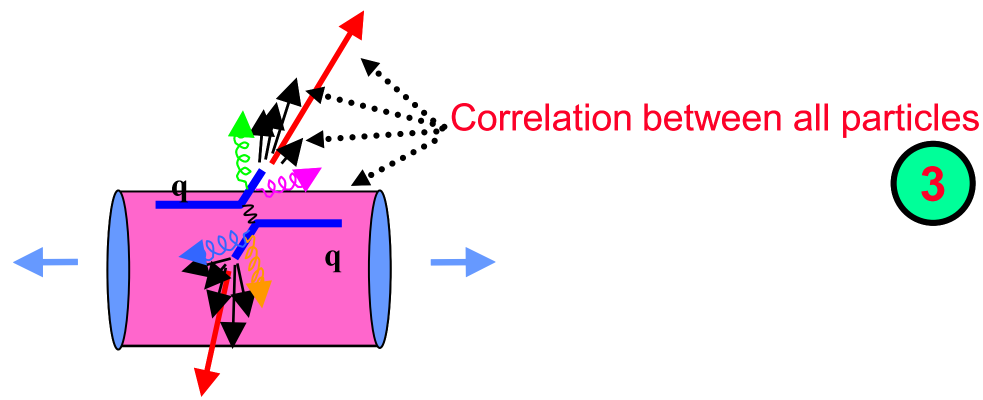




Looking for Structures

Similar to looking for structures in the Galaxy distribution via 'Auto-correlations' (neighbour separation)





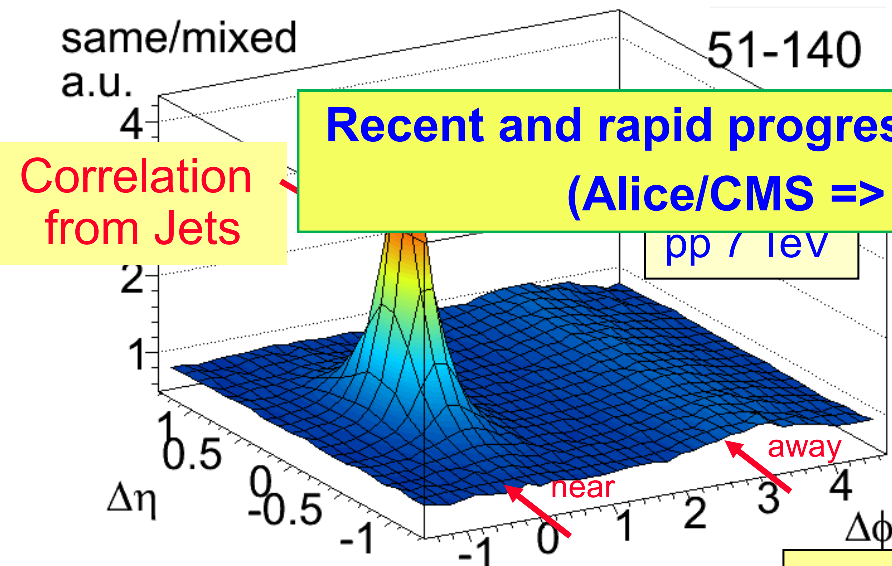
3

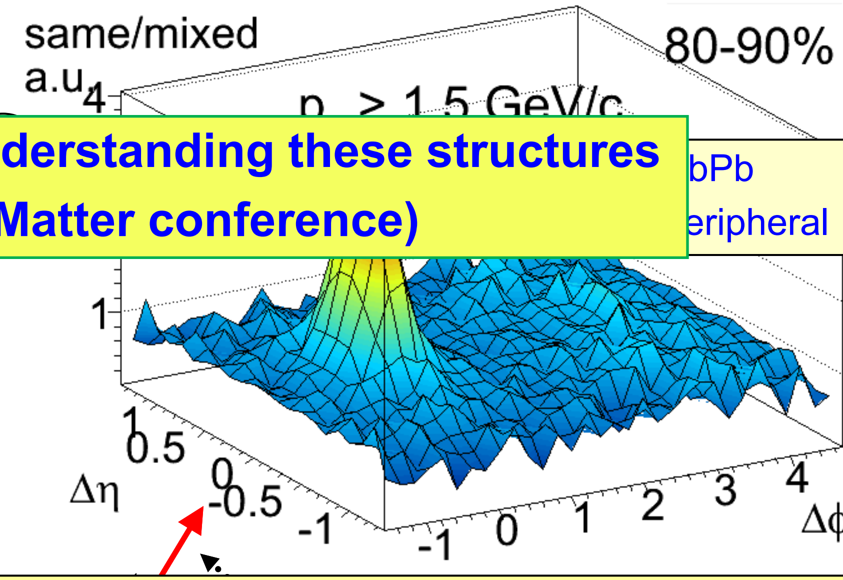
Look for structures in

$d^2N_{ch}/d\Delta\eta d\Delta\phi$ (data)/$d^2N_{ch}/d\Delta\eta d\Delta\phi$ (random)

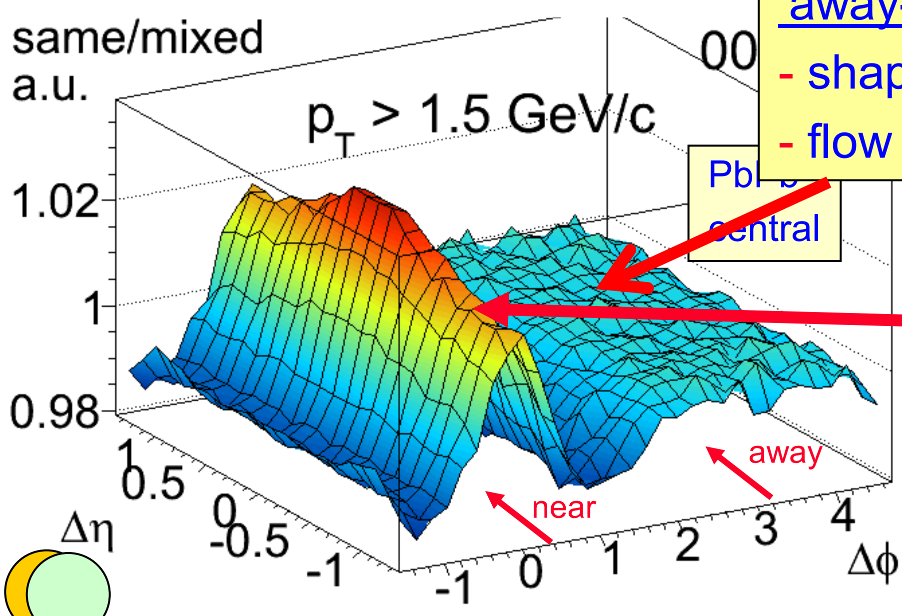
Jet Quenching (?) seen via Multiparticle Correlations

- 'Autocorrelation':





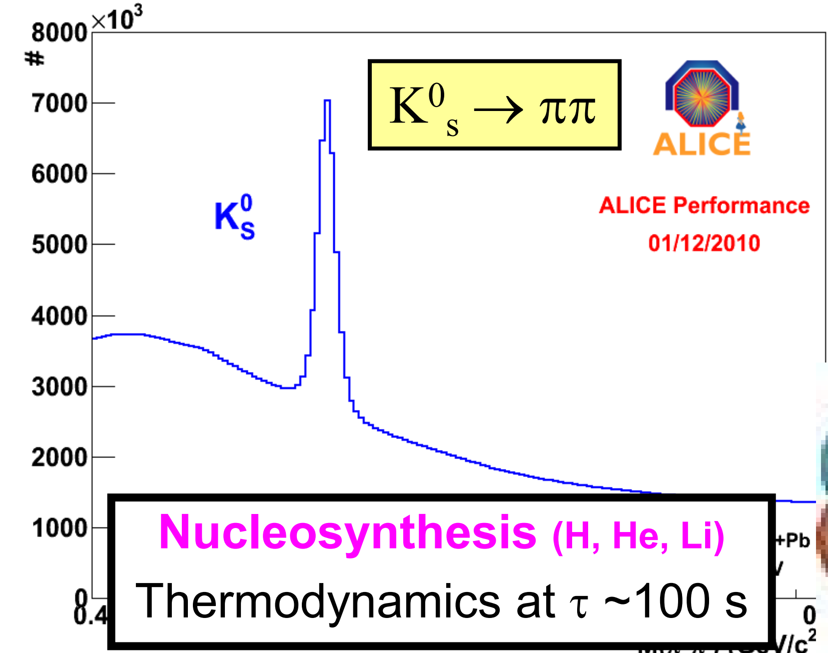
Recent and rapid progress in understanding these structures (Alice/CMS => Quark Matter conference)

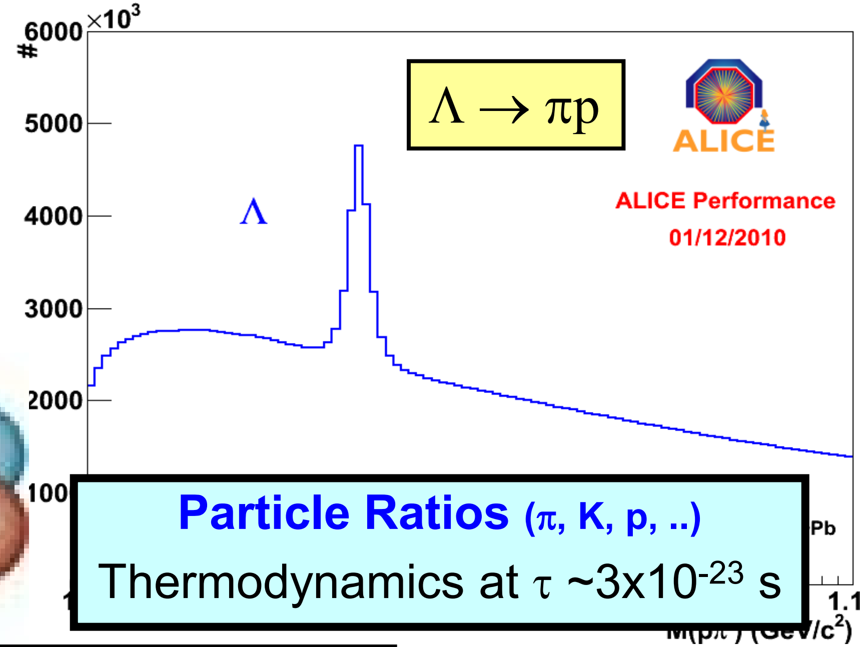


'away-side structure':
- shape changes very quickly with impact parameter
- flow fluctuations, medium response (Mach cone) ?

'near side ridge':
- striking effect, not fully understood
- very 'long' & flat ridge
- smeared 'leftover' of jet ?

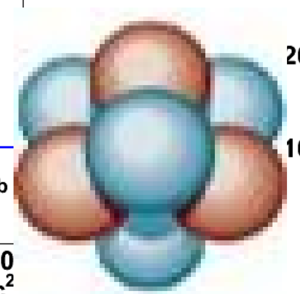
Particle Production in Pb-Pb





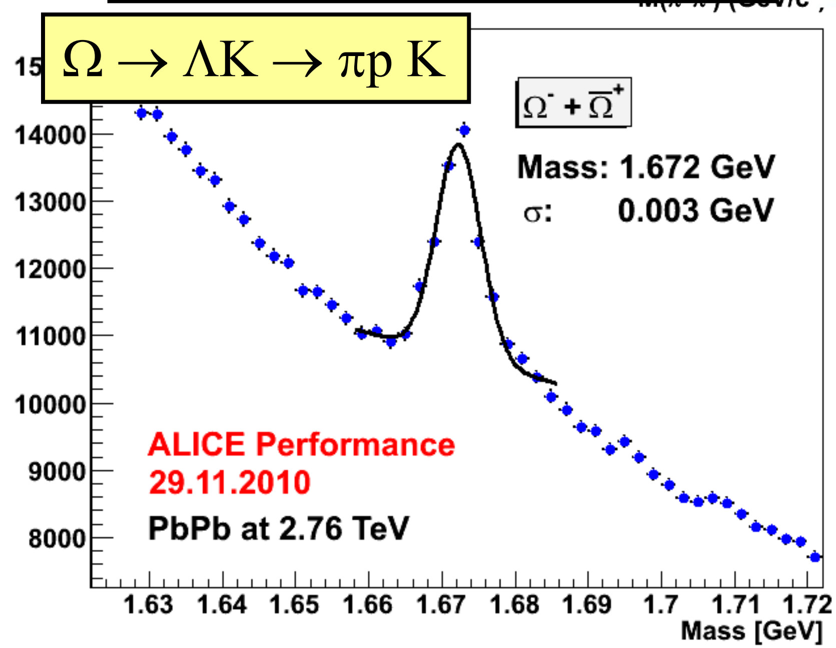
Nucleosynthesis (H, He, Li)

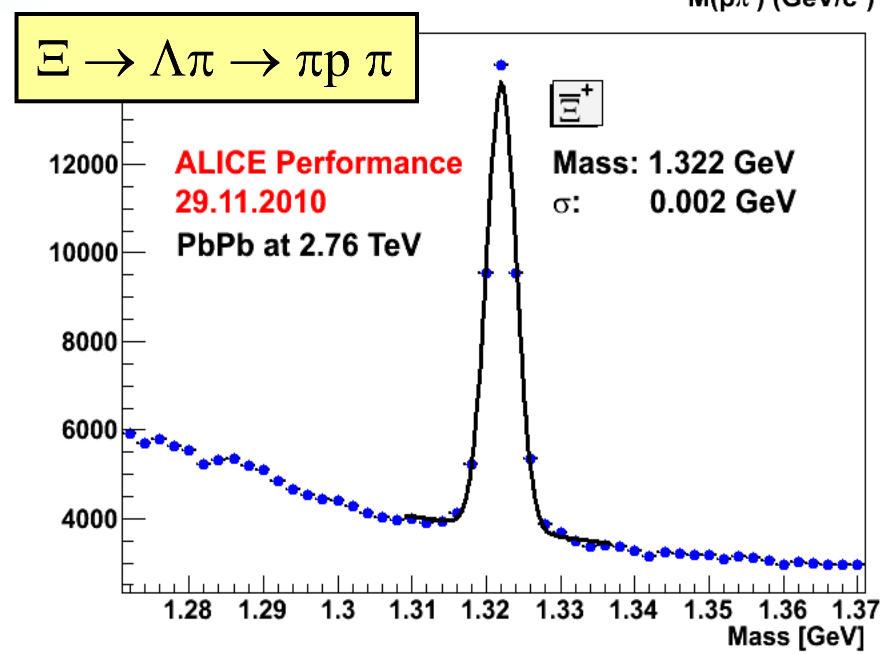
Thermodynamics at τ ~100 s



Particle Ratios (π, K, p, ..)

Thermodynamics at τ ~3×10^{-23} s





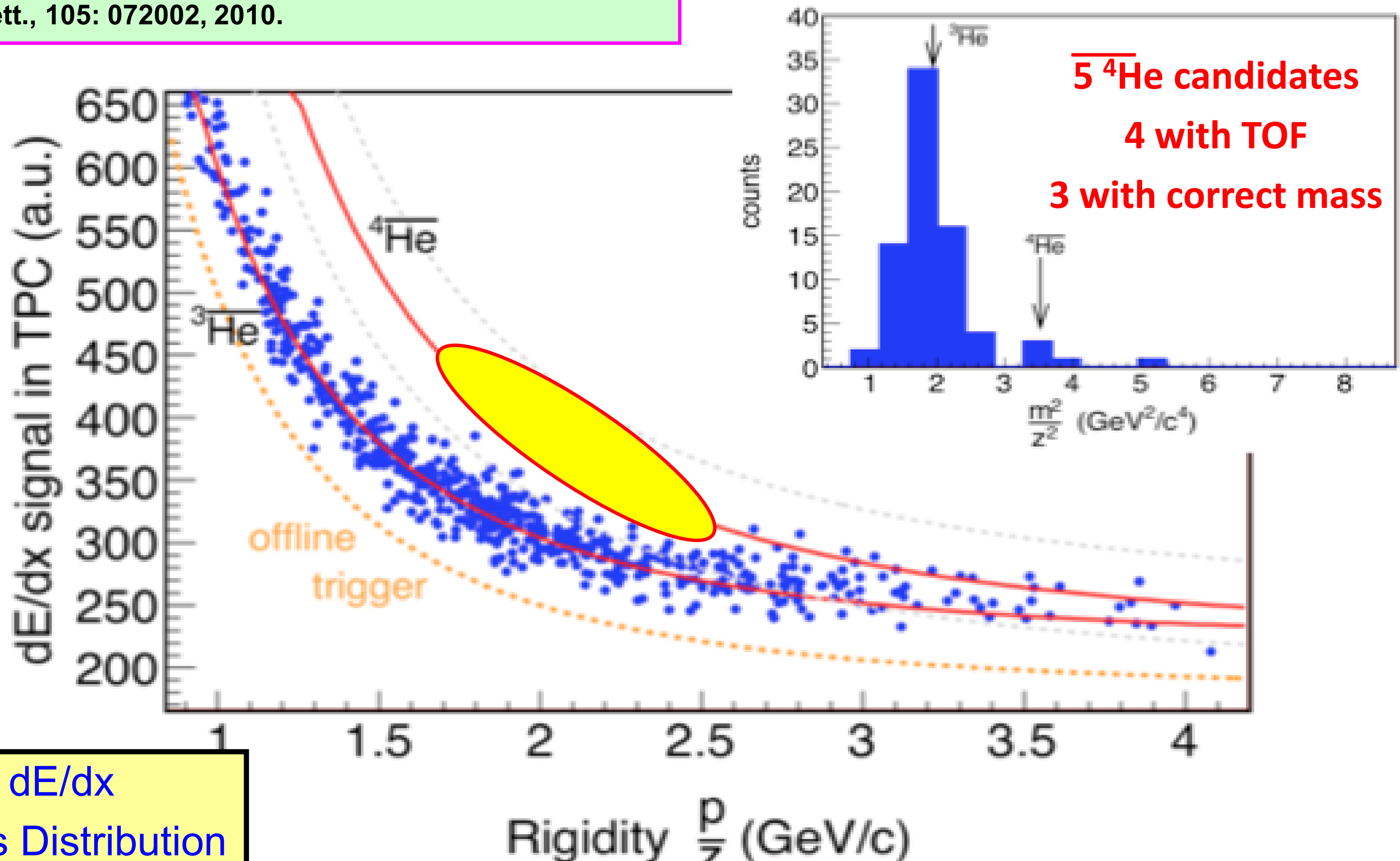
Anti-Nuclei in Pb-Pb

- LHC: Matter ≈ anti-matter

Time of flight (sensitive to *m*/Z-ratio): $m = \frac{z \cdot R}{\sqrt{\gamma^2 - 1}}$

7 TeV: $\bar{p}/p$ = **0.990**±0.006(stat) ±0.014(syst)

Phys. Rev. Lett., 105: 072002, 2010.

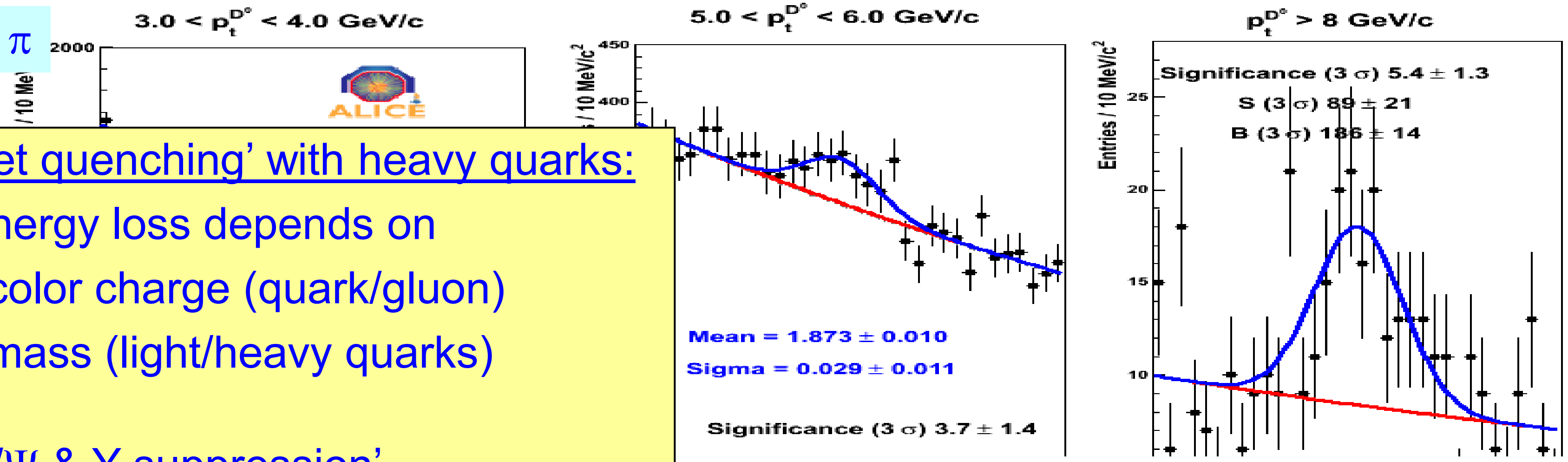


TPC dE/dx

Energy Loss Distribution

Charm in Pb-Pb

$D^0 \to K\pi$



'Jet quenching' with heavy quarks:

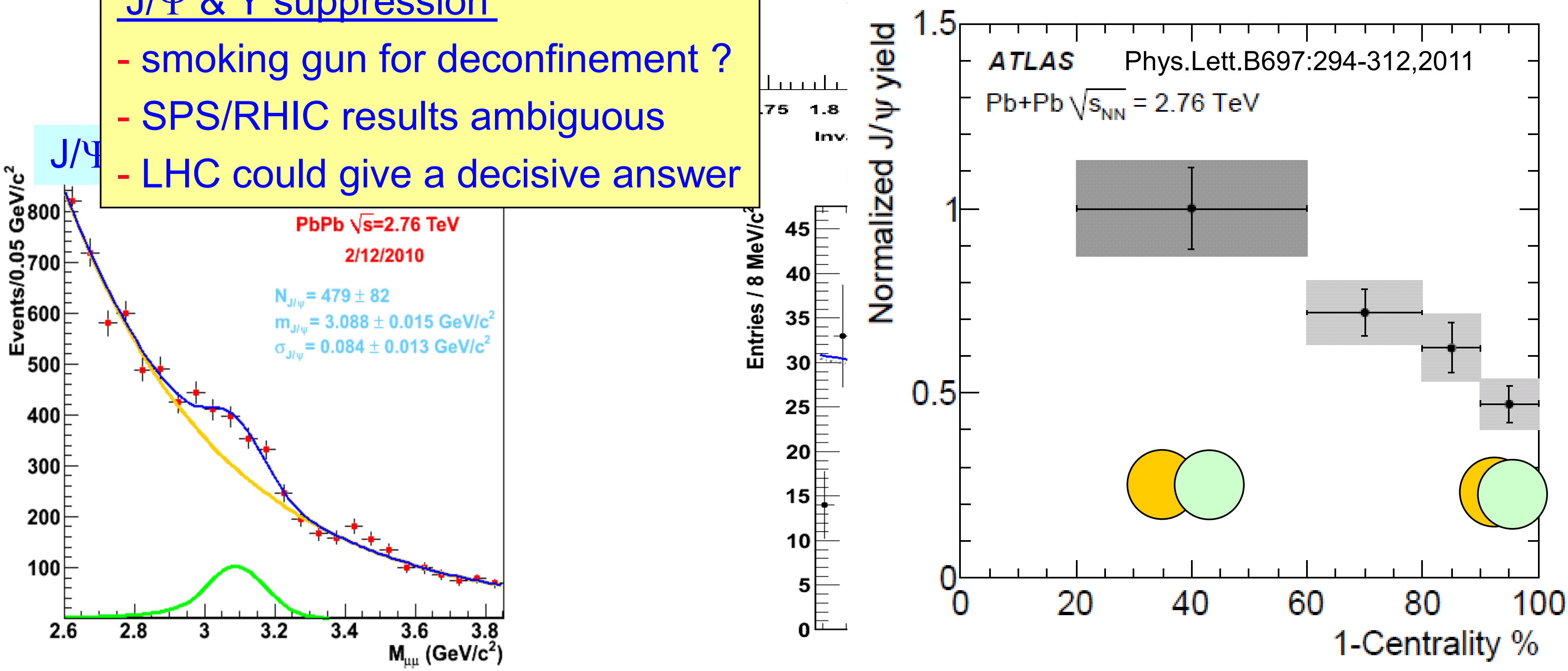
Energy loss depends on

- color charge (quark/gluon)
- mass (light/heavy quarks)

'J/Ψ & Y suppression'

- smoking gun for deconfinement ?
- SPS/RHIC results ambiguous
- LHC could give a decisive answer

J/Ψ



Even QED becomes strong at LHC

- very large em cross sections

  relativistic Lorentz boost amplifies electromagnetic field of nuclei

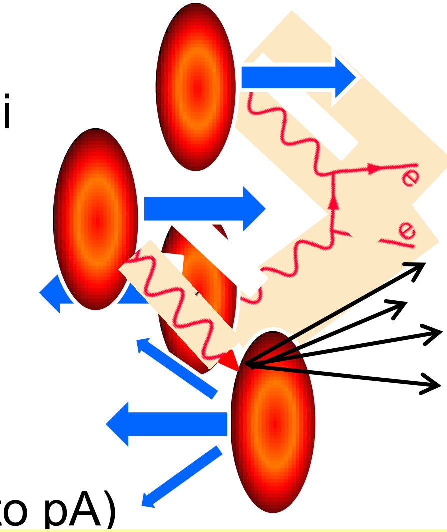
  ⇨ QED e^+e^- pair production: hundreds of kbarn (>10^5 nuclear σ)

  ⇨ em dissociation ~ 200 barn

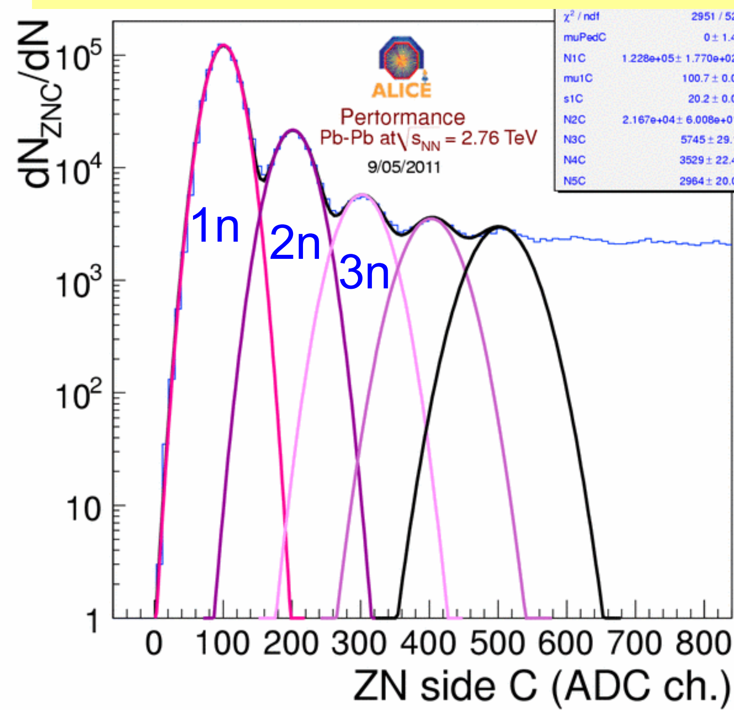
  - one or several neutrons at zero degree
  - $^{208-x}$Pb 'beams' limits LHC intensity (magnet quench)

  ⇨ photonuclear reactions: tens of barns (kinematics very similar to pA)

  - Gamma energy several 100 GeV



Pb + ^{208}Pb → Pb + $^{208-x}$Pb + x n



LHC is a very versatile collider:

pp, AA, pA (2013?)

γγ, γA, γ-Pomeron

Heavy Ions at LHC

- 1) Global characteristics & Quantitative differences @ LHC

⇨ significantly different state of QGP in terms of energy density, lifetime, volume

⇨ large rate for 'hard probes' : jets, heavy quark states (b,c,Υ,J/Ψ),…

- 2) Test & validate the HI 'Standard Model' (< 10 years old !)

QGP = very strongly interacting (almost) perfect **liquid**

⇨ Test predicti

✪ examples:

> 10 year program

where are we after few months* ?

- 3) 'Precision' measurements of QGP parameters now starting

⇨ Quantitative and systematic study of the new state of matter

✪ **Equation-of-State** f(ε,p,T), **viscosity** η (flow), **transport coefficient q** (jet quenching), Debye **screening mass** (Quarkonia suppression), …

- 4) Clarify status of some 'Beyond the HI Standard Model' ideas

⇨ support, but no smoking gun yet: CGC, quark coalescence, ..

⇨ some hints, maybe ?: Chiral magnetic effect ('strong CP violation'), Mach cones, ...

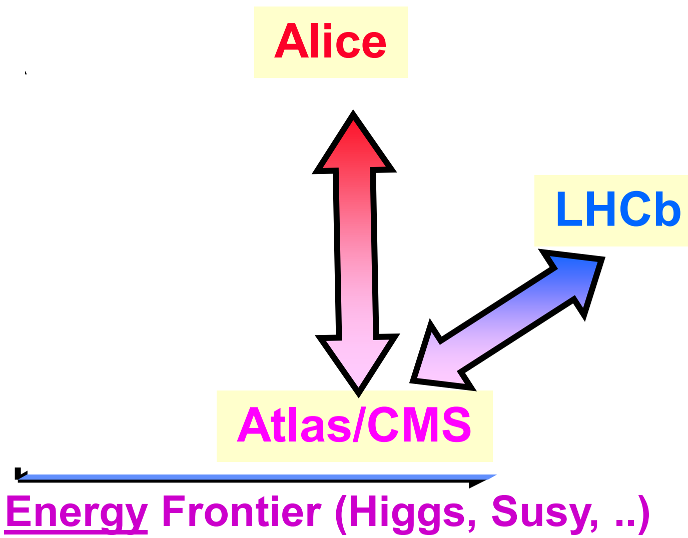
- 5) Surprises ?

⇨ **we are dealing with QCD in the strong coupling limit !**

* Results presented here correspond to status of ~ Jan 2011, new results will be released at Quark Matter 2011 next week !

Versatility of LHC & Complementarily of Experiments
make the whole of LHC larger than the sum of its parts

- **Common Questions**
  - generation of mass
    - **elementary** particles => Higgs => **Atlas/CMS**
    - **composite** particles => QGP => **Alice**
  - broken symmetries
    - **SuperSymmetry**: matter <=> forces => **Atlas/CMS**
    - **ChiralSymmetry**: matter <=> QCD vacuum => **Alice**
    - **CP Symmetry:** matter <=> antimatter => **LHCb**



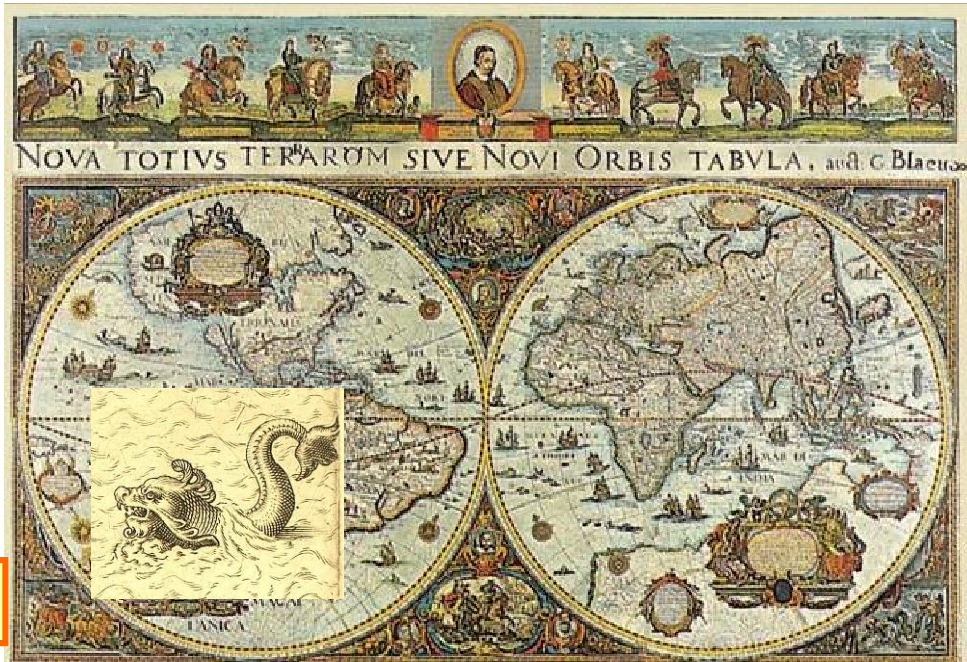
- **Different Approaches**
  - **'Concentrated Energy'** **=> Atlas/CM**
    => new high mass particles
  - **'Distributed Energy'** => **Alice**
    => heat and melt matter
  - **'Borrowed Energy'** => **LHCb**
    => indirect effects of virtual high mass particles

Conclusion

- LHC is a fantastic 'Big Bang' machine
  - ⇨ significant step beyond RHIC
  - ⇨ even for LHC standards, quality of first ion run was outstanding
  - ⇨ very powerful and complementary set of detectors (Atlas/CMS/Alice)

There is plenty of exciting physics (and fun)
at the LHC
exploring QCD in a new domain,
where the strong interaction is really strong !

- Looking forward to continue the journey further into the 'terra incognita' of HI at LHC



Hic sunt Leones !

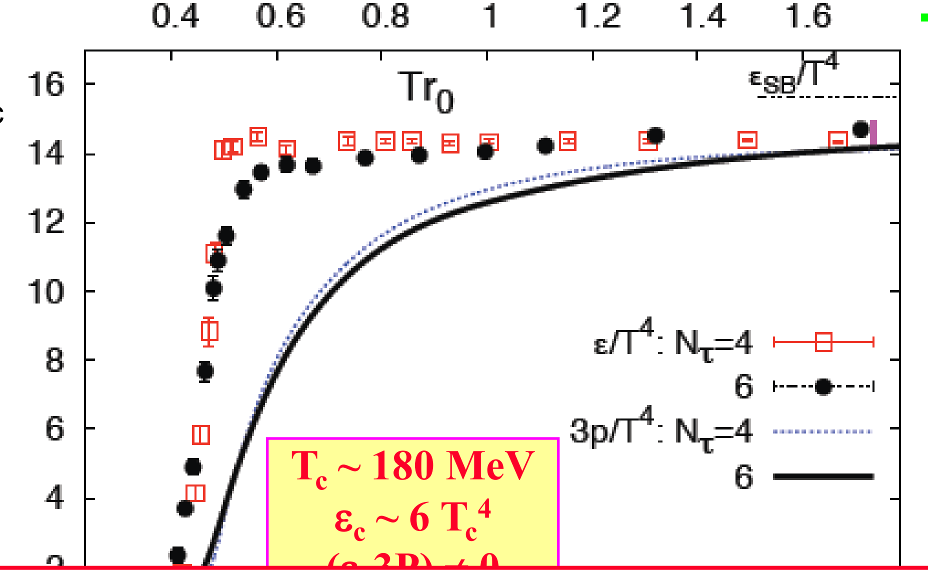
Near (and medium) Term Future

- We have barely scratched the surface, few months into a 10 year program
  - ⇨ need factor ~ 100 in integrated luminosity for rare signals
    - **next year** we should approach **design luminosity** (~20 x higher than 2010)
    - Quarkonia suppression (J/Ψ, Ψ', Y, Y',Y'), heavy Quarks (b,c), γ-jet, ….
  - ⇨ running at full LHC energy
    - gain of 10-15% in **energy density**, larger **cross section** for rare probes
  - ⇨ p – Nucleus comparison data
    - to distinguish **QGP** effects from **nuclear** effects ('shadowing')
    - study of **Color Glass Condensate**
      (yet another exotic dense matter at 'zero temperature')
  - ⇨ running with lower mass ions (Ar-Ar ?)
    - study **volume** effects
    - LHC can achieve much **higher luminosity** with lighter ions

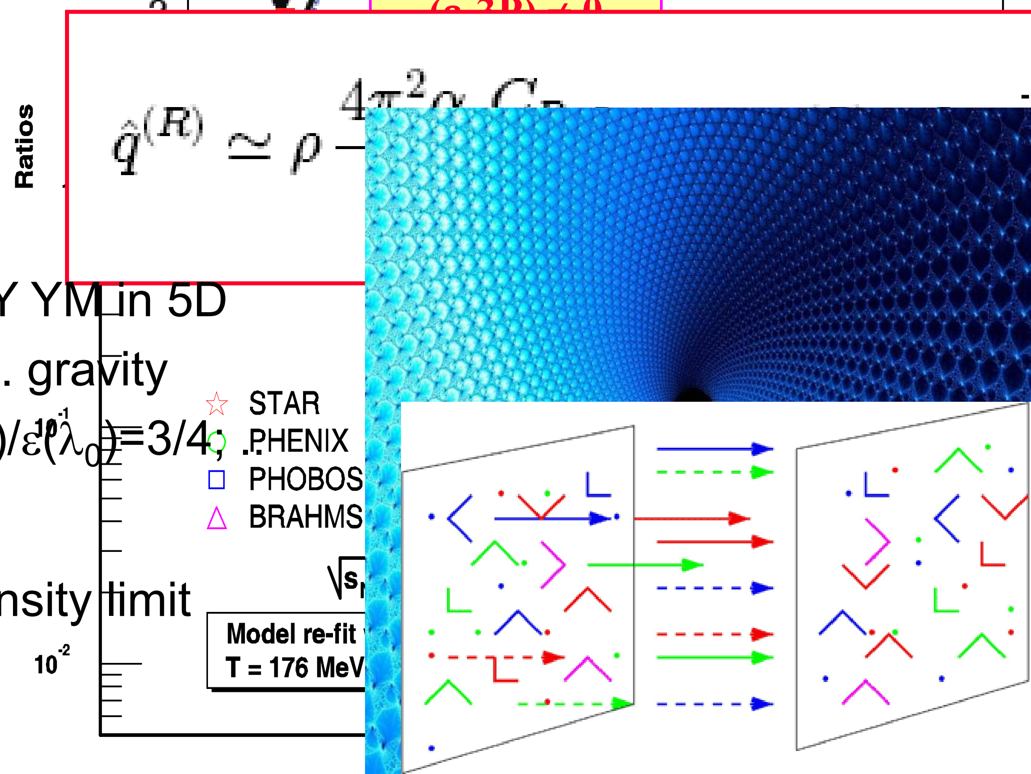
Plenty of work (and exciting physics) ahead !

Theory Tools

- **Lattice QCD**
  - ⇨ ideal for thermodynamics(static), EoS, T_c



- **Pert. QCD**
  - ⇨ cross sections, dynamical coefficients
- **Phenomenology**
  - ⇨ hydrodynamics, thermal models
  - ⇨ event generators (Phytia, Hijing, ..)



- **Duality: AdS/CFT**
  - ⇨ 4D gauge theory equivalent to SuSY YM in 5D
  - ⇨ strong coupling => reduced to class. gravity
  - ⇨ remarkable results: $\eta/s = 1/4\pi$; $\epsilon(\lambda_\infty)/\epsilon(\lambda_0)=3/4$; ..
- **Color Glass Condensate**
  - ⇨ initial state: classsical FT in high density limit