ALICE in the early Universe Wonderland

Suzaku 2011

Exploring the X-ray Universe: Suzaku and Beyond

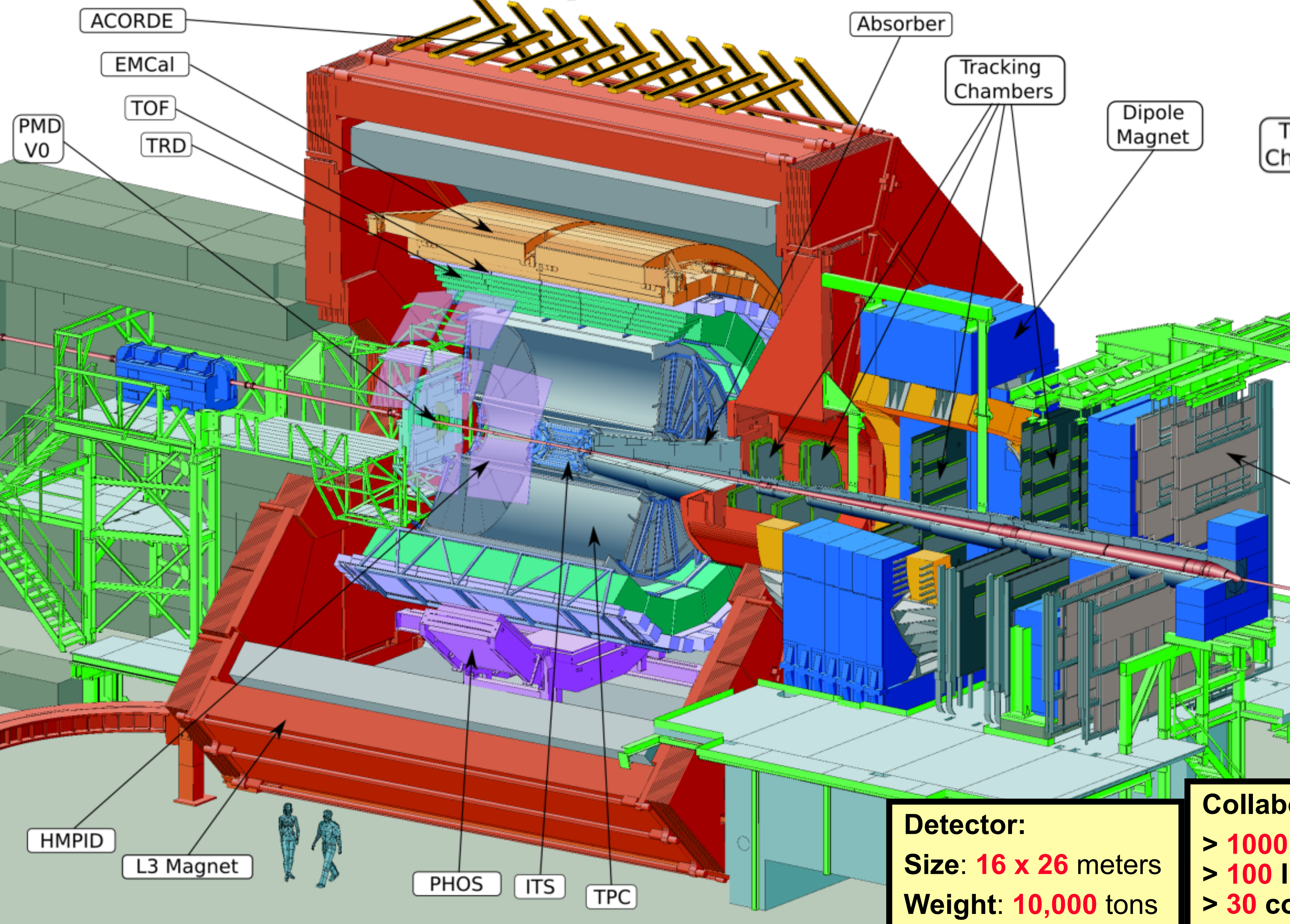
Kavli Institute for Particle Astrophysics and Cosmology
SLAC National Accelerator Laboratory
July 20-22, 2011

Pasquale Di Nezza
National Institute of Nuclear Physics
Italy

INFN Frascati

A Large Ion Collider Experiment

European Organisation for Nuclear Research



Detector:

Size: 16 x 26 meters

Weight: 10,000 tons

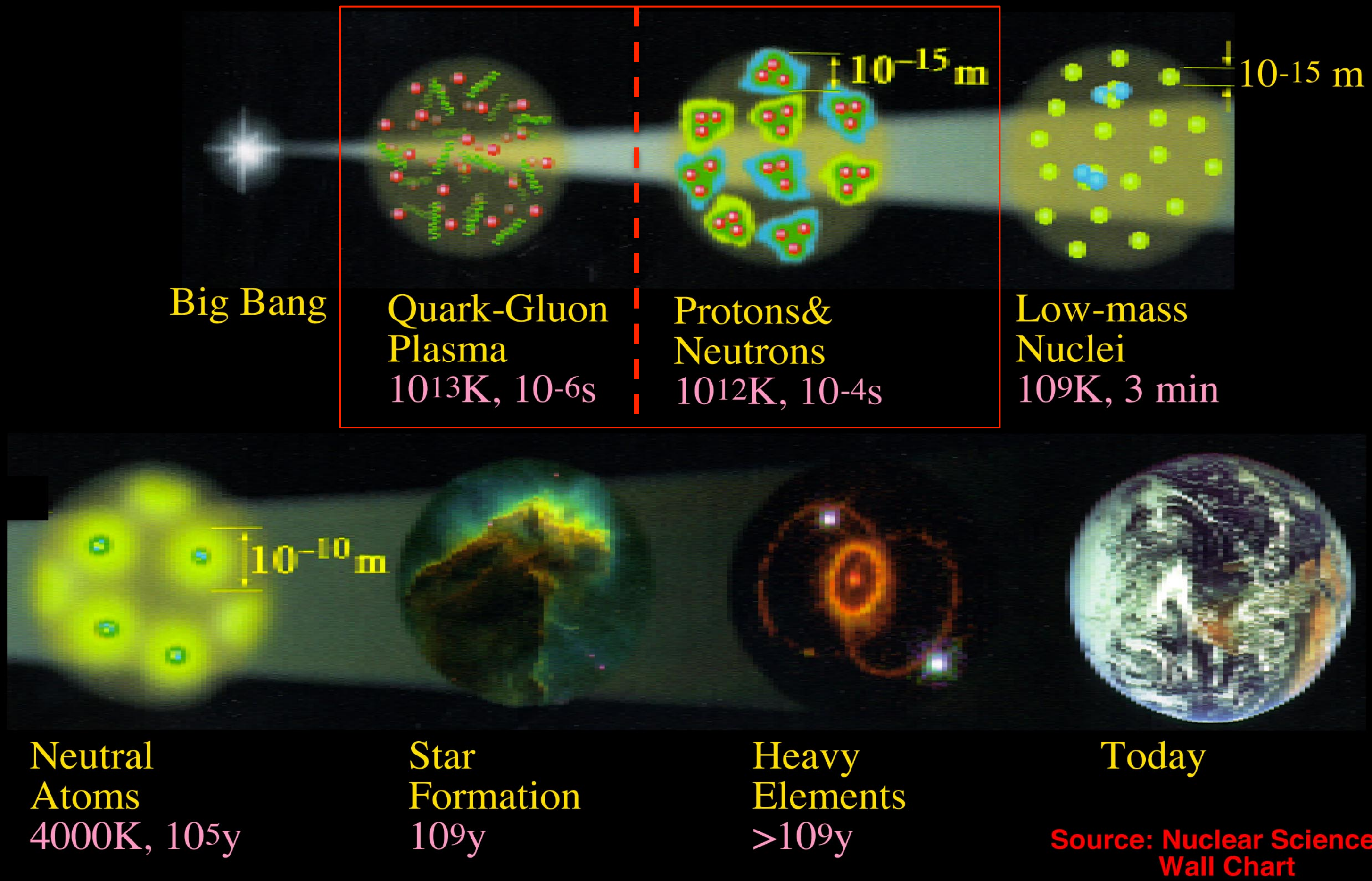
Collaboration:

> 1000 Members

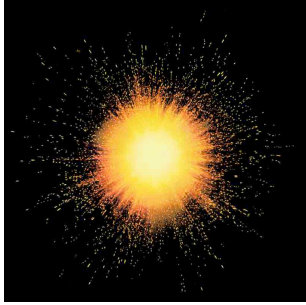
> 100 Institutes

> 30 countries

History of the Universe



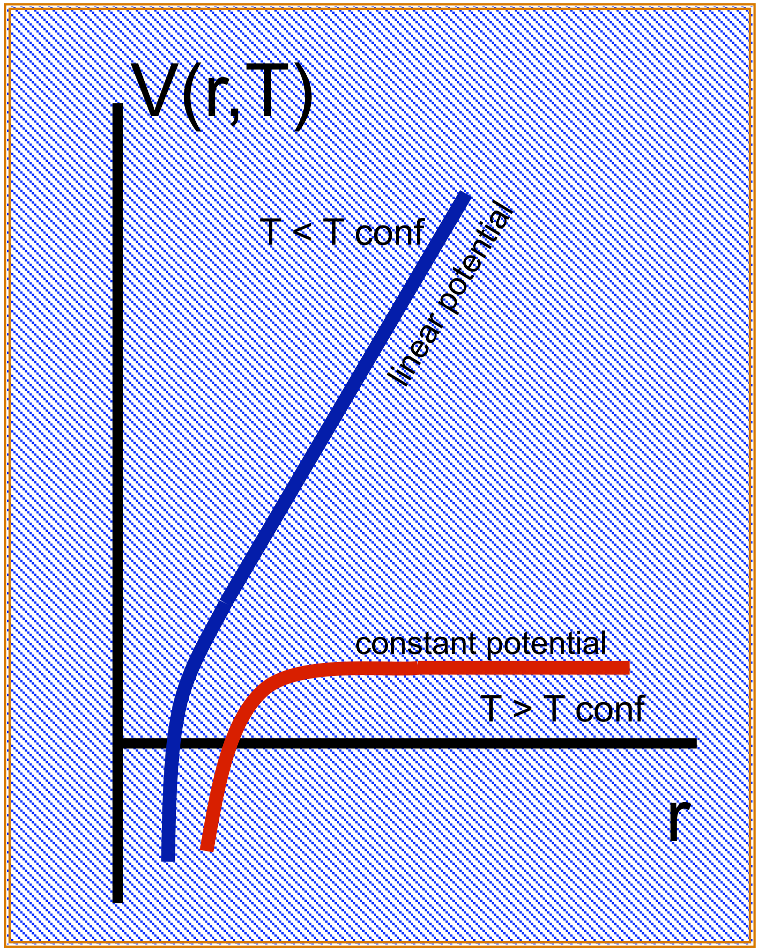
A Mini-Bang in the lab



- We need a small system so that it can be accelerated to ultrarelativistic speed (99.9% c)
- That system (i.e. a chunk of matter and not just a single particle) must follow simple rules of thermodynamics and form a new state of matter in a particular phase
- We can use heavy ions (e.g. Pb). They are tiny ($\sim 10^{-14}$ m) but have a finite volume that can be exposed to pressure and temperature

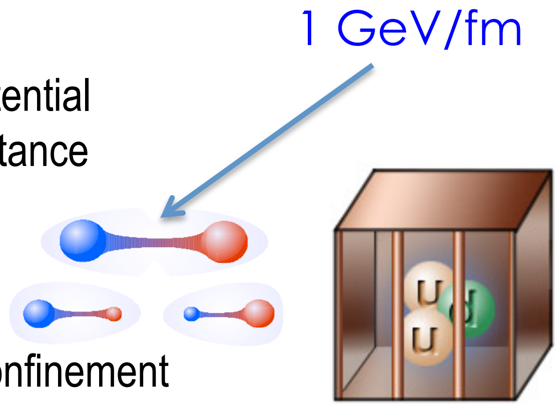
We will try to force matter, through a phase transition, to a new state of matter called "Quark Gluon Plasma"

Confined Potential



The potential between quarks is a function of distance. It also depends on the temperature.

1) At low temperature, the potential increases linearly with the distance between quarks
⇒ quarks are confined;



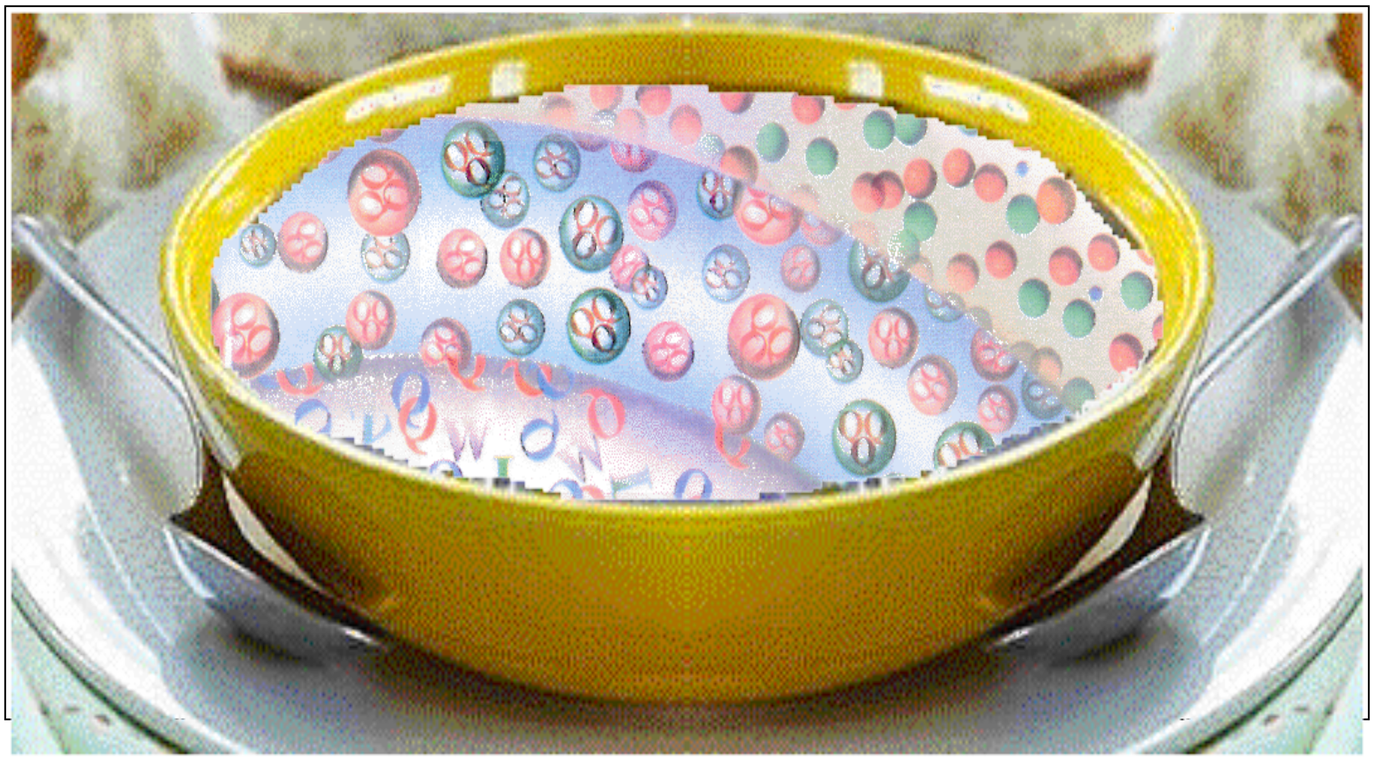
2) At high temperature, the confinement potential is ‘melted’
⇒ quarks are ‘free’.

Note: It is not clear at all if there is a critical ‘temperature’ in high energy collisions

When and how did the transition happen in the early Universe?

Collins and Perry (1975)

Term “quark soup” was originally proposed by Collins and Perry and comes from cosmology…



Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

We first give arguments leading to this idea. It is commonly believed that hadrons consist of quarks[5-7] despite the apparent nonexistence of free quarks.[8] There are two main reasons for this belief. First, a quark model explains[5,6] many properties of the hadron spectrum, and of strong-interaction decays. Secondly we have Bjorken scaling[7] in the deep inelastic scattering of leptons by nucleons. Basically, this indicates that hadrons consist of pointlike objects (partons) which interact weakly with each other when close together. Analysis of the data indicates that partons are the fractionally charged spin-$\frac{1}{2}$ Gell-Mann–Zweig quarks. Since free quarks are not observed,[8] it is assumed that they are permanently bound in hadrons[9] by a mechanism as yet unknown, but much speculated on.

!

A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

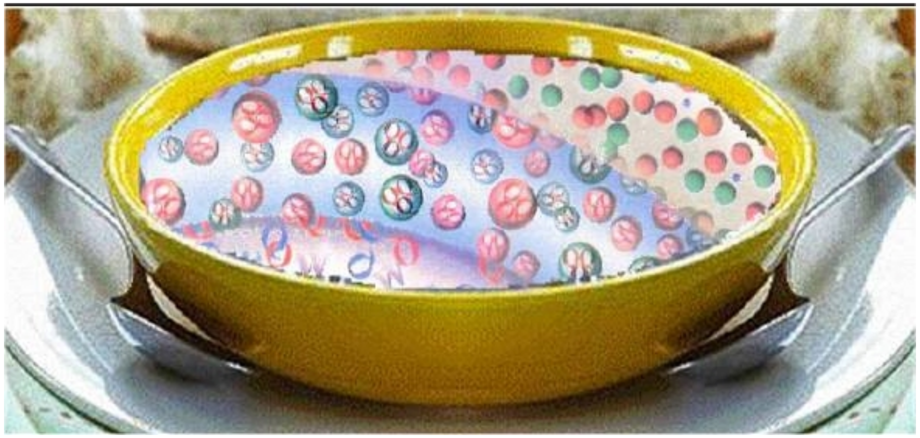
A soup "rich" of information

Space-time evolution of the hadron birth

QCD properties at high temperature: degree of freedom, viscosity, conductivity, …

Elliptic Flow

Chiral symmetry restauration



Freezout

Barionic Puzzle

Plasma instability, color chaos

q-g transition in early Universe cosmological theories

QCD equation state

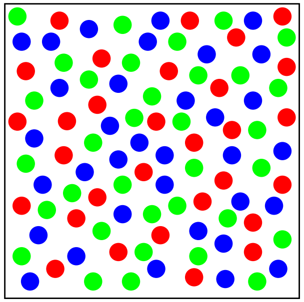
Partonic energy loss

Core of dense stars

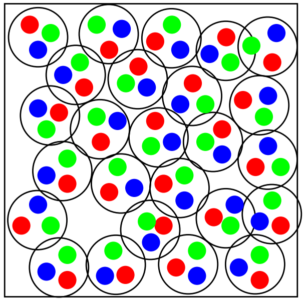
Phase transition in early Universe:

when the Universe cools below 150-200 MeV, i.e. 10^{-5} seconds from the Big Bang

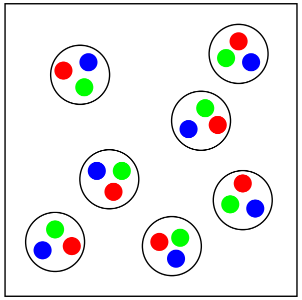
- *Before simply not enough "space" available for hadrons*
- *Color screening and high quark density forbid hadronic scale*



Quark Matter



Nuclear Matter



Nucleon Gas

Cosmological phase transitions

QCD phase transition	*T~175 MeV*
Electroweak phase transition *(bariogenesis, …)*	*T~150 GeV*
Inflation *(primordial densisty fluctuations, primordial magnetic fields, …)*	*T~10^{15} GeV*
GUT phase transition *(monopoles, cosmic strings, …)*	*T~10^{16} GeV*

The Transition

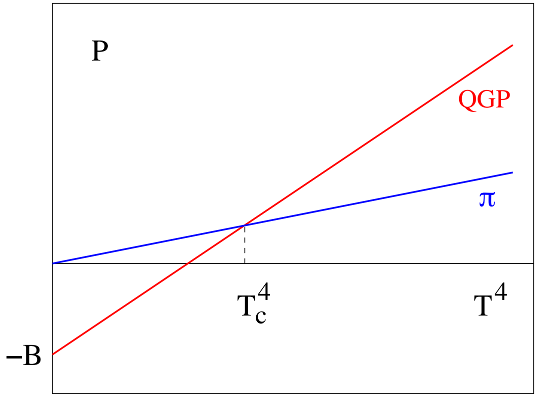
$$P=\frac{\pi^2}{90}NT^4$$

Simplest confined matter: ideal pion gas N=3 →

$$P_\pi=\frac{\pi^2}{90}3T^4\approx\frac{1}{3}T^4$$

Simplest deconfined matter: ideal quark-gluon plasma N=37 →

$$P_{QGP}=\frac{\pi^2}{90}\left\{2_{spin}\cdot 8_{gluons}+\frac{7}{8}\cdot 2_{flavors}\cdot 2_{q\bar{q}}\cdot 2_{spin}\cdot 3_{color}\right\}T^4\text{-}P_{bag}\approx 4T^4\text{-}P_{bag}$$

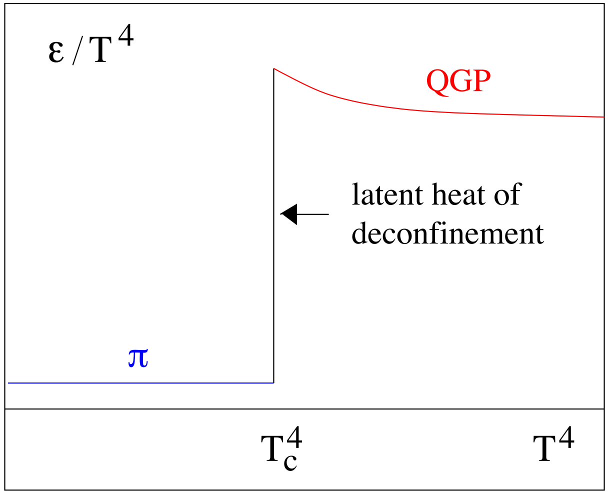


$$T_C^4\approx 0.3B\approx 150\text{-}200\text{ MeV}$$

$$\varepsilon_C\approx 0.5\text{-}1.0\text{ GeV/fm}^3$$

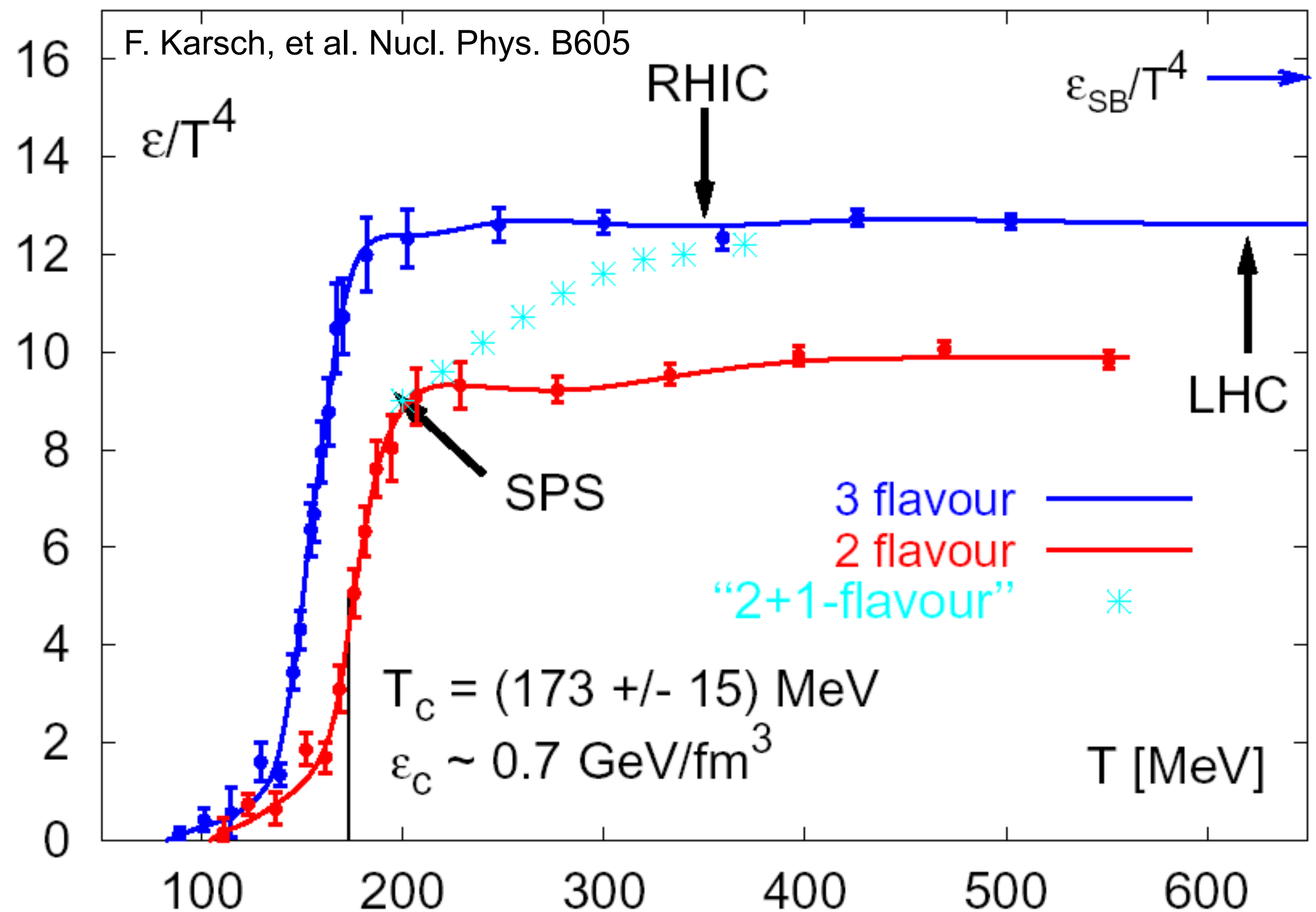
At the critical temperature a strong increase in the degrees of freedom appears:

- ✓ *Gluons, quarks*
- ✓ *Not an ideal gas close to T_C → residual interactions*
- ✓ *At the phase transition dp/dε decreases rapidly by latent heat of deconfinement*

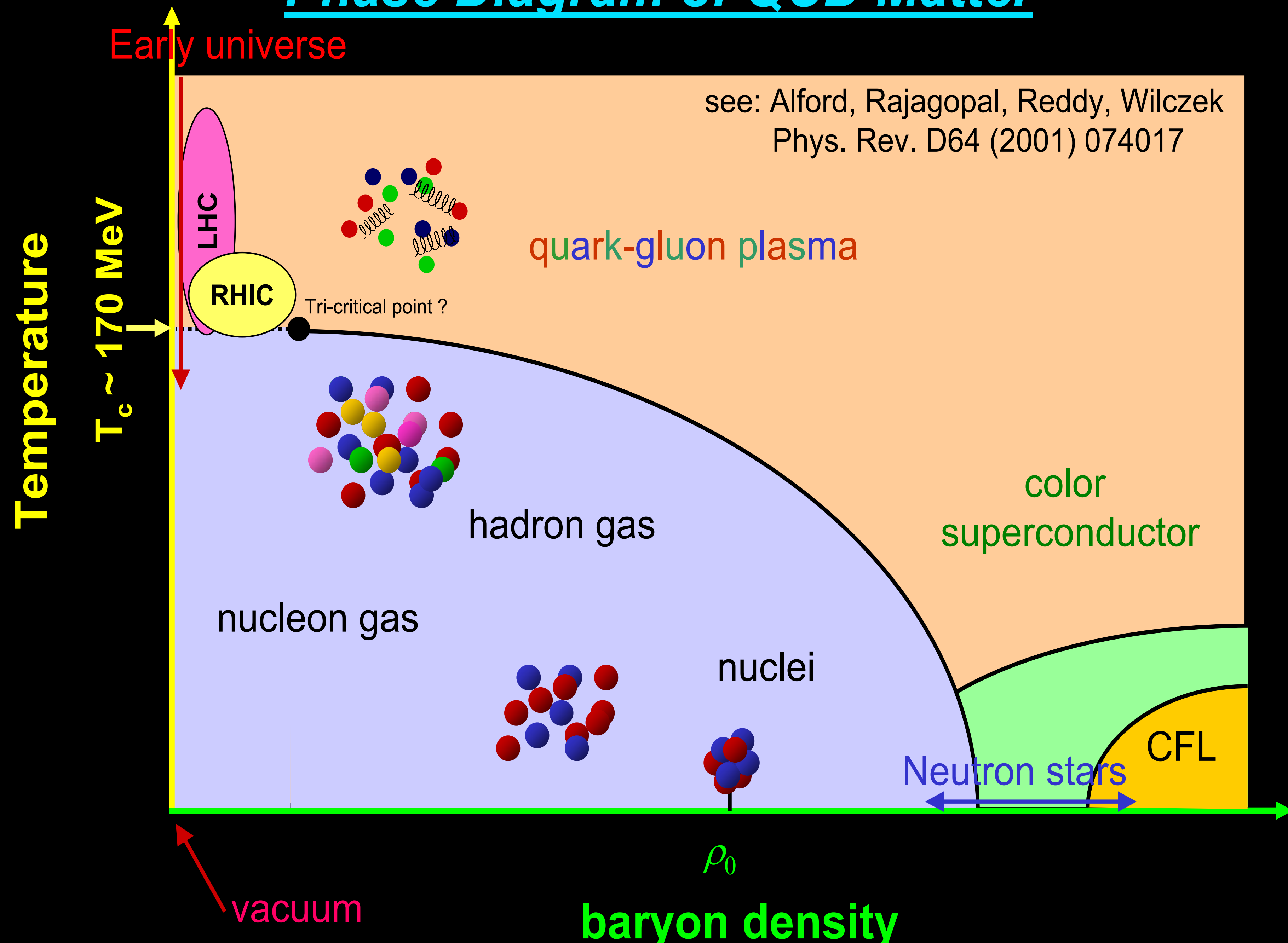


The Transition

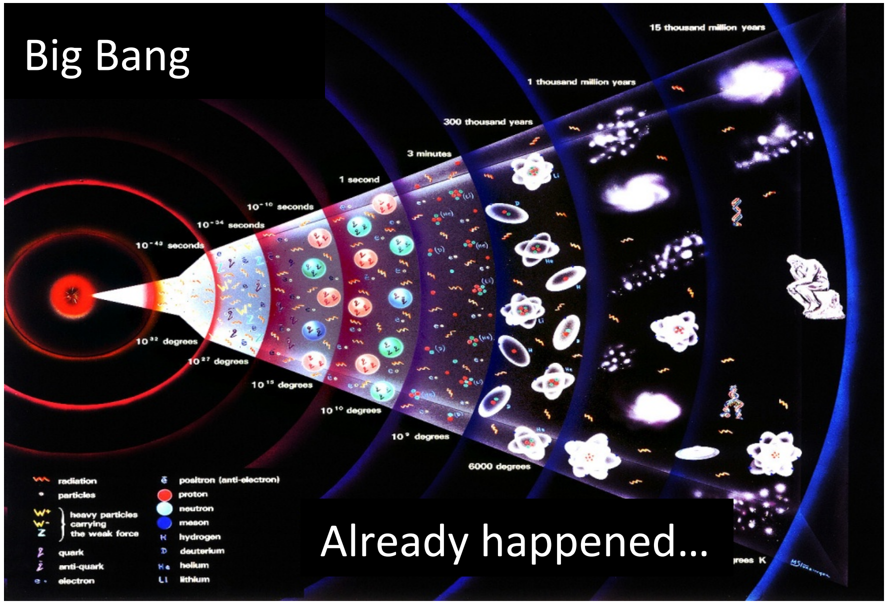
LHC plasma hotter, denser, longer lived

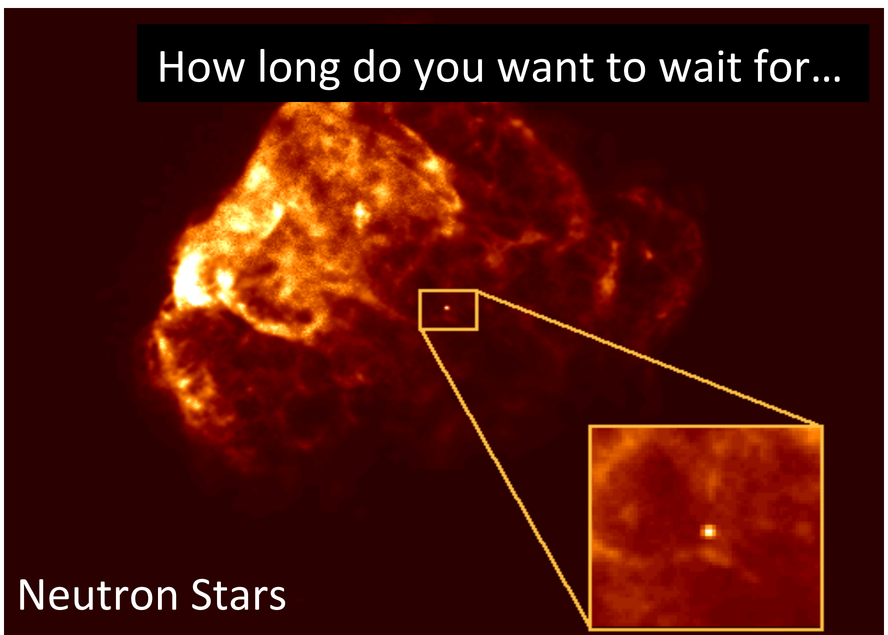


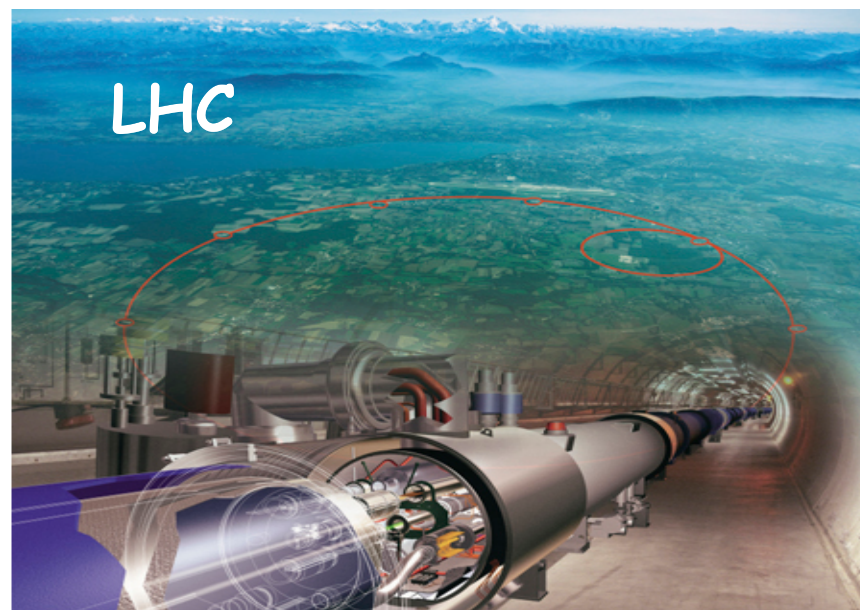
Phase Diagram of QCD Matter



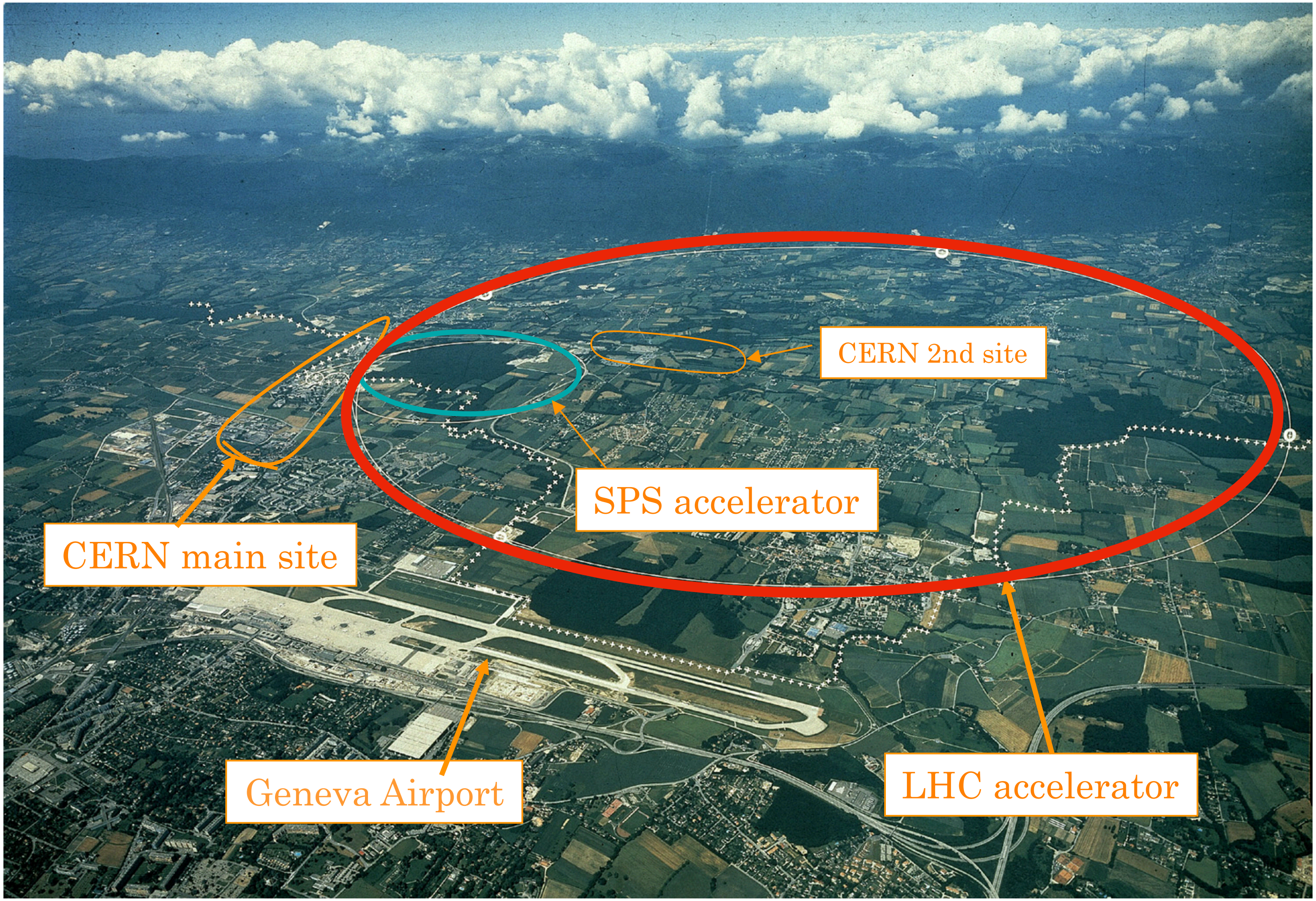
Where can the QGP be produced ?





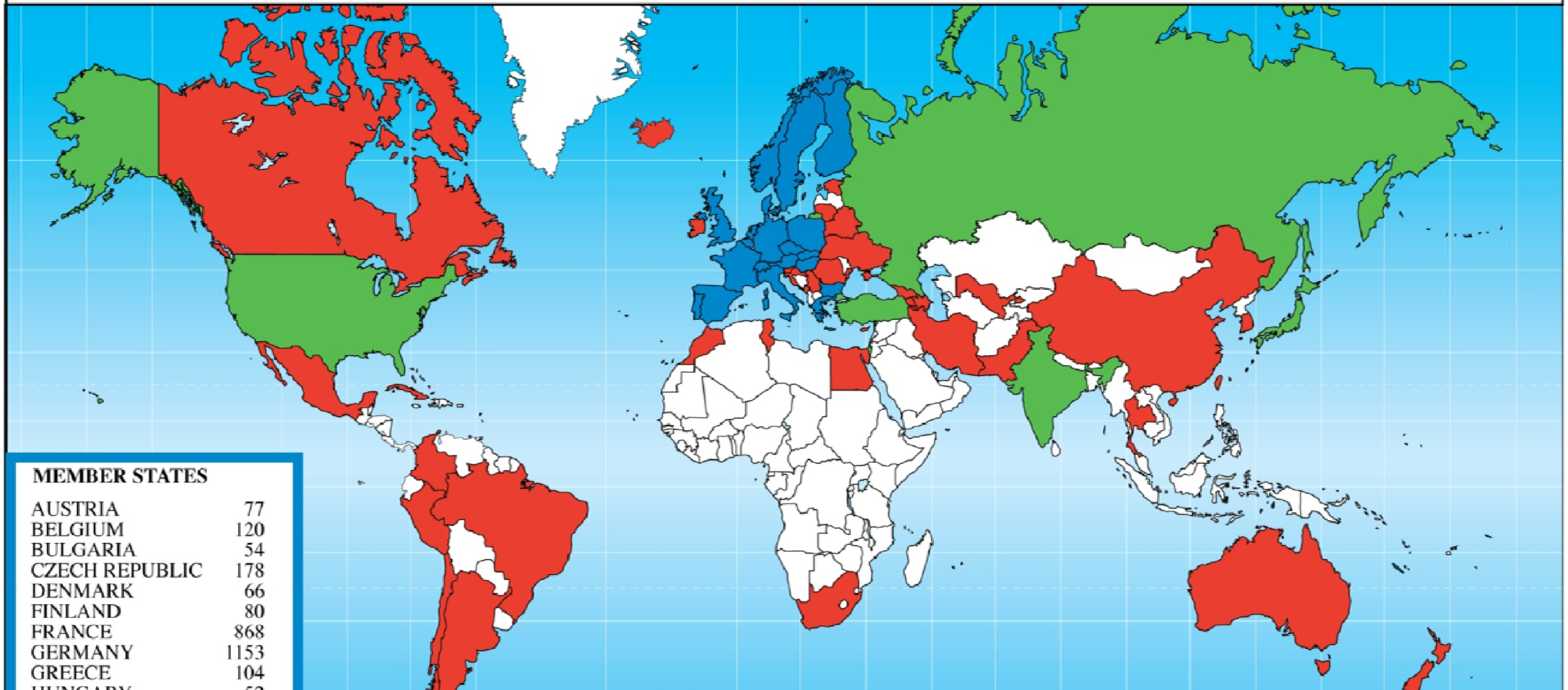


At the LHC it can happen



CERN in Numbers

Distribution of All CERN Users by Nation of Institute on 20 January 2010



MEMBER STATES

AUSTRIA	77
BELGIUM	120
BULGARIA	54
CZECH REPUBLIC	178
DENMARK	66
FINLAND	80
FRANCE	868
GERMANY	1153
GREECE	104
HUNGARY	52
ITALY	1463
NETHERLANDS	170
NORWAY	73
POLAND	191
PORTUGAL	122
SLOVAKIA	55
SPAIN	311
SWEDEN	71
SWITZERLAND	362
UNITED KINGDOM	732

6302

OBSERVER STATES

INDIA	91
ISRAEL	49
JAPAN	204
RUSSIA	901
TURKEY	60
USA	1618

2923

OTHERS

ARGENTINA	8	CROATIA	18	MALTA	2	THAILAND	1
ARMENIA	16	CUBA	4	MEXICO	33	TUNISIA	1
AUSTRALIA	17	CYPRUS	8	MONTENEGRO	1	UKRAINE	17
AZERBAIJAN	1	EGYPT	3	MOROCCO	6	UZBEKISTAN	1
BELARUS	19	ESTONIA	9	NEW ZEALAND	8		
BRAZIL	77	GEORGIA	10	PAKISTAN	15		
CANADA	141	ICELAND	1	PERU	1		
CHILE	2	IRAN	15	ROMANIA	59		
CHINA	78	IRELAND	14	SERBIA	20		
CHINA (TAIPEI)	53	KOREA	64	SLOVENIA	17		
COLOMBIA	9	LITHUANIA	5	SOUTH AFRICA	8		

762

LHC

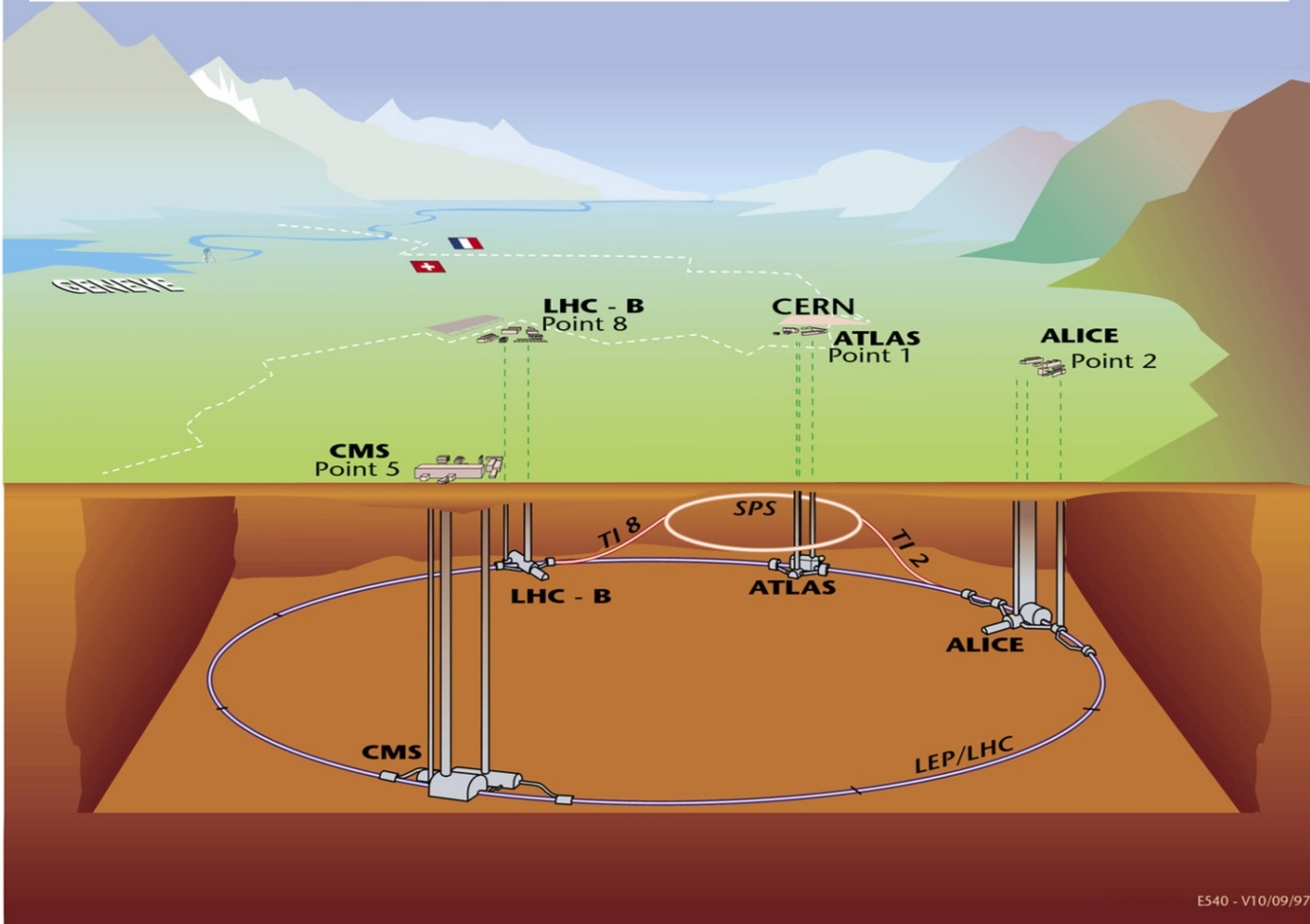
Main Ion-Ion Colliders in the history:

- *AGS* $\sqrt{s}\sim$ 5 GeV
- *SPS* $\sqrt{s}\sim$ 17 GeV
- *RHIC* $\sqrt{s}\sim$ 200 GeV
- *LHC* $\sqrt{s}\sim$ 5500 GeV

1232 superconducting dipoles at 9T
500 superconducting quadrupoles at 250 T/m
4100 superconducting correction magnets
$4x10^5$ tons of material at 1.9 K

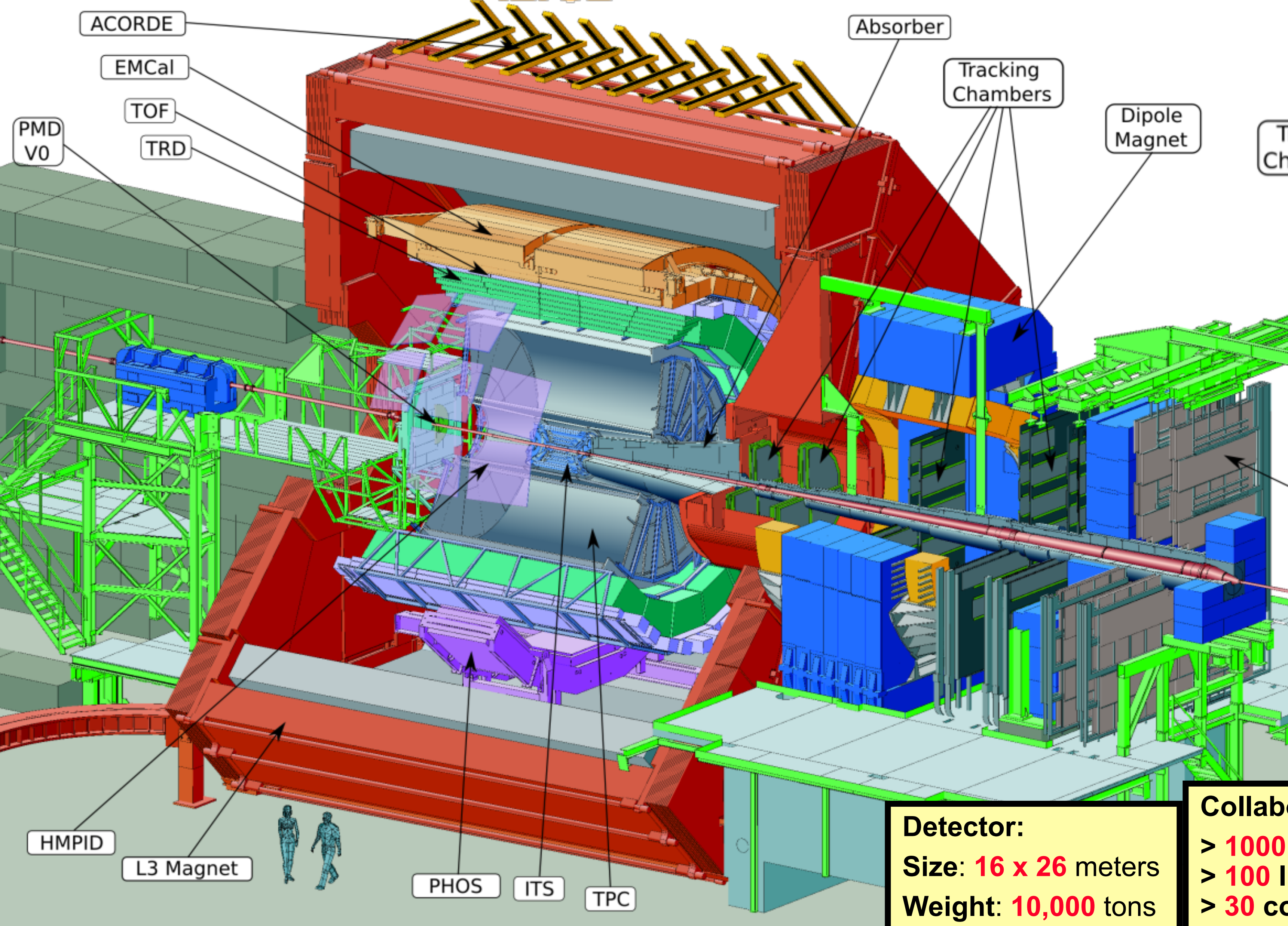
LHC
Total cost 9 GEuro

Overall view of the LHC experiments.



A Large Ion Collider Experiment

European Organisation for Nuclear Research



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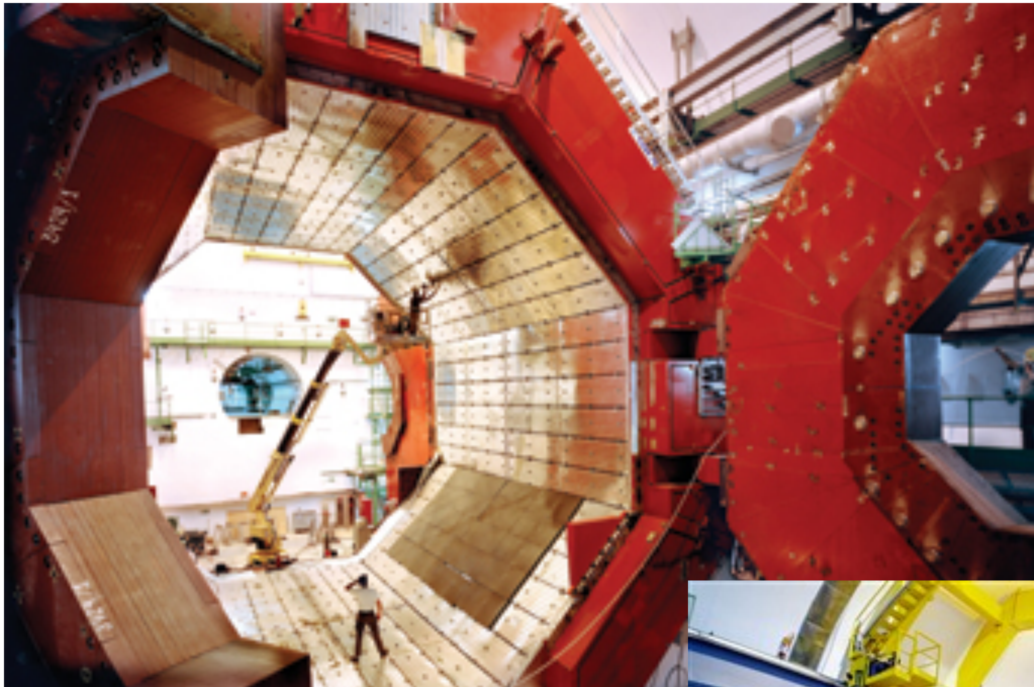
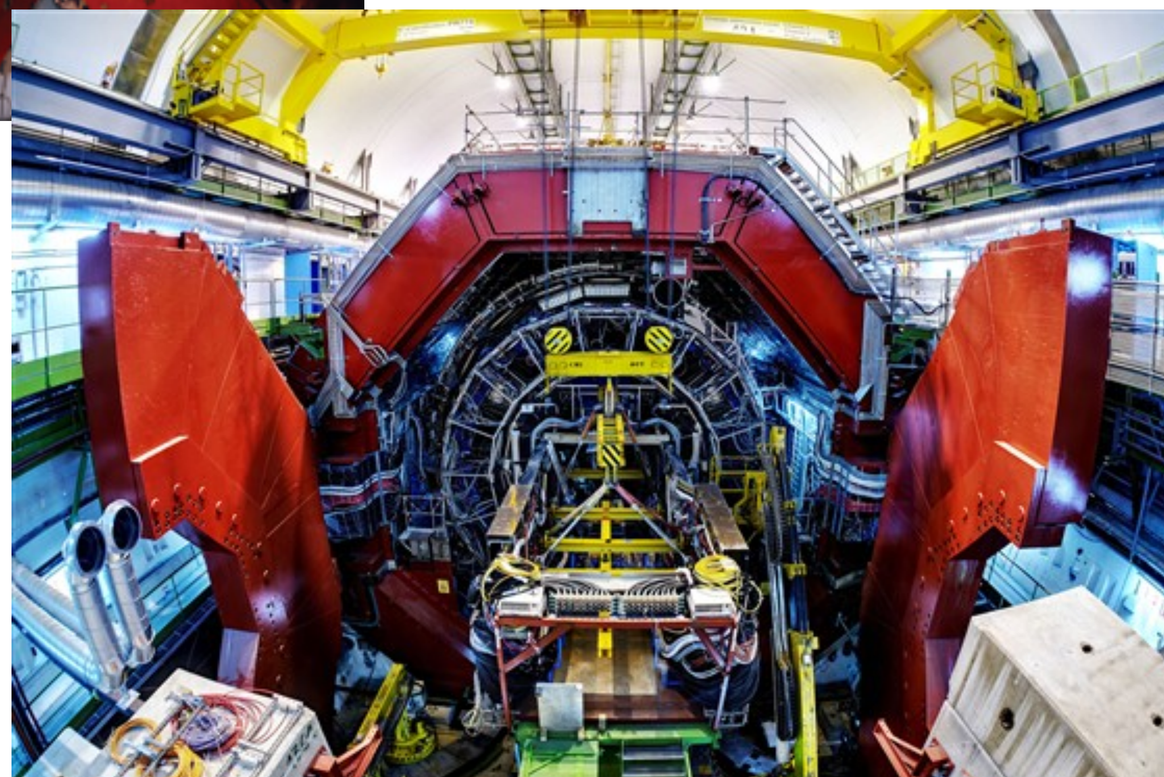
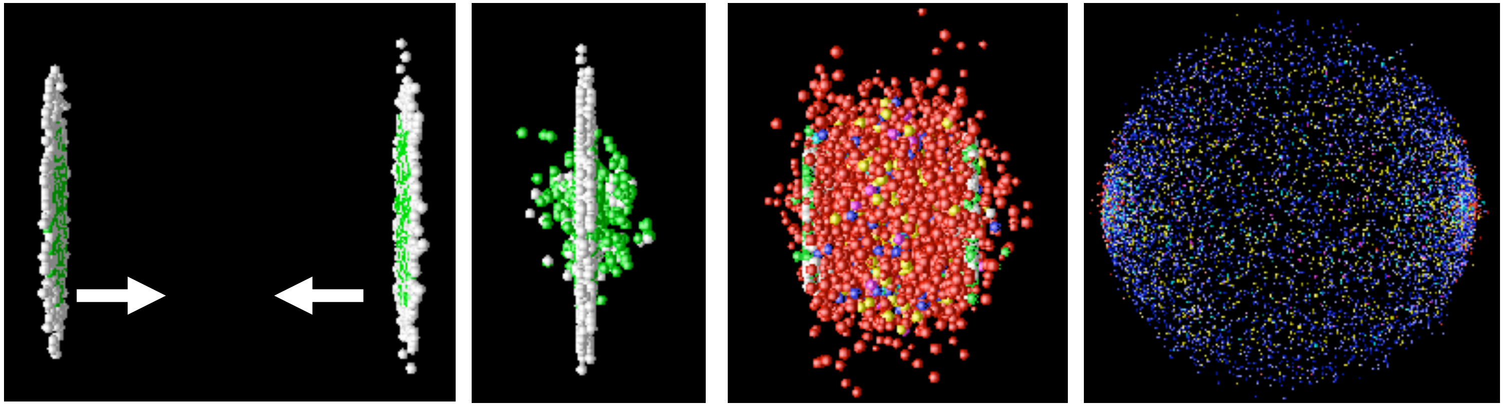


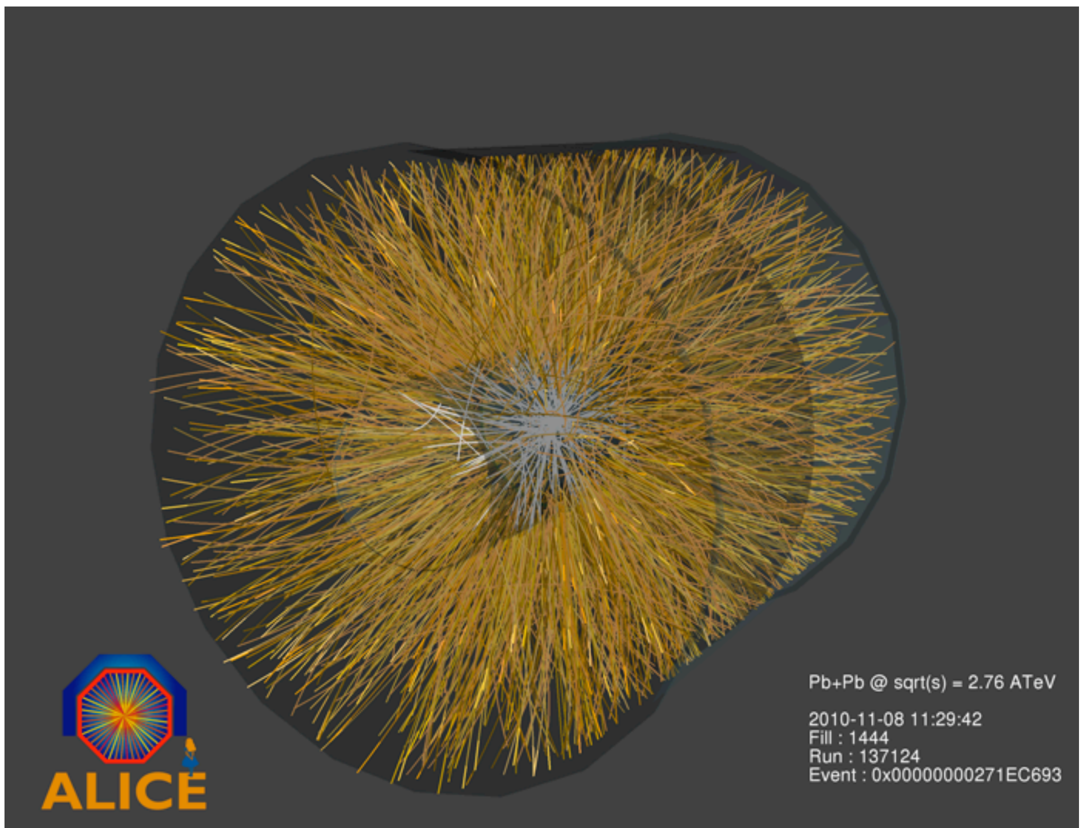
ALICE



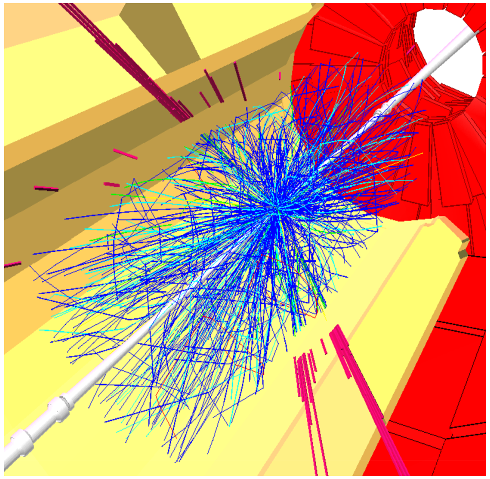


Collision time ~ 10^{-22} s

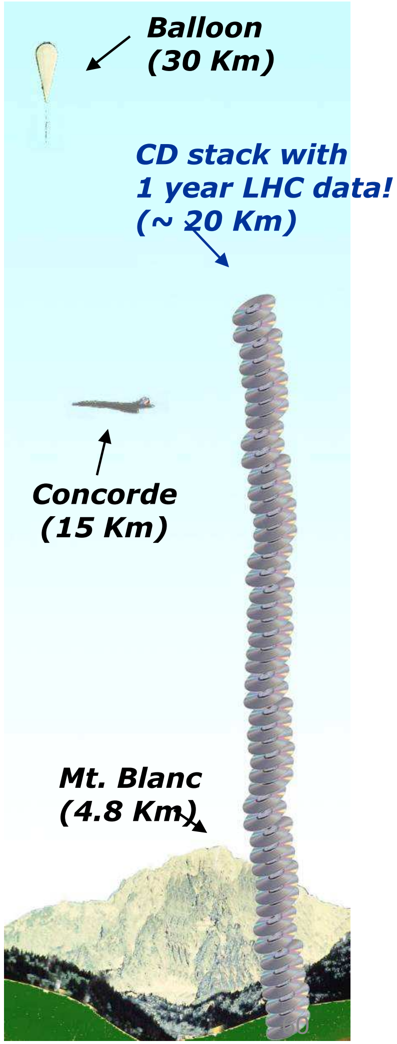
Approach **Collision** **Particle Shower**



Worldwide LHC Computing Grid (wLCG)



WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project's size

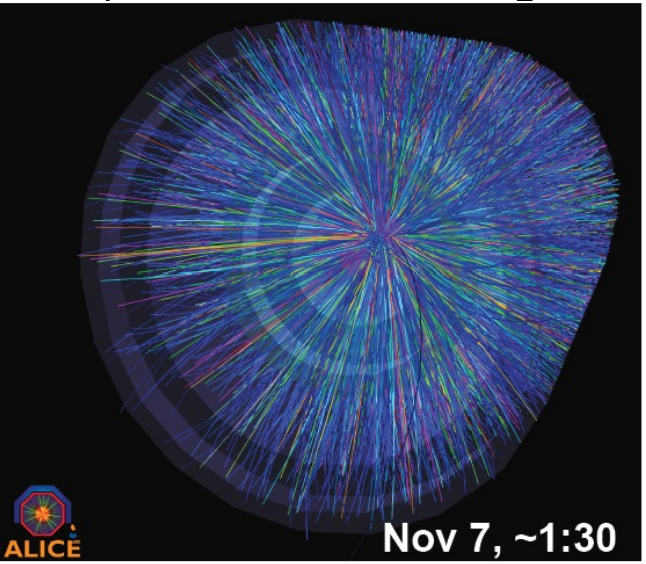


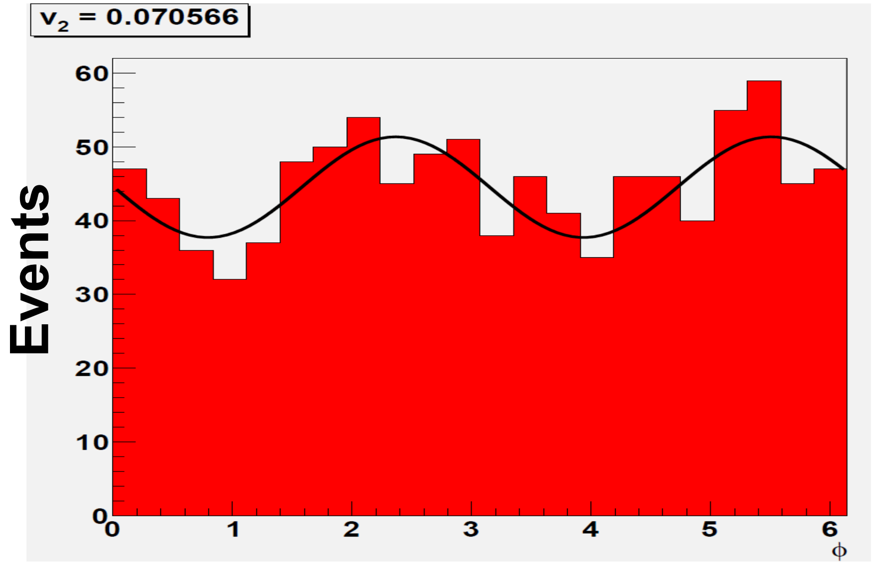
GRID computing developed to solve problem of data storage and analysis

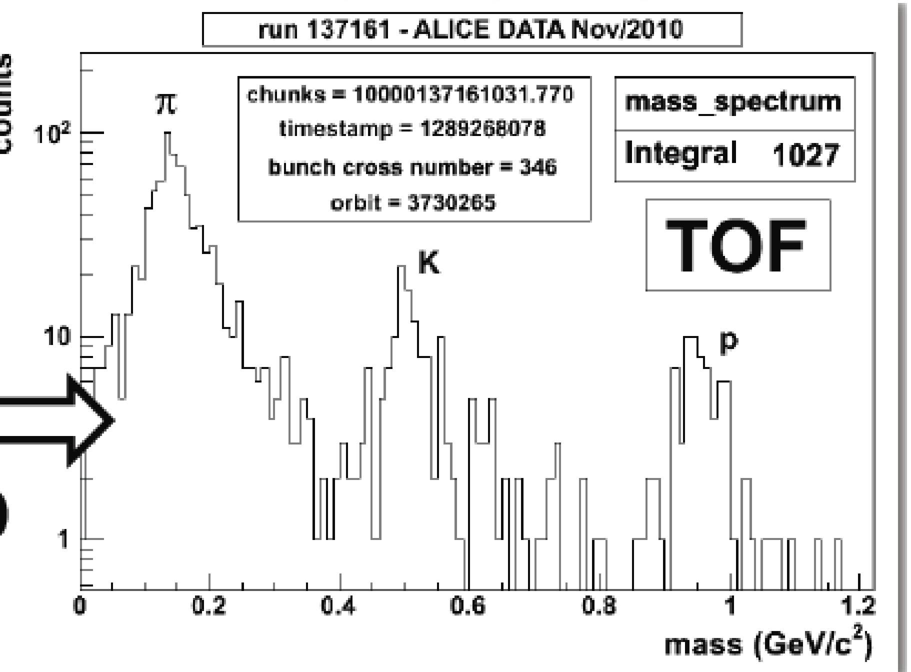
LHC data volume per year:
10-15 Petabytes

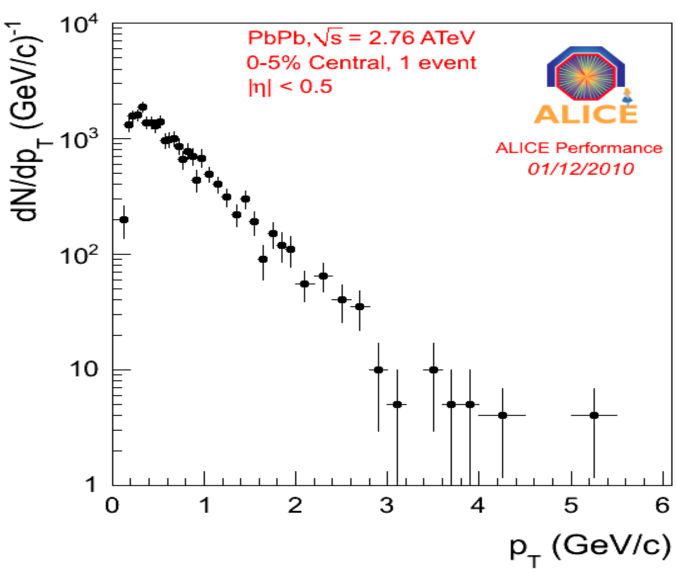
A Single Event

Properties of average events instead of average event properties

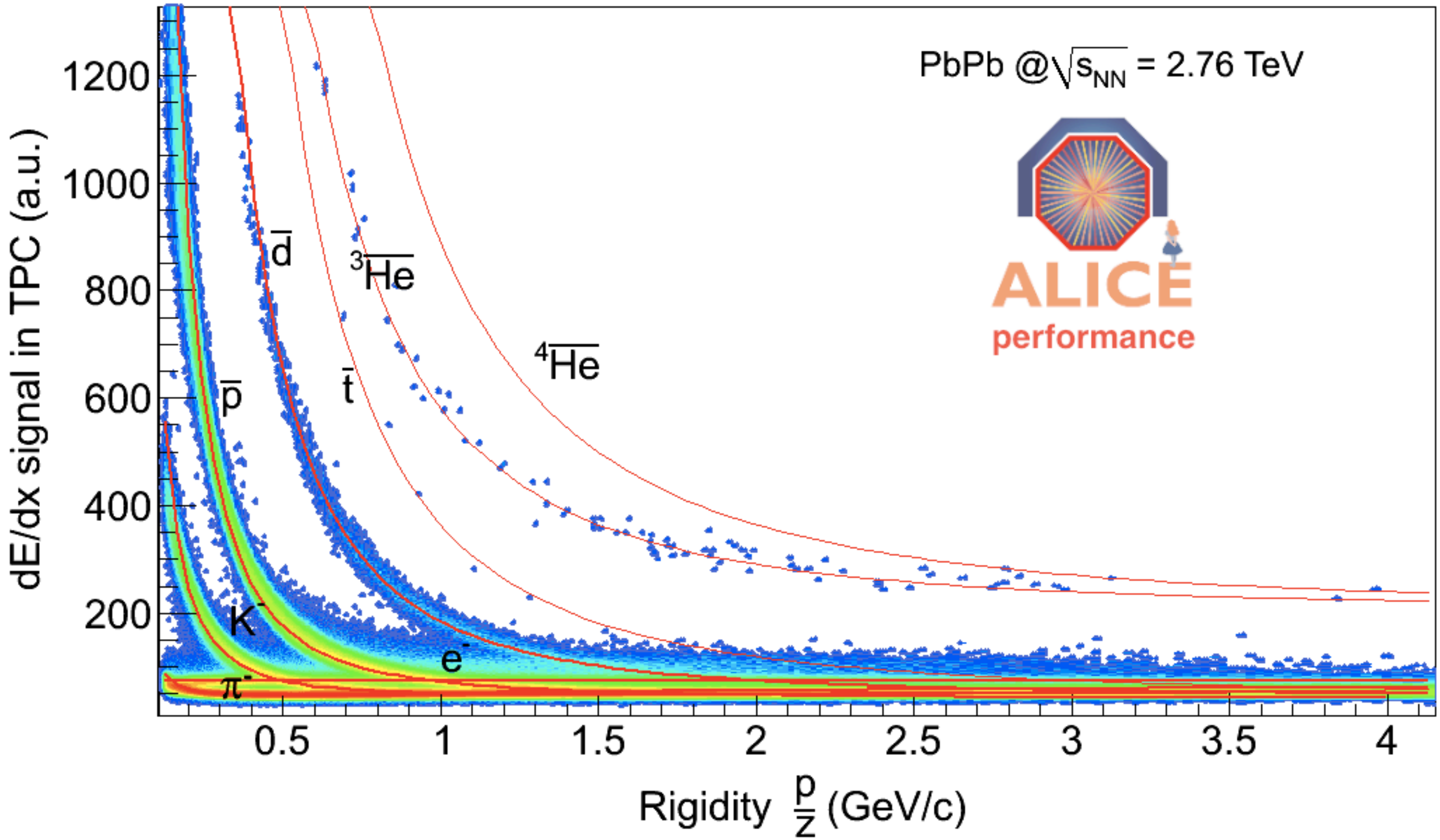








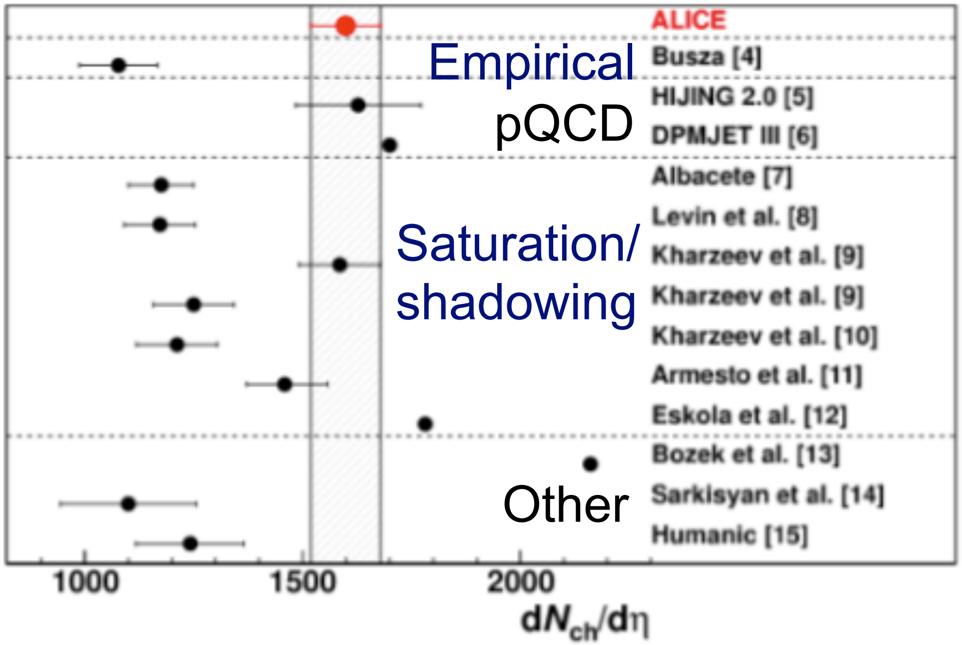
Anti-Nuclei



~ 2 M Pb-Pb Min Bias events

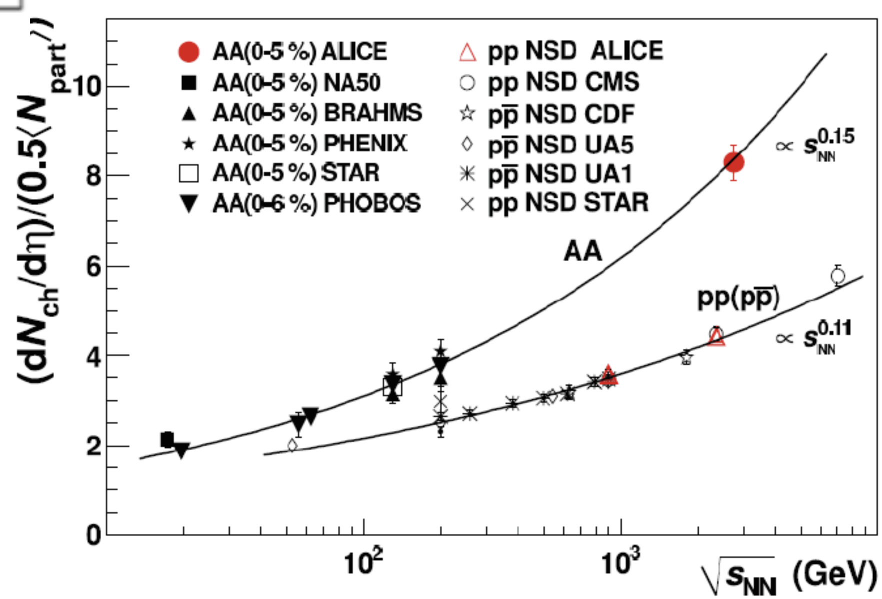
Charge particle multiplicity

$dN_{ch}/d\eta$ = 1584±4(stat)±76 (sys) 5% most central Pb+Pb at 2.76 TeV



Result on high side of expectations

PRL 105, 252301 (2010)



Growth with √s faster in AA than pp
(√s dependent ‘nuclear amplification’)

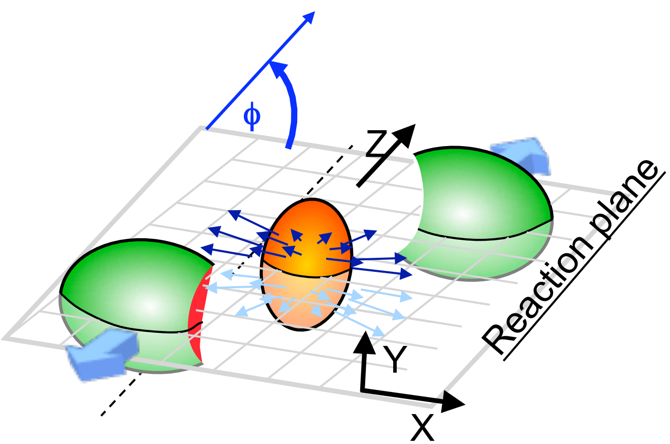
Testing the HI 'Standard Model'

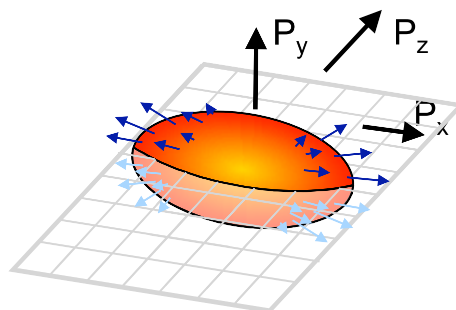
Elliptic Flow: one of the most anticipated answers from LHC

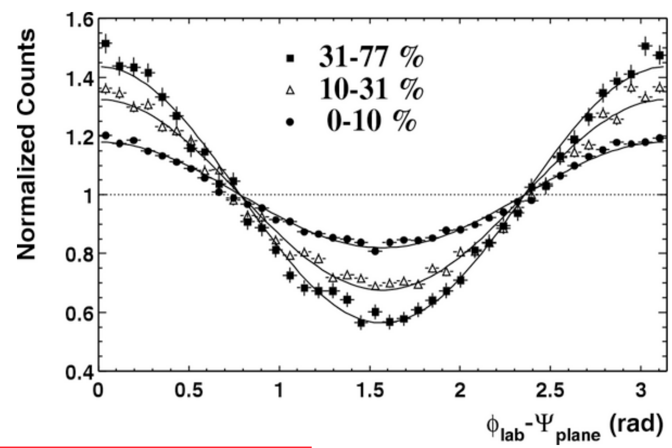
⇨ <u>experimental observation:</u> particles are distributed with azimuthally anisotropy around the scattering plane

⇨ Are we sure Hydro interpretation is correct ?

Initial state spatial an isotropy → Final state momentum isotropy → cos(2ΔΦ) modulation in particle distributions







Elliptic Flow v_2 as interpreted by Hydrodynamics

Pressure gradient converts

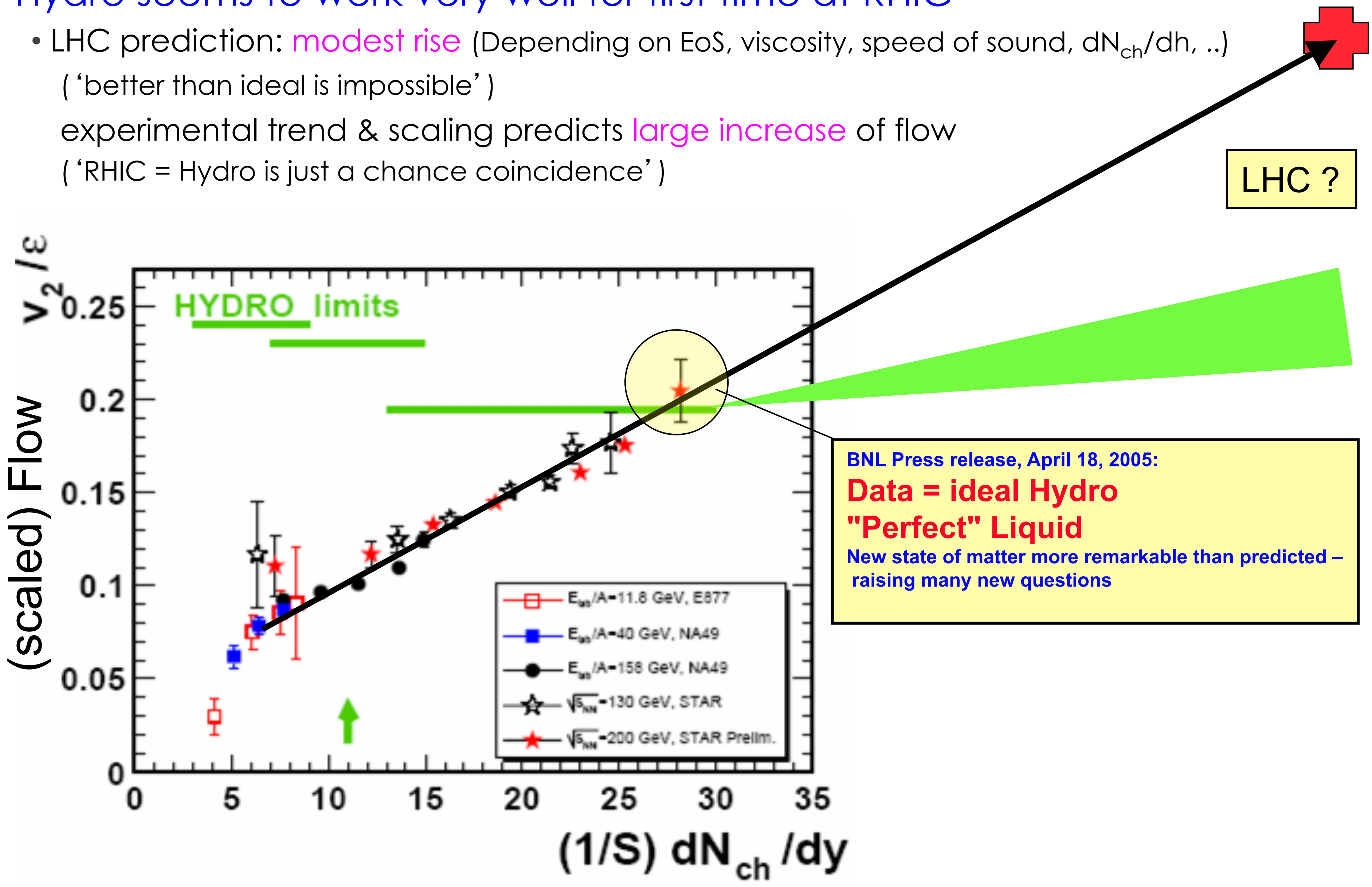
spatial anisotropy → momentum anisotropy

→ particle yield anisotropy

Testing the HI 'Standard Model'

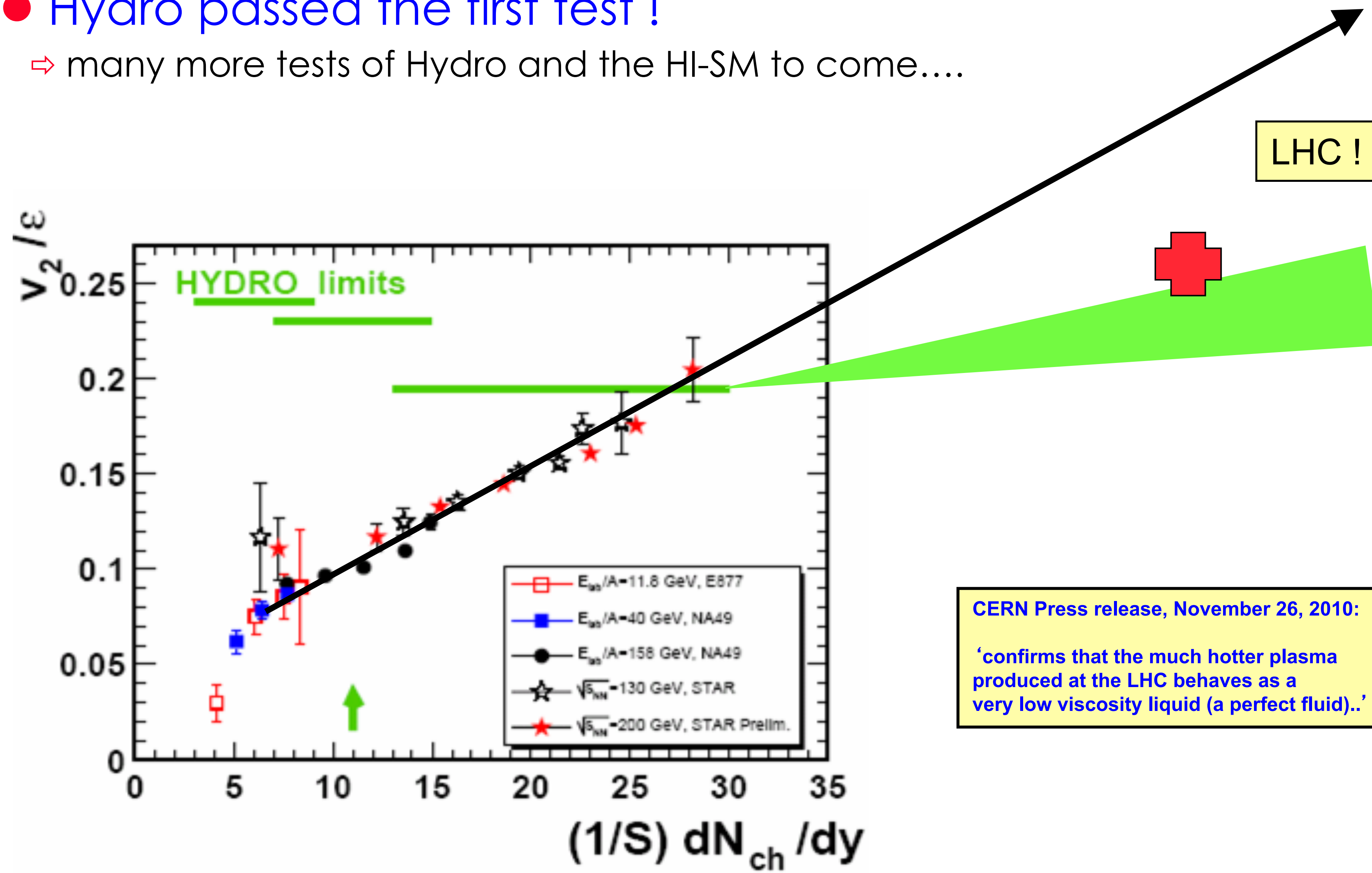
Hydro seems to work very well for first time at RHIC

- LHC prediction: modest rise (Depending on EoS, viscosity, speed of sound, $dN_{ch}/d\eta$, ..)
  ('better than ideal is impossible')
  experimental trend & scaling predicts large increase of flow
  ('RHIC = Hydro is just a chance coincidence')



Testing the HI 'Standard Model'

- Hydro passed the first test !
  - ⇨ many more tests of Hydro and the HI-SM to come….



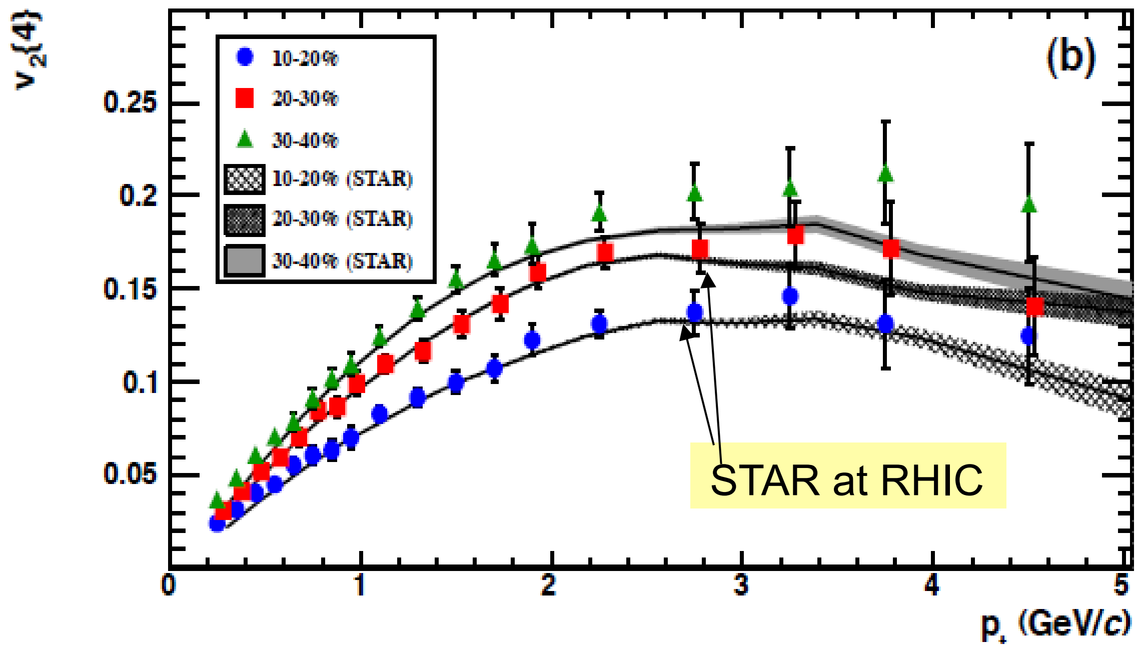
Disclaimer: very rough guesstimate, assuming geometry not to change between RHIC and LHC

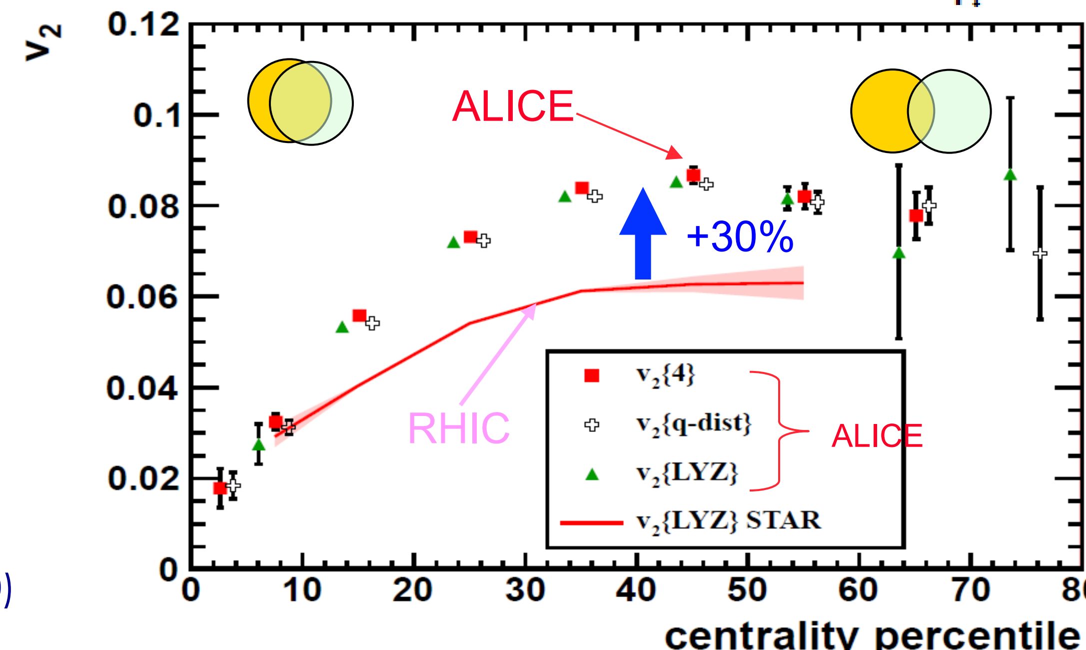
CERN Press release, November 26, 2010:

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

First Elliptic Flow Measurement at LHC

- v_2 as function of p_t
  - ⇨ practically no change with energy !
    - ✪ extends towards larger centrality/higher p_t ?
- v_2 integrated over pt
  - ⇨ 30% increase from RHIC
  - ⇨ <p_t> increases with √s
    - ✪ pQCD powerlaw tail ?
  - ⇨ Hydro predicts increased 'radial flow'
    - ✪ very characteristic p_t and mass dependence; to be confirmed !



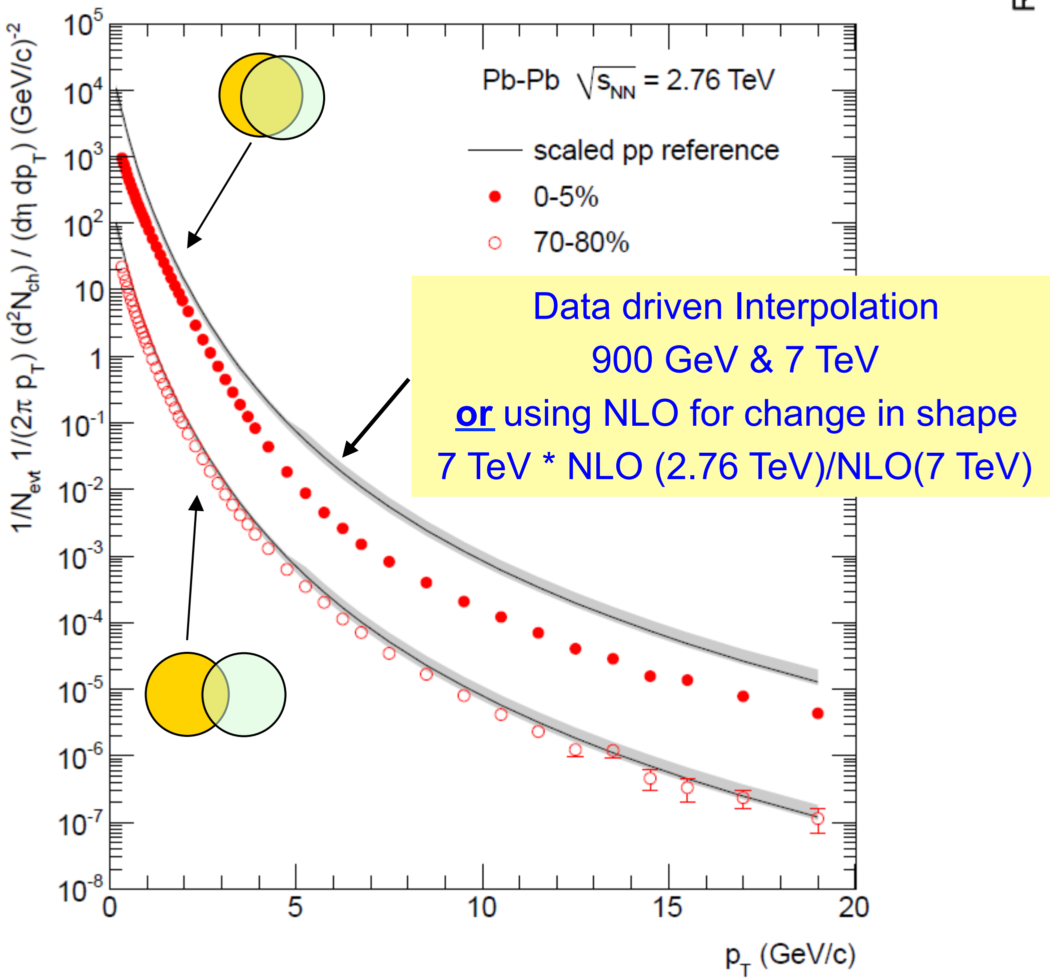


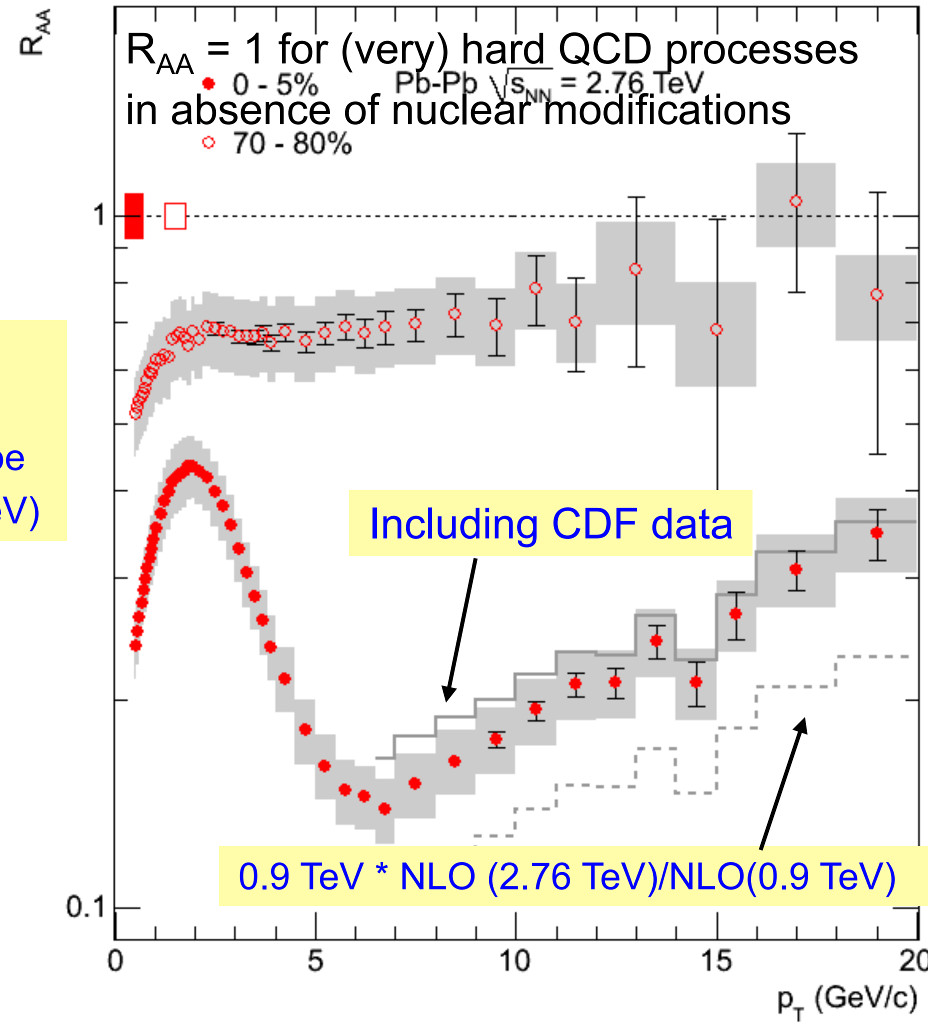
PRL 105, 252301 (2010)

Quenching as seen by p_t spectra

- Suppression of high p_t particles (~ leading jet fragments)
  - ⇨ Minimum R_{AA} ~ 1.5 – 2 x smaller than at RHIC
  - ⇨ Rising with p_t ! (ambiguous at RHIC !)
  - ⇨ accuracy limited by pp reference

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





Global observables summary

- Energy density > 50 GeV/fm^3
- Freeze-out volume ~300 fm^3
- Time scale until decoupling 10 fm/c
- Elliptic flow as expected from hydro-dynamical calculations
- Initial state saturation effects smaller than expected

Can a Black Hole be produced at the LHC?

"It's black, and it looks like a hole. I'd say it's a Black Hole."

- At CM energies above Planck scale, black holes can be produced in particle collisions

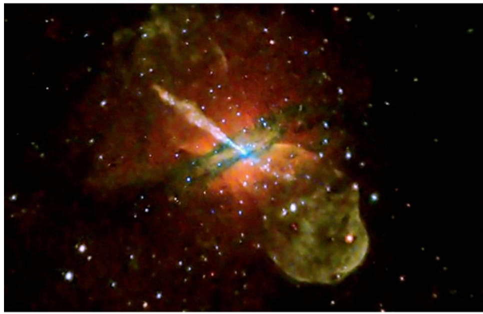
- Naively, the xsection for a BH production is:
  $\sigma \approx \pi R_S^2$ with R_S the Schwarzschild radius

- The production depends on which fraction of available parton energy goes into forming the black hole (trapped behind horizon)

- Energy needed $\sqrt{s} \sim M_{Plank} = 10^{19}$ GeV

No way!

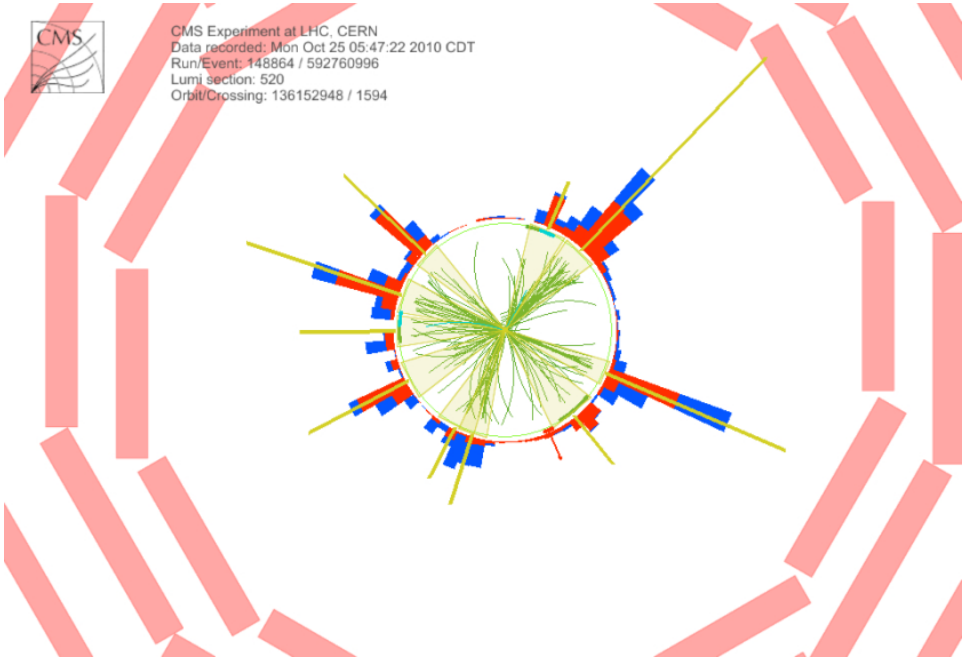
- Impact parameter < R_S (i.e. particles passing within distance smaller than the event horizon)



Black Holes evolution and decay

- Mini black holes produced at LHC would be light and tiny compared to cosmic black holes (~TeV versus ~3 Solar masses)
- This means they would be extremely hot (T~100 GeV) and evaporate almost instantaneously, mainly via Hawking radiation

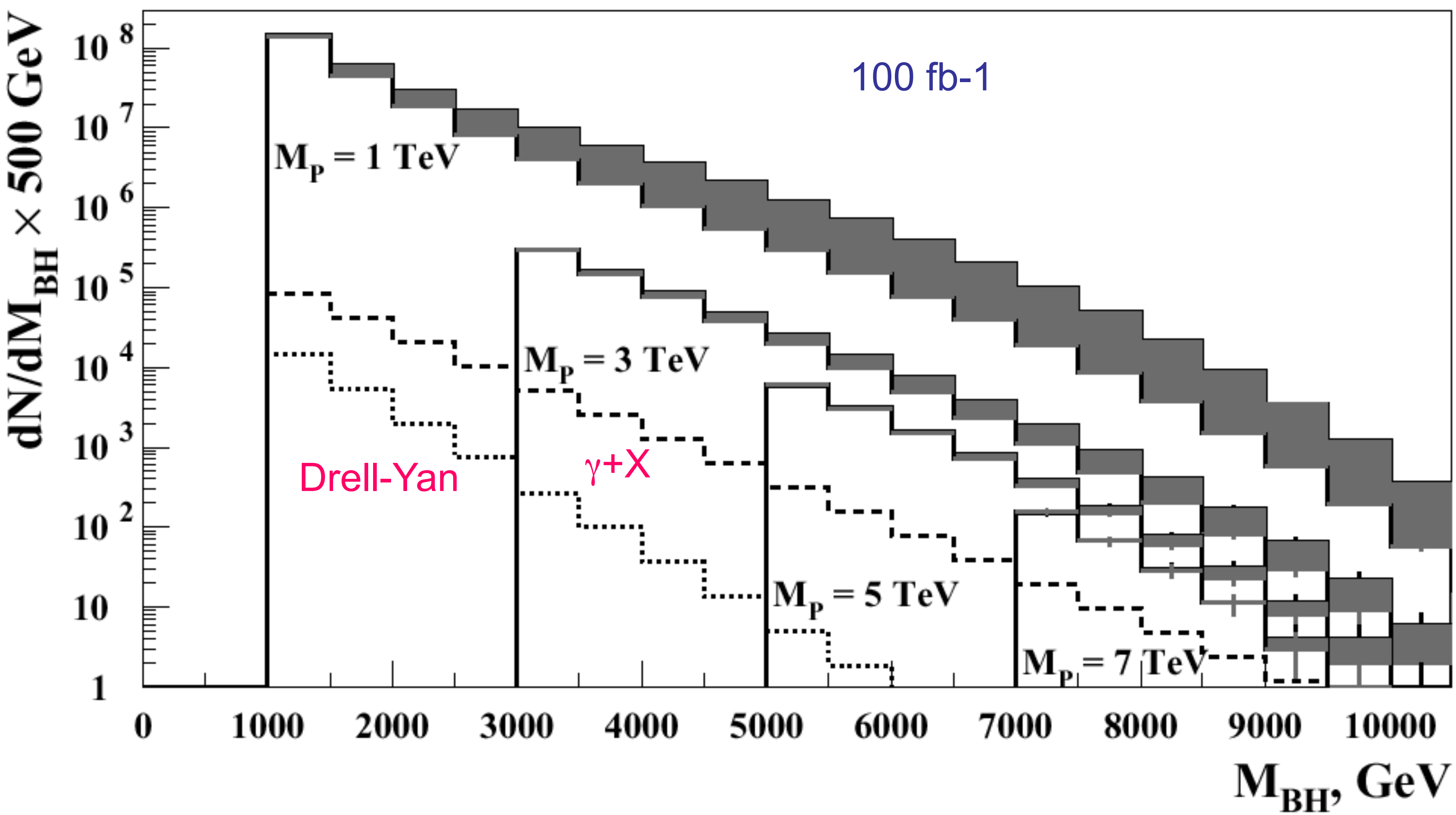
- Typical decay signature:
  ~6 ptc for each decay emitted spherically
    75% quarks and gluons
    10% charged leptons
    5% neutrinos
    5% of photons or W/Z boson
    new ptc around 100 GeV



BH event simulated by CMS

LHC as a Black Hole Factory

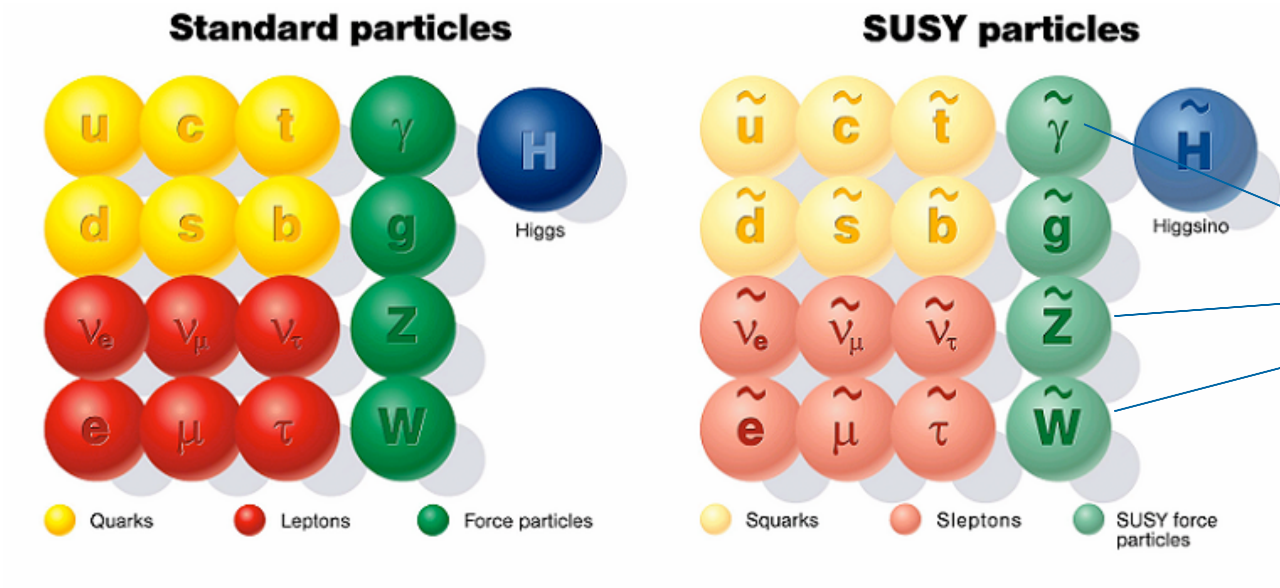
Spectrum of BH produced at the LHC w/ subsequent decay into final states tagged with an electron or a photon [Dimopoulos, G. Landsberg, PRL 87, 161602 (2001)]



For Planck scale up to ~ 5 TeV, clean and large samples of BH's at the LHC

SUSY

SM extension: each boson(fermion) gets a fermion(boson) "superpartner" which differs only in spin

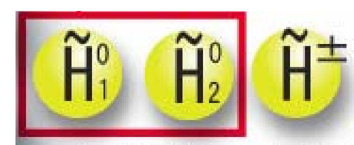


Gauginos mix to form charginos and neutralinos

$$\tilde{\chi}_i^{\pm} \quad \tilde{\chi}_j^{0}$$

Gauginos

Dark Matter candidates



Higgsinos

Some advantages:

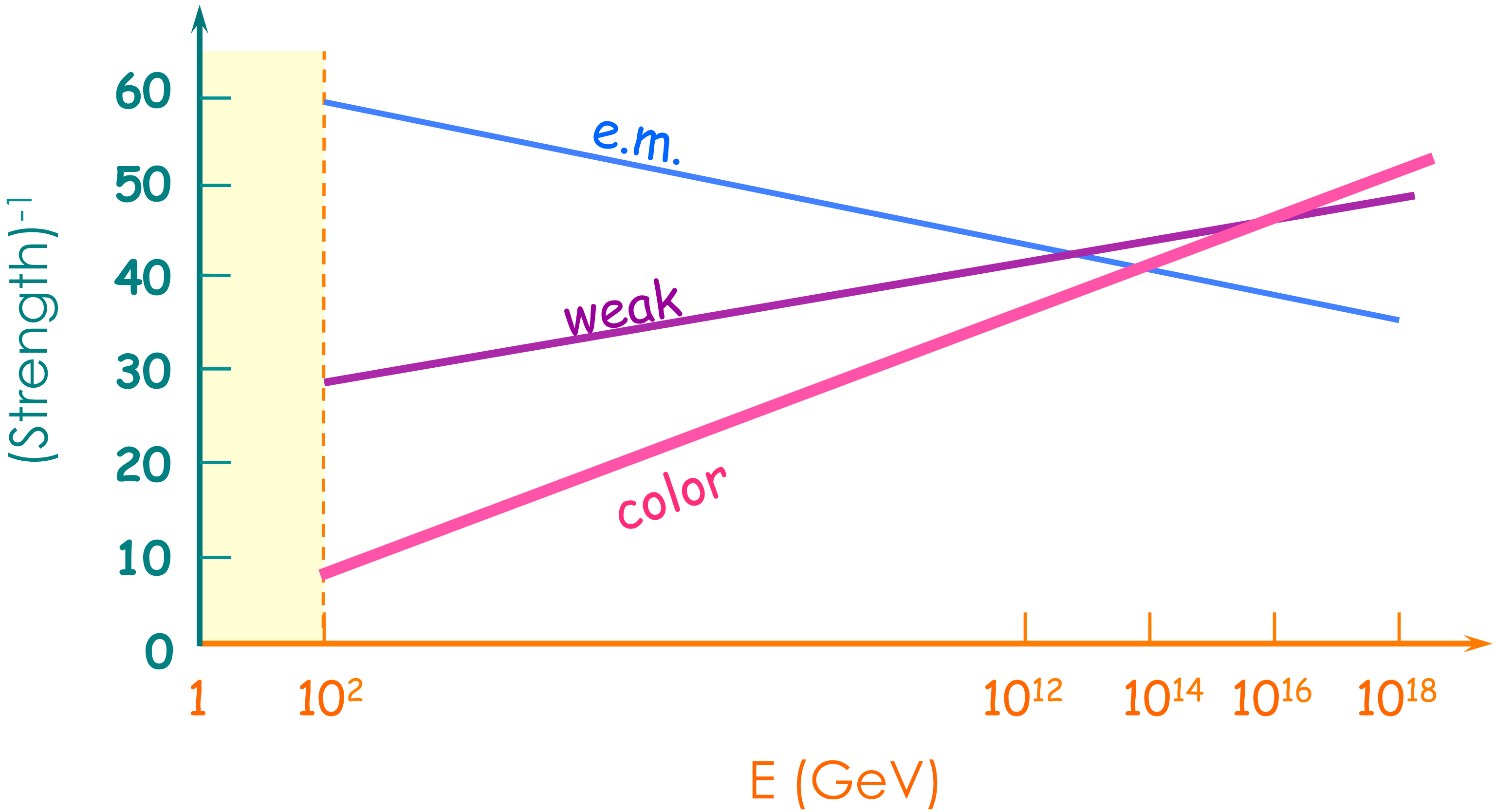
- Offers dark-matter candidate
- Offers possibility of force unification

Popular SUSY model: mSUGRA (Minimal Supergravity)

- SUSY broken via gravitational interactions
- Assuming mass unification at GUT scale reduces vast parameter space to just 5

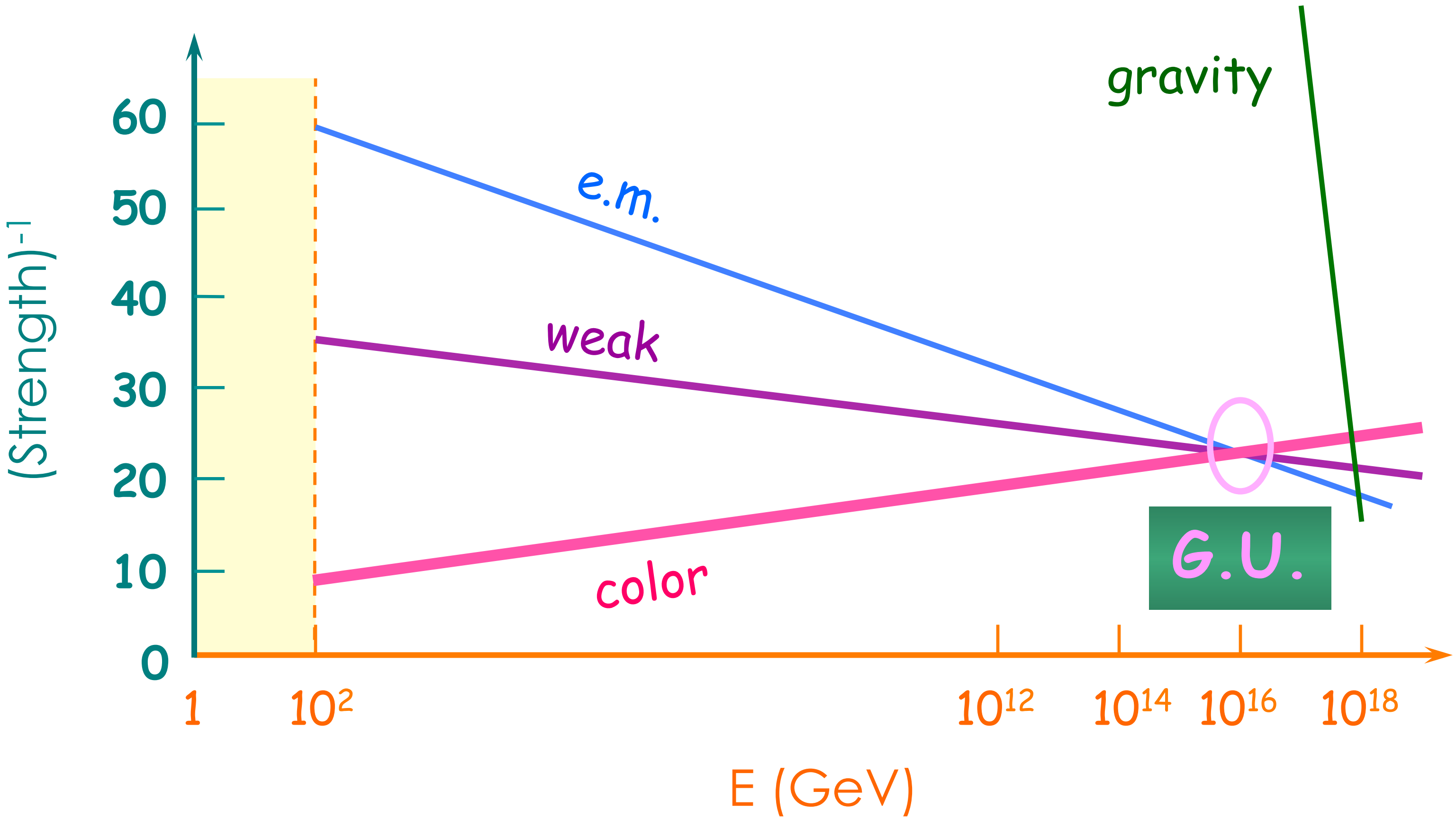
Supersymmetric S.M.

Standard Model

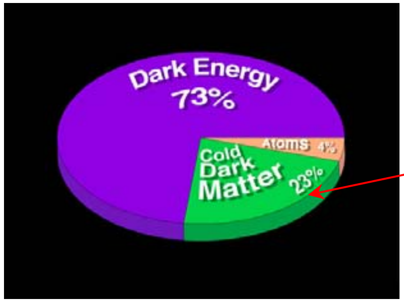


Supersymmetric S.M.

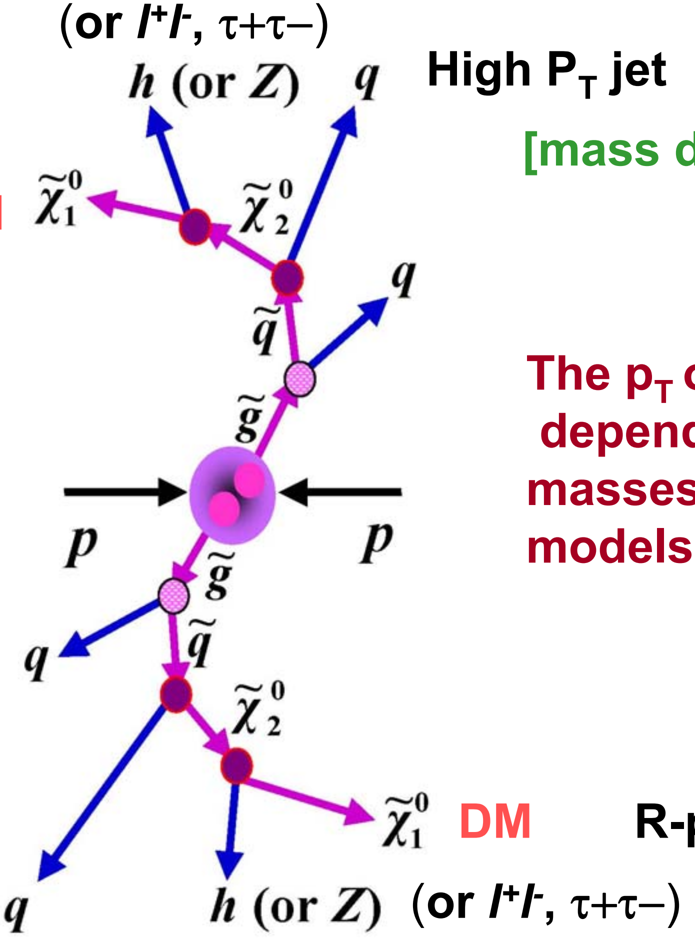
Standard Model + SUSY



SUSY at the LHC



DM



High P_T jet

[mass difference is large]

The p_T of jets and leptons depend on the sparticle masses which are given by models

Colored particles are produced and they decay finally into the weakly interacting stable particle

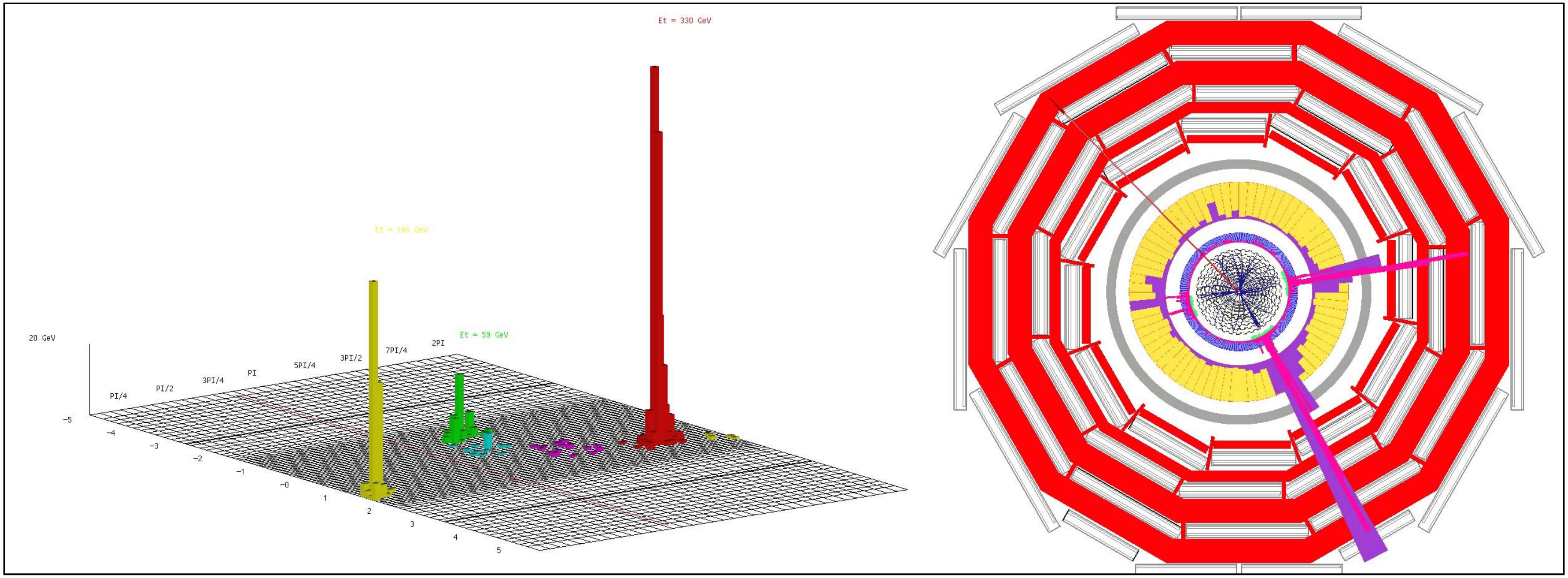
DM

R-parity conserving

High P_T jet

The signal : jets + leptons + missing E_T

Simulated event for SUSY

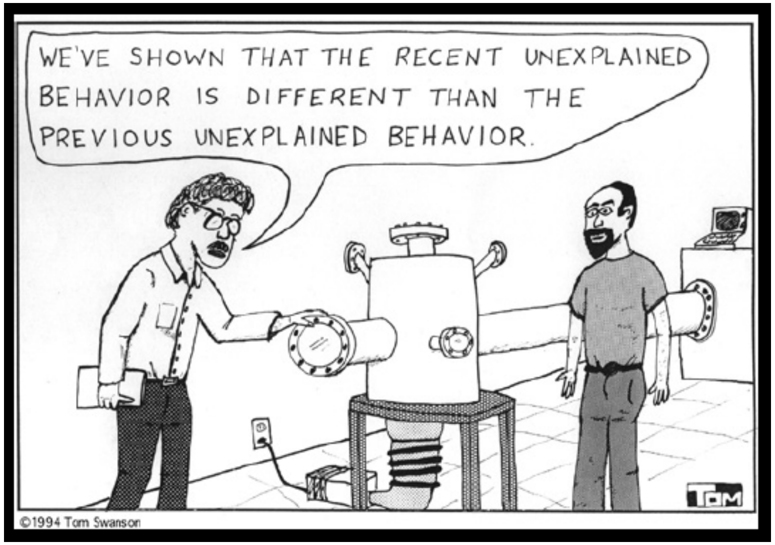


CSM

Conclusions

Alice and the LHC are operating wonderfully showing a highly hot, dense and opaque medium has been generated

A new and unique era for the exploration of the QCD phase diagram just started. The connections with other branches of physics are incredibly high and intriguing



Stay tuned, new and exciting results will come soon!