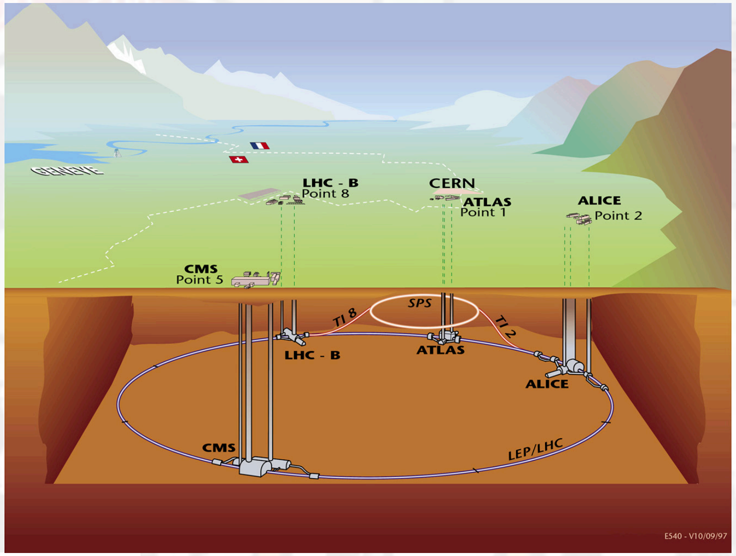
Heavy Ion Physics

Jan Rak and Sami Räsänen
Jyväskylä University & **Helsinki** Institute of Physics, **Finland**



JYVÄSKYLÄN YLIOPISTO
University of Jyväskylä

HELSINKI INSTITUTE OF PHYSICS

ALICE

PHENIX

FYSH550

Relativistic Heavy Ion Physics

Lectures: Jan Rak

Sami Räsänen

Exercises: Sami Räsänen

Grading

- One exam
  - provides “base grade”
  - 80% questions + 20% exercises
- Seminar in groups of two
  - -1, 0 or +1 to the base grade

Lectures

- Start Thursday 15th January 2009
- Continue:
  - Mondays 8-12 or 10-14?
  - Tuesdays 8-12?
- Total of 12 weeks, i.e. 48 hours
- Exceptional dates:
  - 2.2. - 9.2. (4th international workshop High-pT physics at LHC 09)
  - 28.3. - 6.4. (Quark Matter 2009)

Lecture topics

Lecture material: https://trac.cc.jyu.fi/projects/alice/wiki/jan

- Week I: Introduction part 1
- Week II: Introduction part 2
- Week III: Collective phenomena
- Week IV: Photons and π^0
- Week V: Correlations
- Week VI: Jet quenching
- Weeks VII-X: Seminar working on chosen topic
- Weeks XI and XII: Presentations

Topics for seminar works are introduced during weeks IV-VI. We all gather together in weeks VII-X to see progress and to discuss open issues.

ALICE @ JYFL

- Jan Rak
- DongJo Kim
- Sami Räsänen
- Norbert Novitzky
- Jiri Kral




Opportunities

Visit ALICE experiment at CERN

- dead line for applications 31st January
- send free form applications to Sami via email
- see details from

http://www.jyu.fi/static/fysiikka/sekalaista/StudentApplication.pdf

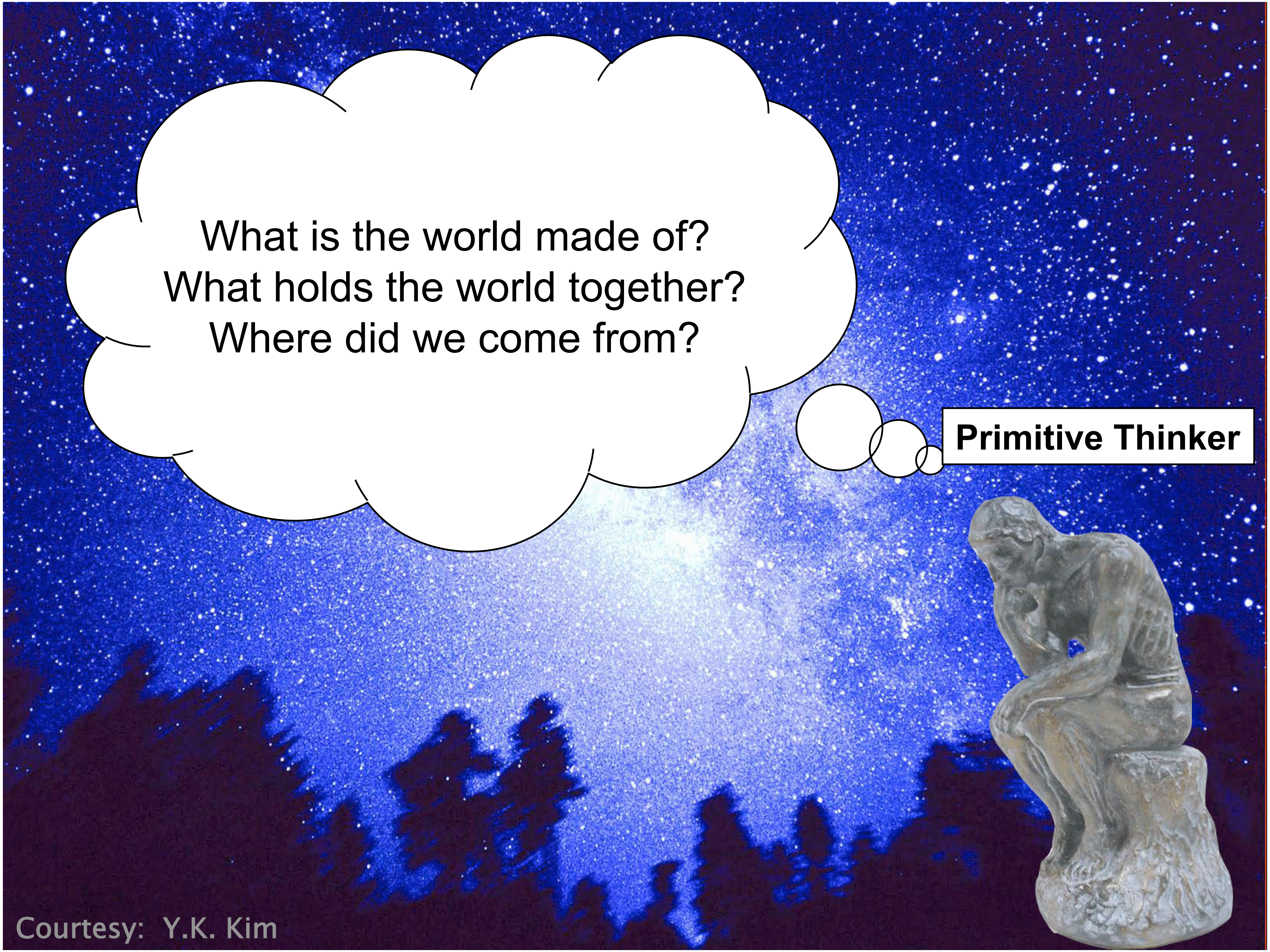
CERN summer student positions (HIP)

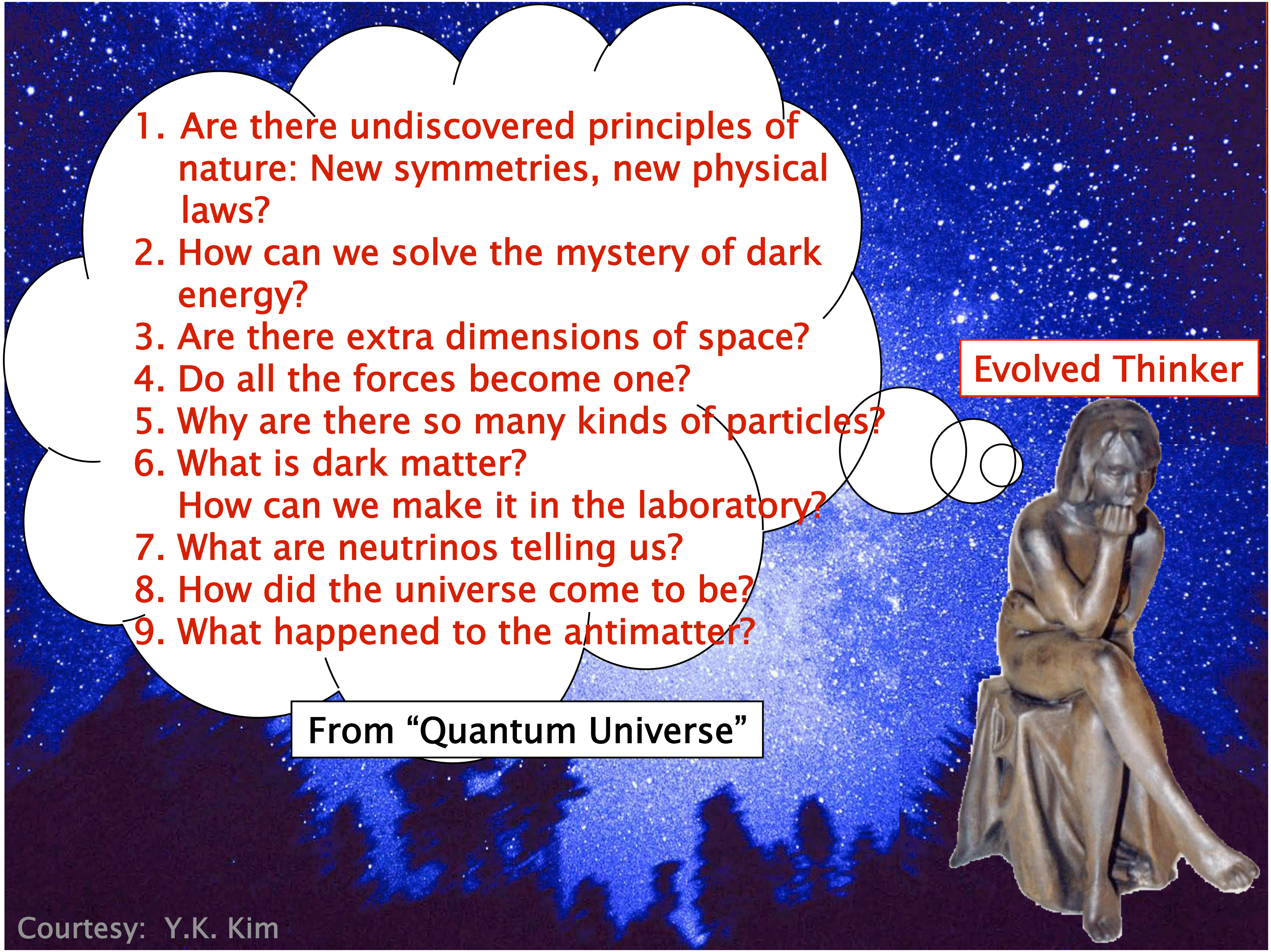
- dead line for applications 31st January
- total of 17 positions, all available for JYFL students
- ALICE groups position is 14. related with EMcal
- further info, instructions and application form

http://www.hip.fi/education/kesaharjoittelu.html

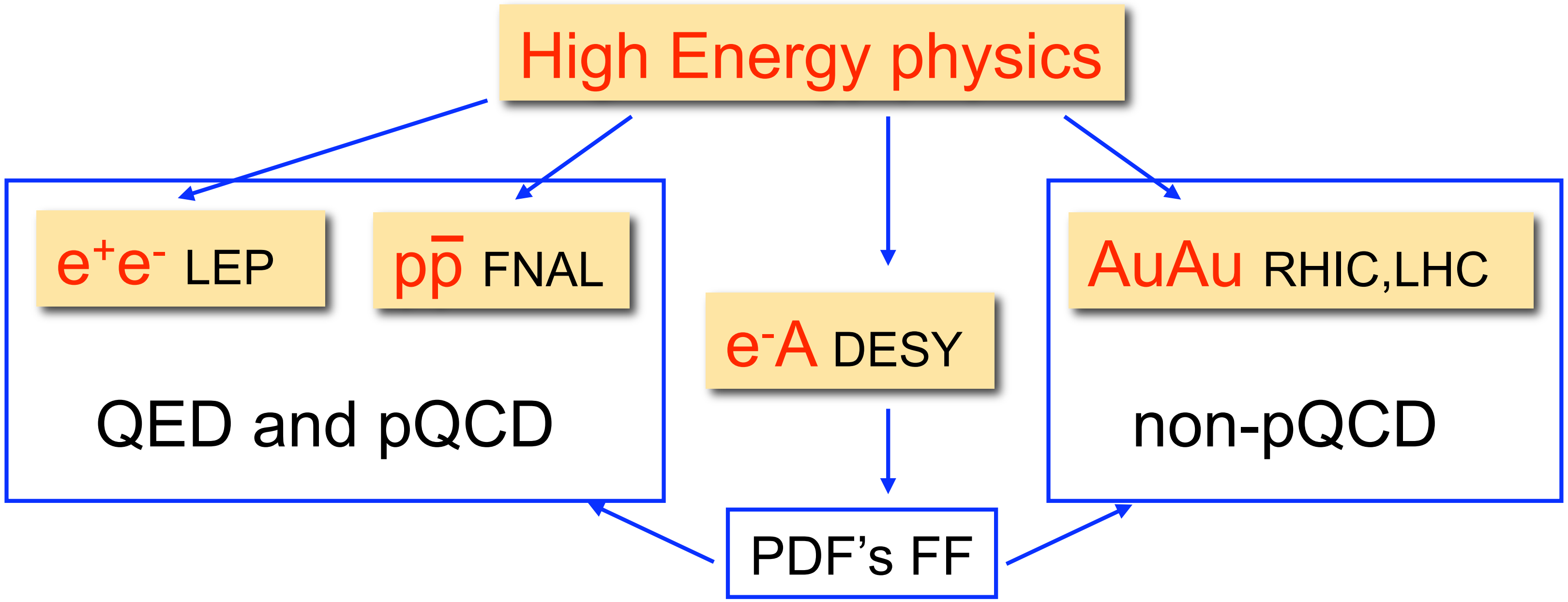
JYFL summer student position

- stay tuned, places should open ~February


What is the world made of?
What holds the world together?
Where did we come from?
Primitive Thinker
Courtesy: Y.K. Kim


1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?
From "Quantum Universe"
Evolved Thinker
Courtesy: Y.K. Kim

High Energy (ultra-relativistic) Heavy Ion physics



Heavy Ion physics:

- nonperturbative QCD phenomena at high-temperature and high-energy density.
- addresses the properties of QCD vacuum relevant to the structure of the early universe
- the origin of particle masses, QCD phase transition
- thanks to the Maldacena discovery of the duality between super gravity in Anti de Sitter space and conformal field theory, heavy ion physics provides a unique testbed for applied string physics.

Some expectations for the LHC

• With coming era of the CERN Large Hadron Collider (LHC), the largest high-energy particle accelerator ever built, many major discoveries are expected.

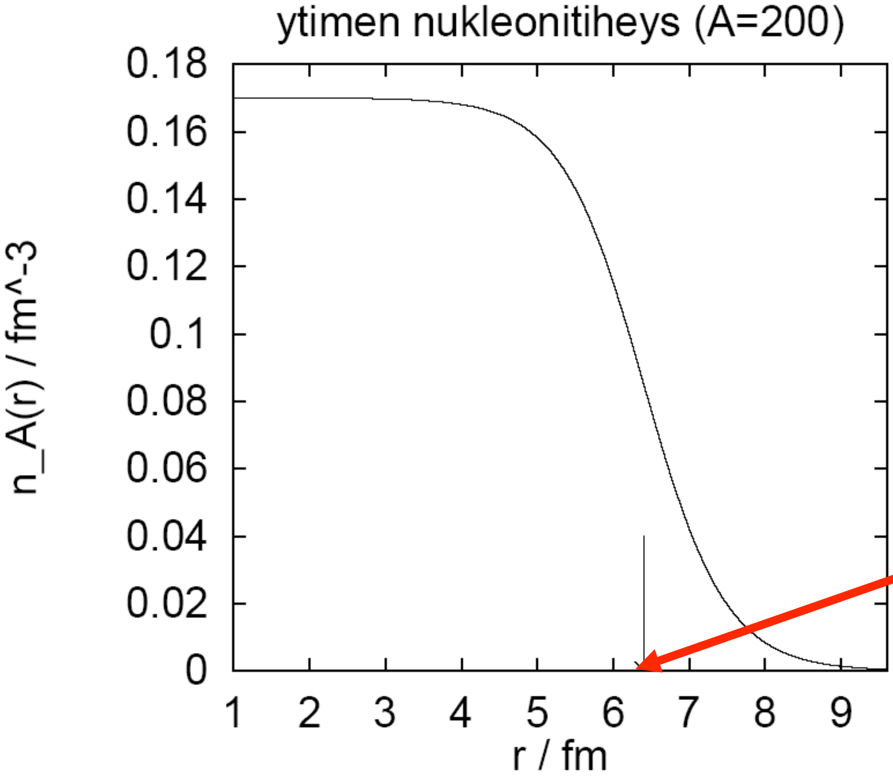
• It is known that the Standard Model (SM) of particles and fundamental forces cannot be a complete theory. Although exceptionally successful in explaining a vast variety of physics phenomena, the SM leaves us with many open questions and problems. Examples include:

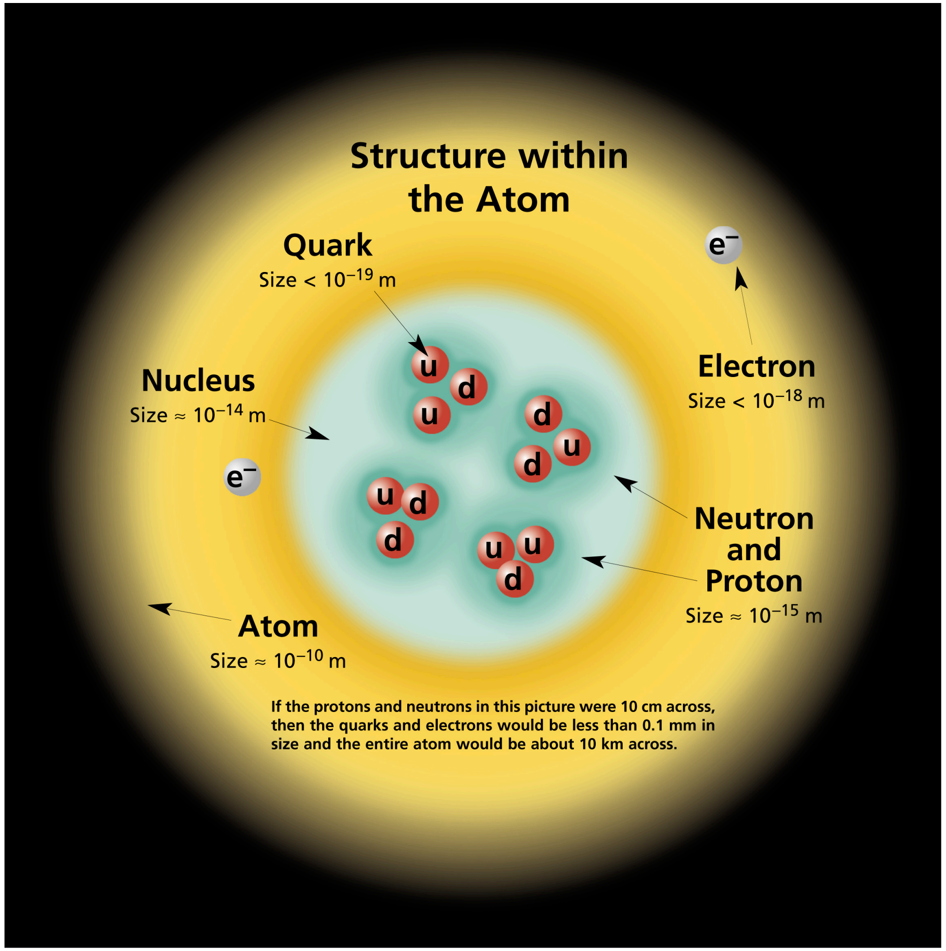
- the disparity between the characteristic strengths of the weak and strong nuclear forces (the "hierarchy problem"),
- numerical quantities which are not predicted by the theory such as the mass of each particle,
- structure of the QCD vacuum, no explanation for quark confinement etc.

• Many extensions to the SM such as string theory, extra dimensions, black holes creation and many others are considered to be within the experimental reach of the LHC.

Recall basic scales:

- Atom ~ 1 Å = 10^{-10} m
- Nucleus ~ 10 fm = 10^{-14} m
- Nucleon (= p tai n) ~ 1 fm
- elementary particles are point like (r < 10^{-18} m) in SM

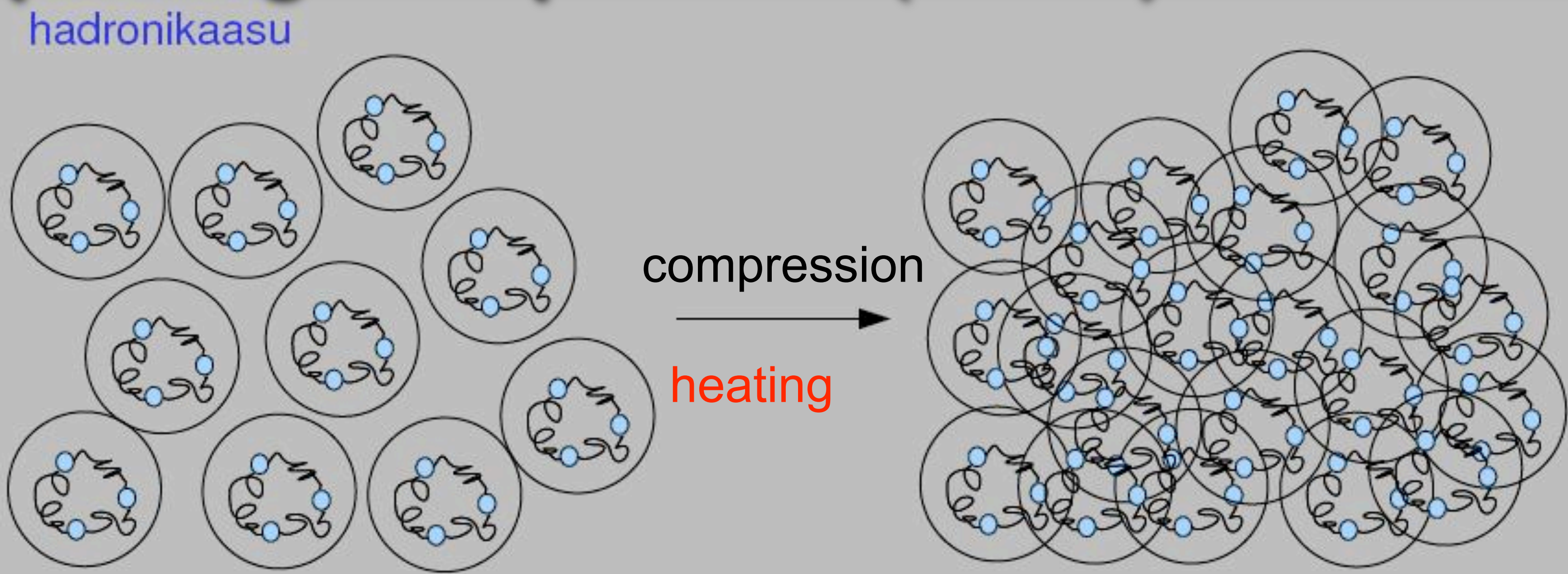




Radius of gold nucleus

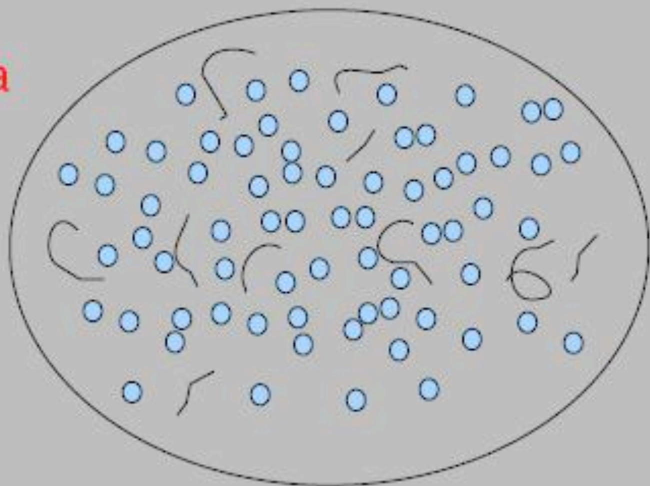
$R_A \sim 1.12 A^{1/3} \sim 6.5$ fm

quark-gluon plasma (QGP): intuition



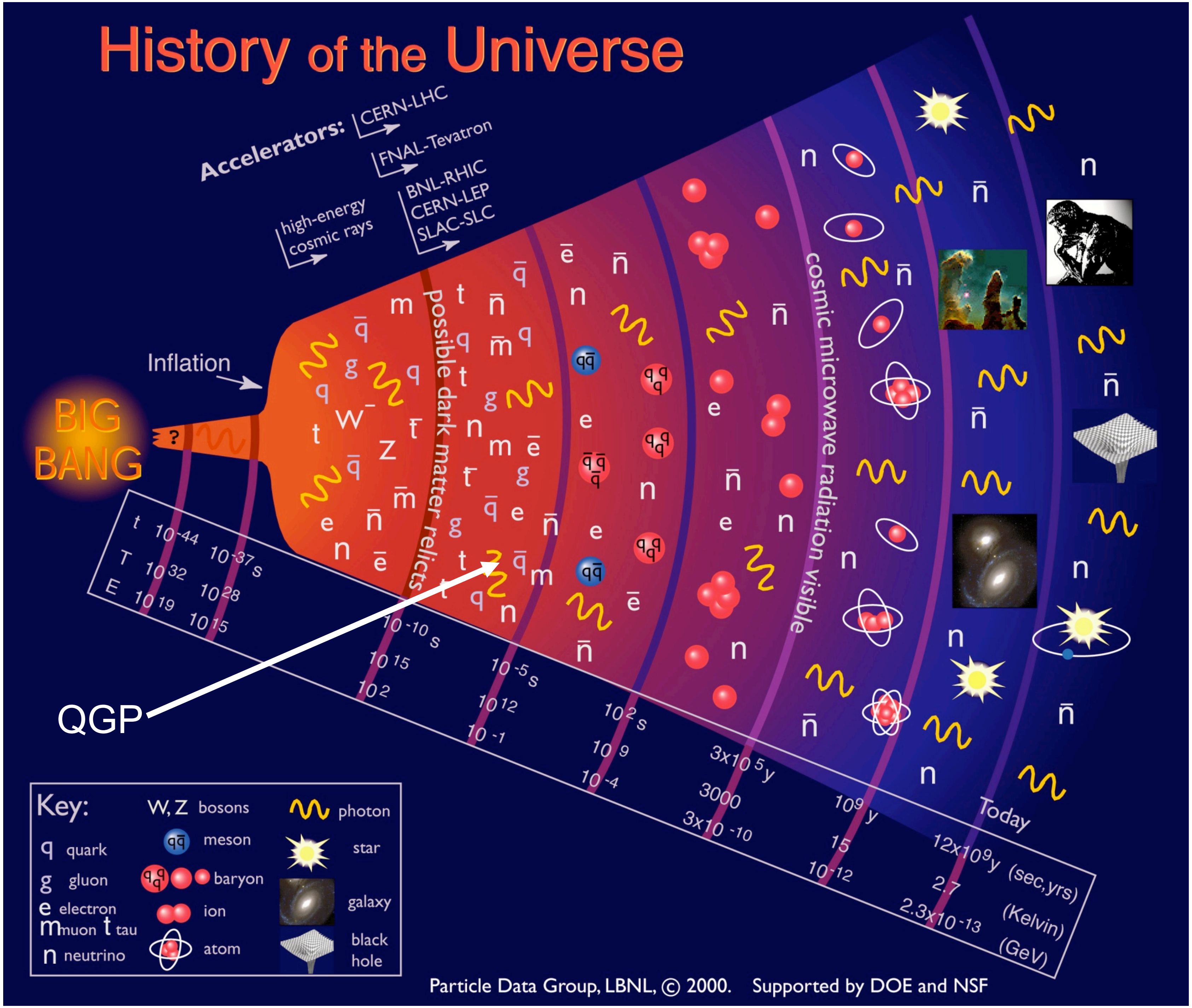
$n \sim 1 / fm^3$

Nucleon density in gold nucleus
$n \sim 200 / [4/3\ \pi\ (6.5\ fm)^3]$
$\sim 0.17 / fm^3$



Nucleons are not “pool balls” with hard surfaces

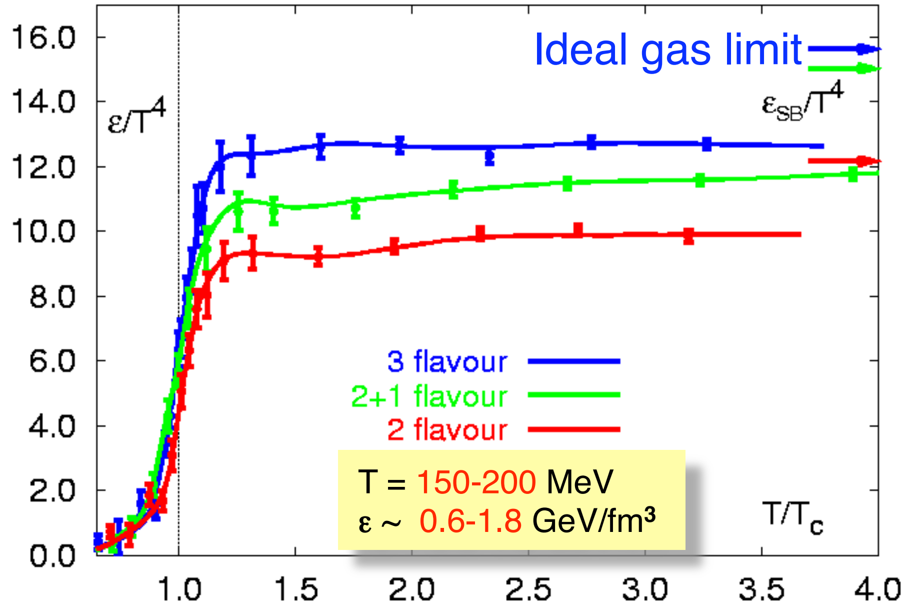
Figure by Harri Niemi



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
QGP
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Lattice QCD calculations verify that deconfinement transition should be a real phase transition.

Heavy ion collisions provide an opportunity to study thermodynamics of strongly interacting matter in laboratory



Lattice QCD, *Lect. Notes Phys* ***583****, 209 (2002)*

Calculations and simulation by Harri Niemi

Some more details when we consider collective phenomena

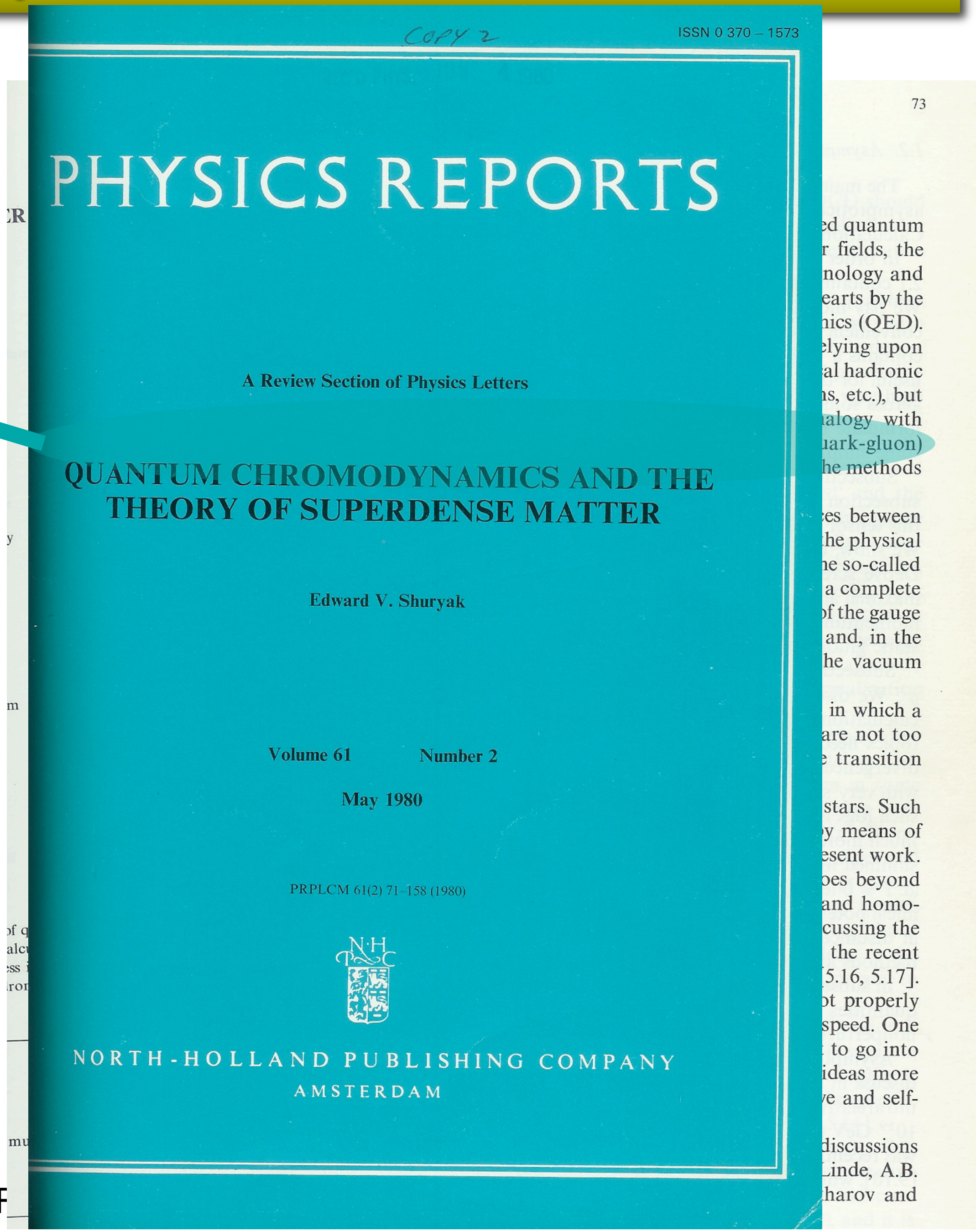
50

Shuryak 1980

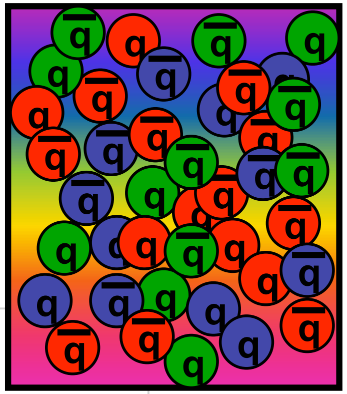
- Shuryak publishes first "review" of thermal QCD- and coins a phrase:

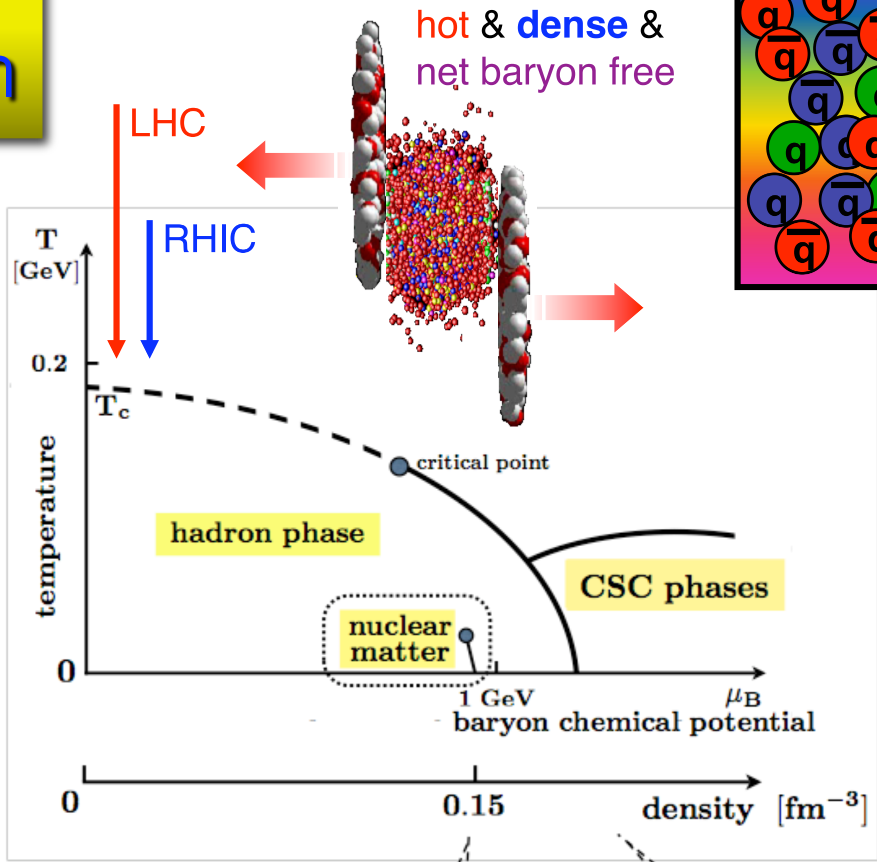
  "*Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma*."

  (QGP)



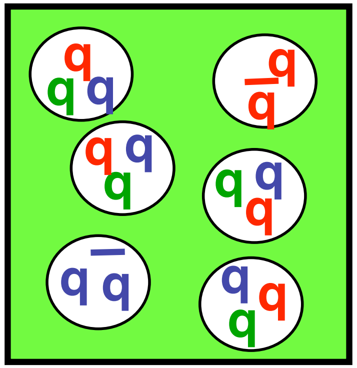
Heavy Ion Physics
1980-2004 old paradigm

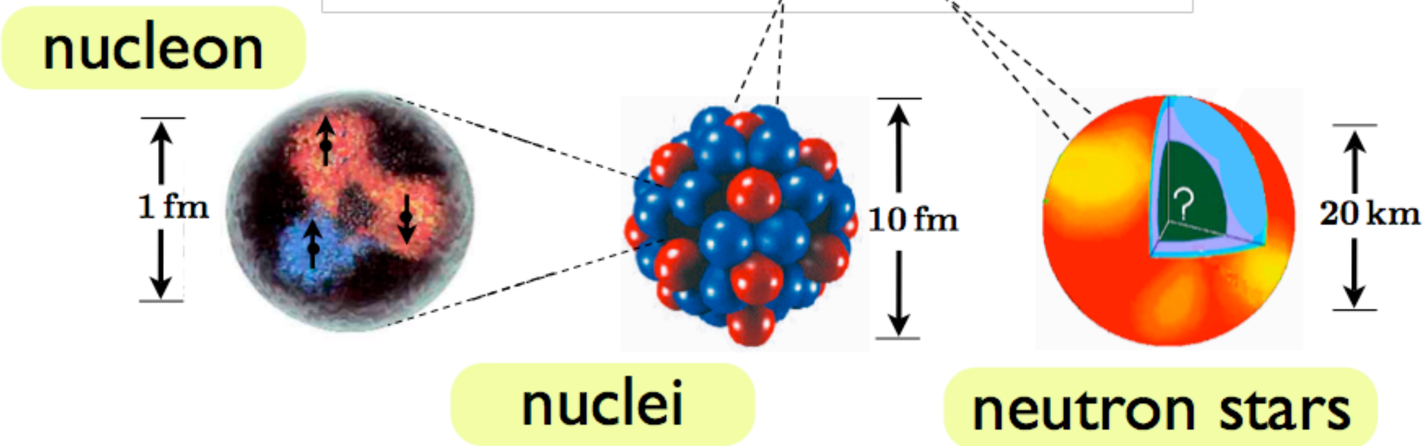




Exploring Phases and Structures of QCD phase diagram

- High temperature T
- High density ε
- Many-body aspects QCD
- Vacuum properties





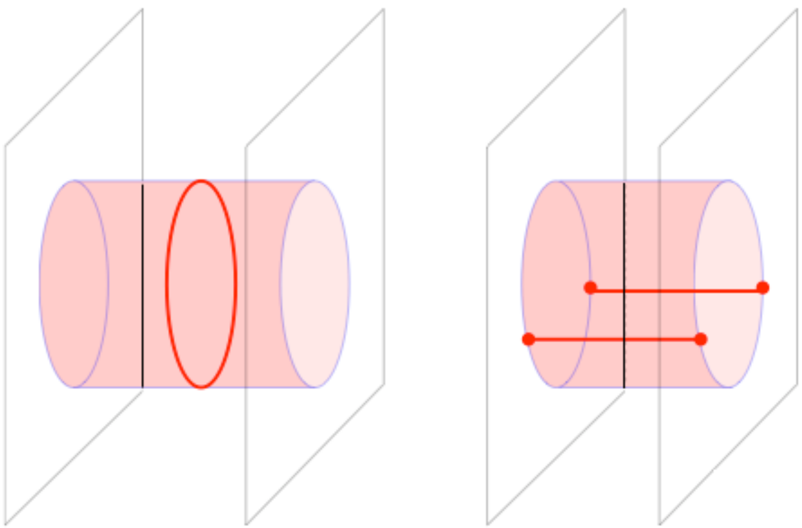
Heavy Ion Physics - new paradigm
Anti de-Sitter/CFT duality conjecture

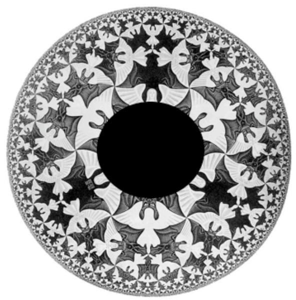
Note: MSc thesis seminar by

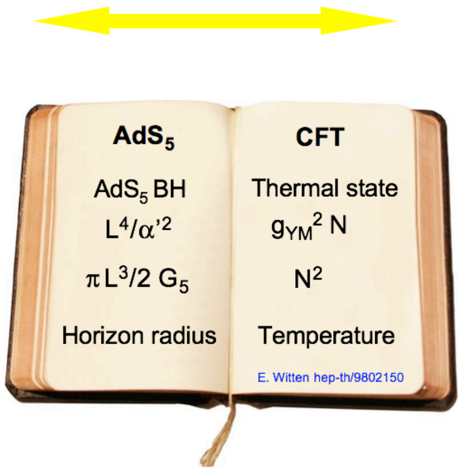
Timo Alho tomorrow

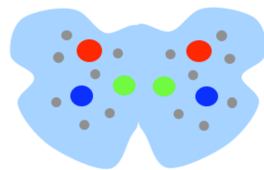
(Friday 16th January 2009)

$$ds^2 = L^2 z^{-2} (dz^2+dx^2+dy^2+dw^2 - dt^2)$$









T>0

Studying heavy-ion collisions you are also studying quantum gravity that is

"blown up and slowed down by a factor of 10^{20}".

Relativistic kinematics

$$p_{\parallel}^{CMS} = \gamma^{CMS}\left(p_{\parallel}^{LAB} - \beta^{CMS} E^{LAB}\right) \qquad p_{\parallel}^{LAB} = \gamma^{CMS}\left(p_{\parallel}^{CMS} + \beta^{CMS} E^{CMS}\right)$$

$$E^{CMS} = \gamma^{CMS}\left(E^{LAB} - \beta^{CMS} p_{\parallel}^{LAB}\right) \qquad E^{LAB} = \gamma^{CMS}\left(E^{CMS} + \beta^{CMS} p_{\parallel}^{CMS}\right)$$

Energy/momentum transformation between any inertial frames e.g. CMS and LAB

Useful to work with four-vectors
-> vectors in Minkowski 4D space
and metric tensor of Mink. space

$$g_{\mu\eta} = g^{\mu\eta} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$x^{\mu} = (x^0, x^1, x^2, x^3) = (t, \vec{x}) = (t, x, y, z)$$

$$p^{\mu} = (E, \vec{p}) = (E, \vec{p}_T, p_z) = (E, p_x, p_y, p_z)$$

$$p^{\mu} p_{\mu} = E^2 - p^2 = m_0^2$$ Famous Invariant

$$x_{\mu} = g_{\mu\eta} x^{\eta} = (t, -x, -y, -z)$$

$$a \cdot b = a^{\mu} b_{\mu} = a_{\mu} b^{\mu} = g_{\mu\eta} a^{\mu} b^{\eta} = a^0 b^0 - \vec{a} \cdot \vec{b}$$

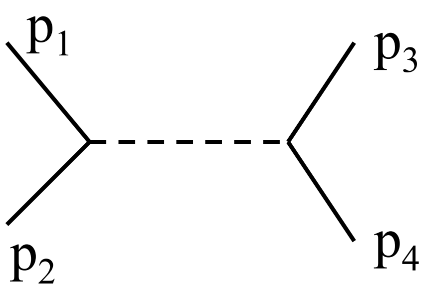
Mandelstam variables

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

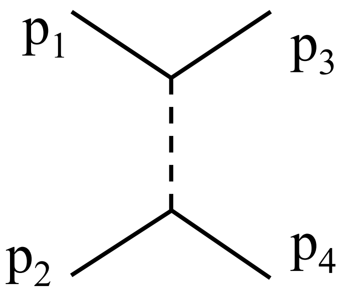
$$s = 4p^2 = 4E_{beam}^2 = E_{cm}^2$$
$$t = -2p^2(1 - \cos\theta)$$
$$u = -2p^2(1 + \cos\theta)$$

$\sqrt{s} = E_{cm}$ = center of mass energy available for particles production!

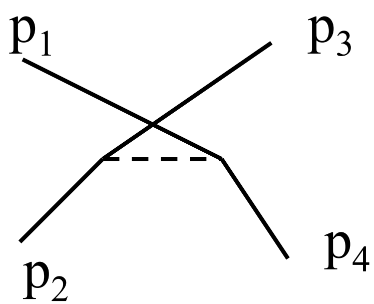
$$s + t + u = 3p_1^2 + p_2^2 + p_3^2 + p_4^2 + 2p_1 \cdot p_2 - 2p_1 \cdot p_3 - 2p_1 \cdot p_4$$
$$= \Sigma p_i^2 + 2p_1 \cdot (p_1 + p_2 - p_3 - p_4) = \Sigma m_i^2$$



s-channel

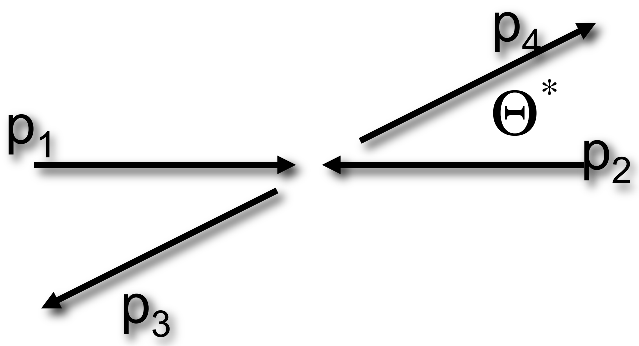


t-channel



u-channel

Kinematics of relativistic particle interaction



momentum conservation: $p_1+p_2=p_3+p_4$

p_i = four momenta of in/out going particles
s,t,u Lorentz invariant quantities

$$s=(p_1+p_2)^2=(p_3+p_4)^2$$
$$t=(p_1-p_3)^2=(p_2-p_4)^2$$
$$u=(p_1-p_4)^2=(p_2-p_3)^2$$

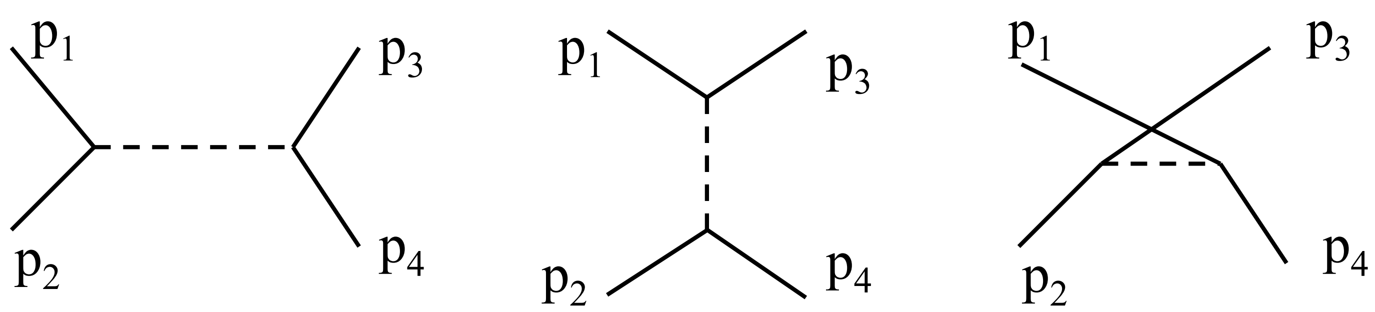
$$s+t+u=\sum_{i=1}^{4}p_i^2=\sum_{i=1}^{4}m_i^2$$

For a given *s*, both *t* and *u* depend linearly on the cos of the CMS deflection angle

$$-t=-(p_1-p_3)^2=2E_1^*E_3^*-m_1^2-m_3^2-2p_1^*p_3^*\cos\Theta^*$$
$$-u=-(p_1-p_4)^2=2E_2^*E_3^*-m_2^2-m_3^2-2p_2^*p_3^*\cos\Theta^*$$

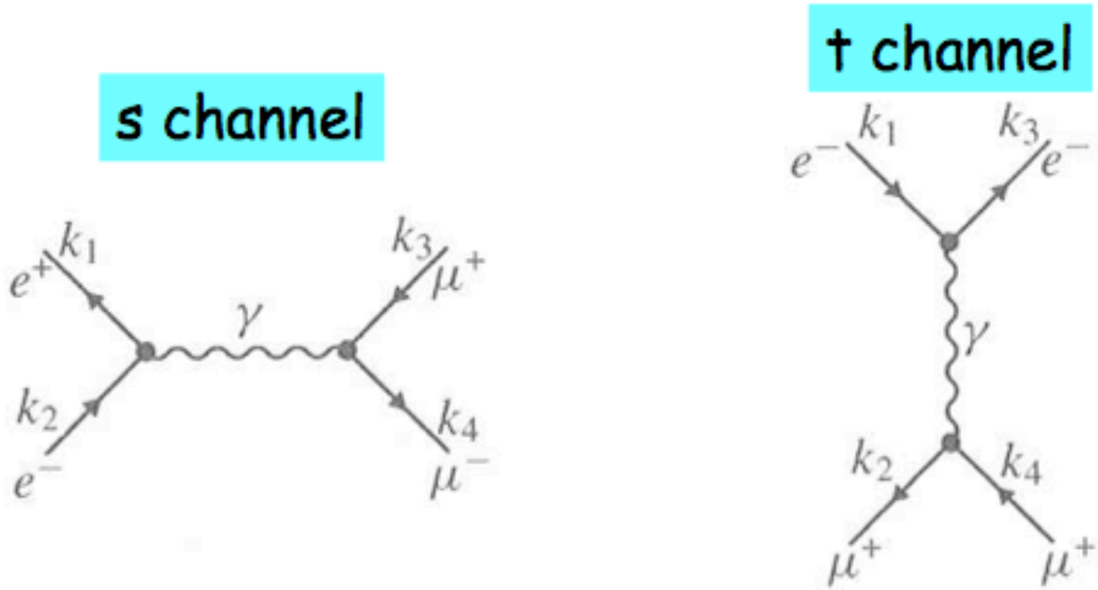
In the case of elastic scattering and for fixed *s*

$$t=-2p^2(1-\cos\Theta^*)$$



s-channel t-channel u-channel

Electron-muon scattering, $e^- \mu^+ \rightarrow e^- \mu^+$



- Mandelstam variables:

  $s = -(k_1 + k_2)^2 = -(k_3 + k_4)^2 = -2k_1k_2 = -2k_3k_4$

  $t = q^2 = (k_1 - k_3)^2 = (k_2 - k_4)^2 = -2k_1k_3 = -2k_2k_4$

  $u = (k_2 - k_3)^2 = (k_1 - k_4)^2 = -2k_2k_3 = -2k_1k_4$

for $m = 0$

$k = (p_x, p_y, p_z, iE)$

Annihilation vs scattering

In the partonis CMS

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

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8p^2}\left(\frac{t^2+u^2}{s^2}\right) = \frac{\alpha^2}{8p^2}\left[\sin^4(\vartheta/2) + \cos^4(\vartheta/2)\right]$$

$$= \frac{\alpha^2}{4s}\left[1+\cos^2\vartheta\right]$$

$$2\sin^2(\vartheta/2) = 1-\cos\vartheta$$

$$2\cos^2(\vartheta/2) = 1+\cos\vartheta$$

$$s = 4p^2$$

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

Crossed channels t ↔ s

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8p^2}\left(\frac{s^2+u^2}{t^2}\right) = \frac{\alpha^2}{8p^2\sin^4(\vartheta/2)}\left[1+\cos^4(\vartheta/2)\right]$$

Fixed target vs collider

$CMS_{NN} \neq LAB$

much of the energy goes towards forward motion of the particles that result from the impact with the target

$$\sqrt{s} \cong \sqrt{m_0 2E_{beam}}$$

$CMS_{NN} = LAB$
$CMS_{ee} = LAB$
$CMS_{partonic} \neq LAB$

the total energy of the two beams is available for producing new particles

$$\sqrt{s} = 2E_{beam}$$

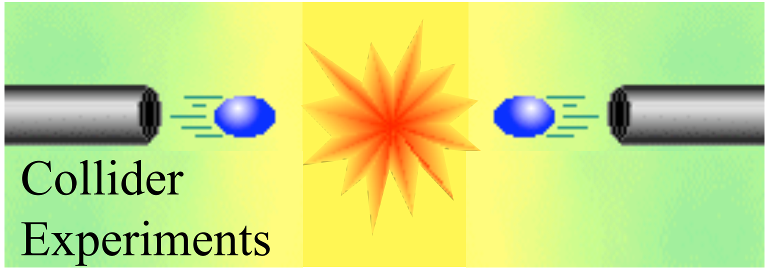
Often used tricks

Fix target CMS != LAB. Fraction of the beam energy is converted (wasted) into a kinetic energy of the center of mass system in LAB frame.

$$P^{\mu}\Big|_{\text{beam}} = (E, \vec{0}_T, p_{\parallel}) \qquad P^{\mu}\Big|_{\text{target}} = (m, \vec{0}_T, 0_{\parallel})$$

$$P_{\parallel}^{\text{LAB,tot}} = P_{\parallel}^{\text{beam}} + P_{\parallel}^{\text{target}} = \left(E_{\parallel}^{\text{beam}} + m_0, \vec{0}_T, p_{\parallel}^{\text{beam}}\right)$$

$$s = P_{\parallel}^{\text{LAB,tot},\mu} P_{\parallel,\mu}^{\text{LAB,tot}} = 2m_0^2 + 2m_0 E_{\parallel}^{\text{beam}} \cong 2m_0 E_{\parallel}^{\text{beam}}$$



$$\sqrt{s} \approx \sqrt{2m_0 E_{\parallel}^{beam}} \overset{SPS}{=} \sqrt{2 \cdot 0.938 GeV \cdot 160 GeV} \approx 17 GeV$$

Rapidity, pseudorapidity

Rapidity y is a Lorentz equivalent of a non-relativistic velocity

$$y = \frac{1}{2}\ln\left(\frac{E + p_{\parallel}}{E - p_{\parallel}}\right) = \frac{1}{2}\ln\left(\frac{1 + \beta_{\parallel}}{1 - \beta_{\parallel}}\right)$$

y is Lorentz additive quantity!

Assume hadron h in CMS of y_h, CMS moves with y_{CMS} with respect to LAB. Then y_h in LAB $= y_h + y_{CMS}$
Pseudorapidity η aproximation for y in the high-energy limit.

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right) = \frac{1}{2}\ln\left(\frac{|p| + p_{\parallel}}{|p| - p_{\parallel}}\right)$$

If no PID we do not no the rest mass and thus no E, we can measure and angle θ wrt beam.

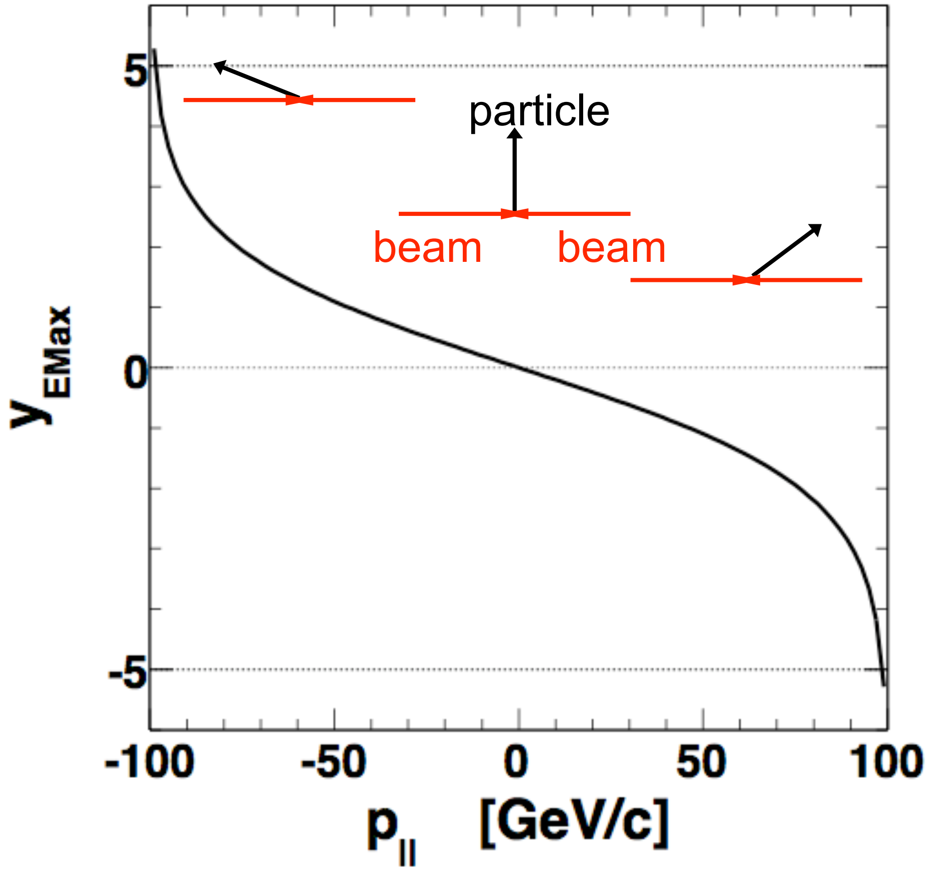
Useful

$$E = m_T \cosh y$$

$$p_{||} = m_T \sinh y$$

$$|p| = p_T \cosh \eta$$

$$p_{||} = p_T \sinh \eta$$

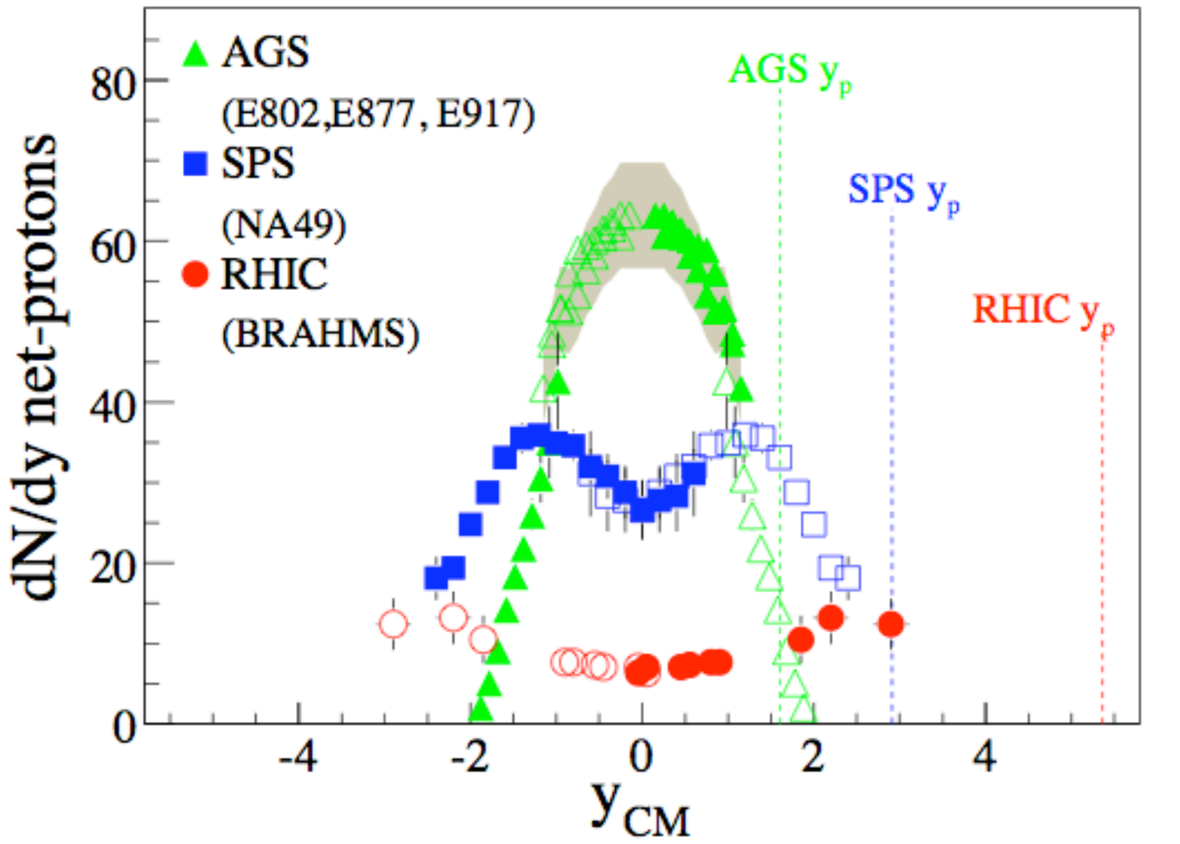


where $m_T = \sqrt{m_0^2 + p^2}$ is so called transverse mass

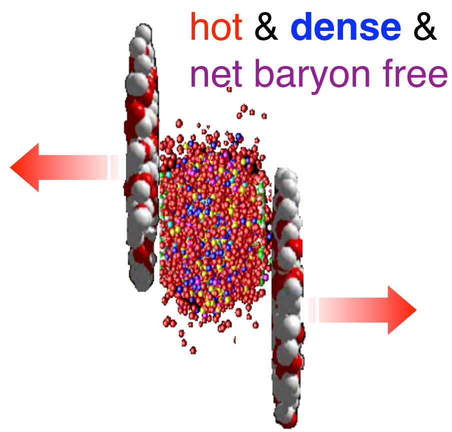
Net baryon densities

	SPS	RHIC	LHC
√s GeV	17	200	5500
dN_{ch}/dy	500	850	2000?
y_{max}	+-2.9	+-5.4	+-9.4

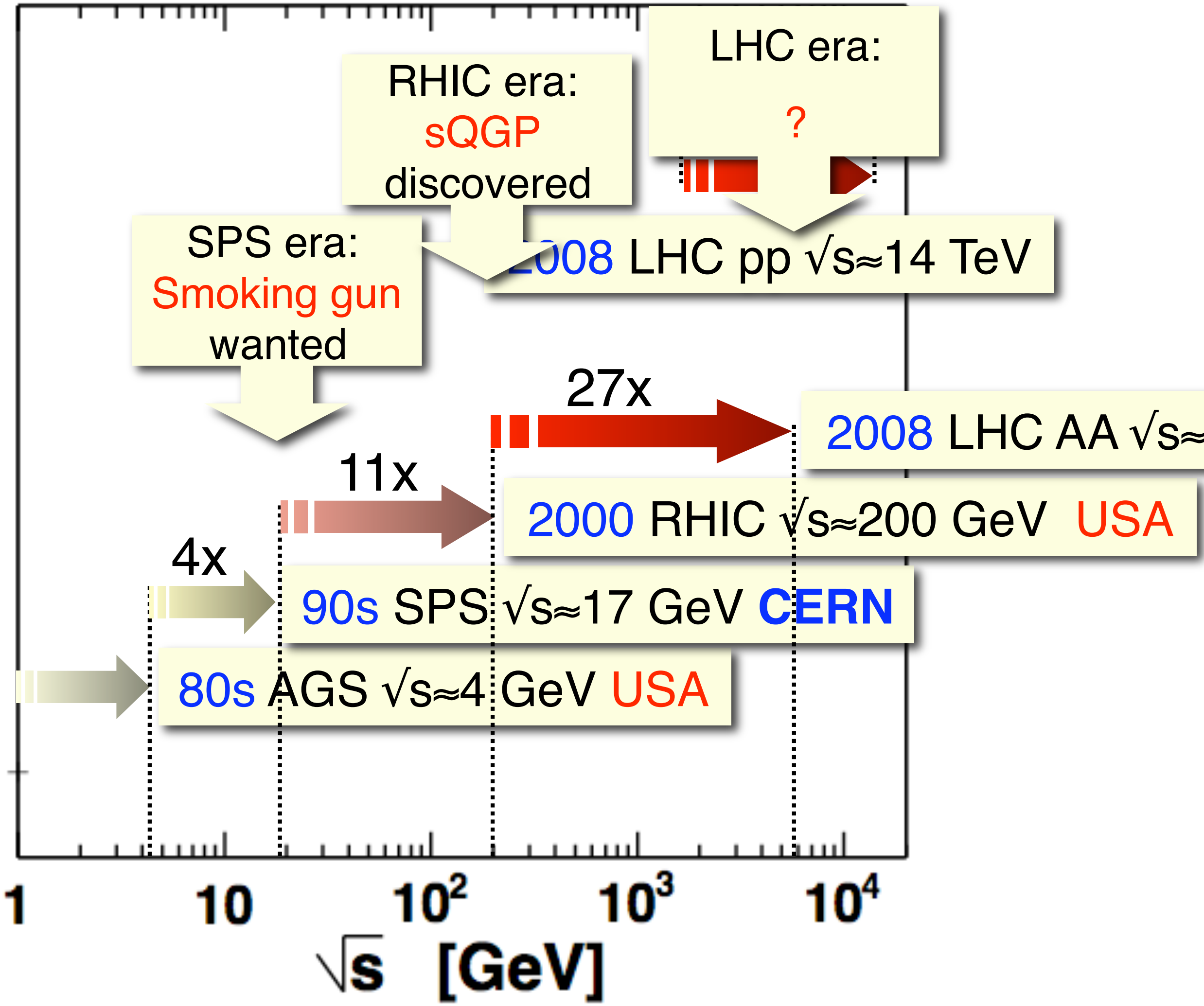
y_{max} is the beam rapidity

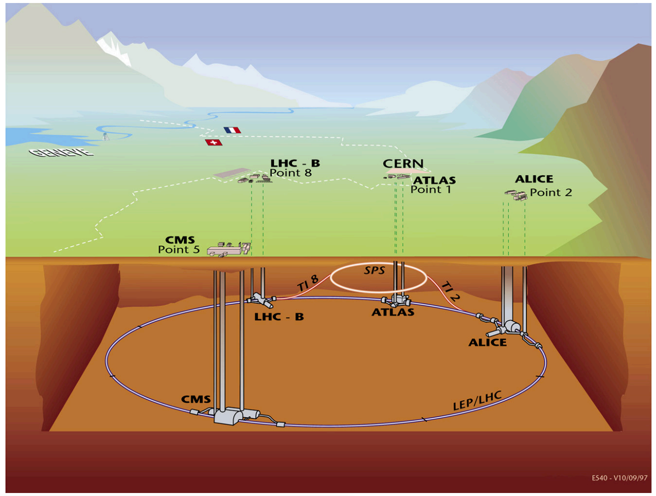


At higher energies the baryon stopping vanishes - baryon free regime.



HI - Center Of Mass Energy regimes

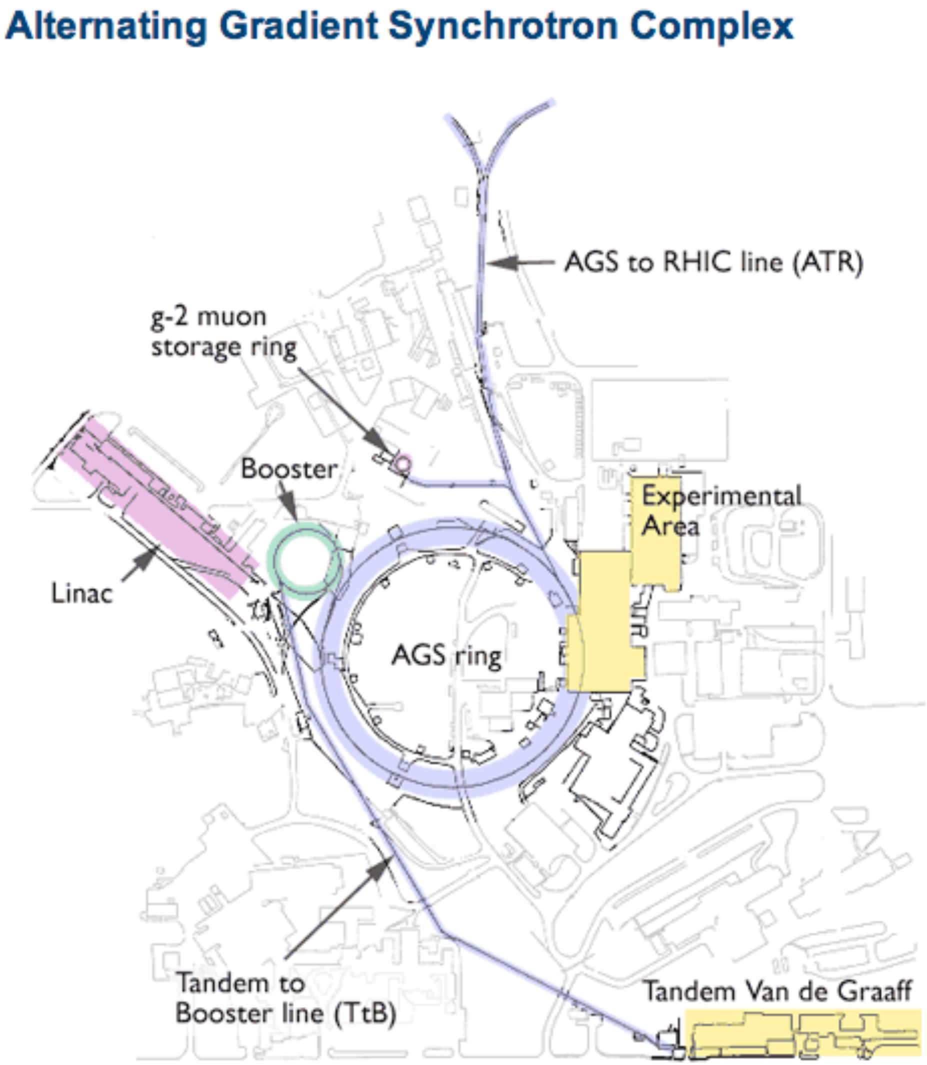




Relativistic **H**eavy **I**on **C**ollider

Brookhaven Nat. Lab. Long Island, USA

AGS



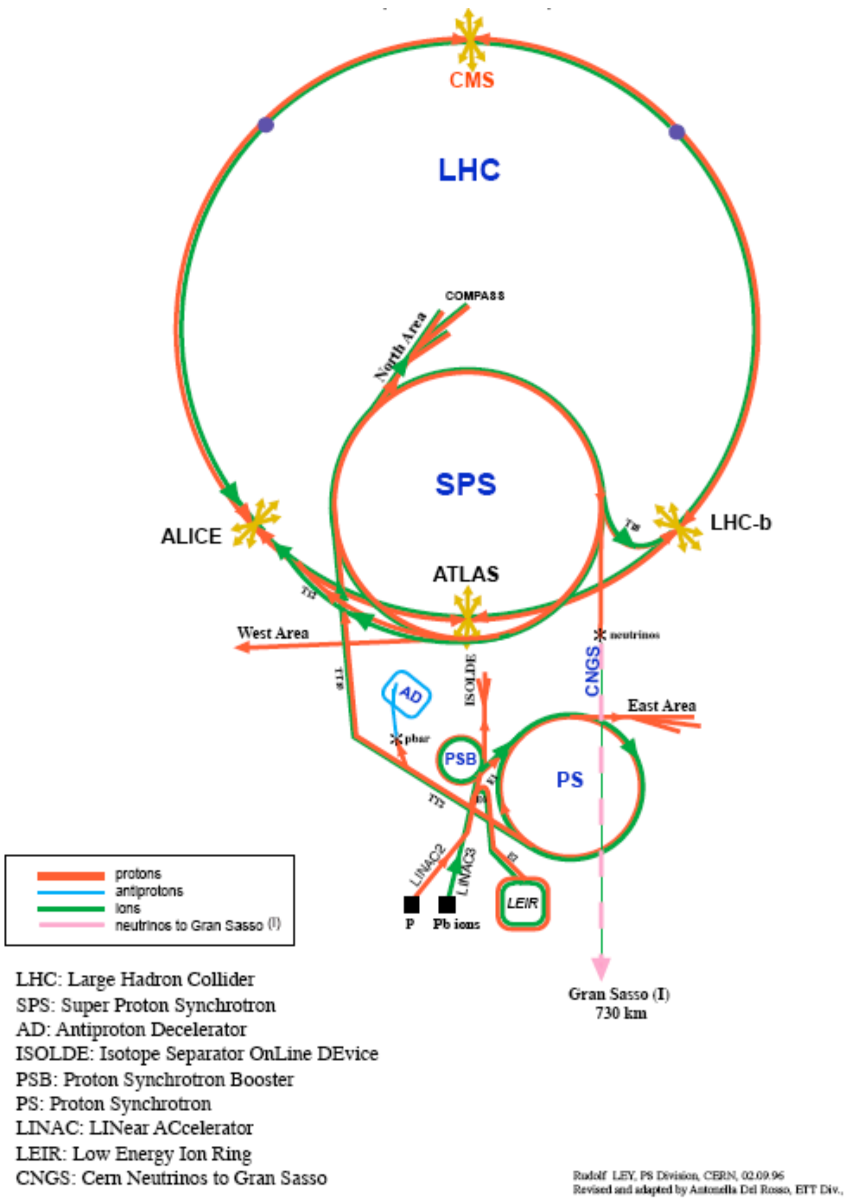
At Brookhaven National Lab.

Long Island (NY area) USA

Fix target $\sqrt{s} \approx 4$ GeV

3 Nobel prizes

SPS - Super Proton Synchrotron

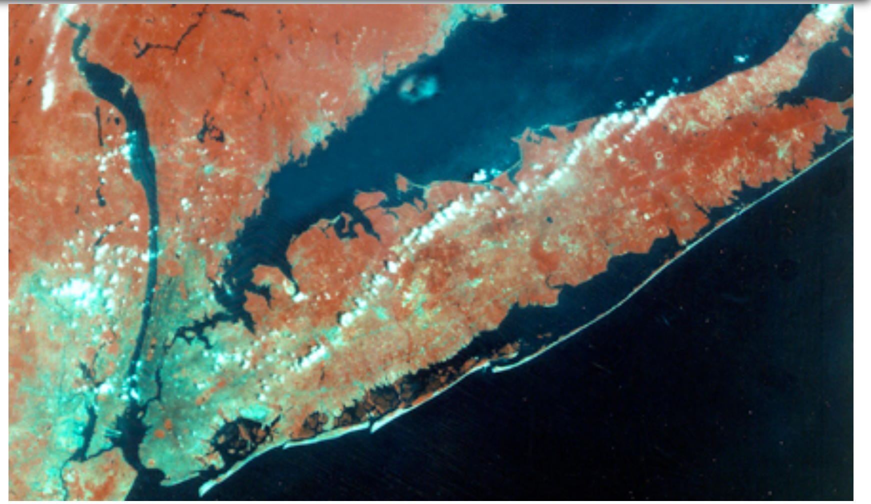


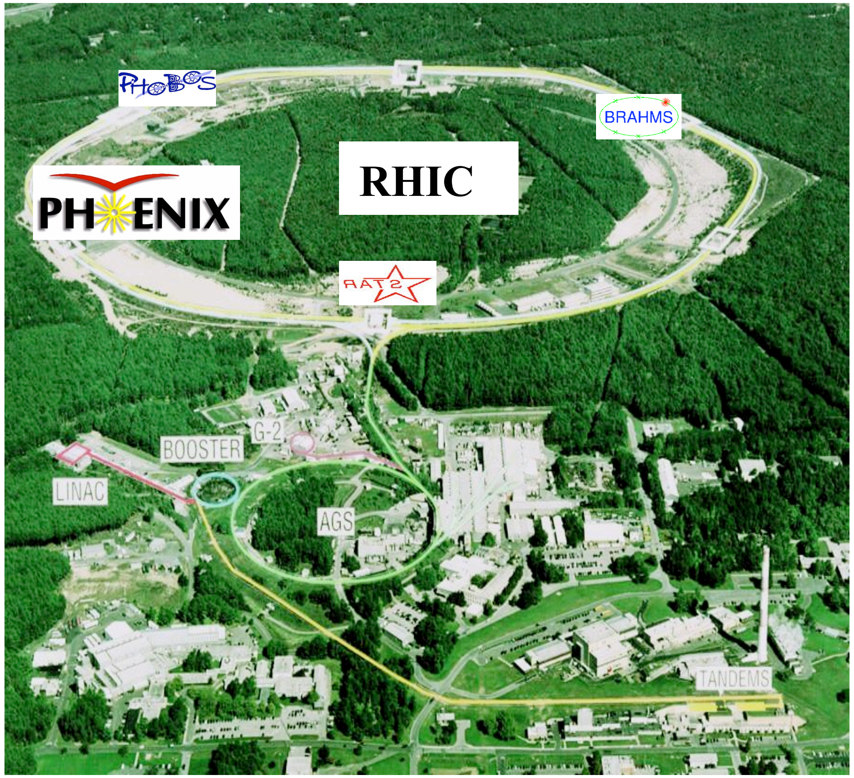
At CERN

Fix target $\sqrt{s} \approx 17$ GeV (E_{beam}=160 GeV)

- Circumference : 6.9 km
- 2.5 km of secondary beam lines.
- protons for fixed target physics at 400 GeV/c
- protons for CNGS experiment at 400GeV/c
- protons for LHC at 450GeV/c
- lead ions for fixed target physics at 400 GeV/c proton equivalent
- machine studies for SPS
- machine studies for LHC
- Injector for the LHC

Relativistic Heavy Ion Collider (RHIC)





RHIC

- Two independent rings 3.83 km in circumference
- Maximum Energy per N-N collision

  $\sqrt{s}$ = 500 GeV p-p (polarized)

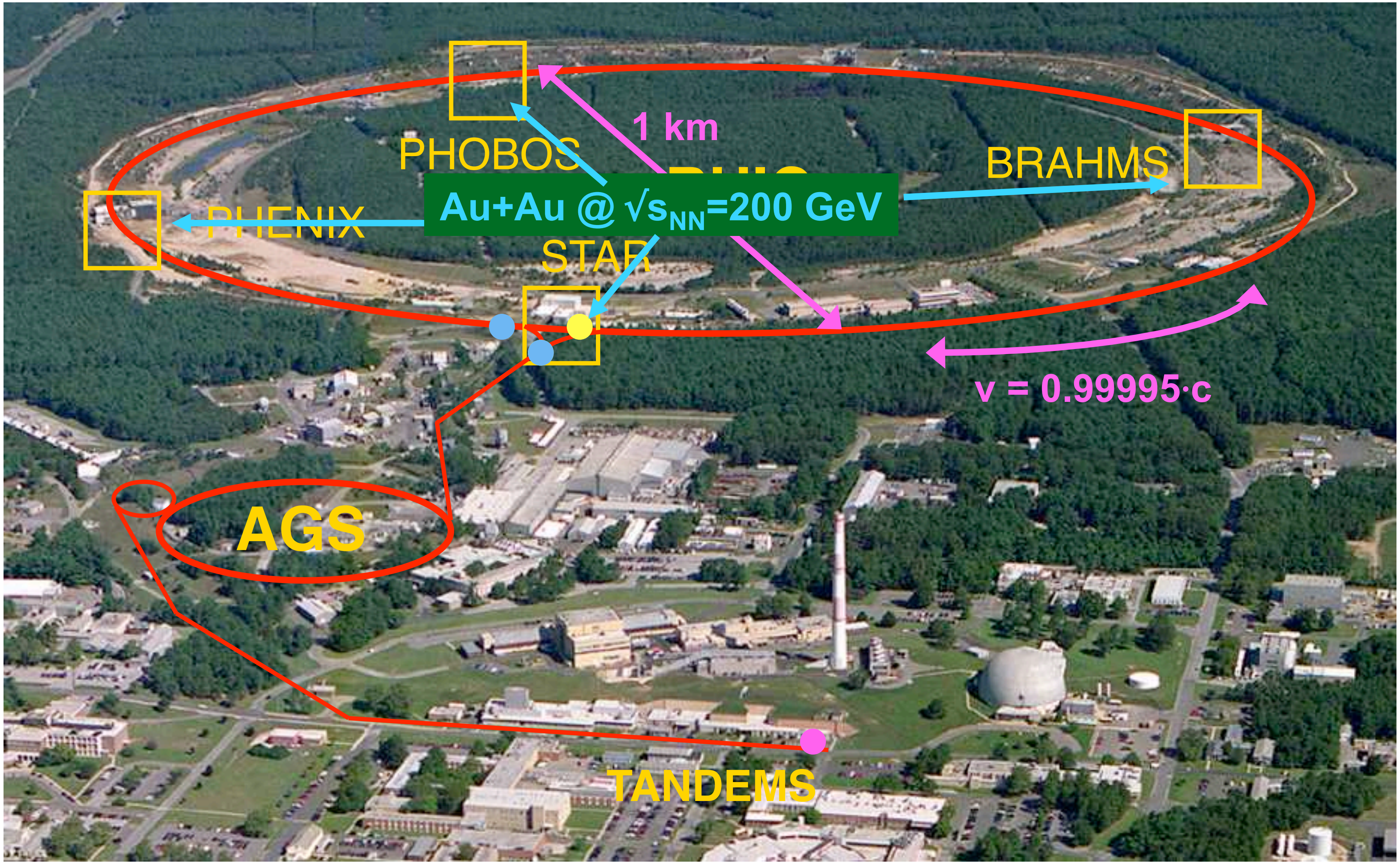
  $\sqrt{s}$ = 200 GeV Au-Au

- Design Luminosity

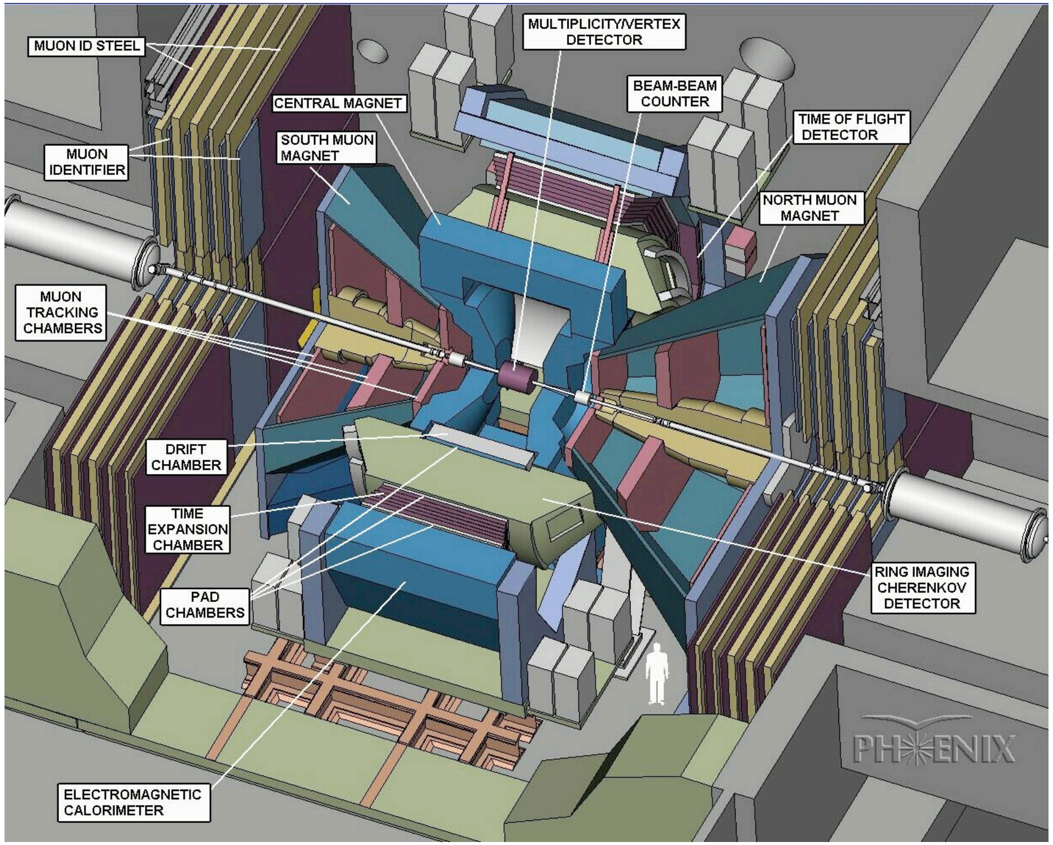
  Au-Au 2×10^{26} $cm^{-2}s^{-1}$

  p - p 2×10^{32} $cm^{-2}s^{-1}$

Relativistic Heavy Ion Collider (RHIC)



PHENIX



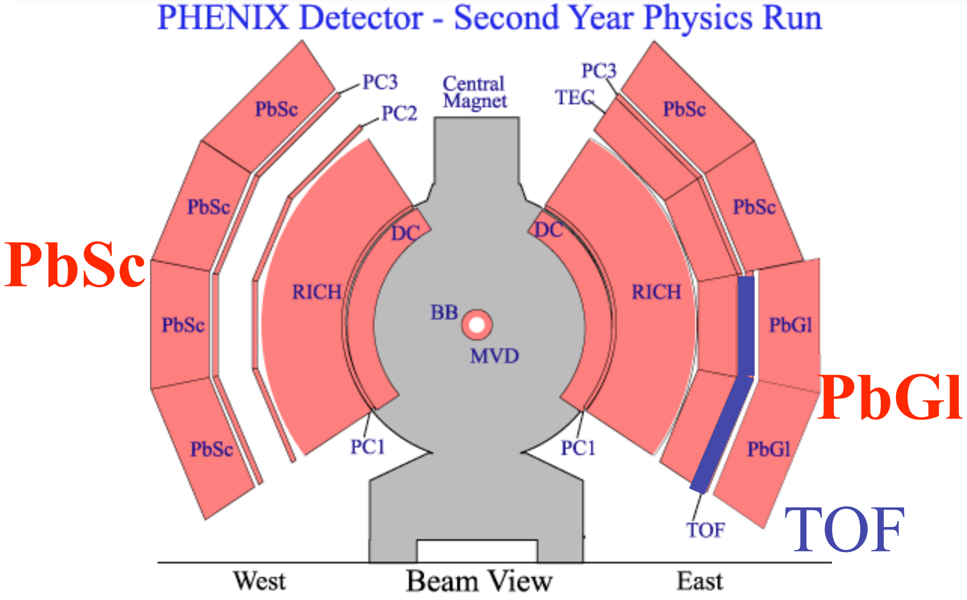
The PHENIX Experiment, main emphasis on electromagnetic probes. Focus:

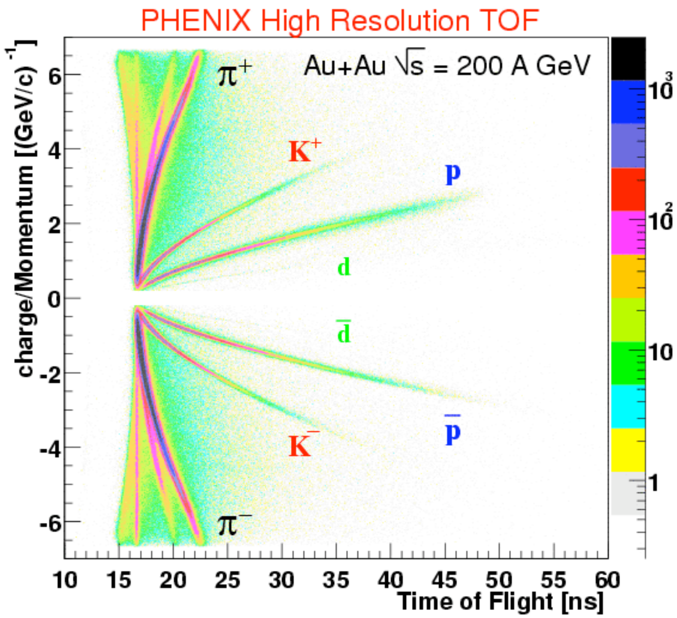
- Rare probes - J/Ψ, Ψ', e^+e^-, $\mu^+\mu^-$, Φ, direct-γ …
- The spin structure of the nucleons

The Configuration:

- 2 Forward Muon Arms
- 2 Central Spectrometer Arms to measure photons, electrons, and hadrons

PHENIX Central Arm



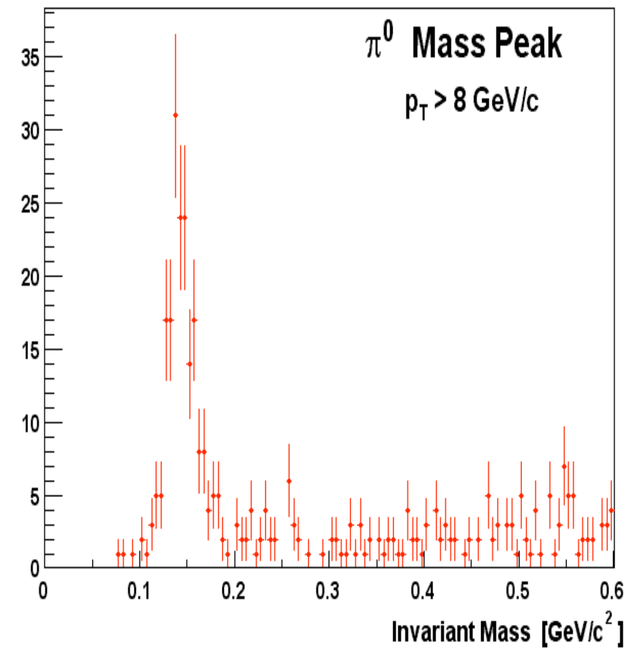


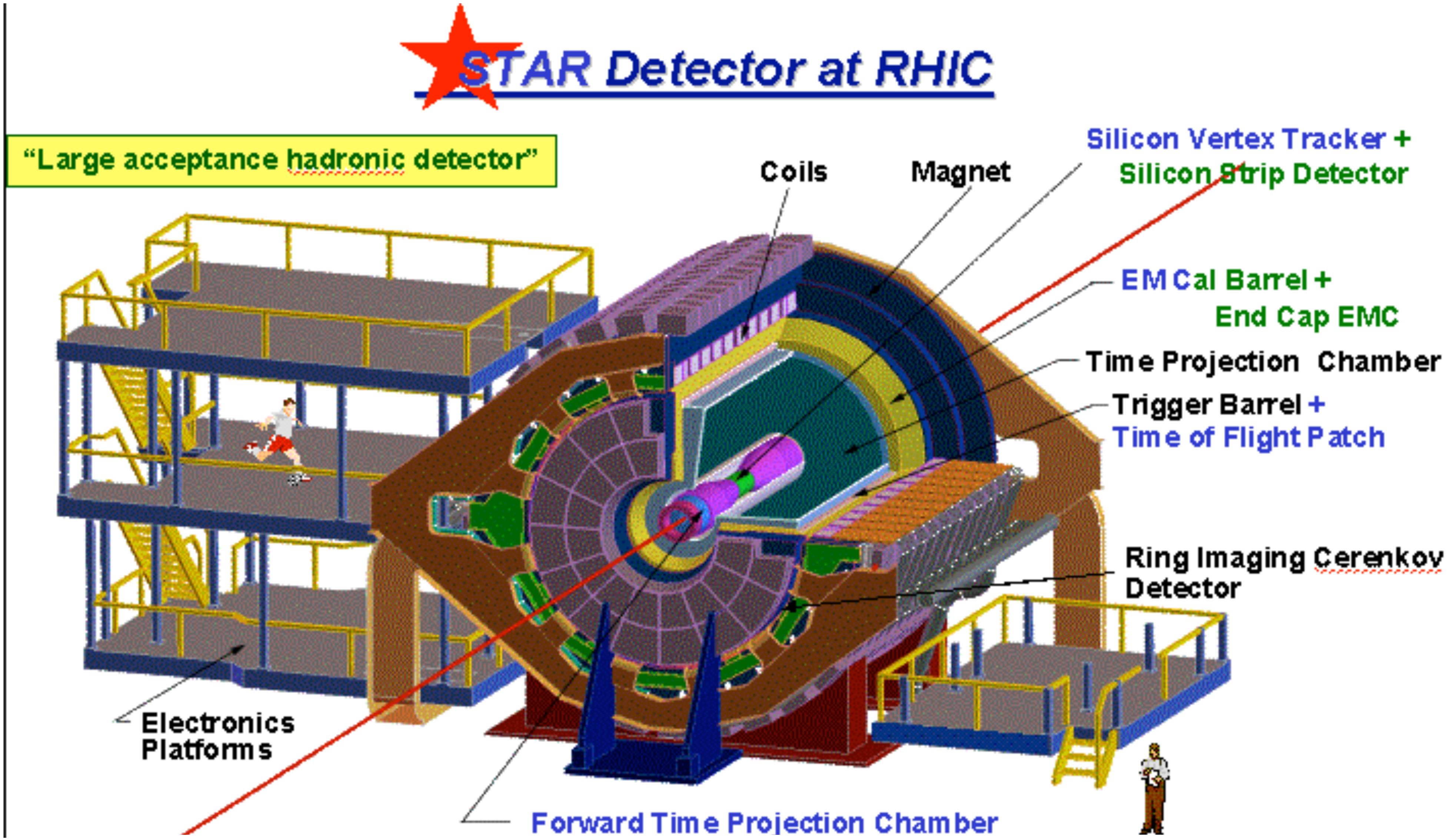
PID by high resolution TOF

- π, K < 2 GeV/c
- proton, anti-proton < 4 GeV/c
- $\Delta\phi = \pi/4$

π^0 measurement by EMCal

- 1<pt<15 GeV/c
- 6 lead- scintillator (PbSc) sectors
- 2 lead- glass (PbGl) sectors
- $|\eta|$<0.38 at midrapidity, $\Delta\phi = \pi$





The STAR Experiment, main emphasis on hadronic probes.

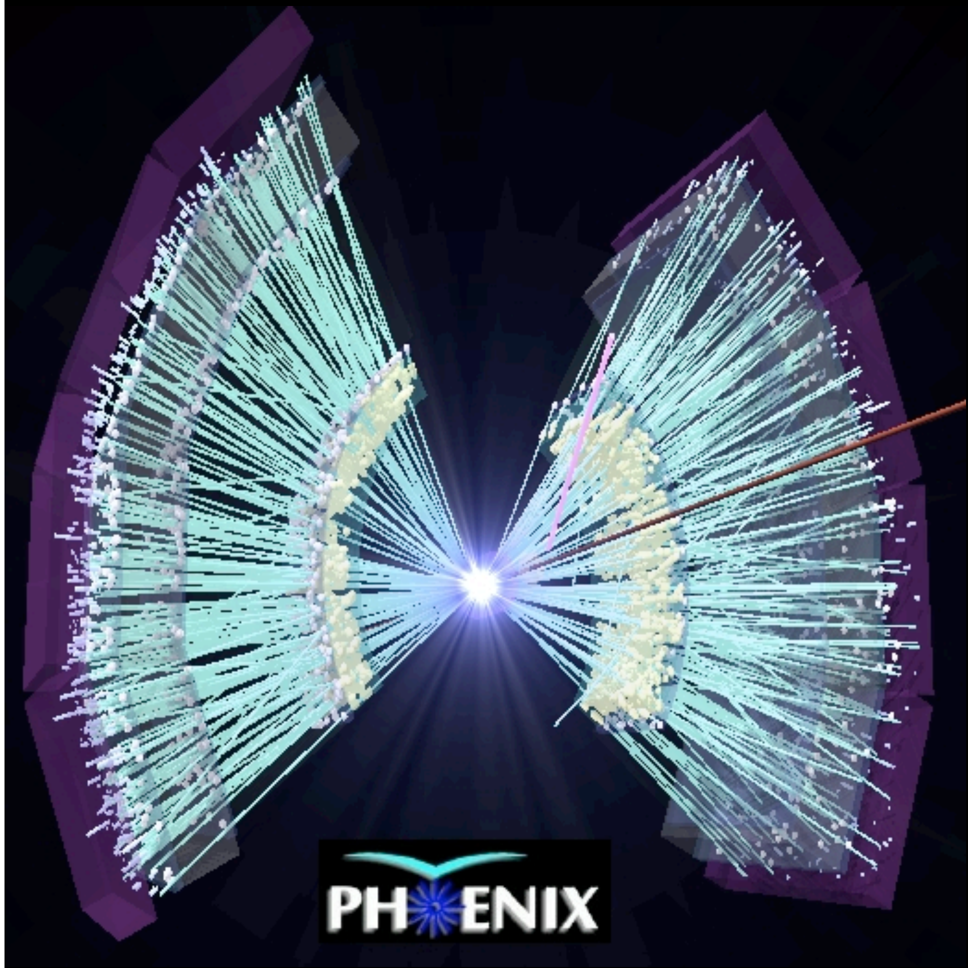
Focus:

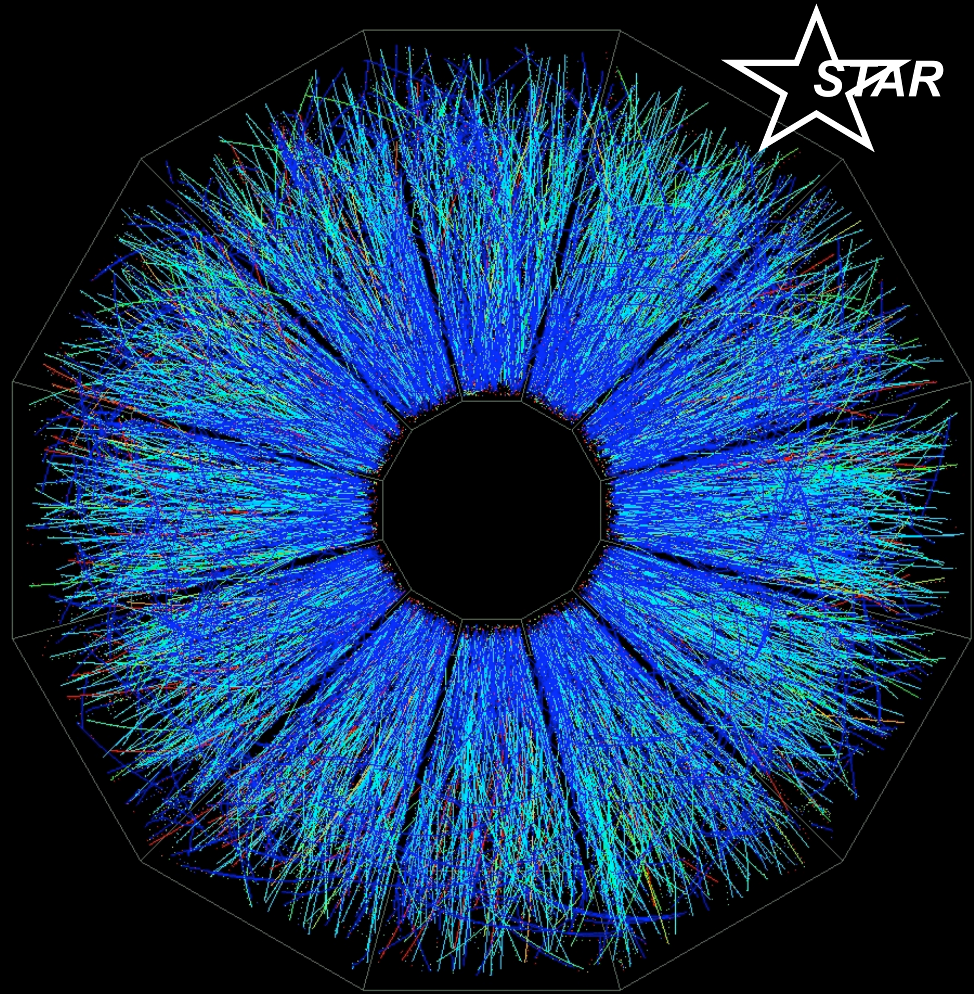
- global observables, event-by-event physics, HBT, strangeness, high-pt jets…

The Configuration:

- large acceptance TPC, Silicon Vertex Tracker, RICH, TOF, EMC…

Au on Au central event at √s=130GeV





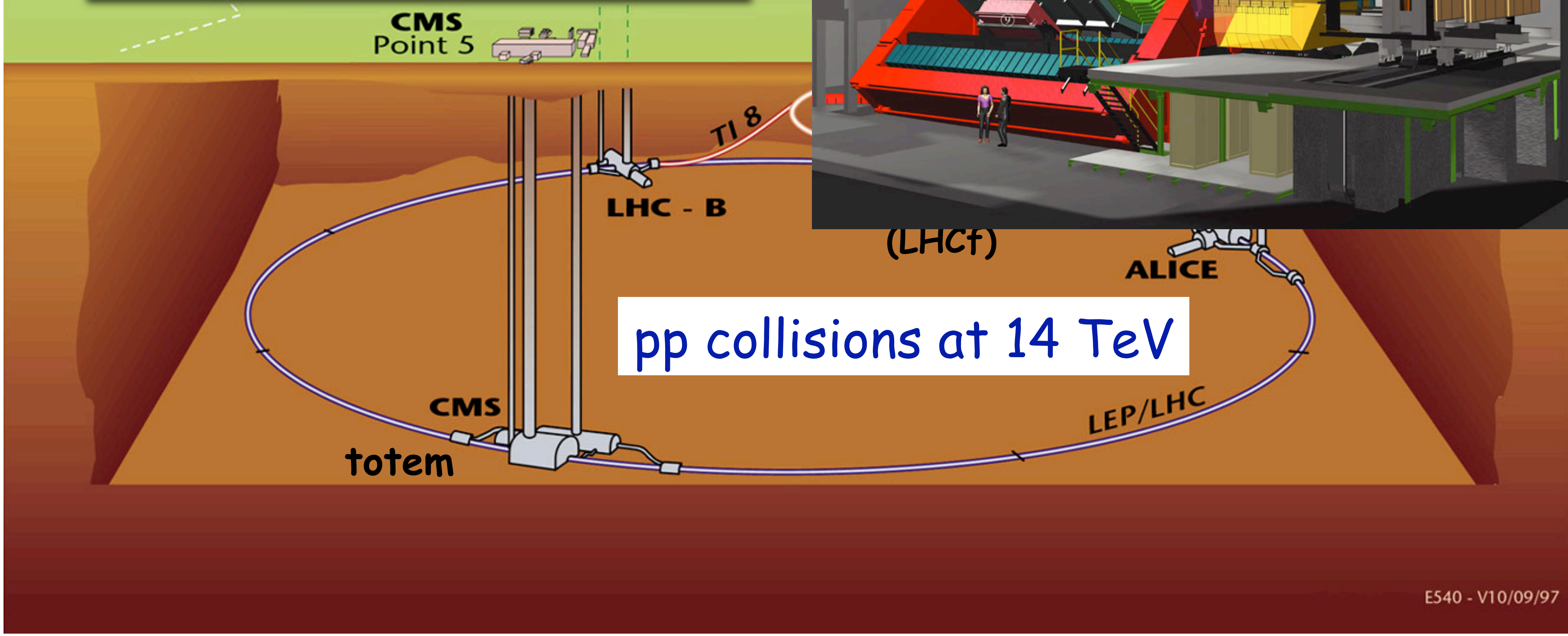
beam view

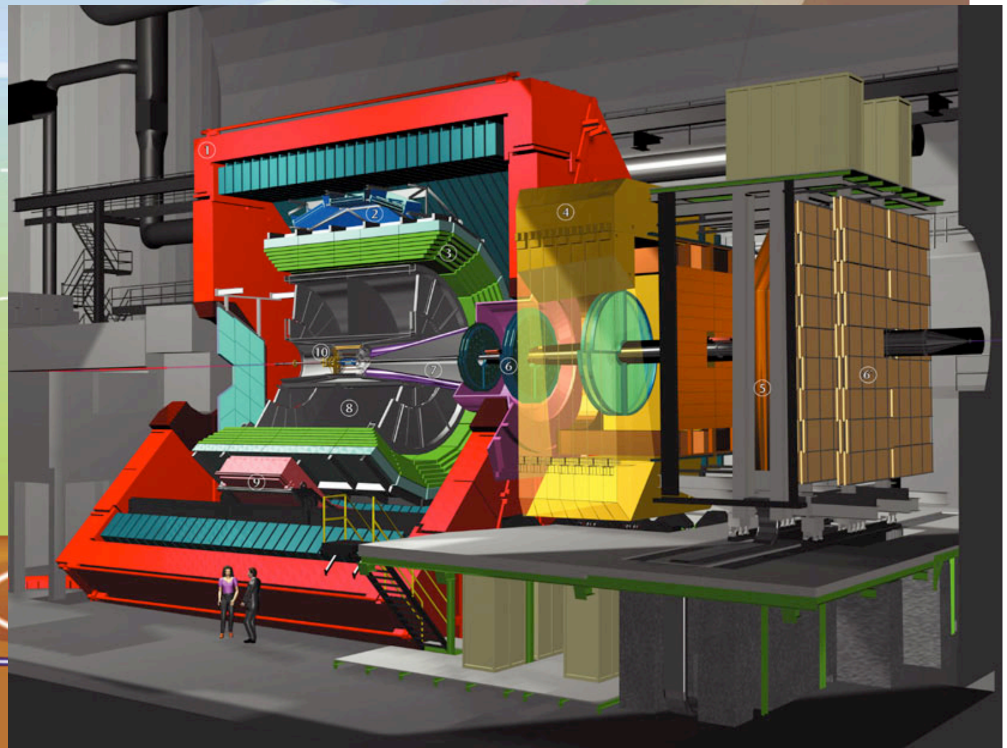
The LHC Machine and Experiments

The Large Hadron Collider (LHC) is being built in a circular tunnel 27 km in circumference. The tunnel is buried around 50 to 175 m underground. It straddles the Swiss and French borders on the outskirts of Geneva

p+p $\sqrt{s}$=14 TeV

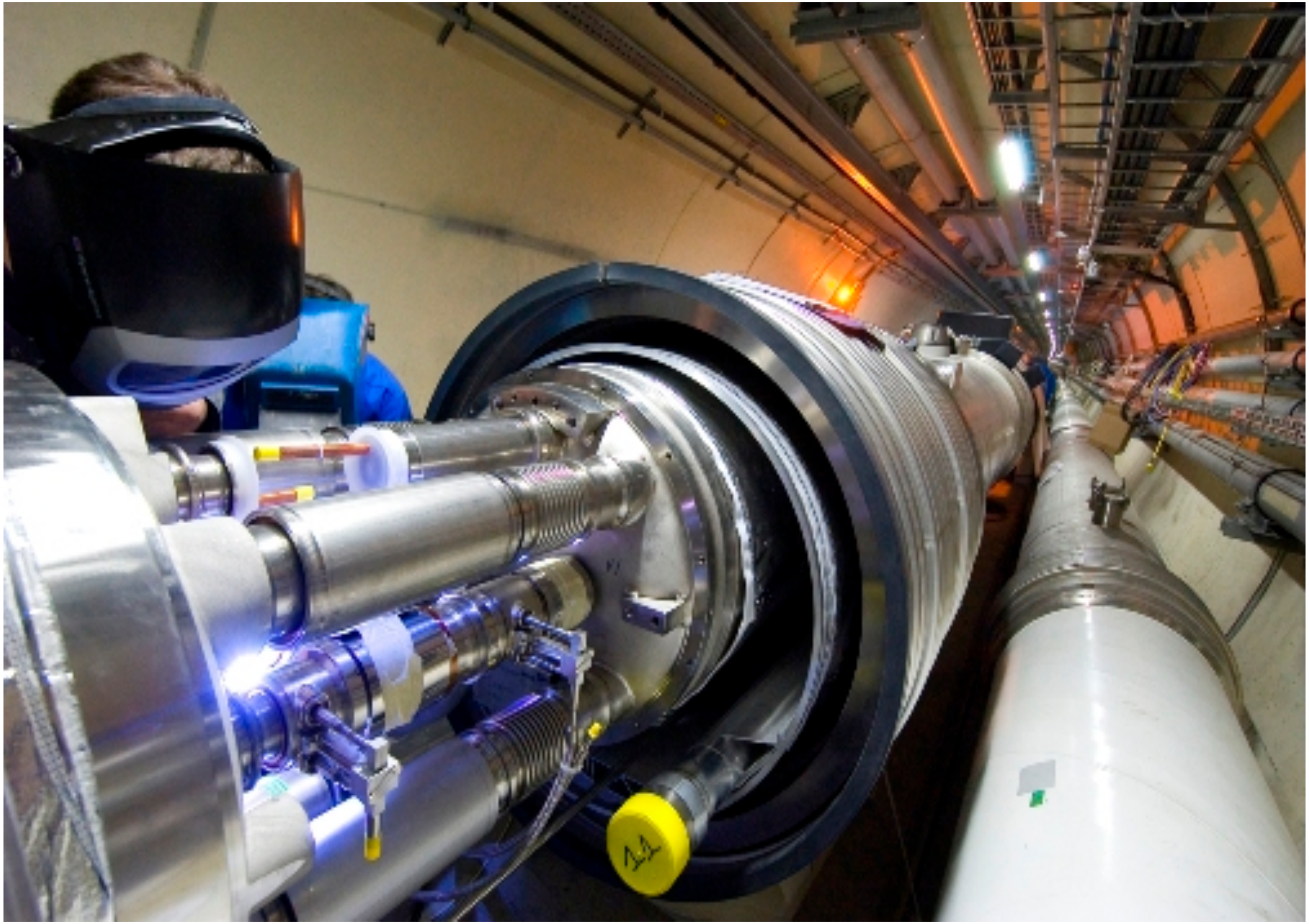
Pb+Pb $\sqrt{s}$=5.5 TeV





pp collisions at 14 TeV

The LHC is Coming!



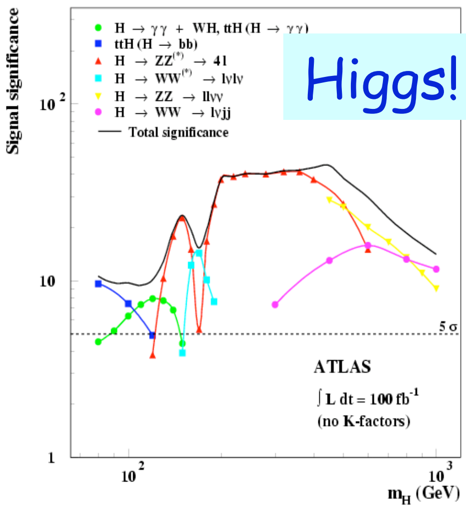
Energy in the LHC: What is "big" vs "small"

Collision energy pp -collisions: E_{cms} = 14 TeV
PbPb -collisions: E_{cms} = 5500 *A* GeV

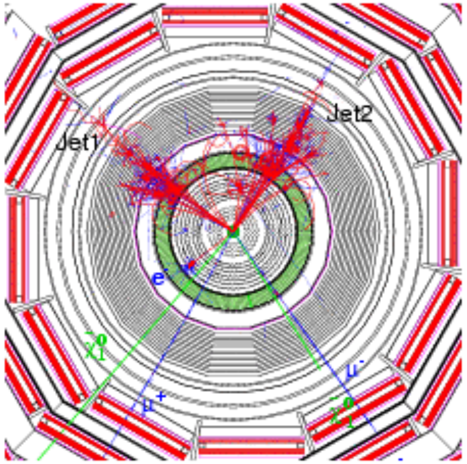
In pp -collision, goal is total 2808 bunches of protons in LHC beams each containing 1.15×10^{11} protons

1) Compare energy of a single proton or lead ion to a kinetic energy of a house fly with mass 12 mg
2) Estimate the time between bunch crossings
3) Compare total energy of proton beams to a kinetic energy of Pendolino train with mass 316 tons
4) Compare energy per mass ratio for a particle in the LHC and a car in high way

Physics at the LHC: pp @ 14 TeV

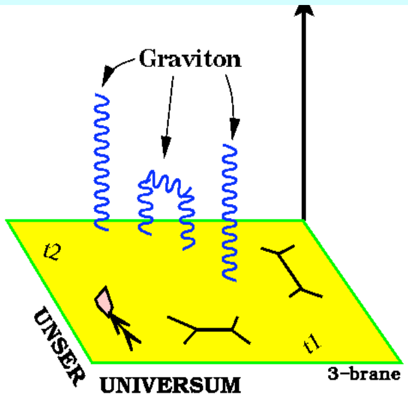


Higgs!

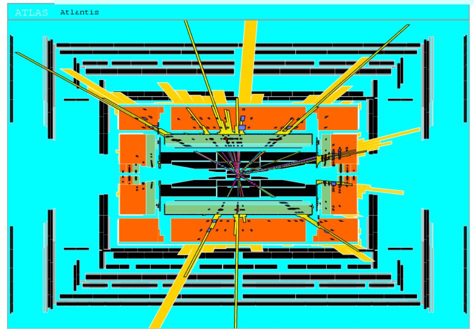


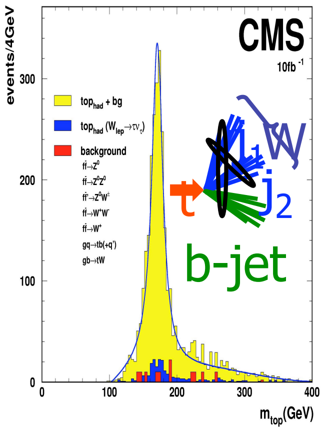
Supersymmetry?

Extra Dimensions?

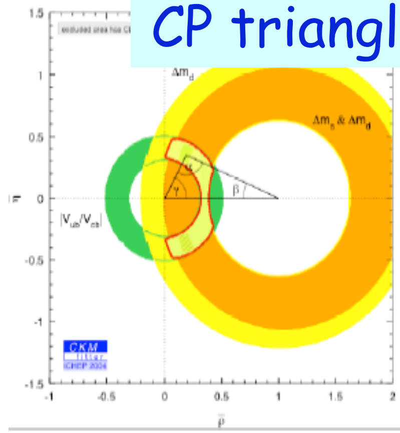


Black Holes???



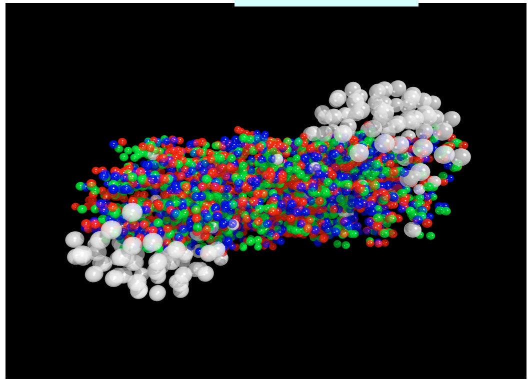


Precision measurements e.g top!



CP triangle!

QGP?



- LHC will explore directly the highly-motivated TeV-scale and say the final word about the SM Higgs mechanism and many TeV-scale New Physics predictions
- Also LHC will be a great machine for: QCD, B-physics, Heavy Ions, EW precision..

WHY HEAVY IONS AT THE LHC?

… factor ~30 jump in √s …

J. Schukraft QM2001:
hotter - bigger -longer lived

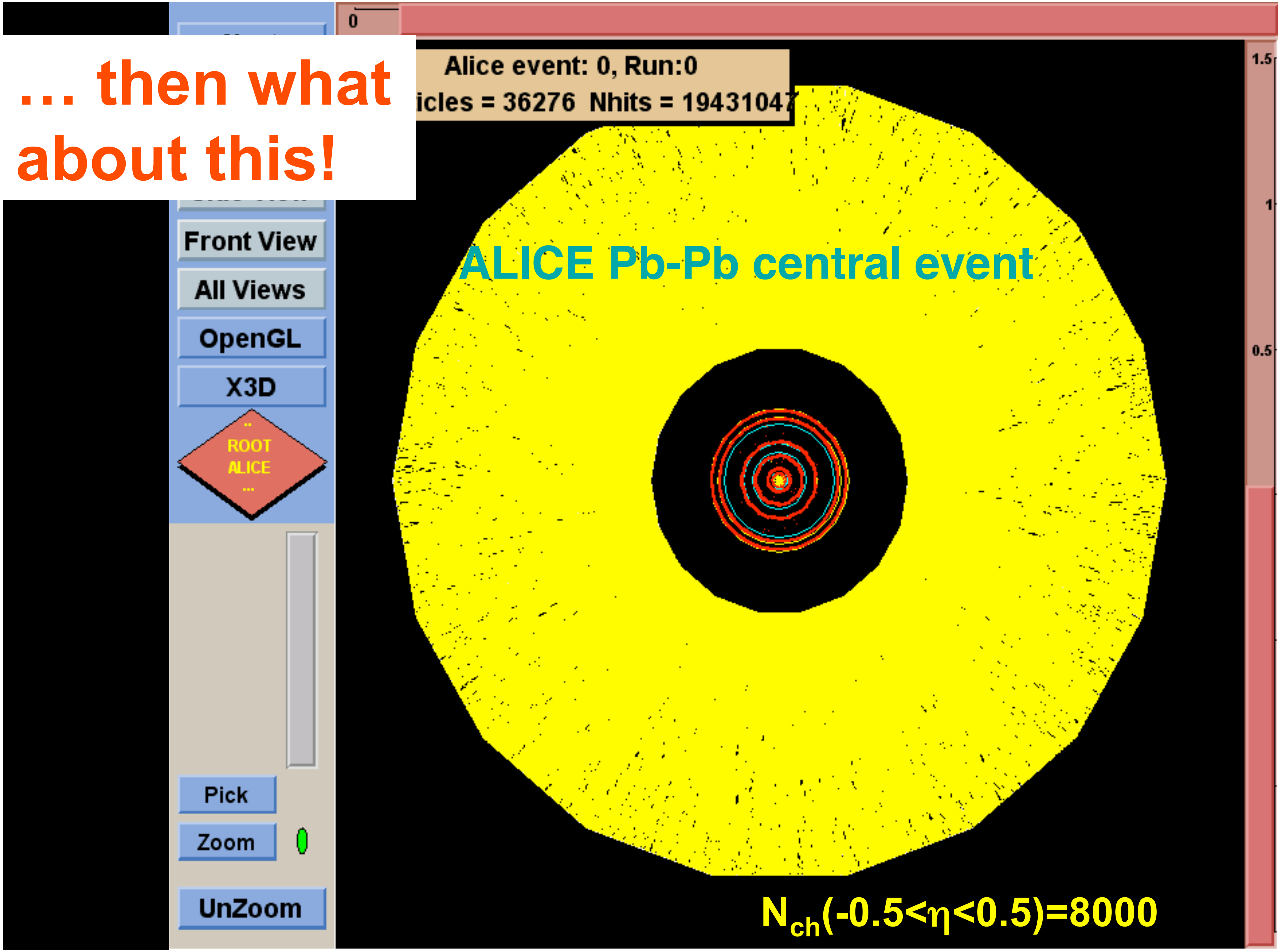
$\varepsilon_{LHC} > \varepsilon_{RHIC} > \varepsilon_{SPS}$

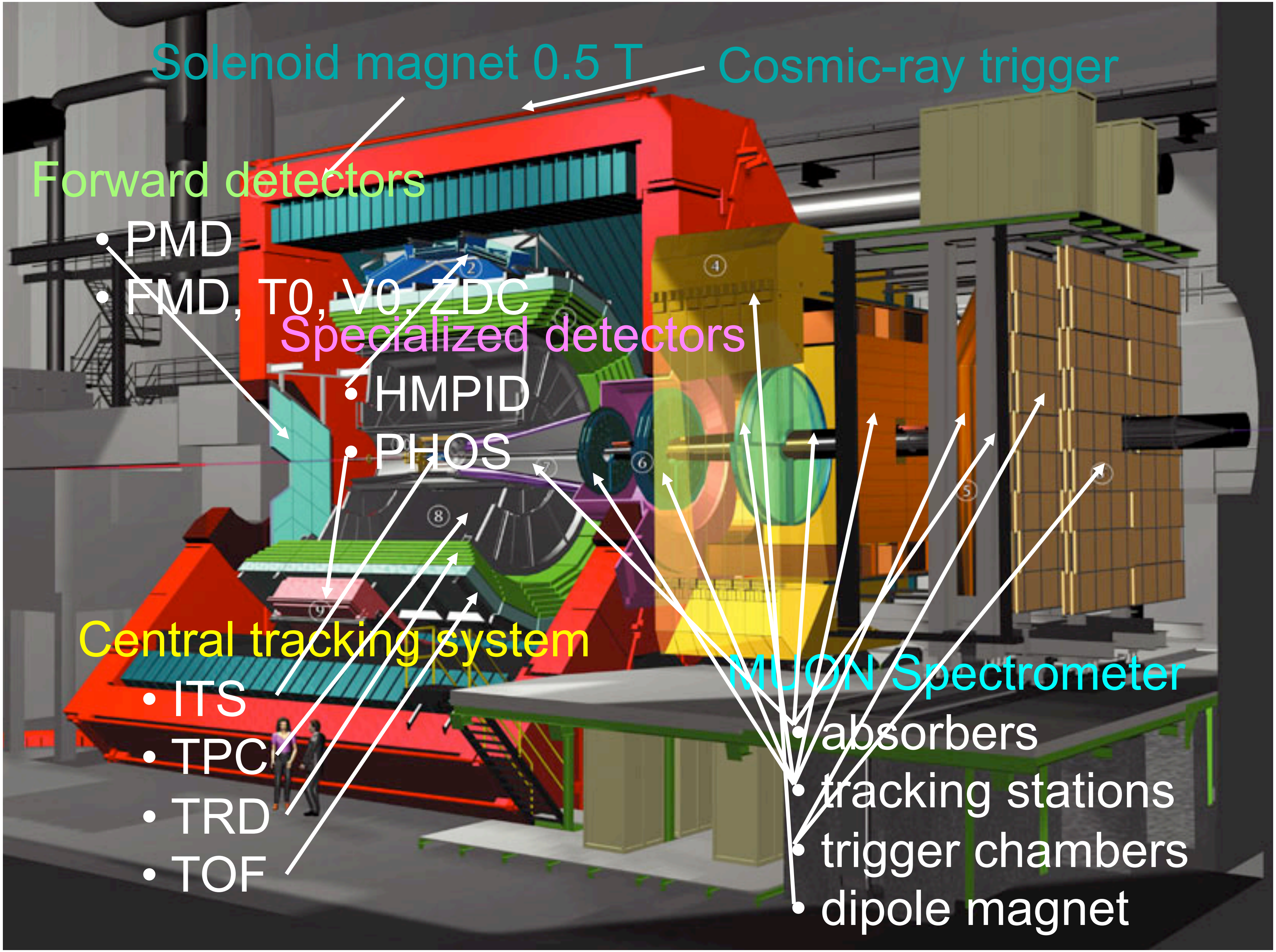
$V_{f\,LHC} > V_{f\,RHIC} > V_{f\,SPS}$

$\tau_{LHC} > \tau_{RHIC} > \tau_{SPS}$

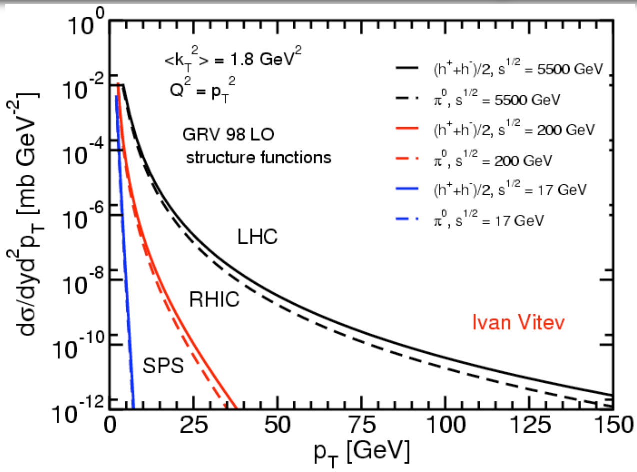
Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	500	850	2–8 x10^3
ε (GeV/fm^3)	2.5	4–5	15–40
V_f(fm^3)	10^3	7x10^3	2x10^4
τ_{QGP} (fm/c)	<1	1.5–4.0	4–10
τ_0 (fm/c)	~1	~0.5	<0.2

… then what about this!

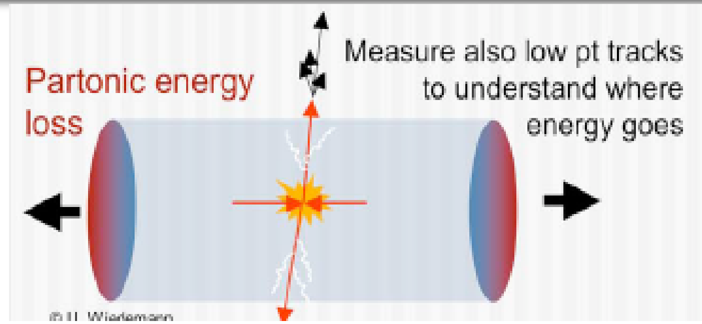



Solenoid magnet 0.5 T
Cosmic-ray trigger
Forward detectors
• PMD
• FMD, T0, V0, ZDC
Specialized detectors
• HMPID
• PHOS
Central tracking system
• ITS
• TPC
• TRD
• TOF
MUON Spectrometer
• absorbers
• tracking stations
• trigger chambers
• dipole magnet

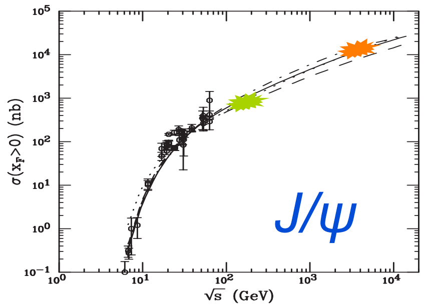
Heavy Ion Physics at the LHC

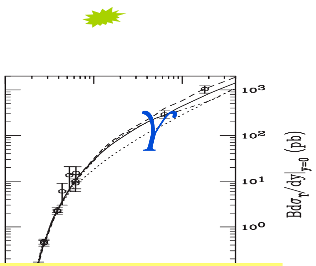


High P_T particle and jet production
Jet-quenching

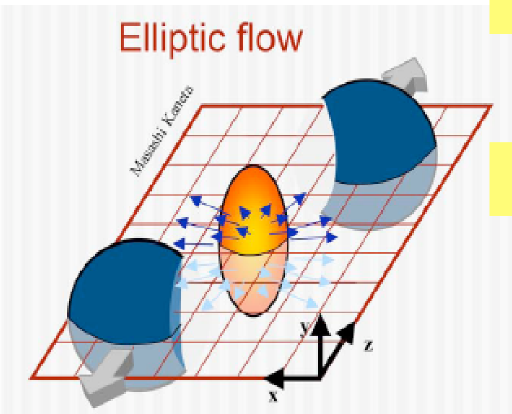


Heavy ions part of the LHC physics program with ALICE, but also CMS and ATLAS

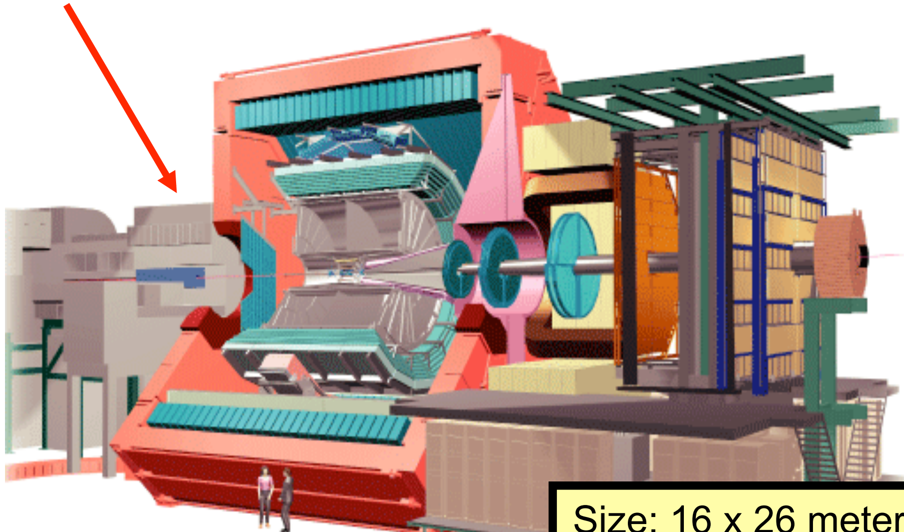




ϒ melt down



Event shapes

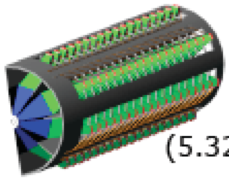


Size: 16 x 26 meters
Weight: 10,000 tons

LHC ready for heavy ions in 2008

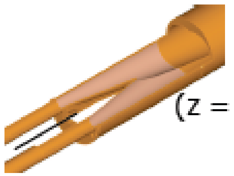
CMS: The Detector

Forward calorimeters



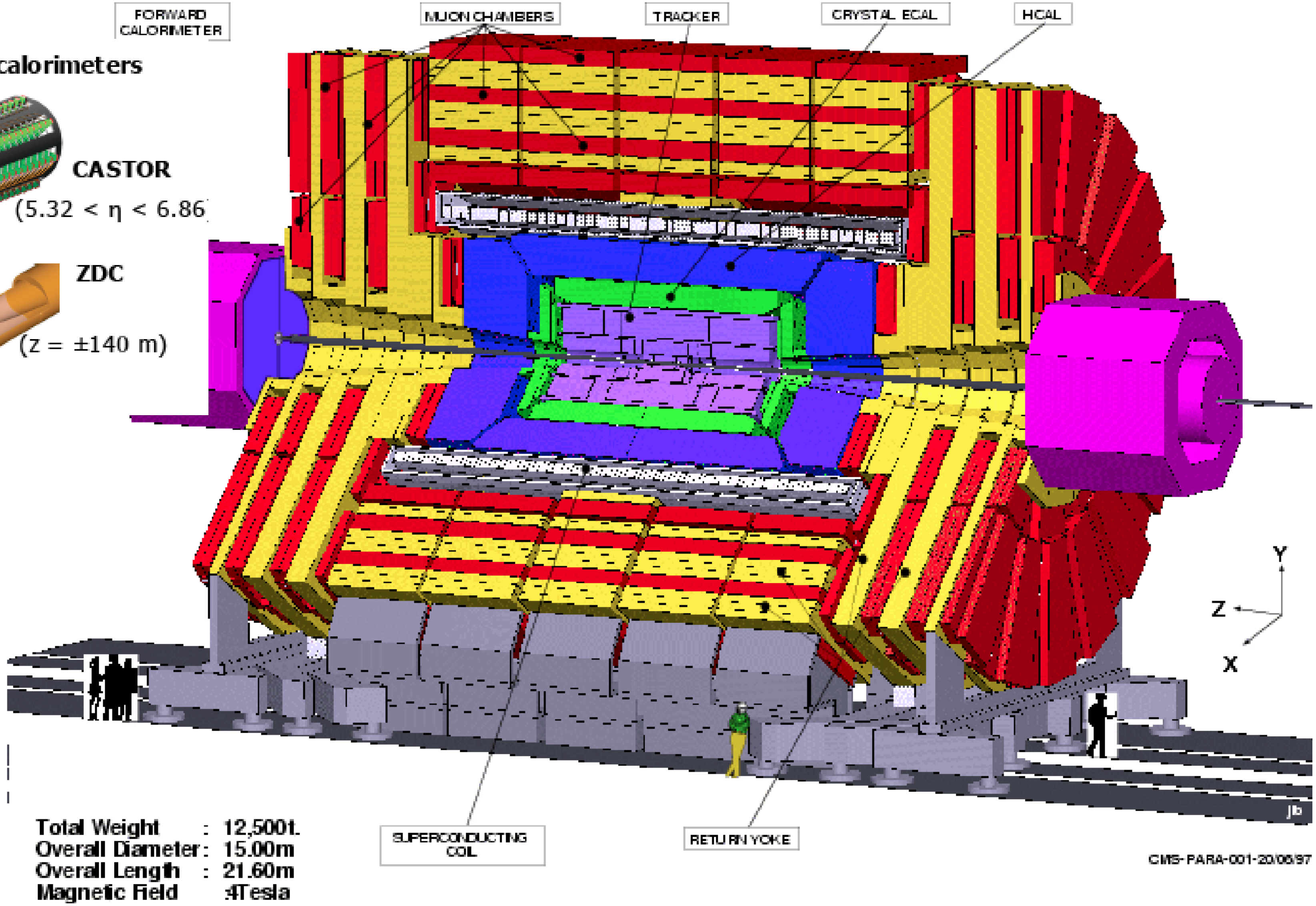
CASTOR

(5.32 < η < 6.86)



ZDC

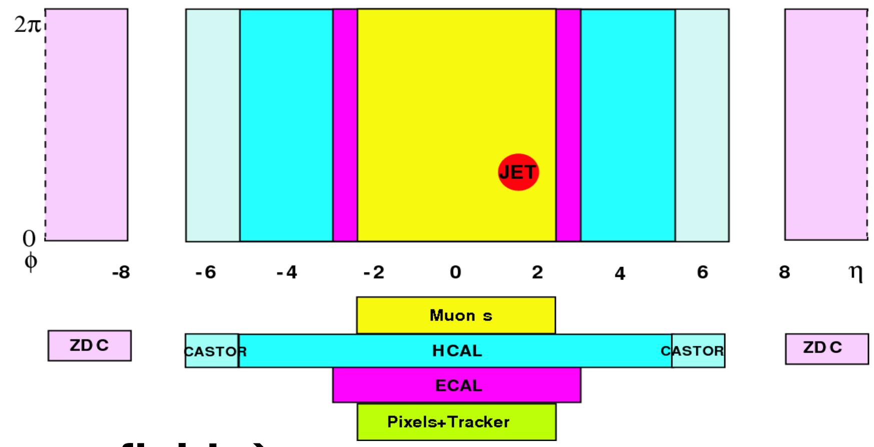
(z = ±140 m)



CMS: Capabilities & Performance

- **Large acceptance** *tracking and calorimetry*:
  - 2π in azimuth (jets,..)
  - Si-tracker |η|<2.5 (b-,c- physics, …)
  - uniquely large range in rapidity
    (|η|<6.6, $|\eta_{neutral}|>8$) (→ forward physics)

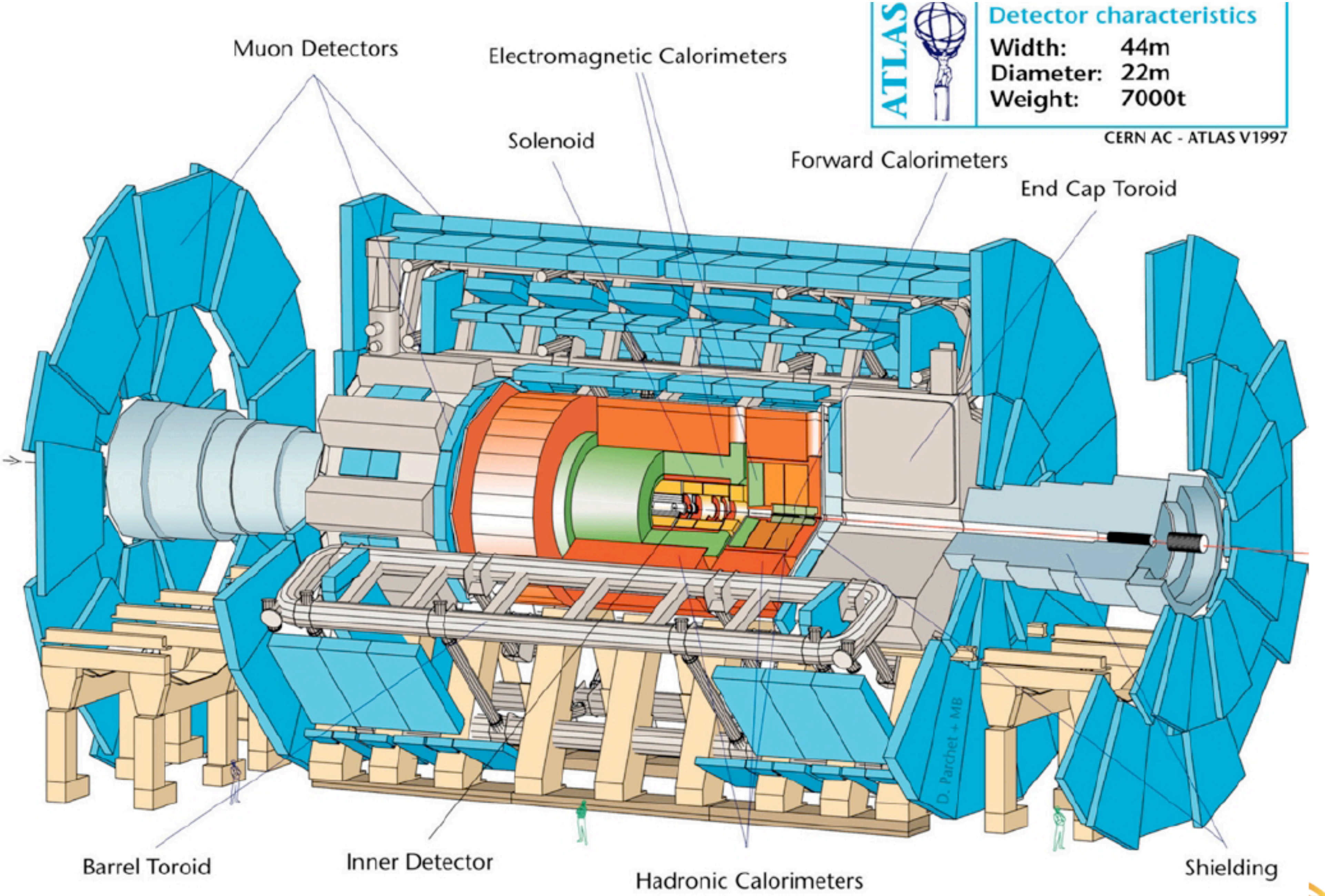
CMS has the coverage to address the physics



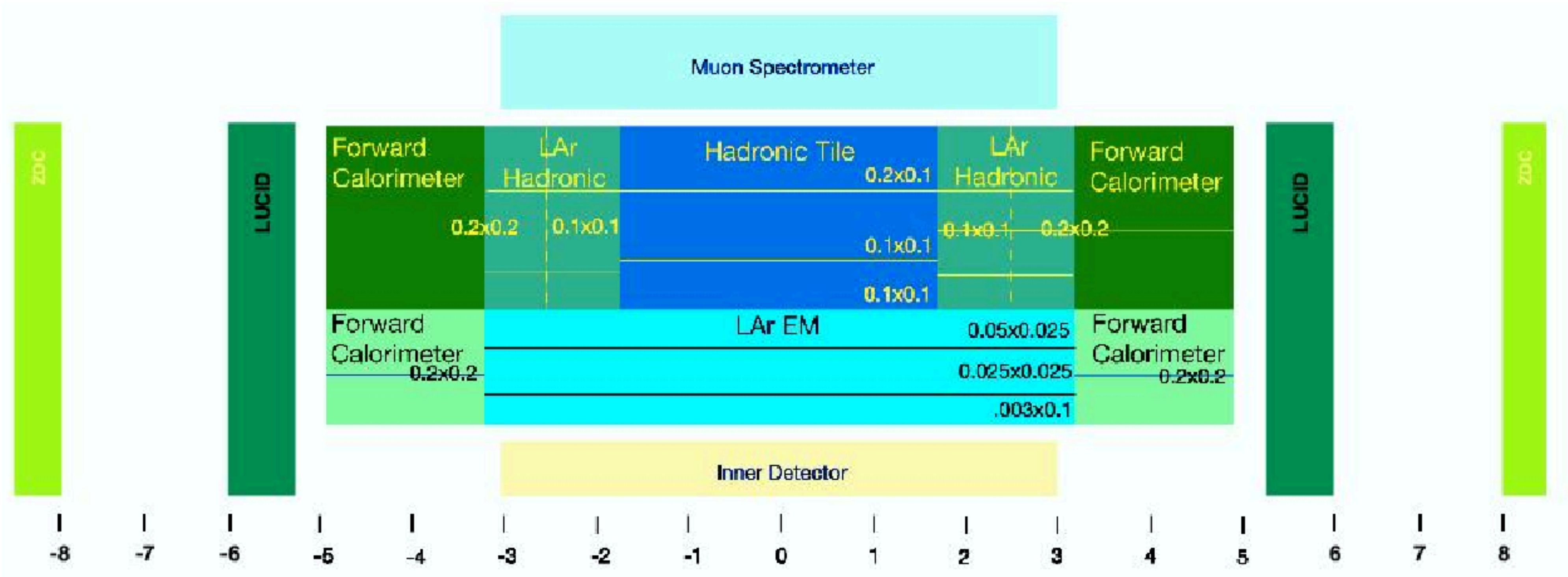
- **High resolution**
  - Granularity of the **Si-pixel layer+4T mag field** →
    $\Delta p_T/p_T < 1.5\%$ for $p_T<50$ GeV/c
  - For jet finding, calorimeters $\sigma_\eta=0.028$ $\sigma_\phi=0.032$

CMS has the detector performance needed to resolve the physics

The ATLAS Detector

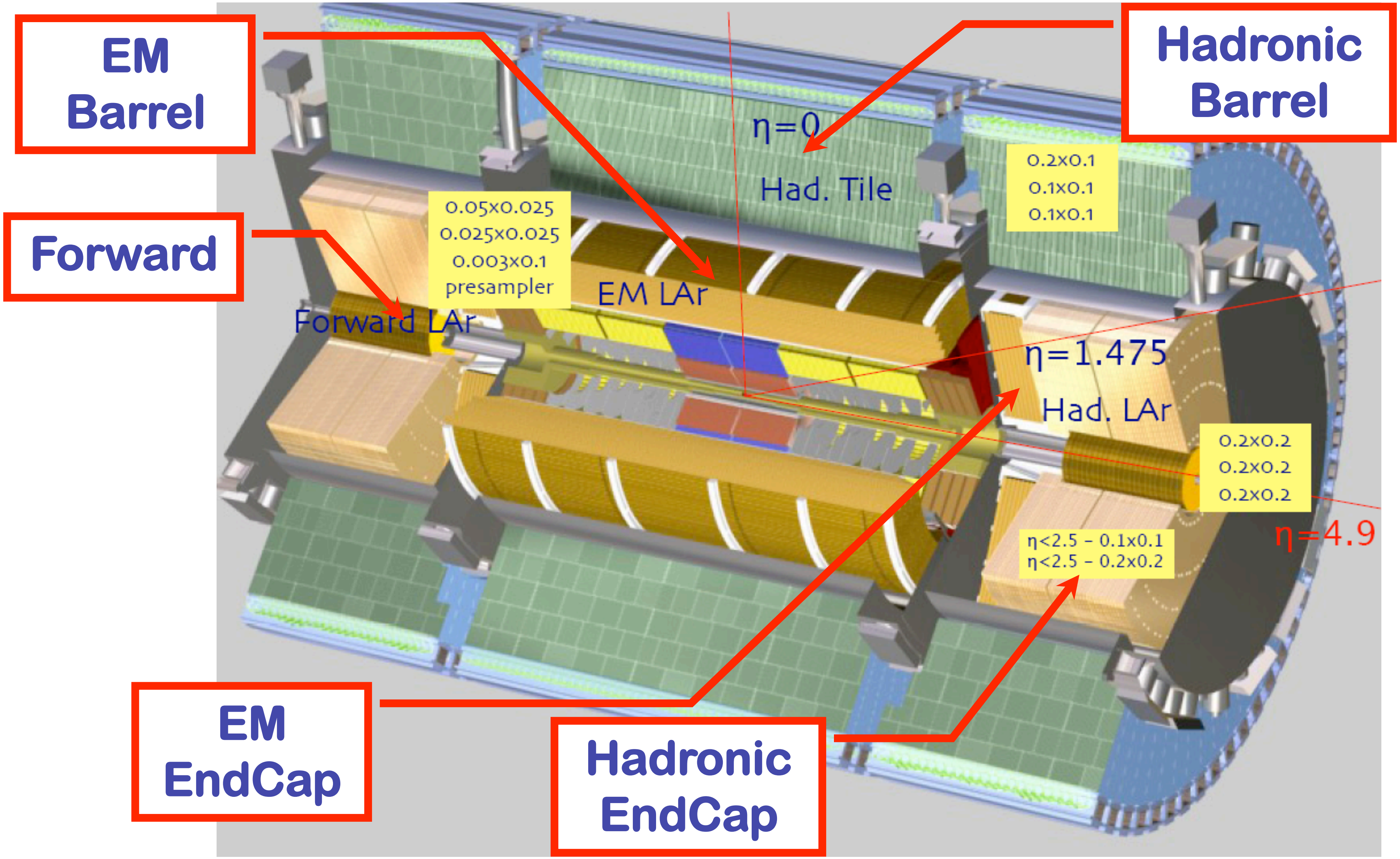


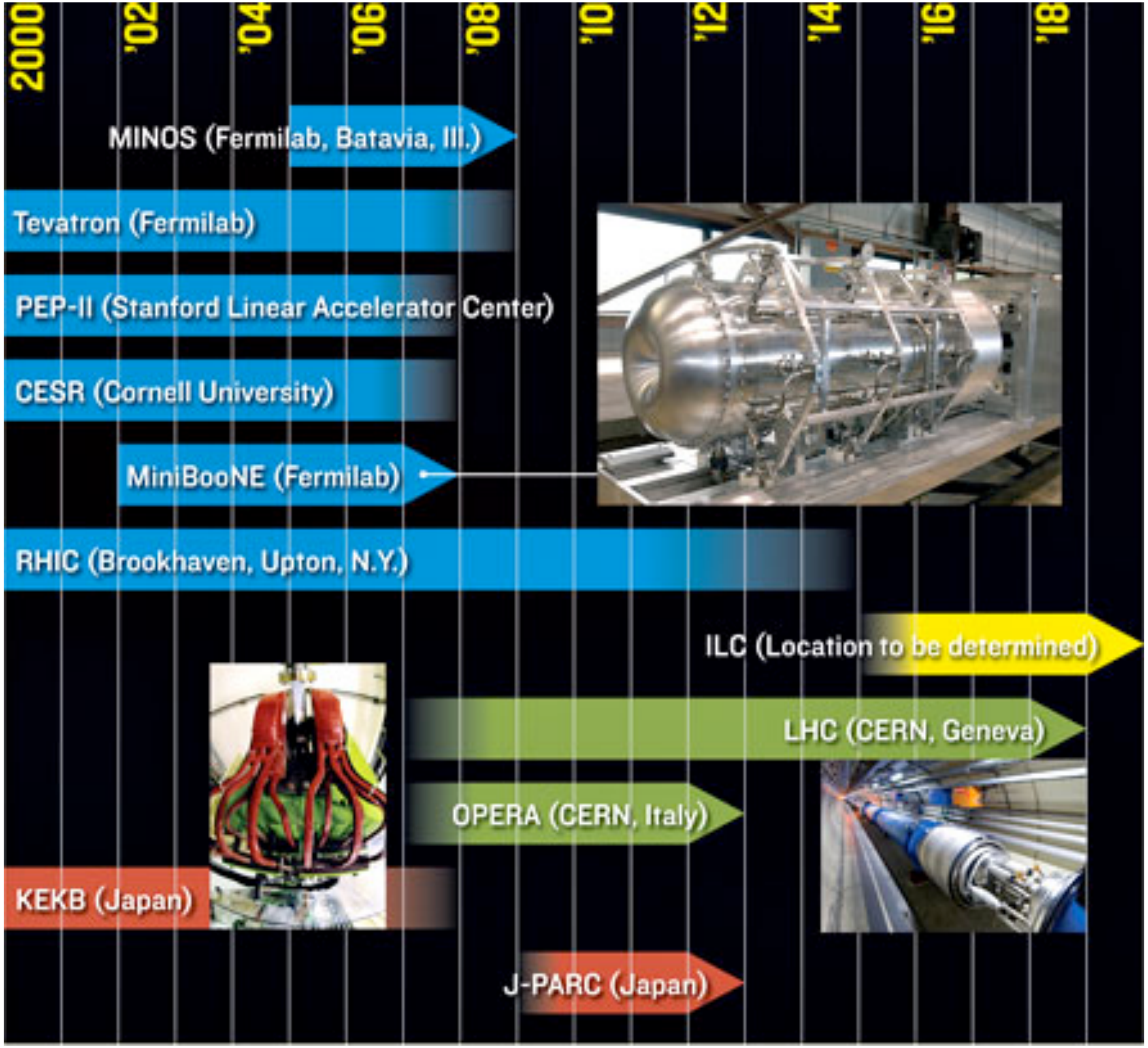
The ATLAS Detector



- Full azimuthal acceptance in all detectors
- Unprecedented pseudorapidity coverage for A+A

ATLAS Calorimetry




2000
'02
'04
'06
'08
'10
'12
'14
'16
'18
MINOS (Fermilab, Batavia, Ill.)
Tevatron (Fermilab)
PEP-II (Stanford Linear Accelerator Center)
CESR (Cornell University)
MiniBooNE (Fermilab)
RHIC (Brookhaven, Upton, N.Y.)
ILC (Location to be determined)
LHC (CERN, Geneva)
OPERA (CERN, Italy)
KEKB (Japan)
J-PARC (Japan)