Exploring Hot Dense Matter at RHIC and LHC

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Lecture 1: Tools
Lecture 2: Initial conditions: partonic structure and global observables
Lecture 3: Collective flow and hydrodynamics
Lecture 4: Jets and other hard probes

My approach to these lectures

The field of hot QCD matter is vast, spanning the boundaries of nuclear, particle and condensed matter physics, and string theory

The field is also relatively young, with many phenomena not yet understood on a fundamental level

- this is an opportunity, but also a barrier to the newcomer to sort out what is really known and what is conjectured

I will make no attempt to be comprehensive

- rather, I will discuss a limited number of topics that are well-established experimentally and have a clear connection to well-founded theory

I am not an expert in all the topics I will present. Ask lots of questions, and those I don't understand we will figure out together

References

QCD

- Particle Data Group topical reviews http://pdg.lbl.gov/2004/reviews/contents_sports.html
- QCD and jets: CTEQ web page and summer school lectures http://www.phys.psu.edu/~cteq/
- Handbook of Perturbative QCD, Rev. Mod. Phys. 67, 157–248 (1995)
- QCD and Collider Physics, R. K. Ellis, W. J. Sterling, D.R. Webber, Cambridge University Press (1996)

Heavy Ion Physics

- Results from the Relativistic Heavy Ion Collider, B. Mueller and J. Nagle; Ann. Rev. Nucl. Part. Sci. 56, 93 (2006), nucl-th/0602029
- Heavy Ion Collisions at the LHC – Last Call for Predictions, N. Armesto et al. (ed).; J. Phys. G35 054001 (2008), arXiv:0711.0974
- New Developments in Relativistic Viscous Hydrodynamics, P. Romatschke; Int. J. Mod. Phys. E19, 1-53 (2010), arXiv:0902.3663
- The theory and phenomenology of perturbative QCD-based jet quenching, A. Majumder and M. van Leeuwen; arXiv:1002.2206
- Gauge/String Duality, Hot QCD and Heavy Ion Collisions, J. Casalderrey-Solana et al.; arXiv:1101.0618

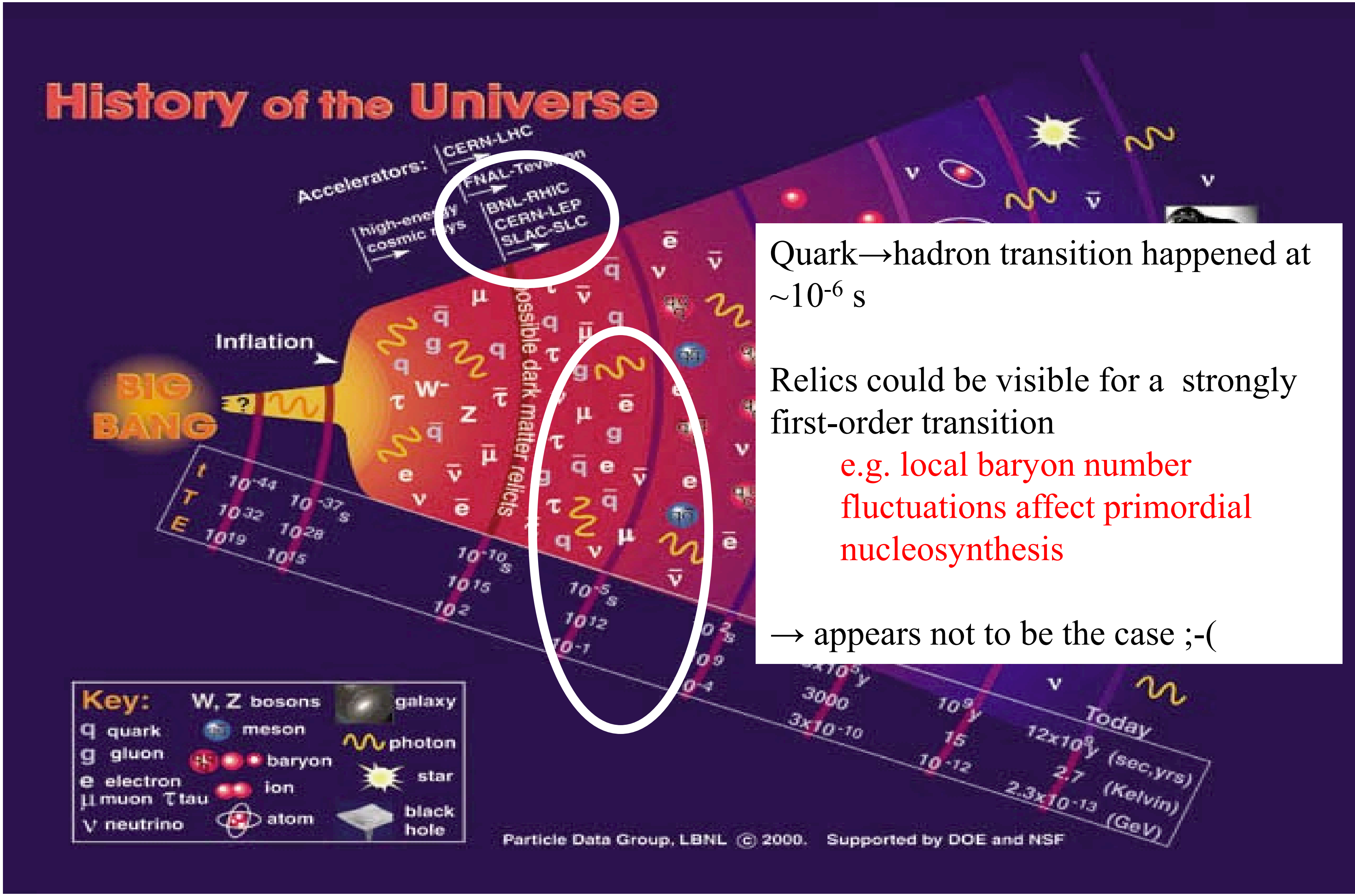
The major heavy ion conference: Quark Matter (http://qm2011.in2p3.fr/node/18)

Outline: Lecture 1

Theory Tools
- Basics of QCD
- Finite Temperature QCD

Experimental Tools
- Colliders
- Detectors

Analysis Tools
- Relativistic Kinematics
- Characterization of nuclear collisions



Quark→hadron transition happened at ~10^{-6} s

Relics could be visible for a strongly first-order transition

e.g. local baryon number fluctuations affect primordial nucleosynthesis

→ appears not to be the case ;-(

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Quantum Chromo-dynamics: the field theory of the strong (nuclear) force

Same basic structure as QED (electromagnetism)….

rks

color $a = 1, \ldots, 3$

….except that gluons (“photons” of strong force) carry (color) charge…

Gluons

$$A_\mu^a \begin{cases} \text{color} & a = 1, \ldots, 8 \\ \text{spin} & \epsilon_\mu^\pm \end{cases}$$

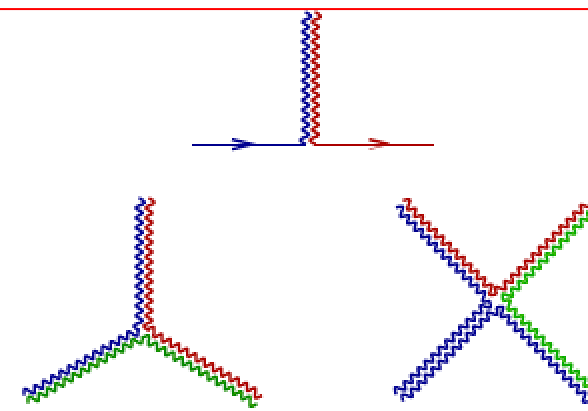
….so they interact among themselves, generating much more complex structures…

Dynamics: Generalized Maxwell (Yang-

$$\mathcal{L} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G_{\mu\nu}^a G_{\mu\nu}^a$$

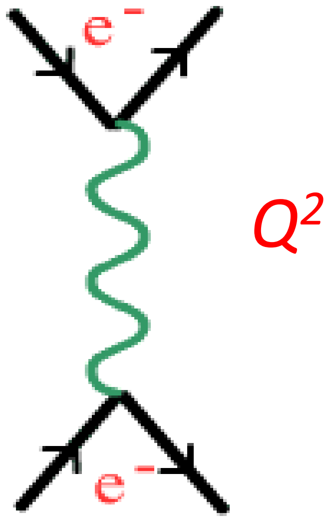
$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$

$$i\not{D} q = \gamma^\mu \left(i\partial_\mu + g A_\mu^a t^a \right) q$$



Field theory: "running" of the coupling

Consider the interaction of two elementary particles:



Momentum transfer Q^2

small $Q^2 \Rightarrow$ large distance scales
large $Q^2 \Rightarrow$ small distance scales

Quantum mechanics:
Virtual pairs (loops) screen bare interaction
$\Rightarrow$ momentum-dependent interaction strength

Running of the coupling: QED vs QCD

negative

QED:

$$\frac{1}{\alpha(Q^2)} \approx \frac{1}{\alpha(\mu^2)} - \frac{1}{3\pi}\log\left(\frac{|Q^2|}{\mu^2}\right)$$

Smaller $|Q^2|$ (larger distance) $\Rightarrow$ weaker coupling

- similar to screening of charge in di-electric material

QCD:

$$\frac{1}{\alpha_S(Q^2)} \approx \frac{1}{\alpha_S(\mu^2)} + \frac{11N_{color} - 2n_{flavor}}{12\pi}\log\left(\frac{|Q^2|}{\mu^2}\right)$$

$=+(33-12)/12\pi$ = positive!

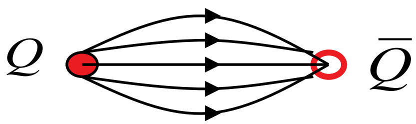
Smaller $|Q^2|$ (larger distance) $\Rightarrow$ larger coupling

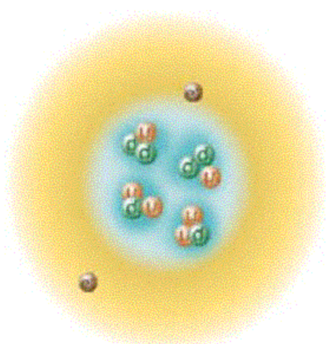
And that makes a huge difference!

QCD: running of α_s

Asymptotic Freedom

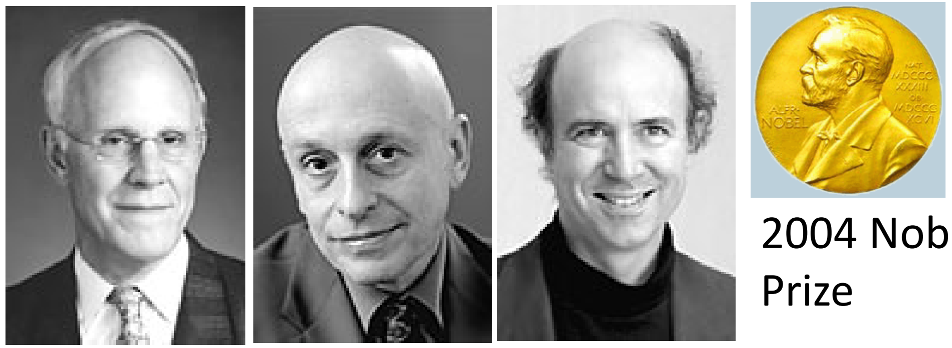
Confinement

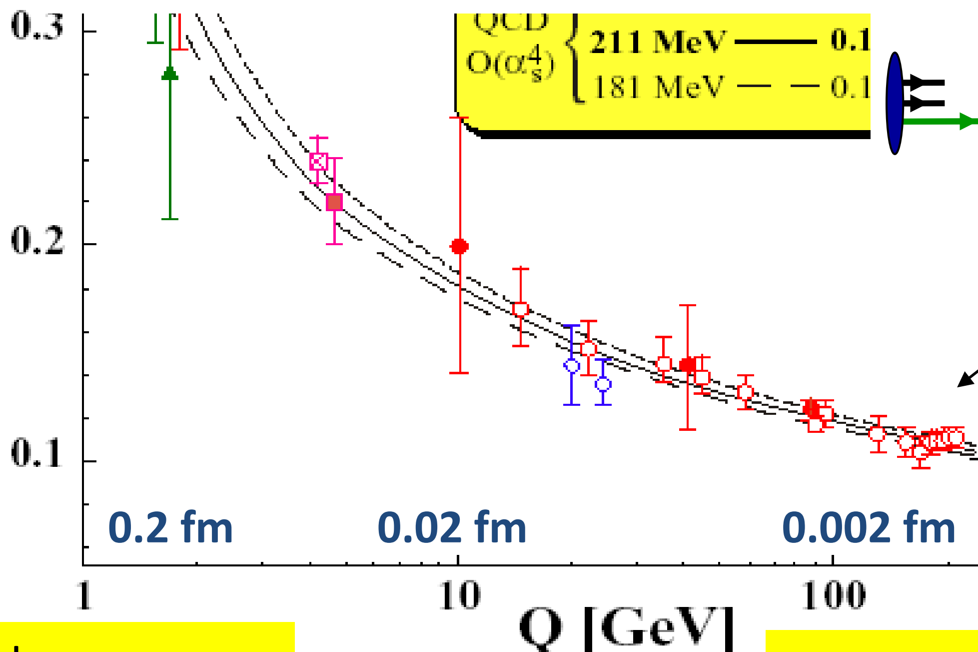


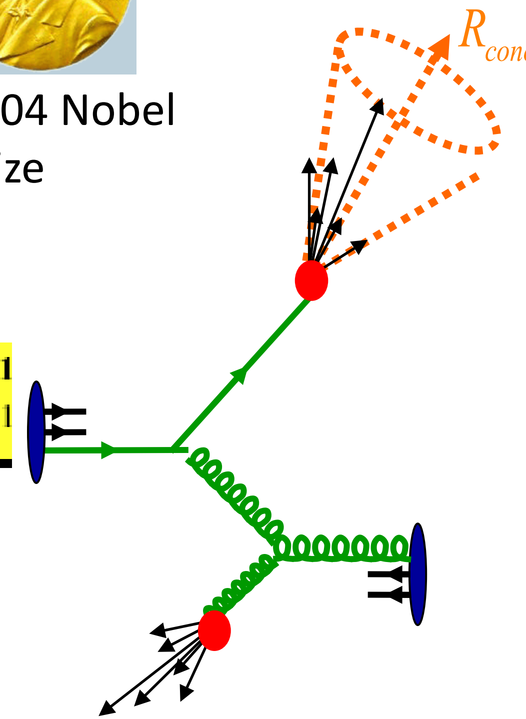


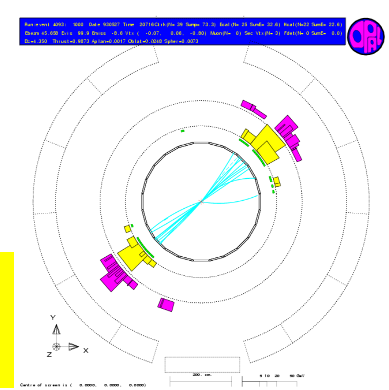
Gross Politzer Wilczek

2004 Nobel Prize







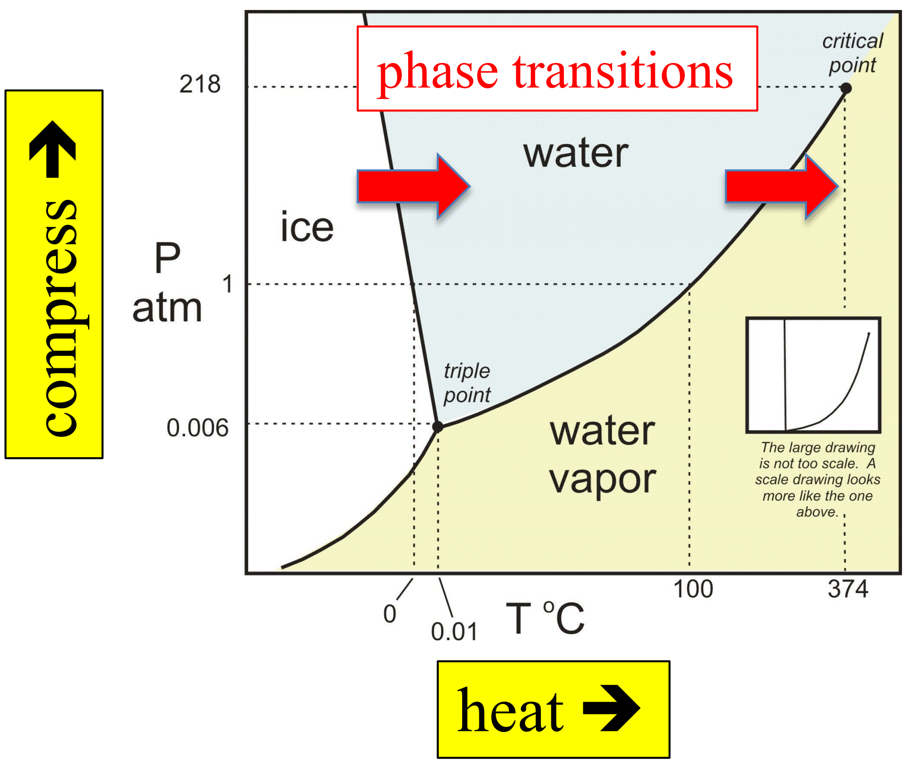


Low momentum

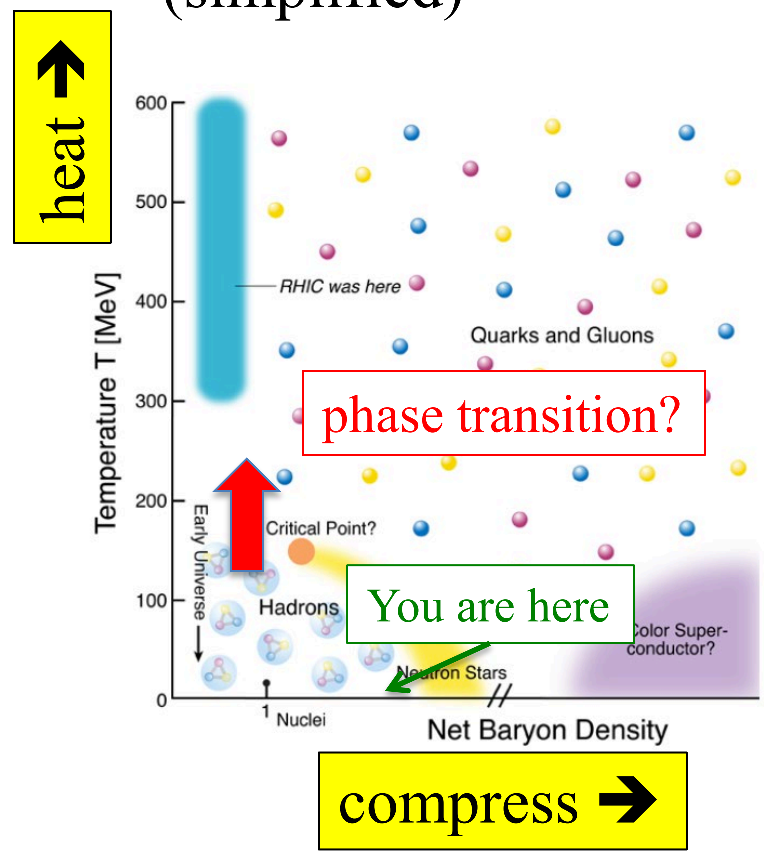
High momentum

Now let's think about "matter"

Phase diagram of water (simplified)



Phase diagram of QCD (simplified)



Quantitative QCD thermodynamics

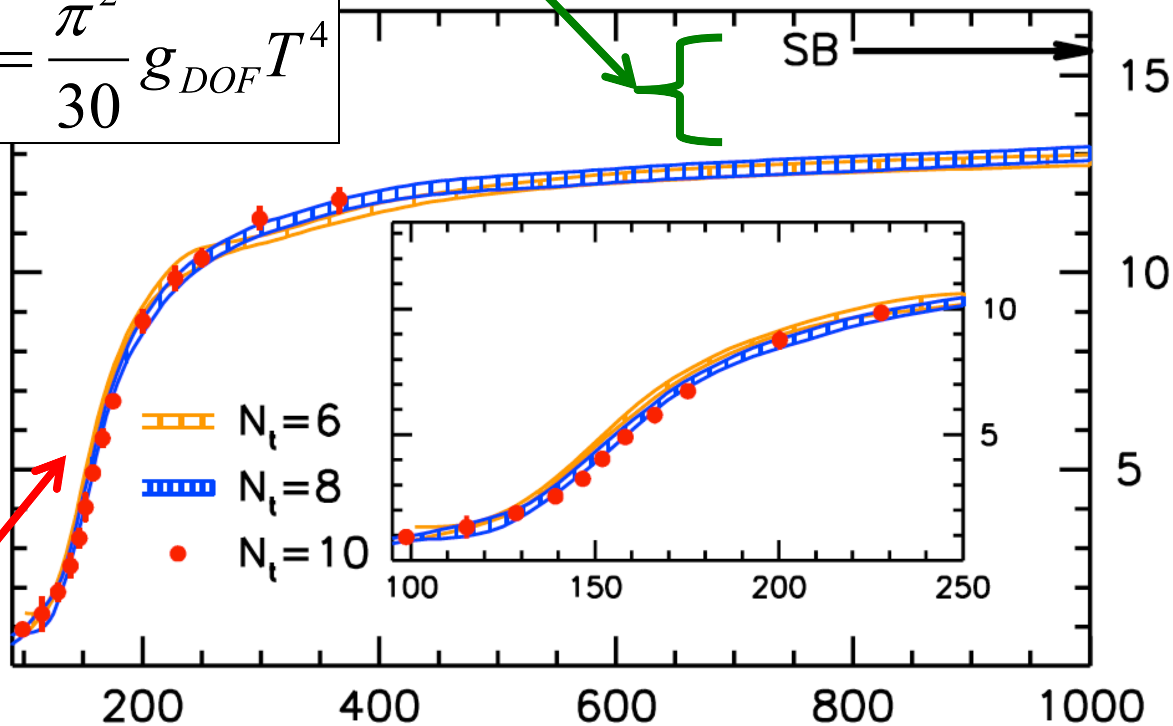
QCD calculated on the lattice (μ_B=0)

Slow convergence to non-interacting Steffan-Boltzmann limit
What carries energy - complex bound states of q+g? "strongly-coupled" plasma?

$$\varepsilon = \frac{\pi^2}{30} g_{DOF} T^4$$

Energy density

$$\frac{\varepsilon}{T^4}$$



Temperature [MeV]

S. Borsanyi et al., JHEP 1011, 077 (2010)

Cross-over, not sharp phase transition
(like ionization of atomic plasma)

Exploration of hot QCD Matter: what are the questions? (partial list)

What is the nature of QCD Matter at finite temperature?

- What is its phase structure?
- What is its equation of state?
- What are its effective degrees of freedom?
  - Is it a (trivial) gas of non-interacting quarks and gluons, or a fluid of interacting quasi-particles?
- What are its symmetries?
- Is it correctly described by Lattice QCD or does it require new approaches, and why?

What are the dynamics of QCD matter at finite temperature?

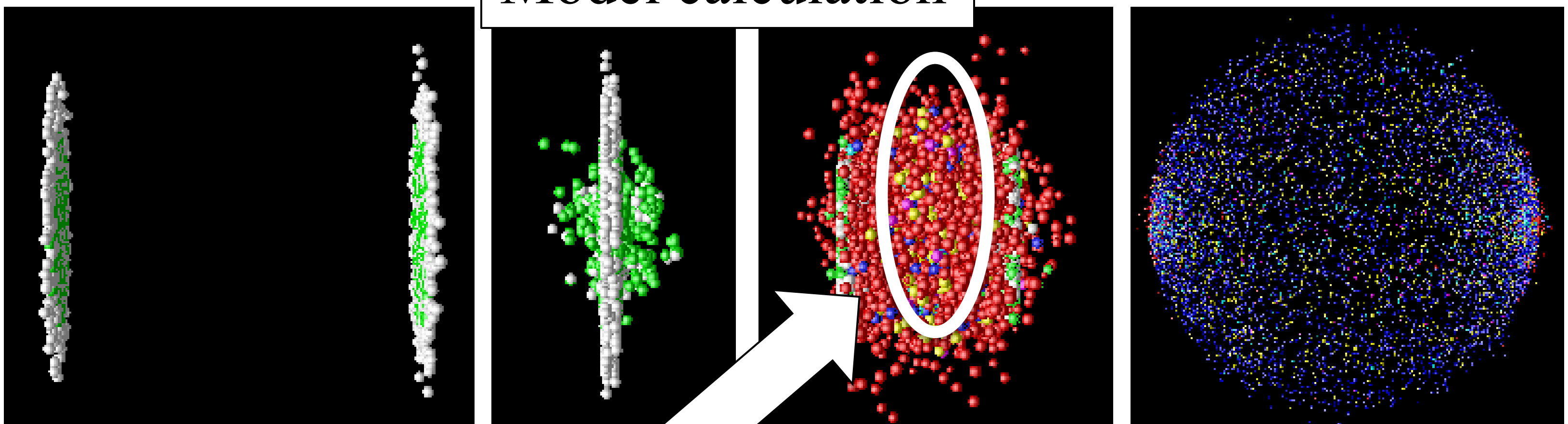
- What is the order of the (de-)confinement transition?
- How is chiral symmetry restored at high T, and how?
- Is there a QCD critical point?
- What are its transport properties?

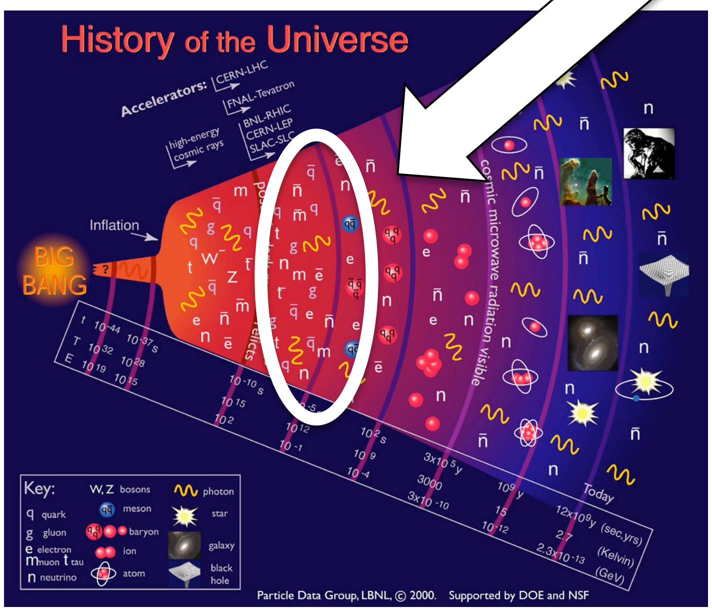
Can QCD matter be related to other physical systems?

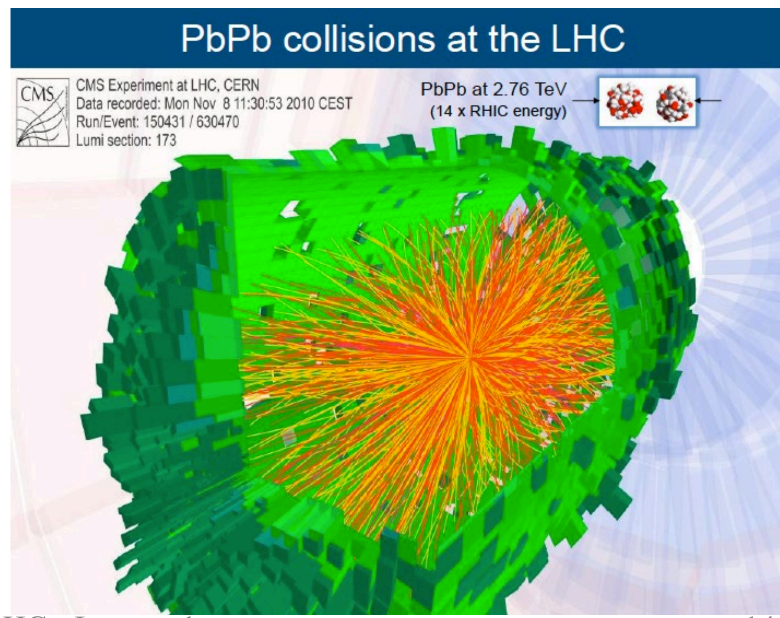
Can we study hot QCD matter experimentally?

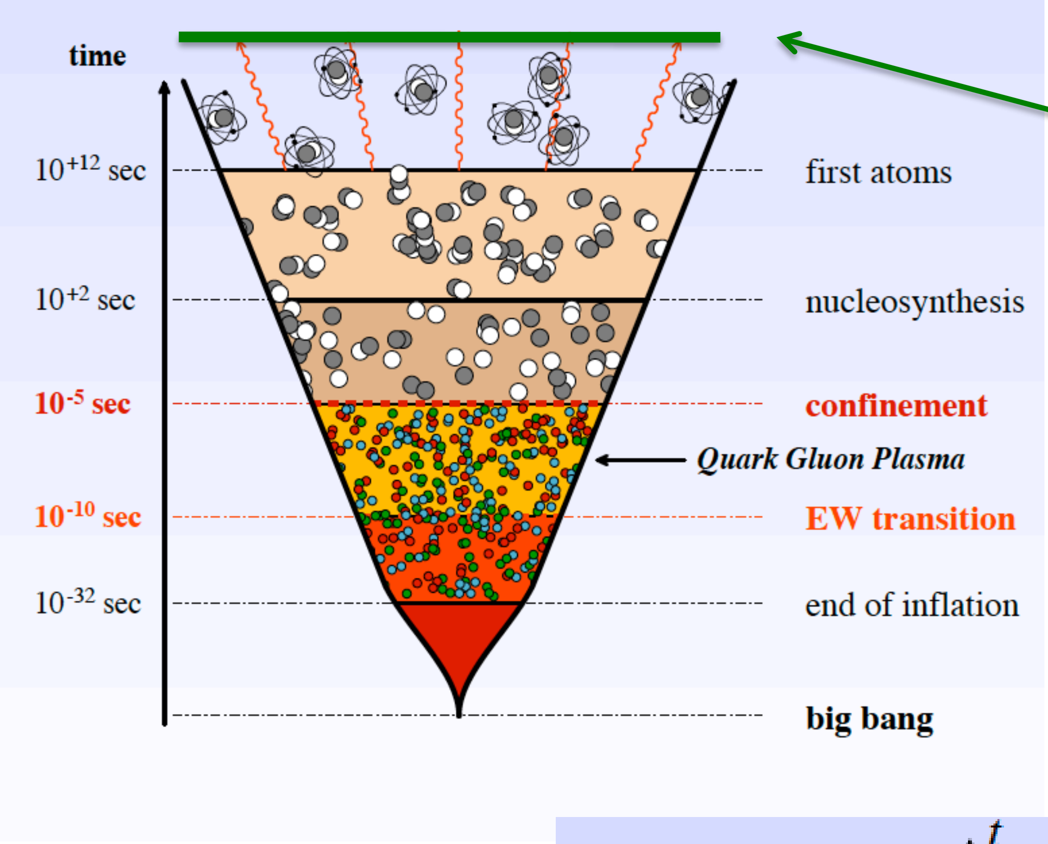
Studying hot QCD in the Laboratory: high energy collisions of heavy nuclei

Model calculation







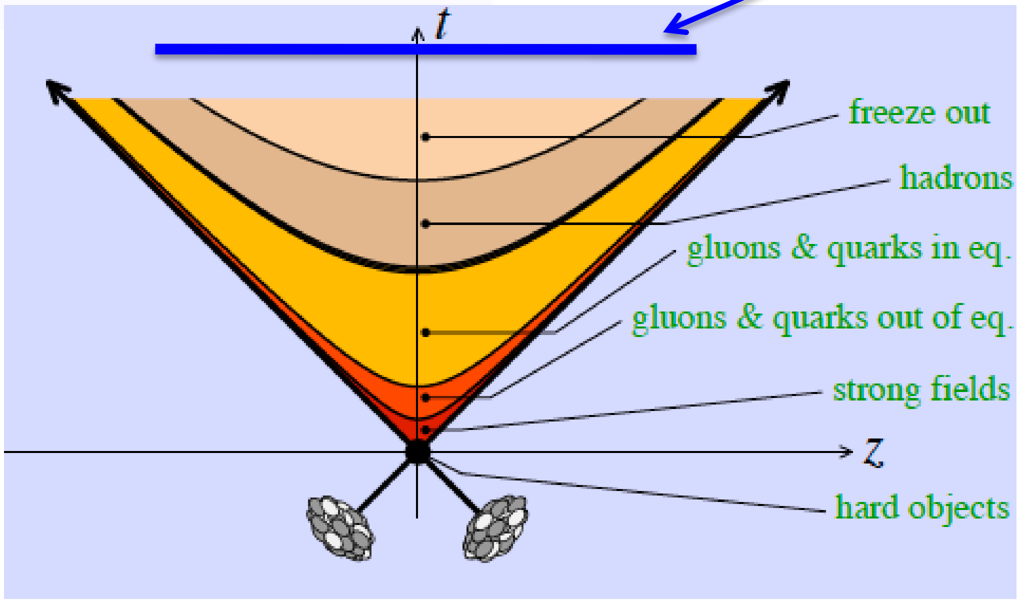


Measurements with telescopes

Evolution of the Early Universe

Measurements with colliders

Evolution of a Heavy Ion Collision



Experimental exploration of hot QCD Matter: what are the issues?

Intensive thermodynamic quantities (T, P, ε, μ,□) are only defined for systems in (quasi- or local-) equilibrium

- QCD Lattice calculates equilibrated matter (e.g. at fixed T)

But nuclear collisions are highly dynamic:

- "Fireball" starts blowing apart the instant it is generated
- Fireball lifetime ~ few fm/c
- no *a priori* reason that quasi-equlibration should be achieved on this time-scale

No *ab initio* theory to describe full dynamical evolution of the fireball

Experimental study of hot QCD Matter: Strategy

Experiment:

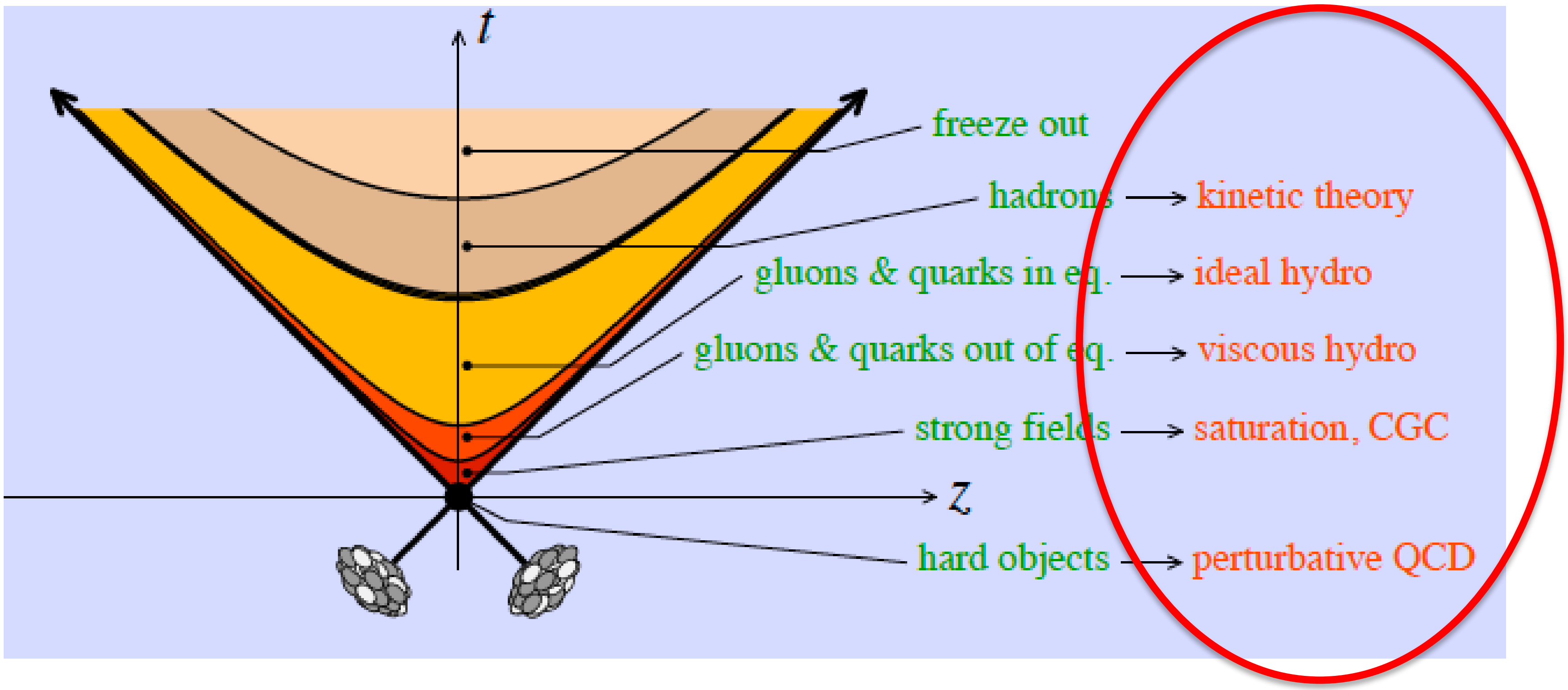
- No *ab initio* theory ➔ interpretation via comparison to reference systems:
  p+p, p/d+A, light ion collisions,…
- Vary system size: quantitative control over collision geometry
- Choose observables with close connection to theory and controlled modeling
- Over-determined measurements: multiple, systematically ~independent observables sensitive to the same underlying physics

Theory: models and effective theories for different stages of fireball evolution

- initial state: modified pdfs, saturation models,…
- hard probes: pQCD-based modeling
- collective expansion: viscous relativistic hydrodynamics
- hadronic phase: detailed Monte Carlos

Experiment+Theory:

- detailed comparison and mutual calibration
- evolution with $\sqrt{s}$: RHIC vs LHC


t
freeze out
hadrons → kinetic theory
gluons & quarks in eq. → ideal hydro
gluons & quarks out of eq. → viscous hydro
strong fields → saturation, CGC
z
hard objects → perturbative QCD

Outline: Lecture 1

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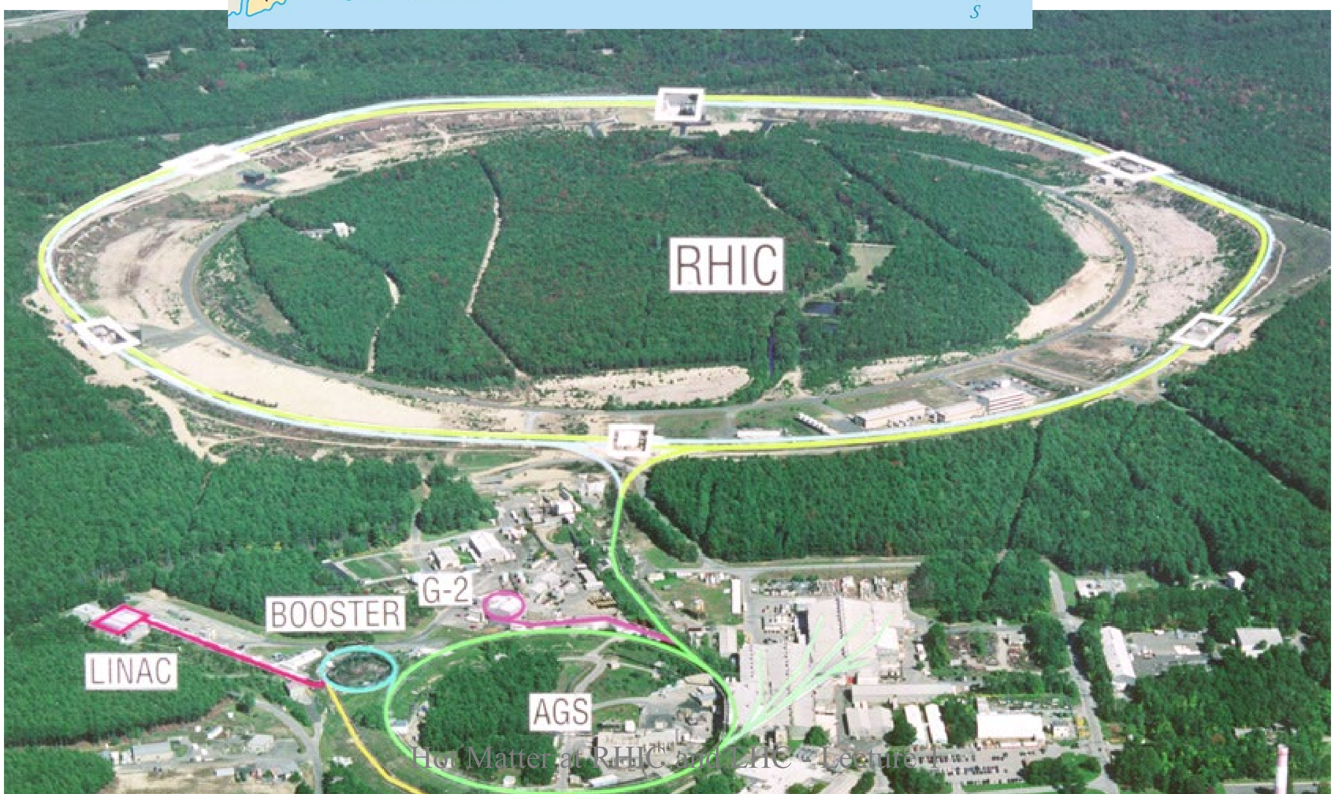
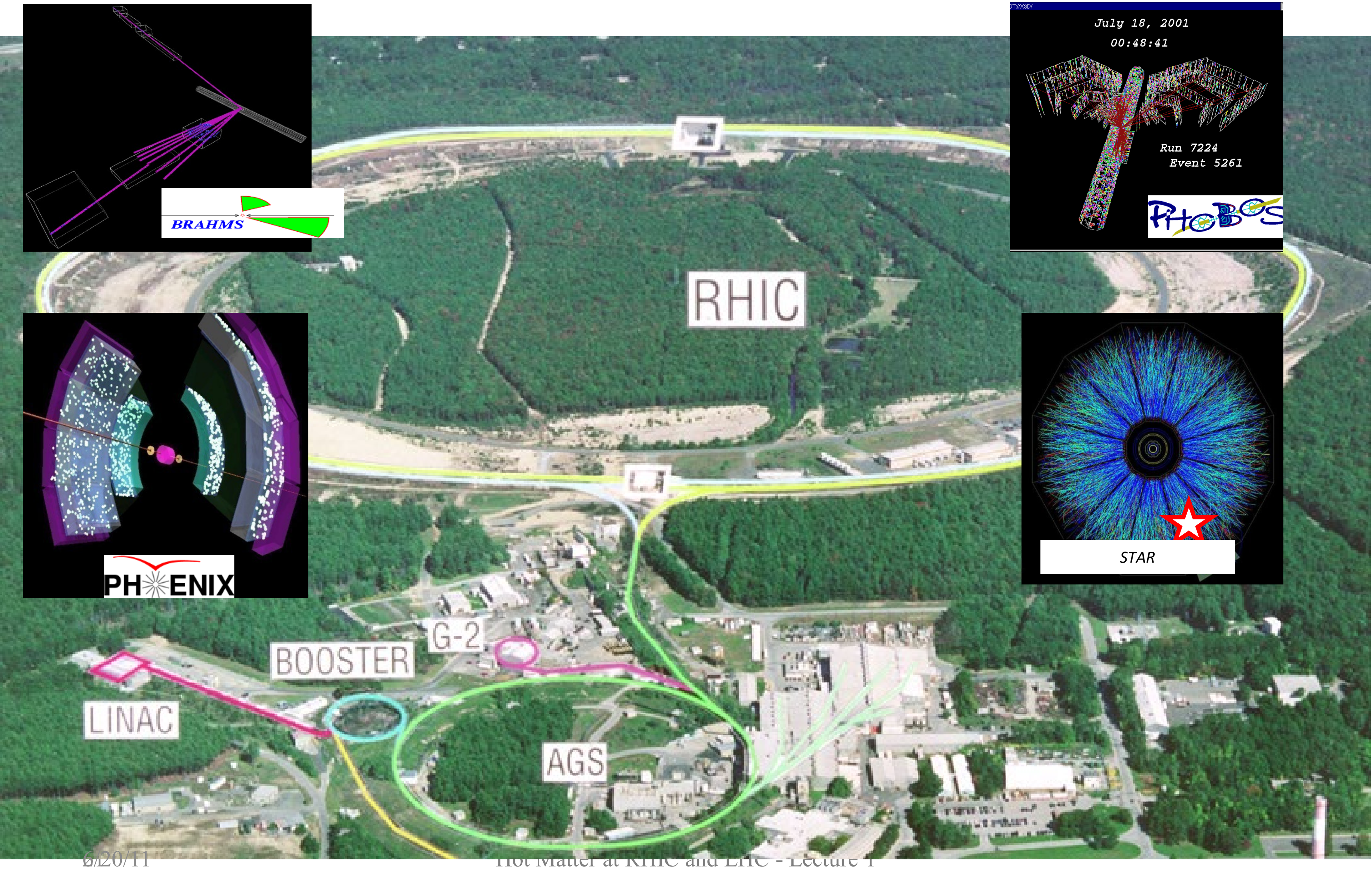
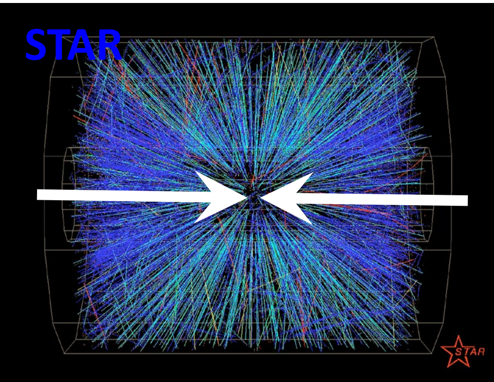
The Relativistic Heavy Ion Collider
Brookhaven National Laboratory



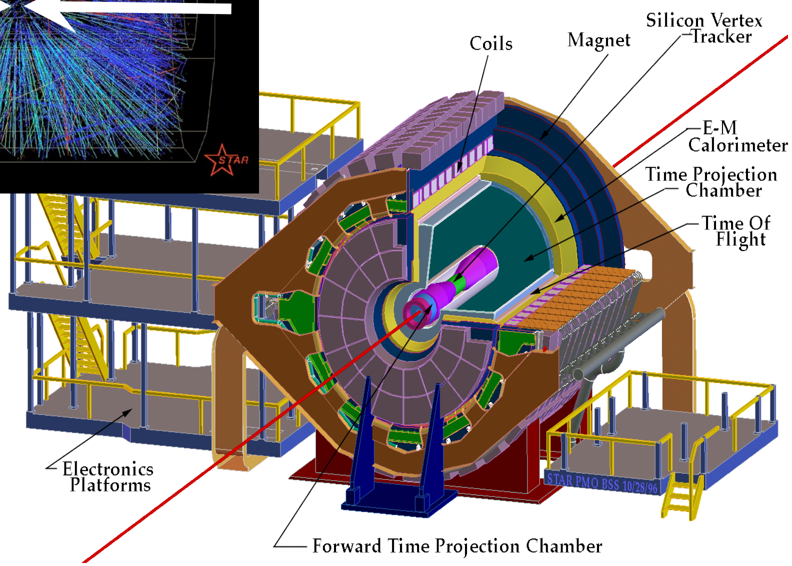
The Relativistic Heavy Ion Collider (BNL)



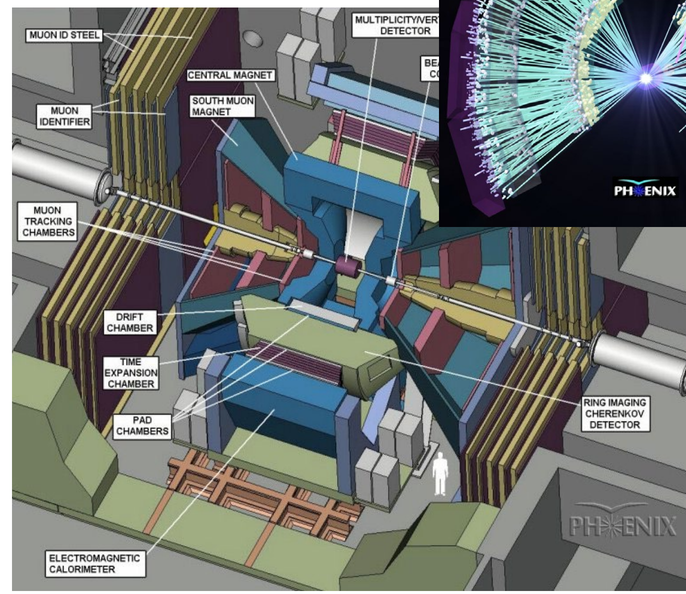
STAR and PHENIX at RHIC

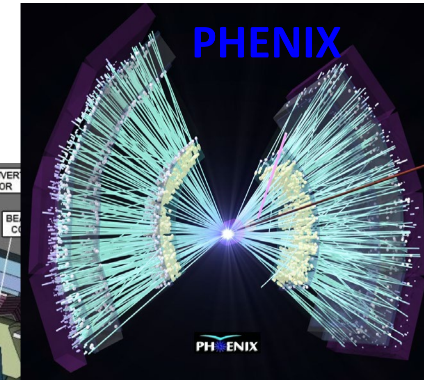


STAR



PHENIX





2π coverage, $-1 < \eta < 1$
for tracking + (coarse) EMCal

Partial coverage 2 x 0.5π, $-0.35 < h < 0.35$
Finely segmented calorimeter
+ forward muon arm

PID by TOF, dE/dx (STAR), RICH (PHENIX)

Optimised for acceptance
(correlations, jet-finding)

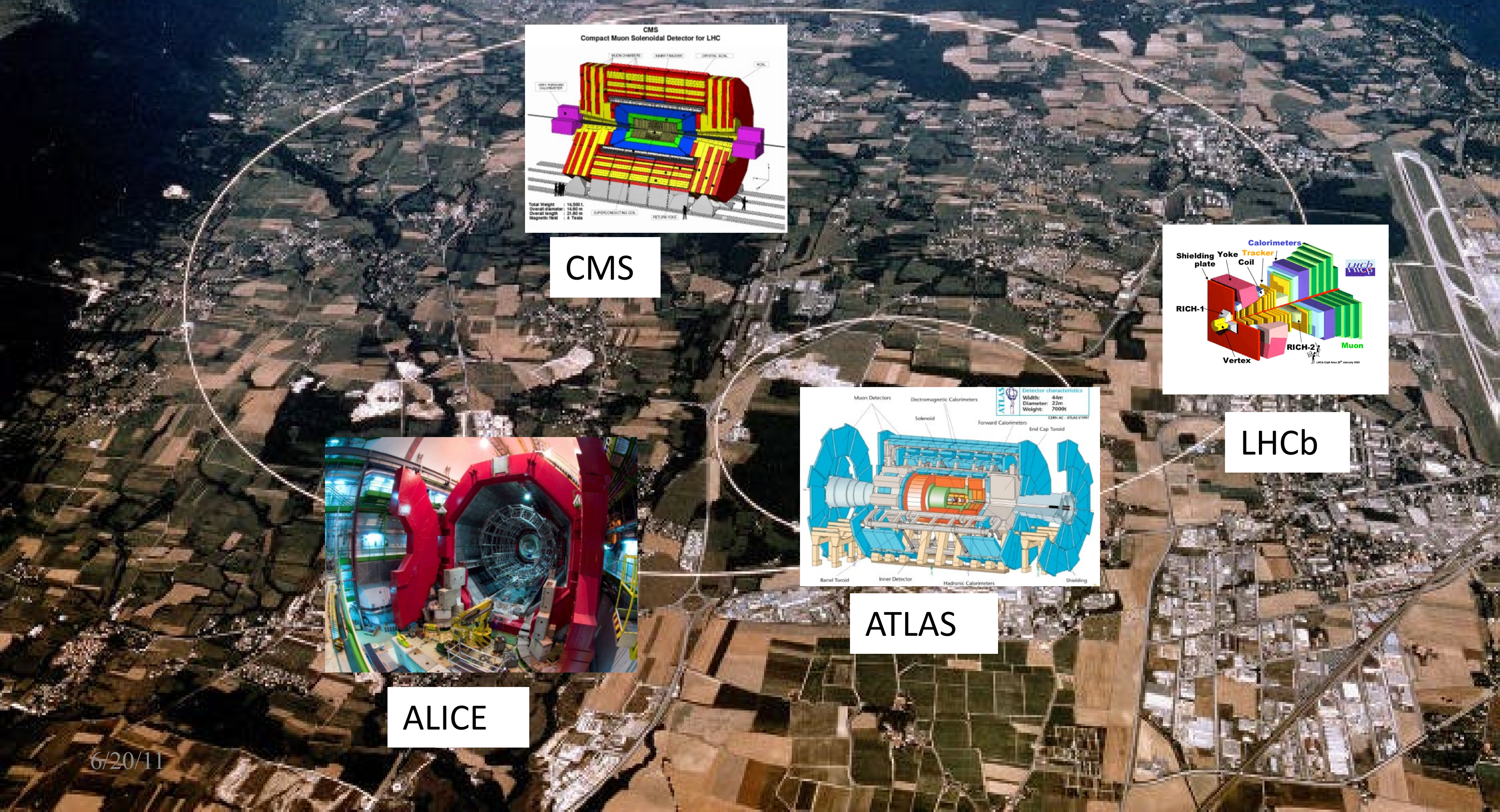
Optimised for high-pt π^0, γ, e, J/ψ
(EMCal, high trigger rates)

(PHOBOS, BRAHMS more specialised)

Large Hadron Collider at CERN

Large Hadron Collider at CERN

p+p at √s=7 (14) TeV
Pb+Pb at √s=2.76 (5.5) TeV
heavy ion running: 4 physics weeks/year



Distribution of All CERN Users by Nation of Institute on 27 October 2009

US is single largest national community

MEMBER STATES

AUSTRIA	76
BELGIUM	112
BULGARIA	50
CZECH REPUBLIC	179
DENMARK	65
FINLAND	86
FRANCE	864
GERMANY	1128
GREECE	106
HUNGARY	54
ITALY	1455
NETHERLANDS	166
NORWAY	76
POLAND	190
PORTUGAL	123
SLOVAKIA	56
SPAIN	303
SWEDEN	72
SWITZERLAND	363
UNITED KINGDOM	728

6252

OBSERVER STATES

INDIA	97
ISRAEL	55
JAPAN	203
RUSSIA	[illegible]
TURKEY	64
USA	1629

2963

OTHERS

		CROATIA	19	MALTA	1	THAILAND	1
ARGENTINA	8	CUBA	4	MEXICO	30	TUNISIA	1
ARMENIA	15	CYPRUS	8	MONTENEGRO	1	UKRAINE	17
AUSTRALIA	15	EGYPT	2	MOROCCO	5	U.A.E.	1
AZERBAIJAN	1	ESTONIA	11	NEW ZEALAND	8	VIETNAM	1
BELARUS	19	GEORGIA	10	PAKISTAN	18		
BRAZIL	71	ICELAND	1	QATAR	1		
CANADA	143	IRAN	12	ROMANIA	53		
CHILE	3	IRELAND	13	SERBIA	20		
CHINA	85	JORDAN	1	SLOVENIA	17		
CHINA (TAIPEI)	57	KOREA	61	SOUTH AFRICA	9		
COLOMBIA	12	LITHUANIA	6	SRI LANKA	1		

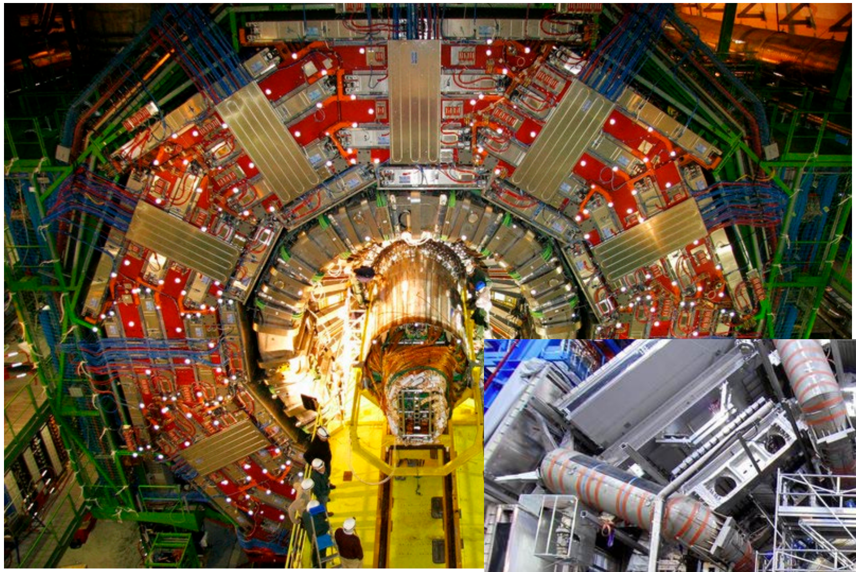
759

CERN: "where the web was born"

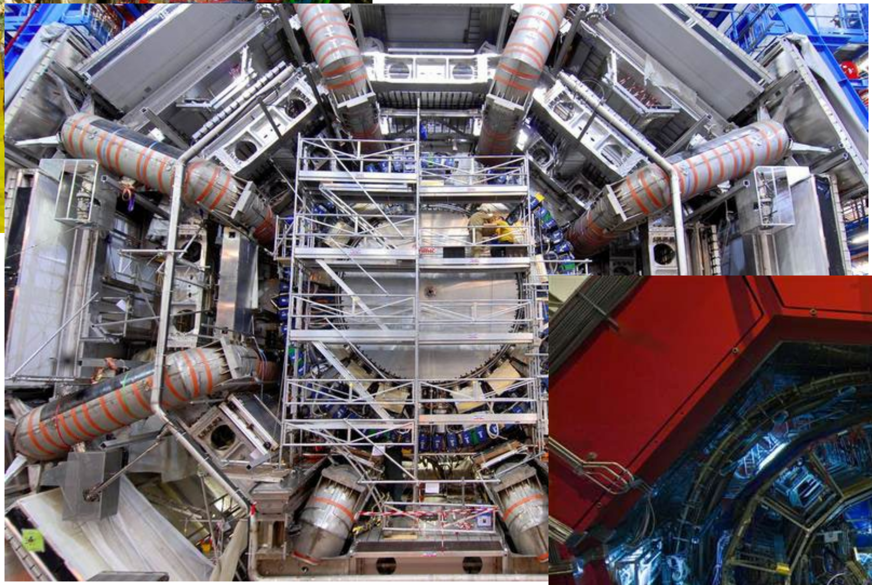
World's first web server (NEXT workstation, 1991)
Invention of HTML (Tim Berners-Lee, 1991)

First IP router in Europe

LHC Detectors for Heavy Ions

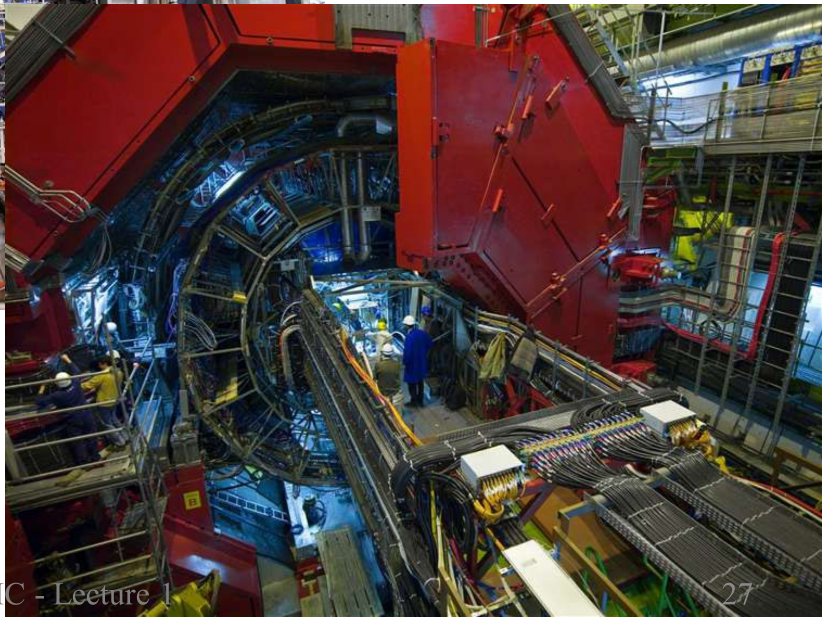


CMS



ATLAS

ALICE

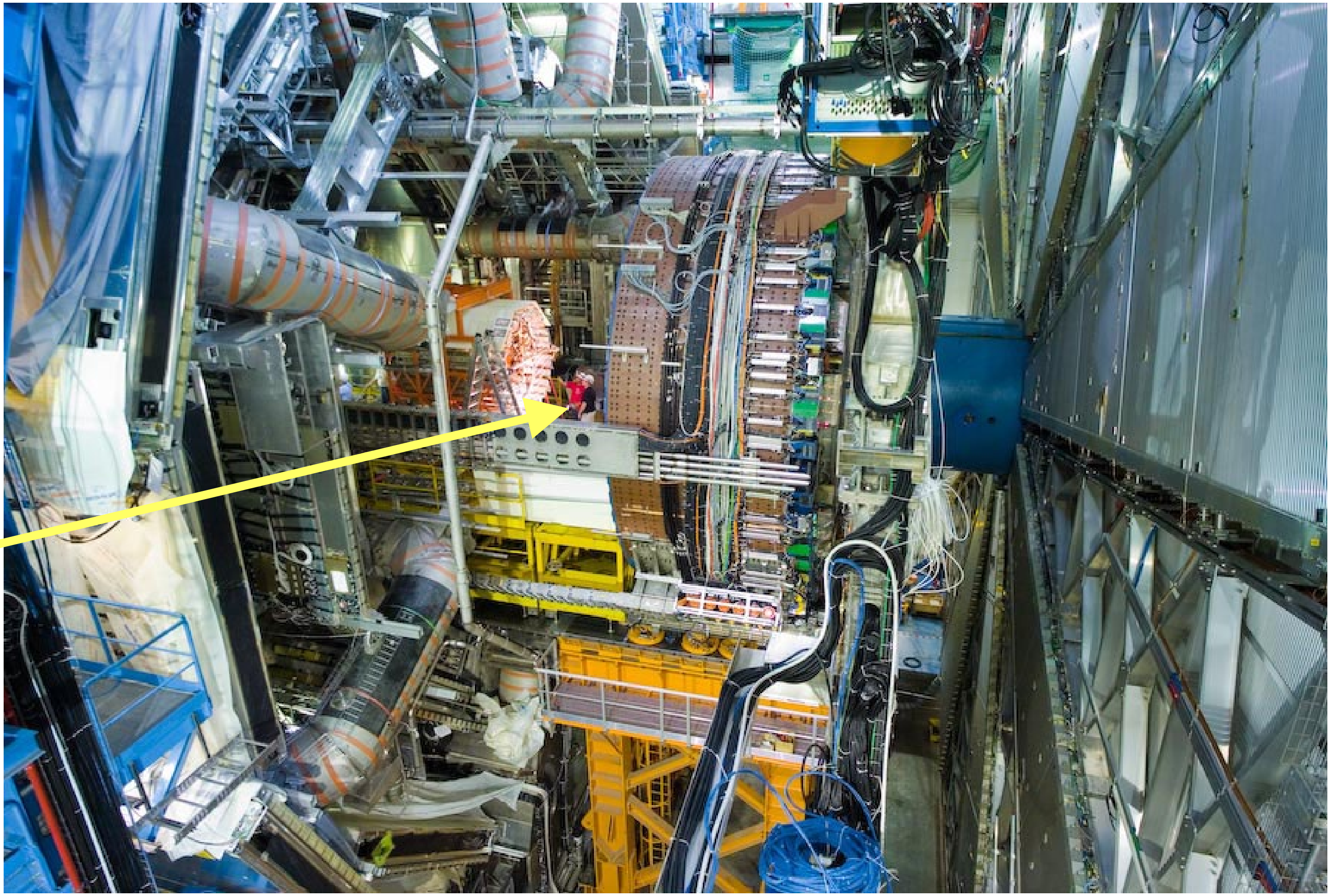


(not to scale: $R_{ATLAS} > R_{CMS} > R_{ALICE}$)

ATLAS

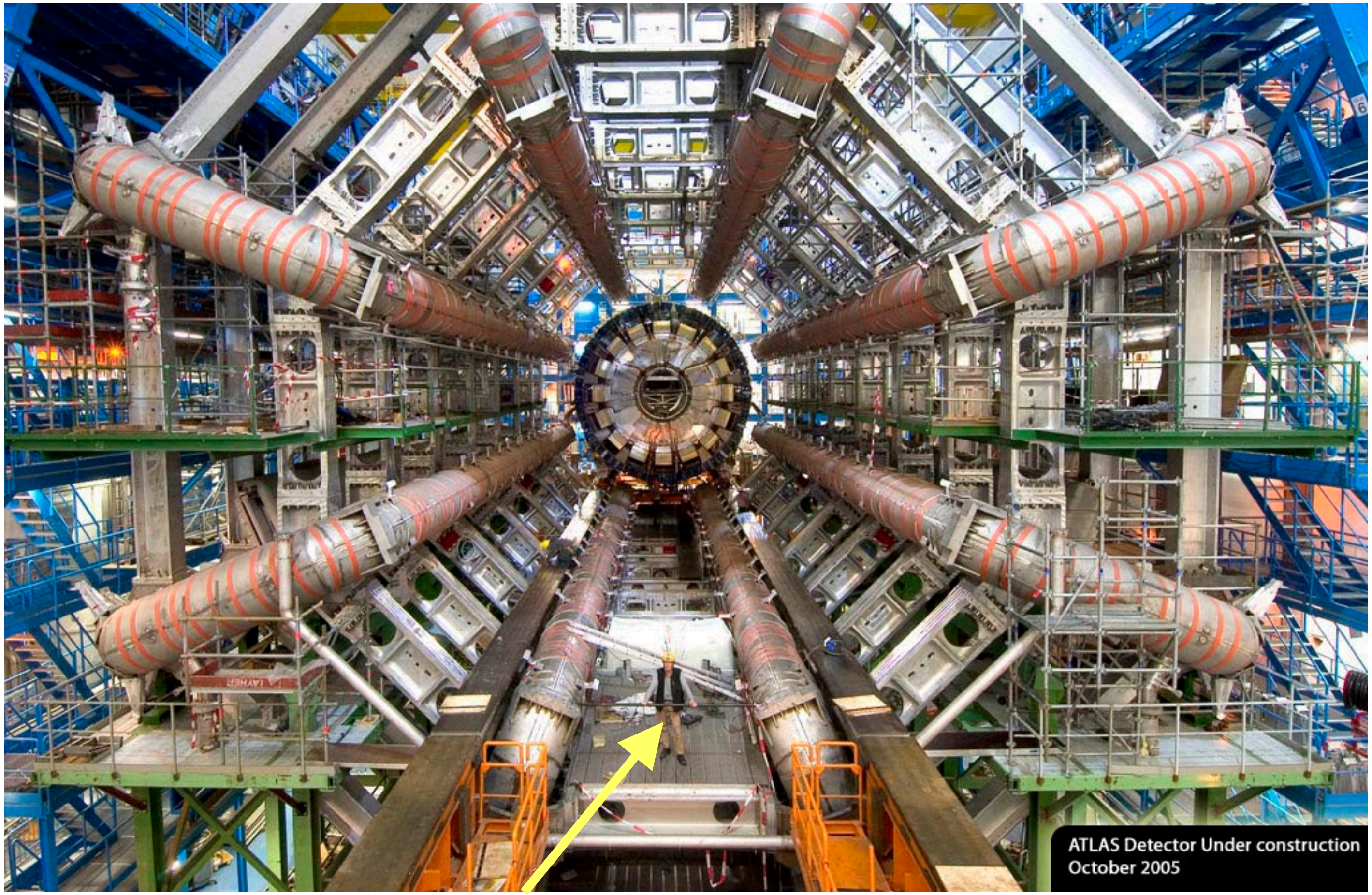
May 2007 (under construction)

People



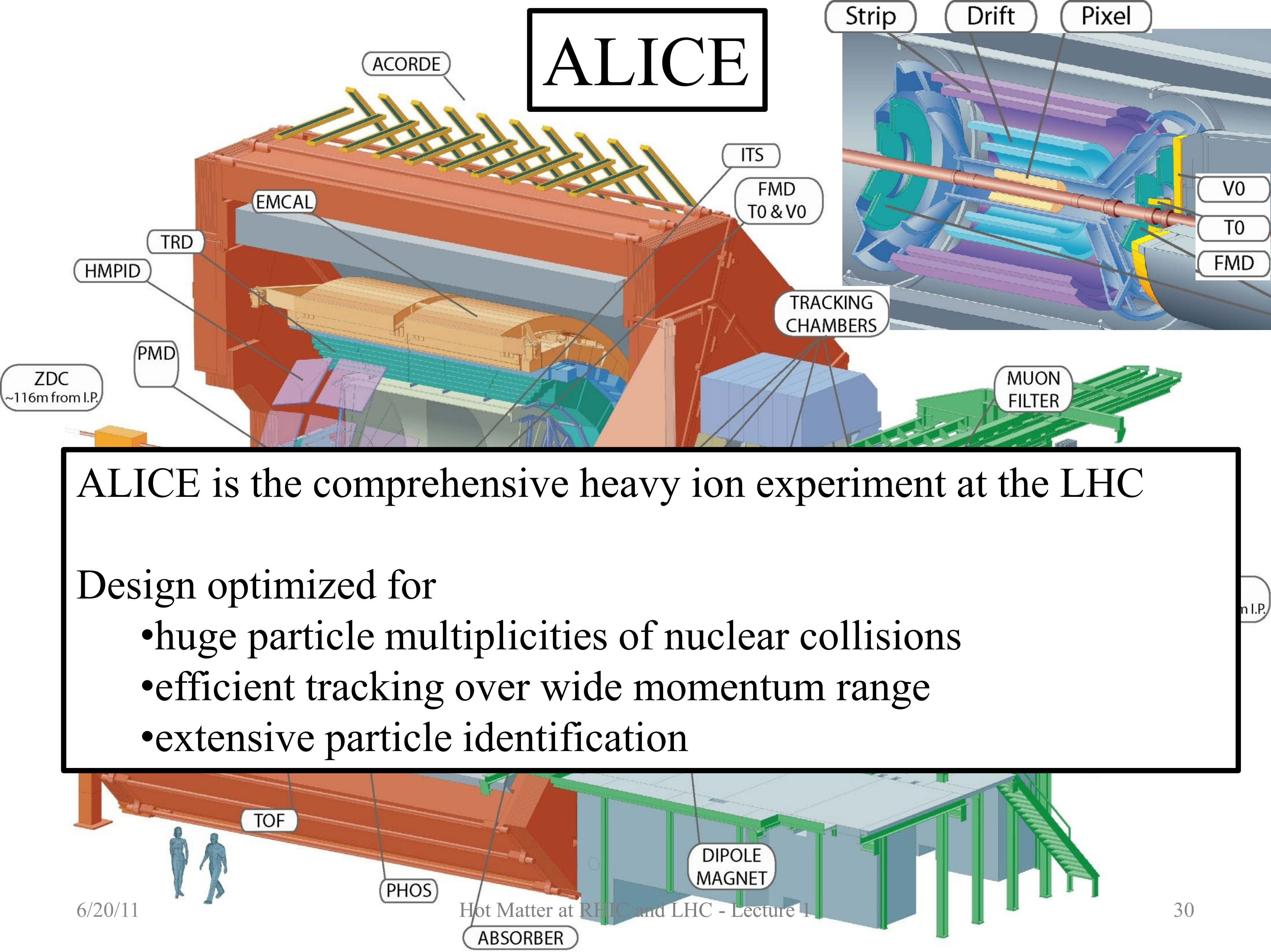
ATLAS

November 2006 (under construction)



Person

ALICE

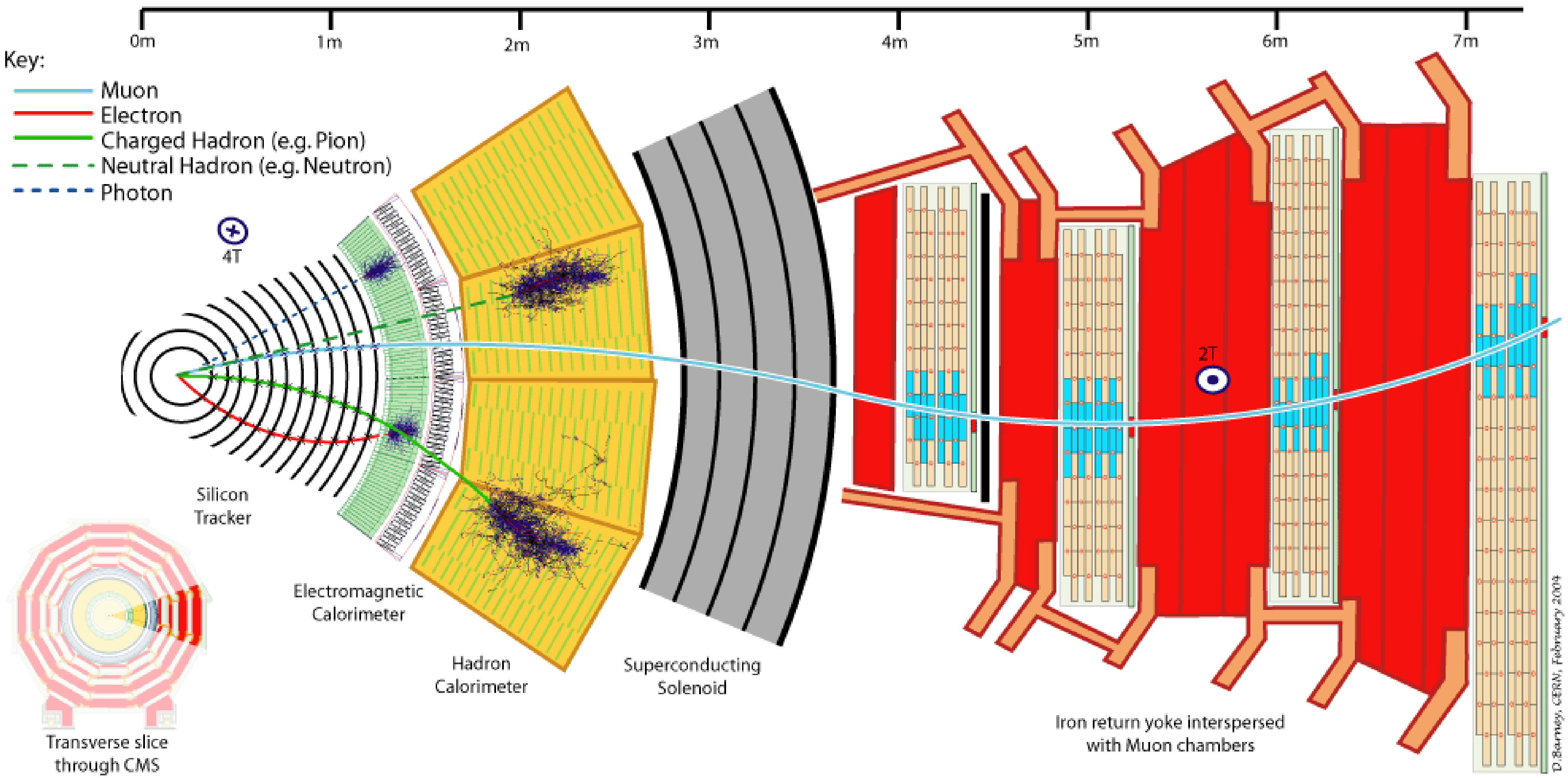


ALICE is the comprehensive heavy ion experiment at the LHC

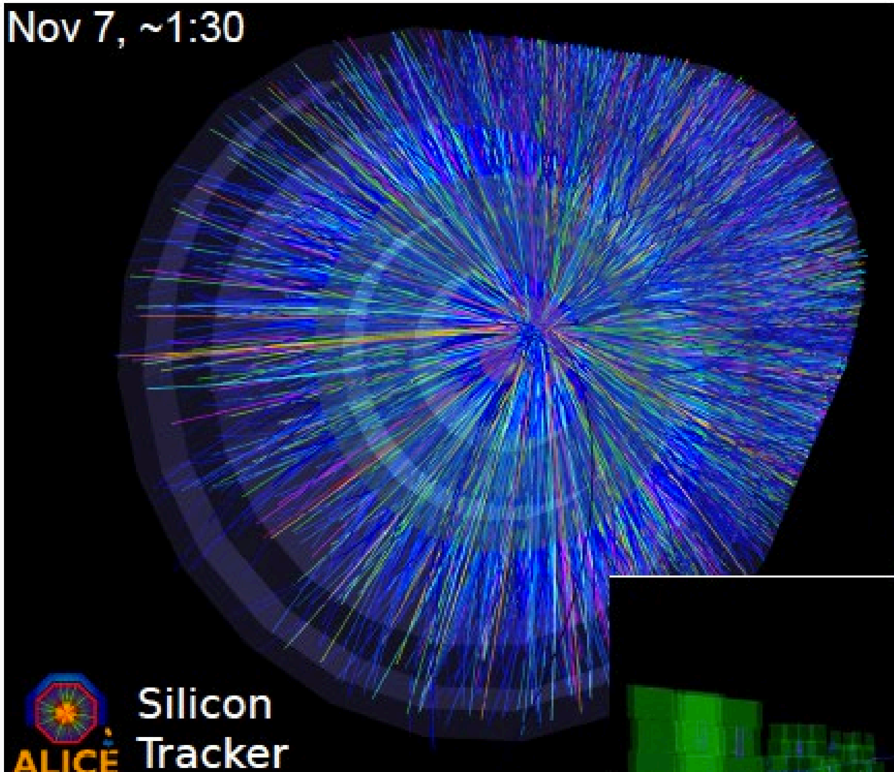
Design optimized for

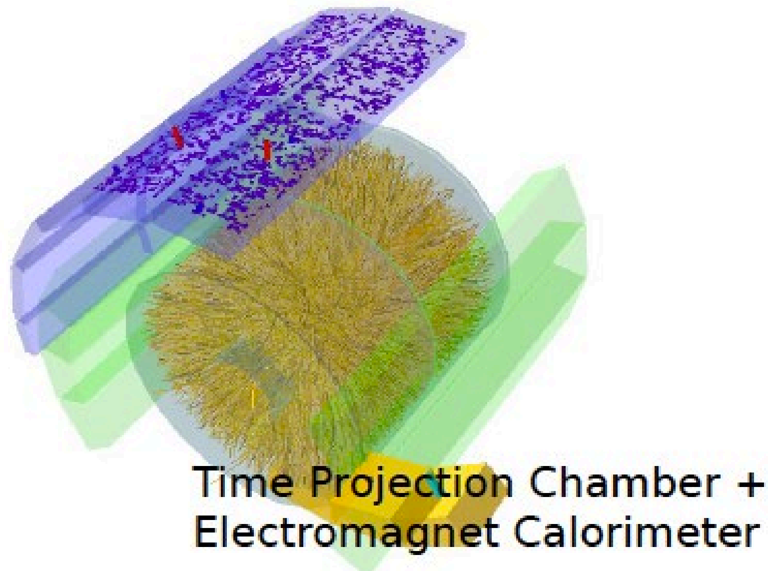
- huge particle multiplicities of nuclear collisions
- efficient tracking over wide momentum range
- extensive particle identification

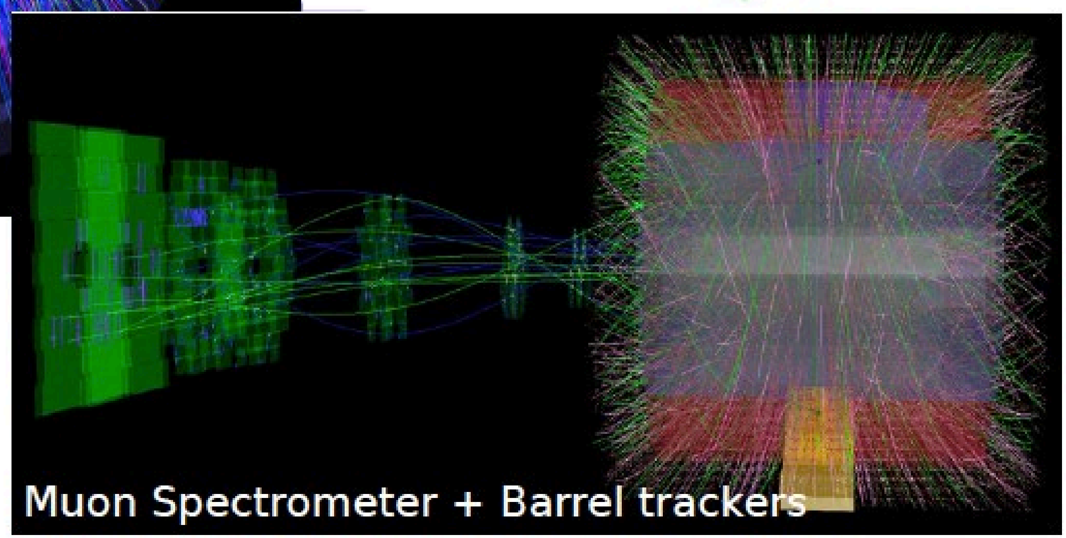
CMS cross section



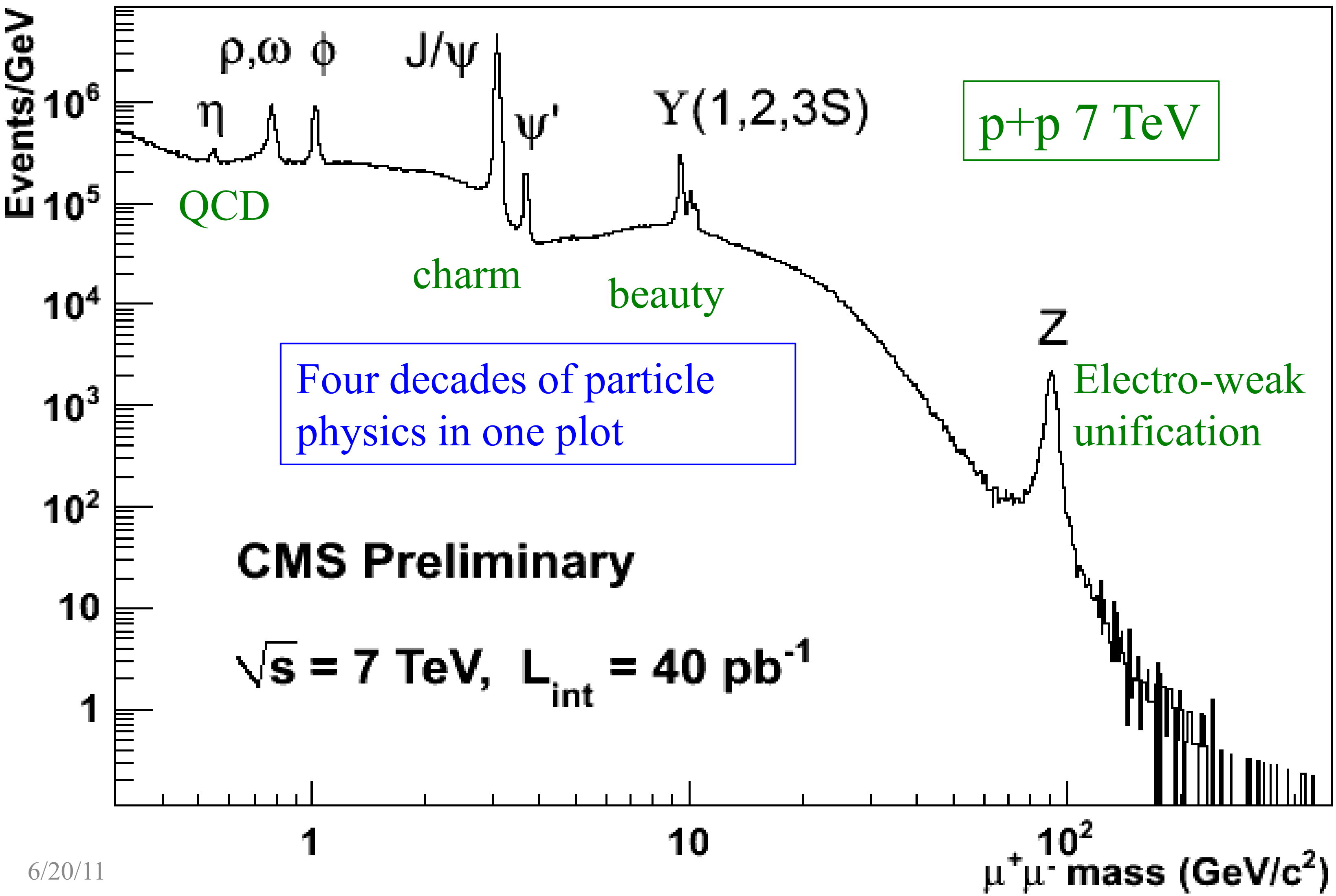
November 7 2010:
First Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



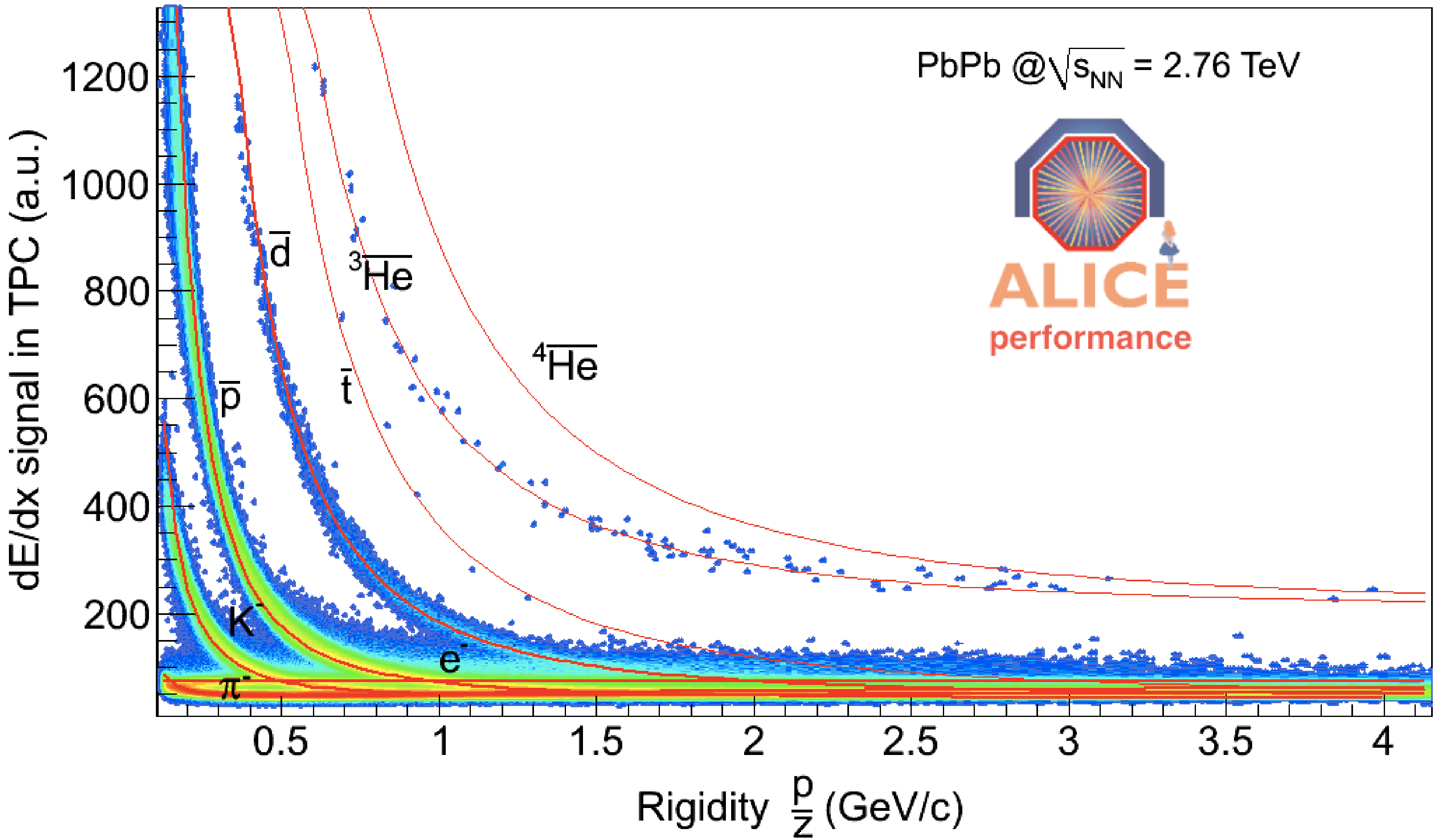




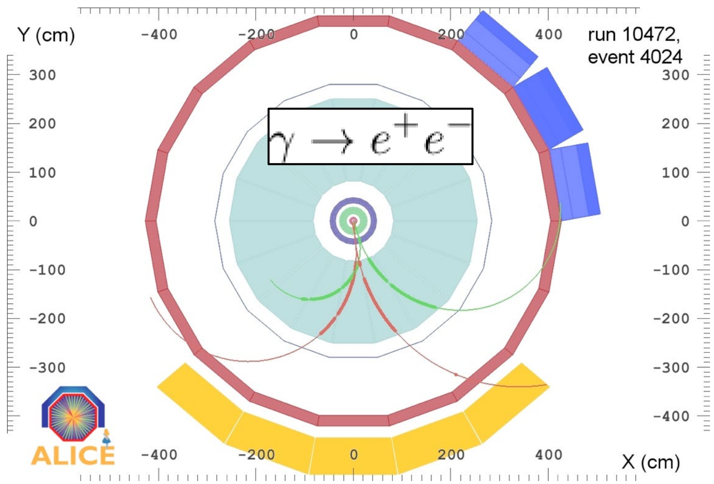
CMS detector performance: di-muon invariant mass spectrum

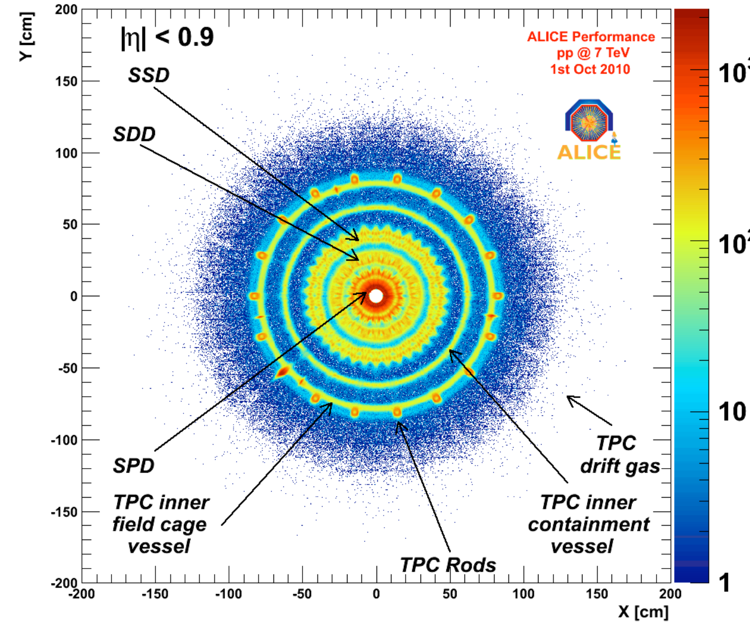


Detector Performance
ALICE Particle ID (TPC dE/dx)

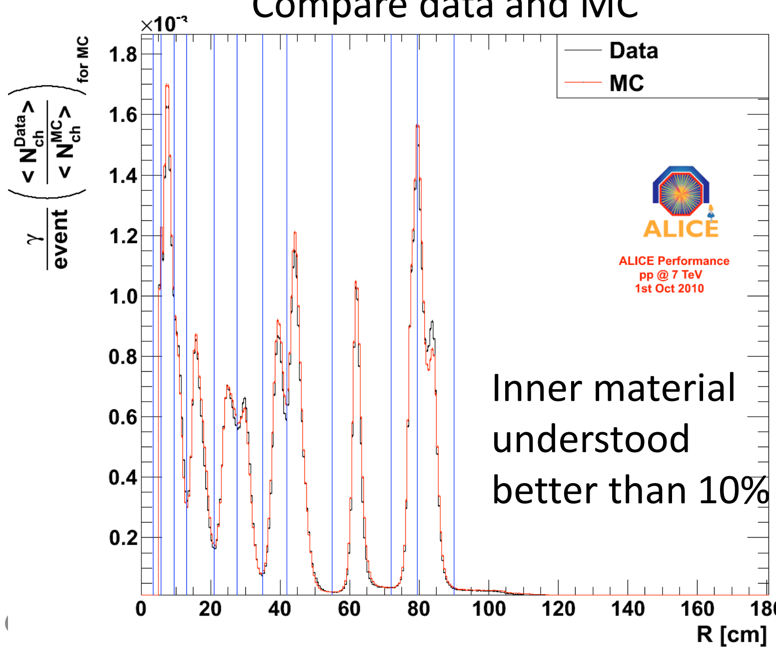


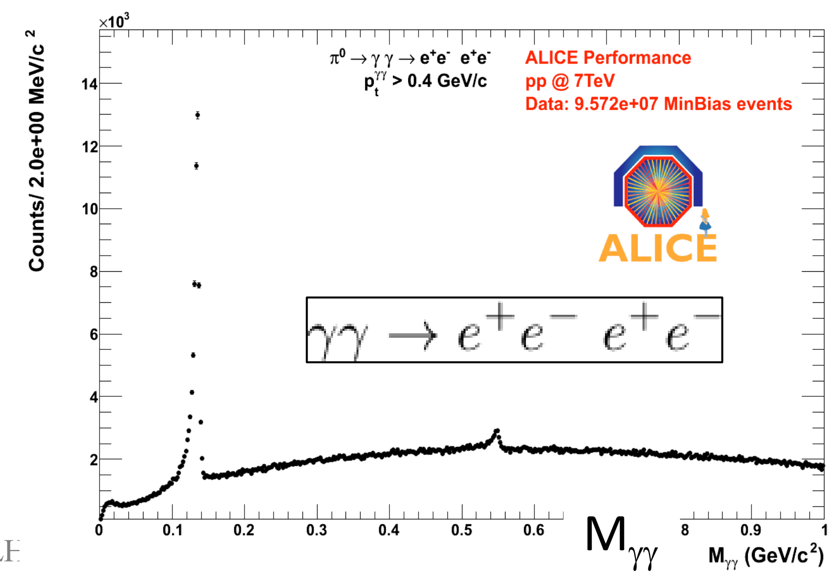
ALICE: Tomography via γ-conversions





Compare data and MC





First LHC Scientific Publication (Dec '09)

ALICE Collaboration: First proton–proton collisions at the LHC as observed with the ALICE...
arXiv: 0911.5430 [hep-ex]

First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at $\sqrt{s} = 900$ GeV

ALICE collaboration

K. Aamodt[78], N. Abel[43], U. Abeysekara[30], A. Abrahantes Quintana[42], A. Acero[63], D. Adamová[86], M.M. Aggarwal[25], G. Aglieri Rinella[40], A.G. Agocs[18], S. Aguilar Salazar[65], Z. Ahammed[55], A. Ahmad[2], N. Ahmad[2], S.U. Ahn[50], R. Akimoto[100], A. Akindinov[68], D. Aleksandrov[70], B. Alessandro[102], R. Alfaro Molina[65], A. Alici[13], E. Almaráz Aviña[65], J. Alme[8], T. Alt[43ii], V. Altini[5], S. Altinpinar[32], C. Andrei[17], A. Andronic[32], G. Anelli[40], V. Angelov[43ii], C. Anson[27], T. Antičić[113], F. Antinori[40iii], S. Antinori[13], K. Antipin[37], D. Antończyk[37], P. Antonioli[14], A. Anzo[65], L. Aphecetche[73], H. Appelshäuser[37], S. Arcelli[13], R. Arceo[65], A. Arend[37], N. Armesto[92], R. Arnaldi[102], T. Aronsson[74], I.C. Arsene[78iv], A. Asryan[98], A. Augustinus[40], R. Averbeck[32], T.C. Awes[76], J. Äystö[49], M.D. Azmi[2], S. Bablok[8], M. Bach[36], A. Badalà[24], Y.W. Baek[50i], S. Bagnasco[102], R. Bailhache[32v], R. Bala[101], A. 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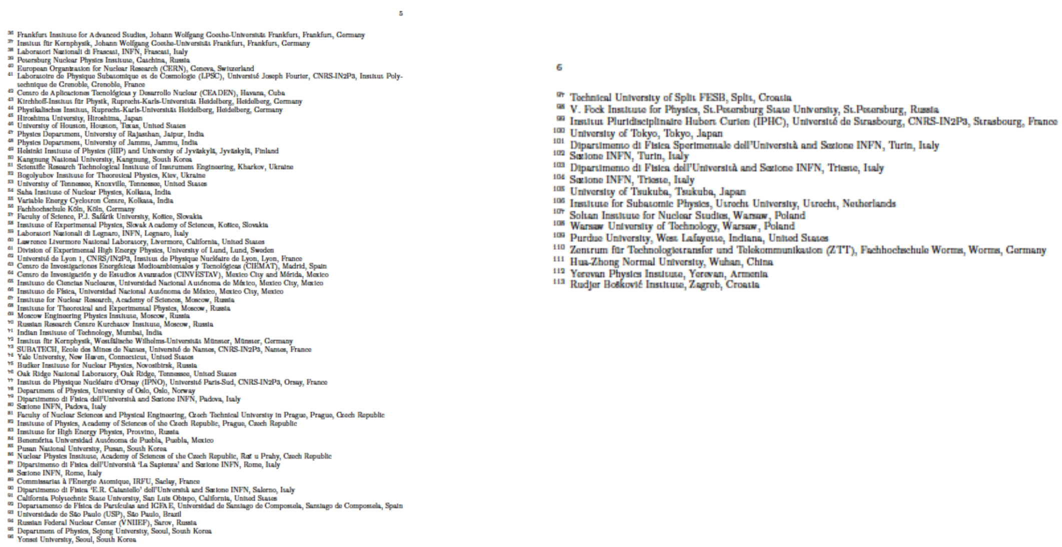


ATLAS and CMS are ~2x larger

Outline: Lecture 1

Theory Tools
- Basics of QCD
- Finite Temperature QCD

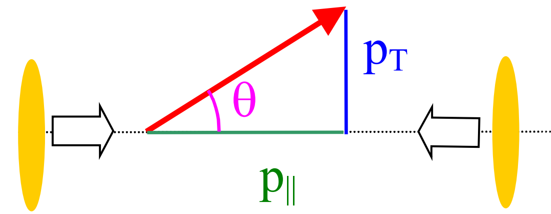
Experimental Tools
- Colliders
- Detectors

Analysis Tools
- Relativistic Kinematics
- Characterization of nuclear collisions

Kinematics for Inclusive Reactions

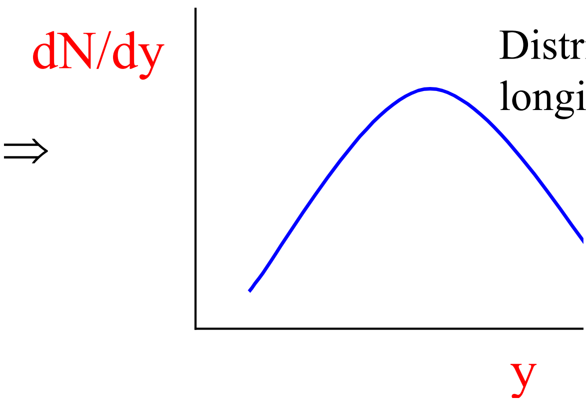
Rapidity

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



Rapidity is differentially boost-invariant

$$\delta y \sim \frac{\delta p_{||}}{E} \Rightarrow$$



Distribution invariant with longitudinal boost

Pseudo-rapidity

$$y \rightarrow \eta = -\ln[\tan(\theta/2)]$$

for m/p <<1

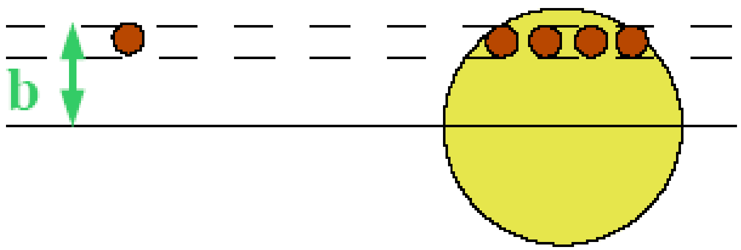
Invariant production cross section

$$E\frac{d^3\sigma}{d^3p} = \frac{d^2\sigma}{2\pi p_T dy dp_T}$$

Nuclear geometry and hard processes: Glauber theory

Glauber scaling: hard processes with large momentum transfer

- short coherence length ⇒ successive NN collisions independent
- p+A is incoherent superposition of N+N collisions



Normalized nuclear density r(*b*,*z*):

$$\int dz\, db\, \rho(b,z) = 1$$

Nuclear thickness function $$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho(b,z)$$

Inelastic cross section for p+A collisions:

$$\sigma_{pA}^{inel} = \int d\vec{b} \left(1 - \left[1 - T_A(b)\, \sigma_{NN}^{inel}\right]^A\right)$$

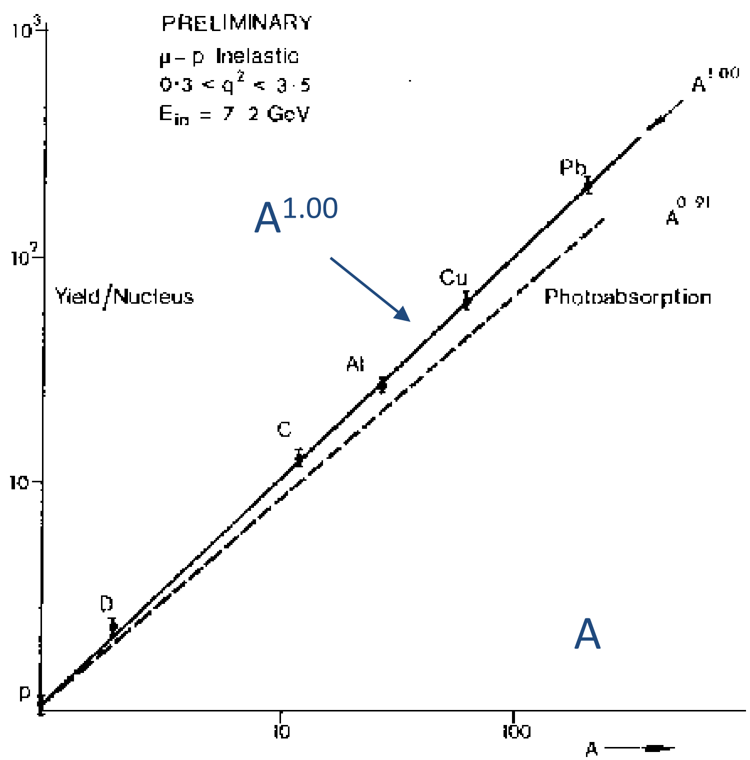
$$\sigma_{pA}^{hard} \simeq A \cdot \sigma_{NN}^{hard} \int d\vec{b}\, T_A(b) = A \sigma_{NN}^{hard}$$

Experimental tests of Glauber scaling: hard cross sections in p(μ)+A collisions

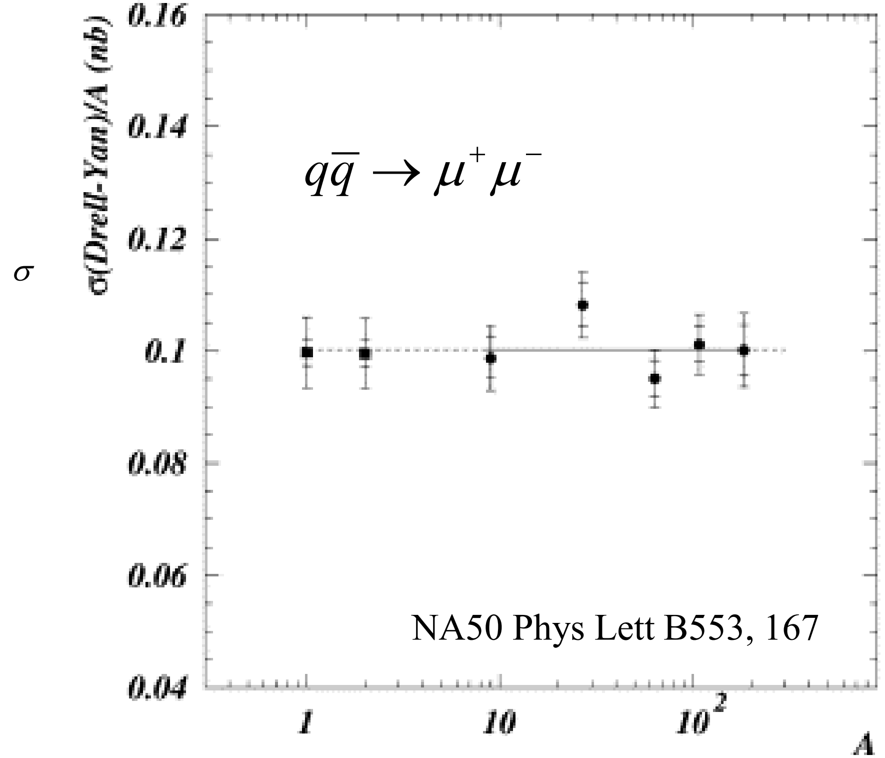
Glauber scaling: $\sigma_{pA}^{hard} = A\sigma_{NN}^{hard}$

σ_{inel} for 7 GeV muons on nuclei

M.May et al, Phys Rev Lett 35, 407 (1975)



$\sigma_{Drell\text{-}Yan}/A$ in p+A at SPS

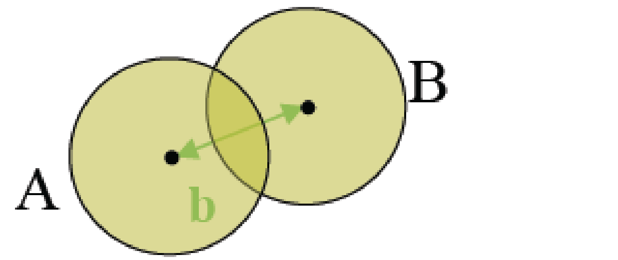


Hard cross sections in p+A scale as $A^{1.0}$

Glauber Theory for A+B Collisions

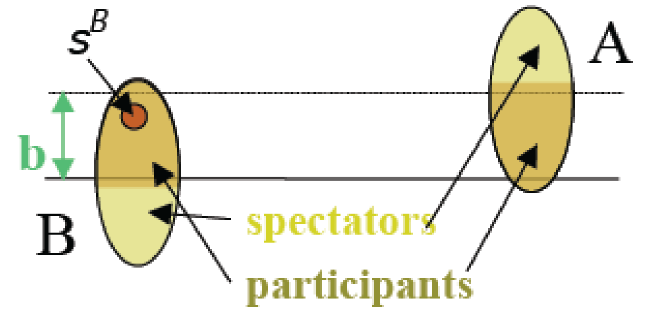
Nuclear overlap function:

$$T_{AB}\left(\vec{b}\right) = \int d\vec{s}\, T_A\left(\vec{s}\right) T_B\left(\vec{s}-\vec{b}\right)$$



Average number of binary NN collisions for B nucleon at coordinate $\mathbf{s_B}$:

$$N_{bin}^{nA}\left(\vec{b}-\vec{s}_B\right) = A \cdot T_A\left(\vec{b}-\vec{s}_B\right) \cdot \sigma_{nn}^{inel}$$



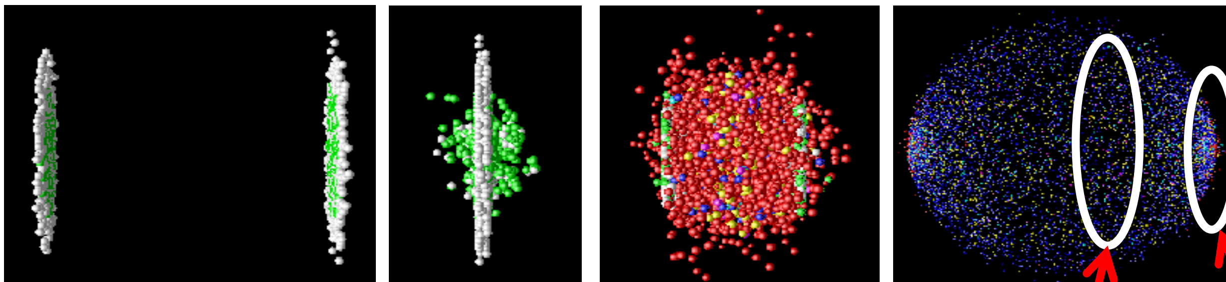
Average number of binary NN collisions for A+B collision with impact parameter b:

$$\begin{aligned} N_{bin}^{AB}(b) &= B \int d\vec{s}_B\, T_B\left(\vec{s}_B\right) \cdot N_{bin}^{nA}\left(\vec{b}-\vec{s}_B\right) \\ &= AB \cdot T_{AB}(b) \cdot \sigma_{nn}^{inel} \end{aligned}$$

Measuring collision geometry I

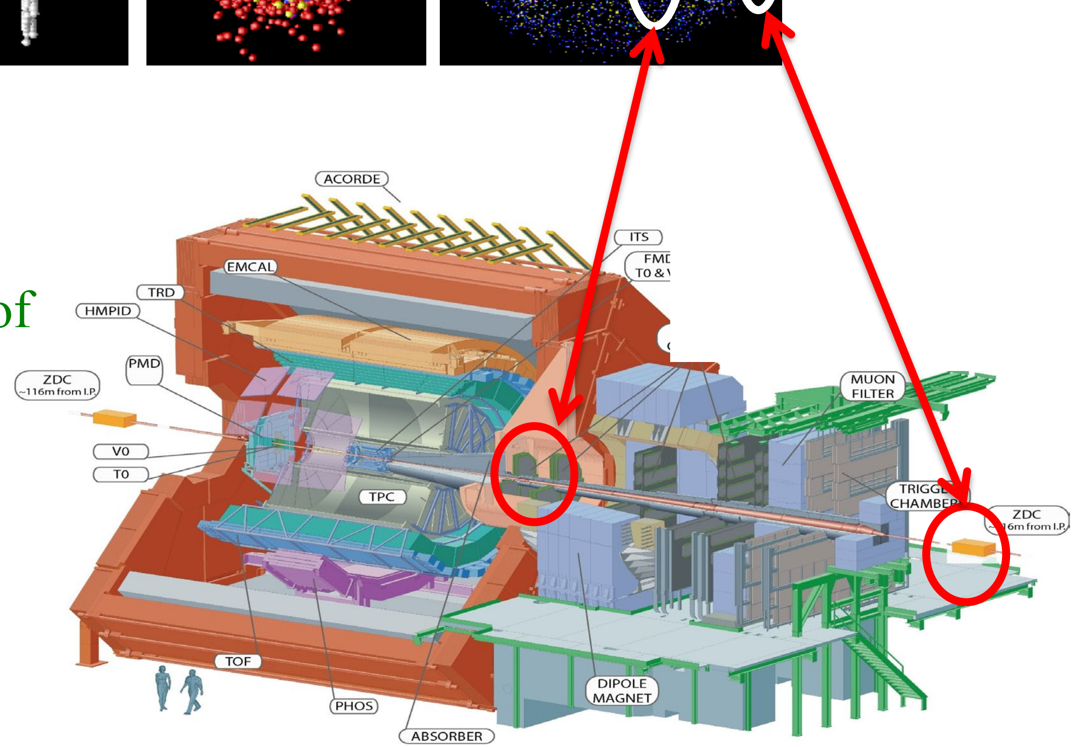
Nuclei are "macroscopic"

➔characterize collisions by impact parameter



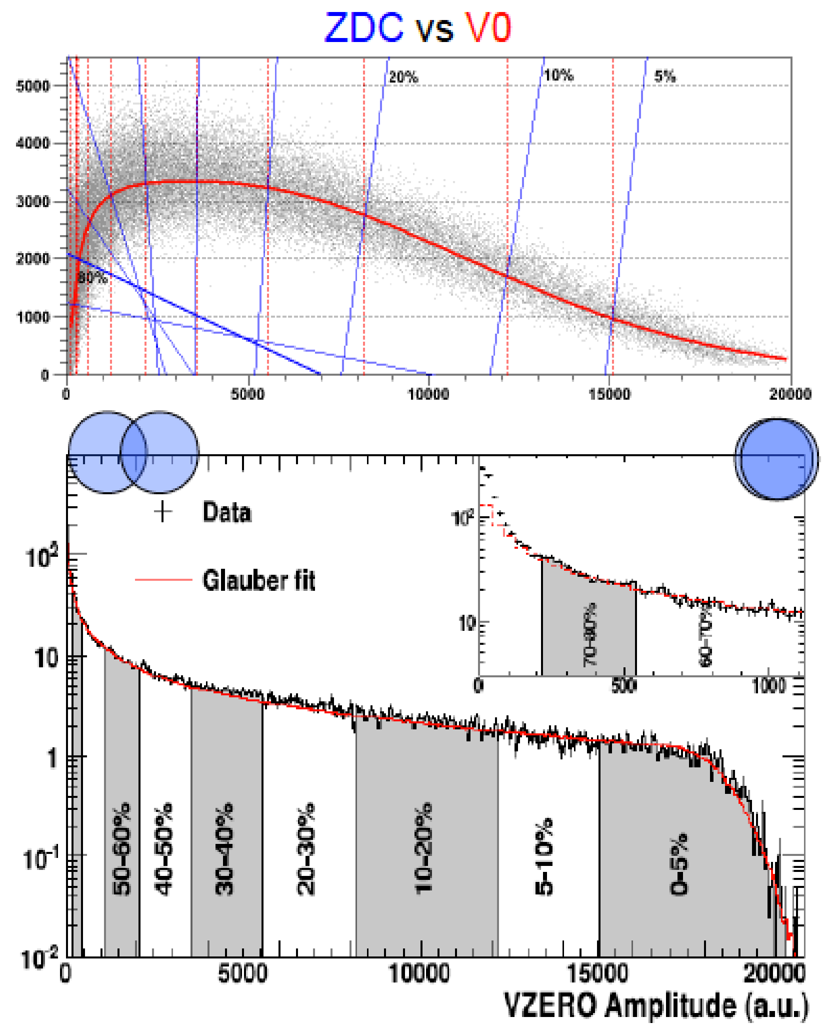
Correlate particle yields from ~causally disconnected parts of phase space

➔ correlation arises from common dependence on collision impact parameter



Measuring collision geometry II

Forward neutrons



Charged hadrons η~3

- Order events by centrality metric
- Classify into percentile bins of "centrality"

HI jargon: "0-5% central"

Connect to Glauber theory via particle production model:

- N_{bin}: effective number of binary nucleon collisions (~5-10% precision)
- N_{part}: number of (inelastically scattered) "participating" nucleons

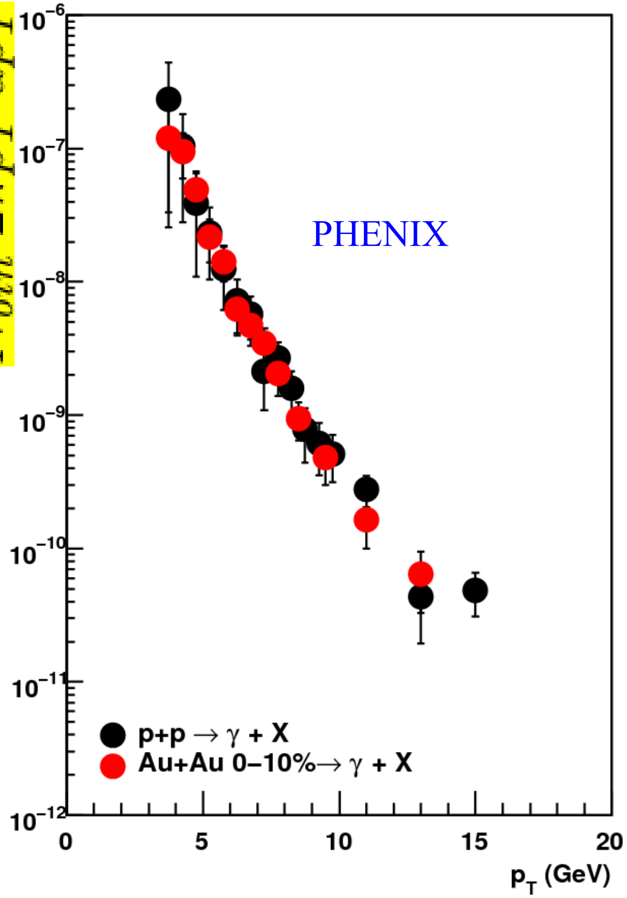
Scaling of cross sections using Glauber theory plays a central role in quantitative analysis of experimental measurements and connection to theory.

Let's test it experimentally in A+A collisions…

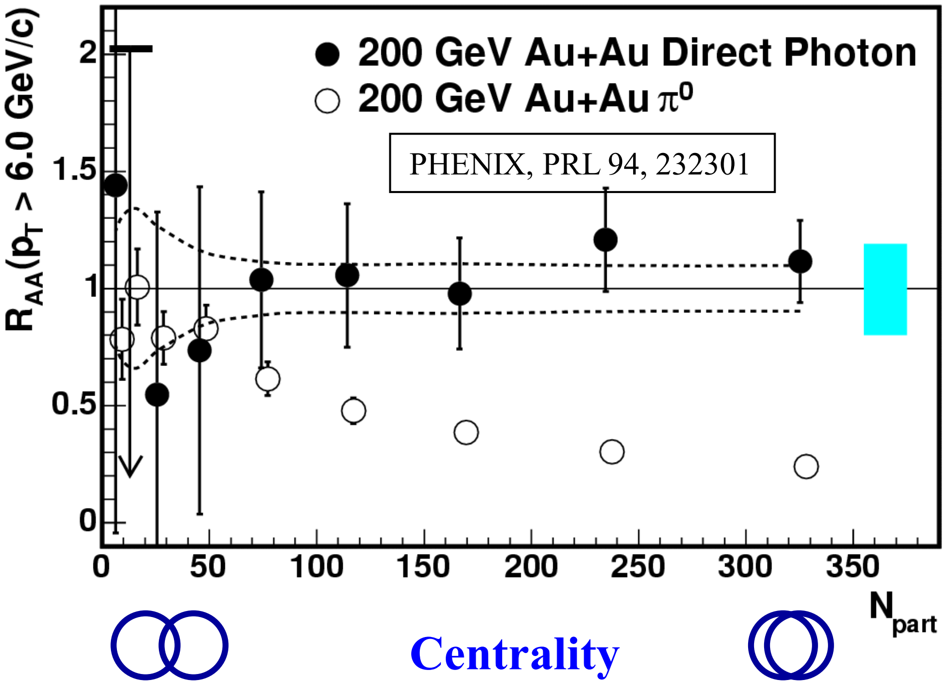
Glauber test at RHIC:
Scaling of direct photon yield in p+p vs. Au+Au

Direct γ: N_{bin}-scaled inclusive yield

$$\frac{1}{N_{bin}}\frac{1}{2\pi p_T}\frac{dN}{dp_T}$$

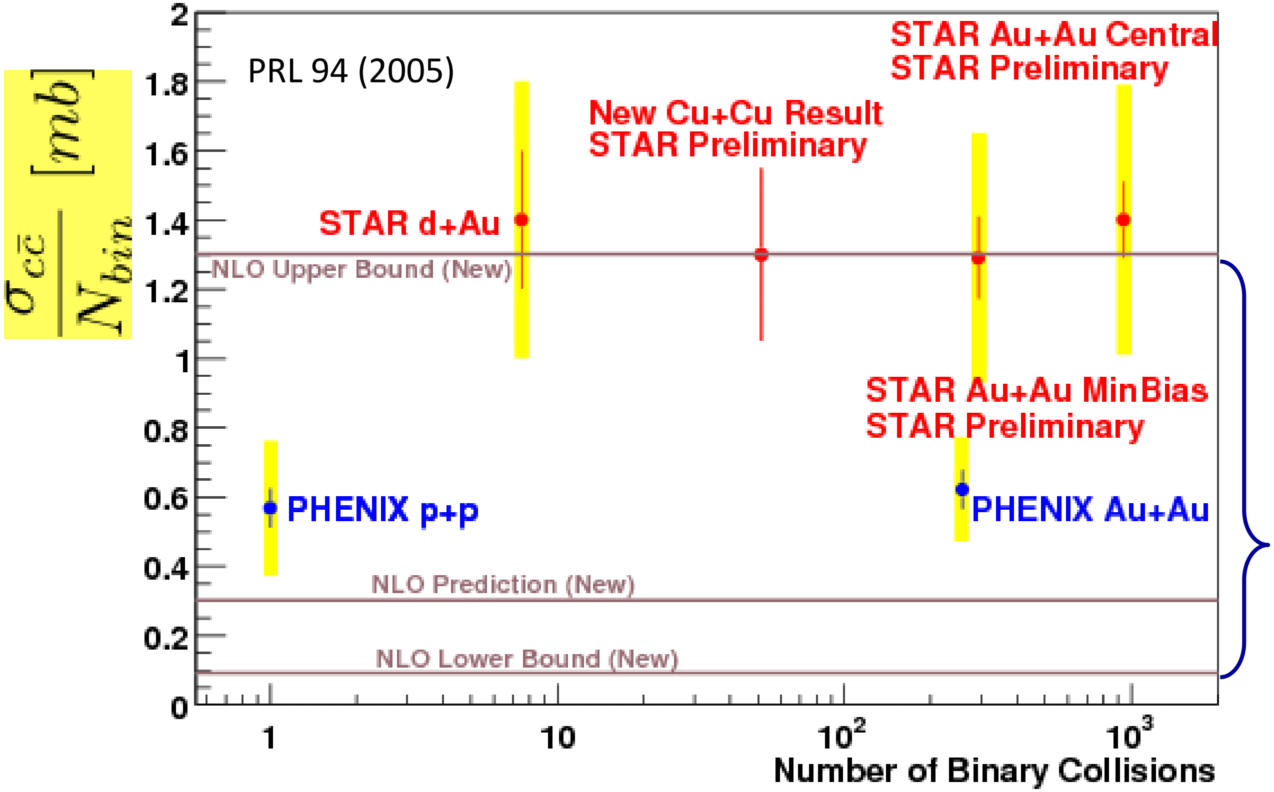


$$R_{AA} = \frac{dN_{Au+Au}/dp_T}{N_{bin}\cdot dN_{p+p}/dp_T}$$



Direct γ yield scales with N_{bin}

Glauber test at RHIC:
Scaling of charm total production cross section

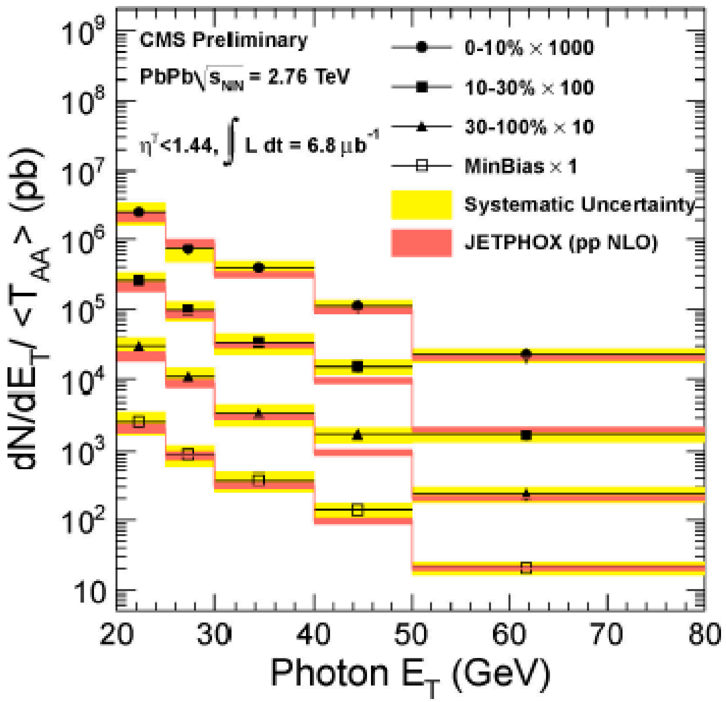


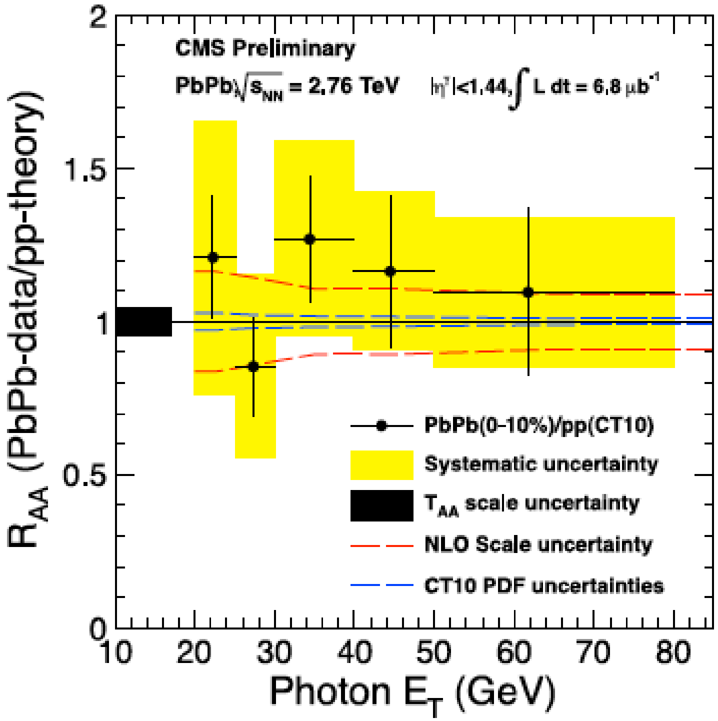
NLO prediction:
m ≈ 1.3 GeV, reasonably hard scale at p_T=0

Total charm cross section scales with N_{bin} in A+A

(Sizable disagreement between STAR and PHENIX ……?)

Glauber test at LHC:
Scaling of direct photon yield in p+p vs Pb+Pb

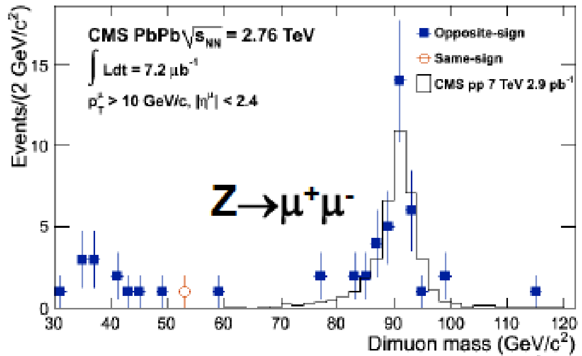


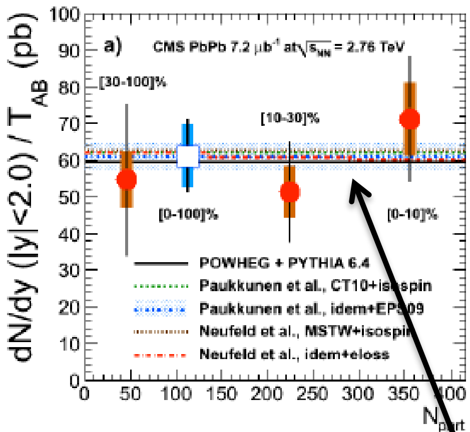


Direct γ yield scales with N_{bin}

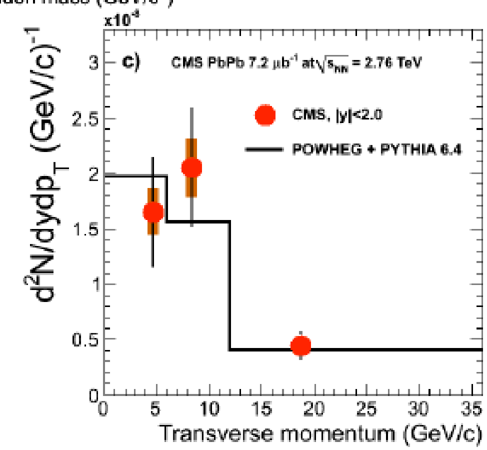
Glauber test at LHC:

Scaling of Z boson yield in p+p vs Pb+Pb





No significant dependence on centrality



p_T dependence consistent with pp

arXiv:1102.5435 accepted by PRL

J Robles (Thu)

Z boson yield scales with N_{bin}

Summary of Lecture 1: what are the questions? (partial list)

What is the nature of QCD Matter at finite temperature?

- What is its phase structure?
- What is its equation of state?
- What are its effective degrees of freedom?
  - Is it a (trivial) gas of non-interacti
    interacting quasi
- W
  t require new

In the following lectures we will address some of these questions, based on results from heavy ion collider experiments at RHIC and LHC together with theoretical calculations.

Wh ies of QCD matter at finite temperature?

- What is the order of the (de-)confinement transition?
- How is chiral symmetry restored at high T, and how?
- Is there a QCD critical point?
- What are its transport properties?

Can QCD matter be related to other physical systems?

Can we study hot QCD matter experimentally?