Heavy-Ion Experiments

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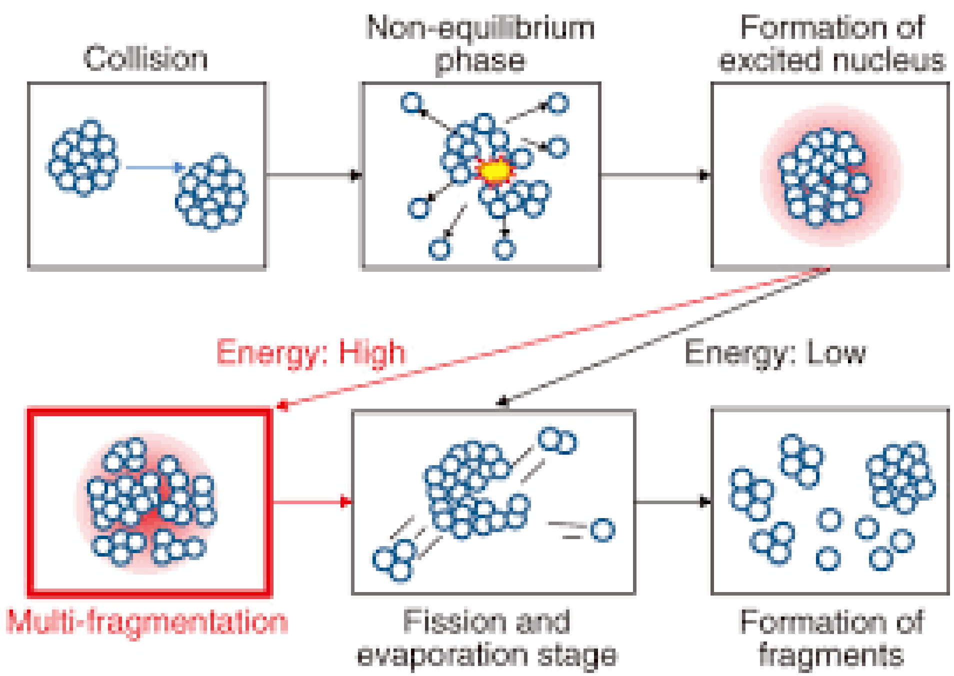
science & technology
Department: Science and Technology
REPUBLIC OF SOUTH AFRICA

NRF National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

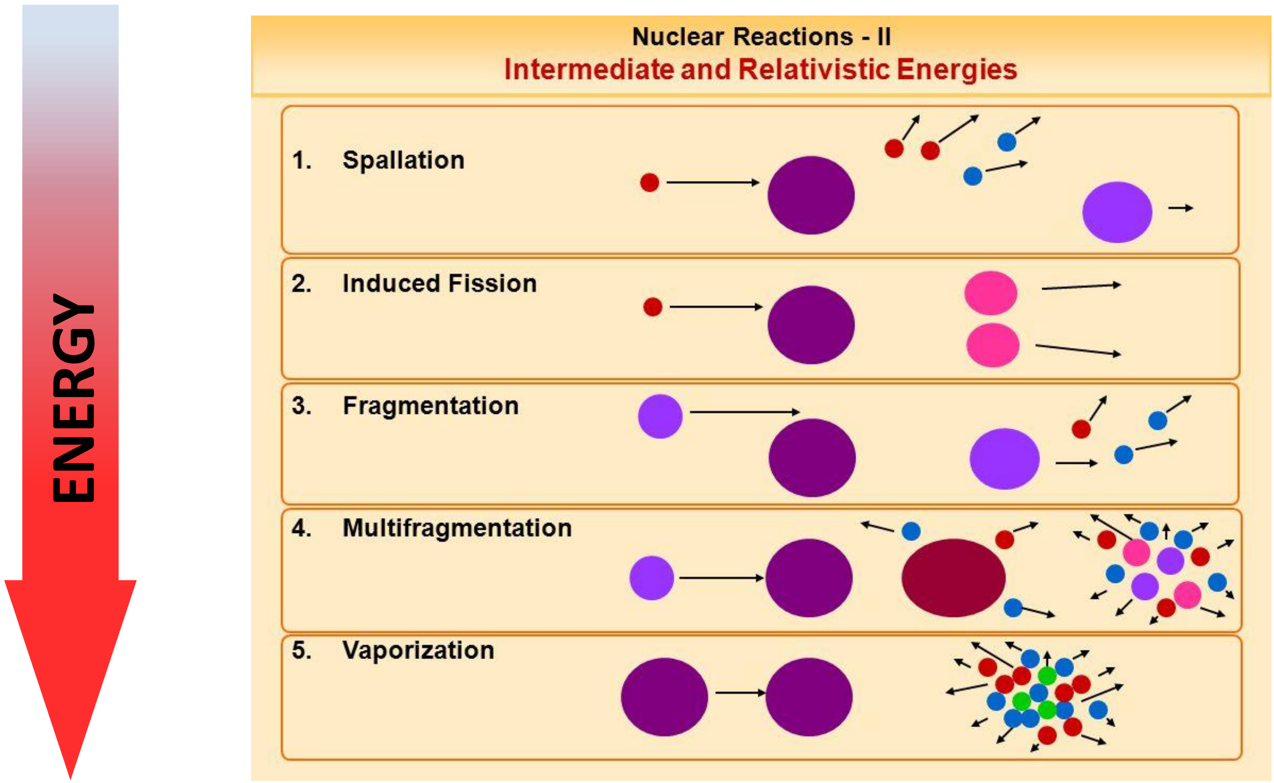
Introduction

Nuclear Physics with Heavy Ions



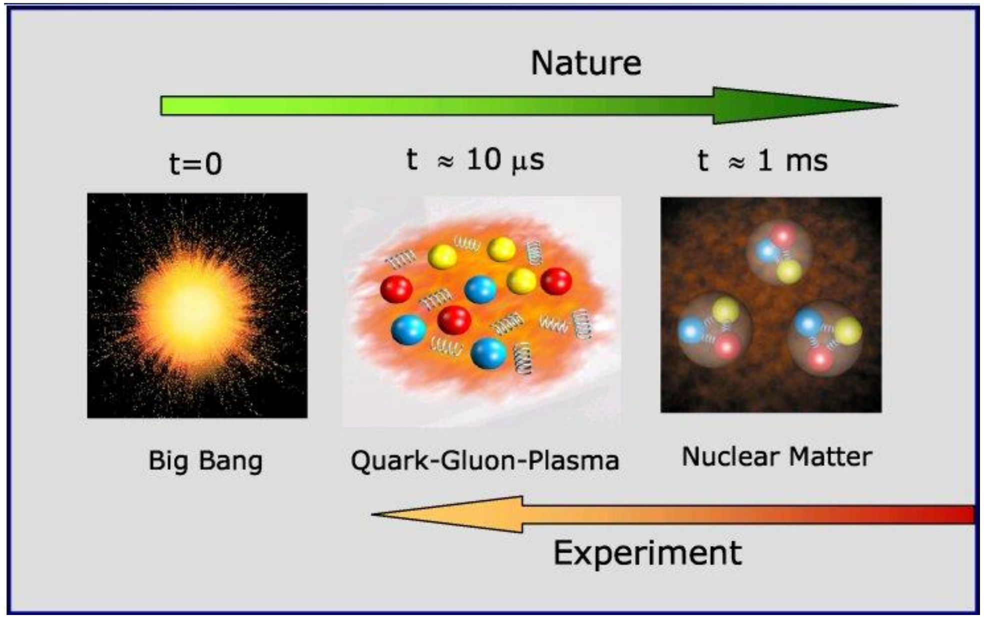
Introduction

Nuclear Physics with Heavy Ions



Introduction

Why do we perform Heavy-Ion Experiments at even higher energies?



Introduction

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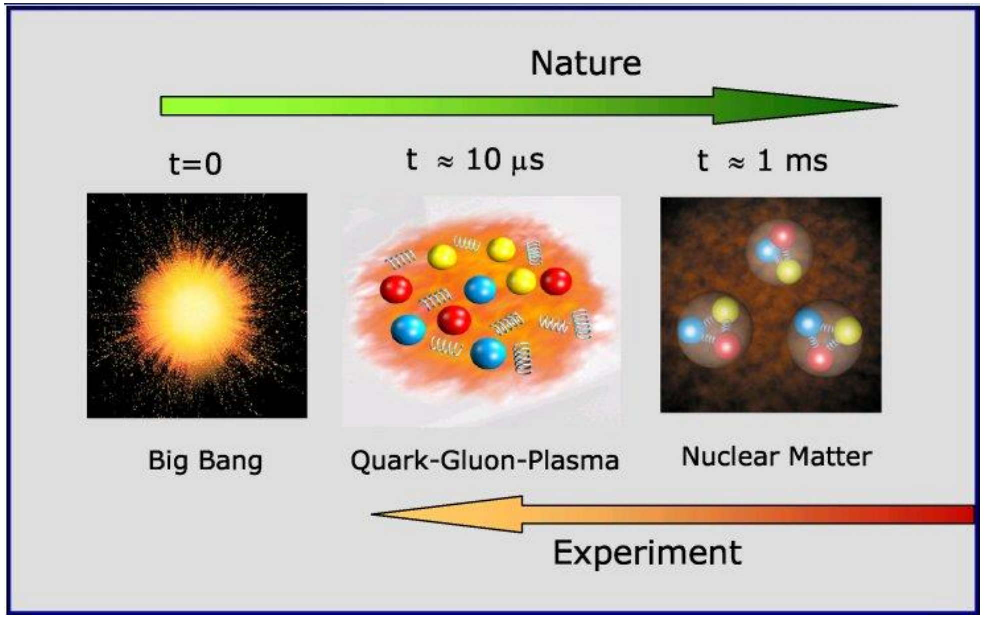
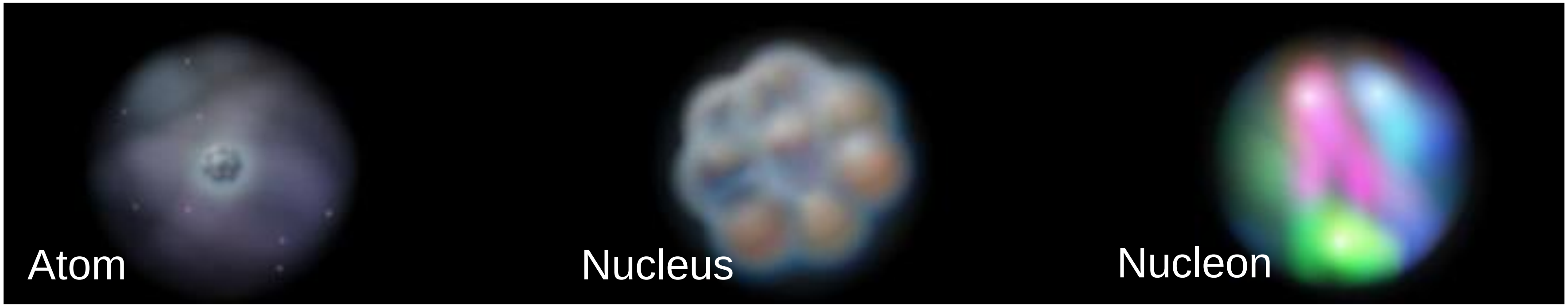


Need high energy densities ➡ **We would need ultra-relativistic heavy ions**

Introduction

Why do we collide Heavy Ions?



Fundamental Questions:

- *Can the quarks inside the protons and neutrons be freed?*
- *Why do protons and neutrons weigh 100 times more than the quarks they are made of?*
- *What happens to matter when it is heated to 100 000 times the temperature at the centre of the Sun?*

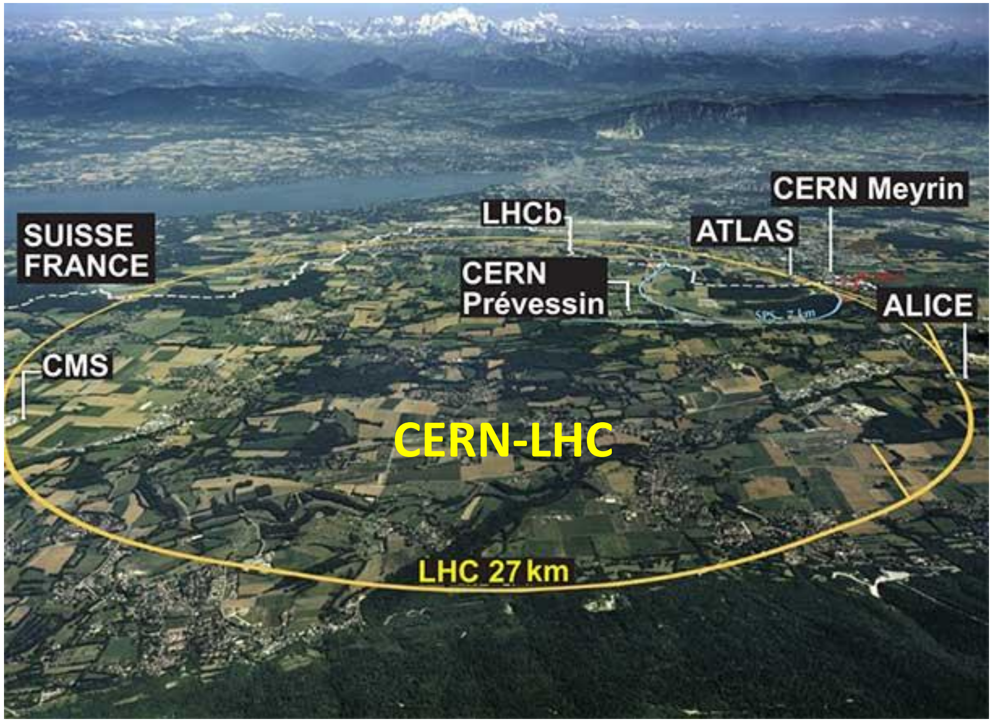
Introduction

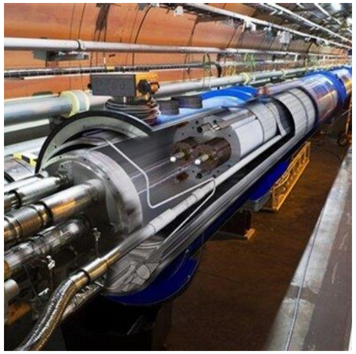
Ultra-relativistic heavy-ion accelerators

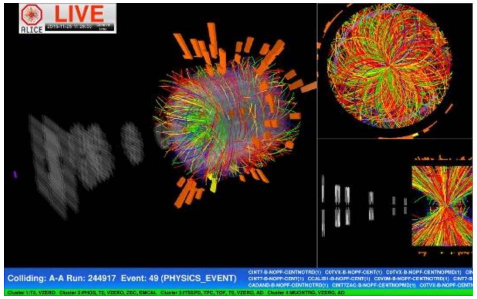
- **BNL-AGS**, early ’90s, Au-Au up to $\sqrt{s_{NN}}$ = 5 GeV
  - Below critical energy density
- **CERN-SPS**, from 1994, Pb-Pb up to $\sqrt{s_{NN}}$ = 17 GeV
  - Estimated energy density ~ 1 × critical value ε_c
  - First signatures of the QGP observed
- **BNL-RHIC**, from 2000, Au-Au $\sqrt{s_{NN}}$ = 8-200 GeV
  - Estimated energy density ~ 10 × critical value ε_c
  - Discovery of several properties of the QGP
- **CERN-LHC**, from 2010, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 – 5.5 TeV
  - Estimated energy density ~ 15-30 × critical value ε_c
  - (Ongoing) Precise characterization of the QGP, new probes available

Introduction

Where do we perform such Heavy-Ion Experiments?

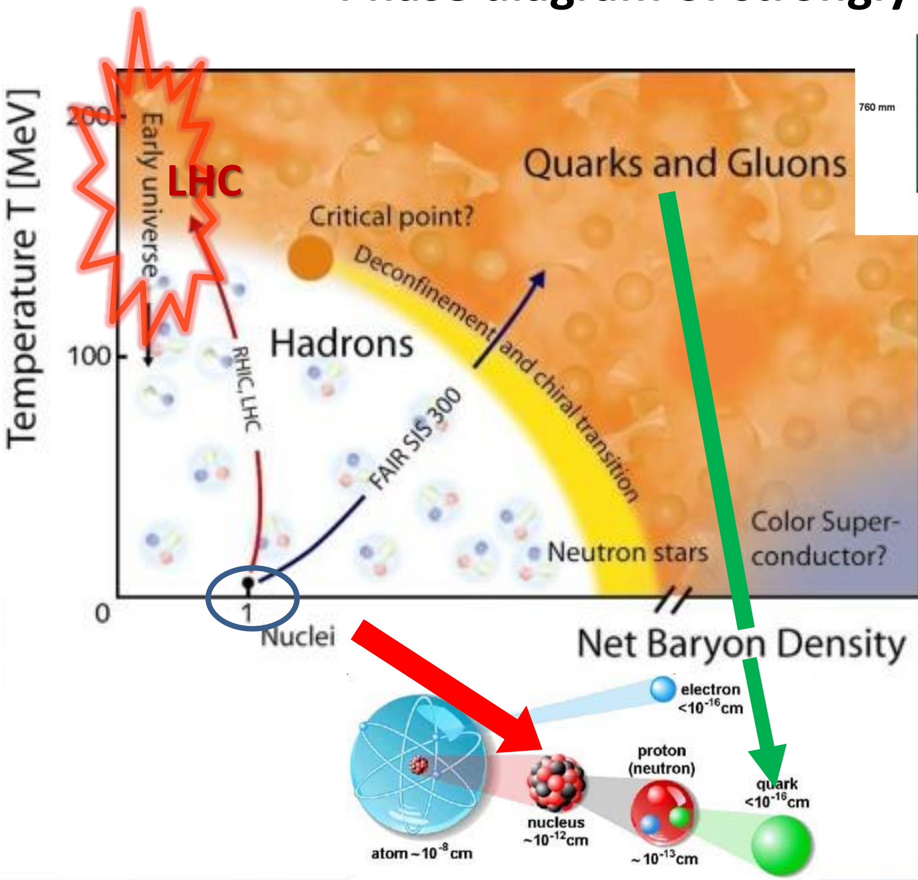


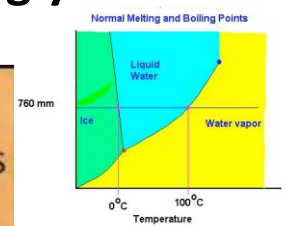




Introduction

Phase diagram of strongly-interacting (QCD) matter



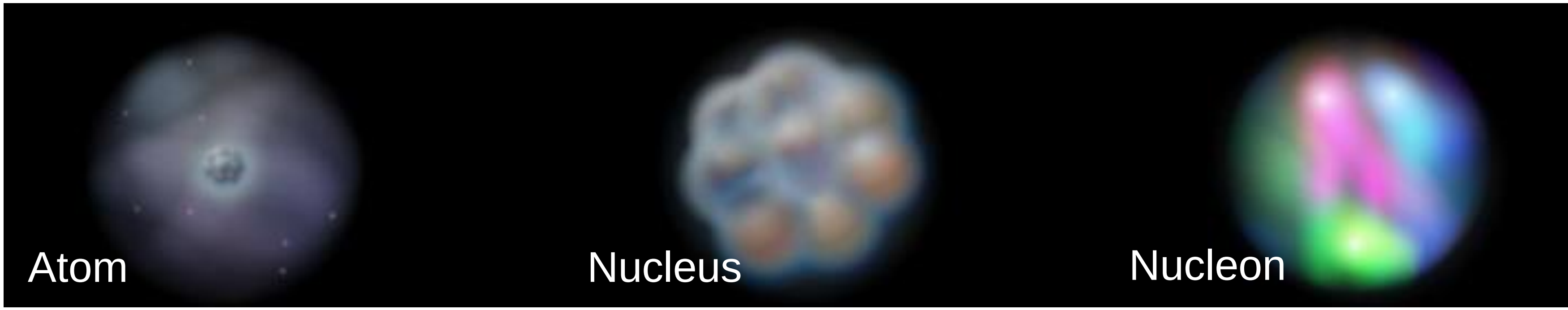


At high energy density ε (high temperature and/or high density) hadronic matter undergoes a Phase transition to the *Quark-Gluon Plasma (QGP)*

- *a state in which colour confinement is removed*
- *and chiral symmetry is approximately restored*
- *a high-density QCD medium of "free" quarks and gluons*

Introduction

Why do we collide Heavy Ions?



<u>Fundamental Questions:</u>

- *Can the quarks inside the protons and neutrons be freed?*

  a state in which colour confinement is removed

- *Why do protons and neutrons weigh 100 times more than the quarks they are made of?*

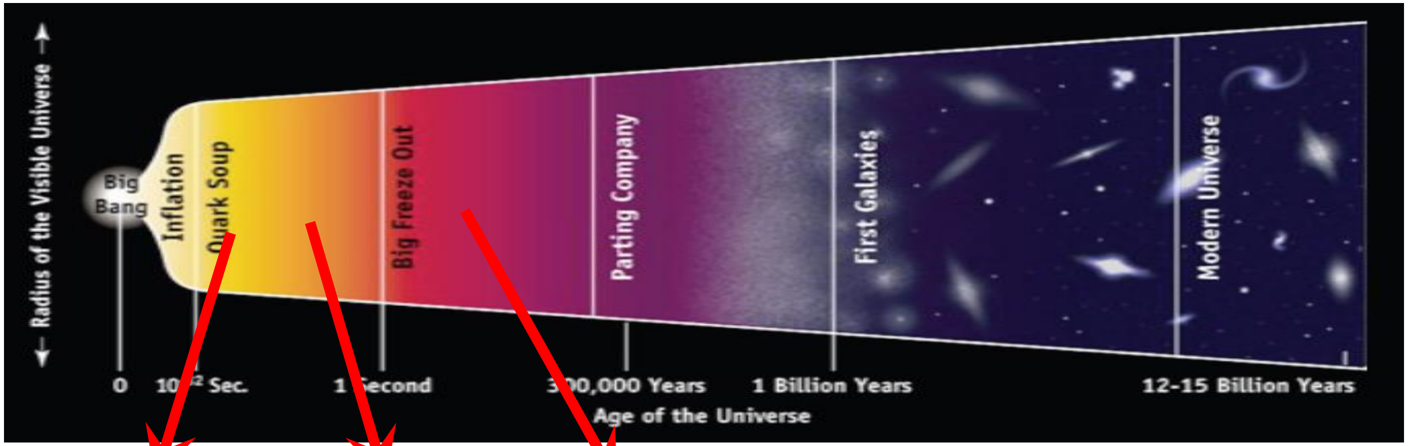
  and chiral symmetry is approximately restored

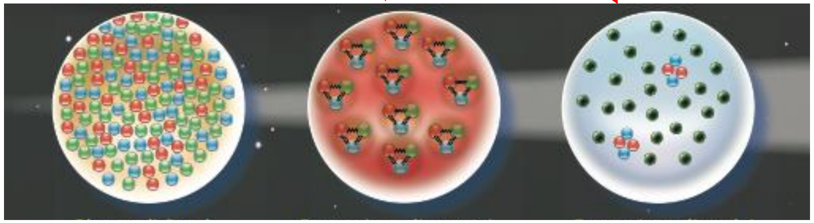
- *What happens to matter when it is heated to 100 000 times the temperature at the centre of the Sun?*

  a high-density QCD medium of "free" quarks and gluons

Introduction

Quark-Gluon Plasma (QGP): the first “matter” in the primordial Universe





quark-gluon plasma

formation of protons/neutrons

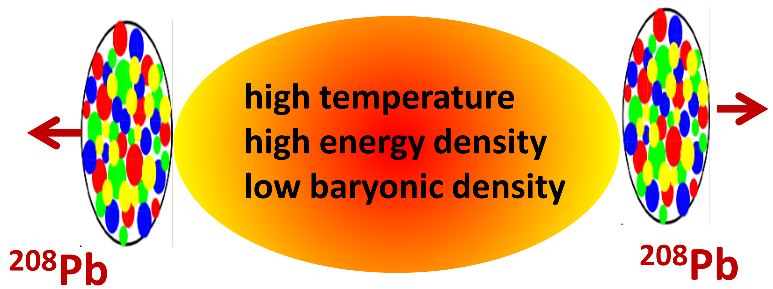
formation of atomic nuclei

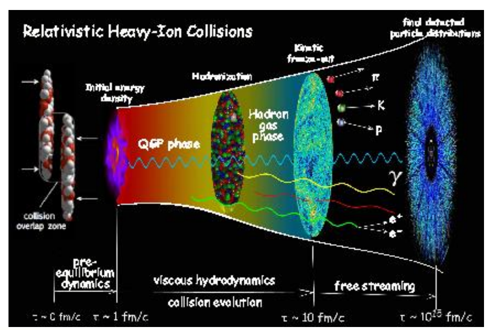
The phase transition from quarks to hadrons occurred in the cooling Universe, 10 μs after the Big Bang

Introduction

The Little Bang in the lab

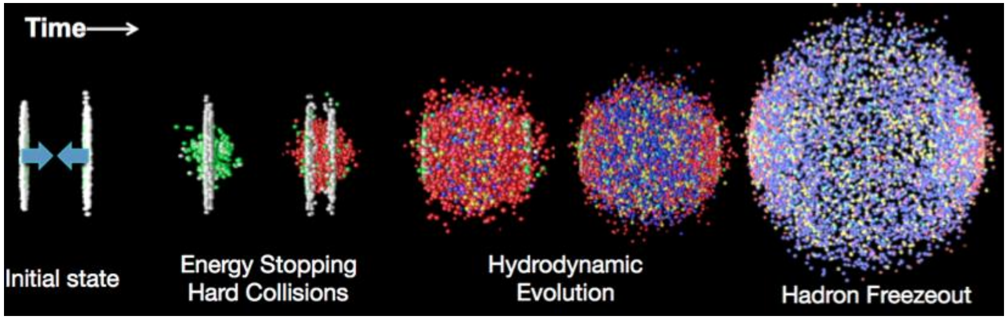
- QCD phase transition (QGP → hadrons) at $t_{Universe}$ ~10 μs
- In **high-energy heavy-ion** collisions, **large** energy densities (> 1 GeV/fm^3) are reached over large volumes (> 1000 fm^3)





Nucleus-nucleus collisions

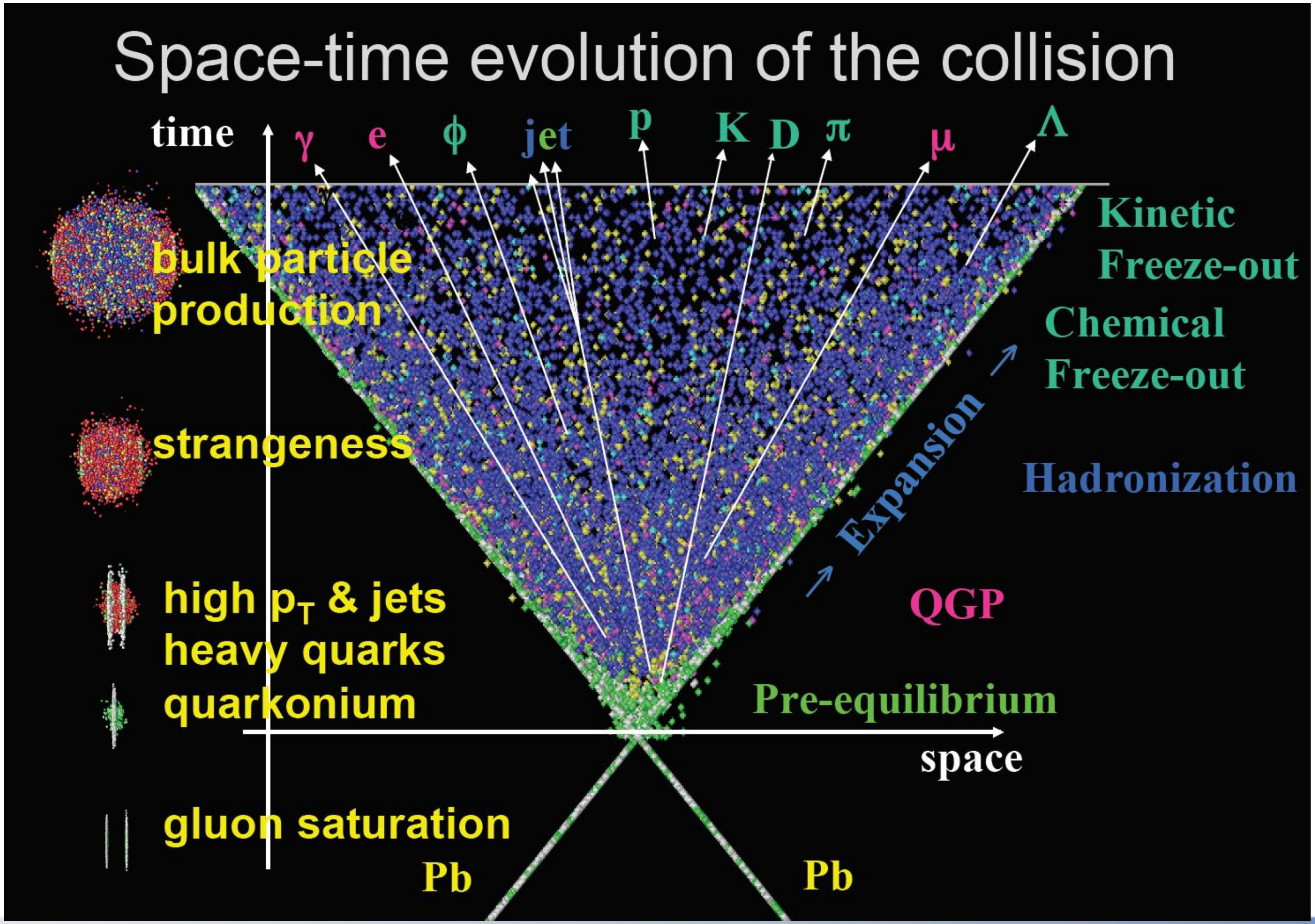
- How can we compress/heat matter to such high energy densities?



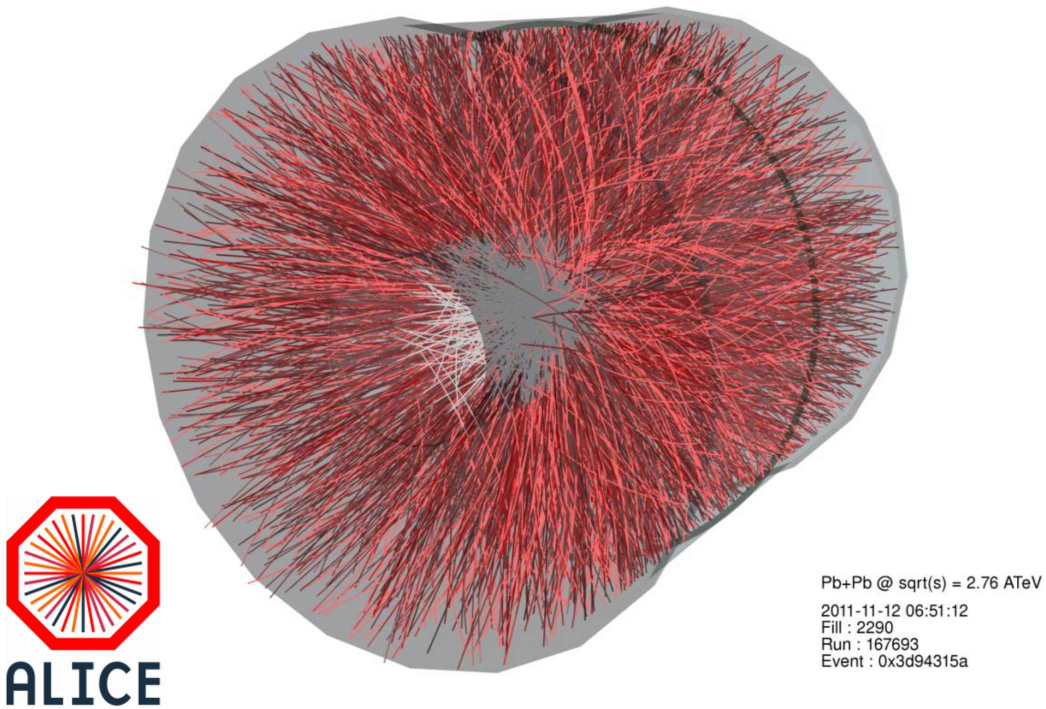
- By colliding two heavy nuclei at ultra-relativistic energies we recreate, for a short time span (about 10^{-23} s, or a few fm/c) the conditions of deconfinement

- As the system expands and cools down it will undergo a phase transition from QGP to hadrons again, like at the very beginning of the Universe: we end up with confined matter again

Evolution of a high-energy nuclear collisions



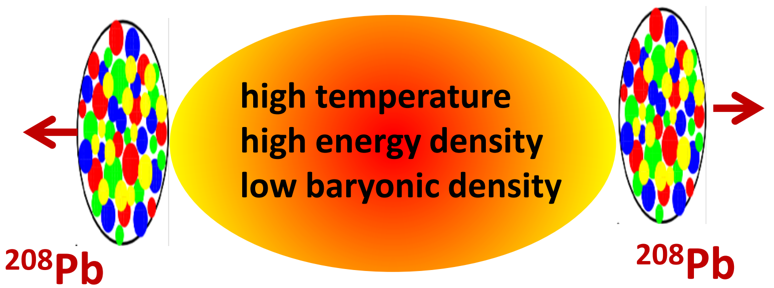
Final state of a high energy nuclear collision



Use particles in the final state to investigate the stages of the collision evolution

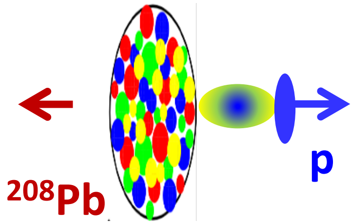
The role of proton-nucleus collisions

- In **high-energy nucleus-nucleus** collisions, **large energy density** (> 1 GeV/fm^3) over **large volume** (>> 100 fm^3)



- **Control experiment**: **high-energy proton-nucleus** collisions, **large energy densities** (?) in a **small volume** → no QGP (?)

Control experiment:



LHC as a Heavy-Ion accelerator

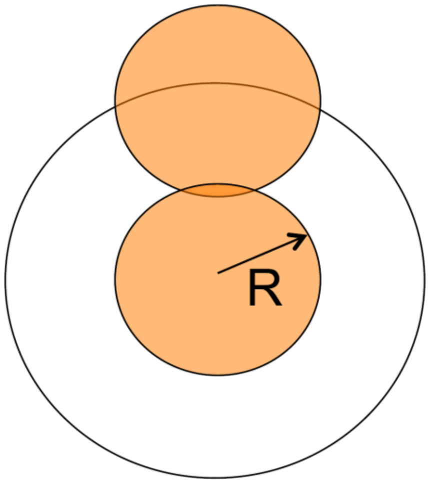
- Fully ionized ^{208}Pb nucleus accelerated in LHC (magnet configuration identical to that for pp), e.g. (2011 numbers):

$$\sqrt{s_{\mathrm{NN}}} = \sqrt{4 p_1 p_2} = \sqrt{4 \frac{Z_1 Z_2}{A_1 A_2} p_p p_p} = \frac{Z}{A}\sqrt{s_{\mathrm{pp}}} = \frac{82}{208}\sqrt{s_{\mathrm{pp}}} = 2.76\ \mathrm{TeV}$$

- … of course, real life is more complicated…
  - ion collimation
  - sensitivity of LHC instrumentation
  - injection chain
  - …

Pb-Pb cross section and interaction rate

- Pb-Pb interaction cross section: $\sigma_{geom} \sim 7.7$ b
  - ^{208}Pb radius, $R \sim 1.2{*}A^{1/3}$ fm ~ 7 fm
  - $\sigma_{geom} \sim \pi\,(2\,R)^2 \sim 7.7$ b

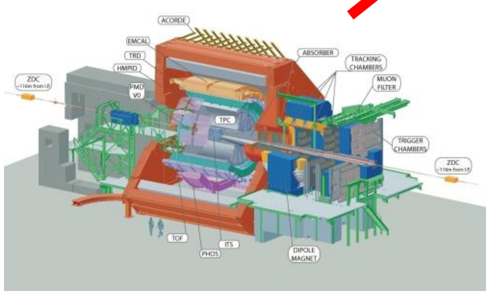


- For 2011 Pb-Pb run:
  - $\sim 1.1\ 10^8$ ions/bunch
  - 358 bunches (200 ns basic spacing)
  - $\beta^* = 1$ m
  - $L \sim 5\ 10^{26}\ cm^{-2}s^{-1}$

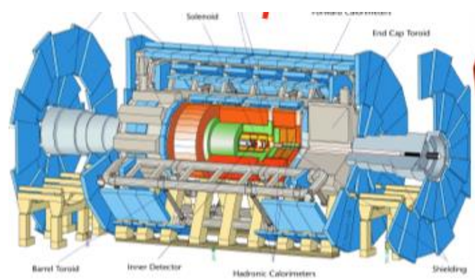
  $\rightarrow R = L\,\sigma_{geom} \sim 4$ kHz interaction rate

1 b (“barn”) = 10^{-28} m^2

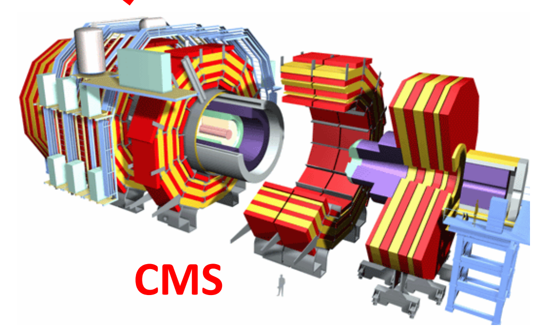
Heavy-ion experiments at the LHC



ALICE



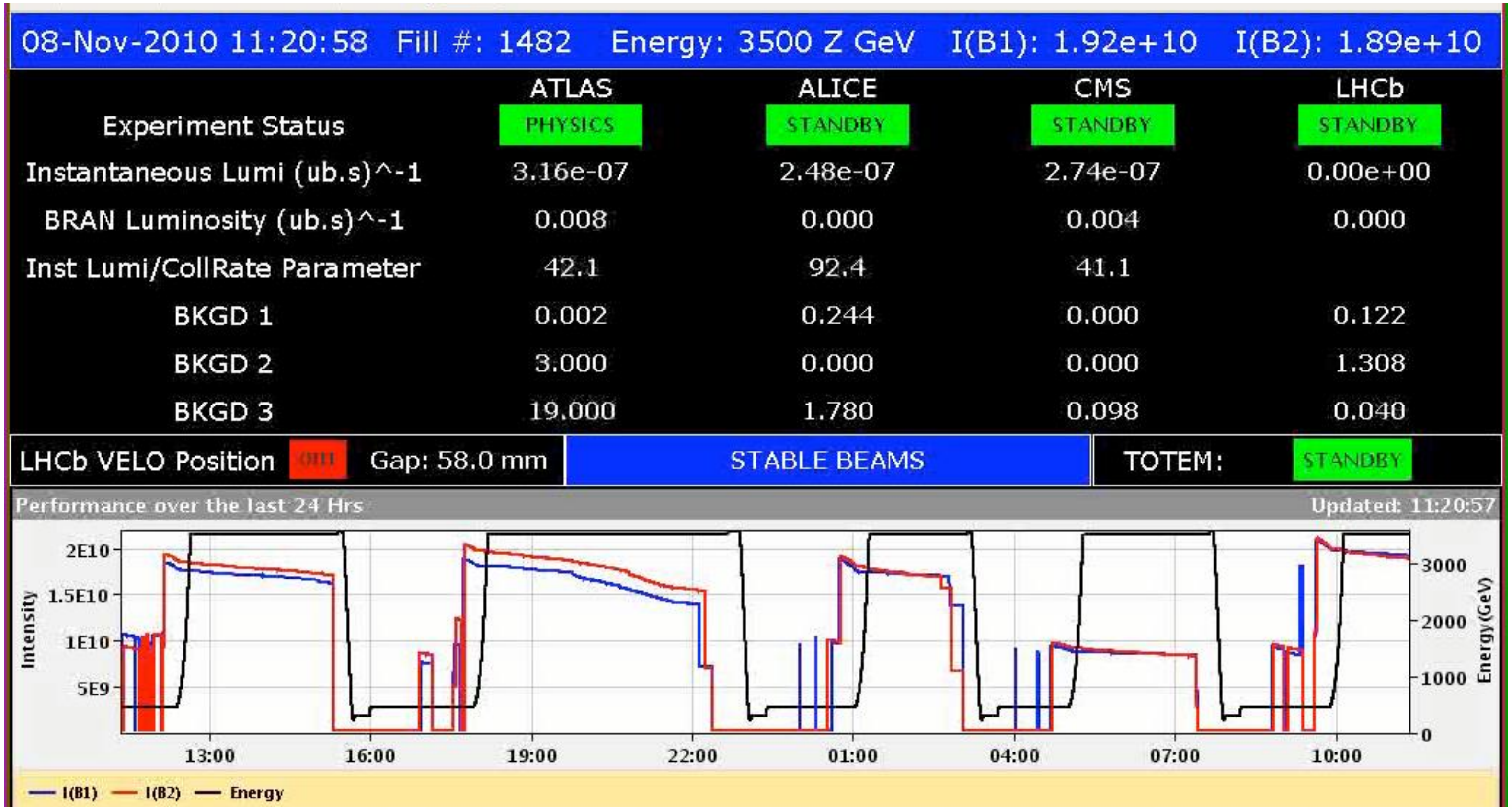
ATLAS



for p-Pb also LHCb

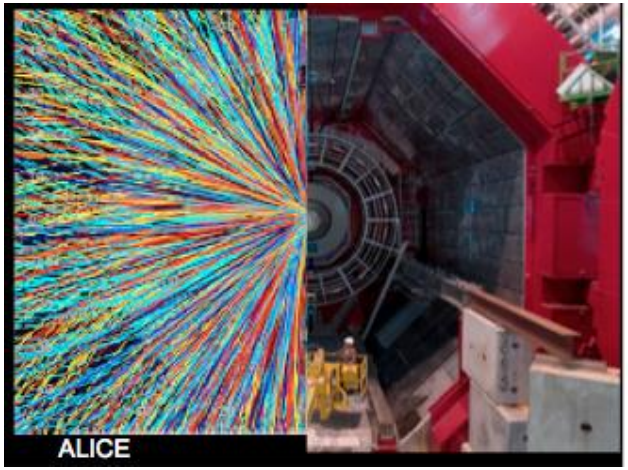
First Pb-Pb collisions in the LHC!

➢ **8 November 2010: the beginning of a new era for Heavy Ion Physics**



Pb-Pb collisions: Event displays

Display of
ONE EVENT!!



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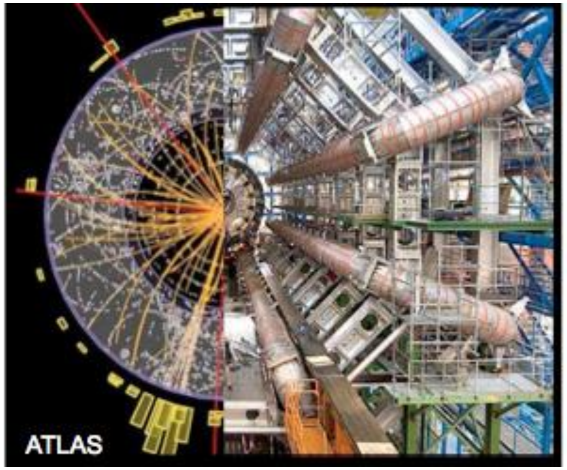
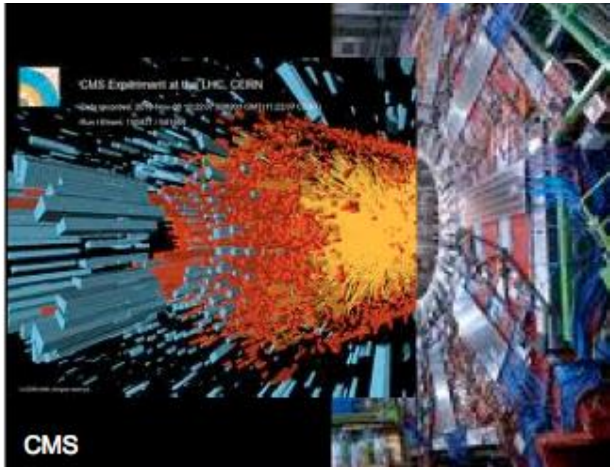
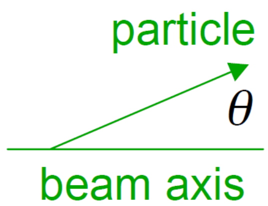




Kinematic Variables

Rapidity: $$y = \frac{1}{2}\ln\left(\frac{E+P_Z}{E-P_Z}\right)$$ dimensionless

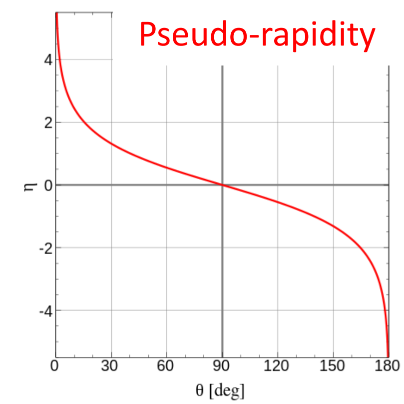
Pseudo-Rapidity: $$\eta = \frac{1}{2}\ln\left(\frac{|P|+P_Z}{|P|-P_Z}\right) = -\ln\left(\tan\frac{\theta}{2}\right)$$



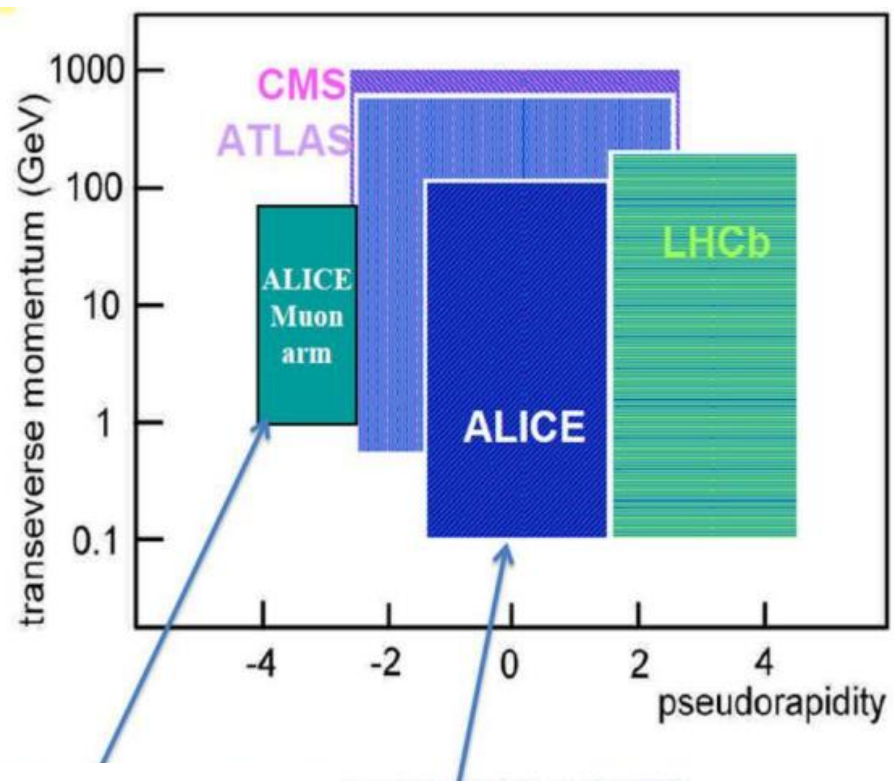
$\eta \to y$ large momentum i.e. $P \to E$

Transverse Momentum: $$p_T = \sqrt{p_X^2 + p_Y^2}$$

Transverse Mass: $$m_T = \sqrt{p_T^2 + m_0^2}$$



Complementary kinematic coverage at the LHC



ALICE Muon Spectrometer

ALICE Central barrel

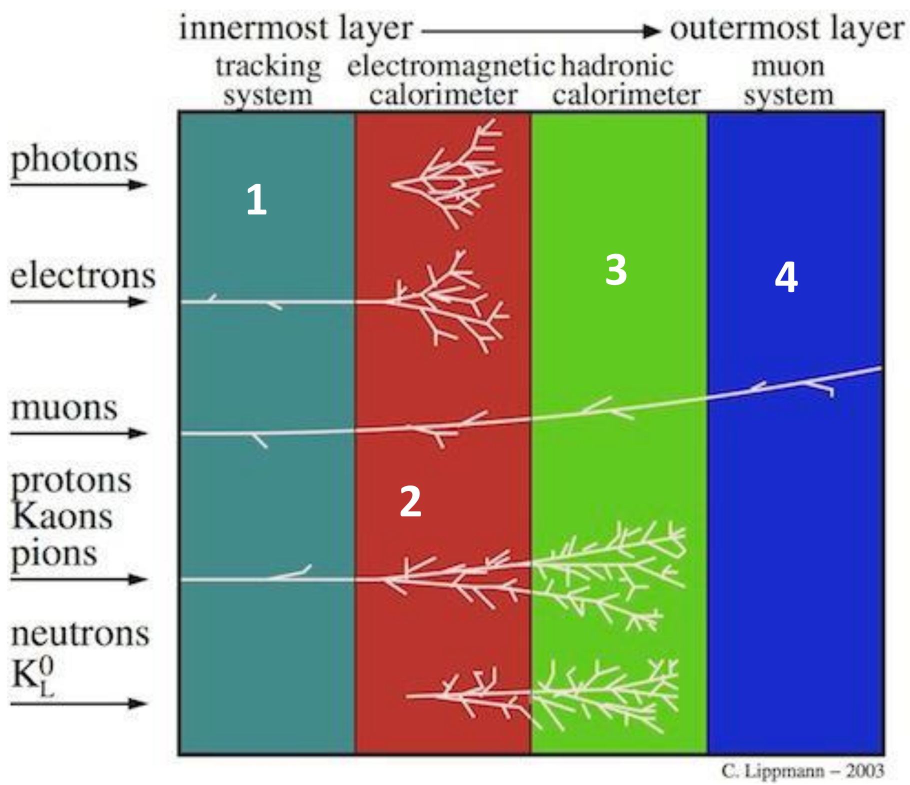
Observables and Probes of the QGP

Phenomenology and measurements from heavy-ion collisions at SPS, RHIC, LHC

➢ Global observables	⟷	the QGP fireball
➢ Strangeness production	⟷	historic signature of the QGP
➢ Anisotropy, correlations	⟷	collective expansion of the QGP
➢ Bulk particle production	⟷	hadronization of the QGP
➢ High-p_T and jets	⟷	opacity of the QGP
➢ Heavy-flavour production	⟷	transport properties of the QGP
➢ Quarkonium production	⟷	deconfinement in the QGP
➢ Surprises from LHC	⟷	p-Pb, HM pp current “hottest topics”

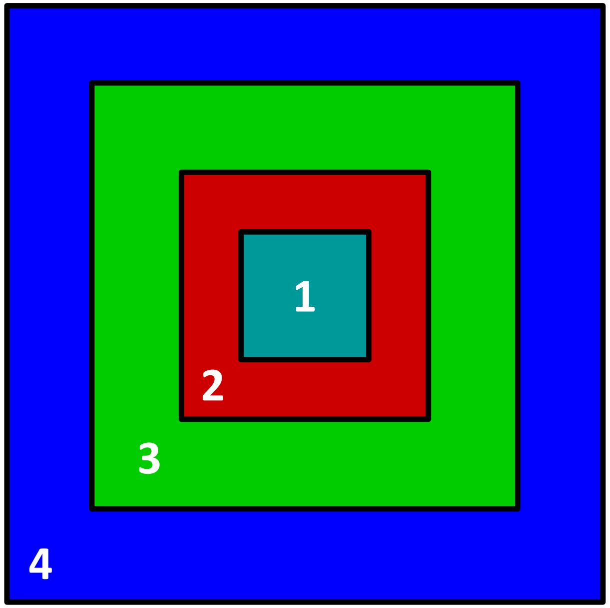
Particle Detectors

Particle Identification



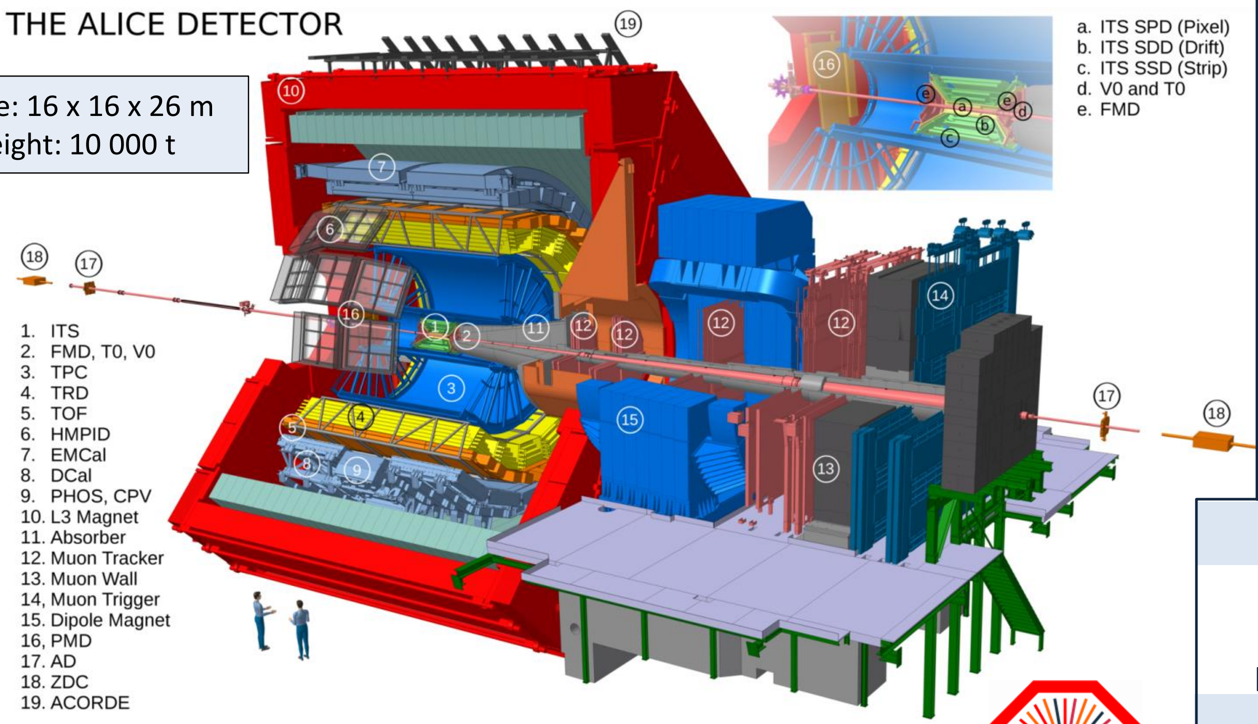
Detector arrangement:

- Onion-like layers



Example of a Detector: ALICE at the LHC

Size: 16 x 16 x 26 m
Weight: 10 000 t



Specificity: 19 sub-detectors, low-momentum tracking and particle identification in a high-multiplicity environment

ALICE

Central barrel ($|\eta|<1$):

Tracking (ITS, TPC), PID (TOF,TRD), calorimeters.

Muon spectrometer:

$-4 < \eta < -2.5$

Forward detectors for triggering, centrality, timing:

V0, T0, ZDC

Run 1 (2009-2013)

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

p-Pb @ $\sqrt{s_{NN}}$=5.02 TeV

pp @ $\sqrt{s}$=0.9, 2.76, 7, 8 TeV

Run 2 (2015-2018)

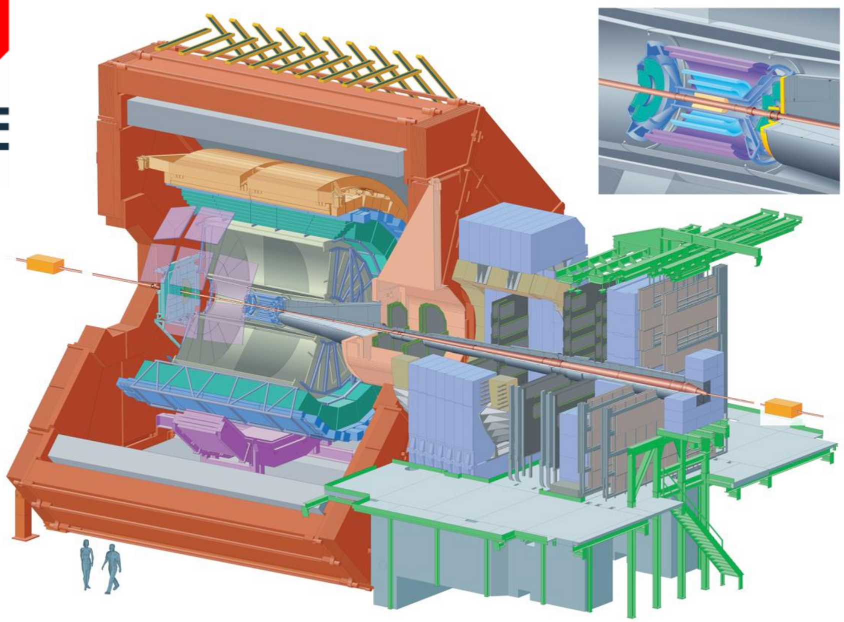
Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

Xe-Xe @ $\sqrt{s_{NN}}$ = 5.44 TeV

p-Pb @ $\sqrt{s_{NN}}$=5.02, 8.16 TeV

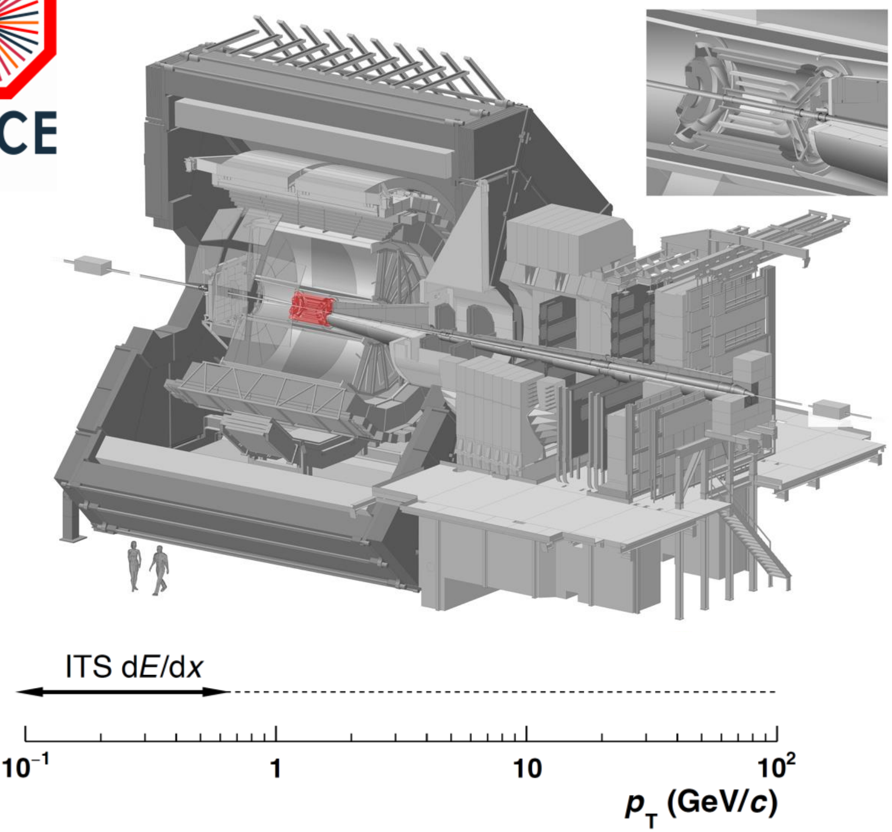
pp @ $\sqrt{s}$= 5, 13 TeV

Particle Identification with the ALICE Detector

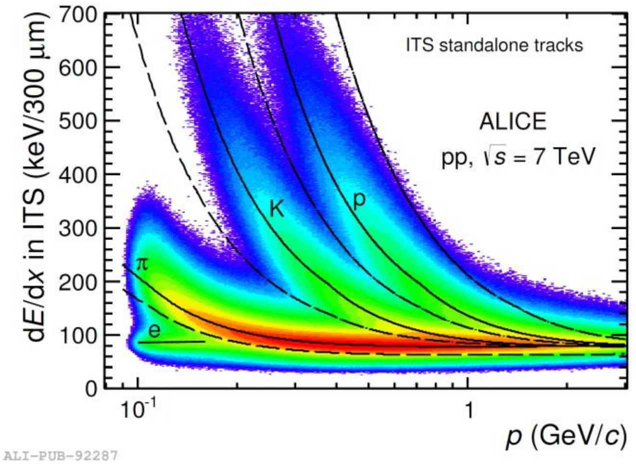


Specificity: low-momentum tracking and particle identification in a high multiplicity environment

Particle Identification with the ALICE Detector



ITS ($|\eta|$<0.9)
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)



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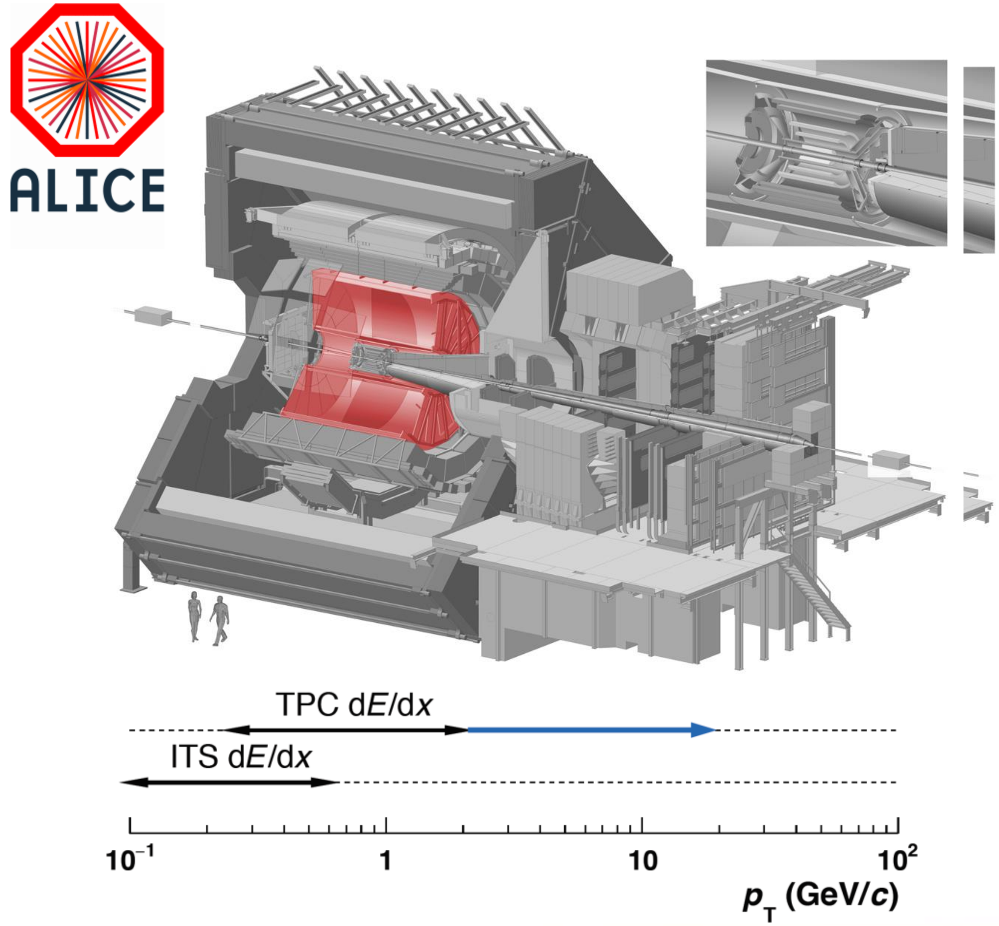
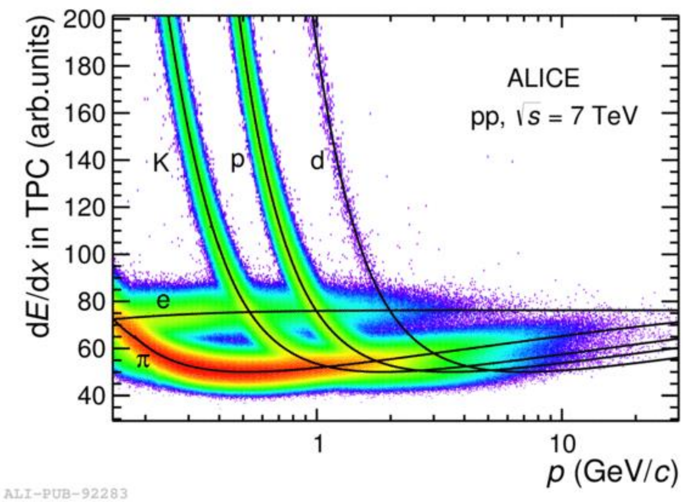
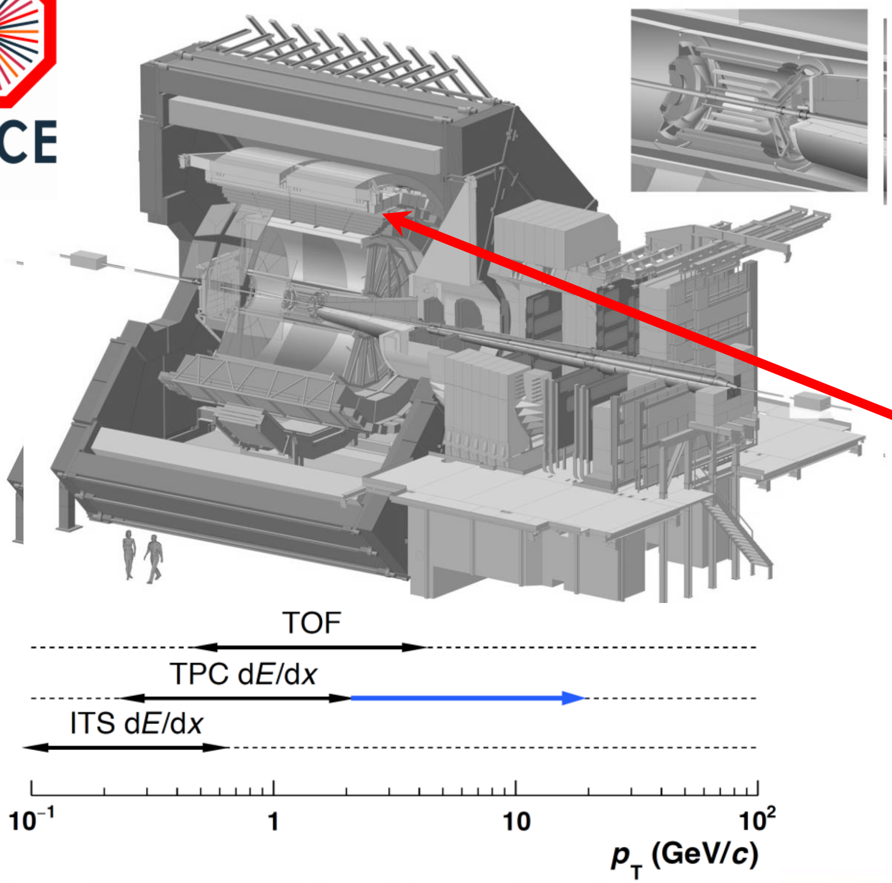


ITS ($|\eta|<0.9$)
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)

TPC ($|\eta|<0.9$)
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)



Particle Identification with the ALICE Detector



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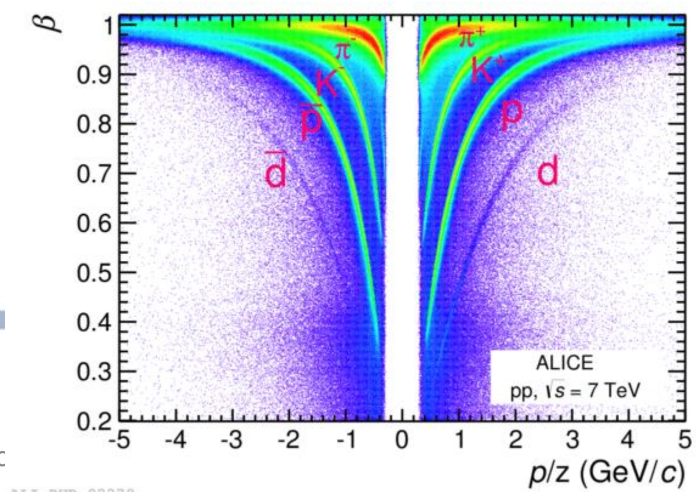
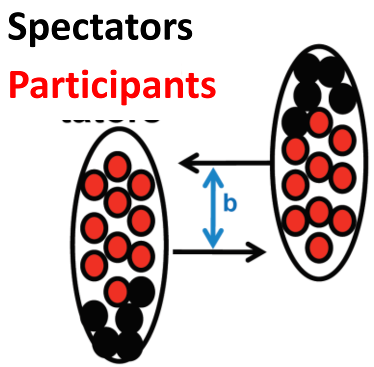
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)

TPC (|η|<0.9)
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)

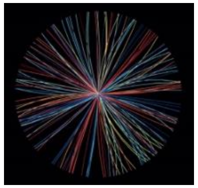
TOF (|η|<0.9)
- Multi-gap resistive plate chambers
- PID via velocity determination

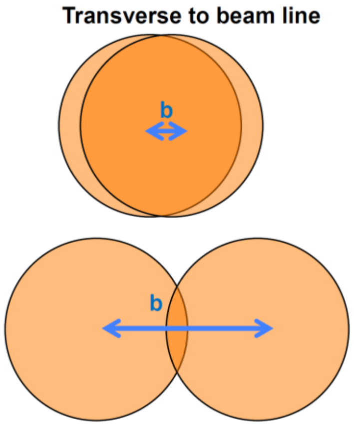


Geometry of a nucleus-nucleus collision



- **Central collisions**
  - small impact parameter b
  - high number of participants
  - high multiplicity
- **Peripheral collisions**
  - large impact parameter b
  - low number of participants
  - low multiplicity

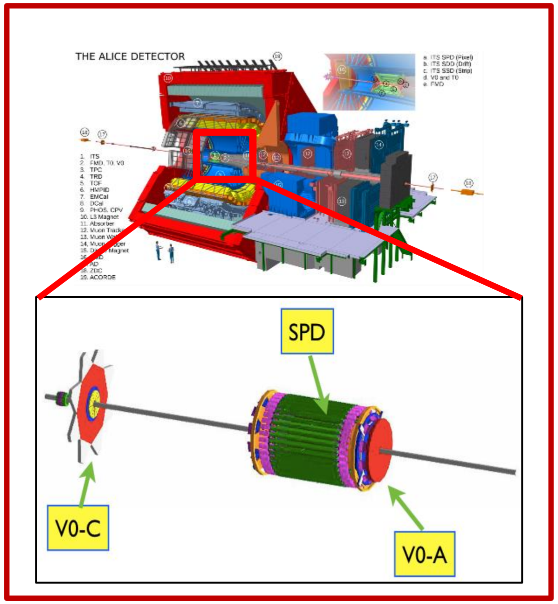




- System size strongly dependent on collision centrality
- Classify events in "centrality classes"
  - In terms of percentiles of total hadronic AA cross section
  - Determine <$N_{participants}$> and <$N_{collisions}$> with a model of the collision
  - geometry (Glauber model)

How do we measure the Centrality?

- Use multiplicity of produced particles in the acceptance of a given detector e.g. SPD
- **Or** “Zero Degree Calorimeters” to measure the energy of the spectator nucleons



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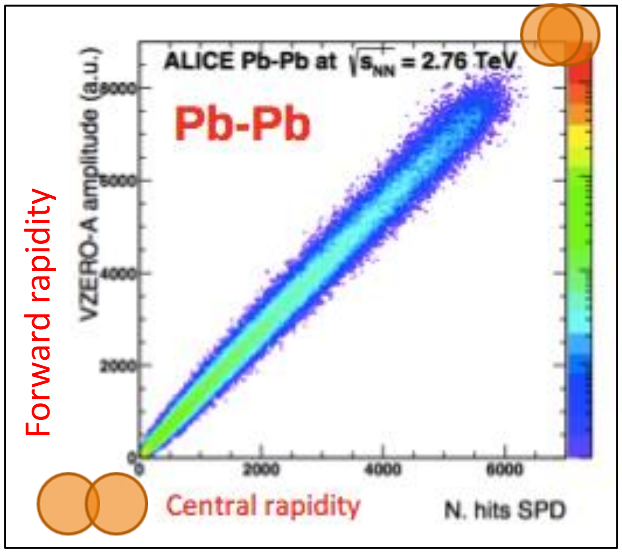

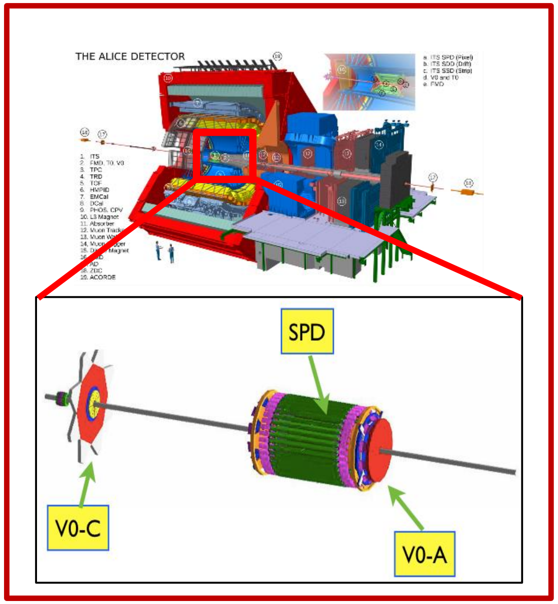

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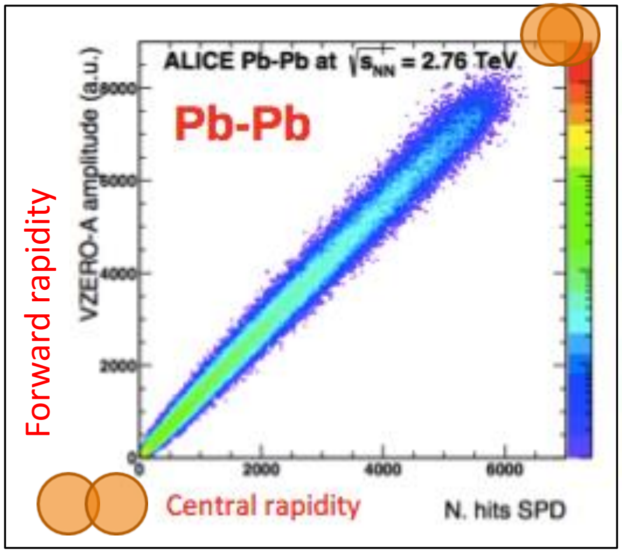
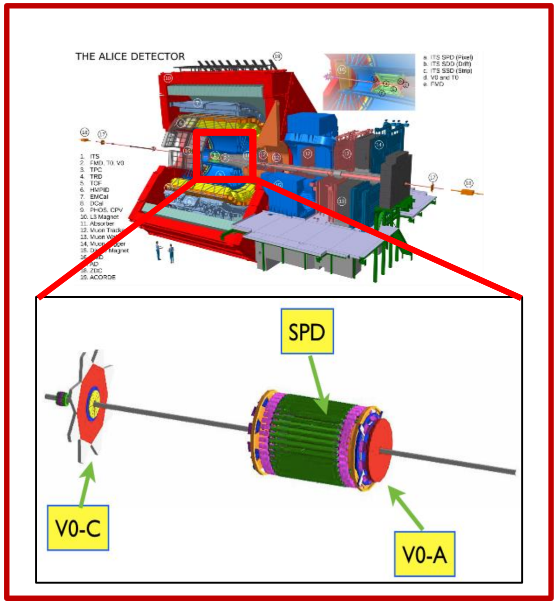
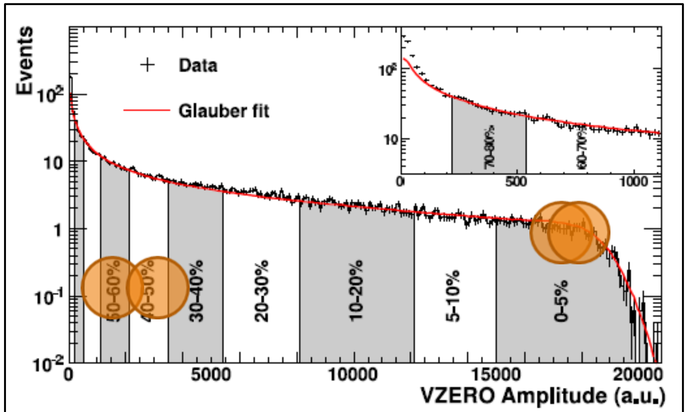






Reproduced by simple model (red):

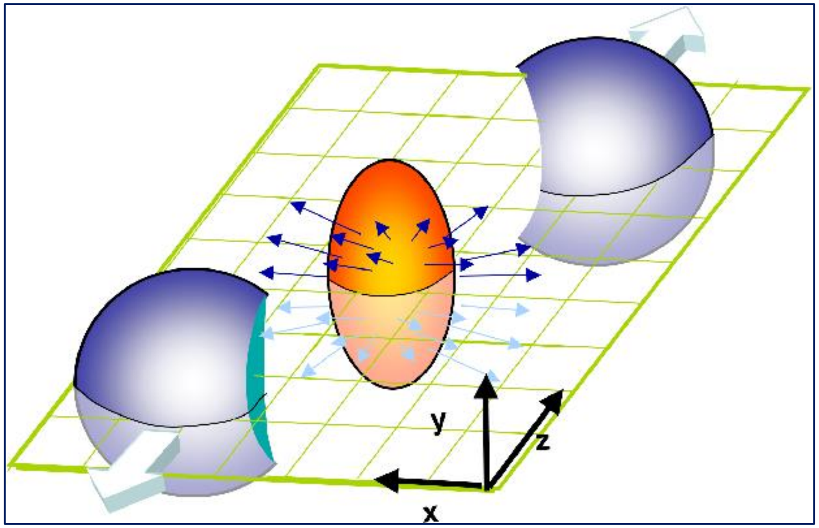
$N_{charged}$ = P x [f Npart + (1-f) Ncoll]

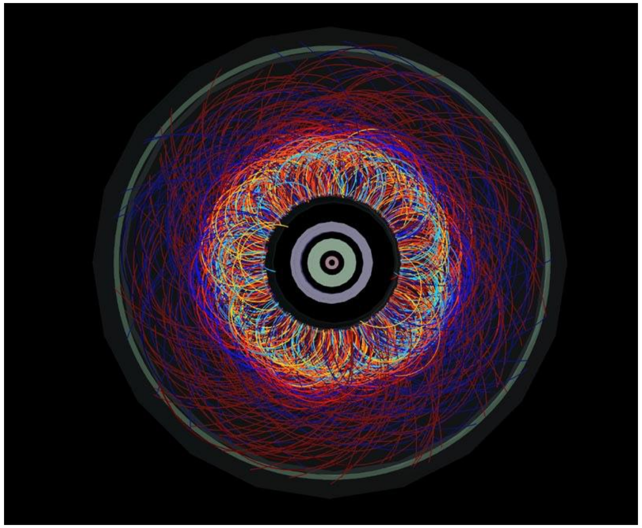
With Npart and Ncoll distributions from Glauber model

Inputs: Wood-Saxon nuclear density profile, inelastic NN cross section

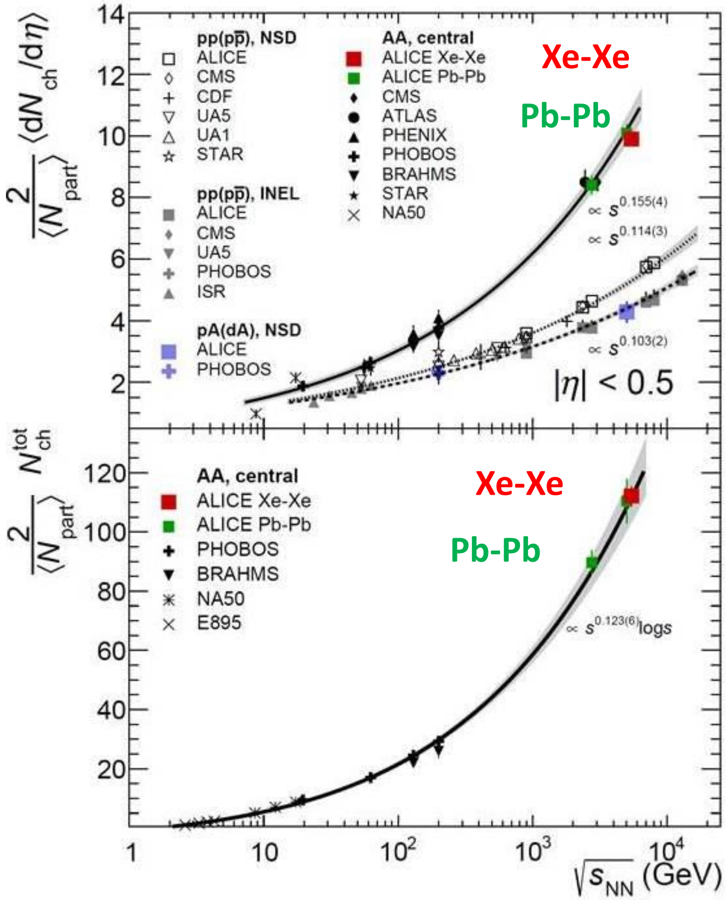
Bulk observables:

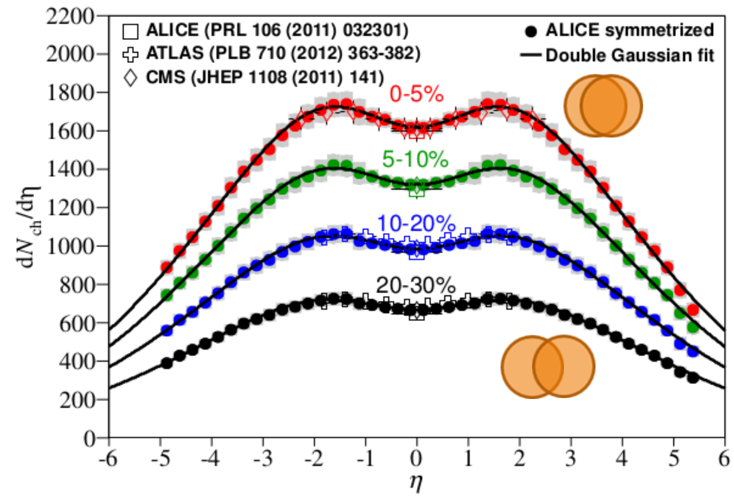
Multiplicity, size and temperature of the system





Particle multiplicity





Central collisions at LHC: ~17 000 charged particles!

x3 increase with respect to RHIC

Charged particle multiplicity densities increase in central A-A collisions stronger than in pp, p-A collisions

Energy density: Bjorken's formula

- To evaluate the energy density reached in the collision:

$$\varepsilon = \frac{E}{V} = \frac{1}{Sc\tau_0}\frac{dE_T}{dy}\bigg|_{y=0}$$

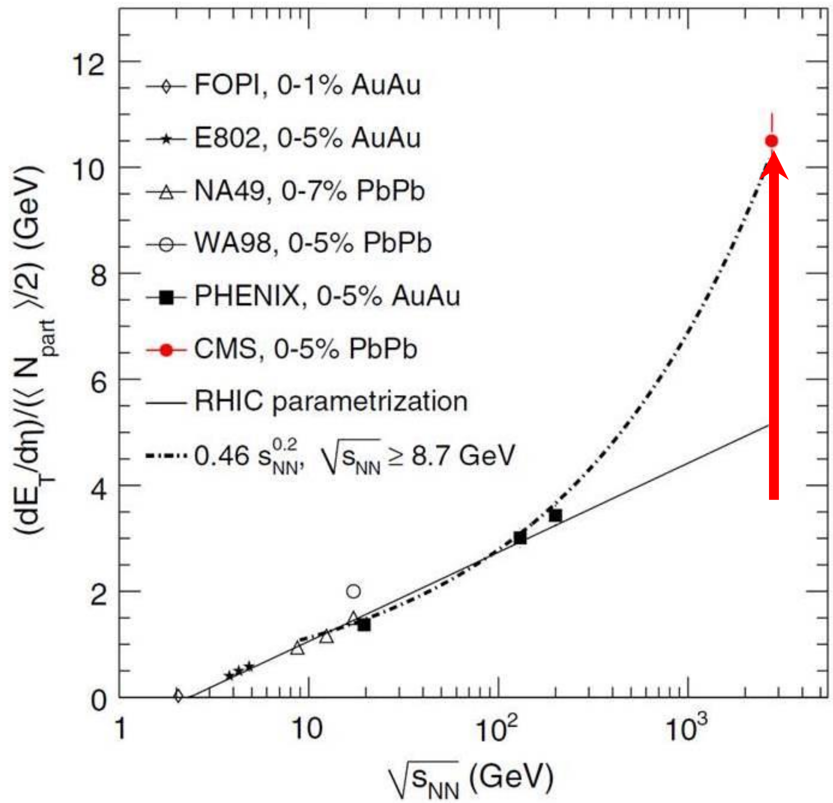
S = transverse dimension of nucleus
τ_0 = "formation time" $\sim 1\ \mathrm{fm}/c$

- Initial time τ_0 normally taken to be ~ 1 fm/c
  - i.e. equal to the "formation time": the time it takes for the energy initially stored in the field to materialize into particles

- Transverse dimension: $S \approx 160\ \mathrm{fm}^2 \qquad (R_A \approx 1.2 A^{1/3}\ \mathrm{fm})$

1 fm/c = 3 10^{-23} s

Energy density at LHC energy

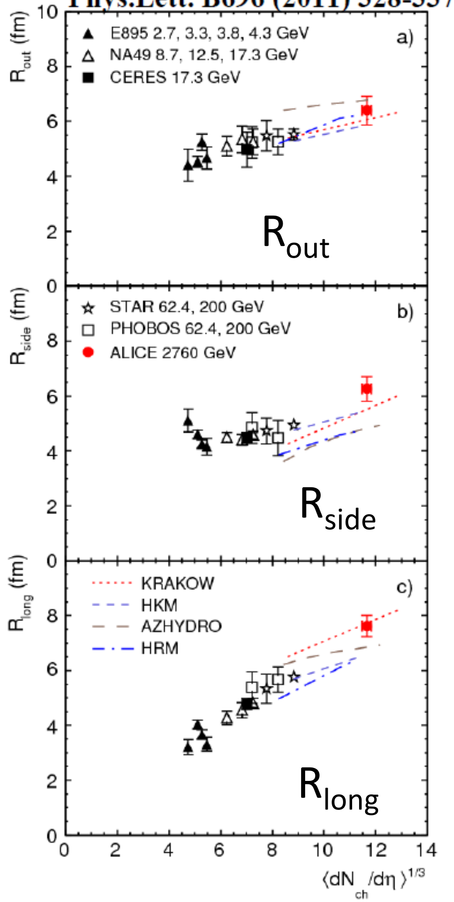


Transverse energy x3 from RHIC to LHC

$$\varepsilon \sim (2000/160)\ \mathrm{GeV/fm^3} \approx 12\ \mathrm{GeV/fm^3}$$

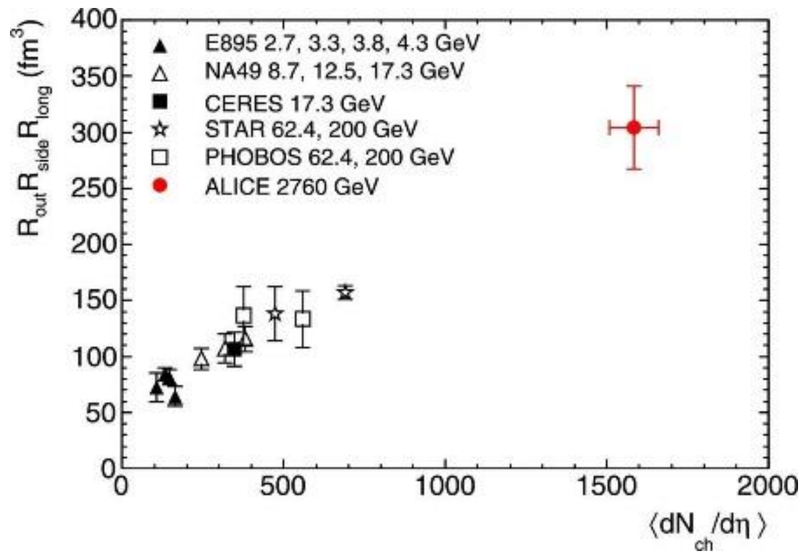
Size of the fireball

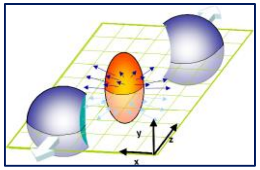
Phys.Lett. B696 (2011) 328-337



From RHIC to LHC:

- increase of size in the 3 dimensions
  - out, long, and side
- "homogeneity" volume ~ 5000 fm^3 ~ x 2



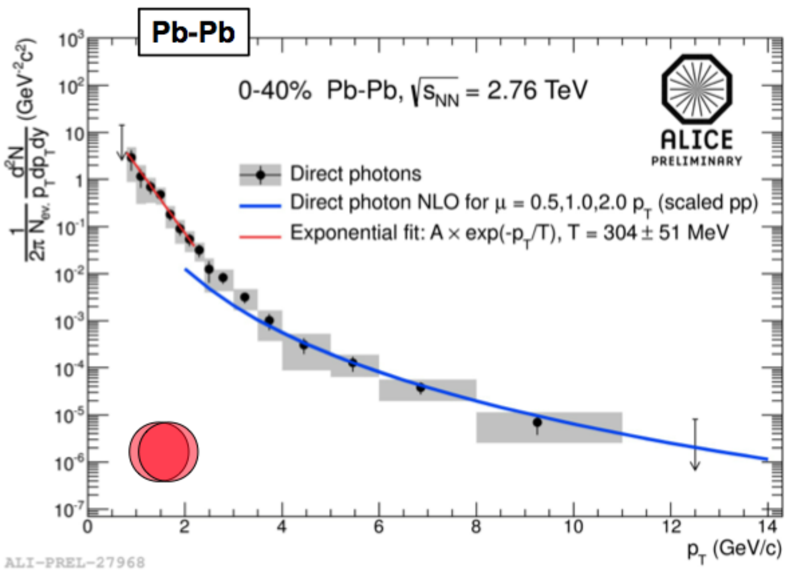


- for comparison: R_{Pb} ~ 7 fm → V ~ 1500 fm^3

→ **substantial expansion!**

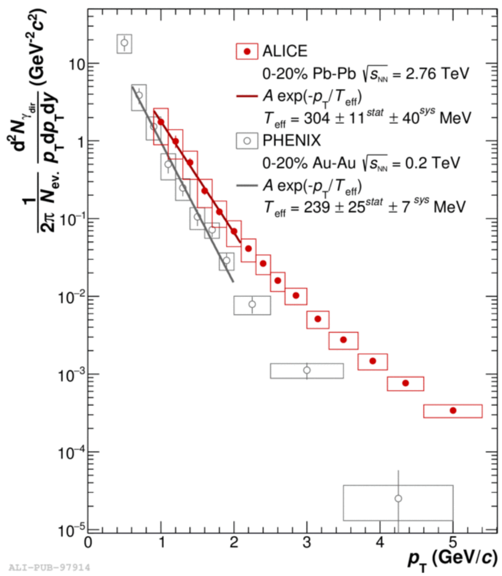
Temperature from Photon spectrum

- Prompt γ = Inclusive γ $- \gamma$ from π^0 decays
  - Direct photons from QCD processes: power law spectrum – dominant at high p_T
  - Thermal photons, emitted by the hot system (analogy with black body radiation): exponential spectrum – dominant at low p_T

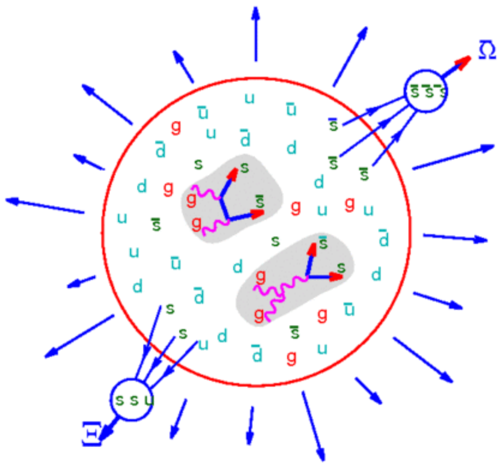


→ From inverse slope:

T = 304 ± 51 MeV
~ 2 Tc
~ 1.4 T_{RHIC}



The first predicted signature of the Quark Gluon Plasma (1982)



Historic QGP signature

- Restoration of χ symmetry $\rightarrow$ increased production of s quarks
  - mass of strange quark in QGP expected to return to current value
    - $m_s \sim 150$ MeV $\sim T_C$

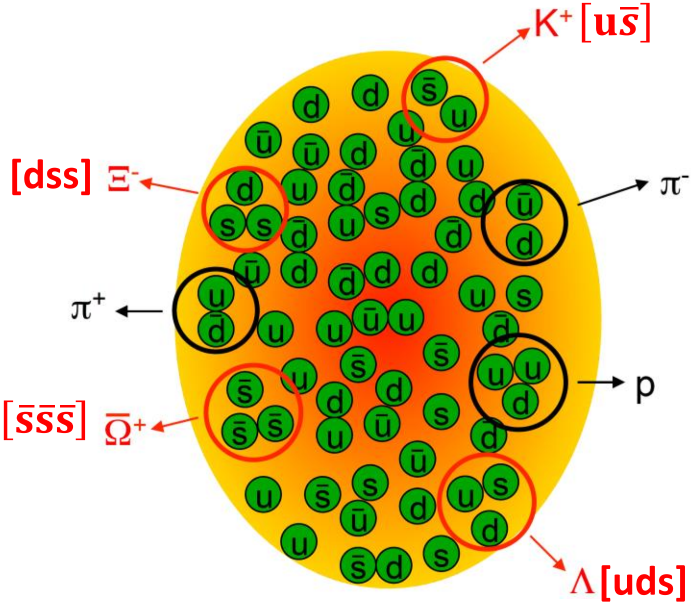
$\rightarrow$ copious production of $s\bar{s}$ pairs, mostly by gg fusion

[Rafelski: PR 88 (1982) 331]
[Rafelski-Müller: PRL 48 (1982) 1066]

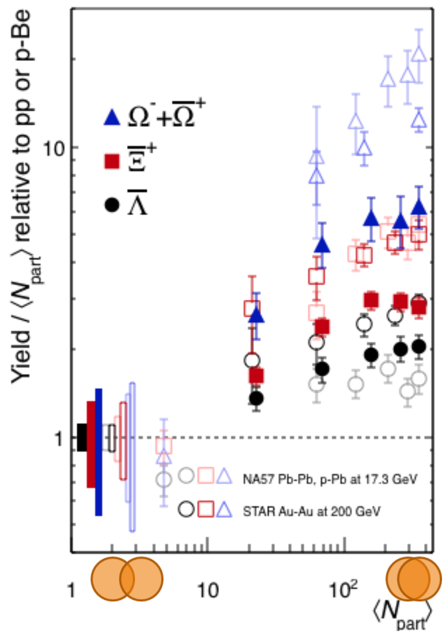
- Deconfinement $\rightarrow$ stronger effect for multi-strange baryons
  - can be built recombining s quarks

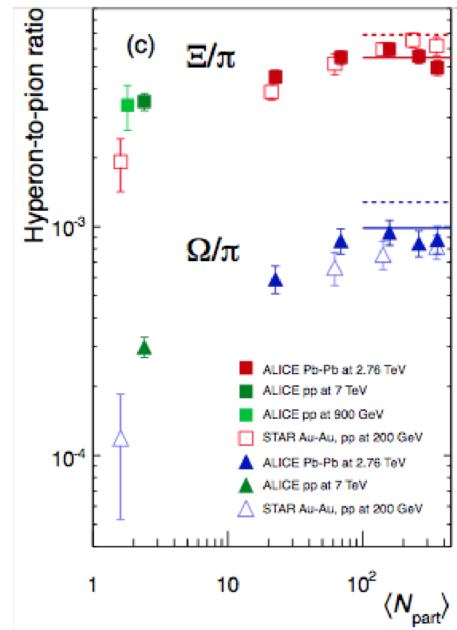
  $\rightarrow$ strangeness enhancement increasing with strangeness content

[Koch, Müller & Rafelski: PR 142 (1986) 167]



Strangeness: SPS, RHIC, LHC



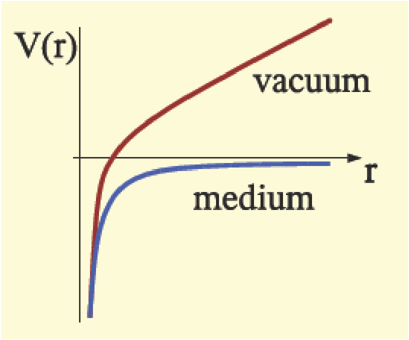


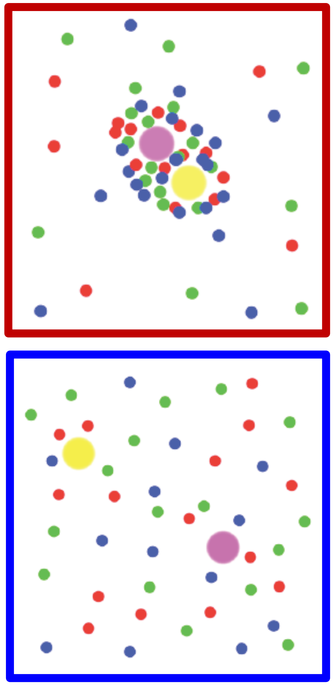
- Enhancement relative to pp also seen at RHIC and LHC
  - decreases with increasing √s: E(17 GeV) > E(200 GeV) > E(2.76 TeV)
  - strange/non-strange increases with √s in pp reference

→ Suggests hadron formation by parton recombination from a strangeness-rich system

Quarkonium suppression in the QGP

- QGP signature proposed by Matsui and Satz, 1986
- In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening):



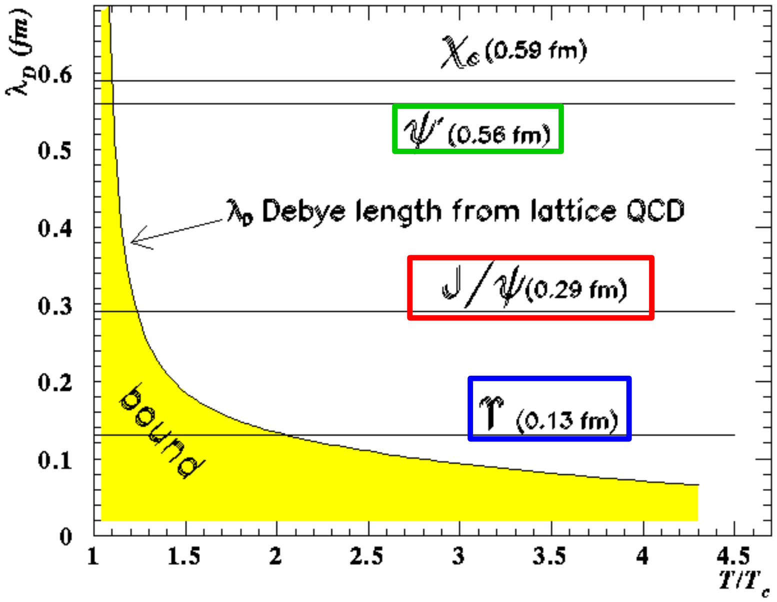


- Charmonium ($c\bar{c}$) and bottonium ($b\bar{b}$) states with r > λ_D will not bind; their production will be suppressed

Matsui, Satz, PLB178 (1986) 416

Quarkonium suppression in the QGP

- λ_D, and therefore which onium states will be suppressed, depends on the temperature:



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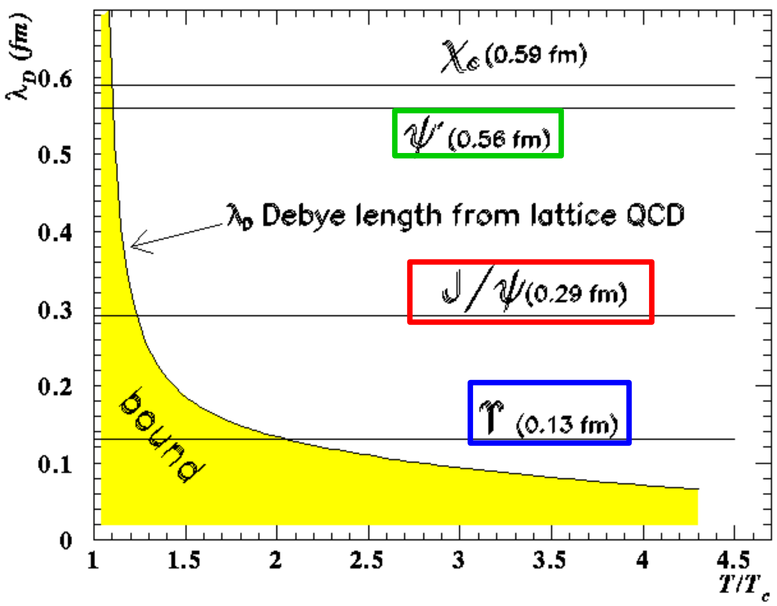

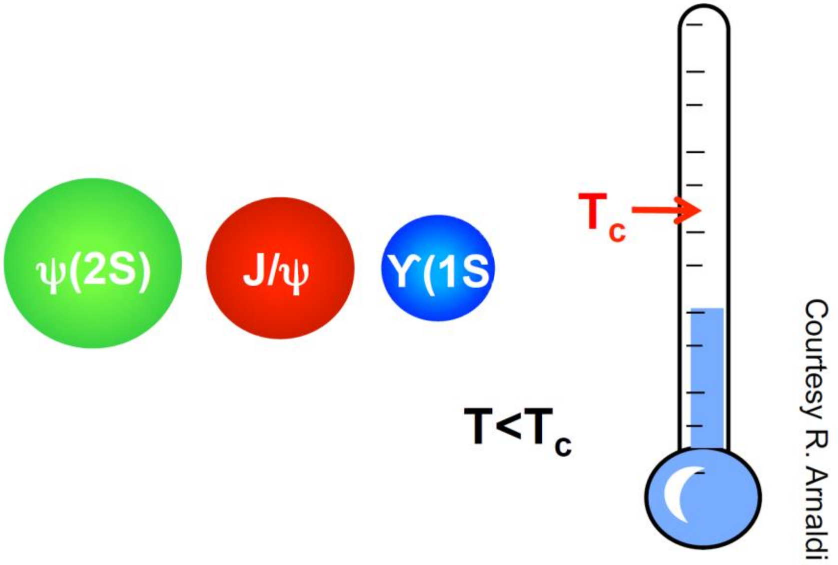

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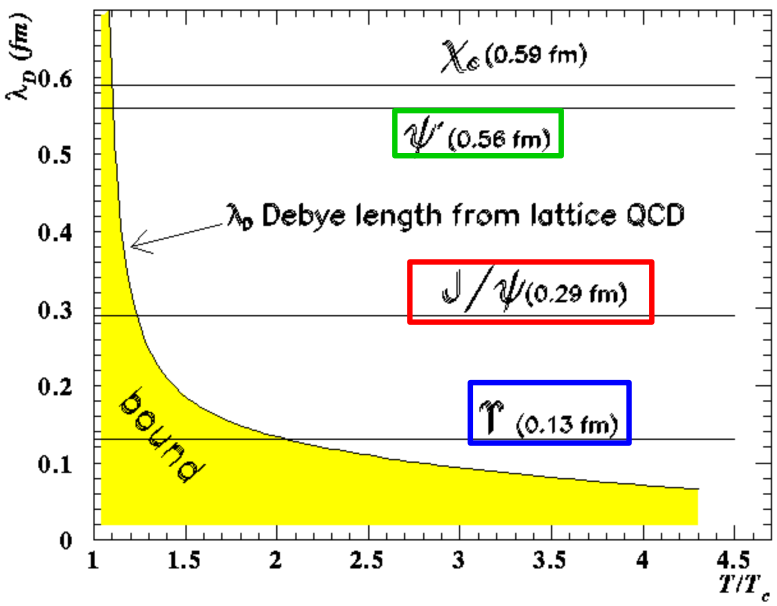

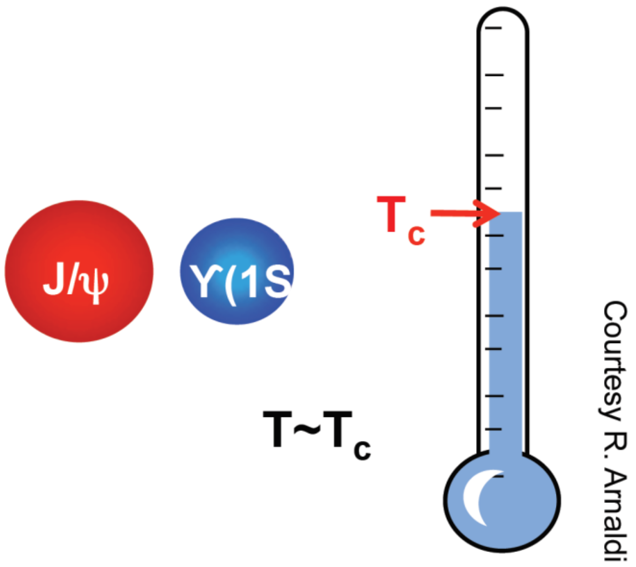

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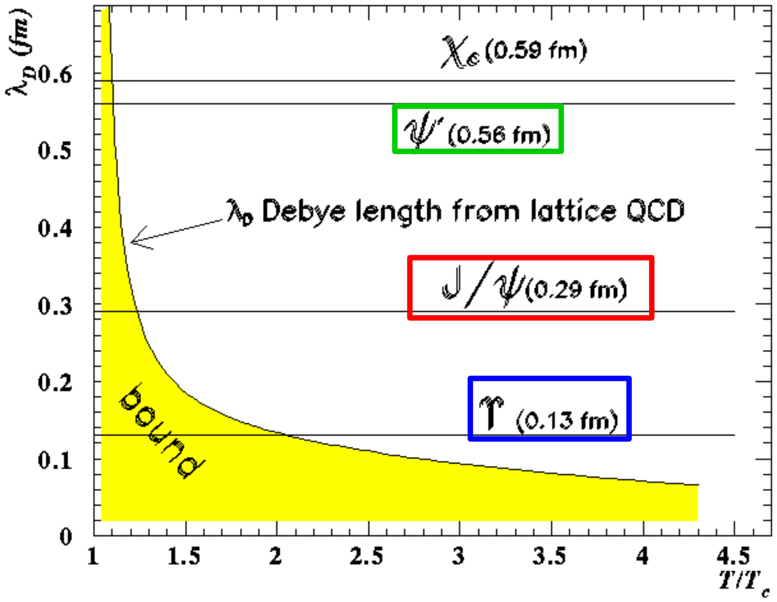

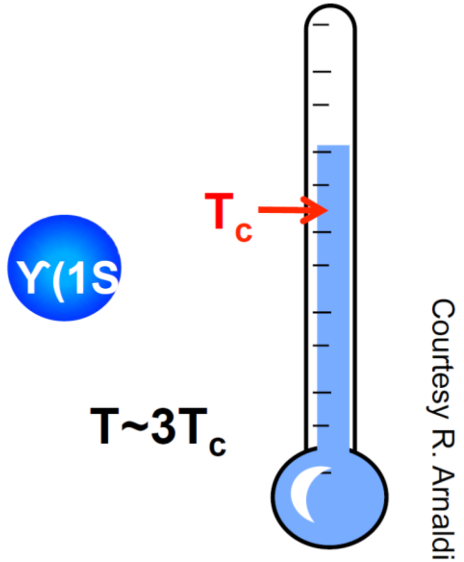

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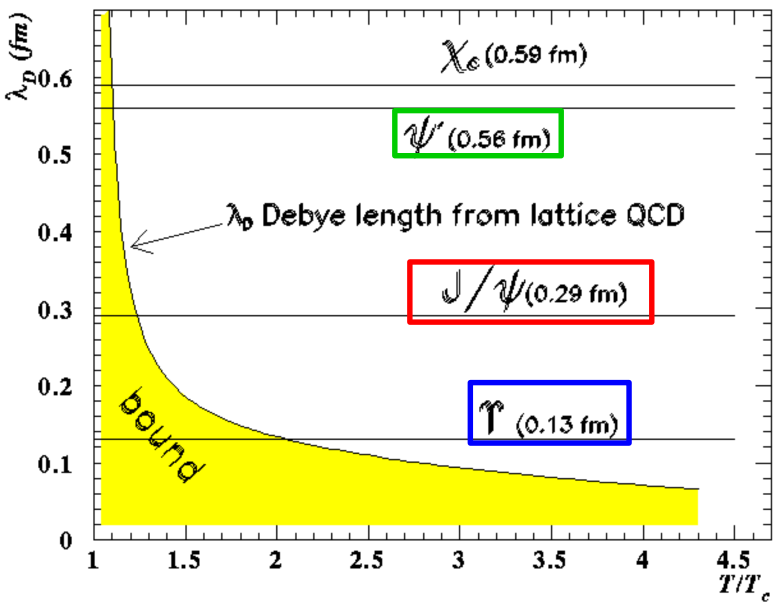
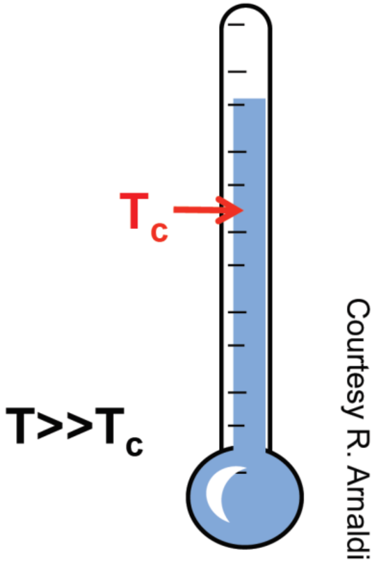
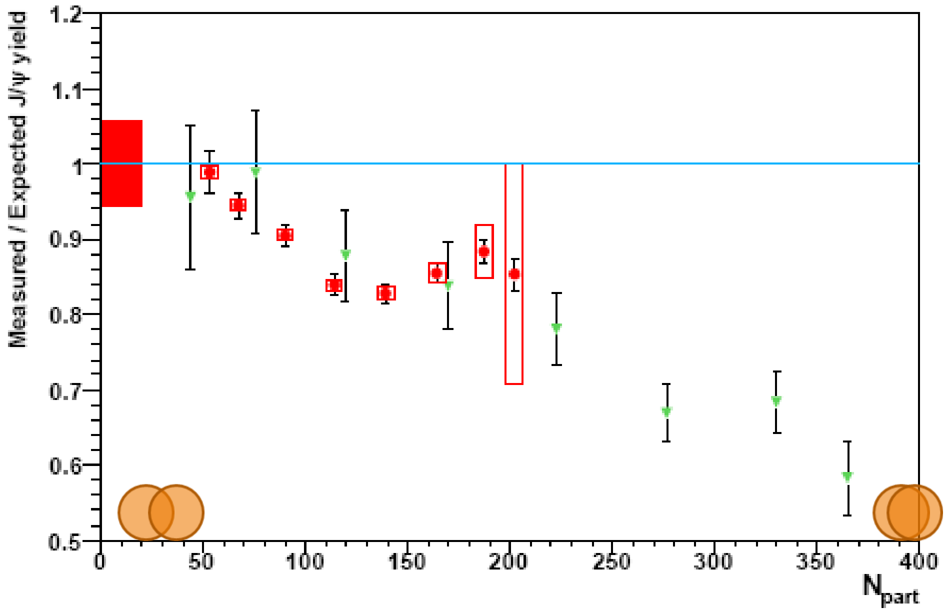




J/Ψ suppression pattern at the SPS

- Suppression observed by the NA50 and NA60 experiments in Pb-Pb at the SPS
- Measured/expected J/ψ yield vs. centrality drops below unity towards more central collisions



How do we measure Medium Effects?

Nuclear modification factor R_{AA}:

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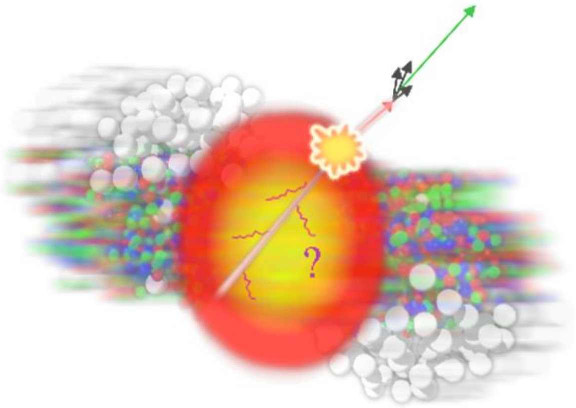
Nuclear modification factor R_{AA}:

$$R_{AA} = \frac{AA}{\text{rescaled } pp} = \frac{d^2N_{AA}/dp_T\, dy}{\langle N_{binary}\rangle\, d^2N_{pp}/dp_T\, dy}$$

The ratio of particles produced in **A-A** to **pp**, normalized to the number of *NN* collisions in **A-A**



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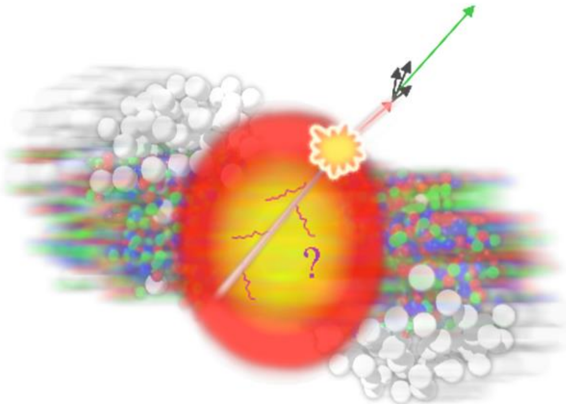


The ratio of particles produced in **A-A** to **pp**, normalized to the number of *NN* collisions in **A-A**

If the Yield scales with the number of binary collisions:

$\rightarrow R_{AA} = 1$

In the presence of Medium Effects:

$\rightarrow R_{AA} \neq 1$

Cold Nuclear Matter Effects (CNM):

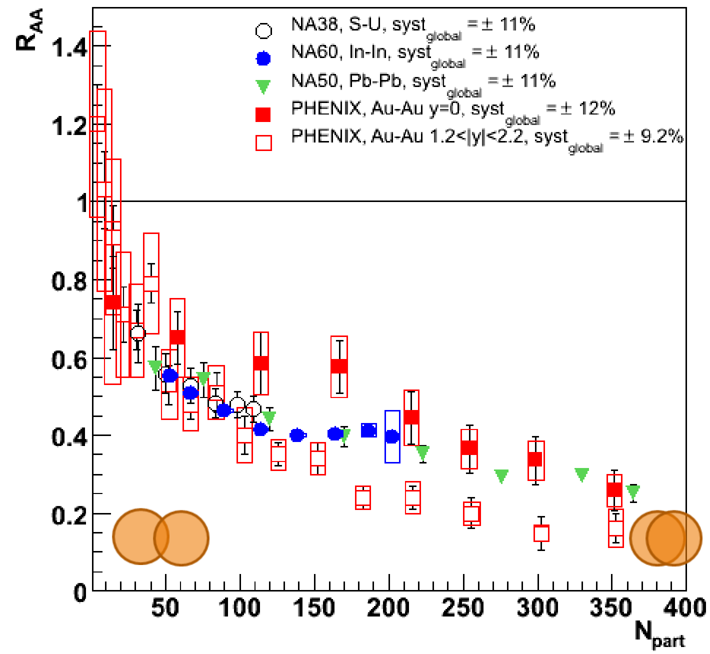
- Nuclear Parton Shadowing
- Parton Energy loss
- $c\bar{c}$ in Medium Break-up

Hot Medium Effects :

- Quarkonium Suppression
- Enhancement due to Recombination

The J/ψ puzzle at RHIC

- At RHIC (PHENIX):
  - same suppression as at the SPS (at the same rapidity)
  - more suppression at forward rapidity
- Why is it not larger at RHIC than at SPS?
  - The medium density increases at RHIC, thus expect more screening
- Why is it not larger at mid-y?
  - The medium density is larger at
  - mid-y, thus expect more screening



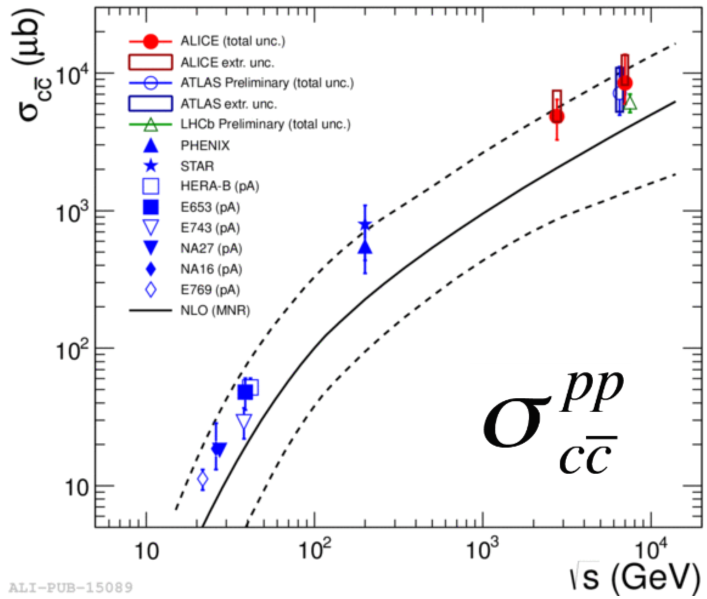
EPJC71(2011)1534

Charmonium regeneration?

- Uncorrelated c quarks from the medium could bind at system hadronization and form charmonium
- At RHIC and LHC, large number of pairs in central collisions:

$$N_{c\bar{c}} = \frac{\sigma_{c\bar{c}}^{pp}}{\sigma_{inel}^{pp}} \cdot N_{coll} \sim \frac{\sigma_{c\bar{c}}^{pp}}{65\text{ mb}} \cdot 1600$$

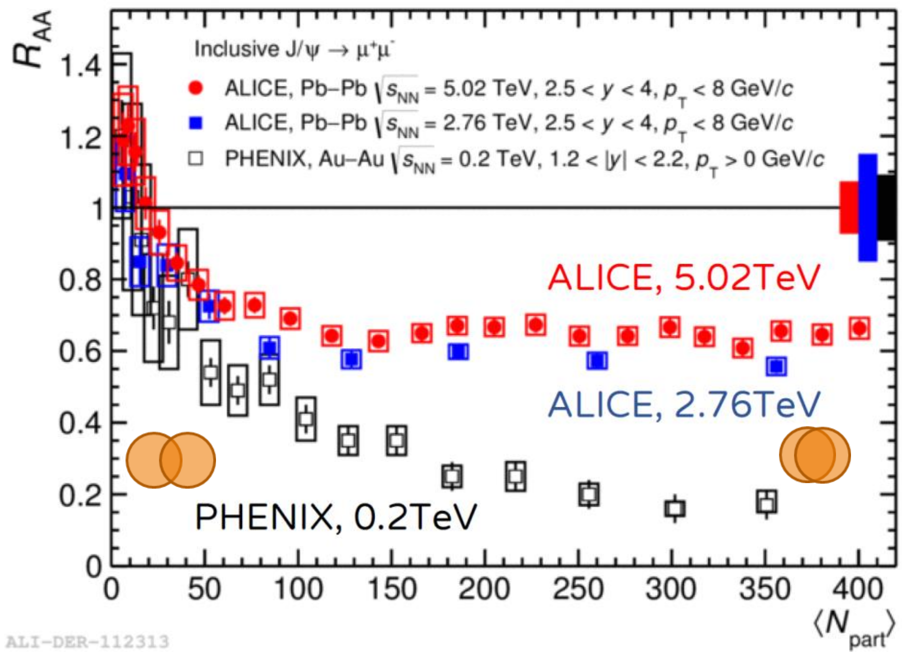
In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60



- Indications that low p_T c quarks may be thermalized (suppression and flow)

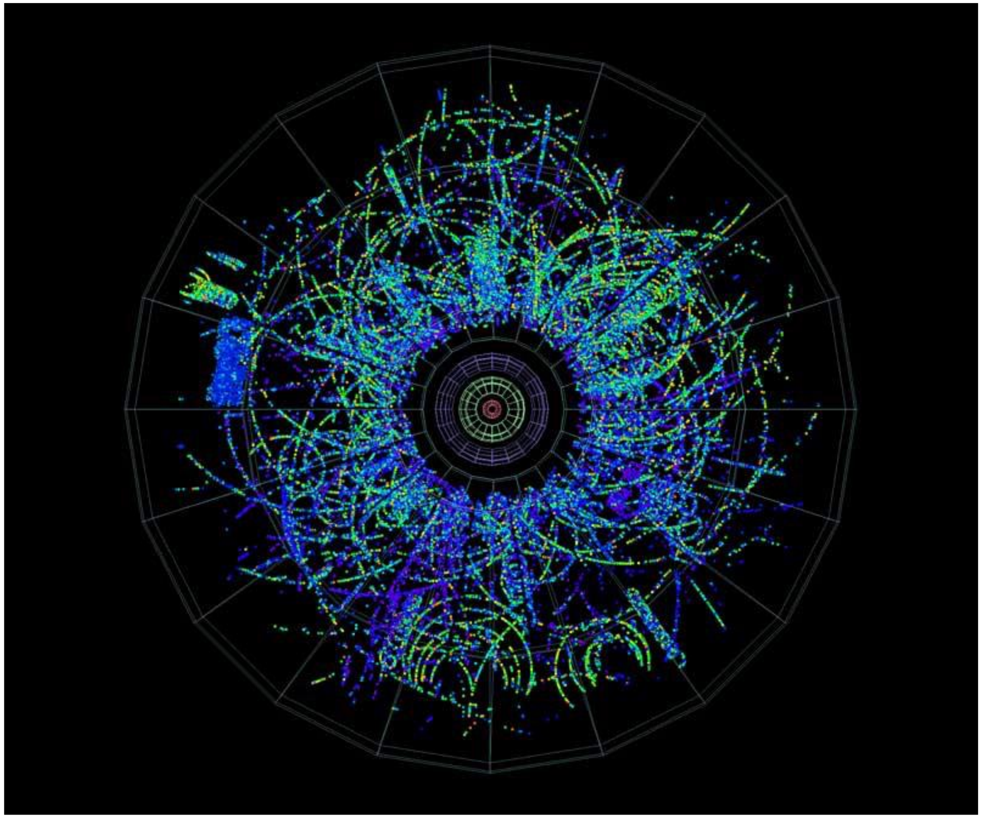
P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196
R. Thews et al, Phys.ReV.C63:054905(2001)

R_{AA} of J/ψ at LHC centrality dependence



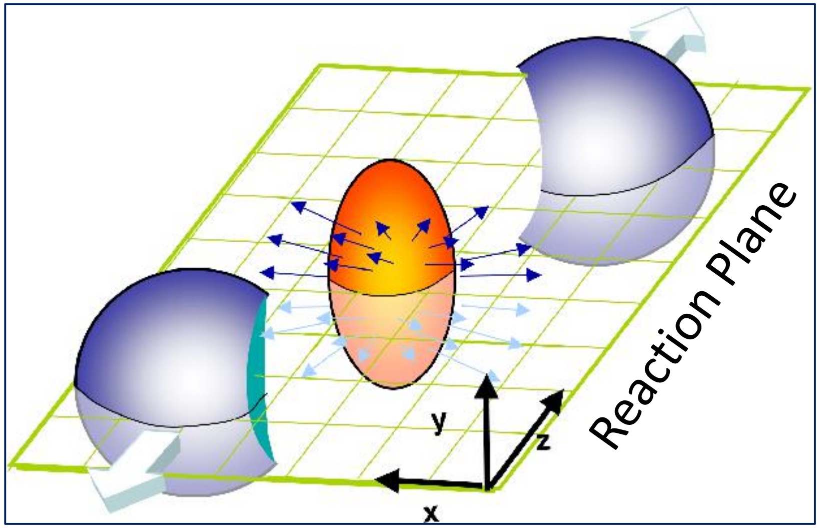
- Constant suppression for N_{par}t >50, at central and forward y
- Smaller than at RHIC in central collisions
- This was the predicted signature of regeneration
- J/Ψ R_{AA} at $\sqrt{s_{NN}}$= 5.02 TeV is systematically higher by ~15% than at $\sqrt{s_{NN}}$= 2.76 TeV

Particle correlations and flow



Anisotropic (Elliptic) Flow

- Non-central collisions are azimuthally asymmetric



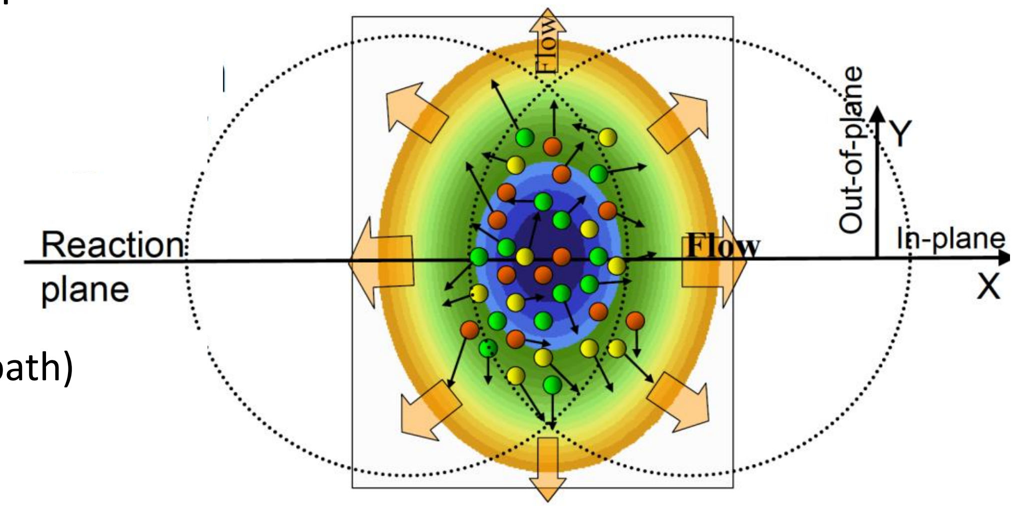
Anisotropic (Elliptic) Flow

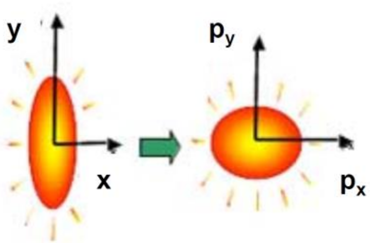
- Non-central collisions are azimuthally asymmetric

→ The transfer of this asymmetry to mom space provides a measure of the strength of collective phenomena

- Large mean free path
  - particles stream out isotropically, no memoryof the asymmetry
  - extreme: ideal gas (infinite mean free path)

- Small mean free path
  - larger density gradient → larger pressure gradient → larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)





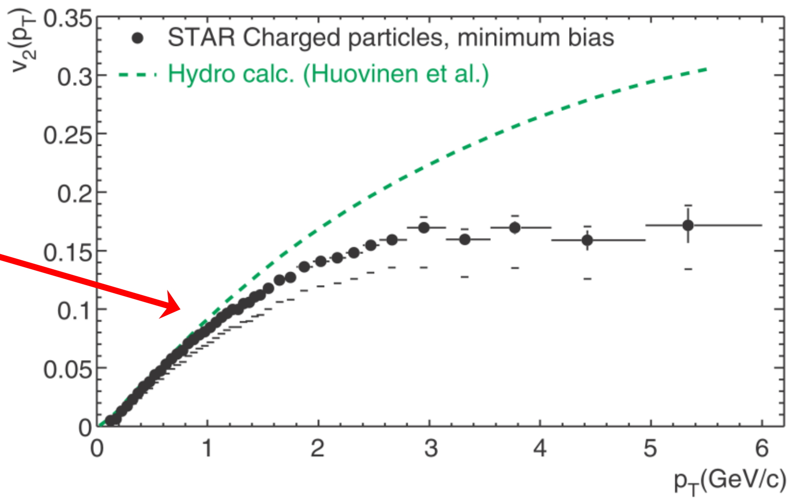
Azimuthal Anisotropy at RHIC

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right)$$

$$v_2 = \langle \cos 2\phi \rangle \quad \text{"elliptic flow"}$$

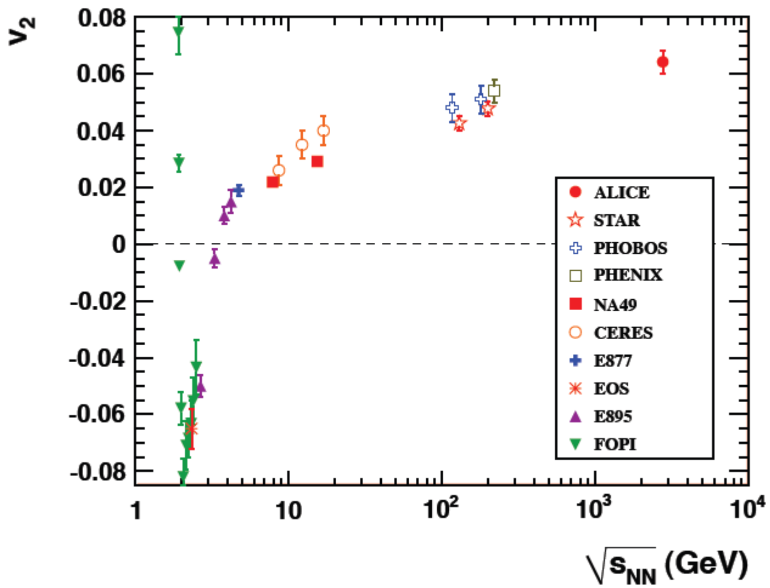
Measurement at RHIC:

- Elliptic flow almost as large as expected at hydro limit!
- Very far from "ideal gas" picture of the QGP
- Looks like a "liquid"
- Particles interact frequently
  → strongly-interacting QGP **(sQGP)**

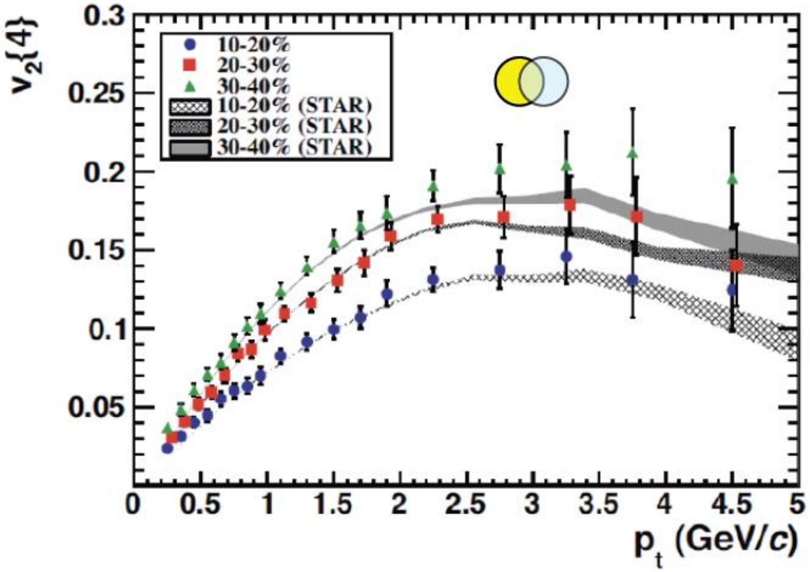


Elliptic flow v_2 at the LHC

- v_2 still large at the LHC



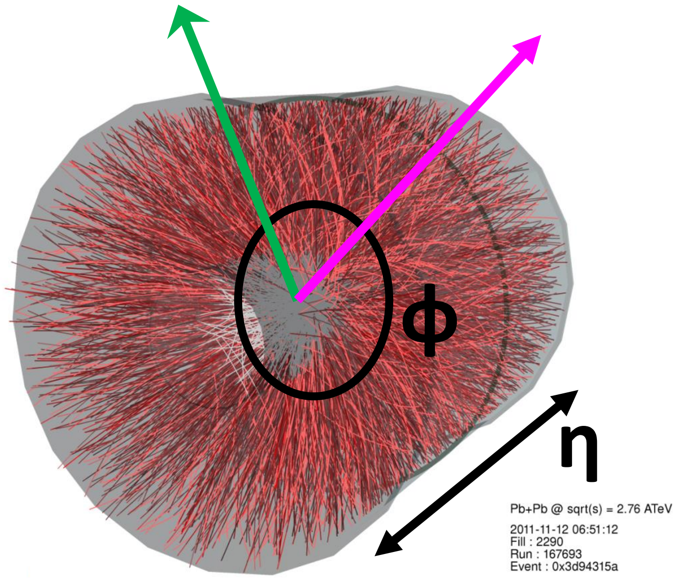
- Stronger flow at larger energy: consistent with Hydrodynamical calculations



- Data favor a constant shear viscosity to entropy density ratio of $\eta/s \sim 0.2$
  - Nearly perfect fluid: $1/4\pi < \eta/s < 3/4\pi$

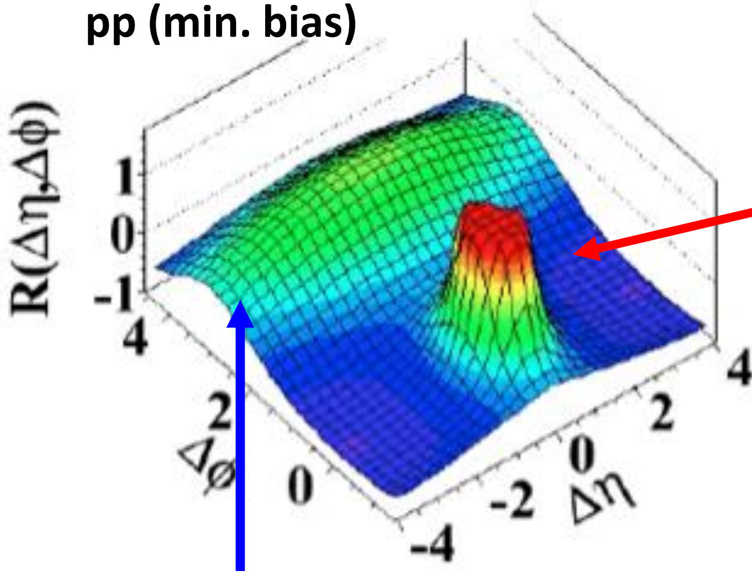
Two-particle correlations

- Widely used analysis technique for heavy ion collisions
- Test long-range correlations between particles that are created in the first stages of the collisions
- Consider a high-pT particle in the event ("trigger particle")
- Correlate all other particles ("associated particles") with it →Δϕ, Δη correlation distributions



Two-particle correlations: Structures in (Δϕ,Δη)

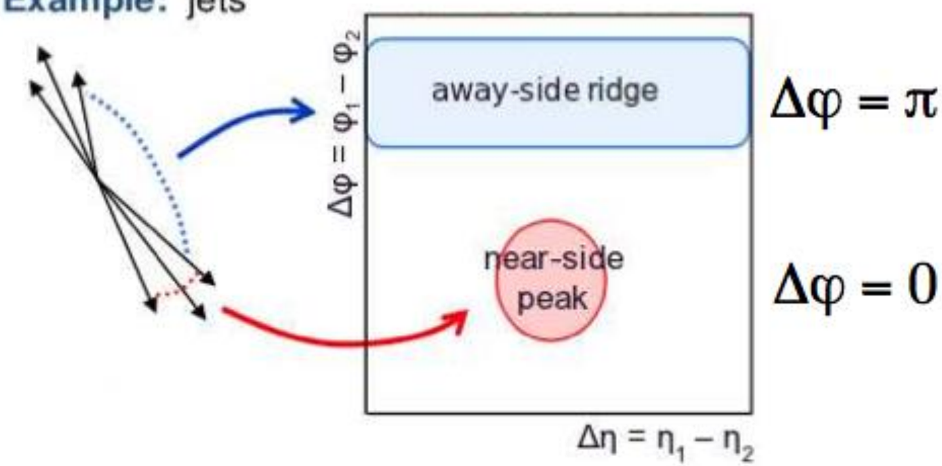
pp (min. bias)



near side jet peak

long range structure in η on away side, “away-side ridge”

CMS, JHEP1009 (2010) 091



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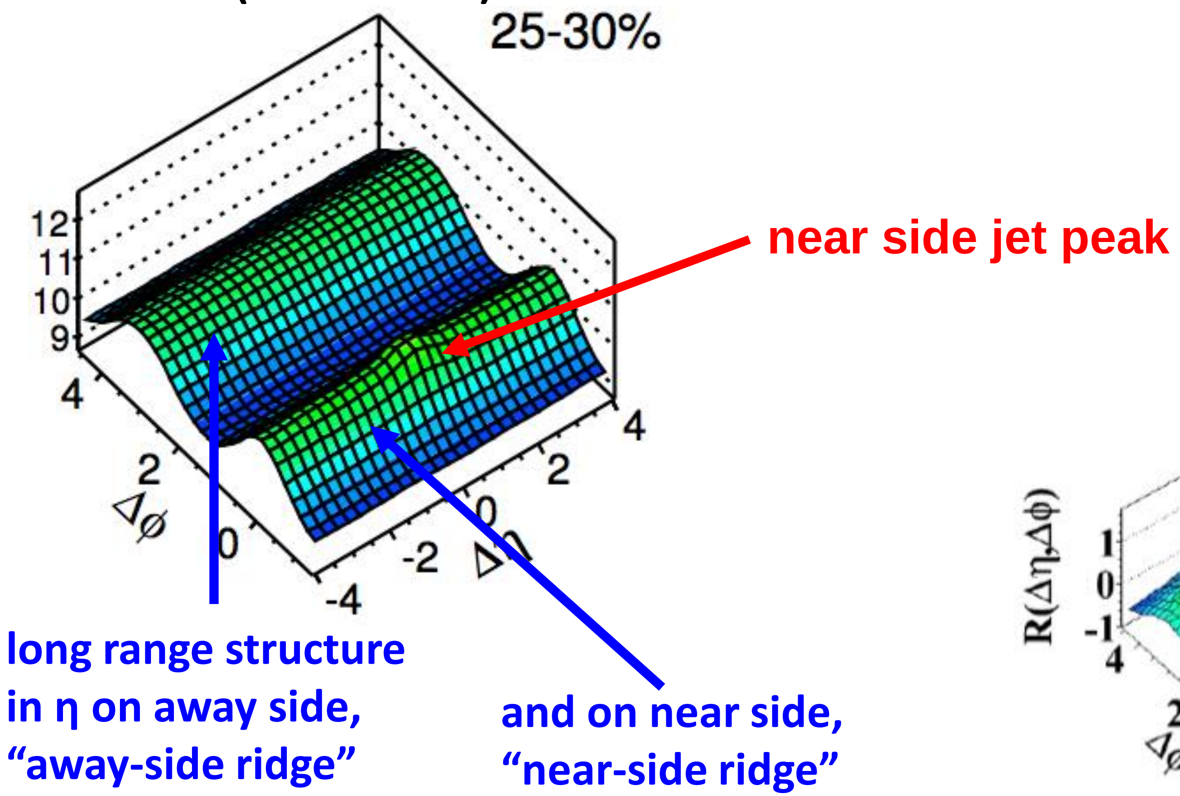
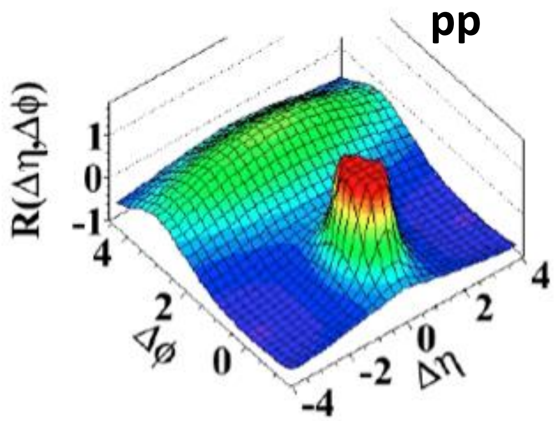
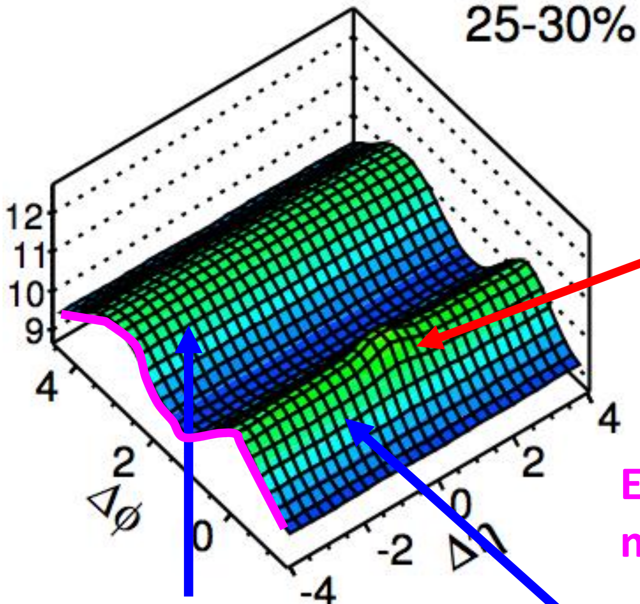


CMS, EPJC 72 (2012) 10052



Two-particle correlations: Structures in (Δϕ,Δη)

Pb-Pb (non-central)



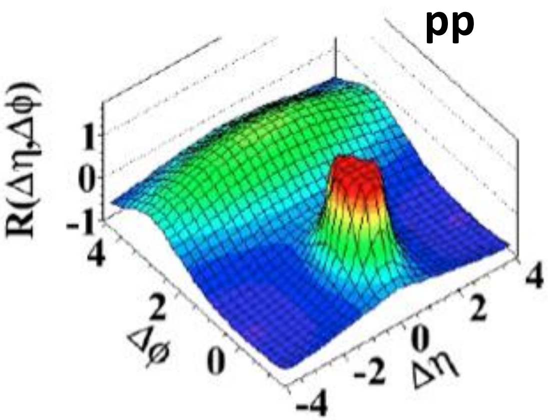
near side jet peak

Elliptic flow modulation

long range structure in η on away side, "away-side ridge"

and on near side, "near-side ridge"

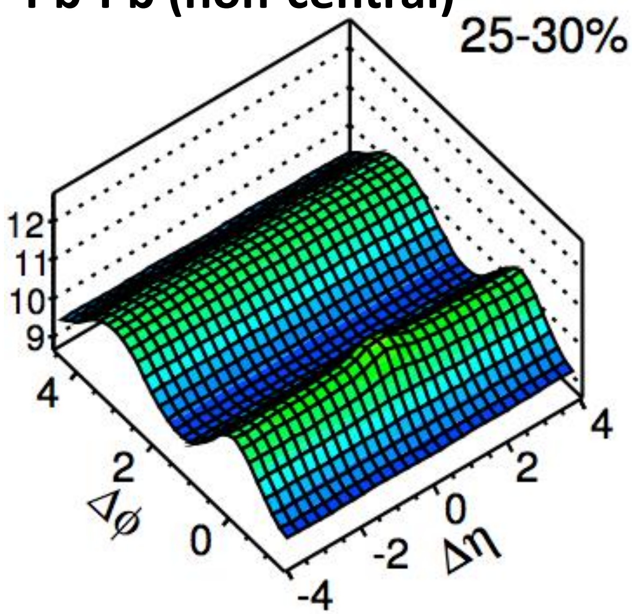
pp



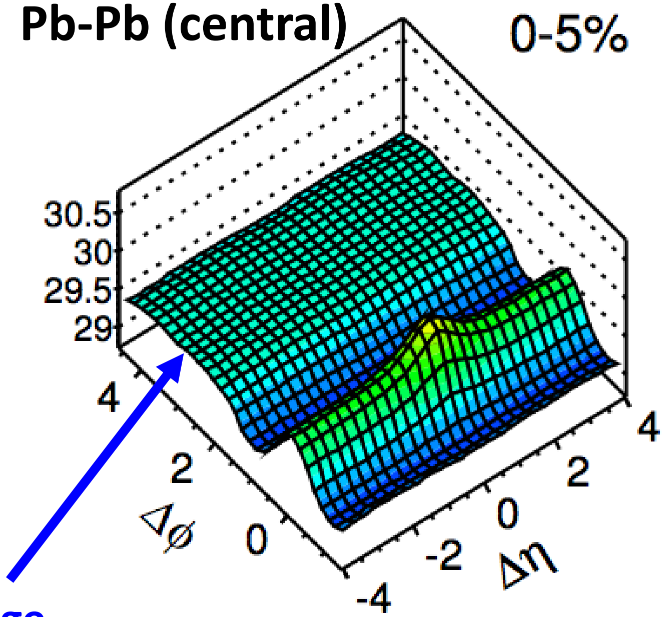
CMS, EPJC 72 (2012) 10052

Two-particle correlations: Structures in (Δϕ,Δη)

Pb-Pb (non-central)



Pb-Pb (central)

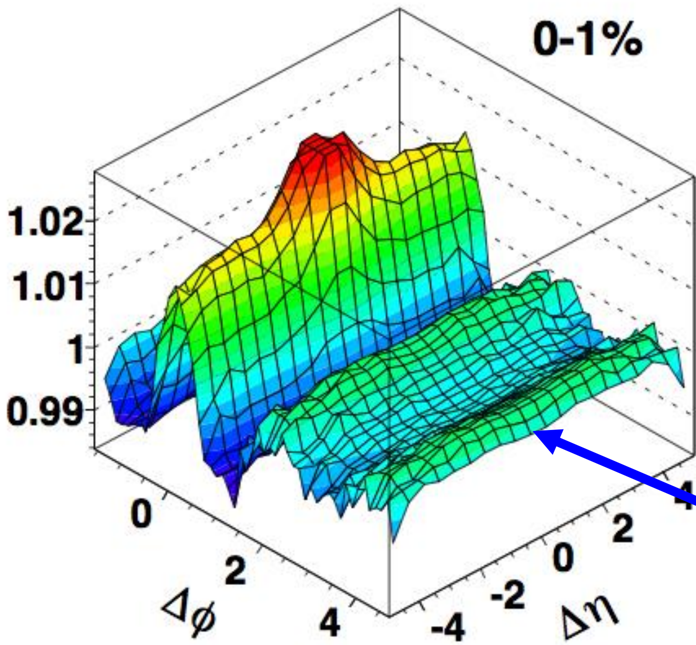


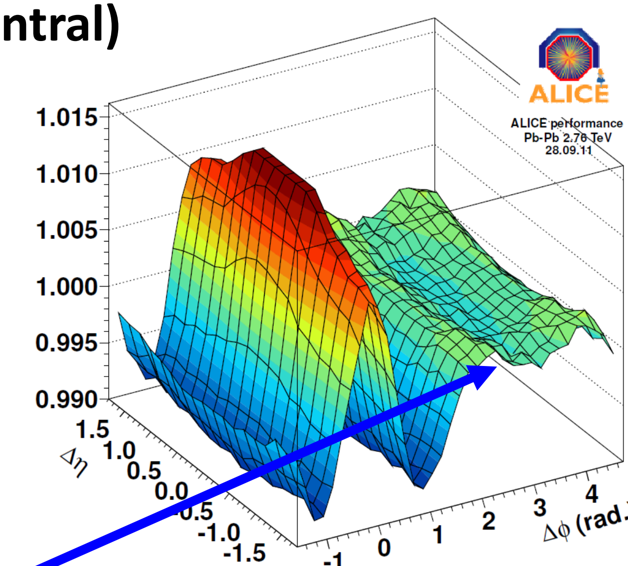
The away-side ridge becomes very broad, a dip in the middle appears

CMS, EPJC 72 (2012) 10052

Two-particle correlations: Structures in (Δφ,Δη)

Pb-Pb (ultra-central)





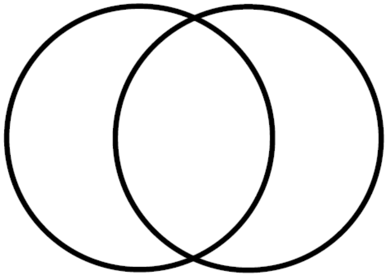
two shoulders
on away side
(at 120° and 240°)
aka "double hump"

ATLAS, PRC86 (2012) 014907

ALICE, PLB708 (2012) 249

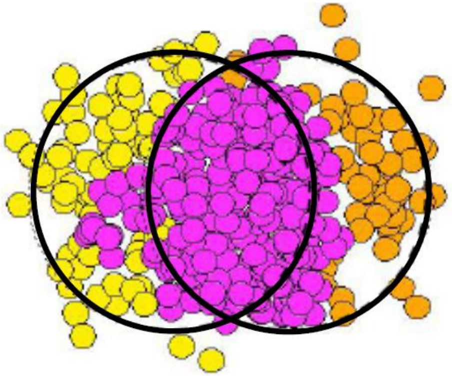
Higher harmonics

- "Ideal" shape of nuclear overlap is elliptic
  - no odd harmonics expected (v3, v5, …)



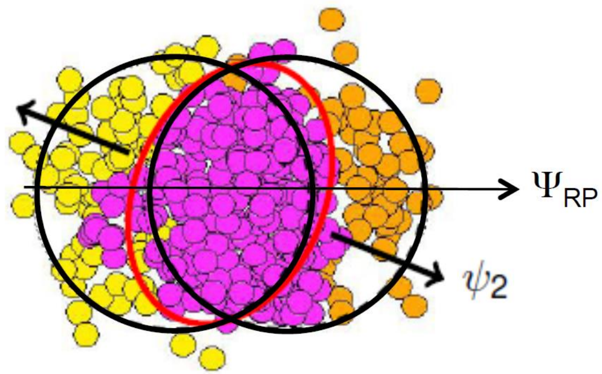
Higher harmonics

- "Ideal" shape of nuclear overlap is elliptic
  - no odd harmonics expected (v3, v5, …)
- but fluctuations in initial conditions:



Higher harmonics

- "Ideal" shape of nuclear overlap is elliptic
  - no odd harmonics expected (v3, v5, …)
- but fluctuations in initial conditions:
  - participants plane $\psi_2 \neq$ reaction plane Ψ_{RP}



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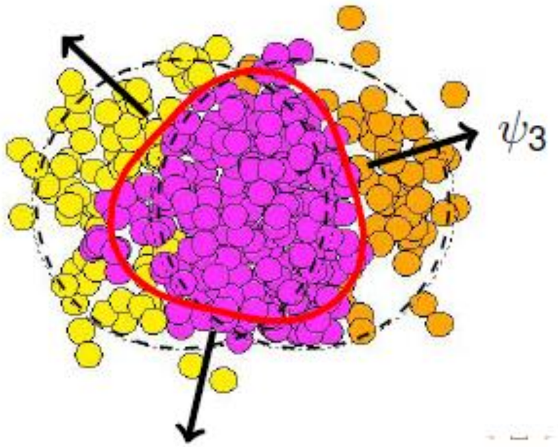
[B Alver & G Roland, PRC81 (2010) 054905]



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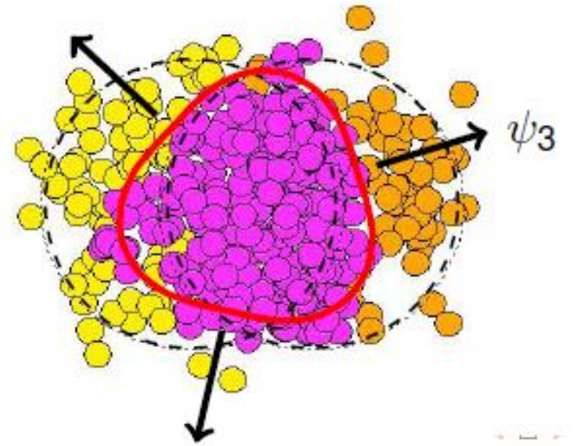
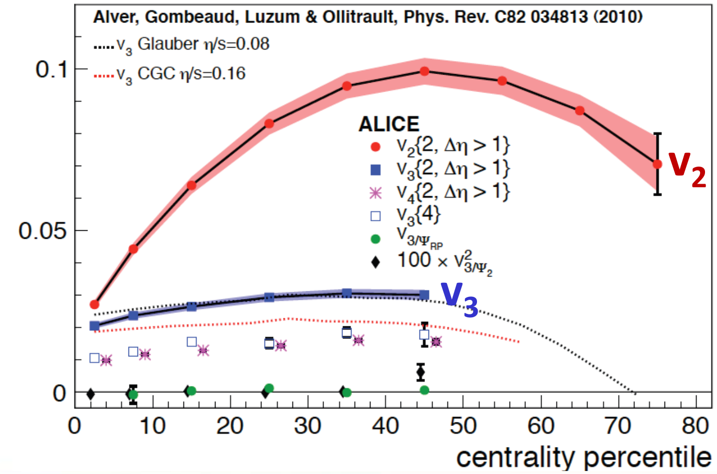
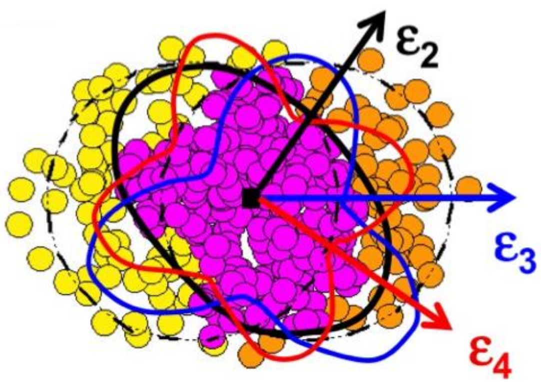
  [B Alver & G Roland, PRC81 (2010) 054905]
- and indeed, **v3 > 0** !
- **v3** has weaker centrality dependence than **v2**
- when calculated wrt participants plane, **v3** vanishes
  - as expected, if due to fluctuations…

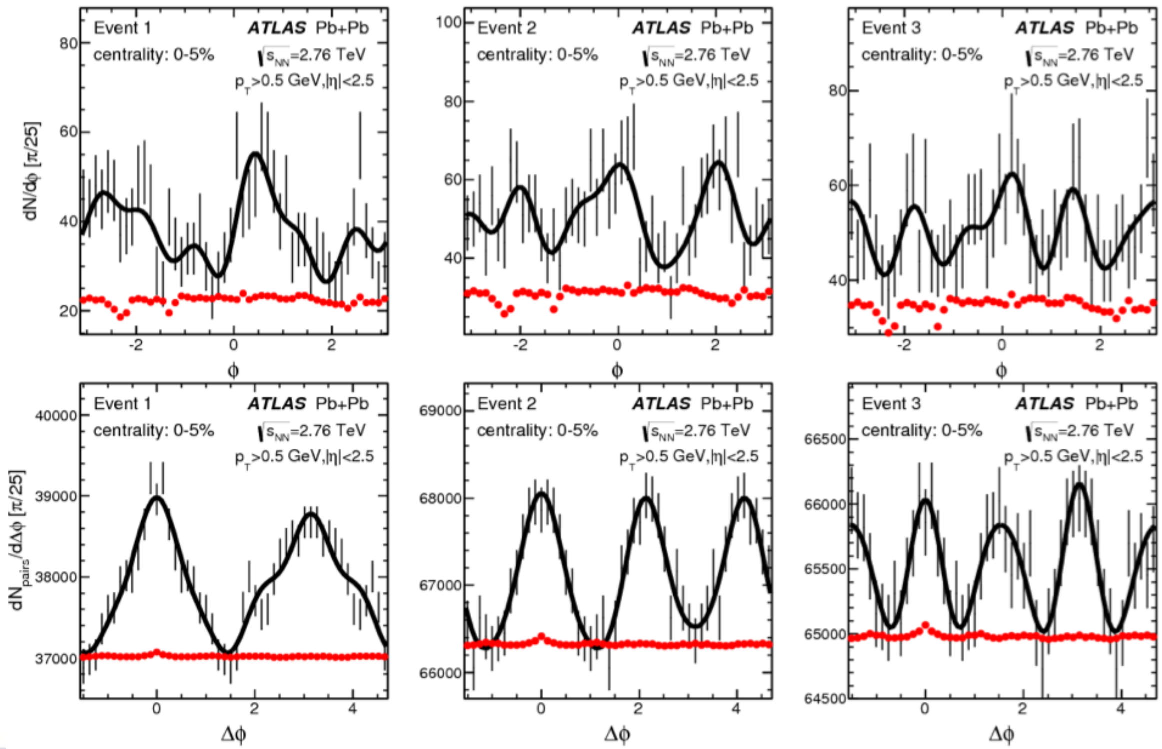




Event-by-event shapes

- And not only v3 (triangular events), also v4, v5, …
- At LHC, multiplicity large enough to “see” event-by-event shapes

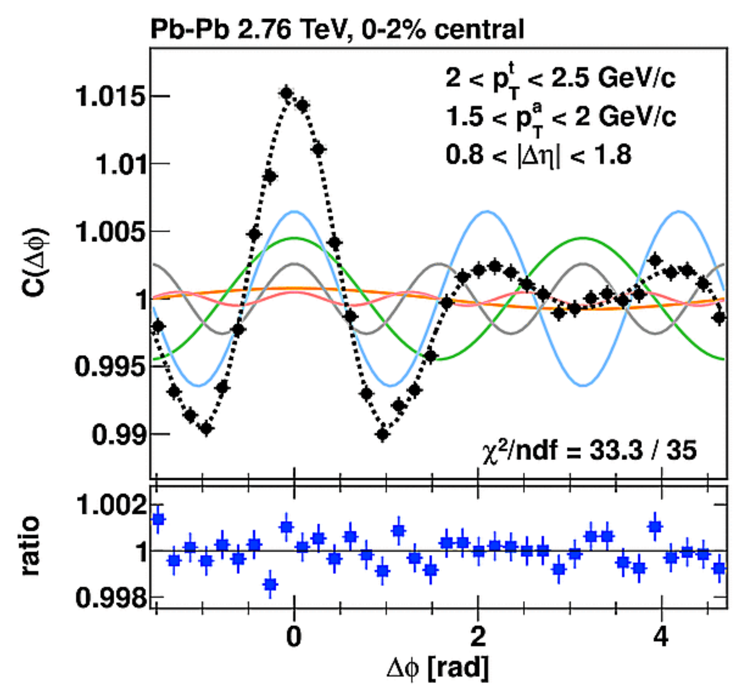




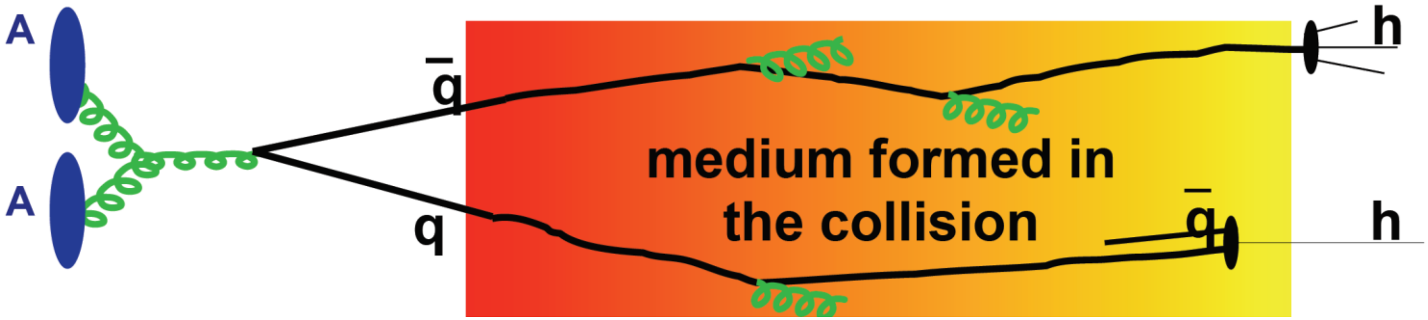
Harmonic decomposition of correlation distribution

- Double hump structure on away-side appears on 1% most central
- First five harmonics describe shape at 10^{-3} level
- Fourier analysis of new data suggests very natural alternative explanation in terms of hydrodynamic response to initial state fluctuations

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T dy}\left(1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right)$$

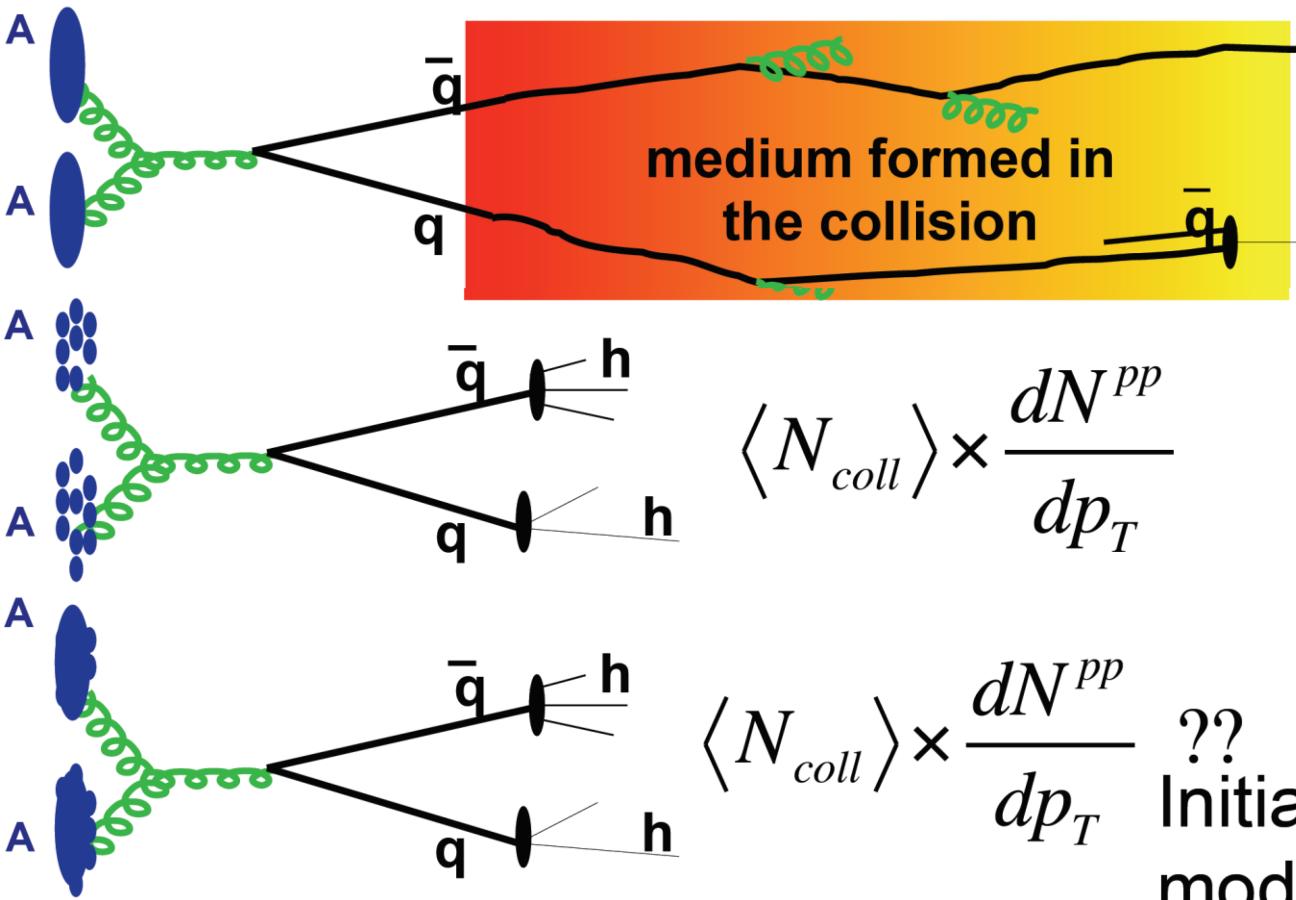


Final-state and initial-state effects



$$\frac{dN^{AA}}{dp_T}$$

Final-state and initial-state effects



$$\frac{dN^{AA}}{dp_T}$$

$$\langle N_{coll} \rangle \times \frac{dN^{pp}}{dp_T}$$

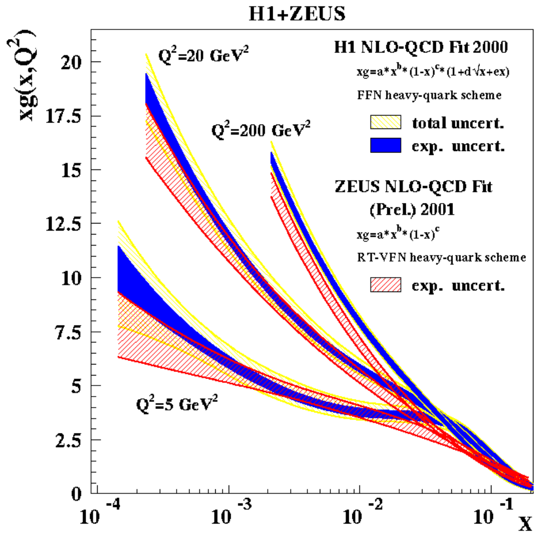
$$\langle N_{coll} \rangle \times \frac{dN^{pp}}{dp_T} \quad ??$$

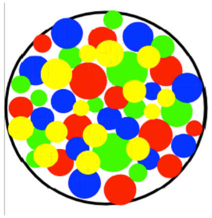
Initial-state modification??

Initial-state saturation / shadowing

Gluon Saturation at small $x_{Bjorken}$

- Initial state: high-*p* nucleus = set of gluons with p^g distribution according to PDF g(*x*Bjorken,Q^2), with $x=p^g/pN$ and Q^2 the scale of the process (~ 1/"area" of the gluon)
- HERA DIS (ep) data: strong rise of $xg(x,Q^2)$ at low-*x* & low-Q^2
- New (unknown) regime of QCD: when gluons are numerous enough (low-*x*) & extended enough (low-Q^2) to overlap → ***Saturation***





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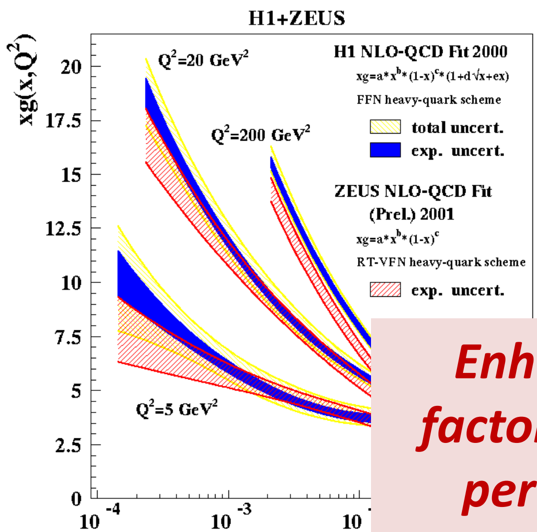
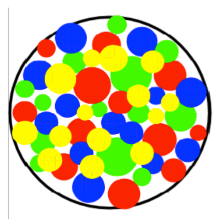
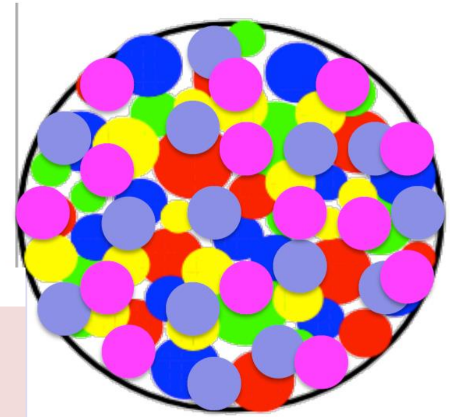


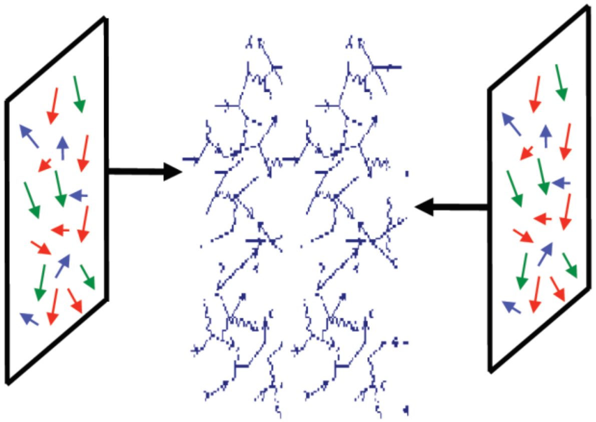




Enhanced in the nucleus: factor $A^{1/3}$ (≈6) more gluons per unit transverse area

Color Glass Condensate?

- Color Glass Condensate:

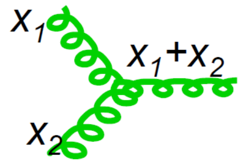


"Color" from the gluon color charge. "Glass" is borrowed from the term for silica and other materials that are disordered and act like solids on short time scales but liquids on long time scales. In the "gluon walls," the gluons themselves are disordered and do not change their positions rapidly because of Lorentz time dilation. "Condensate" means that the gluons have a very high density.

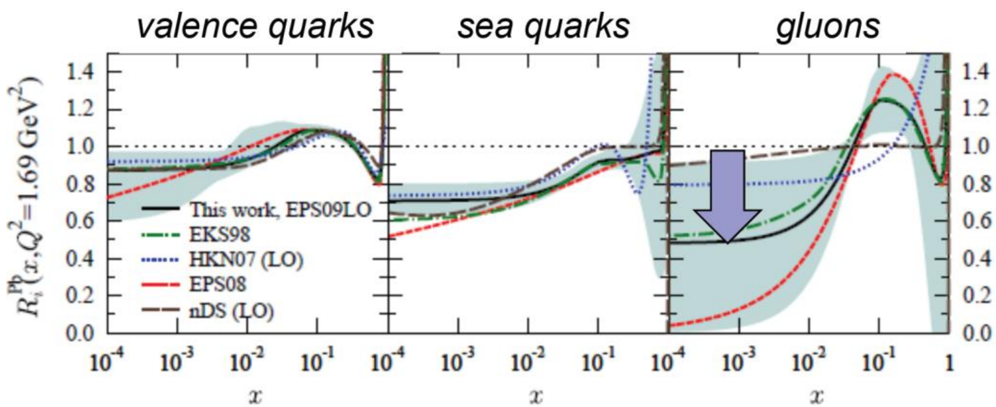
McLerran,Venugopalan PRD49 (1994) 2233

Shadowing Parametrizations

Effective reduction of the parton flux (shadowing)
→ also described with nuclear-modified PDFs



- Shadowing ≈ low-x gluon "fusion": $g_{x1} + g_{x2} \rightarrow g_{x1+x2}$
- Shadowing factor for PDFs: $xG_A(x,Q^2) = A\, x_g(x,Q^2)\, R_G^A(x,Q^2)$



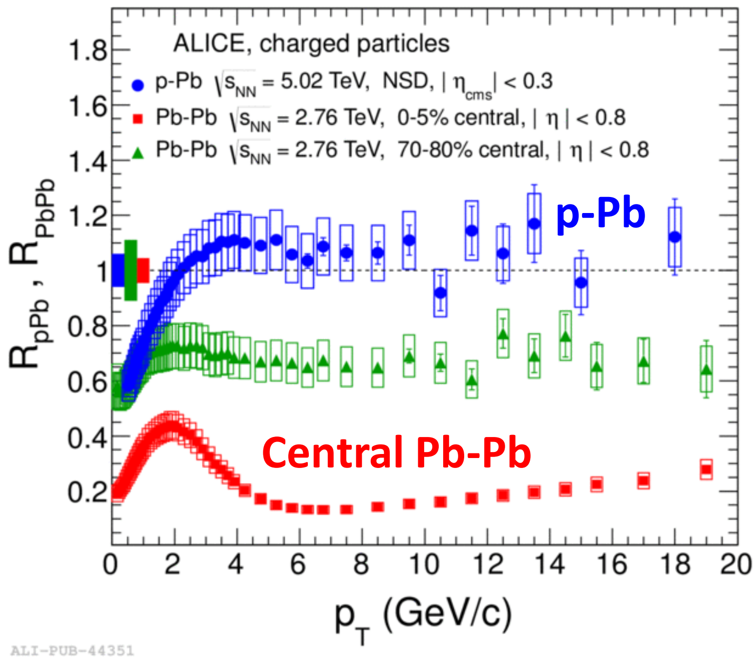
- Most of the low-*x* data are in non-pert. range → limited applicability of pQCD analysis → large uncertainties on R_G^A

see e.g. Eskola et al. JHEP0904(2009)065

Control "experiments": proton-nucleus and medium-blind probes

Nuclear modification factor in proton-nucleus (LHC)

$$R_{AA} = \frac{AA}{\text{rescaled } pp} = \frac{d^2N_{AA}/dp_T\,dy}{\langle N_{binary}\rangle\, d^2N_{pp}/dp_T\,dy}$$

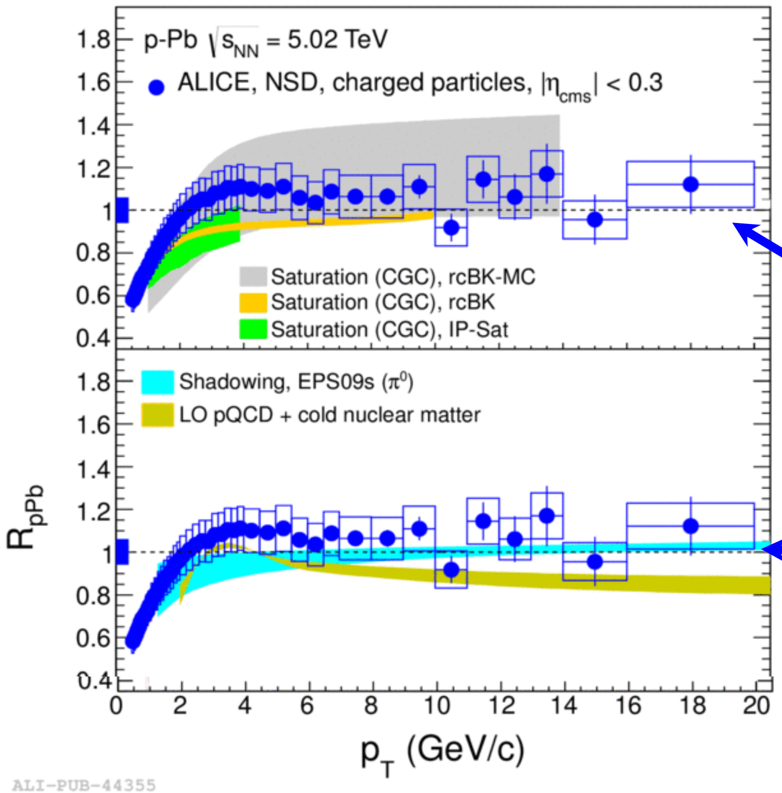


no high-p_T suppression in proton-nucleus

→ *In nucleus-nucleus it must be a final-state effect*

ALICE, PRL110 (2013) 082302

Nuclear modification factor in proton-nucleus (LHC)

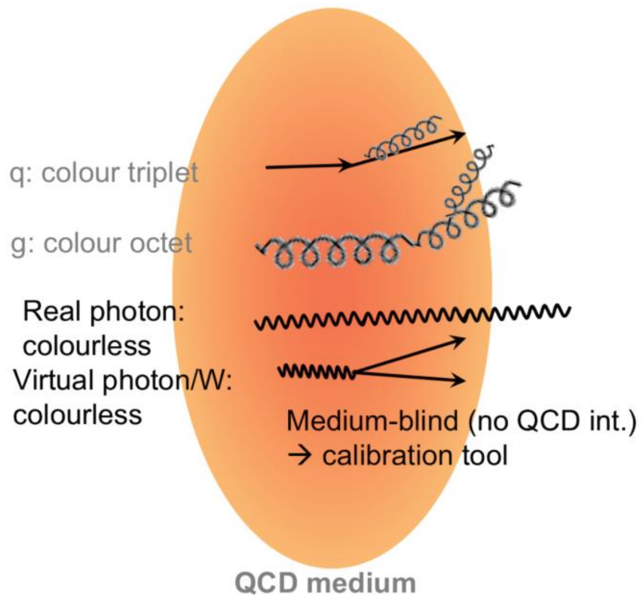


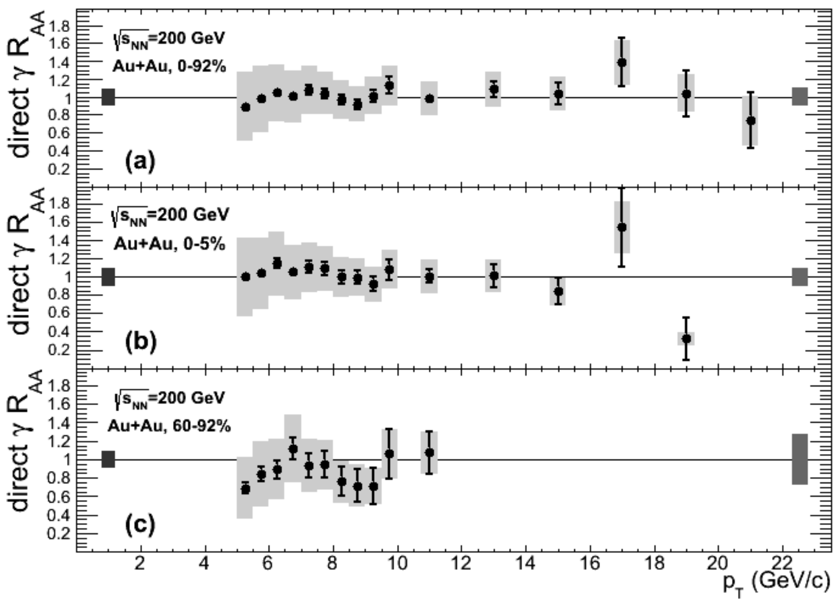
ALICE, PRL110 (2013) 082302

- Good description by calculations including the implementation of a reduction of the effective low-*x* gluon flux, via:
  - Saturation (Color Glass Condensate)
  - Shadowing of gluon densities + standard perturbative QCD

Medium-blind probes

- Photons and electro-weak bosons (W, Z, in their leptonic decay channels) should not “see” the strongly-interacting medium
- Verified with photons at RHIC



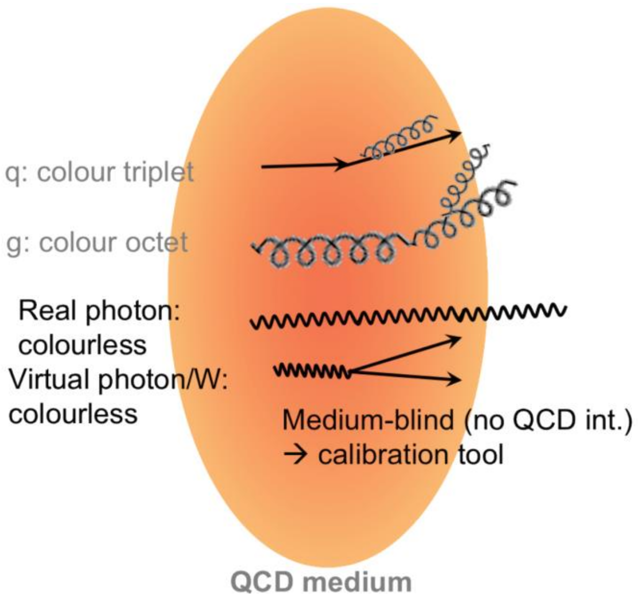


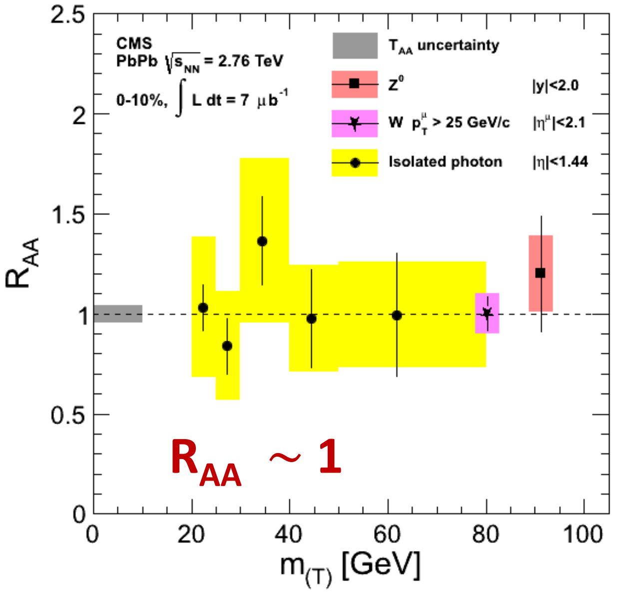
$R_{AA} \sim 1$

PHENIX, PRL109, 152302 (2012)

Medium-blind probes

- Photons and electro-weak bosons (W, Z, in their leptonic decay channels) should not "see" the strongly-interacting medium
- Verified with photons at RHIC; W, Z become available at LHC





CMS, PLB710 (2012) 256, PRL106 (2011) 212301, PLB715 (2012) 66

Physics, especially Experimental Physics,
is tough at times
but most rewarding!!

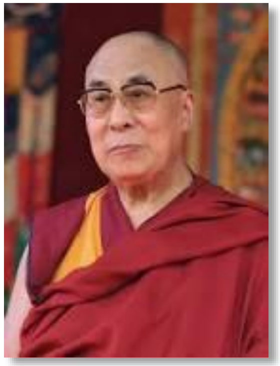
…one learns to hunt as a pack/pride…

“Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand.”

Albert Einstein

“A biased mind can not grasp reality.”

Dalai Lama



Bibliography

Material for this lecture was taken from:

Andrea Dainese at: Eighth joint CERN-Fermilab Hadron Collider Physics Summer School 2013

https://indico.cern.ch/event/226365/contributions/1533465/

How do we measure the Centrality?

Centrality: The energy deposited during the collision is proportional to the number of nucleons participating in the collision.