La matière formée dans les collisions hadroniques (gaz hadronique, QGP)

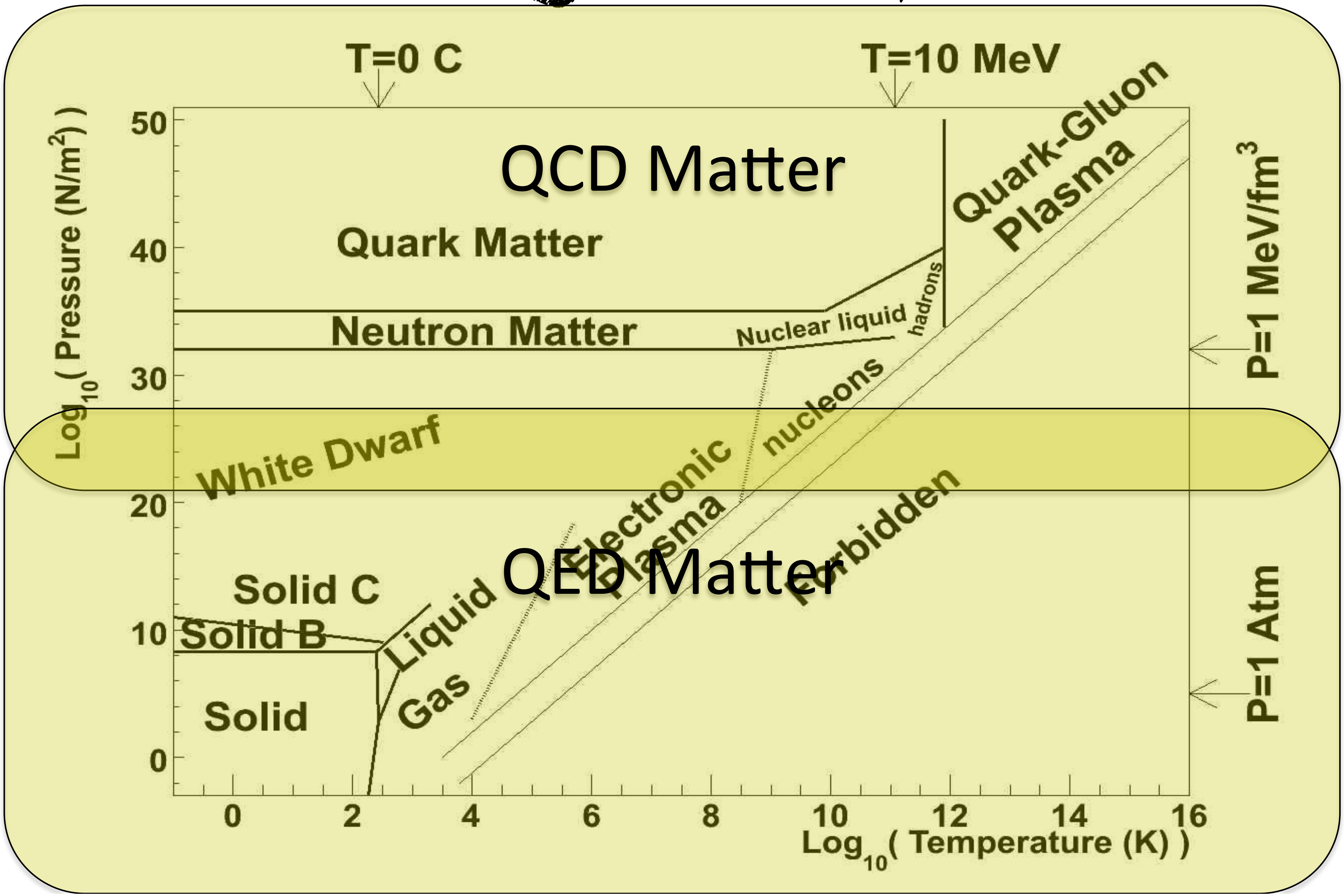
Ginés MARTINEZ

Subatech

CNRS IN2P3 Les deux infinis

Journées SFP/BTPN, 21 et 22 juin 2016, Paris, France

Phase Diagram of Matter



Physics Goals

Cabibbo & Parisi PLB 59 67 (1975)

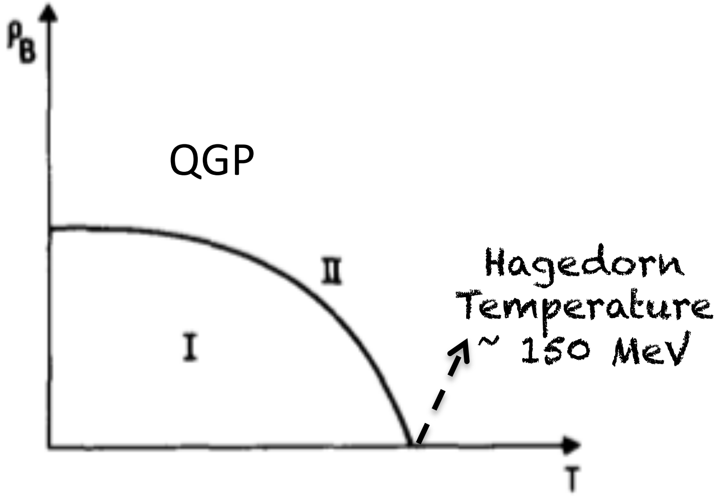
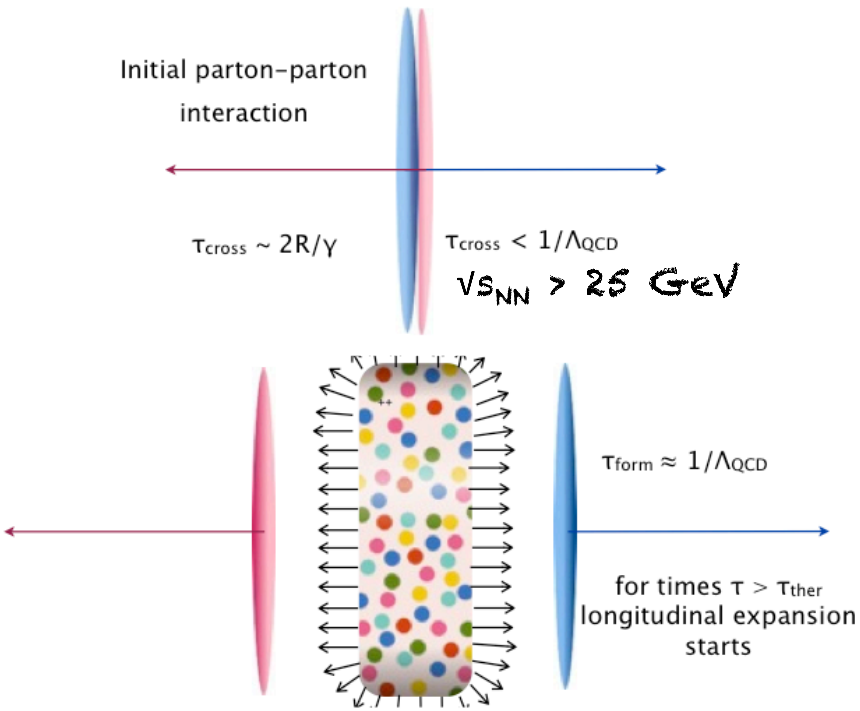


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is th density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Also Collins & Perry PRL 34 61353 (1975)

Bjorken PRD27 140 (1983)



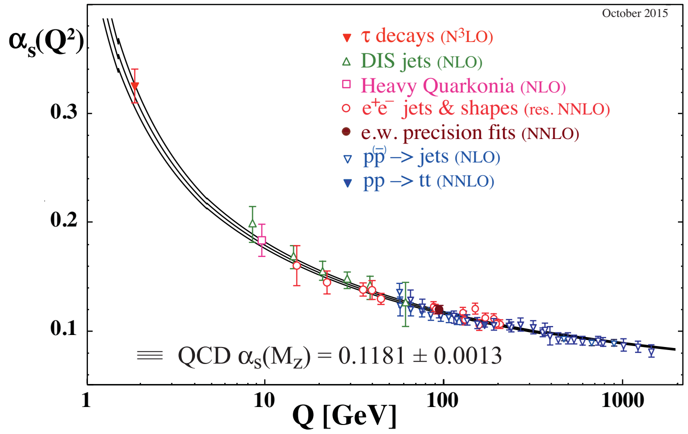
Studying properties of the strongly interacting matter at high temperature (and pressure)

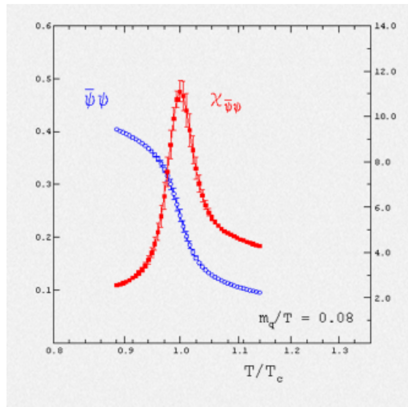
Heavy ion collisions allow us to create this matter in the laboratory

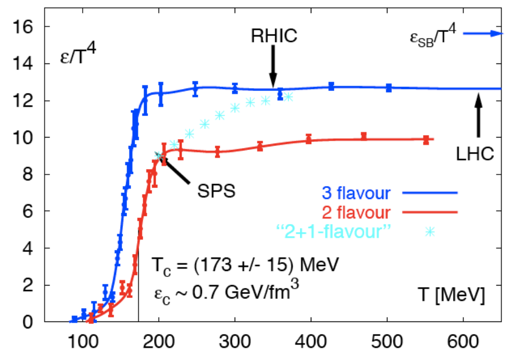
QCD (a quick manual)

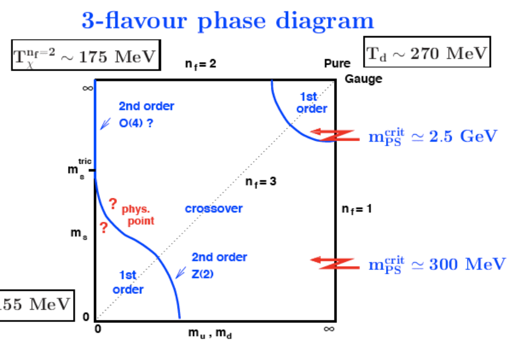
- Quarks (q, Q) and gluons (g)
- q,Q are coloured
- g are coloured
- Strong coupling
- Confinement
- Asymptotic freedom
- Spontaneous Chiral symmetry breaking at scales < Λ_{QCD}
- Light-q, ($m<\Lambda_{QCD}$) spontaneous breaking Chiral symmetry dominates: u, d, s
- Heavy-Q ($m>\Lambda_{QCD}$) explicit chiral symmetry breaking dominates.
- Phase transition $T \sim \Lambda_{QCD}$

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

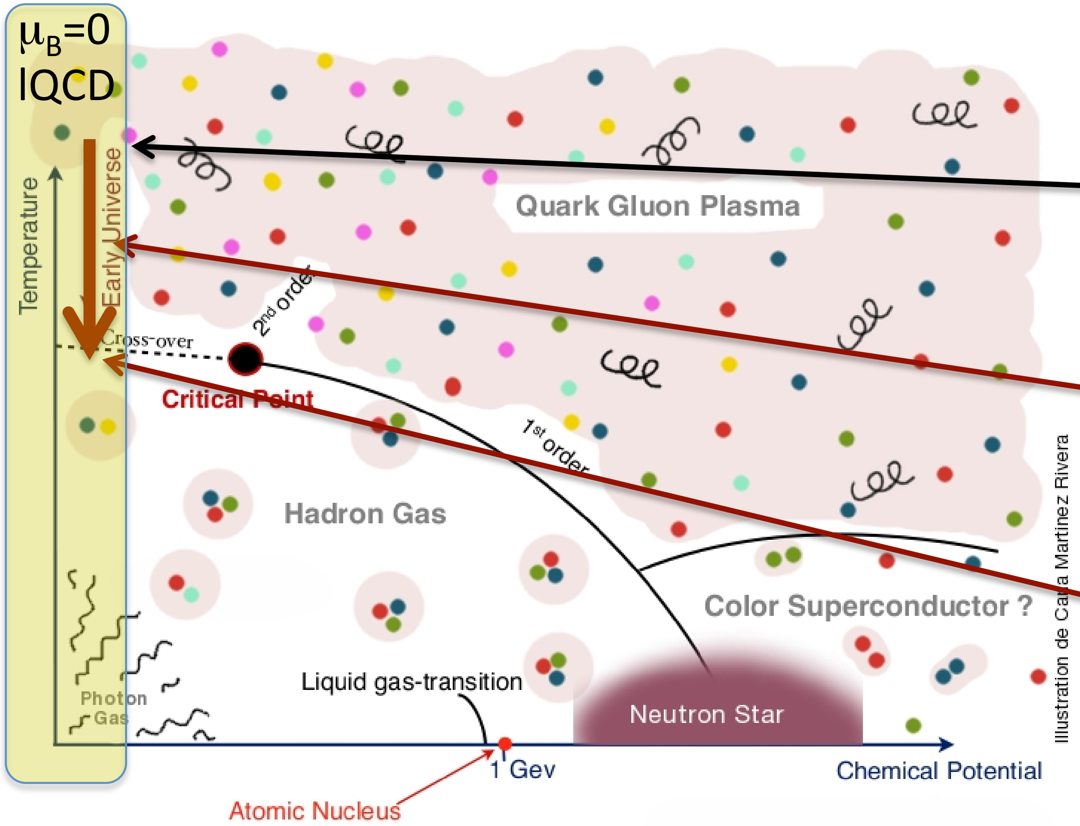


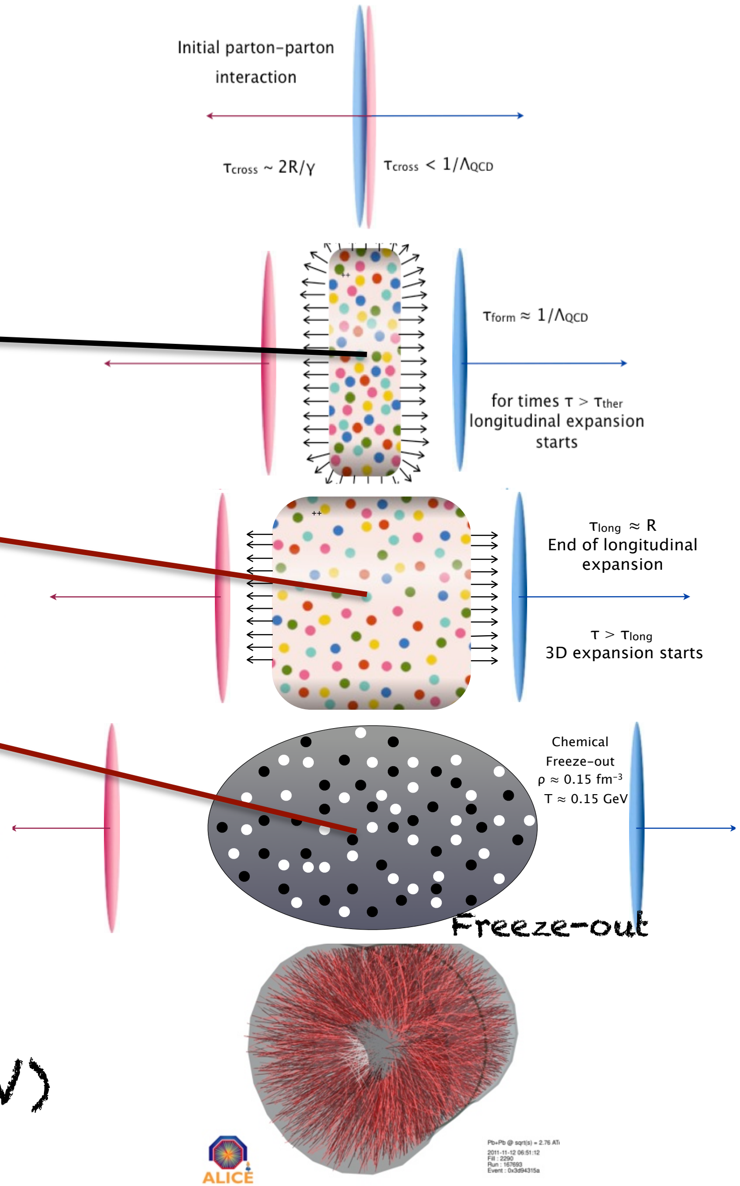






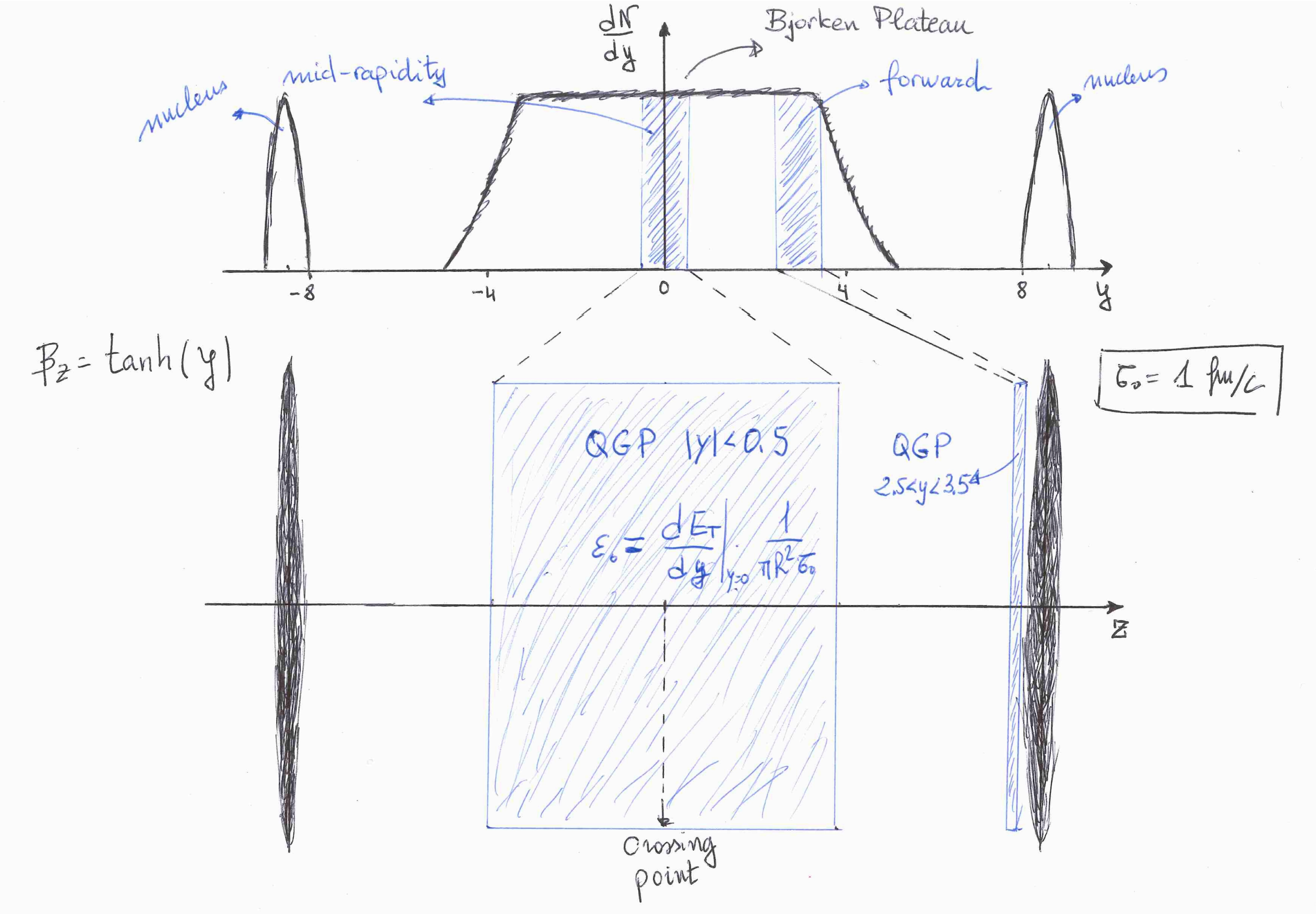
QGP in Heavy Ion Collisions





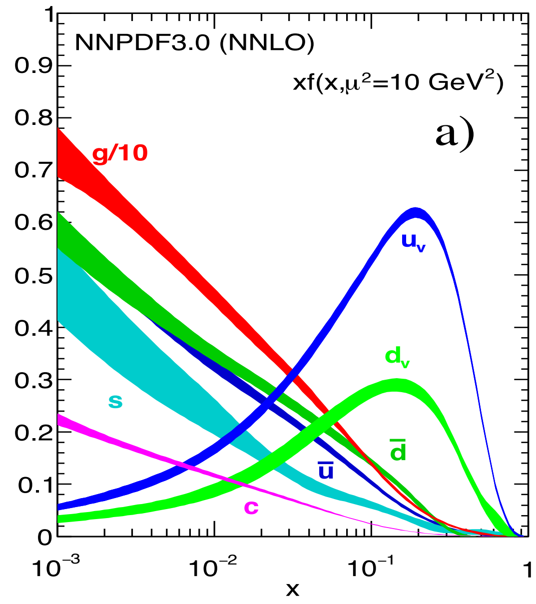
At the LHC, μ_B~0,
ε_0~10-40 GeV/fm³ (T_i~300-450 MeV)

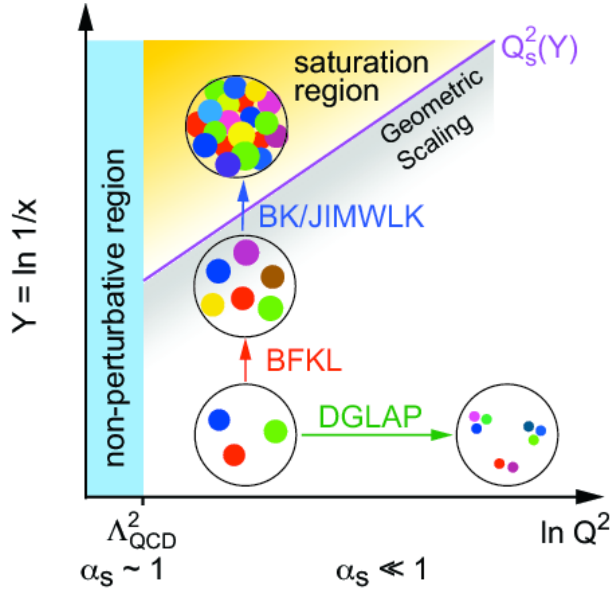
QGP at Back/For-ward



HIC Initial Conditions

- $\langle p_T \rangle$ of hadron produced in relativistic hadron collision ~700 MeV/c
- $X_{bj} \sim 2\langle p_T \rangle e^{\pm y}/\sqrt{s} \sim 10^{-2} - 10^{-6}$
- Collisions of a dense gluon cloud interacting with $\alpha < 1$
- Dense QCD is a regime of QCD that can be then studied in hadronic collisions at relativistic energies. CGC is an effective theory of this QCD-Regime





Key Questions

- What are the fundamental properties of matter at high temperature? What are the properties of the quark gluon plasma?
  - Strongly interacting matter: QCD matter. Matter interacting with the only non-abelian interaction in the Standard Model
  - Importance of QCD theory, namely Lattice QCD
- Hadronic collision dynamics (in the Bjorken regime)?
  - Initial conditions (high gluon density weakly coupled: CGC)
  - Hydrodynamic models (QGP properties)
  - Hadronisation (npQCD).
  - Heavy quarks – QGP coupling (LQCD, pQCD, QGP properties)
  - QGP- high energy particle interaction (pQCD, QGP properties)
- To which extent did these properties govern the evolution of the universe?

Experimental Observables

Soft Probes
Hadron gas
Freeze-out

- Global
- Light hadrons
- Strange hadrons

Hard Probes
Initial State
QGP

- Quarkonia
- Open heavy flavours
- Jets and high pT hadrons
- Electroweak probes
- Exotic

⊗

- Centrality
- Rapidity
- p_T
- Azimuthal angle
- Centre of mass energy
- Reaction plane
- Correlations
- Fluctuations
- Small systems

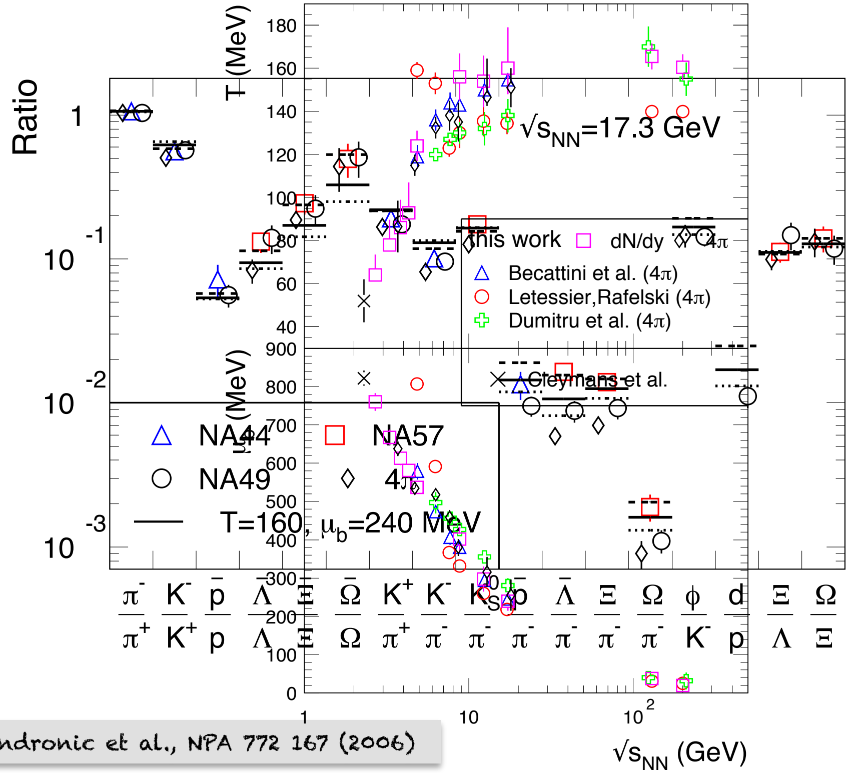
Central Pb–Pb at 5 TeV
~2000 particle/unit of rapidity
{PID, p_T, y, phi}

QCD/Models are crucial in the interpretation of the observables. Due to complexity, a global and coherent scenario is a must

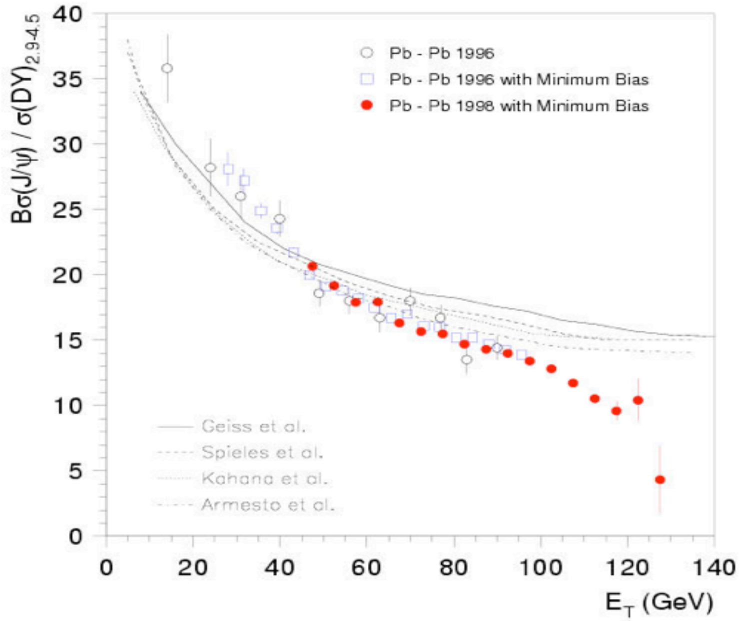
A little bit of history

My personal very brief review

- SPS (1985-) sqr(s)~20 GeV
  - Elliptic flow, particle ratios, jpsi suppression => Hint of a deconfined state of matter
  - Bjorken hypothesis not verified since $2R/\gamma \sim 1/\Lambda_{QCD}$



Andronic et al., NPA 772 167 (2006)



NA50, PLB 477 28 (2000)

RHIC (2000-)

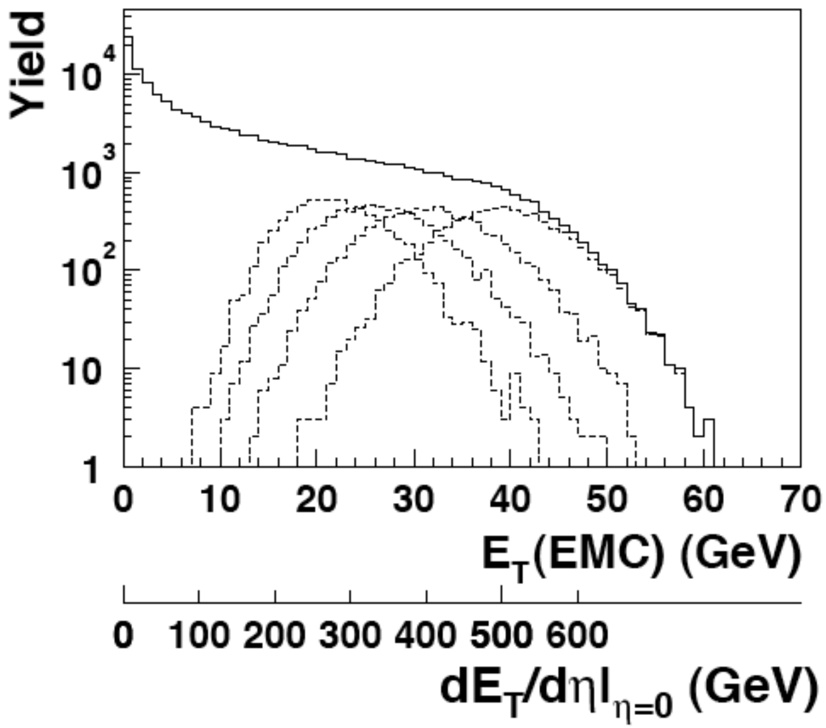
- 3.83 km circumference
- Two separated rings
  - 120 bunches/ring
  - 106 ns bunch crossing time
- A-A, p-A, p-p
- Maximum Beam Energy :
  - 500 GeV for p+p
  - 200A GeV for Au+Au
- Luminosity
  - Au+Au: ~ 10^{27} cm^{-2} s^{-1}
- Mid-rapidity at 90°
- Interaction Point

Upton, Long Island, New York

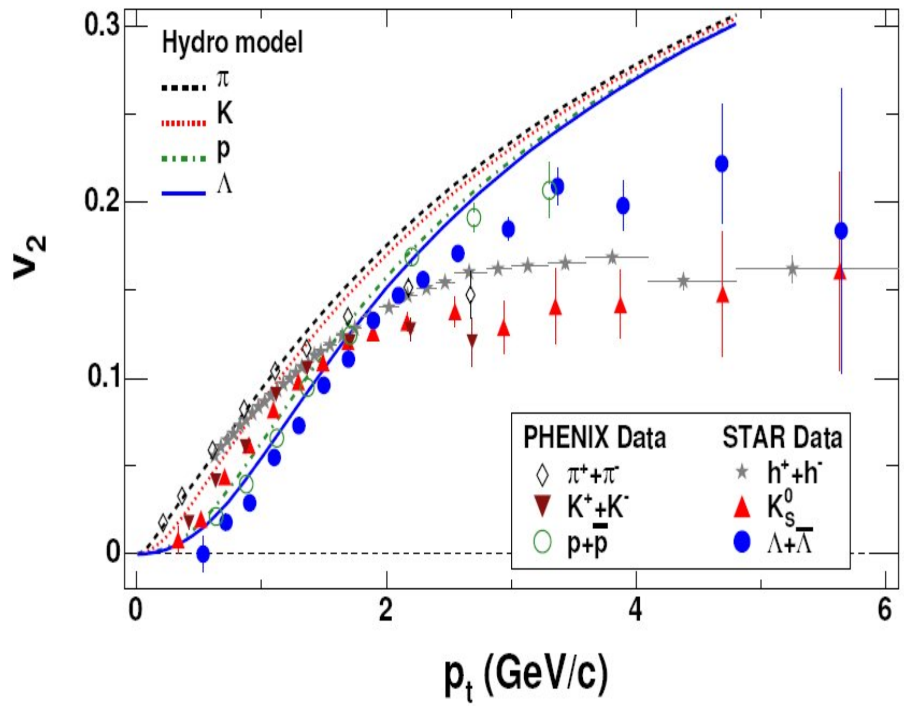
STAR PHENIX PHOBOS BRAHMS

About 300 peer-review papers in exp HIC (2 papers 1000+, 17 500+)

V2 reaches RHD predictions



PHENIX, PRC71, 034908 (2005)



STAR, PRC72(2005)014904

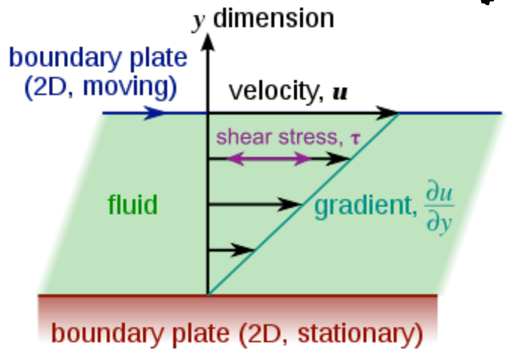
- Central Au-Au 200 GeV, ε_{Bj} ~5-10 GeV/fm^3
- Initial Temperature 230 - 300 MeV (following LQCD)
- Hydro describes very well the HIC evolution (p_T<~2GeV/c)

Strong-QGP concept

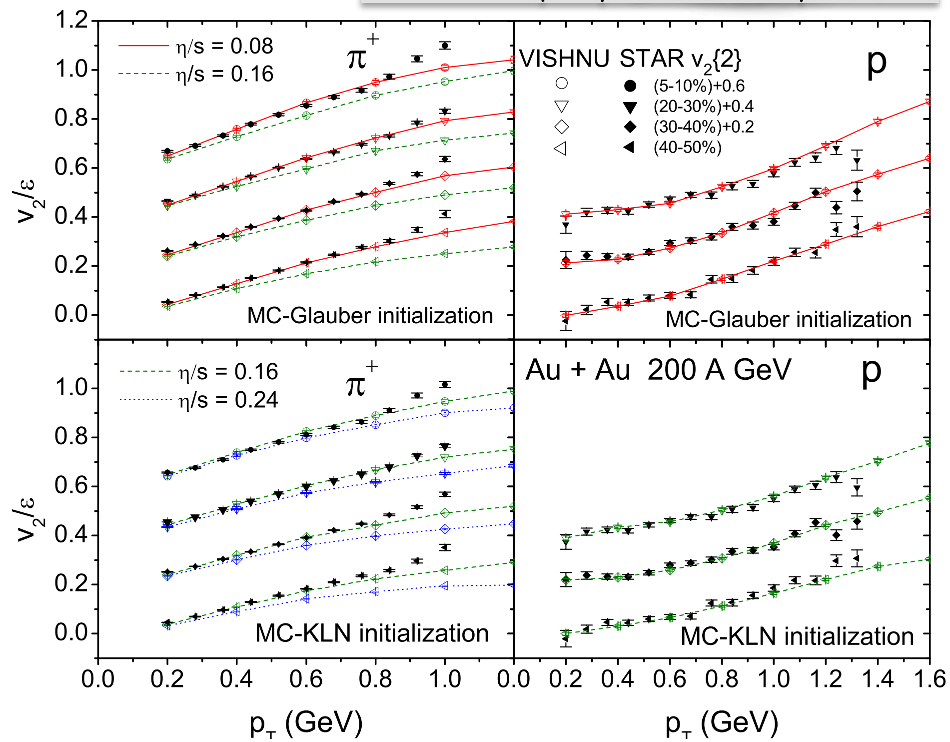
- Success of relativistic hydrodynamics (RHD) to describes the HIC
- Study of QGP shear viscosity (F/A=η(u/y)), and namely η/s (units of ħ)
- From RHD $\eta_{QGP}/s \sim 1/4\pi$
- Strong coupled systems $\eta/s \sim 1/4\pi$ (AdS/CFT correspondence)

Policastro et al, PRL 87 081601 (2001)

- QGP behaves as an ideal liquid

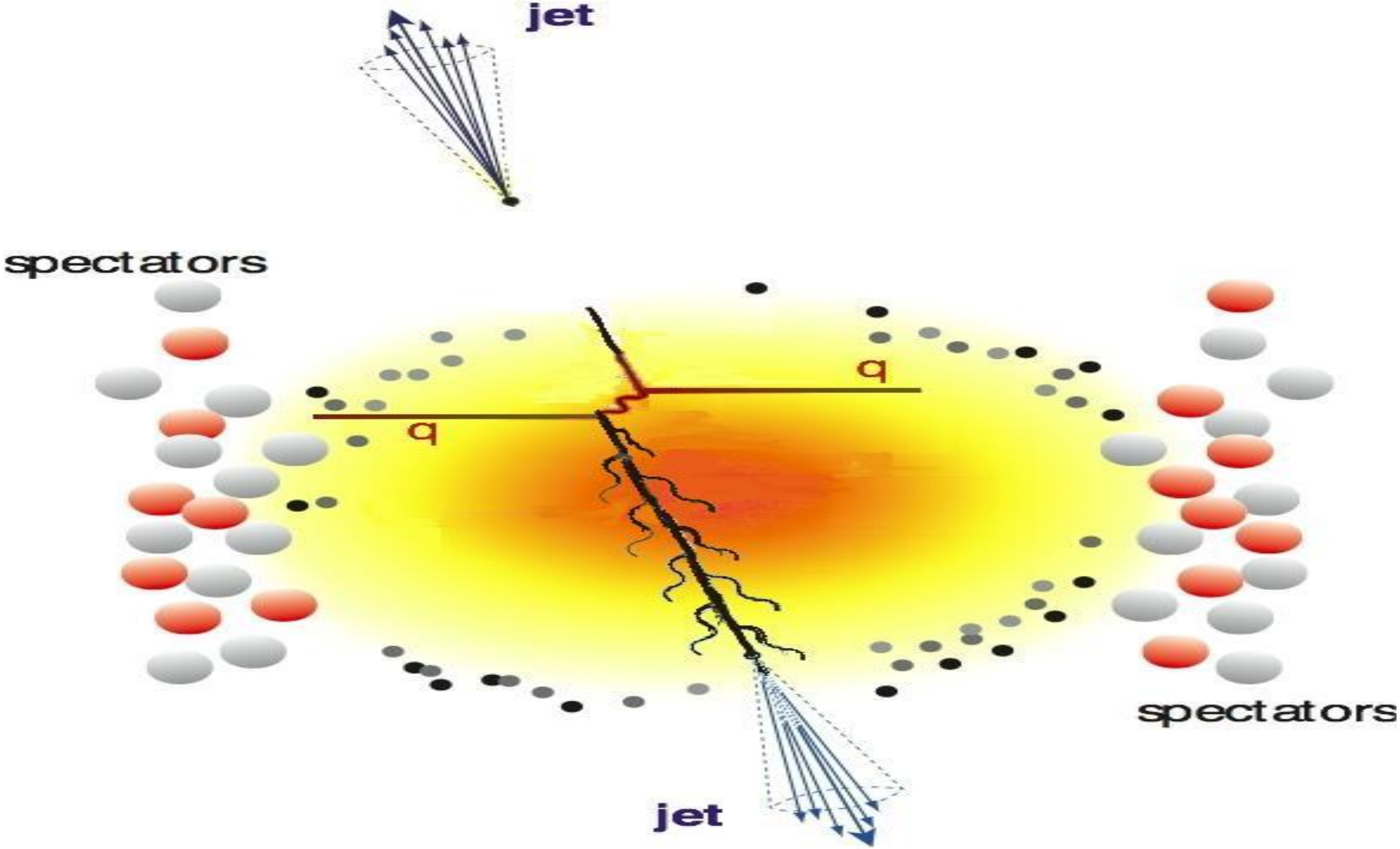


Pitch Drop Experiment (wikipedia)



H Song EPJ A48 (2012) 163

Opacity of the sQGP

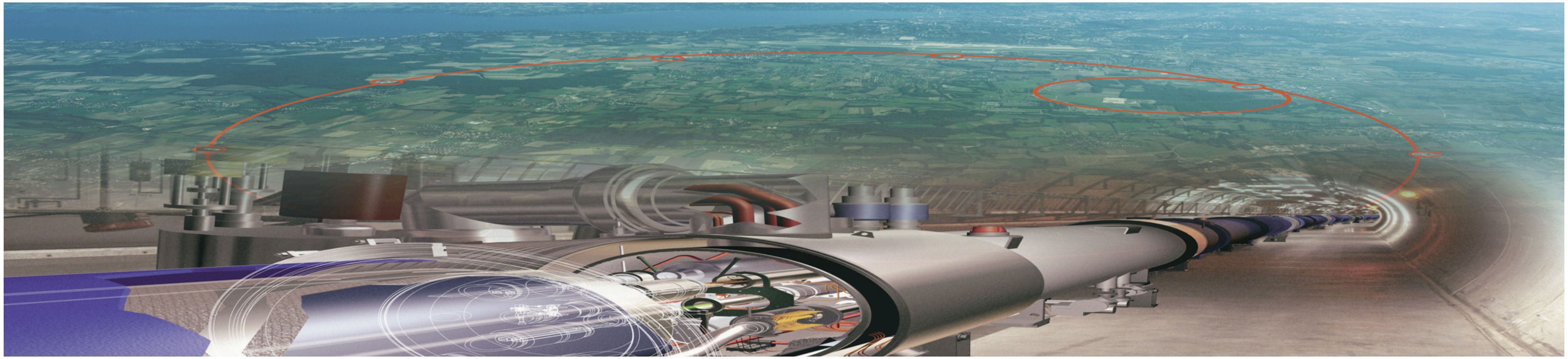


Why HI at the LHC?

Higgs is produced by the gluon fusion channel ;;)

Higher energy density (~x15-x30 beam energy step)

- Larger/Longer/Hotter QGP
- Increase of hard probe cross-sections:
  - Upsilon (but also J/psi)
  - Open beauty (but also open charm)
  - Jet production (until factor 1000)
  - Electroweak boson production



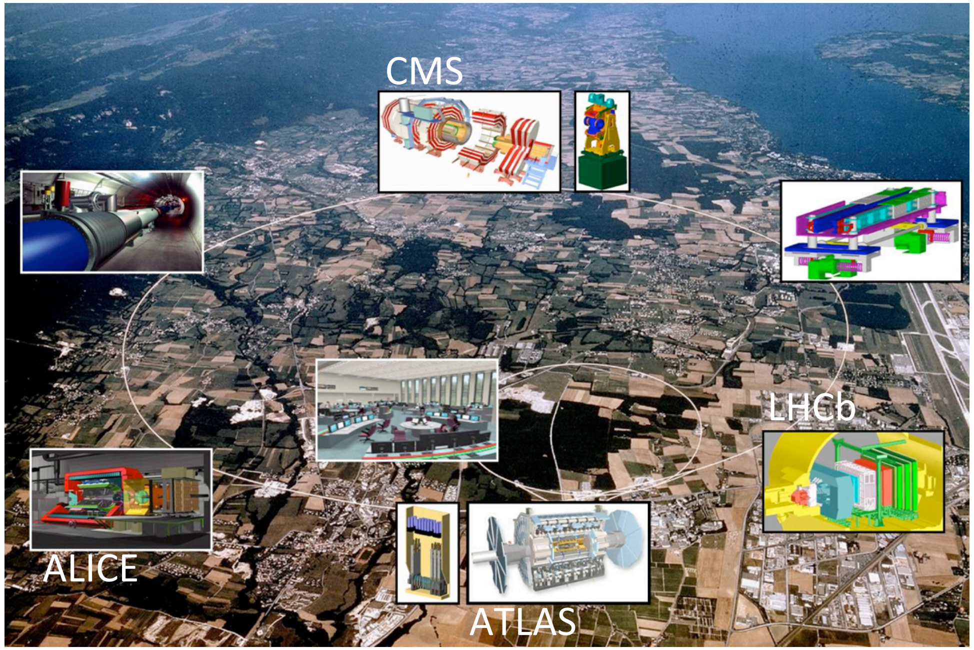
LHC Heavy Ion Program

All LHC experiments have joined the LHC HI program:

- Run1 (2010-2013) Pb-Pb 2.76 TeV 0.1 nb^{-1}, p-Pb 5 TeV
- Run2 (2015-2018) Pb-Pb 5 TeV 1 nb^{-1}, p-Pb 5 TeV, fixed target
- Run3 (2021-2024) Pb-Pb 5 TeV 10nb^{-1}
- Run4 (2027-2030) To be discussed, light ions, fixed target, ...

Rough estimation:

O(1300) experimental physiscists devoted to the HI program. Full LHC community O(6800)

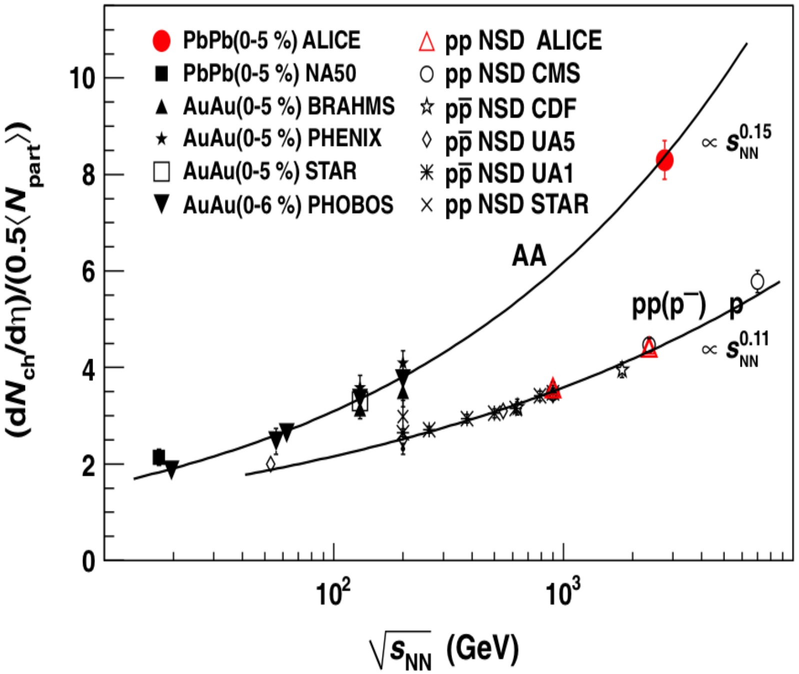


ALICE: devoted to HI. low p_T, PID, open charm, charmonia
CMS/ATLAS: bottomonia, jets, high pT, EW probes
LHCb: pA, low p_T, fixed target

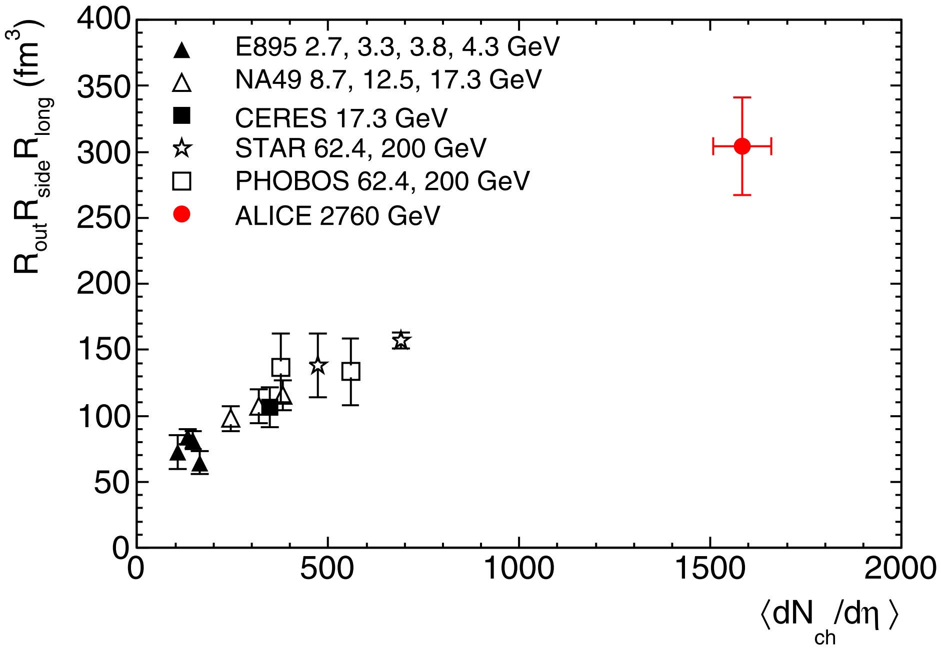
Close to 150 peer-review papers in exp HIC (2 papers 500+, 9 250+)

QGP at the LHC Run1 I

ALICE, PRL 105, 252301 (2010)



ALICE, PLB 396, 328 (2011)



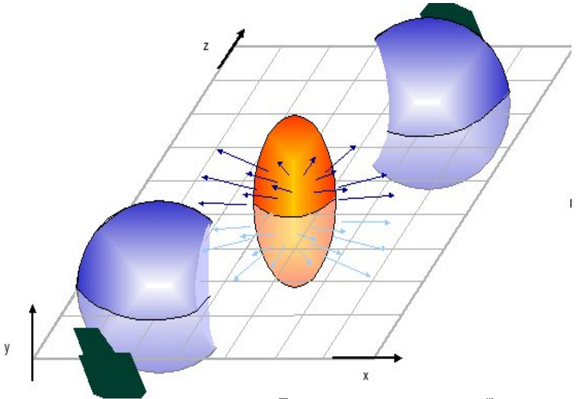
<u>Hotter</u> ➔ x3 initial energy density 15-30 GeV/fm^3

Ti ~ 300 - 400 MeV (30% larger initial temperature)

<u>longer</u> ➔ ~ 10 fm/c until freeze-out

<u>Larger</u> ➔ double volume

QGP at the LHC Run1 II

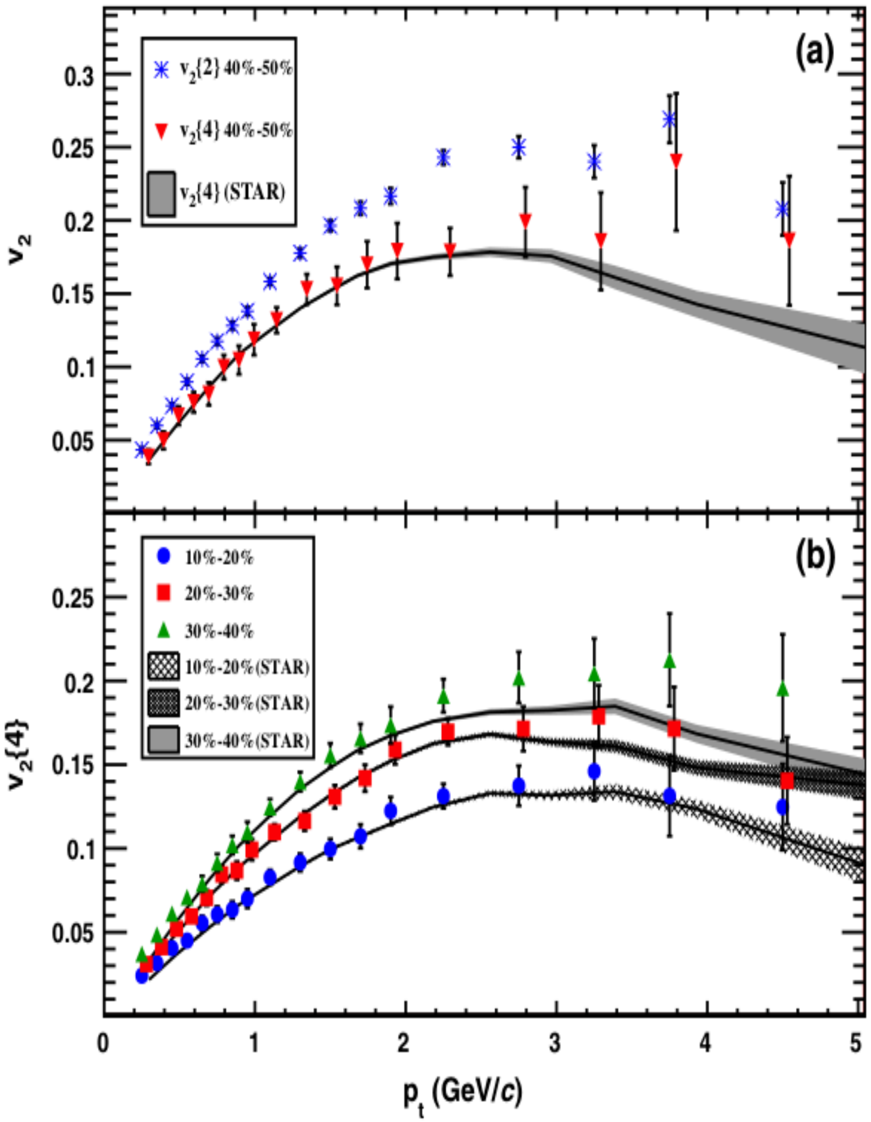


Strong and similar elliptic flow (v2) observed at RHIC and LHC

QGP behaves as a ideal fluid

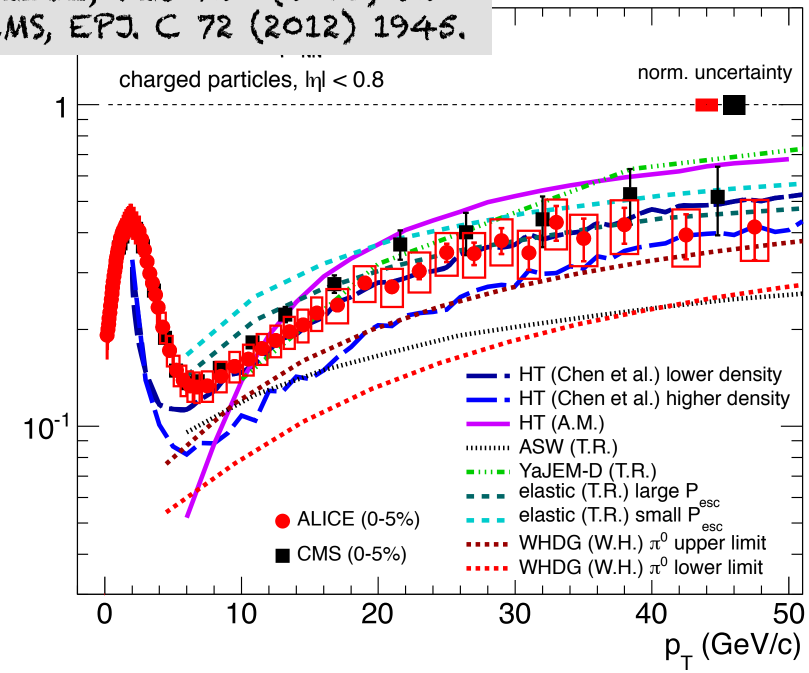
V_2 (also v_3, v_4 ...) constrains the (η/s) QGP via viscous RHD models

ALICE, PRL 105, 252302 (2010)



QGP at the LHC Run1 III

ALICE, PLB 720 (2013) 52
CMS, EPJ. C 72 (2012) 1945.

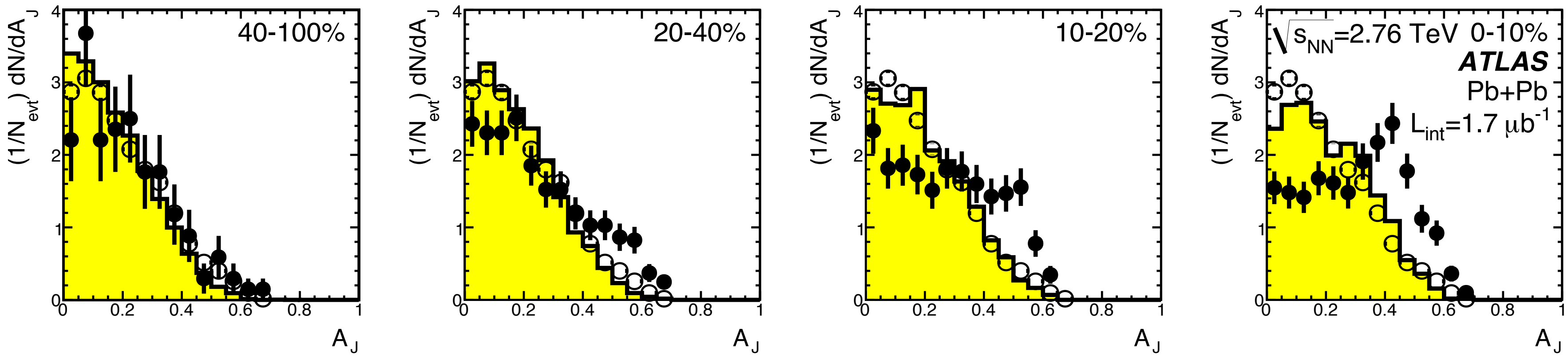


Strong suppression of high pT particles

Increase of R_{AA} with pT

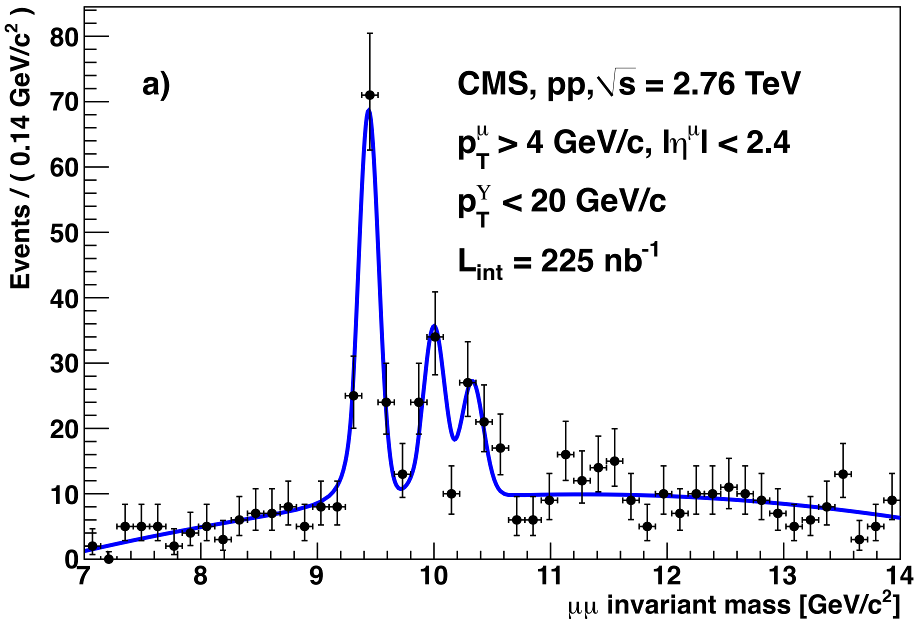
Jet Physics in Heavy ions. i.e. dijet asymmetry

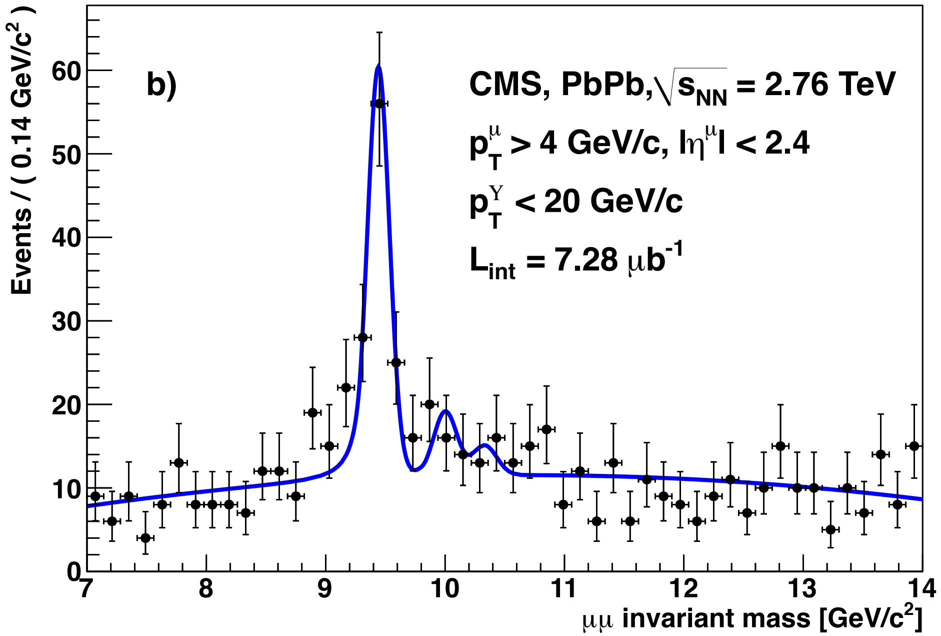
ATLAS, PRL 105, 252303 (2010)



QGP at the LHC Run1 IV

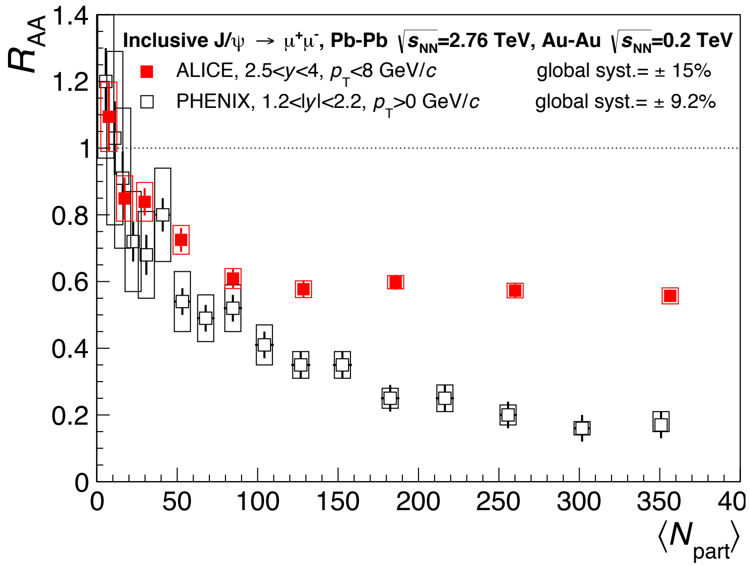
CMS, PRL 107 (2011) 052302
CMS, PRL 109 (2012) 222301

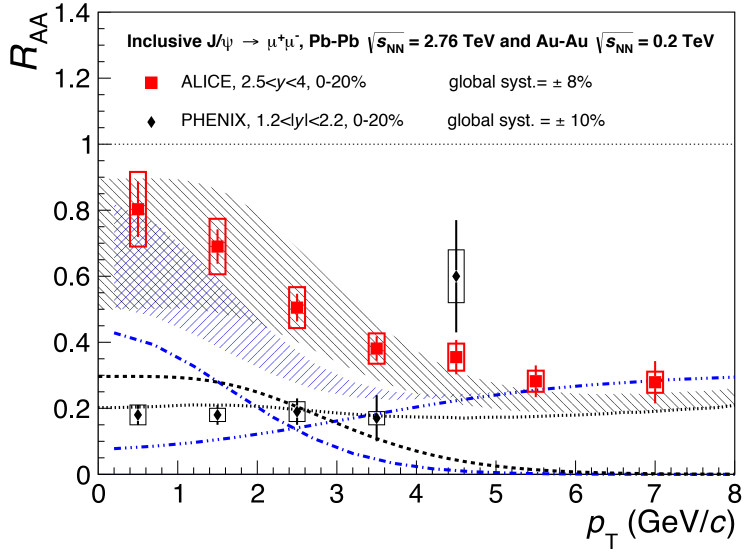




Υ (2S) and Υ (3S) are suppressed.
Υ(1S) partially suppressed, could be indirectly caused by the suppression of excited Υ states.

QGP at the LHC Run1 V

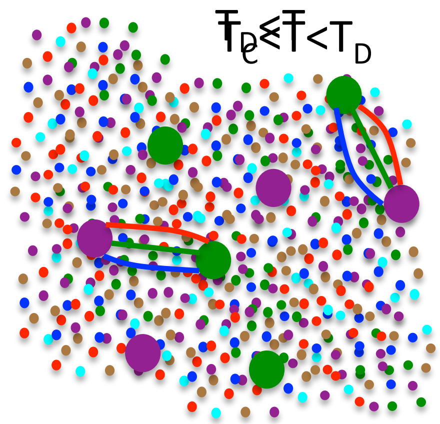




ALICE, PRL 109, 072301 (2012)
ALICE, PLB734 (2014) 314

Recombination scenario is favoured.

Deconfinement of charm quarks in the QGP

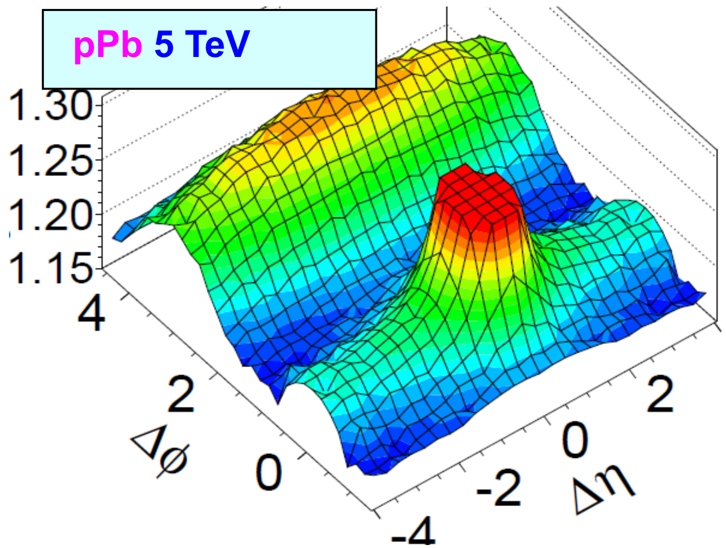


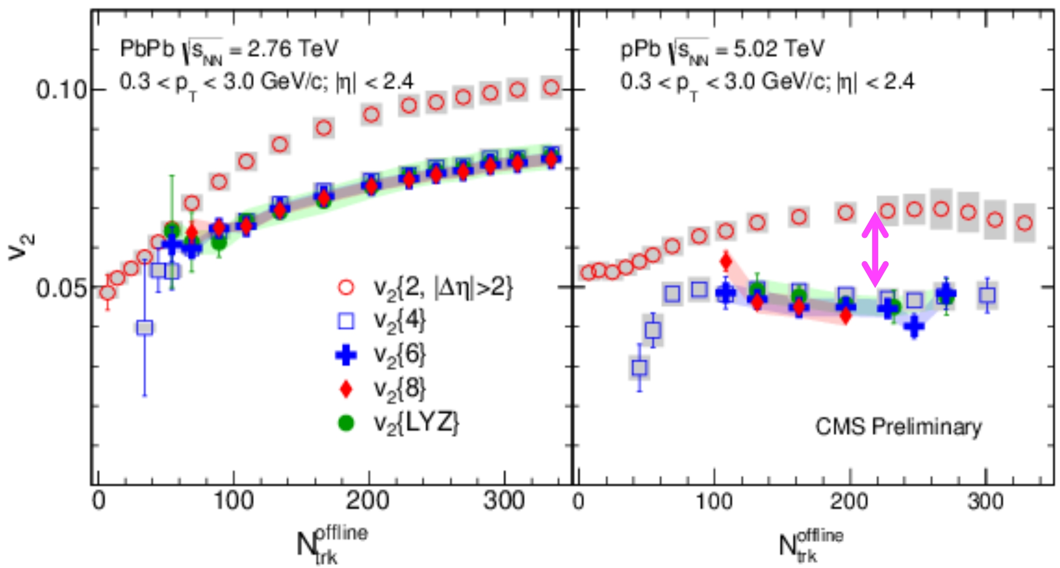
Collectiveness in pPb Run1 VI

ALICE, PLB 719 (2013) 29

Similar to PbPb: v2, ridge, particle ratios, HBT, ...
(also in high multiplicity pp collisions)

- unexpected,
- interesting,
- more experimental studies needed,
- a theoretical framework is needed.



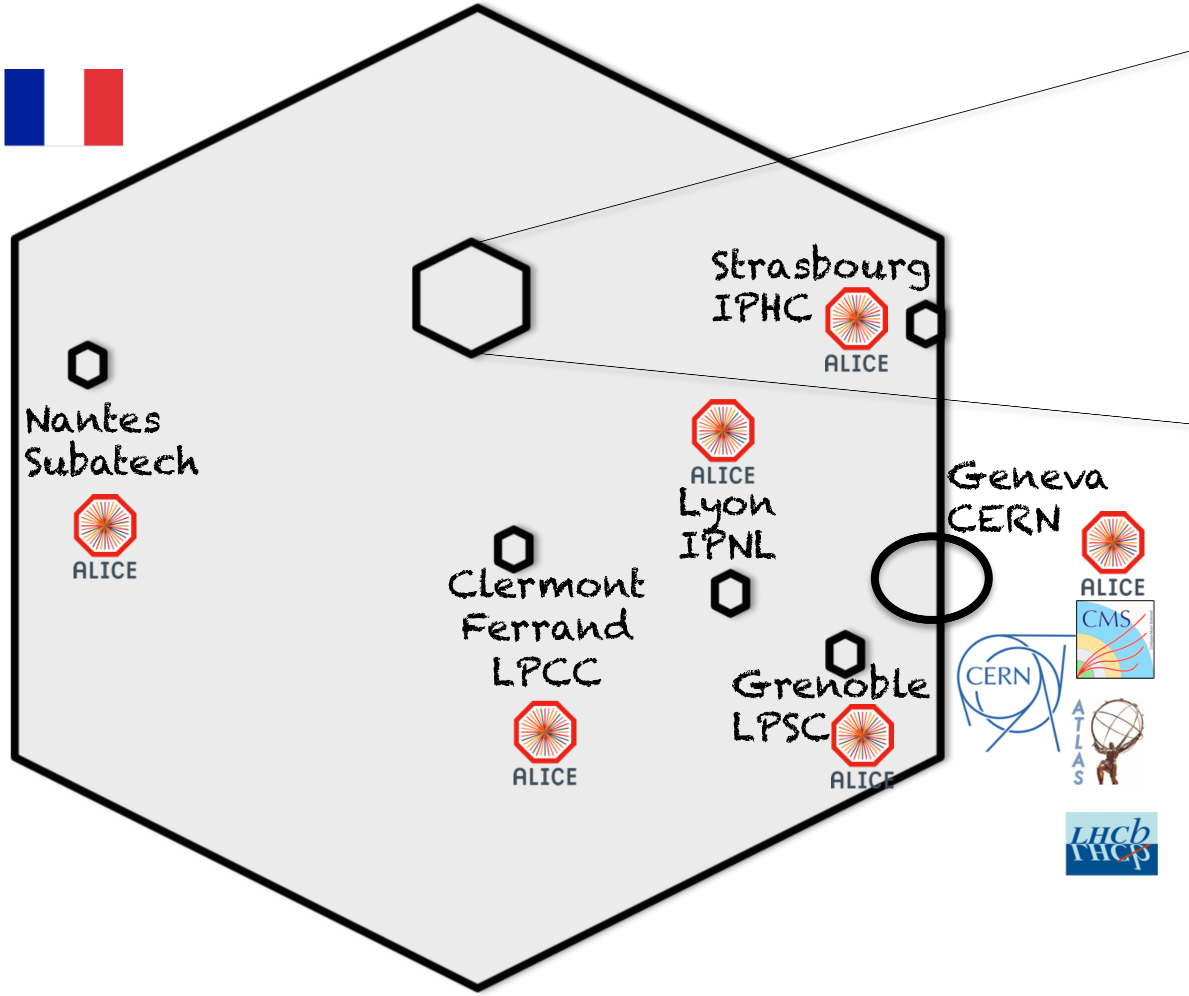


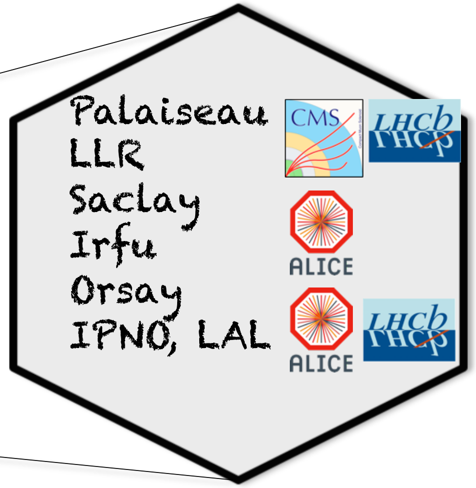
HI Results from LHC Run1

- Larger initial energy density (x3 for ~15 beam energy step and 30% larger initial temperature)
- Confirmation/extension of RHIC results : elliptic flow, high pT suppression
- Jet physics in heavy ion collisions
- Upsilon suppression
- Charm deconfinement
- Collectiveness in small systems

My personal executive summary of HI LHC results Run1(2010-2013)

Ultra Relativistic Heavy Ion Physics in France





ALICE O(58)

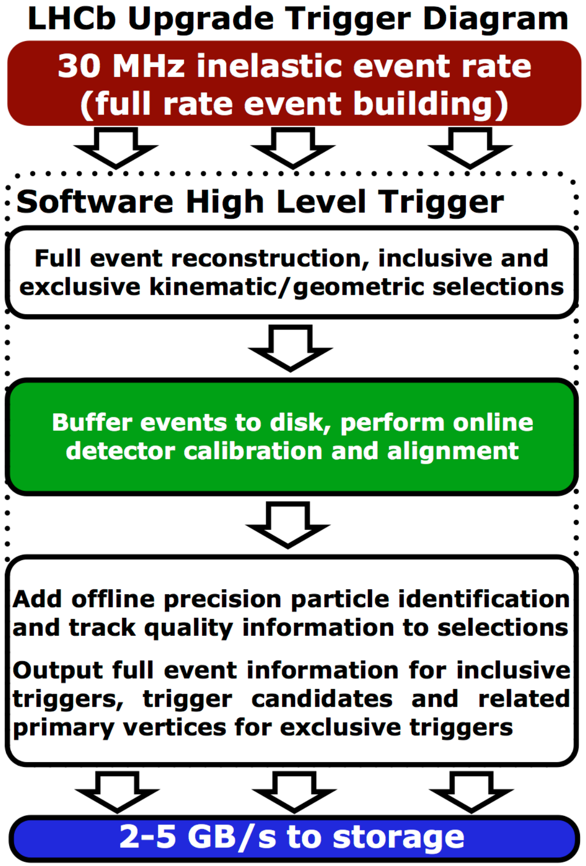
CMS O(10)

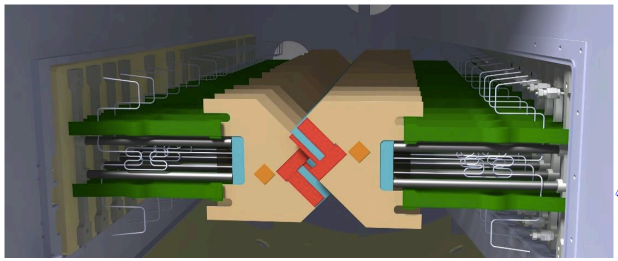
LHCb O(5)

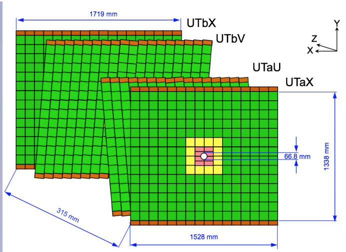
Fixed target O(4)

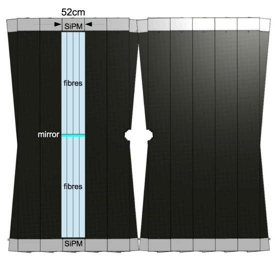
LHCb upgrade for run3-4

- Higher Luminosity (in pp $4\times10^{32} \rightarrow 2\times10^{33}$ cm^{-2} s^{-1})
  - New RO architecture and software triggering
- Higher event multiplicity
  - Larger granularity, namely of the tracking detectors









CMS and ATLAS in Run3-4

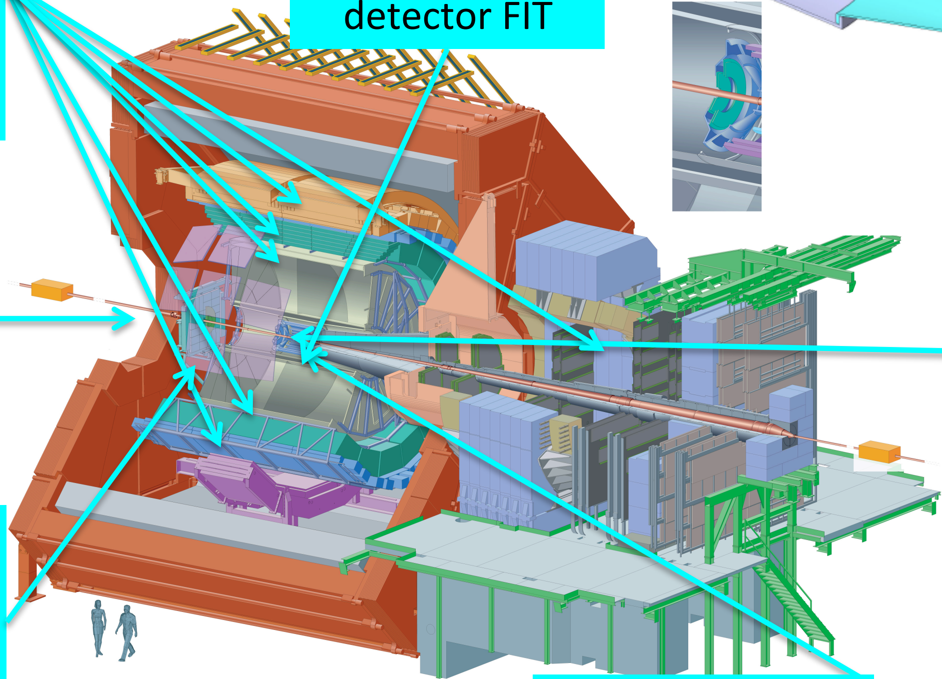
- Higher significance (10 nb^{-1}, 50 kHz PbPb
- Strategy based on triggering on interesting events
- Upsilons
- High pT (particles, jets (b-jets) quarkonia, heavy quarks)
- New observables: photon-jet, Z-Jet etc ...

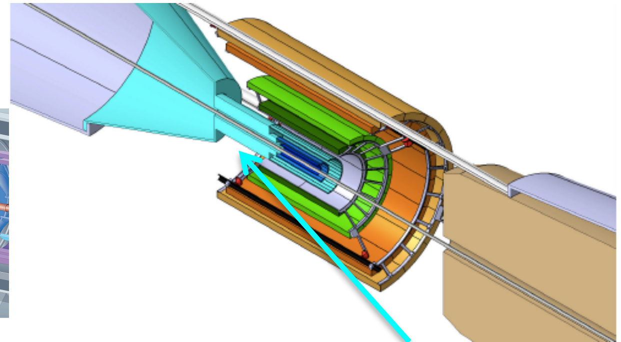
ALICE Upgrade for Run3-4

Better significance ($10 nb^{-1}$, 50 kHz PbPb) and better tracking with Si-pixel and dilepton, quarkonium, open heavy flavour down to p_T=0, and jet structure.

TPC, Muon Spectrometer
TRD, TOF, PHOS, EMCAL/DCAL , ZDC, T0

New MB trigger detector FIT





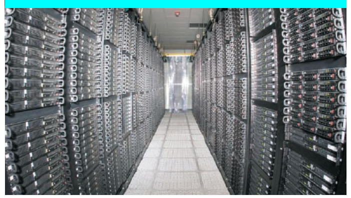
New berilium beampipe smaller radius

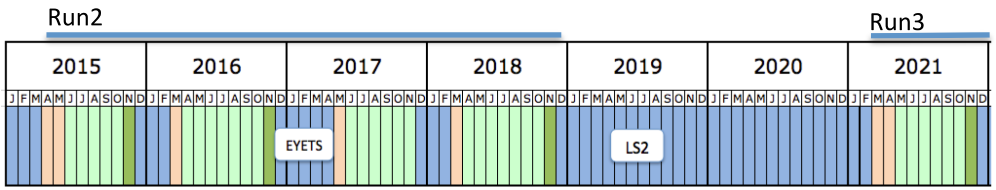
New Internal Tracking System, high resolution, low material budget

New TPC GEM Chambers (low ion backflow, continuous RO)

Muon Forward Tracker, high resolution, low material budget

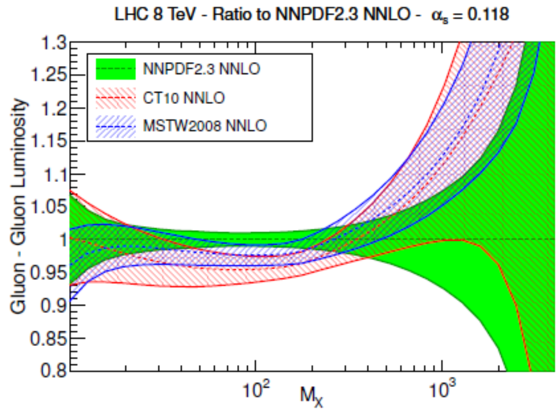
Computing O²

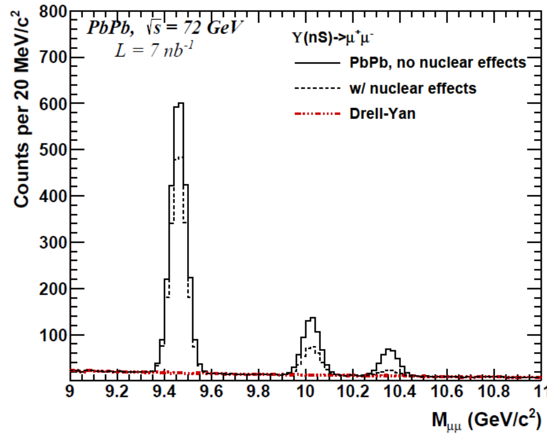




Fixed target at the LHC

- CM energy similar to RHIC (72 and 115 GeV in PbPb AND pA respectively
- Accessing backward rapidities (x_F<0)
- High integrated luminosity
- Different targets
- Polarisation of the target is possible
- Two options:
  - Gas target (being tested by LHCb)
  - Beam extraction with bent crystals





Perspectives 2017-2030 I

Exploiting all the possibilities at the LHC

- Global observables......
- Light hadrons..............
- Strange hadrons..........
- Quarkonia....................
- Open heavy flavours.....
- Electromagnetic probes.
- Jet and high p_T hadrons.
- Exotic...........................

Better Significance
- 10 nb-1
- High precision tracking

New observables
- High precision tracking

Full energy range and system
- Other systems
- Fixed target

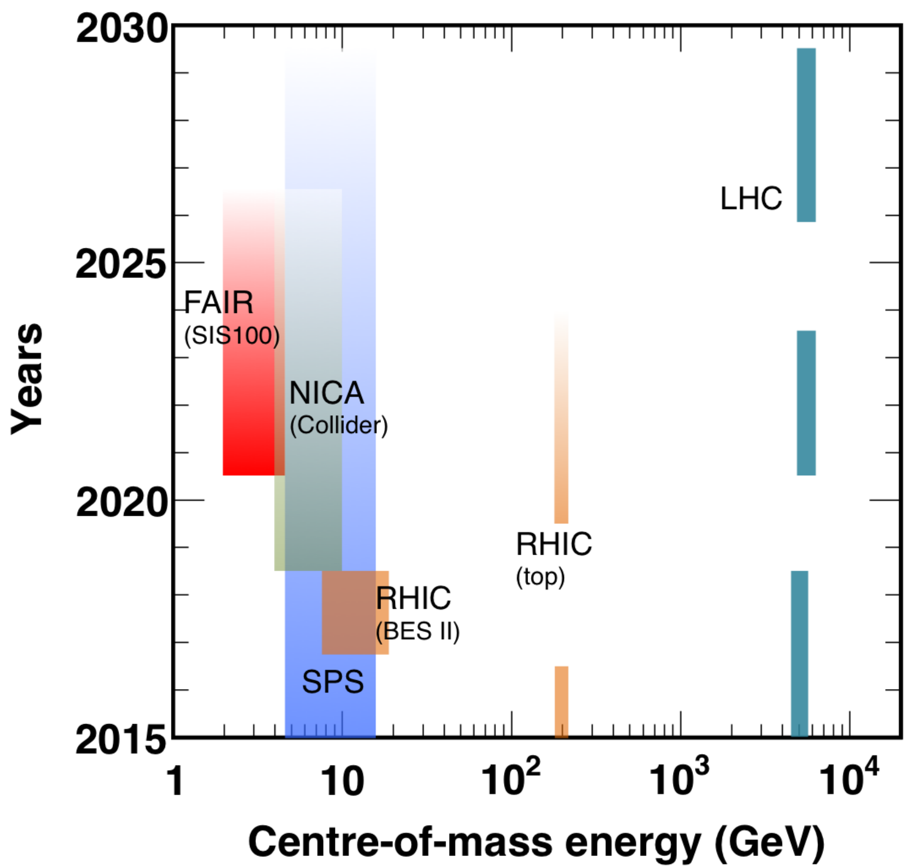
CERN ALICE CMS LHCb ATLAS

Perspectives 2017-2030 II

Other facilities:

- FAIR-CBM
- NICA
- RHIC
- SPS
- J-PARK (~20 GeV)
- FCC (~100 TeV)

Not addressed in this talk

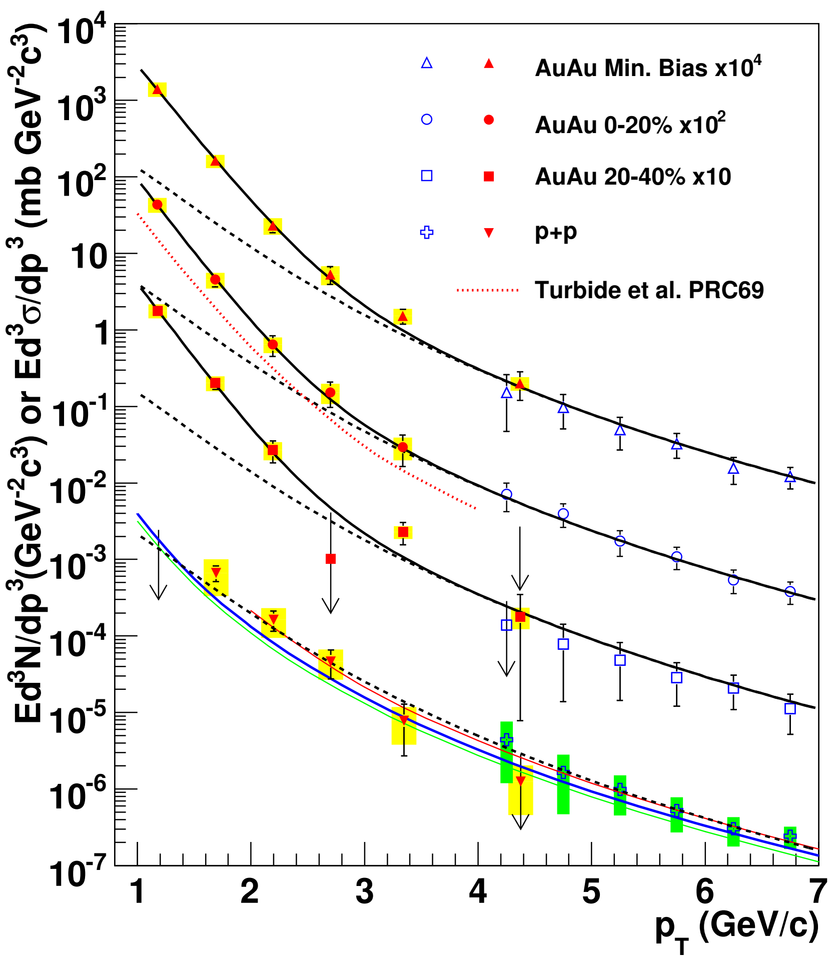


Back-up

Initial Temperature

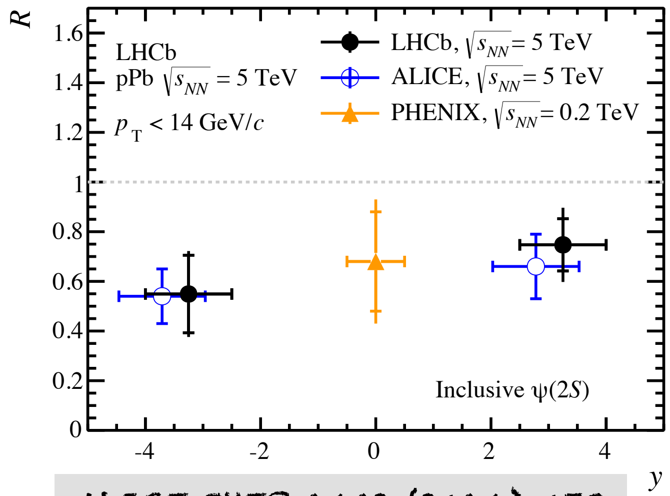
- Difficult measurement
- Virtual photons (m_{ee}<300 MeV)
- T_i ~ 300 - 600 MeV

PHENIX, PRL 104, 132301 (2010)

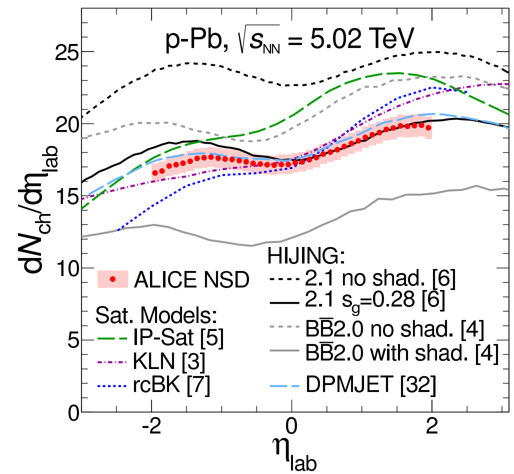


Hard probes in pPb Run1 VI

- Nothing related to collectiveness is observed in small systems, except one puzzling observation
- Noticeable decrease of the Ψ(2S)/J/ψ ratio in pPb collisions
- Also observed in the upsilon family
- Resonance ratio should only depends on the quarkonia wave-function at the origin
- It seems to be correlated with the charged particle multiplicity
- Resonance formation time $1/\Delta M < 0.3$ fm/c
- The particle density at τ=1 fm/c is large in pPb collisions at LHC energies: 8 pre-hadron fm^{-3}. Ψ(2S) quarkonium has a volume ~1.75 fm^3



ALICE JHEP 1412 (2014) 073
LHCb arXiv:1601.07878

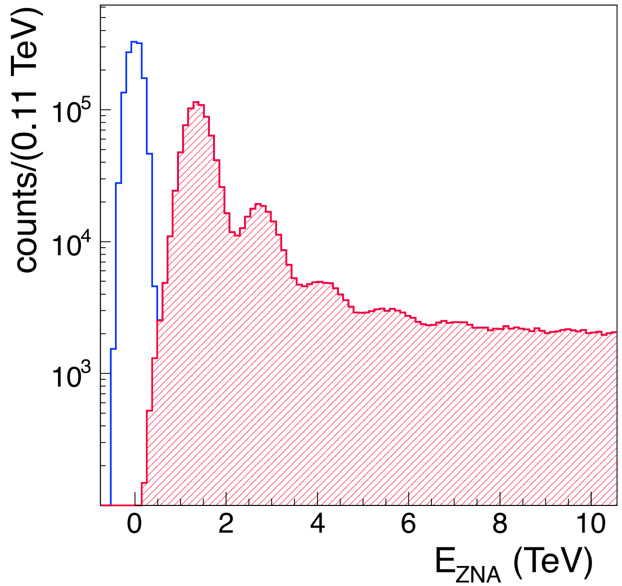


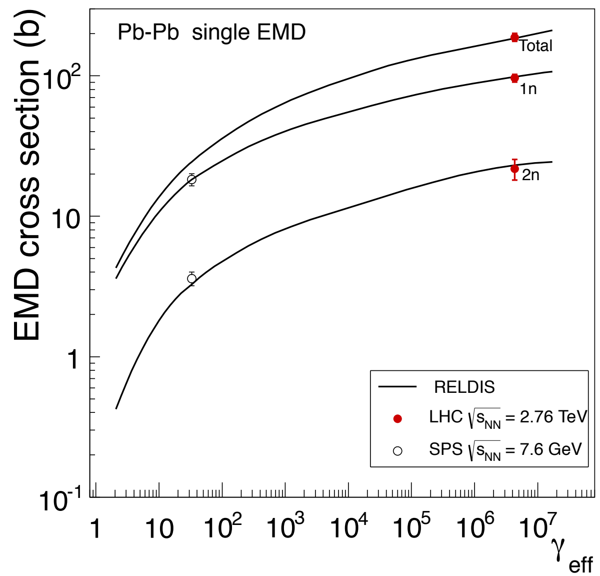
ALICE PRL 110 032301 (2013)

Nuclear Physics at LHC

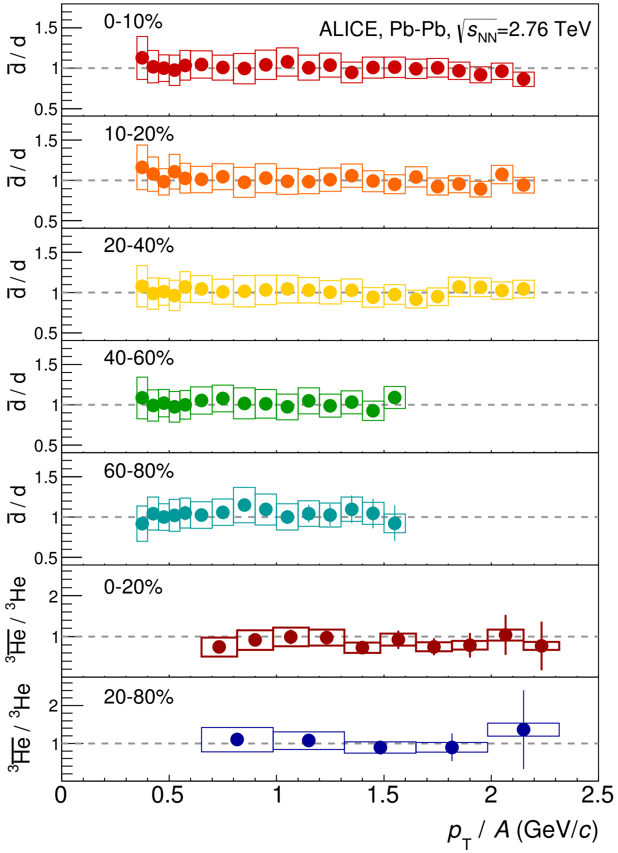
- EM dissociation of the Pb nucleus: GDR excitation and neutron evaporation.
- Limiting factor of the LHC Pb beam lifetime and instantaneous luminosity:
- $\sigma_{\text{single EMD}}$ ~ 200b!

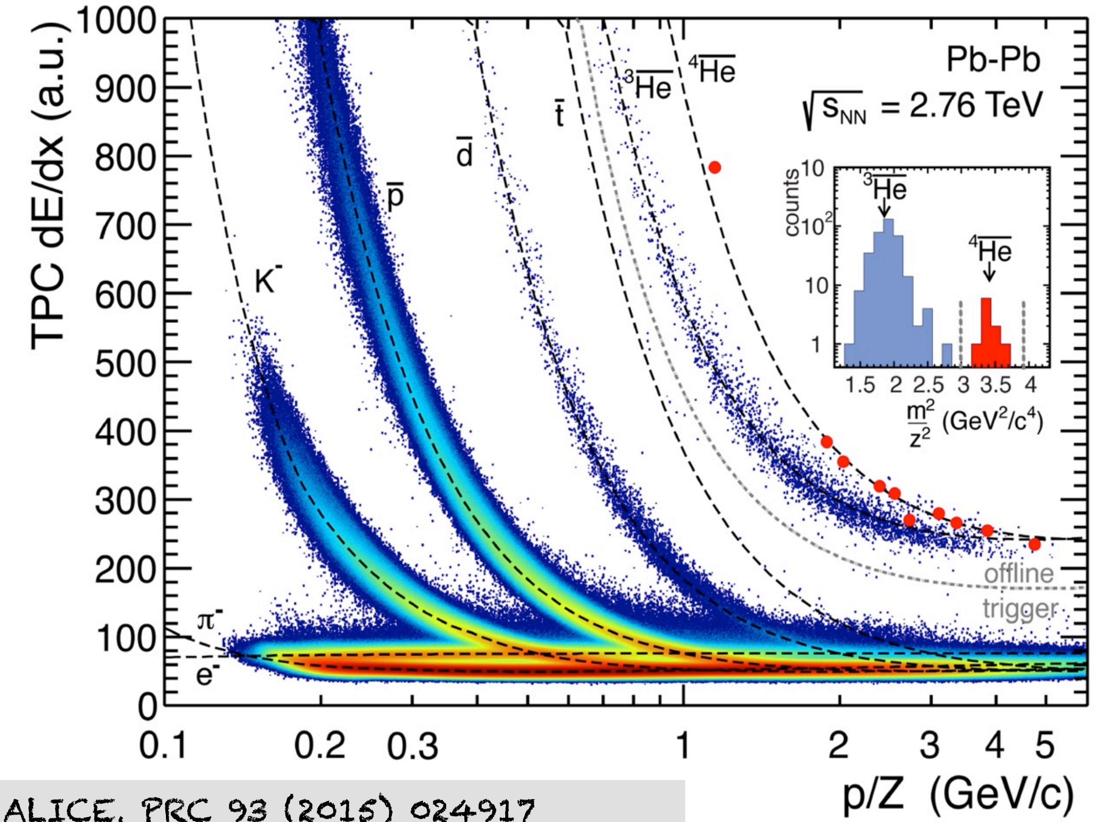
ALICE, PRL109 252302 (2012)





Anti-nucleus factory





ALICE, PRC 93 (2015) 024917
ALICE, Nature Physics 11 (2015) 811

Anti-4He is the heaviest anti-nucleus ever observed
Precision measurement of the nuclei and anti-nuclei mass difference (CPT test)