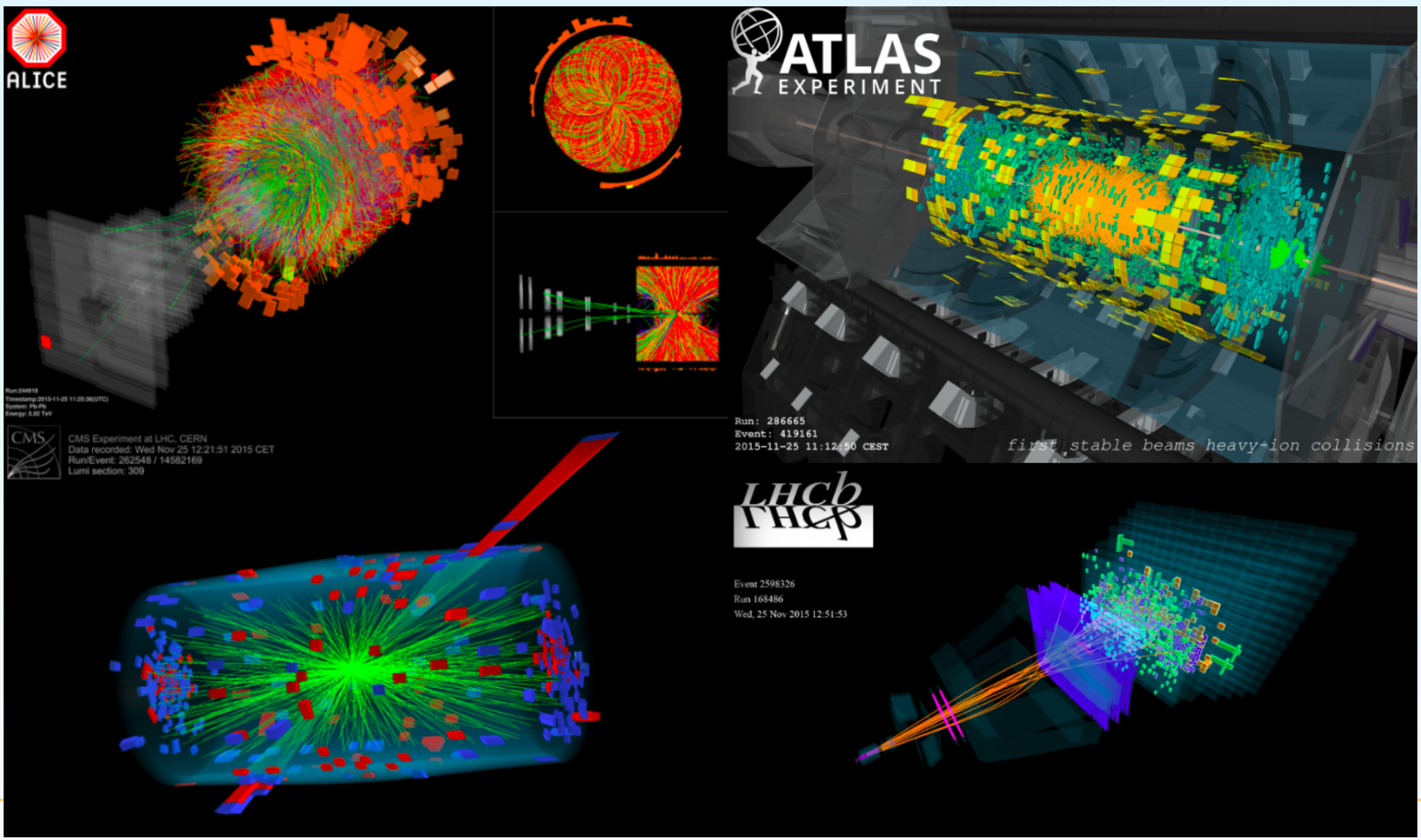
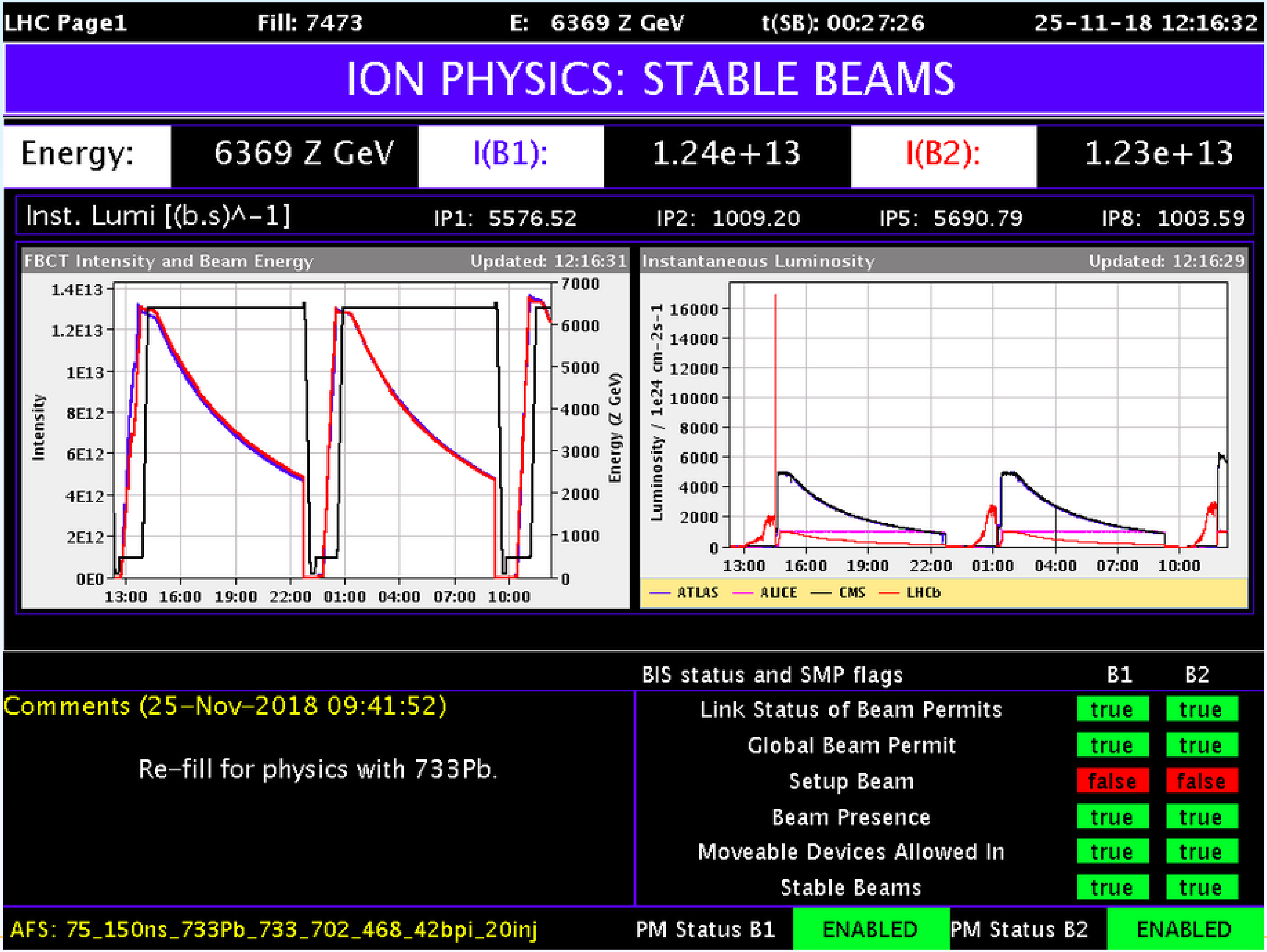
Status of Heavy-Ion Physics at the LHC

Yvonne Pachmayer, Heidelberg University



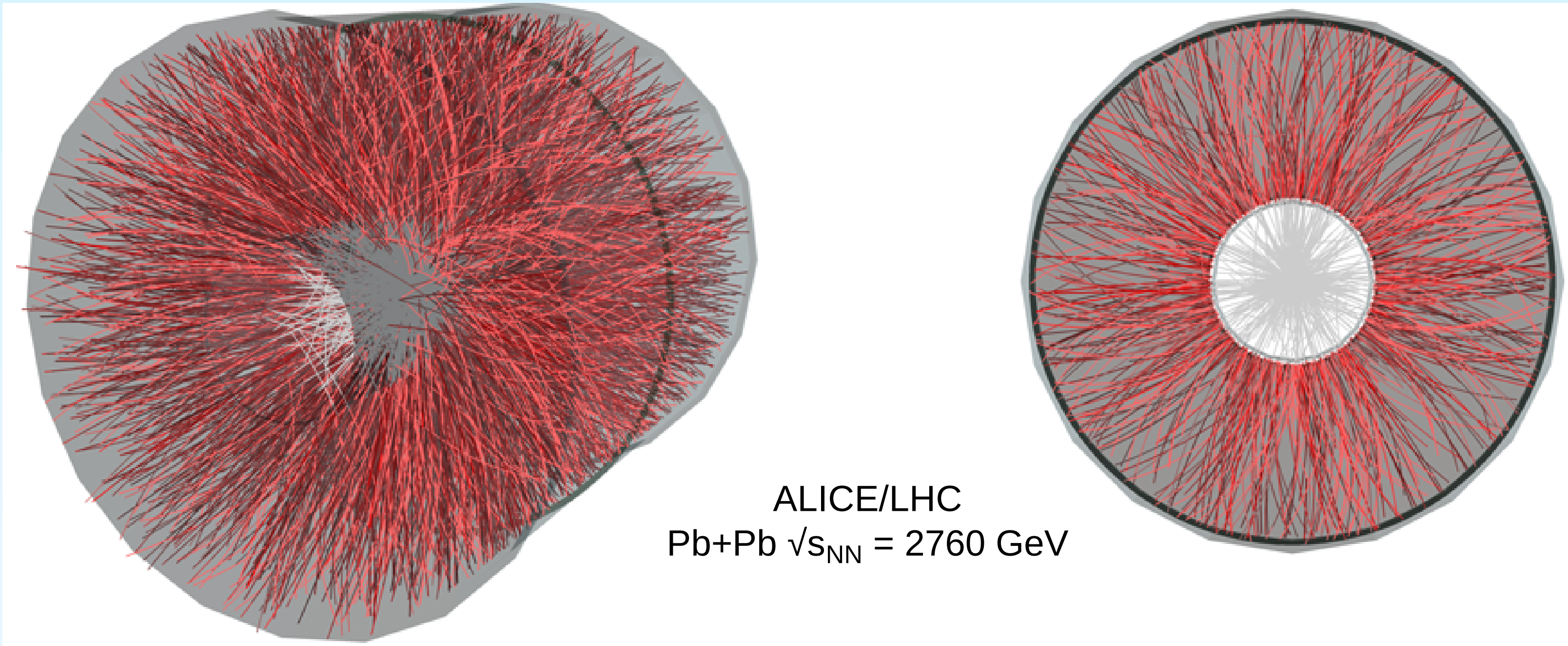
J. Jowett

LHC Page 1



LHC Page1
Fill: 7473
E: 6369 Z GeV
t(SB): 00:27:26
25-11-18 12:16:32
ION PHYSICS: STABLE BEAMS
Energy:
6369 Z GeV
I(B1):
1.24e+13
I(B2):
1.23e+13
Inst. Lumi [(b.s)^-1]
IP1: 5576.52
IP2: 1009.20
IP5: 5690.79
IP8: 1003.59
FBCT Intensity and Beam Energy
Updated: 12:16:31
Intensity
Energy (Z GeV)
Instantaneous Luminosity
Updated: 12:16:29
Luminosity / 1e24 cm-2s-1
ATLAS
ALICE
CMS
LHCb
BIS status and SMP flags
B1
B2
Comments (25-Nov-2018 09:41:52)
Re-fill for physics with 733Pb.
Link Status of Beam Permits
true
true
Global Beam Permit
true
true
Setup Beam
false
false
Beam Presence
true
true
Moveable Devices Allowed In
true
true
Stable Beams
true
true
AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj
PM Status B1
ENABLED
PM Status B2
ENABLED

Motivation: What is the question?



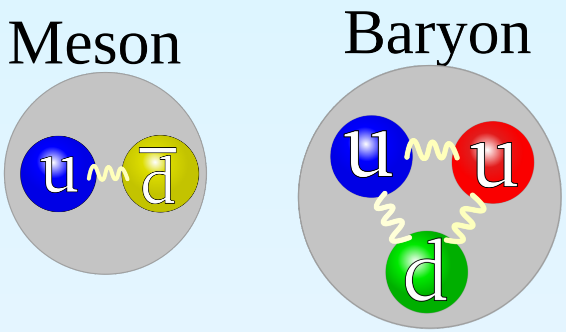
- **What happens if you make matter**
  - Hotter and hotter? Denser and denser?

Solid → liquid → gas → plasma Quark-Gluon Plasma

- **Heavy-ion physics: emergent properties of QCD**
  - Temperature? Phase Transition? Equation of state? Speed of sound? Viscosity?

Properties of the Strong Interaction (I)
Confinement

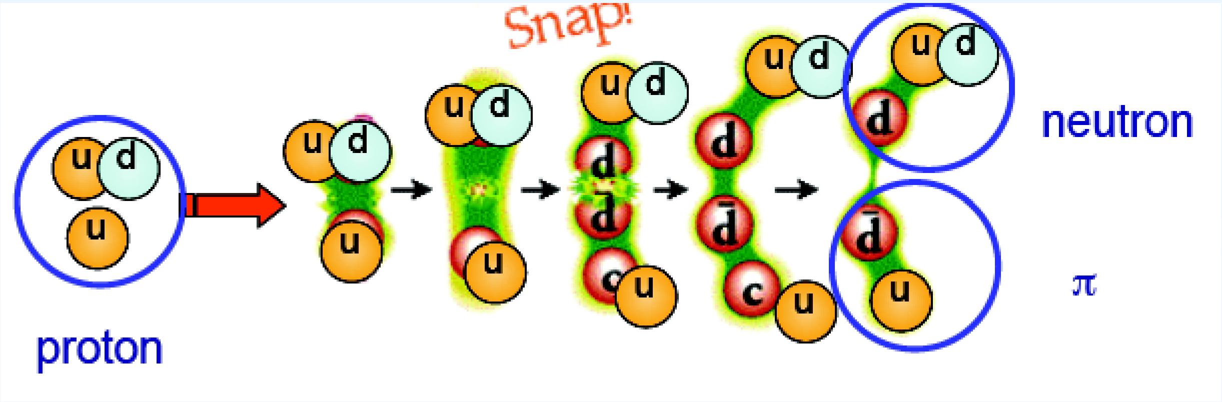
- **Fundamental theory is Quantum Chromodynamics (QCD)**
- **Confinement**
  - Quarks and gluons are not observed as free particles, they are confined in hadrons



  - If the distance between two quarks gets larger, more and more gluons contribute to the interaction between the quarks.
    - Hence the potential energy grows with increasing distance.
    - At some point, enough energy is stored in the field to produce a pair of quarks out of the vacuum.

$$V(r) = \frac{-4\alpha_s(r)}{3r} + kr$$

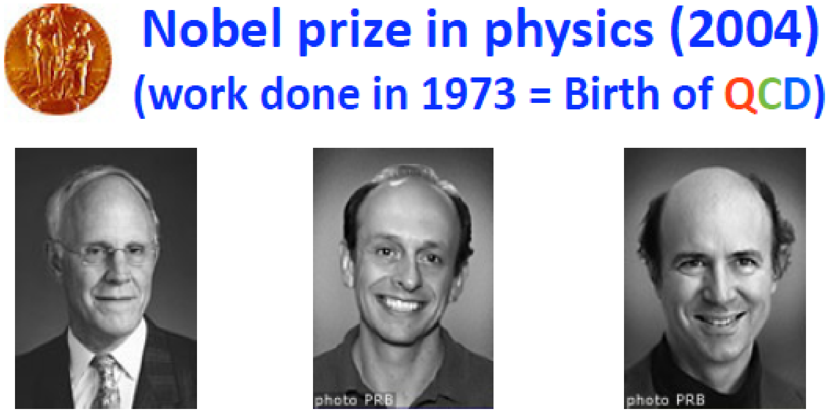
Linear term (often associated with confinement) expected to disappear in the QGP



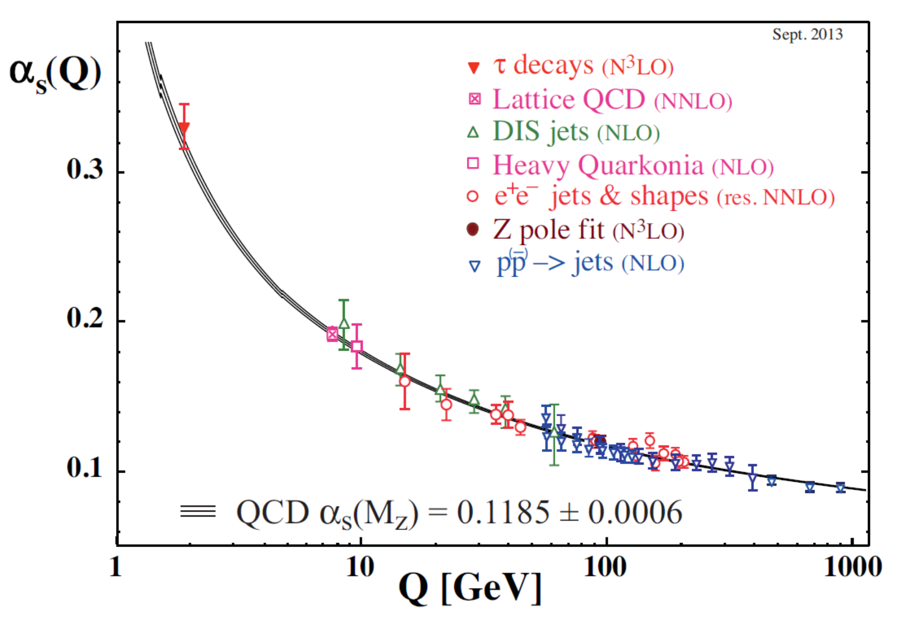
Properties of the Strong Interaction (II)
Asymptotic Freedom

- Coupling α_s between color charges gets weaker for high momentum transfers, i.e. for small distances r

Nobel prize in physics (2004)
(work done in 1973 = Birth of QCD)



David J. Gross   H. David Politzer   Frank Wilczek



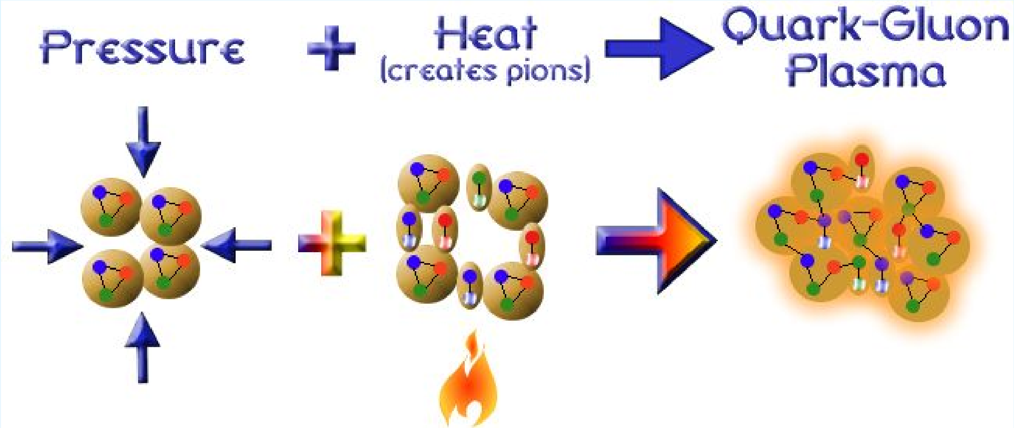
- Vanishing QCD coupling constant at short distances r implies that the interactions of quarks and gluons are negligible at very high temperatures

→ Creation of practically non-interacting Quark-Gluon Plasma at extreme temperatures

The Quark-Gluon Plasma (QGP)

The idea ...

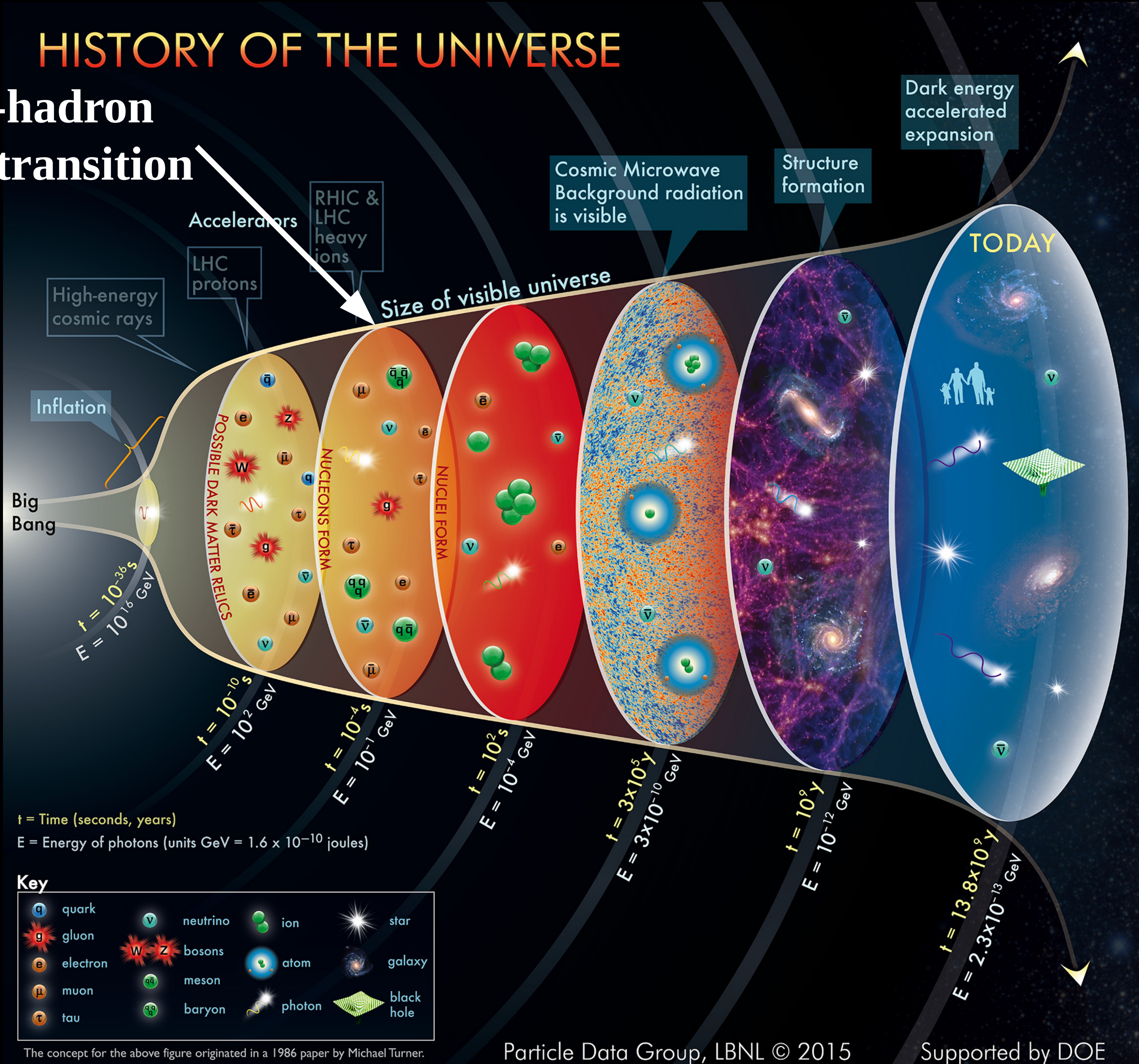
→ Compression and heating of nuclear matter



Phase transition to QGP
$T \approx 10^{12}$ K $\approx 10^{5}$ x sun's core

- **Primordial state of matter: quarks and gluons are liberated (deconfinement)**
- **Evolution of the early universe**
- **QGP may still exist in neutron stars**

quark-hadron phase transition



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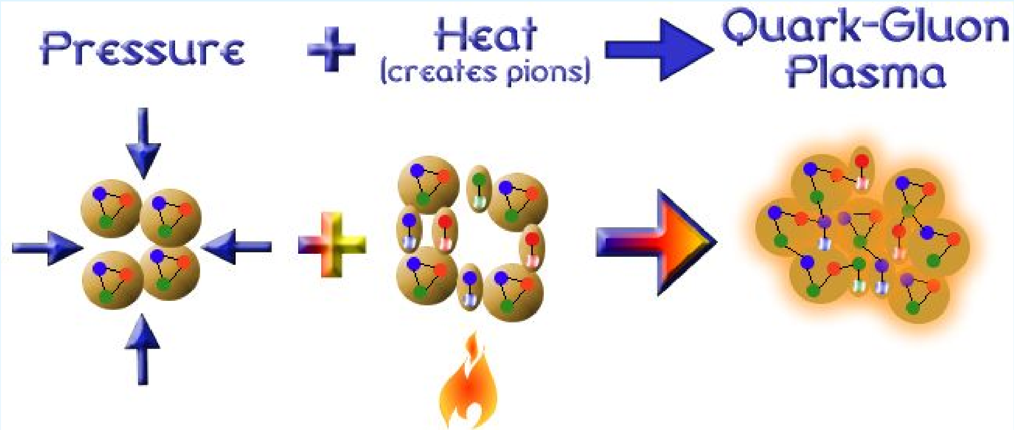

Phase transition to QGP
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- **Primordial state of matter: quarks and gluons are liberated (deconfinement)**
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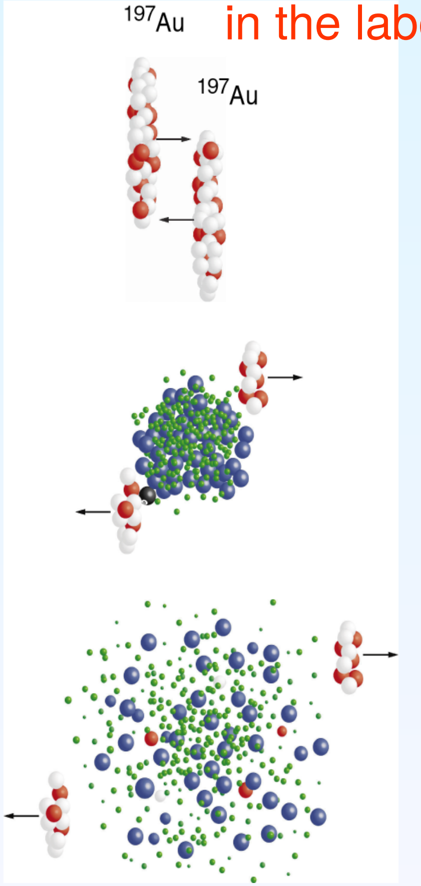
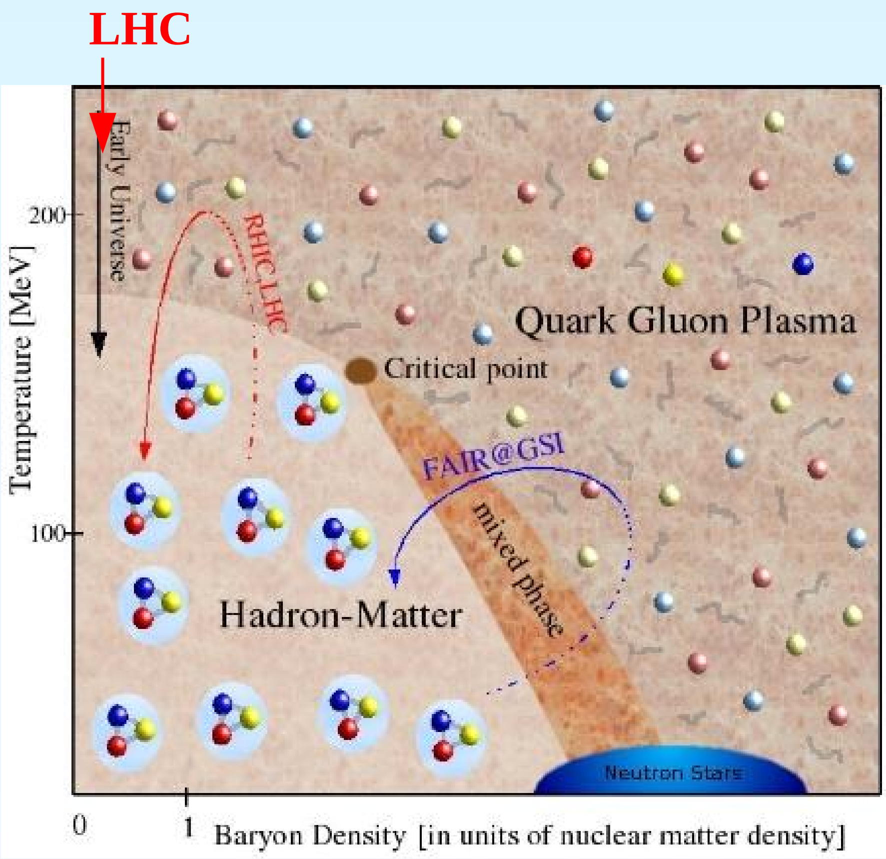
... and its realization

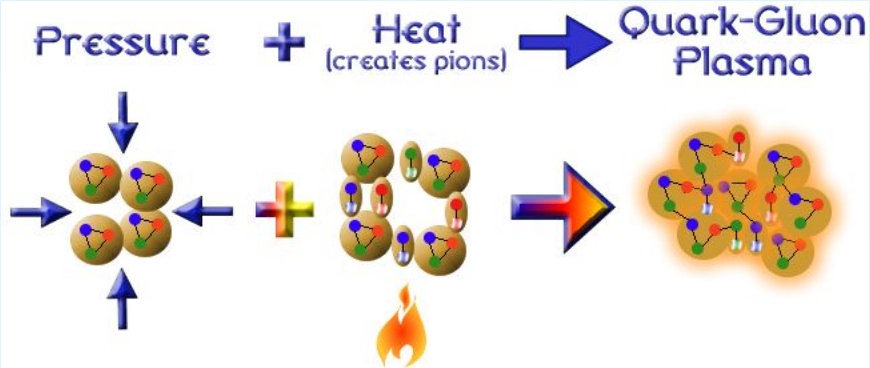
→ Relativistic collisions of heavy nuclei (Au, Pb)

„Little Bang" in the laboratory



Expected QCD Phase Diagram



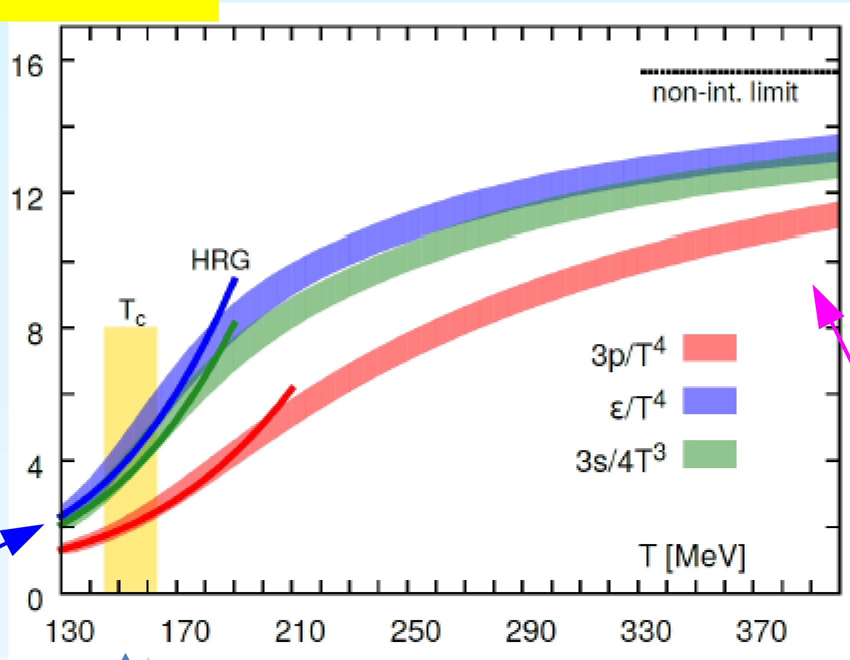


- **QCD matter at extreme conditions: high temperature and/or high density**
- **Deconfined strongly interacting matter with color degrees of freedom**
- **Restoration of chiral symmetry breaking: hadrons are much heavier than their constituents**

Predictions from First Principles: Lattice QCD

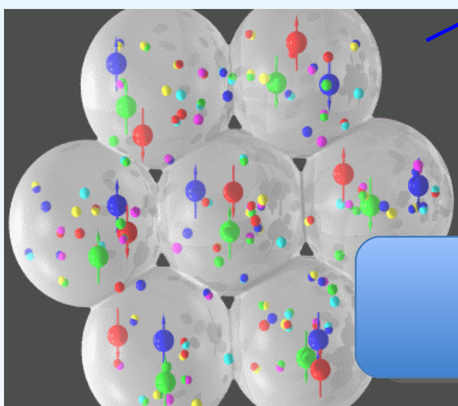
HotQCD: PRD 90 (2017) 094503

ε/T^4 ~ # degrees of freedom

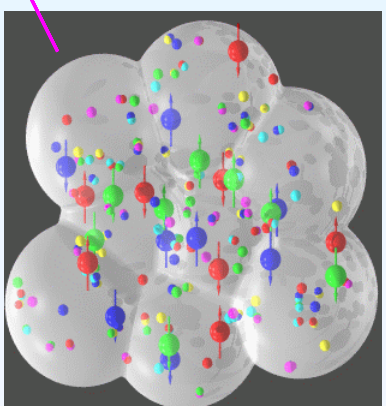


$T_c \approx 154(9)$ MeV

Hadron Gas to QGP phase transition



few d.o.f. → confined

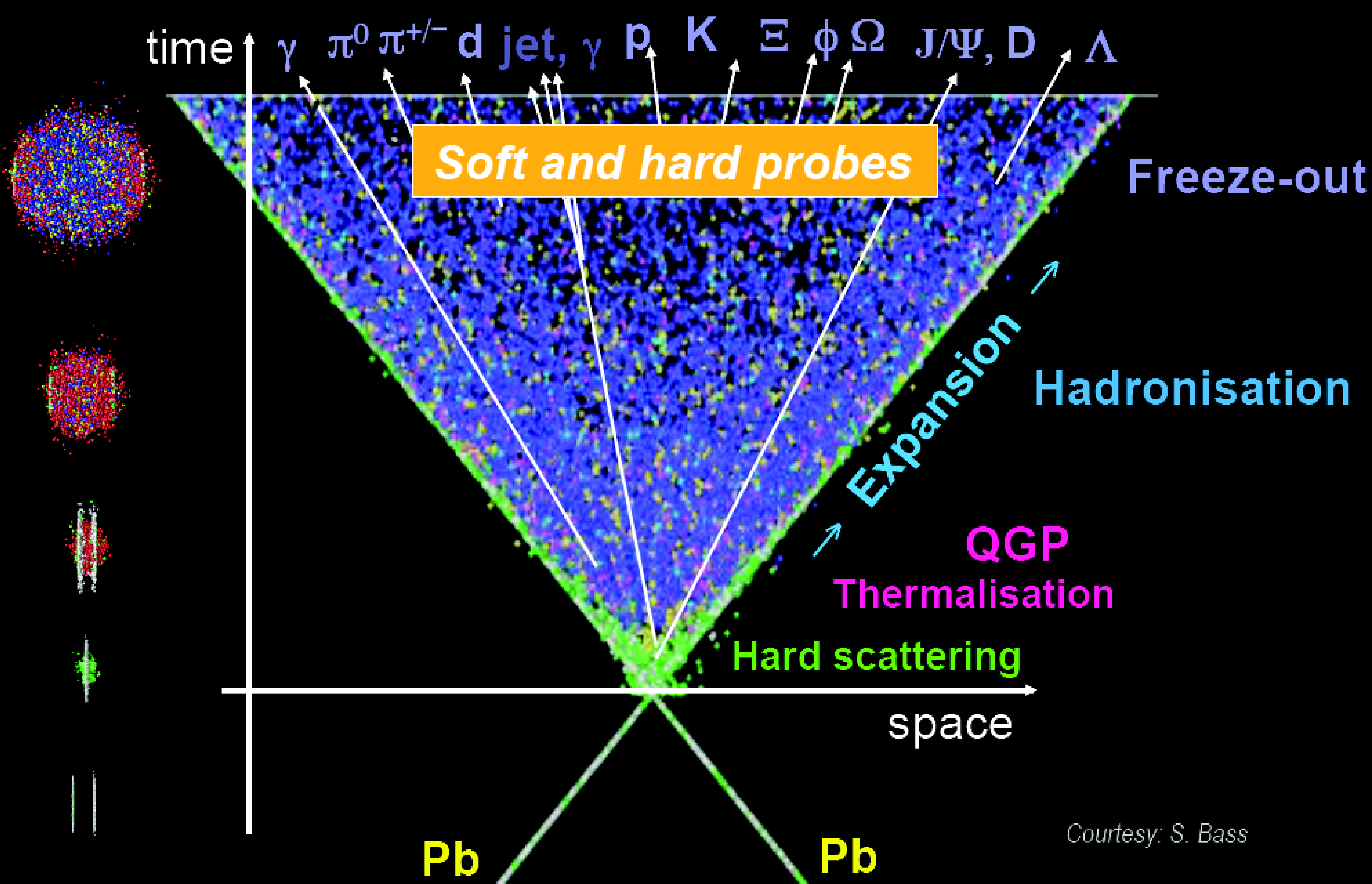


many d.o.f. → deconfined

The Large Hadron Collider

LHC Run 1 and 2	
pp	0.9–13 TeV
p-Pb	5.02 TeV 8.16 TeV
Xe-Xe	5.44 TeV
Pb-Pb	2.76 TeV 5.02 TeV

Space-time evolution of a heavy-ion collision



Example of a Heavy-Ion Experiment

A Large Ion Collider Experiment

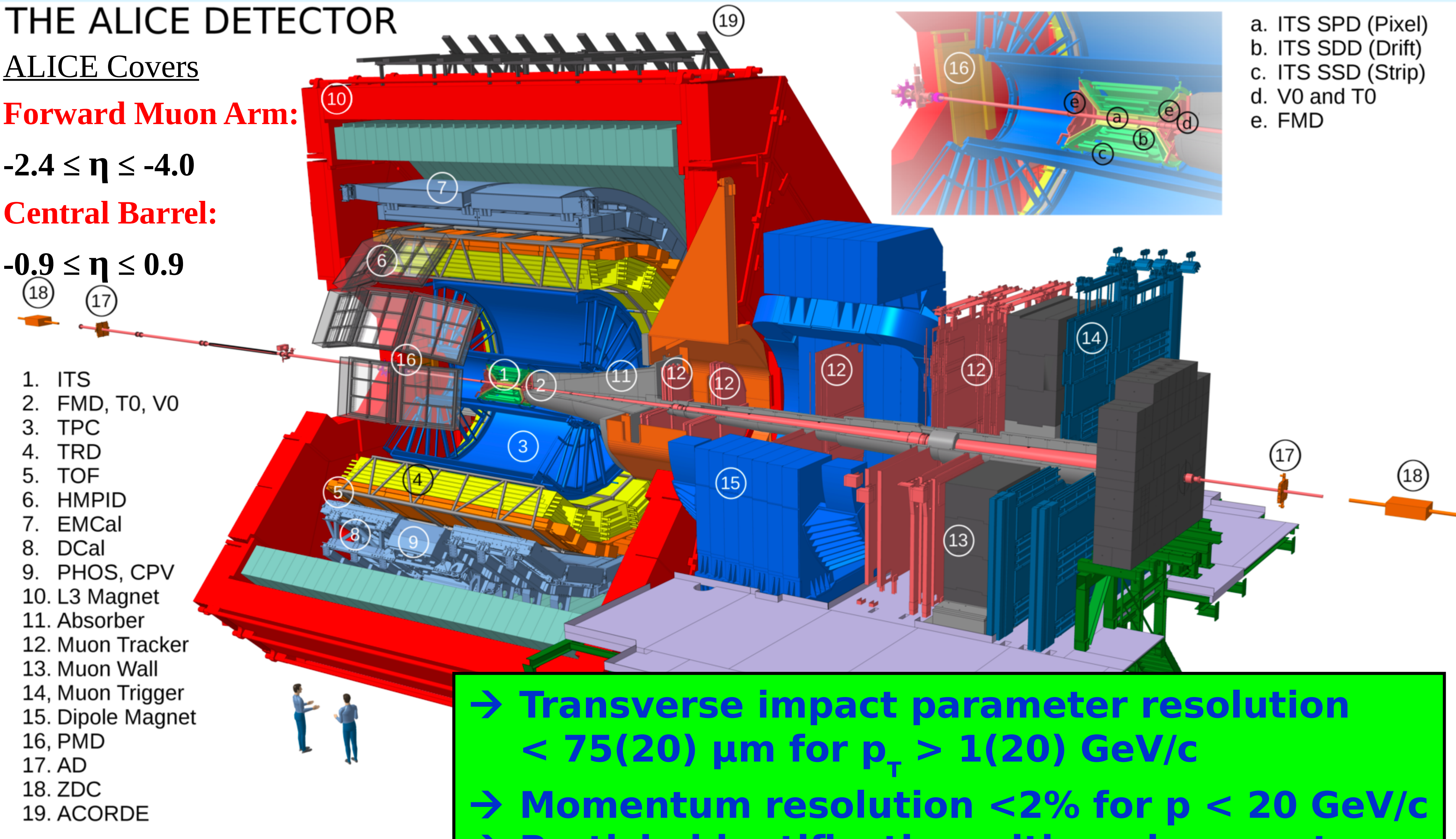
ALICE Covers

Forward Muon Arm:

$-2.4 \leq \eta \leq -4.0$

Central Barrel:

$-0.9 \leq \eta \leq 0.9$

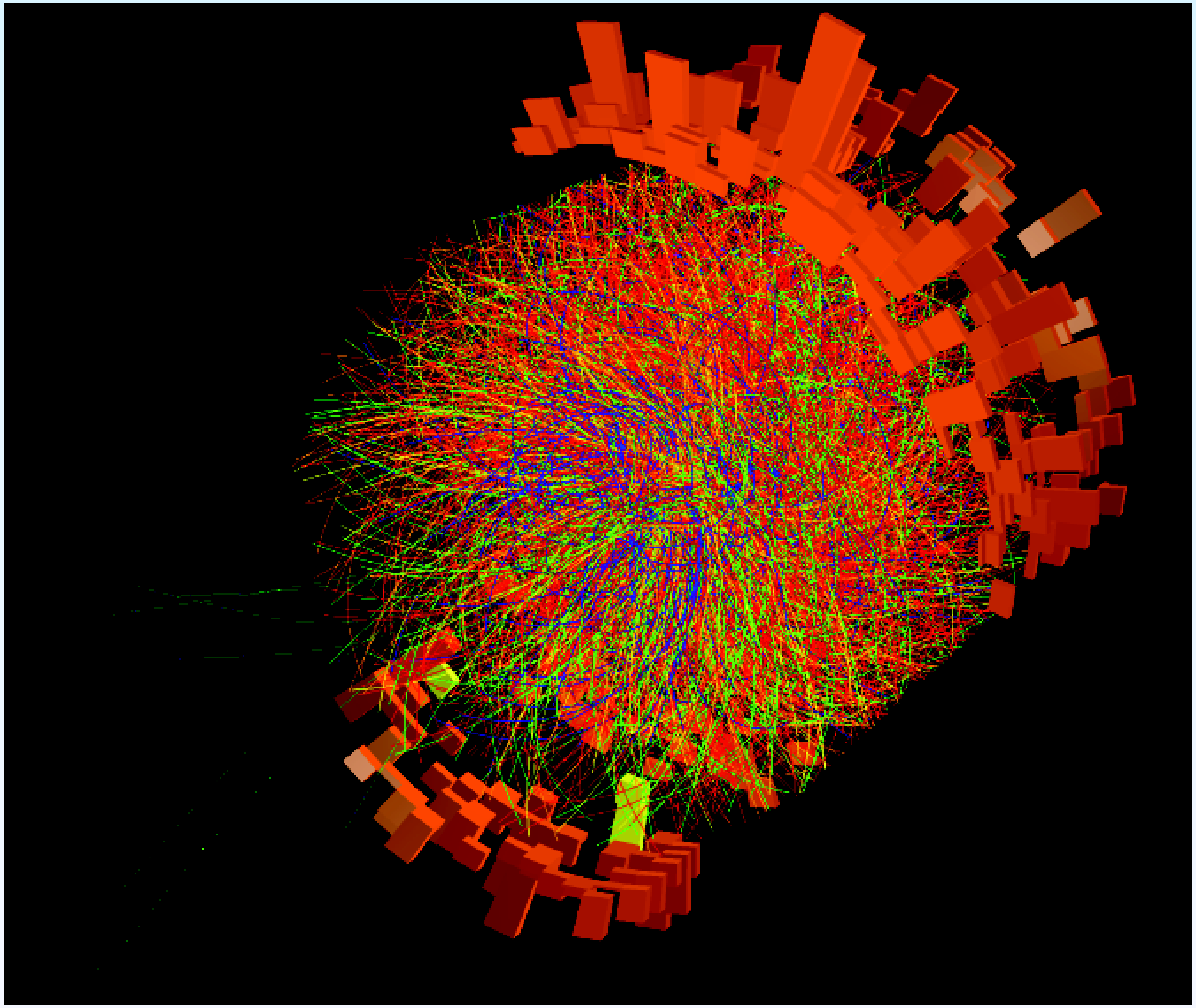


→ **Transverse impact parameter resolution < 75(20) µm for p_T > 1(20) GeV/c**

→ **Momentum resolution <2% for p < 20 GeV/c**

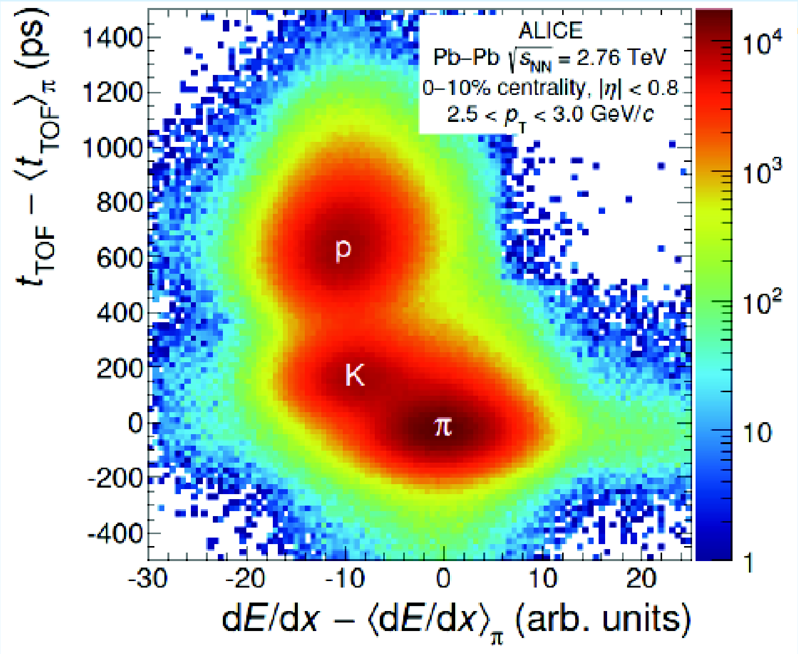
→ **Particle identification with various systems**

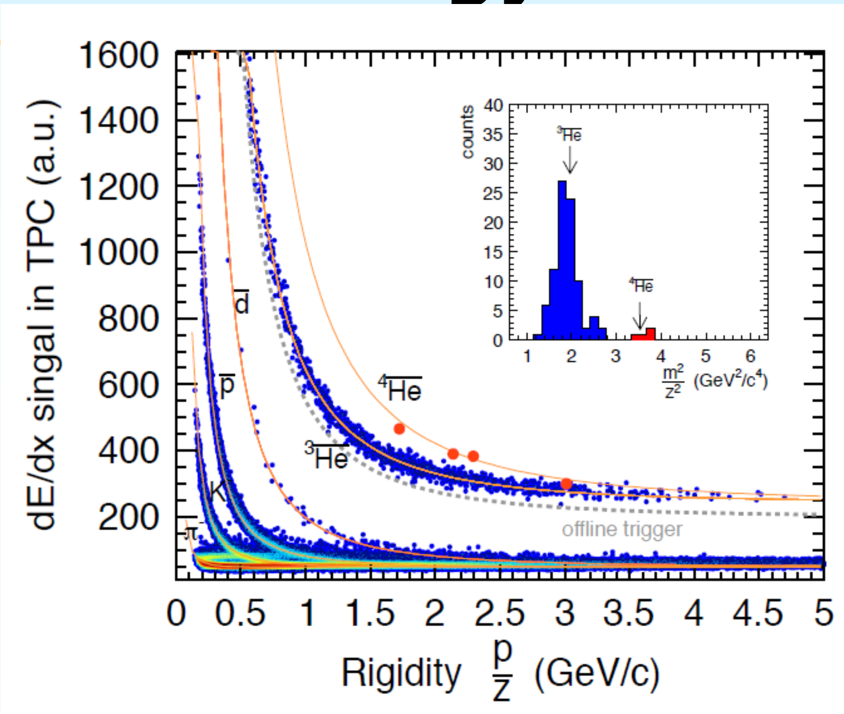
Typical Event Display

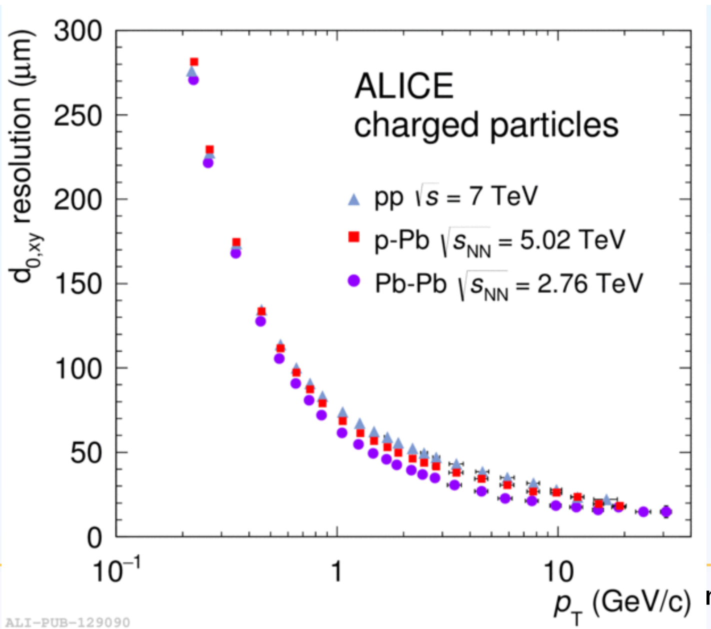


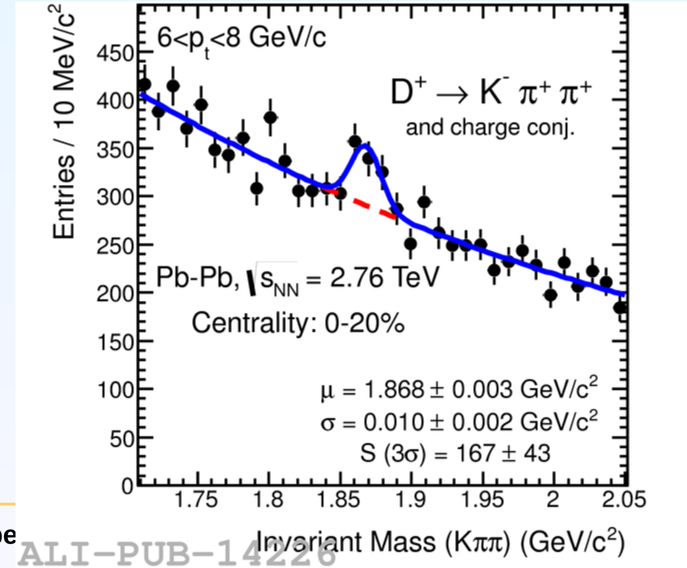
Tracks of particles recorded with the Time Projection Chamber and clusters in the calorimeter for a Pb-Pb collision at $\sqrt{s_{NN}}$ = 5.02 TeV

Experimental Methodology

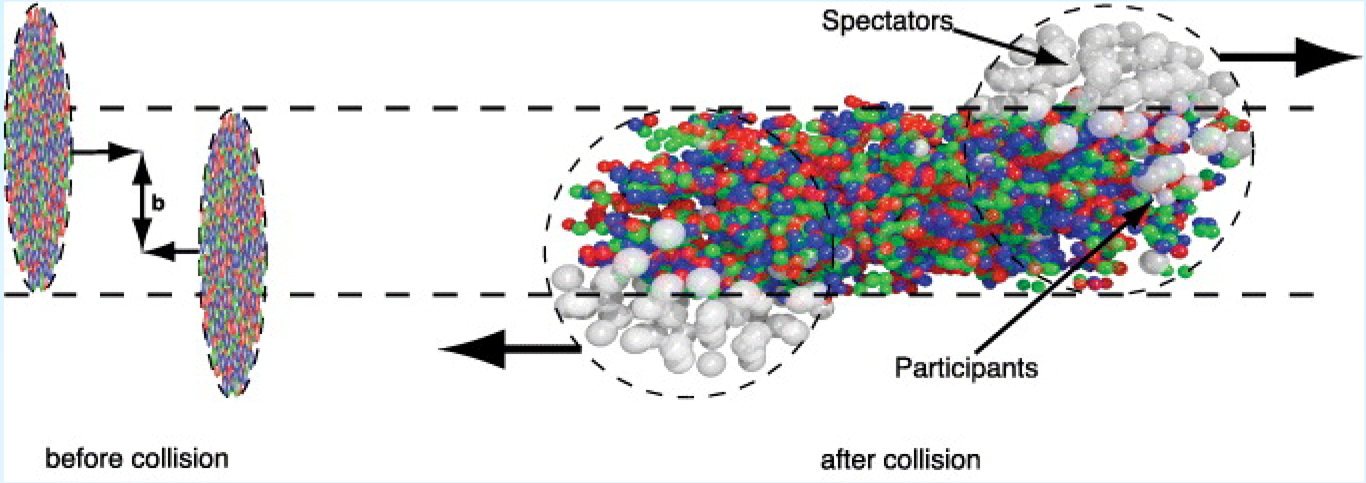




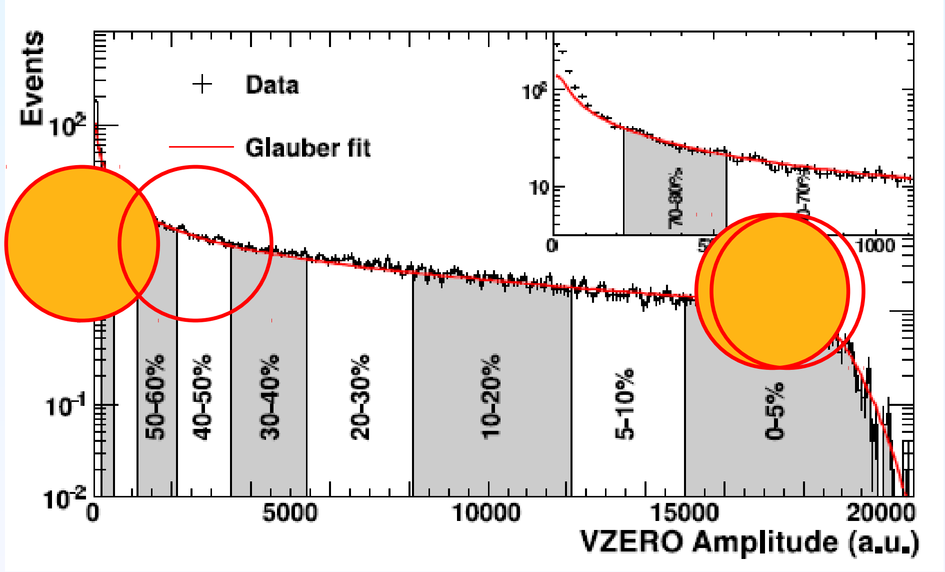




Geometry Plays a Key Role in Ultra-Relativistic Heavy-Ion Physics



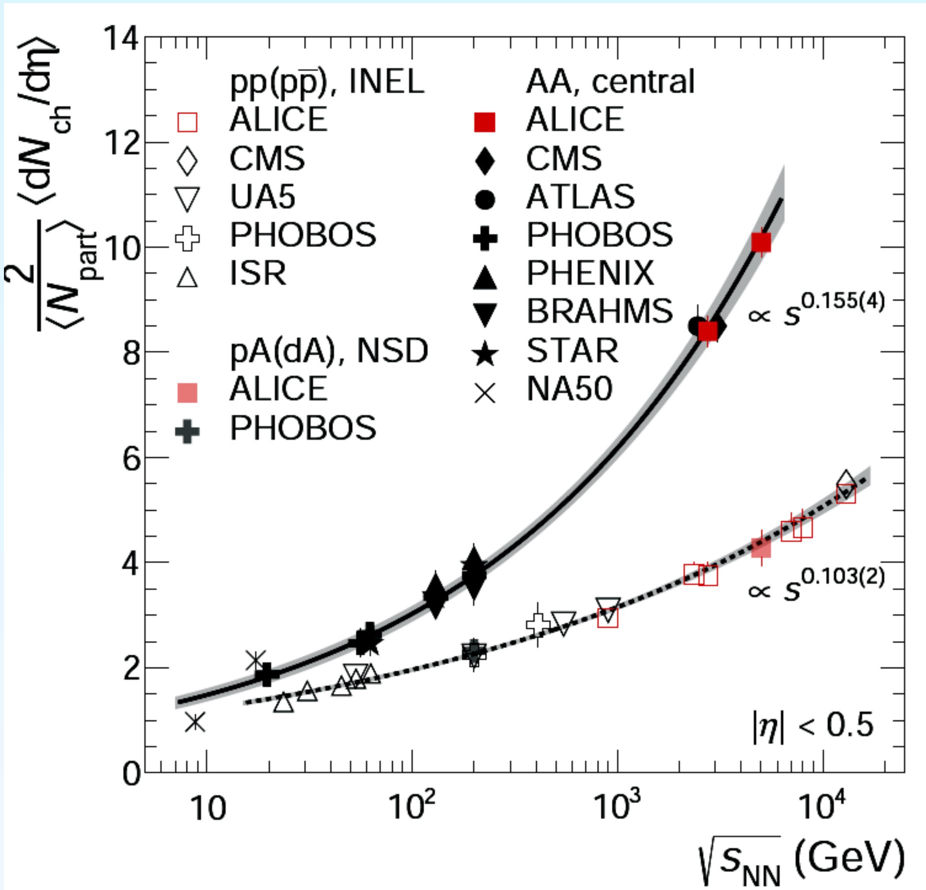
- Number of participants: number of nucleons in the overlap region
- Number of binary collisions: number of inelastic nucleon-nucleon collisions
- Small impact parameter b corresponds to large particle multiplicity



Global Event Observables

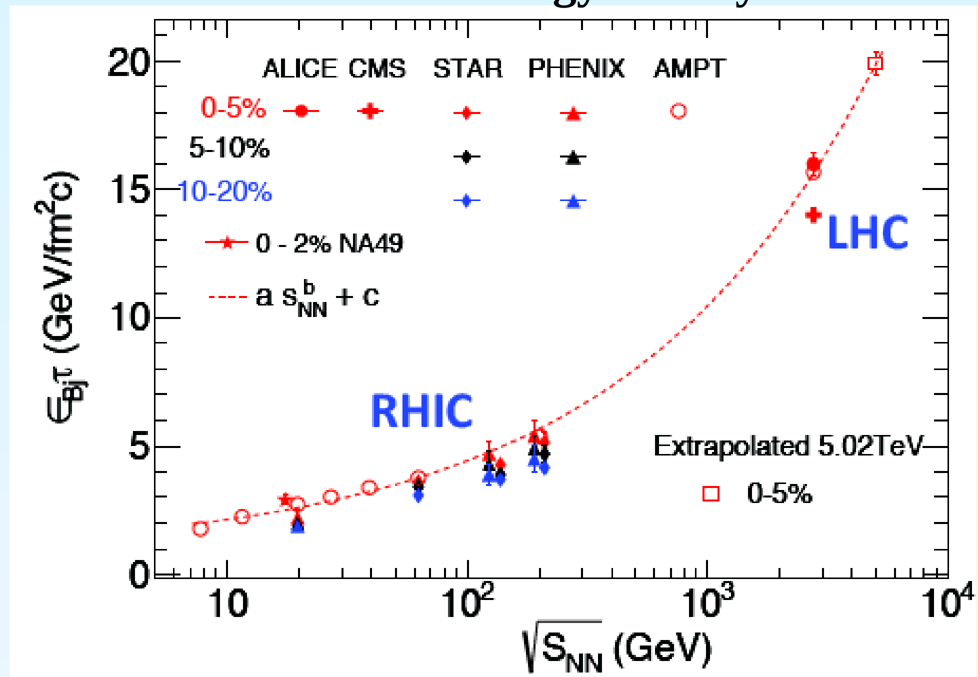
Multiplicity Distribution

Multiplicity density vs. energy

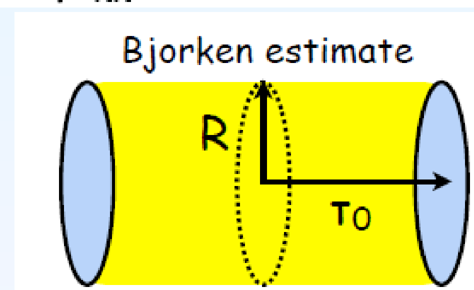


ALICE: PRL 116 (2016) 222302

Estimated energy density



$$\epsilon_{\mathrm{Bj}} = \frac{dE_T/d\eta}{\pi R^2 \tau_0}$$

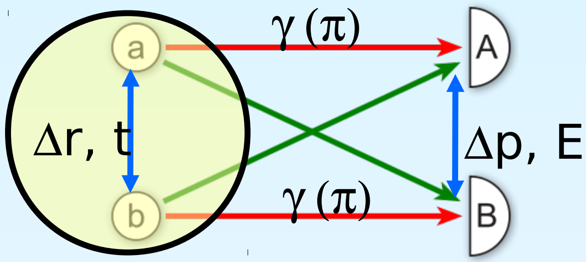


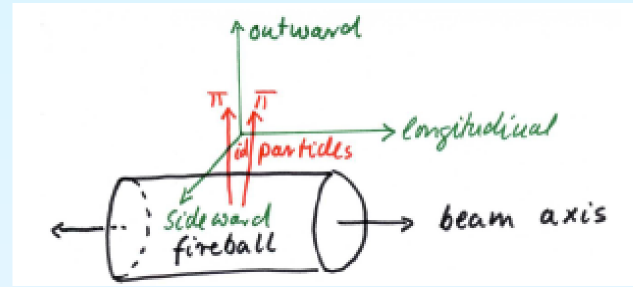
→ $\varepsilon\tau \sim$ 15-18 GeV/fm^{2}c
(~factor 3-4 larger than RHIC)

Global Observables

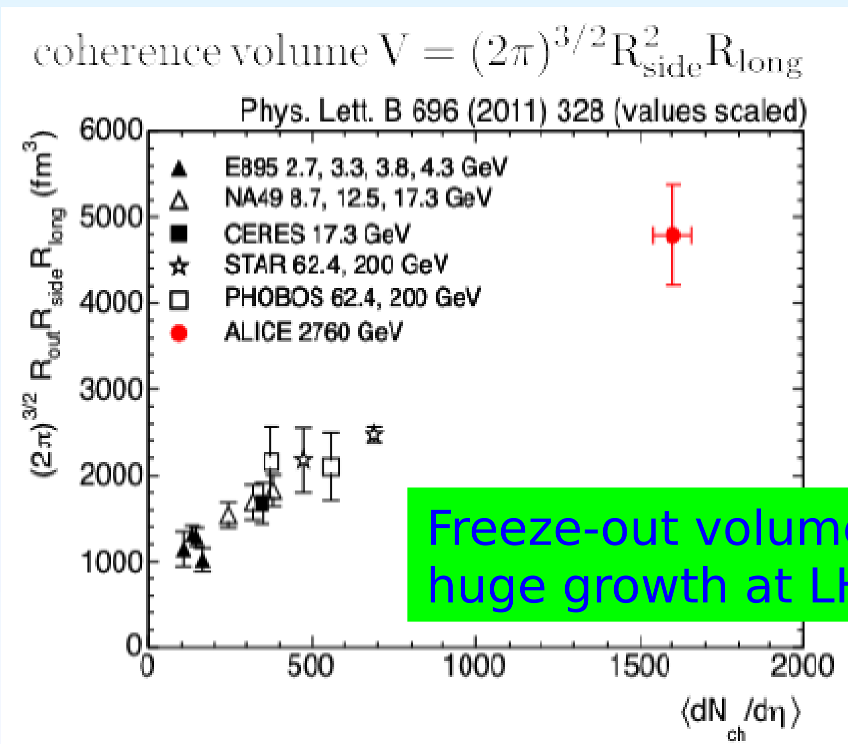
Hanbury Brown-Twiss Interferometry and Space-Time Extent of Fireball

Technique of intensity interferometry developed by Hanbury Brown and Twiss in astrophysics as a means to determine size of distant objects

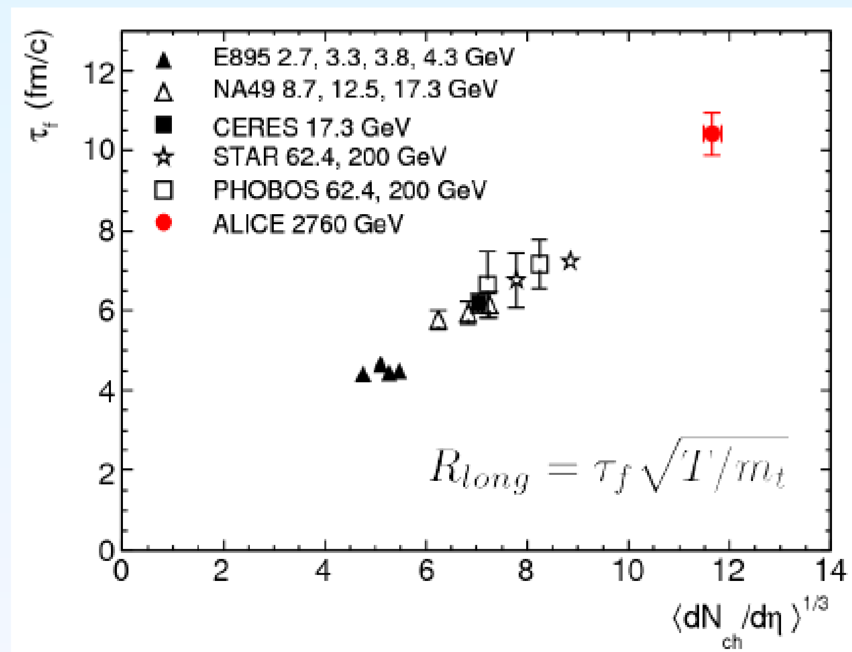




J. Stachel



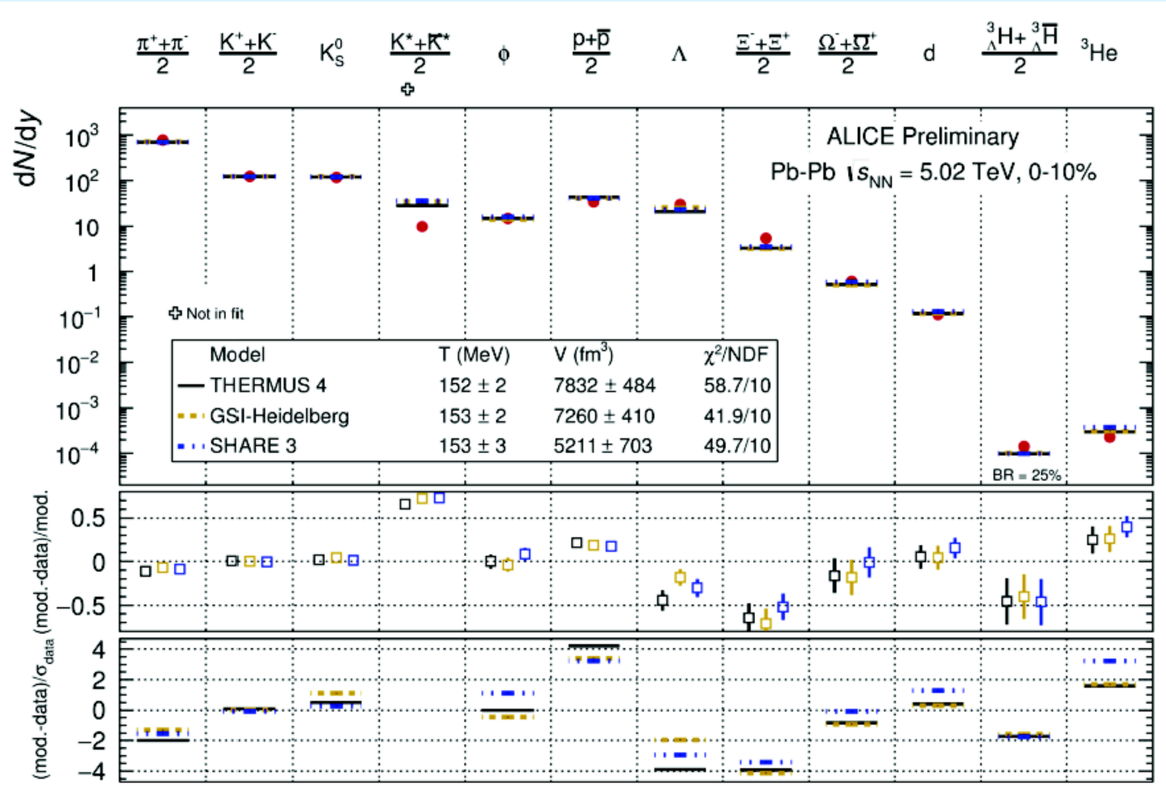
Freeze-out volume
huge growth at LHC



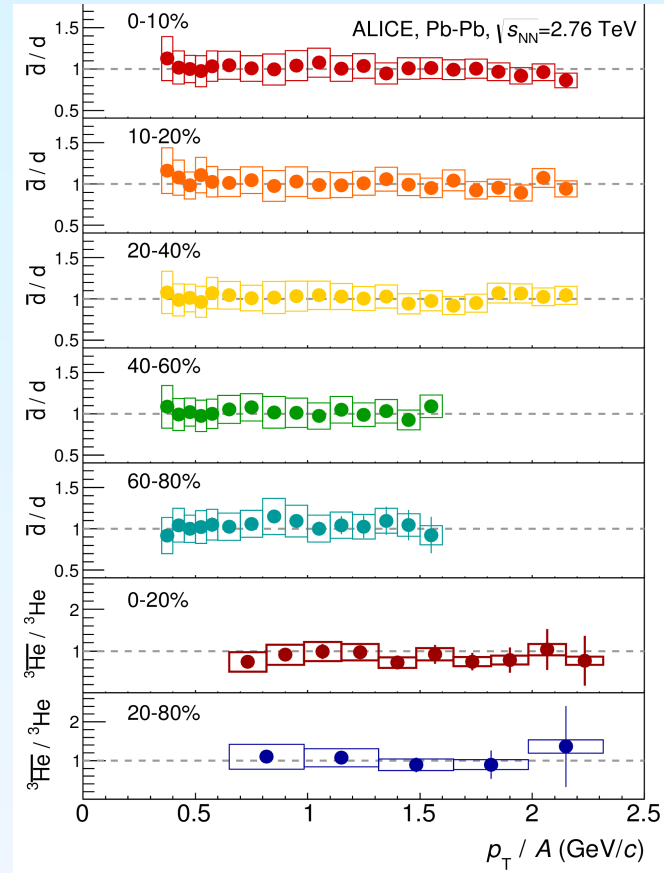
From R_{long}: expansion at LHC 10 fm/c

Thermal Statistical Model: T, V and μ_B

A. Kalweit QM2018



ALICE: PRC93 (2015) 024917

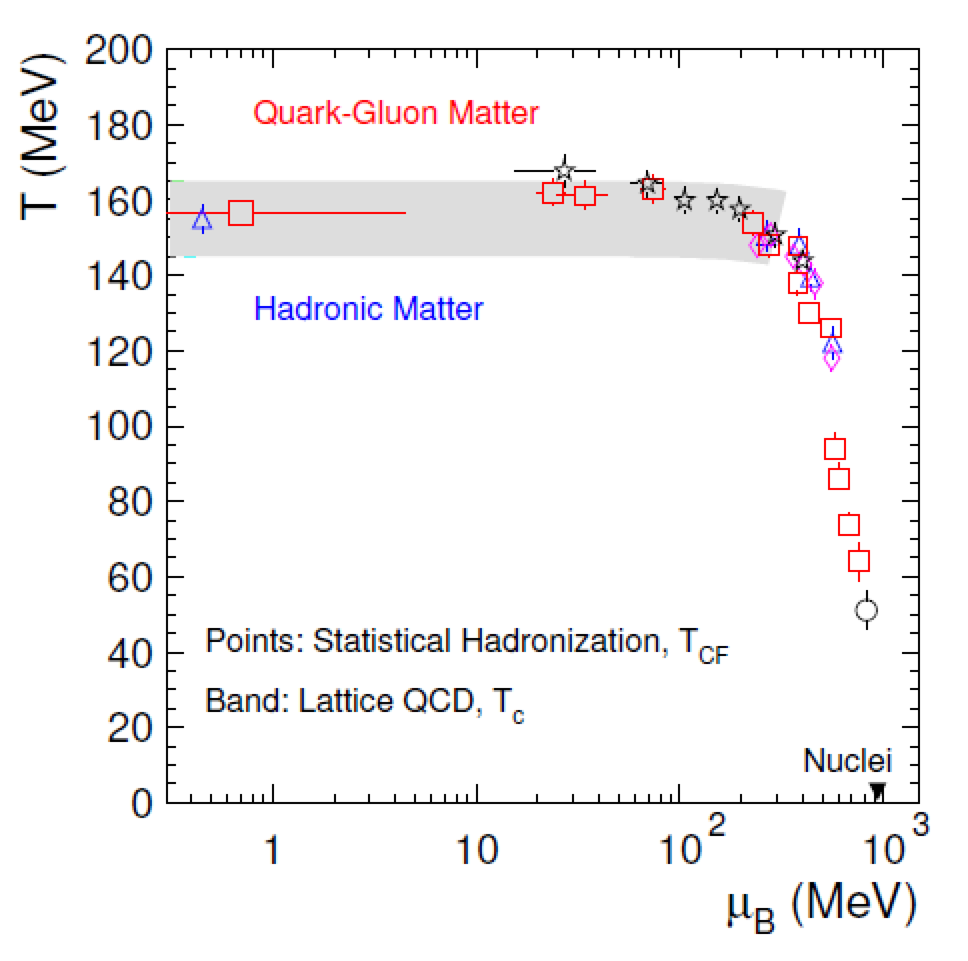


- Yields of light flavour hadrons well described by equilibrium model over 7 orders of magnitude
- Particle/anti-particle ratios at 1

→ T_{ch} = 153 MeV
→ μ_B = 0

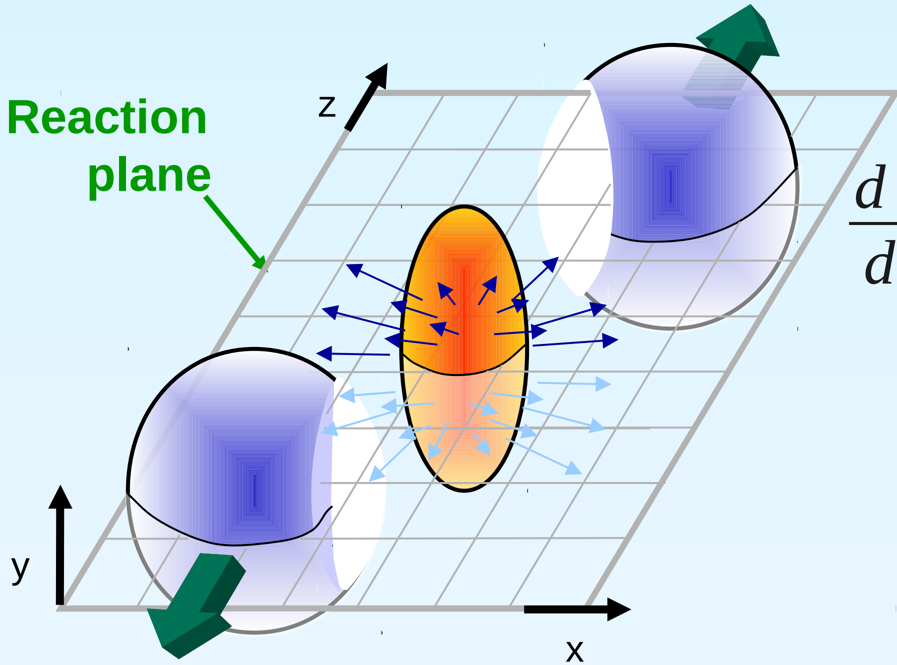
Phenomenological phase diagram of strongly interacting matter

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) no.7723, 321-330



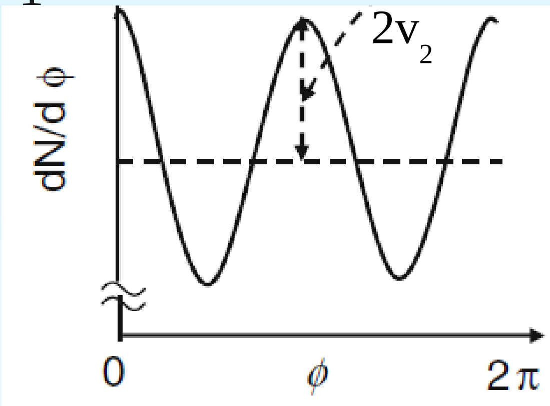
- Chemical freeze-out points resulting from statistical hadronization analysis of hadron yields for central collisions at different energies

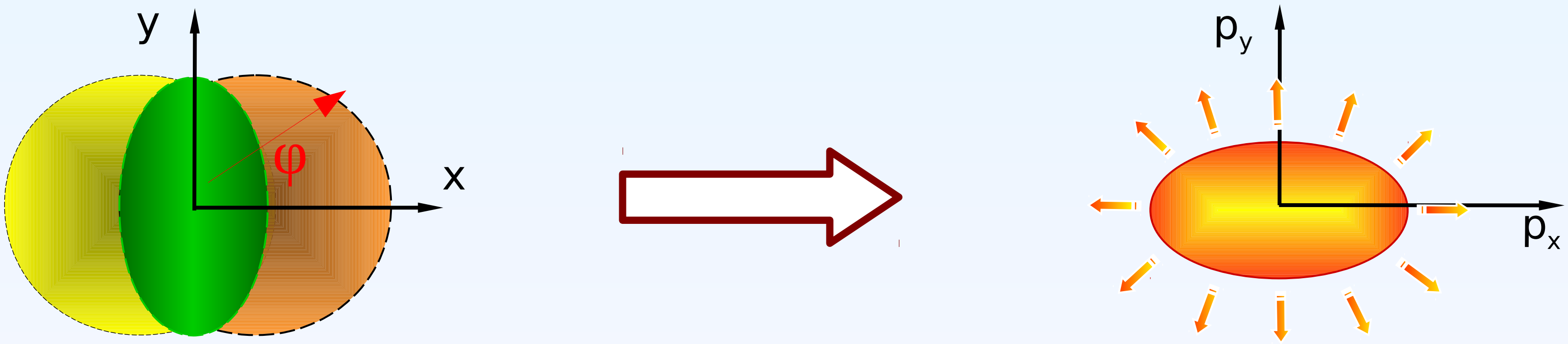
Global Observables
Collective Effects



Fourier decomposition of momentum distribution relative to reaction plane

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos\left(n\left(\varphi - \Psi_{RP}\right)\right)$$



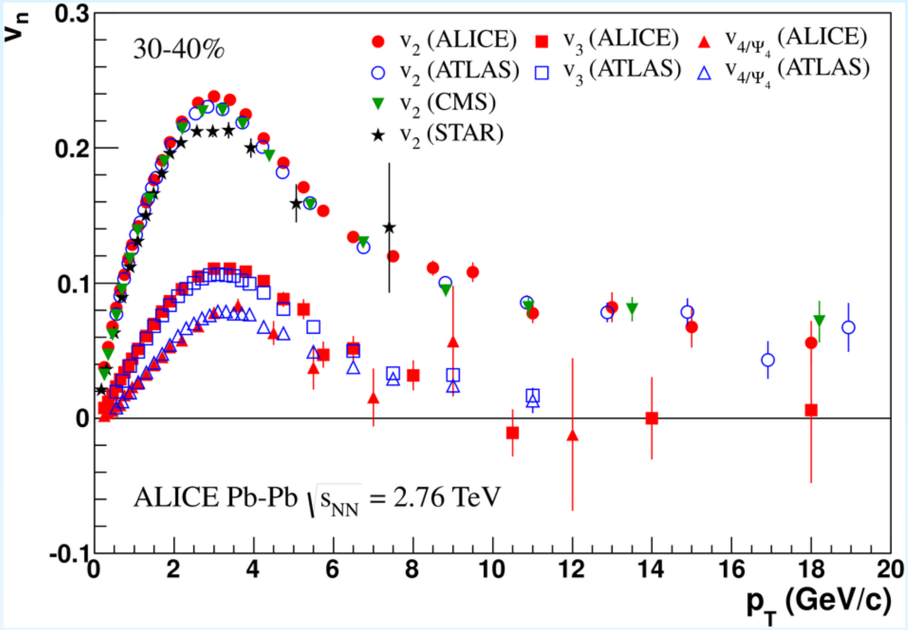


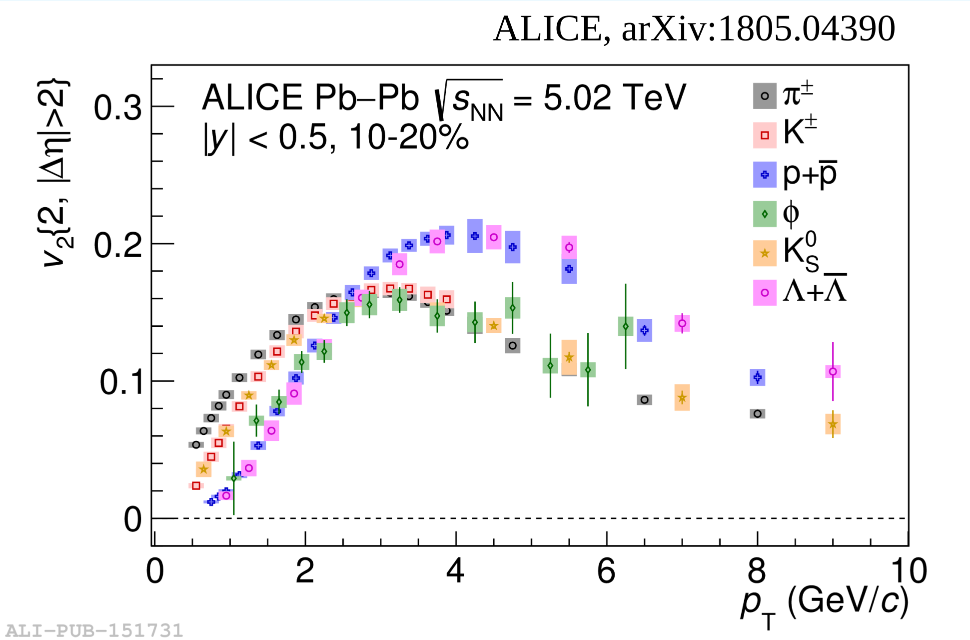
Coordinate space: initial asymmetry

Collective interaction pressure

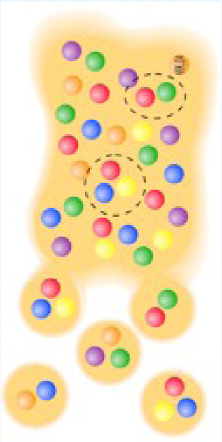
Momentum space: final asymmetry

Collective Behaviour

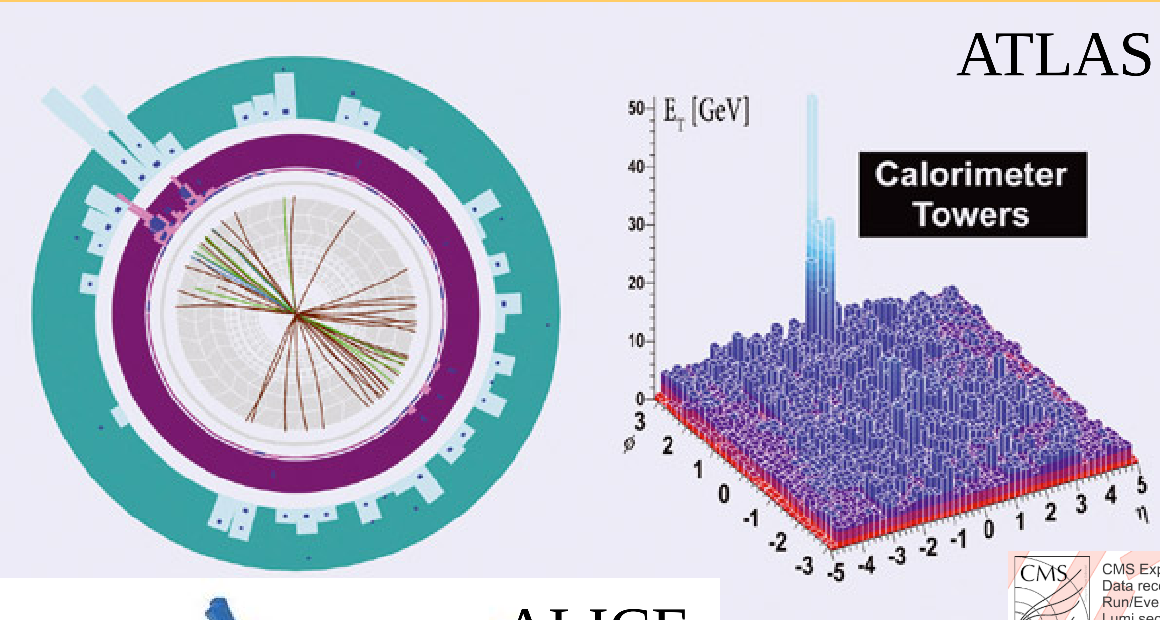




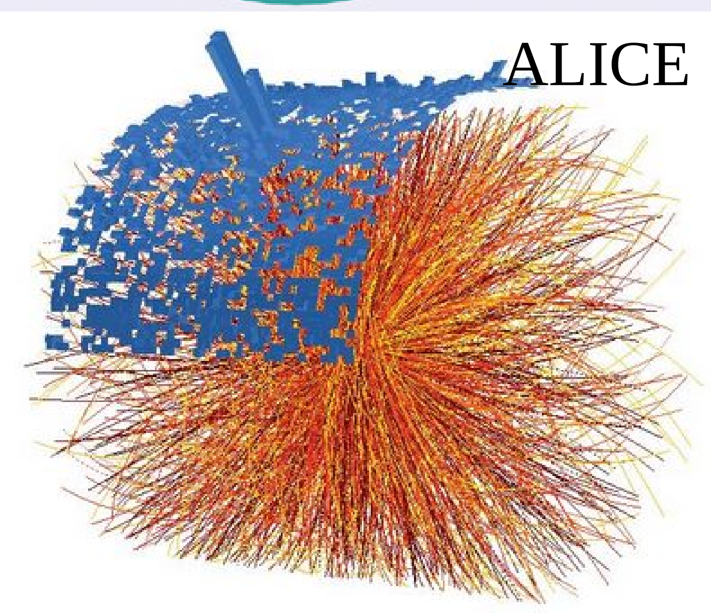
- **Good agreement with hydrodynamical calculations**
  - Strongly-coupled medium with very low shear viscosity (→ $\eta/s = 1/4\pi$; perfect liquid)
- **Mass ordering for p_T < 2 GeV/c interpreted as an interplay of radial and elliptic flow**
- **Interesting difference for mesons and baryons at intermediate p_T**
  - Hadronization via recombination?



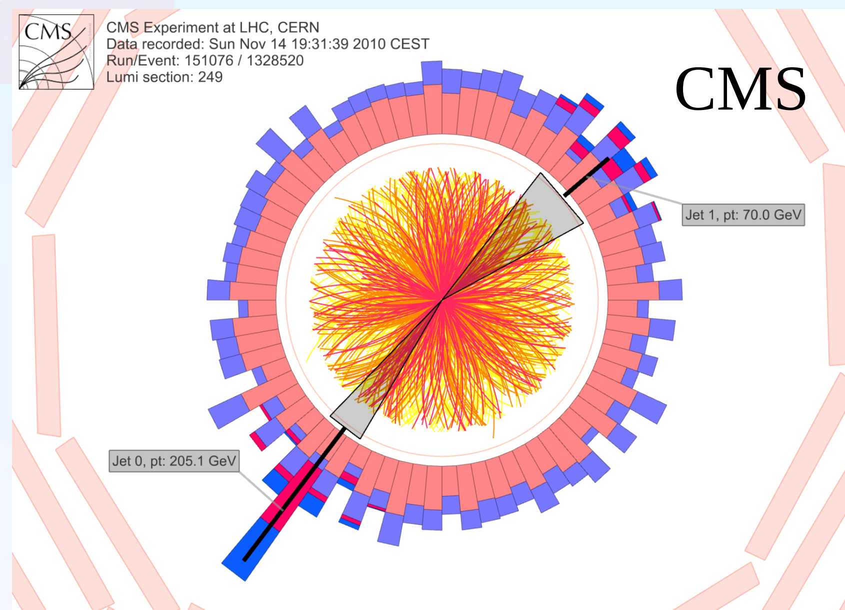
Hard Probes



ATLAS
E_T [GeV]
Calorimeter Towers
φ
η



ALICE



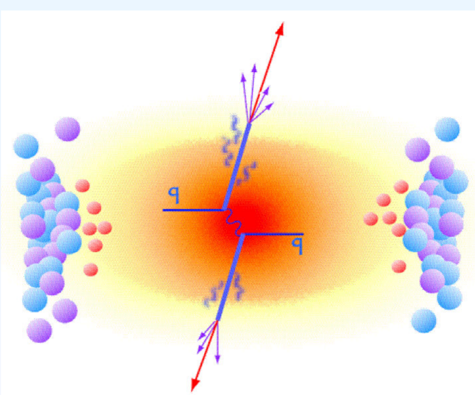
CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

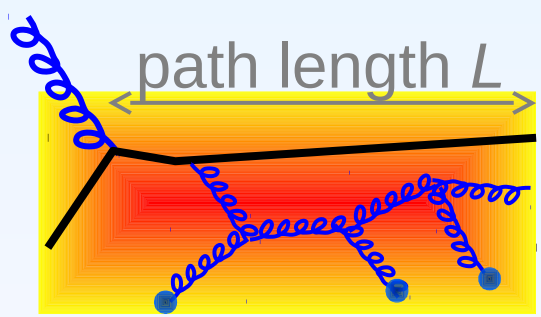
Hard Probes

- **Hard Probes: Jets, open heavy-flavour hadrons (charm and beauty)**
  - Produced at the very early stage of the collision in partonic processes with large Q^2
  - Sensitive to the full history of the collision
  - Study the properties of the deconfined medium produced in Pb-Pb collisions
    - Energy loss different for quarks and gluons (colour factor, dead cone effect)

      Expected behaviour: $\Delta E_g > \Delta E_{charm} > \Delta E_{beauty}$

    - Parton energy loss depends on medium properties, transport coefficients etc.





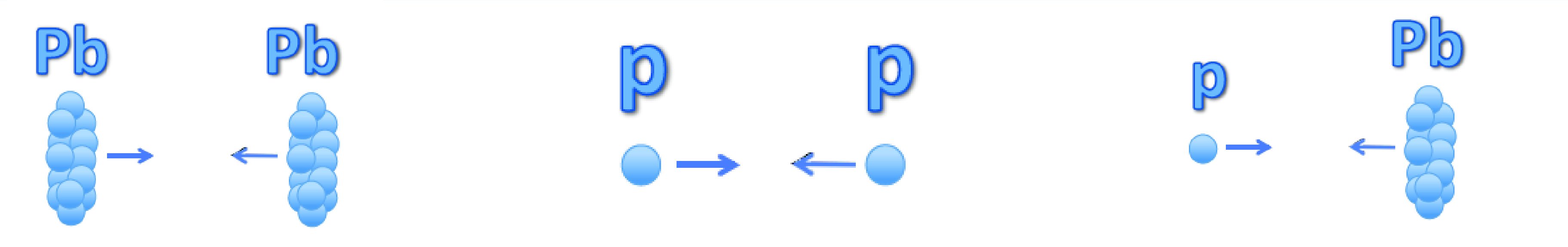
Colour Charge
C_R=3 for gluons, C_R=4/3 for quarks

$$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$$

BDMPS approach

Transport coefficient related to medium characteristics and gluon density

Nuclear Modification Factor R_{AA}



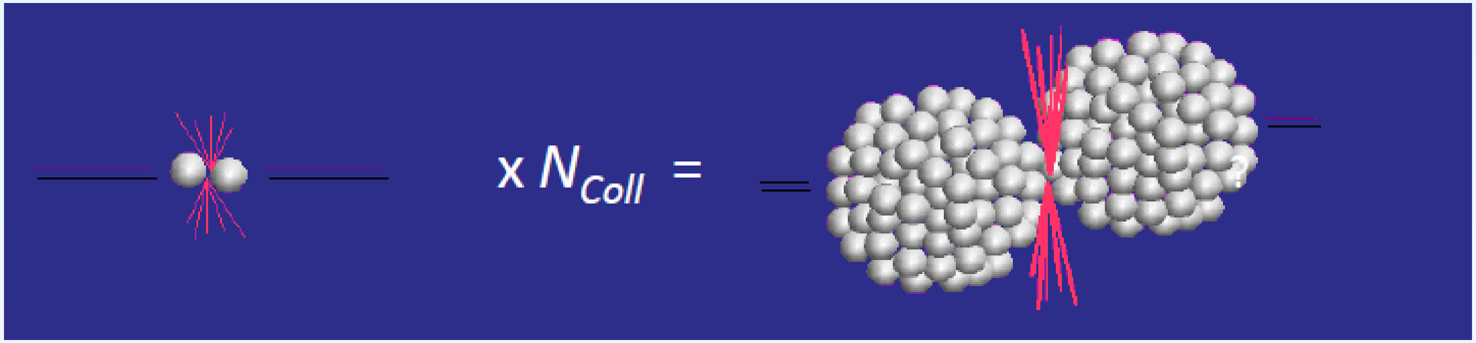
Cold nuclear matter effects
+ hot nuclear matter effects
(related to the Quark-Gluon Plasma)

Elementary collision
No nuclear matter effects

Cold nuclear matter effects -
without Quark-Gluon Plasma

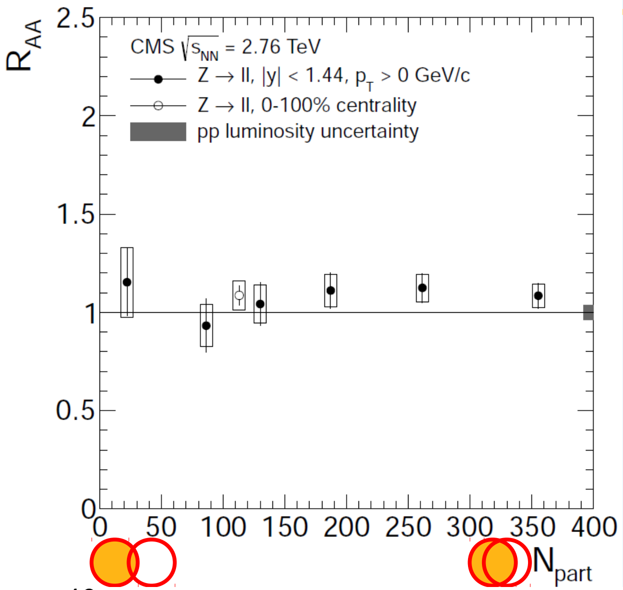
$$R_{AA}(p_T) = \frac{1}{N_{coll}} \cdot \frac{d^2N^{AA}/dp_T\,dy}{d^2N^{pp}/dp_T\,dy}$$

Needs pp reference at same √s !



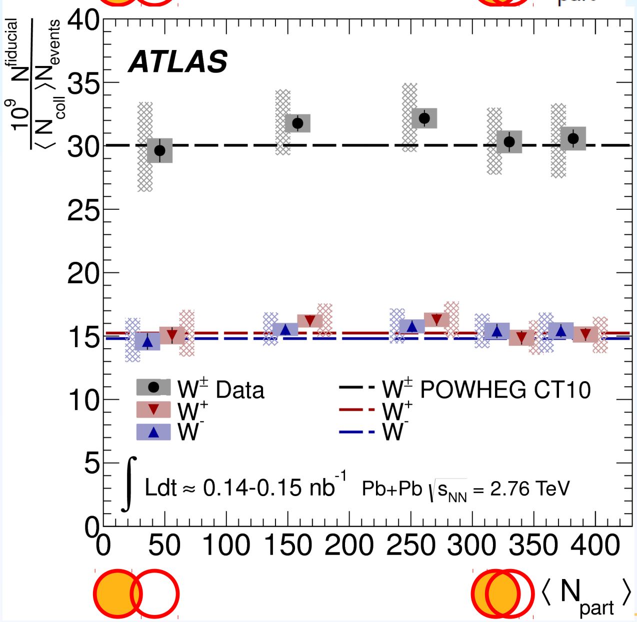
At high p_T: R_{AA} = 1 if no nuclear modification!

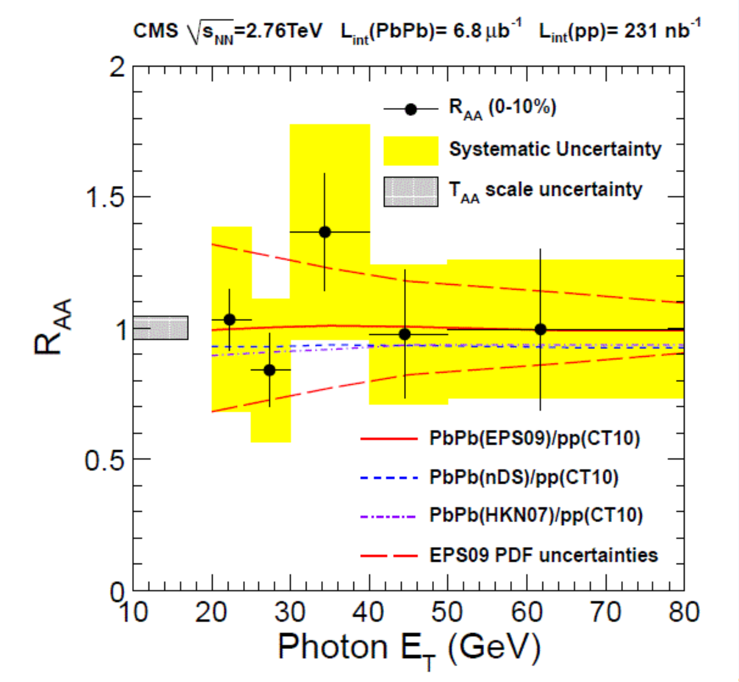
Electromagnetic Probes



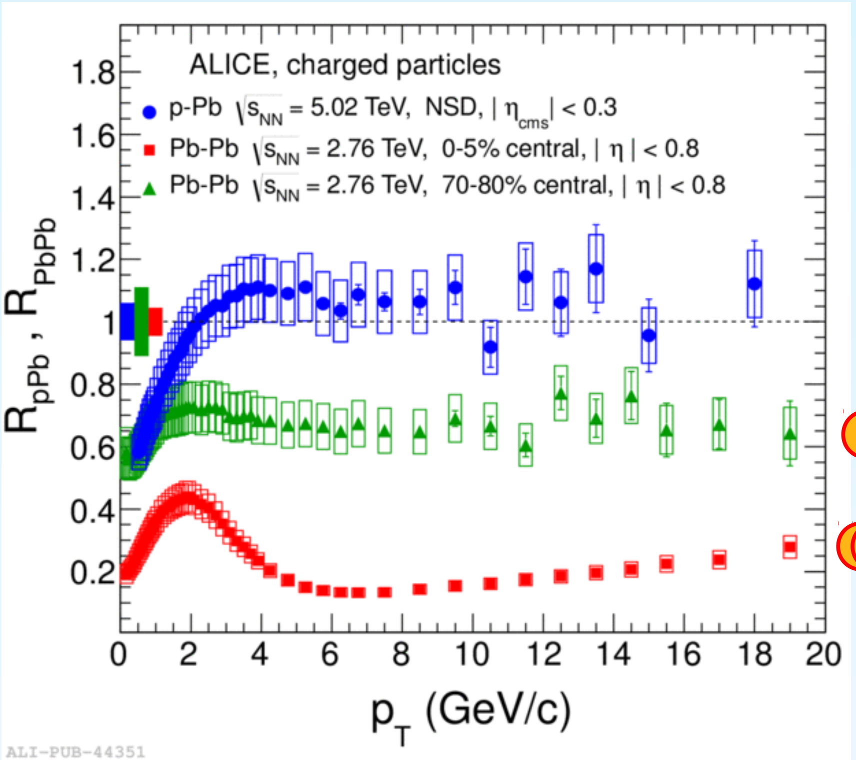
CMS: JHEP03 (2015) 022, PLB715 (2012) 66, PLB710 (2012) 256, CMS-HIN-11-002
ATLAS: PRL110 (2013) 022301, EPJC75 (2015) 23, PRC93 (2016) 034914

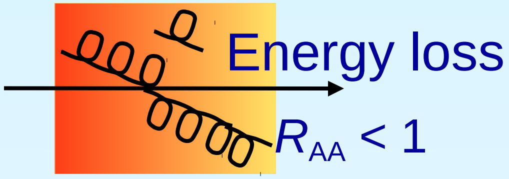
- **Photons, W and Z bosons**
  - Do not carry colour charge → $R_{AA} = 1$
  - → **Scale with N_{coll} independent of centrality**
  - → **Compatible with NLO QCD calculations**

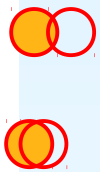




High-p_T hadrons (I)







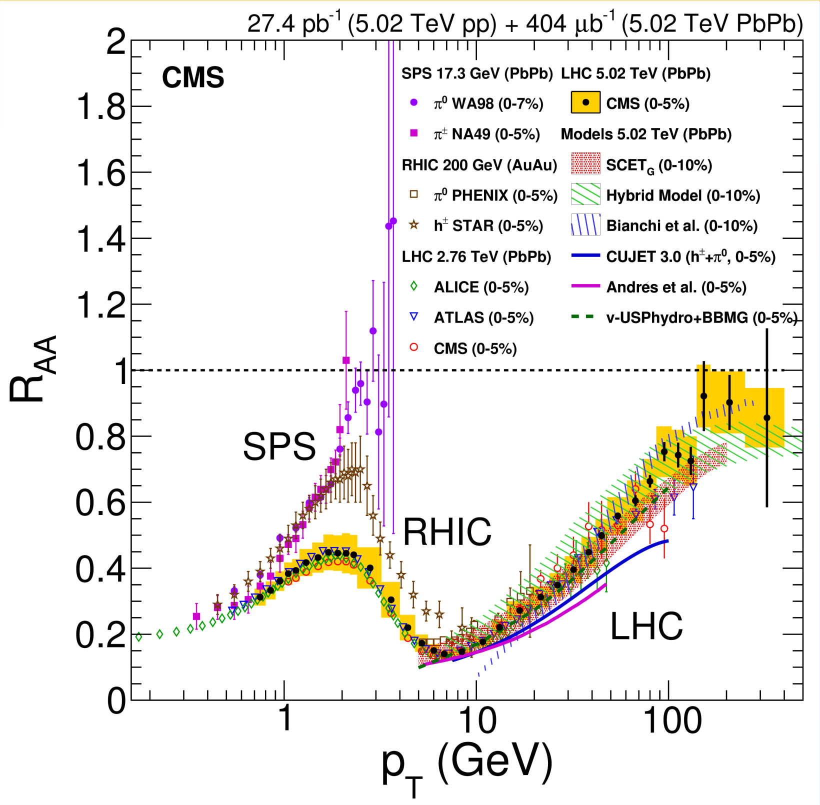
- **In Pb-Pb collision: at high p_T charged hadrons suppressed**
  → final state effect

qhat = 1.2 GeV^2/fm at T = 370 MeV
qhat = 1.9 GeV^2/fm at T = 470 MeV

- **In p-Pb collisions: R_{AA} = 1 → confirms final state effect in Pb-Pb**
  - Initial state effects small

High-p_T hadrons (II)

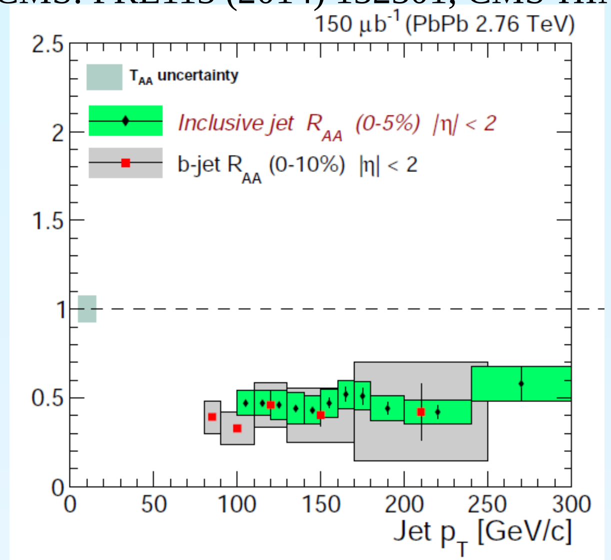
CMS: JHEP 04 (2017) 039



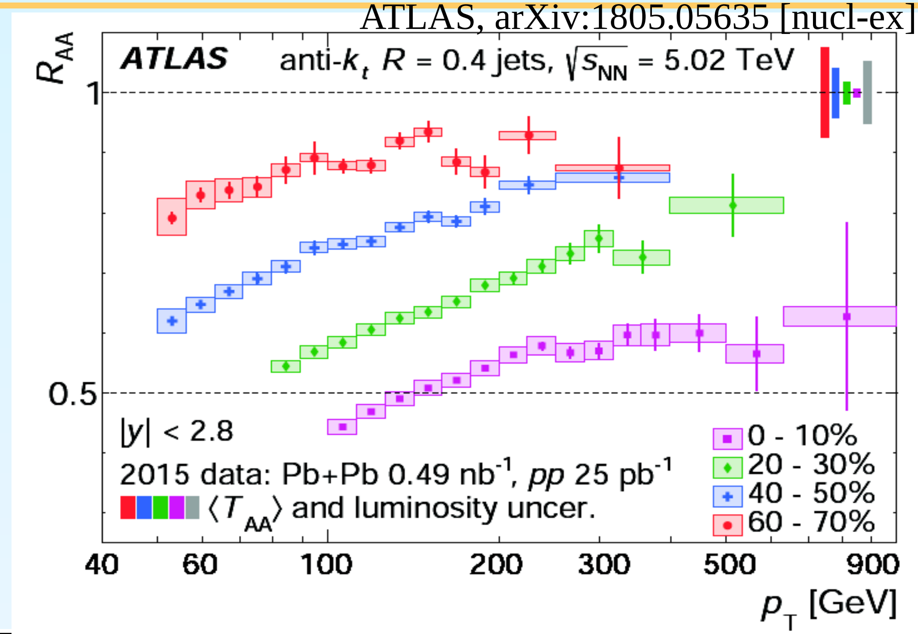
- **LHC vs RHIC**
  - R_{AA}(LHC) < R_{AA}(RHIC) for p_T < 10 GeV/c
  - Intermediate p_T similar R_{AA} despite harder p_T spectrum at LHC → larger ΔE
- **Increase vs p_T indicates $\Delta E/E$ decreases with E**
- **Expected: energy loss depends on transport coefficients and E → in high energy limit $E \gg \Delta E$**

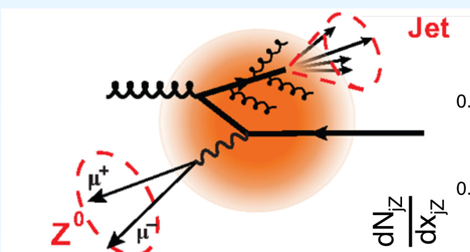
Jet Modification

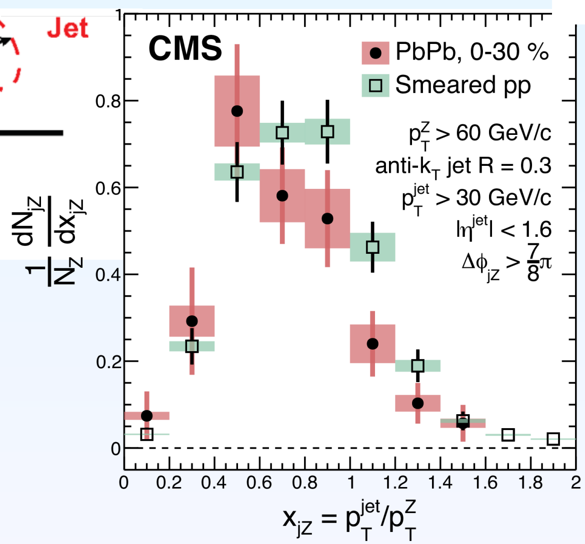
CMS: PRL113 (2014) 132301, CMS-HIN-16-005



ATLAS, arXiv:1805.05635 [nucl-ex]



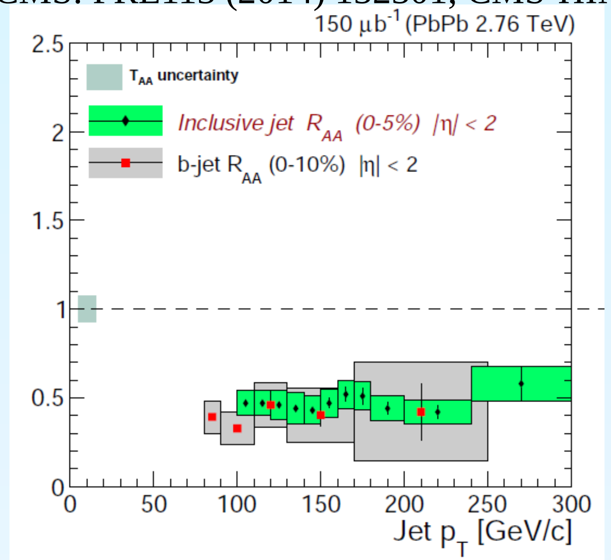




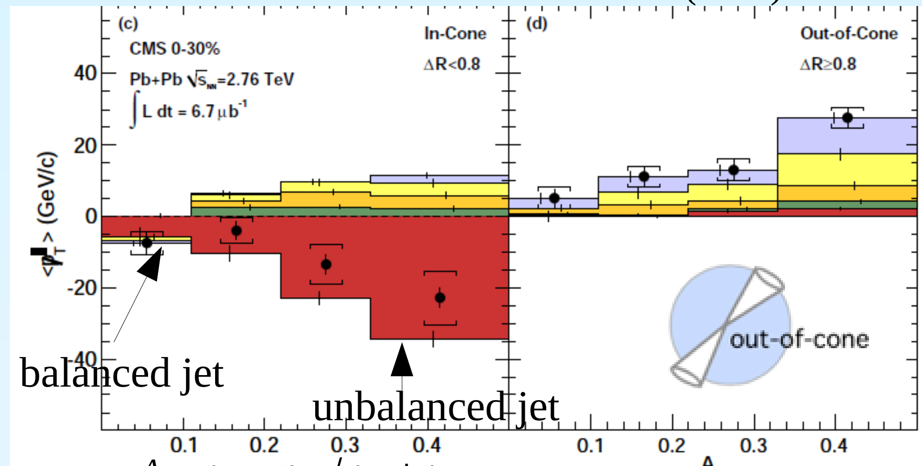
- **Inclusive jet production suppressed**
- **b-jet R_{AA} shows same strong suppression (~3) as inclusive jet R_{AA}**
- **Internal structure of jets is modified**
- **Larger fraction of partons associated with Z bosons lose energy in Pb-Pb compared to pp**

Jet Modification

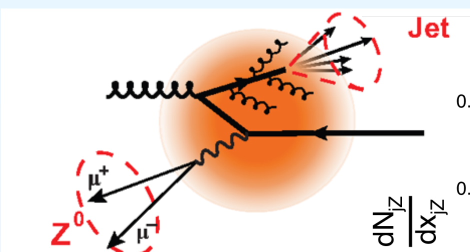
CMS: PRL113 (2014) 132301, CMS-HIN-16-005

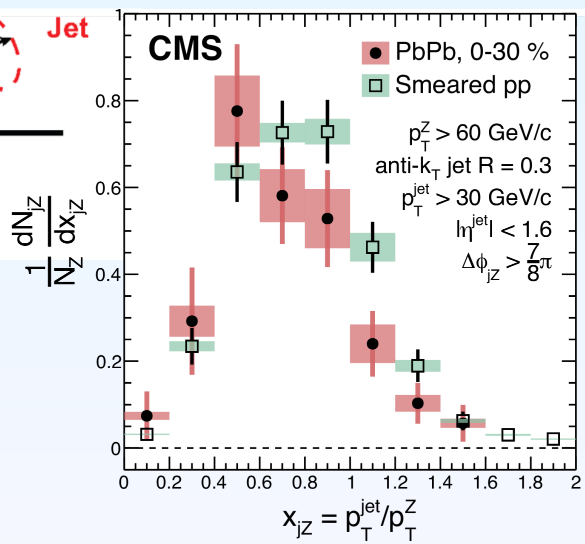


CMS: PRC84 (2011) 024906



$A_J = p_{T,1} - p_{T,2} / p_{T,1} + p_{T,2}$





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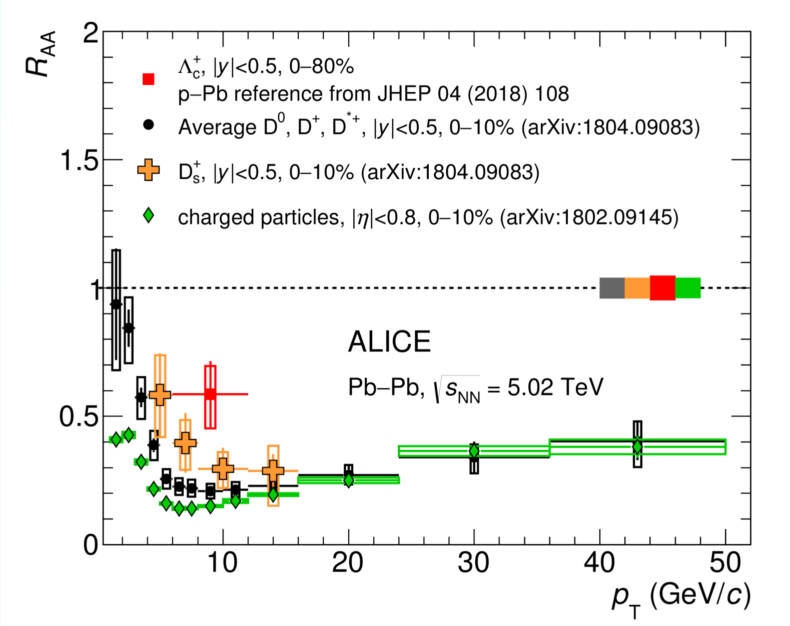
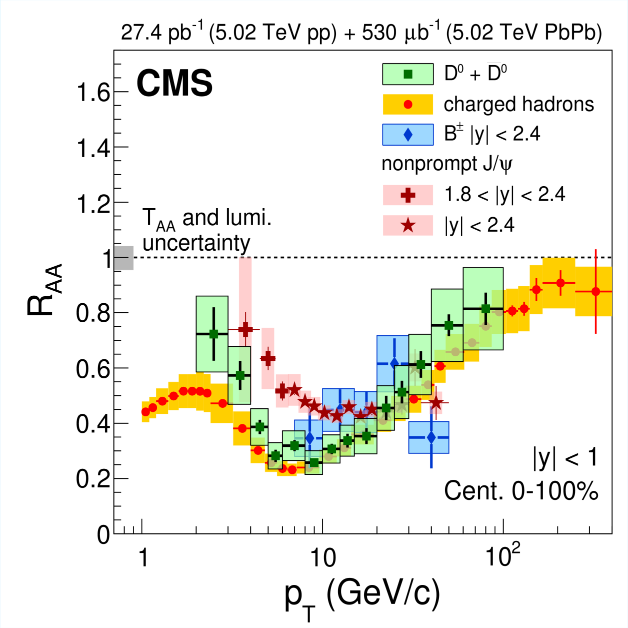
R_{AA}: D- and B-mesons

ALICE: arXiv:1809.10922 [nucl-ex]



CMS: PLB 782 (2018) 474



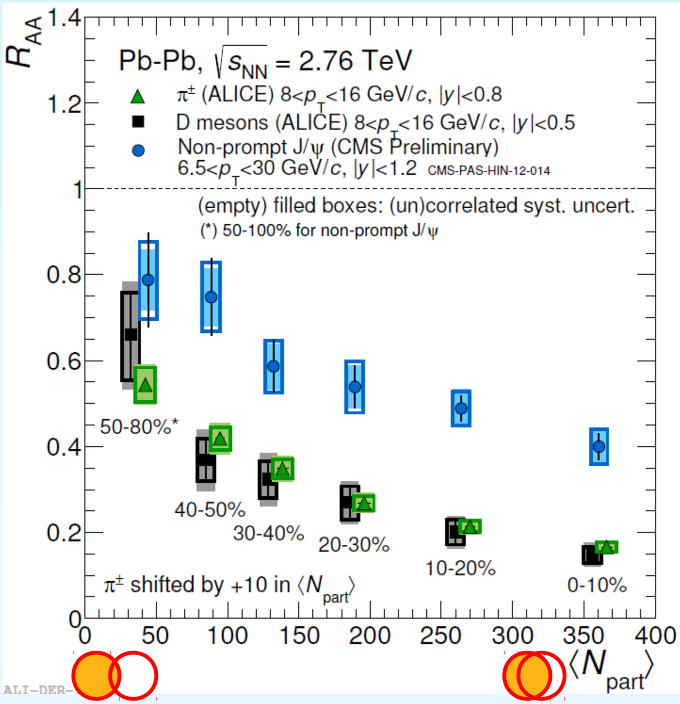
- **Expected behaviour: $\Delta E_g > \Delta E_{charm} > \Delta E_{beauty}$ → R_{AA} (light hadrons) < R_{AA} (D) < R_{AA} (B)**
- **D-meson R_{AA} strongly suppressed**
- **D-meson and pion R_{AA} compatible within uncertainties at high p_T**

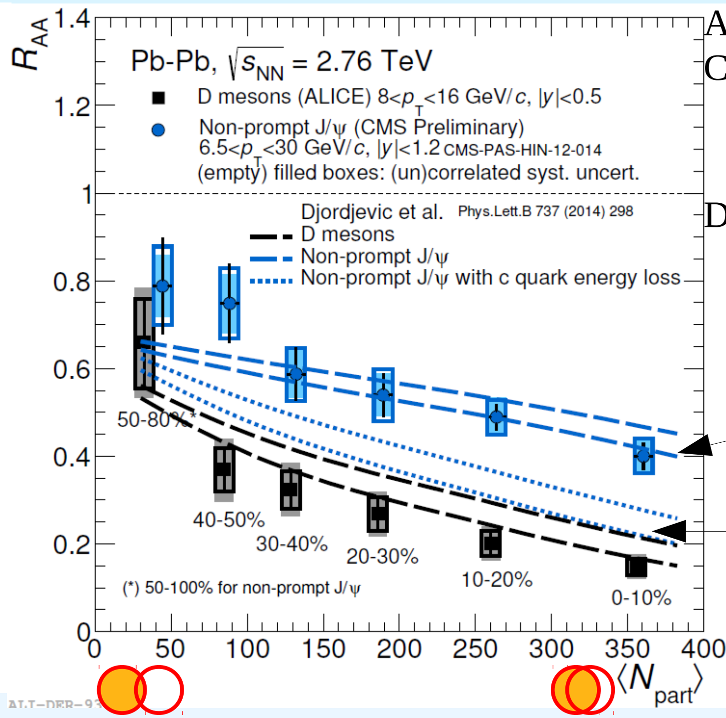
Djordjevic, PRL112 (2014), 042302

  - Described by models including (energy loss hierarchy; different p_T shapes and fragmentation fct)

- **Strange-D hadron measurements hint for a larger R_{AA}**
- **All R_{AA} merge at high p_T**

R_{AA}: D mesons vs J/ψ from B





ALICE: JHEP1511 (2015) 205
CMS: CMS-PAS-HIN-12-014, CMS-PAS-HIN-15-005

Djordjevic, PLB737 (2014) 298
Two mass assumptions for non-prompt J/ψ R_{AA}

b-quark mass

c-quark mass

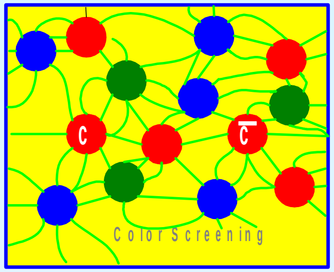
- **Expected behaviour:**

  $\Delta E_g > \Delta E_{charm} > \Delta E_{beauty} \rightarrow R_{AA}$ (light hadrons) $< R_{AA}$ (D) $< R_{AA}$ (B)

- **Clear indication for R_{AA} (B) > R_{AA} (D)**
- **Consistent with the expectation $\Delta E_c > \Delta E_b$**
- **Described by models including quark-mass dependent energy loss**

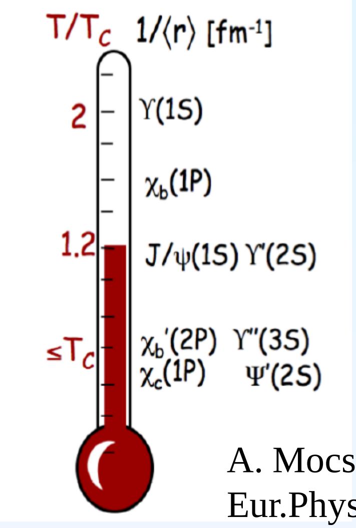
Quarkonia

Quarkonia

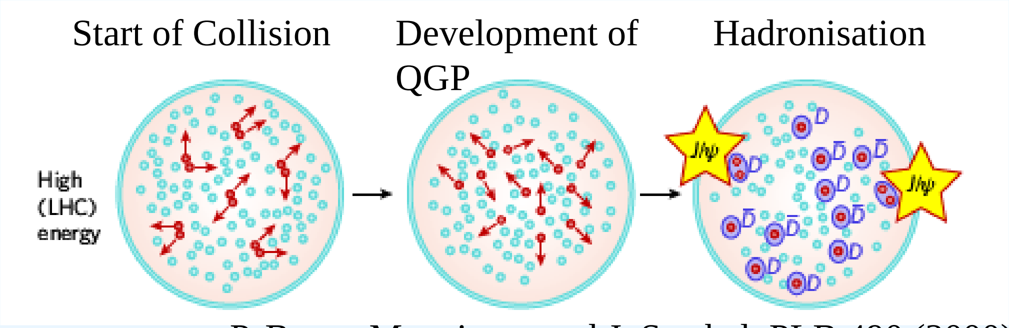


Kluberg and Satz, arXiv:0901.3831

- Original idea (1986): quarkonium production suppressed due to colour screening in the QGP
- Sequential melting: differences in quarkonium binding energies lead to a sequential melting with increasing temperature
- New idea (2000): enhanced quarkonium producion via (re)generation during the QGP phase or at hadronisation

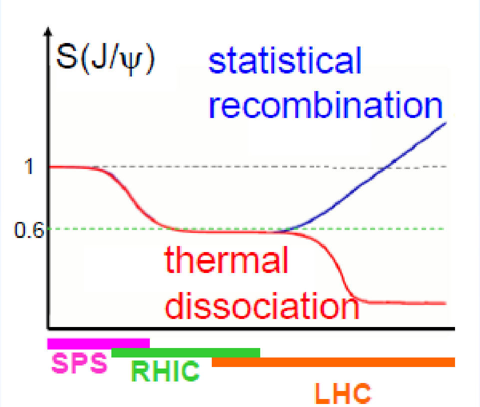


A. Mocsy, Eur.Phys.J.C61,2008



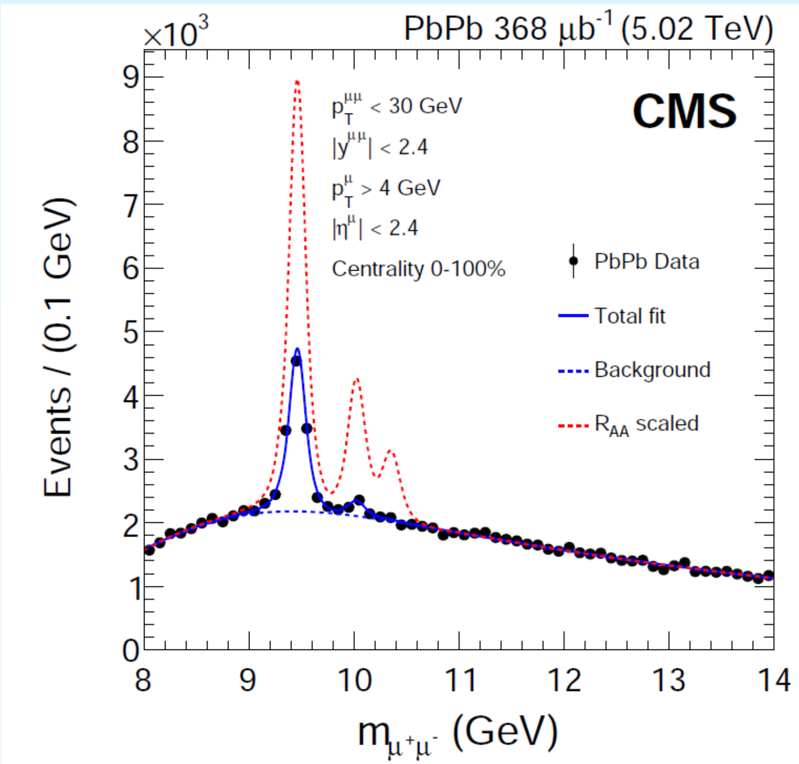
P. Braun-Munzinger and J. Stachel, PLB 490 (2000) 196

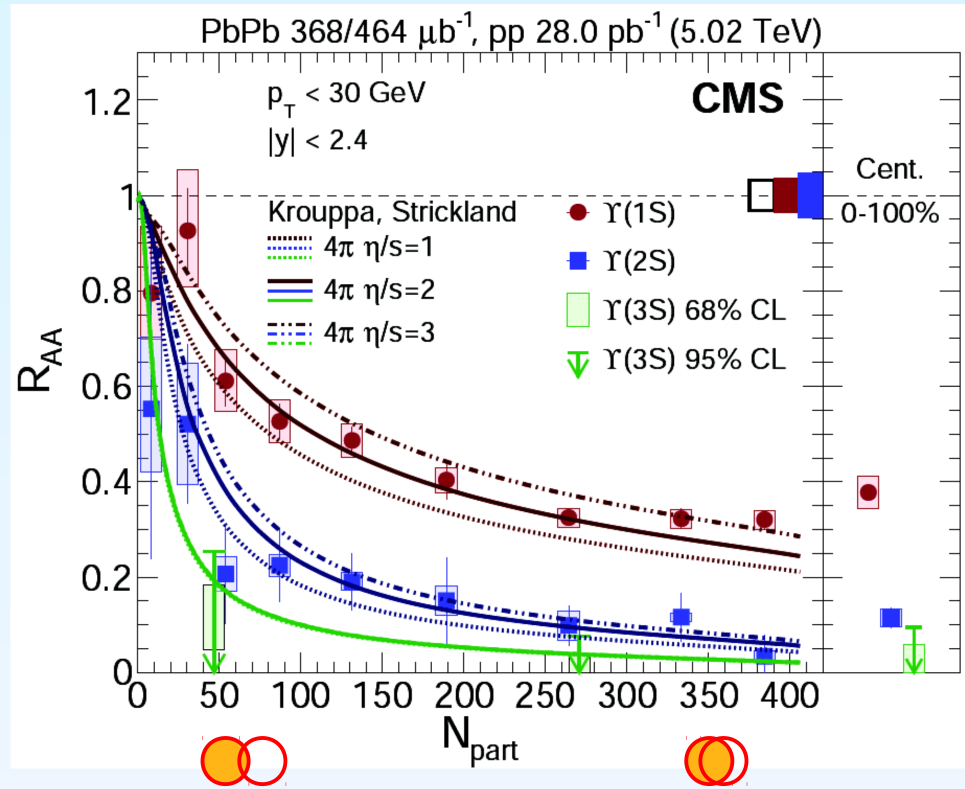
State	J/ψ	χ_c	ψ'
Mass (GeV/c^2)	3.10	3.53	3.68
Radius (fm)	0.25	0.36	0.45



Quarkonia
Bottomonium Suppression

CMS: arXiv:1805.09215

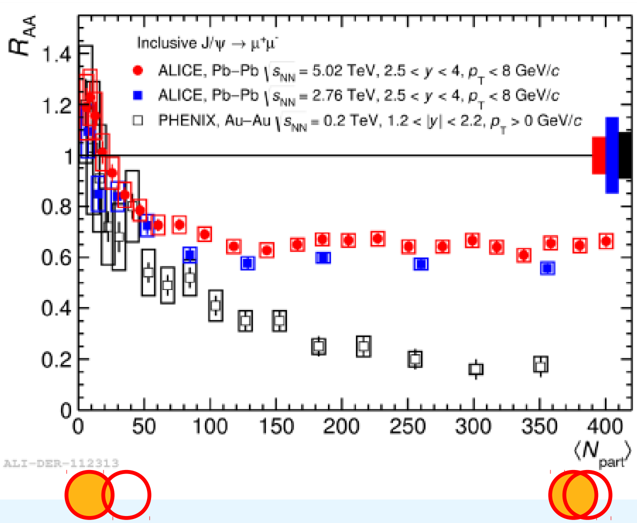


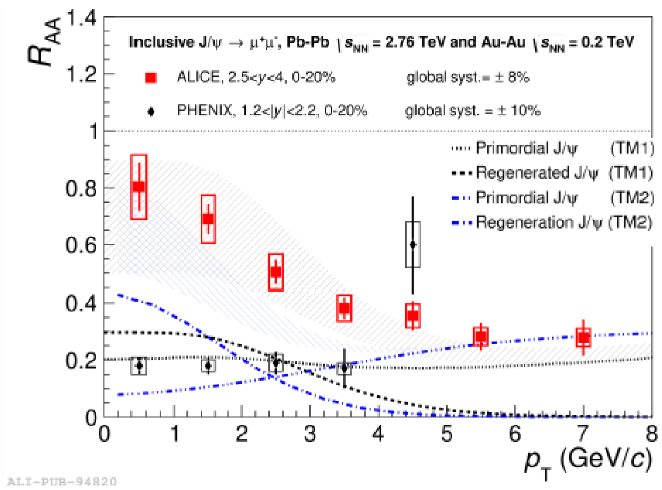


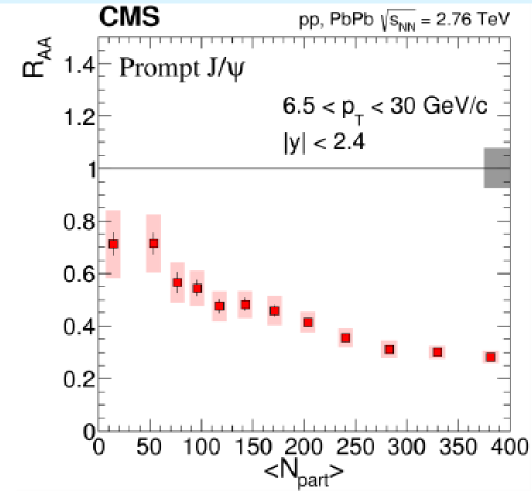
Suppression of Y(1S), Y(2S) and Y(3S) compatible with Debye screening

N_{part} dependence very well reproduced by models which include a fluid with η/s = 2/4π

Quarkonia
J/ψ low p_T enhancement

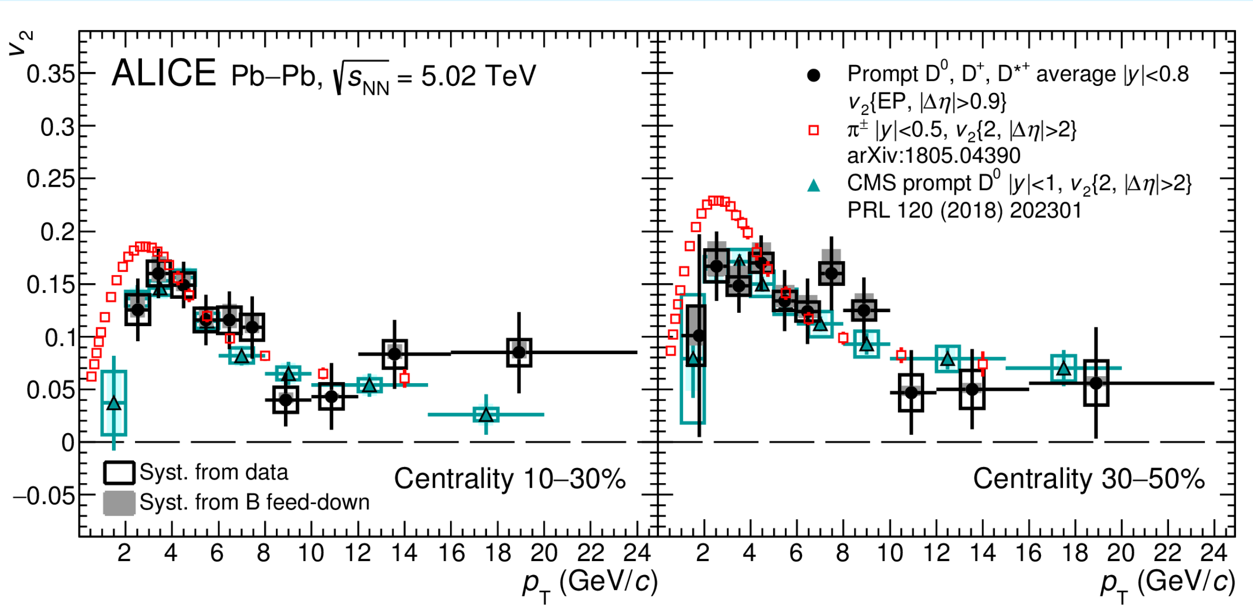






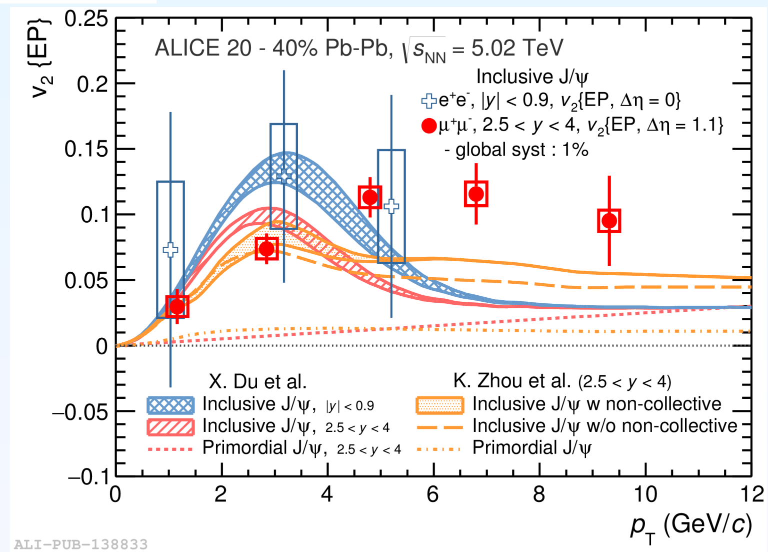
- **Less suppression at LHC than at RHIC**
- **Difference at low p_T, where (re)generation is expected to play an important role**
- **At high-p_T: similar suppression at RHIC and LHC**
- **Re(generated) J/ψ from the combination of random c and $\bar{c}$?**
  → charm flow

Does charm participate in the collective motion?



ALICE: PRL 120 (2018) 102301,
ArXiv: 1805.04390 [nucl-ex],
PRL 119 (2017) 242301
CMS: PRL120 (2018) 202301

- **v_2(D) ≃v_2(π±) for p_T > 4 GeV/*c***
- **Hint of v_2(D) < v_2(π±) for p_T < 4 GeV/*c***
- **(Re)generated J/ψ inherit elliptic flow from deconfined (thermalised) charm quarks**
  - Positive v_2 at mid- and forward rapidity
  - Transport models describe data at low p_T undershoot for p_T > 5 GeV/*c*



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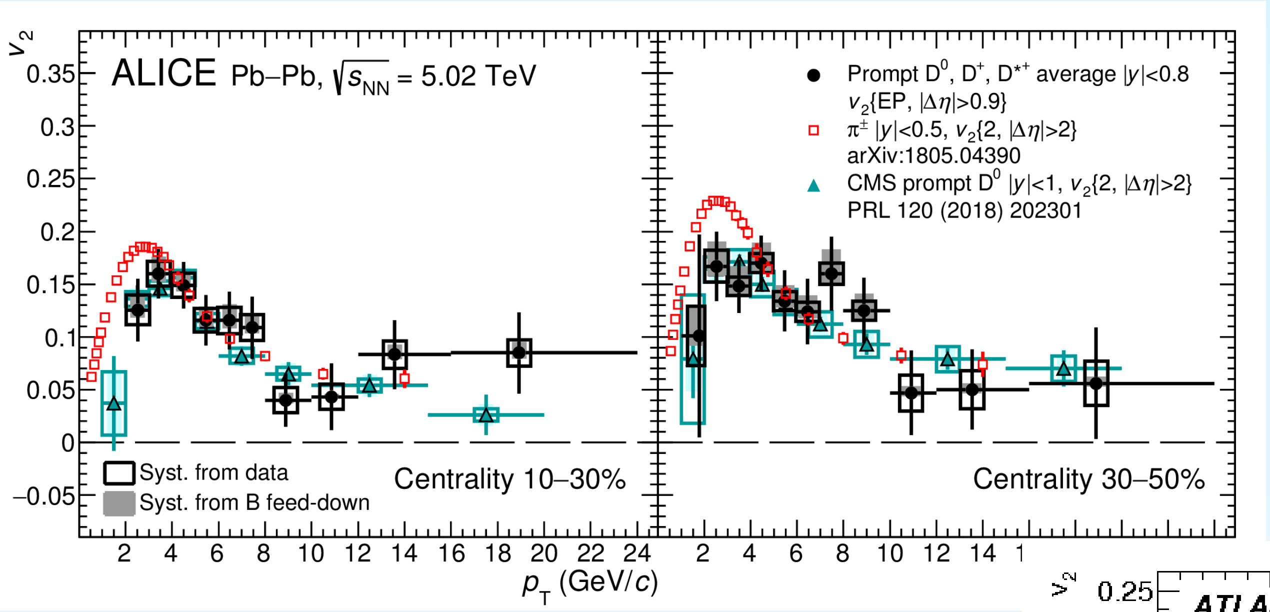

ALICE: PRL 120 (2018) 102301,
ArXiv: 1805.04390 [nucl-ex],
PRL 119 (2017) 242301
CMS: PRL120 (2018) 202301
ATLAS: CERN-EP-2018-170

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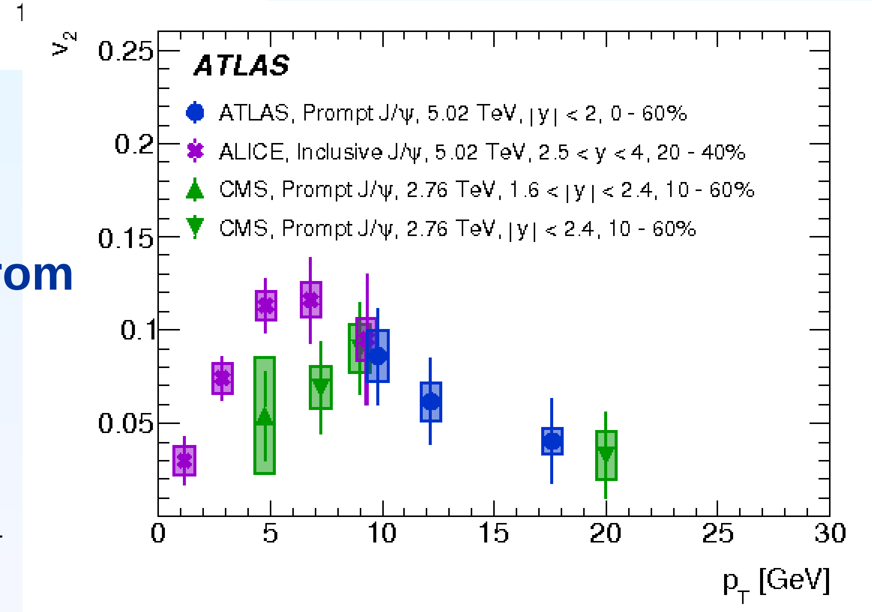
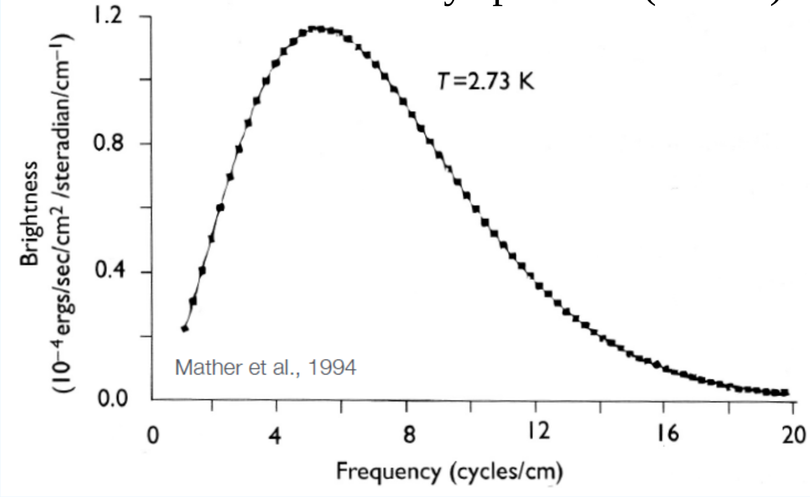


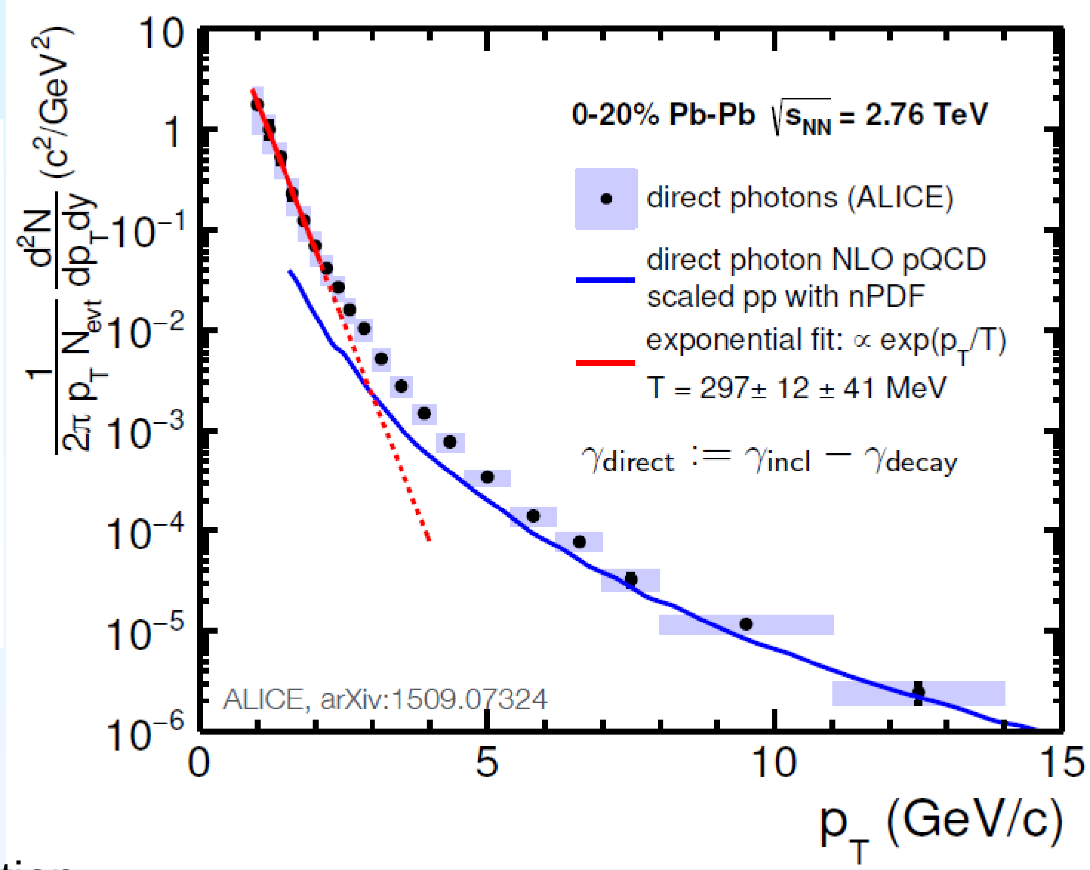
Photons

Photons → Temperature

Direct Photons

CMB black-body spectrum (COBE)





- **QGP photons**
- **Difficult measurement**
  - Subtract decay photon contribution
- **Emission at all stages of the collision**
- **But: blue shifted**

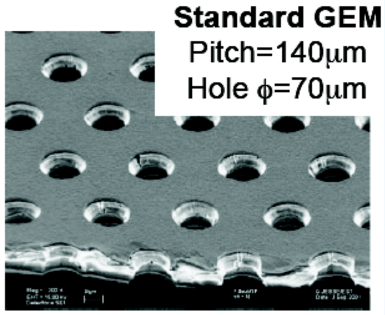
Summary

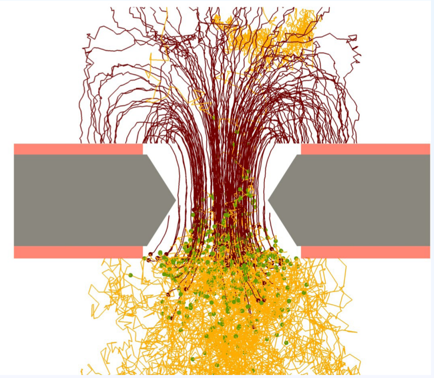
- **Entered the era of quantitative characterisation of the QGP**
  - Global observables → energy density, decoupling time, ...
  - Chemical composition of the fireball as predicted by thermal models
  - Evidence for radial and anisotropic flow → $\eta/s \approx 0.2$
  - Jet quenching observed; first estimate of transport parameters $\approx 2\ \mathrm{GeV}^2/\mathrm{fm}$
  - Expectation $\Delta E_{\mathrm{lightquark}} > \Delta E_{\mathrm{charm}} > \Delta E_{\mathrm{beauty}}$ verified
  - Bottomonium thermometer of the medium → $\eta/s = 2/4\pi$
  - Clear hints for J/ψ (re)generation

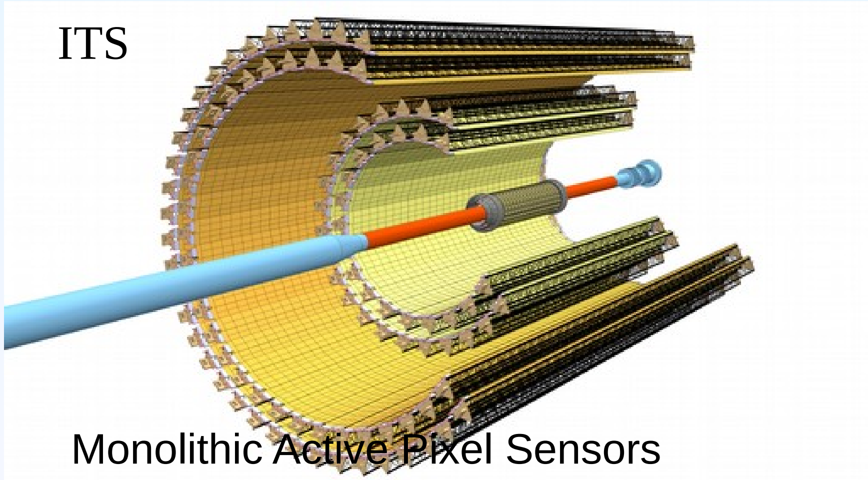
Outlook Run3/Run4

- **LHC Run 3 and 4 (50 kHz Pb-Pb collisions) until 2030**
- **Yellow report in preparation**
- **Detector upgrade for ALICE and LHCb**
  - ALICE continuous readout, new ITS, new online/offline computing system
    - → measurements down to zero p_T
    - → large data samples
    - → unprecedented precision measurements possible

GEM for TPC



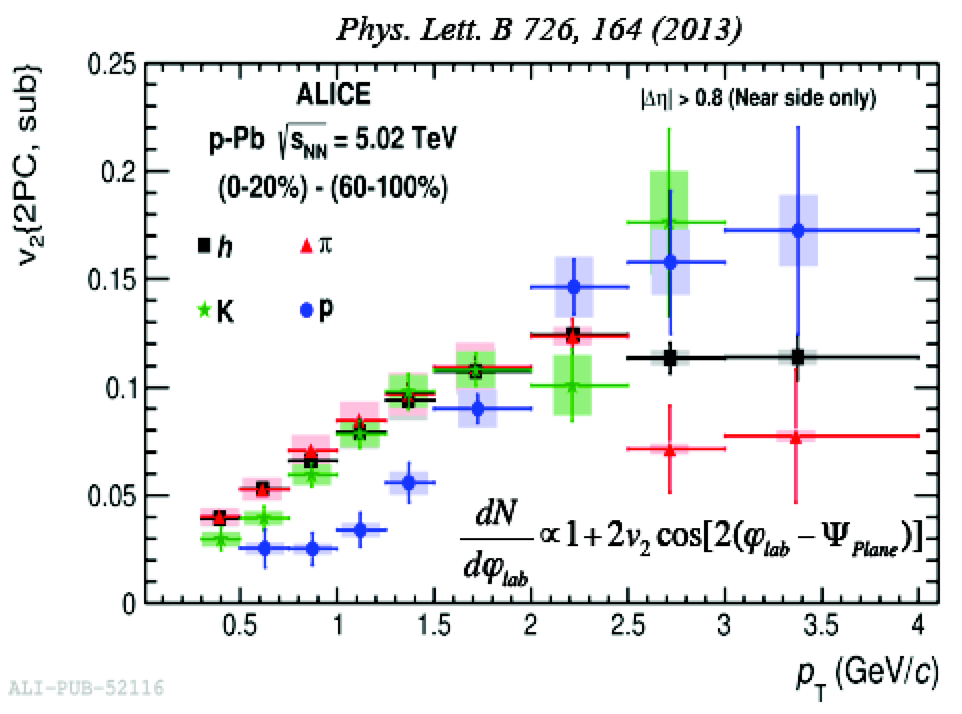




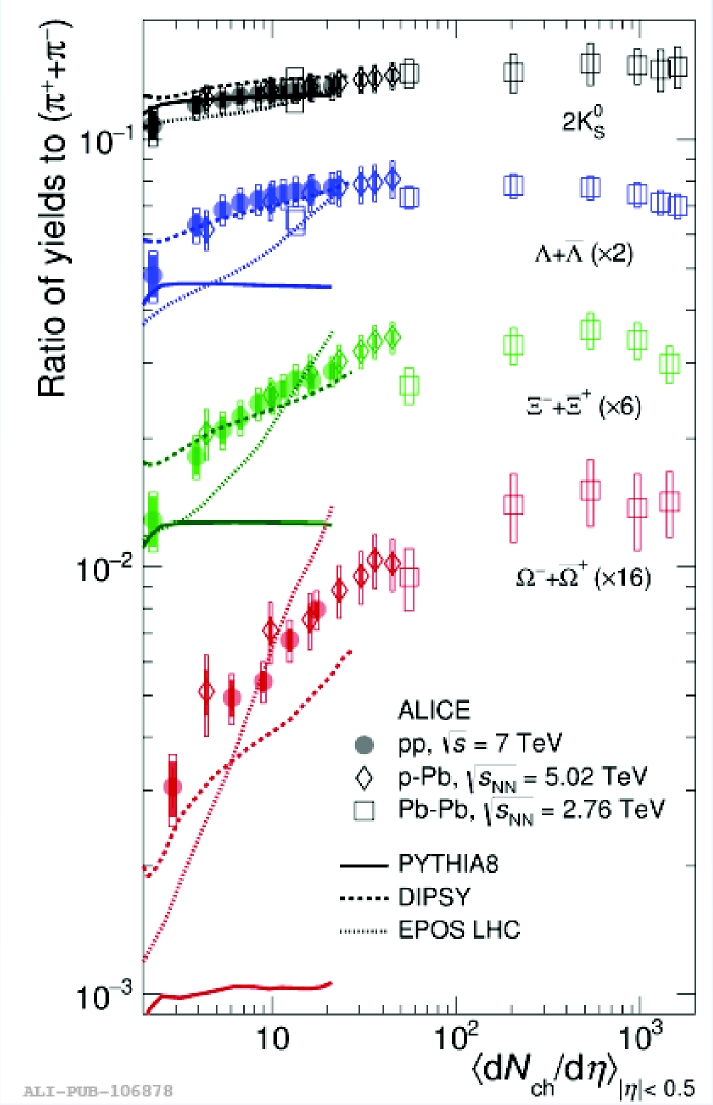
Back-up

Small Systems -
How small can a droplet of QGP matter be?

pp and p-Pb Collisions



ALICE, Nature Physics 13 (2017) 535



- **Elliptic flow**
  - Qualitatively similar to Pb-Pb and consistent with hydrodynamic calculations
    → similar physics (collectivity?) at place?
- **Strangeness enhancement**
  - Production driven by final state rather than collision system or energy?