Recent heavy ion results from the LHC and future perspectives

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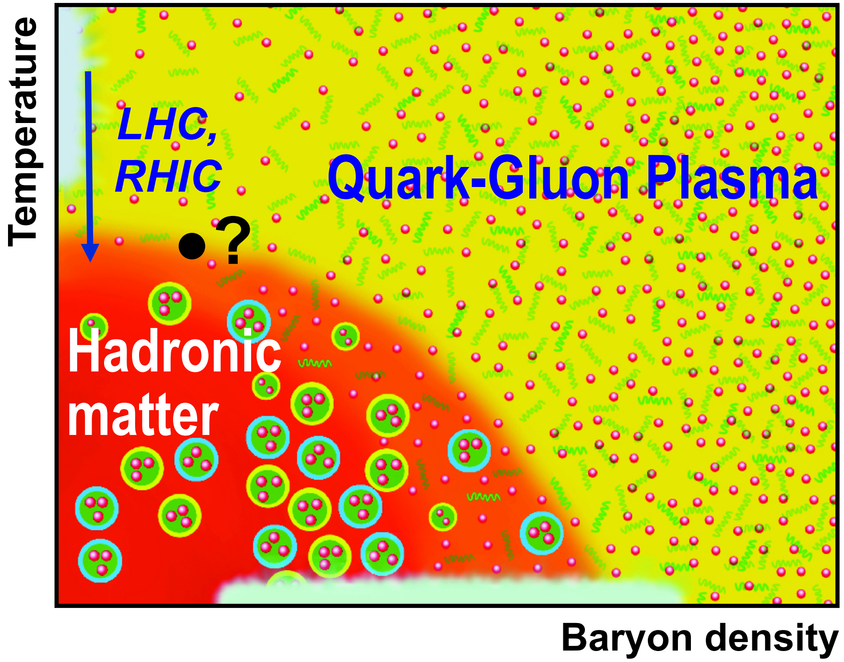
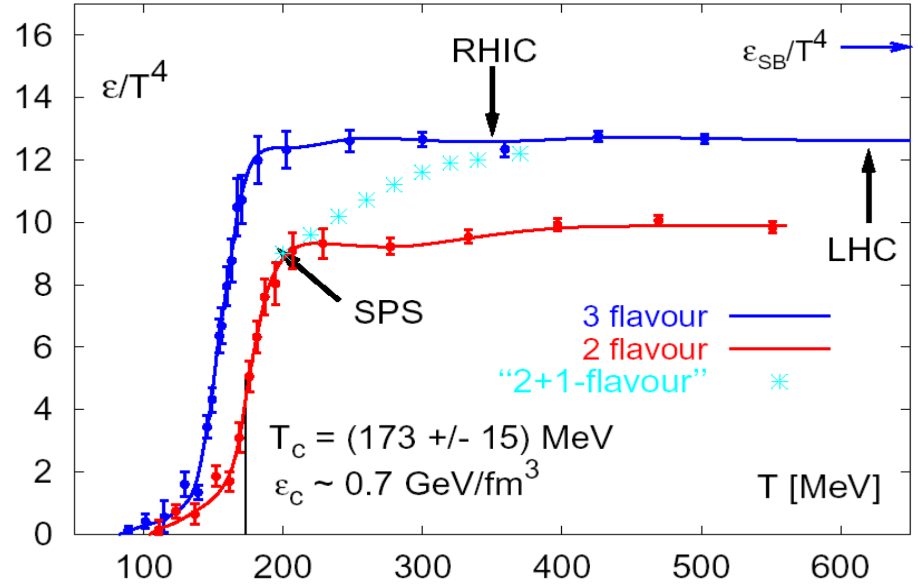
Outline

- Brief intro: Strongly interacting matter at extreme conditions, the Quark-Gluon Plasma (QGP)
- Facilities, experiments and methodologies
- Collision systems
  - pp: Important baseline and test pQCD calculations
  - p-A: Study cold nuclear matter effects (initial state)
  - A-A: Study QGP (final state); determine medium properties
- Selection of recent measurements
  - Global event observables
  - Open heavy flavour (charm and beauty): They allow studying the dynamical properties of the QGP and the degree of thermalisation
- Summary and outlook

QCD phase diagram



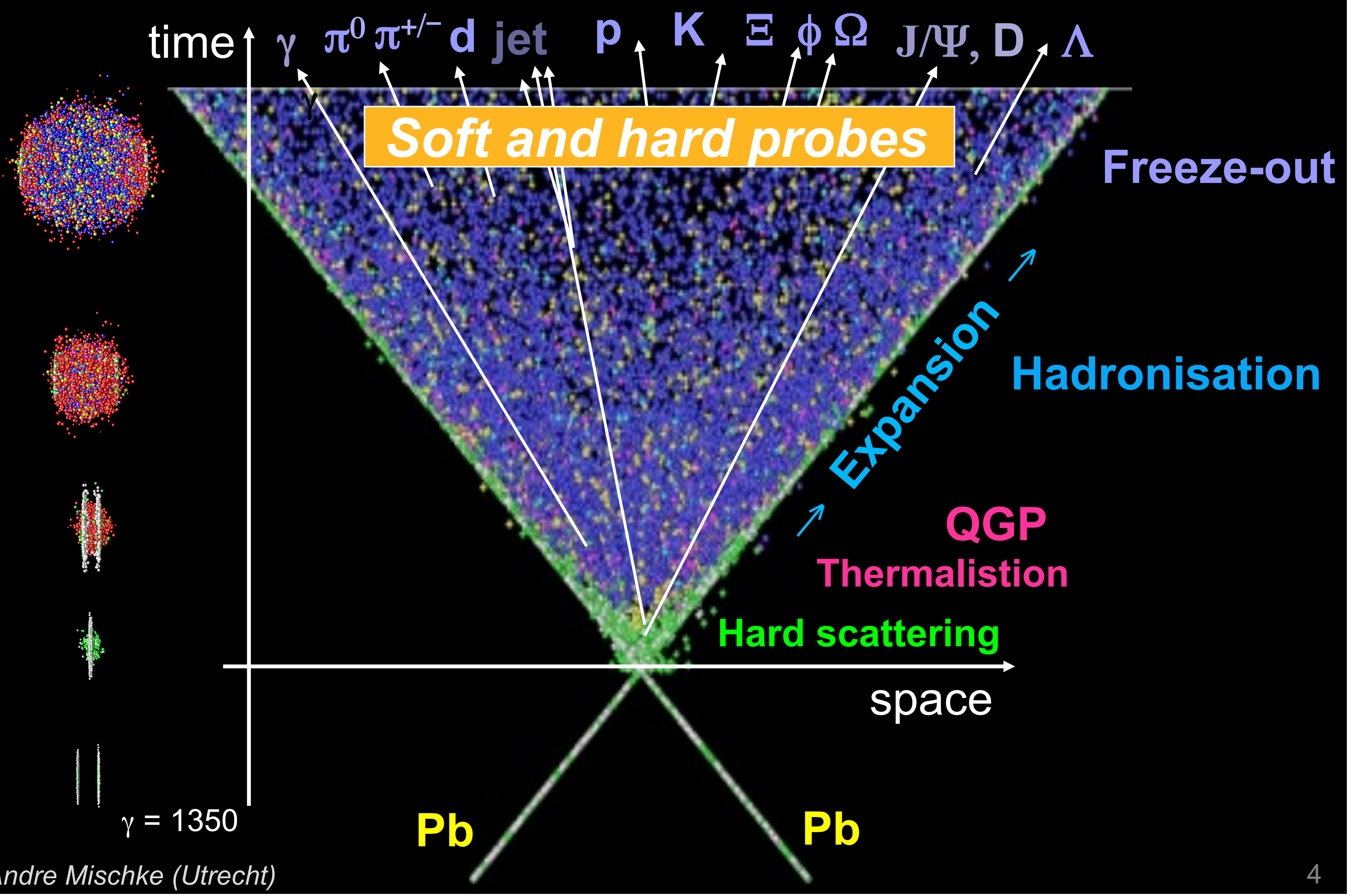


- Extreme conditions: high temperature and/or high density
- Search for the critical point

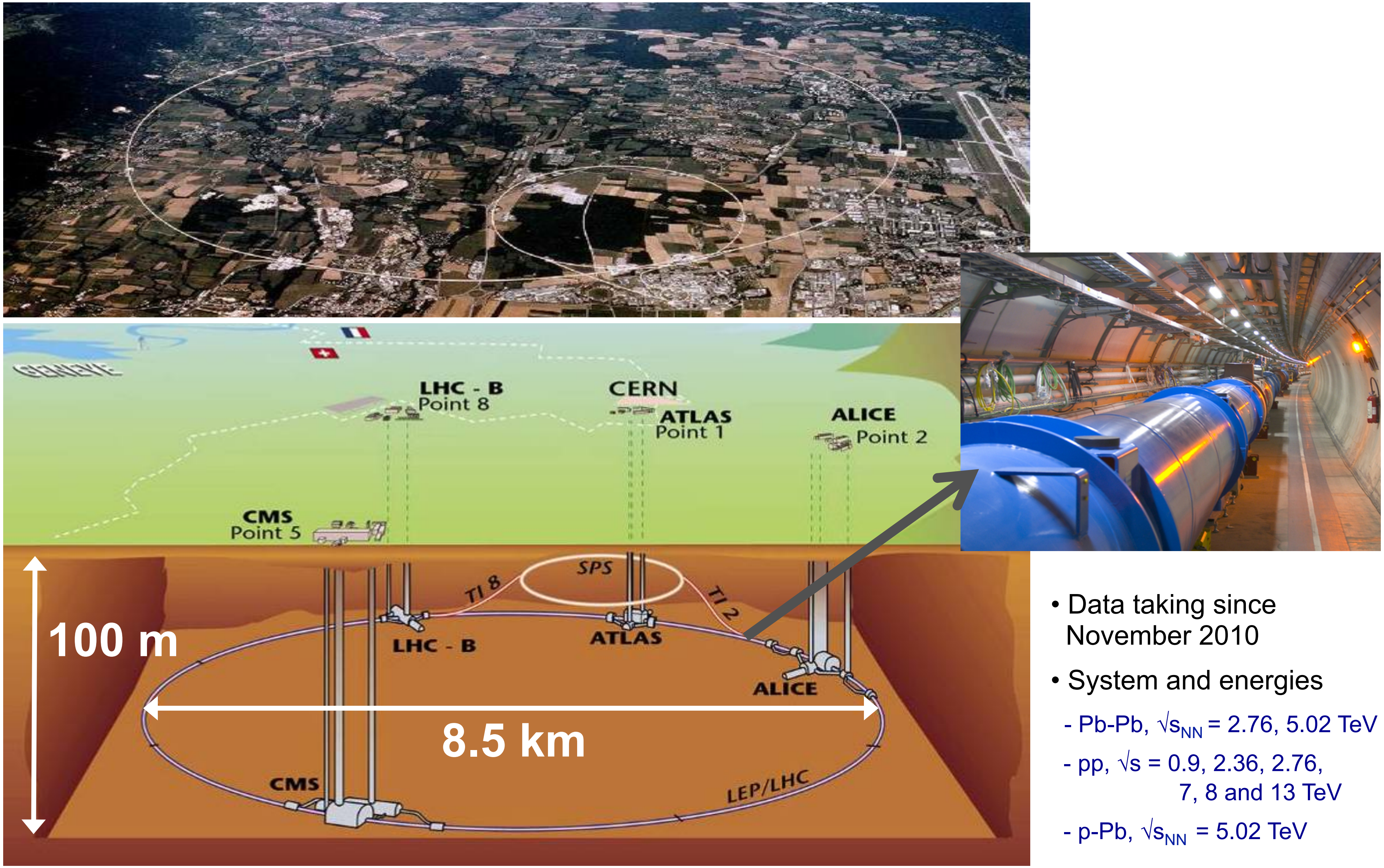
- Lattice QCD predicts a phase transition from hadronic matter to a deconfined state
- Critical energy density

$$\varepsilon_C = (6 \pm 2) T_C^4$$

Space-time evolution of a heavy-ion collision

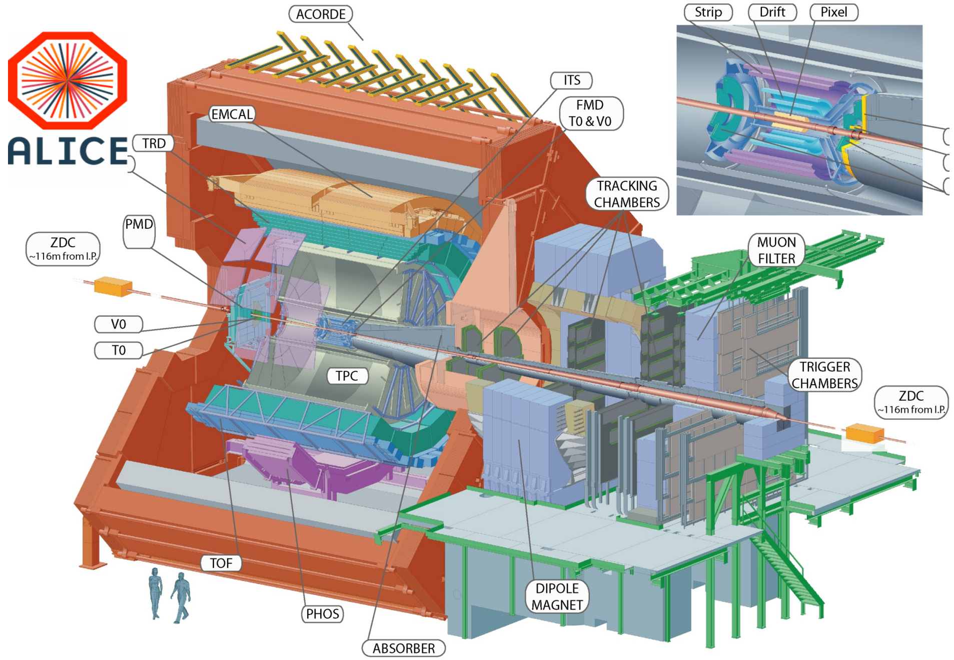


Large Hadron Collider at CERN

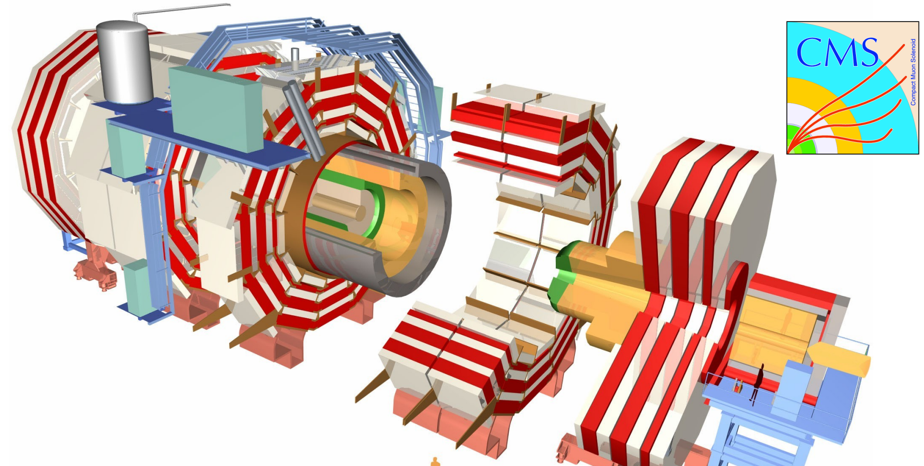


- Data taking since November 2010
- System and energies
  - Pb-Pb, $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
  - pp, $\sqrt{s}$ = 0.9, 2.36, 2.76, 7, 8 and 13 TeV
  - p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

Experiments



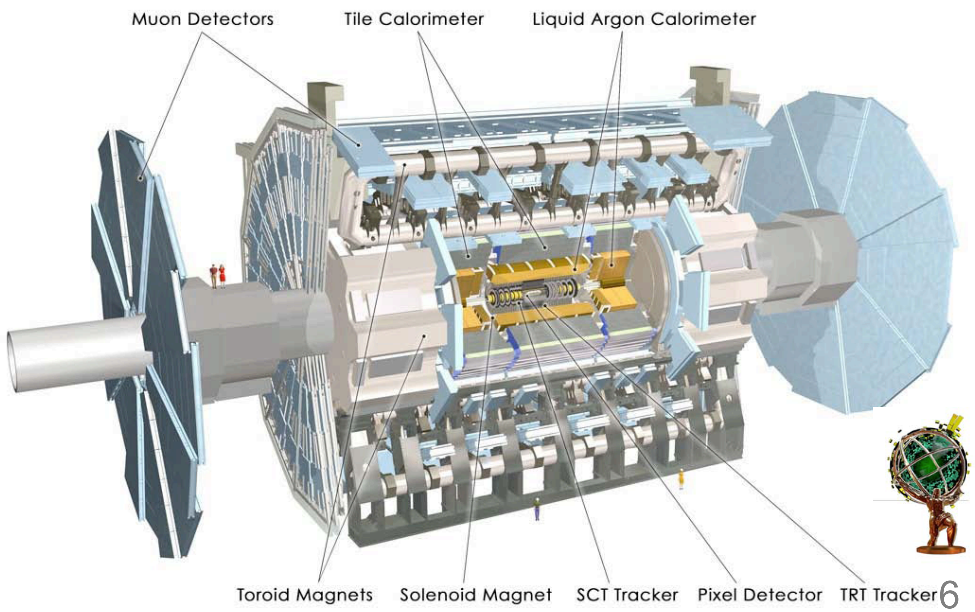
- PID over a very broad momentum range (>100 MeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage $|\eta| < 0.9$ and $-4 < \eta < -2.5$ in forward region
- Impact parameter resolution better than 65 μm for $p_T > 1$ GeV/c



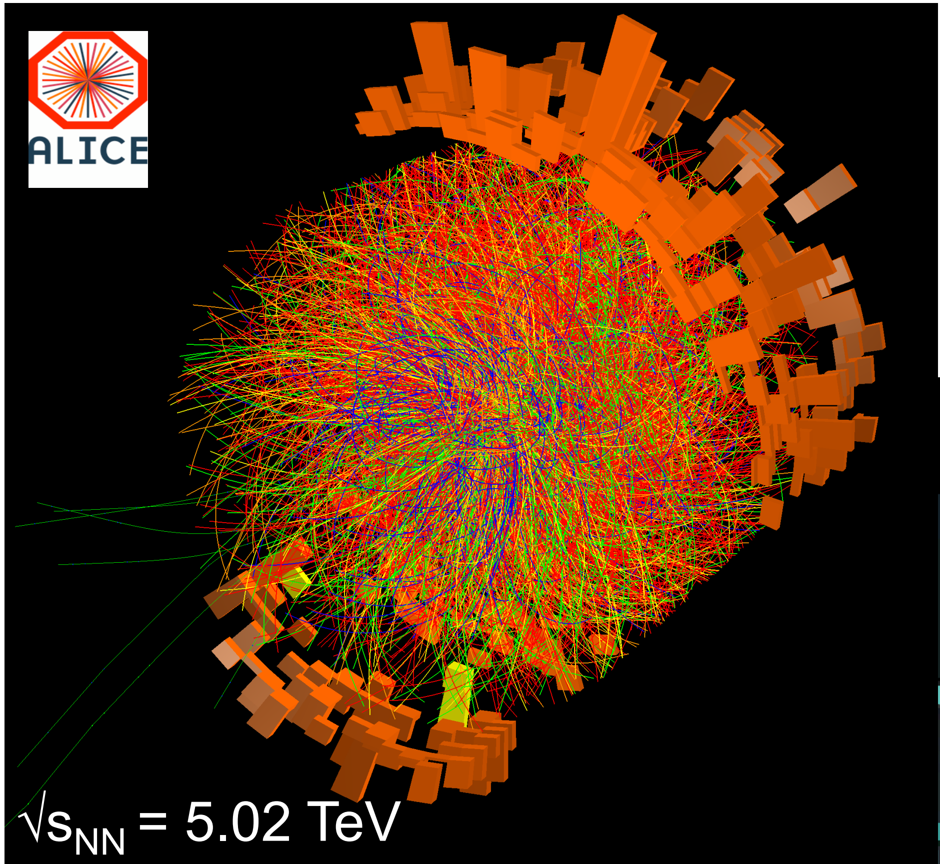
- Tracking (p_T resolution: 1-2% up to $p_T \sim 100$ GeV/c) and calorimetry
- Trigger selectivity over a large range in rapidity and full azimuth

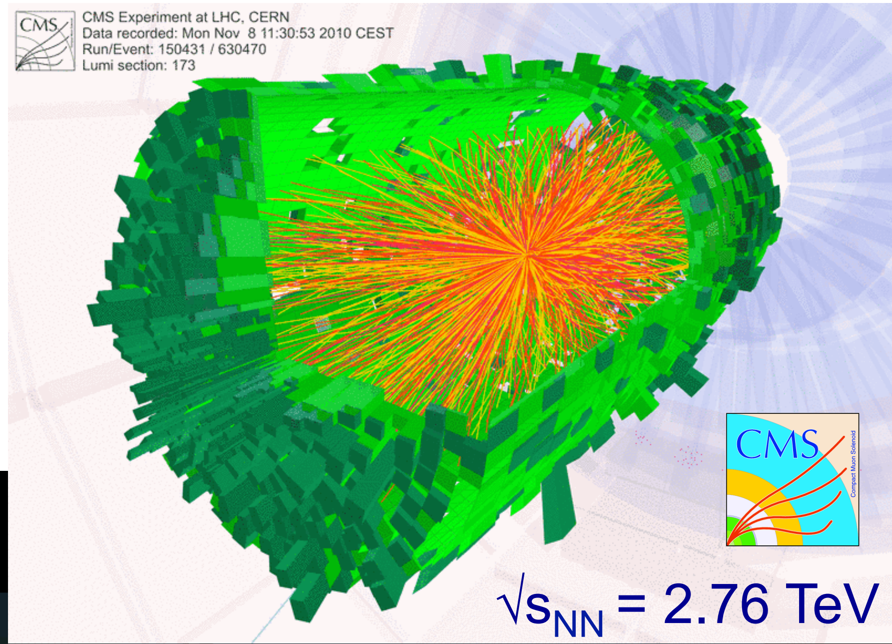
Three main subsystems with a full coverage in azimuth:

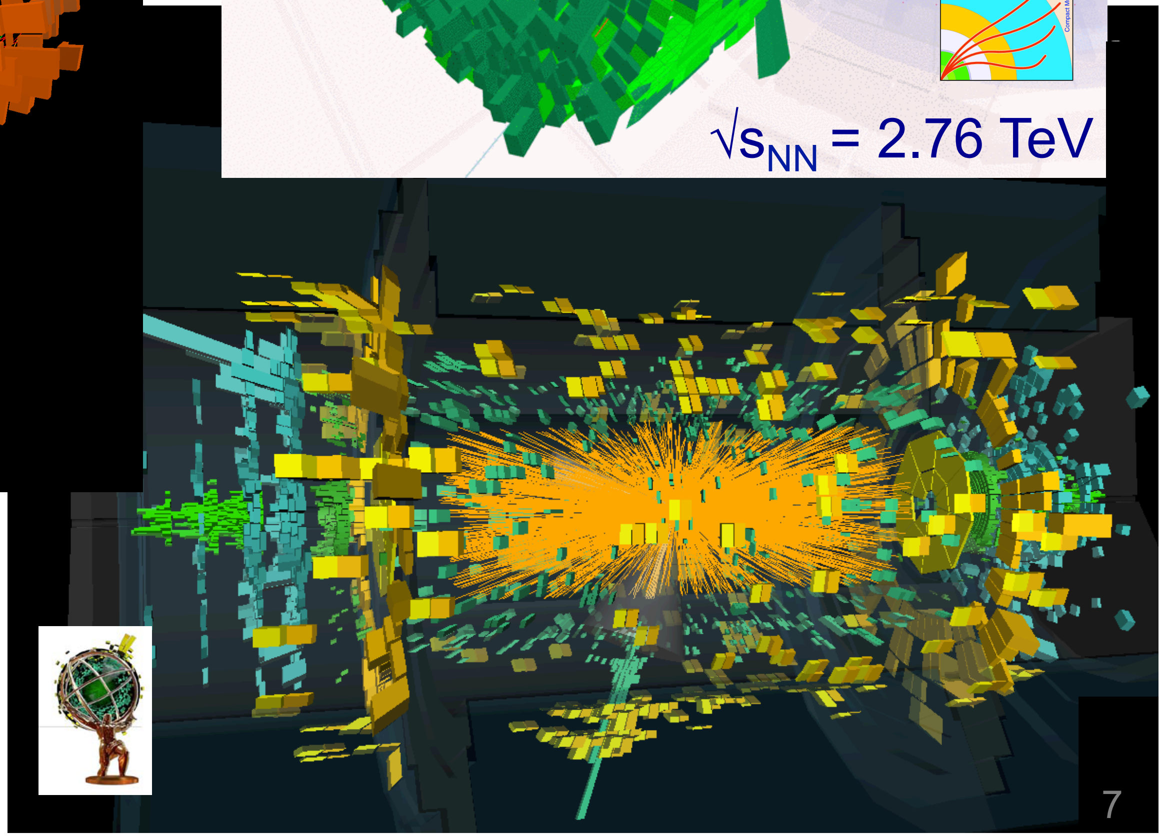
- Inner Detector: tracking $|\eta| < 2.5$
- Calorimetry $|\eta| < 4.9$
- Muon Spectrometer $|\eta| < 2.7$



Typical event displays



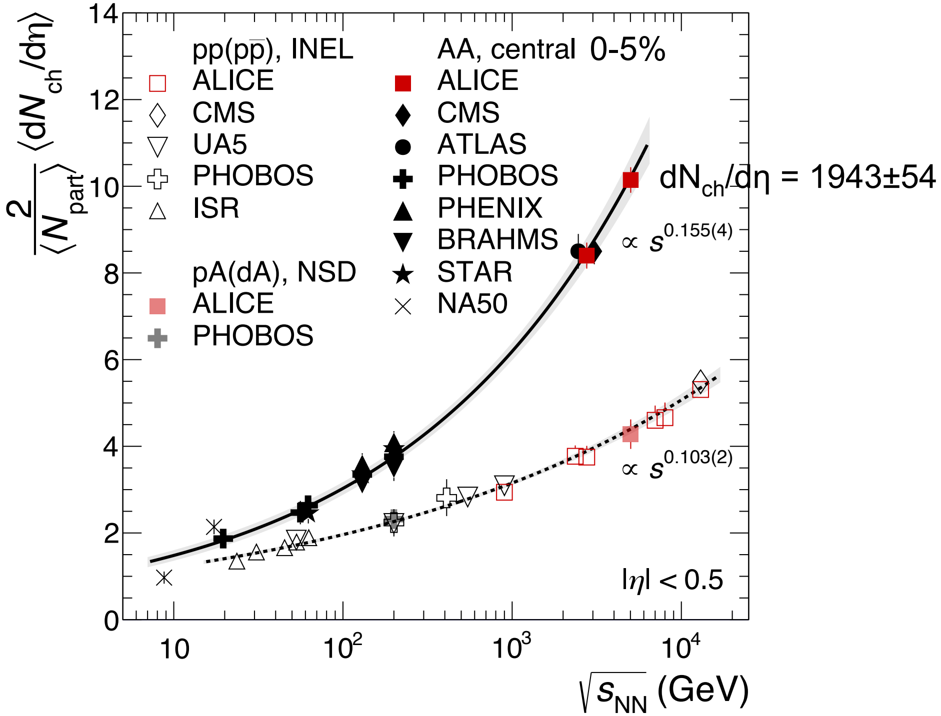




Charged particle multiplicity at 5.02 TeV Pb-Pb

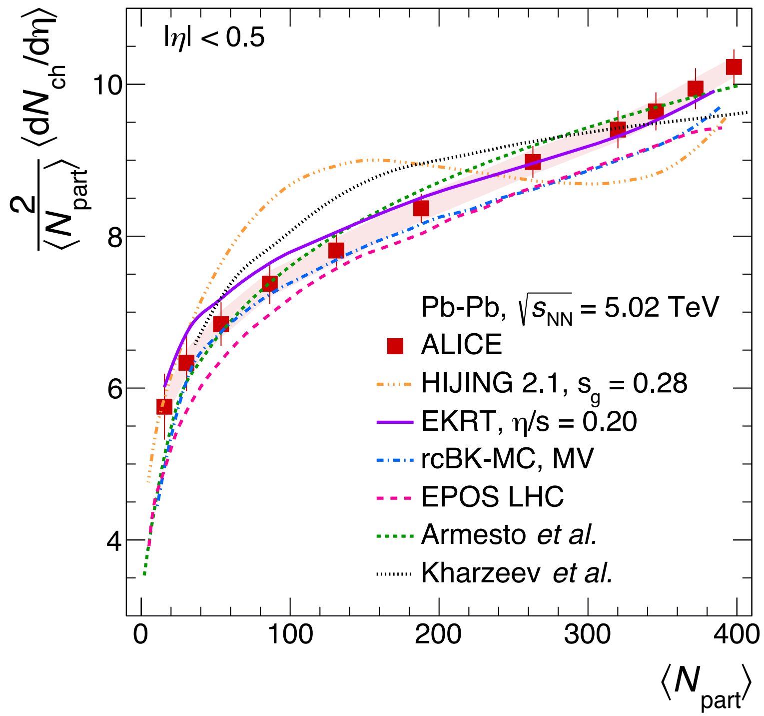
vs. cms energy

arXiv:1512.06104, Phys. Rev. Lett. 105, 252301 (2010)



vs. number of participants

arXiv:1512.06104, Phys. Rev. Lett. 106, 032301 (2011)



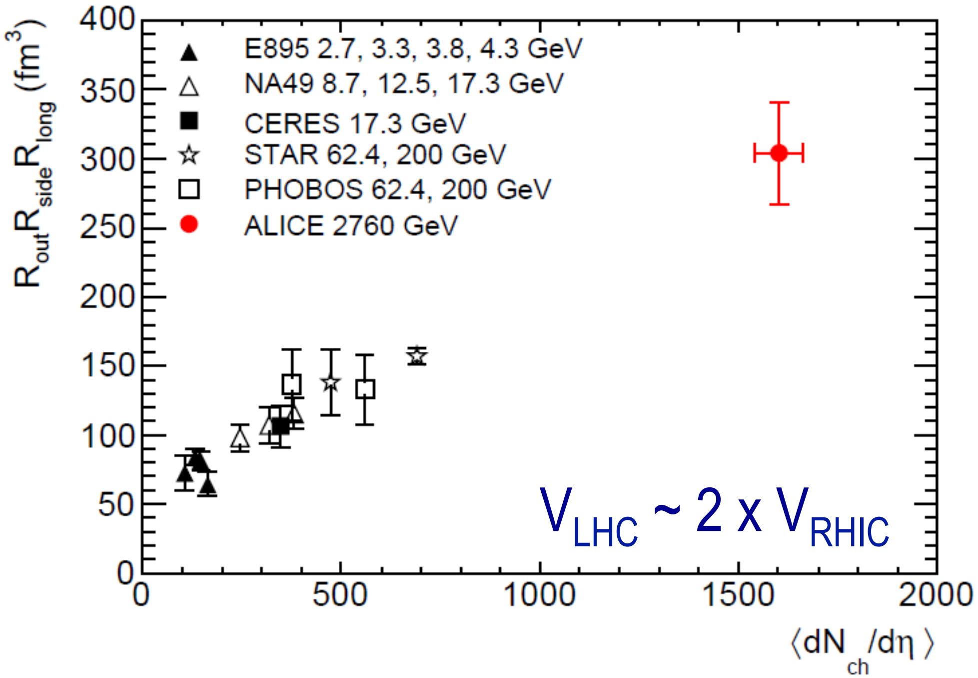
- Power law dependence fits well and faster in Pb-Pb ~$s^{0.155}$ than in pp ~$s^{0.103}$
- Multiplicity ~ 2.5 x N_{RHIC}
- Energy density > 3 x ε_{RHIC}

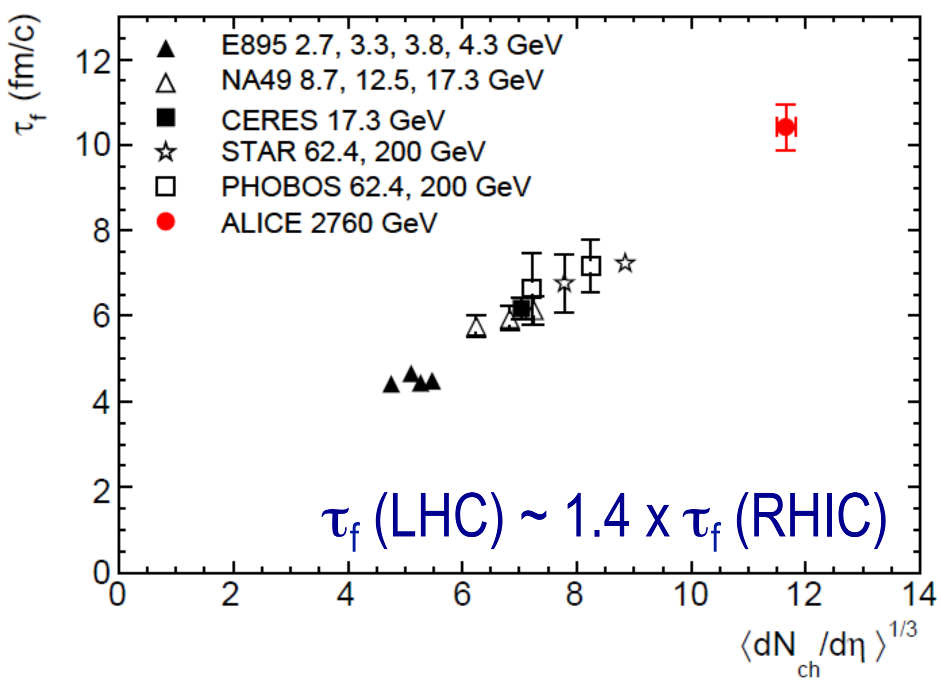
- Very similar centrality dependence at LHC and RHIC (not shown)
  Once corrected for difference in absolute values
- Shape almost energy independent

System size and lifetime at 2.76 TeV Pb-Pb

System size | Lifetime

Phys. Lett. B 696, 328 (2011)



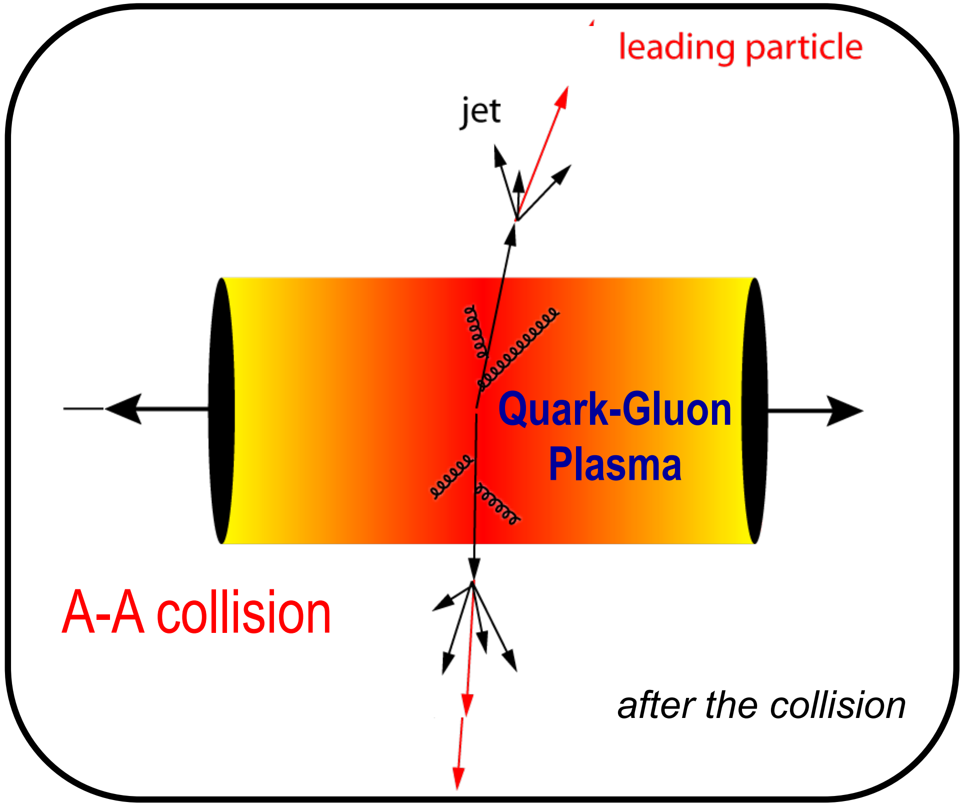


τ_f(central 2.76 TeV Pb-Pb) ~ 10-11 fm/c

Fireball at LHC has larger volume and longer lifetime

→ Hydrodynamic expansion

Probing hot and dense QCD matter

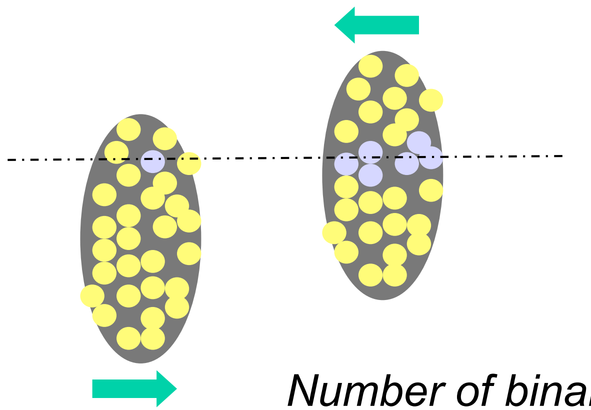


- "Simplest way" to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile

- Heavy-ion collision
  - hard processes serve as calibrated probe (pQCD)
  - partons traverse through the medium and interact strongly
  - suppression pattern provides density measurement
  - General picture: **parton energy loss** through medium-induced gluon radiation and collisions with medium constituents

Quantification of medium effects

Compare particle yield in heavy-ion collisions with the one in proton-proton.



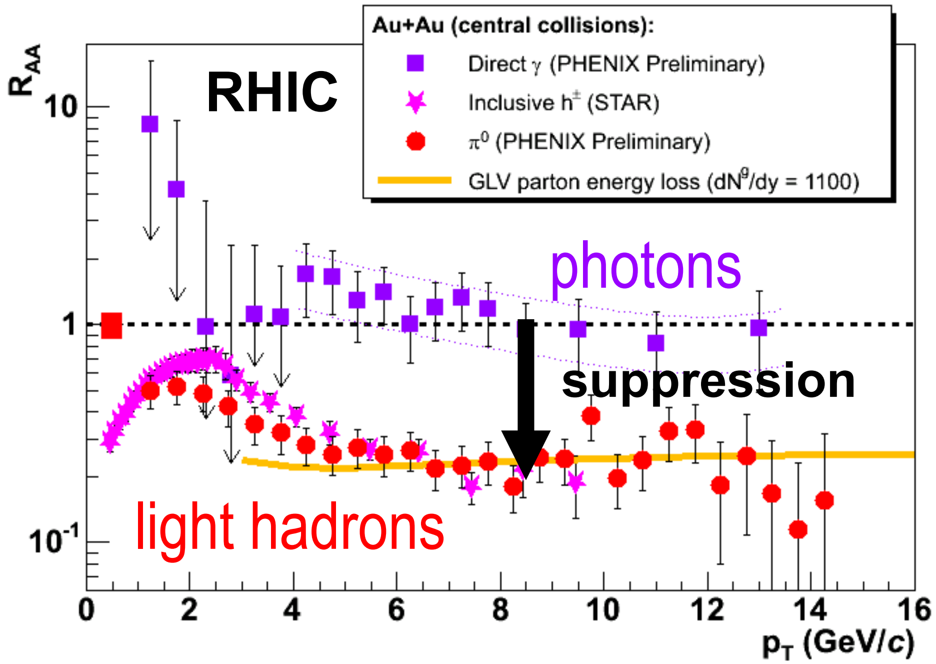
Number of binary collisions from Glauber calculations

Nuclear modification factor

$$R_{\mathrm{AA}}(p_T) = \frac{\mathrm{Yield}_{\mathrm{AA}}(p_T)}{\langle N_{bin} \rangle_{\mathrm{AA}} \, \mathrm{Yield}_{\mathrm{pp}}(p_T)}$$

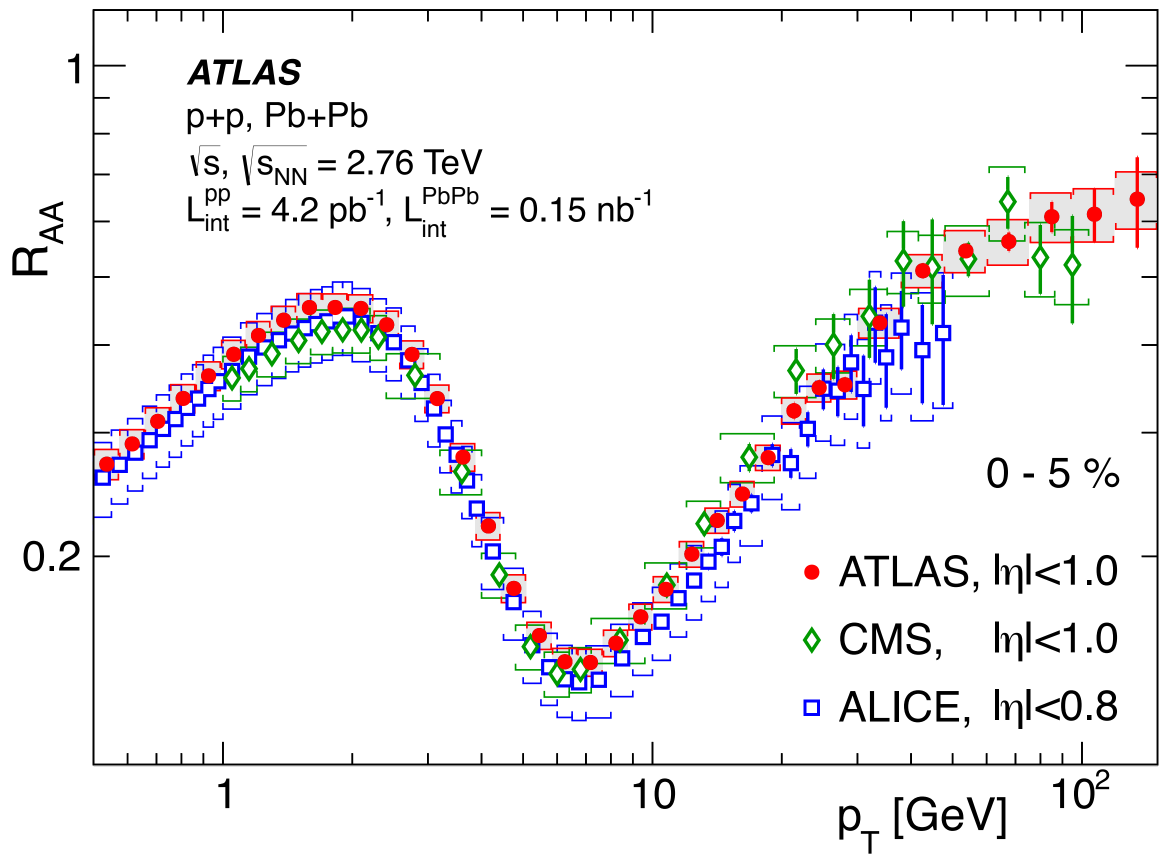
Expectation:

- R_{AA} = 1 for photons
- R_{AA} < 1 for hadrons



R_{AA} for inclusive charged hadrons

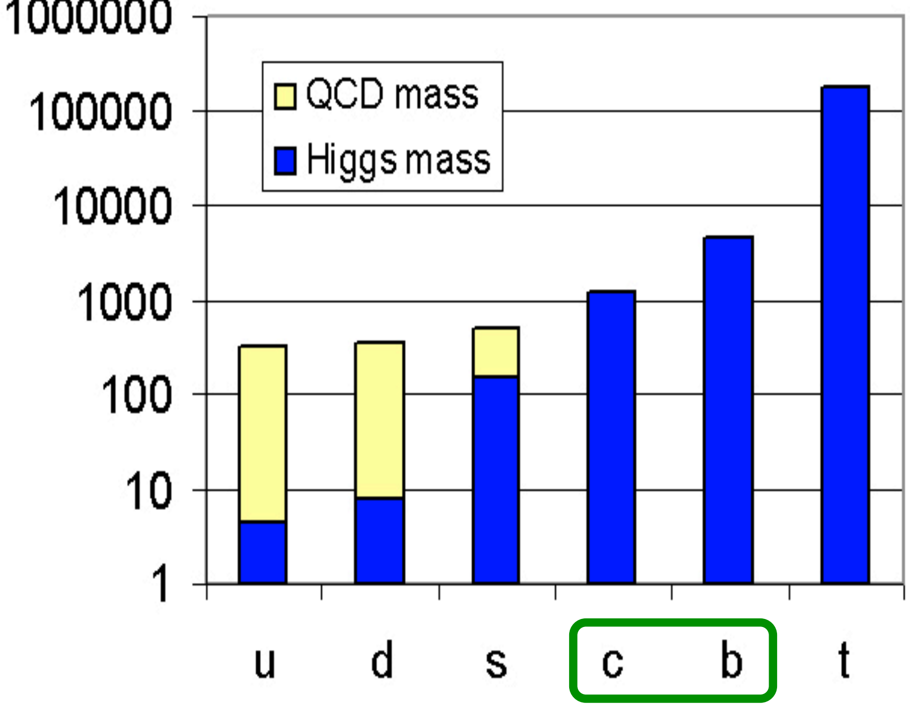
JHEP 09 (2015) 050



- Measurement in broad momentum range: $0.5 < p_T < 150$ GeV/c
- Strong suppression in most central Pb-Pb collisions
- Very good agreement between experiments
- Plateau at high p_T (?)

Heavy quarks are ideal probes

B. Müller, Nucl. Phys. A750 (2005) 84



- Symmetry breaking
  - Higgs mass: electro-weak symmetry breaking → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass
- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP
- Test QCD at transition from perturbative to non-perturbative regime: Charm and beauty quarks provide hard scale for QCD calculations

Energy loss of heavy quarks

(1) Radiative parton energy loss is colour charge dependent (Casimir coupling factor C_R)

R. Baier et al., Nucl. Phys. B483 (1997) 291 ("BDMPS")

$$\langle \Delta E_{medium} \rangle \propto \alpha_S C_R \hat{q} L^2$$

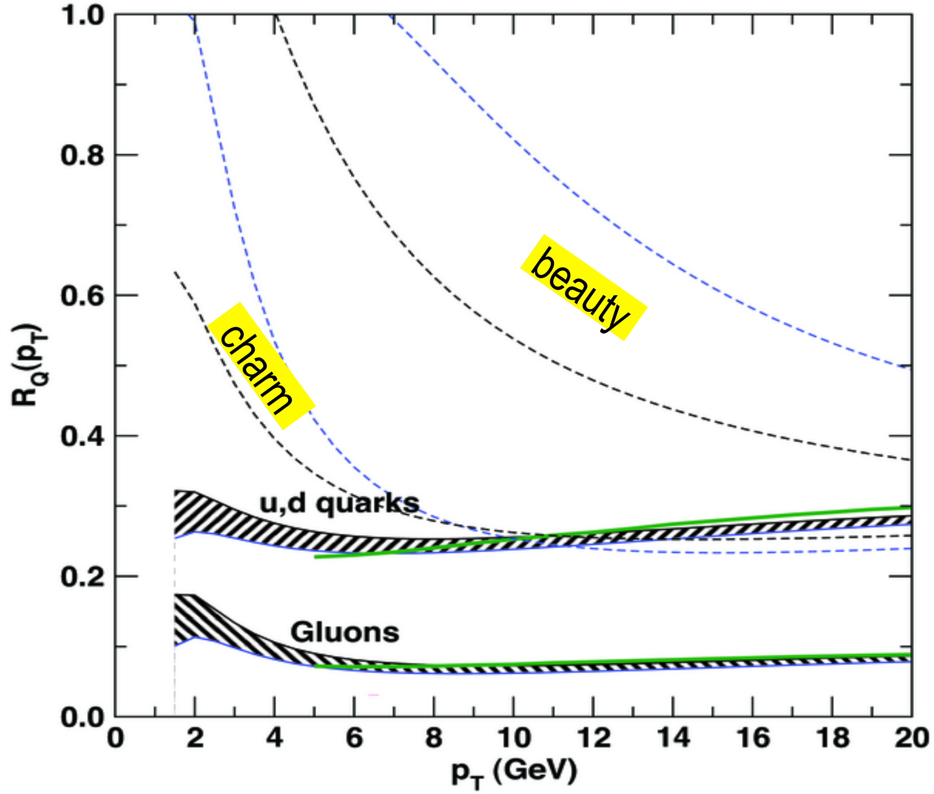
(2) Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

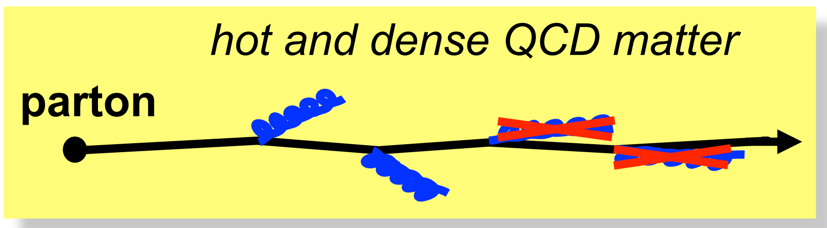
Y. Dokshitzer, D. Kharzeev, PLB 519 (2001) 199, hep-ph/0106202

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

S. Wicks et al., Nucl. Phys. A 784 (2007) 426



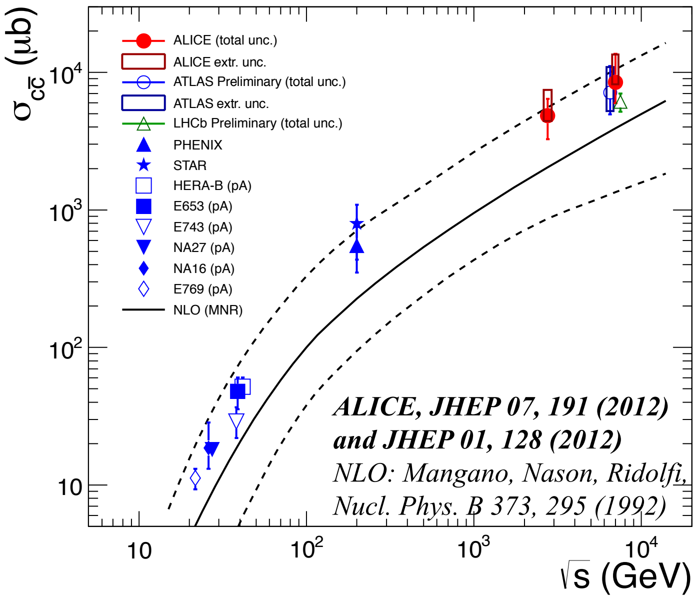


Recent overview papers on HF production in HIC

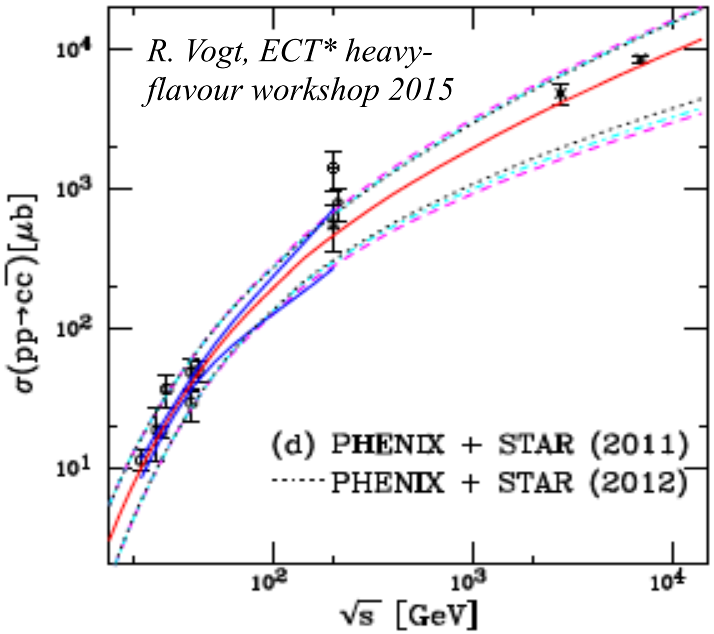
QCD and strongly coupled gauge theories: challenges and perspectives,
EPJC 74 (2014) 2981

Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions,
EPJC 76 3 (2016) 107 (arXiv:1506.03981)

Total charm production cross section in pp



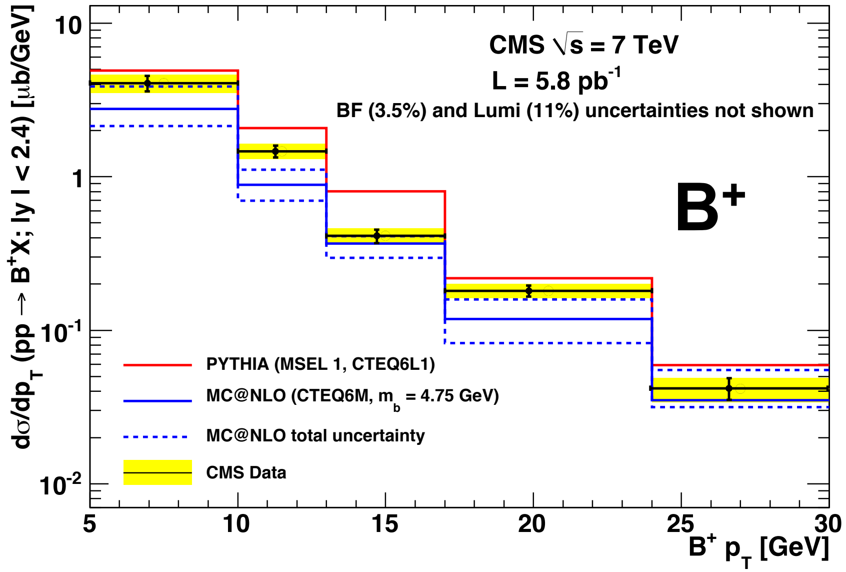
JHEP 1207 (2012) 191

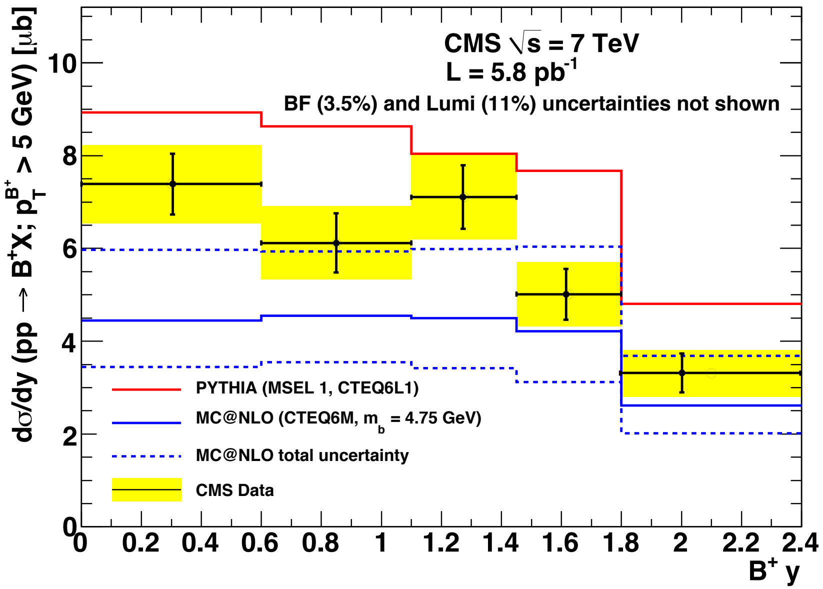


- Very good agreement between LHC experiments
- Consistency with NLO pQCD calculations, although at the upper limit; progress recently
- Run-2 data will provide further constrains
- Note: Parton spectra from pQCD input for energy loss models; baseline for measurements in Pb-Pb

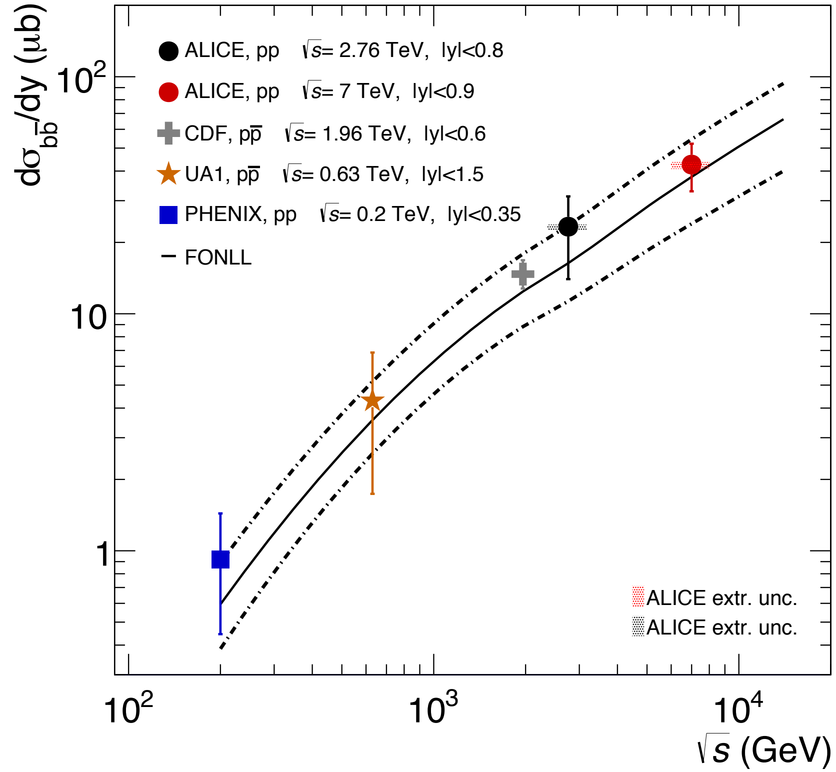
Open-beauty production at the LHC

Phys. Rev. Lett. 106 (2011) 112001



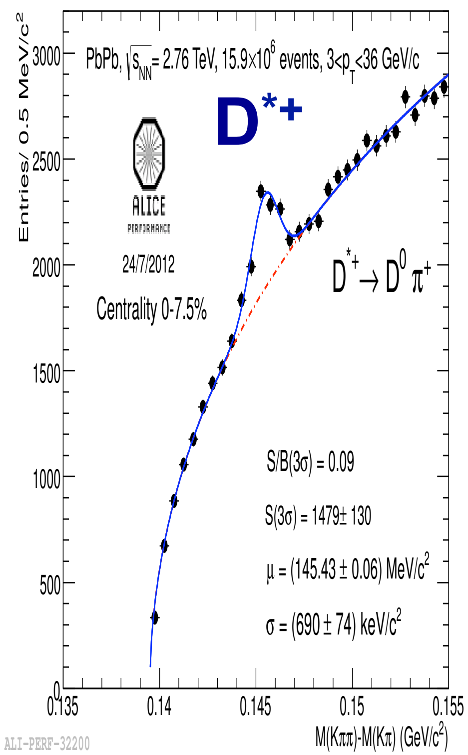


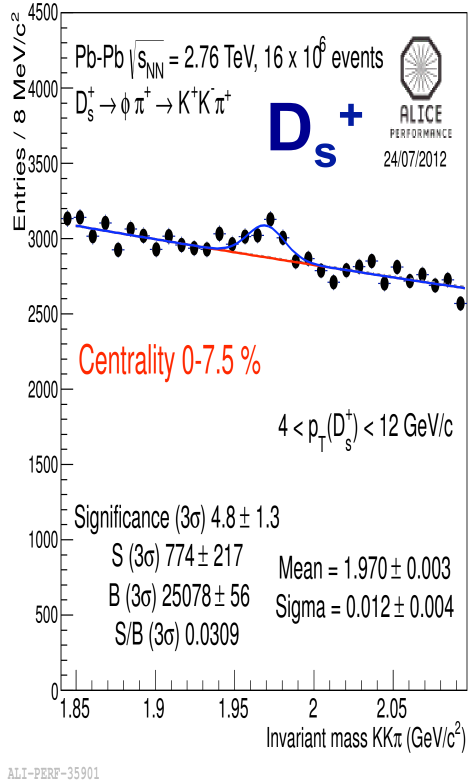
Phys. Lett. B 721 (2013) 13
and 738 (2014) 97

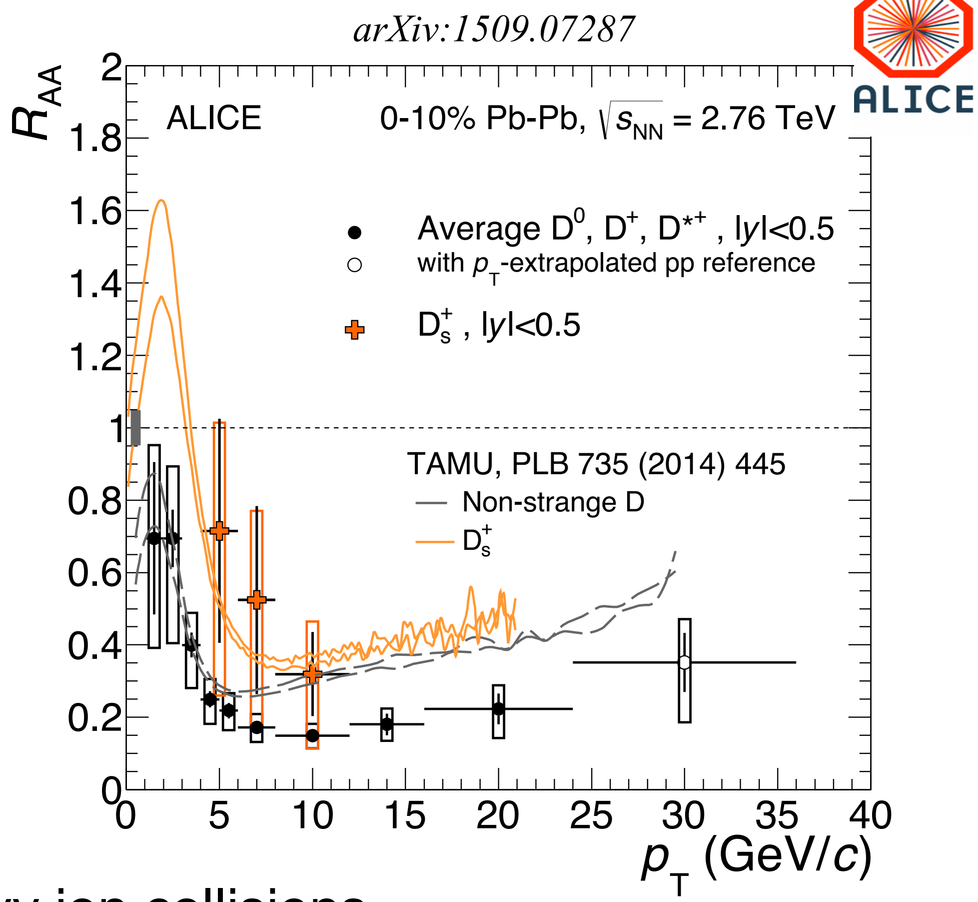


Relatively good description with NLO pQCD calculations

Prompt D meson R_{AA} in Pb-Pb collisions



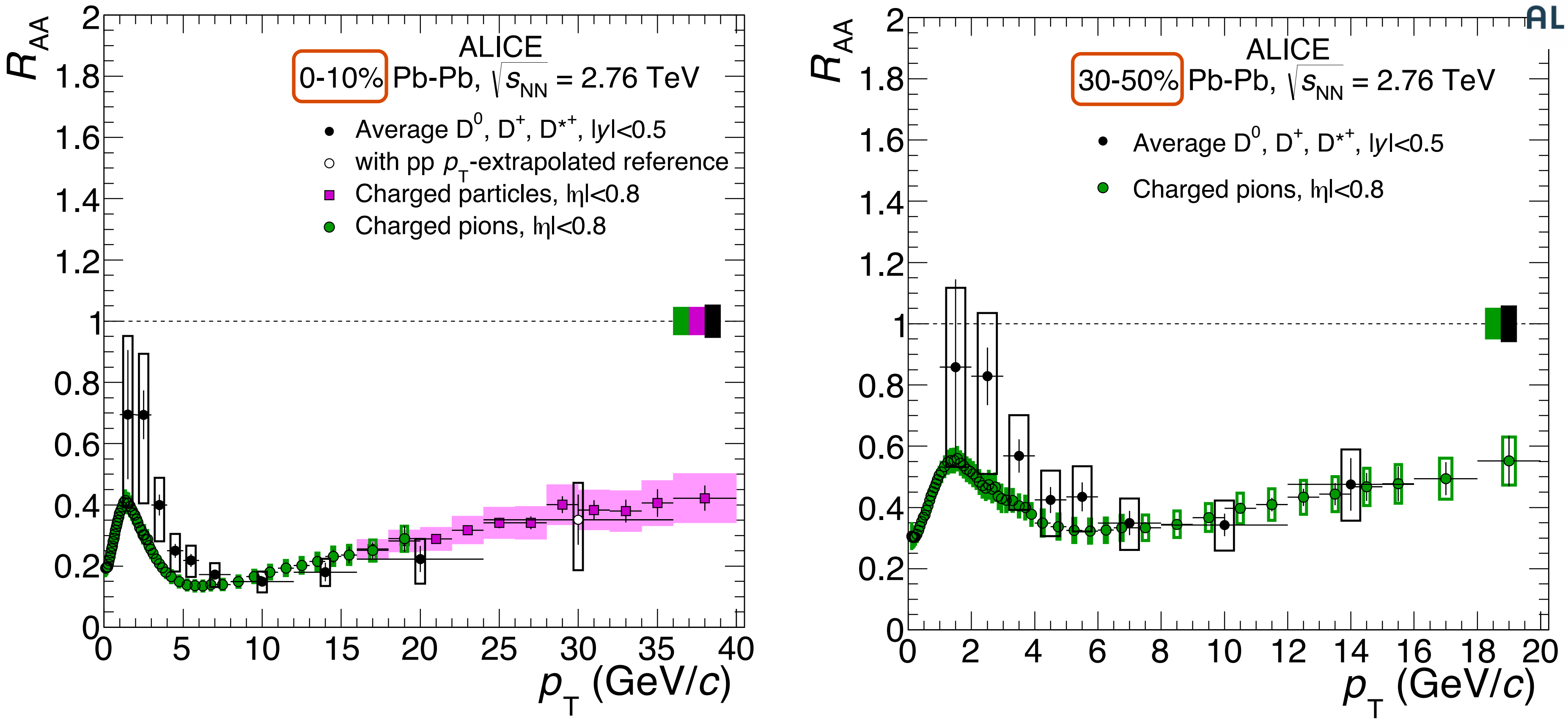




- First $D_s^+(c\bar{s})$ measurement in heavy ion collisions
- Expectation: enhancement of strange D meson yield at intermediate p_T if charm hadronises via recombination in the medium
- Strong suppression (factor 4-5) above 5 GeV/c in most central Pb-Pb, compared to binary scaling from pp

R_{AA}: light versus heavy-quark hadrons

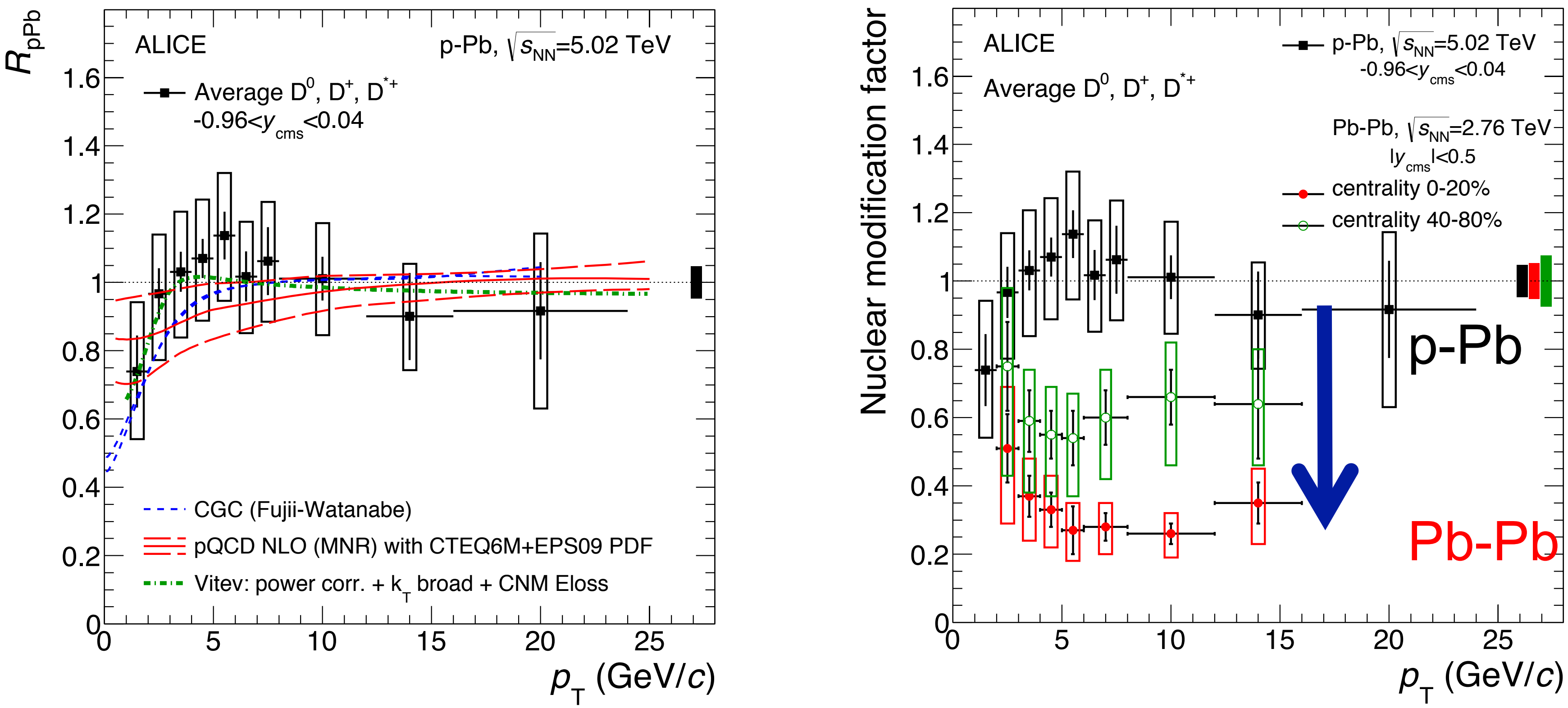
arXiv:1509.06888



- $R_{AA}^{D} > R_{AA}^{pions}$ at low p_T for 10% most central collisions
- Indication for rising R_{AA}?

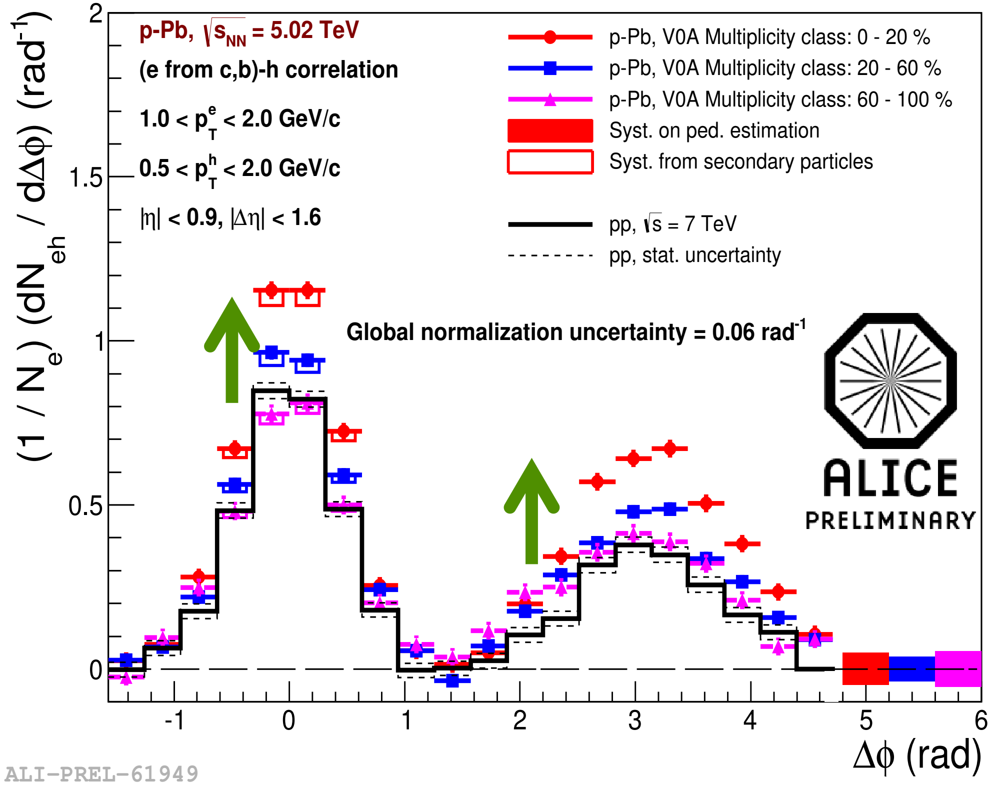
p-Pb: measurement of initial state effects

Phys. Rev. Lett. 113 (2014) 232301



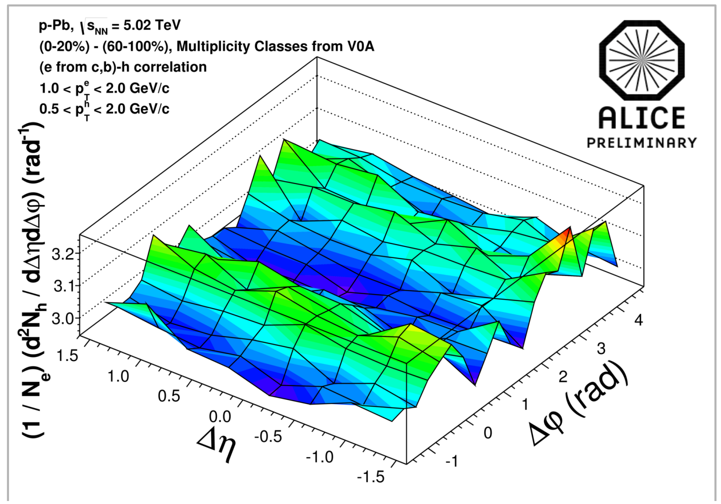
- Important baseline measurement of **cold nuclear matter effects** (e.g., Cronin effect, nuclear shadowing, gluon saturation)
- D meson R_{pA} shows consistency with unity and predictions from shadowing and CGC model predictions
- High-p_T suppression of particle yield in Pb-Pb is a **final state effect**.

Unexpected result: e-h correlations in p-Pb



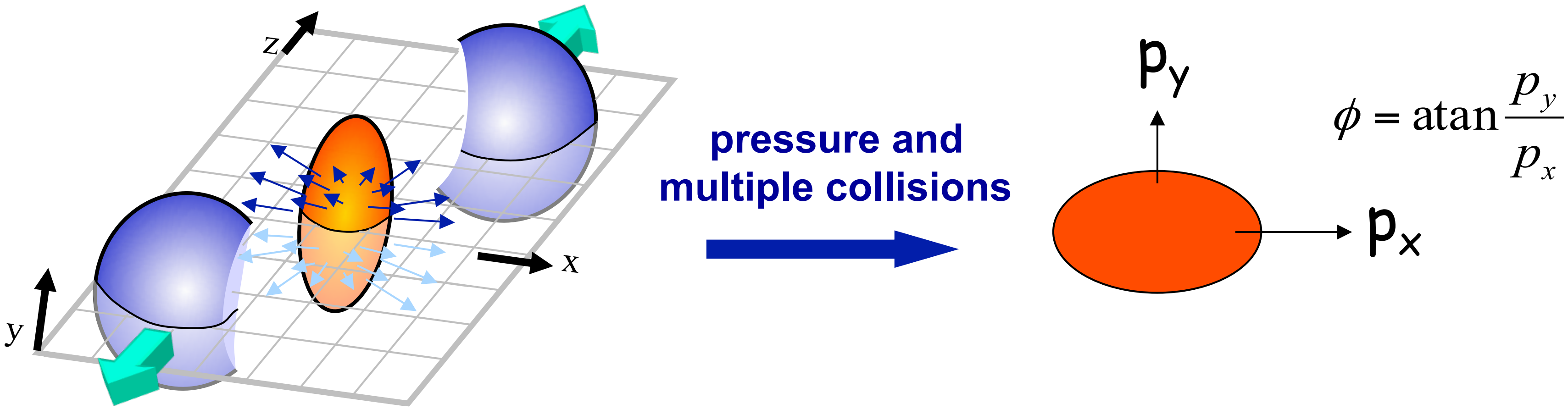
- Most central events have higher correlation yield for low-p_T 'HF → electrons'
- Indication for long-range correlation in Δη; also seen for light flavours
- Hydrodynamics or CGC?
- Theoretical interpretation ongoing

Azimuthal angular correlation between heavy-flavour decay electrons and charged hadrons



Difference of the correlation distribution for high and low multiplicity events

Azimuthal anisotropy



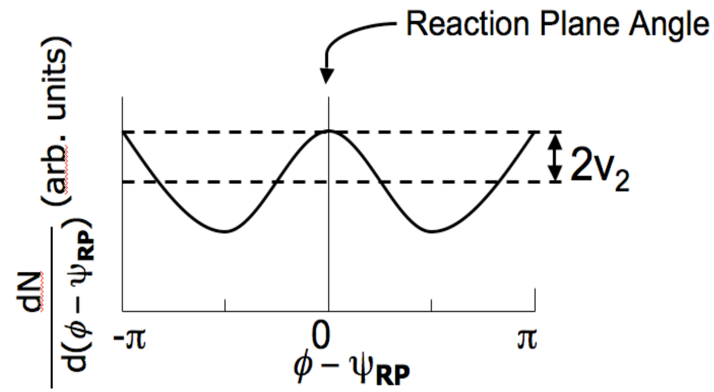
coordinate space:
initial anisotropy

momentum space:
final anisotropy

- Multiple interactions lead to thermalisation → hydrodynamic behaviour of the system
- Pressure gradient generates collective flow → anisotropy in momentum space
- Fourier decomposition:

$$\frac{dN}{d(\varphi - \psi_n)} \propto 1 + 2\sum_{n=1} v_n \cos(n[\varphi - \psi_n])$$

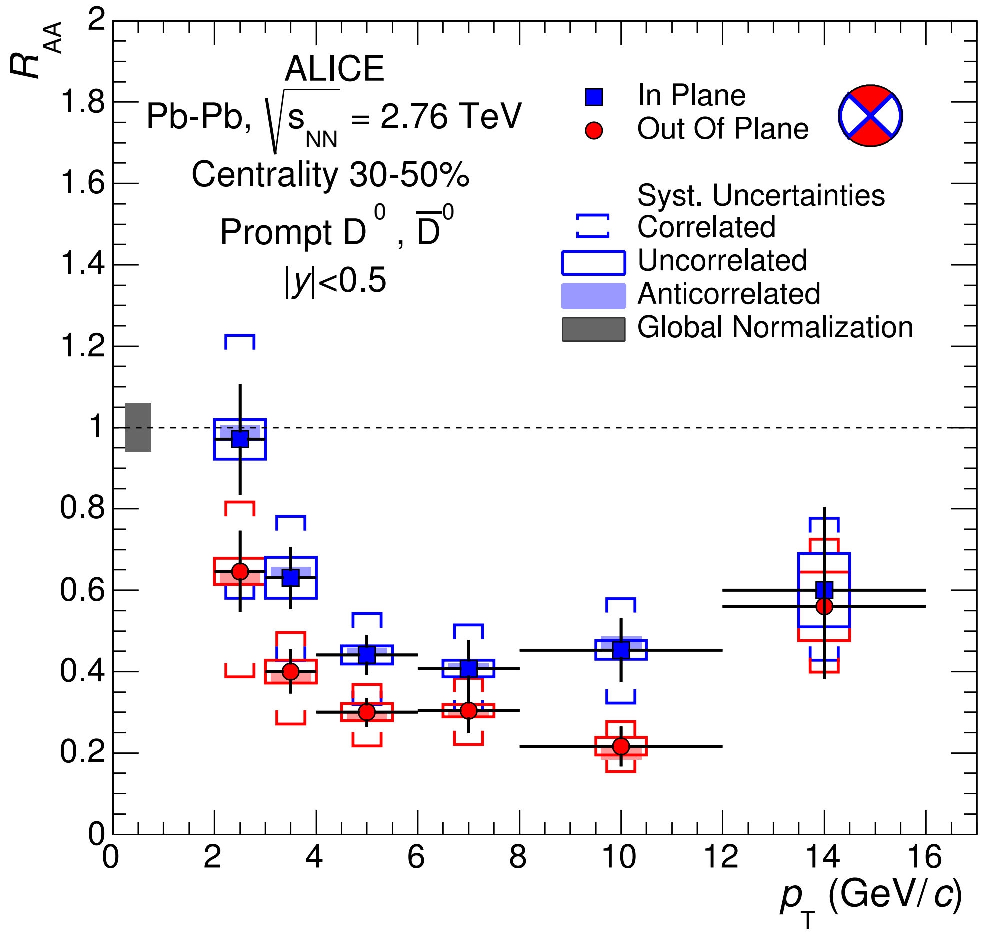
$$v_n = \langle \cos(n[\varphi - \psi_n]) \rangle$$



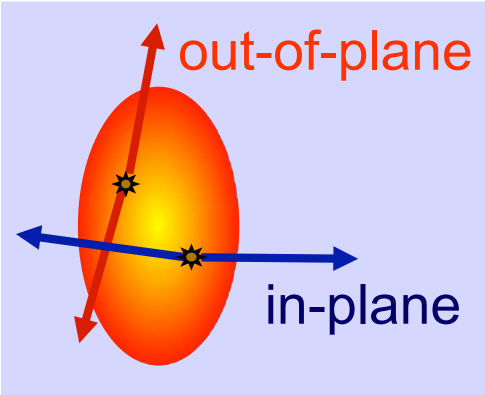
Azimuthal anisotropy = anisotropic flow

Non-scientific analogue

Prompt D^0 R_{AA} versus event plane



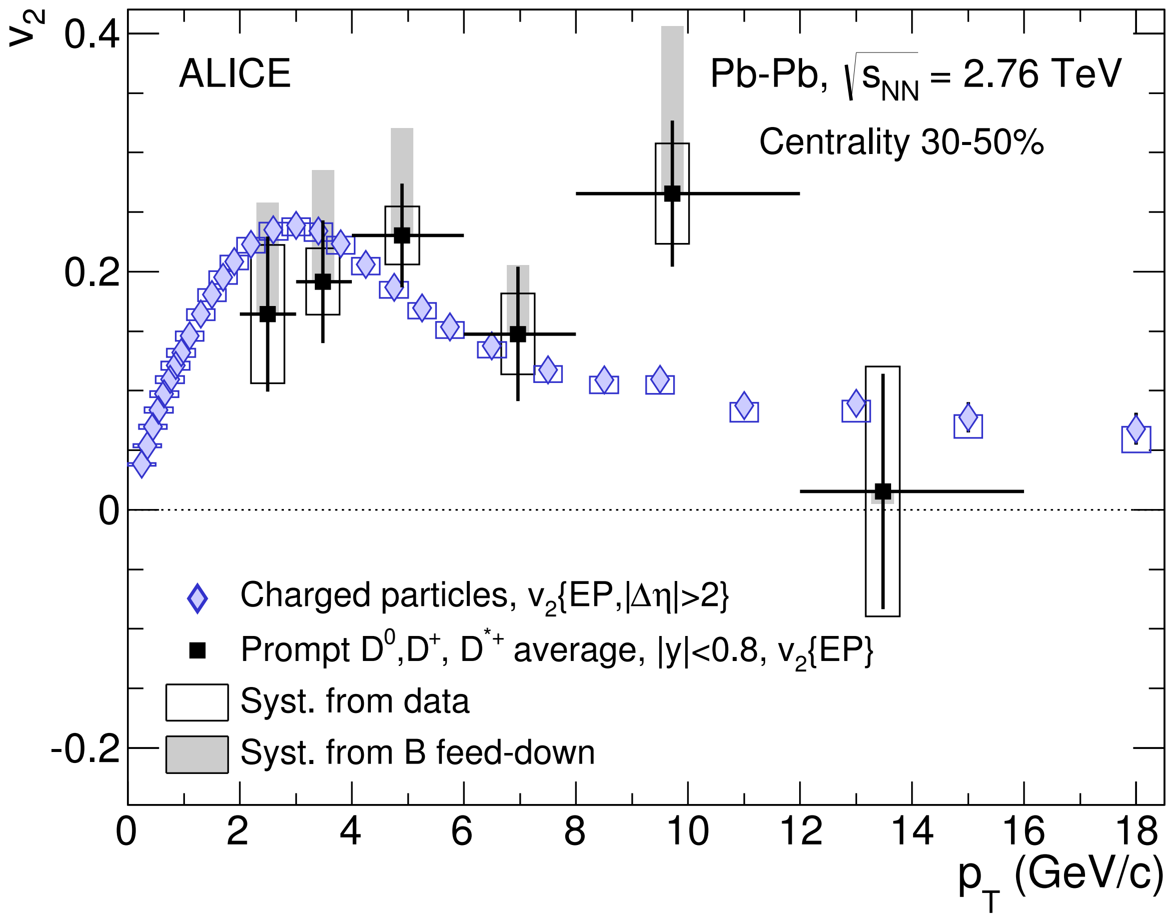
Phys. Rev. C 90 (2014) 034904,
Phys. Rev. Lett. 111 (2013) 102301



More suppression at high p_T out-of-plane with respect to in-plane due to different path length

Azimuthal anisotropy of prompt D mesons

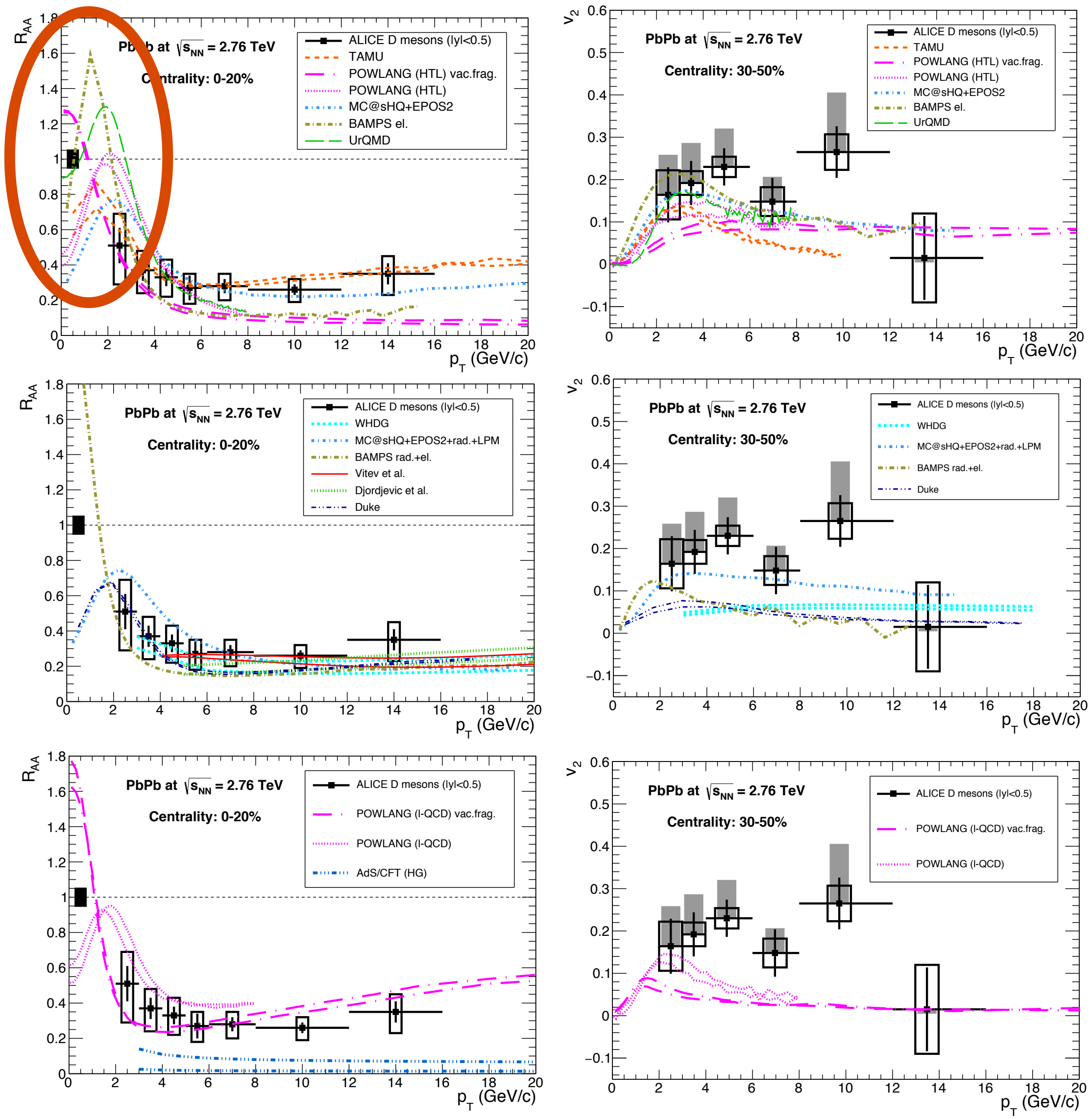
Phys. Rev. Lett. 111 (2013) 102301



- Indication (3-5σ confidence level) for non-zero charm elliptic flow in the p_T range 2-6 GeV/c
- Improved measurement with Run-2 data

Comparison with model calculations: LHC

R_{AA} (0-20%) v_2 (30-50%)



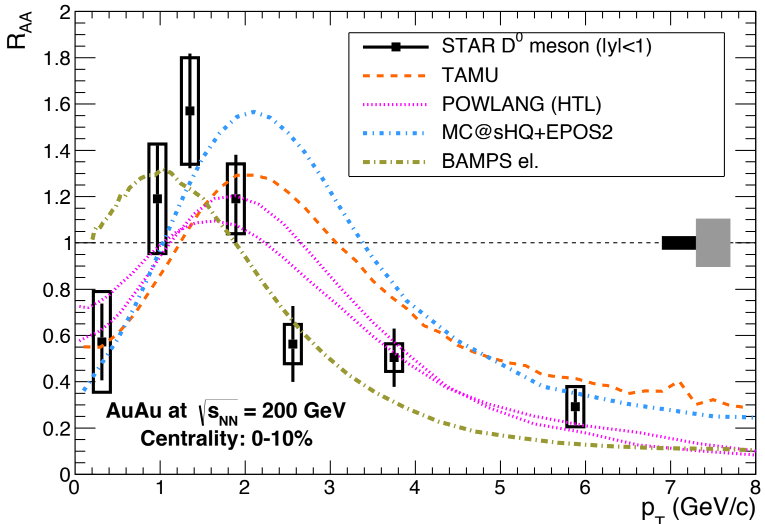
Collisional energy loss only

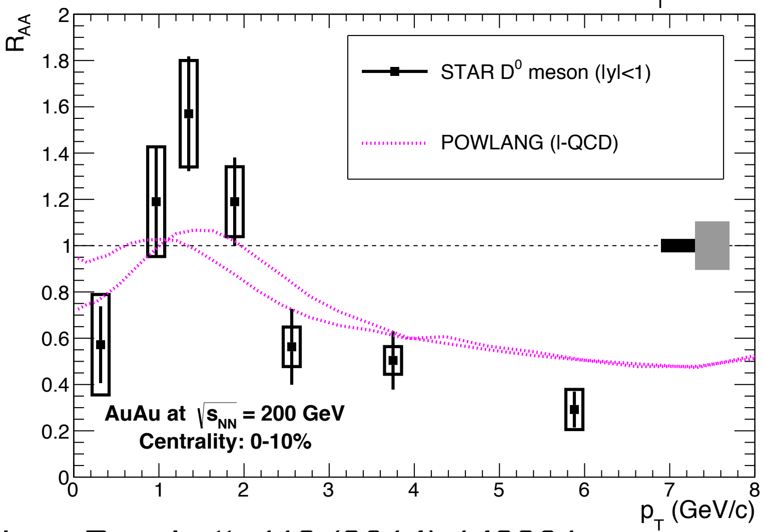
Collisional and radiative energy loss

EPJC 76 3 (2016) 107

Comparison with model calculations: RHIC

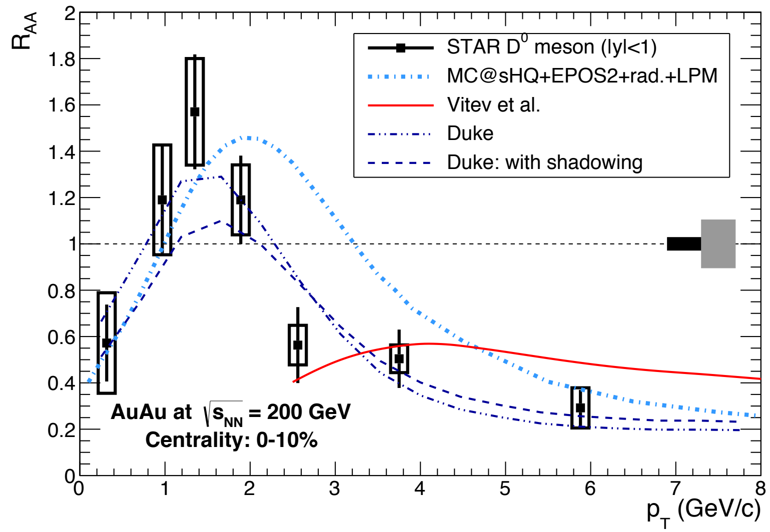
Collisional Eloss only





Phys. Rev. Lett. 113 (2014) 142301
and EPJC 76 3 (2016) 107

Collisional and radiative Eloss

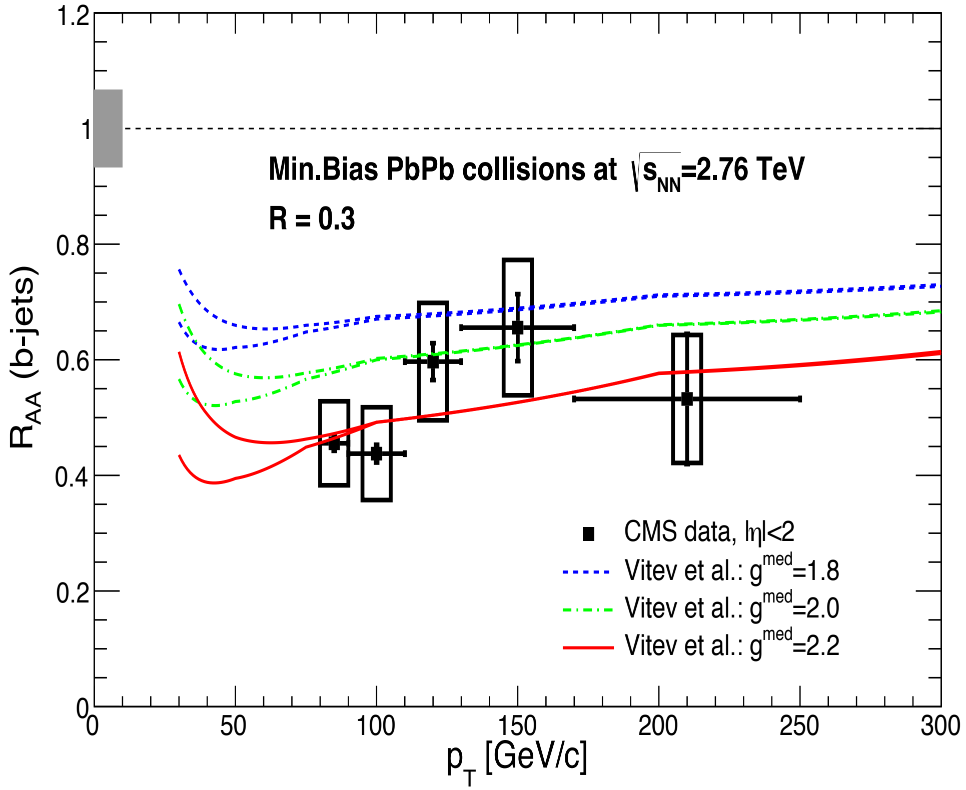


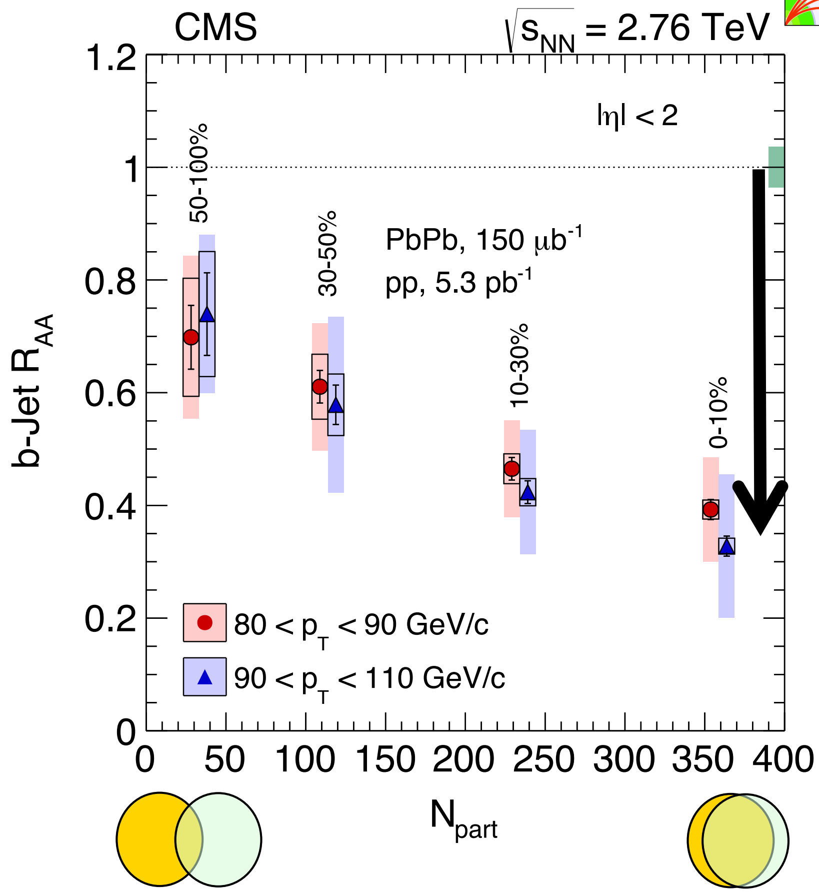
200 GeV

- Maximum at 1.5 GeV/c: effect of radial flow on light and charm quarks
  (TAMU: also flow in hadronic phase)
- Same trend in 193 GeV U+U collisions

R_{AA} of b-tagged jets in Pb-Pb

Phys. Rev. Lett. 113 (2014) 132301

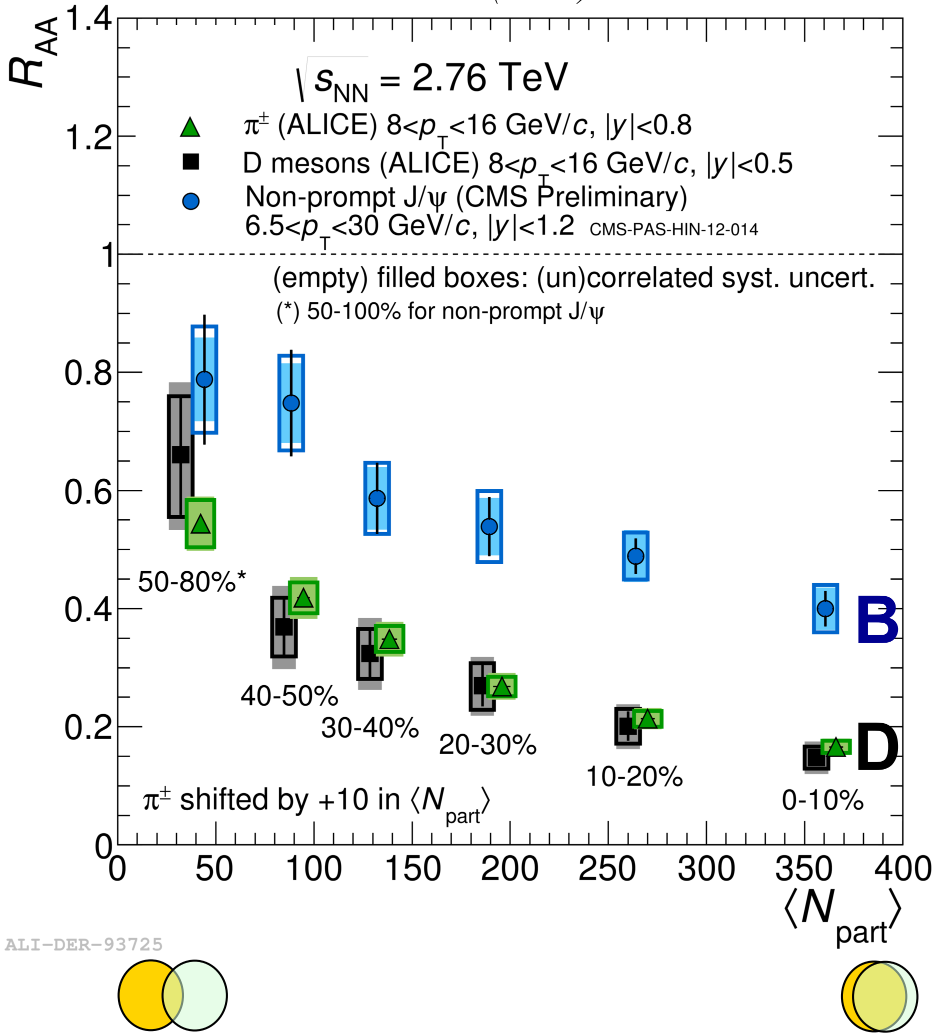




Future precision measurement should allow to constrain quark–medium coupling parameter g^{med}

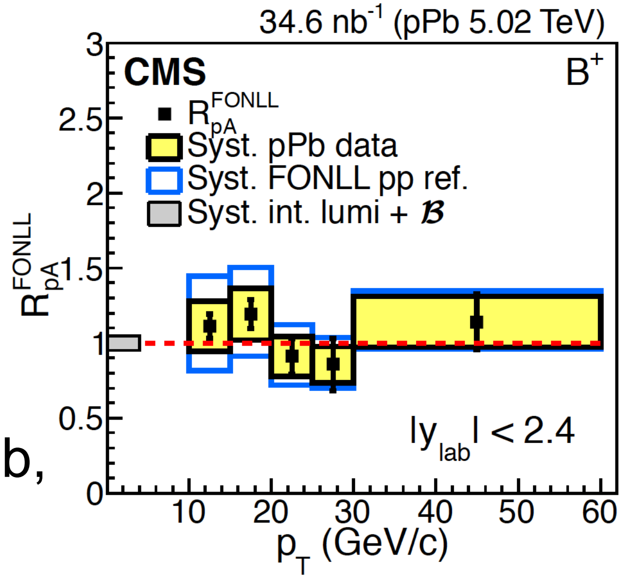
R_{AA} of D and B mesons

JHEP 1511 (2015) 205



- Comparison of prompt D mesons (ALICE) with J/ψ from beauty decays (CMS)
- D and B meson <p_T> ~10 GeV/c
- First indication of quark mass dependence of the parton energy loss: $R_{AA}^{D} < R_{AA}^{B}$

Open beauty in p-Pb,
PRL 116 (2016) 3, 032301



Conclusions

- LHC ideal for studying the properties of hot dense QCD matter

  $\varepsilon_{initial} \gg \varepsilon_{critical}$, large volume, long lifetime, high production rates for rare probes (jets and heavy flavour)

- Lots of measurements from Pb-Pb Run-1

  - High degree of collectivity → perfect liquid
  - Parton-medium interaction → parton energy loss
  - $R_{AA}(\pi) < R_{AA}$(D, single leptons) $< R_{AA}(B \rightarrow J/\psi)$

- p-Pb collisions: More than control measurements; mechanisms at work not fully understood
- Precision measurements needed to gain more insights into energy loss mechanisms and further constraint models
- Many more exciting results ahead of us

  - LHC Run-2 (5.1 TeV, 2015-2017)
  - After detector upgrades (2019/20)