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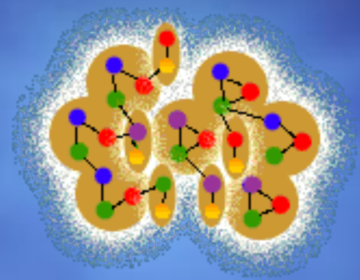

Probing Hot QCD Matter

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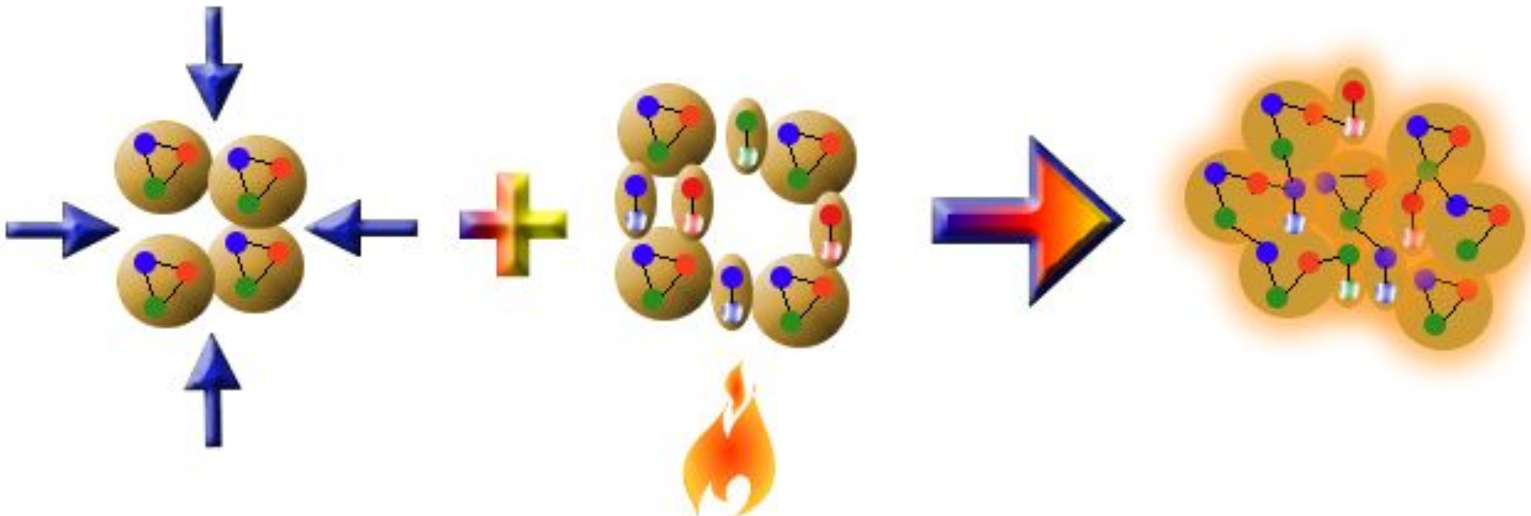
Seminar, School of Physics and Astronomy,
University of Birmingham, UK – 29 January 2015

Outline

- Strongly interacting matter in extremes: the Quark-Gluon Plasma
- Measuring apparatus and methodology
- Recent measurements
  - Global event observables
  - Heavy quarks
- Summary and outlook

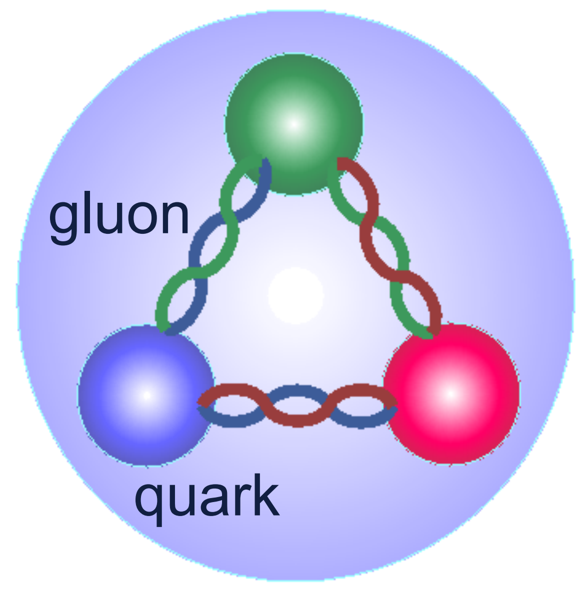
Different phases of matter

Pressure + Heat → Quark-Gluon Plasma



Quark confinement

- Strong interaction described by Quantum-Chromodynamics
- Quarks are confined (hadrons)
- MIT bag model

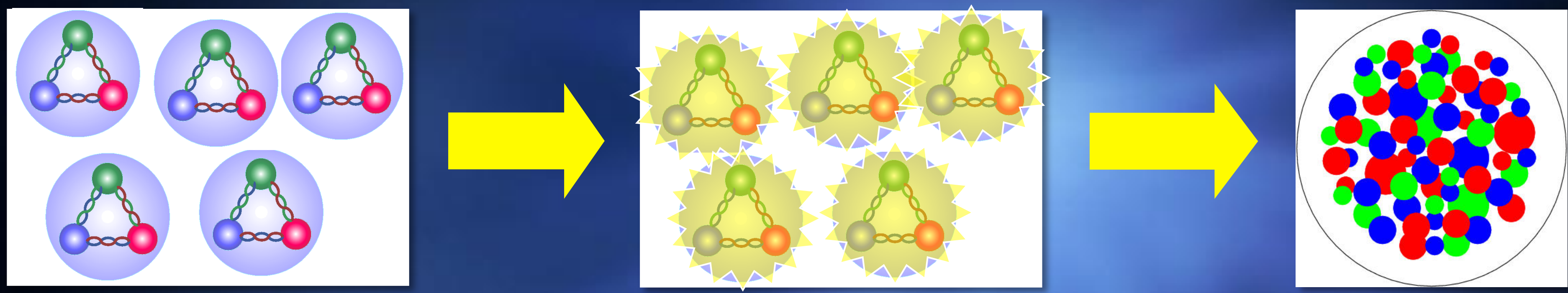


Proton and neutron are colour neutral states

How can we liberate quarks?

Create a Quark-Gluon Plasma

The Quark-Gluon Plasma (QGP)

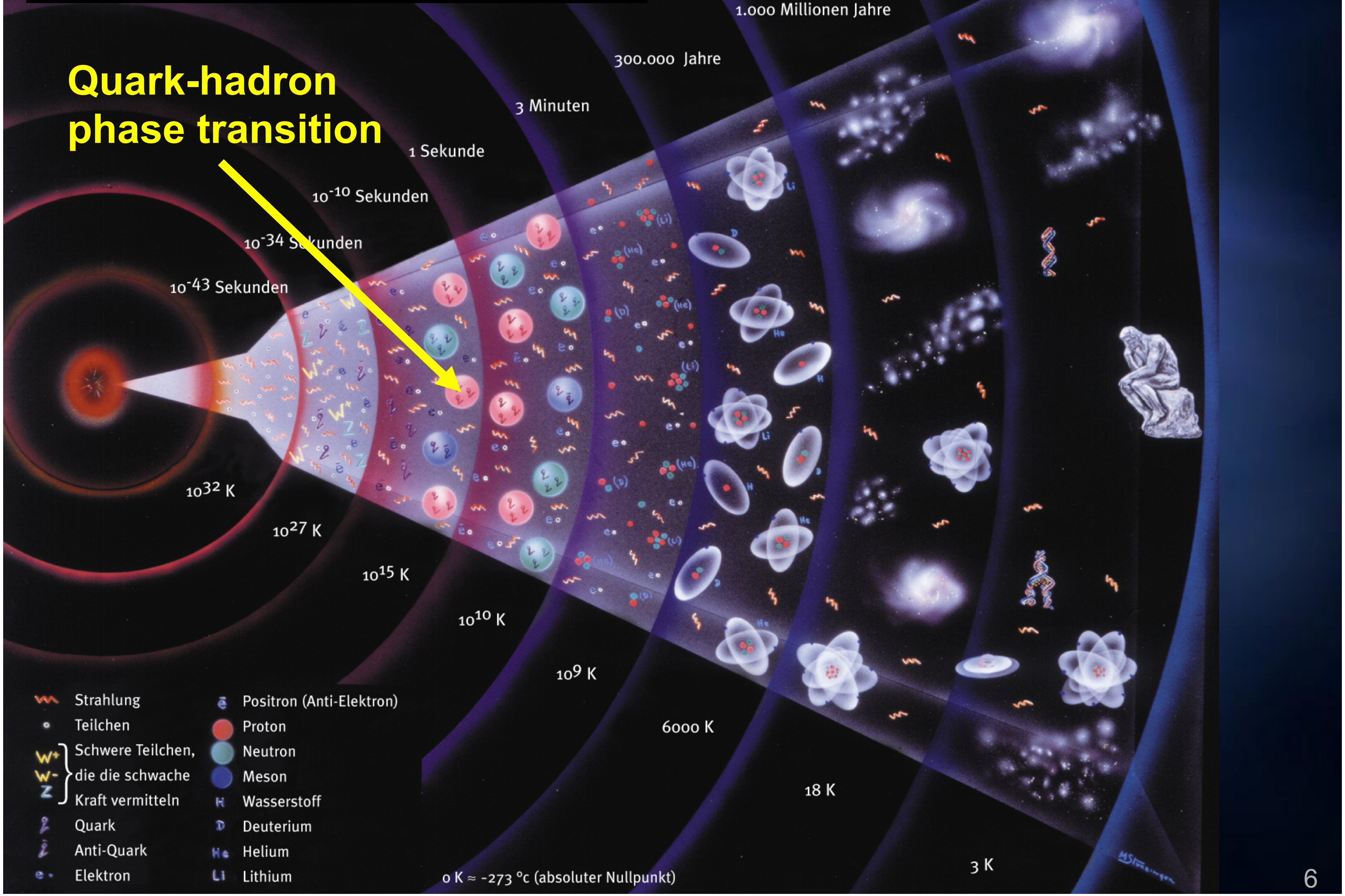


Heat and pressure

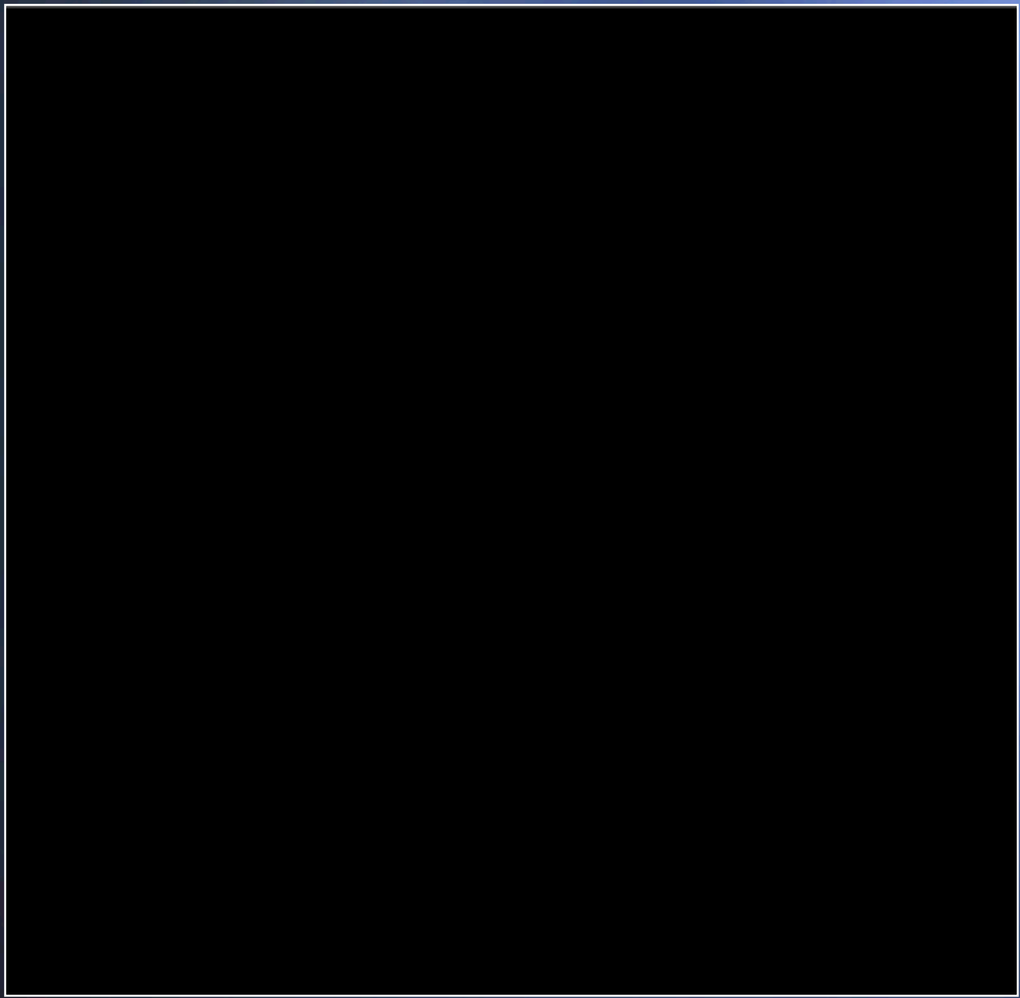
Phase transition to QGP
$T \approx 10^{12}$ K $\approx 10^{5}$x sun's core

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

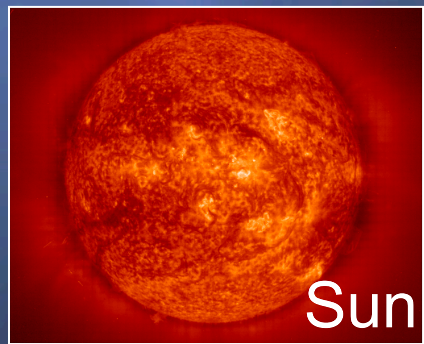
Evolution of the Universe



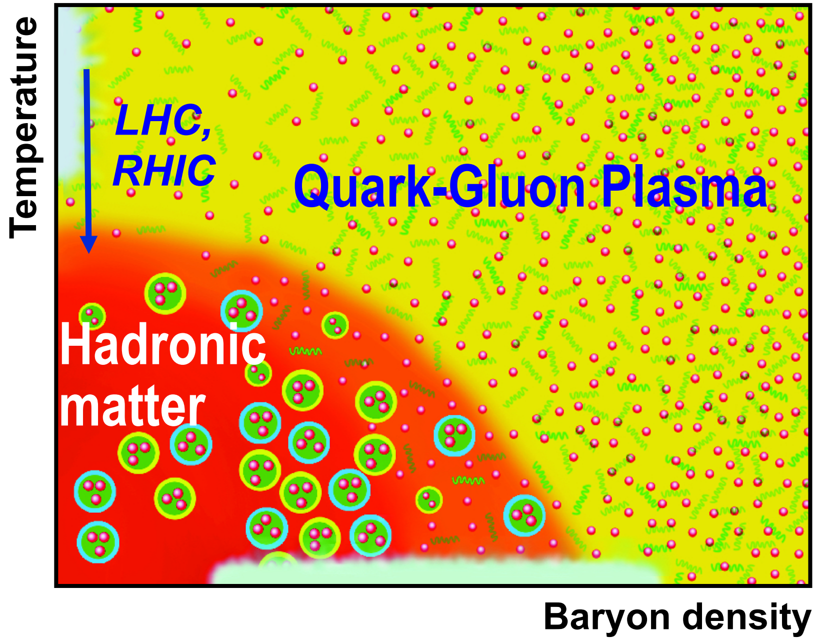
Little bang in the lab

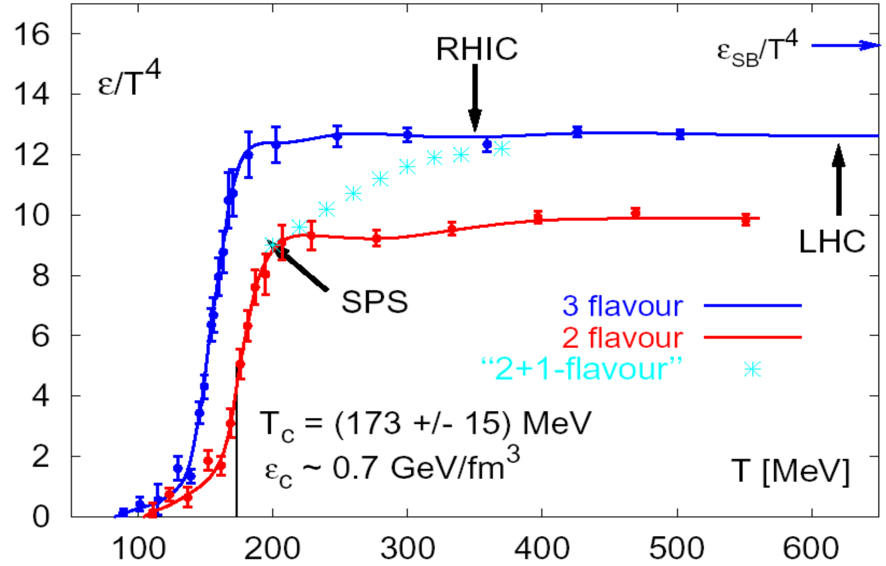


- Temperature:
1000 billion degrees
- Lifetime:
10 microseconds



QCD phase diagram



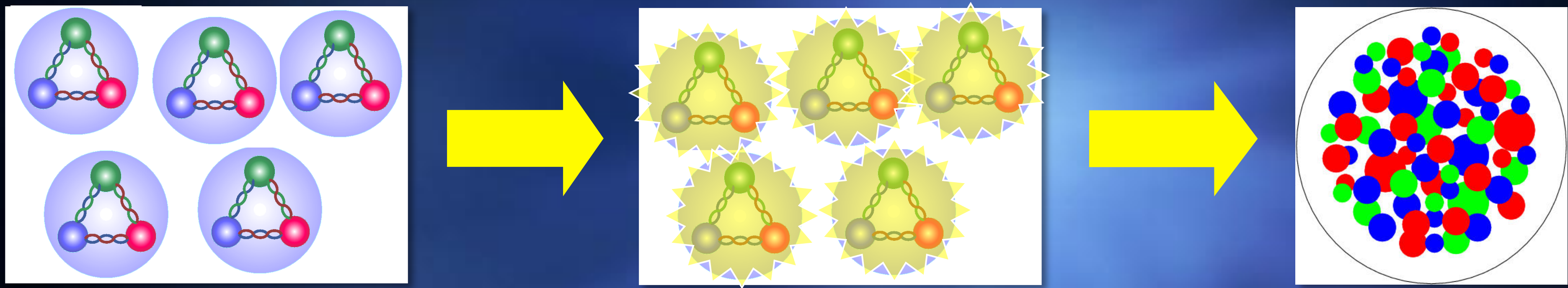


Study strongly interacting matter under extreme conditions: high temperature and high density

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

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

The Quark-Gluon Plasma (QGP)



Heat and pressure

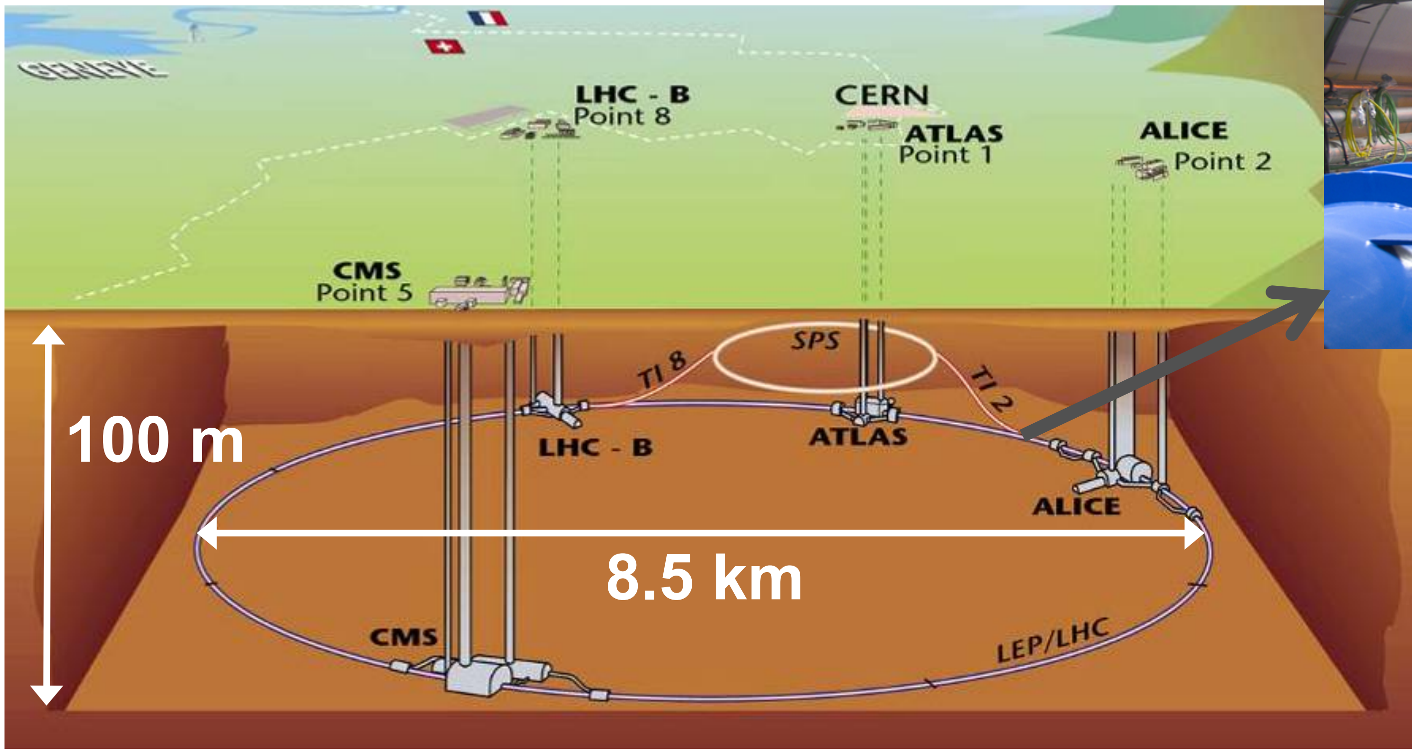
Phase transition to QGP
$T \approx 10^{12}$ K $\approx 10^5$x sun's core

- Novel state of matter: quarks and gluons are liberated (deconfinement)
- Evolution of the early universe
- Produce and study QGP in the laboratory
  - high density and temperature
  - sufficient large reaction volume

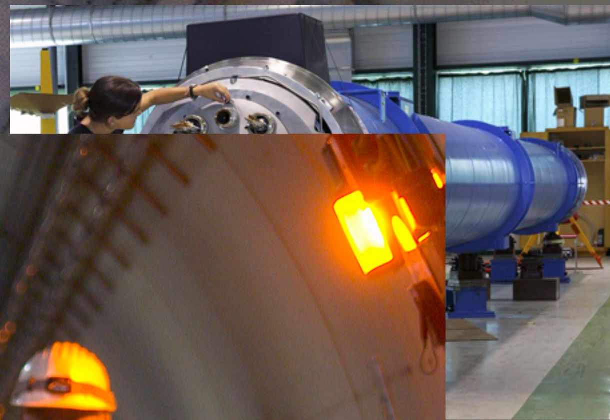
→ Collisions of heavy atomic nuclei (lead or gold)

- Large Hadron Collider: Exploration of the QGP properties

Large Hadron Collider at CERN



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



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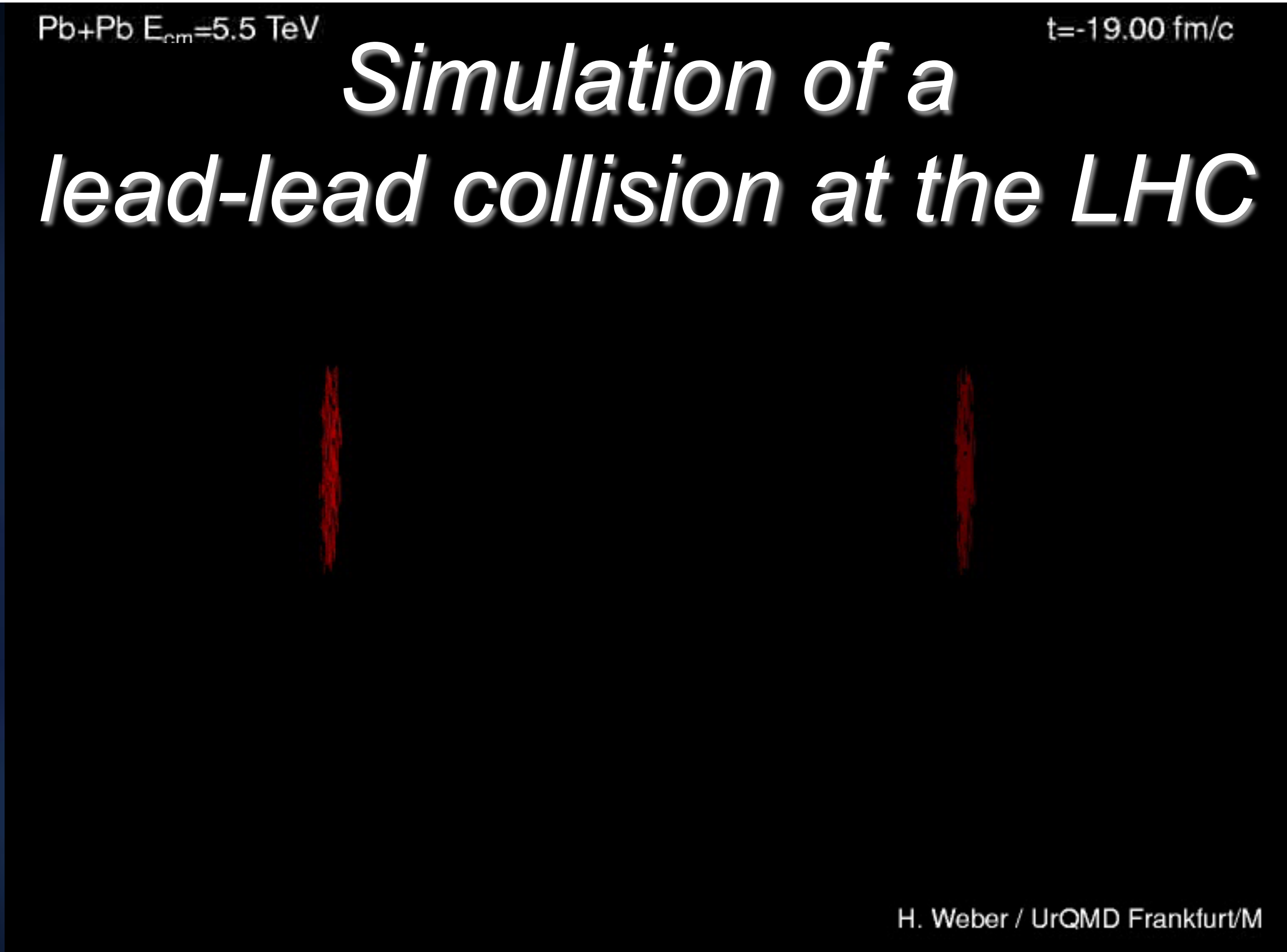
tons)

• 8 Tesla bending field

Simulation of a lead-lead collision at the LHC

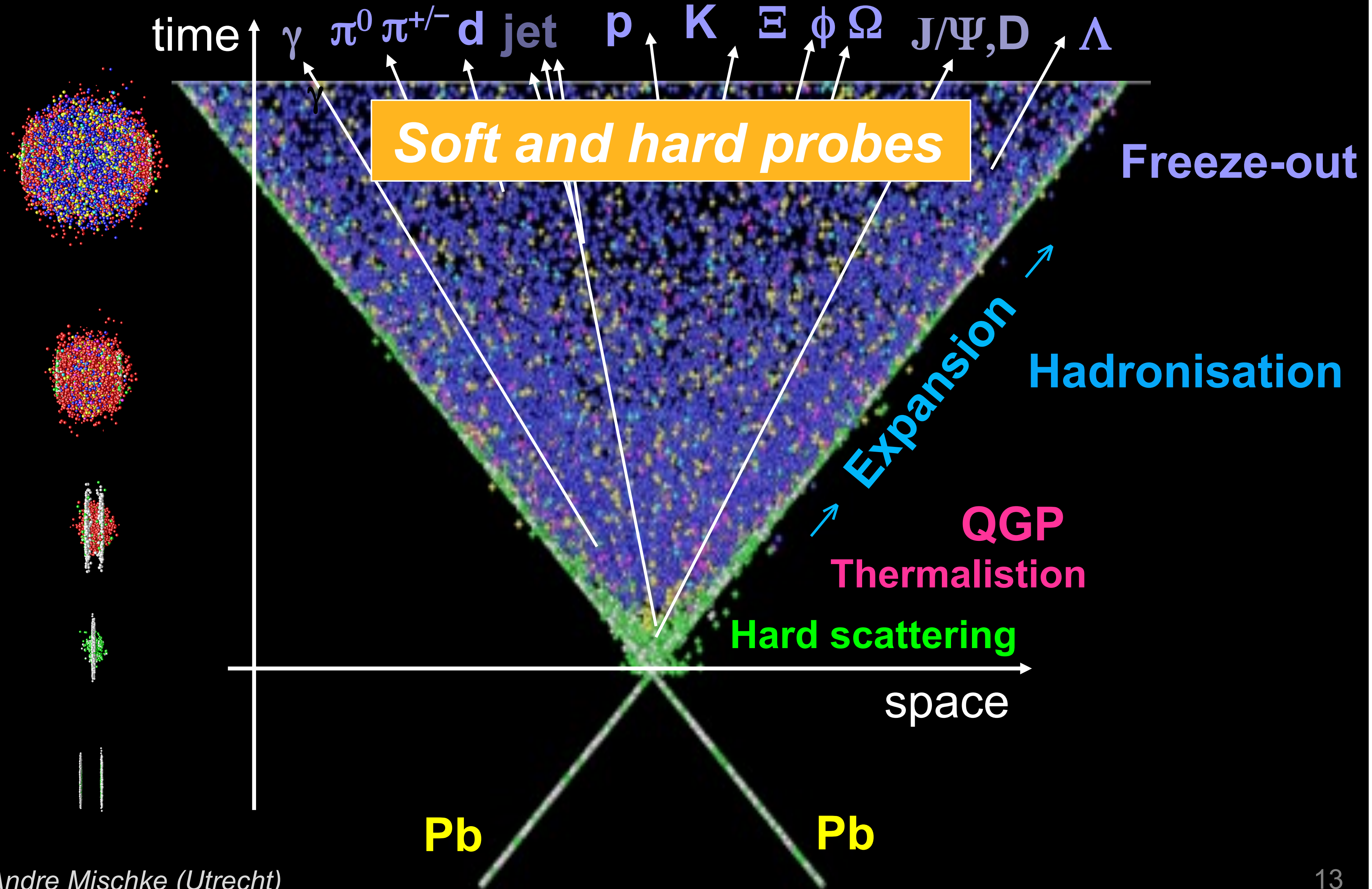
10^{-14} m



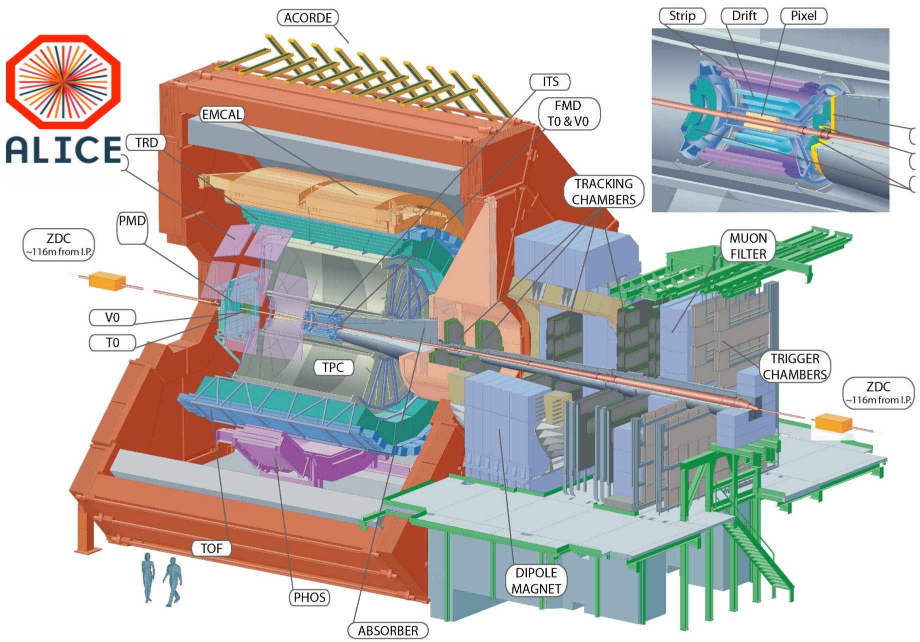
- Time scale ≈ few 10^{-24} s
- Total energy in a lead-lead collision = 1144 TeV = 0.18 mJ

⇒ production of new particles

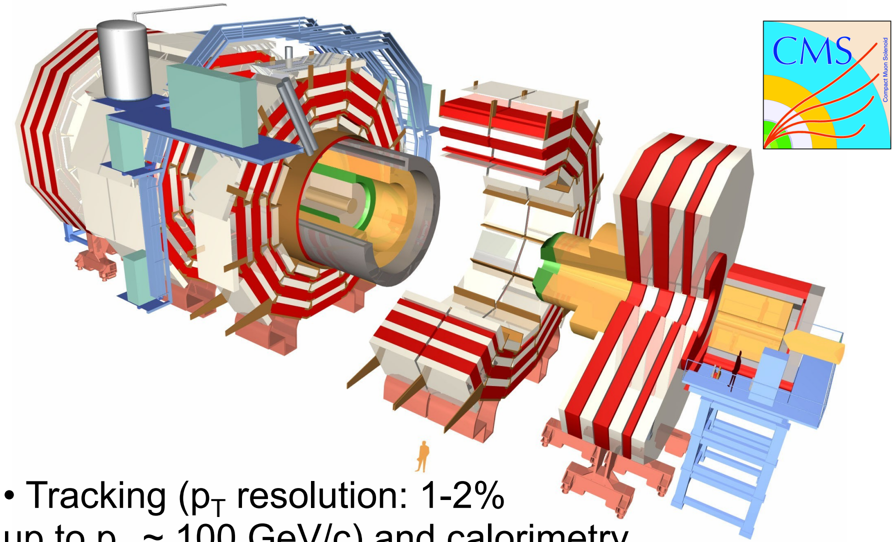
Space-time evolution of a heavy-ion collision



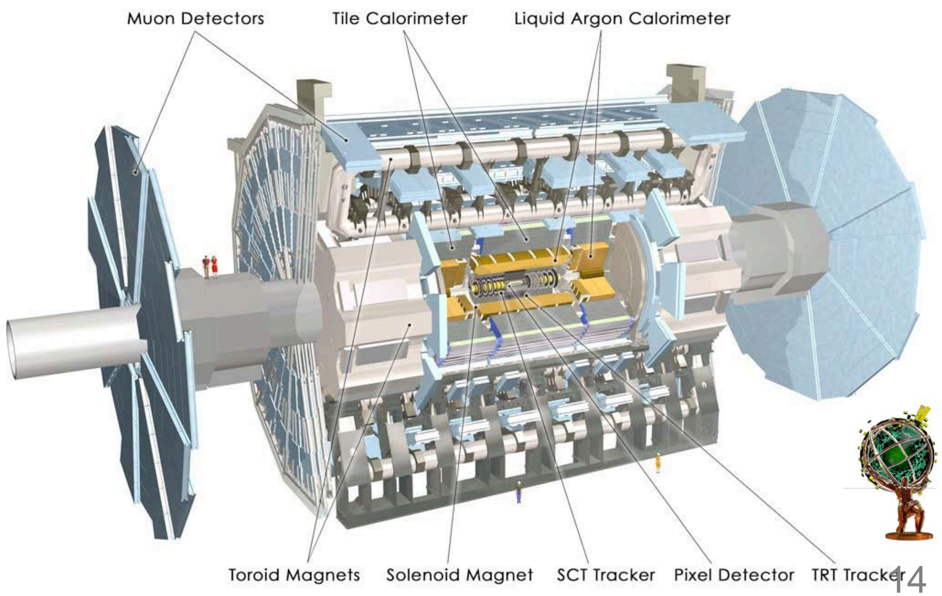
Detectors



- 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



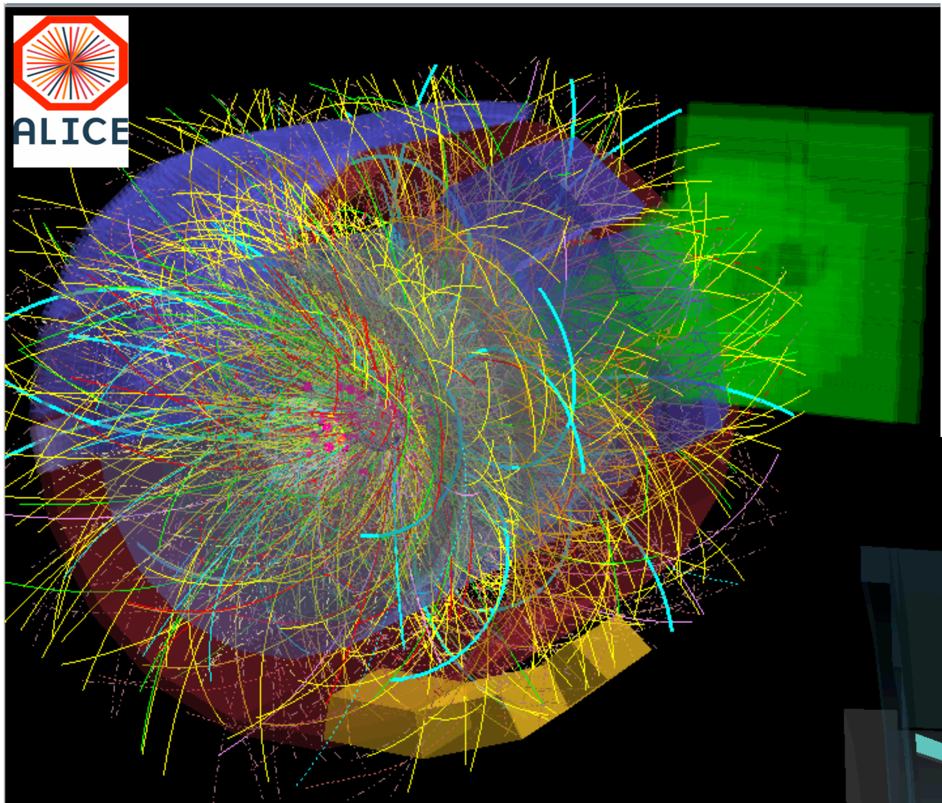
- Tracking (p_T resolution: 1-2% up to $p_T \sim 100$ GeV/c) and calorimetry
- Trigger selectivity over a large range in rapidity and full azimuth

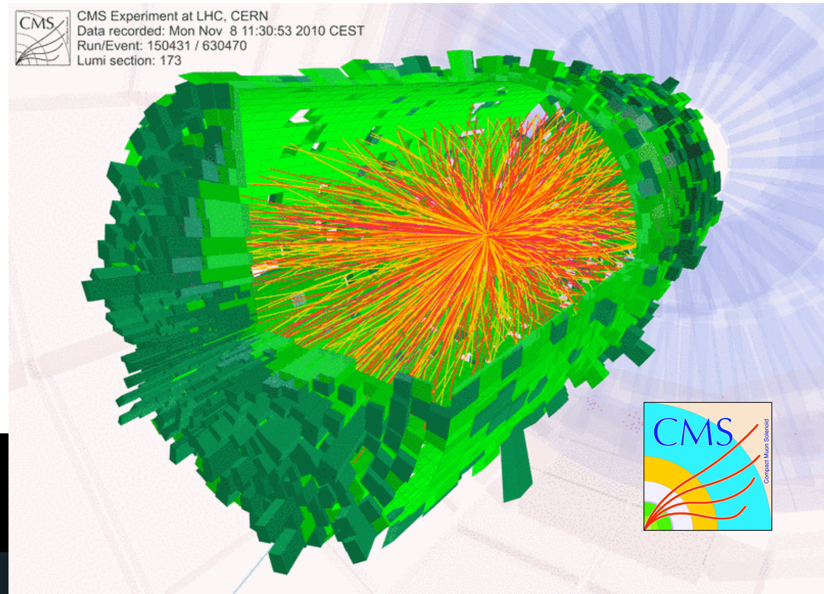


Three main subsystems with a full coverage in azimuth:

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

Typical event displays





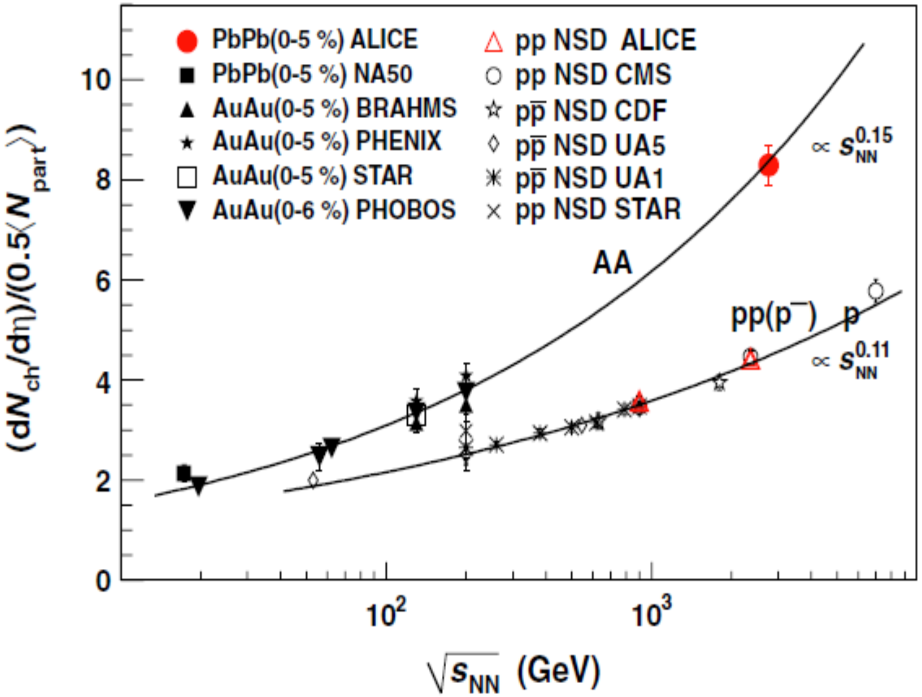
Central lead-lead collision at $\sqrt{s}$ = 2.76 TeV per nucleon-nucleon pair

Global event observables

Charged particle multiplicity

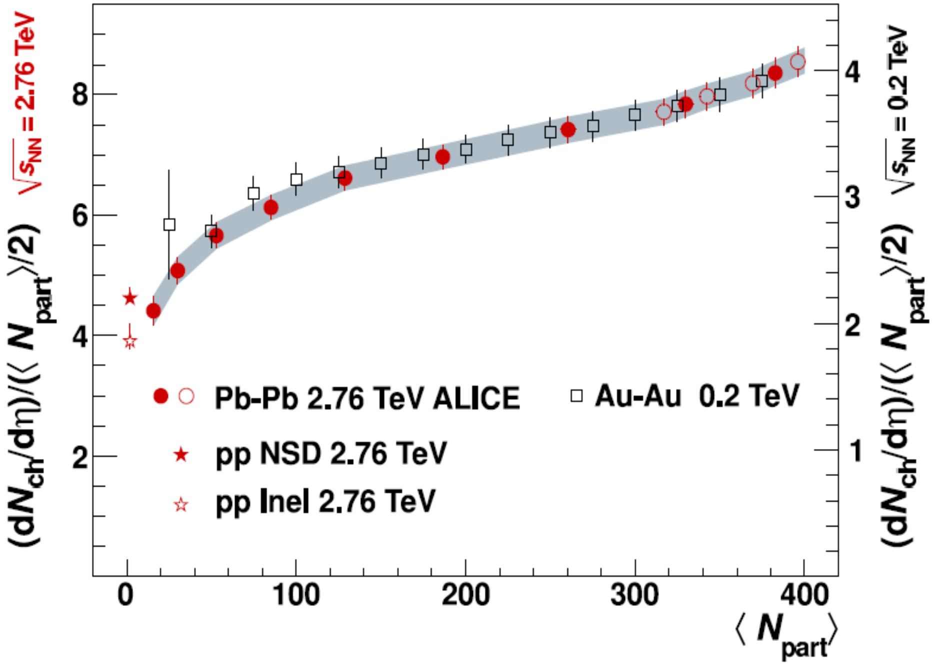
vs. cms energy

Phys. Rev. Lett. 105, 252301 (2010)



vs. number of participants

Phys. Rev. Lett. 106, 032301 (2011)



- Power law dependence fits well and faster in Pb-Pb ~$s^{0.15}$ than in pp ~$s^{0.11}$
- Multiplicity ~ 2 x N_{RHIC}
- Energy density ~ 3 x ε_{RHIC}

- Very similar centrality dependence at LHC and RHIC
  Once corrected for difference in absolute values

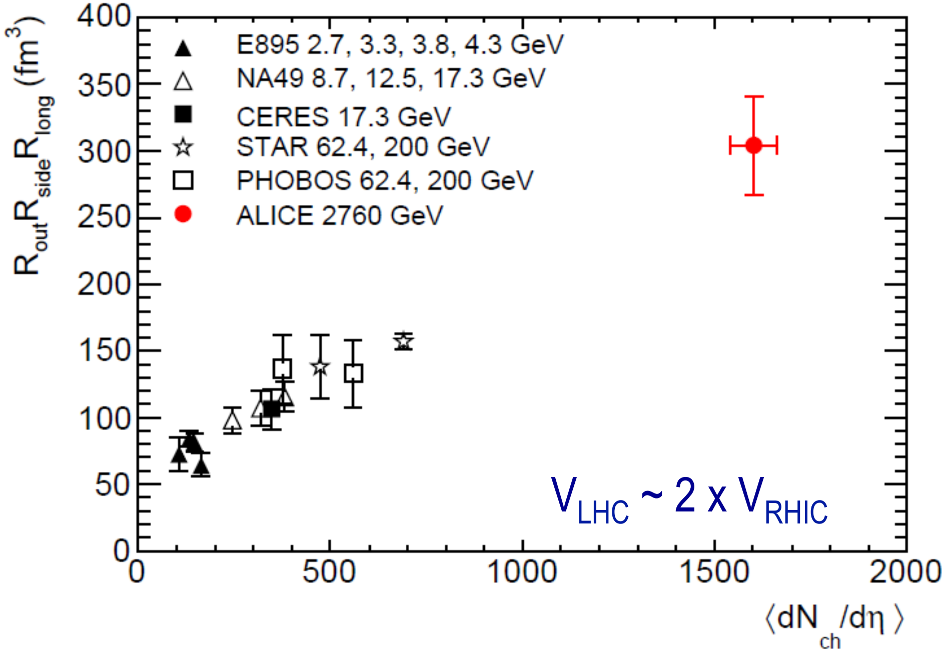
Denser and hotter system

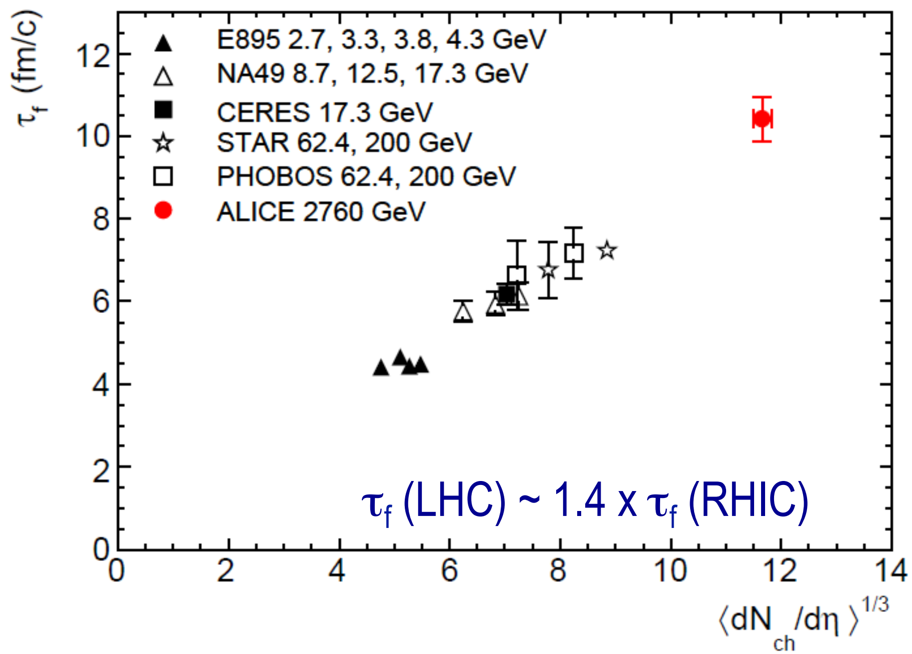
System size and lifetime

System size

Lifetime

Phys. Lett. B 696, 328 (2011)

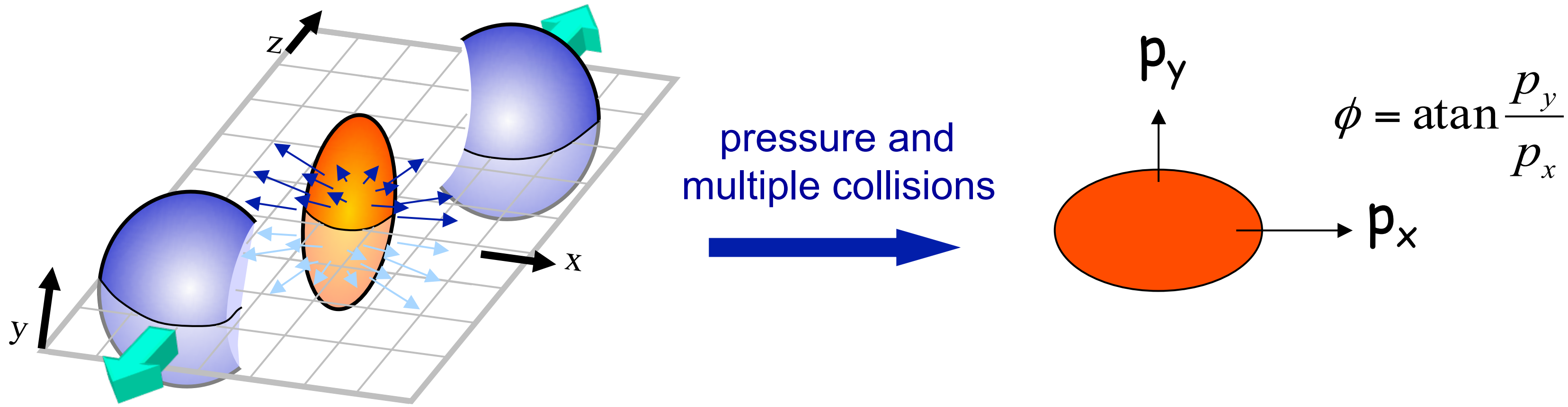




- From Bose-Einstein Correlations analysis (HBT)
- 2 × freeze-out volume and 1.4 × lifetime compared to RHIC

Fireball has larger volume and longer lifetime

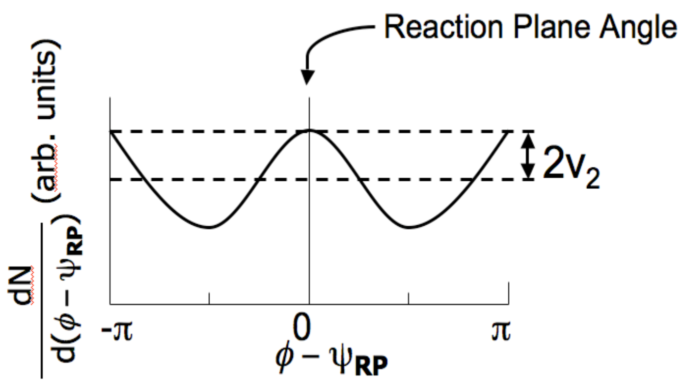
Azimuthal anisotropy



coordinate space: initial anisotropy

momentum space: final anisotropy

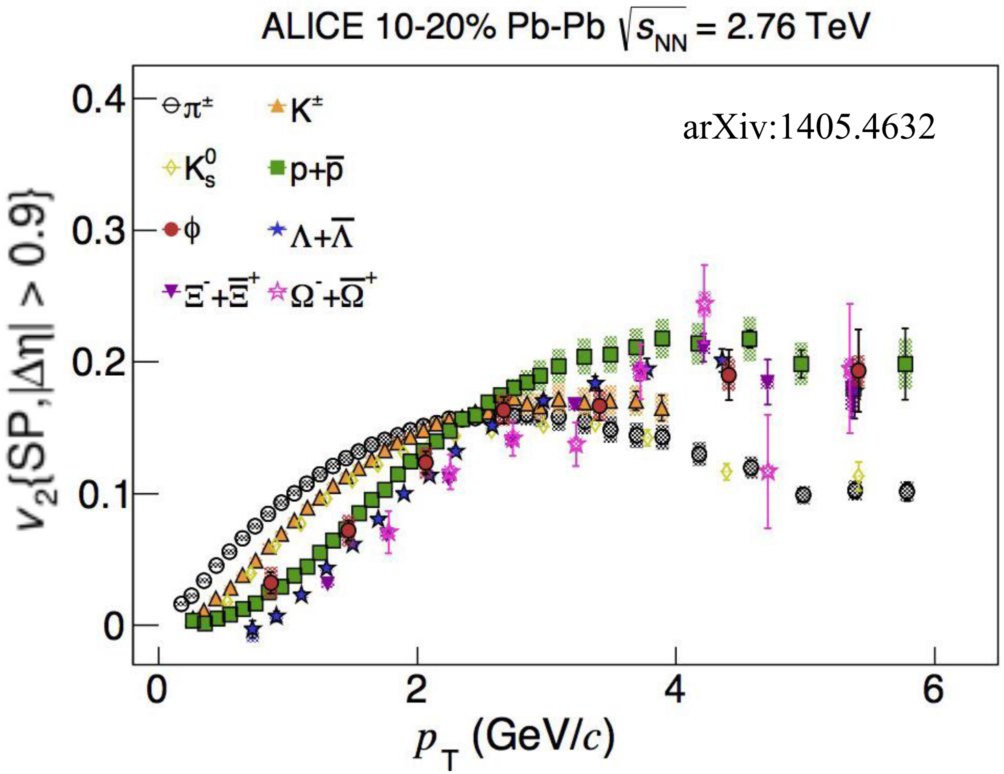
- Multiple interactions lead to thermalisation → hydrodynamic behaviour of the system
- Pressure gradient generates collective flow → anisotropy in momentum space
- Fourier decomposition:



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

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

v_2 of identified particles in Pb-Pb



Why?

- Constraints on initial conditions, such as particle production mechanisms
- Probes freeze-out conditions of the system
- Checks number of constituents quarks scaling

- Low p_T: mass ordering observed → interplay between radial and elliptic flow
- Qualitative description with hydrodynamical calculations and hadronic cascade model → small η/s favoured
- High p_T: particles tend to group into mesons and baryons

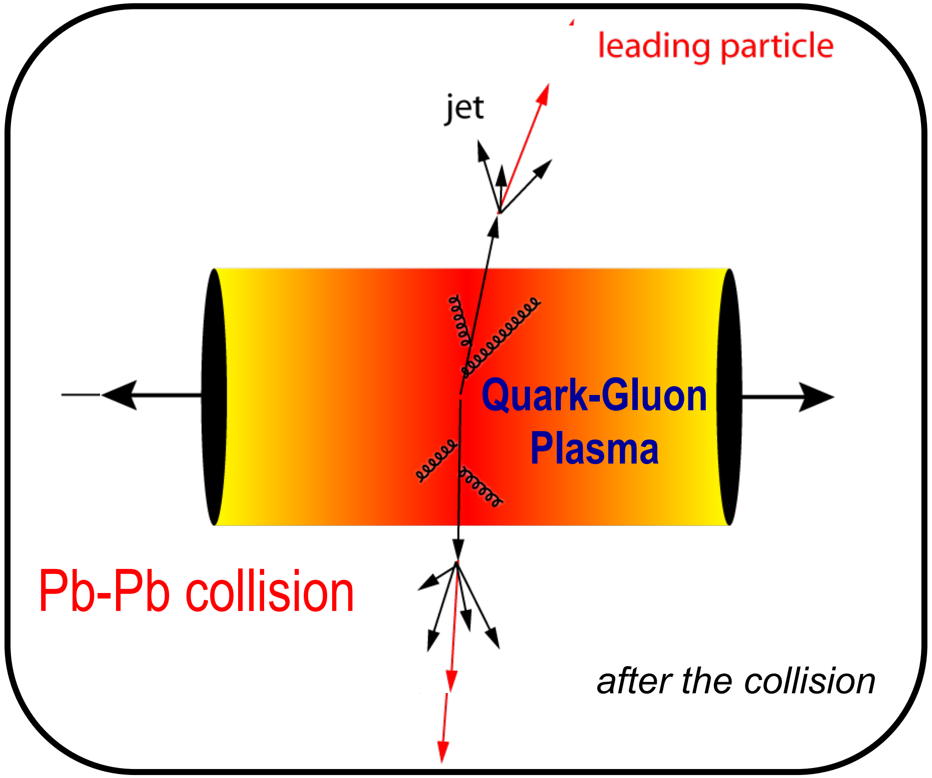
Collectivity in particle emission

- Collective motion of particles gives information about the toughness (viscosity)
- Quark matter is the most perfect fluid in the world
- It has less friction than super-fluid helium

•

Heavy quarks
(charm and beauty)

Probing hot and dense QCD matter



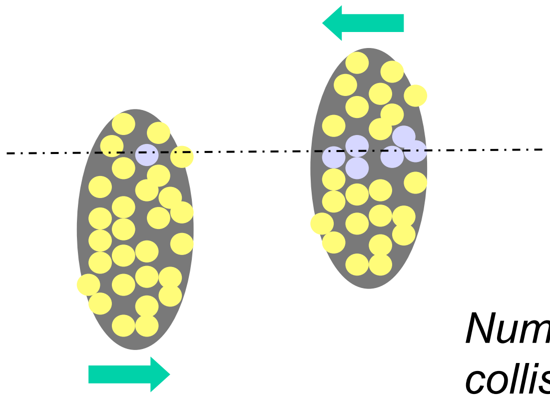
- "Simplest way" to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile

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

Quantify medium effects with **nuclear modification factor**

Quantification of medium effects

Compare particle yield in lead-lead with the one in proton-proton collisions



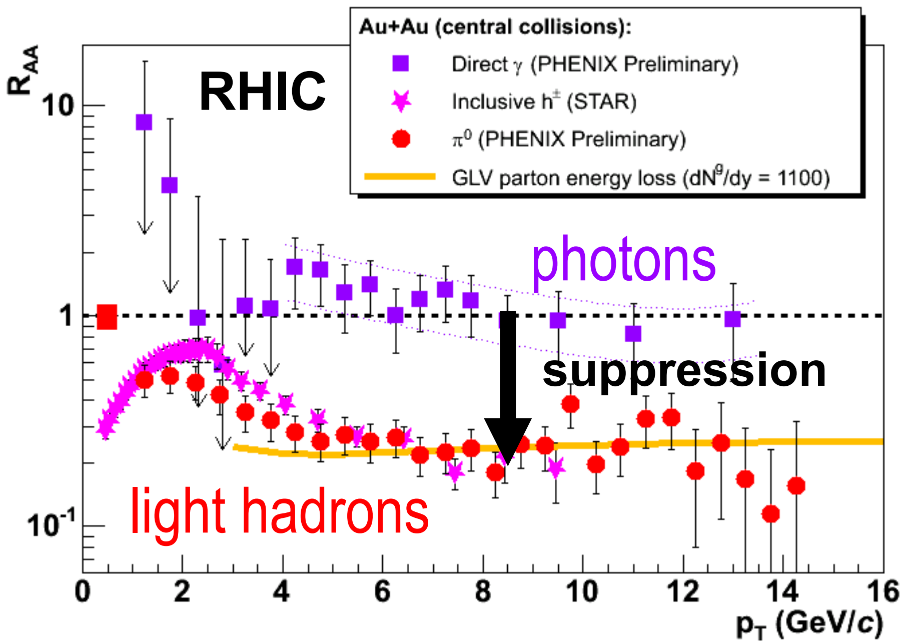
Number of binary collisions from Glauber calculations

Nuclear modification factor:

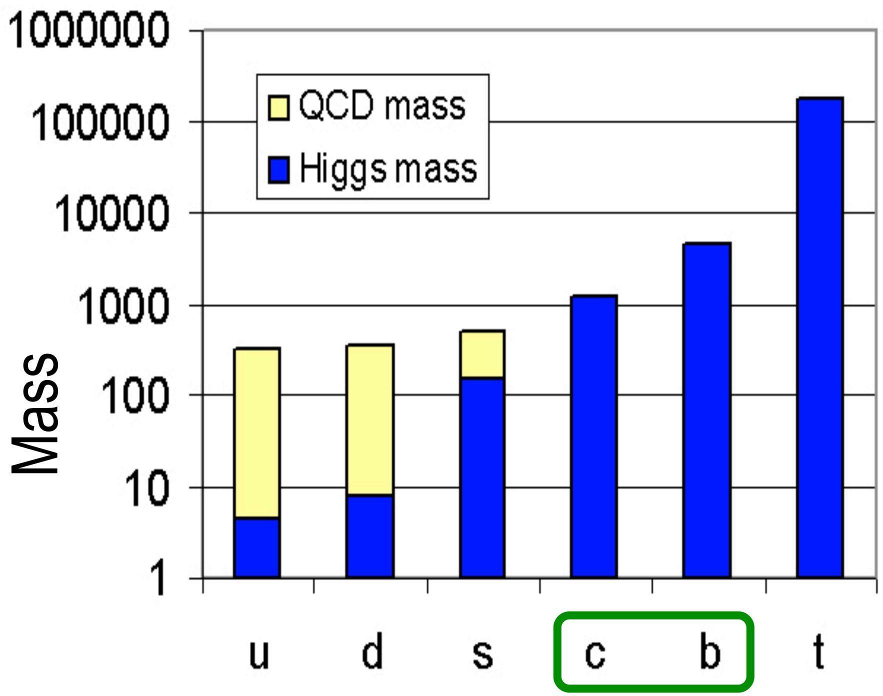
$$R_{\mathrm{AA}}(p_T) = \frac{\mathrm{Yield}_{\mathrm{AA}}(p_T)}{\langle N_{bin} \rangle_{\mathrm{AA}} \, \mathrm{Yield}_{\mathrm{pp}}(p_T)}$$

$R_{AA} = 1$ for photons

$R_{AA} < 1$ for hadrons



Heavy quarks are ideal probes



• Charm and beauty quarks
  - 250-450 times heavier than light quarks
  - short life times: 120-500 μm

• **They are abundantly produced at the LHC; predominantly in the early phase of the collisions**

• Symmetry breaking
  - Higgs mass: electro-weak symmetry breaking → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass

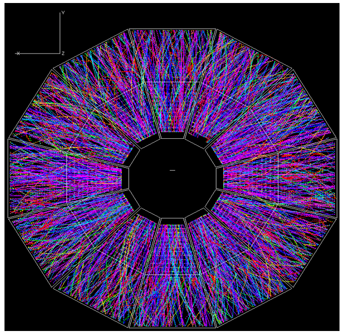
• Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP

• Test QCD at transition from perturbative to non-perturbative regime: c and b quarks provide hard scale for QCD calculations

Time evolution of a heavy-ion collision

Thermalization of QGP

Hadronisation: QGP lifetime?



Quarkonia melts and flow develops

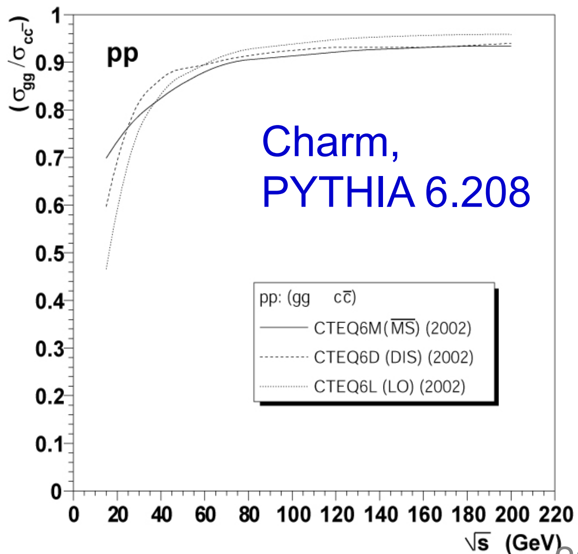
~0.1 ~1 ~10 10^{15} *time scale* (fm/c)

Parton energy loss

Charm production

$\tau \sim \hbar/2m_Q$

- Gluon fusion dominates → sensitivity to initial state gluon distribution *M. Gyulassy and Z. Lin, Phys. Rev. C51, 2177 (1995)*
- Heavy quarks transverse through the QCD medium and interact strongly with it → **energy loss**
- Due to their mass (m_Q >> T_c, Λ_{QCD}) → **higher penetrating power**



Energy loss of heavy quarks in QCD matter

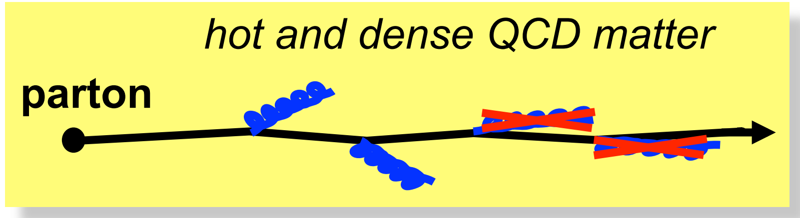
- Radiative parton energy loss is colour charge dependent (Casimir coupling factor C_R)

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

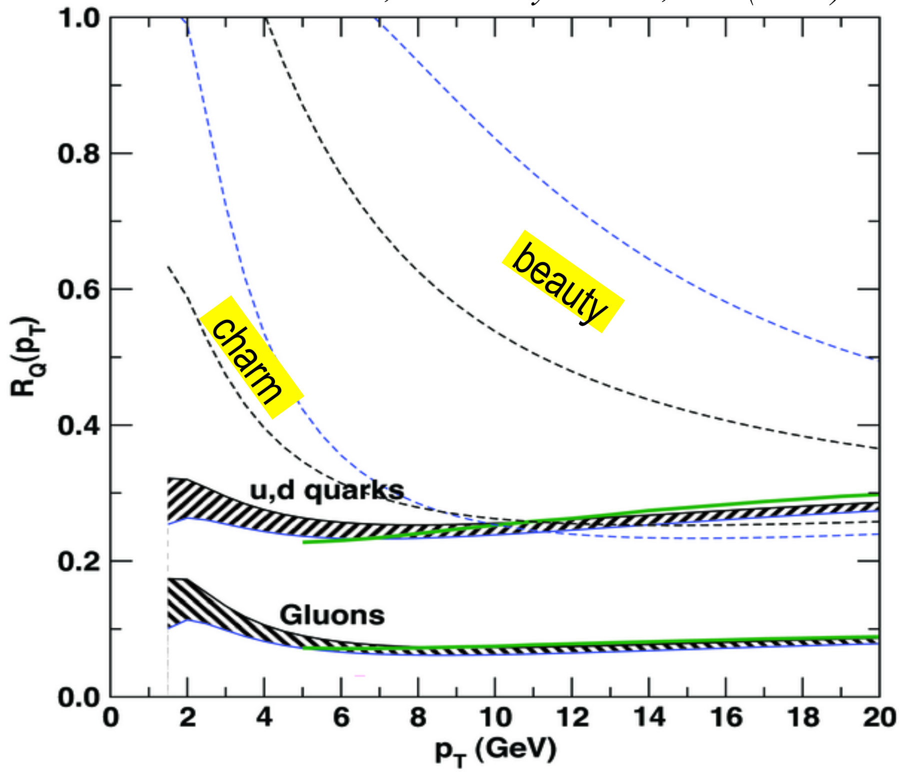
- Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

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

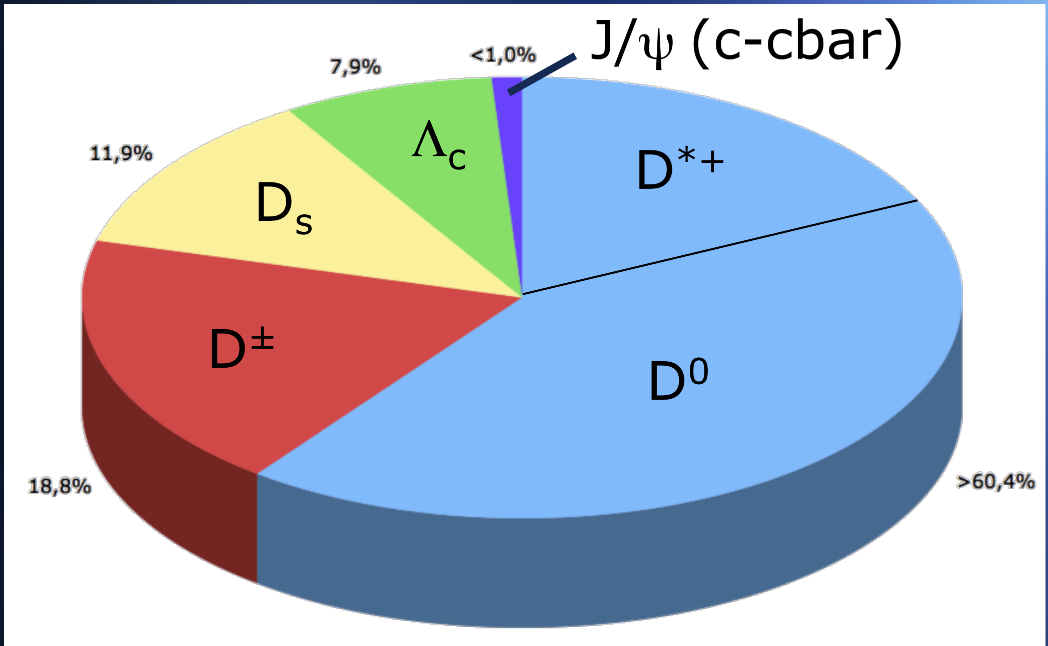
$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

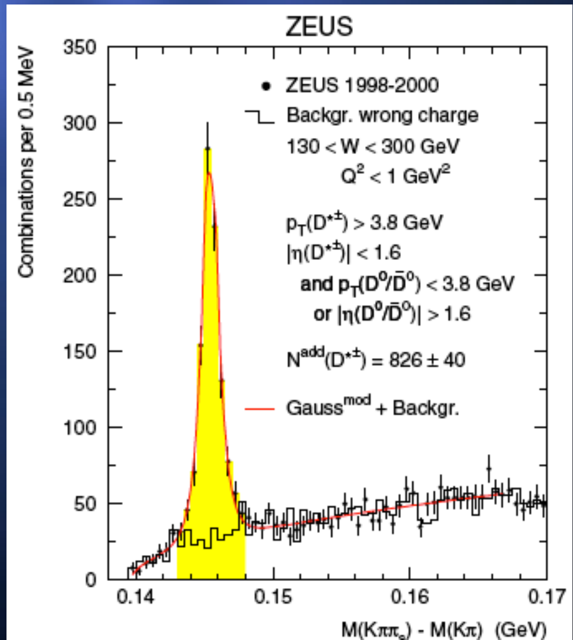


S. Wicks et al., Nucl. Phys. A784, 426 (2007)



Final state particles containing charm quarks



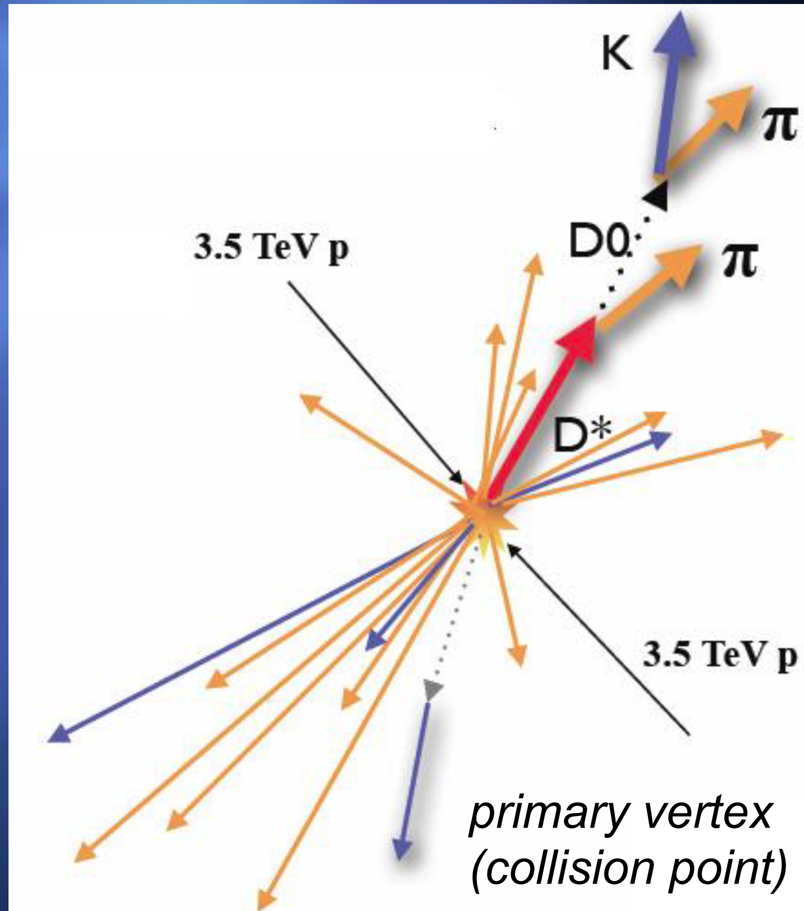


My favorite is the $D^{*+} = |cd\rangle$

- narrow resonance (~0.1 MeV/c^2)
- 3-body decay

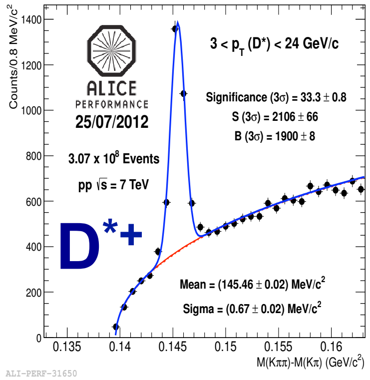
Reconstruction of charged D* mesons

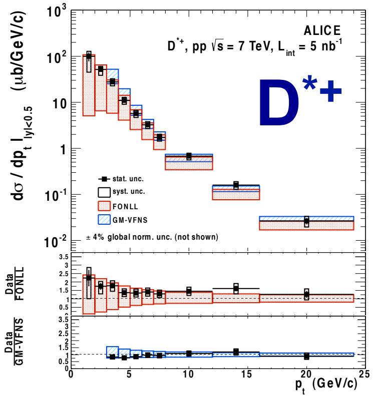
- Short life time
- Reconstruction of
  - displaced vertices (accuracy better than 75 μm)
  - particle trajectories
- Particle identification

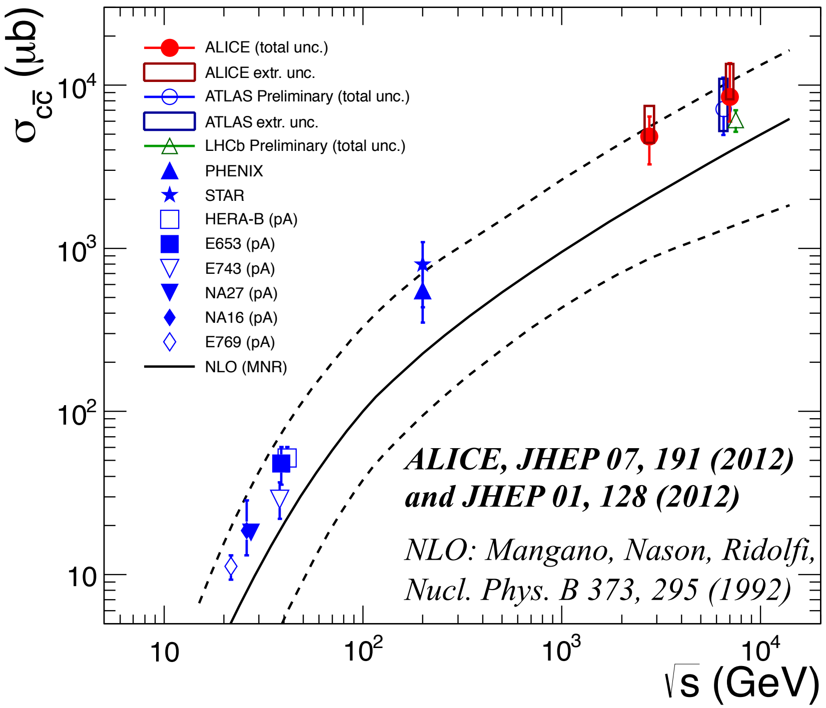


- Rest mass charged D* is 2010.28 ± 0.13 MeV$/c^2$
- D^{*+} short mean lifetime: $(6.9 \pm 1.9) \times 10^{-21}$ s
- D^{*+} has following main decay channels:
  - $\mathbf{D^{*+} \rightarrow D^0 \pi_s^+}$ $\quad$ **($\Gamma_i/\Gamma = 67.7 \pm 0.5\%$)**
  - $D^{*+} \rightarrow D^+ \pi_s^0$ $\quad$ ($\Gamma_i/\Gamma = 30.7 \pm 0.5\%$)
  - $D^{*+} \rightarrow D^+ \gamma$ $\quad$ ($\Gamma_i/\Gamma = 1.6 \pm 0.4\%$)
- D^0 rest mass is 1864.63 ± 0.14 Mev$/c^2$
- D^0 mean lifetime $(4.101 \pm 0.015) \times 10^{-13}$ s, decay channel:
  - $D^0 \rightarrow K^- \pi^+$ $\quad$ ($\Gamma_i/\Gamma = 3.89 \pm 0.05\%$)
- Total branching ratio of $D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow (K^- \pi^+) \pi_s^+$ is $\Gamma_i/\Gamma = 2.63\%$

Total charm production cross section in pp





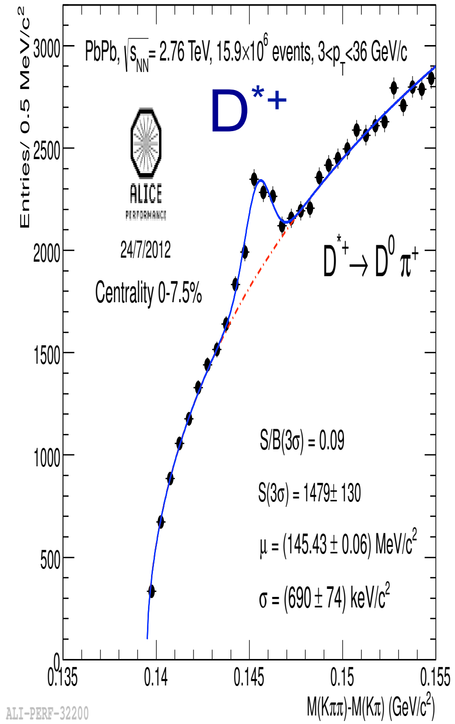


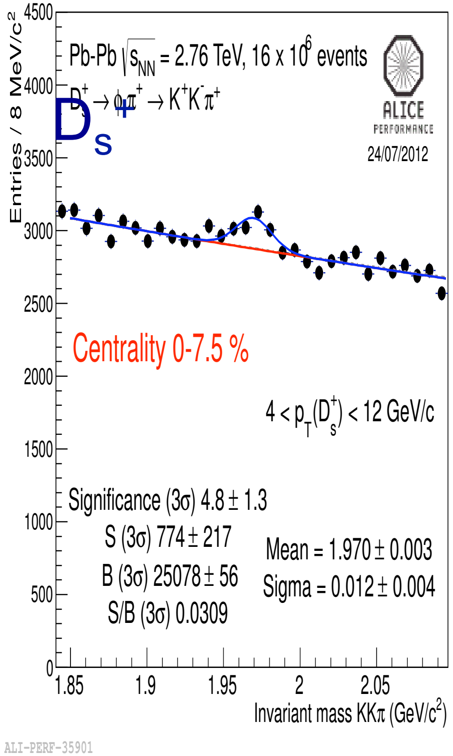
- Very good agreement between LHC experiments
- Consistency with NLO pQCD calculations, although at the upper limit

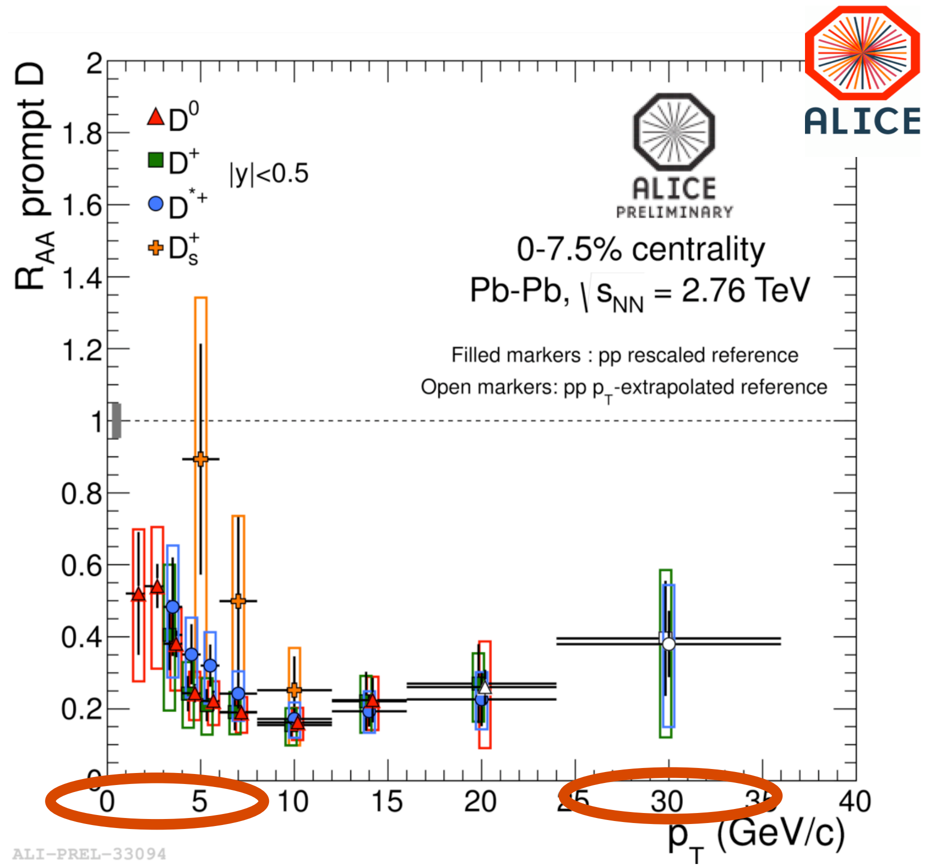
→ Parton spectra from pQCD input for energy loss models

→ Baseline for measurements in Pb-Pb

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

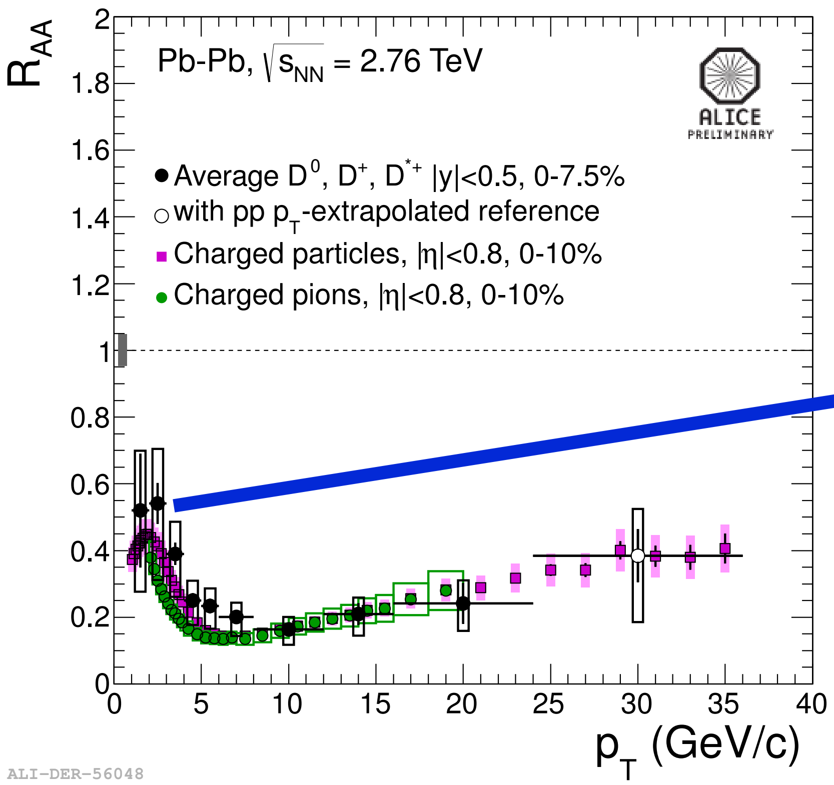


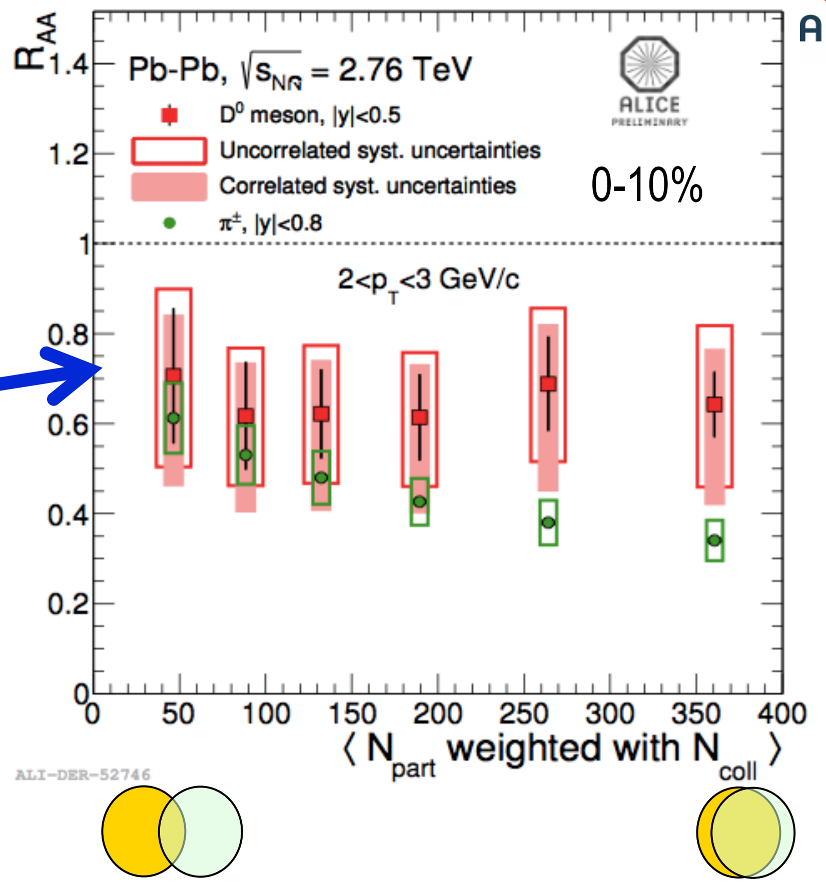




- First $D_s^+(c\bar{s})$ measurement in heavy ion collisions
- Expectation: enhancement of strange D meson yield at intermediate p_T if charm hadronizes via recombination in the medium
- Strong suppression (factor 4-5) above 5 GeV/c in most central Pb-Pb, compared to binary scaling from pp

R_{AA}: light versus heavy quark hadrons





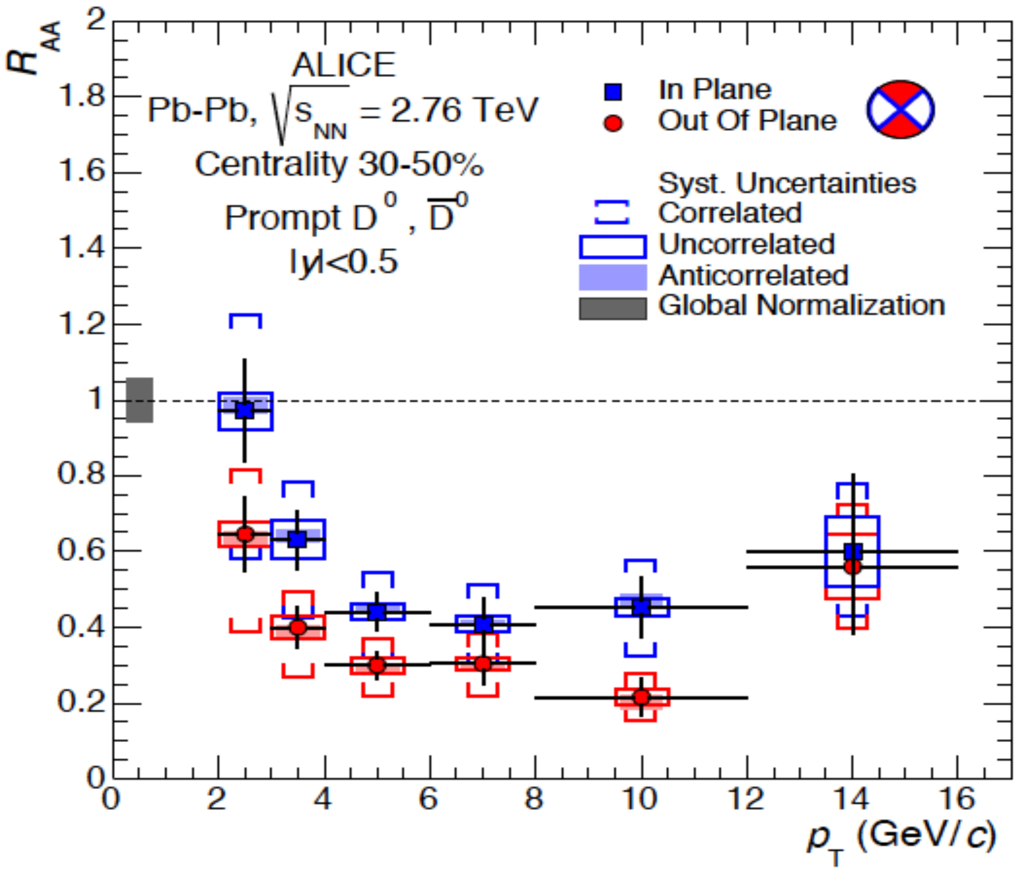
D^0

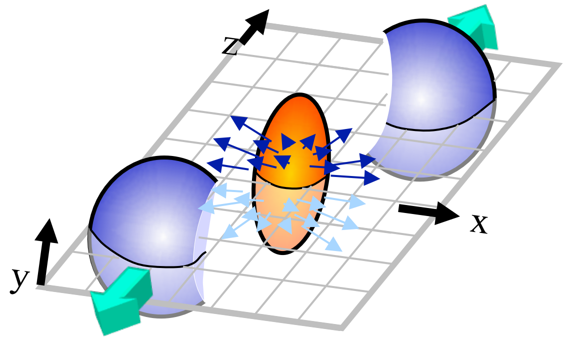
$\pi^{\pm}$

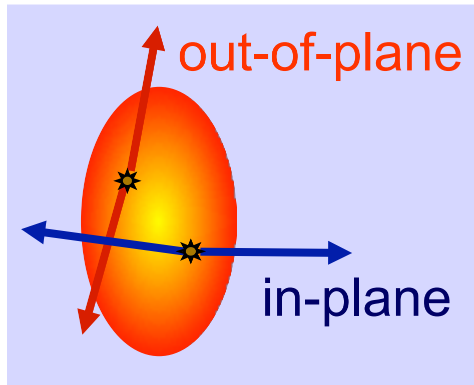
$R_{AA}^{\text{D meson}} > R_{AA}^{\text{pions}}$ at low p_T?

→ More data needed for final conclusion

Prompt D^0 meson R_{AA} versus event plane

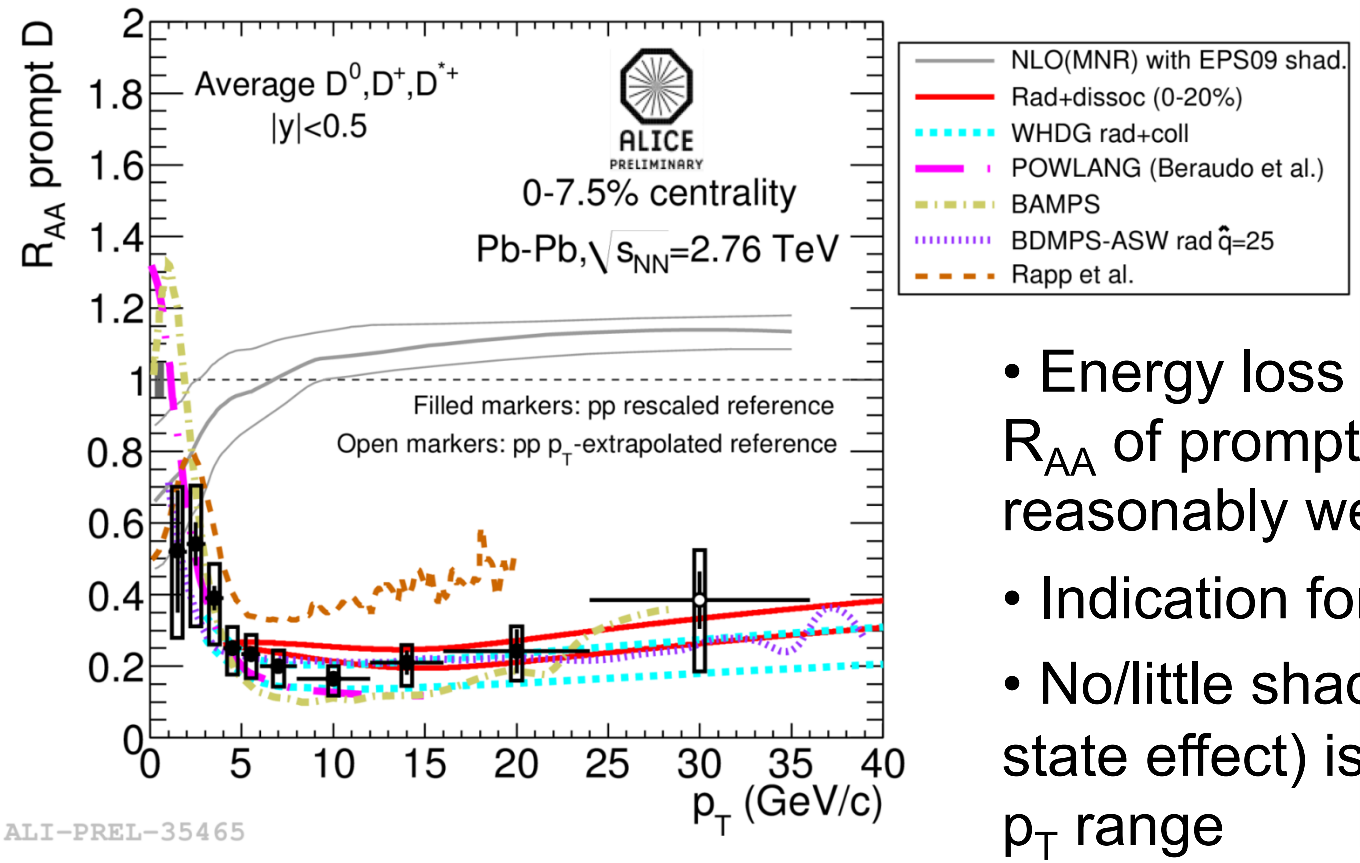






More suppression at high p_T out-of-plane with respect to in-plane due to different path length

Comparison with model calculations

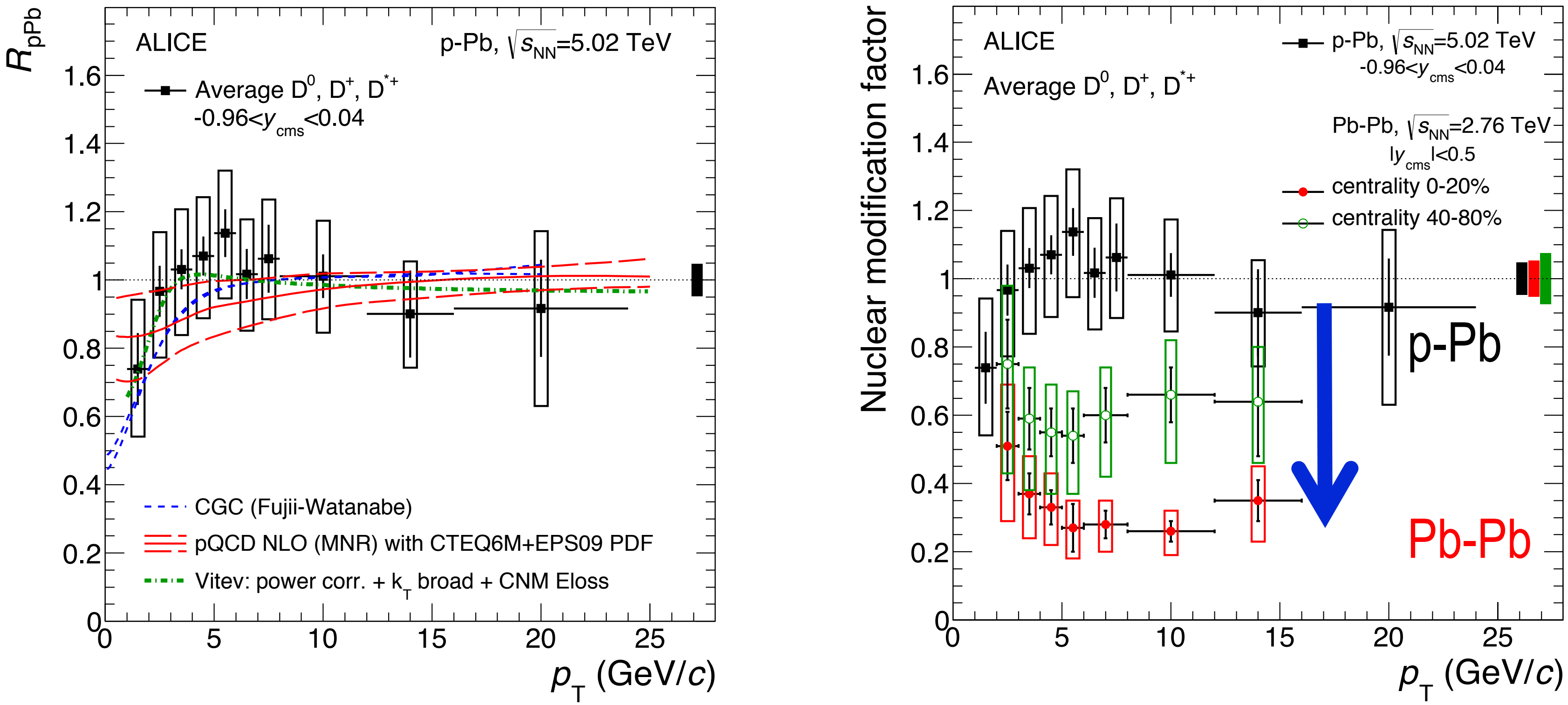


- Energy loss models describe R_{AA} of prompt D mesons reasonably well
- Indication for rising R_{AA}?
- No/little shadowing (initial-state effect) is expected in this p_T range

- Rad.+dissoc.: R. Sharma, I. Vitev and B.W. Zhang, Phys. Rev. C80, 054902 (2009), Y. He, I. Vitev and B.W. Zhang, Phys. Lett. B 713, 224 (2012)
- WHDG (coll.+rad. Eloss in anisotropic medium): W.A. Horowitz and M. Gyulassy, J. Phys. G38, 124114 (2011)
- POWLANG (coll. Eloss using Langevin approach): W.M. Alberico et al., Eur. Phyis J. C71,1666 (2011)
- BAMPS (coll. Eloss in expanding medium): O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. G38, 124152 (2011)
- Coll. + LPM rad. energy loss: P. B. Gossiaux, R. Bierkandt, and J. Aichelin, Phys. Rev. C79, 044906 (2009)
- BDMPS-ASW: N. Armesto, A. Dainese, C.A. Salgado and U.A. Wiedemann, Phys. Rev. D71, 054027 (2005)
- Coll. Eloss via D mesons resonances excitation + Hydro evolution: M. He, R.J. Fries and R. Rapp, Phys. Rev. Lett. 110, 112301 (2013)

p-Pb: measurement of initial state effects

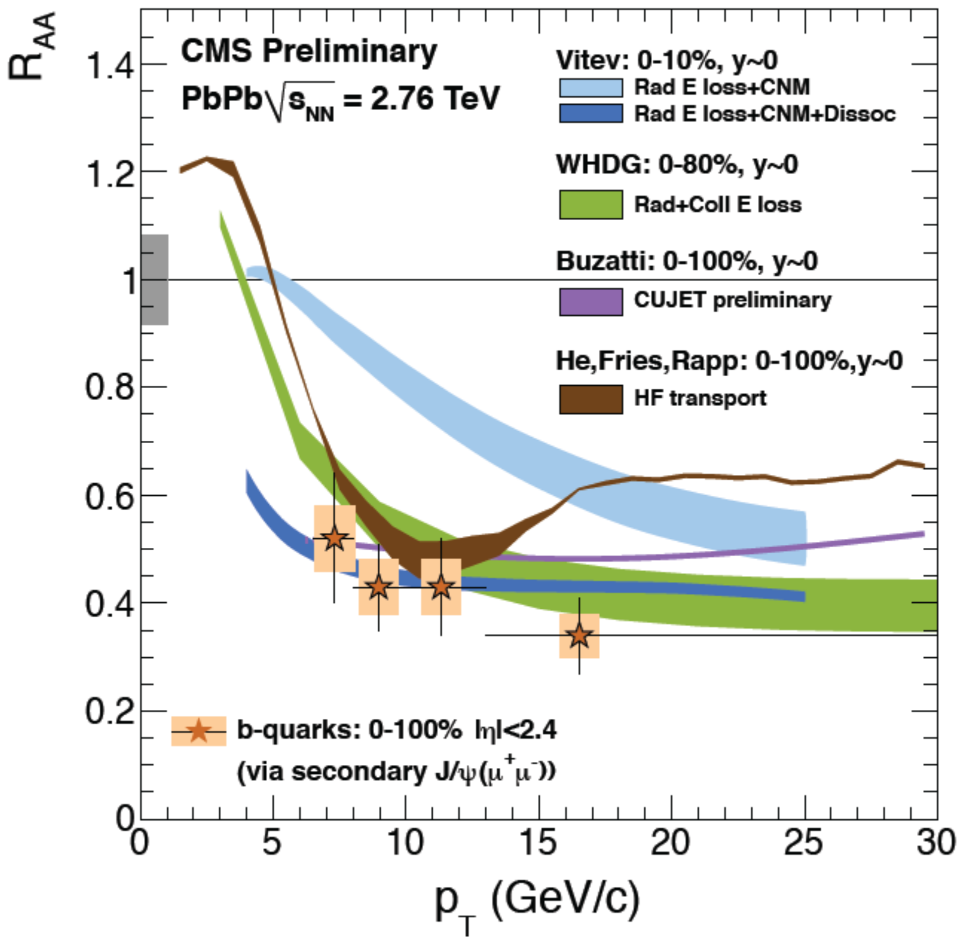
Phys. Rev. Lett. 113 (2014) 232301

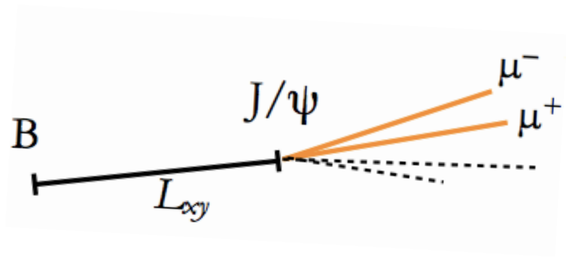


- Important baseline measurement of cold nuclear matter effects (e.g., Cronin effect, nuclear shadowing, gluon saturation)
- D meson R_{pA} shows consistency with unity and predictions from shadowing and CGC model predictions
- High-p_T suppression of particle yield in Pb-Pb is a final state effect

Beauty R_{AA} via non-prompt J/ψ

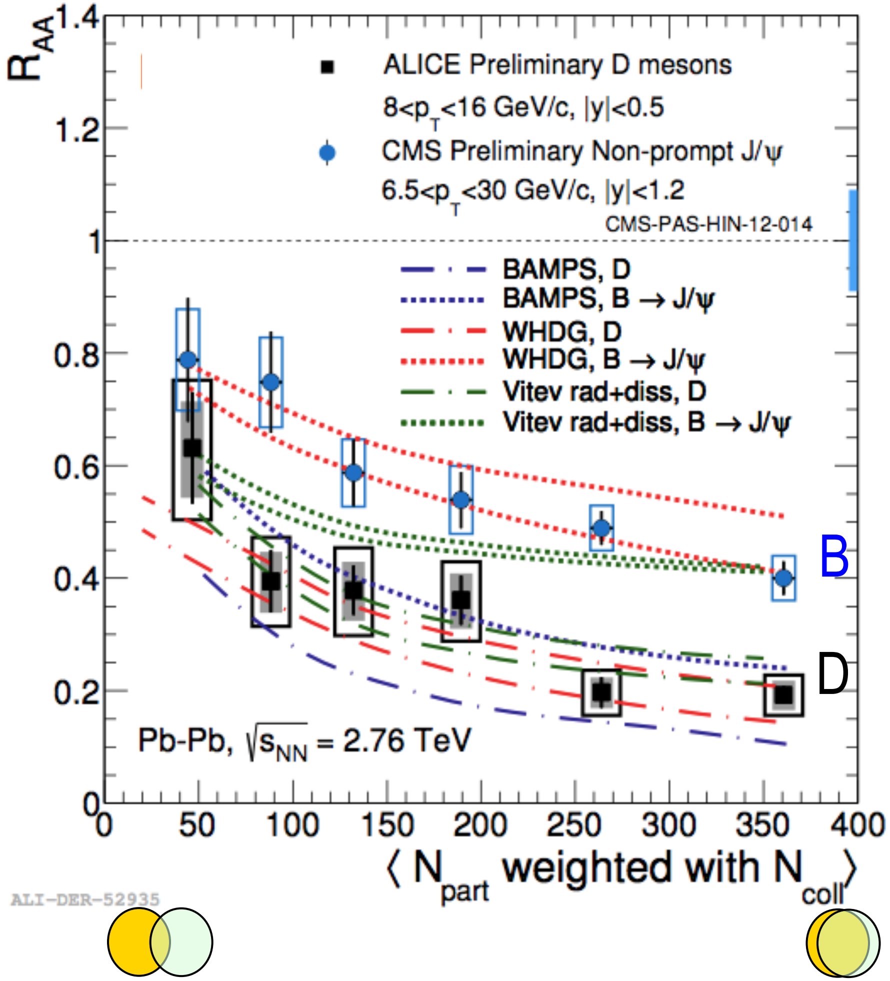
CMS PAS HIN-12-014



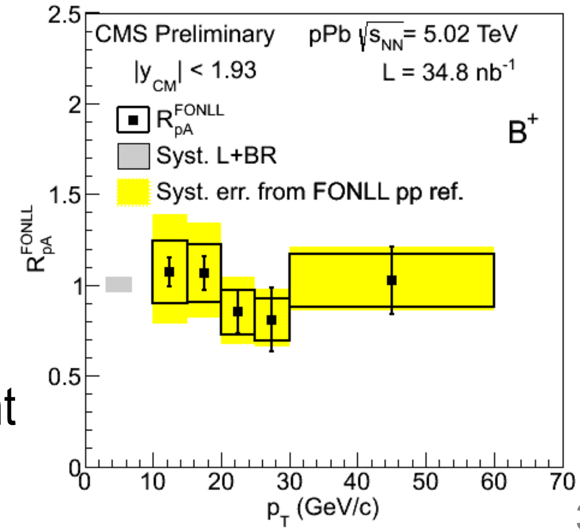


- Non-prompt J/ψ in the most central collision (0-10%) is suppressed by a factor of 2.5
- More data needed

R_{AA} of D and B mesons



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



First open beauty measurement in p-Pb by CMS (QM 2014)

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
- Many results from Pb-Pb data from Run-1
  - High degree of collectivity → perfect liquid
  - Parton-medium interaction → parton energy loss mechanisms
- 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 model calculations
- Many more exciting results ahead of us
  - LHC Run-2 (5.1 TeV, 2015-2017)
  - After detector upgrades (2018/19)