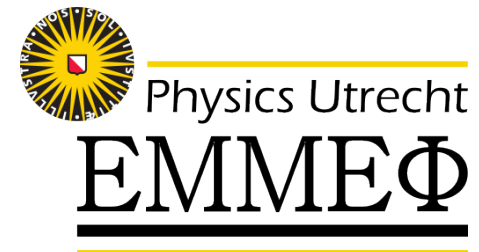


Recent heavy ion results from the LHC and future perspectives



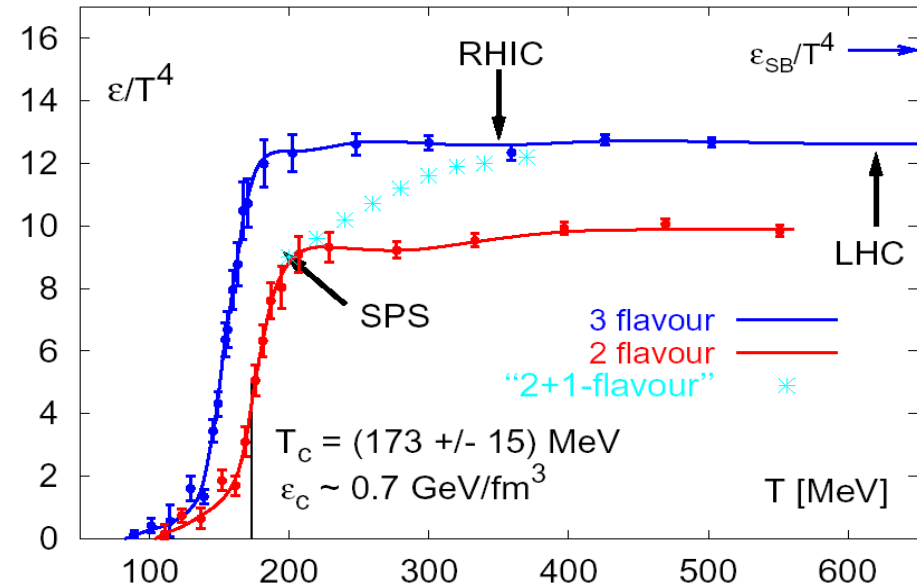
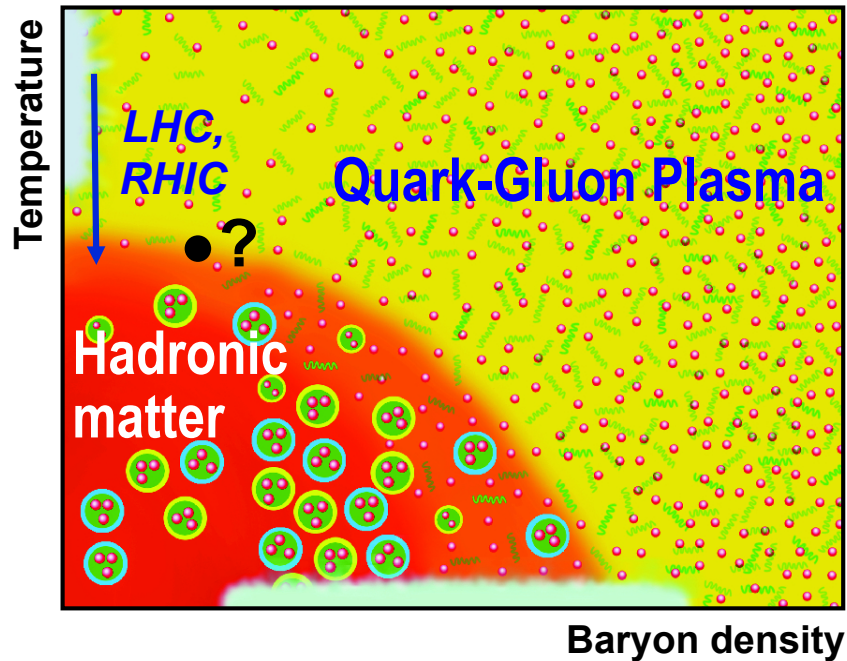
André Mischke
Utrecht University

Excited QCD 2016
Costa da Caparica, Portugal – 6-12 March 2016

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



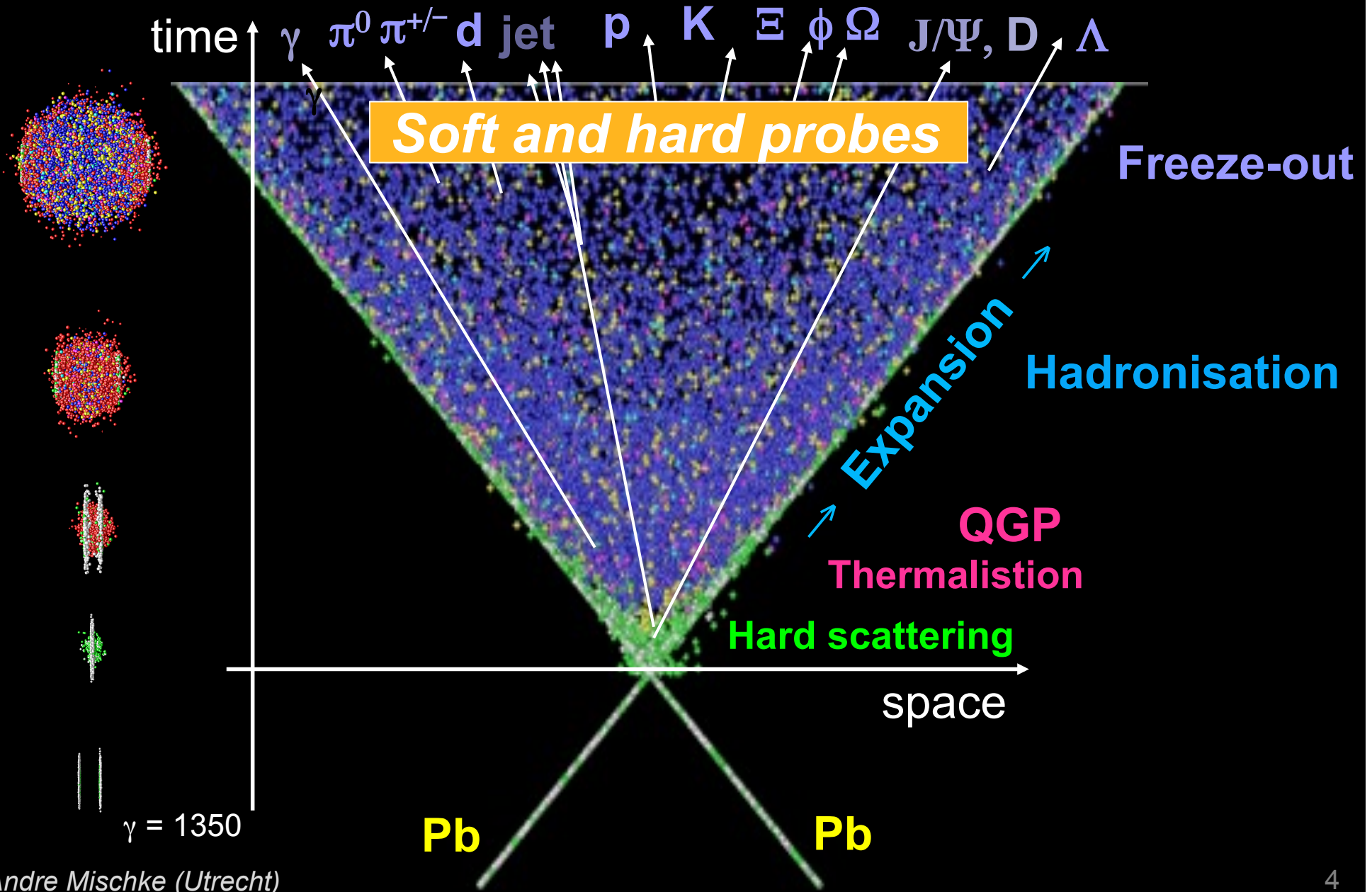
- Extreme conditions: high temperature and/or high density
- Search for the **critical point**

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

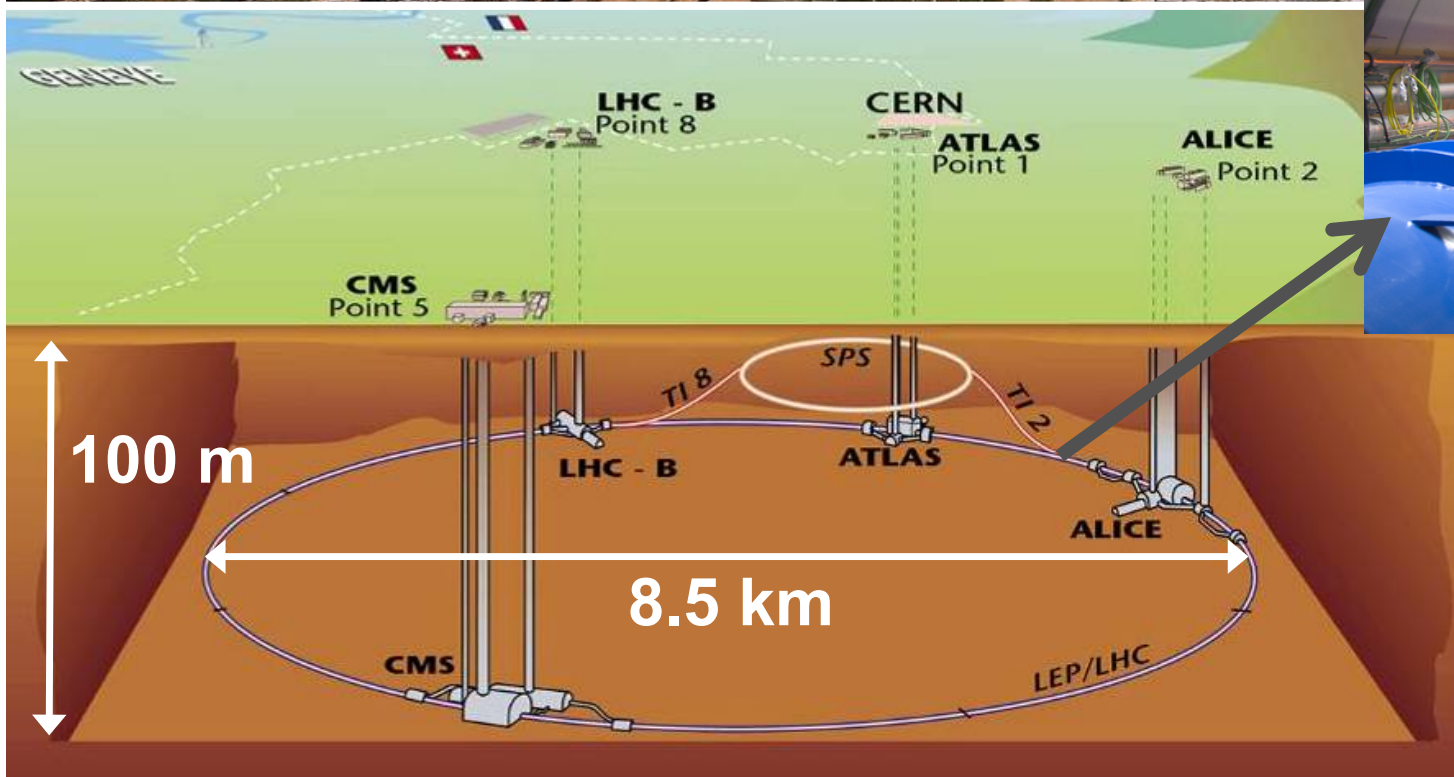
- Critical energy density

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

Space-time evolution of a heavy-ion collision

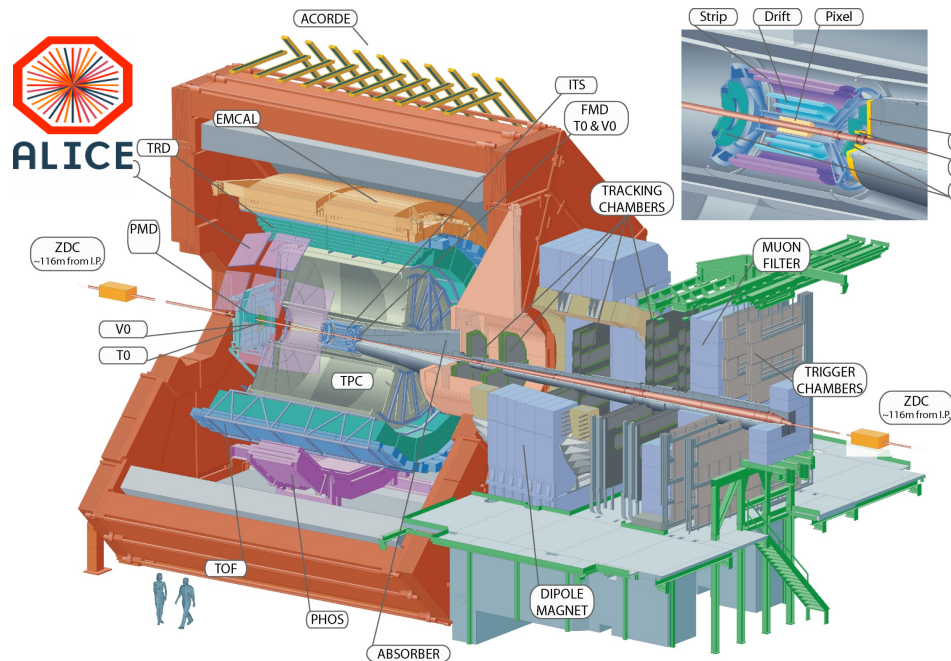


Large Hadron Collider at CERN



- 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

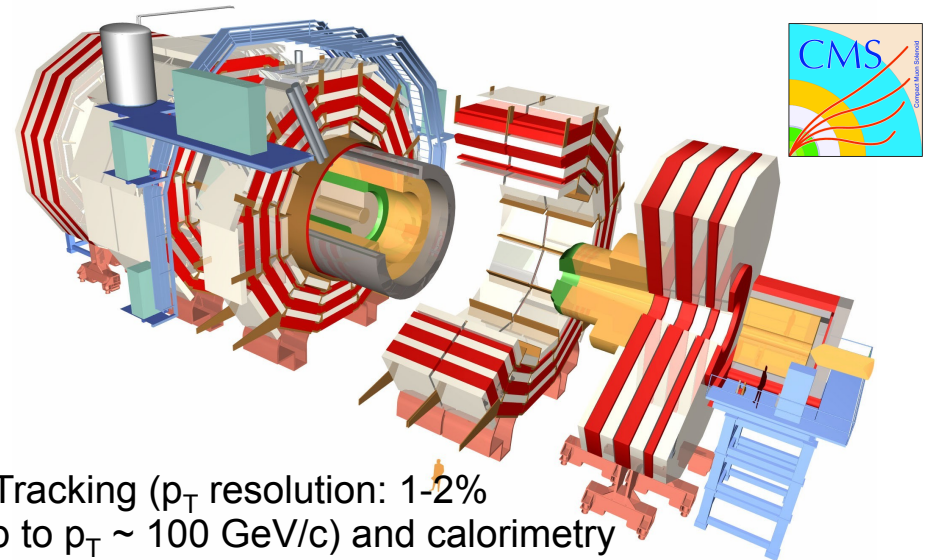
Experiments



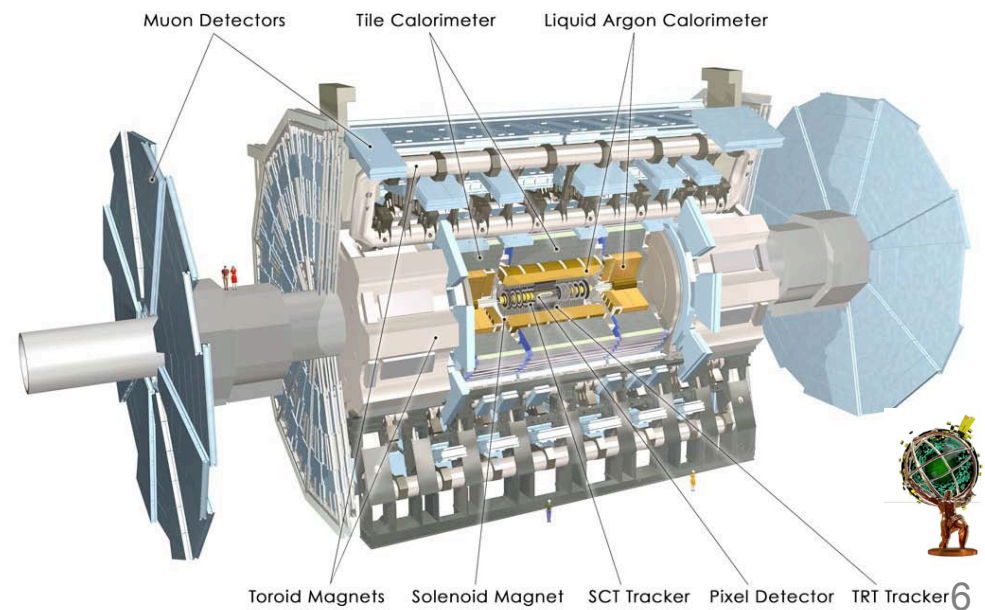
- PID over a very broad momentum range (>100 MeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage $|\eta| < 0.9$ and $-4 < \eta < -2.5$ in forward region
- Impact parameter resolution better than $65 \mu\text{m}$ for $p_T > 1$ GeV/c

Three main subsystems with a full coverage in azimuth:

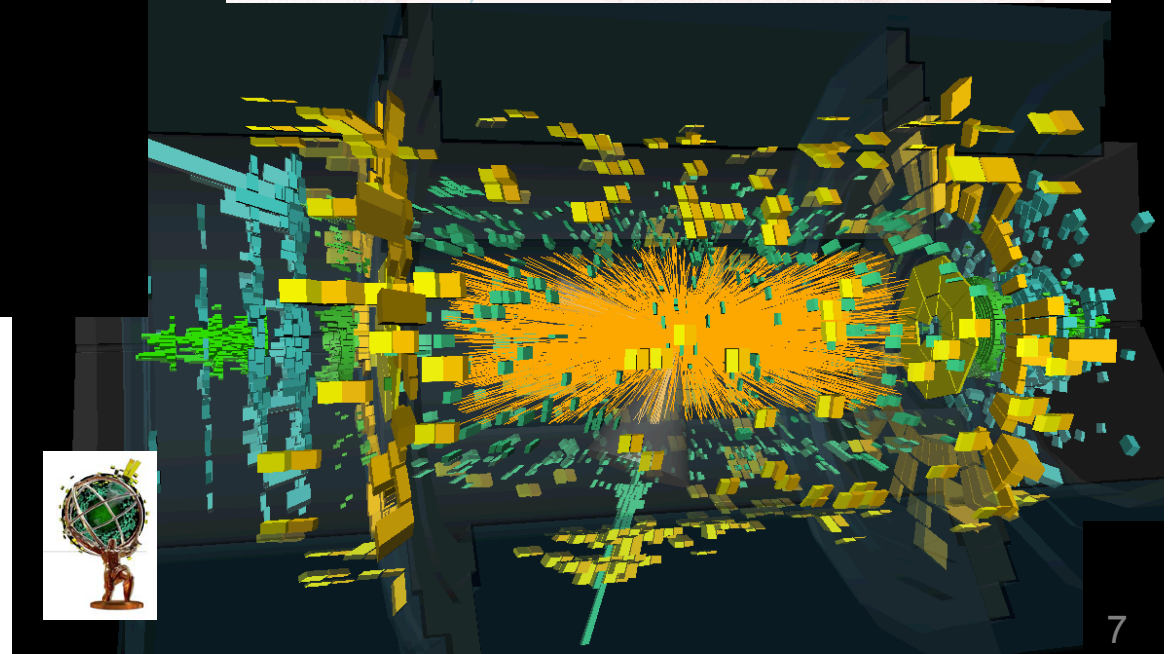
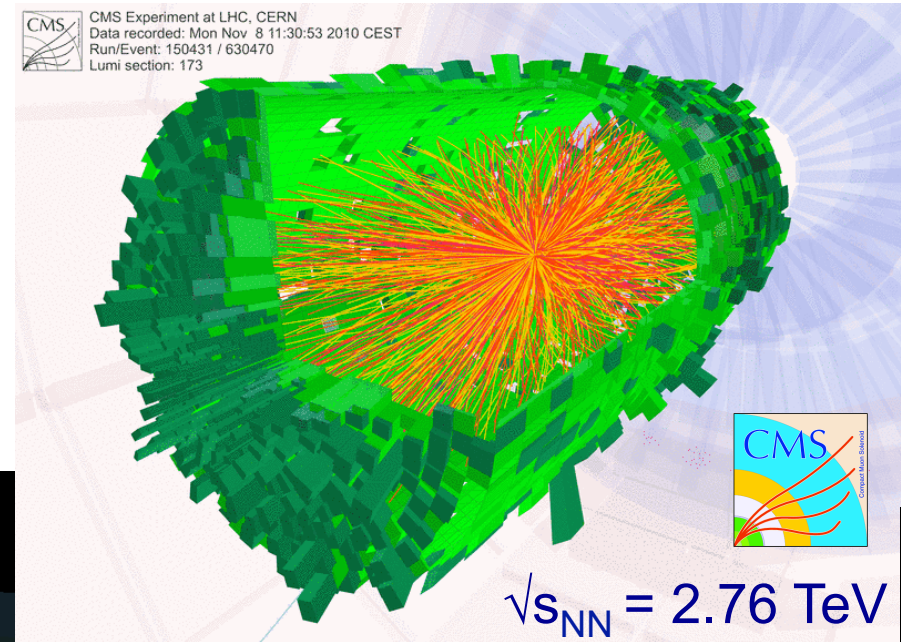
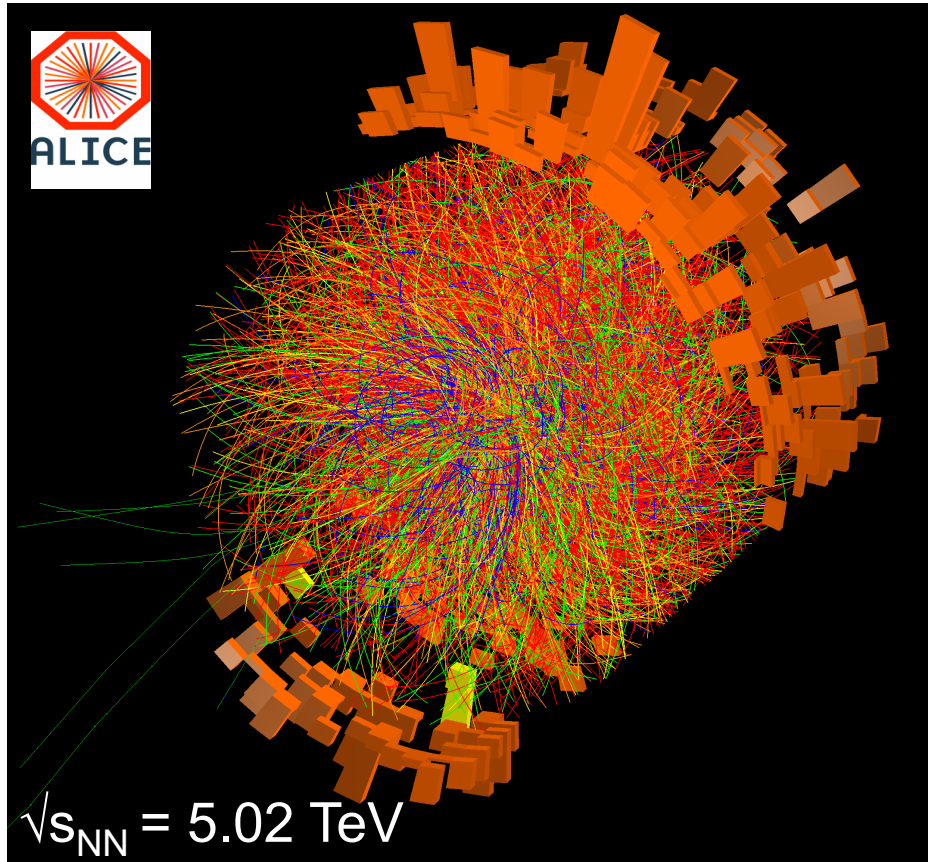
- Inner Detector: tracking $|\eta| < 2.5$
- Calorimetry $|\eta| < 4.9$
- Muon Spectrometer $|\eta| < 2.7$



- 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



Typical event displays



Charged particle multiplicity at 5.02 TeV Pb-Pb

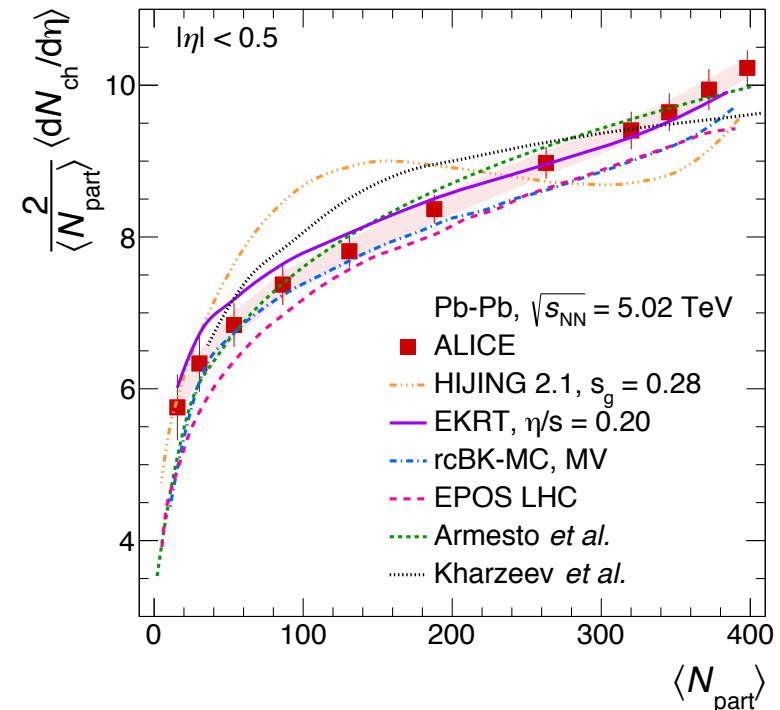
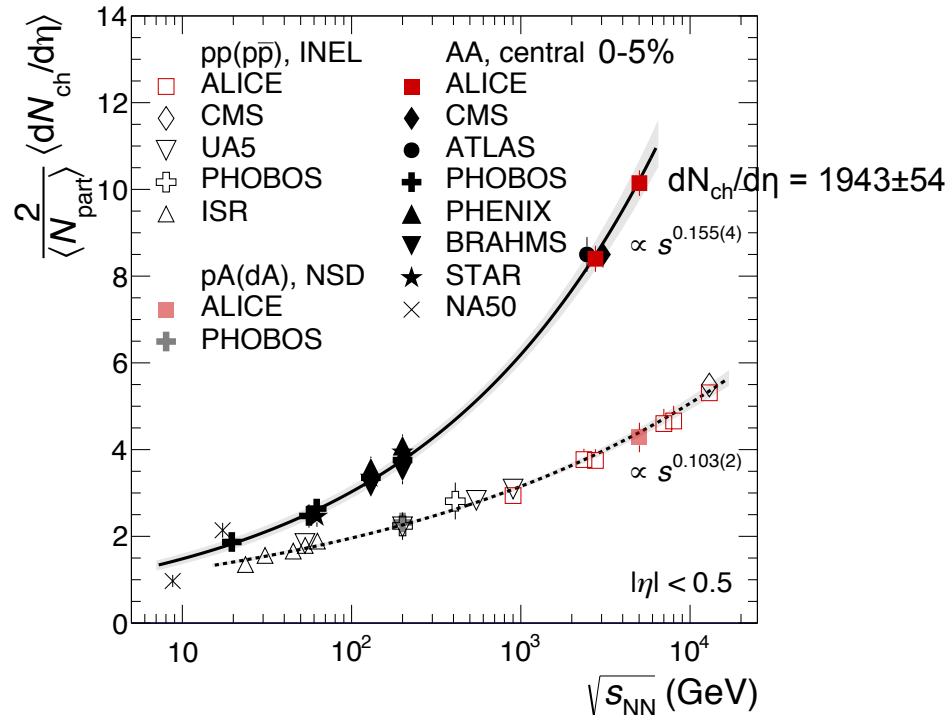
vs. cms energy

vs. number of participants



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

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



- Power law dependence fits well and faster in Pb-Pb $\sim s^{0.155}$ than in pp $\sim s^{0.103}$
- Multiplicity $\sim 2.5 \times N_{RHIC}$
- Energy density $> 3 \times \epsilon_{RHIC}$

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

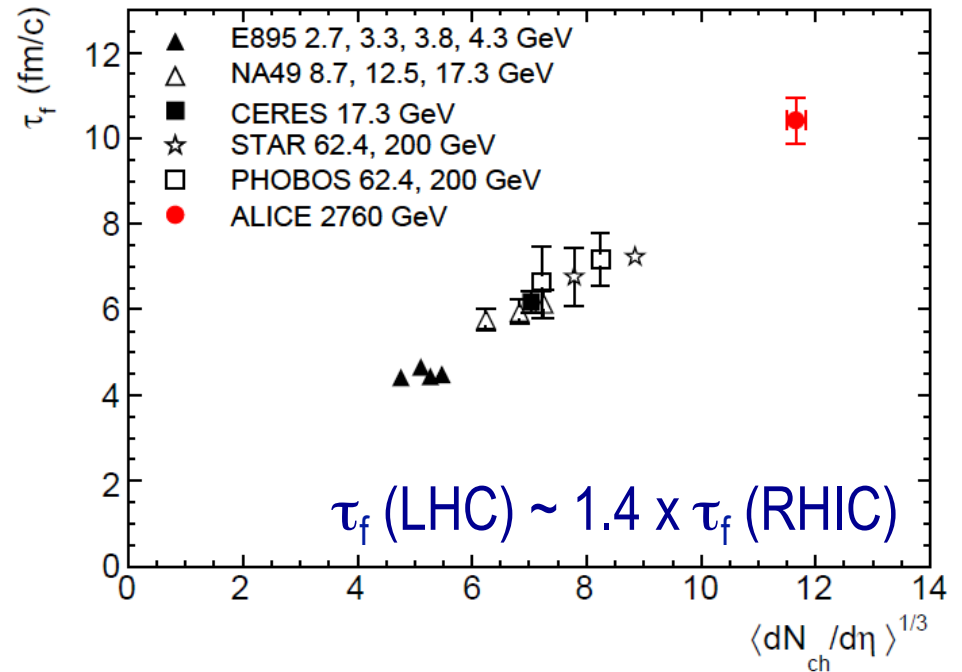
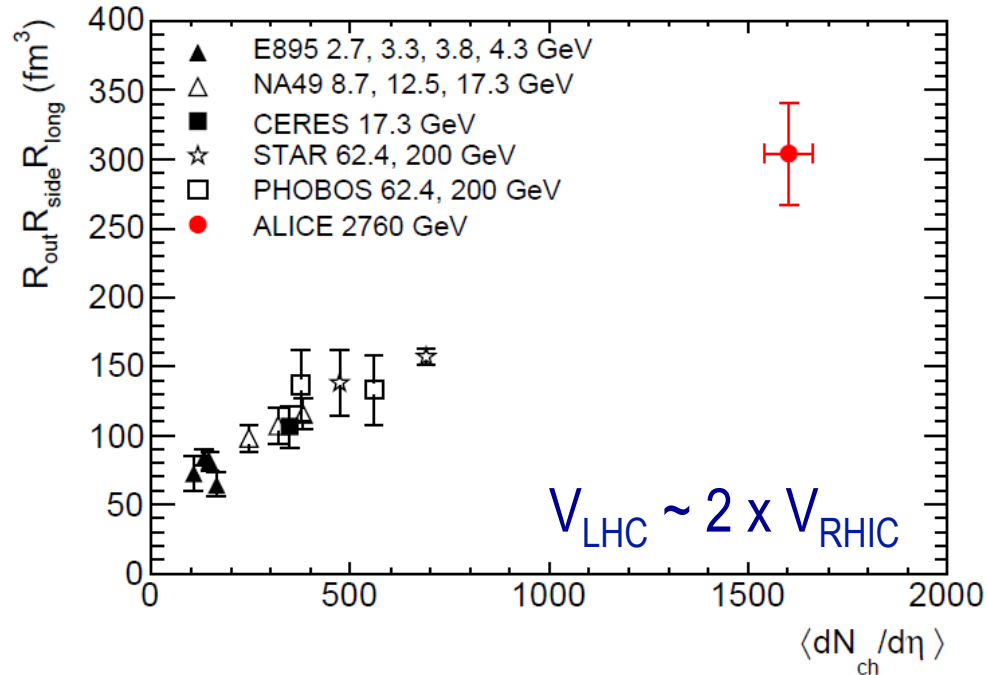
System size and lifetime at 2.76 TeV Pb-Pb



System size

Lifetime

Phys. Lett. B 696, 328 (2011)

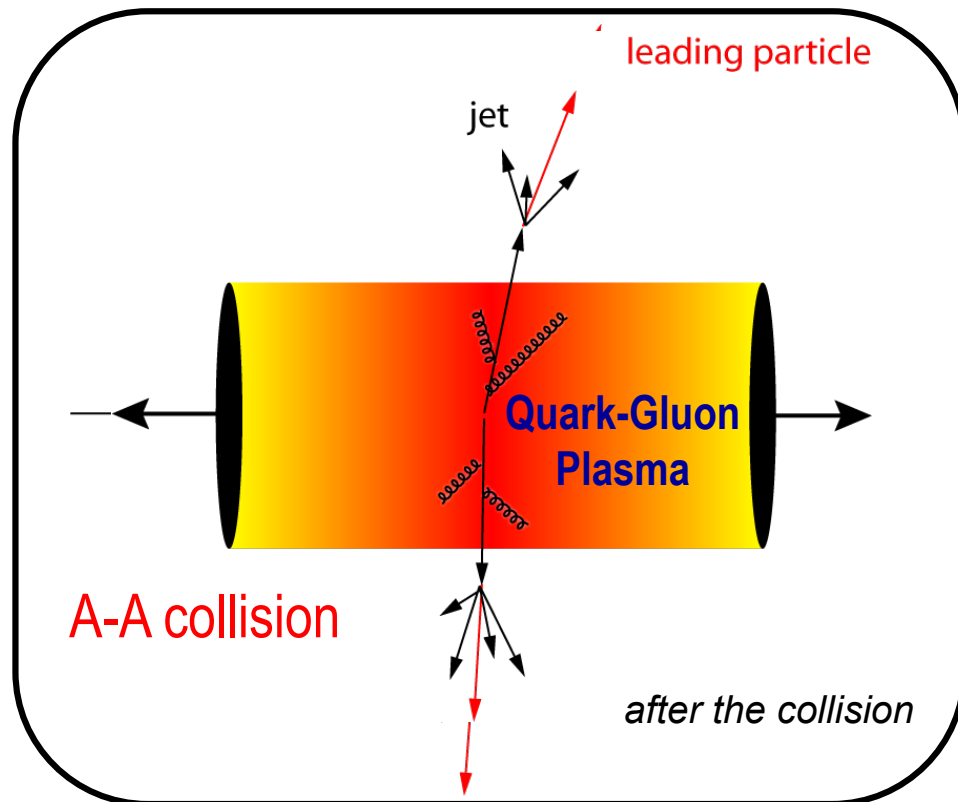


$\tau_f(\text{central } 2.76 \text{ TeV Pb-Pb}) \sim 10\text{-}11 \text{ fm/c}$

Fireball at LHC has larger volume and longer lifetime

→ Hydrodynamic expansion

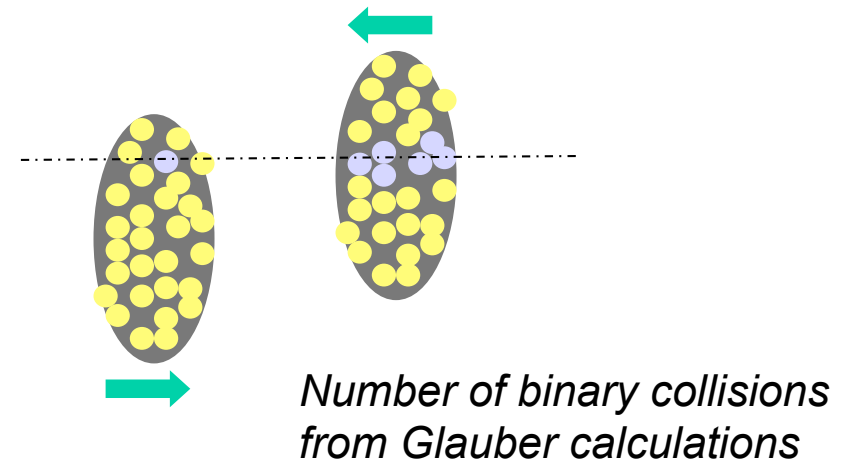
Probing hot and dense QCD matter



- “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.



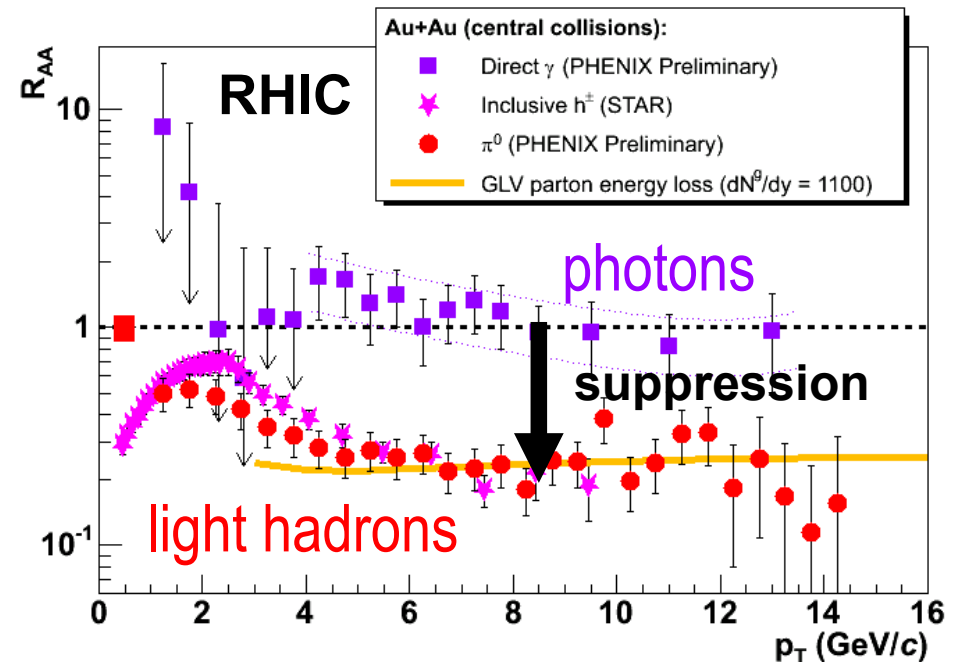
Nuclear modification factor

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

Expectation:

$$R_{AA} = 1 \text{ for photons}$$

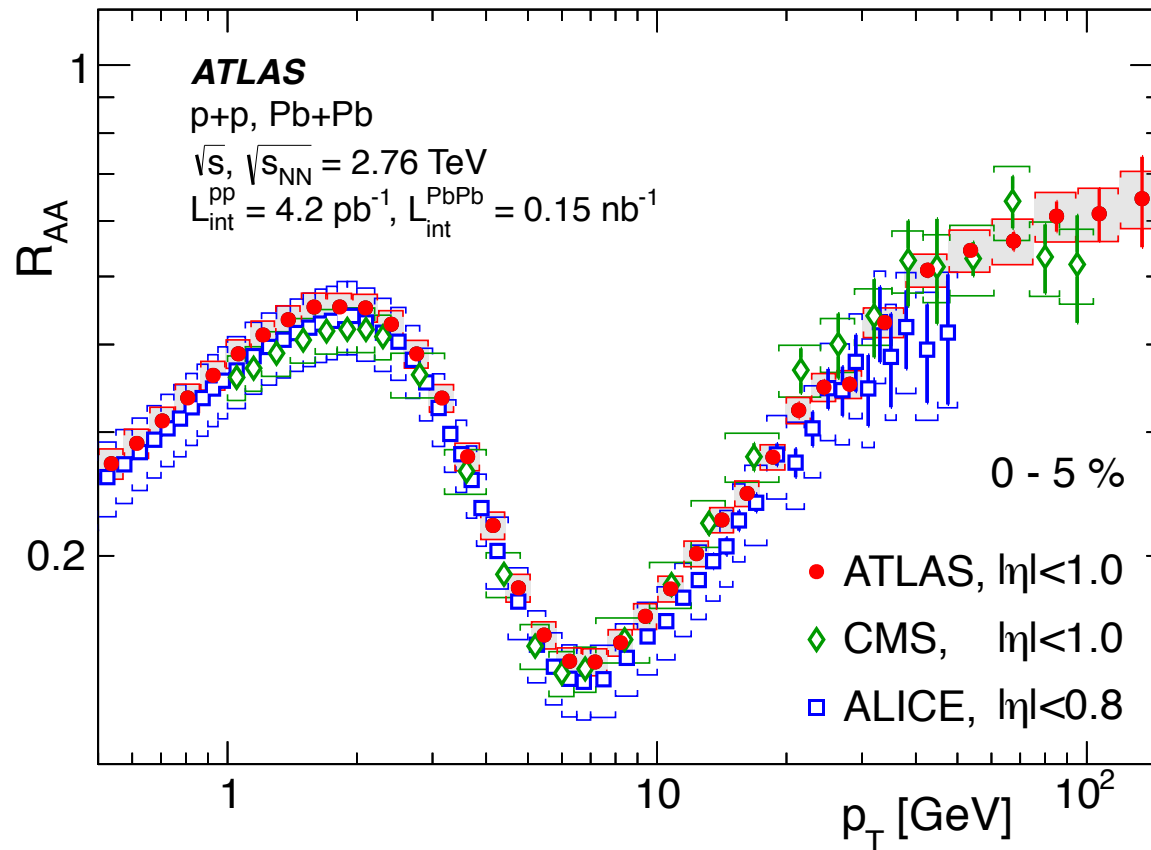
$$R_{AA} < 1 \text{ for hadrons}$$



R_{AA} for inclusive charged hadrons

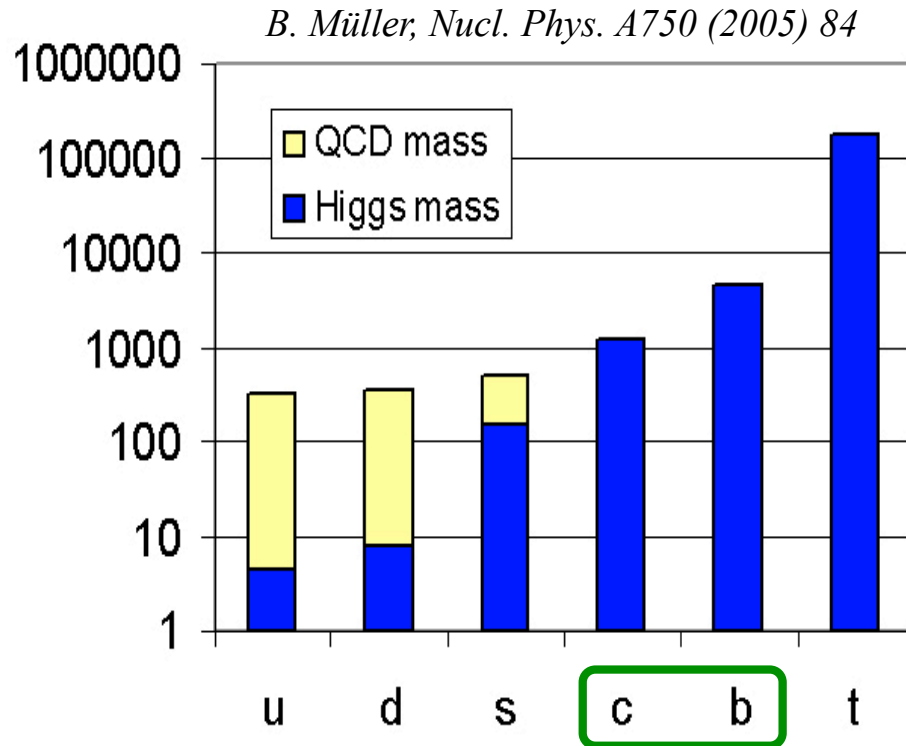


JHEP 09 (2015) 050



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

Heavy quarks are ideal probes



- 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")

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

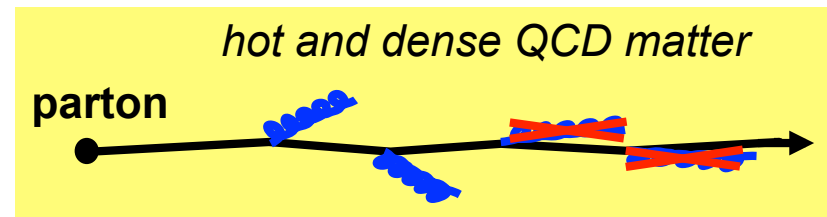
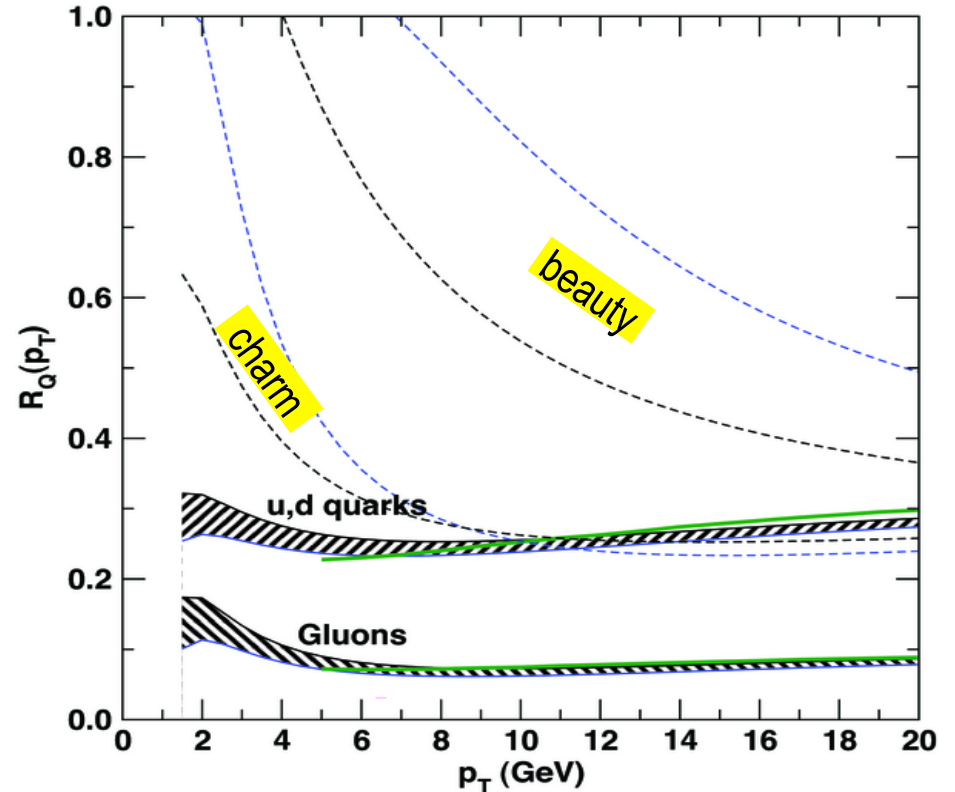
(2) **Dead-cone effect:** gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

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

THE EUROPEAN
PHYSICAL JOURNAL C

Eur. Phys. J. C (2014) 74:2981
DOI 10.1140/epjc/s10052-014-2981-5

Review

QCD and strongly coupled gauge theories: challenges and perspectives

N. Brambilla^{1,2,3,*}, S. Eidelman^{2,3,*}, P. Foka^{4,5,†}, S. Gardner^{2,3,†}, A. S. Kronfeld^{6,*}, M. G. Alford^{7,†}, R. Alkofer^{8,†}, M. Butenschön^{9,†}, T. D. Cohen^{10,†}, J. Erdmenger^{11,†}, L. Fabbietti^{12,†}, M. Faber^{13,†}, J. L. Gaiyy^{14,15,†}, B. Ketzer^{1,5,†}, H. W. Lin^{16,†}, F. J. Llanes-Estrada^{17,†}, H. B. Meyer^{18,†}, P. Pakhlov^{19,20,†}, E. Pallante^{21,†}, M. I. Polikarpov^{19,20,†}, H. Satz^{22,†}, A. Schmitt^{23,†}, W. M. Snow^{24,†}, A. Vairo^{1,†}, R. Vogt^{25,26,†}, A. Vuorinen^{27,†}, H. Wittig^{28,†}, P. Arnold^{29,†}, P. Christakoglou^{29,†}, P. Di Nezza^{30,†}, Z. Fodor^{31,22,32,†}, X. Garcia i Tormo^{33,†}, R. Hillfloh^{34,†}, M. A. Janik^{35,†}, A. Kalyan^{36,†}, D. Keane^{37,†}, E. Kiritsis^{38,39,40,†}, A. Mischke^{41,†}, R. Mink^{42,†}, G. Odyniec^{43,†}, K. Papadodimas^{44,†}, A. Pich^{44,†}, R. Pittar^{45,†}, J.-W. Qiu^{46,47,†}, G. Ricciardi^{48,49,†}, C. A. Salgado^{50,†}, K. Schwenzer^{2,†}, N. G. Stefanis^{51,†}, G. M. von Hippel^{52,†}, V. I. Zakharov^{11,19,20,52}

¹ Physik Department, Technische Universität München, James-Frank-Str. 1, 85748 Garching, Germany
² Budker Institute of Nuclear Physics, SB RAS, Novosibirsk 630090, Russia
³ Novosibirsk State University, Novosibirsk 630090, Russia
⁴ GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany
⁵ Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA
⁶ Theoretical Physics Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510-5011, USA
⁷ Department of Physics, Washington University, St. Louis, MO 63130, USA
⁸ University of Graz, 8010 Graz, Austria
⁹ Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090 Wien, Austria
¹⁰ Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742-4111, USA
¹¹ Max-Planck-Institute for Physics, Föhringer Ring 6, 80805 Munich, Germany
¹² Excellence Cluster "Origin and Structure of the Universe", Technische Universität München, 85748 Garching, Germany
¹³ Atominstutit, Technische Universität Wien, 1040 Vienna, Austria
¹⁴ Hampton University, Hampton, VA 23668, USA
¹⁵ Jefferson Laboratory, Newport News, VA 23606, USA
¹⁶ Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
¹⁷ Department Física Teórica I, Universidad Complutense de Madrid, 28040 Madrid, Spain
¹⁸ PRISMA Cluster of Excellence, Institut für Kernphysik und Helmholtz Institut Mainz, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
¹⁹ Institute of Theoretical and Experimental Physics, Moscow 117218, Russia
²⁰ Moscow Institute for Physics and Technology, Dolgoprudny 141700, Russia
²¹ Centre for Theoretical Physics, University of Groningen, 9747 AG Groningen, The Netherlands
²² Institut de Physique Nucléaire CNRS/IN2P3, Université Paris-Saclay, 91191 Orsay, France
²³ Institut für Theoretische Physik, Technische Universität Wien, 1040 Vienna, Austria
²⁴ Center for Exploration of Energy and Matter and Department of Physics, Indiana University, Bloomington, IN 47408, USA
²⁵ Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
²⁶ Physics Department, University of California, Davis, CA 95616, USA
²⁷ Department of Physics and Helsinki Institute of Physics, University of Helsinki, Helsinki, P.O. Box 64, 00014, Finland
²⁸ Department of Physics, University of Virginia, 382 McCormick Rd., P.O. Box 400714, Charlottesville, VA 22904-4714, USA
²⁹ NIKHEF, Science Park 105, 1099 XG Amsterdam, The Netherlands
³⁰ Istituto Nazionale di Fisica Nucleare (INFN), Via E. Fermi 40, 00044 Frascati, Italy
³¹ Wuppertal University, 42119 Wuppertal, Germany
³² Eötvös University, 1117 Budapest, Hungary
³³ Forschungszentrum Jülich, 52425 Jülich, Germany
³⁴ Albert Einstein Center for Fundamental Physics, Institut für Theoretische Physik, Universität Bern, Sidlerstr. 5, 3012 Bern, Switzerland
³⁵ Faculty of Physics, Warsaw University of Technology, 00-662 Warsaw, Poland
³⁶ European Organization for Nuclear Research (CERN), Geneva, Switzerland
³⁷ Department of Physics, Kent State University, Kent, OH 44242, USA
³⁸ Crete Center for Theoretical Physics, Department of Physics, University of Crete, 71003 Heraklion, Greece
³⁹ Laboratoire APC, Université Paris Diderot, Paris Cedex 13, Sorbonne Paris Cité 75205, France
⁴⁰ Theory Group, Physics Department, CERN, 1211, Geneva 23, Switzerland
⁴¹ Faculty of Science, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands
⁴² Moscow Physical Engineering Institute, Moscow 115409, Russia
⁴³ Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA

Springer

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

A. Andronic^{1,†}, F. Arleo^{2,3,†}, R. Arnaldi^{4,†}, A. Beraudo^{5,†}, E. Bruna^{6,†}, D. Caffarini^{7,†}, Z. Conesa del Valle^{8,†}, J.G. Contreras^{9,†}, T. Dahme^{10,†}, A. Dainese^{11,†}, M. Djordjevic^{12,†}, E.G. Ferreiro^{13,†}, H. Fujii^{14,†}, P.R. Goswami^{15,†}, R. Granier de Cassagnac^{16,†}, C. Hadjidakis^{17,†}, M. He^{18,†}, H. van Hees^{19,†}, W.A. Horowitz^{20,†}, R. Kolevatov^{21,†}, B.Z. Kopeliovich^{22,†}, J.P. Lansberg^{23,†}, M.P. Lombardo^{24,†}, C. Lourenço^{25,†}, G. Martinez-Garcia^{26,†}, L. Massacrier^{27,†}, C. Mironov^{28,†}, A. Mischke^{29,†}, M. Nahrgang^{30,†}, M. Nguyen^{31,†}, J. Nystrand^{32,†}, S. Peigné^{33,†}, S. Porteboeuf-Houssais^{34,†}, I.K. Pyatshnikov^{35,†}, A. Rakoza^{36,†}, R. Rapp^{37,†}, P. Robbe^{38,†}, M. Rosati^{39,†}, P. Rosnet^{40,†}, H. Satz^{41,†}, R. Schicker^{42,†}, I. Schienbein^{43,†}, I. Schmidt^{44,†}, E. Scapparino^{45,†}, R. Sharma^{46,†}, J. Stachel^{47,†}, D. Stocco^{48,†}, M. Strickland^{49,†}, R. Tleuepiev^{50,†}, B.A. Trzeciak^{51,†}, J. Uphoff^{52,†}, I. Vitev^{53,†}, R. Vogt^{54,†}, K. Watanabe^{55,†}, H. Wochter^{56,†}, P. Zhuang^{57,†}

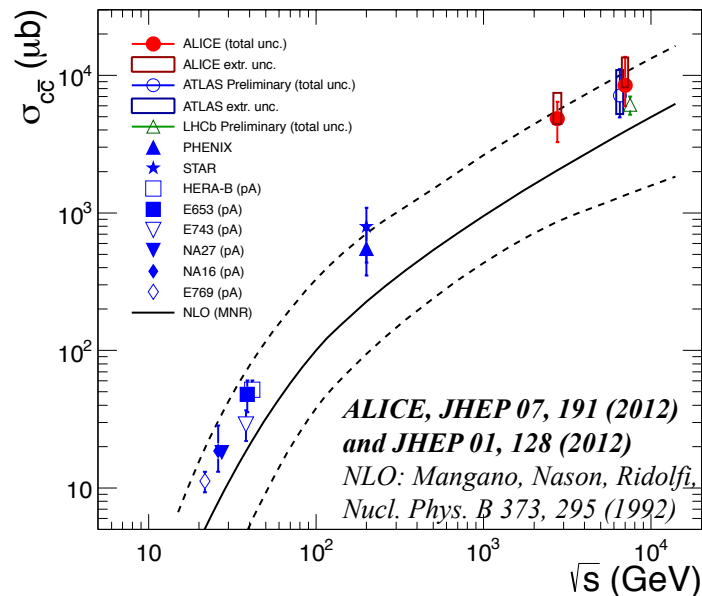
¹ Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
² Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
³ Laboratoire d'Annecy-le-Vieux de Physique Théorique (LAPTh), Université de Savoie, CNRS, Annecy-le-Vieux, France
⁴ INFN, Sezione di Torino, Torino, Italy
⁵ European Organization for Nuclear Research (CERN), Geneva, Switzerland
⁶ Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS/IN2P3, Orsay, France
⁷ Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
⁸ Excellence Cluster Universe, Technische Universität München, Munich, Germany
⁹ INFN, Sezione di Padova, Padova, Italy
¹⁰ Institute of Physics, University of Belgrade, Belgrade, Serbia
¹¹ Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
¹² Institute of Physics, University of Tokyo, Tokyo, Japan
¹³ SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS/IN2P3, Nantes, France
¹⁴ Department of Applied Physics, Nanjing University of Science and Technology, Nanjing, China
¹⁵ IAS and Institute for Theoretical Physics, Frankfurt, Germany
¹⁶ Department of Physics, University of Cape Town, Cape Town, South Africa
¹⁷ Department of High Energy Physics, Saint-Petersburg State University Upanovskaya 1, Saint-Petersburg, Russia
¹⁸ Departamento de Física, Universidad Técnica Federico Santa María, and Centro Científico-Tecnológico de Valparaíso, Valparaíso, Chile
¹⁹ INFN, Sezione di Pisa, Pisa, Italy
²⁰ LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
²¹ Institute for Subatomic Physics, Faculty of Science, Utrecht University, Utrecht, the Netherlands
²² Department of Physics, Dalhousie University, Dartmouth, USA
²³ Department of Physics and Technology, University of Bergen, Bergen, Norway
²⁴ Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS/IN2P3, Clermont-Ferrand, France
²⁵ Commissariat à l'Energie Atomique, IFPL, Saclay, France
²⁶ Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, USA
²⁷ Iowa State University, Ames, USA
²⁸ Fakultät für Physik, Universität Bielefeld, Bielefeld, Germany
²⁹ Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
³⁰ Laboratoire de Physique Subatomique et Cosmologie, Université Grenoble Alpes, CNRS/IN2P3, Grenoble, France
³¹ Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai, India
³² Department of Physics, Kent State University, Kent, United States
³³ Université de Lyon, Université Jean 1, CNRS/IN2P3, IPH-Ecole, Villeurbanne, France
³⁴ Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany
³⁵ Theoretical Division, Los Alamos National Laboratory, Los Alamos, USA
³⁶ Physics Division, Lawrence Livermore National Laboratory, Livermore, USA
³⁷ Physics Department, University of California, Davis, USA
³⁸ Institute of Physics, University of Tokyo, Tokyo, Japan
³⁹ Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan, China
⁴⁰ Physics Department, Tsinghua University and Collaborative Innovation Center of Quantum Matter, Beijing, China

1

Sapere Gravis European network

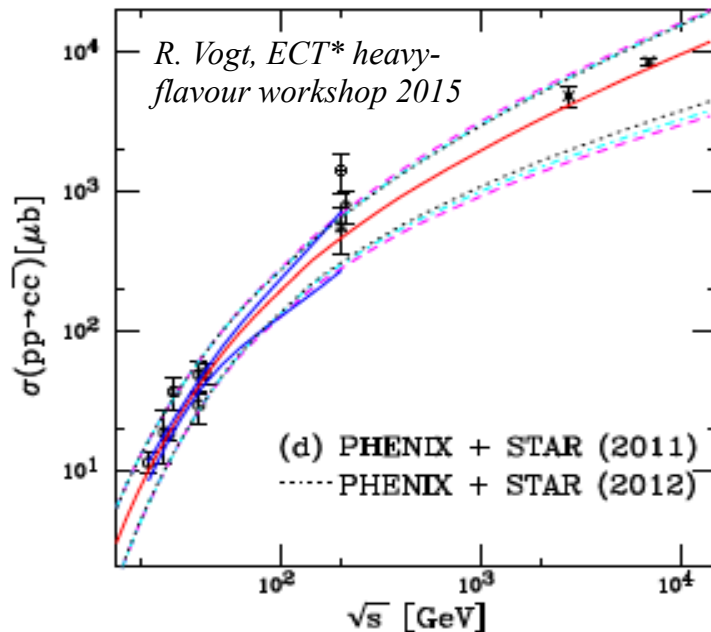
Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions, EPJC 76 3 (2016) 107 (arXiv:1506.03981)

Total charm production cross section in pp



JHEP 1207 (2012) 191

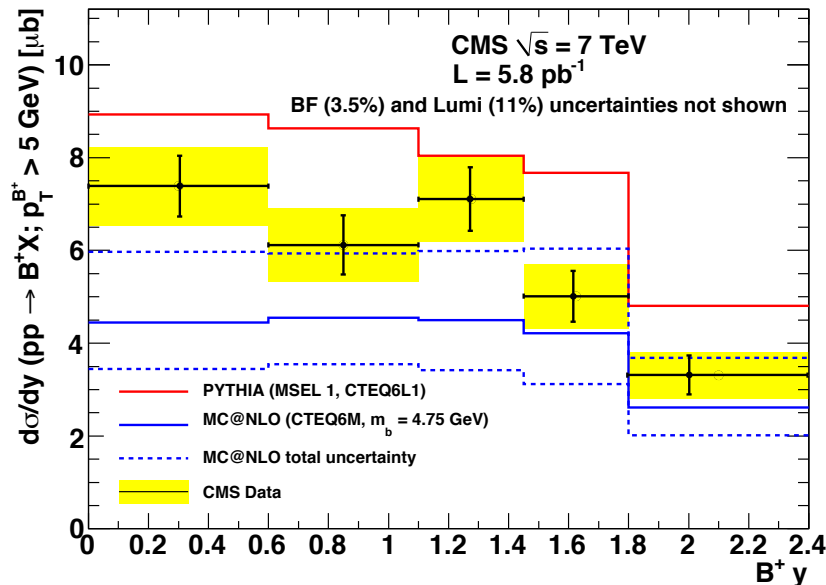
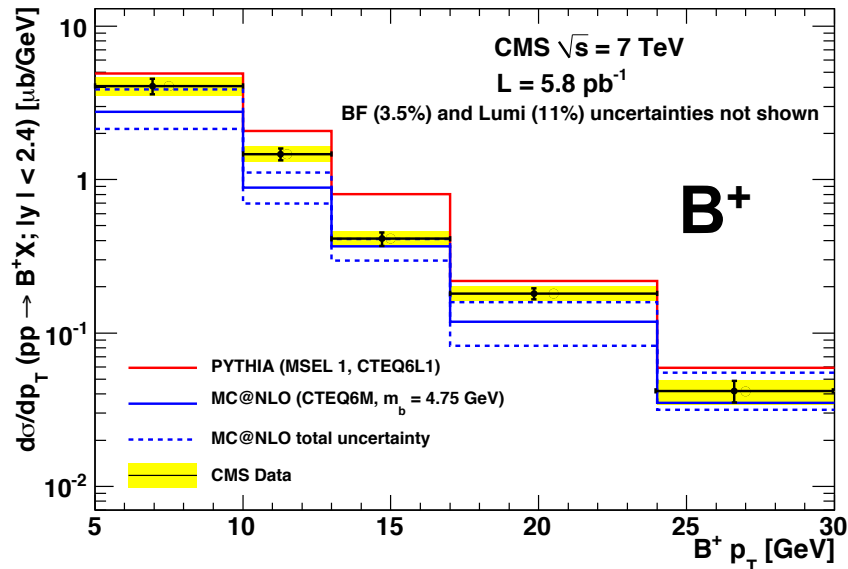
- Very good agreement between LHC experiments
- Consistency with NLO pQCD calculations, although at the upper limit; progress recently
- Run-2 data will provide further constrains
- Note: Parton spectra from pQCD input for energy loss models; baseline for measurements in Pb-Pb



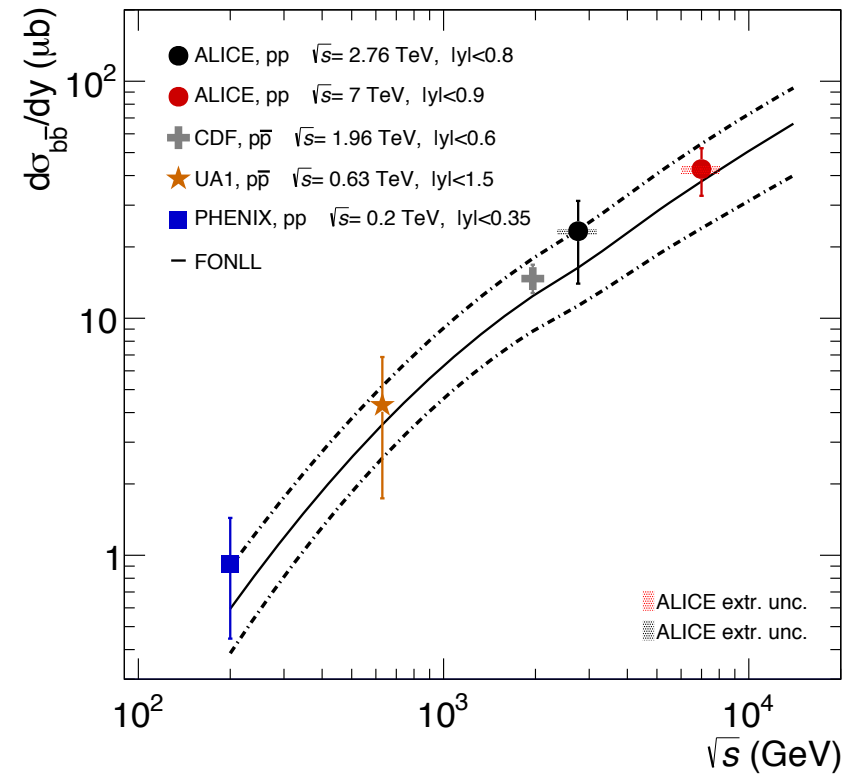
Open-beauty production at the LHC



Phys. Rev. Lett. 106 (2011) 112001



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



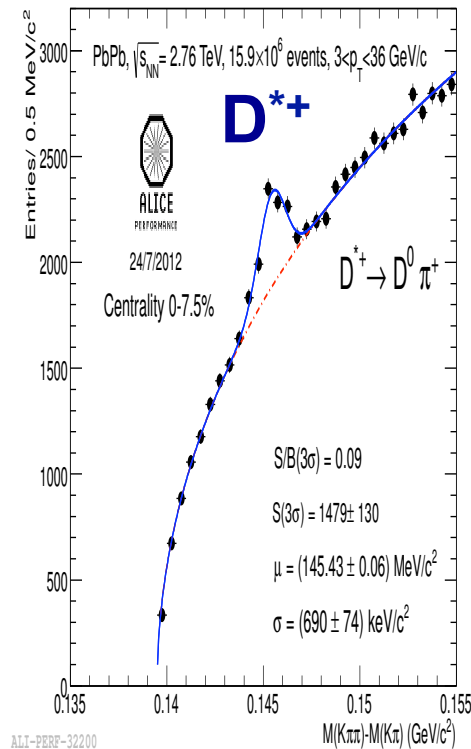
Relatively good description
 with NLO pQCD calculations

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

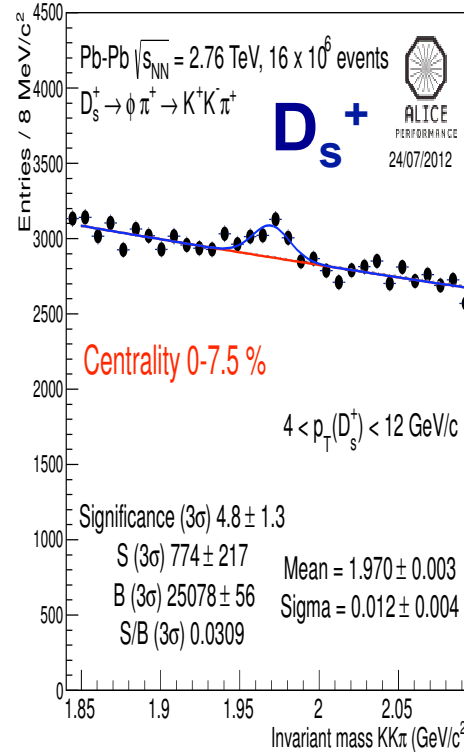
arXiv:1509.07287



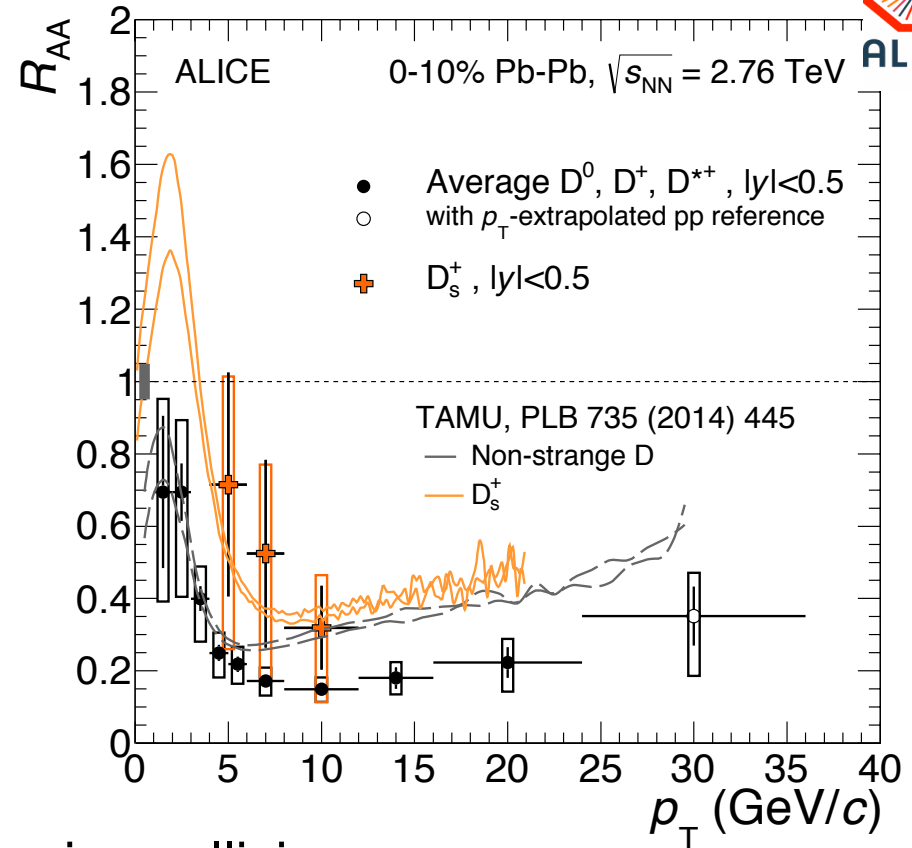
ALICE



ALI-PERF-32200



ALI-PERF-35901



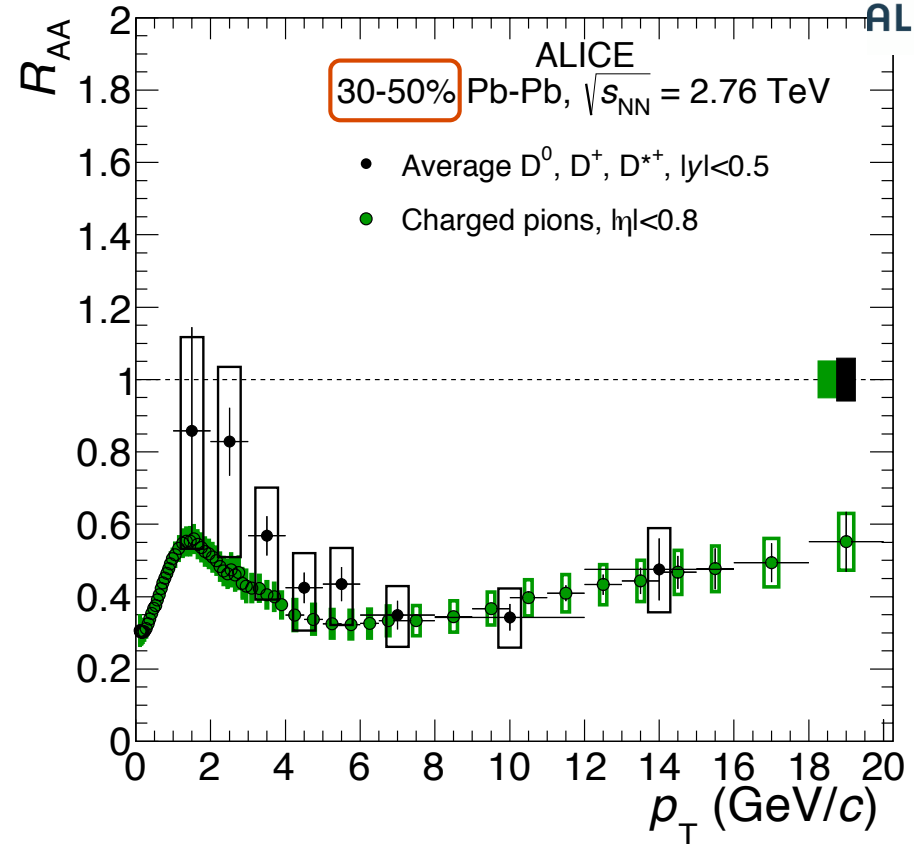
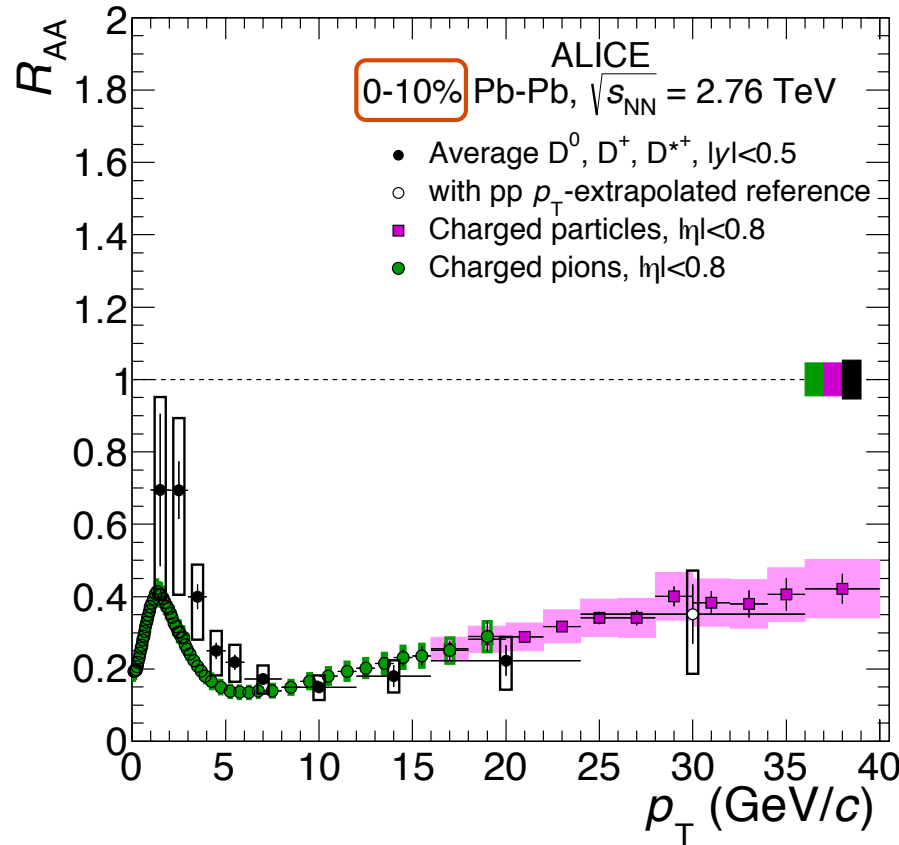
- First $D_s^+(c\bar{s})$ measurement in heavy ion collisions
- Expectation: enhancement of strange D meson yield at intermediate p_T if charm hadronises via recombination in the medium
- Strong suppression (factor 4-5) above 5 GeV/c in most central Pb-Pb, compared to binary scaling from pp

R_{AA} : light versus heavy-quark hadrons

arXiv:1509.06888



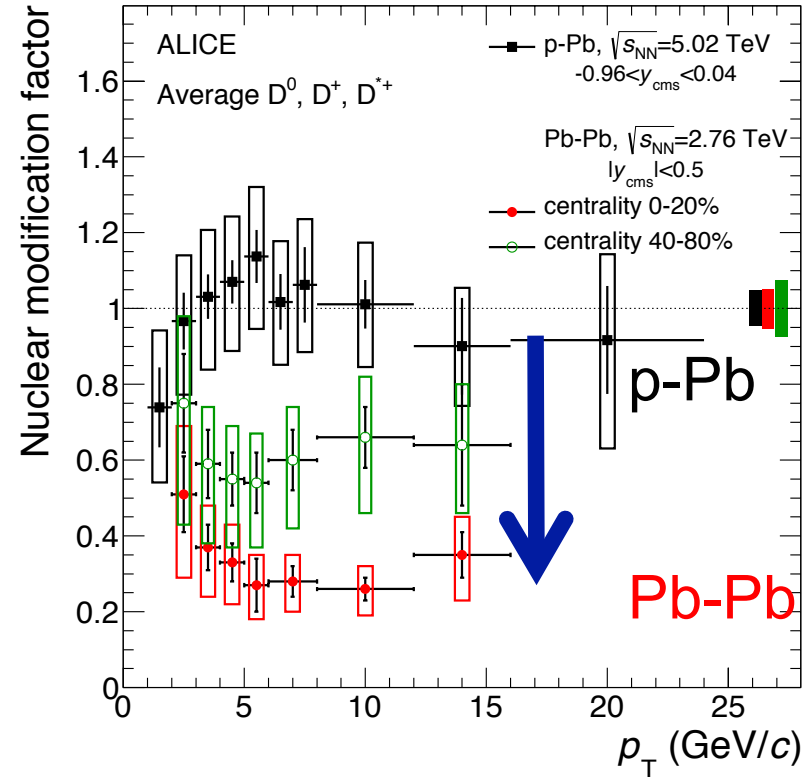
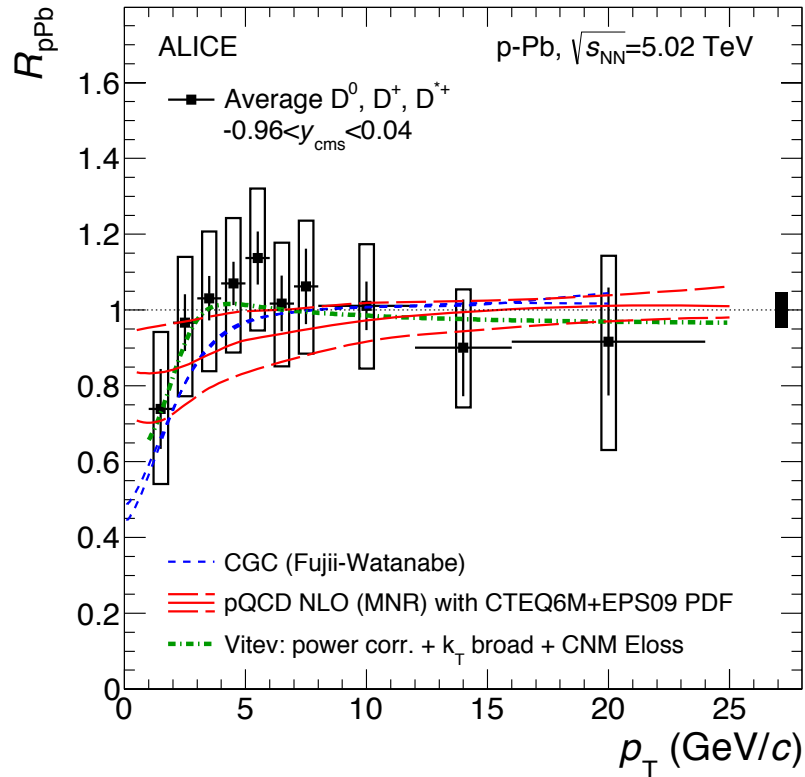
ALICE



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

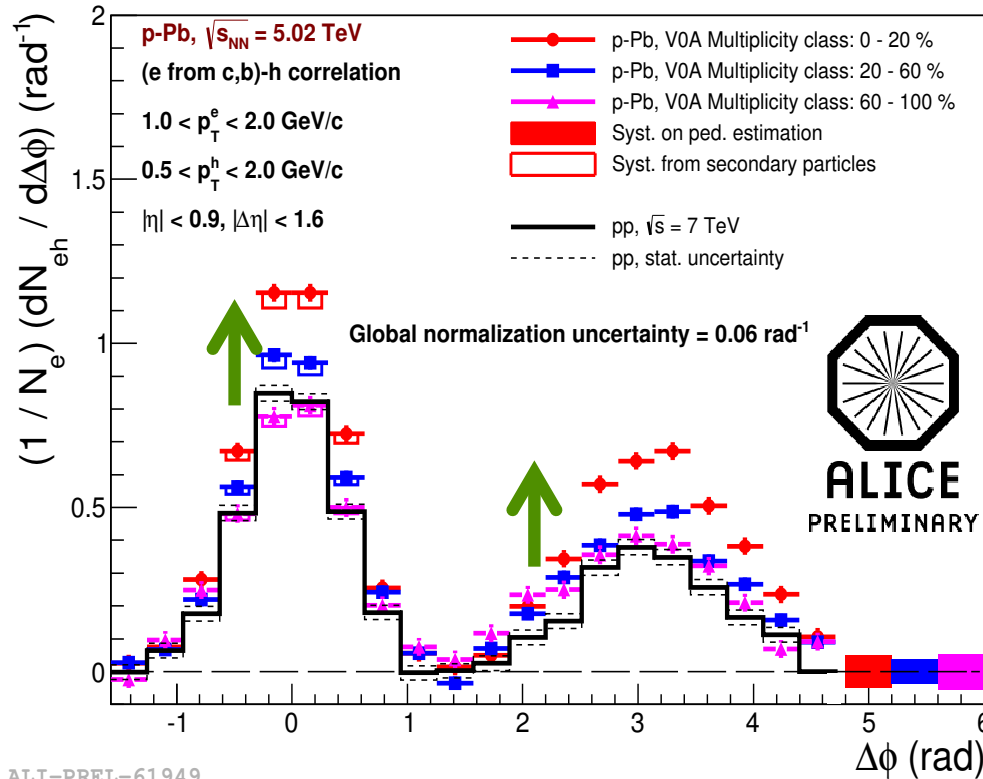
p-Pb: measurement of initial state effects

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

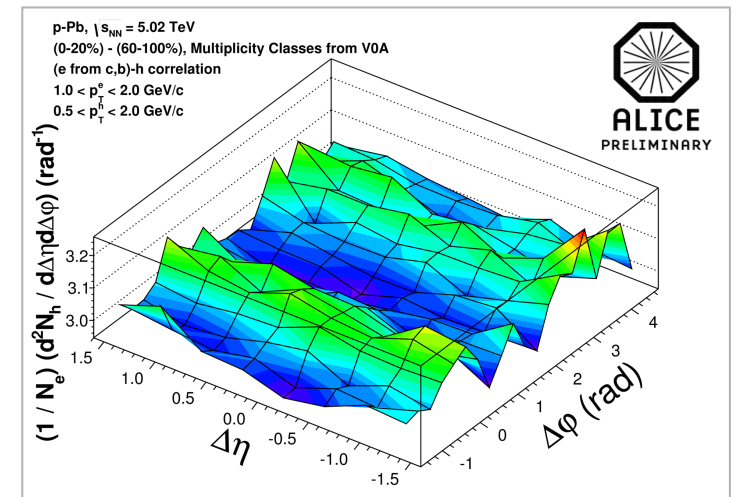


ALI-PREL-61949

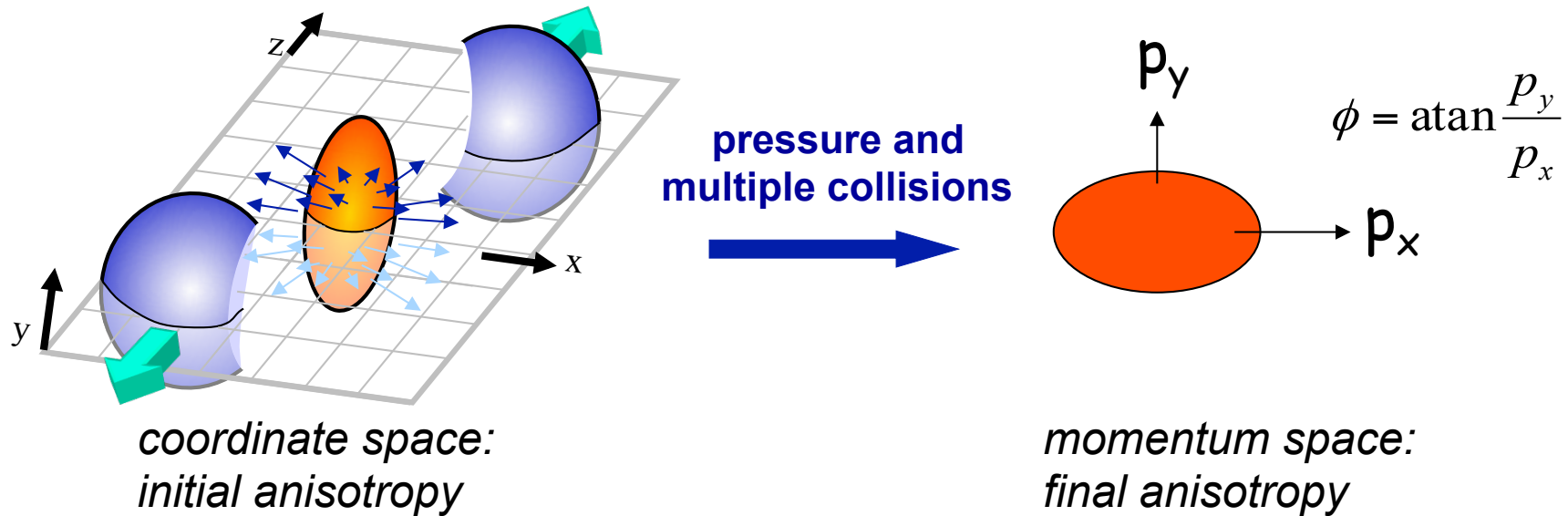
Azimuthal angular correlation between heavy-flavour decay electrons and charged hadrons

Difference of the correlation distribution for high and low multiplicity events

- Most central events have higher correlation yield for low- p_T ‘HF \rightarrow electrons’
- Indication for long-range correlation in $\Delta\eta$; also seen for light flavours
- Hydrodynamics or CGC?
- Theoretical interpretation ongoing



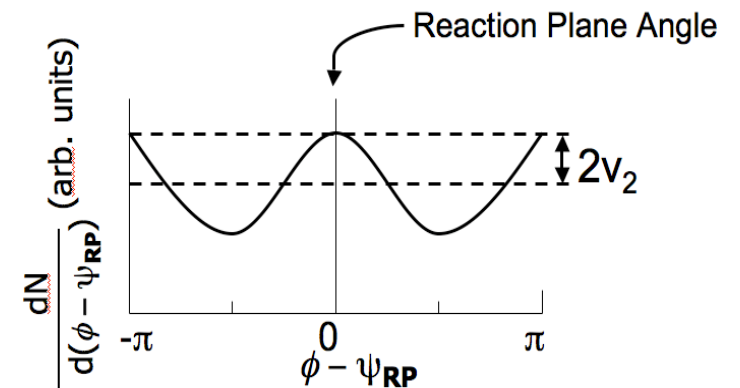
Azimuthal anisotropy



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

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

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

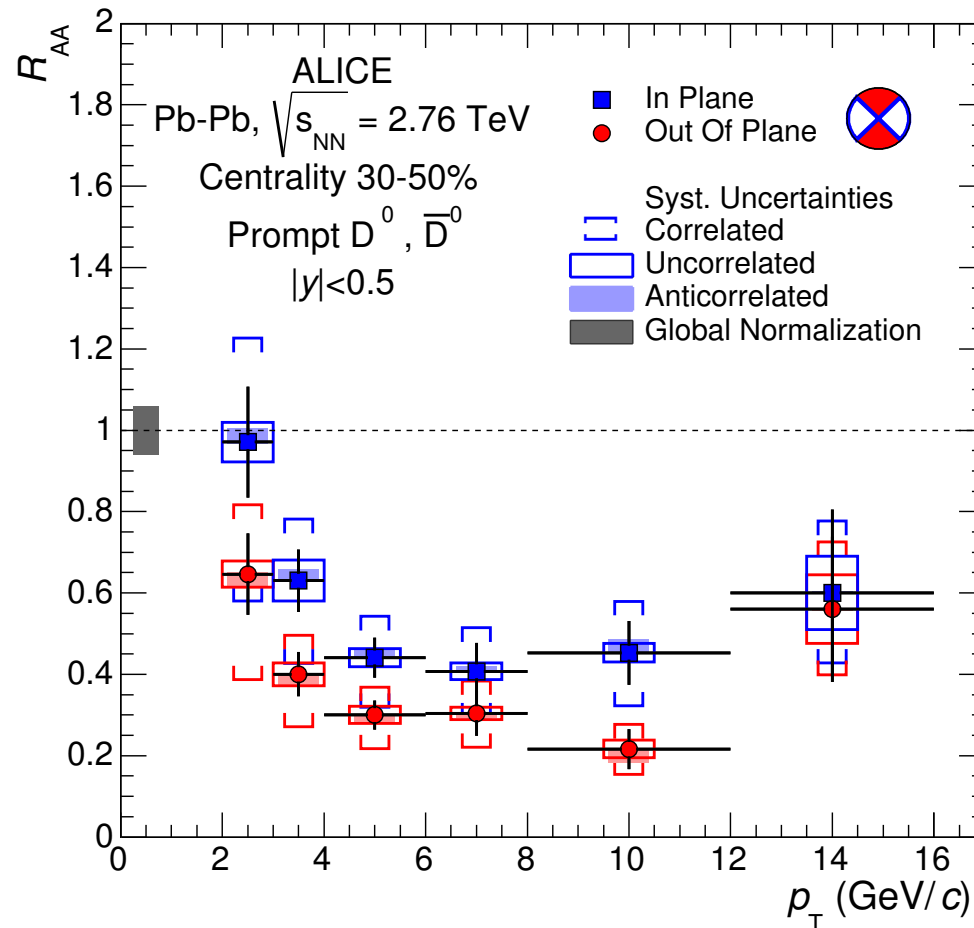


Azimuthal anisotropy = anisotropic flow

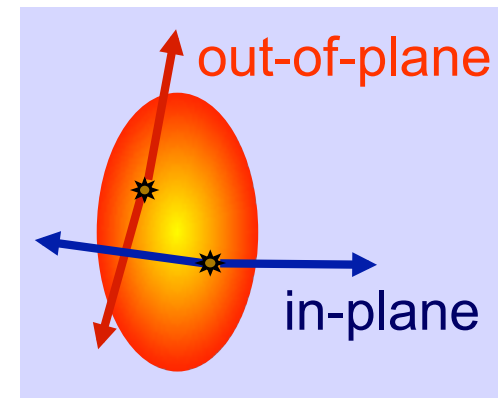
Non-scientific analogue



Prompt D^0 R_{AA} versus event plane



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

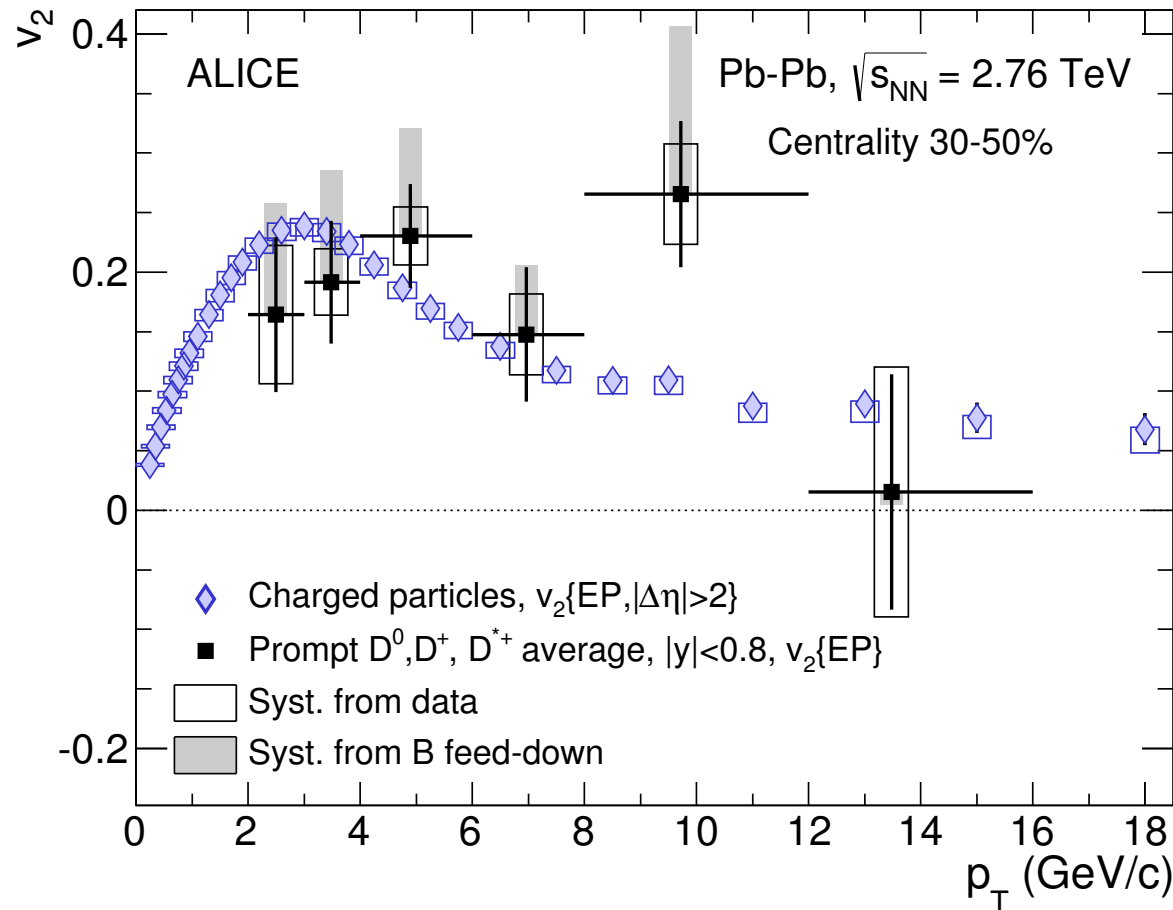


More suppression at high p_T out-of-plane with respect to in-plane due to different path length

Azimuthal anisotropy of prompt D mesons



Phys. Rev. Lett. 111 (2013) 102301

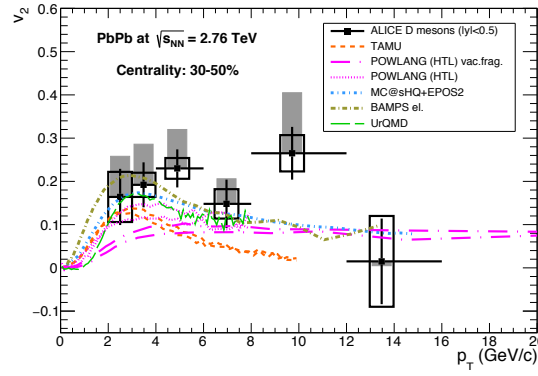
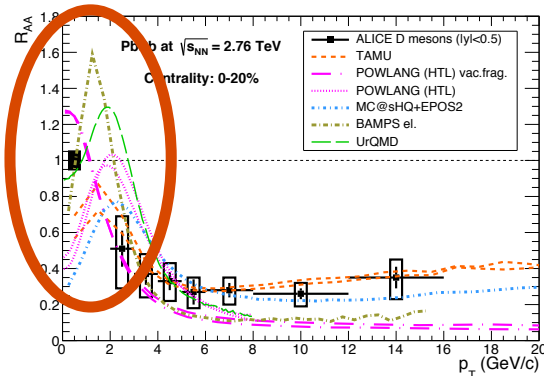


- Indication (3-5 σ confidence level) for non-zero charm elliptic flow in the p_T range 2-6 GeV/c
- Improved measurement with Run-2 data

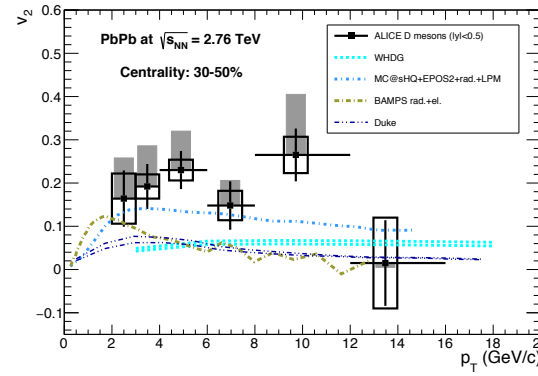
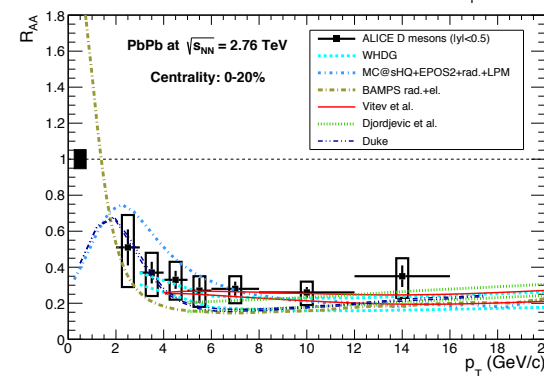
Comparison with model calculations: LHC

R_{AA} (0-20%)

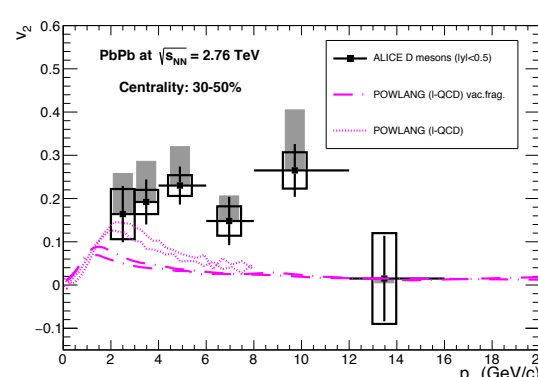
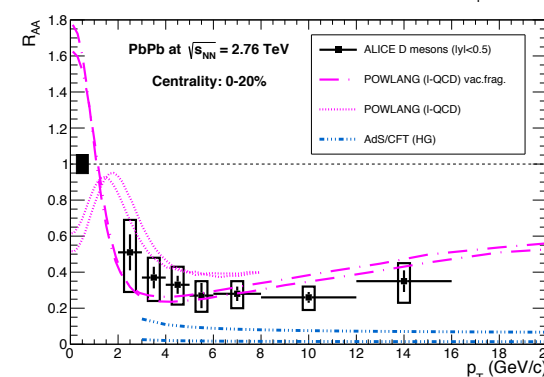
v_2 (30-50%)



Collisional energy loss only



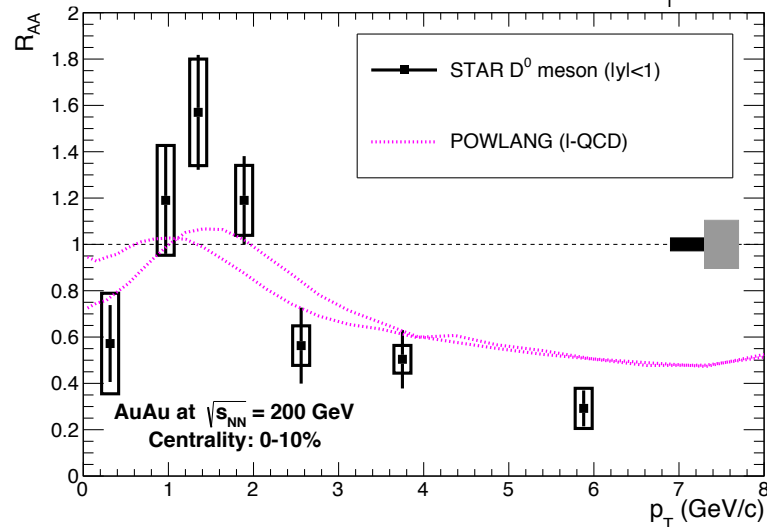
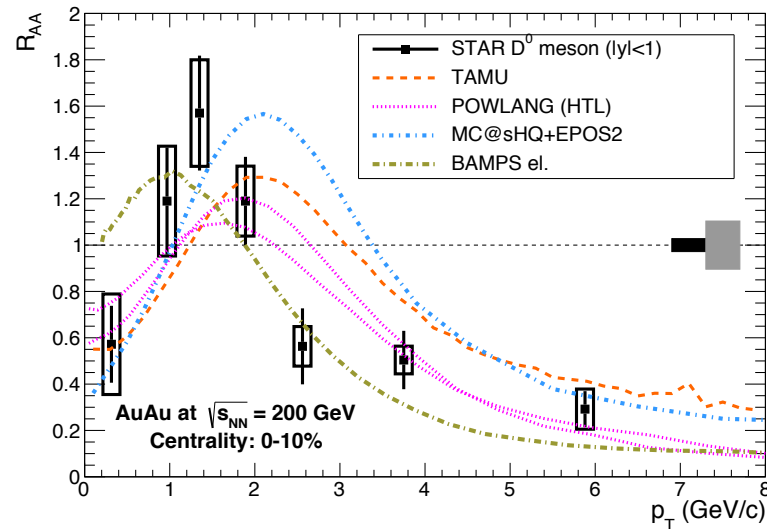
Collisional and radiative energy loss



EPJC 76 3 (2016) 107

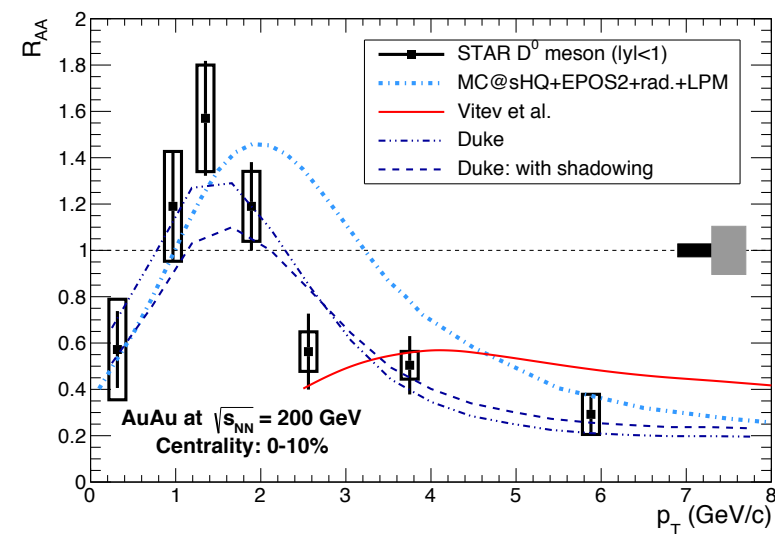
Comparison with model calculations: RHIC

Collisional Eloss only



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

Collisional and radiative Eloss



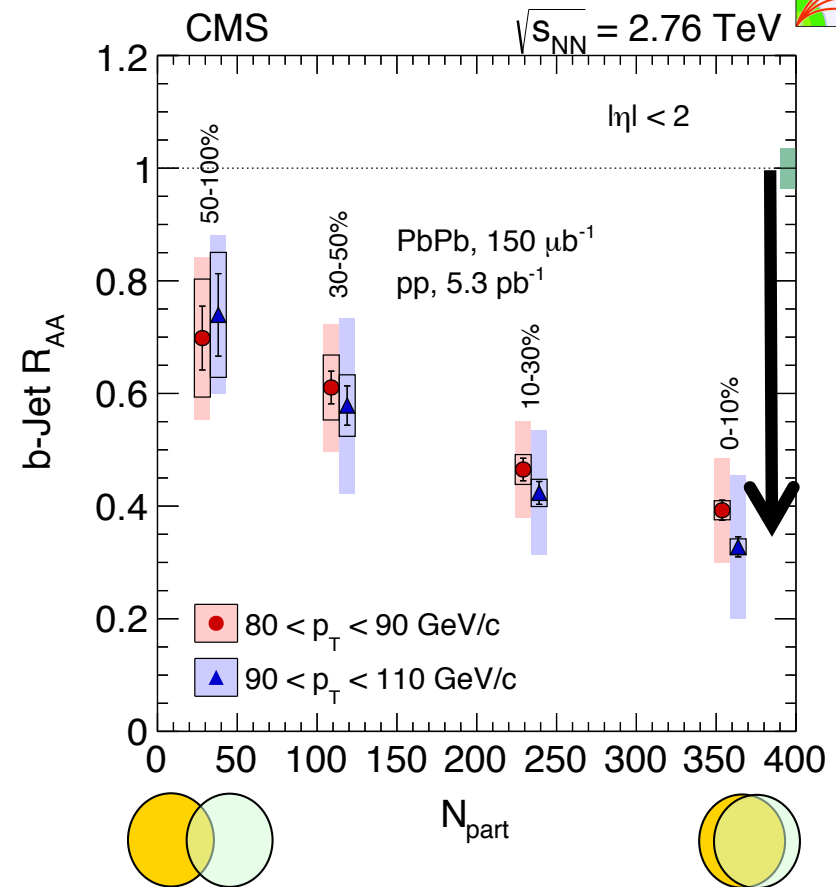
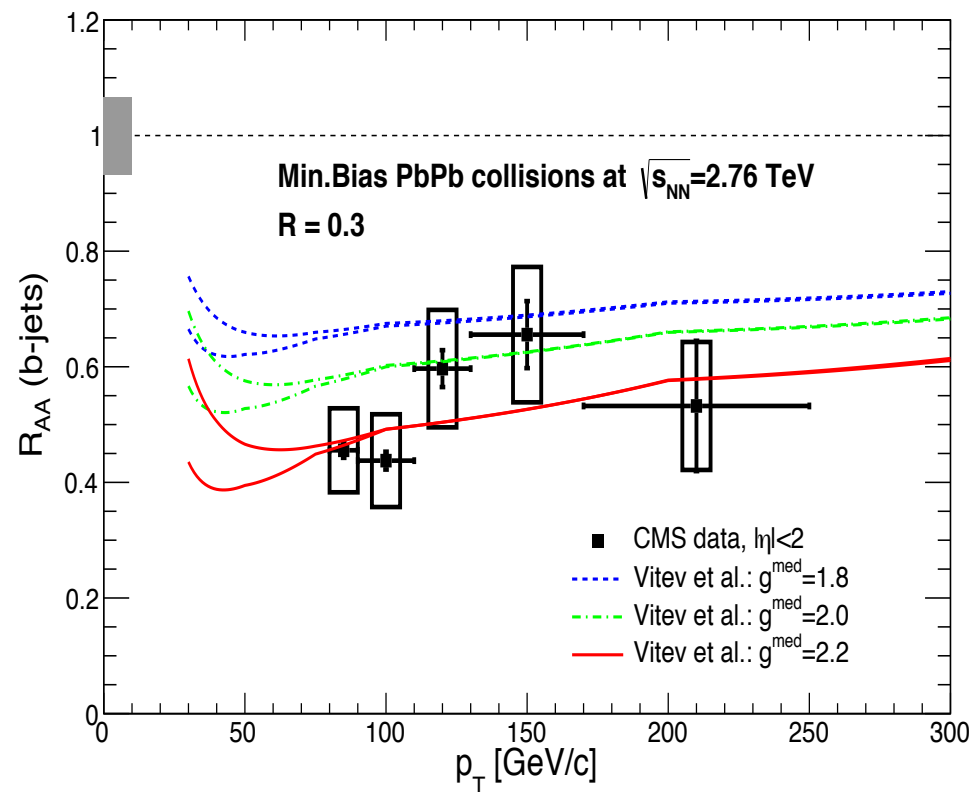
200 GeV

- 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

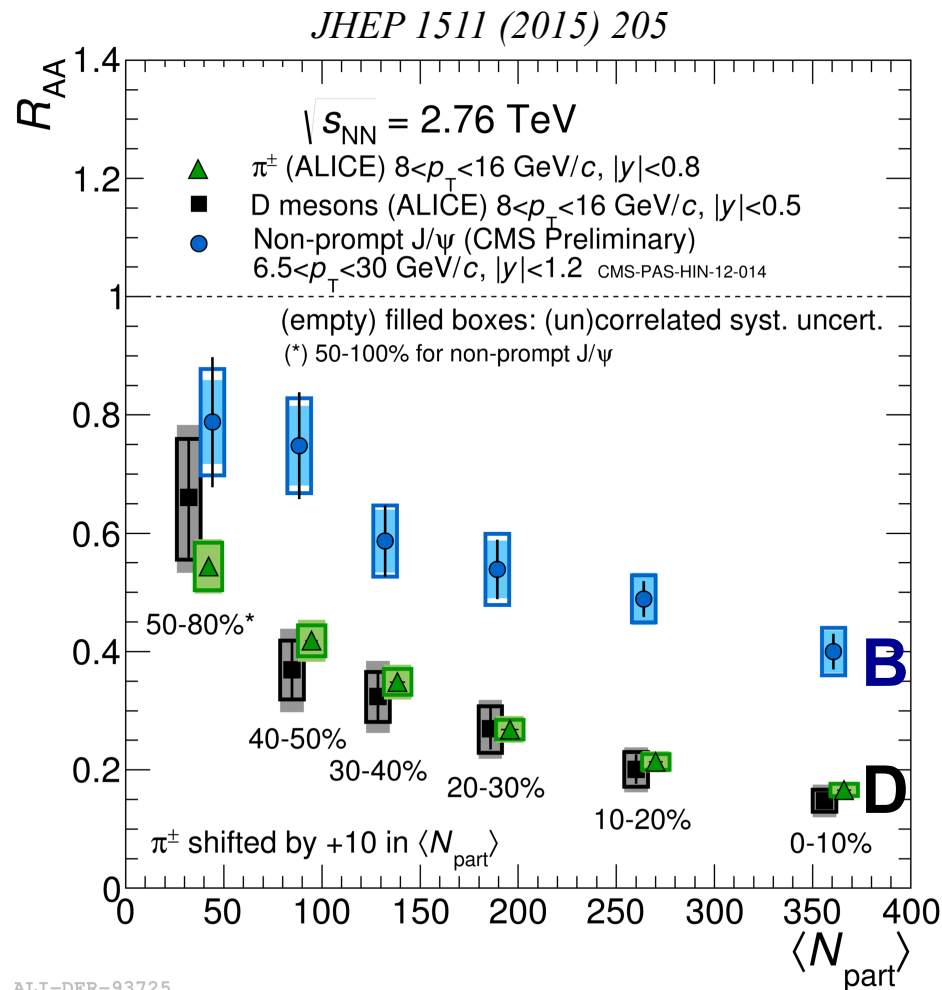
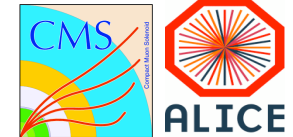


Phys. Rev. Lett. 113 (2014) 132301

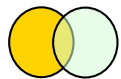


Future precision measurement should allow to constrain quark–medium coupling parameter g^{med}

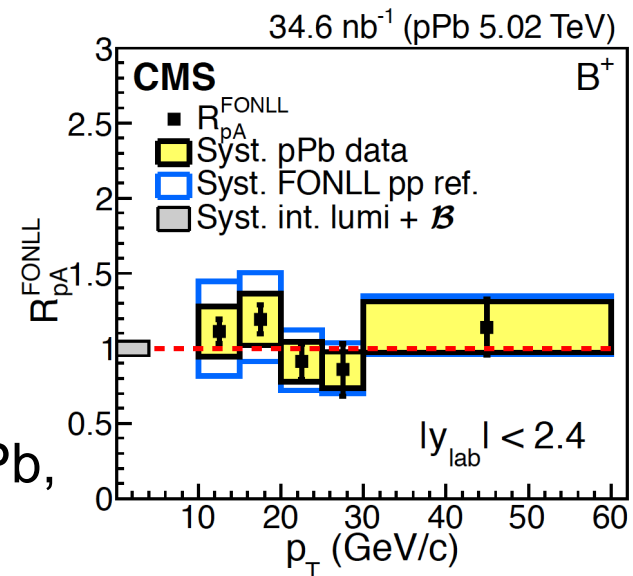
R_{AA} of D and B mesons



ALI-DER-93725



- Comparison of prompt D mesons (ALICE) with J/ ψ from beauty decays (CMS)
- D and B meson $\langle p_T \rangle \sim 10 \text{ GeV}/c$
- 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
 - $\varepsilon_{\text{initial}} \gg \varepsilon_{\text{critical}}$, 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 \rightarrow perfect liquid
 - Parton-medium interaction \rightarrow parton energy loss
 - $R_{AA}(\pi) < R_{AA}(D, \text{single leptons}) < R_{AA}(B \rightarrow J/\psi)$
- 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)