Heavy quarks as a probe of QGP

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HELMHOLTZ GEMEINSCHAFT

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BMBF Forschungsschwerpunkt ALICE Experiment 201
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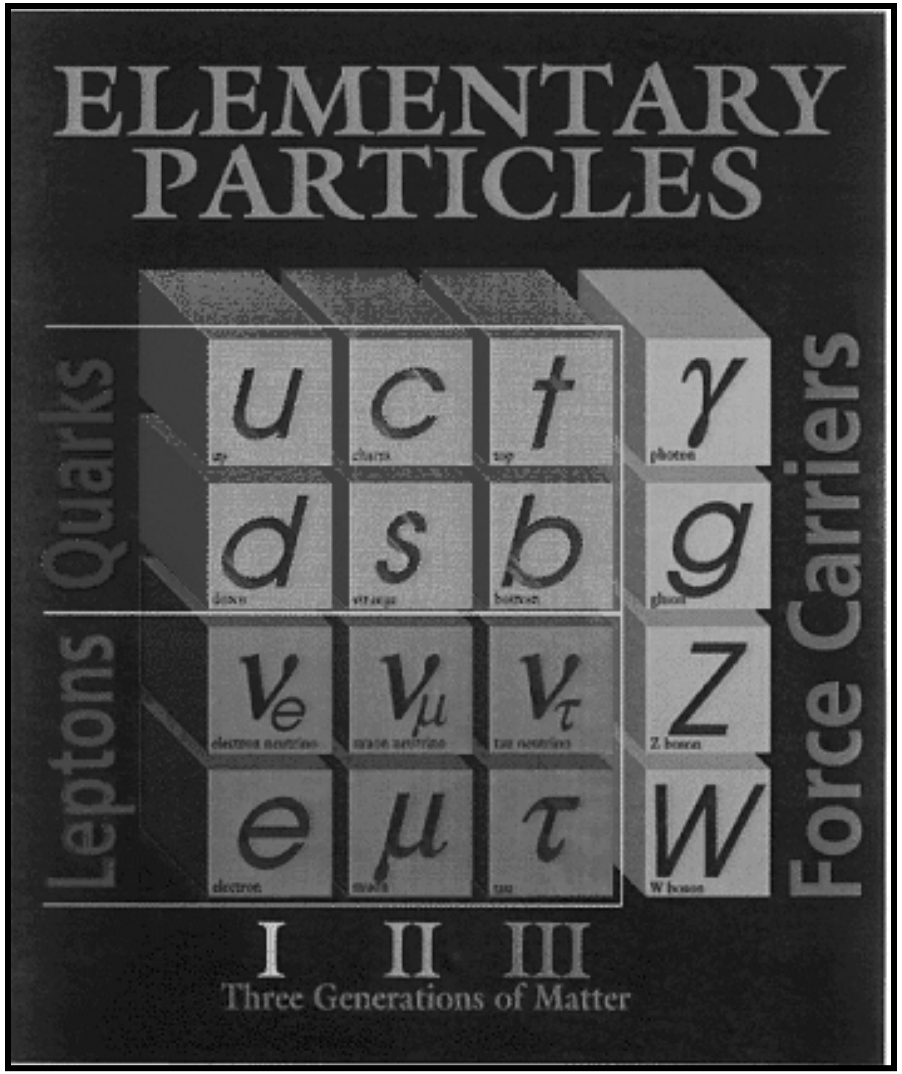
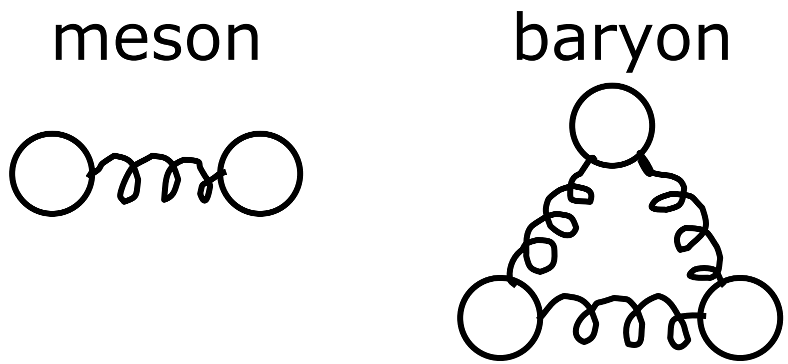
Building Blocks of Matter

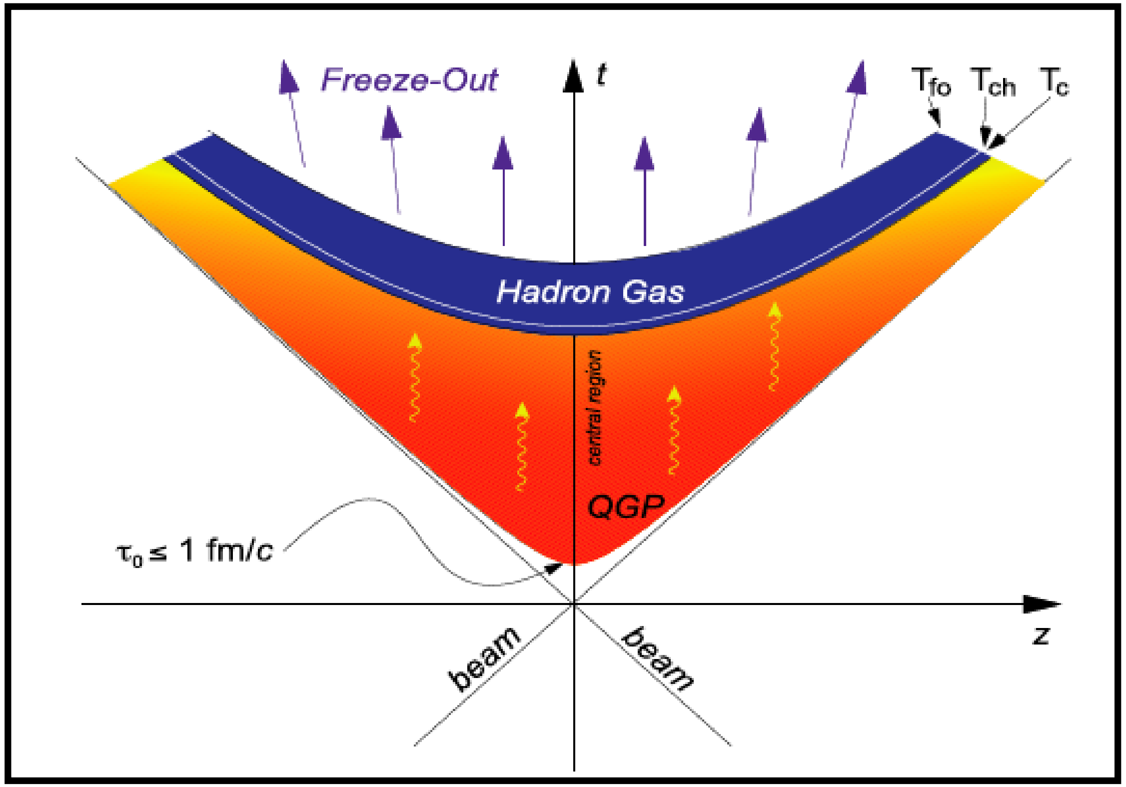


1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:



3) Gluons and quarks, or partons, typically exist in a color singlet state: confinement.

Time Scales



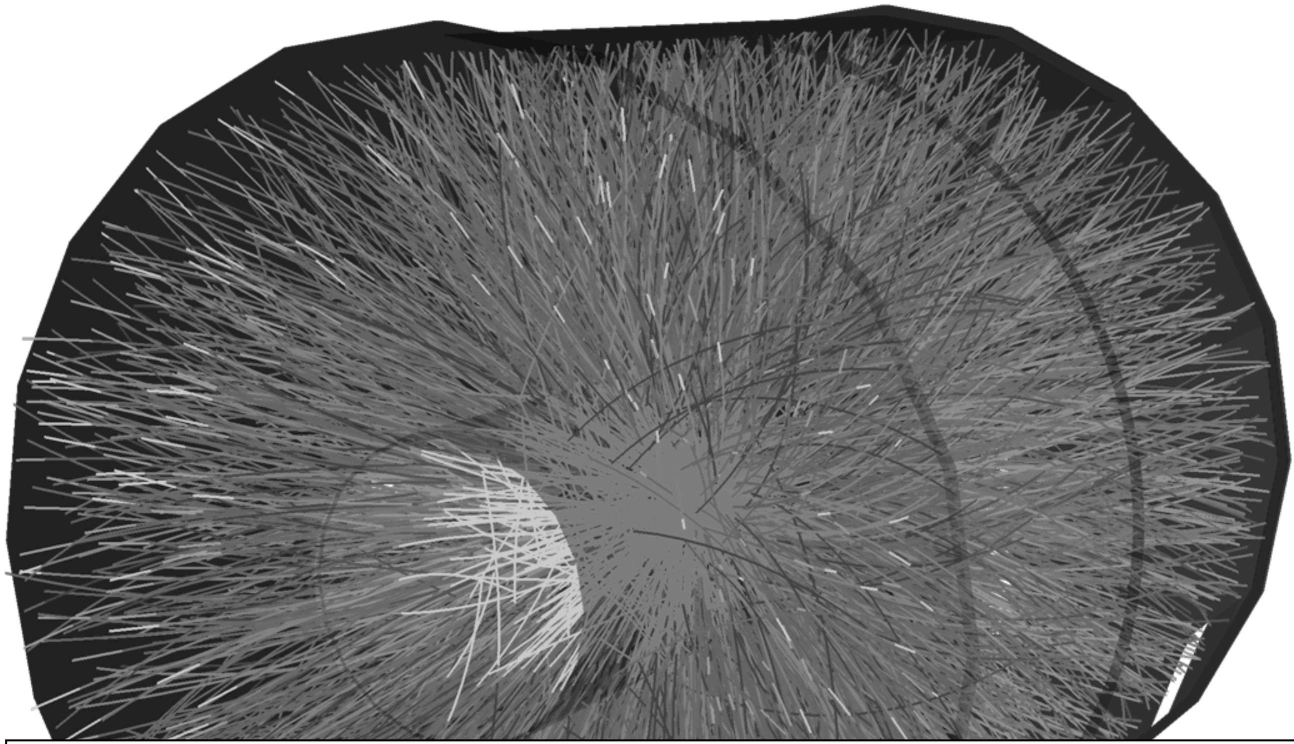
Plot: courtesy of R. Stock.

- **QGP life time**
  10 fm/c ≈ 3•10^{-23} s
- **thermalization time**
  0.2 fm/c ≈ 7•10^{-25} s
- **formation time**
  (e.g. charm quark):
  $1/2m_c$ = 0.08 fm/c
  ≈ 3•10^{-25} s
- **collision time**
  $2R/\gamma$ = 0.005 fm/c
  ≈ 2•10^{-26} s

Outline

- Introduction
- Charm-quark production in pp
- Charm-quark production in Pb-Pb
- Summary

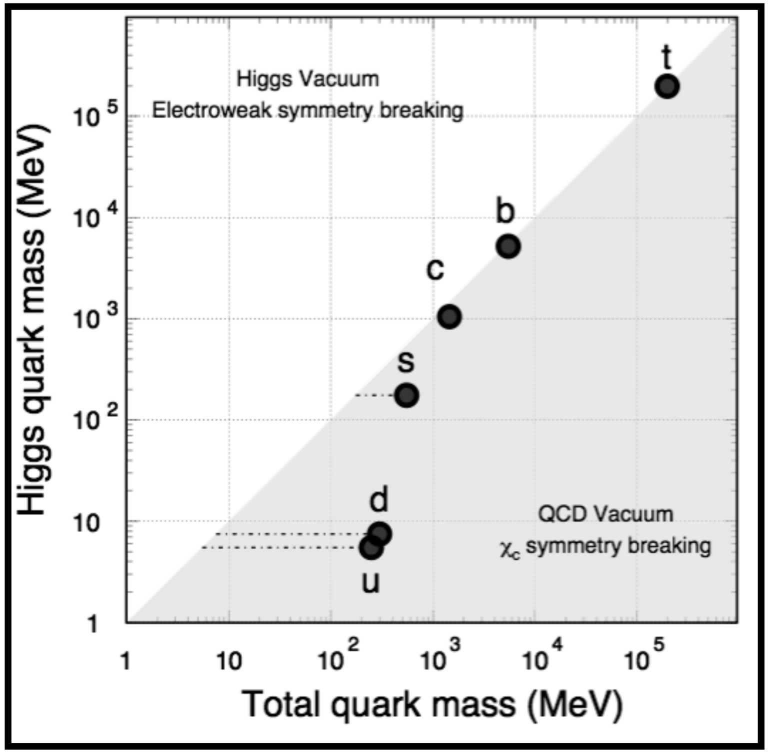
Erste Bleikollisionen in ALICE !



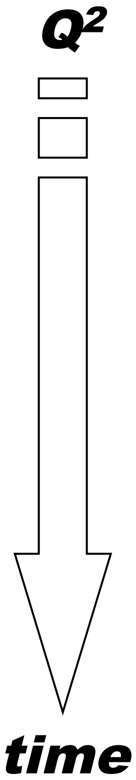
ALICE is designed for

- Highest multiplicities dN/dη up to 6000
- Excellent tracking & particle identification down to lowest momentum ~ 100 MeV/c

Heavy - flavor: a unique probe



X. Zhu, M. Bleicher, S.L. Huang, K.S., H. Stöcker, N. Xu, and P. Zhuang, PLB 647 (2007) 366.



$m_{c,b}$ » Λ_{QCD} : new scale

$m_{c,b}$ ≈ const., $m_{u,d,s}$ ≠ const.

initial conditions:

$\sigma_{c\bar{c}}$, $\sigma_{b\bar{b}}$

test pQCD, μ_R, μ_F
probe gluon distribution

early partonic stage:

diffusion (γ), drag (α)
flow, jets, correlations
probe thermalization

hadronization:

chiral symmetry restoration
confinement
statistical coalescence
J/ψ enhancement / suppression

Mass in the Standard Model (I)

- From the Higgs mechanism (fundamental) for vector bosons:

$$M_{W^+} = M_{W^-} = \frac{1}{2} v g$$

$$M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}$$

- v = 246 GeV, is vacuum expectation of the Higgs field
- g and g' are coupling constants

Mass in the Standard Model (II)

- From Yukawa coupling to the Higgs field ('put in by hand') for charged fermions, e.g. electron:

$$m_e = \frac{\lambda_e v}{\sqrt{2}}$$

- λ_e is free parameter

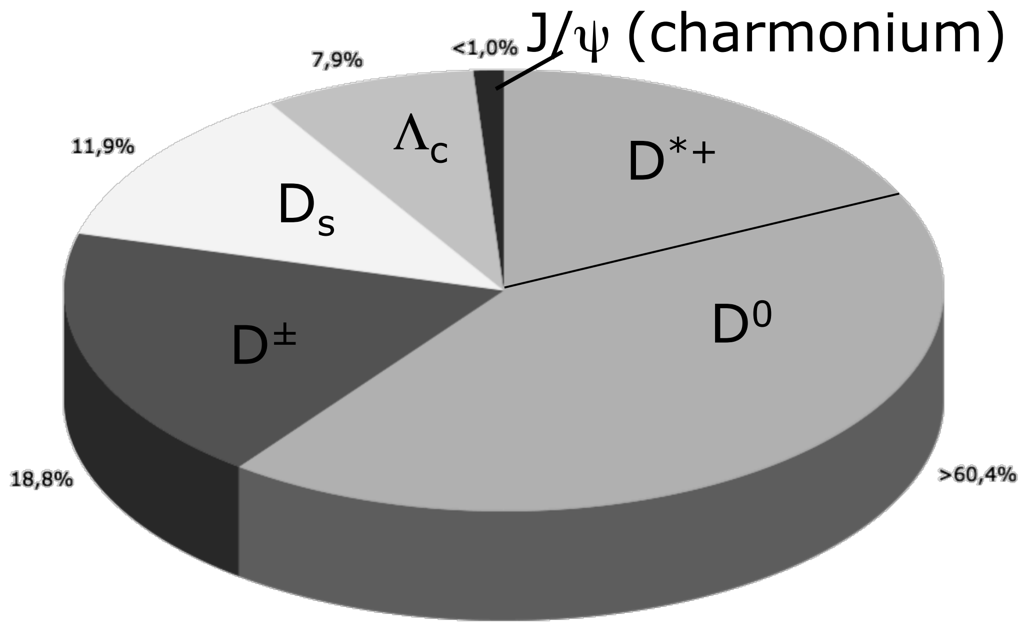
- Higgs decay: $\Gamma(h \rightarrow ee) \propto \lambda_e^2$
- Check experimentally for heaviest fermions (b-quark and tau-lepton)

Mass of the proton

- 3 quarks: uud
- Each quark weighs less than 10 MeV
- But: protons weighs 938 MeV !
- Yukawa coupling of fermions to the Higgs field generates < 1% of proton mass

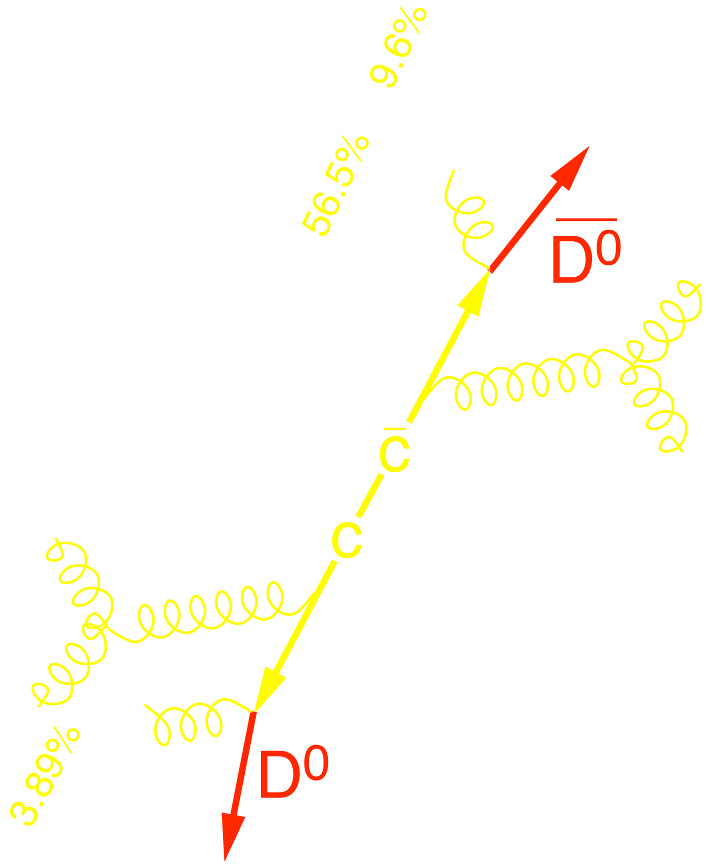
- 99% comes from kinetic energy of bound quarks and thus from strong interactions

Where does all the charm go ?



- **Total charm** cross section: **open-charmed** hadrons, e.g. **D^0, D^+, D^{*+},** Λ_c, … and **c,b → e(μ)** + X
- Quarkonia, e.g. **J/ψ** carries ≈**1%** of **total charm**

Heavy-quark detection



Open-charm reco. in ALICE

$D^0 \rightarrow K\pi$
$D^+ \rightarrow K\pi\pi$
$D^* \rightarrow D^0\pi$
$D_s \rightarrow KK\pi$

Under study:
$D^0 \rightarrow K\pi\rho$
$\Lambda_c \rightarrow pK\pi$
$\Lambda_c \rightarrow \Lambda\pi$
$\Lambda_c \rightarrow K^0{}_S\pi$

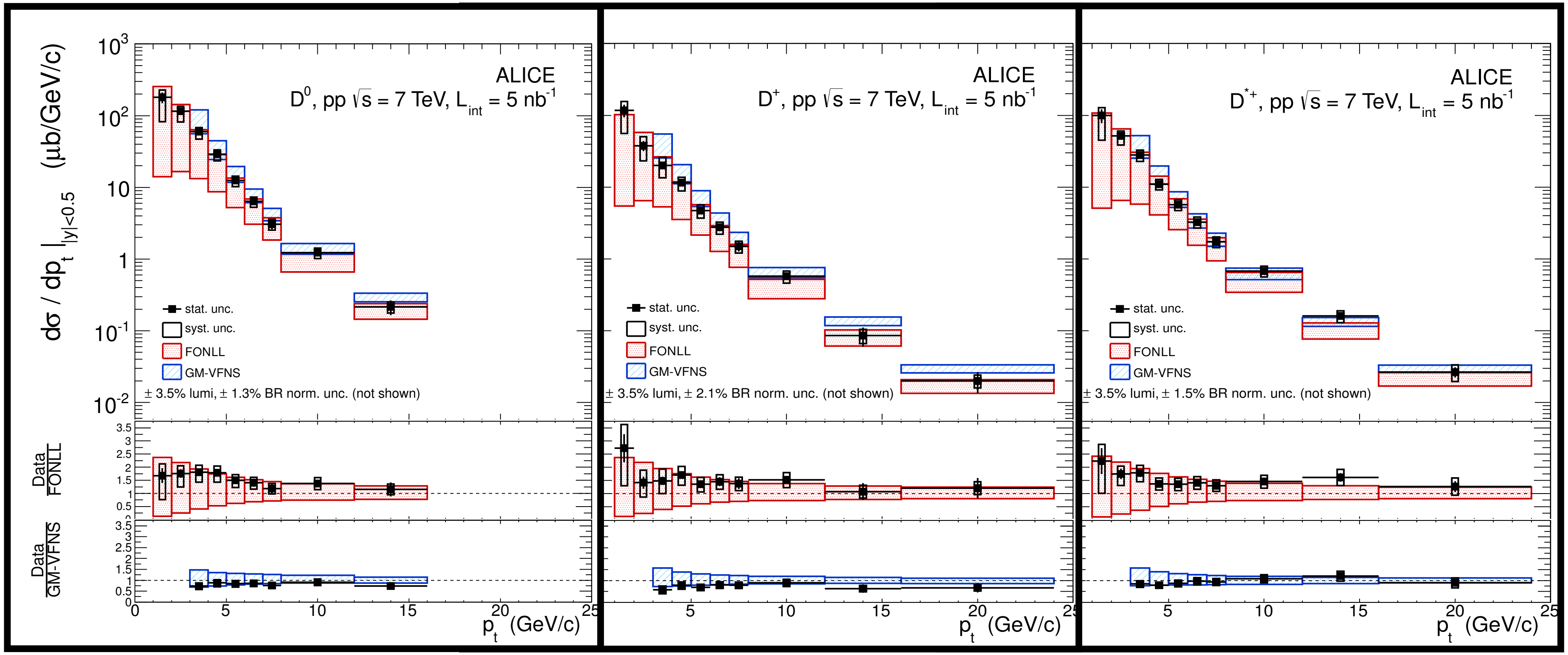
plot: courtesy of D. Tlusty.

- e.g., $D^0 \rightarrow K^- + \pi^+$, $c\tau$ = 123 μm
- **displaced** decay **vertex** is **signature** of **heavy-quark decay**

Charm-quark production pp collisions

Open-charm spectra from pp @ 7 TeV

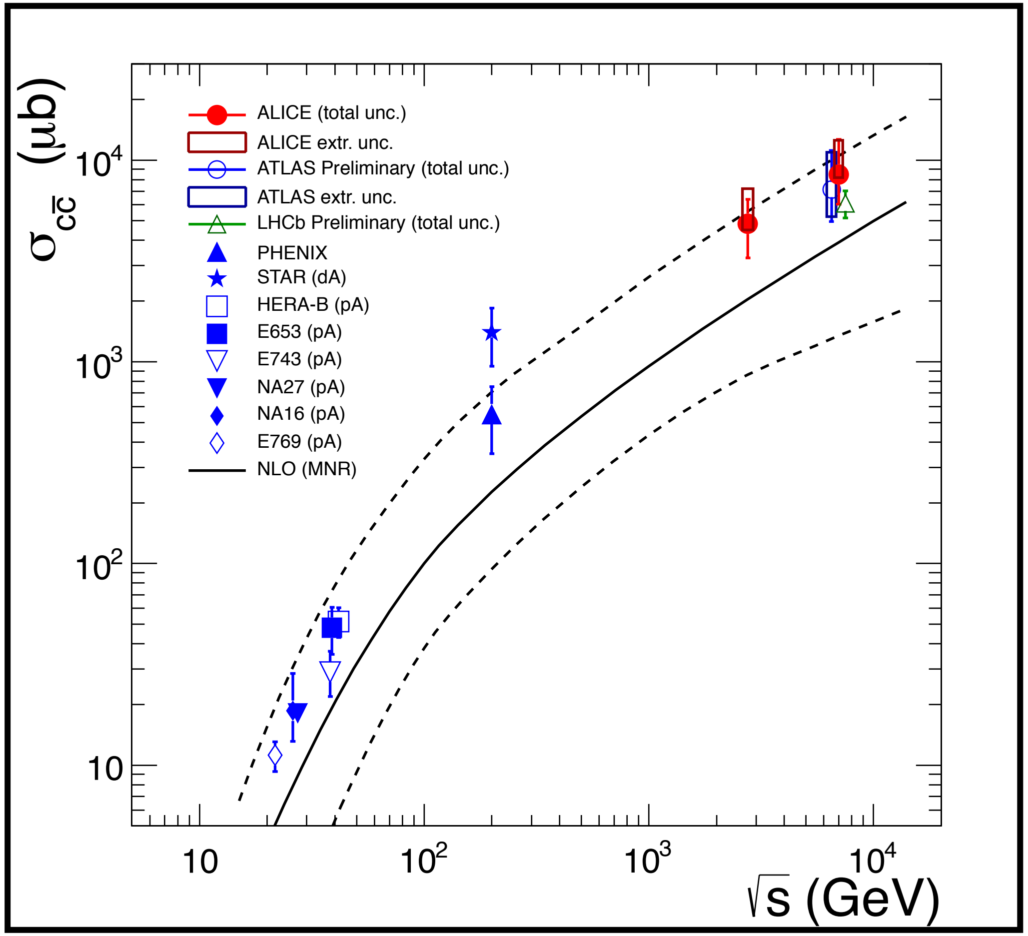
ALICE, JHEP 1201 (2012) 128; arXiv:1111.1553 [hep-ex];
D* analysis: Y. Wang, PhD thesis, Univ. Heidelberg, in preparation;
F. Schaefer, bachelor thesis, Univ. Heidelberg (2012).



covers spectrum from 1 up to 24 GeV/c

Open-charm cross section

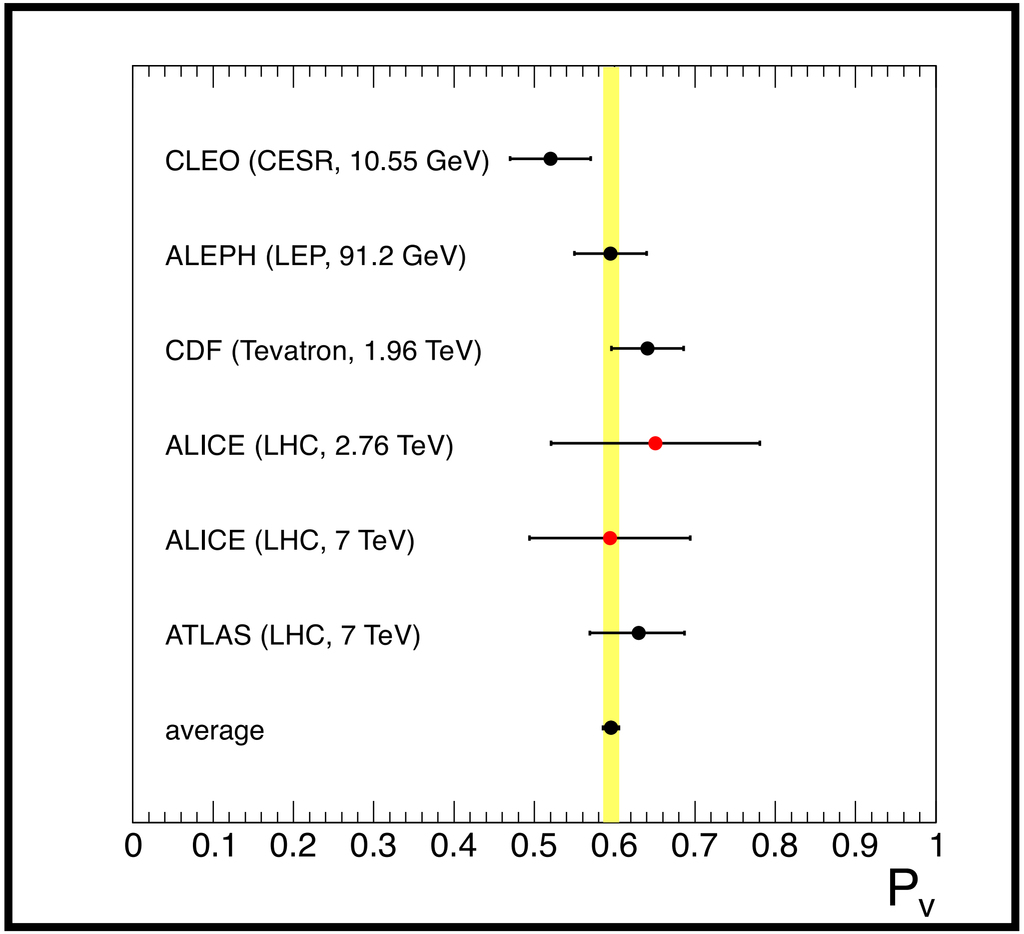
ALICE, arXiv:1205.4007 [hep-ex];
J. Wilkinson, bachelor thesis, Univ. Heidelberg (2011);
S. Stiefelmaier, bachelor thesis, Univ. Heidelberg (2012);
H. Cakir, bachelor thesis, Univ. Heidelberg, in preparation.



- LHC: First collider measurements at TeV scale
- ATLAS & LHCb agree with ALICE
- 10x more charm at LHC than at RHIC (larger factors at high-p_T: 10^4 - 10^5)

Charm hadronization

ALICE, arXiv:1205.4007 [hep-ex];
J. Wilkinson, bachelor thesis, Univ. Heidelberg (2011);
S. Stiefelmaier, bachelor thesis, Univ. Heidelberg (2012).



- Pv: fraction of D-mesons in vector state (V) to all mesons (V+S), Pv = V / (V+S)
- World average: Pv = 0.60 ± 0.01
- Stat. model, T=164 ± 10 MeV: Pv = 0.58 ± 0.13, agrees with data
- HQET predicts Pv = 3/(3+1) = 0.75

Charm hadronization, cont'ed

- Pv independent on collision energy and system
- Charm quark does not remember how it was created
- In hindsight, justifies factorization Ansatz
- Charm hadronization described by stat. model
- N.B. Lund fragm. + Clebsch-Gordan coupling: Pv = 0.63
- HQEFT ($m=\infty$), mass differences negligible,

  NOT justified for charm

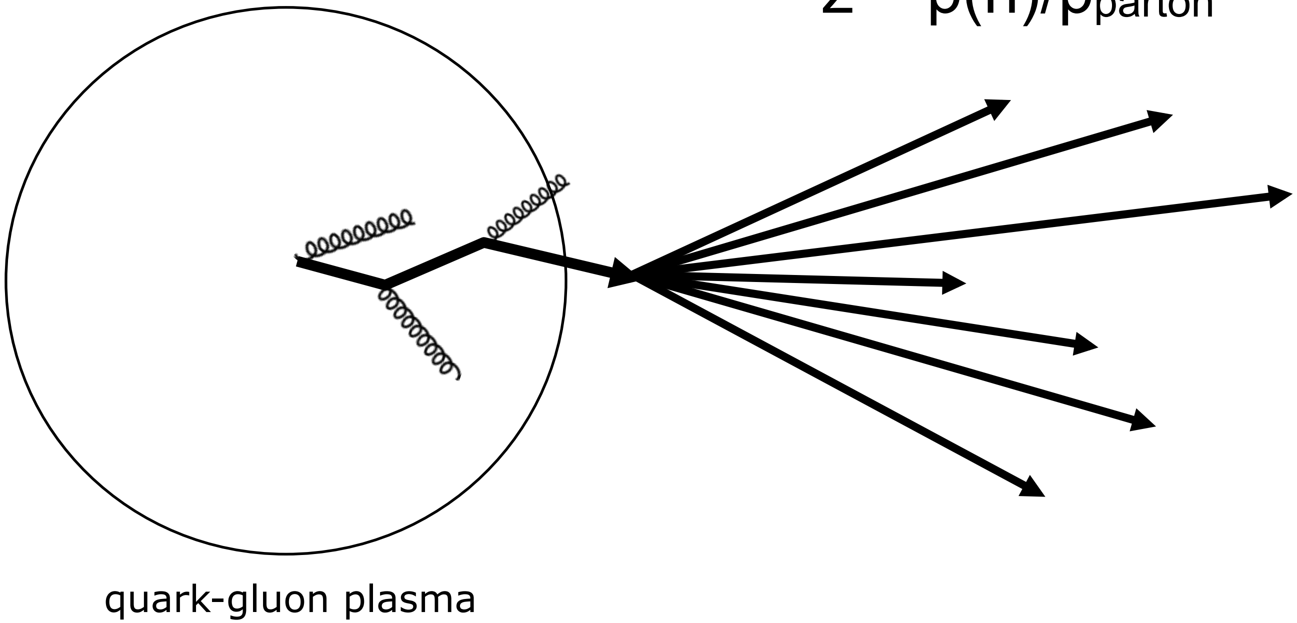
  but exp. checked for B mesons ($\Delta m/m$ = 40 MeV/5000 GeV)

Charm-quark production Pb-Pb collisions

Energy loss in the medium

J.D. Bjorken, PRD 27 (1983) 140.

$z = p(h)/p_{parton}$



Fast parton (i.e. charm quark) propagates in the medium

Loses energy due to gluon bremsstrahlung + elastic collisions

Appears as D-meson at lower momentum wrt pp collisions

→ probe QGP

Parton energy loss

Access medium properties: transport coefficients

$$\hat{q} = \frac{\langle p_T^2 \rangle}{L}$$

transverse momentum diffusion rate

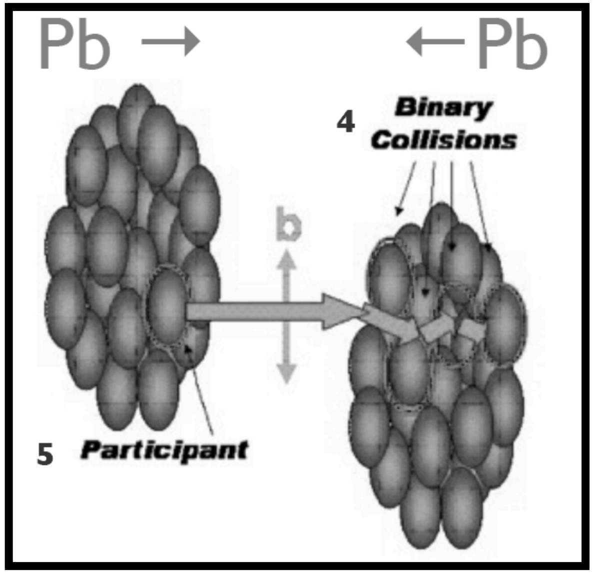
$$\hat{e} = \frac{\langle \Delta E \rangle}{L}$$

elastic energy loss rate

Nuclear Modification Factor - R_{AA}

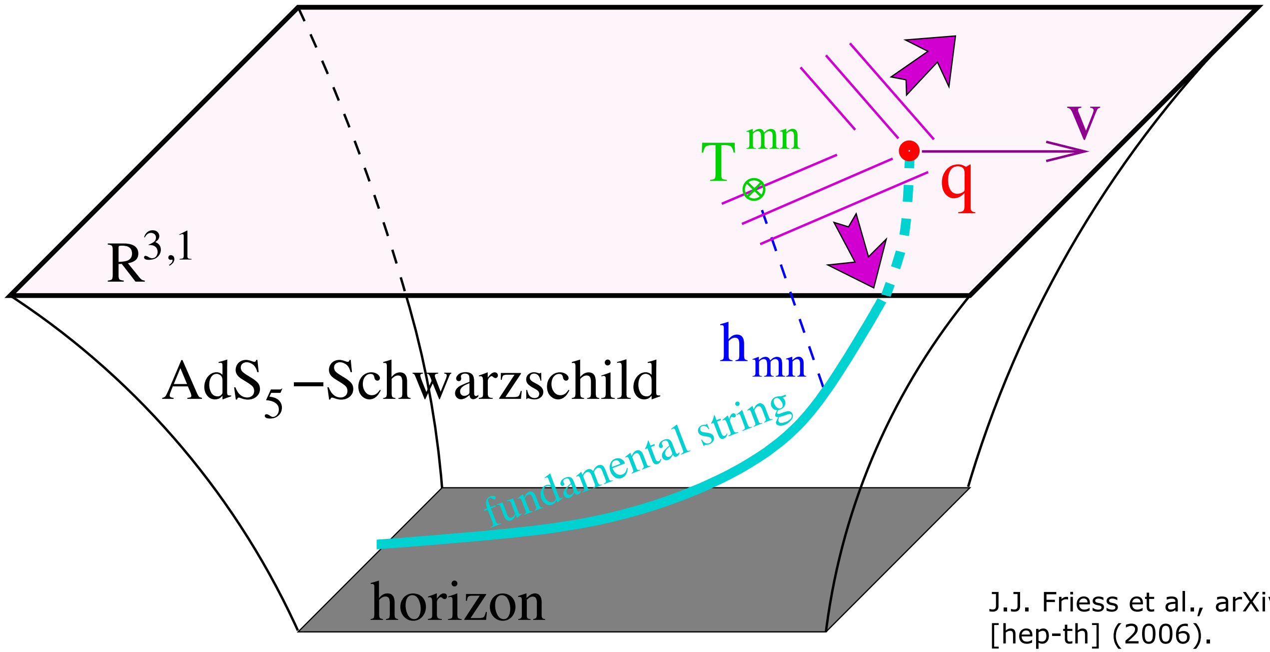
$$R_{AA}(p_T) = \frac{1}{\langle N_{\rm coll} \rangle} \cdot \frac{{\rm d}N_{AA}/{\rm d}p_T}{{\rm d}N_{pp}/{\rm d}p_T}$$

- define R_{AA}, expect unity in the absence of nuclear effects (for hard processes)
- N_{coll} = number of binary nucleon-nucleon collisions



- at RHIC, suppression of factor ~5
- at LHC, suppression of factor ~6
- strong medium effects !

AdS/CFT correspondence

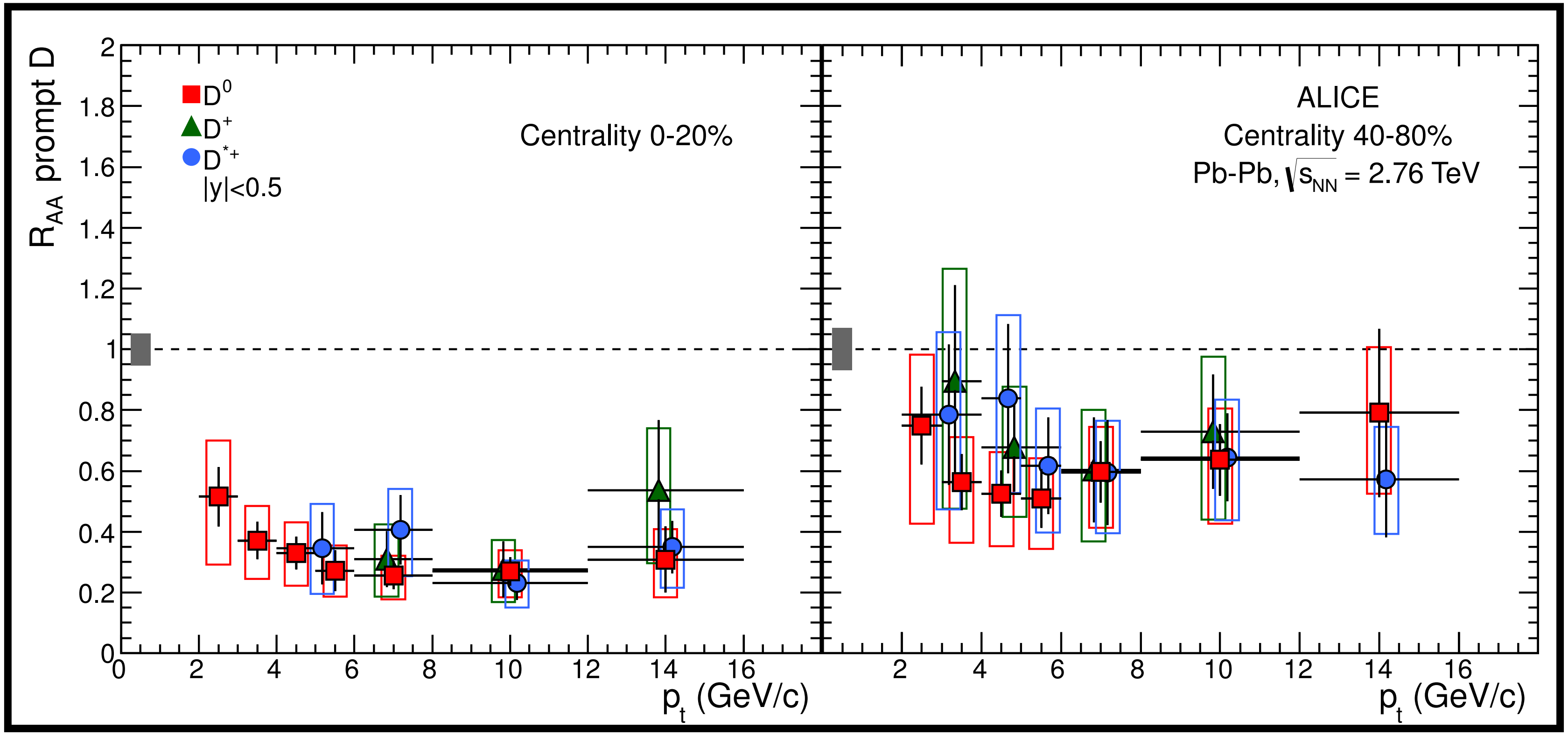


J.J. Friess et al., arXiv:0607022 [hep-th] (2006).

- Maldacena conjecture: string theory and conformal QFT mathematically equivalent
- heavy-quark energy loss modeled by embedding a string in AdS space
- Prediction: **strong suppression** for **charm, small** for **beauty**

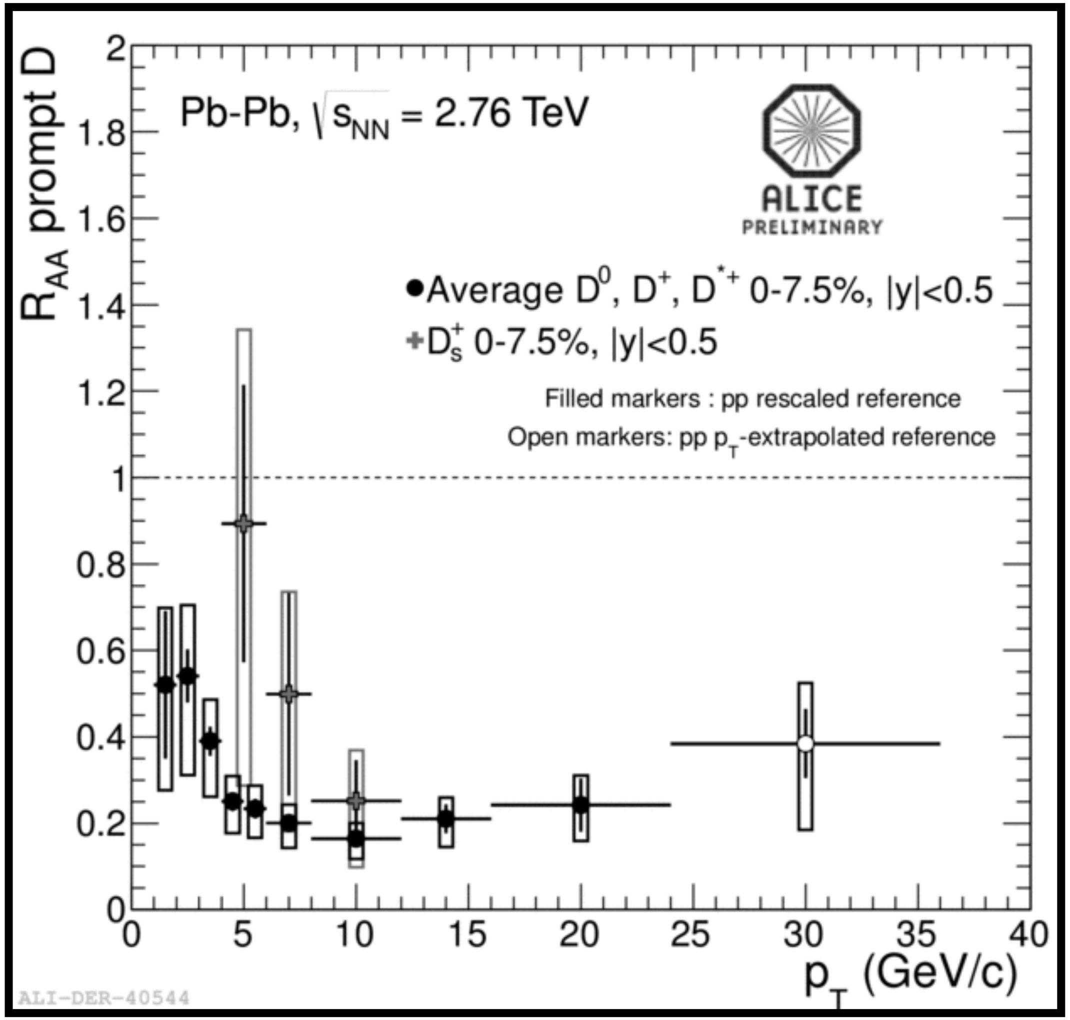
Charm nuclear modification factor

ALICE, arXiv:1203.2160 [nucl-ex].



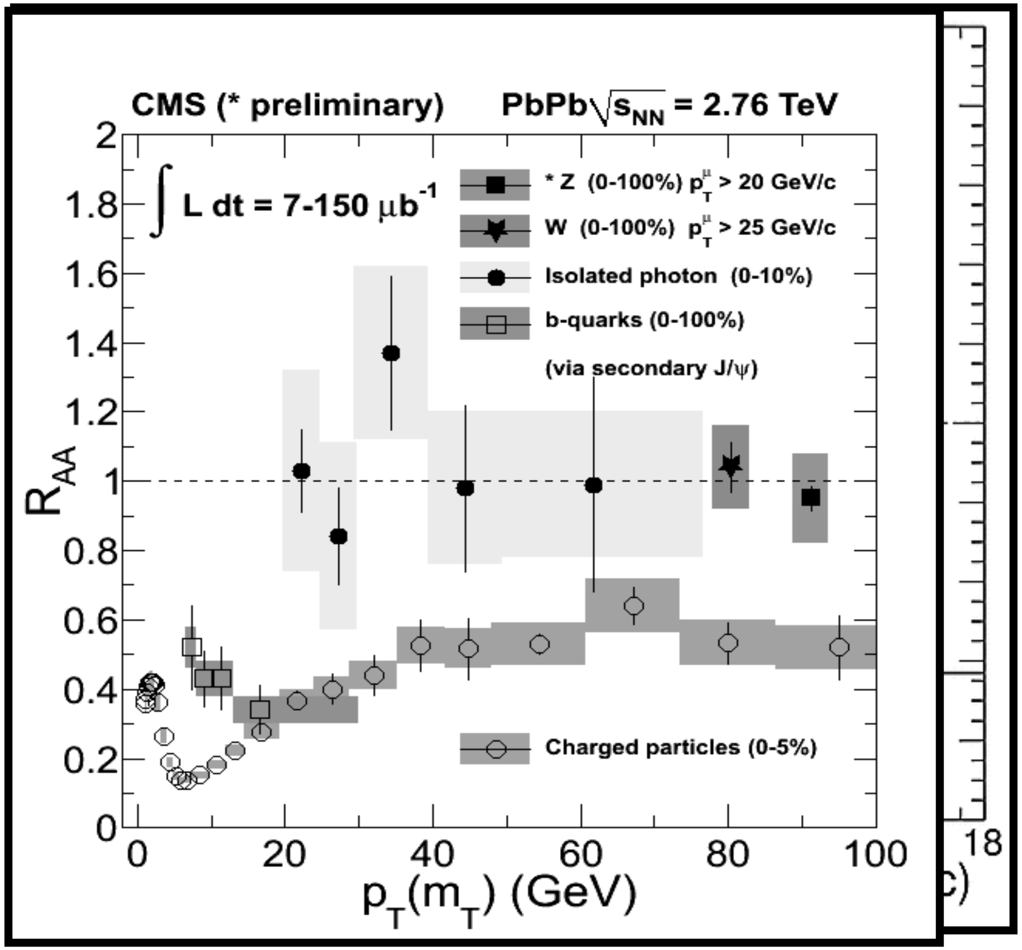
- In Pb-Pb collisions: Charmed hadrons are suppressed by factor ~3-4 when compared to simple binary collision scaling from pp

Charm: Nuclear Modification



- In Pb-Pb collisions: Suppresion by factor ~5 when compared to simple binary scaling from pp
- Covers 1 – 36 GeV/c
- pp reference measured only up to 24 GeV/c + extrapolation

Comparison to other hadrons



- Mass ordering in RAA?
  J/ψ ← B (upper)
  D (middle)
  π (lower)

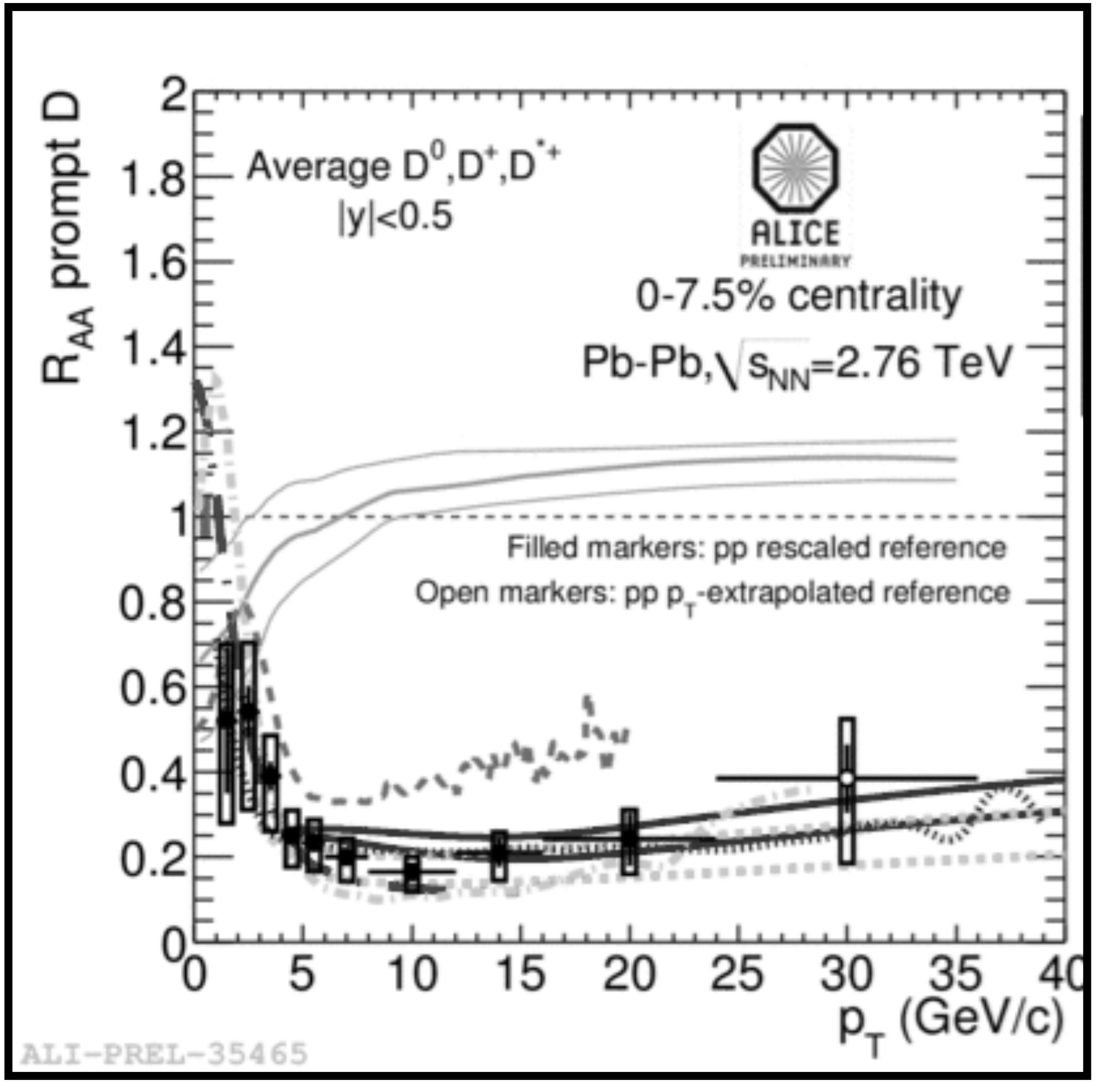
- γ,W,Z-bosons:
  $R_{AA} \approx 1$ (!)
  checks normalization, does not probe the medium

ALICE, arXiv:1203.2160 [nucl-ex],
CMS Z-boson: Phys. Rev. Lett. 106 (2011)212301.

Vector bosons: some remarks

- γ : no color charge → does not interact with the QGP medium
- $W^{\pm}$ and Z: decay before QGP is formed, into lepton pairs (ee, $\mu\mu$, $\tau\tau$);
  → decay daughters do not interact with the medium
- R_{AA} expected to be unity – and observed !

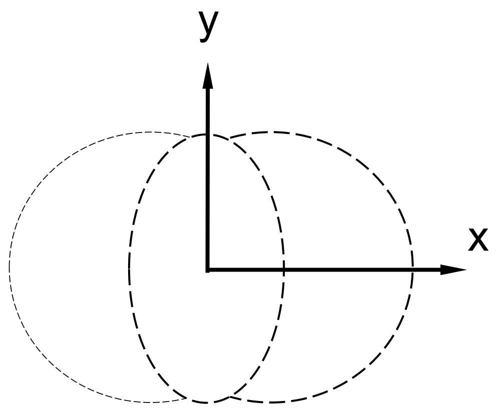
Model calculations

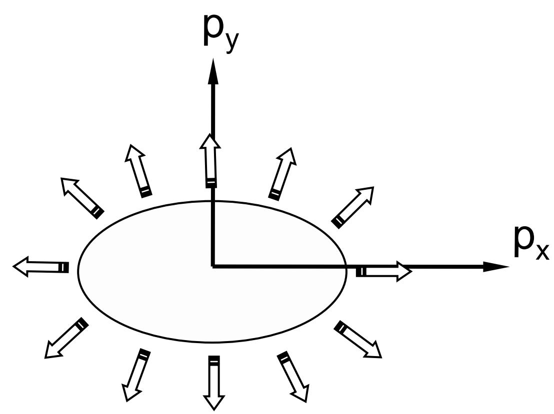


- Rising R_{AA} solely due to spectrum in pp
- Still have to learn from theory about medium properties, i.e. qhat, ehat
- Not an initial state effect
- To be checked with p+Pb collisions (2013)

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇔ momentum-space-anisotropy

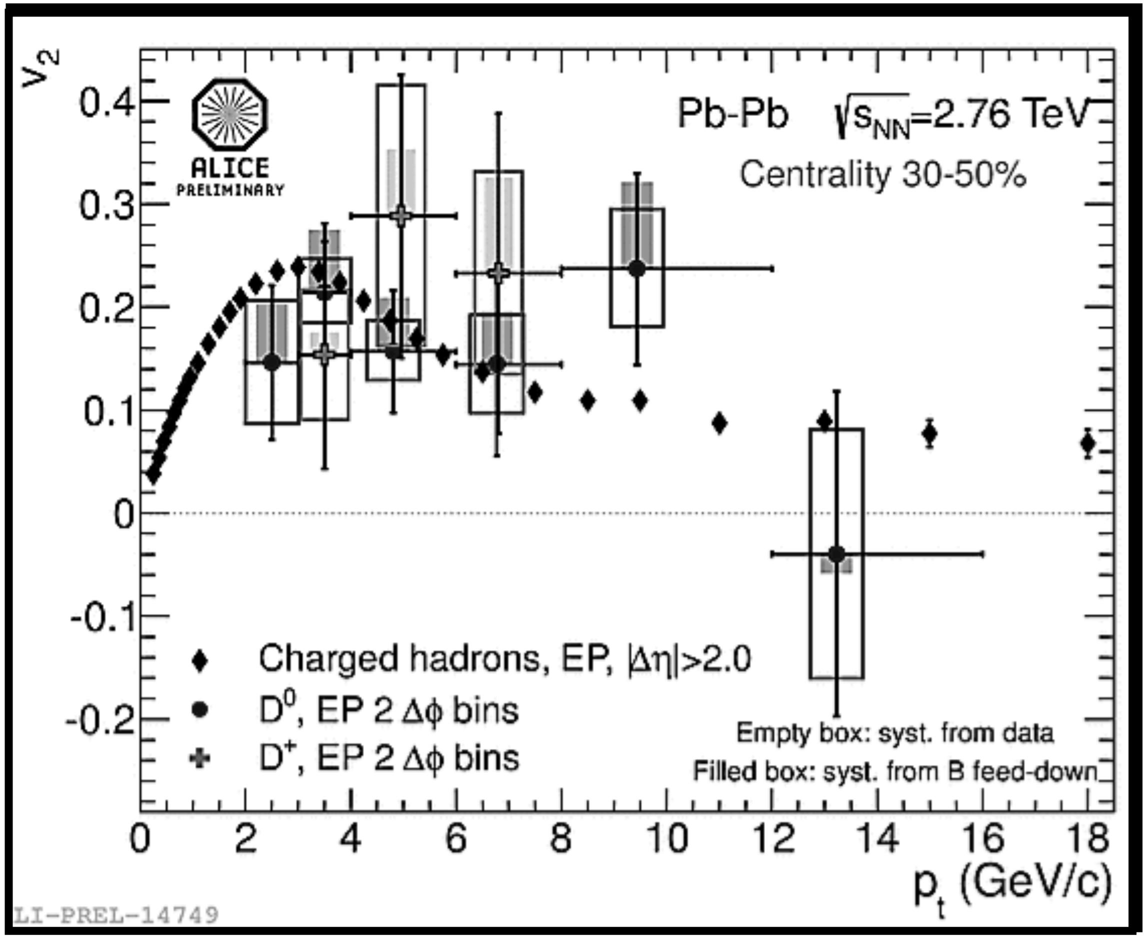




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \ \ \varphi = \tan^{-1}(\frac{p_y}{p_x})$$

Initial/final conditions, EoS, degrees of freedom

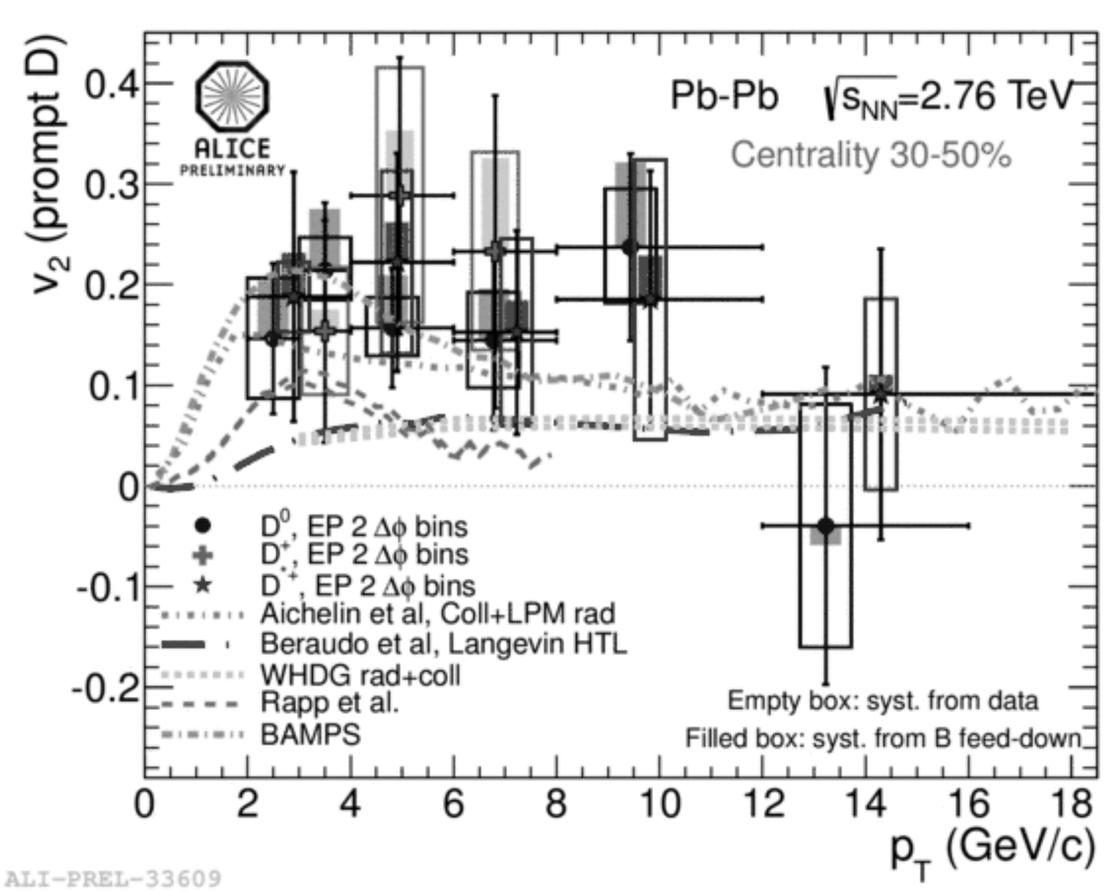
2^{nd} Fourier Coefficient – v_2



D-meson v2 analysis:
R. Grajcarek, PhD thesis,
Univ. Heidelberg (2013).

- Substantial v_2 of charm, comparable to charged hadrons

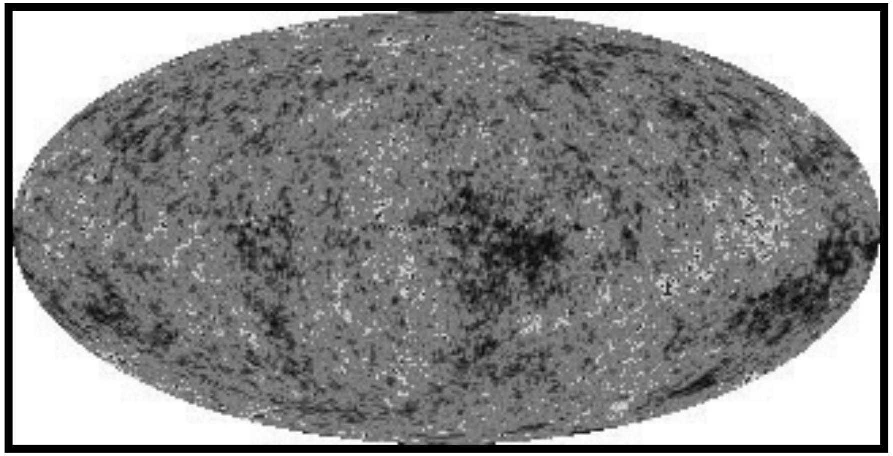
v_2 - Model calculations

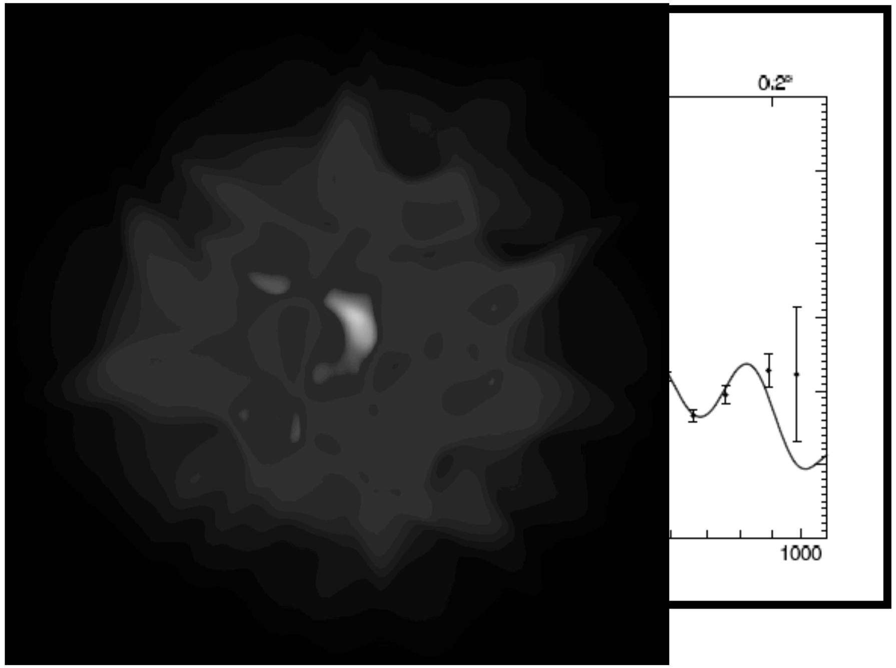


- Models needs to simultaneously describe v_2 and R_{AA}
- Stringent constraint, gets tougher with more precision/data

Next steps

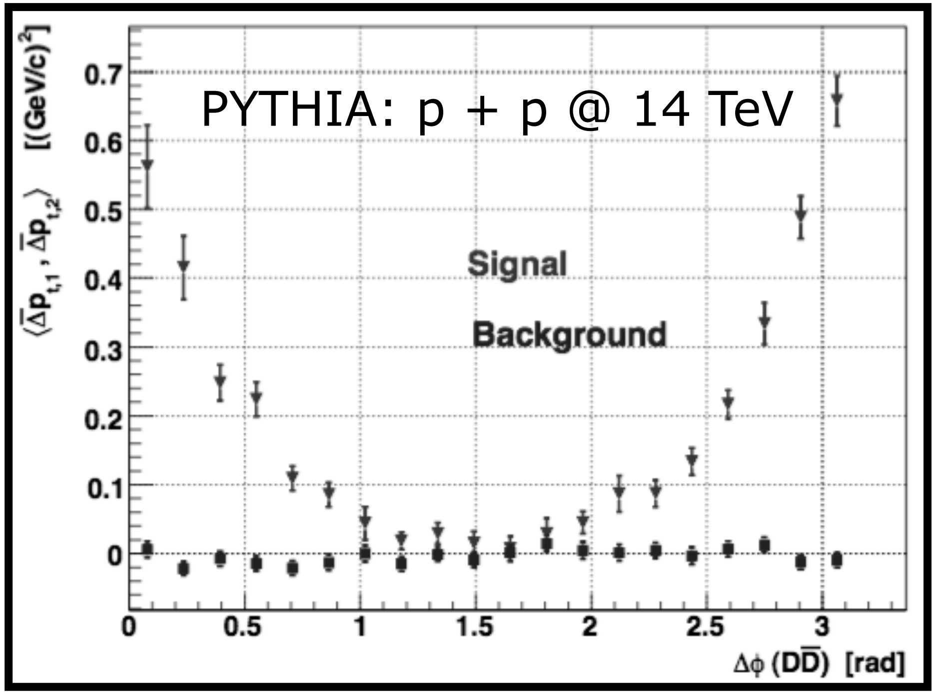
- Extract power spectrum of v_n, like WMAP*
- Compare pp high multiplicity vs Pb+Pb
- Mach cone vs medium response for heavy-quarks (well defined probes)
- η/s

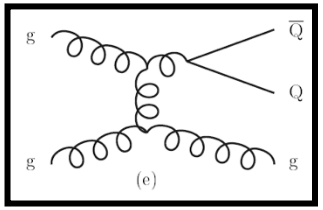


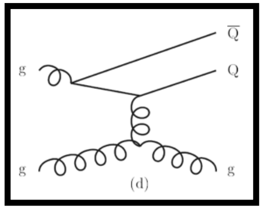


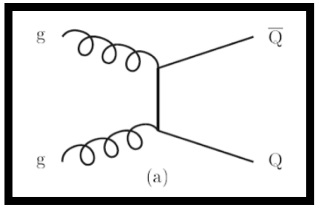
*WMAP data: The NASA/WMAP Science team; http://map.gsfc.nasa.gov/media/080997/index.html.
QGP plot: B. Schenke, S. Jeon, and C. Gale, arXiV:1109.6289.

Heavy – quark Correlations





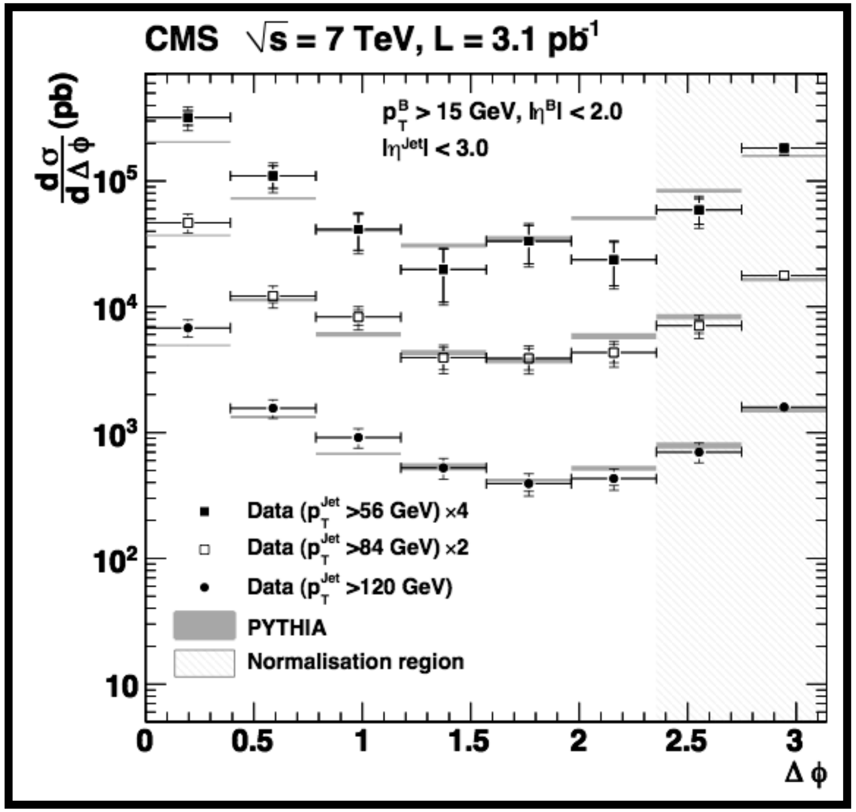




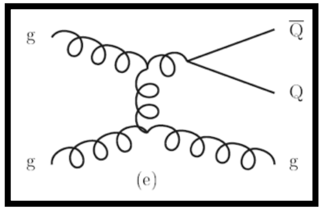
- Charm and anti-charm quarks created in pairs and thus correlated
- Look for modifications in Pb+Pb collisions
- Study transport properties / thermalization

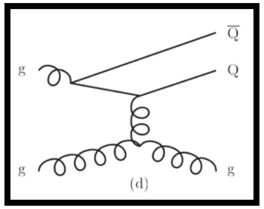
X. Zhu, M. Bleicher, S.L. Huang, K.S., H. Stöcker, N. Xu, and P. Zhuang, PLB 647 (2007) 366.
G. Tsildeakis, H. Appelshäuser, K.S., J. Stachel, NPA 858 (2011) 86; arXiv: 0908.0427 [nucl-ex].

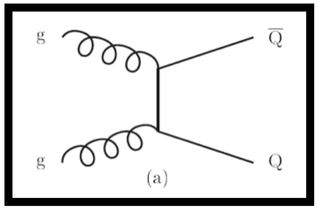
Heavy – quark Correlations*



- CMS trigger: inspected 200 x 10^9 p+p collisions
- B–Bbar, establish correlations exist in p+p !
- Look out for modifications in Pb+Pb

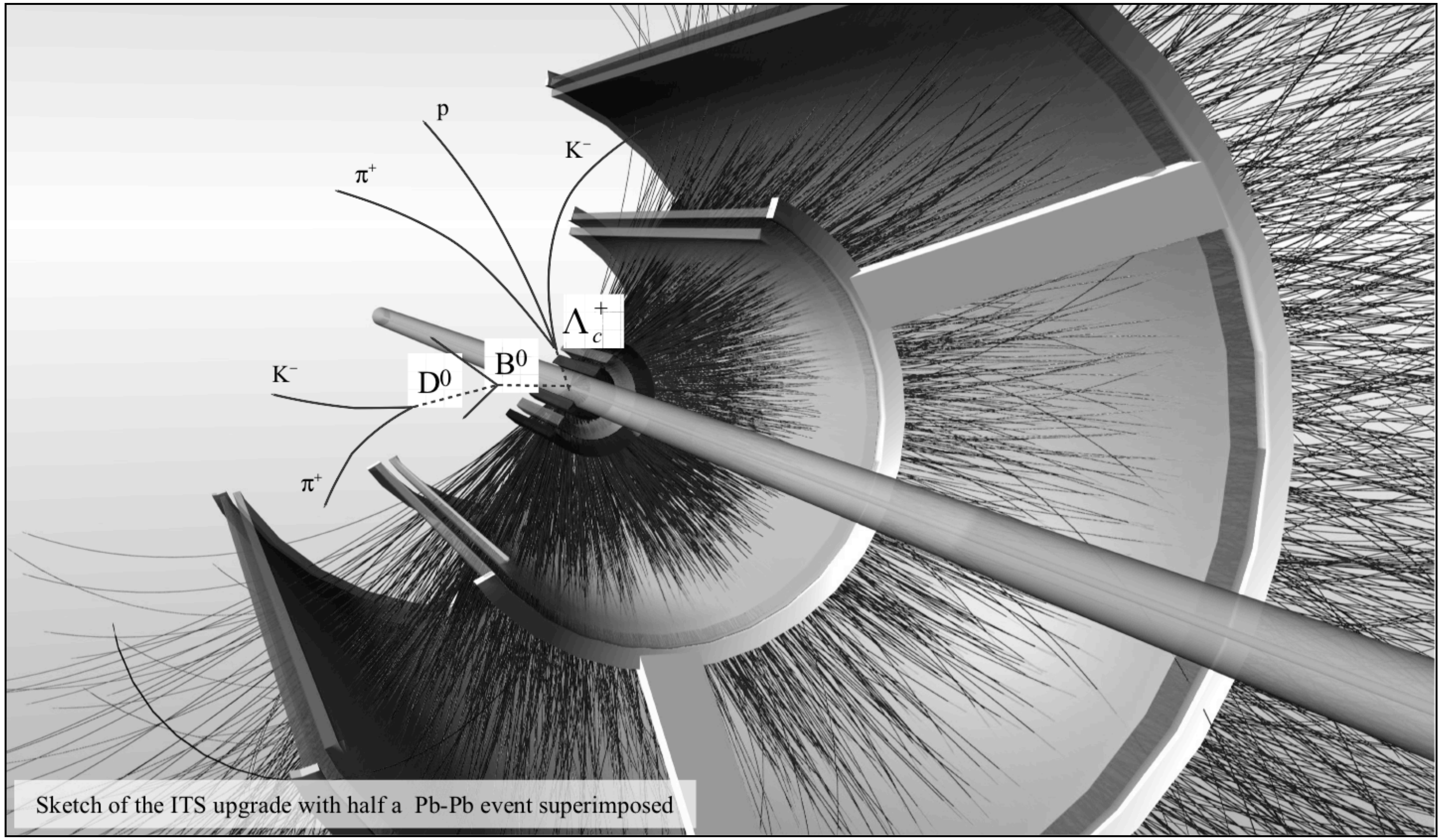






*CMS collaboration:JHEP 1102 (2011) 136; arXiv:1192.3194v2 [hep-ex].

Upgrading the Inner Detector



- upgrade Concept recently approved by the ALICE Collaboration
- targeted for 2017-2018 LHC shutdown
- Conceptual Design Report CERN-LHCC-2012-005

Lesson learnt

- 99% of all visible mass comes from breaking of chiral symmetry in strong interactions
- Heavy quarks (charm and bottom) are unique probes of a QGP
- LHC is the ultimate machine for characterizing QGP by hard probes (heavy quarks, jets, …)
- Parton energy loss gives in QGP gives access to QGP transport coefficients (qhat, ehat)
- Observable is nuclear modification factor R_{AA}
- Control measurement: Vector boson (γ,W,Z) R_{AA}= 1

ALICE - Jetzt geht's los !