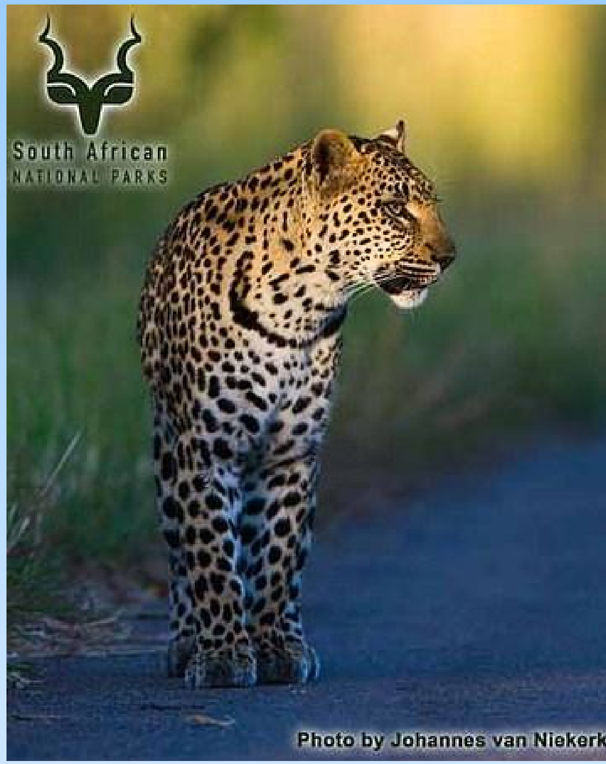
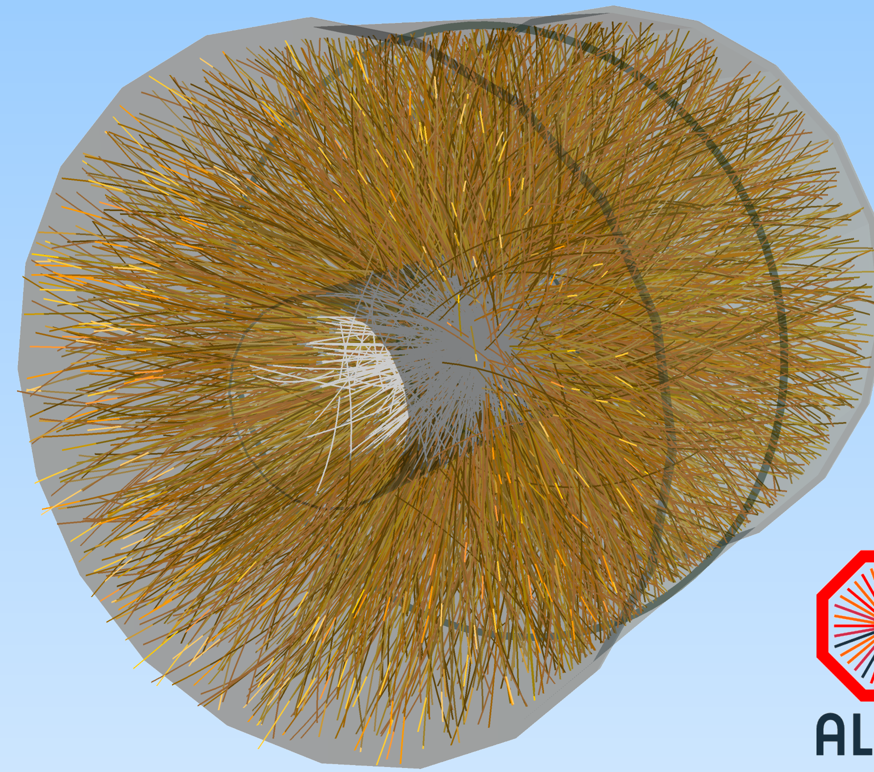




ALICE

Heavy-flavor physics with ALICE at the LHC

Silvia Masciocchi, GSI and EMMI
for the ALICE Collaboration

Kruger Park, December 1-6, 2014

EMMI

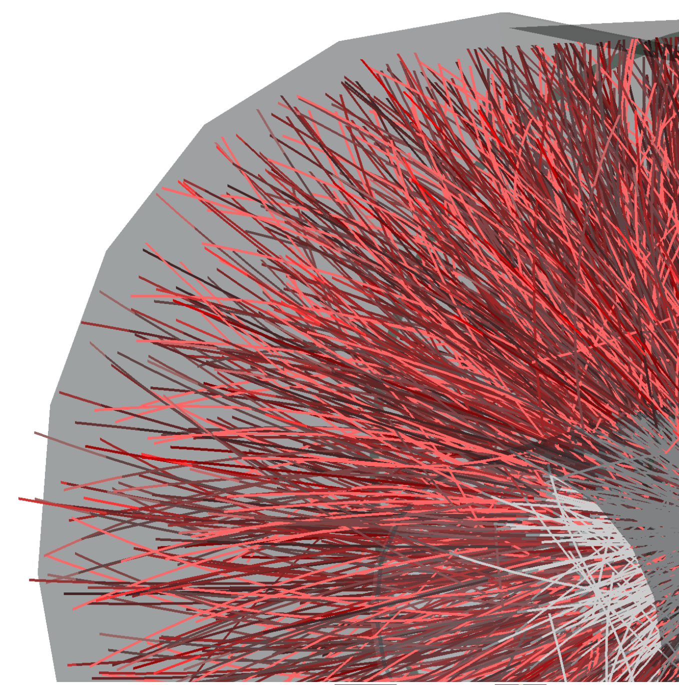
GSI

Outline

- Heavy-flavor physics
- ALICE at the LHC
- Selection of Run1 results
  - pp: charm and beauty production cross sections
  - p-Pb: cold nuclear matter effects
  - Pb-Pb: heavy-flavor energy loss and thermalization
- Conclusions and outlook

UCT+iThemba: Single muon analyses
KJ Senosi
"W production in p-Pb"

Talk on Thursday



Heavy-flavor physics

Charm: m ~ 1.5 GeV/c^2

Beauty: m ~ 5 GeV/c^2

Heavy quarks: hard probes even at low momentum

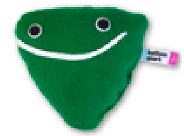
Study:

- Heavy-quark production in hadronic collisions
- Heavy quarks as probes of the quark-gluon plasma
- Heavy-quark fragmentation

Pictures from http://www.particlezoo.net/

Heavy-flavor production: pp

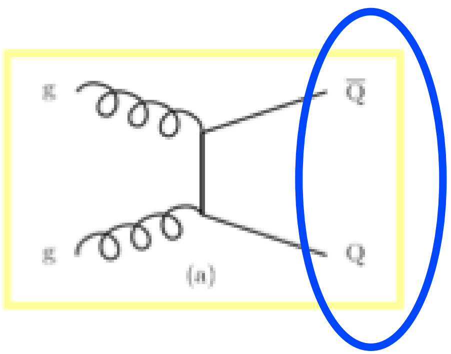
Charm: m ~ 1.5 GeV/c^2



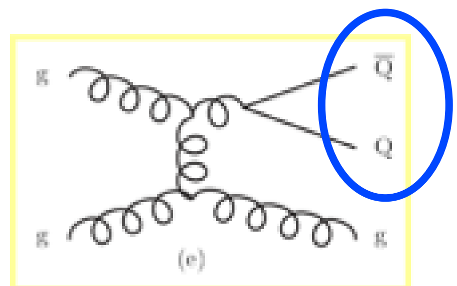
Beauty: m ~ 5 GeV/c^2

Large mass → **perturbative QCD approaches used!**

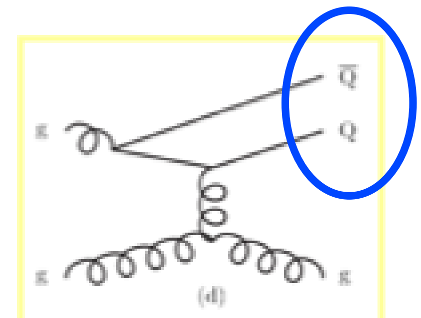
Dominant production diagrams: gluon-gluon fusion, hard scattering



Pair production
(LO)



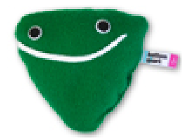
Gluon splitting
(NLO)



Flavor excitation
(NLO)

Heavy-flavor production: pp

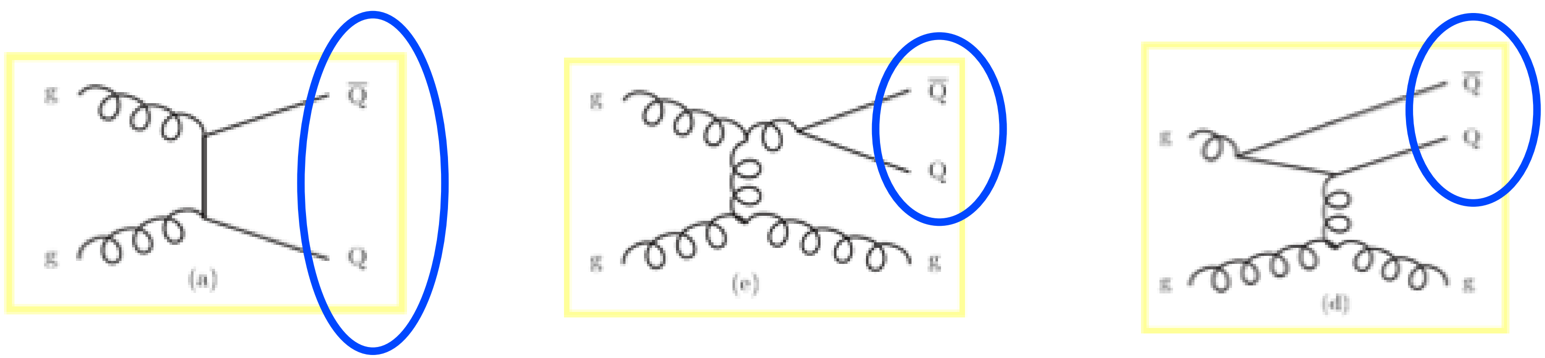
Charm: m ~ 1.5 GeV/c^2



Beauty: m ~ 5 GeV/c^2

Large mass → **perturbative QCD approaches used!**

Dominant production diagrams: gluon-gluon fusion, hard scattering



Pair production (LO) | Gluon splitting (NLO) | Flavor excitation (NLO)

Different angular correlation of Q and $\overline{Q}$

→ use correlations to determine relative contribution of different production mechanisms

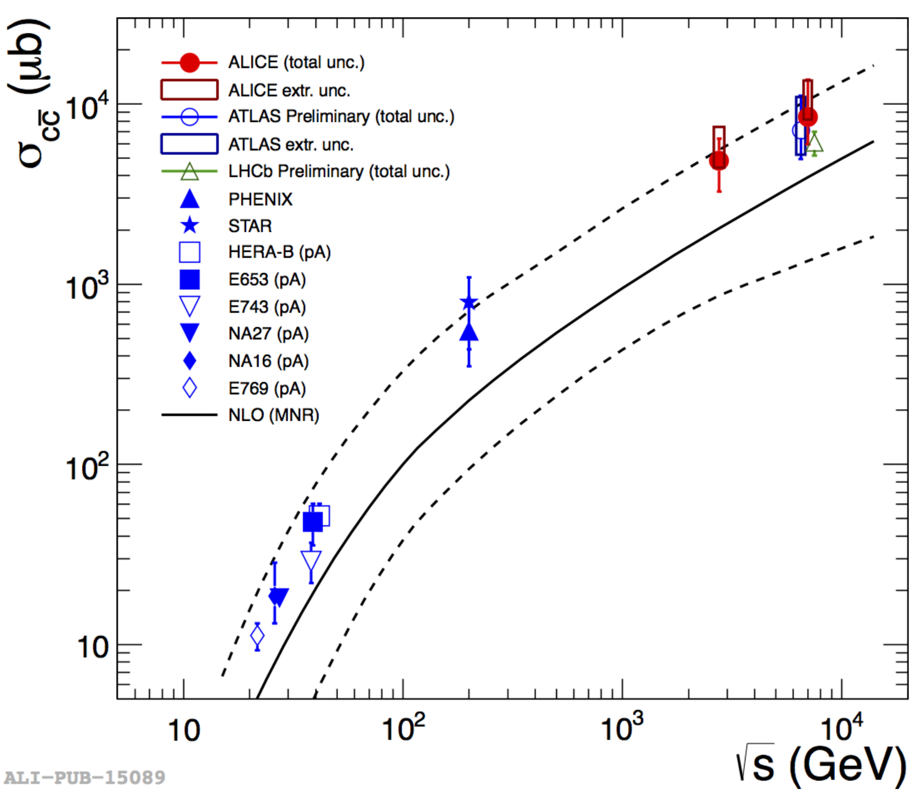
Total(*) cross section in pp: 2.76 and 7 TeV

ALICE

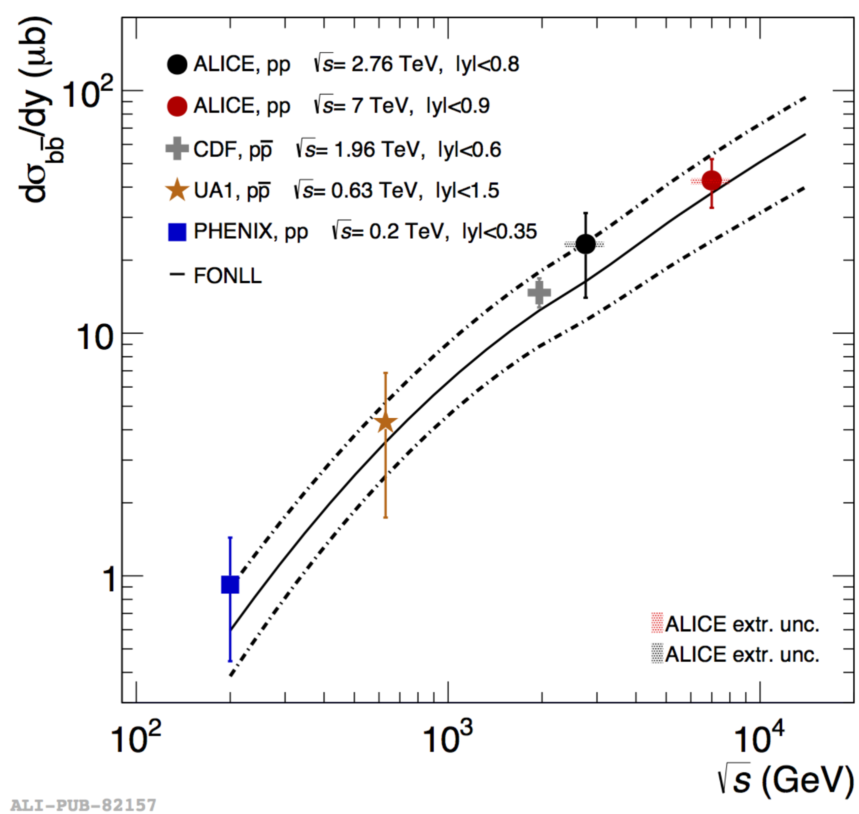
LHC energies: large production cross sections!

Charm

JHEP 1207 (2012) 191



Beauty



arXiv:1405.4144

Abundant hard probe at the LHC!

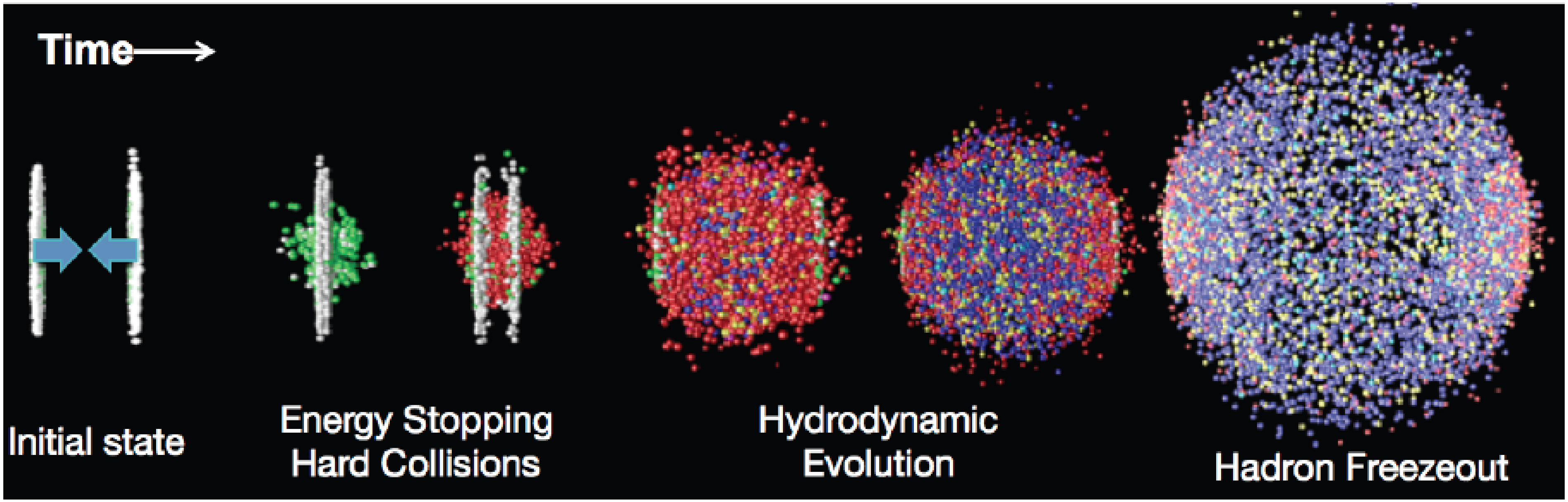
(*) integrated over y and p_T

pQCD: large theoretical uncertainties

Relativistic heavy-ion collisions

LHC in 2010 and 2011: Pb–Pb collisions $\sqrt{s_{NN}}$ = 2.76 TeV

Creation of deconfined, strongly interacting matter:
the quark-gluon plasma



Thermalization
equilibrium is established
(t < 1 fm/*c*)

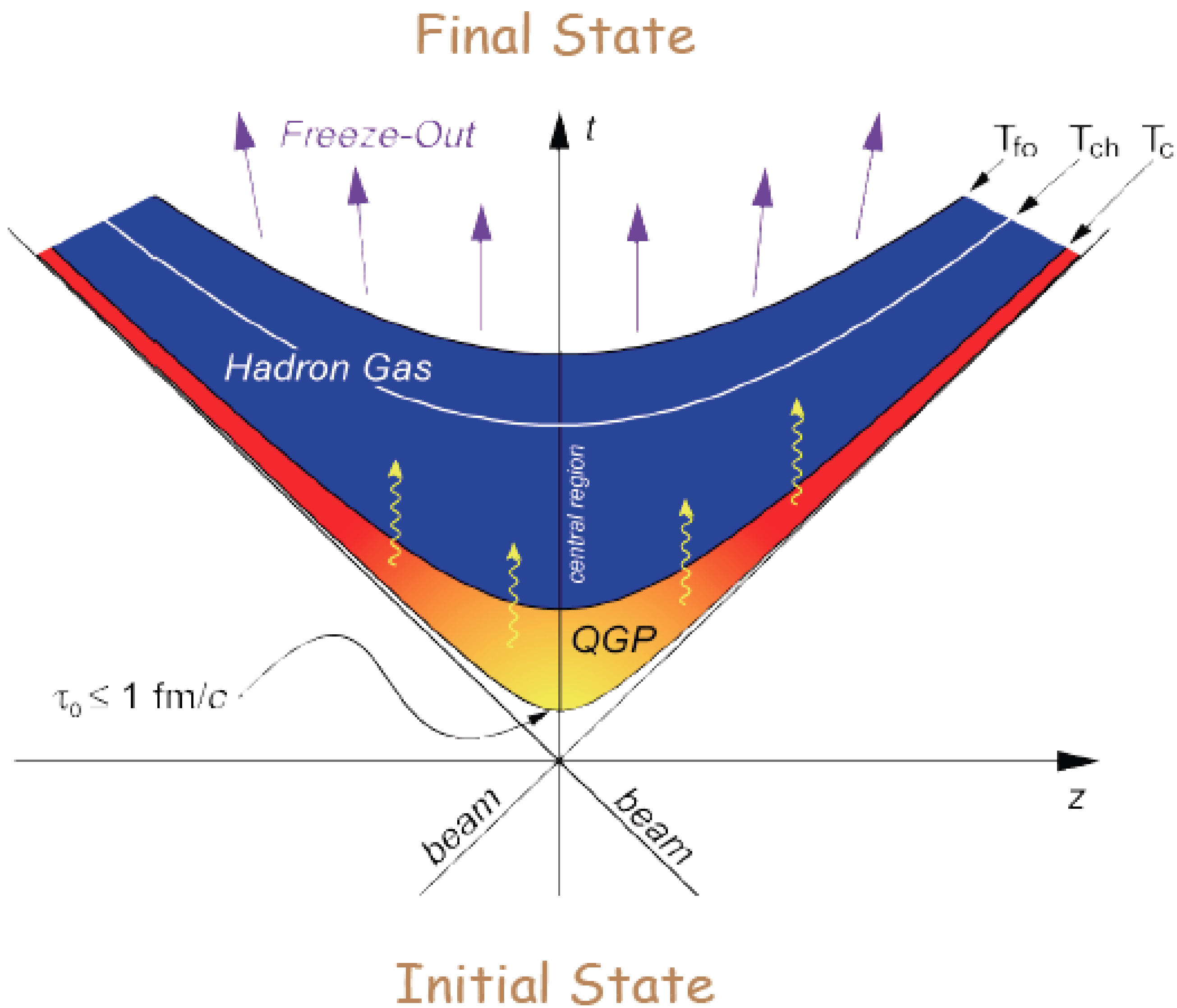
Expansion and cooling:
(t < 10-15 fm/*c*)

Chemical freeze-out
(particle yields)
Kinetic freeze-out
(particle spectra)

Time scales at the LHC

TIME

- QGP lifetime
  10 fm/c
  ≈ $3 \cdot 10^{-23}$ s
- Thermalization time
  0.02 fm/c
  ≈ $7 \cdot 10^{-25}$ s
- Formation time:
  e.g. charm:
  $1/(2m_c) \approx 0.08$ fm/c
  ≈ $3 \cdot 10^{-25}$ s
- Collision time:
  $2R/\gamma \approx 0.005$ fm/c
  ≈ $2 \cdot 10^{-26}$ s

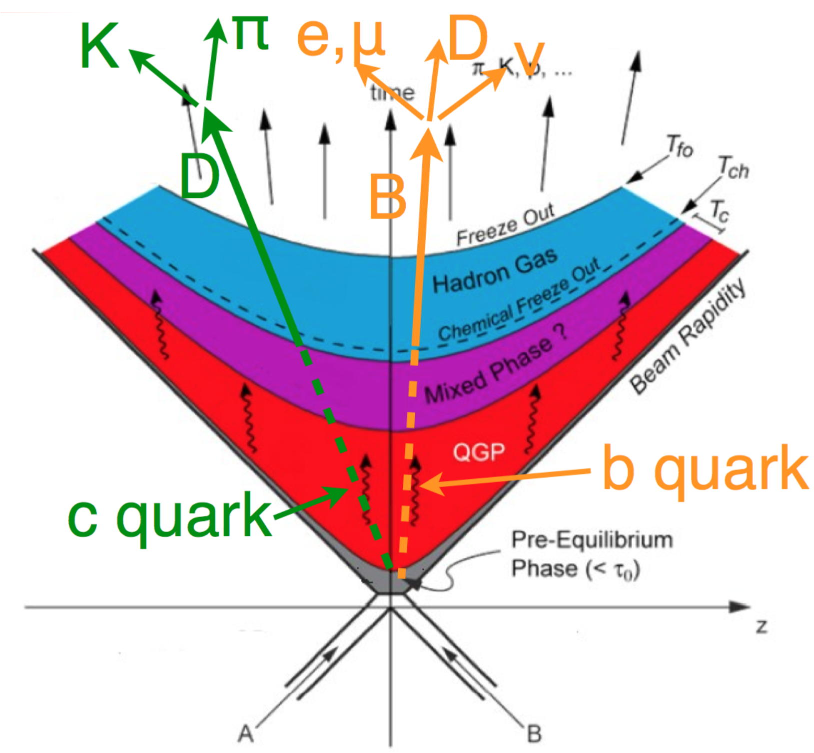


Heavy flavors, probes of the QGP

- Heavy quarks produced in initial hard scattering processes
- Time scale: charm and beauty are produced before the thermalized QPG phase
- Flavor is conserved by the strong interaction

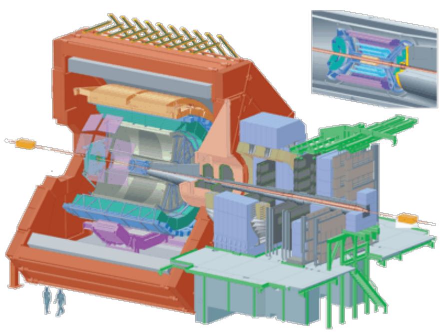
Heavy flavors experience the full evolution of the deconfined medium

→ QGP transport coefficients

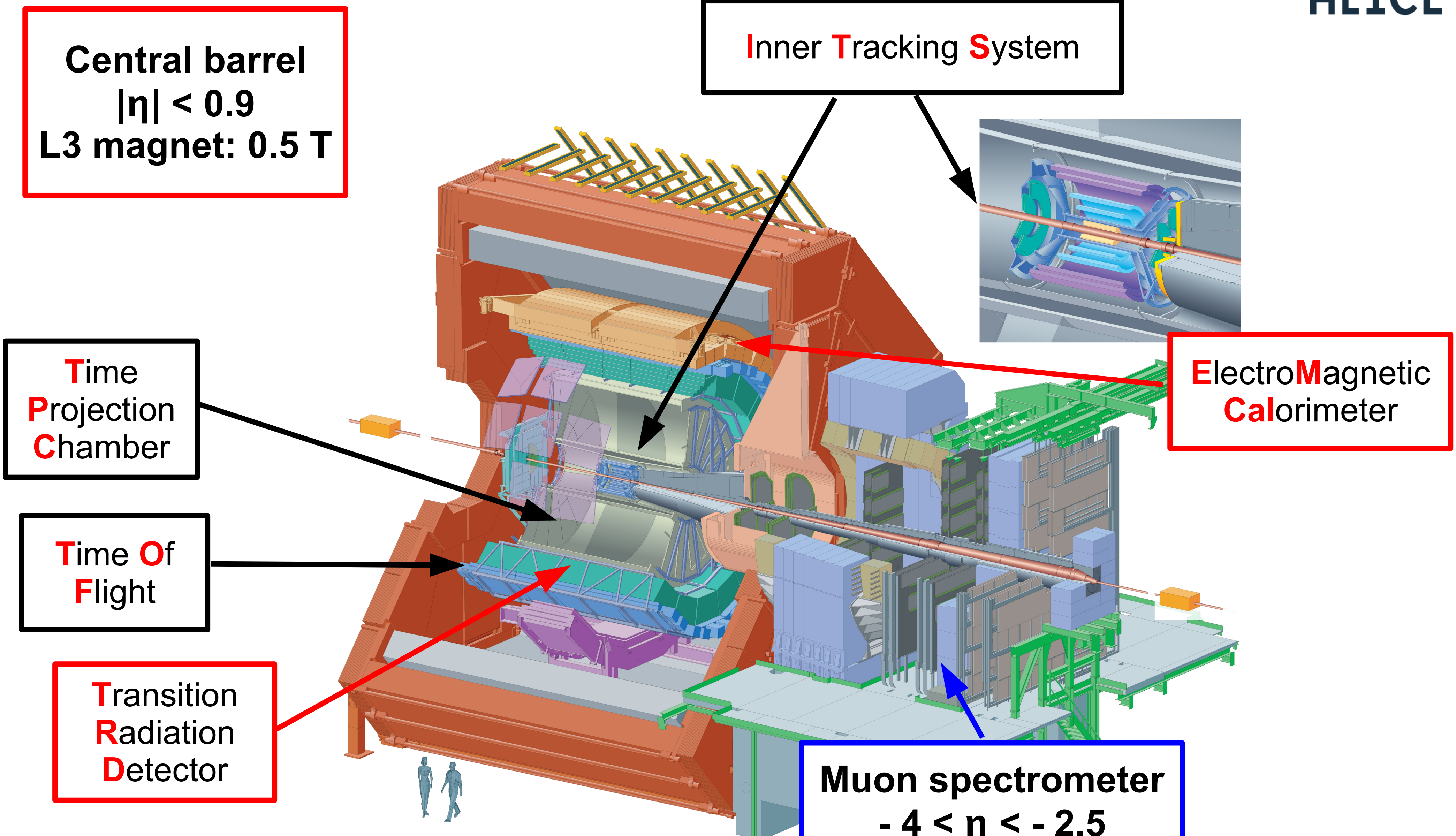


ALICE at the LHC

A Large Ion Collider Experiment



The ALICE spectrometer

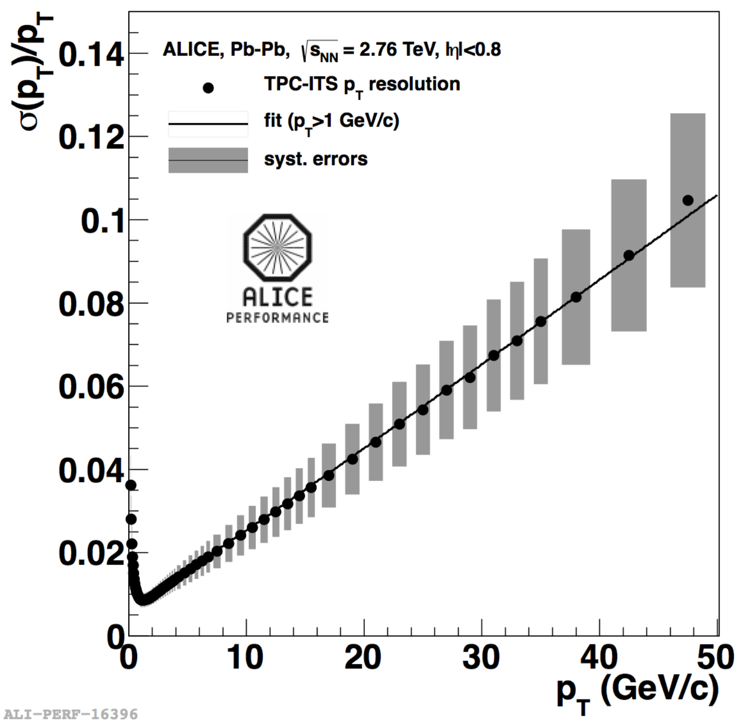


High resolution for heavy flavors

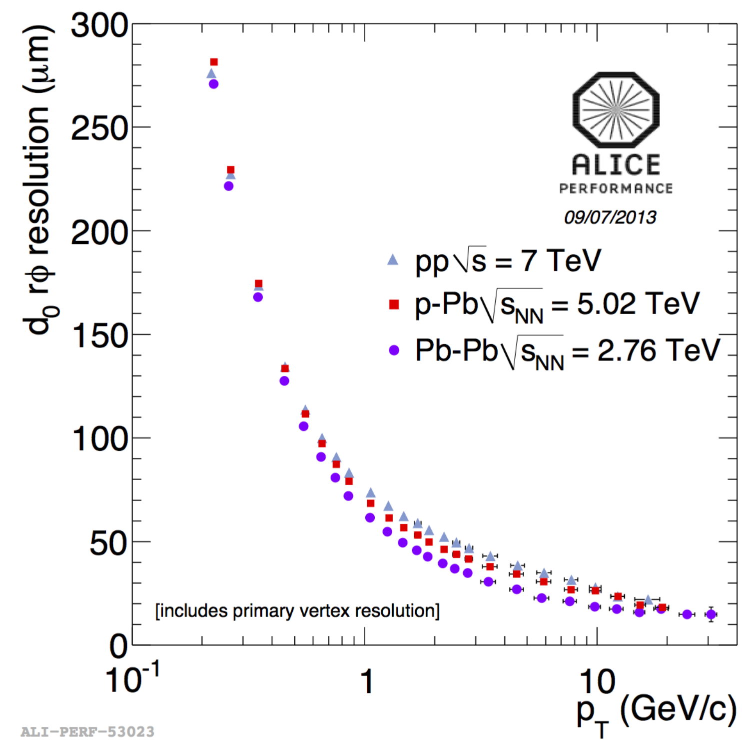
Good momentum resolution over a wide range: 0.1 – 50 GeV/*c*

cτ ≈ few 100 μm
High resolution tracking

Low B=0.5T → low p_T coverage!

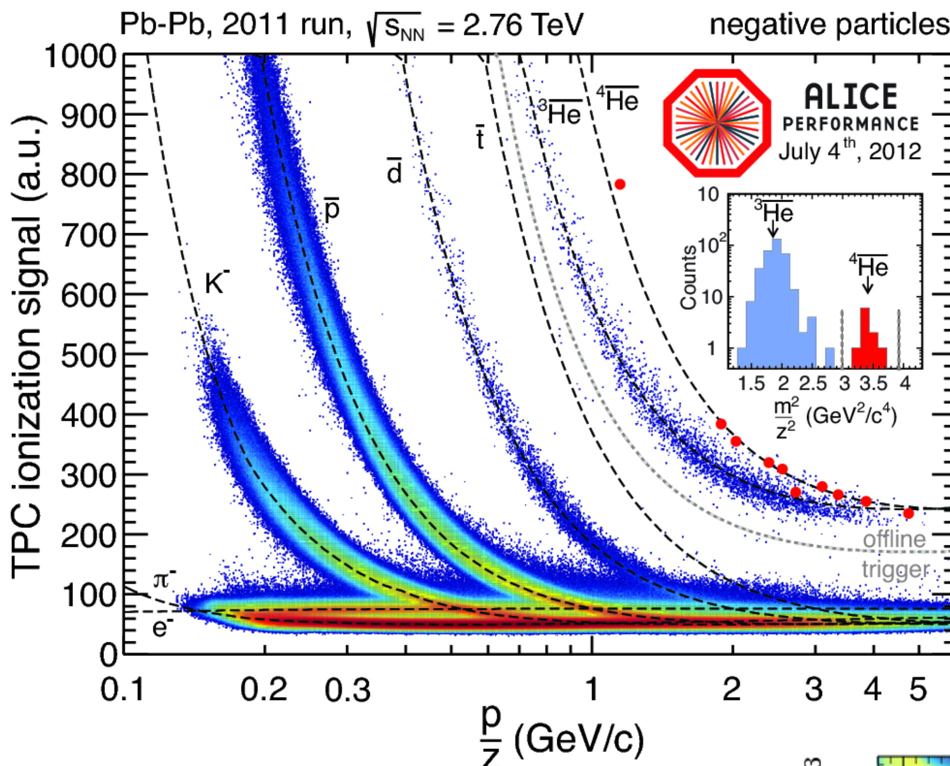


Resolution on impact parameter to primary ≈ 60-70 μm at p_T = 1 GeV/*c*

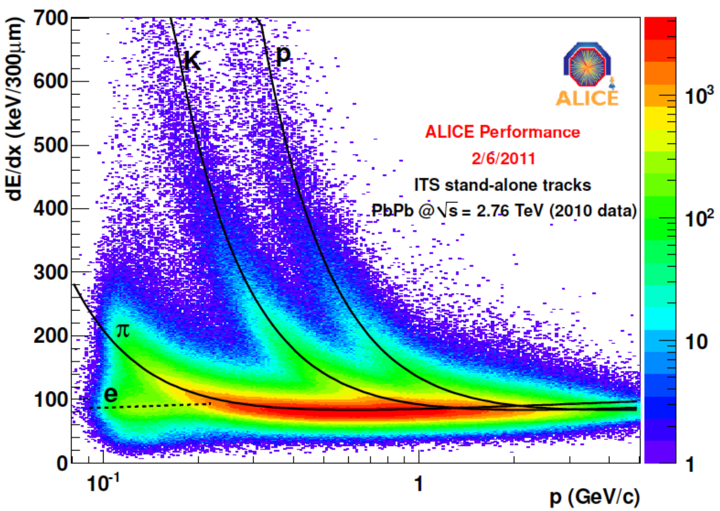


Particle identification

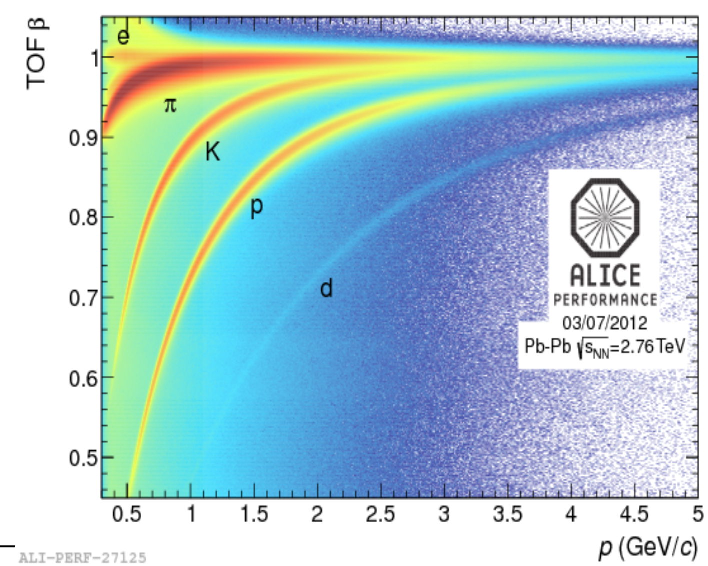
Time Projection Chamber



Inner Tracking System

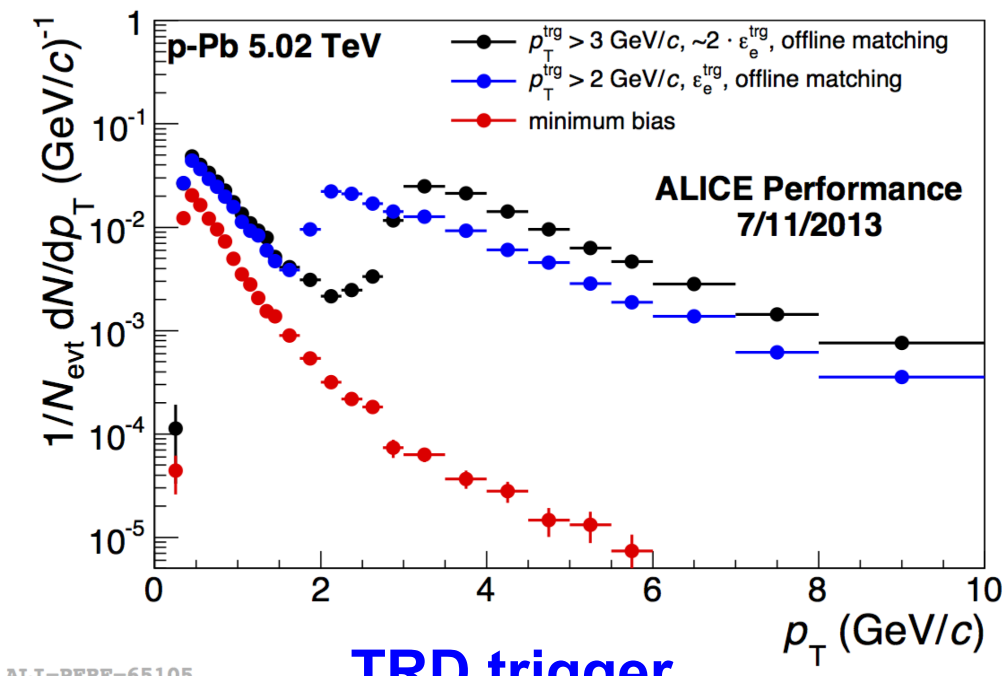


Time of Flight



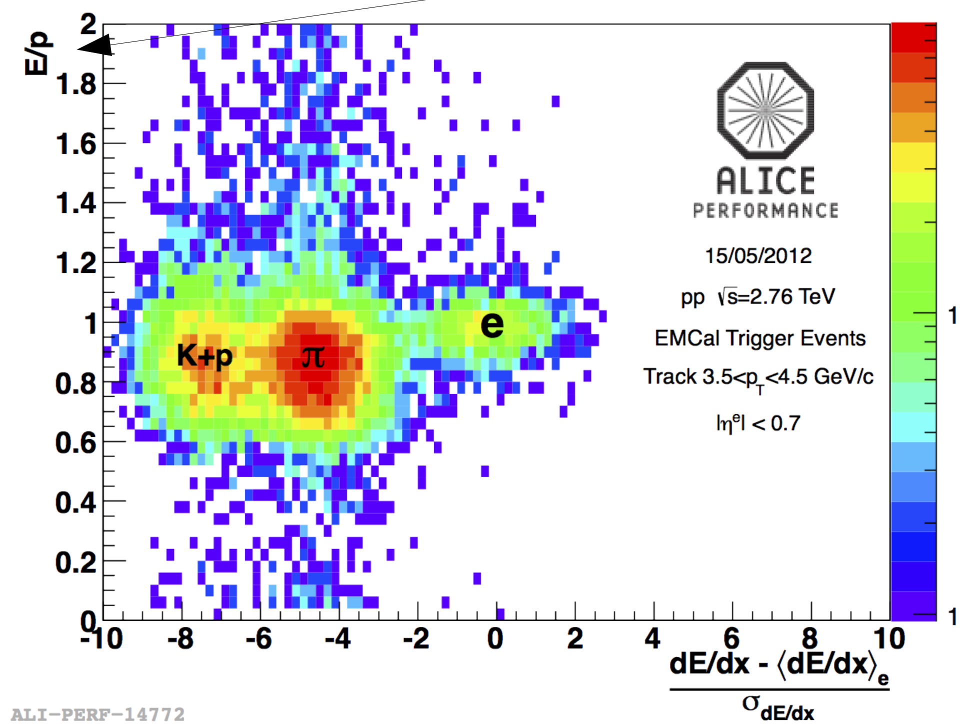
Heavy flavors and triggers

- Low-p_T heavy-flavor production ← minimum bias events
- High-p_T region accessed
  - with very high statistics (D meson analysis)
  - with electron (TRD, EMCal) and muon triggers

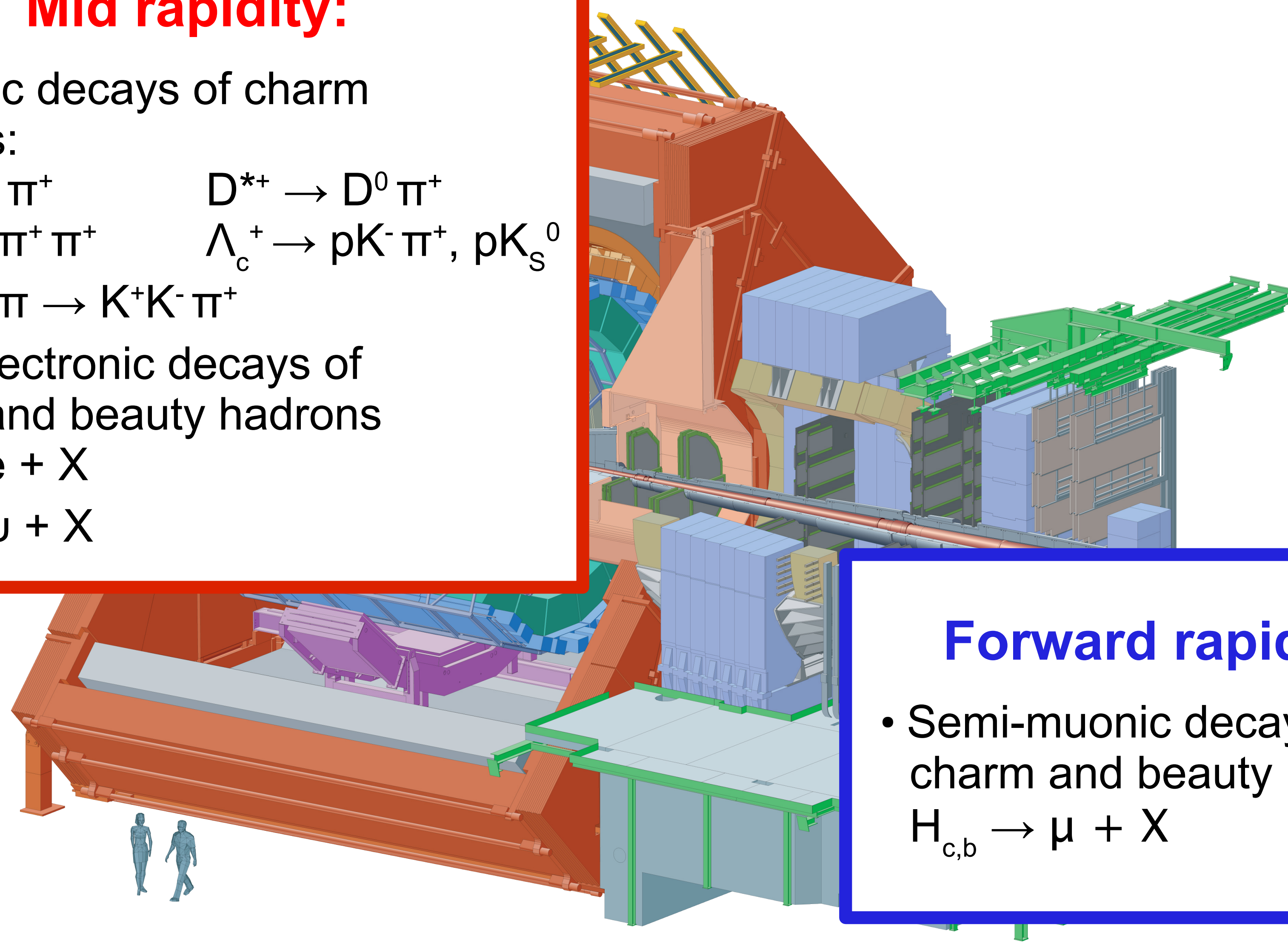


TRD trigger

EMCal E/p



The ALICE heavy-flavor program



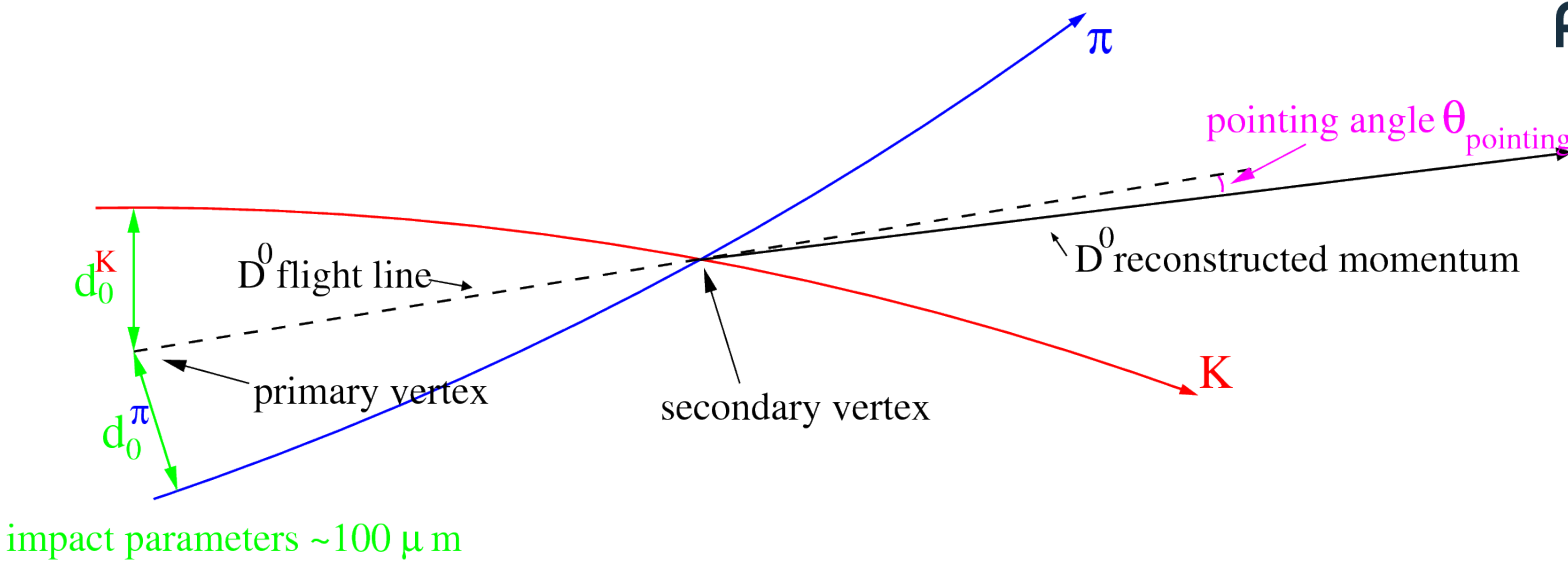
Mid rapidity:

- Hadronic decays of charm hadrons:
  $D^0 \rightarrow K^- \pi^+$ $\quad$ $D^{*+} \rightarrow D^0 \pi^+$
  $D^+ \rightarrow K^- \pi^+ \pi^+$ $\quad$ $\Lambda_c^+ \rightarrow pK^- \pi^+, pK_S^0$
  $D_s^+ \rightarrow \varphi\pi \rightarrow K^+ K^- \pi^+$
- Semi-electronic decays of charm and beauty hadrons
  $H_{c,b} \rightarrow e + X$
- $B \rightarrow J/\psi + X$

Forward rapidity:

- Semi-muonic decays of charm and beauty hadrons
  $H_{c,b} \rightarrow \mu + X$

D-meson reconstruction

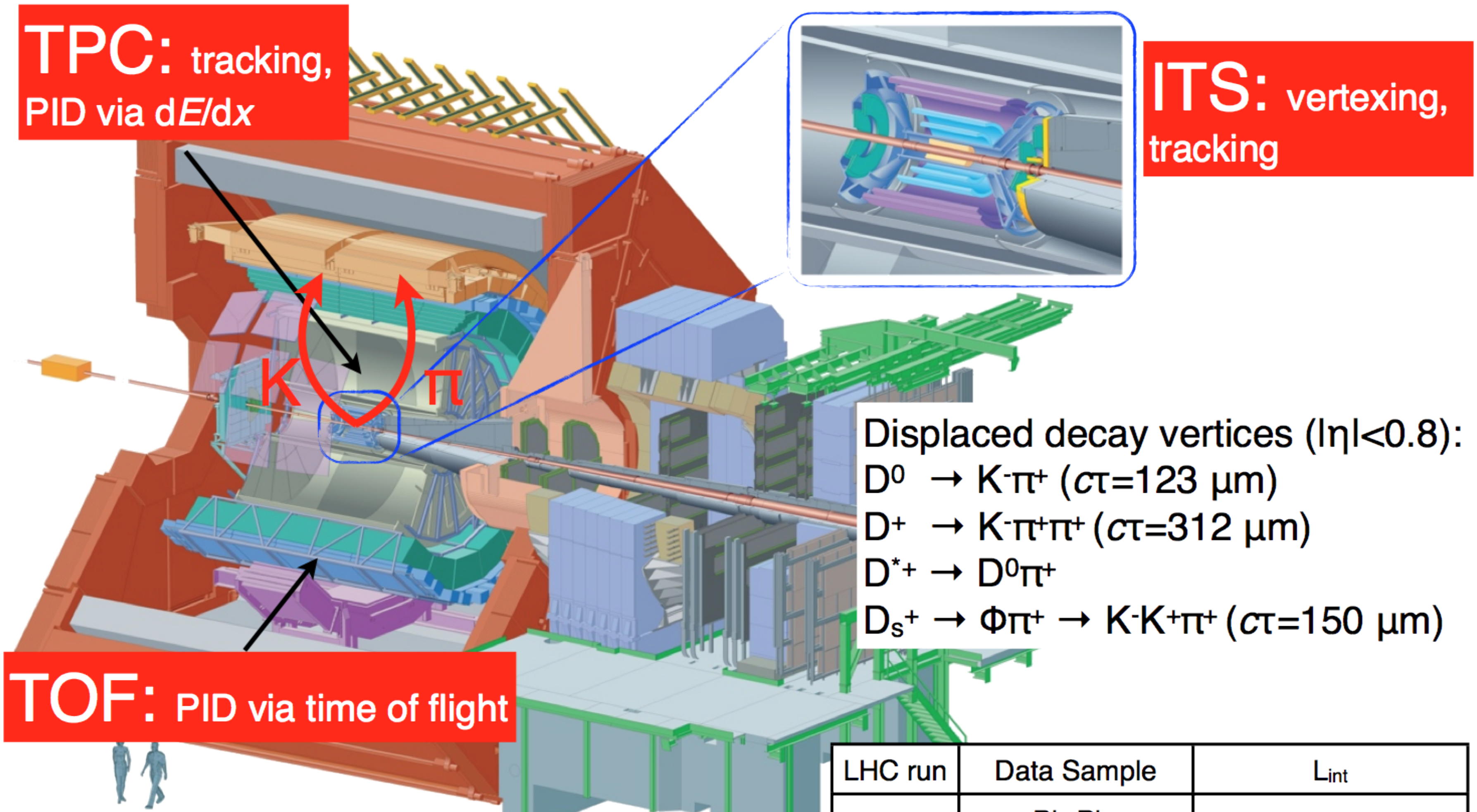


- Reconstruction of secondary vertices
- Particle identification
- Invariant mass analysis

- Minimum bias data
- Mid-rapidity

Talk by Massimo Masera
on Wednesday afternoon!!

D-meson reconstruction



Displaced decay vertices (|η|<0.8):

$D^0 \rightarrow K^-\pi^+$ ($c\tau$=123 μm)

$D^+ \rightarrow K^-\pi^+\pi^+$ ($c\tau$=312 μm)

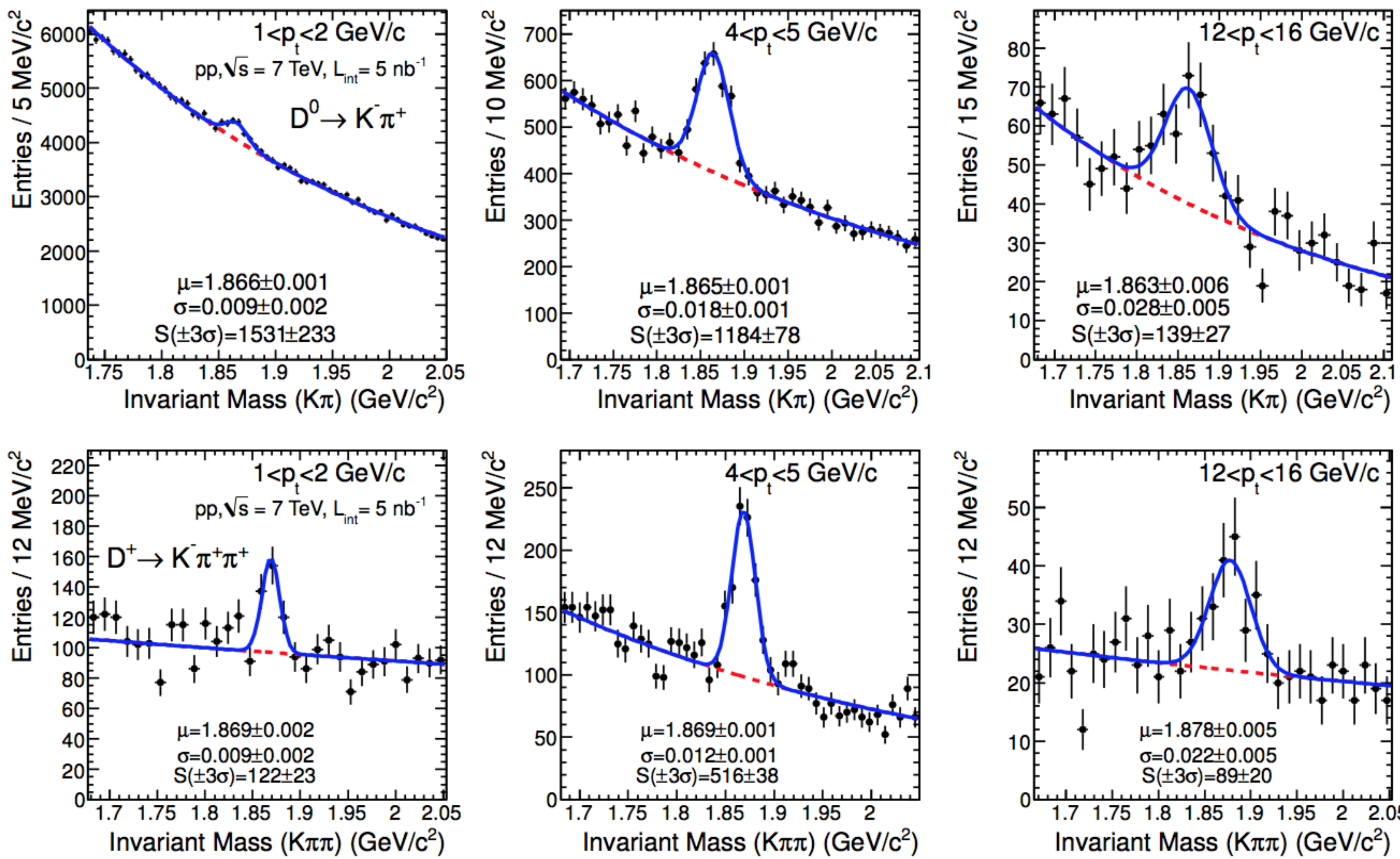
$D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \Phi\pi^+ \rightarrow K^-K^+\pi^+$ ($c\tau$=150 μm)

LHC run	Data Sample	L_{int}
2010	Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV	2.12 μb^{-1} (0-80%)
2011	Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV	23 μb^{-1} in 0-10% 6.2 μb^{-1} in 10-50%

D mesons: invariant mass analysis

JHEP01(2012)128

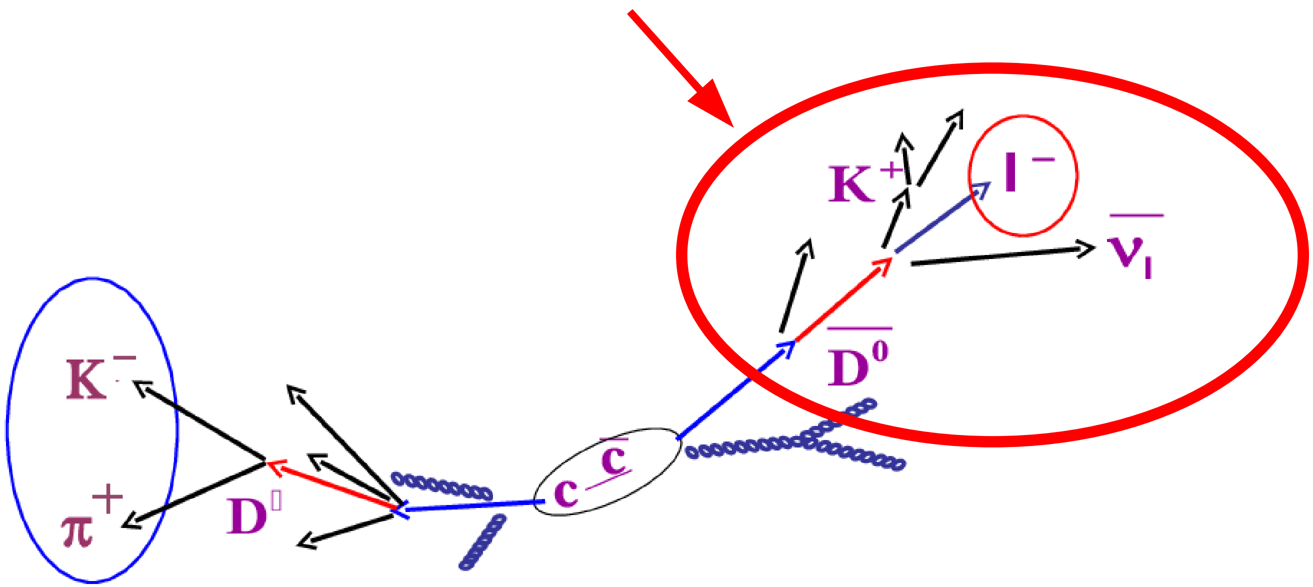


Key issue: extend low-p_T reach

very challenging S/B conditions

Semileptonic decays

Measure the $c\bar{c}$ and $b\bar{b}$ production cross sections through **semi-leptonic decays** of open charm and open beauty hadrons:



Branching Ratios:

$c \rightarrow e + X$ $\mathcal{O}(9.6\%)$

$b \rightarrow e + X$ $\mathcal{O}(11\%)$

$b \rightarrow c \rightarrow e + X$ $\mathcal{O}(10\%)$

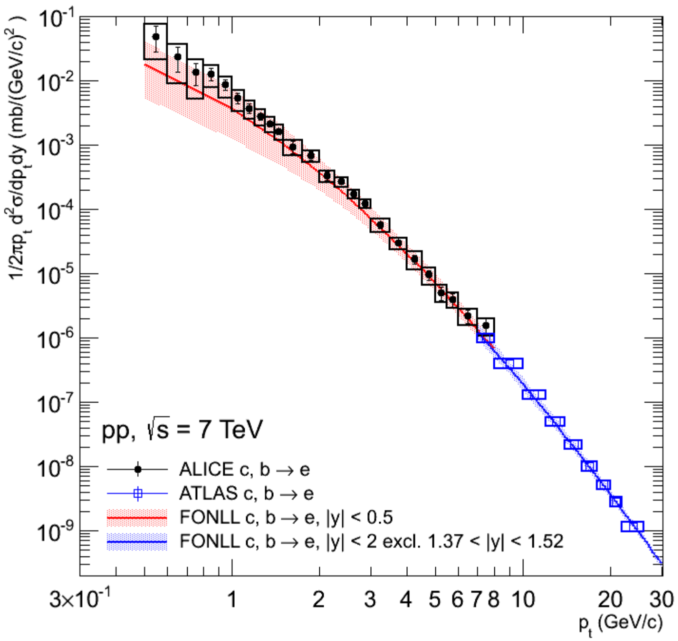
In ALICE:
Electrons at mid rapidity
Muons at forward rapidity

Semileptonic decays

Electrons at mid rapidity

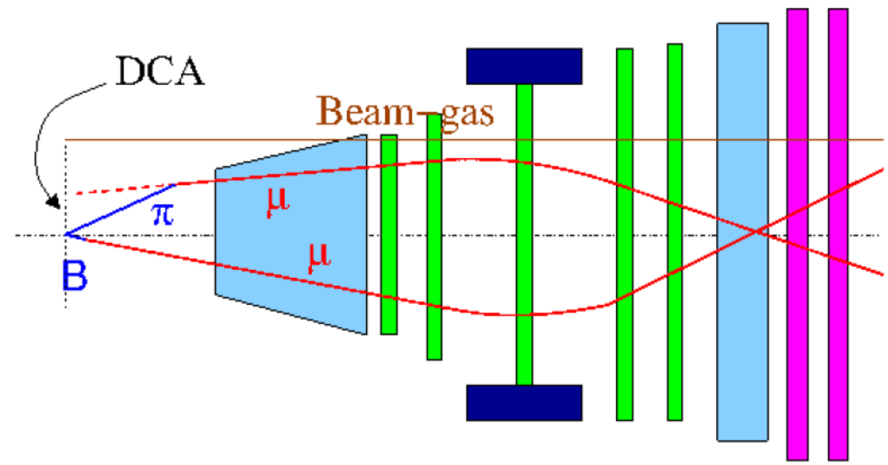
Large background subtracted by

- Cocktail method or
- Photonic background reconstruction



ALICE: Phys.Rev. D86 (2012) 112007
ATLAS: Phys.Lett. B707 (2012) 438

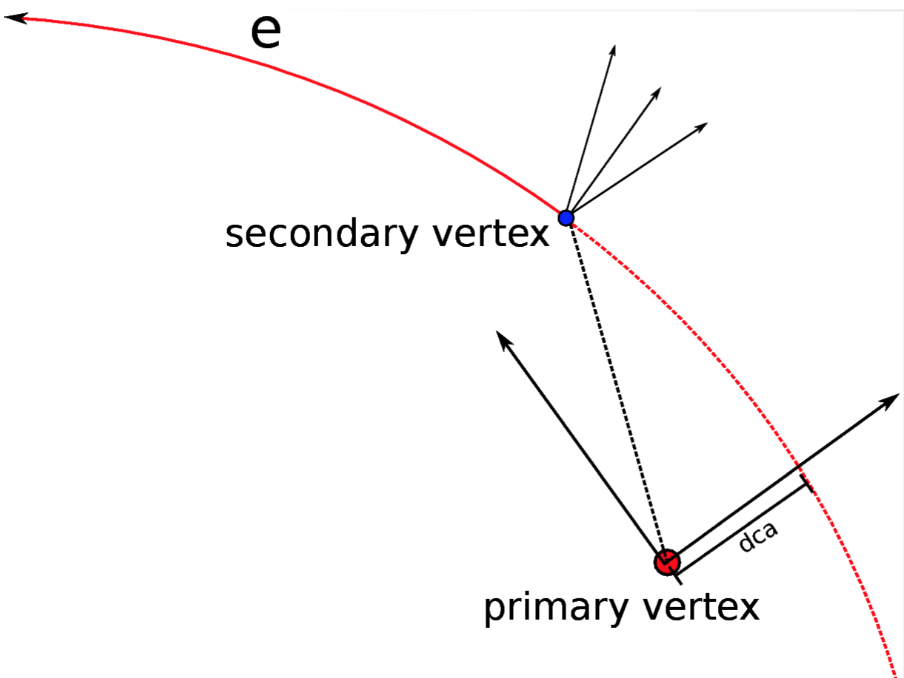
Muons at forward rapidity

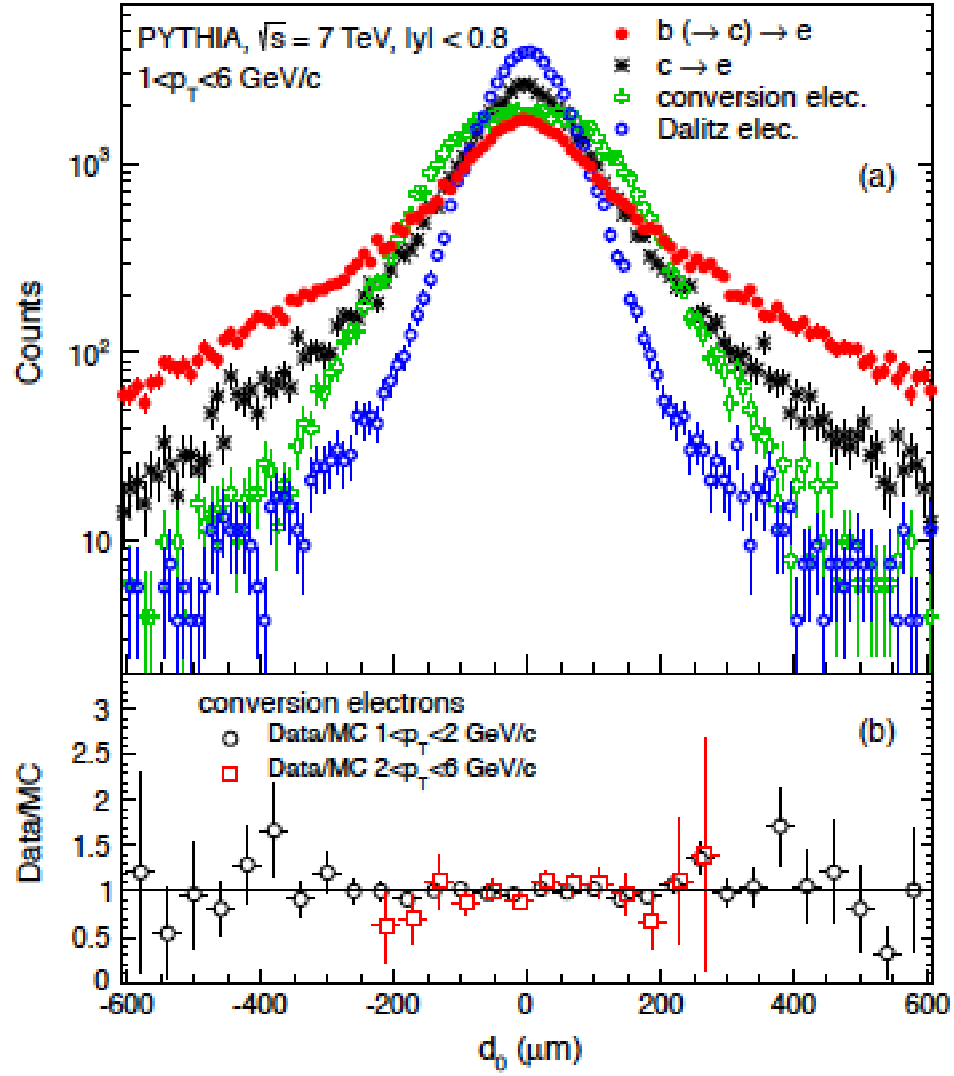


- Trigger from muon chambers
- Impact parameter used to reject part of beam-gas interactions and decays
- Remaining background ($\mu \leftarrow \pi$, K) subtracted with a data-tuned MC cocktail
- Low p_T cut to reject π, K decays > 2 (4) GeV/*c* in pp (Pb-Pb)

Semileptonic decays: beauty

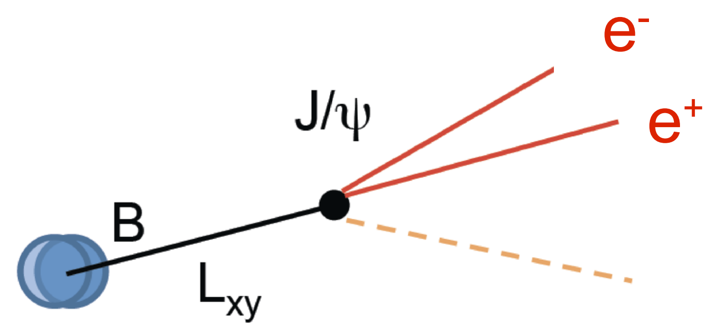
Exploit longer lifetime of beauty hadrons
→ larger **impact parameter of electrons** to the primary vertex





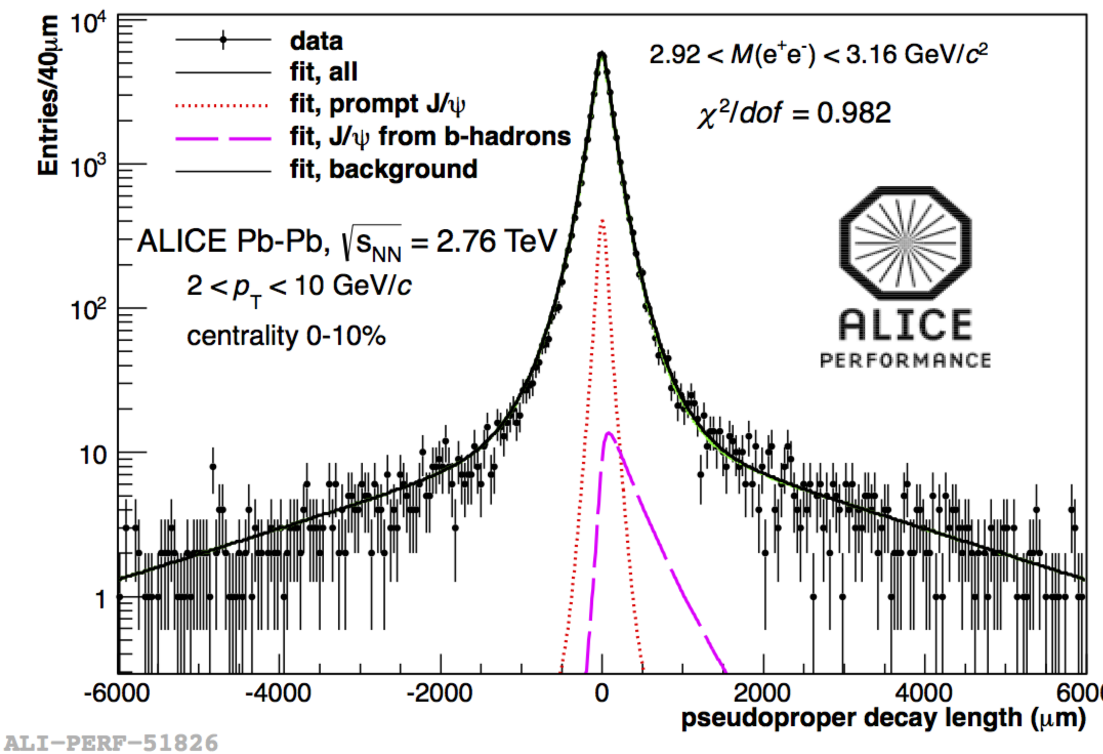
Phys.Lett. B721 (2013) 13-23

Beauty via non-prompt J/ψ

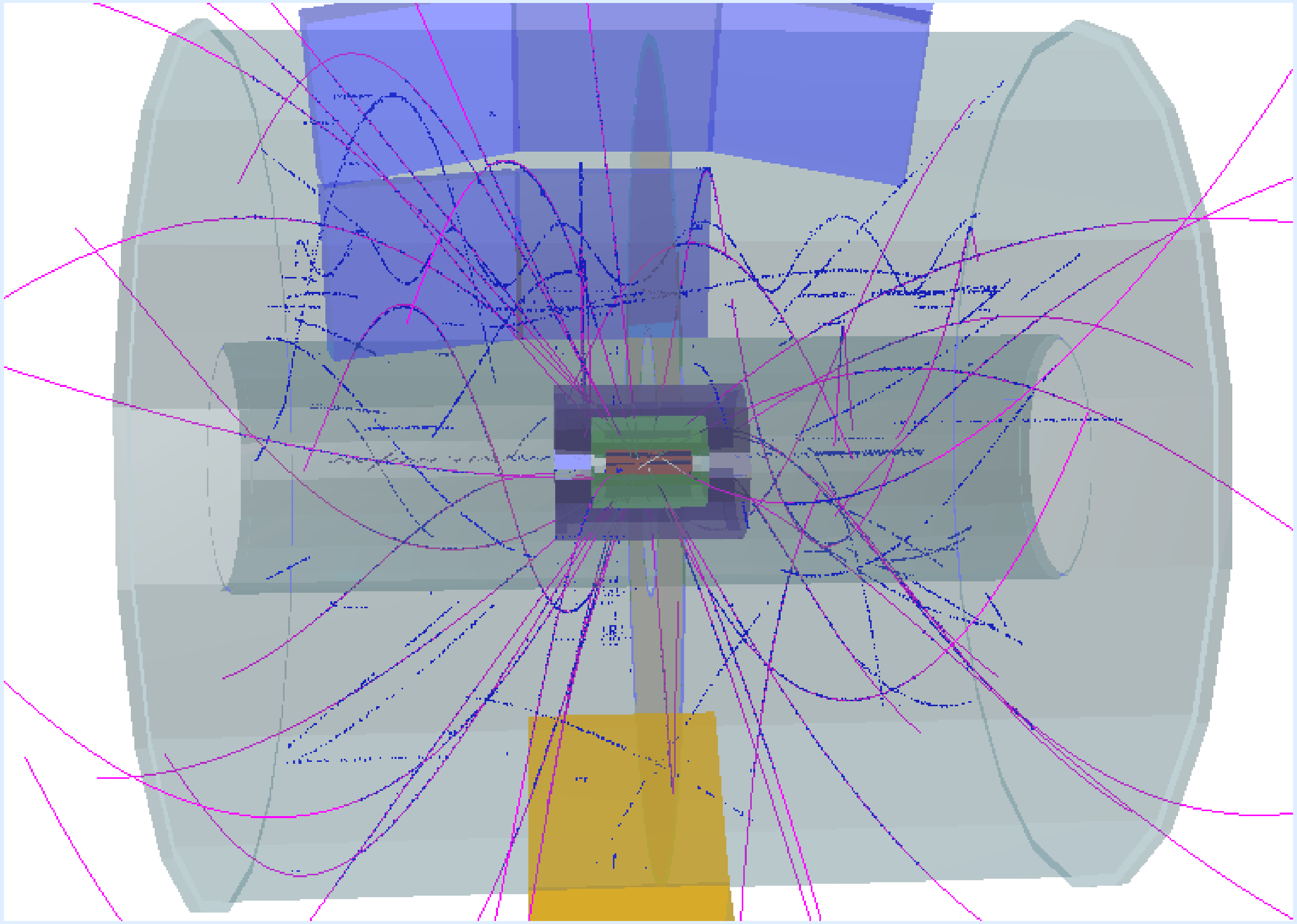


- Detect J/ψ decay vertices detached from the primary interaction

- Measure the pseudo-proper decay length



Proton - proton results



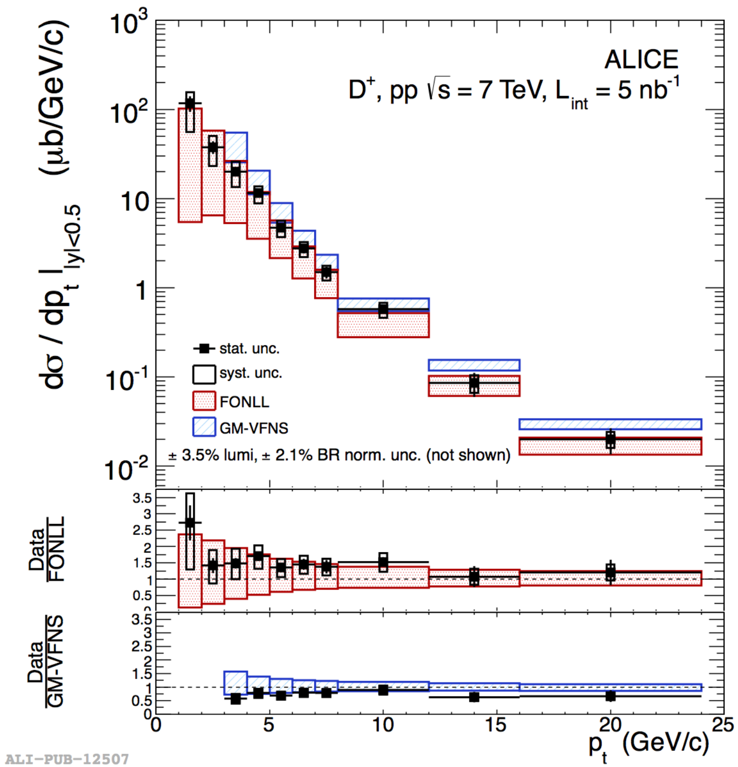
pp 7 TeV: p_T and y differential cross section

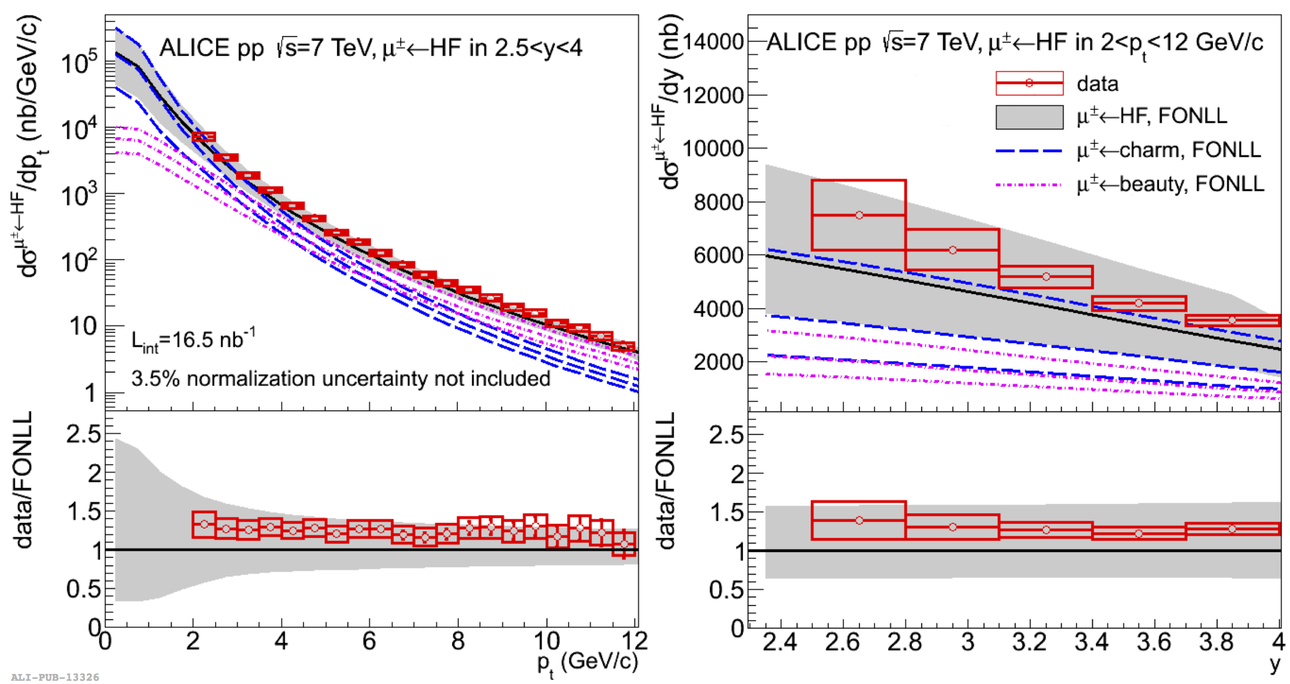
D mesons: D^0, D^+, D^{*+} (D_s)

JHEP01 (2012) 128

$HF_{c,b} \rightarrow \mu$

PLB 708 (2012) 265





Data are well described by pQCD predictions (FONLL, GM-VFNS, k_T-factorization)* within uncertainties

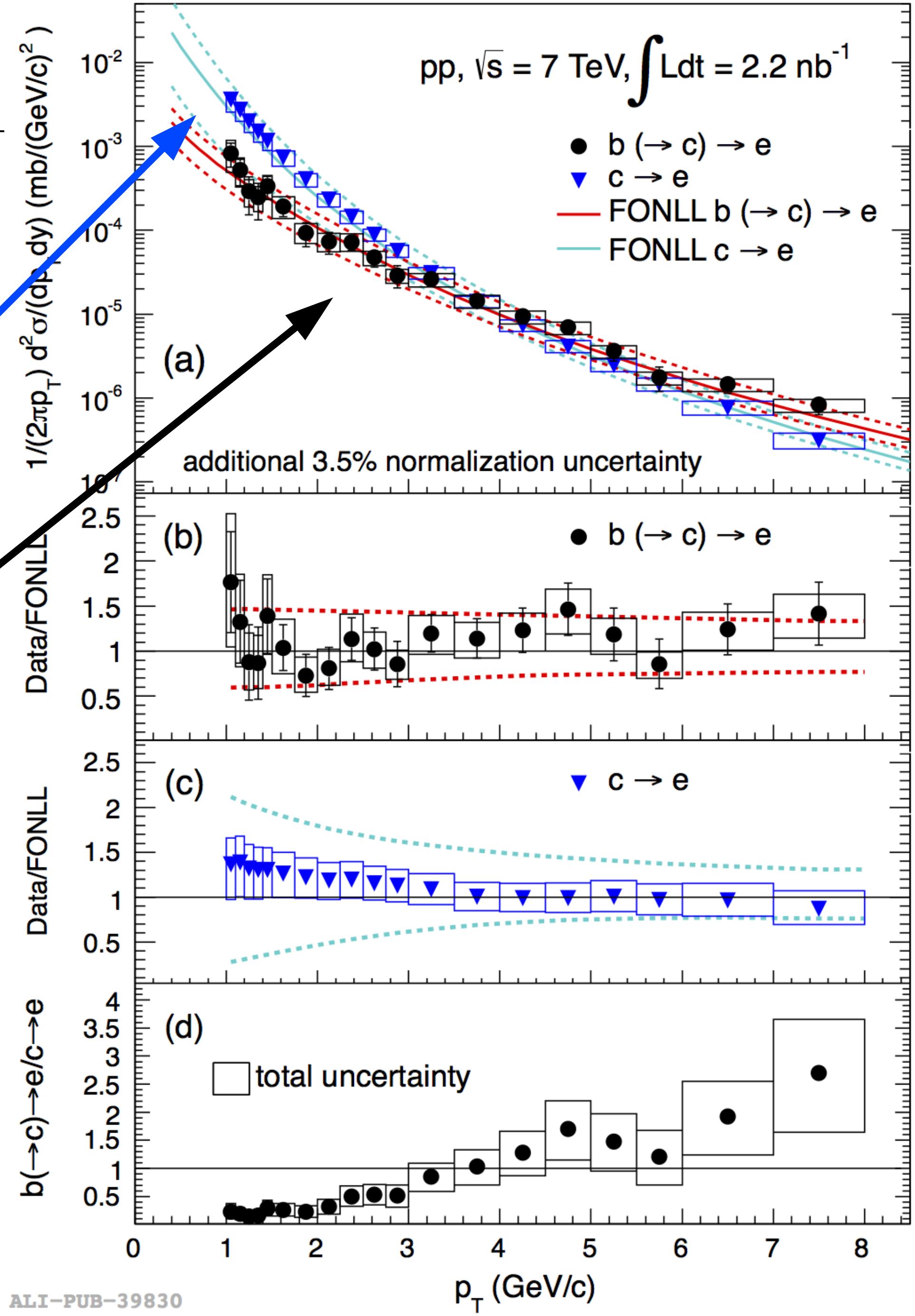
Important test of pQCD

(*) references in spares

pp: charm and beauty

- Electron analysis
- Mid rapidity
- pp 2.76 and 7 TeV

Charm
and
beauty
are measured, separately



Good description by FONLL

Phys.Lett. B721 (2013) 13-23

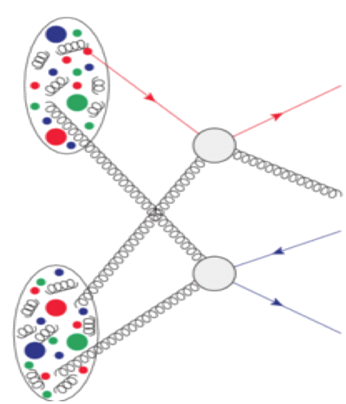
D-meson yields vs multiplicity

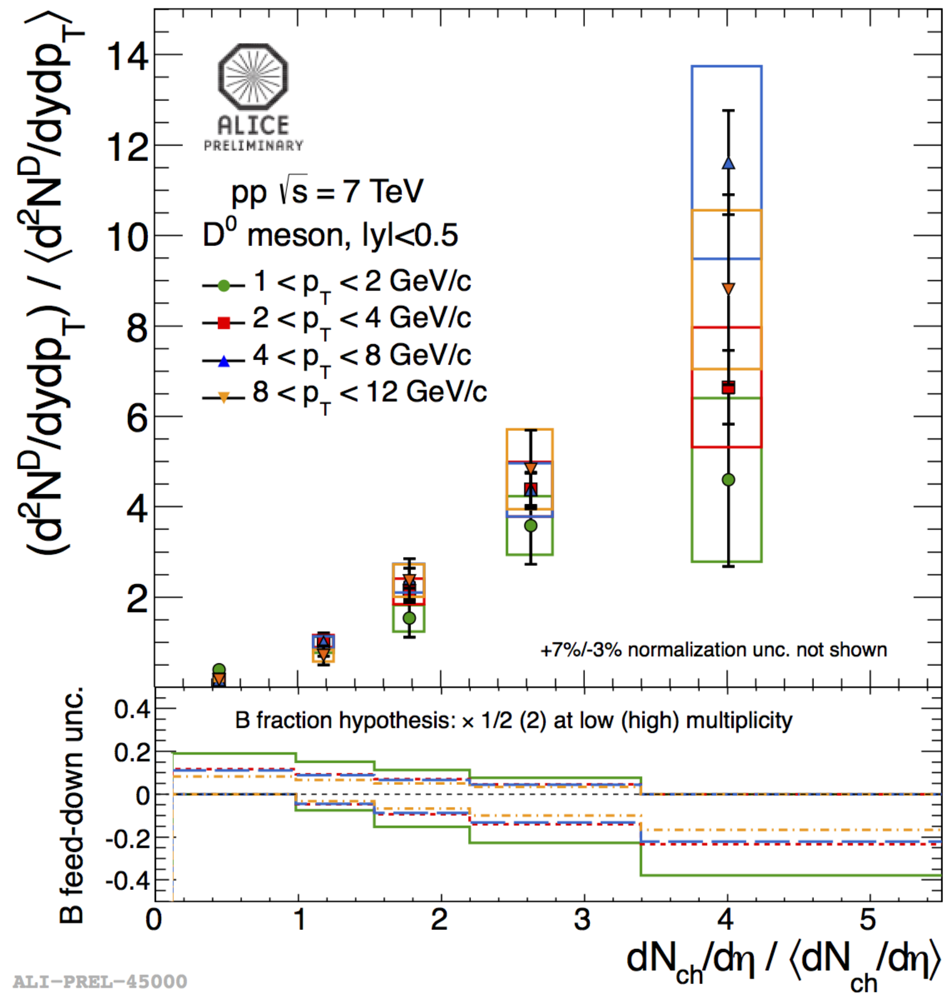
Self-normalized D-meson yields
vs charged track multiplicity

- Yield per event increases with multiplicity
- Run1 statistics not yet sufficient to study differences in p_T bins
  - Run2 larger statistics
  - High multiplicity trigger

→ Possibility to discriminate among models!

- pp: mostly due to Multi-Parton Interactions (MPI)





pp: summary and outlook

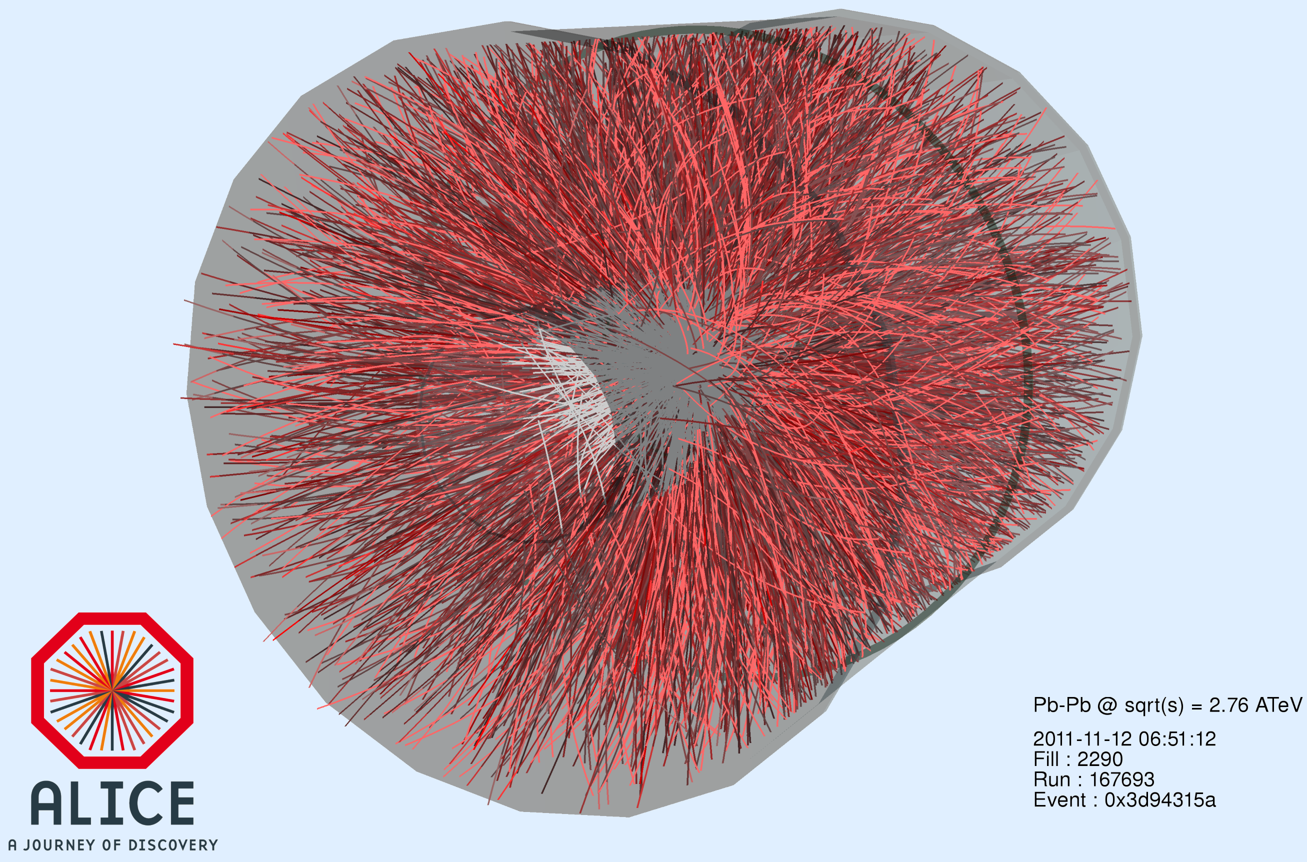
- Charm and beauty production cross sections:
  - Total and differential in p_T and rapidity (mid and forward), vs $\sqrt{s}$ and vs charged track multiplicity
- All results well described by pQCD predictions

- **To do: low and high p_T, reduce uncertainties**

Theory affected by very large uncertainties:
affect extrapolations in p_T and η, interpolations in $\sqrt{s}$.

Measurements now more precise
Can we infer limits on theoretical uncertainties?

Lead - lead results



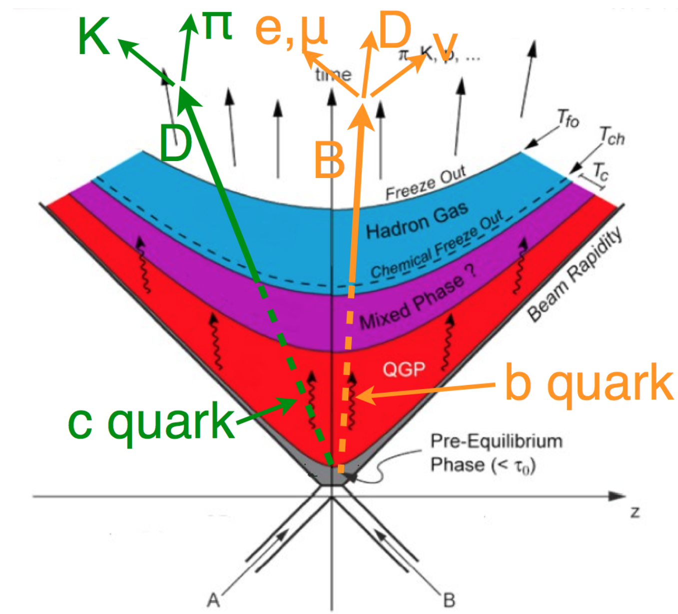
Expected in 1 Pb-Pb collision at $\sqrt{s_{NN}}$=2.76 TeV:

$\approx$ 60 $c\bar{c}$ $\approx$ 2 $b\bar{b}$

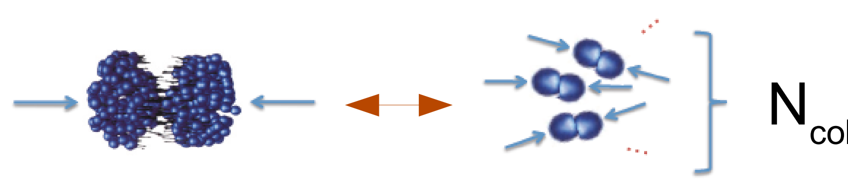
(MNR, shadowing: EKS98, EPS08. Factor 2 uncertainty)

Pb-Pb: energy loss

- Heavy quarks: probes of the QGP, through its whole evolution
- Strongly interacting medium
  → heavy quarks loose energy
- Quantifier:
  the nuclear modification factor



$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \cdot \frac{1}{N_{coll}}$$

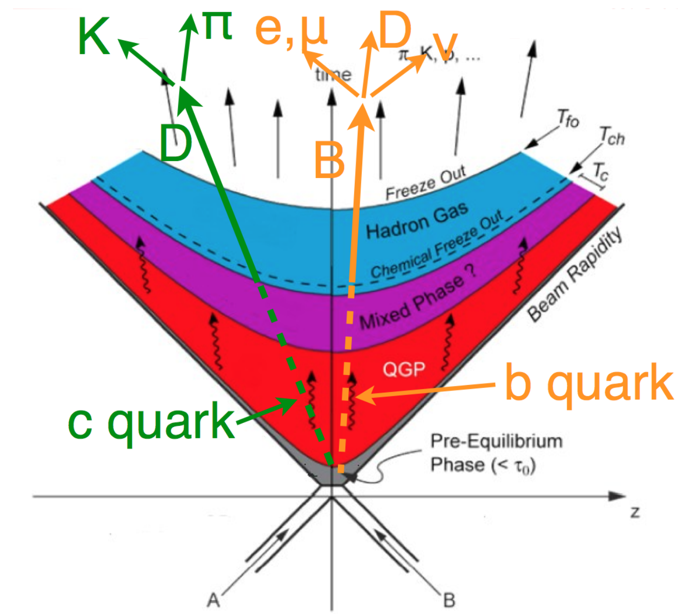


R_{AA} = 1 binary scaling

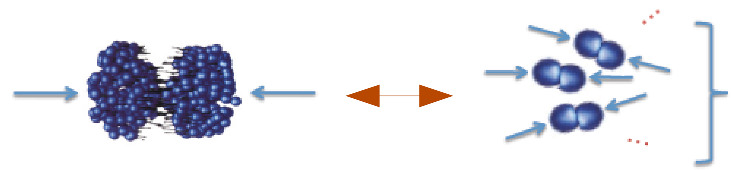
$R_{AA} \neq 1$ medium effect

Pb-Pb: energy loss

- Heavy quarks: probes of the QGP, through its whole evolution
- Strongly interacting medium
  → heavy quarks loose energy
- Quantifier:
  the nuclear modification factor



$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \cdot \frac{1}{N_{coll}}$$



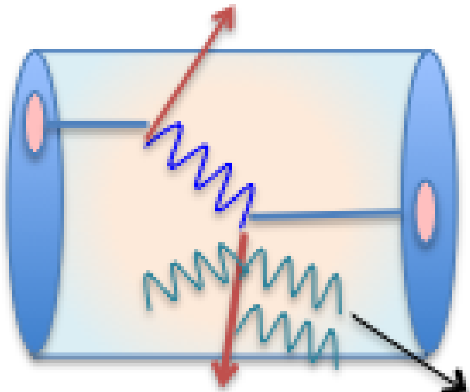
$R_{AA} = 1$ binary scaling

$R_{AA} \neq 1$ medium effect

Proton – proton is the reference

In-medium parton energy loss

- Energy loss by:
  - Medium-induced gluon radiation
  - Collisions with medium constituents



- Depends on: Compare
  - Color charge $\Delta E_{gluon} > \Delta E_{q}$ → to light hadrons
  - Parton mass $\Delta E_{c} > \Delta E_{b}$ → charm and beauty

- Considering all effects together: the predicted energy loss is

$$\Delta E_{gluon} \geq \Delta E_{q \approx c} > \Delta E_{b}$$

- Thinking of the spectra modification (R_{AA}), we could expect:

$$\text{“suppression”: } \pi \geq D > B$$

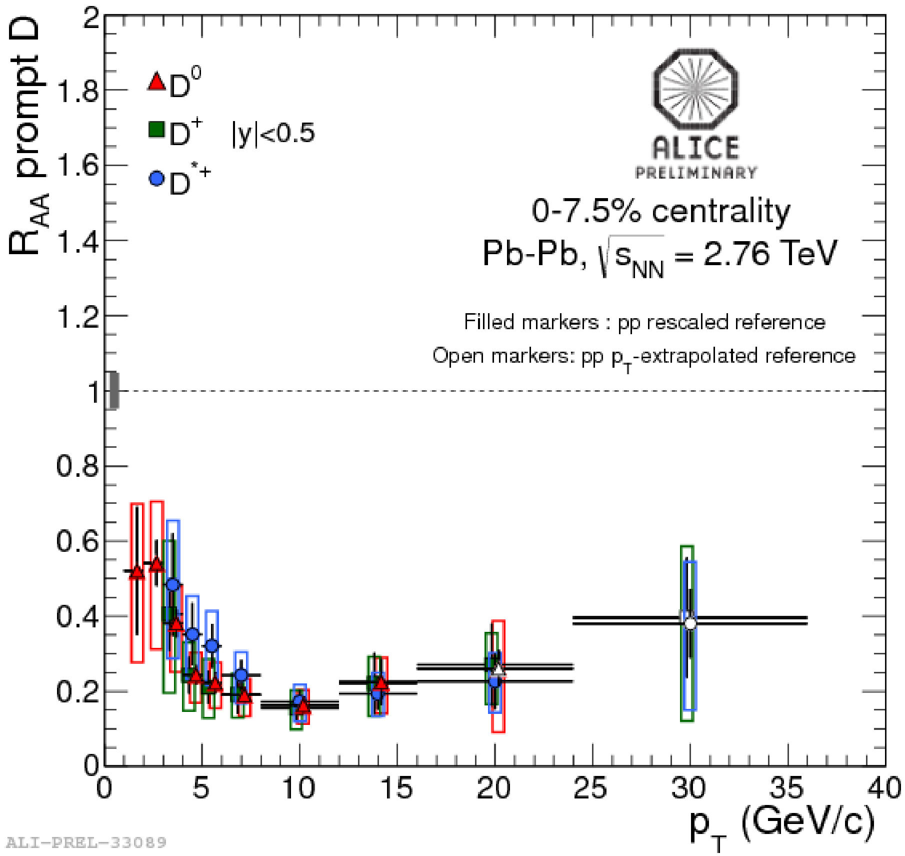
$$R_{AA}^{\pi} \leq R_{AA}^{D} < R_{AA}^{B}$$

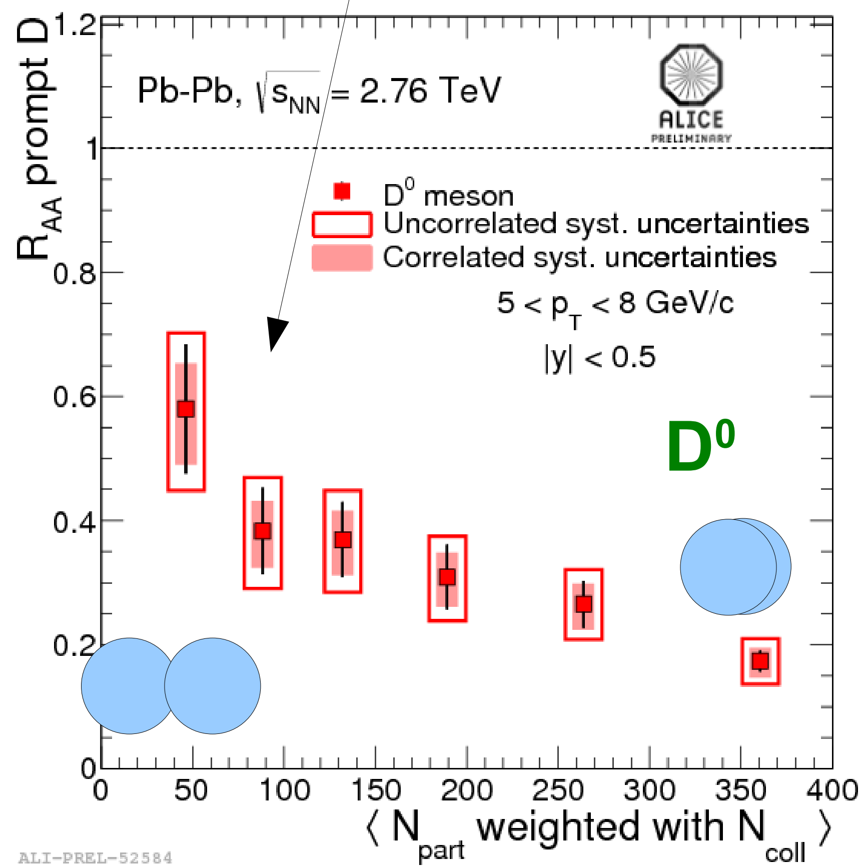
consider that other effects contribute, like different production kinematics and fragmentation of light and heavy quarks

Pb-Pb: D meson R_{AA}

Prompt D^0, D^+, D^{*+}

R_{AA} Nuclear modification factor vs p_T and collision centrality





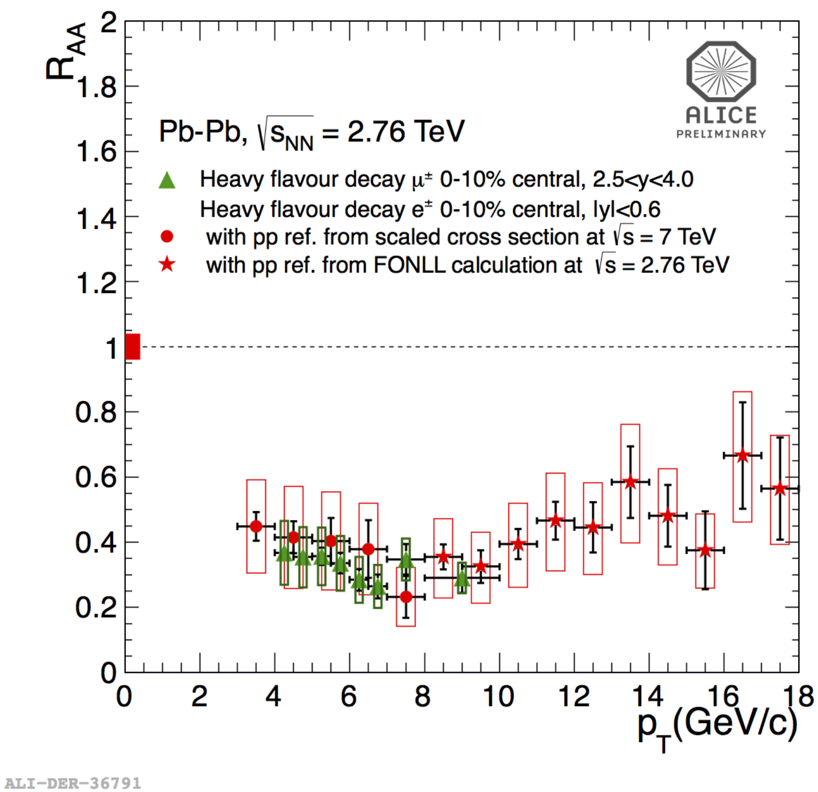
Charm mesons exhibit strong suppression

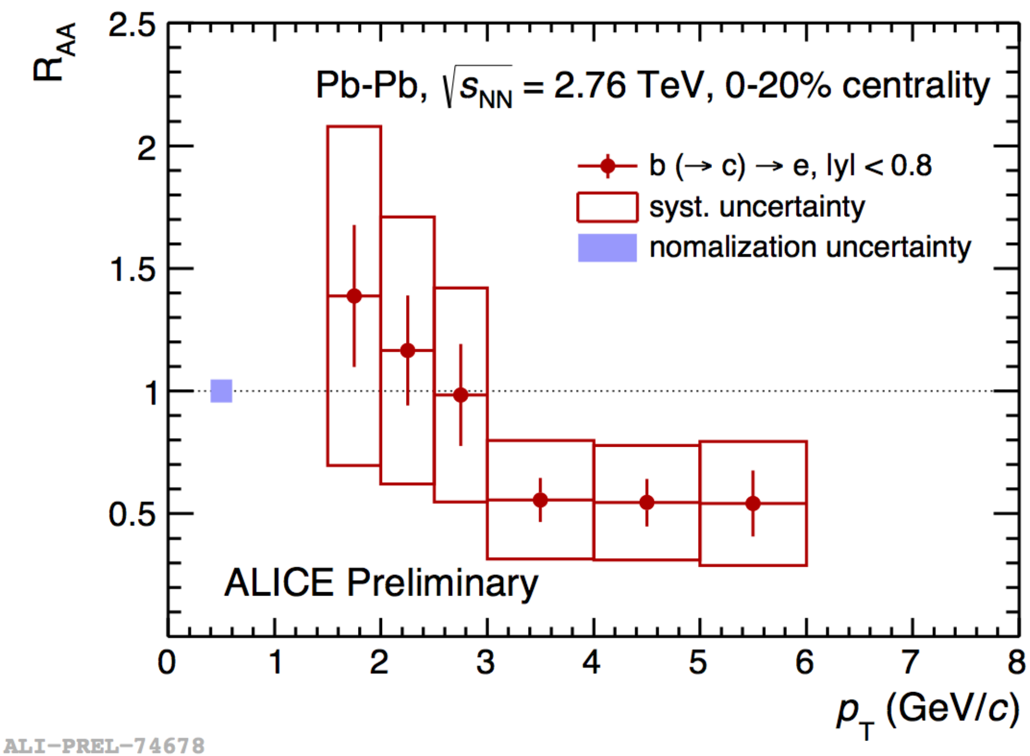
Pb-Pb: R_{AA} of leptons from HF hadron decays

$HF_{c,b} \rightarrow \mu$ 2.5<y<4.0

$HF_{c,b} \rightarrow e$ |y|<0.6

Electron at mid rapidity: beauty R_{AA}

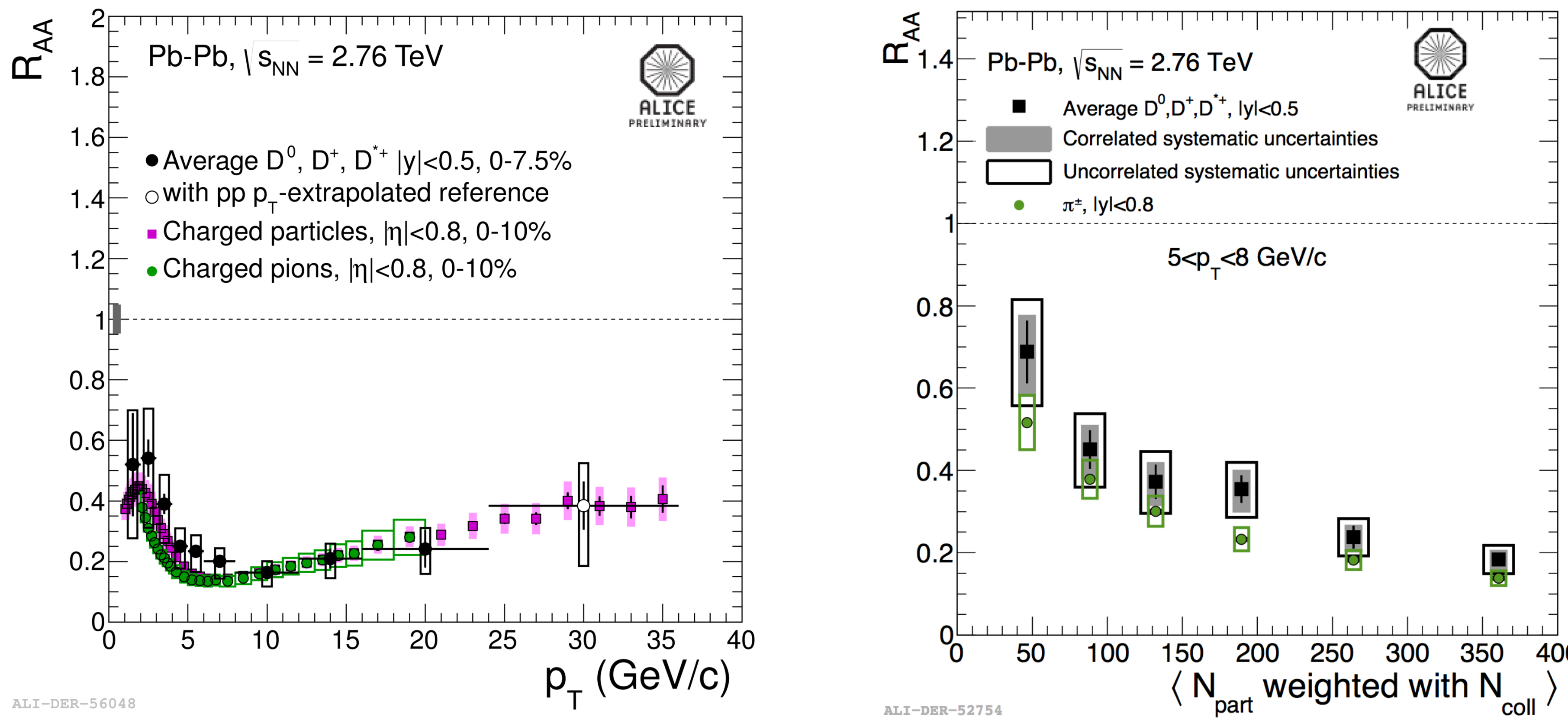




Suppression of leptons from charm-hadron decays, similar at mid and at forward rapidity.
Hint for suppression of beauty-decay electrons

Mass ordering of energy loss

Charm compared to light hadrons (π)

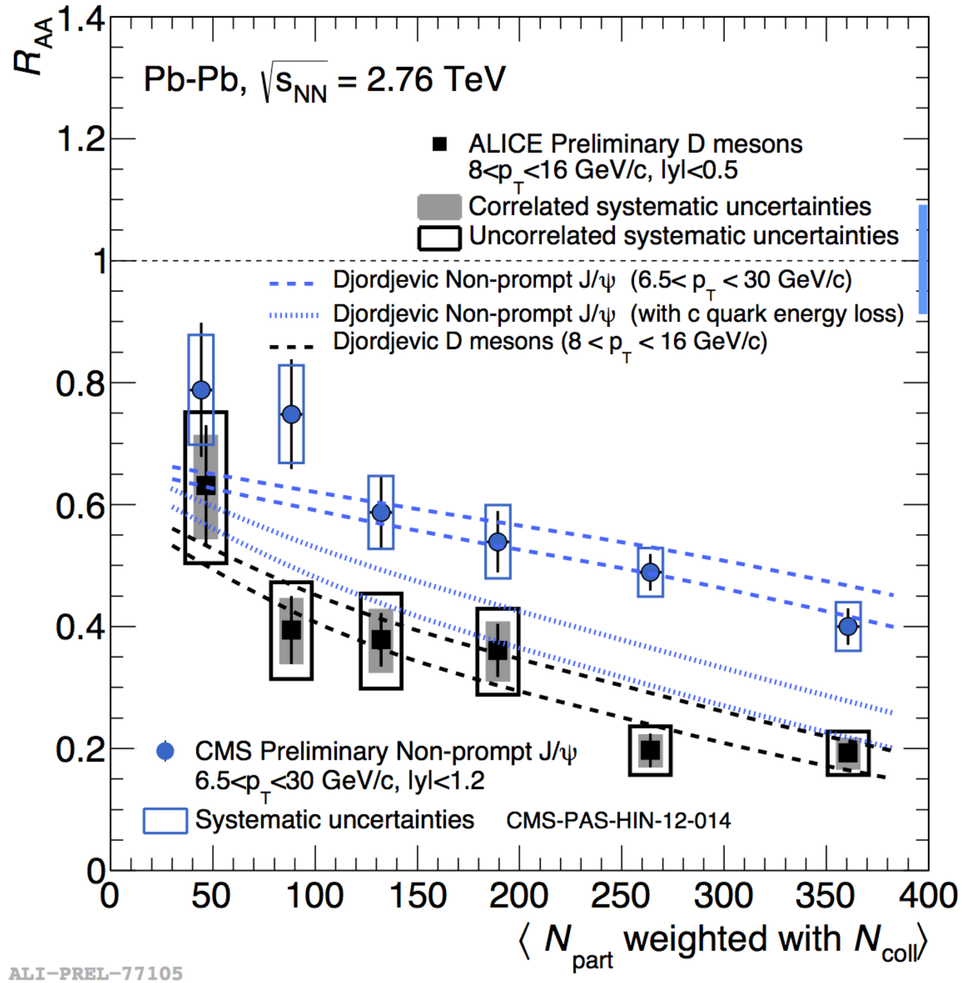


No evident ordering with current results

D meson and π R_{AA} compatible within uncertainties

Mass ordering of energy loss

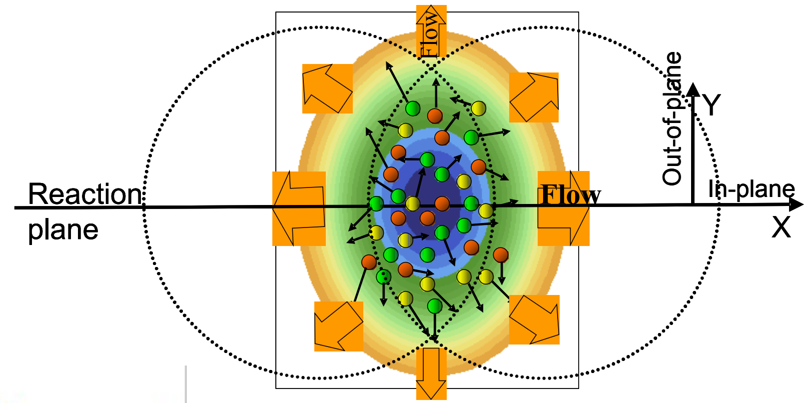
Charm compared to **beauty (B → J/ψ)**



- Similar kinematic region selected
- Indication of mass ordering in central Pb-Pb collision

  $R_{AA}(D) < R_{AA}(B \rightarrow J/\psi)$
- Comparison with theoretical model based on pQCD
  Djordjevic, PL B734(2014)286

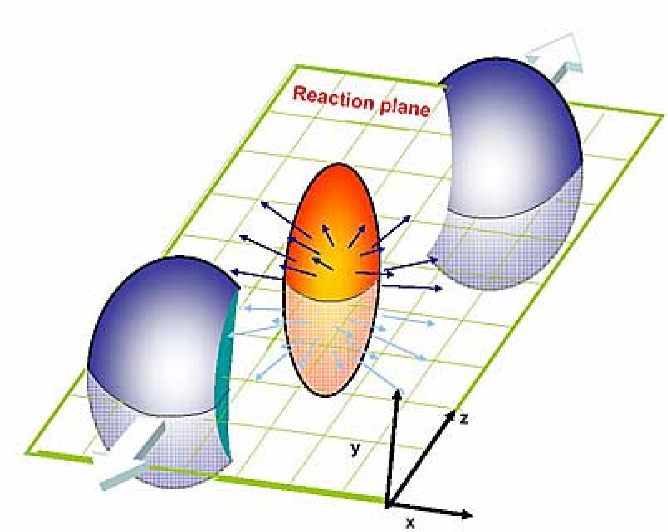
Pb-Pb: elliptic flow



- Initial spatial asymmetry in semi-central collisions → azimuthal anisotropy of final hadrons

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$

- Degree of participation of charm to the collective motion of the medium: $v_2 > 0$ at low p_T
- Path length dependence of energy loss: at high p_T



Pb-Pb: heavy-flavor v_2 measurements

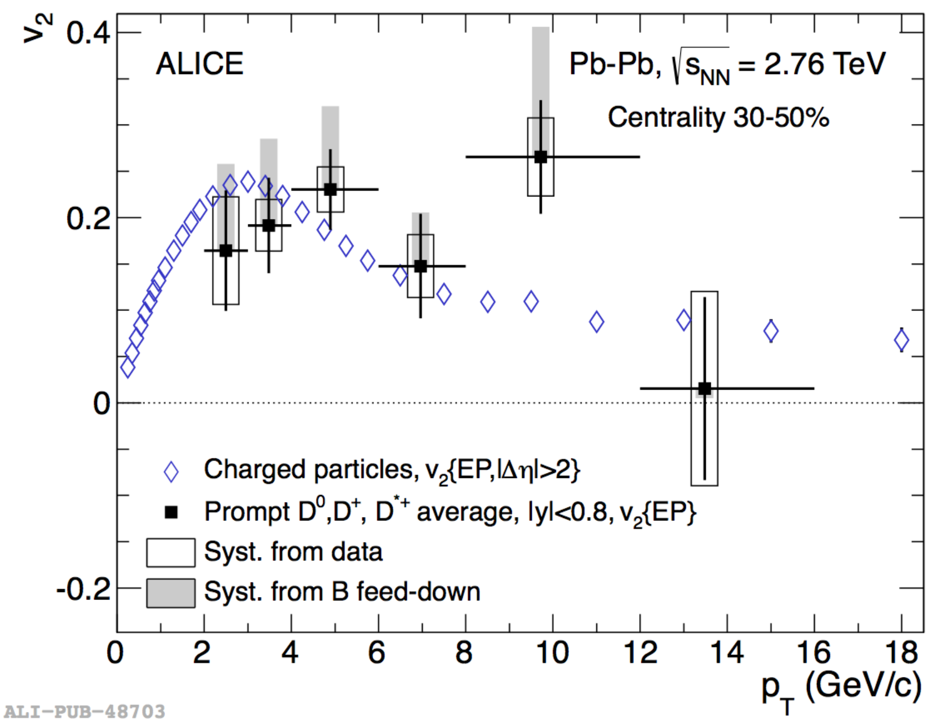
Prompt D meson v_2 compared to v_2 of charged particles

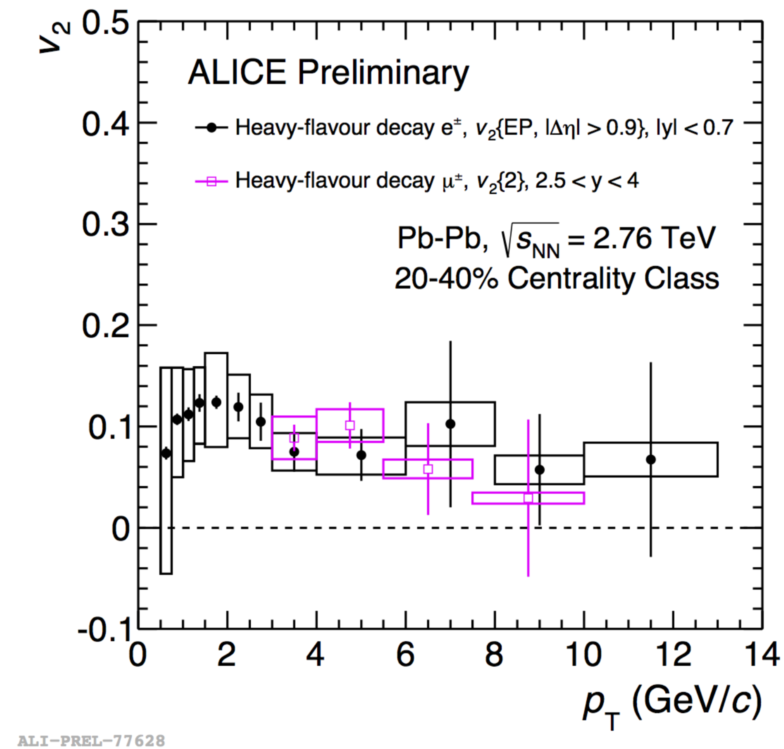
Comparable behavior!

Electrons and muons from heavy-flavor hadron decays

Similar at different rapidity

PRL 111(2013)102301
PRC90(2014)034904



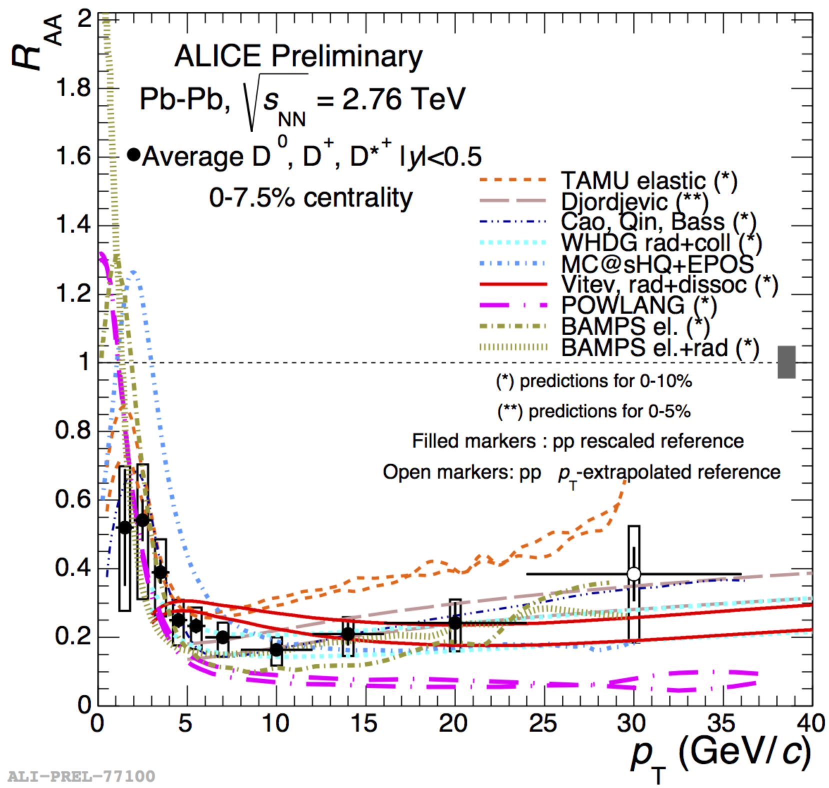


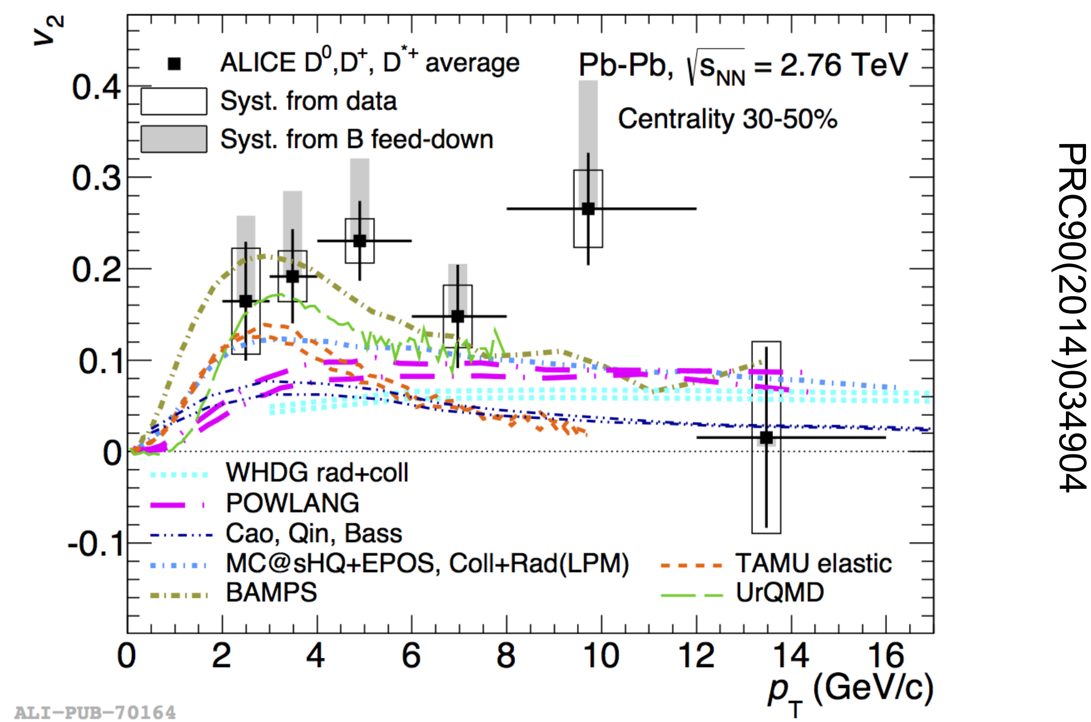
Non-zero v_2 coefficient at low p_T: hint for participation of charm to the collective motion

Pb-Pb: theory models

(*) references in spares

Theoretical model to translate the measured observables to fundamental properties of the QGP: transport coefficients





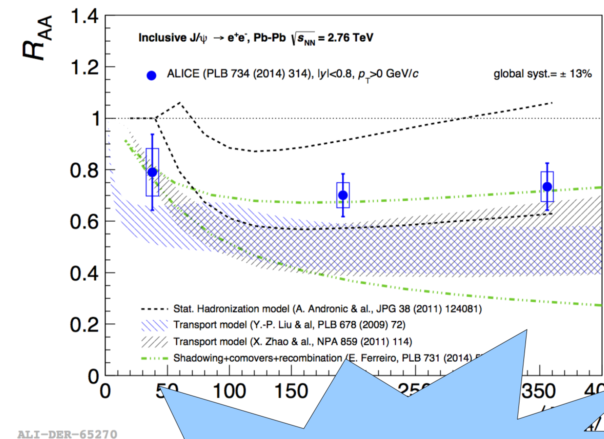
Simultaneous description of R_{AA} and v_2 challenging!

Data start to be precise enough to constrain energy loss models

Pb-Pb: outlook

- Extend measurements to low p_T and high p_T
- Essential to determine $\sigma_{c\bar{c}}$ in Pb-Pb collisions

Discriminate models which interpret J/ψ suppression at the LHC

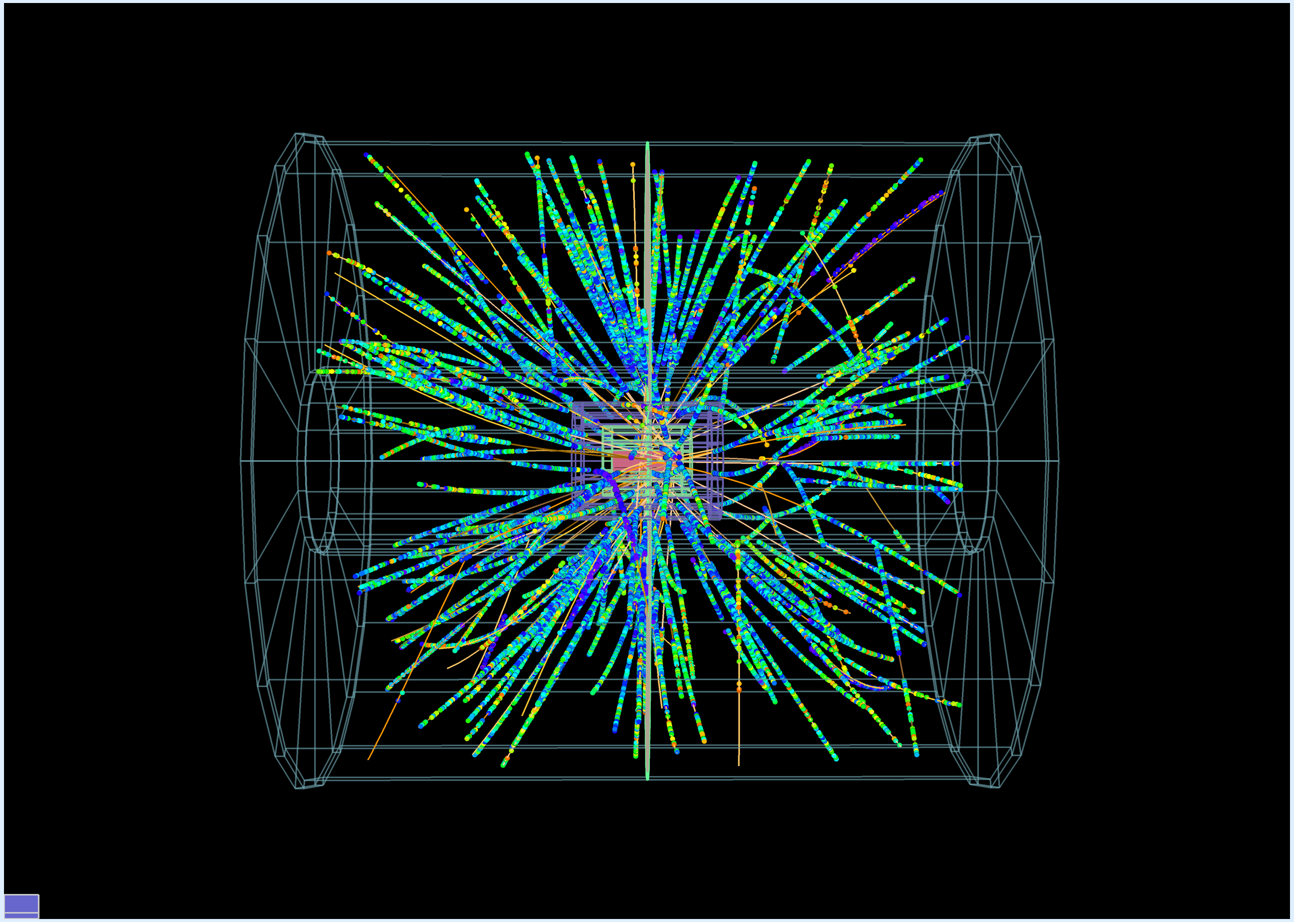


Talk by Ionut Arsene yesterday!

- Extend beauty measurements
  - p_T range, uncertainties, new methods

- Important work on the theoretical side!

Proton - lead results

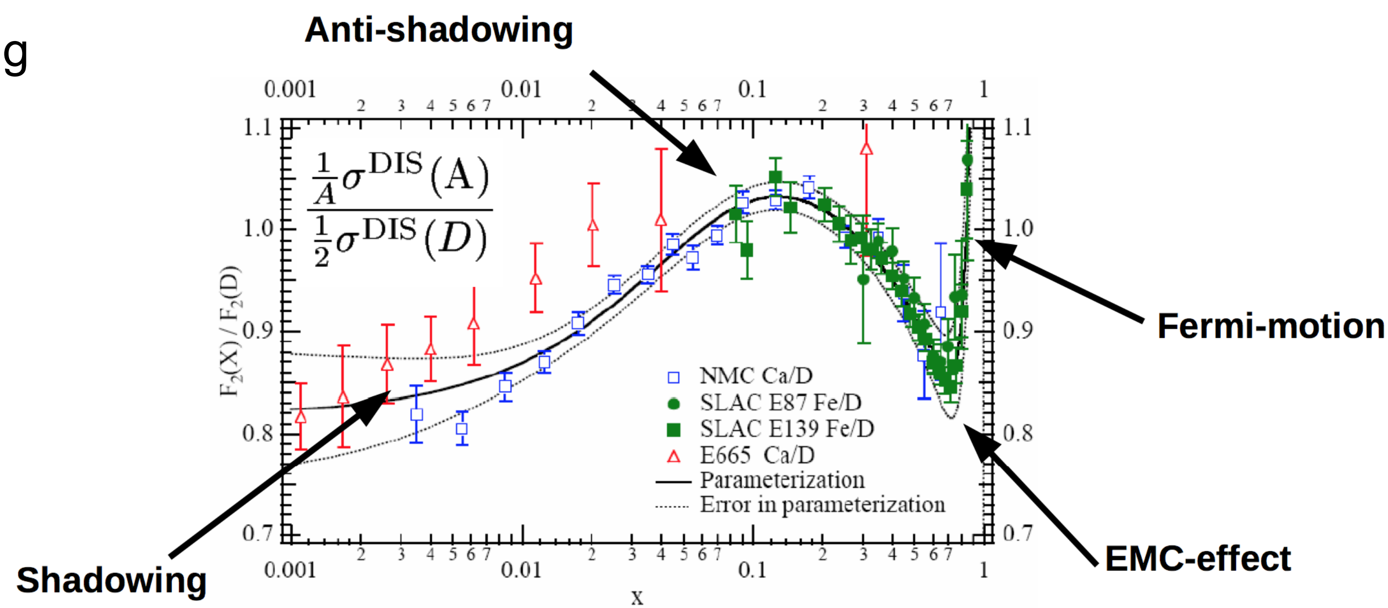


Cold-nuclear matter effects

What is the effect of having a nucleus as incoming projectile?

Modification of nuclear PDFs:

Gluon saturation/shadowing at low x, k_T-broadening, CNM energy loss ...



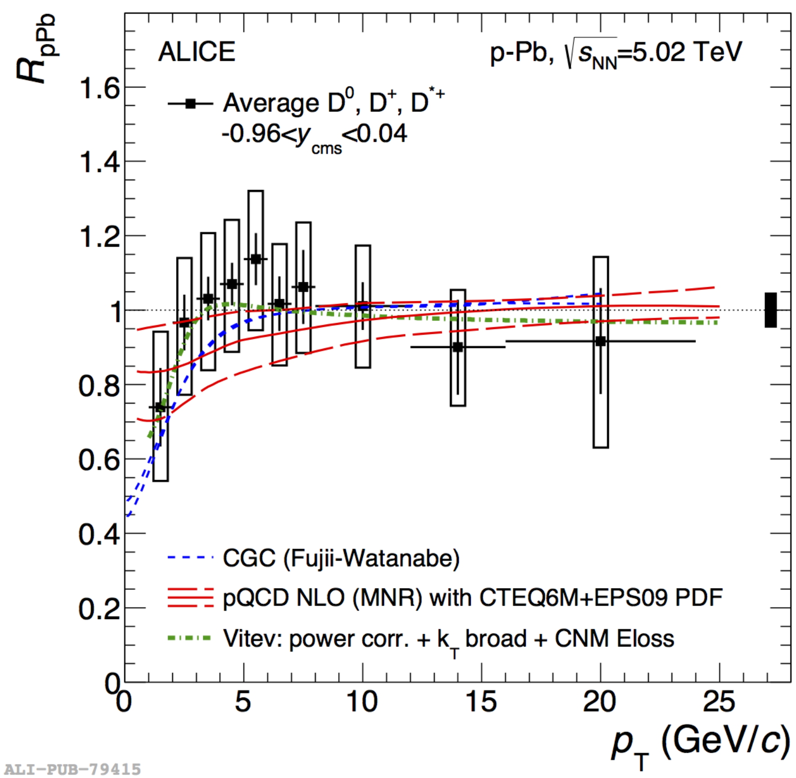
EPS90 Eskola, Paukkunen, Salgado

Investigated with p-Pb collisions to discriminate between initial-state and final-state effects ($\sqrt{s_{NN}}$ = 5.02 TeV)

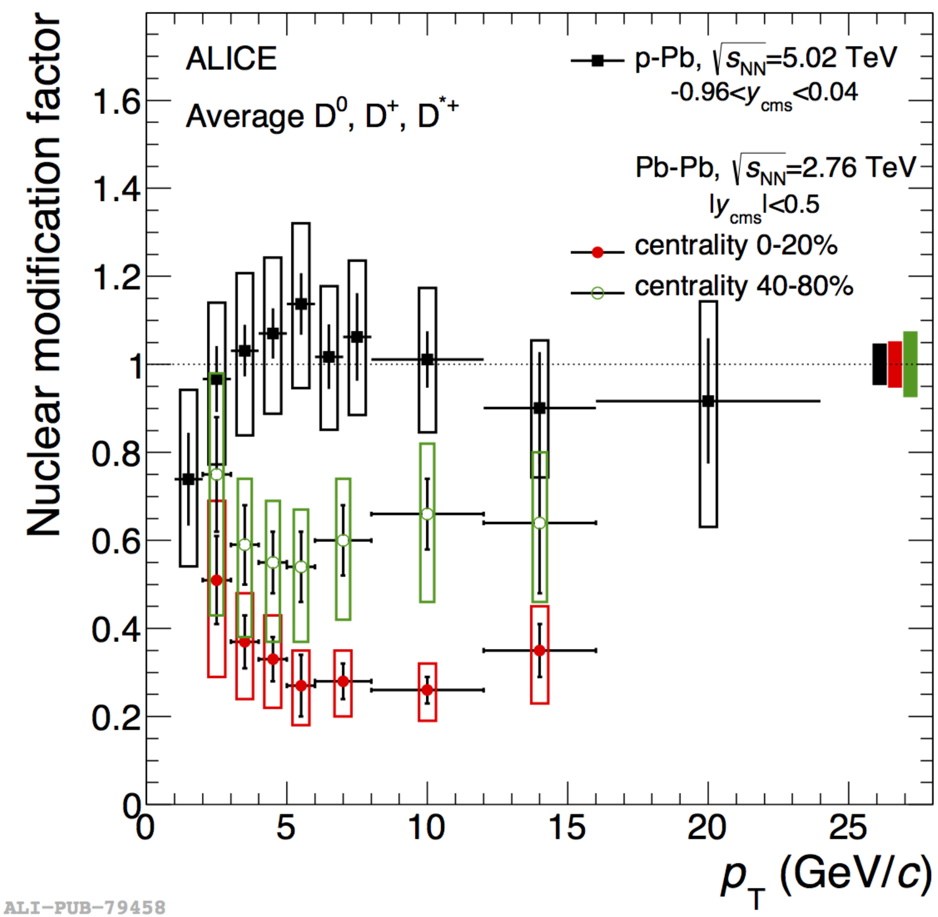
D meson R_{pPb}

$$R_{pPb}(p_T) = \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T} \cdot \frac{1}{A}$$

arXiv: 1405.3452



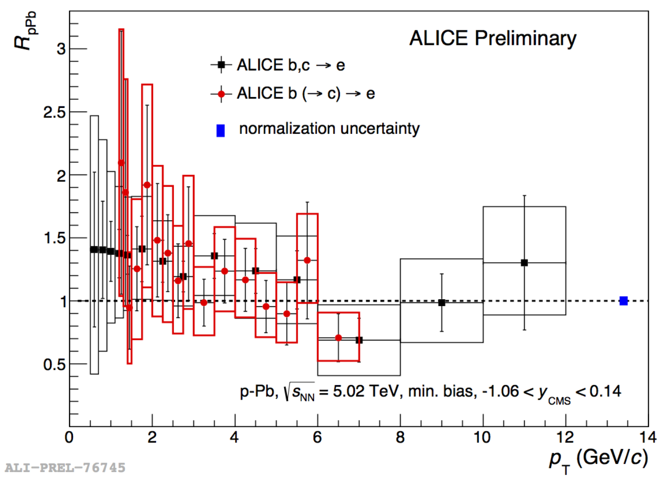
Compared to R_{AA}:

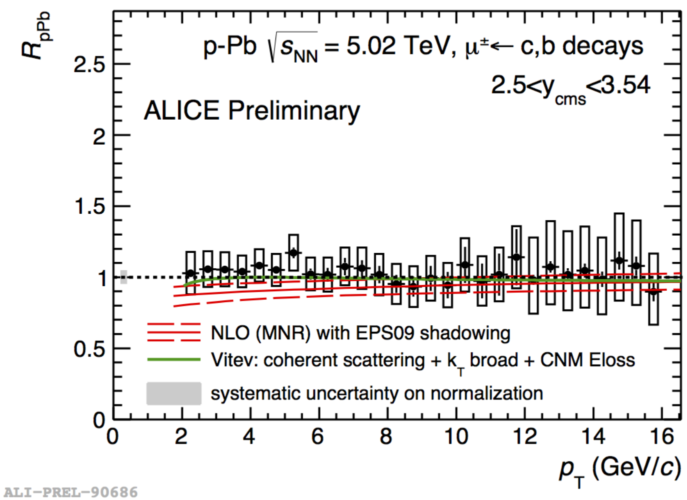


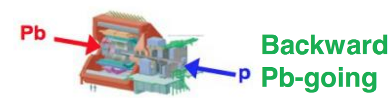
The suppression at large p_T in Pb-Pb collisions is a final-state effect

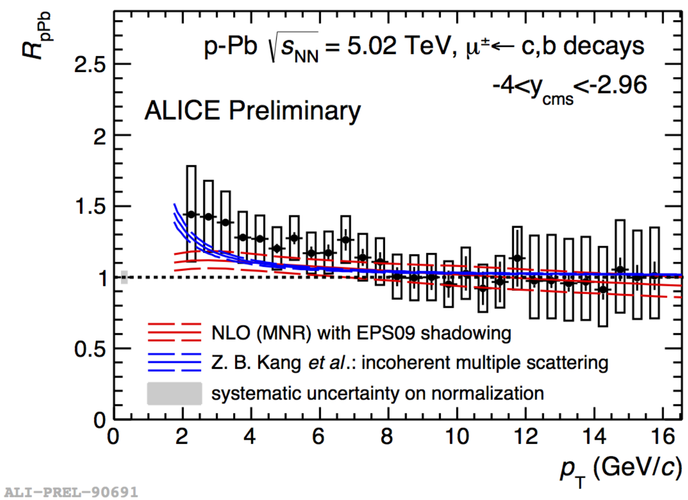
Electron and muon R_{pPb}

- Electrons at mid rapidity (inclusive and beauty)
- Muons at forward rapidity







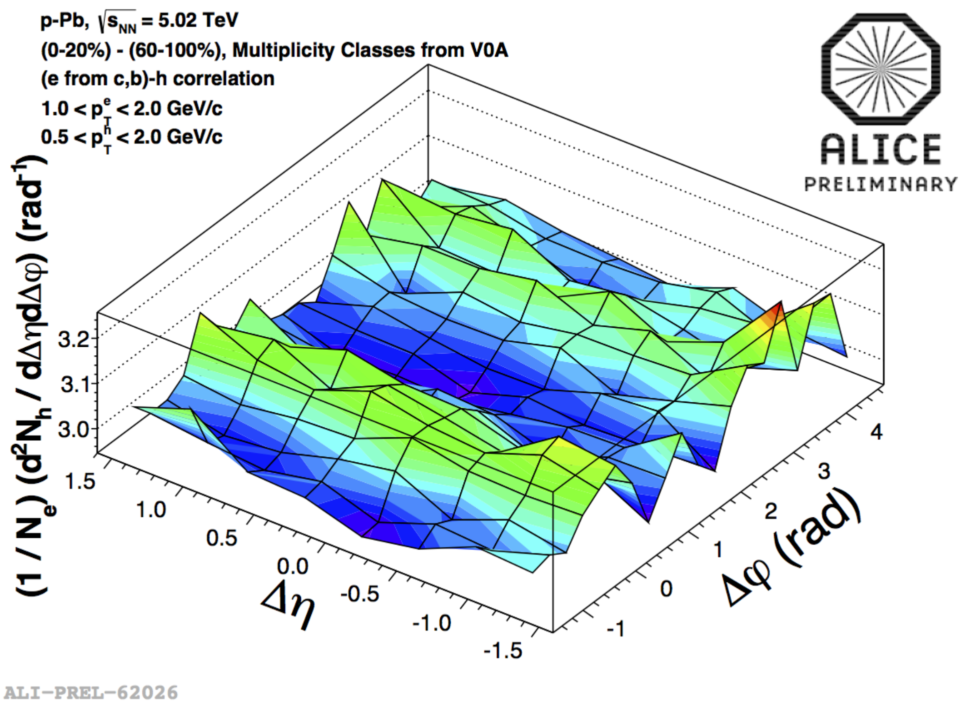


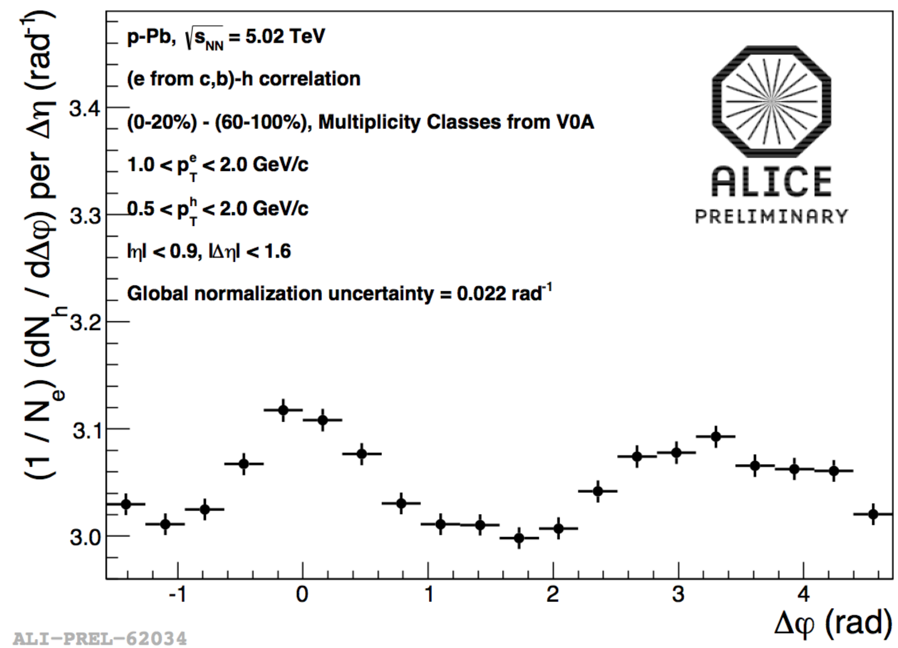
- Cold nuclear matter effects small in measured p_T range
- pQCD + shadowing / cold nuclear matter effects describe the data*

(*) references in spares

p-Pb: electron-hadron correlations

Angular correlations in low-multiplicity events (60-100%) subtracted from high-multiplicity events (0-20%), to remove jet correlations:

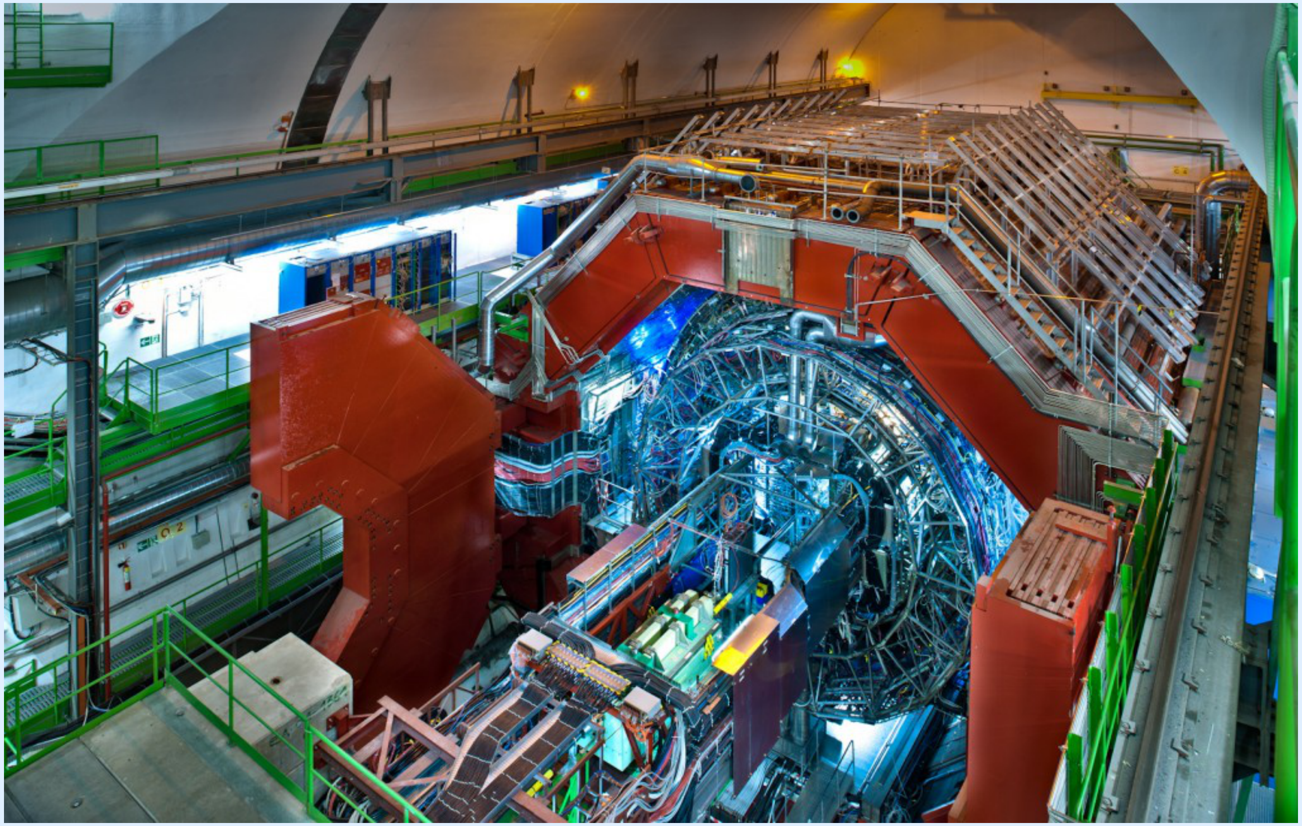




Double ridge similar to light-flavor sector: PL B719(2013)29

- Color Glass Condensate in initial state Dusling, Venugopalan PR D87(2013)094034
- Hydrodynamics in final state Bozek, Broniowski PL B718(2013)1557

Concluding ...



Outlook

Run2: 2015-2018

- pp collisions at $\sqrt{s}$ = 13 TeV, Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.1 TeV
- Significant increase of statistics in all systems!
- More statistics will also allow to reduce partly the systematic uncertainties (possibility to perform many more studies)
- Extend p_T range, to 0 (D^0) and to high p_T
- More beauty, correlations, heavy-flavor in jets

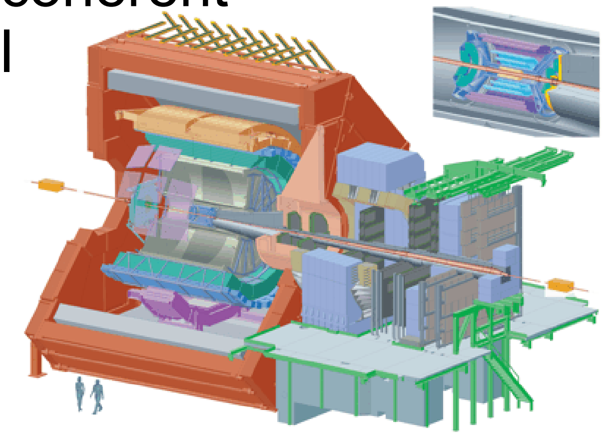
Run3: 2020-2023

- Pb-Pb collisions up to 50 kHz!
- Entirely new ITS (reduced material, improved resolution)
- 10 times more statistics ...
- … together with better resolution → access to rare signals, heavy-flavor hadrons (Λ_c, Λ_b, etc), B meson full reconstruction

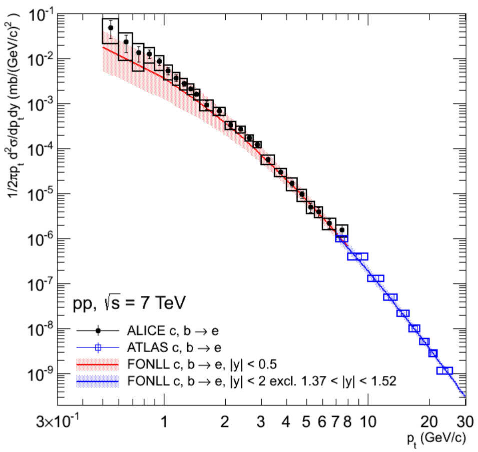
Talk by Massimo Masera on Wednesday afternoon!!

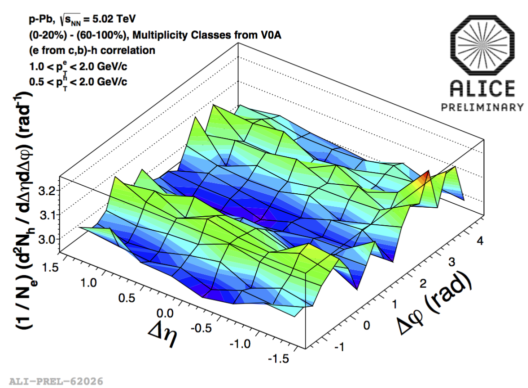
Conclusions

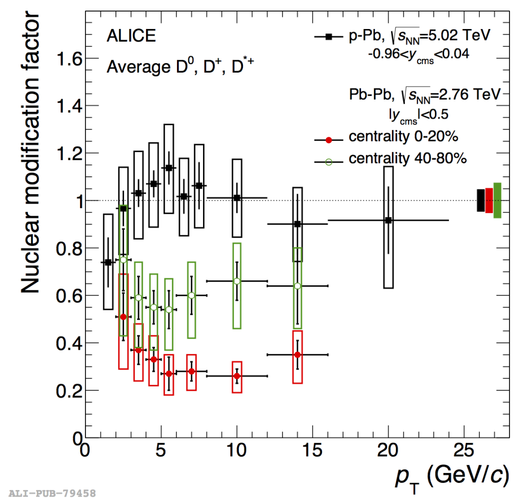
- Heavy quarks are excellent probes of strongly-interacting matter produced in heavy-ion collisions
- Heavy quarks are interacting with the dense medium and being significantly slowed down, by collisional and radiative energy loss
- Flow measurements hint at participation of charm to the collective motion of the medium
- Important theoretical work needed now, to provide coherent description of observables and extract fundamental properties of the QGP
- ALICE is the perfect place for heavy-flavor physics

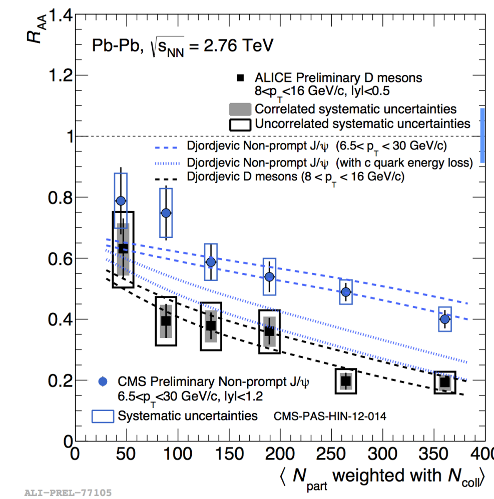


Conclusions









Stay tuned

new results soon!!

Spares

Theory references

- pp

  Perturbative QCD

  - FONLL: JHEP 1210(2012)37
  - GM-VFNS: EPJ C72(2012)2082
  - k_T factorization: arXiv:1301.3033

- Cold nuclear matter effects

  R_{pPb} D mesons

  - CGC calculations: H. Fuji, K. Watanabe, arXiv:1308.1258
  - MNR (NP B373(1992)295) pQCD calculations with EPS09 parametrization of nuclear PDFs (JHEP 04467(2009)065)
  - Energy loss in cold nuclear matter: I. Vitev, PR C75(2007)064906

Theory references

- R_{pPb} electrons
  - FONLL pQCD calculation with EPS09 shadowing parametrization
    M. Cacciari et al, JHEP 006(2001)0103; K. Eskola et al., JHEP 04(2009)065

- R_{pPb} muons
  pQCD models including cold nuclear matter effects
  - MNR: M. Mangano et al., NP B373(1992)295; K. Eskola et al., JHEP 04(2009)065;
  - I. Vitev, PR C75(2007)064906
  - Z. Kang at al., arXiv:1409.2494

Theory references

- pp

  Perturbative QCD

  - FONLL: JHEP 1210(2012)37
  - GM-VFNS: EPJ C72(2012)2082
  - k_T factorization: arXiv:1301.3033

- Cold nuclear matter effects

  R_{pPb} D mesons

  - FONLL: M. Cacciari et al, JHEP 006(2001)0103; K. Eskola et al., JHEP 04(2009)065
  - MNR: M. Mangano et al., NP B373(1992)295; I. Vitev, PR C75(2007)064906; Z. Kang at al., arXiv:1409.2494

Theory references - Pb-Pb

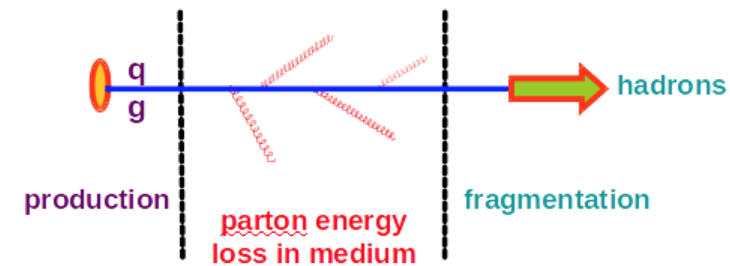
- QCD-based models with in-medium radiative/collisional energy loss
  - Dokshitzer, Kharzeev, PL B519(2001)199
  - Armesto et al., PRD 69(2004)114003
  - Djorjevic et al., NP A783(2007)493
- Mass hierarchy of parton energy loss included
  - Djorjevic, PL B734(2014)286
  - Wicks et al., NP A872(2011)265
- More
  - BAMPS, JPG 38(2011)124152
  - WHDG, JPG 38(2011)124114
  - Vitev et al., PR C(2009)054902

Theory references - Pb-Pb

- Description of R_{AA} and v_2
  - TAMU elastic: PL B735(2014)445
  - Djordjevic: PL B734(2014)286
  - Cao, Qin, Bass: PR C88(2013)044907
  - WHDG rad+coll: NP A872(2011)265
  - MC@sHQ+EPOS: PR C89(2014)014905
  - Vitev, rad+dissoc: PR C80(2009)054902
  - POWLANG: JP G38(2011)124144
  - BAMPS: PL B717(2012)430

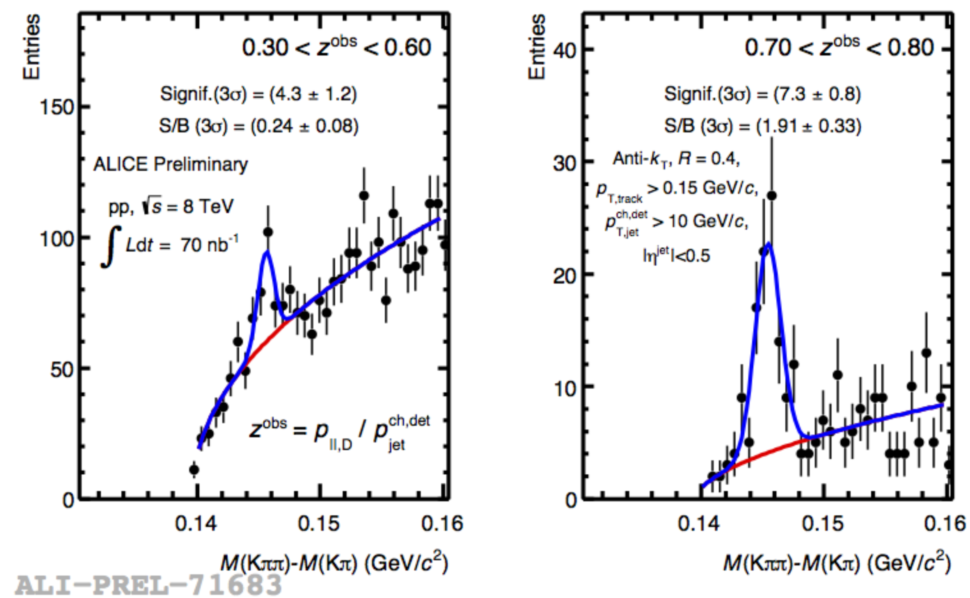
Heavy-flavor fragmentation

- Important to understand interplay between production, interaction with medium, and fragmentation



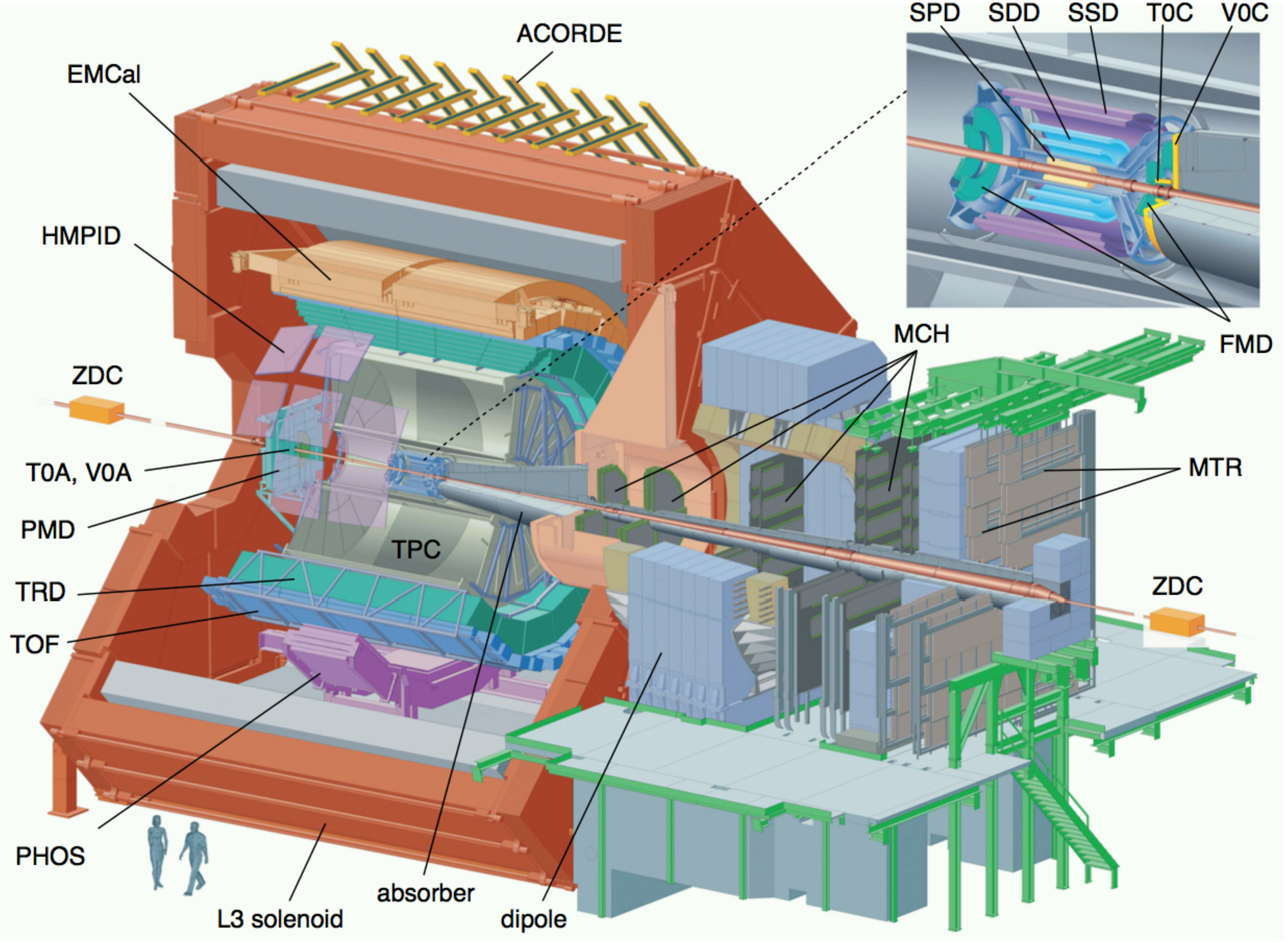
- ATLAS results on charm fragmentation in pp not described by theory at low p_T and low z PRD 85 (2012)

- ALICE has the best chance to address this region with low p_T coverage and particle identification
  - D^{*+} in jets
  - Important program for Run2 (statistics)



The ALICE spectrometer

LHC Point 2
52 m
underground



Total weight : 16000 t
Overall diameter : 16 m
Overall length : 26 m
Magnetic field : 0.5 Tesla

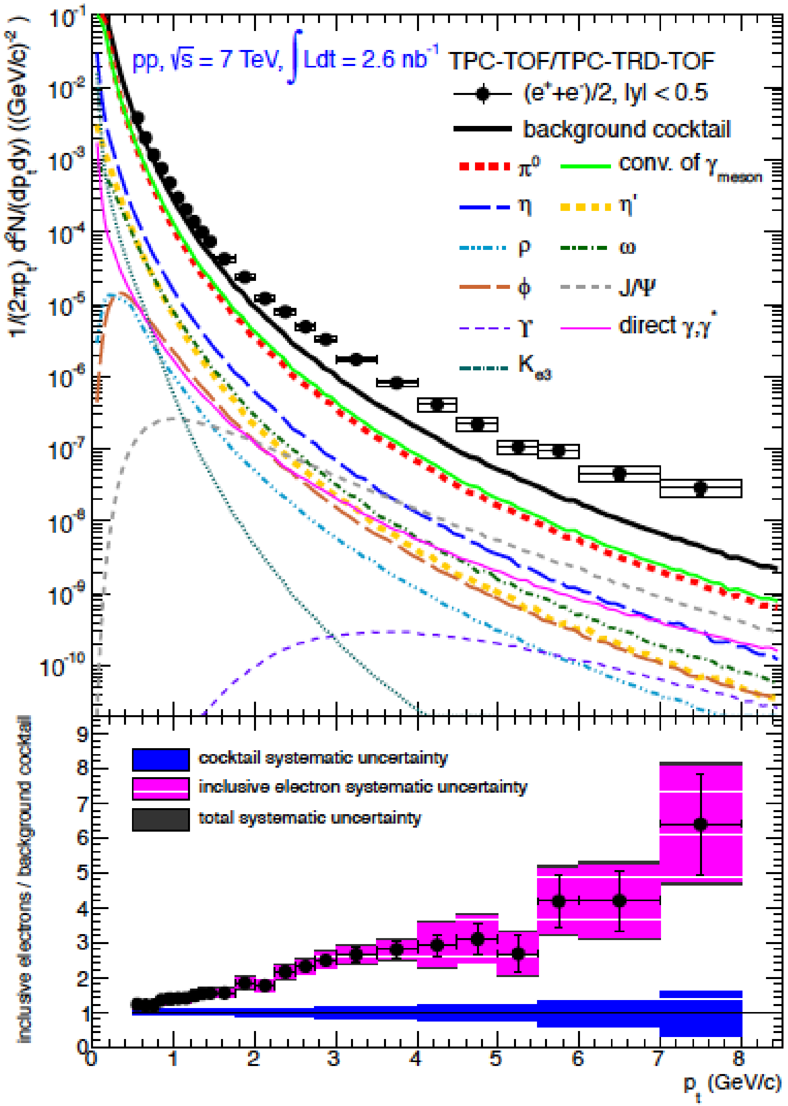
Inclusive electrons in pp at √s=7 TeV

Inclusive electron spectrum

Electron ID with TPC and TOF-TRD or EMCal

Cocktail of "background" electrons

- Dalitz decays. Input: the measured π^0 spectrum
- Heavier mesons by m_T scaling
- Photon conversions
- J/ψ, Υ
- QCD photons (γ, γ*)

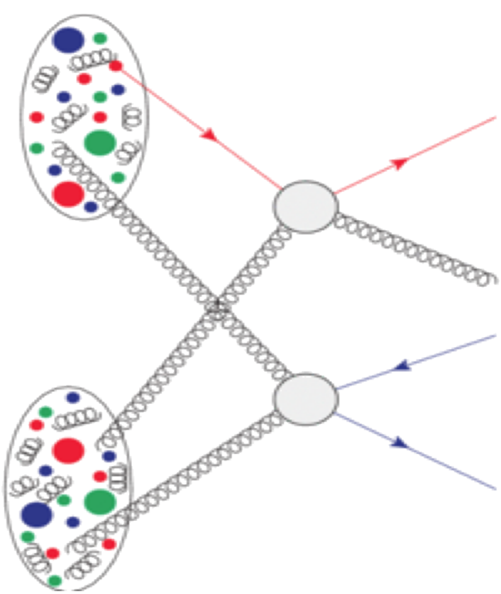


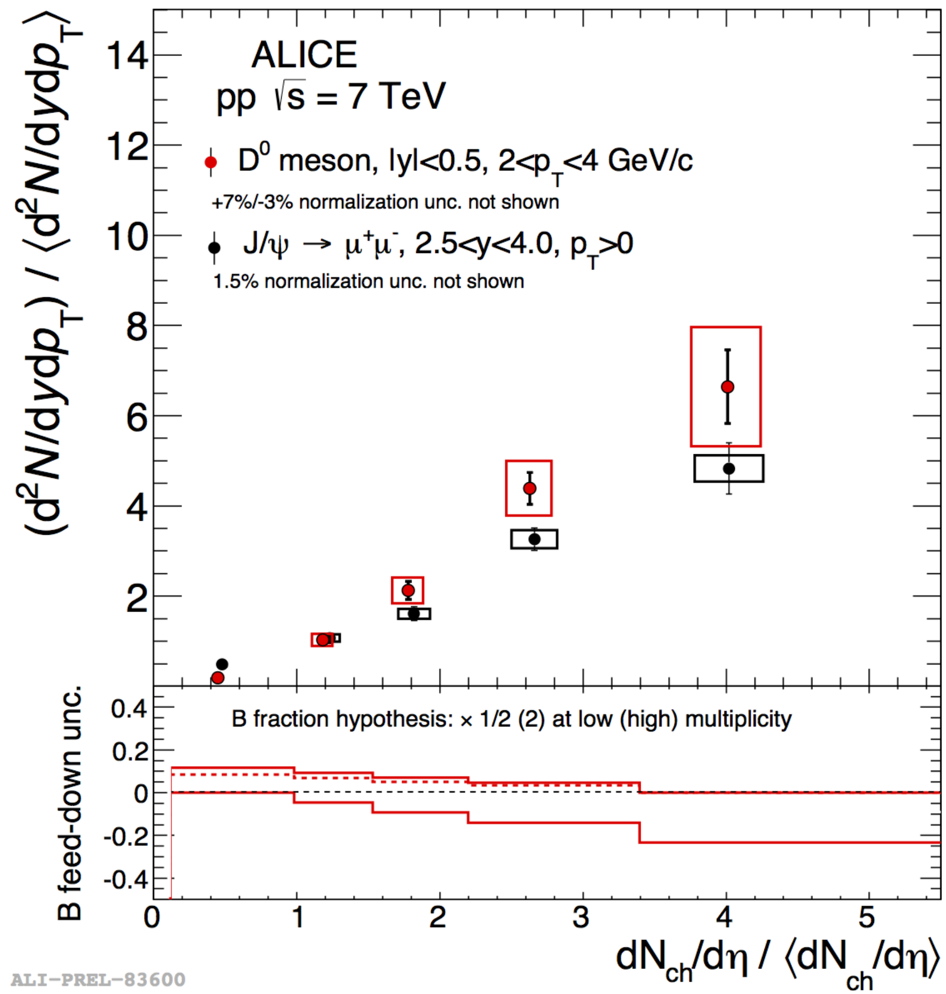
Phys.Rev. D86 (2012) 112007

D-meson yields vs multiplicity

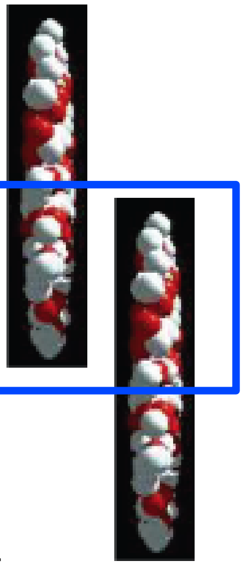
Self-normalized D-meson yields vs charged track multiplicity

- Yield per event increases with multiplicity
- Similar behavior to J/ψ production, also at mid rapidity



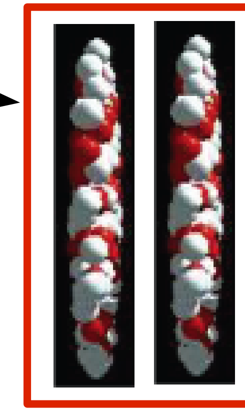


Geometry of a Pb-Pb collision

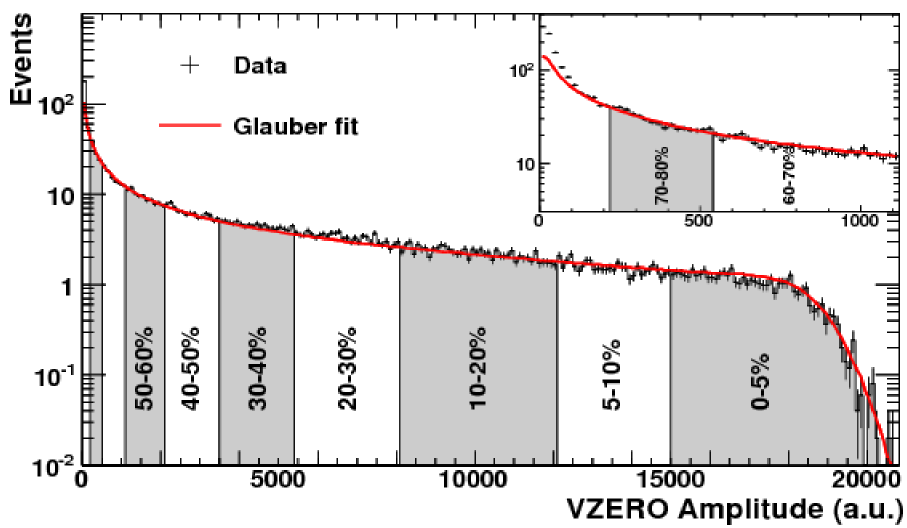


Central collisions → high number of **participants**
→ high multiplicity

Peripheral collisions → low number of **participants**
→ low multiplicity



E.g. measure by VZERO scintillators + reproduced by Glauber model fit

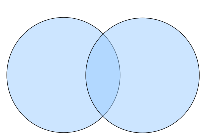


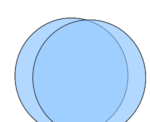
Centrality: percentile of total hadronic cross section

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

arXiv:1301.4361

peripheral





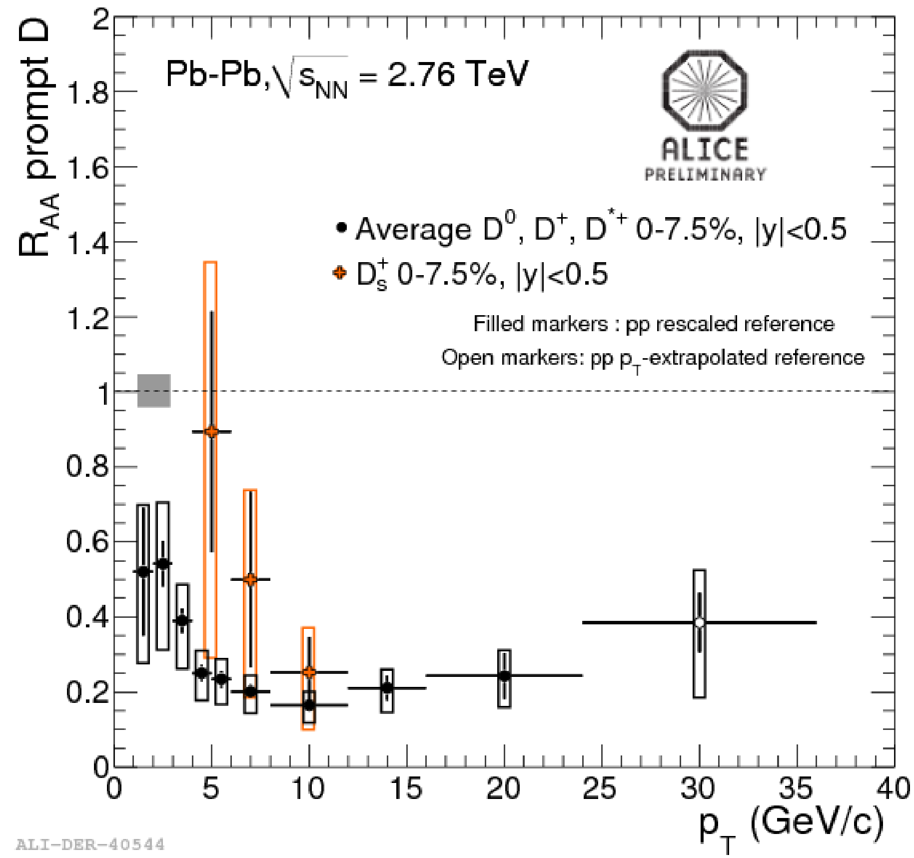
central

Charm: D_s mesons

D^0, D^+, D^{*+} **averaged**

D_s

expected to be slightly different from non-strange D mesons at intermediate p_T: possible enhancement due to recombination / coalescence



Kuznetsova, Rafelski, EPJC 51(2007) 113; He et al, PRL 110(2013)112301; Andronic, PLB 659(2008)149

p-Pb: D-hadron correlations

- Sensitive to contributions from the different production mechanisms
- Sensitive to charm fragmentation: parton shower, hadronization

- pp: within uncertainties, described by PYTHIA
- p-Pb: compatible with pp after baseline subtraction

No indication for
cold nuclear matter effects