Heavy flavour measurements
by the ALICE experiment at LHC

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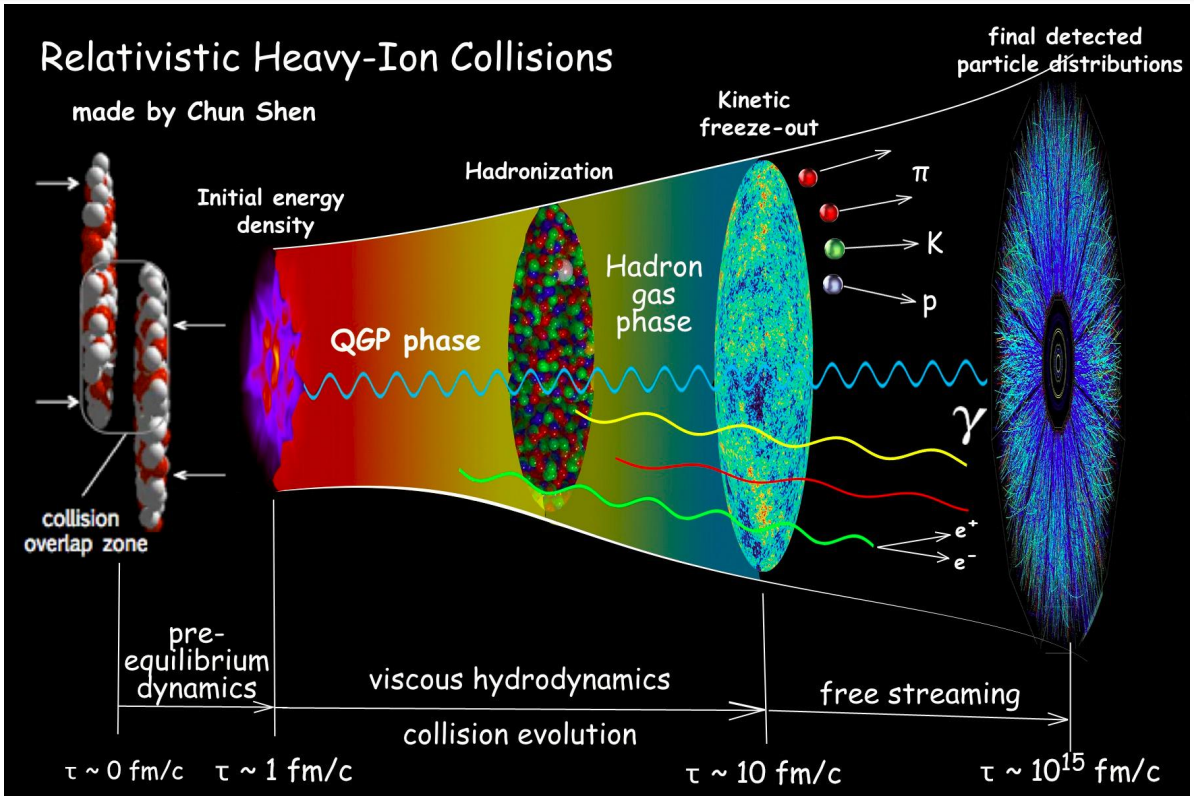
The Quark Gluon Plasma



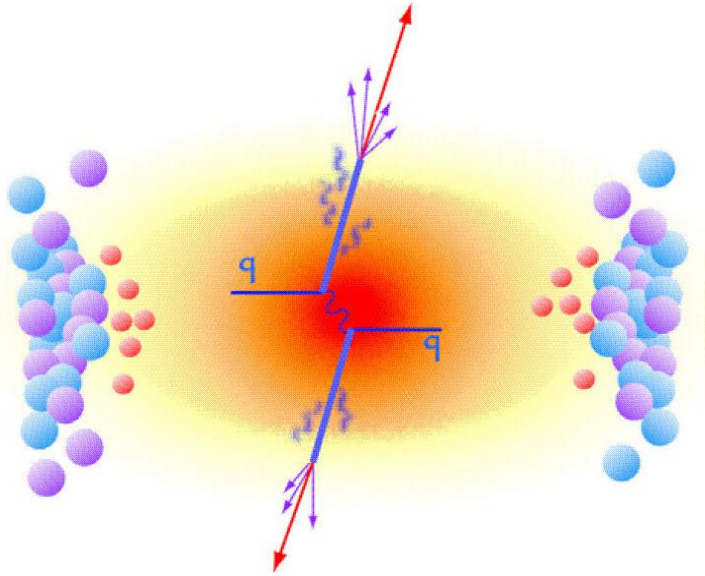
Heavy-ion collisions are hot and dense enough to deconfine quarks!

- Theory expectations: gas-like material where quarks roam freely
- Experimental findings: a nearly perfect fluid of quarks! → **sQGP**
  - strongly coupled
  - extremely low viscosity

sQGP: experimental approaches

- **"Hard" probes**
  - few particles with high momenta
  - produced in the early stages
  - penetrate the plasma
  - **Modification in the medium**

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dy}{dN_{pp}/dy}$$



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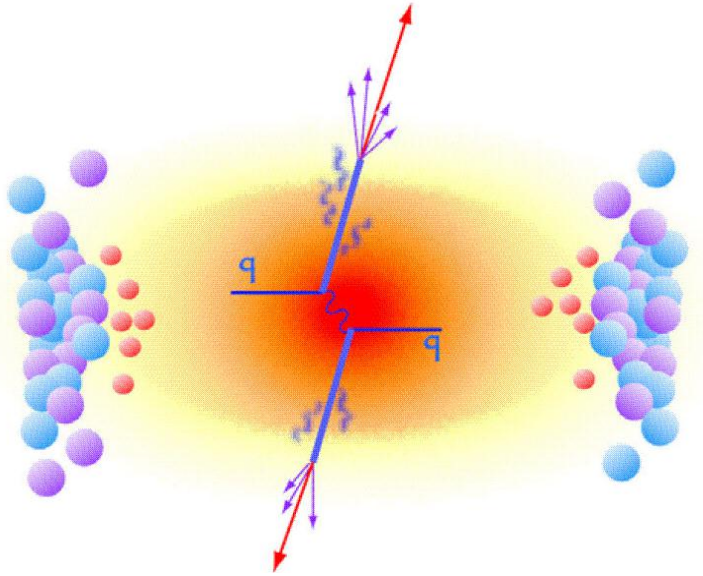
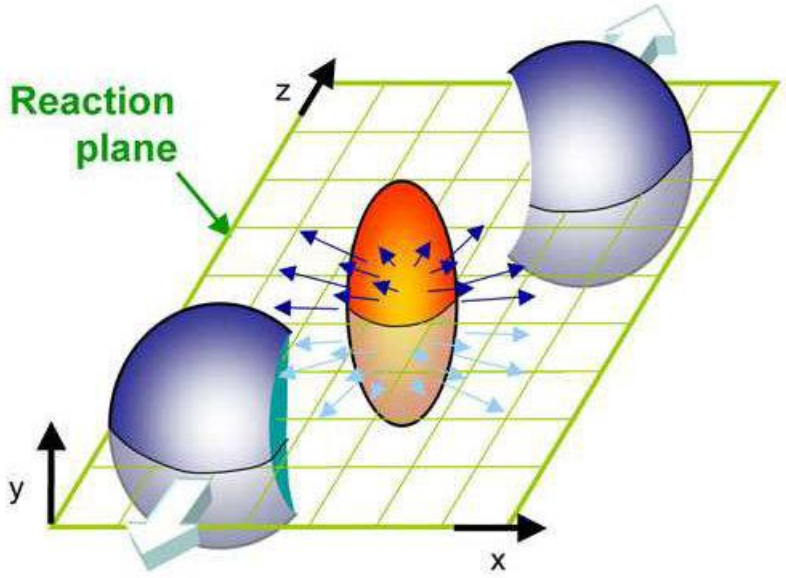




- **"Soft" processes**
  - Many particles with low momenta
  - Information from late stages
  - **Collective dynamics ("flow")**

$$\frac{dN}{d\phi} \sim 2v_2 \cos\left(2\left(\phi - \phi_{RP}\right)\right)$$

  - **Thermal behaviour ...**

Heavy-flavour (HF) probes

- Heavy quarks are produced early

  $\tau_{c,b} \sim \frac{1}{2}\, m_{c,b} \sim 0.1$ fm $\ll \tau_{QGP} \sim$ 5-10 fm

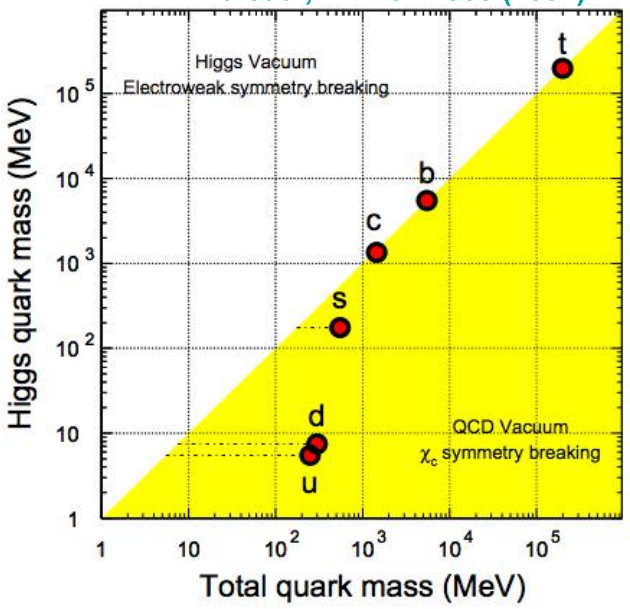
- Heavy quarks are (almost) conserved

  $m \gg \Lambda$ (m_c~1.5 GeV, m_b~5 GeV)

  - No flavour changing
  - Negligible thermal production

  → Very little production or destruction in the sQGP

X. Zhu et al, PLB 647 366 (2007)



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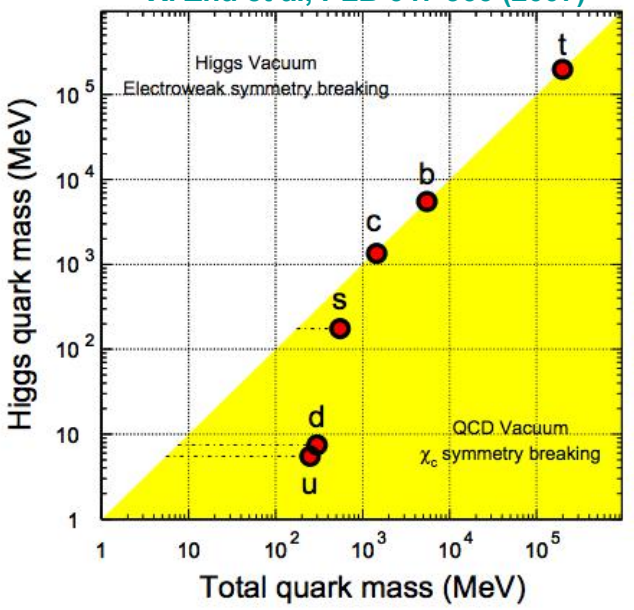
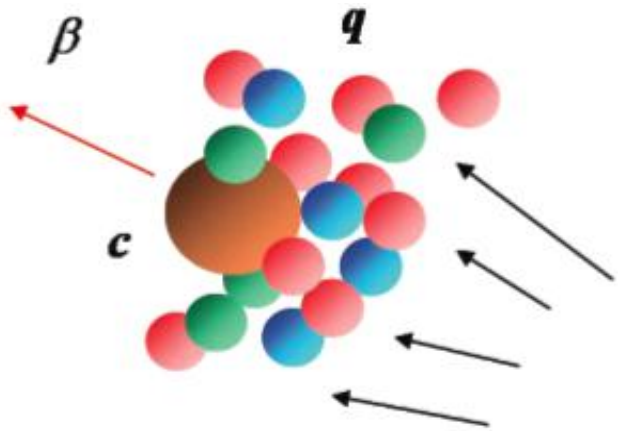


- Transport through the whole system
  - Kinematical properties changed within the sQGP: **collisional and radiative energy loss**
  - Access to **transport properties** of the system
  - ...down to **low momenta**
  - **Heavy vs. light? Charm vs. bottom?**



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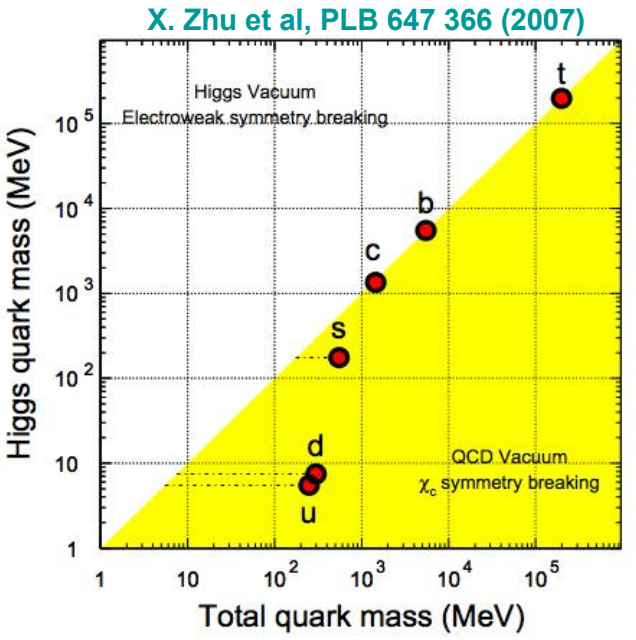

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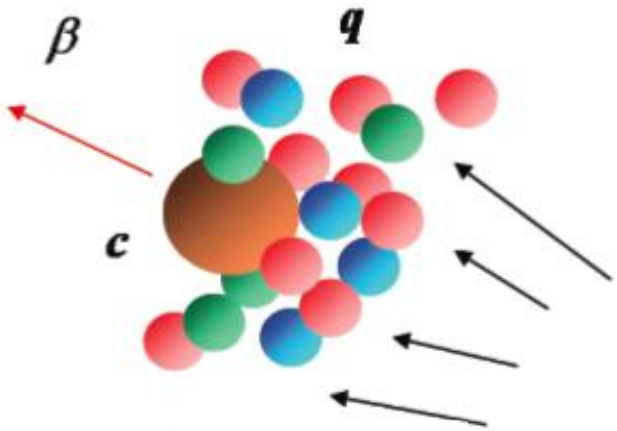
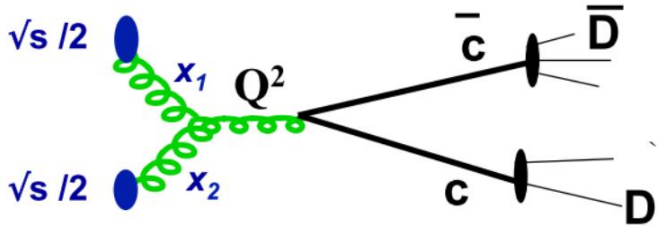


Penetrating probes down to low momenta!

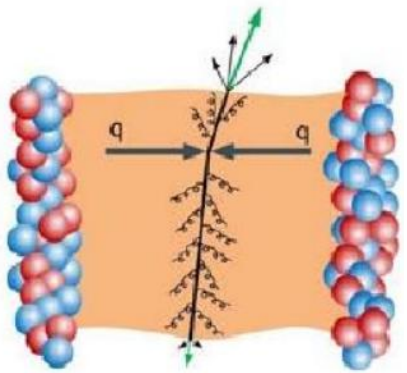
Systems and processes

- **pp collisions**: Reference system and pQCD benchmark



- **p-A collisions**: Understand cold nuclear matter (CNM) effects

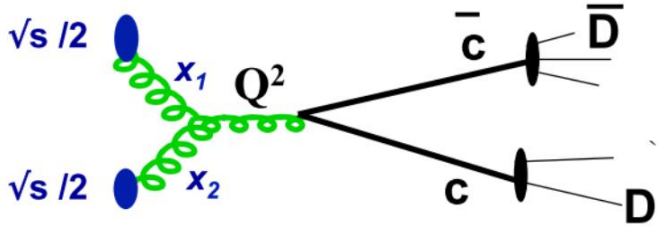
- **A-A collisions**: Hot medium effects (in addition)



A+A

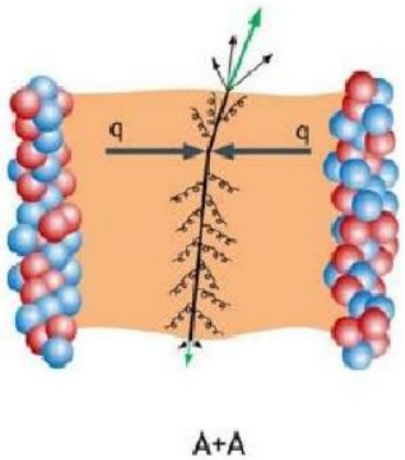
Systems and processes

- **pp collisions**: Reference system and pQCD benchmark
  - Investigate production mechanisms
    - LO: q-q annihilation, g-g fusion
    - NLO: gluon splitting
    - Multi-parton interactions



- **p-A collisions**: Understand cold nuclear matter (CNM) effects
  - PDF modification: (anti)shadowing, gluon saturation
  - Energy loss in CNM, k_T-broadening

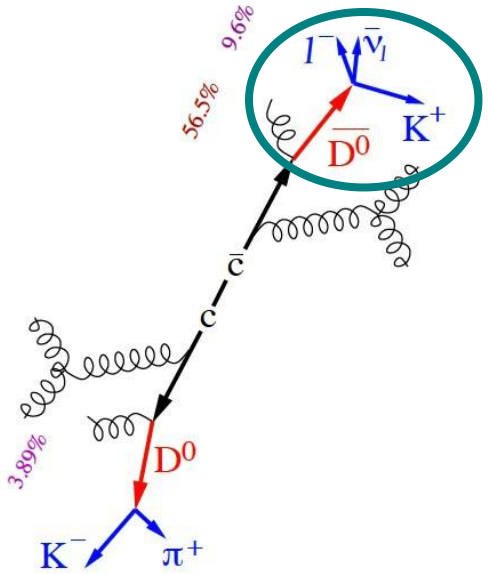
- **A-A collisions**: Hot medium effects (in addition)
  - Parton energy loss → *nuclear modification* R_{AA}
    - Radiative versus collisional?
    - Expected ordering by mass:
      $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow R_{AA}^{h} < R_{AA}^{D} < R_{AA}^{B}$
  - Collectivity → *asymuthal anisotropy* v_2
    - Dynamics; rescattering?
    - Thermalization of heavy flavours?



Experimental access to open HF

- Indirect semi-leptonic decays
  - higher branching ratio, easier trigger
  - a mixture of *c, b* contributions

  → *b* can be isolated via displaced electrons



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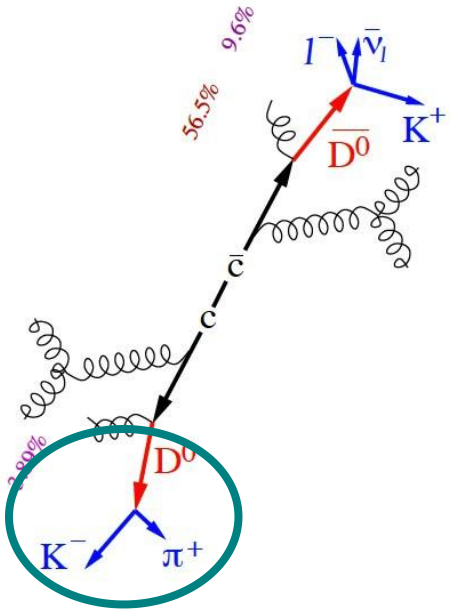
  - Access to kinematics
  - High background (→ secondary vertex)



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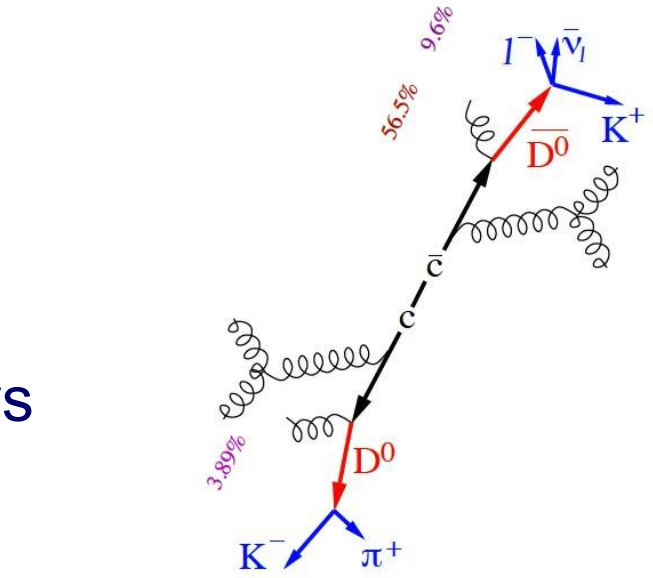

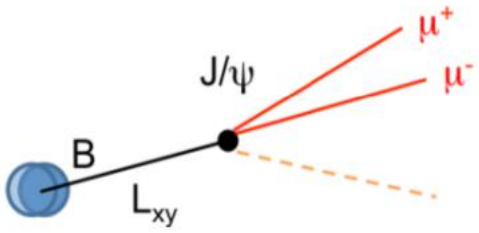

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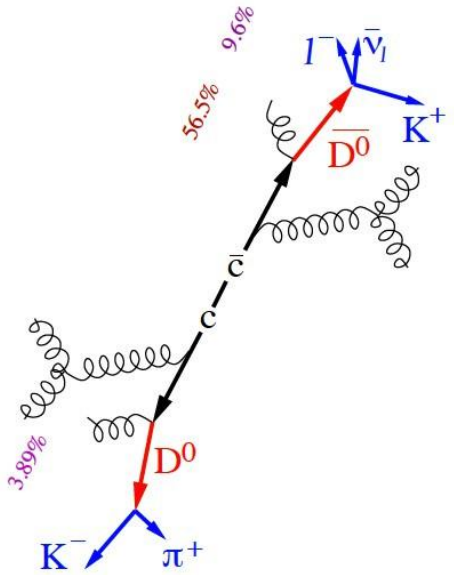

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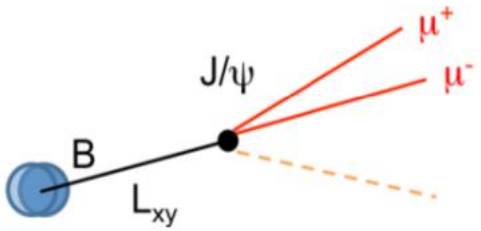
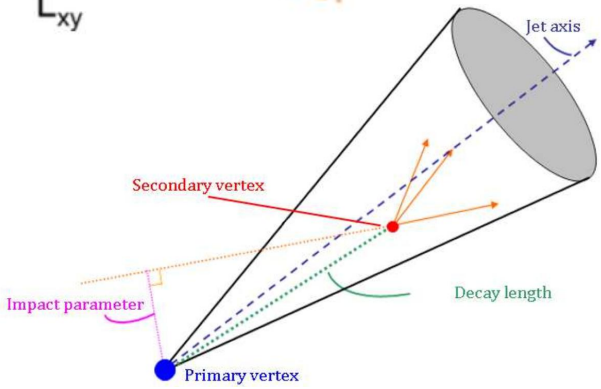
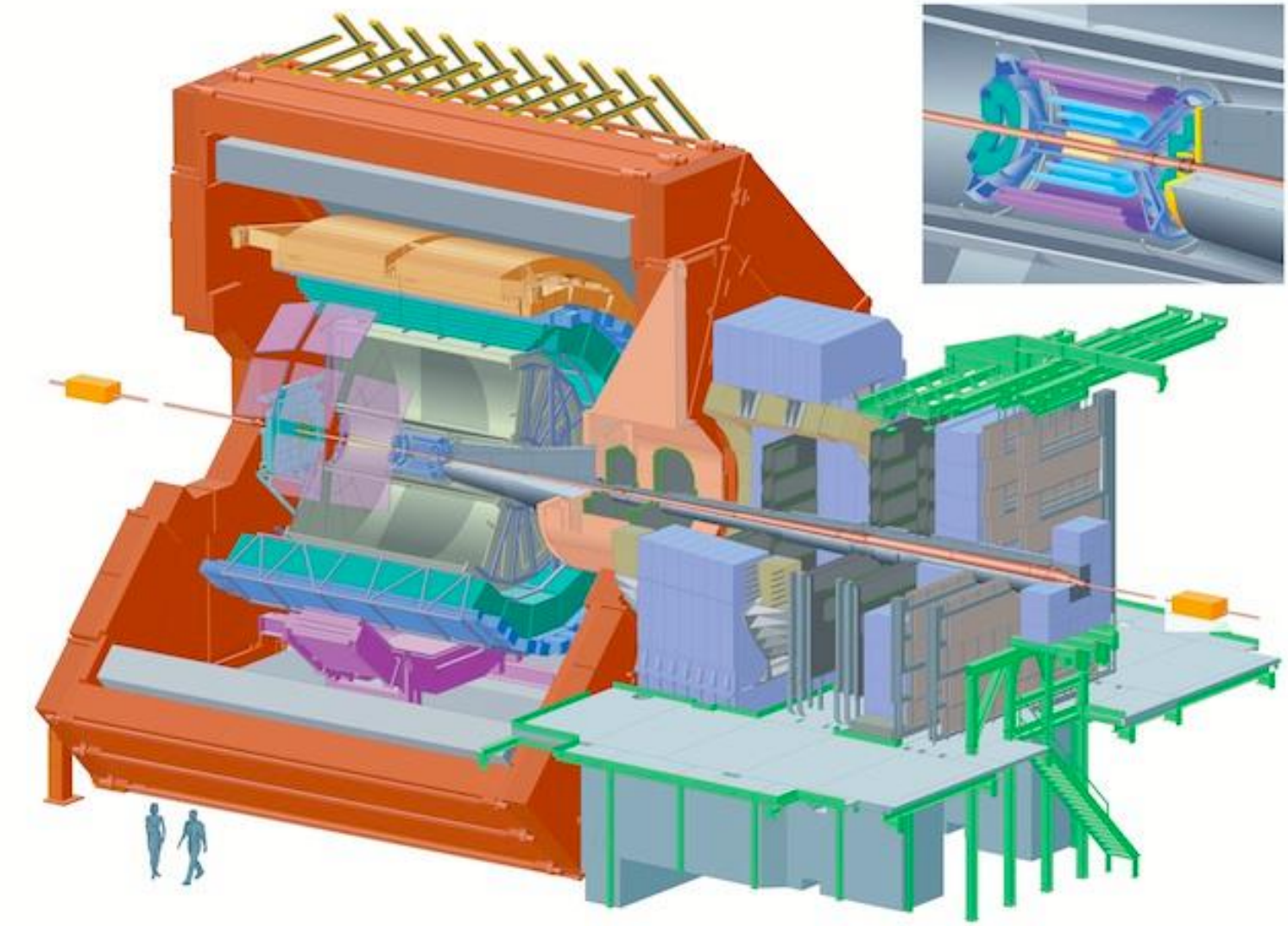


- Full jet reconstruction: D in jets, b-tagging
  - Insight to fragmentation properties
  - Tag via secondary vertex or impact parameter

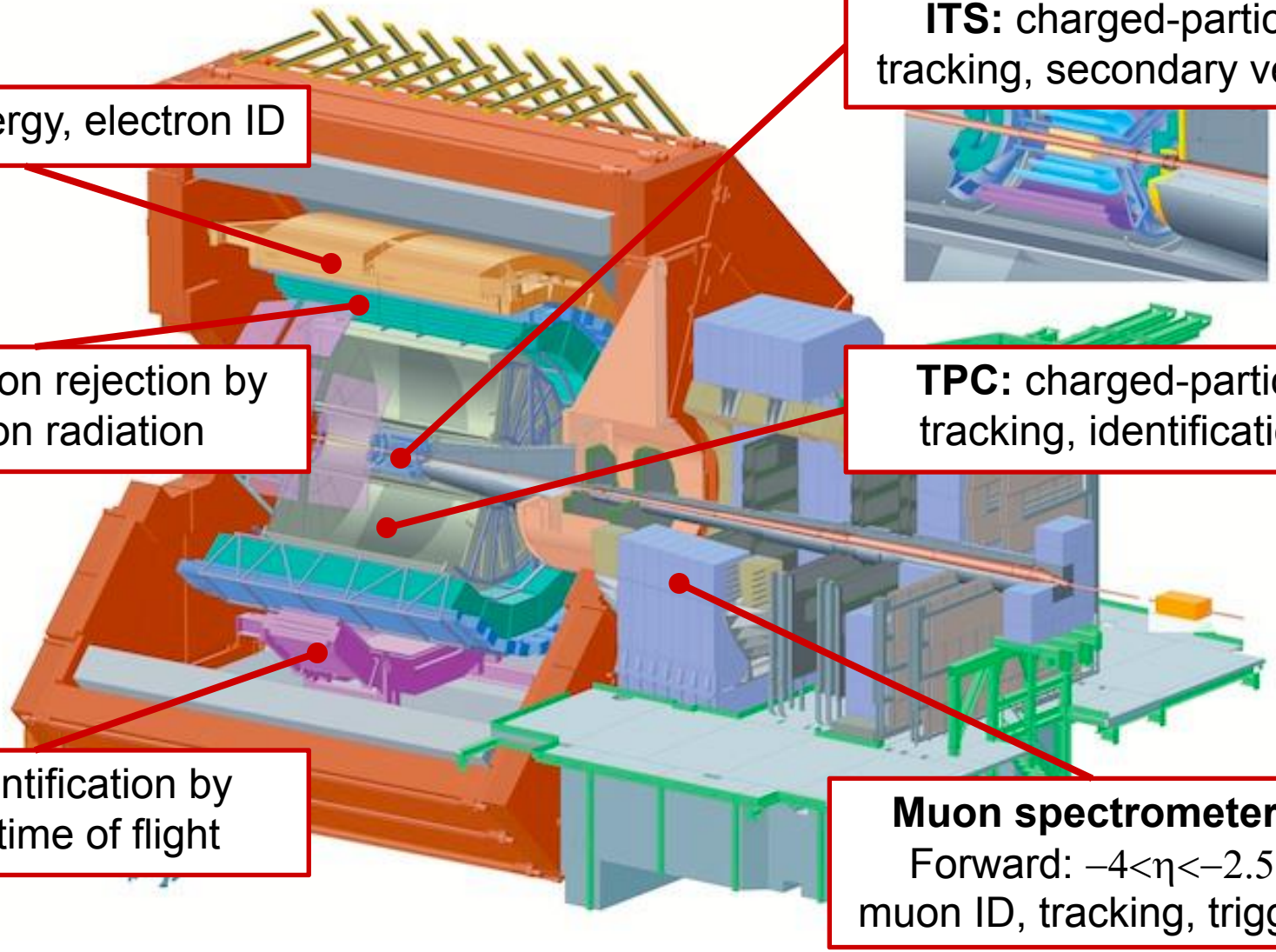


ALICE



- A dedicated heavy-ion experiment at the LHC

ALICE



ITS: charged-particle tracking, secondary vertex

EMCal: energy, electron ID

TRD: hadron rejection by transition radiation

TPC: charged-particle tracking, identification

TOF: identification by precise time of flight

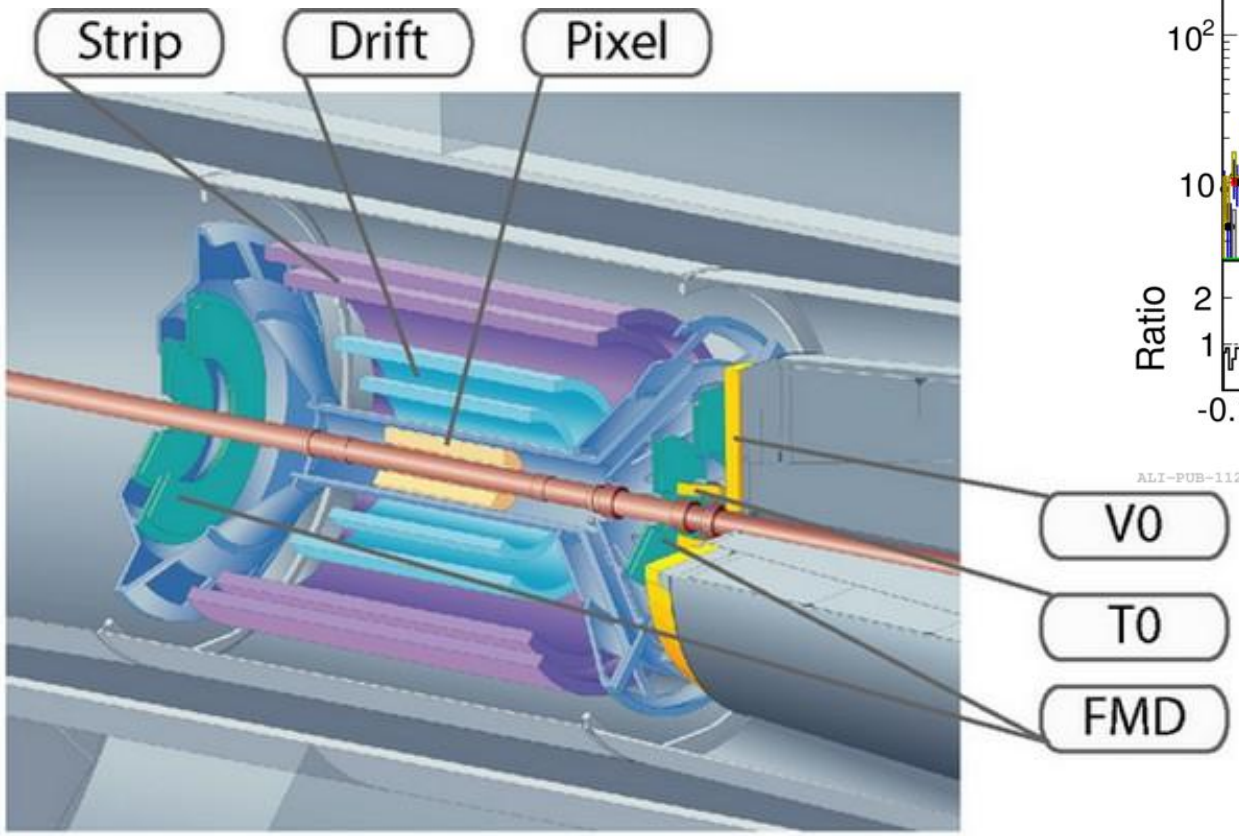
Muon spectrometer:
Forward: $-4<\eta<-2.5$
muon ID, tracking, trigger

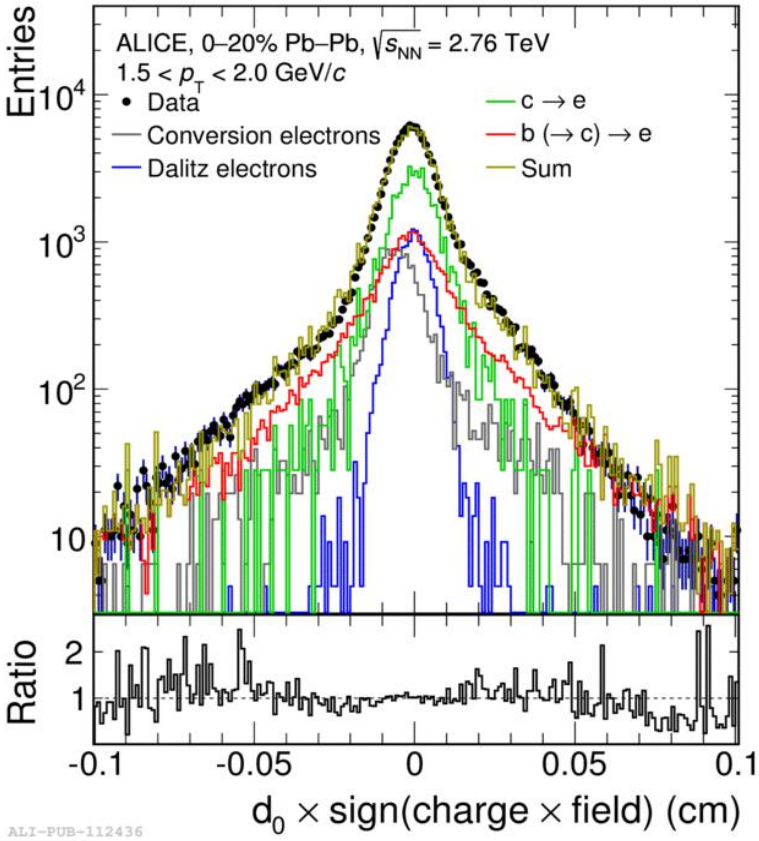
- A dedicated heavy-ion experiment at the LHC

ITS

- Semiconducting technology
- Resolves secondary vertex

heavy quark lifetimes: $c\tau(D) \sim 100\text{-}300\ \mu m$
$c\tau(B) \sim 400\text{-}500\ \mu m$
Secondary vertex resolution: $<100\ \mu m$



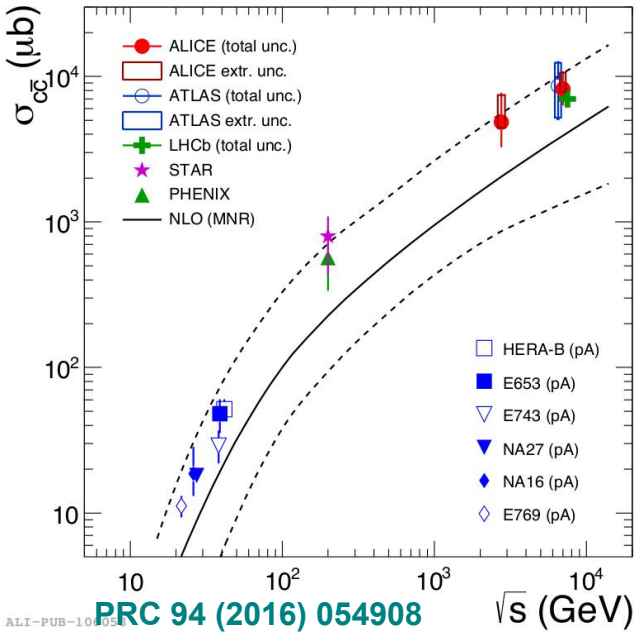


arXiv:1609.03898

pp collisions

learning about pQCD

D^0 mesons vs. pQCD calculations



Calibration of HF models: x-section vs. $\sqrt{s}$

- ALICE data from D^0 fits in world data trend
- pQCD models give adequate description with sizeable uncertanties

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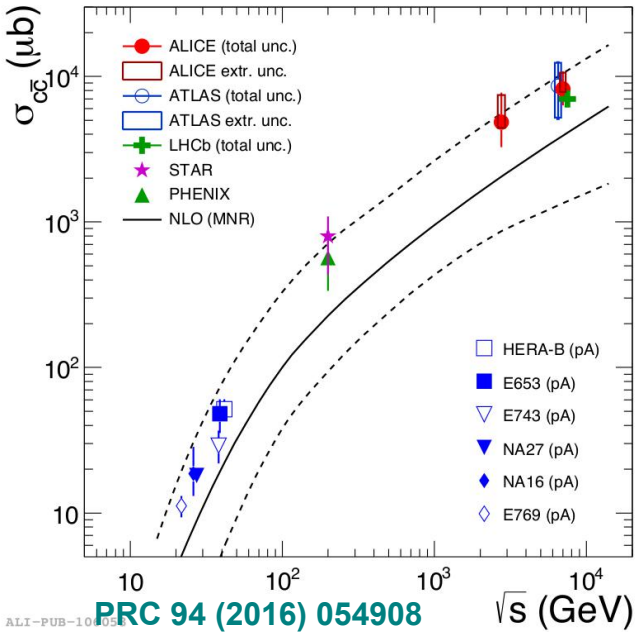

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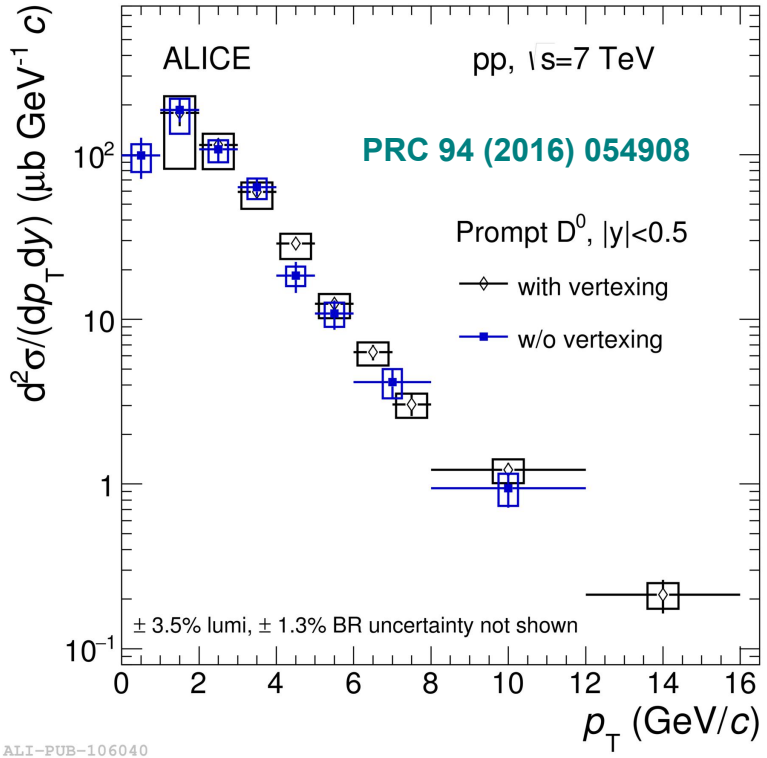
p_T-spectrum: reference for heavy ions

- Vertex reconstruction helps at higher p_T
- Very low p_T: only PID, no topological cuts



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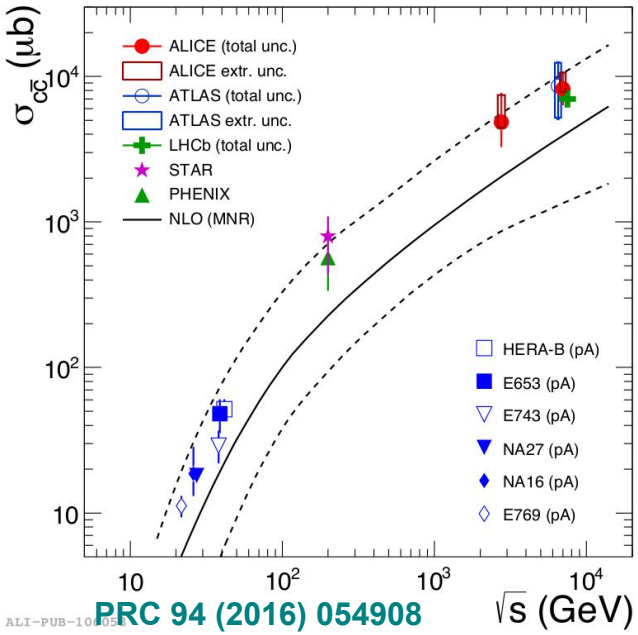

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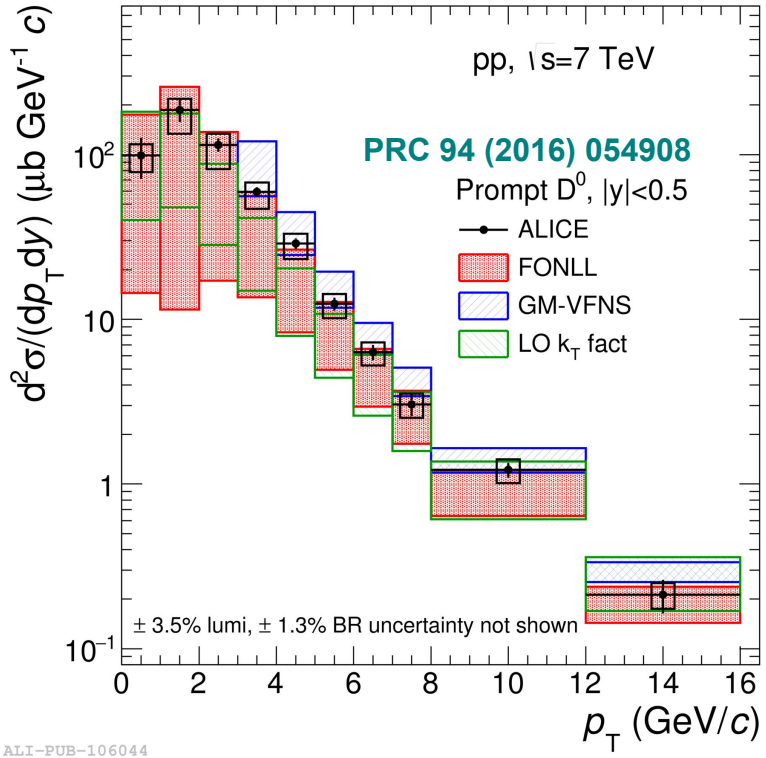
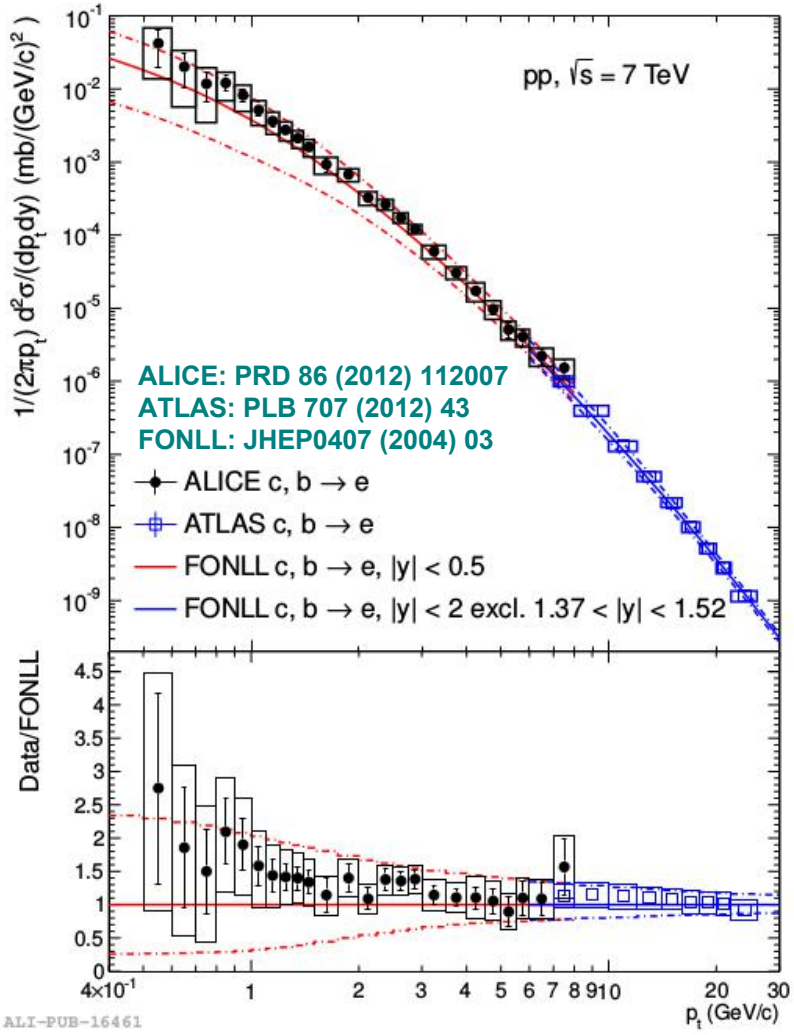


Agreement with pQCD models

FONLL: JHEP0407 (2004) 033
GM-VFNS: EPJ C72 (2012) 2082
LO k_T-fact.: PRD 87 (2013) 094022

HF electrons vs. calculations



- FONLL pQCD provides good description over a wide p_T range

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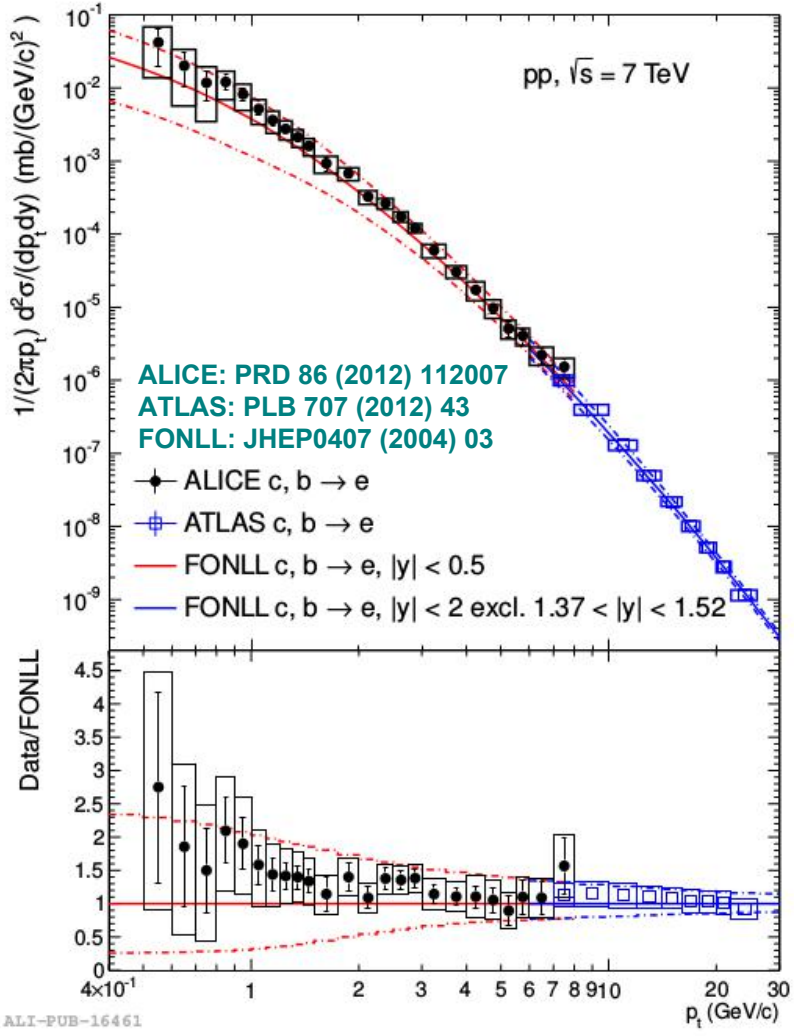

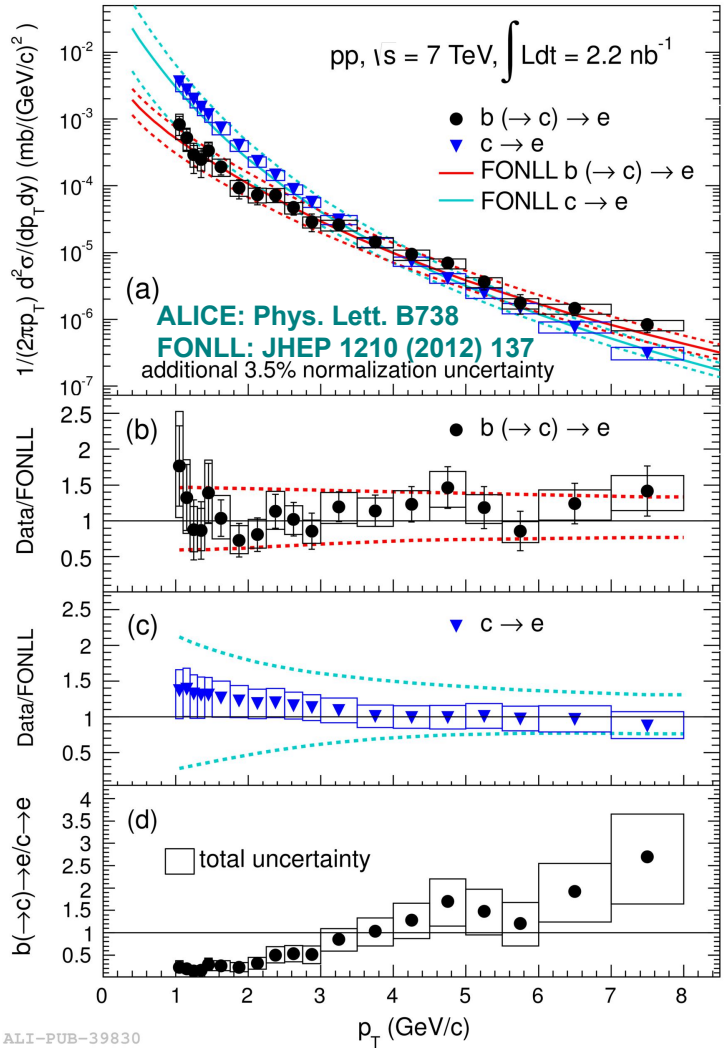

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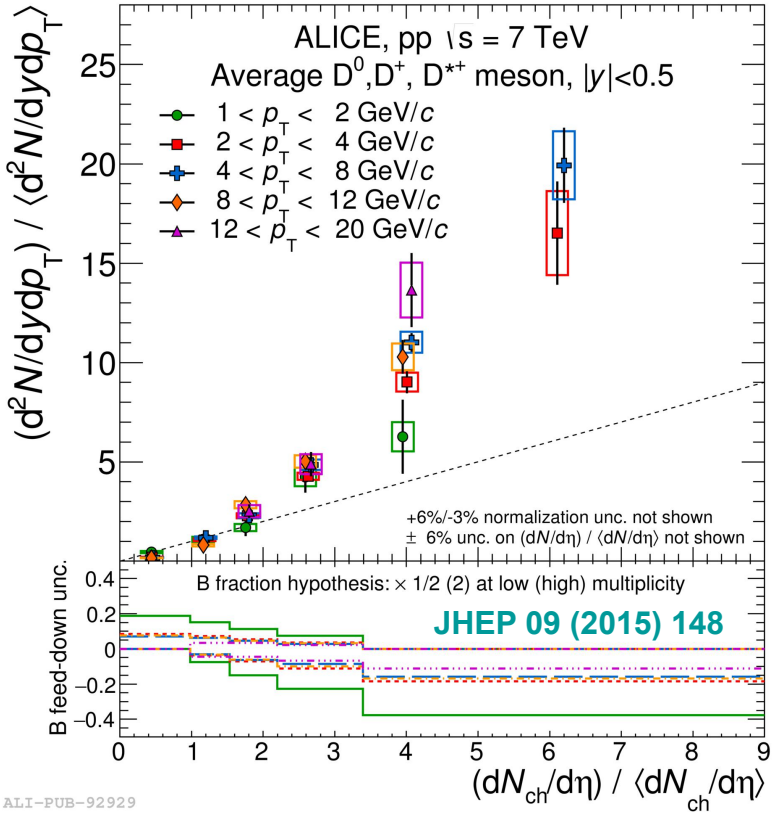
- Both for beauty and charm

Production vs. event activity



- Production of **D mesons** increases steeper than linear with multiplicity

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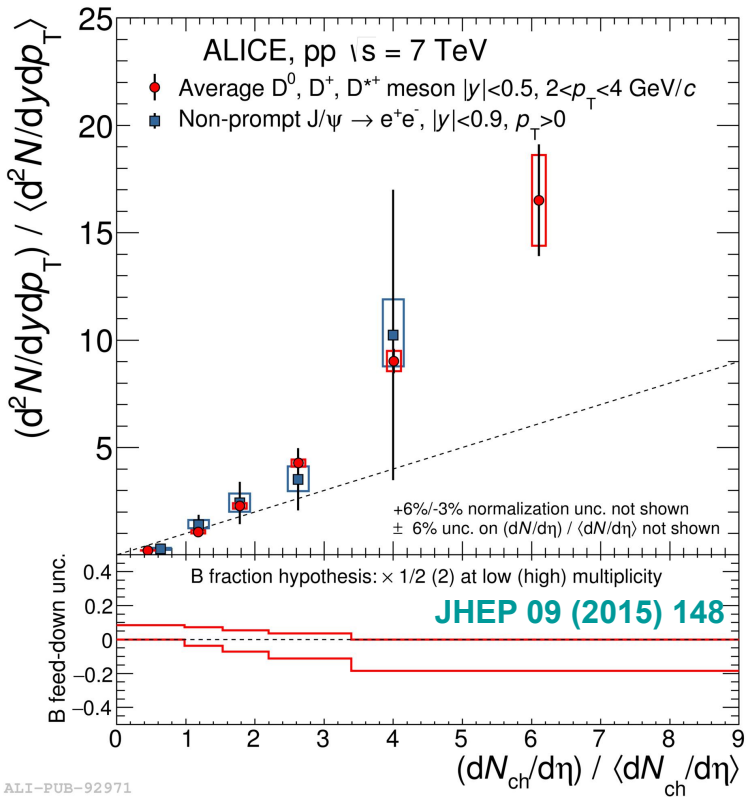
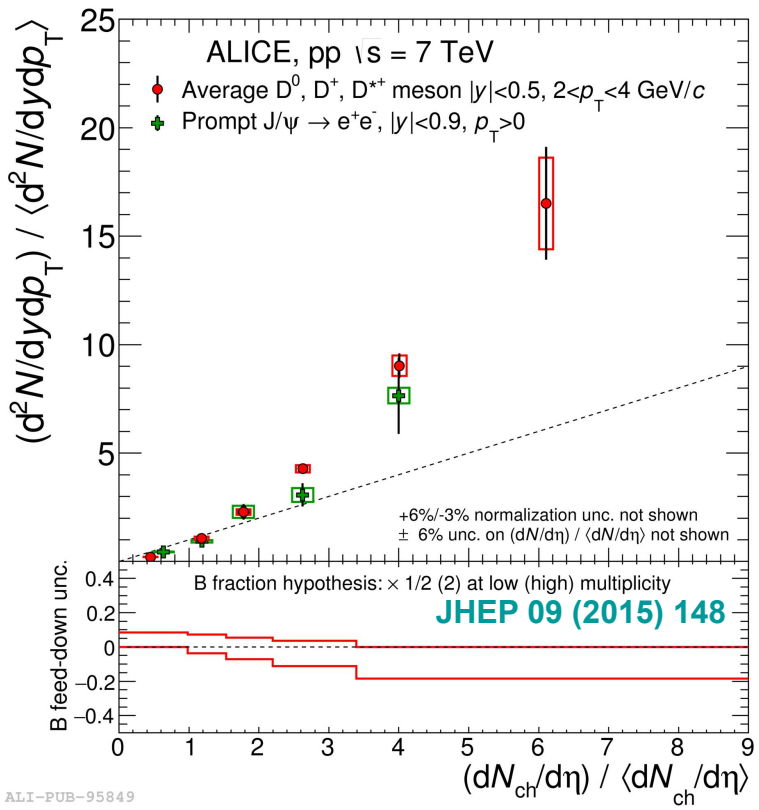


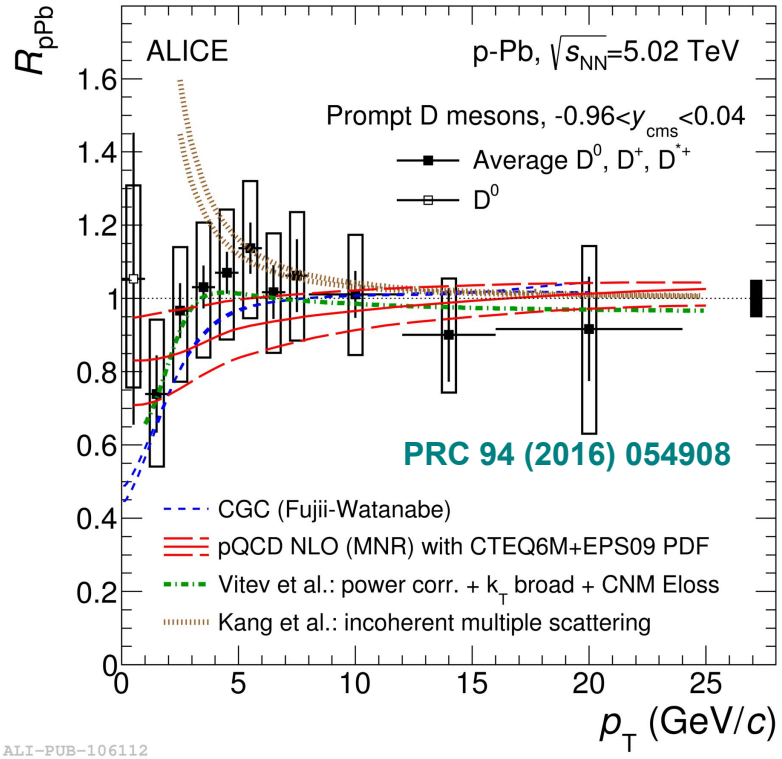


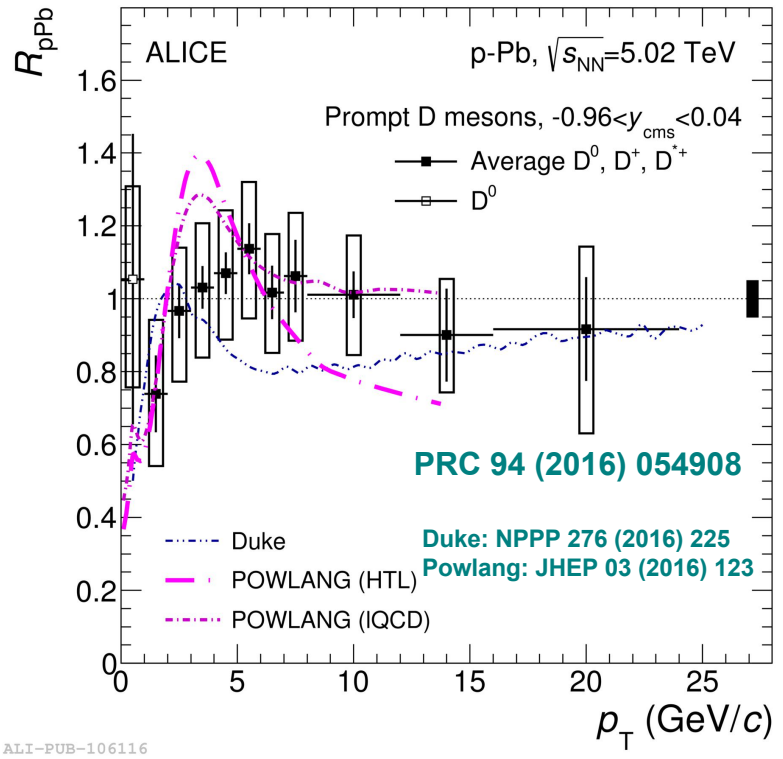
- Production of **D mesons** increases steeper than linear with multiplicity
- Same trend in **non-prompt (B→)J/Ψ** as well as **prompt J/Ψ** yields
  - → No strong flavor dependence
  - → Charm production appears to be independent of hadronization!
- Understanding: **multiple parton interactions**

p-A collisions

cold nuclear matter effects

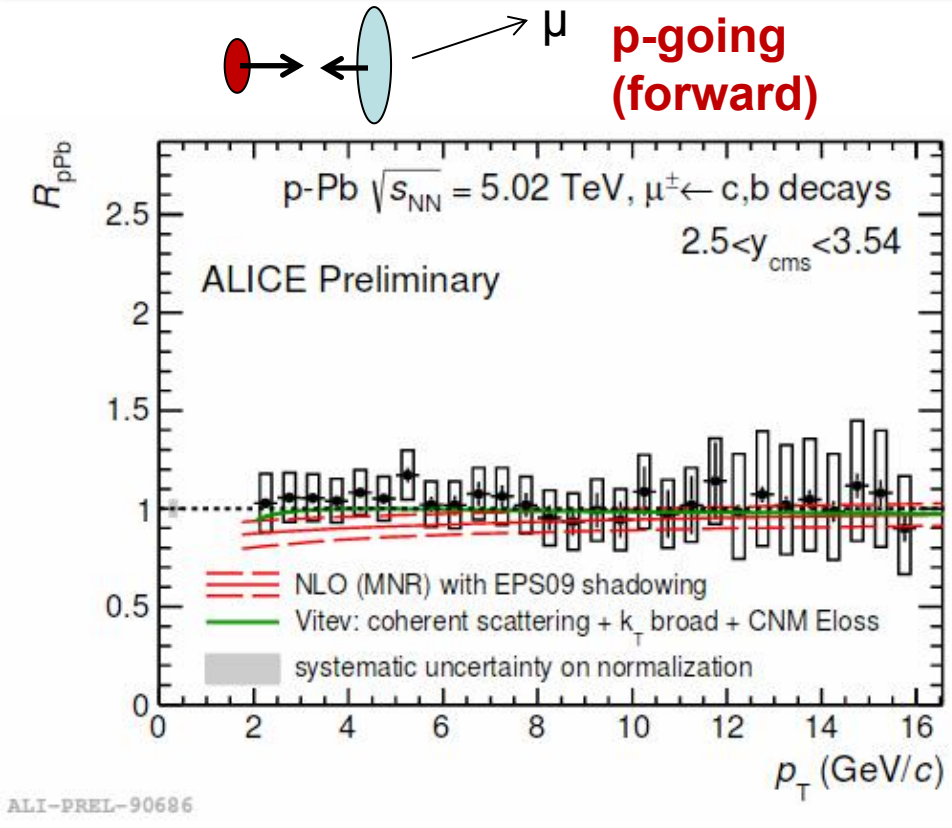
D mesons in p-Pb collisions

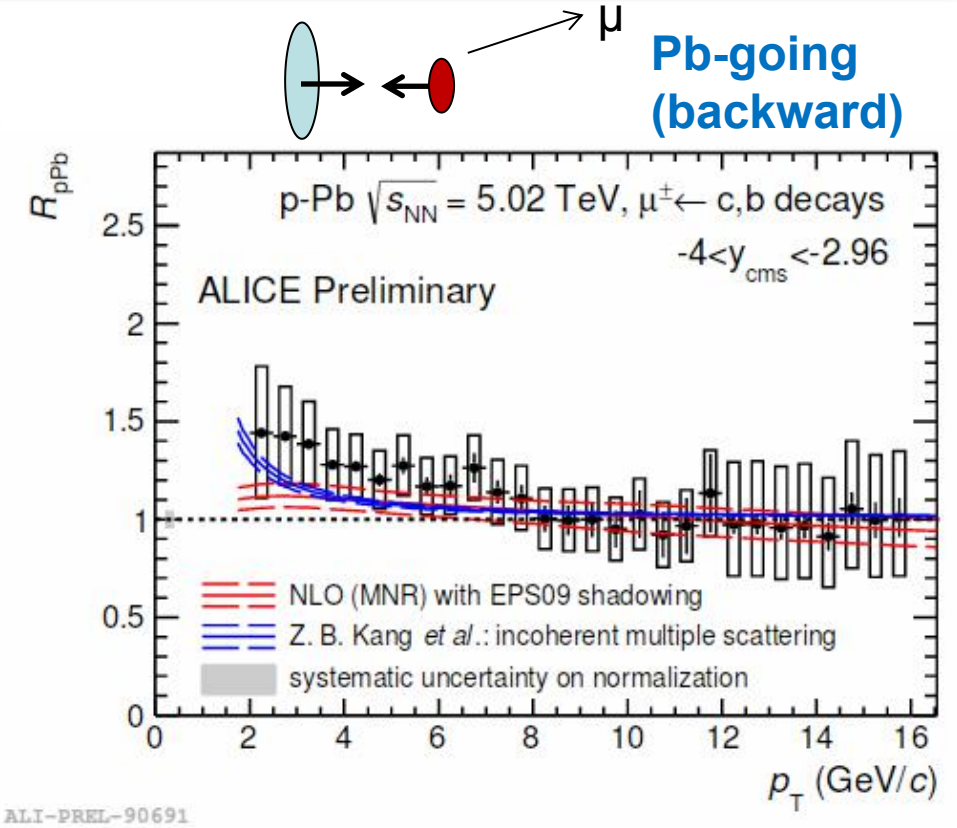




- Nuclear modification is moderate in p-Pb collisions
- No indication of CNM effects from intermediate to high p_T
- Data described by models containing initial-state and CNM effects
- Hot quark matter in a small volume cannot be excluded
  - Scenarios involving more than 20% nuclear modification are unlikely

Forward and backward: muons



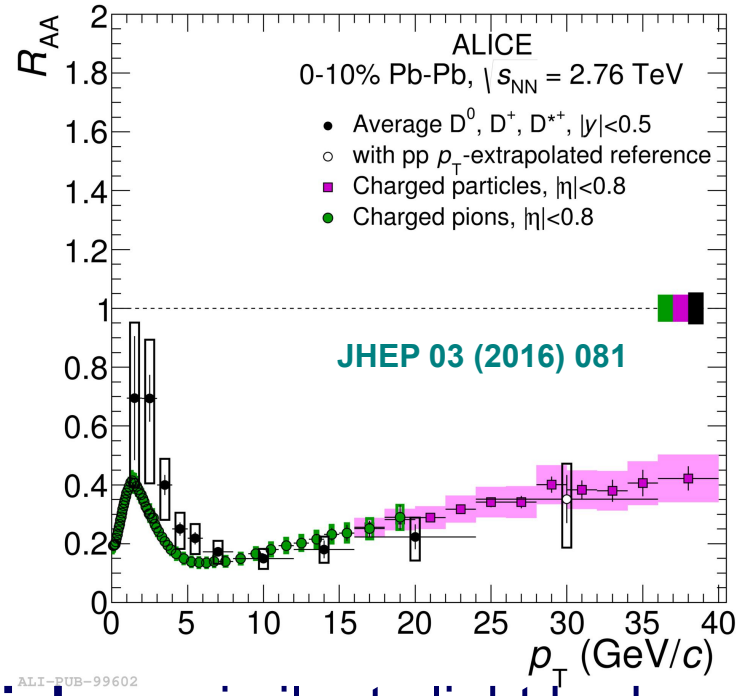


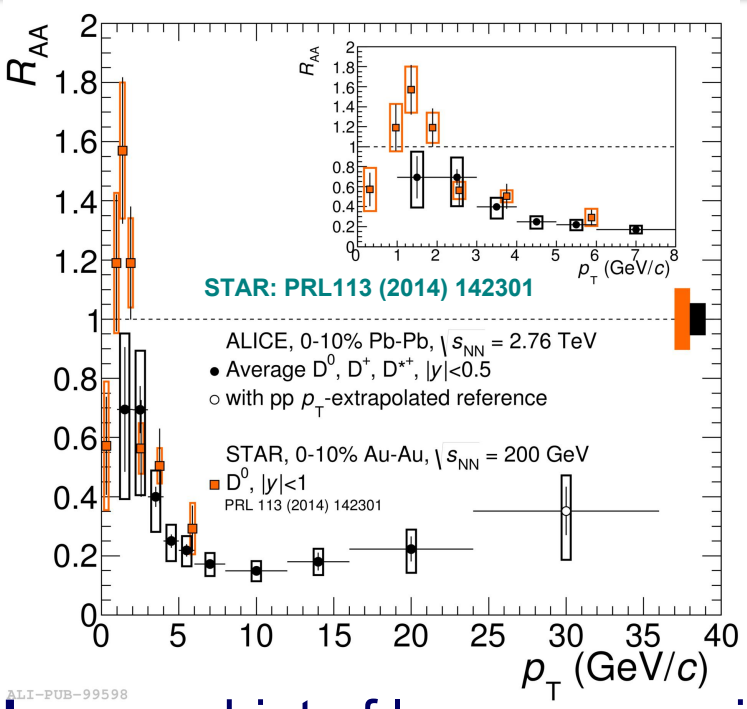
- Heavy flavour decay muons probe the nPDFs at different *x* values
- HF decay muon production is consistent with no nuclear modification
  - **Hint of an enhancement of backward intermediate-p_T HF decay muons**
- Measurements understood by models within uncertainties

A-A collisions

hot nuclear matter effects

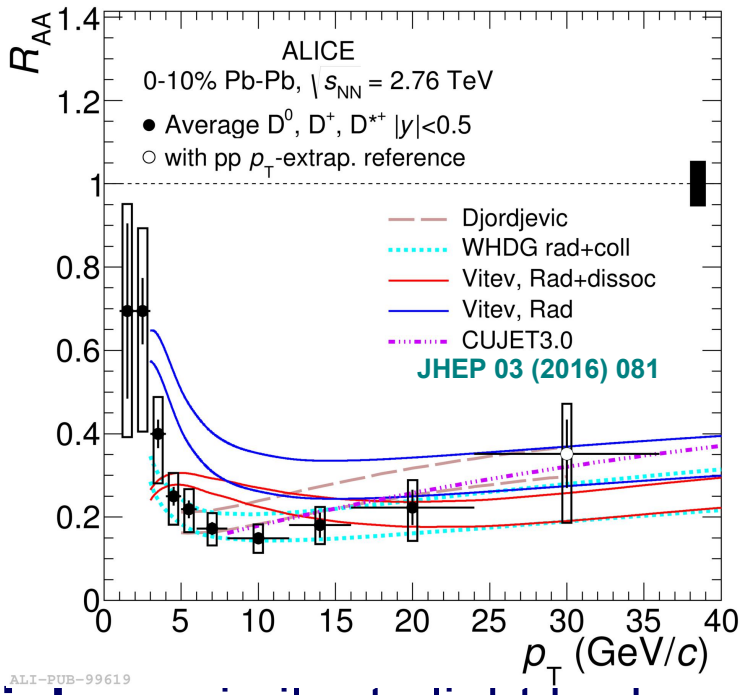
D mesons in Pb-Pb collisions

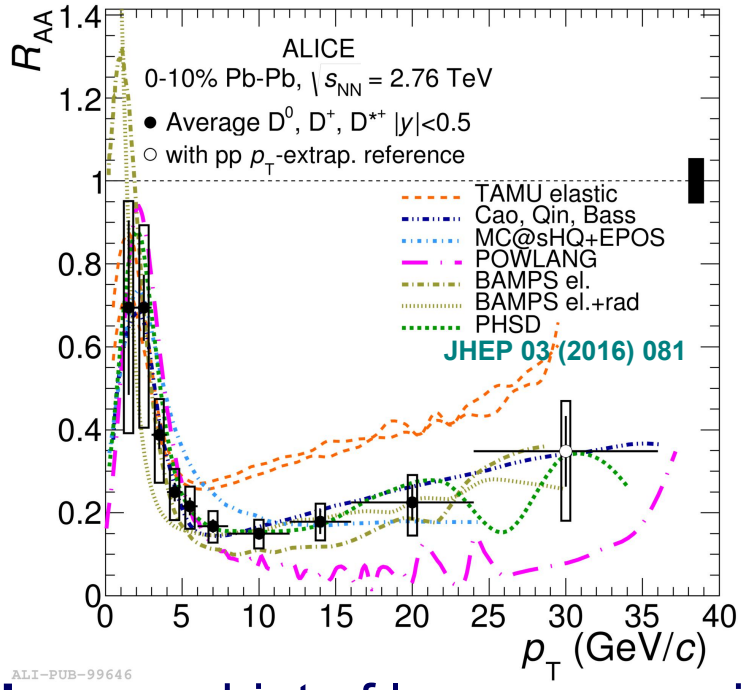




- **High-p_T**: similar to light hadrons
  - ~5x suppression at p_T~5 GeV/c
  - → **strong interaction with medium**
- **Low-p_T:** hint of less suppression
  - Trend is not as strong as at RHIC
  - → **charm-light quark coalescence?**
  - *(Note: also less shadowing, steeper pp spectrum, different radial flow at RHIC!)*

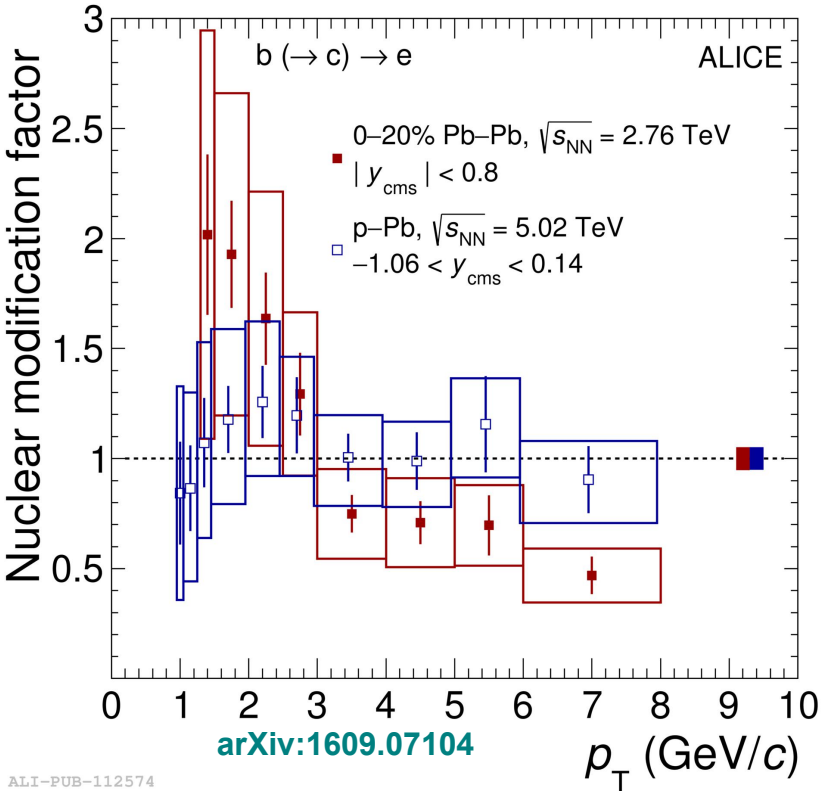
D mesons in Pb-Pb collisions

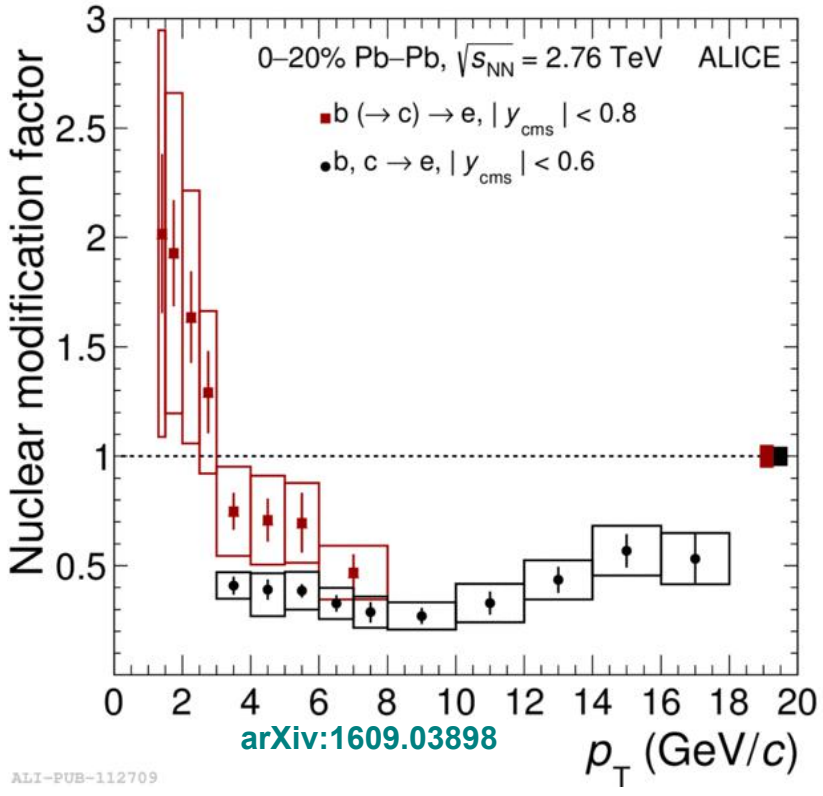




- **High-p_T**: similar to light hadrons
  - ~5x suppression at p_T~5 GeV/c
  - → **strong interaction with medium**
- **Low-p_T:** hint of less suppression
  - Trend is not as strong as at RHIC
  - → **charm-light quark coalescence?**
  - *(Note: also less shadowing, steeper pp spectrum, different radial flow at RHIC!)*
- Several models with different ingredients describe the structure!
  - FONLL or NLO production
  - Collisional vs. radiative energy loss
  - Hydro vs. Glauber
  - Different fragmentation ...

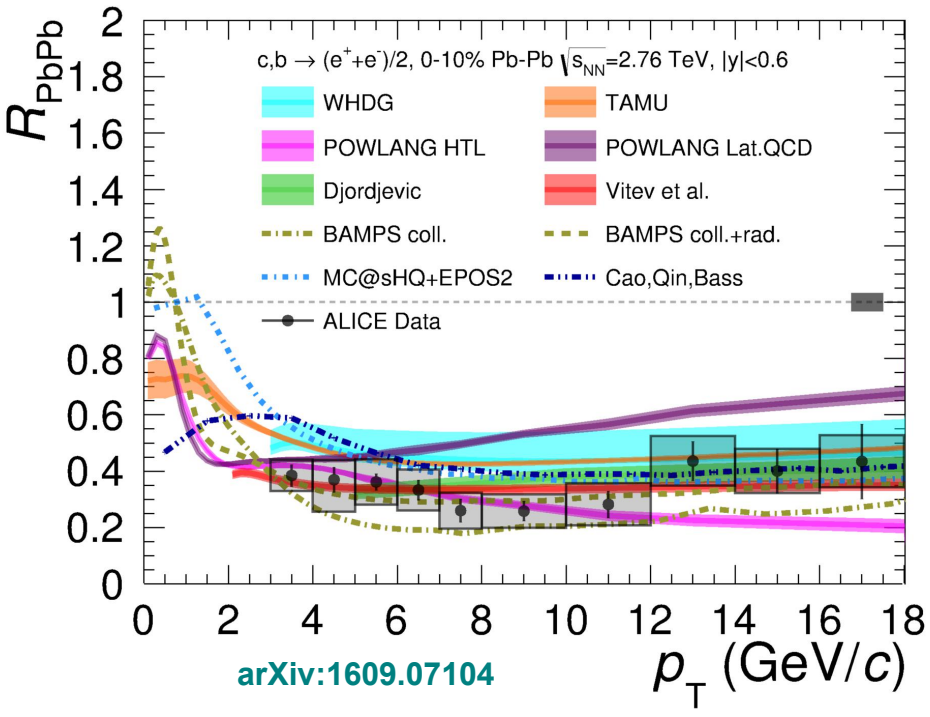
HF electrons in p-Pb and Pb-Pb



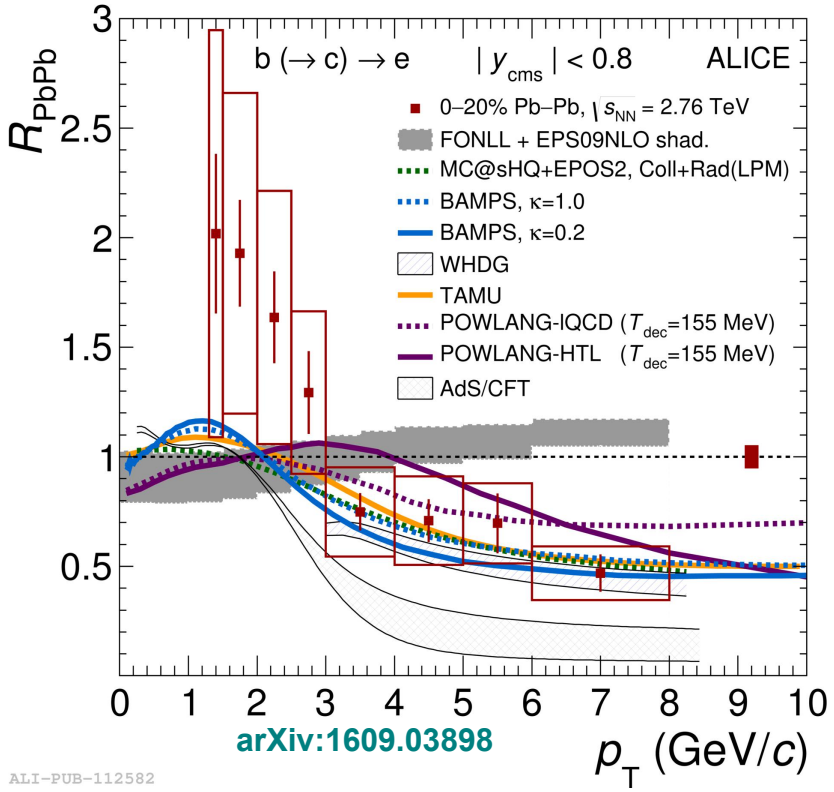


- Significant suppression of HF electrons from intermediate p_T upwards
  - Note: (c,b)→e production in p-Pb collisions consistent with unity
- Separated beauty-decay electrons hint a weaker suppression

HF electrons in Pb-Pb - models



ALI-PUB-114081

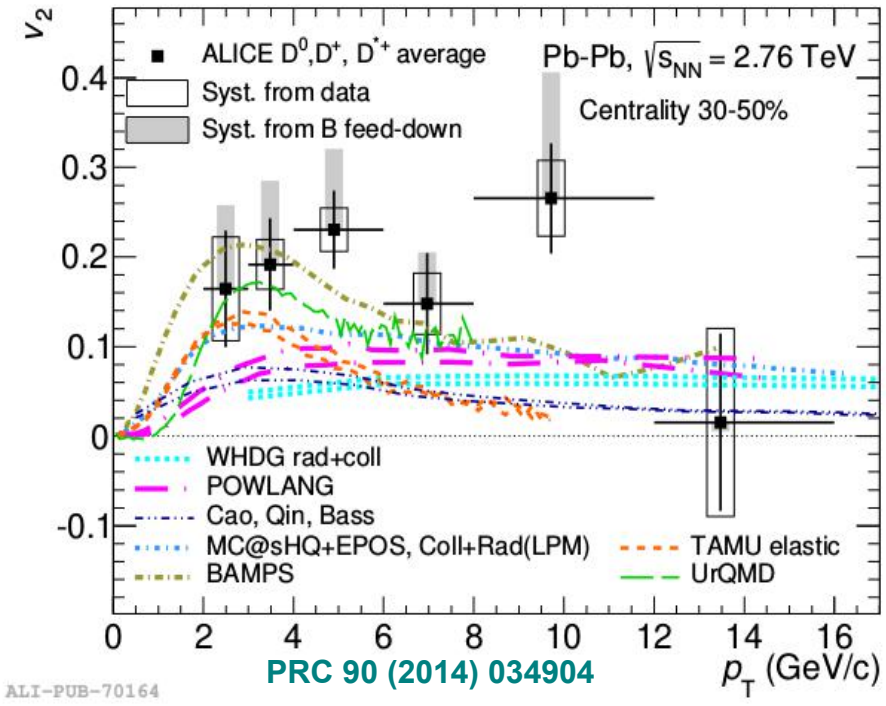


ALI-PUB-112582

- Significant suppression of HF electrons from intermediate p_T upwards
  - Note: (c,b)→e production in p-Pb collisions consistent with unity
- Separated beauty decay electrons hint a weaker suppression
- Models describe both c and b within uncertainties
  - Difference understood by quark mass dependent energy loss

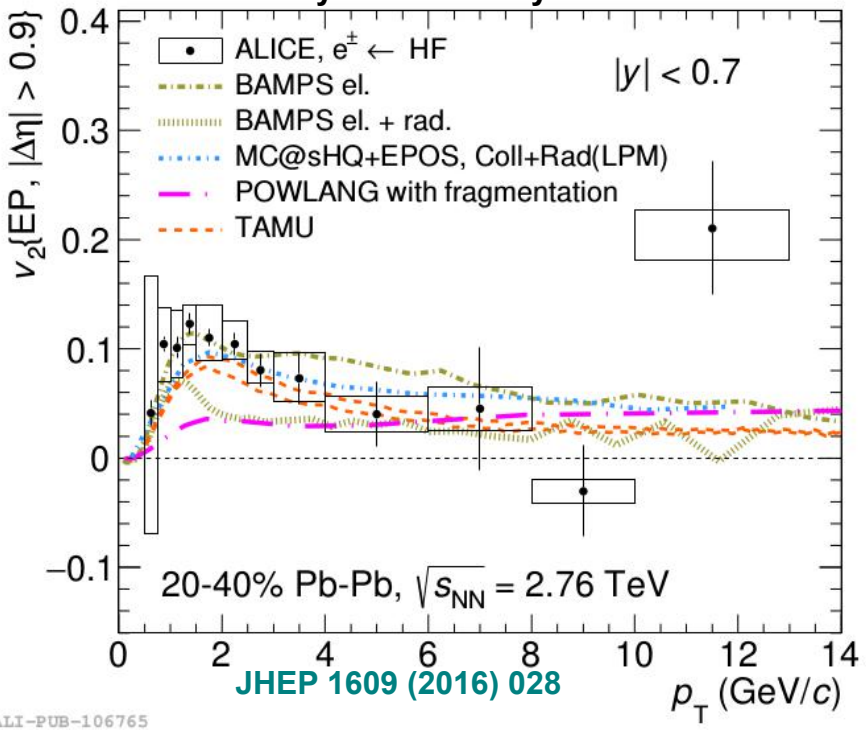
Azimuthal anisotropy

D mesons



PRC 90 (2014) 034904

Heavy flavour decay electrons



JHEP 1609 (2016) 028

- A significant v_2 of HF is observed at the LHC: both D and HFE
  - Note: a similar v_2 is measured for heavy-flavor muons, PLB 753 (2016) 41
- Models in which charm picks up flow via recombination or collisional energy loss do better

Azimuthal anisotropy

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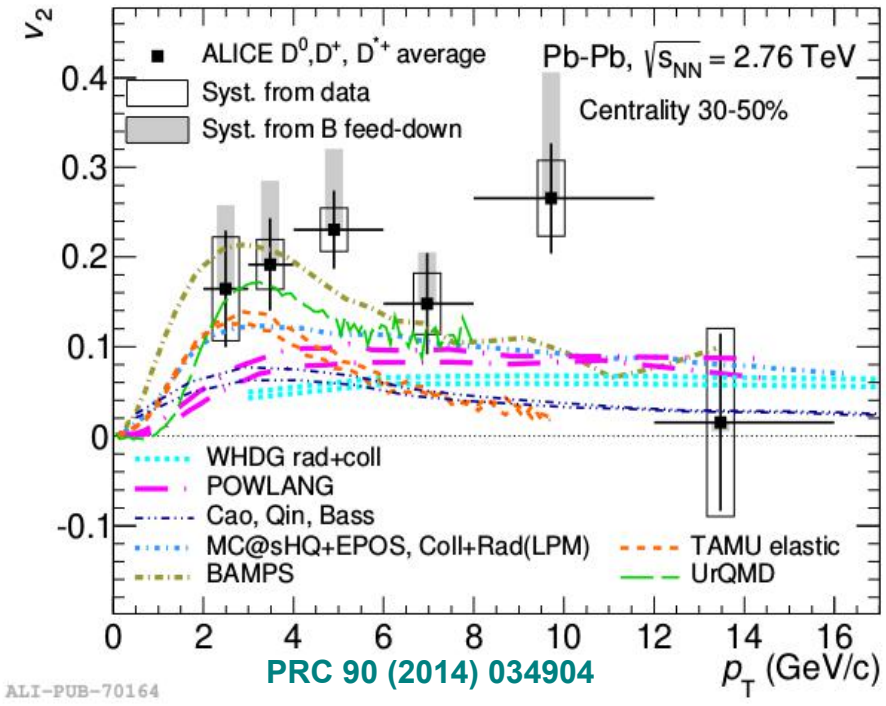

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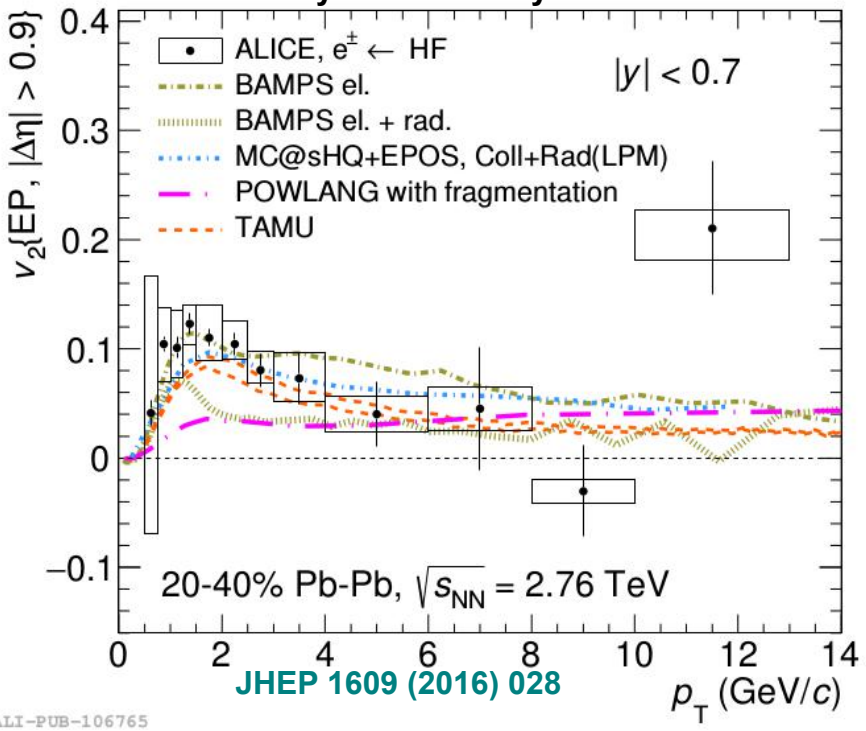

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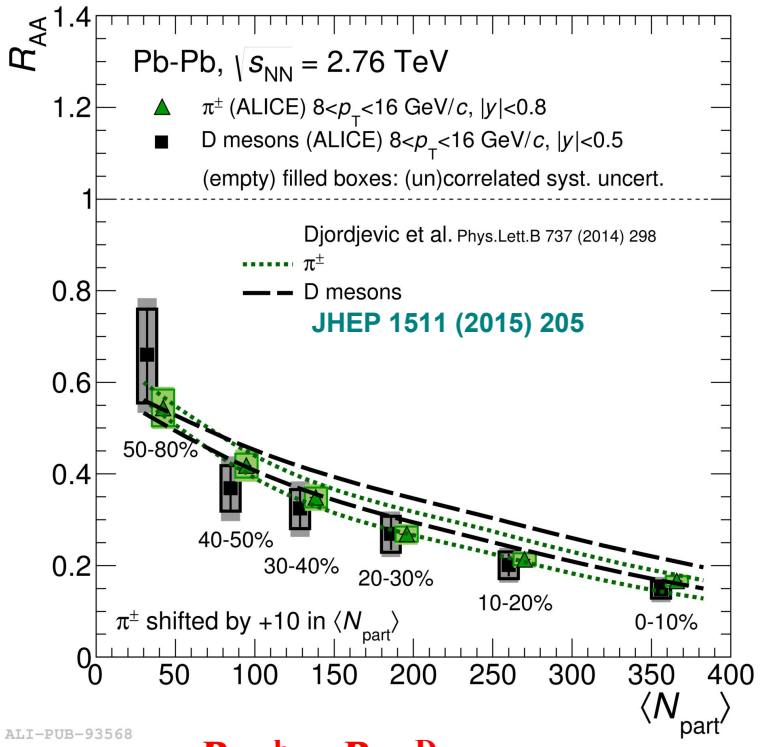
R_{AA} and v_2 together provide strong constraints on models

D-meson suppression vs. N_{part}

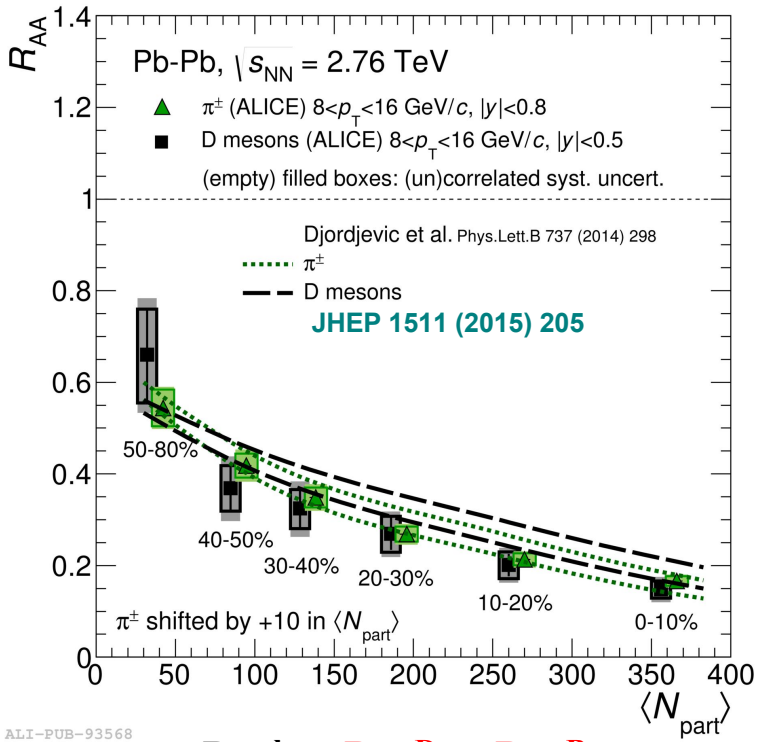


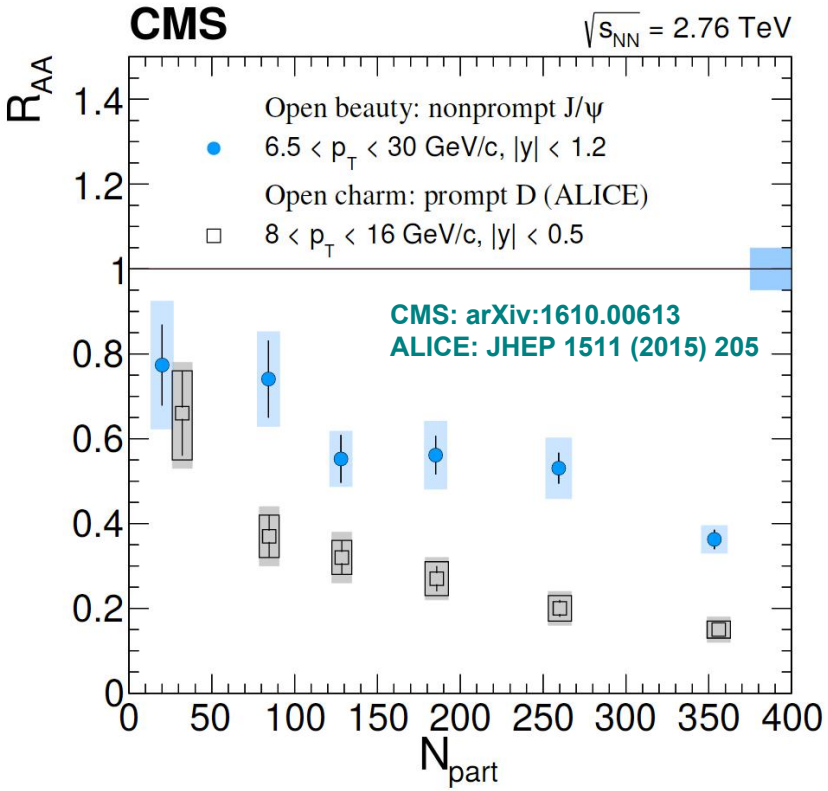
$$R_{AA}^{h} = R_{AA}^{D}$$

- D-meson suppression at high p_T consistent with pions

  Understanding: different fragmentation levels out expected ordering

Non-prompt J/ψ suppression





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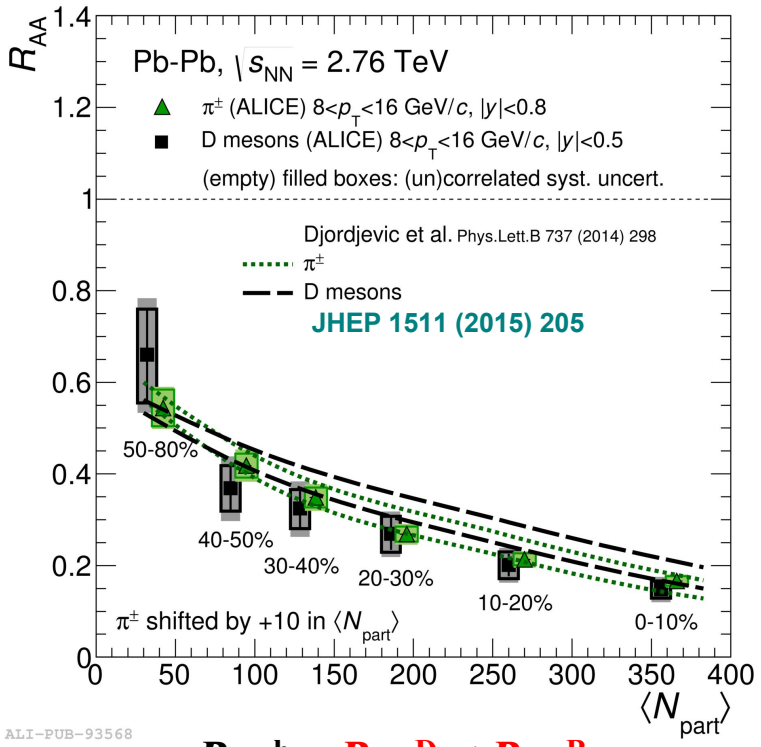

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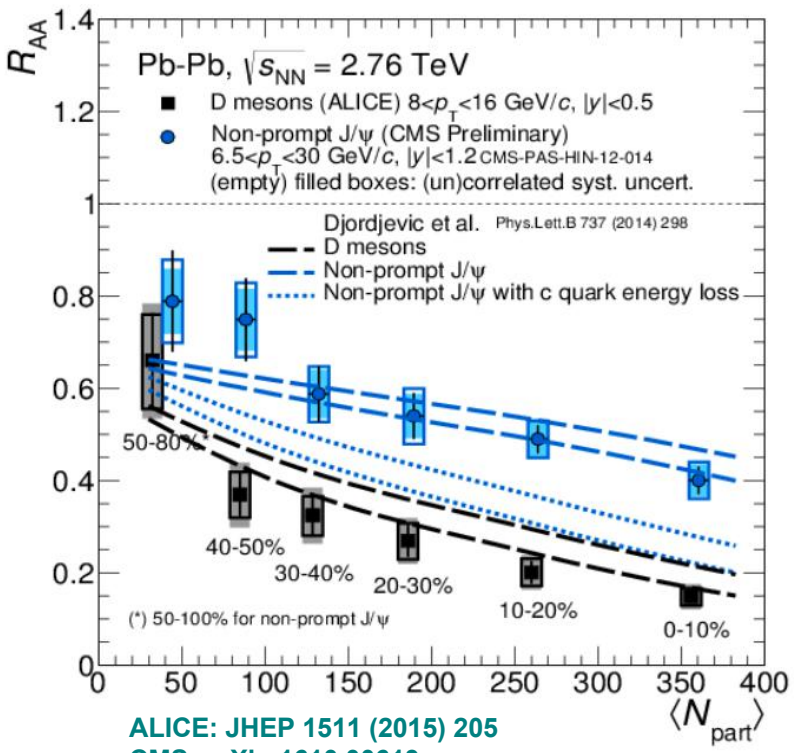

ALICE: JHEP 1511 (2015) 205
CMS: arXiv:1610.00613
Model: Djordjevic, PLB 737 (2014) 298

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  Model understanding: different parton masses cause different energy loss in similar kinematic range

Summary

Heavy flavour in pp collisions

- pQCD models give adequate description of HF production vs. p_T
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- Forward-backward: different initial/CNM effects; model selectivity
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Hot nuclear matter

- High-p_T suppression: $R_{AA}^{\pi} \sim R_{AA}^{D}$ (consistent with $\Delta E_{u,d,s} > \Delta E_c$)
- Low-p_T: coalescence of charm and the flowing medium
  - *Lack of detailed understanding: v_2 and R_{AA}?*
- Ordering of c, b at intermediate p_T: $R_{AA}^{B} > R_{AA}^{D}$

Outlook

LHC in Run-II: a real heavy-flavour factory!

- Higher luminosity
- pp collisions at $\sqrt{s}$=5 to 13 TeV
- p-Pb, Pb-Pb collisions at $\sqrt{s}$=5.02 TeV (ongoing 8.16 TeV p-Pb)

- Precision charm: greater model selectivity
  - Smaller uncertainities, measurements down to p_T=0
  - Λ_c : coalescence and hadronization on the HF sector
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  - Understanding colour charge / mass effects
  - Full b-tagged jets and D in jets: insight to HF fragmentation

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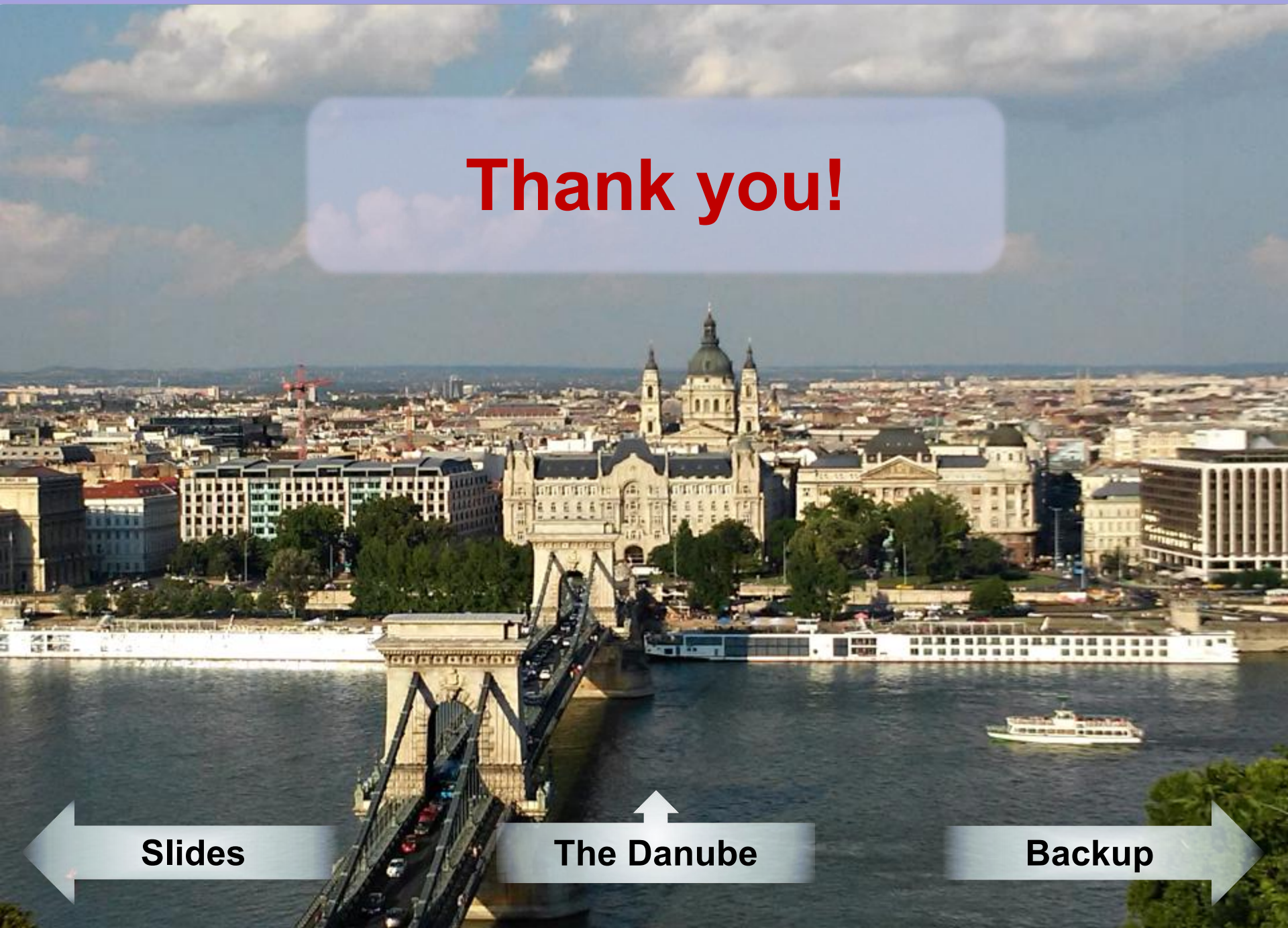
ALICE upgrades: precision beauty measurements

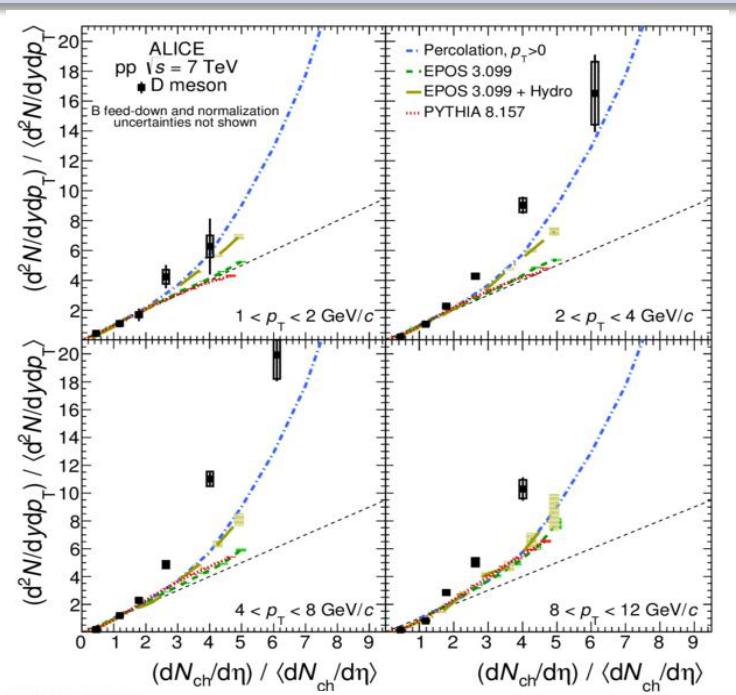
- Detector upgrades: ITS, TPC, readout, Muon Forward Tracker
- Goal: 2 orders of magnitude gain in luminosity w.r.t. Run-I

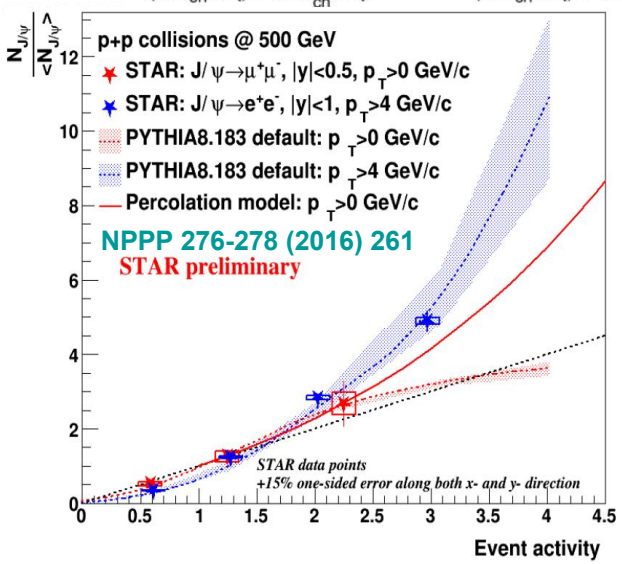


Thank you!

Slides The Danube Backup

Multi-parton interactions?

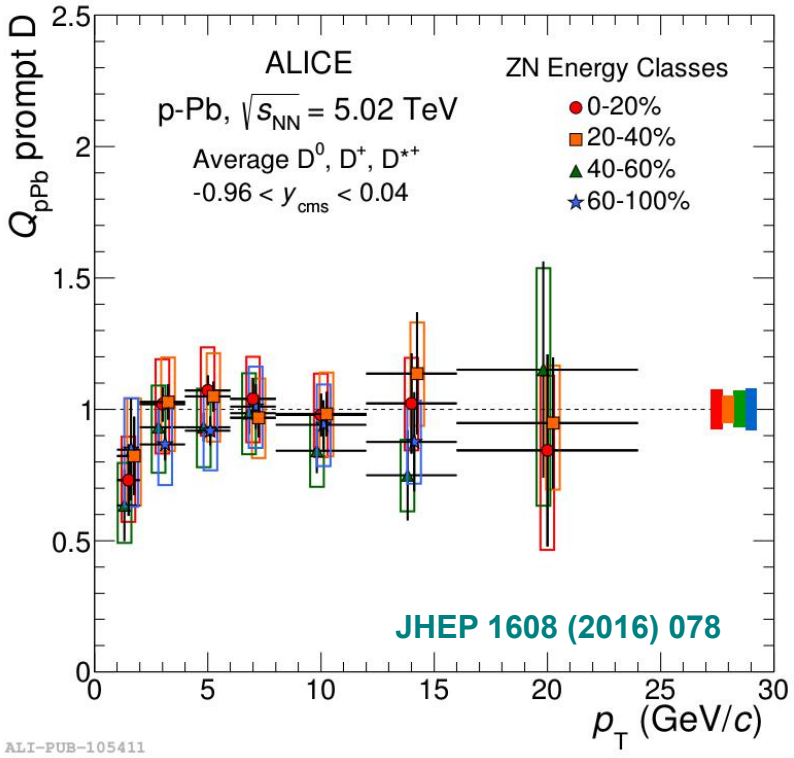




- Steeper-than linear increase
  - in D meson yields vs. multiplicity
- No strong flavour-dependence
  - Non-prompt J/ψ follows D trend
- Universal trend
  - RHIC 500 GeV up to LHC 7 TeV
  - Prompt J/ψ follows the same trend

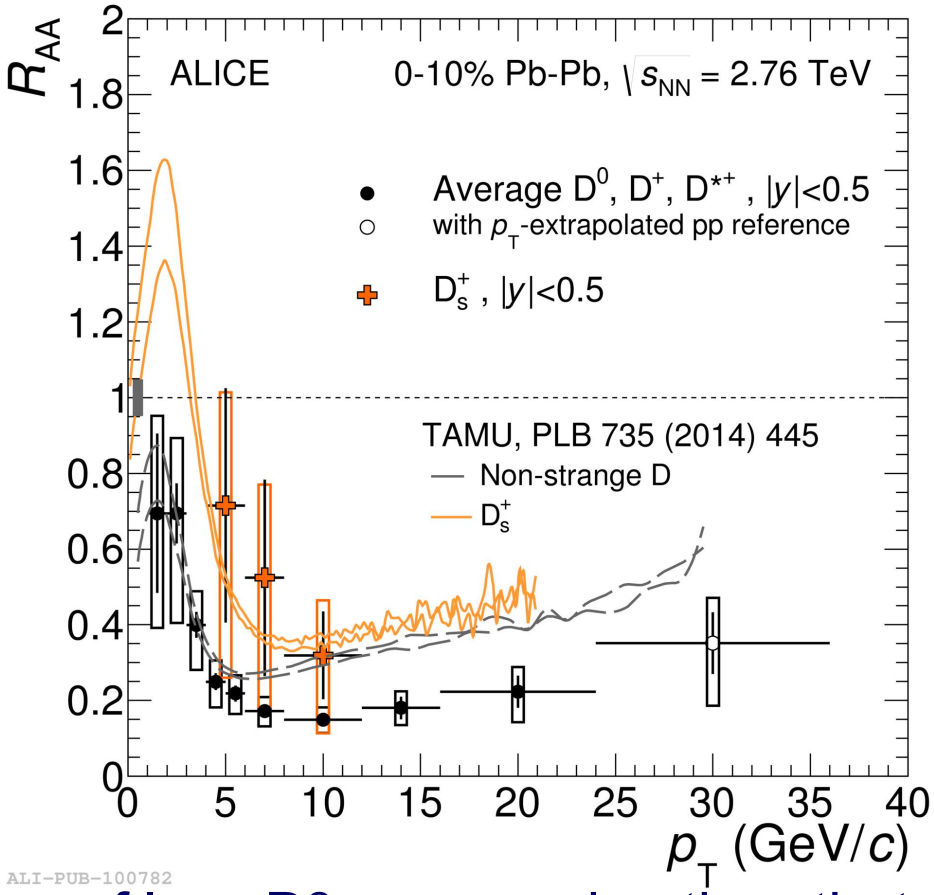
  → **Charm production appears independent of hadronization!**
- Models that include multi-parton interactions tend to describe it
  - Percolation: qualitative agreement
  - EPOS+Hydro gets trend right
  - PYTHIA8: acceptable description

D mesons in p-Pb vs., centralities



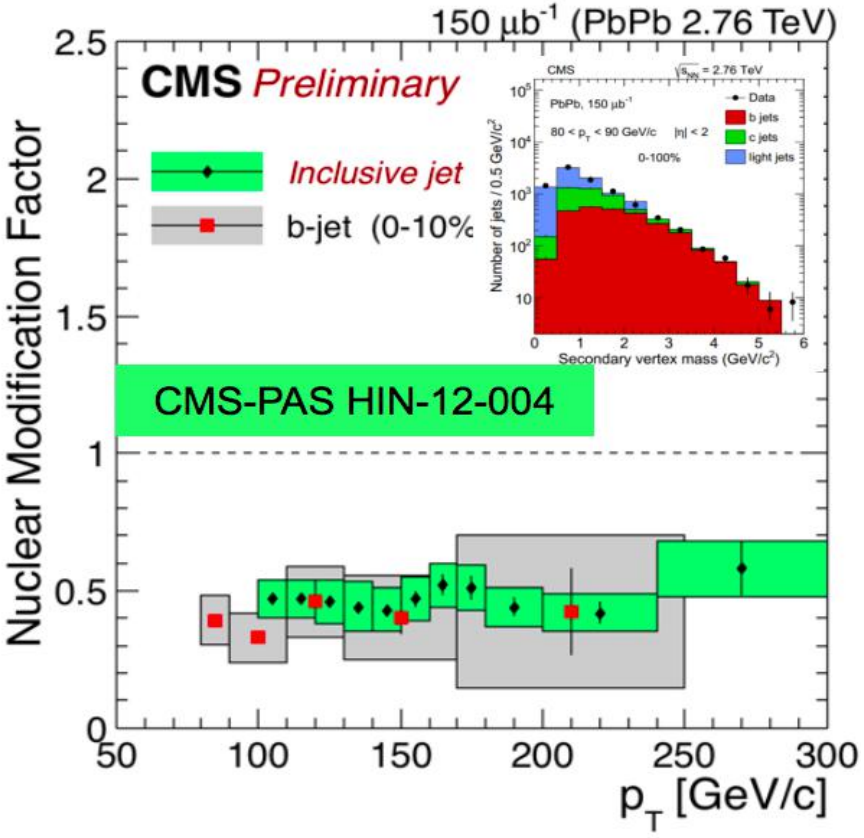
- Nuclear modification is moderate in p-Pb in all centrality classes
- No indication of CNM effects at intermediate to high p_T

D_s mesons in Pb-Pb collisions

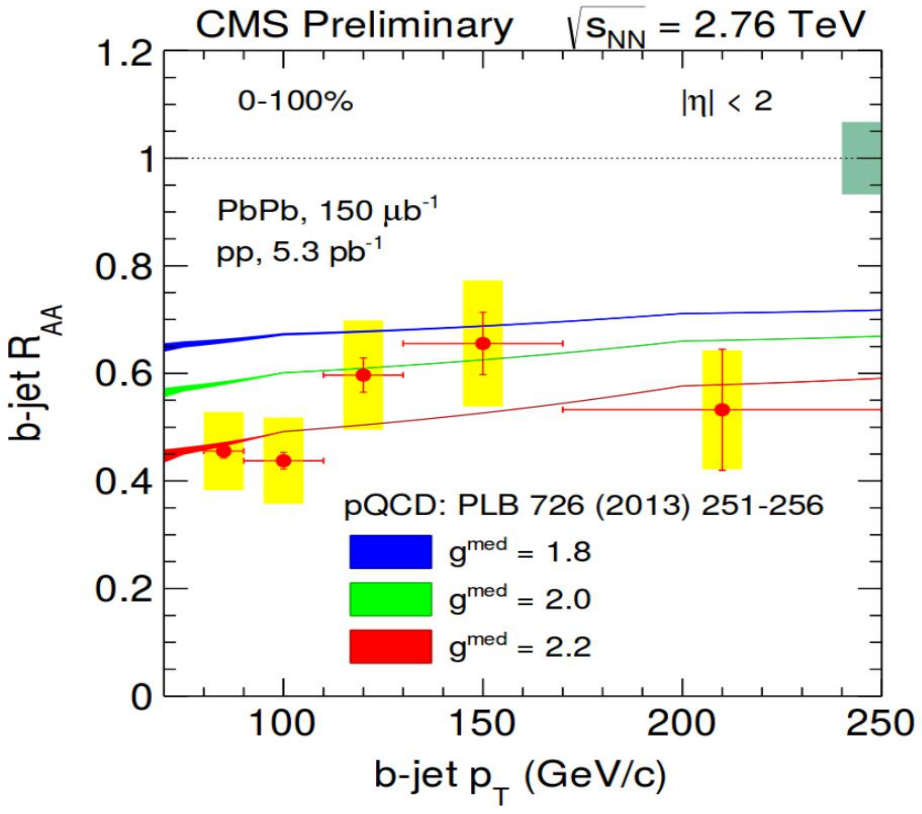


- Indication of less D_s suppression than that of D
- Consistent with stronger strange-charm coalescence

Full B-jet reconstruction (CMS)



R_{AA}(b-jet) ~ R_{AA}(h-jets)



Huang-Bo-Vitev, PLB 726, 251 (2013)

- Very high p_T: similar inclusive and b-jet suppression
- Colour charge effects? Contribution of gluon splitting?

→ Future precise measurements towards lower p_T

b-jet tagging performance