Quarkonia and open heavy-flavour measurements in pp collisions with ALICE

Grazia Luparello for the ALICE Collaboration
INFN Trieste

7th Large Hadron Collider Physics
Puebla, 20 - 25 May 2019

Charm and beauty in pp collisions?

- **Test perturbative QCD**
  - Large quark mass (m_c ~ 1.3 GeV/c^2 and m_b ~ 4.2 GeV/c^2) provides a hard scale
  - Cross sections can be calculated with pQCD down to low p_T

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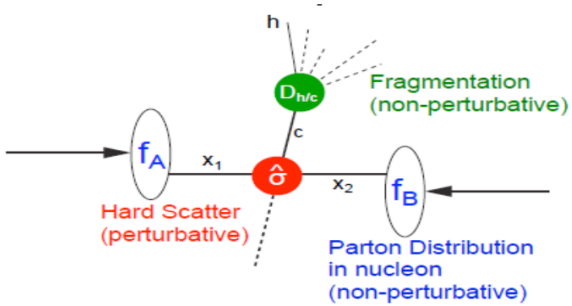
1) Open HF production sensitive to**:**

- Parton Distribution Functions (PDF)
- Cross section at partonic level (pQCD)→ perturbative
- Fragmentation from parton to hadron → non-perturbative



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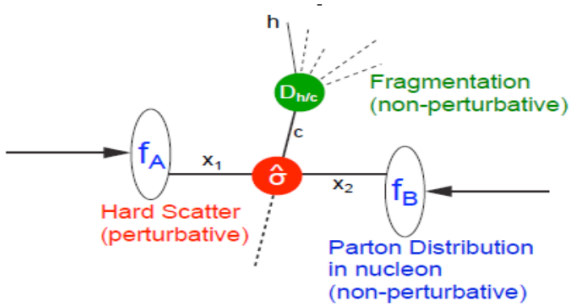

2) Quarkonia ($c\bar{c}$ and $b\bar{b}$ bound states)

- $Q\bar{Q}$ pair production → perturbative
- Evolution of the $Q\bar{Q}$ pair in a bound state→ non-perturbative

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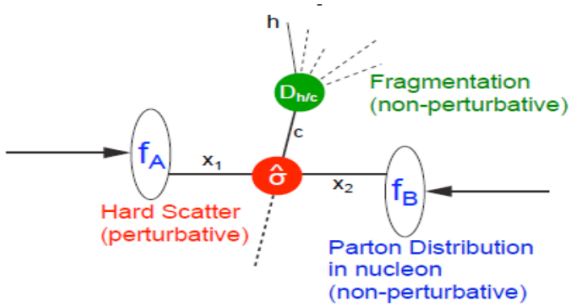

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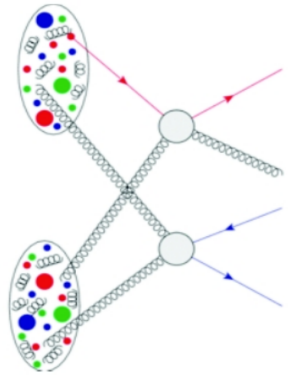


- In addition: **multiplicity dependent measurements**
  - **Interplay between soft and hard mechanisms** of particle production
  - Study the role on **Multiple Parton Interactions (MPI)**

  (See also C. Jahnke, QCD/HF May 23rd)

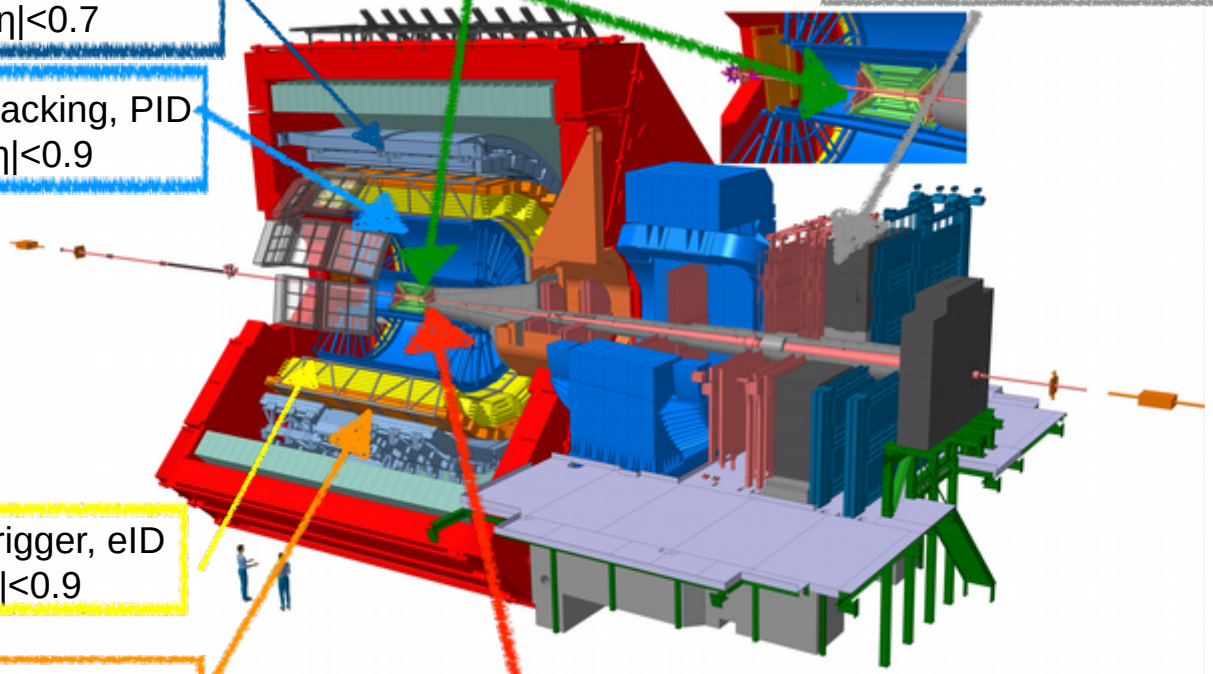
ALICE Detector and HF identification

ITS: vertexing, tracking, PID
|η|<0.9

Muon Spectrometer:
tracking, trigger
-4<η<-2.5

EMCal: trigger, eID
|η|<0.7

TPC: tracking, PID
|η|<0.9



TRD: trigger, eID
|η|<0.9

TOF: PID |η|<0.9

V0: trigger and event characterisation

Fully reconstructed D and Λ_c hadronic decays

$D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \Phi\ \pi^+ \rightarrow K^-K^+\pi^+$

$\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow K_0^s\ p$

Semi-leptonic decays

$D, B \rightarrow \mu^{\pm} X$

$D, B, \Lambda_c^+, \Xi_c^0 \rightarrow e^{\pm} X$

Quarkonia leptonic decays

$J/\Psi \rightarrow \mu^+\mu^-, e^+e^-$

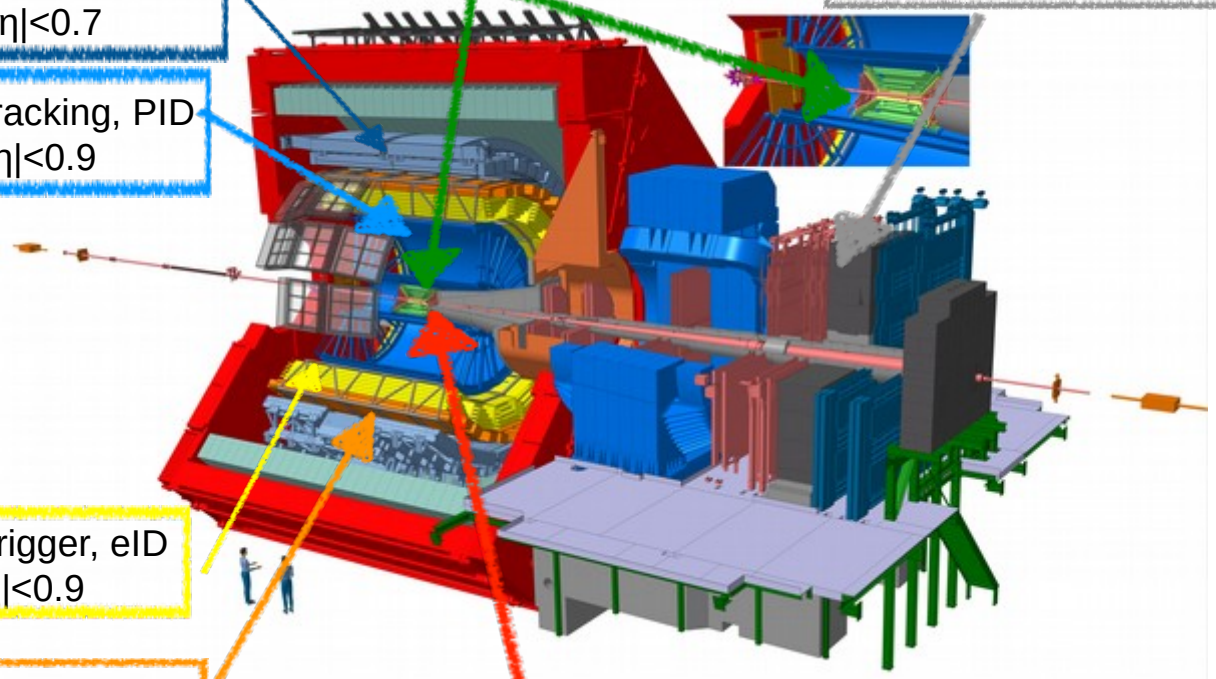
$\Psi(2S) \rightarrow \mu^+\mu^-$

$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \rightarrow \mu^+\mu^-$

HF-tagged jets

(See M. Mazzilli, QCD/HF May 21st)

Data sample



√s (TeV)	Year	MB evts.	$\int L dt$ (nb^{-1})
2.76	2011	58M	1.1
5.02	2017	990M	19
7	2010	370M	6.0
8	2012	100M	1.8
13	2016	190M	3.3

+ triggered data samples at all energies

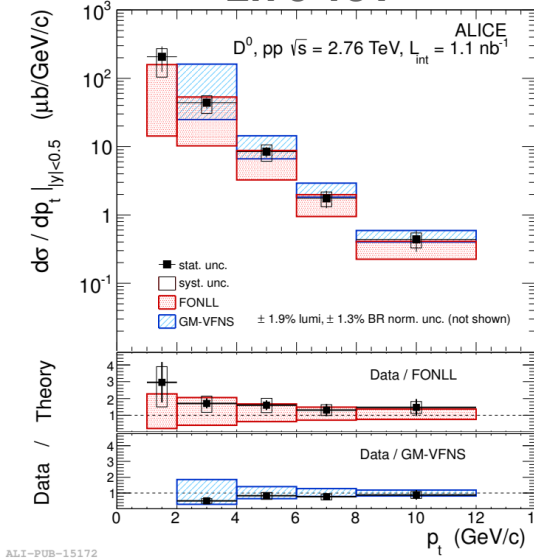
Multiplicity integrated measurements

D-meson cross sections @ different energies

- On the upper edge of the FONLL calculations
- Similar to what observed at Tevatron and RHIC

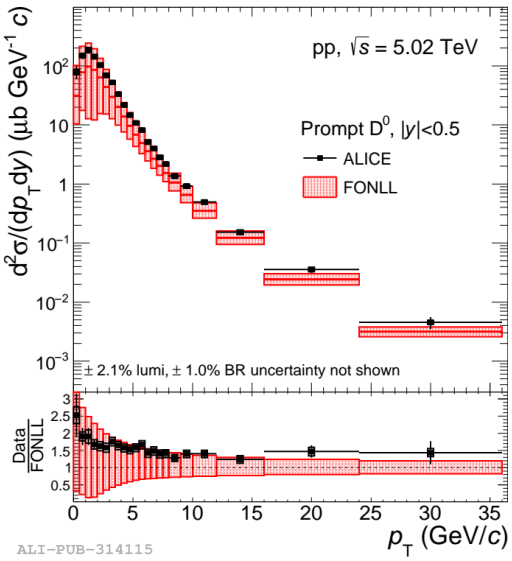
Cacciari et al. JHEP 1210 (2012) 137

2.76 TeV



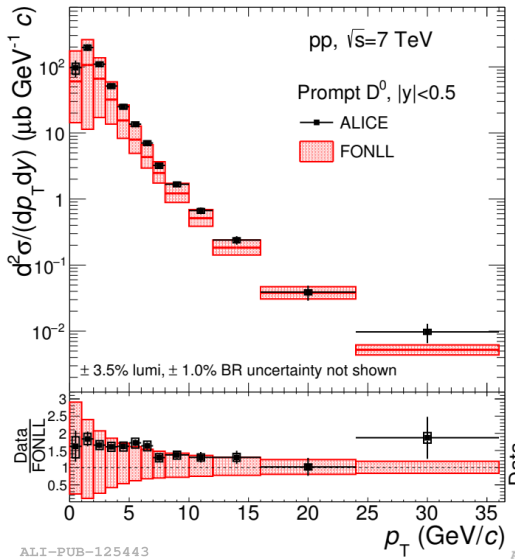
ALICE, JHEP 1207 (2012) 191

5.02 TeV



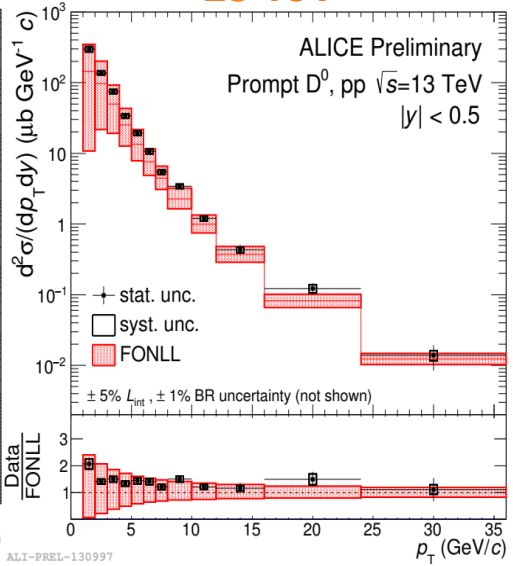
ALICE, arXiv:1901:07979

7 TeV



ALICE, EPJ C77 (2017) 550

13 TeV



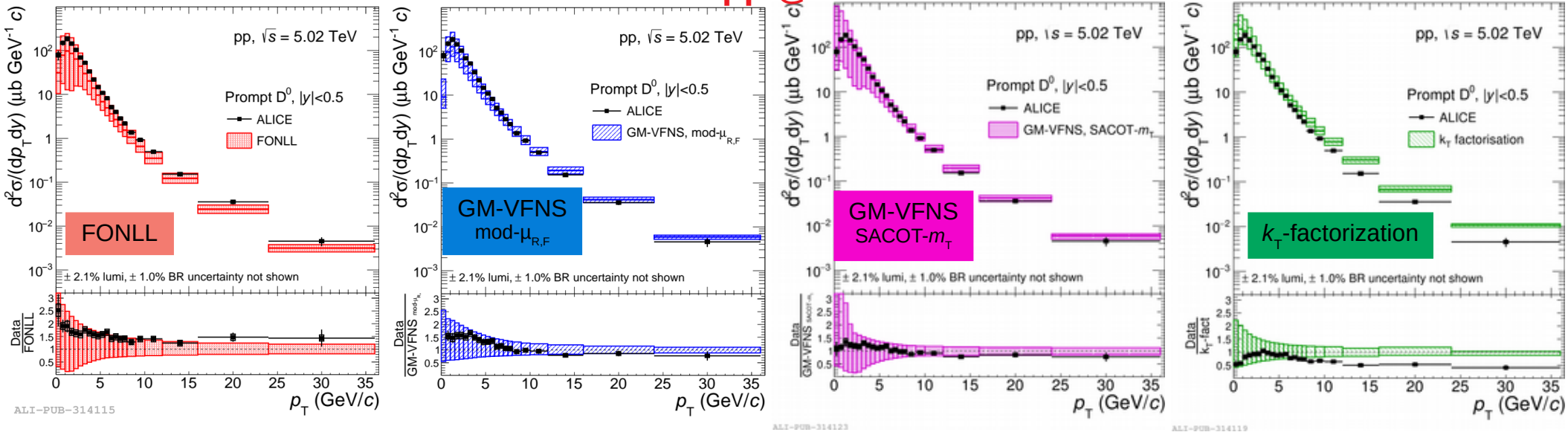
D-meson cross sections compared with models

Comparison with several pQCD models @ fixed energy → agreement within uncertainties

- Non strange D mesons overestimated/underestimated by theory in different p_T ranges
- Data have smaller uncertainties than theoretical calculations
  - Large unc. at low p_T dominated by factorisation and renormalisation scale of the perturbative calculation

ALICE, arXiv:1901:07979

pp @ 5 TeV



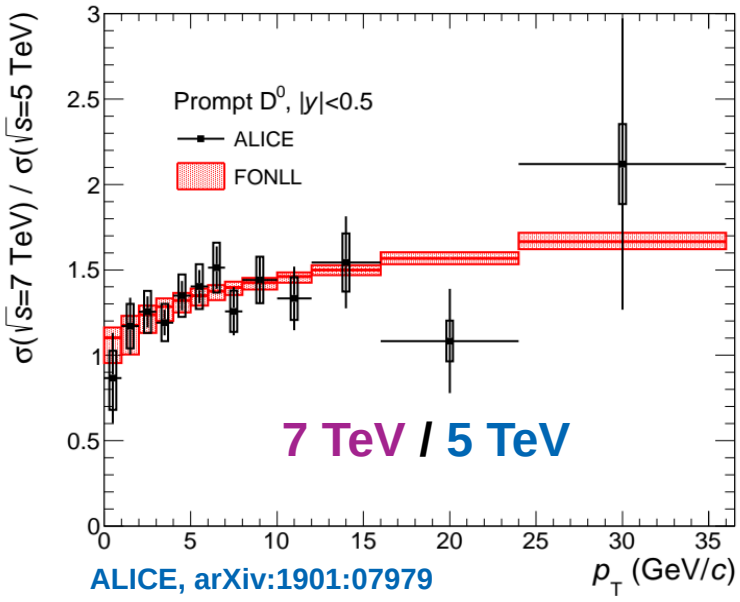
Cacciari et al. JHEP 1210 (2012) 137 Kniehl et al., EPJ C72 (2012) 2028 Maciula, Szczurek, PRD 87 (2013) 094022

D-meson cross section ratios: energy dependence

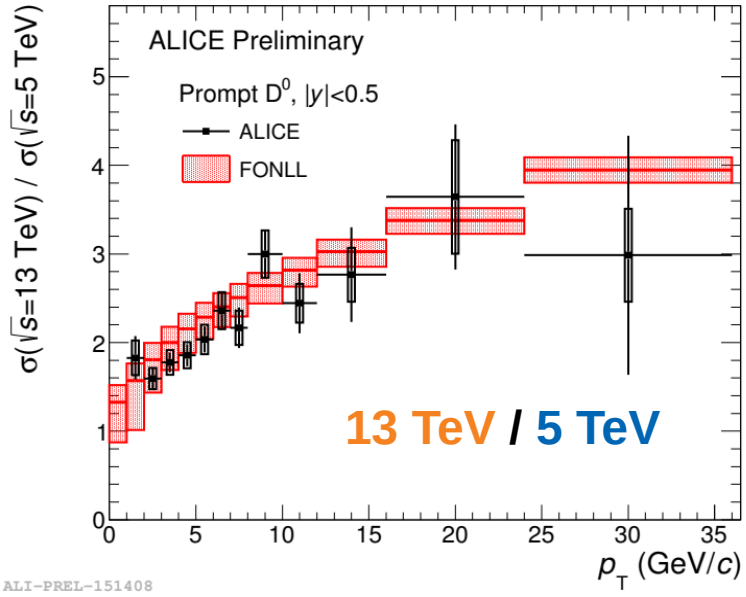
Constraint to gluon PDF at small Bjorken-*x*

- Theoretical calculations uncertainties partially cancel in the ratio
  - Normalisation and factorisation scales, PDF partially cancel out
  - m_Q, fragmentation functions, BR fully correlated

Data compatible with FONLL calculations



ALICE, arXiv:1901:07979



ALI-PREL-151408

D-meson cross section ratios: *y* dependence

Constraint to gluon PDF at small Bjorken-*x*

- Theoretical calculations uncertainties partially cancel in the ratio
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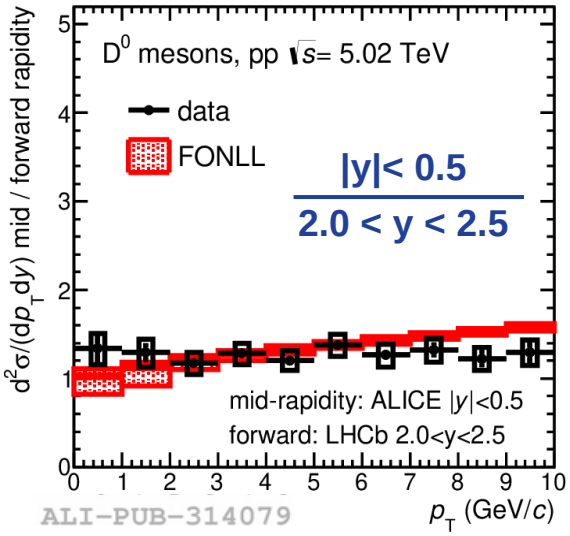
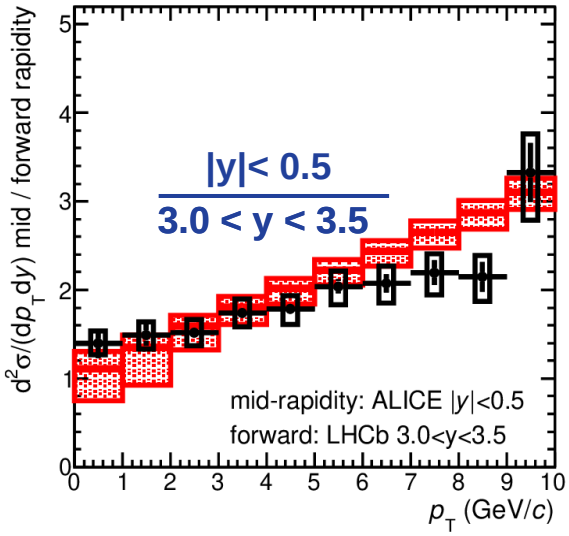
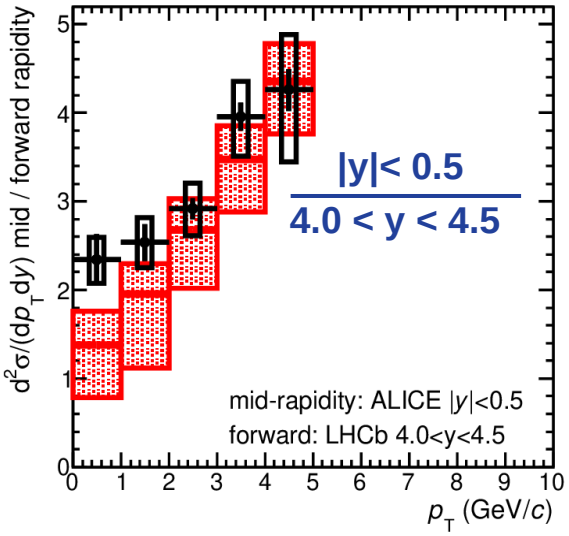
  - m_Q, fragmentation functions, BR fully correlated

Data compatible with FONLL calculations



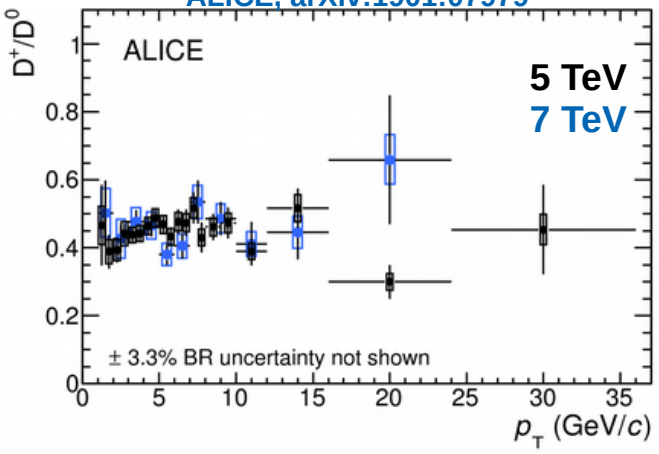




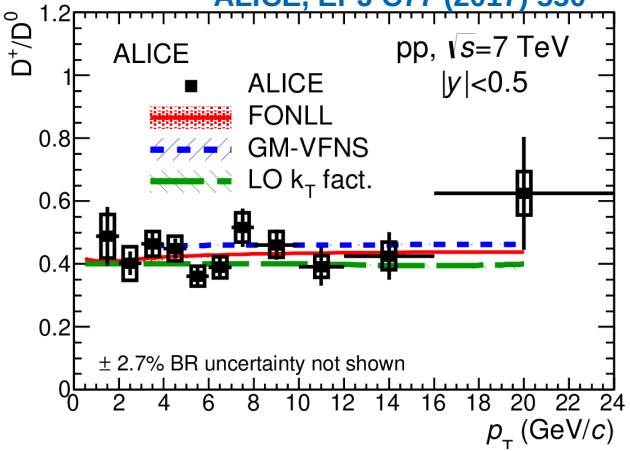
ALICE, arXiv:1901:07979

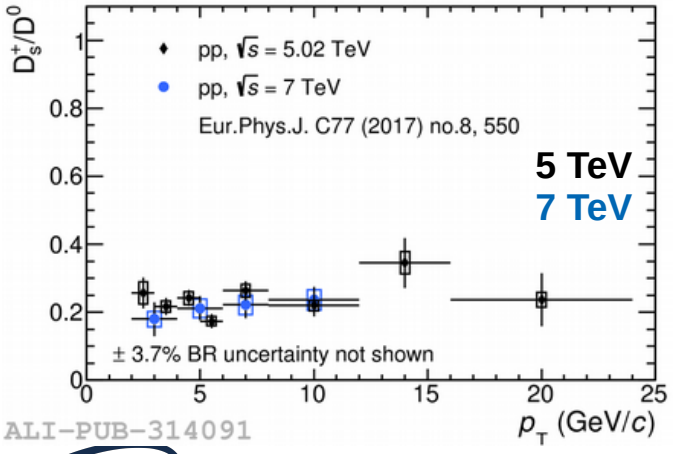
Particle ratios

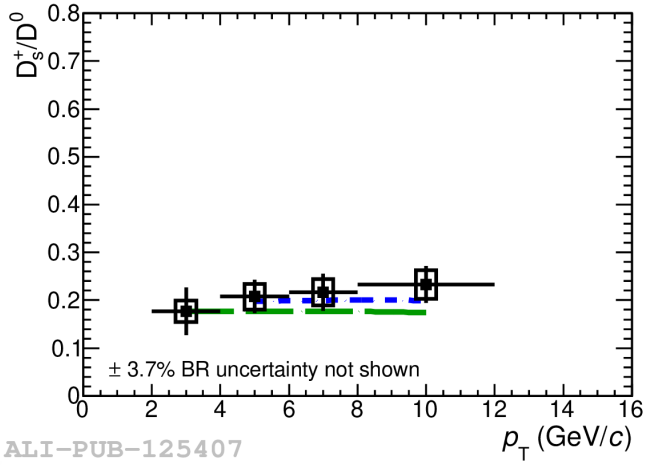
ALICE, arXiv:1901:07979



ALICE, EPJ C77 (2017) 550







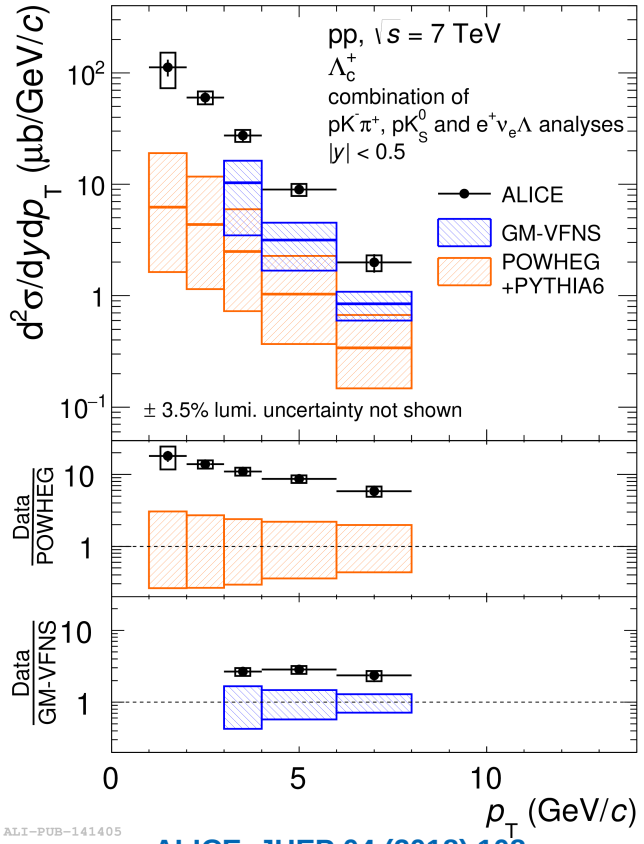
Sensitive to ratio of fragmentation functions

- Independence on collision energy
- Compatible with ratios measured in e^+e^- and ep collisions
- Agreement with models

Universality of D-meson fragmentation functions

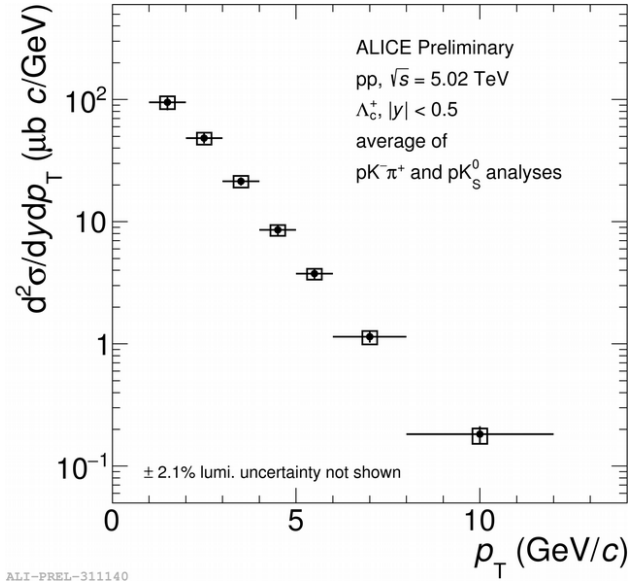
Λ_c^+ production cross section

7 TeV



ALICE, JHEP 04 (2018) 108

5 TeV



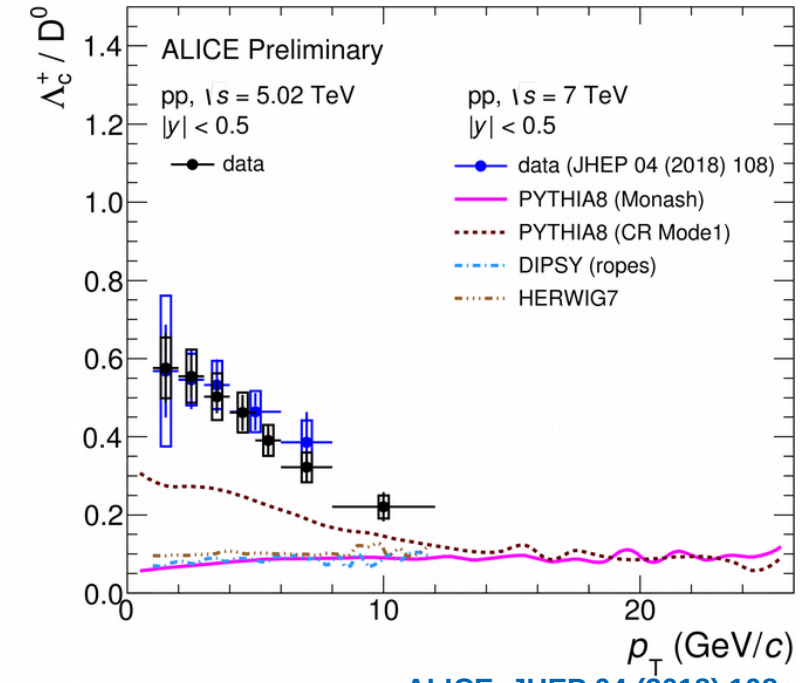
GM-VFNS: EPJ C41 (2005) 199
POWHEG: JHEP 0709 (2007) 126

p_T differential cross-section underestimated by pQCD calculations which describe D-meson production

- Fragmentation fractions $f(c\rightarrow\Lambda_c)$ tuned on e^+e^- data
- Extended p_T interval of the measurement @5 TeV

Λ_c^+ / D^0 ratio

5 TeV
7 TeV



ALICE, JHEP 04 (2018) 108

PYTHIA8 Monash: EPJ C74 (2014) 3024
PYTHIA8 CR Mode1:JHEP 08 (2015) 003
DIPSY: JHEP 08 (2011) 103
HERWIG7: EPJ C58 (2008) 639-707

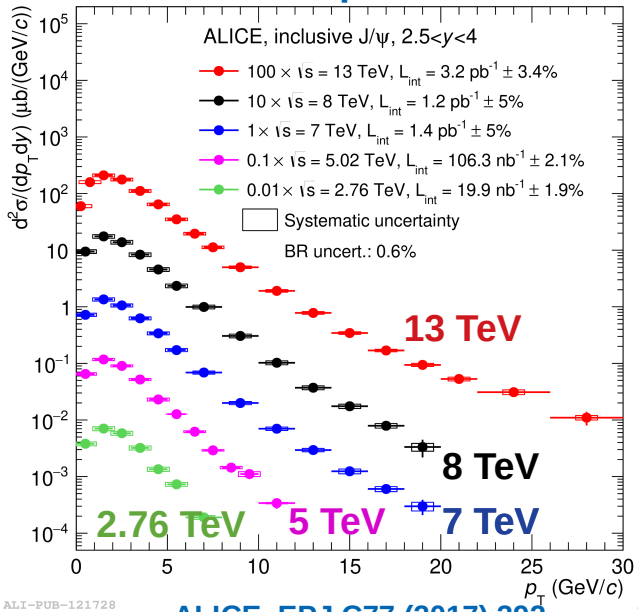
- **Λ_c^+ / D^0 compatible at different energies**
- Λ_c^+ / D^0 ratios higher than previous measurements in e^+e^- and ep collisions at lower centre-of-mass energies (ranging from 0.1 to 0.22)

- **Λ_c^+ / D^0 underestimated by models**
  - PYTHIA8 with enhanced colour reconnection mode closer to data

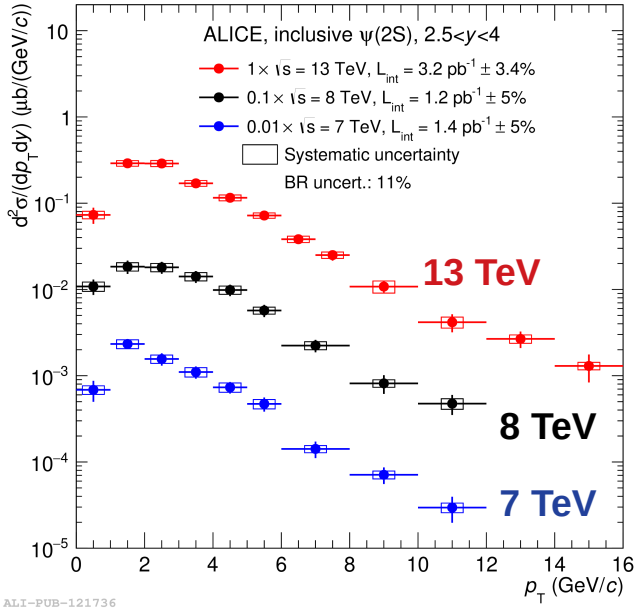
Quarkonium production @ different energies

- Spectra become harder with increasing energy
- Change of slope at high p_T @ 13 TeV (due to non-prompt J/ψ contribution)
- No energy dependence of the ψ(2S)-to-J/ψ ratio

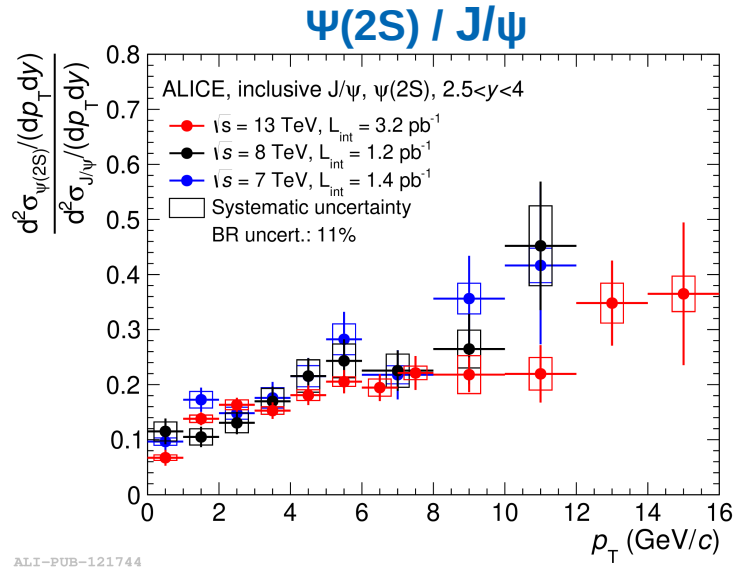
J/ψ



ψ(2S)



Ψ(2S) / J/ψ



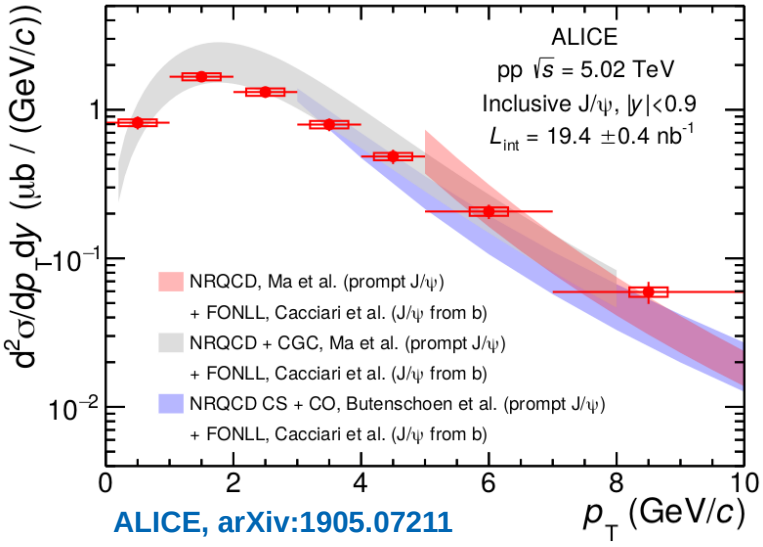
ALICE, EPJ C77 (2017) 392

J/ψ production: comparison with models

Inclusive charmonium cross section well described by pQCD models

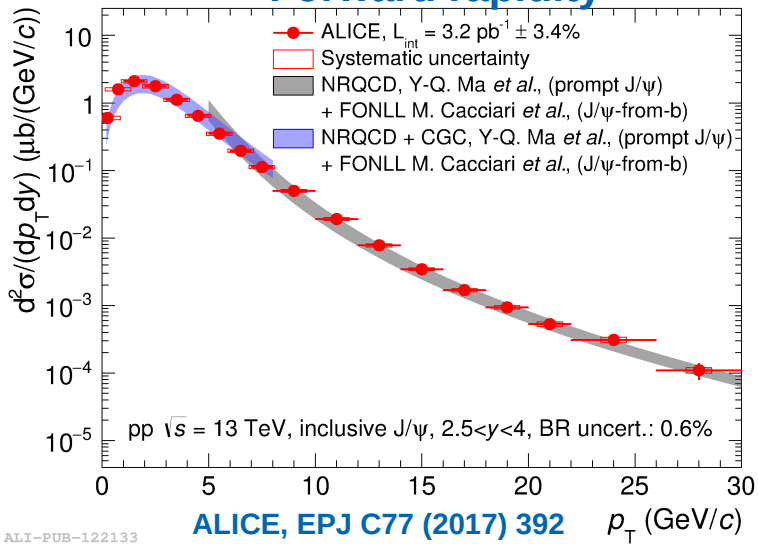
- Low p_T: NRQCD with CGC description of the proton reproduces data (b-decay contribution small)
- Non-prompt J/ψ added via FONLL to the NRQCD

Mid-rapidity



ALICE, arXiv:1905.07211

Forward rapidity



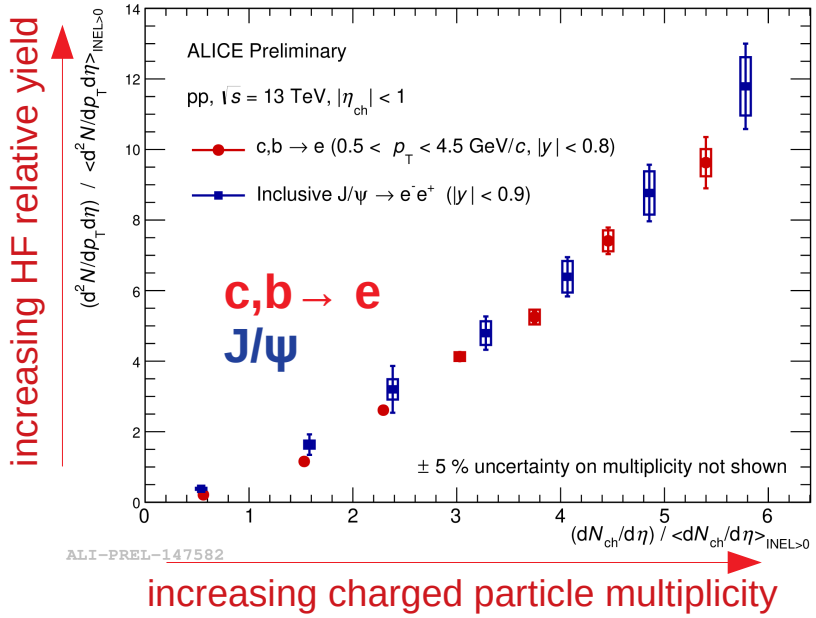
ALICE, EPJ C77 (2017) 392

NRQCD: PRL 106 (2011) 042002
NRQCD + CGC: PRL 113 (2014) 192301
NRQCD CS + CO: PRL 106 (2011) 022003
FONLL: JHEP 1210 (2012) 137

Multiplicity dependent measurements

HF production at mid-rapidity vs. multiplicity

Faster than linear increase
Similar trend for both open and hidden charm (both measured at mid-rapidity)



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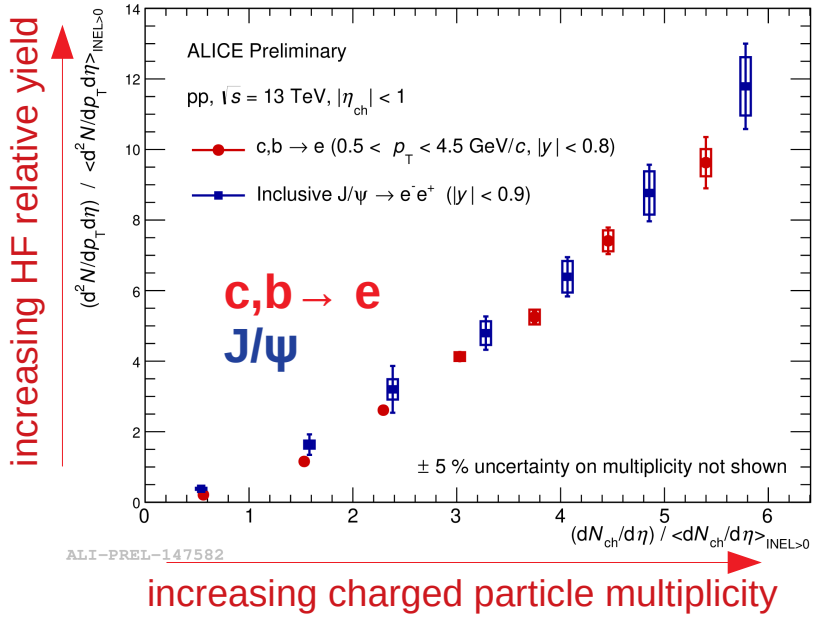
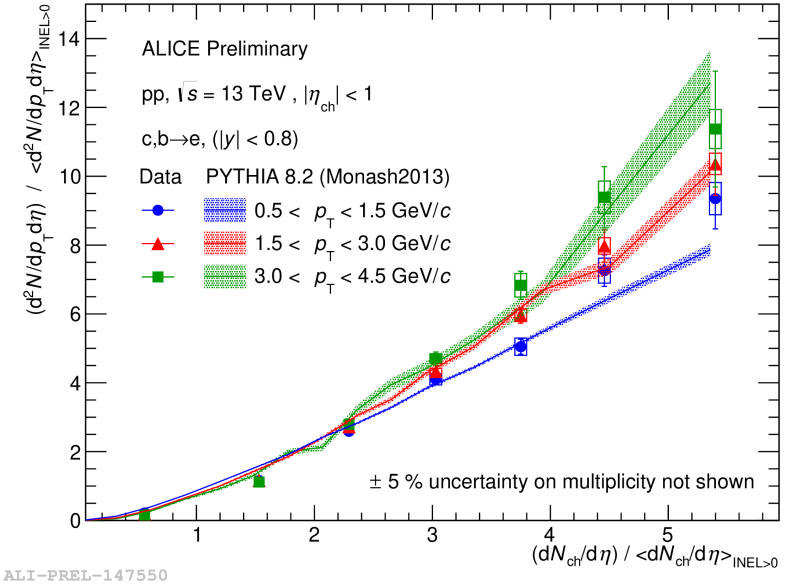
Faster increase at high p_T → Fair agreement with PYTHIA8.2 (Monash2013 tune)





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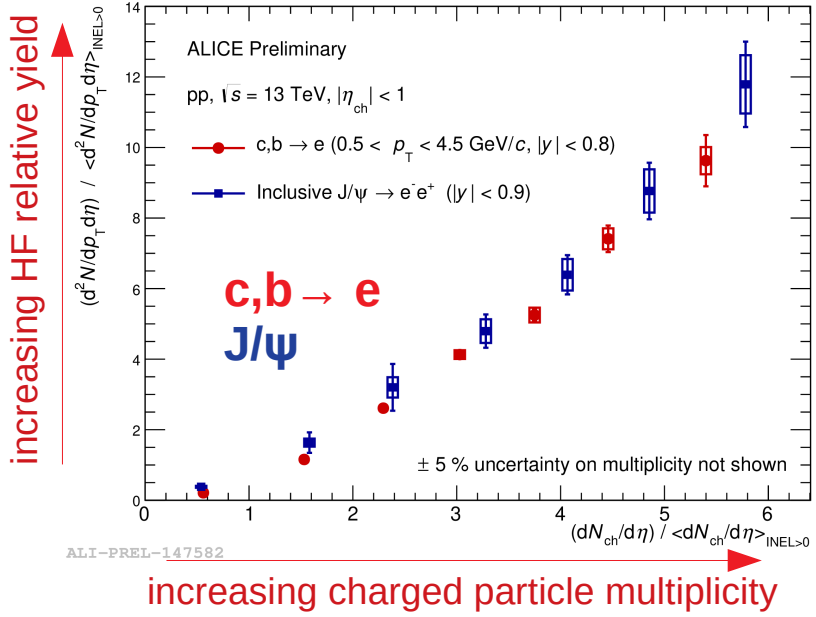
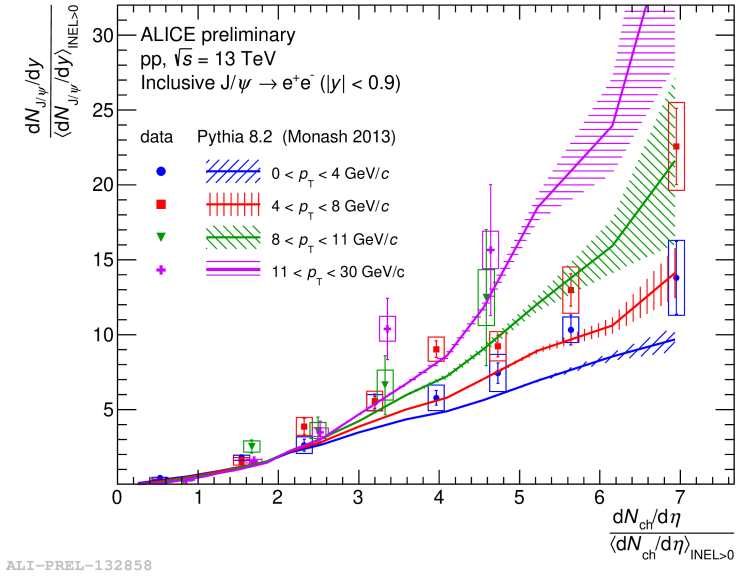
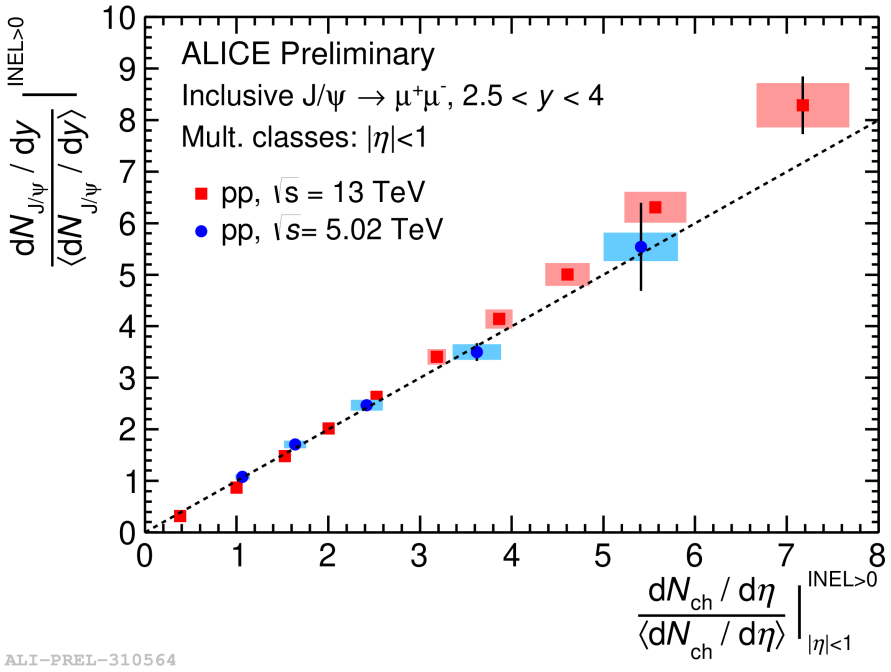




J/ψ production at forward rapidity vs. multiplicity

Linear increase of J/ψ yield at forward rapidity with charged particle mult. at mid-rapidity

- **No energy dependence**



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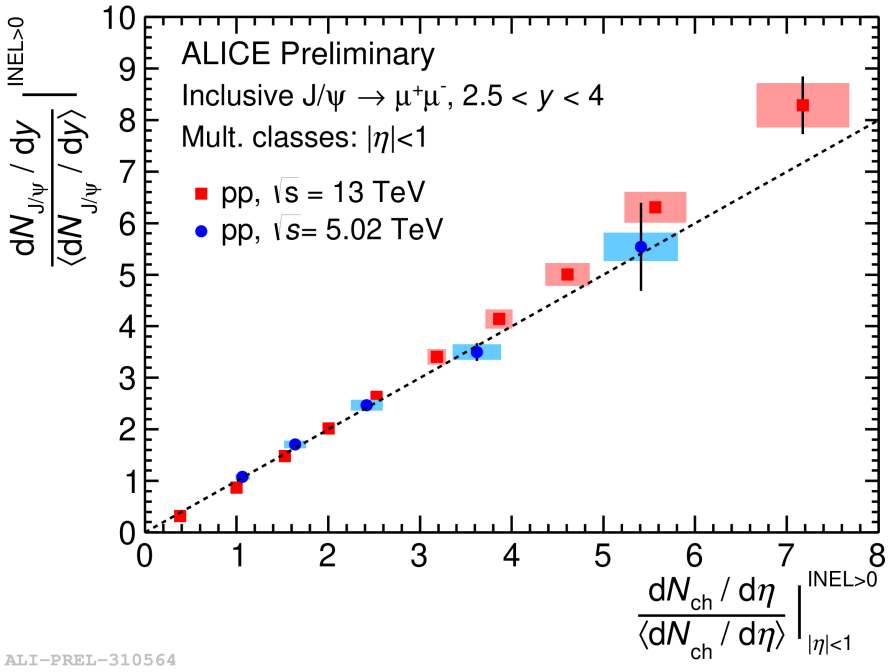
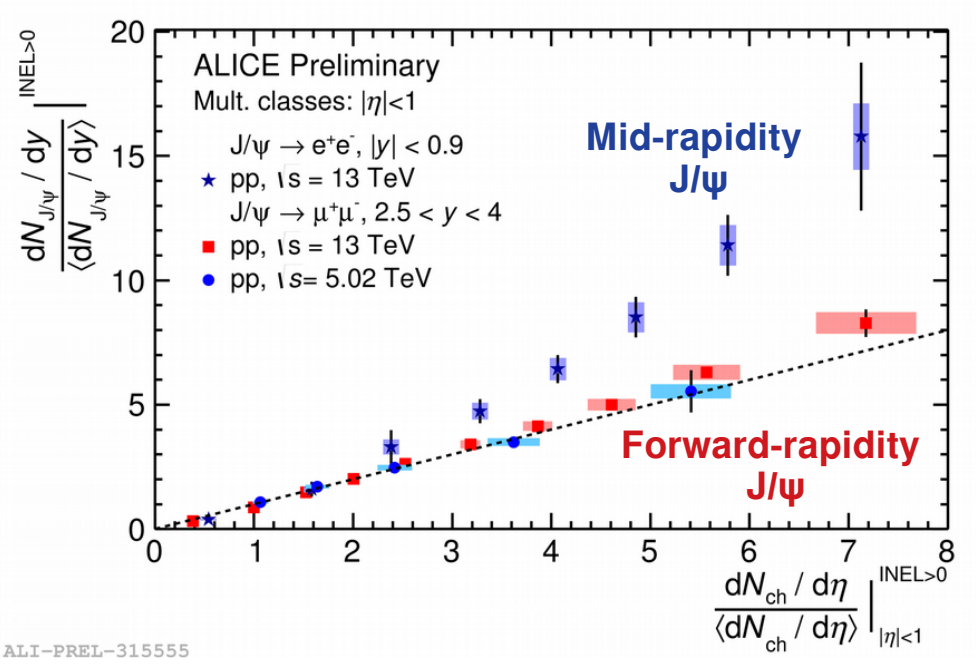
Linear increase of J/ψ yield at forward rapidity with charged particle mult. at mid-rapidity

- **No energy dependence**

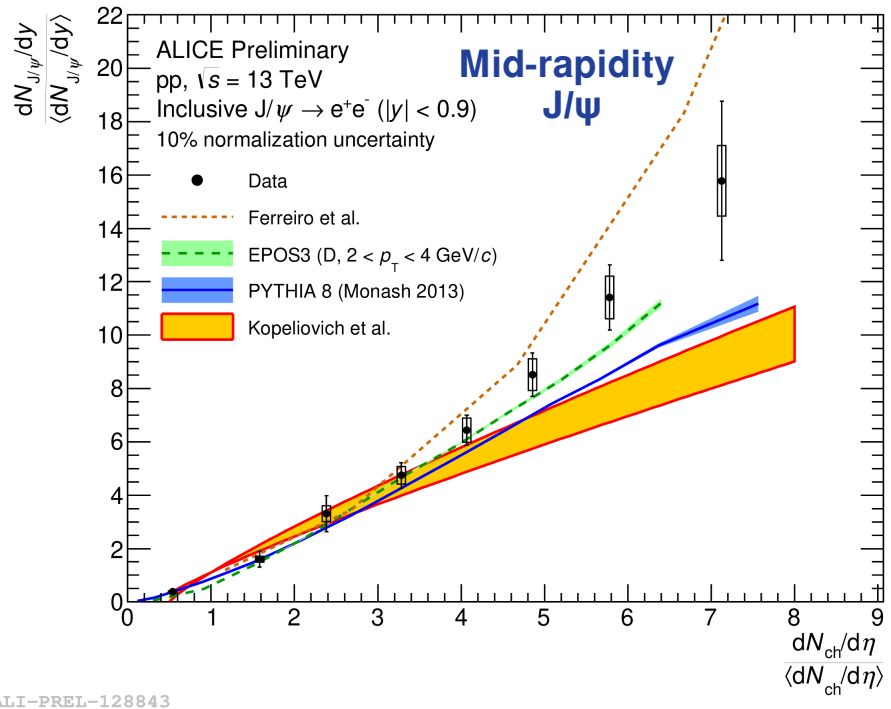
Faster than linear increase if both J/ψ yield and charged particle mult. measured at mid-rapidity

- Possible bias due to auto-correlations?





J/ψ vs. multiplicity: comparison with models



Percolation Model PRC 86 (2012) 034903; arXiv:1501.03381 (2015)
Mimic MPI via interactions of colour sources with finite spatial extensions

EPOS3 (with Hydro) Phys. Rept. 350 (2001) 93-289; PRC 89 (2014) 064903
Parton based Gribov-Regge formalism, MPI proportional to multiplicity

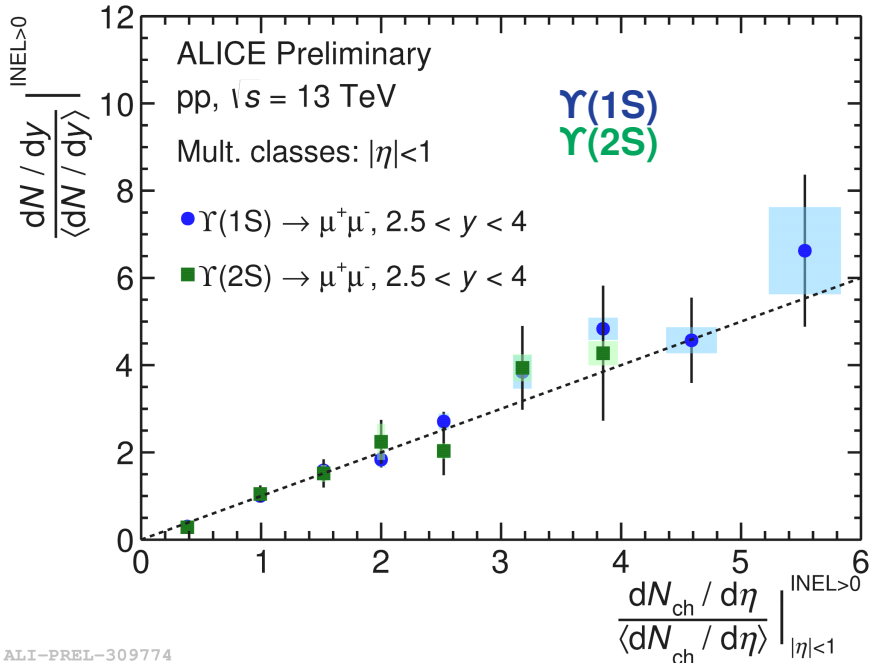
PYTHIA8 Comput.Phys.Comm. 178 (2008) 852-867
Hard processes in MPI (new wrt PYTHIA6)

Kopeliovich et al. PRD 88 (2013) 116002
Contributions of higher Fock states

- **Models reproduce the data at low multiplicity while deviate at high multiplicity**

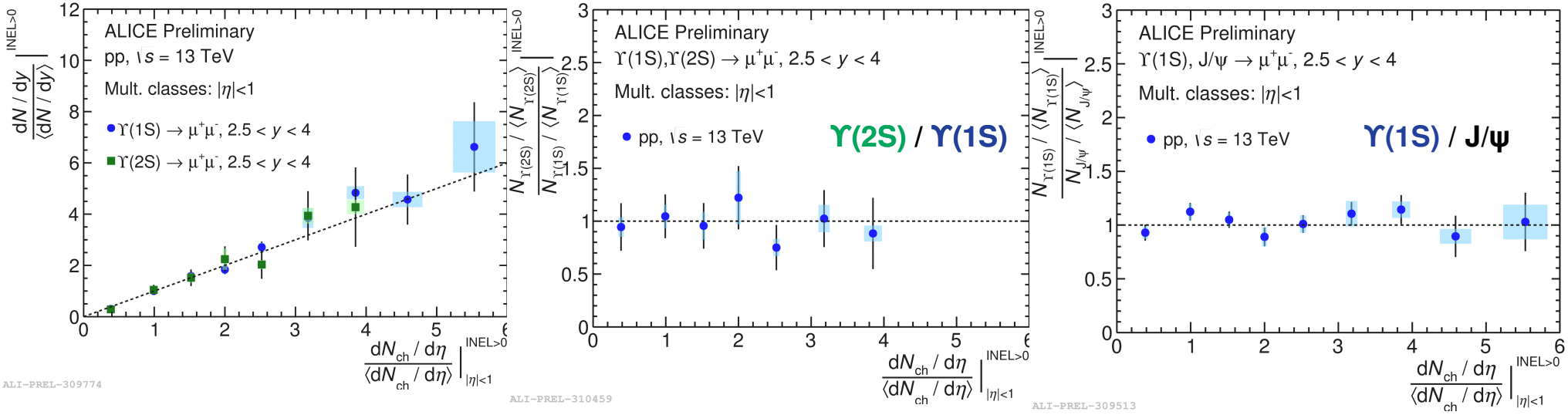
ϒ production vs. charged-particle multiplicity

Linear increase of the ϒ(1S) and ϒ(2S) with charged-particle multiplicity



ϒ production vs. charged-particle multiplicity

Linear increase of the ϒ(1S) and ϒ(2S) with charged-particle multiplicity



Double ratios **ϒ(2S)/ϒ(1S)** and **ϒ(1S)/J/ψ** are compatible with unity within uncertainties independently on charged-particle multiplicity

Also consistent with the decrease with multiplicity of the CMS ϒ(2S)/ϒ(1S) ratio

The multiplicity dependence production is the same for J/ψ, ϒ(1S) and ϒ(2S)

Conclusions

- **Systematic measurement of open-heavy-flavour and quarkonia production at different energies and at both mid- and forward rapidity**
  - D-meson and J/ψ production well described by theoretical models
    - Energy and rapidity ratios can constrain gluon PDF at small Bjorken-*x*?
  - Baryon production not described by models and event generators

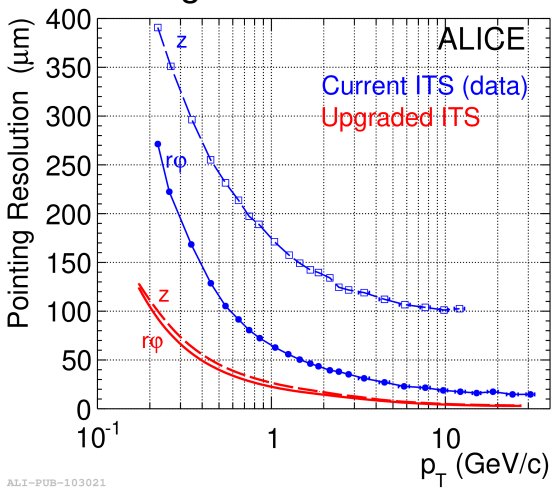
- **HF production vs. multiplicity**
  - Steep increase of HF production with charged-particle multiplicity
    - Faster than linear increase for HF measured at mid-rapidity
    - Linear increase for HF measured at forward rapidity
  - No dependence on collision energy, mass or quark content observed
  - Models including MPI describe qualitatively the observed trends at mid-rapidity

Back up slides

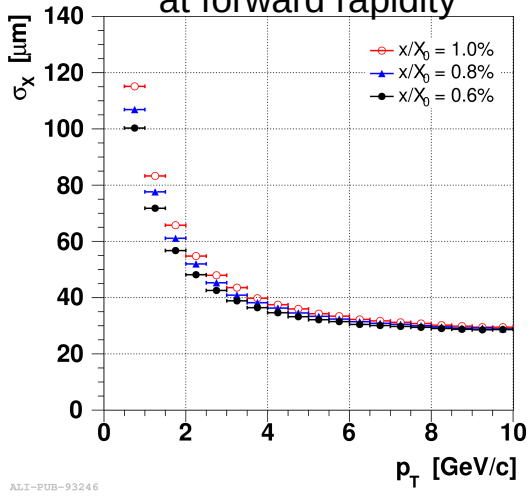
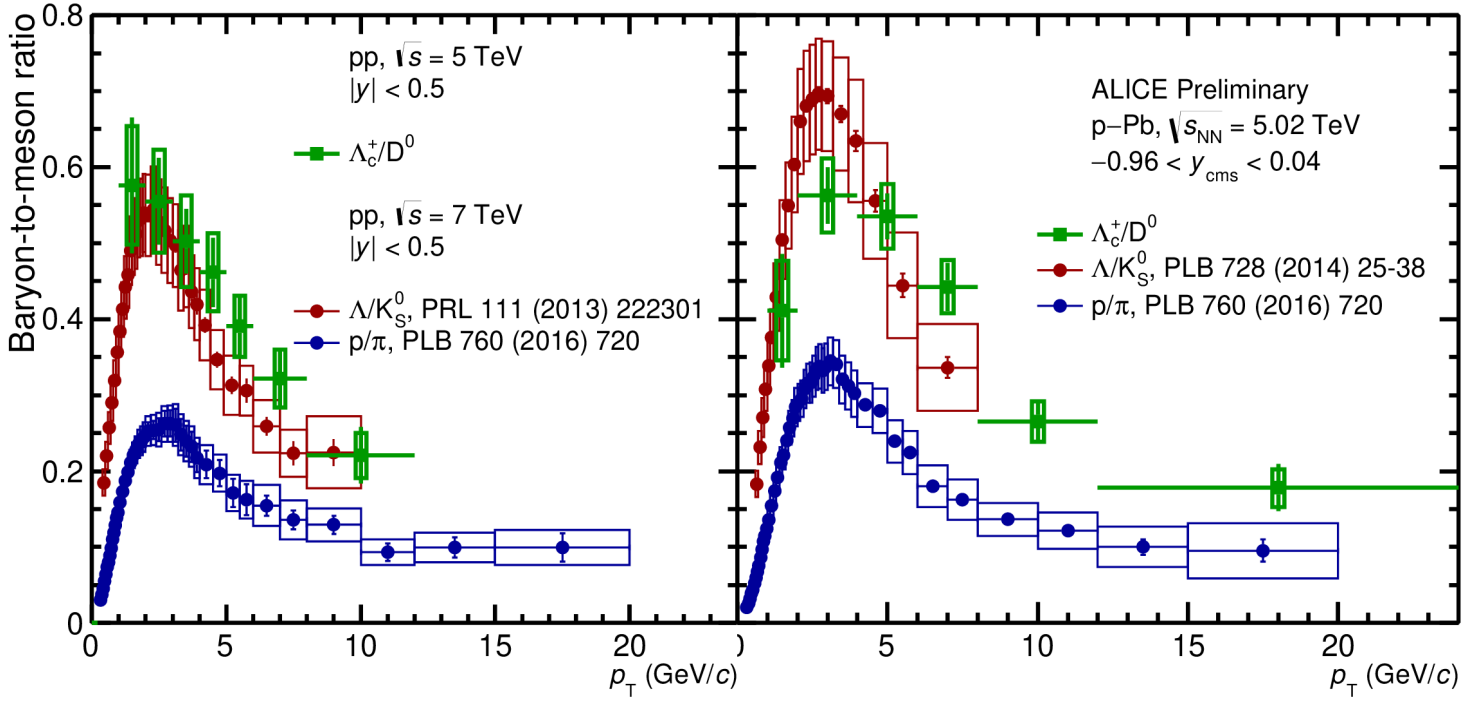
Toward LHC Run 3 & 4

- **Major upgrade of ALICE apparatus during Long Shutdown 2 (2019-2020)**
- **Goals: study rare low p_T probes** (heavy flavour and quarkonia, low mass dielectrons, nuclei)
  - Non triggerable probes → need continuous readout at 50kHz (in Pb-Pb collisions)
  - Improve tracking resolution at low p_T and vertexing
  - Add secondary vertex reconstruction for measurements in the forward region
- Data taking during Run 3-4 (2021-2029) and at 10 nb^{-1}

Pointing resolution in the ITS



Tracking precision vs muon p_T at forward rapidity



Λ_c^+/D^0, Λ_c/K^0_S, p/π