Multiplicity dependence of open charm production in pp and p-Pb collisions

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Outline

- Introduction:
  - motivation,
  - selection of related measurements
- Results: measurements of
  - heavy-flavour production at central rapidity
  - vs. multiplicity at central and forward rapidity,
  - in pp and p-Pb collisions.
- Comparison with models

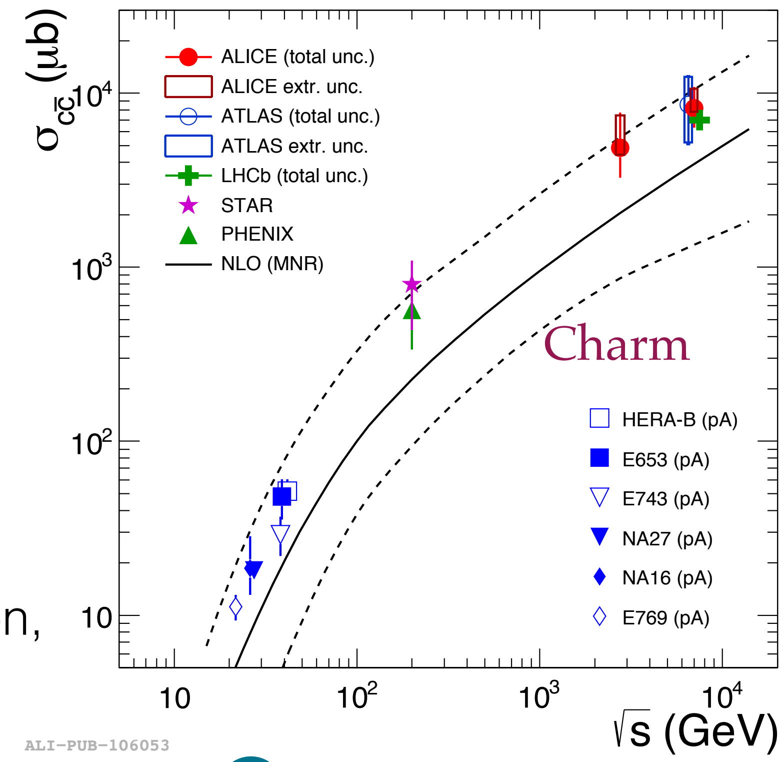
Motivation

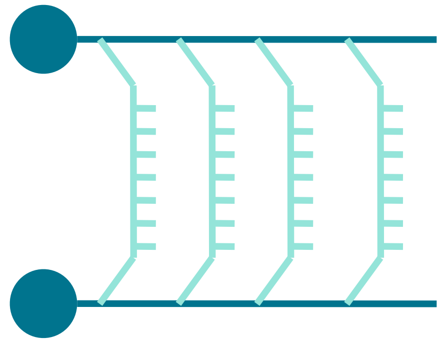
- **Charm and beauty are produced in hard partonic collisions**
  - Tool to tag hard processes with $Q^2 > (2m)^2 \sim 10$ GeV^2.
  - Cross section **calculable with pQCD** based on the factorisation approach.

- **Test multiple parton interactions (MPI)**
  - Naive picture:
    - several hard partonic interactions are possible in a pp collision,
    - the number of parton interactions is related to the primary charged-particle multiplicity.
  - More complex picture:
    - role of collision geometry (impact parameter, transverse structure),
    - final-state effects (colour reconnection, saturation, percolation),
    - collectivity at high multiplicities?

- **Investigate the interaction between the hard and soft components in the full pp collision;**
  - the underlying event final-state particles are not associated to the hard scattering.

S.Porteboeuf, Thu. talk





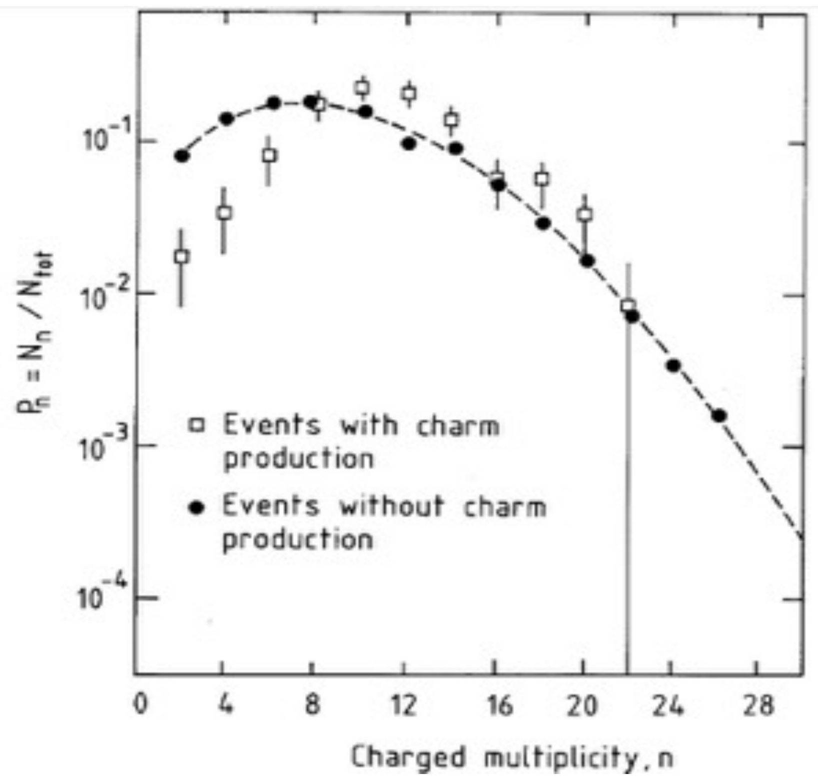
R. Bernhard et al, DESY-PROC-2009-06; arXiv:1003.4220
L. Frankfurt et al., Phys. Rev. Lett. 101, 202003 (2008).
M. Strikman, Prog. Theor. Phys. Suppl. 187, 289 (2011).
M. Strikman, Phys. Rev. D84, 011501(R) (2011).
E. G. Ferreiro et al, Phys.Rev. C86 (2012) 034903.
PHOBOS, Phys. Rev. C 83, 024913 (2011)
K. Werner at al. Phys. Rev. C83:044915, 2011
K. Werner at al. J. Phys. Conf. Ser.316:012012, 2011

Selection of measurements

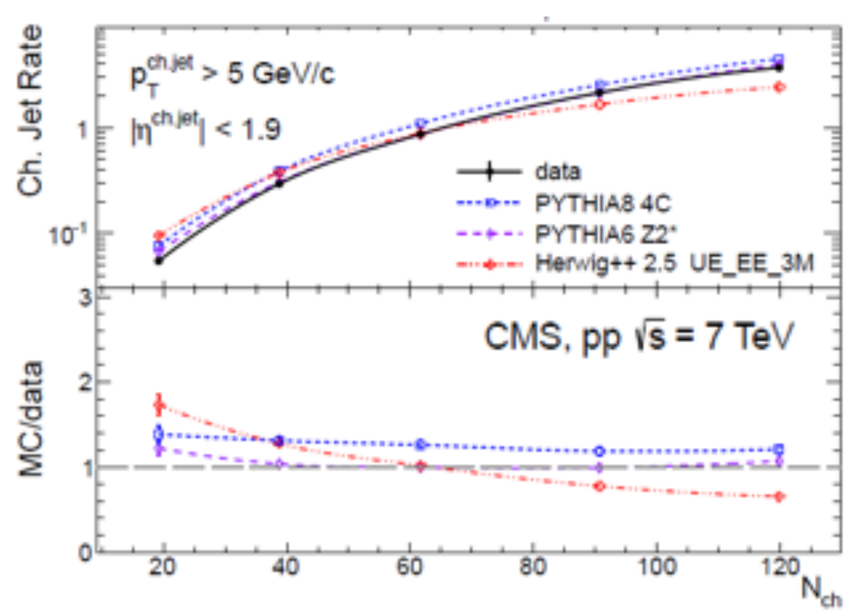
NA27 Coll. Z.Phys.C41:191,1988.

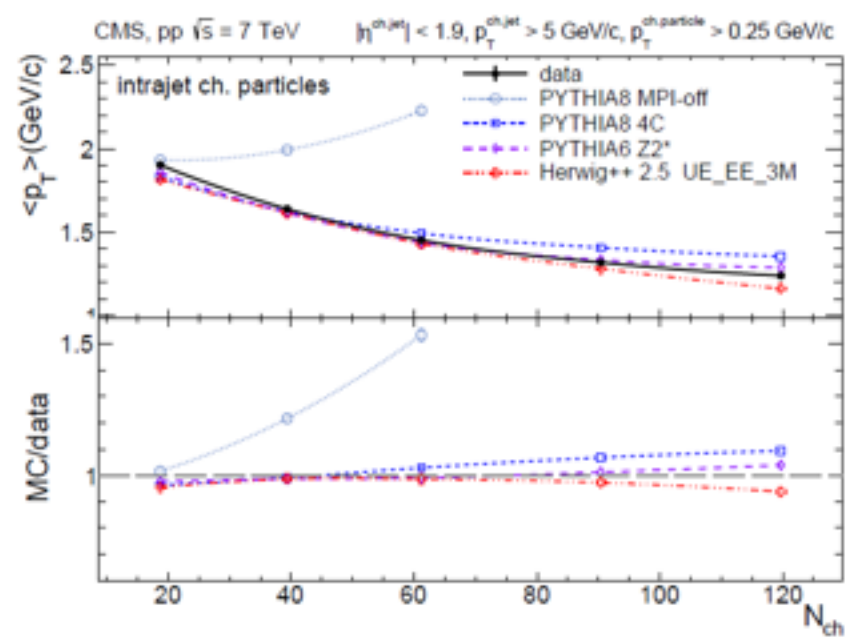
- **NA27 observed that events with charm have on average a larger charged-particle multiplicity, in pp collisions at 400 GeV.**

  "It is clear from fig.1 that the multiplicity distributions for interactions with and without charm are different. … It is natural to interpret these differences by the more central nature of collisions leading to charm production."



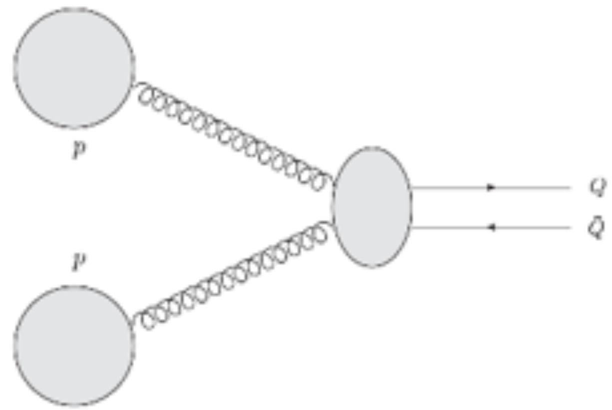
- **CMS jets & underlying event vs. multiplicity (pp at 7 TeV):**
  - larger number of (semi) hard parton interactions, (mini)jets,
  - softer distribution of hadrons inside jets,
  - **MPI mechanism crucial to describe data.**



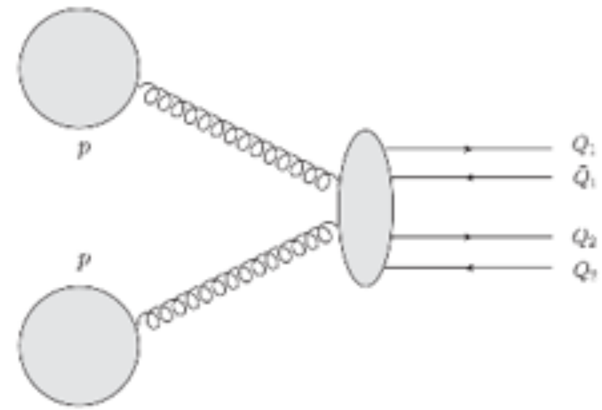


CMS, EPJ C73 (2013) 2674

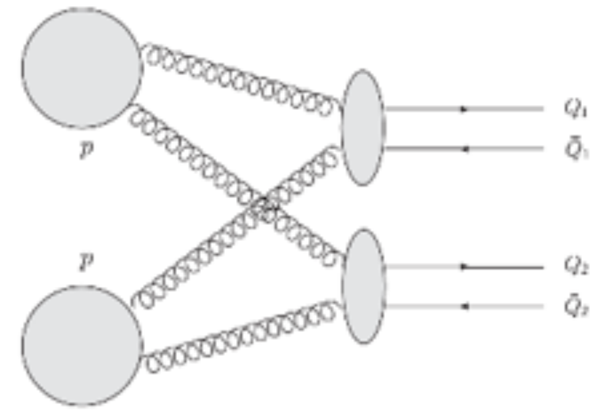
Charm and Multi-Parton Interactions



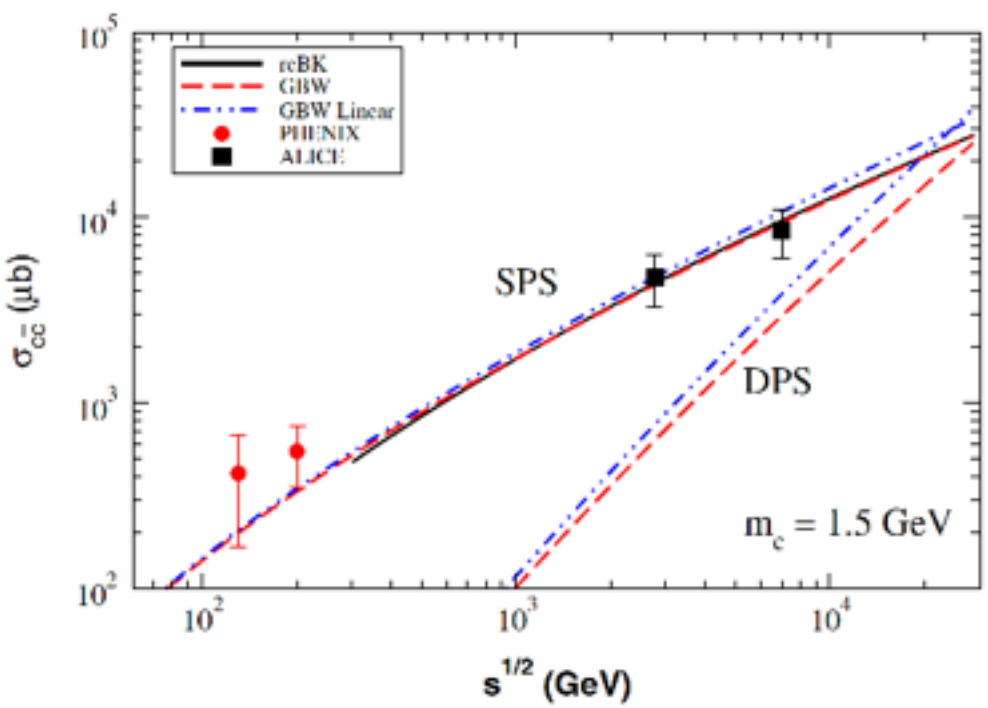
Single production

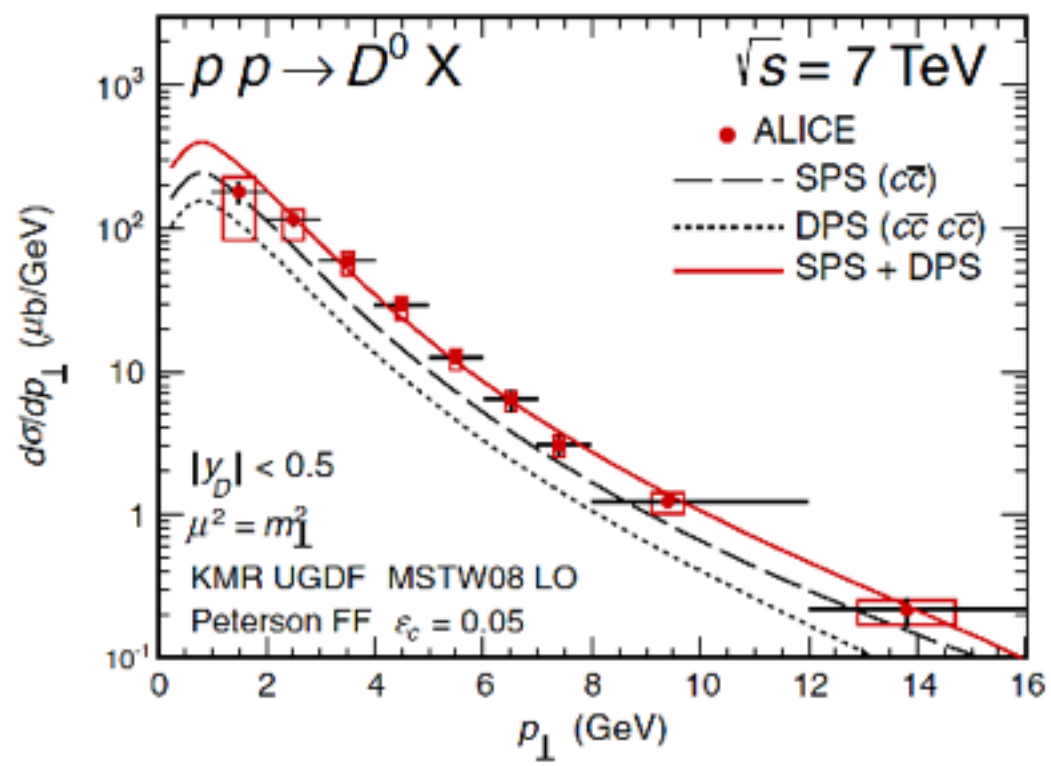


Double production by SPS



Double production by DPS



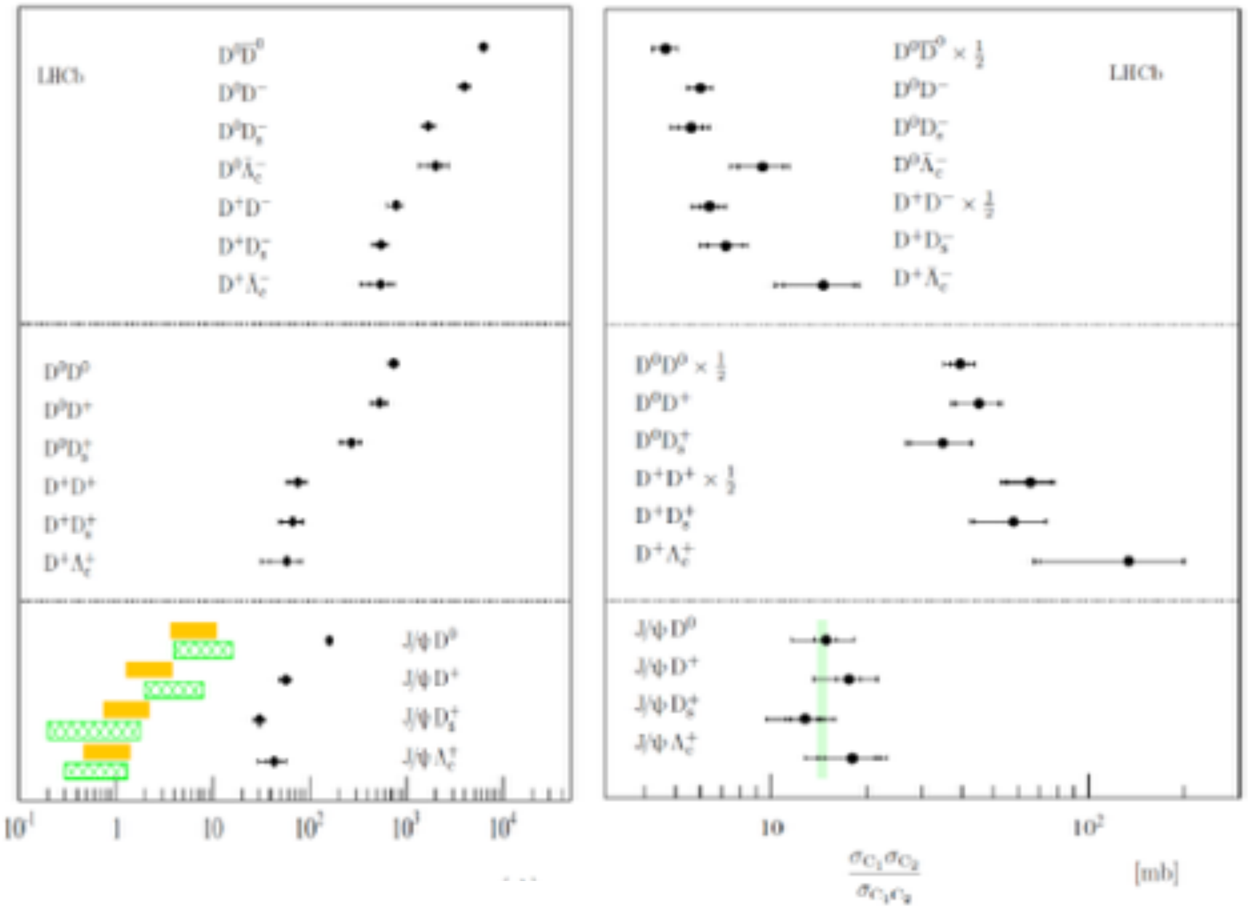


- **Contribution from Double Parton Scattering increasing with √s expected to be comparable to Single Parton Scattering for the LHC run II**
- **Improved description of charm results with calculations of SPS+DPS**

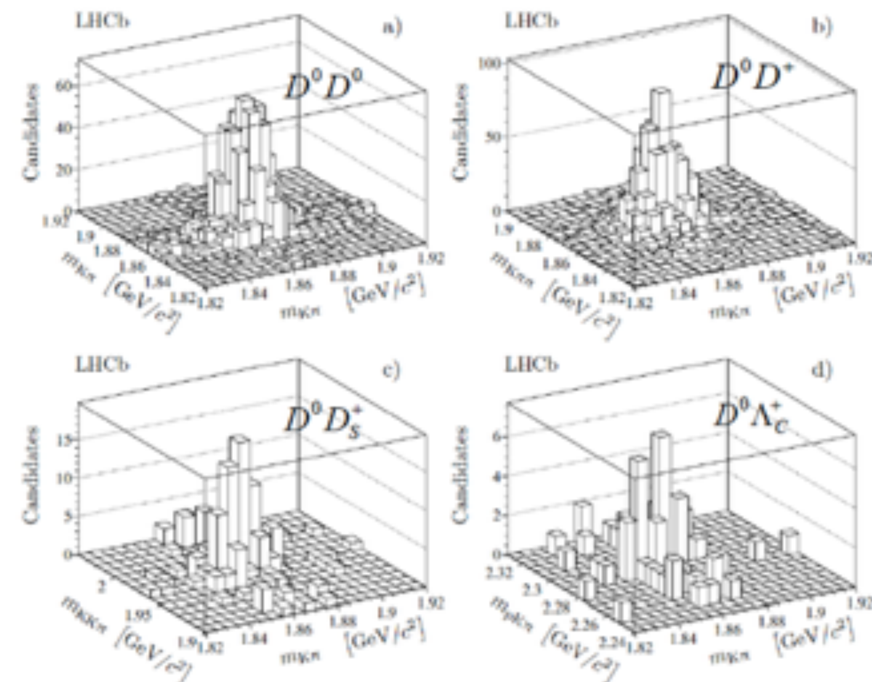
E.R. Cazaroto et al, Phys. Rev. D 88 (2013) 034005

M. Maciula, A. Szczurek, Phys. Rev. D 87 094022 (2013); A. Hameren, M. Maciula, A. Szczurek, arXiv:1402.6972 (2014)

Double charm production

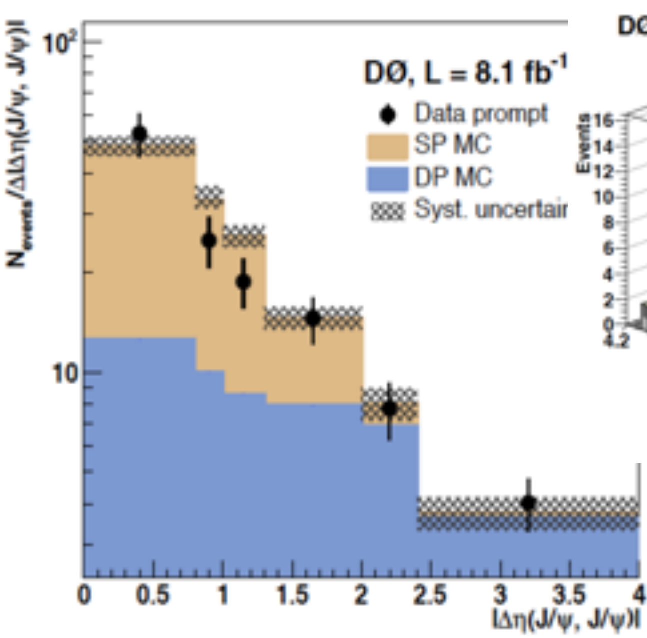


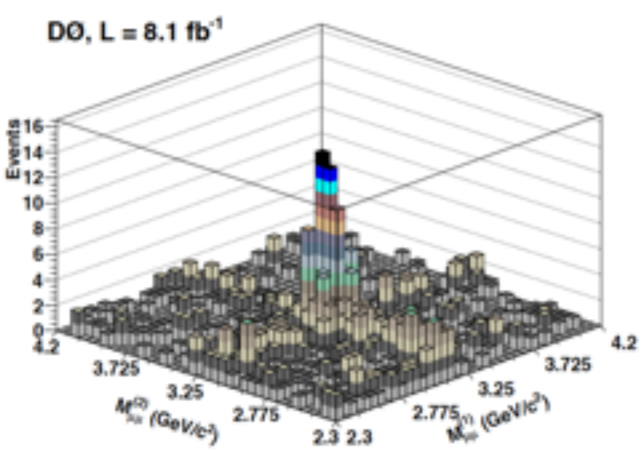
$$\sigma^{\rm DPS}(C_1C_2) = k \times \frac{\sigma(C_1)\sigma(C_2)}{\sigma_{\rm eff}^{\rm DPS}}, \qquad k = \frac{1}{2}\,(1) \text{ for } C_1 = (\neq) C_2$$



[LHCB, JHEP 06 (2012) 141]
[LHCB, PLB 707 (2012) 52]

J.Li, Friday talk





J/ψ+J/ψ

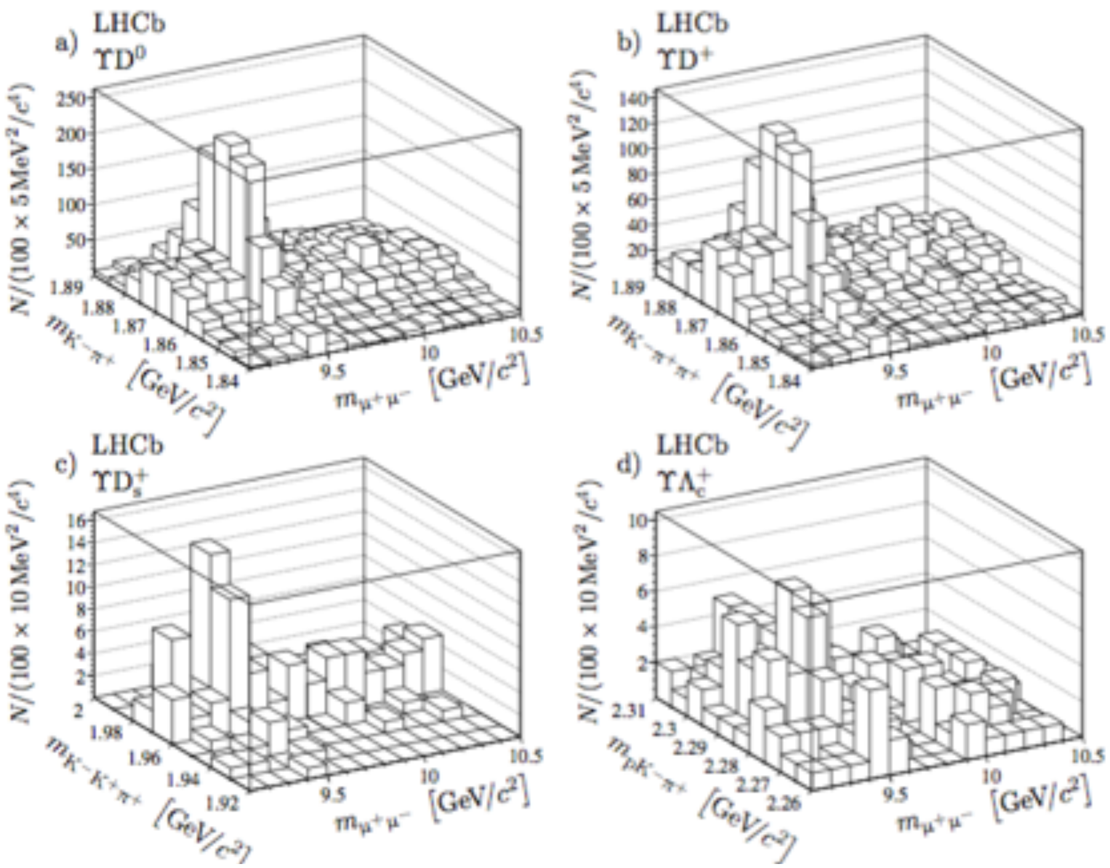
[D0, arXiv:1406.2380 (2014)]

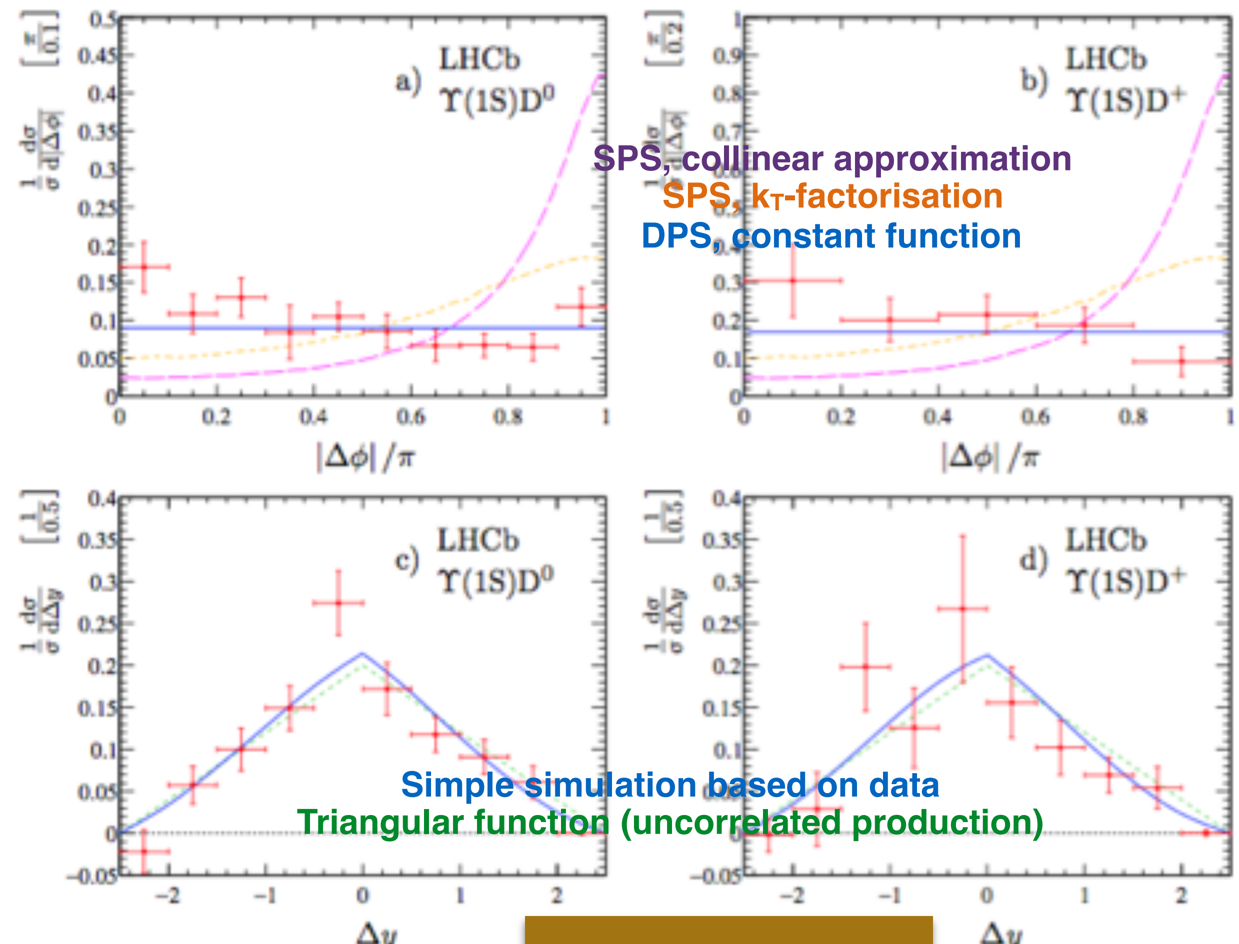
➡ **Theoretical predictions from gg fusion underestimate LHCb J/ψ C cross section, whereas DPS estimates (from CDF multi-jets) agree with LHCb J/ψ C cross section**

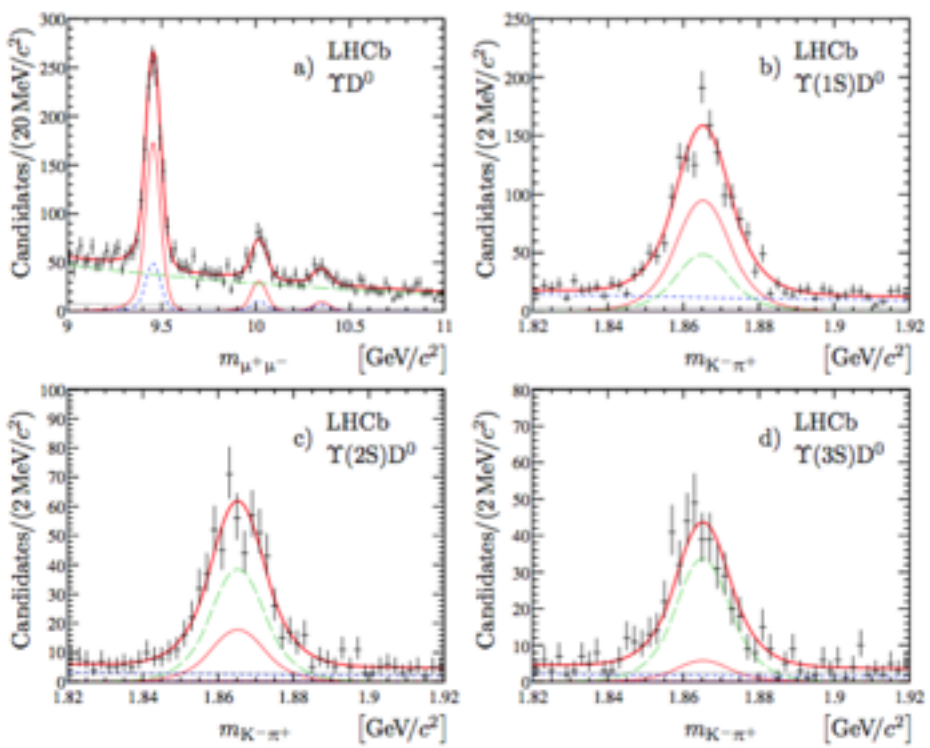
➡ **D0 J/ψ+J/ψ DPS contribution is consistent with the CDF 4-jet low-pt results, but lower than the W(ɣ)+jet results → smaller distance between gluons than q-q or q-g ?**

Kom et al PRL 107 (2011) 082002; Baranov et al, PLB 705 (2011) 116; Novoselov, arXiv:1106.2184; Luszczak et al, arXiv:1111.3255

Associated charm and beauty production







[LHCB, JHEP 07 (2016) 052]

J.Li, Friday talk

➡ **Υ+D Δϕ distribution (ctt fit p-value of 6-12%) indicates that SPS contribution to data is small. Δy distribution has no sensitivity within uncertainties.**

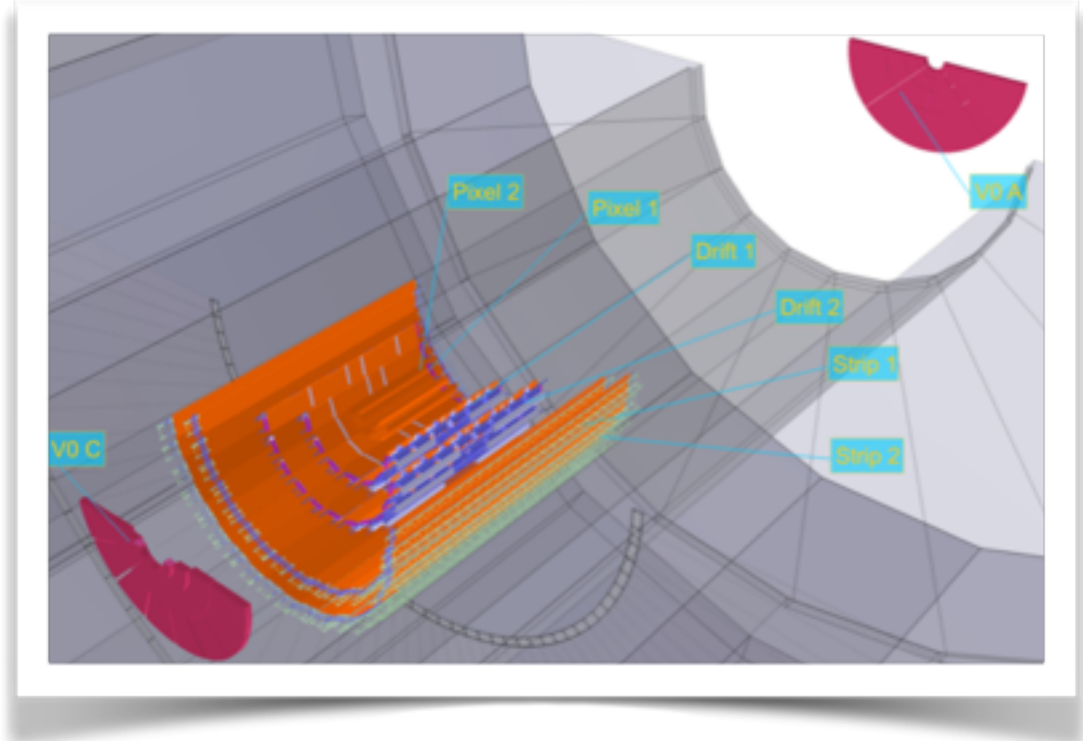
➡ **Υ+D cross section in agreement with DPS expectations, and significantly exceeding SPS ones.**

➡ **Effective cross section in agreement with most previous estimates.**

Results in pp collisions at 7 TeV as a function of charged-particle multiplicity

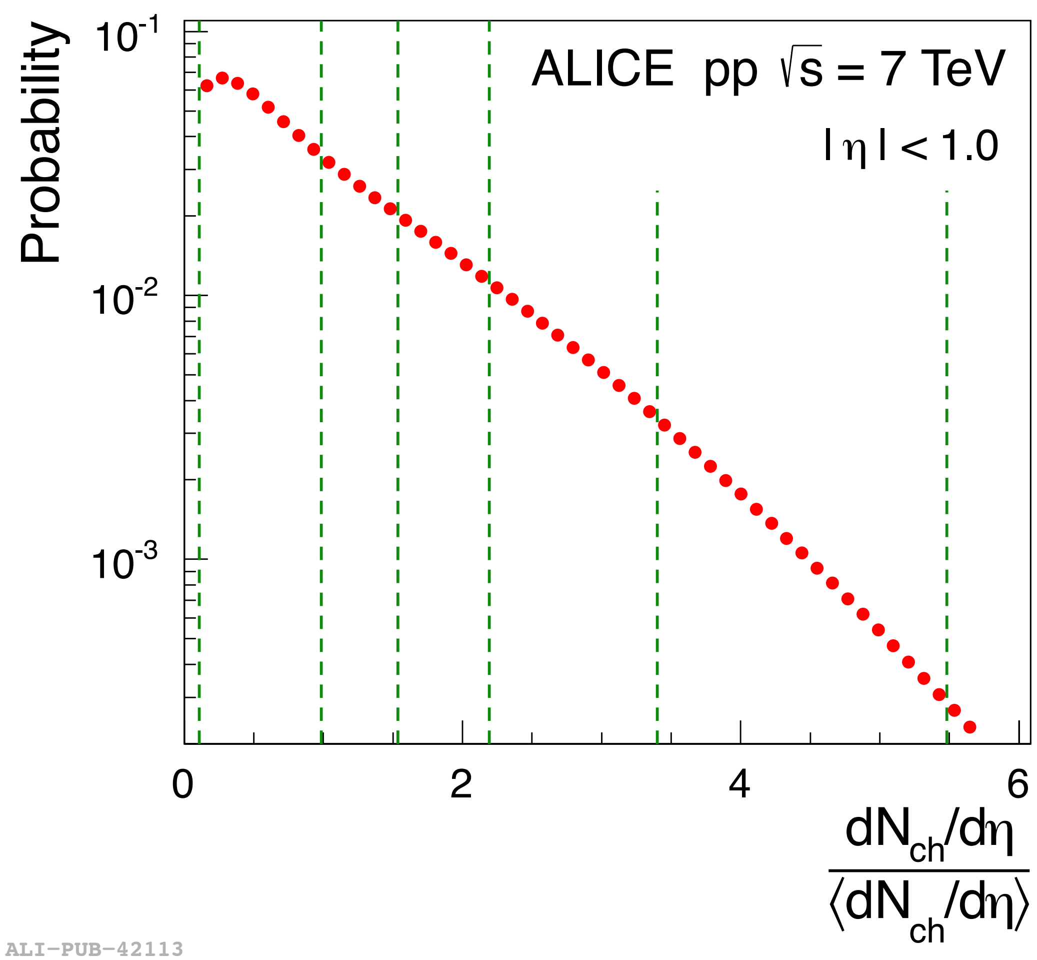
Multiplicity measurements in ALICE

- Multiplicity estimators:
  - number of track segments (or *tracklets*) of the **Silicon Pixel Detector** (2 innermost layers of the *Inner Tracking System*).
  - sum of amplitudes in the **V0** scintillator arrays



SPD layers of radii of 3.9 cm (1cm from beam vacuum tube) and 7.6 cm. Formed by 9.8×10^6 pixels of size $50(r\phi) \times 425(z)$ μm^2, with intrinsic spatial resolution of $12(r\phi) \times 100(z)$ μm^2.

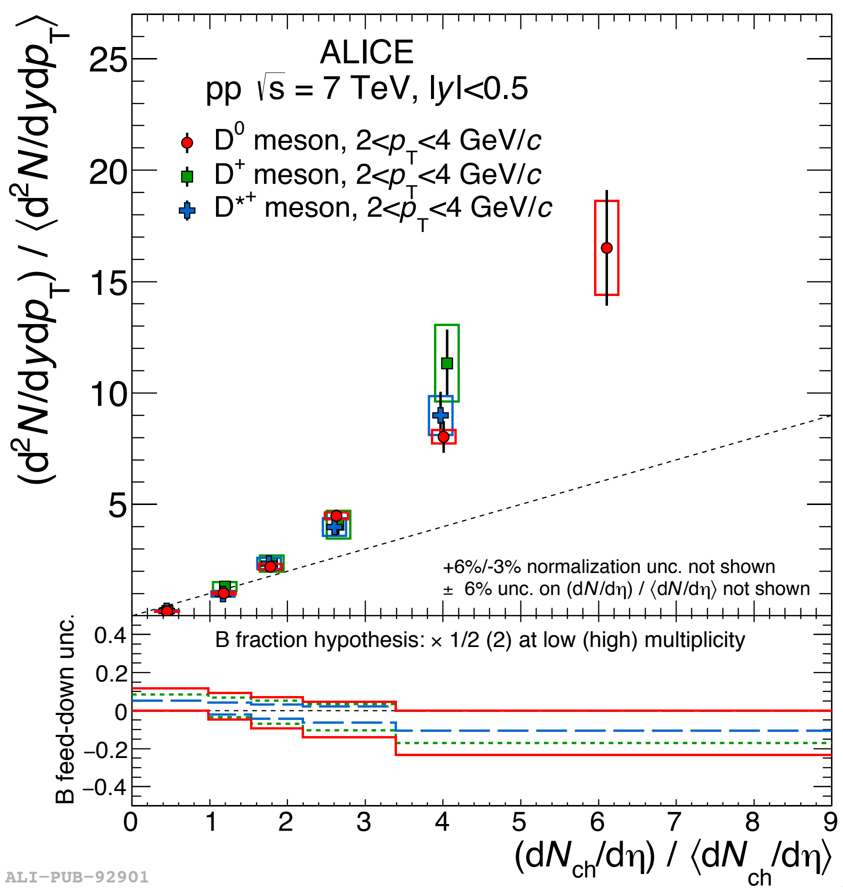
V0 scintillator arrays at $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$

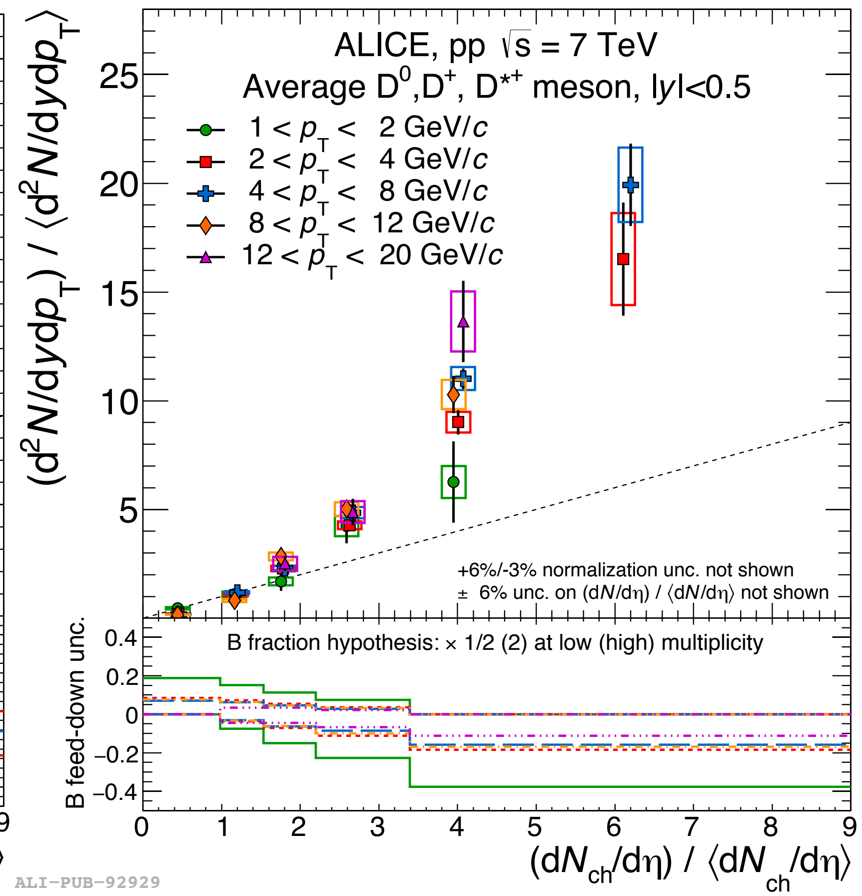


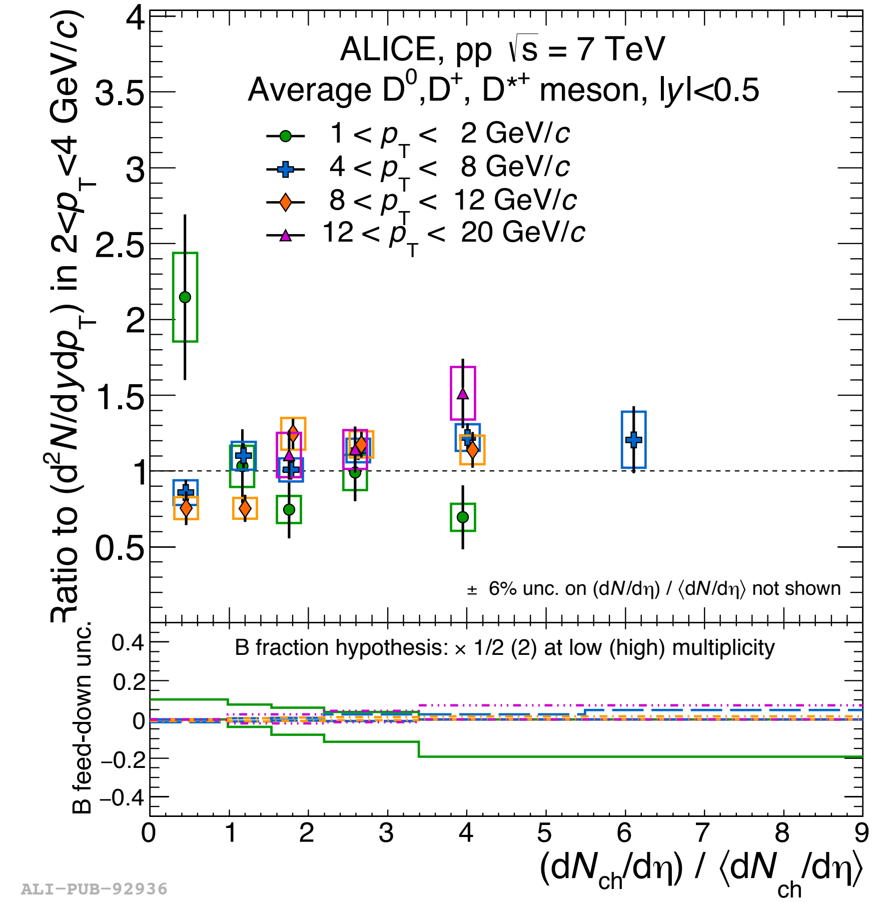
- $N_{tracklets} \propto dN_{ch}/d\eta$
- $\langle dN_{ch}/d\eta \rangle = 6.01 \pm 0.01(\text{stat.})\ ^{+0.20}_{-0.12}(\text{syst.})$ for $|\eta|<1.0$ in pp collisions at 7 TeV

ALICE Coll., Eur. Phys. J. C 68 (2010) 345.
ALICE Coll., Phys. Lett. B 712 (2012) 3, 165–175

Open charm vs. multiplicity





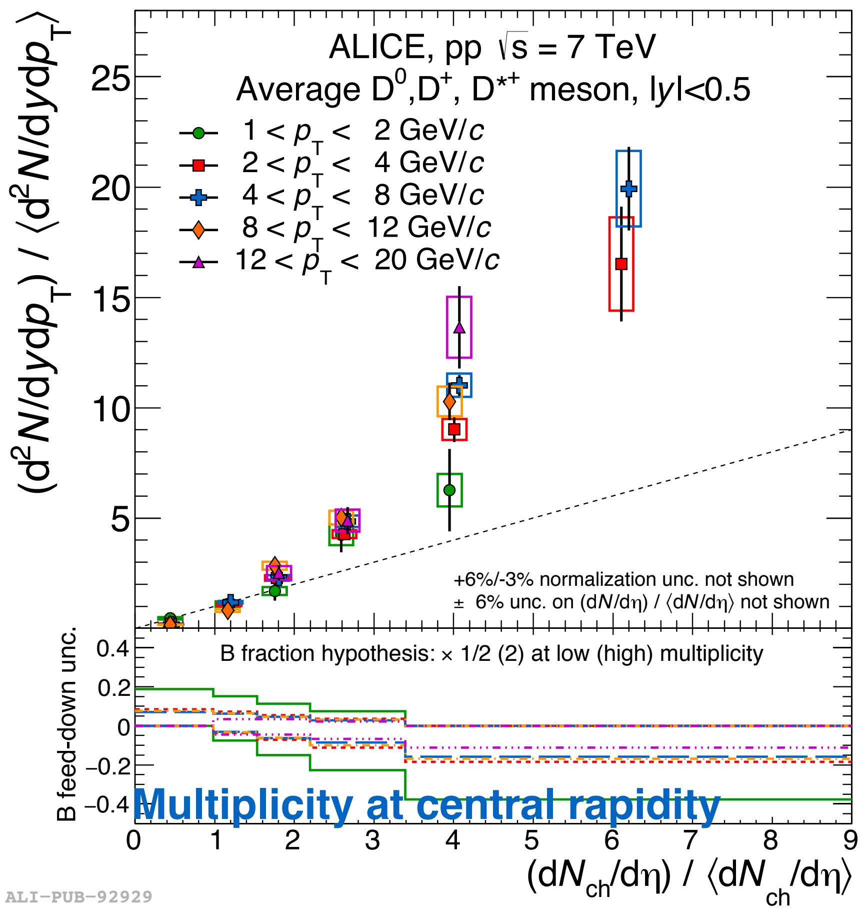


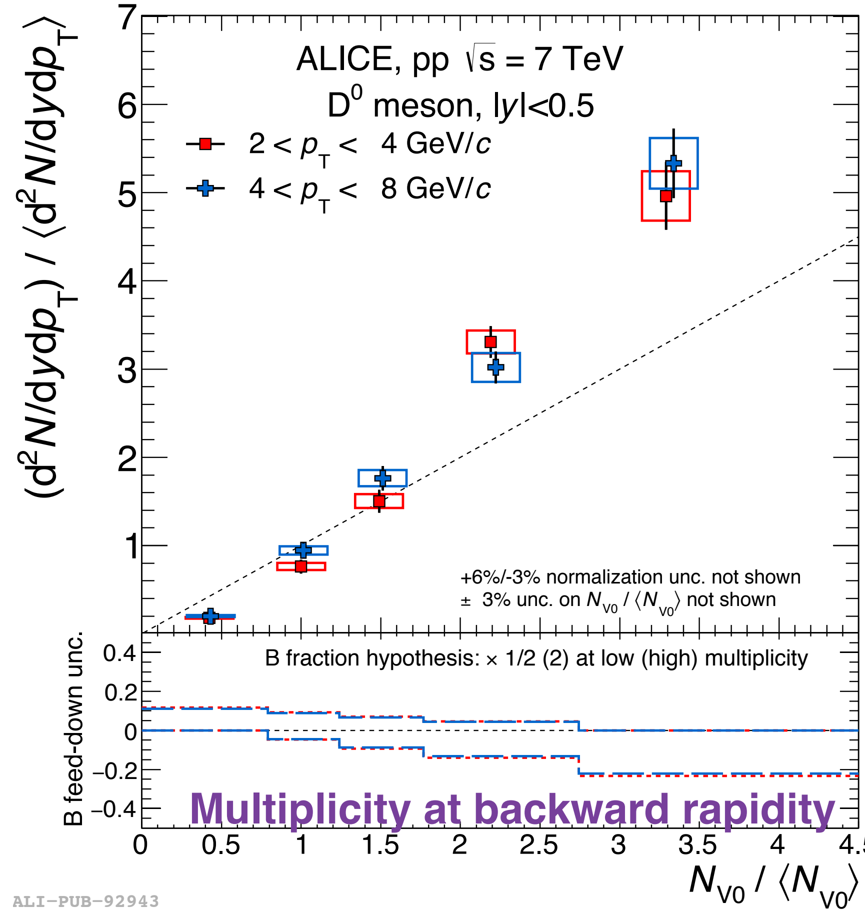
- **The results of D^0, D^+ and D^{*+} are consistent within uncertainties.**
- **Increase of D-meson yields with charged-particle multiplicity at mid rapidity:**
  - **faster-than-linear increase at large multiplicities,**
  - **independent of p_T within uncertainties.**

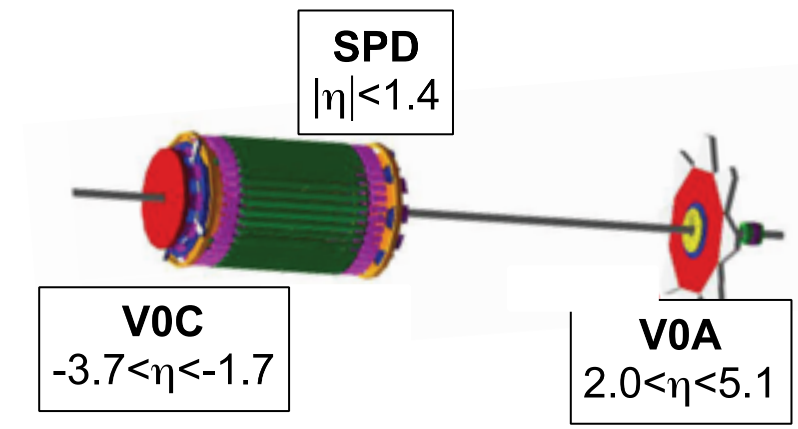
ALICE, JHEP 09 (2015) 148.

Error bars: statistical uncertainty.
Vertical size of boxes : systematic uncertainties but feed-down.
Bottom panels lines: relative feed-down systematic uncertainties.
Not shown : systematic uncertainty on $(dN/d\eta)/\langle dN/d\eta \rangle$. and normalisation.

Introducing an η gap on the multiplicity measurement







- Test possible auto-correlations using multiplicity measured in a different rapidity range than heavy-flavour yields (minimise the influence of heavy-quark fragmentation and heavy-flavour hadron decays in the multiplicity estimation).
- **Qualitatively similar increasing trend of D-meson yields when an η gap is introduced between the regions where the D mesons and the multiplicity are measured.**

ALICE, JHEP 09 (2015) 148.

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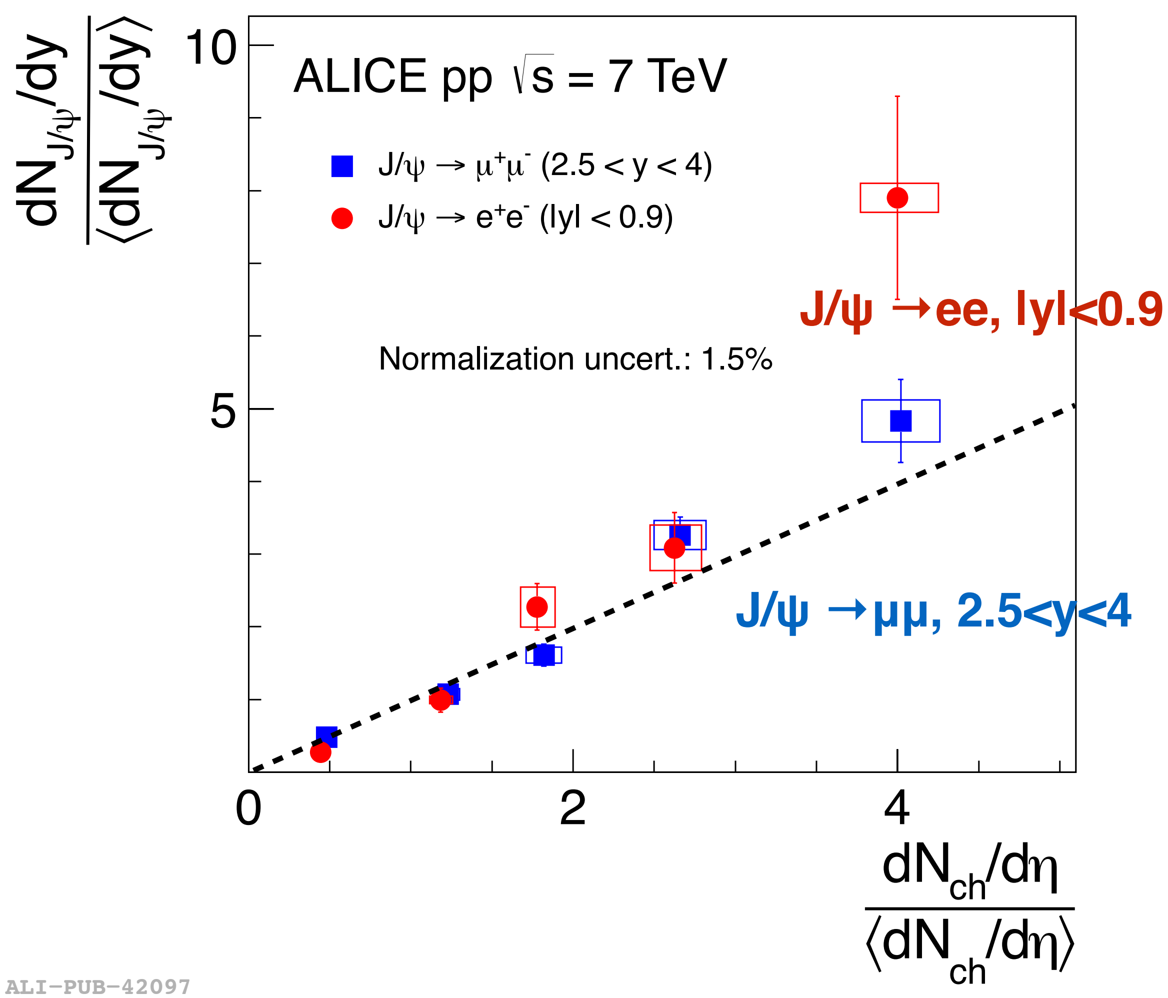
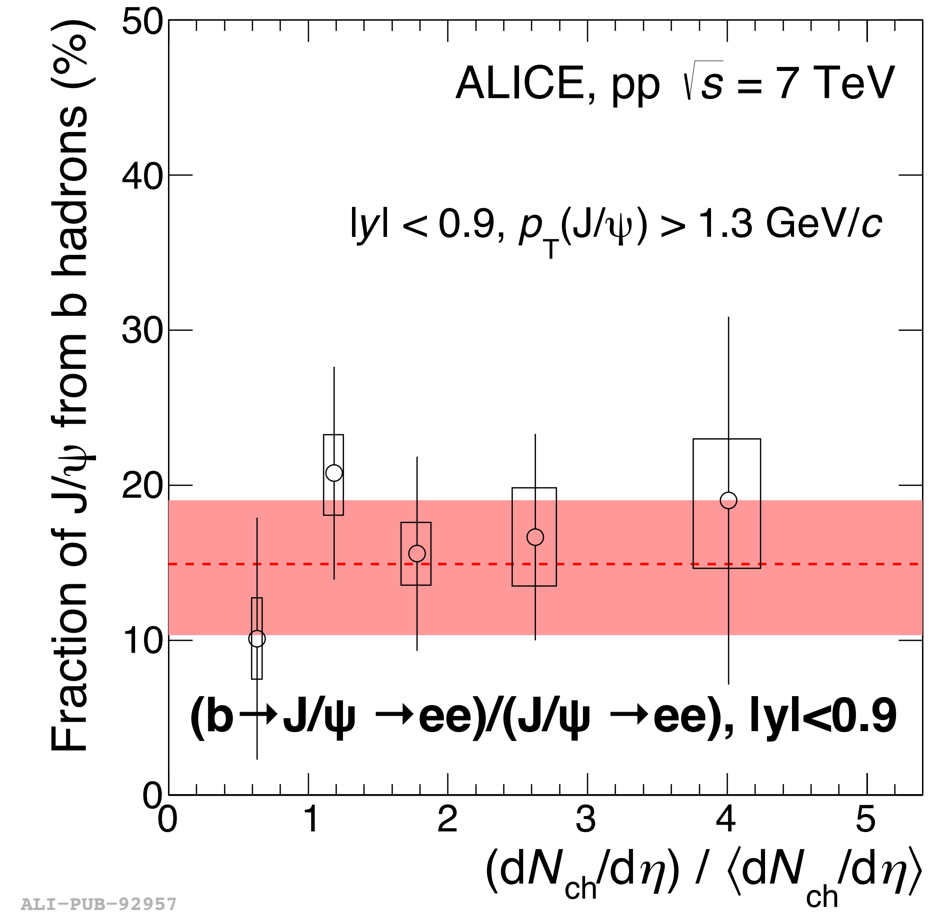
Charmonia vs. multiplicity





- **Increase of J/ψ yields as a function of multiplicity at mid rapidity.**
  - **Similar increase of J/ψ yields measured at central and forward rapidity.**
- **The fraction of non-prompt J/ψ in the inclusive yields shows no multiplicity dependence with multiplicity within uncertainties.**

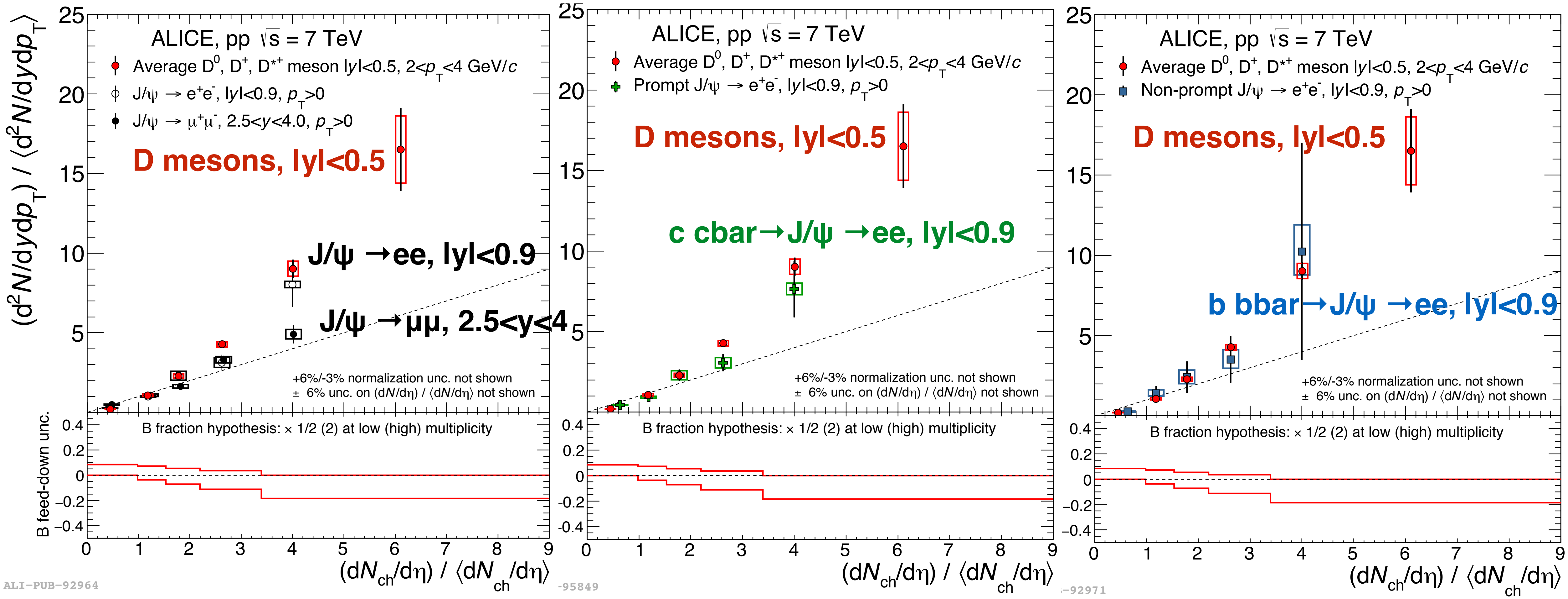
ALICE, Phys.Lett. B712 (2012) 165–175
ALICE, JHEP 09 (2015) 148.

Error bars: statistical uncertainty.

Horizontal size of boxes : systematic uncertainty on $(dN/d\eta)/\langle dN/d\eta \rangle$.

Vertical size of boxes : systematic uncertainties but feed-down.
Not shown : normalisation systematic uncertainty.

Comparison of open and hidden heavy flavours



- **Similar increase of open charm, open beauty and charmonia yields as a function of charged-particle multiplicity at mid rapidity.**
  - **Caveats: different rapidity and p_T interval of the measurements.**
  - **Likely related to heavy-flavour production processes, and not significantly influenced by hadronisation.**

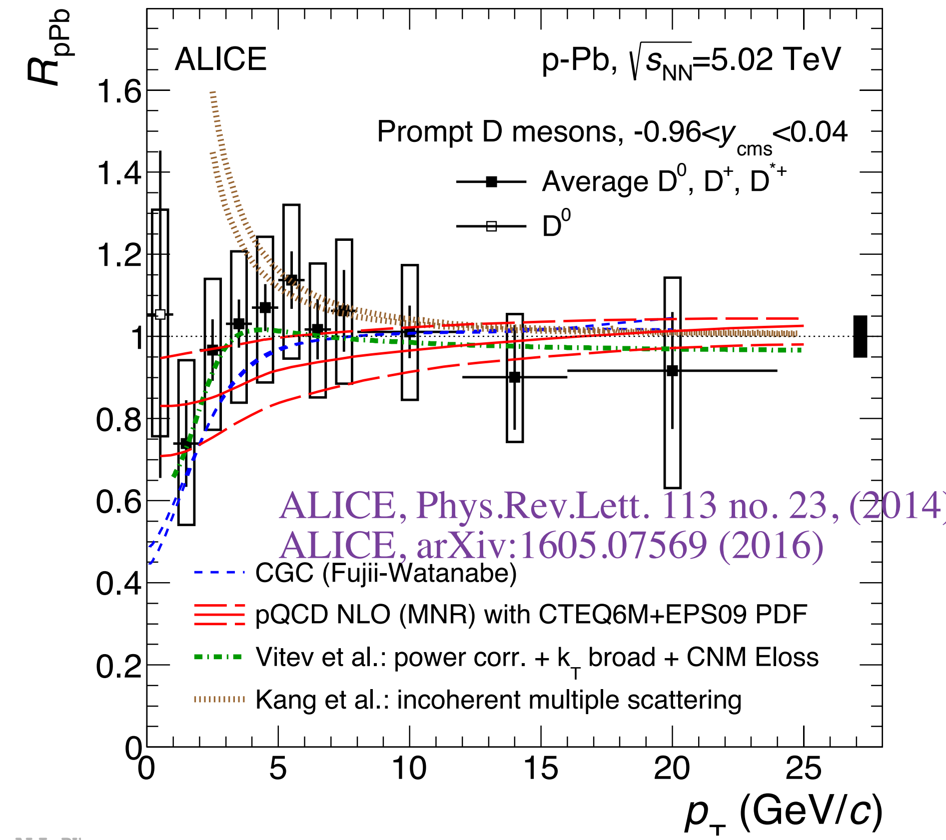
ALICE, Phys.Lett. B712 (2012) 165–175
ALICE, JHEP 09 (2015) 148.

Error bars: statistical uncertainty.
Vertical size of boxes : systematic uncertainties but feed-down.
Bottom panels lines: relative feed-down systematic uncertainties.
Not shown : systematic uncertainty on $(dN/d\eta)/\langle dN/d\eta\rangle$. and normalisation.

Results in p-Pb collisions at 5.02 TeV

Heavy-flavour production in p-Pb collisions

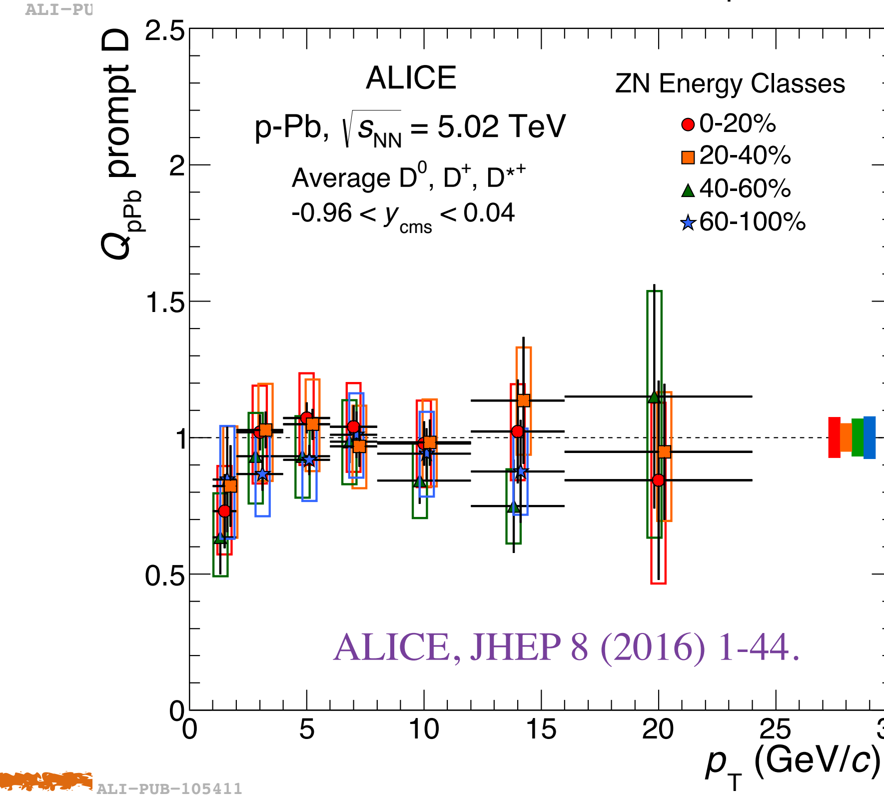
- As in pp collisions,
- **HF yield expected to scale with the number of binary nucleon-nucleon collisions.**
- **Nuclear environment influence (p-Pb collisions):**
  - **shadowing (PDF modifications in nuclei) and gluon saturation,**
  - **k_T broadening (multiple soft scatterings),**
  - **energy loss (initial/final state or coherent),**
  - **collective effects (hydrodynamics)?**



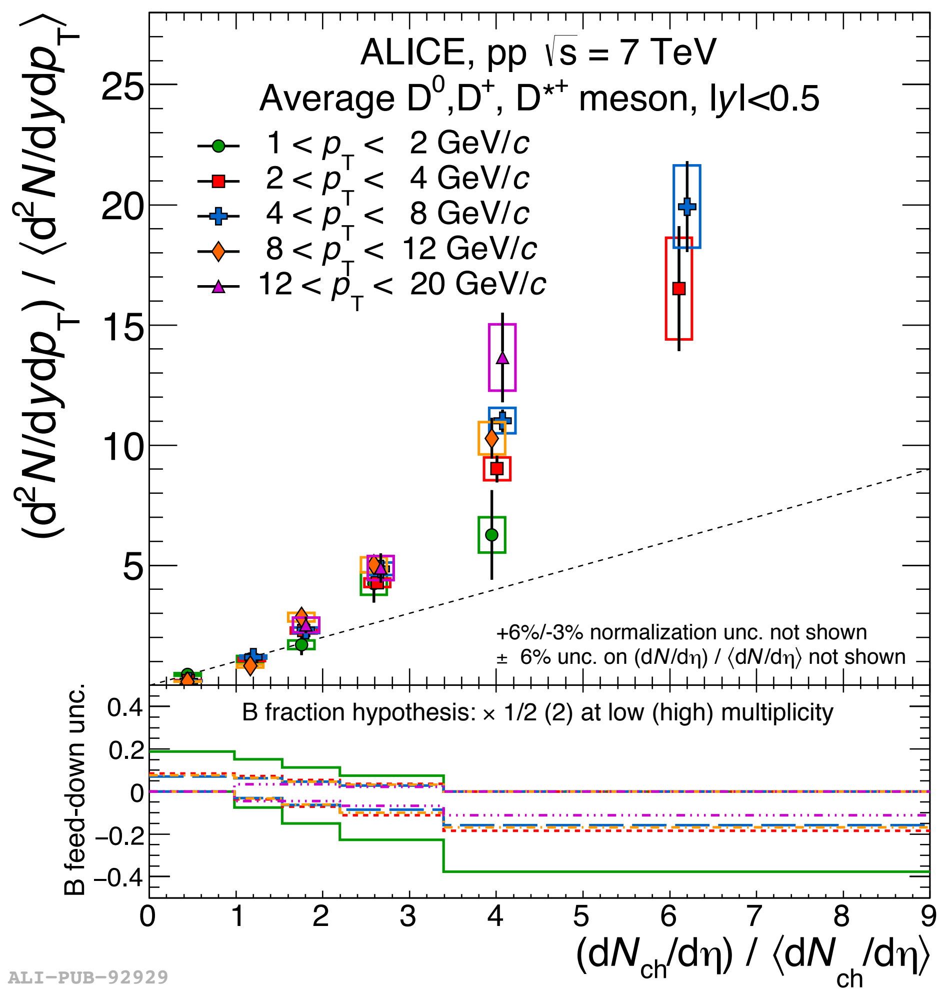
- Observable:

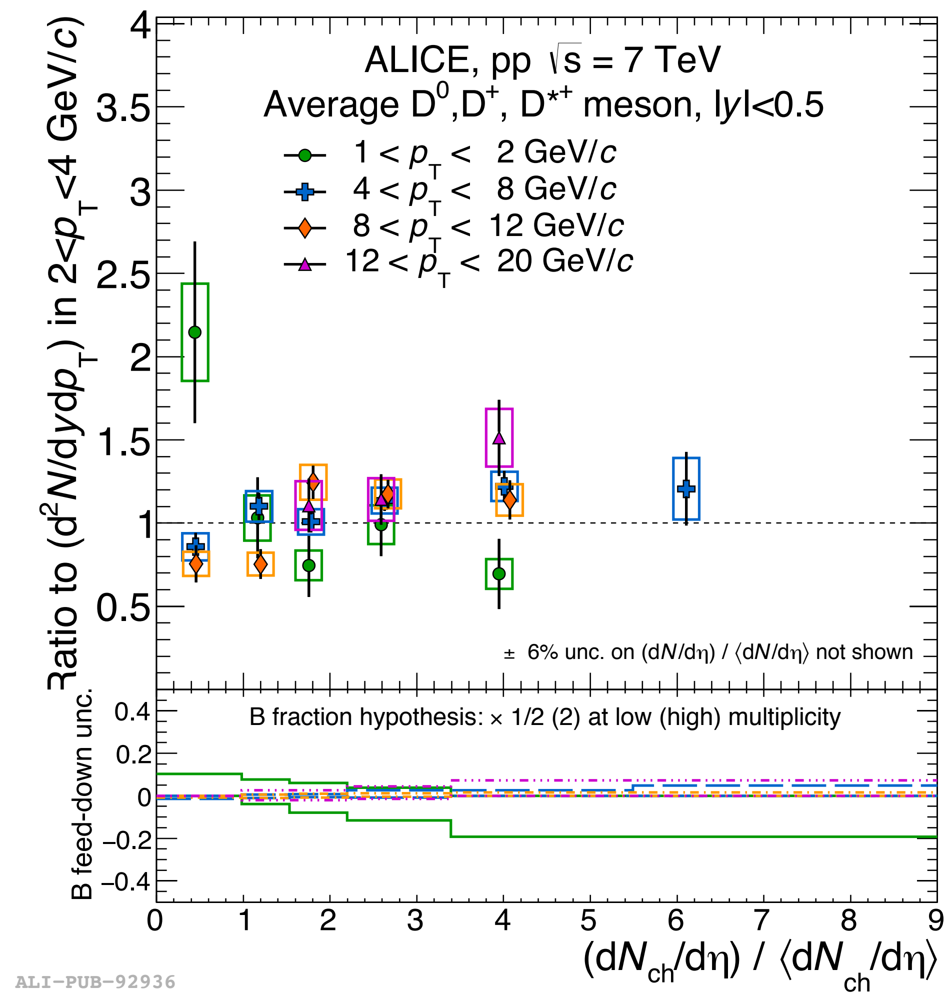
$$R_{AB} = \frac{1}{\langle T_{AB}\rangle}\frac{dN_{AB}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{\langle N_{coll}\rangle_{AB}}\frac{dN_{AB}/dp_T}{dN_{pp}/dp_T}$$

- **Measurements:**
  - **prompt D-meson R_{pPb} is close to unity at high p_T**
  - **no centrality dependence of R_{pPb} within uncertainties,**
  - **Relatively well described by models including cold nuclear matter effects.**



Open charm vs. multiplicity





- **Increase of D-meson yields with charged-particle multiplicity at mid rapidity:**
  - **slightly faster-than-linear increase at large multiplicities,**
  - **independent of p_T within uncertainties.**

ALICE, JHEP 8 (2016) 1-44.

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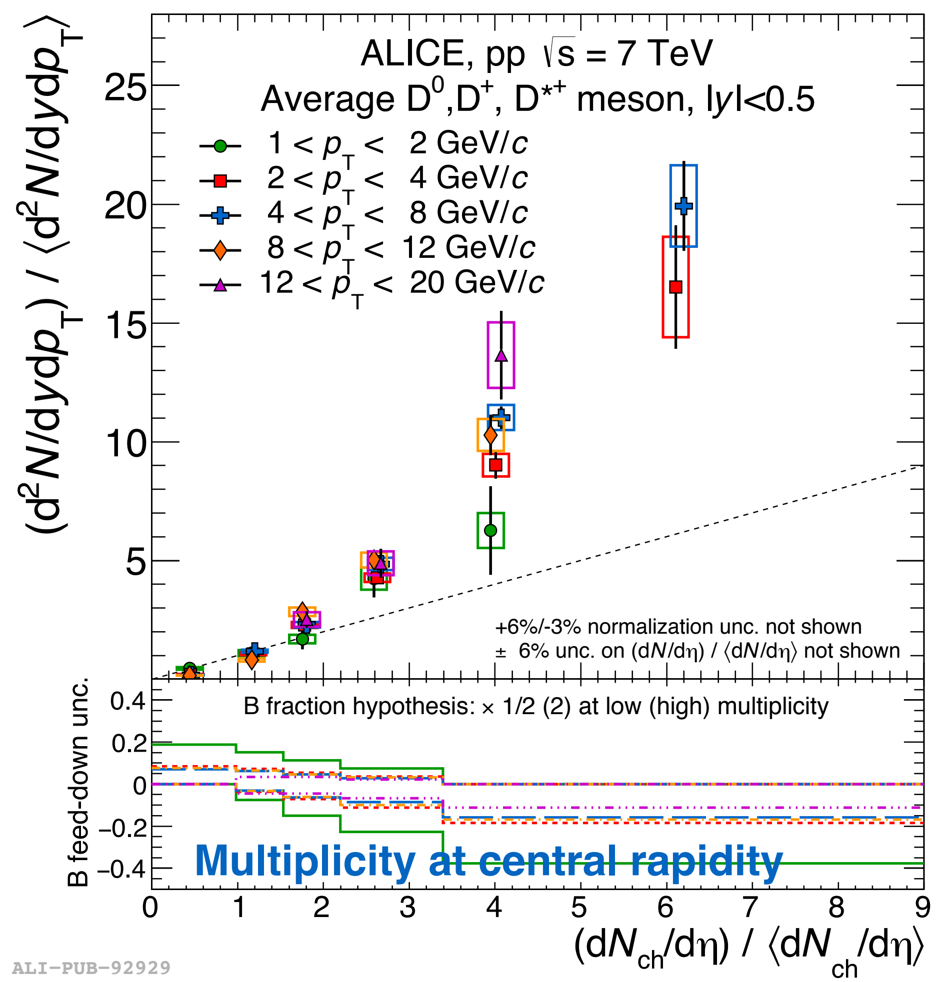
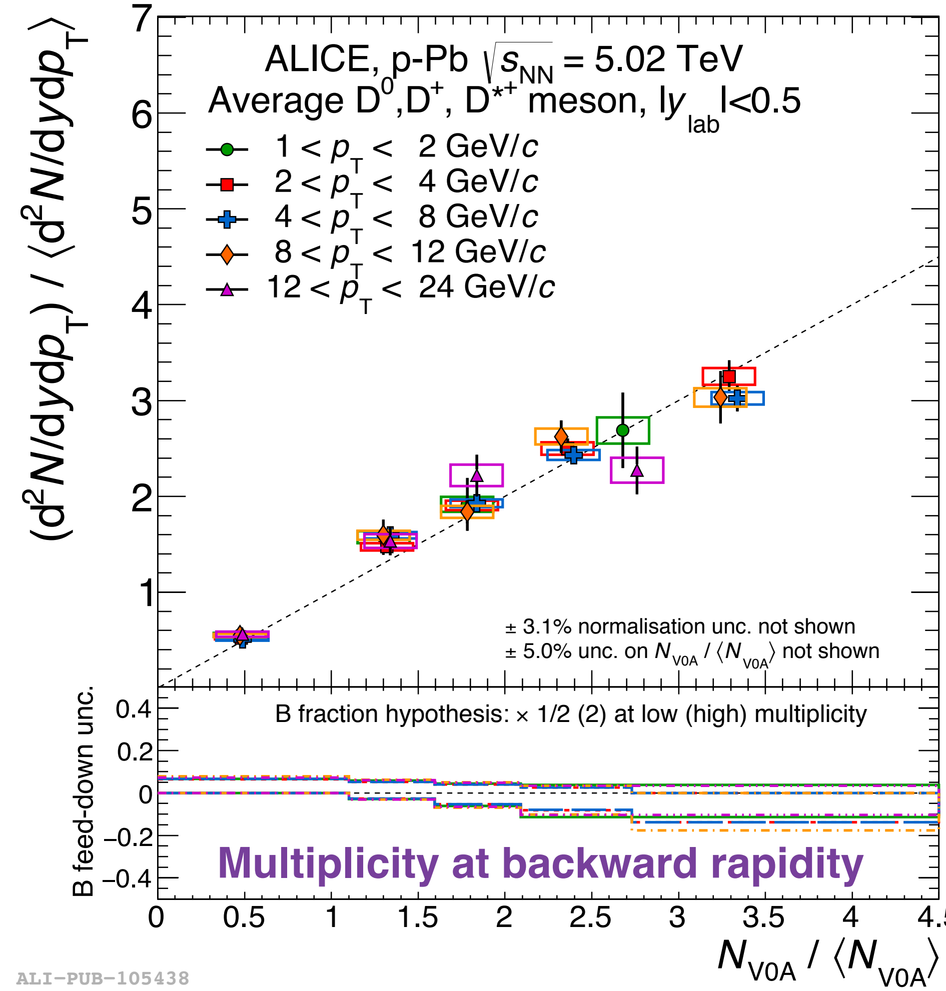
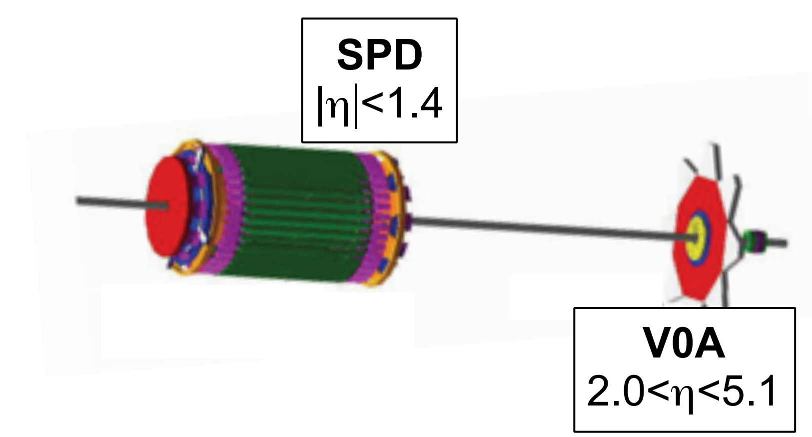
Introducing an η gap on the multiplicity measurement





- Test auto-correlations on the multiplicity estimation.
- **Nearly linear increase with multiplicity at backward rapidity (Pb-going direction).**
  Results consistent in the measured interval within uncertainties.



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ALICE, JHEP 8 (2016) 1-44.

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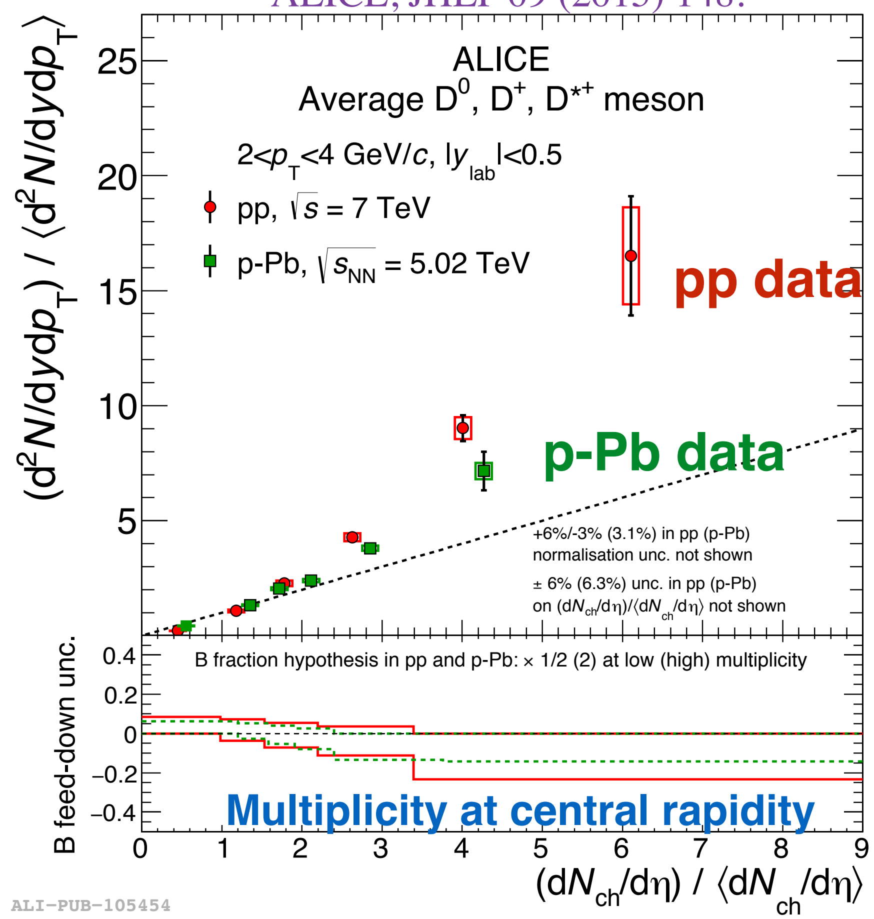
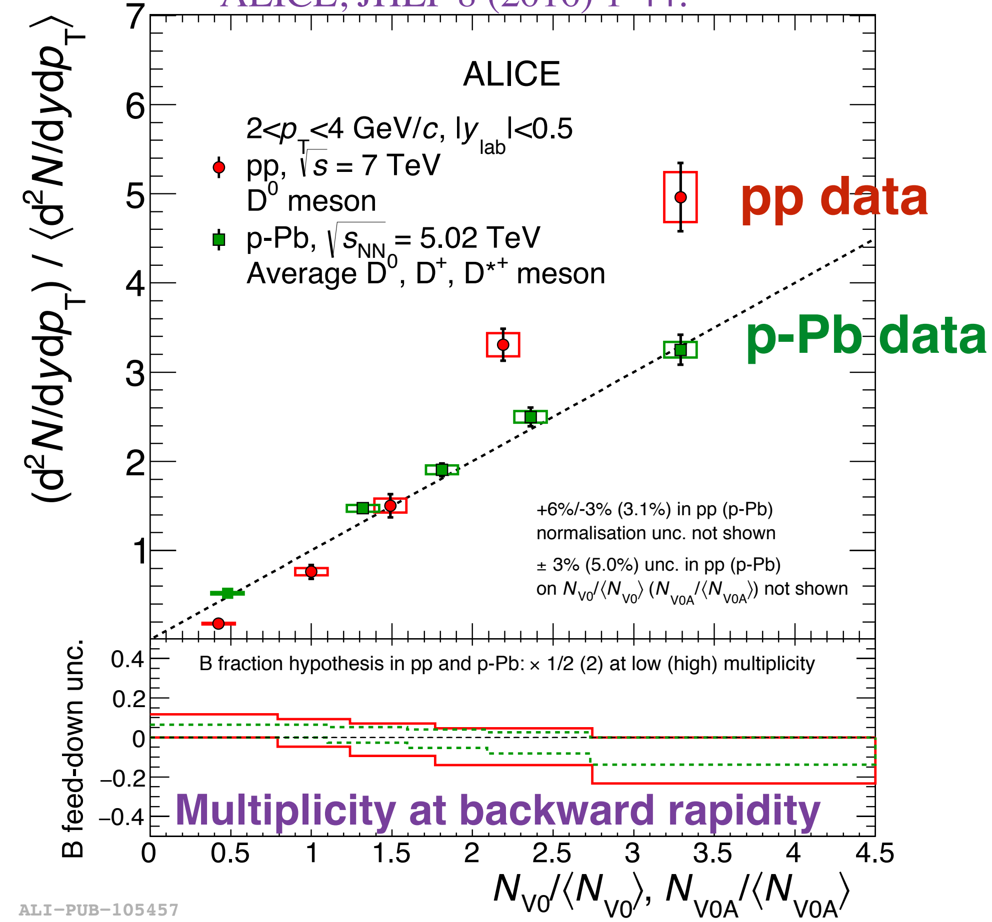
Open charm in pp and p-Pb collisions

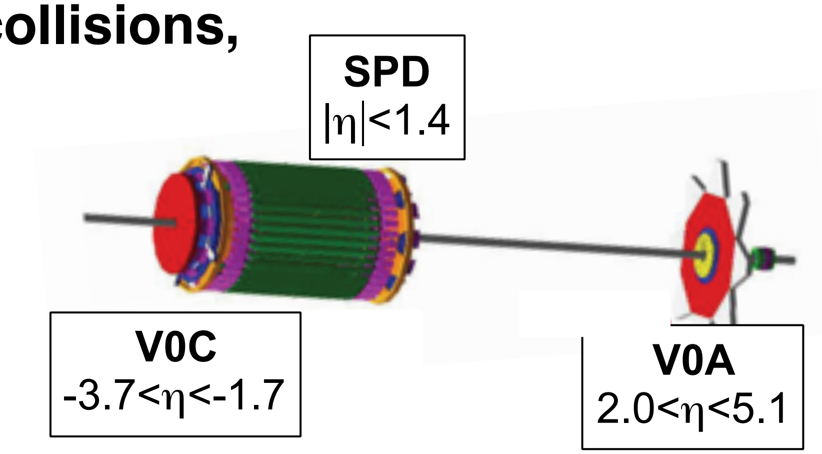
ALICE, JHEP 09 (2015) 148.



ALICE, JHEP 8 (2016) 1-44.



- **Multiplicity at mid rapidity: similar trend for D-meson results in pp and p-Pb collisions.**
- **Multiplicity at large (backward) rapidities:**
  - **measured in different η ranges in pp and p-Pb collisions,**
  - **faster increase of D-meson yields in pp than in p-Pb collisions.**



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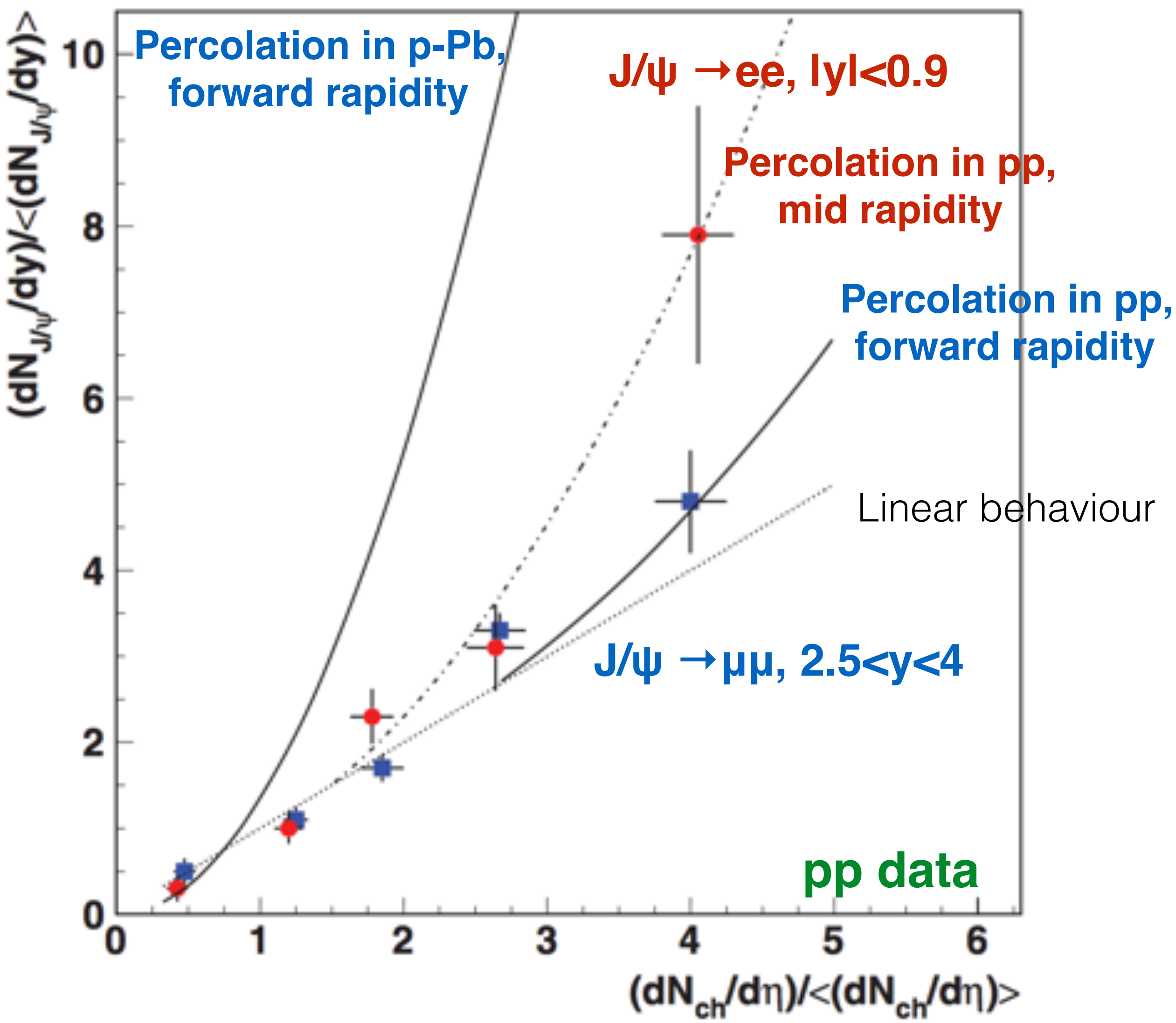
Comparison with models

J/ψ in pp collisions vs. percolation model



- **Percolation**:
  - interactions driven by the **exchange of colour sources** (strings ~ MPI scenario);
  - the strings **have a finite spatial extension and can interact**,
    - at high density the coherence leads to a reduction of their number, i.e. a reduction of charged-particle multiplicity,
    - heavy-flavours are less affected due to the smaller transverse size of hard sources;

✿ **faster-than-linear increase of J/ψ yield with multiplicity**

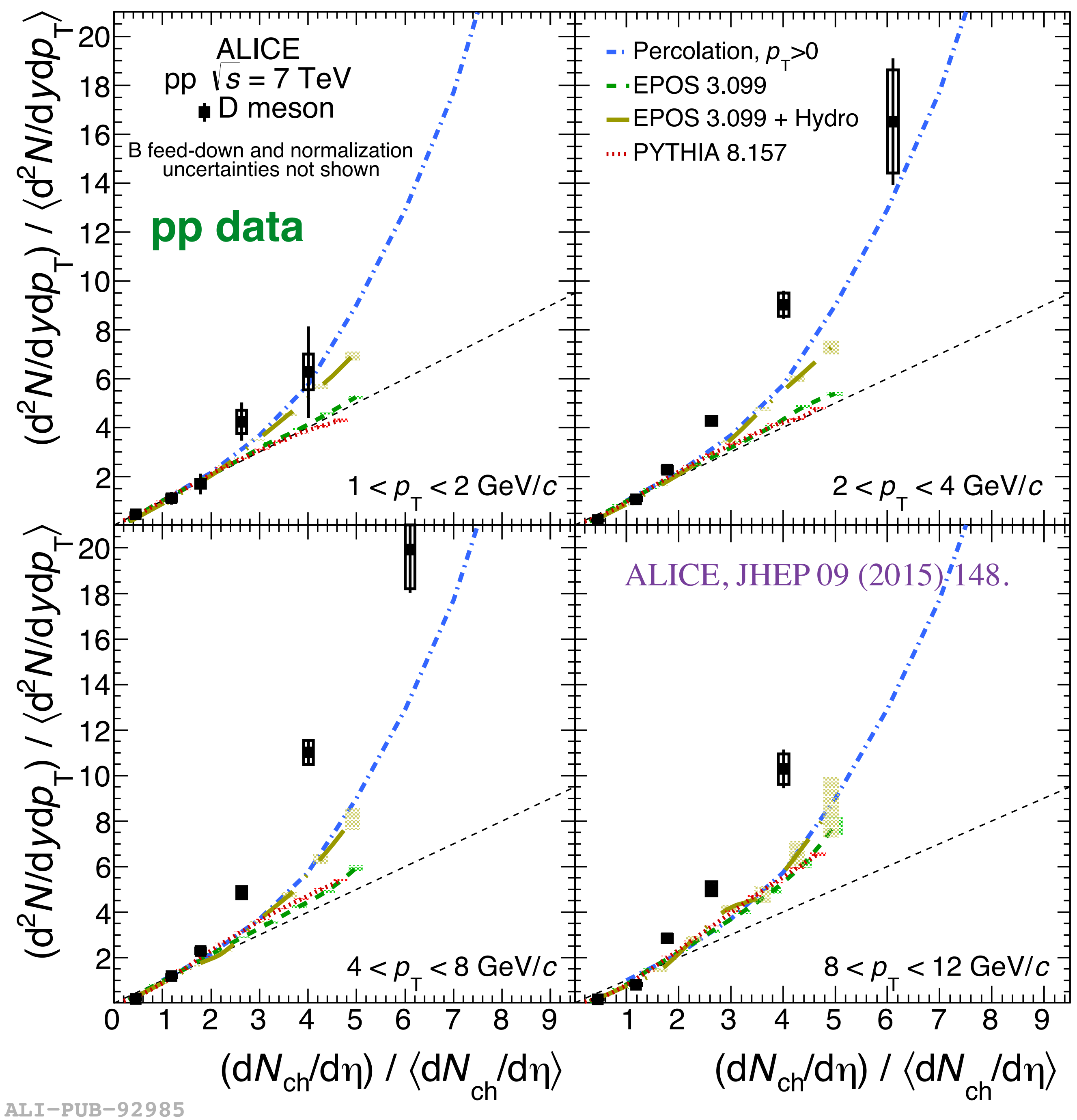
ALICE, Phys.Lett. B712 (2012) 165–175

E. G. Ferreiro and C. Pajares, Phys.Rev. C86 (2012) 034903.

D mesons in pp collisions vs. models

E. G. Ferreiro and C. Pajares, Phys.Rev. C86 (2012) 034903.

E. G. Ferreiro and C. Pajares, arXiv:1501.03381 (2015).



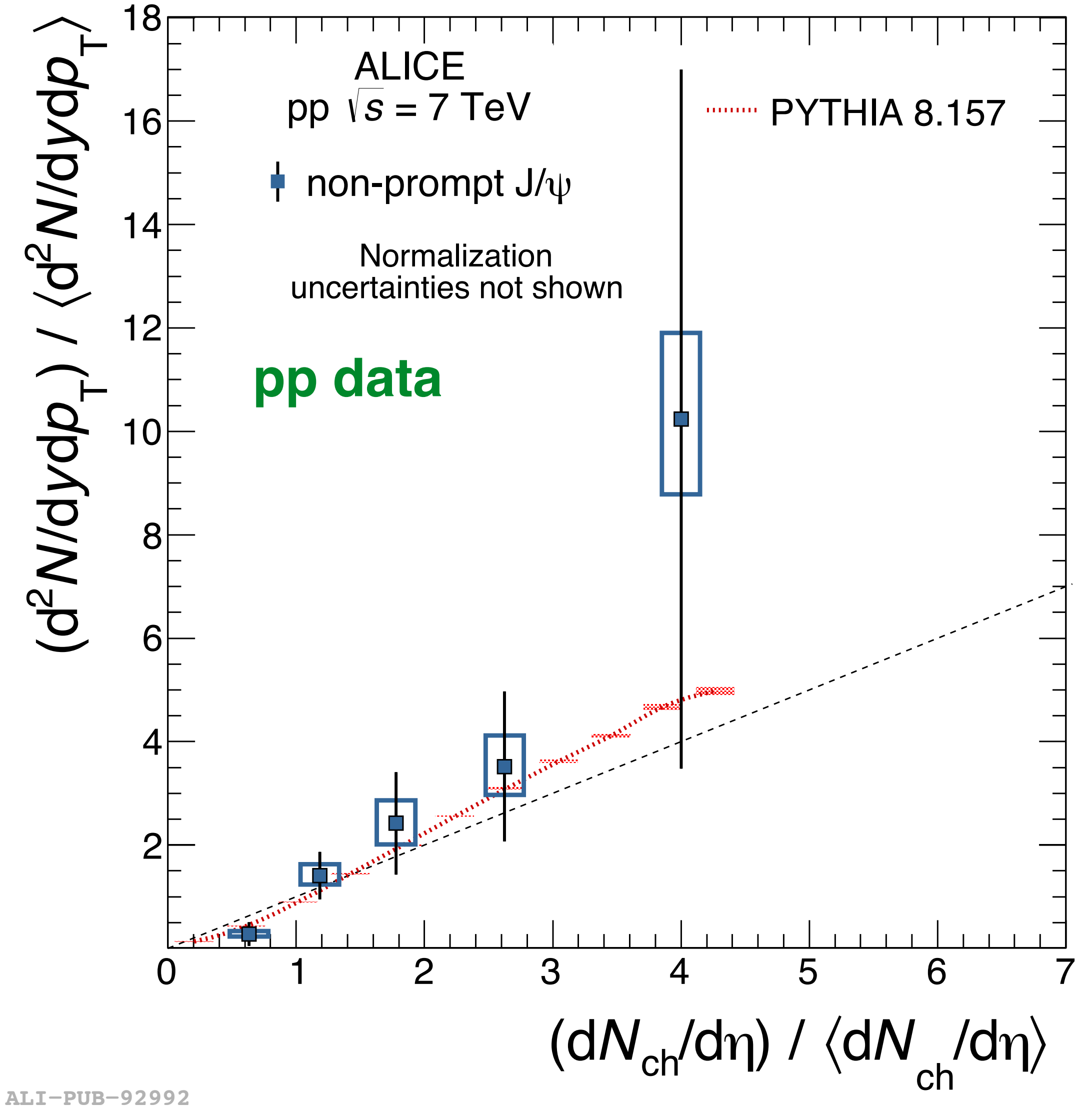
- **Percolation**:
  - interactions driven by the **exchange of colour sources** (strings ~ MPI scenario);
  - the strings **have a finite spatial extension and can interact**,
- **EPOS 3 (event generator)**
  - **Initial conditions**
  - **Hydrodynamical evolution:**
- **PYTHIA 8:**
  - SoftQCD process selection,
  - including colour reconnection,
  - as well as MPI,
  - and diffractive processes

H. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, Phys.Rept. 350 (2001) 93–289

K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys.Rev. C89 (2014) 064903

T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput.Phys.Commun. 178 (2008) 852–867

Non-prompt J/ψ in pp collisions vs. models



- **PYTHIA 8:**
  - SoftQCD process selection,
  - including colour reconnection,
  - as well as MPI,
  - and diffractive processes

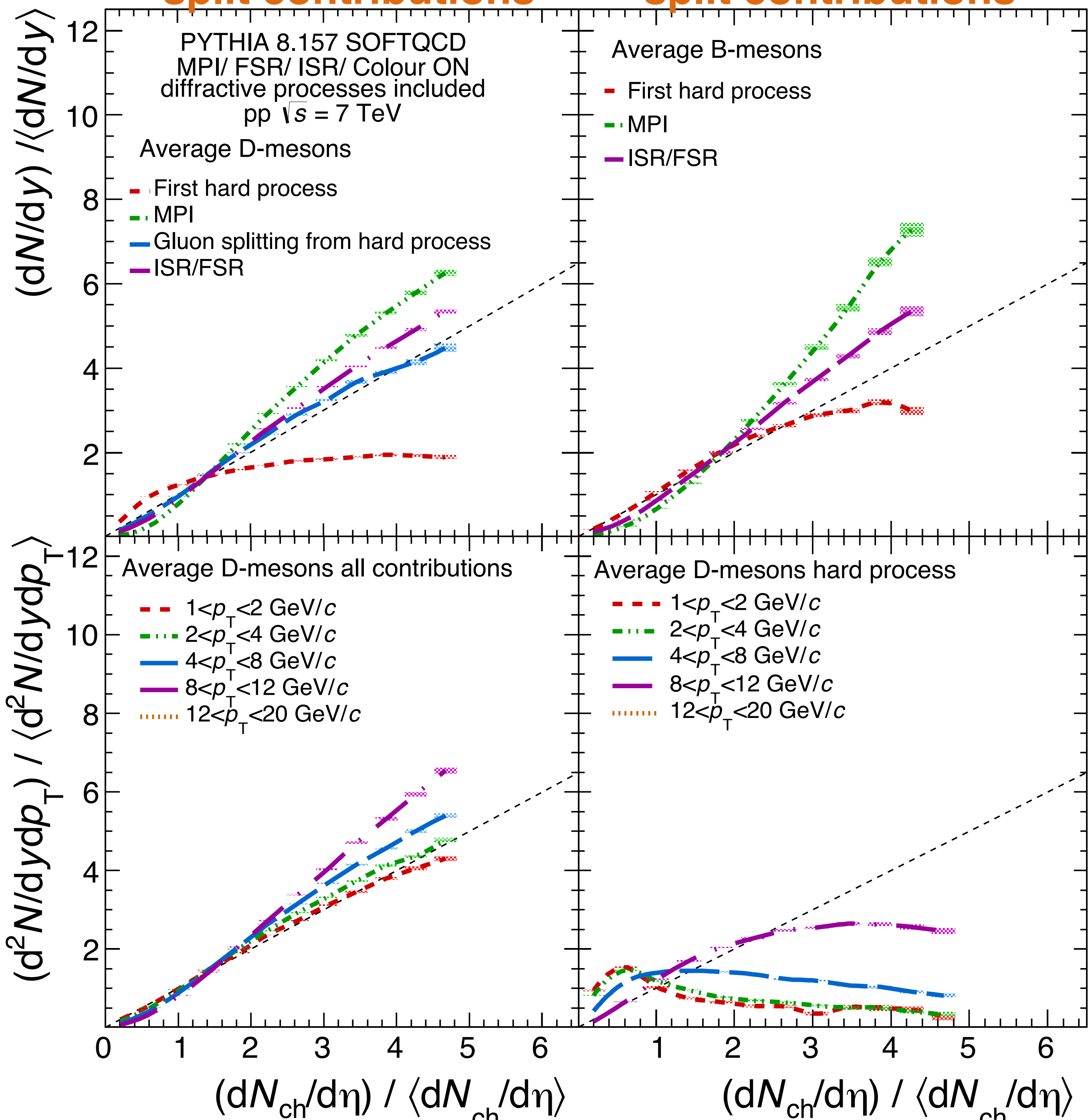
✿ **nearly linear trend of B-hadron yield with multiplicity.**

ALICE, JHEP 09 (2015) 148. T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput.Phys.Commun. 178 (2008) 852–867

More details on PYTHIA 8

D hadrons,
split contributions

B hadrons,
split contributions



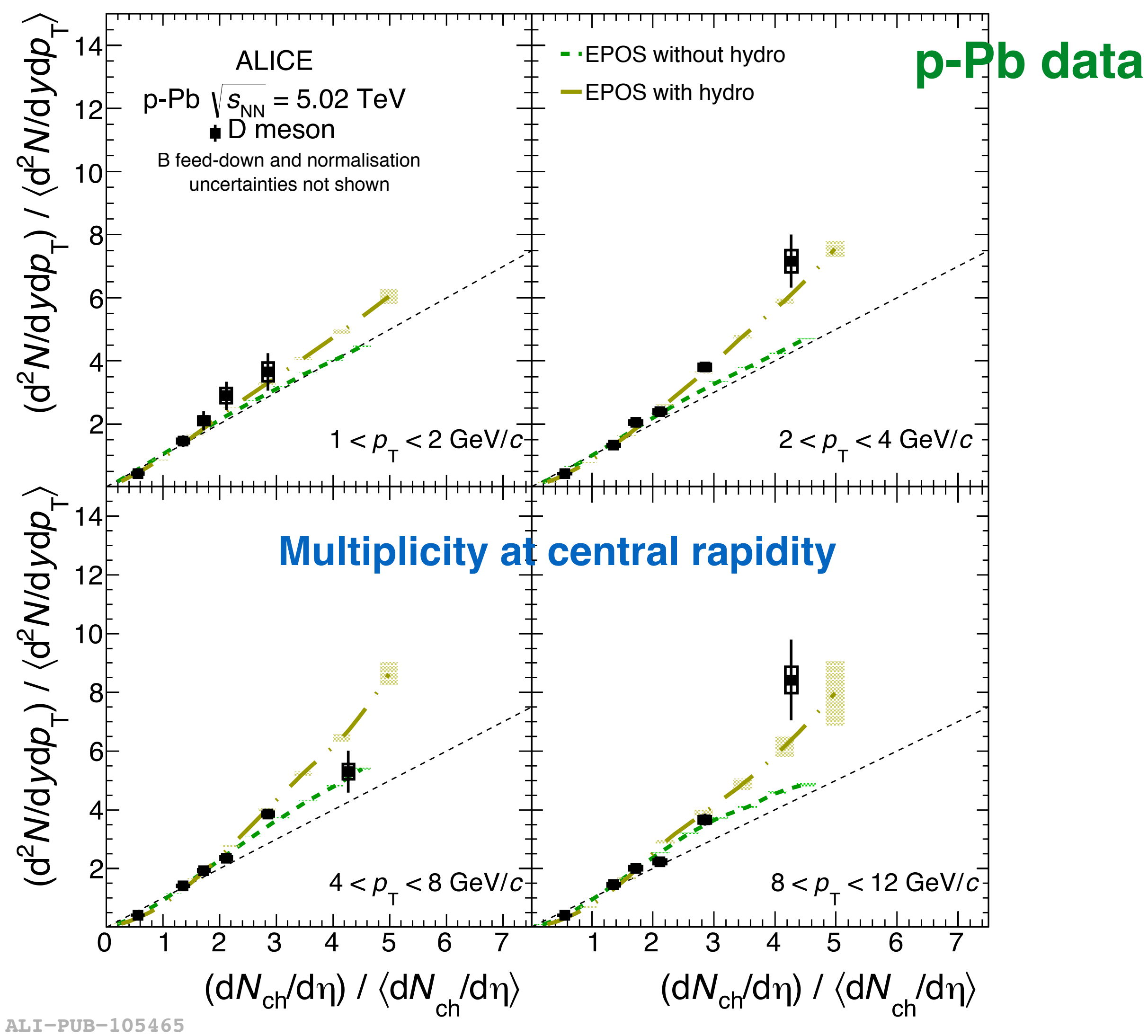
D mesons, all processes, p_T dependence

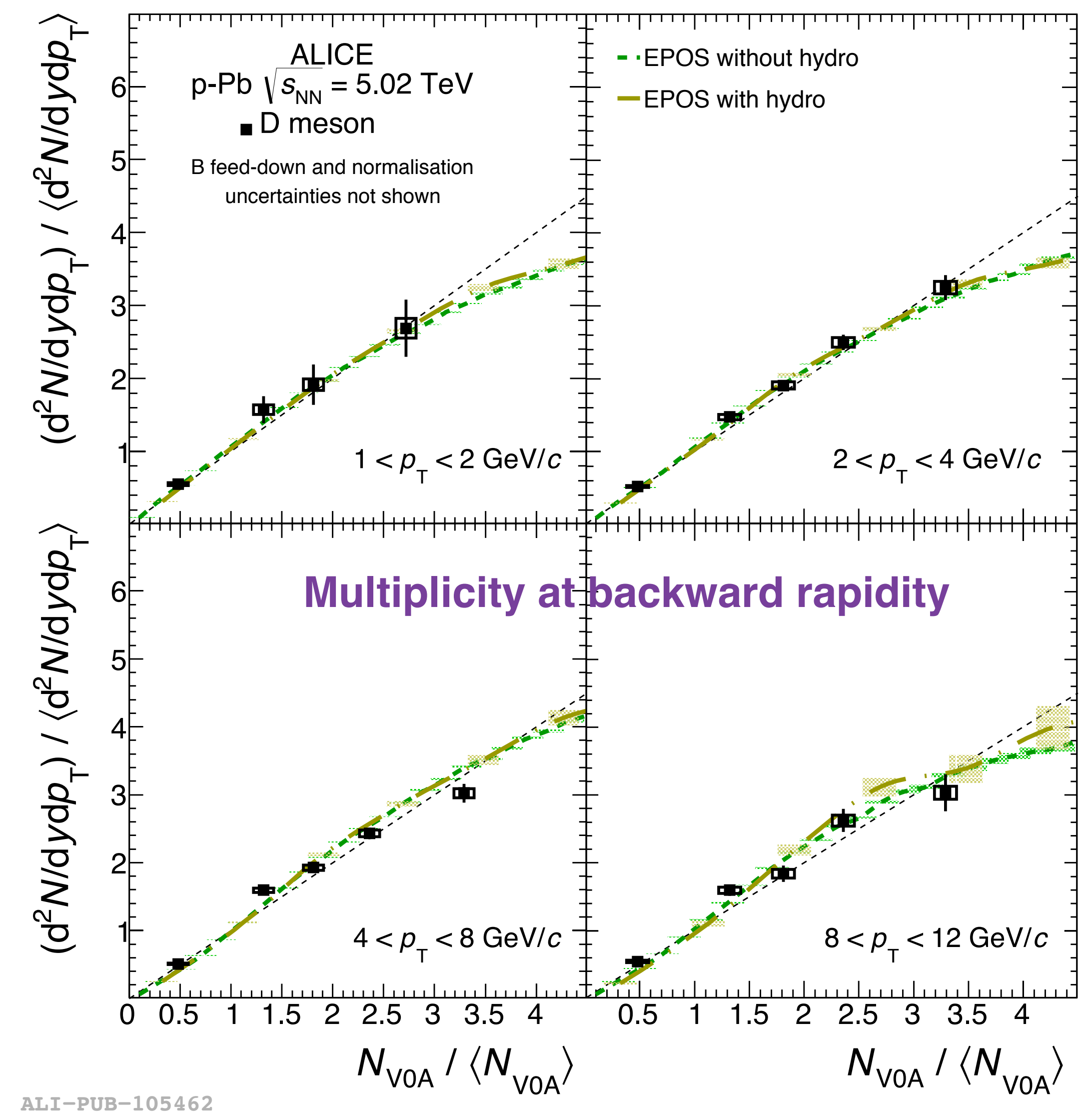
D mesons, first hard process, p_T dependence

- Calculation: SoftQCD process selection, including colour reconnection and diffractive processes.
- Contributions of:
  - **first hard process** ≈ hardest process
    ✿ **weak dependence on multiplicity** (slight increase at low multiplicities followed by a saturation)
  - **MPI** ≈ subsequent hard process
    ✿ **increasing trend vs. multiplicity**
  - **gluon splitting from hard process**
    ✿ **increasing trend vs. multiplicity**
  - **initial and final-state radiation**
    ✿ **increasing trend vs. multiplicity**

T. Sjostrand, S. Mrenna, and P. Z. Skands,
Comput.Phys.Commun. 178 (2008) 852–867

D mesons in p-Pb collisions vs. models





- **EPOS 3 with initial conditions and hydrodynamic evolution estimates:**
  - **a faster-than-linear increase of D-meson yields with multiplicity at mid rapidity,**
  - **approximately linear trend with multiplicity at backward rapidity (reduced influence of hydro on charged-particle production at backward rapidity).**

H. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, Phys.Rept. 350 (2001) 93–289
K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys.Rev. C89 (2014) 064903

Summary

- Heavy-flavour hadron yield increases with charged-particle multiplicity in pp collisions
  - Faster-than-linear increase at high multiplicities.
  - Similar trend for open and hidden heavy-flavours
    ⇨ related to charm and beauty production mechanisms (small influence of hadronisation)
- Models including multiple parton interactions reproduce the measurements.

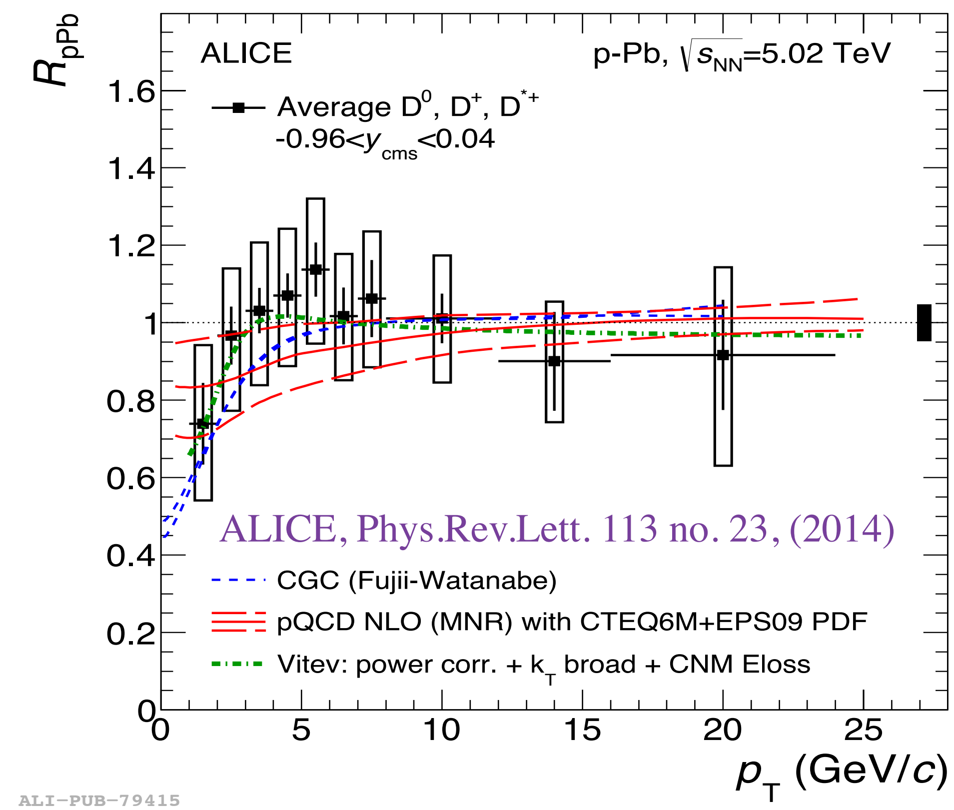
- In p-Pb collisions, heavy-flavour hadron yield increases with charged-particle multiplicity
  - With multiplicity at mid rapidity: similar trend for D-meson results in pp and p-Pb collisions.
  - With multiplicity at large (backward) rapidities: faster increase of D-meson yields in pp than in p-Pb collisions.
- EPOS 3 calculations reproduce the observed D-meson trend.
  Missing model calculations for beauty-hadron and charmonia production.

- Future directions: higher multiplicities, higher $\sqrt{s}$, fine p_{T} intervals, angular correlations,…

Charmonia vs multiplicity in pp and pPb

Heavy-flavour production in p-Pb collisions

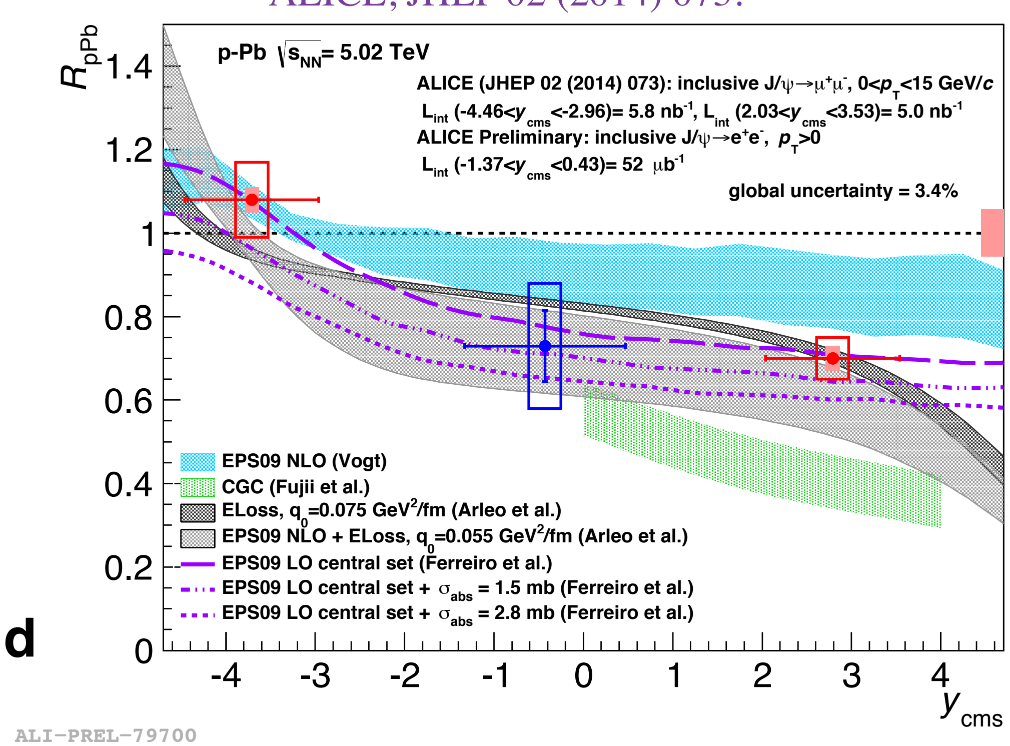
- As in pp collisions,
- **HF yield expected to scale with the number of binary nucleon-nucleon collisions.**
- **Nuclear environment influence (p-Pb collisions):**
  - **shadowing (PDF modifications in nuclei) and gluon saturation,**
  - **energy loss (initial/final state or coherent),**
  - **nuclear absorption.**



- Observable:

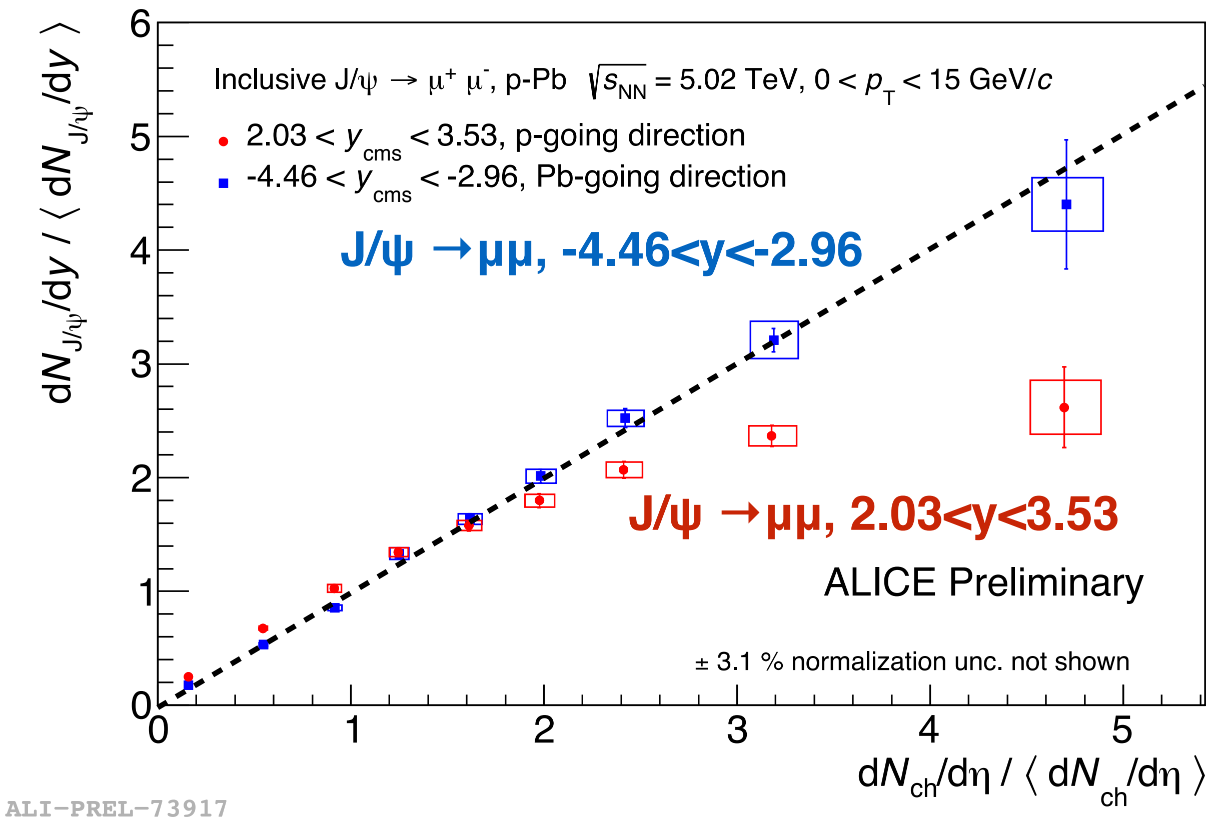
$$R_{AB} = \frac{1}{\langle T_{AB} \rangle} \frac{dN_{AB}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{\langle N_{coll} \rangle_{AB}} \frac{dN_{AB}/dp_T}{dN_{pp}/dp_T}$$

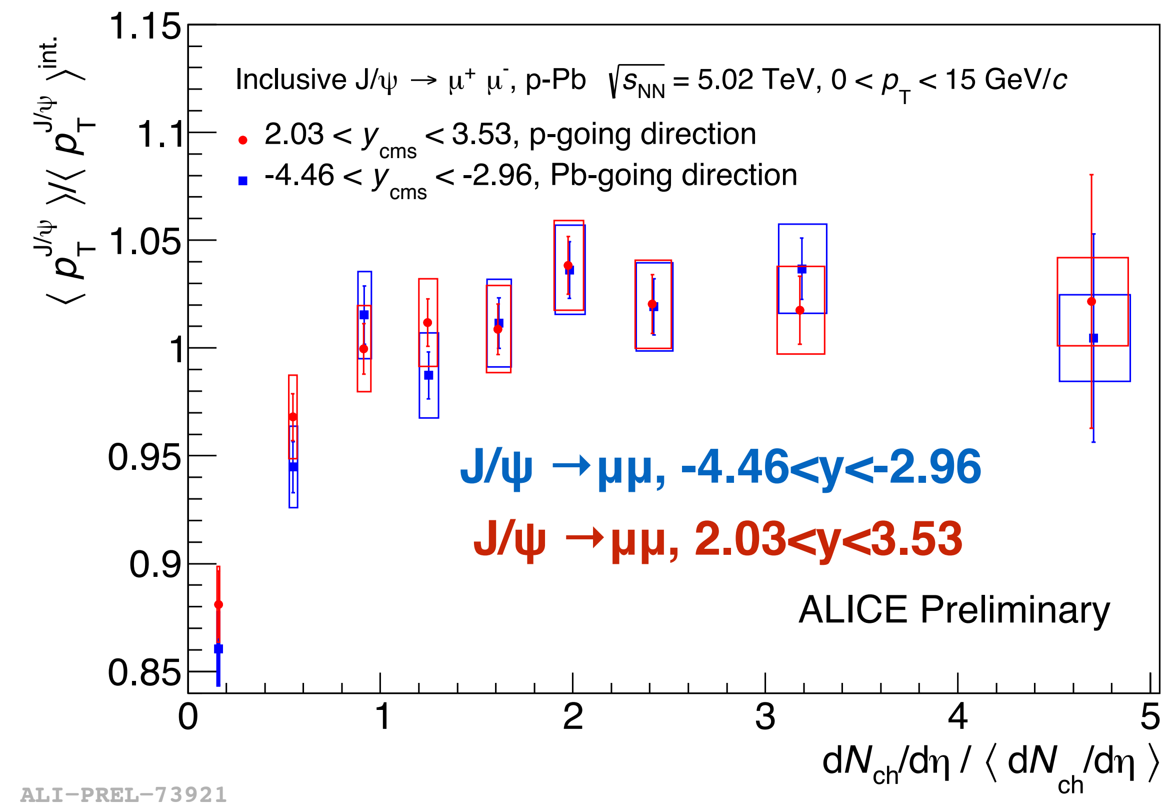
ALICE, JHEP 02 (2014) 073.



- **Measurements:**
  - **prompt D-meson R_{pPb} is close to unity at high p_T**
  - **J/ψ suppression (R_{pPb}<1) at positive *y* (p-going, low-*x* in Pb nucleus) and low p_T.**
  - **Relatively well described by models including cold nuclear matter effects.**

Charmonia vs. multiplicity





- **J/ψ yields vs. multiplicity (with multiplicity measured at mid rapidity):**
  - **increase of J/ψ yields measured at backward rapidity (Pb-going direction),**
  - **deviation of the linear increase at forward rapidity (p-going direction).**
- **J/ψ average p_T, $p_T/\langle p_T \rangle$, increases with multiplicity and seems to saturate at about $(dN_{ch}/d\eta)/\langle dN_{ch}/d\eta \rangle \sim 1.5$, independently of J/ψ rapidity.**

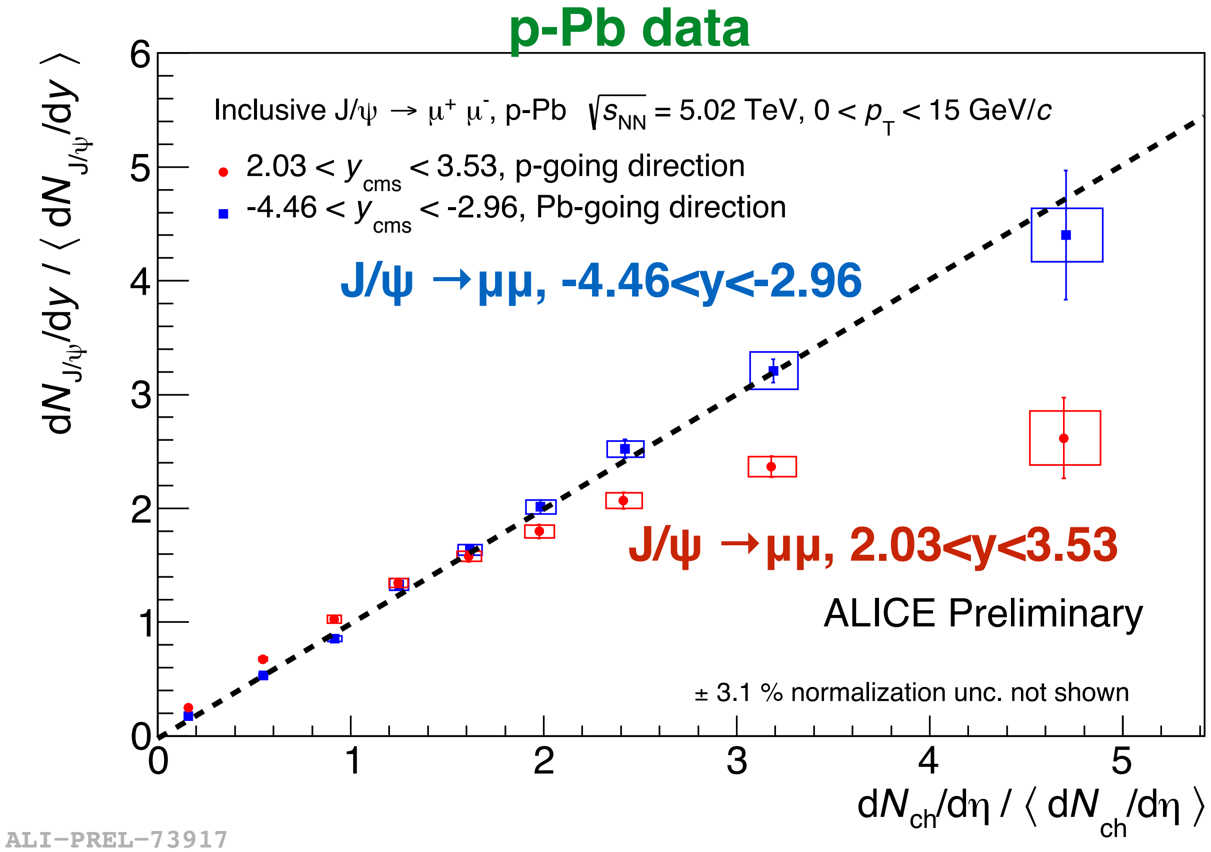
Note: J/ψ yields measured in the p-going direction probe low-*x* gluons

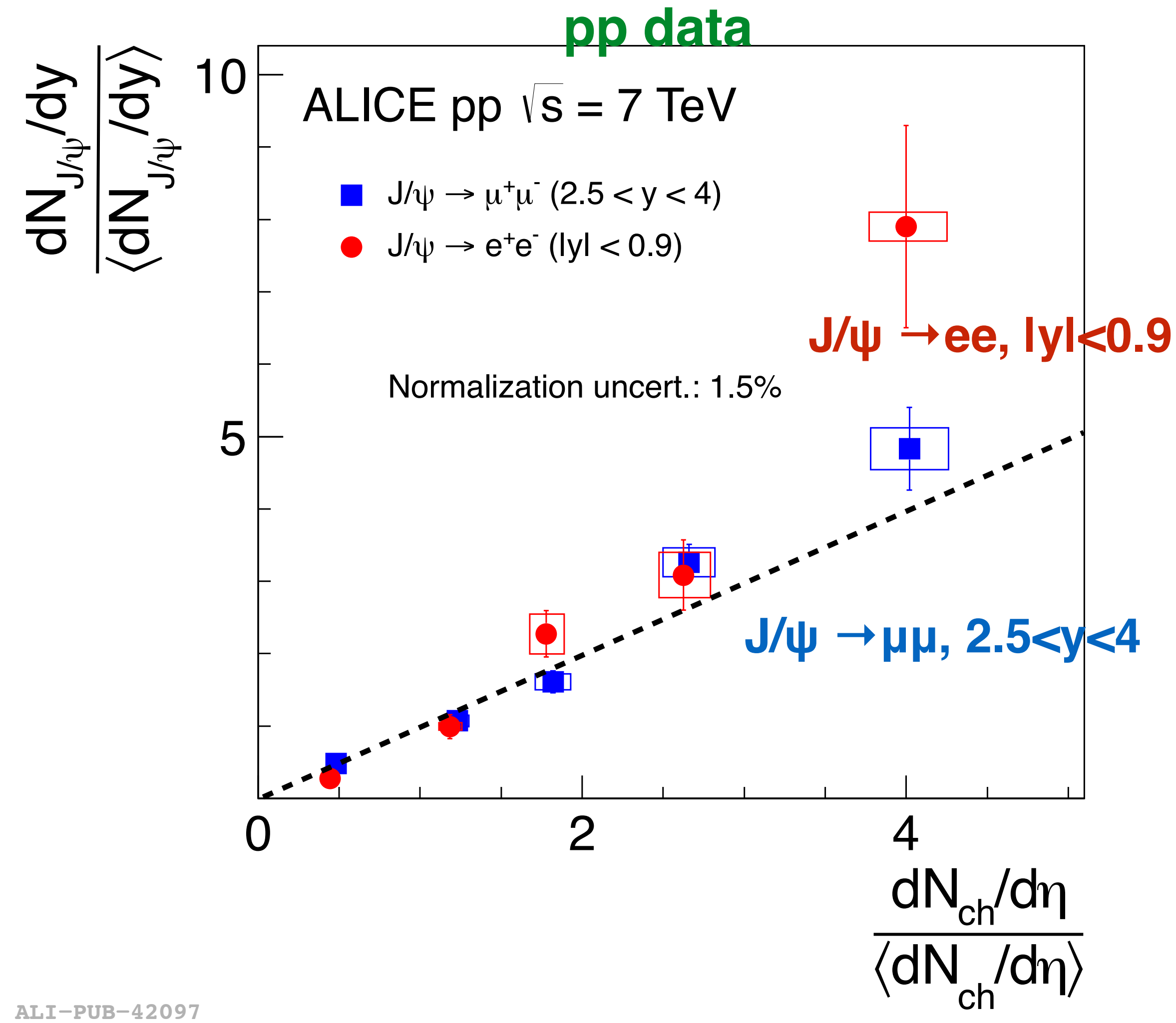
Error bars: statistical uncertainty.

Horizontal size of boxes : systematic uncertainty on $(dN/d\eta)/\langle dN/d\eta \rangle$.

Vertical size of boxes : systematic uncertainties but feed-down.
Not shown : normalisation systematic uncertainty.

Charmonia in pp and p-Pb collisions





- **Multiplicity at mid rapidity:**
  - **similar trend for J/ψ yields measured in pp and p-Pb collisions at backward rapidity (Pb-going direction),**
  - **deviation of J/ψ yields measured at forward rapidity (p-going direction).**

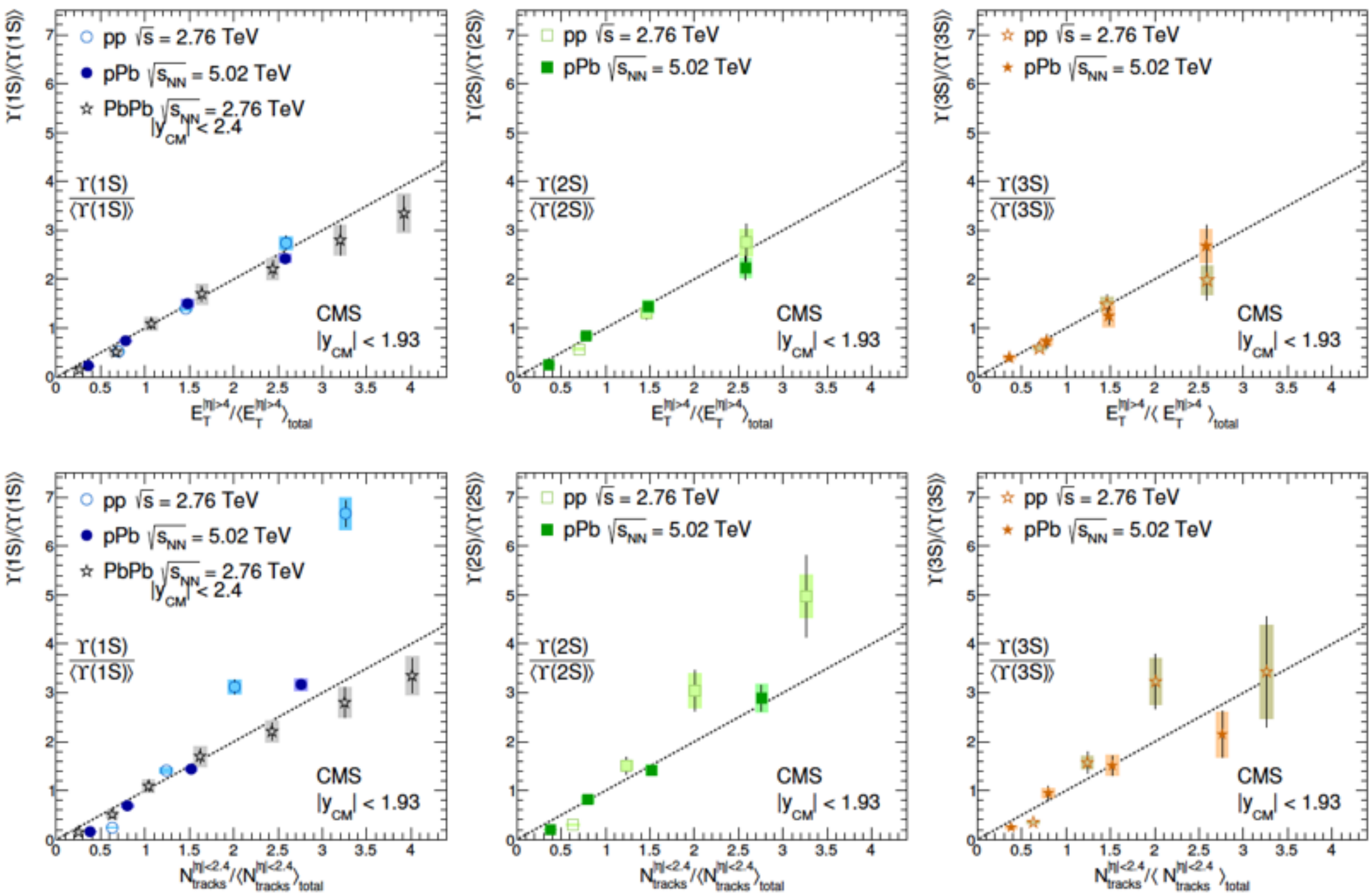
ALICE, Phys.Lett. B712 (2012) 165–175

Note: J/ψ yields measured in the p-going direction probe low-*x* gluons

Error bars: statistical uncertainty.
Horizontal size of boxes : systematic uncertainty on $(dN/d\eta)/\langle dN/d\eta \rangle$.
Vertical size of boxes : systematic uncertainties but feed-down.
Not shown : normalisation systematic uncertainty.

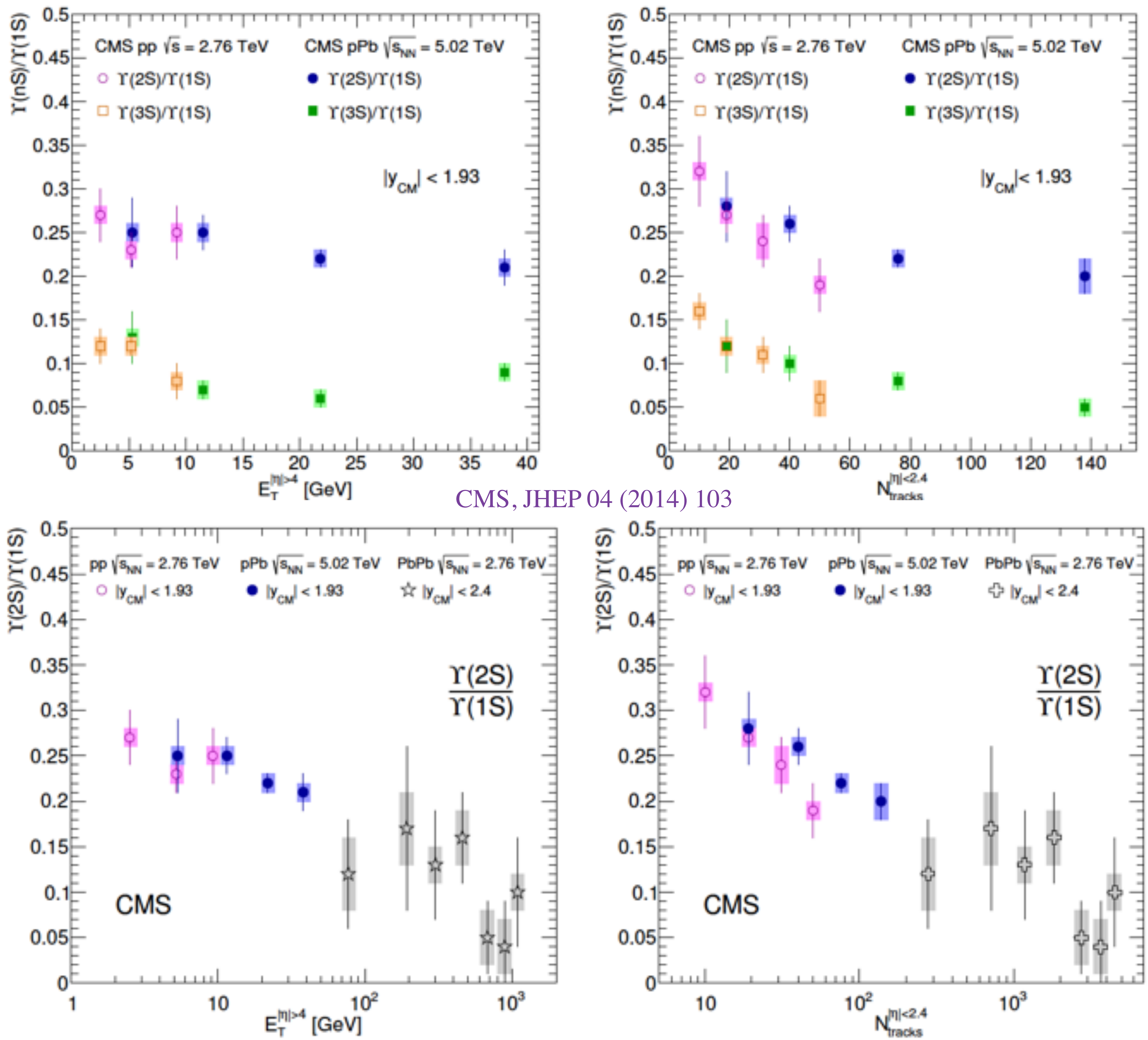
Bottomonia vs multiplicity in pp and pPb

CMS Bottomonia vs. multiplicity



CMS, JHEP 04 (2014) 103

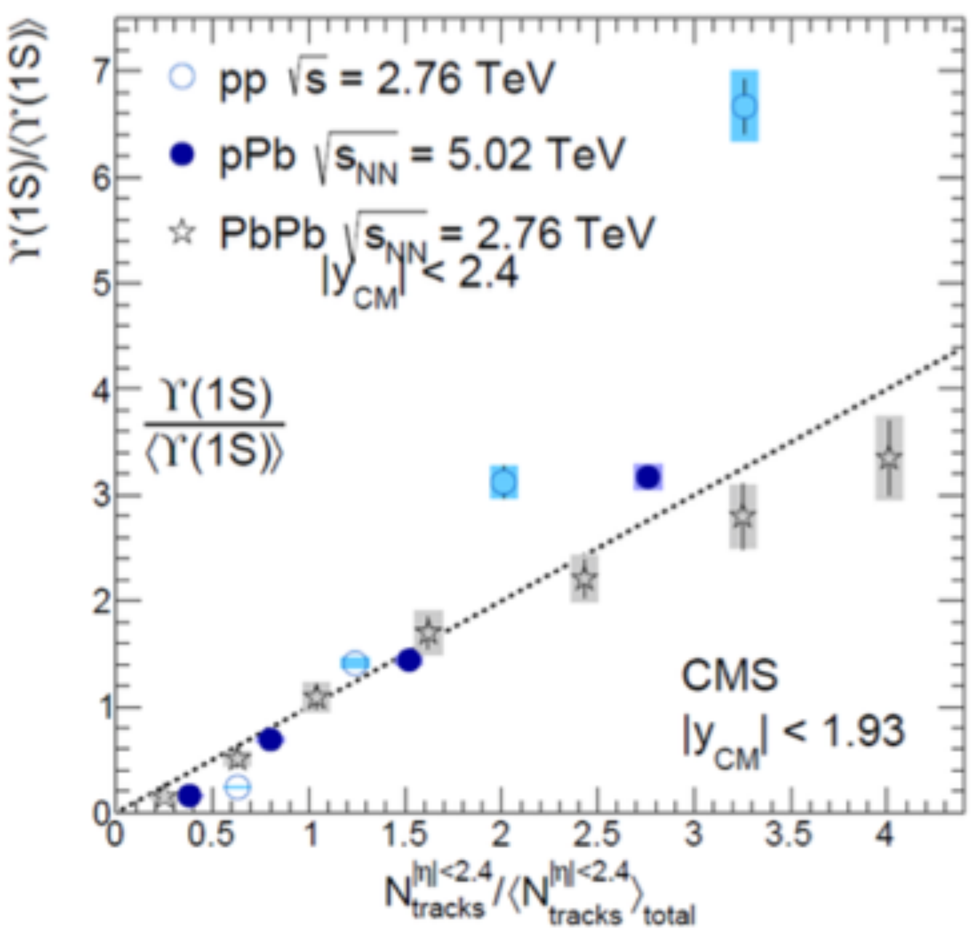
CMS Bottomonia vs. multiplicity

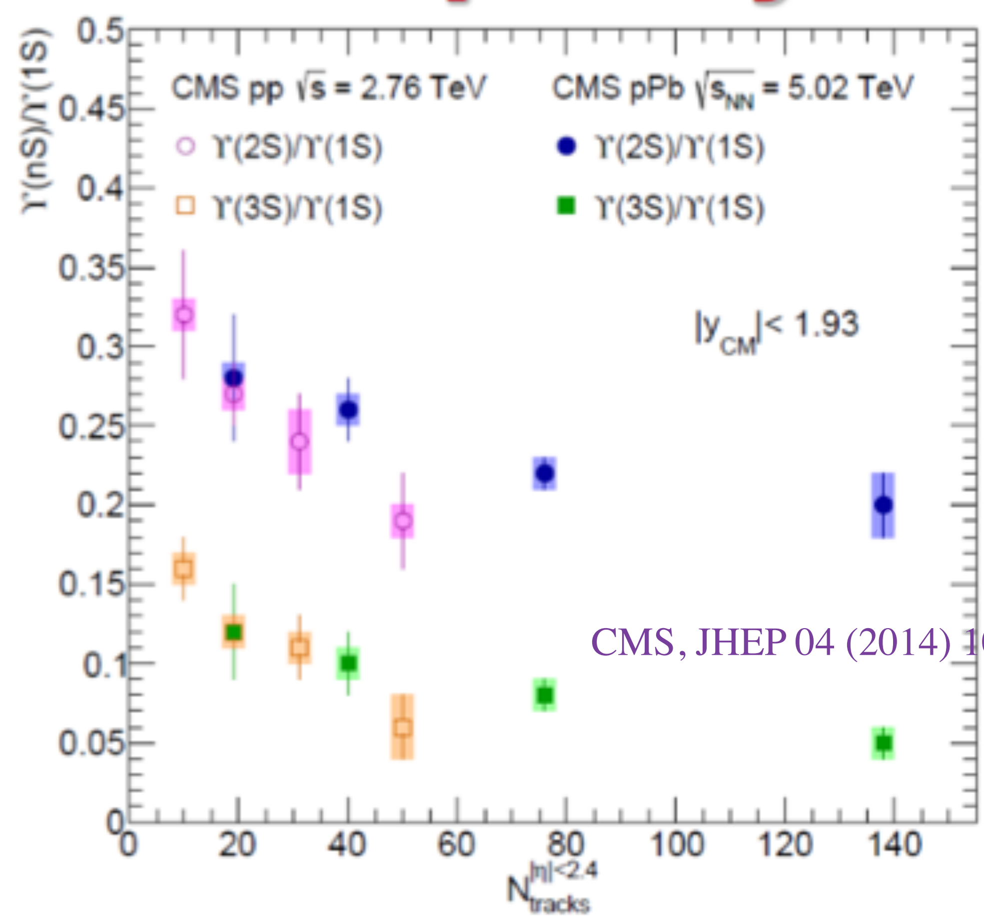


CMS, JHEP 04 (2014) 103

CMS Bottomonia vs. multiplicity

Bottomonia vs. multiplicity





CMS, JHEP 04 (2014) 103

- Yield of Υ increases with multiplicity
  - ⇨ Similar in pp, p-Pb and Pb-Pb
  - ⇨ In Pb-Pb (and p-Pb) number of nucleon-nucleon collisions increases with multiplicity

CMS, JHEP 1404 (2014) 103

- Υ(nS) production ratios depend on multiplicity
  - ⇨ Ground state Υ(1S) systematically produced with more particles?
  - ⇨ Excited states more easily dissociated by interactions with other particles?

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F. Prino, CERN seminar 2015

Summary

- **Heavy-flavour hadron yield increases with charged-particle multiplicity in pp collisions**
  - **Faster-than-linear increase at high multiplicities.**
  - **Similar trend for open and hidden heavy-flavours**
    ⇨ related to charm and beauty production mechanisms (small influence of hadronisation)
- **Models including multiple parton interactions reproduce the measurements.**

- **In p-Pb collisions, heavy-flavour hadron yield increases with charged-particle multiplicity at mid rapidity**
  - **D mesons increase faster than J/ψ.**
    In particular for J/ψ yields measured at forward rapidity (p-going direction).
  - **J/ψ average p_T increases with multiplicity and seems to saturate at high multiplicities, independently of J/ψ rapidity.**
- **EPOS 3 calculations reproduce the observed D-meson trend.**
  Missing model calculations for beauty-hadron and charmonia production.

- **Future directions: higher multiplicities, higher $\sqrt{s}$, fine p_T intervals, angular correlations,…**