Open heavy-flavour production as a function of multiplicity in pp collisions at the LHC

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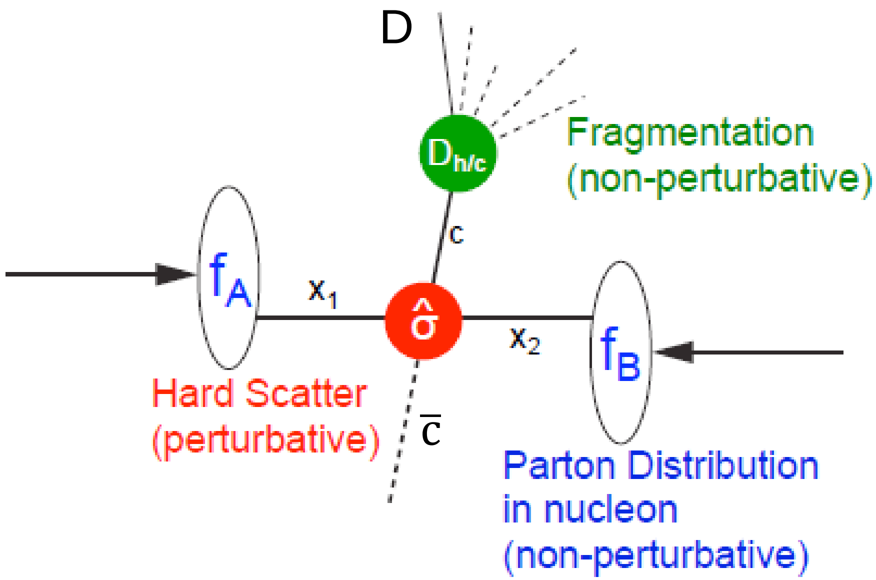
Outline

- Physics motivation
  - ⇨ Heavy-flavour production mechanisms in pp collisions
  - ⇨ Interplay between hard and soft processes of particle production
  - ⇨ Multi-Parton Interactions (MPI)
- Data analysis
  - ⇨ Multiplicity estimation
  - ⇨ D-meson reconstruction
  - ⇨ J/ψ from B-hadron decays
- Results
  - ⇨ Multiplicity dependence of open heavy-flavour production in pp collisions
  - ⇨ Comparison between open charm, open beauty and charmonia
- Comparison to model calculations
  - ⇨ PYTHIA, EPOS event generators
  - ⇨ Calculations with the percolation model
- Comparison to results in p-Pb collisions
- Conclusions

Physics motivation

Heavy flavours in pp collisions

- Heavy quarks (charm and beauty) produced in partonic scattering processes with large Q^2
- Production cross section can be calculated with perturbative QCD calculations based on the factorization approach

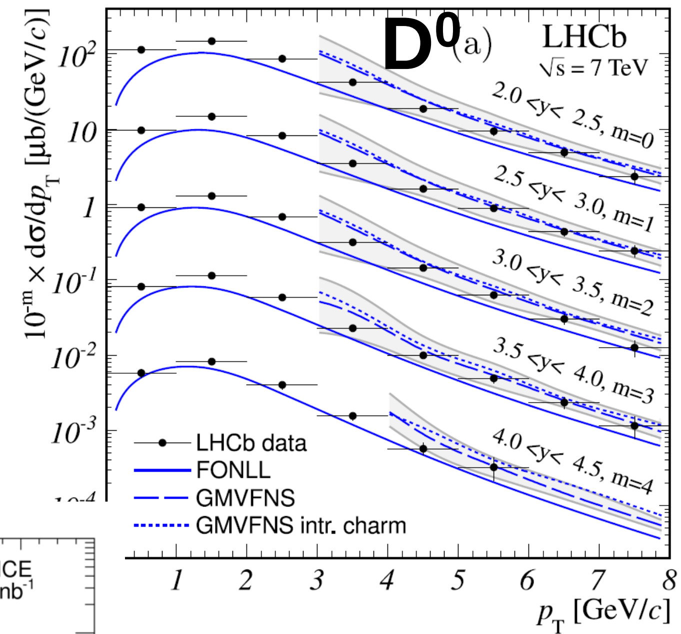


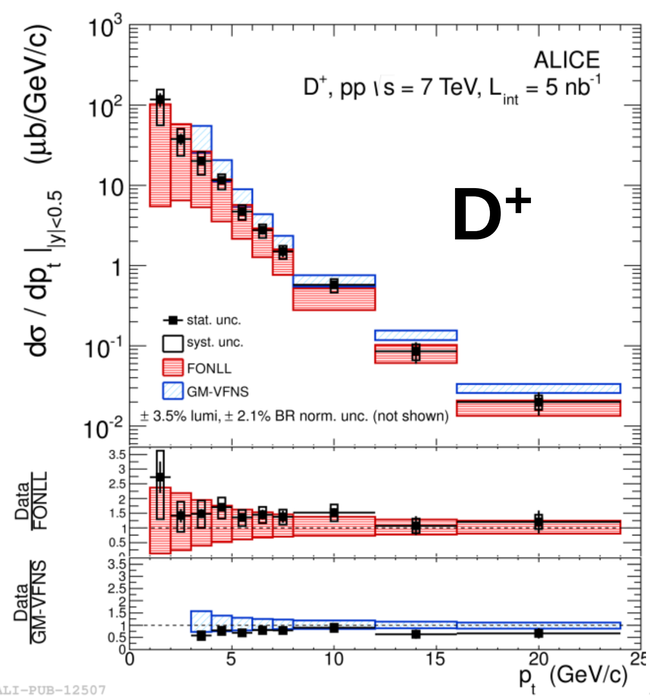
$$\sigma_{hh\to Hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \hat{\sigma}_{ab\to q\bar{q}} \otimes D_{q\to H}(z_q, Q^2)$$

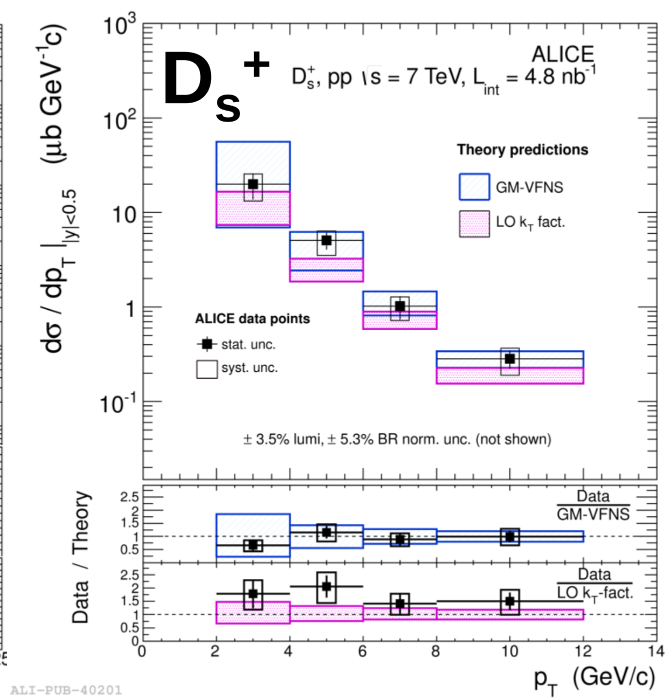
📖 Mangano et al., Nucl. Phys. B373 (1992) 295
📖 Cacciari et al., JHEP 05 (1998) 007
📖 Kniehl et al., PRD 71 (2005) 014018
📖 Jung et al., JHEP 1101 (2011) 085

Open charm in pp collisions

- Measurements at the LHC described by pQCD calculations within uncertainties
  - ⇨ **FONLL**
    - 🕮 **Cacciari et al., JHEP 1210 (2012) 137**
  - ⇨ **GM-VFNS**
    - 🕮 **Kniehl et al., EPJ C72 (2012) 2082**
  - ⇨ **LO k_T-factorization**
    - 🕮 **Maciula, Szczurek, PRD 87 (2013) 094022**







🕮 **ALICE, JHEP 1201 (2012) 128**

🕮 **ALICE, PLB 718 (2012) 279**

🕮 **LHCb, Nucl.Phys. B871 (2013) 1**

Open beauty in pp collisions

- Measurements at the LHC described by pQCD calculations within uncertainties
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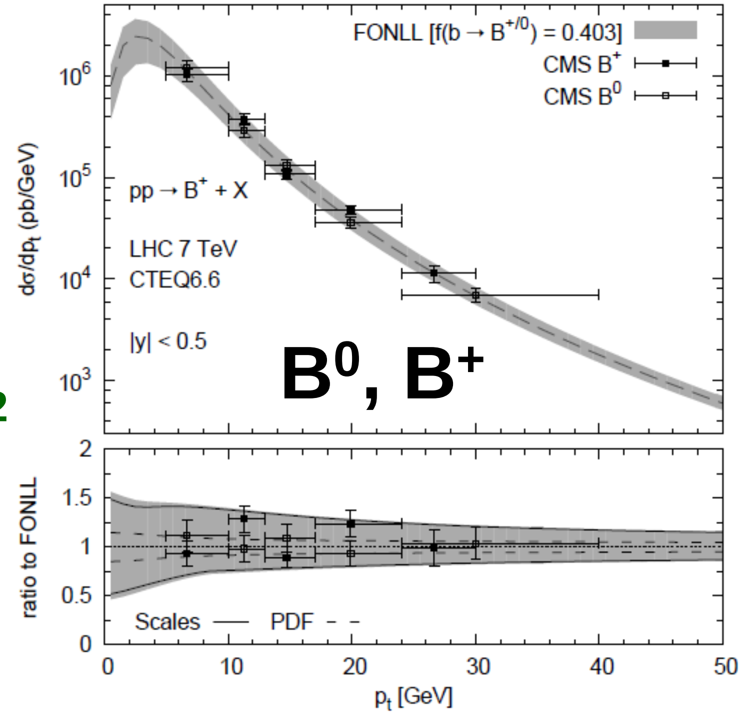
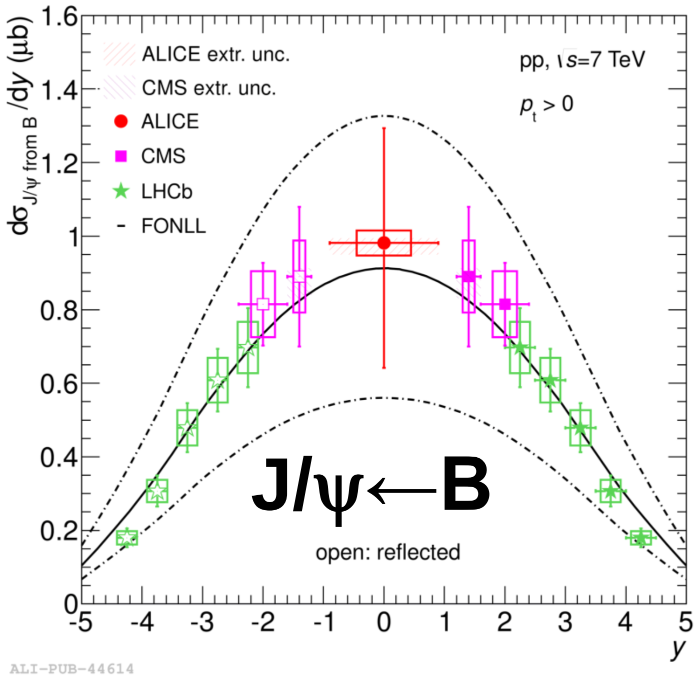
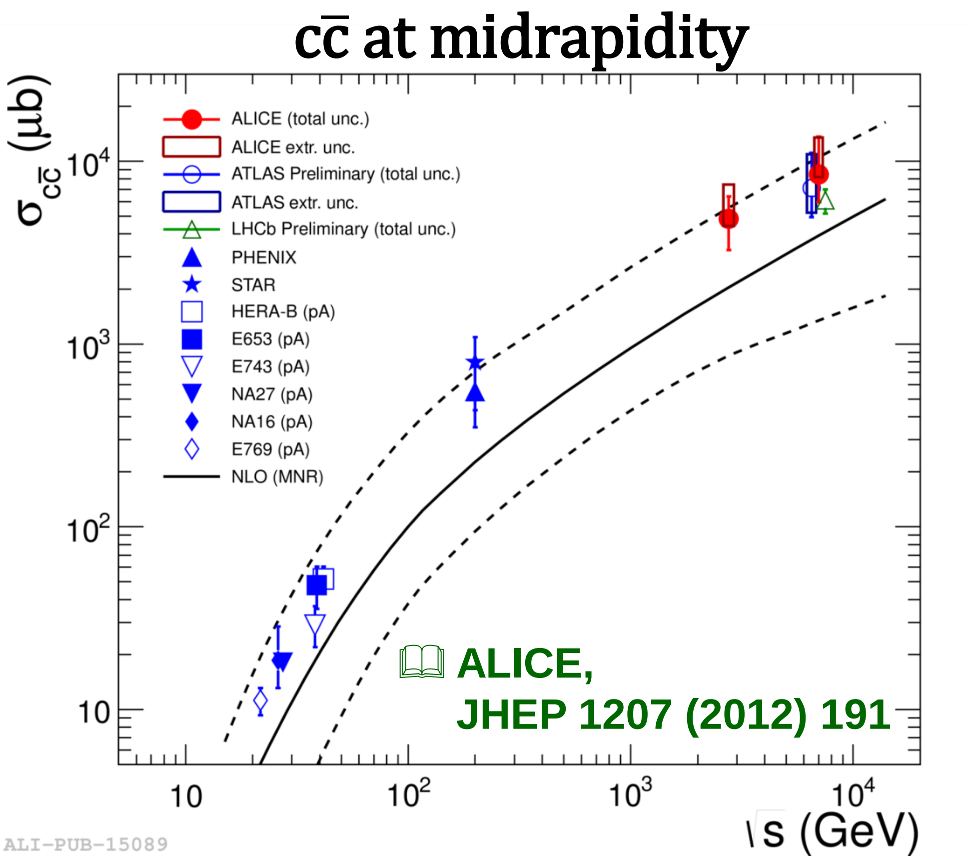


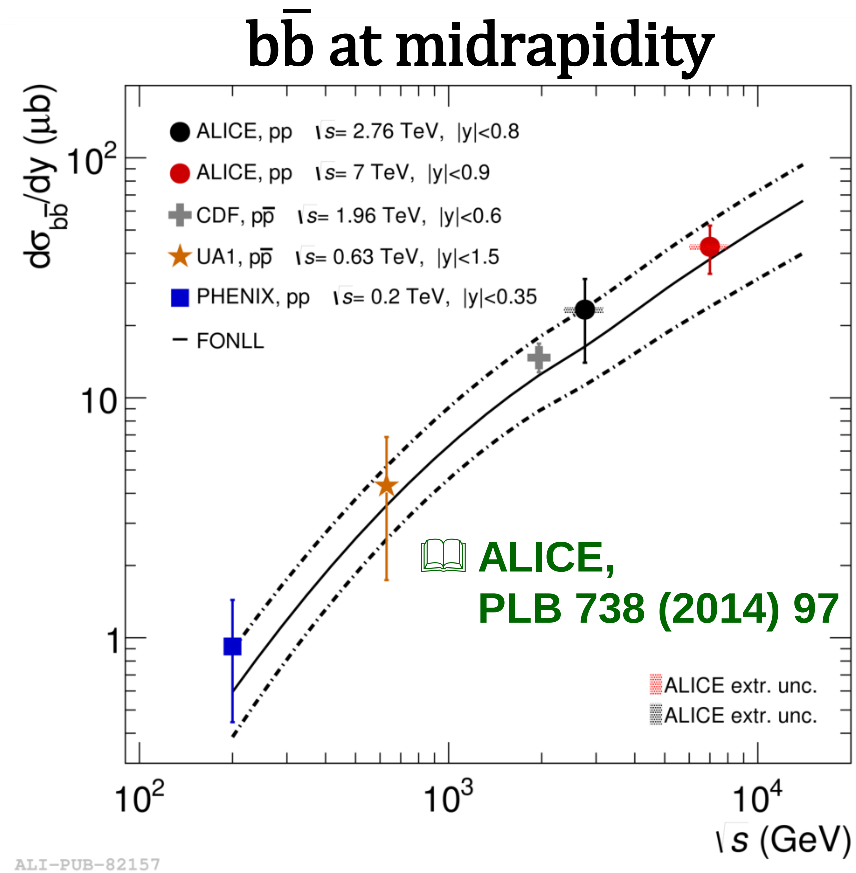
Cacciari et al., JHEP 1210 (2012) 137
CMS, PRL 106 (2011) 112001
CMS, PRL 106 (2011) 252001



ALICE, JHEP 1211 (2012) 065
CMS, EPJ C71 (2011) 1575
LHCb, EPJ C71 (2011) 1645

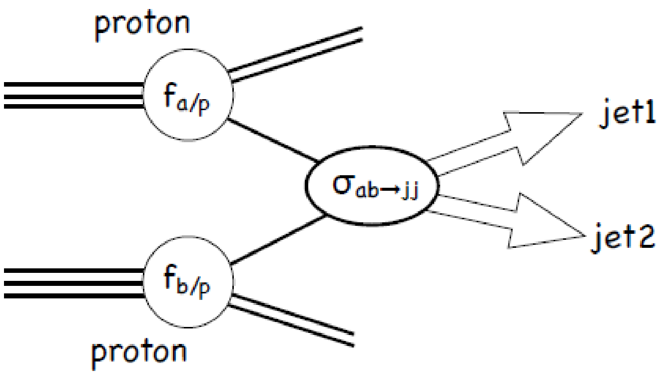
Heavy-flavour cross section

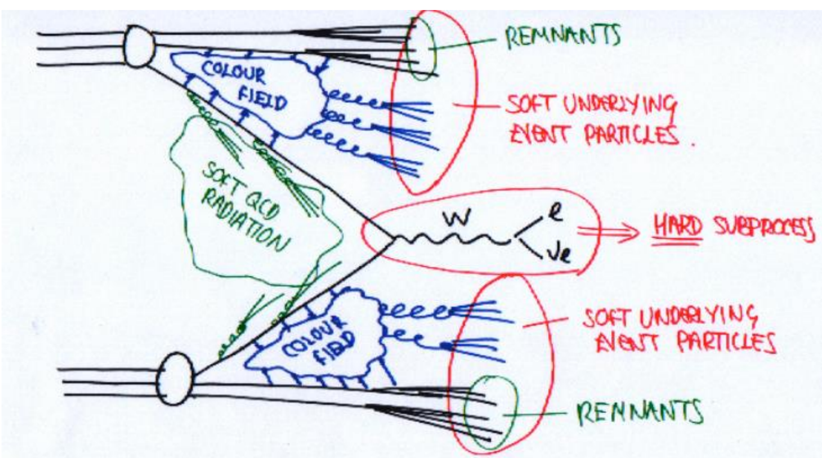




- Total charm and beauty production cross section described by pQCD calculations within uncertainties
  - ⇨ Charm on the upper edge of the theoretical uncertainty band at all collision energies

Hard scattering and underlying event



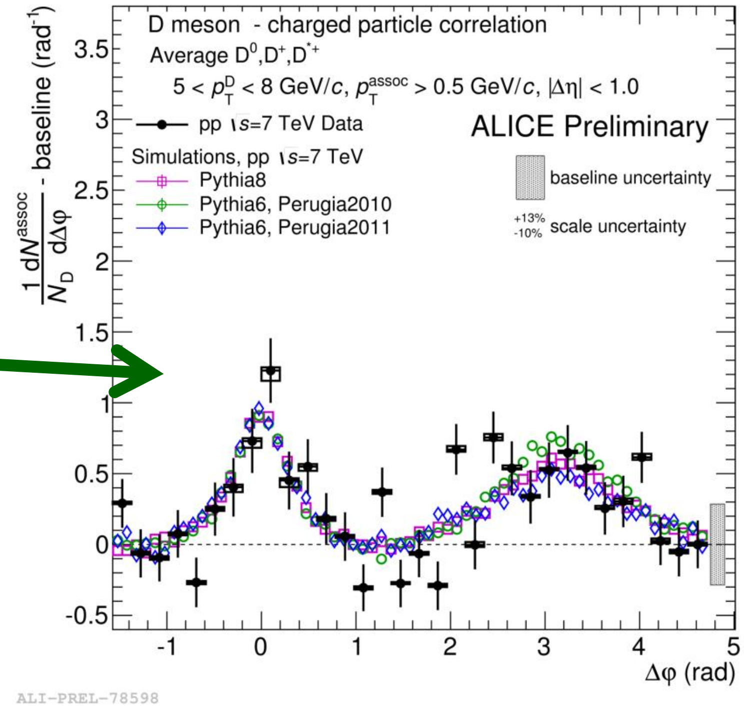


from M. Lancaster (UCL)

- Two component approach:
  - ⇨ Hard scattering process
    - ✓ ***Large Q^2, perturbative QCD***
    - ✓ ***Dijet***
    - ✓ ***Initial/Final state radiation***
  - ⇨ Underlying event (UE) = final state particles not associated to the hard scattering
    - ✓ ***(perturbative) (mini)jets produced in softer multi-parton interactions (MPI)***
    - ✓ ***Soft hadronic processes***
    - ✓ ***Fragmentation of beam remnants***

More differential measurements

- More differential measurements → deeper insight into charm production in pp collisions
- D-hadron **angular correlations**
  - ⇨ Charm quark fragmentation
  - ⇨ $c\bar{c}$ production mechanism
- Charm and beauty hadron **production as a function of the multiplicity** of charged particles produced in the collision
  - ⇨ Interplay between hard and soft processes
  - ⇨ Multi-Parton Interactions

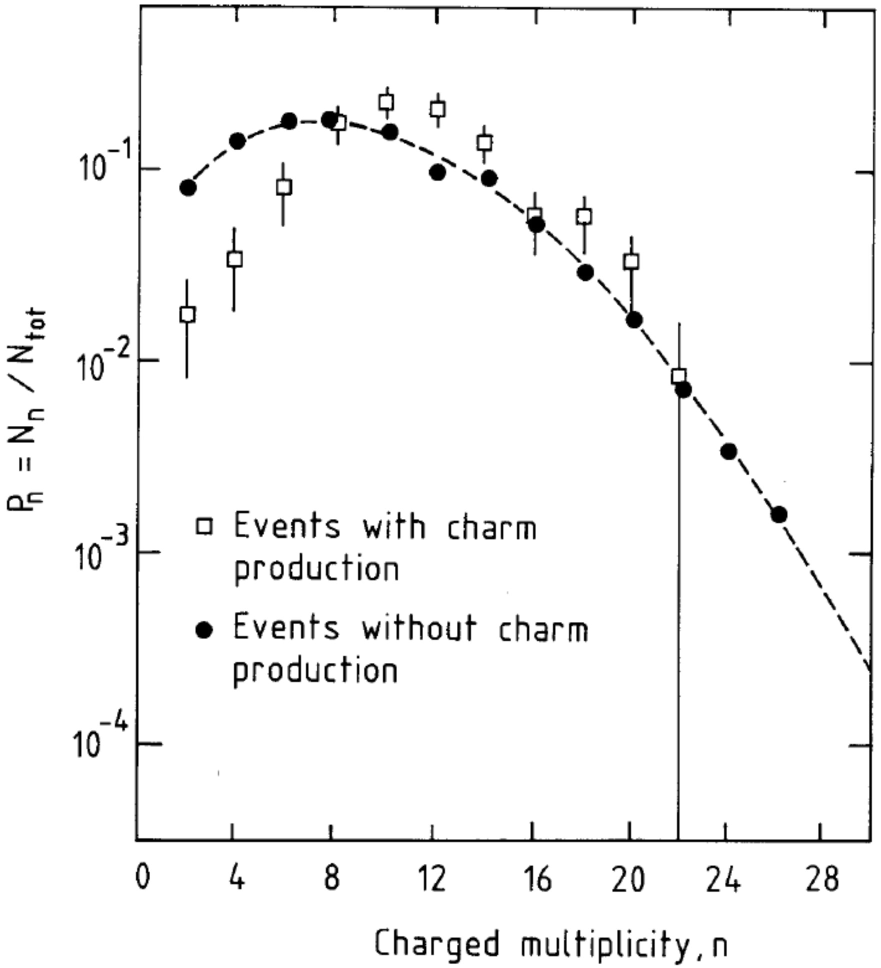


FOCUS OF TODAY'S SEMINAR

ALICE, arXiv:1505.00664

Charm production vs. multiplicity

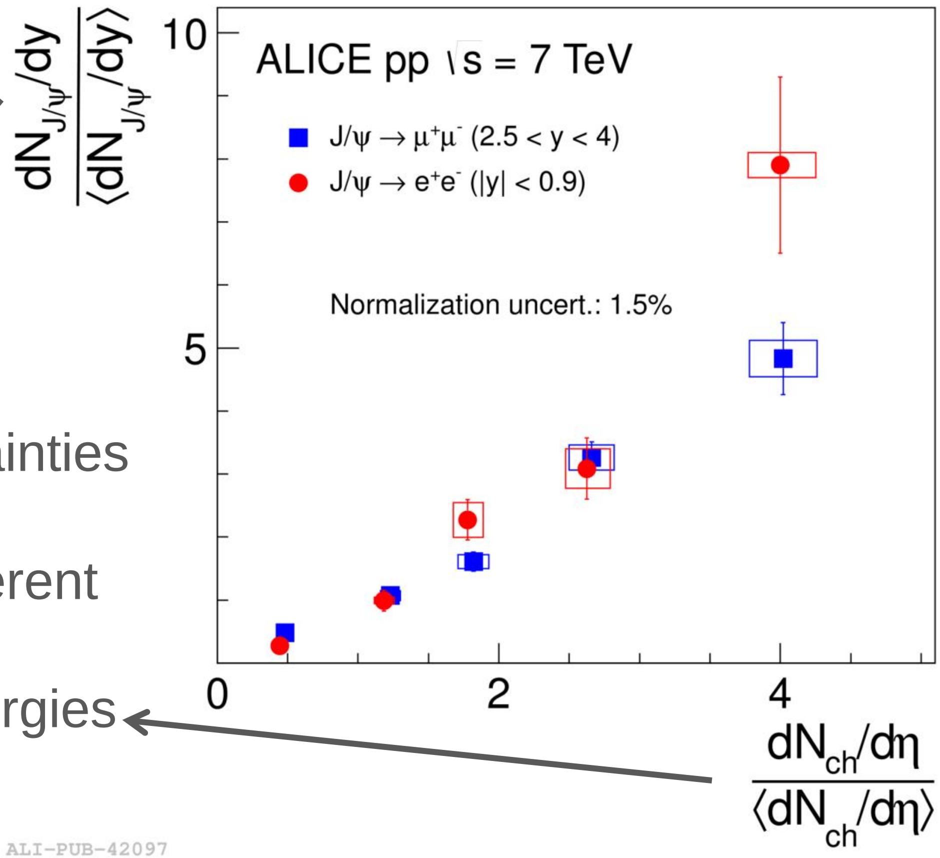
- NA27 and LEBC-EHS Collaboration
  - ⇨pp collisions at SPS
  - ⇨p_{BEAM} = 400 GeV
- Different multiplicity distributions for events with and without charm production
- "… It is natural to interpret these differences by the more *central* nature of collisions leading to charm production."



📖 **Aguilar-Benitez et al., Z. Phys C41 (1988) 191**

J/ψ production vs. multiplicity

ALICE, PLB 712 (2012) 165



Self-normalized quantities

- Some uncertainties cancel out
- Compare different experiments / systems / energies

- Per-event J/ψ yield increases approximately linearly with multiplicity
  - ⇨ Hadronic activity accompanying J/ψ production?
  - ⇨ Multi-Parton interactions?

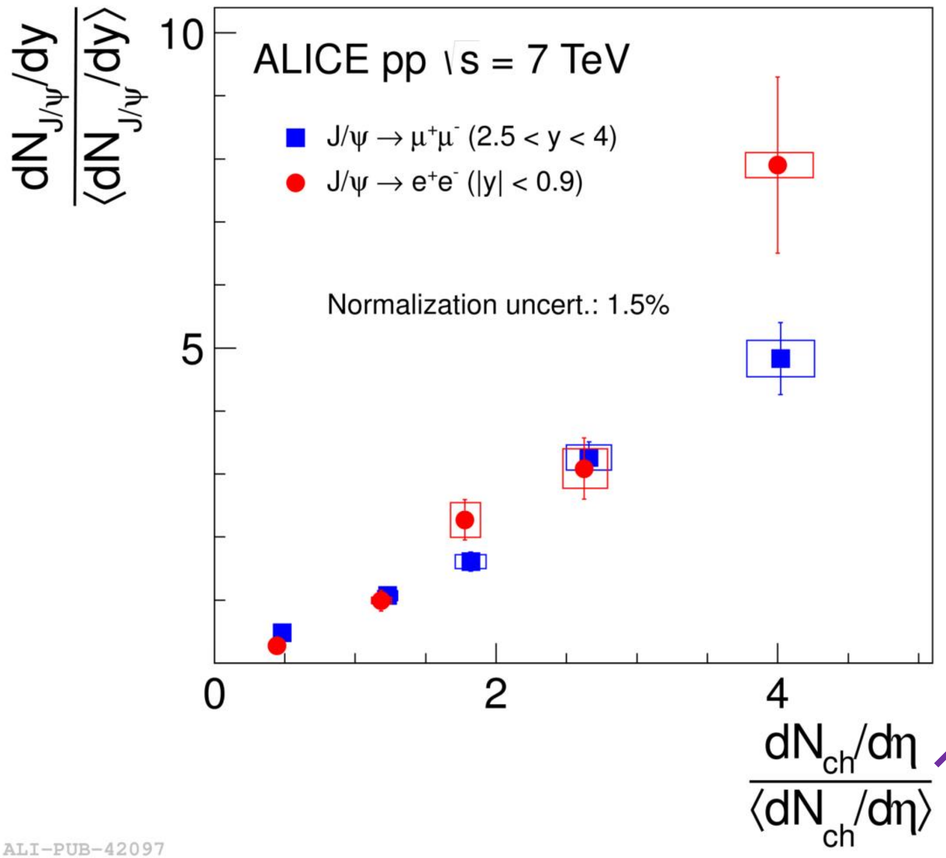
LHCb, PLB 707 (2012) 52

LHCb, JHEP 06 (2012) 141

J/ψ production vs. multiplicity

ALICE, PLB 712 (2012) 165

Hard process yield



Charged particle multiplicity
- Dominated by soft processes ?
- Coincides with KNO scaling variable

Koba, Nielsen, Olesen, Nucl.Phys. B40 (1972) 317

- Per-event J/ψ yield increases approximately linearly with multiplicity
  - ⇨ Hadronic activity accompanying J/ψ production?
  - ⇨ Multi-Parton interactions?

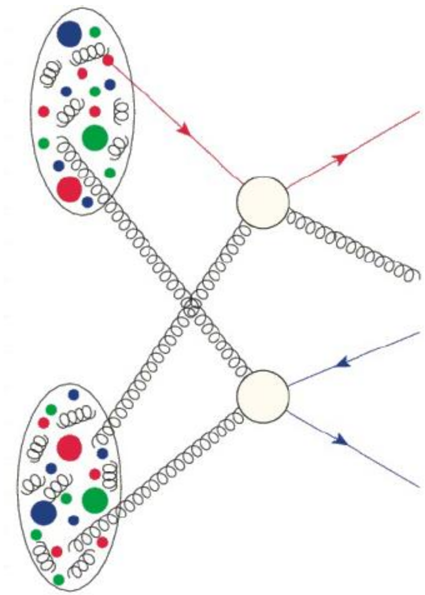
LHCb, PLB 707 (2012) 52

LHCb, JHEP 06 (2012) 141

Multi Parton Interactions

- Naïve picture
  - ⇨ Several interactions at the partonic level occur in parallel
    - ✓ ***At LHC energies: cross section for 2-2 parton scatterings with $\sqrt{Q^2}$ ~ few GeV/c exceed the total hadronic cross section***

      📖 **Bartalini, Fano, arXiv:1003.4220**
  - ⇨ Yield of particles from hard processes should increase with multiplicity



- More complex picture
  - ⇨ Role of collision geometry (impact parameter + transverse structure of proton)

    📖 **Frankfurt, Strikman, Weiss, PRD 83 (2011) 054012**

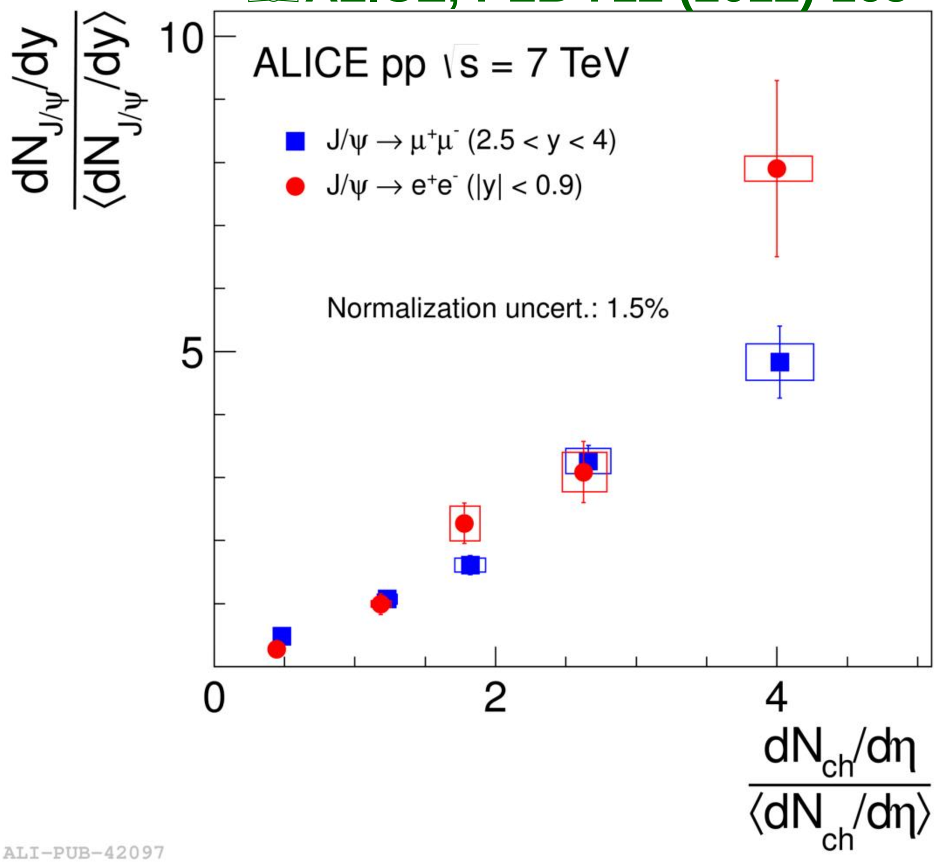
    📖 **Azarkin, Dremin, Strikman, PLB 735 (2014) 244**
  - ⇨ Final state: color reconnections, saturation, string percolation

    📖 **Ferreiro, Pajares, PRC 86 (2012) 034903**
  - ⇨ Collectivity in pp for sufficiently high multiplicities?
    - ✓ ***Multiplicities in high multiplcity pp collisions at the LHC similar to peripheral Cu-Cu at RHIC***

      📖 **Werner et al., PRC 83 (2011) 044915**

How to gain more insight?

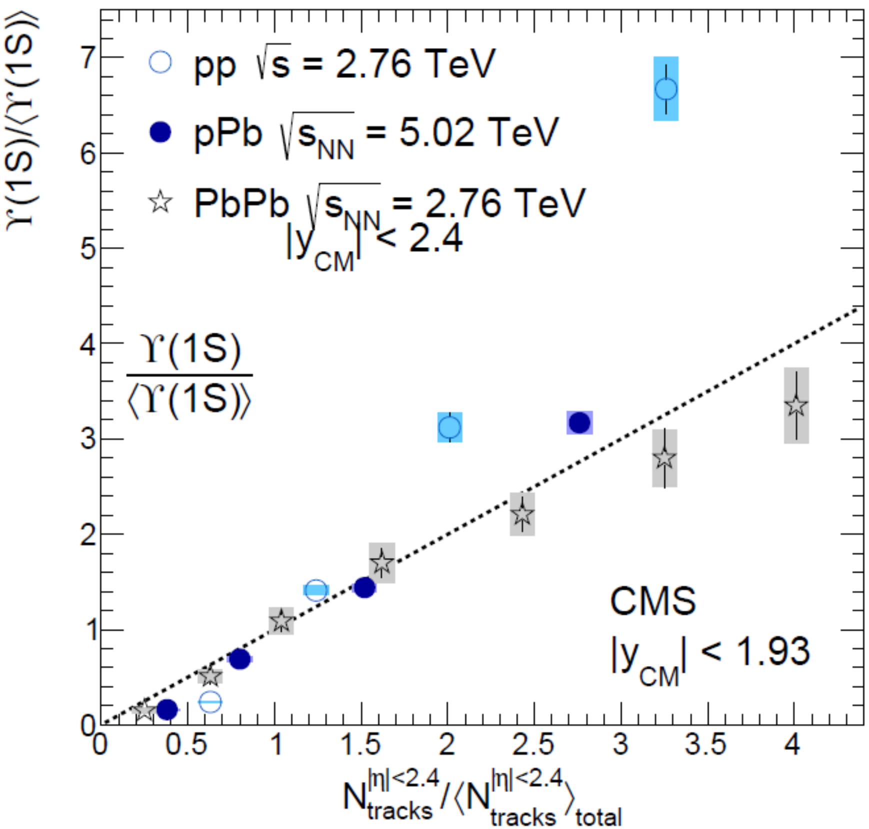
📖 ALICE, PLB 712 (2012) 165

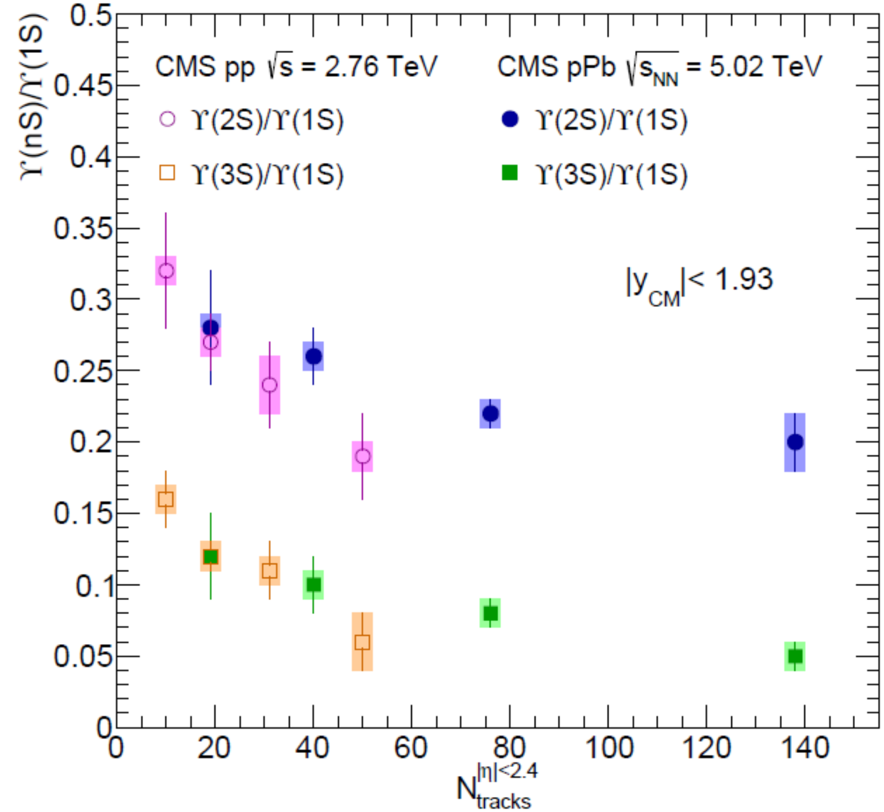


- Extend to **open charm** (D mesons)
  - ⇨ Compare open/hidden charm production
  - ⇨ Study yield of D mesons vs. multiplicity in $\boldsymbol{p_T}$ **intervals**
- Extend to **open beauty production**
  - ⇨ Via non-prompt J/ψ
- Extend to **higher multiplicities**
  - ⇨ Clearer picture of the trend. Linear? Stronger than linear?

(Selection of) other studies as a function of multiplicity in pp collisions at the LHC

Bottomonia vs. multiplicity

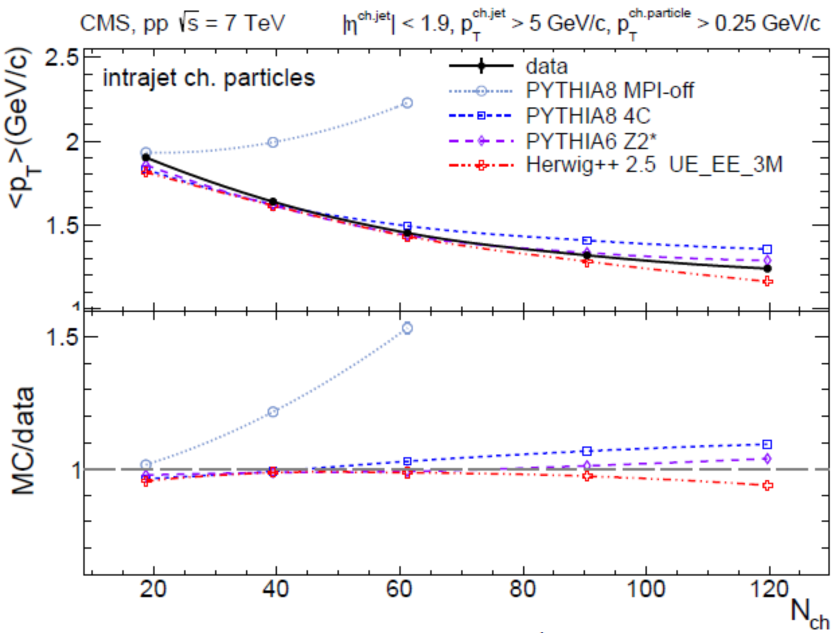


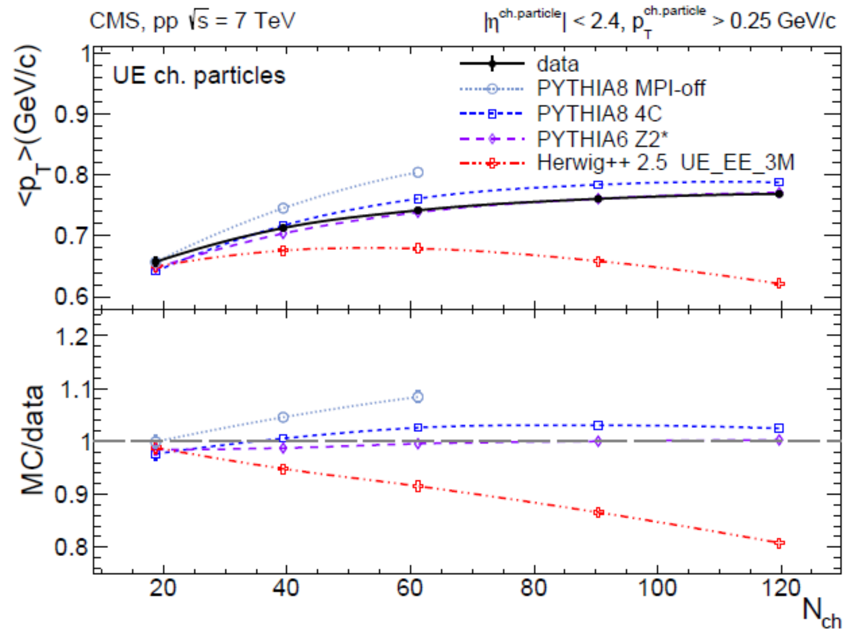


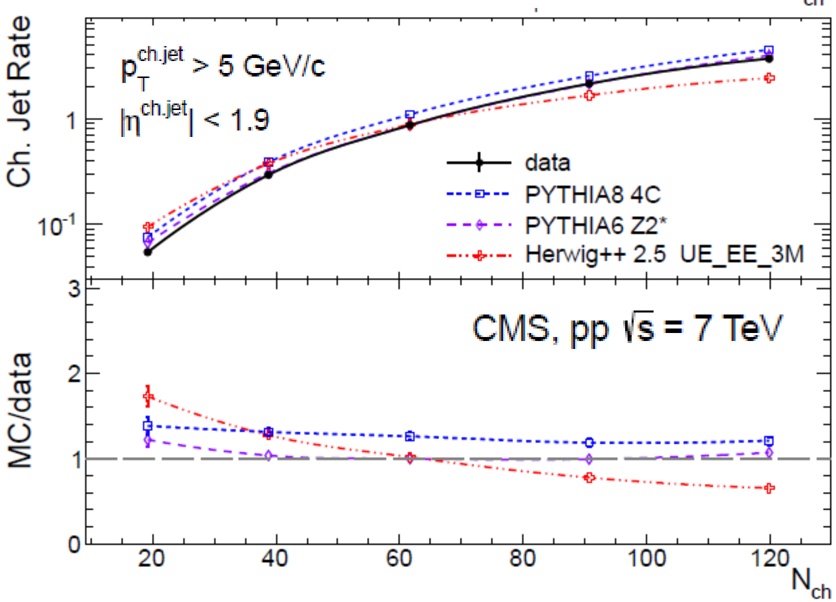
- Yield of Υ increases with multiplicity
  - ⇨ Similar in pp, p-Pb and Pb-Pb
  - ⇨ In Pb-Pb (and p-Pb) number of nucleon-nucleon collisions increases with multiplicity
- Υ(nS) production ratios depend on multiplicity
  - ⇨ Ground state Υ(1S) systematically produced with more particles?
  - ⇨ Excited states more easily dissociated by interactions with other particles?

📖 **CMS, JHEP 1404 (2014) 103**

Jets and UE vs. multiplicity







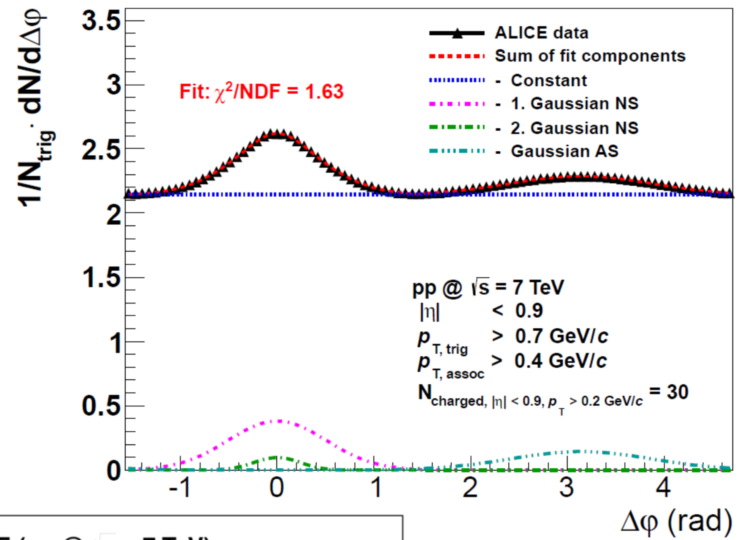
- High-multiplicity events:
  - Larger number of (semi) hard parton interactions, (mini)jets
  - Softer distribution of hadrons inside jets
- Multi-Parton Interaction (MPI) mechanism critical to reproduce the features of the data

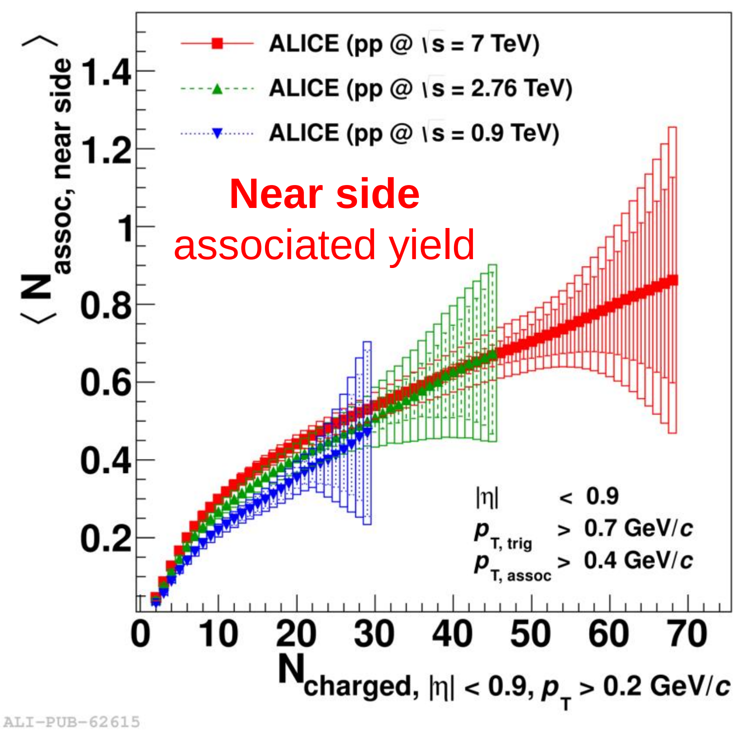
CMS, EPJ C73 (2013) 2674

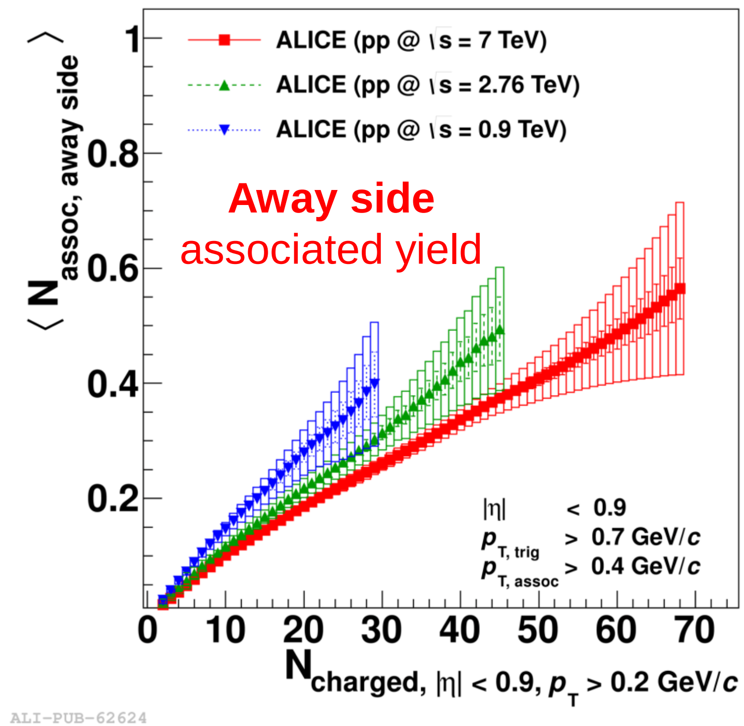
Mini jets in pp vs. multiplicity

- **Mini jets**: bundles of particles from semi-hard partonic scatterings
- **How**: from 2-particle correlations, associated yields in near and away sides

📖 **ALICE, JHEP 09 (2013) 049**







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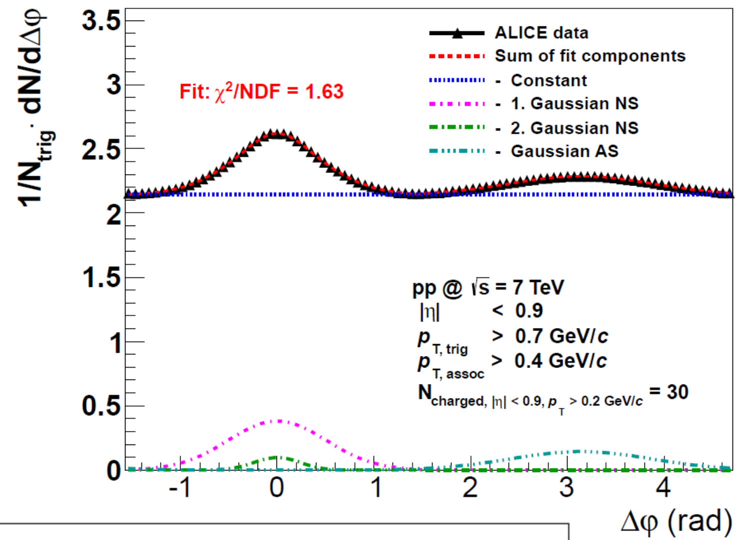
- **How**: from 2-particle correlations, associated yields in near and away sides

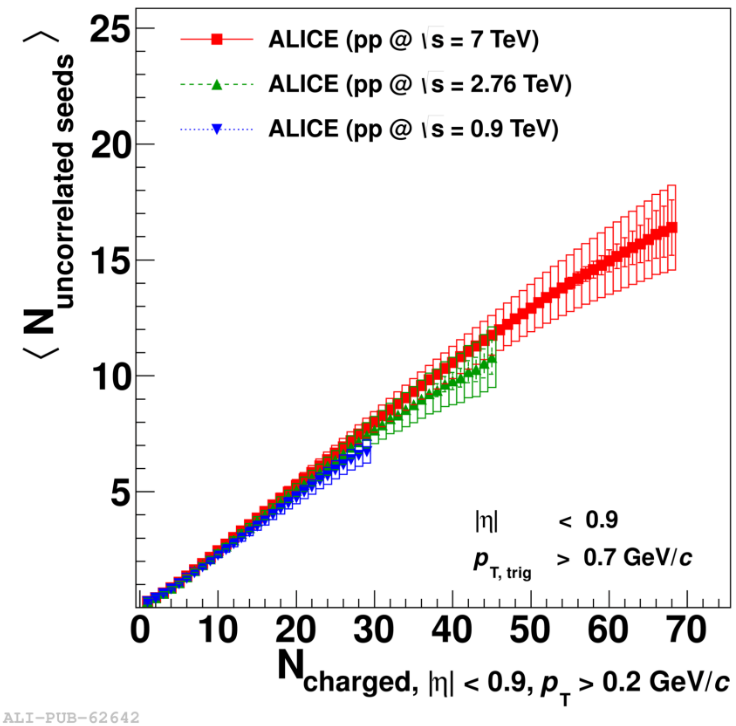
📖 ALICE, JHEP 09 (2013) 049



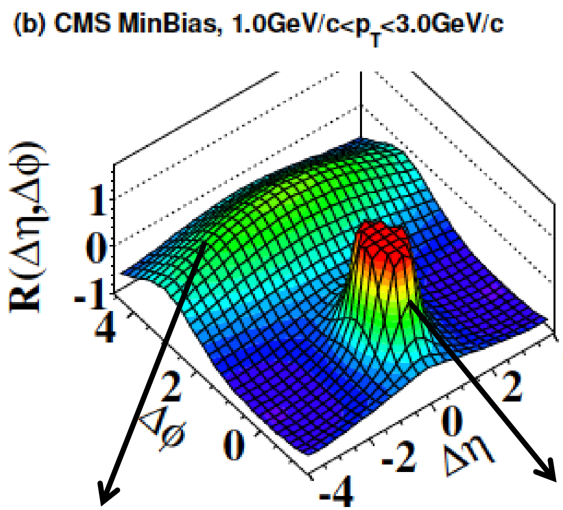
- Uncorrelated seeds = number of independent sources of particle production

$$< N_{\text{uncorrelated seeds}} >= \frac{< N_{\text{trigger}} >}{< 1 + N_{\text{assoc, near+away}} >}$$

  - In PYTHIA strongly correlated with number of MPIs
  - Linearly increasing with multiplicity at low multiplicity
  - Levels off at high multiplicities

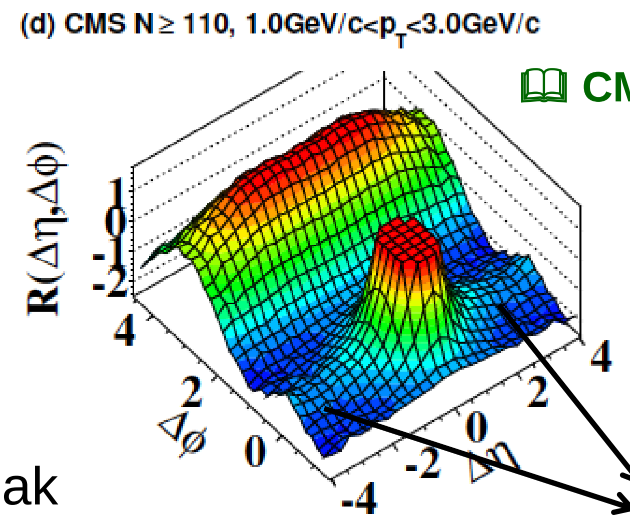


Angular correlations: pp collisions, high multiplicity



Jet peak

Recoil jet on the away side



📖 CMS, JHEP 1009 (2010) 091

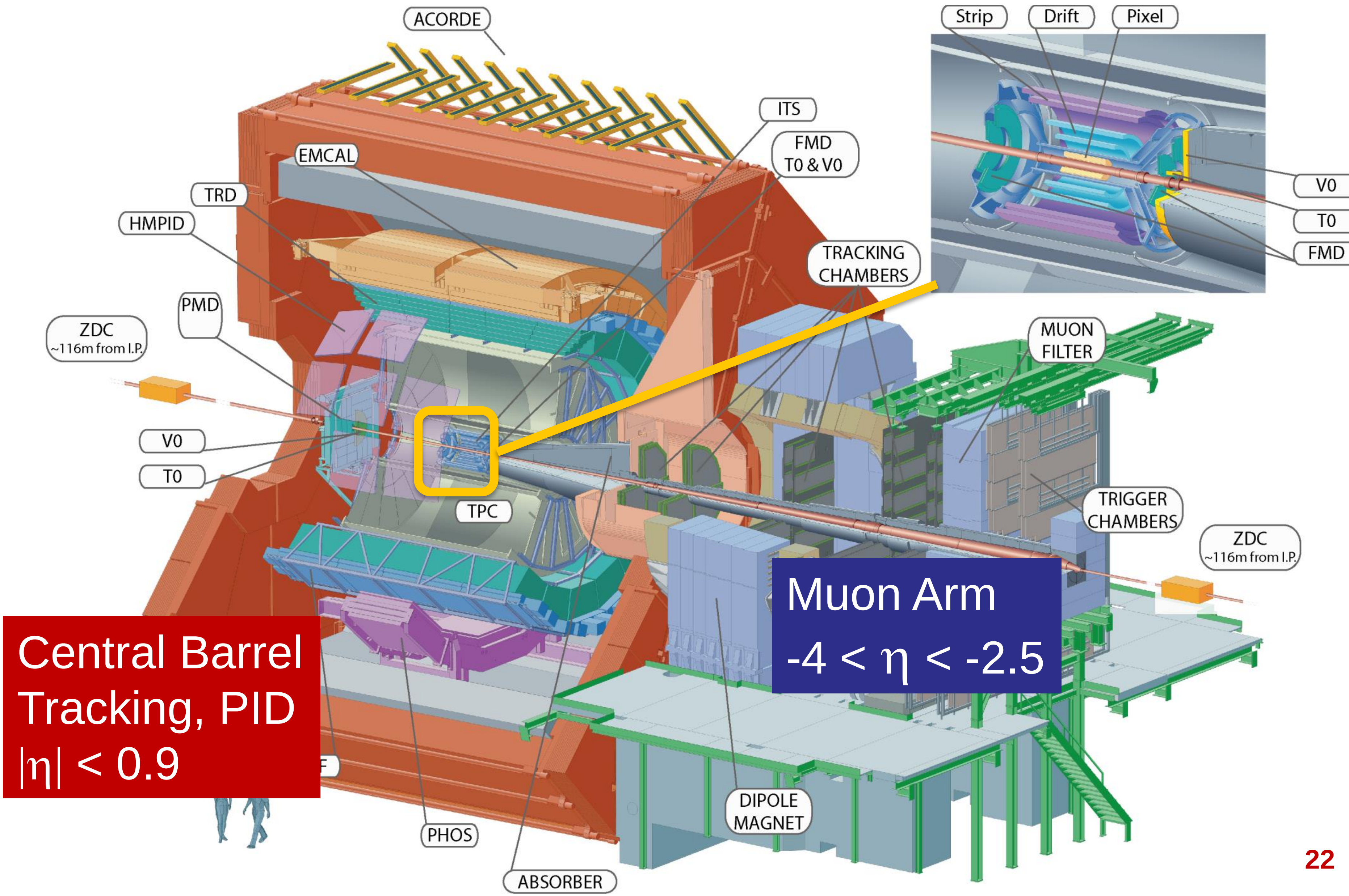
High-multiplicity pp events
8x average multiplicity
-> **near side ridge** along Δη: origin?

- Ridge in Pb-Pb collisions described by hydrodynamics
  - ⇨ Initial state geometrical anisotropy + collective expansion
- Also observed in high multiplicity **p-Pb** collisions at the LHC

📖 CMS, PLB 718 (2013) 795
📖 ALICE, PLB 719 (2013) 29

Heavy-flavour vs. multiplicity: Data analysis

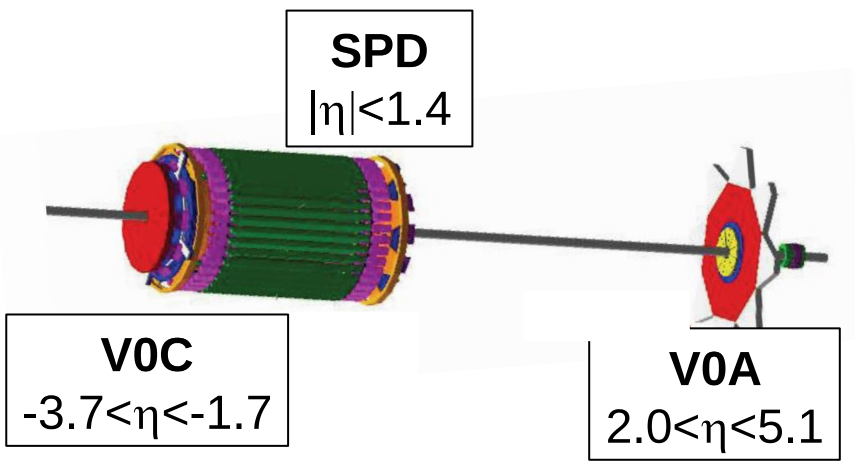
ALICE at the LHC



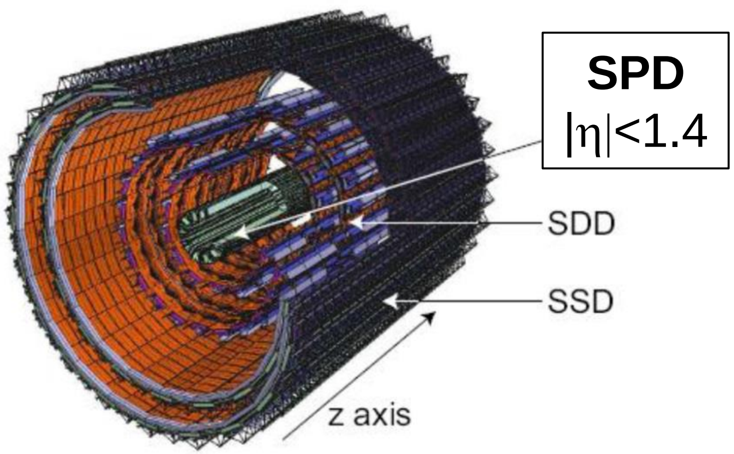
Data sample

pp collisions at $\sqrt{s}$ = 7 TeV

- Minimum-bias trigger
  - ⇨Signal in V0A or V0C or SPD
- N. events = $314 \cdot 10^6$
- $\int L dt$ = 5 nb^{-1}

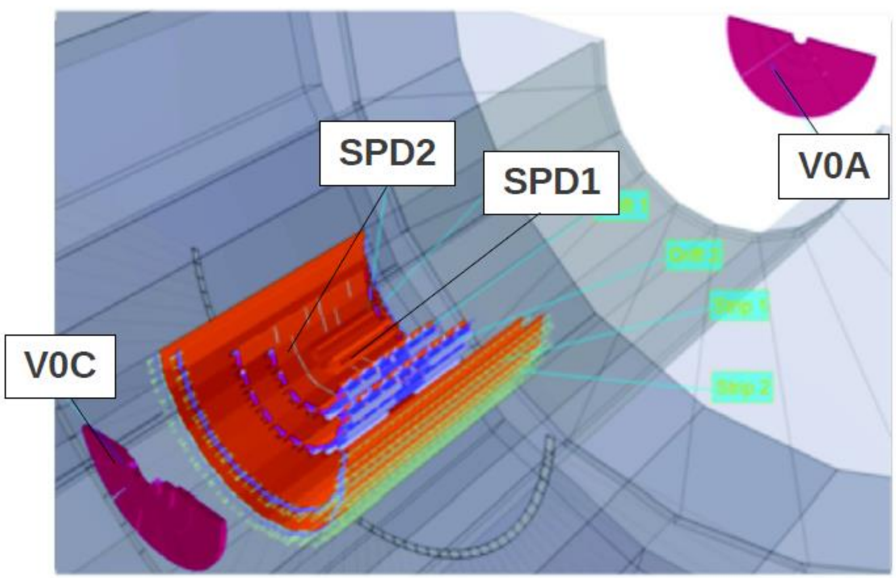


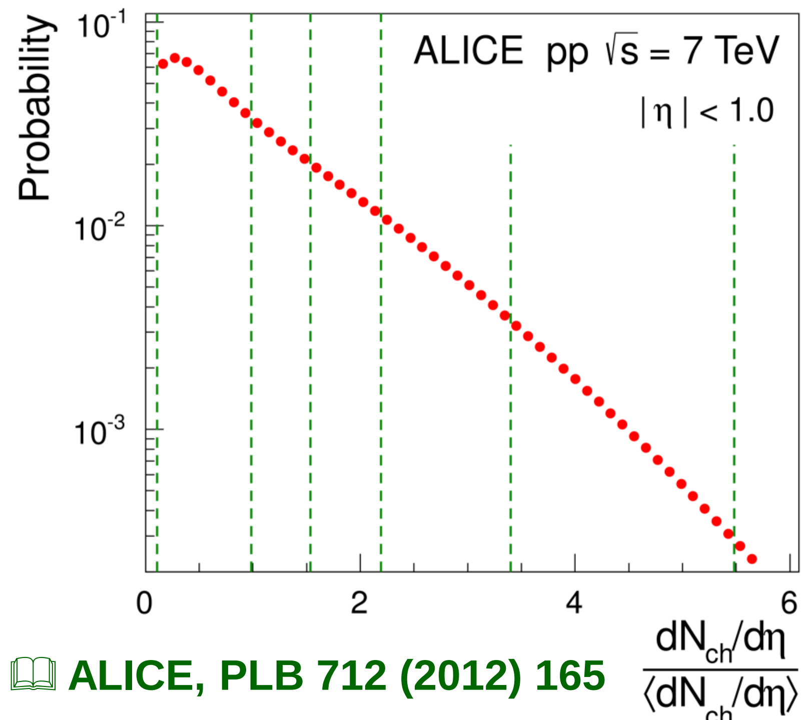
- High-multiplicity trigger
  - ⇨Threshold on number of fired chips in SPD
- N. events = $6 \cdot 10^6$
- $\int L dt$ = 14 nb^{-1}



Multiplicity estimation

- Number of tracklets in the two innermost ITS layers
  - ⇨ Silicon Pixel Detectors, pseudo-rapidity range: **|η|<1.0**
  - ⇨ $N_{\text{tracklets}} \propto dN_{ch}/d\eta$
  - ⇨ $\langle dN_{ch}/d\eta \rangle = 6.01 \pm 0.01(\text{stat.})^{+0.20}_{-0.12}(\text{syst.})$ in $|\eta| < 1$
- Sum of amplitudes in the V0 scintillator arrays
  - ⇨ N_{V0}, pseudo-rapidity range **-3.7<η<-1.7** and **2.8<η<5.1**





📖 ALICE, PLB 712 (2012) 165

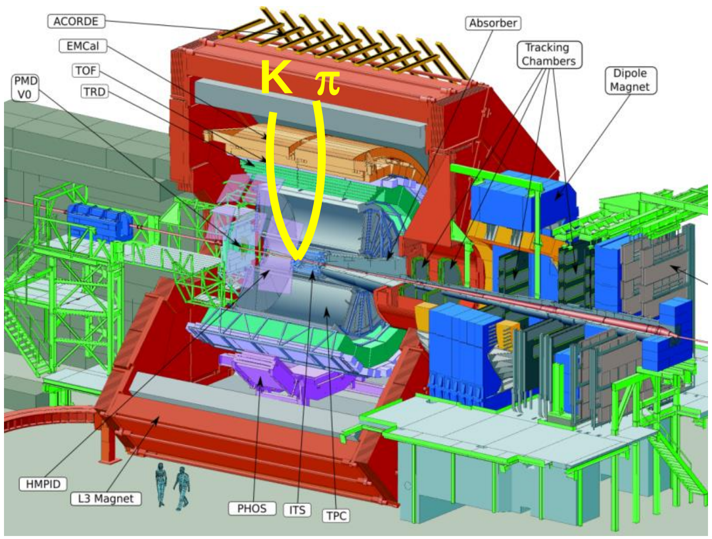
$N_{tracklets}$ intervals

- Number of tracklets in the two innermost ITS layers
  - Silicon Pixel Detectors, pseudo-rapidity range: **|η|<1.0**
  - $N_{\mathrm{tracklets}} \propto dN_{\mathrm{ch}}/d\eta$
  - $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle = 6.01 \pm 0.01(\mathrm{stat.})^{+0.20}_{-0.12}(\mathrm{syst.})$ in $|\eta| < 1$

$N_{\mathrm{tracklets}}$	$(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^j$	$(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)^j/\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	$N^{\mathrm{D}^0}_{\mathrm{events}}/10^6$	$N^{\mathrm{J}/\psi}_{\mathrm{events}}/10^6$	
[1,8]	2.7	$0.45^{+0.03}_{-0.03}$	155.1	–	MB trigger
[4,8]	3.8	$0.63^{+0.04}_{-0.04}$	–	89.0	MB trigger
[9,13]	7.1	$1.18^{+0.07}_{-0.07}$	46.2	50.5	MB trigger
[14,19]	10.7	$1.78^{+0.10}_{-0.11}$	32.0	35.5	MB trigger
[20,30]	15.8	$2.63^{+0.15}_{-0.17}$	24.7	28.0	MB trigger
[31,49]	24.1	$4.01^{+0.23}_{-0.25}$	7.9	9.5	MB trigger
[50,80]	36.7	$6.11^{+0.35}_{-0.39}$	1.7	–	High Mult trigger

Open charm

D-meson reconstruction



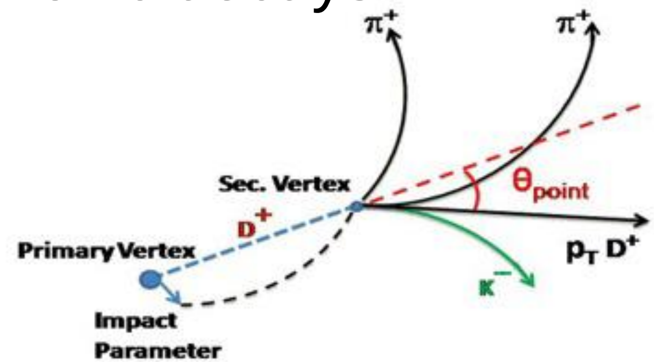
Full reconstruction of D-meson hadronic decays

$D^0 \to K^- \pi^+$

$D^+ \to K^- \pi^+ \pi^+$

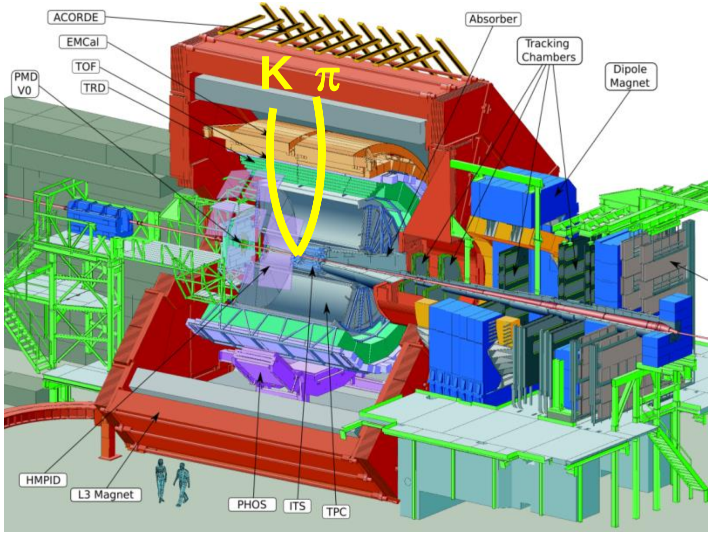
$D^{*+} \to D^0 \pi^+$

$D_s^+ \to K^- K^+ \pi^+$



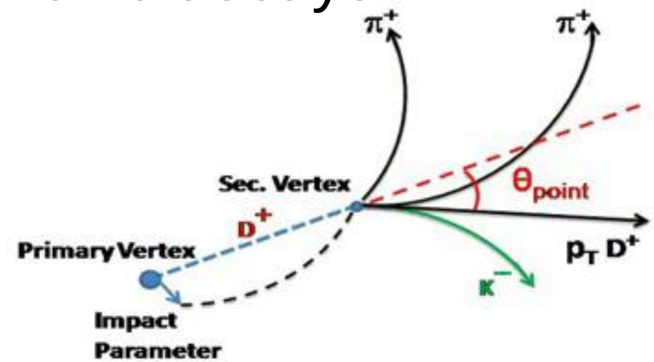
- Analysis strategy
  - ⇨ Invariant mass analysis of fully reconstructed decay topologies displaced from the primary vertex
  - ⇨ Background reduction via:
    - ✓ ***Geometrical selections on the decay vertex***
    - ✓ ***Particle identification of the decay products***
- Feed down from B (10-15 % after cuts) subtracted using pQCD (FONLL) predictions

D-meson reconstruction

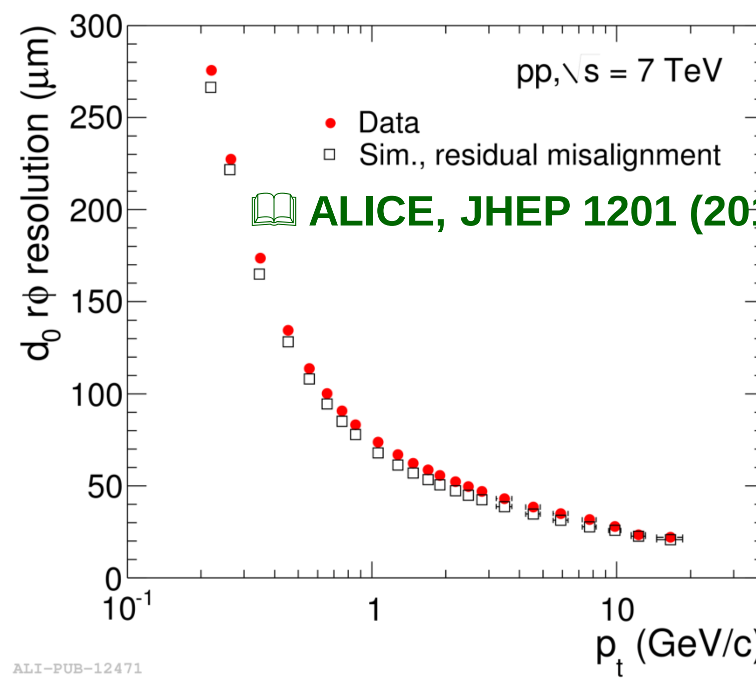


Full reconstruction of D-meson hadronic decays

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

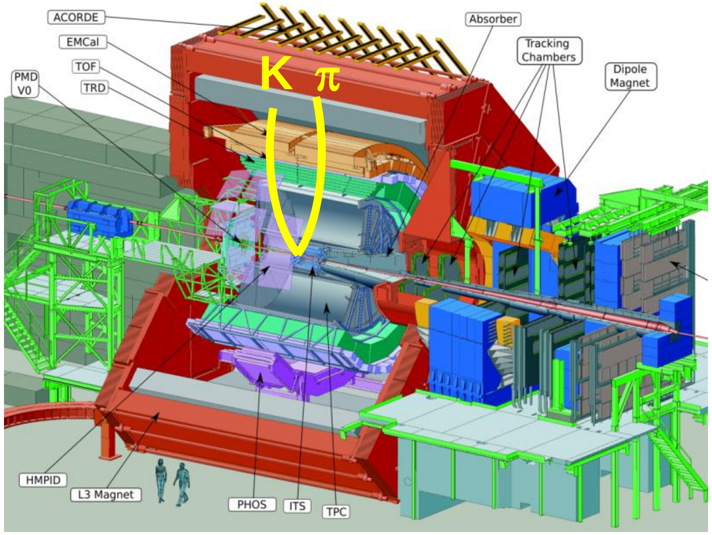


- **Geometrical selections**
  - ⇨ Track impact parameter (resolution ≈ 75 μm at p_T = 1 GeV/c)
  - ⇨ Decay length
  - ⇨ Pointing of the D-meson momentum to the primary vertex



📖 **ALICE, JHEP 1201 (2012) 128**

D-meson reconstruction



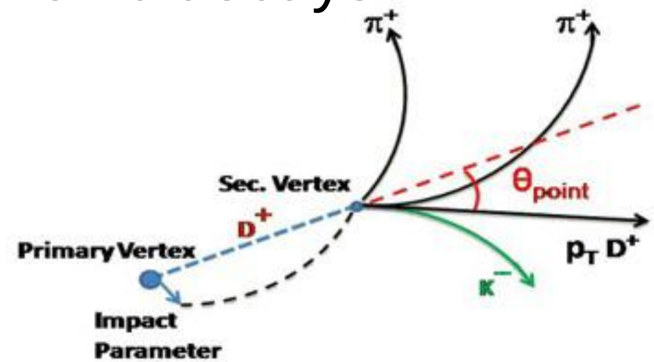
Full reconstruction of D-meson hadronic decays

$D^0 \rightarrow K^- \pi^+$

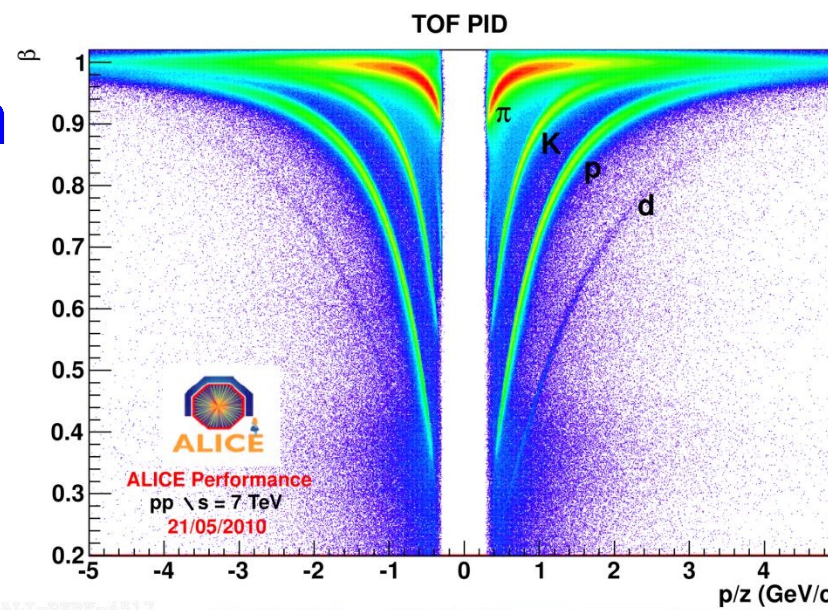
$D^+ \rightarrow K^- \pi^+ \pi^+$

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

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



- PID selection: 3σ cuts on
  - ⇨ d*E*/dx in TPC
  - ⇨ Time-of-flight from interaction point to TOF detector



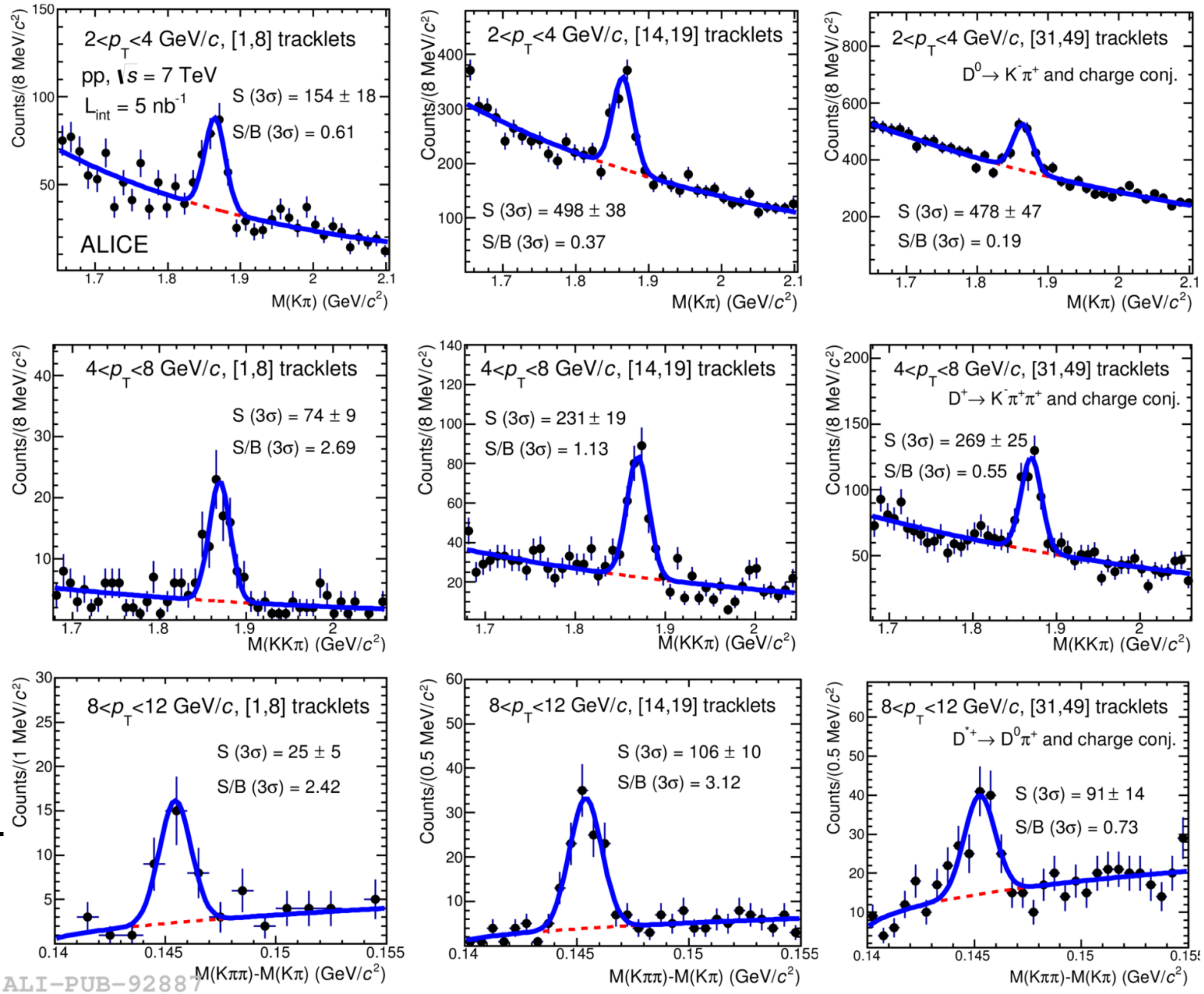
D^0, D^+, D^{*+} invariant mass

Low multiplicity | **Mid multiplicity** | **High multiplicity**

D^0 Low p_T

D^+ Mid p_T

D^{*+} High p_T



📖 **ALICE, arXiv:1505.00664**

Corrections and systematics

$$\frac{d^2N^{\mathrm{D}}/dydp_{\mathrm{T}}}{\left\langle d^2N^{\mathrm{D}}/dydp_{\mathrm{T}}\right\rangle} = \frac{N^{\mathrm{mult}}_{\mathrm{raw\,D}}/(\varepsilon^{\mathrm{mult}}_{\mathrm{D}} \times N^{\mathrm{mult}}_{\mathrm{event}})}{N^{\mathrm{tot}}_{\mathrm{raw\,D}}/(\varepsilon^{\mathrm{tot}}_{\mathrm{D}} \times N^{\mathrm{tot}}_{\mathrm{event}}/\varepsilon_{\mathrm{trigger}})}$$

D-meson yield / event in multiplicity intervals corrected for reconstruction efficiency

D-meson yield / event multiplicity integrated, corrected for reconstruction and trigger efficiencies

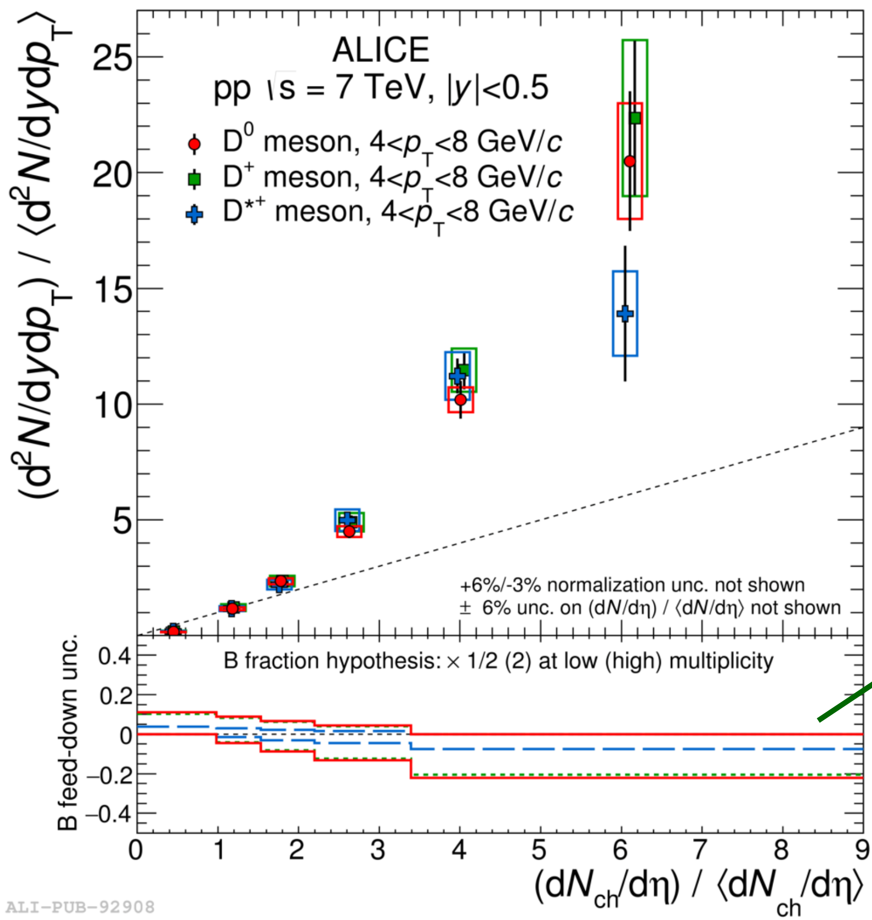
- Sources of systematics
  - **Raw yield** extraction
    - ✓ ***D-meson line shape***
    - ✓ ***Background fit function***
    - ✓ ***3-15% depending on p_T, multiplicity, species***
  - **Primary vertex** determination
    - ✓ ***With/without D-meson decay tracks***
    - ✓ ***Negligible effect***
  - Selection and PID **efficiency**
    - ✓ ***Same selection used in all multiplicity intervals***
    - ✓ ***Negligible residual effect due to multiplicity dependence of efficiency***
  - **Fraction of prompt** D mesons in the raw yield
    - ✓ ***Assumed to be the same in all multiplicity bins (cancels out in the ratio)***
    - ✓ ***Uncertainty by varying the D←B contribution by a factor 1/2 (2) at low(high) multiplicity***

Corrections and systematics

$$\frac{d^2N^D/dydp_T}{\langle d^2N^D/dydp_T\rangle} = \frac{N^{mult}_{raw\,D}/(\varepsilon^{mult}_D \times N^{mult}_{event})}{N^{tot}_{raw\,D}/(\varepsilon^{tot}_D \times N^{tot}_{event}/\varepsilon_{trigger})}$$

D-meson yield / event in multiplicity intervals corrected for reconstruction efficiency

D-meson yield / event multiplicity integrated, corrected for reconstruction and trigger efficiencies



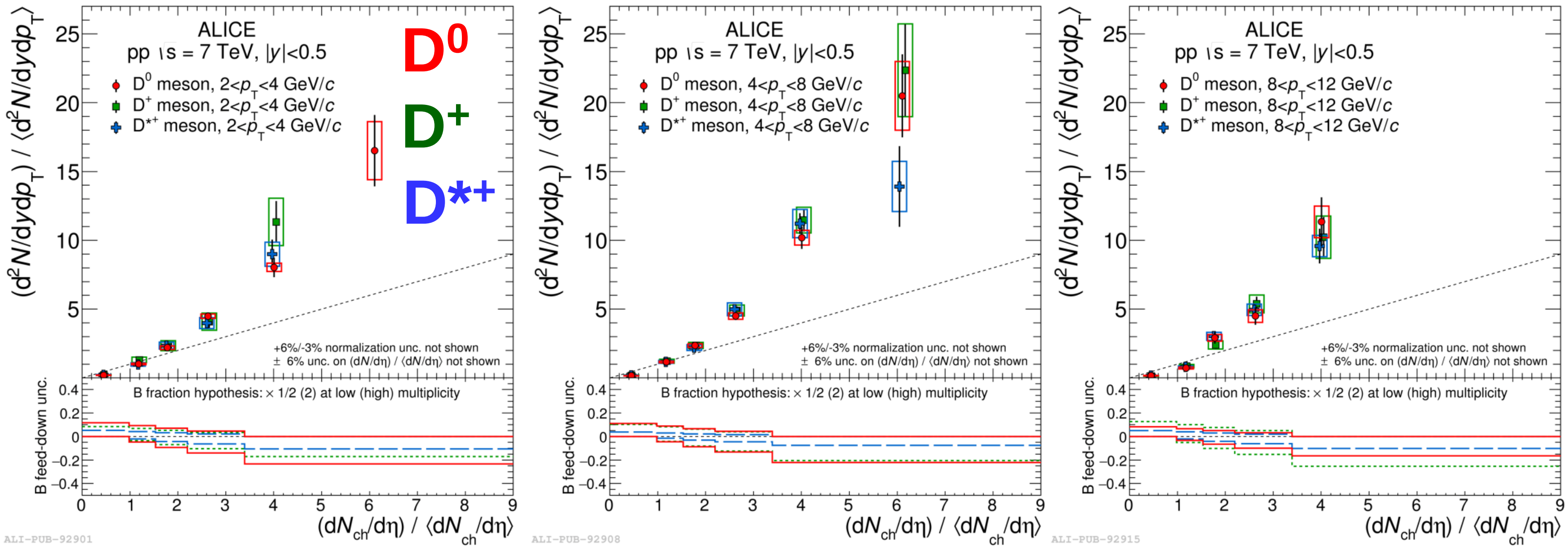
Contribution of D from B decays:

- assumed independent of multiplicity
- uncertainty by varying the D←B contribution by a factor 1/2 (2) at low(high) multiplicity

📖 ALICE, arXiv:1505.00664

D^0, D^+, D^{*+} yield vs. multiplicity

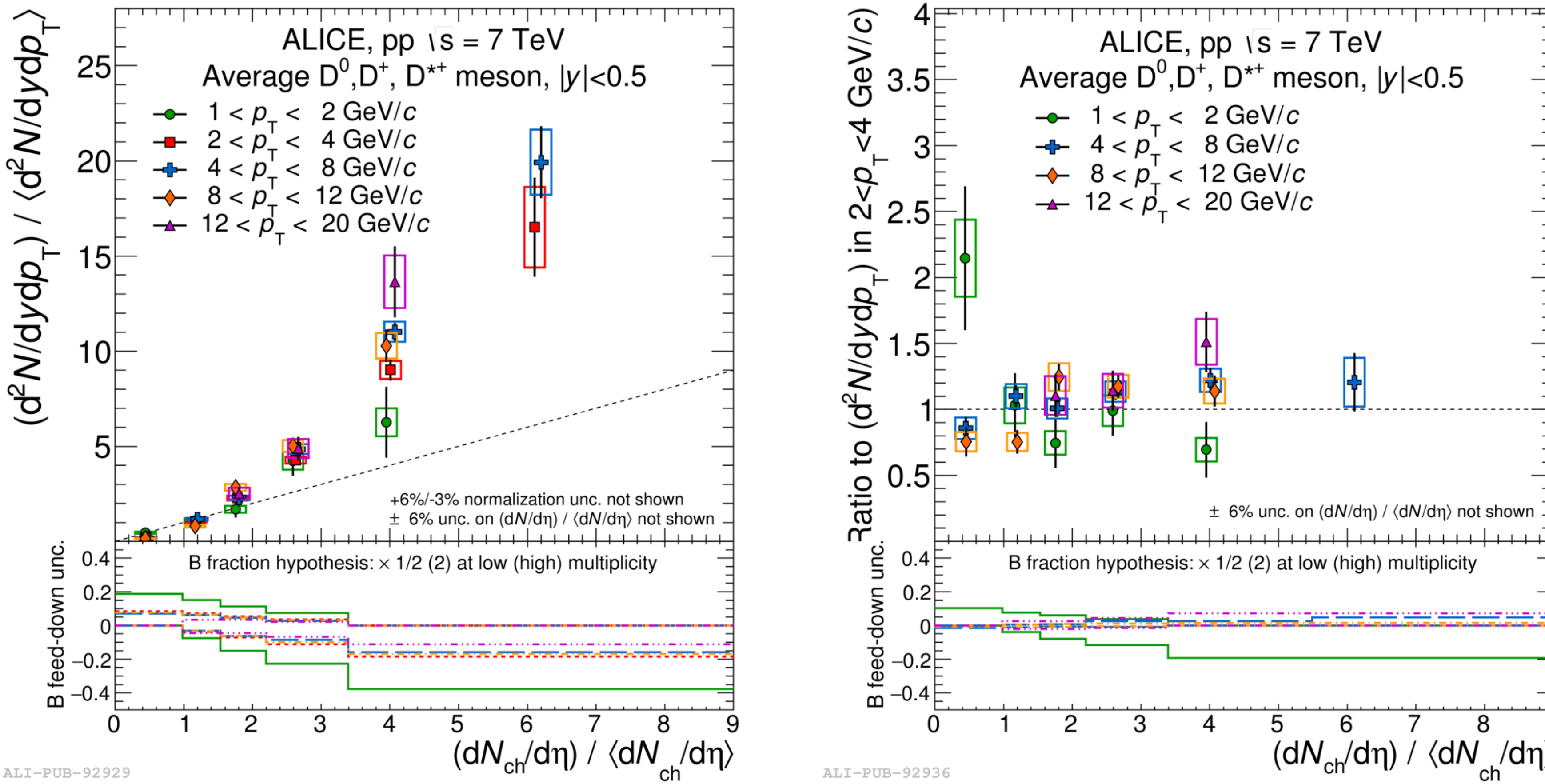
$2<p_T<4$ GeV/c | $4<p_T<8$ GeV/c | $8<p_T<12$ GeV/c



- D-meson per-event yields increase with charged-particle multiplicity
  - ⇨ Similar trend in different p_T intervals
  - ⇨ Faster than linear increase
- D^0, D^+ and D^{*+} results compatible within uncertainties
  - ⇨ Compute the average of the three meson species

📖 **ALICE, arXiv:1505.00664**

D-meson yield vs. multiplicity p_T dependence?

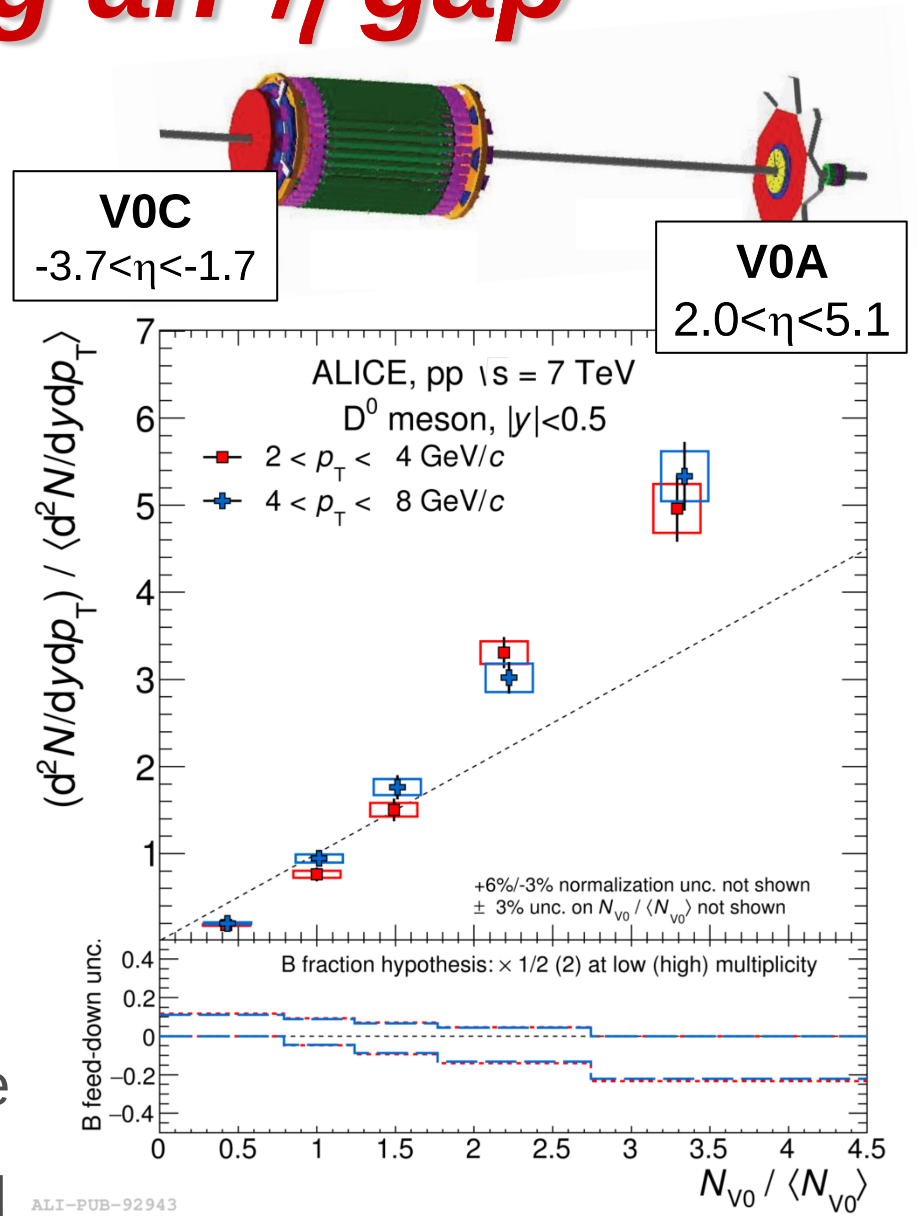


- Trend of D-meson yield vs. multiplicity **independent of p_T** within uncertainties

ALICE, arXiv:1505.00664

Introducing an η gap

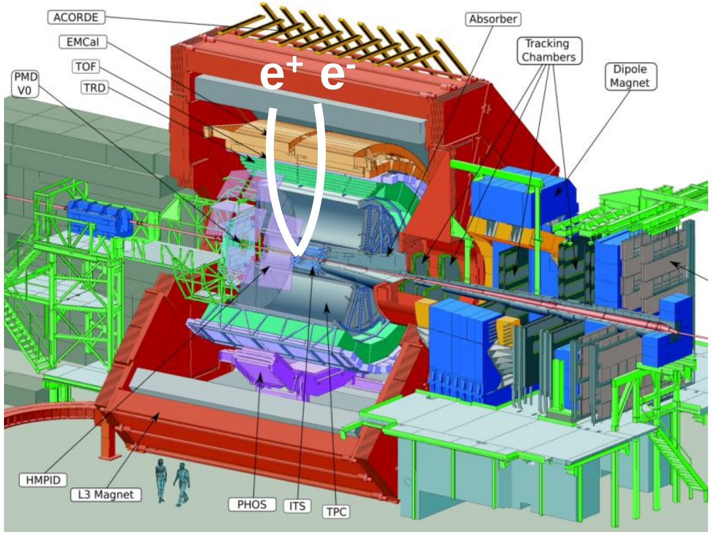
- Charged-particle multiplicity measured in the same η range as D mesons
- Multiplicity estimation includes:
  - ⇨ D-meson decay particles
  - ⇨ Particles produced in the charm-quark fragmentation
- Test effect of possible auto-correlations using the multiplicity measured in the V0 detector
  - ⇨ Qualitatively similar increasing trend when an η gap is introduced between the regions in which D mesons and multiplicity are measured



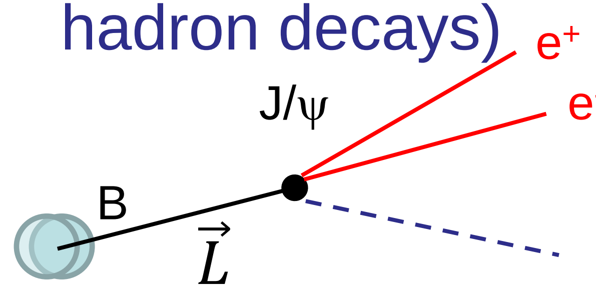
📖 **ALICE, arXiv:1505.00664**

J/ψ from beauty-hadron decays

J/ψ from beauty-hadron decays

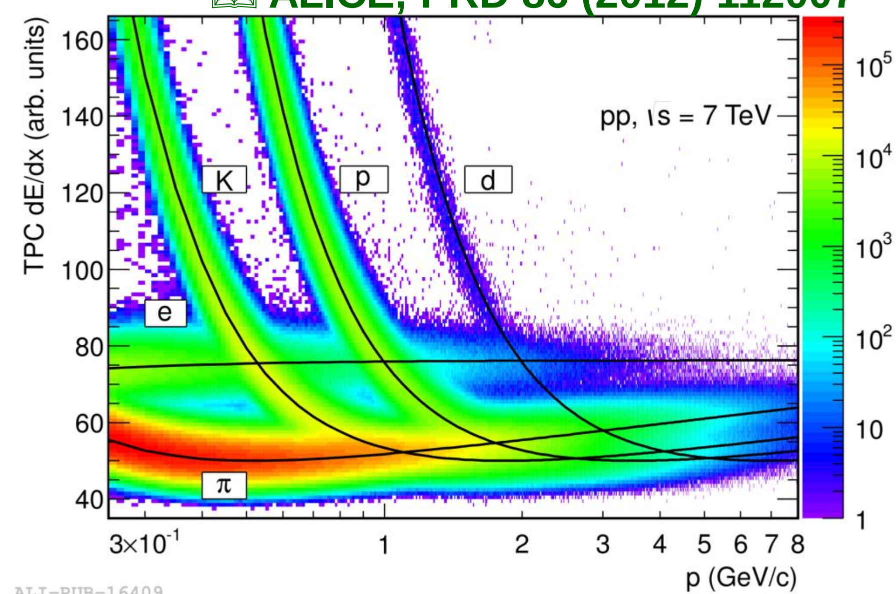


Displaced J/ψ (from beauty-hadron decays)

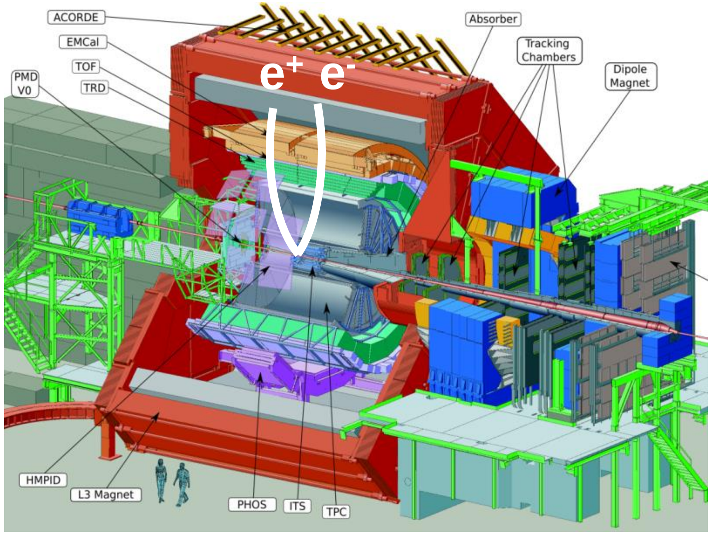


- Analysis strategy
  - ⇨ Electron identification based on energy loss in TPC
    - ✓ ***3σ cut around expected $e^{\pm}$ dE/dx***
    - ✓ ***3.5σ (3σ) exclusion band around expected π(p) dE/dx***

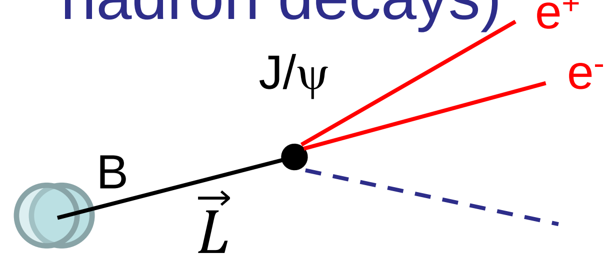
ALICE, PRD 86 (2012) 112007



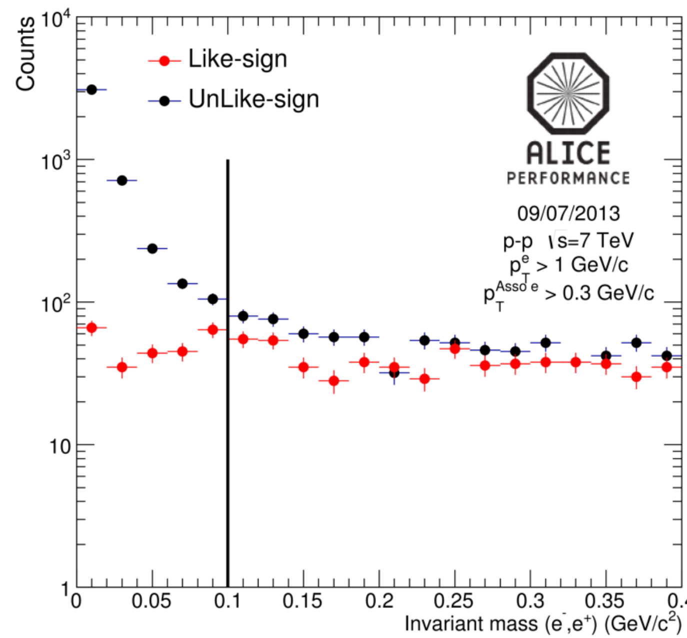
J/ψ from beauty-hadron decays



Displaced J/ψ (from beauty-hadron decays)



- Analysis strategy
  - ⇨ Electron identification based on energy loss in TPC
  - ⇨ Reduction of background from γ conversions and π^0 Dalitz decays
    - ✓ ***Excluding $e^{\pm}$ that form e^+e^- pairs with invariant mass < 100 MeV/c^2***



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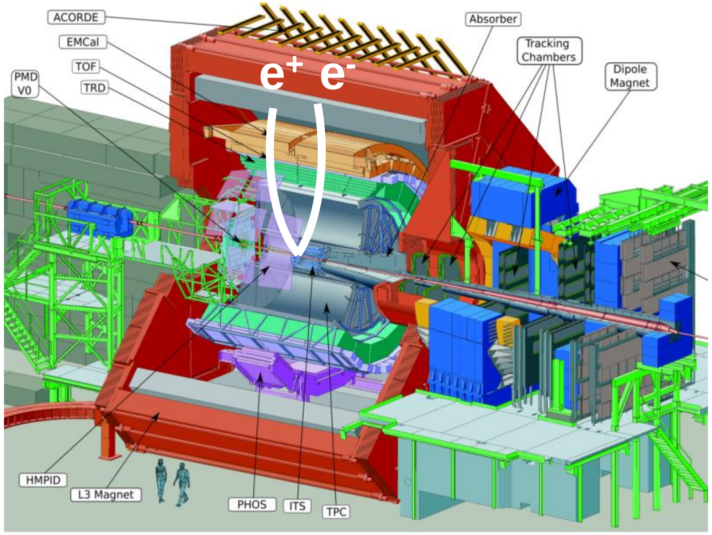
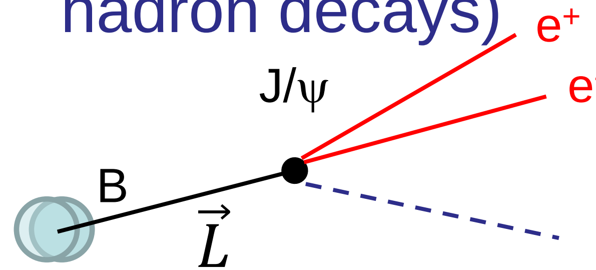
J/ψ from beauty-hadron decays



Displaced J/ψ (from beauty-hadron decays)

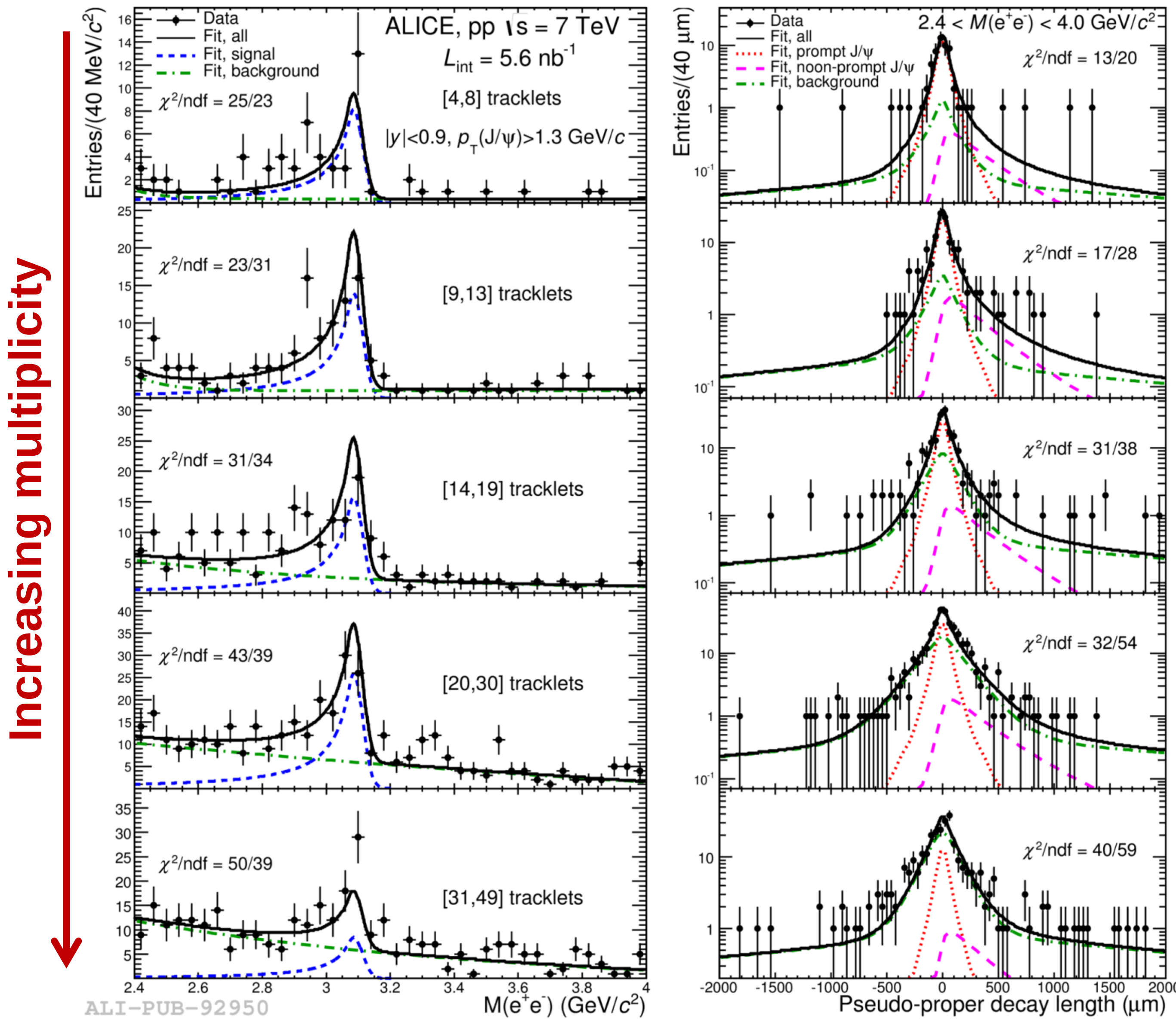


- Analysis strategy
  - Electron identification based on energy loss in TPC
  - Reduction of background from γ conversions and π^0 Dalitz decays
  - J/ψ production vertex reconstruction
  - Simultaneous fit to invariant mass and pseudo-proper decay length (x) distributions

$$x = L_{xy} \cdot \frac{M_{J/\psi} \cdot c}{p_T^{J/\psi}}$$

$$L_{xy} = \vec{L} \cdot \frac{\vec{p}_T^{\,J/\psi}}{\left|\vec{p}_T^{\,J/\psi}\right|}$$

Non-prompt J/ψ: fits



- Fraction of non-prompt J/ψ from 2D un-binned log-likelihood fit to:
  - ⇨ Invariant mass $M(e^+e^-)$
  - ⇨ Pseudo-proper decay length x

$$x = L_{xy} \cdot \frac{M_{J/\psi} \cdot c}{p_T^{J/\psi}}$$

📖 **ALICE, arXiv:1505.00664**

Corrections and systematics

- Fraction of reconstructed non-prompt J/ψ:
  - Raw value f'_B extracted from 2D un-binned log-likelihood fits
  - Corrected for acceptance x efficiency

$$f'_B = \frac{N^{raw}_{J/\psi\leftarrow B}}{N^{raw}_{J/\psi\,prompt} + N^{raw}_{J/\psi\leftarrow B}} \longrightarrow f_B = \left(1 + \frac{1-f'_B}{f'_B} \cdot \frac{\langle A\times\varepsilon\rangle_B}{\langle A\times\varepsilon\rangle_{prompt}}\right)^{-1}$$

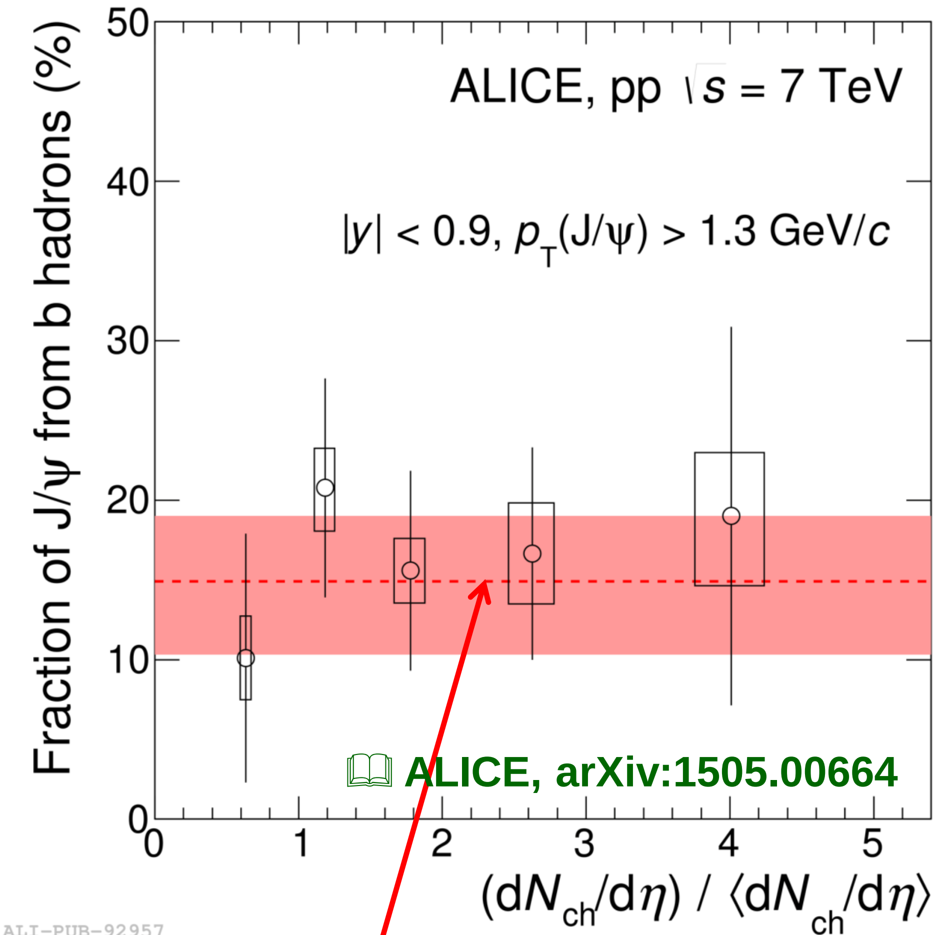
  - ✓ ***3% difference between A x ε of prompt and non-prompt J/ψ***

- Extrapolation from p_T>1.3 GeV/c to p_T>0
  - Extrapolation factor: $\alpha_{extr} = 0.99^{+0.01}_{-0.03}$
    - ✓ ***Based on FONLL (non-prompt) and phenomenological (prompt) p_T shapes***
  - NOTE: p_T>1.3 GeV/c selection needed because of the non-negligible amount of J/ψ emitted with large opening angle with respect to the beauty-hadron direction at low p_T

Corrections and systematics

- Sources of systematic uncertainty
  - **Primary vertex** determination
    - ✓ ***With/without removing J/ψ decay tracks (resolution and bias)***
    - ➢ ***Effect: 19% at low multiplicity → 3% at high multiplicity***
  - **Resolution** of pseudo-proper decay length (***x***)
    - ✓ ***Due to imperfect description of x variable in the simulations***
    - ➢ ***Effect: 8% at low multiplicity → 20% at high multiplicity***
  - **Generated J/ψ p_T distributions** in MC
    - ✓ ***Effect on $A \times \varepsilon$ (~ 1%)***
    - ✓ ***Effect on x resolution (within the estimated uncertainty)***
  - **Modeling of J/ψ from beauty** pseudo-proper decay-length distribution
    - ✓ ***Beauty-hadron decay kinematics and p_T spectra***
    - ➢ ***Effect: 3%, independent of multiplicity***
  - **Background modeling** in the fit
    - ✓ ***Use side-bands for x distributions***
    - ✓ ***Use LS to check the invariant mass distribution***
    - ➢ ***Effect: ~7% , independent of multiplicity***
  - **Extrapolation** to p_T=0
    - ➢ ***Effect: 3%***

Fraction of non-prompt J/ψ



Multiplicity integrated value $<f_B>$

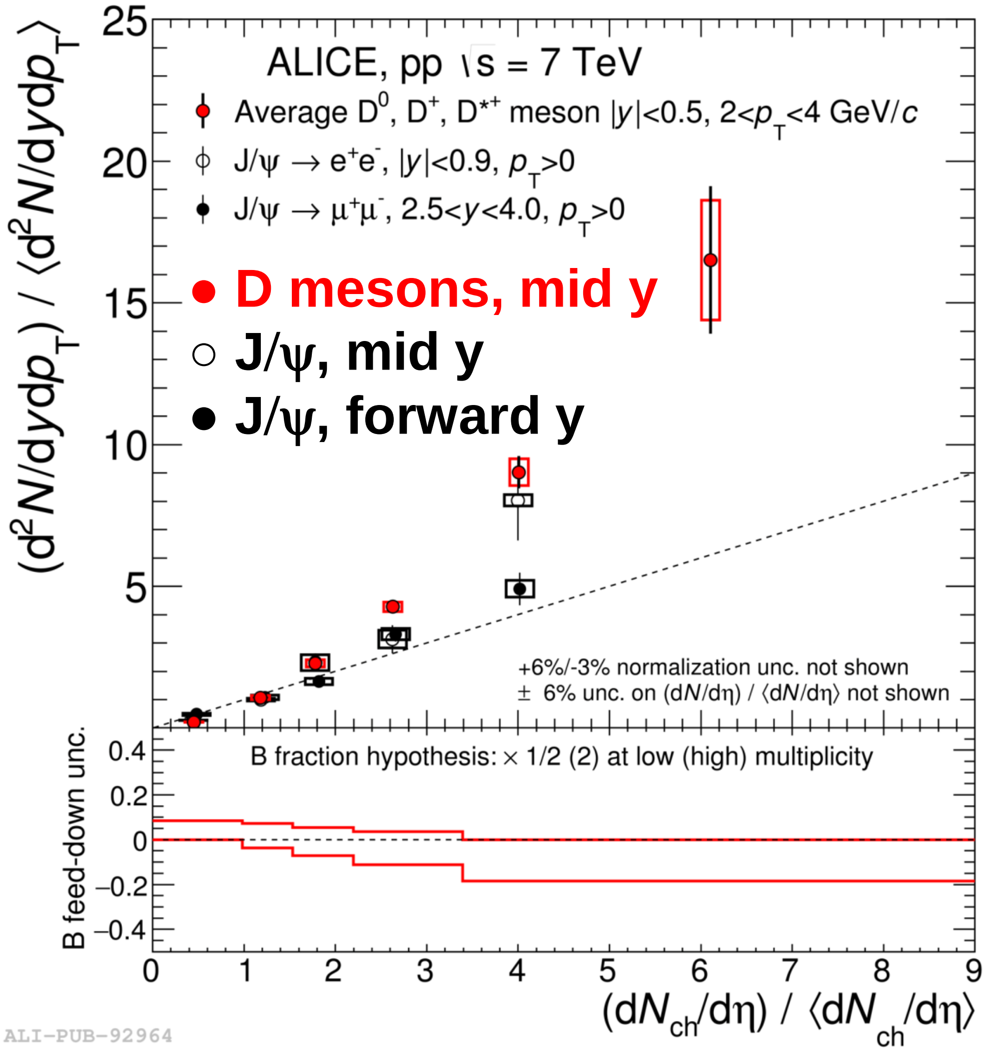
- Fraction of non-prompt J/ψ
  - ⇨ Approximately flat as a function of multiplicity
- Non-prompt J/ψ yield relative to the multiplicity integrated one computed as:

$$\frac{dN_{J/\psi}^{non-prompt}/dy}{\left\langle dN_{J/\psi}^{non-prompt}/dy \right\rangle} = \frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle} \cdot \frac{f_B}{\langle f_B \rangle}$$

Inclusive J/ψ result from:
ALICE, PLB 712 (2012) 165

Open charm, charmonia and open beauty

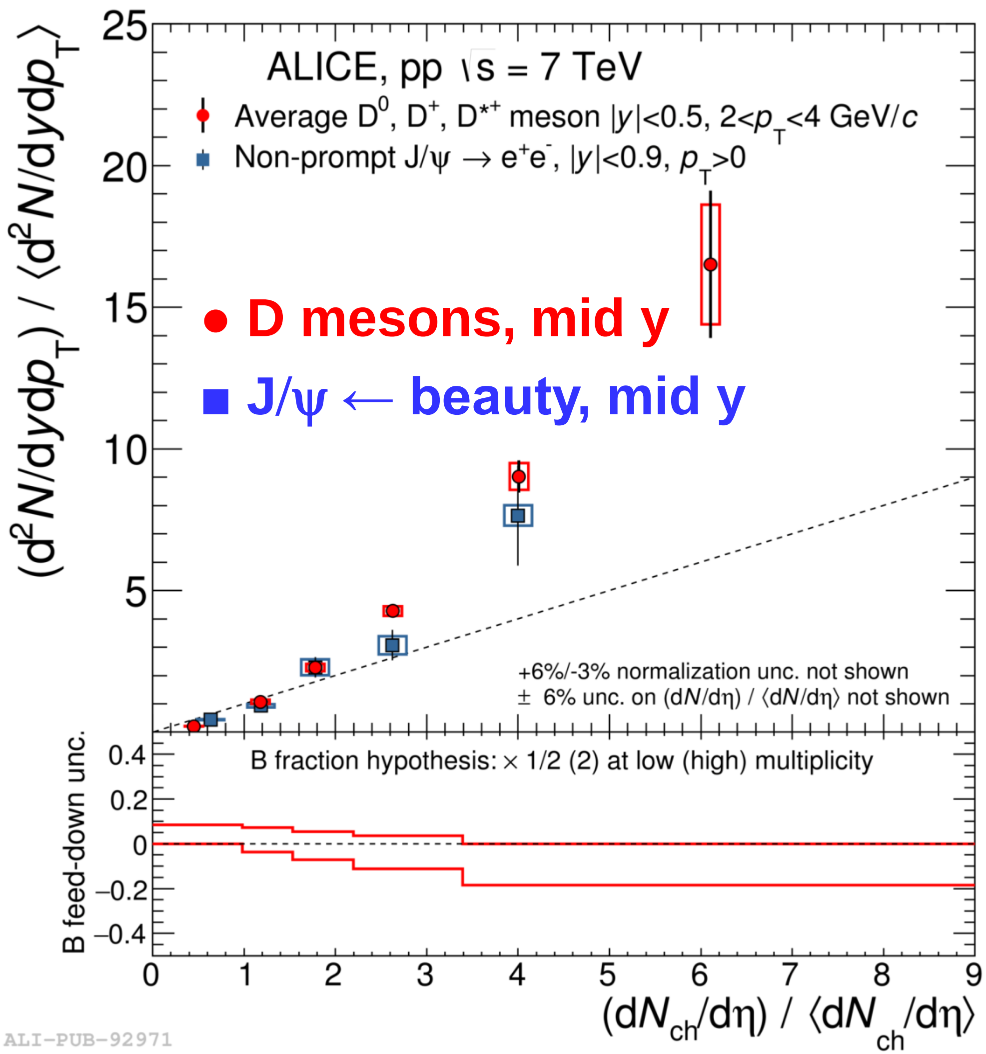
D mesons vs. inclusive J/ψ



- Similar increase with multiplicity of per-event yield of open and hidden charm
- Inclusive J/ψ measured at mid (e^+e^-) and forward ($\mu^+\mu^-$) rapidity
  - ⇨ Forward rapidity J/ψ and charged multiplicity measured in different η regions

ALICE, arXiv:1505.00664
Inclusive J/ψ result from:
ALICE, PLB 712 (2012) 165

Open charm vs. open beauty



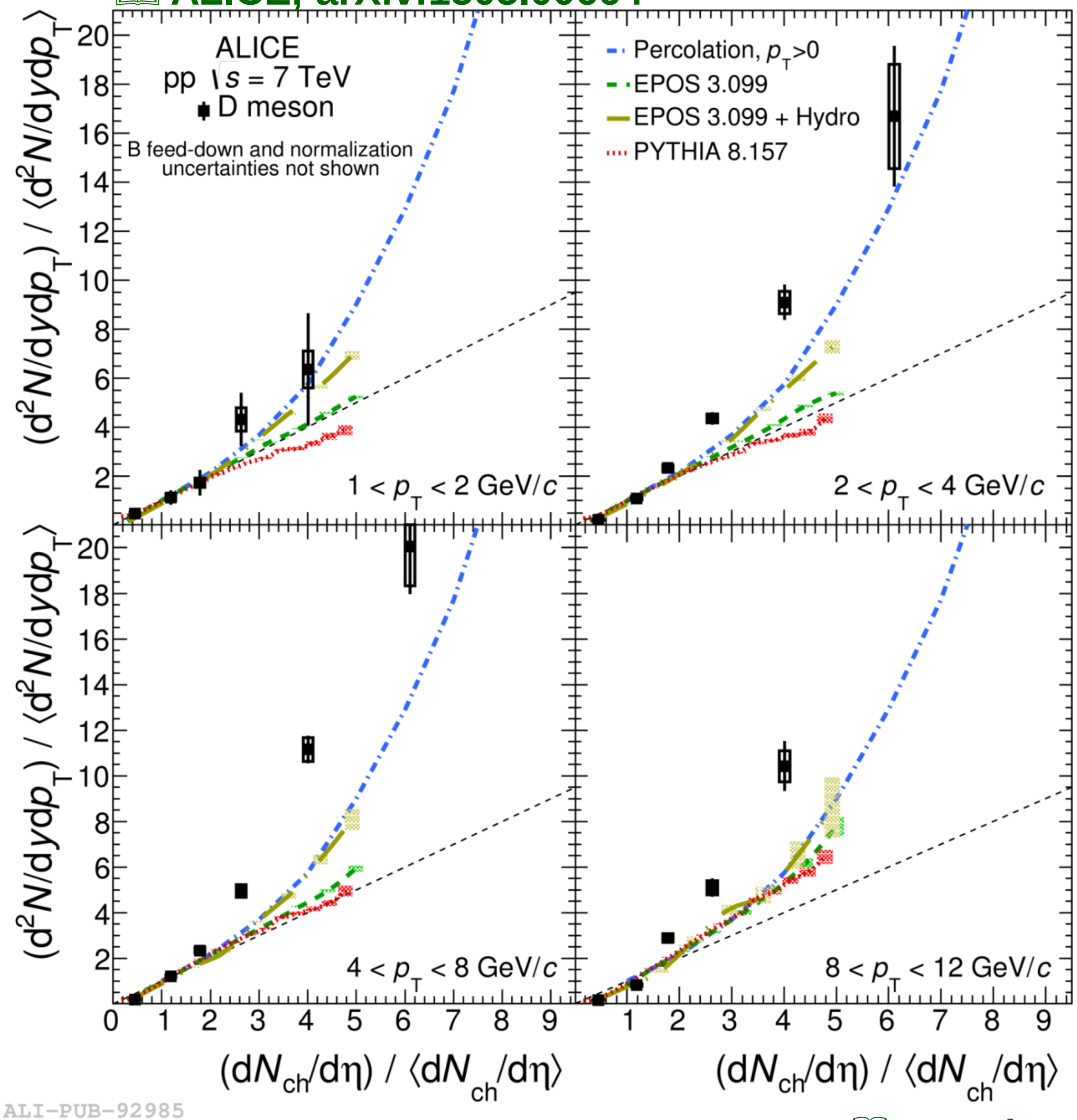
- Similar increase with multiplicity of per-event yield of open charm and beauty production

ALICE, arXiv:1505.00664

Comparison to model calculations

Model calculations

ALICE, arXiv:1505.00664

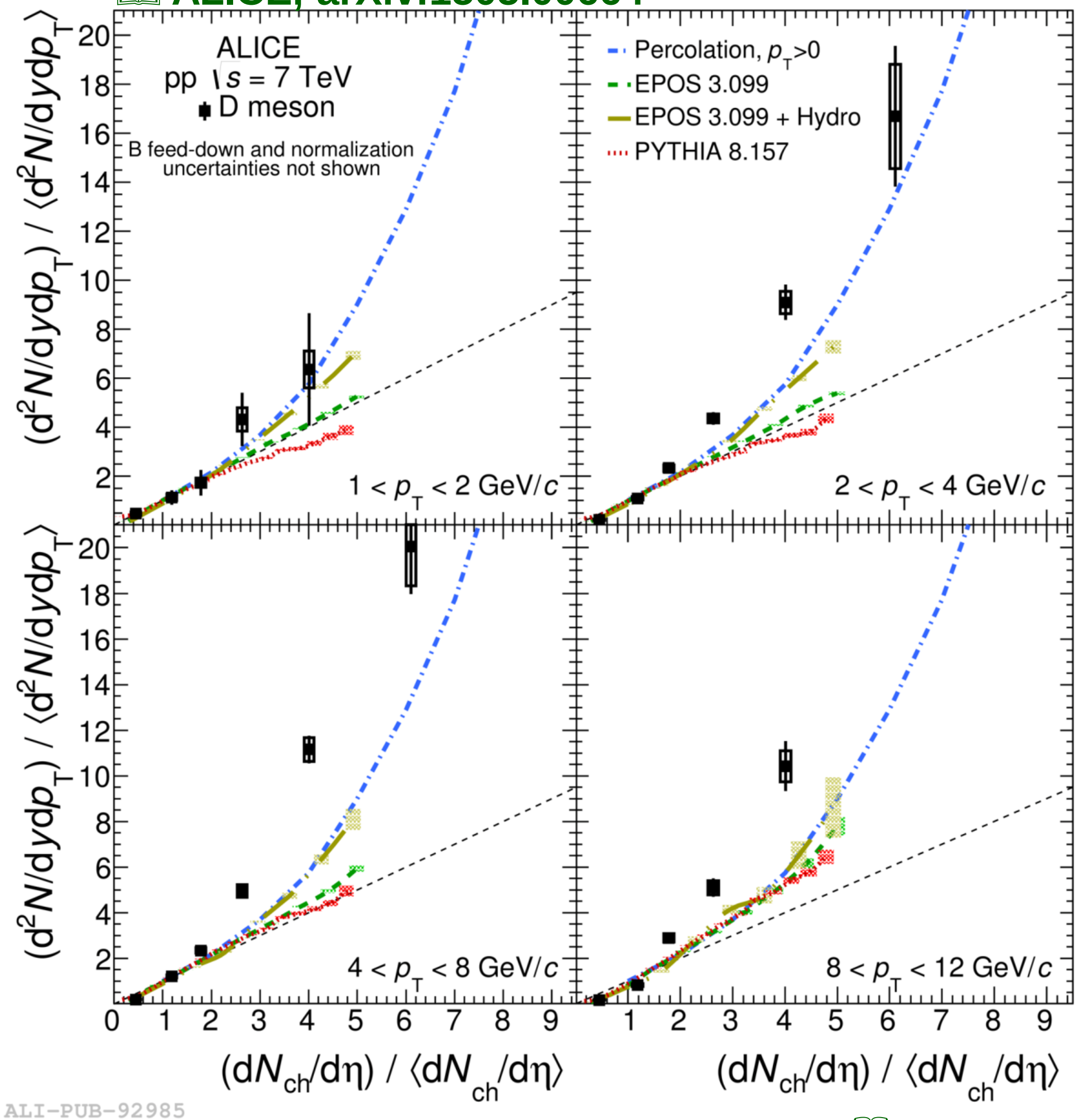


- Percolation model
  - Elementary sources of particle production: colour ropes/strings formed in parton-parton collisions
    - ✓ ***Close to MPI scenario***
  - Colour strings have finite spatial extension and interact
    - ✓ ***At high densities: overlap among the sources -> reduction of their number***
    - ✓ ***Affects more soft sources (larger transverse size) and charged multiplicity***
  - More than linear increase of D-meson yield with multiplicity

Ferreiro, Pajares, PRC 86 (2012) 034903

Model calculations

ALICE, arXiv:1505.00664

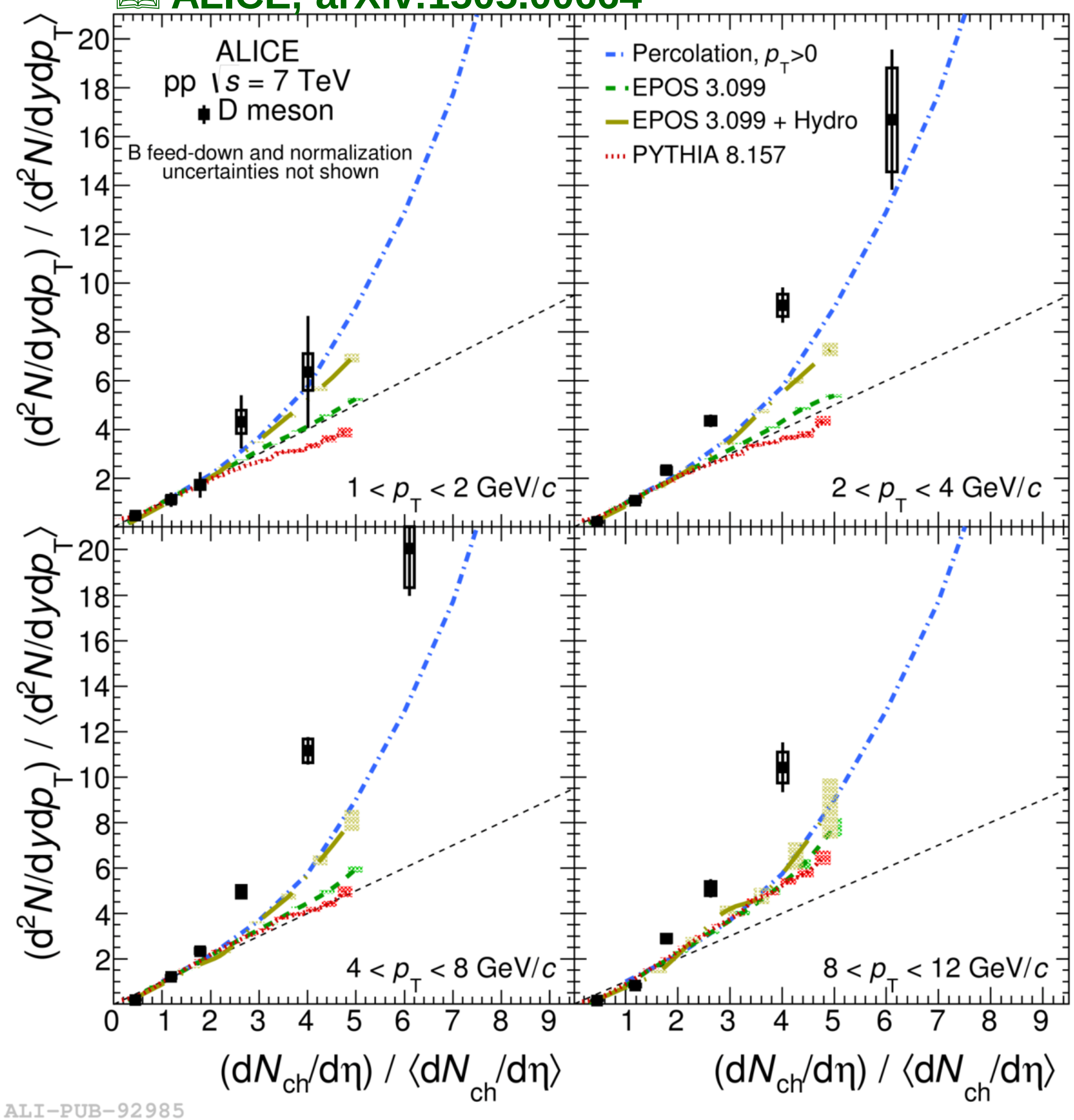


- EPOS 3.099
  - ⇨ Initial conditions
    - ✓ ***Gribov-Regge multiple-scattering formalism***
    - ✓ ***Saturation scale to model non-linear effects***
    - ✓ ***Hadronization via string fragmentation***
    - ✓ ***Number of MPI directly related to multiplicity***
  - ⇨ Hydrodynamical evolution
    - ✓ ***Can be applied to the dense core of the collision***
    - ✓ ***Results in a stronger than linear increase of D-meson yield with multiplicity***

Werner et al., PRC 89 (2014) 064903

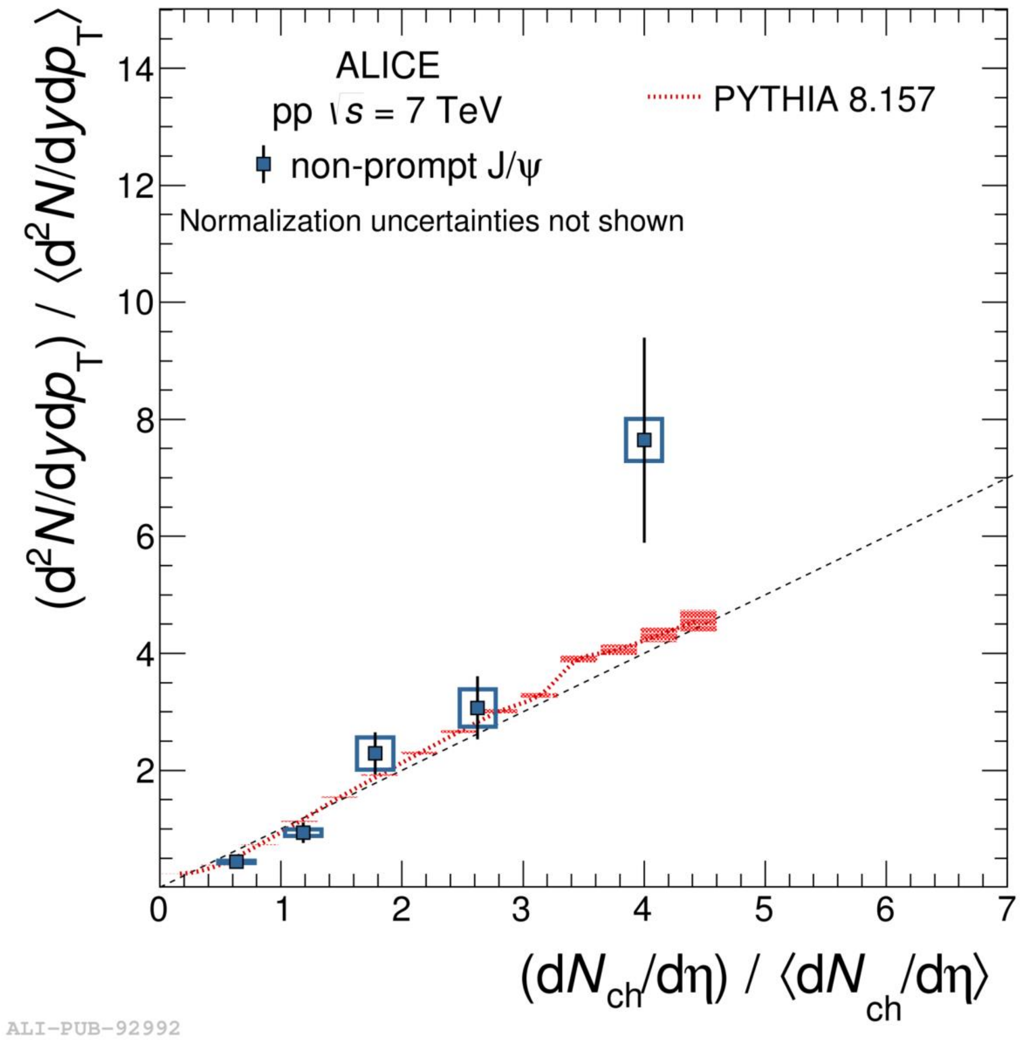
Model calculations

ALICE, arXiv:1505.00664



- PYTHIA 8
  - Soft-QCD tune
  - Colour reconnections
  - Multi-parton interactions
  - Initial and Final state radiation (ISR/FSR)
  - Almost linear increase of D-meson yield with multiplicity
    - ✓ ***Trend depends on p_T***

Non-prompt J/ψ vs. PYTHIA8

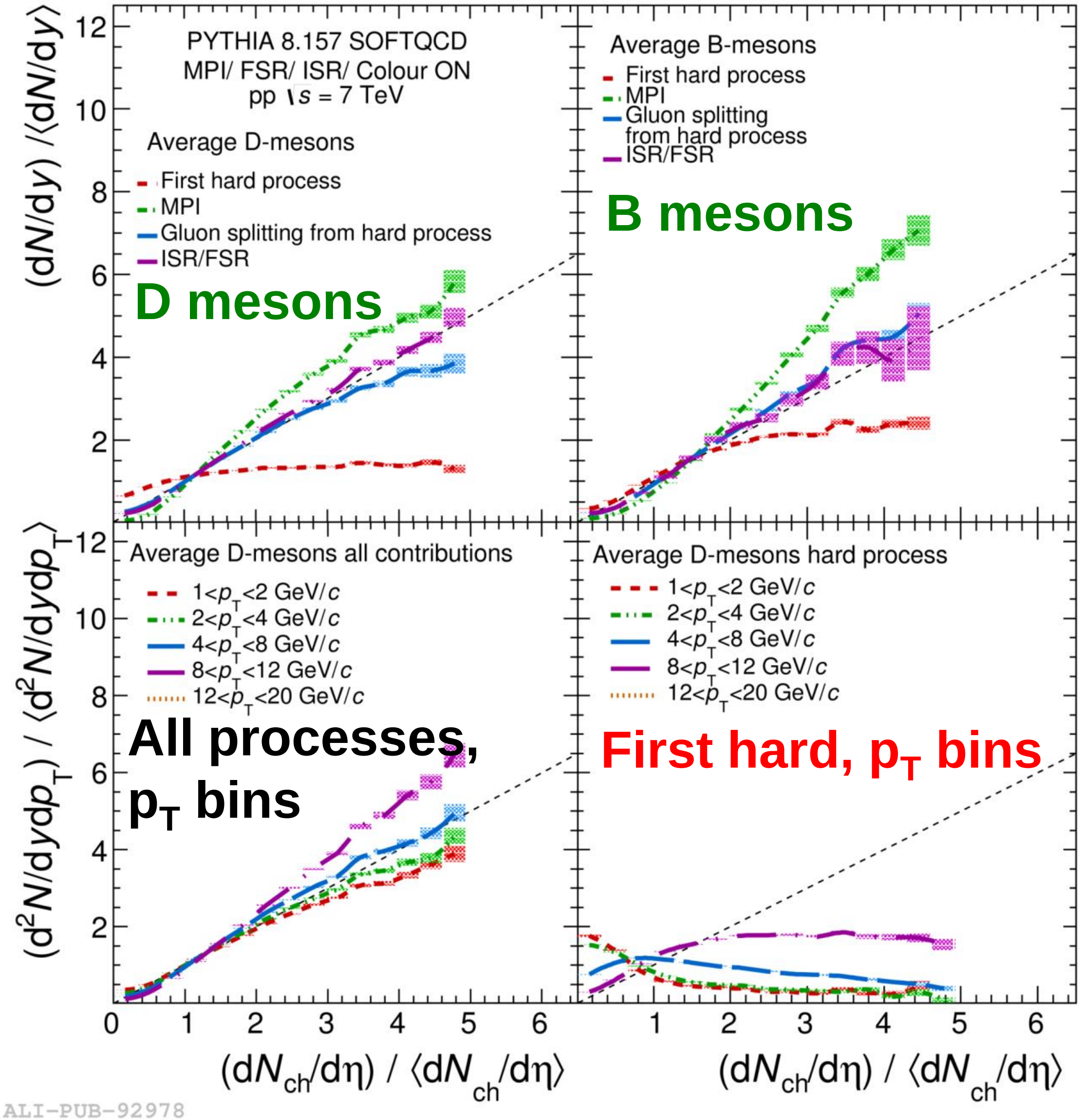


- PYTHIA 8
  - Soft-QCD tune
  - Colour reconnections
  - Multi-parton interactions
  - Initial and Final state radiation (ISR/FSR)
  - Almost linear increase of beauty-hadron yield with multiplicity

ALICE, arXiv:1505.00664

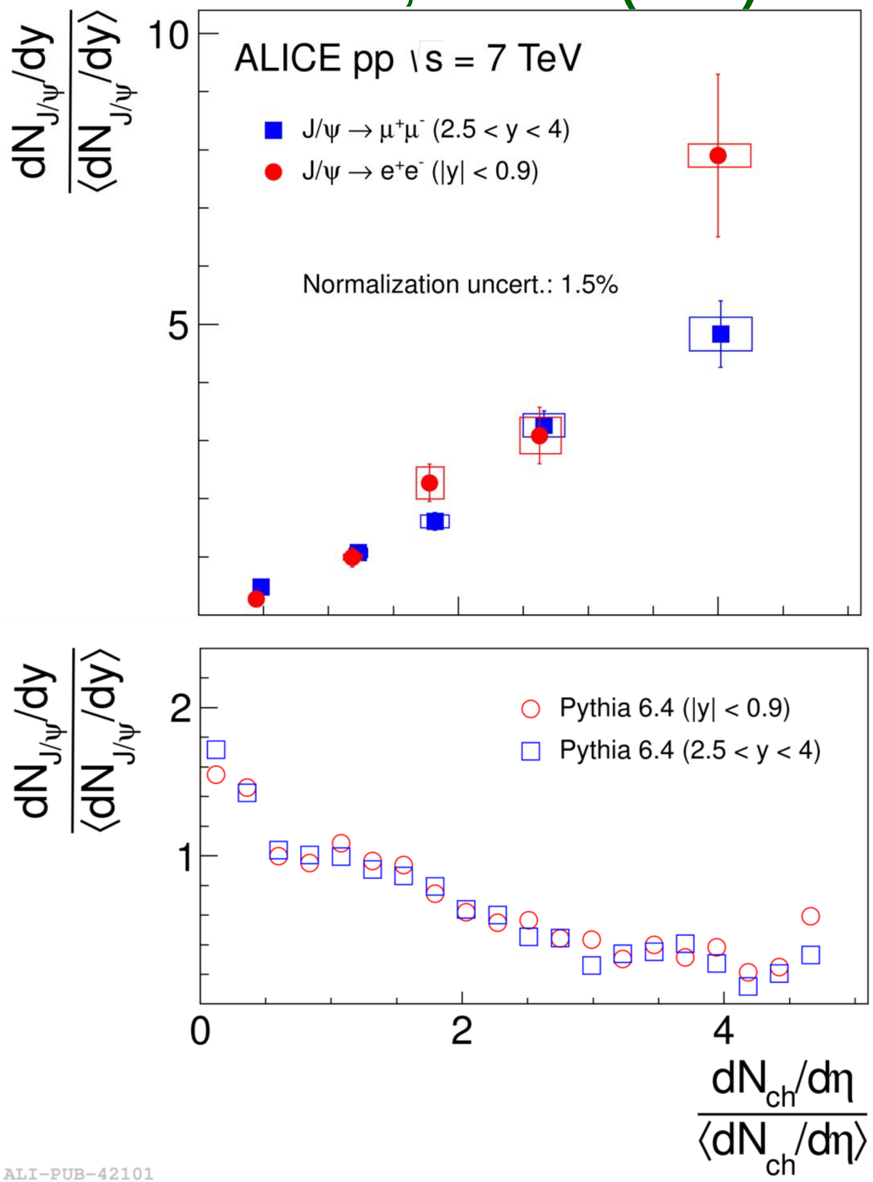
Going deeper into PYTHIA8

- Split by process:
  - First hard = hardest process
    - ✓ *~ flat D-meson yield with multiplicity*
  - MPI = subsequent hard processes
    - ✓ *Increasing D-meson yield with multiplicity*
  - Splitting of a gluon from a hard process
    - ✓ *Increasing D-meson yield with multiplicity*
  - Initial and Final state radiation (ISR/FSR)
    - ✓ *Increasing D-meson yield with multiplicity*



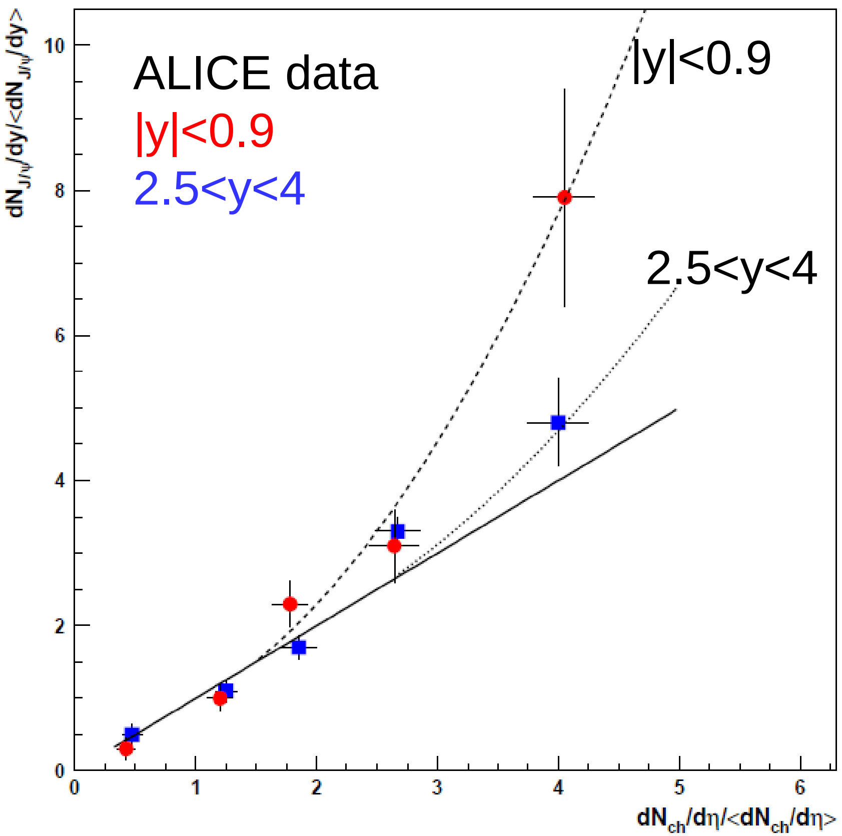
Back to PYTHIA 6 predictions

📖 **ALICE, PLB712 (2012) 165**



- PYTHIA 6.4, Perugia 2011 tune
  - ⇨ Direct J/ψ production only
  - ⇨ MPI without charm production in subsequent interactions
  - ⇨ Fails to reproduce the measured trend
- Improvement of MPI scenario in PYTHIA 8
  - ⇨ Charm produced also in subsequent MPIs

J/ψ results vs. percolation model

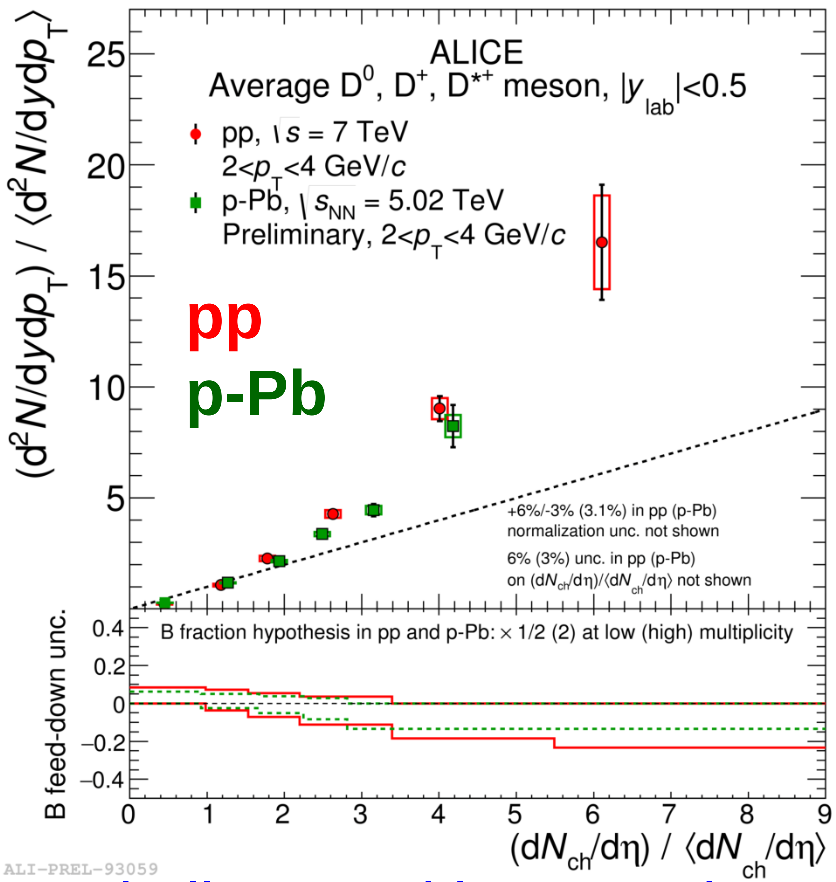


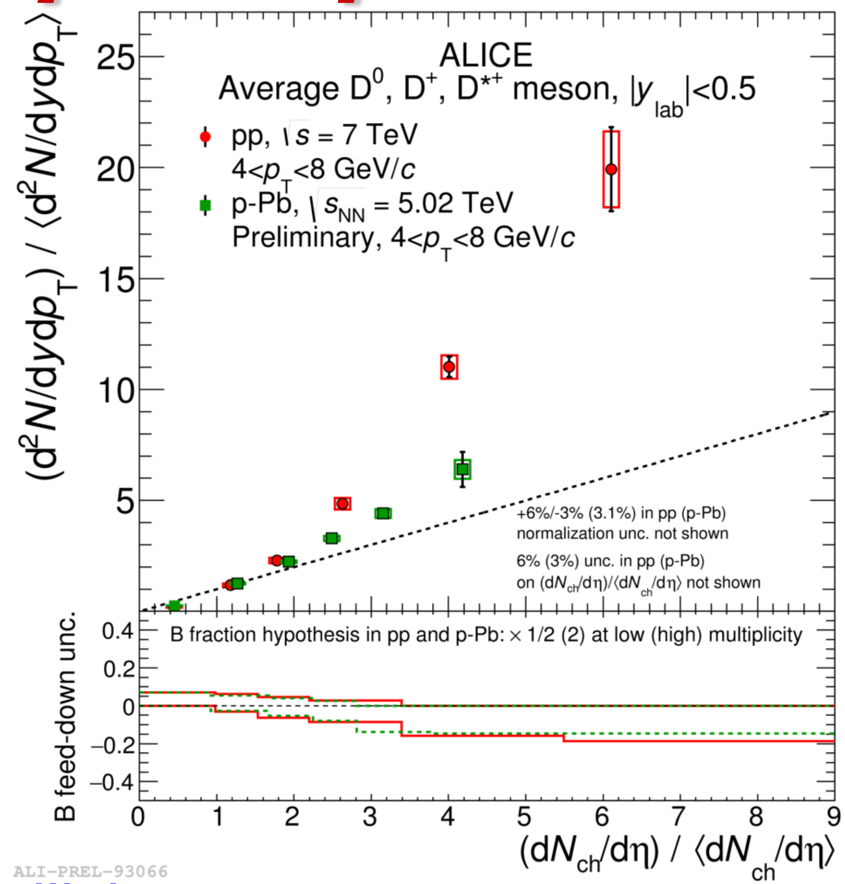
📖 **Ferreiro, Pajares, PRC 86 (2012) 034903**

- Percolation model
  - ⇨ Elementary sources of particle production: colour ropes/strings formed in parton-parton collisions
    - ✓ ***Close to MPI scenario***
  - ⇨ Colour strings have finite spatial extension and interact
    - ✓ ***At high densities: overlap among the sources -> reduction of their number***
    - ✓ ***Affects more soft sources (larger transverse size) and charged multiplicity***
  - ⇨ More than linear increase of J/ψ yield with multiplicity

Comparison to results in p-Pb collisions

D mesons: pp vs. p-Pb

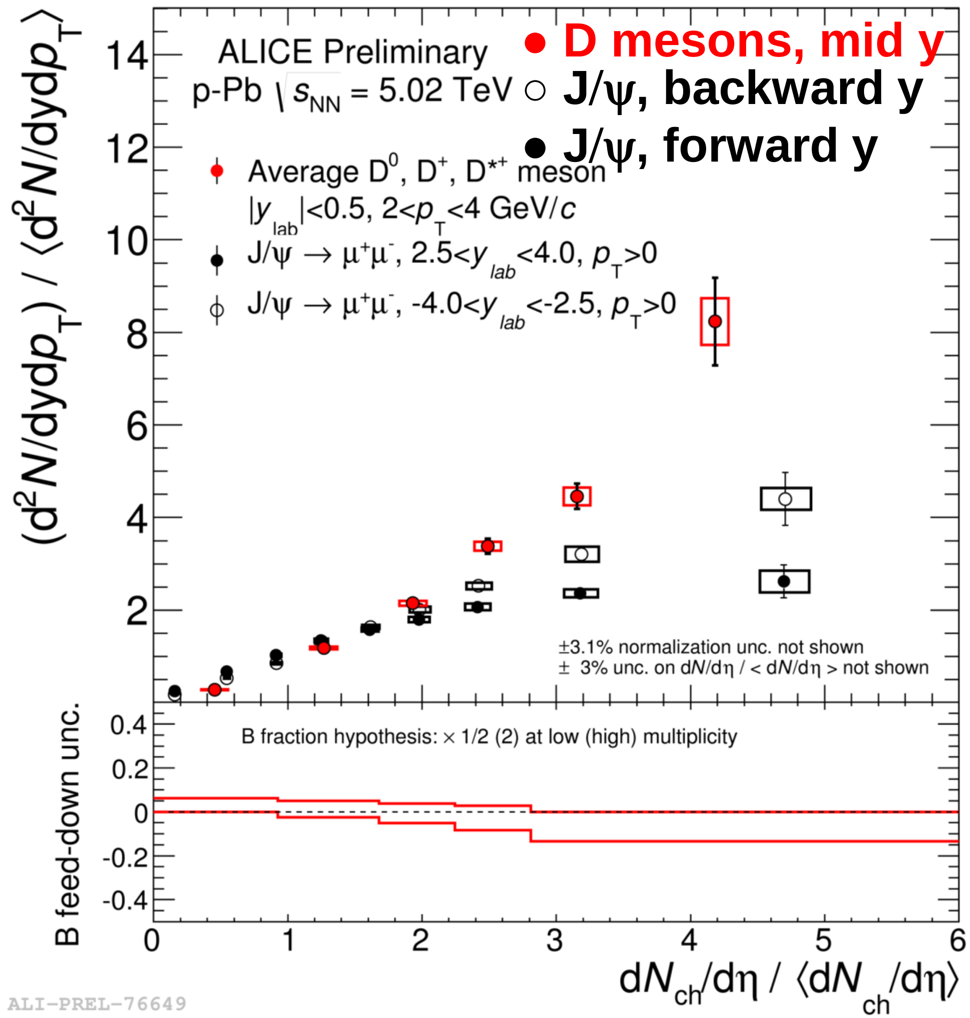




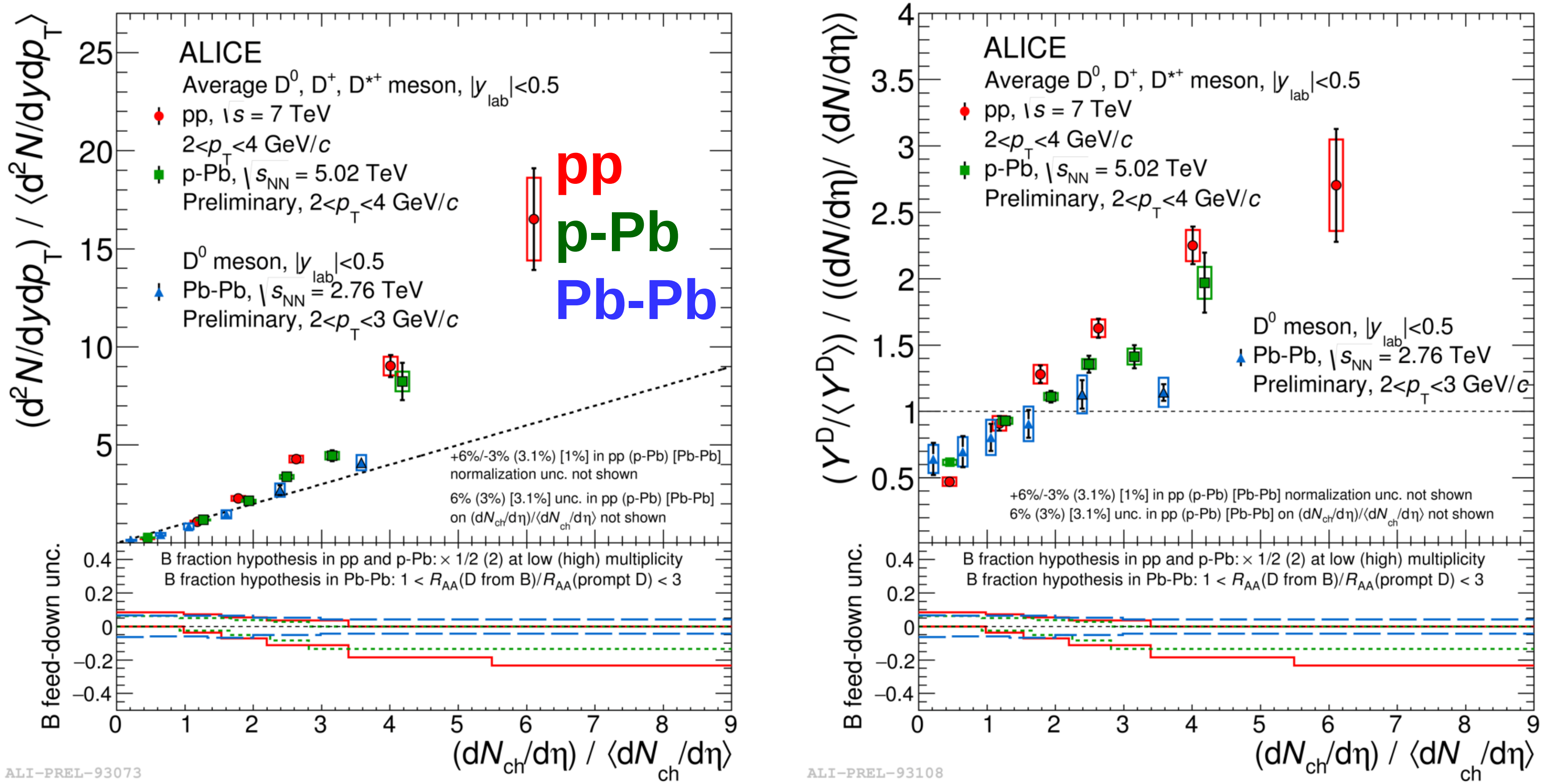
- Similar trend in pp and p-Pb collisions
- Caveat:
  - ⇨ dN/dη~4<dN/dη> in **pp** from many **MPIs** + high number of fragments per parton
  - ⇨ dN/dη~4<dN/dη> in **p-Pb** also from **multiple** (and softer) **nucleon-nucleon collisions**

D mesons and J/ψ in p-Pb

- Similar increasing trend of D and J/ψ yields with multiplicity in p-Pb collisions at low multiplicities
- Deviation at high multiplicities
- NOTE:
  - Different p_T and y ranges for D's and J/ψ
  - Different probed values of Bjorken x
  - Different Cold Nuclear Matter effects



D mesons: pp vs. p-Pb vs. Pb-Pb



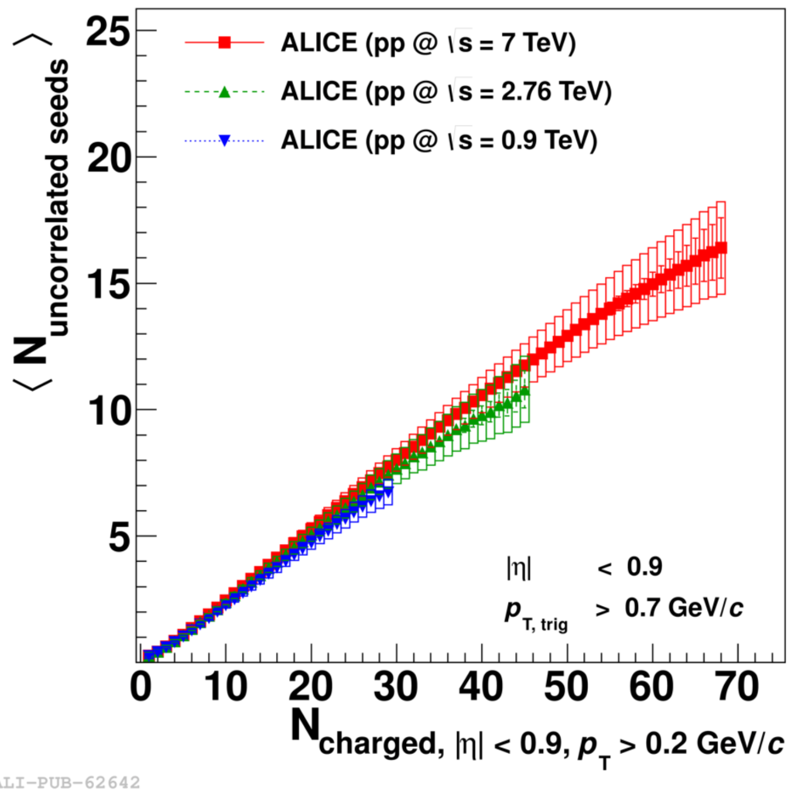
- Comparison to Pb-Pb
  - ⇨ NOTE: in-medium parton energy loss + radial flow modify the p_T distribution of D mesons in a centrality/multiplicity dependent way in Pb-Pb

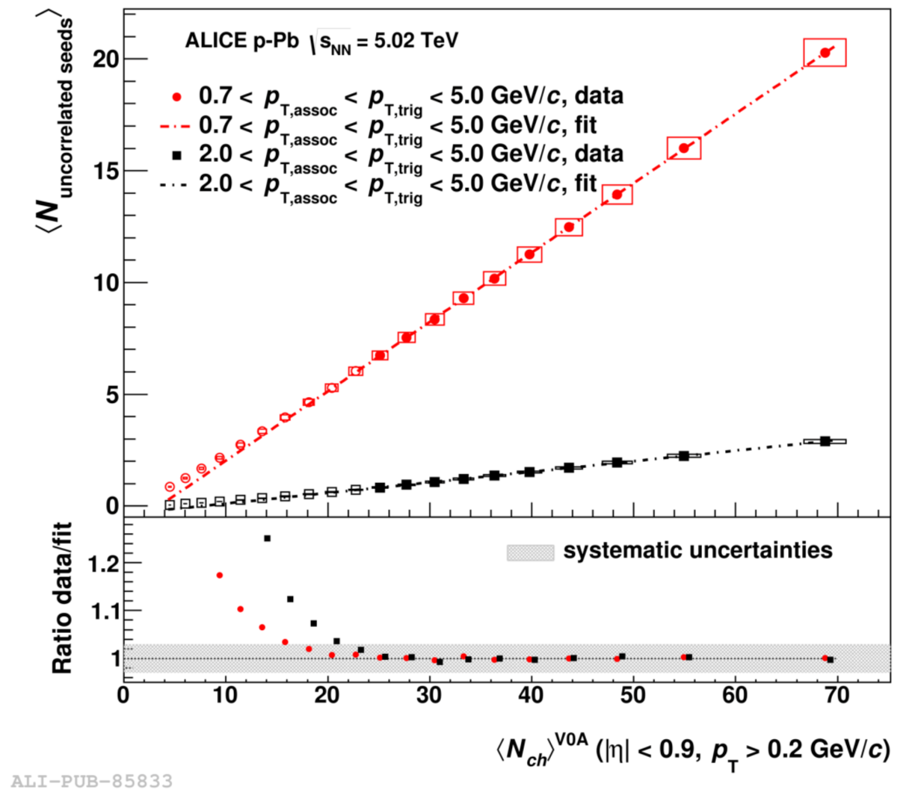
Conclusions

- Heavy-flavour (charm and beauty) hadron yield in pp collisions increases with the multiplicity of charged particles produced in the collision
  - ⇨Similar trend for open charm, charmonium and open beauty
    - ✓ ***Small effect due to hadronization? Trend dictated by charm and beauty quark production mechanism***
  - ⇨Faster than linearly for high multiplicities
  - ⇨No dependence on p_T observed for D mesons within current uncertainties
- Models including MPI can reproduce the observed trend
- Future directions (Run II):
  - ⇨Higher multiplicities and higher $\sqrt{s}$
  - ⇨D mesons in finer p_T intervals
  - ⇨Angular correlations between heavy-flavour particles and hadrons in high-multiplicity events

Backup

Uncorrelated seeds: pp vs. p-Pb

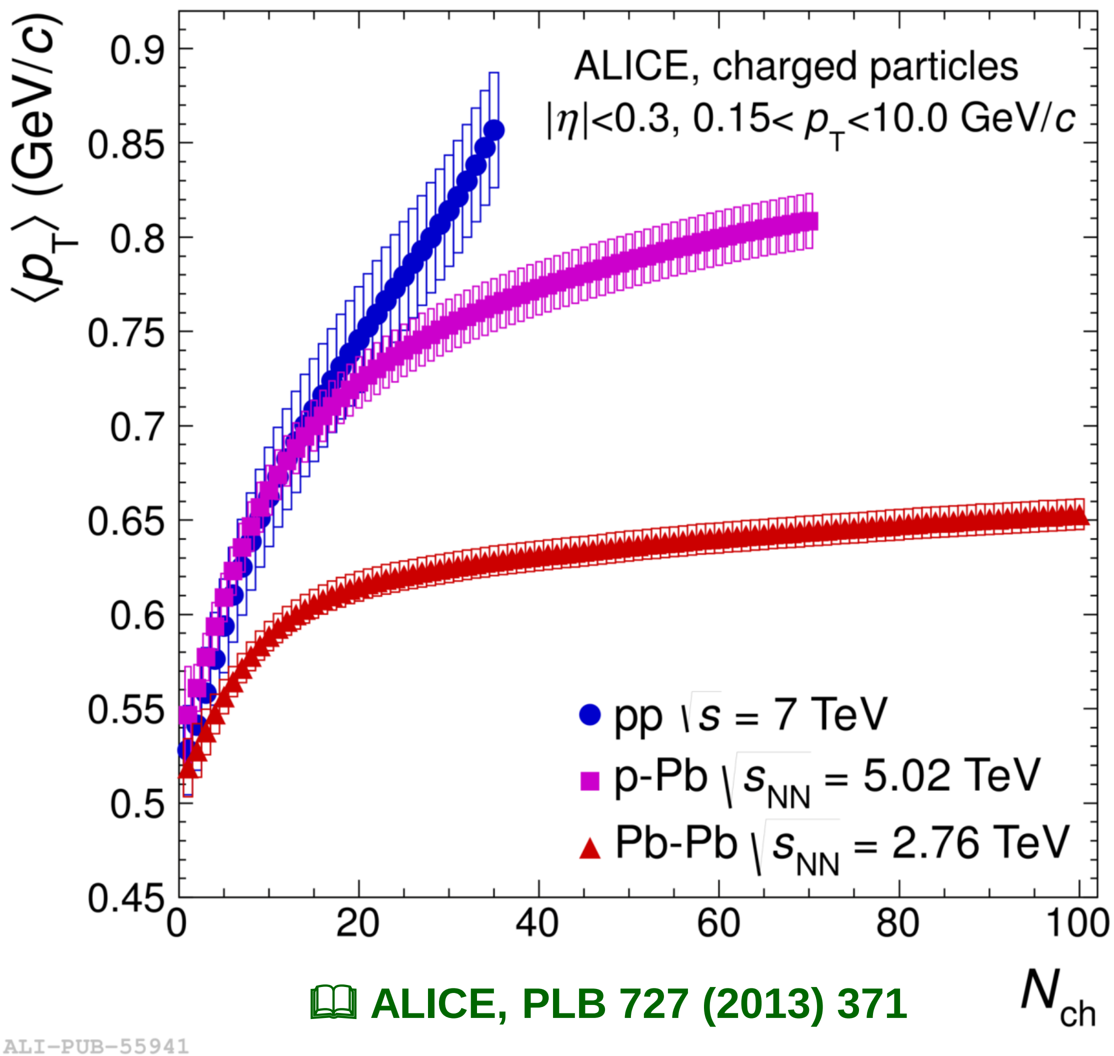




- Number of uncorrelated seeds grows linearly with multiplicity in p-Pb
- Levelling off in pp

ALICE, JHEP 09 (2013) 049

Mean p_T in pp, p-Pb and Pb-Pb



📖 **ALICE, PLB 727 (2013) 371**

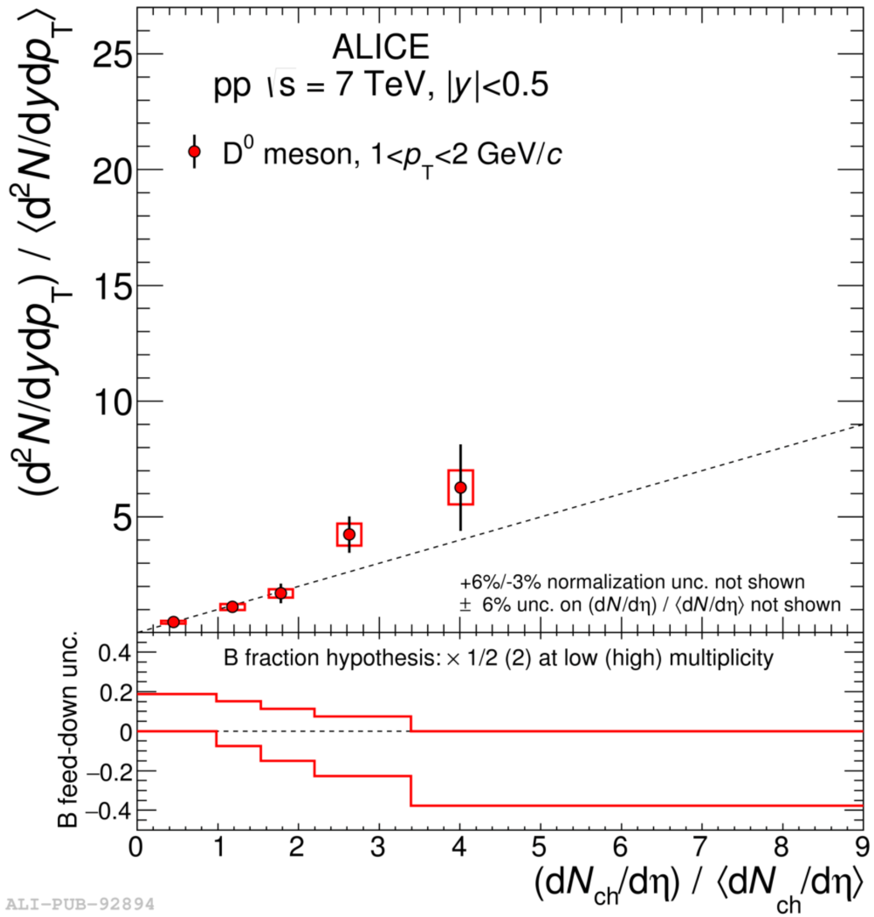
- Three different √s for pp, p-Pb and Pb-Pb
  - ⇨ but √s dependence expected to be weak
- Much stronger increase of <p_T> in p-Pb than in Pb-Pb
- p-Pb follows pp up to N_{ch}~14-15
- N_{ch}>14 corresponds to
  - ⇨ ~10% of pp x-section:
    - ✓ ***pp already highly biased***
  - ⇨ 50% of p-Pb x-section
    - ✓ ***only centrality bias***

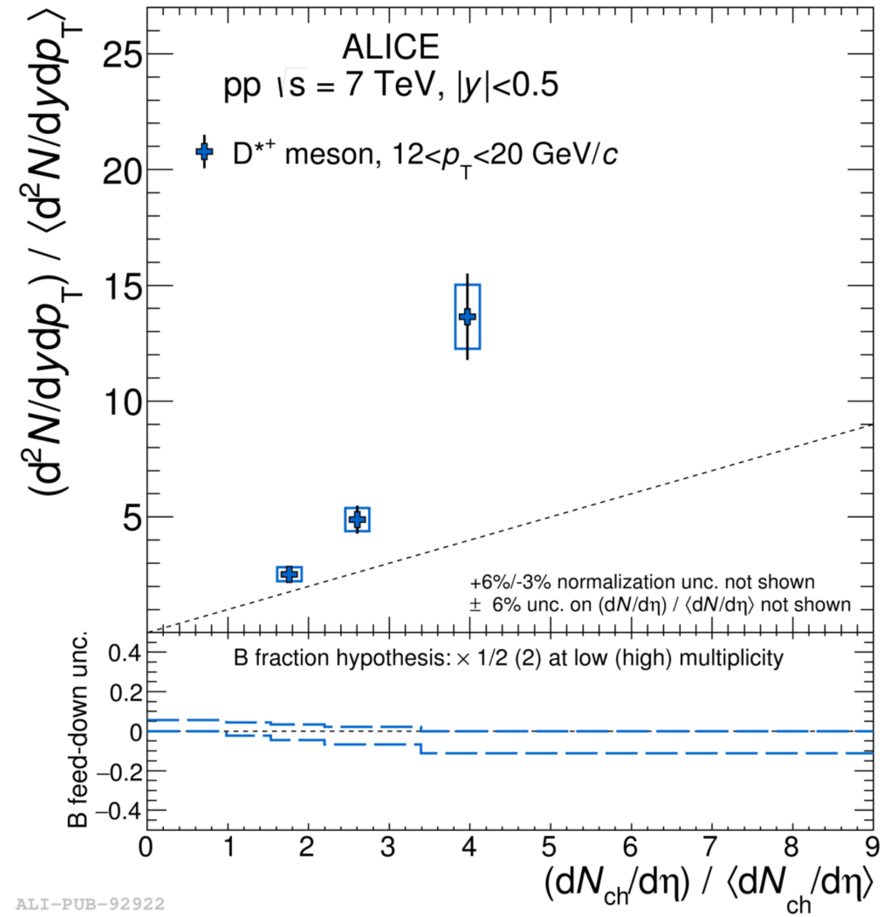
PYTHIA8 – process breakdown

- Relative amount of contributions to HF production in PYTHIA8

Origin of c and b quark content	D mesons	B mesons
First hard process	12%	37%
gluon fusion	3%	15%
c/b sea	9%	22%
Hard process in MPI	22%	23%
Gluon splitting from hard process	6%	included in ISR/FSR
ISR/FSR	60%	40%
Remnant	$< 0.3\%$	$< 0.5\%$

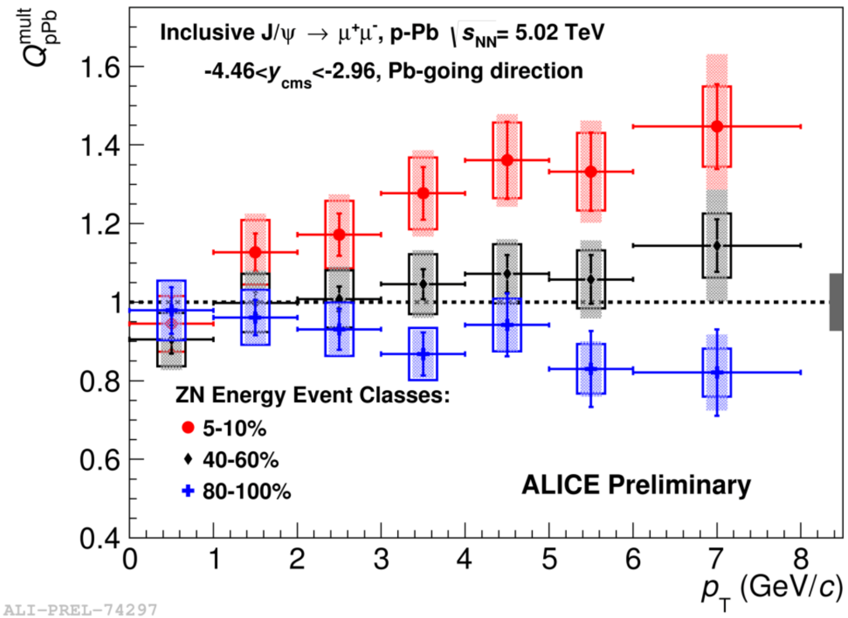
D-mesons, other p_T bins

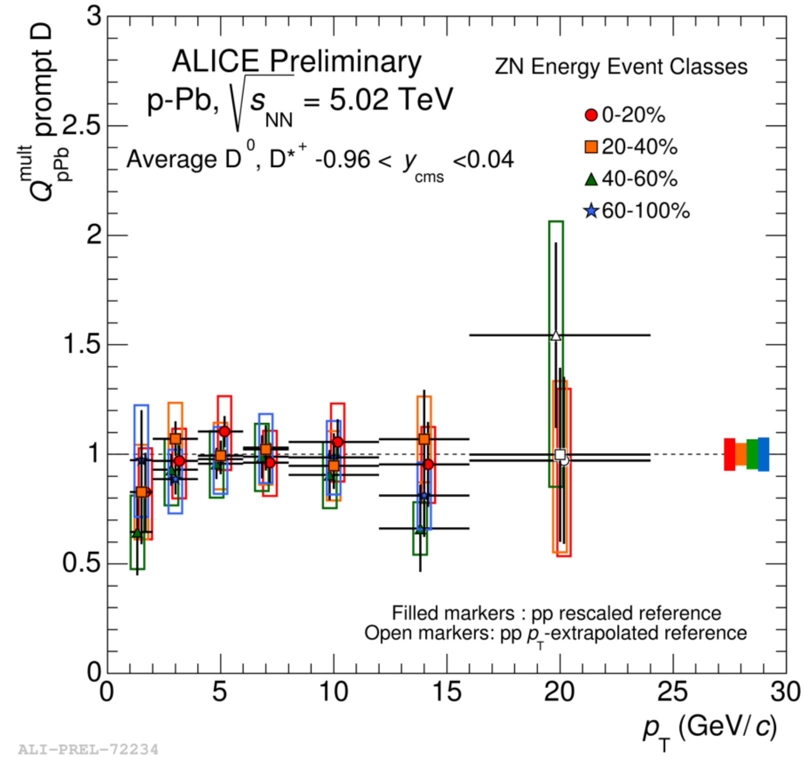


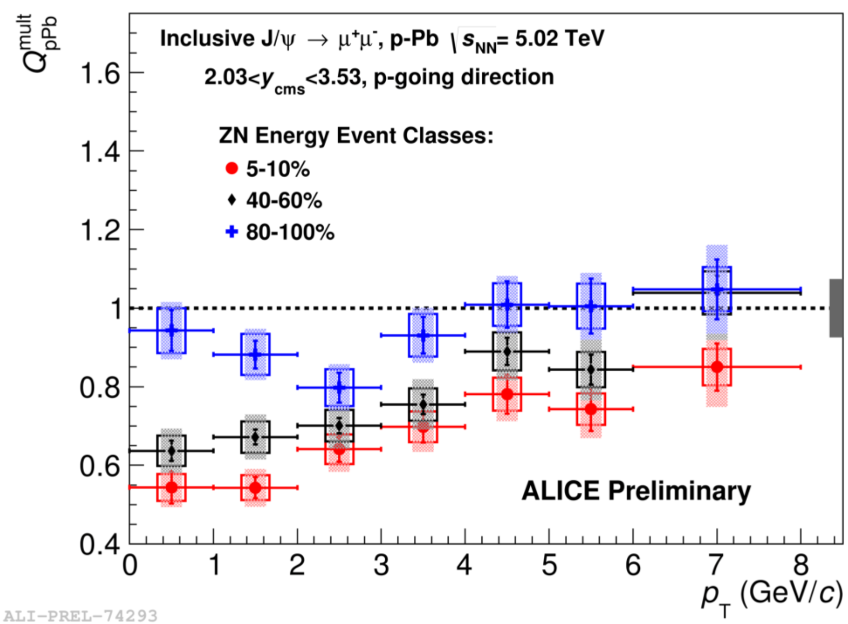


📖 **ALICE, arXiv:1505.00664**

J/ψ and D mesons, p-Pb vs. pp







- No modification of D-meson production in p-Pb compared to pp at mid y at all multiplicities
  - ⇨ R_{pPb} and Q_{pPb} ~ 1
- Multiplicity/centrality dependent modification of J/ψ at forward and backward y
  - ⇨ Cold nuclear matter effects