Quarkonia and open heavy-flavours in high-multiplicity proton-proton collisions with ALICE

F. Fionda[(1)],
on behalf of the ALICE Collaboration

[(1)]University of Bergen, Norway

"Sixth Annual Conference on Large Hadron Collider Physics"
Bologna, 4-10 June 2018

Heavy-flavour production vs multiplicity

- ✔ Heavy-flavour (HF) quarks (charm and beauty) are produced in hard scattering processes
  - ✔ multiplicity dependent production measurements allow to
    → ***study interplay between soft and hard particle production mechanisms***

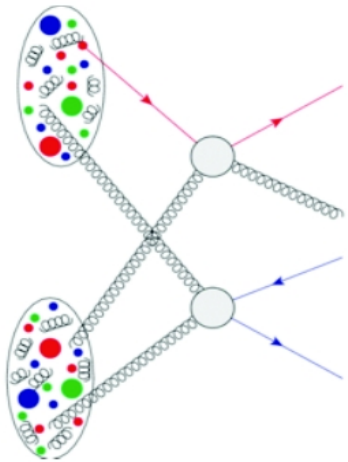
Heavy-flavour production vs multiplicity

- ✔ Heavy-flavour (HF) quarks (charm and beauty) are produced in hard scattering processes
  - ✔ multiplicity dependent production measurements allow to
    study interplay between soft and hard particle production mechanisms

- ✔ Several models that are able to describe qualitatively observed features as a function of multiplicity are based on ***Multiple Parton Interactions (MPI)***

  (1) Initial hard scattering process: ***relevant for HF quarks production***

  (2) Underlying event (UE):
  – semi-hard MPI interactions → **still relevant for *hard processes* at LHC energies !**
  – soft hadronic processes → important for "bulk" particle production (including multiplicity)



shed light on MPI → additional selections (e.g. event shape) and new "observables" (e.g. HF-hadron correlations) provide relevant constraints to MPI-based models

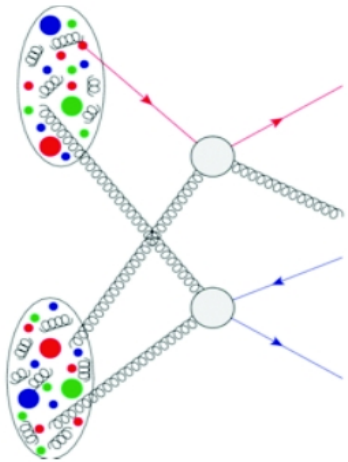
Heavy-flavour production vs multiplicity

- ✔ Heavy-flavour (HF) quarks (charm and beauty) are produced in hard scattering processes
  - ✔ multiplicity dependent production measurements allow to
    study interplay between soft and hard particle production mechanisms

- ✔ Several models that are able to describe qualitatively observed features as a function of multiplicity are based on ***Multiple Parton Interactions (MPI)***

  (1) Initial hard scattering process: ***relevant for HF quarks production***

  (2) Underlying event (UE):
  – semi-hard MPI interactions → **still relevant for *hard processes* at LHC energies !**
  – soft hadronic processes → important for "bulk" particle production (including multiplicity)

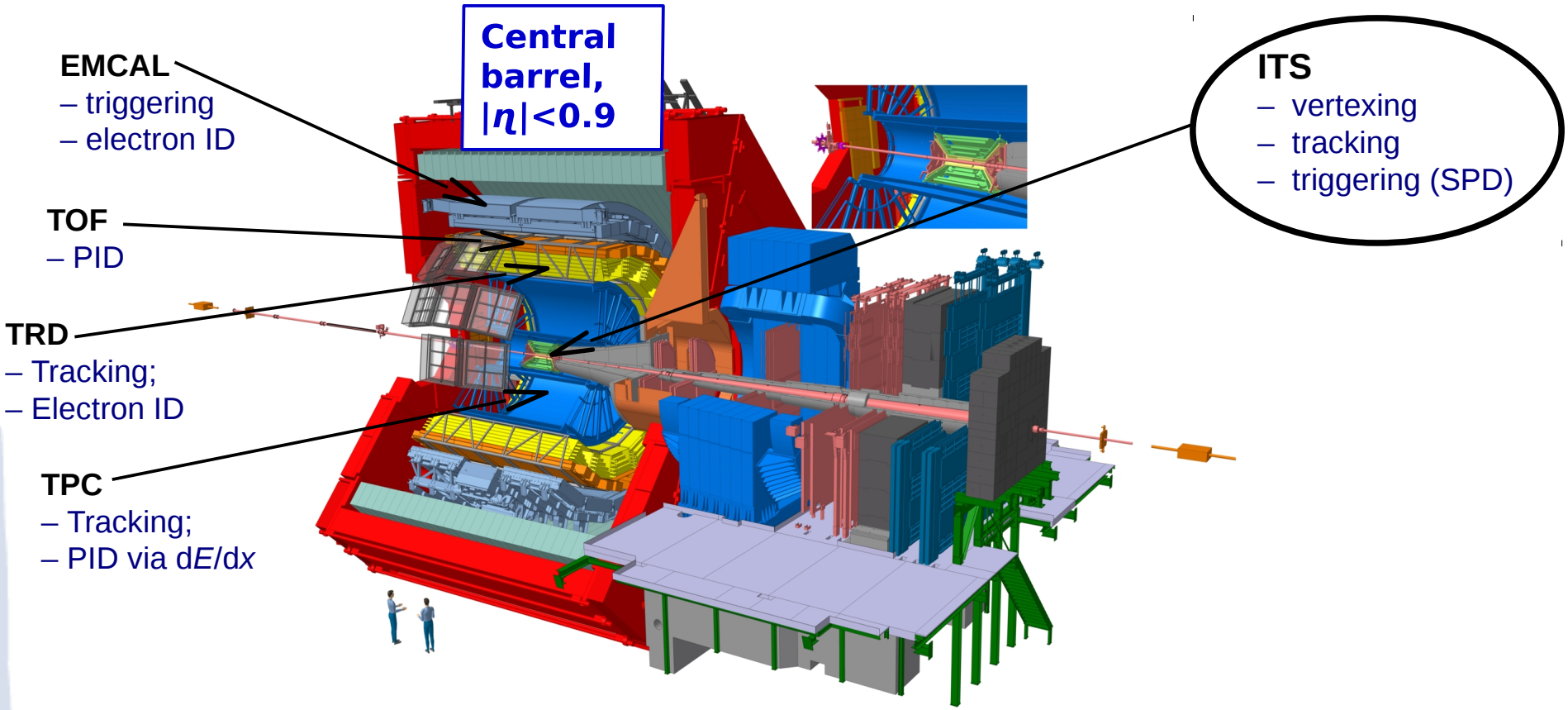


shed light on MPI → additional selections (e.g. event shape) and new "observables" (e.g. HF-hadron correlations) provide relevant constraints to MPI-based models

- ✔ ***Intriguing observation***: multiplicity-dependent studies in small colliding systems show remarkable similarities with AA collisions (e.g. strong hints for collectivity, strangeness enhancement,...)

phenomena considered signatures of deconfinement in heavy-ions observed in high-multiplicity pp !

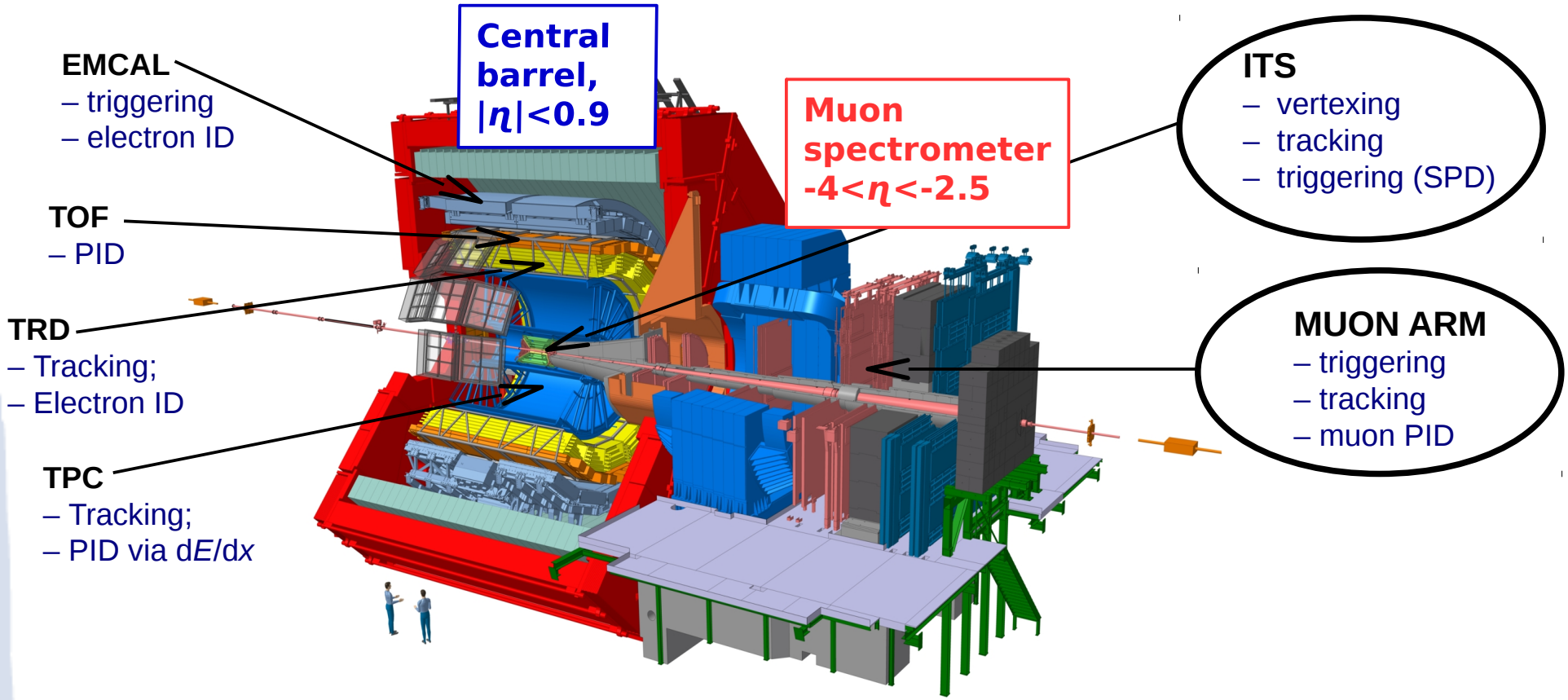
The ALICE detector



✔ Multiplicity dependent heavy-flavour analyses in pp collisions ($\sqrt{s}$ = 5, 7, 8, 13 TeV):

$D^0 \rightarrow K^-\pi^+$ $D^+ \rightarrow K^-\pi^+\pi^+$ $D^{*+} \rightarrow D^0\pi^+$	+	D^0 vs spherocity
$J/\psi \rightarrow e^+e^-$ $B \rightarrow J/\psi \rightarrow e^+e^-$ $c, b \rightarrow e+X$		J/ψ–*h* correlations HF-cross sections from dielectron continuum

The ALICE detector



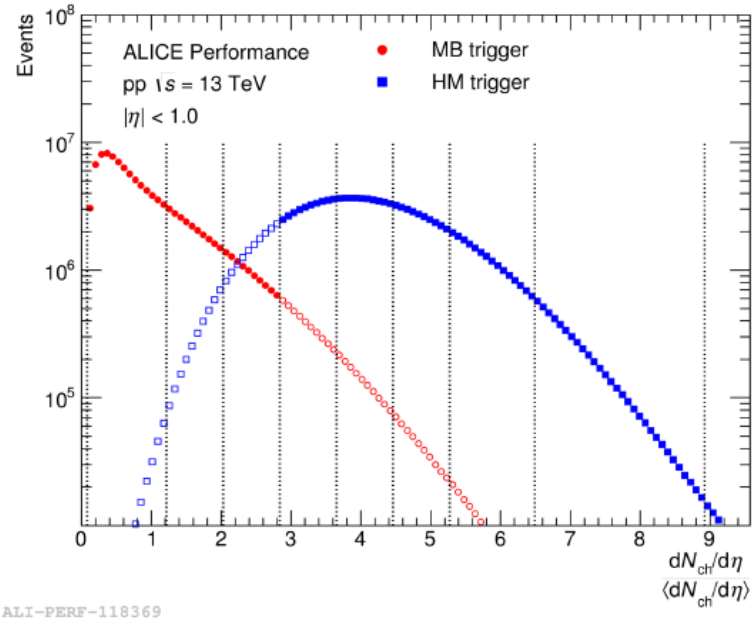
✔ Multiplicity dependent heavy-flavour analyses in pp collisions ($\sqrt{s}$ = 5, 7, 8, 13 TeV):

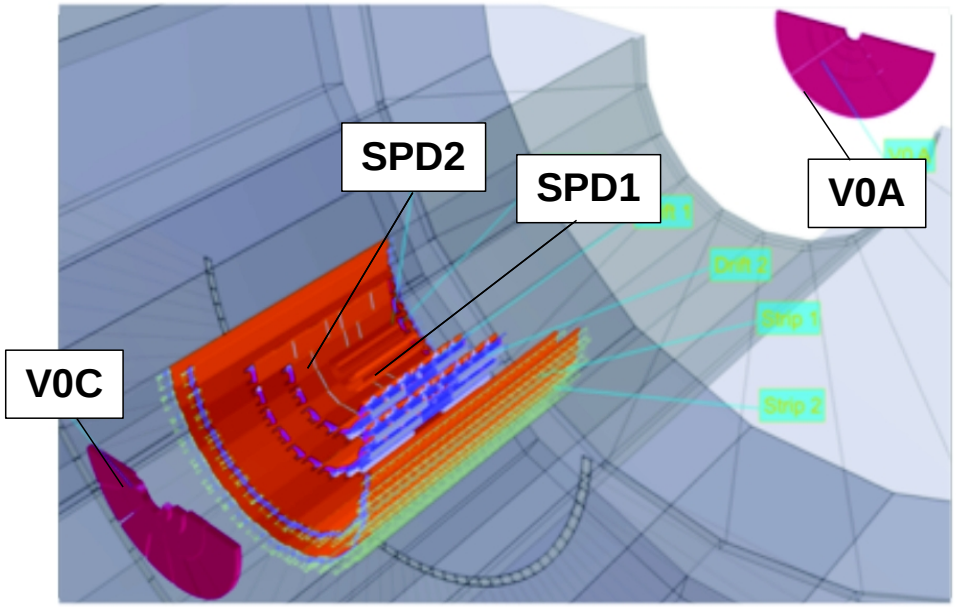
$D^0 \to K^-\pi^+$ $D^+ \to K^-\pi^+\pi^+$ $D^{*+} \to D^0\pi^+$	+	D^0 vs spherocity
$J/\psi \to e^+e^-$ $B \to J/\psi \to e^+e^-$ $c, b \to e+X$		J/ψ–h correlations HF-cross sections from dielectron continuum

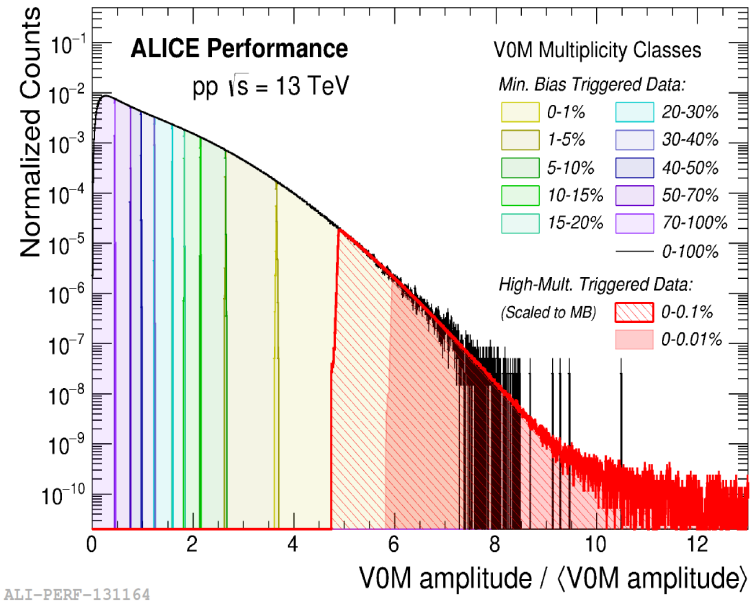
$J/\psi \to \mu^+\mu^-$
$c, b \to \mu+X$

Multiplicity selection

- Multiplicity estimators used to define event classes:
  - **Mid-*y*: number of reconstructed tracklets** in the two innermost layers of the ITS ($|\eta| < 1$), consisting of Silicon Pixel Detectors (**SPD**)
  - **Forward-*y*: percentiles of the V0M amplitude** distribution measured in the V0A+V0C detectors (arrays of scintillators placed on each side of the interaction region, covering the pseudo-rapidity regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$)
    - used for triggering high-multiplicity events in Run II







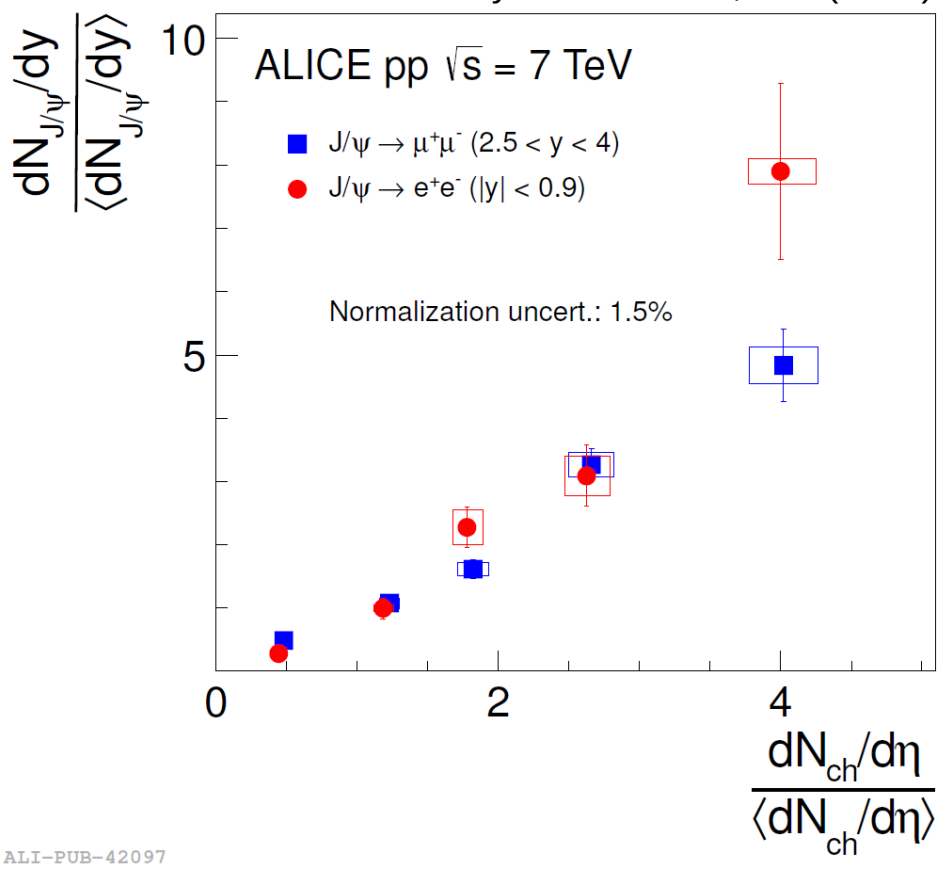
HF-hadron production vs multiplicity

- summary of Run I results
- latest results from Run II

Inclusive J/ψ yields vs multiplicity

RUN I

Phys. Lett. B 712, 165 (2012)

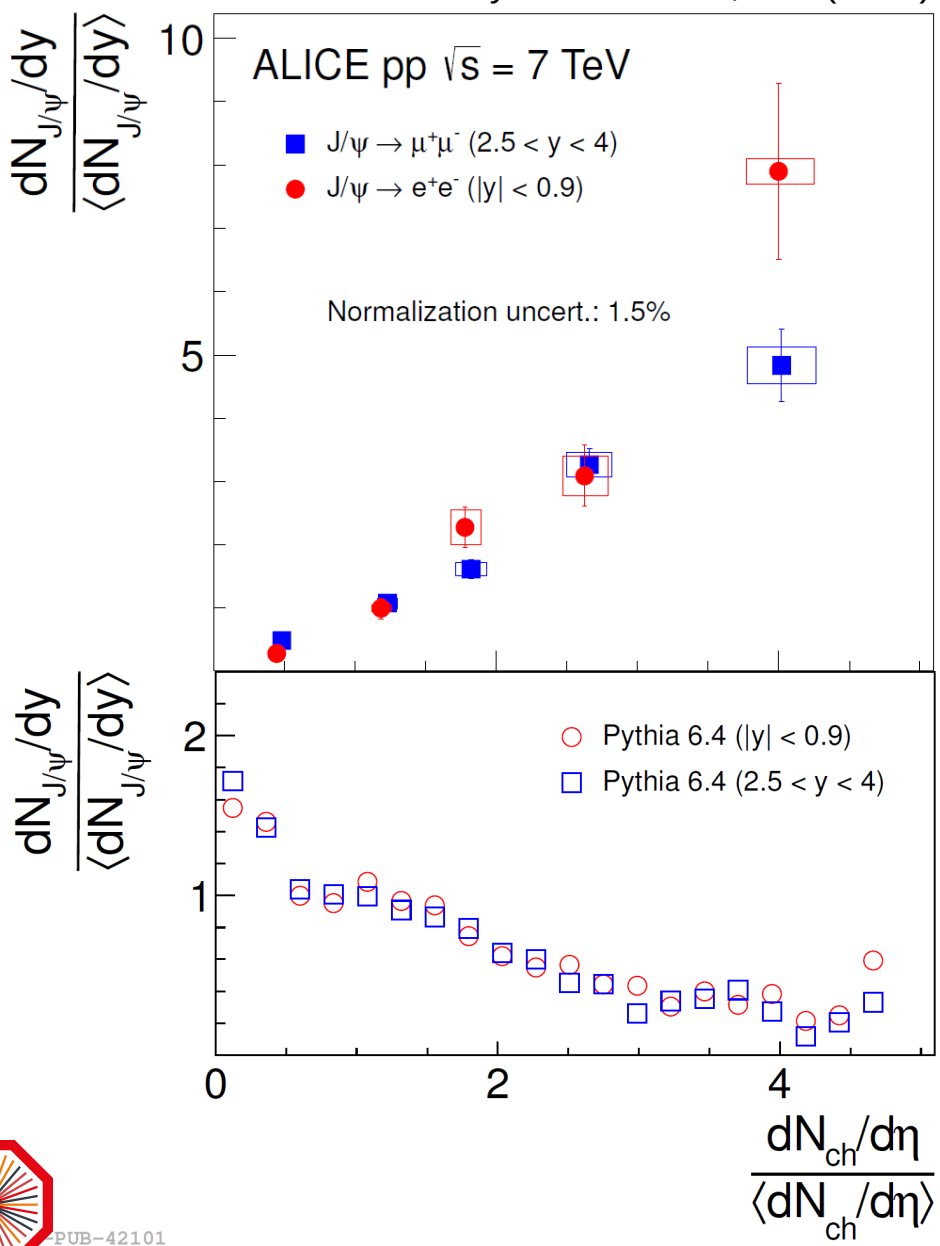


- ✔ Approximately linear increase of J/ψ yield (p_T>0 GeV/c) with charged-particle density
- ✔ Multiplicity dependent measurements of J/ψ extended up to **4 times** the minimum-bias multiplicity

Inclusive J/ψ yields vs multiplicity

RUN I

Phys. Lett. B 712, 165 (2012)

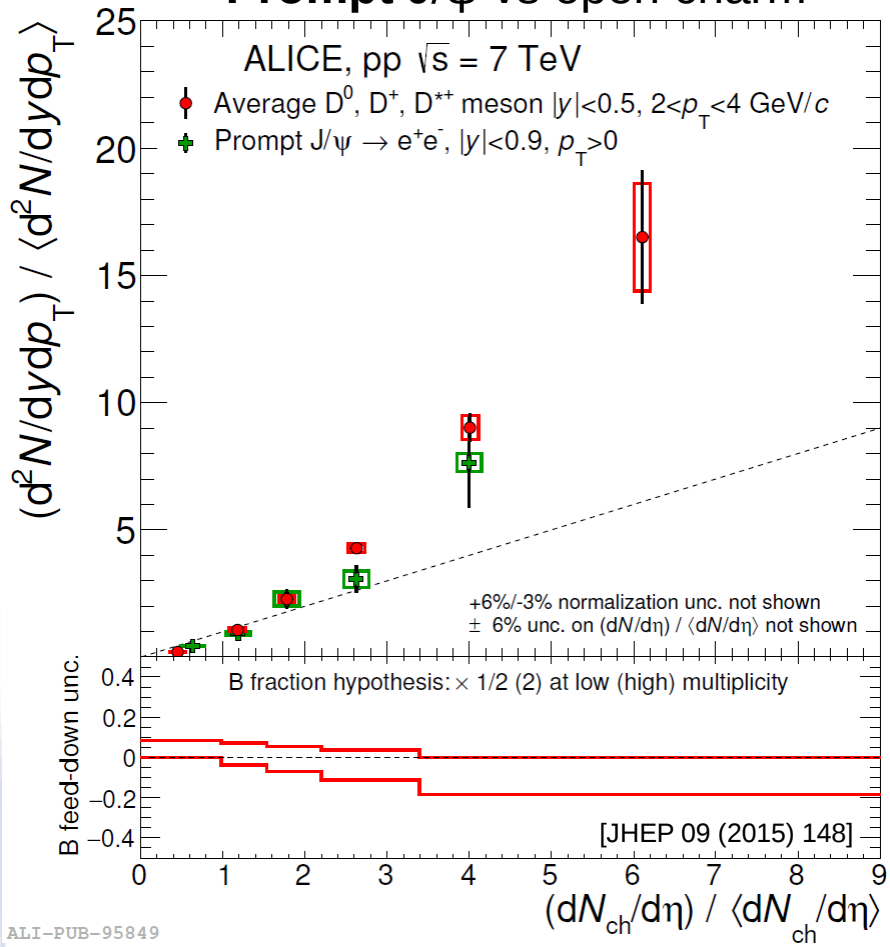


- Approximately linear increase of J/ψ yield (p_T>0 GeV/c) with charged-particle density
- Multiplicity dependent measurements of J/ψ extended up to **4 times** the minimum-bias multiplicity
- Relative yields versus multiplicity not reproduced by PYTHIA 6.4 simulations (J/ψ produced only in the main hard scattering)

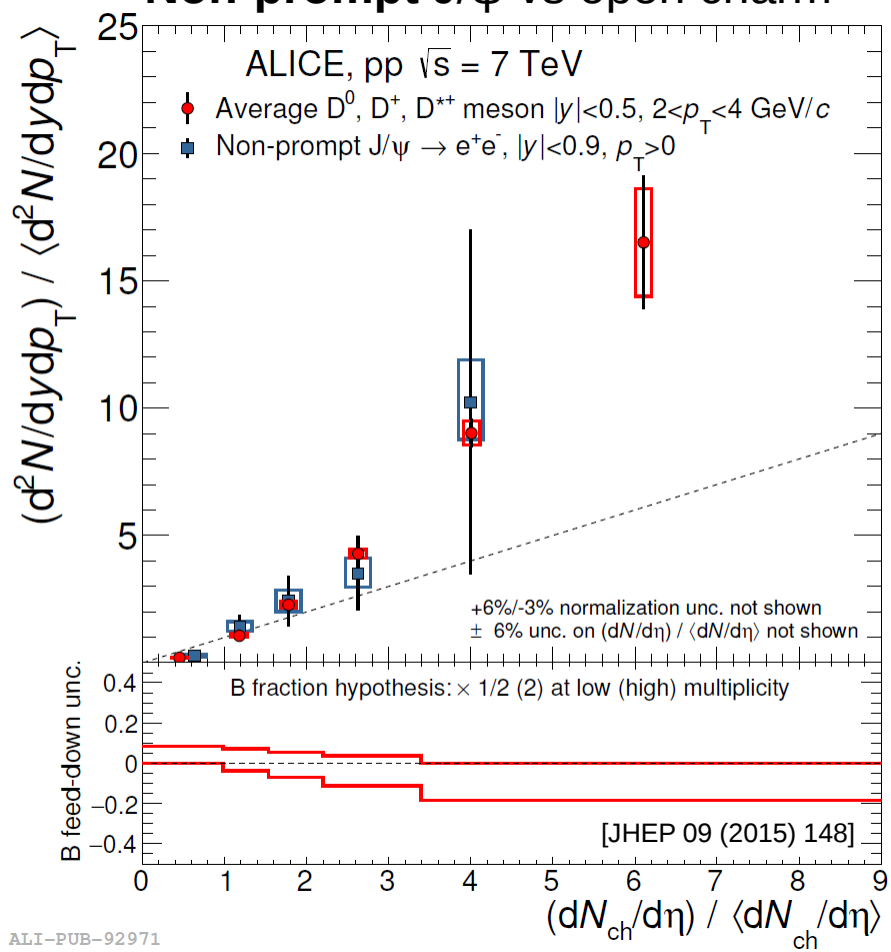
Comparison of (non-)prompt J/ψ with open charm

RUN I

Prompt J/ψ vs open charm



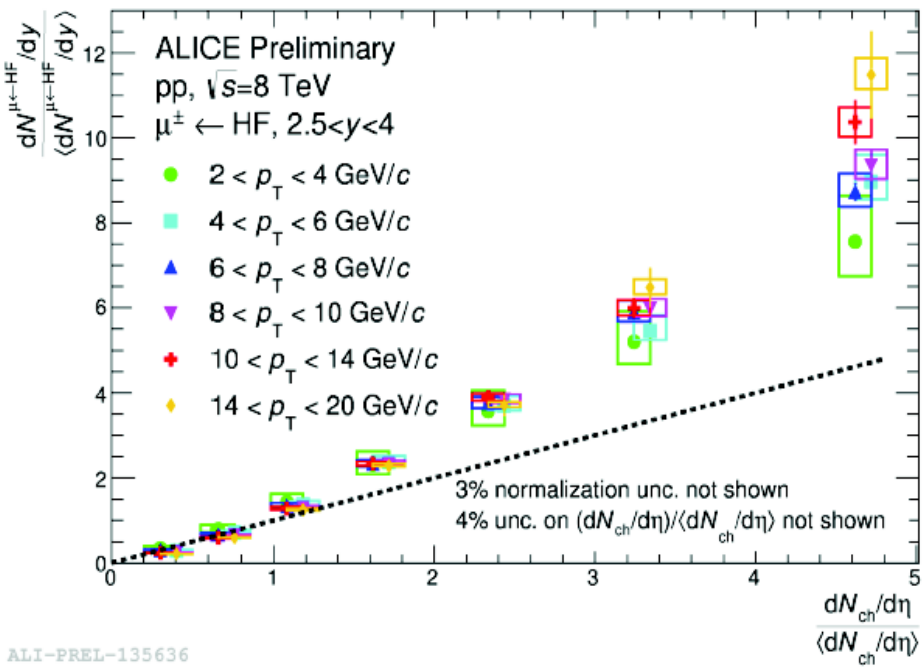
Non-prompt J/ψ vs open charm

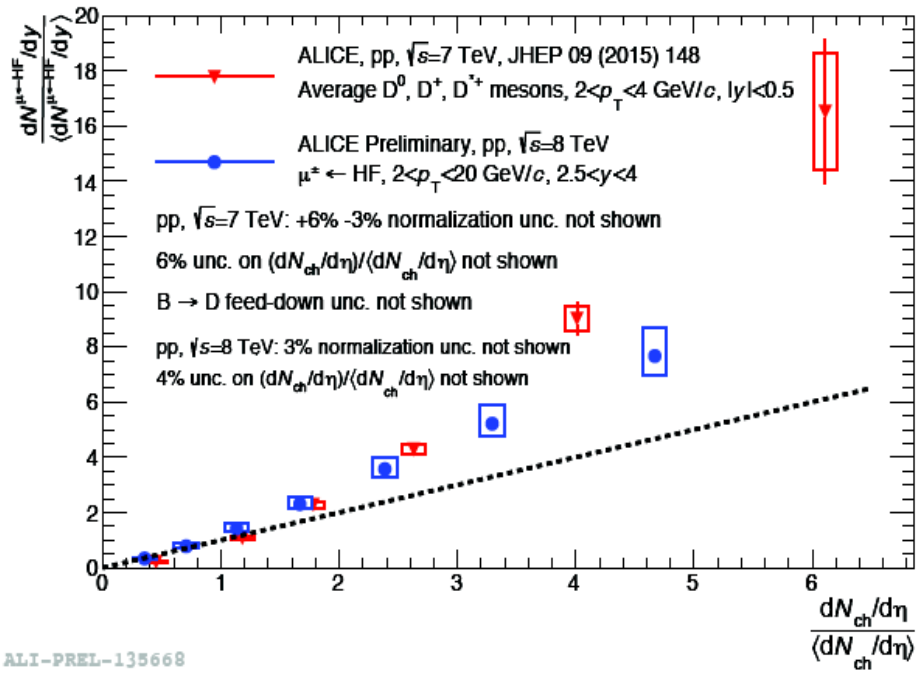


- ✔ Similar trend for prompt J/ψ and open charm → suggests that it is mainly related to the $c\bar{c}$ production processes and it's not significantly affected by hadronization
- ✔ Similar trend for open charm and beauty, but larger statistical uncertainties for the latter → significant improvement expected using Run II data !

HF decay muon production vs multiplicity

RUN I

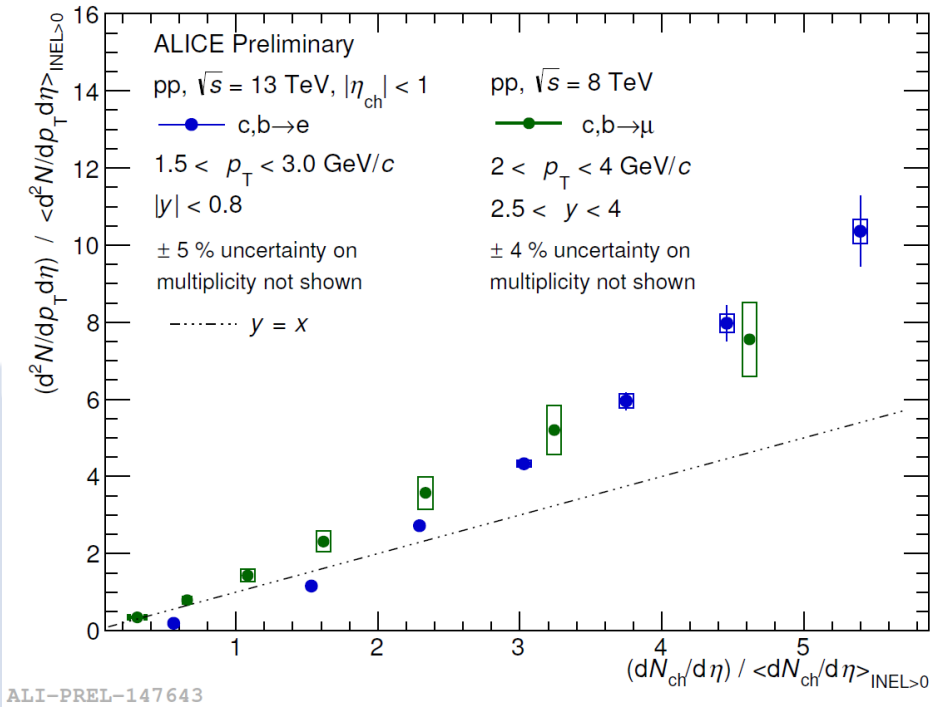


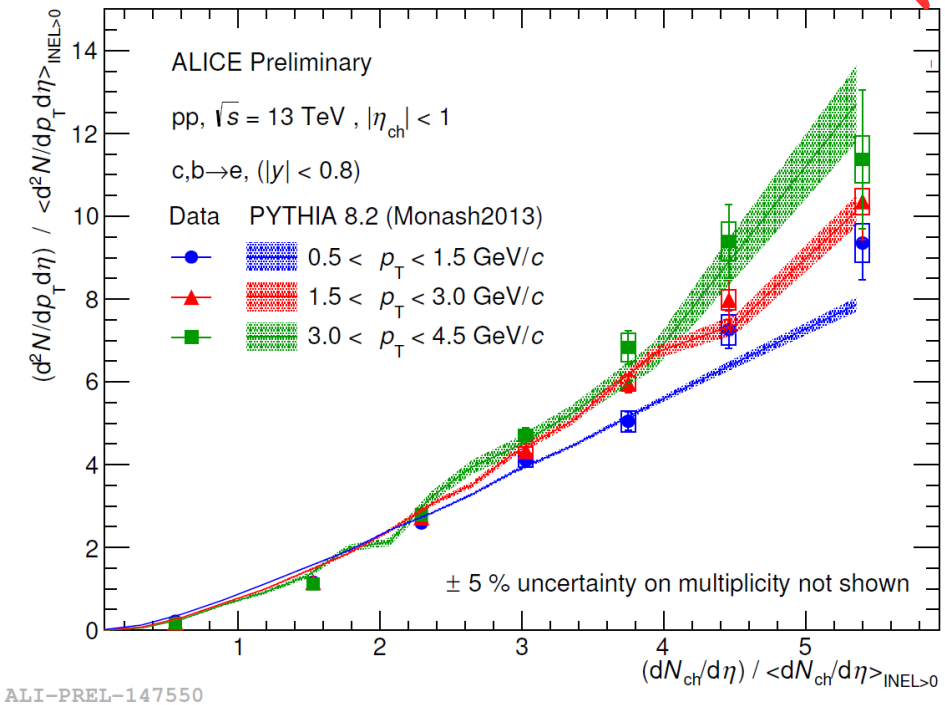


- ✔ HF decay muons reconstructed at forward rapidity show faster than linear increase vs multiplicity
- ✔ Steepness more pronounced at high p_T (not possible to conclude due to large uncertainties)
- ✔ Future D meson measurements may clarify whether D mesons at mid-rapidity have a stronger increase than HF decay muons in $2.5 < y < 4$
  - ✔ possible “auto-correlation” effects due to the overlapping between pseudo-rapidity regions of HF measurements and multiplicity estimator

HF decay electron production vs multiplicity

Run II



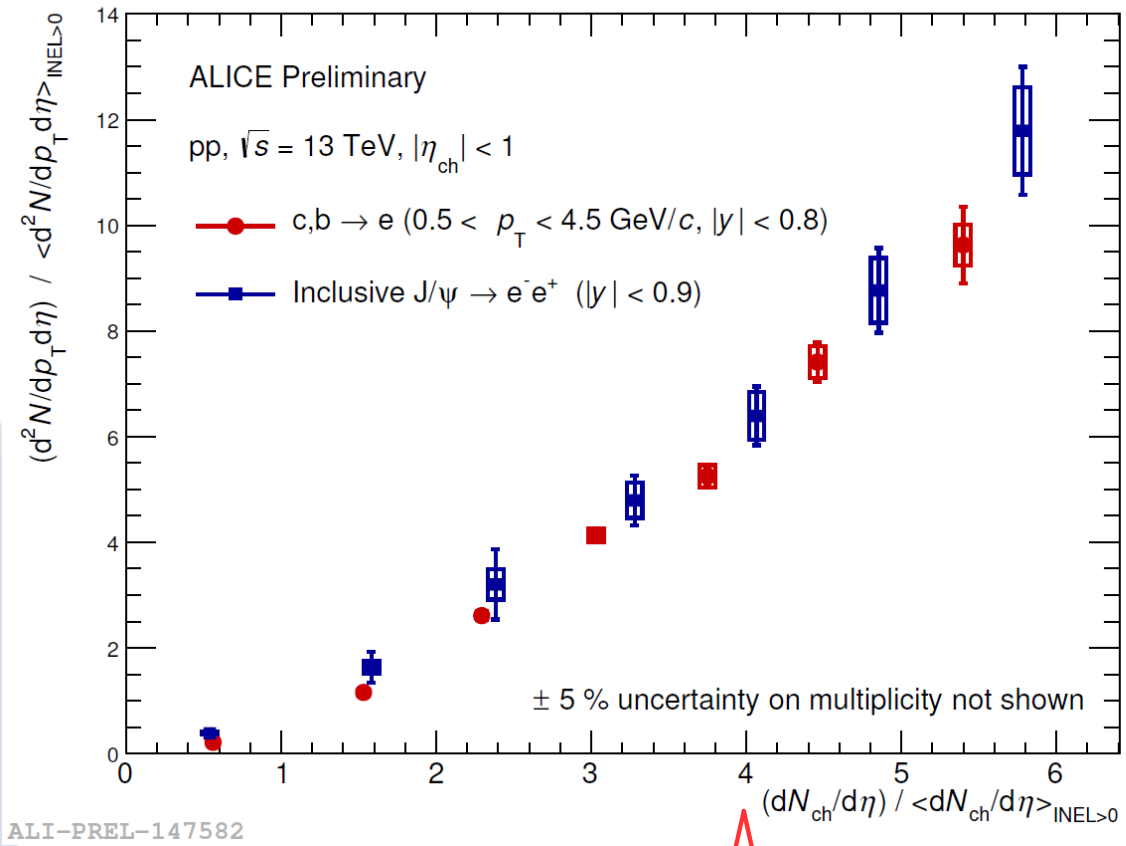


- ✔ Faster than linear trend observed also for HF decay electrons
- ✔ Different trend, especially at low multiplicity, compared to HF decay muons → possible "auto-correlation" effects ?

- ✔ Faster increase observed at high p_T
- ✔ Fair agreement with PYTHIA 8.2 (Monash2013 tune)

Inclusive J/ψ yields vs multiplicity in pp at √s = 13 TeV

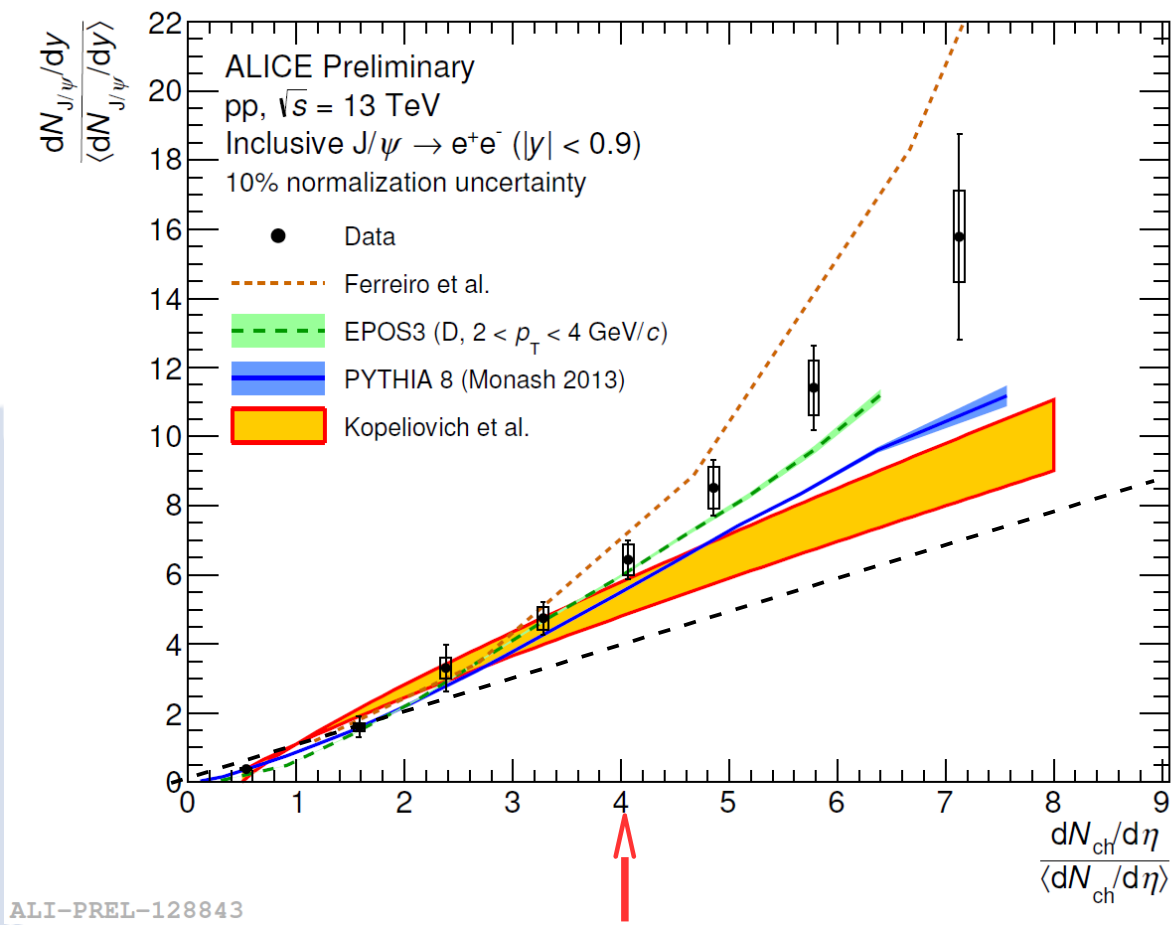
Run II



RUN I mult. reach for J/ψ

- ✔ Significantly higher multiplicities exploited thanks to high-multiplicity triggered data!
- ✔ Very similar trend observed for open and hidden HF measurements → confirmation of Run I results

Inclusive J/ψ yields vs multiplicity in pp at √s = 13 TeV



RUN I mult. reach for J/ψ

- ✔ Significantly higher multiplicities exploited thanks to high-multiplicity triggered data!
- ✔ Very similar trend observed for open and hidden HF measurements → confirmation of Run I results

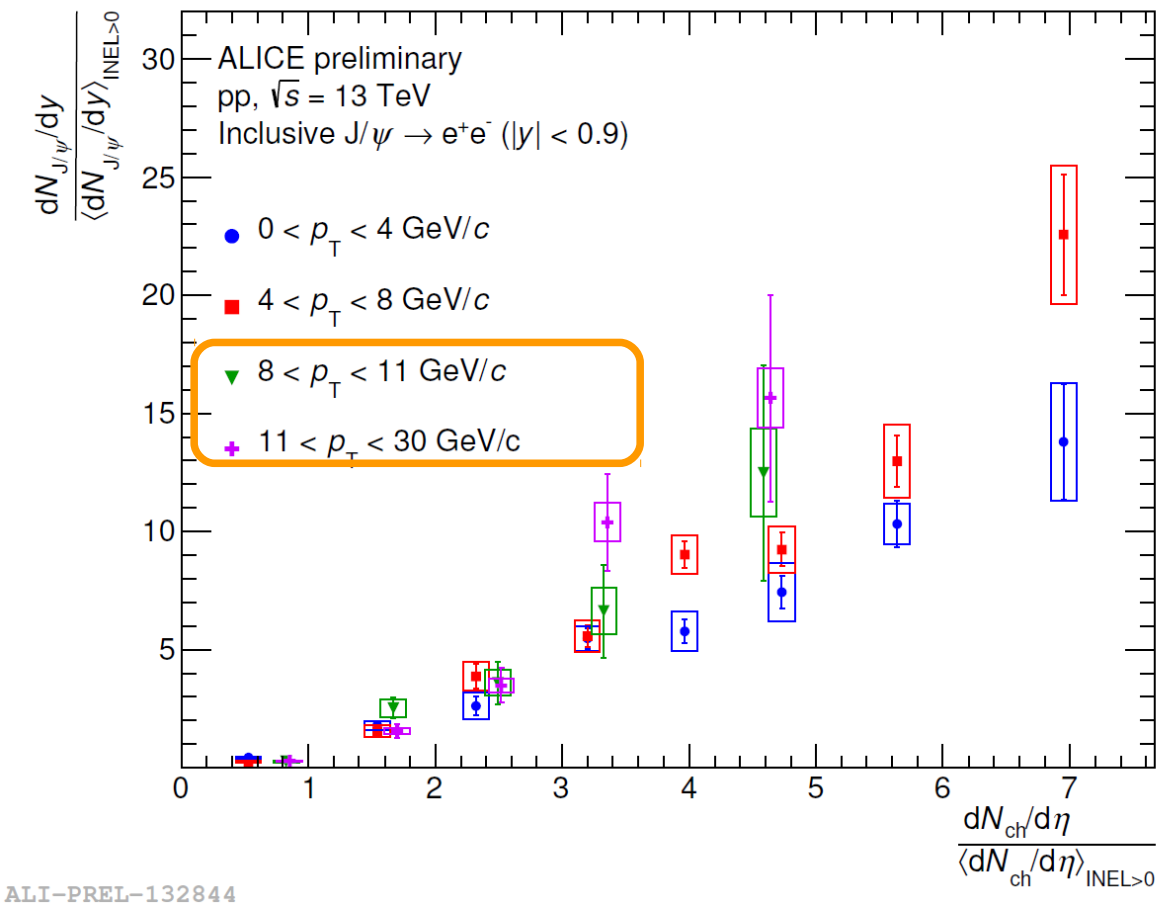
Run II

- ✔ **PYTHIA8 (Monash 2013)**
  - ✔ Initial hard processes
  - ✔ Hard processes in MPI
  - ✔ ISR / FSR
- ✔ **EPOS3**
  - ✔ Gribov-Regge formalism (MPI included)
  - ✔ Hydro evolution of the system
- ✔ **Kopeliovich et al.**
  - ✔ contributions of higher Fock states
- ✔ **Percolation model**
  - ✔ Soft sources stronger affected than hard sources with increasing density (multiplicity)

Ferreiro, Pajares, PRC86 (2012) 034903
EPOS3, Werner et al., Phys.Rept.350 (2001) 93
PYTHIA8, Sjostrand et al., Comput.Phys.Comm.178(2008)
Kopeliovich et al., PRD88 (2013) 116002

Inclusive J/ψ yields vs multiplicity in pp at √s = 13 TeV

Run II

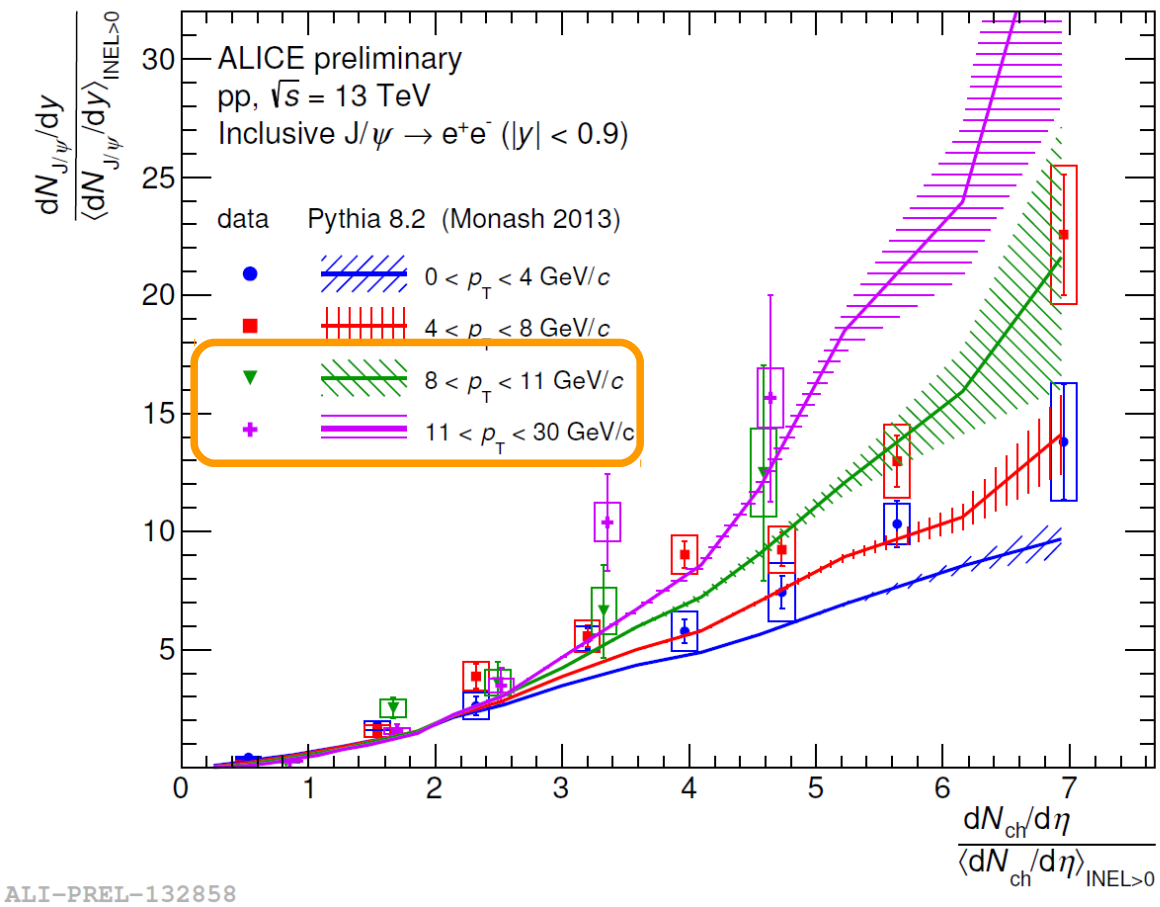


- ✔ **EMCAL** analysis significantly extends the p_T range (up to 30 GeV/*c*)

- ✔ Faster than linear increase observed also in p_T bins
- ✔ Slope increases with the transverse momentum of J/ψ

Inclusive J/ψ yields vs multiplicity in pp at √s = 13 TeV

Run II

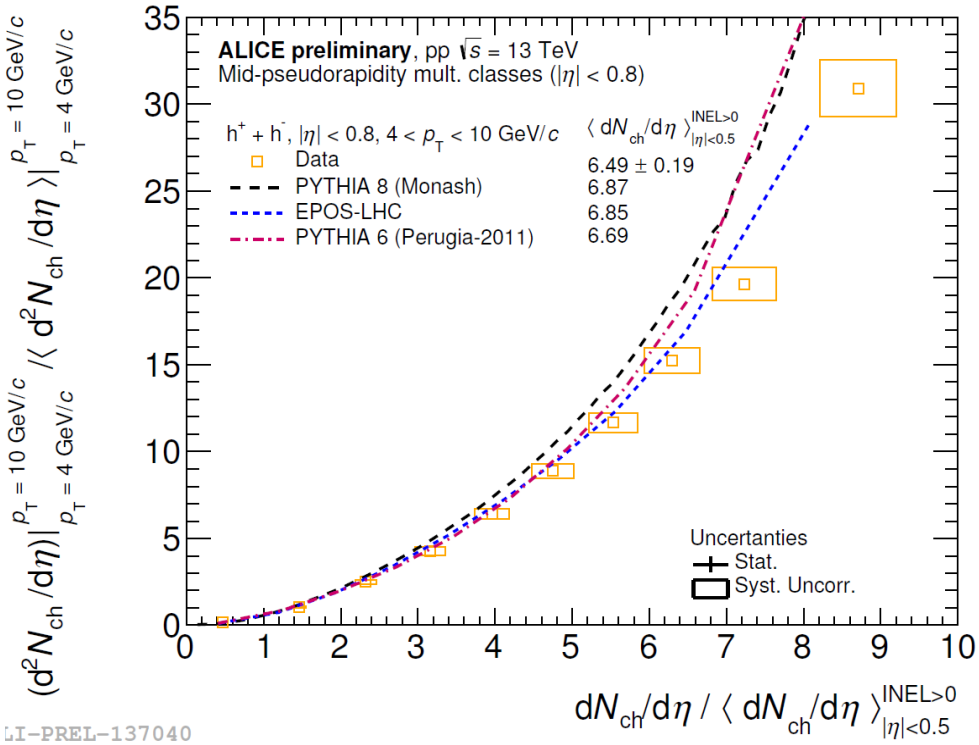


- ✔ **EMCAL** analysis significantly extends the p_T range (up to 30 GeV/*c*)
- ✔ PYTHIA8 calculations qualitatively describe the p_T dependent trends seen in data

- ✔ Faster than linear increase observed also in p_T bins
- ✔ Slope increases with the transverse momentum of J/ψ

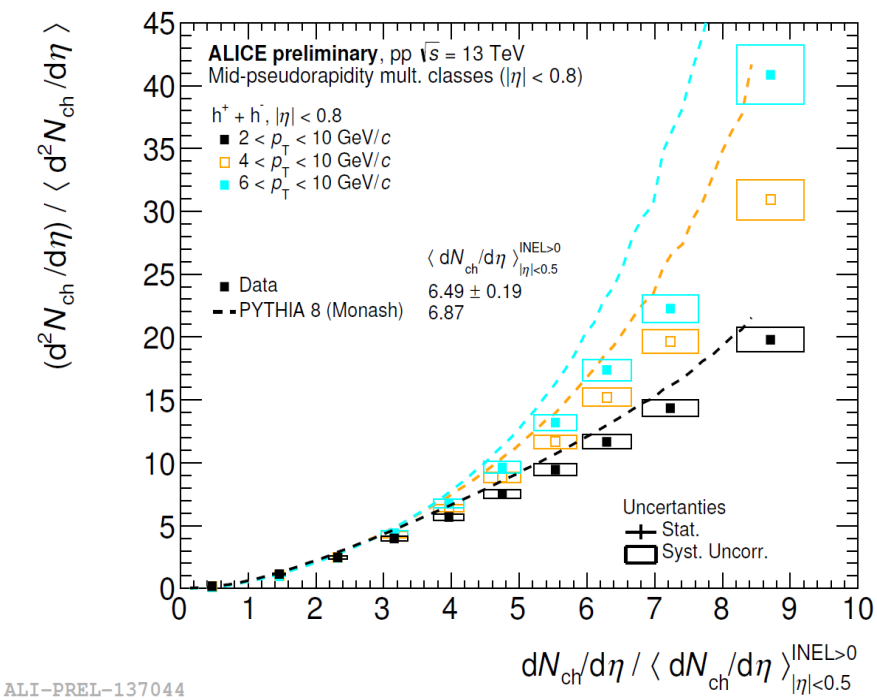
High-p_T inclusive charged particles

Run II



What about other hard processes ?

- ✔ Stronger increase with increasing p_T
- ✔ Qualitatively reproduced by PYTHIA models



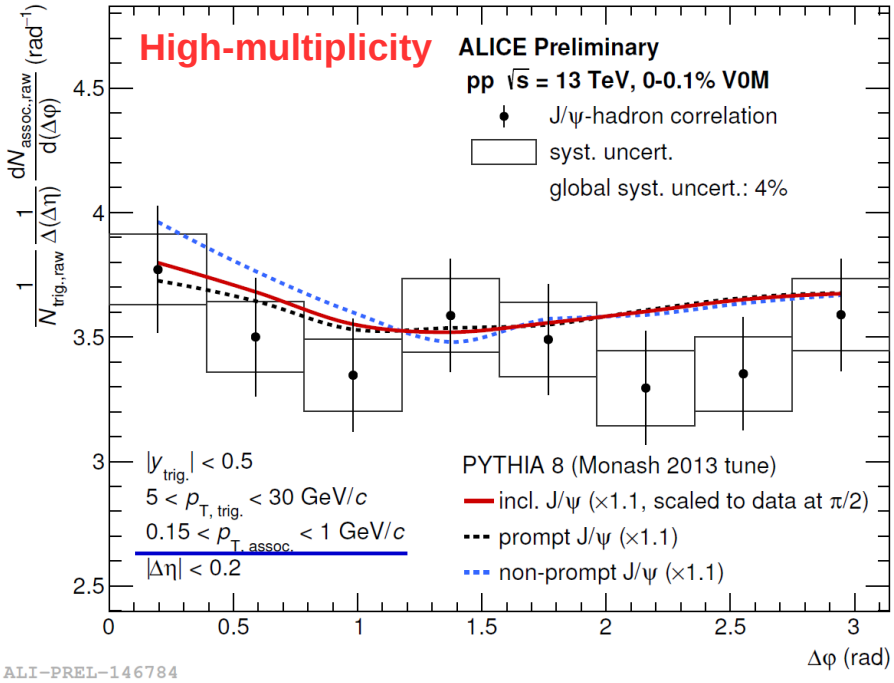
- ✔ Faster than linear increase observed for charged hadrons at high p_T
- ✔ **Similar trend for all hard processes !**
- ✔ All Monte Carlo models reproduce quite well the results for p_T > 4 GeV/c

Outlook:
Multiplicity dependent HF-analyses based on “new” observables

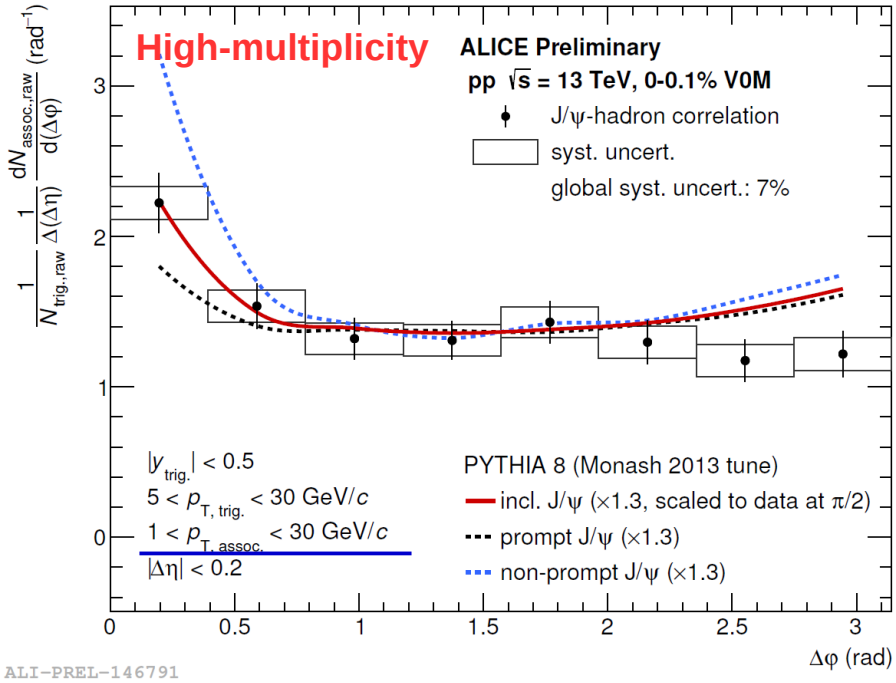
J/ψ-hadron correlations

Run II

J/ψ-(**low-p_T**)-hadron correlations



J/ψ-(**high-p_T**)-hadron correlations



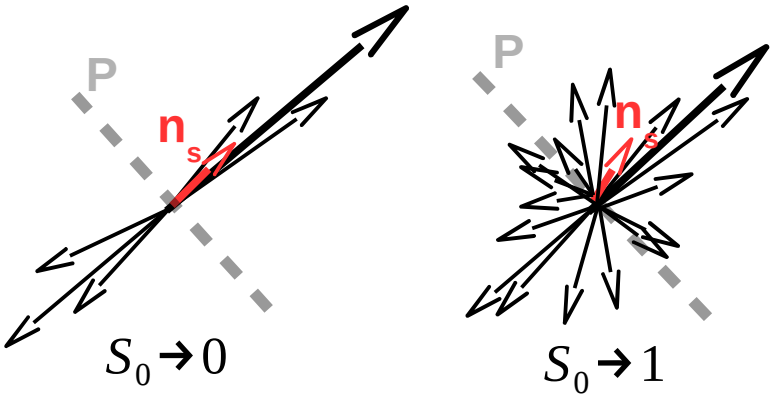
- ✔ Clear near side peak observed by correlating high-p_T J/ψ (p_T > 5 GeV/*c*) and hadrons with p_T > 1 GeV/*c*
- ✔ Qualitative good agreement observed with PYTHIA8 simulations
- ✔ Usage of full Run II statistics (gain of a factor ~100 expected for p_T(J/ψ) > 5 GeV/*c*) will improve significantly uncertainties allowing finer kinematic scan → **powerful tool to constraint models!**

D^0 production vs spherocity

$$S_0 \equiv \frac{\pi^2}{4} \min_{\hat{\mathbf{n}}_\mathbf{s}} \left(\frac{\sum_i |\vec{p}_{\mathrm{T},i} \times \hat{\mathbf{n}}_\mathbf{s}|}{\sum_i p_{\mathrm{T},i}} \right)^2$$

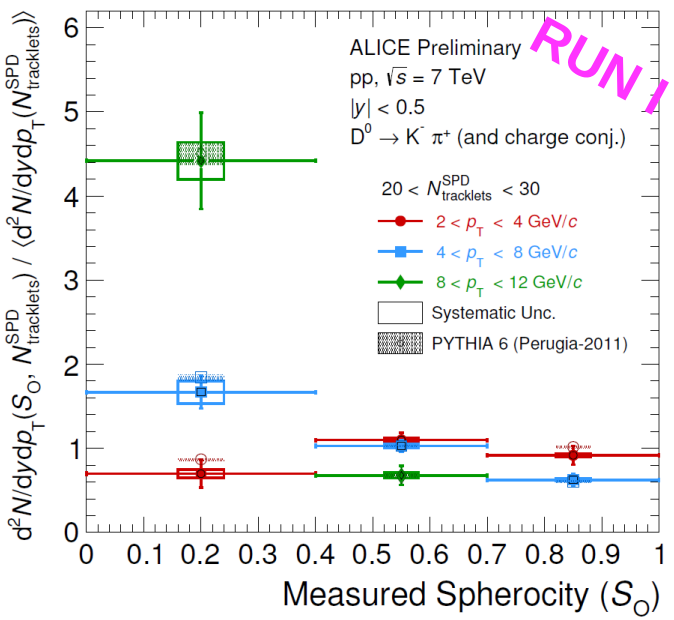
[$p_T \geq 0.15$ GeV/c, $|\eta| < 0.8$]

n_s defined in order to minimize the ratio above (~axis of the main scattering)

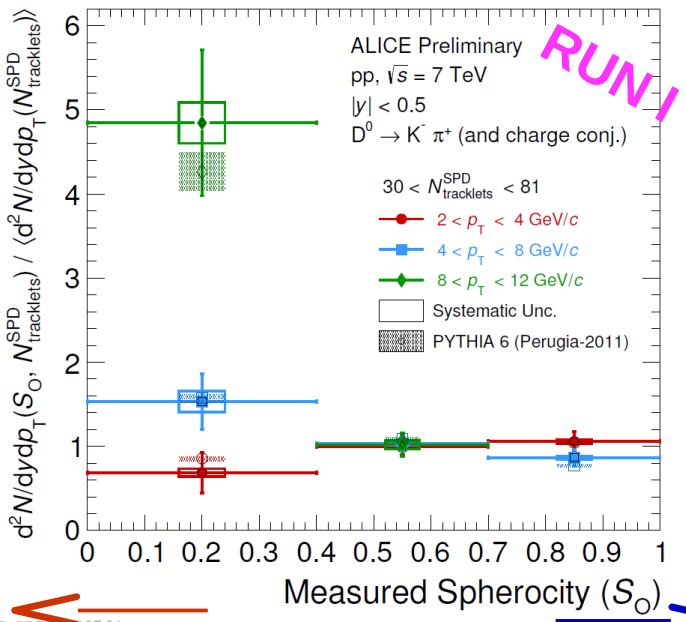


$S_0 =$
- **0 → "jet-like" events**
- **1 → "isotropic" events**

Low multiplicity



High multiplicity



← **pencil-like** **isotropic** →

- ✔ Significant improvement expected using Run II statistics
- ✔ More differential studies (both in S_0 and multiplicity) will provide additional constraints for further tuning and/or new model ingredients !

Conclusions / Outlook

- ✔ Highlights of HF-hadron production measured by ALICE as a function of multiplicity in pp collisions at several $\sqrt{s}$ have been presented:
  - ✔ Steep dependence of open and hidden heavy-flavour yields vs multiplicity; similar trend observed for high-p_T light flavour hadrons
  - ✔ Steepness increases with the p_T of the particles
  - ✔ Models including HF-production in MPI describe qualitatively the observed trends

- ✔ Exploit full available statistics of minimum-bias and high-multiplicity triggered events of Run II datasets:
  - ✔ usage of finer p_T / multiplicity bins, significant improvement for statistics-hungry analyses (e.g. non-prompt J/ψ)
  - ✔ more differential measurements based on new "observables" (e.g. event shape selection using "spherocity", J/ψ-hadron correlations, etc.) will give further insight into HF-production mechanisms
  - ✔ more quantitative studies of possible auto-correlation bias effects comparing results based on multiplicity estimators defined in different pseudo-rapidity regions

Conclusions / Outlook

- ✔ Highlights of HF-hadron production measured by ALICE as a function of multiplicity in pp collisions at several $\sqrt{s}$ have been presented:
  - ✔ Steep dependence of open and hidden heavy-flavour yields vs multiplicity; similar trend observed for high-p_T light flavour hadrons
  - ✔ Steepness increases with the p_T of the particles
  - ✔ Models including HF-production in MPI describe qualitatively the observed trends

- ✔ Exploit full available statistics of minimum-bias and high-multiplicity triggered events of Run II datasets:
  - ✔ usage of finer p_T / multiplicity bins, significant improvement for statistics-hungry analyses (e.g. non-prompt J/ψ)
  - ✔ more differential measurements based on new "observables" (e.g. event shape selection using "spherocity", J/ψ-hadron correlations, etc.) will give further insight into HF-production mechanisms
  - ✔ more quantitative studies of possible auto-correlation bias effects comparing results based on multiplicity estimators defined in different pseudo-rapidity regions

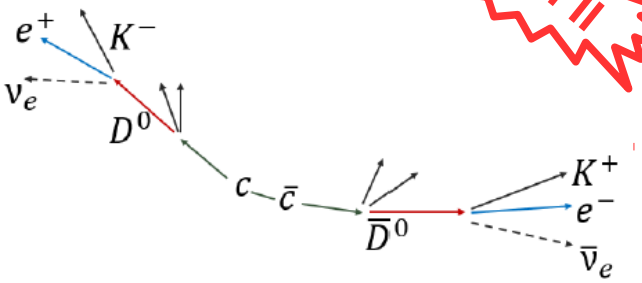
Thank you for your attention !

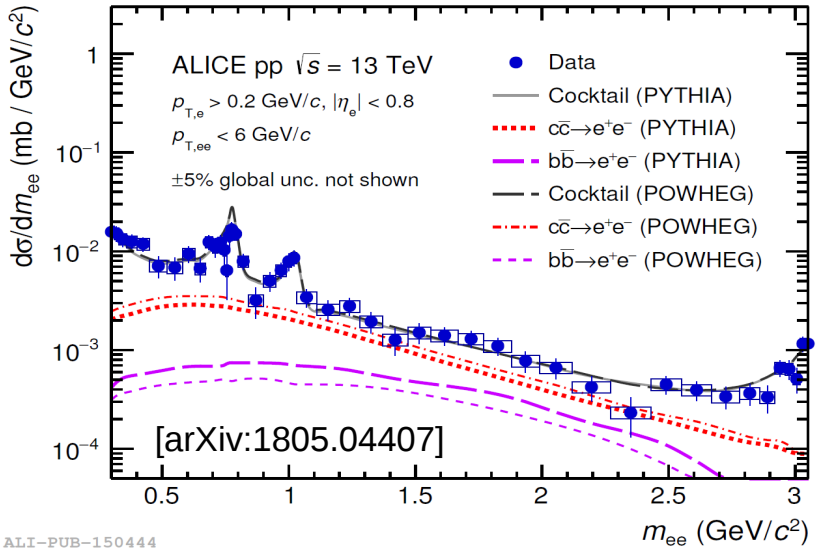
BACK-UP

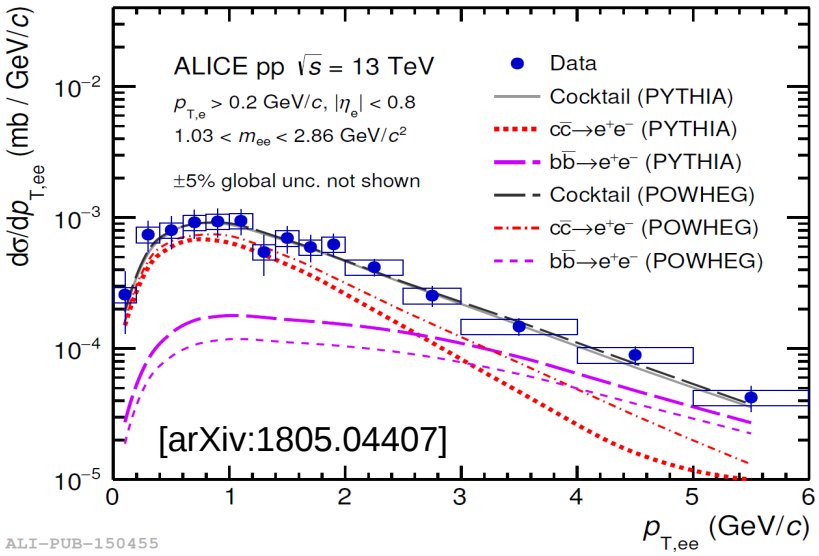
HF-cross sections from dielectron continuum

Run II

		PYTHIA	POWHEG
MB	$d\sigma_{c\bar{c}}/dy\|_{y=0}$	$974 \pm 138\,(\text{stat.}) \pm 140\,(\text{syst.})$ μb	$1417 \pm 184\,(\text{stat.}) \pm 204\,(\text{syst.})$ μb
	$d\sigma_{b\bar{b}}/dy\|_{y=0}$	$79 \pm 14\,(\text{stat.}) \pm 11\,(\text{syst.})$ μb	$48 \pm 14\,(\text{stat.}) \pm 7\,(\text{syst.})$ μb
HM	$d\sigma_{c\bar{c}}/dy\|^{HM}_{y=0}$	$4.14 \pm 0.67\,(\text{stat.}) \pm 0.66\,(\text{syst.})$ μb	$5.95 \pm 0.91\,(\text{stat.}) \pm 0.95\,(\text{syst.})$ μb
	$d\sigma_{b\bar{b}}/dy\|^{HM}_{y=0}$	$0.29 \pm 0.07\,(\text{stat.}) \pm 0.05\,(\text{syst.})$ μb	$0.17 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$ μb



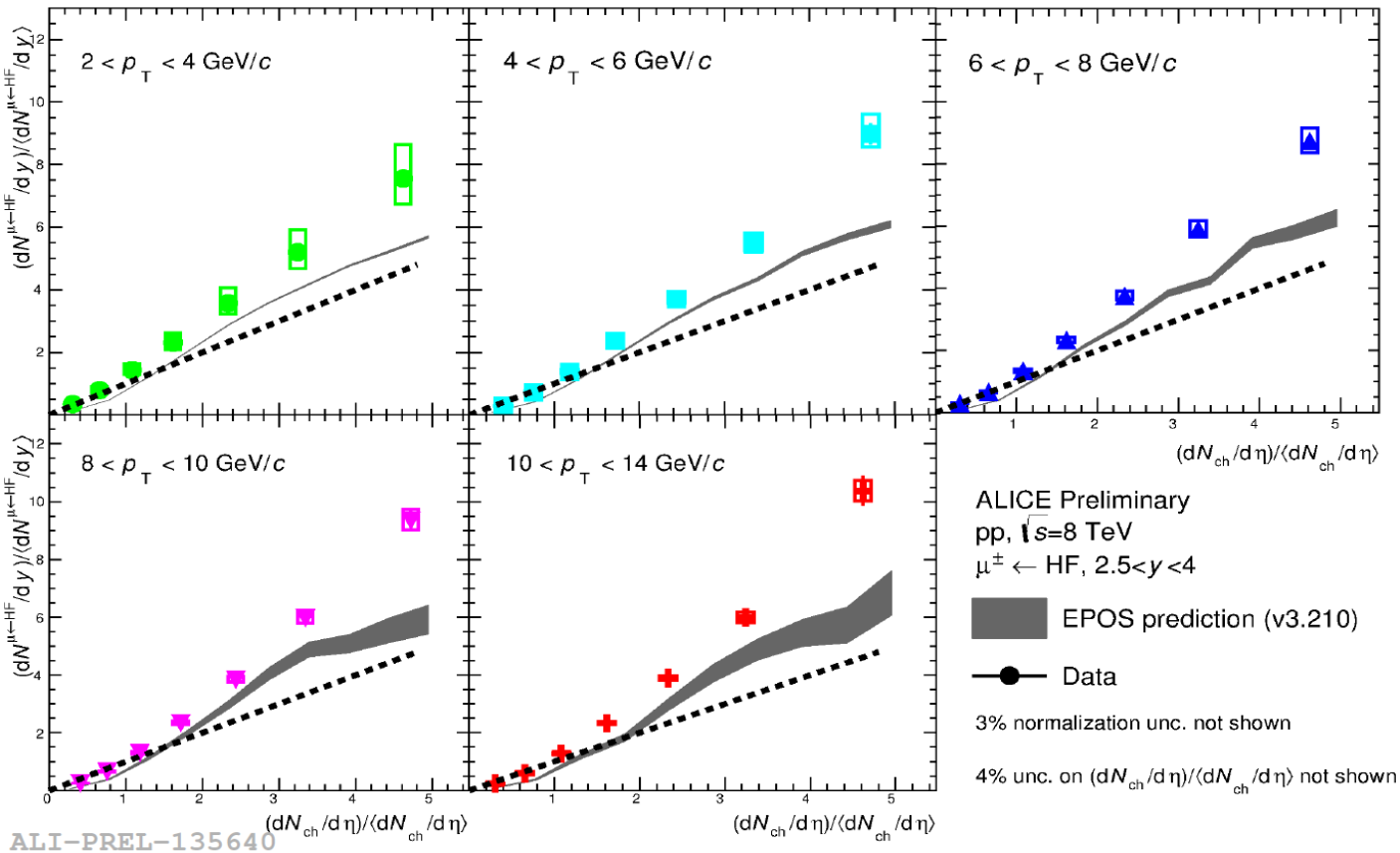




- ✔ Intermediate mass region of dielectron pairs ($1.03 < m_{ee} < 2.86$ GeV/c^2) dominated by open HF decays
- ✔ Simultaneous fits of m_{ee} and $p_{T,ee}$, using PYTHIA and POWHEG templates to extract HF cross sections
  - ✔ Different kinematic correlations of heavy-quark pairs in the two generators imply different acceptance for e^+e^- (from HF)
  - ✔ Additional constraints provided for tuning of Monte Carlo in order to reduce model dependence

HF decay muon production vs multiplicity

RUN I



- HF decay muons reconstructed at forward rapidity show faster than linear increase vs multiplicity
- Steepness more pronounced at high p_T (not possible to conclude due to large uncertainties)
- EPOS calculations underestimate HF decay muon production at high-multiplicity