Measurement of D_{s1}^{+} and D_{s2}^{*+} production, and D^{*+} spin alignment in pp at $\sqrt{s} = 13$ TeV

ALICE

Hard Probes 2023, Aschaffenburg - 29/03/2023

Stefano Politanò

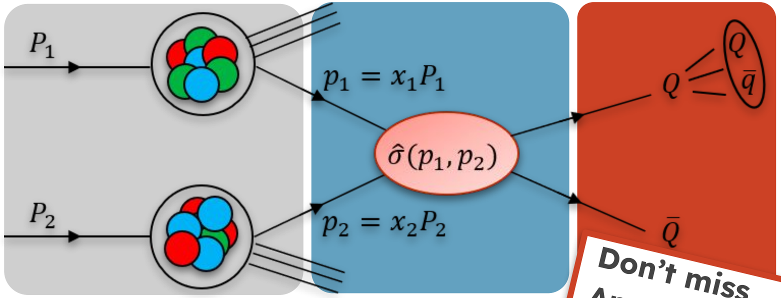
Politecnico and INFN Torino, on behalf of the ALICE Collaboration

1859

INFN

- Heavy quarks produced in initial hard-scattering processes in hadronic collisions

- Heavy-flavour (HF) hadron production measurements:
  - test pQCD calculations
  - reference for Pb–Pb



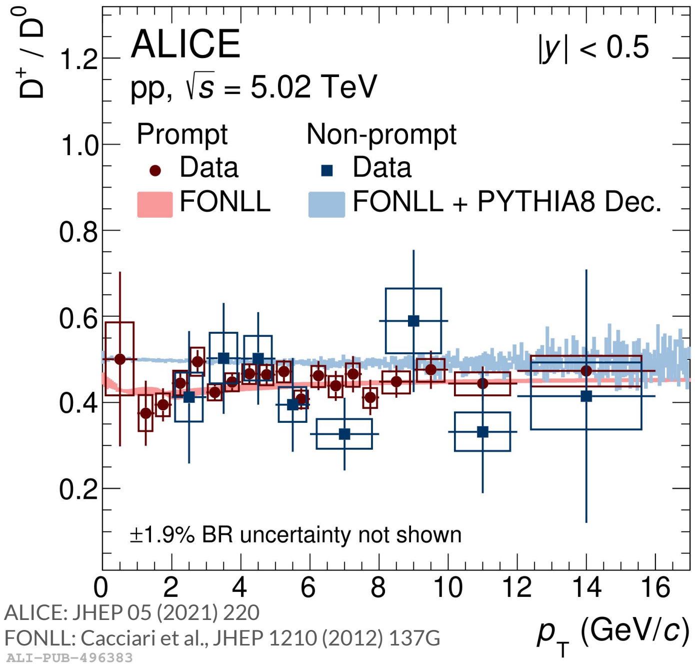
Don't miss Annalena's talk! (28/03, 16:50)

- Factorisation approach of production cross section
  - fragmentation functions ($D_c \to H_c$): phenomenological functions parameterised on e^+e^- and e^-p collision data → no dependence on colliding system assumed

    ➡ Ratios of particle species sensitive to HF quark hadronisation

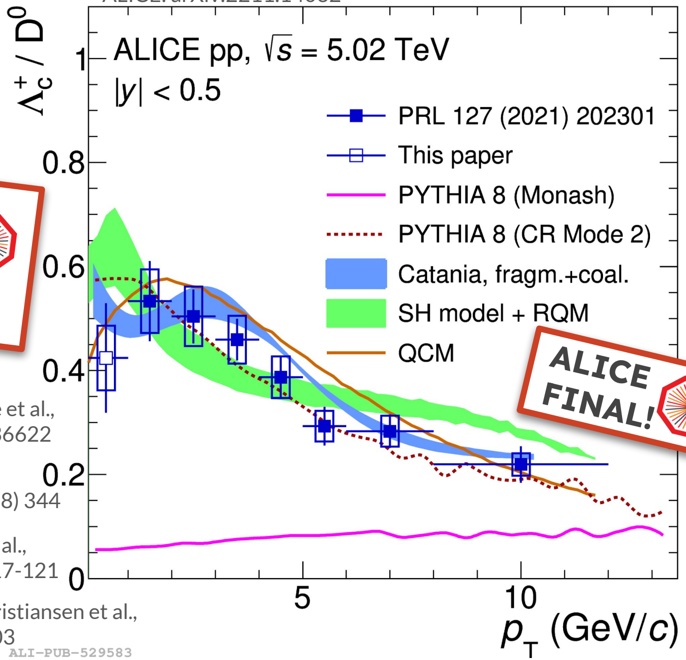
$$\frac{d\sigma^{H_c}}{dp_T} = \boxed{\mathrm{PDF}(x_1, \mu_F)\ \mathrm{PDF}(x_2, \mu_F)} \otimes \boxed{\frac{d\sigma^c}{dp_T^c}(x_1, x_2, \mu_R, \mu_F)} \otimes \boxed{D_{c\to H_c}(z = p_{H_c}/p_c, \mu_F)}$$

Parton distribution functions (PDFs) | Hard scattering cross section (pQCD) | Fragmentation function (FF)



ALICE: JHEP 05 (2021) 220
FONLL: Cacciari et al., JHEP 1210 (2012) 137G

ALICE: arXiv:2211.14032



Don't miss Annalena's talk! 28/03, 16:50

ALICE FINAL!

Catania: Minissale et al., PLB 821 (2021) 136622

QCM: Song et al., EPJ C78 no. 4 (2018) 344

SHM+RQM: He et al., PLB 795 (2019) 117-121

PYTHIA8+CR: Christiansen et al., JHEP 08 (2015) 003

Meson sector: *so far so good*

- No significant p_T dependence on meson-to-meson ratios
  - Good agreement with model calculations based on factorisation approach and FFs universality

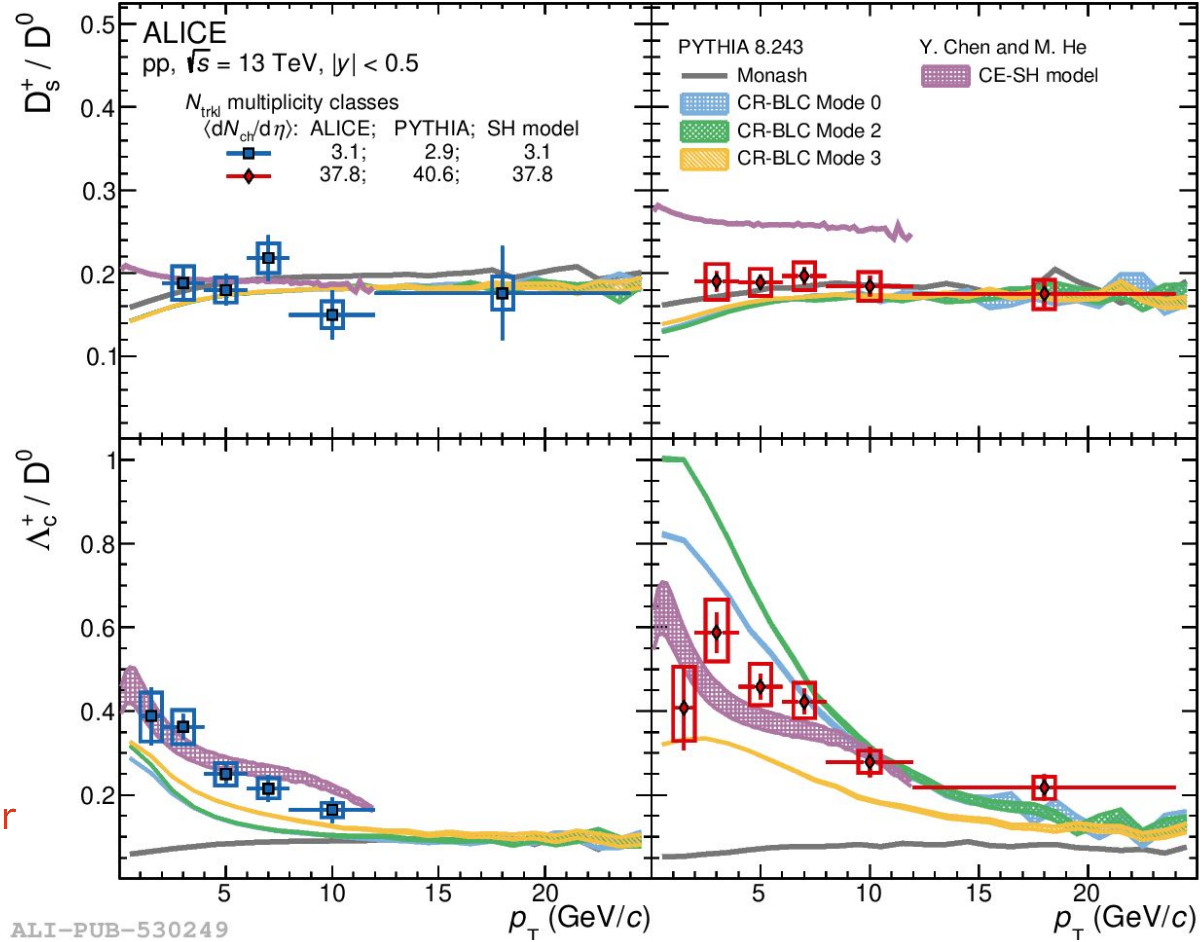
Baryon sector: *the cool kid on the block!*

- Strong p_T dependence
  - Ratio significantly higher w.r.t. e^+e^- and e^-p collisions
    - ➡ Ratio well described by additional hadronization mechanism scenarios (SHM+RQM, Catania, CR, QCM)

S. Politanò (PoliTO)
stefano.politano@cern.ch

ALICE: PLB 829 (2022) 137065   CE-SH: PLB 815 (2021) 136144
CR-BLC: JHEP 08 (2015) 003   PYTHIA: EPJC 74 (2014) 8

- No significant dependence on charged-particle multiplicity in meson sector
- Strong dependence observed in charm baryon sector in $1 < p_T < 12$ GeV/c
  - Well described by color reconnection/SHM models
- Are we missing something for mesons?
  - How can we further test QCD-inspired models?
    - ➡ Excited states and their properties!

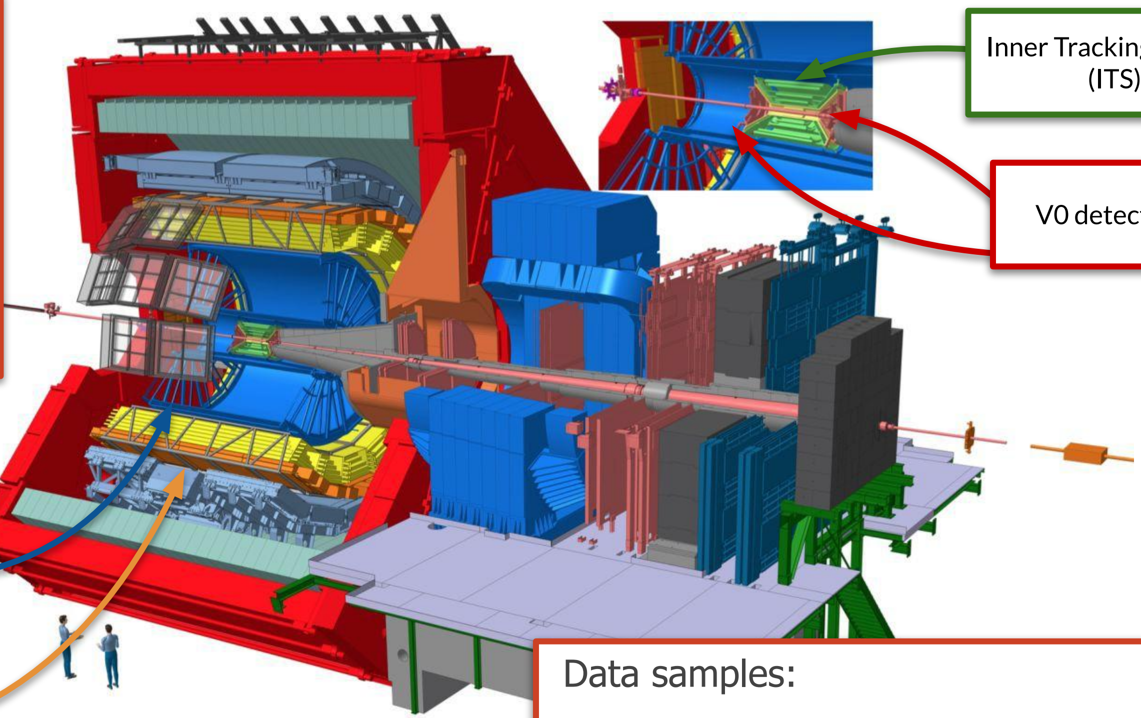


A Large Ion Collider Experiment

S. Politanò (PoliTO)
stefano.politano@cern.ch

D-meson excited states
reconstructed via hadronic decays
in HM and MB pp collisions

- $D^{*+} \rightarrow D^0\pi^+$
- $D_{s1}^{\ +} \rightarrow D^{*+}K^0_{\ s} \rightarrow D^0\pi^+\pi^-\pi^+$
- $D_{s2}^{\ *+} \rightarrow D^+K^0_{\ s} \rightarrow D^0\pi^+\pi^-\pi^+$



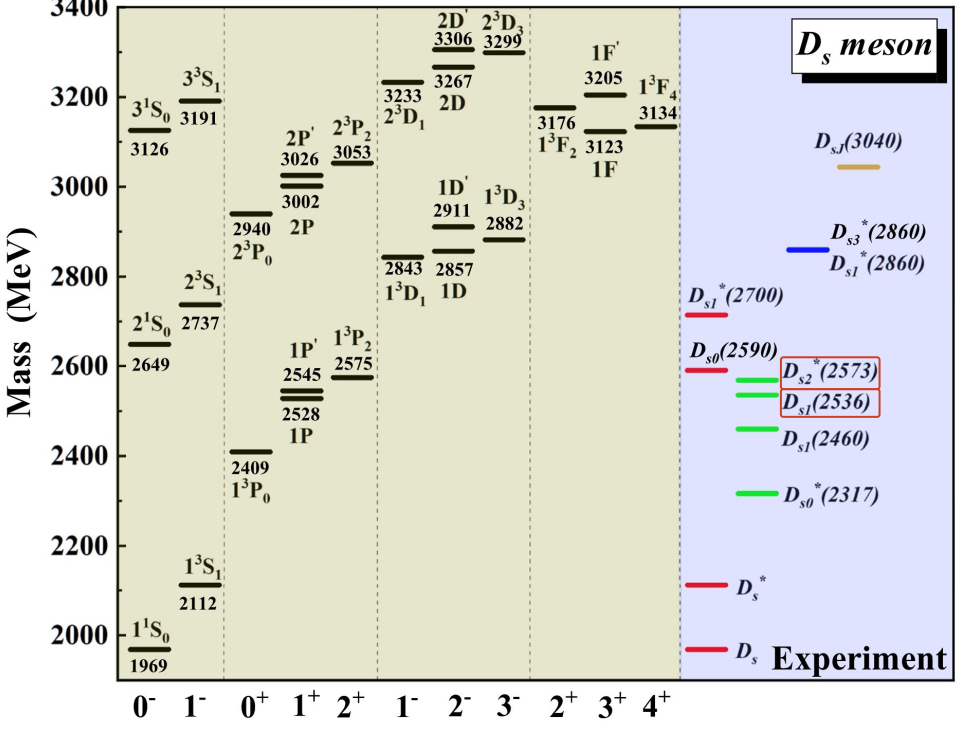
Data samples:

- pp $\sqrt{s}$ = 13 TeV (2016-2018):
  - ➡ Minimum bias (MB, $\mathcal{L}_{int} \sim 32\ nb^{-1}$)
  - ➡ High multiplicity (HM, $\mathcal{L}_{int} \sim 8\ pb^{-1}$)

The excited D_s meson puzzle

S. Politanò (PoliTO)
stefano.politano@cern.ch

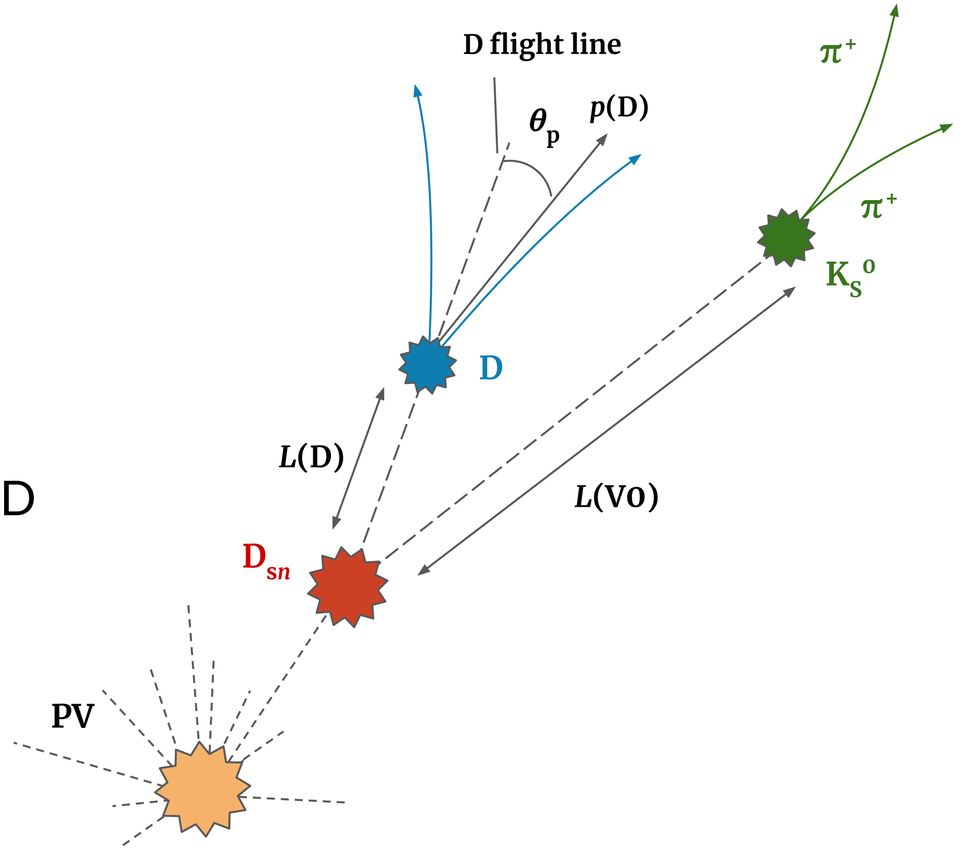
Ni et al., PRD 105 (2022) 5, 056006



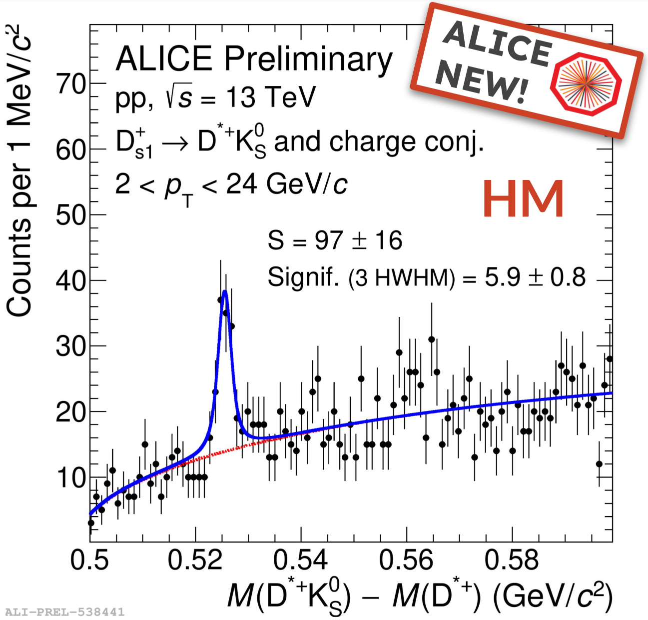
- Very large zoo of D_s-meson resonances predicted, but only a few measured
  - Measurements at LHC mainly focus on resonance properties, not production (JHEP 10 (2012) 151, JHEP 02 (2016) 133)
  - Hadronisation in charm-meson sector similar to lepton collisions for resonances?
  - Investigate hadronic rescattering phase
  - Investigate multiplicity dependence
    - ➡ Test recombination/SHM/CR scenarios

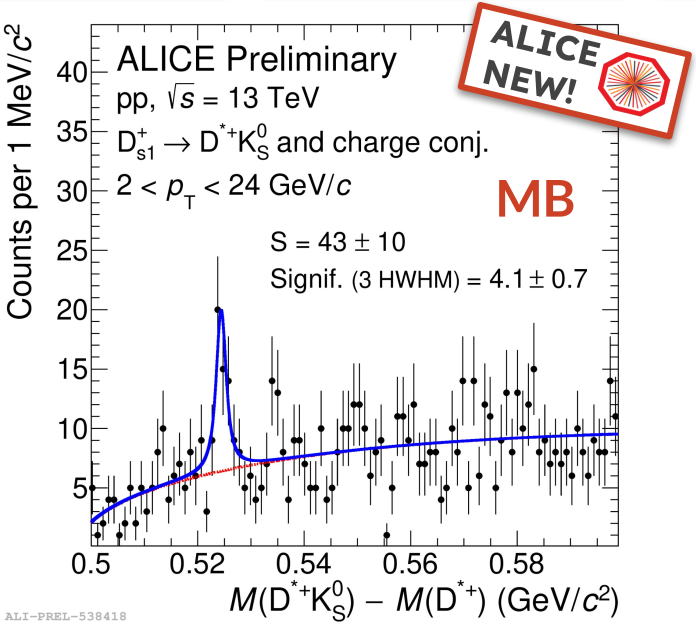
S. Politanò (PoliTO)
stefano.politano@cern.ch

- D_{s1}^{+} and D_{s2}^{*+} resonances decay in D-meson + V0:
  - $D_{s1}^{+} \rightarrow D^{*+} K_S^0$
  - $D_{s2}^{*+} \rightarrow D^{+} K_S^0$
- D^{*+}/D^{+} selected via Machine Learning (ML) multiclass classification to reject large combinatorial background and b→D contribution
- K_S^0 selected via linear selections
- No further selection on D_s resonance states



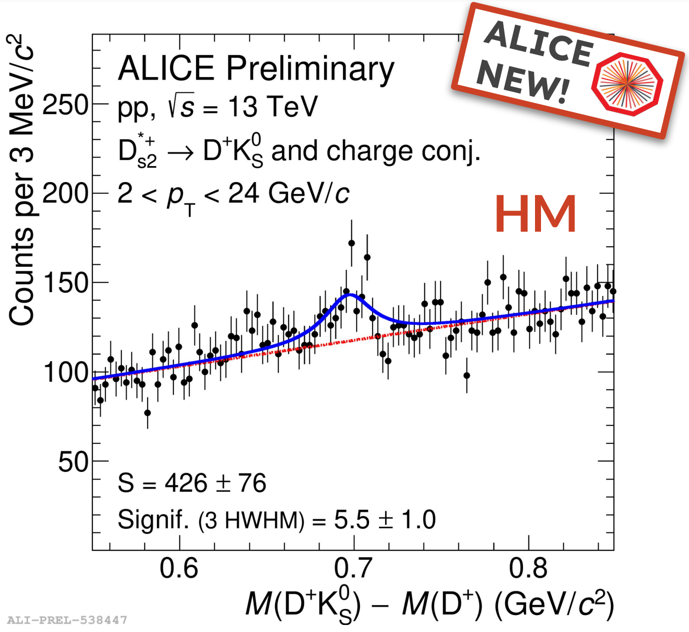
S. Politanò (PoliTO)
stefano.politano@cern.ch

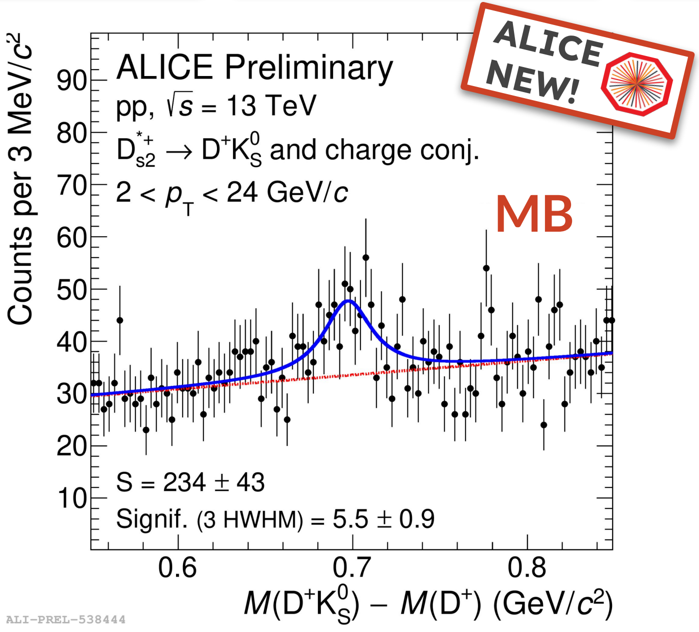




- D_{s1}^+ state measured in MB and HM samples
  - Select signal in a “confidence region” with enough counts: 2 < p_T < 24 GeV/c
  - Voigtian function for the signal (Γ = 0.9 MeV/c^2)
  - Exponential times power-law for the background

S. Politanò (PoliTO)
stefano.politano@cern.ch

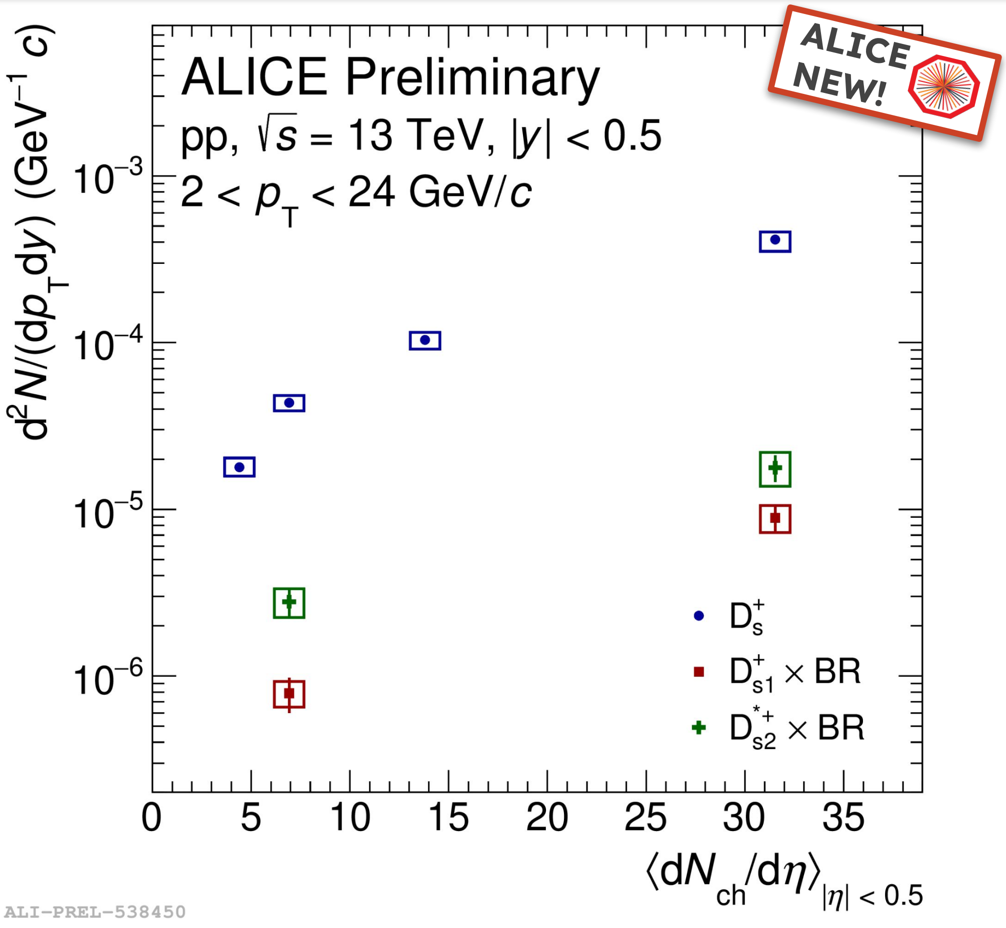




- D_{s2}^{*+} state measured in MB and HM samples
  - Select signal in a “confidence region” with enough counts: $2 < p_T < 24$ GeV/c
  - Voigtian function for the signal (Γ = 17 MeV/c^2)
  - First-order polynomial for the background

stefano.politano@cern.ch

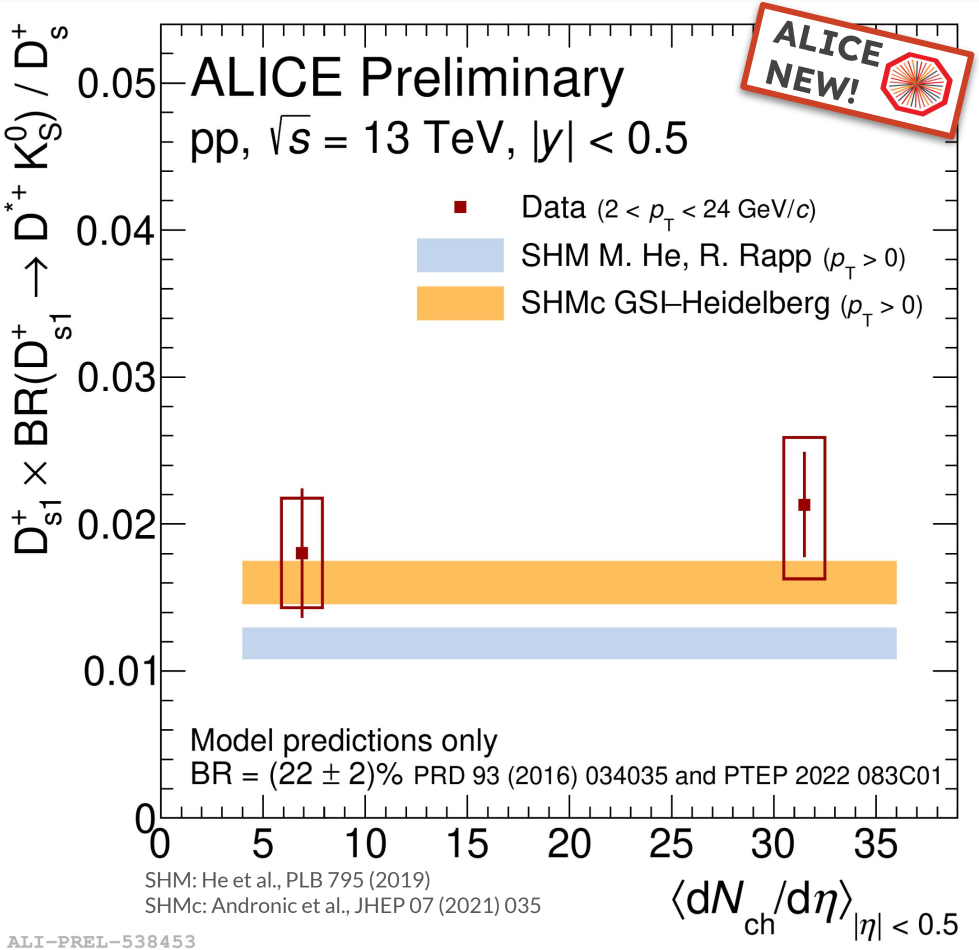
D_s resonance corrected yields vs. multiplicity



- First measurement of D_{s1}^+ and D_{s2}^{*+} production at the LHC
  - Compared to ground state in MB and HM vs. multiplicity
  - Larger production of ground state compared to resonance, as expected

    ➡ No available measurement of D_s^+ resonance BR

D_{s1}^{+}/D_s p_T-integrated yield ratio vs. multiplicity

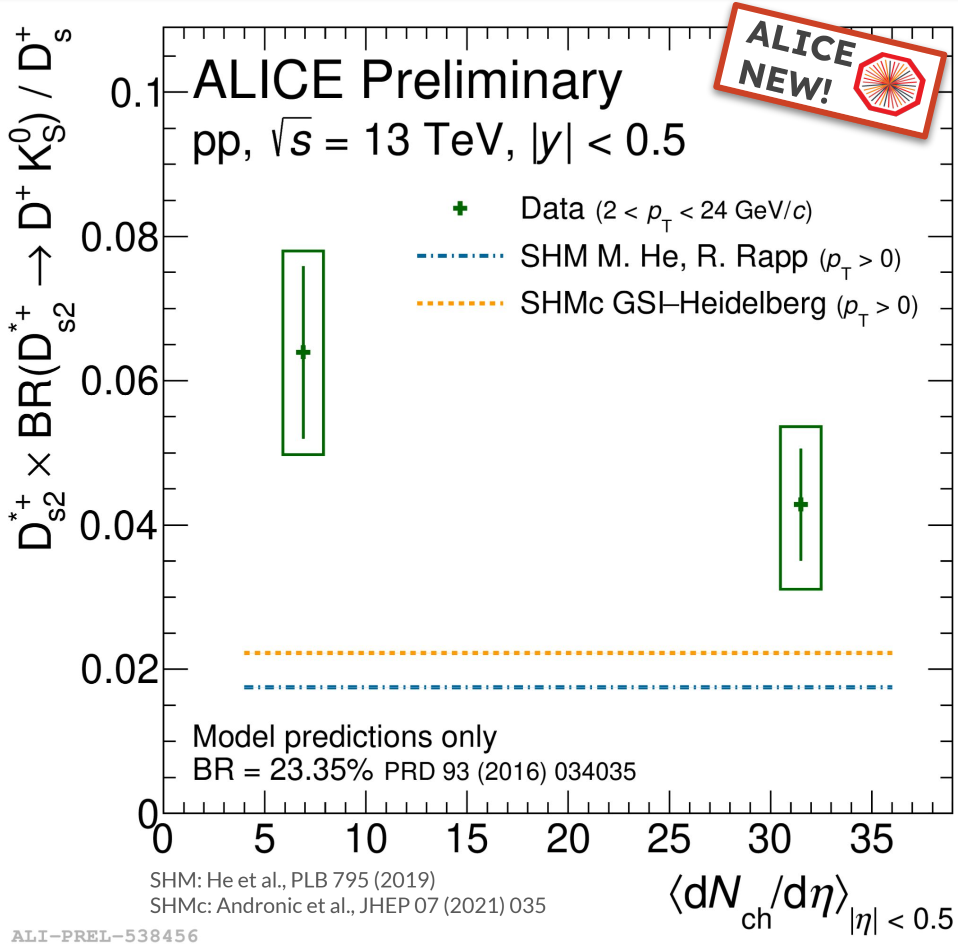


SHM: He et al., PLB 795 (2019)
SHMc: Andronic et al., JHEP 07 (2021) 035

ALI-PREL-538453

- D_{s1}^{+}/D_s^{+} p_T-integrated yield ratio
  - ratio to ground states factorises strangeness and charm dependencies for predictions
  - no multiplicity dependence explicitly expected from SHM and SHMc
    - ➡ no multiplicity dependence observed in data
    - ➡ models compatible with data

S. Politanò (PoliTO)
stefano.politano@cern.ch



SHM: He et al., PLB 795 (2019)
SHMc: Andronic et al., JHEP 07 (2021) 035

ALI-PREL-538456

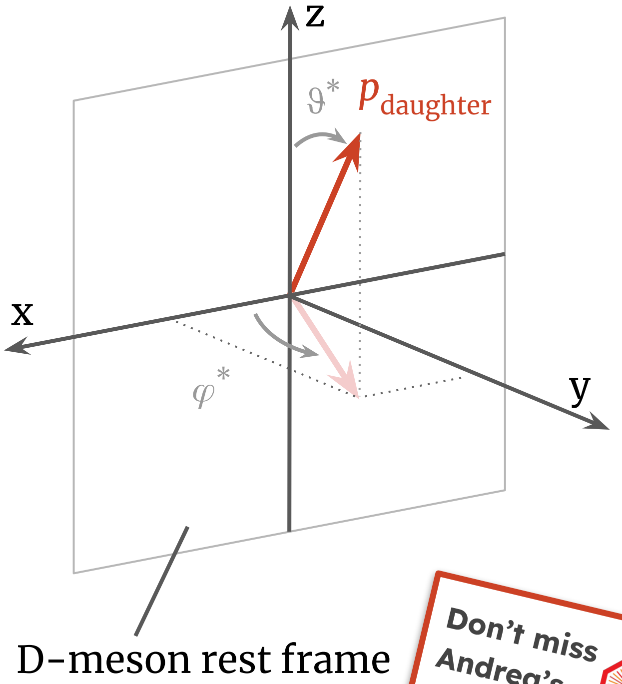
- D_{s2}^{*+}/D_s^+ p_T-integrated yield ratio
  - ratio to ground states factorise strangeness and charm dependencies for predictions
  - no multiplicity dependence explicitly expected from SHM and SHMc
    - ➡ multiplicity dependence not expected in SHM
    - ➡ hint of enhancement at low mult. might arise from hadronic rescattering due to D_{s2}^{*+} lifetime ($\tau(D_{s2}^{*+}) \sim 11.61$ fm/c; $\tau(D_{s1}^{+}) \sim 219$ fm/c))
    - ➡ some tension with models , about 2.5σ (1.5σ) at low (high) mult.

S. Politanò (PoliTO)
stefano.politano@cern.ch

- Spin properties in HF quark-to-hadron transition not settled yet
- Spin polarisation:
  - Spin alignment with respect to a chosen direction (helicity axis)
  - Experimentally measured as anisotropies in the decay product angular distributions:

$$\frac{dN}{d\cos\theta^*} \propto [1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta^*]$$

  - Spin density matrix element:
    - ➡ $\varrho_{00} = 1/3 \rightarrow$ No spin alignment
    - ➡ $\varrho_{00} \neq 1/3 \rightarrow$ Spin alignment

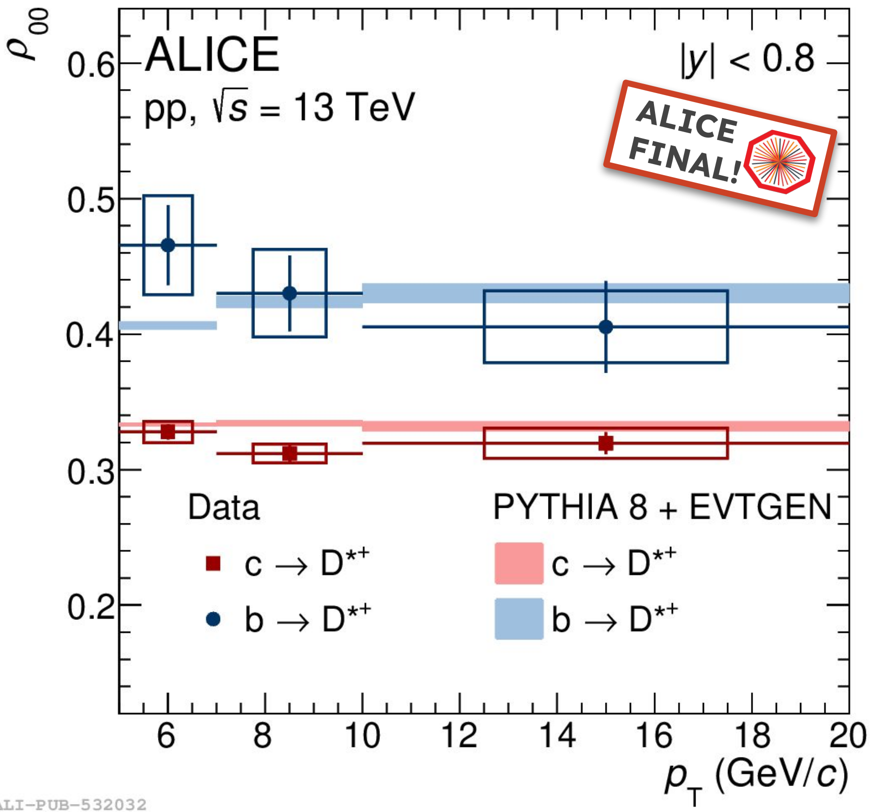


S. Politanò (PoliTO)
stefano.politano@cern.ch

ALICE

- First measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC
  - ϱ_{00}(prompt D^{*+}) = 0.324 ± 0.004 (stat.) ± 0.008 (syst.)
    - ➡ Prompt D^{*+} compatible with no polarization
  - ϱ_{00}(non-prompt D^{*+}) = 0.455 ± 0.022 (stat.) ± 0.035 (syst.)
    - ➡ Non-prompt D^{*+} ϱ_{00} > 1/3 due to the helicity conservation
    - ➡ B(S=0) → D*+(S=1) + X

ALICE: arXiv:2212.06588 PYTHIA + EvtGen: EPJC 74 (2014) + NIM Vol. 462 (2001)

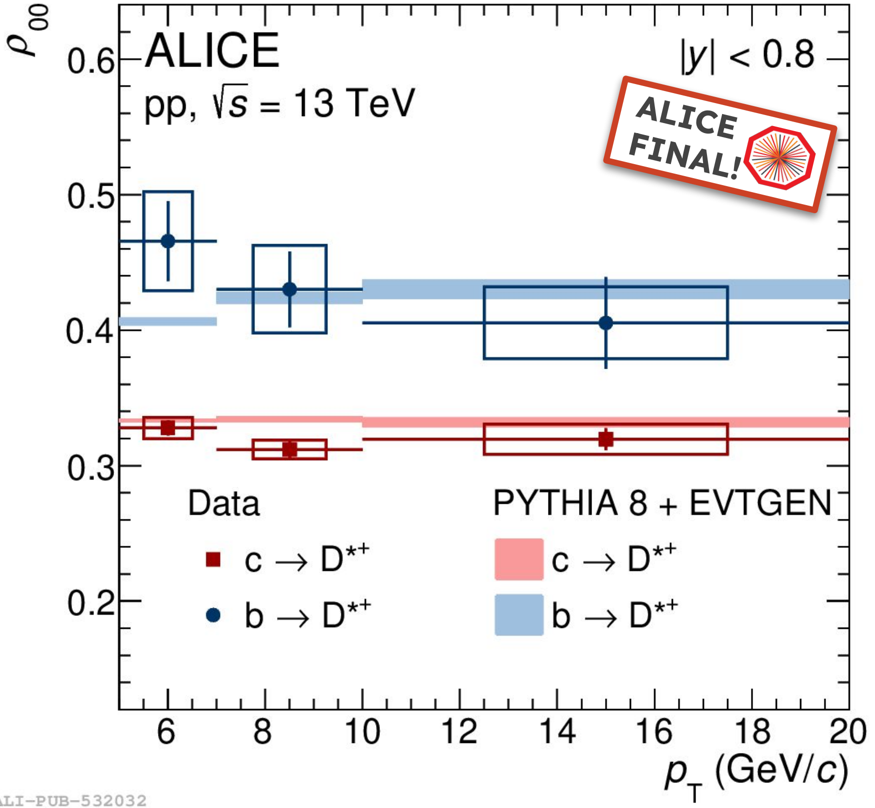


ALI-PUB-532032

S. Politanò (PoliTO)
stefano.politano@cern.ch

- First measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC
  - PYTHIA8 + EvtGen describes both the components
    - ➡ helicity conservation implemented in EvtGen
  - Important baseline for A–A collisions
    - ➡ disentangle medium-induced from genuine polarisation effects

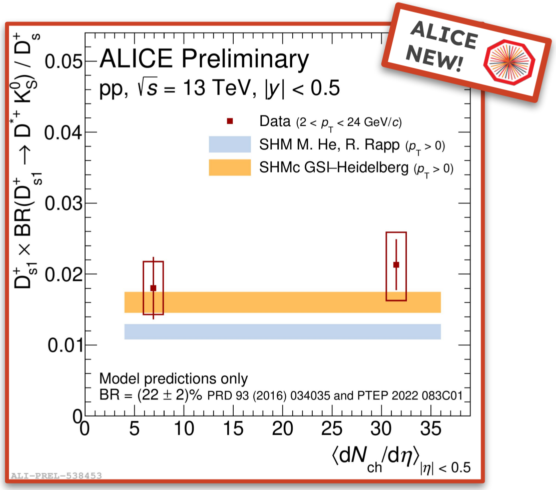
ALICE: arXiv:2212.06588 PYTHIA + EvtGen: EPJC 74 (2014) + NIM Vol. 462 (2001)

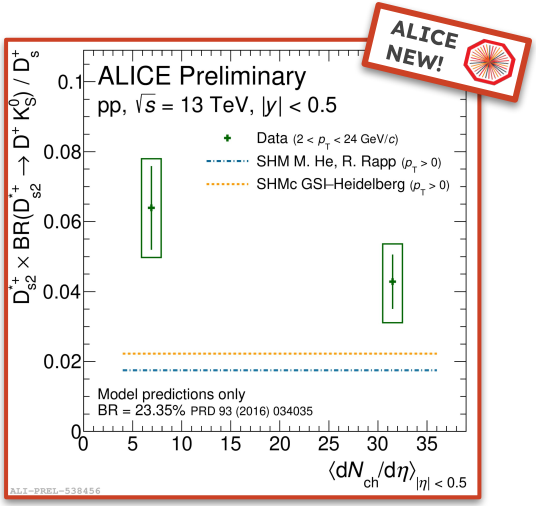


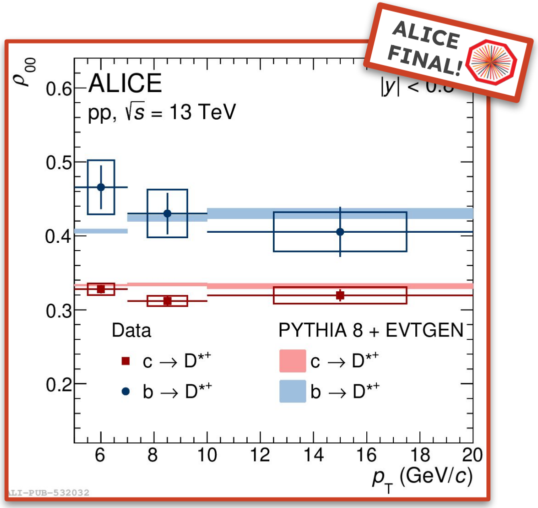
ALI-PUB-532032

S. Politanò (PoliTO)
stefano.politano@cern.ch

- Charm hadron production can be further investigated via D-meson resonance production studies
- First measurement of D_{s1}^{+} and D_{s2}^{*+} production at the LHC
- Excited-to-ground state ratios vs. multiplicity compared to SHM-based models → tension compared to expectations found in D_{s2}^{*+} case
- First measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC
  - Prompt D^{*+} not aligned; non-prompt D^{*+} aligned







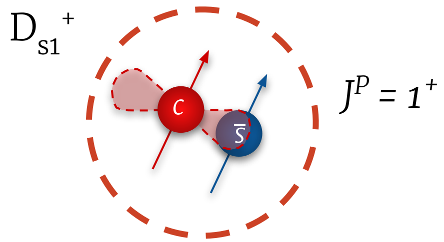
Additional material

S. Politanò (PoliTO)
stefano.politano@cern.ch

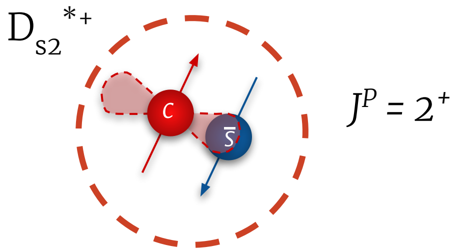
ALICE

Quantum numbers:

- heavy-quark limit: properties of heavy-light meson determined by light-quark
- L is the orbital angular momentum
  - $j_q = L \oplus s_q \rightarrow j_{s\text{-bar}} = 1/2,\ 3/2$
  - $J = j_q \oplus s_Q \rightarrow J = 0, 1; 1, 2;$



- **Spectroscopy notation**: $n^{(2S+1)}\,L_J$
  - natural spin-parity: $J^P = 0^+, 1^-, 2^+$
  - unnatural spin-parity: $J^P = 0^-, 1^+, 2^-$
- **PDG notation**: $D_{sJ}^{*}(m)^{0/\pm}$, where the $*$ subscript indicate natural spin-parity



S. Politanò (PoliTO)
stefano.politano@cern.ch

ALICE

Initial state	Final state	Width (MeV)	B.R. (%)
$D_s(1^3P_0)$	$D_s^*\gamma$	0.00901	0.00407
2484	DK	221	99.8
	Total	221	100
$D_s(1P_1)$	$D_s\gamma$	0.0152	11.2
2549	$D_s^*\gamma$	0.00540	3.99
	D^*K	0.129	95.3
	Total	0.135	100
$D_s(1P_1')$	$D_s\gamma$	0.00923	0.00659
2556	$D_s^*\gamma$	0.00961	0.00687
	D^*K	140.	100
	Total	140.	100
$D_s(1^3P_2)$	$D_s^*\gamma$	0.0189	0.188
2592	DK	9.40	93.4
	D^*K	0.545	5.41
	$D_s\eta$	0.105	1.04
	Total	10.07	100

Phys. Rev. D 93, 034035 (2016)

- $BR(D_{s1}^{+} \to D^*K) = 95.3\%$
  - Two possible charge states: $D^{*0}K^+$ and $D^{*+}K^0$
    - ➡ $D^{*+}K^0 = (0.85 \pm 0.12)\, D^{*0}K^+$

$D_{s1}(2536)^+$ DECAY MODES	Fraction (Γ_i/Γ)
$D^*(2010)^+K^0$	0.85 ± 0.12
$(D^*(2010)^+K^0)_{S-wave}$	0.61 ± 0.09
$D^+\pi^-K^+$	0.028 ± 0.005
$D^*(2007)^0K^+$	DEFINED AS 1

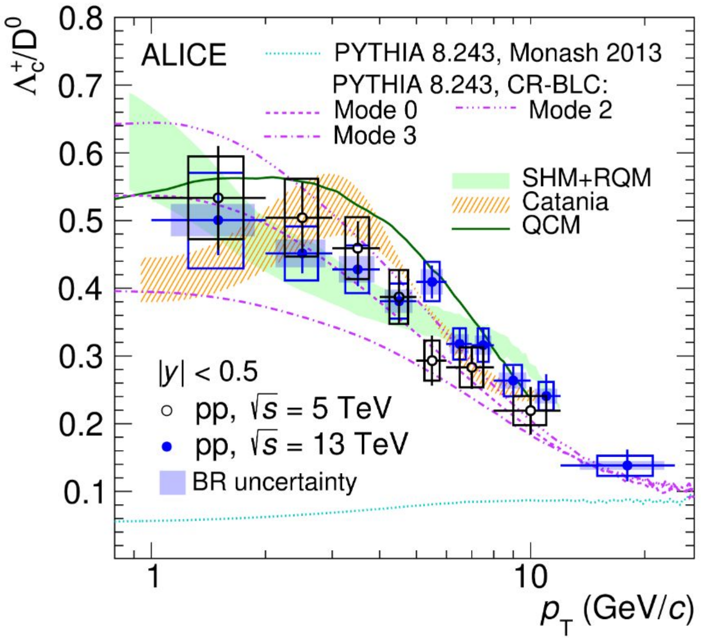
    - ➡ 50% K_S^0 – 50% K_L^0
    - ➡ **$BR(D_{s1}^{+} \to D^{*+}K_S^0) = (22 \pm 2)\%$**
- $BR(D_{s2}^{*+} \to DK) = 93.4\%$
  - Two possible charge states: D^0K^+ and D^+K^0
    - ➡ No information, assume 50% – 50%
    - ➡ 50% K_S^0 – 50% K_L^0
    - ➡ **$BR(D_{s2}^{*+} \to D^+K_S^0) = 23.35\%$**

BACK TO SLIDES!

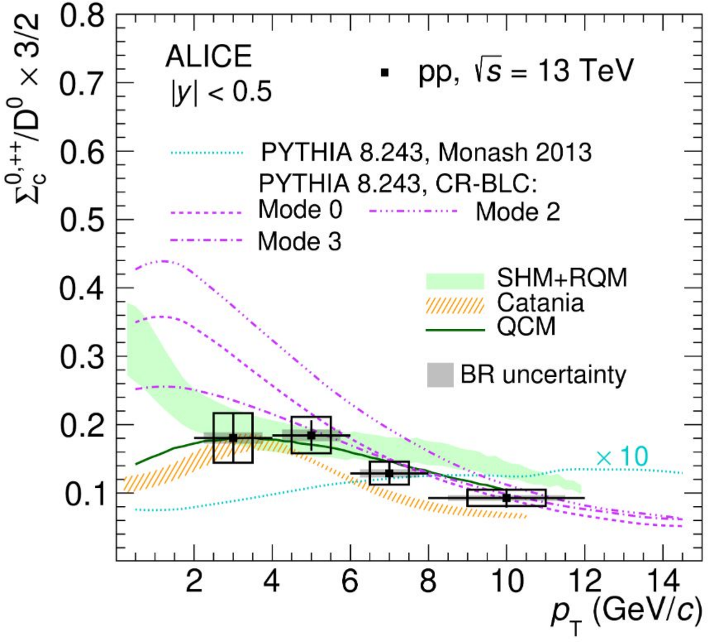
S. Politanò (PoliTO)
stefano.politano@cern.ch

ALICE

- Strong p_T dependence on baryon-to-meson ratios
  - Ratio significantly higher than e^+e^- and e^-p collisions (LEP average: 0.113 ± 0.013 ± 0.006)
    - ➡ Ratio well described by charm-enriched scenarios (SHM+RQM, Catania, CR, QCM)



ALI-DER-493896

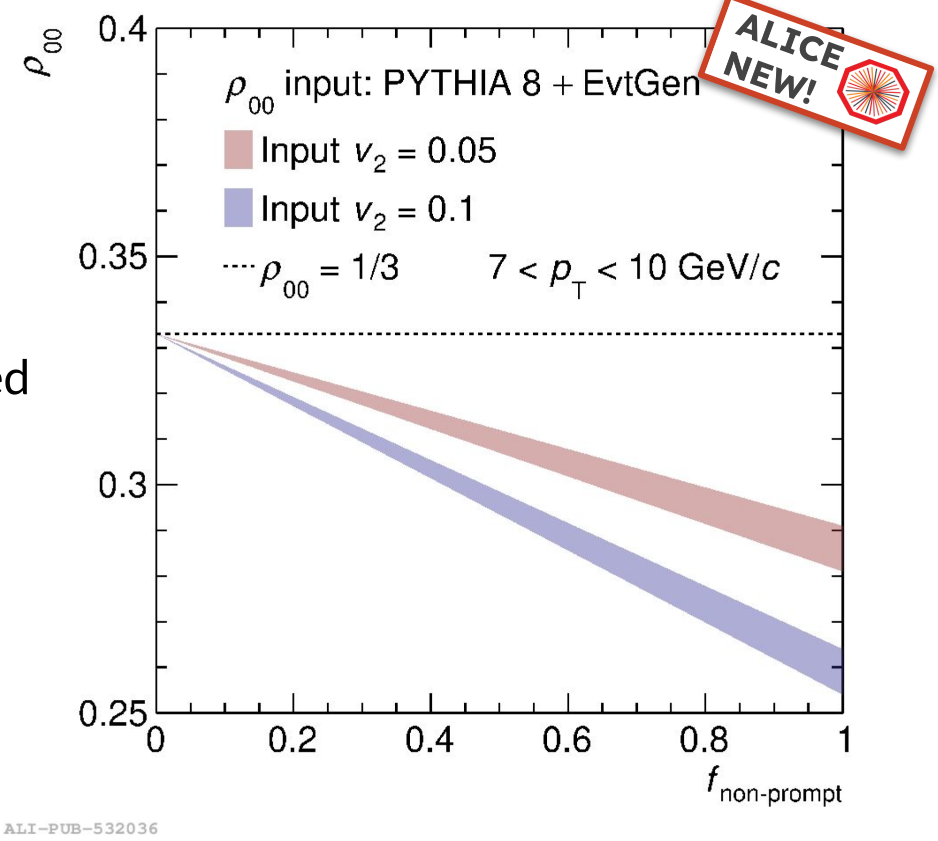


ALI-DER-493901

S. Politanò (PoliTO)
stefano.politano@cern.ch

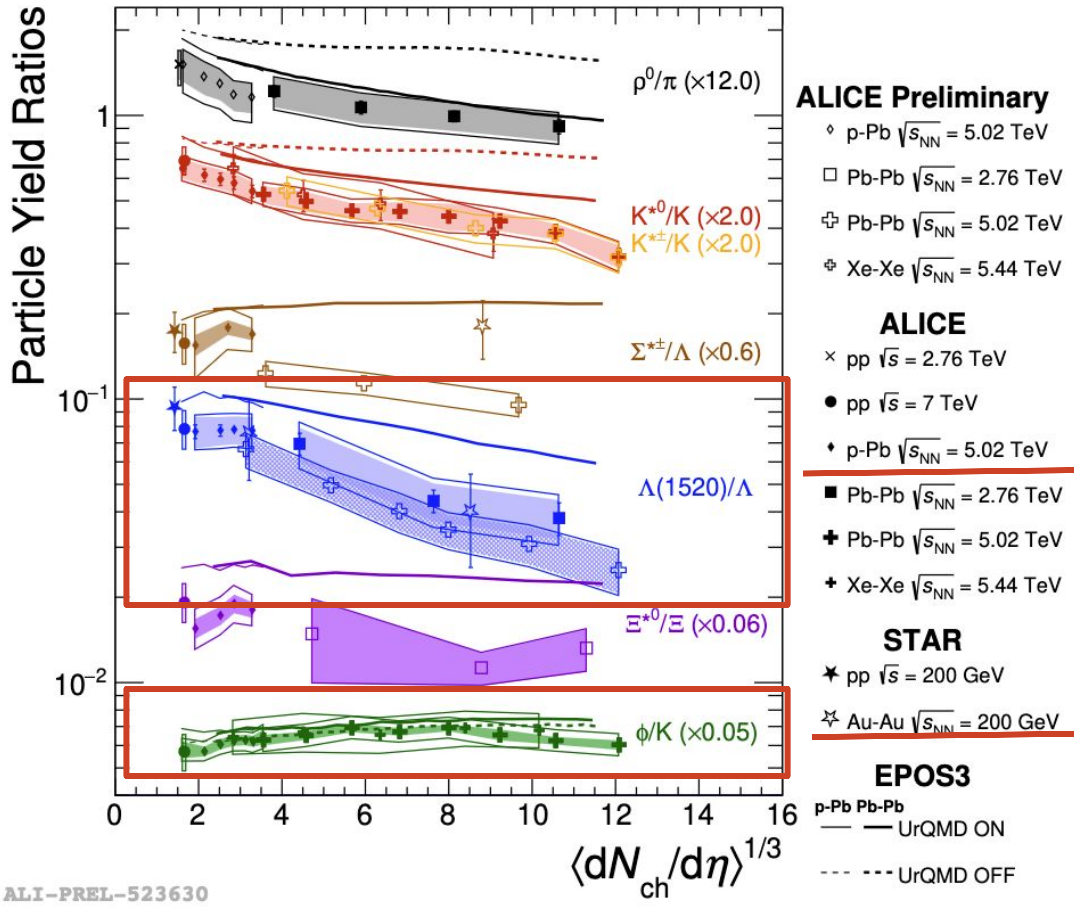
- First measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC
  - PYTHIA8 + EvtGen manages to describe both the components
    - ➡ helicity conservation implemented in EvtGen
  - Important baseline for A–A collisions
    - ➡ Non-prompt D^{*+} spin alignment + elliptic flow mimic global spin alignment in heavy-ion collisions

ALICE: arXiv:2212.06588 PYTHIA + EvtGen: EPJC 74 (2014) + NIM Vol. 462 (2001)



BACK TO SLIDES!

S. Politanò (PoliTO)
stefano.politano@cern.ch



Almost same lifetime as D_{s2}^{*+}

D_{s1}^{+} lifetime ~5 times larger that ϕ lifetime

Hard Probes 2023, 29/03/2023

BACK TO SLIDES!