Characterisation of charm-quark fragmentation via azimuthal correlations of charm hadrons and charged particles

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Heavy-flavour physics

Heavy-flavour (HF) quark mass of the order of ~GeV/c^2

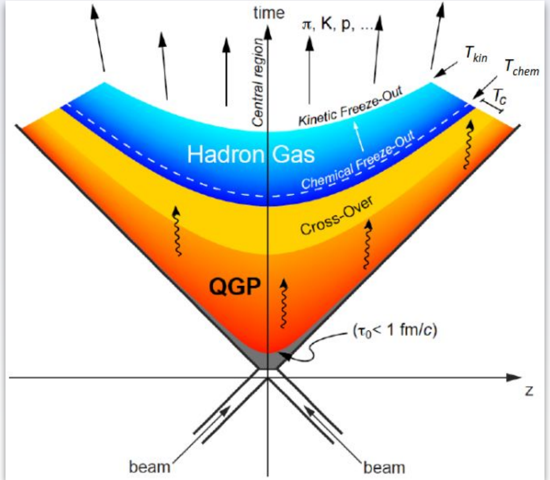
→ mainly produced in **hard-scattering** processes

→ **thermal** production/annihilation negligible

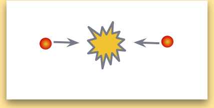
In Pb-Pb collisions, produced **before** the QGP formation

τ_{QGP} ~ 1 fm/c (production timescale: $\Delta\tau$ ~ 1/Q ~ 1/2m)

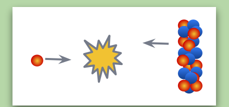
→ Full evolution of the system experienced



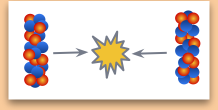
Measurement of HF hadrons: access to charm and beauty quarks dynamics



Test for pQCD
Reference for Pb–Pb
Hadronisation



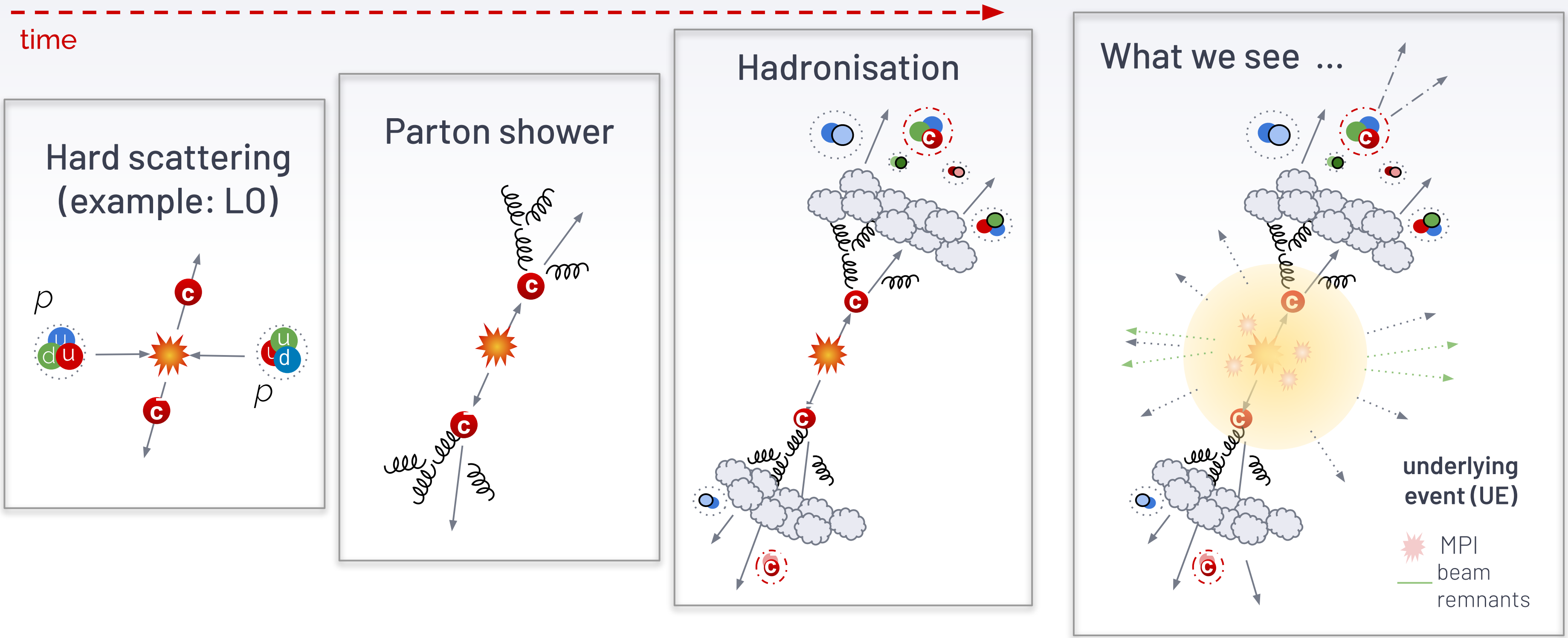
Cold Nuclear Matter (**CNM**) effects
Modification of PDFs in nuclei
Hot nuclear matter effects
Flow



Hot nuclear matter effects
Energy loss in the QGP
Modification to hadronisation

From HF quarks to hadrons

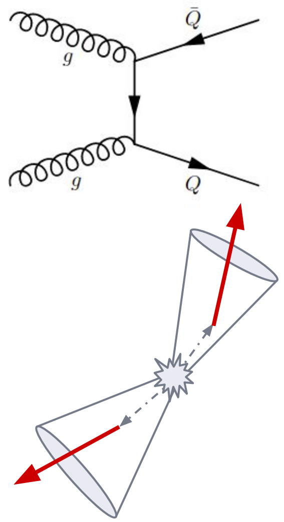
From heavy-quark production to final state particles



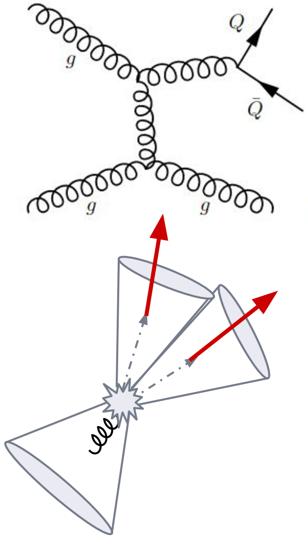
Azimuthal correlations between HF particles

Footprints of HF-quark production mechanisms

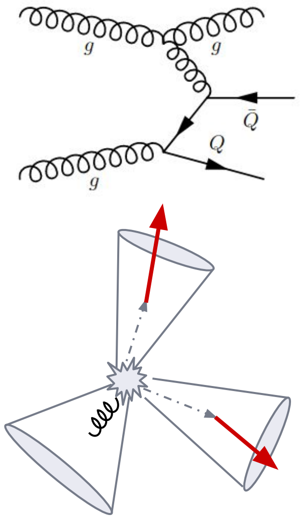
LO: pair production (PP)

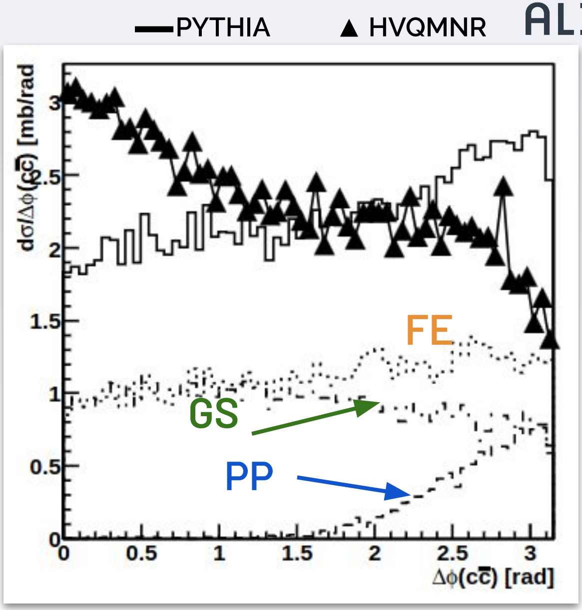


NLO: gluon splitting (GS)



NLO: flavour excitation (FE)





arXiv:hep-ph/0311048

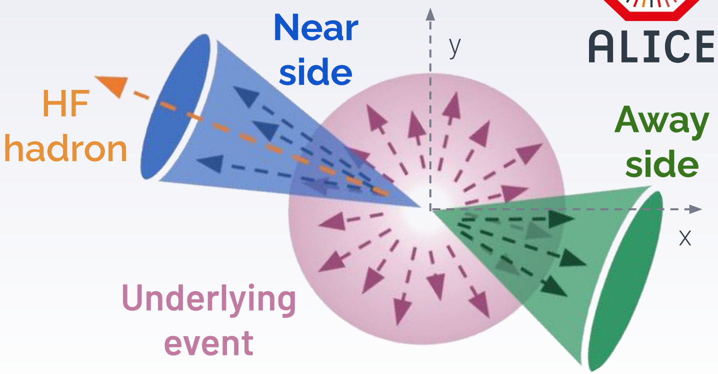
Correlations between:

- HF - HF → ideal probe
- HF - h → sensitivity

Azimuthal correlations of HF and charged particles

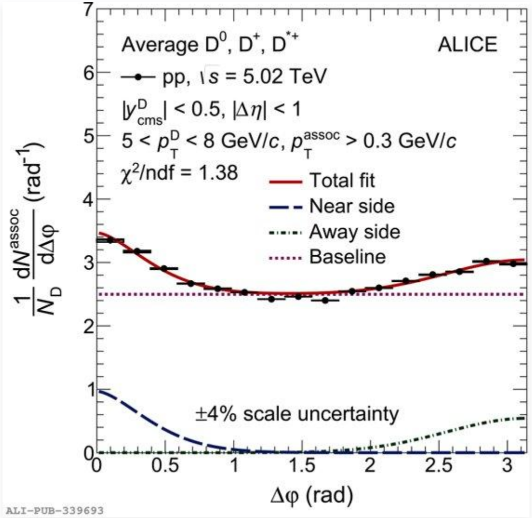
Investigation of heavy-flavour quark fragmentation

The heavy-flavour jet is characterised with:
- → Angular opening
- → Multiplicity of particles
- → Momentum distribution among its constituents



Validation of parton-shower models and Monte Carlo generators

Possible modifications induced in the charm-jet by a different hadronisation mechanisms



EPJC 80 (2020) 979

Enhanced Λ_c^+/D^0 production ratio in pp

ALICE

Open heavy-flavour hadron production cross section calculated by factorisation approach:

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

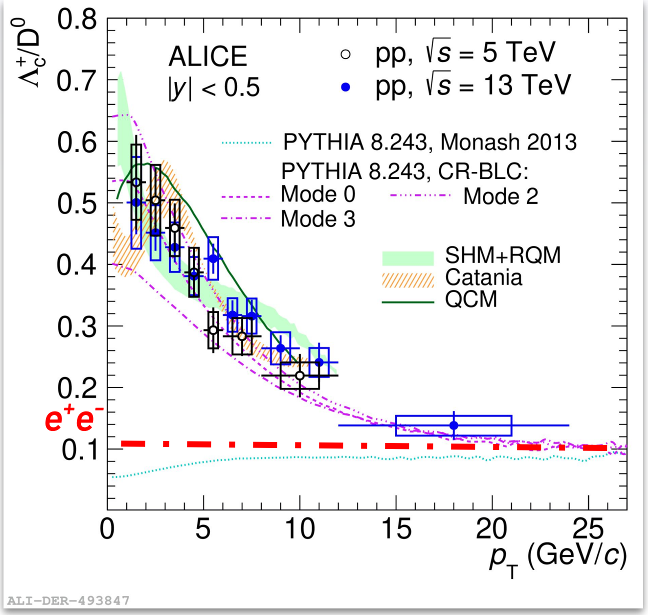
Parton distribution functions

Hard scattering cross section (pQCD)

Fragmentation function (hadronisation)

Assumed **universal** across collision systems (ee,..., AA)

PRL 128 (2022) 012001



LEP: (0.113 ± 0.013 ± 0.006) EPJC 75 (2015) 19

p_T-dependent enhancement of Λ_c^+/D^0 ratio in *pp* than e^+e^-

✗ PYTHIA 8 Monash, tuned on e^+e^-, significantly underestimates the data

Enhanced Λ_c^+/D^0 production ratio in pp

ALICE

Open heavy-flavour hadron production cross section calculated by factorisation approach:

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

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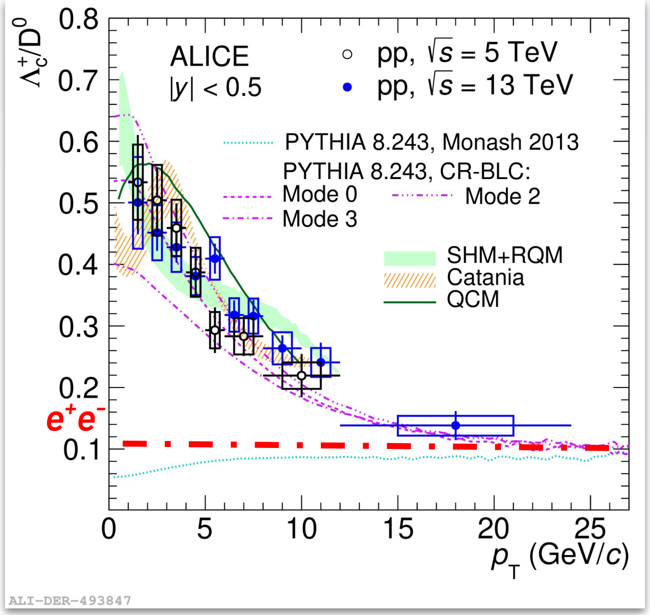
PRL 128 (2022) 012001



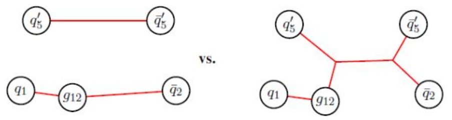
LEP: (0.113 ± 0.013 ± 0.006) EPJC 75 (2015) 19

p_T-dependent enhancement of Λ_c^+/D^0 ratio in *pp* than e^+e^-

Different hadronisation mechanism proposed:

CR modes in PYTHIA 8

JHEP 1508 (2015) 003



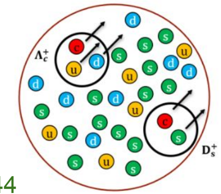
Coalescence in:

→ Catania

arXiv:2012.12001

→ QCM

EPJC (2018) 78:344



Augmented charm feed-down in SHM+RQM

→ PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c

→ RQM: + 18 Λ^*_c, 42 Σ^*_c, 62 Ξ^*_c, 34 Ω^*_c

PLB 795 (2019) 117-121

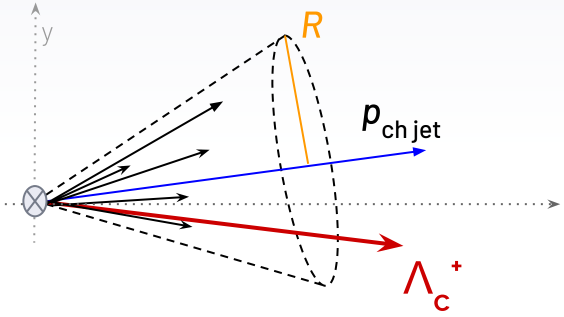
Charm-tagged jets

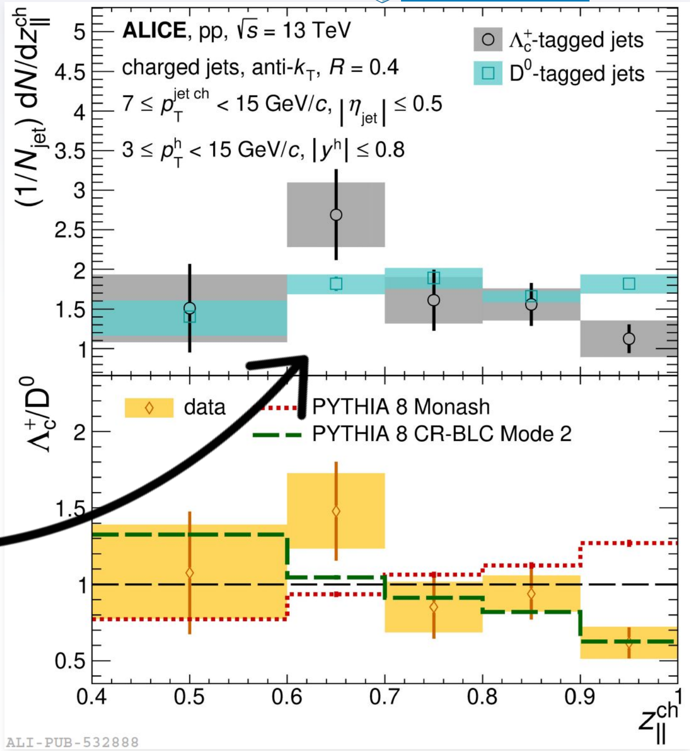
→ Probe the fragmentation of charm quarks into charm mesons and baryons

[arXiv:2301.13798](https://arxiv.org/abs/2301.13798)

Longitudinal momentum fraction

$$z_{||} = \frac{\vec{p}_{\mathrm{ch\ jet}} \cdot \vec{p}_{\mathrm{HF}}}{\vec{p}_{\mathrm{ch\ jet}} \cdot \vec{p}_{\mathrm{ch\ jet}}}$$





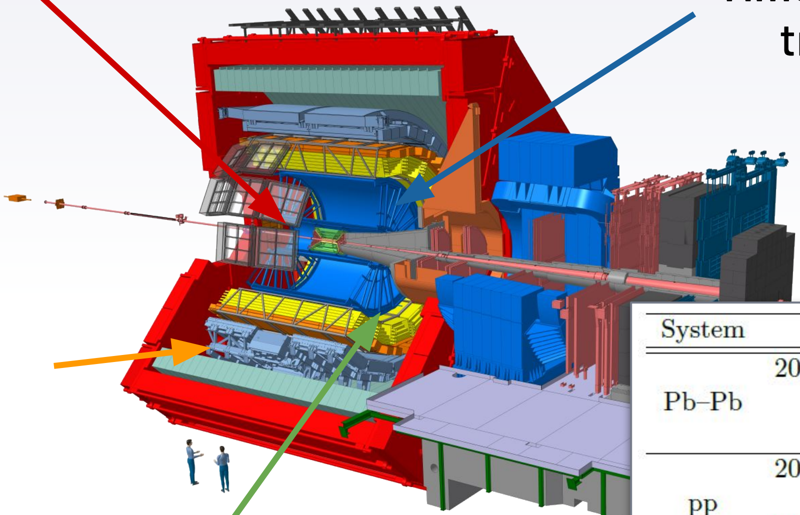
- ➢ hint of **softer fragmentation** into Λ_c^+ than D^0
  - → does this reflect in **azimuthal correlations**?
- ➢ Better reproduced by PYTHIA8, CR mode 2 than Monash

Charm hadron - charged particles azimuthal correlation analyses

A Large Ion Collider Experiment

V0:
trigger and event selection

Time Projection Chamber (TPC):
tracking and **PID** via dE/dx



Time-Of-Flight Detector (**TOF**):
PID via time of flight

Inner Tracking System (ITS):
tracking, **vertexing**

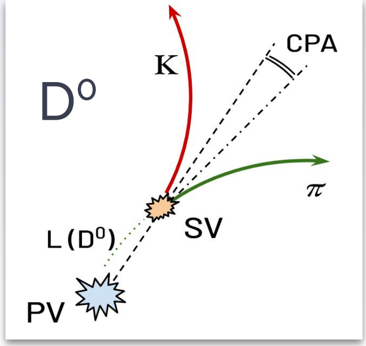
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb–Pb	2010-2011	2.76	$\approx 75\,\mu b^{-1}$
	2015	5.02	$\approx 250\,\mu b^{-1}$
	2018	5.02	$\approx 1\,nb^{-1}$
pp	2009-2013	0.9, 2.76	$\approx 200\,nb^{-1}$, $\approx 100\,nb^{-1}$
		7, 8	$\approx 1.5\,pb^{-1}$, $\approx 2.5\,pb^{-1}$
	2015-2017	5.02	$\approx 1.8\,pb^{-1}$
	2015-2018	13	$\approx 25\,pb^{-1}$

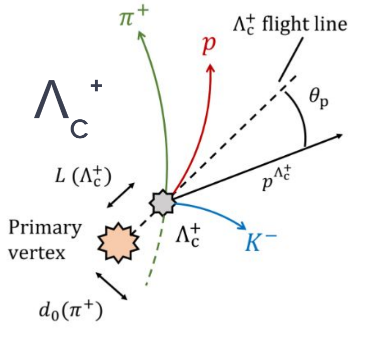
For these analyses

Selected ***pp minimum-bias*** events:
$N_{evt} = 1.7B$, $L_{int} \sim 29\ nb^{-1}$

Trigger candidate reconstruction

Two trigger charm hadron cases are analysed:





Hadron	Mass (MeV/c)	$c\tau$ (μm)	Decay (BR)
D^0	1864.84±0.05	123	$K^-\pi^+$((3.95±0.03)%)
Λ_c^+	2286.46±0.14	60.4	$pK^-\pi^+$ ((6.26±0.29) %)

Identification performed through variables related to

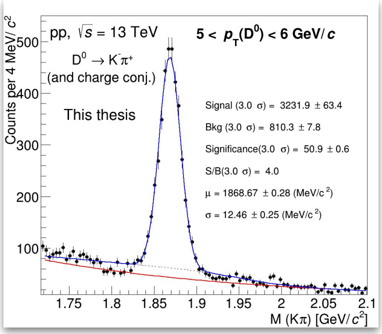
→ the **displaced decay topology**

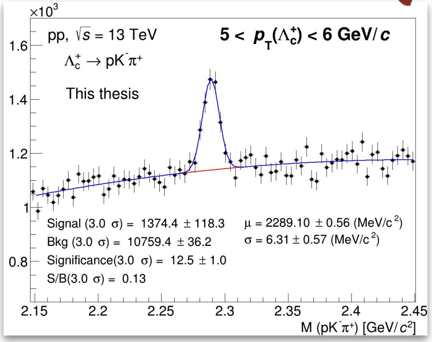
→ daughter **PID information** in TPC and TOF detectors

Rectangular selections

ML selections

XGBoost





Associated particles

Only "primary" particles [1] considered:

→ $|\eta| < 0.8$ (Barrel acceptance)

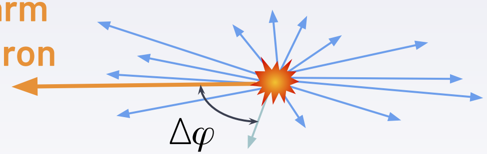
→ satisfying **tracking** requirements (**ITS**, **TPC**)

→ $DCA_{xy,z} < 1$ cm

1) ALICE "primary" particles

Building ($\Delta\varphi$,$\Delta\eta$) angular correlation distributions

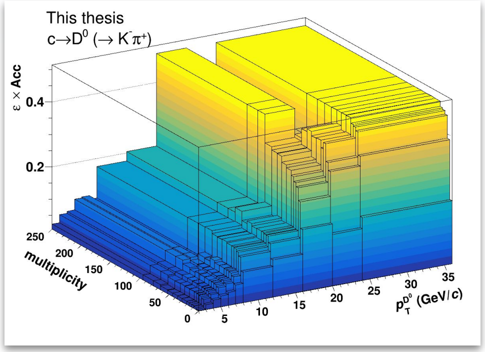
The angular separation ($\Delta\varphi$,$\Delta\eta$) between each candidate and charged associated particles is stored in 2D angular correlation distributions.

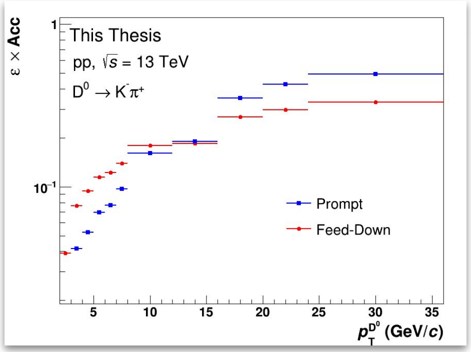


Each correlation pair is weighted by:

Trigger candidate reconstruction efficiency

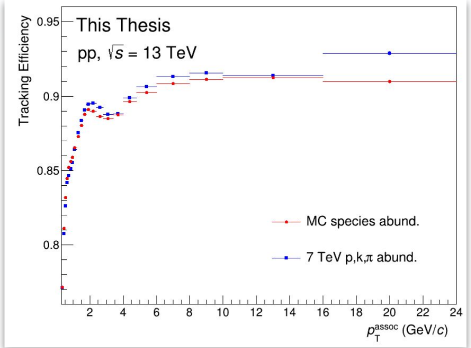
ε x Acc (tracklets mult, p_T)





Associated particle tracking efficiency

ε_{track} (p_T, η, z_{vtx})

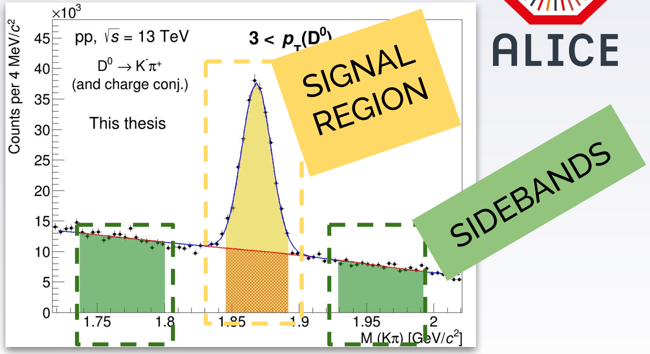


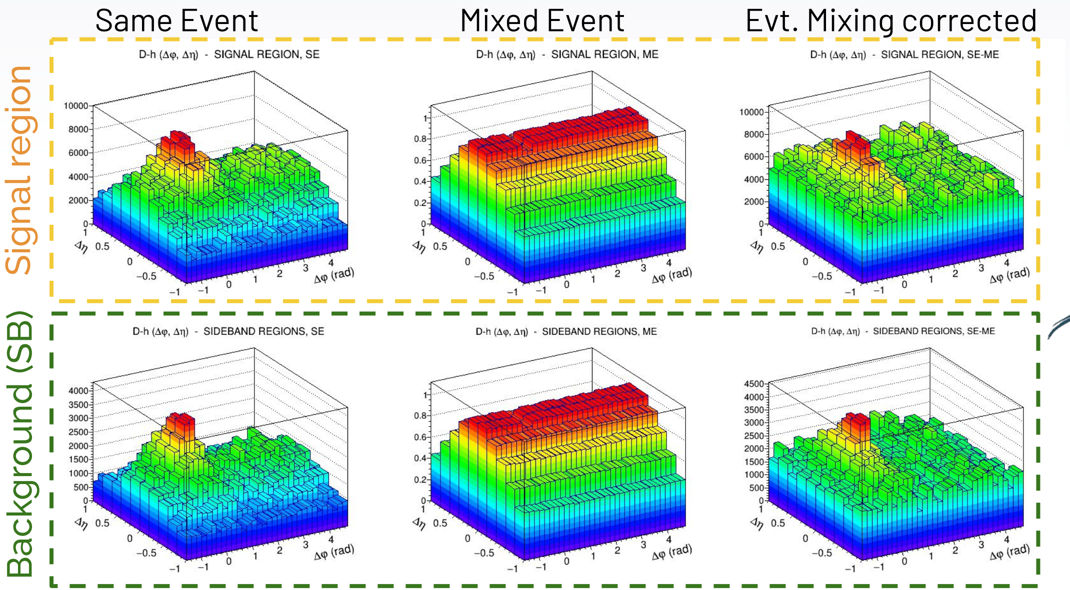
Angular correlation distributions ($\Delta\varphi$,$\Delta\eta$) are then built in separate transverse momentum intervals.

Event-mixing & background subtraction

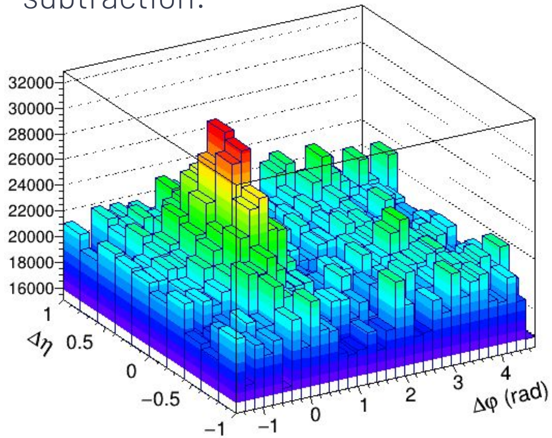
A M_{inv} based analysis is performed to extrapolate signal correlation distributions

→ The **Evt. Mixing correction** is applied considering events with similar features (pool) in terms of **event multiplicity**, and $\mathbf{z_{vtx}}$ position.





After pool integration and background subtraction:

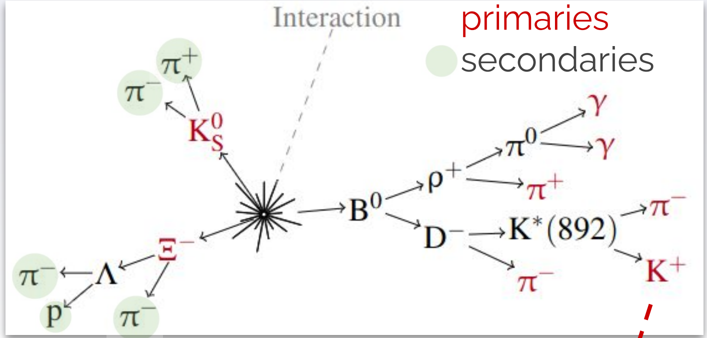


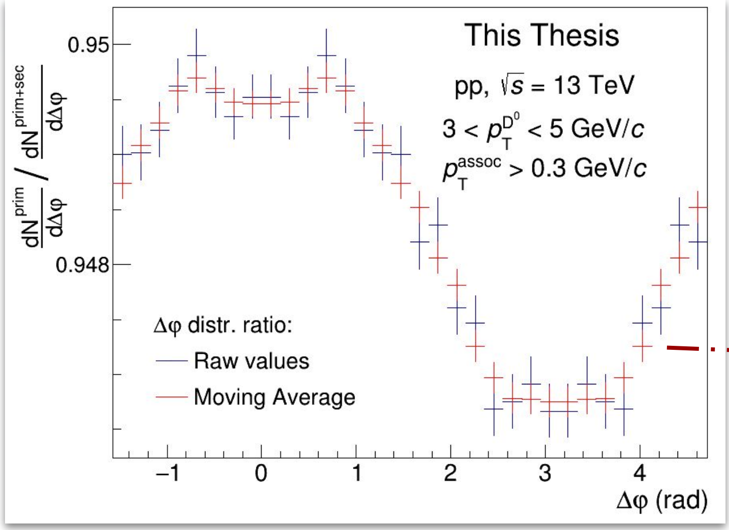
Secondary particle contamination

Stable particles surviving **DCA** cuts, generally coming from:

- interaction of primary tracks with the **detector material**
- products of **weak decays** (excluding HF fragments)

The contamination is estimated from Monte Carlo simulations





Δφ-distributions computed considering only primaries and associated inclusive sample to determine the Δφ-modulation

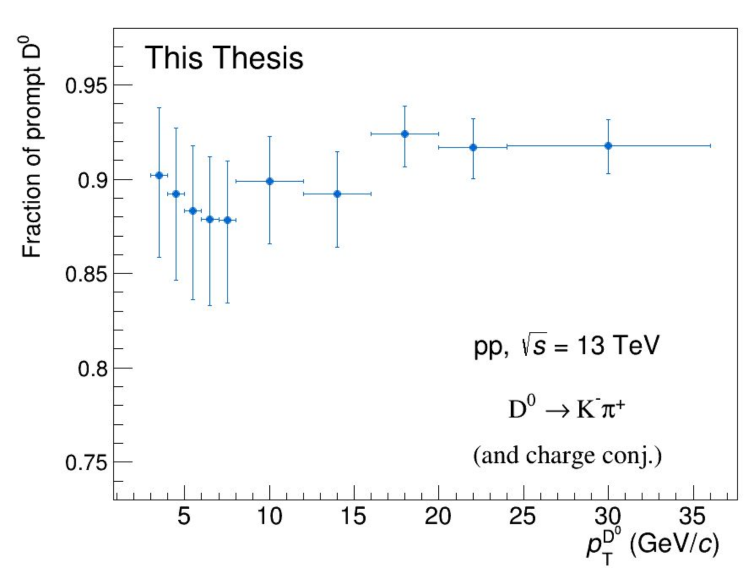
The **moving average** $(\Delta\varphi)$ is considered as a bin-by-bin modulation of the azimuthal correlation distribution.

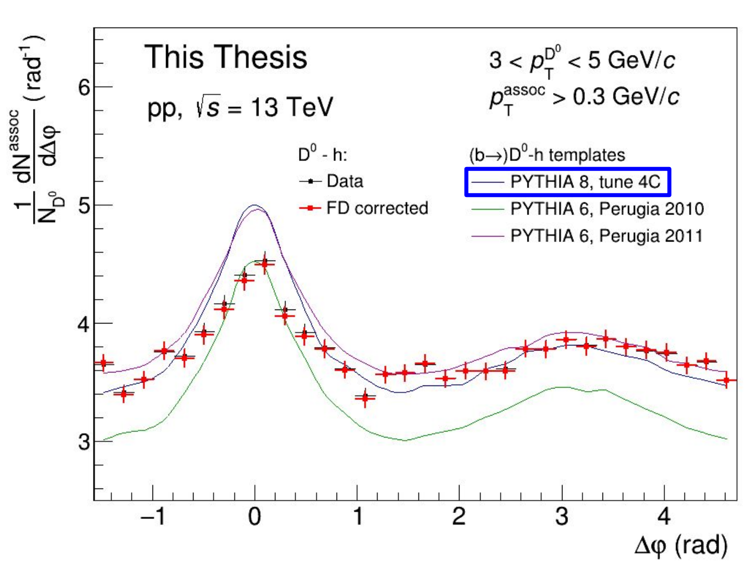
Beauty feed-down subtraction

Contamination from beauty feed-down is subtracted considering:

→ fraction of non-prompt charm hadrons $f_{\text{prompt}} = 1 - \frac{N_{\text{raw}}^{\text{D}+\overline{\text{D}}\,\text{feed-down}}}{N_{\text{raw}}^{\text{D}+\overline{\text{D}}}}$

→ non prompt H_c-h correlation MC templates $\tilde{C}_{\text{prompt}}(\Delta\varphi) = \frac{1}{f_{\text{prompt}}}\left(\tilde{C}_{\text{inclusive}}(\Delta\varphi) - (1 - f_{\text{prompt}})\tilde{C}^{\text{MC templ}}_{\text{feed-down}}(\Delta\varphi)\right)$





*Λ_c: beauty $d\sigma^{\text{FONLL}}/dp_T$, FF $(b \rightarrow \Lambda_b)$ LHCb, $\Lambda_b \rightarrow \Lambda_c$ performed by PYTHIA 8

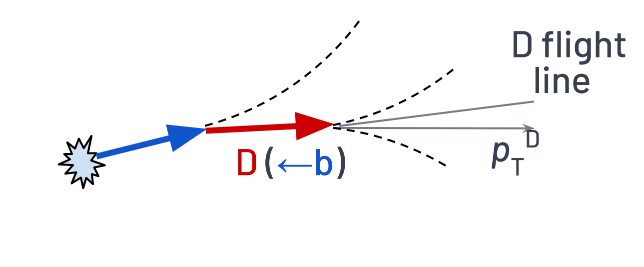
Beauty bias in azimuthal correlations

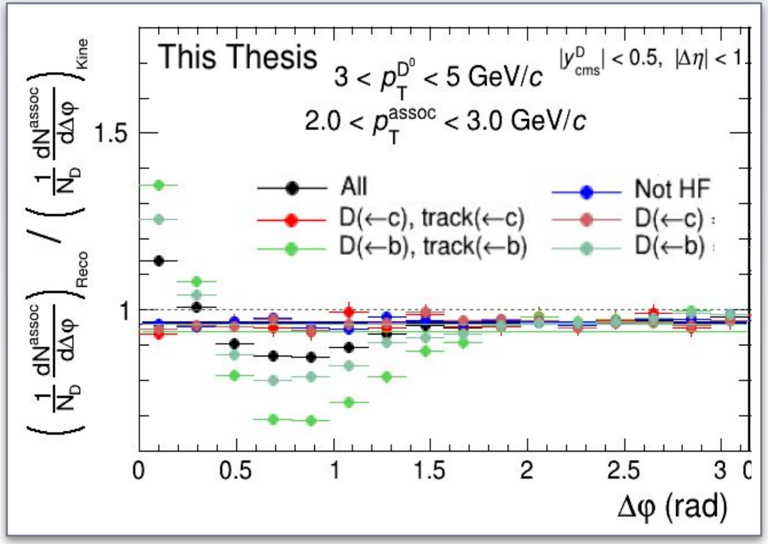
From MC simulations:

→ difference between generated and reconstructed level in $\Delta\varphi$ correlation distributions with **beauty-origin**

- enhancement at $\Delta\varphi$ ~ 0, followed by a depletion

→ induced by **topological selections** on the non-prompt hadron (mainly $\cos\theta_P$)





$$C(\Delta\varphi)_{corr} = C(\Delta\varphi)_{raw} \cdot \left[\frac{c \to D^0|_{amplit}}{(b+c) \to D^0|_{amplit}} \cdot f_{prompt} + \frac{b \to D^0|_{amplit}}{(b+c) \to D^0|_{amplit}} \cdot \frac{(1 - f_{prompt})}{modul} \right]$$

A $\Delta\varphi$-dependent modulation around $\Delta\varphi$~0, is therefore applied to the correlation distribution.

Fit of the azimuthal correlation distributions

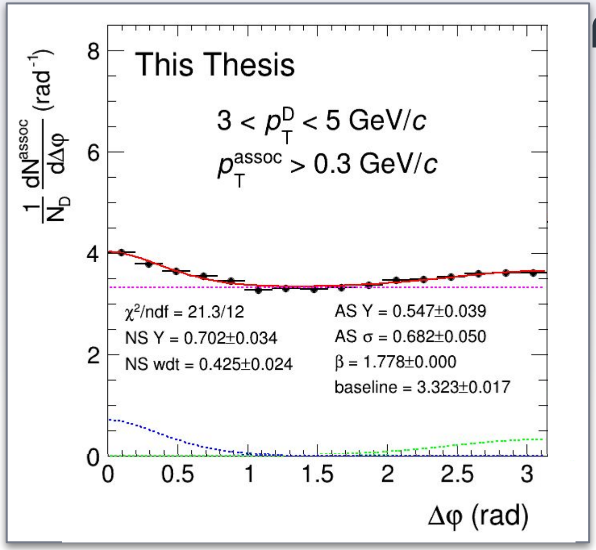
→ D^0 distributions averaged with D^+ and D^* results

The fully corrected azimuthal correlation distribution are then fitted considering the periodic function:

Baseline — Near-side — Away-side

$$f(\Delta\varphi) = a + \frac{Y_{NS} \times \beta}{2\alpha\,\Gamma(1/\beta)} \times e^{-\left(\frac{\Delta\varphi}{\alpha}\right)^{\beta}} + \frac{Y_{AS}}{\sqrt{2\pi}\sigma_{AS}} \times e^{-\frac{(\Delta\varphi-\pi)^2}{2\sigma_{AS}^2}}$$

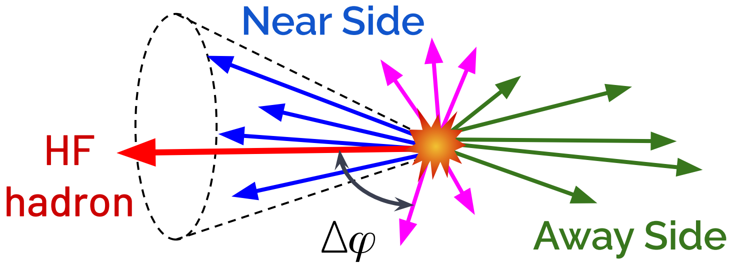
Generalized Gaussian → β is fixed to Monte Carlo templates



The properties of the peaks are described by:

→ Y_{NS}, Y_{AS} are the **per-trigger associated particle yields**

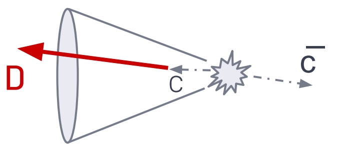
→ σ_{NS}, σ_{AS} the **widths of the two peaks**



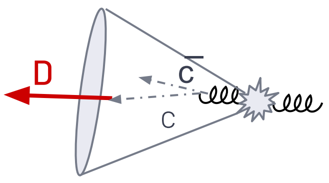
D-h near-side properties comparison with √s

Near-Side: description of charm-jet constituents, their momentum and angular displacement wrt the trigger

LO: pair production



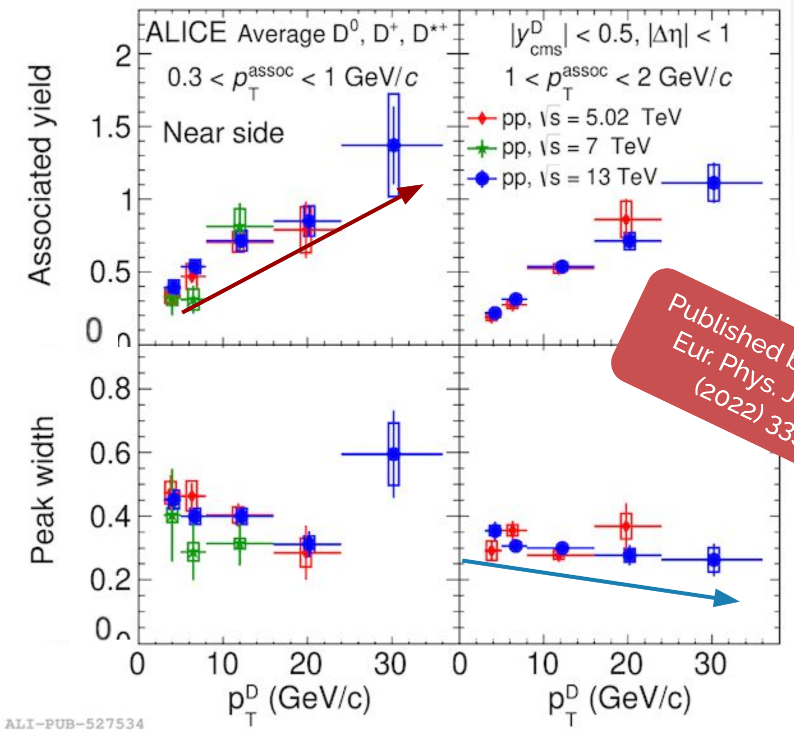
NLO: gluon splitting



With increasing p_T^D:

- → More energetic parton
  - → more phase space for other fragments
    - → increasing yields
- → Larger heavy-quark boost
  - → more collimated shower
    - → sharpening of the peak

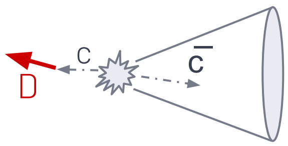
No centre-of-mass energy dependence



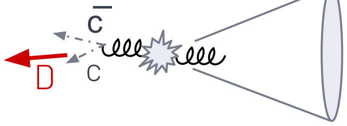
D-h away-side properties comparison with √s

Away-Side provide description of the recoil-jet, not necessarily developed by a charm

LO: pair production



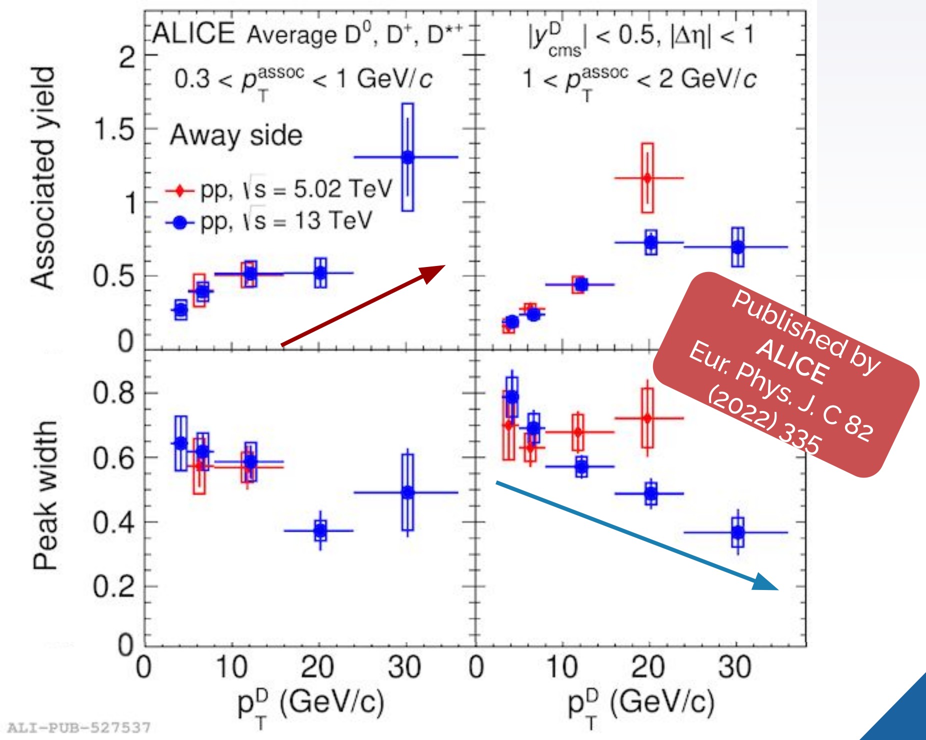
NLO: gluon splitting



As for the NS, with increasing p_T^D:

→ More energetic parton
- → more phase space for other fragments
  - → **increasing yields**
- → more collimated shower
  - → **sharpening of the peak**

No centre-of-mass energy dependence



Near-side characterisation in MC predictions

Validation of charm-jet description by **Monte Carlo** generators

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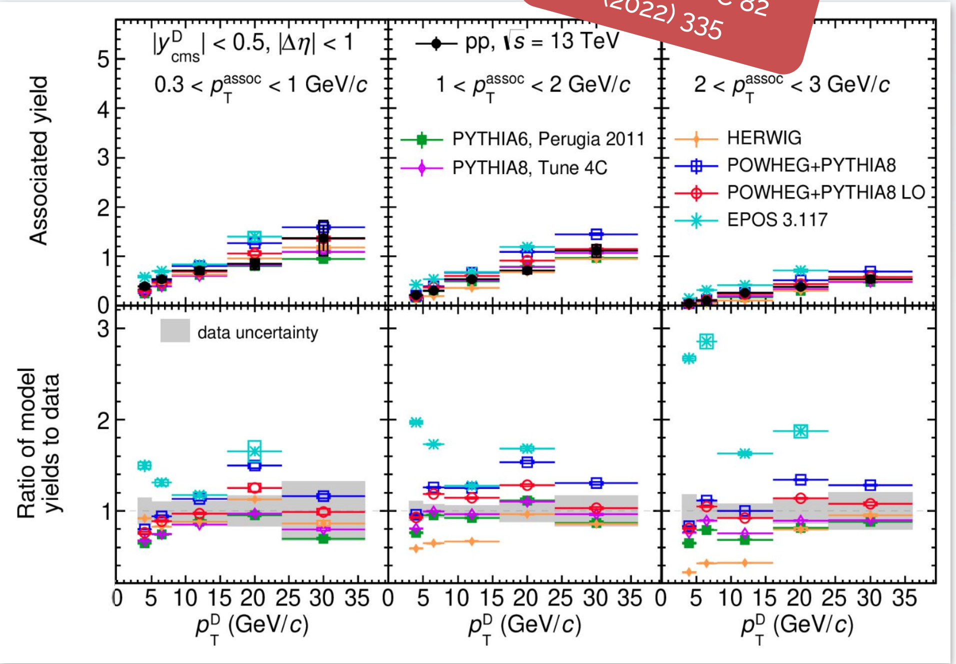
Eur. Phys. J. C 82 (2022) 335

NS yields:

- ➔ Larger values at high-p_T(D) by POWHEG+PYTHIA8 than PYTHIA8 because of GS contribution
- ➔ About 10% larger yields for POWHEG+PYTHIA8 w.r.t. POWHEG+PYTHIA8 LO
  → more collinear production via GS
- ➔ HERWIG tends to underestimate the NS yields at low p_T(D) and at high p_T(assoc)
- ➔ EPOS overestimates the yields over the whole pT range



PYTHIA8 and POWHEG+PYTHIA8 provide the best description

In **Backup** more details

Comparison Λ_c^+ vs D measurements

D mesons - h

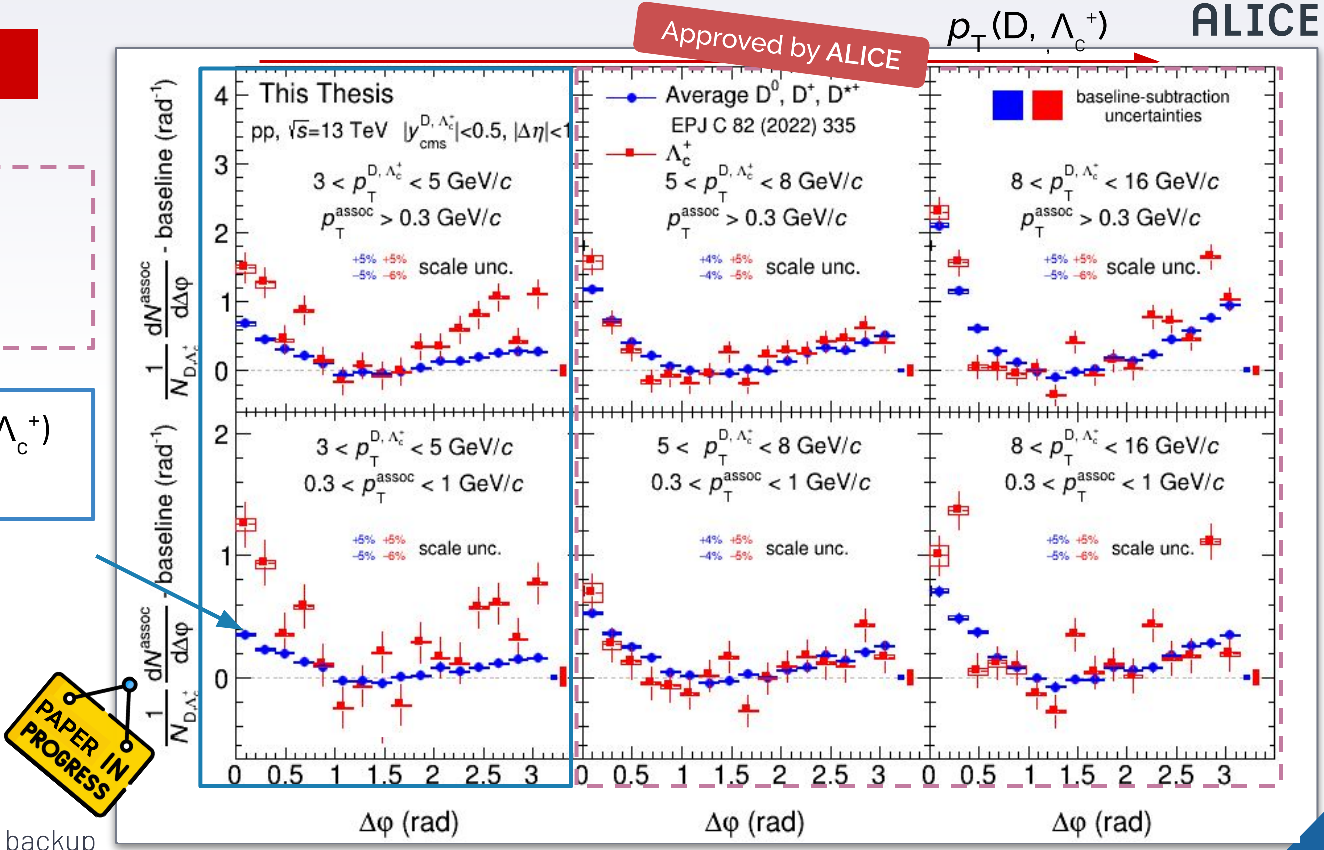
Λ_c^+- h

Eur. Phys. J. C 82, 335 (2022)

→ good agreement between the $\Delta\varphi$ distribution for $p_T(\Lambda^+_c) > 5$ GeV/c

→ small deviations in NS peaks

→ Significant deviation for low-$p_T(\Lambda_c^+)$ from D-h measurements



*Other transverse momentum intervals in backup

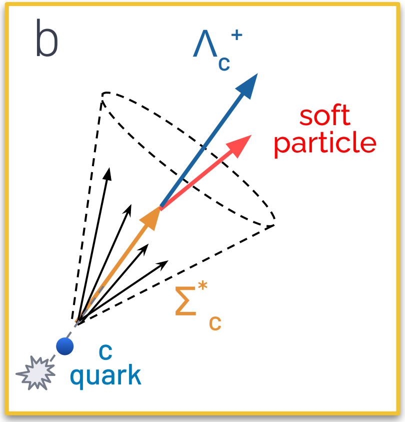
Characterisation of the Λ_c^+-jet

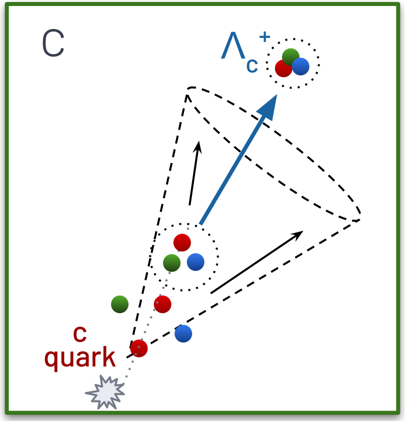
Higher **NS yields** in Λ_c^+-h than D-h at low-p_T:

a) different energy of the charm quark as a consequence of a softer Λ_c^+ fragmentation

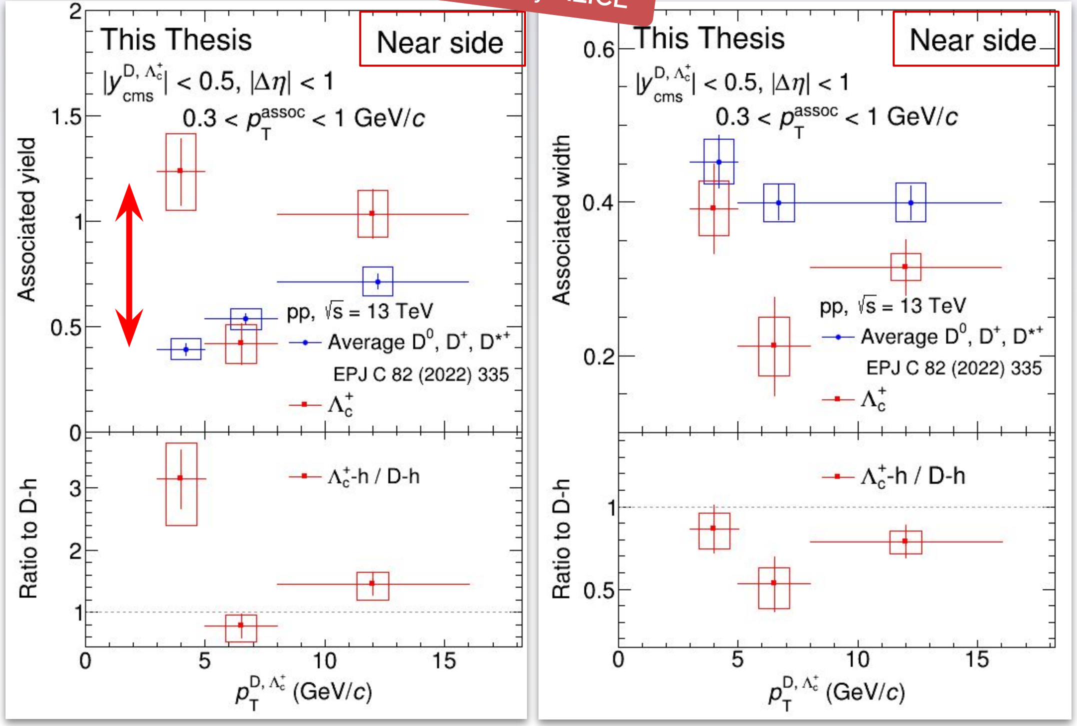
b) decay of higher mass charm states (SHM+RQM)

c) hadronisation by coalescence





Approved by ALICE



*Other transverse momentum intervals in **backup**

Characterisation of the recoil-jet

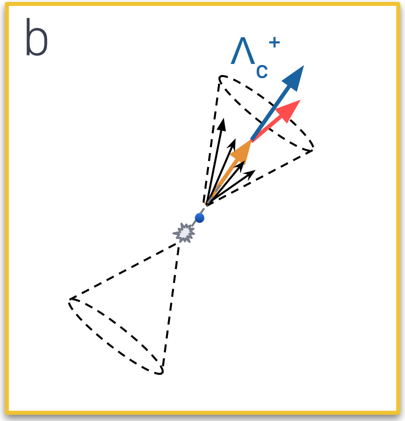
The difference between Λ_c^+ and D fragmentation and/or hadronisation reflects also in the AS.

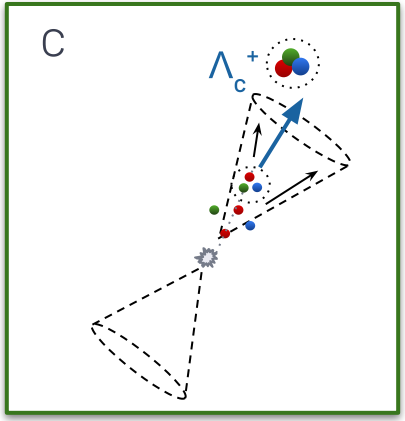
a) different energy of the charm quark as a consequence of a softer Λ_c^+ fragmentation

Less probable hypothesis:

b) decay of higher mass charm states (SHM+RQM)

c) hadronisation by coalescence





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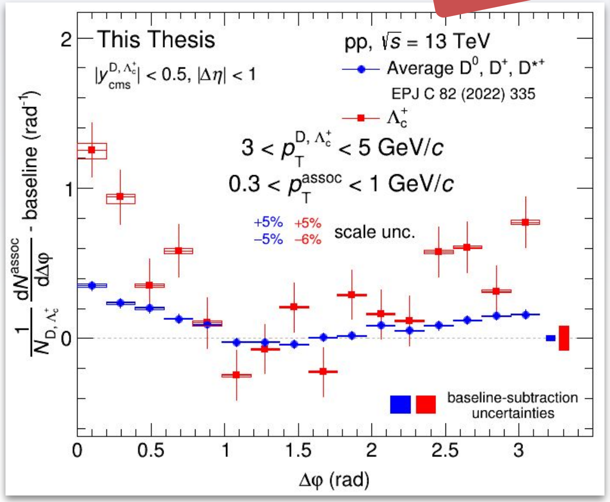
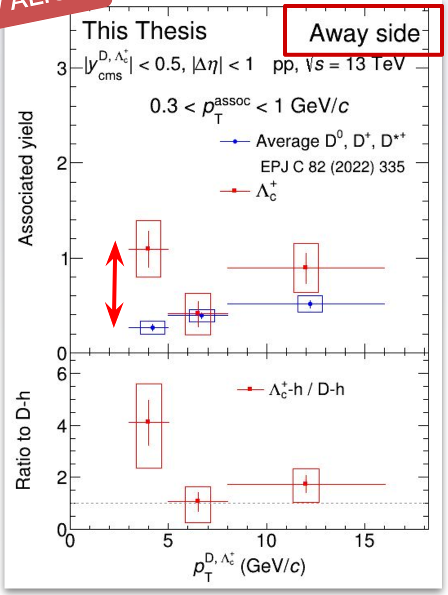




Difference between charm-to-meson and charm-to-baryon fragmentation

*Other transverse momentum intervals in **backup**

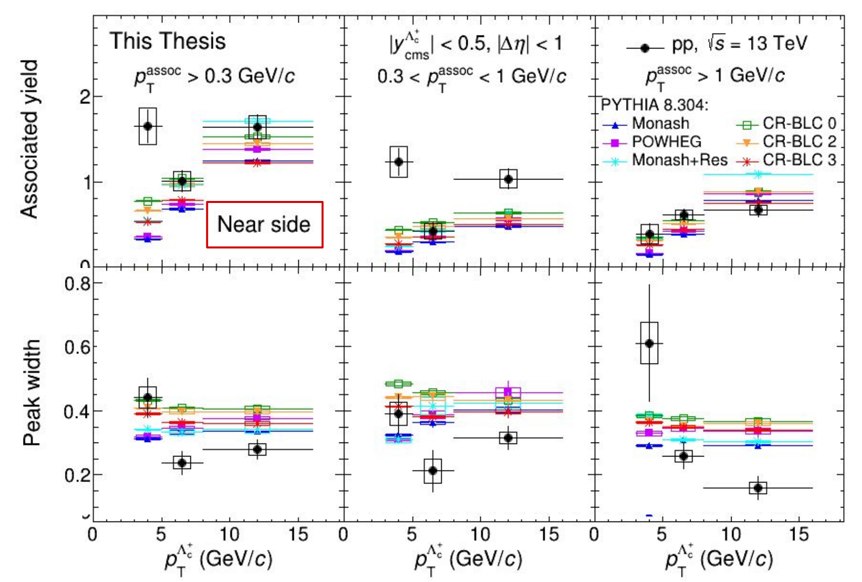
Λ_c^+-h in MC simulations

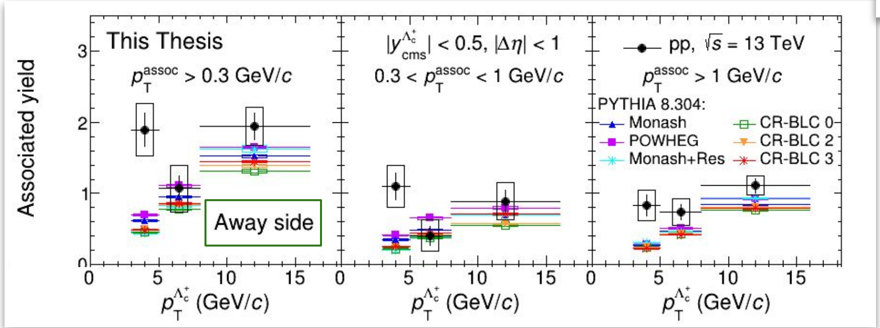
PYTHIA 8 expectations could be tested
→ Monash, CR modes, POWHEG+PYTHIA8

PYTHIA 8 Monash+Reso including SHM+RQM baryons

At small p_T^{assoc}, discrepancies in the NS & AS yields
→ Hierarchies in models:
NS: Monash < mode 3 < mode 2 < mode 0
AS: opposite

→ Reso impacts more for $p_T(\Lambda_c^+) > 5$ GeV/c





charm-to-baryon fragmentation not properly described by MC generators

PYTHIA 8 CR-BLC modes, despite predicting the Λ_c^+/D^0 p_T-dependence, are not able to fully describe the charm-jet fragmentation

Summary

Charm fragmentation detailed with D-h correlations in pp at $\sqrt{s}$=13 TeV
→ no modification depending on the centre-of-mass energy
→ sharpening of correlation peaks with increasing trigger p_T
→ PYTHIA8 and POWHEG+PYTHIA8 reproducing within uncertainties the data
→ confirming what observed in D-jets

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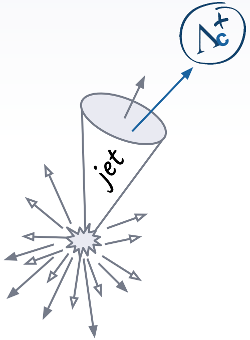


Hint of softer fragmentation Λ^+_c-h correlations as in Λ^+_c- jets
→ discrepancies in Λ^+_c-h can help in constraining Monte Carlo models
→ PYTHIA8 CR modes despite reproducing the in-jet Λ_c^+/D^0 ratio, fails with correlations
→ in contact with authors for modified hadronisation predictions

Approved by ALICE
Paper in preparation

Thanks for your attention!

Participation to conferences

TALKs

- 10^{th} International Workshop on CHARM Physics - CHARM2020
  "Charm jet and correlation measurements with ALICE in pp and p-Pb collisions at the LHC"
- Quark-Gluon Plasma Characterisation with Heavy Flavour Probes, ECT* Workshop, Trento, Nov 2021,
  "*Charm fragmentation studies with ALICE at the LHC*"
- 108° Congresso Nazionale della Società Italiana di Fisica, SIF 2022, Milano, Set 2022,
  "*Charm jets and correlations with ALICE at the LHC*"
- 11^{th} International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Mar 2023
  "First measurements of in-jet fragmentation and correlations of charmed mesons and baryons in pp collisions with ALICE"

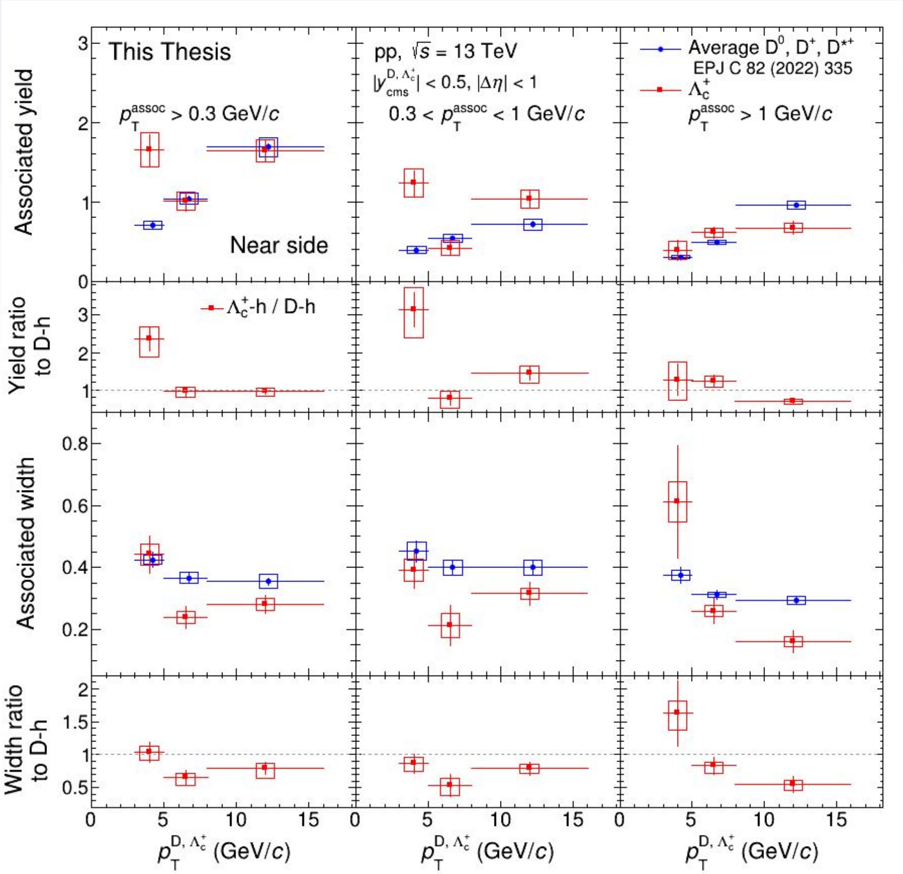
POSTERs

- XXIXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Krakow, April 2022,
  "*Beauty measurement prospects with ALICE 3*" (POSTER)
- Quinto Incontro Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, May 2022,
  "*Investigating heavy-flavour fragmentation and hadronization with jets and correlation measurements with ALICE*" (POSTER)
- 152th LHCC meeting, Nov 2023
  "*Azimuthal correlation between D mesons and charged particles in pp collision at $\sqrt{s}$ =13 TeV with ALICE*" (POSTER)

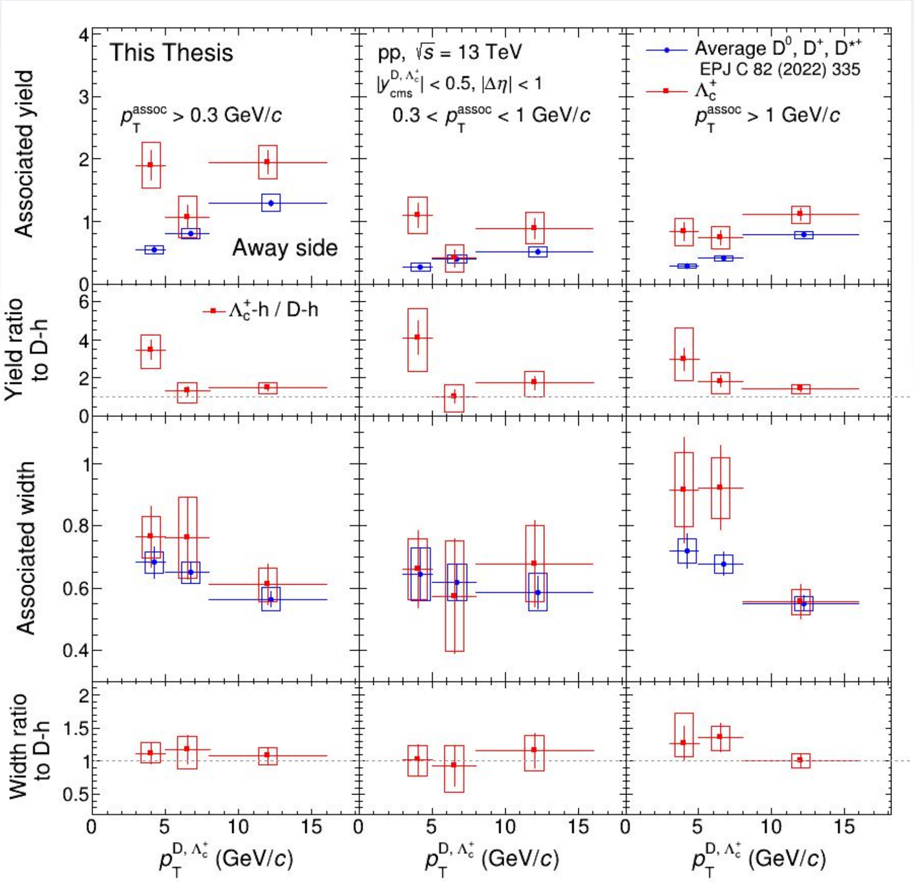
Additional Material

Results

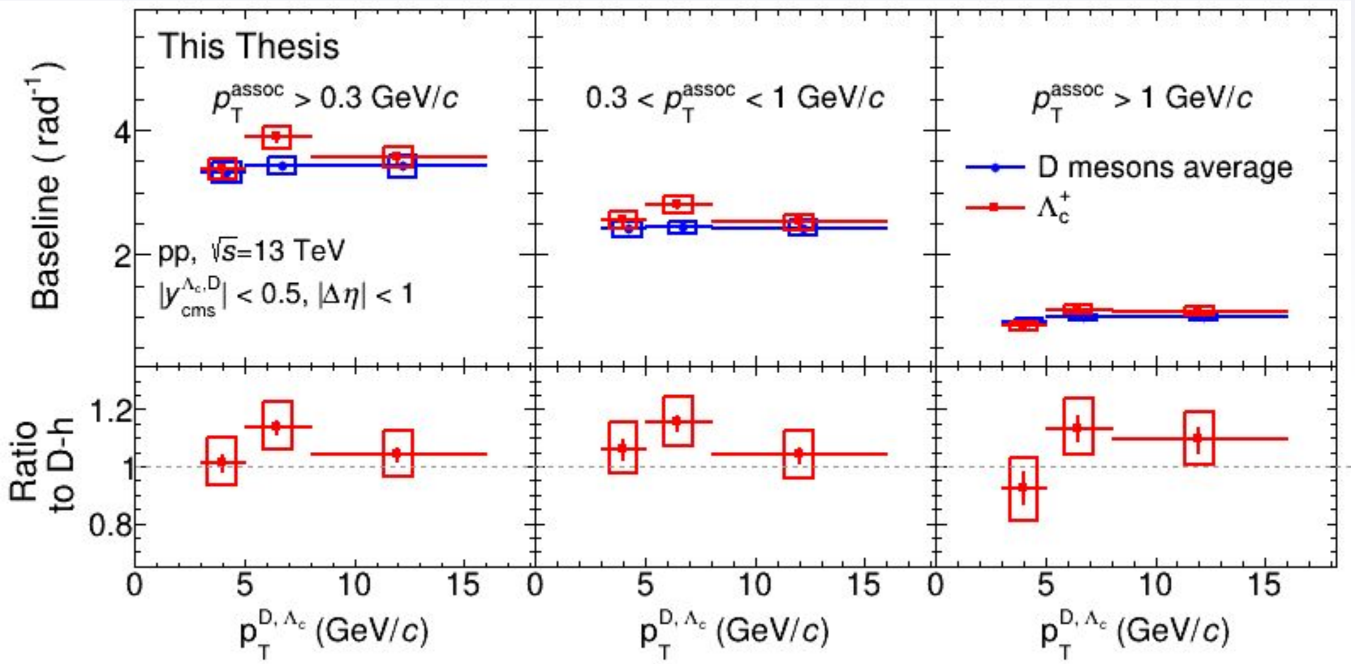
Λ_c^+-h correlations: Near-side



Λ_c^+-h correlations: Away-side

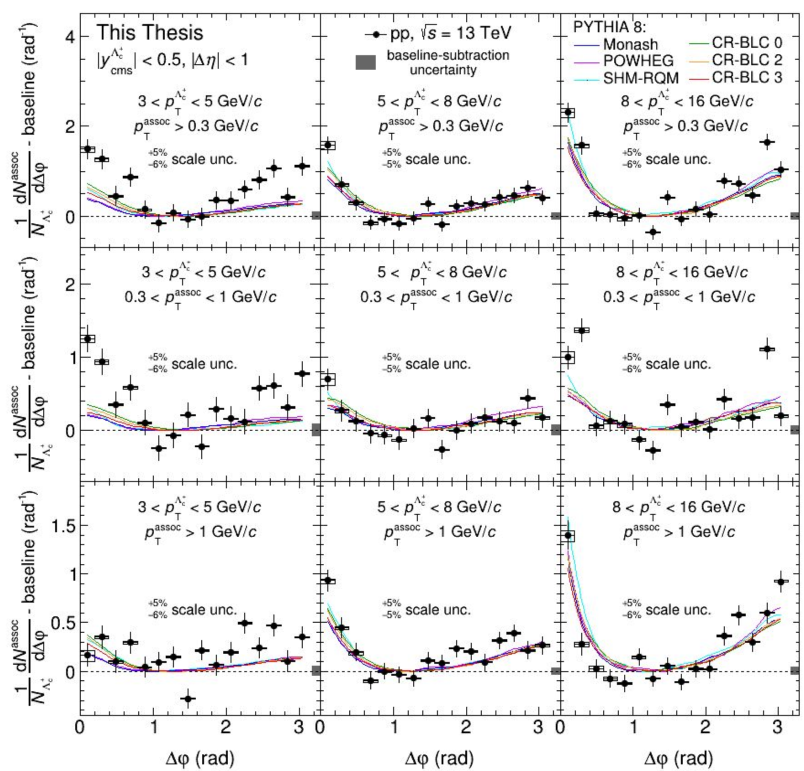


Λ_c^+-h correlations: Baseline

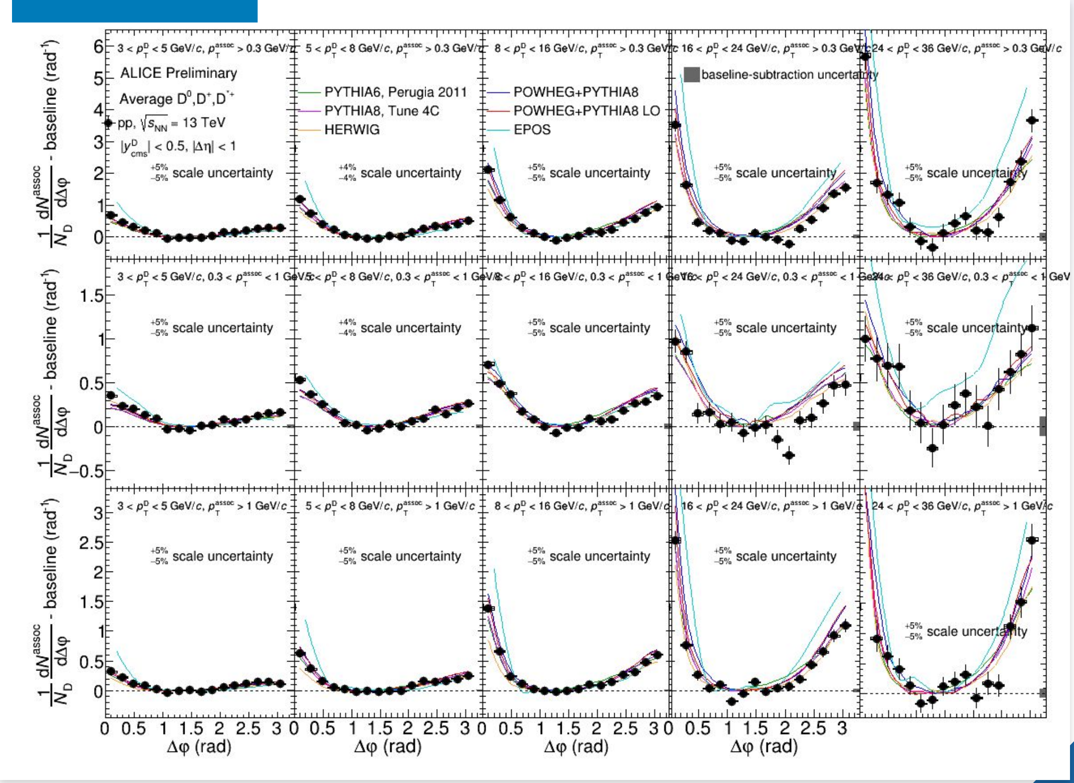


Δφ comparison with model predictions

Λ_c^+- h

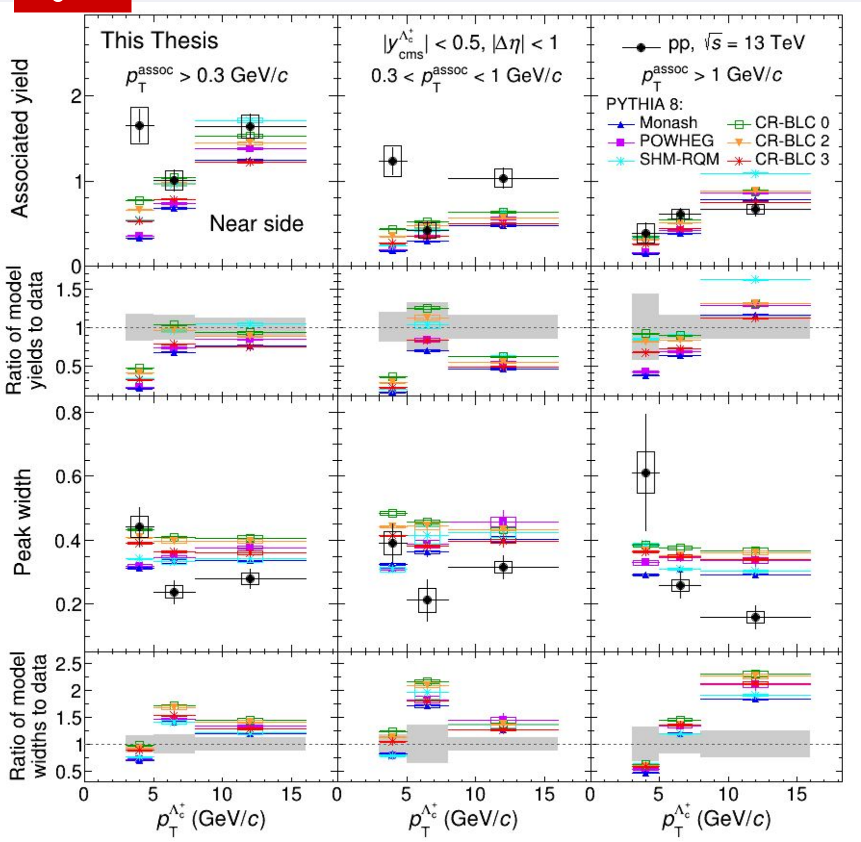


D mesons - h



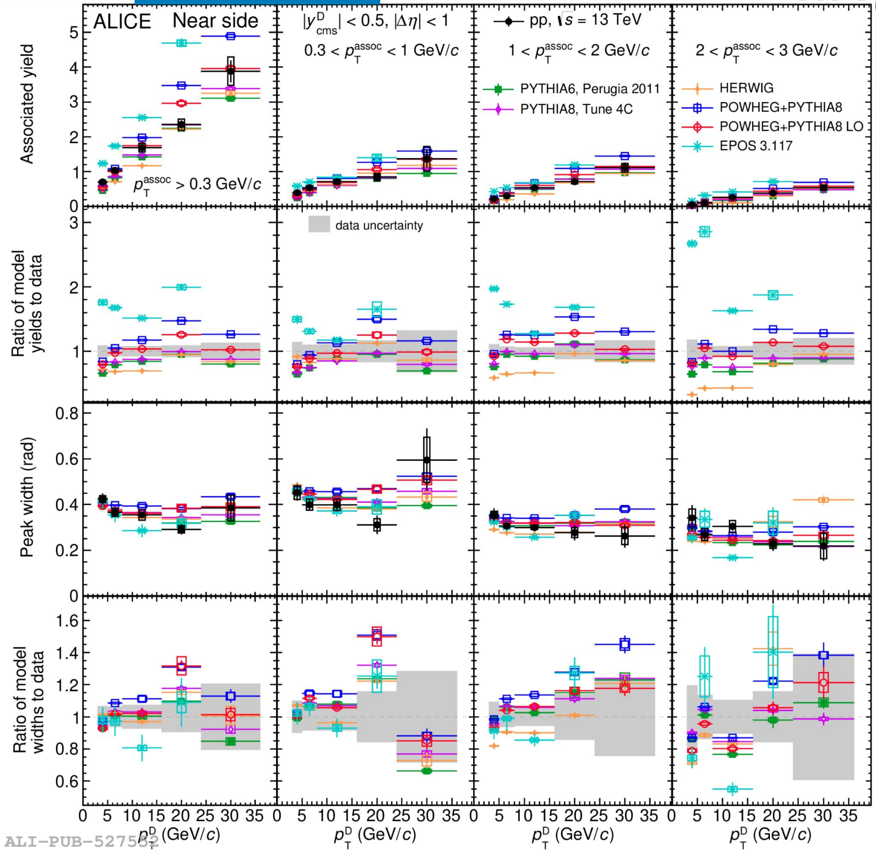
Near-side

Λ_c^+- h



D mesons - h

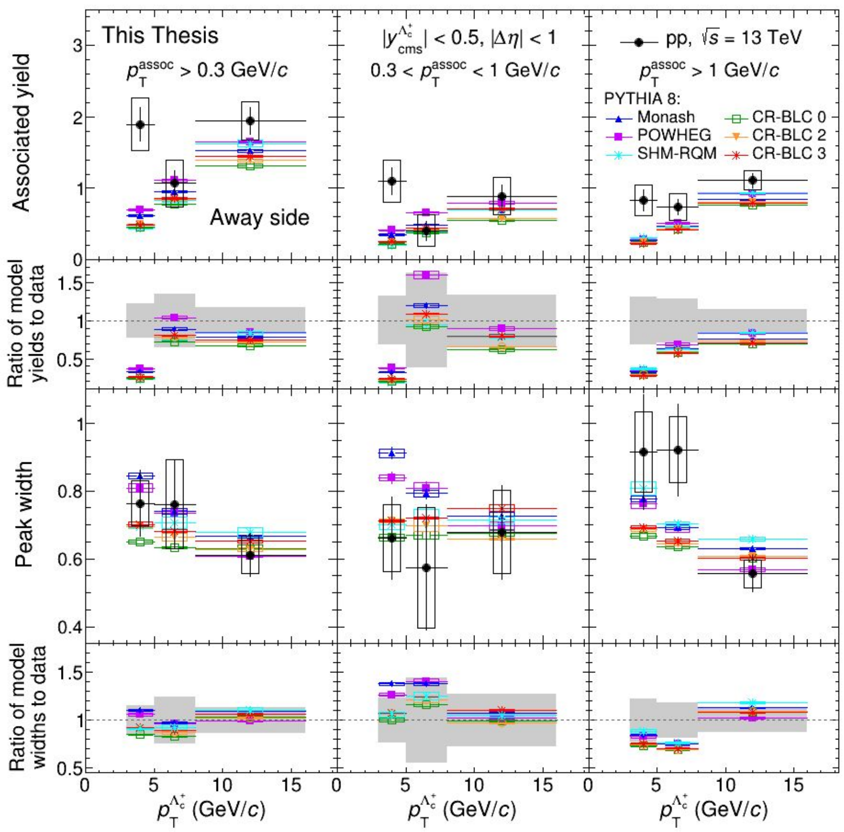
[Eur. Phys. J. C 82, 335 (2022)]



Antonio Palasciano

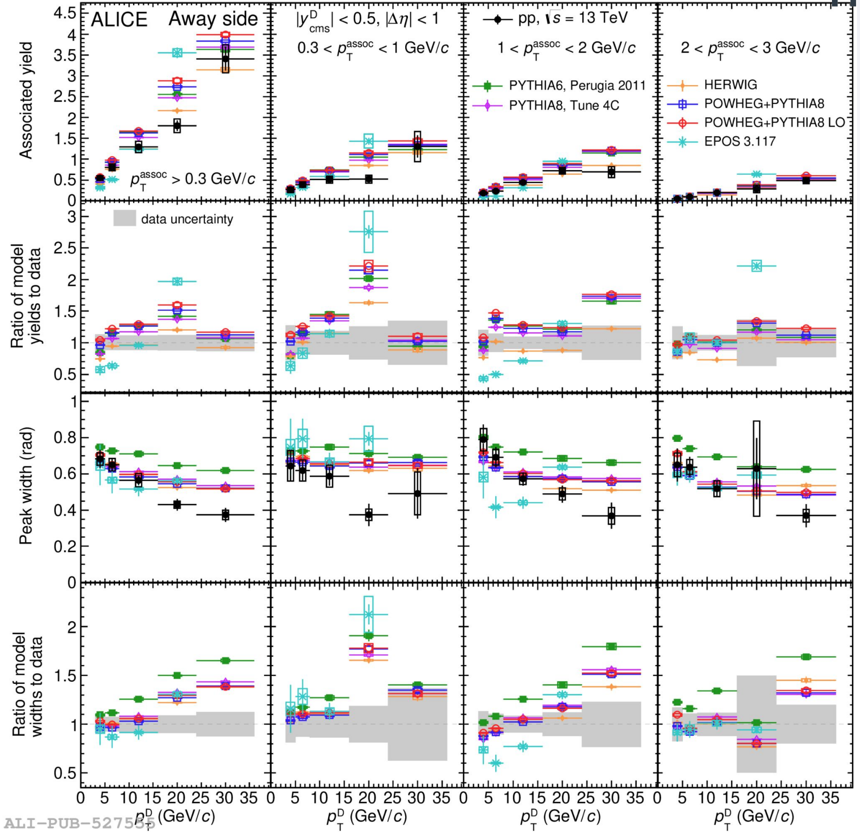
Away-side

Λ_c^+- h



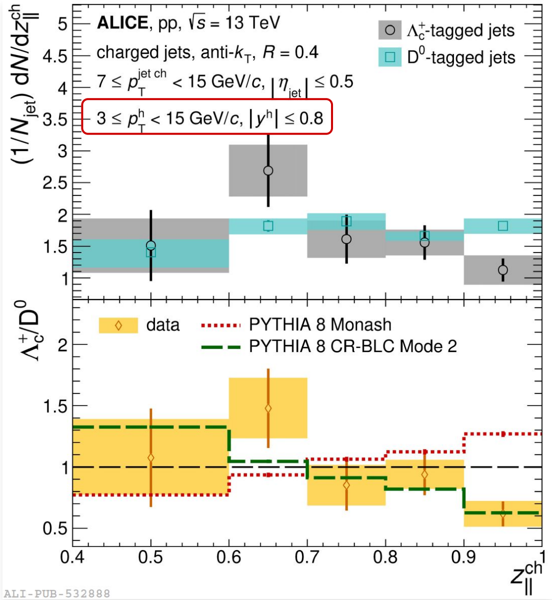
D mesons - h

[Eur. Phys. J. C 82, 335 (2022)]



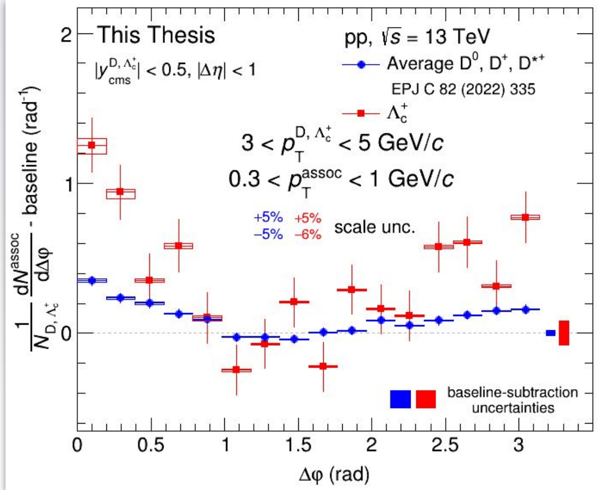
ALICE

Softer fragmentation, why?



To the **same charm quark energy**, a less energetic Λ_c than D meson

→ more phase-space available for other particles in the charm jet

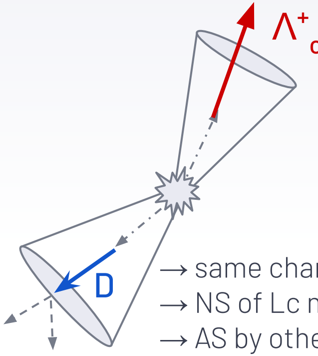


The Λ^+_c-h near-side is more populated than in the D-h

- observed only for low-p_T^{assoc}
- only for low-$p_T(\Lambda_c)$

hadronisation?

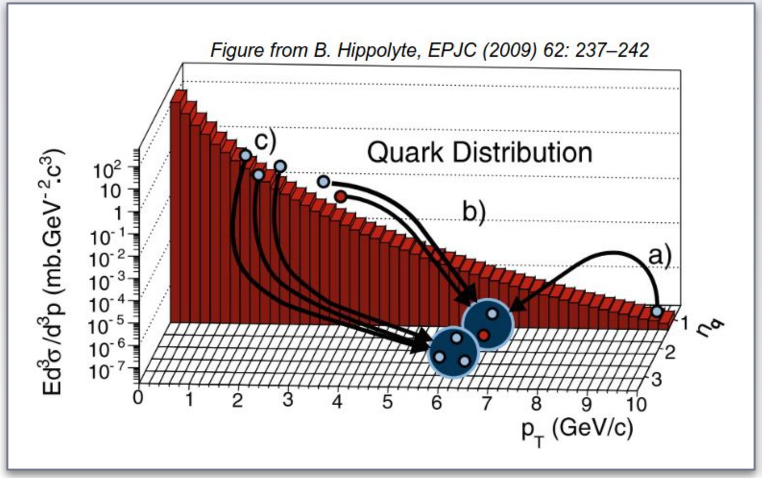
Most likely. in Λ^+_c-h

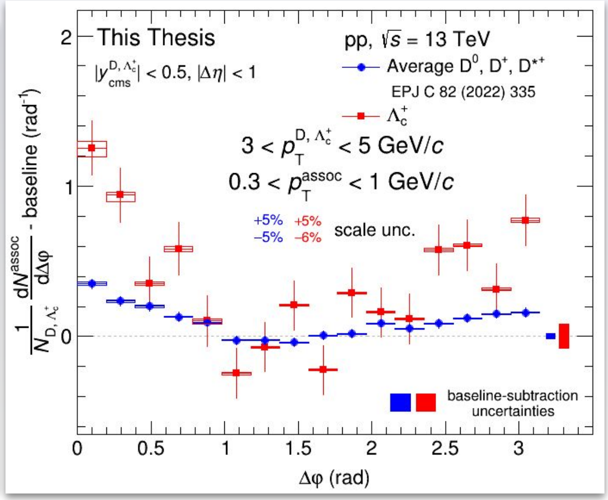


→ same charm energy
→ NS of Lc more populated
→ AS by other charm, with the pattern of D-h AS

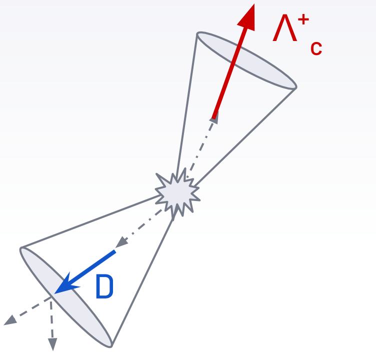
Enhancement in AS, tells us the **softer fragmentation** is ***a good hypothesis***

Is it coalescence?





Most likely. in Λ^+_c-h



In most of the models, it requires a rich parton environments:

→ high-mult, QGP droplets (Catania)
  → many not-correlated particles
  → larger baseline → NOT OBSERVED

- need for another (2x) parton to coalesce with (?)
- $p_T^{\Lambda c,\ coal} > p_T^{\Lambda c,\ fragm}$
  charm shower jet related to fragmentation
    → smaller yields in NS → LARGER OBSERVED

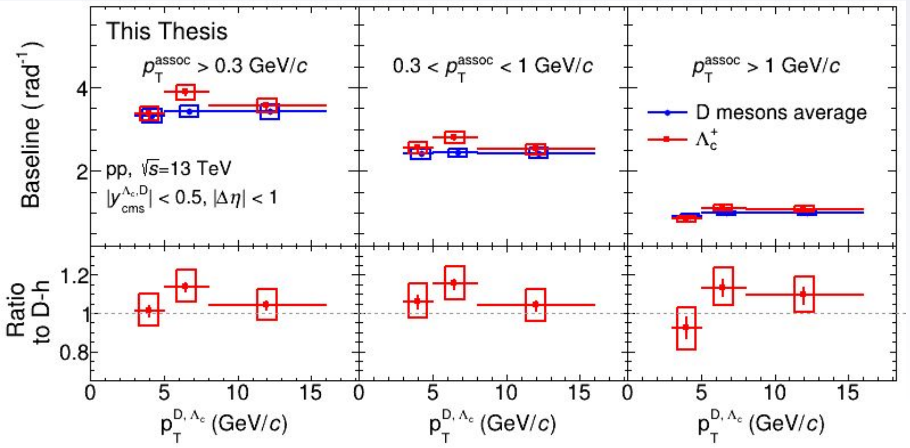
Enhancement in AS, tells us the coalescence is **NOT *a good hypothesis***

Influence of event multiplicity?

Baseline → **Underlying event**
(particles not correlated)

- compatibility in 1σ between **D-h** and **Λ^+_c-h**

→ no evidence of potential biases originated by the increasing Λ^+_c/D^0 with multiplicity

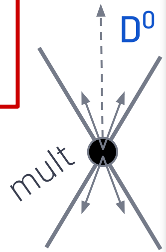


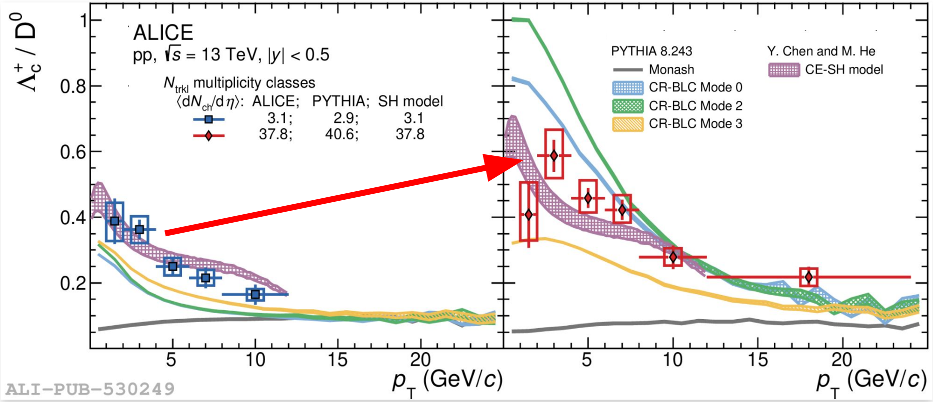
Open question:

→ is this increase related to the larger in-jet particle production?

→ is this related to the hint of slightly larger baseline in 5-8?

In case of QGP droplets (Catania) what we would see?





Analyses details

Antonio Palasciano

Candidate selection with Machine Learning

ALICE

Trigger particle: $\Lambda_c \rightarrow pK^- \pi^+$

Λ_c decay mode	Branching Ratio(Γ_i/Γ_{tot})
$pK^-\pi^+$	(6.23±0.33)%
$p\bar{K}^*(892)^0$	(2.13±0.30)%
$\Delta(1232)^{++}K^-$	(1.18±0.27)%
$\Lambda(1520)\pi^+$	(2.43±0.6)%
$pK^-\pi^+$ nonResonant	(3.8±0.4)%

Pre-Selections[1]:

$\Lambda_c^+ \rightarrow pK^-\pi^+$	p_T interval (GeV/c)
p_T(K) (GeV/c)	> 0.4
p_T(p) (GeV/c)	> 0.5
p_T(π) (GeV/c)	> 0.4
DCA	< 0.05
dist_{12}	> 0.01
σ_V	< 0.06
decay length	> 0.005
$\cos\theta_p$	$> 0.$

– 7 $p_T(\Lambda_c)$ intervals: 3-4, 4-5, 5-6, 6-7, 7-8, 8-12, 12-16 GeV/c

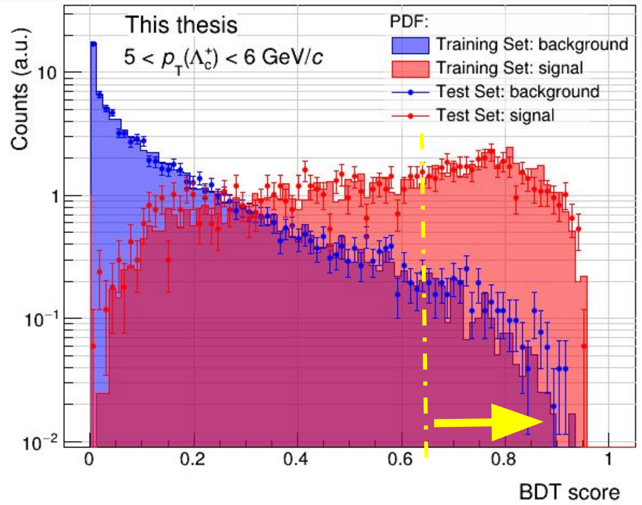
– **Binary classification** algorithm: XGBOOST, through hype4ml package
Topological and PID variables were considered for the discrimination
(more info on variables are in the Additional Material)

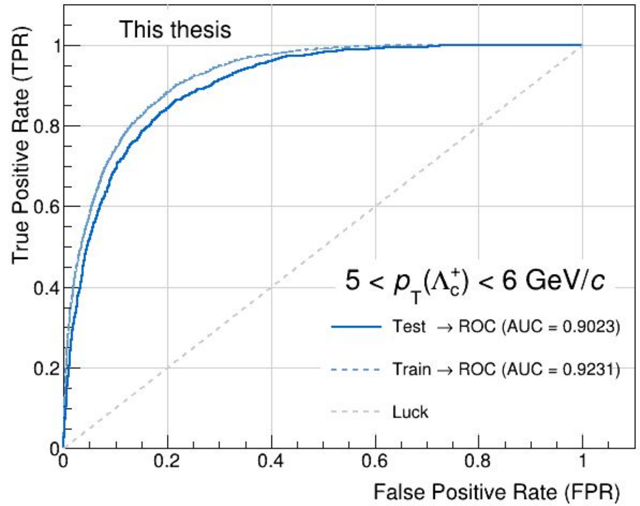
Number of signal and background for train and test of the model

p_T	# prompt Λ_c	# Background
$3-4$	$6.5 \cdot 10^3$	$3 \cdot N_{Sig}$
$4-5$	$6.0 \cdot 10^3$	$3 \cdot N_{Sig}$
$5-6$	$4.8 \cdot 10^3$	$3 \cdot N_{Sig}$
$6-7$	$3.3 \cdot 10^3$	$3 \cdot N_{Sig}$
$7-8$	$2.3 \cdot 10^3$	$5 \cdot N_{Sig}$
$8-12$	$4.1 \cdot 10^3$	$5 \cdot N_{Sig}$
$12-16$	$1.2 \cdot 10^3$	$8 \cdot N_{Sig}$

Model performances

The trained model provides a BDT score for the classification between **background** and **signal** candidates





→ the agreement between training and test samples is a test against **overfitting**
→ the separation between classes provides indication on the BDT cut value

The ROC (and the ROC(AUC)) give indication about the discrimination performances of the model

Definition of the ML working point

The expected significance and the S/B were computed:

Signal (ML): $S_{\mathrm{ML}} = 2 \cdot \frac{\mathrm{d}\sigma_{\mathrm{pp}}^{FONLL,\Lambda_c^+}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\sigma_{MB}^{\mathrm{pp}}} \cdot \Delta p_{\mathrm{T}} \Delta y \cdot BR \cdot (\epsilon \times Acc)_{ML}$

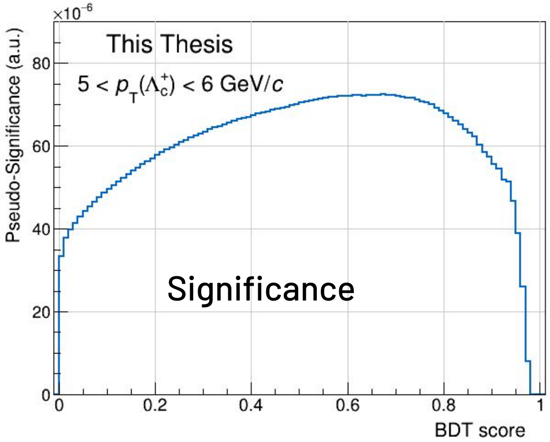
Background (ML): integral under the peak region ($\pm 3\sigma$) obtained from the M_{inv} sideband fit function

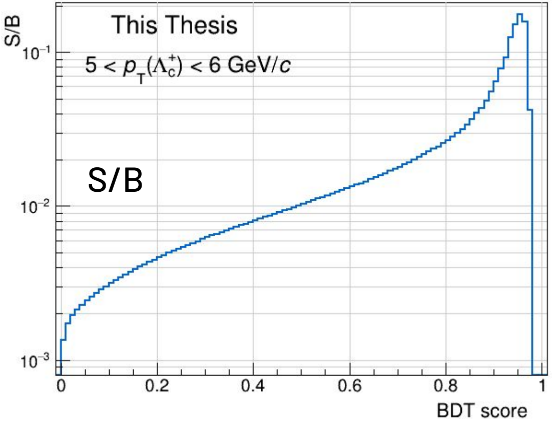
Max of **S/B** and **Significance** (per-event) not best choice:

→ correlation distributions built up to the background subtraction;

→ a scan in BDT score to test possible $\Delta\varphi$ dependence on BDT value

→BDT score inducing smaller stat. fluctuation was chosen





Associated charged particles

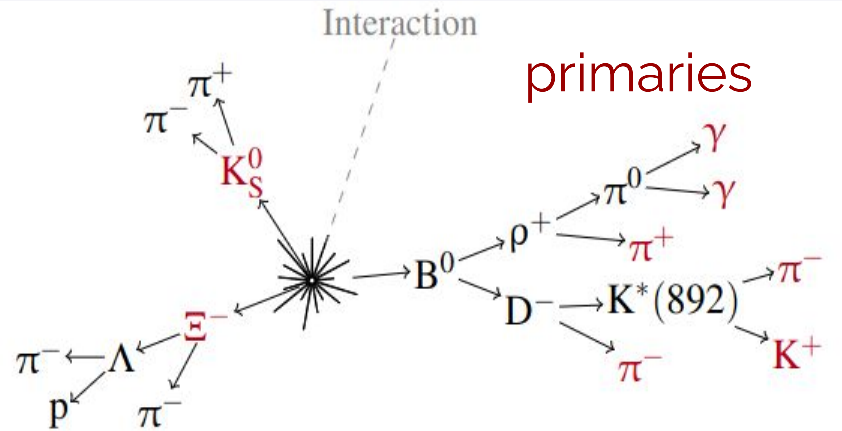
"Associated particles"

Physics selection: Physical primary

Kinematic cuts: $-0.8 < \eta < 0.8$

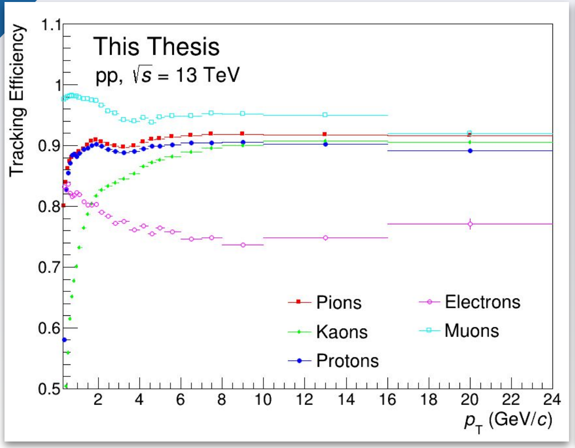
Quality cuts:
```
SetRequireSigmaToVertex(kFALSE);
SetRequireTPCRefit(kTRUE);
SetRequireITSRefit(kFALSE);
SetMinNClustersITS(2);
SetMinNCrossedRowsTPC(70);
SetMinRatioCrossedRowsOverFindableClustersTPC(0.8);
SetMaxChi2PerClusterTPC(4);
SetMaxDCAToVertexZ(1.);
SetMaxDCAToVertexXY(1.);
```

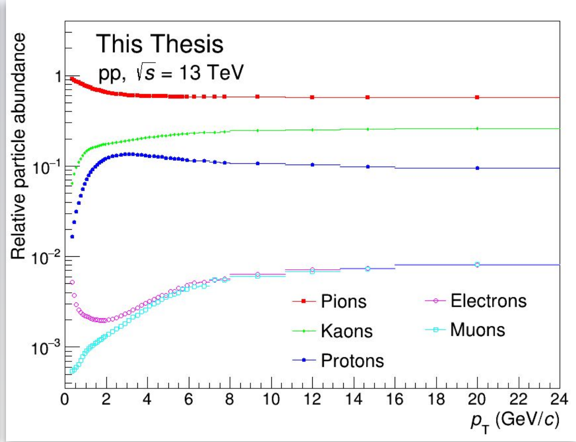
"prompt particles produced at the primary vertex"



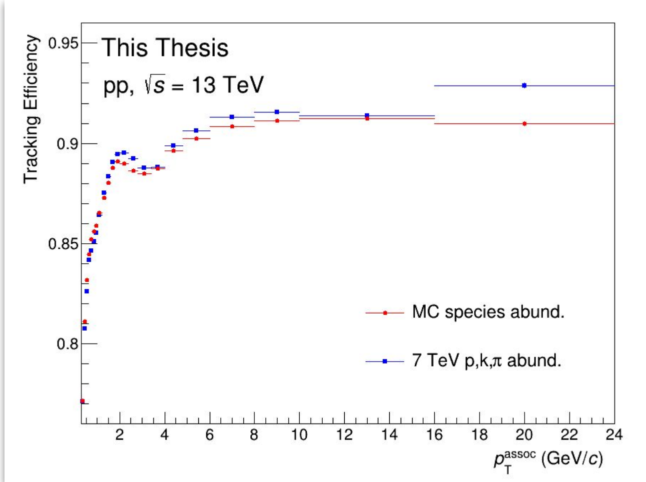
In these analyses, only **e, μ, π, K, p** are taken into account

Associated particle efficiency





Starting from MC simulations, the efficiency per species is computed and averaged with its relative abundance



Because of difference in particle abundance with respect to data, a reweighting procedure is considered

π, K, p: relative reweight to data abundancies, then the sum is scaled to its overall MC fraction — **e (MC abundancy)** — **μ (MC abundancy)**

$$\varepsilon^j_{All5Part} = \left[\sum_i^{\pi,K,p} \varepsilon^j_i \cdot \frac{N_i^{Data}(p_T)}{N_{\pi+K+p}^{Data}(p_T)}\right] \cdot \frac{N_{\pi+K+p}^{MC}(p_T)}{N_{All5Part}^{MC}(p_T)} + \varepsilon^j_e \cdot \frac{N_e^{MC}(p_T)}{N_{AllPart}^{MC}(p_T)} + \varepsilon^j_\mu \cdot \frac{N_\mu^{MC}(p_T)}{N_{All5Part}^{MC}(p_T)}$$

j = period

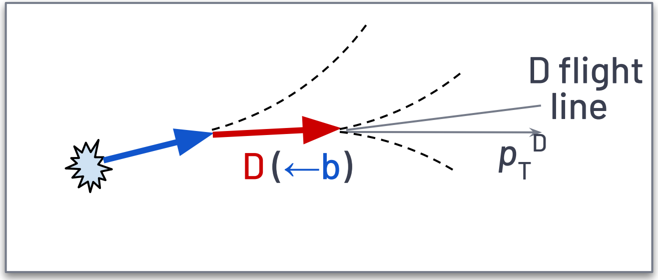
A weighted average on the number of event per data acquisition period is then performed for the extraction of the final tracking efficiency

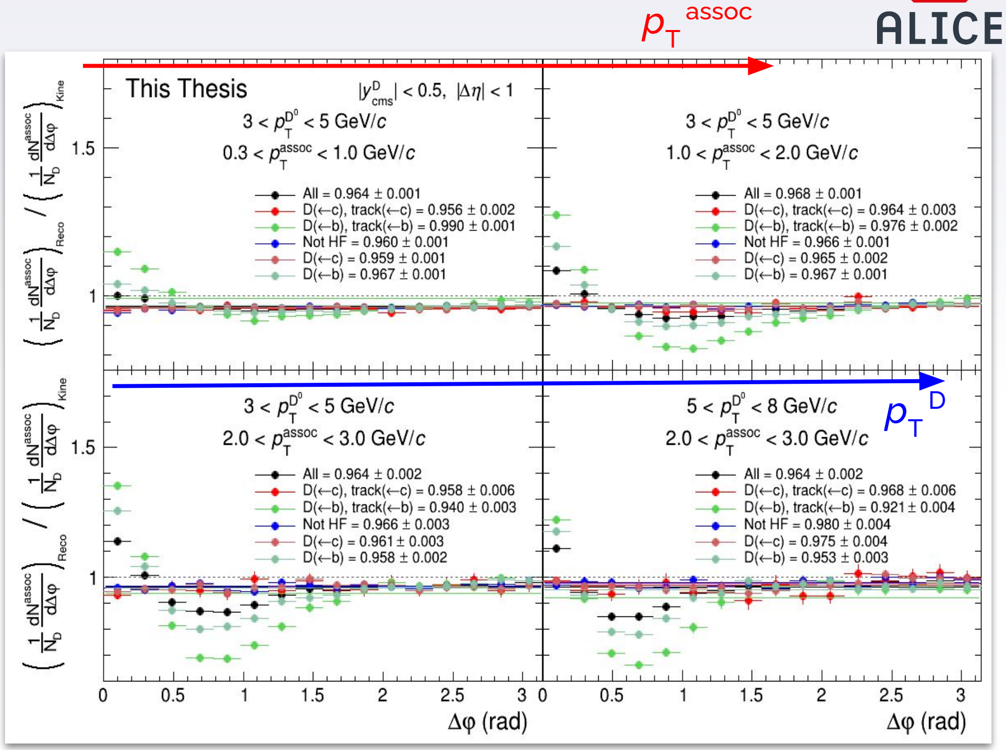
Beauty bias in azimuthal correlations

Difference between generated and reconstructed level in correlation distributions with **beauty-origin**

- enhancement at $\Delta\varphi \sim 0$, followed by a depletion

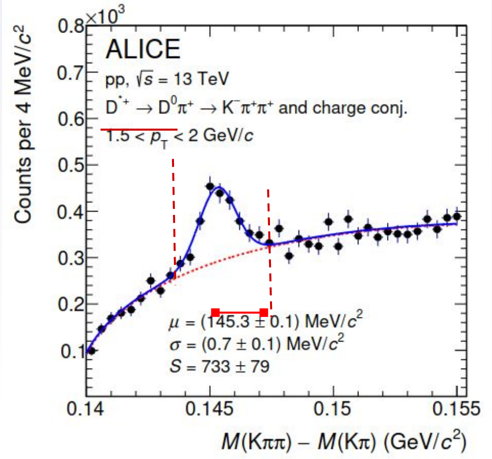
→ induced by topological selections (mainly $\cos\theta_P$)

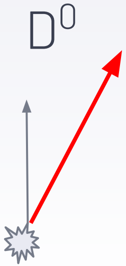


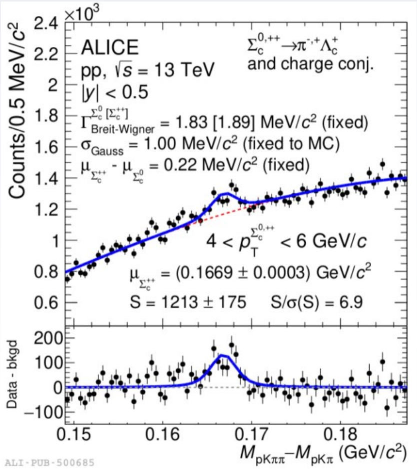


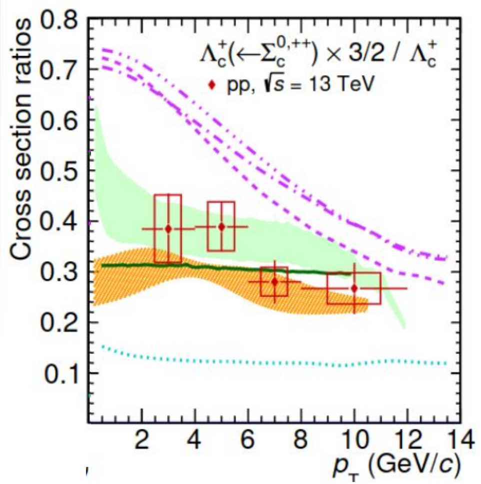
A $\Delta\varphi$-dependent modulation around $\Delta\varphi$~0, is therefore applied to the correlation distribution.

Soft-π subtraction









Cut on the D^0+track M_{inv}:

➢ if $(m^{D^*}-3\sigma) < M_{inv} < (m^{D^*}+3\sigma)$,
→ assoc. track not accounted in correlations

For the Λ_c, this is not feasible

→ Monte Carlo driven approach

a) simulation of the $\Sigma_c^{0,++}(2455) \rightarrow \Lambda_c^+ + \pi^+ (\pi^-)$ decay kinematics

b) computation of \dphi $\Lambda_c^+ - \pi^+$ distributions

c) subtraction from data correlation distributions

→ $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})$ measured spectrum

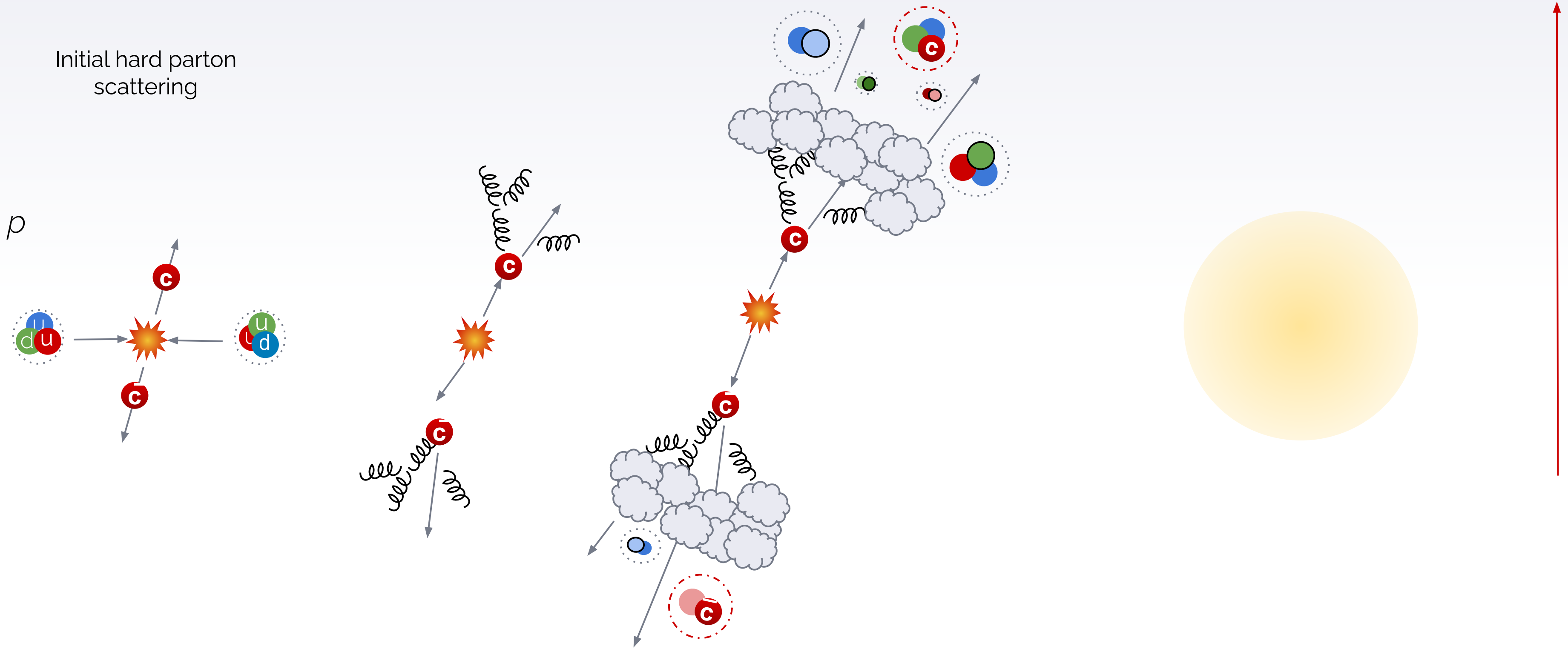
→ π efficiency correction over reweighted eff. map

More about introduction

Antonio Palasciano

Overview

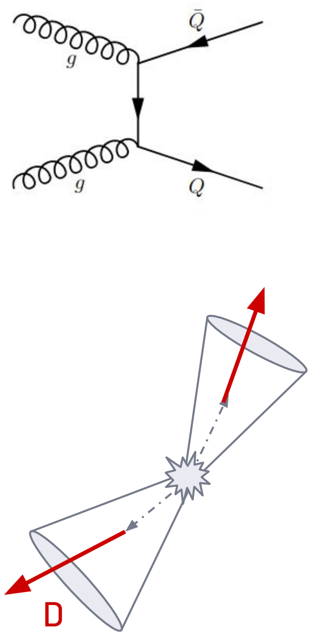
Initial hard parton
scattering



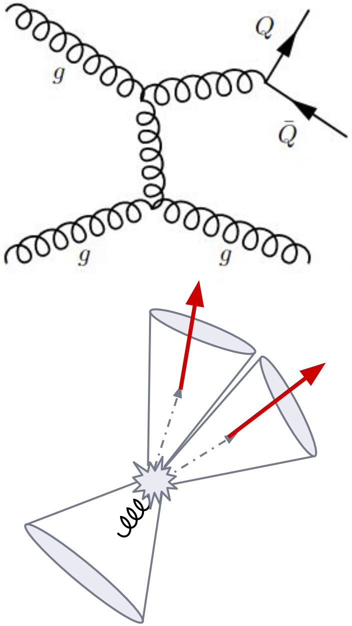
HF azimuthal correlations

Footprints of charm production mechanisms

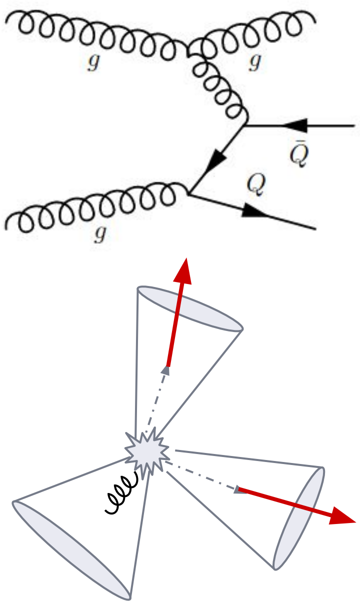
LO: pair production (PP)

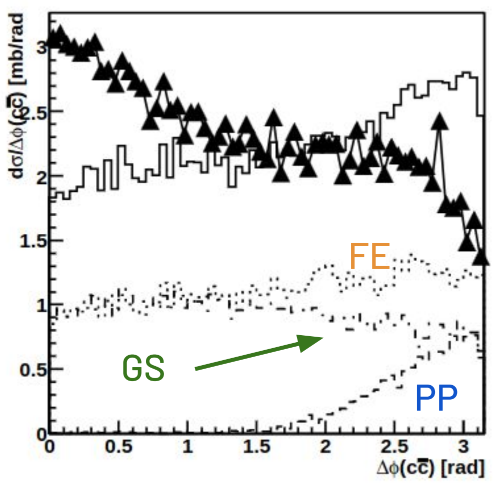


NLO: gluon splitting (GS)



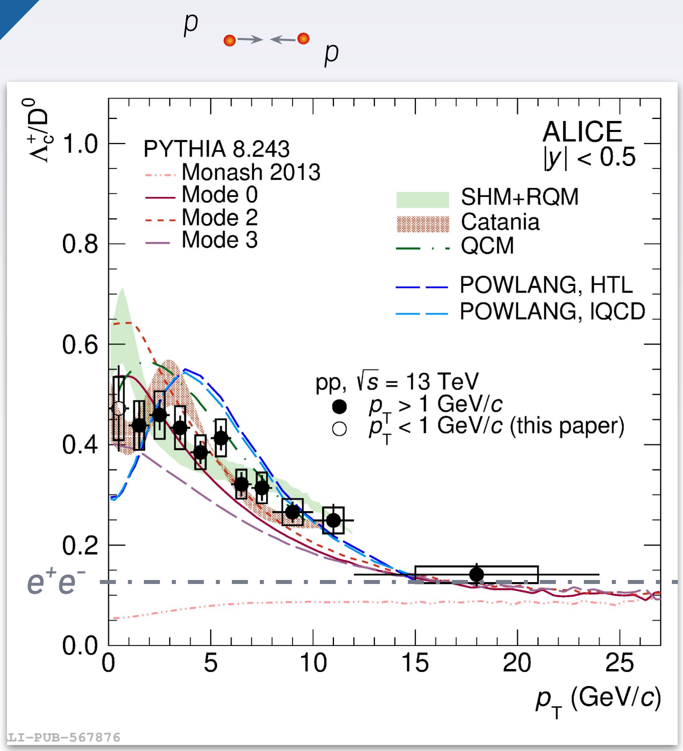
NLO:flavour excitation(FE)





Λ_c^+/D^0 ratio in pp

ALICE



LEP: (0.113 ± 0.013 ± 0.006)
EPJC 75 (2015) 19

Significant enhancement of Λ_c^+/D^0 ratio in *pp* than e^+e^- observed at different collision energy

✗ PYTHIA 8 Monash, tuned on e^+e^-, underestimates data

✓ CR-BLC reconciles PYTHIA predictions with measurements:
→ "junction" topologies in MPI enhance baryon production

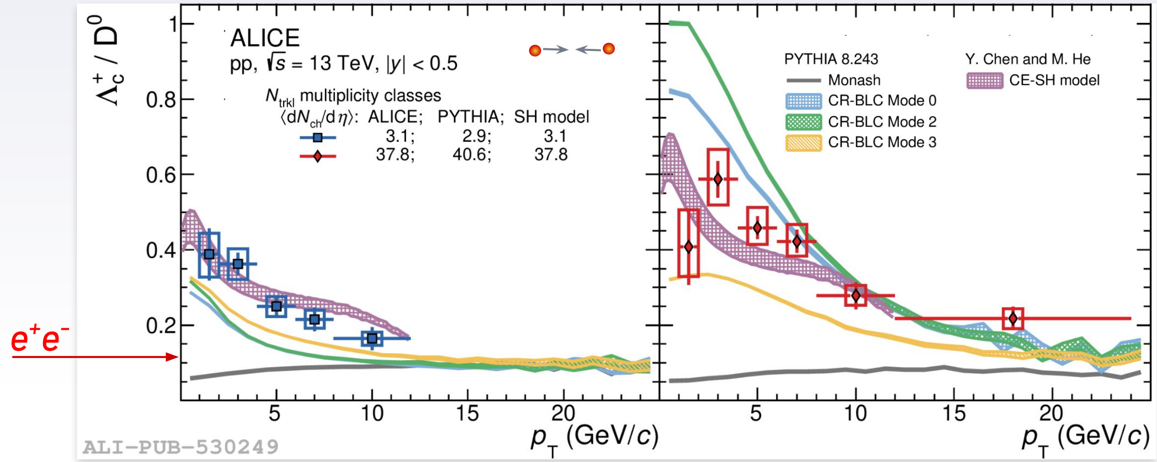
A good agreement is observed:

✓ **Catania:** thermalized system of u,d,s and g
→ Hadronization via interplay of fragmentation and coalescence

✓ **SHM**: quark hadronisation driven by statistical weights
+RQM: Augmented set of excited charm baryon states

✓ Quark (re)combination Mechanism
- charm is combined with co-moving light antiquark or two quarks.
- charm baryon abundances determined by thermal weights.

Λ_c^+/D^0 ratio vs Multiplicity



[PLB 829 (2022) 137065](PLB 829 (2022) 137065)

→ Multiplicity dependence observed in $1 < p_T < 12$ GeV/c

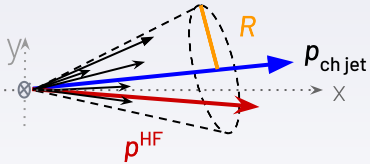
→ enhancement of Λ_c^+/D^0 ratios in pp w.r.t. LEP measurements also in the lowest multiplicity interval.

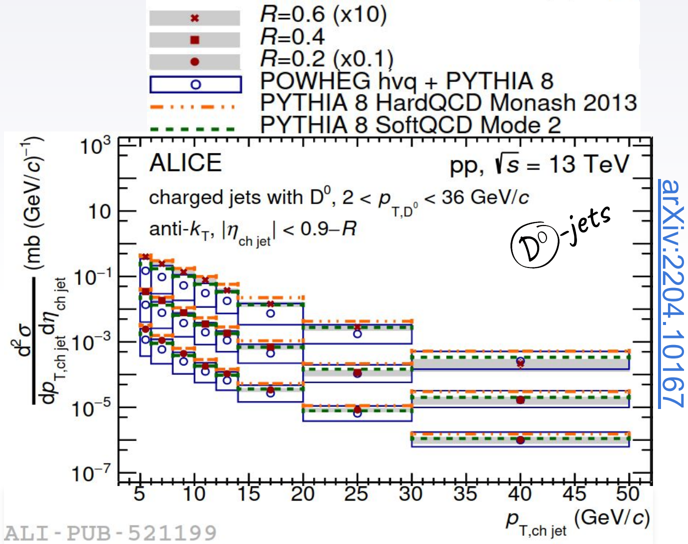
From the comparison with models:

✗ PYTHIA Monash does not reproduce the multiplicity dependence, underestimating the ratios

✓ PYTHIA CR-BLC, CE-SH provide qualitative good description of the p_T evolution and multiplicity dependence.

Production of charm-jets



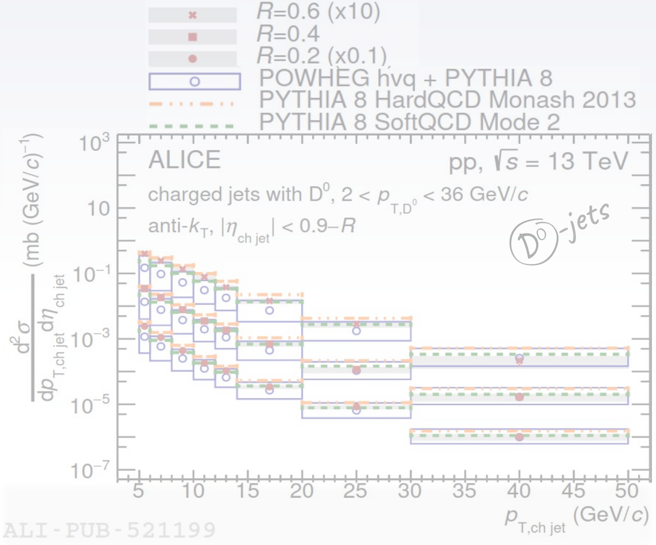


➢ MC generators providing overall good description of the spectrum

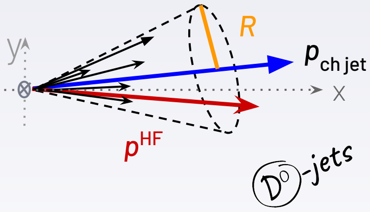
PYTHIA: JHEP 1508 (2015) 003 POWHEG: JHEP 06 (2010) 043

Charm-tagged jets

Production of charm-jets



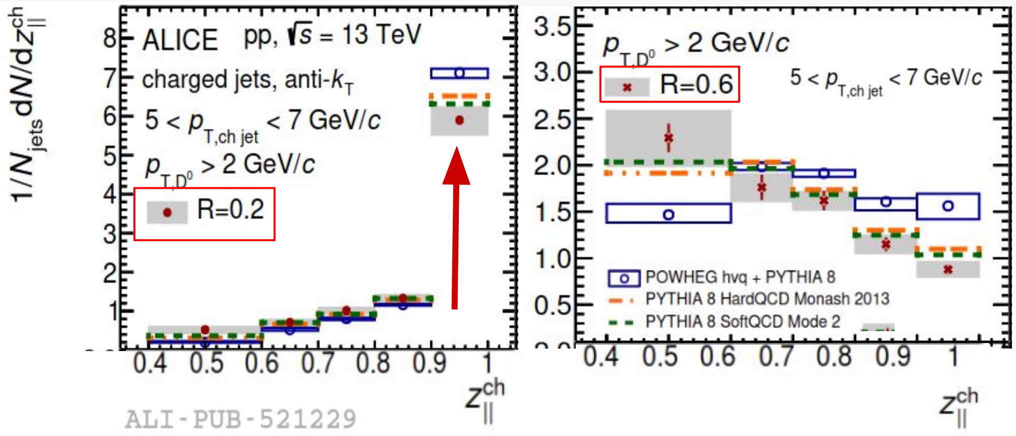
arXiv:2204.10167



Fragmentation of charm

Longitudinal momentum fraction

$$z_{||} = \frac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$$

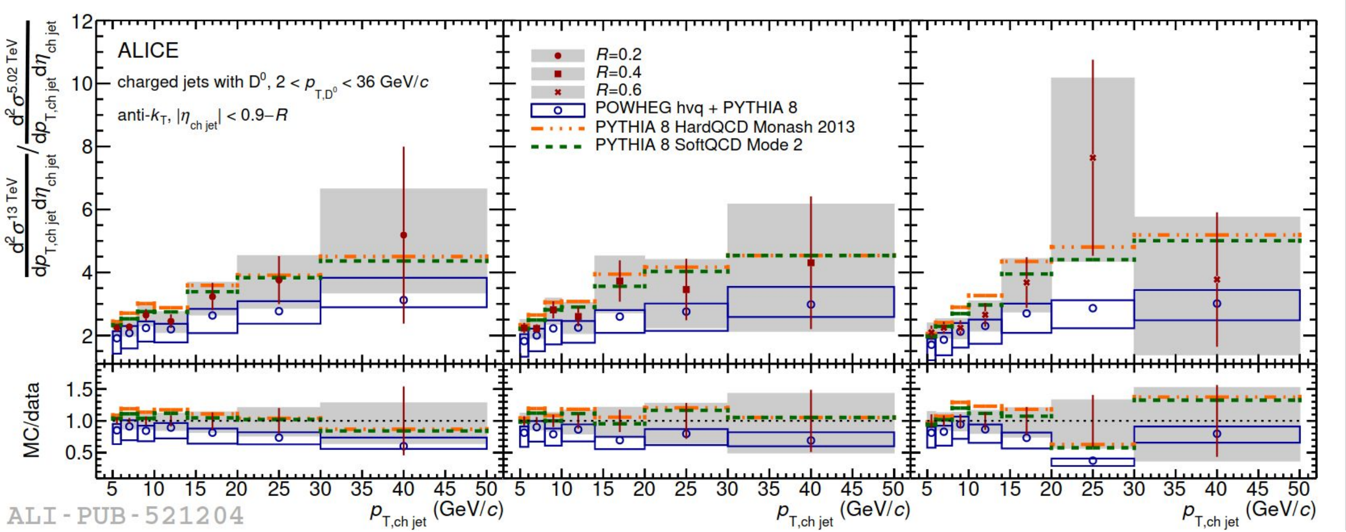


- ➢ MC generators providing overall good description of the spectrum
- ➢ R=0.2, small $\vec{p}_{\text{ch jet}}$ → D^0 carries a large fraction of $\vec{p}_{\text{ch jet}}$
- ➢ R=0.6 → hint of softer fragmentation wrt models

PYTHIA: JHEP 1508 (2015) 003 POWHEG: JHEP 06 (2010) 043

D⁰ - jets

arXiv:2204.10167



Hardening of the $p_{\mathrm{T,ch\ jet}}$ spectra with increasing centre-of-mass energy.

→ PYTHIA SoftQCD correctly reproduce the data

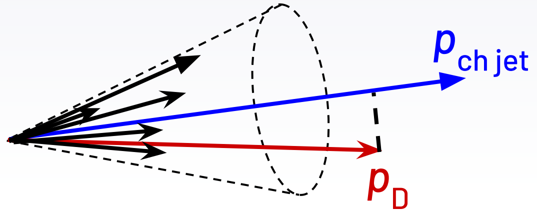
→ POWHEG + PYTHIA 8 simulation tends to underestimate the measured cross section ratios

PYTHIA: JHEP 1508 (2015) 003
POWHEG: JHEP 06 (2010) 043

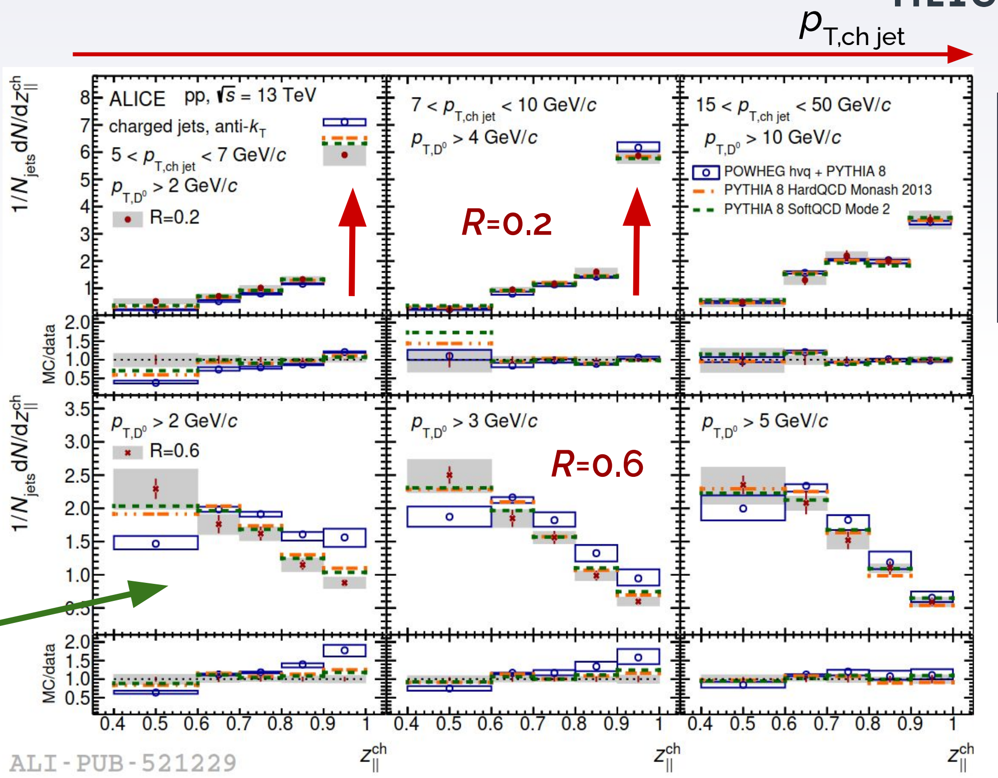
D^0-jets: longitudinal momentum fraction

Longitudinal momentum fraction

$$z_{||} = \frac{\vec{p}_{\rm ch\ jet} \cdot \vec{p}_{\rm HF}}{\vec{p}_{\rm ch\ jet} \cdot \vec{p}_{\rm ch\ jet}}$$



- ➢ For 5 < pT, ch jet < 10 GeV/c and R=0.2 D^0 carries a large fraction of $\vec{p}_{\rm ch\ jet}$
- ➢ Hint of softer fragmentation compared to model predictions



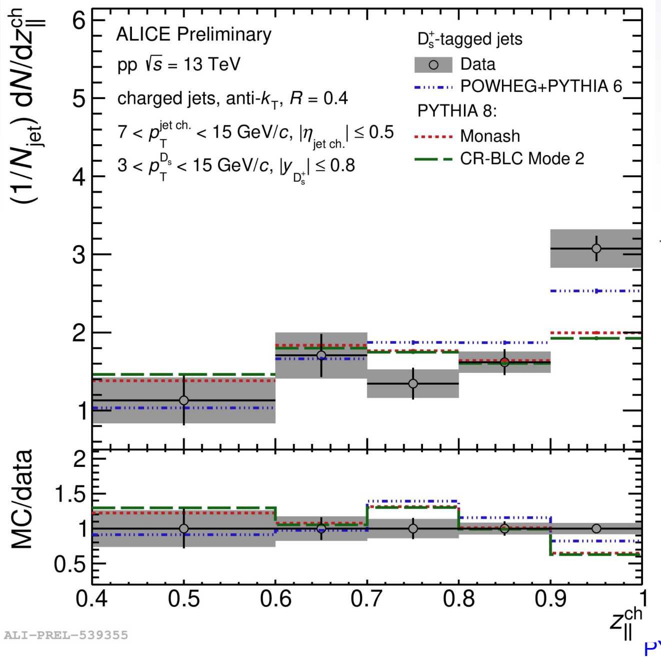
arXiv:2204.10167

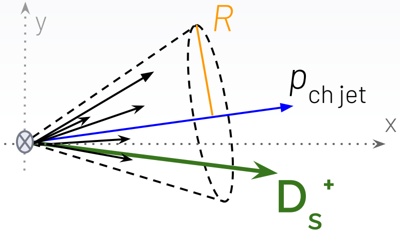
PYTHIA: JHEP 1508 (2015) 003
POWHEG: JHEP 06 (2010) 043

First measurement of D_s^+-jets

Highlight possible differences in the charm fragmentation due to the strange-quark content of the tagged meson

➢ Good compatibility between models and data



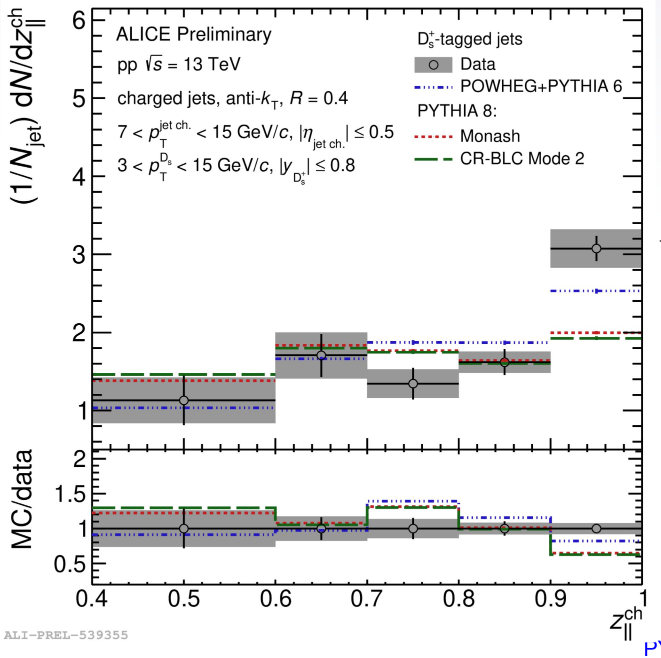


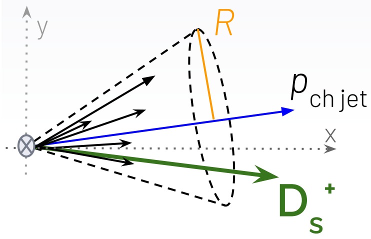
PYTHIA: JHEP 1508 (2015) 003
POWHEG: JHEP 06 (2010) 043

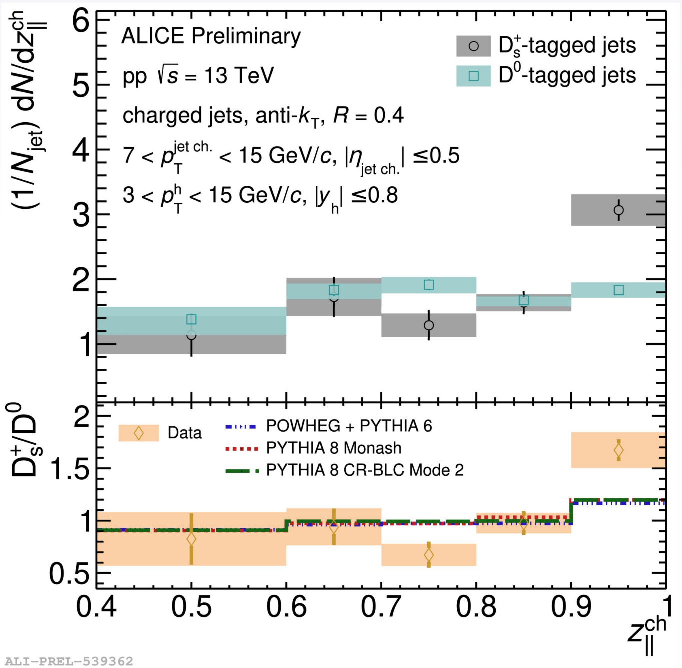
First measurement of D_s^+-jets

Highlight possible differences in the charm fragmentation due to the strange-quark content of the tagged meson

- Good compatibility between models and data
- hint of harder fragmentation with respect to D^0







PYTHIA: JHEP 1508 (2015) 003
POWHEG: JHEP 06 (2010) 043

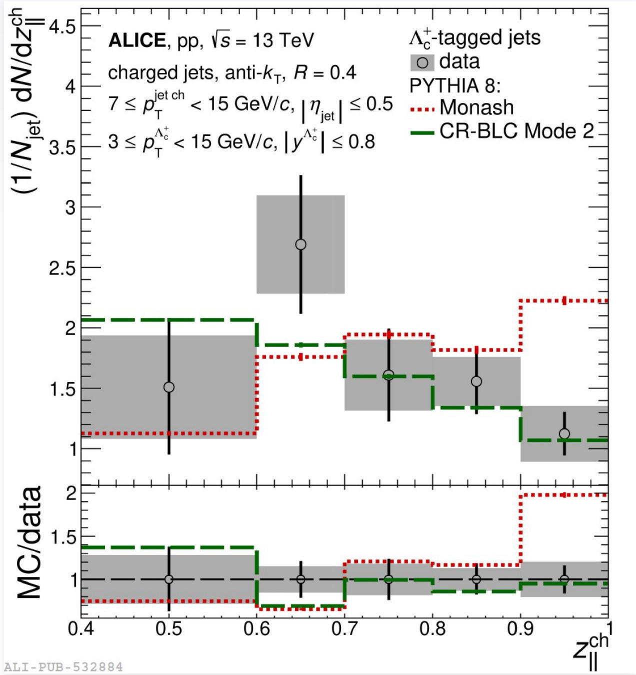
Λ_c^+-jets

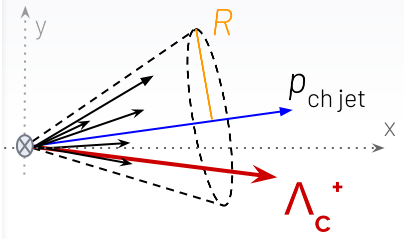
→ Probe the fragmentation of charm quarks into charm baryons

ALICE

- ➢ slightly harder fragmentation in PYTHIA8 Monash
- ➢ good agreement with PYTHIA8 CR-BLC, mode 2

arXiv:2301.13798





PYTHIA: JHEP 1508 (2015) 003

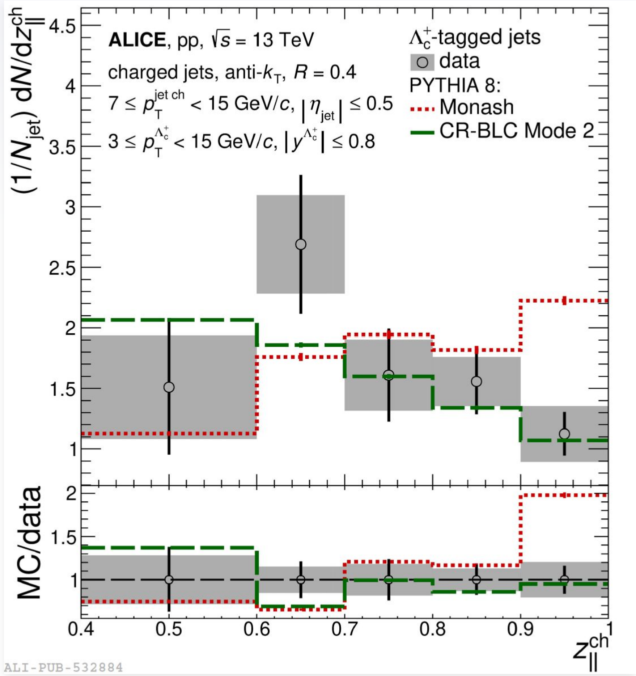
Λ_c^+-jets

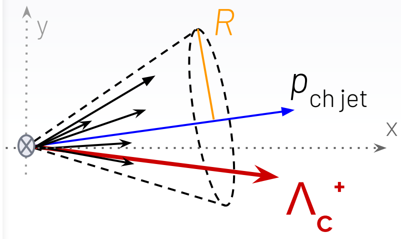
→ Probe the fragmentation of charm quarks into charm baryons

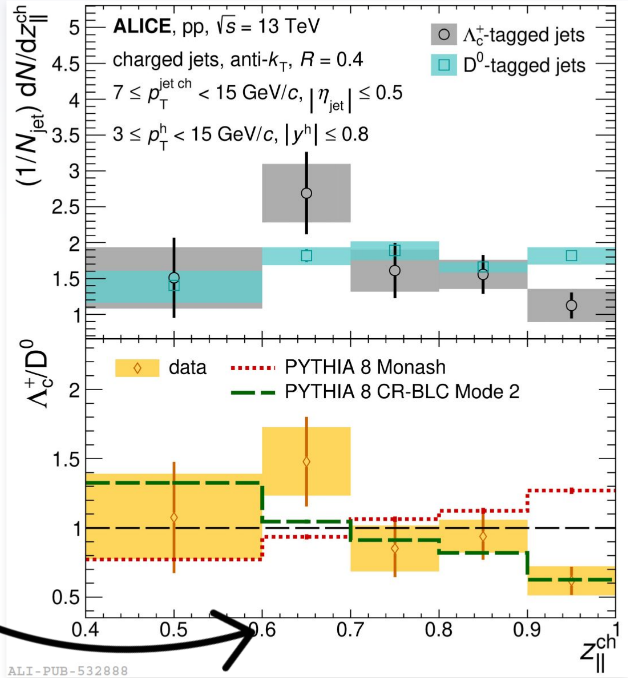
- ➢ slightly harder fragmentation in PYTHIA8 Monash
- ➢ good agreement with PYTHIA8 CR-BLC, mode 2

- ➢ hint of softer fragmentation into Λ_c^+ than D^0
- ➢ Correctly reproduced by PYTHIA8, CR-BLC mode 2

arXiv:2301.13798







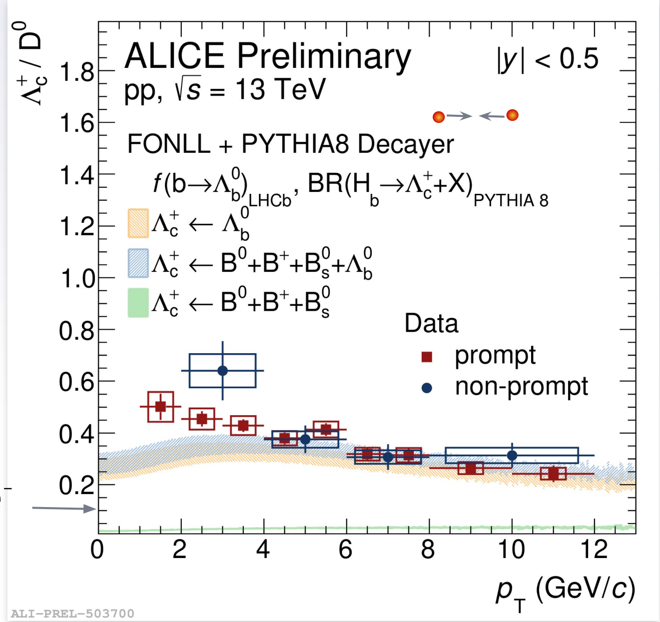
Λ_c^+ softer fragm. than D^0

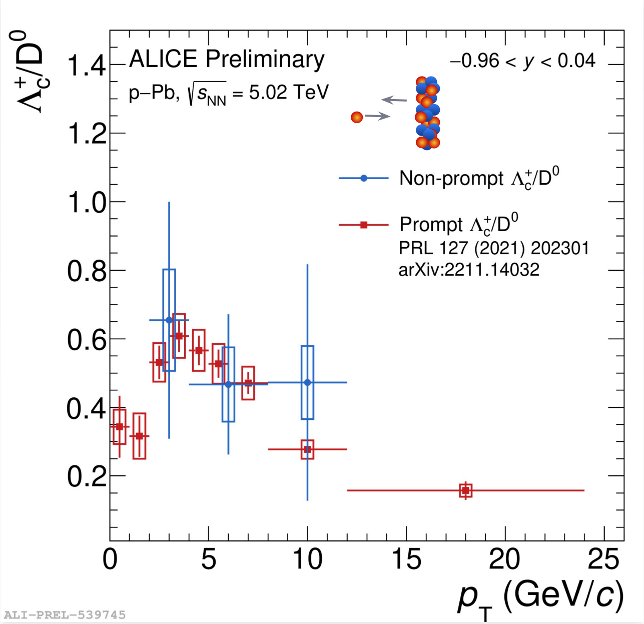
PYTHIA: JHEP 1508 (2015) 003

Non-prompt Λ_c^+/D^0 ratio

$f(b \rightarrow \Lambda_b^+)$

Phys. Rev. D 100, 031102(R)





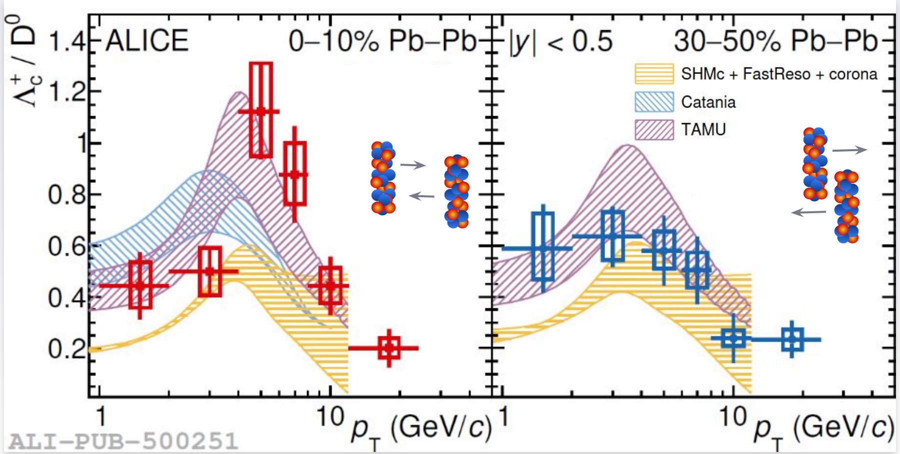
→ Similar baryon-to-meson enhancement between **prompt** and **non-prompt** Λ_c^+/D^0 ratio

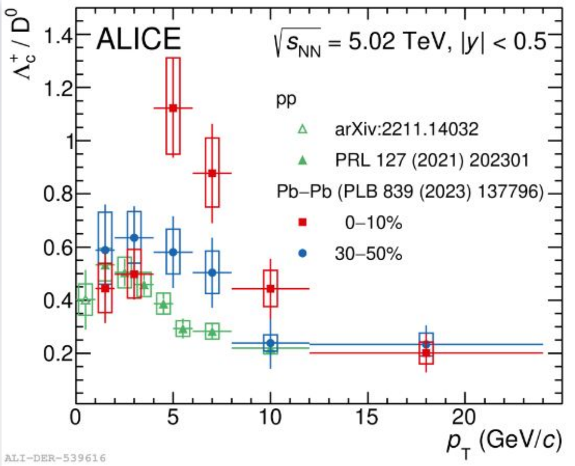
→ Measurement compatibility between collision systems

Non-prompt Λ_c^+ simulations with FONLL (LHCb FF $b\rightarrow\Lambda_b^+$) + PYTHIA8 decayer

☀ most of non-prompt Λ_c^+ from Λ_b^+ decays → access to **beauty**-baryon production

Λ_c^+/D^0 ratio in Pb–Pb





Phys. Lett. B 839 (2023) 137796

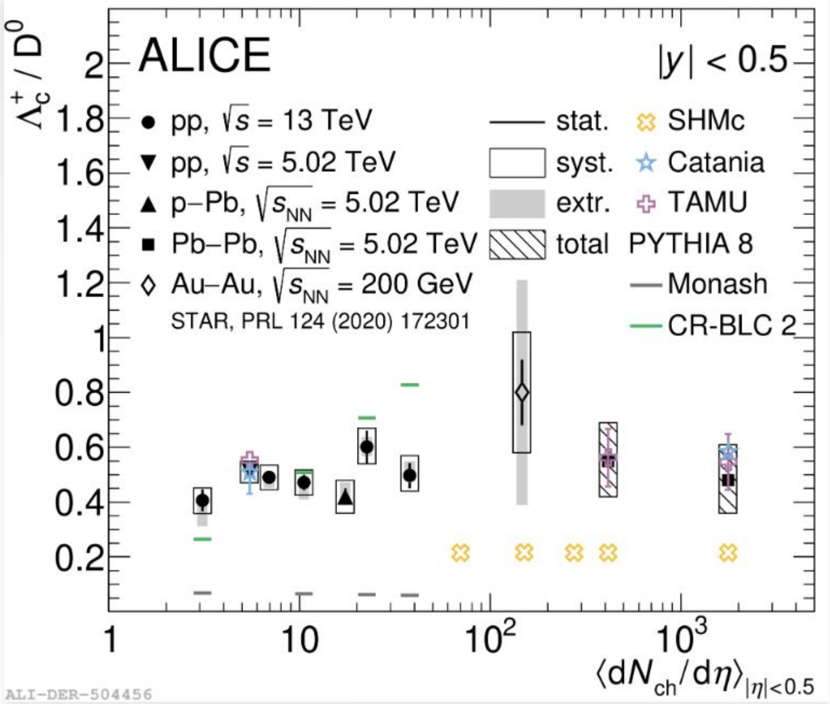
- enhancement in Λ_c^+/D^0 ratios observed in Pb–Pb collisions
  → in central (0-10%) Pb–Pb collisions, for $4 \le p_T < 8$ GeV/c, larger than pp (3.7σ)
- SHMc (statistical hadronization + charm) and Catania models able to catch the evolution with p_T
- Best description by TAMU (hydro. + fragmentation + coalescence + extra c-baryons)

Baryon-to-meson enhancement due to an interplay of radial flow and recombination?

P_T-integrated Λ_c^+/D^0 ratio

ALICE

pp, p–Pb, Pb–Pb as function of event multiplicity



No dependence of the p_T-integrated ratio on collision system and energy within uncertainties

Momenta redistribution can justify the differences in the p_T-differential ratio across collision systems

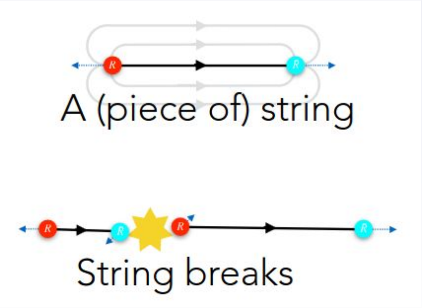
Flat trend reproduced by Catania, TAMU
(hadronization via fragmentation+recombination)

Monash fails to describe the data

p–Pb: Phys. Rev. C 104, 054905 Pb–Pb: Phys. Lett. B 839 (2023) 137796

Models in details

PYTHIA 8: Lund fragmentation model

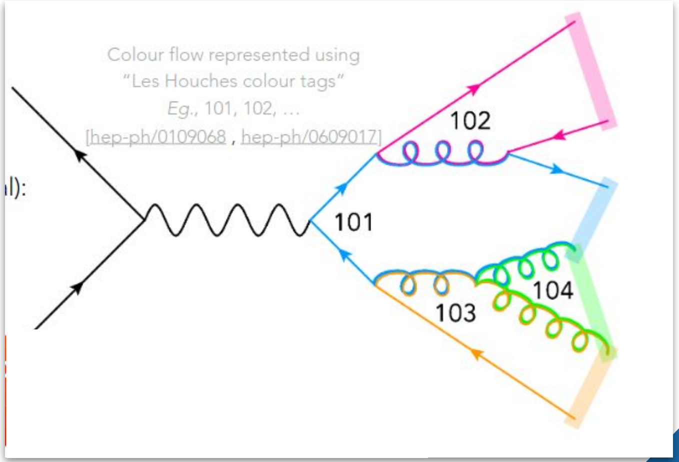


1) A given colour charge stretched in a **confinement field** to nearest anti-colour charge
2) Given sufficient energy, confinement field can break down by spontaneous ***qq pair creation***

? Between which partons should confining potentials form?

Starting point for **MC generators** = **Leading Colour limit $N_c \to \infty$**
- Probability for any given colour charge to accidentally be same as any other → 0.
- Each colour appears only once & is matched by a unique anticolour.

Corrections are expected to be about ~ $1/N_C$ ~ 10 %

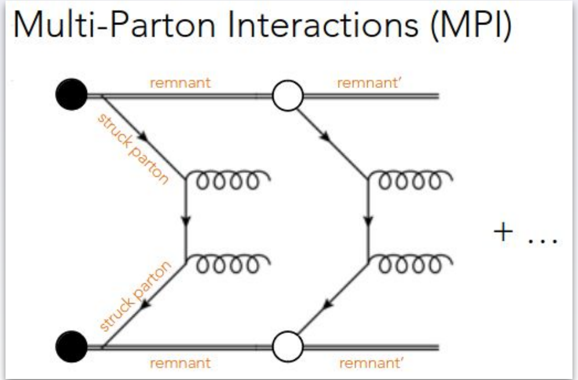


PYTHIA 8: Lund fragmentation model

How many parton systems are there in pp collisions?

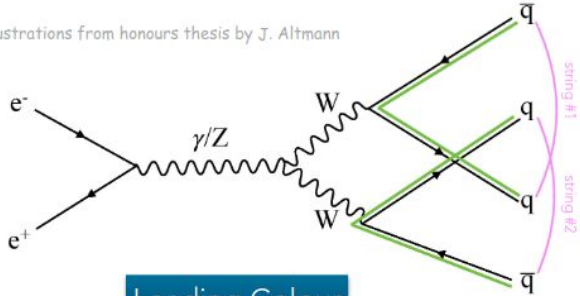
⟶ can have very many parton systems within a single pp collision (esp. in high-multiplicity events)

⟶ All within ~ transverse size of a proton (= right on top of each other)

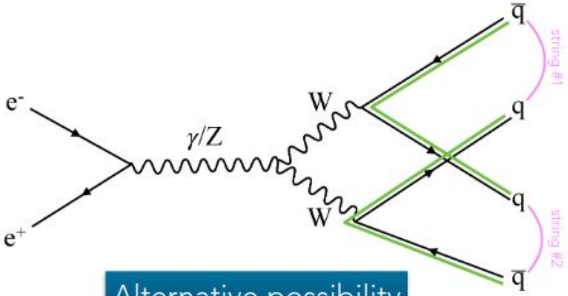


From:
Skands, QCD-Based CR in Pythia & Close-Packing

Illustrations from honours thesis by J. Altmann



Leading Colour



Alternative possibility

Probability for uncorrelated $q\bar{q}$ pair to **accidentally** be in colour-singlet state follows from $3 \otimes \bar{3} = 8 \oplus 1$
☛ 1 in 9 ☚
$= 1/N_C^2$

PYTHIA 8: Lund fragmentation model

MPI + showers $\Longrightarrow$ partons with LC connections

Idea: restore missing ($1/N_C^2$) colour correlations stochastically. Approximate all **LC-unconnected partons** as uncorrelated and consider SU(3) rules:

(1) $3 \otimes \bar{3} = 8 \oplus 1$ for uncorrelated colour-anticolour pairs (allows "dipole CR")

(2) $3 \otimes 3 = 6 \oplus \bar{3}$ for uncorrelated colour-colour pairs (allows "junction CR")

Technically: done by assigning all partons "colour indices" from 0 to 8.

E.g., any parton given colour index 0 can be confined with any parton with anti-index 0.

This reproduces the 1/9 stochastic probability in **eq.(1).**

Index 0 can also combine with *two* other partons (with indices 3 and 6) representing the confining (colour-neutral) combination of R, G, and B

This gives a decent approximation to the 3/9 probability in **eq.(2).**

Represented by "string junctions" in Pythia [hep-ph/0212264] $\Longrightarrow$ a new source of baryons and anti-baryons.

Finally, choose between which ones to actually set up confining potentials

Smallest measure of "invariant string length" $\propto$ number of hadrons produced ("λ measure")

ALICE

From:

Skands, *QCD-Based CR in Pythia & Close-Packing*

PYTHIA 8: Color-reconnections beyond leading color

ALICE

Reconnections occur between two string pieces

→ only if in ***causal contact*** (*compatible formation time* $\tau_{form} \sim 1/m_{string}$)

! Resolve each other in between ***formation*** and ***hadronisation*** τ
(+ relative string boost)

- Mode 0: no time-dilation constraints. m_0 controls the amount of CR (mode 0);
- Mode 2: time dilation using the boost factor obtained from the final-state mass of the dipoles, requiring all dipoles involved in a reconnection to be causally connected (strict);
- Mode 3: time dilation as in Mode 2, but requiring only a single connection to be causally connected (loose).

Parameter	Monash	Mode 0	Mode 2	Mode 3
StringPT:sigma	= 0.335	= 0.335	= 0.335	= 0.335
StringZ:aLund	= 0.68	= 0.36	= 0.36	= 0.36
StringZ:bLund	= 0.98	= 0.56	= 0.56	= 0.56
StringFlav:probQQtoQ	= 0.081	= 0.078	= 0.078	= 0.078
StringFlav:ProbStoUD	= 0.217	= 0.2	= 0.2	= 0.2
StringFlav:probQQ1toQQ0join	= 0.5, 0.7, 0.9, 1.0	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275
MultiPartonInteractions:pT0Ref	= 2.28	= 2.12	= 2.15	= 2.05
BeamRemnants:remnantMode	= 0	= 1	= 1	= 1
BeamRemnants:saturation	-	= 5	= 5	= 5
ColourReconnection:mode	= 0	= 1	= 1	= 1
ColourReconnection:allowDoubleJunRem	= on	= off	= off	= off
ColourReconnection:m0	-	= 2.9	= 0.3	= 0.3
ColourReconnection:allowJunctions	-	= on	= on	= on
ColourReconnection:junctionCorrection	-	= 1.43	= 1.20	= 1.15
ColourReconnection:timeDilationMode	-	= 0	= 2	= 3
ColourReconnection:timeDilationPar	-	-	= 0.18	= 0.073

String Formation Beyond Leading Colour

Relative boost causal contact condition

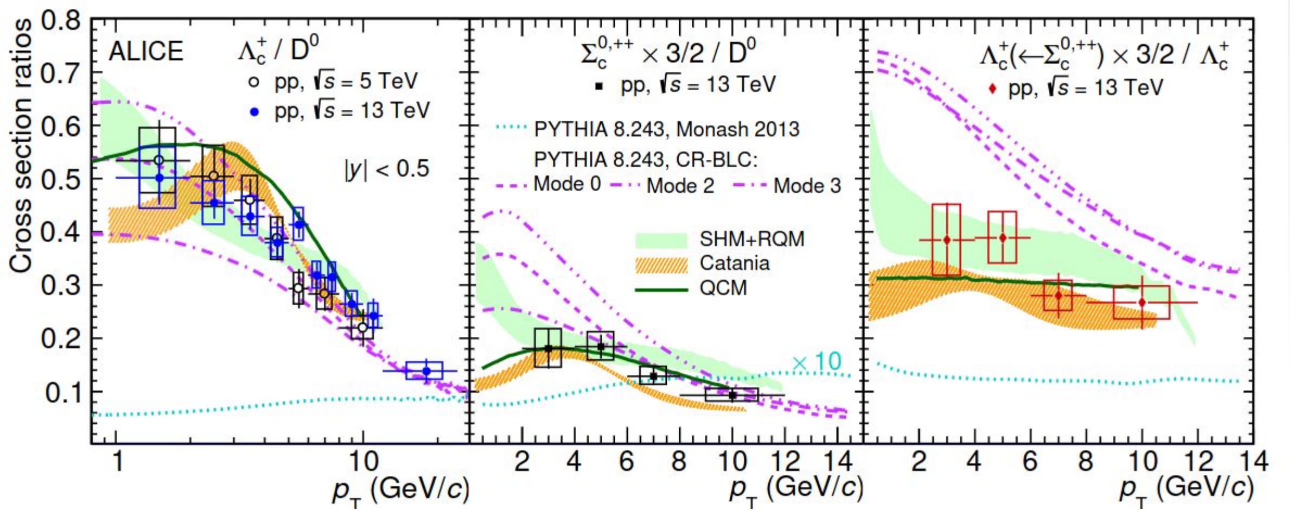
$$\gamma\, \tau_{\text{form}} < C_{\text{time}}\, \tau_{\text{had}} \Rightarrow \frac{\gamma\, c}{m_{\text{string}}\, r_{\text{had}}} < C_{\text{time}}$$

C_{time} size of the allowed relative boost factor for reconnections to occur

$r_{had} \sim \tau_{had}\, c \sim 1\,\text{fm}$ $\quad m_0 \sim \Lambda_{QCD}$

PYTHIA 8: Color-reconnections beyond leading color

QCD CR model(s): Junctions drive order-of-magnitude increase at low-p_T Λ_c/D^0
→ mode 2 > mode 0 > mode 3



- Mode 0: no time-dilation constraints. m_0 controls the amount of CR (mode 0);
- Mode 2: time dilation using the boost factor obtained from the final-state mass of the dipoles, requiring all dipoles involved in a reconnection to be causally connected (strict);
- Mode 3: time dilation as in Mode 2, but requiring only a single connection to be causally connected (loose).

"Neither CR nor junction fragmentation were specifically designed/optimised for ***heavy quarks****"*

"Needs further thought & theoretical work"

📚 *Skands, QCD-Based CR in Pythia & Close-Packing*