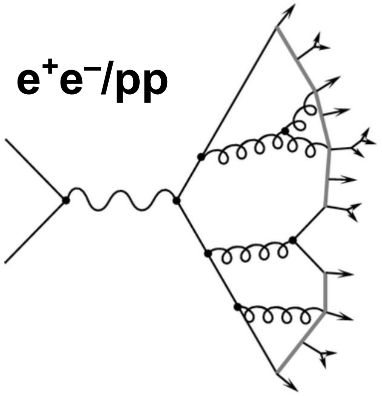
Hadronization of heavy-quarks: from elementary processes to heavy-ion collisions

Andrea Dubla

22/11/2023

Hadronisation

e^+e^-/pp



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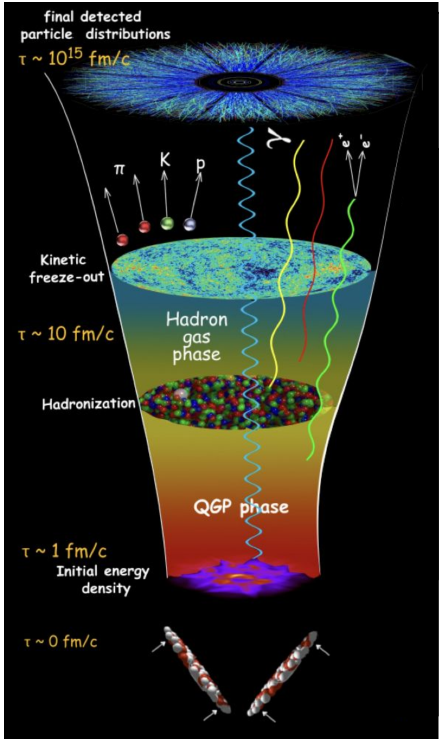


- ➢ **Hadronisation in elementary reactions:** the mechanism by which quarks and gluons produced in hard partonic scattering processes form hadrons

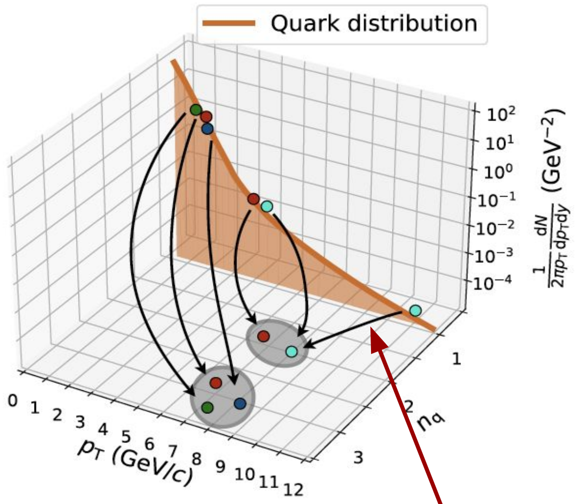
- ➢ **No first-principle description of hadron formation**
  - Non-perturbative problem, not calculable with pQCD
  - Necessary to resort to models and make use of phenomenological parameters

- ➢ **Hadronisation of the QGP medium**
  - Transition from a deconfined medium composed of quarks, antiquarks and gluons to color-neutral hadronic matter

➢ Hadronization of QGP: is it different from e^+e^-/pp in which no thermalized partons is formed?

Fragmentation and coalescence

- **Fragmentation functions** $D_{q \to h}(z,Q^2)$:
  - Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition*
  - z is the fraction of the parton momentum taken by the hadron h
  - Parameterized on data (e^+e^-) and assumed to be **"universal"**
  - Event generators: string fragmentation



Fragmenting parton:
$p_h = z \cdot p_q$ with $z<1$

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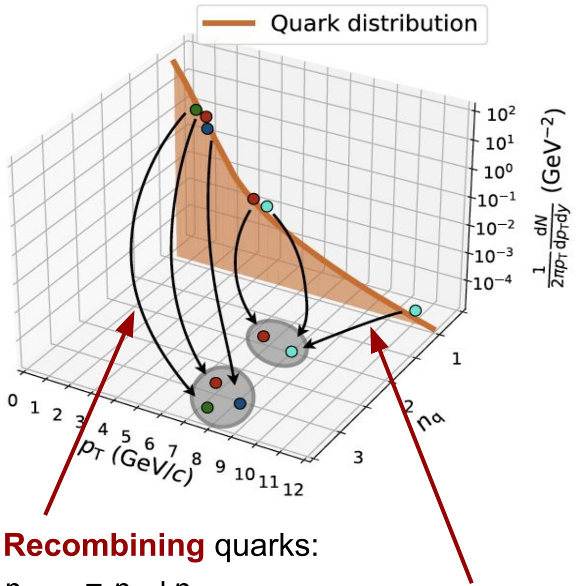
- **Coalescence/recombination**:
  - Single parton description is not be valid anymore
  - No need to create $q\bar{q}$ pairs via string fragmentation
  - Partons that are *"close" to each other in phase space* (position and velocity) can **recombine** into hadrons



Recombining quarks:

$p_{meson} = p_{q1} + p_{q2}$

$p_{baryon} = p_{q1} + p_{q2} + p_{q3}$

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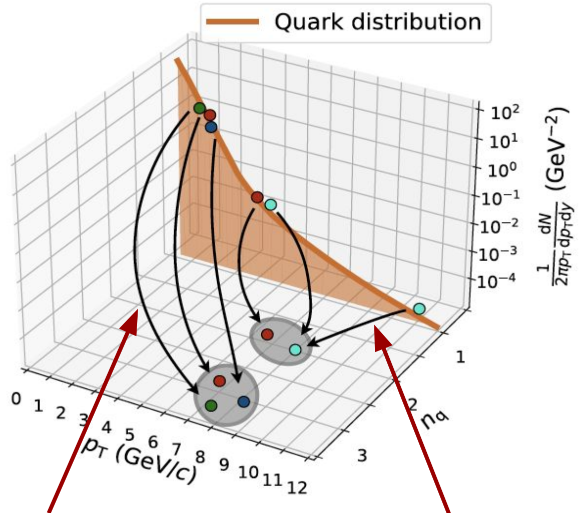
- **Coalescence vs. fragmentation:**
  - Competing mechanisms, dominant in different p_T regions
  - **Recombination depends on "environment"**, i.e. density and momentum distribution of surrounding (anti)quarks



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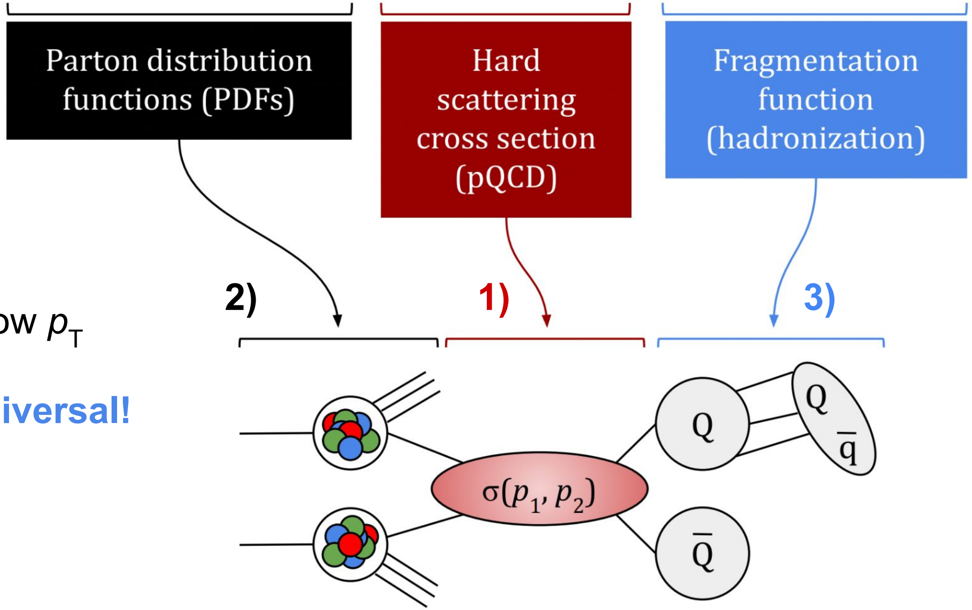
$p_h = z \cdot p_q$ with $z<1$

The factorization approach

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



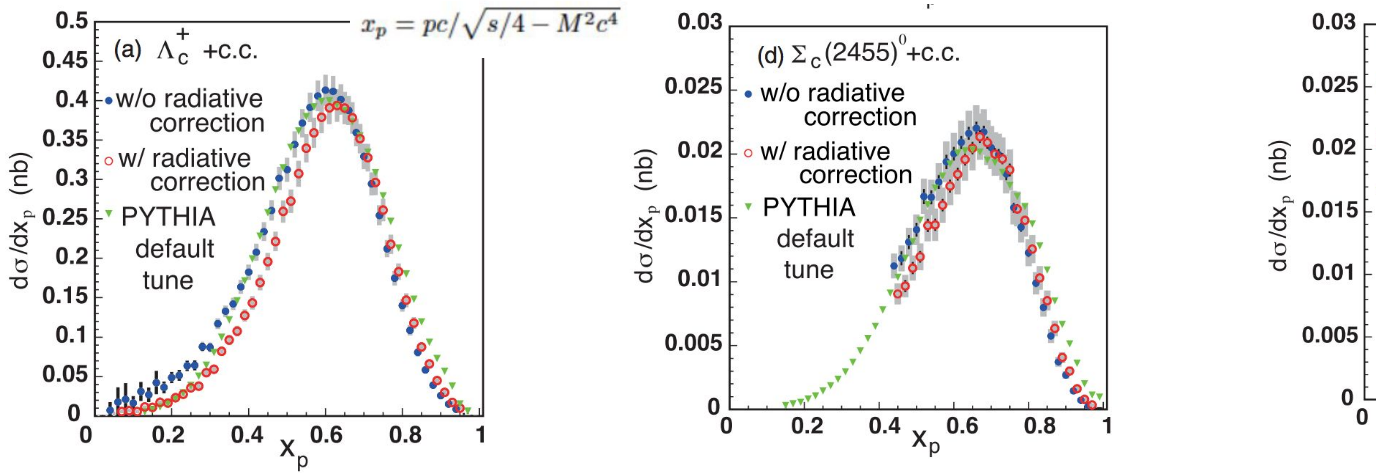
1) Hard scattering:
- large quark mass provides hard scale
- pQCD can calculate cross sections down to low p_T

2) PDF → from ep collisions

3) FF → from e^+e^- collisions – **thought to be universal!**
Independent on collision system and energy

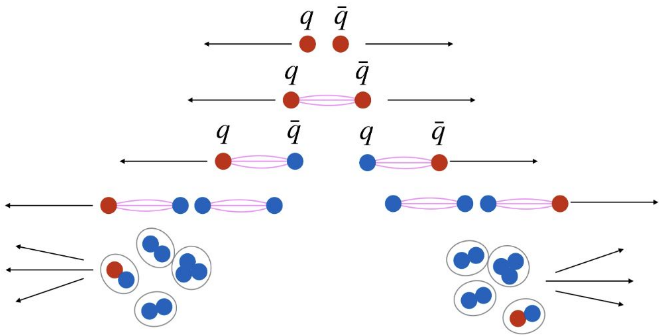
➢ **To isolate FF: hadron-to-hadron production ratios** are effective for probing hadronisation, PDFs and partonic cross sections cancel in the yield ratios

Charm baryons in e^+e^-



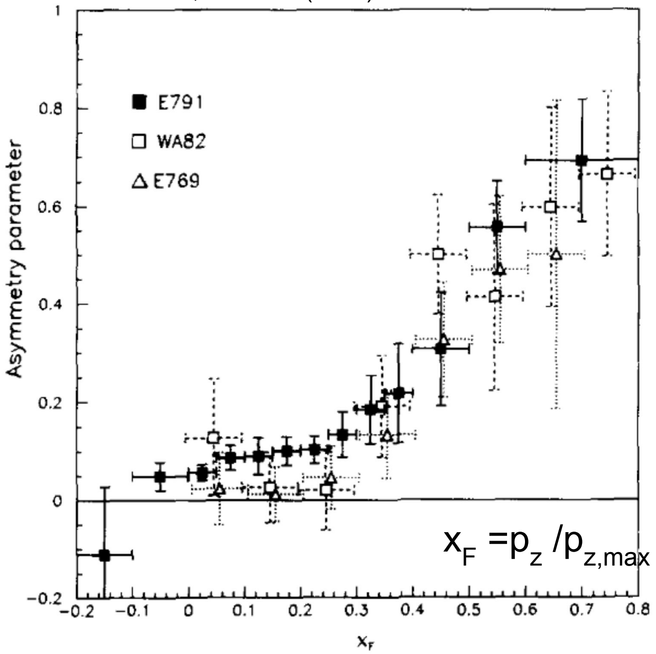
Belle: PRD 97, 072005 (2018)

➢ Charm baryons vs PYTHIA in e^+e^-
  - **Standard PYTHIA** with string fragmentation describe the experimental data



Leading particle effect

WA82, PLB 305 (1993) 402
E791, PLB 371 (1996) 157



$x_F = p_z / p_{z,max}$

$$A(x_F) = \frac{\left(\frac{d\sigma}{dx_F}\right)^{D^-} - \left(\frac{d\sigma}{dx_F}\right)^{D^+}}{\left(\frac{d\sigma}{dx_F}\right)^{D^-} + \left(\frac{d\sigma}{dx_F}\right)^{D^+}}$$

- ➢ Measurements of charm production in **pion-nucleon collisions**
- ➢ At large x_F: favoured the production of hadrons sharing valence quarks with beam hadrons
  - D^- meson shares the d quark with the π^- projectile → favored over D^+
- ➢ **Break-up of independent fragmentation at forward rapidity**

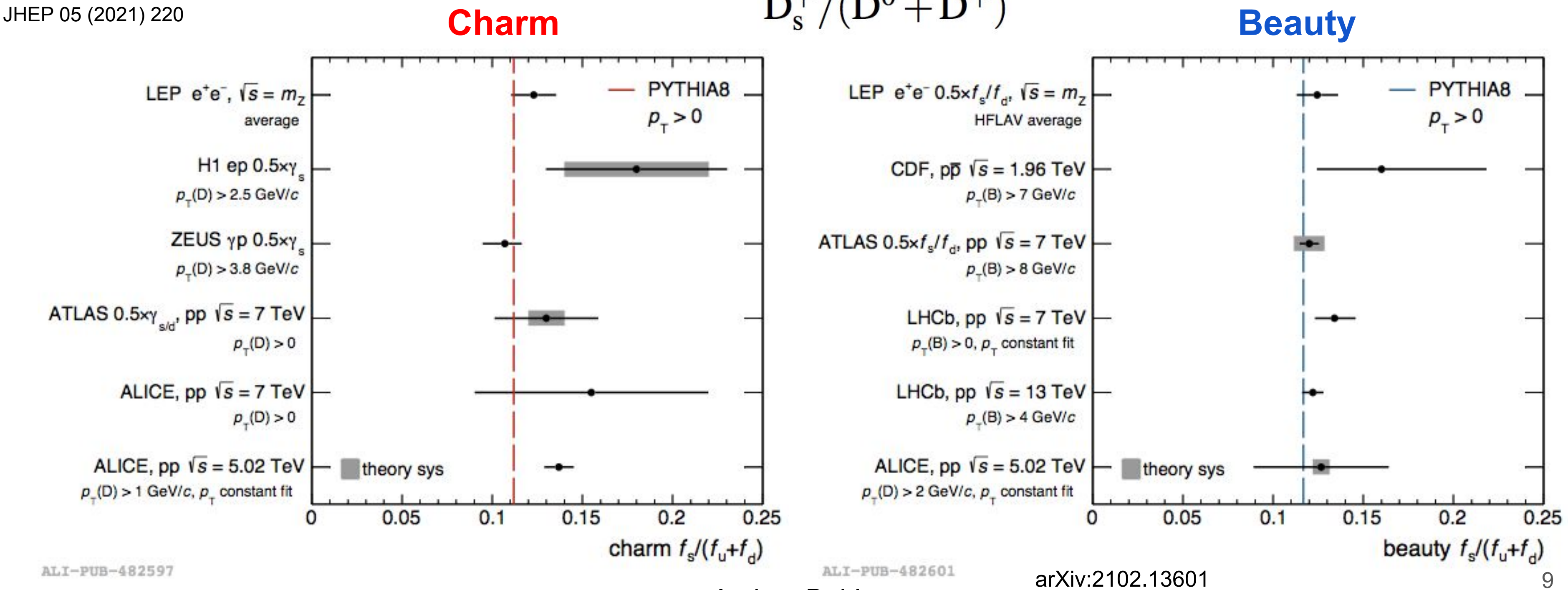
➢ **A reservoir of particles leads to significant changes in hadronisation**

Charm and beauty fragmentation to mesons

- Ratio of fragmentation fractions (FF) to meson with and w/o strange quark content similar for charm and beauty
- **No significant dependence on energy and collision system at midrapidity**

JHEP 05 (2021) 220

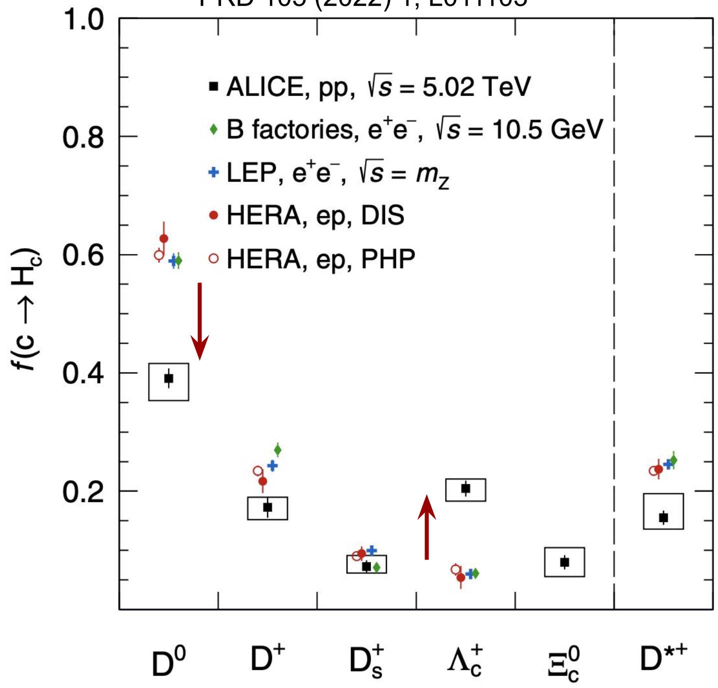
$D_s^+/(D^0+D^+)$



arXiv:2102.13601

Fragmentation universality?

PRD 105 (2022) 1, L011103

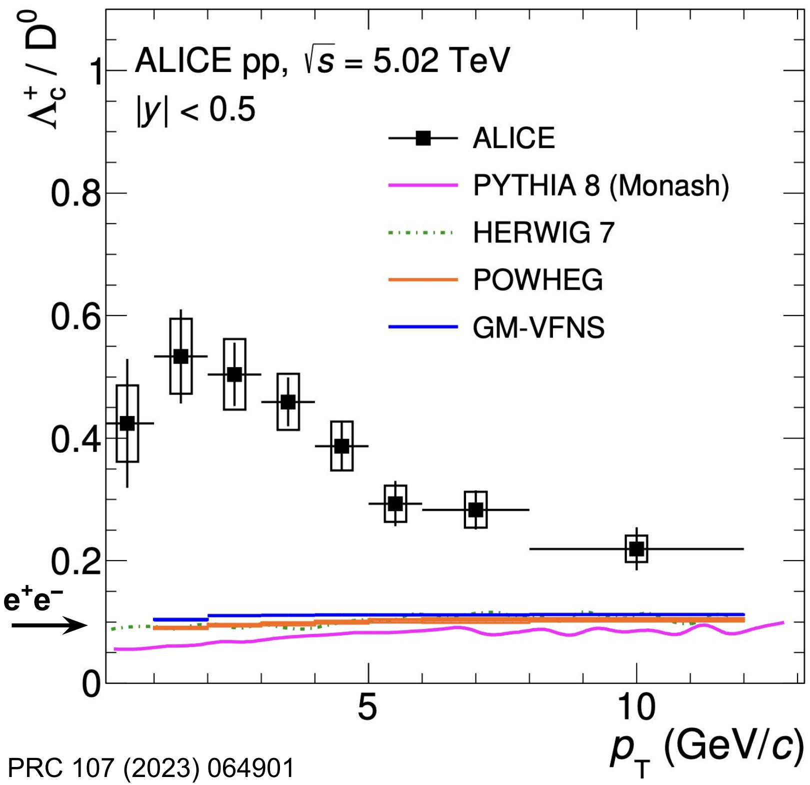


- ➢ Measurement of fragmentation fractions in pp collisions at LHC compared to e^+e^- (ep) collisions at lower $\sqrt{s}$
  - Indication that parton-to-hadron fragmentation depends on the collision system
  - Assumption of their universality not supported by the measured cross sections

→ Independent fragmentation picture not valid in partonic-color-rich environment

→ Break-down of universality of fragmentation functions

How MC generators perform at LHC?



PRC 107 (2023) 064901

The MC generators

- **PYTHIA 8** with Monash tune and colour reconnection
  Eur. Phys. J. C74 no. 8, (2014) 3024
- **HERWIG 7** where hadronisation is implemented via clusters Eur. Phys. J. C58 (2008) 639–707
- **POWHEG** matched to PYTHIA 6 to generate the parton shower JHEP 09 (2007) 126
- **GM-VFNS** pQCD calculations → compute the ratios of the Λ_c and D^0 cross sections
  Phys. Rev. D 101 (2020) 114021

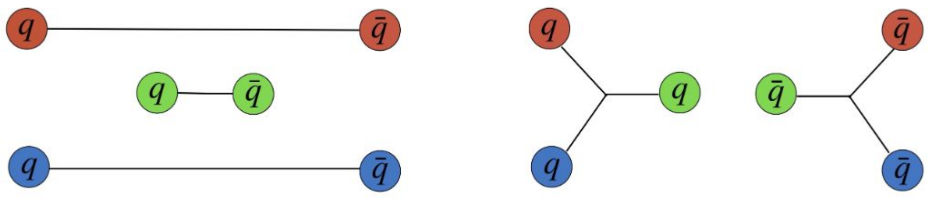
➢ Fragmentation processes tuned on charm production measurements in e^+e^- collisions, → Λ_c/D^0 ~ 0.1 mild p_T-dependence.

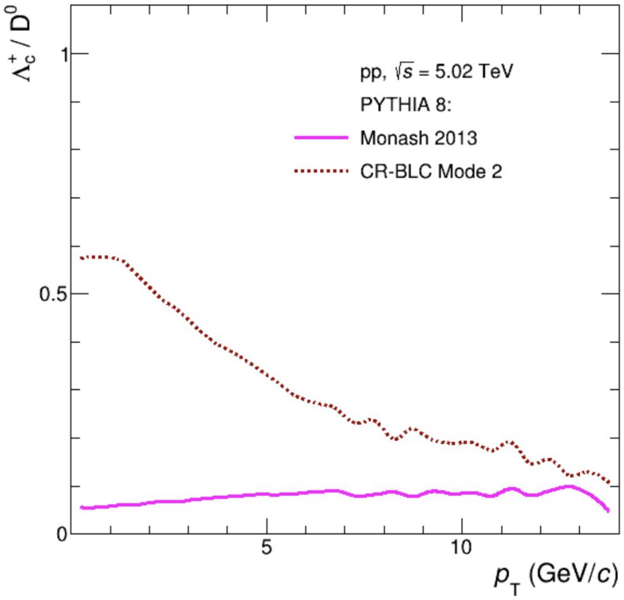
➢ Significantly underestimate the data at low p_T, while at high p_T the discrepancy is reduced

Can we explain the measured baryon enhancement?

PYTHIA 8 new Color Reconnection

- ➢ **PYTHIA8 with String Formation beyond Leading Colour (CR-BLC)** JHEP 1508 (2015) 003
  - Introduce new ‘junction topologies for baryon enanchement’





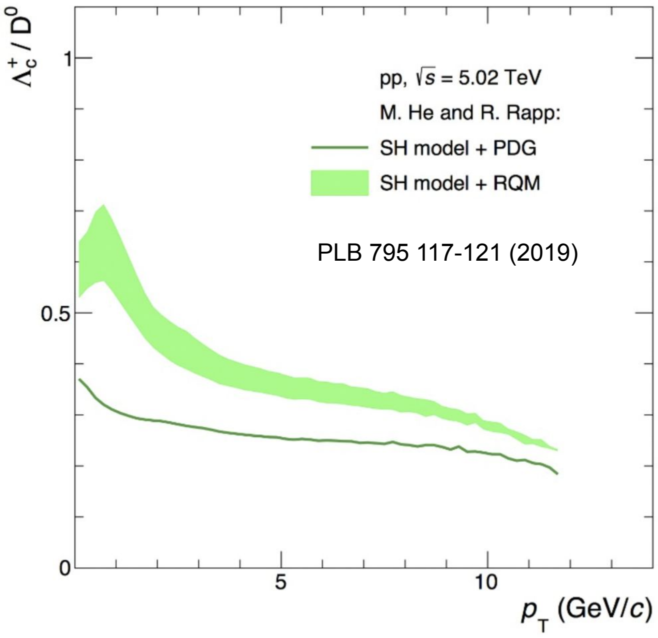
- ➢ CR allows to combine partons from different MPIs to minimize string length → used in Monash tune
- ➢ New CR-BLC
  - Minimization of the string length over all possible configurations
  - Include CR with MPIs and with beam remnants

SHM with additional baryon resonances

➢ **He and Rapp (SHM+RQM)**,
  - SHM: production via statistical weights (scaling with mass) and FF based on e^+e^-
  - Feed-down from augmented set of charm-baryon states based on Relativistic Quark Model

□ PDG: 5 Λ_C (I=0) , 3 Σ_C (I=1), 8 Ξ_C (I=1/2), 2 Ω_C (I=0)➔ missing baryons?!
RQM: 18 extra Λ_C , 42 extra Σ_C, 62 extra Ξ_C, 34 extra Ω_C up to 3.5 GeV
➔ supported by lattice PRD 84 (2011) 014025; PoS LAT. 2014 (2015) 084; PLB 737 (2014) 210

n_i $(\cdot 10^{-4}\ \mathrm{fm}^{-3})$	D^0	D^+	D^{*+}	D_s^+	Λ_c^+	$\Xi_c^{+,0}$	Ω_c^0
PDG(170)	1.161	0.5098	0.5010	0.3165	0.3310	0.0874	0.0064
PDG(160)	0.4996	0.2223	0.2113	0.1311	0.1201	0.0304	0.0021
RQM(170)	1.161	0.5098	0.5010	0.3165	0.6613	0.1173	0.0144
RQM(160)	0.4996	0.2223	0.2113	0.1311	0.2203	0.0391	0.0044

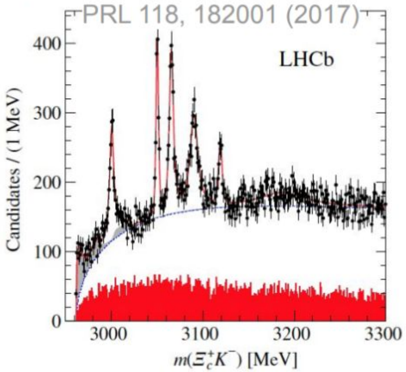


➢ Similar work performed for beauty hadrons and a similar effect is observed

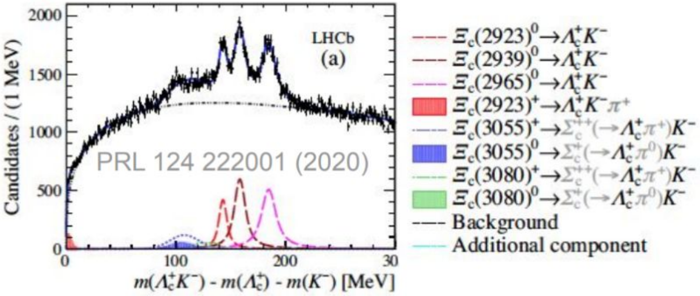
PRL 131 (2023) 1, 012301

New resonance states popping up

Ω_c excited states

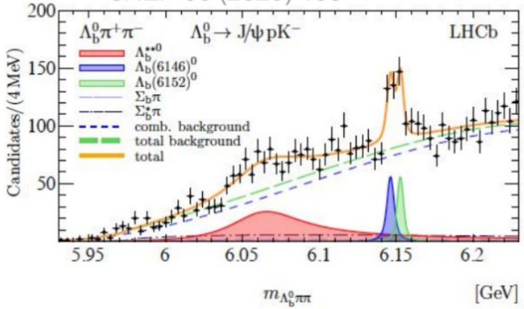


Ξ_c excited states

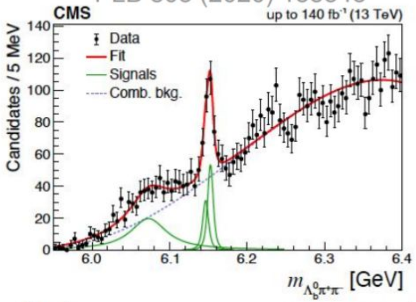


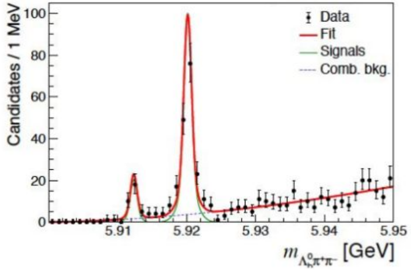
Λ_b excited states

JHEP 06 (2020) 136

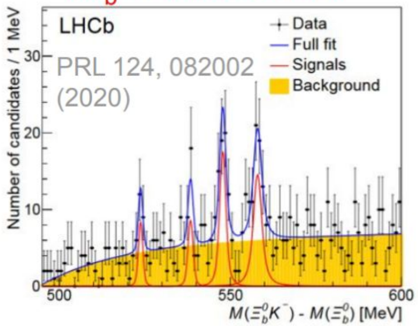


PLB 803 (2020) 135345





Ω_b excited states



- ➢ Typically those are not measurements of (prompt) cross sections. **Prospects?**

- ➢ Many states with relatively narrow widths, $\Gamma \sim 10$ MeV

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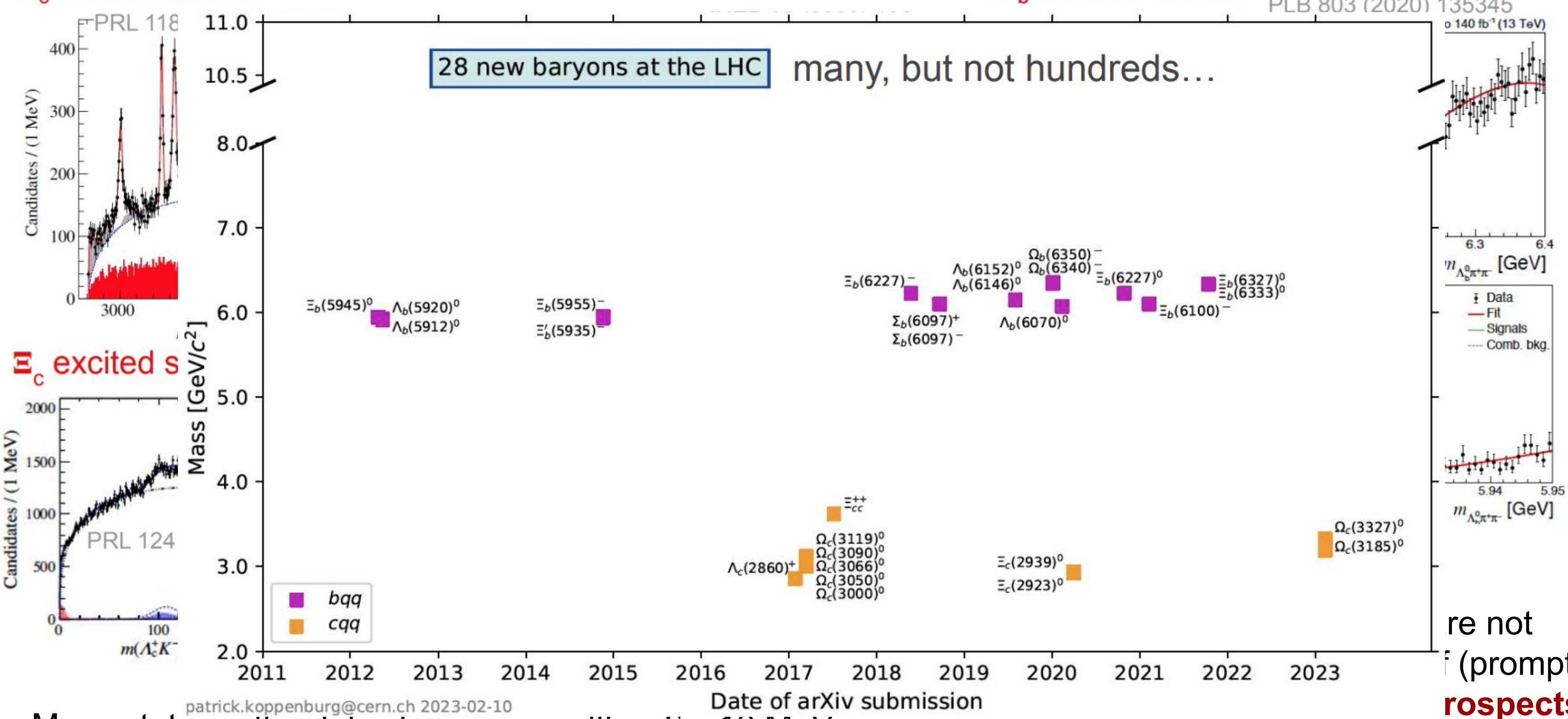
New resonances states popping up

Ω_c excited states

Λ_b excited states



Ξ_c excited s

➢ Many states with relatively narrow widths, Γ ~ 10 MeV

re not

f (prompt)

rospects?

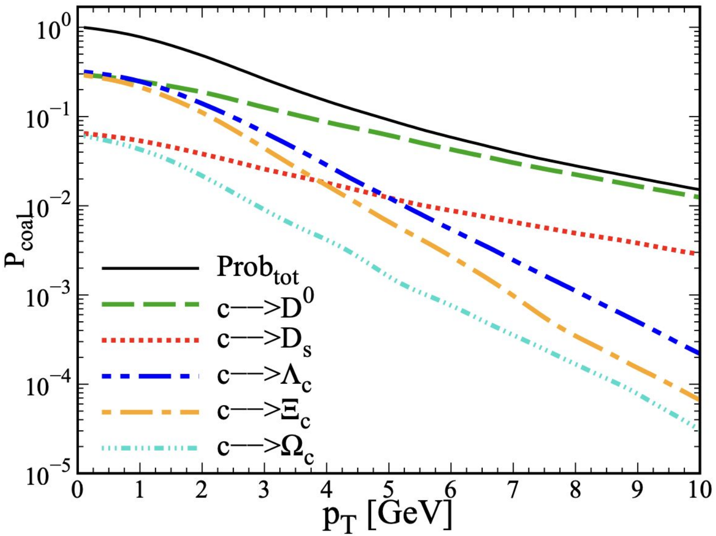
Parton coalescence in pp

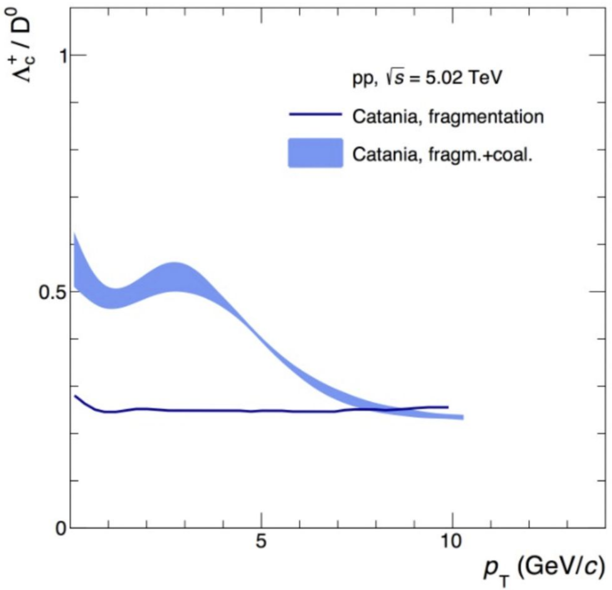
➢ **Catania:** Transport model with hadronization via coalescence+fragmentation

- Thermal spectra for light quark below 2 GeV/*c*
- Charm quark spectrum from FONLL
- List of excited resonances from PDG

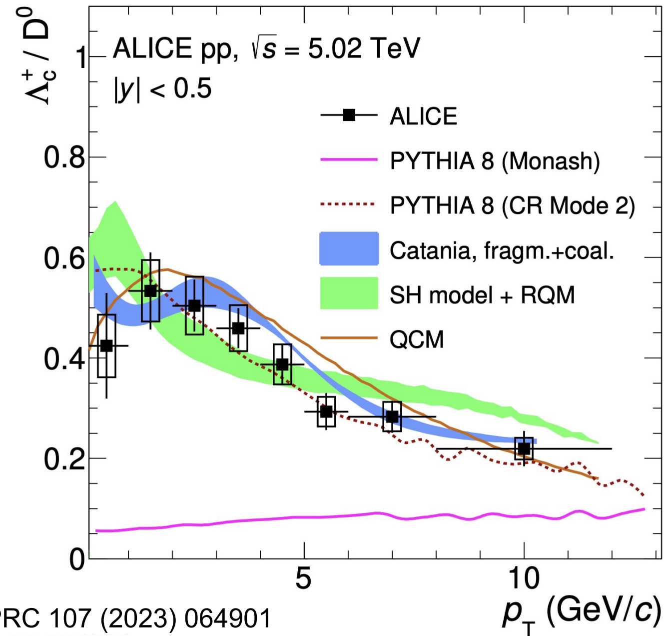
PLB 821 (2021) 136622
EPJC (2018) 78:348

At $p_T \approx 0$, a charm quark only hadronize via coalescence, while at high p_T fragmentation becomes dominant



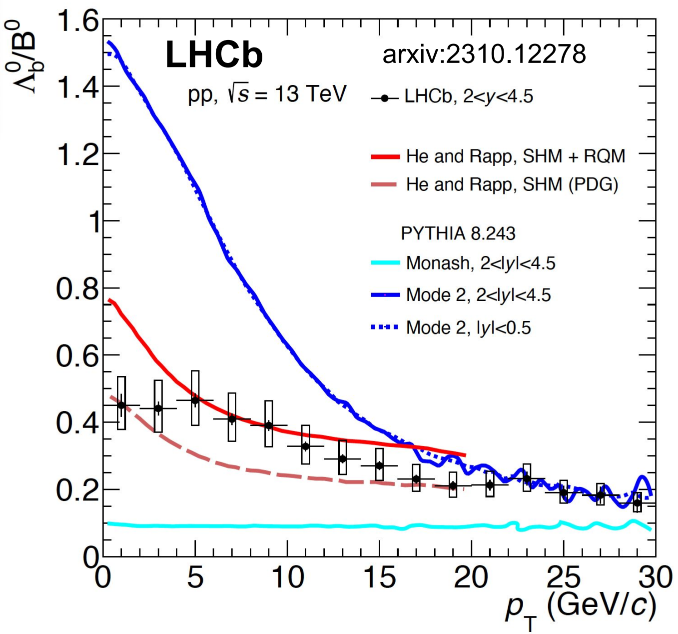


Baryon/meson ratio in pp



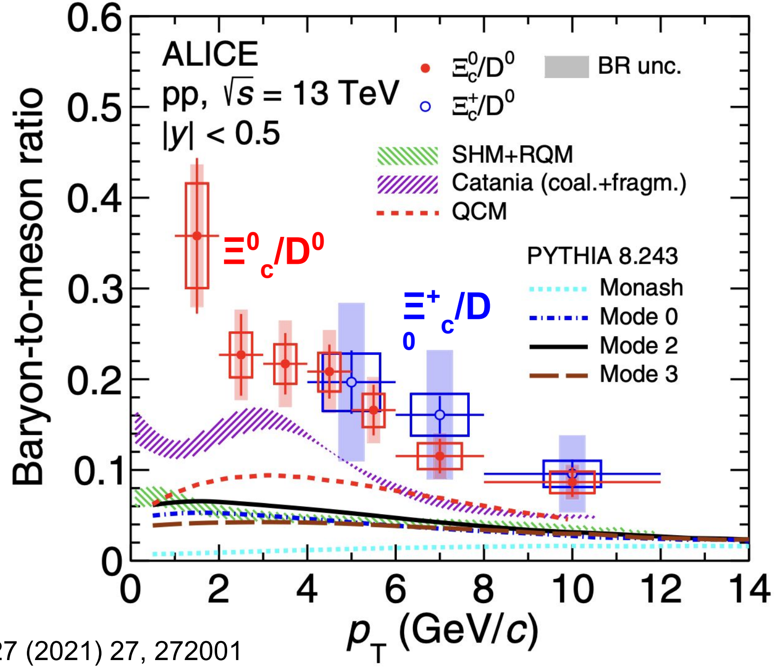
PRC 107 (2023) 064901

Similar observation in the beauty sector

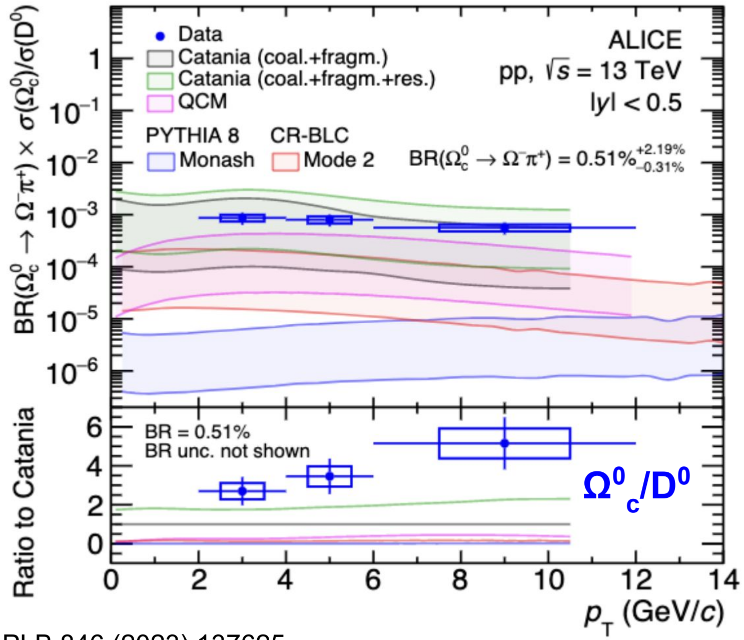


- ➢ CR Modes BLC in PYTHIA 8, SHM+RQM, Catania (and QCM) enhance the baryon yield and better describe the data
- ➢ **Do the model also describe measurements at forward rapidity?**
  - Is there any obvious difference (parton density, heavy-quark density)?

A common trend for charm baryons



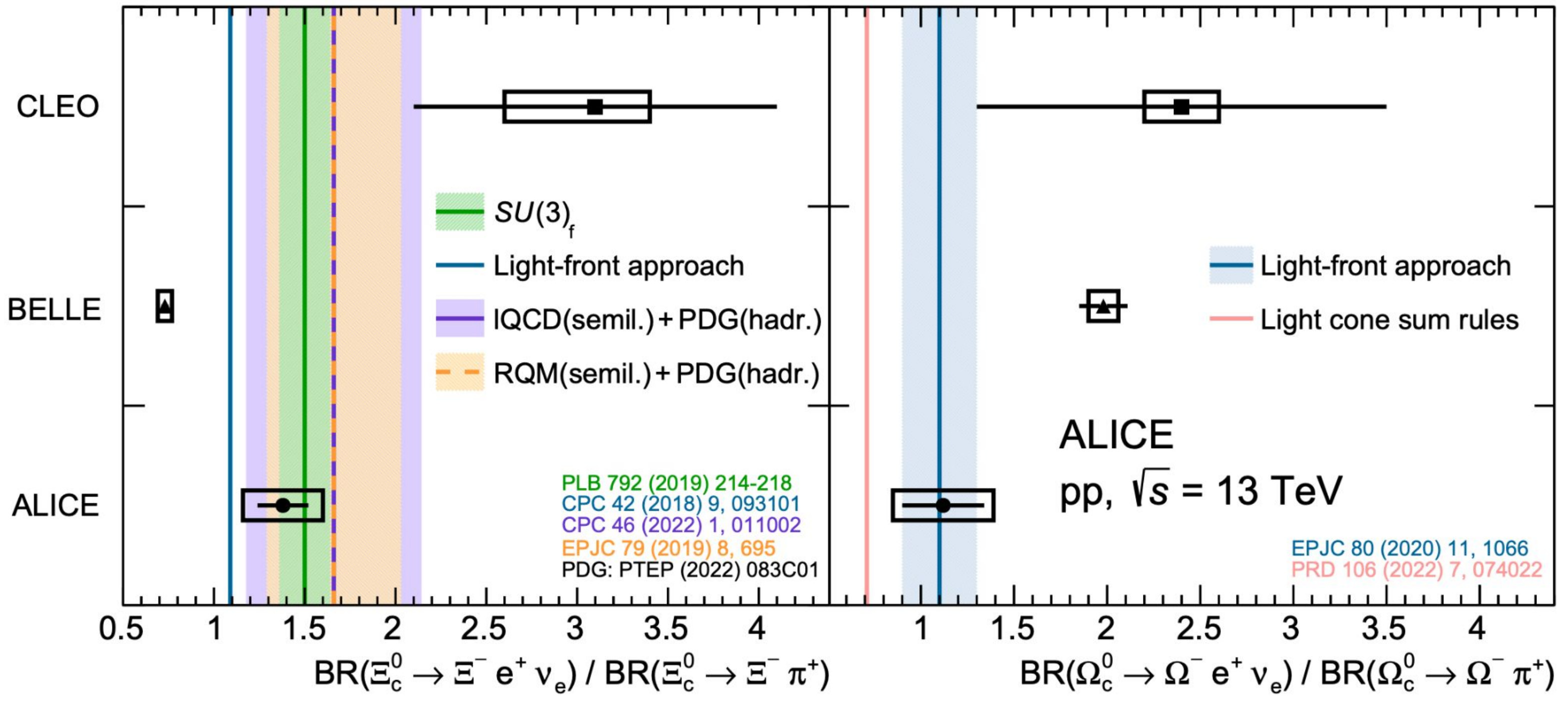
PRL 127 (2021) 27, 272001



PLB 846 (2023) 137625

➢ **For charm baryons with strang content the enhancement is even larger!**
- Additional challenges from strange-quark production
- Coalescence is the model that gets consistently closer to data

A limiting factor and the first results

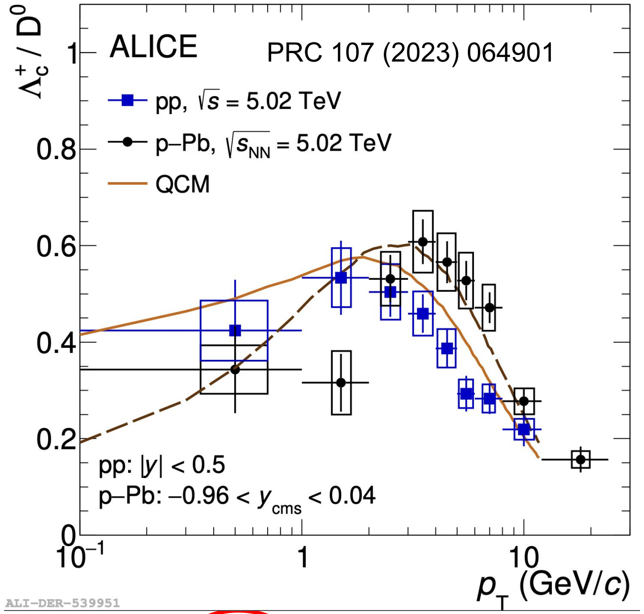


➢ **ALICE started performing first BR measurements of rare probes**

- Run 3 will help in reducing uncertainties and solving some discrepancies

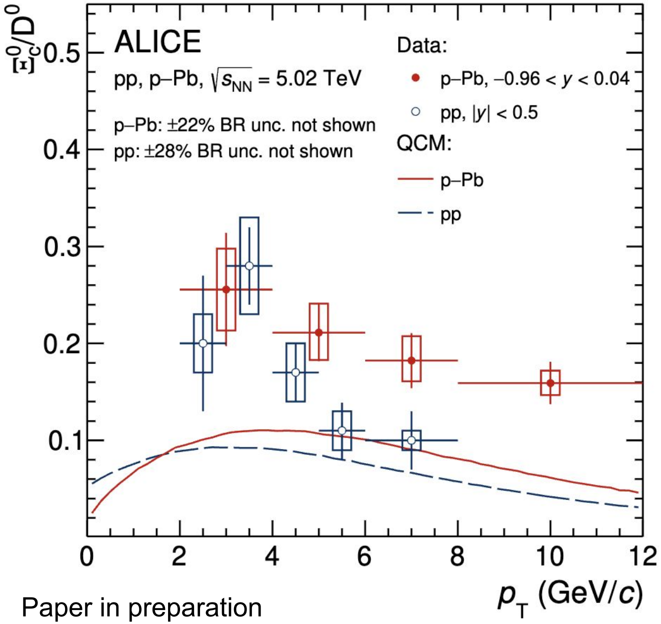
Ξ^0_c PRL 127 (2021) 27, 272001
Ω^0_c: paper in preparation

Baryon/meson ratio in p-Pb



	Λ_c^+/D^0
pp	0.47 ± 0.04 (stat.) ± 0.04 (syst.)
p–Pb	0.42 ± 0.04 (stat.) ± 0.06 (syst.)

	$\langle p_T \rangle$ (GeV/c)	
	pp	p–Pb
D^0	2.06 ± 0.03 (stat.) ± 0.03 (syst.)	2.07 ± 0.02 (stat.) ± 0.04 (syst.)
Λ_c^+	1.86 ± 0.06 (stat.) ± 0.03 (syst.)	2.29 ± 0.06 (stat.) ± 0.06 (syst.)



Paper in preparation

- Do we see radial flow in p-Pb collisions?
- **Can coalescence redistribute along p_T the same Λ_c and Ξ_c baryon enhancements?**

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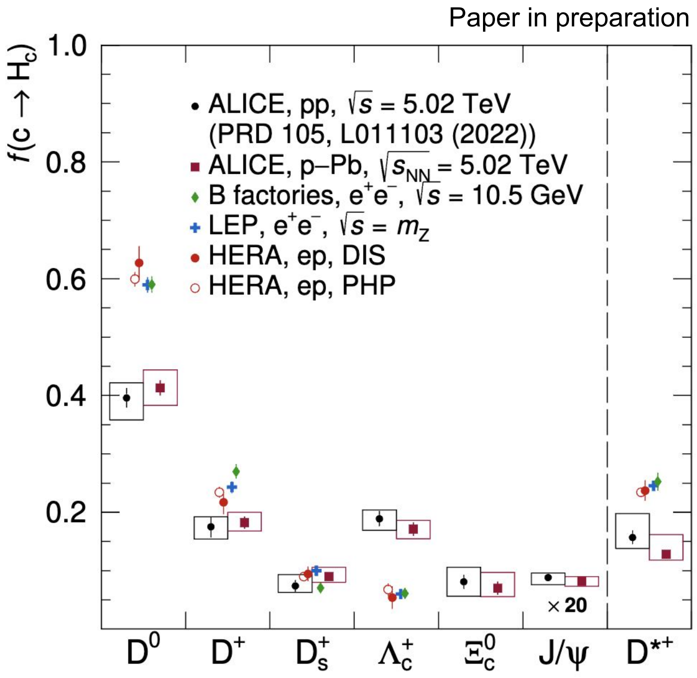
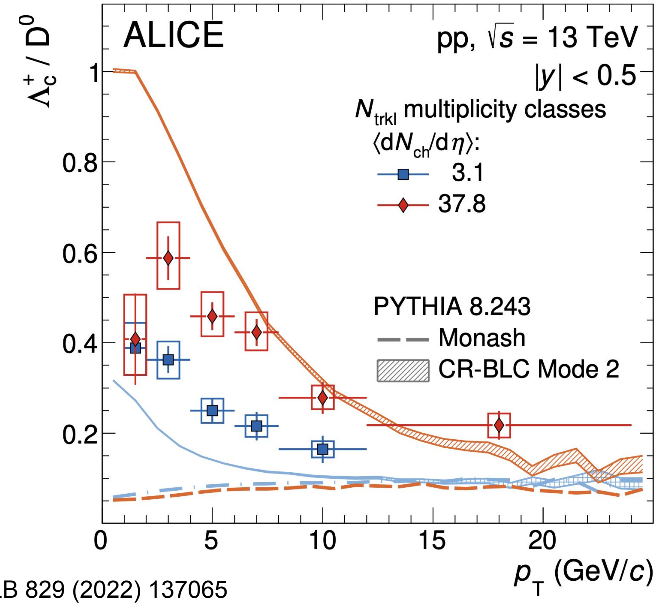
Fragmentation fractions in p-Pb

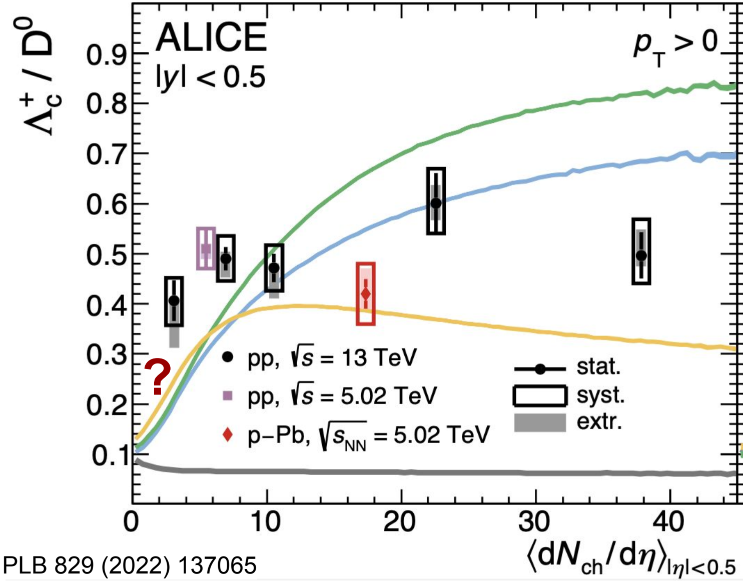


➢ Charm fragmentation fractions at the LHC do not depend on colliding system and energy!

Baryon-to-meson ratio vs multiplicity



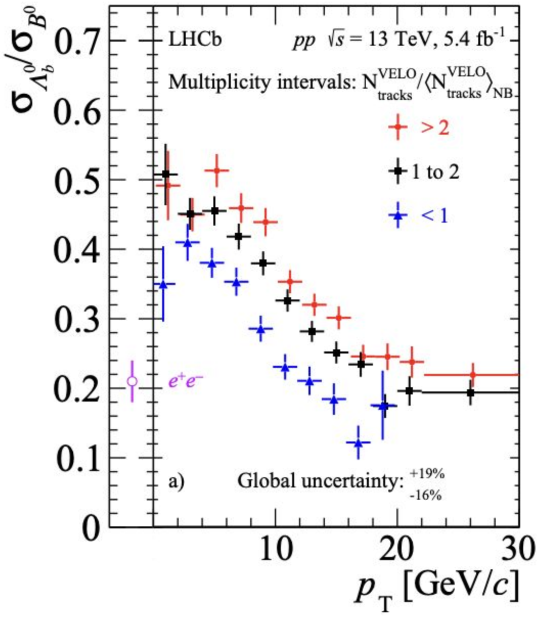
PLB 829 (2022) 137065

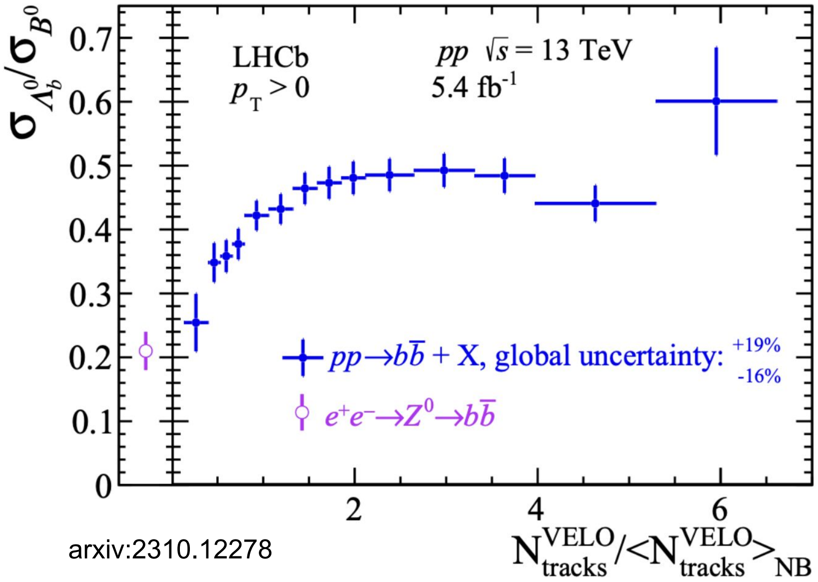


PLB 829 (2022) 137065

- ➢ Baryon/meson ratios in pp collisions: different p_T trend depending on multiplicity
  - Larger baryon production at intermediate p_T with increasing multiplicity
- ➢ No modification of p_T-integrated Λ_c/D^0 as a function of multiplicity
- ➢ **Towards very low multiplicity** - would it be possible to reach the e^+e^- limit?

Baryon-to-meson ratio vs multiplicity



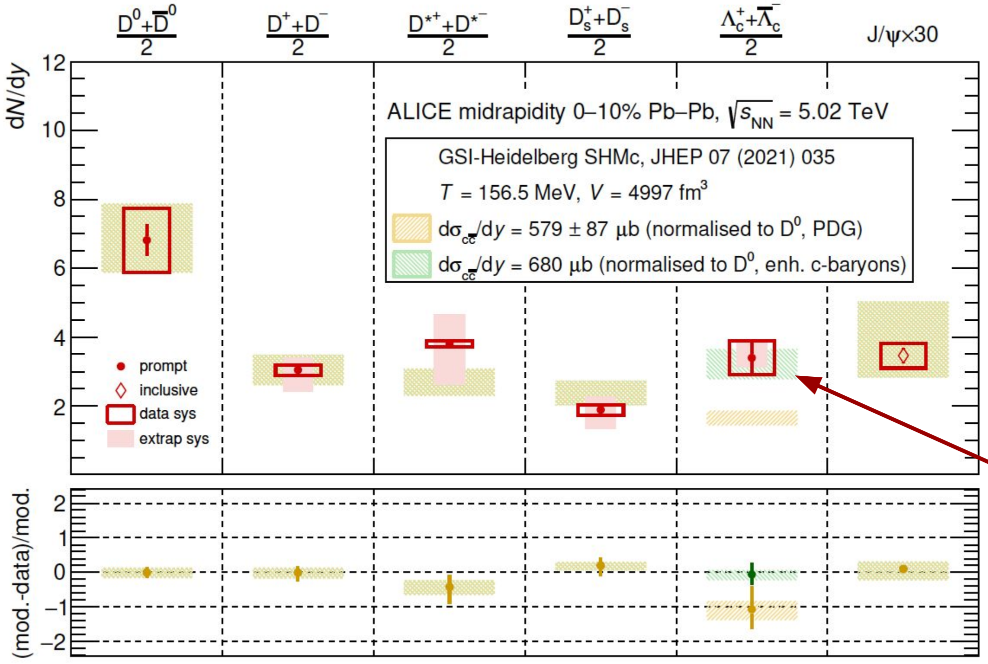


arxiv:2310.12278

- ➢ Baryon/meson ratios in pp collisions: different p_T trend depending on multiplicity
  - Larger baryon production at intermediate p_T with increasing multiplicity
- ➢ **In the beauty sector the e^+e^- limit is reached**
- ➢ ALICE measured non-prompt Λ_c production ($|y| < 0.5$) in pp and p-Pb collisions arXiv:2308.04873

SHM with charm (SHMc)

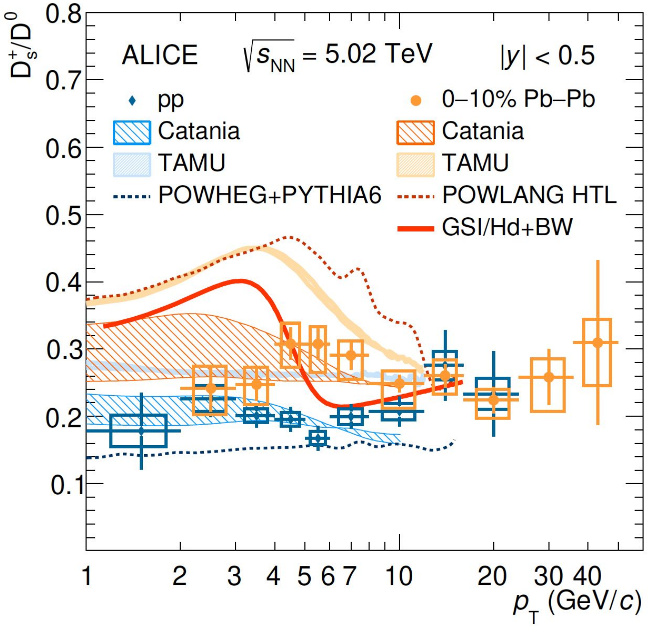
Extremely good description of particle yield in the light flavour sector!

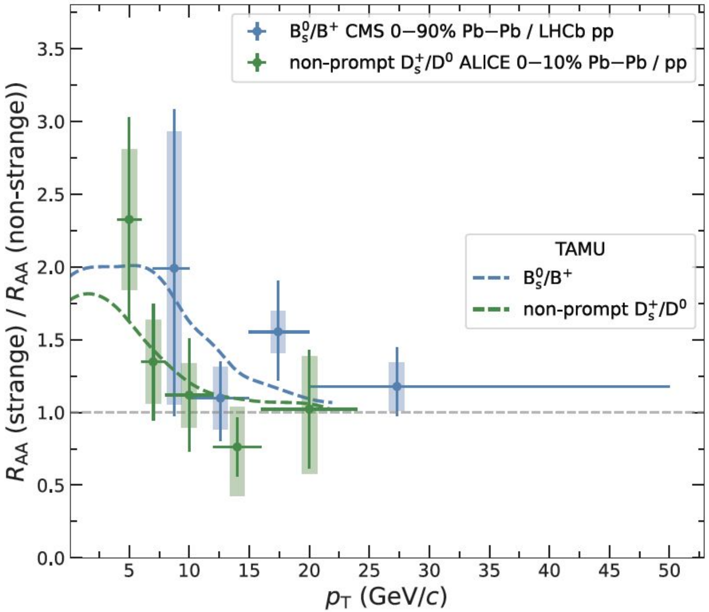


arXiv:2211.04384

- Measured p_T-integrated yields of open charm mesons and J/Ψ midrapidity described by SHMc within uncertainties
  - Charm content determined by cross section and not by fireball temperature
  - Assume (full) charm quark thermalisation in the QGP
  - Charm quarks distributed to hadrons according to thermal weights
- **Yield of Λ_c baryons captured** assuming an enhanced production of charmed baryons

Open charm and beauty hadrochemestry

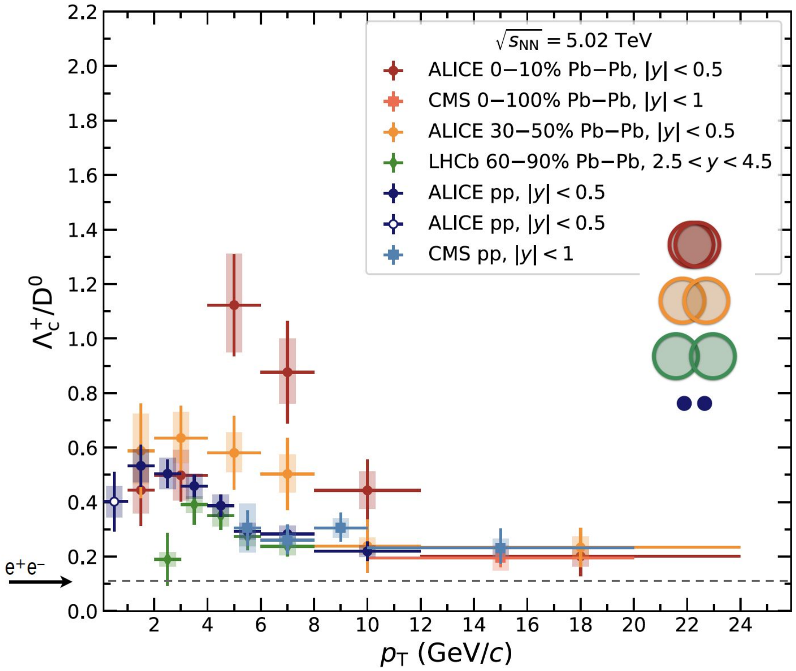




➢ Coalescence of heavy quarks with light quarks from the QGP affects **HF hadrochemestry**

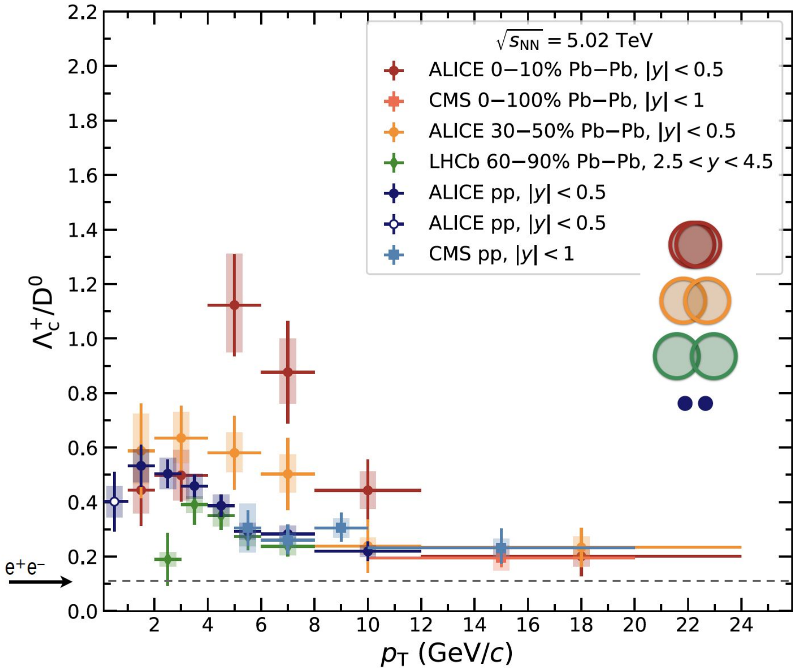
- **Enhanced D_s(B_s)** yield relative to non-strange mesons (strange quarks abundant in QGP)
- D_s/D^0 ratios in central Pb-Pb hint at enhancement at mid-p_T relative to pp
- Similar indication observed in the strange-beauty sector (B_s and non-prompt D_s)

Λ_c in Pb-Pb



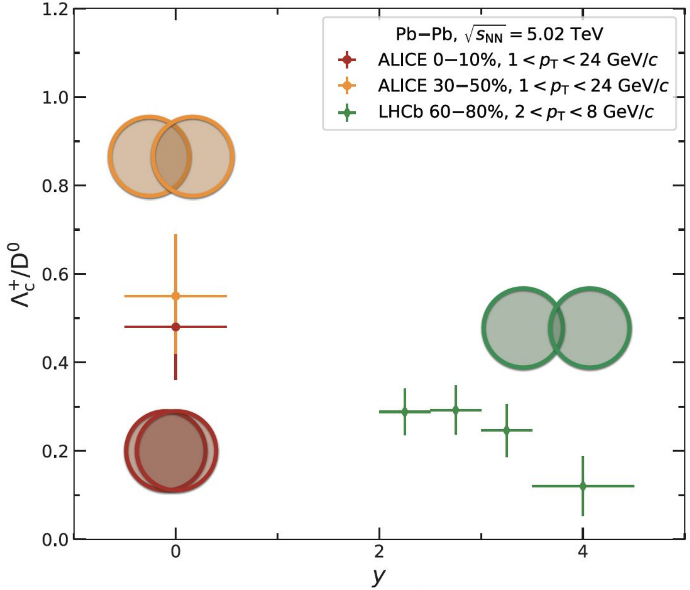
- **Λ_c/D^0 in heavy-ion collision** is higher at intermediate p_T wrt e^+e^- and pp
  - Higher probability to hadronise via coalescence?
  - Radial flow?
  - An interplay of the two effect?

Λ_c in Pb-Pb



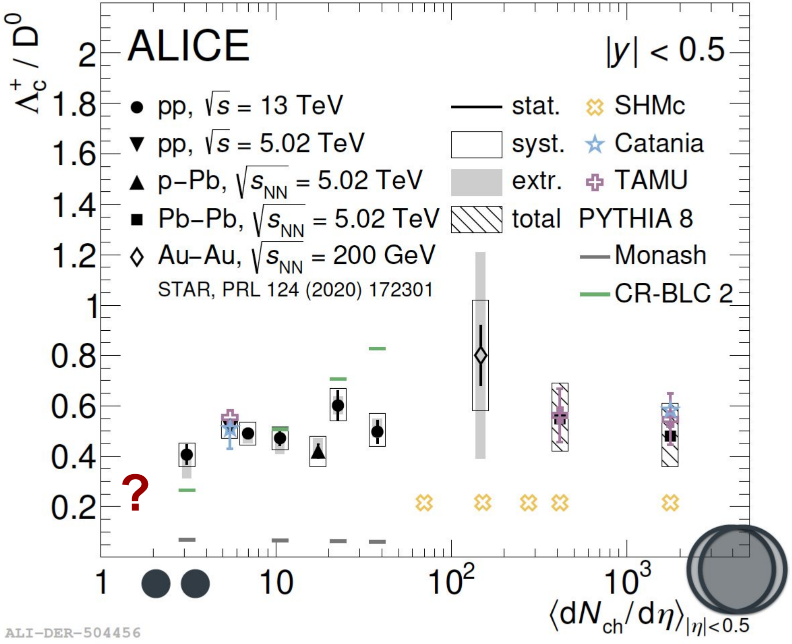
➢ **Λ_c/D^0 in heavy-ion collision** is higher at intermediate p_T wrt e^+e^- and pp

- Higher probability to hadronise via coalescence?
- Radial flow?
- An interplay of the two effect?



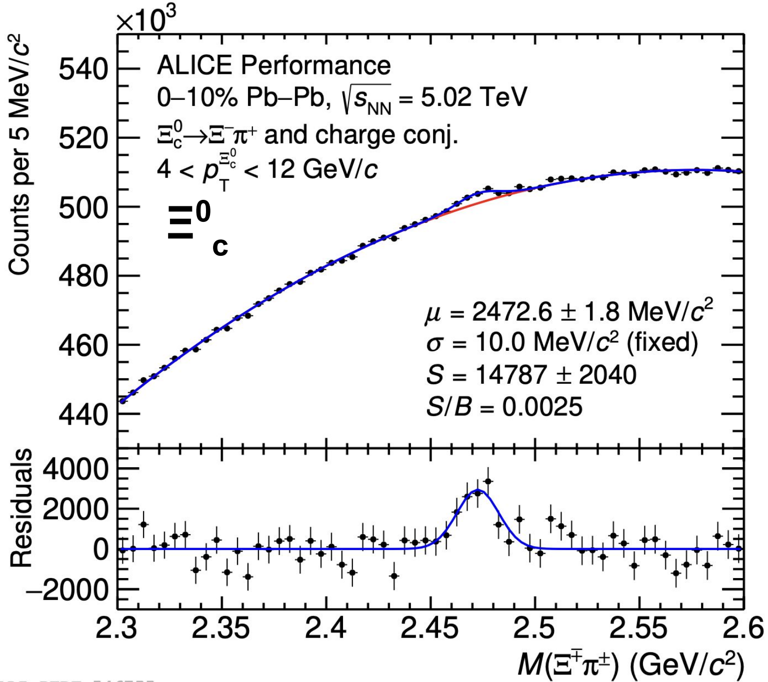
➢ Possible rapidity dependence need further investigation - what do models (coalescence) predict?

Baryon-to-meson ratio vs multiplicity



- ➢ No modification of p_T-integrated Λ_c/D^0 from pp to Pb-Pb
- ➢ **Towards very low multiplicity** - would it be possible to reach the e^+e^- limit?
- ➢ **Prospect:** measure Ξ_c and Ω_c baryons in heavy-ion collisions

Baryon-to-meson ratio vs multiplicity



- ➢ No modification of p_T-integrated Λ_c/D^0 from pp to Pb-Pb
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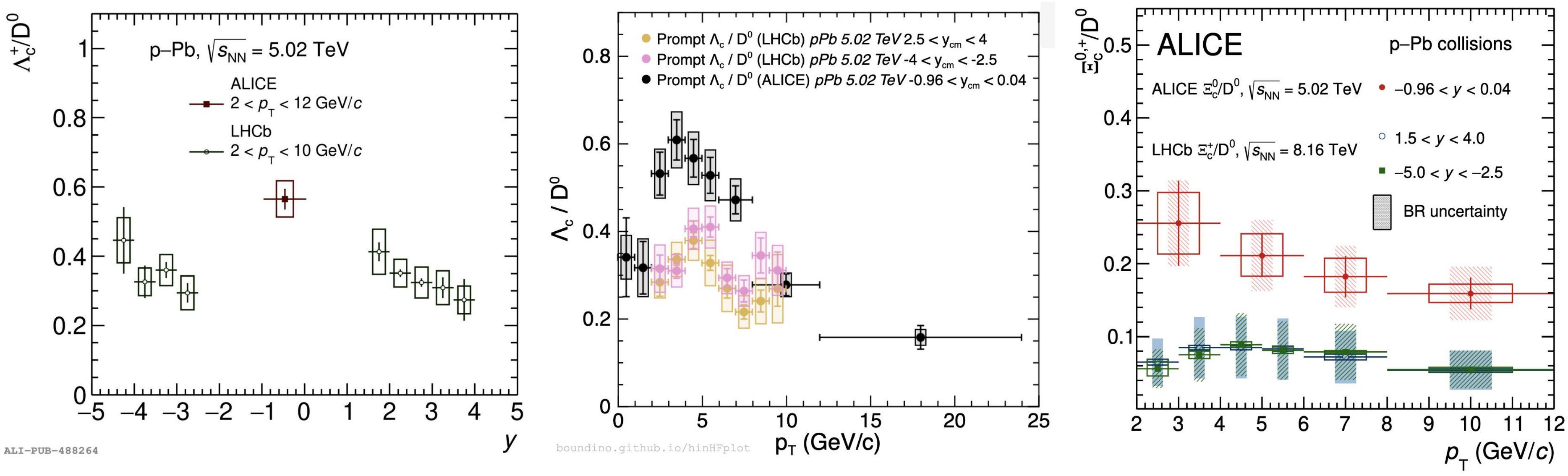
Perspectives

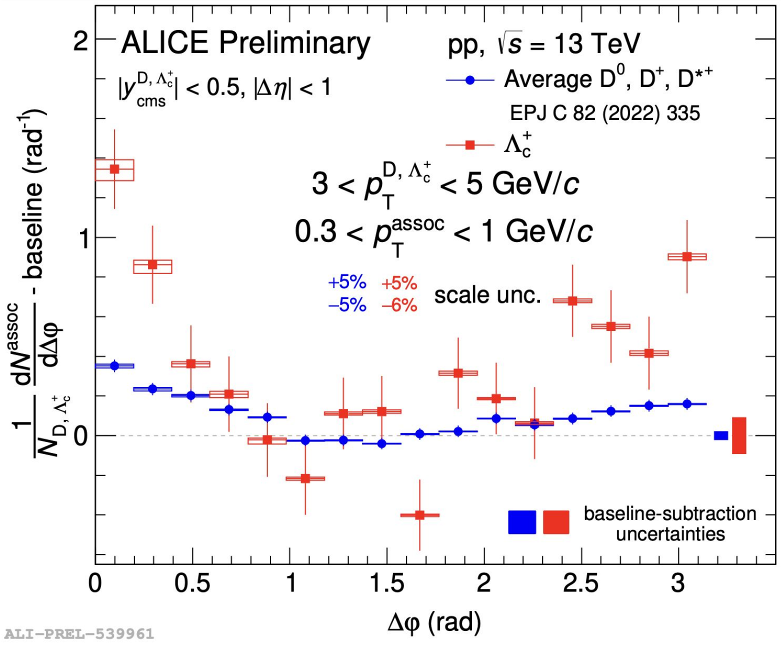
The rapidity puzzle

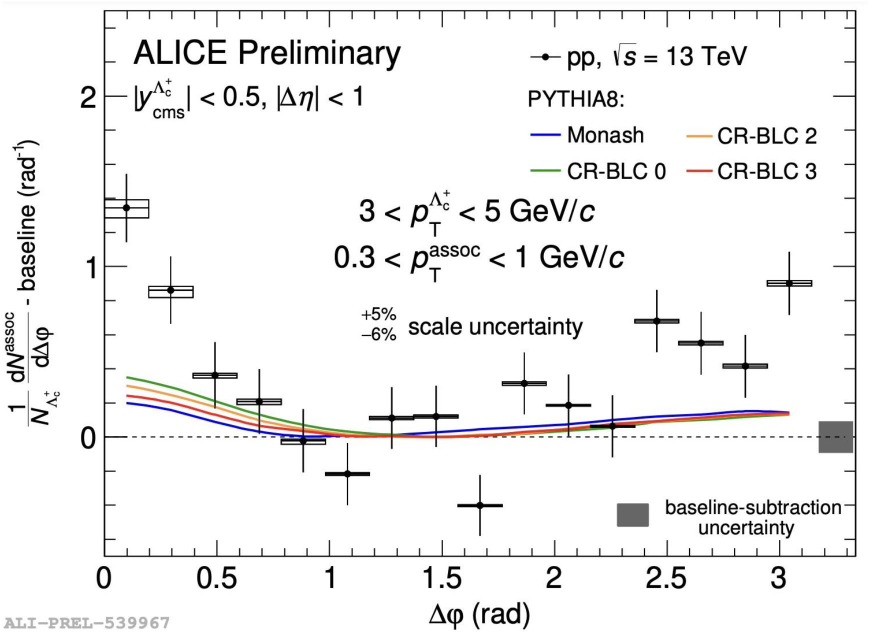


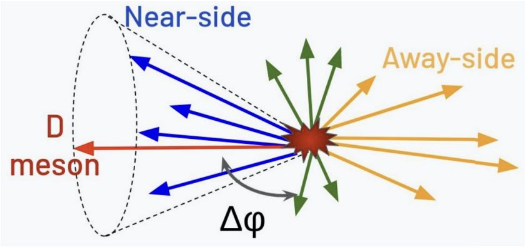
➢ **Recurrent picture:** stronger enhancement at midrapidity than at forward rapidity
→ Possible trend to be revisited with Run 3 data (also in pp)?

➢ What should we expect in coalescence models and SHMc? Flat in rapidity?

More differential - correlations and jets







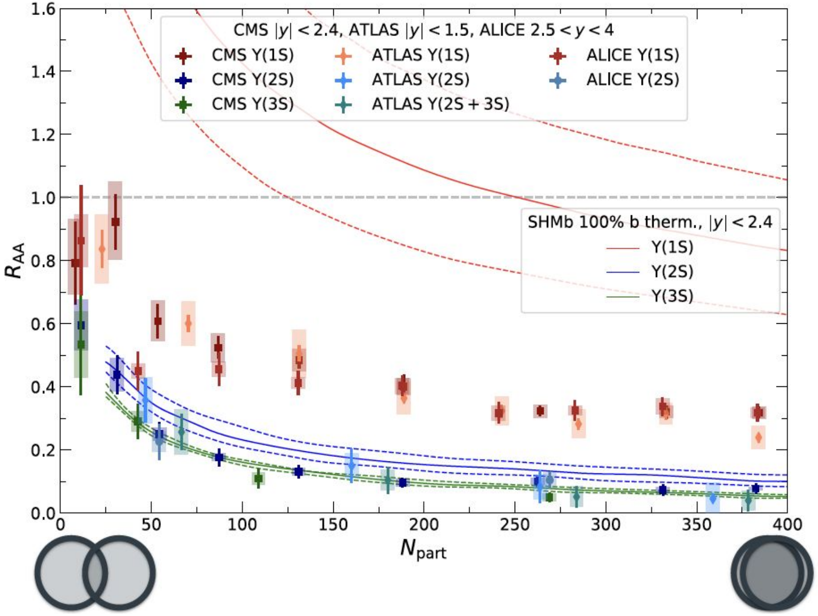
- ➢ Near-side and away-side peak yields larger for Λ_c–h than D–h → not described by PYTHIA colour-reconnection modes
- ➢ Impact of softer Λ_c fragmentation? → hints from Λ_c-tagged jets analysis: arXiv:2301.13798

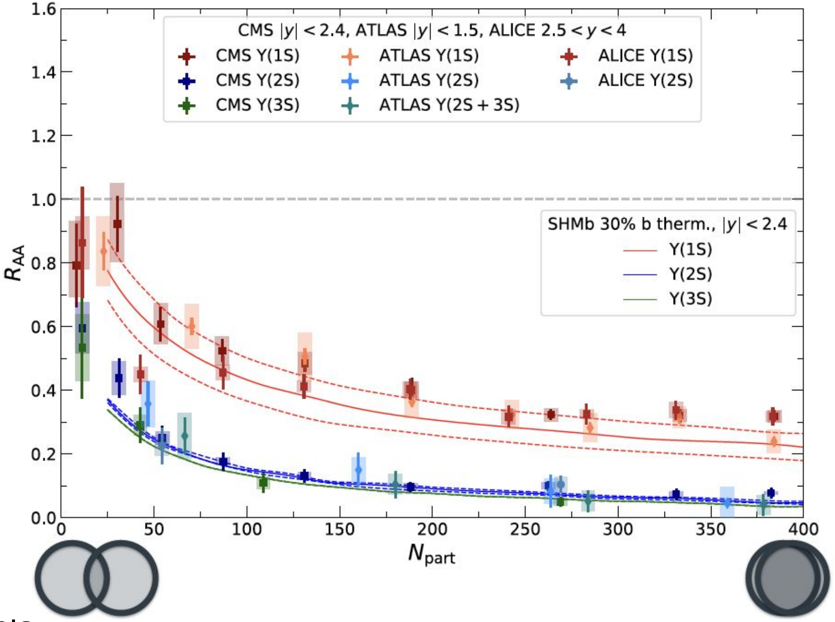
SHM with beauty

➢ Y largely overestimated if 100% of beauty quarks assumed to be thermalized.
  - Does beauty quark reach thermal equilibrium
  - v_2 is compatible with zero

➢ **Y described if 30% of beauty quarks assumed to thermalize.**
  - Reach partial equilibrium?
  - **Presence of currently unknown open beauty states will lead to a reduction of the bottomonia yields.**

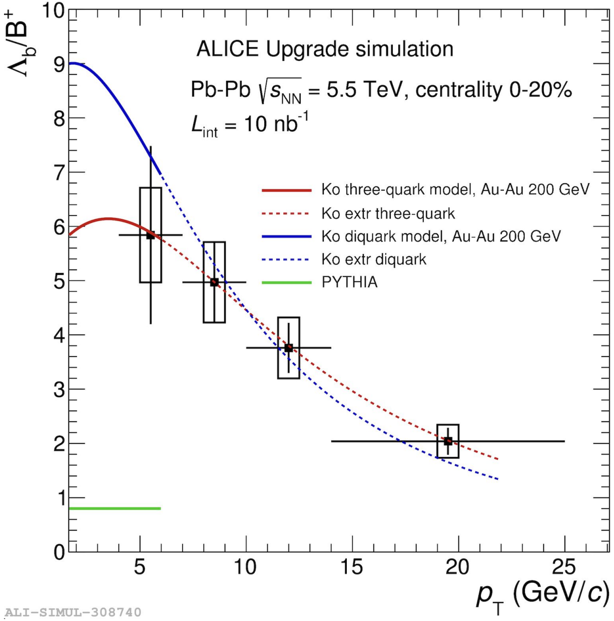
CMS: PRL 120 (2018) 142301

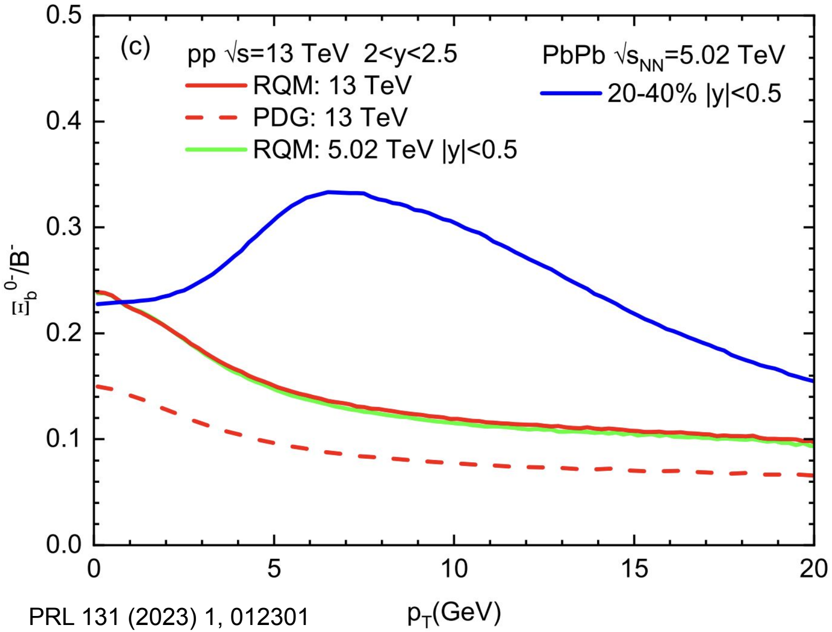




SHMb: Acta Phys.Polon.Supp. 16 (2023) 1, 107

Beauty hadrons in Pb-Pb





PRL 131 (2023) 1, 012301

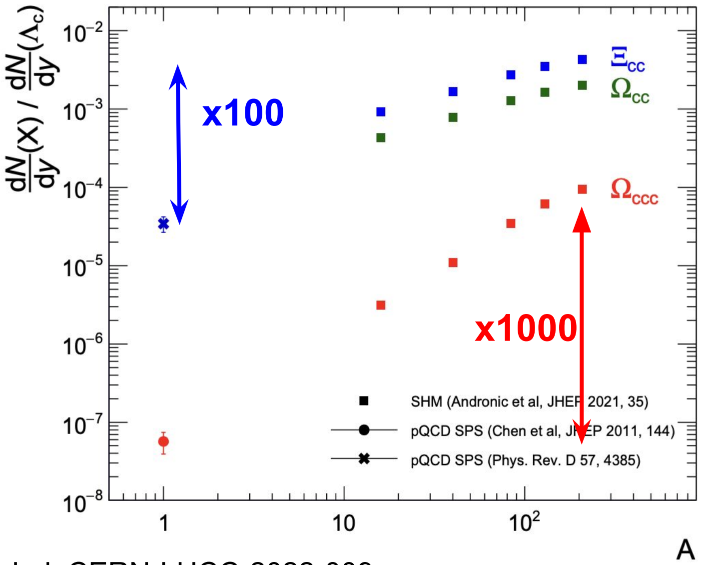
- **Full reconstruction of beauty hadrons will be at reach in Run 3-4**
  - Reconstruction of $\Lambda^0_b \to \Lambda^+_c \pi^-$ (BR = 4.9 10^{-3})
    - Will be affected by large uncertainties and limited to p_T > 4-5 GeV/c in Run 3 and Run 4
  - Enhancement expected also for beauty-strange baryons

Loi: CERN-LHCC-2022-009

Multi-charm hadron states

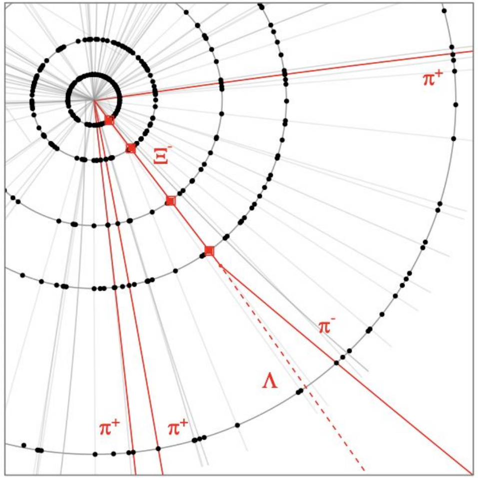
- Crucial new insight by measuring baryons containing multiple charm quarks (Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ω_{cc}^{+}, Ω_{ccc}^{++})
- Yields of multi-charm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models - production in single hard scattering disfavored

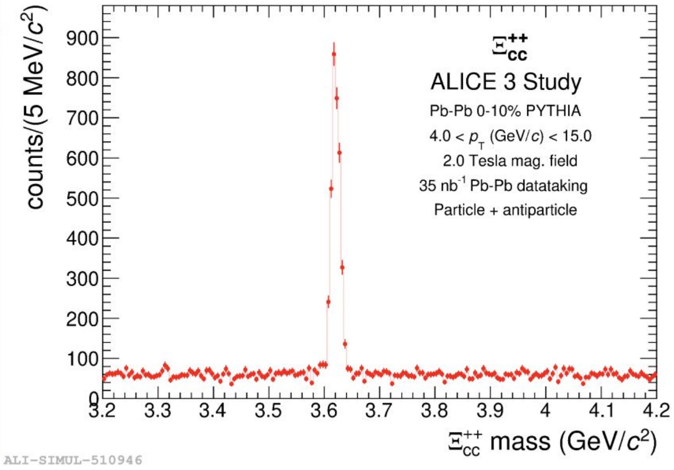
➢ Direct window on hadron formation from QGP and unique testing ground for charm deconfinement and thermalisation



Loi: CERN-LHCC-2022-009

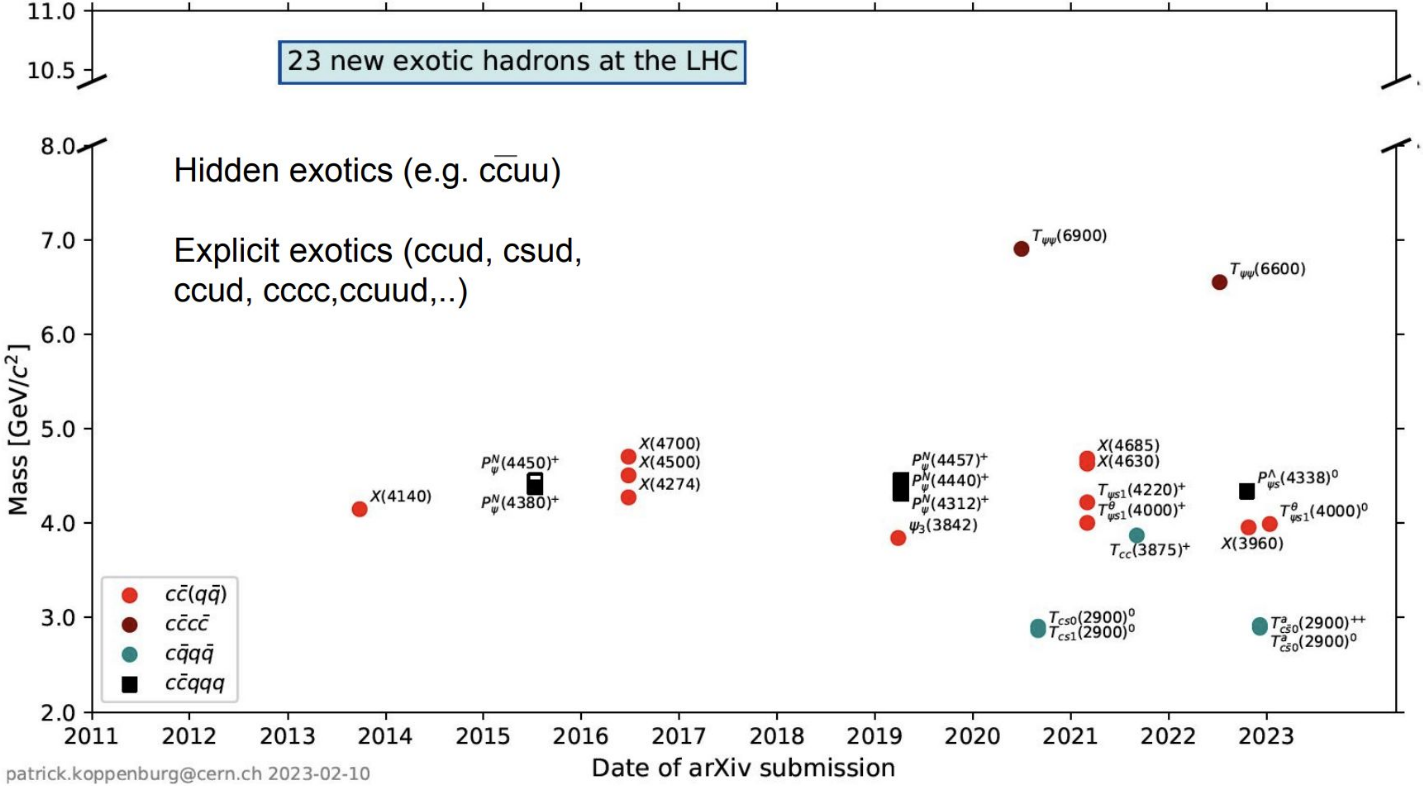
strangeness tracking





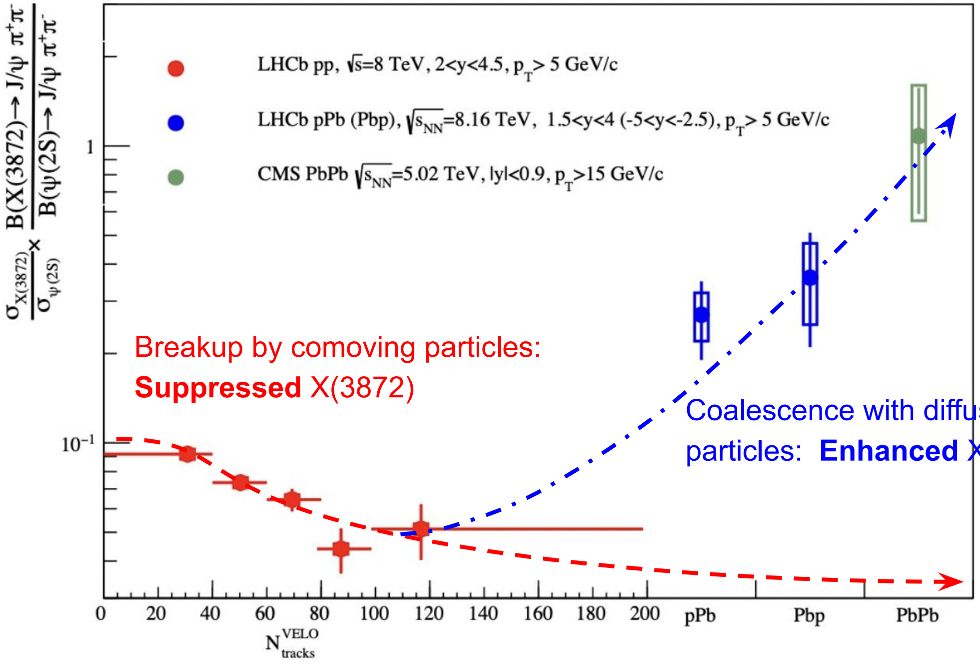
Andrea Dubla

Exotica: a galaxy of spettroscopy



Another window on coalescence

- **Relevance of coalescence in large systems?**
  - X(3872) → form from suppression to enhancement?
  - Stress test with system size scan: *ep* → *eA* → *pp* → *pO* → *OO* → *pA* → *ArAr* → *XeXe* → *PbPb*



- Extension of measurements toward **low p_T is crucial**
- Centrality dependence

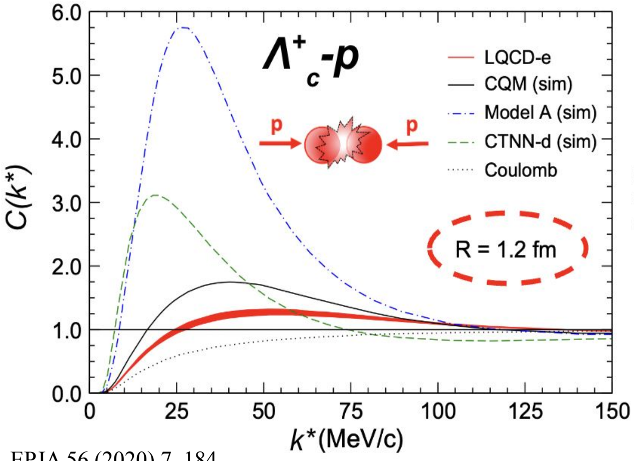
- Further studies will also shed light on the **internal structure** of these exoctic objects → femtoscopy

Loi: CERN-LHCC-2022-009
H. Zhang et al., PRL 126(2021) 012301
B. Wu et al., EPJA 57(2021) 122

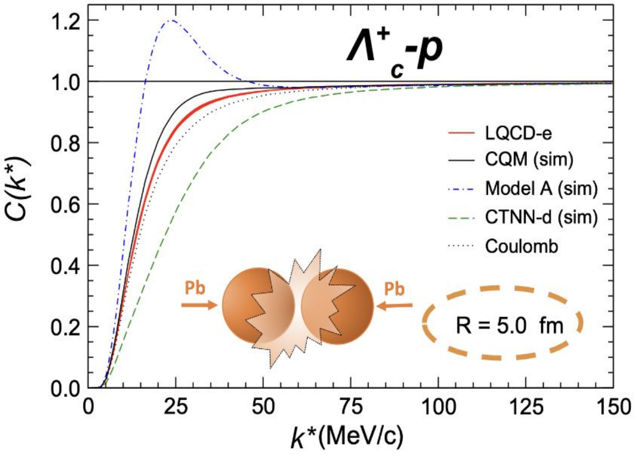
LHCb:
- PRL 126 (2021) 092001
- LHCb-CONF-2022-001

CMS:
- PRL 128 (2022) 3, 032001

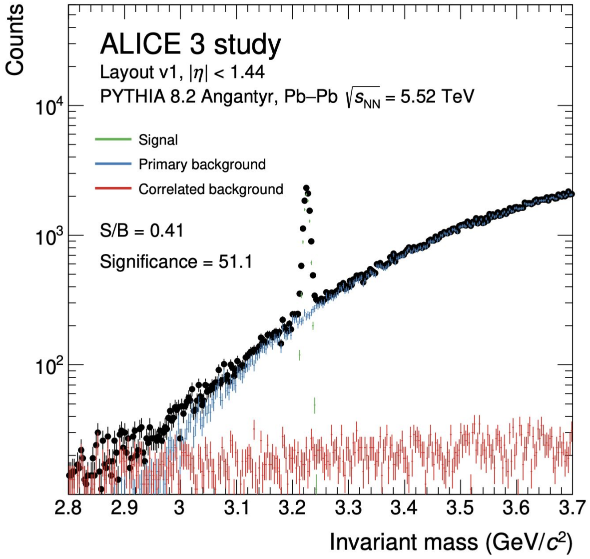
Charm hypernuclei



EPJA 56 (2020) 7, 184



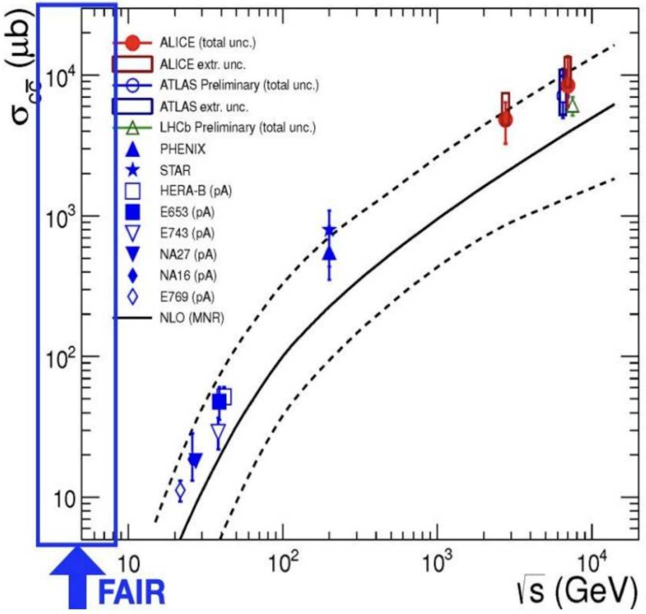
Loi: CERN-LHCC-2022-009



- ➢ Possibility to **constrain the Λ_c-N interaction potential**
  - Distinct source size dependence of the correlation function in presence of bound states → interplay of the scattering length with the inter-particle distance (source size)
- ➢ Possibility of performing a **full decay reconstruction** will soon become feasible $c_d \rightarrow dK^- \pi^+$

CBM related opportunities

➢ **Program of CBM at FAIR** includes measurements in the charm sectors



➢ Charm production via **subthreshold mechanisms** in pp/HI

PRC 95, 014911 (2017)

- charm hadron production is driven by multistep scatterings of nucleons and their resonances

➢ **pp/pA:** bean energy 29 GeV will open the possibility to study:

- **pD and pΛ_c interactions** (femtoscopy)
- **exotic states** with hidden charm

➢ **HI**: CBM is best suited for measurements of **charmed nuclei** due to the high baryon density created and the expected high statistics measurements (modulo sub-production).

Conclusion

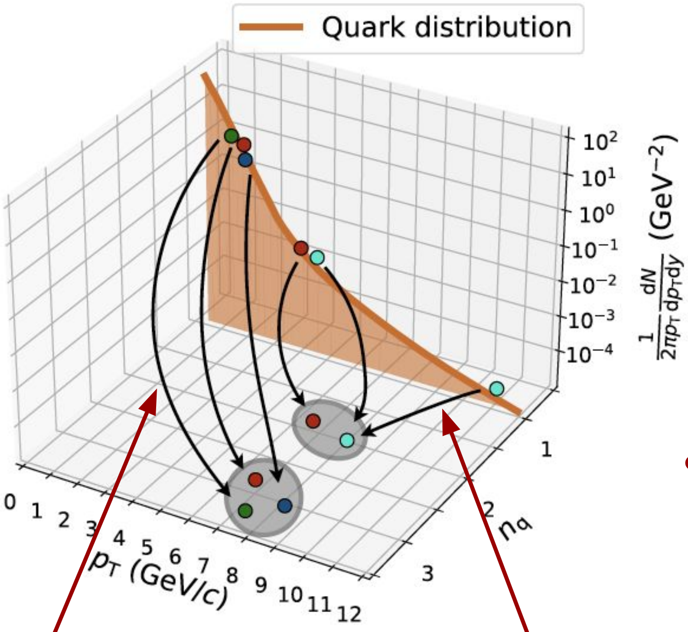
- **Hadronisation studied with heavy-flavour hadrons**
  - LHC data challenge the universality of fragmentation function
  - Clear signs of coalescence in open charm measurements (and in J/Ψ - not shown today)
  - Baryon enhancement present even at low mult. pp – can we reach an e^+e^- limit in pp?
  - **short term goal:** measurements of strange-charm baryons in HI collisions

Outlook:

- Beauty: need of precise measurements of hadrochemistry, p_T spectra and v_n for different hadrons
  - Accessible with precision with future large pp and Pb-Pb data samples
- Multi-charm hadron, B_c, and exotica will 'soon' be at reach (at least in pp collisions)
  - They can open a new window for further testing coalescence and statistical hadronization
- Charm studies at FAIR within the CBM experiment

Thank you all for the attention

Quark coalescence/recombinaton



- Single parton description may not be valid anymore
- No need to create qq pairs via splitting/string breaking
- Partons that are *"close" to each other in phase space* (position and momentum) can **recombine** into hadrons
- Initially thought to happen only in heavy-ion collisions

Recombining quarks:

$p_{meson} = p_{q1} + p_{q2}$;

$p_{baryon} = p_{q1} + p_{q2} + p_{q3}$

Fragmenting parton:

$p_h = z \cdot p_q$ with $z<1$

- **Recombination vs. fragmentation:**
  - Competing mechanisms, dominant in different p_T regions
  - **Recombination depends on "environment"**, i.e. density and momentum distribution of surrounding (anti)quarks
  - Recombination naturally enhances baryon/meson ratios at intermediate p_T

Greco et al., PRL 90 (2003) 202302
Fries et al., PRL 90 (2003) 202303
Hwa, Yang, PRC 67 (2003) 034902

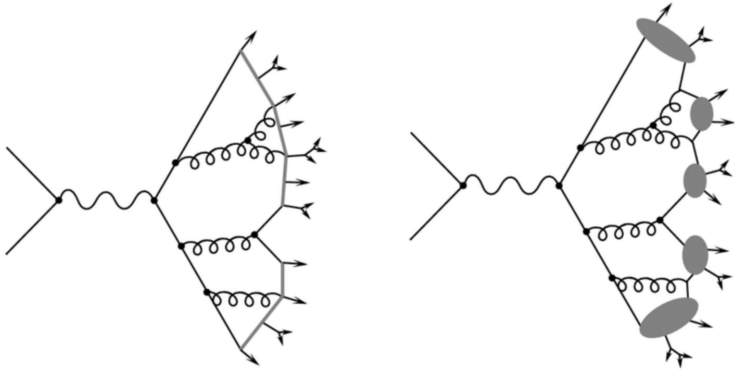
Independent fragmentation

- Inclusive hadron production from hard-scattering processes (large Q^2):
  - Factorization of: PDFs, partonic cross section (pQCD), fragmentation function

$$\sigma_{pp\to hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z, Q^2)$$

- **Fragmentation functions** $D_q\to h(z,Q^2)$:
  - Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition*
  - *z* is the fraction of the parton momentum taken by the hadron h
  - Parameterized on data (e^+e^-) and assumed to be "universal"

- In **event generators:** final stage of the parton shower interfaced to non-perturbative hadronisation models
  - (a) **String fragmentation** (e.g. Lund model in PYTHIA)
  - (b) **Cluster decay** in HERWIG

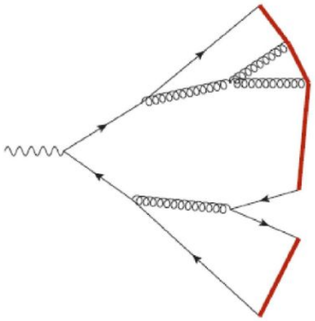


(a) String hadronization **(b)** Cluster hadronization

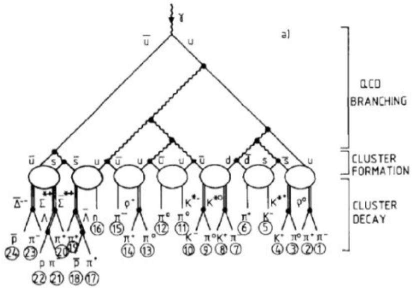
Hadrons from parton shower

- On a microscopic level hadronisation of jets modeled with:
  - Perturbative evolution of a parton shower with DGLAP down to a low-virtuality cut-off Q0
  - Final stage of parton shower interfaced to a non perturbative hadronisation model

- **String fragmentation** (e.g. Lund model in PYTHIA)
  - Strings = colour-flux tubes between q and $\bar{q}$ end-points
  - Gluons represent kinks along the string
  - Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs



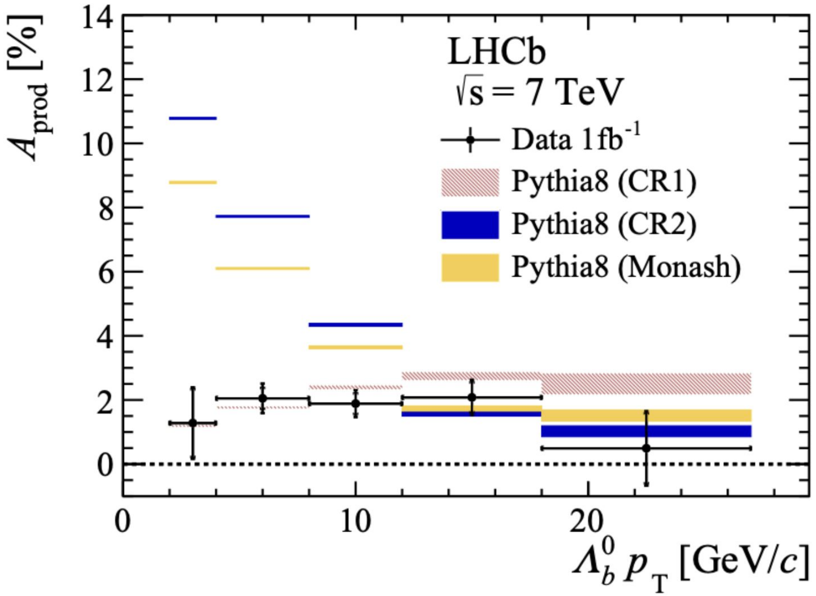
- **Cluster decay** in HERWIG
  - Shower evolved up to a softer scale
  - All gluons forced to split into $q\bar{q}$ pairs
  - Identify colour-singlet clusters of partons following color flow
  - Clusters decay into hadrons according to available phase space



Asymmetry in pp

- Differential measurements of the asymmetry between Λ^0_b and anti-Λ^0_b baryon production rates

$$A_P \equiv \frac{\sigma(pp \to \Lambda_b^0 Y) - \sigma(pp \to \bar{\Lambda}_b^0 Y)}{\sigma(pp \to \Lambda_b^0 Y) + \sigma(pp \to \bar{\Lambda}_b^0 Y)}.$$



LHCb: JHEP 10 (2021) 060

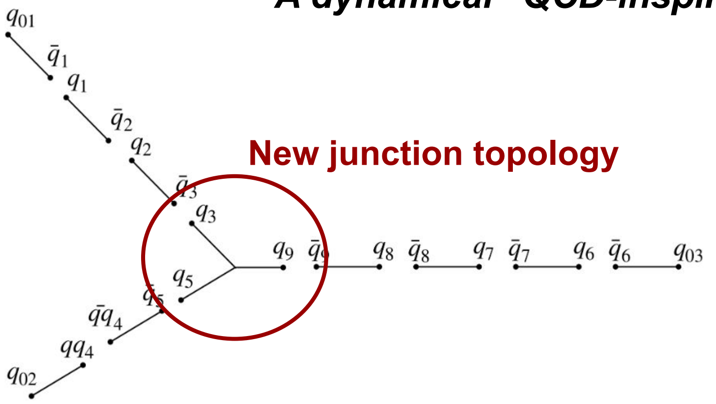
PYTHIA: JHEP 1508 (2015) 003

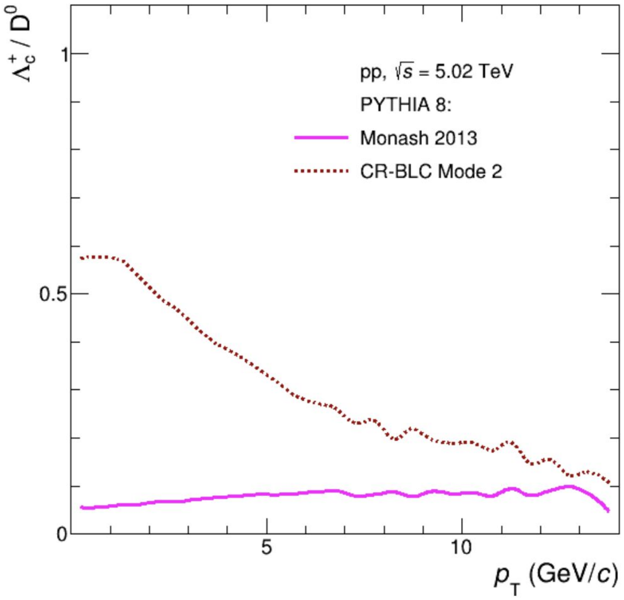
- Key source of low p_T Λ^0_b in PYTHIA with CR-BLC → combination of a b quark with the proton beam remnants. The same does not apply for the anti-Λ^0_b as there are not anti-q remnant at the LHC.
- QCD CR-BLC adds large amounts of low-p_T junctions, forming more anti-Λ^0_b and Λ^0_b baryons in equal amounts, diluting the asymmetry.

PYTHIA 8 new Color Reconnection

- **PYTHIA8 with String Formation beyond Leading Colour (CR-BLC)** JHEP 1508 (2015) 003
  - Introduction of new 'junction topologies for baryon enanchement'

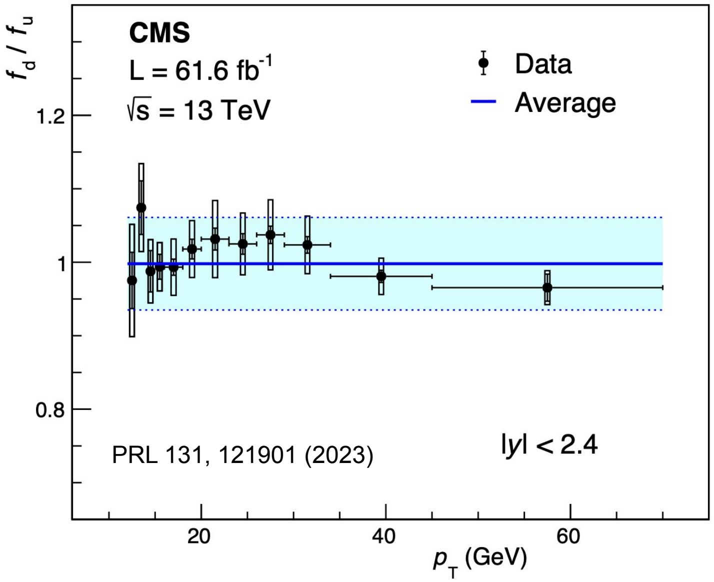
A dynamical "QCD-inspired" way for coalescence?

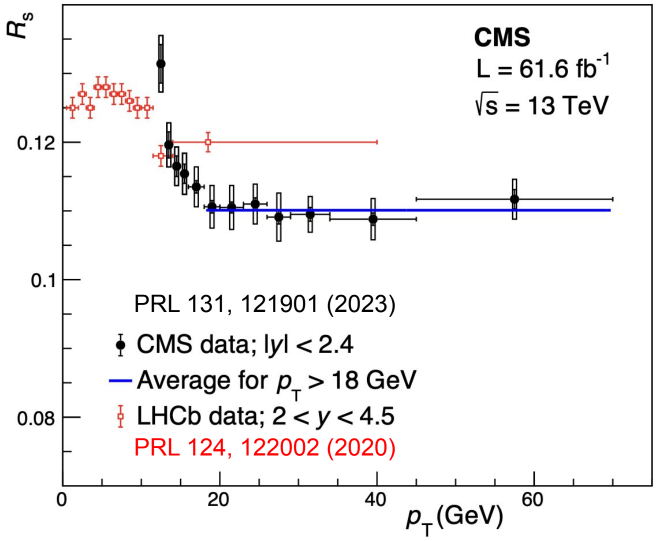




- CR allows to combine partons from different MPIs to minimize string length → used in Monash tune
- New CR-BLC
  - Minimization of the string length over all possible configurations
  - Include CR with MPIs and with beam remnants

Charm and beauty fragmentation to meson

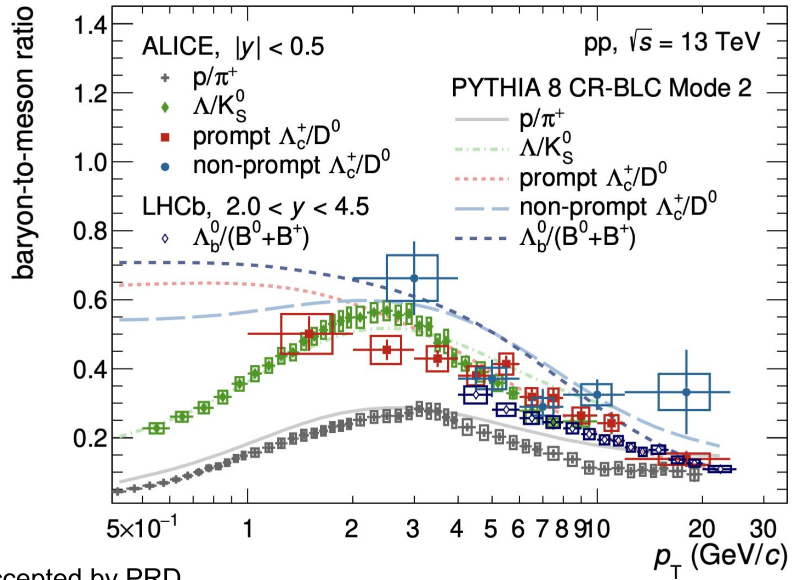




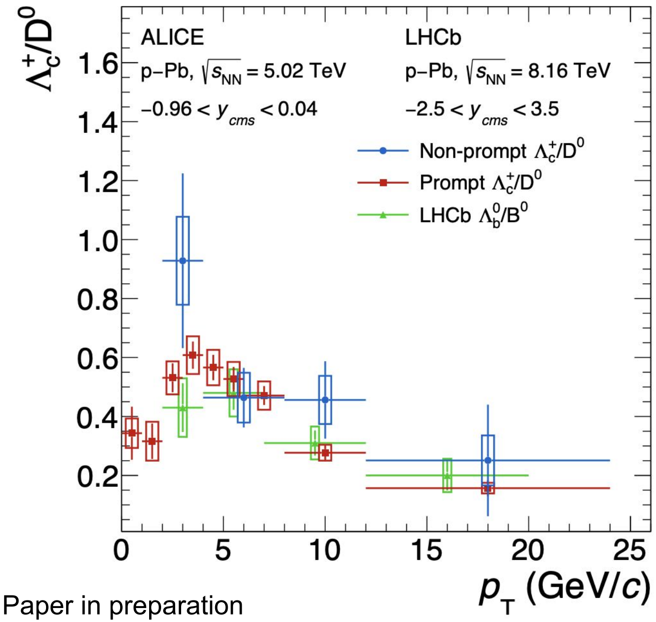
- Direct CMS measurements of ground-state B mesons at 13 TeV: → Non-strange B-meson ratio:
  - no dependence on p_T or rapidity
  - consistent with isospin invariance

- $R_S = f_s/f_u$ → p_T dependence for p_T < 18 GeV/c and constant at large p_T
  - Consistent with LHCb (significant p_T dependent only at 13 TeV)

Baryon-to-meson ratio – beauty



Accepted by PRD

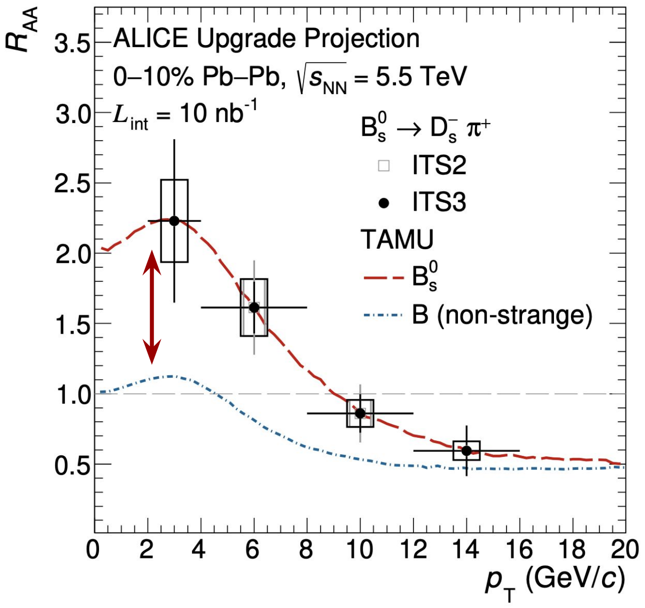


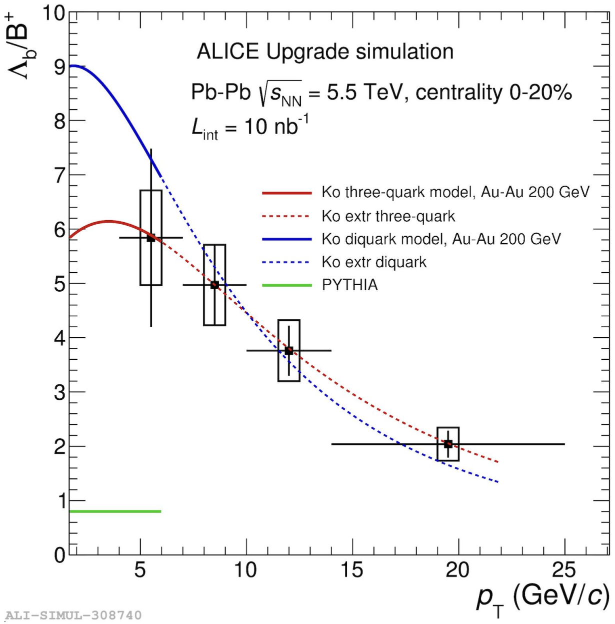
Paper in preparation

- ➢ First measurement of non-prompt charm-baryon production ($|y| < 0.5$) in pp and p-Pb collisions
- ➢ Prompt and non-prompt Λ_c^+/D^0 ratio similar in both pp and p-Pb collisions
  - similar baryon-to-meson enhancement compared to e^+e^-

Andrea Dubla

Beauty hadrons in Pb-Pb





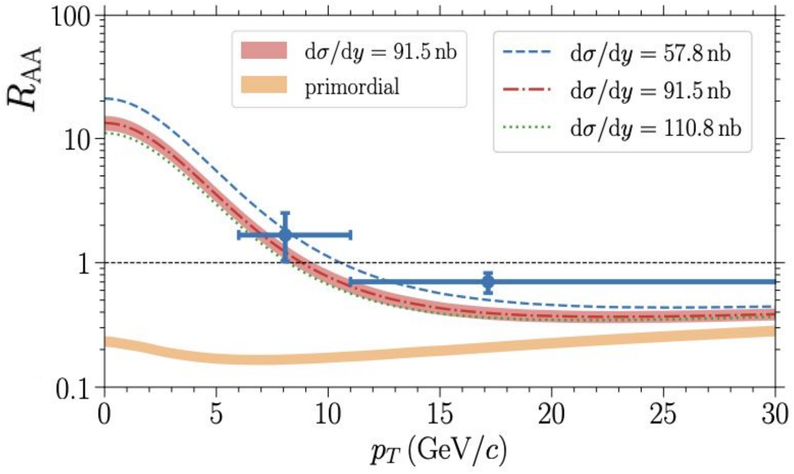
- **Full reconstruction of beauty hadrons will be at reach in Run 3-4**
  - Expected enhancement in B^0_s in Pb-Pb collisions will be quantifiable for the first time
  - Reconstruction of $\Lambda^0_b \to \Lambda^+_c \pi^-$ (BR = 4.9 10-3)
    - Will be affected by large uncertainties and limited to p_T > 4-5 GeV/c in Run 3 and Run 4

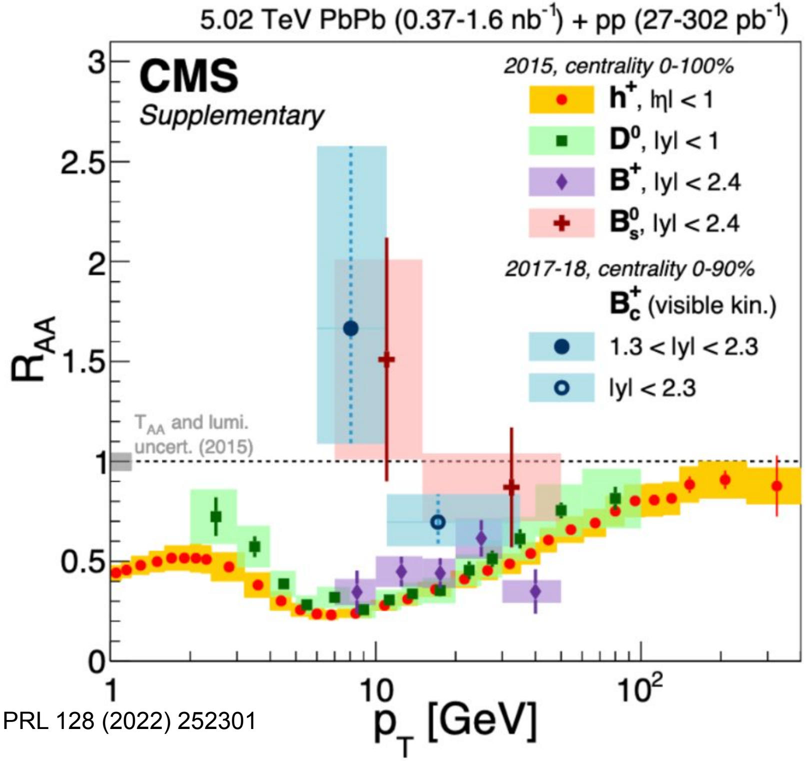
Andrea Dubla

A new and challenging probe of QGP

- ➢ B_c^+ production in heavy-ion collisions is an ideal probe to be sensitive both to dead cone effect and statistical recombination
  - *CMS: used 2018 Pb-Pb data!*
  - *ALICE, LHCb: Possible first look with Run 3/4*
- ➢ **Largest contribution from recombination**

arXiv:2302.11511



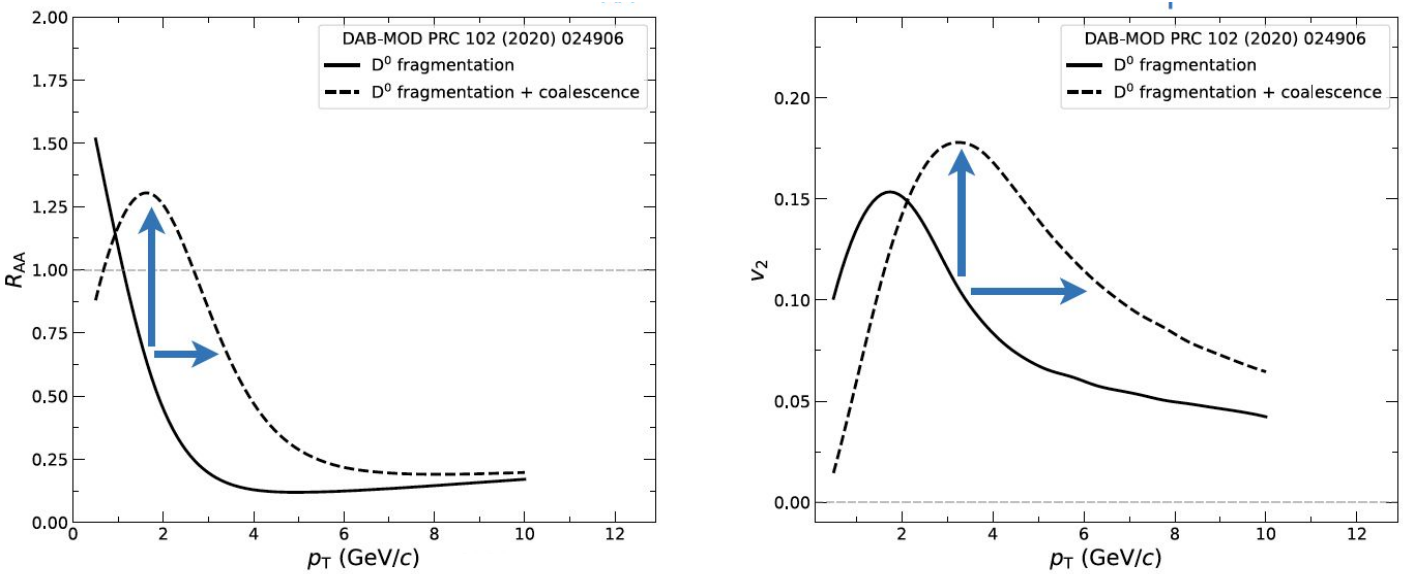


PRL 128 (2022) 252301

Andrea Dubla

Modification of p_T distributions

Nuclear modification factor | **Elliptic flow**

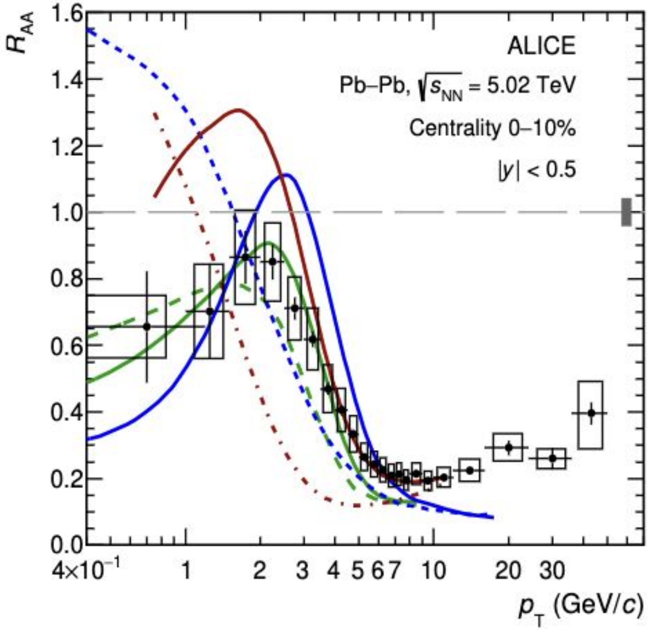


➢ **Coalescence** of heavy quarks with light quarks from the QGP affects **HF hadron momentum distributions**

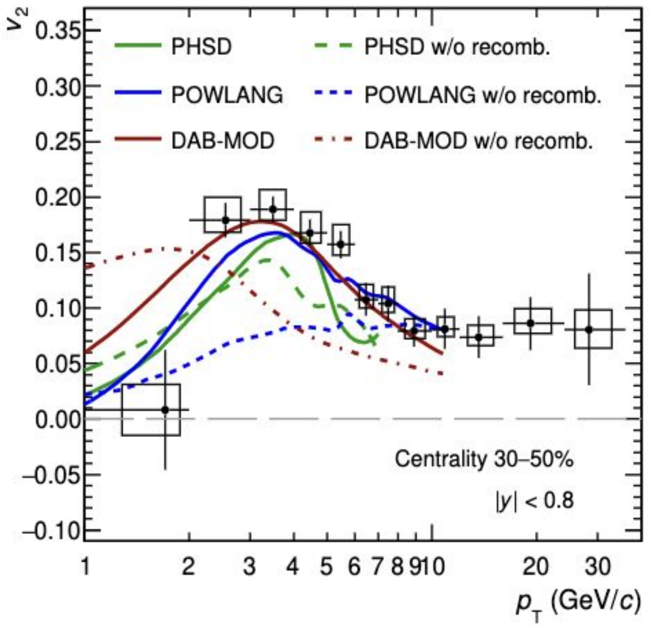
- HF hadrons pick-up the radial and elliptic flow of the light quark

Modification of p_T distributions

Nuclear modification factor



Elliptic flow

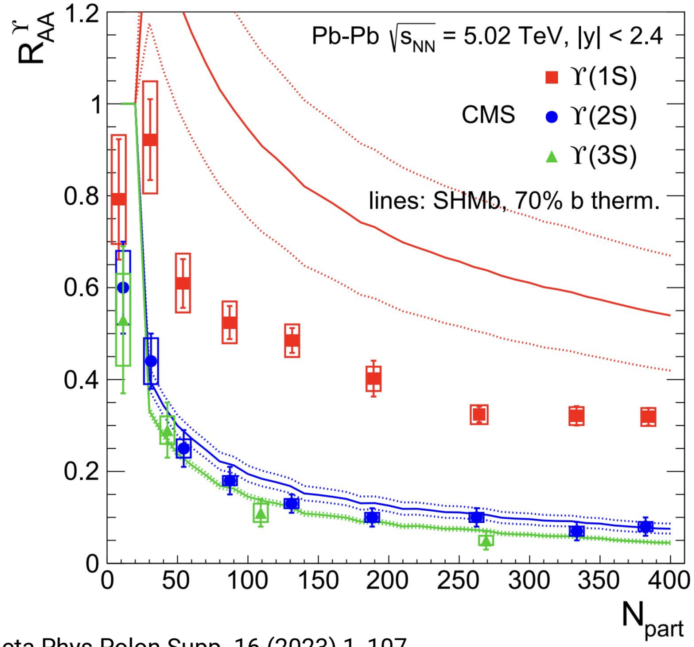


➢ **Coalescence component is crucial to describe the data at low/mid p_T**

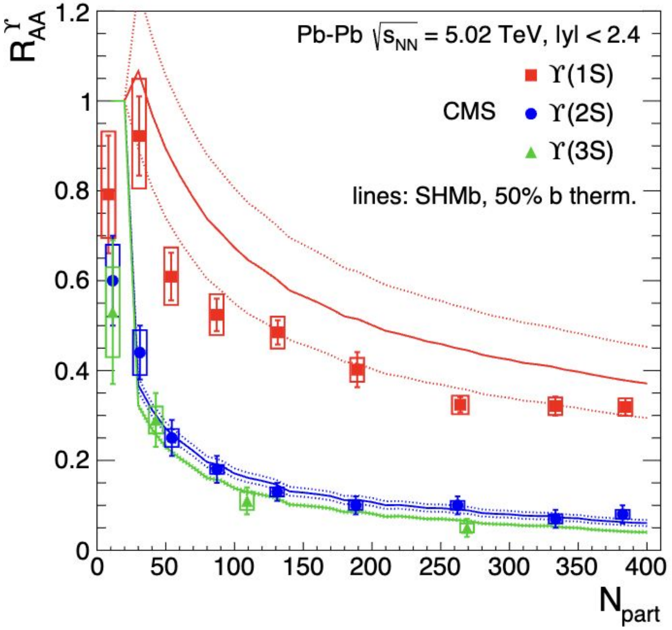
Bottomonia states

- ϒ largely overestimated if 100% of beauty quarks assumed to be thermalized.
  - Does beauty quark reach thermal equilibrium
  - v_2 is compatible with zero

CMS: PRL 120 (2018) 142301



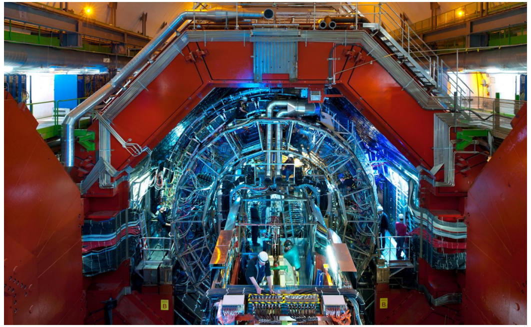
- **ϒ described if 30% of beauty quarks assumed to thermalize.**
  - Reach partial equilibrium?
  - **Presence of currently unknown open beauty states will lead to a reduction of the bottomonia yields.**



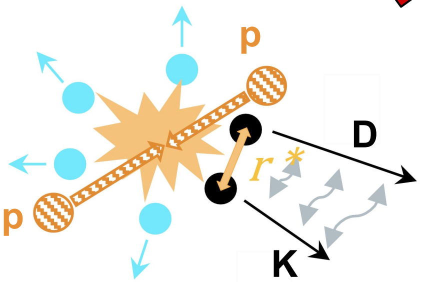
SHMb: Acta Phys.Polon.Supp. 16 (2023) 1, 107

A schematic view of femtoscopy

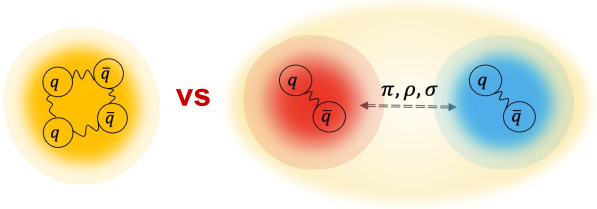
ALICE at the LHC



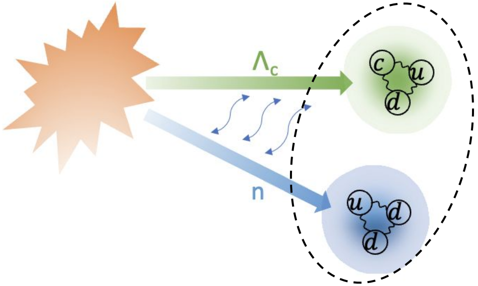
Femtoscopy



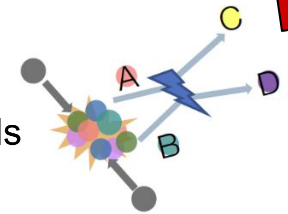
Test of first principle calculations and asses the nature of exotic states



Charm nuclei formation



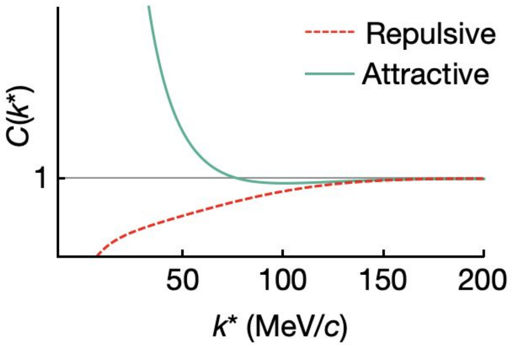
Direct access to coupled channels



Femtoscopy for hadronic interactions

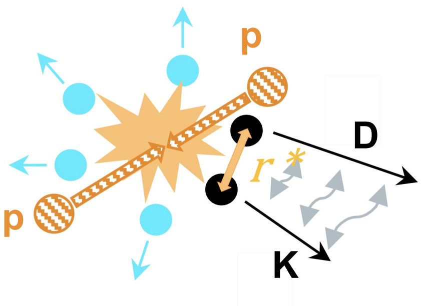
➢ Features of the residual strong interaction are mapped into the correlation function

Correlation function



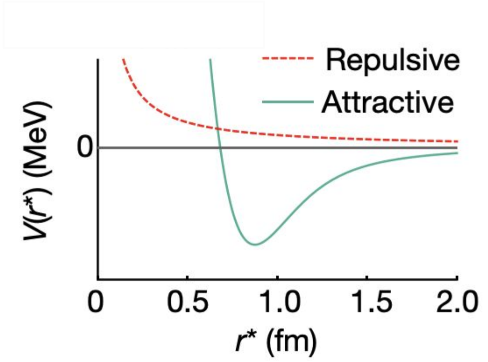
=

Emitting source *S(r*)*



⊗

Interaction potential



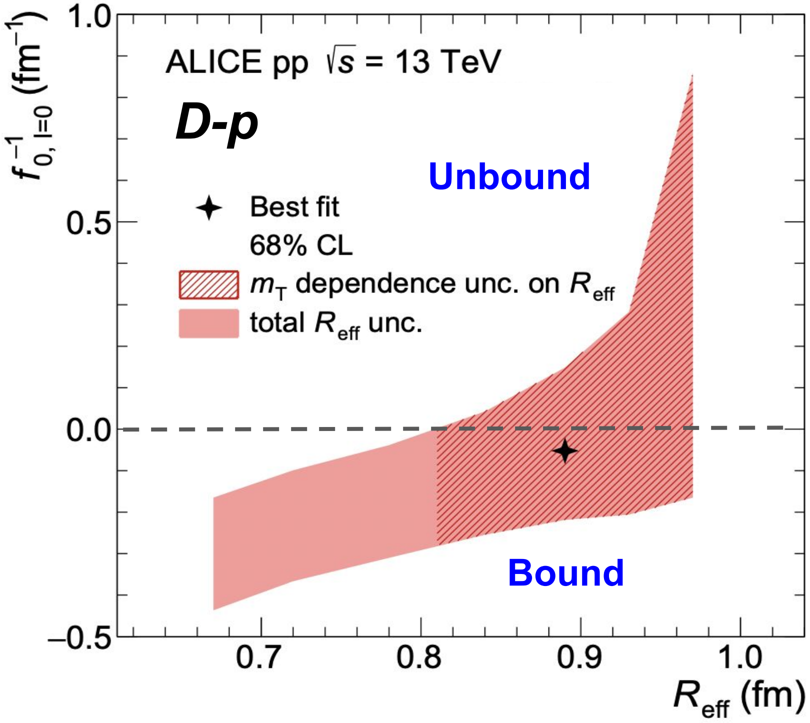
Nature 588 (2020) 232–238

Schrödinger eq. → two particle wave function

Koonin-Pratt eq: $C(k^*) = \int S(r^*)|\Psi(k^*, r^*)|^2 d^3r$

- > 1 if the interaction is attractive
- = 1 if there is no interaction
- < 1 if the interaction is repulsive

A proof of principle



- **D-p measurements:**
  confidence interval of scattering length for isospin I = 0 channel evaluated by comparing data with correlation function using a Gaussian potential modelled with a ρ-meson exchange
  - Indicate either rather shallow attracting interaction or strong attractive interaction with formation of a bound state

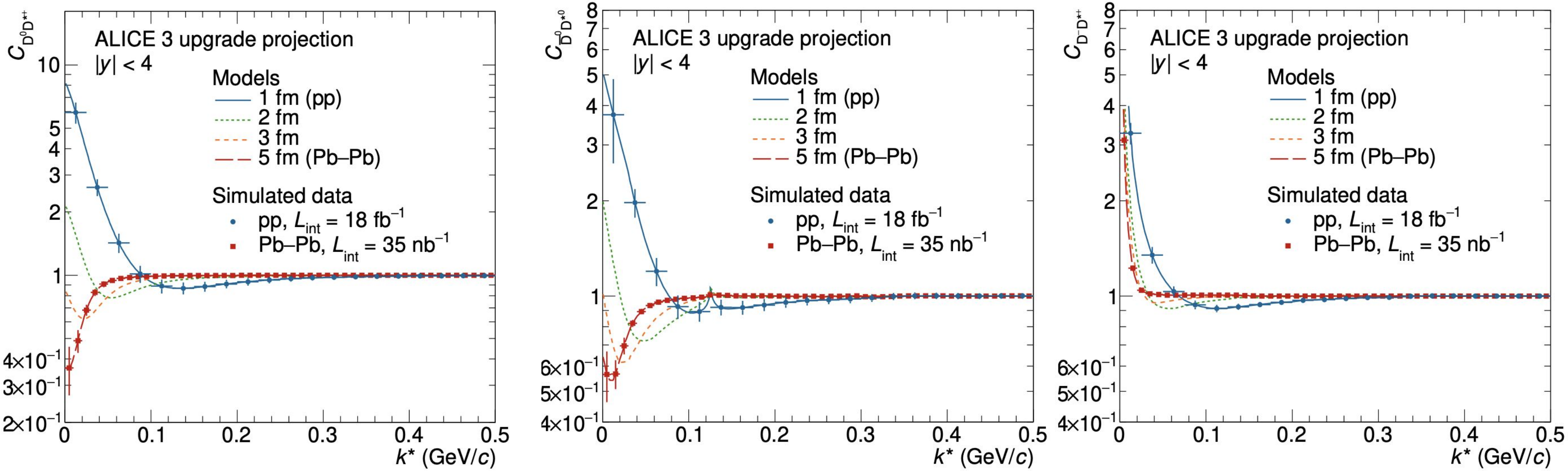
$$\text{Weinberg compositeness: } X = \sqrt{\frac{1}{1+2r/a}}$$

$X = 1$ composite (molecule)

$X = 0$ elementary

arXiv:2201.05352 [nucl-ex]

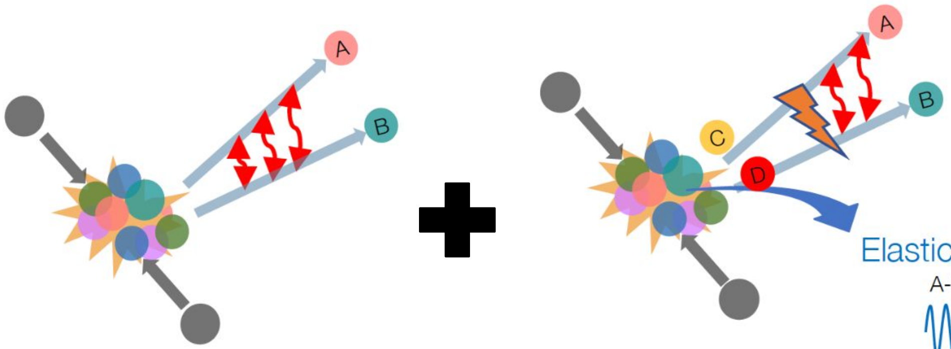
Projections for ALICE 3



T_{cc}

X(3872)

Coupled channels



- strong coupling to systems preserving the same global quantum numbers for the pair of interest can occur

Elastic/Inelastic channels

Elastic/Inelastic wave functions

$$C_{A-B}(k^*) = \int S(r)\, |\psi_{1\to 1}(k^*, r)|^2\, d^3r + \sum_{j\neq 1} w_j \int S(r) \left|\psi_{j\to 1}\left(k_j^*, r\right)\right|^2 d^3r = \mathcal{N}(k*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

elastic
A-B → A-B

inelastic
C-D → A-B, …

w_j → isospin symmetry dependence

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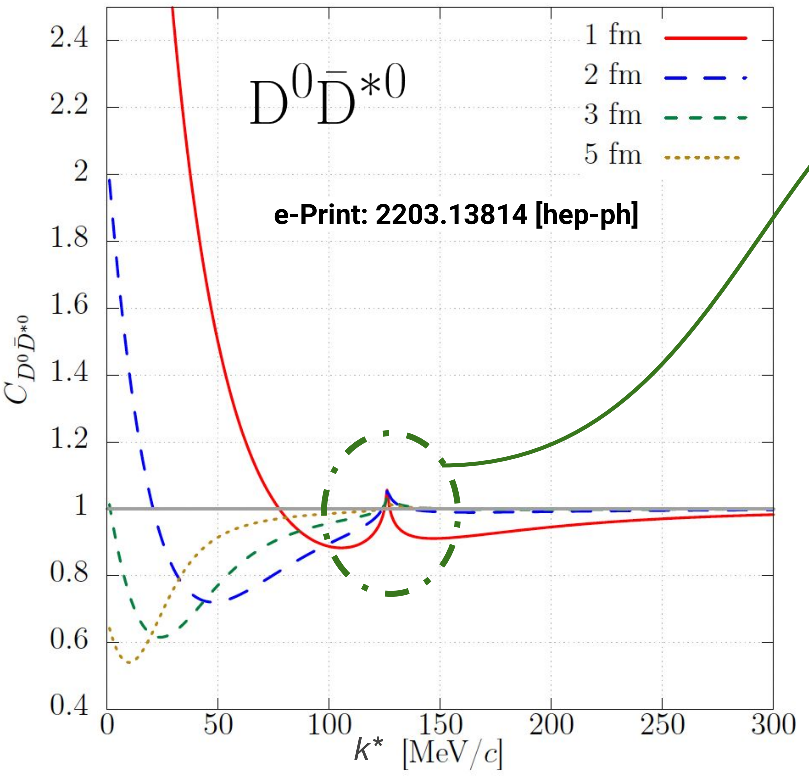
Coupled channels



$D^0\bar{D}^{*0} \rightarrow D^+\bar{D}^{*-}$

- ➢ The characteristic strong source size dependence with the shallow bound state is found in $D^0\bar{D}^{*0}$ → **cusp structure** at the $D^+\bar{D}^{*-}$ threshold (k^* = 126 MeV/c) reflects the difference of Isospin 0 and 1 interaction

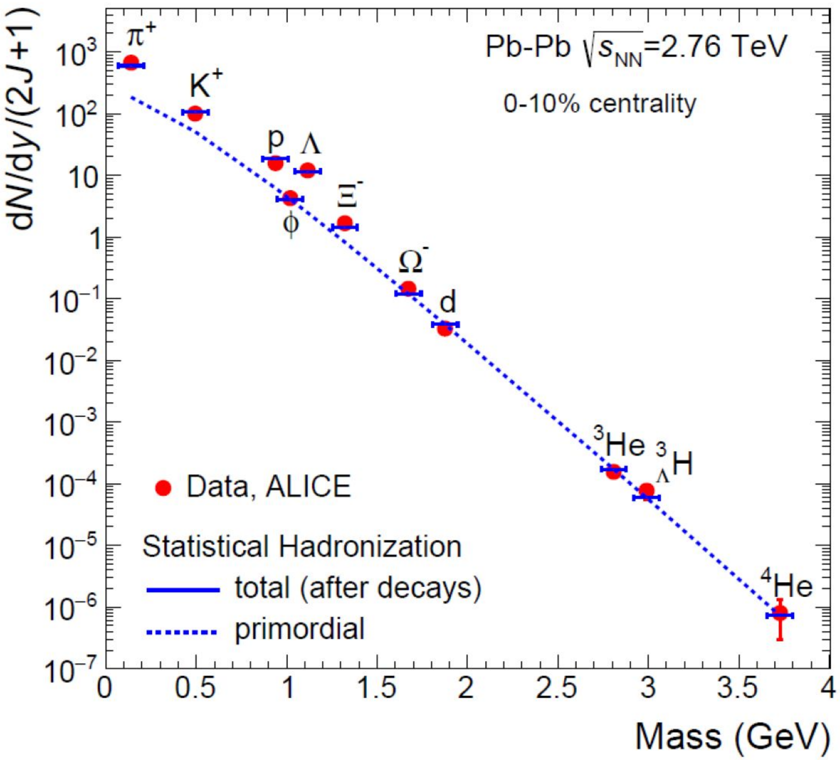
- ➢ This is because the coupled-channel source effect by the $D^+\bar{D}^{*-}$ channel is stronger for the smaller source case.

What is next?

- **CHAIN will open new frontiers in nuclear and particle physics**
- In 10 years from now it will be possible to study the internal structure of several pentaquarks (P_c) measuring correlations of Σ_c-D, Ξ_c-D and other exotica like *Y, Z* states with $D_s D_s^*$ as well as with bottom quark via BB^*

State	Mass [MeV]	Width [MeV]	S-wave threshold [MeV]
X(3940)	3942 ± 9	37	$D^*\overline{D}^*$ (-75 ±9)
X(4140)	4147 ± 4.5	83 ± 21	$D_s\overline{D}_s^*$ ($-66^{+4.9}_{-3.2}$)
X(4274)	4273 ± 8.3	56 ± 11	$D_s\overline{D}_s^*$ ($-49.1^{+19.1}_{-9.1}$)
$Z_b(10610)$ [14]	10607 ± 2.0	18.4 ± 2.4	$B\overline{B}^*$ (4 ± 3.2)
$Z_b^{\pm}(10650)$	10652.2 ± 1.5	11.5 ± 2.2	$B^*\bar{B}^*(+2.9)$
$P_c^+(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$\Sigma_c\bar{D}(-9.7)$
$P_c^+(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c\bar{D}^*(-21.8)$
$P_c^+(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Sigma_c\bar{D}^*(-4.8)$

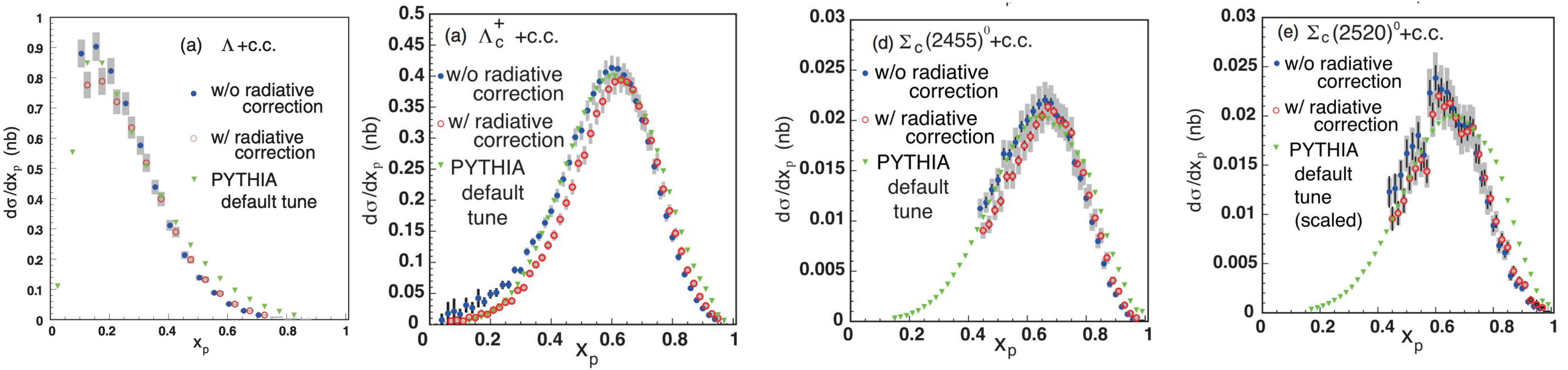
Statistical hadronization

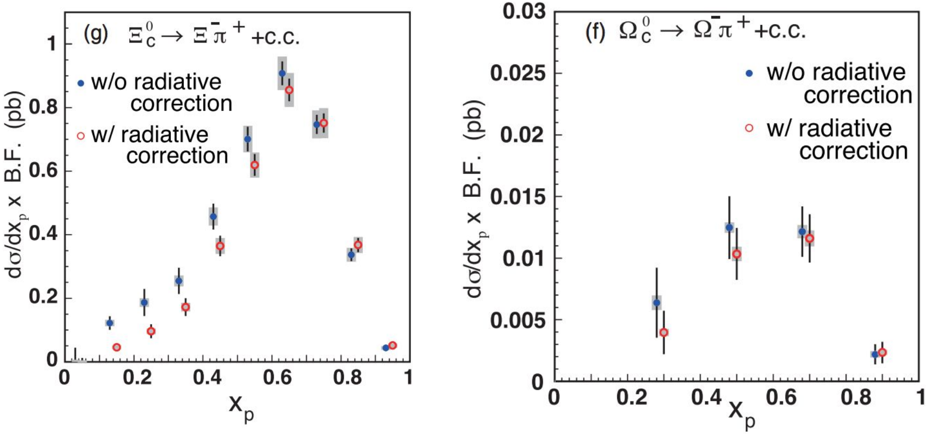


- Abundances of light and strange hadrons and nuclei:
  - Follow equilibrium populations of a **hadron-resonance gas in chemical and thermal equilibrium**
  - Freeze-out temperature T_{ch} ~ 155 MeV
- Thermal origin of particle production
  - Macroscopic description of the hadron gas in terms of thermodynamic variables
- **Statistical hadronisation models** (SHM)
  - Yields depend on:
    - Hadron masses (and spins)
    - Chemical potentials
    - Temperature and volume of the fireball

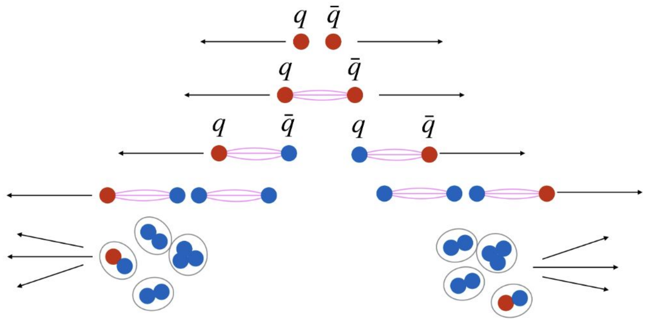
Andronic et al, Nature 561 (2018) 7723, 321

The smallest system - e^+e^-





- Charm baryons vs PYTHIA in e^+e^-
  - **Standard PYTHIA** describe the data



Belle: PRD 97, 072005 (2018)

$x_p = pc/\sqrt{s/4 - M^2c^4}$

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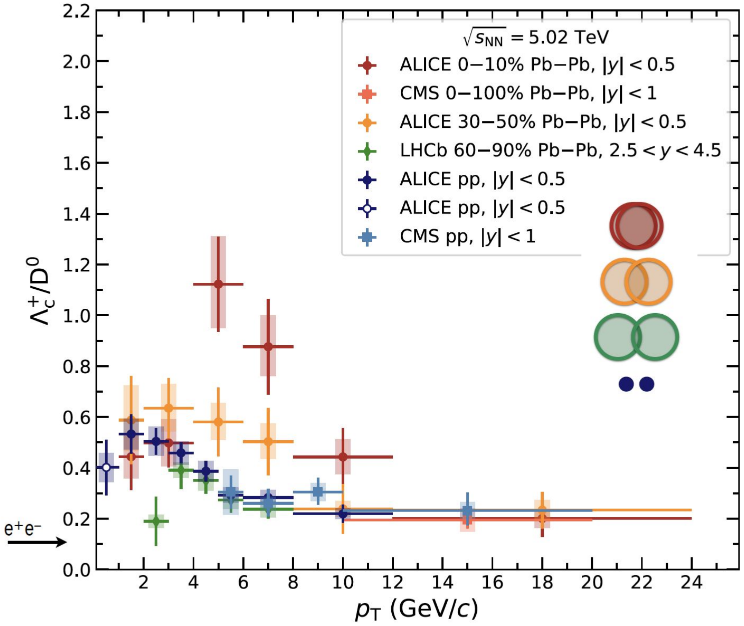
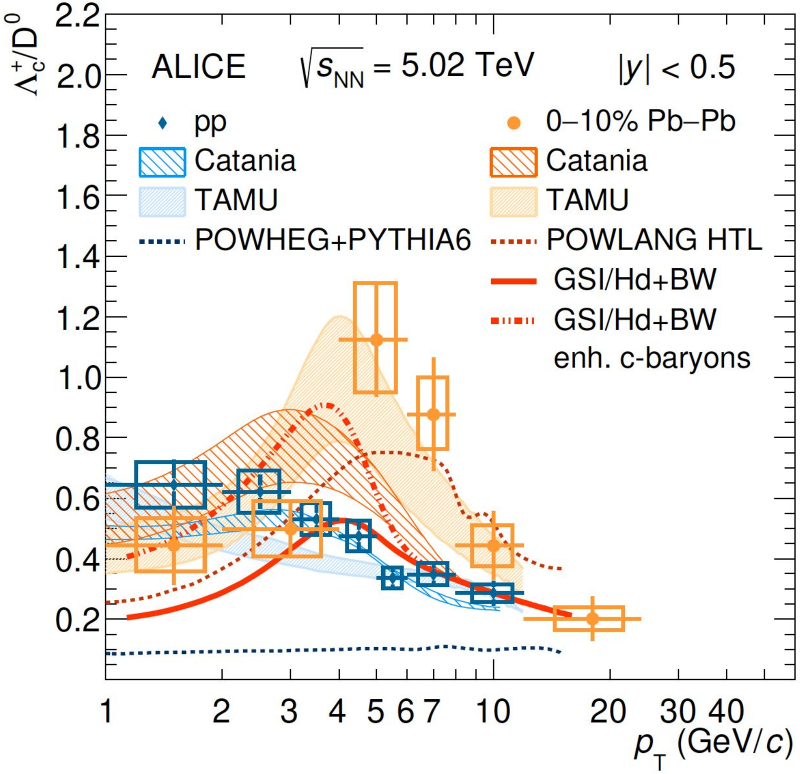
Λ_c in Pb-Pb





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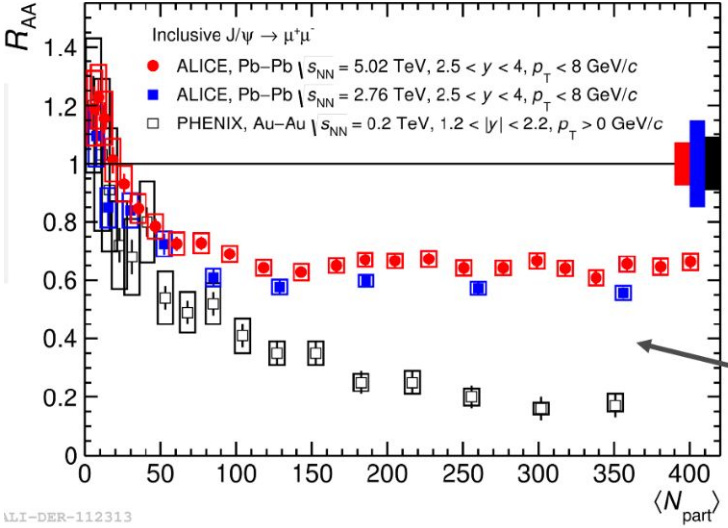
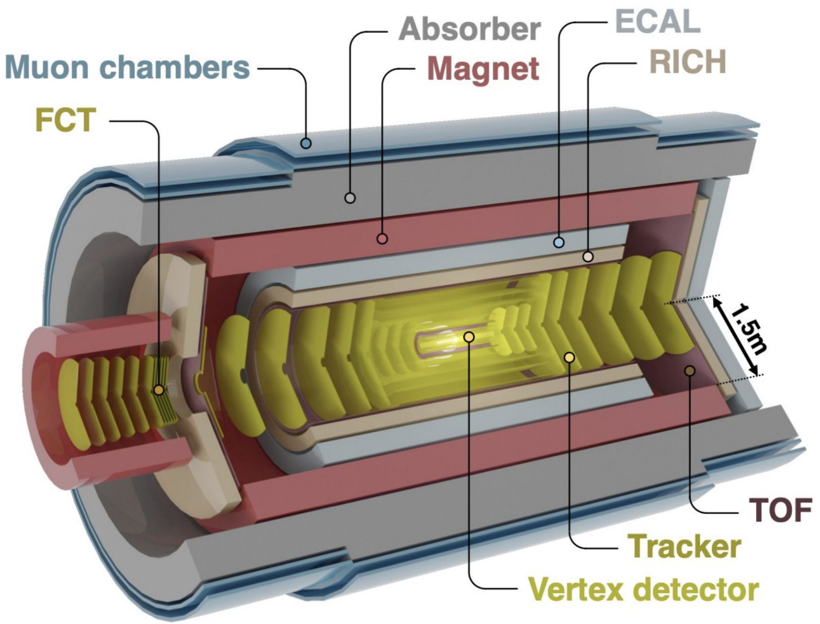


J/ψ Yield vs. centrality and $\sqrt{s_{NN}}$

- Less suppression at LHC ($\sqrt{s_{NN}}$=**2.76**, **5.02** TeV) than at RHIC ($\sqrt{s_{NN}}$=**200** GeV)

Beyond Run 4: ALICE 3

Main requirements:
- Increased readout rate, reduced data size for storage (online data reduction)
- Improved tracking and vertexing performance at low p_T for background suppression
- Preserve and enhance particle identification (PID) capabilities



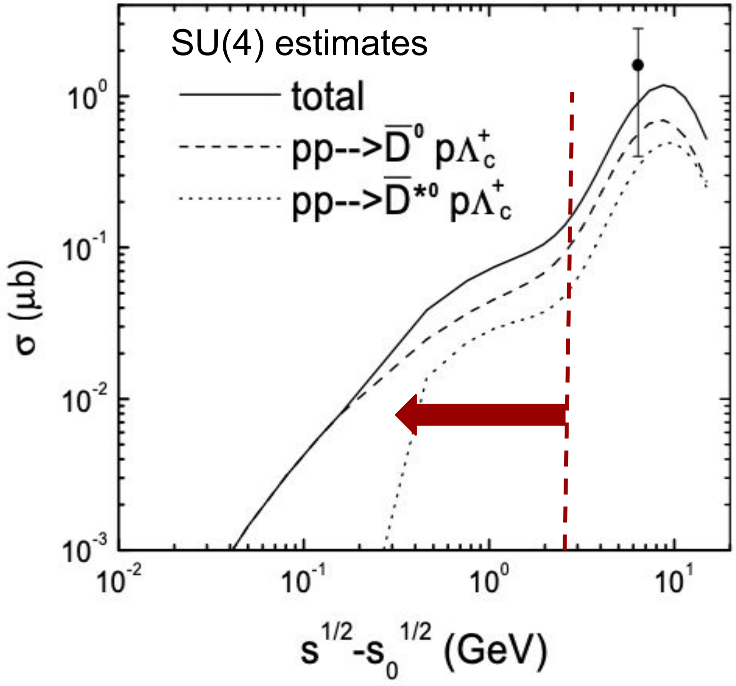
- ➢ Compact and lightweight **all-silicon tracker**
  - p_T resolution better than 1%@1 GeV/c
- ➢ **Retractable vertex detector** with excellent pointing resolution - About 3-4 μm @ 1 GeV/c
- ➢ **Large acceptance**: $-4 < \eta < 4$, $p_T > 0.02$ GeV/c
- ➢ **PID capabilities** via TOF, RICH, and ECAL
- ➢ **Continuous read-out and online processing**
  - Large data sample to access rare signals

Loi: CERN-LHCC-2022-009

CBM related opportunities

- ➢ **Extended program of CBM at FAIR** performing new measurements in the charm sectors
  - 29 GeV proton beams is being explored – charm production and charm-N interaction

NPA728 (2003) 457-470



- ➢ **Perspectives**
  - first time **near-threshold** charm production
  - Can **intrinsic charm** of nucleon enhance production cross section? (Analogy of ss-bar content in nucleon and Φ meson production)
  - **pD and pΛ_c interactions** become possible (femtoscopy)
  - **Exotic states** with hidden charm