Appendix for Jets and HF Studies for ES

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ePIC and EIC Physics Readiness Workshop (2nd edition)

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Running Scenario

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG
Note: the eA luminosity is per nucleon					

- Plan to use:
  - ep @ 10x130: $L \sim 10$ fb^{-1}; eAu @ 10x100: $L \sim 1$ fb^{-1}
  - ep @ 10x250: $L \sim 10$ fb^{-1}

D Heavy flavor measurements and jets

D.1 Jets in Cold Nuclear Matter . . . . . .

D.2 Hadronization of charm quarks . . . . . .

D.3 Heavy Flavor in Cold Nuclear Matter . . . . .

Simulation Samples

ep @ 10x130: $L \sim 10$ fb^{-1}; eAu @ 10x100: $L \sim 1$ fb^{-1}
ep@ 10x250: $L \sim 5$ fb^{-1}

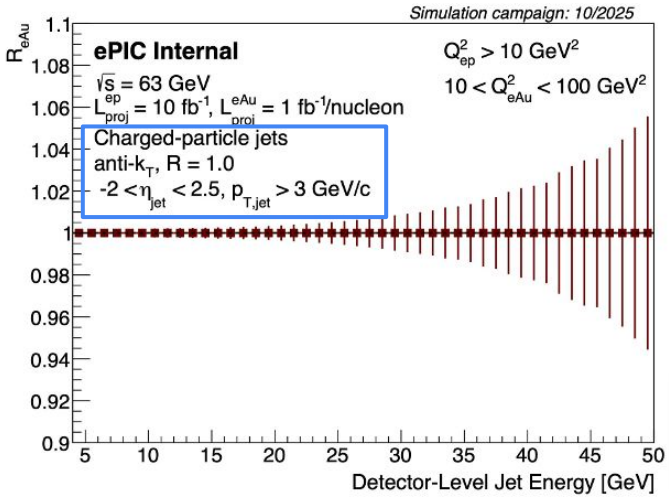
		10x100	10x130	10x250
ep	D0	✓✓	submitted	submitted
	Lc	✓✓		submitted
	DIS	✓✓	✓✓	✓✓
		10x100		
eAu	D0	✓✓		
	Lc	✓✓		
	DIS	✓✓		
		10x115		
eRu/Cu	DIS	✓✓		

Jets in Cold Nuclear Matter

- Jets Nuclear Modification Factor (R_{eA}):
  - Initial state effects + Final state effects
    - Collisional energy loss, Radiative energy loss
  - Current plot for statistical projection in ES draft
    - e+p, e+Au, 10x100, October campaign
    - Plot to be updated with new samples
  - **Data Sample for ES**
    - eAu @ 10x100: $L \sim 1$ fb^{-1} , ep @ 10x130: $L \sim 10$ fb^{-1}
    - **Binning in different (x_B, Q^2) due to different energi**
    - **Apply a reweighting based on (x_B, Q^2)**

Nuclear modification factor: $R_{eA} = \frac{\sigma_{eA}}{A \times \sigma_{ep}}$

Include theoretical predictions



Excellent statistical precision on the nuclear modification factor

ePIC will provide unique sensitivity to jet modification in cold nuclear matter

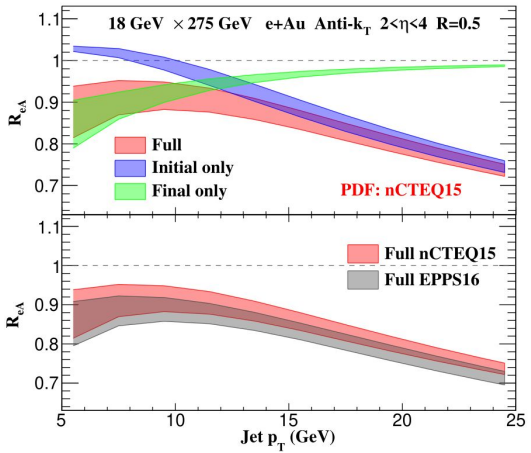
Jets in Cold Nuclear Matter

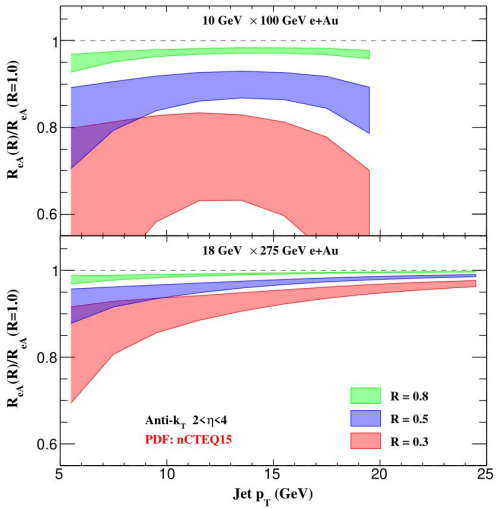
- Jets R_{eA} for different Jet Radii: Accessing Final State Effects
  - Observable
    - R_{eAu} for different jet radii (initial effects cancel out, remaining final state effects)
  - Current plot for statistical projection in ES draft
    - e+p, e+Au, 10x100, October campaign
    - Plot to be updated with new samples
  - Request theoretical predictions

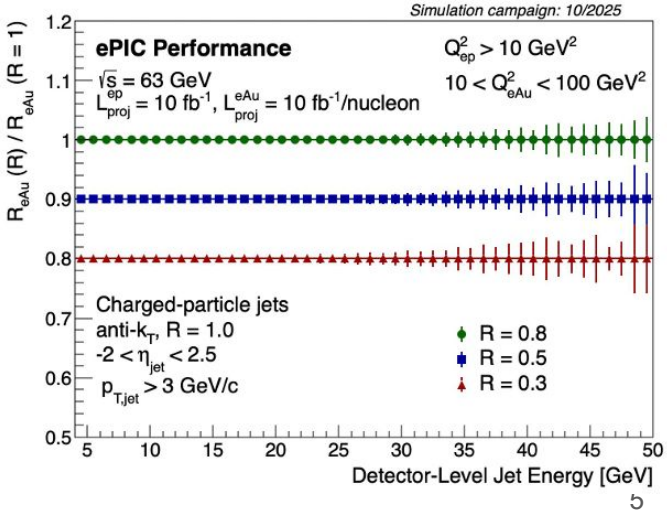
Excellent statistical precision on the Ratio

Include theoretical predictions

Hai Tao Li, Ze Long Liu, Ivan Vitev arXiv:2110.04858 [hep-ph]







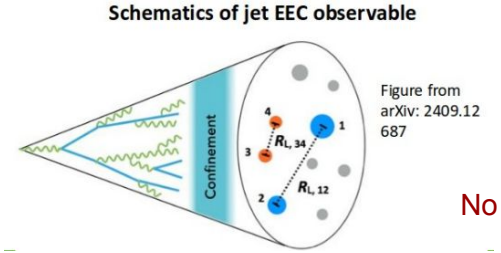
Energy-Energy Correlator

- Energy-energy Correlator (EEC_{e+Au}/EEC_{e+p})
  - How the energy carried by particles is correlated as a function of their angular separation in an event
  - Cold nuclear matter effects
  - First look using October campaign ep, eAu @ 10x100 data
  - For ES: eAu @ 10x100: $L \sim 1\ fb^{-1}$, ep @ 10x130: $L \sim 10\ fb^{-1}$

To be included in ES

EEC in ep in sensitive:
Perturbative (small R_L), Transition (intermediate R_L), Non-perturbative (large R_L)

- Initial-state effects (nPDF)
- Final-state effects (switched off in BeAGLE)



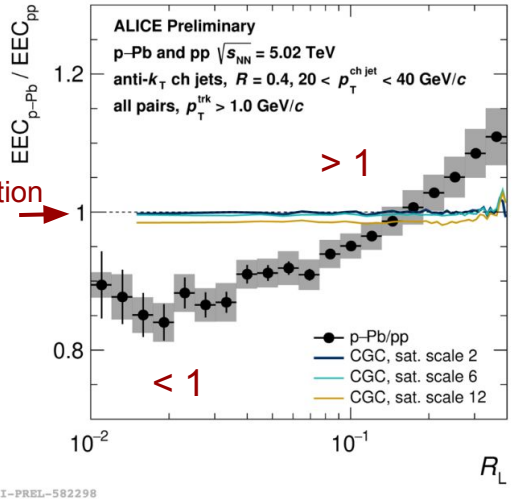
$$\mathrm{EEC}(R_L) = \frac{1}{p_{T,\mathrm{jet}}^2} \sum_{i<j} p_{T,i}\, p_{T,j}\, \delta(R_L - R_{ij})$$

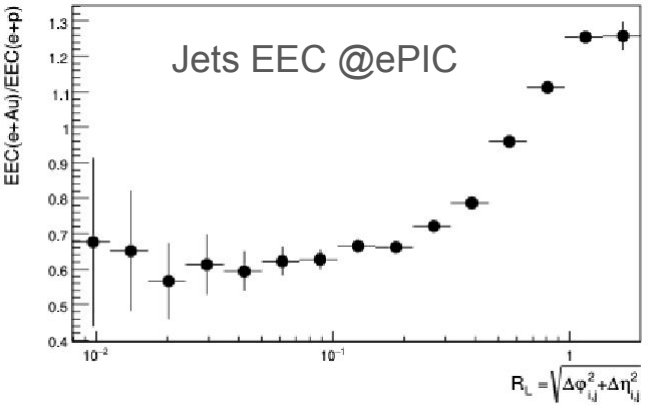
$$R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

R_{ij}: Angular distance between i and j tracks

arXiv:2510.16195 [nucl-ex]

No modification

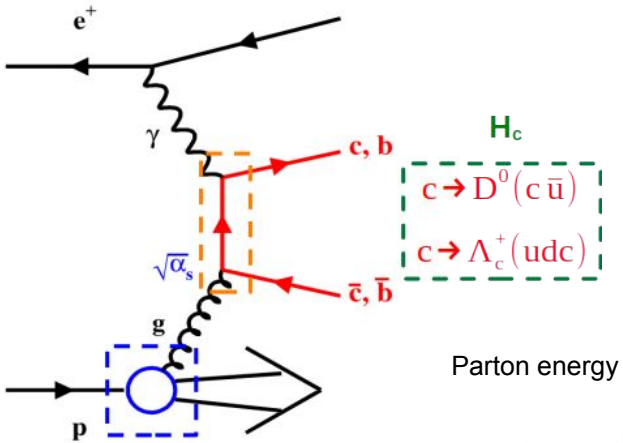




Charm-quark Hadronization

- Λ_c/D^0 ratio in e+p collisions

Photon-Gluon Fusion (PGF)



https://doi.org/10.1016/j.ppnp.2015.06.002

QCD Factorization Approach (PGF)

$$d\sigma^{PGF}_{\gamma p \to H_c X} = F_{g/p} \otimes d\sigma_{\gamma g \to c\bar{c}} \otimes D_{c \to H_c}$$

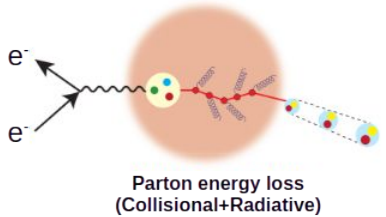
$F_{g/p}$ (x, μ^2): Parton Distribution Function (PDF)

$d\sigma$: Hard parton scattering cross section for PGF

$D_{c->Hc}$ (z, μ^2): Fragmentation function (Hadronization)

Fragmentation variable: $z = \frac{p_{H_c}}{p_c}$

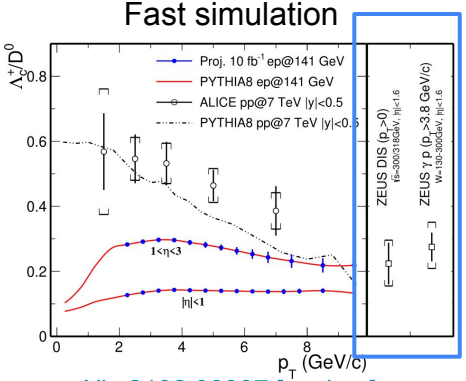
Parton energy loss (Collisional+Radiative)

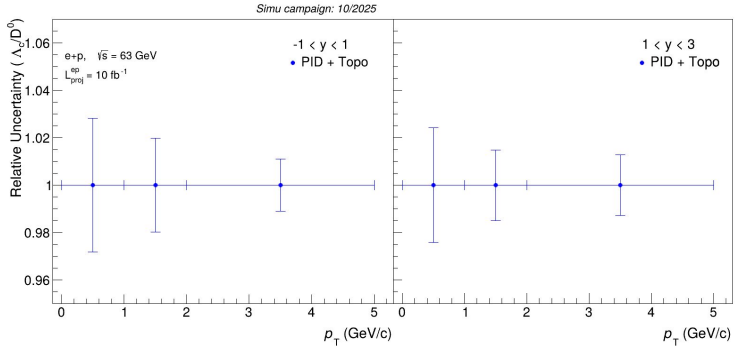


- Hadronization in ep and eA collisions
  - R_{eA} vs p_T, x_B, and z
  - Shadowing, multiple scattering, gluon saturation
  - Energy loss and hadronization in CNM

Hadronization of charm quarks

Fast simulation

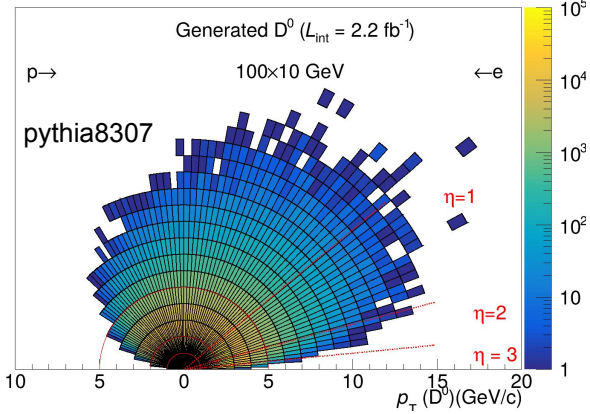


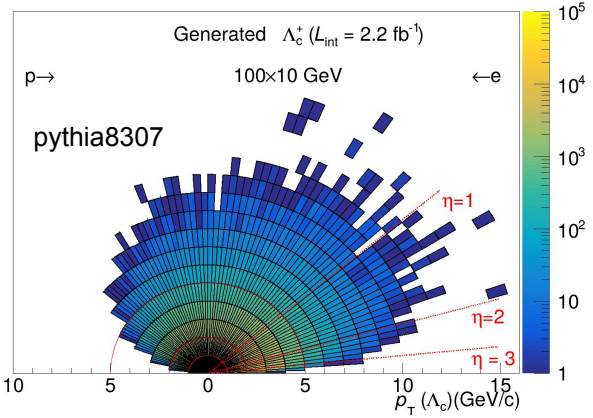


[arXiv:2102.08337 [nucl-ex]](arXiv:2102.08337 [nucl-ex])

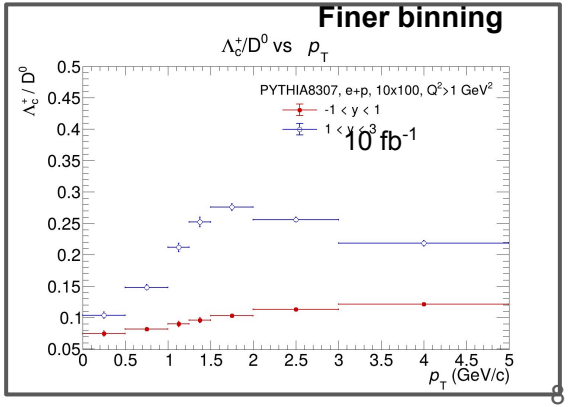
- Good statistical precision
- Ratio shows rapidity and p_T dependence
- Change energy: e+p, 10x250, 5 fb^{-1}
- Further hadronization modification in nuclear matter with different environment

Events = 1B





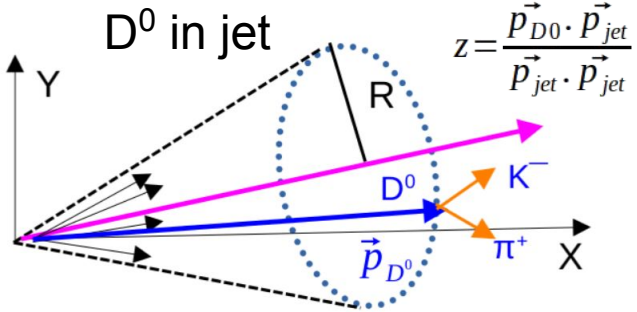
Finer binning



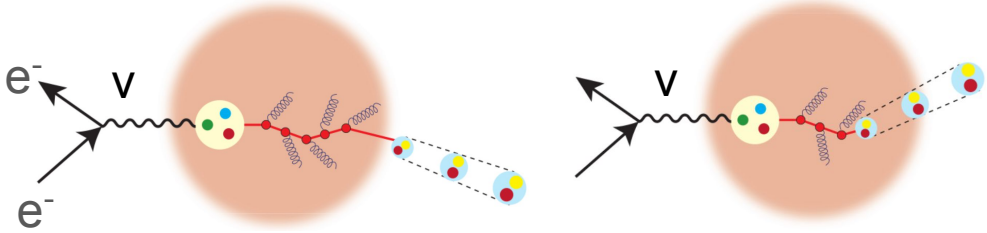
Heavy Flavor in Cold Nuclear Matter

Work in progress

- Hadronization of charm-quark in eA collisions
  - Prehadron absorption inside the nuclear matter
  - Heavy-quark energy loss
  - Observable R_{eAu} vs z (fragmentation variable) for different v range
  - eAu @ 10x100: $L \sim 1$ fb^{-1} , ep @ 10x130: $L \sim 10$ fb^{-1}



arXiv:2501.18044 [nucl-ex]

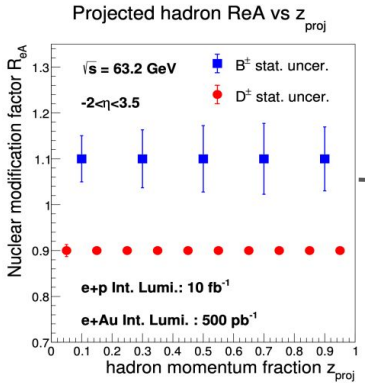


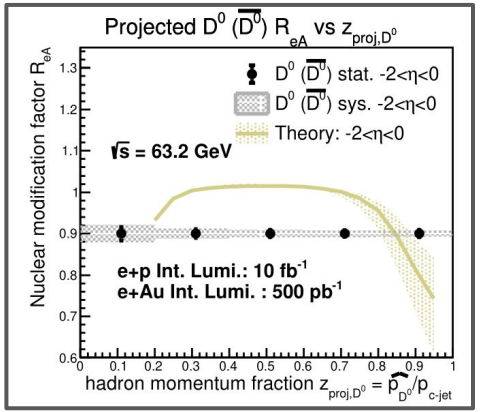
arXiv:hep-ph/0311220

Alberto Accardi, arXiv:nucl-th/0609010
DOI:10.1016/S0375-9474(03)00670-5

Request predictions

Placeholder figure



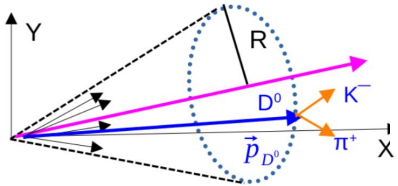


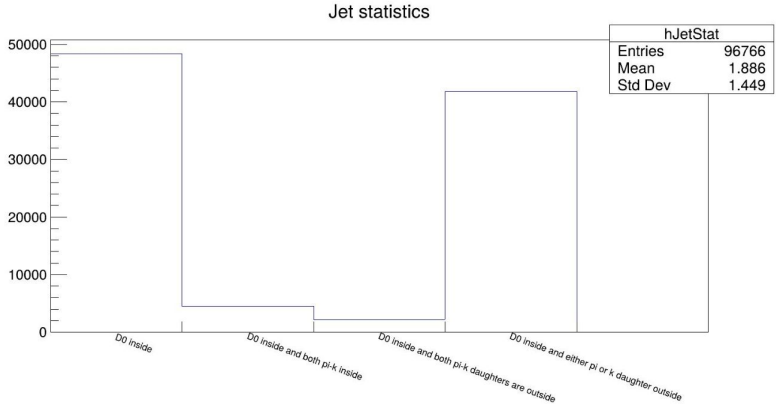
$R_A(p_T)$ binned in z_h: Probes hadron formation length (inside vs outside the nucleus)

Heavy Flavor in Cold Nuclear Matter

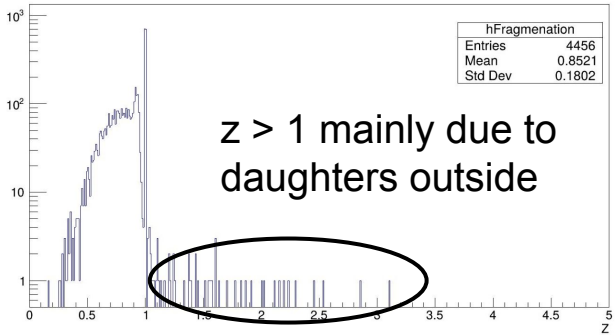
Work in progress

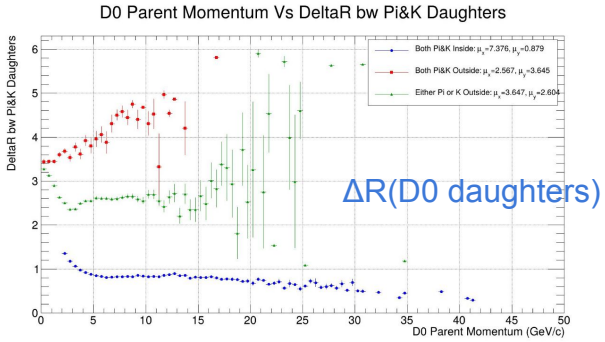
- Charged jet reconstruction with anti-k_T algorithm (default)
  - Radius parameter 1
  - Study of matching D^0 with the jet
  - One of the daughters is outside (z>1)
  - Perform jet reconstruction using D^0-meson tagging

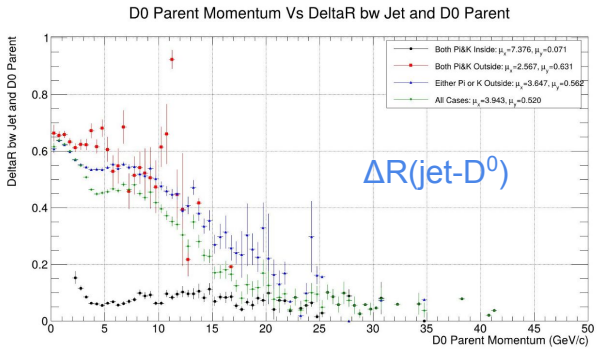




Fragmentation Variable (Z) :







Summary and Future Steps

- Physics analyses rather than performance
  - **Jet Nuclear Modification (R_{eA})**: nPDF effects + final-state energy loss in CNM (Dener)
  - **Jet R_{eA} ratio between different radii**: final-state energy loss (Dener)
  - **D^0 R_{eA} vs. z**: nuclear absorption vs. energy loss (Gurtaj, Shyam, Rongrong)
  - **Λ_c/D^0 ratio in ep**: charm quark hadronization (Shyam)
  - **D^0 jet Energy-energy Correlator (EEC) in ep/eAu:** (Xuan)
- Polish the text
- Systematics
- Further request theorists for predictions in progress

Thank you for your attention!

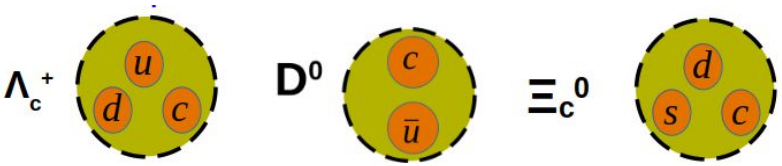
Charm-quark Hadronization

JHEP 12 (2023) 086

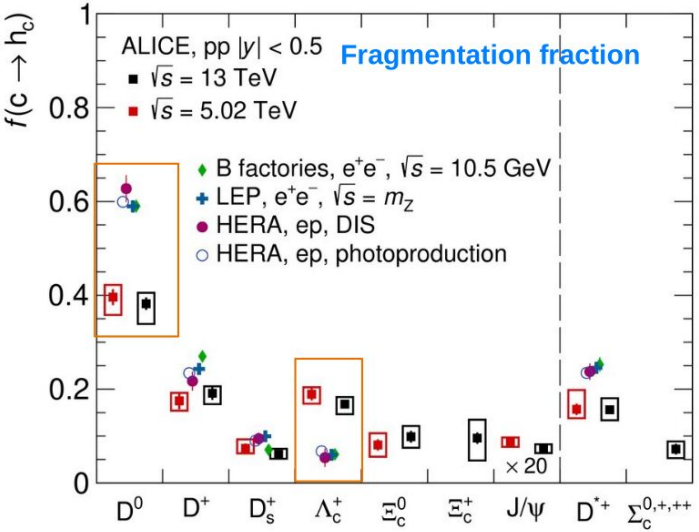
JHEP 05 (2021) 220

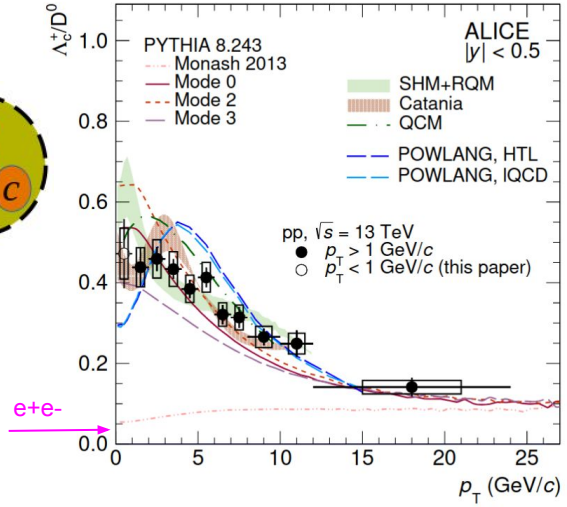
Charm quark hadronization=>Charm mesons/baryons

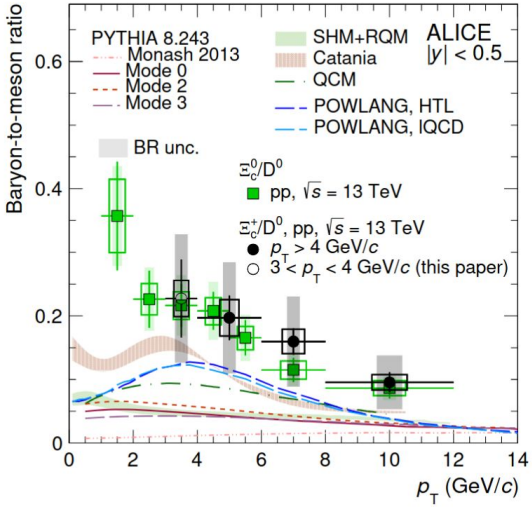
Prompt charm hadrons



Violation of universality of fragmentation fraction







0.113 ± 0. 013±0.006

LEP average, EPJC 75, 19 (2015)

S.Kumar, Slides

$$\left(\frac{\Lambda_c^+}{D^0}\right)_{e^+e^-} \approx \frac{f(c\to\Lambda_c^+)}{f(c\to D^0)} \approx \frac{0.065}{0.59} \approx 0.11$$

Violation of universality of fragmentation function?