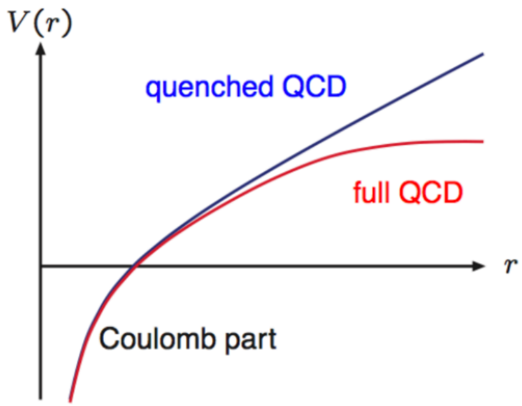
EIC Physics Hadronization - Sec. 7.4

I. Vitev for the Physics WG

Fourth Yellow Report Workshop, November 19 -21, 2020,

Berkeley, CA

Physics of Hadronization



$$V(r) \approx -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r \approx -\frac{0.13}{r} + r$$

$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm}$$

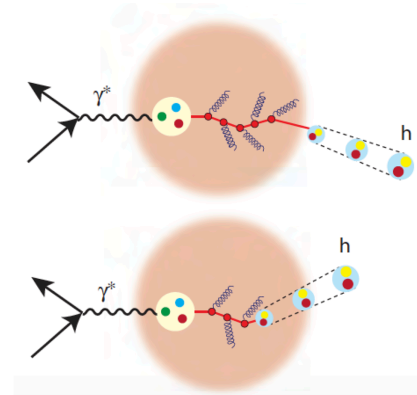
B. Webber (1999)

- The coulomb part is related to the structure of hadrons
- The linear part of related to hadron production / hadronization

- Perturbative hadronization

$$\mathscr{P}_{A/j}(z, P_T) = \frac{1}{2z(2\pi)^3}\int dx^-\, d^2x_T\, e^{ik^+x^- - ik_T\, x_T} \times \tfrac{1}{3}\,\mathrm{tr}_{\mathrm{color}}\,\tfrac{1}{2}\,\mathrm{tr}_{\mathrm{Dirac}}\{\gamma^+\langle 0|\psi(x)a^\dagger_A(P^+,0)a_A(P^+,0)\bar{\psi}(0)|0\rangle\}$$

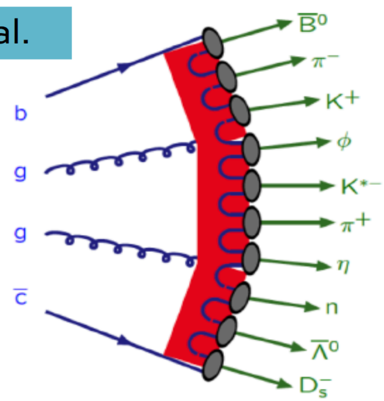
- Hadronization in the nuclear environment



- Hadronization in event generators

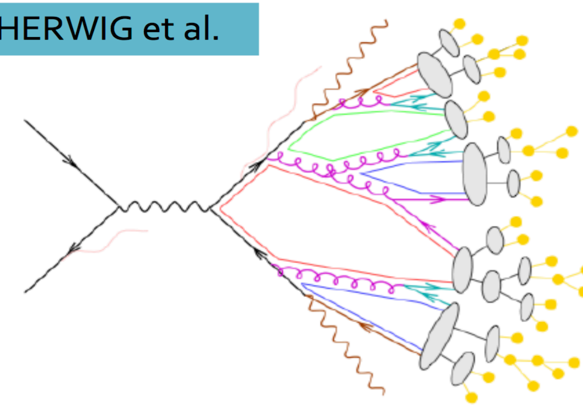
String fragmentation

PYTHIA et al.



Cluster hadronization

HERWIG et al.



Light Flavor Fragmentation

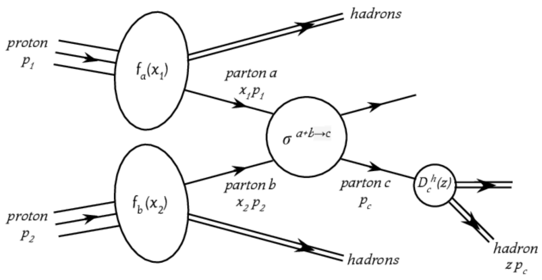
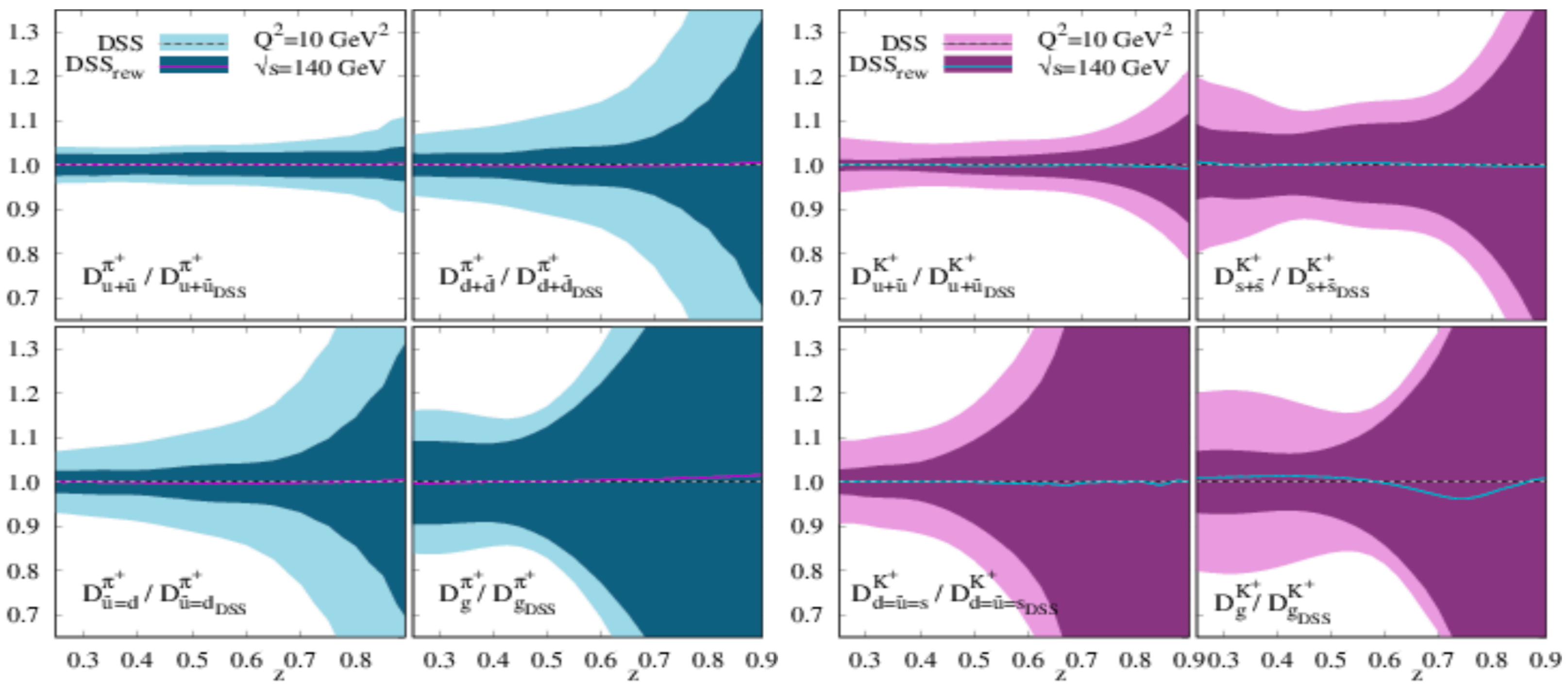


Diagram showing the three elements of pQCD factorization: parton distribution functions f a,b (x), partonic cross sections σ a+b→c , and fragmentation functions D h c (z).

- Data from electron-positron annihilation mostly con-strain the singlet combination of the FFs. Proton-proton collisions primarily constrain gluon FFs
- Production of light mesons in SIDIS - primary channel for the differentiation between the fragmentation of light quarks and anti-quarks. High sensitivity to the separation of quark flavors



E. Aschenauer *et al. 2019*

Global DSS analyses withthe inclusion of EIC pseudo-data, at a c.m.s. energy$\sqrt{s}$=140 GeV

Polarized Lambda Fragmentation

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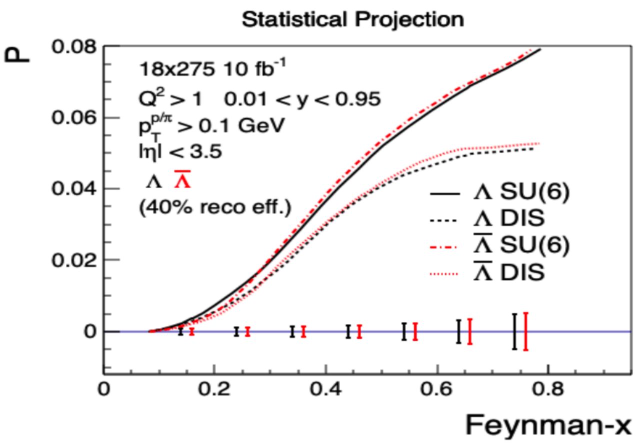
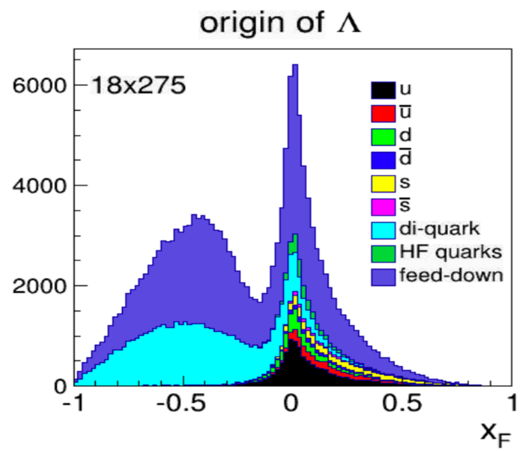
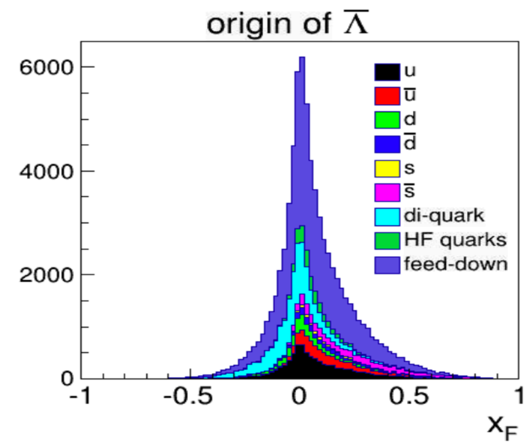
General questions of polarized fragmentation

A. Metz et al. 2016

Spin transfer to Λ - both longitudinal and transverse (strange quark helicity or transversity)



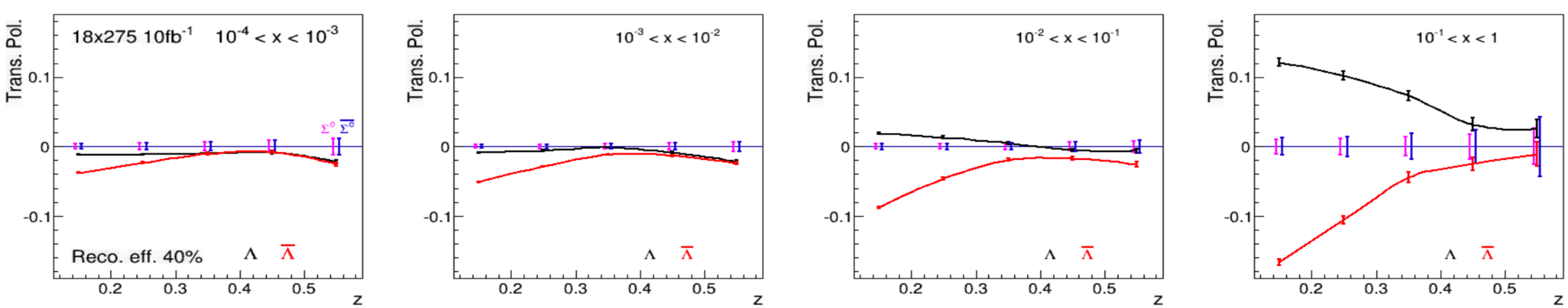




Projection of longitudinal spin transfer for Λ and ̅Λ from proton beam at 18×275 GeV at EIC. The two righthand panels show the origin of the reconstructedΛ/̅Λ. In the current fragmentation re-gion a significant fraction originates from feed-down. A dominant part of the feed-down component is contributed byΣ0→Λγ.

Callos et al. 2020

T-odd fragmentation-polarization fragmentation function D⊥1T



Projected Λ polarization using the extraction for the highest energy configuration. The projected uncertainty on Σ0 polarization is also shown. No feed-down which most likely reduces the magnitude of the asymmetries.

Partial wave decomposition of polarized and unpolarized di-hadron FFs including TMDs

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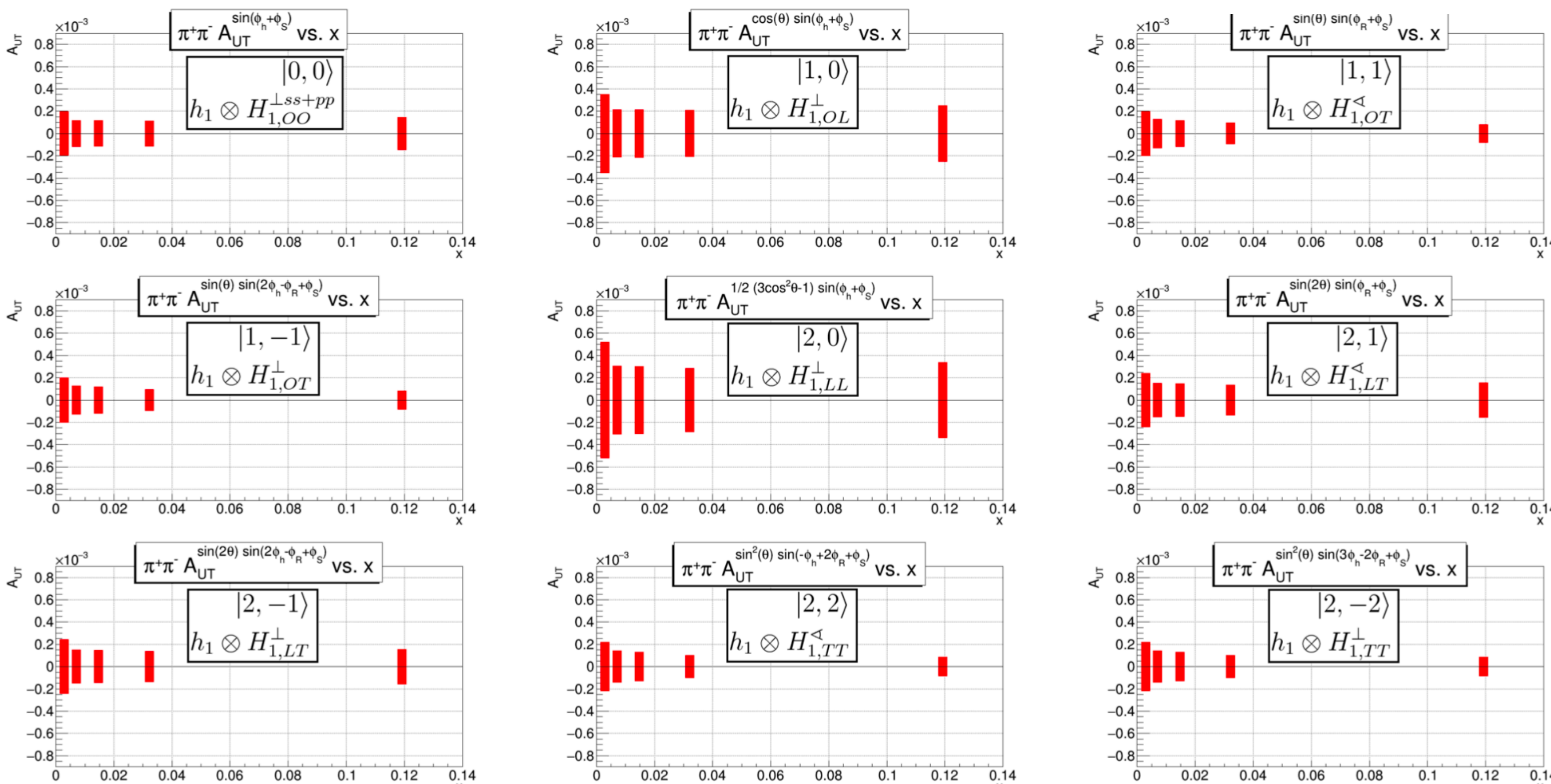
Di-hadron FFs are more powerful than single-hadron FFs, due to the additional degrees of freedom. This allows FFs to exist that do not have a single-hadron analog *S. Gliske et al. 2015*

$$F_{UT,L}^{P_{\ell,m}\sin((1+m)\phi_h - m\phi_{R_\perp} - \phi_S)} = 0,$$

$$F_{UT,T}^{P_{\ell,m}\sin((1+m)\phi_h - m\phi_{R_\perp} - \phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{k}_T|}{M}\cos(\phi_k + m\phi_p - (1+m)\phi_h)(f_{1T}^{\perp} D_1^{|\ell,m\rangle} + \mathrm{sign}[m] g_{1T} G_1^{|\ell,m\rangle})\right],$$

$$F_{UT}^{P_{\ell,m}\sin((1-m)\phi_h + m\phi_{R_\perp} + \phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{p}_T|}{M_h}\cos((1-m)(\phi_p - \phi_h)) h_1 H_1^{\perp|\ell,m\rangle}\right],$$

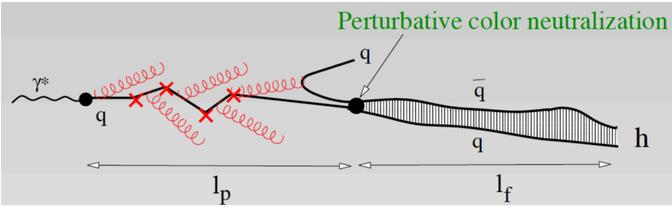
$$F_{UT}^{P_{\ell,m}\sin((3-m)\phi_h + m\phi_{R_\perp} - \phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{k}_T|^2|\boldsymbol{p}_T|}{2M^2 M_h}\cos((m-3)\phi_h + 2\phi_k + (1-m)\phi_p) h_{1T}^{\perp} H_1^{\perp|\ell,m\rangle}\right].$$



Projections nine partial waves contributing at twist-2 to A_{UT} using L=10 fb−1of data at 5×41. The labels on the figure indicate the m,l state and which PDF and FF the

More sensitive at lower center of mass energies

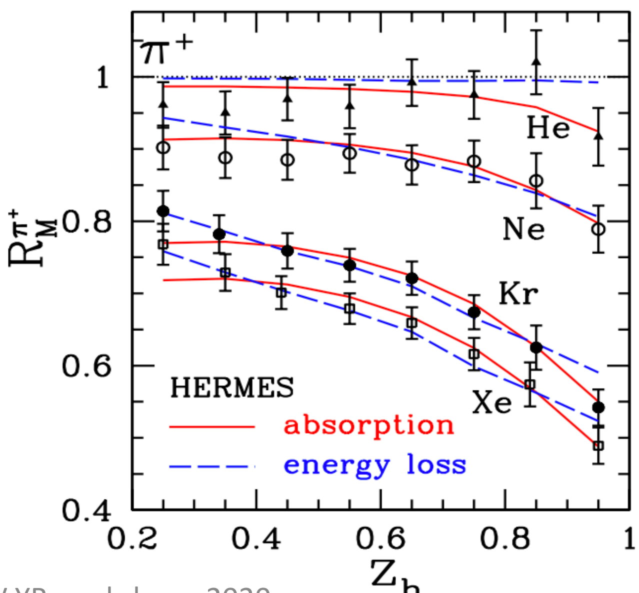
Hadronization in nuclei



A. Accardi et al. 2009

- The space-time picture of hadronization
- Competing physics explanations based on energy loss and absorption

Light hadron measurements cannot differentiate between competing mechanisms

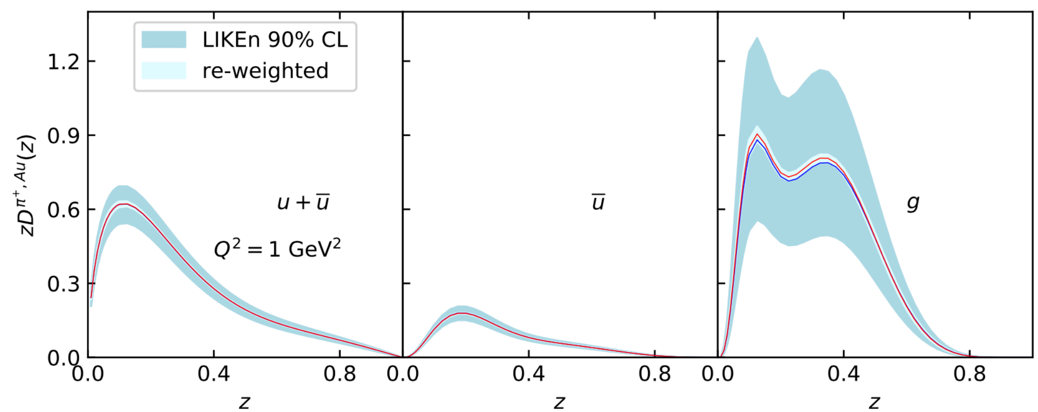


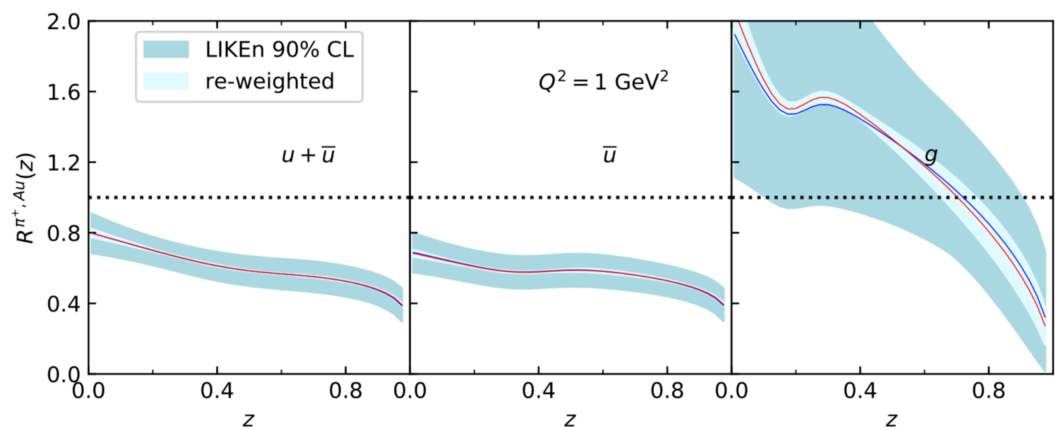
Attempt to parametrize nFFs assuming universality.

- A way of estimating what the differences might be coming form underlying physics

Effect of 10 fb-1 EIC data

Sassot et al. 2009





Heavy meson tomography

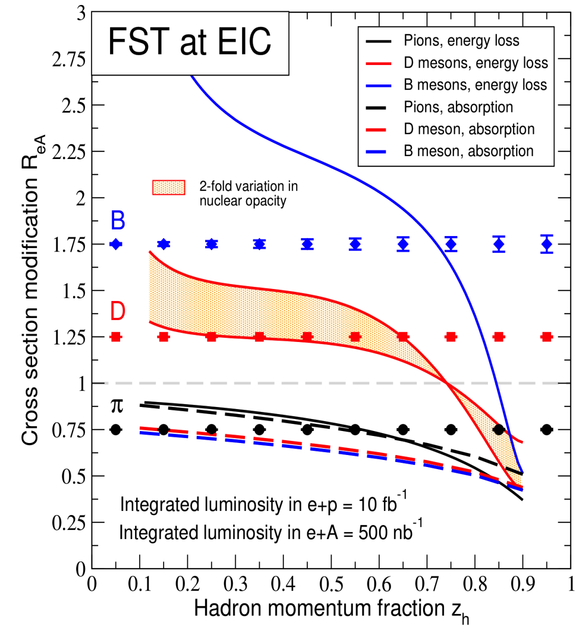
https://indico.bnl.gov/event/9273/

Normalized by inclusive large radius jet production. To LO equivalent inclusive normalization. Idea is to eliminate nPDF effects

$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{e+Au}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{e+p}}$$

Heavy flavor can differentiate between energy loss and absorption models. Allows to develop theory further

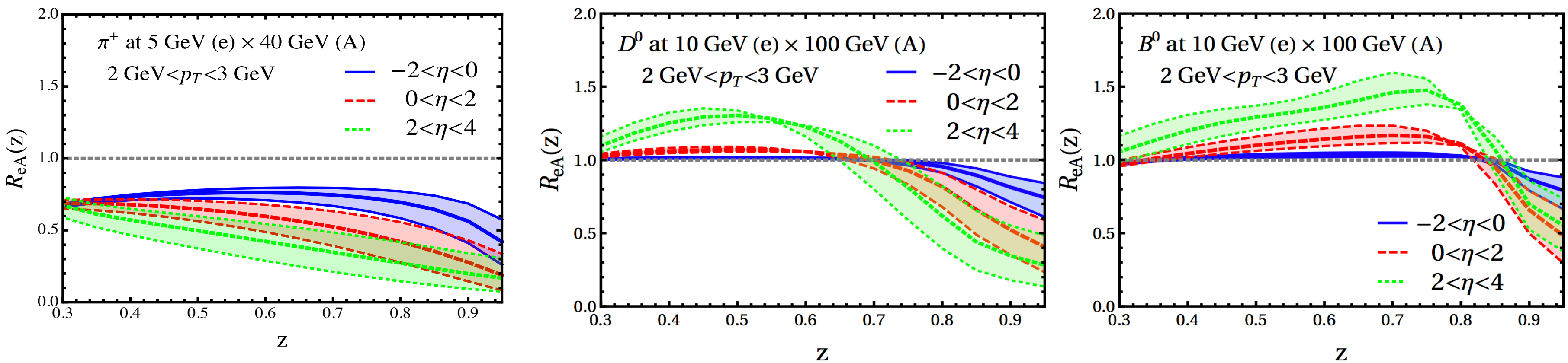
The larger CM energies imply partonic interactions



Help constrain the transport properties of nuclear matter:

Z. Liu et al. 2020

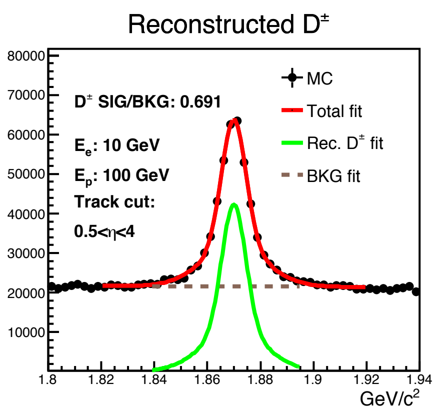
$$2\frac{\mu^2}{\lambda g} = 0.12\,\frac{GeV^2}{fm}\quad (vary\ \times 2,/2)$$

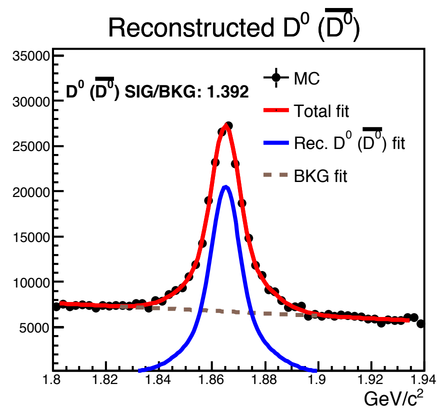


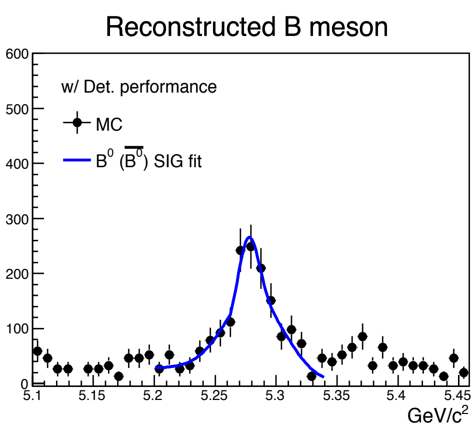
- It is beneficial to look at forward rapidities and lower CM energies

Heavy meson reconstruction

- PYTHIA simulation for 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}, 500 pb^{-1} for eA .
- Reconstructed D-meson and B-meson mass distributions *X. Li et al. 2020*



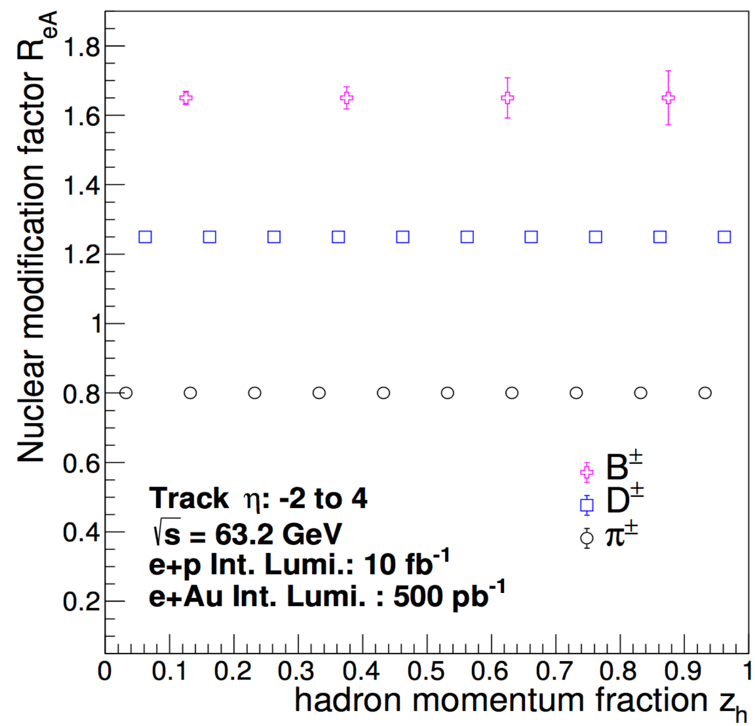




- Clear D-meson and B-meson reconstruction

Excellent statistics, differentially in rapidity

Projected hadron R_{eA} vs z_h

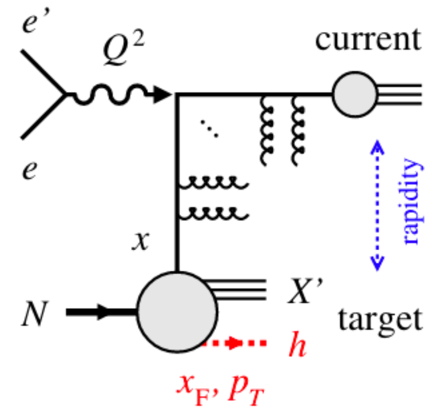


It is beneficial to look at forward rapidities and lower CM energies

Together with D meson back-to-back correlations to study TMD – basis for out tracking request *X. Dong et al. 2020*

Target Fragmentation

See for example CFNS workshop on target fragmentation https://indico.bnl.gov/event/9287/



Fragmentation at large Feynman-x $e+p \rightarrow e'+X+h(x_F,p_T)$

Limited knowledge from HERA. Quantum numbers matter in the large x_F region

- x-dependence of target fragmentation: qualitative changes of the x_F distributions of p and n depending on the x of the removed parton: $\propto(1-x_F)$ at $x>0.2$; constant in x_F at $x\sim0.2$; $\propto 1/x_F$ at $x \ll 0.1$
- Spin dependence and polarization transfer: Fragmentation into self-analyzing Λ baryons, use of the Collins asymmetry
- Quark vs. gluon fracture functions: how the hadronization process changes depending on whether a quark or gluon is removed from the nuclear wavefunctiopn
- Correlations of target and current fragmentation: *correlations could be revealed in back-to-back pion correlations with $p_T \approx 0.5$ GeV and moderate rapidity separations$\Delta\eta \approx 4$*

An important requirement is continuous coverage in x_F from~1 down to~0.1, without gaps between the central (η<4) and forward detectors

New Particle Production Mechanisms

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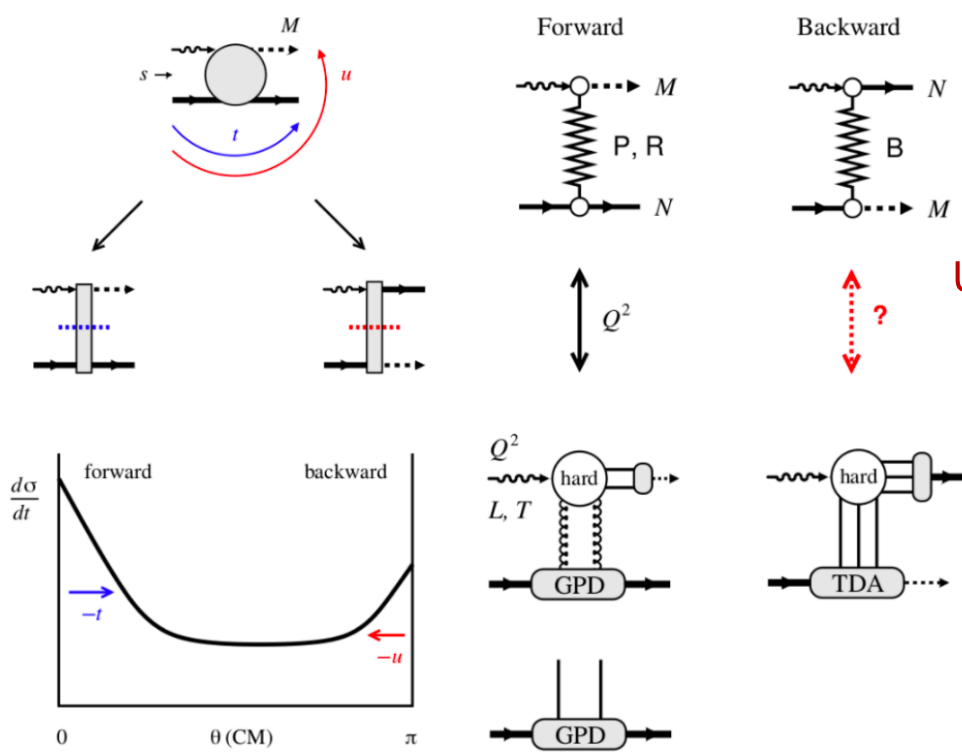
- Pomerons – quantum numbers of the vacuum $J^{PC}=0^{++}$

  Predominantly produce vector mesons in the final state

- Reggeons - summed meson trajectories carry a wider range of quantum numbers
- Odderons – three gluon color singlet exchanges

  Mandatory to explain the difference between p-p and pbarp scattering



TOTEM collaboration may have observed the Odderon (2017)

At the EIC - $f_2(1270)$ via photon-Odderon fusion

U-channel exclusive vector mesons -omega

$$\frac{d\sigma}{dt} = A(s/1\mathrm{GeV})^B \exp(-Ct)$$

A≈18μb/GeV^2 and B=−1.92 C≈10 GeV^{-2}

$$\frac{d\sigma}{du} = A(s/1\mathrm{GeV})^B \exp(-Cu)$$

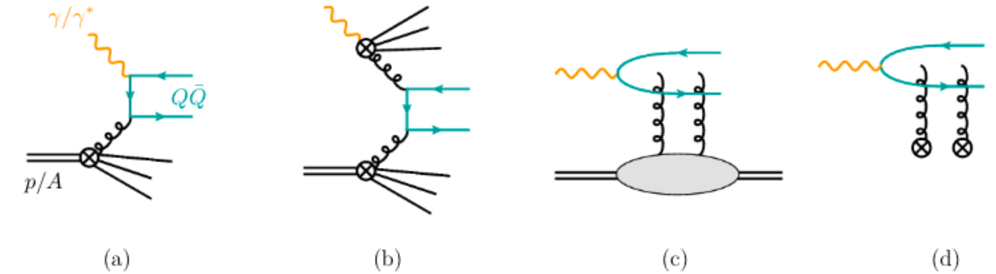
A≈4.4μb/GeV^2 and B=−1.92 C≈21 GeV^{-2}

The decay $\omega \rightarrow \pi^0\gamma$ could be studied with far-forward calorimetry.

U-channel electroproduction - π 0,π±,ρ,η,η and φ

Quarkonia and exotics

$$\mathcal{L}_{\text{NRQCD}_G} = \mathcal{L}_{\text{NRQCD}} + \mathcal{L}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) + \mathcal{L}_{g-G/C}(A_s^{\mu,b}, A^{\mu,a}_{G/C}) + \psi \leftarrow\rightarrow \chi$$



Illustrative examples of quarkonium production mechanism in ep and eA colliders: (a) Direct photo/lepto-production, (b) resolved-photon quarkonium production,(c) exclusive quarkonium production, and (d) heavy quark pair production and subsequent Glauber/Coulomb gluon exchanges with nuclear matter

Y. Makris *et al. 2020*

Constrain LDMEs

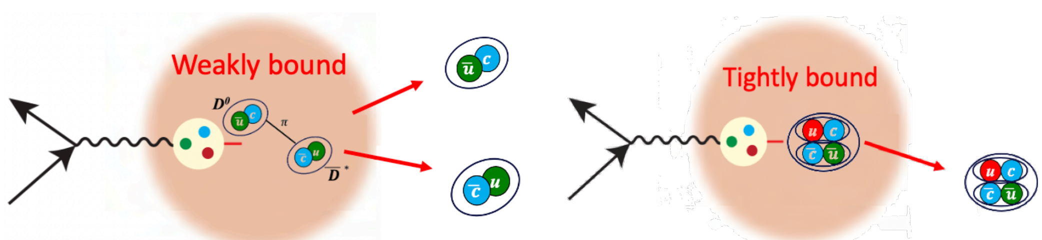
Understand TMD production of quarkona (and shape functions)

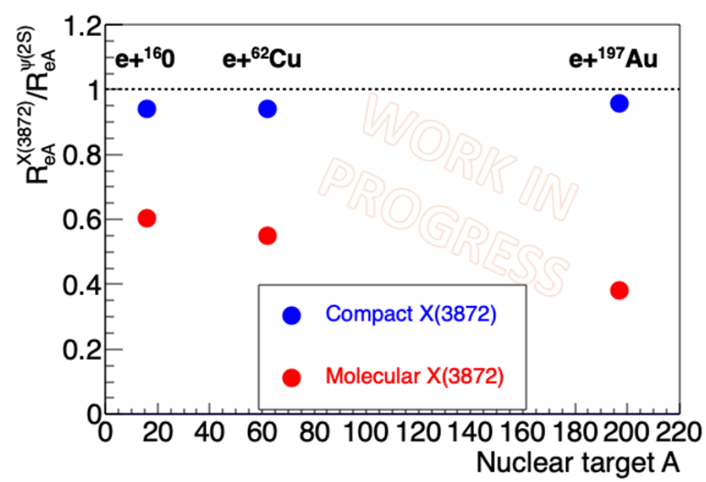
Develop EFTs of quarkonia in matter (indications from HI collisons)

Open quantum systems approach at EIC

New exotic state structure studies at the EIC

Use eA collisions – nucleus as a filter to differentiate between tightly bound (quark) and molecular states





Relative modification of X(3872)/ $\psi(2S)$ projection at $\sqrt{s}$ = 63.2GeV

M. Durham *et al. 2020*

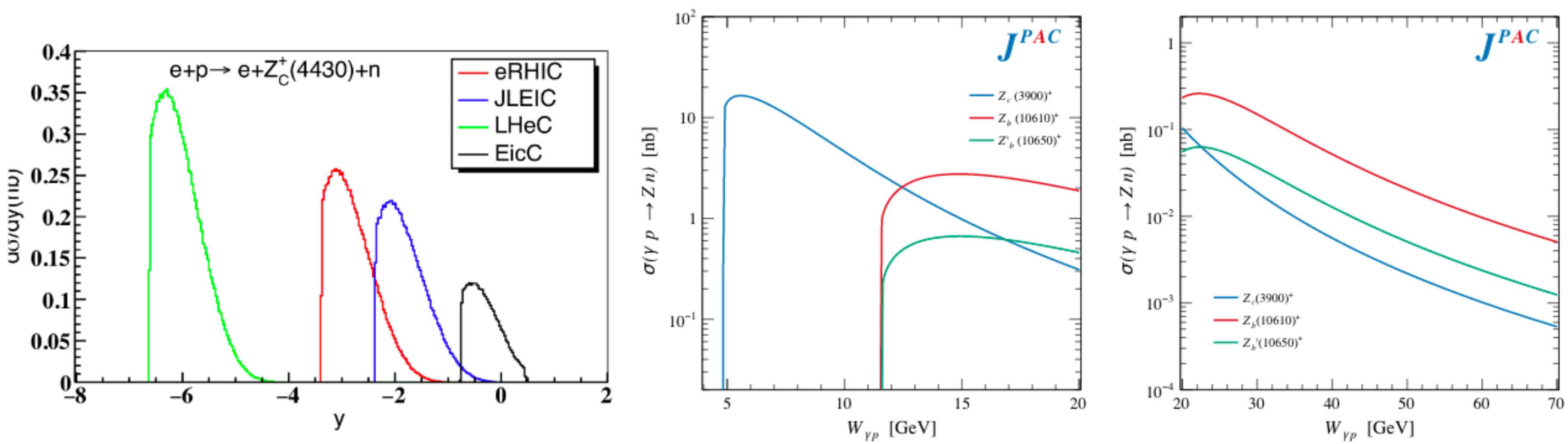
Spectroscopy

Tetraquark states X, Z … ; Pentaquark states P …

- *Photoproduction through photon-Pomeron fusion lead predominantly to $J^{PC}=1^{--}$ states like the J/ψ, etc., so is only sensitive to exotic with those quantum numbers*
- *Photon-Reggeon fusion leads to states with a wider range of spin, parity and even charge*

$$\sigma(ep \to eX^+n) = \int \frac{dk}{k} dQ^2 \frac{d^2N_\gamma(k,Q^2)}{dk\,dQ^2} \times \sigma_{\gamma^* p \to X^+ n}(W, Q^2),$$

$$\sigma_{\gamma^* p \to X^+ n}(W, Q^2) = \left(\frac{M_X^2}{M_X^2+Q^2}\right)^\eta \sigma_{\gamma p \to X^+ n}(W, Q^2=0) f(M_X),$$



Z^+ photoproduction rapidity distributions and integrated cross section predictions for fixed-spin exchange, valid at low energies (center), and for Regge exchange, valid at high energies (right)

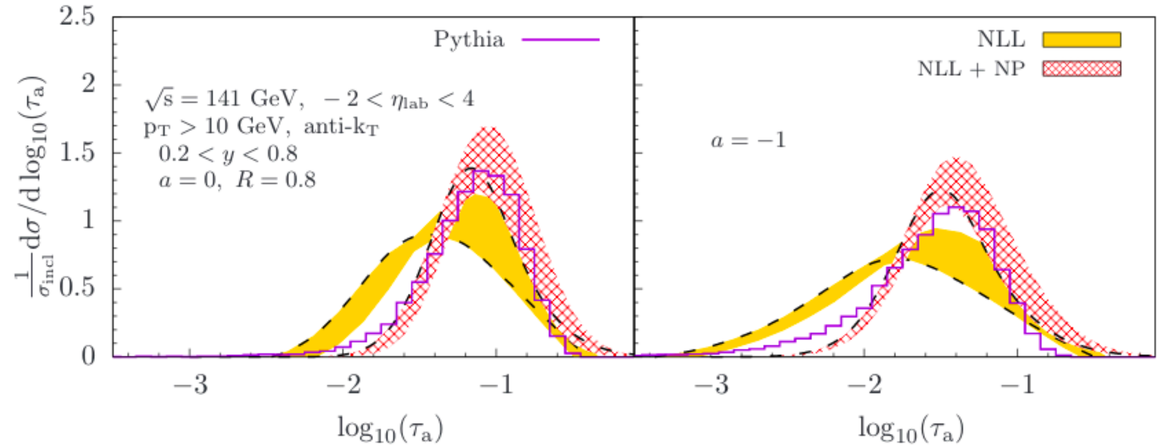
JLab energies - u-channel production, Expect for EIC t-channel production

S. Kein *et al. 2019*

M. Albaladejo *et al. 2020*

Jets

- The idea behind inclusive jets was of course to minimize hadronization effects



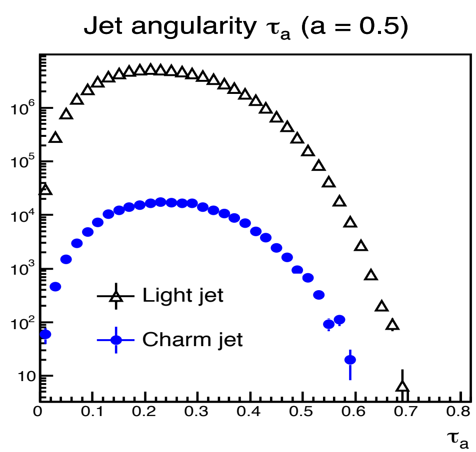
At the EIC jet energies are relatively low and hadronization effects are expected to play a significant role

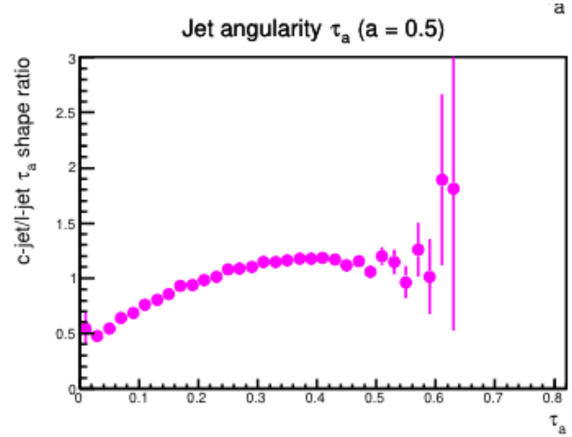
Hadronization is important when we look inside jets: shapes, fragmentation functions, angularities

L. Cunqueiro *et al. 2020*

$$\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta \mathcal{R}_{iJ}\right)^{2-a}$$

- Heavy flavor jet tagging and sub-structure





E_e: 10 GeV
E_p: 100 GeV
Integrated Lumi: 10 fb^{-1}

Have been studies experimentally

Can be used to differentiate between light and heavy flavor jets

P. Wong *et al. 2020*

- Energy loss of jets in e+A is important but in a different section

In place of conclusions

The chapter on hadronization covers an impressive number of topics

Thanks to all the PWG members who contributed to chapter 7.4 !