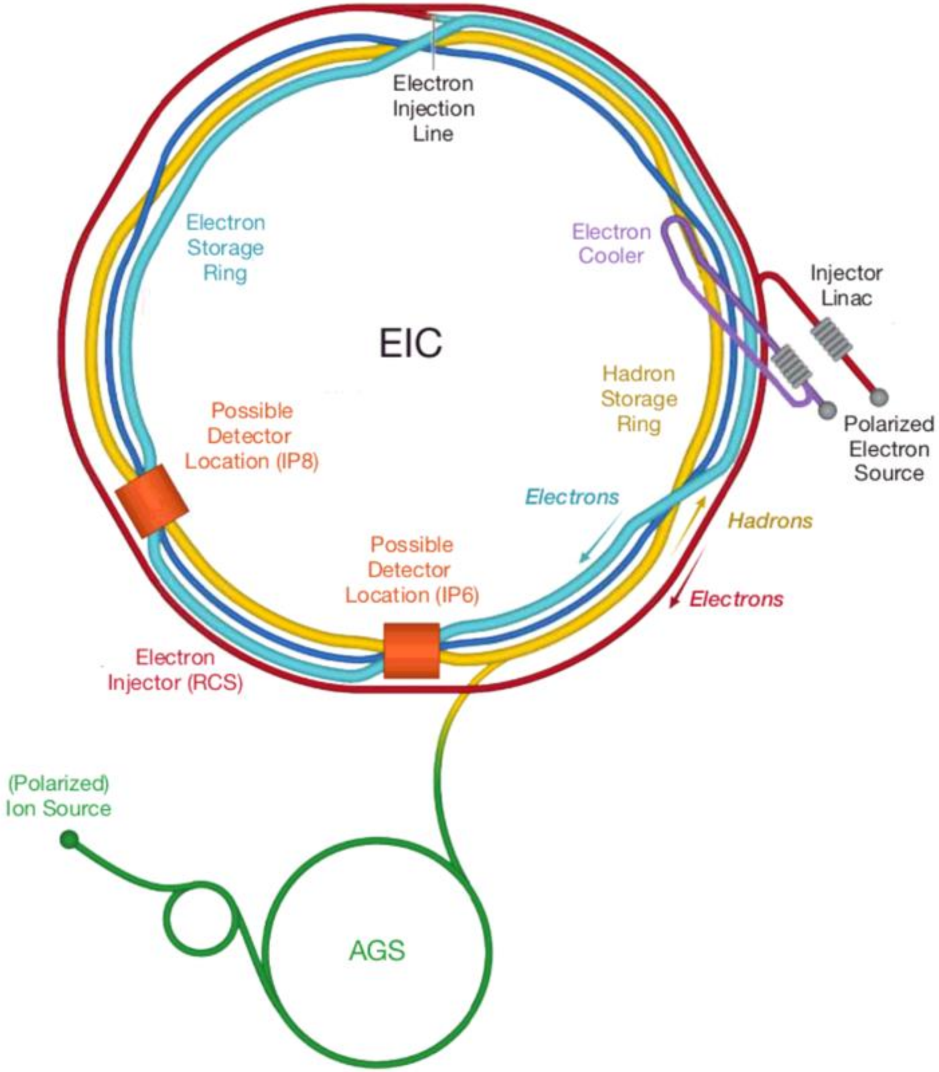
Jets and Heavy Flavor at the EIC

Xinbai Li (xinbai@mail.ustc.edu.cn)

I Contents



- EIC Detector Setup
- Cold Nuclear Medium Effect
- Multi-Dimensional Imaging of the Nucleon
- Origin of the Hadron Mass
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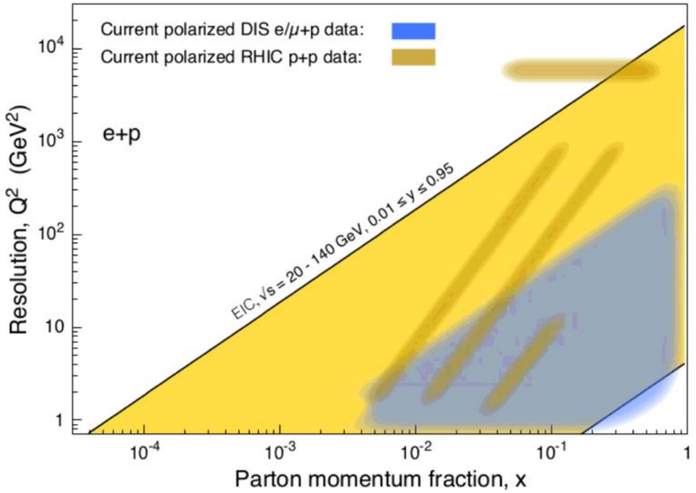
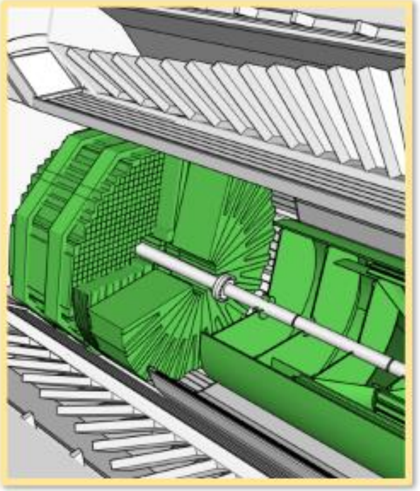
- Summary



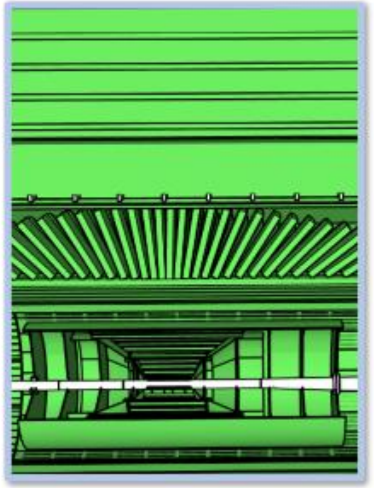
EIC Detector Setup



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)



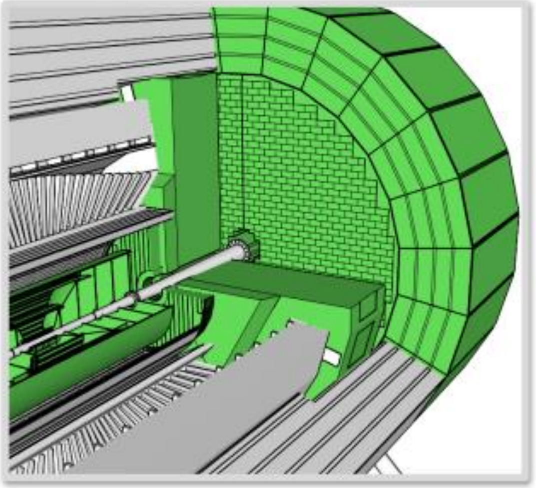
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- µRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- µRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

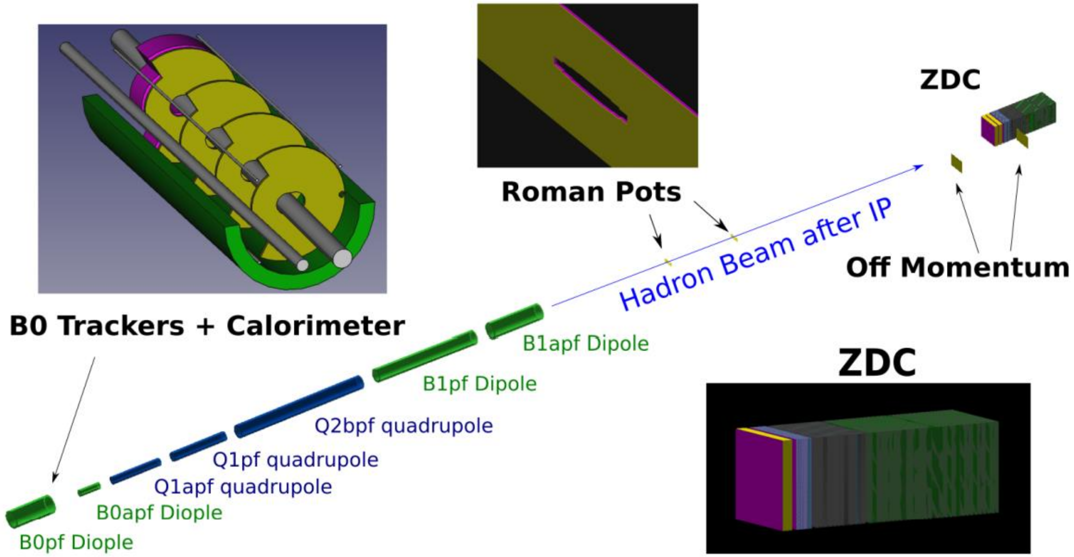
PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

ECCE

e-going ←

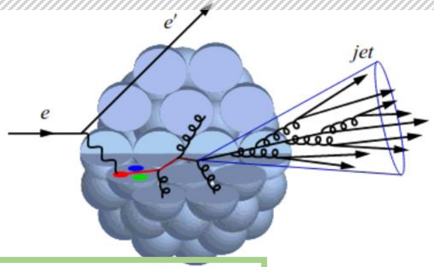
h-going →



Charged jet	Tracking
Calorimeter jet	Calorimeter
h/e-PID	Cherenkov/CAL +TOF
exclusive background	Far forward detector

I Jet Production and Modification in e+A

Study cold nuclear matter properties with jets at the EIC



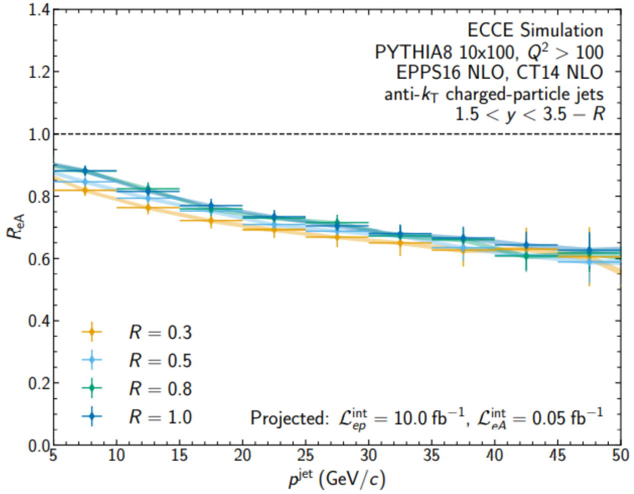
Initial-state modification:

nuclear parton distribution functions (nPDFs)

Final-state effects:

interactions between the jet and cold nuclear matter

$$R_{eA} = \frac{\alpha \frac{d^2\sigma}{dy\, dp^{jet}}\big|_{eA}}{\frac{d^2\sigma}{dy\, dp^{jet}}\big|_{ep}},$$

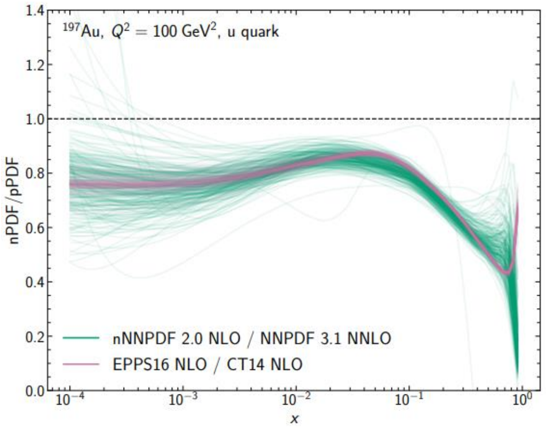


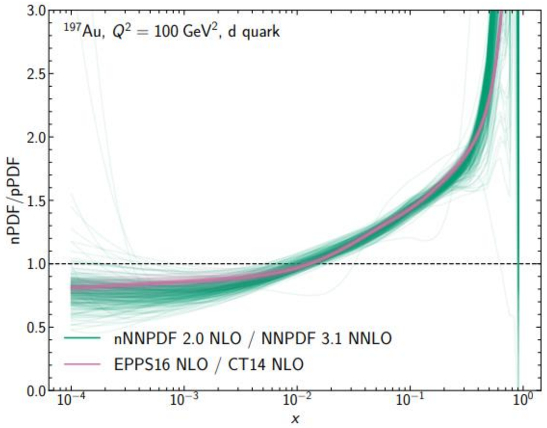
$R_{eA}(R)/R_{eA}(R = 1.0)$ Isolate nuclear effects

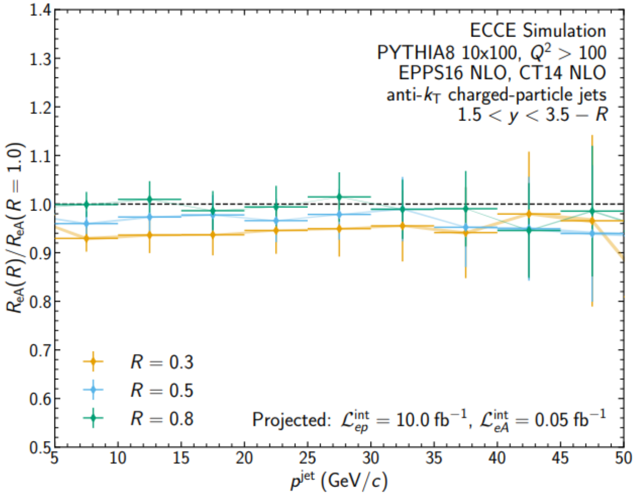
$$r = \frac{\text{nPDF}(x, Q^2)}{\text{protonPDF}(x, Q^2)},$$

Isolate nPDFs

$$Q_{\kappa,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^{\kappa}} \sum_{i \in \text{jet}} Q_i \left(p_T^i\right)^{\kappa}, \quad \kappa > 0.$$







FF Evolution in Cold Nuclear Medium

Inclusive hadron production cross section as:

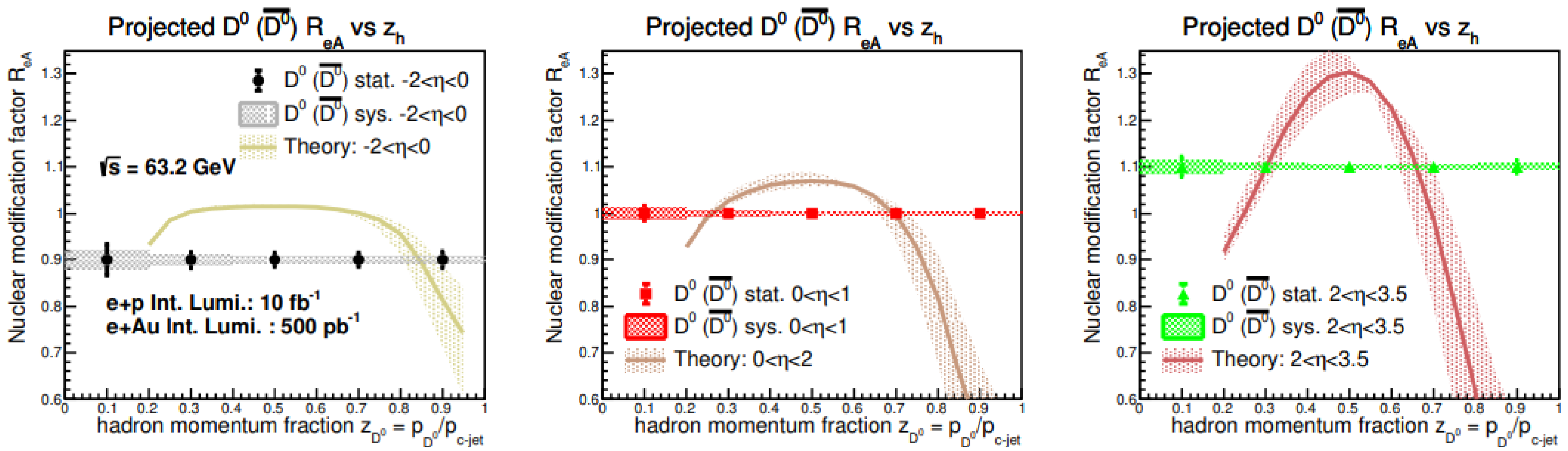
$$\sigma_{e+p/A} = f_a^{p/A}(x, Q^2) \otimes H_{a\gamma*\to c} \otimes D_c^{e+p/A}(z, \mu),$$

With better understanding of in-medium parton showers, the traditional energy loss can be generalized to fragmentation function evolution in the presence of nuclear matter:

$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)\left(P_{ji}(z,\alpha_s(\mu)) + P_{ji}^{\text{med}}(z,\mu)\right)$$

H. T. Li, Z. L. Liu, I. Vitev, Phys. Lett. B 816 (2021) 136261.

e-going | central | h-going



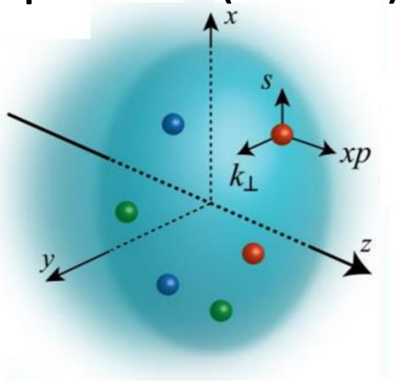
Multi-Dimensional Imaging of the Nucleon

Generalized transverse momentum dependent parton distributions (GTMDs) / Wigner Function

$w_p^u(x, k_T, r_T)$

5D Dist.

Transverse Momentum Dep. Dist. (TMDs)



$d^2 r_T$

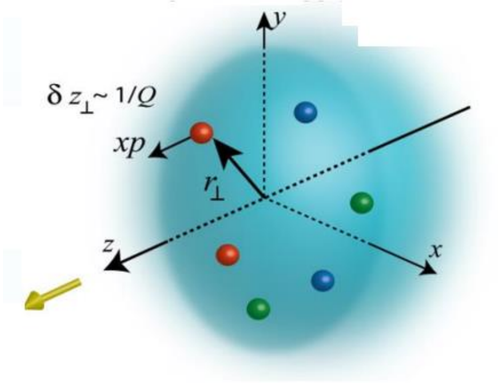
$d^2 k_T$

$f_1^u(x, k_T)$
$h_1^u(x, k_T)$

"3D" imaging

Generalized Parton Dist. (GPDs)

GPD



$d^2 k_T$

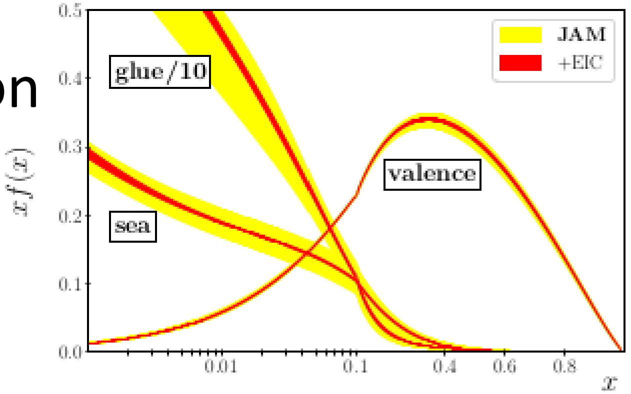
$d^2 r_T$

$f_1^u(x)$, $h_1^u(x)$

Fourier transform

$$f(x, b, Q^2) \equiv \int \frac{d^2\Delta}{(2\pi)^2} e^{-i(\Delta b)} \, \mathrm{GPD}(x, t = -\Delta^2, Q^2)$$

Parton Distribution Functions (PDFs)



Imaging in position space

EIC YR

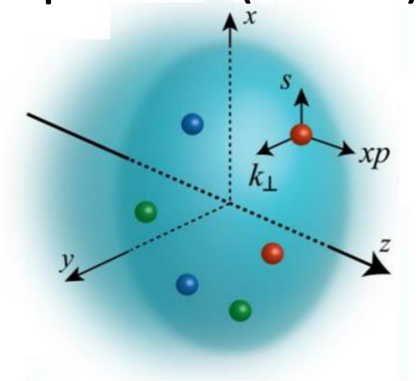
Multi-Dimensional Imaging of the Nucleon

Generalized transverse momentum dependent parton distributions (GTMDs) / Wigner Function

$w_p^u(x, k_T, r_T)$

5D Dist.

Transverse Momentum Dep. Dist. (TMDs)



$d^2 r_T$

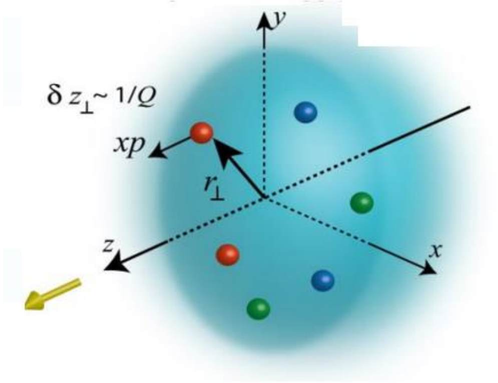
$d^2 k_T$

$f_1^u(x, k_T)$
$h_1^u(x, k_T)$

“3D” imaging

GPD

Generalized Parton Dist. (GPDs)



$d^2 k_T$

$d^2 r_T$

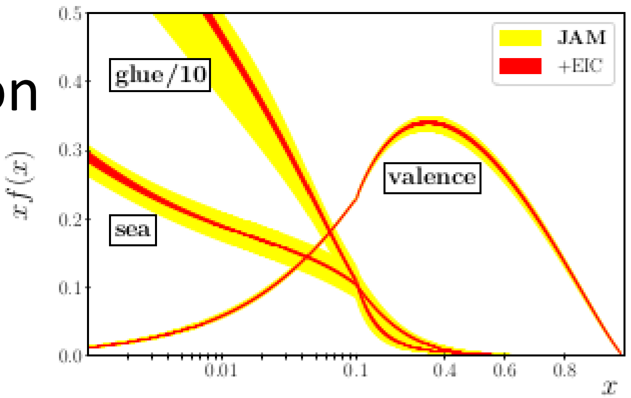
$f_1^u(x), h_1^u(x)$

Fourier transform

$$f(x, b, Q^2) \equiv \int \frac{d^2\Delta}{(2\pi)^2} e^{-i(\Delta b)} \, \mathrm{GPD}(x, t = -\Delta^2, Q^2)$$

Imaging in position space

Parton Distribution Functions (PDFs)



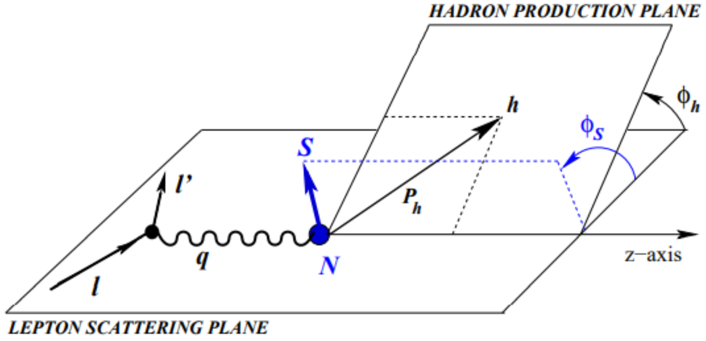
EIC YR

Multi-Dimensional Imaging of the Nucleon

In eight leading-twist TMDs

$f_{1T}^{\perp a}(x, k_\perp)$ is the Sivers function, appearing in the distribution of unpolarized partons a inside a polarized proton. It links the parton intrinsic motion to the proton spin:

$$f_1^a(x, \boldsymbol{k}_\perp; \boldsymbol{S}) = f_1^a(x, k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp a}(x, k_\perp)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}}_\perp)\,.$$



$H_1^{\perp q}(z, P_\perp)$ is the Collins function, describing the fragmentation of a polarized quark into a spinless (or unpolarized) hadron:

$$D_1^q(z, \boldsymbol{P}_\perp; \boldsymbol{s}_q) \;=\; D_1^q(z, P_\perp) + \frac{P_\perp}{zM_h} H_1^{\perp q}(z, P_\perp)\, \boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{P}}_\perp)\,.$$

Main access at the EIC : transverse single-spin asymmetries (SSAs)

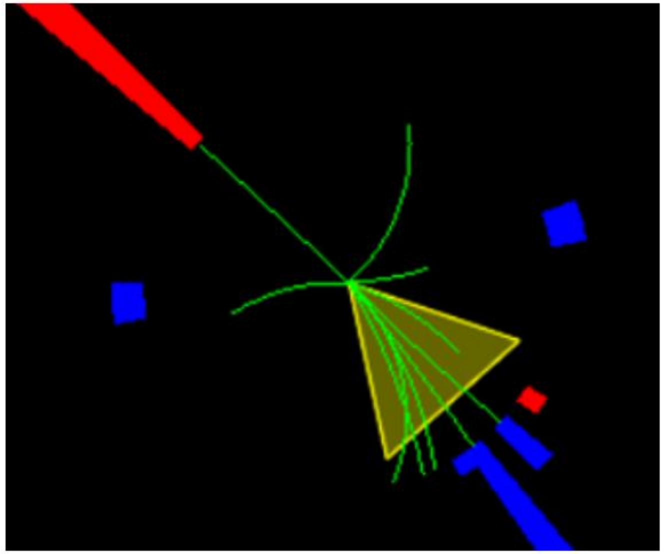
$$A_{UT}\left(\varphi_h^l, \varphi_S^l\right) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$= A_{UT}^{\text{Collins}} \sin(\phi_h + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi_h - \phi_S) + A_{UT}^{\text{Prezzelosity}} \sin(3\phi_h - \phi_S)$$

D. Boer, et al., arXiv:1108.1713

A novel way!

$$e + p(\vec{s}_T) \to e + (\text{jet}(\vec{q}_T)\, h(z_h, \vec{j}_T)) + X\,,$$



Traditional way

D meson pair production
Charged dihadron production
Dijet production

Multi-Dimensional Imaging of the Nucleon

$$e + p(\vec{s}_T) \to e + (\text{jet}(\vec{q}_T)\, h(z_h, \vec{j}_T)) + X\,,$$

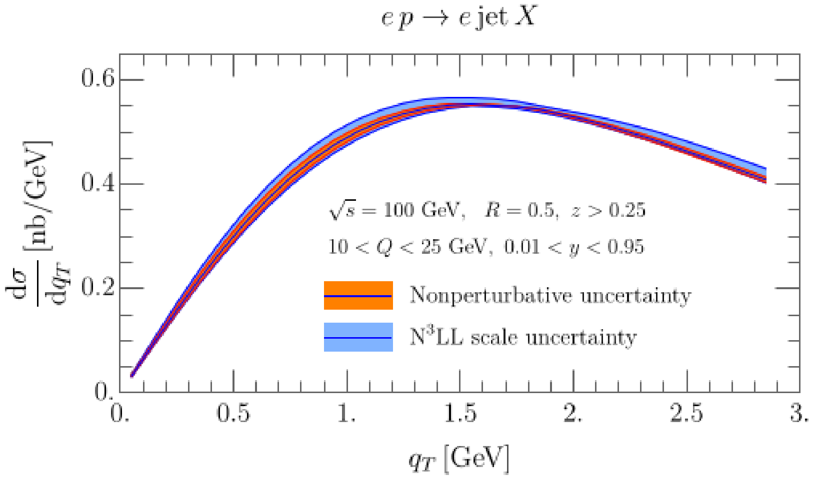
$\vec{q}_T$ is the imbalance of the transverse momentum of the final-state electron and jet.

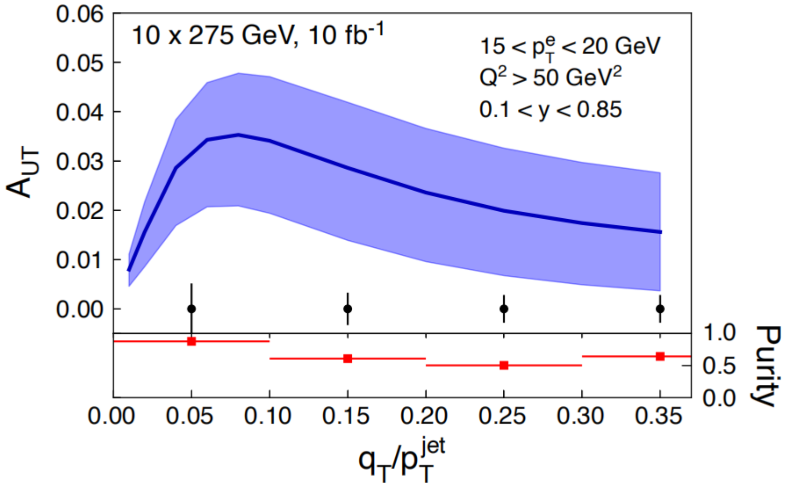
$\vec{j}_T$ is the transverse momentum of hadrons inside the jet with respect to the jet axis.

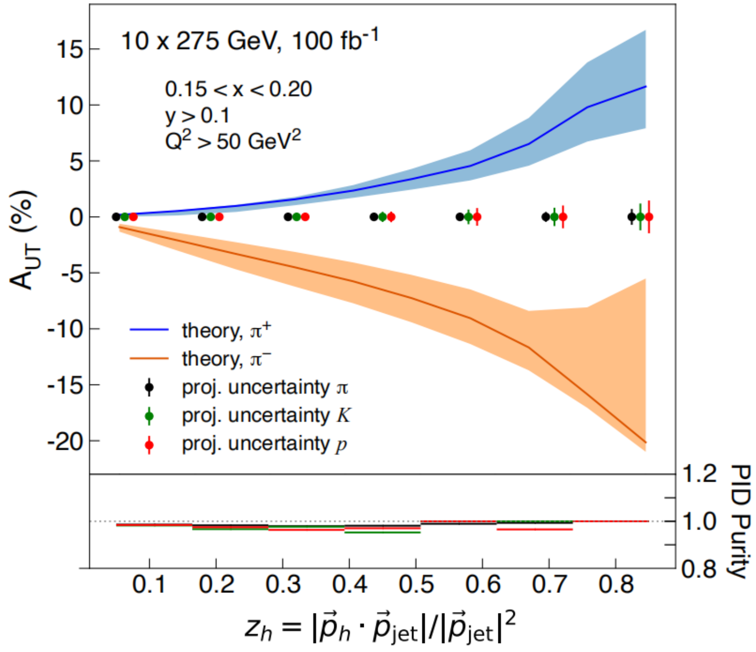
For an incoming transversely polarized proton, the transverse spin vector $\vec{s}_T$ is correlated with the imbalance momentum $\vec{q}_T$, which leads to a $\sin(\phi_s - \phi_q)$ modulation of the electron-jet cross section.

The imbalance $\vec{q}_T$ is only sensitive to TMD PDFs, while the $\vec{j}_T$ is sensitive to TMD FFs alone.

M. Arratia, Z.-B. Kang, A. Prokudin, F. Ringer, Phys. Rev. D 102 (7)(2020) 074015







Significantly reduce the current theoretical uncertainties

IV Proton Mass; Higher Q2: Looking to EIC

Higher Q2 provides a more rigorous connection between cross section and the matrix element.

Boussarie & Hatta et al, Phys.Rev.D 101 (2020) 11, 114004

$$M_N = M_m + M_q + M_g + M_a$$

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b\, m_p$$

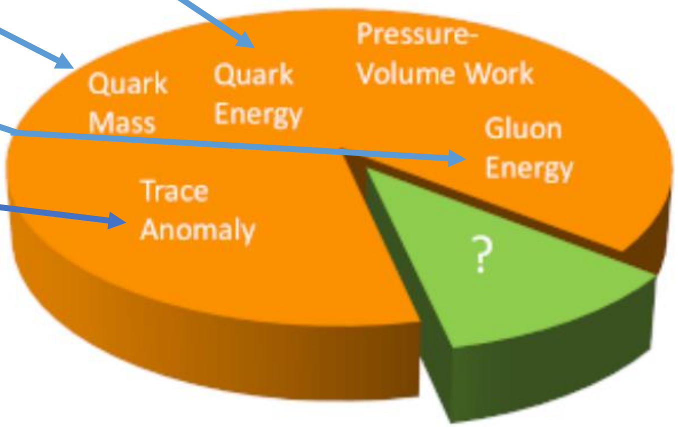
$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) m_p$$

$$M_g = \frac{3}{4}(1-a)\, m_p$$

$$M_a = \frac{1}{4}(1-b)\, m_p$$

$$T^\mu_\mu = \frac{\tilde{\beta}(g)}{2g} G^2 + \sum_{q=u,d,s} m_q (1+\gamma_m)\bar{\psi}_q \psi_q$$

Trace Anomaly **Light Quark Mass**



near-threshold J/ψ and ϒ production

$$\left.\frac{d\sigma_{\gamma N \to J/\psi N}}{dt}\right|_{t=0} = \frac{3\Gamma\left(J/\psi \to e^+e^-\right)}{\alpha m_{J/\psi}} \left(\frac{k_{J/\psi N}}{k_{\gamma N}}\right)^2 \left.\frac{d\sigma_{J/\psi N \to J/\psi N}}{dt}\right|_{t=0}$$

$$F_{J/\psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - \left\langle N \left| \sum_{i=u,d,s} m_i \bar{q}_i q_i \right| N \right\rangle\right)$$

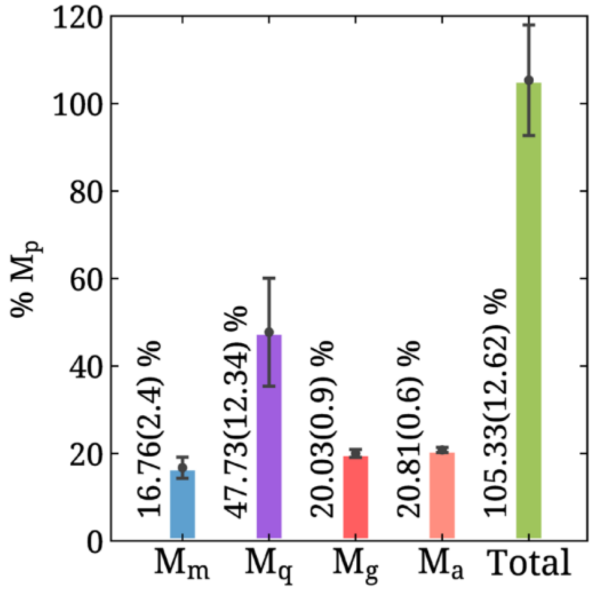
$$\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - 2bM_N^2\right)$$

$$\simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 \boxed{(1-b),}$$

$$\left.\frac{d\sigma_{J/\psi N \to J/\psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi} \frac{1}{m_{J/\psi}^2 \left(\lambda^2 - m_N^2\right)} \left|F_{J/\psi N}\right|^2 .$$

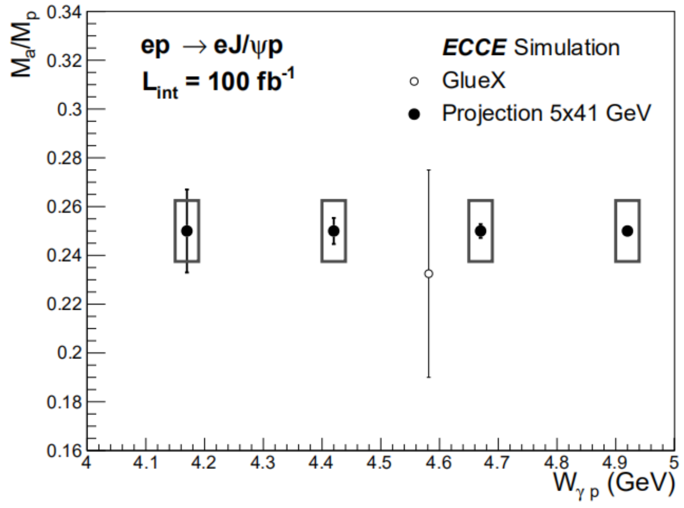
IV Proton Mass; Higher Q2: Looking to EIC

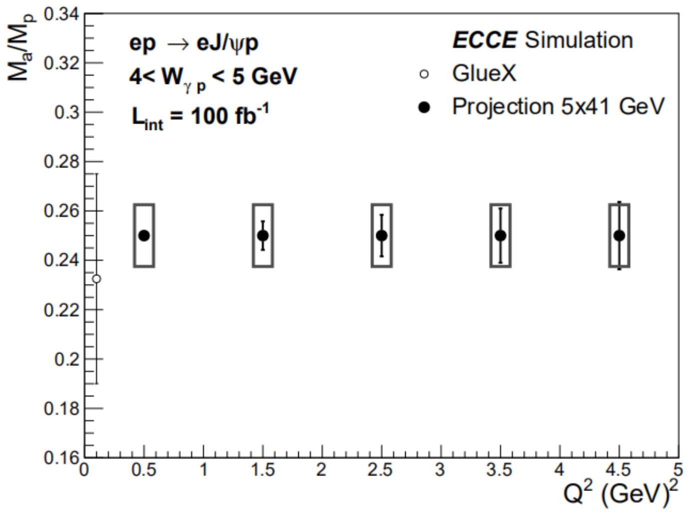
Lattice is the only first-principles approach to understand non-perturbative QCD dynamics



C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)

C. Alexandrou et al., (ETMC), PRL 116, 252001 (2016)





Event generator: eSTARLight

Di-electron reconstruction

Large Q^2 lever arm will allow to constraint the production mechanism and reduce the model dependence of the trace anomaly contribution

- $a(\mu)$ related to PDFs, well constrained
- ***$b(\mu)$* related to quarkonium-proton scattering amplitude *$T_{\psi p}$* near-threshold**

IV Proton Mass; Higher Q2: Looking to EIC

Near Threshold

Proton Mass

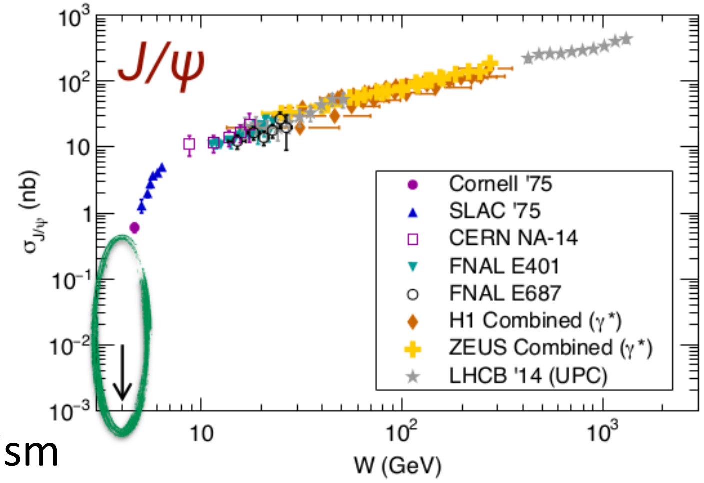
Mass radius

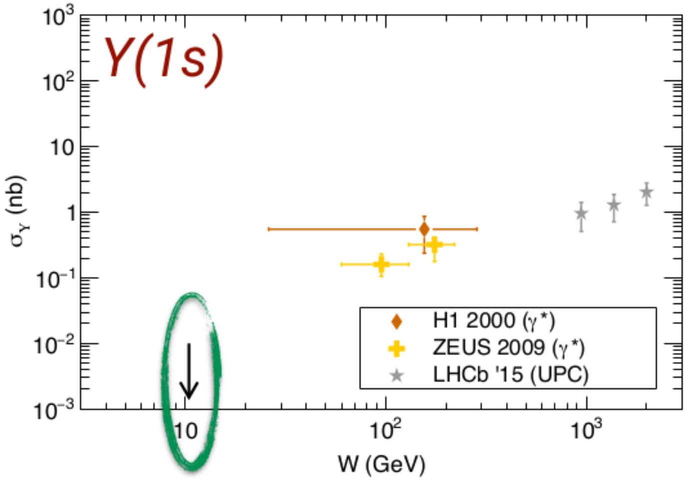
Production Mechanism

Pentaquark state

Broader fields:
stellar dynamics

…



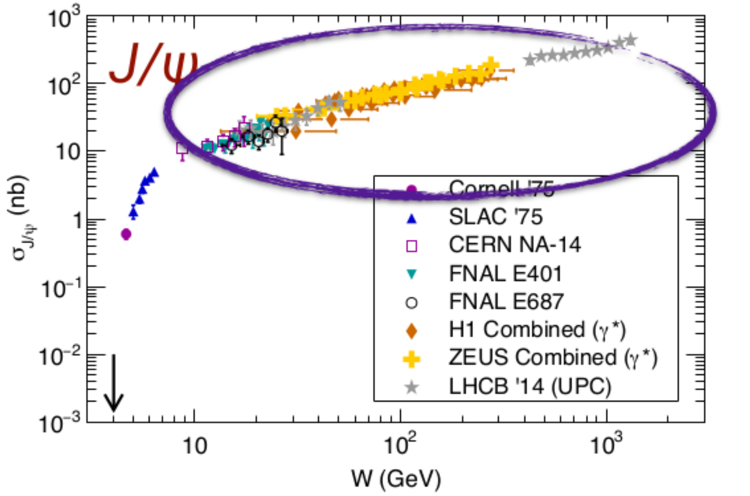


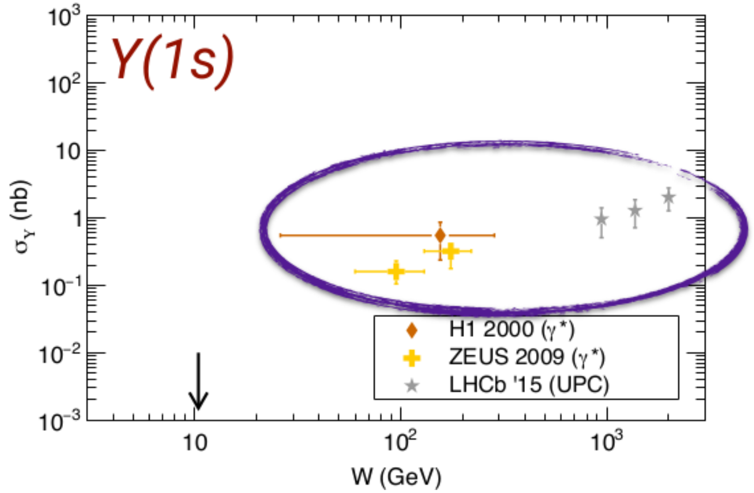
- J/ψ production at Jefferson Lab
- $\Upsilon(1s)$ production at an EIC

High Energies

Gluon GPD
3D tomography

…





From S.Joosten's slides

- J/ψ production at an EIC
- $\Upsilon(1s)$ production at an EIC

Photoproduction; Mass Radius

$$T^{\mu}_{\mu} = \underbrace{\frac{\tilde{\beta}(g)}{2g} G^2}_{\text{Trace Anomaly}} + \underbrace{\sum_{q=u,d,s} m_q (1+\gamma_m) \bar{\psi}_q \psi_q}_{\text{Light Quark Mass}}$$

Trace Anomaly **Light Quark Mass**

Charge radius from spatial distribution of quarks: form factors in electron scattering experiments.

$$\frac{d\sigma_{\gamma p \to J/\psi p}}{dt} \propto \left| \langle p' | T | p \rangle \right|^2 .$$

Kharzeev, PRD 104 (2021) 054015; Wang et al., PRD 103 (2021) L091501; Mamo and Zahed, PRD 101 (2020) 086003; PRD 103 (2021) 094010

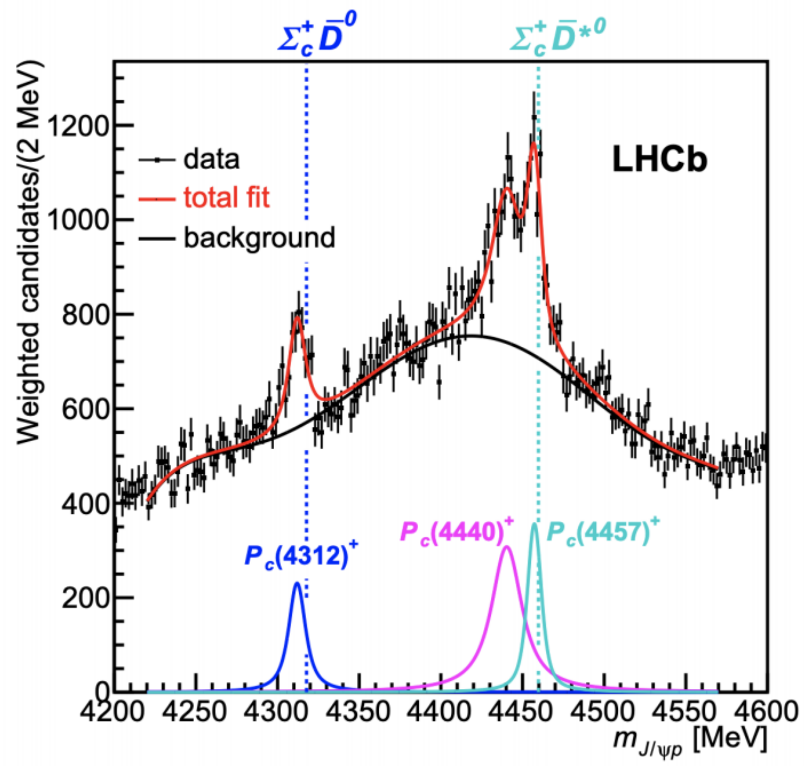
$$\langle R_m \rangle = \frac{6}{m_p} \frac{dG}{dt}\bigg|_{t=0}$$

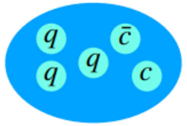
Mass radius from gravitational form factors (GFF) in photoproduction! In the non-relativistic limit.

Photoproduction; Pentaquark ?

In 2015, exotic-like structures in the channel were found.

Aaij et al. [LHCb], PRL 115 (2015) 072001;
Aaij et al. [LHCb], PRL 122 (2019) 222001



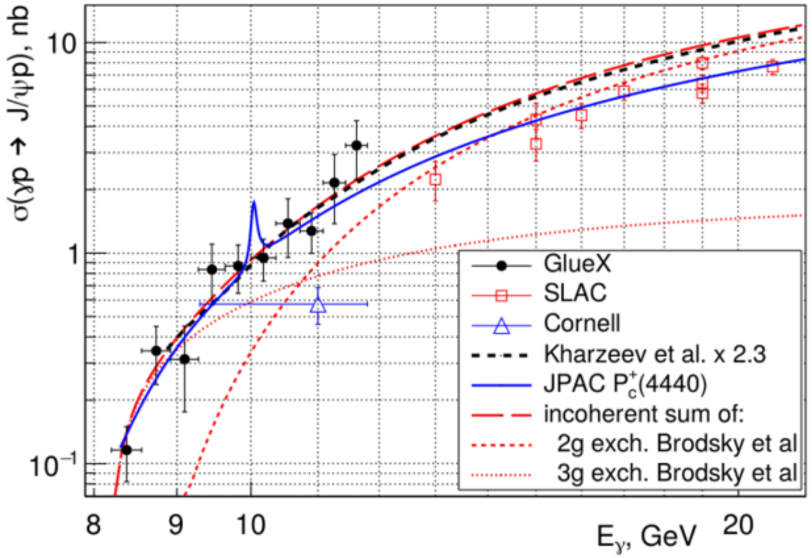


GlueX data for threshold J/ ψ production mechanism.

Ali et al., PRL 123 (2019) 072001;
Brodsky et al., PLB 498 (2001) 23

Set upper limits to $\sigma(\gamma p \to P_c) \times \mathcal{B}(P_c \to J/\psi p)$

Hiller Blin et al., PRD 94 (2016) 034002;
Winney et al., PRD 100 (2019) 034019



Larger statistics will be accessed at the EIC

From Astrid N. Hiller Blin's slides

Photoproduction; Nuclear Medium Modification

According to pQCD, the forward scattering cross section of J/ψ photoproduction is proportional to the square of the gluon density distribution

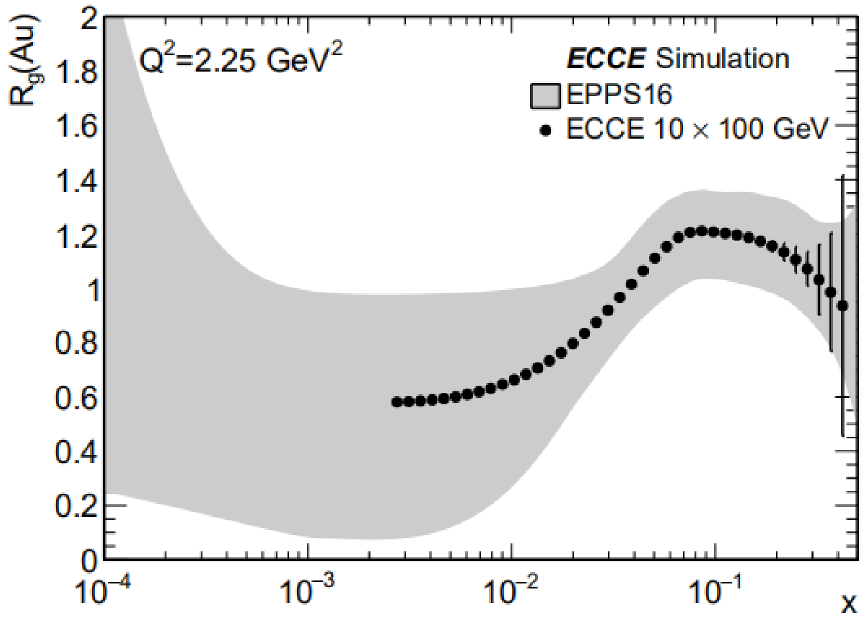
$$\left.\frac{d\sigma(\gamma A \to VA)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^{\xi}} 16\pi^3 \left[x g_A(x,\mu^2) \right]^2$$

The nuclear gluon shadowing can be model-independently quantified by R_g

$$R_g = \sqrt{\frac{\left.\frac{d\sigma(\gamma A \to VA)}{dt}\right|_{t=0}}{\left.\frac{d\sigma(\gamma p \to Vp)}{dt}\right|_{t=0}}}$$

Momentum fraction x:

$$x = \frac{M_V e^y}{2E_N}.$$



VI Summary

- R_{eA} of jet as a key to understanding nuclear medium effect and hadronization.
- A novel way: hadron in jet probes TMD PDFs independently of TMD FFs.
- Photoproduction of heavy quarkonium off nucleon targets can give insight about gluon distributions in the nucleon, trace anomaly contribution to the proton mass, mass radius and pentaquark evidence.
- Jets and HF are powerful probes of EIC physics.

Backup

Backup: Jet based TMD PDFs

LO cross section:

$$\frac{d\sigma}{dy_e\, d^2\vec{p}_T^{\,e}} = \sigma_0 \sum_q e_q^2\, f_q(x,\mu)\,,$$

where the scale is chosen at the order of the hard scale of the process $\mu \sim p_T^e = |\vec{p}_T^{\,e}|$. The prefactor σ_0 is given by

$$\sigma_0 = \frac{\alpha\alpha_s}{sQ^2}\frac{2(\hat{s}^2+\hat{u}^2)}{\hat{t}^2}\,.$$

The Bjorken x variable can be expressed as:

$$x = \frac{p_T^e e^{y_e}}{\sqrt{s} - p_T^e e^{-y_e}}\,.$$

$$\hat{s} = xs\,,$$

$$\hat{t} = -Q^2 = -\sqrt{s}\,p_T^e e^{y_e} = -x\sqrt{s}\,p_T^{\rm jet}\,e^{-y_{\rm jet}}\,,$$

$$\hat{u} = -x\sqrt{s}\,p_T^e e^{-y_e} = -\sqrt{s}\,p_T^{\rm jet}\,e^{y_{\rm jet}}\,,$$

$$y = 1 - \frac{p_T^e}{\sqrt{s}}e^{-y_e}\,,$$

The Sivers asymmetry and electron-jet decorrelation

$$\frac{d\sigma(\vec{s}_T)}{d\mathcal{PS}} = F_{UU} + \sin(\phi_s-\phi_q)F_{UT}^{\sin(\phi_s-\phi_q)}\,,$$

$$A_{UT}^{\sin(\phi_s-\phi_q)} = \frac{F_{UT}^{\sin(\phi_s-\phi_q)}}{F_{UU}}\,.$$

$$F_{UU} = \sigma_0\, H_q(Q,\mu)\sum_q e_q^2\, J_q(p_T^{\rm jet}R,\mu)$$
$$\times \int \frac{d^2\vec{b}_T}{(2\pi)^2}\, e^{i\vec{q}_T\cdot\vec{b}_T}\, f_q^{\rm TMD}(x,\vec{b}_T,\mu)\, S_q(\vec{b}_T, y_{\rm jet}, R,\mu)\,,$$

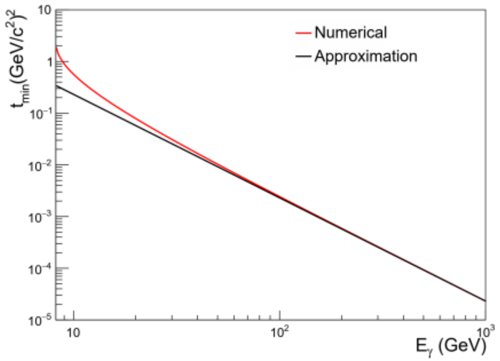
The Collins asymmetry and jet substructure

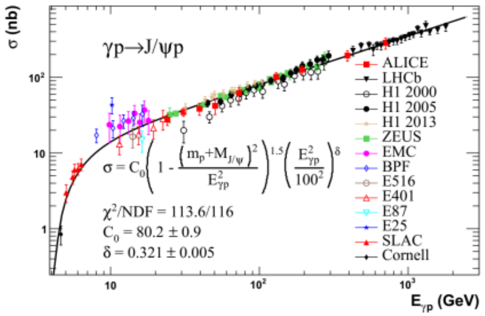
$$F_{UU}^h = \sigma_0\, H_q(Q,\mu)\sum_q e_q^2\, \mathcal{G}_q^h(z_h,\vec{j}_T,p_T^{\rm jet}R,\mu)$$
$$\times \int \frac{d^2\vec{b}_T}{(2\pi)^2}\, e^{i\vec{q}_T\cdot\vec{b}_T}\, f_q^{\rm TMD}(x,\vec{b}_T,\mu)\, S_q(\vec{b}_T, y_{\rm jet}, R,\mu)\,.$$

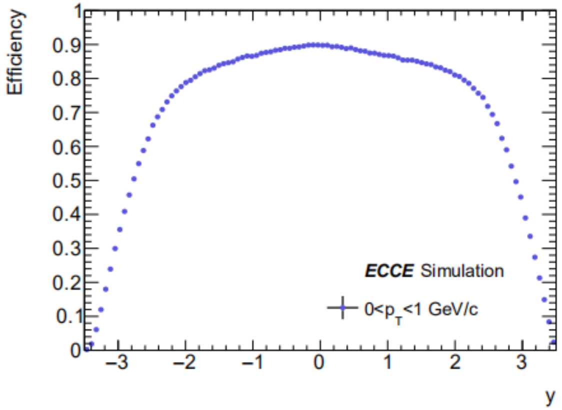
$$\frac{d\sigma^h(\vec{s}_T)}{d\mathcal{PS}\,dz_h\,d^2\vec{j}_T^{\,h}} = F_{UU}^h + \sin(\phi_s-\phi_h)F_{UT}^{\sin(\phi_s-\phi_h)}\,, \qquad A_{UT}^{\sin(\phi_s-\phi_h)} = \frac{F_{UT}^{\sin(\phi_s-\phi_h)}}{F_{UU}^h}\,.$$

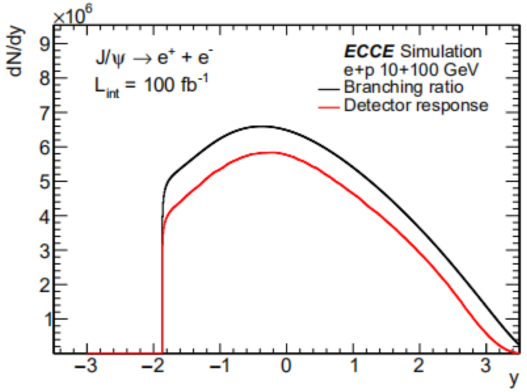
$$\mathcal{G}_q^h(z_h,\vec{j}_T,p_T^{\rm jet}R) = \int \frac{d^2\vec{b}'_T}{(2\pi)^2}\, e^{i\vec{j}_T\cdot\vec{b}'_T/z_h}\, D_{h/q}^{\rm TMD}(z_h,\vec{b}'_T,p_T^{\rm jet}R)\,.$$

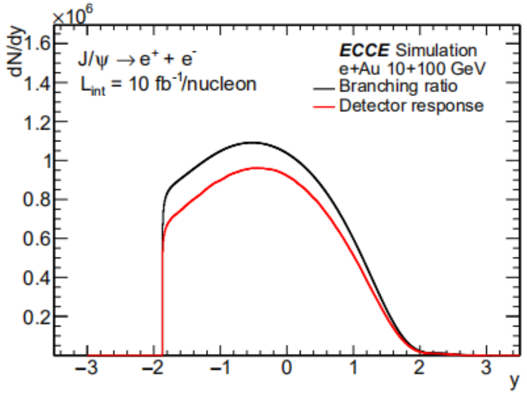
Backup: Two improvements and detection

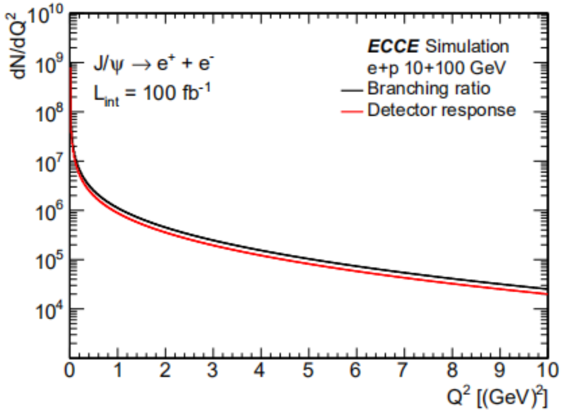


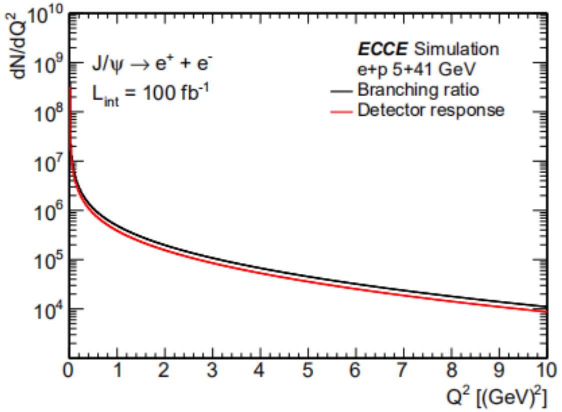












Backup: Proton Mass Workshop

- Workshop on **Non-perturbative color forces in QCD**
  March 26-28, 2012, Temple Univ (Z.-E.M)
- 1st Proton Mass workshop, **The Proton Mass: At the heart of most visible matter**
  March 28-29, 2016, Temple Univ (Z.-E. M, J. Qiu)
- 2nd Proton mass workshop, **The Proton Mass: At the heart of most visible matter**
  April 3-7, 2017, ECT* (Z.-E.M, B. Pasquini, J. Qiu, M. Vanderhaeghen)
- **3rd Proton Mass Workshop: Origin and Perspective**
  January 14-16, 2021, ANL (I. Cloët, X. Ji, Z.-E.M, J. Qiu)
- 4th Proton Mass Workshop, **Origin of the Visible Universe: Unraveling the Proton Mass**
  December 6-10, 2021, INT (I. Cloët, Z.-E.M, B. Pasquini)

Backup: Proton Mass Workshop

1. **Broader questions**
    1. The nucleon mass is the most crucial gravitational charge in the universe below the scale of galaxies. How does the strong interaction scale or mass affect the visible universe?
    2. Can the nucleon's transverse momentum parton distributions reveal the temperature at which the nucleon is formed?
    3. What determines the QCD scale?
    4. What does QCD dynamics predict about the proton mass if the scale is just a parameter?
    5. How would the physical world (condensed matter, chemistry, and biology) change if Λ_QCD is increased or decreased by a factor of 2?
    6. What is the interplay between the Higgs and QCD mass generation mechanisms?
2. **Fundamentals of QCD**
    1. What is the role of the trace anomaly in QCD? Does it reflect both color confinement and dimensional transmutation?
    2. What is the role of chiral symmetry breaking (CSB) in determining the nucleon mass? What is the interplay between the CSB and color confinement?
    3. Why are the nucleon resonances (with change of spin and isospin) separated by a large mass gap?
    4. Can a relativistic Virial theorem tell us something deeper about the origin of mass?
3. **Lattice QCD calculations questions**
    1. Can one calculate the anomaly contribution on the lattice?
    2. Can the lattice calculate the mass distribution in the nucleon?
    3. Why is the color magnetic field depleted inside the proton?
    4. How does the kinetic energy of quarks balance the color confinement energy of the gluon?
    5. Should a glue ball mass be lighter or heavier than the proton mass or 2 pions mass? If so why?
4. **Hadron models questions**
    1. What is the relation between the trace anomaly and the MIT bag constant?
    2. Can AdS/CFT models tell us something deep about the proton mass?
    3. Can 2D models, or simple 4D models (sigma model, NJL model, etc.) tell us something about the mass?
    4. What is the interplay of the Higgs mechanism and QCD mass generation for the mass of hadrons (meson, baryons, XYZ, etc.) with heavy flavors?

Backup: R_{eA} for OHF (open heavy flavor)