Tetraquark Production by Intrinsic Charm at the EIC

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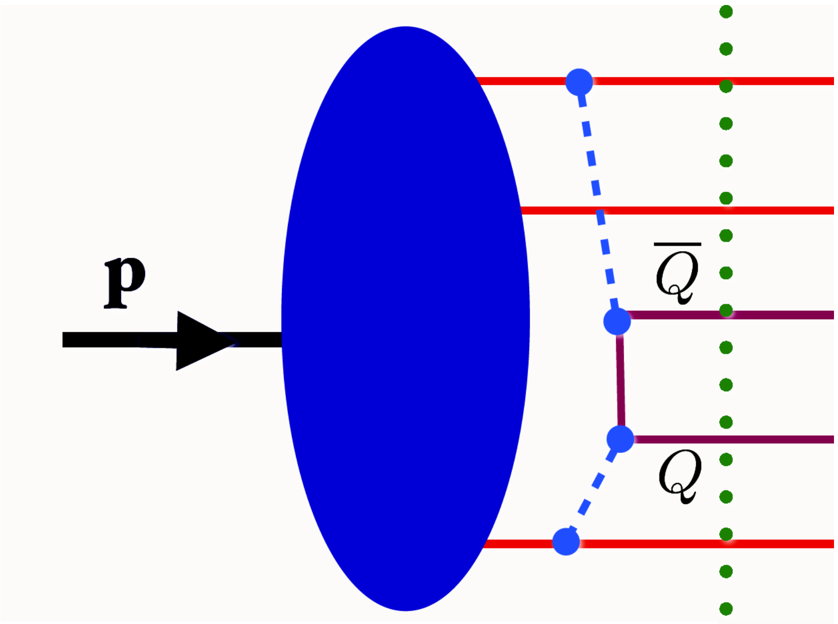
What is Intrinsic Charm?

Proton wavefunction can be expanded as sum over complete basis of quark and gluon states: $|\Psi_p\rangle = \sum_m |m\rangle \, \psi_{m/p}(x_i, k_{T,i}, \lambda_i)$

$|m\rangle$ are color singlet state fluctuations into Fock components $|uud\rangle$, $|uudg\rangle \cdots |uudc\overline{c}\rangle$

The intrinsic charm fluctuations can be freed by a soft interaction if the system is probed during the time $\Delta t = 2p_{\rm lab}/M^2_{c\overline{c}}$ that the fluctuations exist

Dominant Fock state configurations have minimal invariant mass, $M^2 = \sum_i m^2_{T,i}/x_i$, where $m^2_{T,i} = k^2_{T,i} + m^2_i$ is the squared transverse mass of parton i in the state; corresponds to configurations with equal rapidity constituents



Intrinsic Charm is a Long-Standing Puzzle in QCD

Intrinsic charm in the proton $|uudc\bar{c}\rangle$, was first proposed in the 1980's

If this state dominates the wavefunction, the charm quarks carry a larger fraction of the hadron momentum, enhancing charm production in the forward x_F region

A number of experimental hints have been seen, no conclusive results

- **Charm structure function, F_2^c, large at largest x and highest Q^2 measured (EMC)**
- **Leading charm asymmetries consistent with intrinsic charm predictions (D^- over D^+ in $\pi^- p$ interactions, E791)**
- **Double J/ψ production observed at high pair x_F by NA3**
- **Forward charm production observed in many fixed-target experiments (WA82, WA89, E791, SELEX and others)**
- **Proposed explanation of high energy astrophysical neutrino rate at Ice Cube (Brodsky and Laha)**
- **LHCb $Z+c$-jet measurements at forward rapidity consistent with intrinsic charm**

Global PDF analyses have tried incorporating intrinsic charm and reported a range of possible contributions from 0 to 1%, most lately the NNPDF Collaboration (Nature) and the CTEQ Collaboration

At colliders, intrinsic charm is boosted to high rapidity and detection is less likely, fixed-target configurations may be better for discovery measurement

Heavy Flavor Production by Intrinsic Charm

Probability distribution of five-particle Fock state of the proton:

$$dP_{\mathrm{ic}\,5} = P^0_{\mathrm{ic}\,5} N_5 \int dx_1 \cdots dx_5 \int dk_{x\,1} \cdots dk_{x\,5} \int dk_{y\,1} \cdots dk_{y\,5} \frac{\delta(1 - \sum_{i=1}^5 x_i)\delta(\sum_{i=1}^5 k_{x\,i})\delta(\sum_{i=1}^5 k_{y\,i})}{(m_p^2 - \sum_{i=1}^5 (\widehat{m}_i^2/x_i))^2}$$

$i = 1, 2, 3$ **are** u, u, d **light quarks, 4 and 5 are** c **and** $\overline{c}$**,** N_t **normalizes the probability to unity and** P^0_{ic} **scales the normalized probability to the assumed intrinsic charm content: 0.1%, 0.31% and 1% are used to represent the range of probabilities assumed previously (based on original Brodsky** *et al.* **model**

The IC cross section is determined from soft interaction scale breaking coherence of the Fock state, $\mu^2 = 0.1$ **GeV**^{2}

$$\sigma_{\mathrm{ic}}(pp) = P_{\mathrm{ic}\,5} \sigma^{\mathrm{in}}_{pN} \frac{\mu^2}{4\widehat{m}_c^2}$$

The cross sections from intrinsic charm are then obtained by multiplying by the normalization factor for the CEM to the J/ψ **while we assume direct correspondence with IC cross section for** $\overline{D}^0$

$$\sigma^{\overline{D}}_{\mathrm{ic}}(pp) = \sigma_{\mathrm{ic}}(pp) \quad , \sigma^{J/\psi}_{\mathrm{ic}}(pp) = F_C \sigma_{\mathrm{ic}}(pp)$$

The A **dependence is the same for both** $\overline{D}$ **and** J/ψ

$$\sigma_{\mathrm{ic}}(pA) = \sigma_{\mathrm{ic}}(pp)\, A^\beta \quad , \beta = 0.71 \ \ (\mathrm{NA3})$$

Other assumptions of intrinsic charm distributions in the nucleon are the meson cloud model ($c(x) \neq \overline{c}(x)$**) and a sea-like distribution (**$c(x) = \overline{c}(x) \propto \overline{d}(x) + \overline{u}(x)$**)**

Combining Perturbative and Nonperturbative (Intrinsic) Charm

J/ψ and D meson production included

The production cross sections are calculated with a combination of perturbative QCD and intrinsic charm contributions; in $p+p$ collisions:

$$\begin{aligned}\sigma_{pp}^{\overline{D}} &= \sigma_{\rm OHF}(pp) + \sigma_{\rm ic}^{\overline{D}}(pp) \\ \sigma_{pp}^{J/\psi} &= \sigma_{\rm CEM}(pp) + \sigma_{\rm ic}^{J/\psi}(pp)\end{aligned}$$

The D meson and J/ψ cross sections are computed at NLO in the color evaporation model for $p+p$ and $p+A$ interactions; $\sigma_{\rm ic}$ is the intrinsic charm cross section using Brodsky *et al.* "flavor" of IC

In $p+A$ collisions:

$$\begin{aligned}\sigma_{pA}^{\overline{D}} &= \sigma_{\rm OHF}(pA) + \sigma_{\rm ic}^{\overline{D}}(pA) \\ \sigma_{pA}^{J/\psi} &= \sigma_{\rm CEM}(pA) + \sigma_{\rm ic}^{J/\psi}(pA)\end{aligned}$$

SMOG J/ψ Results Compared to Calculations

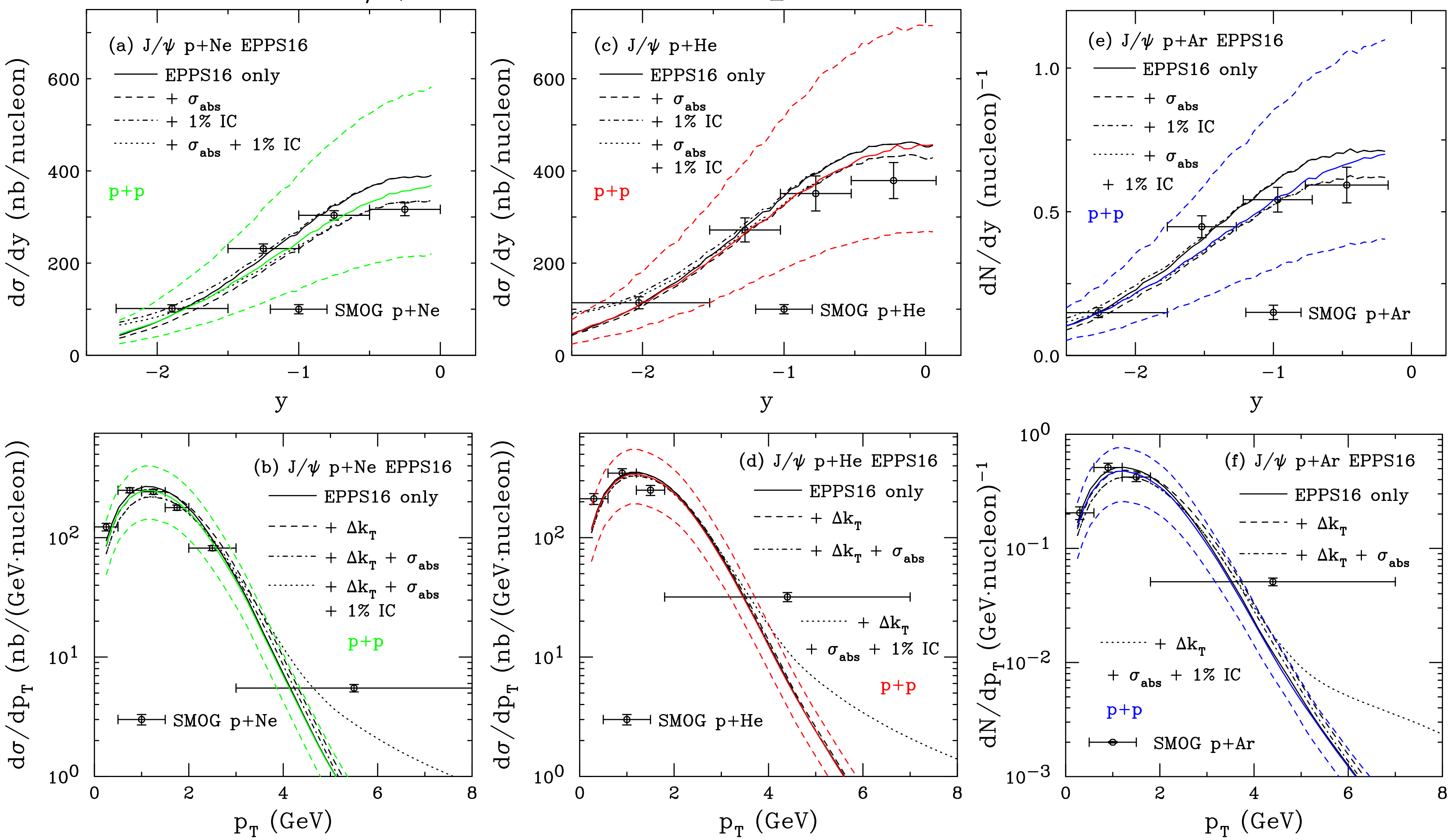


Figure 2: The J/ψ cross section as a function of y in (a), (c), (e) and p_T in (b), (d), (f) for $p+$Ne ($\sqrt{s_{NN}} = 68.5$ GeV) in (a) and (b); $p+$He ($\sqrt{s_{NN}} = 86.6$ GeV) in (c) and (d); and $p+$Ar ($\sqrt{s_{NN}} = 110.4$ GeV) in (e) and (f). The black curves are the $p+A$ calculations. The colored curves (solid and dashed) show the CEM $p+p$ calculations (no IC). The $p+A$ rapidity distributions are shown for EPPS16 only (solid); EPPS16 with absorption (dashed); EPPS16 and $P^0_{\rm ic\,5} = 1\%$ (dot-dashed); and EPPS16, absorption, and $P^0_{\rm ic\,5} = 1\%$ (dotted). The p_T distributions show EPPS16 only (solid); EPPS16 with k_T kick (dashed); EPPS16, absorption, and k_T kick (dot-dashed); and EPPS16, absorption, k_T kick and $P^0_{\rm ic\,5} = 1\%$ (dotted). The $p+$Ne data are from arXiv:2211.11645; the $p+$He and $p+$Ar data are from PRL **122**, 132002 (2019).

Intrinsic Charm Can be Used to Study Exotics

A_NDY Collaboration reported purported double Υ state in $\sqrt{s_{NN}} = 200$ GeV collisions with average mass 18.15 GeV – less than the mass of 2 Υ(1S) states (unike NA3 double J/ψ data)

Calculated double Υ mass distributions from $|uudb\bar{b}b\bar{b}\rangle$ states gave larger values for the combined mass than reported by A_NDY but results were compatible with $b\bar{b}b\bar{b}$ tetraquark masses, particularly with a b quark mass of 4 GeV (RV and Aaron Angerami, PRD 104, 094025 (2021))

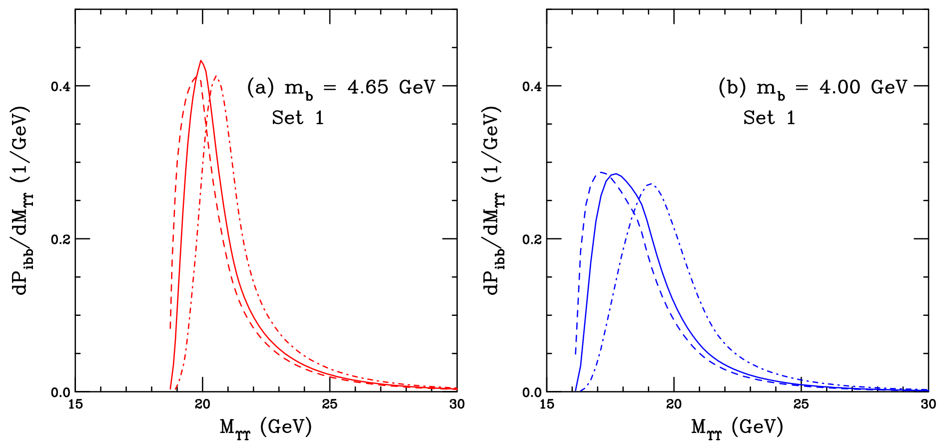


Figure 3: The probability for double Υ production from a seven-particle Fock state as a function of the pair mass for three different k_T integration ranges are shown: $k_q^{\max} = 0.2$ GeV, $k_b^{\max} = 1.0$ GeV and $k_\Upsilon^{\max} = 1.0$ GeV (solid); $k_q^{\max} = 0.1$ GeV, $k_b^{\max} = 0.5$ GeV and $k_\Upsilon^{\max} = 0.5$ GeV (dashed); and $k_q^{\max} = 0.4$ GeV, $k_b^{\max} = 2.0$ GeV and $k_\Upsilon^{\max} = 2.0$ GeV (dot-dashed). All distributions are normalized to unity. In (a) $m_b = 4.65$ GeV while in (b) $m_b = 4.0$ GeV. From PRD **104**, 094025 (2021).

Calculating Tetraquark Mass Distribution

A number of tetraquark candidate states have been discovered in the last few years, with the $X(3872)$ as the first candidate, seen by Belle

Potential exotic charm states increased dramatically at the LHC, especially in LHCb, with 1, 2 or 4 charm or anticharm quarks in the state

The production of these tetraquark candidates through intrinsic charm states can be studied by extending the picture of intrinsic charm as coming from a 5-particle $|uudc\overline{c}\rangle$ state to 7- and 9-particle Fock states

Higher particle numbers are not considered, if a tetraquark candidate state requires more than 9 partons, its antiparticle state is considered, for example, the $T_{cc}^{+}(cc\overline{u}\overline{d})$ requires an 11-particle state, $|uudc\overline{c}c\overline{c}u\overline{u}d\overline{d}\rangle$, so the $T_{cc}^{-}(\overline{c}\overline{c}ud)$, requiring a 7-particle state, is studied instead

Some of the candidate states can be considered to be bound meson pairs while others can only be bound (produce a mass peak) if the constitutent partons are uncorrelated (independent of each other)

Tetraquarks as Meson Pairs

Start from basic "n" particle probability distribution

$$dP_{{\rm ic}\,n} = P^0_{{\rm ic}\,n} N_n \int dx_1 \cdots dx_n \int dk_{x\,1} \cdots dk_{x\,n} \int dk_{y\,1} \cdots dk_{y\,n} \frac{\delta(1-\sum_{i=1}^n x_i)\delta(\sum_{i=1}^n k_{x\,i})\delta(\sum_{i=1}^n k_{y\,i})}{(m_p^2 - \sum_{i=1}^n (m_{T\,i}^2/x_i))^2}$$

Then constrain the kinematics of the meson pair

This results in a fairly narrow mass distribution for low internal k_T of the constituent partons

$$\frac{dP_{{\rm ic}\,n}}{dM^2_{\rm TQ}} = \int \frac{dx_{M_1}}{x_{M_1}} \frac{dx_{M_2}}{x_{M_2}} \int dm^2_{M_1} dm^2_{M_2} \int dk_{x\,M_1} dk_{y\,M_1} dk_{x\,M_2} dk_{y\,M_2} \int \frac{dx_{\rm TQ}}{x_{\rm TQ}} \int dk_{x\,{\rm TQ}} dk_{y\,{\rm TQ}} \; dP_{{\rm ic}\,n}$$
$$\times\, \delta\left(\frac{m^2_{T,M_1}}{x_{M_1}} - \frac{m^2_{T\,4}}{x_4} - \frac{m^2_{T\,7}}{x_7}\right) \delta(k_{x\,4} + k_{x\,7} - k_{x\,M_1}) \delta(k_{y\,4} + k_{y\,7} - k_{y\,M_1}) \delta(x_{M_1} - x_4 - x_7)$$
$$\times\, \delta\left(\frac{m^2_{T,M_2}}{x_{M_2}} - \frac{m^2_{T\,5}}{x_5} - \frac{m^2_{T\,6}}{x_6}\right) \delta(k_{x\,5} + k_{x\,6} - k_{x\,M_2}) \delta(k_{y\,5} + k_{y\,6} - k_{y\,M_2}) \delta(x_{M_2} - x_5 - x_6)$$
$$\times\, \delta\left(\frac{M^2_{T,{\rm TQ}}}{x_{\rm TQ}} - \frac{m^2_{T,M_1}}{x_{M_1}} - \frac{m^2_{T,M_2}}{x_{M_2}}\right) \delta(k_{x\,M_1} + k_{x\,M_2} - k_{x\,{\rm TQ}}) \delta(k_{y\,M_1} + k_{y\,M_2} - k_{y\,{\rm TQ}}) \delta(x_{\rm TQ} - x_{M_1} - x_{M_2})$$

Tetraquarks as Four Independent Partons

In some cases, such as $T_{\psi s}(c\bar{c}s\bar{u})$, treating the state as a meson pair means that the "light" meson orbits around a more stationary heavy one and assuming a higher mass of hte tetraquark means that the light meson gets further away and less bound

Release the kinematic constraints for meson pairs and conserve momentum among individual partons

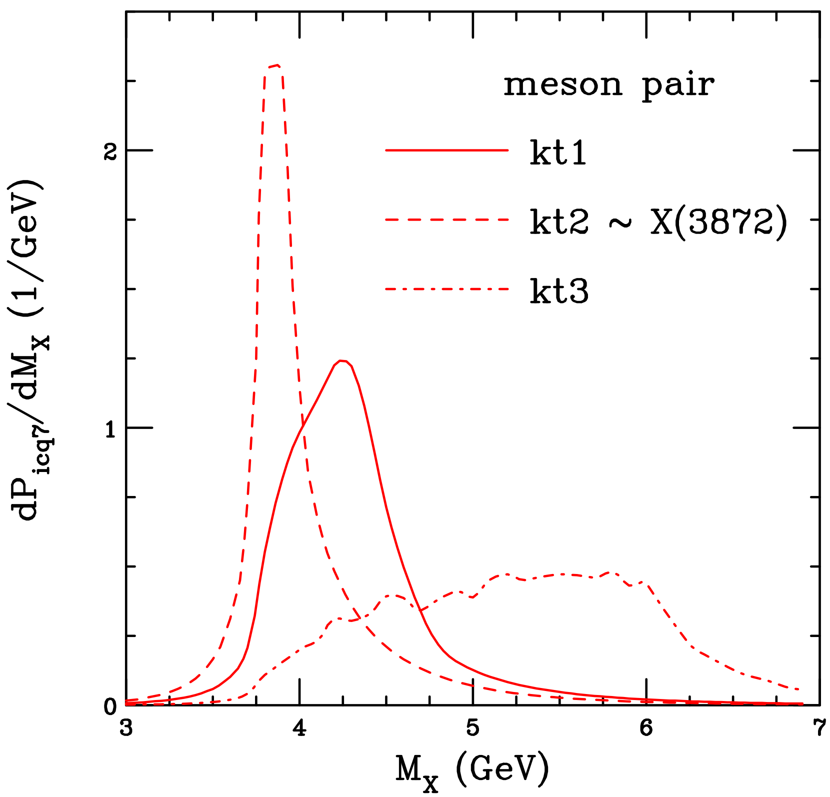
These mass distributions are broader than the meson pair assumption and thus potentially less bound

$$\begin{aligned}\frac{dP_{\mathrm{ic}\,n}}{dM^2_{\mathrm{TQ}}} \; = \; & \int \frac{dx_{\mathrm{TQ}}}{x_{\mathrm{TQ}}} \int dk_{x\,\mathrm{TQ}} dk_{y\,\mathrm{TQ}} \; dP_{\mathrm{ic}\,n} \; \delta\left(\frac{M^2_{T,\mathrm{TQ}}}{x_{\mathrm{TQ}}} - \frac{m^2_{T,4}}{x_4} - \frac{m^2_{T,5}}{x_5} - \frac{m^2_{T,6}}{x_6} - \frac{m^2_{T,7}}{x_7}\right) \\ & \times \delta(k_{x\,4} + k_{x\,5} + k_{x\,6} + k_{x\,7} - k_{x\,\mathrm{TQ}}) \delta(k_{y\,4} + k_{y\,5} + k_{y\,6} + k_{y\,7} - k_{y\,\mathrm{TQ}}) \\ & \times \delta(x_{\mathrm{TQ}} - x_4 - x_5 - x_6 - x_7)\end{aligned}$$

Tetraquark Mass Distributions by Intrinsic Charm

Left-hand side shows $X(3872)$ as a $D\overline{D}$ meson pair while the right-hand side is $T_{\psi s}$ as four independent partons

"ktX" indicates the k_T integration range with kt2 the smallest and kt3 the largest



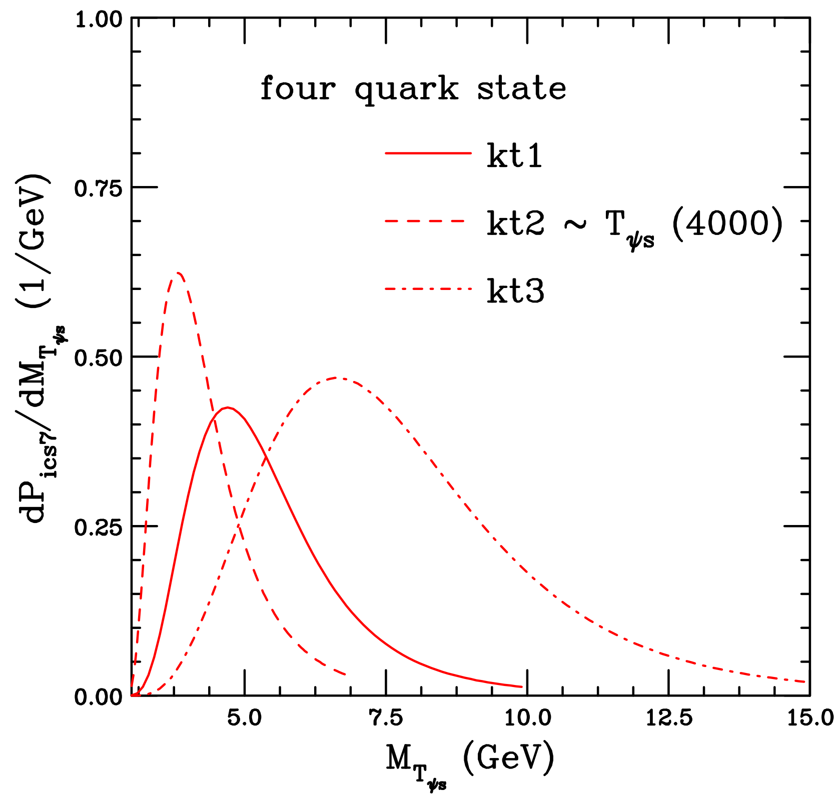


Figure 4: (Left) The $X(3872)$ probability distribution, calculated assuming that the X is a bound meson pair as a function of mass of the state. (Right) The $T_{\psi s}$ probability distribution, calculated assuming as a function of mass of the state. Calculations are nade for different assumptions of the k_T integration range. (RV, arXiv:2405.09018.)

How Important is This at the LHC?

The improved color evaporation model can describe the LHCb data at 13 TeV very well without intrinsic charm (IC on the plot)

At 5 TeV and high p_T the ICEM and intrinsic charm contributions become comparable

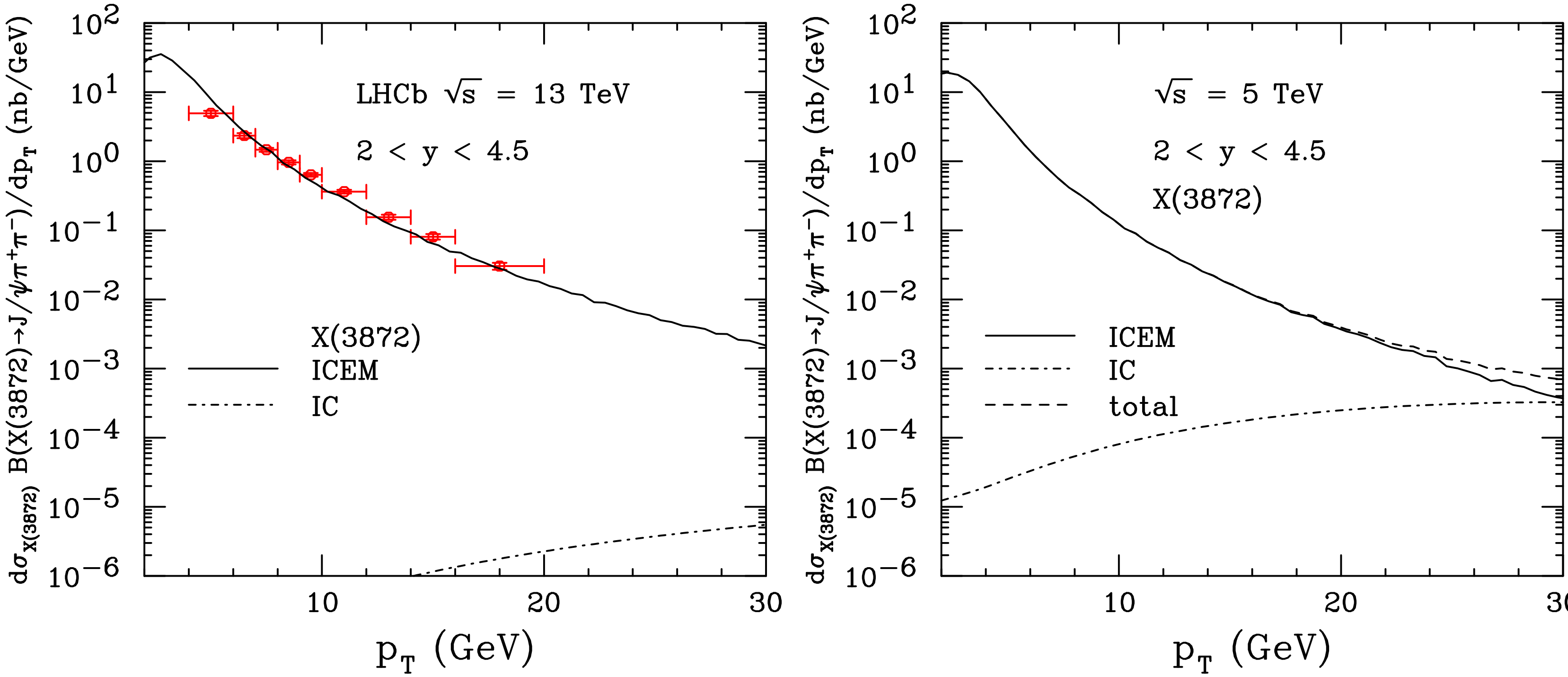


Figure 5: (Left) The $X(3872)$ p_T distribution from the ICEM (solid) and intrinsic charm (dot-dashed) contributions at $\sqrt{s} = 13$ TeV in the rapidity interval $2 < y < 4.5$, The same calculation at 5 TeV. (RV, arXiv:2405.09018.)

Lower Energies Enhance the Chance of Measurement

The small intrinsic charm contribution at high p_T at 13 TeV is not surprising based on the rapidity distributions (left), the rapidity range of the LHCb data captures only about 0.1% of the intrinsic charm distribution at 13 TeV

The lower energy of 5 TeV captures more of the p_T distribution, making the contribution competitve with the perturbative one at high p_T

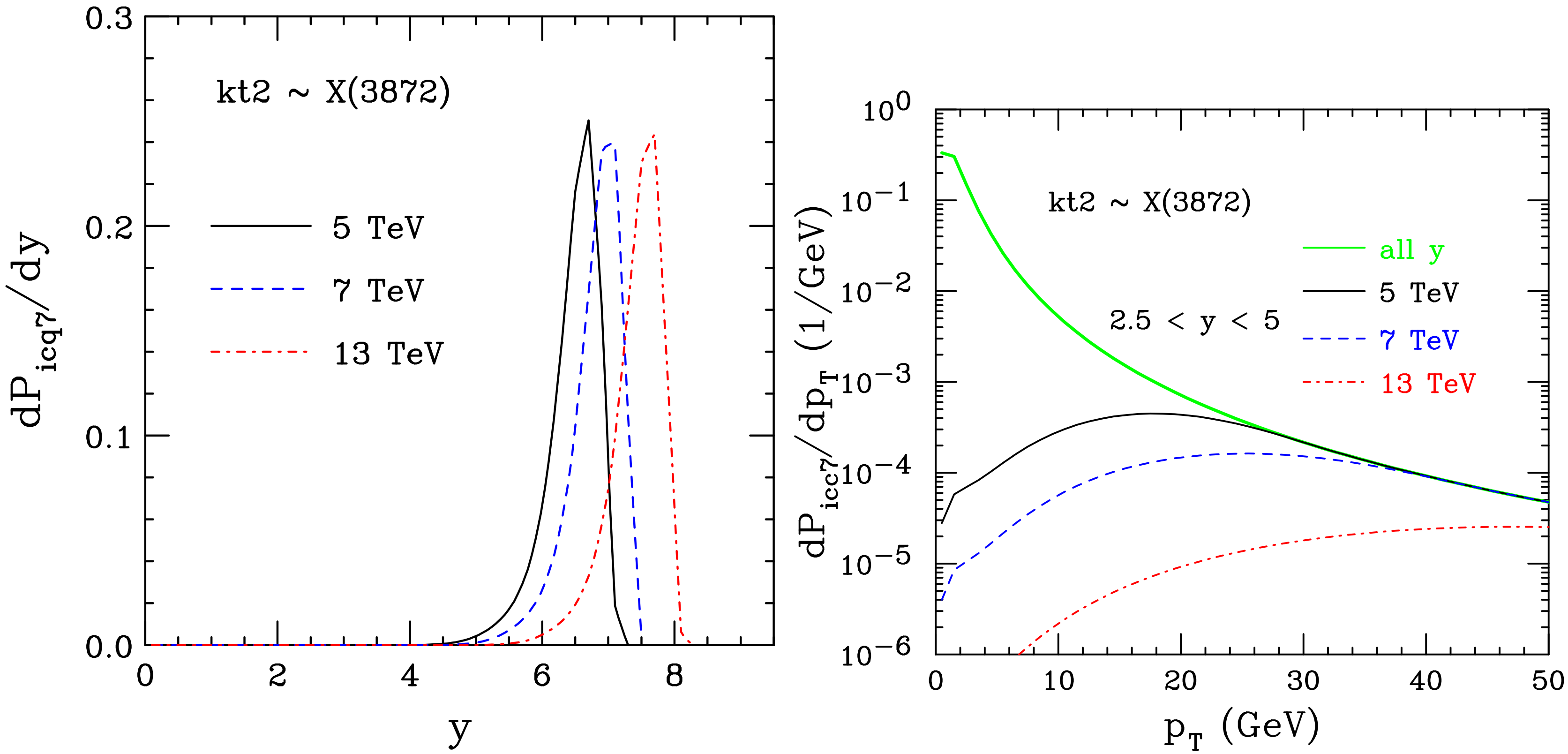


Figure 6: (Left) The $X(3872)$ p_T distribution from the ICEM (solid) and intrinsic charm (dot-dashed) contributions at $\sqrt{s} = 13$ TeV in the rapidity interval $2 < y < 4.5$, The $X(3872)$ rapidity distributions from intrinsic charm at 5, 7 and 13 TeV. (RV, arXiv:2405.09018.)

What about the EIC?

Assume that the tetraquark candidate is produced in the proton along its direction

Looked at rapidity and p_T distributions for $E_p = 41$, 100 and 275 GeV; p_T distributions are calculated for $0 < y < 2$ and $2 < y < 4$

Calculations done for $X(38720$, $X_s(4000)$ (an estimated average mass of the lower mass $X_s(c\overline{s}\overline{c}s)$ states) and $T_{cc}^{-}(\overline{c}\overline{c}ud)$ (because the $T_{cc}^{+}(cc\overline{u}\overline{d})$ can only be produced from an 11-particle state, only states with at most 9 particles are considered)

$X(3872)$ Kinematic Distributions

The tetraquark distribution is independent of energy as a function of x but is boosted along the direction of the proton as a function of y

At central rapidities, the tetraquark can take up a large fraction of the energy. Note that high p_T corresponds to $y \to 0$ while low p_T for intrinsic charm corresponds to high rapidity. The higher the proton energy, the more the tetraquark moves to higher rapidity and the less of its distribution is captured in the central region. On the other hand, at low E_0 there is no phase space for production at forward rapidity and high p_T, only the highest proton beam energy captures most of the rapidity distribution

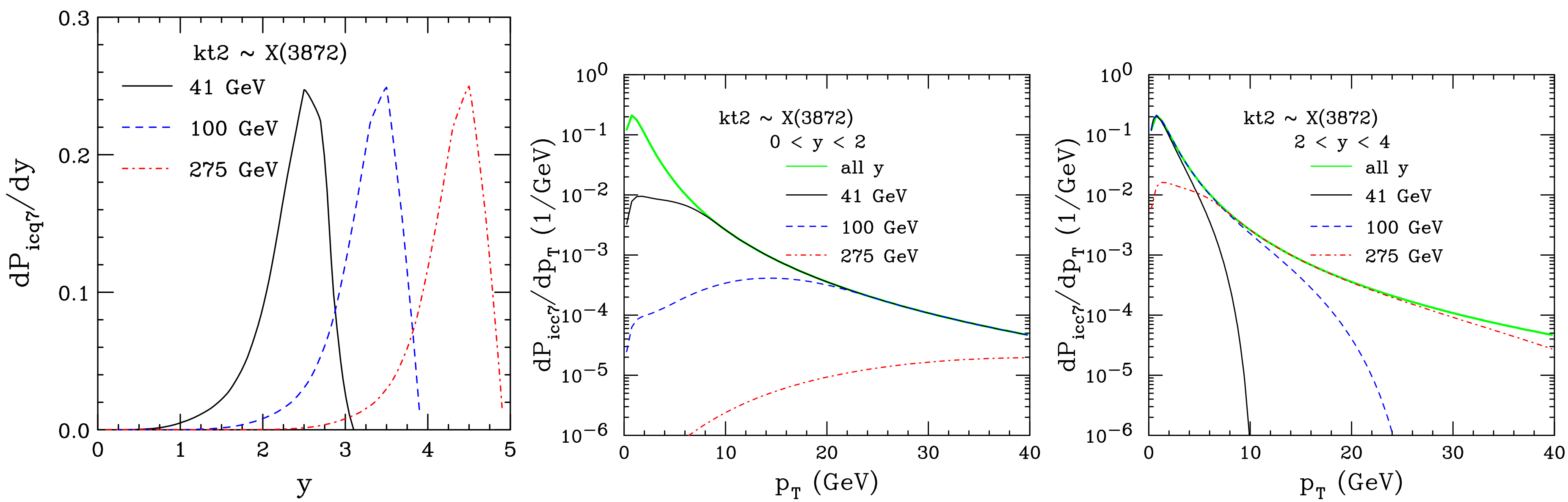


Figure 7: (Left) The $X(3872)$ y distribution from intrinsic charm for $E_p = 41$, 100, and 275 GeV. The p_T distributions at the same energies are shown for $0 < y < 2$ (Center) and $2 < y < 4$ (Right).

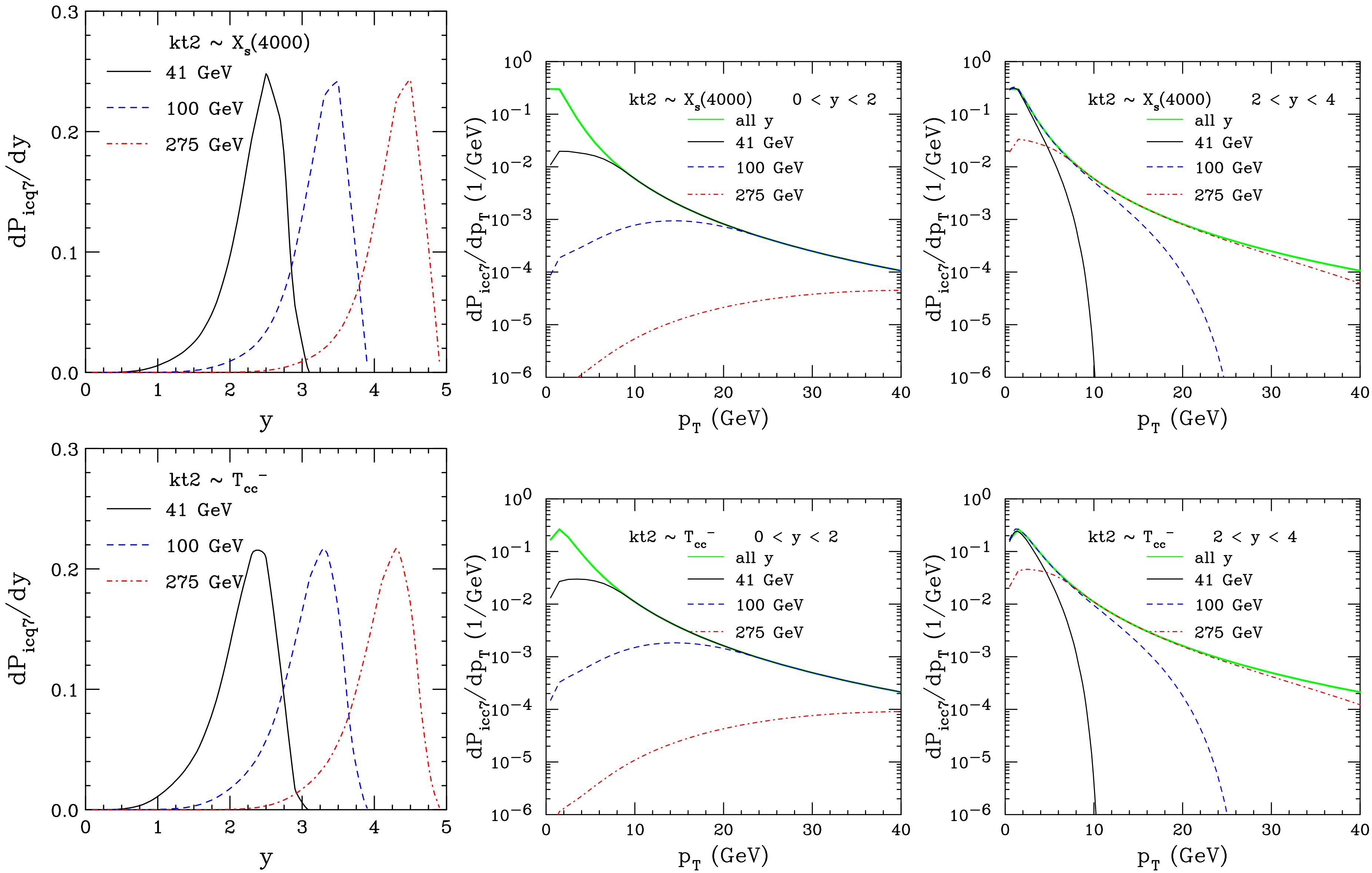


Figure 8: (Top) $X_s(4000)$. (Bottom) T_{cc}^{-}. (Left) The y distribution from intrinsic charm for $E_p = 41$, 100, and 275 GeV. The p_T distributions at the same energies are shown for $0 < y < 2$ (Center) and $2 < y < 4$ (Right).

Summary

Intrinsic charm, new in the 1980's is experiencing a renaissance of new interest

Model calculations in good agreement with the SMOG $p + A$ cross section data

More fixed-target data, from SMOG, NA60+, and elesewhere will add to the overall production picture

Intrinsic charm-like states could be used to study exotic hadron production, can distinguish between types of internal tetraquark structure

Charm tetraquarks can be measured near midrapidity at the EIC, particularly at lower proton beam energies

Thank You!