Jets and Longitudinal Proton Structure at the EIC

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Outline

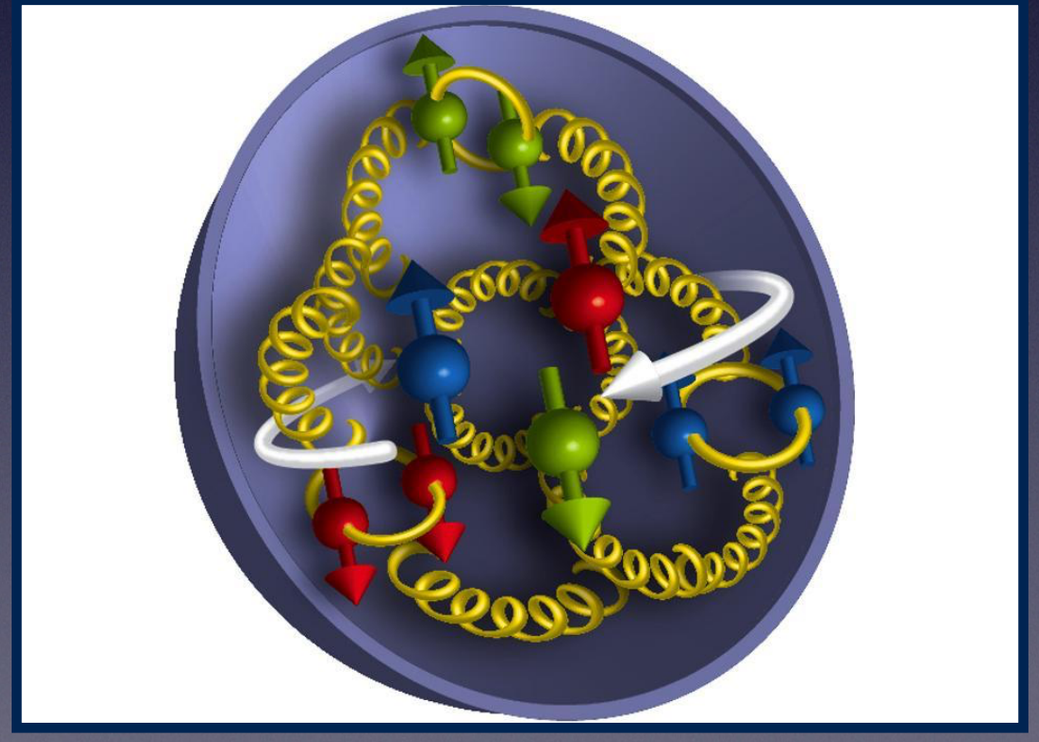
- Motivation and current status of polarized PDFs
- Relevance of jets at the EIC
- Theoretical calculations and phenomenology

Puzzles in proton structure

- Even after several decades of study, simple aspects of QCD still surprise us

How is the proton spin formed from its microscopic constituents?

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



Quark spin **Gluon spin** **Orbital**

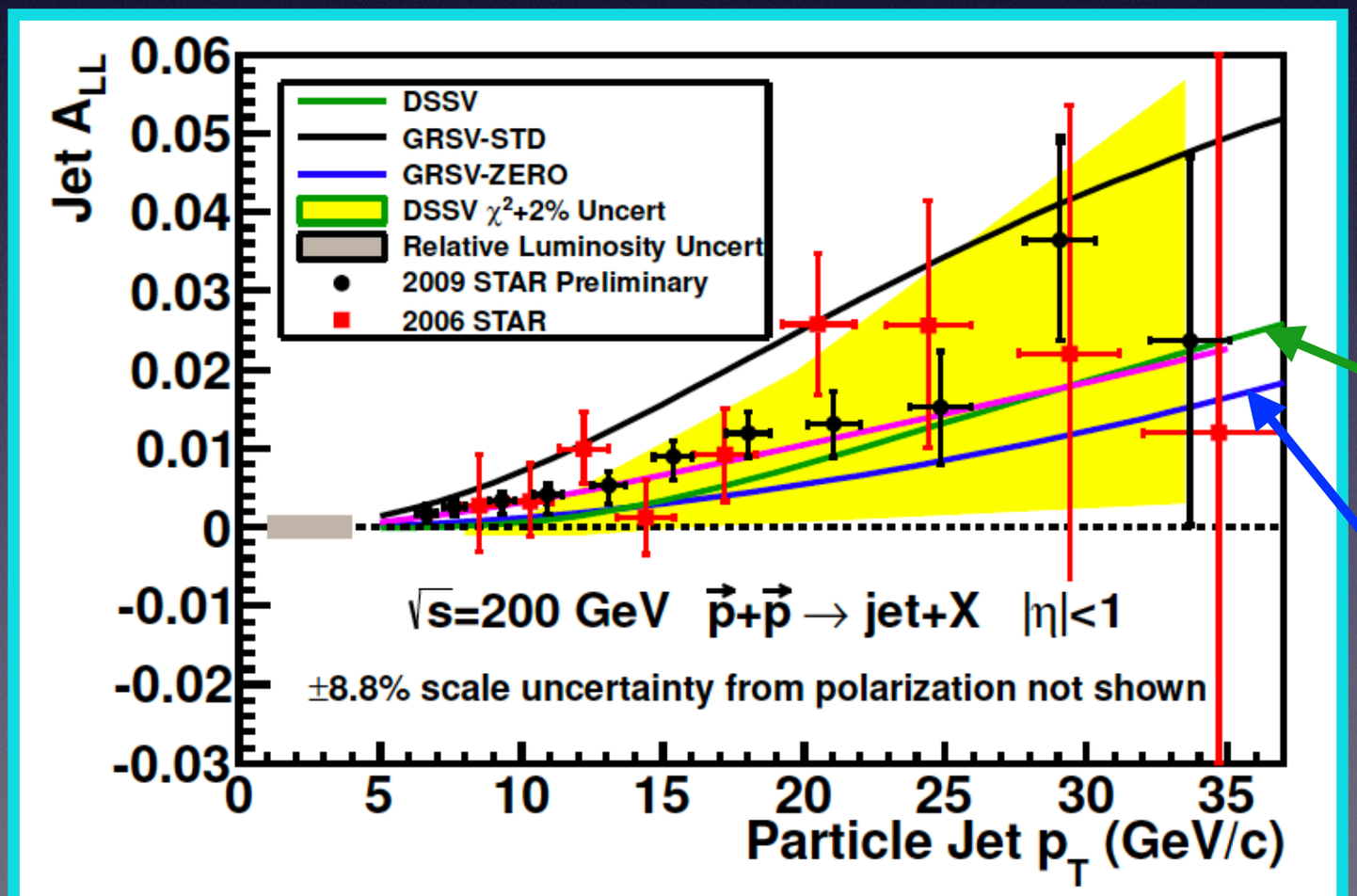
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{G+q}$$

Goal: precision determination of polarized PDFs

Jets at RHIC: recent progress

- In the past several years we have obtained initial insights into these questions from RHIC data

STAR, 1303.0543



$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

$$\mathcal{A}_{LL} \sim \int dx_1 \int dx_2 \Delta f_i(x_1) \Delta f_j(x_2) \hat{\sigma}_{ij}$$

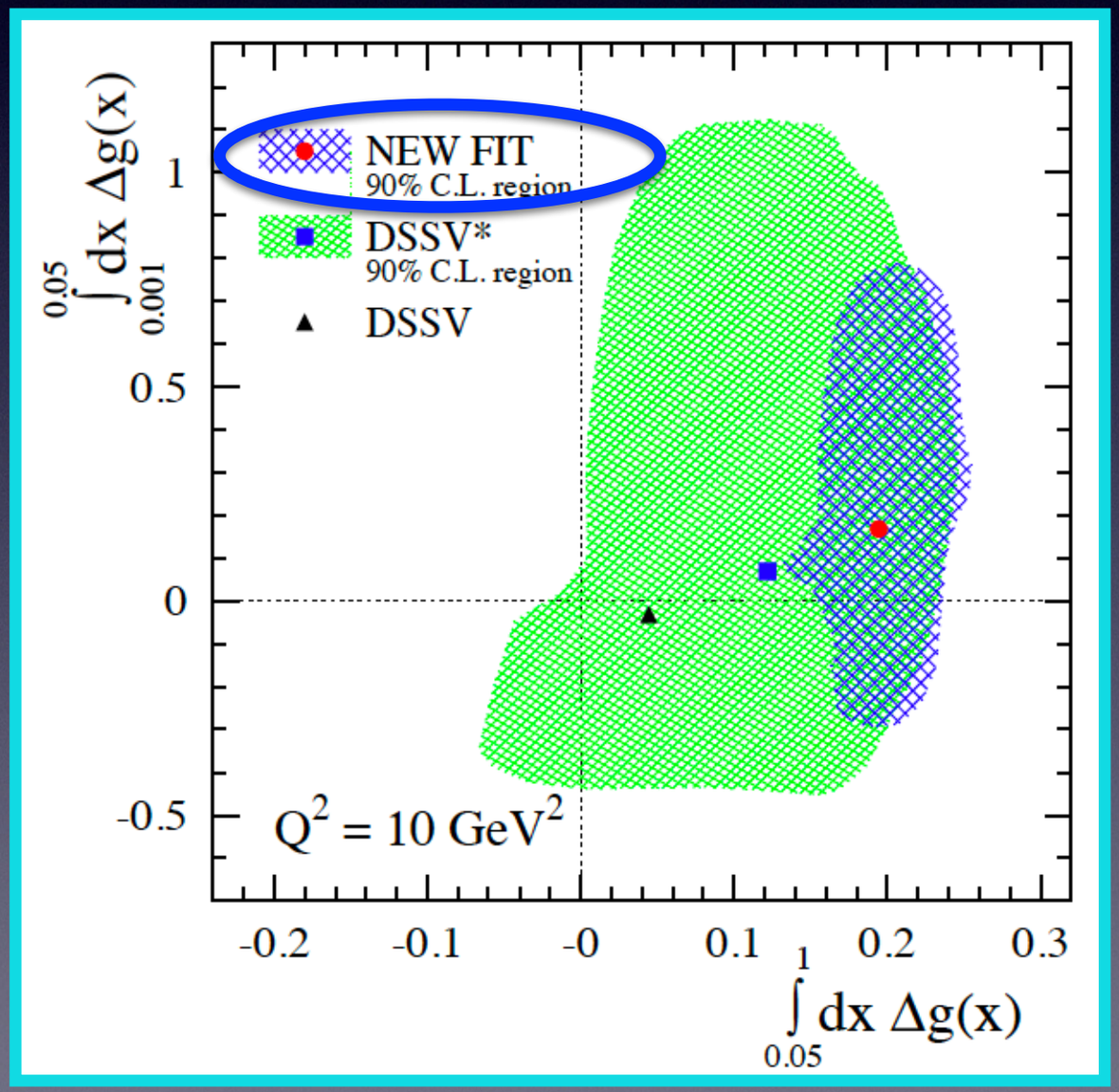
with gluon polarization

without gluon polarization

2009 jet data shows preference for non-zero gluon polarization

Jets at RHIC: recent progress

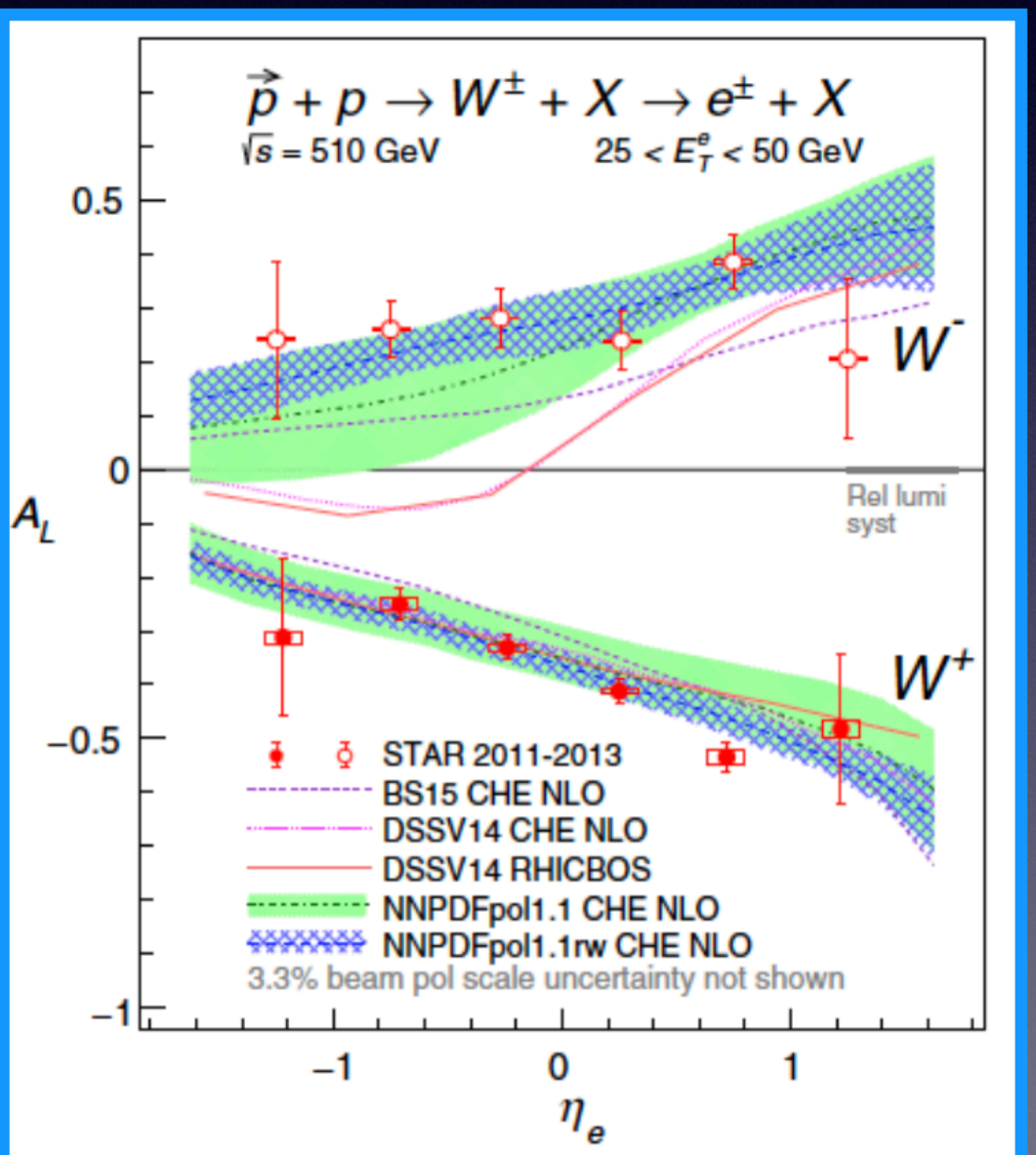
- Jet double-longitudinal spin asymmetries provide evidence of non-zero gluon polarization at high Bjorken-x in the proton.



de Florian, Sassot, Stratmann, Vogelsang 1404.4293

W at RHIC: recent progress

- Longitudinal single spin asymmetries in W production provide a glimpse of flavor structure in the polarized quark sea.



$$A_L \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

$$y_W \gg 0 \to x_1 \gg x_2 : A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)}, A_L^{W^-} \approx -\frac{\Delta d(x_1)}{d(x_1)}$$

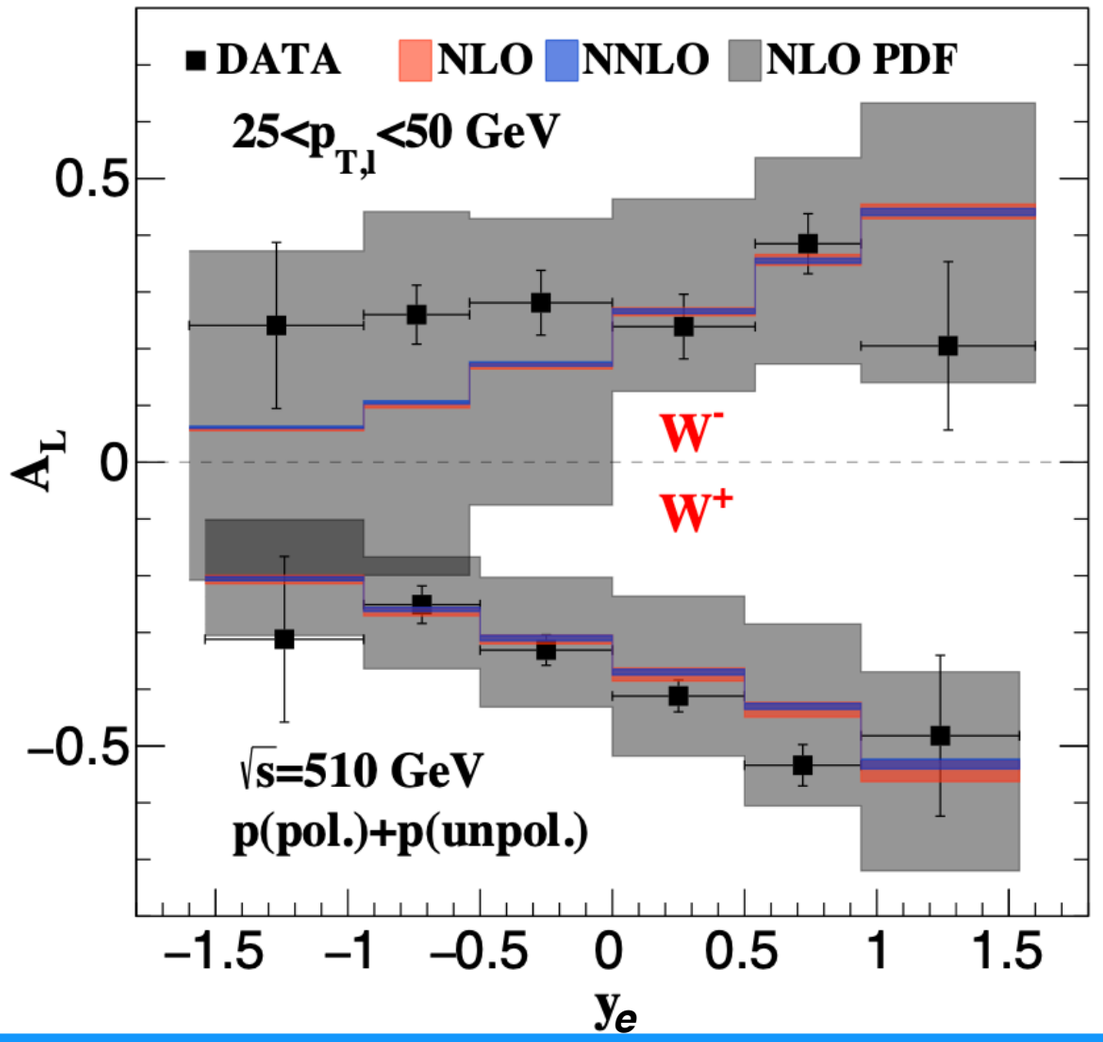
$$y_W \ll 0 \to x_2 \gg x_1 : A_L^{W^+} \approx \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, A_L^{W^-} \approx \frac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}$$

$A_L^{W-} > 0$ and $A_L^{W+} < 0$ at negative η_e indicate a positive $\Delta\bar{u} - \Delta\bar{d}$

W at RHIC: recent progress

- Longitudinal spin asymmetries in W production provide a glimpse of flavor structure in the polarized quark sea.

RB, H.T.Li, Petriello, 2101.02214



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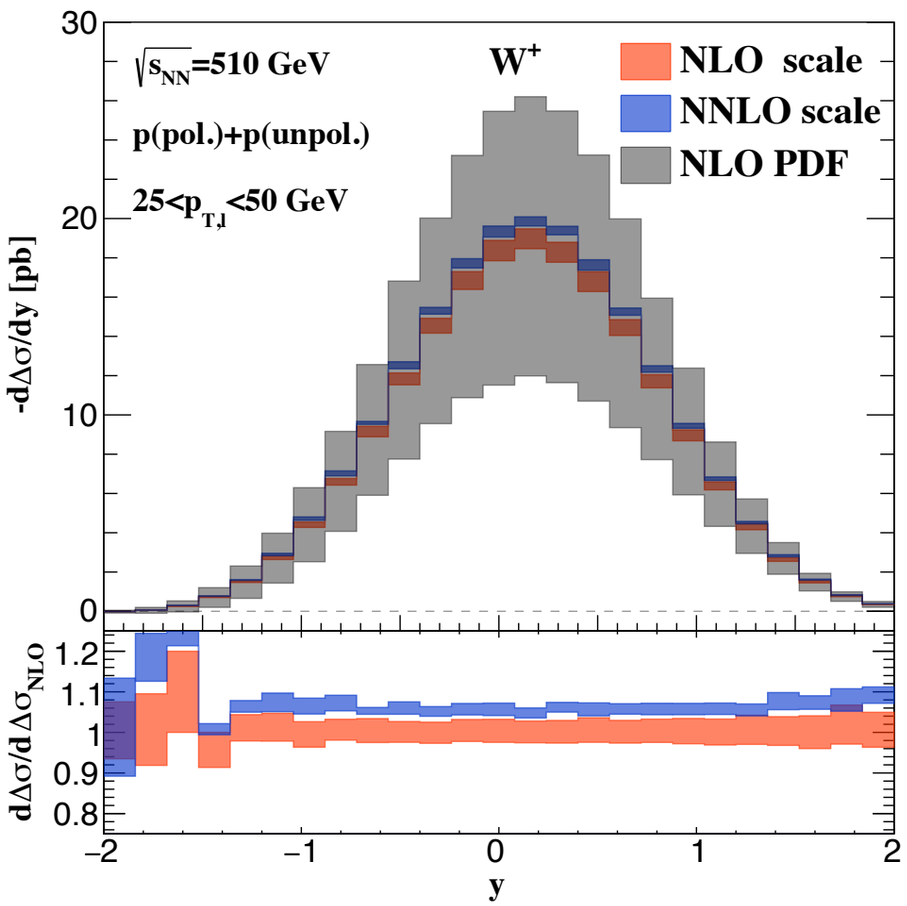
$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

Now known at NNLO. Excellent stability under pQCD makes this a powerful probe of polarized sea PDFs.

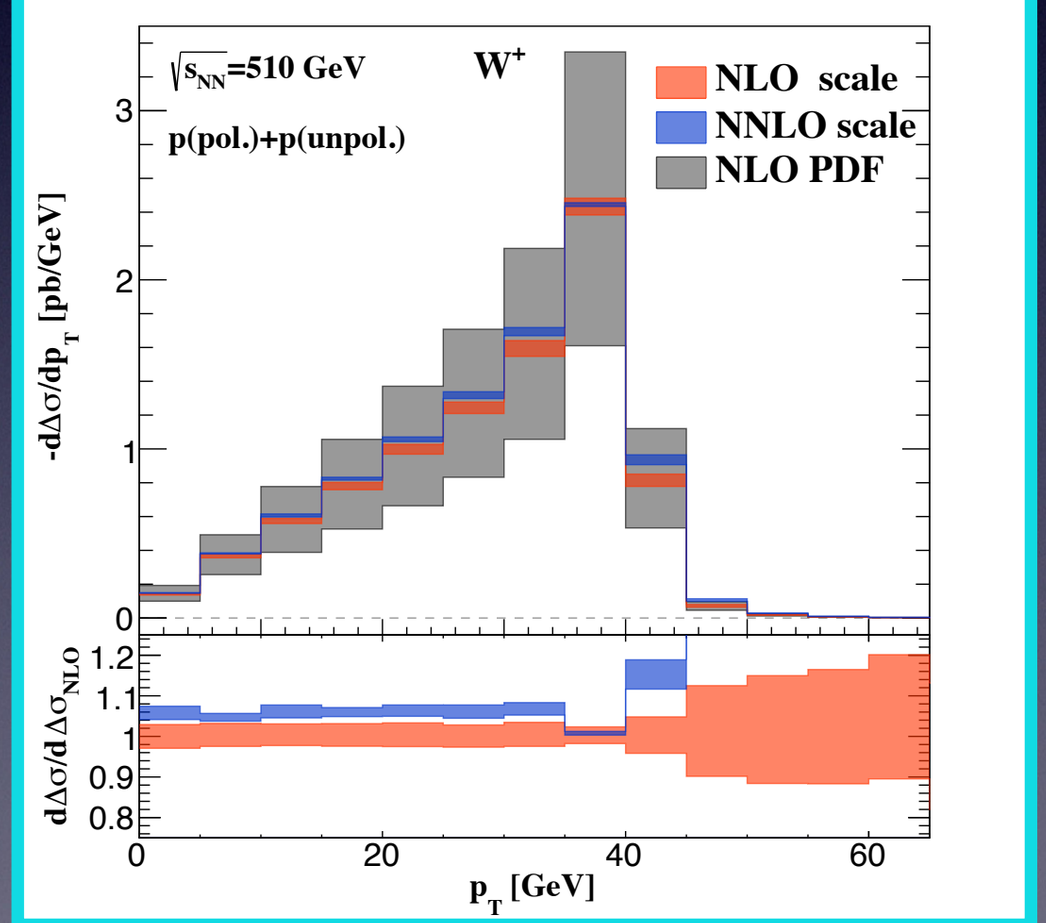
Distributions for W production at RHIC

- PDF errors dominate over QCD scale errors for multiple distributions. NNLO QCD corrections enhance the NLO result by ~6%, constant over much of phase space.

RB, H.T. Li, Petriello 2101.02214



Corrections to lepton rapidity distribution have little-to-no dependence on y



QCD corrections become large above the Jacobian peak $p_T=M_W/2$

Distributions for W production at RHIC

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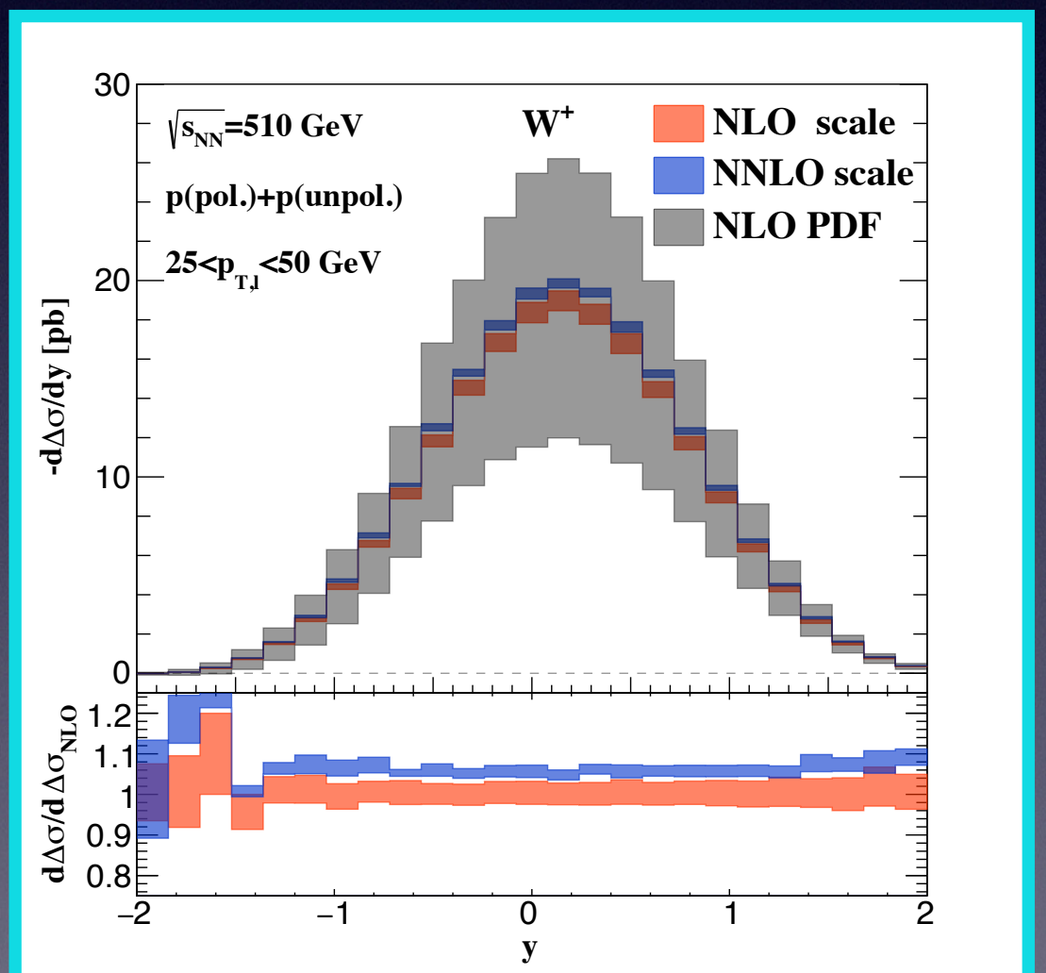
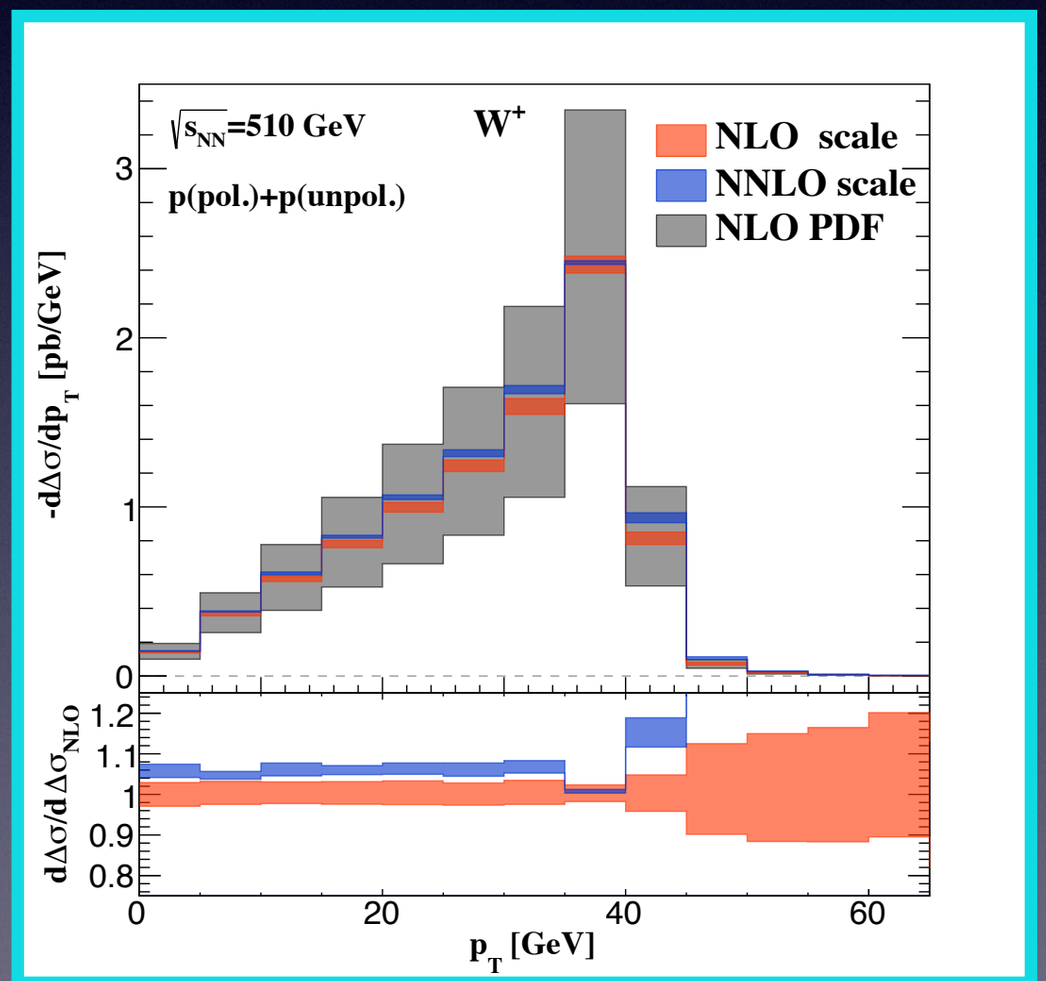


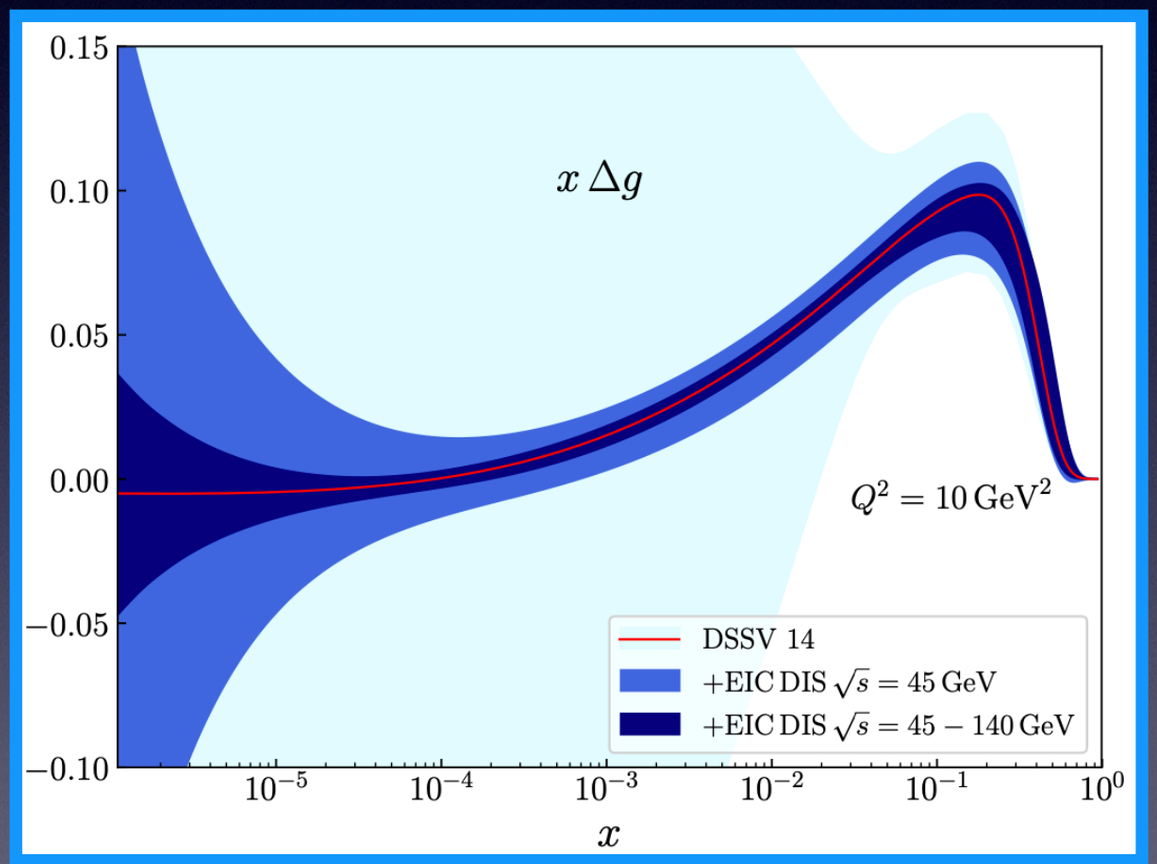


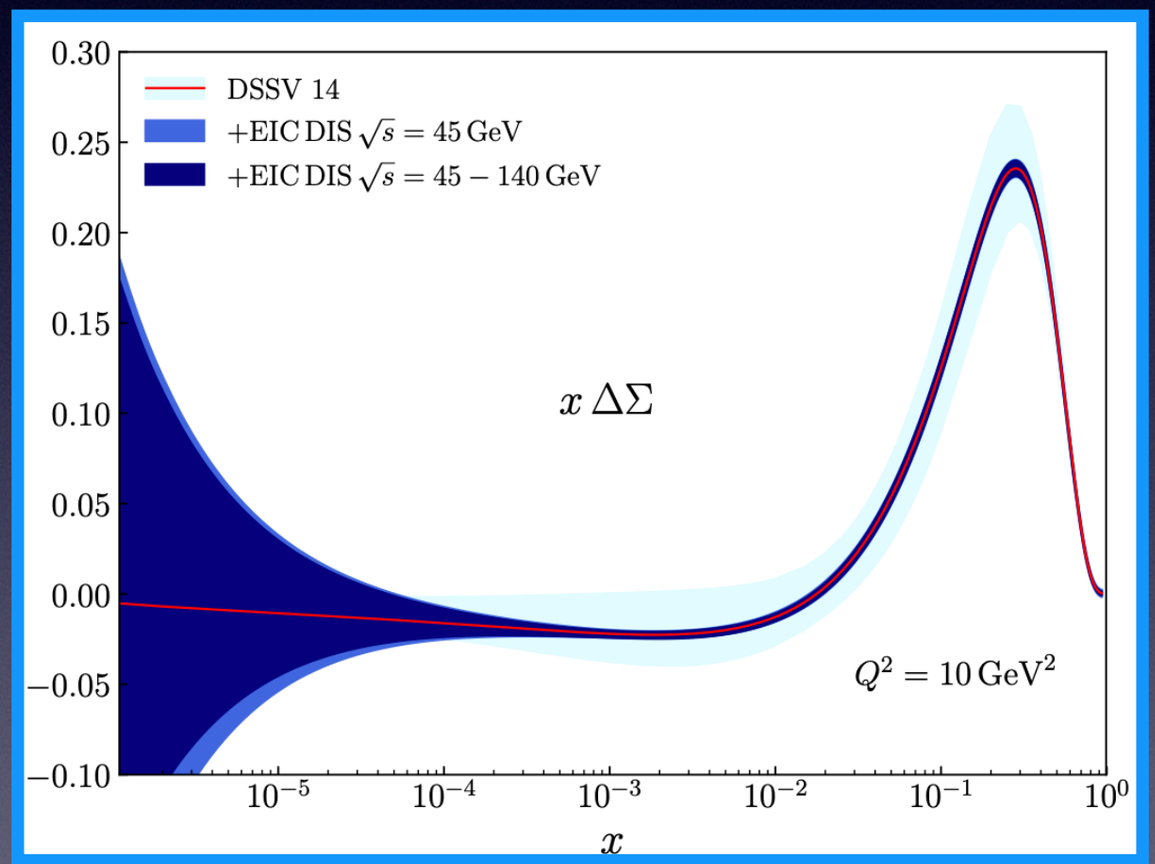
NNLO result not contained in NLO error band; *possibly* due to having PDF to only NLO accuracy

Future projections at the EIC

- A precision determination of polarized PDFs will first come from the EIC.

Borsa, Lucero, Sassot, Aschenauer, Nunes, 2007.08300

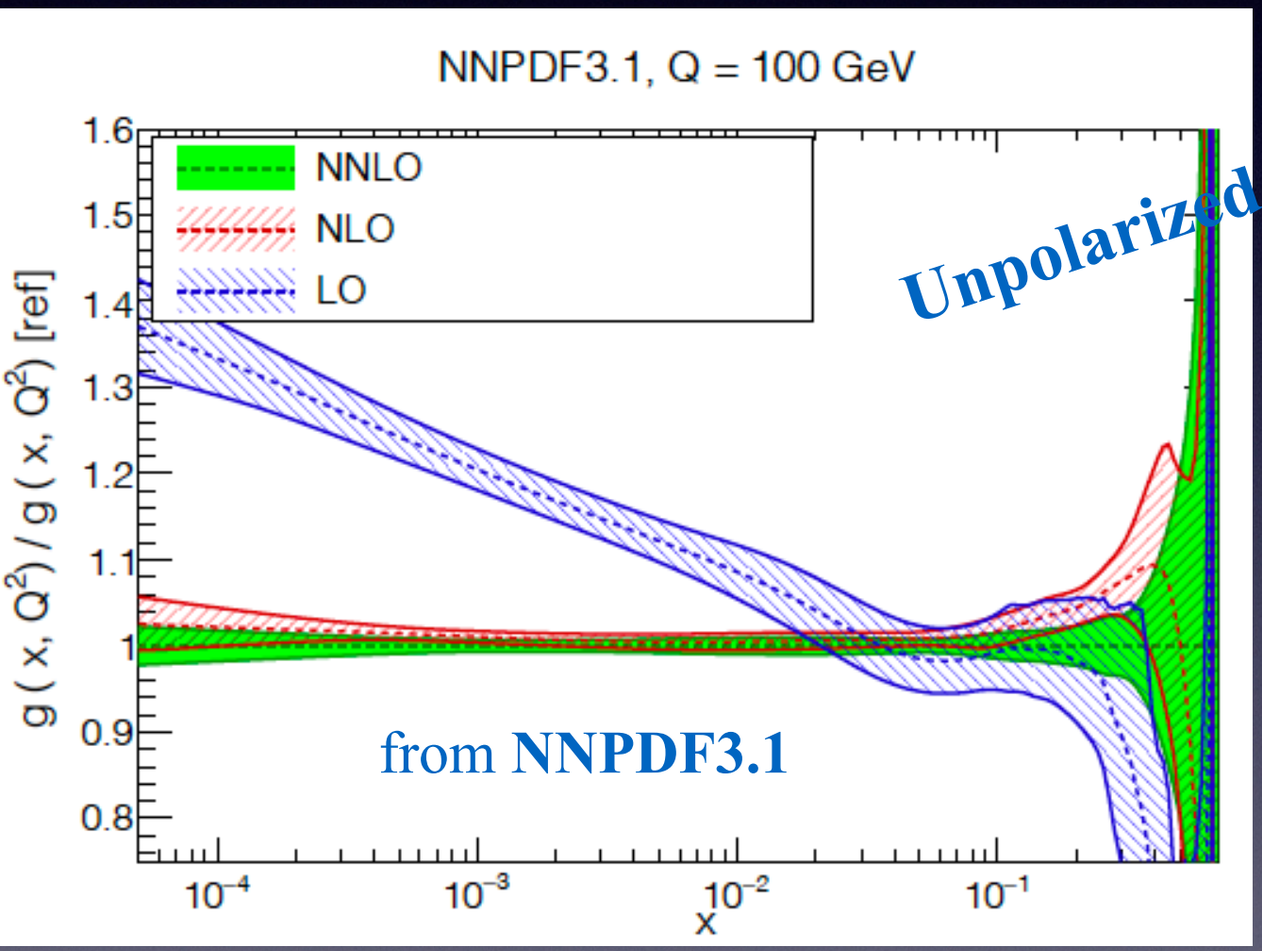




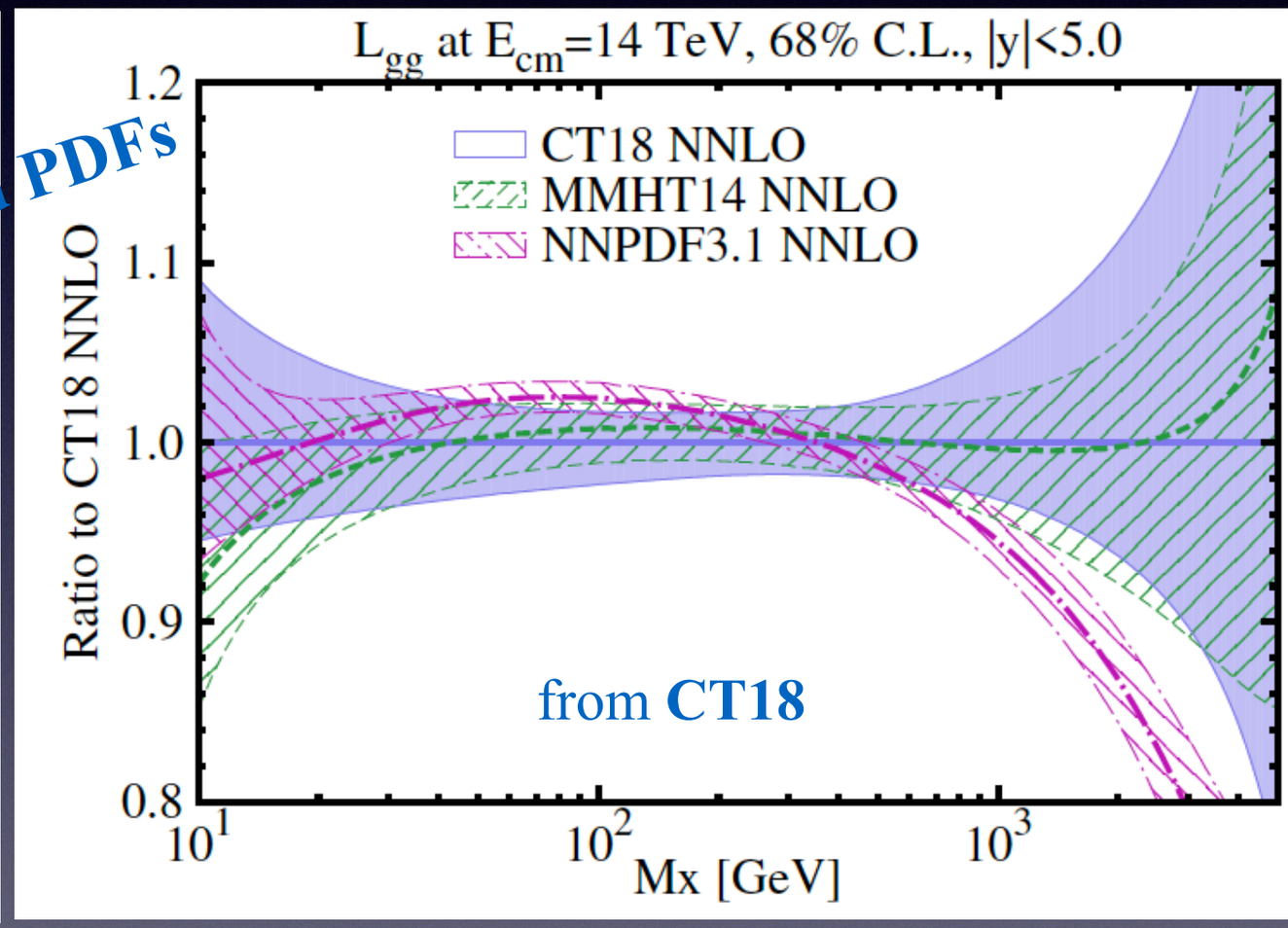
Combination of DIS and pion, kaon SIDIS simulated data. Δg probed through scaling violations of g_1 (polarized structure function) at much lower x-values than at RHIC

Polarized vs unpolarized PDFs at NNLO

- Current extractions of polarized PDFs are only available at NLO with large uncertainties.



Unpolarized PDFs

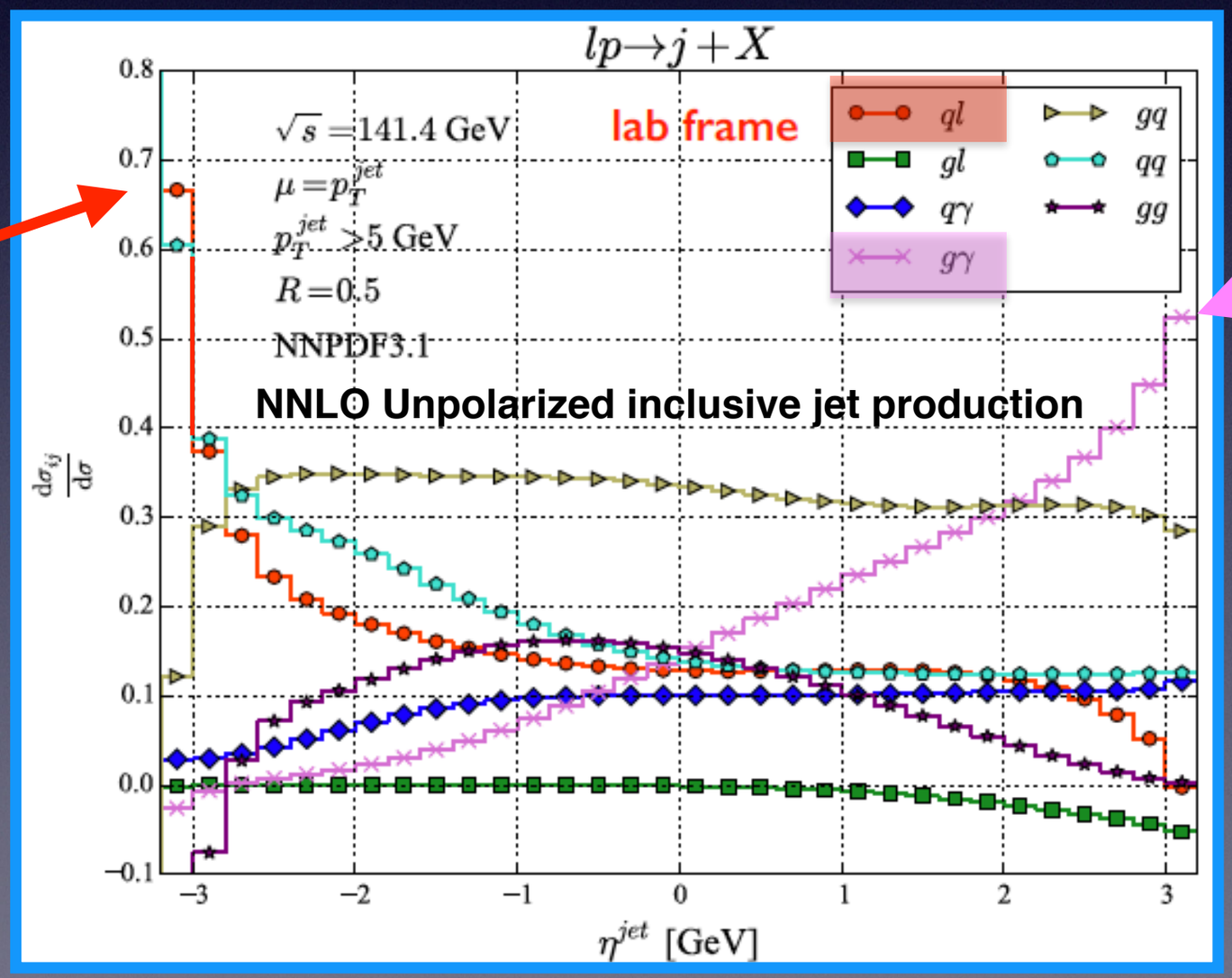


Long-term goal: NNLO extraction of polarized PDFs . Our understanding of unpolarized PDFs at this level has had a profound impact on our ability to understand LHC data.

Jets and longitudinal proton structure

- Jets can play an important role in disentangling the structure of the proton.

Abelof, RB, Liu, Petriello, 1607.04921



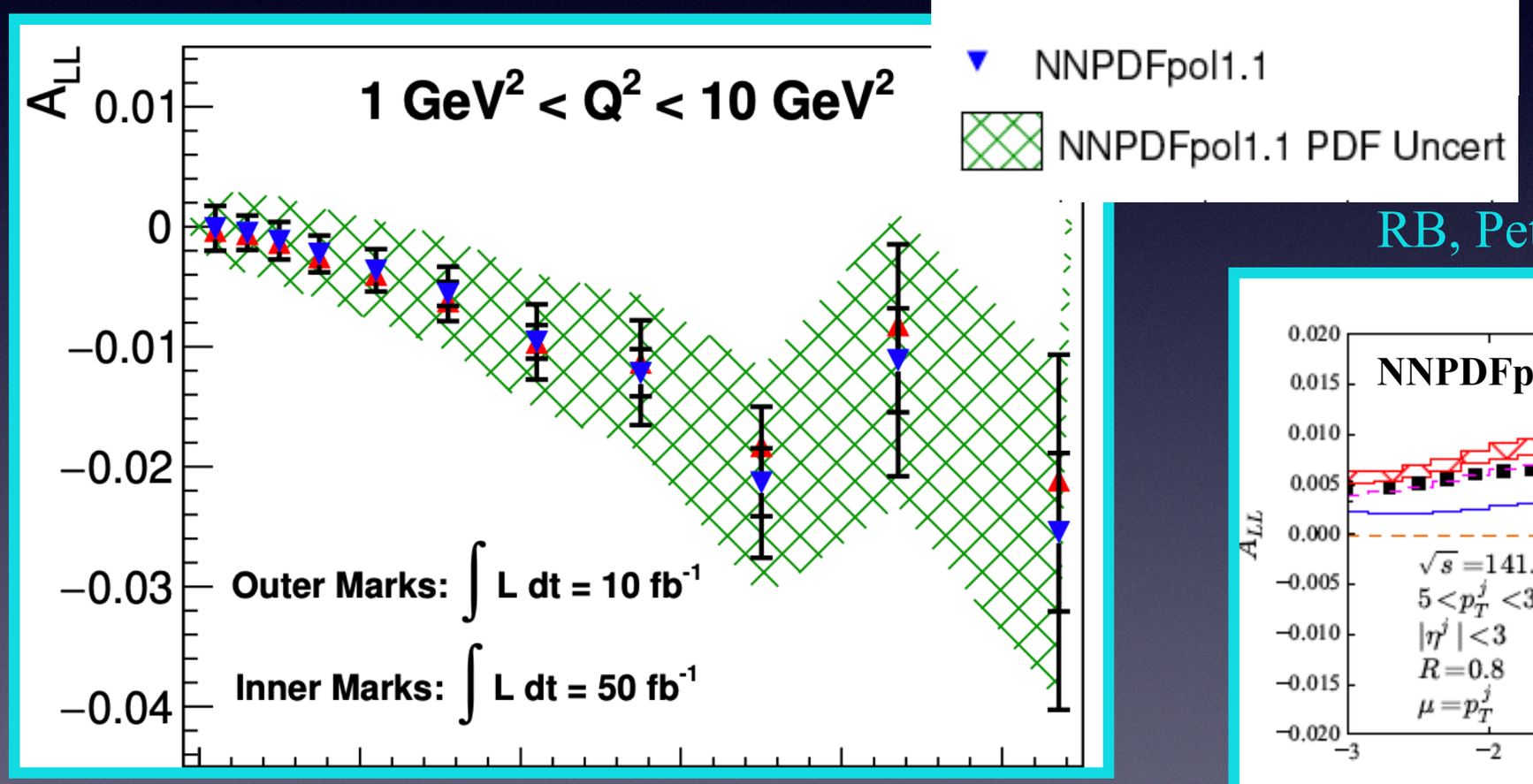
quark-dominated

gluon-dominated

Different regions of jet phase space give access to different parton distributions

Jets and longitudinal proton structure

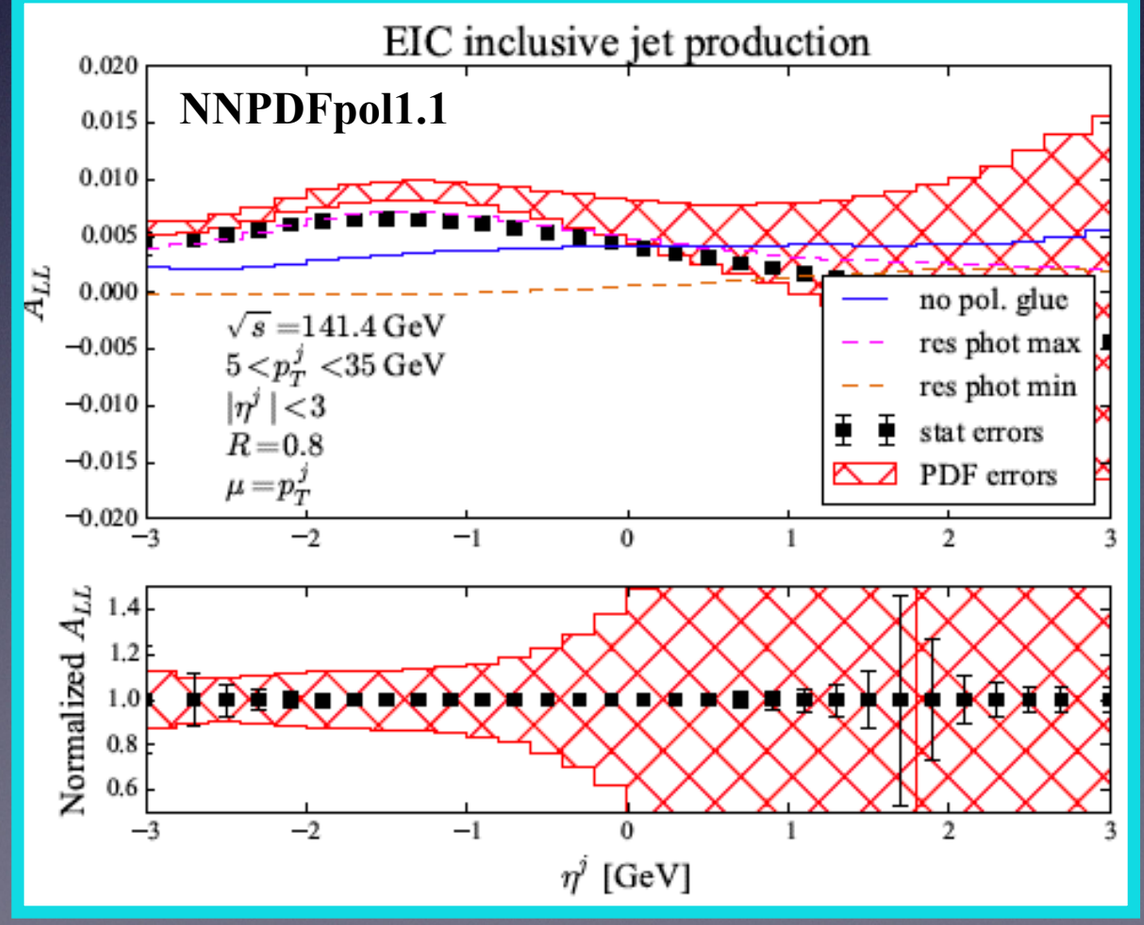
- Polarized PDF errors are larger than the estimated experimental errors. These distributions can improve current PDF extractions. They can provide cross-checks of polarized gluon determination from g1.



Dijet Mass [Gev/c²]

Page, Chu, Aschenauer, 1911.00657

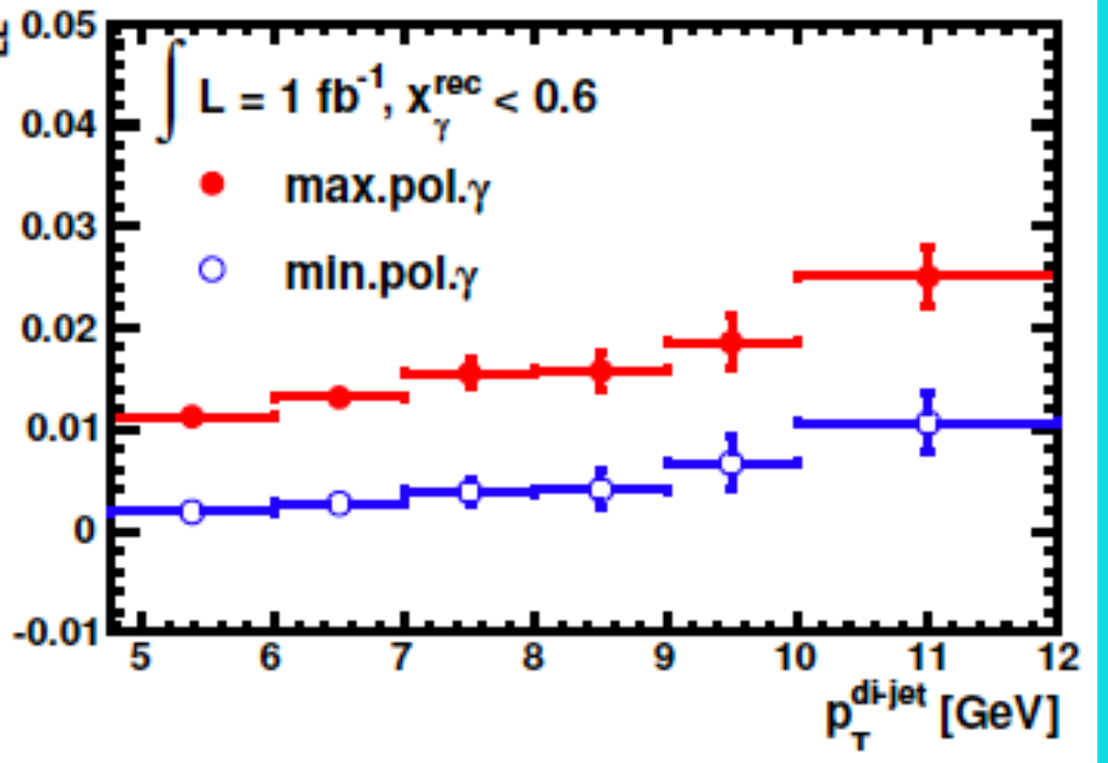
RB, Petriello, Xing 1806.07311

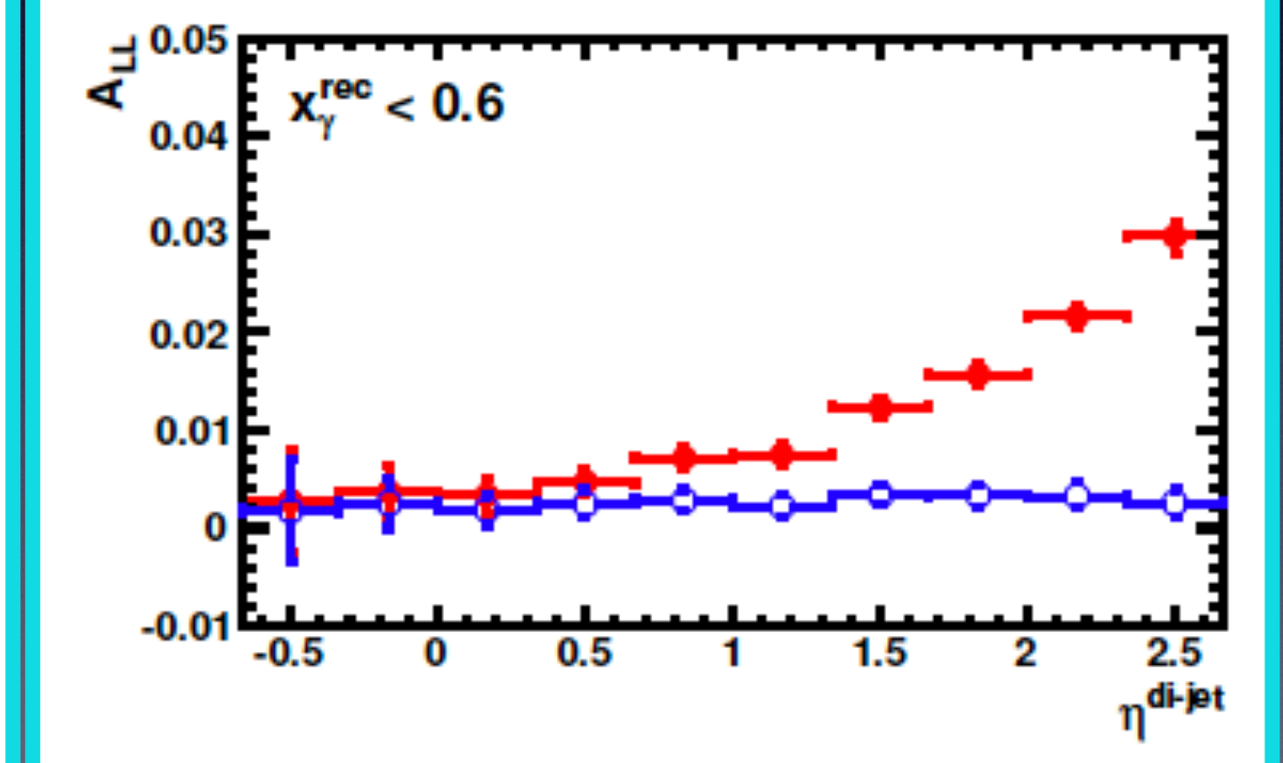


Jets and longitudinal photon structure

- Polarized dijet production at the EIC will provide our first view of longitudinal photon structure, which is currently based on models only.

Chu, Aschenauer, Lee, Zheng 1705.08831





Two assumptions regarding polarized photon distributions at μ≈0.5 GeV:

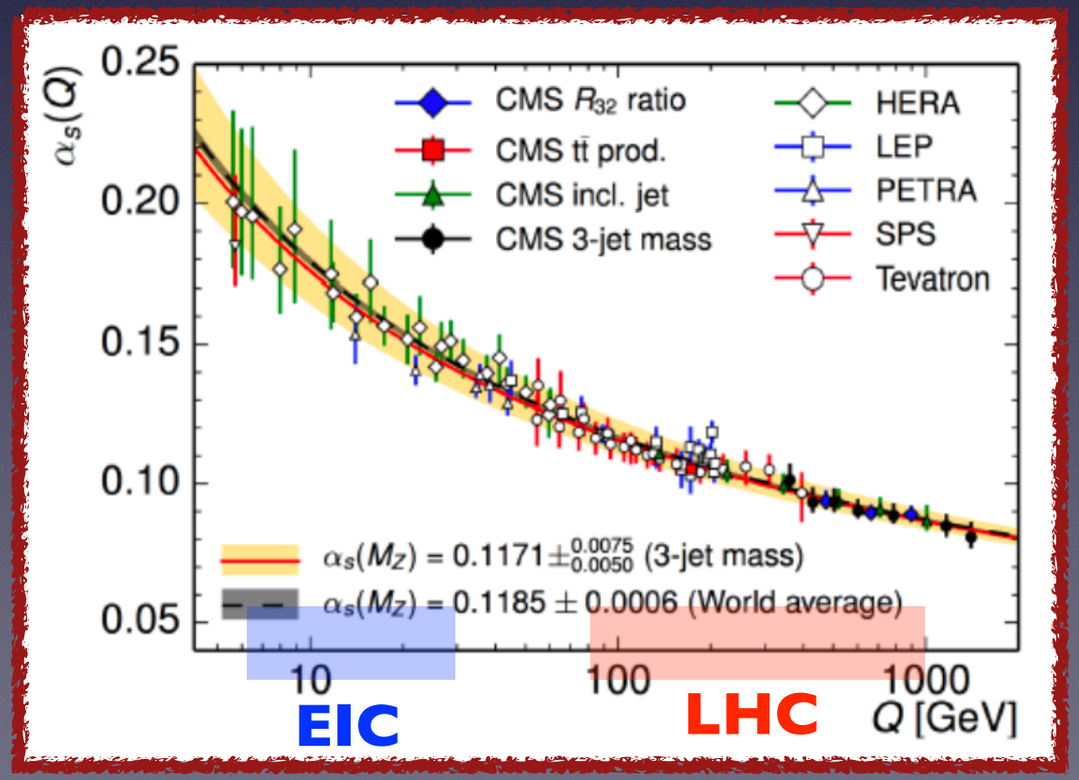
minimal: $\Delta f^\gamma(x,\mu^2) = 0$

maximal: $\Delta f^\gamma(x,\mu^2) = f^\gamma(x,\mu^2)$

pQCD framework

- Jet observables relevant for longitudinal proton/photon structure can be systematically calculated using the perturbative expansion in collinear factorization.

$$\sigma_{ep\to X} = \int dx_1 dx_2 f_{i/e}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) \sigma_{ij\to X}(x_1,x_2,\mu^2)$$



$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)} + \ldots\right)$$

LO predictions | NLO corrections | NNLO corrections | NNNLO corrections

EIC: perturbative, but corrections larger than at LHC. Must be included for any quantitative analysis

Inclusive jet production at the EIC

- Review the theoretical calculation and phenomenology of jet production at higher orders at the EIC.

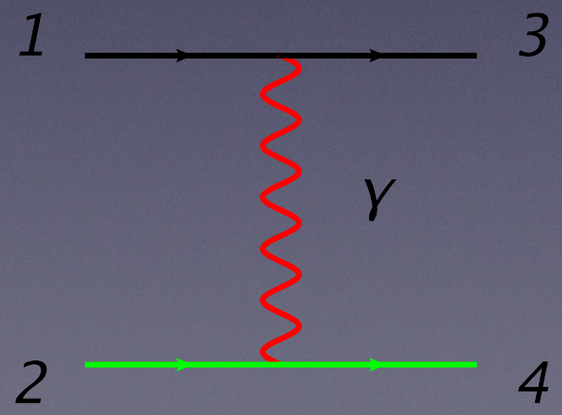
DIS: ep→eX

- lepton tagged
- Cut on Q^2
- hard scale: Q

Inclusive jet production: ep→jX

- lepton *not* tagged
- Cut on p_{Tjet}
- hard scale: p_{Tjet}

$q(p_1)+l(p_2) \rightarrow q(p_3)+l(p_4)$

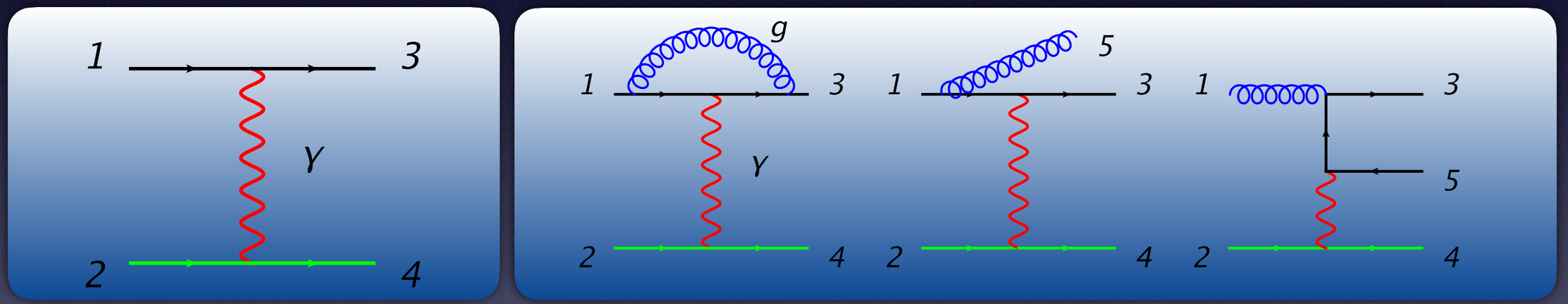


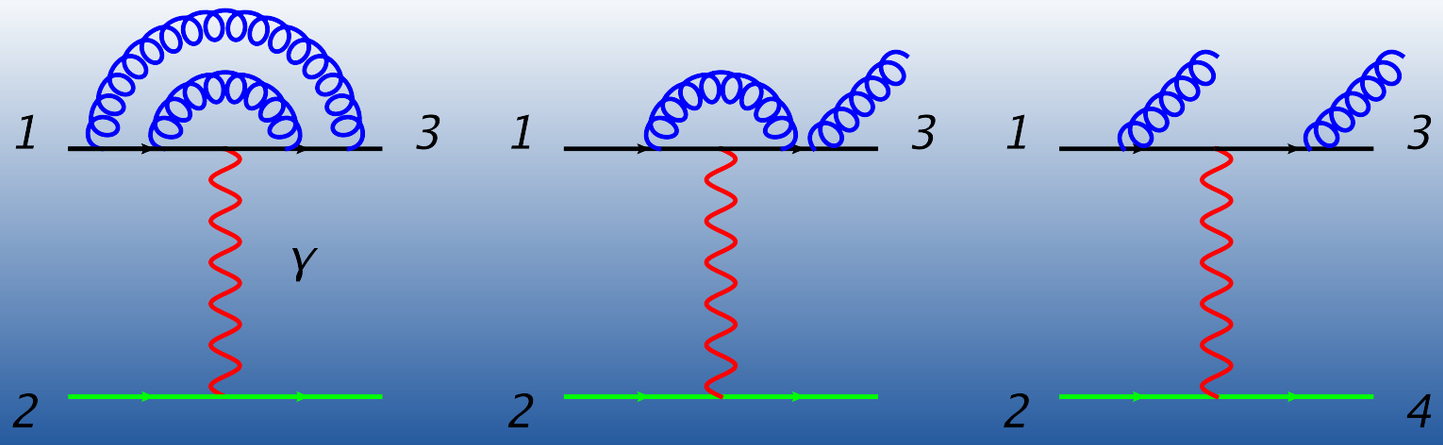
- Leading order: identical for both processes, lepton recoils against a jet

Inclusive jet production at the EIC

- Three distinct contributions through $O(\alpha_S^2)$:

(1) DIS process: $q_1+l_2 \rightarrow q_3+l_4+X$, begins at $O(\alpha_s^0)$. Q^2>0

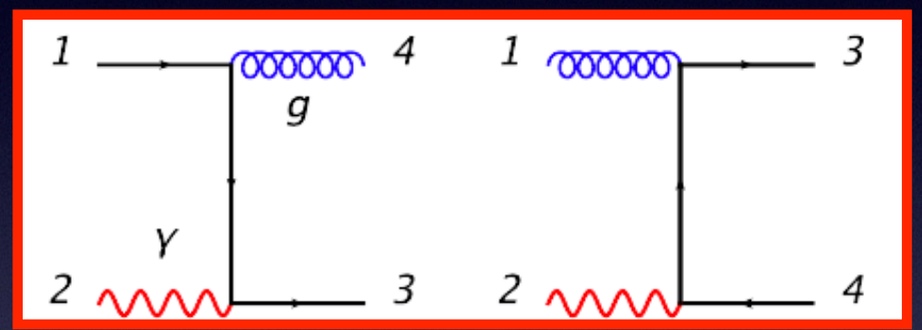




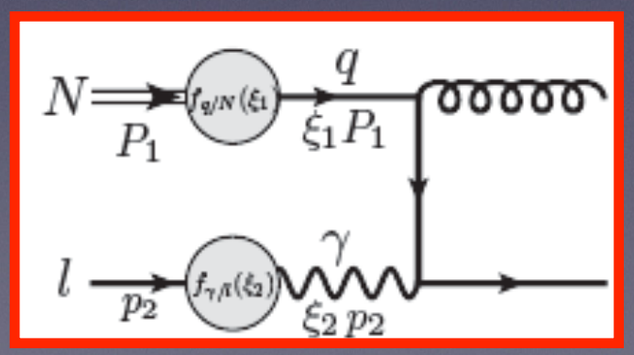
Inclusive jet production at the EIC

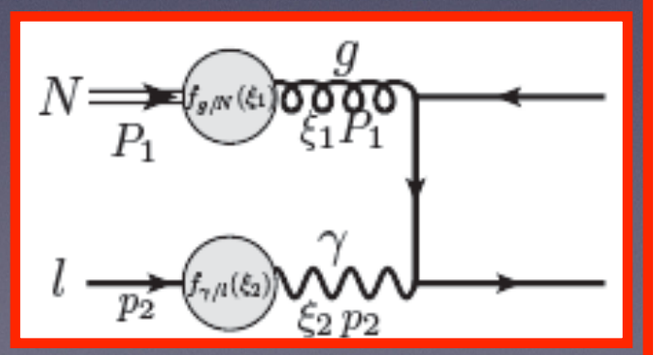
- Three distinct contributions through $O(\alpha_S^2)$:

(2) Weizsacker-Williams (WW) photon process: $q/g_1+\gamma_2 \rightarrow q_3+g/q_4+X$, begins at $O(\alpha_s^1)$



lepton collinear to the beam ($Q^2 \simeq 0$), with two jets balancing in the transverse plane; on-shell photon scattering with quark ➡ differentiates DIS and inclusive jet production





$$f_{\gamma/l}(\xi) = \frac{\alpha}{2\pi} P_{\gamma l}(\xi) \left[\ln\left(\frac{\mu^2}{\xi^2 m_l^2} \right) - 1 \right] + \mathcal{O}(\alpha^2)$$

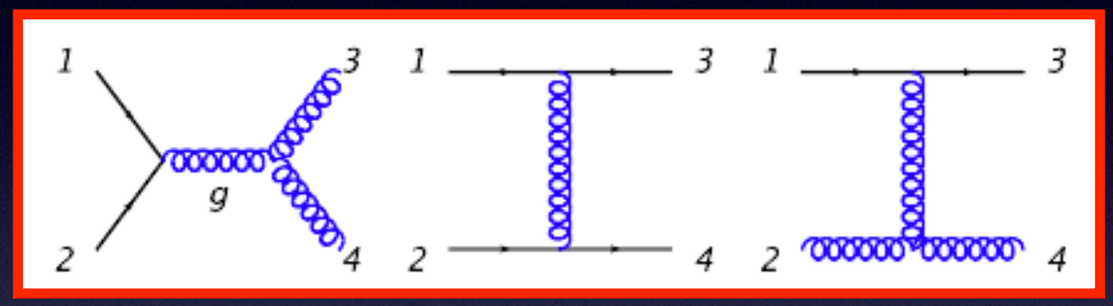
$$P_{\gamma l}(\xi) = \frac{1 + (1-\xi)^2}{\xi}$$

this calculation also available from Hinderer, Schlegel, Vogelsang PRD92 (2015)

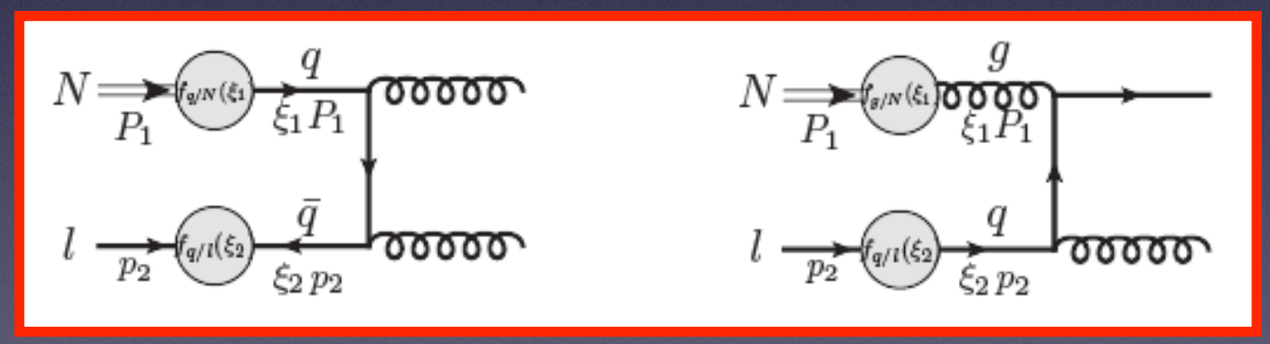
Inclusive jet production at the EIC

- Three distinct contributions through $O(\alpha_S^2)$:

(3) Resolved photon process:
$q/g_1+q/g_2 \rightarrow q/g_3+q/g_4+X$,
formally begins at $O(\alpha_s^2)$



Incoming lepton can split into a quark, leading to parton-parton scattering channels.



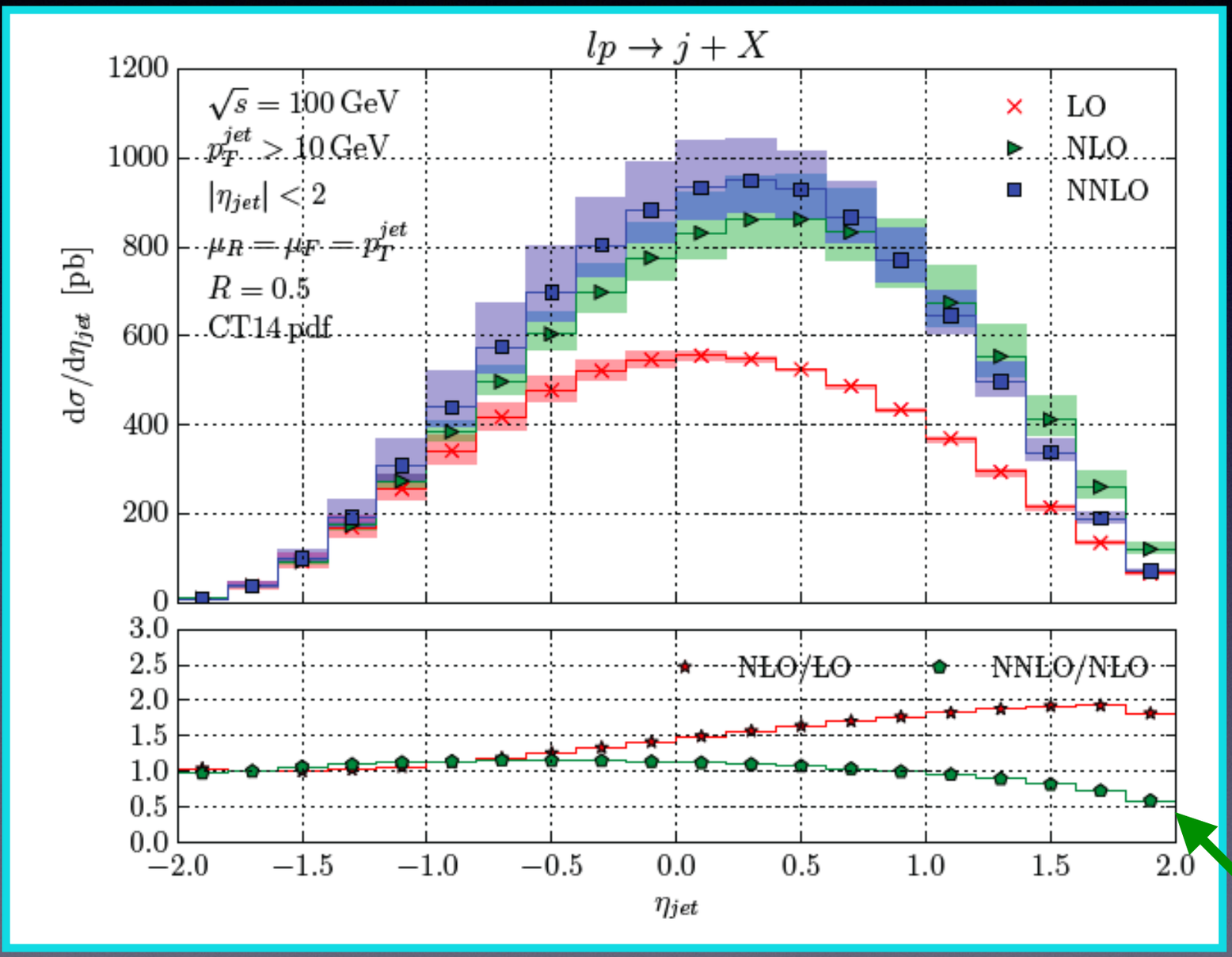
$$\int \frac{d\xi_1 d\xi_2 dy}{\xi_1 \xi_2 y} \Delta f_{i/P}(\xi_1) \Delta f_{j/\gamma}(\xi_2/y) \Delta P_{\gamma l}(y) \Delta \hat{\sigma}_{ij}(y)$$

polarized proton PDFs

polarized photon PDFs

polarized QED splitting function

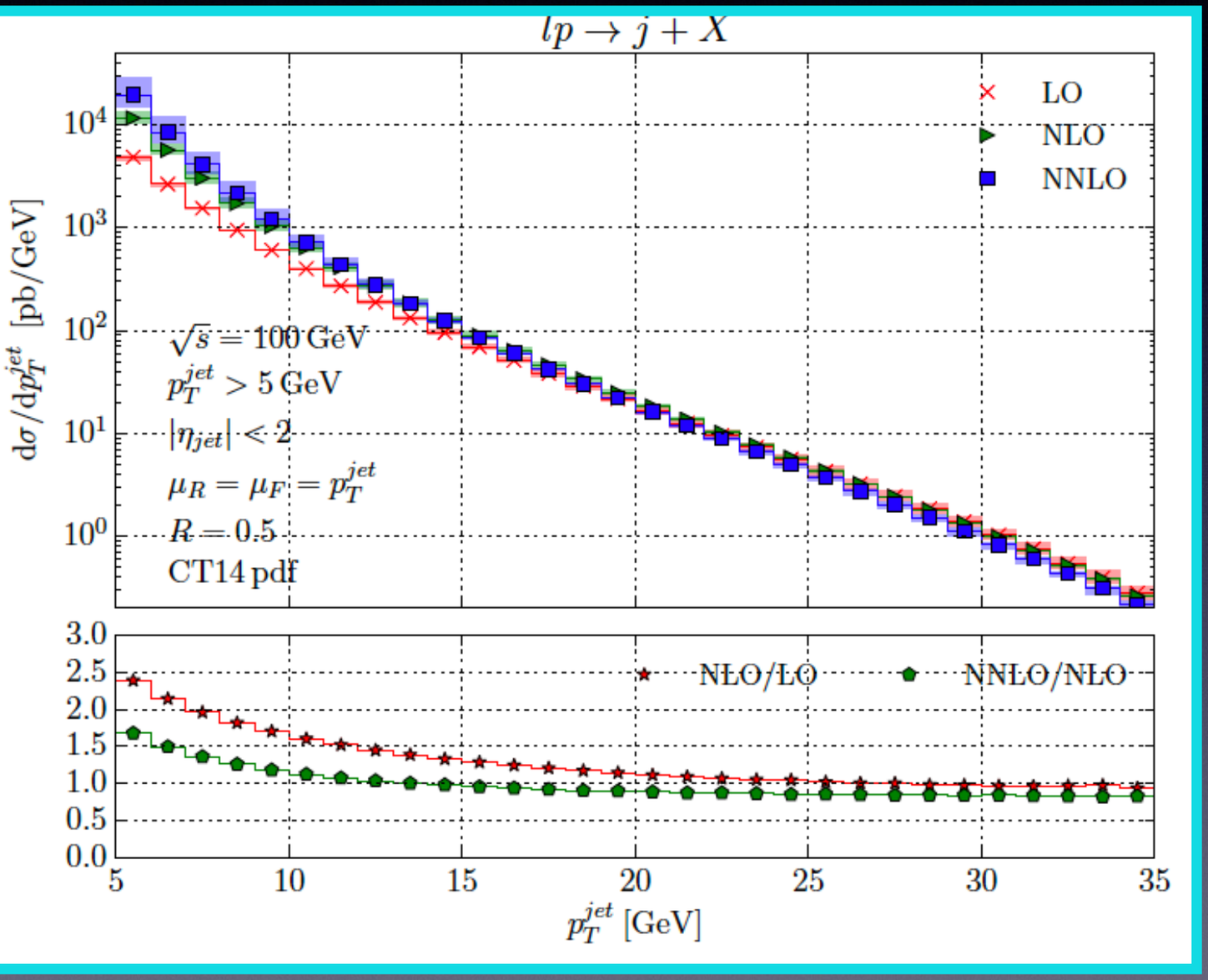
Inclusive jet production: unpolarized



Abelof, RB, X. Liu, Petriello, 1607.04921

- Requires $O(\alpha_s^2)$ for accurate prediction; WW photons at $O(\alpha_s)$ give large correction (Hinderer, Schlegel, Vogelsang 1505.06415).
- Larger-than-expected scale dependence at $O(\alpha_s^2)$ from resolved photon terms.
- $O(\alpha_s^2)$ leads to slight decrease at high eta

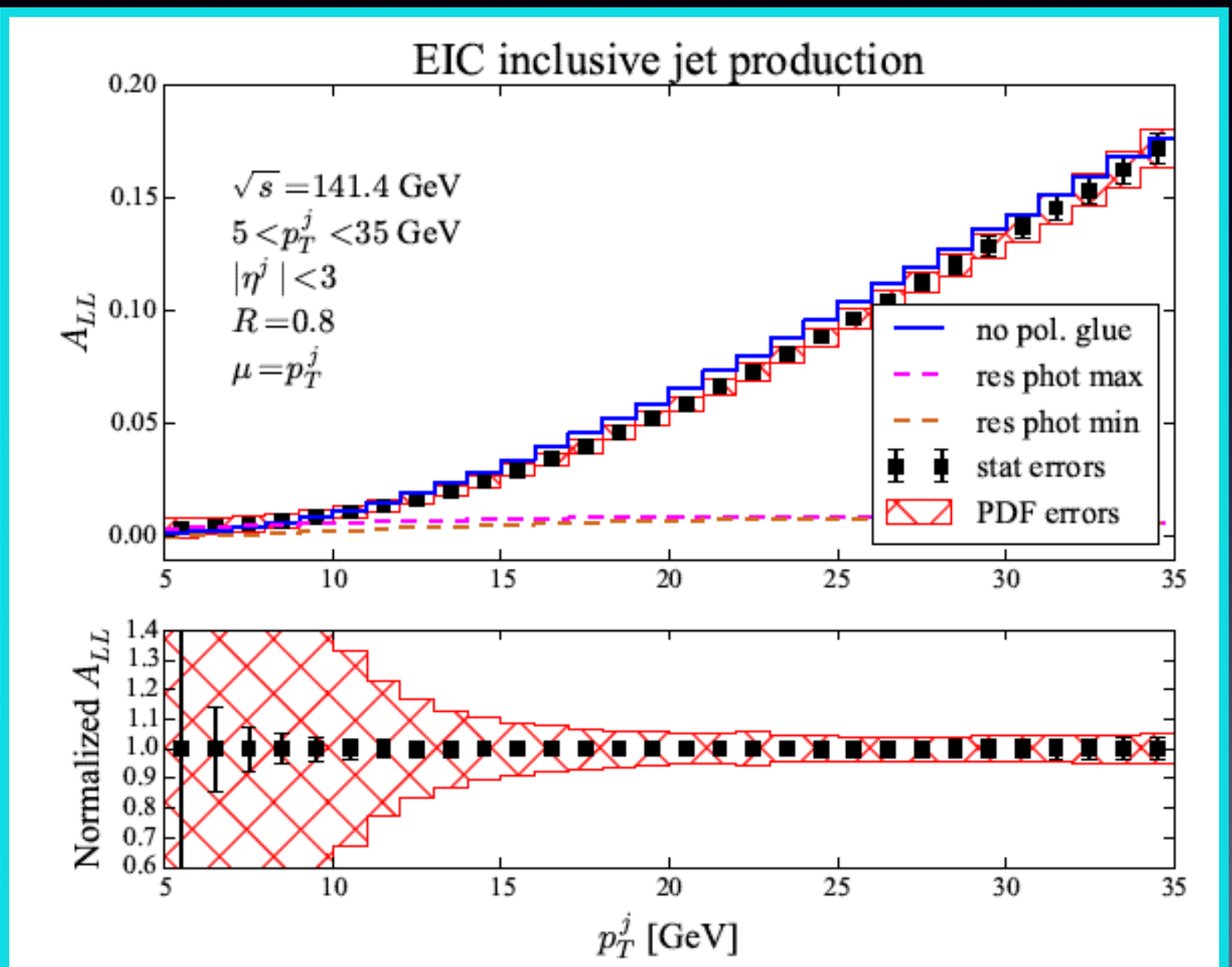
Inclusive jet production: unpolarized



Abelof, RB, X. Liu, Petriello, 1607.04921

- Large corrections at low jet transverse momentum at both NLO and NNLO
- Splitting of jets into multiple jets through real-radiation corrections at higher orders leads to this effect
- NNLO corrections enhance the distribution at low p_{Tj}. K-factor remains near unity at higher p_{Tj}.

Inclusive jet production: polarized

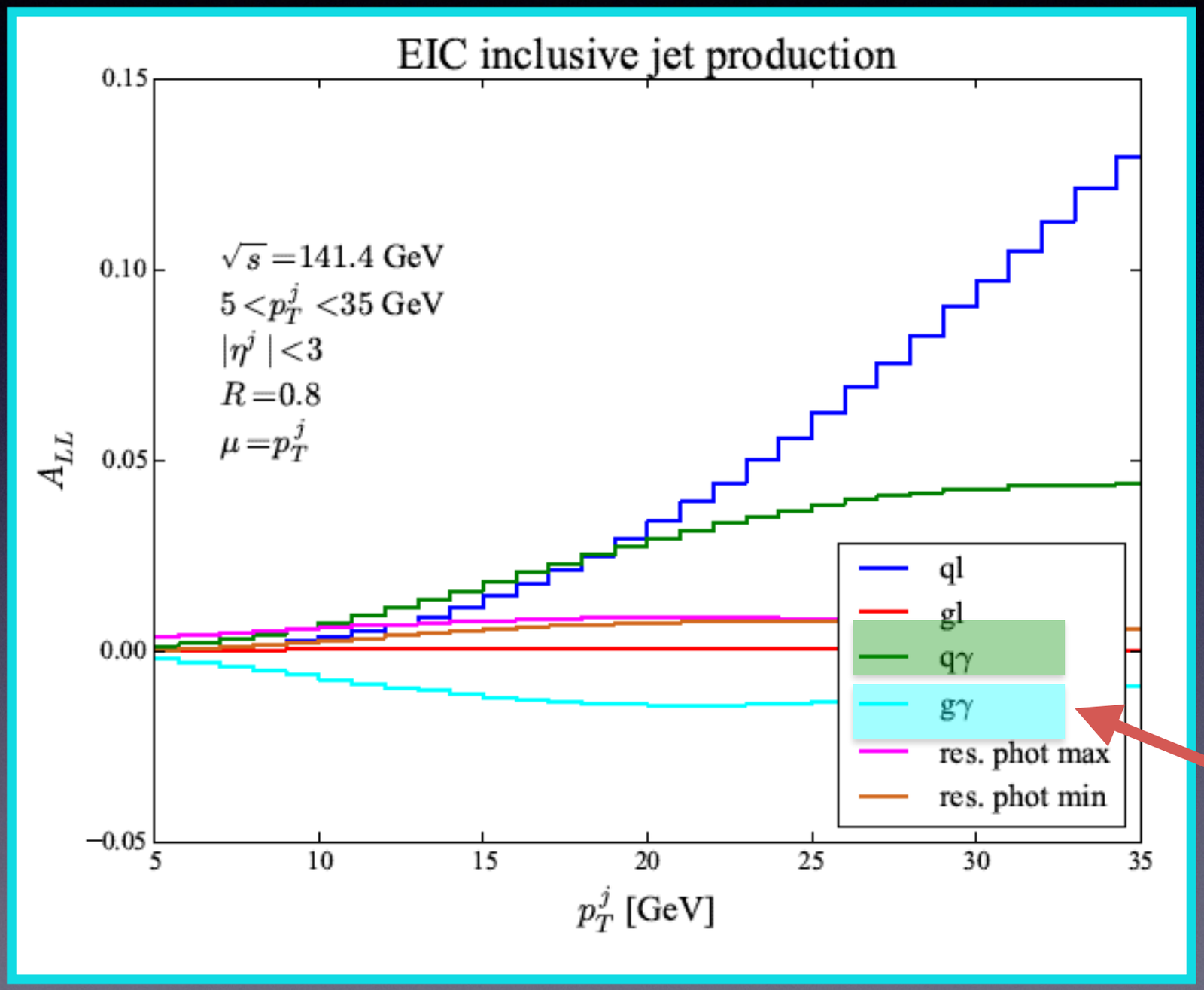


- A_{LL} grows to ~20%
- Different polarized $\Delta f_{i/\gamma}$ give small effects, except at low pTj.
- Turning off $\Delta f_{g/P}$ leads to observable difference at intermediate pTj.
- PDF errors larger than estimated statistical errors for much of pTj range.

Assuming 10 fb^{-1} and 100% polarization for ep

RB, Petriello, Xing 1806.07311: NLO analysis with resolved photons

Inclusive jet production: polarized

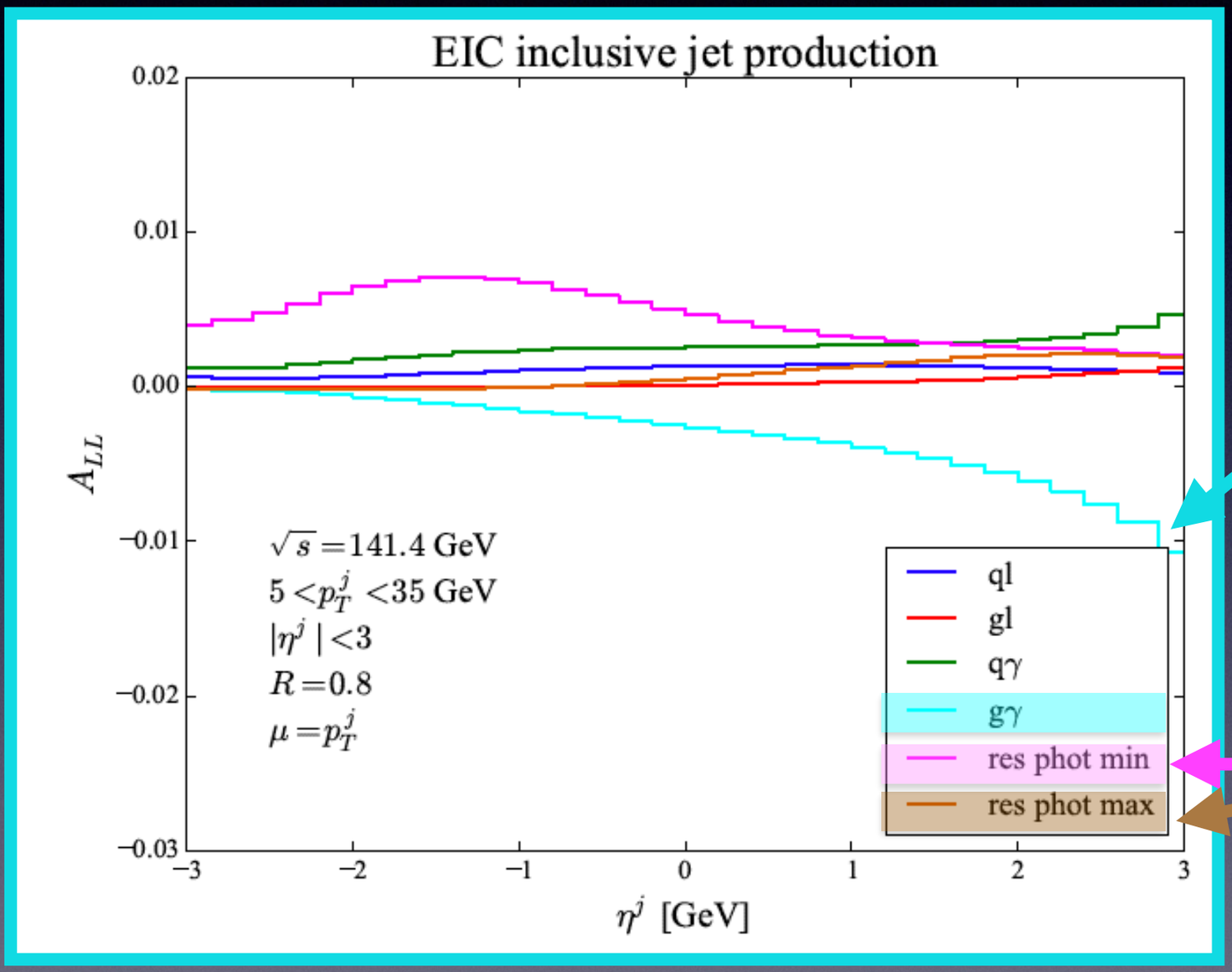


- ql channel dominates at high pT; gl channel small throughout
- At intermediate pT we get contributions from qγ and gγ

Sensitive to Δfg/P through WW photon processes at intermediate jet momenta

RB, Petriello, Xing 1806.07311: NLO analysis with resolved photons

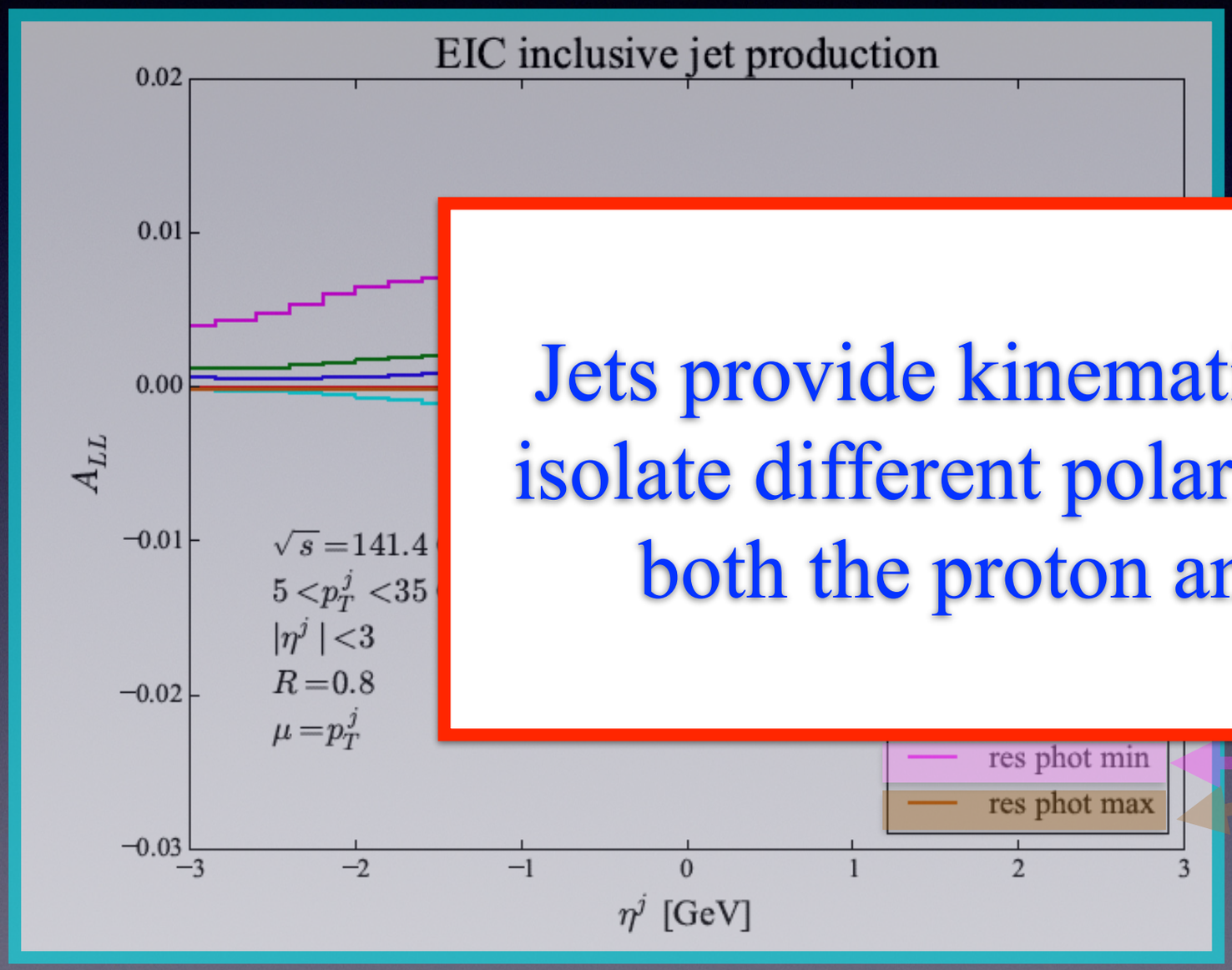
Inclusive jet production: polarized



- gγ channel dominates at forward eta region
- Sensitive to $\Delta f_i/\gamma$ at backward eta

RB, Petriello, Xing 1806.07311: NLO analysis with resolved photons

Inclusive jet production: polarized



Jets provide kinematic handles to isolate different polarized PDFs of both the proton and photon

- gγ channel
- at
- a region
- o $\Delta f_i/\gamma$ at backward eta

RB, Petriello, Xing 1806.07311: NLO analysis with resolved photons

Summary

- We are making strides to bring our understanding of polarized proton structure to the same quantitative level as unpolarized proton structure with an EIC.

- Will need global fits with numerous data sets, precision cross section calculations to achieve this goal.

- Jets can play an important role in this quest; they offer kinematic handles to separate different PDFs.

- Several needed theoretical calculations have become available.