Jets for longitudinal spin physics

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Jets for 3D imaging at the EIC

November 25, 2020

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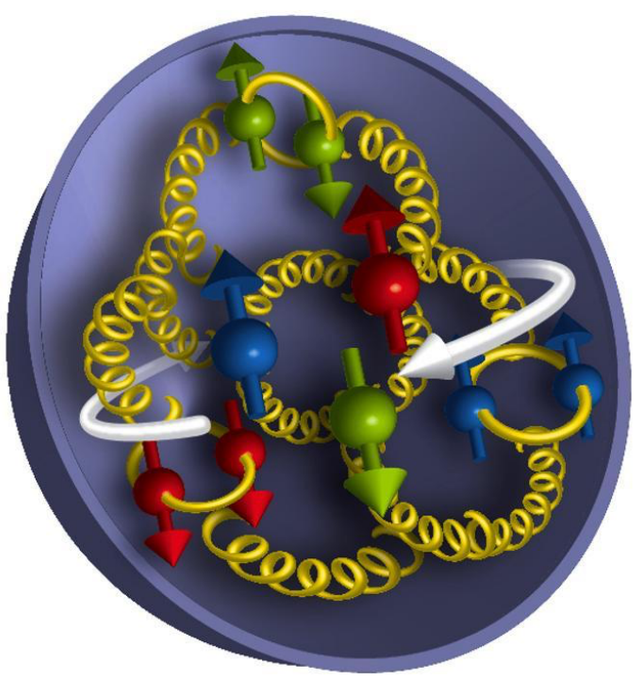
Outline

- Motivation and current status of polarized PDFs
- The role played by jets at an EIC
- Status of theoretical calculations, phenomenology

Puzzles in proton structure

- How proton structure emerges from QCD still puzzles us today
- From the 2012 EIC white paper:

> **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?



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

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

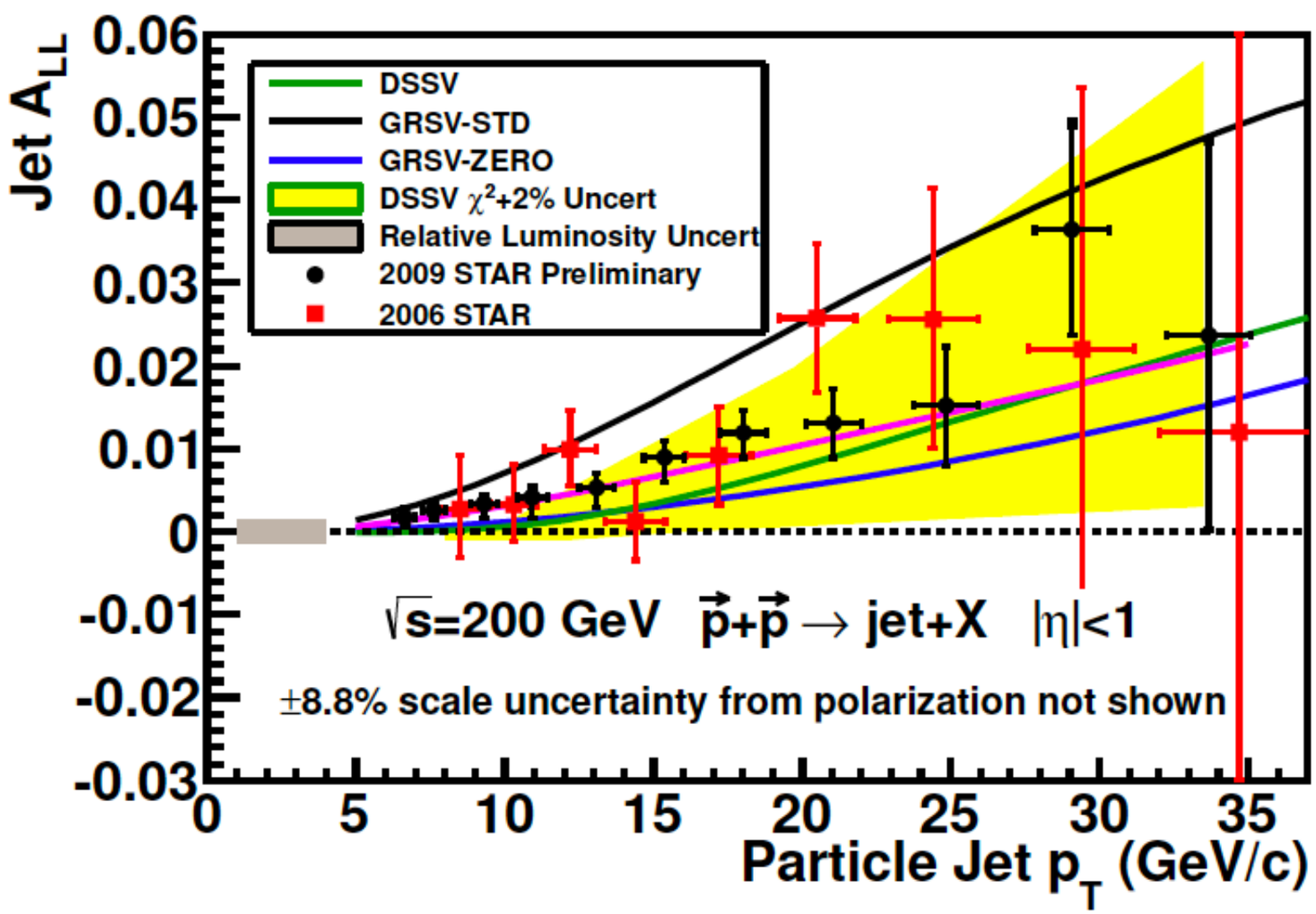
Goal: precision determination of polarized PDFs

Recent progress: jets at RHIC

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

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

STAR, 1303.0543



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

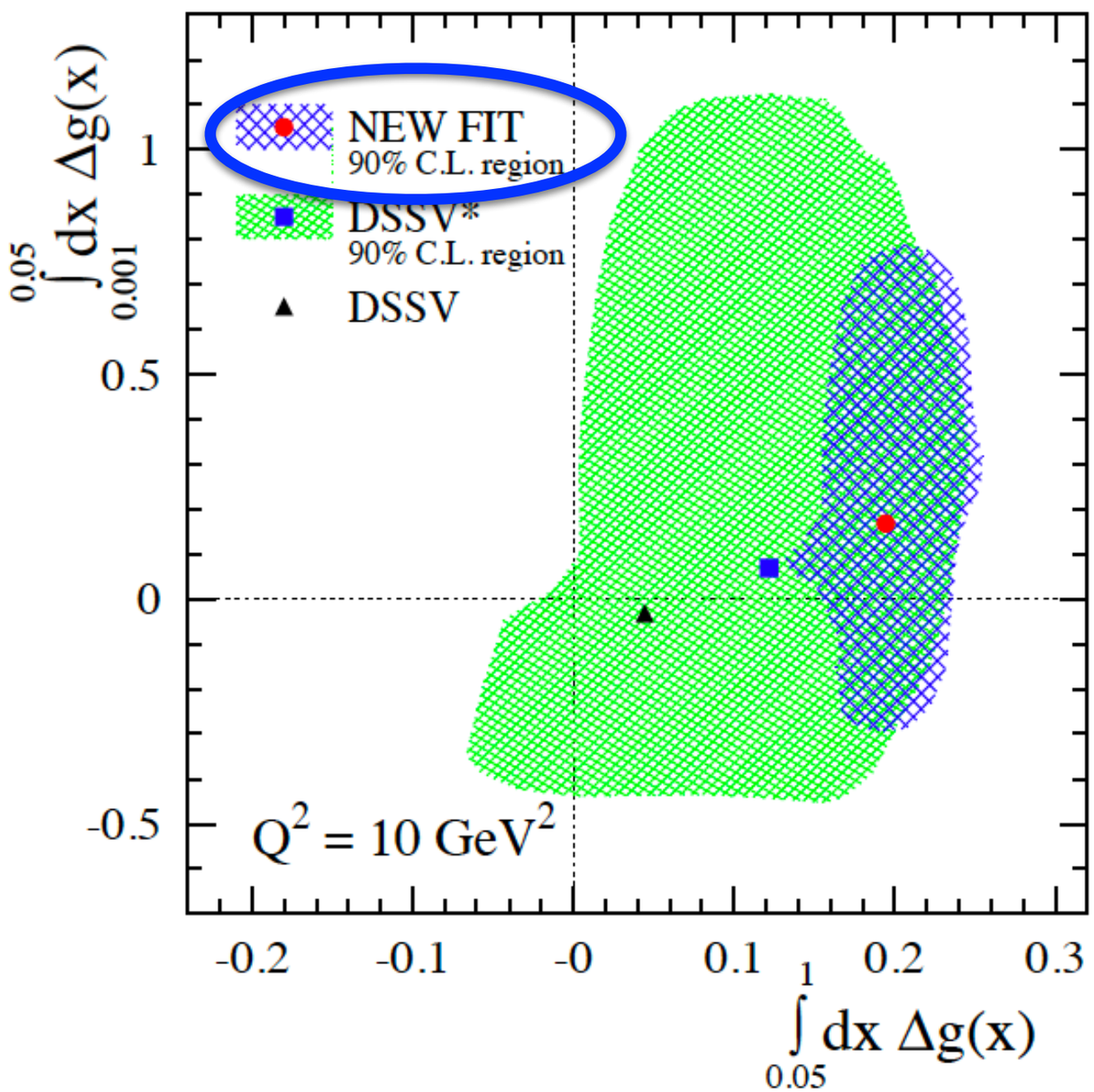
with gluon polarization

without gluon polarization

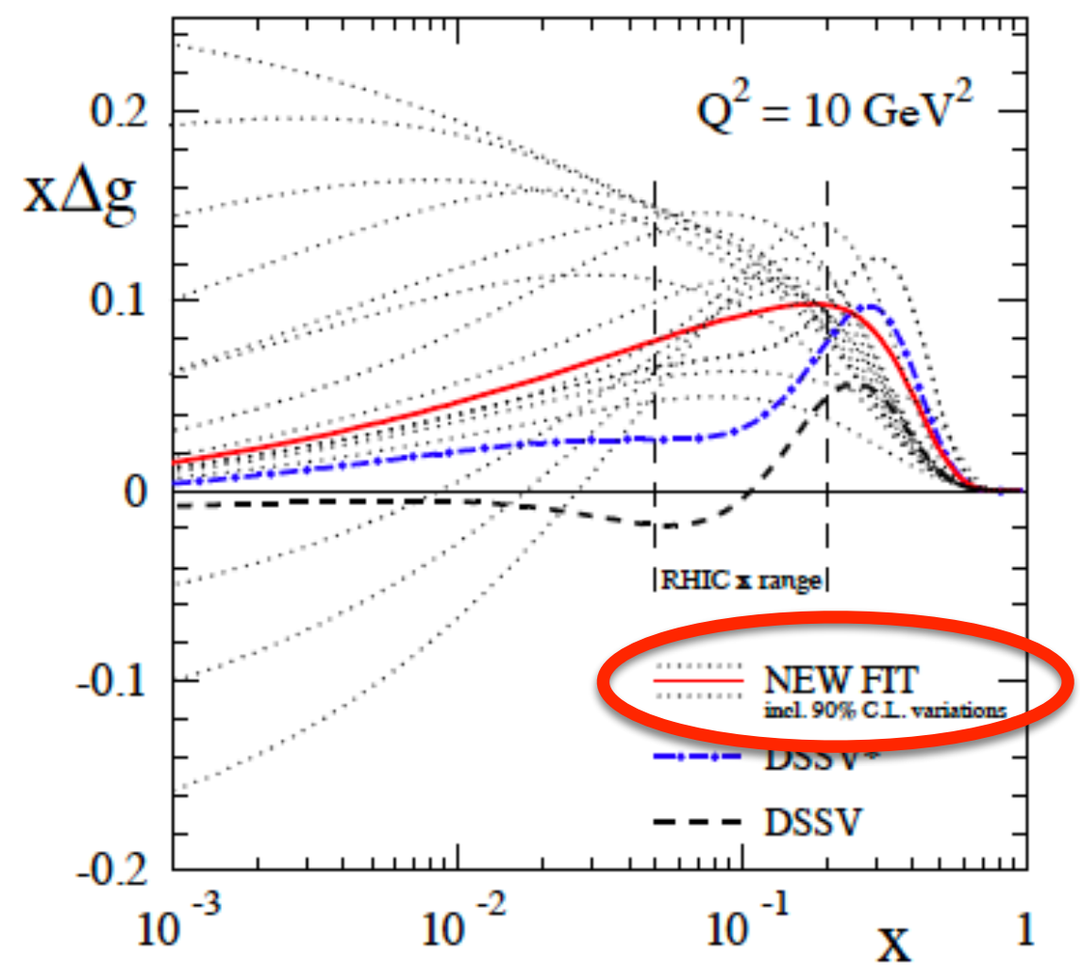
2009 jet data shows clear preference for non-zero gluon polarization

Recent progress: jets at RHIC

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



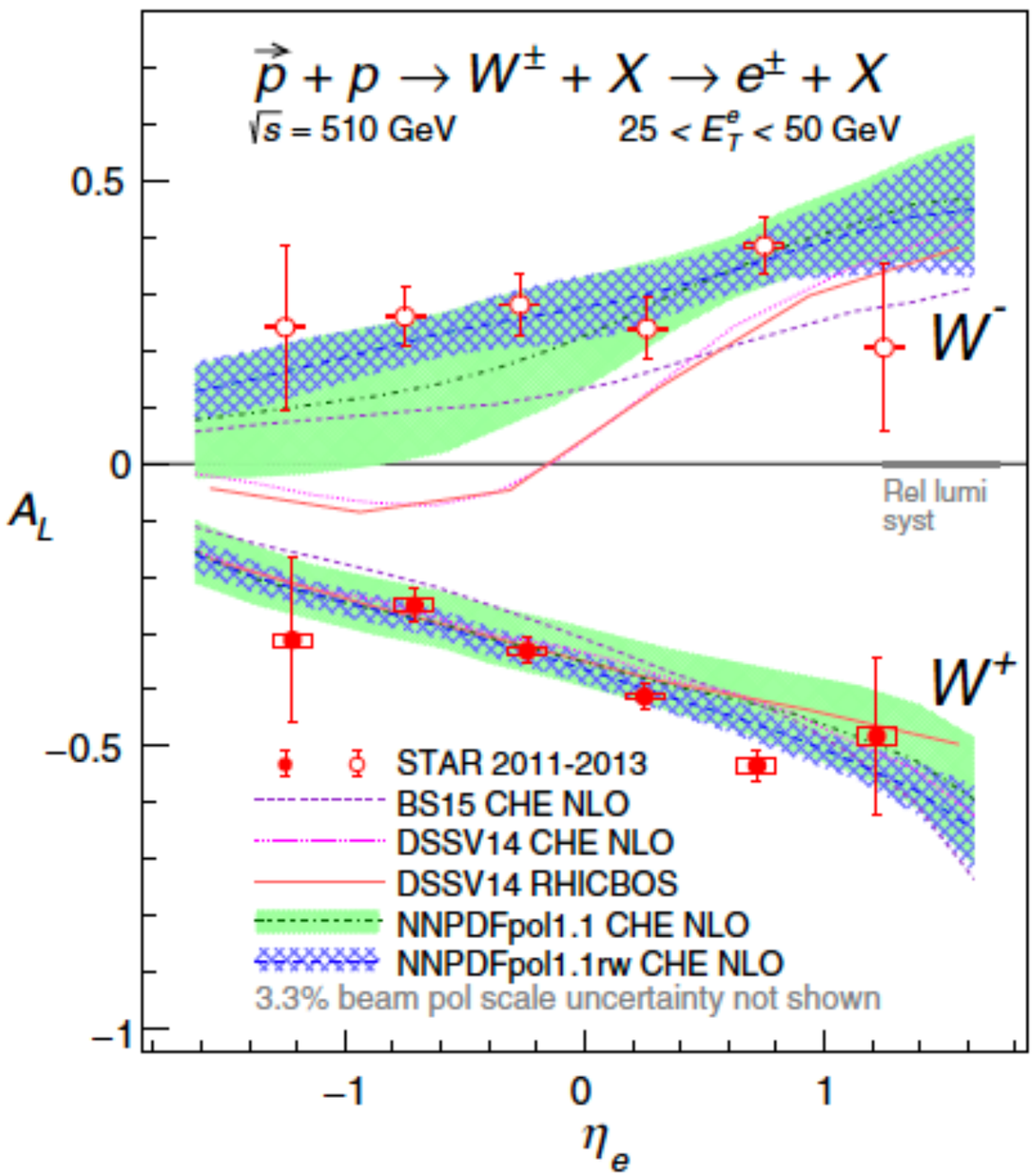
Dotted lines: alternate fits within 90% CL



de Florian, Sassot, Stratmann, Vogelsang 1404.4293

Recent progress: W at RHIC

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



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

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

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

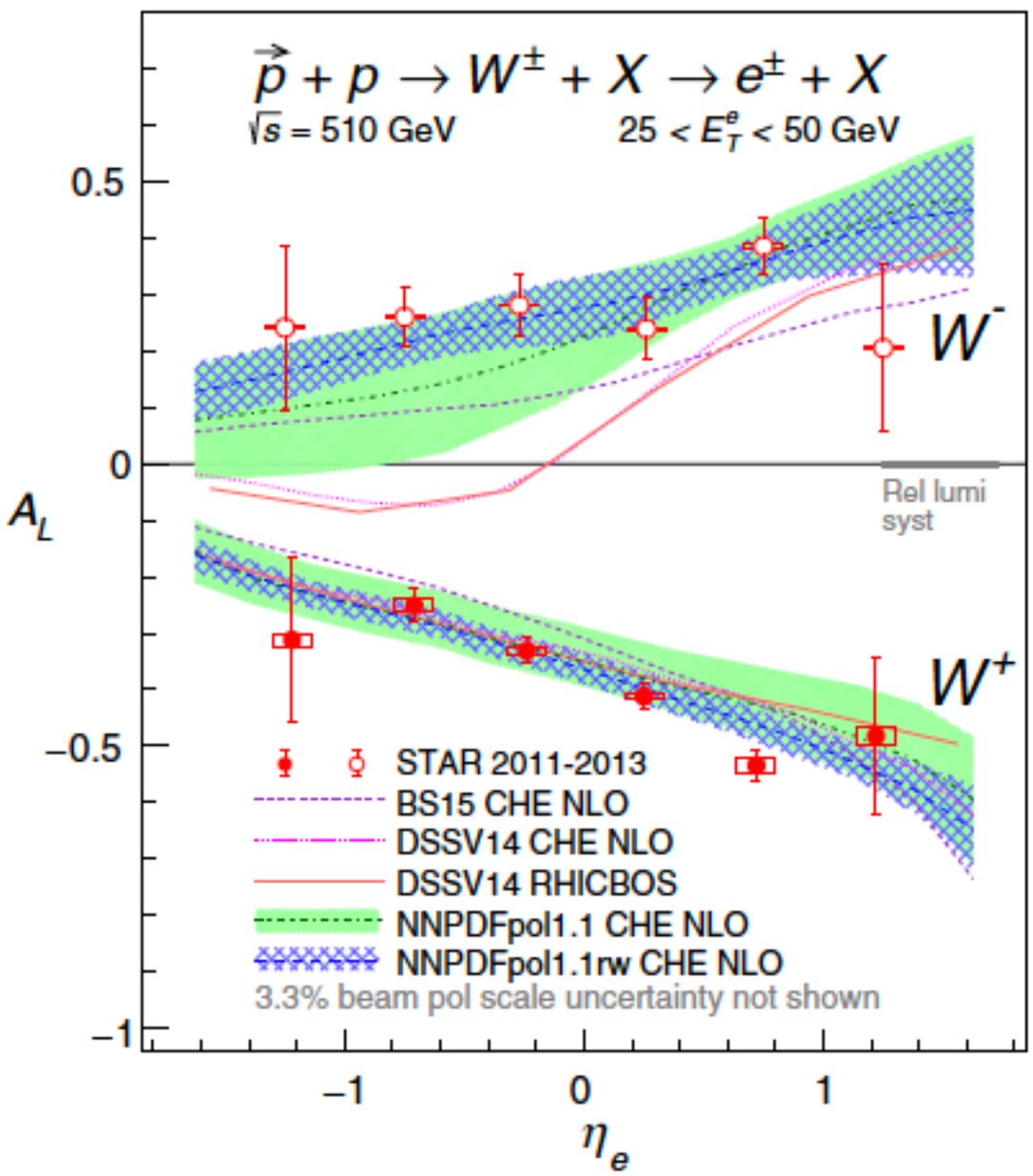
$$y_W \gg 0 \to x_1 \gg x_2 : A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)}, A_L^{W^-} \approx -\frac{\Delta d(x_1)}{d(x_1)}$$

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

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

Recent progress: W at RHIC

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



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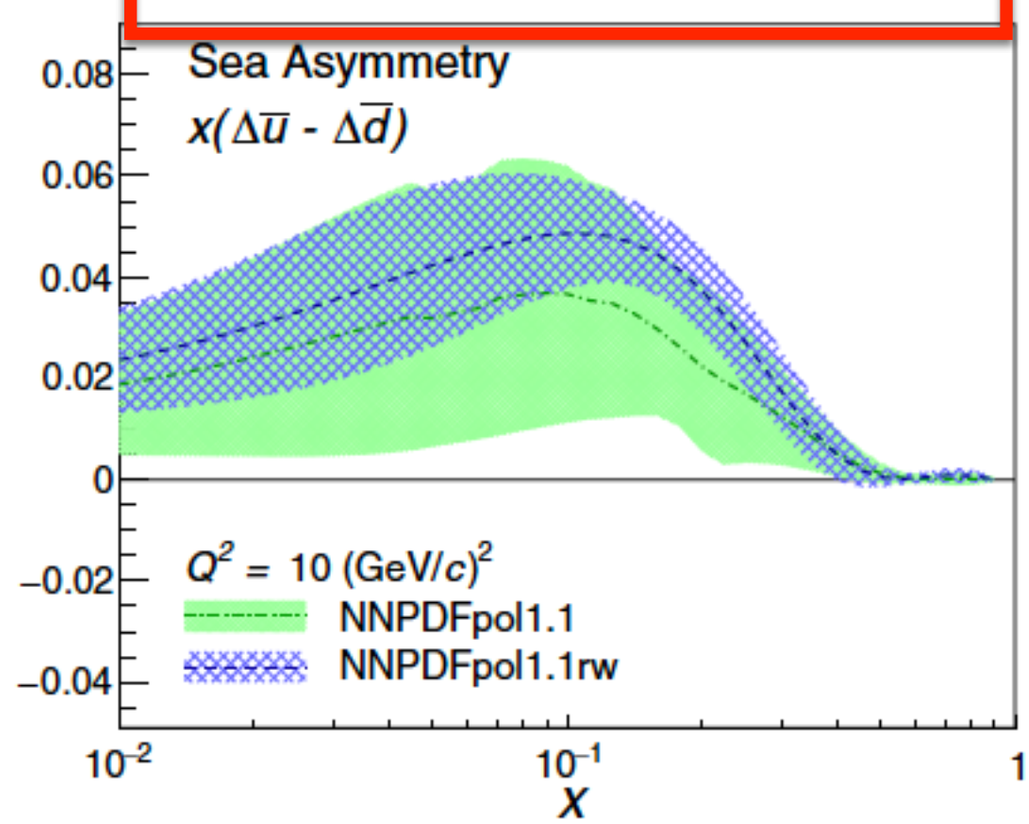
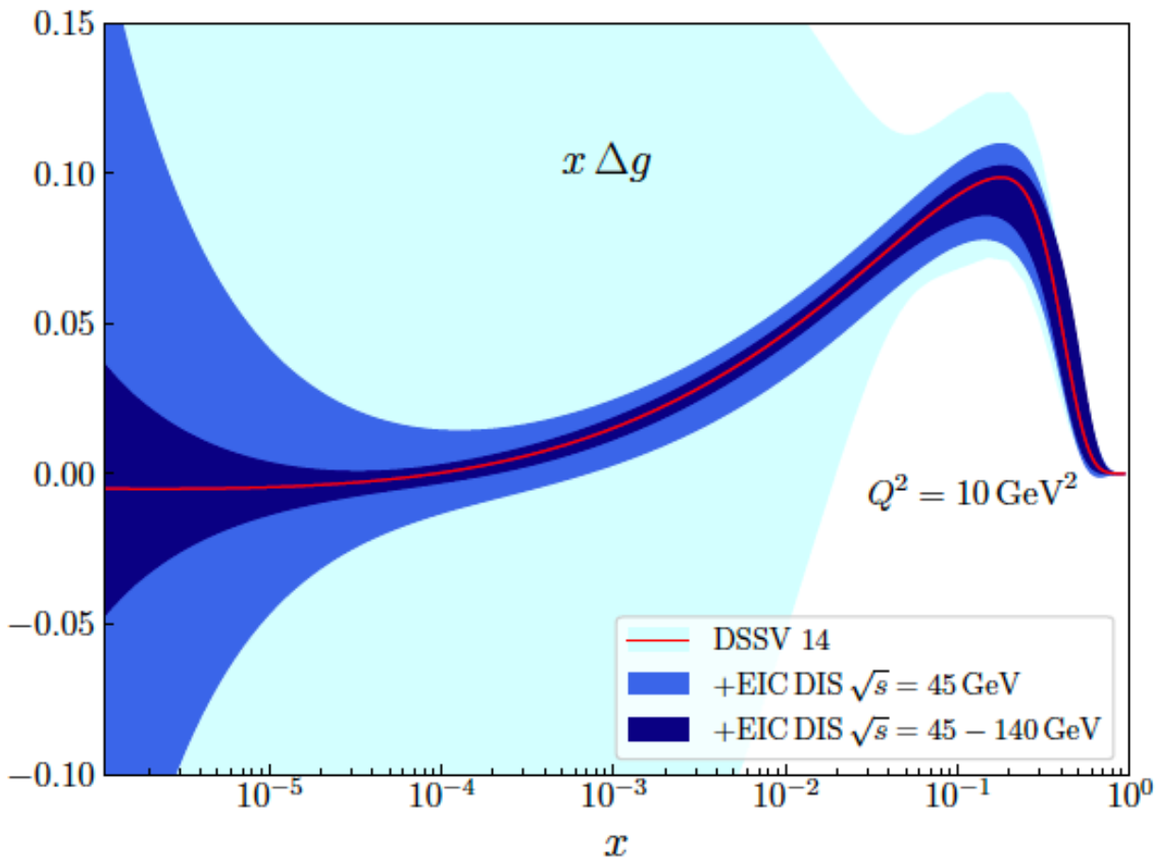
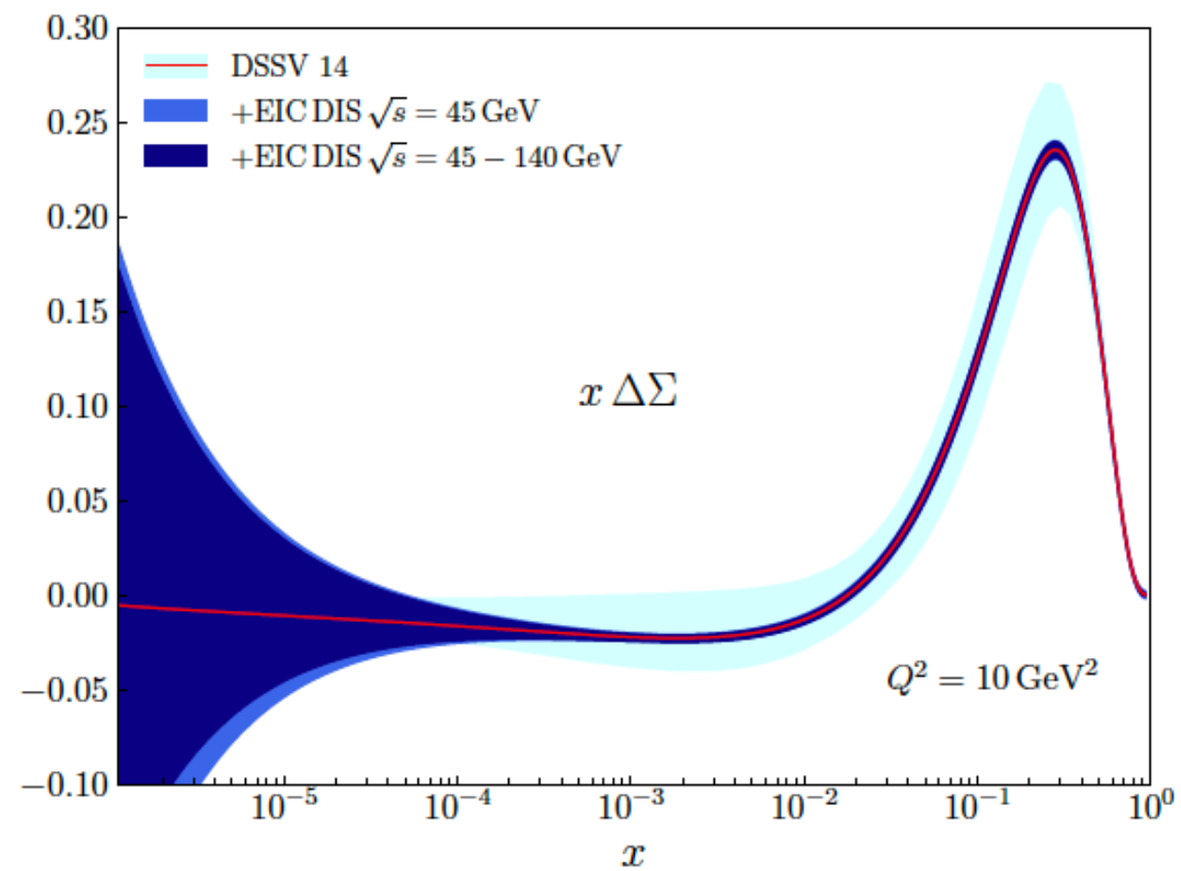


Future projections at the EIC

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

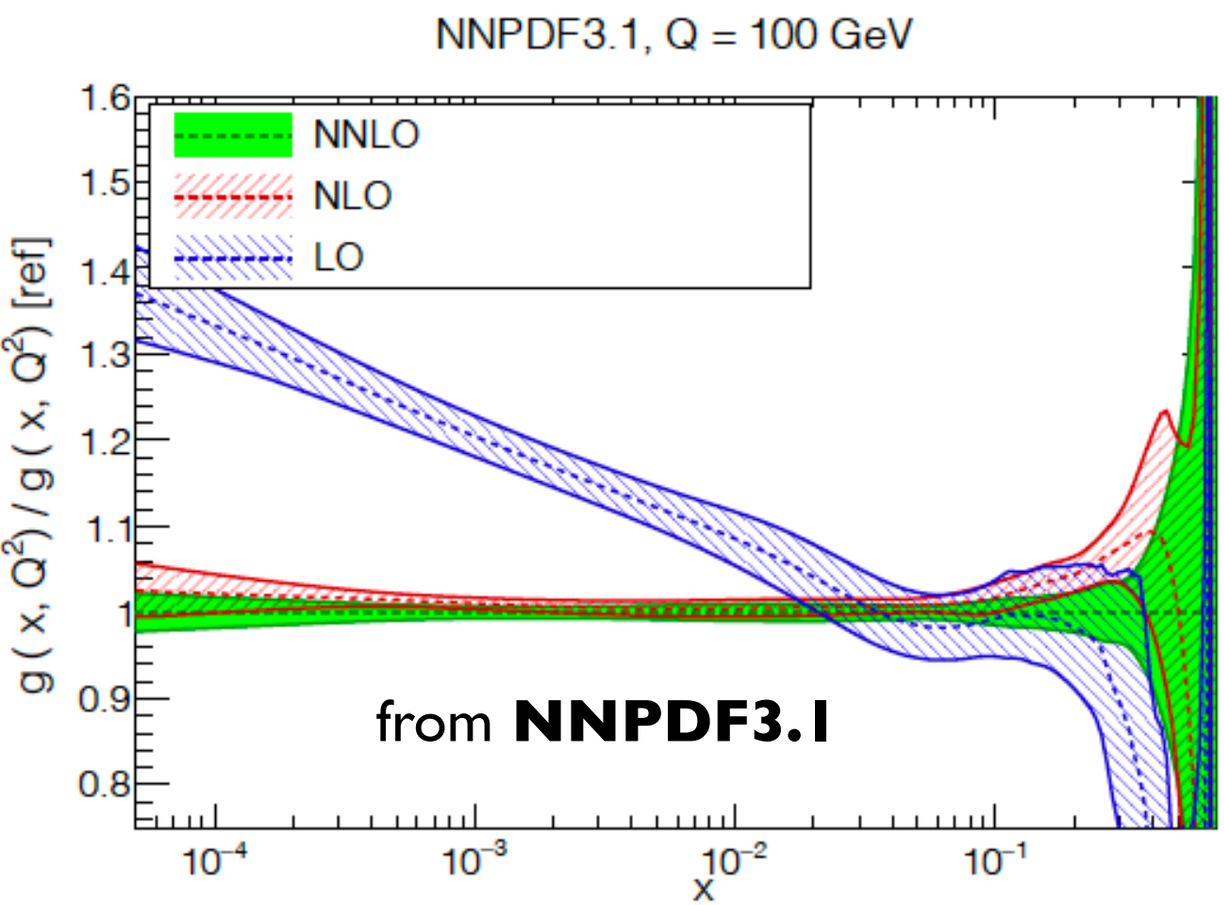


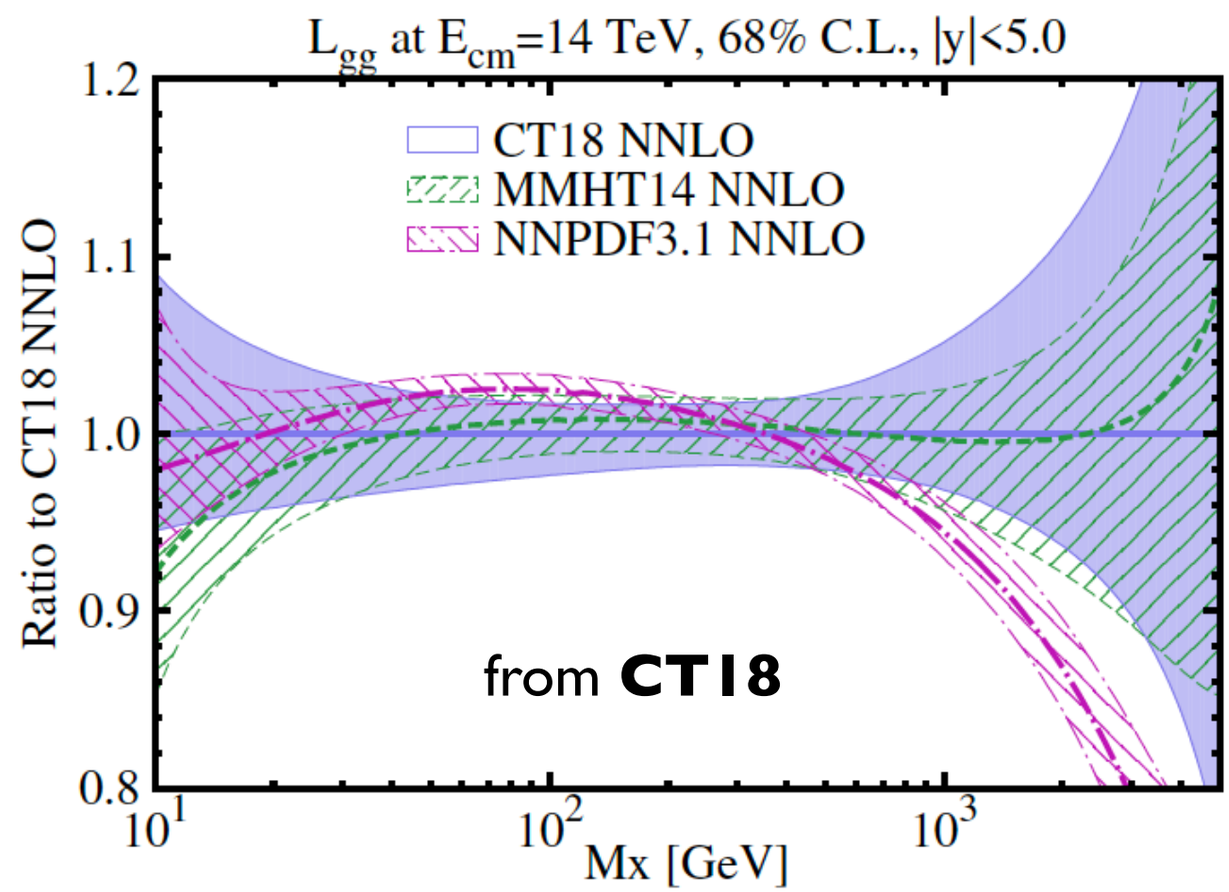


Combination of DIS and pion, kaon SIDIS simulated data. Δg probed through scaling violations of g_1 at much lower x-values than at RHIC

Bora, Lucero, Sassot, Aschenauer, Nunes 2007.08300

Polarized PDFs at NNLO

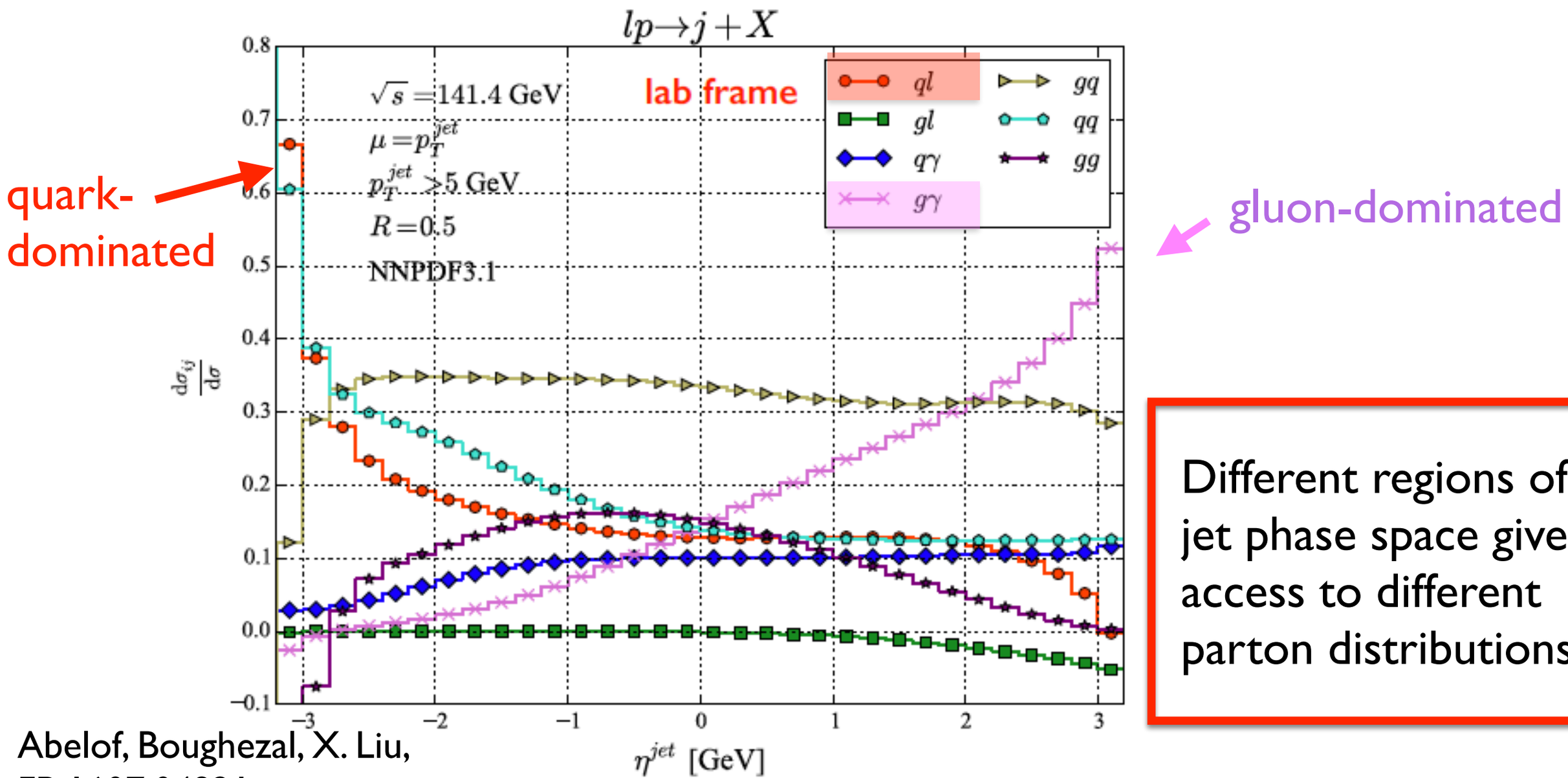




Long-term goal: NNLO extraction of polarized PDFs and FFs. Our understanding of unpolarized PDFs at this level has had a profound impact on our ability to understand LHC data.

Jets and longitudinal proton structure

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

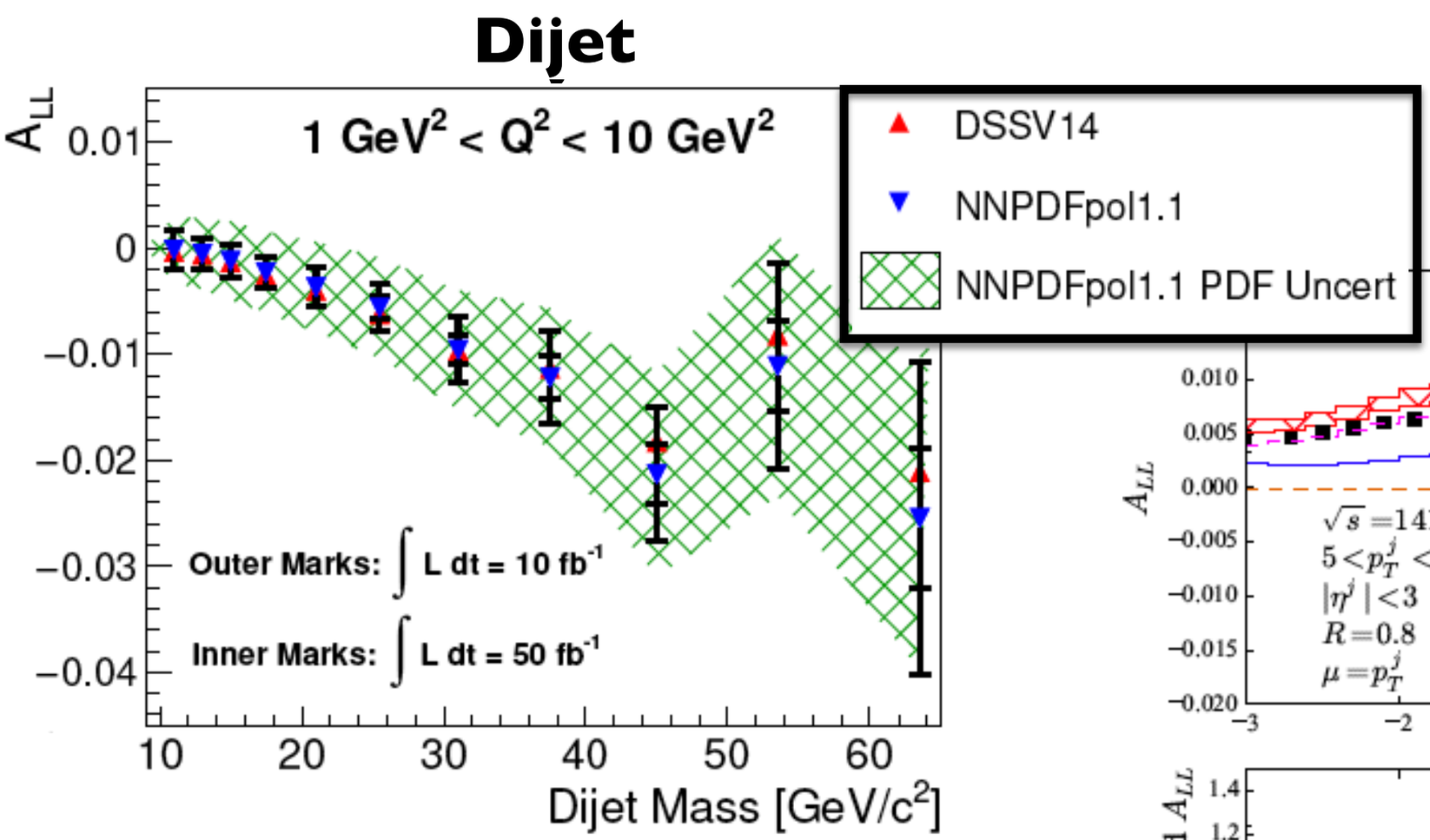


Different regions of jet phase space give access to different parton distributions

Abelof, Boughezal, X. Liu, FP 1607.04921

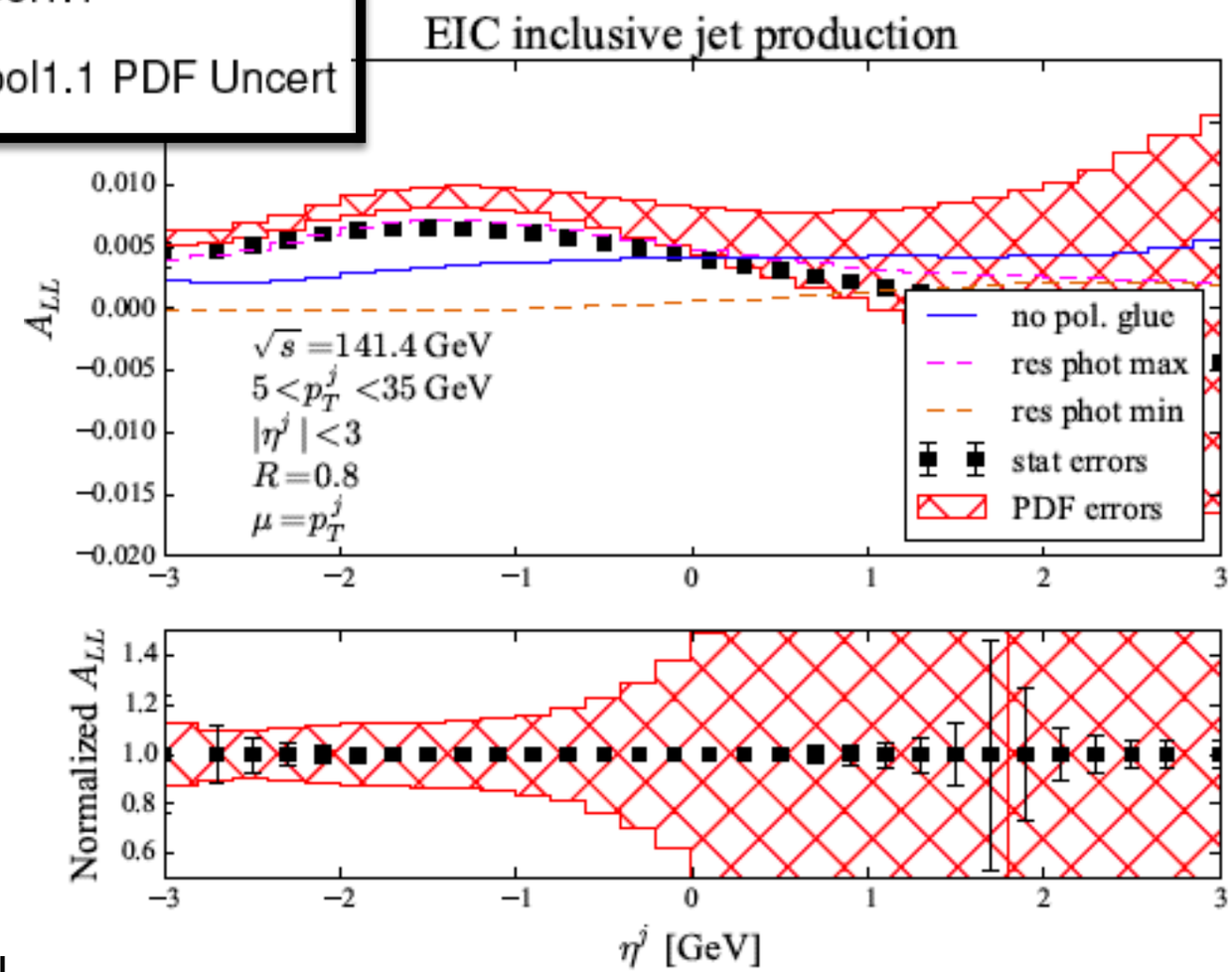
Jets and longitudinal proton structure

- PDF errors larger than estimated experimental errors. These distributions can improve current PDF extractions. They have different systematic errors than g_1 and can provide cross-checks



Page, Chu, Aschenauer, 1911.00657

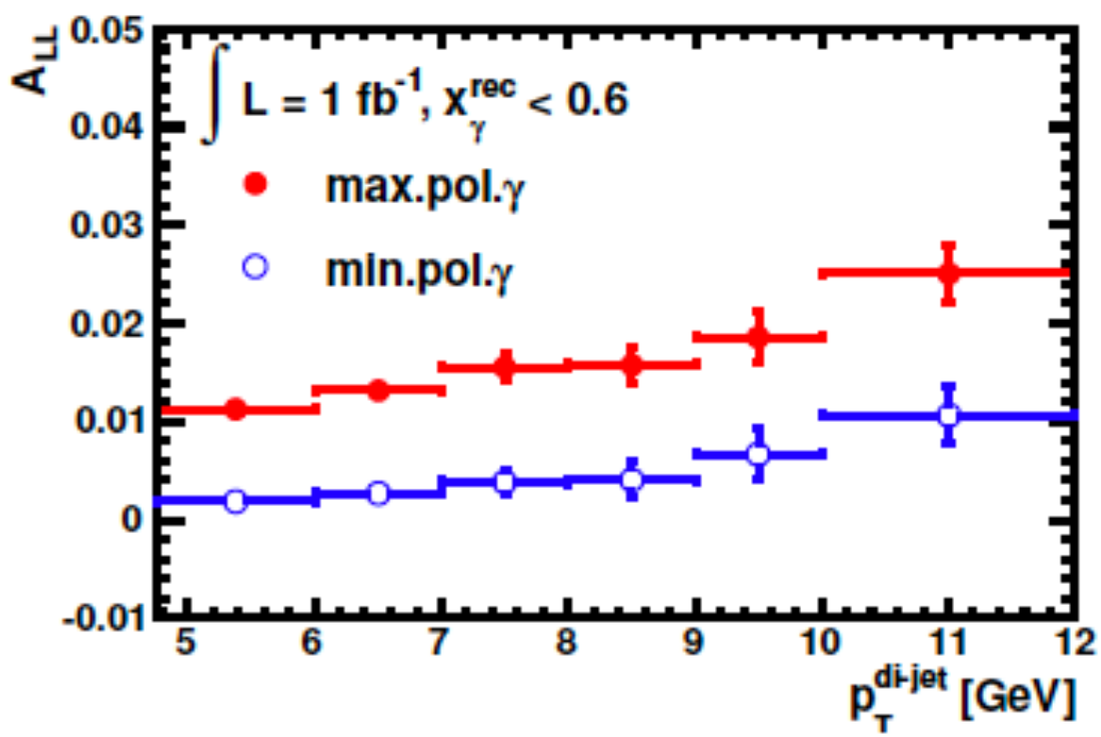
Boughezal, FP, Xing 1806.07311

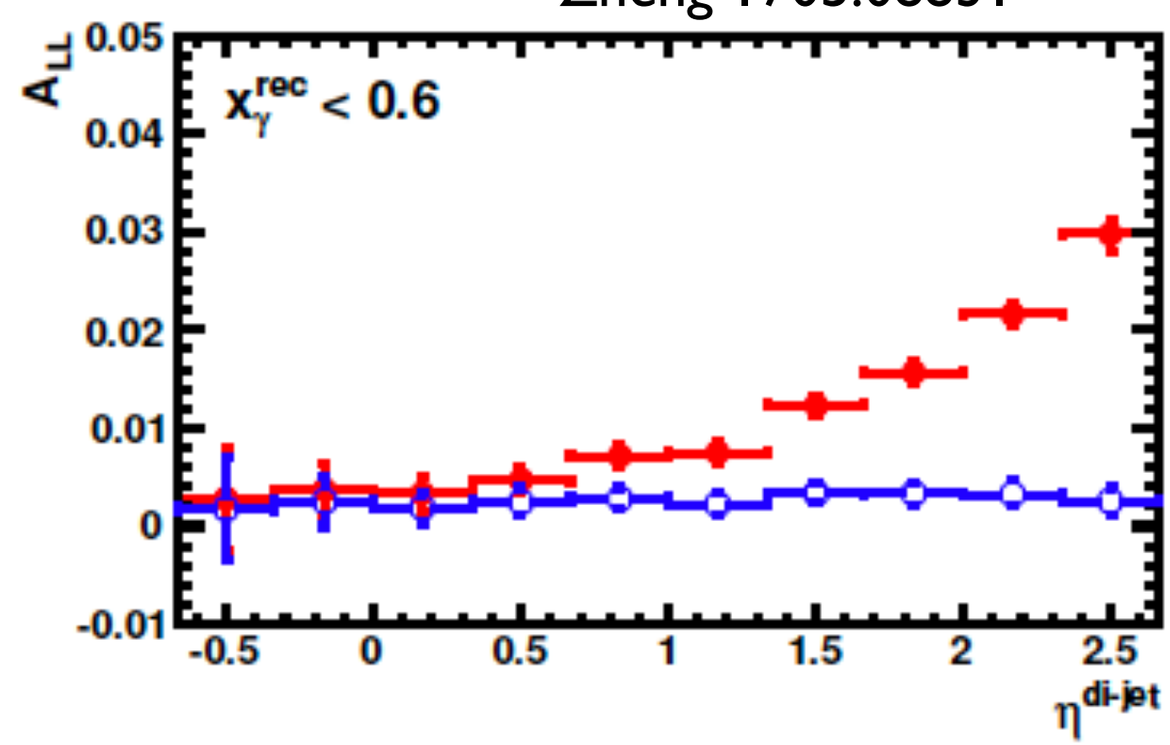


Jets and longitudinal photon structure

- 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





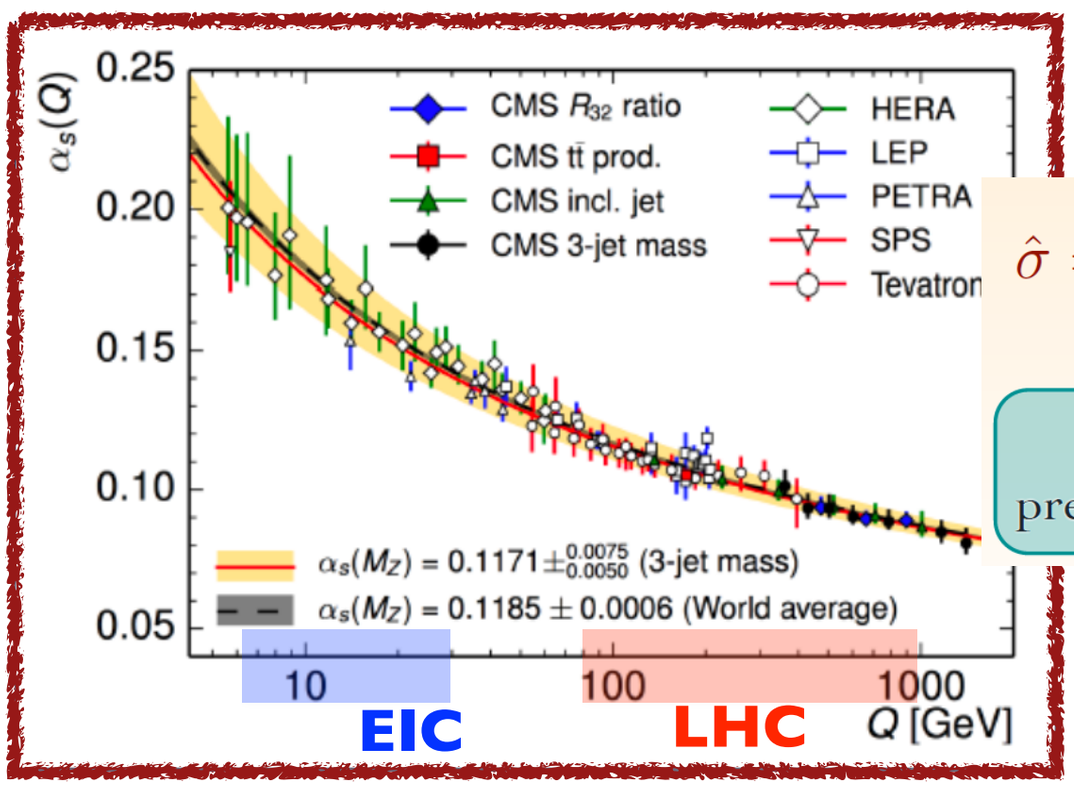
minimal: $\Delta f^\gamma(x,\mu^2) = 0$

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

pQCD framework

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

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



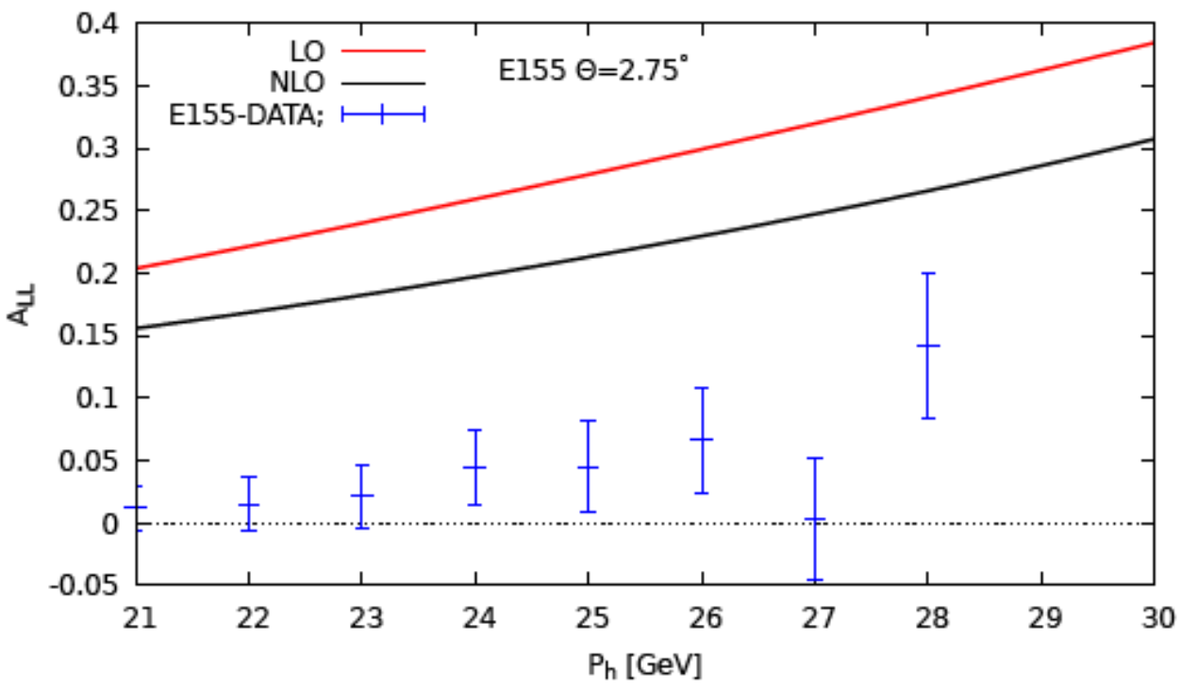
$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)} + \ldots\right)$$

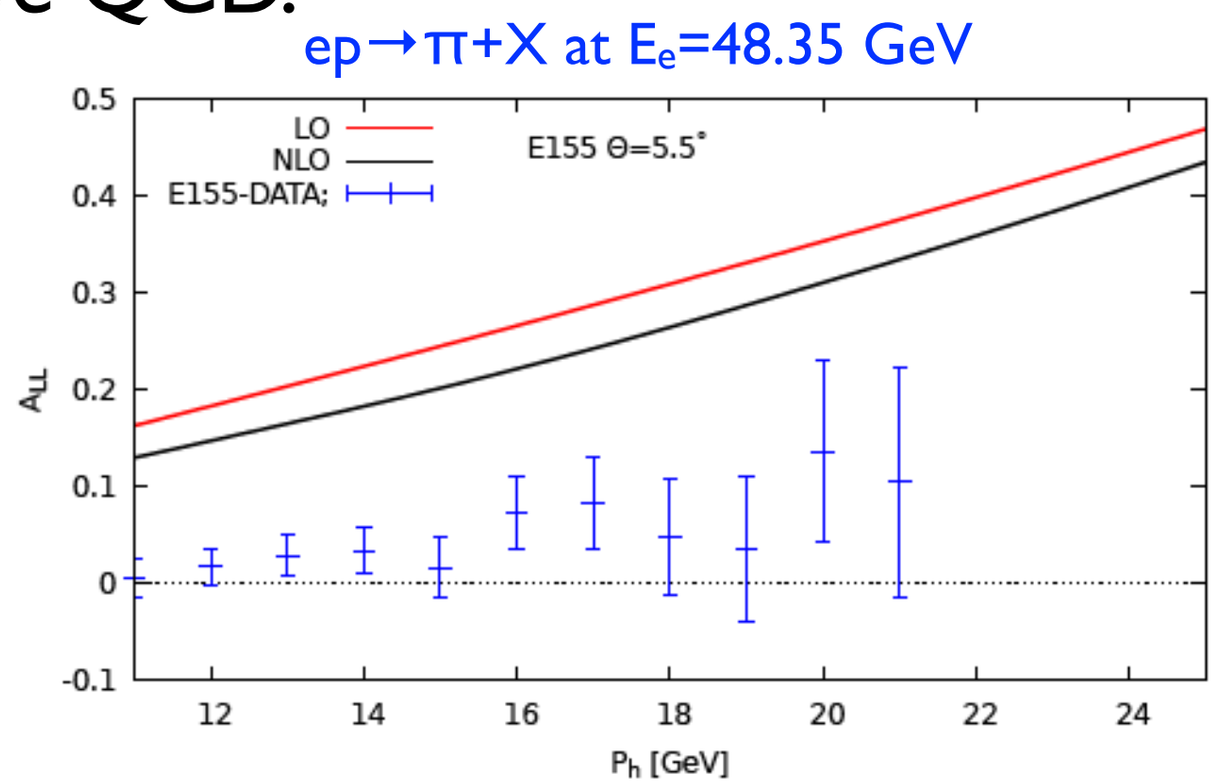
LO predictions | NLO corrections | NNLO corrections | NNNLO corrections

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

pQCD framework

- Jets at the EIC will also probe open questions regarding the region of validity of perturbative QCD.





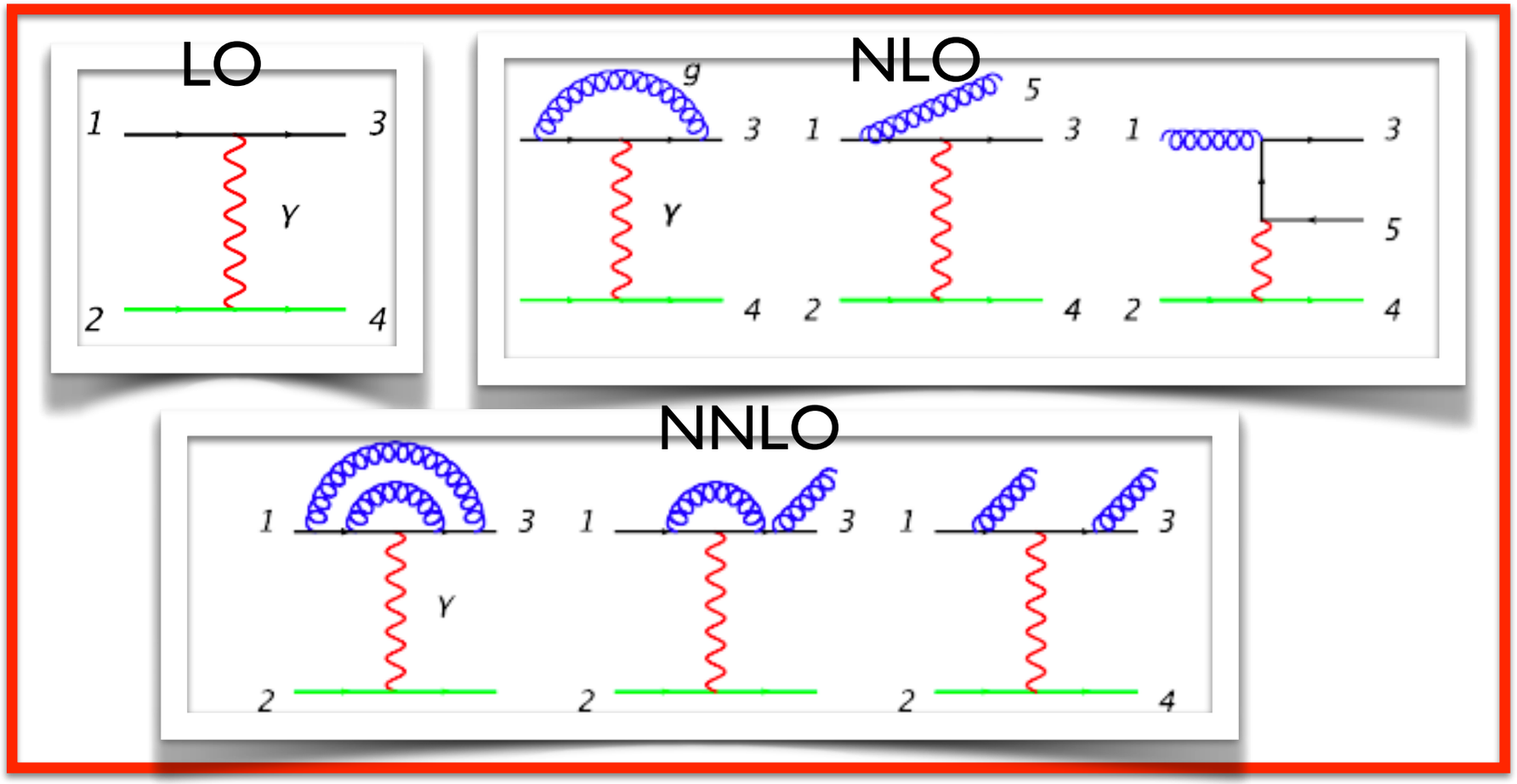
Poor agreement and large corrections for associated asymmetry in hadron production at E155; higher-twist? PDFs or FFs? Revisit this issue with jets and the larger kinematic lever arm at the EIC

Inclusive jet production at the EIC

- Review the structure and phenomenology of jet production at higher orders at the EIC.
- Three distinct contributions through $O(\alpha_s^2)$:

(1) DIS process:
$q_1+e_2 \rightarrow q_3+l_4+X$

Begins at $O(\alpha_s^0)$



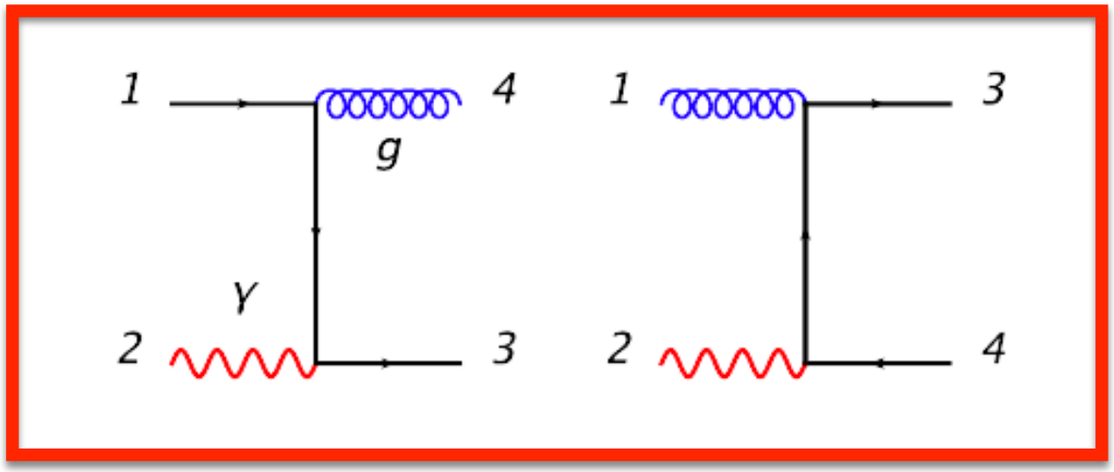
Inclusive jet production at the EIC

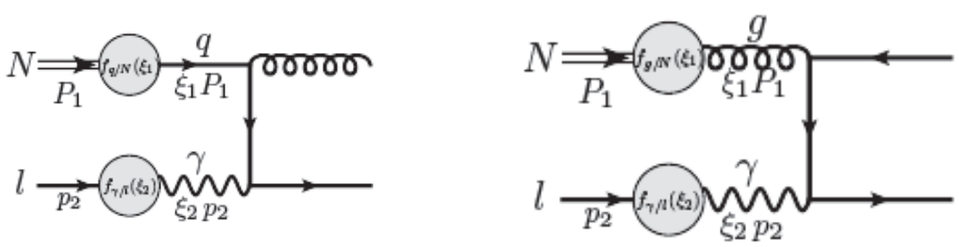
- Three distinct contributions through $O(\alpha_s^2)$:

(2) Weizsacker-Williams (WW) photon process:

$q/g_1+\gamma_2 \rightarrow q_3+g/q_4+X$

Begins at $O(\alpha_s^1)$





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

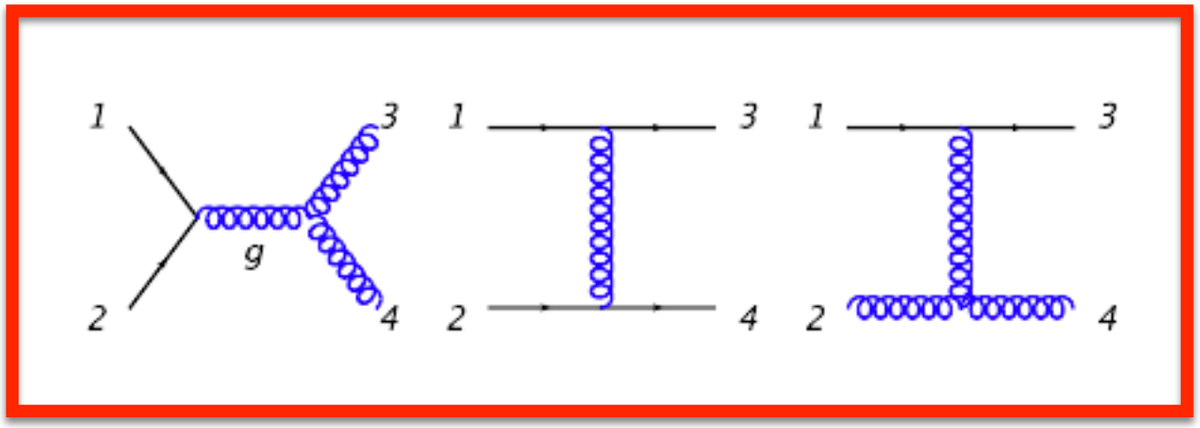
$Q^2 \simeq 0$

Inclusive jet production at the EIC

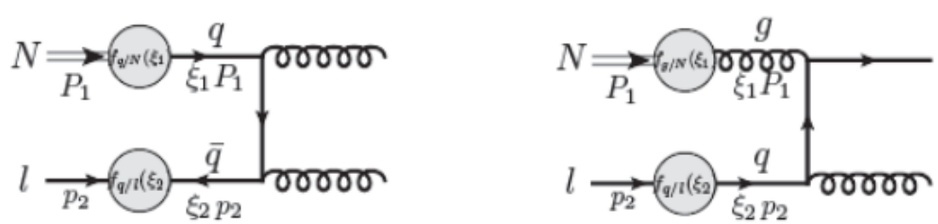
- Three distinct contributions through $O(\alpha_s^2)$:

(3) Resolved photon process:

$q/g_1 + q/g_2 \rightarrow q/g_3 + g/q_4 + X$



Formally begins at $O(\alpha_s^2)$



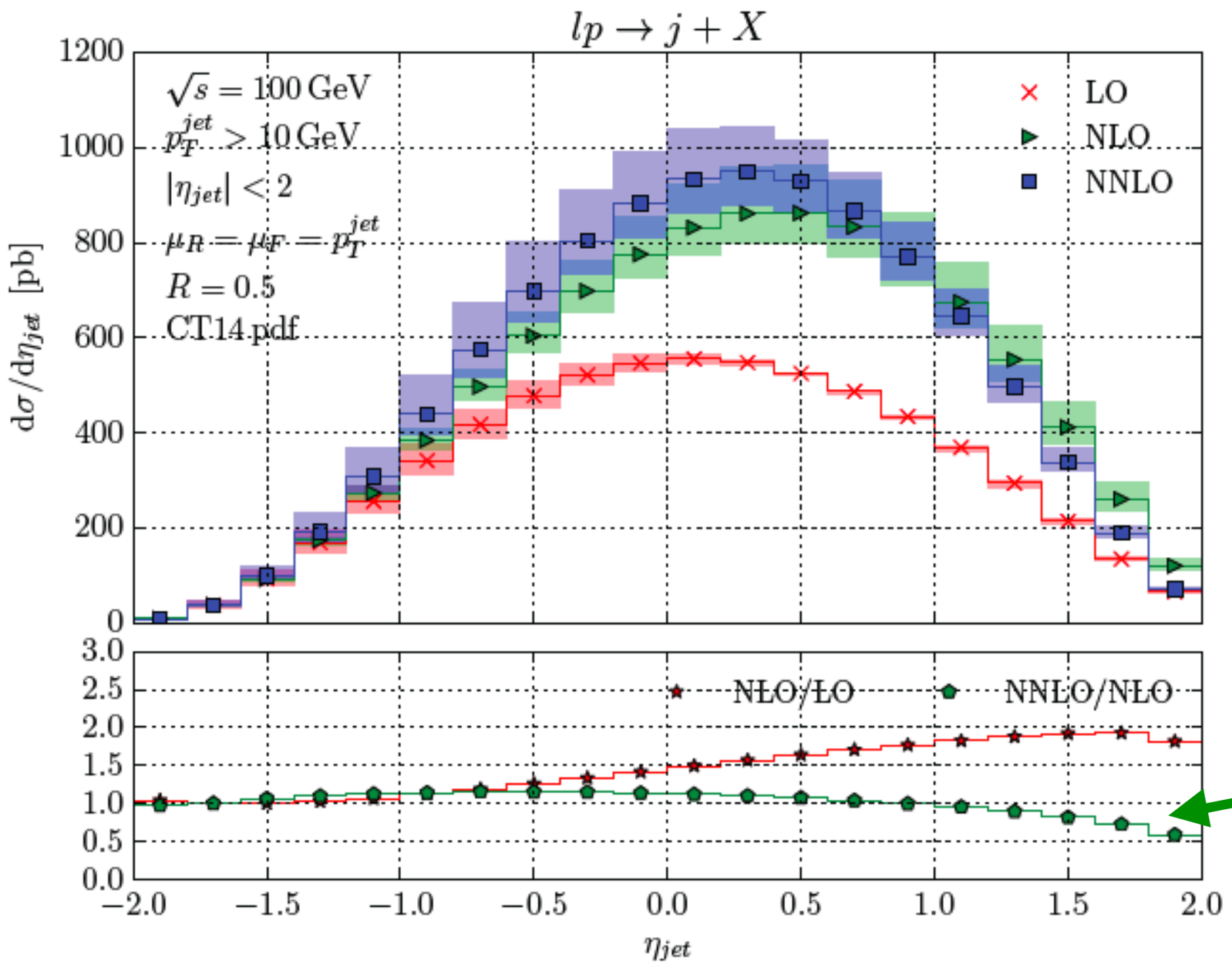
$$\int \frac{d\xi_1 d\xi_2 dy}{\xi_1 \xi_2 y} \Delta f_{i/P}(\xi_1) \Delta f_{j/\gamma}(\xi_2/y) \Delta P_{\gamma l}(y) \Delta\hat{\sigma}_{ij}(y)$$

polarized proton PDFs

polarized photon PDFs

polarized QED splitting function

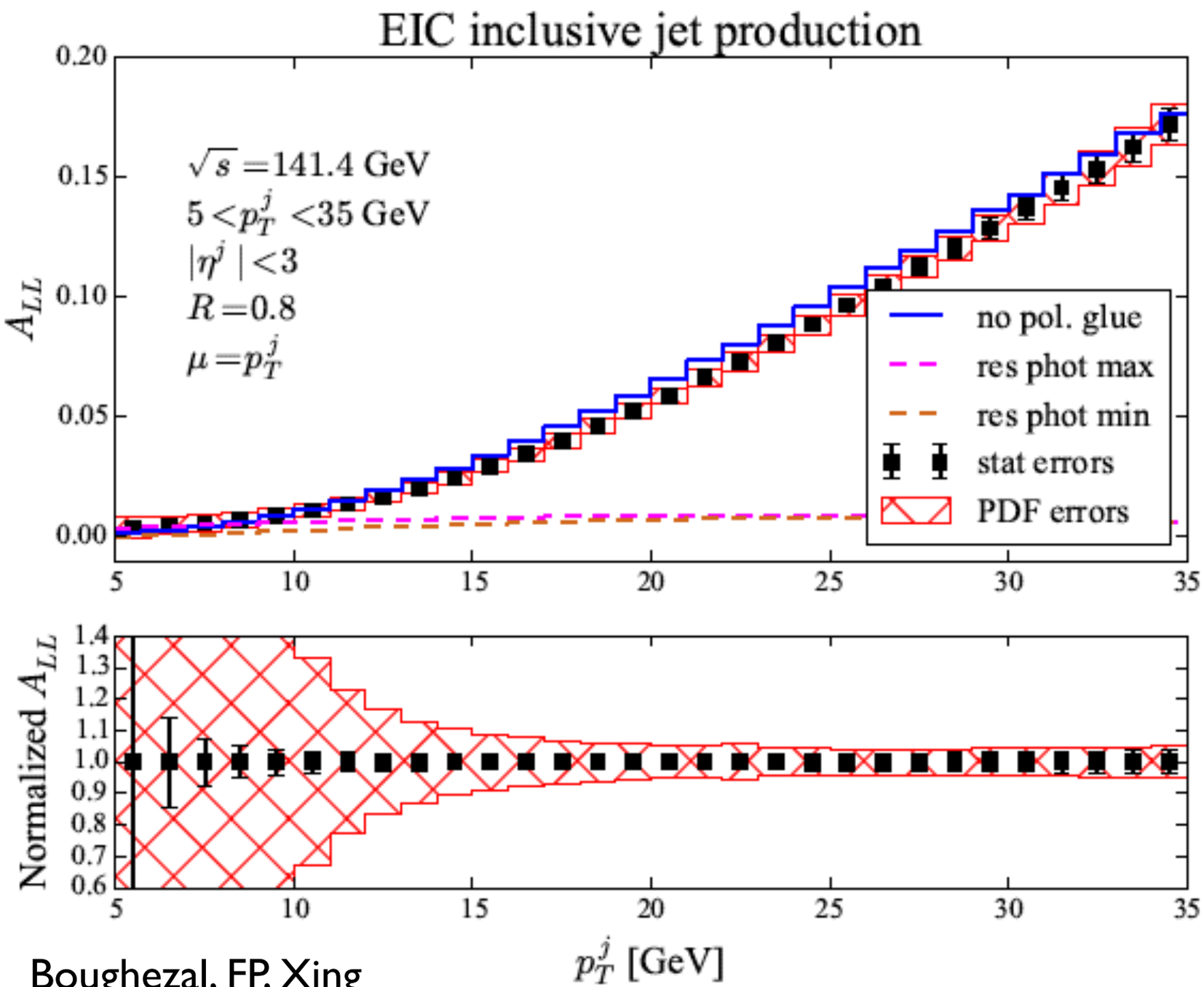
Inclusive jet production: unpolarized



- 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

Abelof, Boughezal, X. Liu, FP 1607.04921

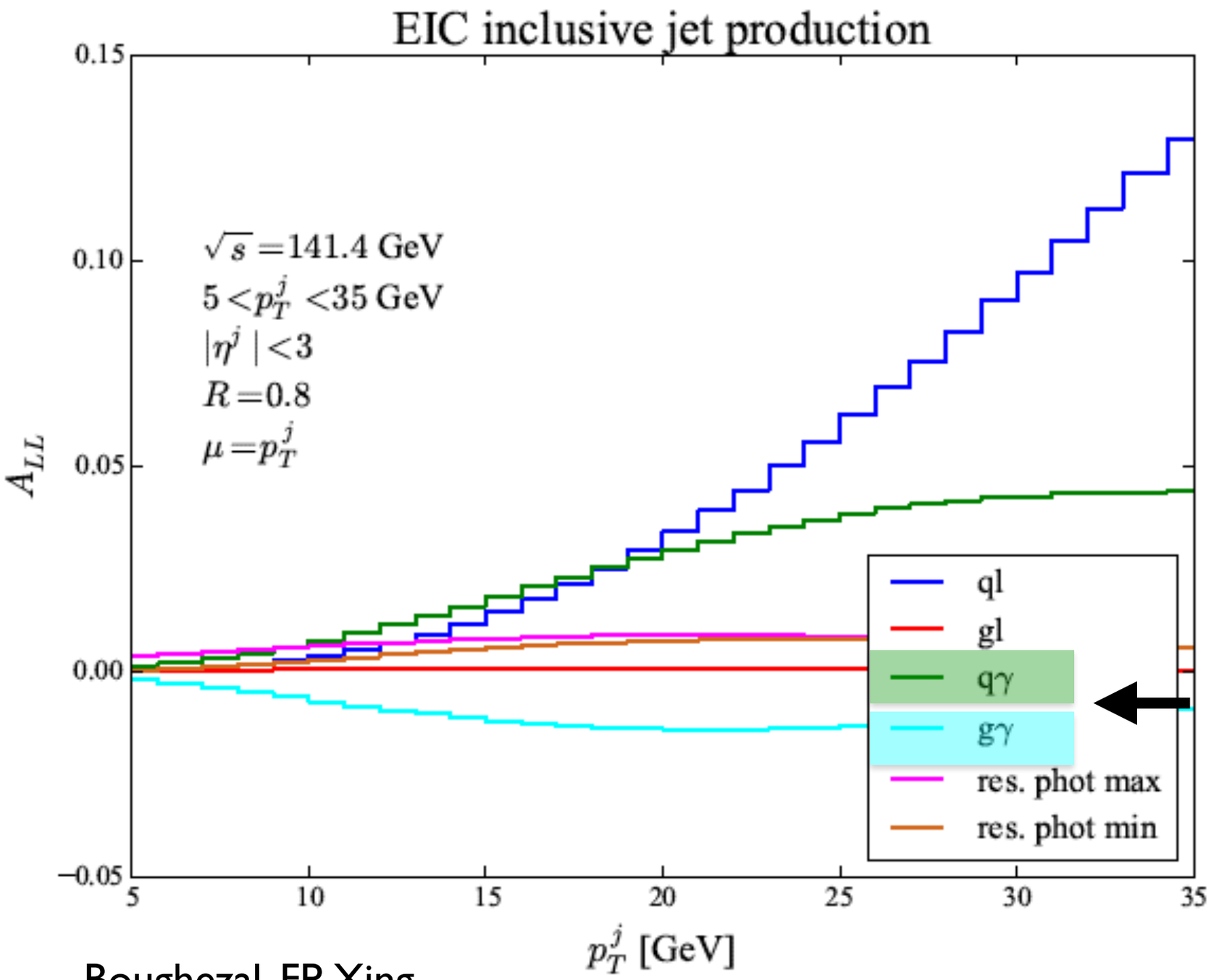
Inclusive jet production: polarized



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

Boughezal, FP, Xing
1806.07311: NLO analysis with resolved photons

Inclusive jet production: polarized

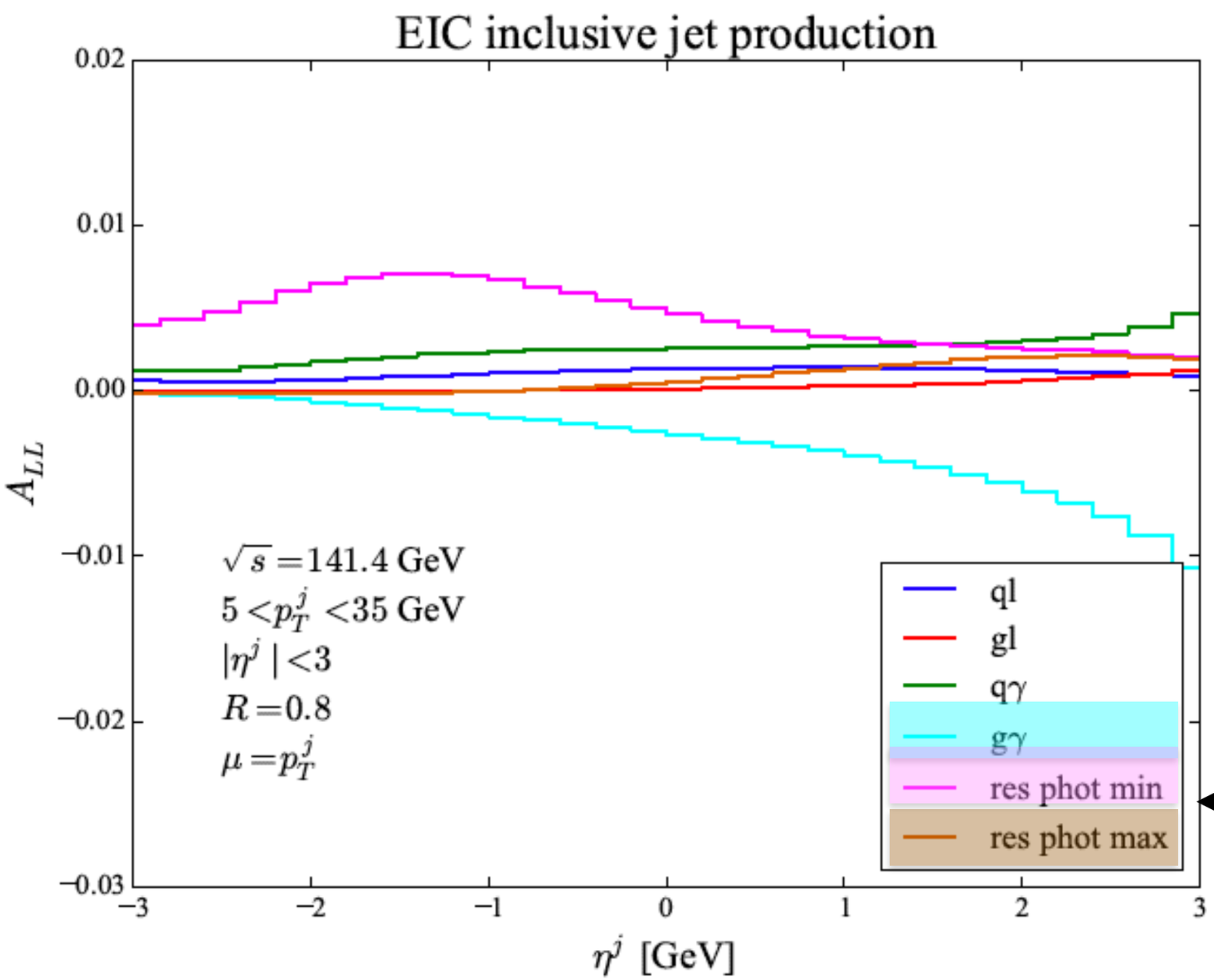


- ql channel dominates at high p_T; gl channel small throughout
- At intermediate p_T get contributions from qγ and gγ

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

Boughezal, FP, Xing
1806.07311: NLO analysis with resolved photons

Inclusive jet production: polarized

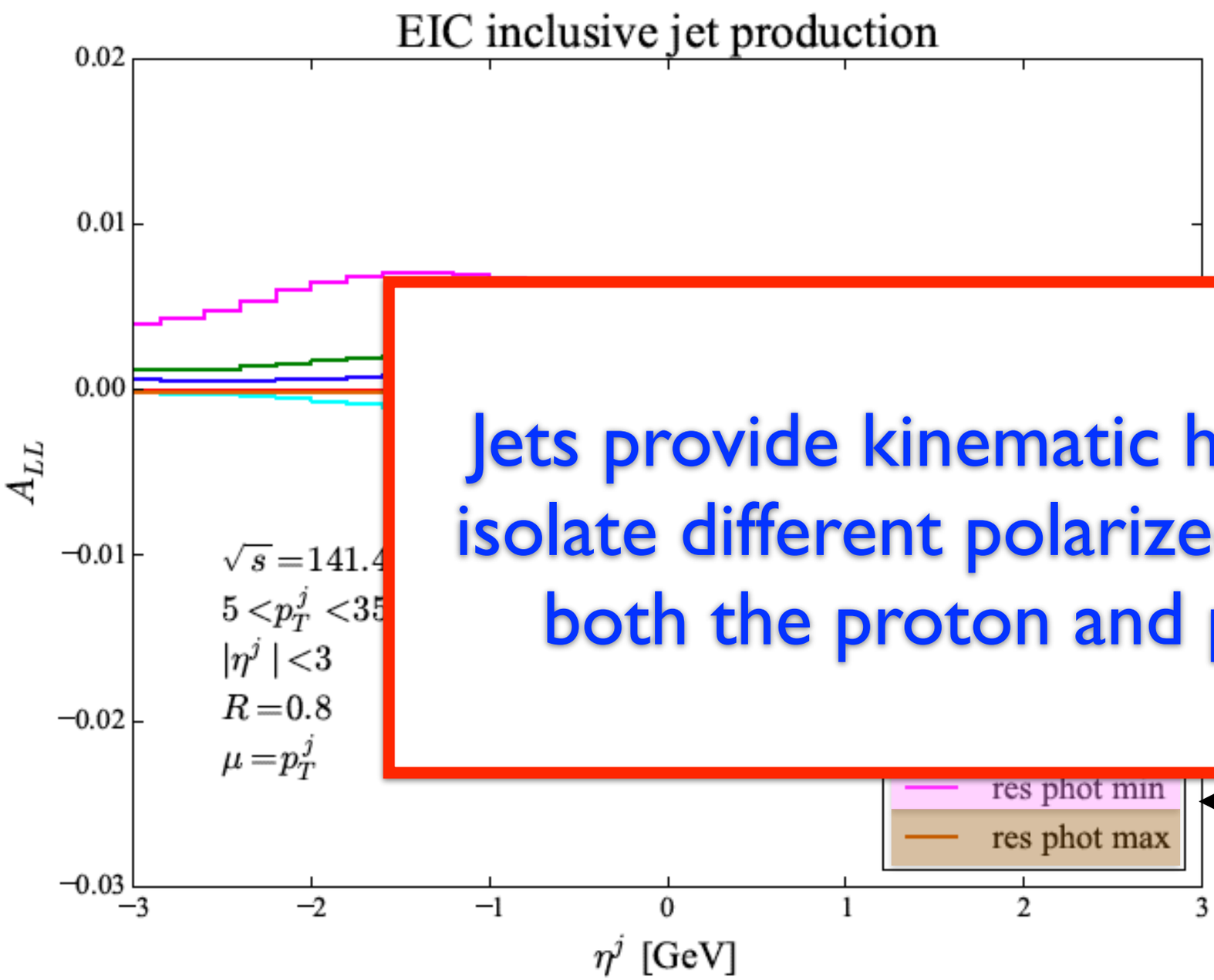


- gγ channel dominates at forward eta

Sensitive to $\Delta f_i/\gamma$ at backward eta

Boughezal, FP, 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

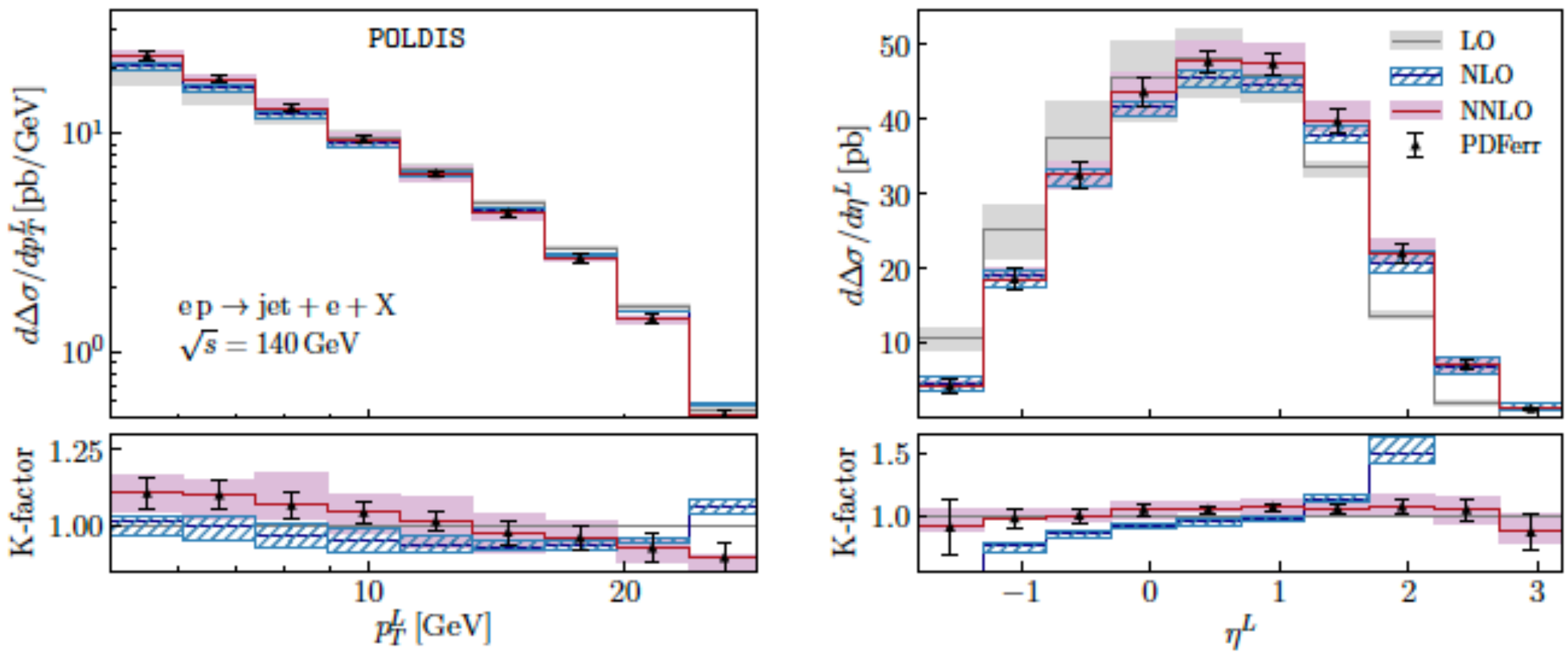
ominates at

sensitive to $\Delta f_i/\gamma$ at backward eta

Boughezal, FP, Xing
1806.07311: NLO analysis with resolved photons

Inclusive jet production: polarized

- New result: inclusive jet production in polarized DIS through NNLO (n.b. no WW or resolved photons)

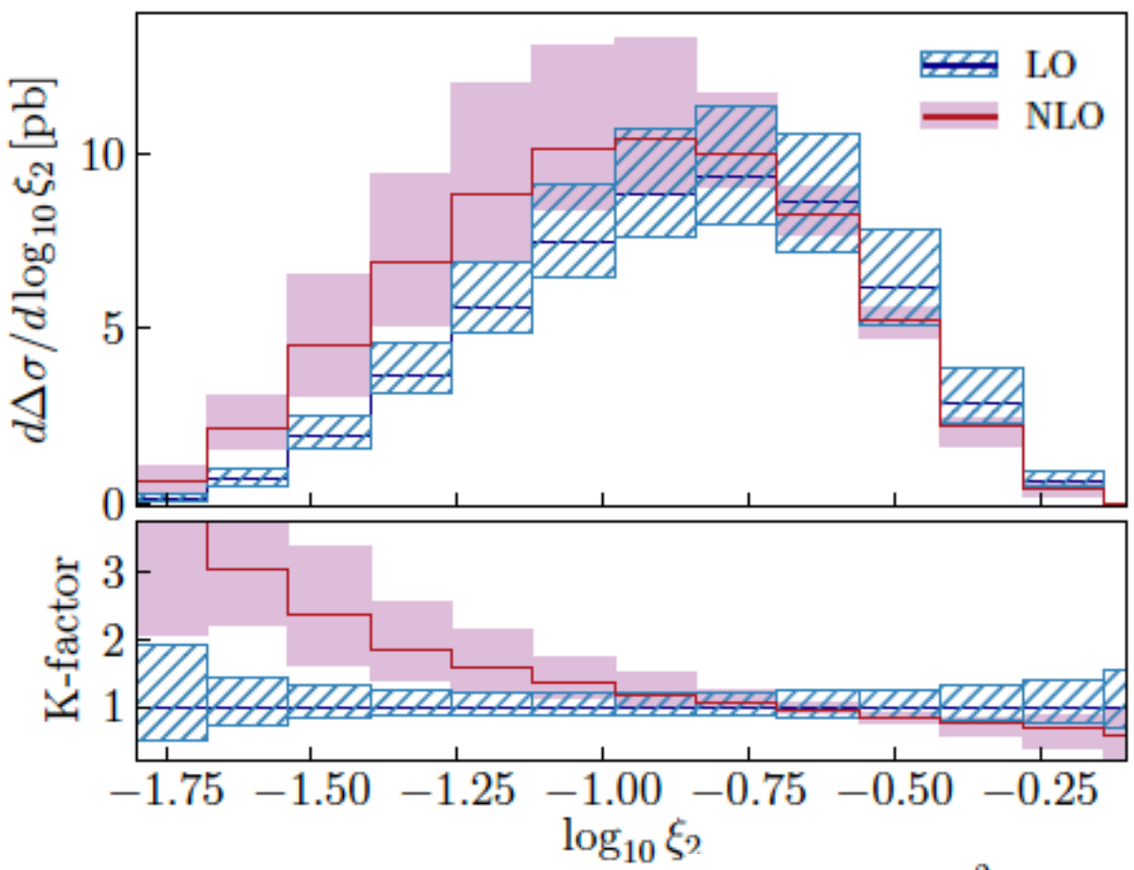


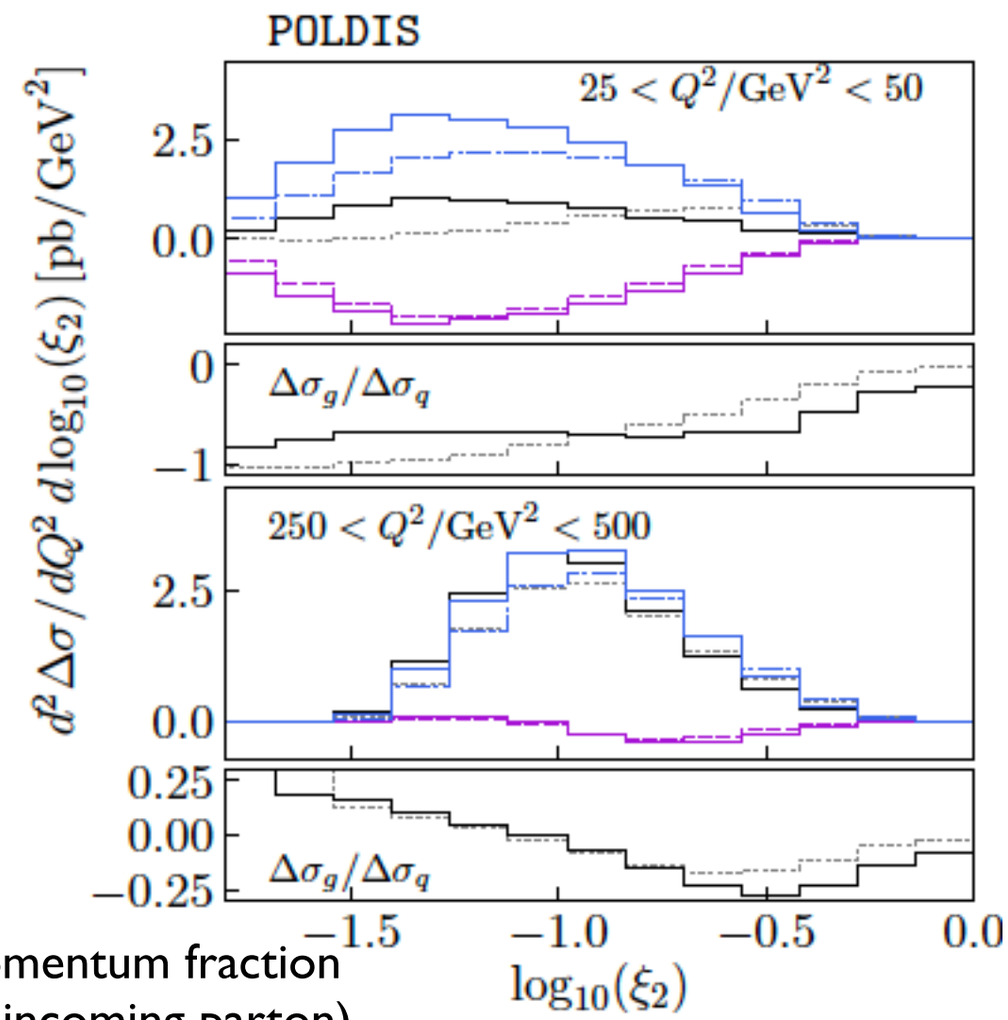
Good perturbative behavior of the DIS process observed

Borsa, de Florian, Pedron 2010.07354

Di-jet production: polarized

- NLO calculation for di-jet production in polarized DIS (n.b. no WW or resolved photons)





$\xi_2 = x(1 + \frac{M_{12}^2}{Q^2})$ (at LO, momentum fraction carried by incoming parton)

Improved scale dependence on NLO; can enhance gluon contribution in certain regions of final-state phase space

Conclusions

- We can bring our understanding of longitudinal 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 in this quest: offer kinematic handles to separate different PDFs, independent of FFs
- The needed theoretical calculations are available