Higher-order pQCD and jet physics at an EIC

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Probing Nucleons and Nuclei in High Energy Collisions

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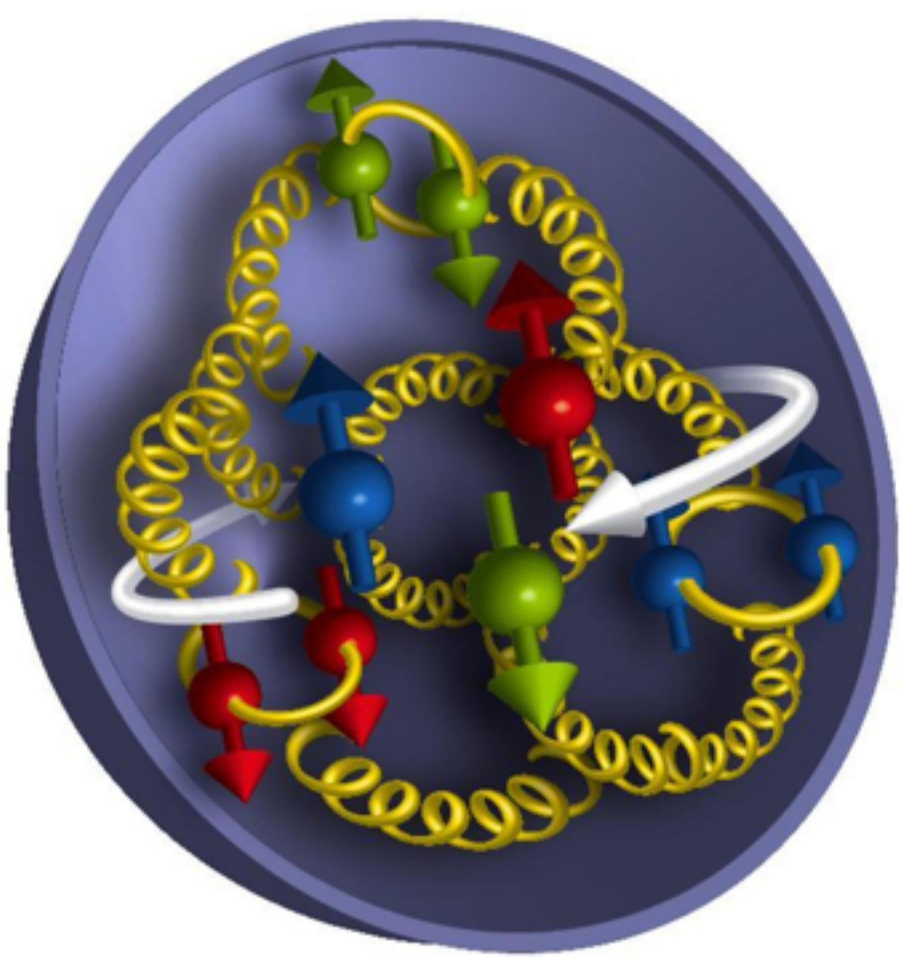
The proton spin

- Even after four decades of study, aspects of QCD still surprise us today.



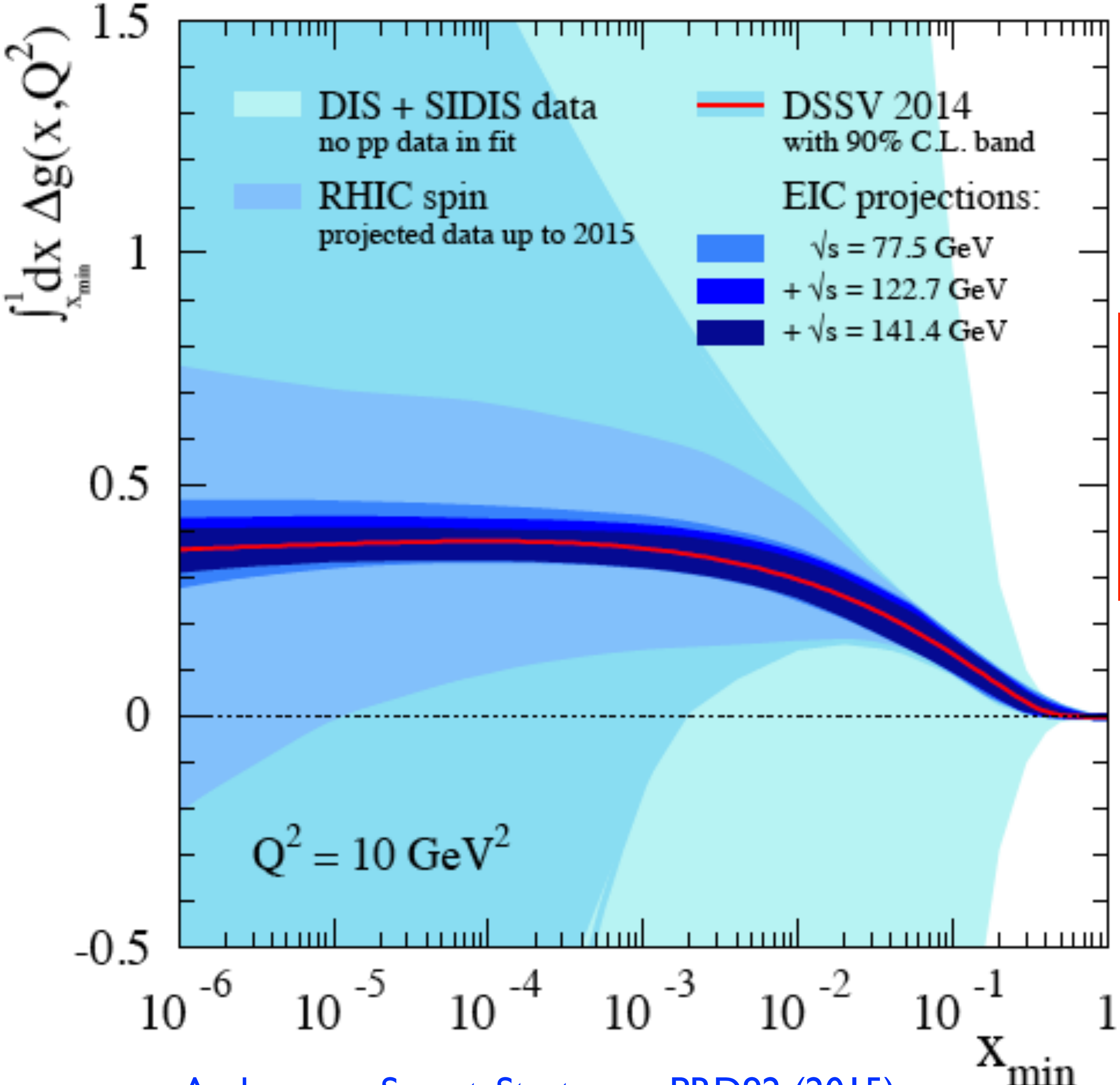
How is the proton spin formed from its microscopic constituents?

Quark spin Gluon spin Orbital

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

Only ~30% ? Lattice suggest that this is not 70%

A definitive answer to this questions will require a future electron-ion collider (EIC)

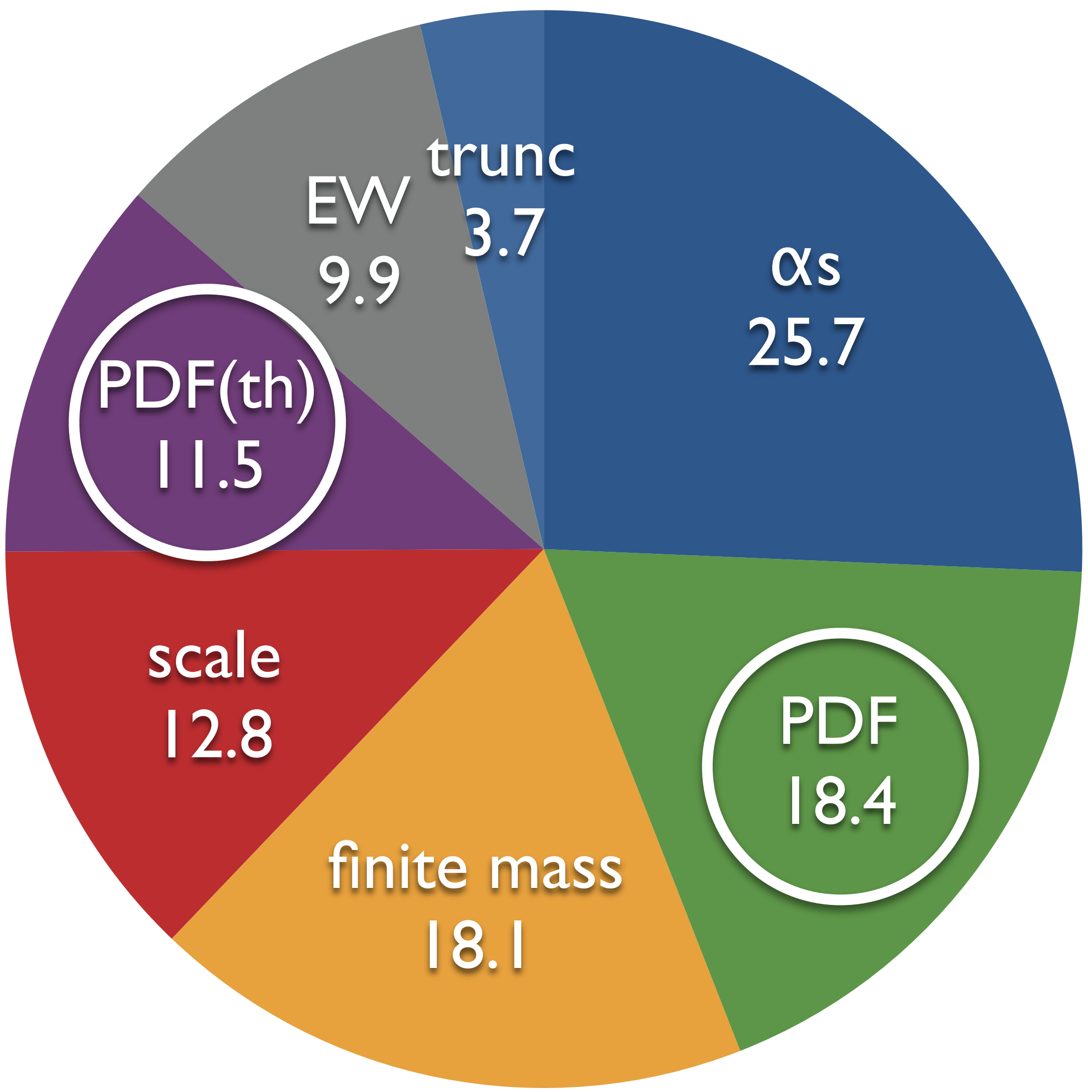


Precision probes of the proton spin structure are possible at an EIC

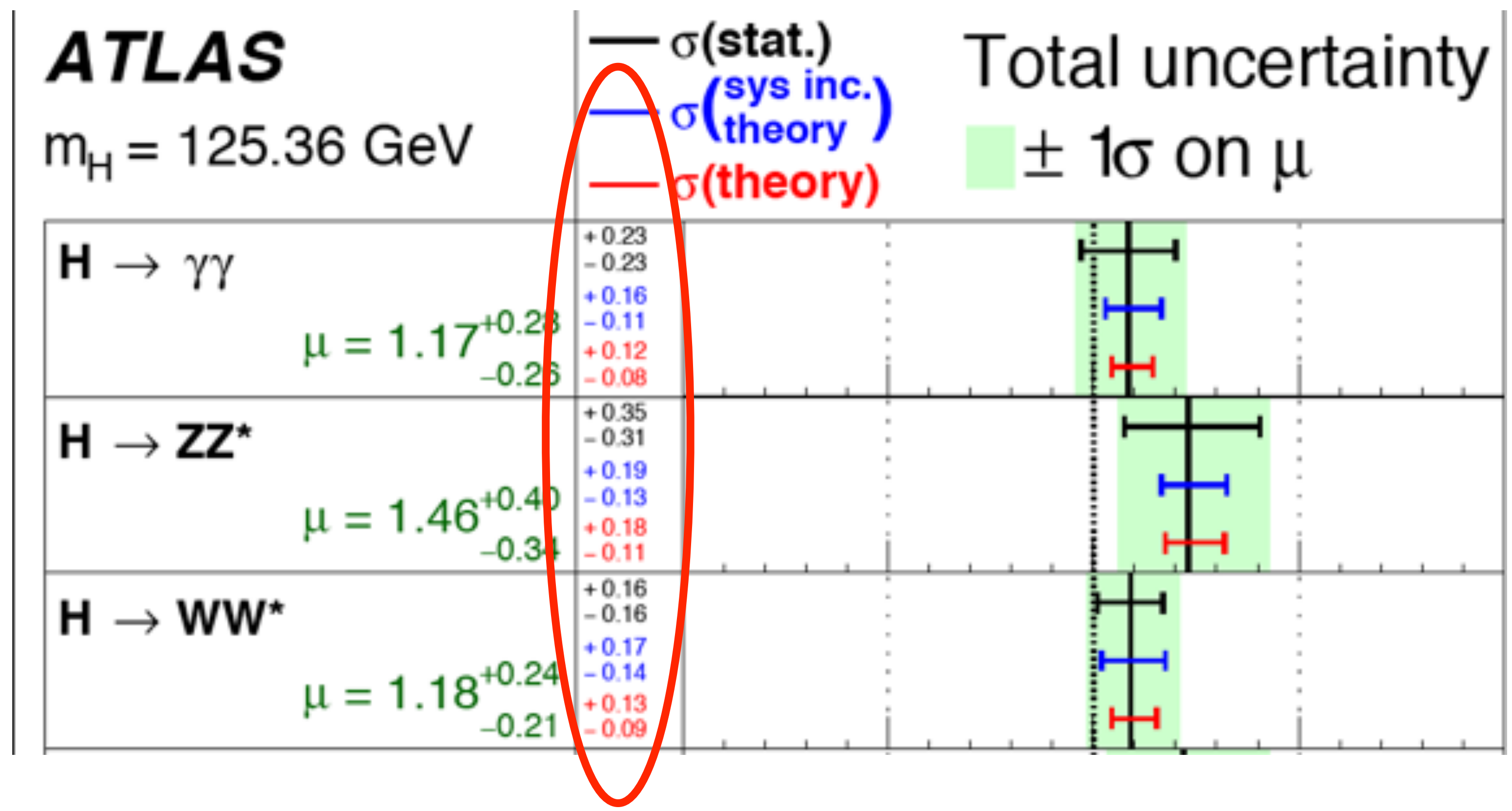
Aschenauer, Sassot, Stratmann PRD92 (2015)

Proton structure at high energies

- Understanding proton structure is also critical to our pursuit of physics beyond the Standard Model.



Breakdown of residual theory errors on Higgs production cross section in %



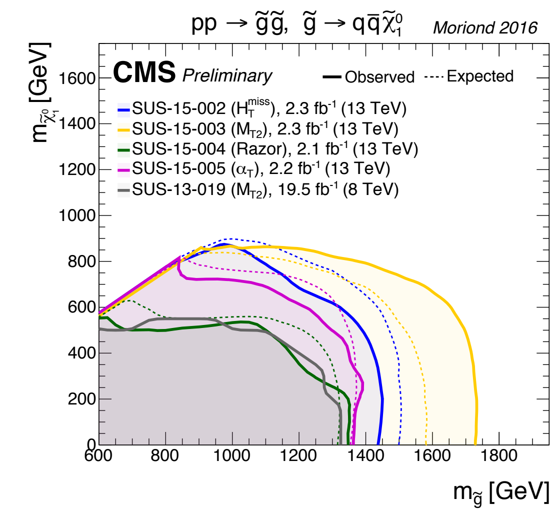
Proton structure as encoded by parton distribution functions (PDFs) form one of the largest uncertainties on the Higgs production cross section

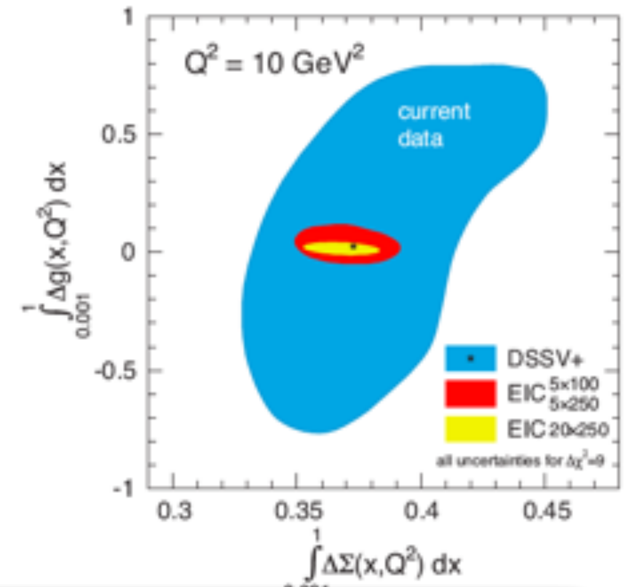
The role of pQCD

- Similar roles of pQCD at the LHC and at a future EIC:

  LHC: disentangle pQCD effects from new beyond-the-SM phenomena (SUSY, dark matter, extra dimensions, …)

  EIC: disentangle pQCD effects from the measurements of nucleon structure (helicity PDFs, higher-twist, …)



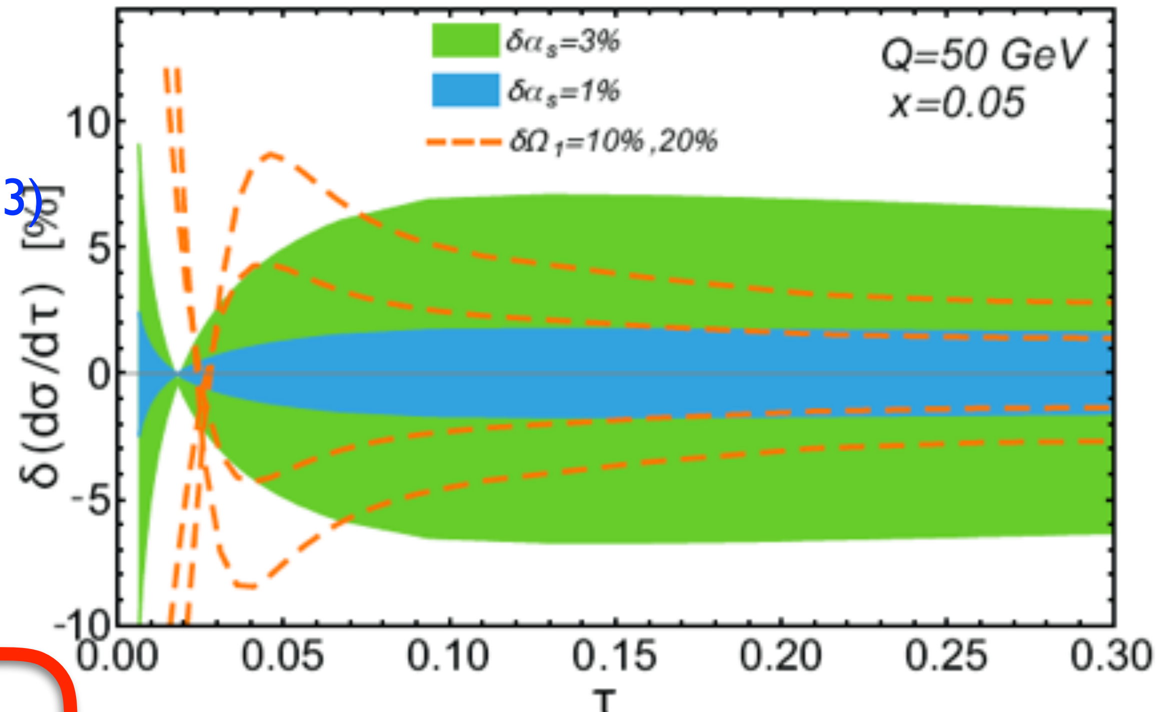


➡ **Extracted TMDs depend on the scheme (UV) and perturbative order (LO, NLO, NNLL, …), at which the hard part and the TMD evolution kernels, were calculated!**

Jet physics at the EIC

- Numerous motivations for studying inclusive jet production at a future EIC; already many talks at this workshop
  - Investigation of proton structure, the focus of this talk
  - Determination of higher-twist properties of the proton Z. Kang, Metz, Qiu, Zhou PRD84 (2011)
  - Measure properties of the nuclear medium with event shapes Z. Kang, Liu, Mantry, Qiu PRD88 (2013)
  - Measurement of the strong coupling constant through DIS event shapes

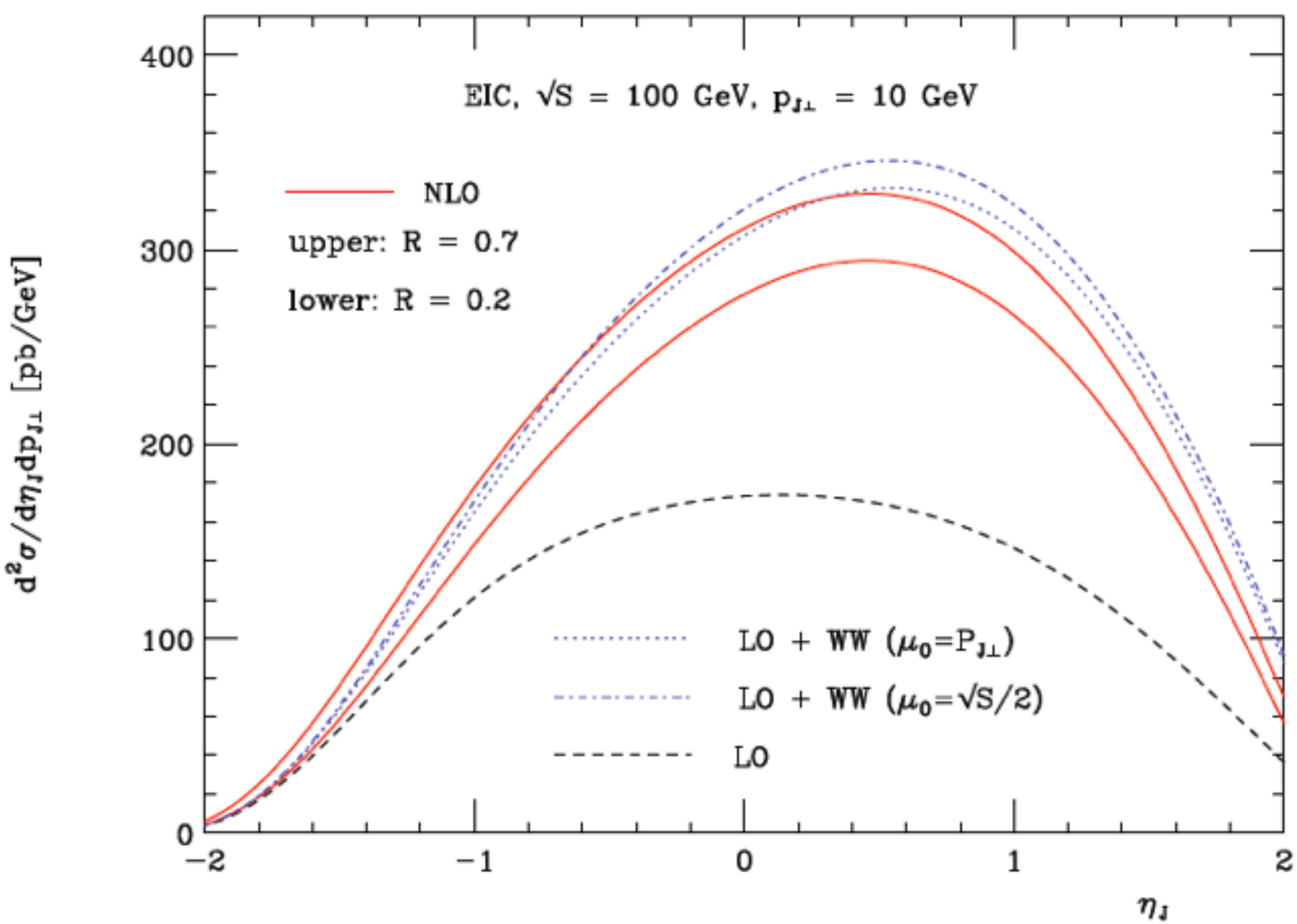
    D. Kang, Lee, Stewart arXiv:1601.01499



The precision of an EIC plays a critical role in all of these measurements!

The challenge: large pQCD effects

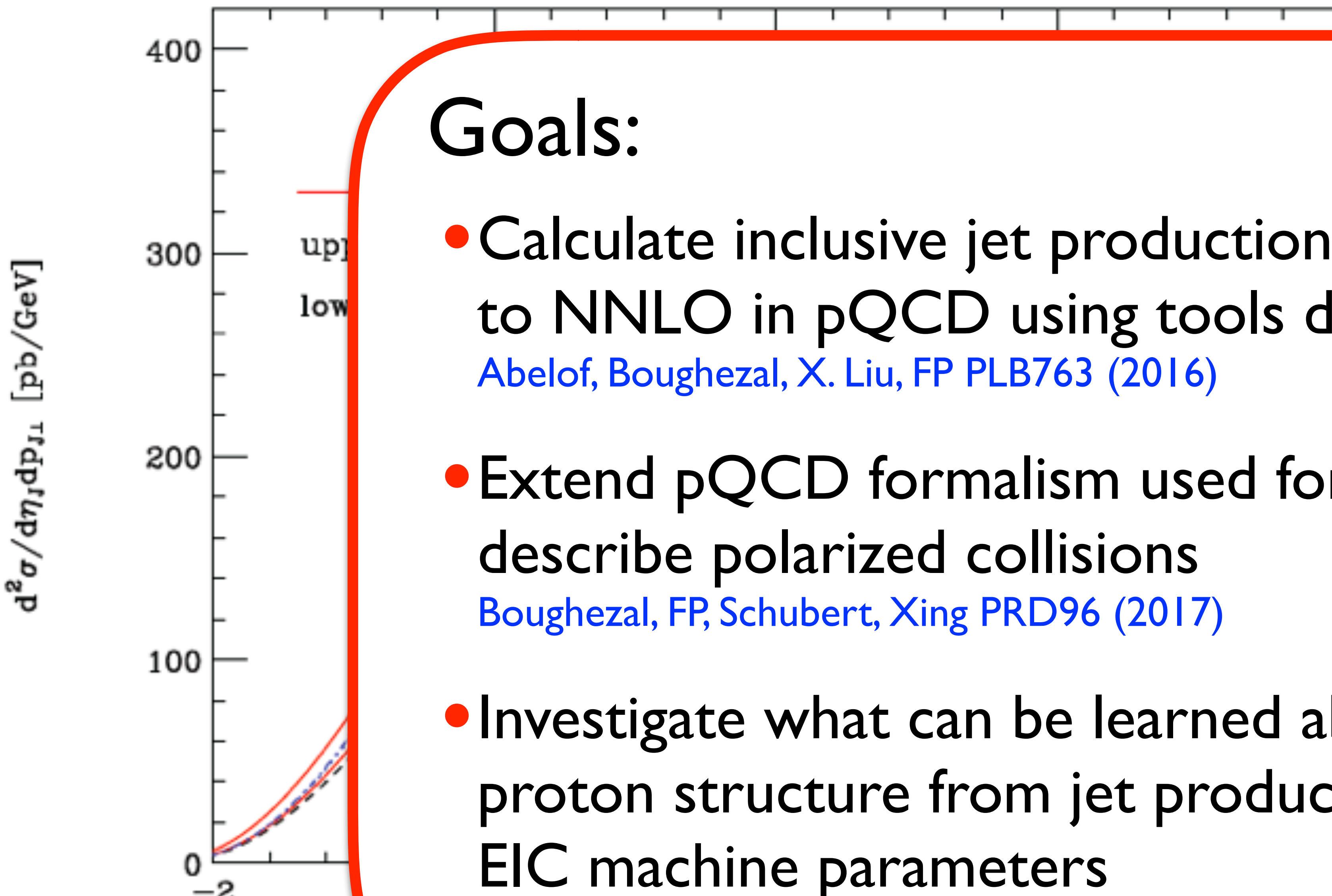
- Motovation: calculation of inclusive jet production through NLO



Hinderer, Schlegel, Vogelsang PRD92 (2015)

- Large NLO perturbative corrections, O(100%)
- Can we go to NNLO to facilitate precision EIC measurements?

The challenge: large pQCD effects



Hinderer, S

Goals:

- Calculate inclusive jet production in unpolarized DIS to NNLO in pQCD using tools developed for LHC
  Abelof, Boughezal, X. Liu, FP PLB763 (2016)
- Extend pQCD formalism used for NNLO to also describe polarized collisions
  Boughezal, FP, Schubert, Xing PRD96 (2017)
- Investigate what can be learned about polarized proton structure from jet production for different EIC machine parameters
  Boughezal, FP, Xing PRD98 (2018)

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0%)

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surements?

Theoretical framework and setup

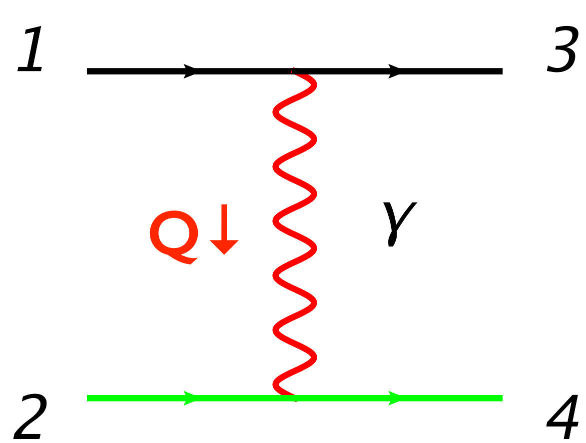
- We assume standard collinear factorization:

$$\sigma_{eN\to X} = \int dx \underbrace{f_{i/N}(x, \overbrace{\mu_F}^{\text{factorization scale}})}_{PDF} \underbrace{\hat{\sigma}_{il\to X}(x,\mu_F)}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

DIS: eN→eN

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

q(p₁)+l(p₂)→q(p₃)+l(p₄)



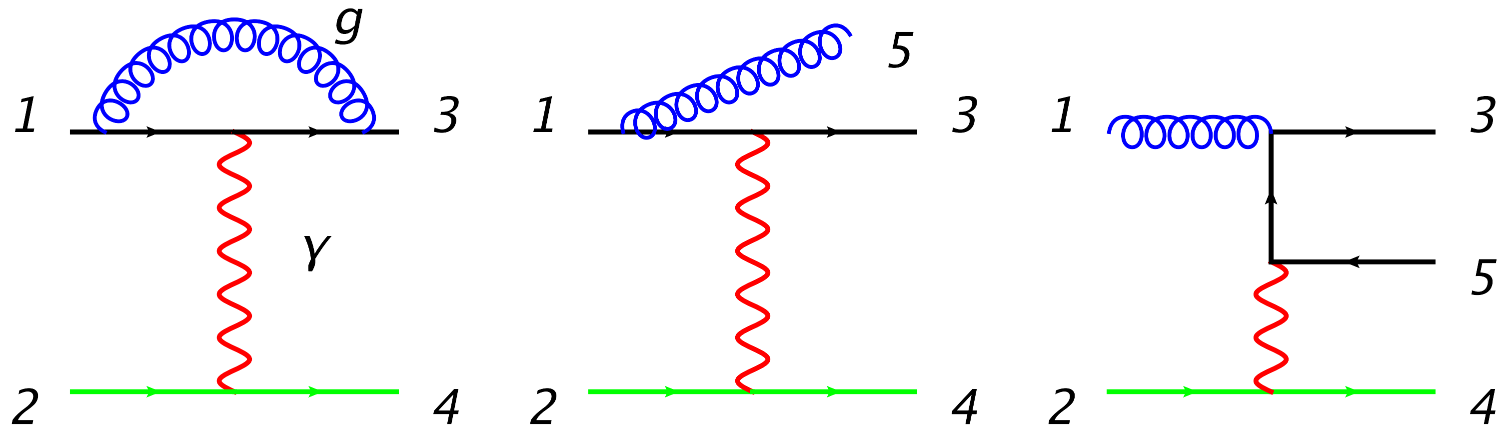
Inclusive jet production: eN→jX

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

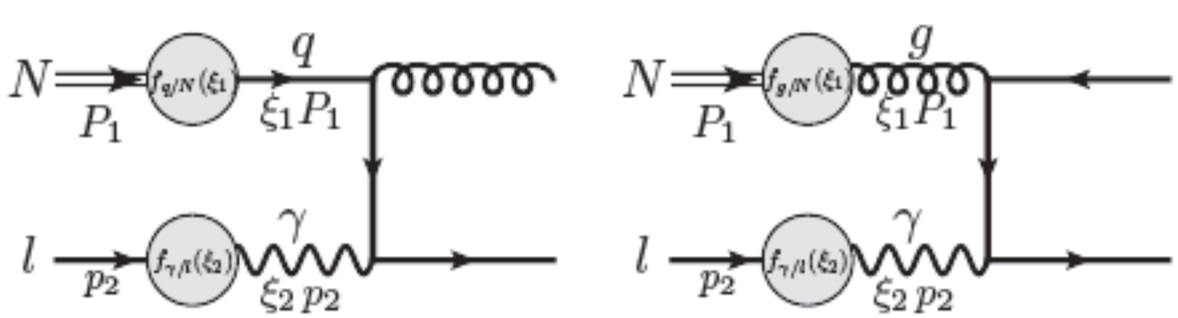
- **Leading order**: identical for both processes, lepton recoils against a jet

NLO $O(\alpha^2\alpha_S)$ corrections

- Typical real and virtual corrections to the quark-lepton scattering processes; new contribution from gluon-lepton scattering→ calculation amenable to standard techniques



- New configuration: lepton collinear to the beam (Q^2~0), with two jets balancing in the transverse plane; on-shell photon scattering with quark→differentiates DIS and inclusive jet production



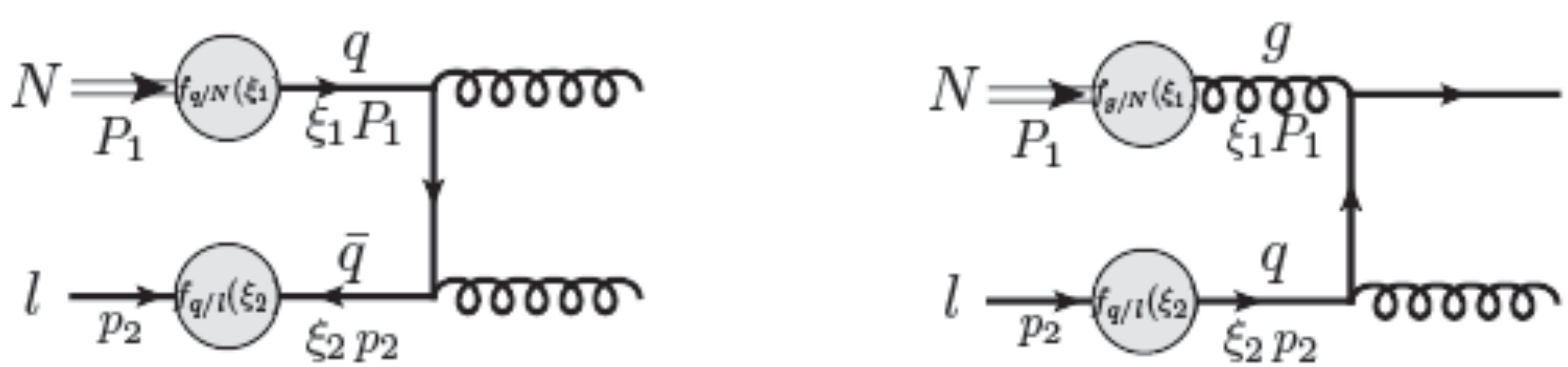
$$f_{\gamma/l}(\xi) = \frac{\alpha}{2\pi} P_{\gamma l}(\xi) \left[\ln\left(\frac{\mu^2}{\xi^2 m_l^2} \right) - 1 \right] + \mathcal{O}(\alpha^2)$$

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

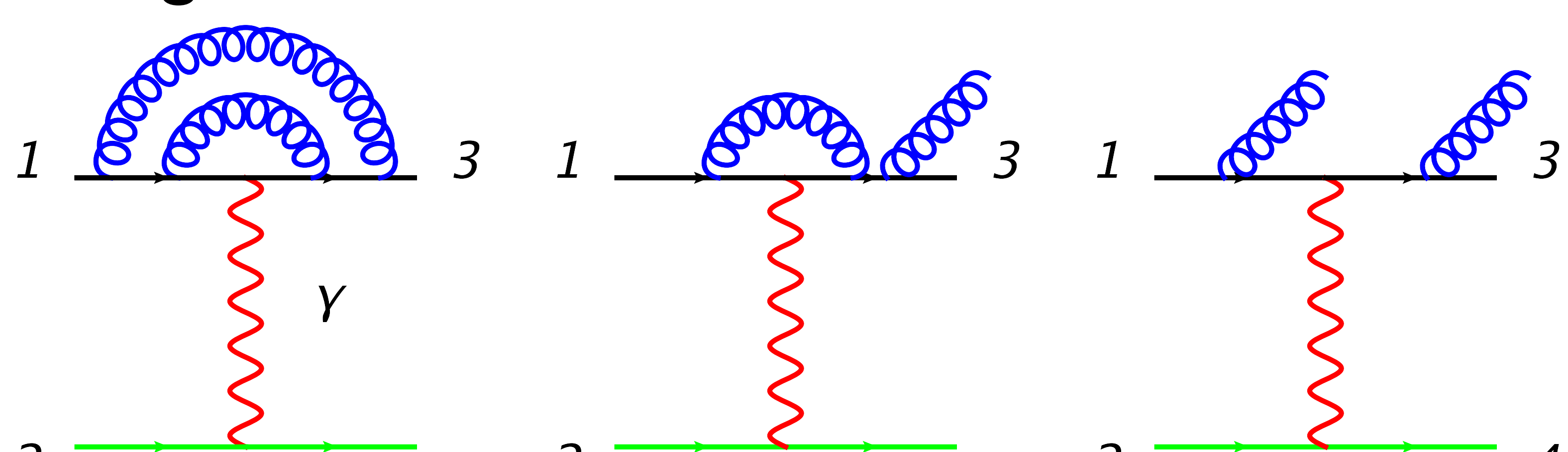
this calculation also available from Hinderer, Schlegel, Vogelsang PRD92 (2015)

NNLO $O(\alpha^2\alpha_S^2)$ corrections

- New configuration: incoming lepton can split into a quark, leading to parton-parton scattering channels. They first appear at this order, and are therefore effectively leading order in our treatment.



- Standard NLO corrections to quark-photon scattering
- Double-virtual, real-virtual, and double-real corrections to quark-lepton scattering



N-jettiness subtraction

Enormous progress solving this problem for LHC physics!

- We can simplify such calculations using a global event shape variable first introduced in soft-collinear effective theory (SCET)

$$\tau_N = \sum_k \min\{n_i \cdot q_k\}$$

N-jettiness, an event shape variable (similar to thrust)
Stewart, Tackmann, Waalewijn PRL 105 (2010)

light-like directions of initial beams and final-state jets

momenta of final-state partons

Intuition:

$\tau_N \sim 0$: all radiation is either soft, or collinear to a beam/jet

$\tau_N > 0$: at least one additional jet beyond Born level is resolved

N-jettiness subtraction

Boughezal, Focke, X. Liu, FP, PRL 115 (2015); Gaunt, Stahlhofen, Tackmann, Walsh JHEP1509 (2015)

$$\sigma = \int d\tau_N \frac{d\sigma}{d\tau_N}\theta(\tau^{cut} - \tau_N) + \int d\tau_N \frac{d\sigma}{d\tau_N}\theta(\tau_N - \tau^{cut})$$

a simpler effective theory description is available for the region

have one more resolved jet than at Born level; **only need NLO in this region!**

Stewart, Tackmann, Waalewijn PRL 105 (2010)

$$\frac{d\sigma}{d\tau_N}(\tau_N \ll Q) \sim H \otimes B_a \otimes S \otimes \left[\prod_{n=1}^{N} J_n\right]$$

hard scales in the process (e.g., transverse momenta of jets)

describes hard radiation

describes radiation collinear to initial-state beams (matches onto collinear PDFs); ***universal***

describes soft radiation; ***universal***

describes radiation collinear to final-state jets; ***universal***

N-jettiness subtraction

$$\frac{d\sigma}{d\tau_N}(\tau_N \ll Q) \sim H \otimes B_a \otimes S \otimes \left[\prod_{n=1}^{N} J_n\right]$$

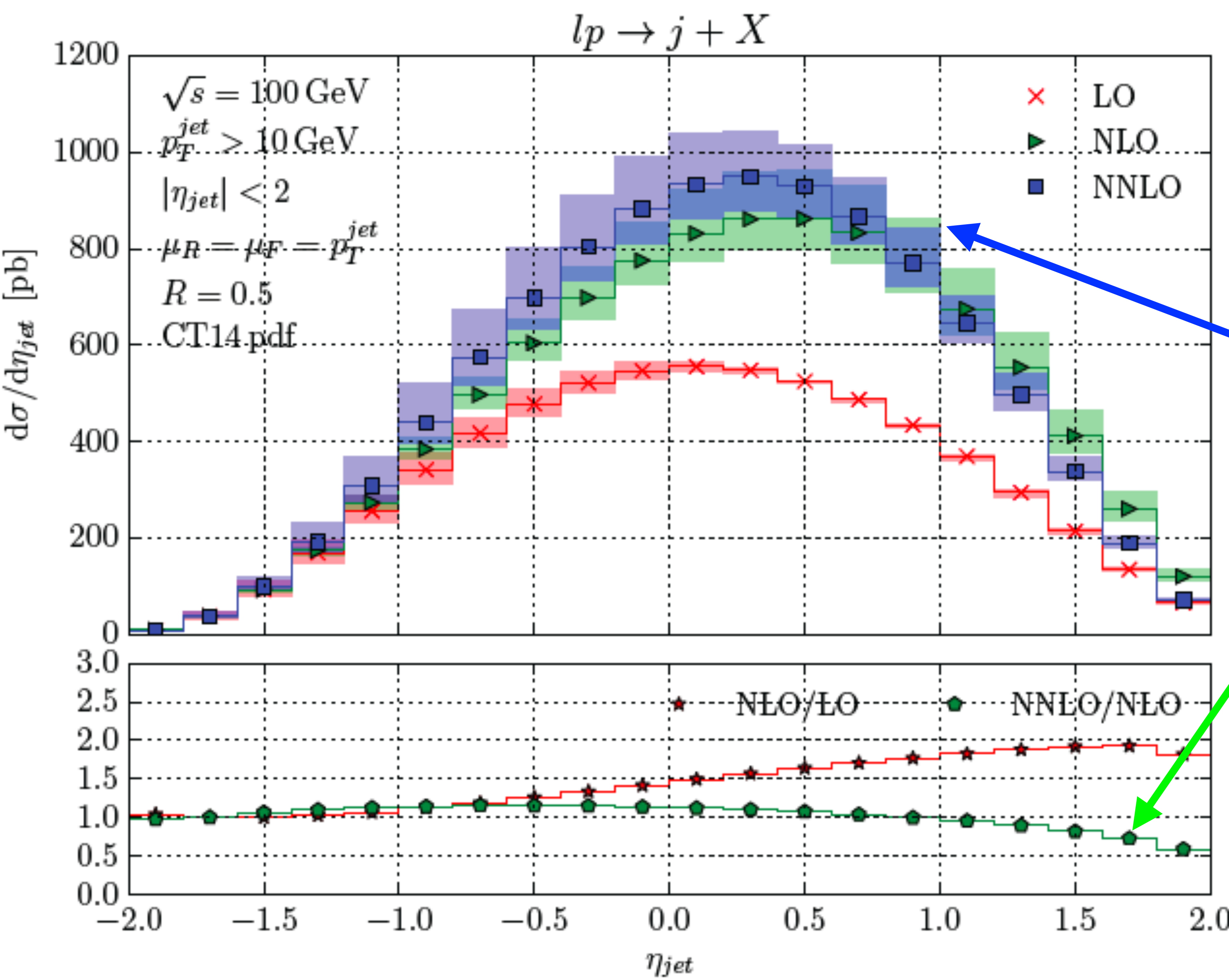
- Expand this formula to $O(\alpha_S^2)$, and turn off all resummation, to get the NNLO cross section below the cut. Need each of these separate functions to NNLO.

  - *H*@NNLO: Matsuura, van der Merck, van Nerven (1988)
  - *B*@NNLO: Gaunt, Stahlhofen, Tackmann (2014); Boughezal, FP, Schubert, Xing (2017)
  - *S*@NNLO: Boughezal, X. Liu, FP (2015)
  - *J*@NNLO: Becher, Neubert (2006); Becher, Bell (2011)

Within the past few years all ingredients have become available to apply this idea to jet production at the EIC!

EIC jet production at NNLO

- We can now revisit inclusive jet production at a future EIC

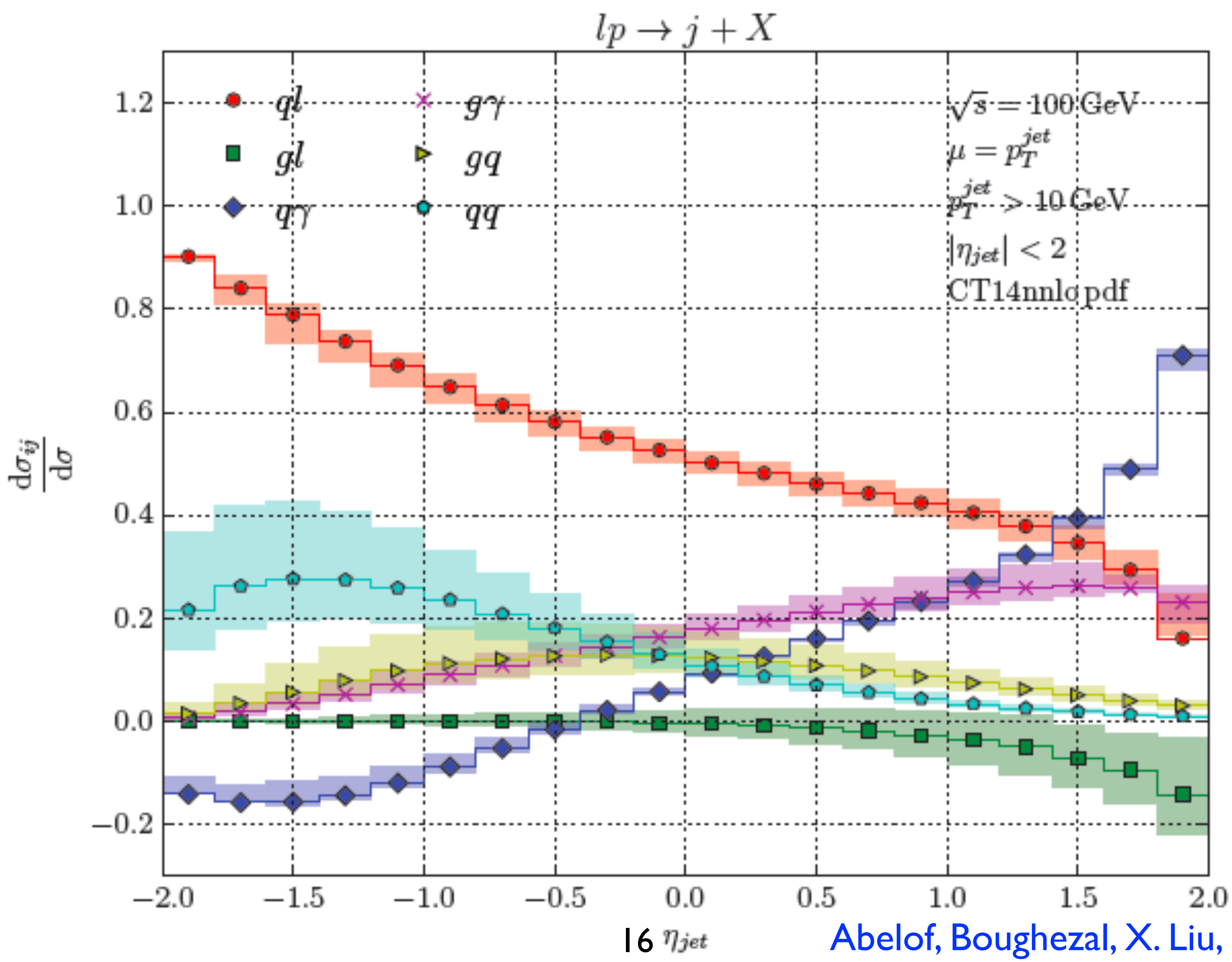


- **Perturbation theory stabilizes at NNLO!**
- Sizable corrections in the forward region; don't want to confuse this with PDF x dependence!

Abelof, Boughezal, X. Liu, FP, PLB 763 (2016)

EIC jet production at NNLO

- Jet distributions at the EIC are an excellent probe of PDFs; no single channel dominates over all of phase space, indicating that different kinematic regions provide access to different partonic luminosities.



Abelof, Boughezal, X. Liu, FP, PLB 763 (2016)

Polarized collisions

- We are interested in polarized proton structure at an EIC; need to extend N-jettiness subtraction to handle polarized collisions
- Schematic form of factorization theorem for unpolarized and longitudinally polarized collisions:

unpolarized: $d\sigma/d\tau \sim H \otimes B \otimes J \otimes S$

polarized: $d\Delta\sigma/d\tau \sim \Delta H \otimes \Delta B \otimes J \otimes S$

known helicity-dependent 2-loop virtual corrections

two-loop helicity-dependent beam function; **unknown**!

Operator definition and matching

- The longitudinally-polarized quark beam function has an operator definition:

$$\Delta B_q(t,x,\mu) = \langle p_n(P^-),+|\theta(\omega)\bar{\chi}_n(0)\delta(t-\omega\hat{p}^+)\frac{\bar{n}\cdot\gamma\gamma_5}{2}[\delta(\omega-\overline{\mathcal{P}}_n)\chi_n(0)]|p_n(P^-),+\rangle$$

quark operator:

$$\chi_n(y) = W_n^\dagger(y)\xi_n(y)$$

$$W_n(y) = \left[\sum_{\text{perms}} \exp\left(-\frac{g}{\overline{\mathcal{P}}_n}\bar{n}\cdot A_n(y)\right)\right]$$

right-handed minus left-handed helicity difference

Variables:

x=Bjorken-x

t=N-jettiness value

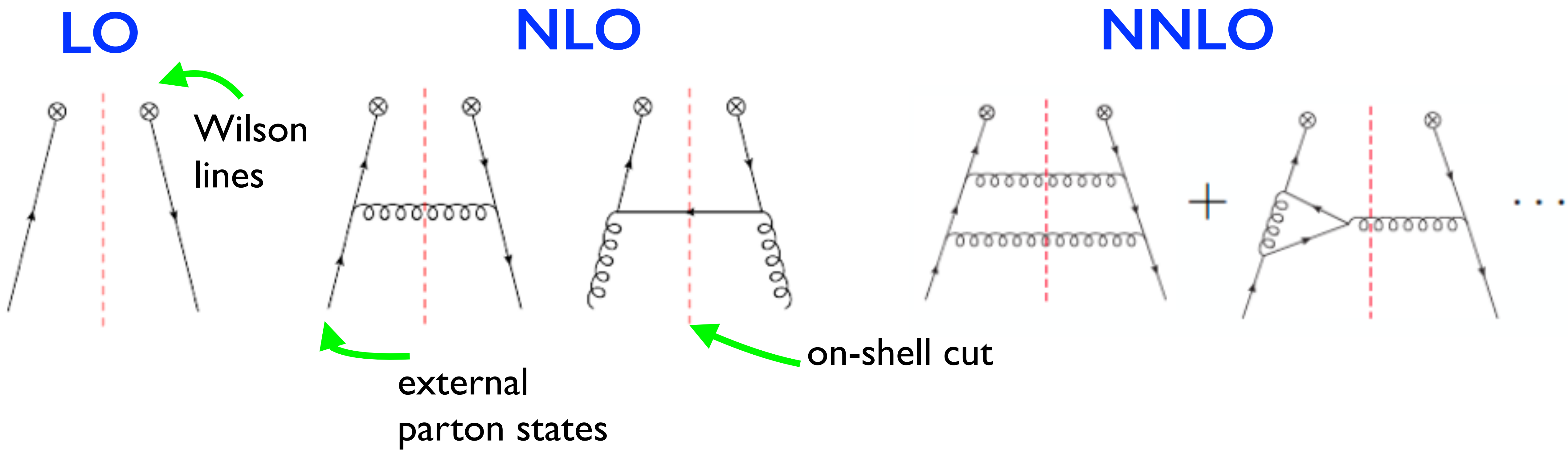
- For $t \gg \Lambda^2_{QCD}$, can match to the standard polarized PDFs:

$$\Delta B_i(t,x,\mu) = \sum_j \int_x^1 \frac{d\xi}{\xi}\Delta I_{ij}\left(t,\frac{x}{\xi}\right)\Delta f_j(\xi,\mu)$$

perturbative matching coefficients; **need to calculate!**

Calculation of the matching coefficients

- Replace external protons by partons to facilitate calculation of ΔI_{ij}. Well-defined diagrammatic expansion at each order in perturbation theory



- Use integration-by-parts and differential equation machinery to facilitate NNLO calculation. UV poles the same as in unpolarized case, IR poles match those of polarized PDFs. Treatment of γ_5 in HVBM scheme:

$$\gamma_5 \equiv \frac{i}{4!}\epsilon^{\mu\nu\rho\sigma}\gamma_\mu\gamma_\nu\gamma_\sigma\gamma_\rho \longrightarrow \{\gamma_5, \tilde{\gamma}_\mu\} = 0, \quad [\gamma_5, \hat{\gamma}_\mu] = 0$$

Boughezal, FP, Schubert, Xing PRD96 (2017)

Calculation of the matching coefficients

- Replace external protons by partons to facilitate calculation of ΔI_{ij}. Well-defined diagrammatic expansion at each order in perturbation theory

logarithms of N-jettiness

$$\Delta\mathcal{I}^{(2)}_{qq'}(t,z,\mu) = \frac{1}{\mu^2}\mathcal{L}_1\left(\frac{t}{\mu^2}\right)4\Delta P^{(0)}_{qg}\otimes\Delta P^{(0)}_{gq'} + \frac{1}{\mu^2}\mathcal{L}_0\left(\frac{t}{\mu^2}\right)\left[4\Delta P^{(1)}_{qq'} + 2\Delta I^{(1)}_{qg}(z)\otimes\Delta P^{(0)}_{gq'}\right]$$
$$+\,\delta(t)C_F T_R\Big\{(1+z)\Big[-8\mathrm{Li}_3(1-z)+8\ln(z)\mathrm{Li}_2(z)-8\ln(1-z)\mathrm{Li}_2(z)+\frac{10}{3}\ln^3(z)-4\ln(z)\ln^2(1-z)$$
$$-\frac{8}{3}\pi^2\ln(z)+\frac{4}{3}\pi^2\ln(1-z)\Big]+(1-z)\Big[4\mathrm{Li}_2(z)-4\pi^2+\frac{13-17z}{1-z}\ln^2(z)+10\ln^2(1-z)$$
$$-20\ln(z)\ln(1-z)\Big]+(38-2z)\ln(z)-24(1-z)\ln(1-z)+64(1-z)\Big\}. \quad (65)$$

Simple analytic expressions for all matching coefficients; **ready for phenomenology!**

- Us …
NNL … e, IR poles match those of polarized PDFs. Treatment of γ_5 in HVBM scheme:

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Boughezal, FP, Schubert, Xing PRD96 (2017)

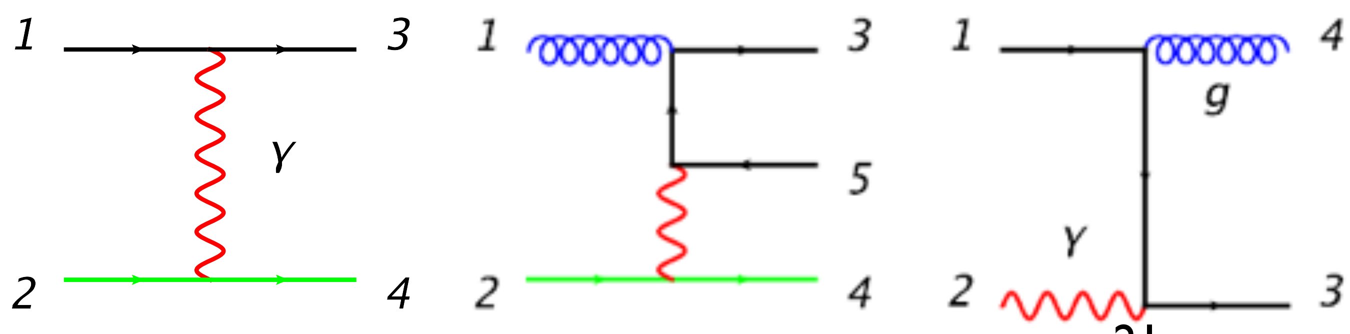
Setup for EIC pheno study

- **Goal**: study the sensitivity of inclusive jet production at an EIC to polarized PDFs. Similar framework as the unpolarized setup described before with two differences: work to NLO in QCD (major effect of NNLO is to reduce scale uncertainty, not to shift central values), included resolved photons

Double-longitudinal spin asymmetry:

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

$$\Delta\sigma_{LL} = \underbrace{\Delta\sigma_{LO} + \Delta\sigma_{NLO}} + \Delta\sigma_{res}$$



Same diagrams as unpolarized case; now sensitive to polarized proton PDFs $\Delta f_{q/P}$, $\Delta f_{g/P}$

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$$\Delta\sigma_{LL} = \Delta\sigma_{LO} + \Delta\sigma_{NLO} + \underbrace{\Delta\sigma_{res}}$$

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

polarized proton PDFs

polarized photon PDFs

polarized QED splitting function

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Inclusive jet production sensitive to both polarized proton and photon structure

Summary of partonic structure:

Partonic channel	Q^2 region	Contributing PDFs
ql	$Q^2 > 0$	$f_{q/H}, \Delta f_{q/H}$
gl	$Q^2 > 0$	$f_{g/H}, \Delta f_{g/H}$
$q\gamma$	$Q^2 \approx 0$	$f_{q/H}, f_{\gamma/l}, \Delta f_{q/H}, \Delta f_{\gamma/l}$
$g\gamma$	$Q^2 \approx 0$	$f_{g/H}, f_{\gamma/l}, \Delta f_{g/H}, \Delta f_{\gamma/l}$
qq	$Q^2 \approx 0$	$f_{q/H}, f_{q/\gamma}, \Delta f_{q/H}, \Delta f_{q/\gamma}$
qg	$Q^2 \approx 0$	$f_{q/H}, f_{q/\gamma}, \Delta f_{q/H}, \Delta f_{q/\gamma}, f_{g/H}, f_{g/\gamma}, \Delta f_{g/H}, \Delta f_{g/\gamma}$
gg	$Q^2 \approx 0$	$f_{g/H}, f_{g/\gamma}, \Delta f_{g/H}, \Delta f_{g/\gamma}$

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Focus here on $\Delta f_{i/P}$; $\Delta f_{i/\gamma}$ studied in Chu, Aschenauer, Lee, Zheng PRD96 (2017)

Summary of partonic structure:

Partonic channel	Q^2 region	Contributing PDFs
ql	$Q^2 > 0$	$f_{q/H}, \Delta f_{q/H}$
gl	$Q^2 > 0$	$f_{g/H}, \Delta f_{g/H}$
$q\gamma$	$Q^2 \approx 0$	$f_{q/H}, f_{\gamma/l}, \Delta f_{q/H}, \Delta f_{\gamma/l}$
$g\gamma$	$Q^2 \approx 0$	$f_{g/H}, f_{\gamma/l}, \Delta f_{g/H}, \Delta f_{\gamma/l}$
qq	$Q^2 \approx 0$	$f_{q/H}, f_{q/\gamma}, \Delta f_{q/H}, \Delta f_{q/\gamma}$
qg	$Q^2 \approx 0$	$f_{q/H}, f_{q/\gamma}, \Delta f_{q/H}, \Delta f_{q/\gamma}, f_{g/H}, f_{g/\gamma}, \Delta f_{g/H}, \Delta f_{g/\gamma}$
gg	$Q^2 \approx 0$	$f_{g/H}, f_{g/\gamma}, \Delta f_{g/H}, \Delta f_{g/\gamma}$

Run parameters

- Jets are reconstructed using the anti-k_T algorithm with R=0.8 (R=0.2 also studied).
- Central scale choice $\mu = p_T^j$
- NNPDF3.1 unpolarized PDFs, NNPDFpol1.1 polarized PDFs (DSSV also studied)
- Assume 10 fb^{-1} of integrated luminosity to estimate statistical errors

Assumed EIC energies and kinematic coverages:

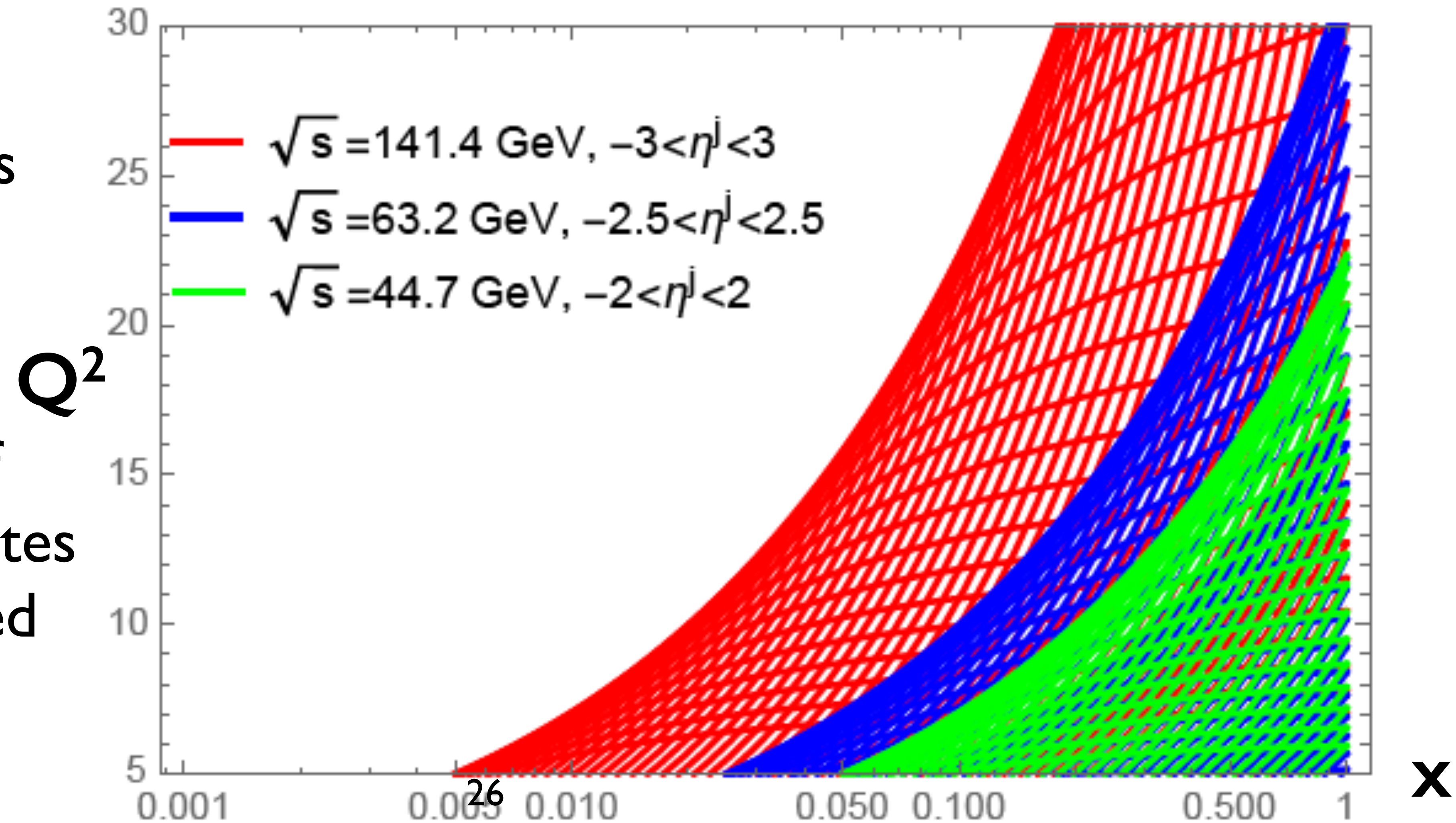
$\sqrt{s}$	p_T^{jet} range	$\eta^j et$ range
141.4 GeV	$5\,\mathrm{GeV} \leq p_T^j \leq 35\,\mathrm{GeV}$	$-3 \leq \eta^j \leq 3$
63.2 GeV	$5\,\mathrm{GeV} \leq p_T^j \leq 30\,\mathrm{GeV}$	$-2.5 \leq \eta^j \leq 2.5$
44.7 GeV	$5\,\mathrm{GeV} \leq p_T^j \leq 20\,\mathrm{GeV}$	$-2 \leq \eta^j \leq 2$

Run parameters

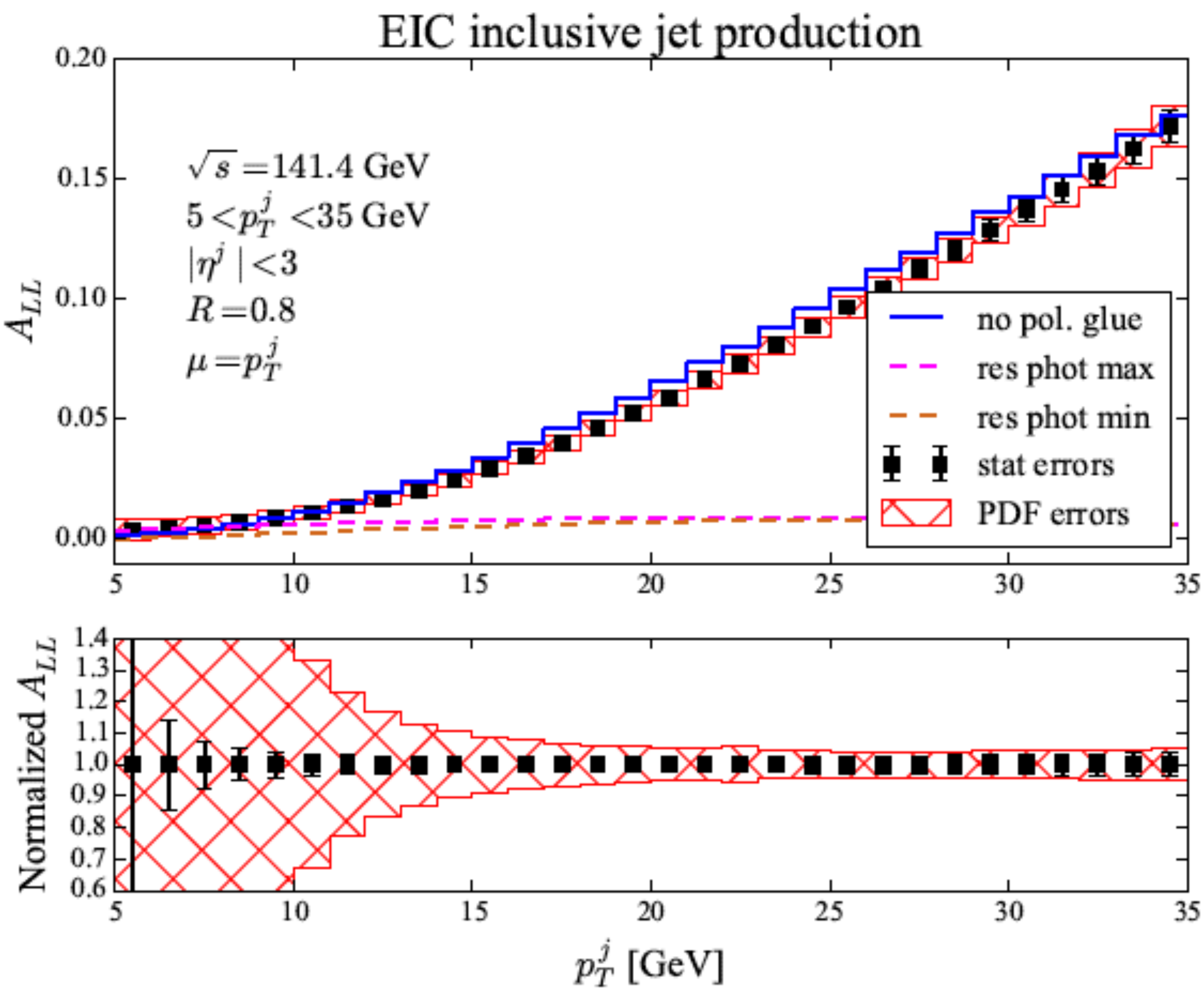
- Jets are reconstructed using the anti-k_T algorithm with R=0.8 (R=0.2 also studied).
- Central scale choice $\mu=p_T^j$
- NNPDF3.1 unpolarized PDFs, NNPDFpol1.1 polarized PDFs (DSSV also studied)
- Assume 10 fb^{-1} of integrated luminosity to estimate statistical errors

Mapped to the Q^2 vs Bjorken-x plane:

Lower-x coverage of $\sqrt{s}$=141.4 GeV dictates much of the observed phenomenology



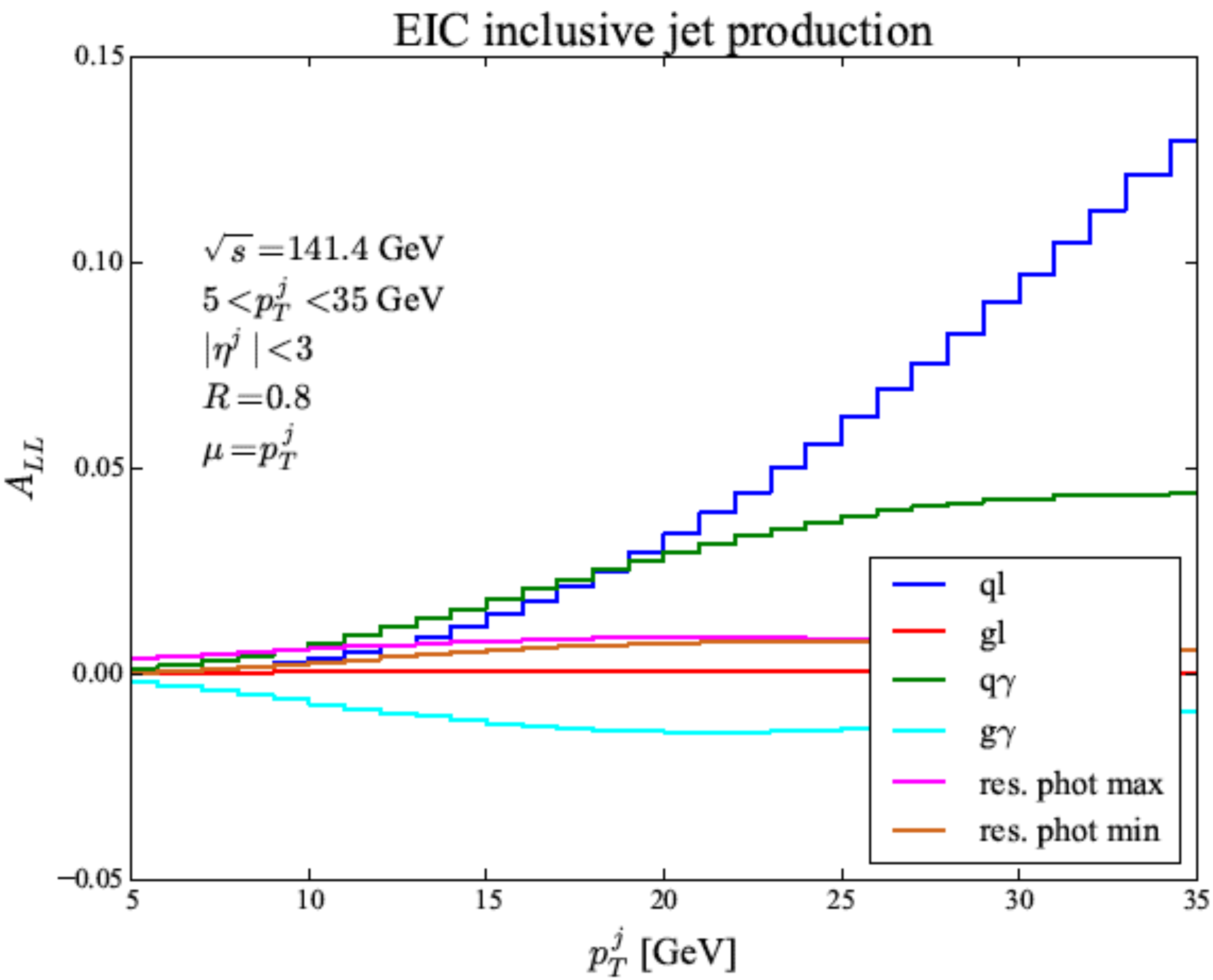
$\sqrt{s}$=141.4 GeV: jet p_T



- A_{LL} grows to ~20% at high p_T
- 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 stat errors; opportunity for EIC to improve our knowledge of Δf!

Boughezal, FP, Xing PRD98 (2018)

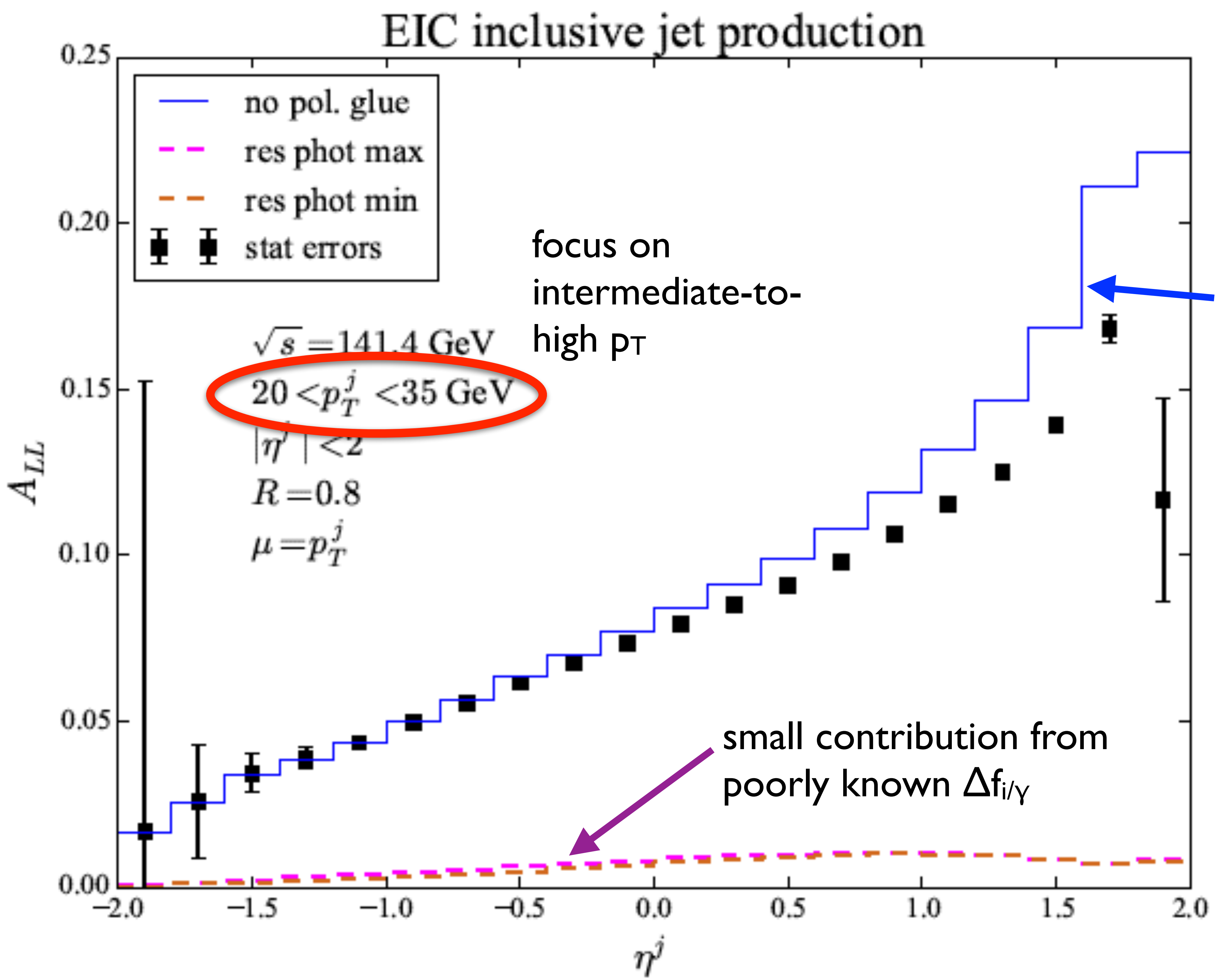
$\sqrt{s}$=141.4 GeV: jet p_T partonic structure



- ql channel dominates at high p_T; gl channel small throughout
- At intermediate p_T get contributions from qγ and gγ; intermediate p_T region of inclusive jet production sensitive to $\Delta f_{g/P}$

Boughezal, FP, Xing PRD98 (2018)

$\sqrt{s}$=141.4 GeV: $\Delta f_{g/P}$ access



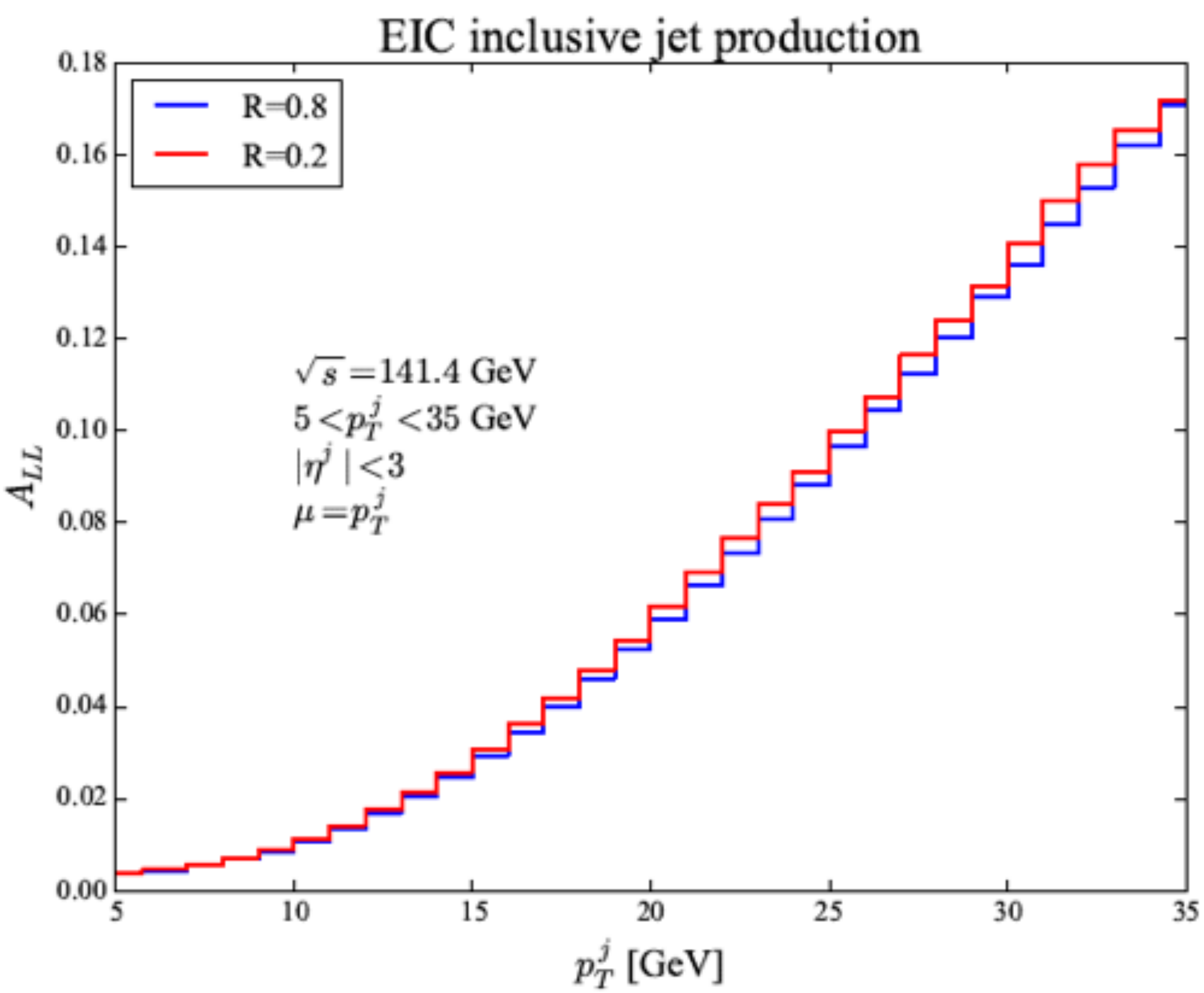
focus on intermediate-to-high p_T

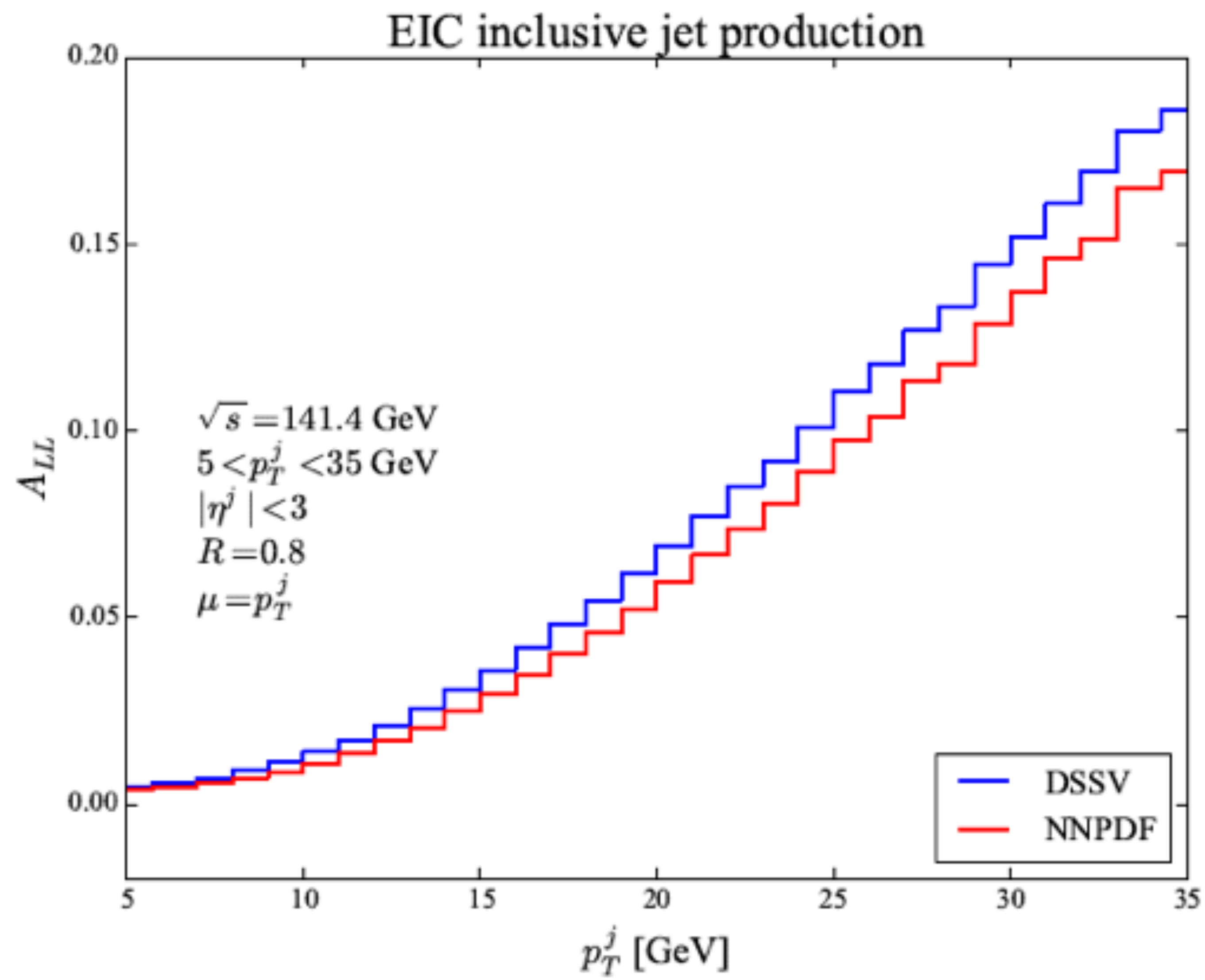
turning off polarized gluon leads to adifferent shape of the jet pseudorapidity distribution; larger than estimated statistical errors

small contribution from poorly known $\Delta f_{i/\gamma}$

Boughezal, FP, Xing PRD98 (2018)

$\sqrt{s}$=141.4 GeV: PDF, R dependence



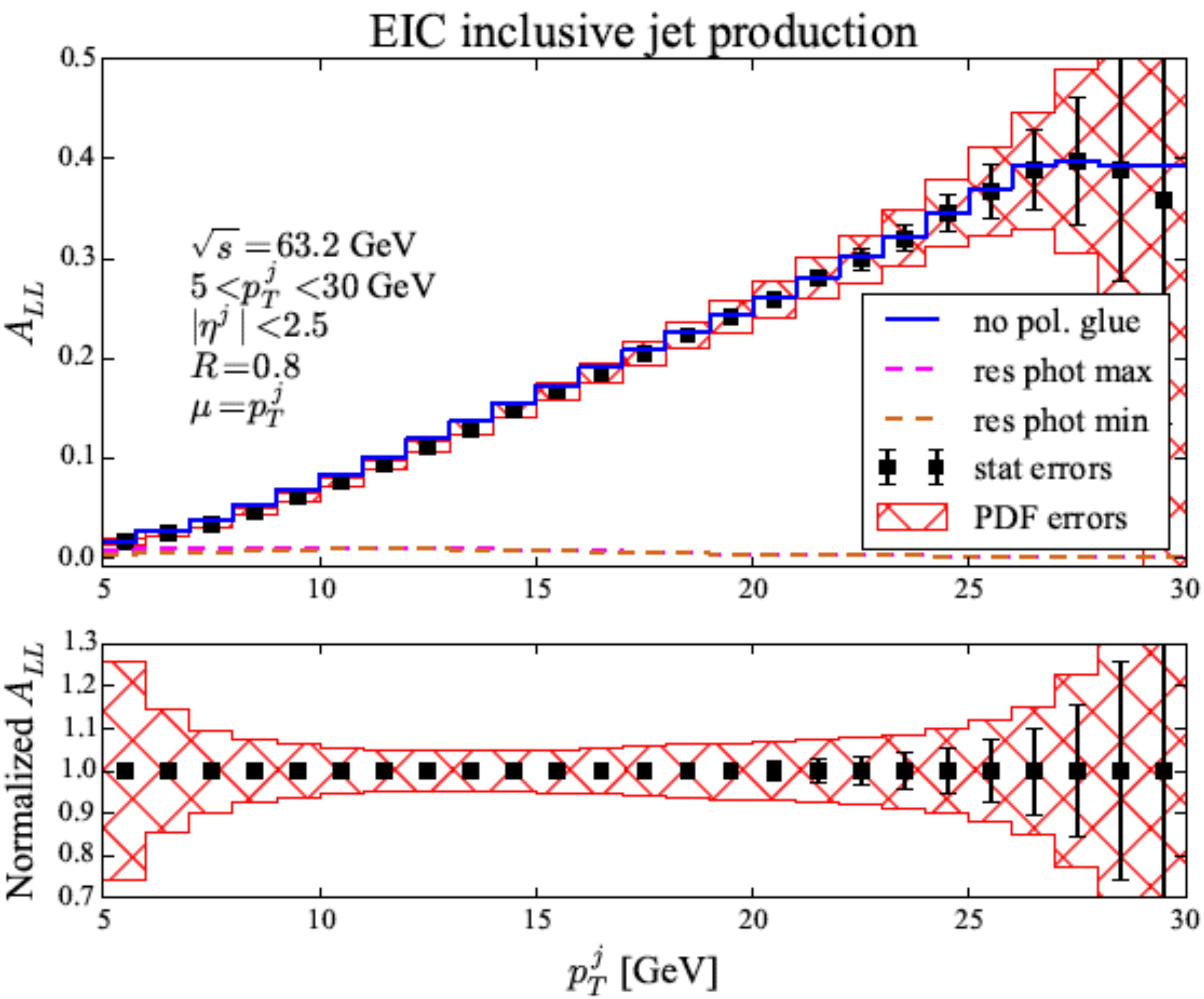


Small dependence on jet radius R for studied distributions

Measurable difference between DSSV and NNPDF polarized PDFs

Boughezal, FP, Xing PRD98 (2018)

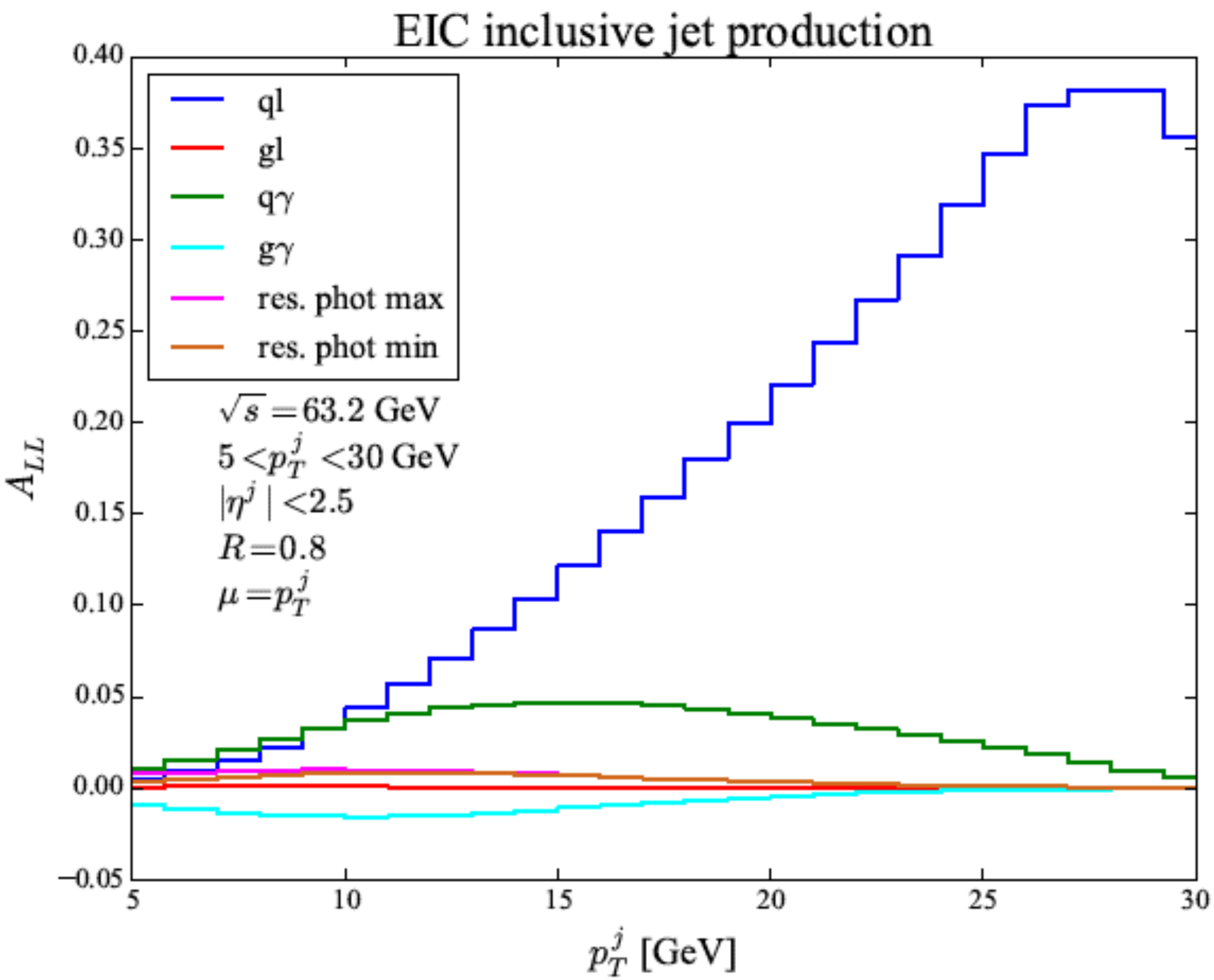
Results for $\sqrt{s}$=63.2 GeV



- A_{LL} grows to ~40% at high p_T
- PDF errors still larger than statistical errors; can learn about polarized PDFs

Boughezal, FP, Xing PRD98 (2018)

Results for $\sqrt{s}$=63.2 GeV



- Dominated by ql channel
- Sensitivity to $\Delta f_{g/P}$ at low p_T, where it must be disentangled from $\Delta f_{i/\gamma}$. In general less sensitivity to these quantities and fewer handles to disentangle them at lower energies
- Similar conclusions for $\sqrt{s}$=44.7 GeV

Boughezal, FP, Xing PRD98 (2018)

Summary

- All ingredients now available for an NNLO description of both polarized and unpolarized observables in collinear factorization for EIC physics
- Inclusion of NNLO corrections to inclusive jet production leads to the expected stabilization of the pQCD expansion
- Inclusive jet production at an EIC is sensitive to the polarized PDFs of both the proton and photon; can separate these quantities with appropriate kinematic selections
- We find that a higher energy EIC leads to broader sensitivity to polarized PDFs than lower energies
- Feedback welcome!