Jet Physics and Polarized PDFs at an EIC

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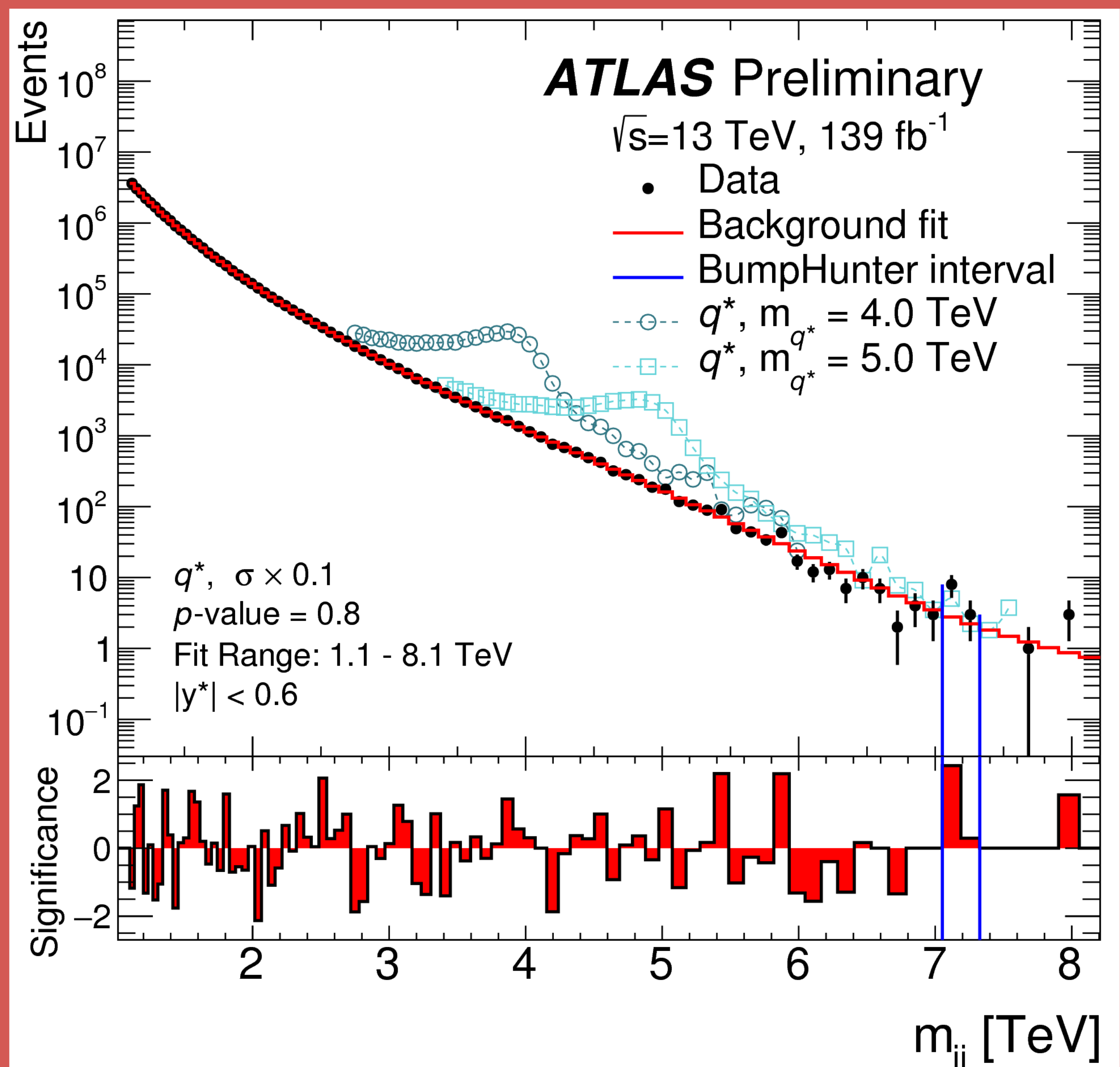
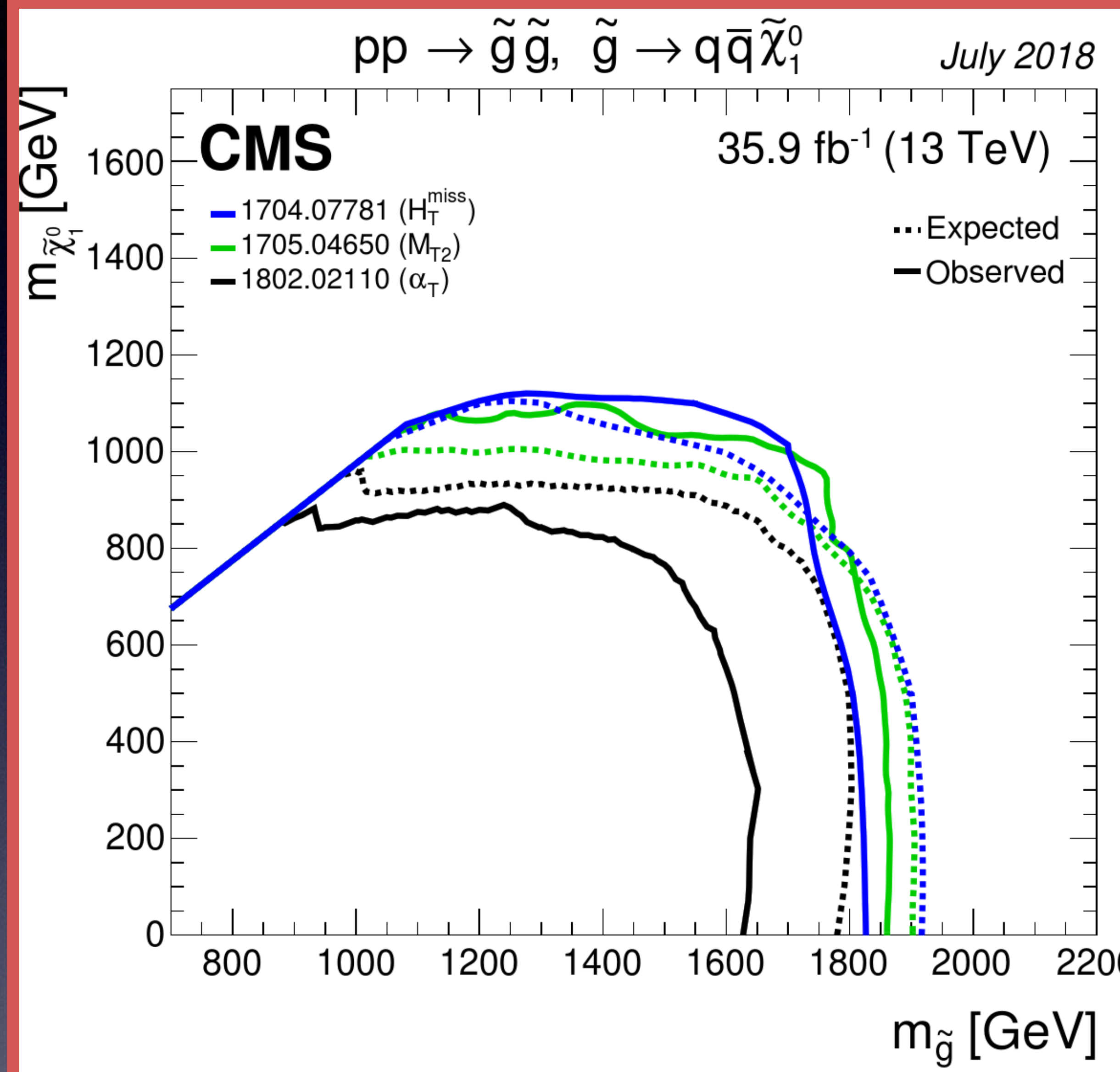
LPC workshop on physics connections between the LHC and EIC

Fermilab, Nov. 14, 2019

Why are jets interesting at the LHC?

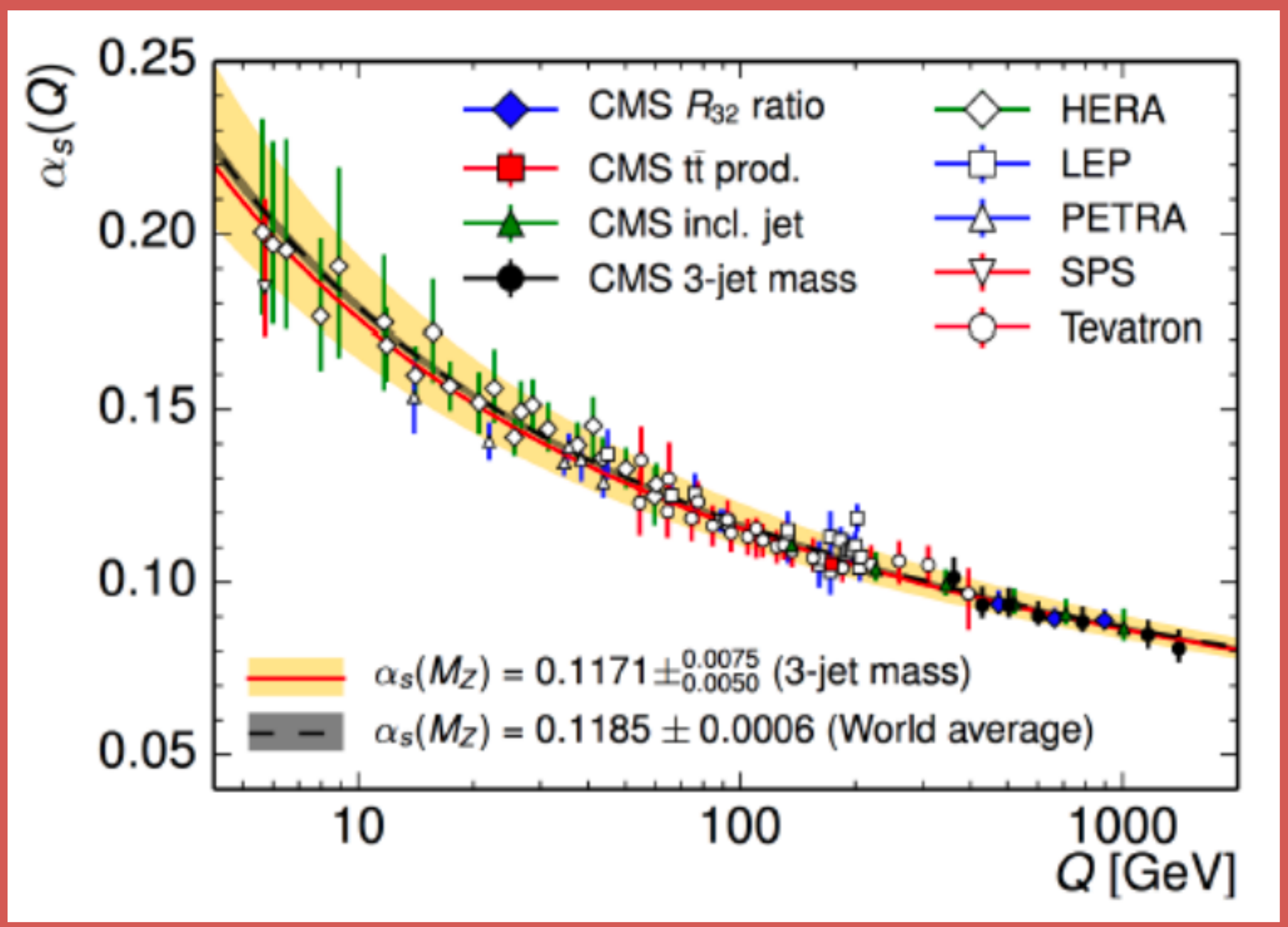


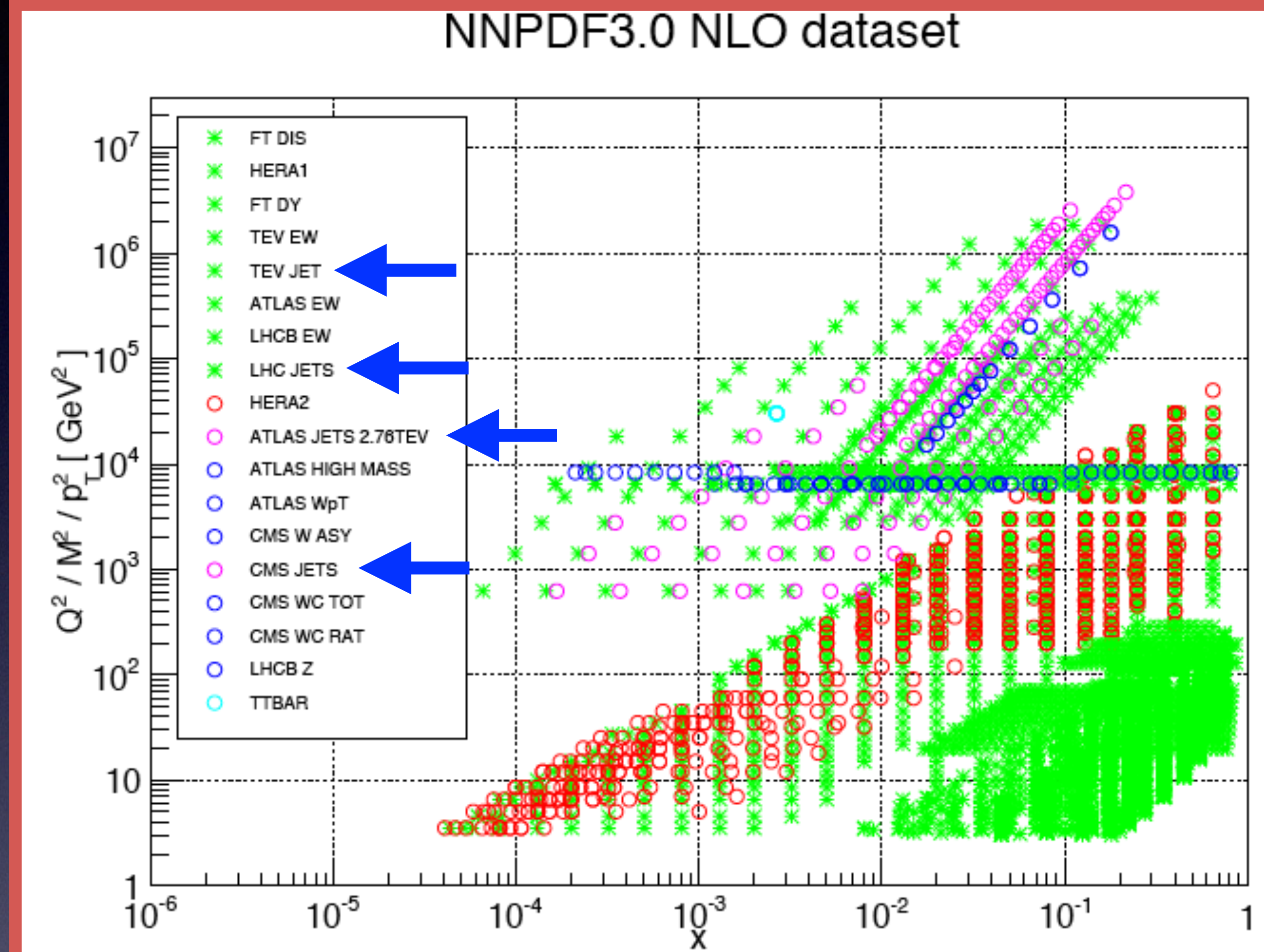


Di-jet resonance searches probe the highest accessible energy scales at the LHC

Jets are a hallmark of many BSM signatures, including much of SUSY parameter space

Why are jets interesting at the LHC?



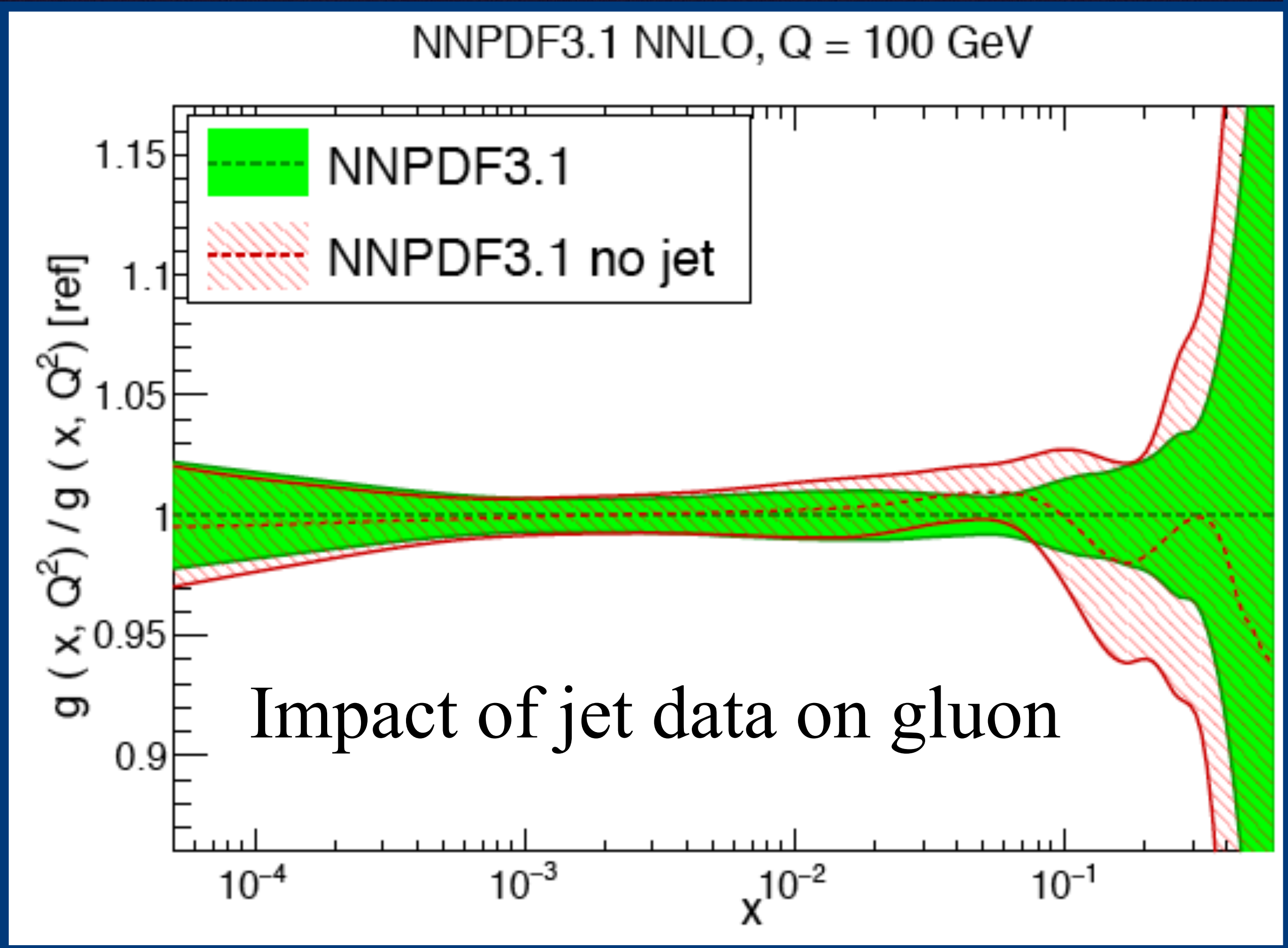


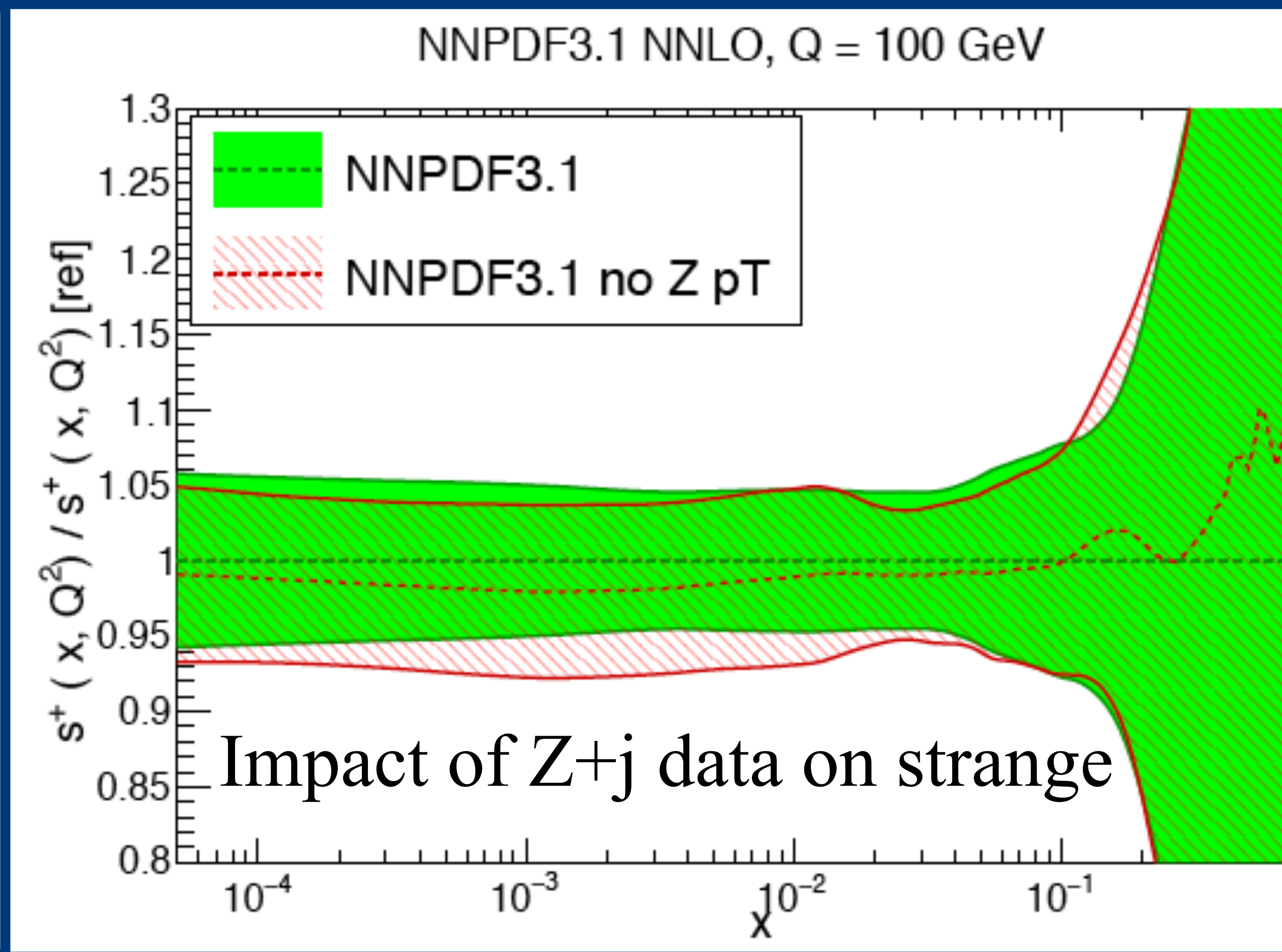
Through jets we access fundamental parameters and predictions of QCD such as $\alpha_S(M_Z)$ and α_S running

Jets form a critical input to current PDF fits

Jets for PDFs at the LHC

- Jets are needed to understand both the high-x region relevant for BSM searches, and the low-to-intermediate-x ones needed for Higgs physics

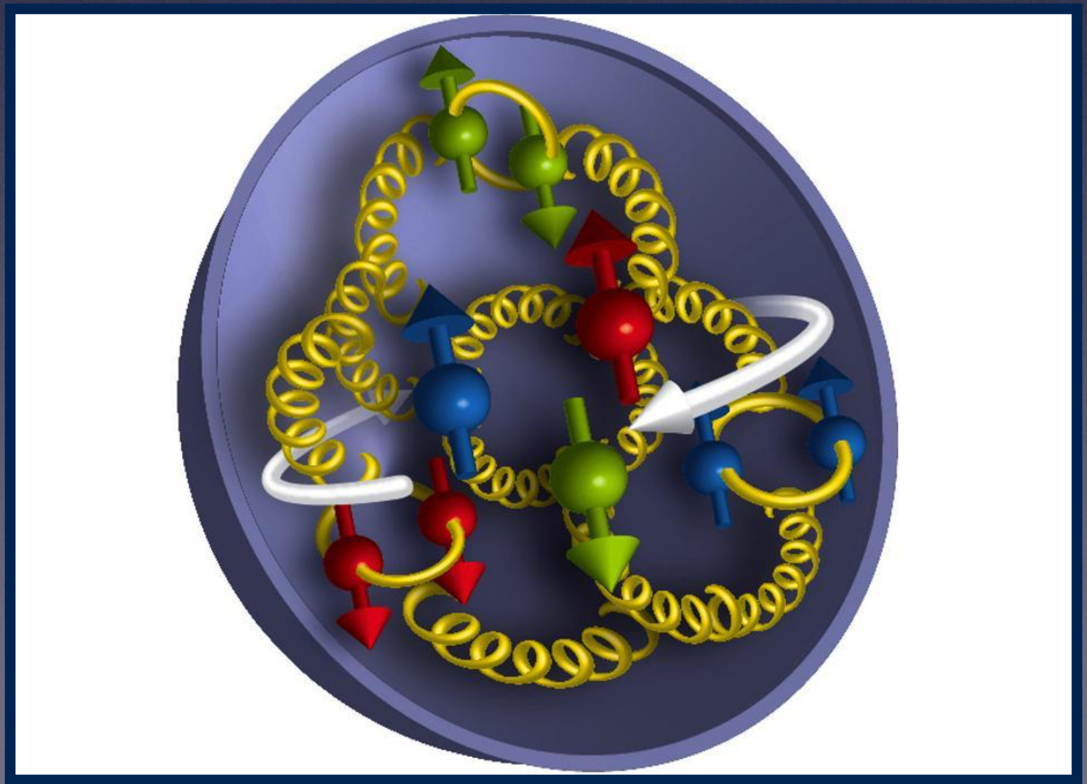




Jets in nuclear physics

- Jets play an important role in understanding simple aspects of QCD at the nuclear level.

How is the proton spin formed from its microscopic constituents?



Quark spin

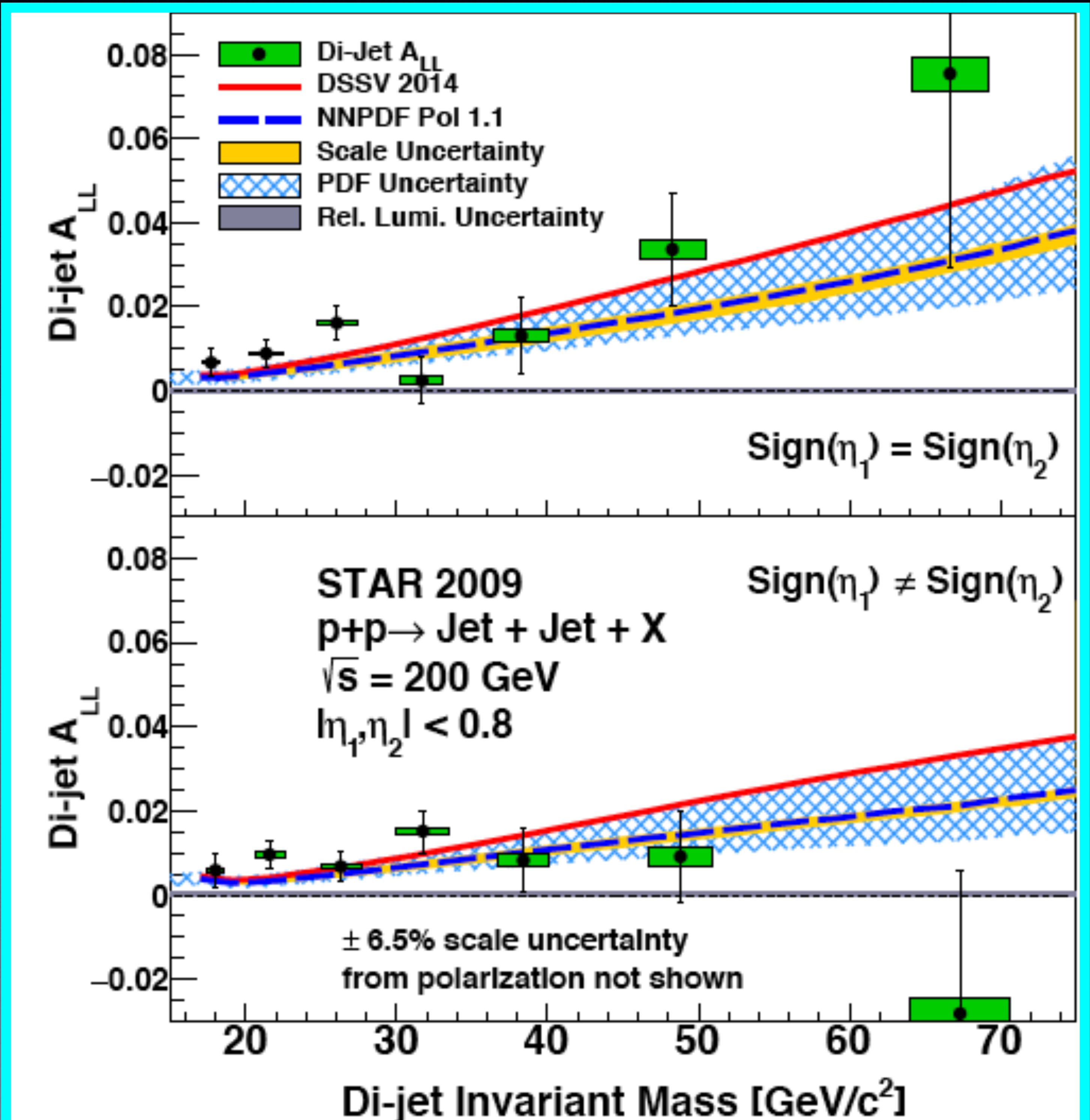
Gluon spin

Orbital

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

Jet measurements at RHIC have played a critical role in establishing what we do know about Δg

STAR, PRD95 071103 (2017)



Longitudinal double-spin asymmetry:

$$\mathcal{A}_{\rm LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}}$$

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

Directly sensitive to polarized proton distributions

DSSV 2014 and NNPDFPol1.1 have ΔG>0

The measured A_{LL} indicates a positive ΔG!

Jet physics at the EIC

- Numerous motivations for studying inclusive jet production at a future EIC:
  - Investigation of proton structure, the focus of this talk
  - Determination of higher twist operators 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!

How do we study jets?

- Parton-shower Monte Carlo simulations (HERWIG, PYTHIA, SHERPA,…)
- Jet substructure (Grooming, Trimming, Soft-Drop,…)
- **Perturbative QCD**

How do we study jets?

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- **Perturbative QCD**

Jets amenable to first-principle, systematically improvable QCD calculations!

- The key principle is *factorization*: separate long and short distance physics

long distance: 1/GeV **short distance: 1/TeV**

renormalization scale

$$\sigma = \int dx_1 f_{q/p}(x_1,\mu^2) \int dx_2 f_{\bar{q}/p}(x_2,\mu^2)\, \hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2)\,, \quad \hat{s} = x_1 x_2 s$$

measure

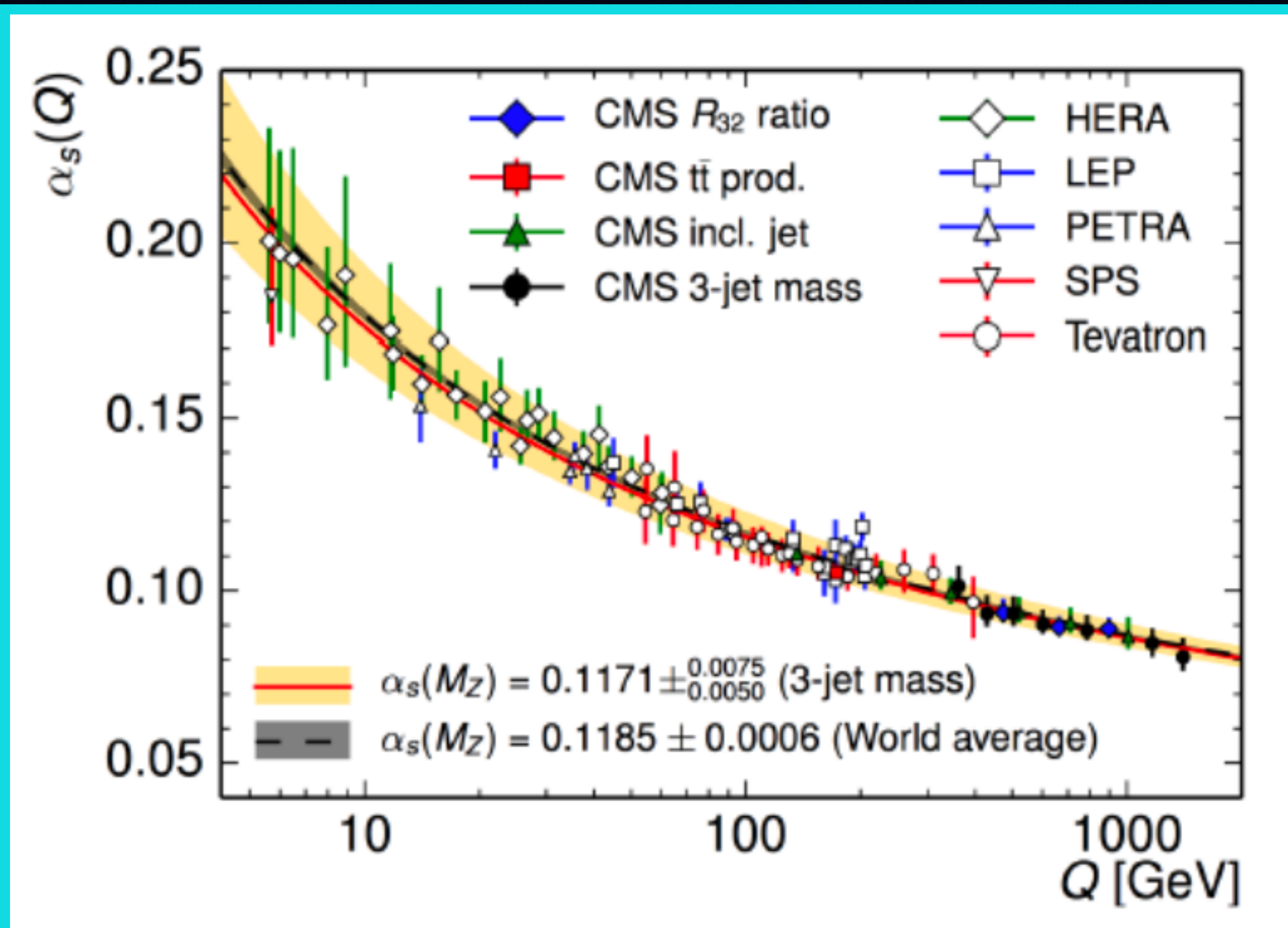
extract from data

factorization scale

calculate

Partonic cross section

$$\sigma = \int dx_1 f_{q/p}(x_1, \mu^2) \int dx_2 f_{\bar{q}/p}(x_2, \mu^2)\, \hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2), \qquad \hat{s} = x_1 x_2 s$$



Asymptotic freedom allows us to compute the partonic cross section in perturbation theory

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

LO predictions

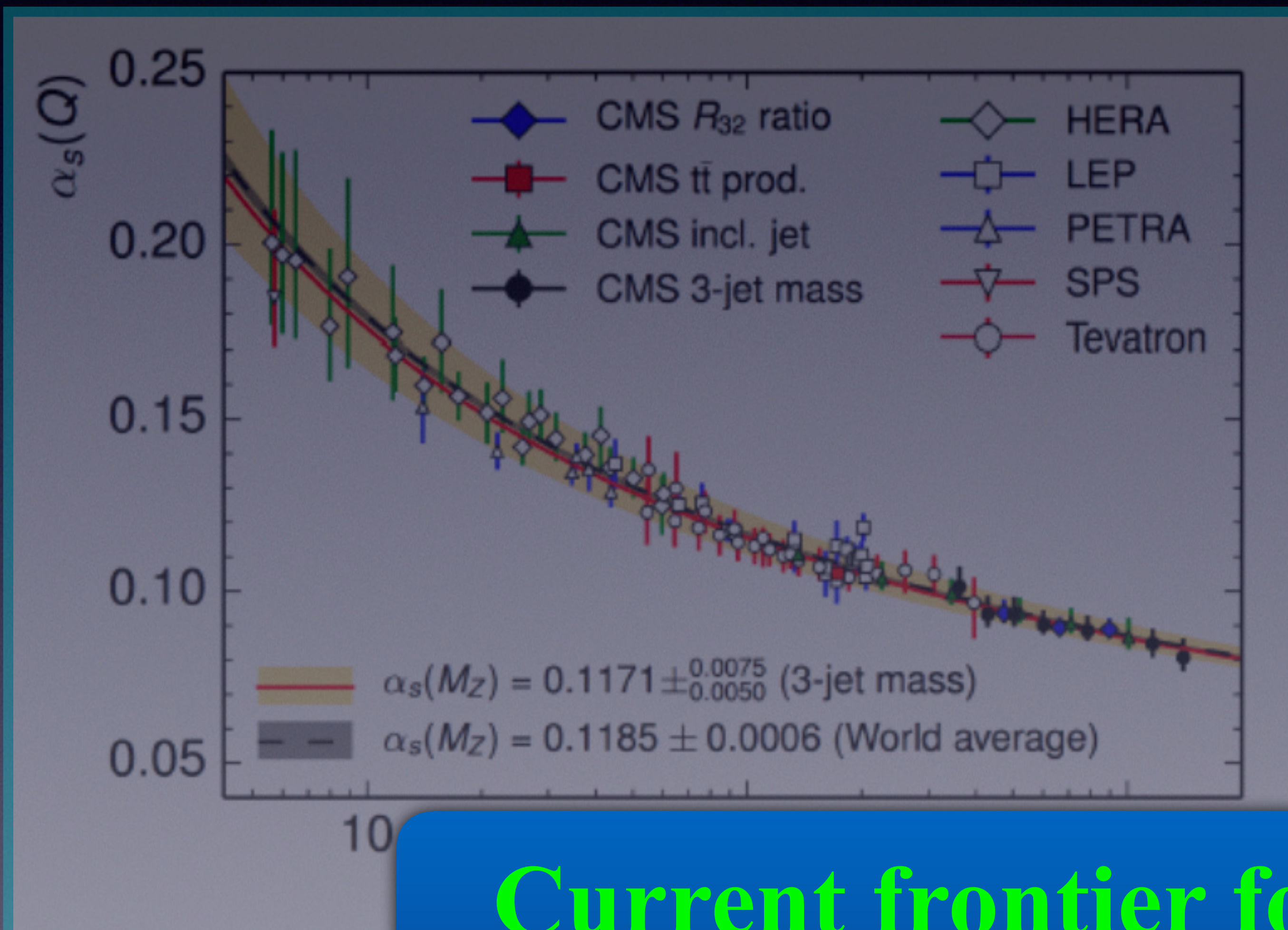
NLO corrections

NNLO corrections

NNNLO corrections

Partonic cross section

$$\sigma = \int dx_1 f_{q/p}(x_1,\mu^2) \int dx_2 f_{\bar{q}/p}(x_2,\mu^2)\, \hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2) \qquad \hat{s} = x_1 x_2 s$$



Asymptotic freedom allows us to compute the partonic cross section in perturbation theory

Current frontier for jets: next-to-next-to leading order (NNLO) in α_S

$$\sigma^{(3)} + \dots \Big)$$

LO predictions

NLO corrections

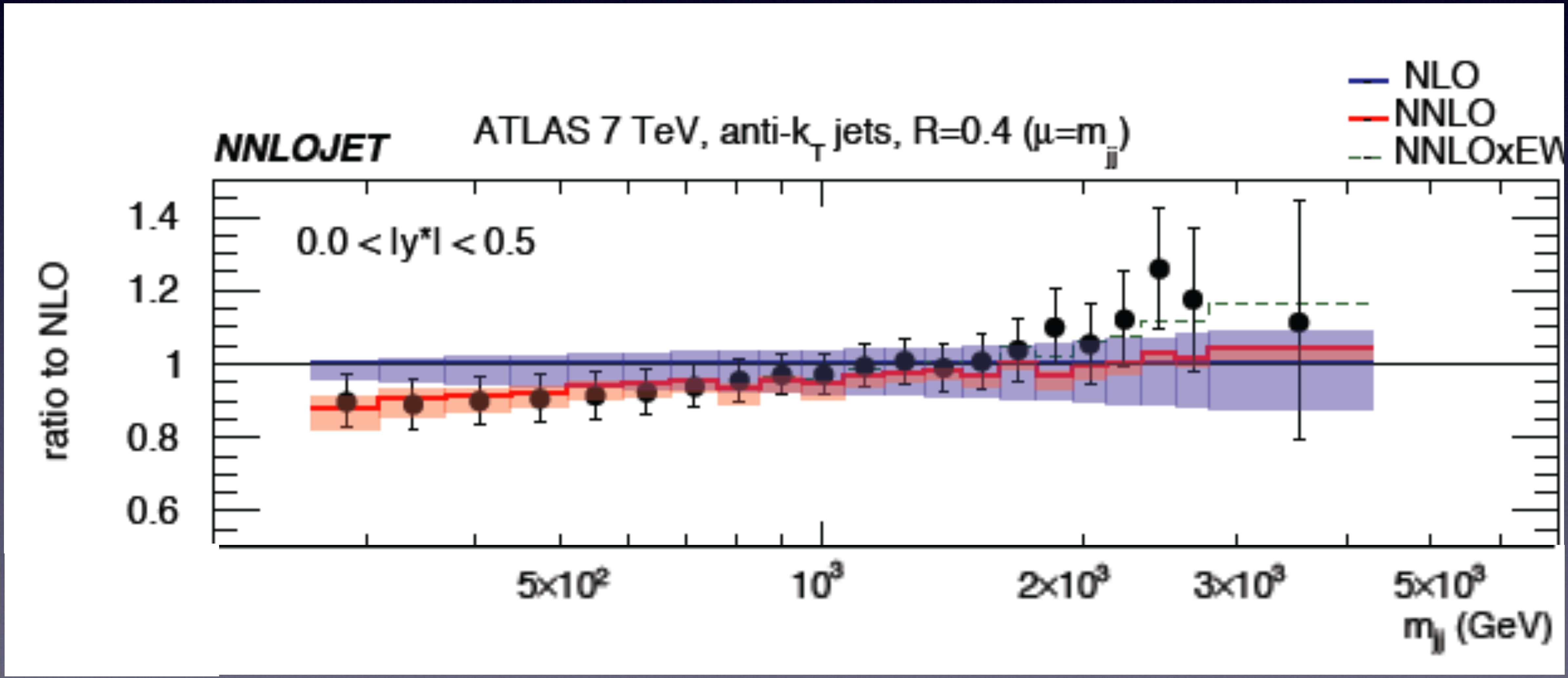
NNLO corrections

NNNLO corrections

Comparison with LHC jet data

Dijet production at NNLO

- Numerous important applications of di-jet production at the LHC, including searches for new physics, measurements of α_s, and determination of the high-x gluon.

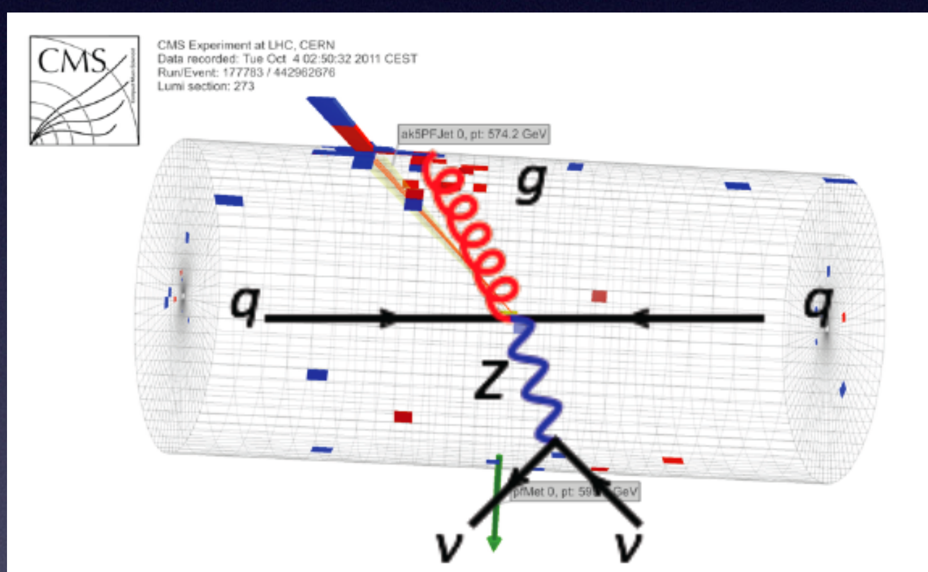


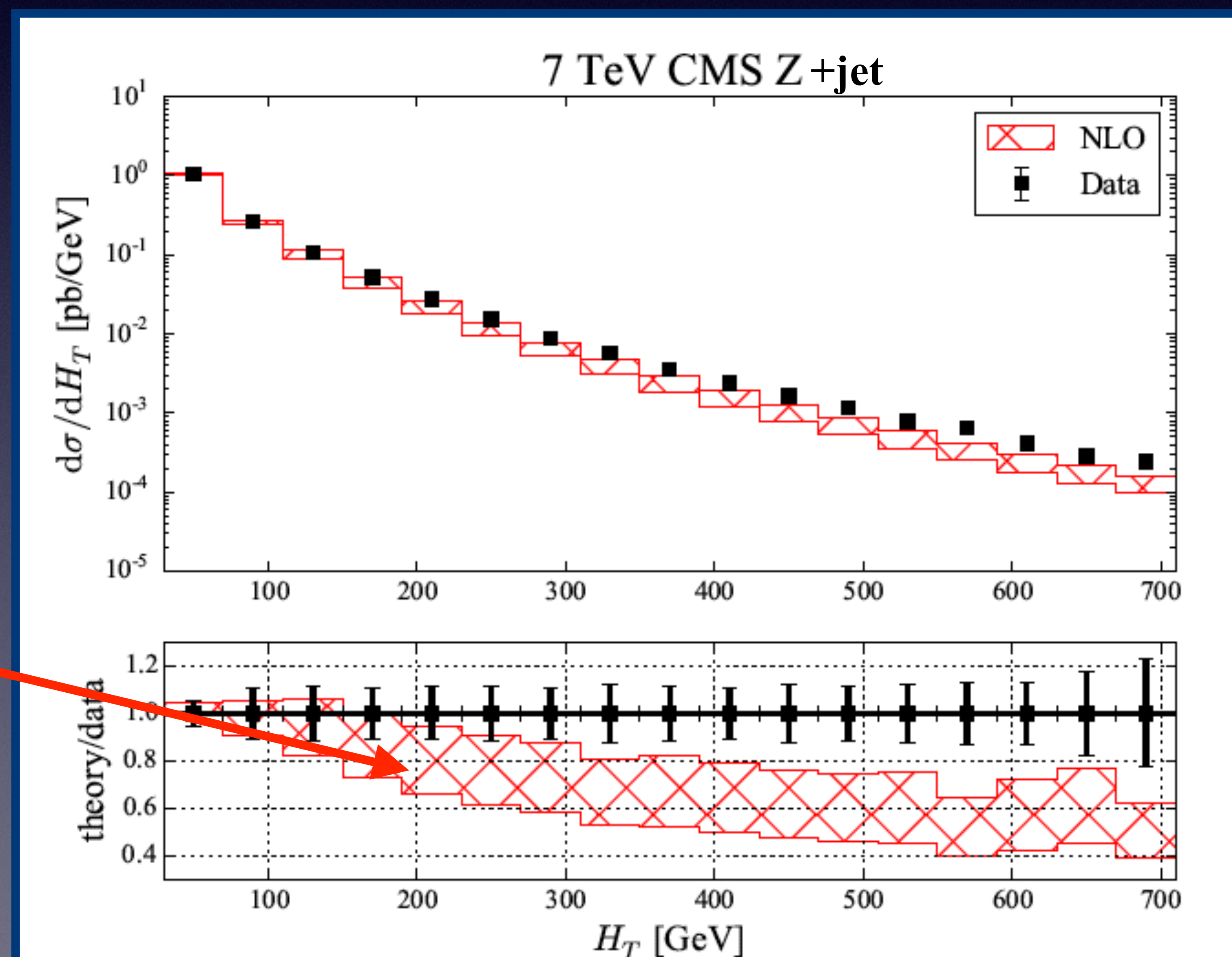
Currie, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Pires (2017)

Improved data/theory agreement in the central y* region!

Z+jet

- An important background to dark matter searches at the LHC through Z+jet→νν+jet.





NLO theory badly undershoots data

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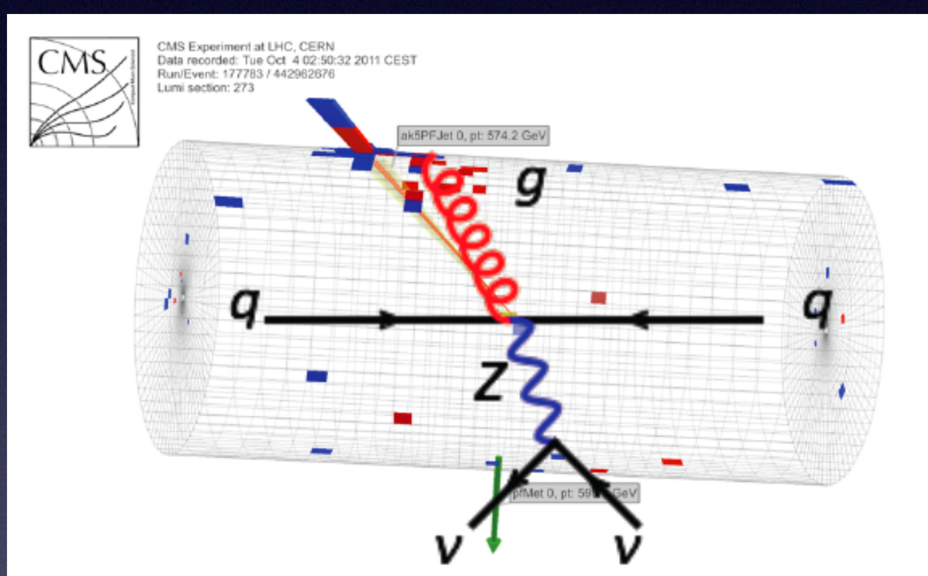
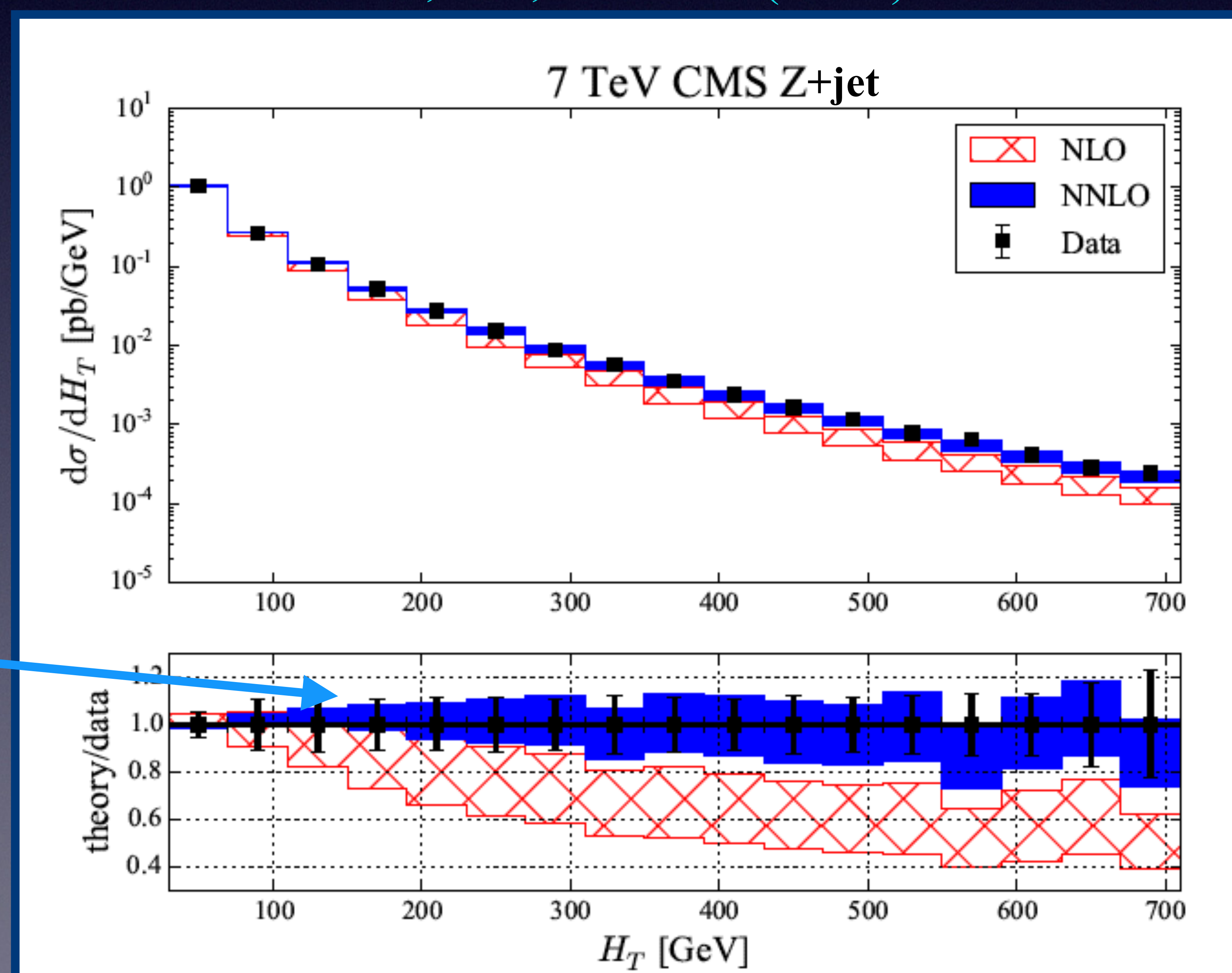


Excellent agreement of NNLO with data!

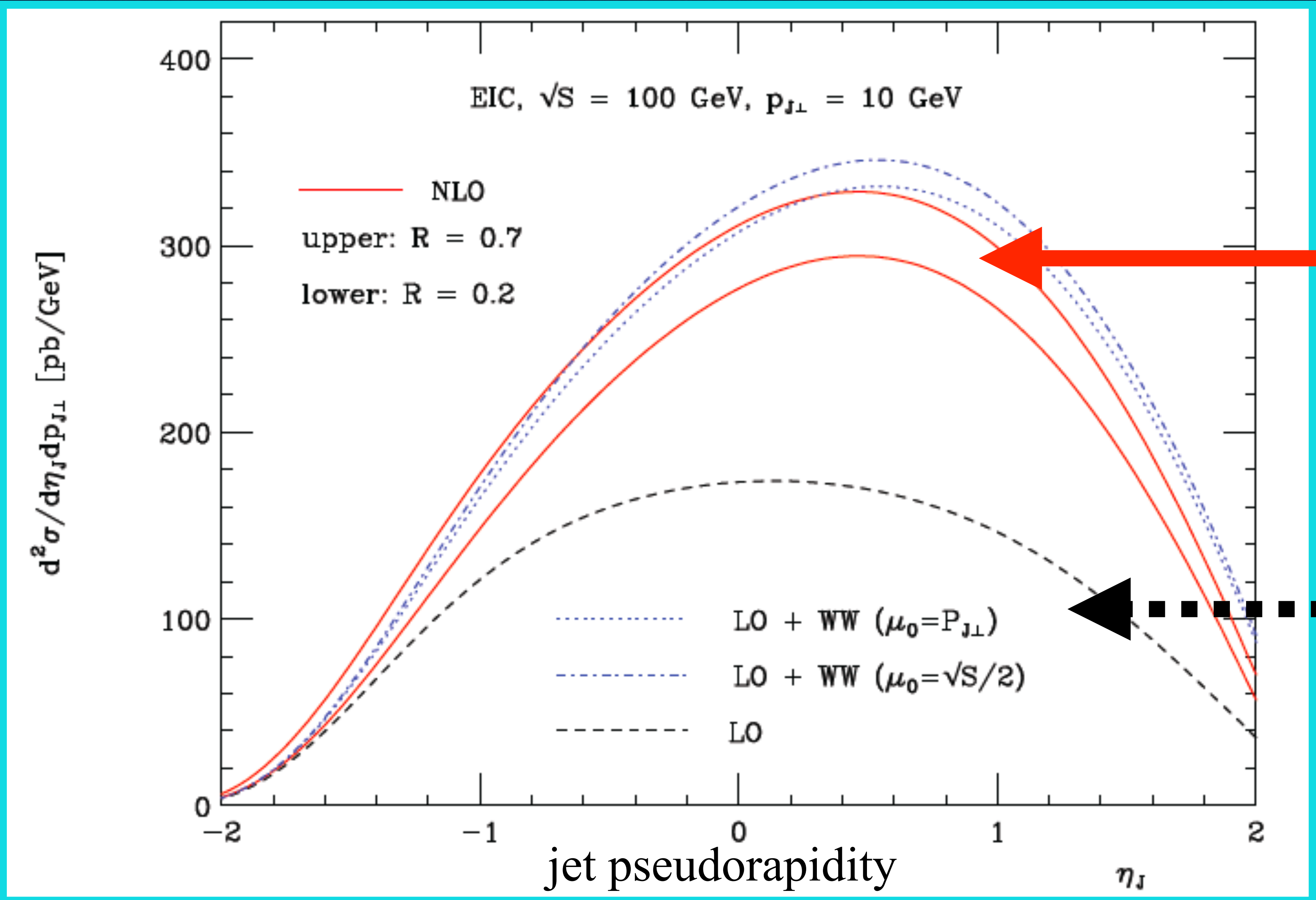
RB, Liu, Petriello (2016)



Jet physics at an EIC

Jet physics at an EIC

- Here is an example of inclusive jet production at the EIC: an important probe of the gluon spin, nuclear medium properties, and other quantities.



A factor of 2 increase in going from LO to NLO for jet production at a future EIC!

WW: Weizsacker-Williams contributions

Hinderer, Schlegel, Vogelsang PRD92 (2015)

Jet physics at an EIC

Goals:

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

Theoretical framework and setup

- We assume standard collinear factorization:

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

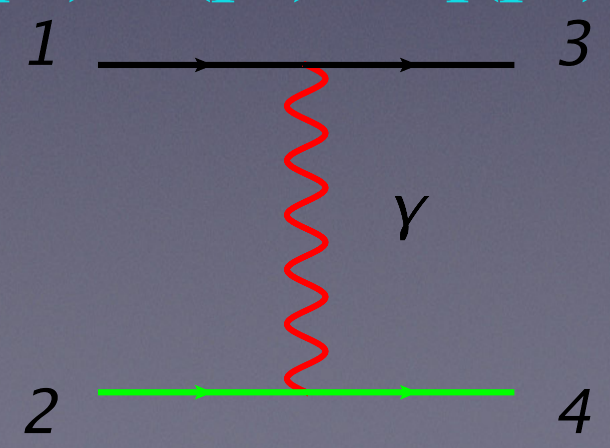
DIS: eN→eN

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

Inclusive jet production: eN→jX

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

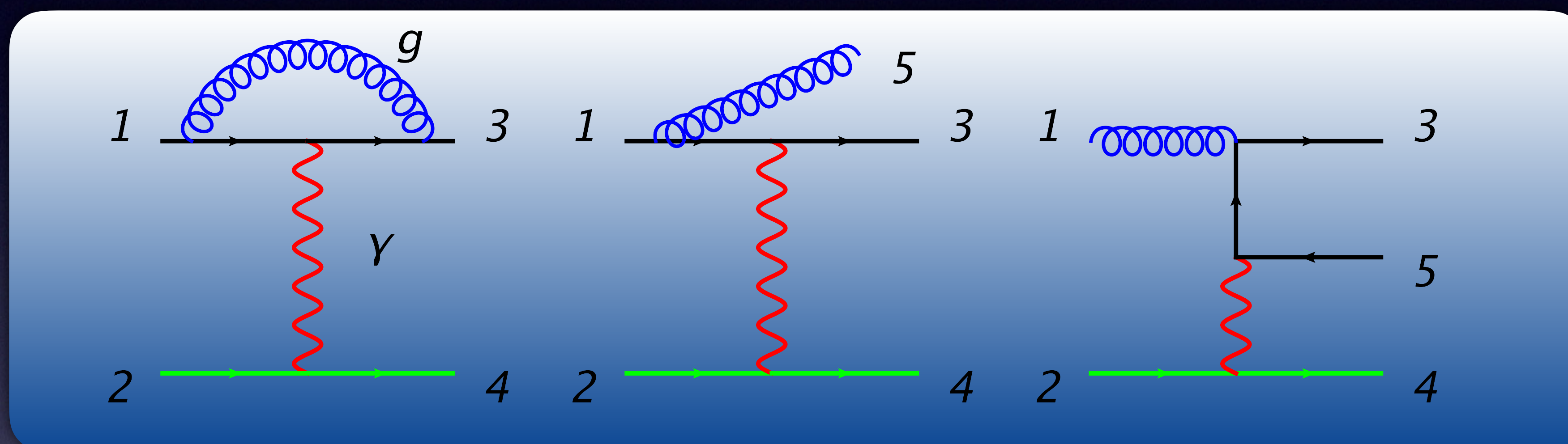
$q(p_1)+l(p_2)\to q(p_3)+l(p_4)$



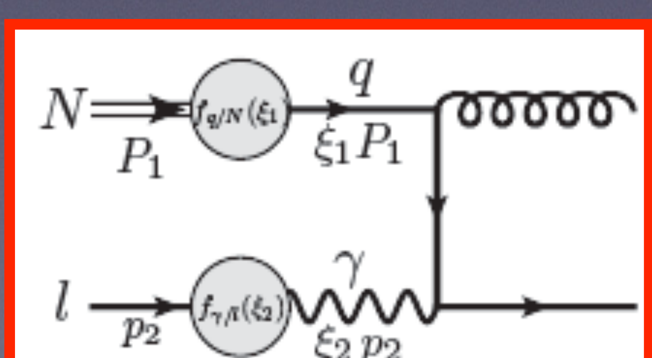
- Leading order: identical for both processes, lepton recoils against a jet

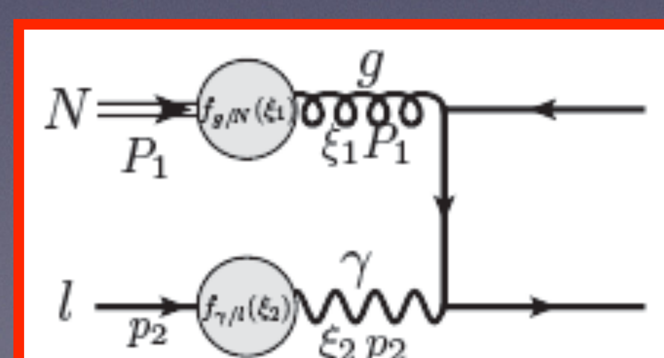
NLO $O(\alpha^2\alpha_S)$ corrections

- Some typical real and virtual corrections to the quark-lepton scattering processes; new contribution from gluon-lepton scattering. Calculation follows standard techniques.



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





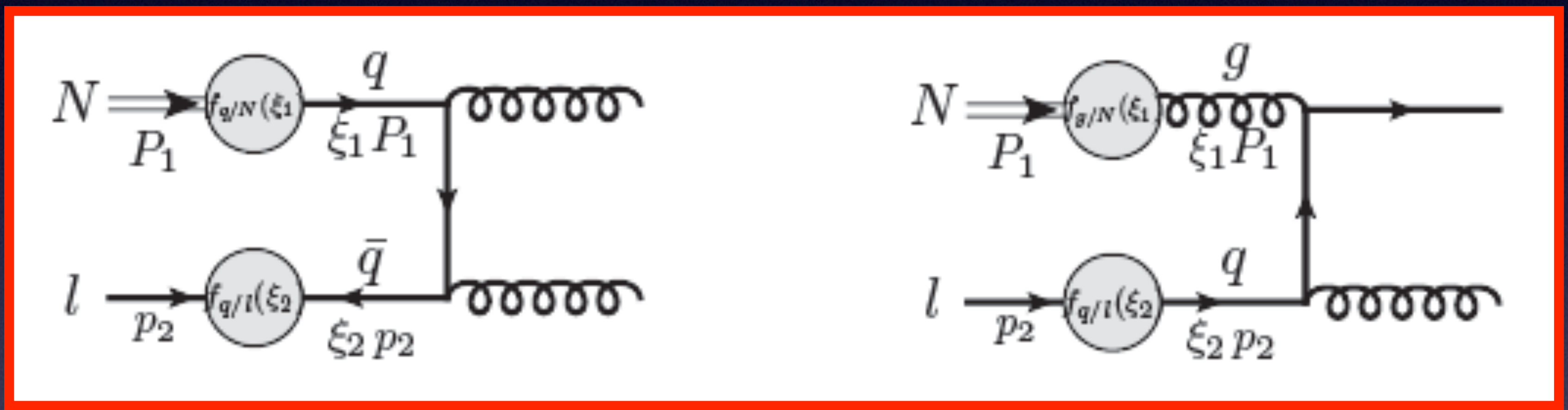
$$f_{\gamma/l}(\xi) = \frac{\alpha}{2\pi} P_{\gamma l}(\xi) \left[\ln\left(\frac{\mu^2}{\xi^2 m_l^2} \right) - 1 \right] + \mathcal{O}(\alpha^2)$$

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

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

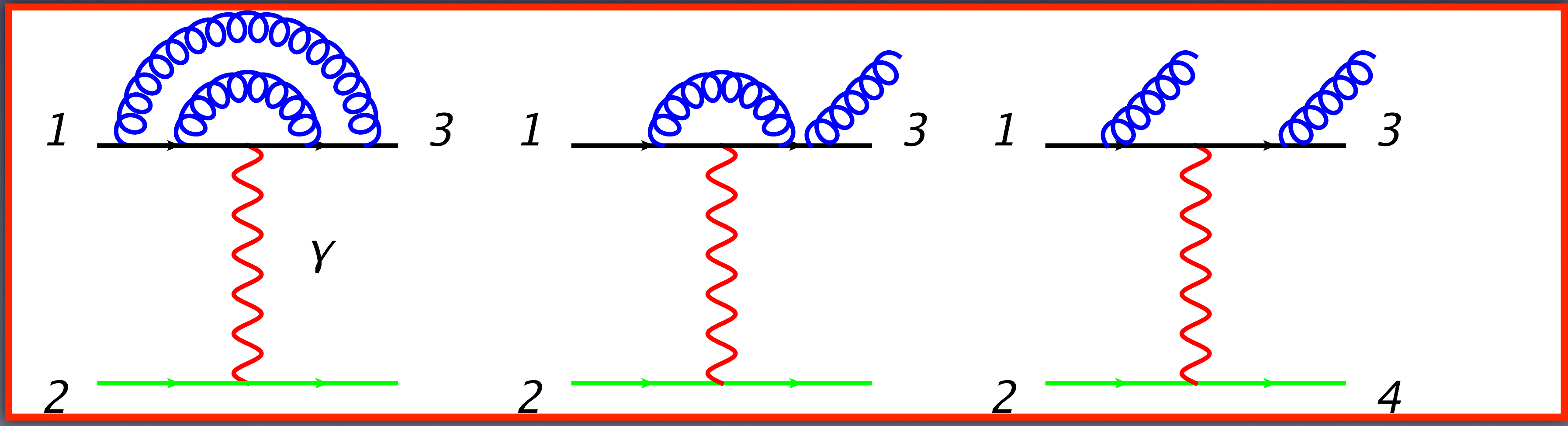
NNLO $O(\alpha^2\alpha_S{}^2)$ corrections

- 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. In this unpolarized case we use a simple model for the relevant distributions. These contributions will be considered carefully in the polarized case.



- Standard NLO corrections to quark-photon scattering.

- Double-virtual, real-virtual and double real corrections to quark-lepton scattering.



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

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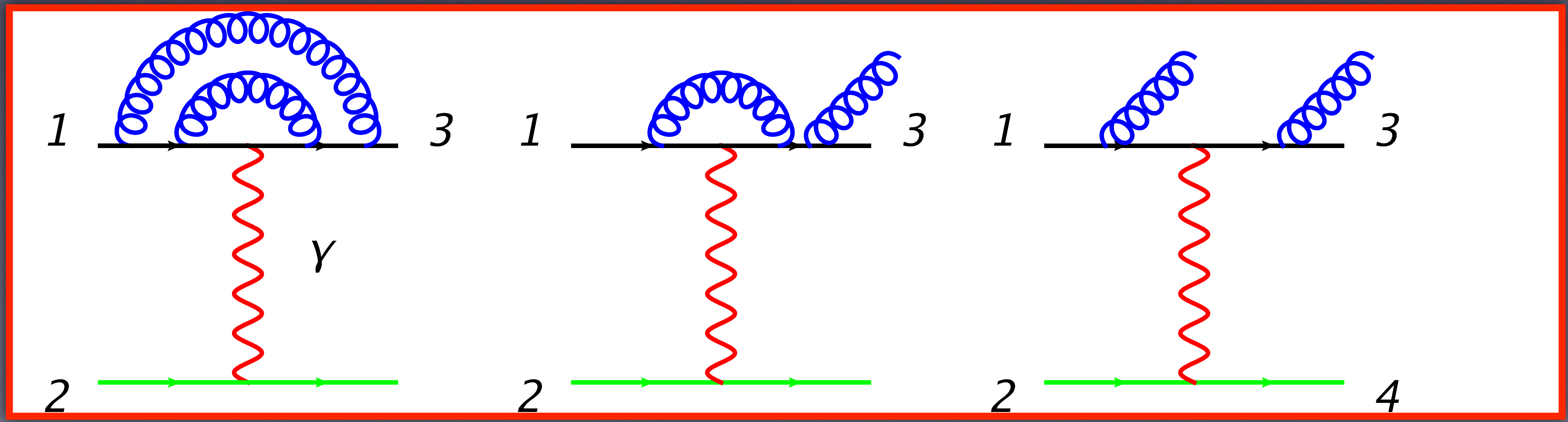
Complicated problem that took many years to solve in the context of LHC physics!

- Standard N

- Double-virtual, real-virtual and double real corrections to quark-lepton scattering.



Contain IR singularities that need to be extracted

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)

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

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

RB, Focke, X. Liu, Petriello, 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 this 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

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

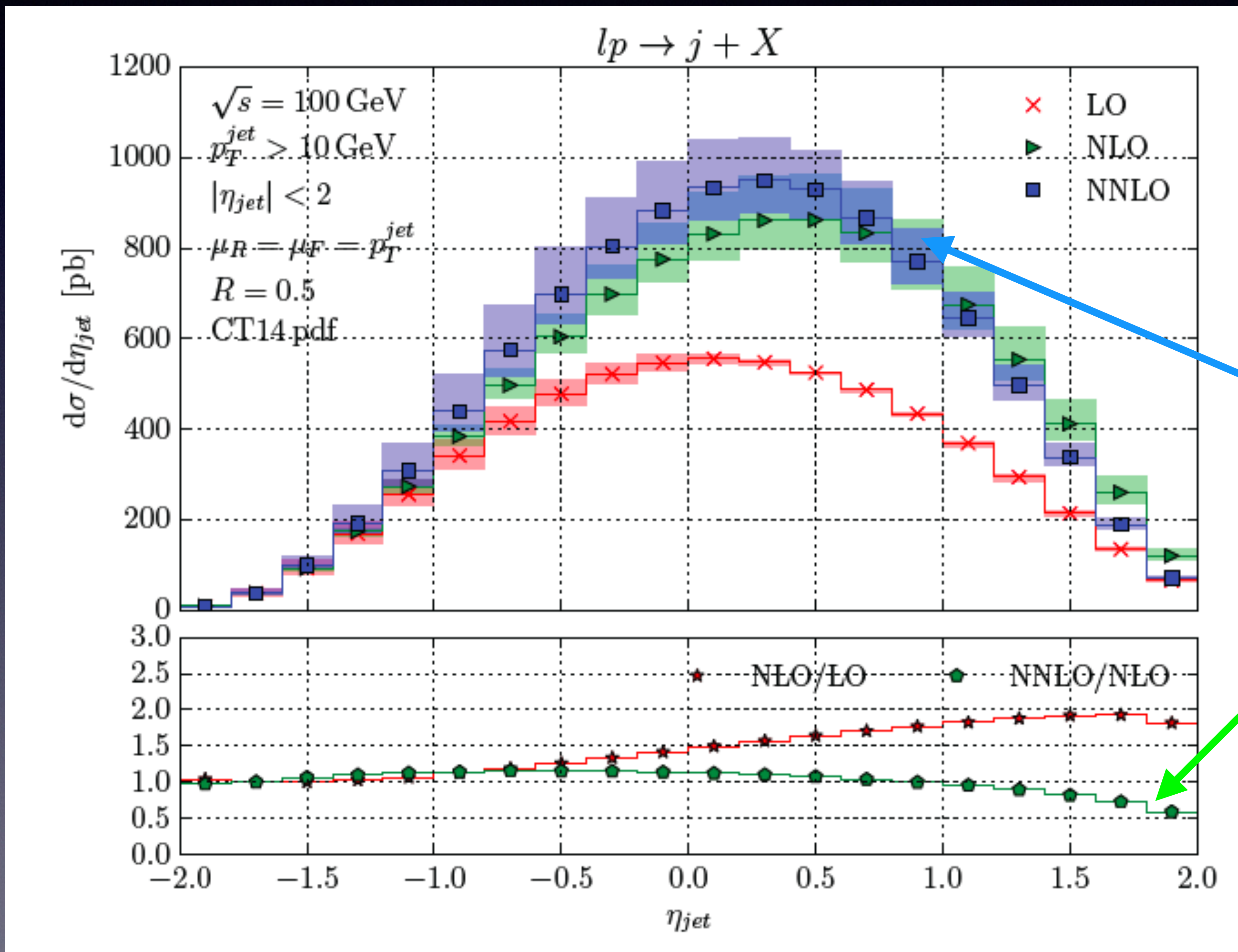
- Expand this formula to $O(\alpha_S^2)$ to get the NNLO cross section below the cut. Need each of these separate functions to NNLO.

  - *H*@NNLO: Matsuura, van der Merck, van Nerven (1988)
  - *B*@NNLO: Gaunt, Stahlhofen, Tackmann (2014); RB, Petriello, Schubert, Xing (2017)
  - *S*@NNLO: RB, Liu, Petriello (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



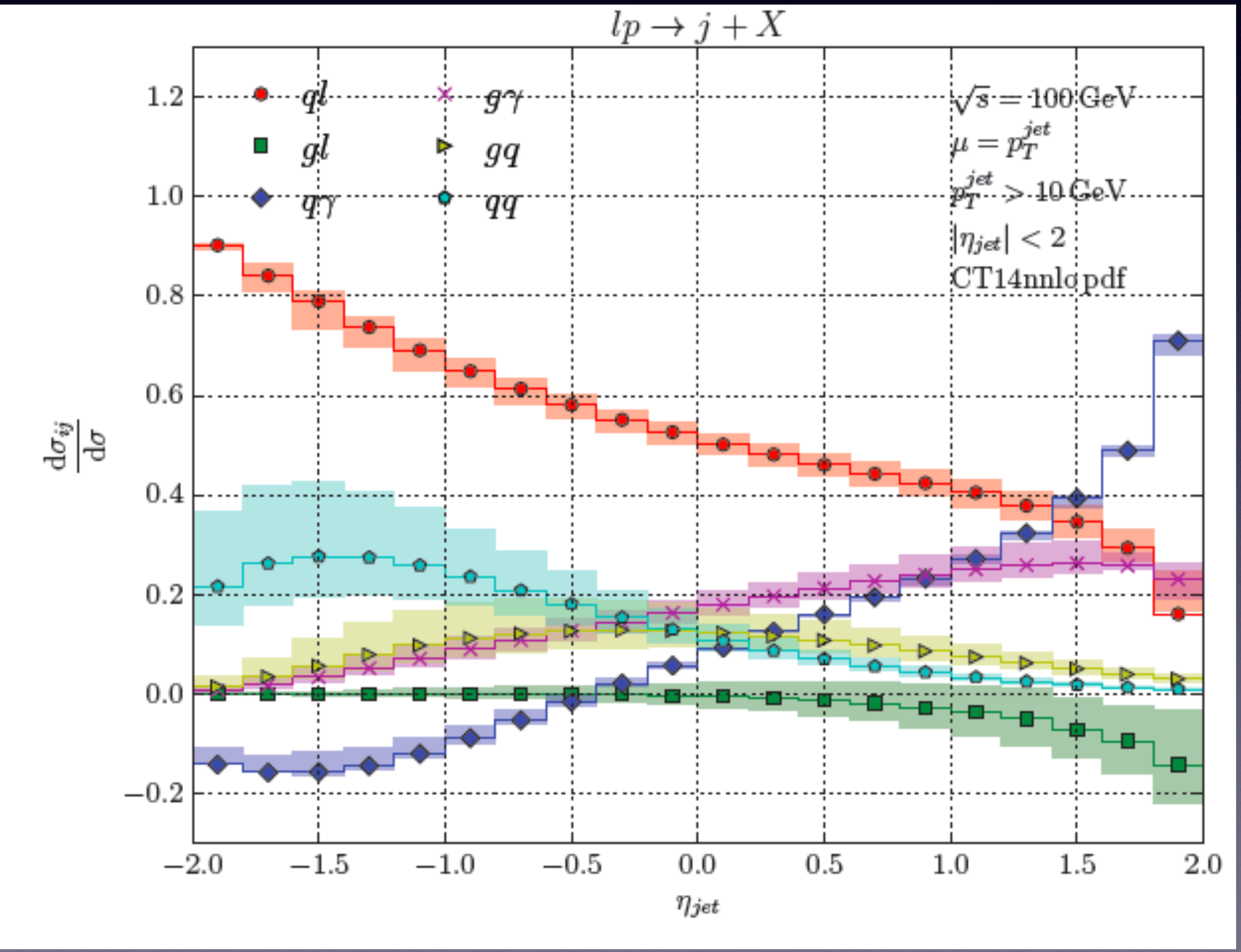
Perturbation theory stabilizes at NNLO!

Sizable corrections in the forward region; if not accounted for could be mistaken for a PDF shape!

Abelof, RB, X. Liu, Petriello, 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 the phase space, indicating that different kinematic regions provide access to different partonic luminosities.



Abelof, RB, Liu, Petriello PLB 763 (2016)

Polarized collisions

- We are interested in polarized proton structure at an EIC; need to extend the N-jettiness subtraction to handle polarized collisions

- Schematic form of the 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!**

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known helicity-dependent 2-loop virtual corrections

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

- We have provided this missing ingredient (RB, Petriello, Schubert, Xing PRD96 (2017))

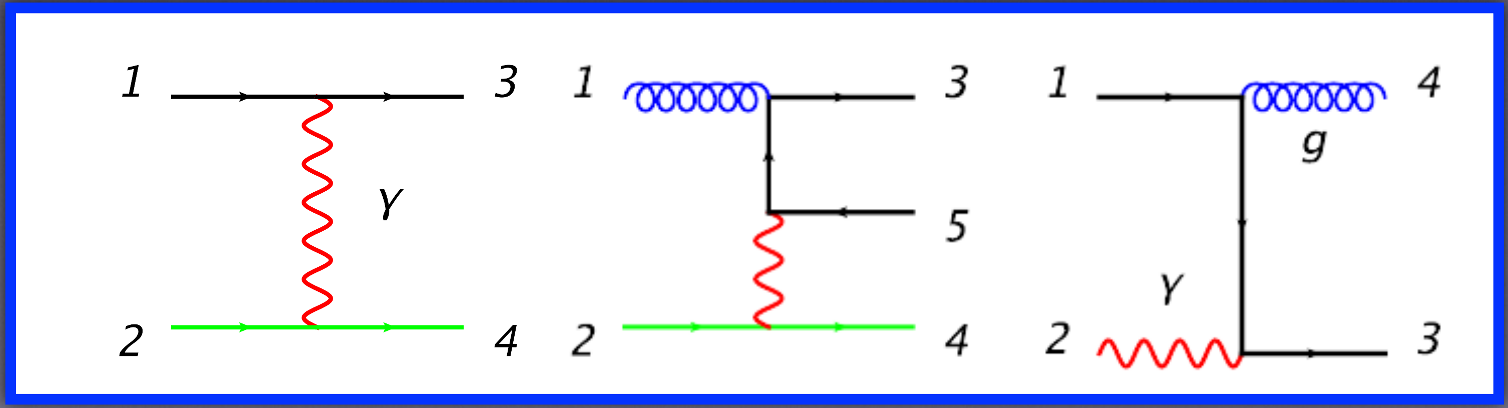
Setup for EIC pheno study

- **Goal:** study the sensitivity of inclusive jet production at an EIC to polarized PDFs. Similar framework as the unpolarized setup described before except that we now include a more detailed analysis of the resolved photon distribution contributions in our study.

Double-longitudinal spin asymmetry:

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

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



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

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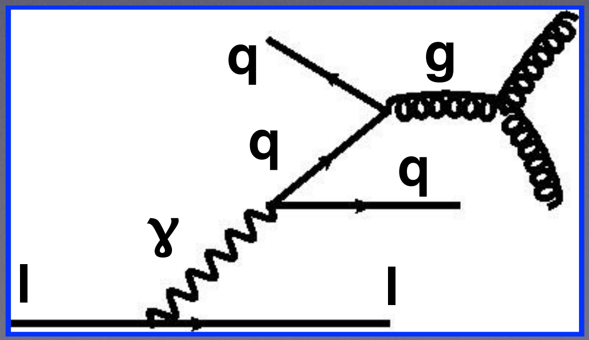
$$\boxed{\Delta\sigma_{LL} = \Delta\sigma_{LO} + \Delta\sigma_{NLO} + \underbrace{\Delta\sigma_{res}}}$$

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

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	$Q^2 \approx 0$	$f_{g/H}, f_{g/\gamma}, \Delta f_{g/H}, \Delta f_{g/\gamma}$

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 except that
distr

By measuring this process over its entire kinematic region we have access to many interesting PDFs!

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Partonic channel	Q^2 region	Contributing PDFs
ql	$Q^2 > 0$	$f_{q/H}, \Delta f_{q/H}$
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$g\gamma$	$Q^2 \approx 0$	$f_{g/H}, f_{\gamma/l}, \Delta f_{g/H}, \Delta f_{\gamma/l}$
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 jet 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	$5\,\mathrm{GeV} \leq p_T^j \leq 20\,\mathrm{GeV}$	$-2 \leq \eta^j \leq 2$

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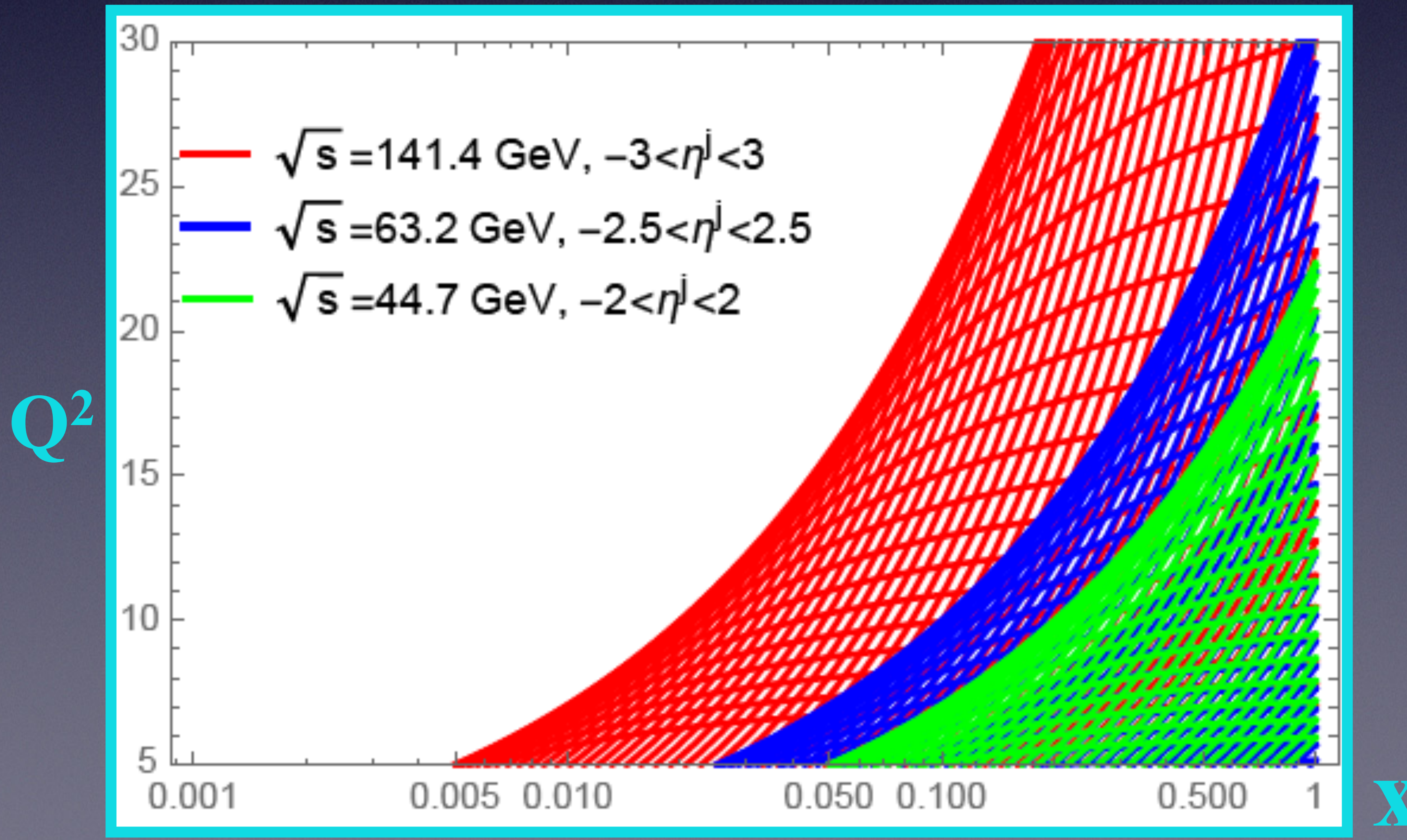
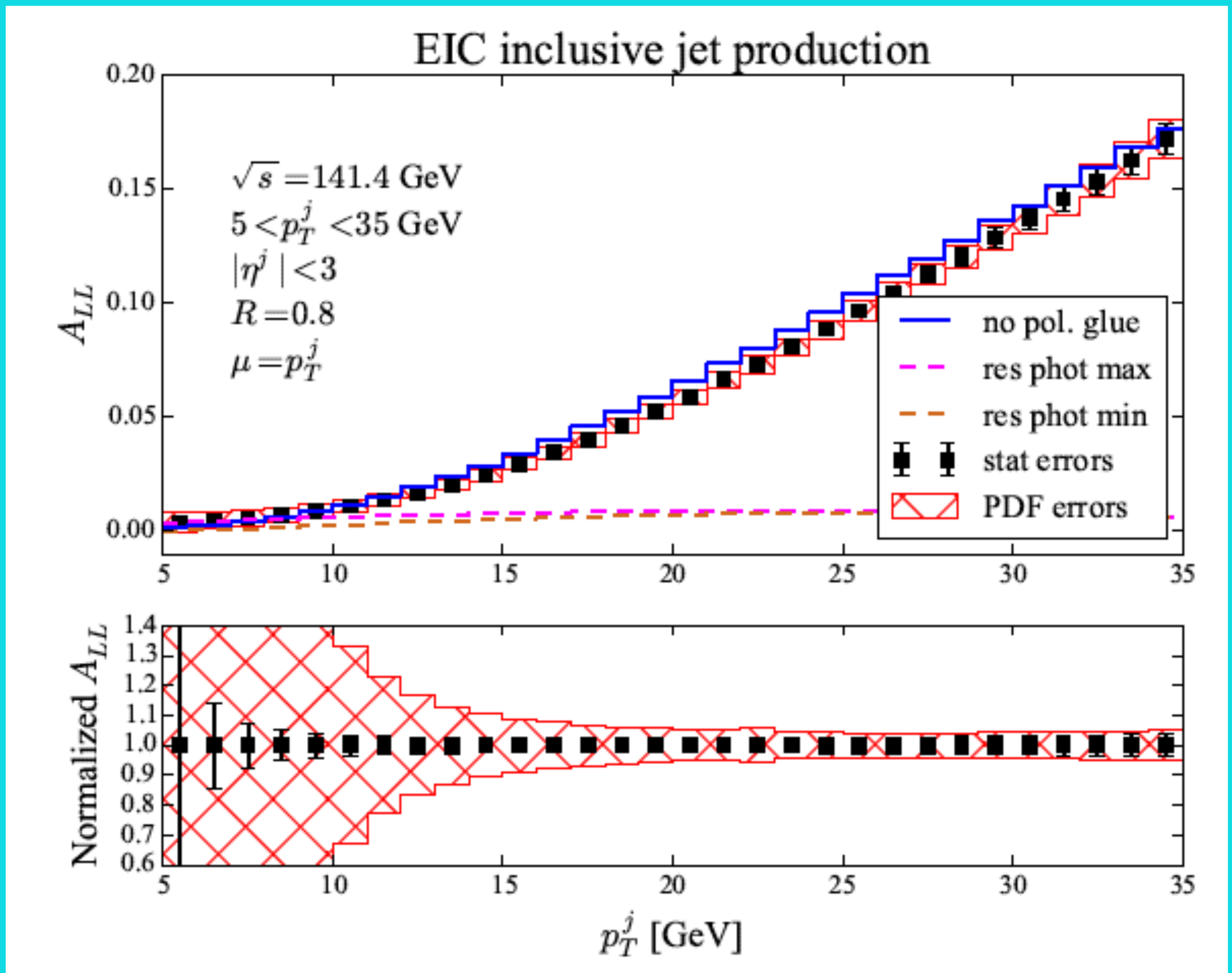
- Assume 10 fb^{-1} of integrated luminosity to estimate statistical errors

Mapped the studied range of (pTj,etaj) to the Q^2 vs Bjorken-x plane:

Lower-x coverage of √s=141.4 GeV dictates much of the observed phenomenology



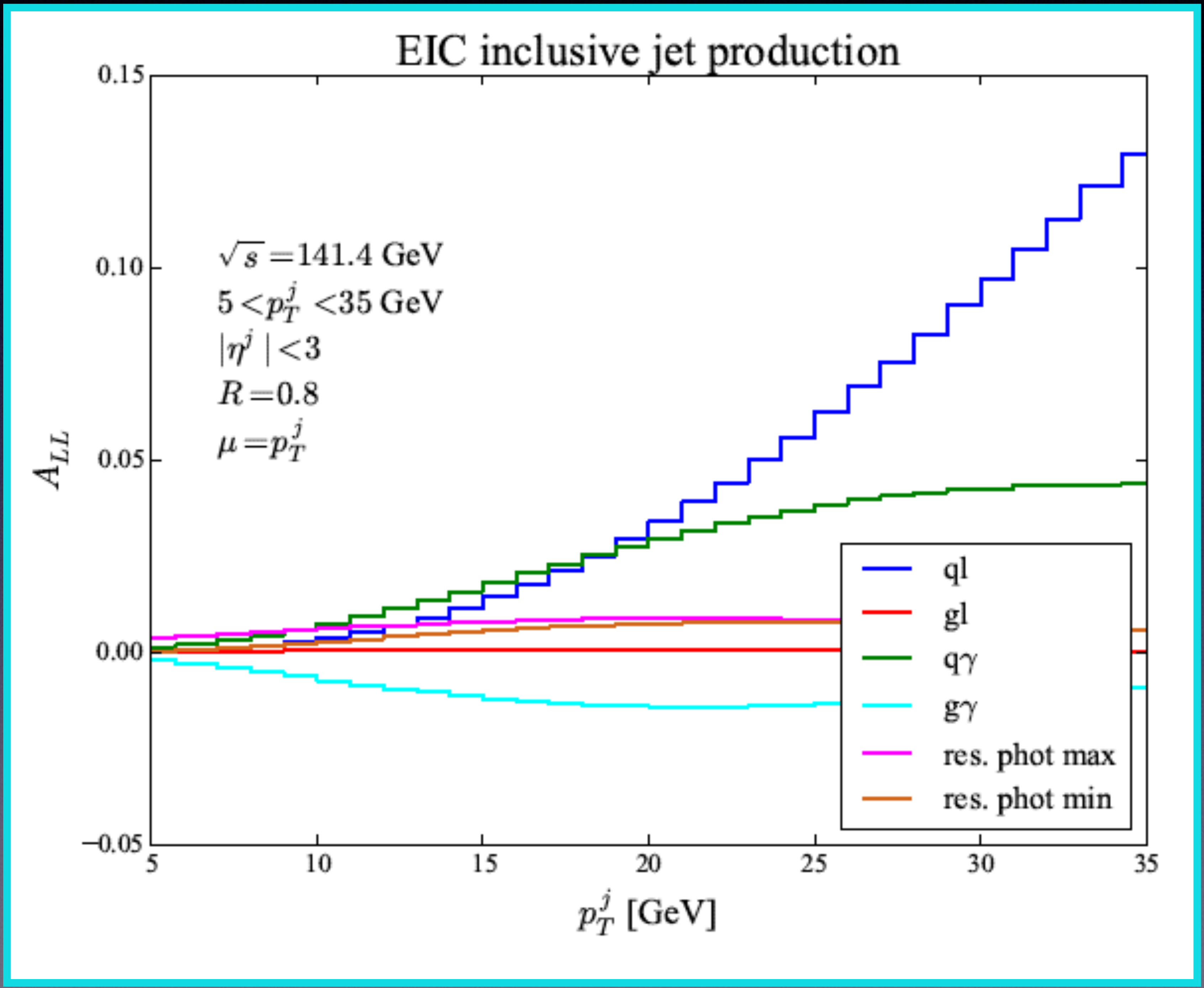
$\sqrt{s}$=141.4 GeV: jet p_T



RB, Petriello, Xing PRD98 (2018)

- A_{LL} grows to **~ 20%** at high pT
- Different polarized $\Delta f_{i/\gamma}$ give small effects, except at low pT
- Turning off $\Delta f_{g/P}$ leads to observable difference at intermediate pT larger than the statistical error
- PDF errors much larger than estimated stat errors at intermediate to low pT; opportunity for EIC to improve our knowledge of Δf!

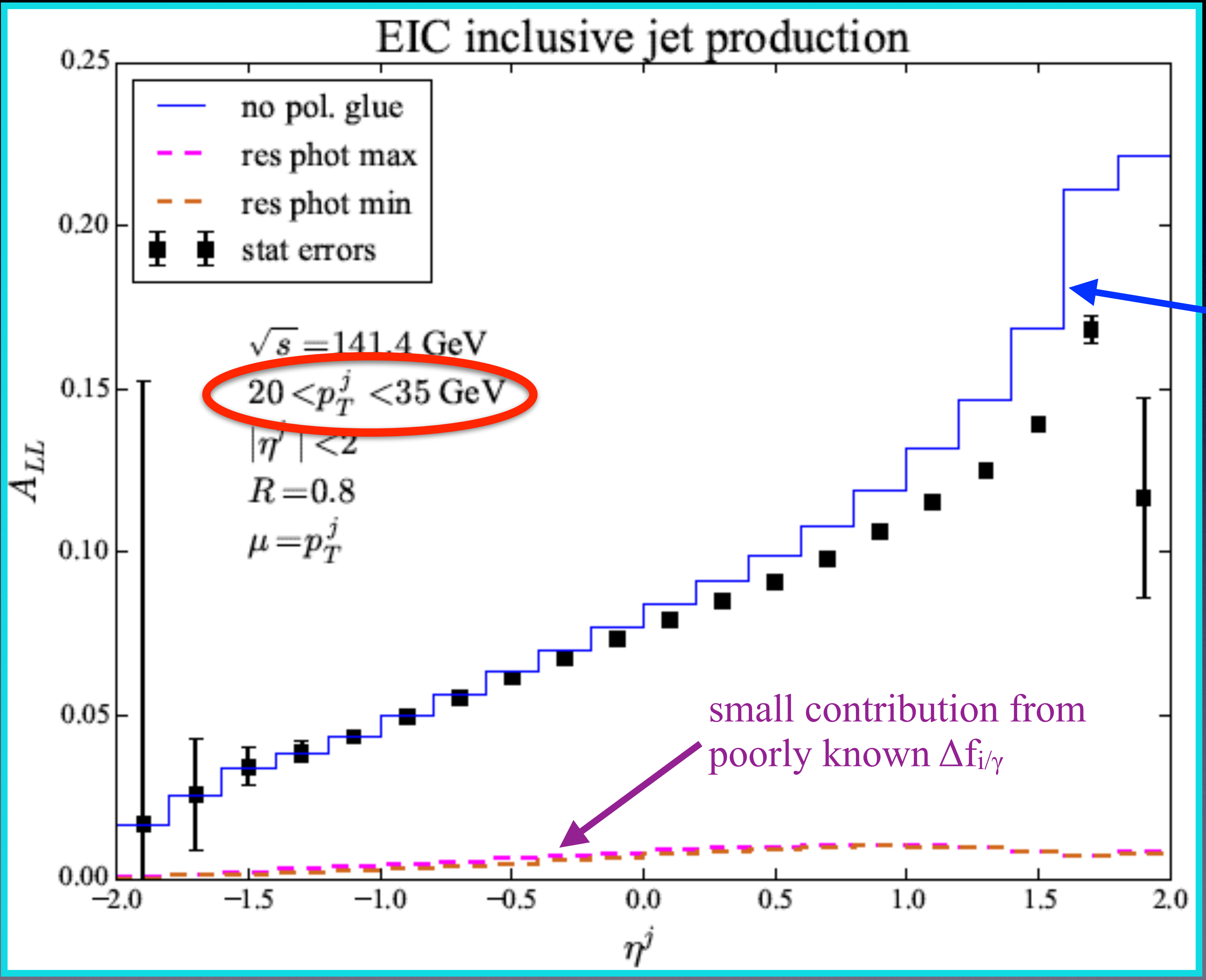
$\sqrt{s}$=141.4 GeV: jet p_T partonic structure



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

RB, Petriello, Xing PRD98 (2018)

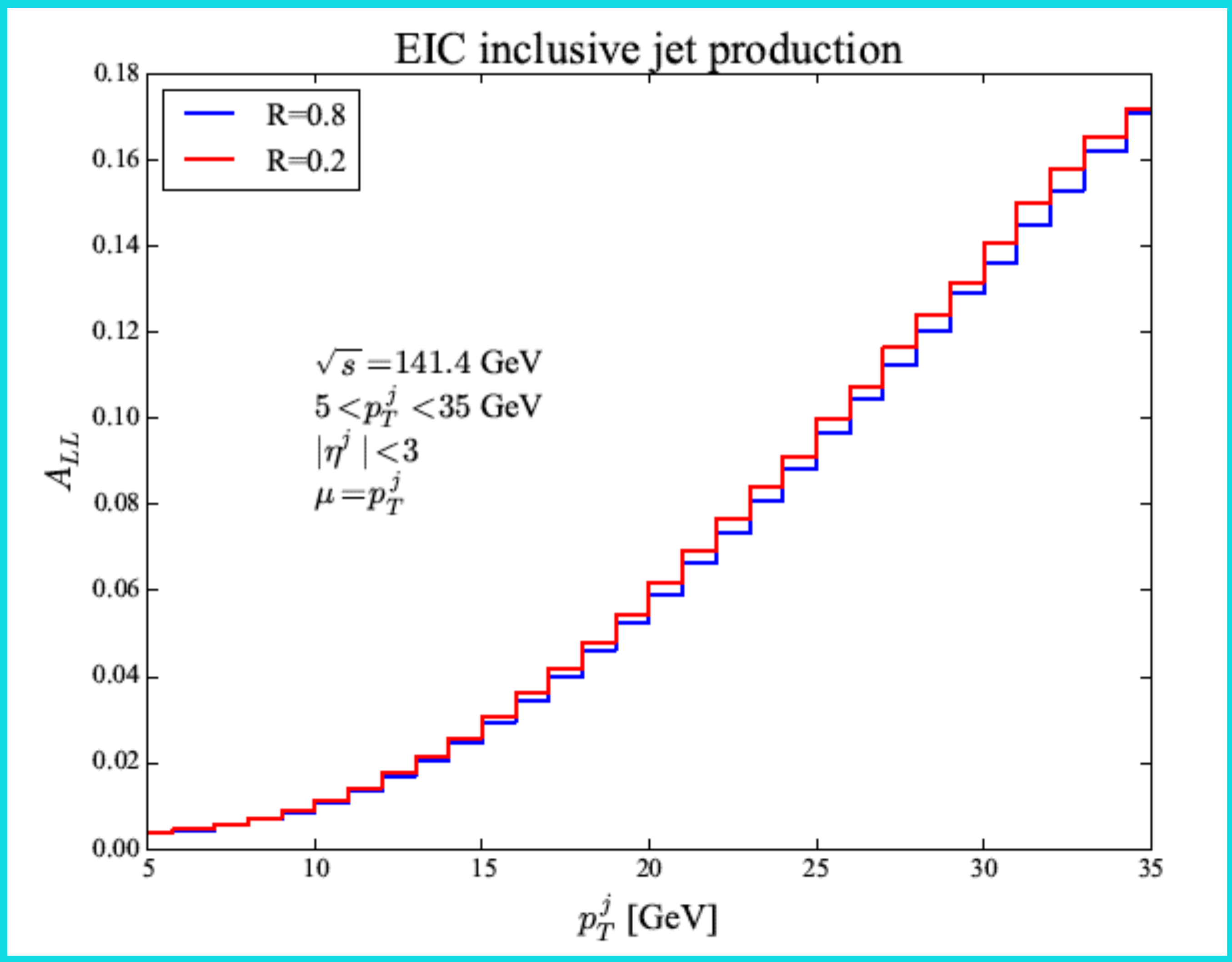
$\sqrt{s}$=141.4 GeV: $\Delta f_{g/P}$ access

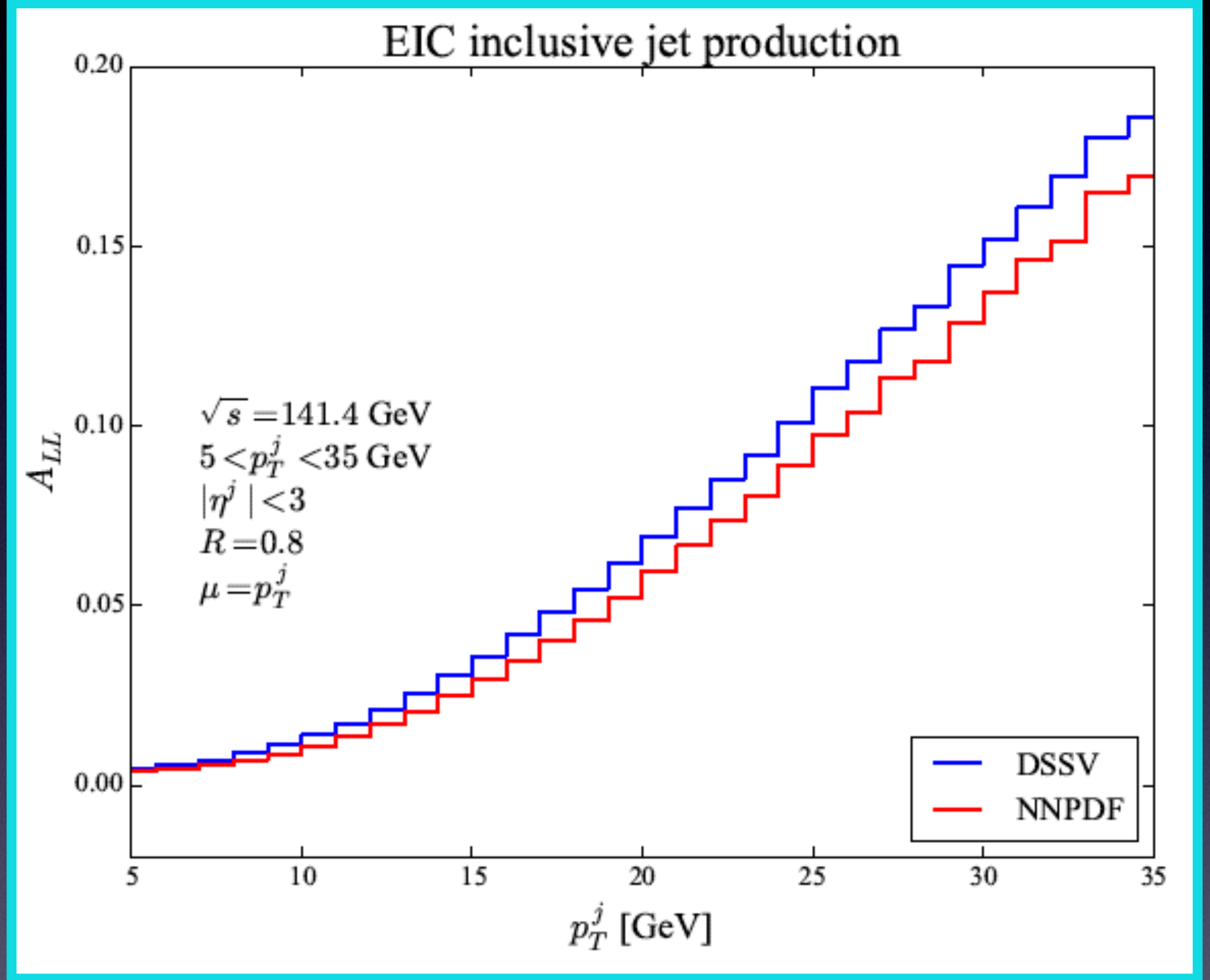


turning off polarized gluon leads to a different shape of the jet pseudo-rapidity distribution in the positive etaj region; larger than the estimated statistical errors

RB, Petriello, Xing PRD98 (2018)

√s=141.4 GeV: PDF, R dependence



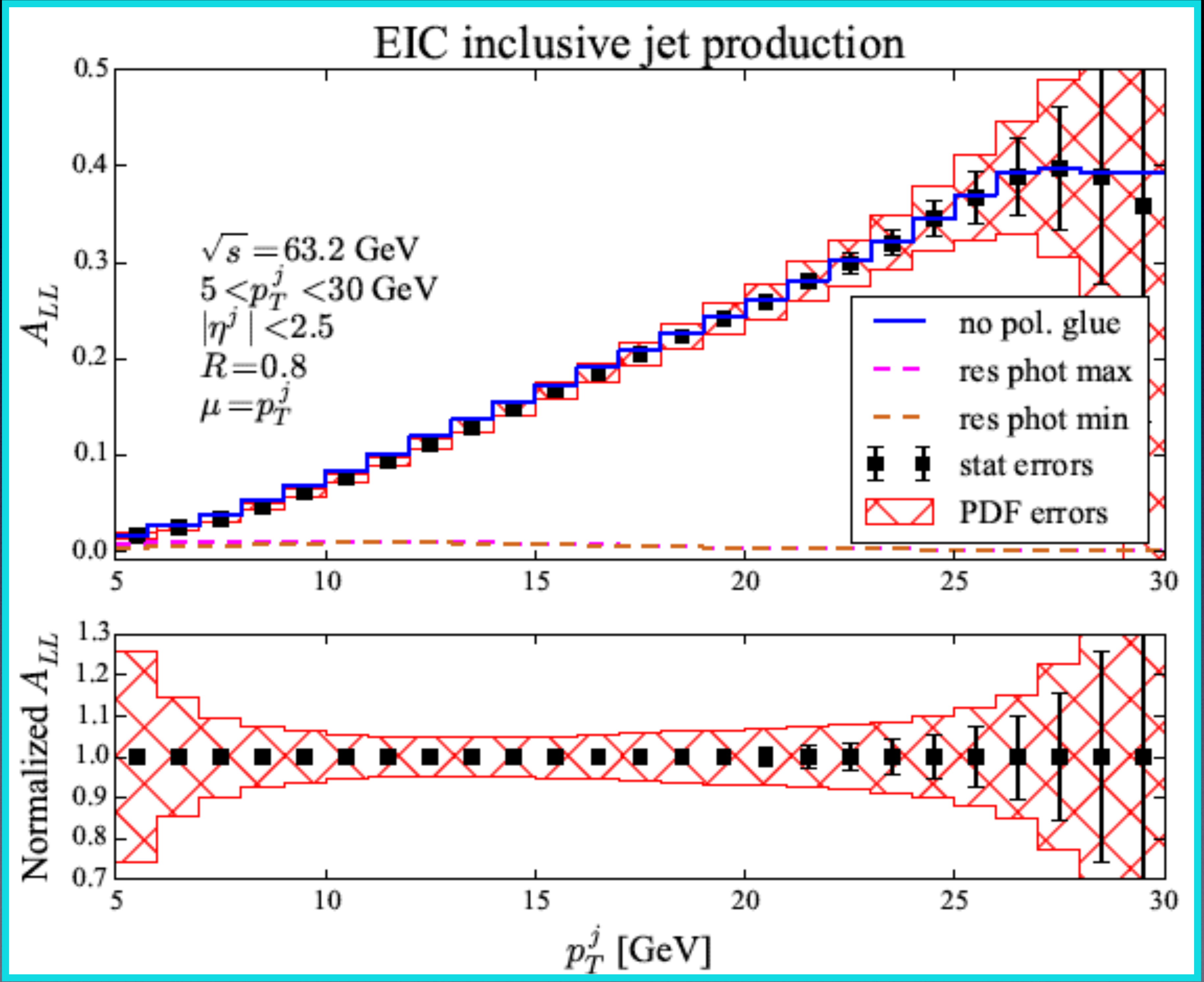


Small dependence on jet radius R for the studied distributions

Measurable difference between DSSV and NNPDF polarized PDFs

RB, Petriello, Xing PRD98 (2018)

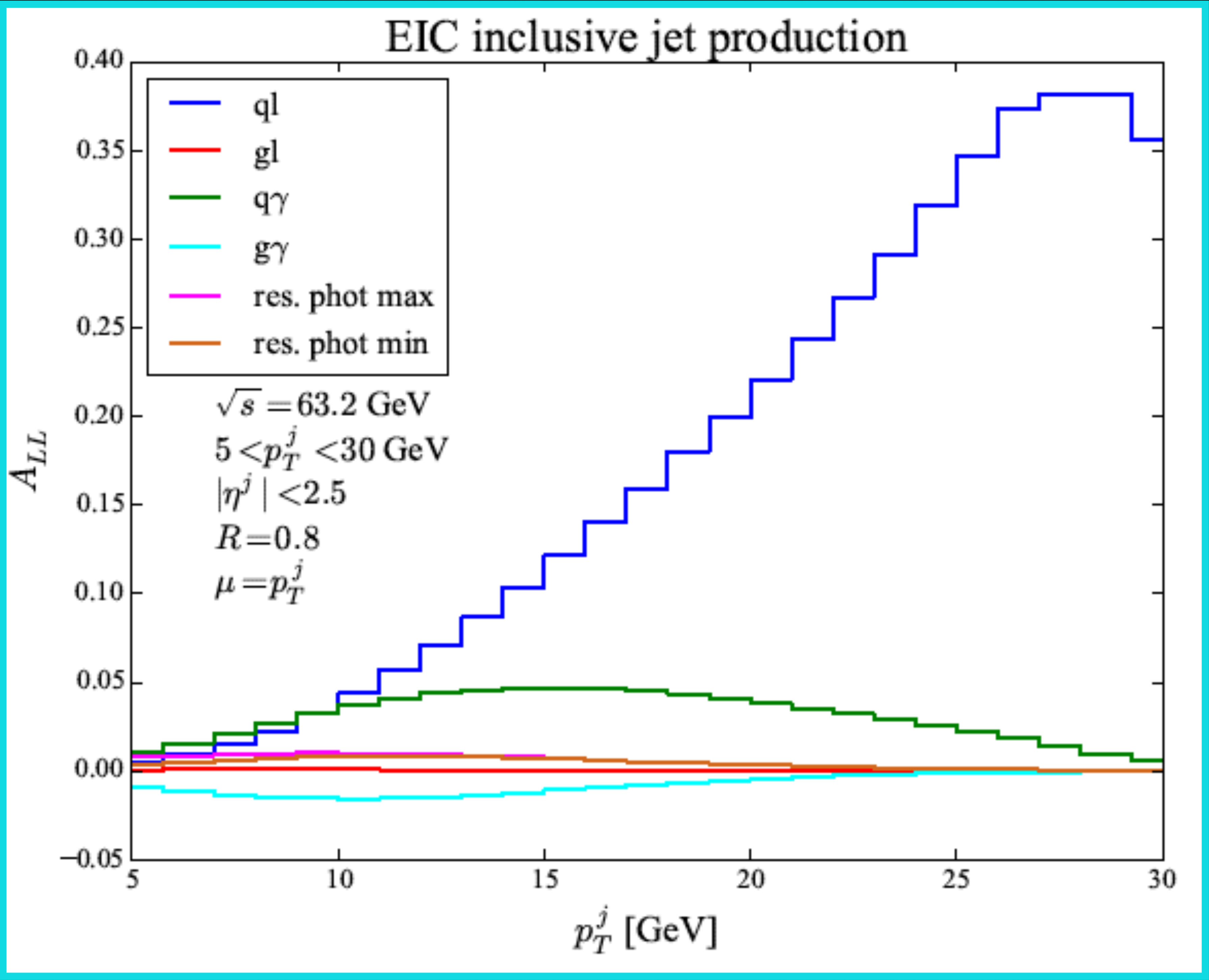
Results for √s=63.2 GeV



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

RB, Petriello, Xing PRD98 (2018)

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



RB, Petriello, Xing PRD98 (2018)

- Dominated by ql channel
- Sensitivity to $\Delta f_{g/P}$ in a limited range of low pT, where it must be disentangled from $\Delta f_{i/\gamma}$ and larger theoretical errors.
- Similar conclusions for $\sqrt{s}$=44.7 GeV

Summary

- All ingredients now available for an NNLO description of both polarized and unpolarized observables in collinear factorization for EIC physics
- Inclusion of NNLO correction 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