Higher-order pQCD and jets

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QCD Evolution 2019

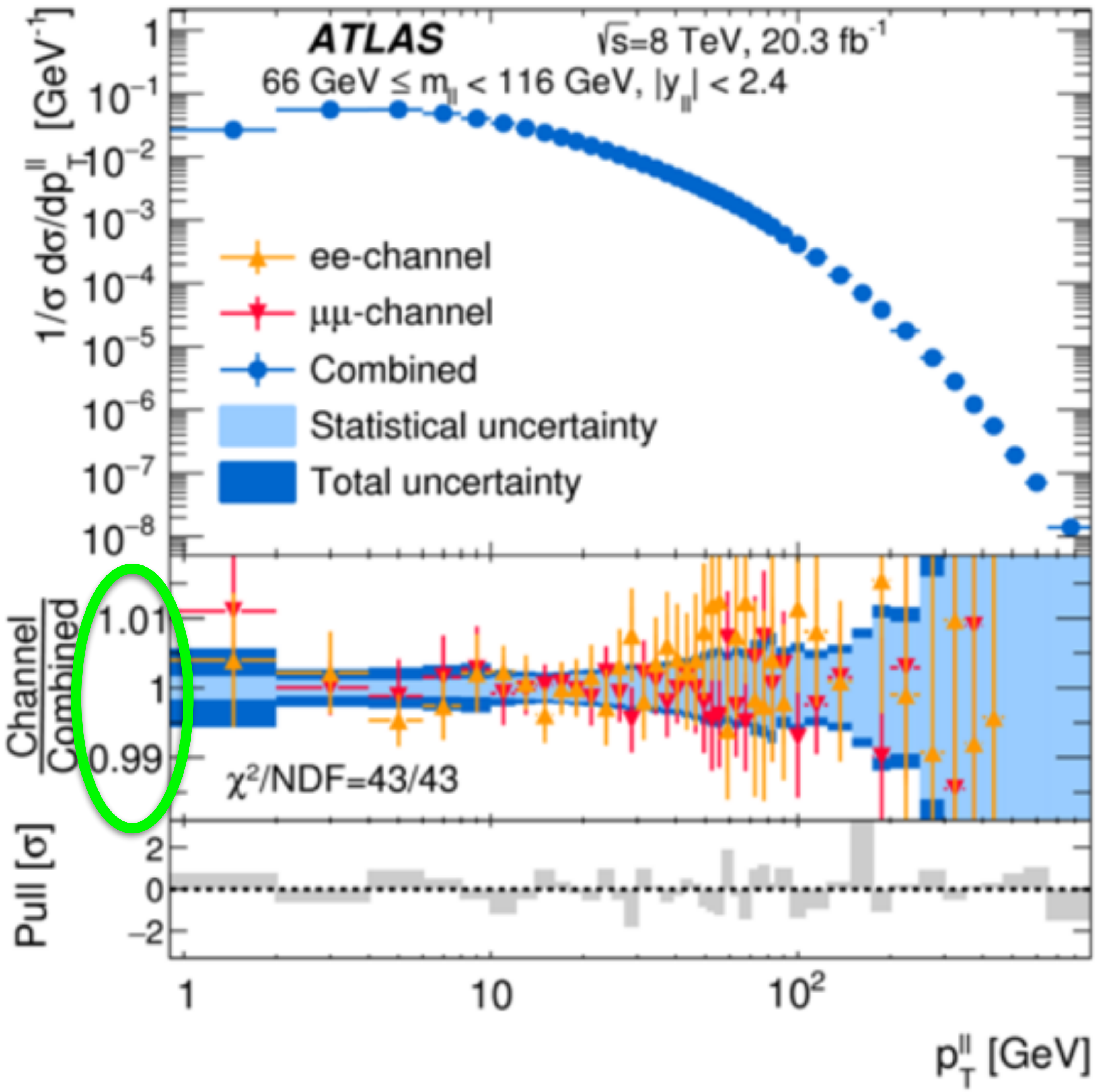
May 17, 2019

NORTHWESTERN UNIVERSITY

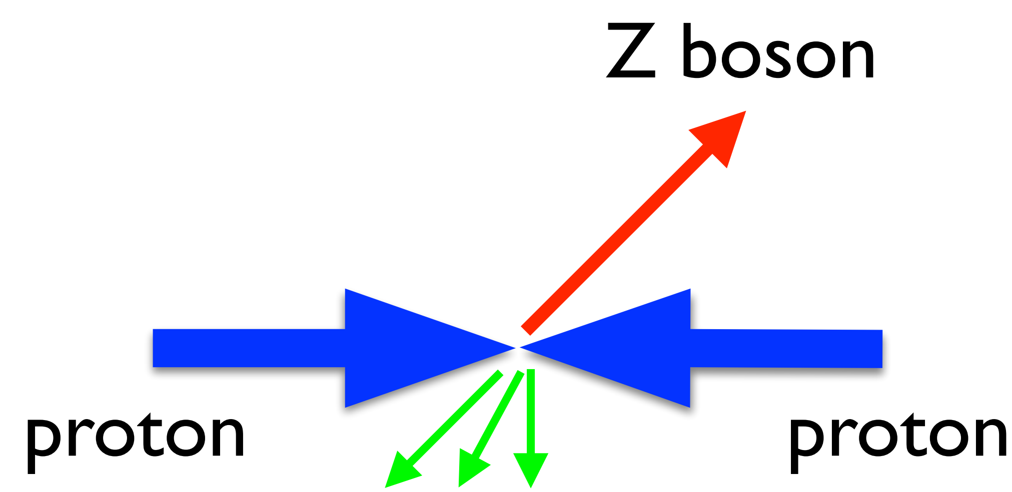
Argonne NATIONAL LABORATORY

Major theme of this talk is precision theory for jets at both the LHC and potential future machines. Why is precision relevant now more than ever?

We are confronting the limitations in our ability to understand hadron collider data now!

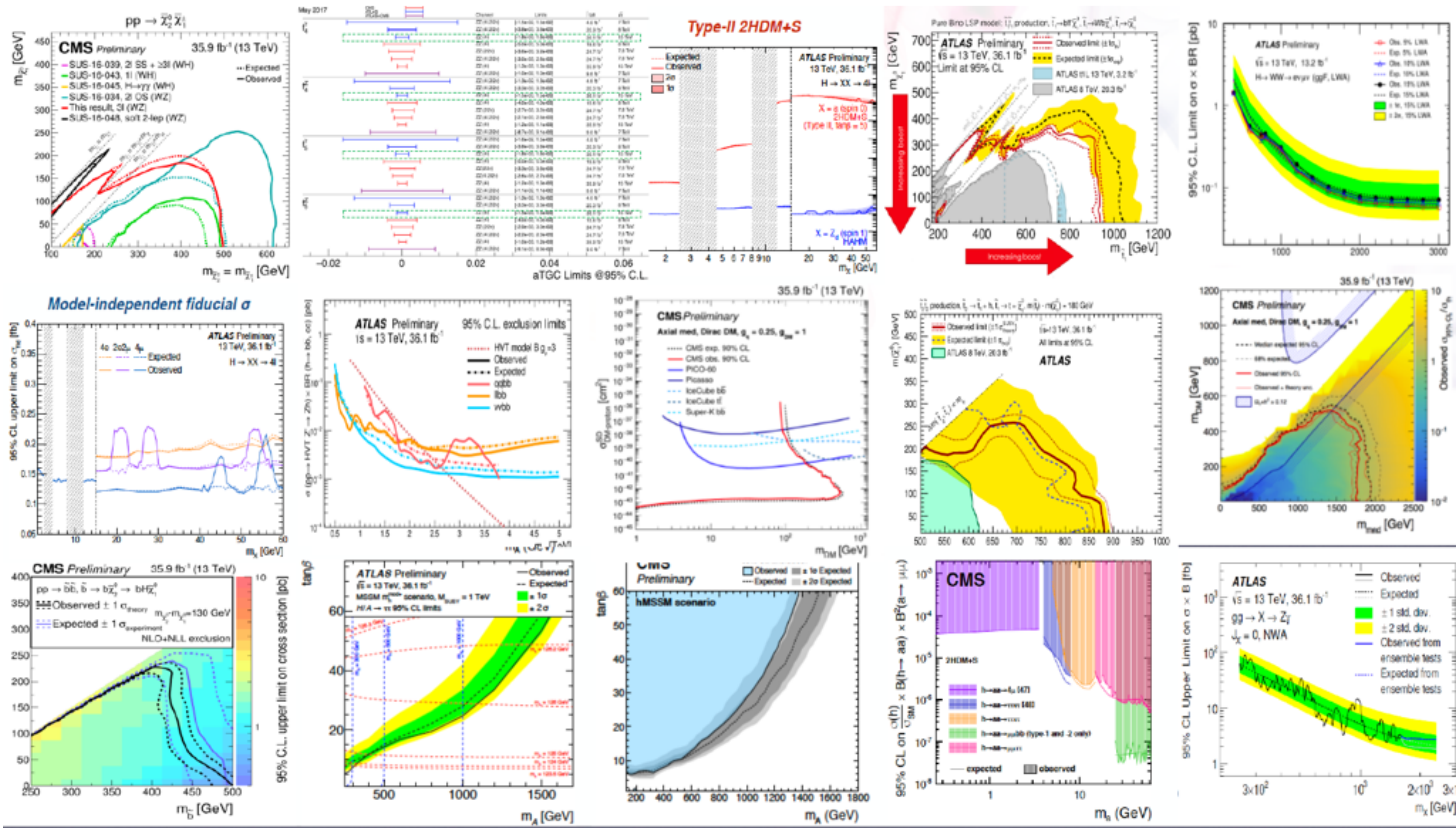


Sub-percent experimental errors over two decades of energy and 8 decades of cross section!



p_T=momentum transverse to proton direction

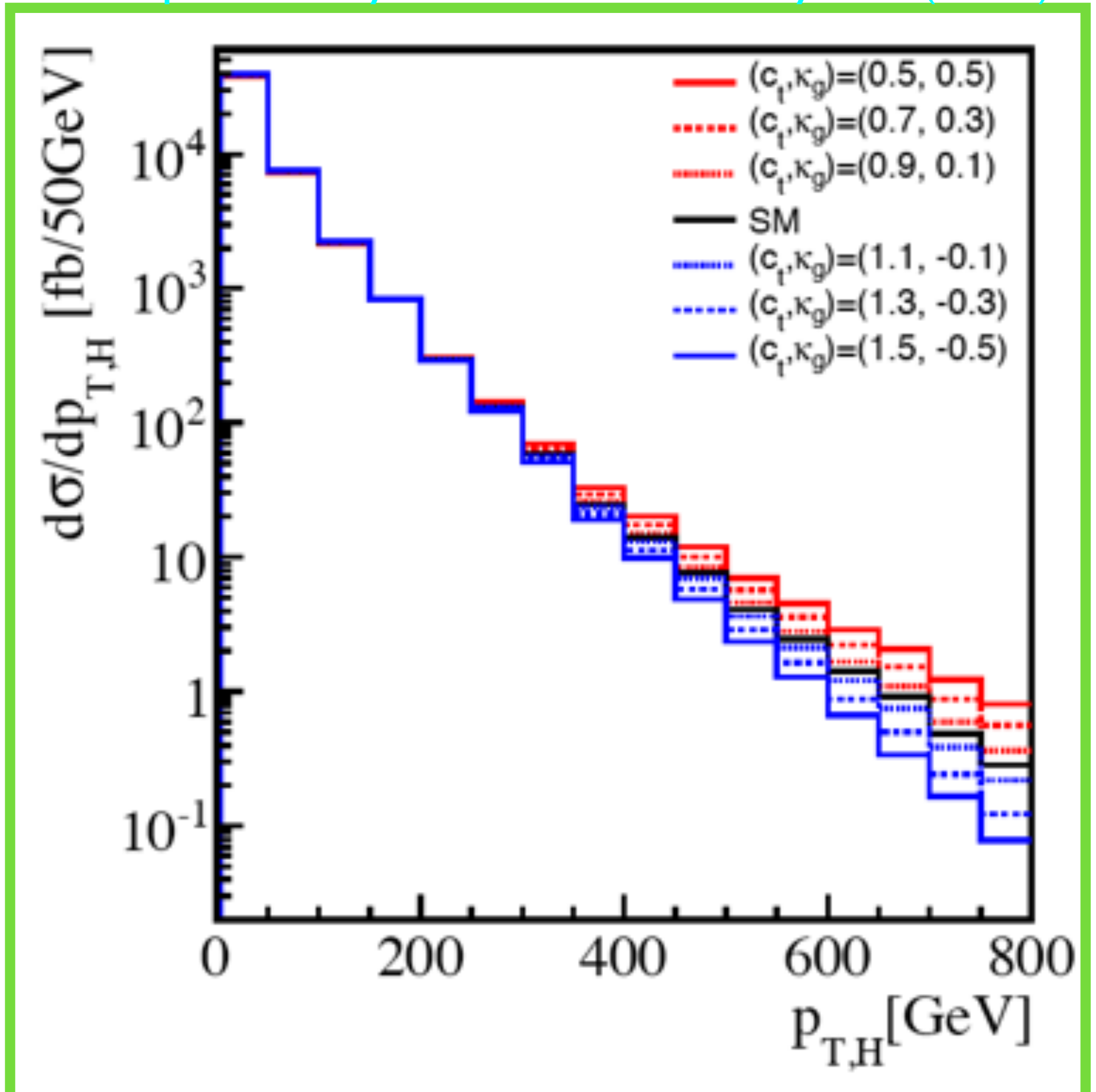
No hints for physics beyond the Standard Model so far; any deviations are likely small, subtle and hard to find!



What can be hiding in a few percent % ?

- The Higgs transverse momentum p_{TH} is one of several examples where precision could be key in discovering new physics

Schlaffer, Spannowsky, Takeuchi, Weiler, Wyman (2014)

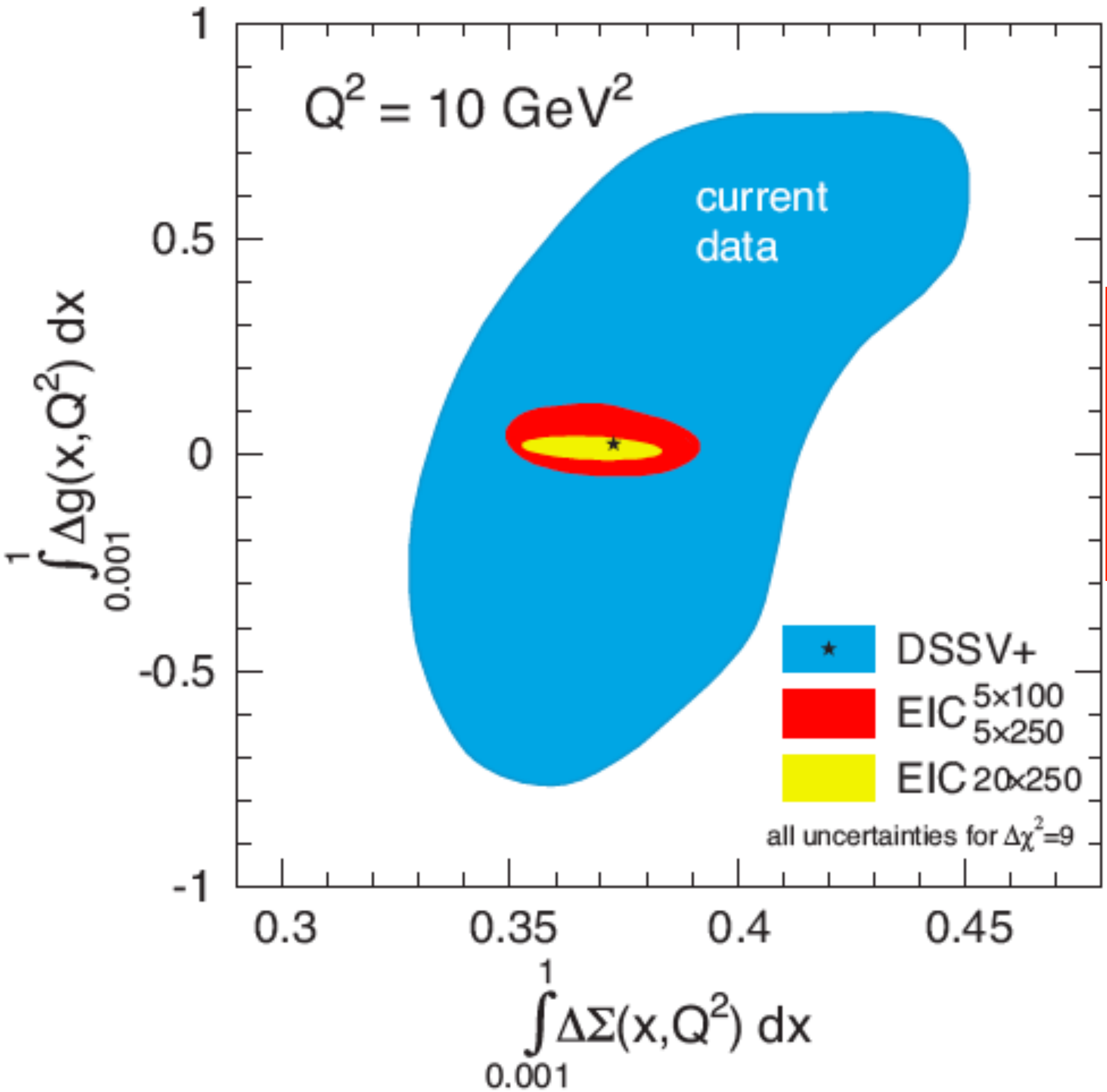


$$\frac{\sigma(c_t, \kappa_g)}{\sigma_{SM}} = (c_t + \kappa_g)^2$$

SM: c_t=1, κ_g=0

- Large changes in the high p_{TH} spectrum due to new physics, while low p_{TH} spectrum unchanged at the few % level (up to ~300 GeV)
- LHC has so far measured the low p_{TH} spectrum. It will measure the high p_{TH} spectrum as it moves to higher luminosity

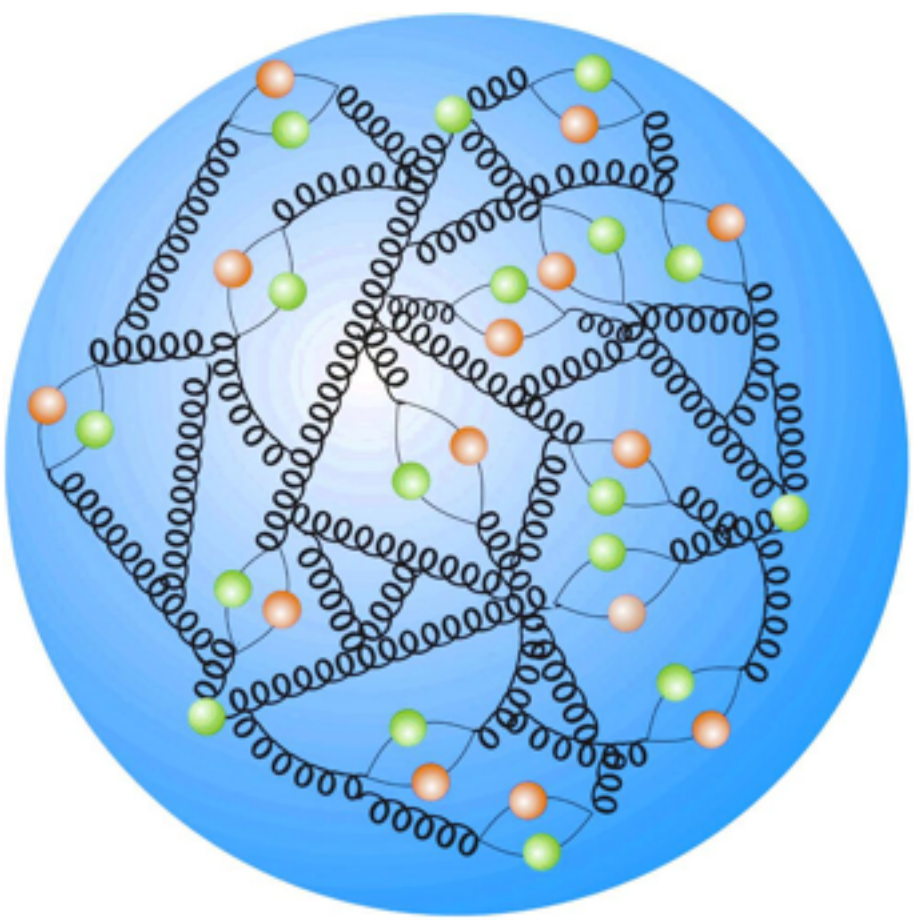
Precision is not limited to the LHC program. A definitive answer to questions such as the microscopic origin of the proton spin will require precision studies at a future electron-ion collider (EIC)

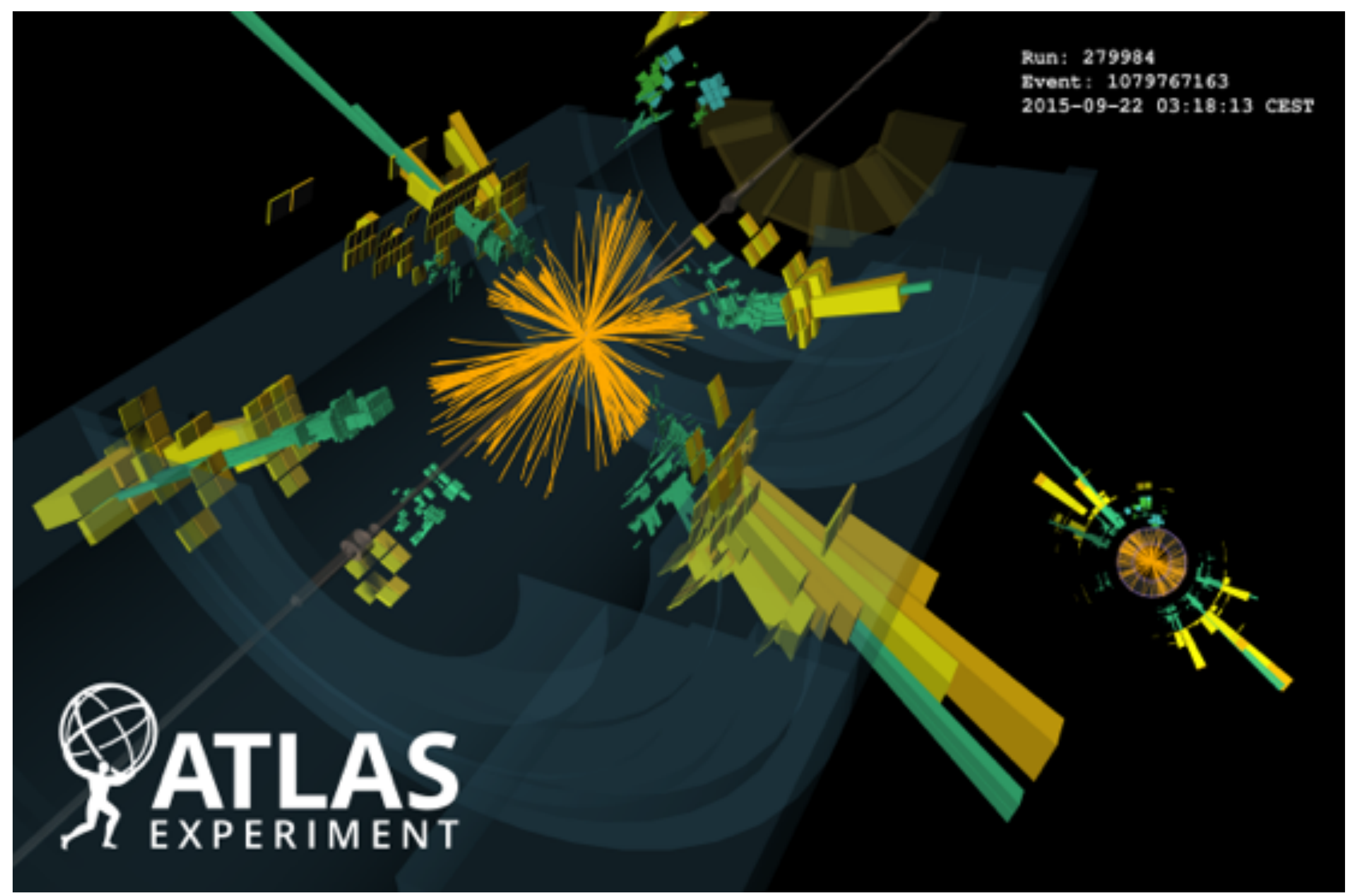


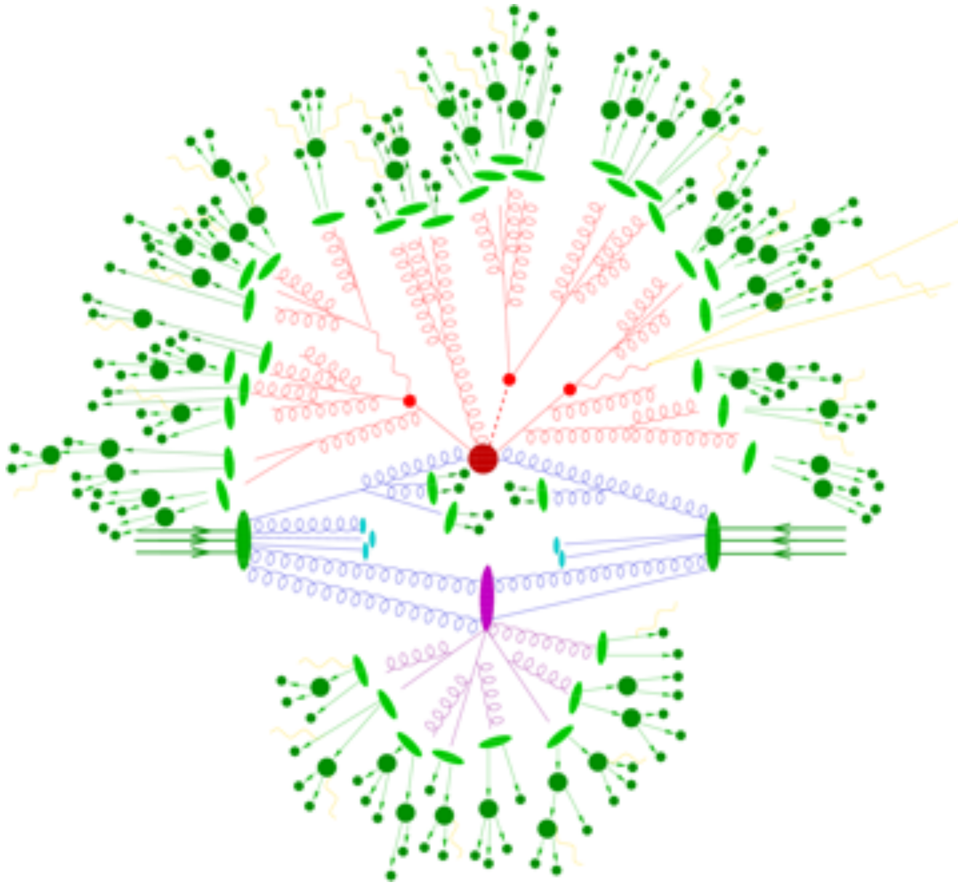
Percent-level probes of the proton spin structure are possible at an EIC!

Precision at a hadron machine means QCD. QCD is a rich, fascinating theory: from a simple Lagrangian emerges numerous complex phenomena, such as confinement of quarks/gluons into hadrons, and jet production at high energies

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q} \left[i\gamma^\mu (\partial_\mu - igA_\mu) - m_q \right] q$$







Factorization

How does theory allow us to peer into the inner hard-scattering in this complex event?

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

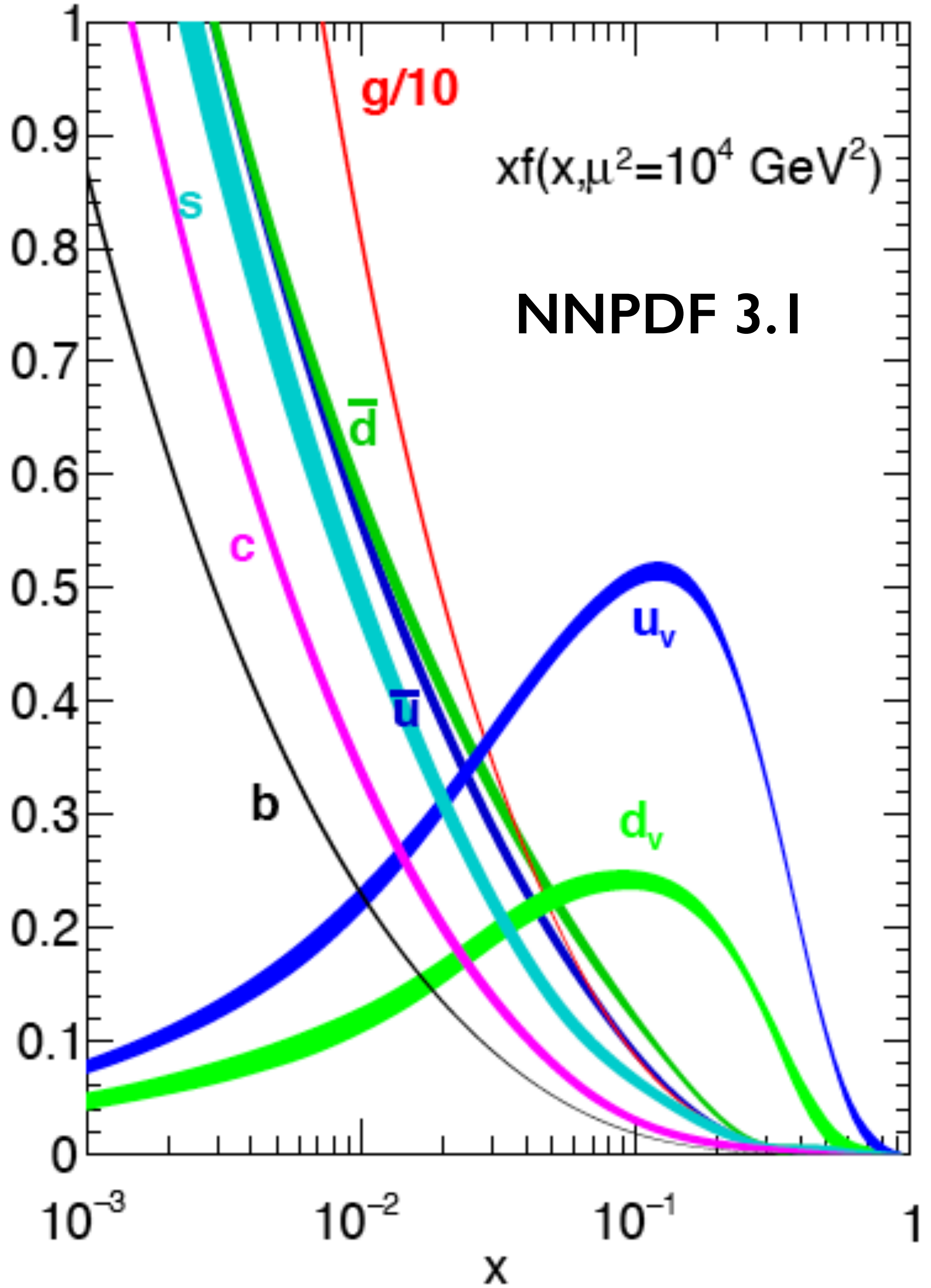
long distance: 1/GeV — **short distance: 1/TeV**

$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}}$$

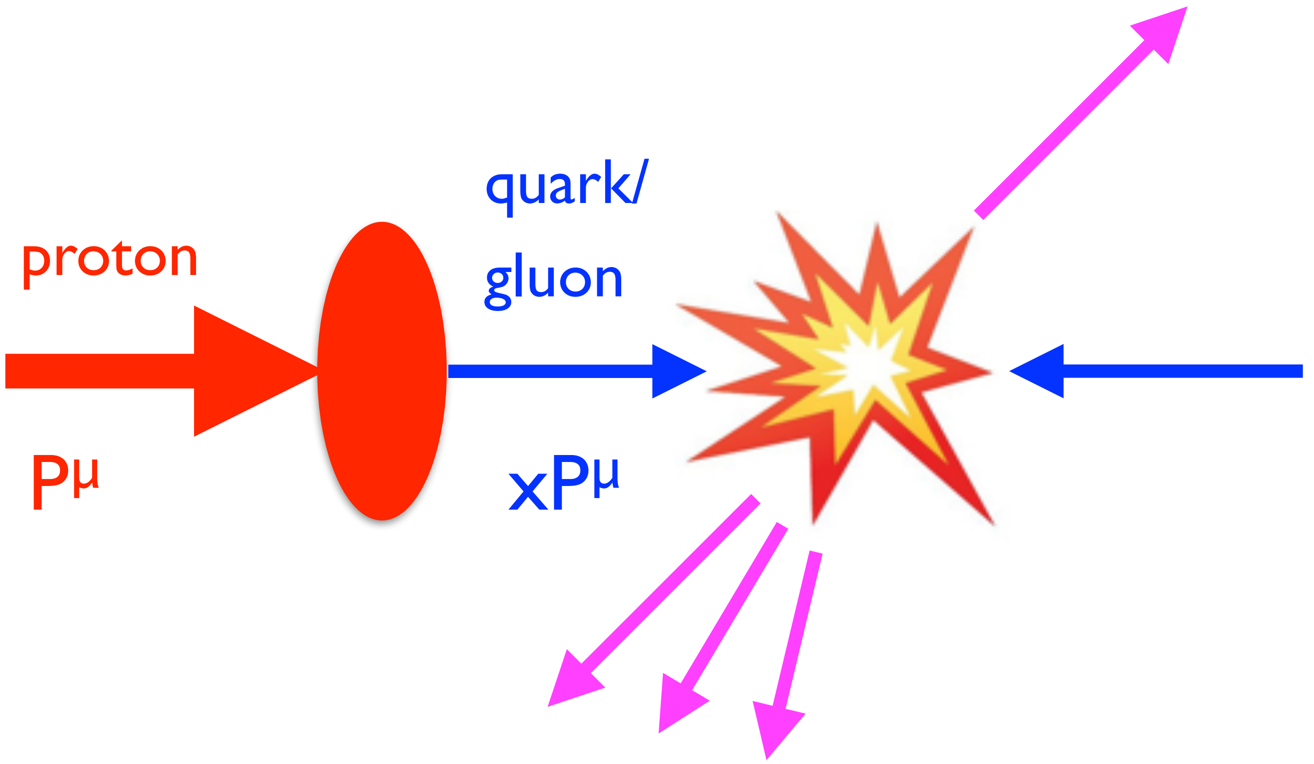
↑ measure — ↑ extract from data — ↑ calculate

PDFs

$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}}$$

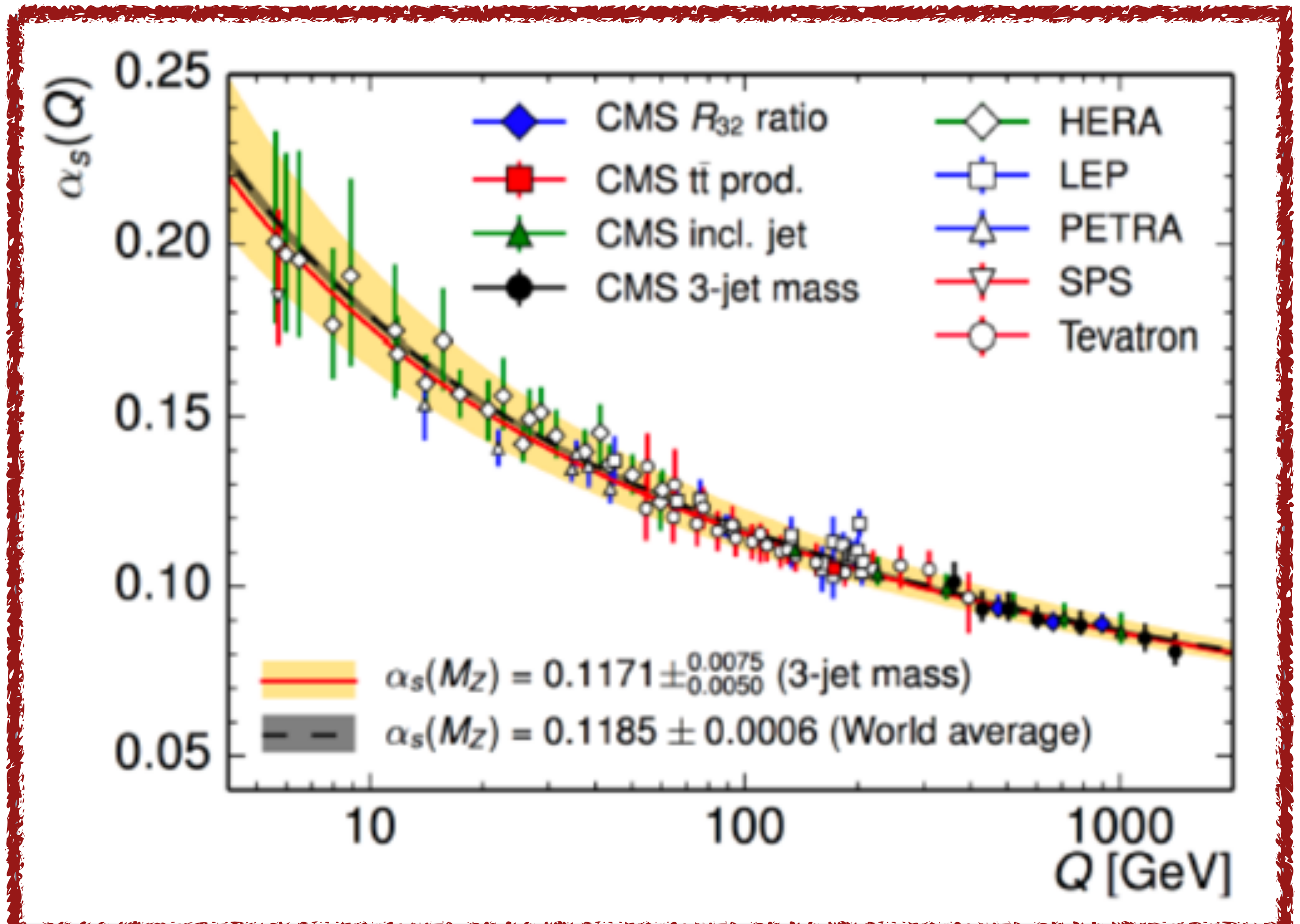


The PDFs measure the longitudinal momentum distribution of quarks and gluons inside the proton



Partonic cross section

$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}}$$



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

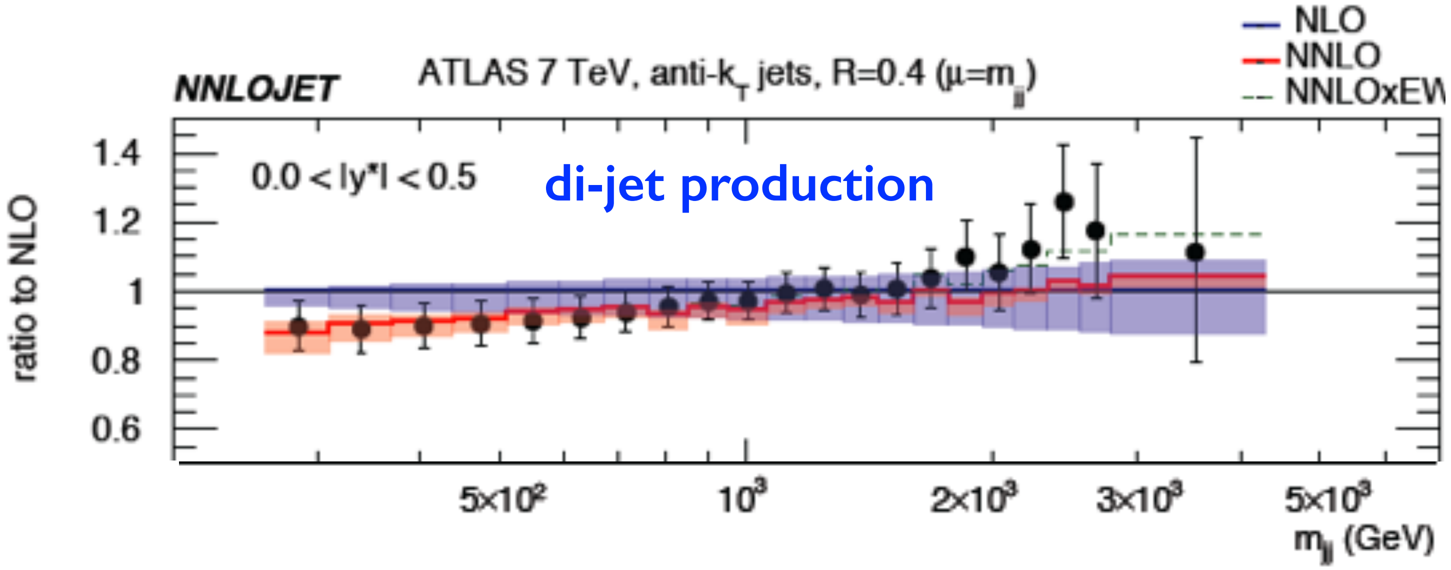
$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \dots \right)$$

LO predictions

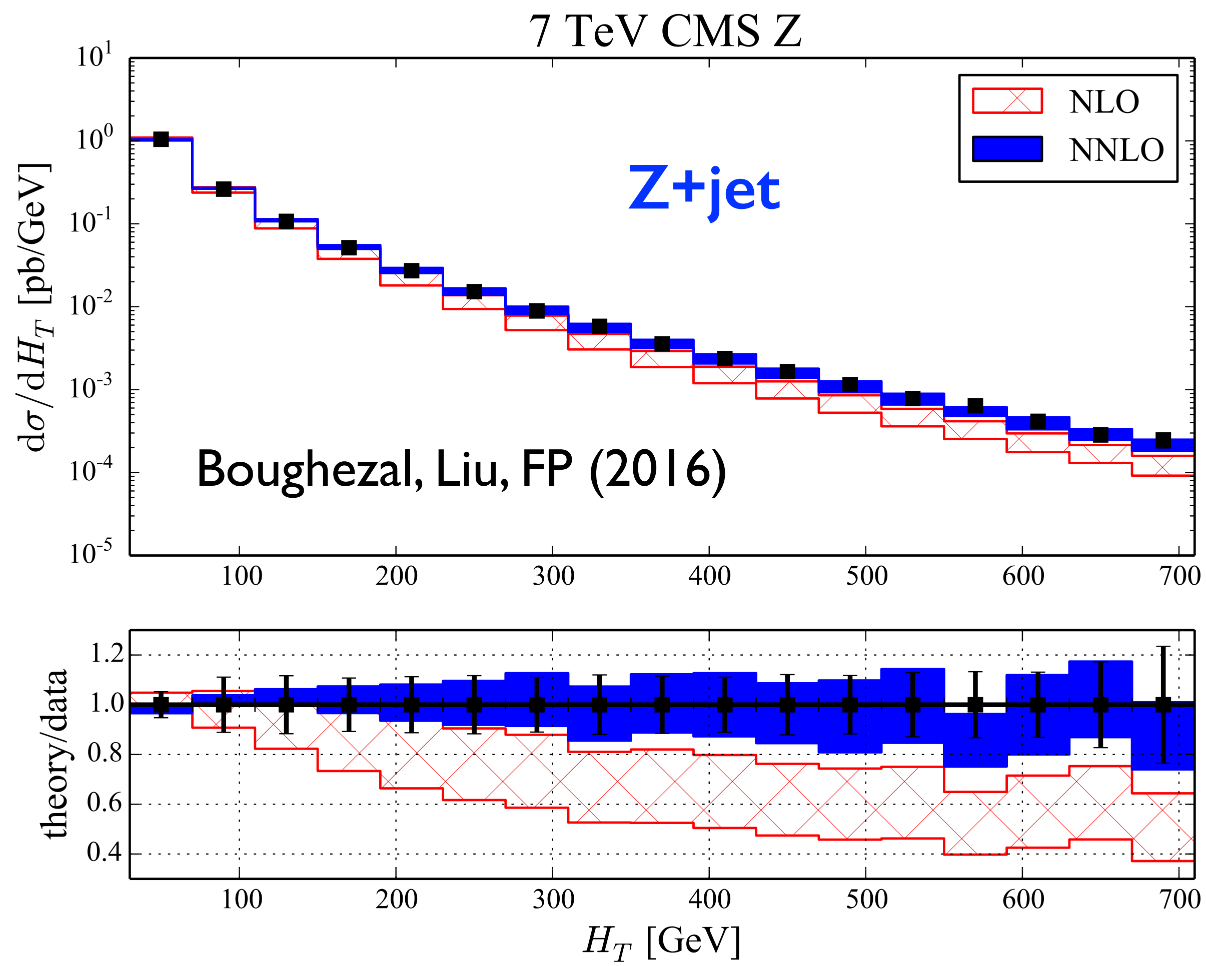
NLO corrections

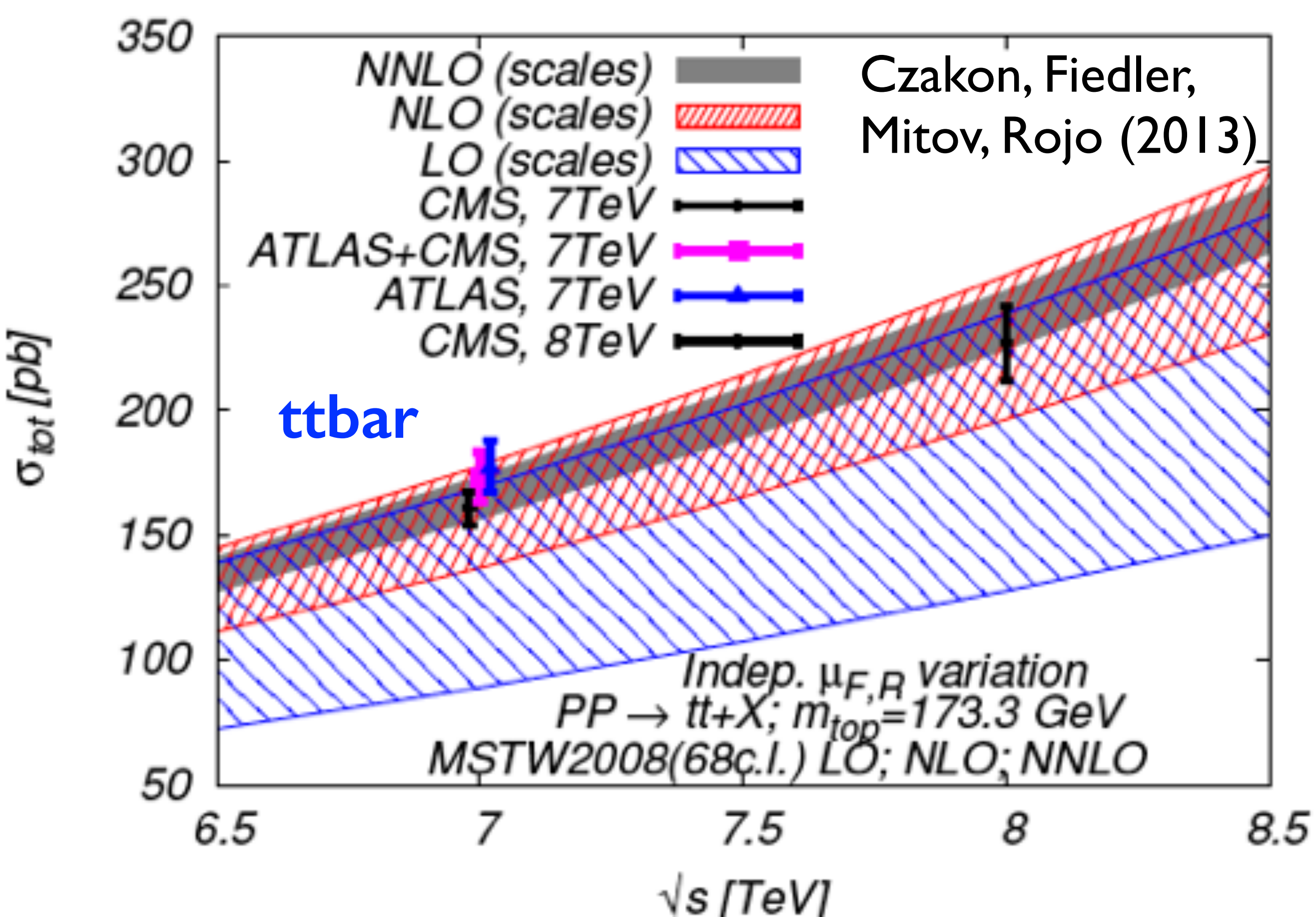
NNLO corrections

NNNLO corrections



Currie, A. Gehrmann, T. Gehrmann, Glover, Huss, Pires (2017)





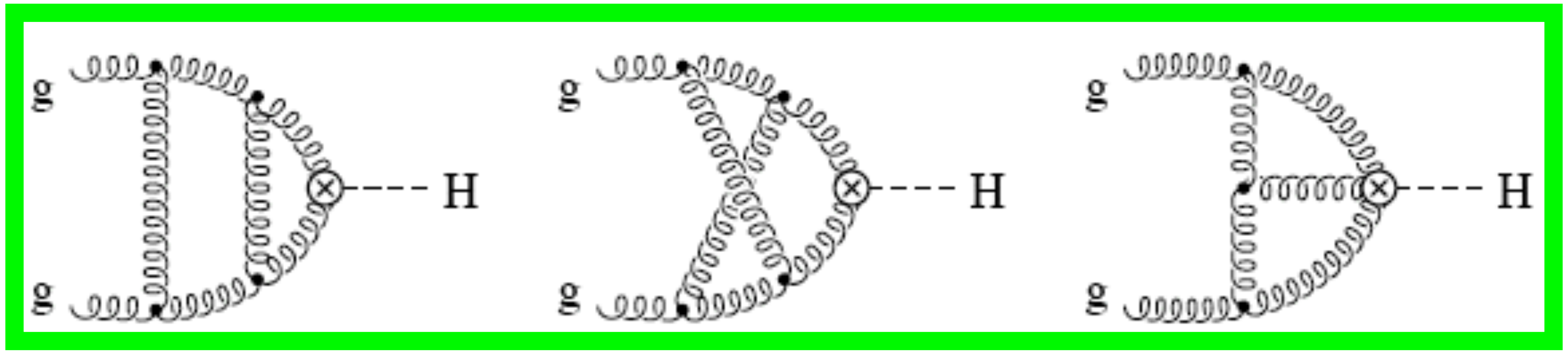
Many examples show that:

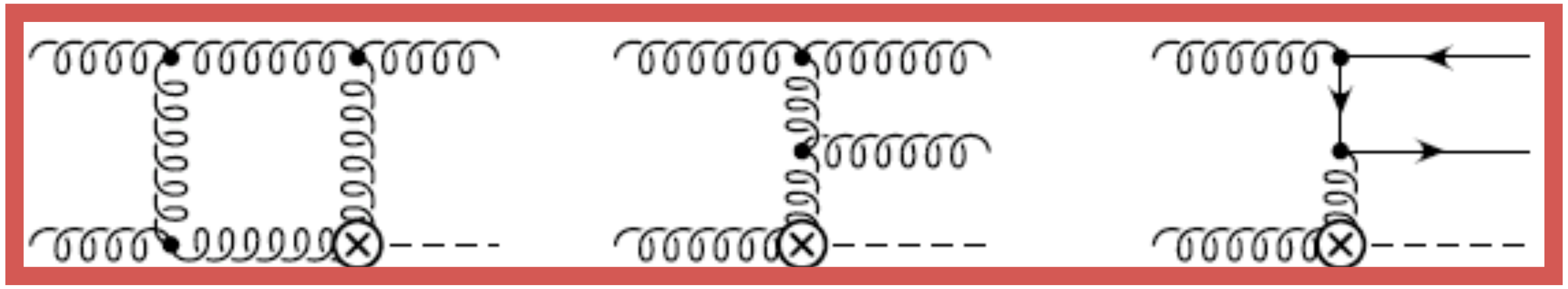
LO: rough estimate only
NLO: first quantitative estimate
NNLO: needed for precision!

Why is NNLO difficult?

- Draw and calculate all Feynman diagrams that appear at **NNLO**, or **O(α_S^2)** in perturbation theory. Higgs production as an example:

A small sample:





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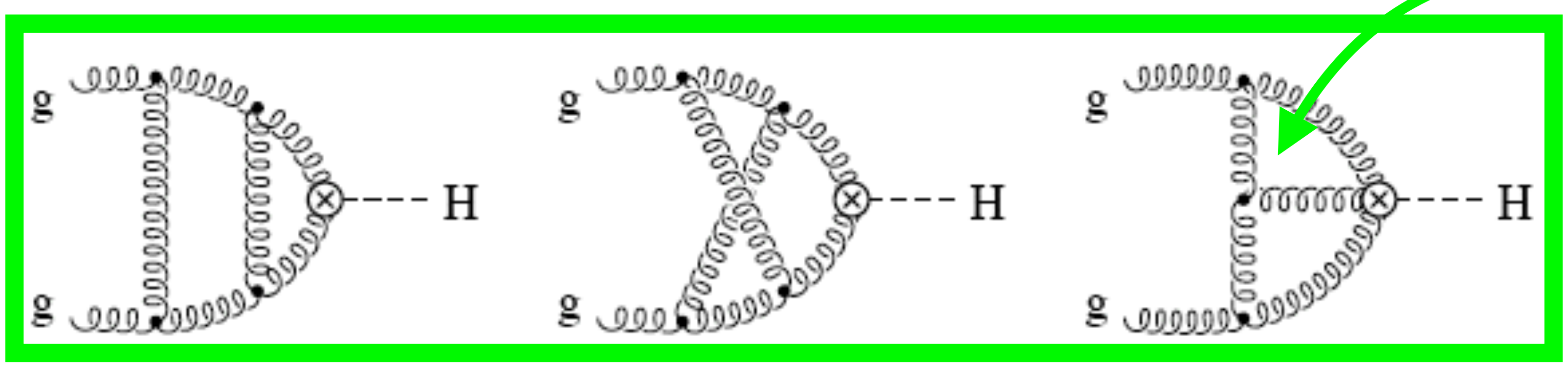
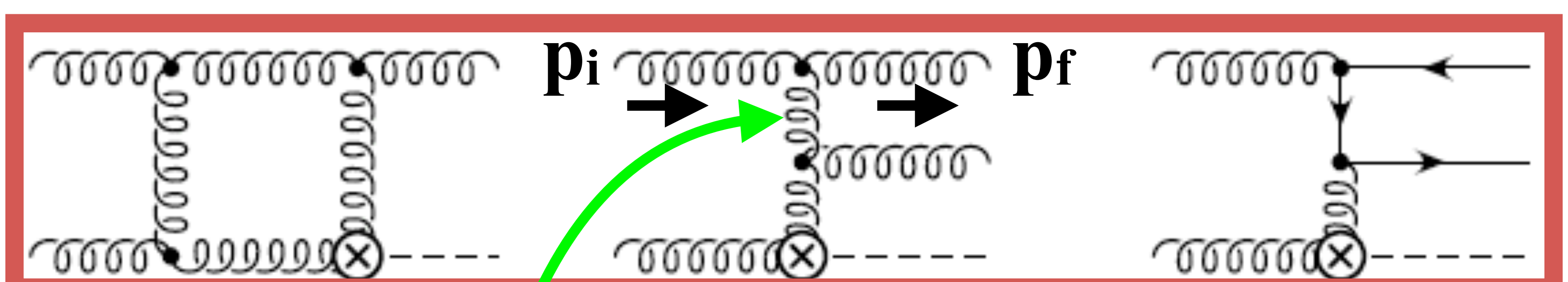
A small sample:

Singularities appear here in the loop integral that cancel the ones below



$= +\infty$



$= -\infty$

$$\frac{1}{2p_i \cdot p_f} = \frac{1}{2E_iE_f(1-\cos\theta_{if})}$$

Singular when $E_f \to 0$ **(soft singularity)** or $\theta_{if} \to 0$ **(collinear singularity)**

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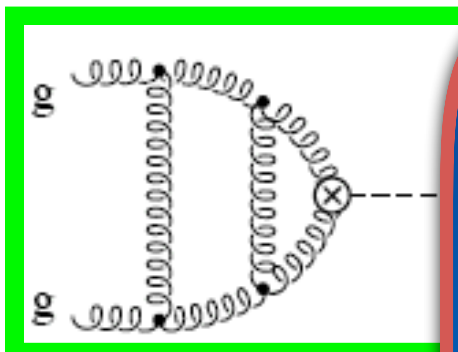
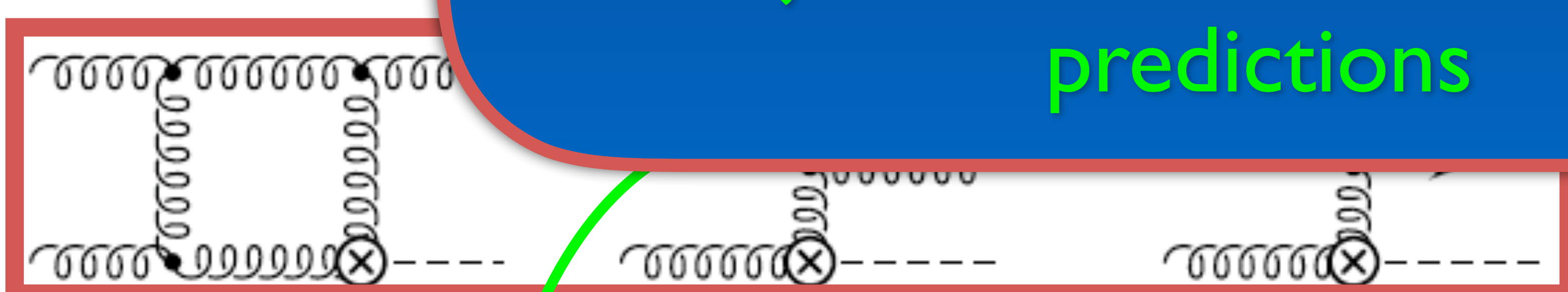


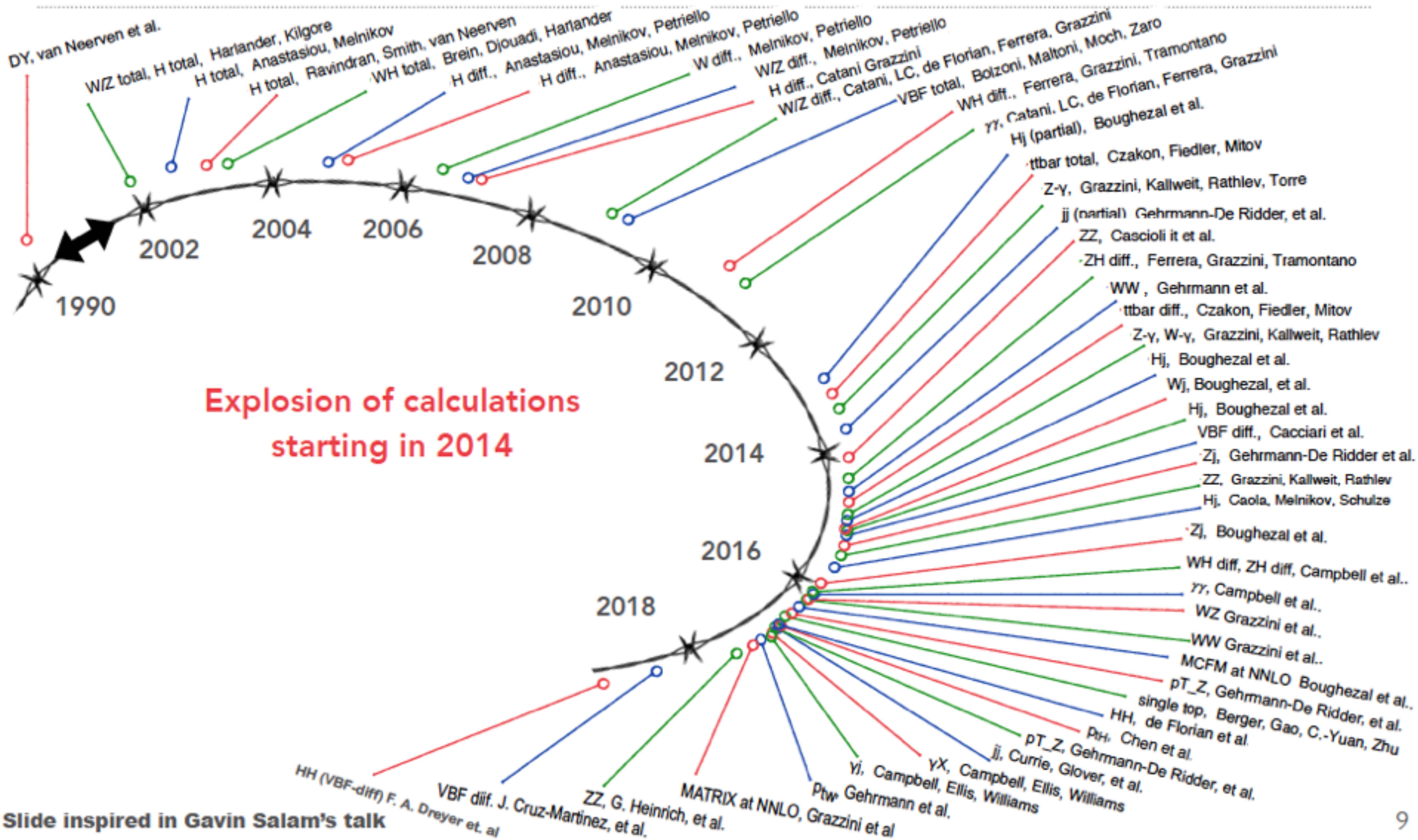


Deriving an organizing principle to extract and cancel singularities for arbitrary processes and observables was the major obstacle in obtaining NNLO predictions

$$\frac{1}{2p_i \cdot p_f} = \frac{1}{2E_iE_f(1-\cos\theta_{if})}$$

Singular when $E_f \rightarrow 0$ (soft singularity) or $\theta_{if} \rightarrow 0$ (collinear singularity)

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



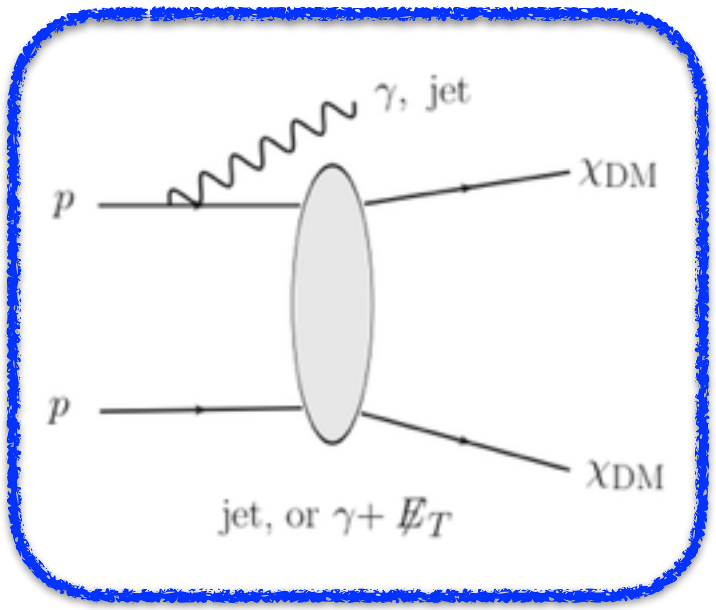
Slide inspired in Gavin Salam's talk

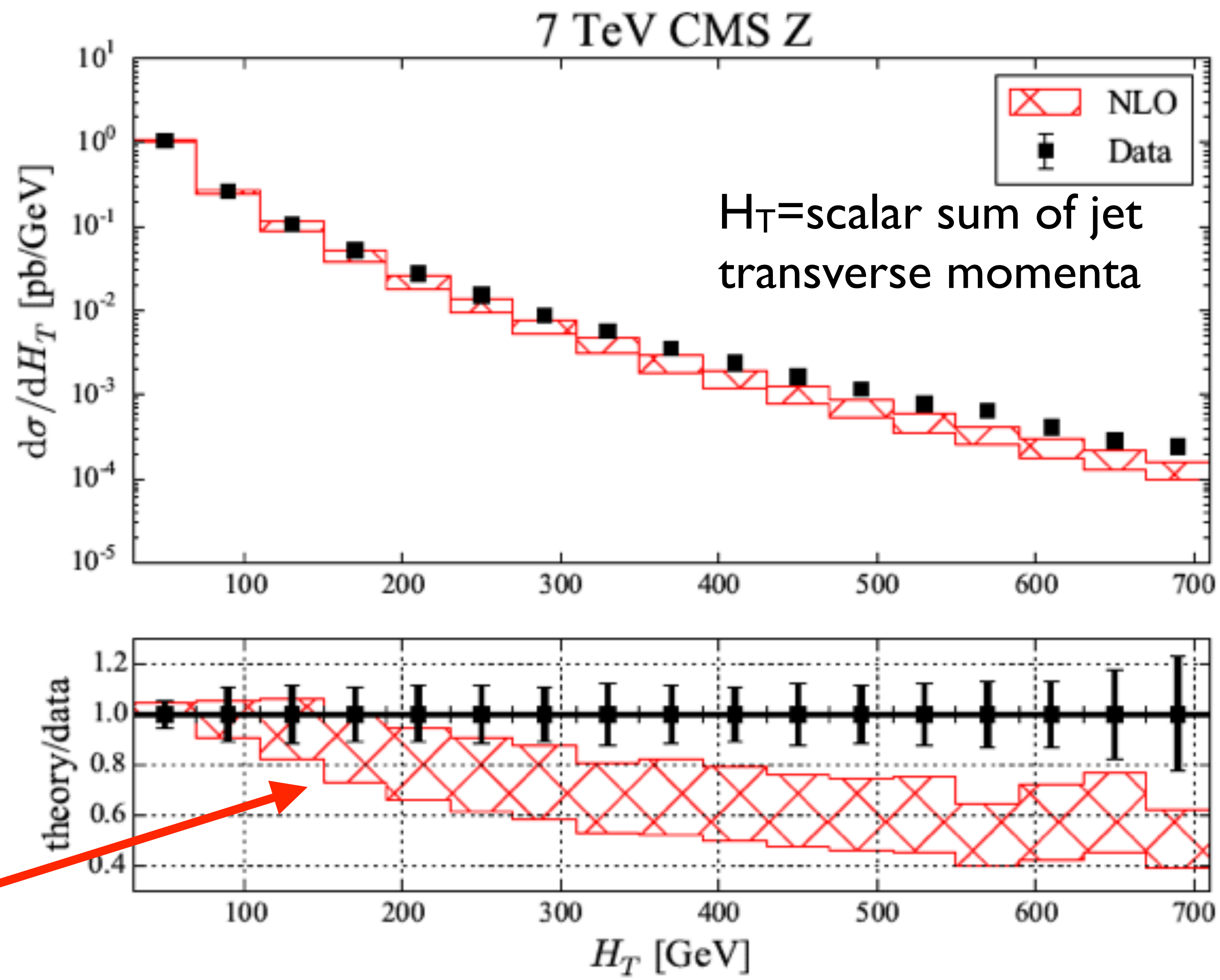
L. Cieri, Moriond 2019

This explosion of new NNLO results was made possible thanks to many new ideas!

Theory versus data in the NNLO era

- First example: gauge boson plus jet production. This is an important background to dark matter searches at the LHC through Z+jet→νν+jet





Boughezal, Liu, FP (2016)

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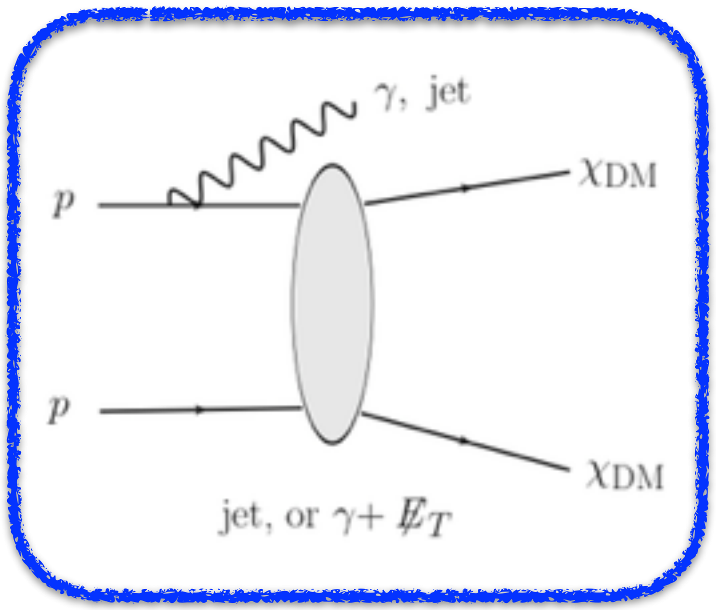
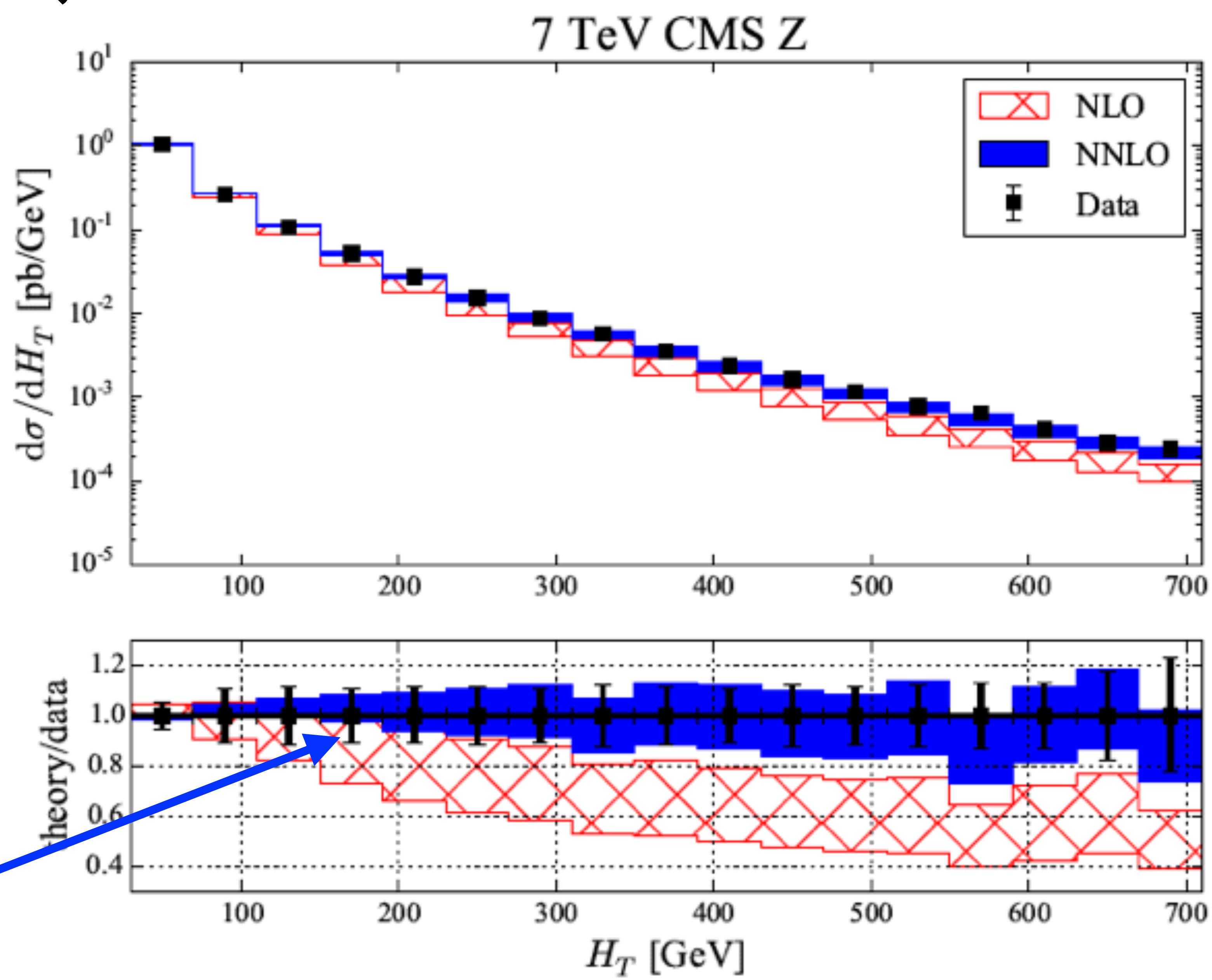
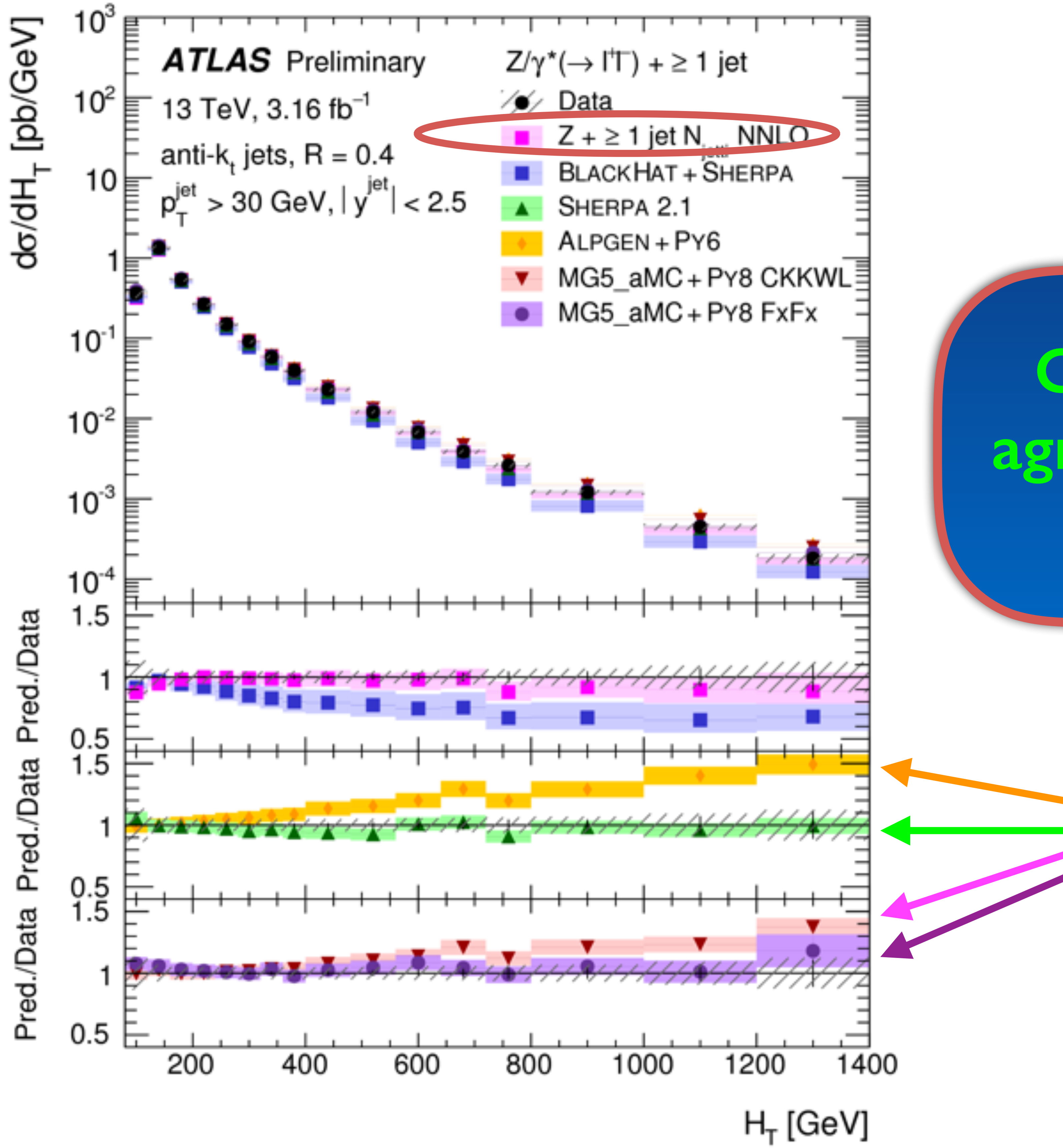




Excellent agreement with NNLO!

Boughezal, Liu, FP (2016)

Theory versus data in the NNLO era

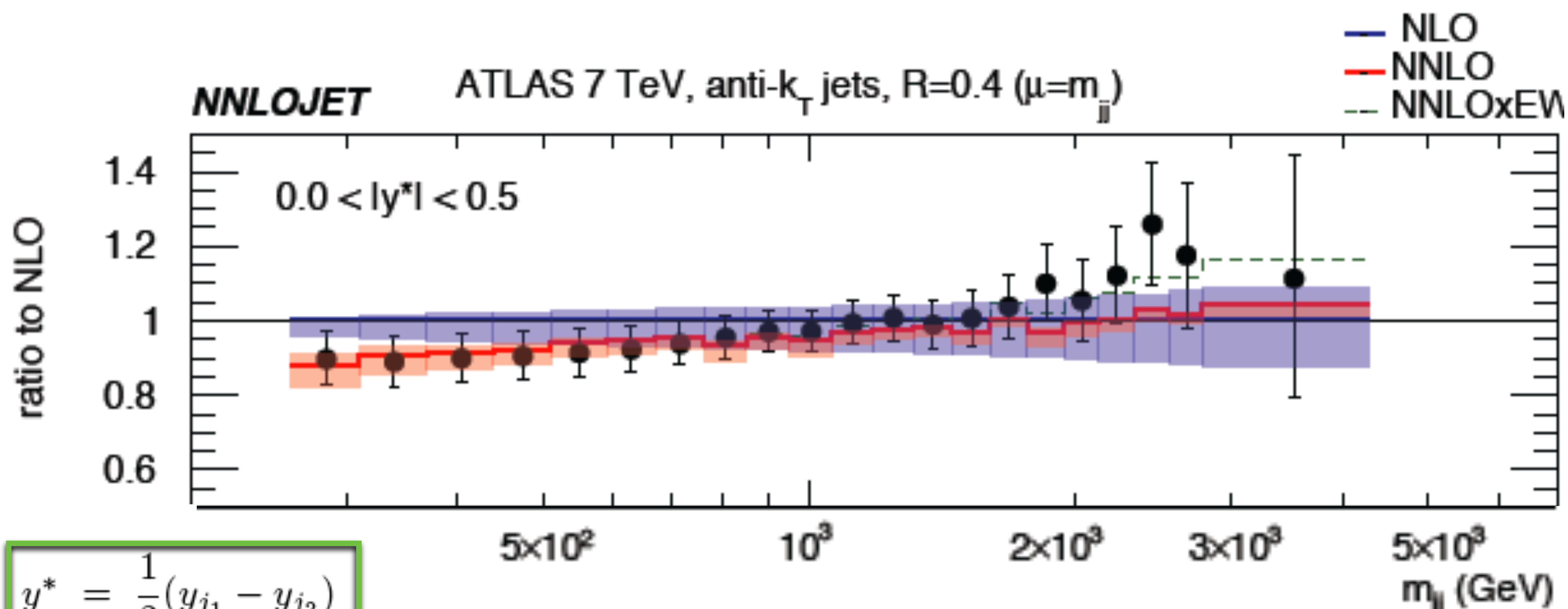


Continued excellent agreement with data at 13 TeV!

Other LO/NLO+parton shower approaches have mixed success in describing the data

Theory versus data in the NNLO era

- Second example: di-jet production. 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



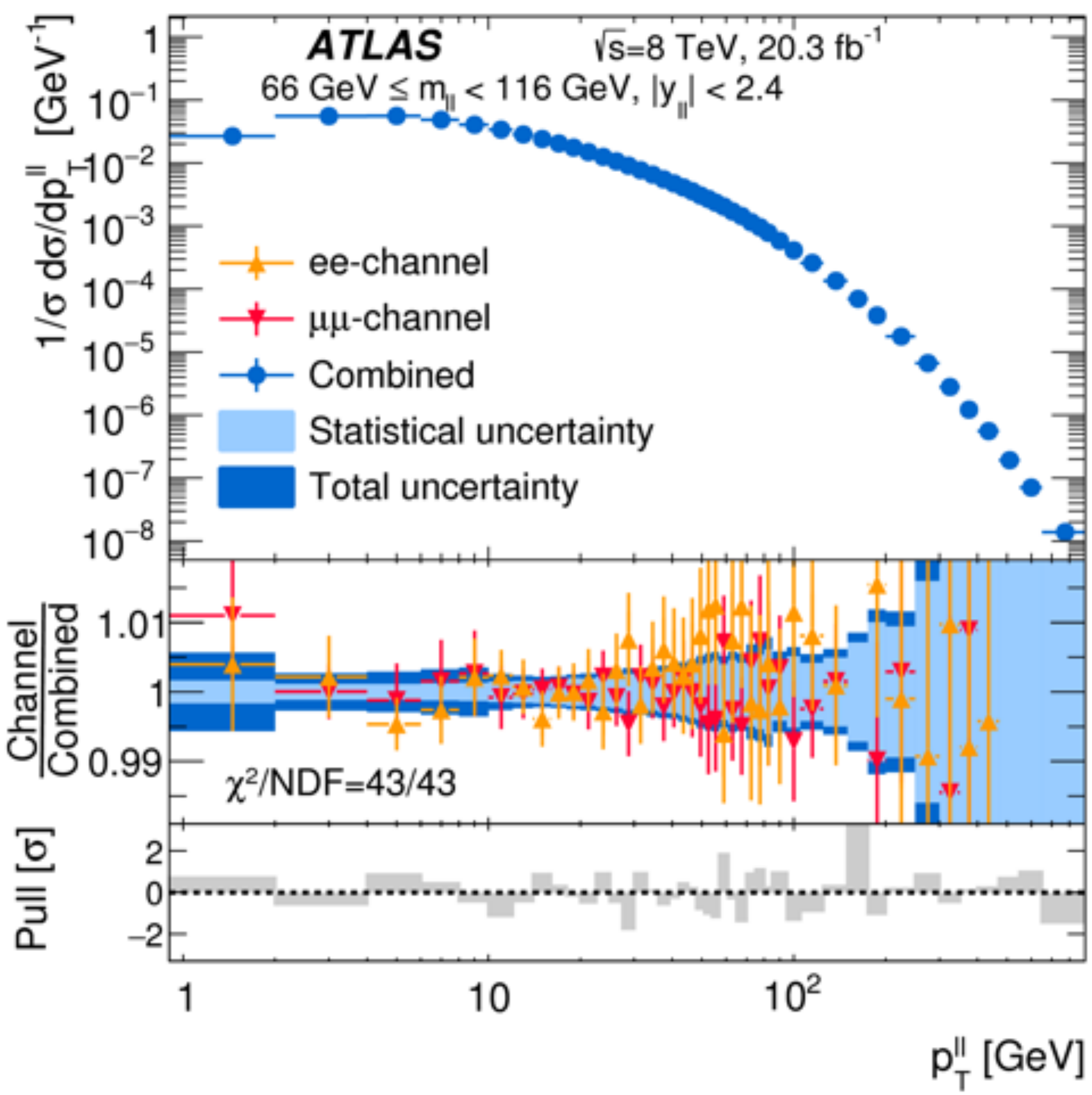
$$y^* = \frac{1}{2}(y_{j_1} - y_{j_2})$$

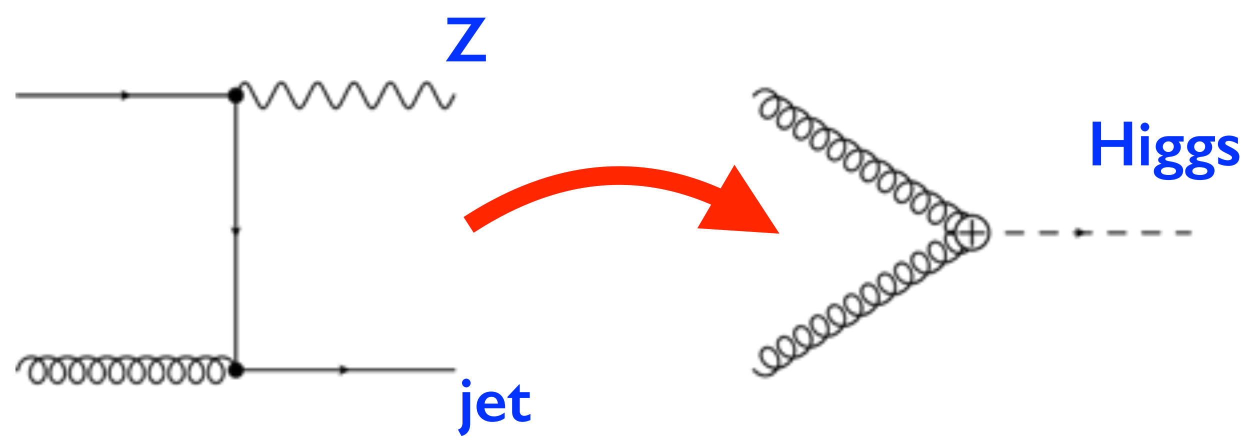
Currie, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Pires (2017)

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

The Z-boson transverse momentum

- The Z-boson transverse momentum spectrum measurement has reached a remarkable precision at the LHC, with errors below 1% over a large range

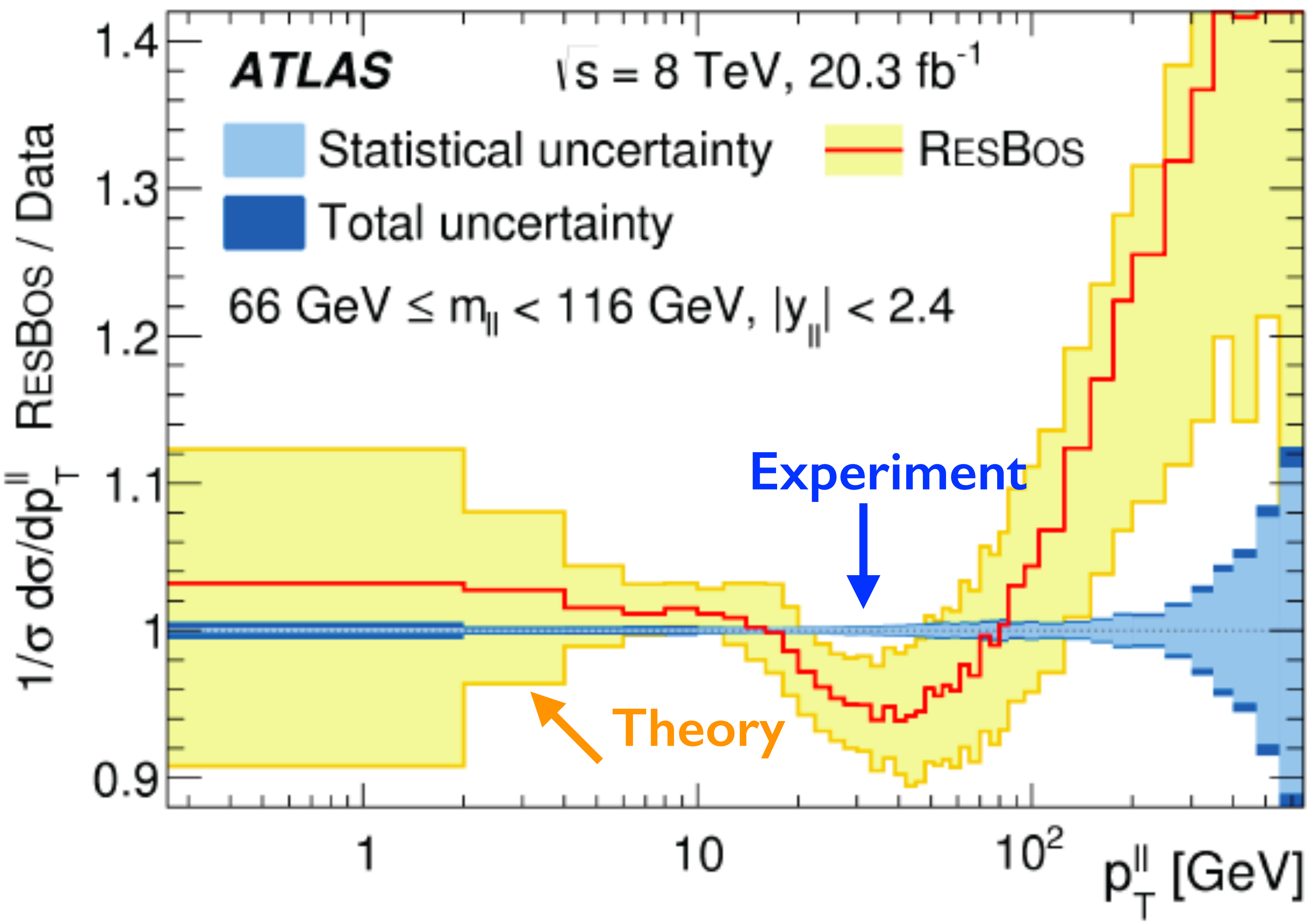




The leading-order cross section for this process depends on the gluon PDF; we can learn about the gluon distribution entering Higgs production from this data!

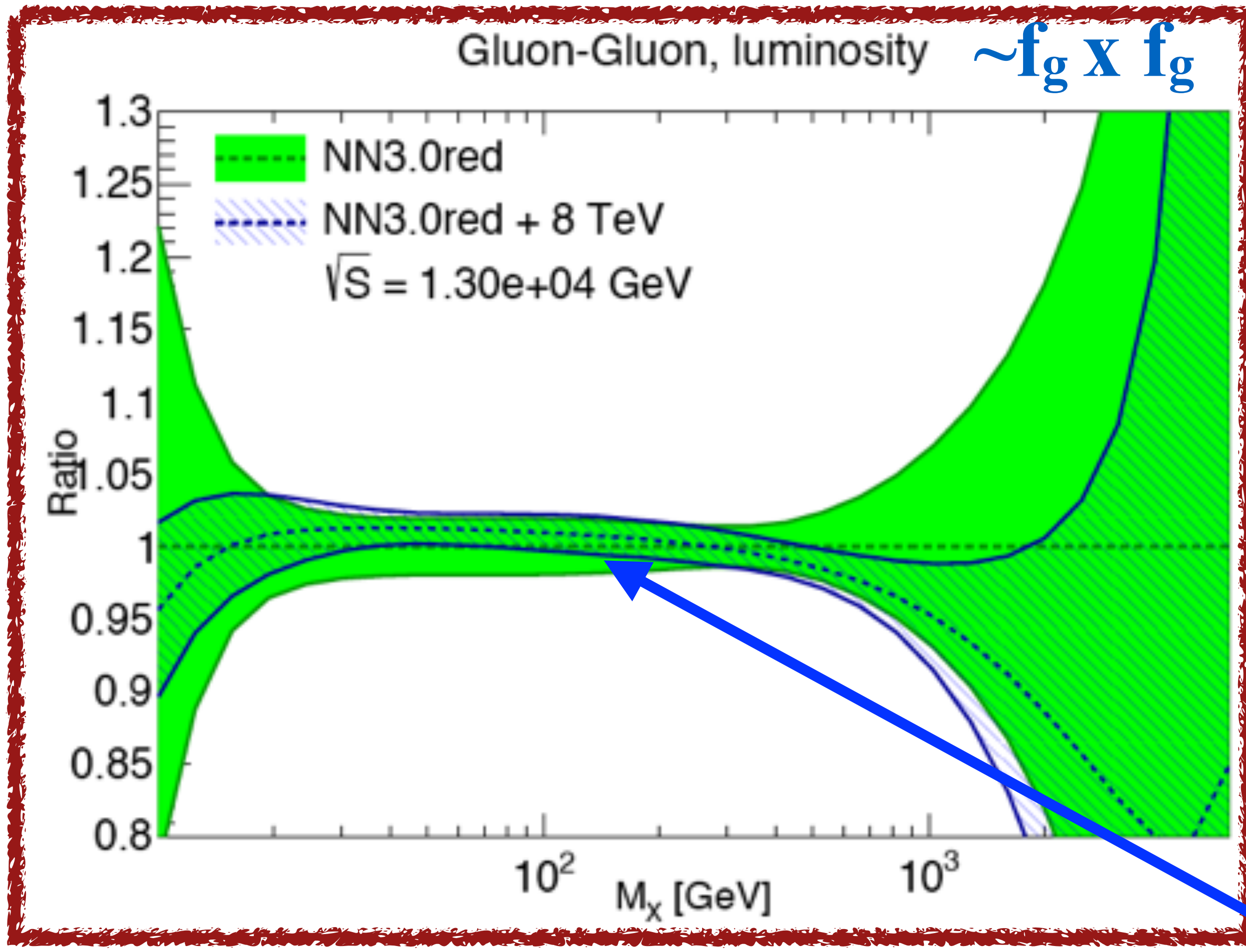
Comparison with NLO theory

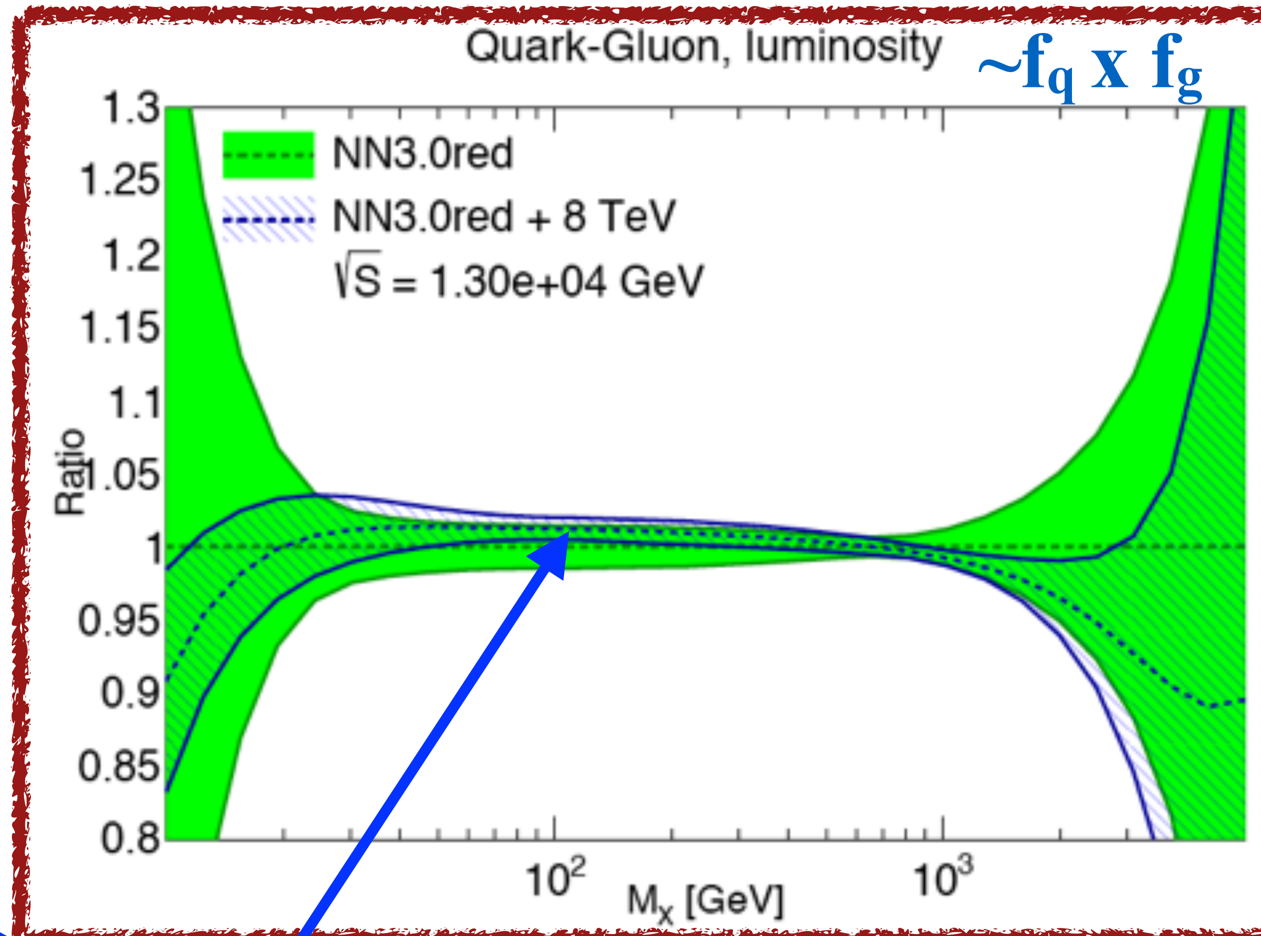
- NLO theory errors more than an order of magnitude larger than experimental ones; can't use this data to measure the gluon without NNLO!



Impact on PDFs from Z-pT

- After incorporating NNLO, errors shrink to the point that this data can be used. Improvements with respect to a pre Z-pT baseline fit:



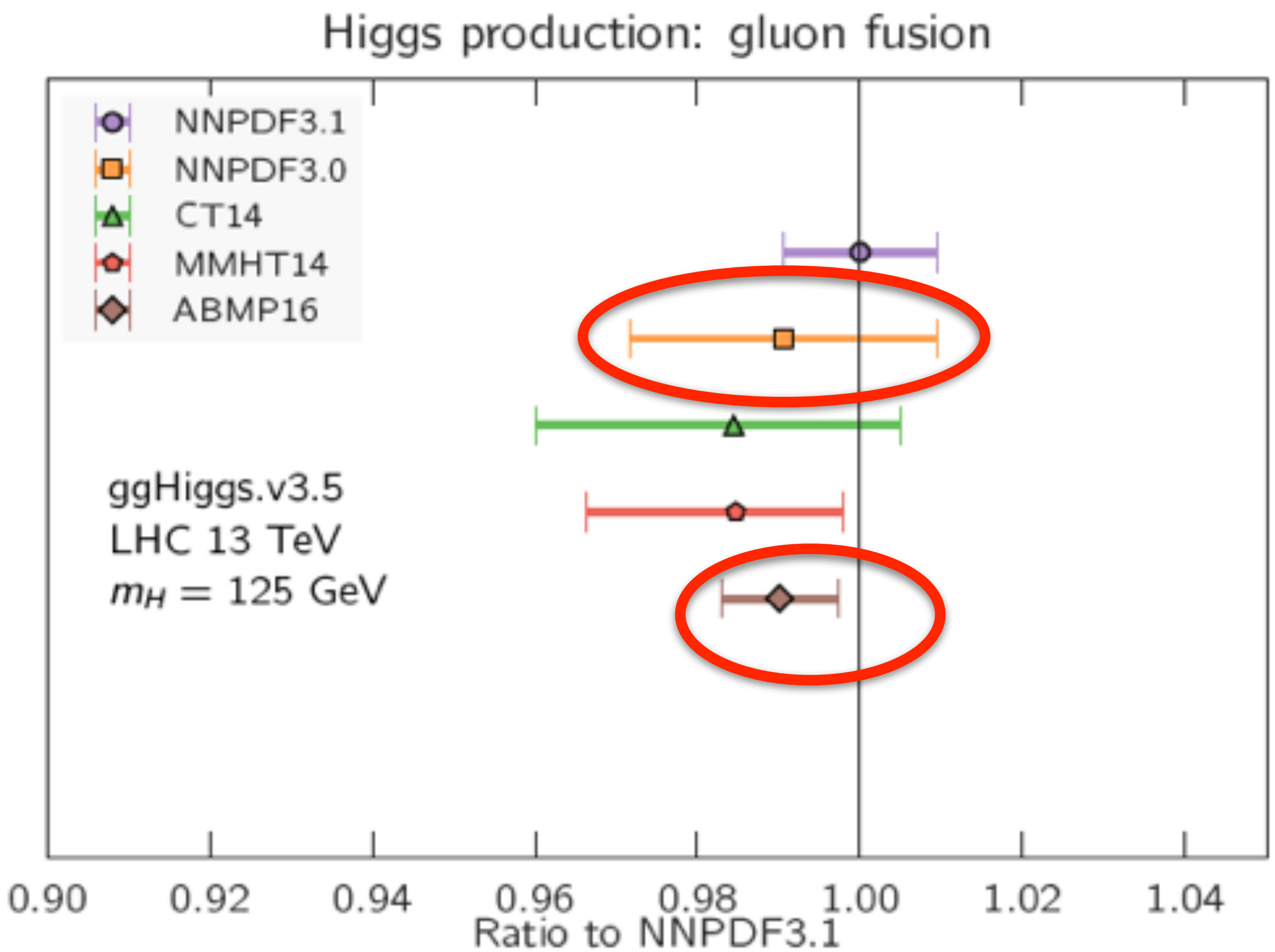


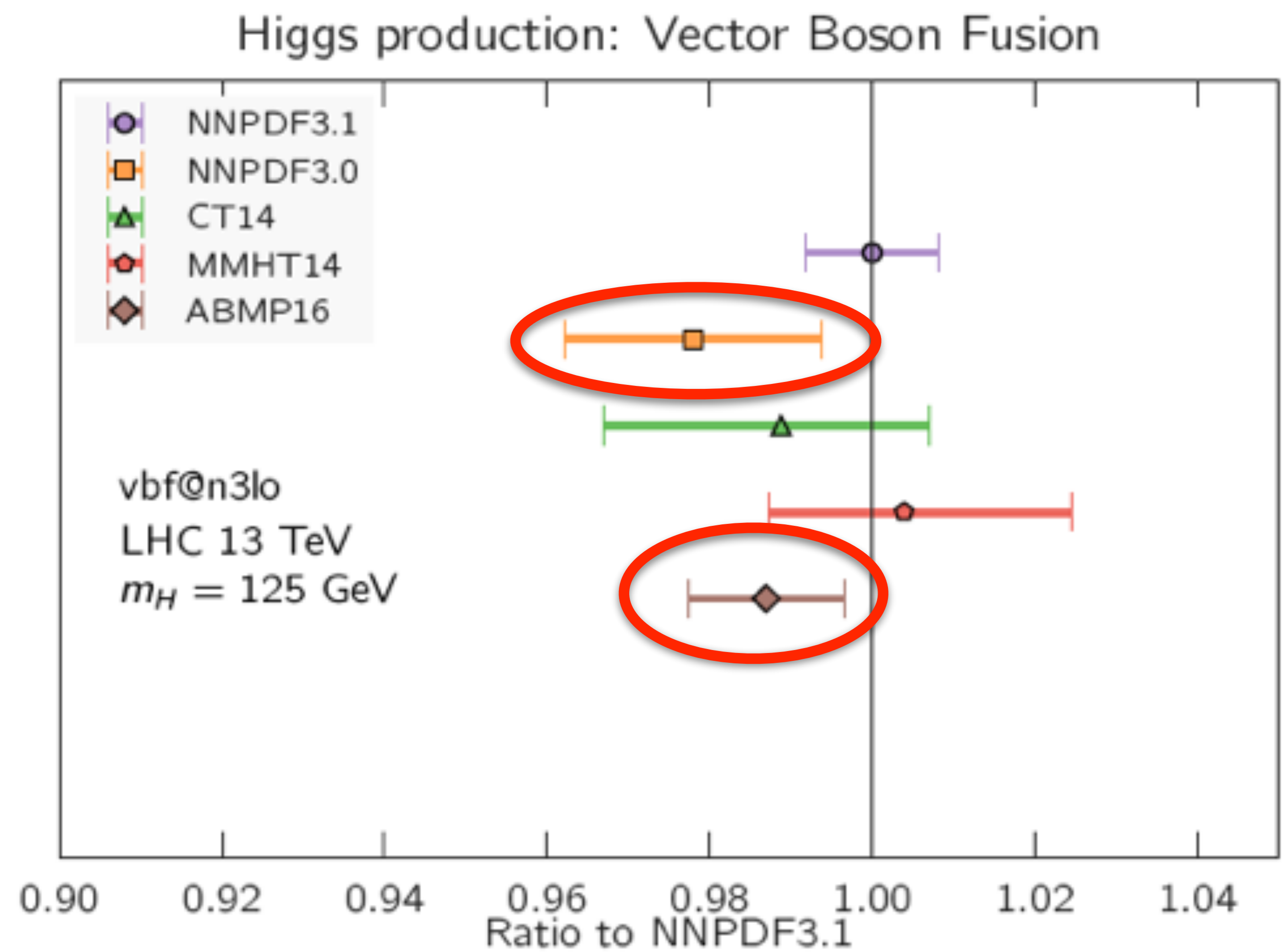
Boughezal, Guffanti, FP, Ubiali (2017)

Gluon-gluon and quark-gluon luminosity errors reduced right near M_X~m_H=125 GeV!

Impact on global fit from Z-pT

In the NNPDF 3.1 global fit, when also combined with the top-quark and jet production now available at NNLO, the PDF errors on the gluon-fusion and VBF production modes are reduced by nearly a factor of 2 with respect to NNPDF 3.0



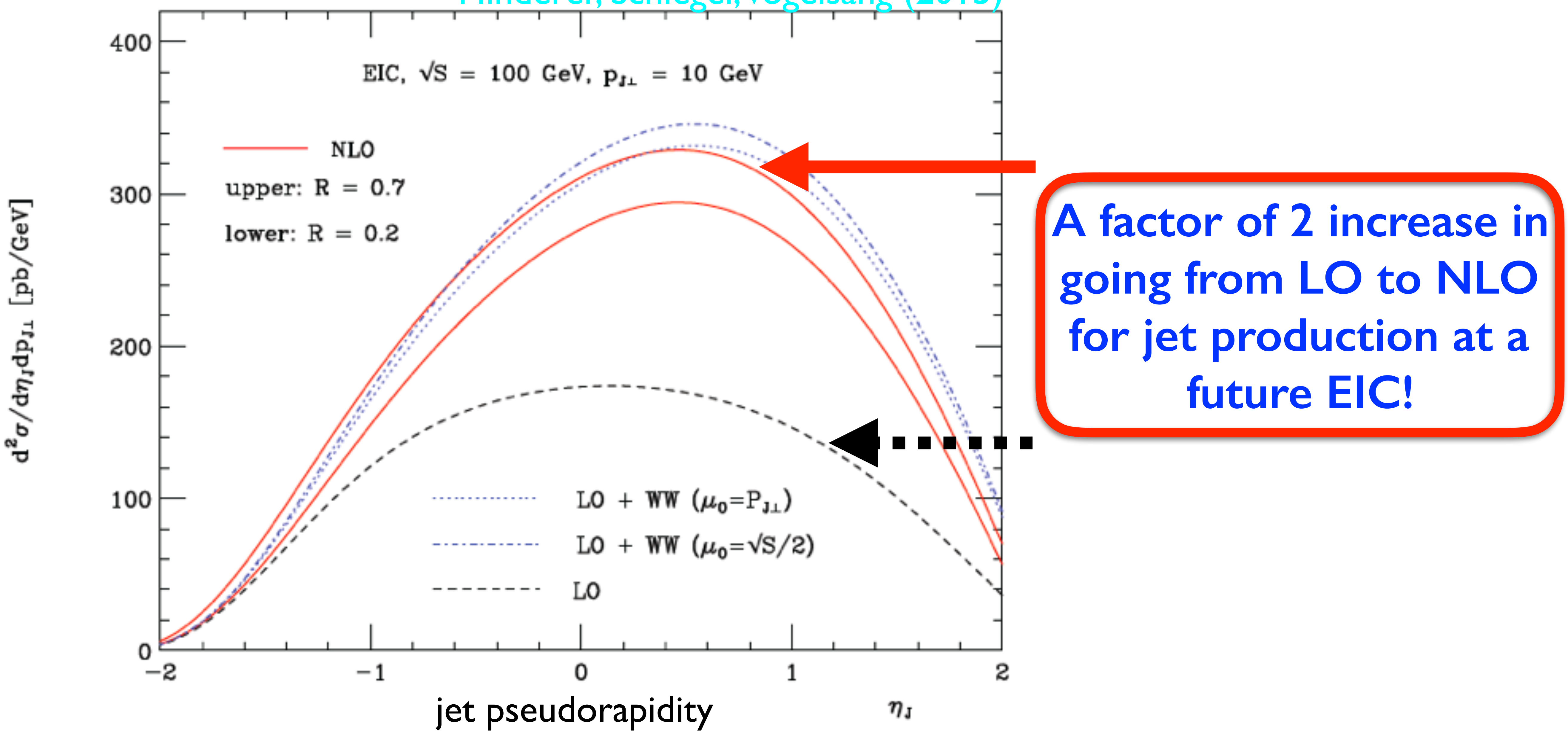


NNPDF 2017

The future: jet physics at an EIC

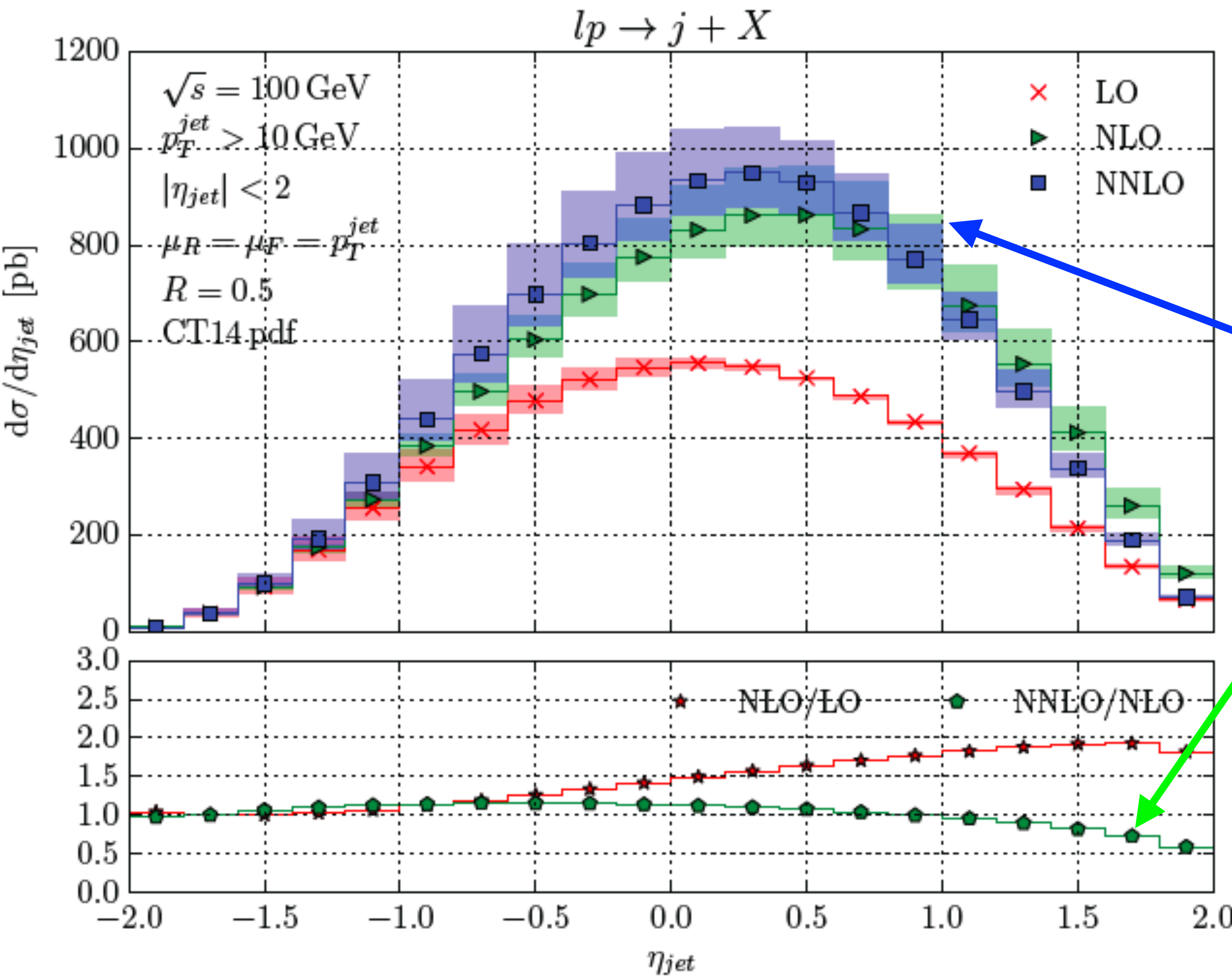
- Precision theory is also poised to be a critical part of a future EIC program. Here is an example of inclusive jet production: an important probe of the gluon spin, nuclear medium properties, and other quantities.

Hinderer, Schlegel, Vogelsang (2015)



EIC jet production at NNLO

- Theory advances important at the LHC also allow for a NNLO calculation of EIC jet production

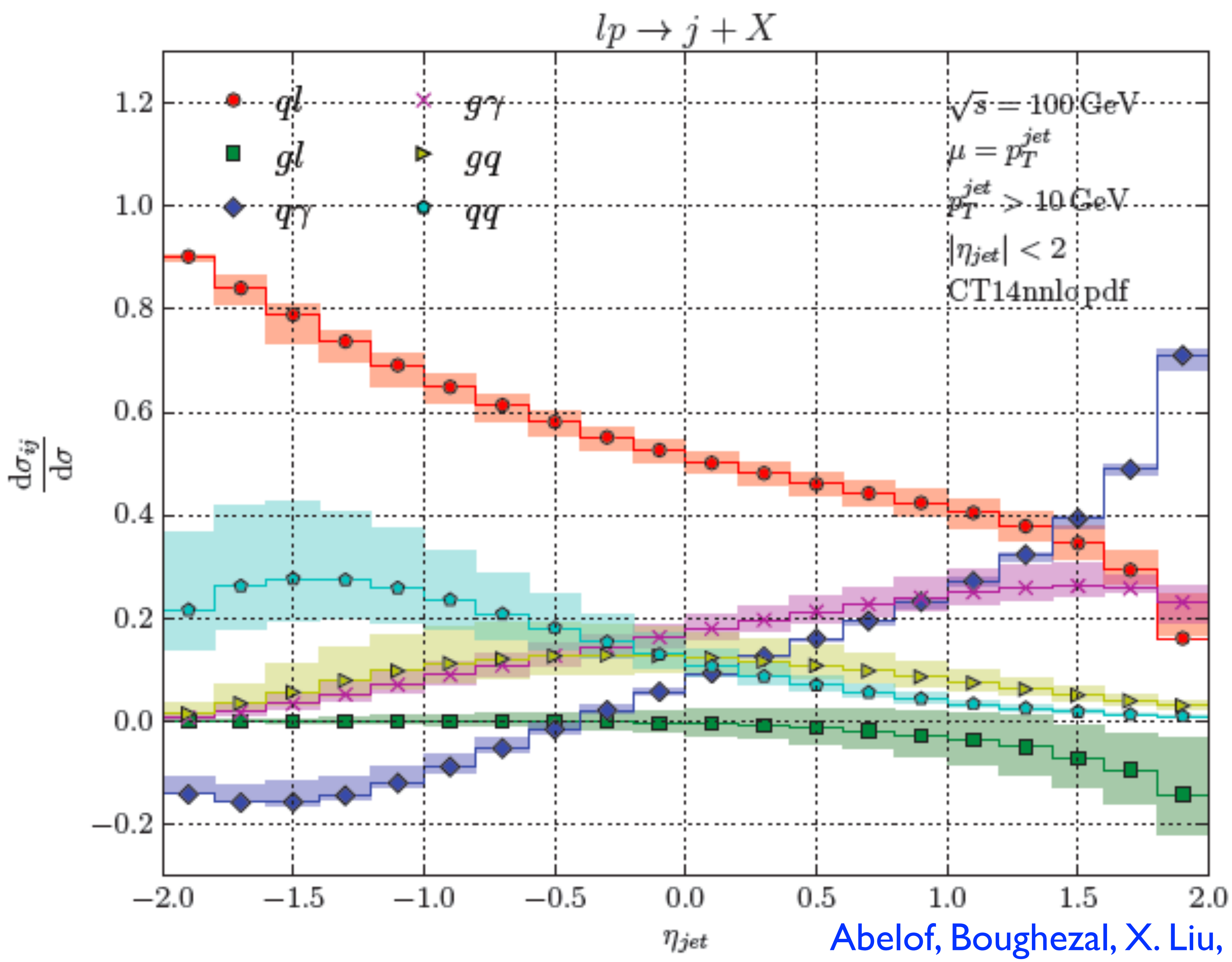


- **Perturbation theory stabilizes at NNLO!**
- Sizable corrections in the forward region; don't want to confuse this with PDF x dependence!

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)

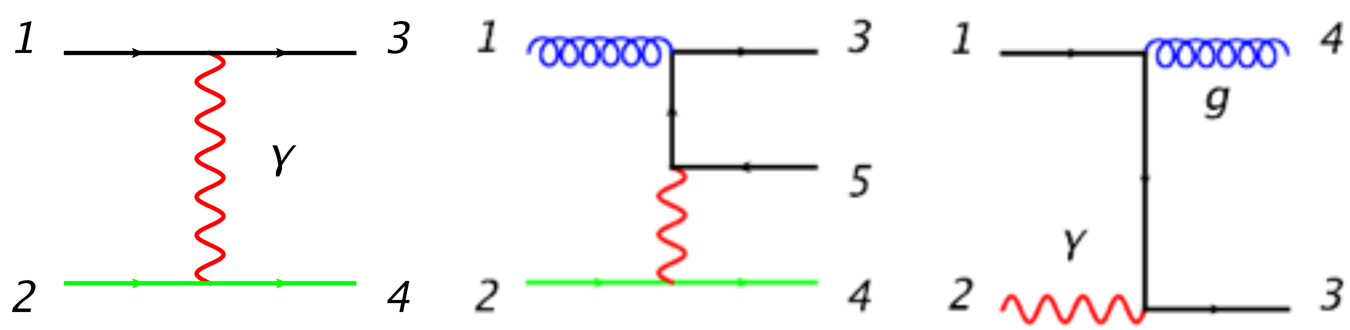
Polarized collisions at an EIC

- Can extend the theoretical formalism for NNLO to handle polarized collisions
- **Goal**: study the sensitivity of inclusive jet production at an EIC to polarized PDFs

Double-longitudinal spin asymmetry:

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

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



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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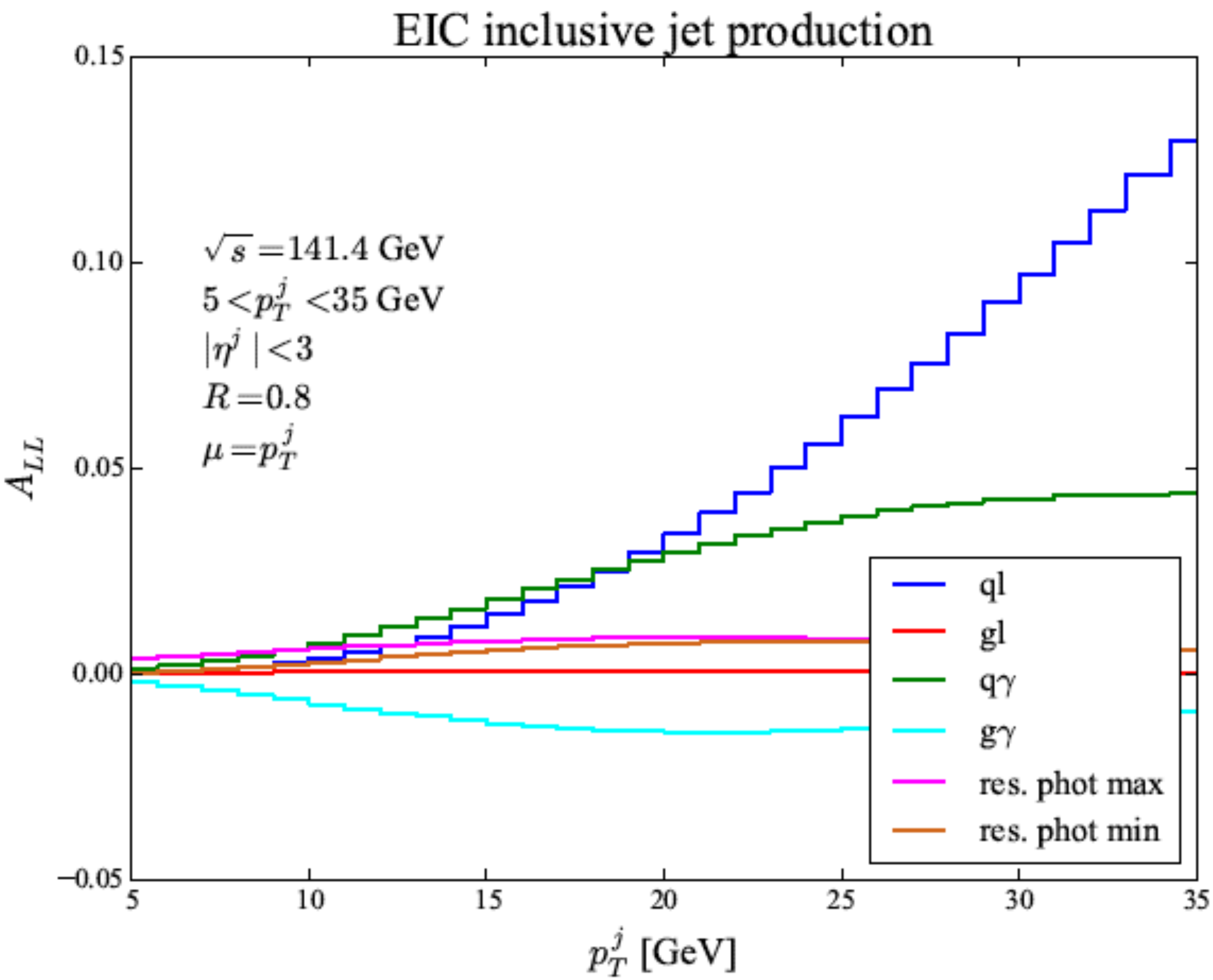
- **Goal**: study the sensitivity of inclusive jet production at an EIC to polarized PDFs

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

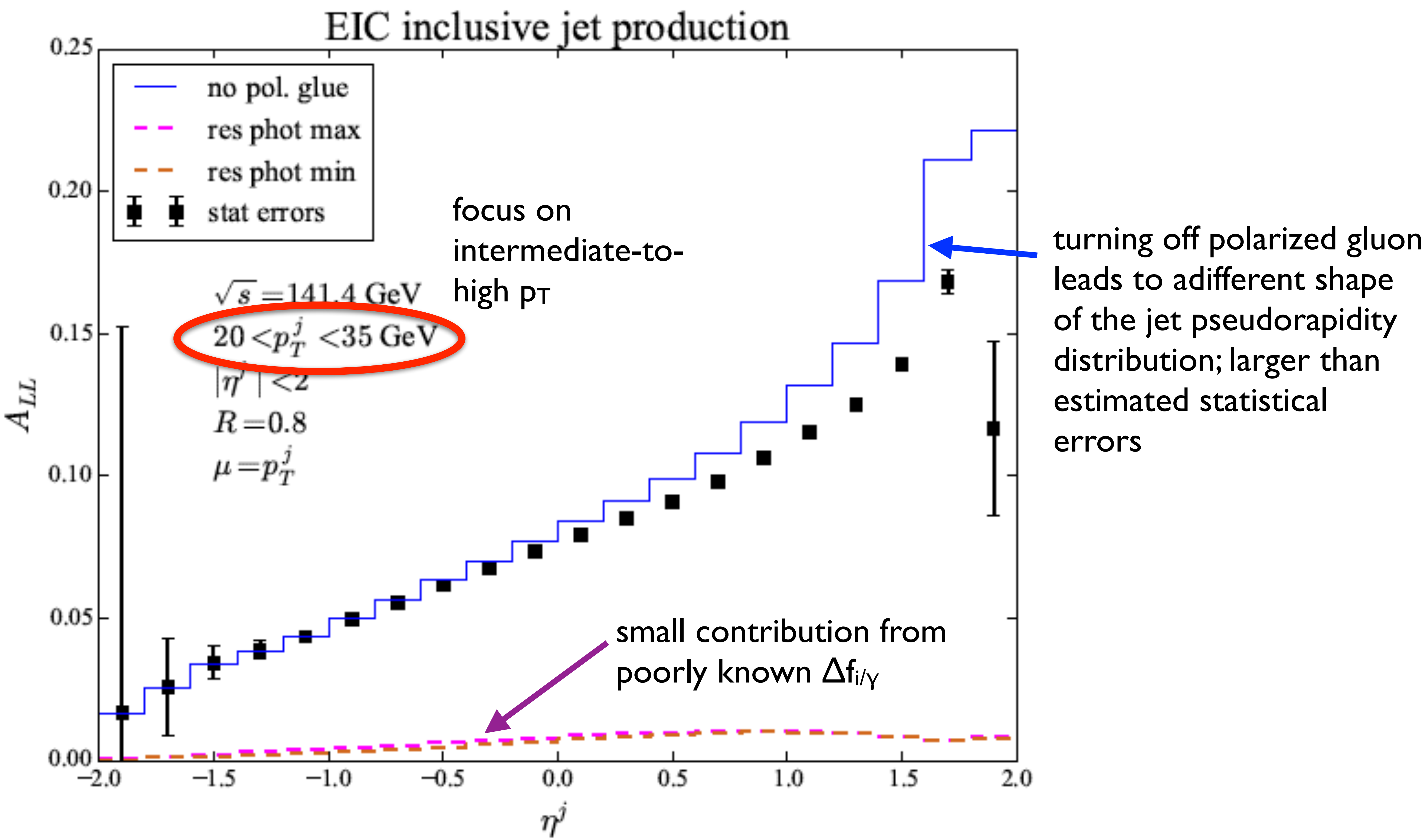
$\sqrt{s}$=141.4 GeV: jet p_T partonic structure



- 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



Boughezal, FP, Xing PRD98 (2018)

Summary

- All ingredients now available for an NNLO description of jet cross sections at the LHC and potential future machines
- Inclusion of NNLO corrections leads to a greatly improved description of data, enabling applications ranging from dark matter searches to probes of proton structure
- Can apply techniques developed for LHC to EIC studies also
- 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