# Measuring the gluon distribution with jets: from the LHC to an EIC

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Santa Fe Jets and Heavy Flavor workshop
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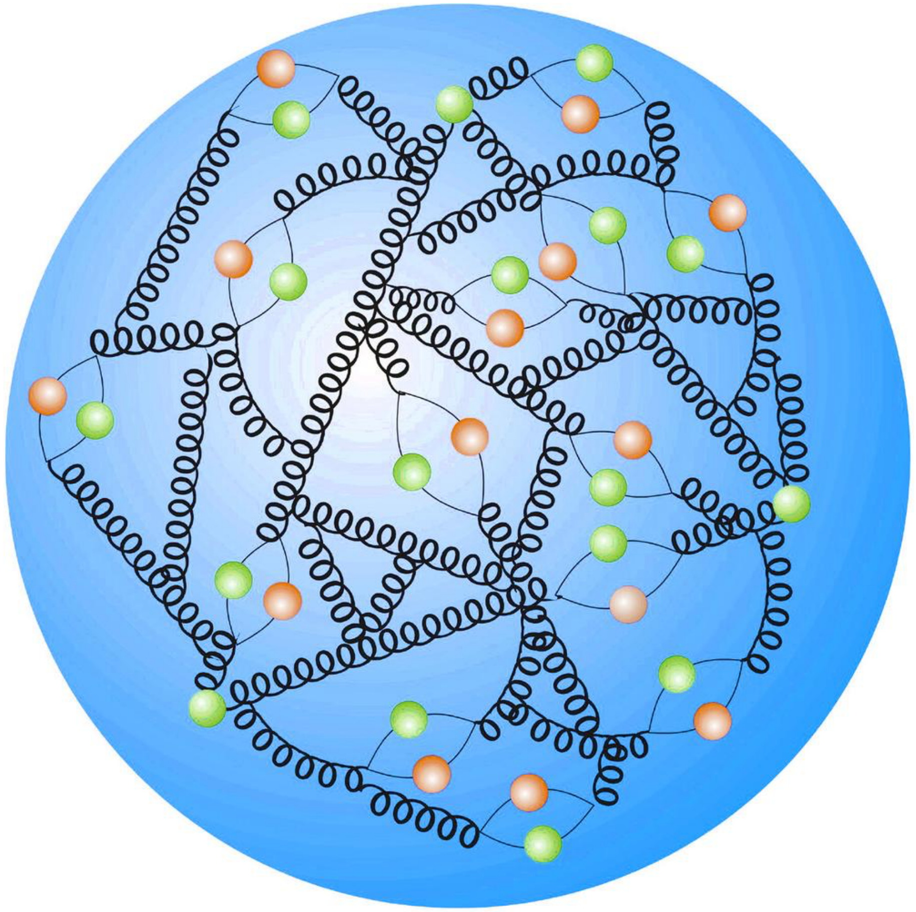
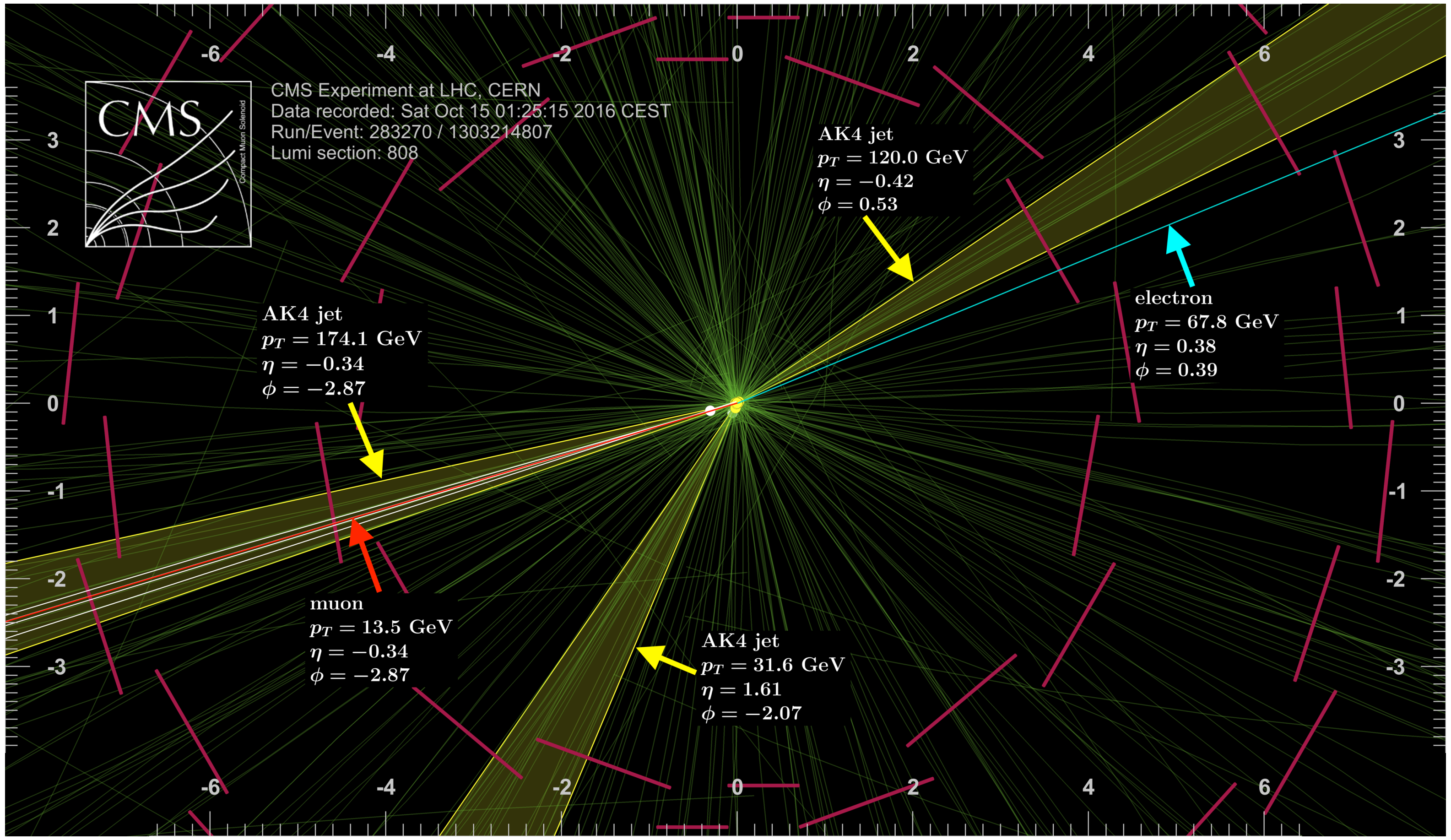
# Emergent phenomena in QCD

- 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

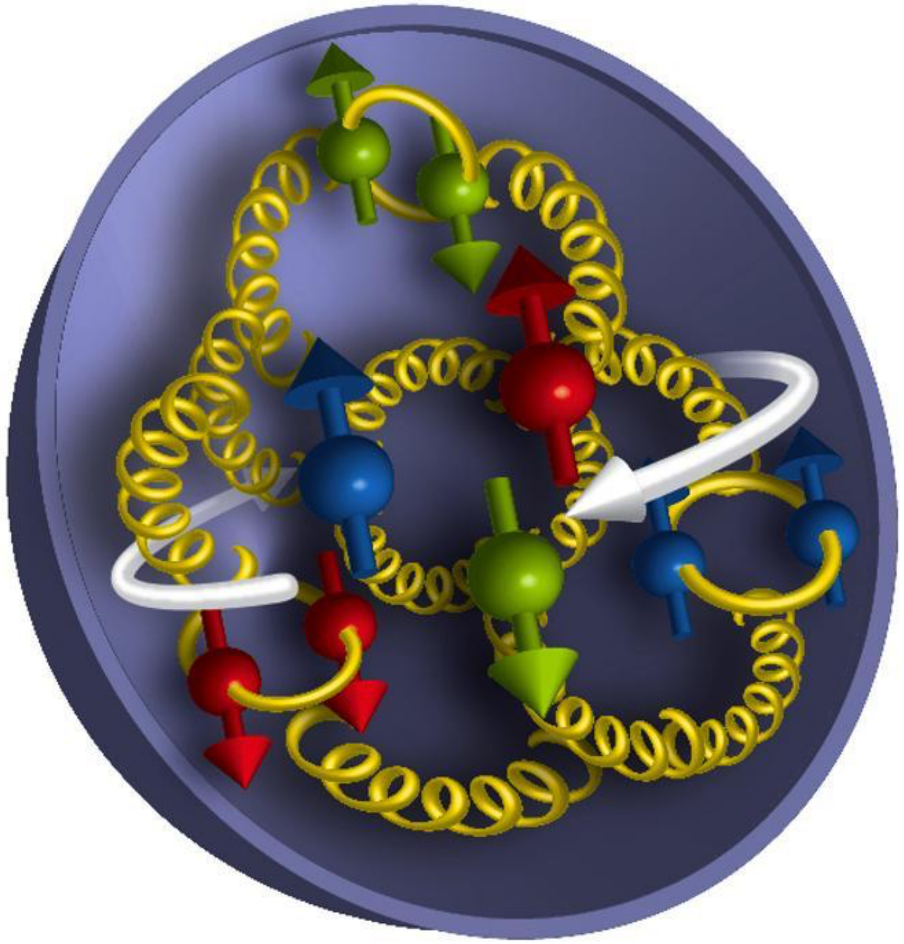
$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q} \left[ i\gamma^{\mu}(\partial_{\mu} - igA_{\mu}) - m_q \right] q$$





# 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%

# The proton spin

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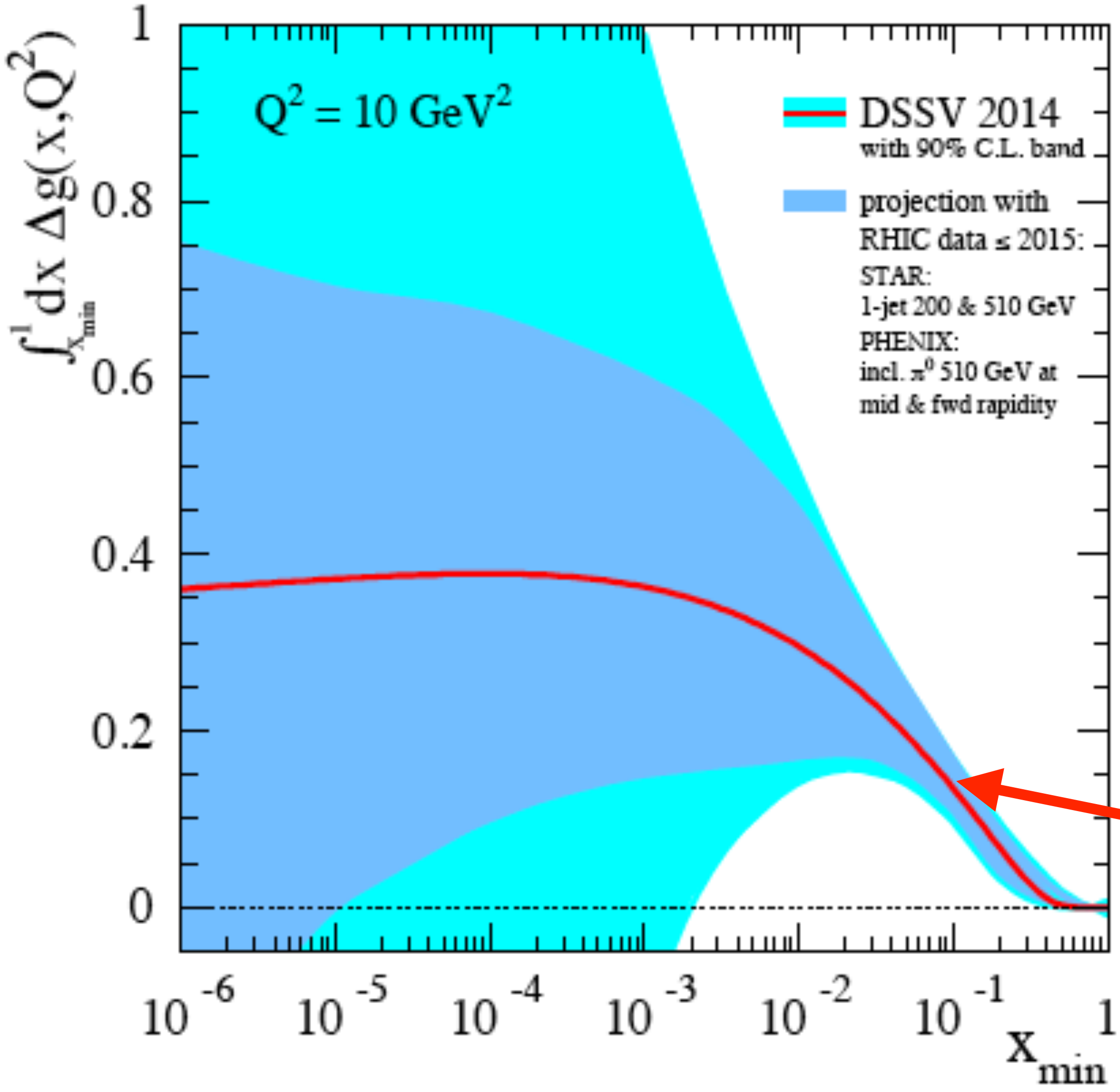

momentum fraction of
proton carried by gluon

**How is the proton spin formed from its microscopic constituents?**

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

First glimpses of the gluon spin contribution are being provided by RHIC; large errors still

# The proton spin

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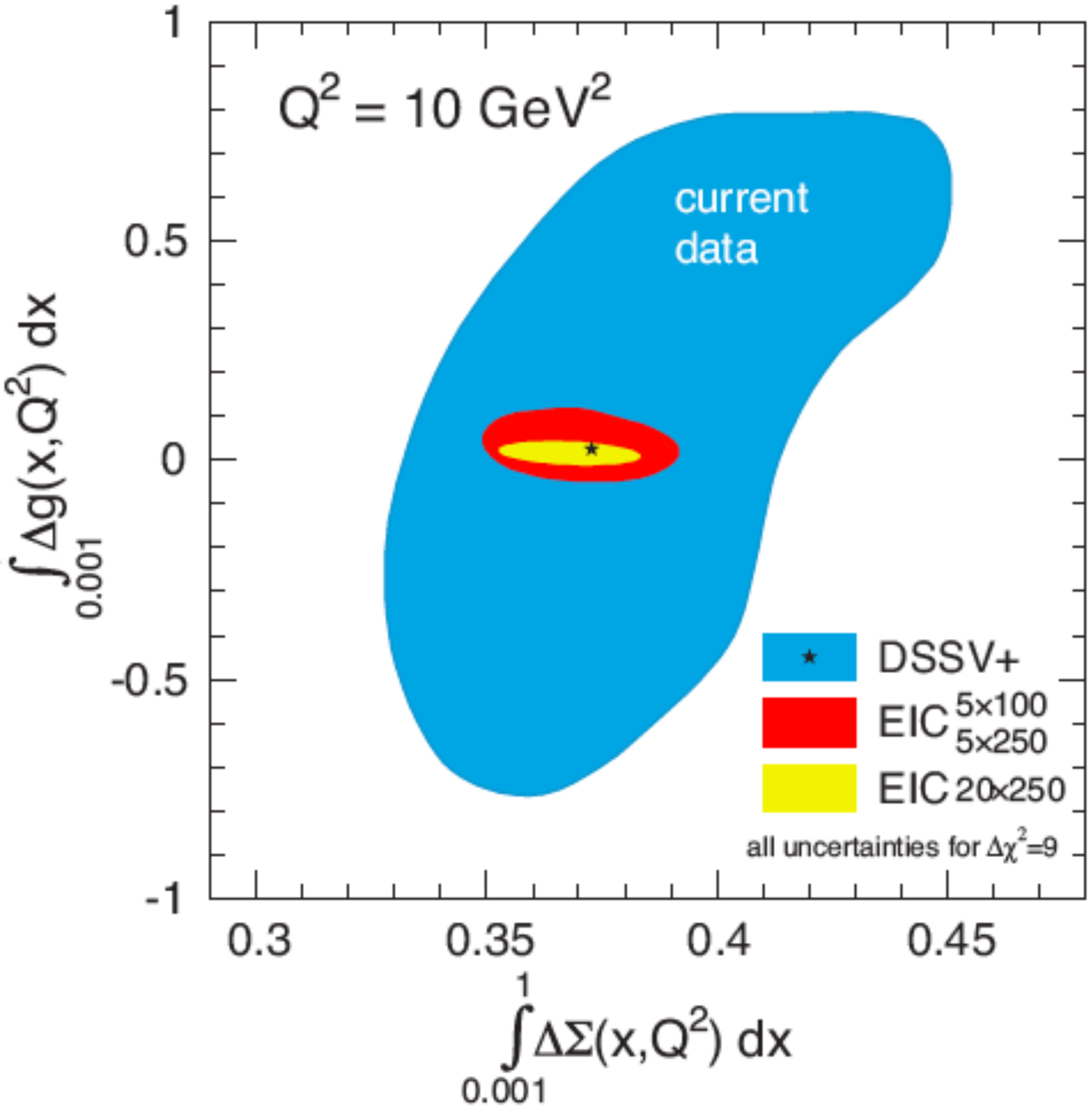


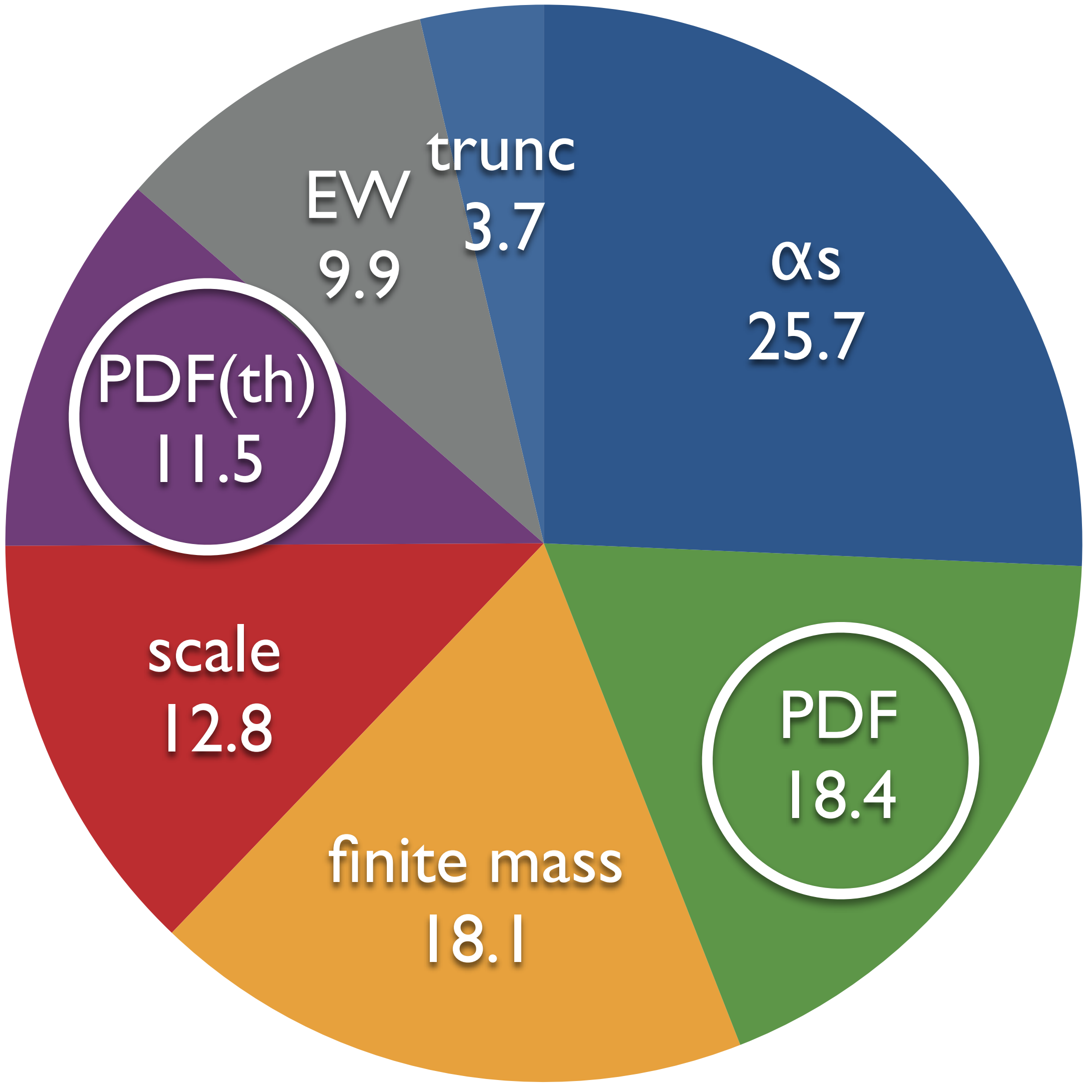
**How is the proton spin formed from its microscopic constituents?**

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

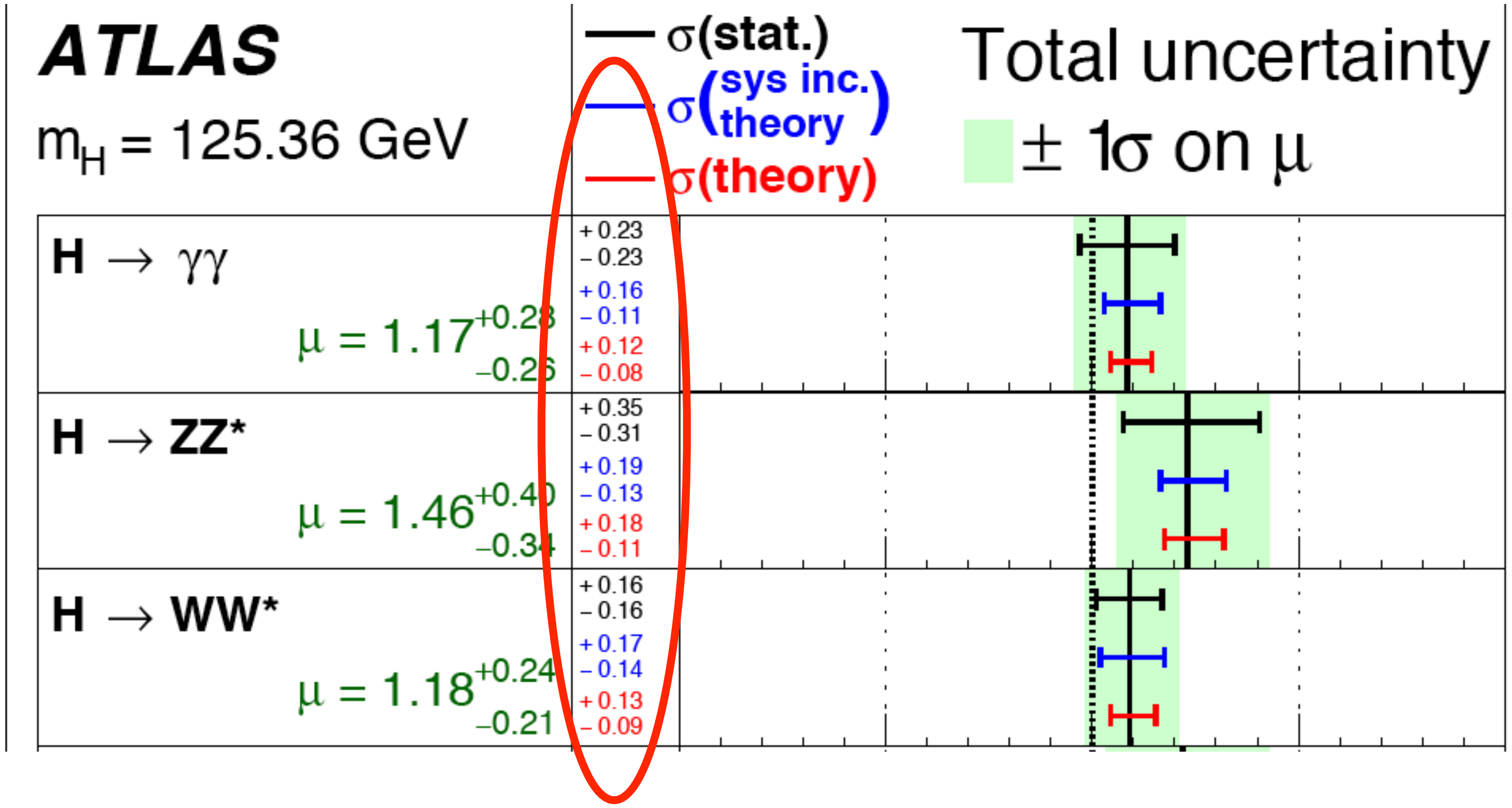
The EIC will provide the first precision probe of the gluon spin

# Proton structure at high energies

- Understanding proton structure is not only important for our understanding of QCD; it is 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!**

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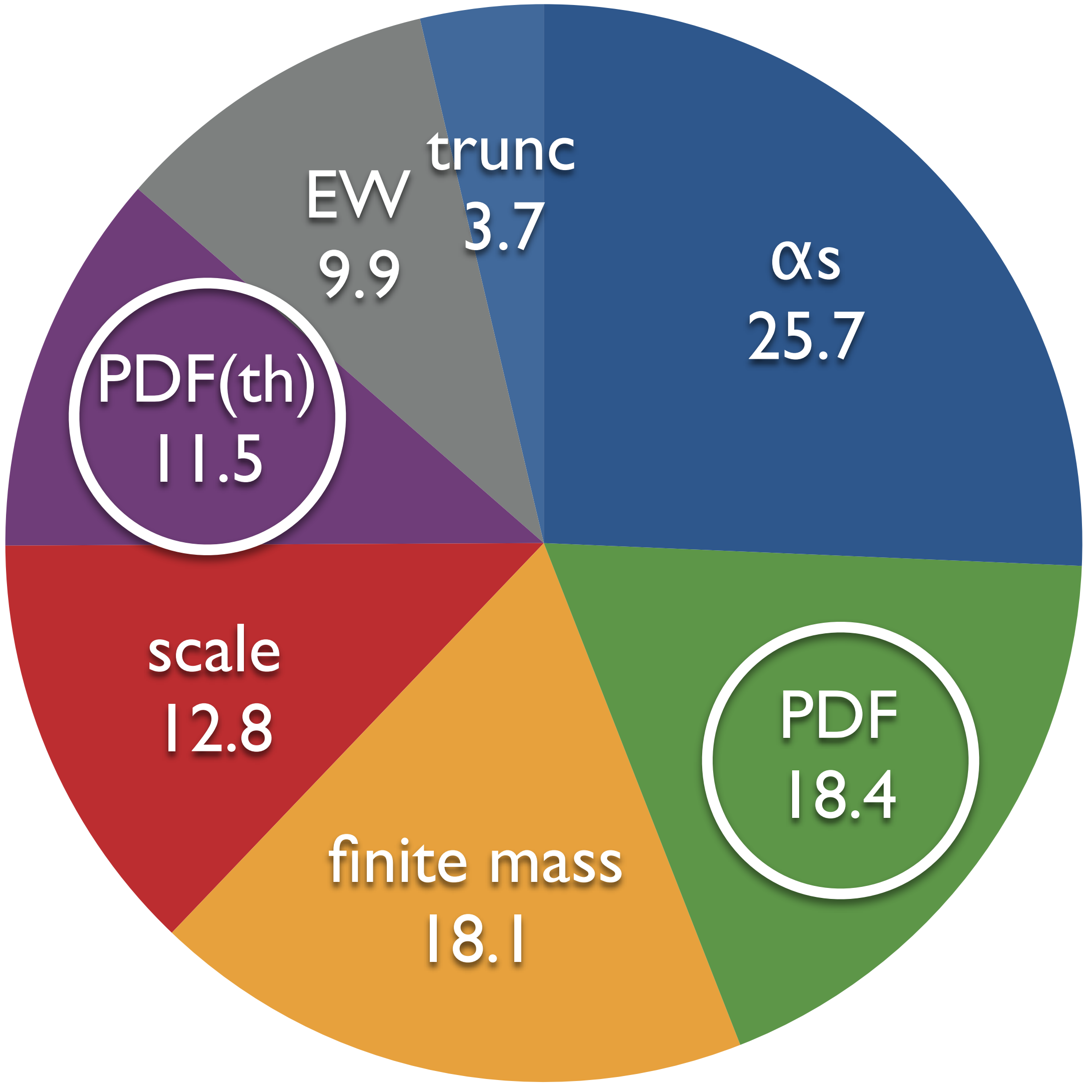

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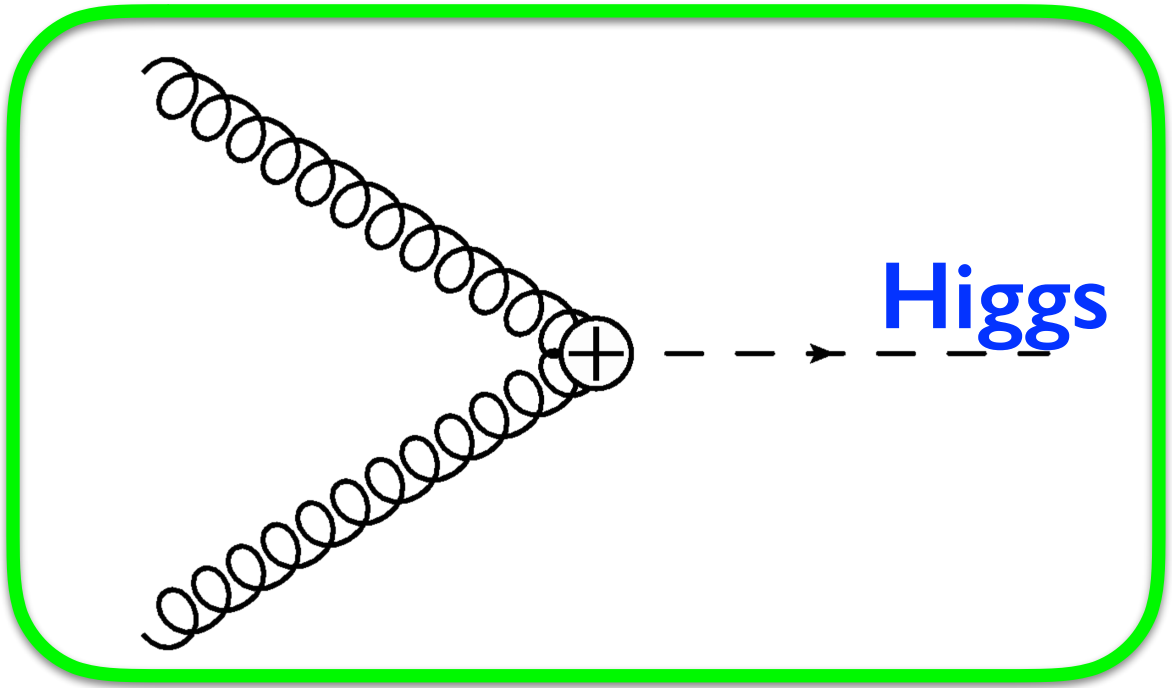


**Reducing the uncertainty on the Higgs production cross section at the LHC requires an improved understanding of the proton's gluon content!**

# Imaging the proton

- How do we study the structure of the proton? We rely upon QCD factorization. In the typical high-energy case collinear factorization applies:

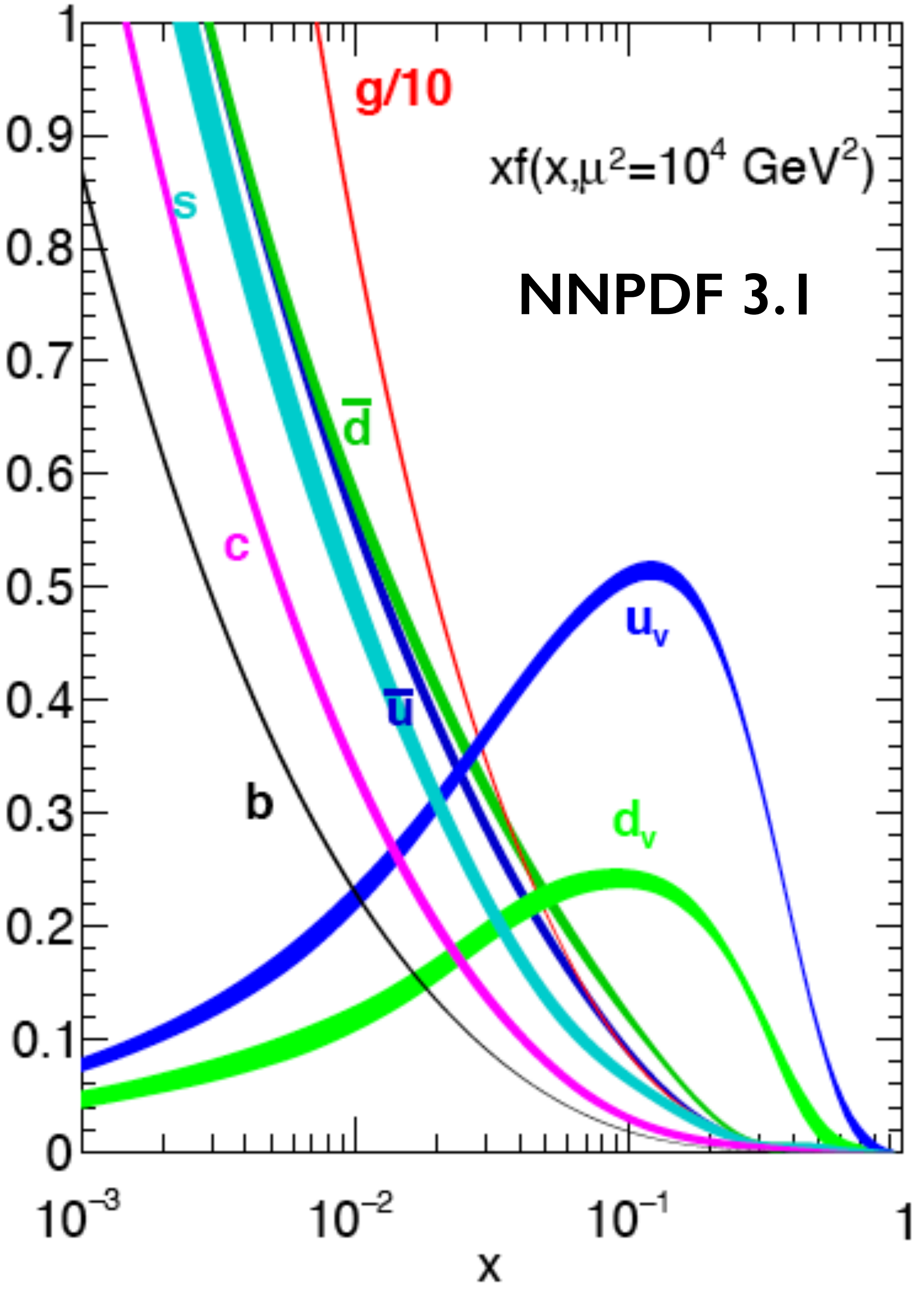
$$\underset{\underset{\text{measure}}{\uparrow}}{\sigma_{h_1 h_2 \to X}} = \int dx_1 dx_2 \, \underset{\underset{\text{extract}}{\uparrow}}{\underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs}} \, \underset{\underset{\text{calculate}}{\uparrow}}{\underbrace{\sigma_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}}} + \underset{\underset{\text{ignore (?)}}{\uparrow}}{\underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}}$$

# Imaging the proton

- How do we study the structure of the proton? We rely upon QCD factorization. In the typical high-energy case collinear factorization applies:

$\sigma_{h_1 h_2 \to X}$

measure



$$\underbrace{\mu_F^2)}\,\underbrace{\sigma_{ij\to X}(x_1,x_2,\mu_F^2,\{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

calculate

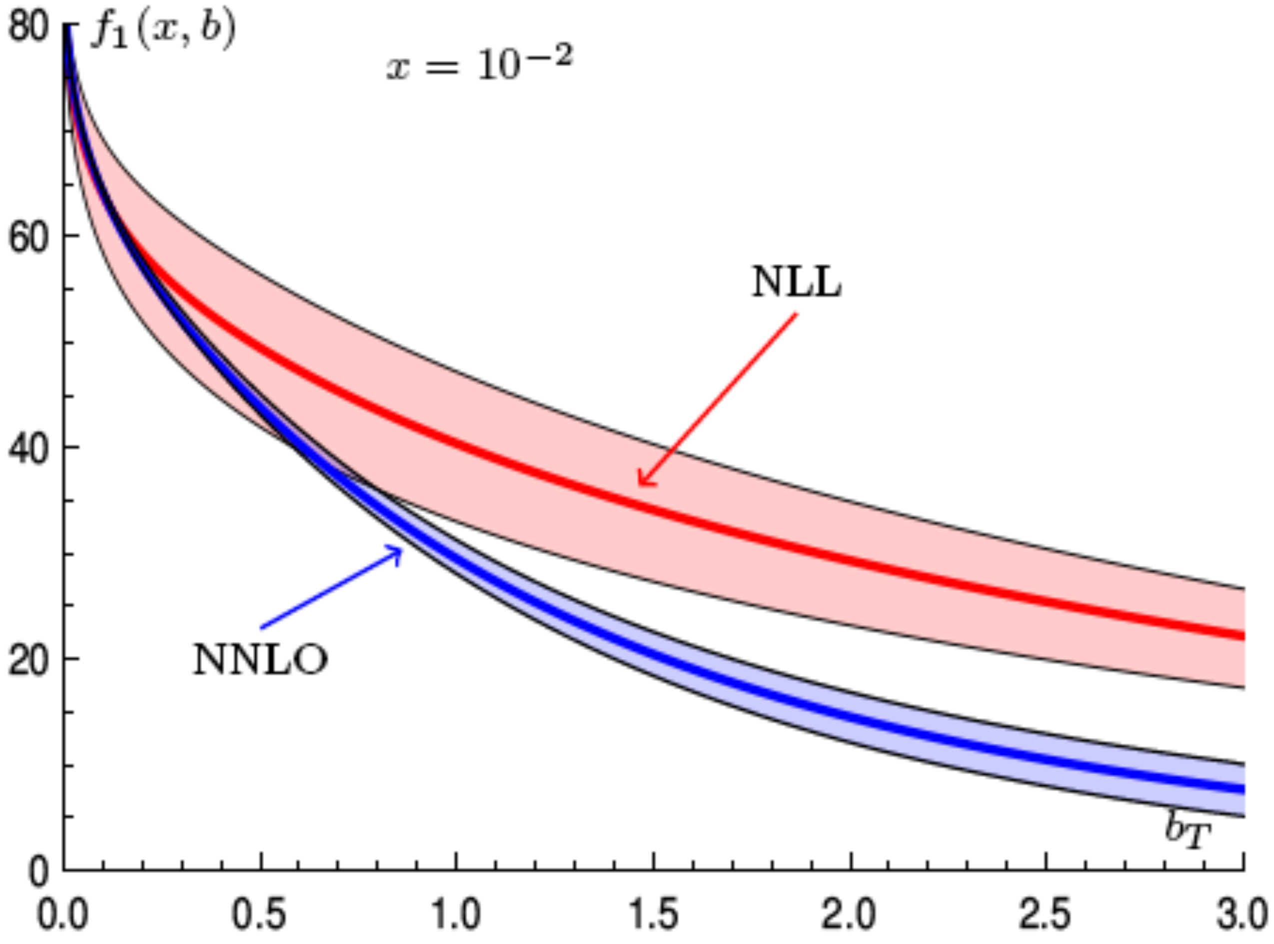
ignore (?)

This is the standard 1-dimensional longitudinal imaging in Bjorken-x of the proton

# Imaging the proton

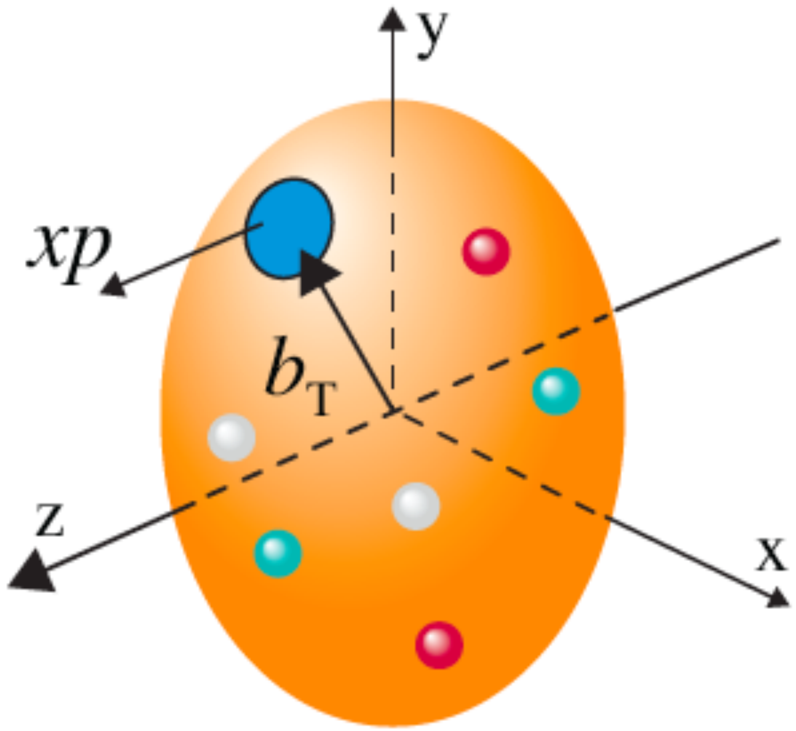
- A critical aspect of this is the perturbative order of the partonic cross section used! A recent example using the TMDPDFs at low $q_T$:

$$\frac{d\sigma}{dq_T^2 dQ^2} \sim \sigma_0 \, H(Q, mu) \int \frac{d^2 b_T}{(2\pi)^2} e^{iq_T \cdot b_T} f(x_1, b_T; \mu) f(x_2, b_T; \mu)$$



from A. Vladimirov, INT 2017

transverse-momentum dependent PDFs (TMDPDFs)



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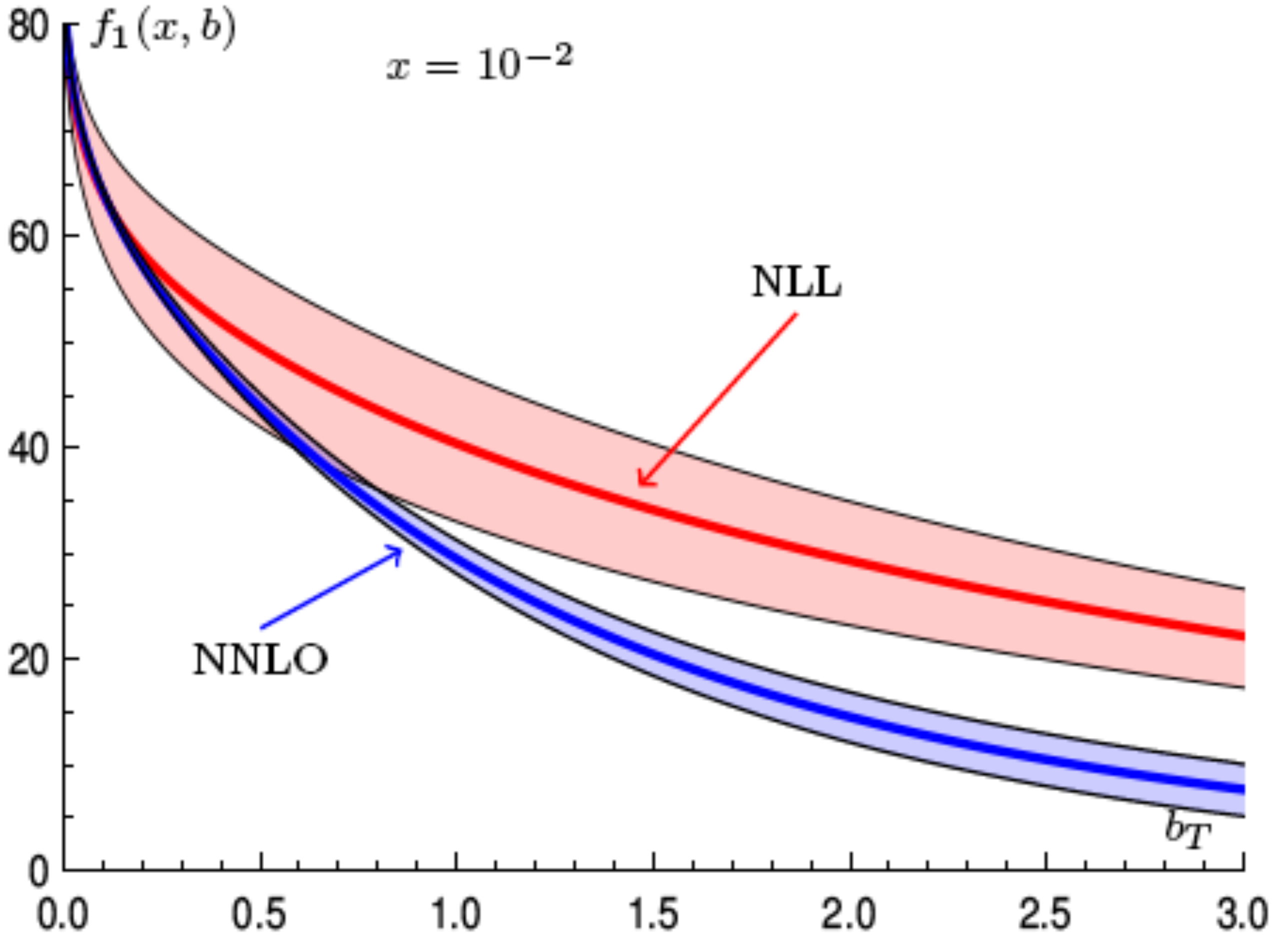


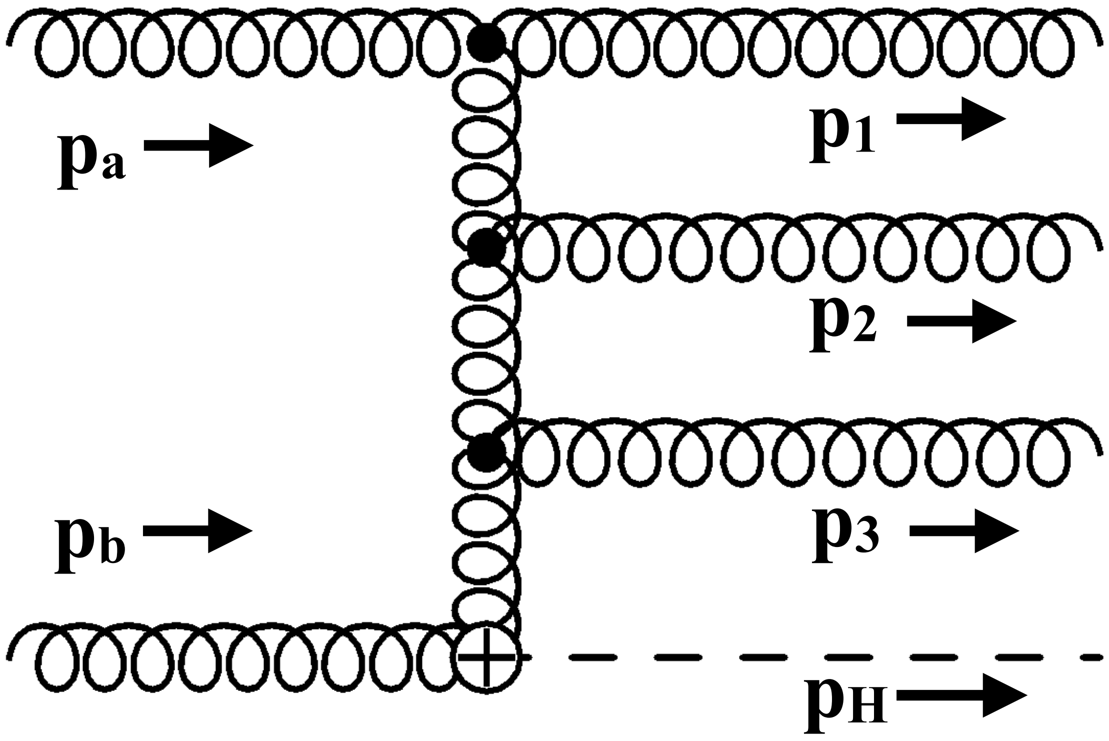
from A.Vladimirov, INT 2017

Accuracy and precision for proton structure requires perturbative QCD at next-to-next-to-leading order!

# Anatomy of a NNLO calculation

- What are the difficulties in achieving NNLO precision in perturbative QCD.> Let's study an example contribution to see what can occur during a calculation.

**Higgs+jet:**



What kind of singularities can occur at NNLO?

$p_1$, $p_2$ soft

$p_1||p_3$, $p_2$ soft

$p_1||p_2||p_3$

$p_2||p_3$, $p_1$ soft

$p_1||p_a$, $p_2||p_b$

+many more!

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

# N-jettiness subtraction

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

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

***N-jettiness***, an event shape variable (similar to thrust); introduced by Stewart, Tackmann, Waalewijn (2009)

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, Liu, FP, PRL 115 (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 (2009)

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

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

describes hard radiation

describes radiation collinear to initial-state beams; ***universal***

describes soft radiation; ***universal***

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

# N-jettiness subtraction

Boughezal, Focke, Liu, FP, PRL 115 (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

th

av

have one more resolved jet

**Major advantages of N-jettiness subtraction:**

- Universal, process independence objects clearly identified
- Recycle known NLO results for above-cut contributions
- Applicable to problems in both particle and nuclear physics

(e.g.,

jets)

describes hard radiation

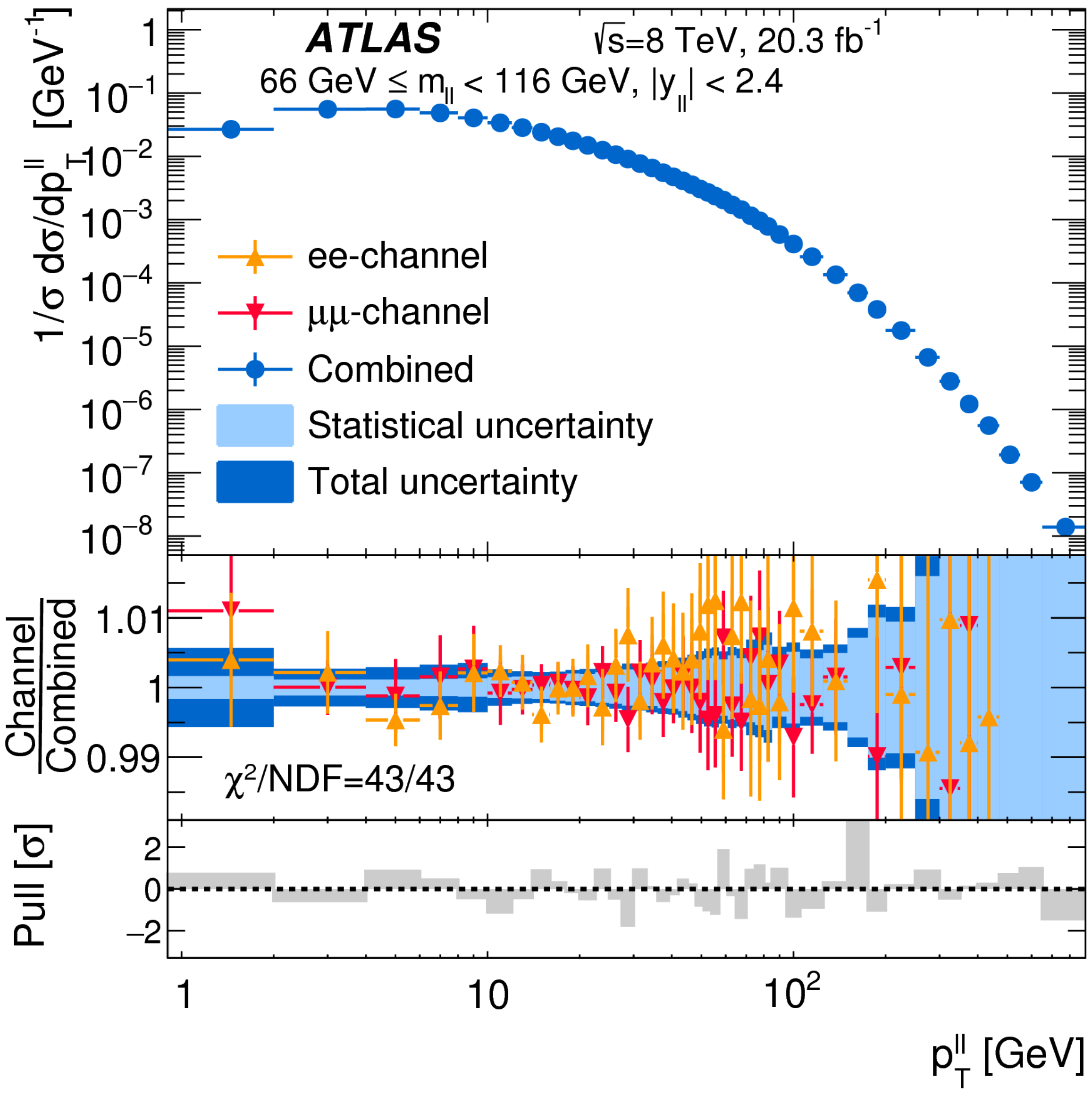
describes radiation collinear to initial-state beams; *universal*

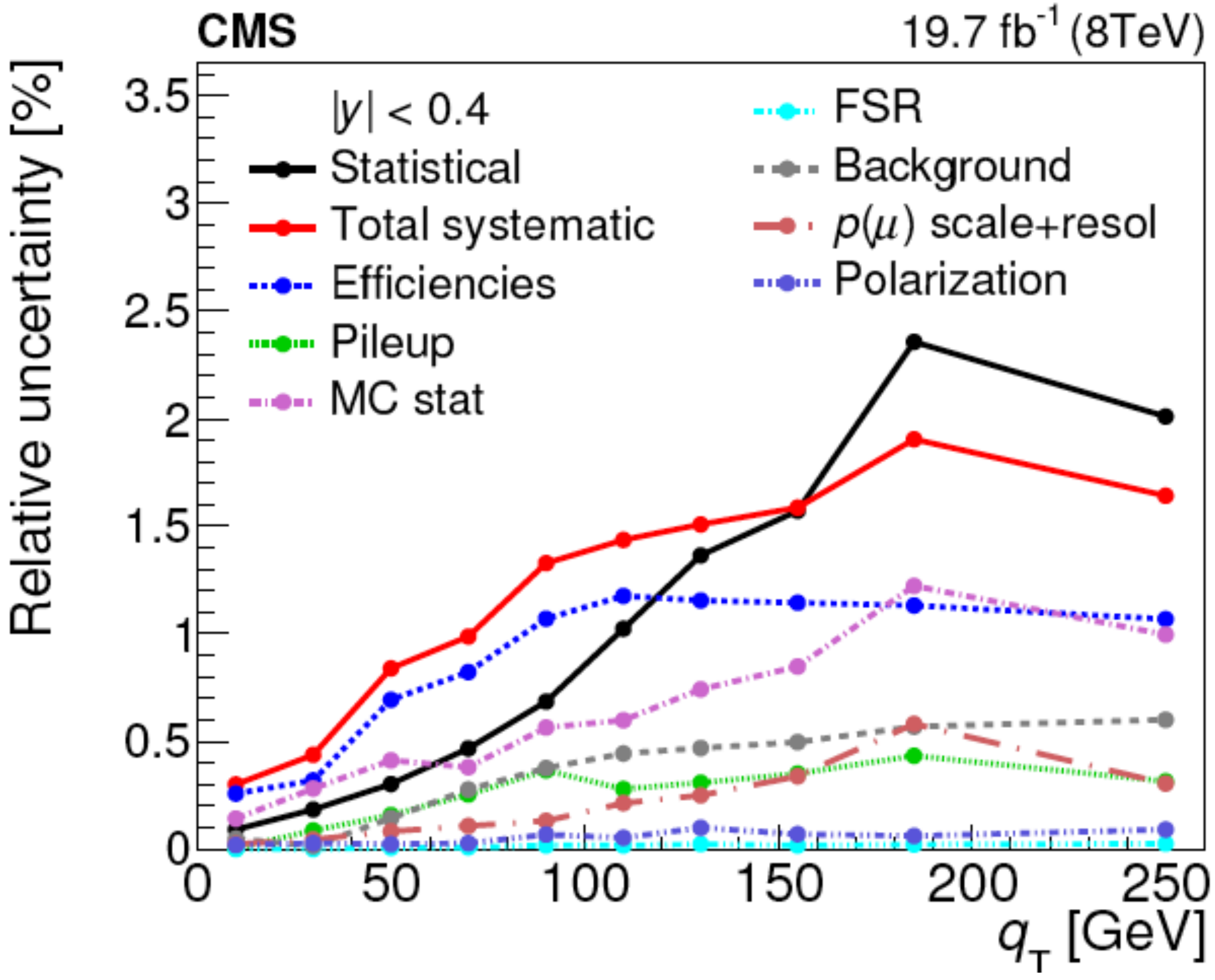
describes soft radiation; *universal*

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

# 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





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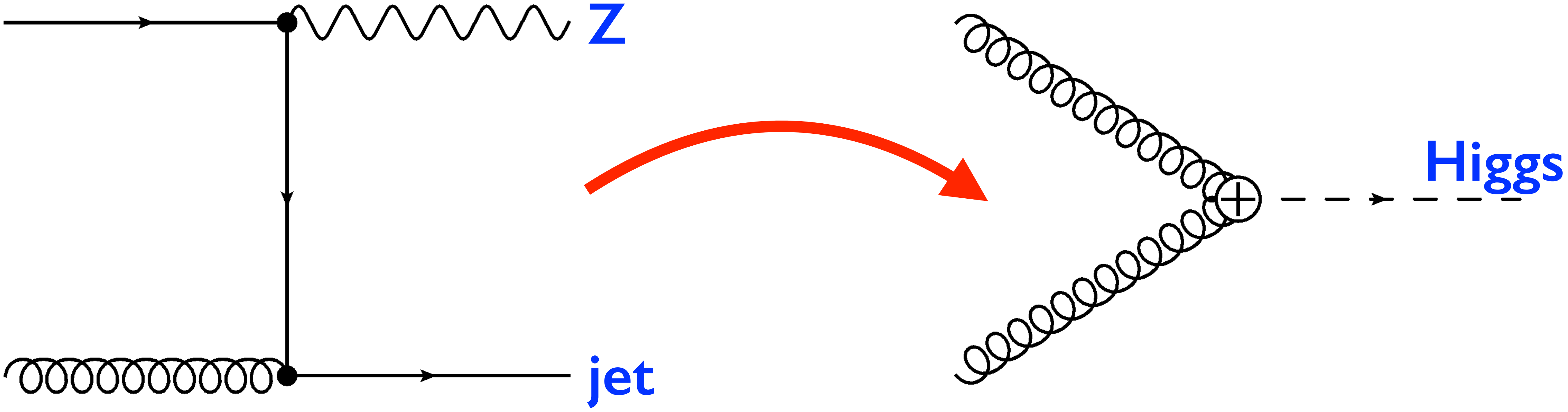
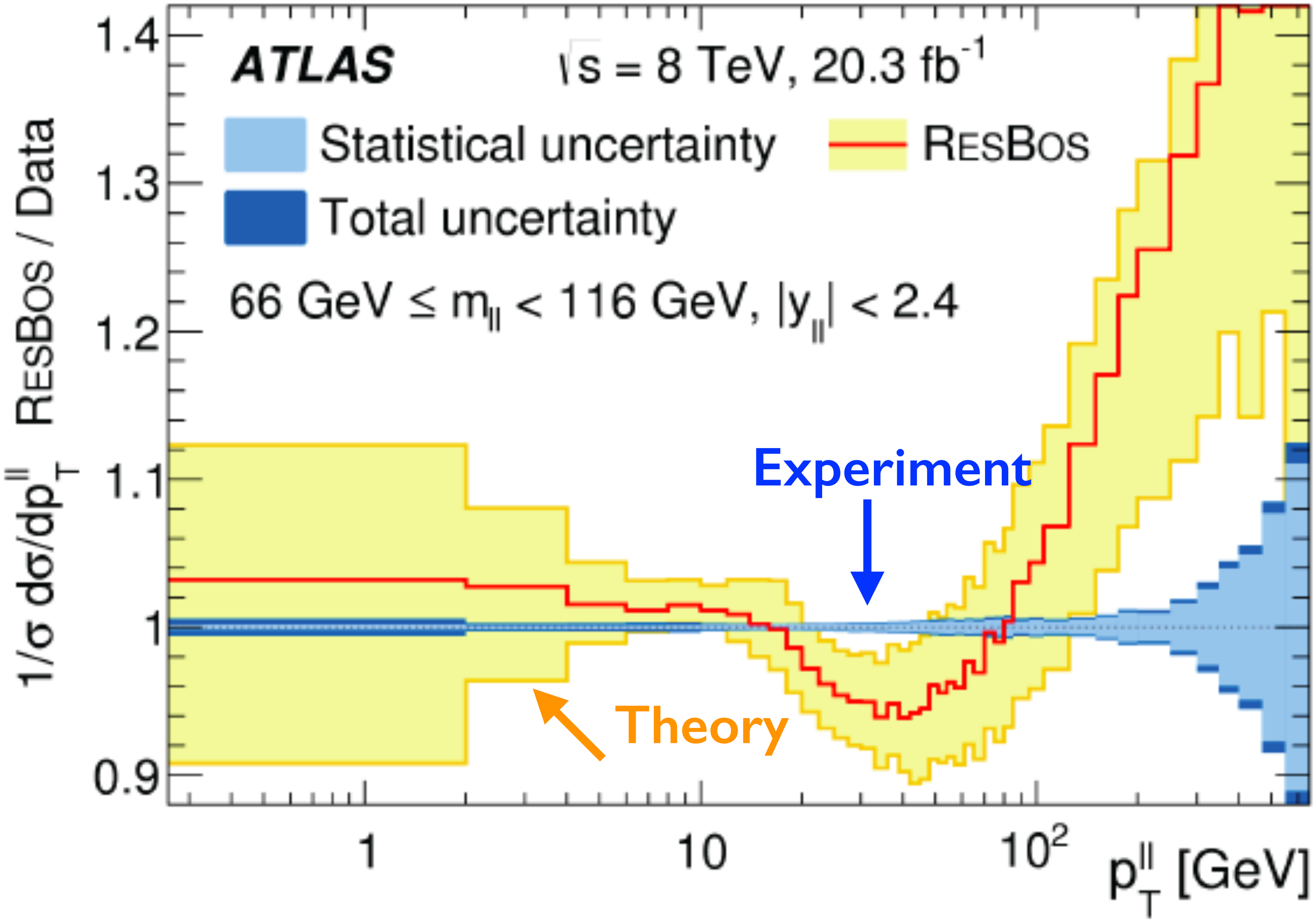


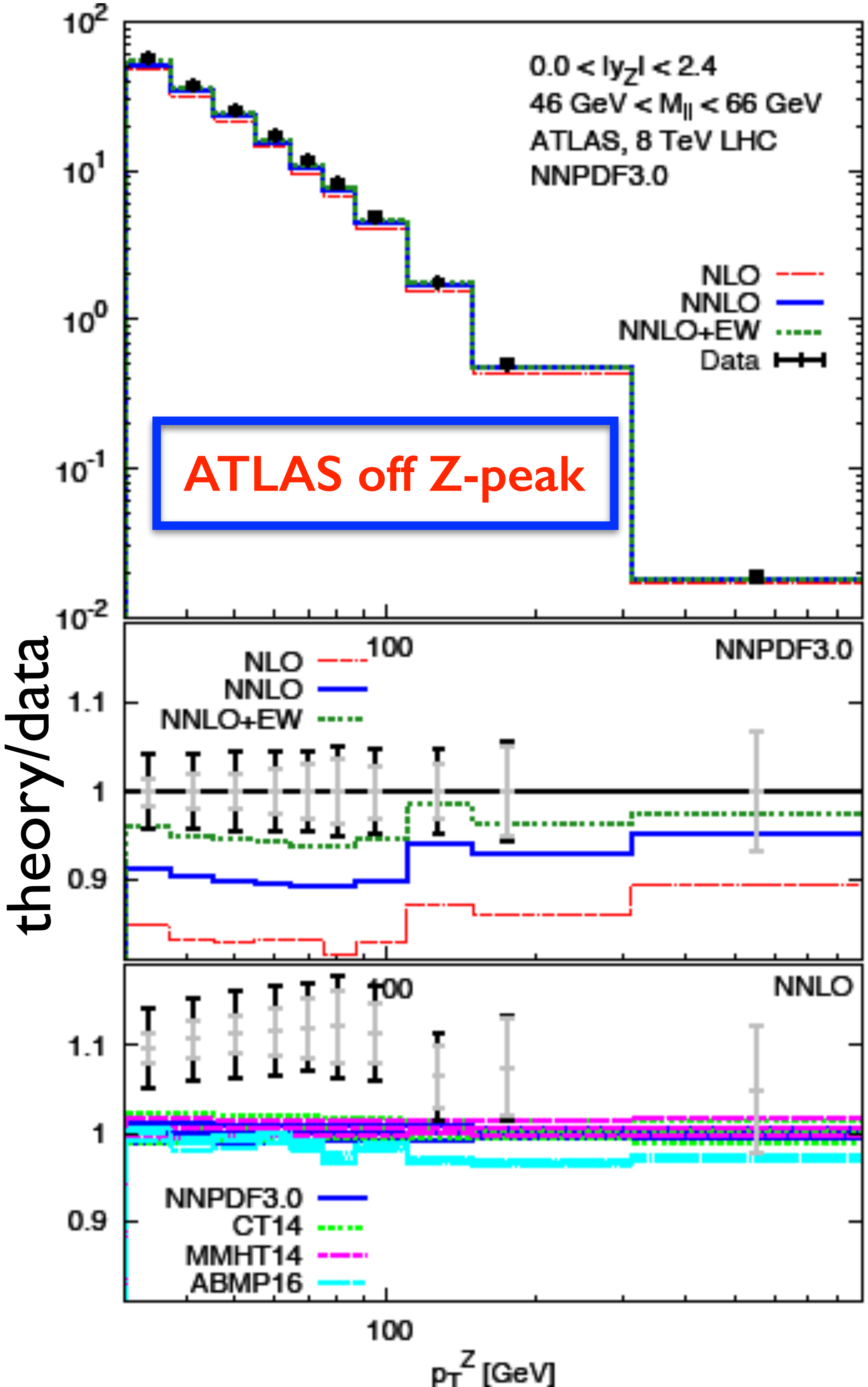
**Can learn about the gluon distribution entering Higgs production from this data!**

# 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!



# Comparison with NNLO theory



**ATLAS off Z-peak**

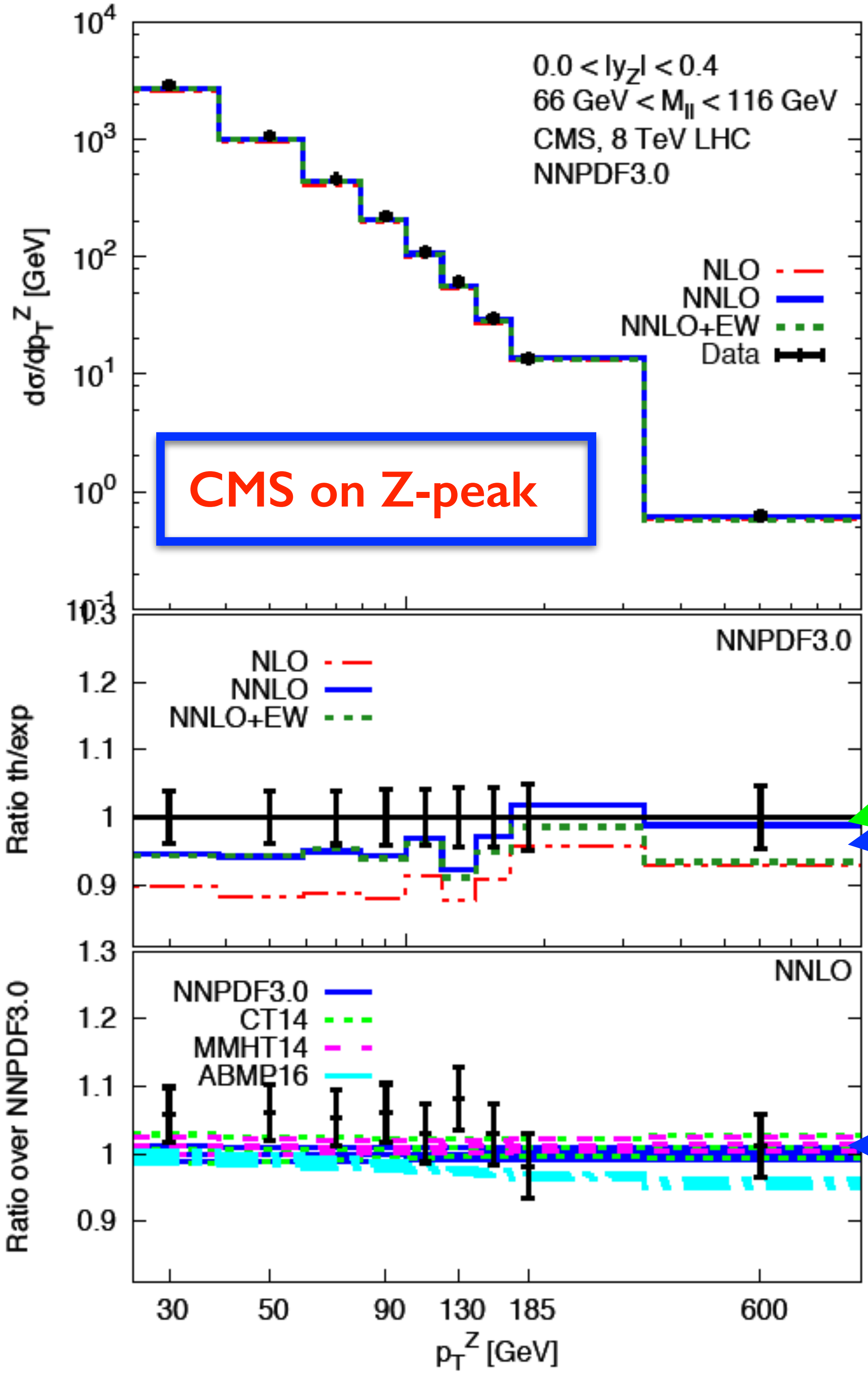
- We have performed an NNLO QCD calculation using N-jettiness subtraction and extensively compared with ATLAS and CMS
- We have combined NNLO QCD and NLO electroweak corrections for this prediction

Note the importance of NNLO QCD+NLO EW as compared to just NNLO QCD in the off-peak data

No current PDF set describes this well; feed this information back into the PDF fit!

Boughezal, Guffanti, FP, Ubiali JHEP 1707 (2017)

# Comparison with NNLO theory



**CMS on Z-peak**

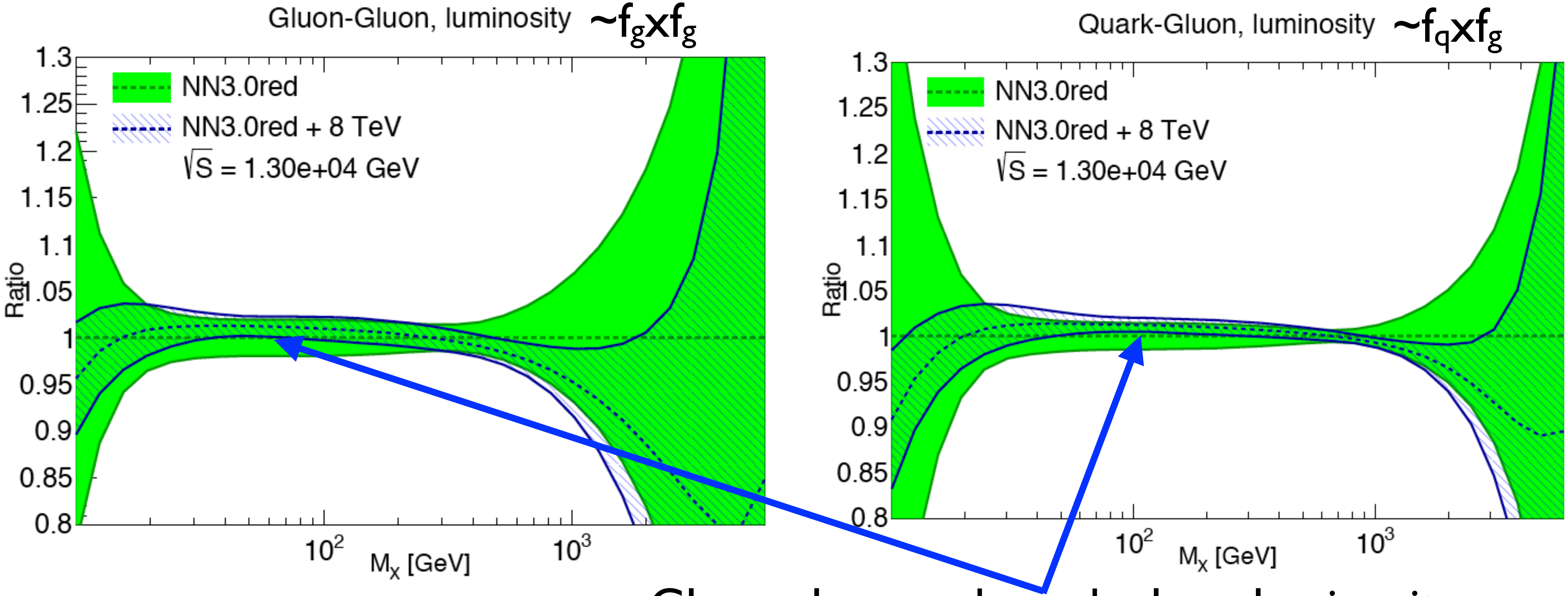
- We have performed an NNLO QCD calculation using N-jettiness subtraction and extensively compared with ATLAS and CMS data.
- We have combined NNLO QCD and NLO electroweak corrections for this prediction

NLO EW as not as important on-peak; NNLO QCD leads to a much improved description

Better than off-peak, but still no current PDF set describes this well; feed this information back into the PDF fit!

Boughezal, Guffanti, FP, Ubiali JHEP 1707 (2017)

# Impact on PDFs


Gluon-Gluon, luminosity $\sim f_g x f_g$

Quark-Gluon, luminosity $\sim f_q x f_g$

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

| | Before $p_T^Z$ data | After $p_T^Z$ data |
|---|---|---|
| $\sigma_{gg \to H}$ [pb] | $48.22 \pm 0.89$ (1.8%) | $48.61 \pm 0.61$ (1.3%) |
| $\sigma_{\mathrm{VBF}}$ [pb] | $3.92 \pm 0.06$ (1.5%) | $3.96 \pm 0.04$ (1.0%) |

**PDF error on Higgs cross sections reduced!**

Boughezal, Guffanti, FP, Ubiali JHEP 1707 (2017)

# Impact on PDFs

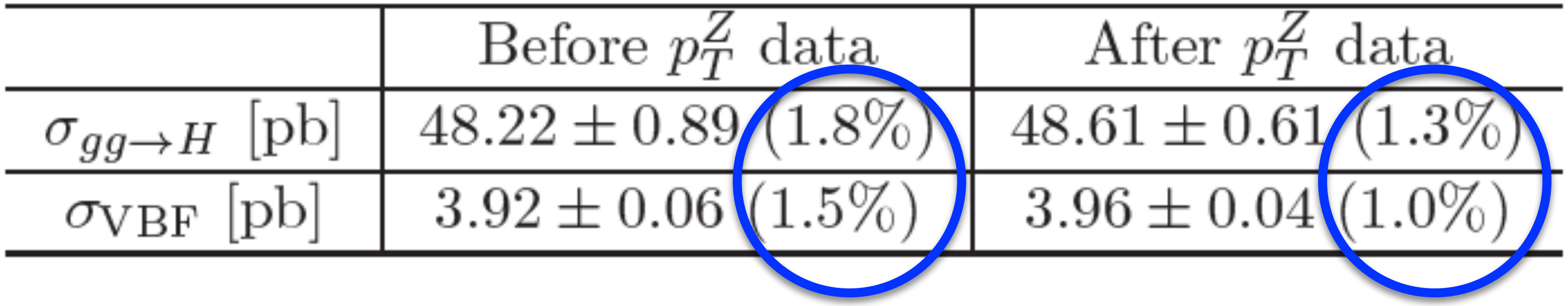
**P5 report:**

**Building for Discovery**

Strategic Plan for U.S. Particle Physics in the Global Context

*"The full discovery potential of the Higgs will be unleashed by **percent-level precision** studies of the Higgs properties."*

**We're getting to our goal!**



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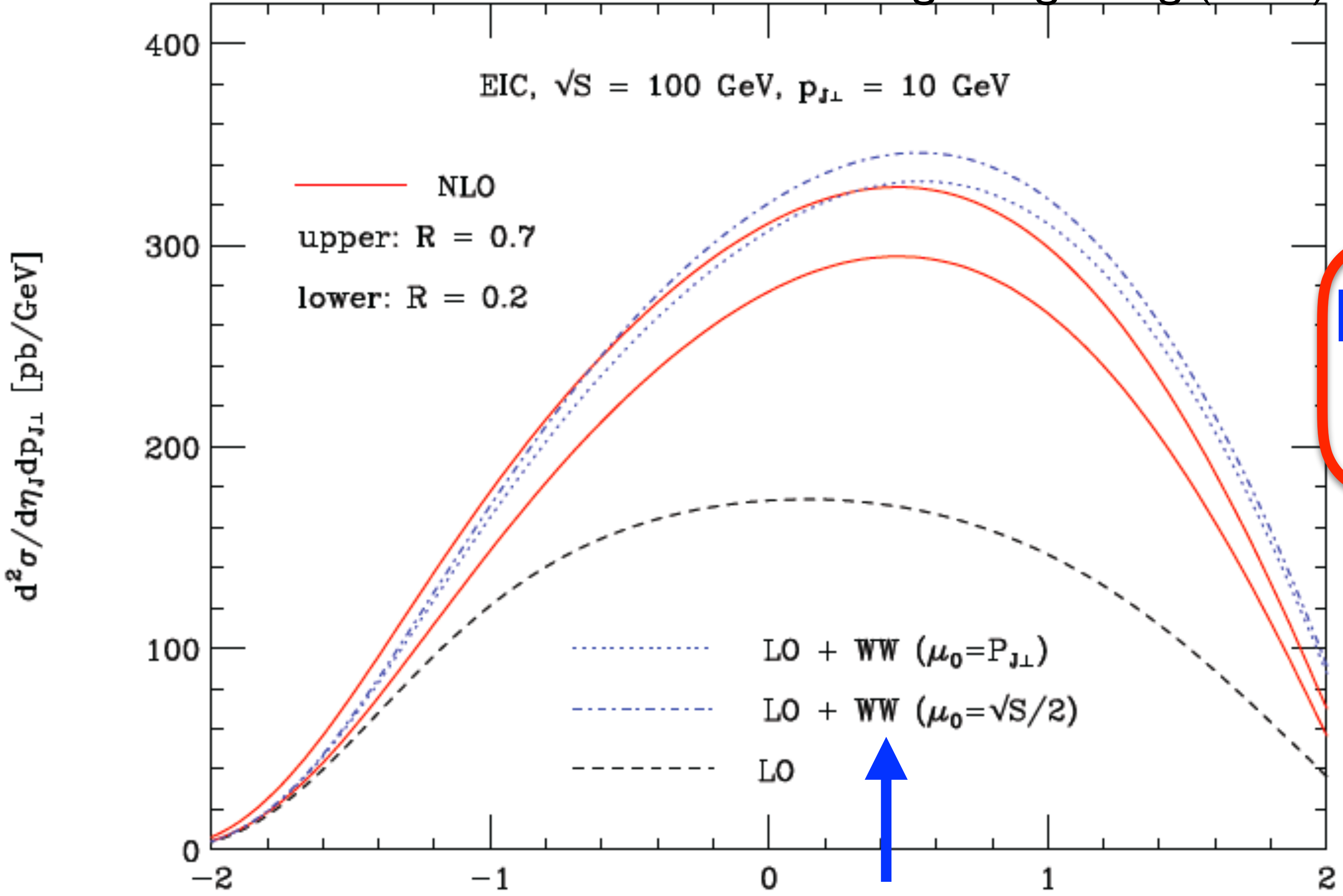
# Jet physics at an Electron-Ion Collider

- Proton structure studies will be a central aspect of a future EIC. Jets will play an important role these probes, just as at the LHC.



Hinderer, Schlegel, Vogelsang (2015)

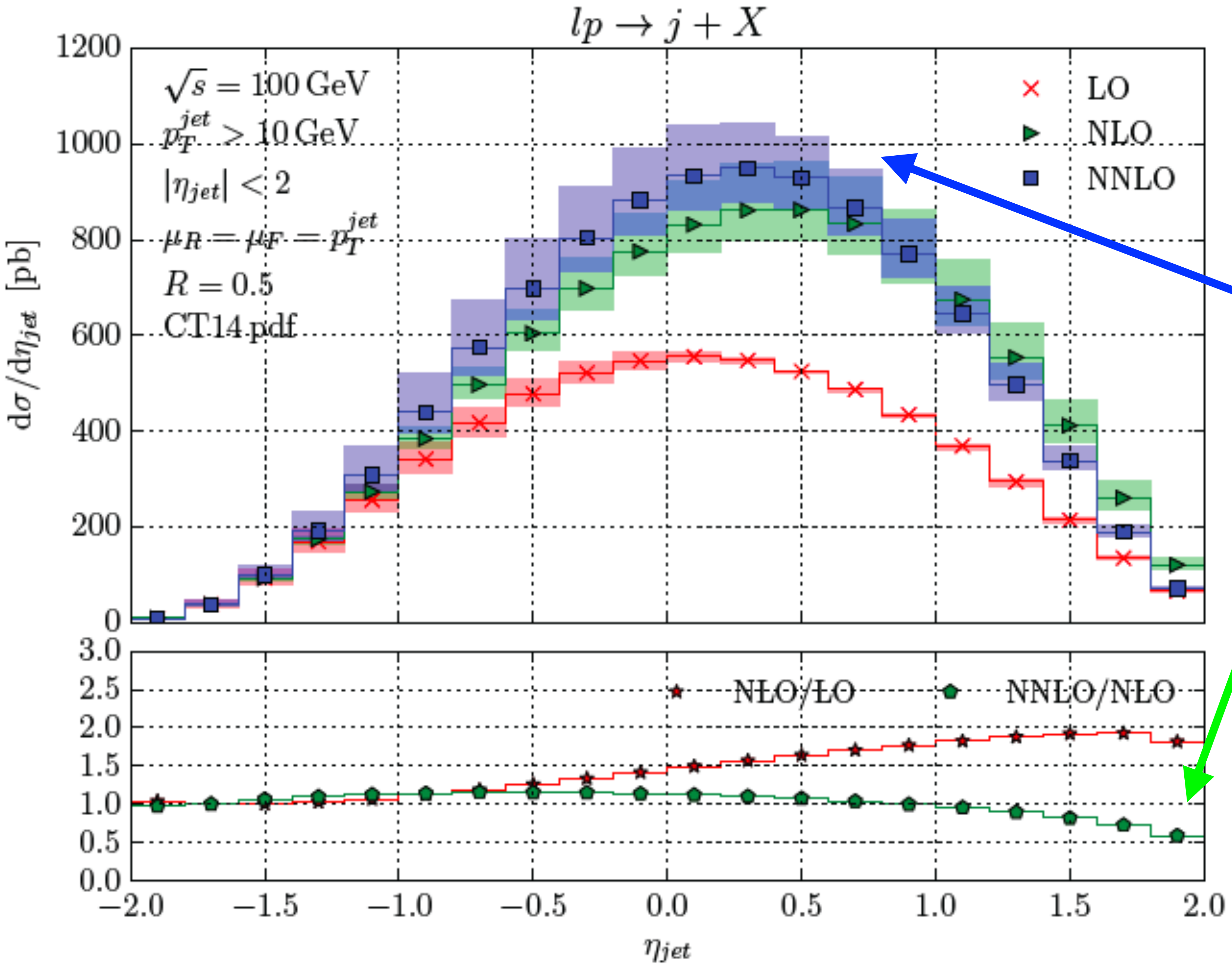
It is a challenge to theory to match this precision!

γ+p→jet+X contribution

$\eta_J$ = jet pseudorapidity

# EIC jet production at NNLO

- N-jettiness subtraction allows for a NNLO calculation of EIC jet production!

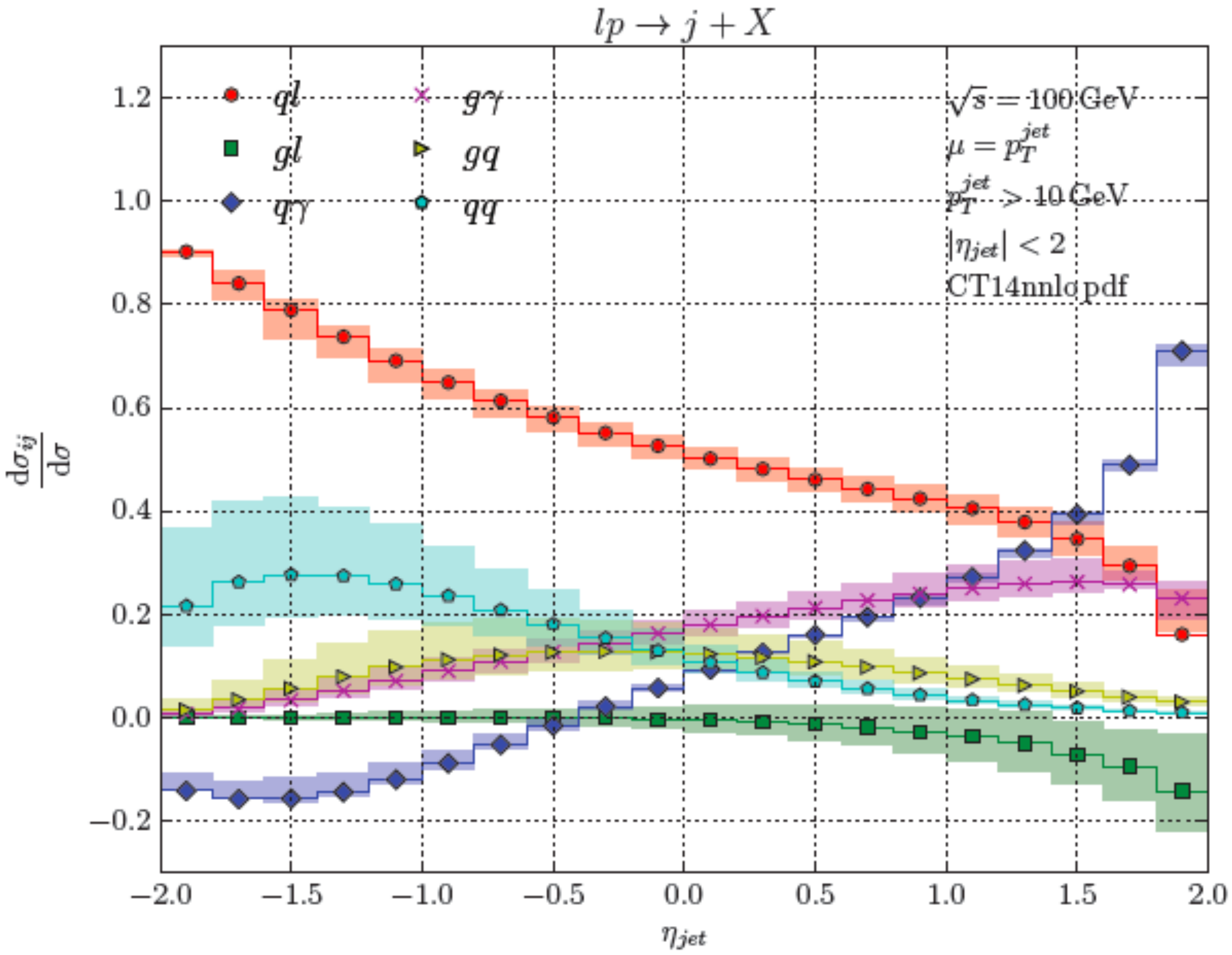


- **Perturbation theory stabilizes at NNLO!**
- Large corrections in the forward region; don’t want to confuse this with PDF x dependence!

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

# EIC jet production at NNLO

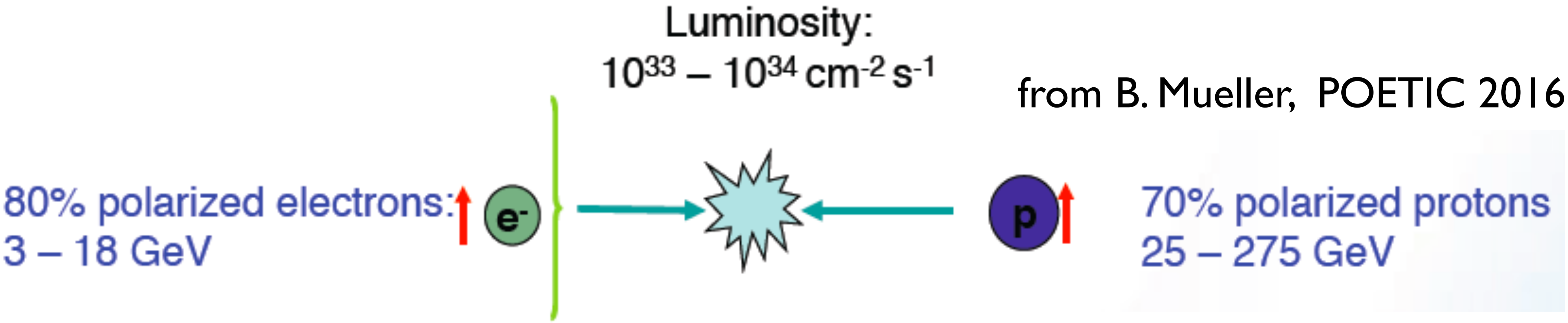
- Jet distributions at the EIC are an excellent probe of PDFs; no single channel dominates over all of phase space, indicating that different kinematic regions provide access to different partonic luminosities.



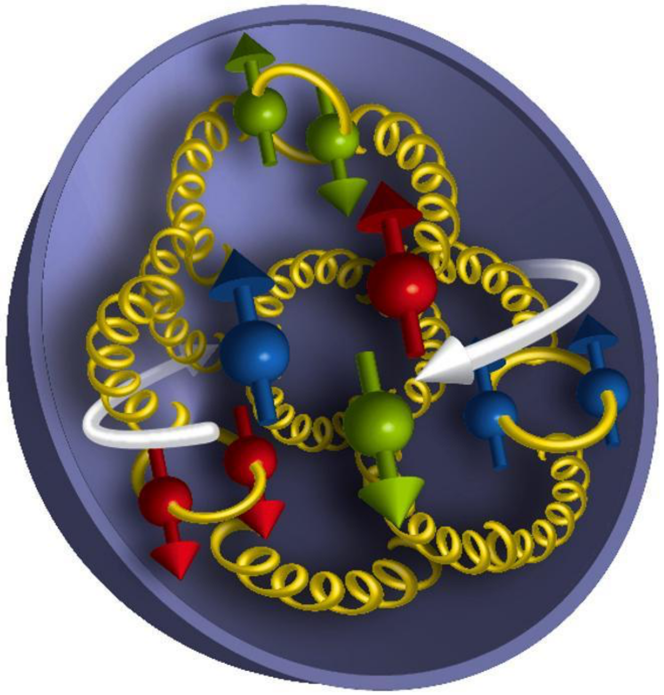
Abelof, Boughezal, Liu, FP, PLB 763 (2016)

# Polarized jet production

- We are also interested in polarized collisions at the EIC.



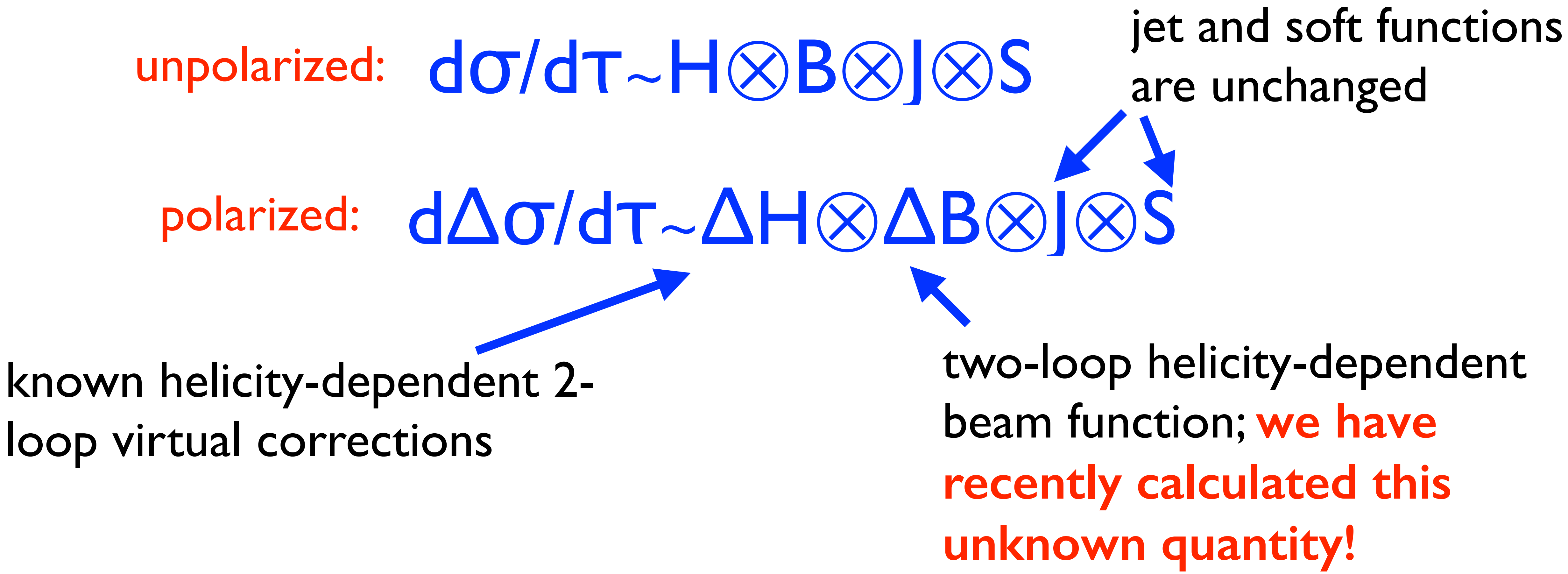
from B. Mueller, POETIC 2016



Need to formulate N-jettiness subtraction to handle polarized collisions!

# Extending to polarized collisions

- Schematic form of factorization theorem for unpolarized and longitudinally polarized collisions (Δ denotes the different between right-handed and left-handed polarizations):



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

jet and soft functions are unchanged

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; **we have recently calculated this unknown quantity!**

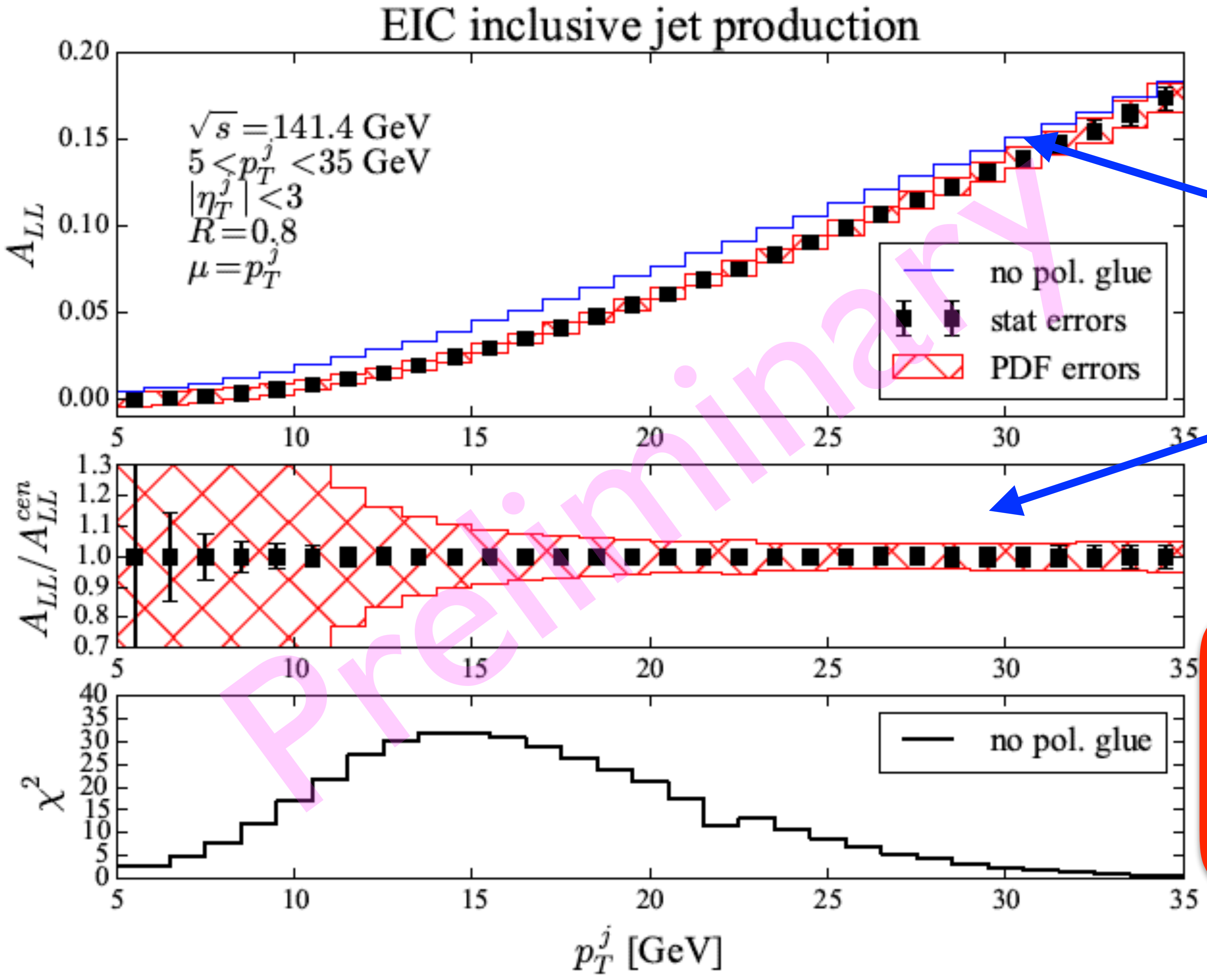
All ingredients now known!

Boughezal, FP, Schubert, Xing PRD 96 (2017)

# Polarized PDFs at the EIC

- Polarization asymmetries in EIC jet production are a powerful probe of gluon and quark distributions!

$$A_{LL} = \frac{\sigma_{LL} + \sigma_{RR} - \sigma_{LR} - \sigma_{RL}}{\sigma_{LL} + \sigma_{RR} + \sigma_{LR} + \sigma_{RL}}$$



results with polarized gluon turned off

PDF errors larger than expected statistical errors over much of phase space

Can learn about polarized PDFs from jet measurements!

Boughezal, FP, Xing, in progress

# Polarized PDFs at the EIC

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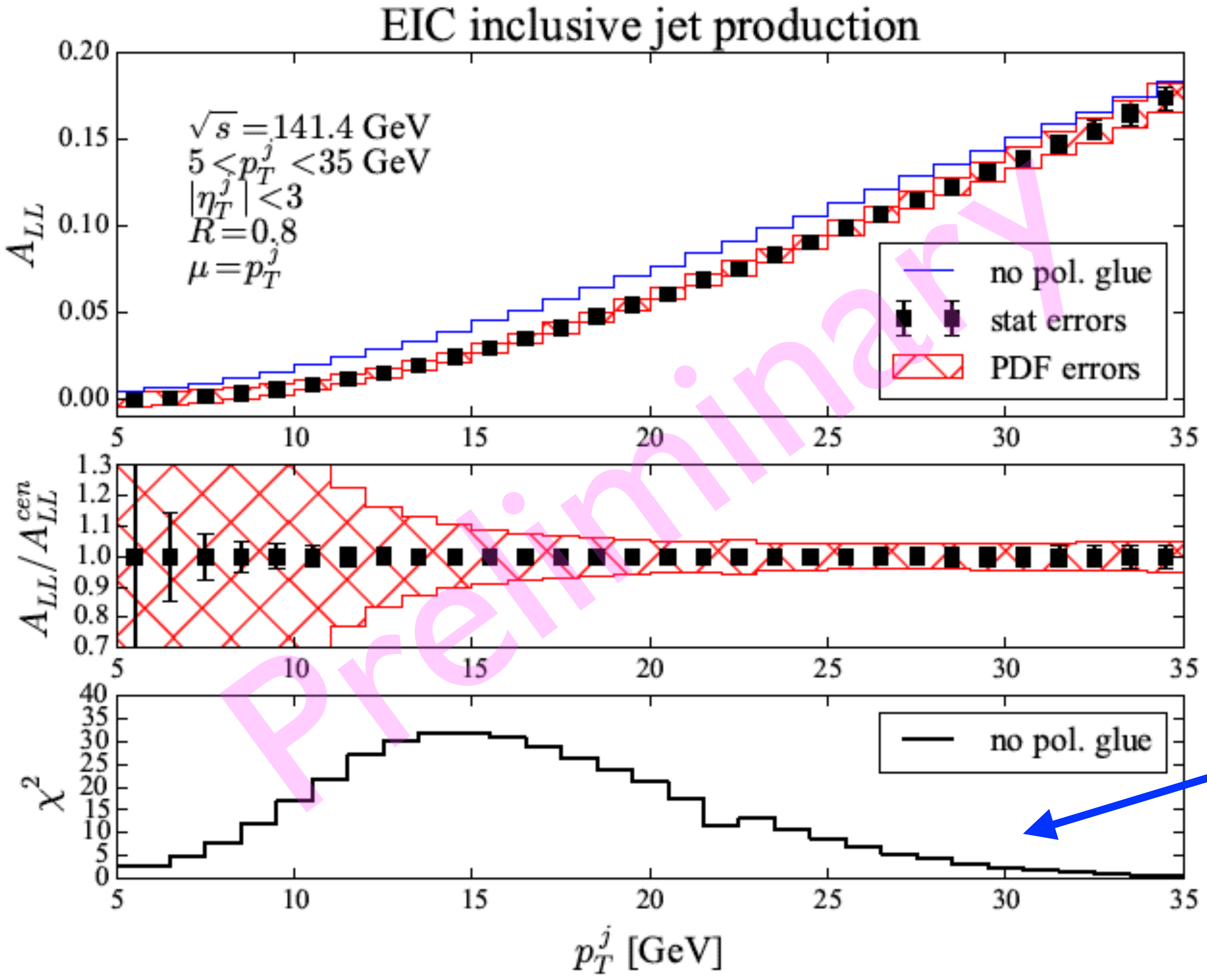

$$\chi^2 = \frac{(A_{LL} - A_{LL}^{\text{no glue}})^2}{\sigma^2_{A_{LL}}}$$

Very sensitive to polarized gluons!

Boughezal, FP, Xing, in progress

# Summary

- Understanding the gluon distribution in the proton is central to pressing questions across energy scales
- New developments using SCET allow predictions that match the experimental precision for the data sets need to understand glue
- The Z-boson transverse momentum spectrum greatly improves our understanding of the unpolarized gluon in the proton, and correspondingly the Higgs cross section
- Jet measurements at a future EIC will help determine the gluon contribution to the proton spin
- Looking forward to more data!