Resummation at the LHC: recent progress and future challenges

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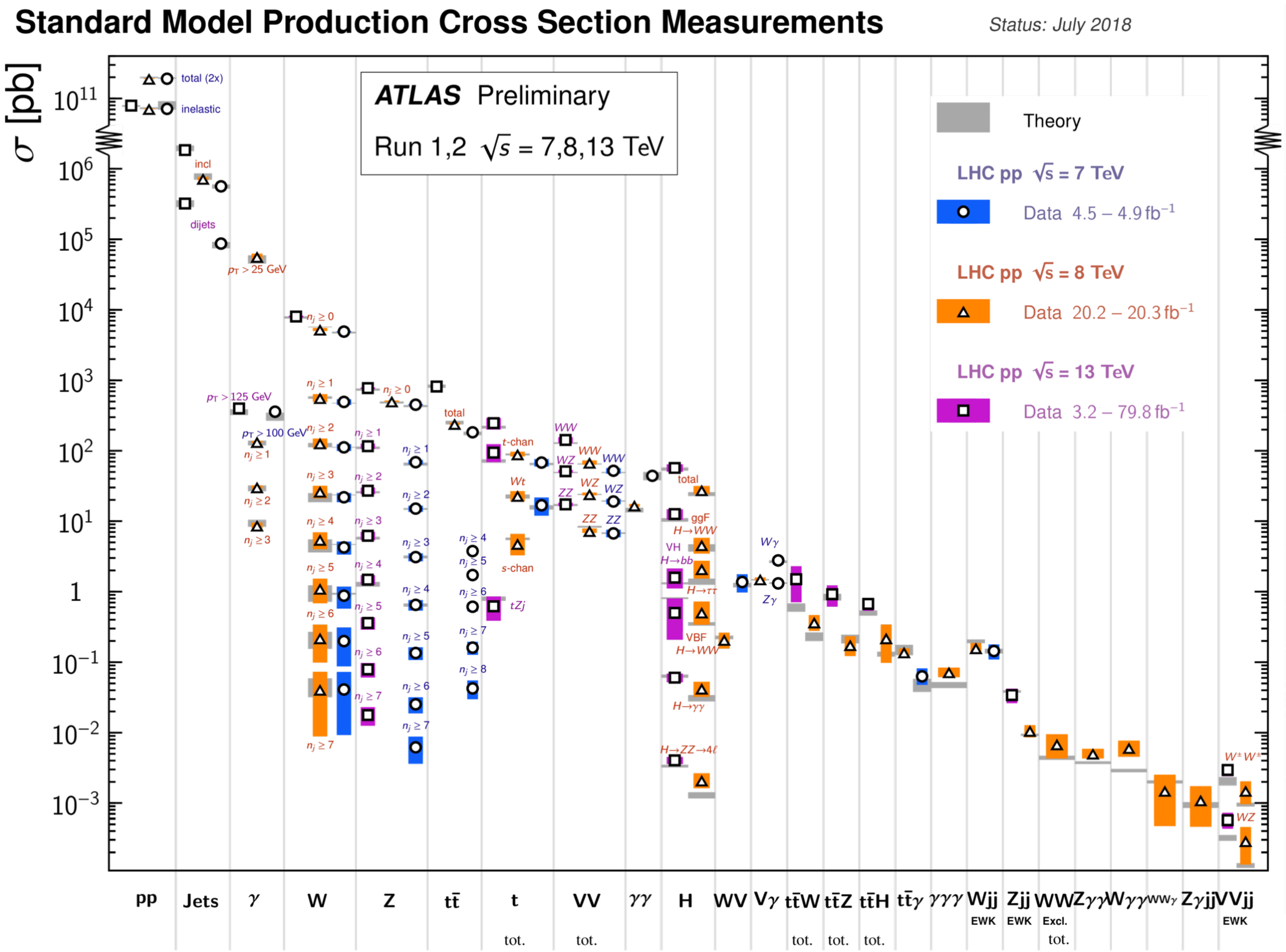
Standard Model at the LHC

- Most of the SM Lagrangian has passed several tests with outstanding precision at the LHC



$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \psi + h.c. \\
& + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

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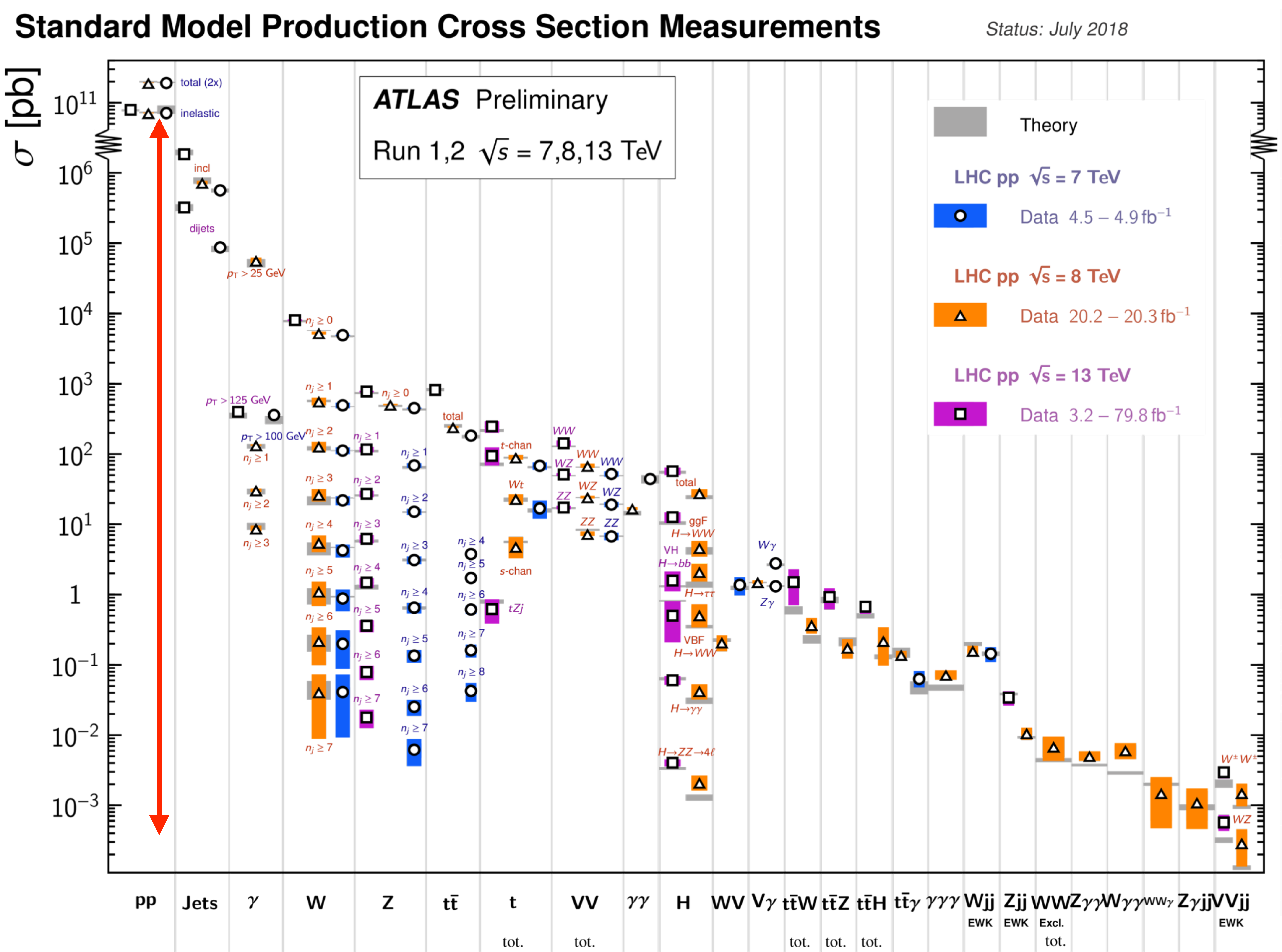

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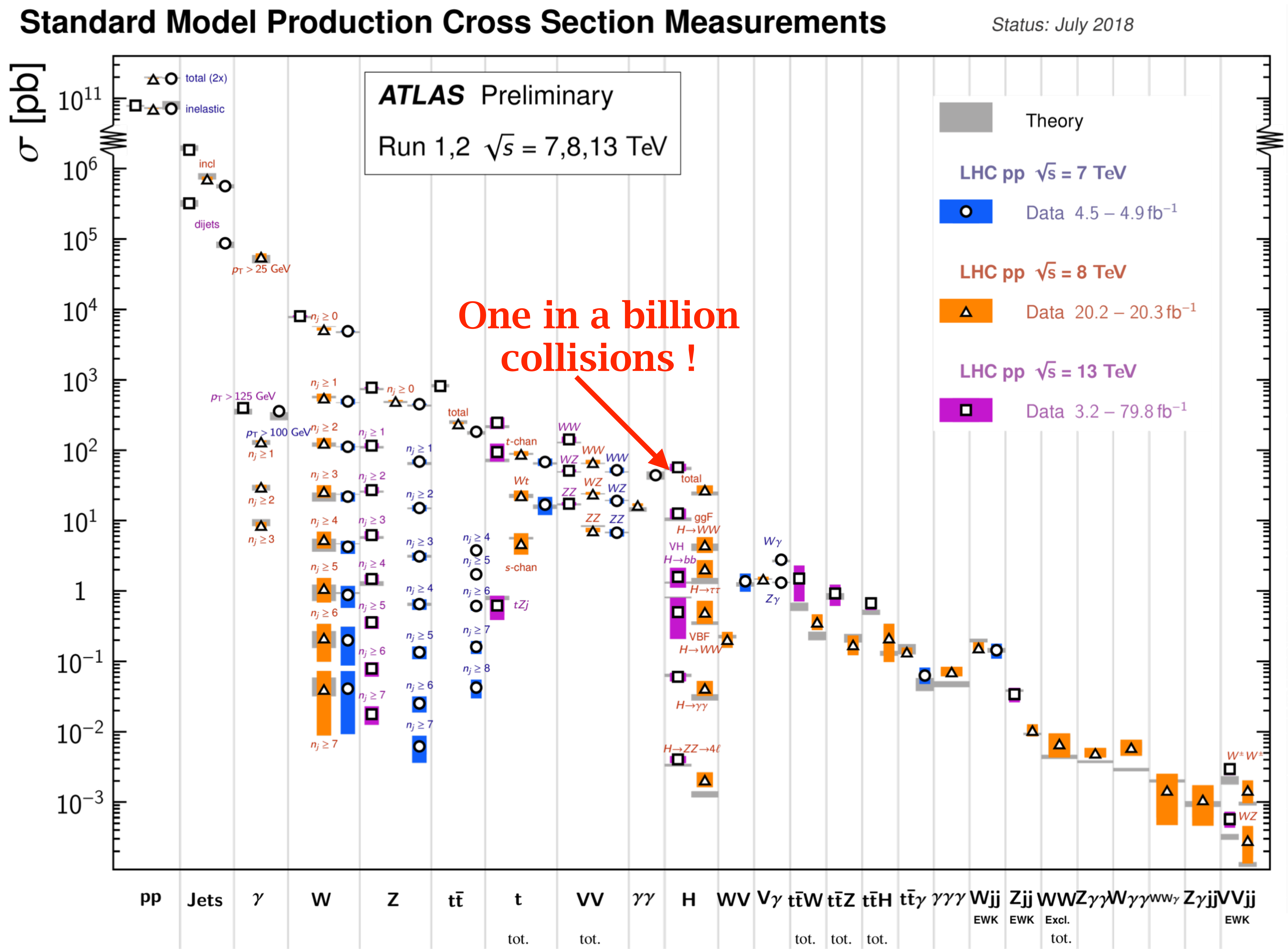
$$+ \bar{\psi}_i y_{ij}\psi_j\phi + h.c.$$
$$+ |D_\mu\phi|^2 - V(\phi)$$

Standard Model at the LHC

- Some aspects are less precisely established experimentally, or not at all. Need to go differential…



One in a billion collisions !

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

$$\boxed{\begin{aligned} &+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi) \end{aligned}}$$

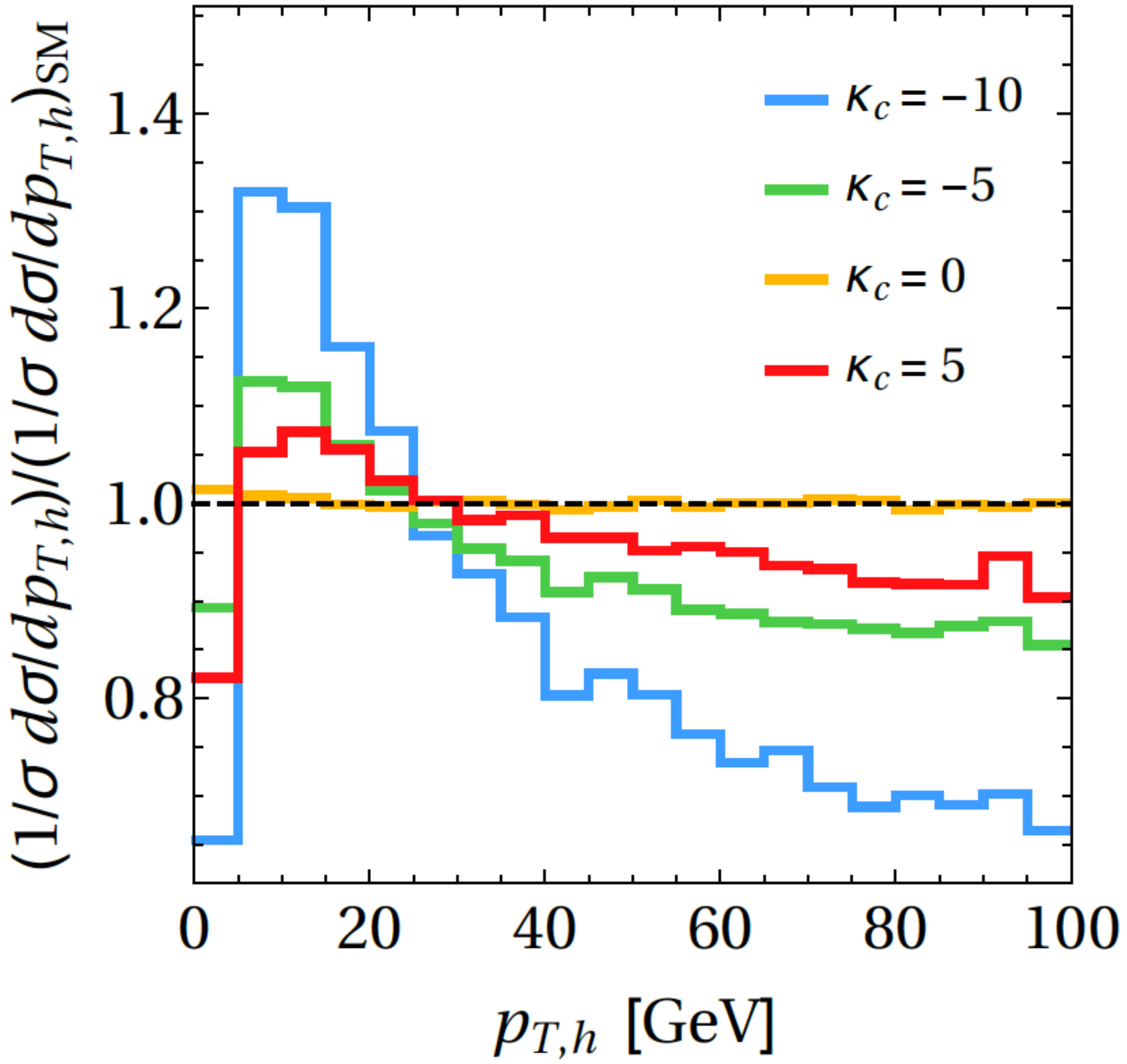
- **New physics can be encoded in small deviations in kinematic distributions**

e.g. Yukawa couplings

- Interplay between production modes leads to sensitivity to light-quark couplings at small p_T^H

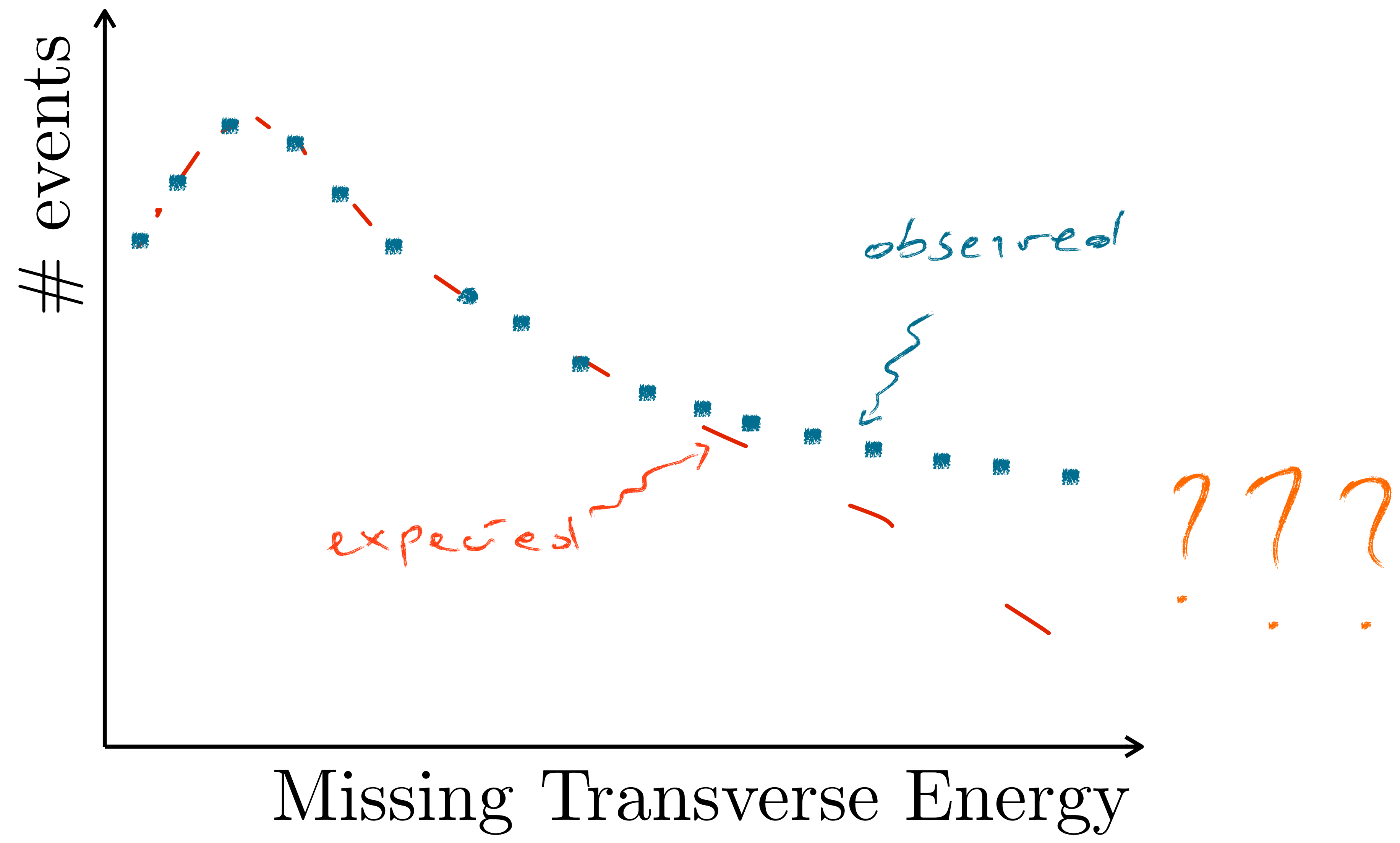
[Bishara, Haisch, PM, Re ’16;
see also Soreq, Zhu, Zupan ’16]

$$y_f^{\mathrm{SM}} = \sqrt{2}\frac{m_f}{v}\kappa_f$$



e.g. NP searches in boosted regimes

- Regimes with large momentum transfer indirectly sensitive to heavy new physics states - look for (mild) effects on kinematics
- Precise comparison between Theory and Data is necessary: mismodelling or actual signal ?

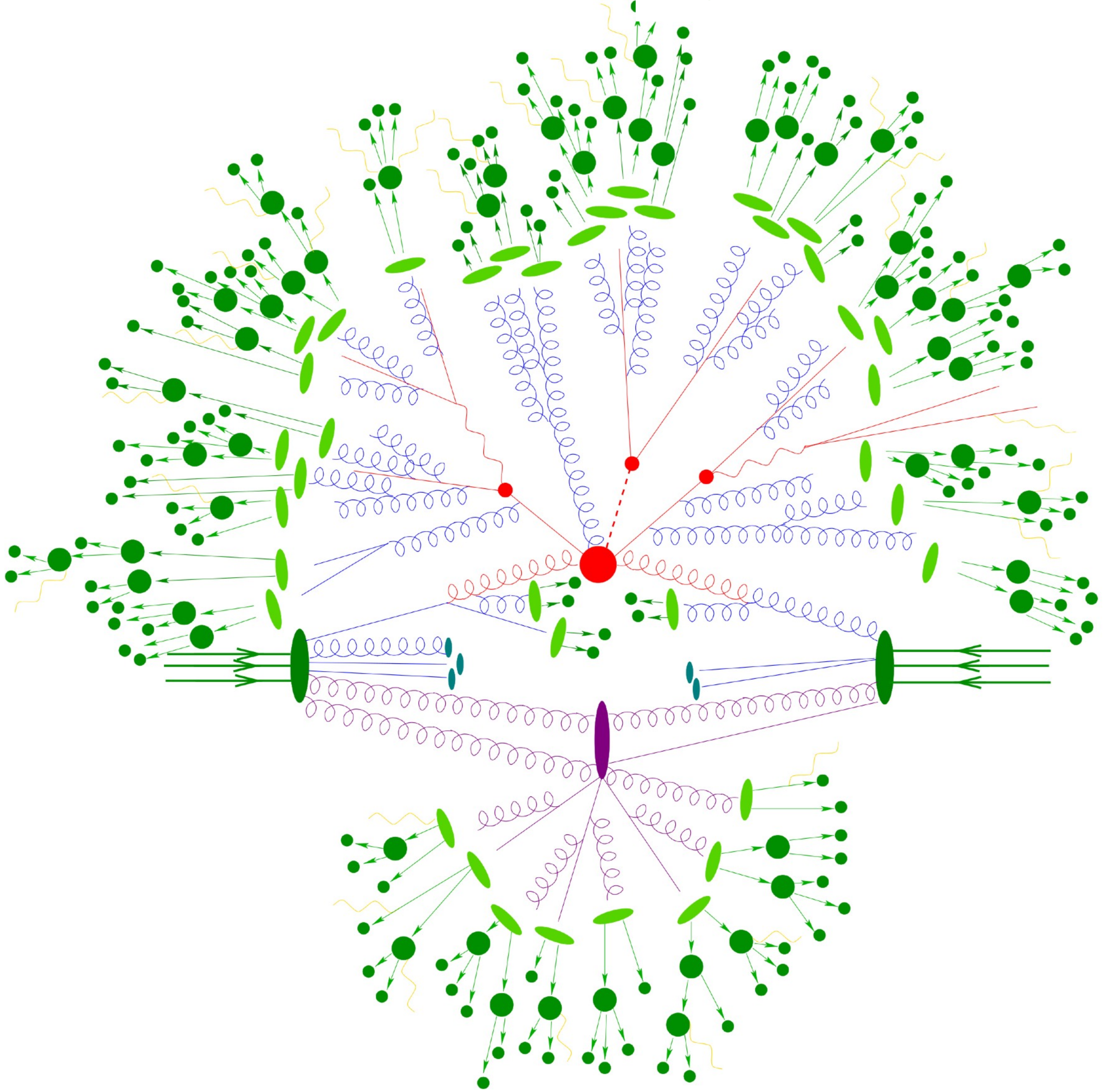


- Demanding a more exclusive description of final states comes with complications

☑ Hard scattering provides a good description of sufficiently hard final states (IRC safety)

$$\sigma \sim \sigma_{\mathrm{BORN}}\left(1 + \alpha_s + \alpha_s^2 + \alpha_s^3 + \ldots\right)$$

Image credit: Stefan Hoeche



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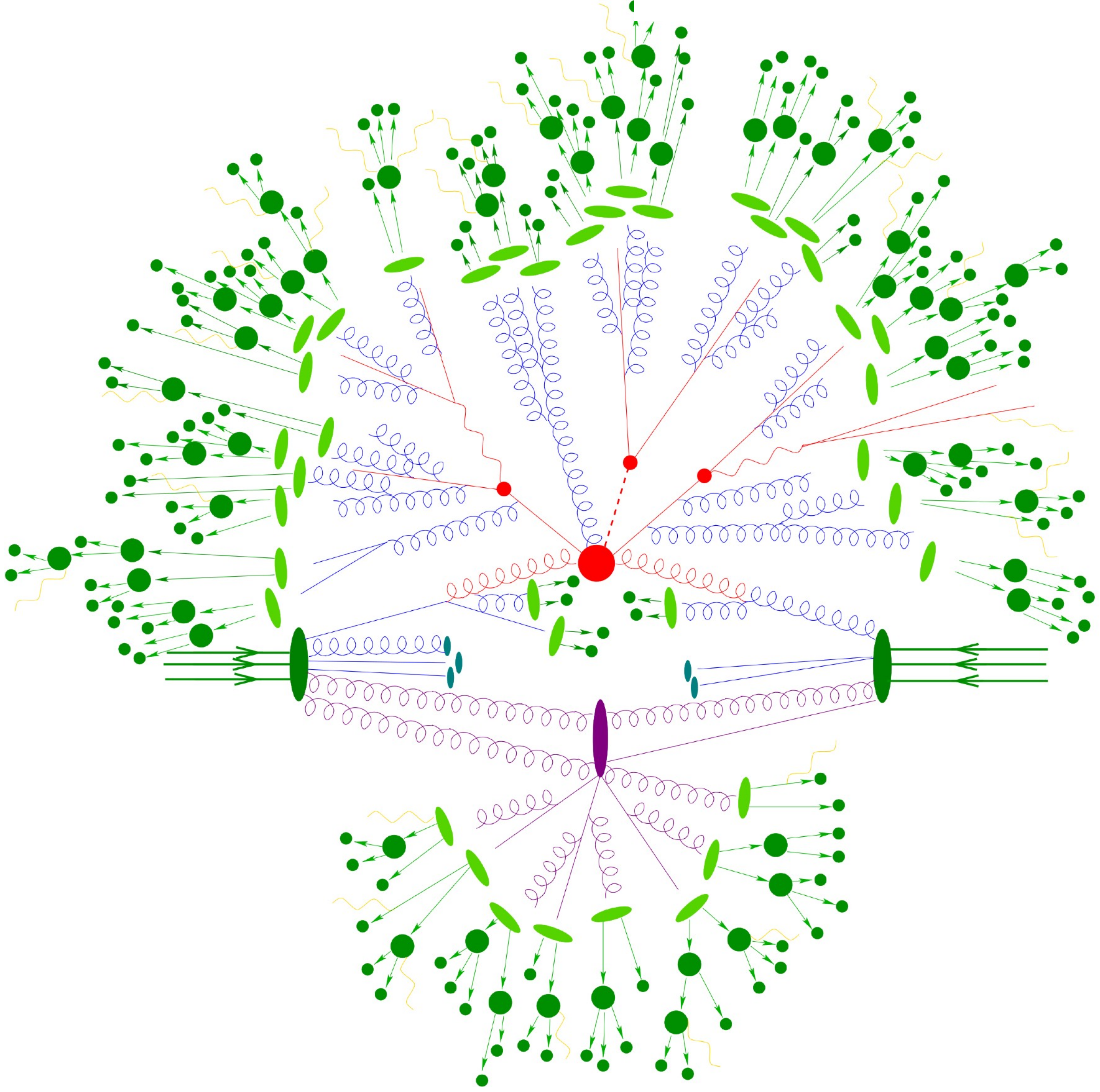
☑ Multiscale dynamics becomes dominant whenever a large gap between scales is present

  - observables sensitive to soft or collinear radiation (differential distributions, jet vetoes, …)
  - reaction depends on disparate scales (production at threshold, masses, …)

$$\sigma \sim \sigma_{\mathrm{BORN}} \left(1 - \alpha_s L^2 + \frac{1}{2}\alpha_s^2 L^4 - \frac{1}{6}\alpha_s^3 L^6 + \dots \right)$$

Image credit: Stefan Hoeche



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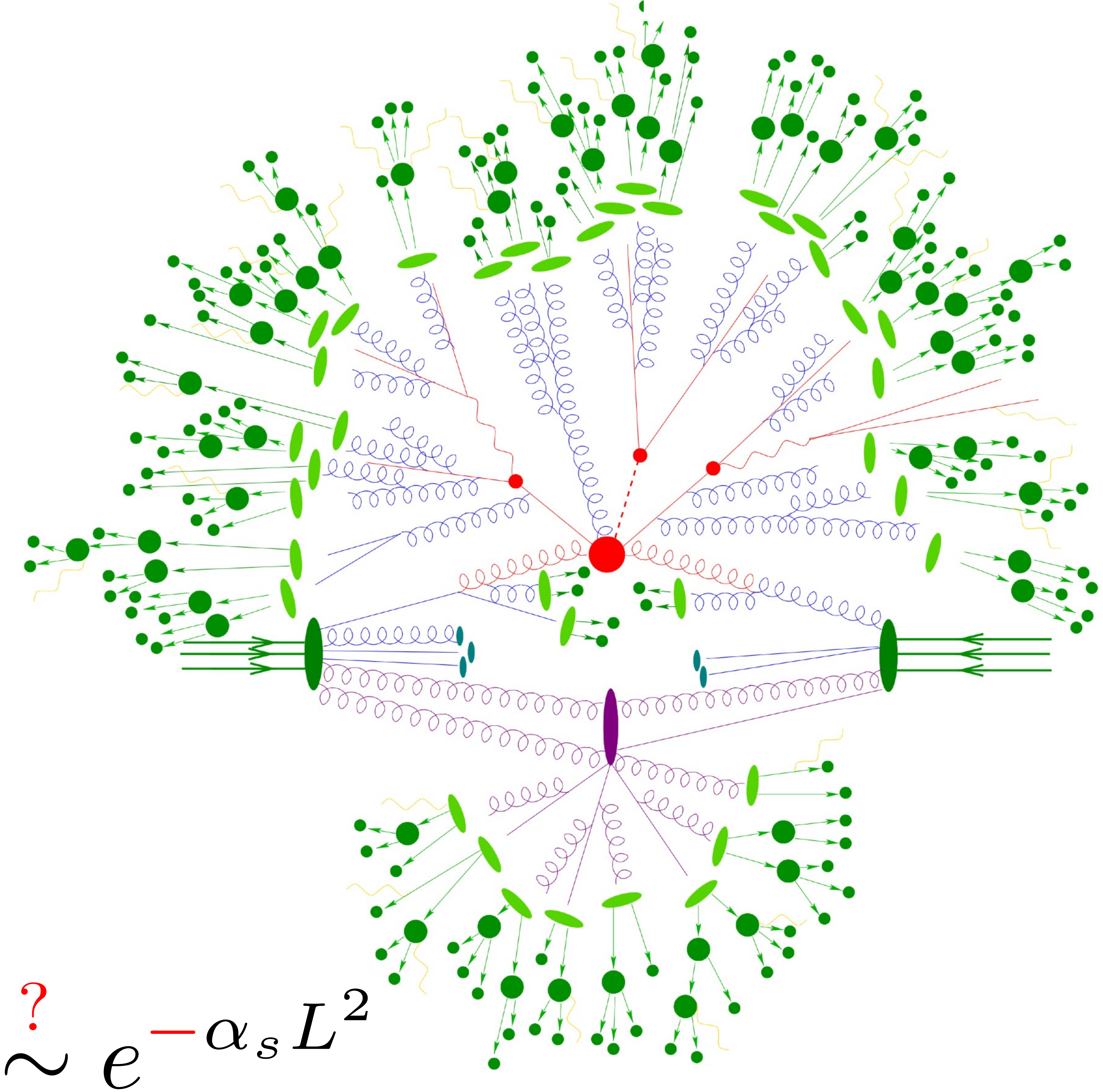
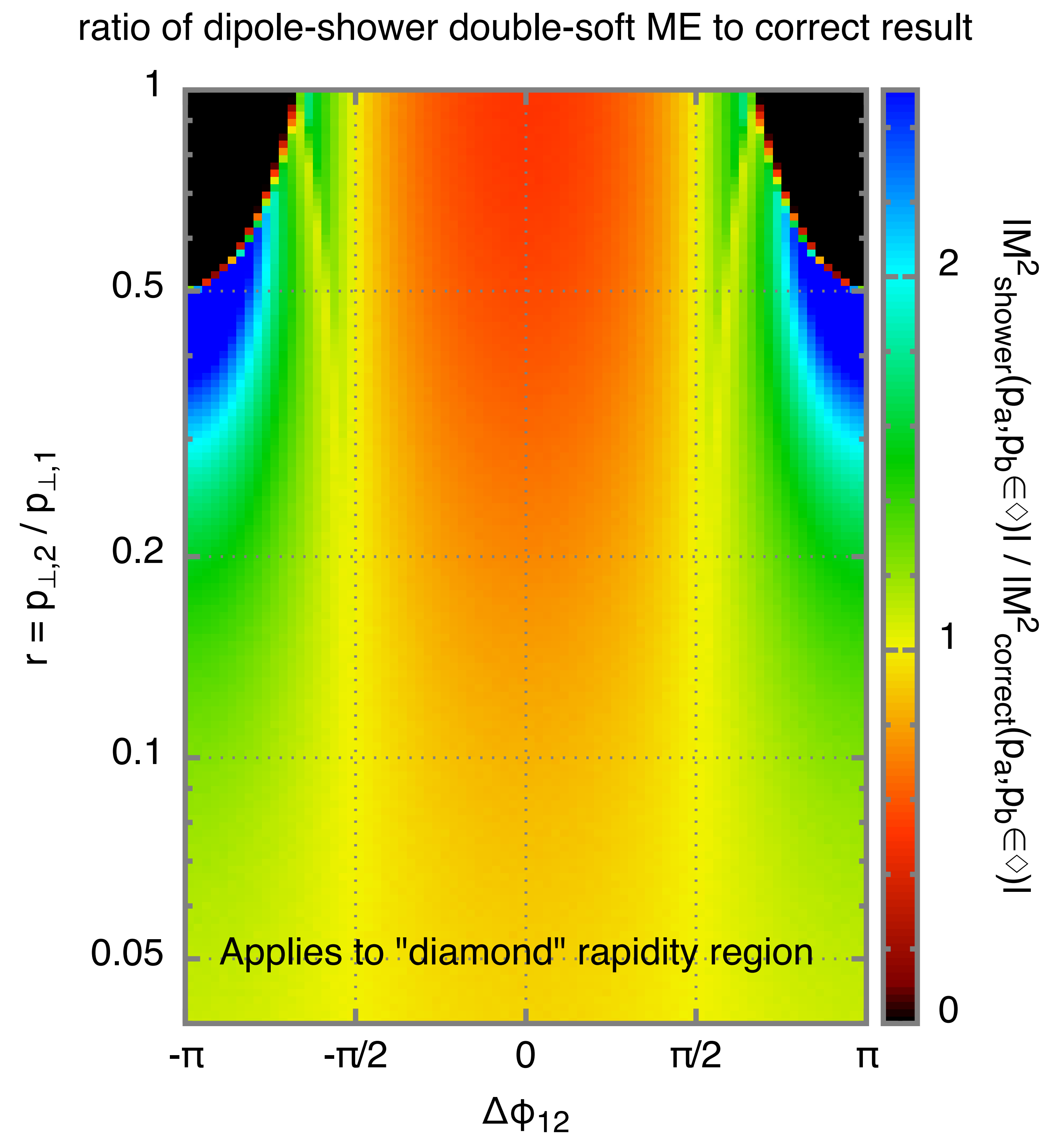


Image credit: Stefan Hoeche

Resummation at the LHC

- understanding of multi-scale dynamics plays an important role in several aspects of LHC physics

☑ Design of more accurate event generators & parton shower algorithms



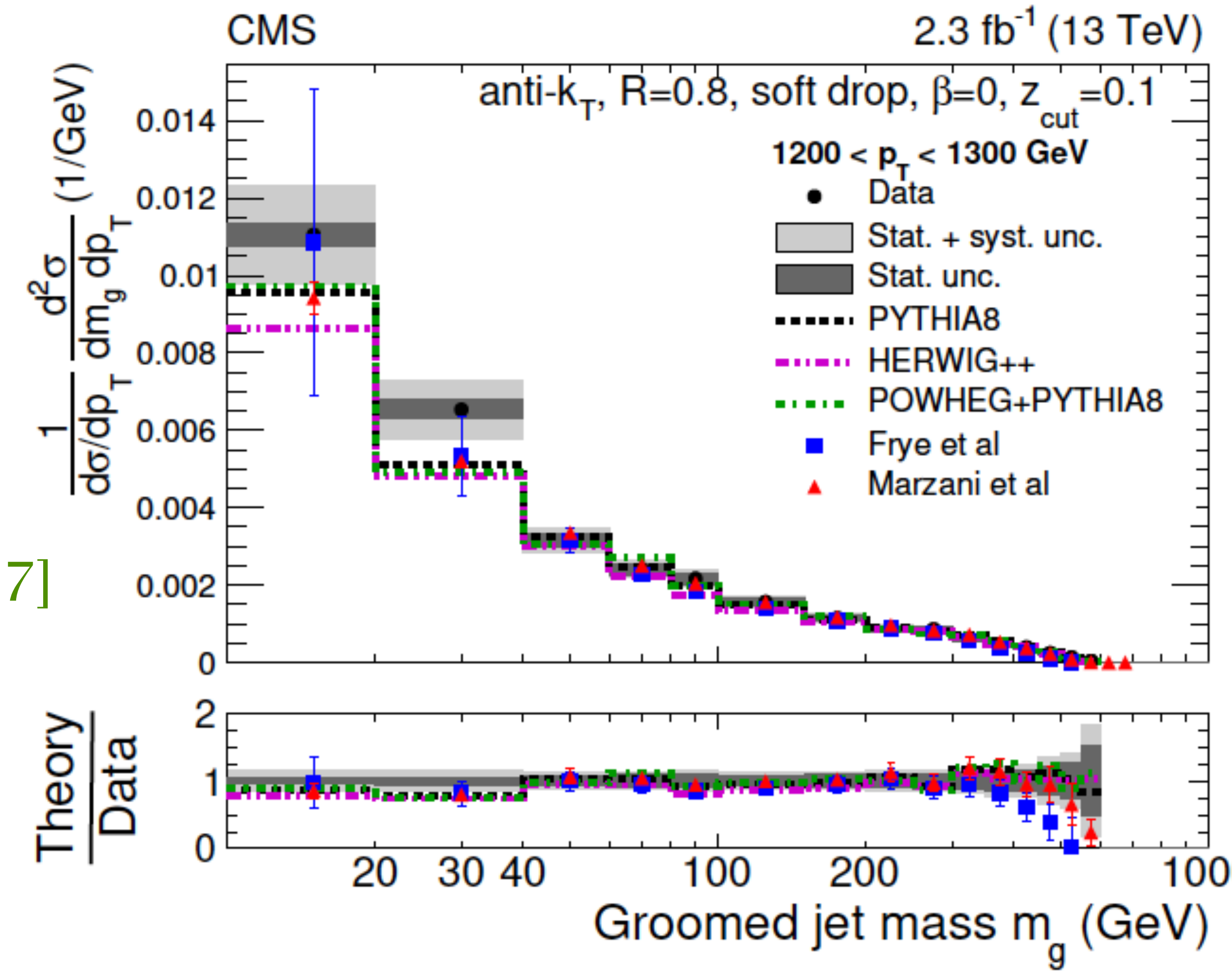
[Dasgupta, Dreyer, Hamilton, PM, Salam '18]

☑ Control over infrared structure of the theory (extraction of parton densities, subtraction methods for higher order computations)

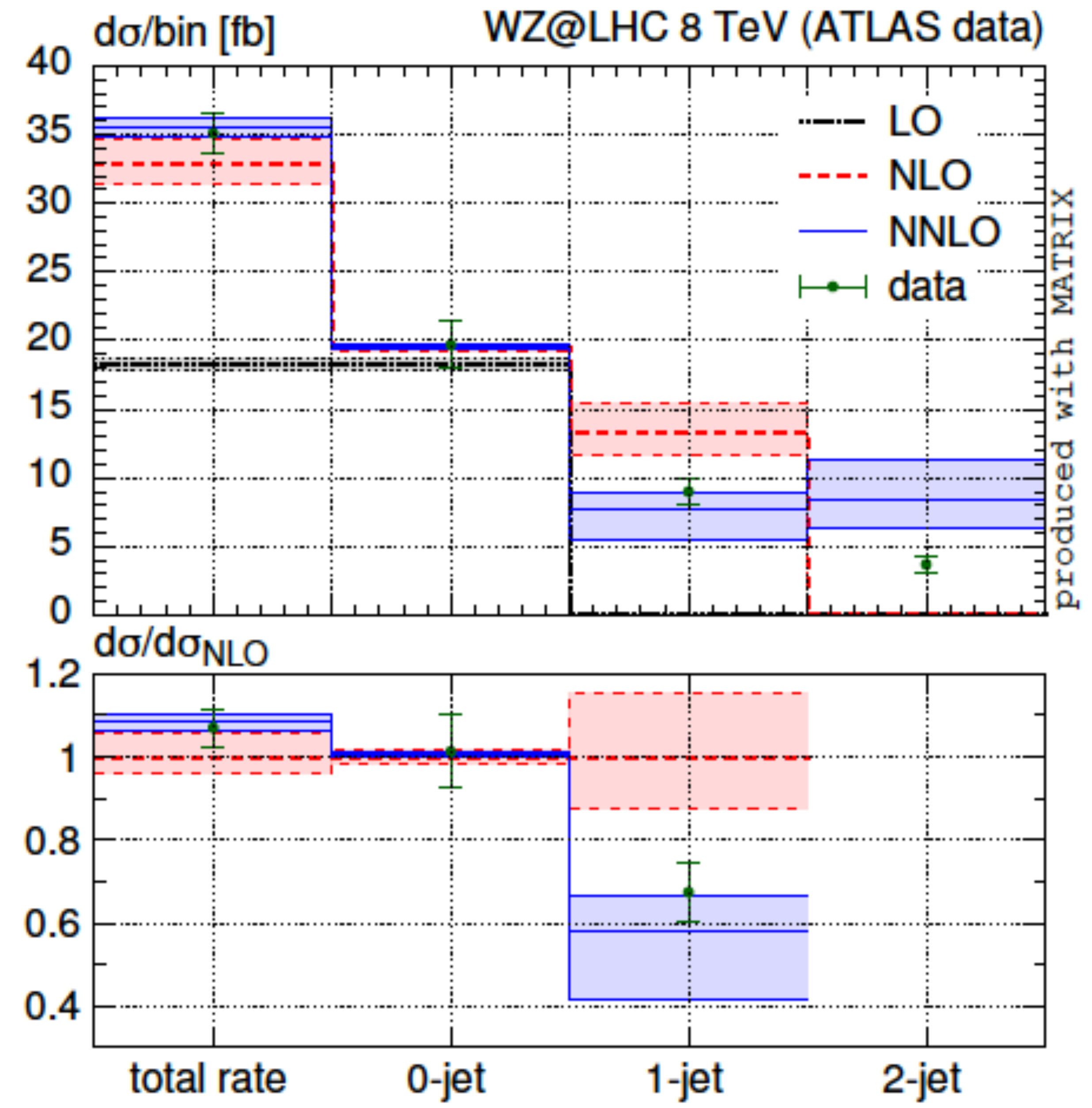
[>> talks by D. Walker & R. Röntsch]

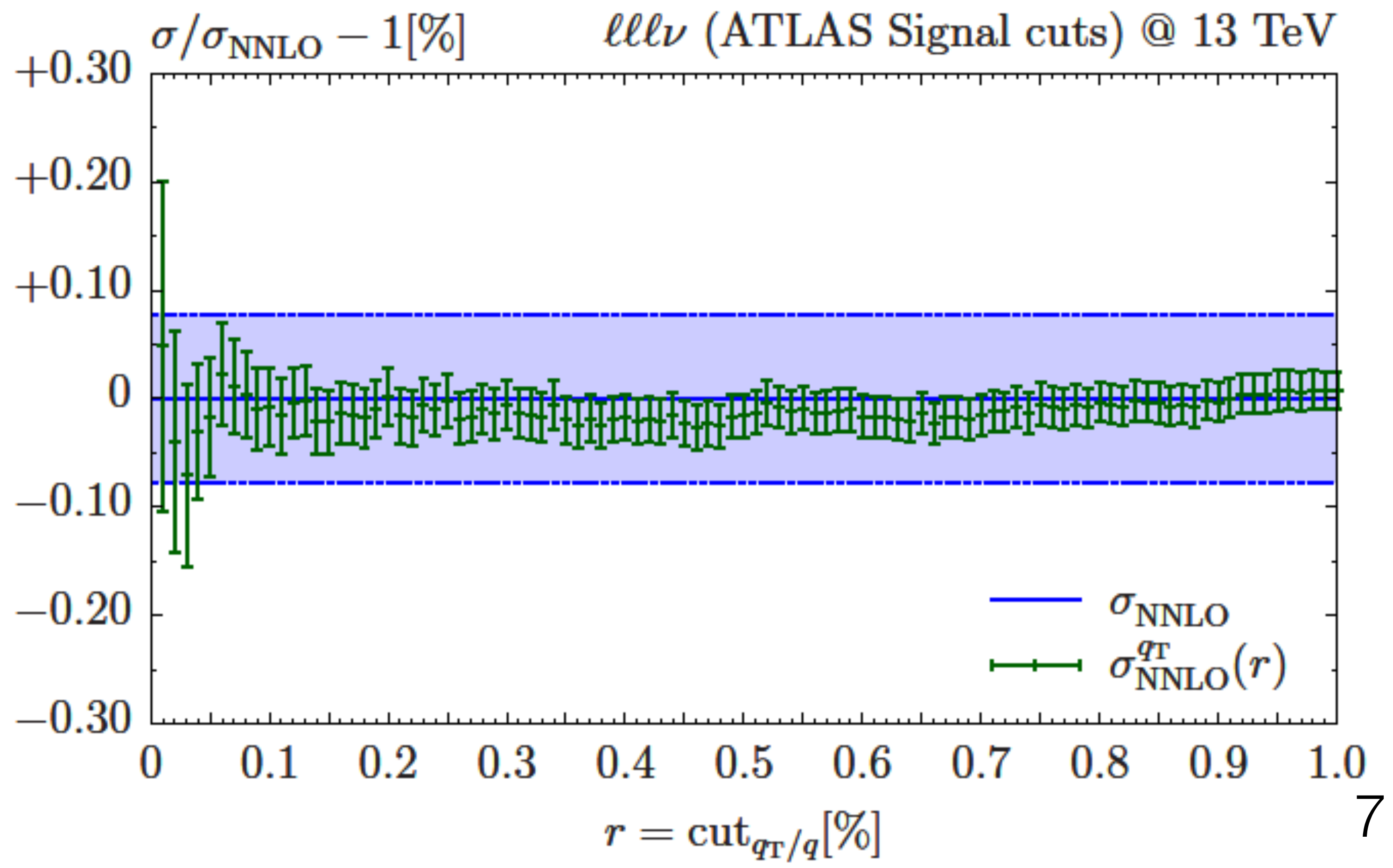
☑ Accurate predictions in infrared sensitive kinematic regimes (differential distributions, jets & their substructure)

CMS [JHEP 11 (2018) 113]



[Grazzini, Kallweit, Rathlev, Wiesemann '17]

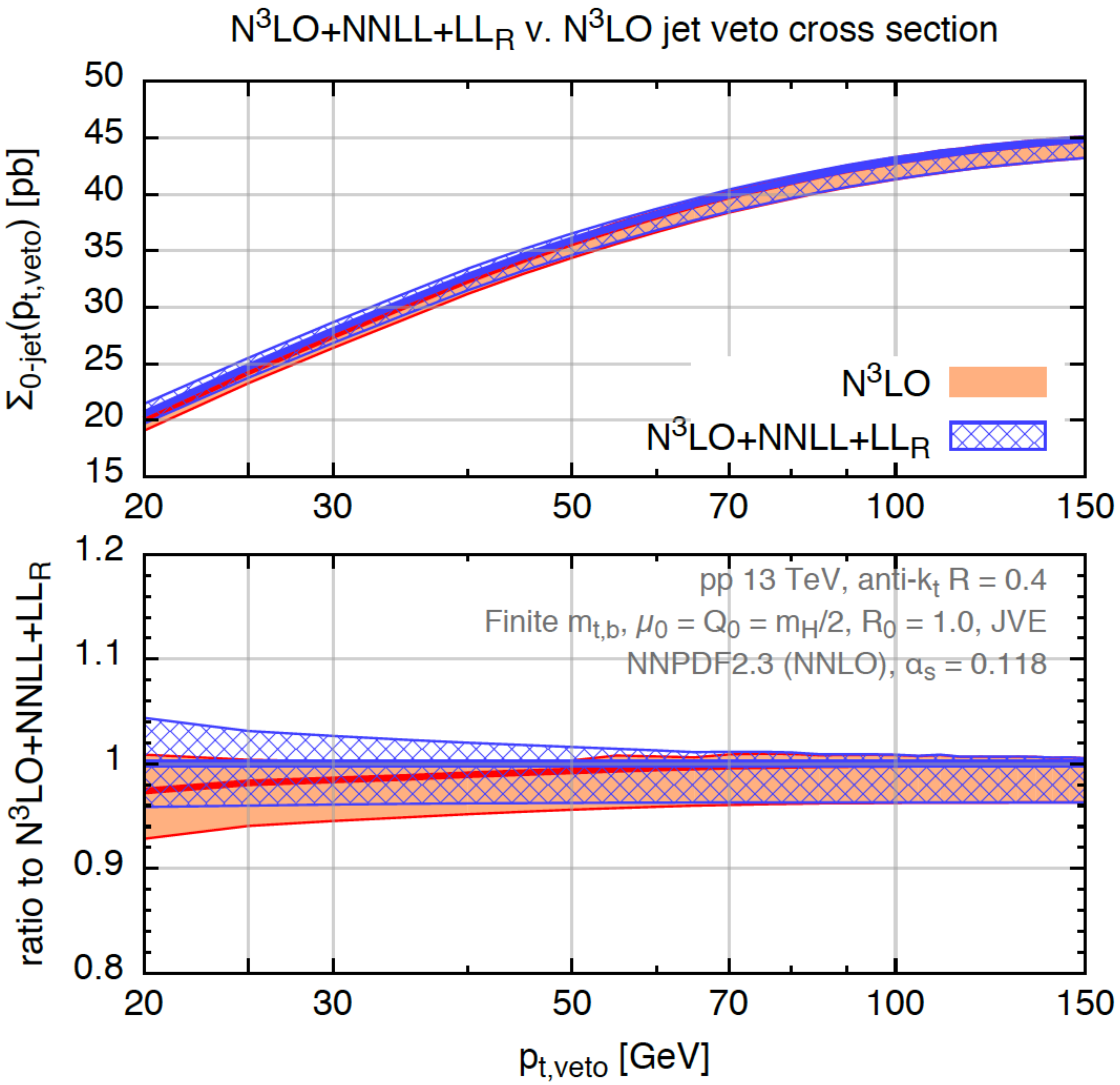




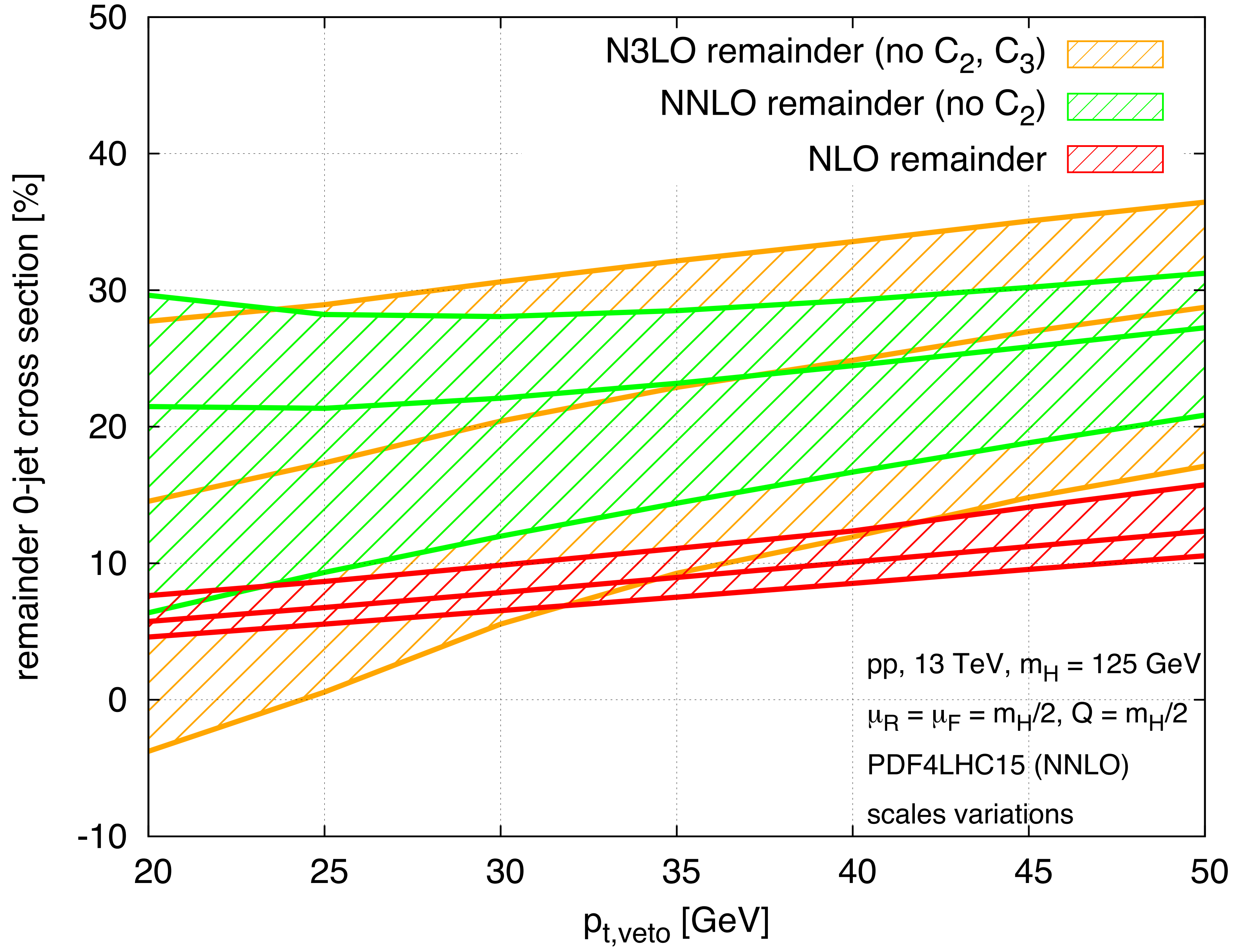
Understanding observables with jets

- Higgs + 0-jet cross section known with very high precision (3-4% uncertainty)

[Banfi, Caola, Dreyer, PM, Salam, Zanderighi, Dulat '15]
see also: [Banfi, PM, Salam, Zanderighi '12]
[Becher, Neubert, Rothen '13]
[Stewart, Tackmann, Walsh, Zuberi '13]



- ~ 70-90% of the perturbative series at 30 GeV is made of logarithms. Resummation provides the bulk of higher order corrections (beyond N^3LO)



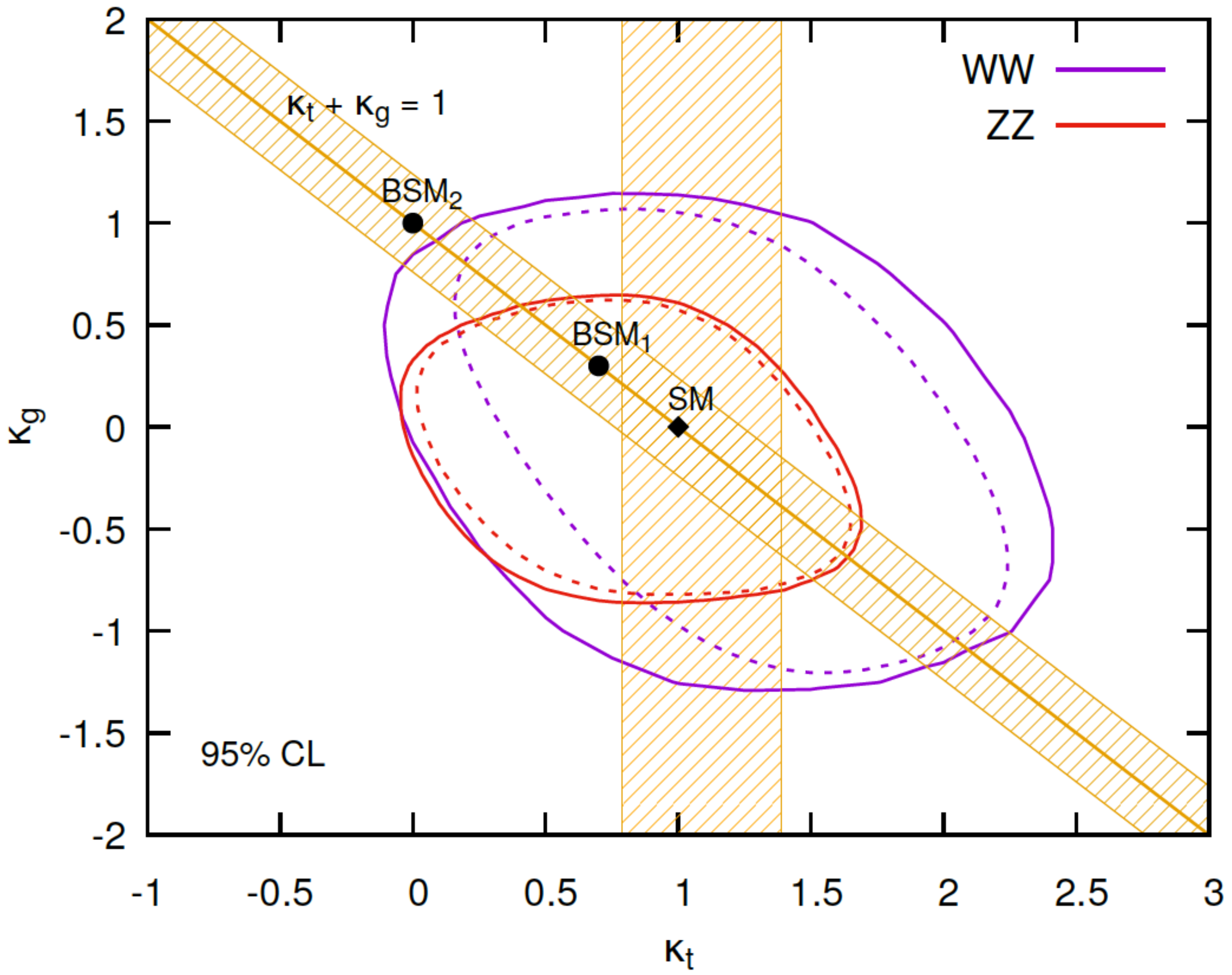
- Possible future improvements from resummation of subleading-power corrections. First steps in this area recently

[Moult, Stewart, Vita '18]
[van Beekveld, Beenakker, Basu, Laenen, Misra, Motylinski '19]
[Bahjat-Abbas, Bonocore, Damste, Laenen, Magnea, Vernazza, White '19]

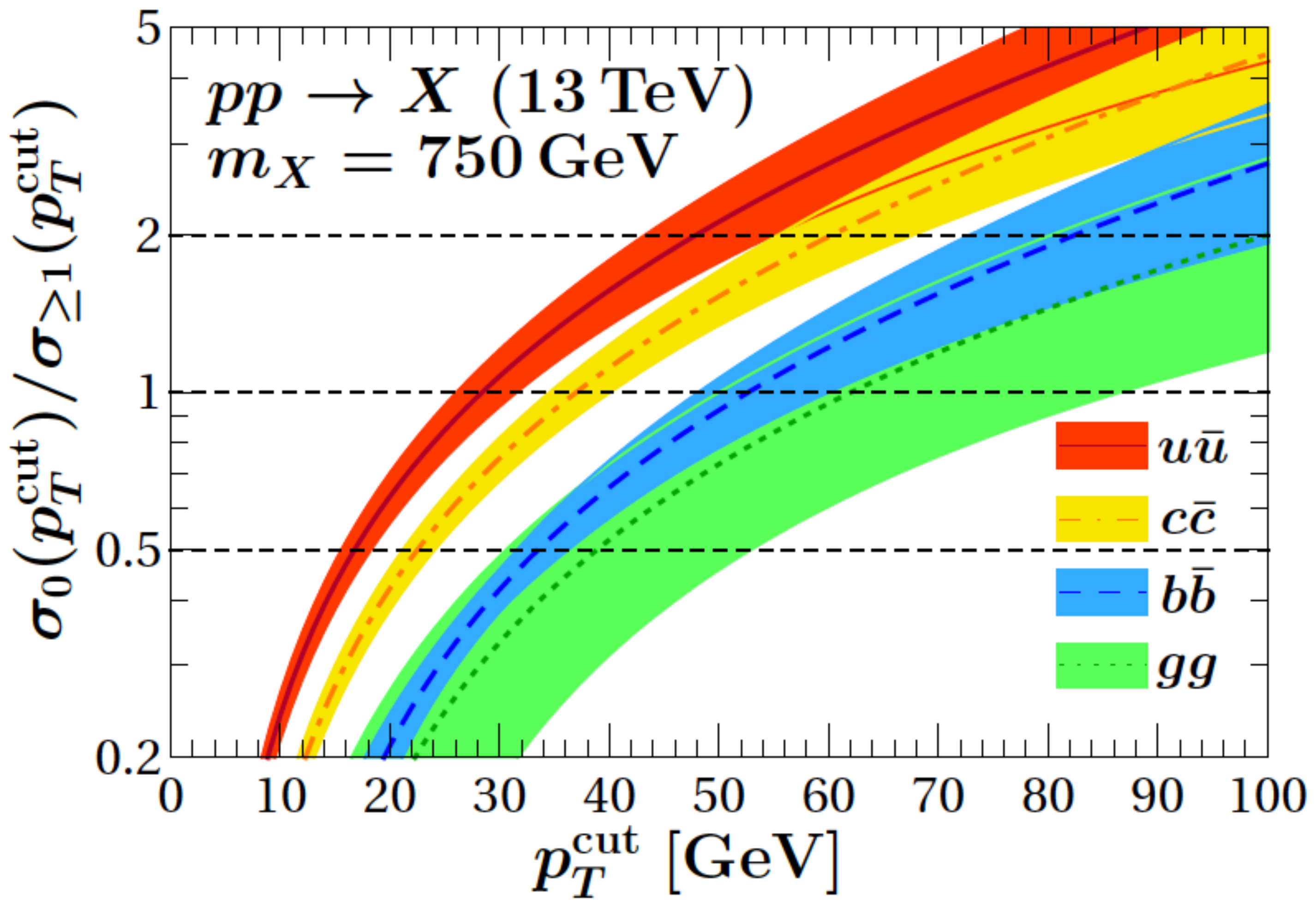
Jet vetoes: recent developments

- ☑ Exclusion of BSM models

[Arpino, Banfi, Jaeger, Kauer '19]

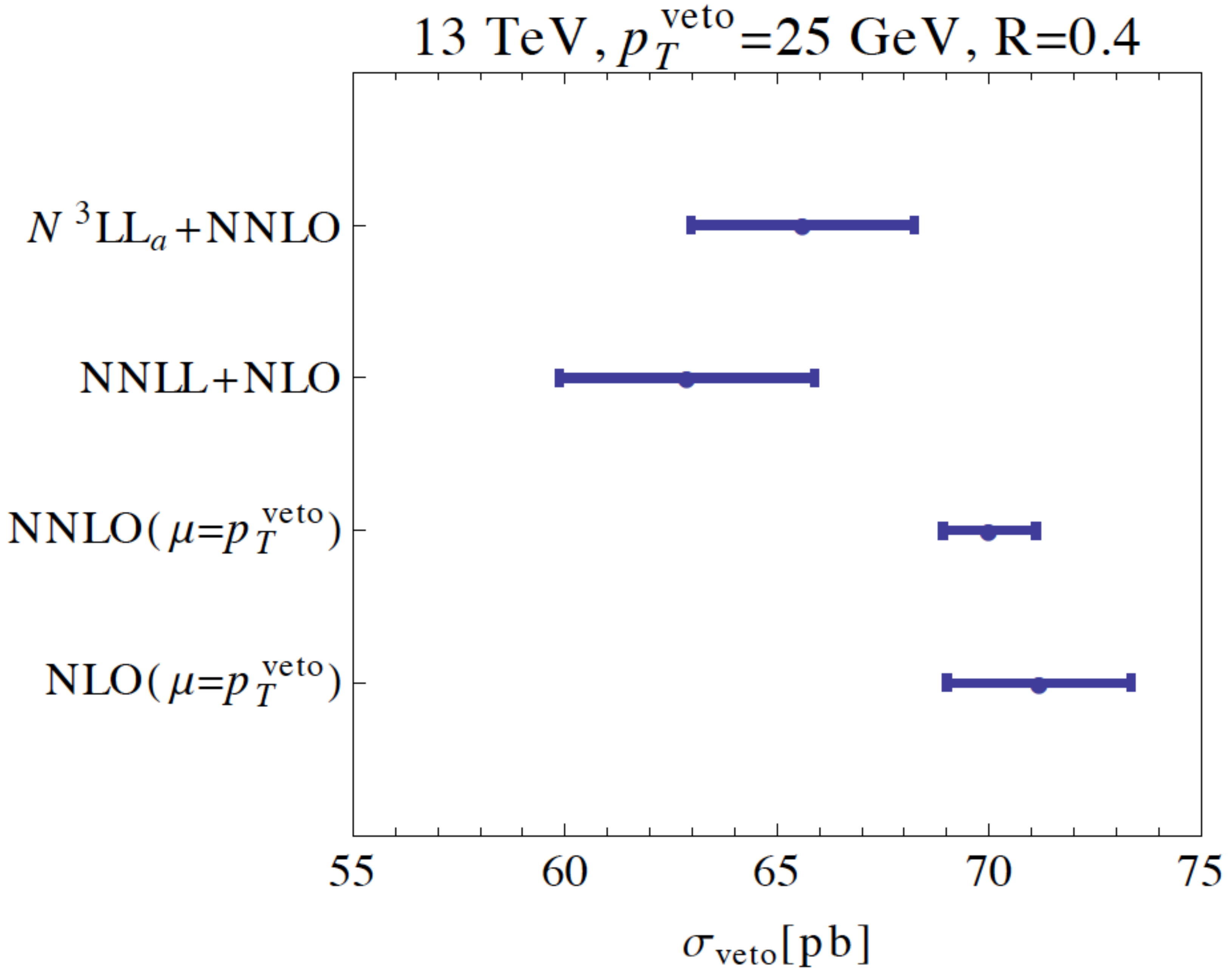


[Ebert, Liebler et al. '16]



- ☑ Extension to complex final states, e.g. WW

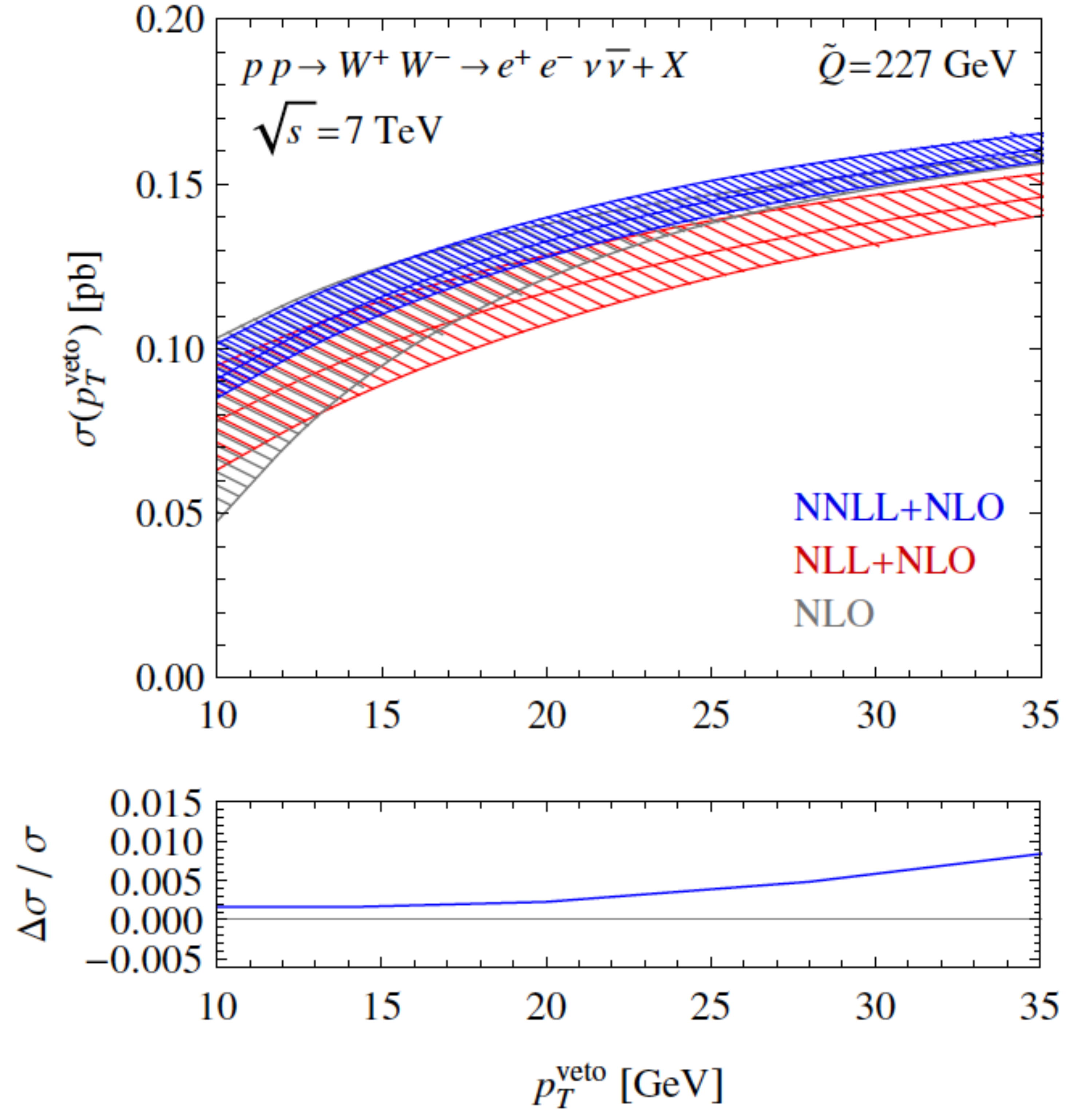
[Dawson, Jaiswal, Li, Ramani, Zeng '16]

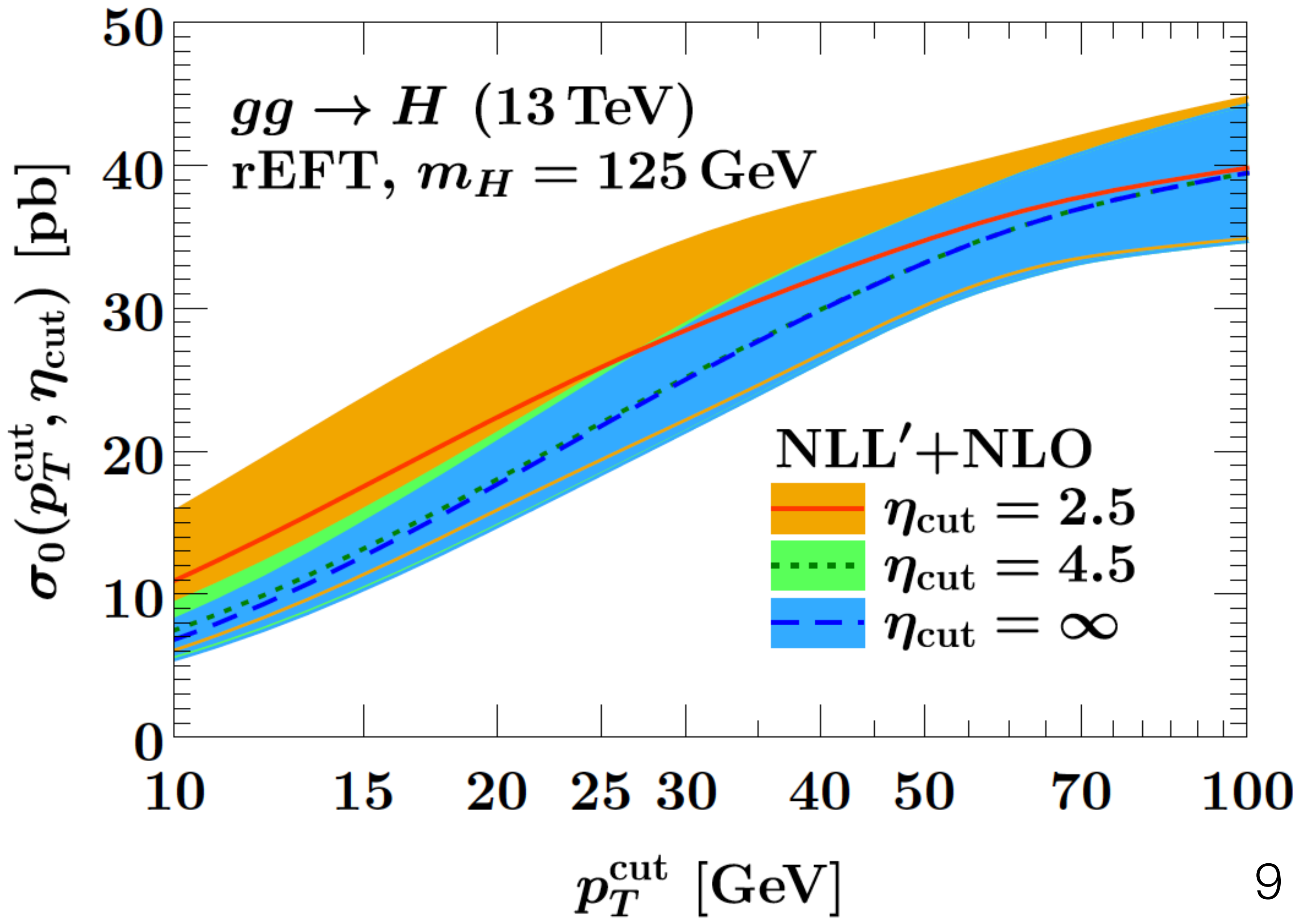


- ☑ Impact of cuts on leading jet's rapidity

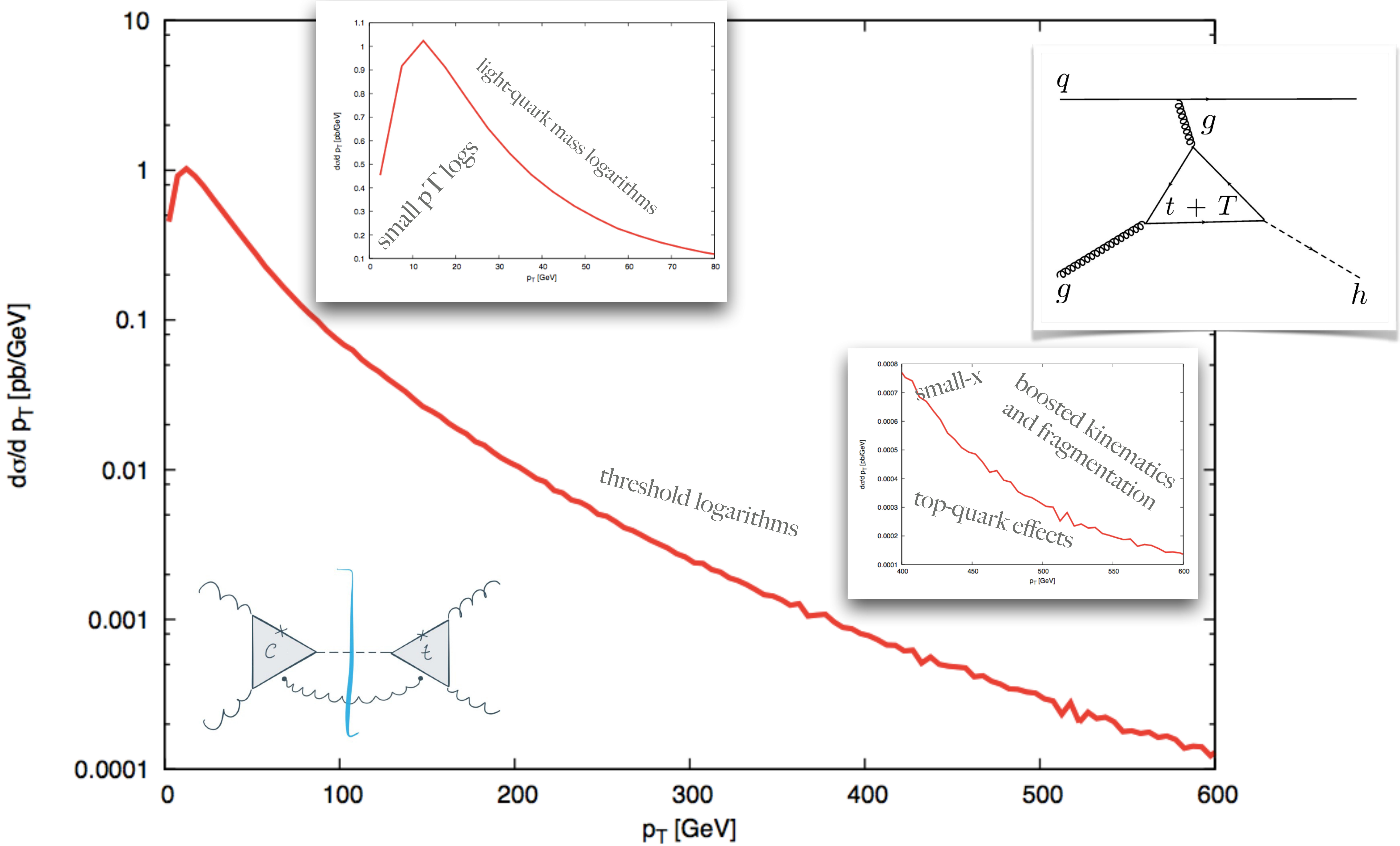
[Michel, Pietrulewicz, Tackmann '18]

[Becher, Frederix, Neubert, Rothen '15]





Higgs p_T distribution



small pT logs

light-quark mass logarithms

threshold logarithms

small-x

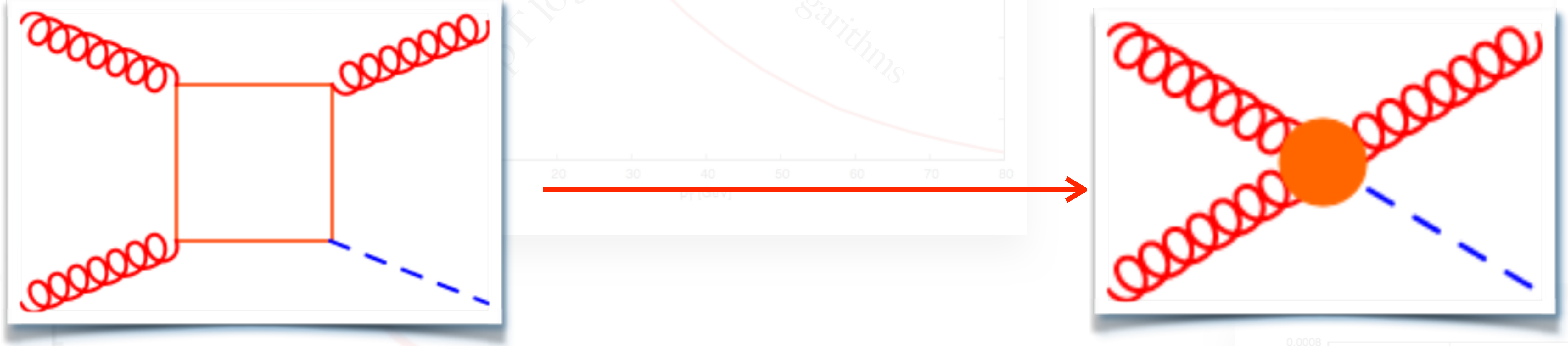
boosted kinematics and fragmentation

top-quark effects

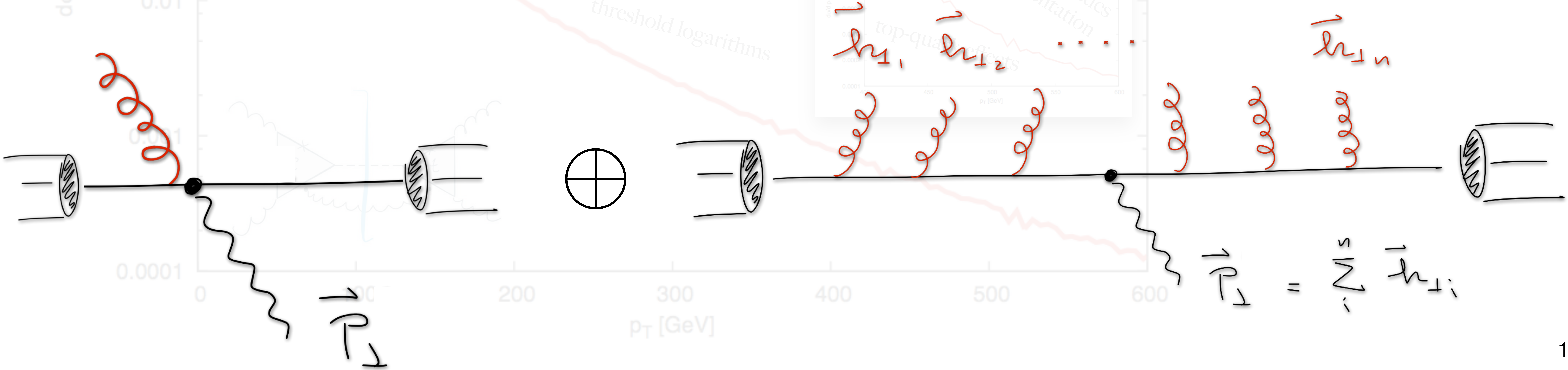
Higgs p_T distribution

- High precision predictions (NNLO QCD) known for H+jet final states in the heavy-top EFT ($p_T << m_{top}$)

[Boughezal, Caola, Melnikov, Petriello, Schulze '15]
[Caola, Melnikov, Schulze '15]
[Boughezal, Focke, Giele, Liu, Petriello '15]
[Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '16]

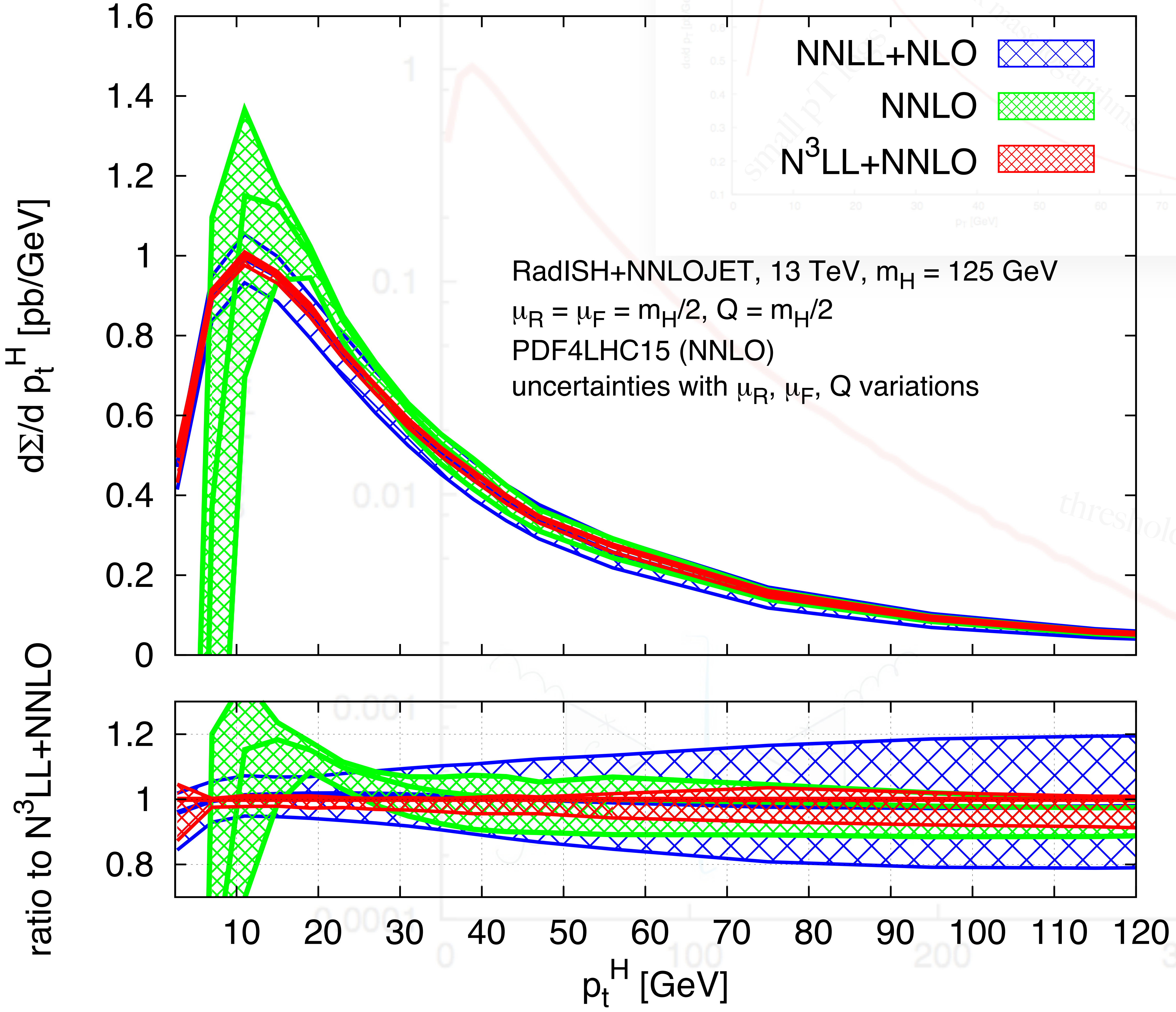


- Matching to resummation allows one to extend the prediction to $p_T \sim 0$, now available up to N^{3}LL

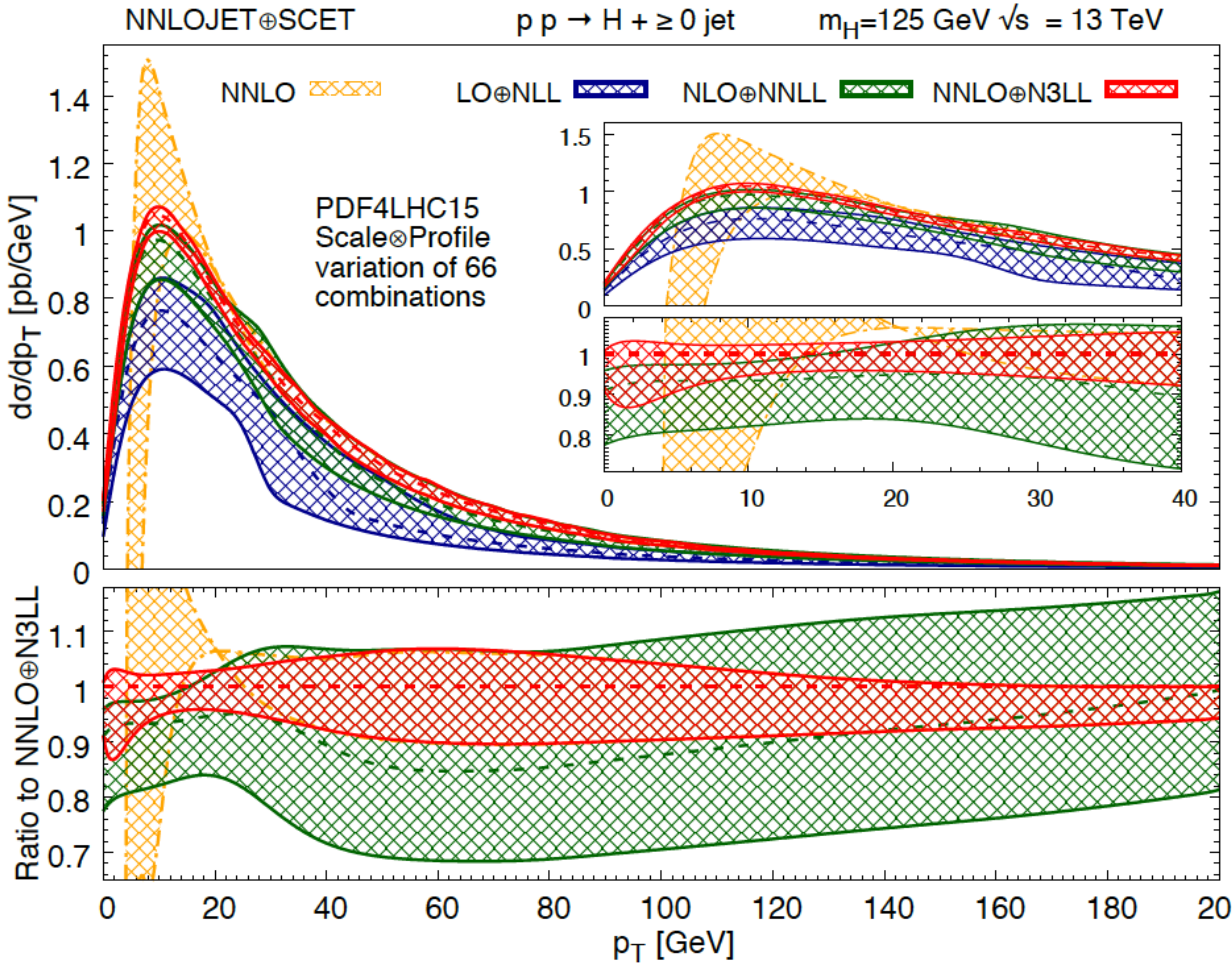


Higgs p_T distribution

- Two independent calculations with different methods: ~5% residual uncertainty in the spectrum
- Good agreement between different matching schemes to fixed order -> robust control over theory



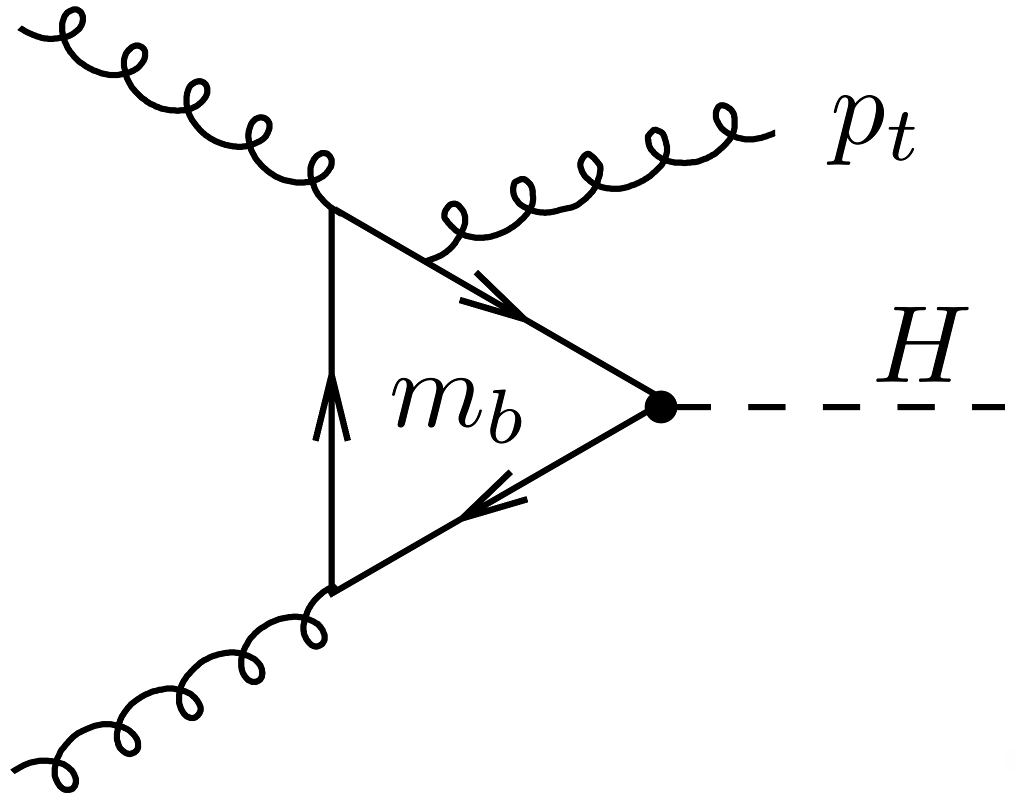
[Bizon, Chen, Gehrmann, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli ’18]



[Chen, Gehrmann, Glover, Huss, Li, Neill, Schulze, Stewart, Zhu ’18]

Higgs p_T distribution: quark masses

- Small p_T distribution sensitive to ***interference*** with light-quark-mediated production

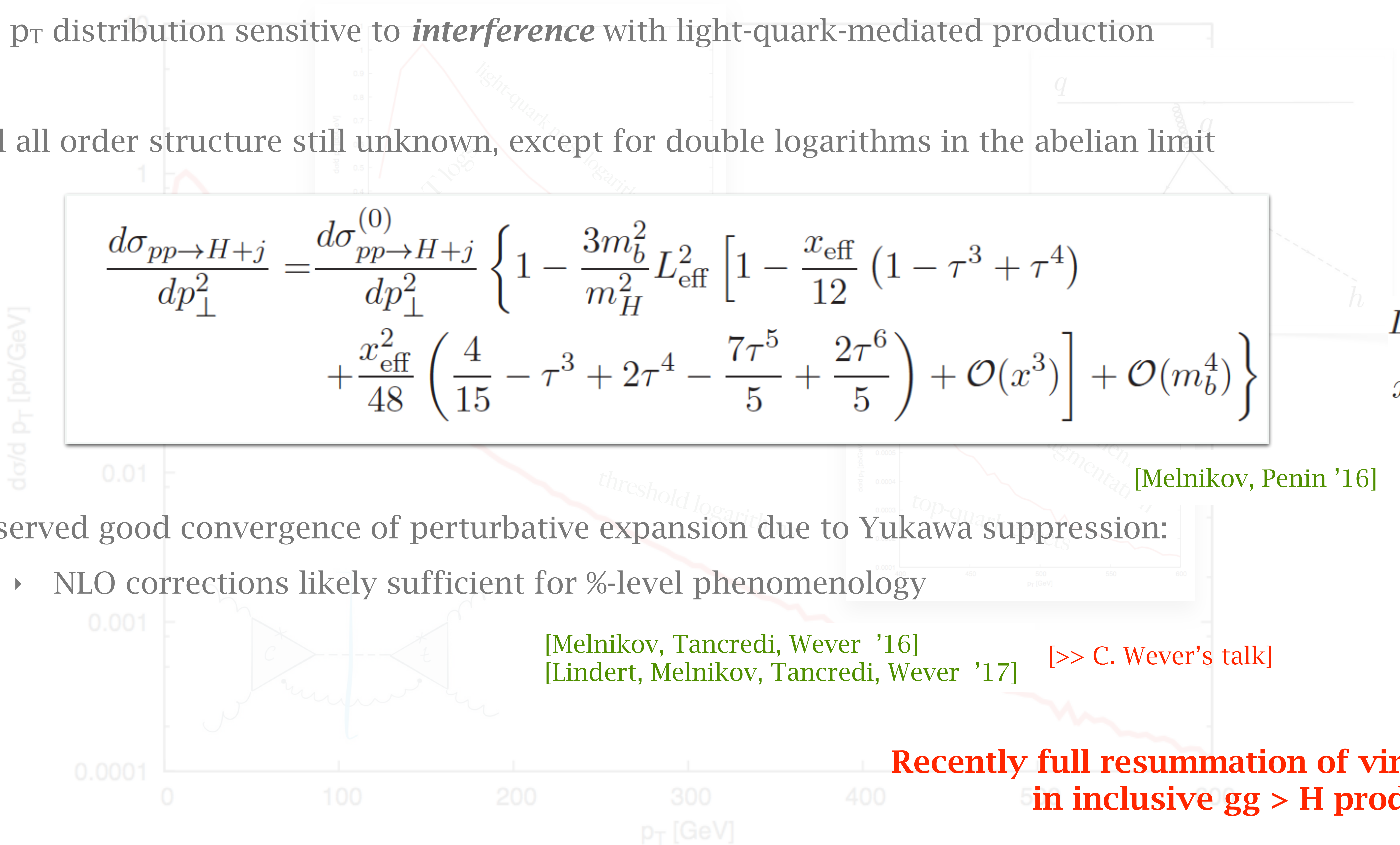


- In the regime $m_H \gg p_T \gg m_q$ amplitudes develop non-Sudakov double logarithm

$$\sim y_q \frac{m_q}{m_H} \ln^2 \frac{m_H^2}{m_q^2}, \quad y_q \frac{m_q}{m_H} \ln^2 \frac{p_t^2}{m_q^2}$$

- Very involved loop amplitudes & *standard* p_T resummation structure breaks down
  - similar structure appears for $p_T^H >> m_t$

Higgs p_T distribution: quark masses



- Small p_T distribution sensitive to ***interference*** with light-quark-mediated production
  - Full all order structure still unknown, except for double logarithms in the abelian limit

$$\frac{d\sigma_{pp\to H+j}}{dp_\perp^2} = \frac{d\sigma^{(0)}_{pp\to H+j}}{dp_\perp^2}\left\{1 - \frac{3m_b^2}{m_H^2}L_{\rm eff}^2\left[1 - \frac{x_{\rm eff}}{12}\left(1-\tau^3+\tau^4\right) + \frac{x_{\rm eff}^2}{48}\left(\frac{4}{15}-\tau^3+2\tau^4-\frac{7\tau^5}{5}+\frac{2\tau^6}{5}\right)+\mathcal{O}(x^3)\right]+\mathcal{O}(m_b^4)\right\}$$

$$\tau = \frac{\ln(m_b^2/p_\perp^2)}{\ln(m_b^2/m_H^2)}$$

$$L_{\rm eff} = \ln(m_H^2/m_b^2)$$

$$x_{\rm eff} = \frac{\alpha_s C_F}{2\pi}L_{\rm eff}^2$$

[Melnikov, Penin ’16]

  - Observed good convergence of perturbative expansion due to Yukawa suppression:
    - NLO corrections likely sufficient for %-level phenomenology

[Melnikov, Tancredi, Wever ’16]
[Lindert, Melnikov, Tancredi, Wever ’17]

[>> C. Wever’s talk]

Recently full resummation of virtual corrections in inclusive gg > H production

[Liu, Penin ’18]

[Caola, Lindert, Melnikov, PM, Tancredi, Wever '18]

Higgs p_T distribution: quark masses

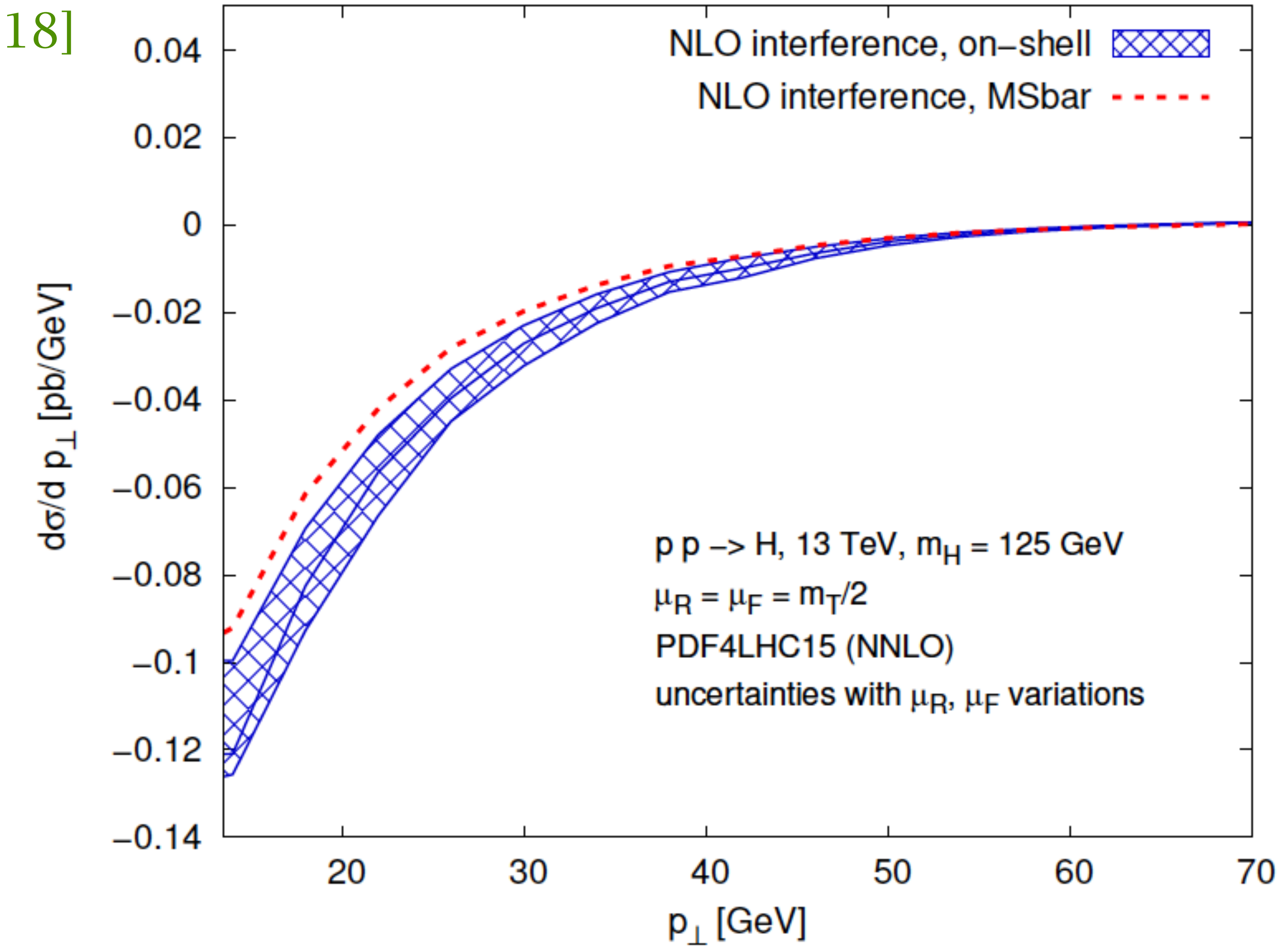
- NLO corrections to the interference allow for a detailed study of the matching to NNLL resummation:
  - choice of a (multiplicative) scheme that **preserves *form factor structure*** for

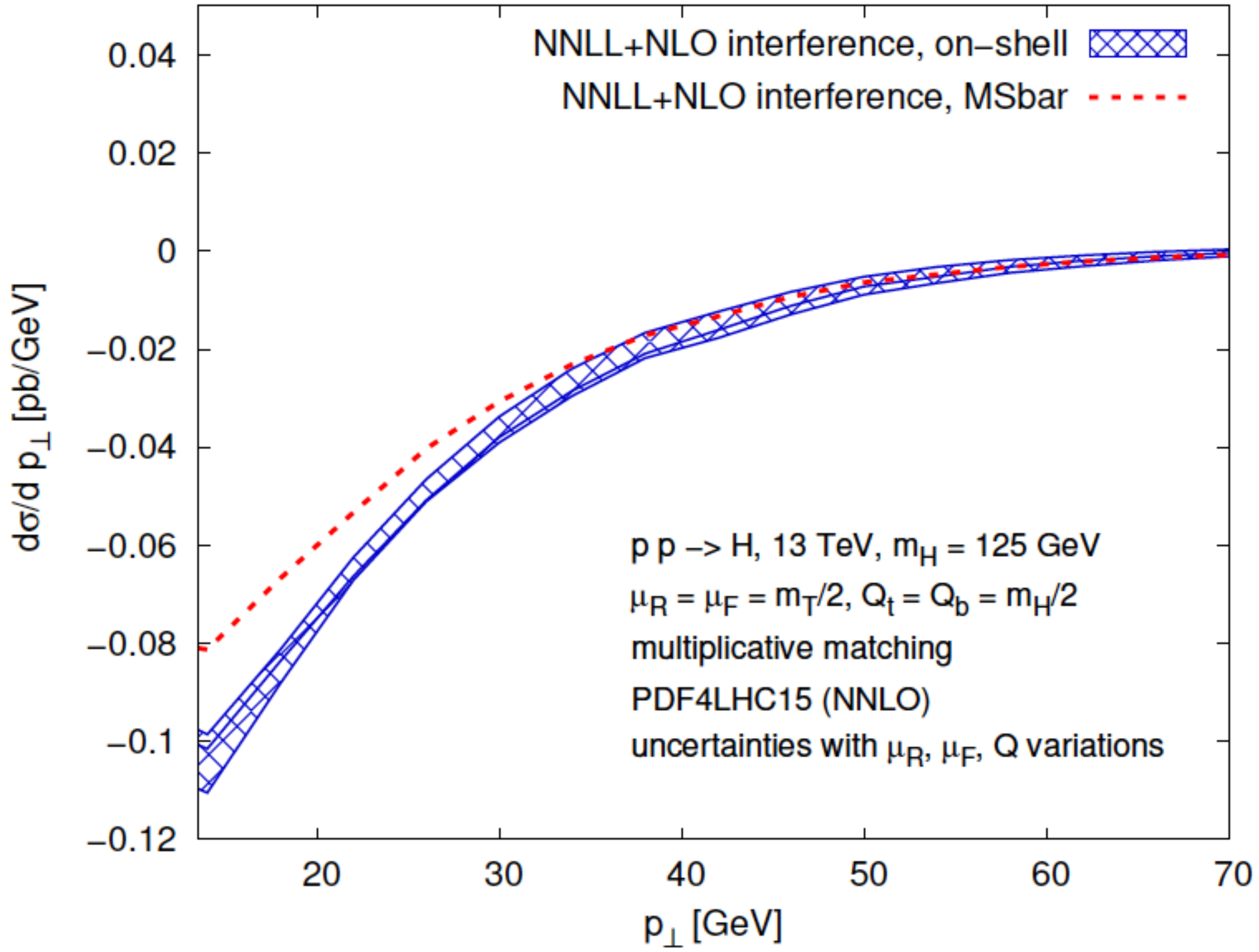
$$m_H \gg p_T \gg m_q$$

    - small resummation scale dependence (**~m_b vs. ~$m_H/2$**)

- ~15-20% uncertainty in the interference, translates into a ~1-2% uncertainty in the physical distribution [backup]

- The bottom-mass scheme is the leading source of uncertainty —> higher order corrections or new theory input to improve further



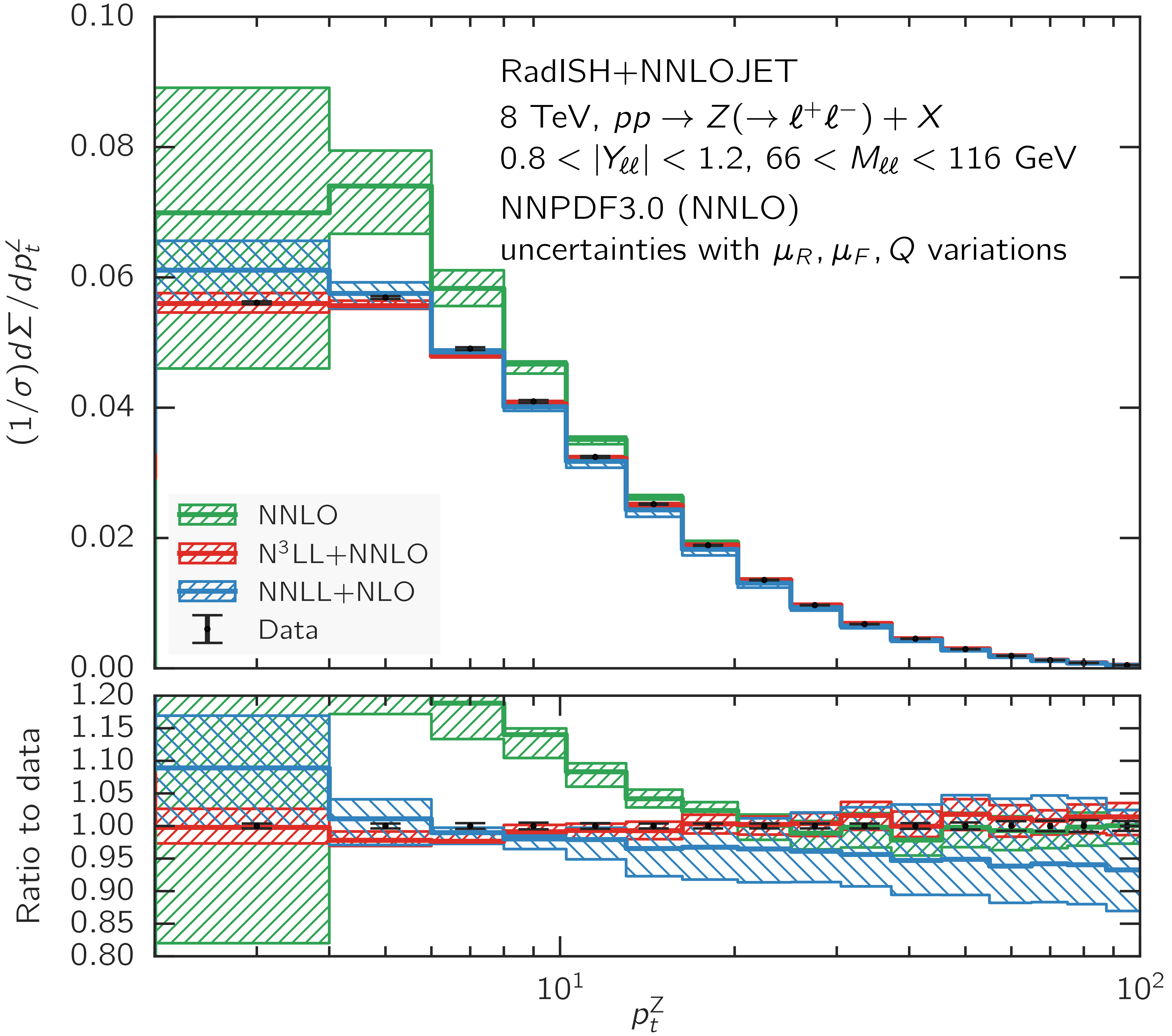


Electro-Weak physics

- This type of technology can be exploited where experimental precision is highest. E.g. the Z p_T spectrum
- Precise knowledge of the spectrum is instrumental in the extraction of SM parameters e.g. M_W, strong coupling, parton densities

  [>> talks by E. Yatsenko, M. Chiesa, & N. Vranjes]

- Data and fiducial cuts from [ATLAS 1512.02192]
- **Scale uncertainties below the 5% level**
  - Similar findings for the ϕ^*_η angular observable [backup]
- Below this level of precision many corrections play a role, some of which are of non-perturbative nature



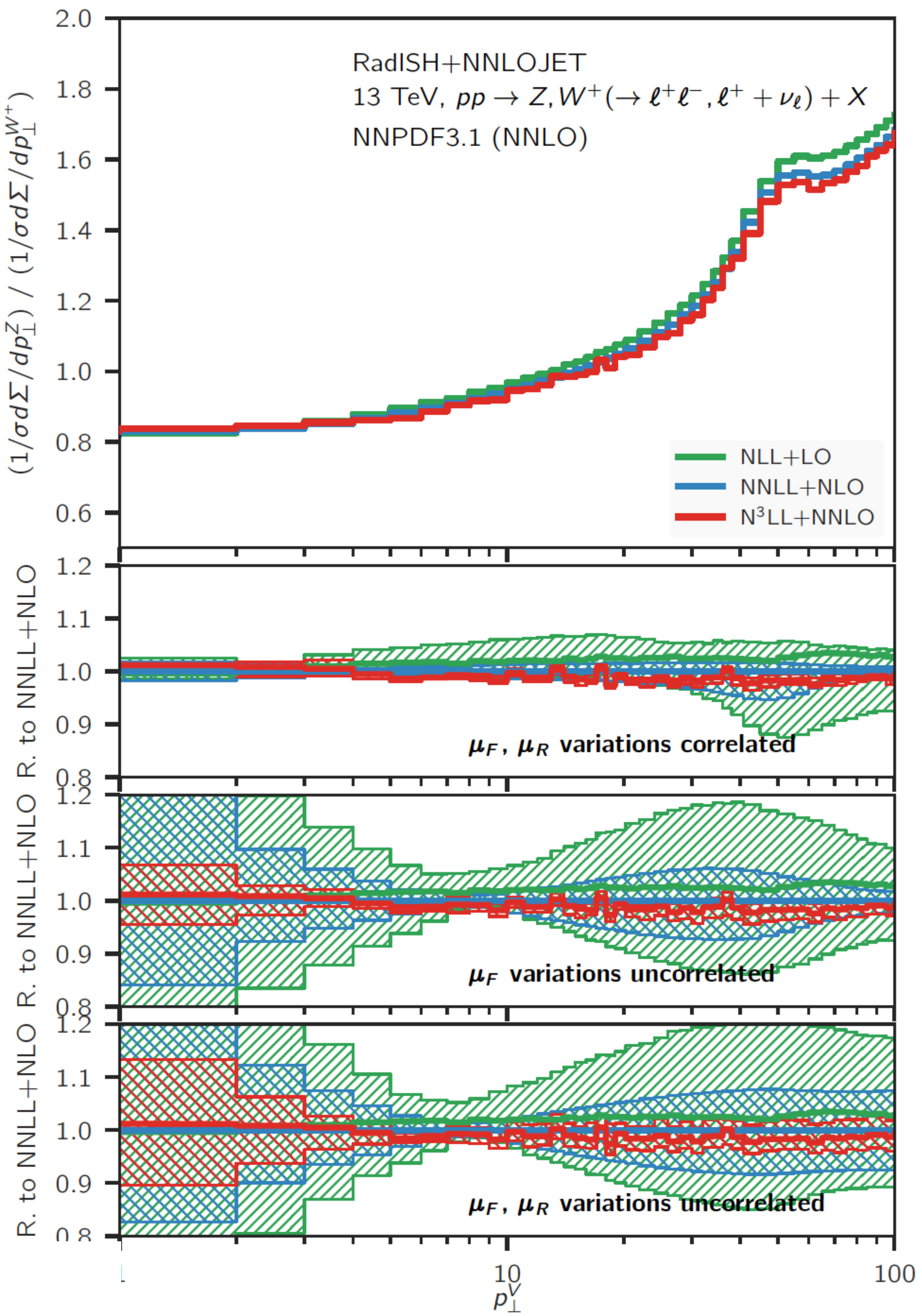
[Bizon, Chen, Gehrmann - De Ridder, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli '18]

Electro-Weak physics

- Experimental data is sub-percent accurate, we must do better. Rely on data-driven approaches whenever possible

$$\frac{1}{\sigma^{\mathrm{W}}}\frac{d\sigma^{\mathrm{W}}}{dp_\perp} \simeq \frac{1}{\sigma^{\mathrm{Z}}_{\mathrm{data}}}\frac{d\sigma^{\mathrm{Z}}_{\mathrm{data}}}{dp_\perp}\,\frac{\frac{1}{\sigma^{\mathrm{W}}_{\mathrm{theory}}}\frac{d\sigma^{\mathrm{W}}_{\mathrm{theory}}}{dp_\perp}}{\frac{1}{\sigma^{\mathrm{Z}}_{\mathrm{theory}}}\frac{d\sigma^{\mathrm{Z}}_{\mathrm{theory}}}{dp_\perp}}$$

  - excellent perturbative convergence for the ratio of distributions !
  - % residual uncertainty at N³LL+NNLO (massless QCD + quark thresholds in PDFs)
  - Study of other sources of correlation necessary



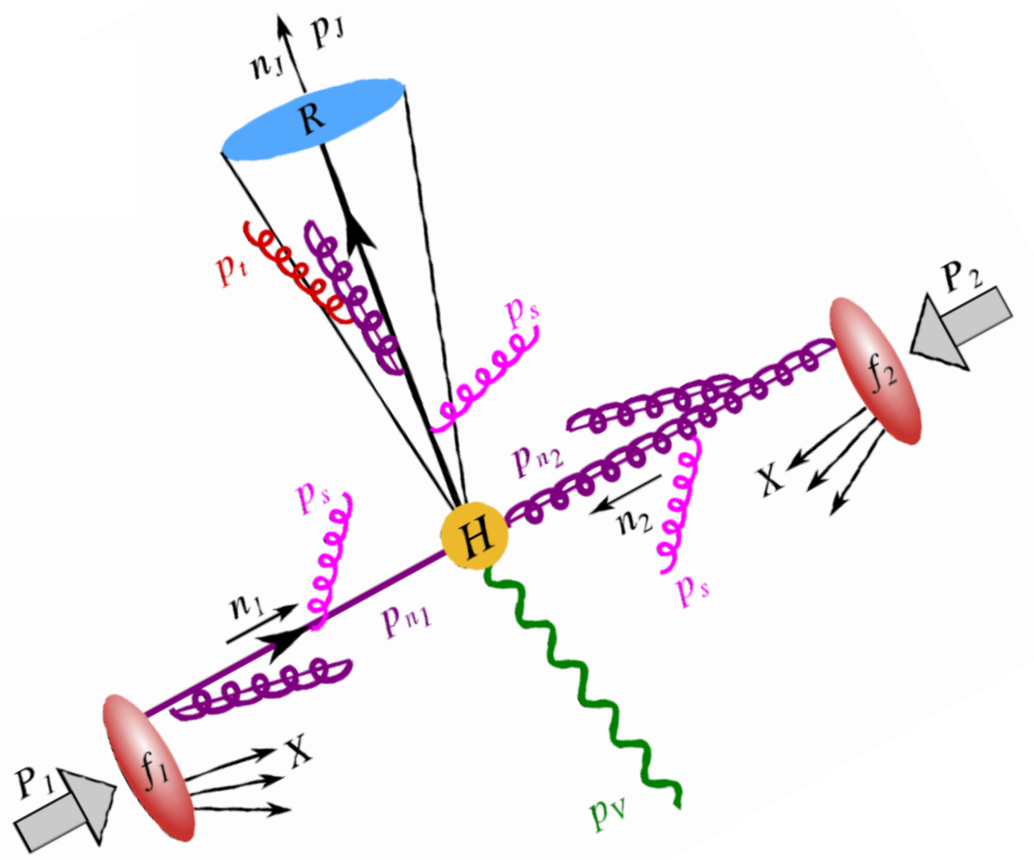
[Bizon, Gehrmann - De Ridder, Gehrmann, Glover, Huss, PM, Re, Rottoli, Walker '19]

Going more differential

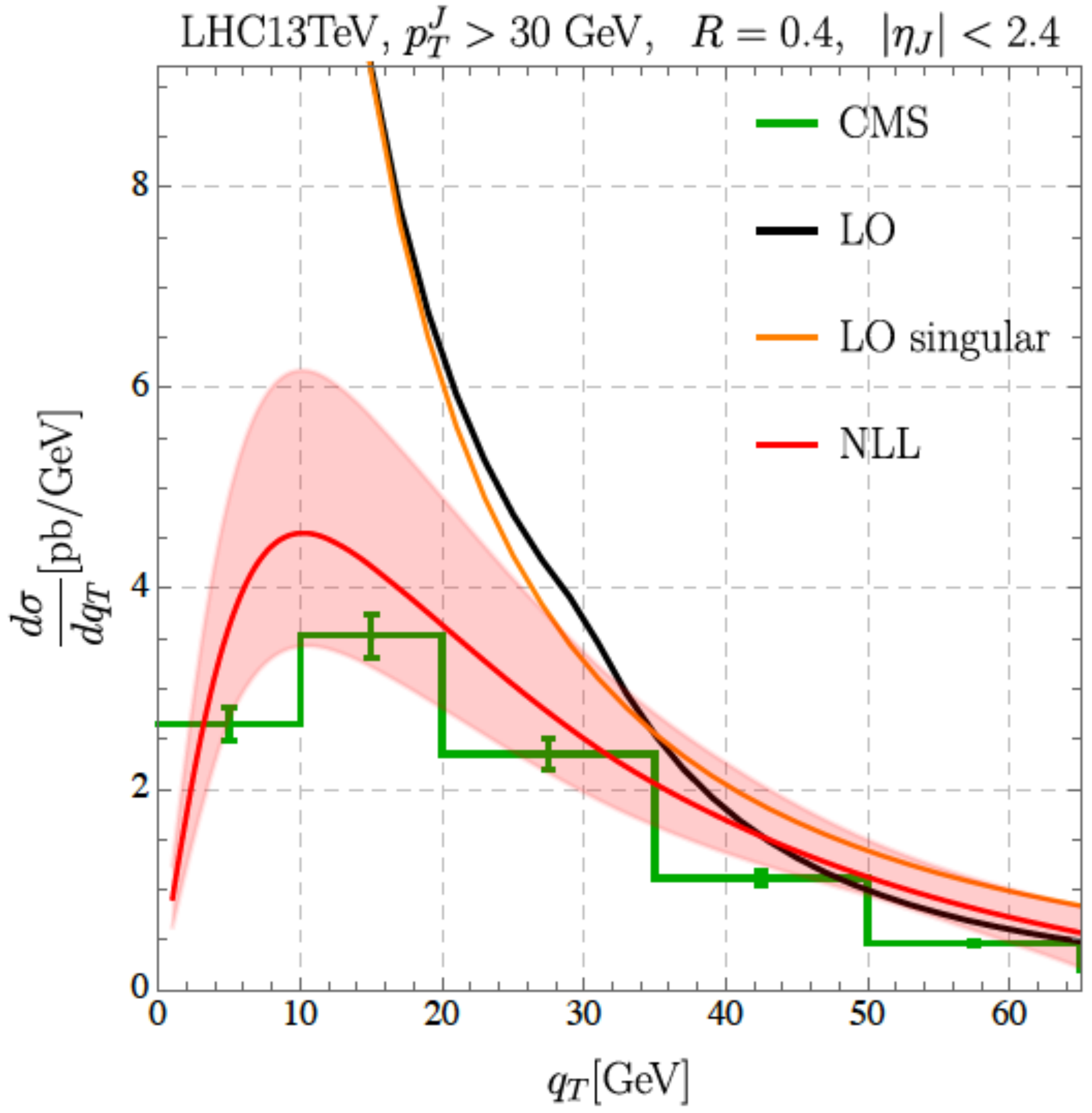
- First steps towards a better understanding of more exclusive and non-global observables at hadron colliders

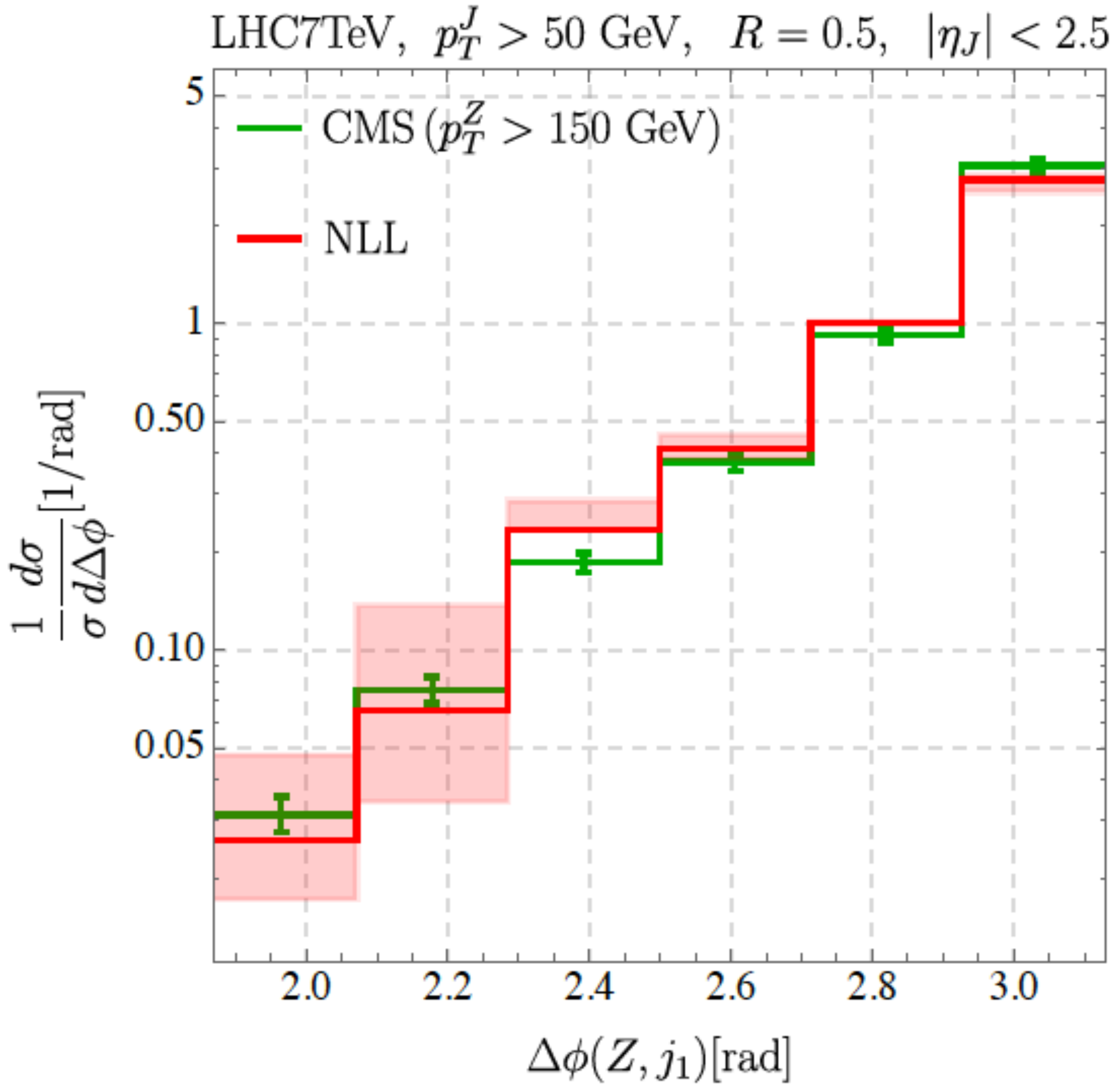
e.g. Boson-jet correlations

[Chien, Shao, Wu '19]



$$\vec{q}_T = \vec{p}_T^{\,J} + \vec{p}_T^{\,V}$$





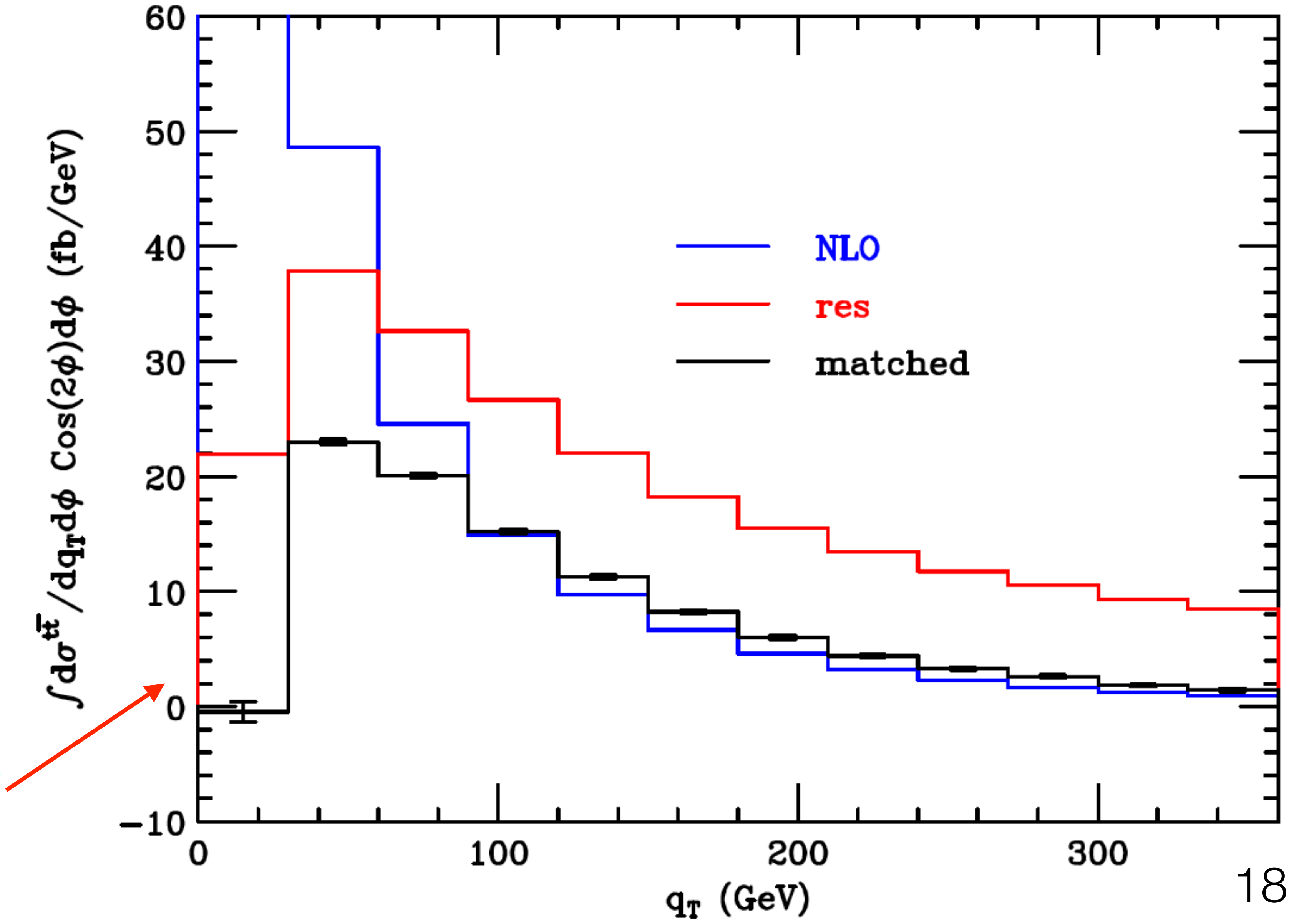
e.g. azimuthal correlations in the production of pairs of heavy particles

[Catani, Grazzini, Sargsyan '17]

$$\frac{d\sigma^{NLO}}{dM^2 d^2\boldsymbol{q_T}} \propto \delta^{(2)}(\boldsymbol{q_T}) + \alpha_S \left\{ \left(a_2 \left[\frac{1}{q_T^2} \ln\left(\frac{M^2}{q_T^2}\right) \right]_+ + a_1 \left[\frac{1}{q_T^2}\right]_+ + a_0\, \delta^{(2)}(\boldsymbol{q_T}) + \frac{a_{\rm corr}(\hat{\boldsymbol{q}}_T)}{q_T^2} \right) + \ldots \right\}, \langle a_{\rm corr}(\hat{\boldsymbol{q}}_T)\rangle_{\rm av.} = 0$$

resummation at small p_T instrumental to make correlations finite. e.g. ttbar production

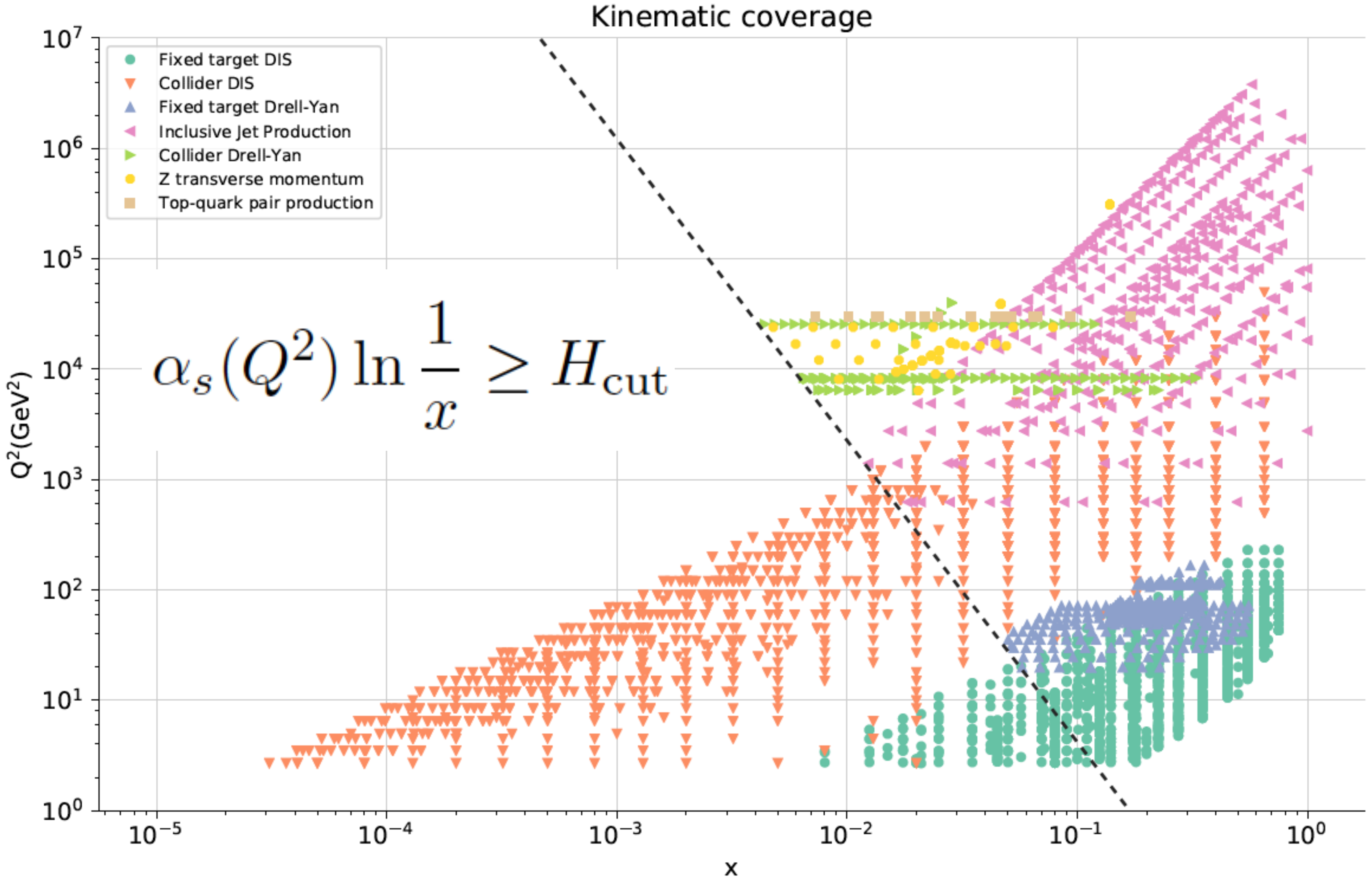
$$\frac{d\sigma_n^{(\rm res)}}{dM^2 dq_T^2} \propto q_T^n$$



Fundamental parameters: PDFs

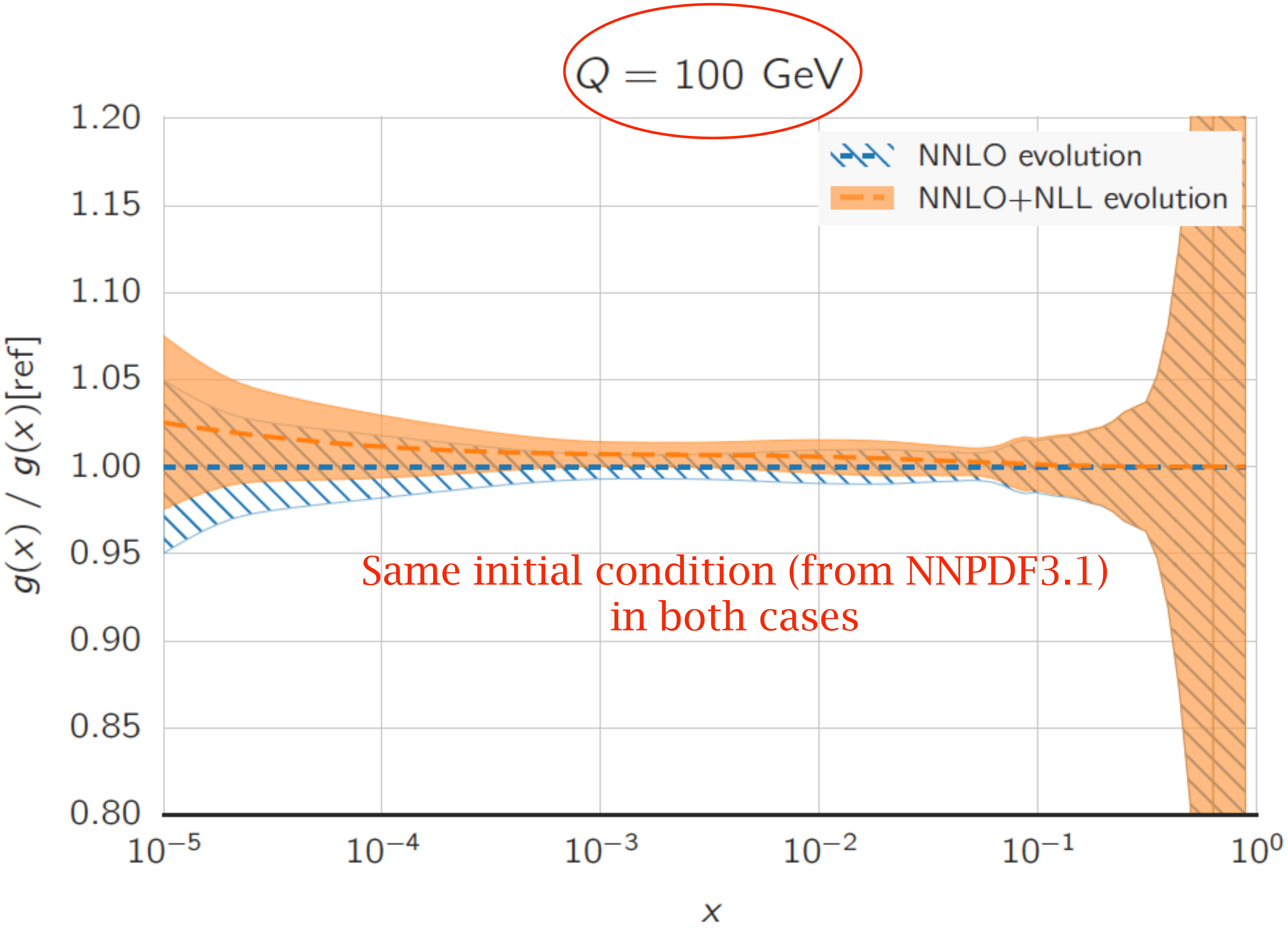
[Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli '18]

- Modern PDF fits contain small-x data from HERA (mainly) and LHCb
- One may wonder how important the impact of the resummation of ln(x) is
- small-x resummation leads to moderate corrections to the PDF evolution to high scales …



$$\alpha_s(Q^2)\ln\frac{1}{x} \geq H_{\text{cut}}$$

$Q = 100$ GeV



Same initial condition (from NNPDF3.1) in both cases

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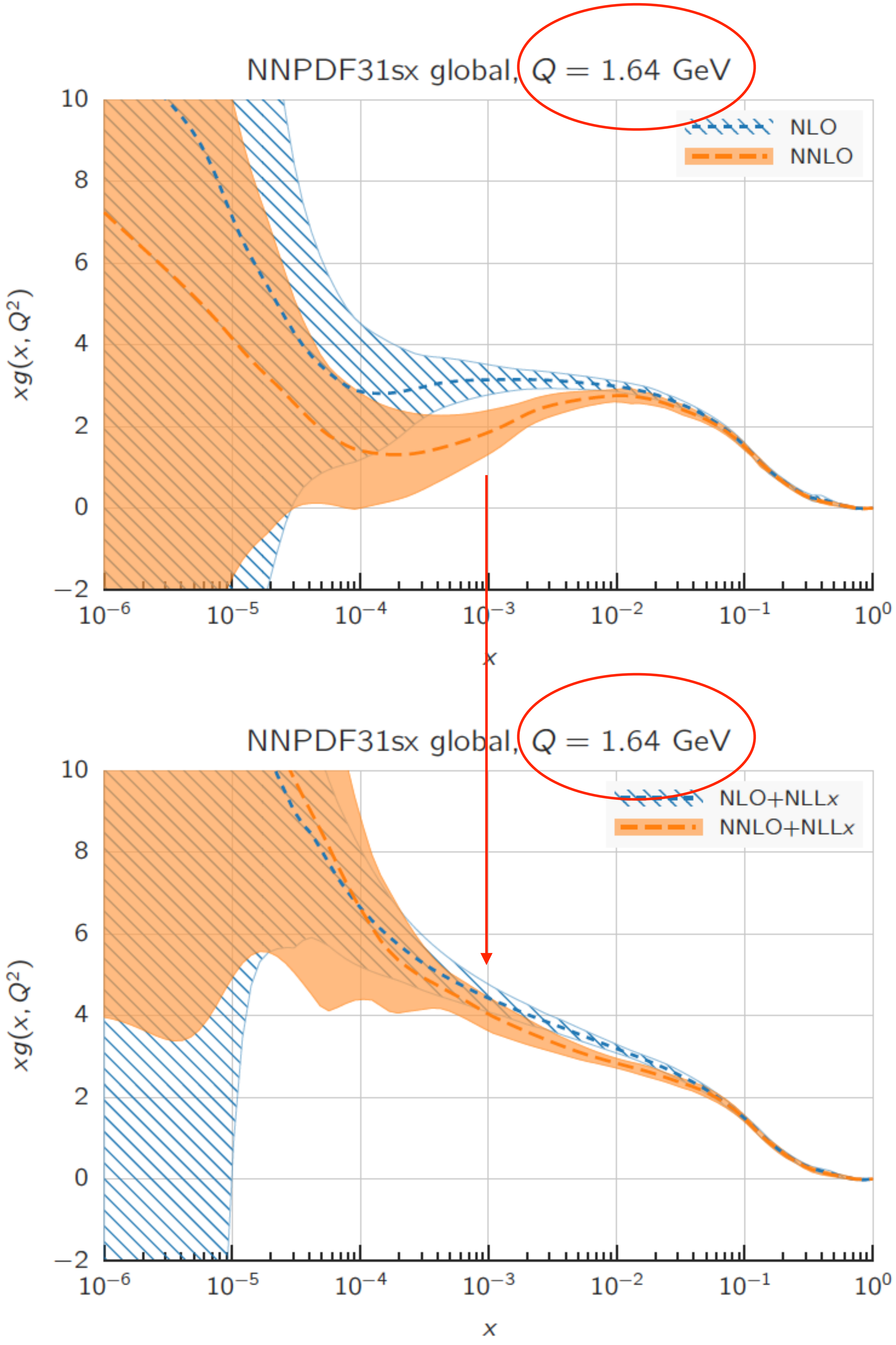
- … however, the initial condition at the low scale may change substantially



Higgs cross section at high energies

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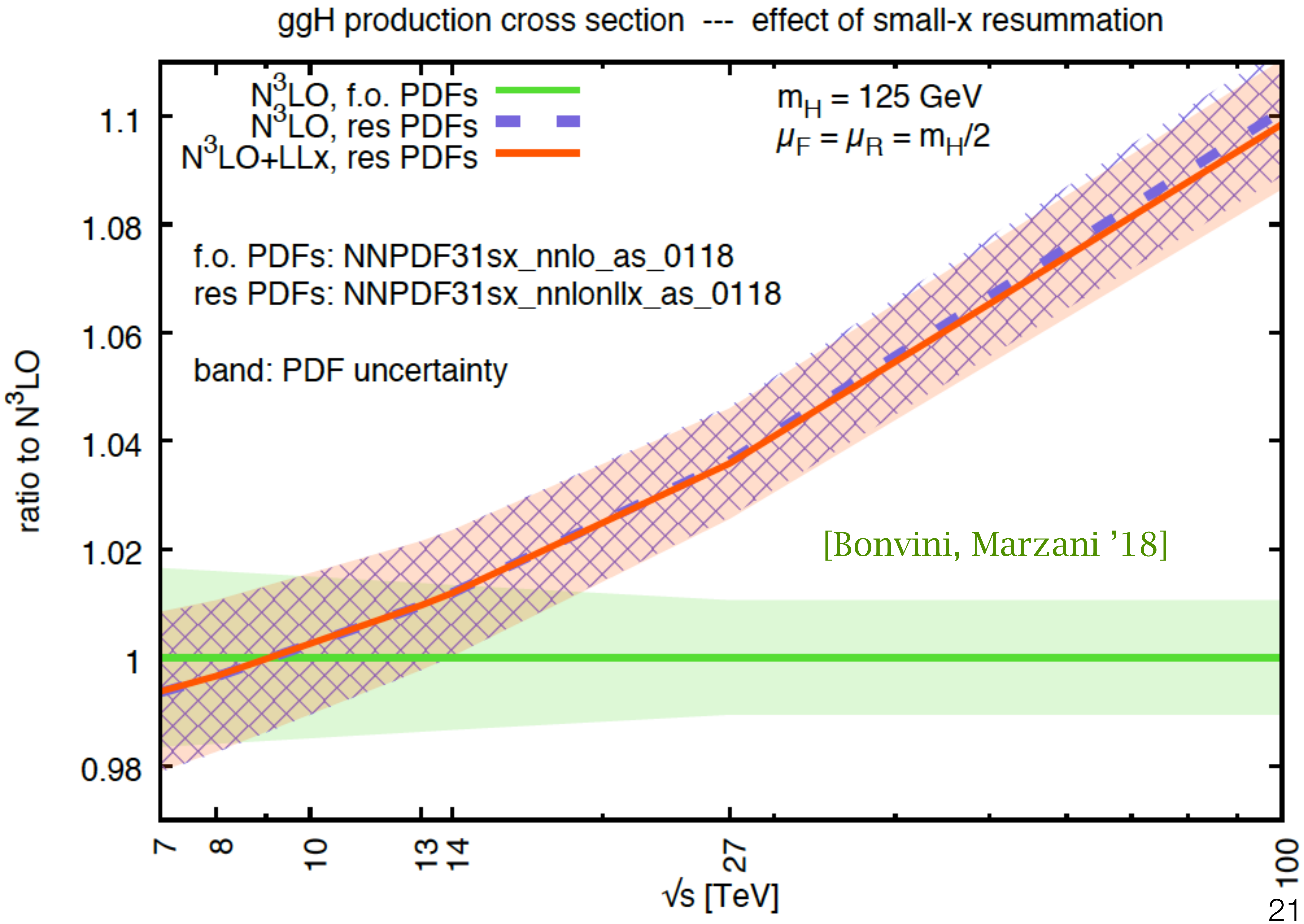
- … however, the initial condition at the low scale may change substantially
- Sizeable corrections to high-energy processes. e.g. Higgs cross section at 27-100 TeV 4-10% larger than N^3LO
- Difficult to test these conclusions at current LHC experiments (Drell-Yan at LHCb ?)



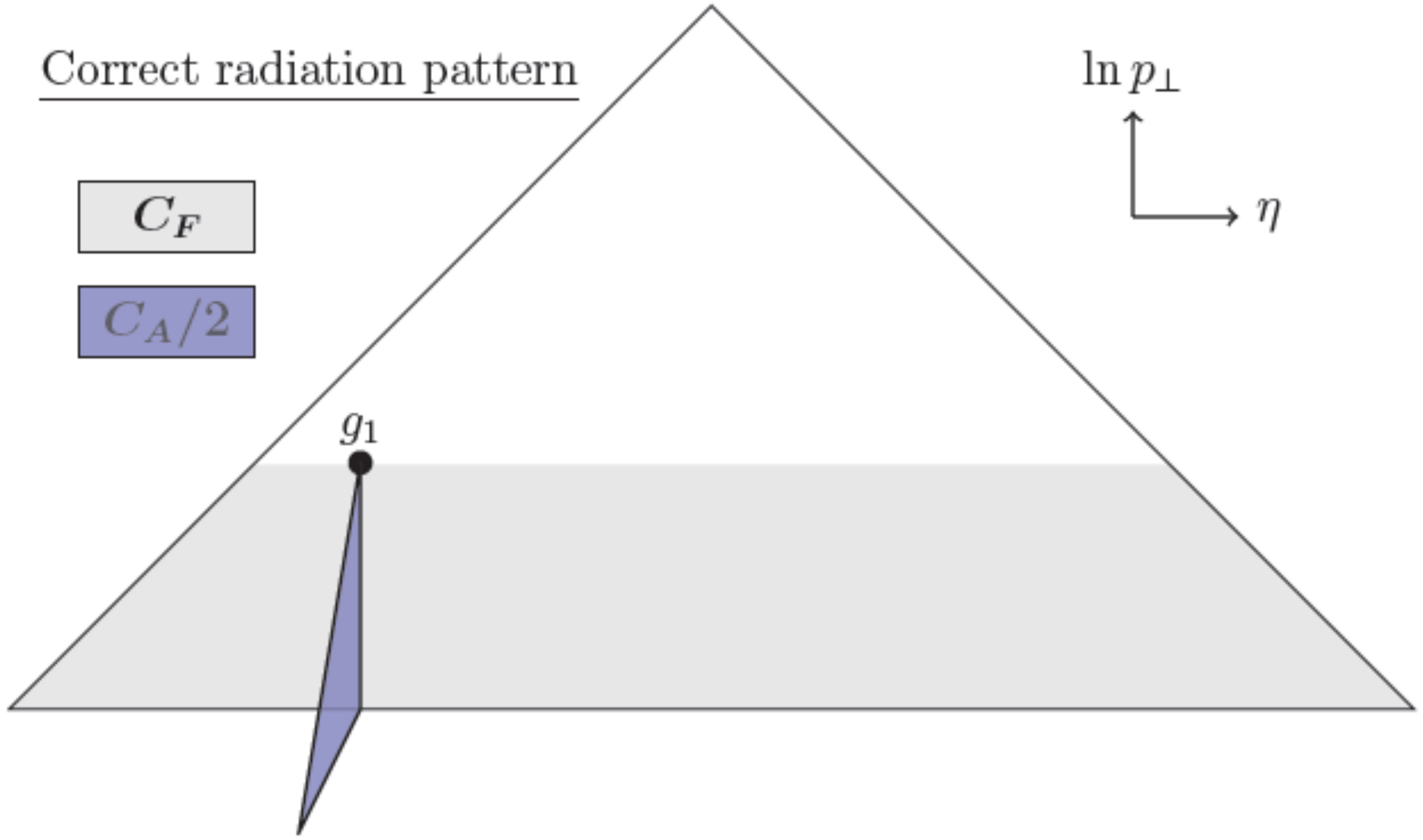
[Bonvini, Marzani ’18]

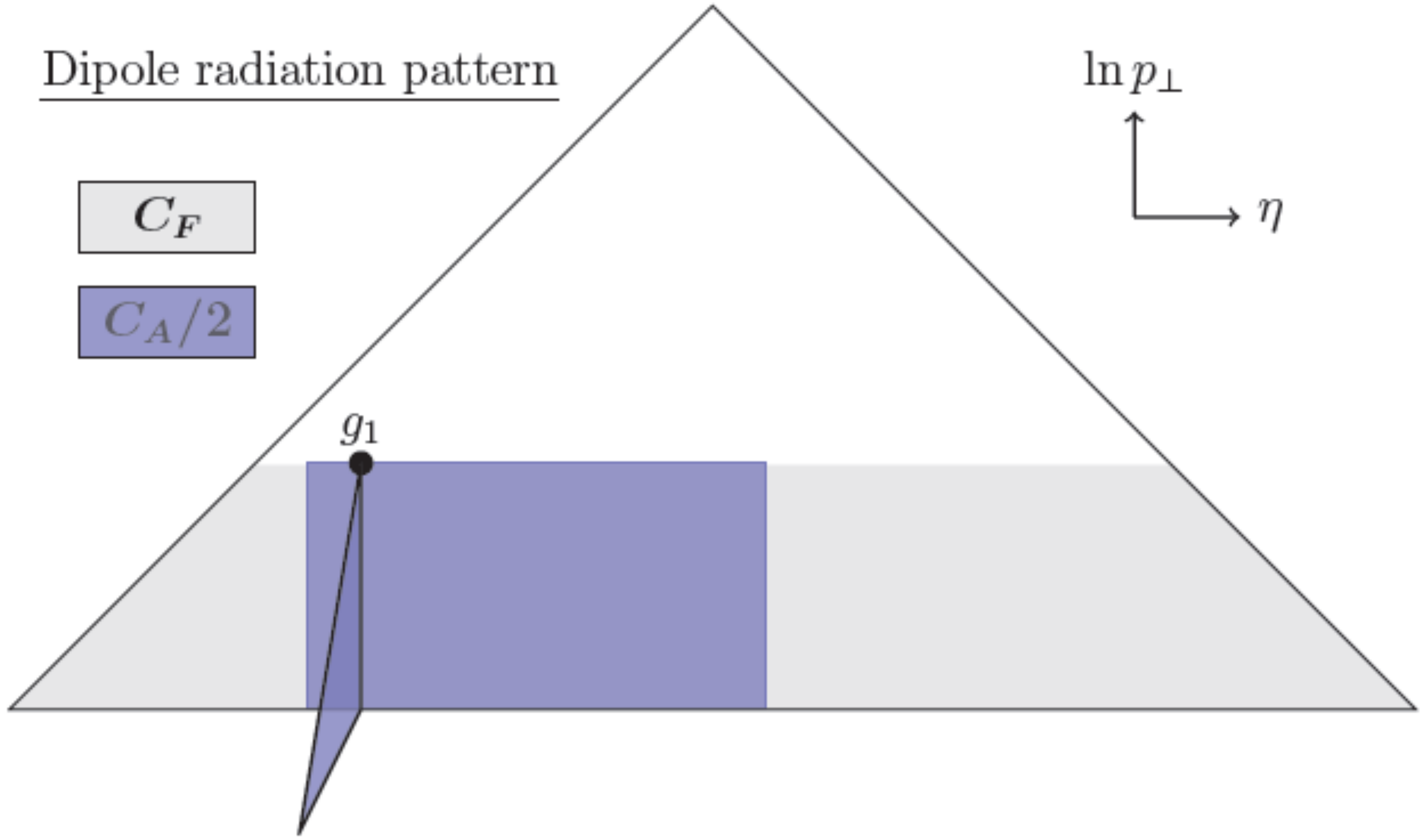
Understanding parton showers from resummations

- The key to control and improve future parton shower algorithms (PS) may lie in their link to resummations
  - **Resummations as limiting case of PS dynamics**
  - **Assess perturbative accuracy of PS & devise new algorithms**

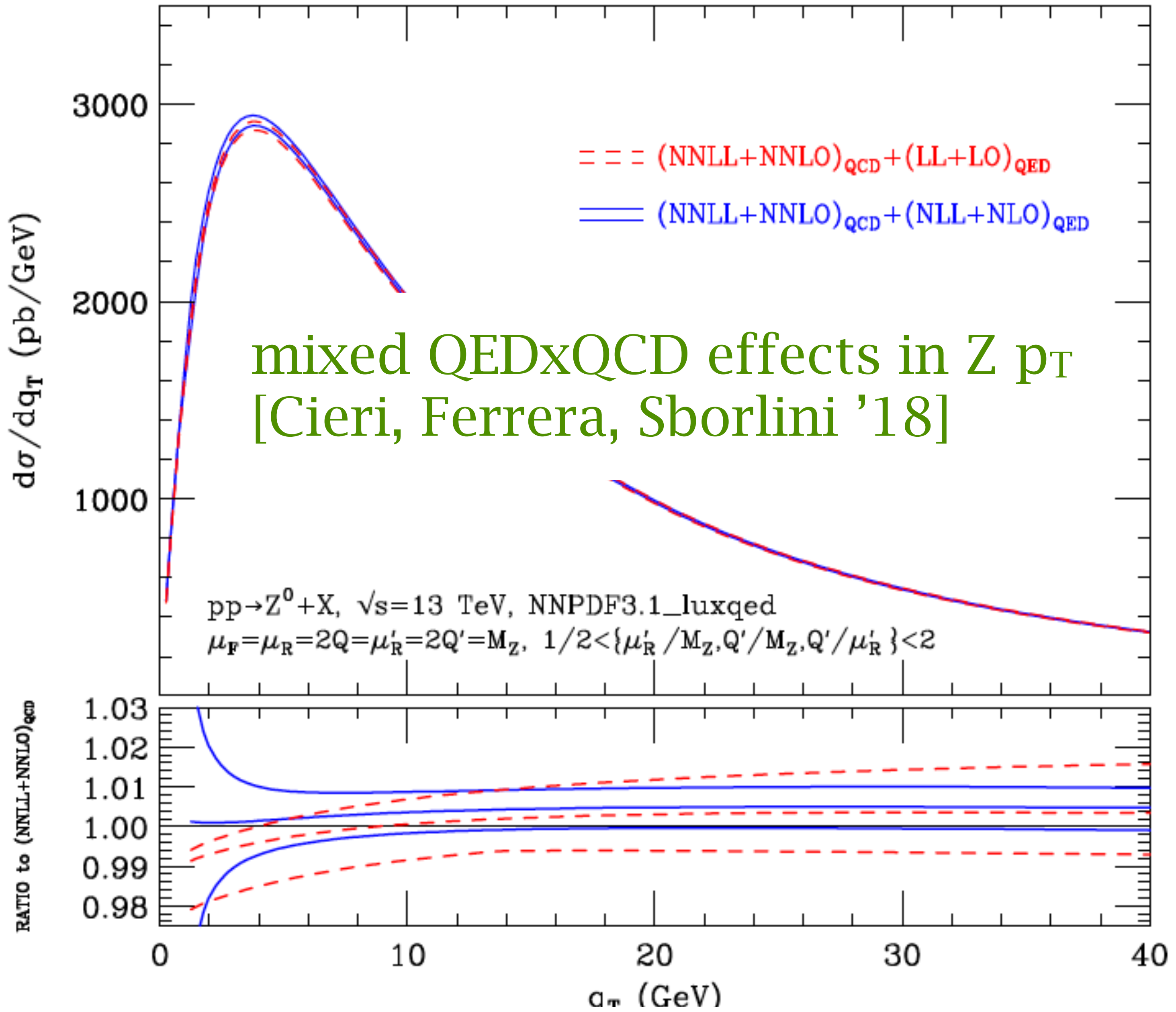
Study of radiation pattern unveils important constraints to go beyond LL in future designs

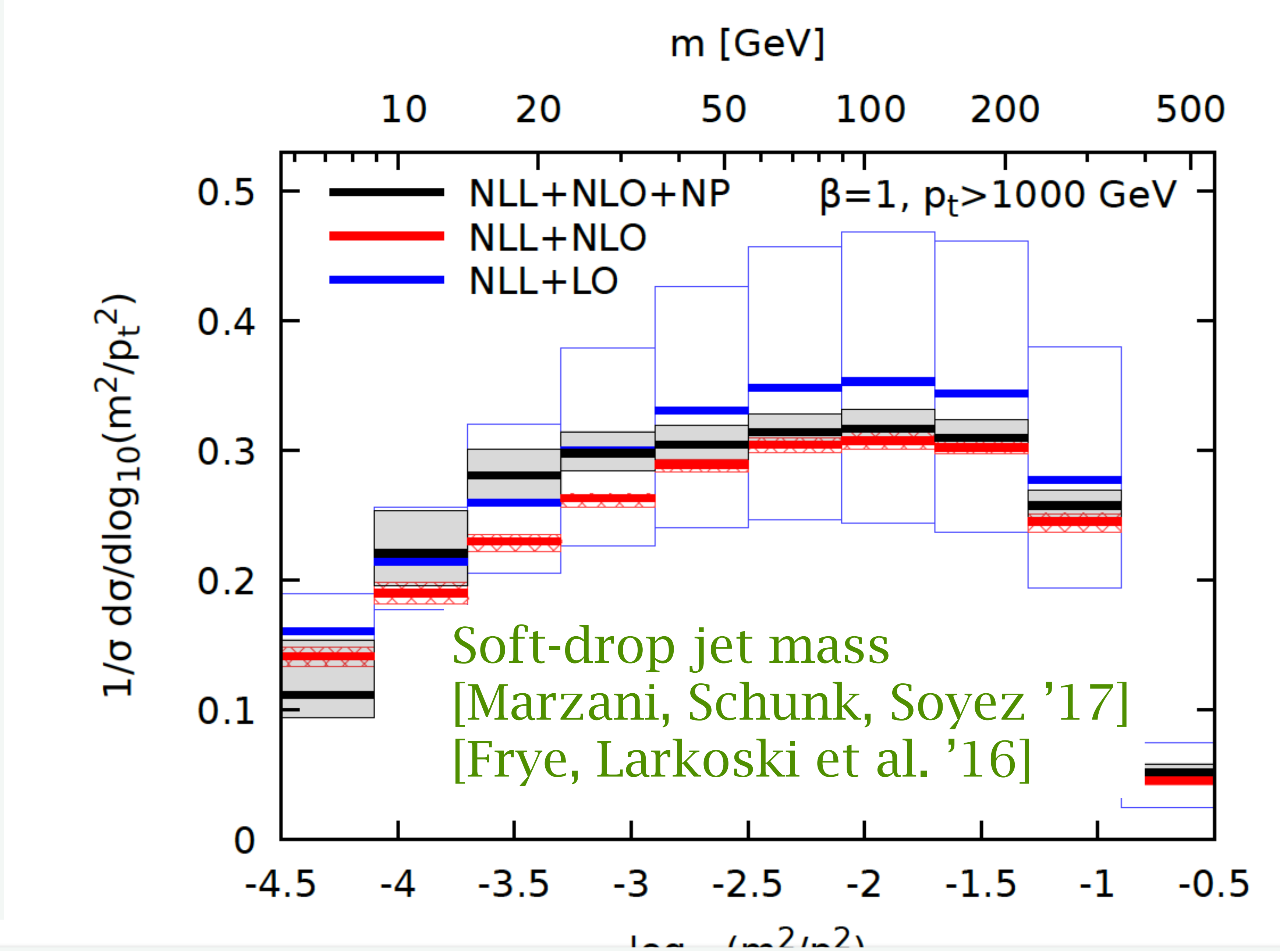
[Dasgupta, Dreyer, Hamilton, PM, Salam ’18]
Related studies also in
[Hoang, Plaetzer, Samitz ’18] [>> A. Hoang’s talk]
[Bewick, Ravasio, Richardson, Seymour ’19]

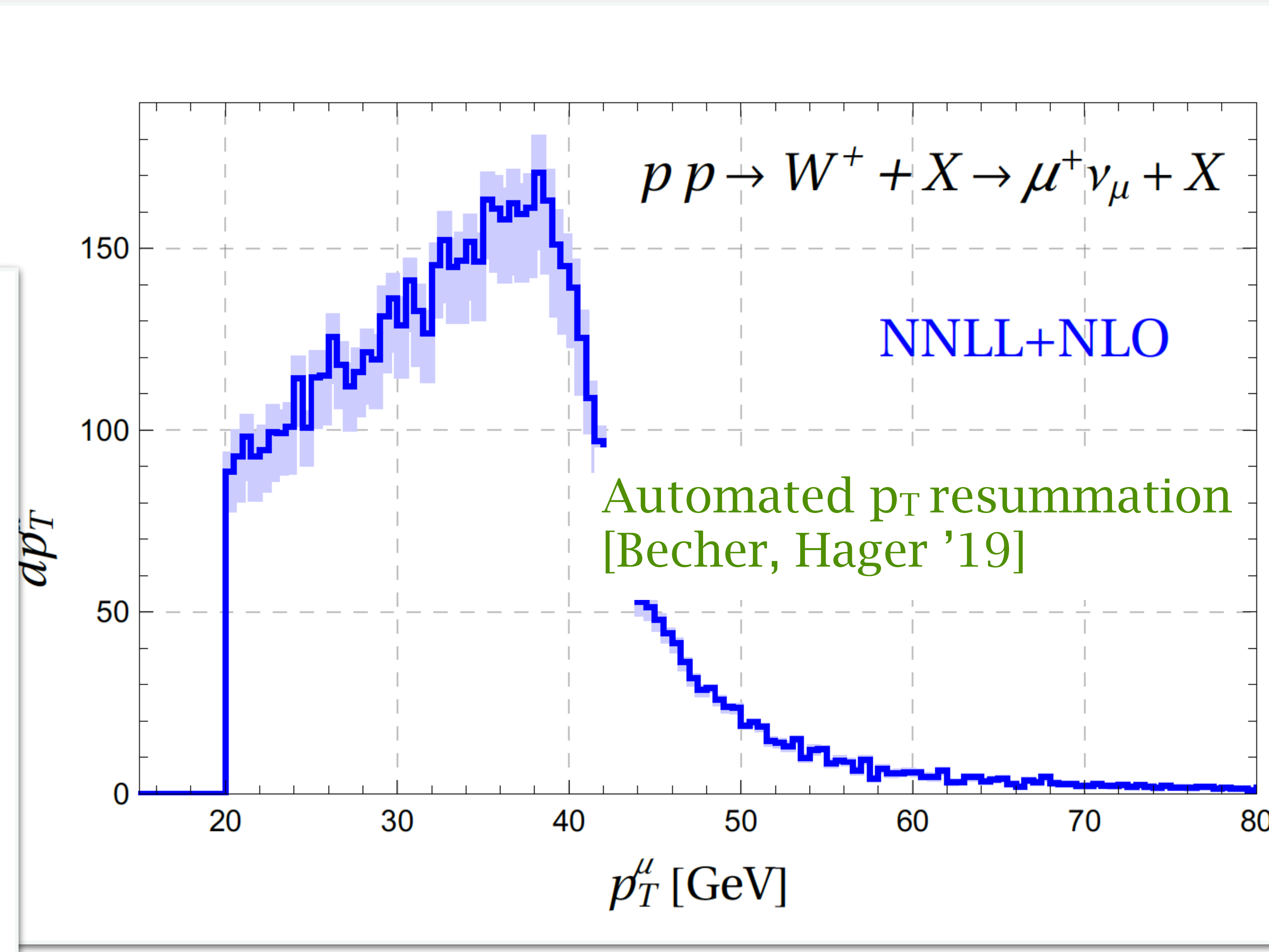


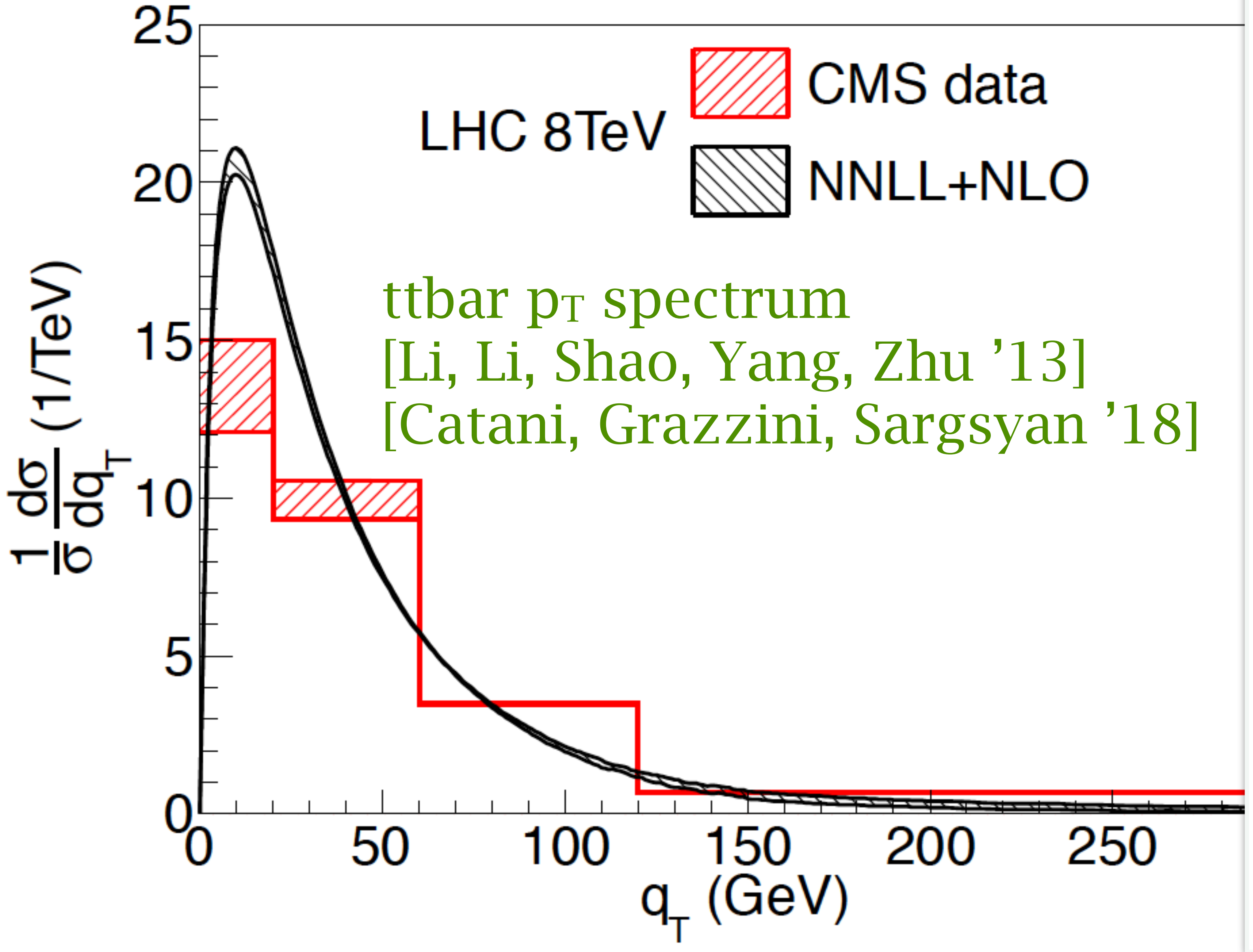


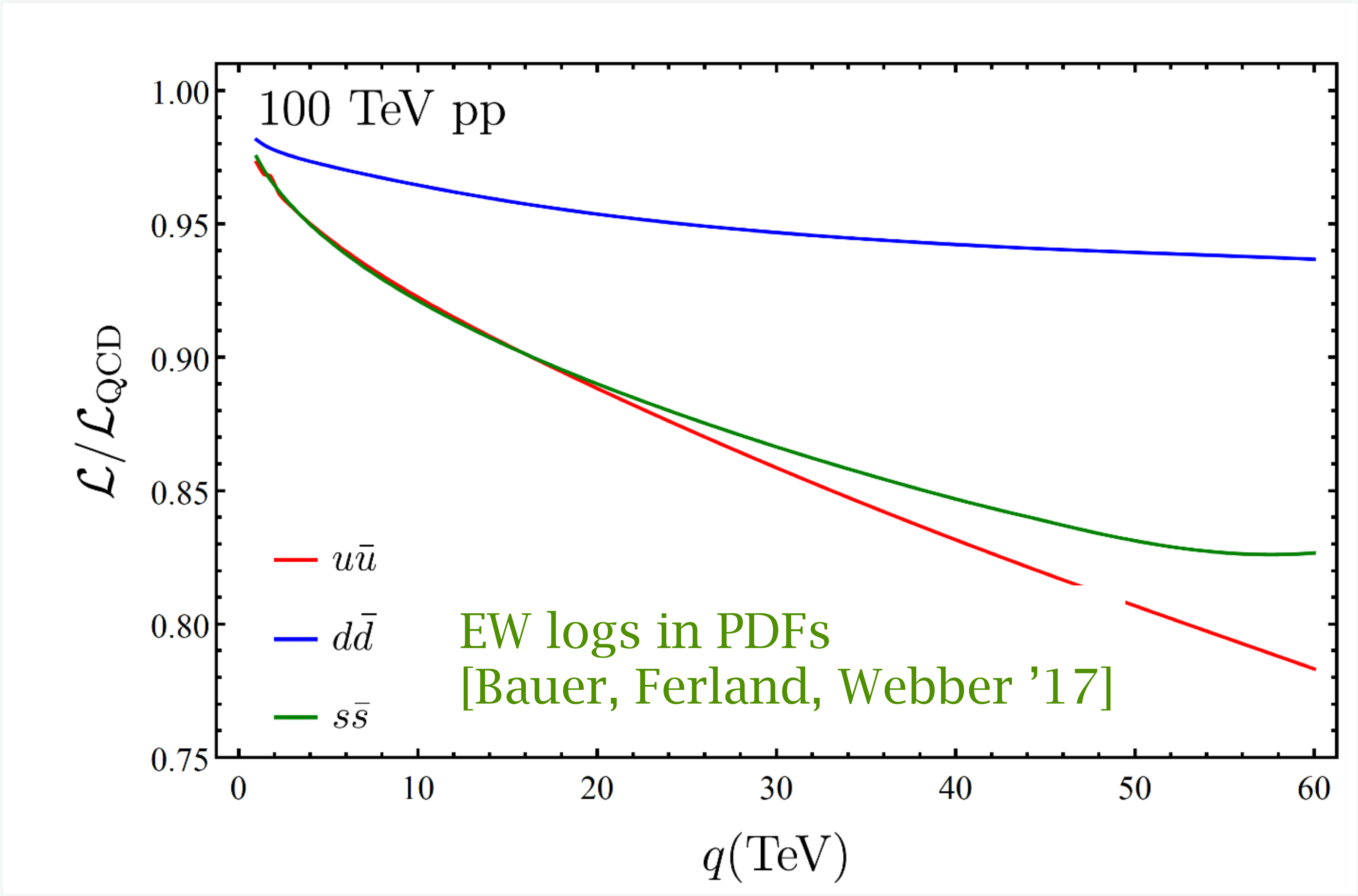
…just a glimpse, much more out there

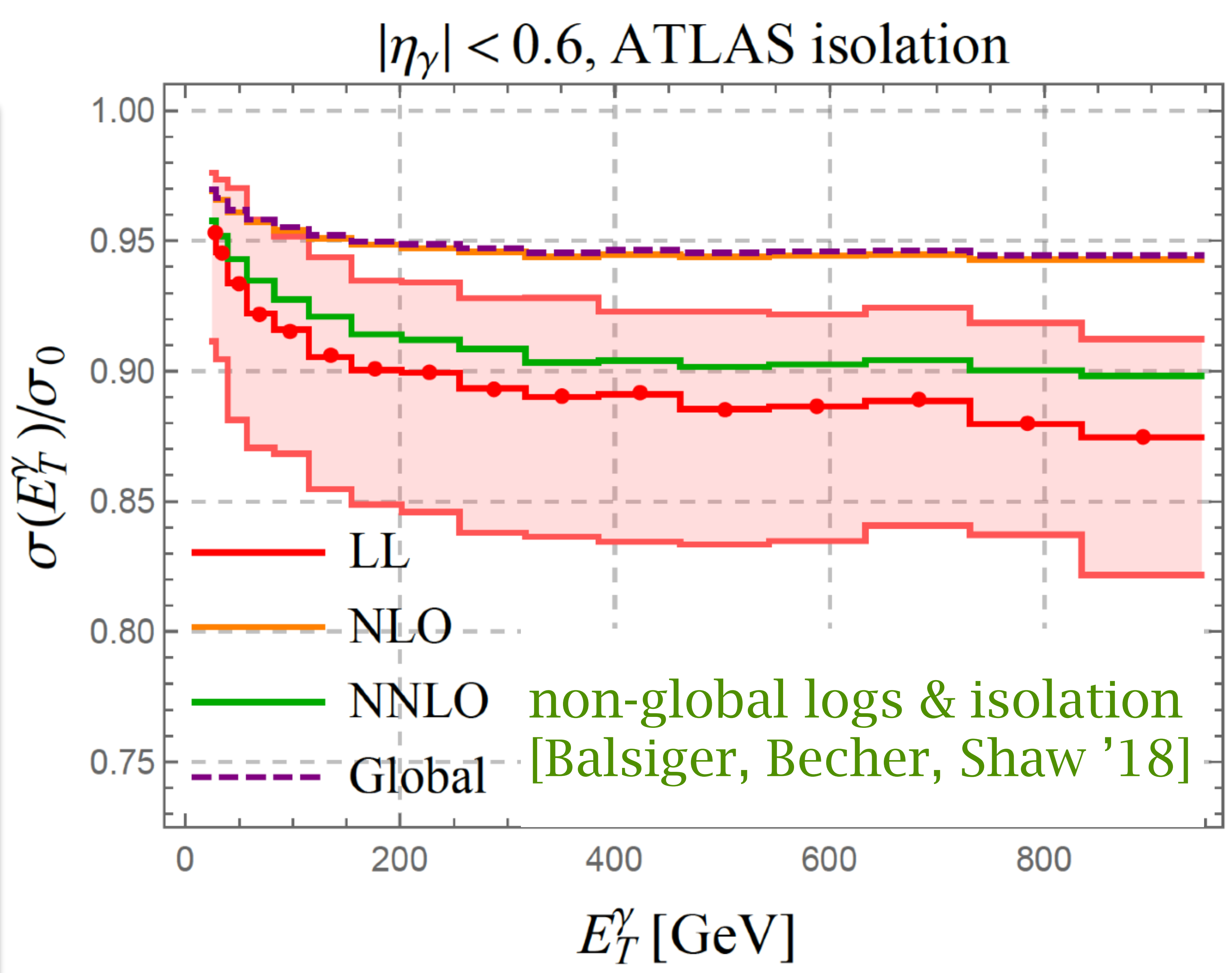

mixed QEDxQCD effects in Z p_T
[Cieri, Ferrera, Sborlini '18]


Soft-drop jet mass
[Marzani, Schunk, Soyez '17]
[Frye, Larkoski et al. '16]


NNLL+NLO
Automated p_T resummation
[Becher, Hager '19]


ttbar p_T spectrum
[Li, Li, Shao, Yang, Zhu '13]
[Catani, Grazzini, Sargsyan '18]


EW logs in PDFs
[Bauer, Ferland, Webber '17]


non-global logs & isolation
[Balsiger, Becher, Shaw '18]

Conclusions

- The future LHC programme deeply relies on precision (both for SM & BSM searches). Achieving the accuracy demanded by experiments requires **joint efforts in different areas of QCD**

- Understanding of infrared and all-order dynamics is crucial to control the theory at the few-% level in exclusive measurements

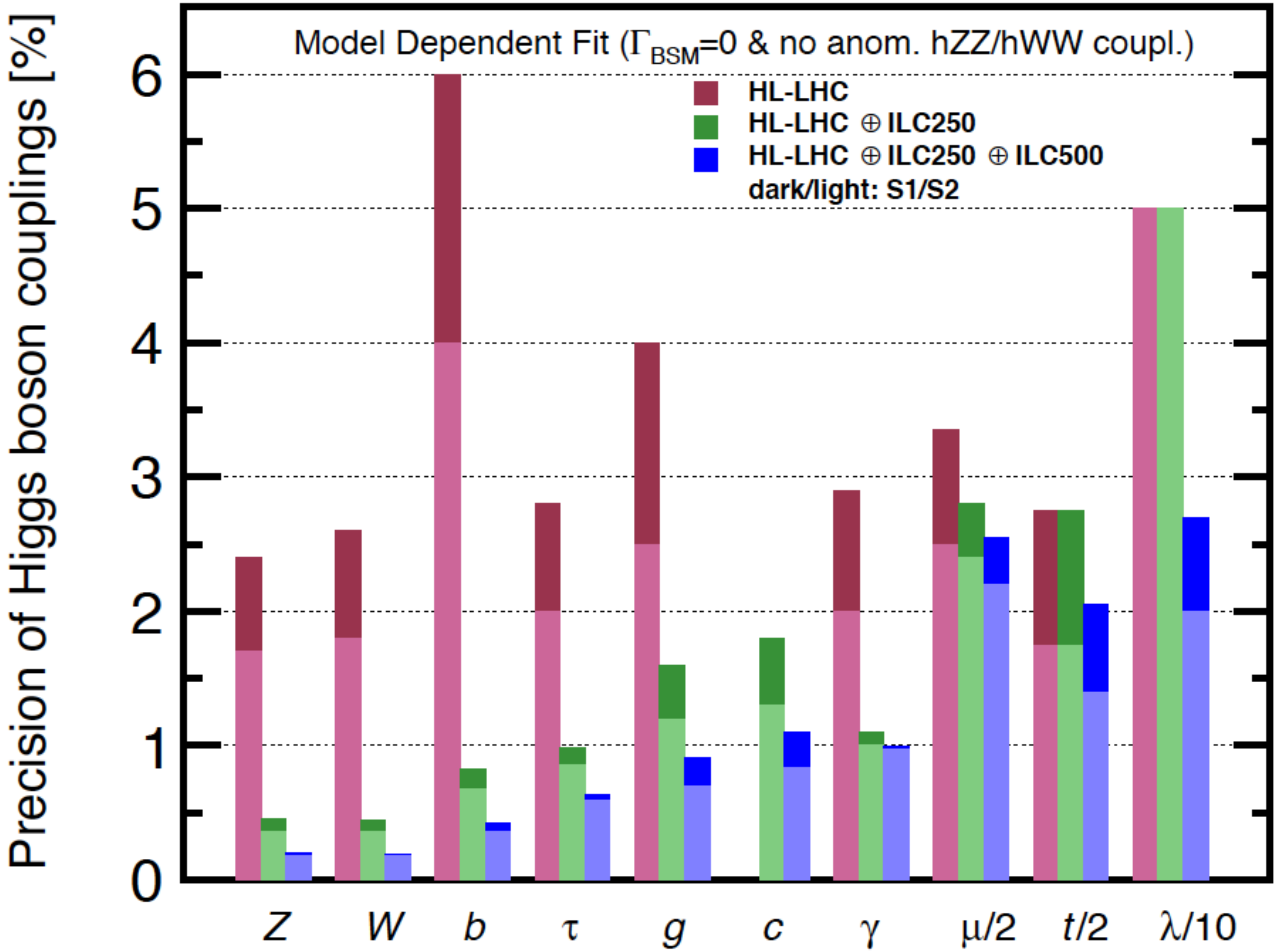
- Impressive progress in the past 10 years has led to the evolution of technology that allows us to tackle several problems of phenomenological relevance
  - precise predictions, subtractions, & event generators
  - better-behaved observables & substructure of jets

- Much more to be done on the theory side (multi-leg reactions, multi-differential/scales & exclusive measurements) … exciting times ahead !

Thank you for listening

Search for new physics at the LHC

The charm Yukawa: future prospects



NNLO calculations for LHC

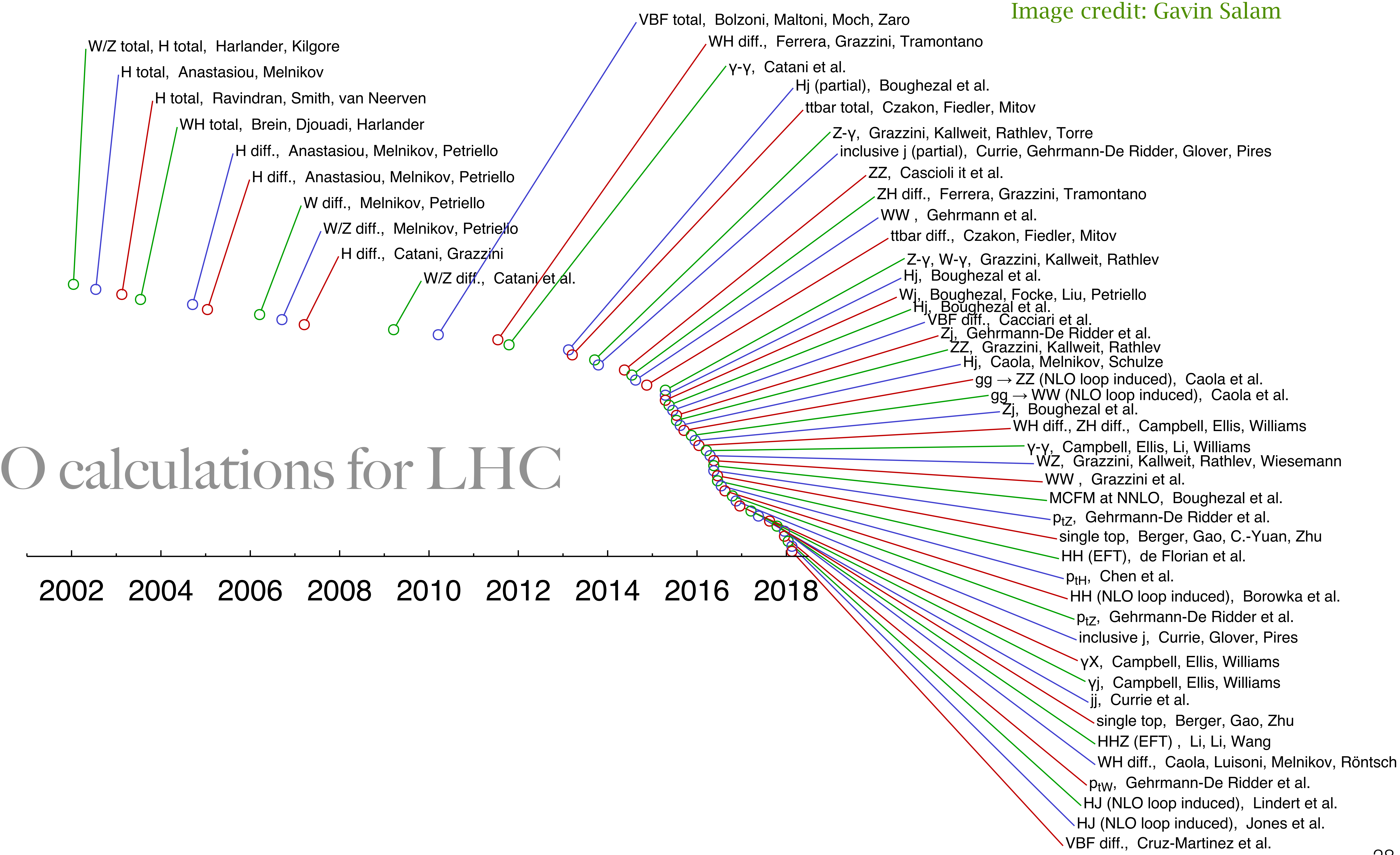
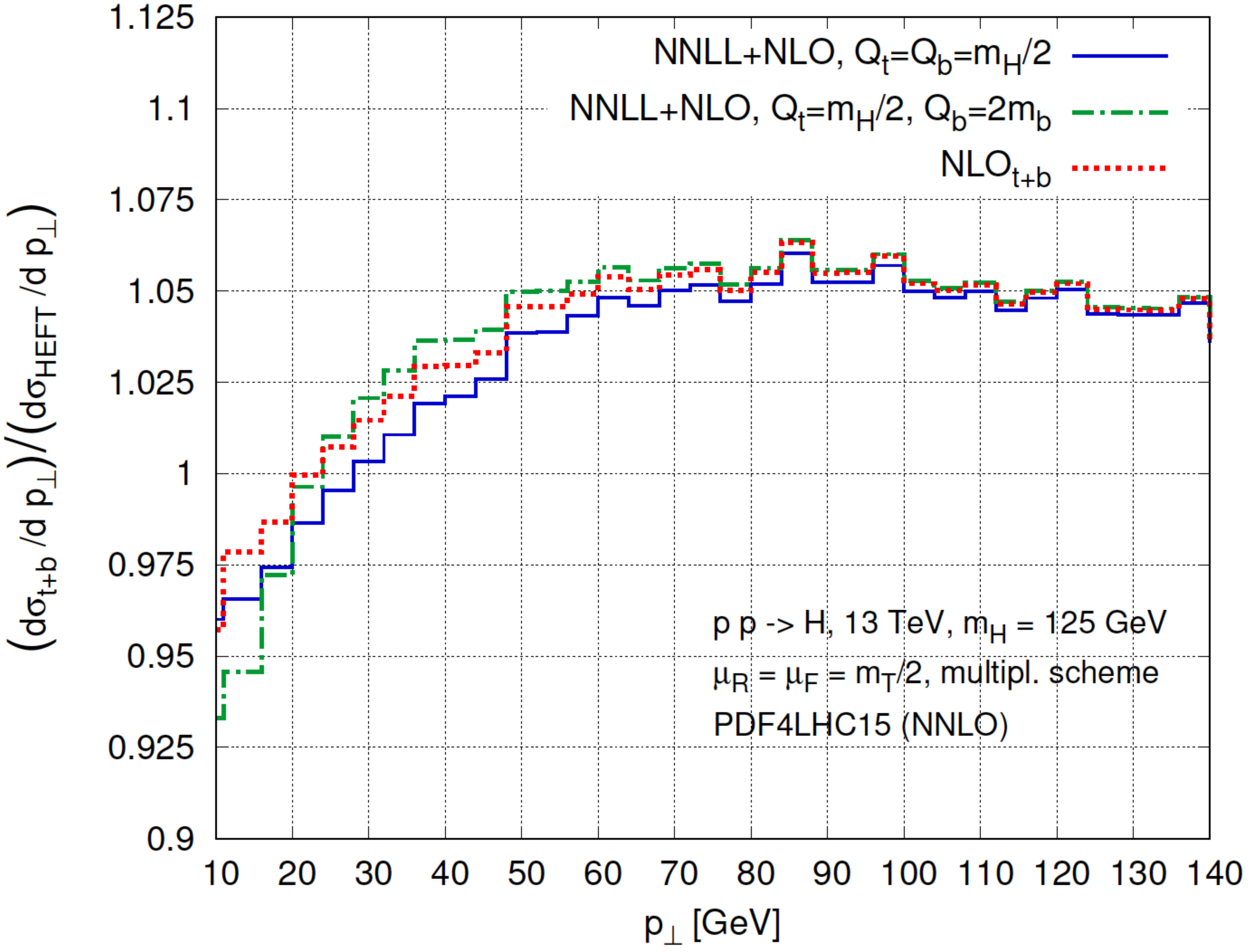


Image credit: Gavin Salam

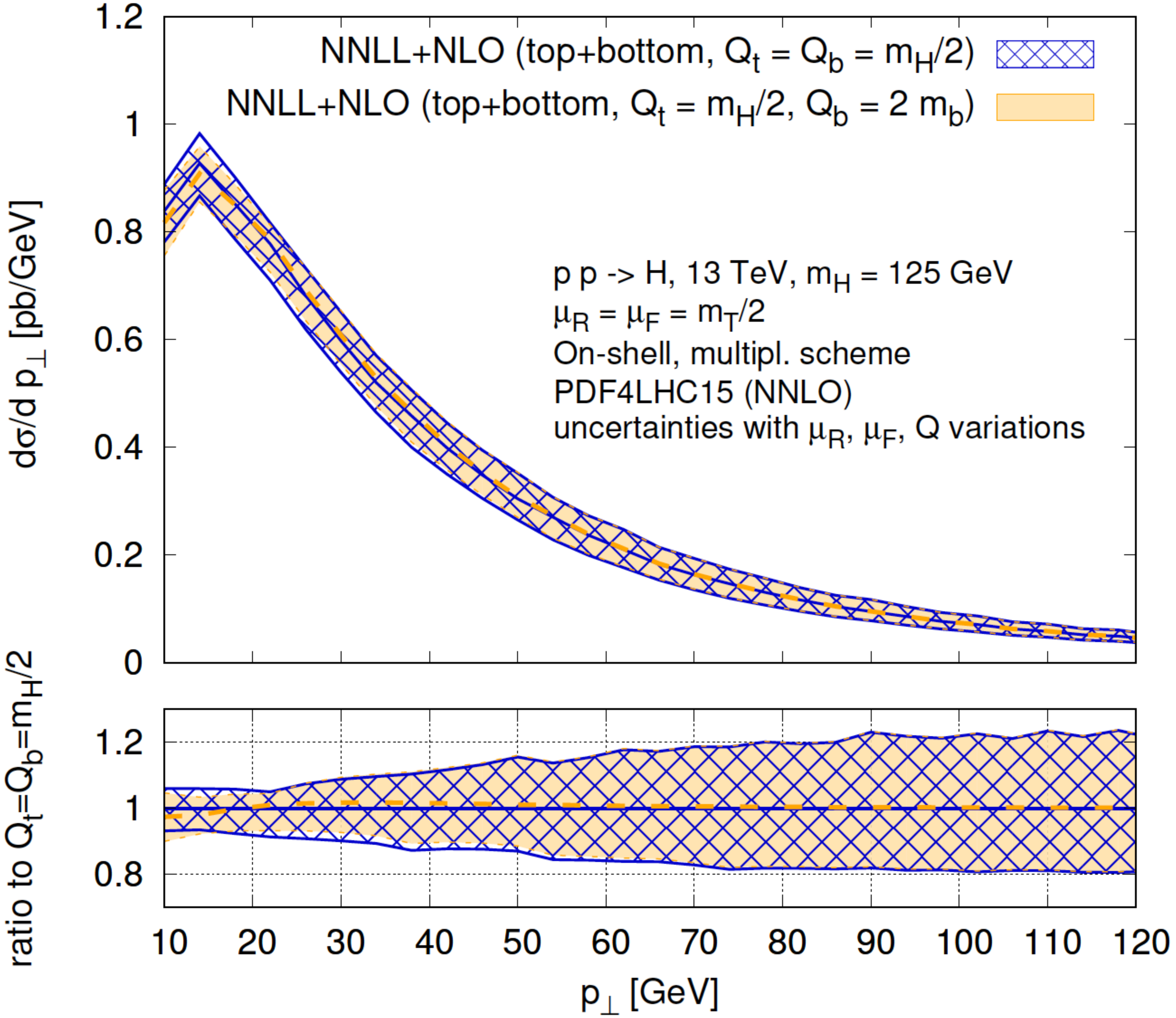
[Caola, Lindert, Melnikov, PM, Tancredi, Wever '18]

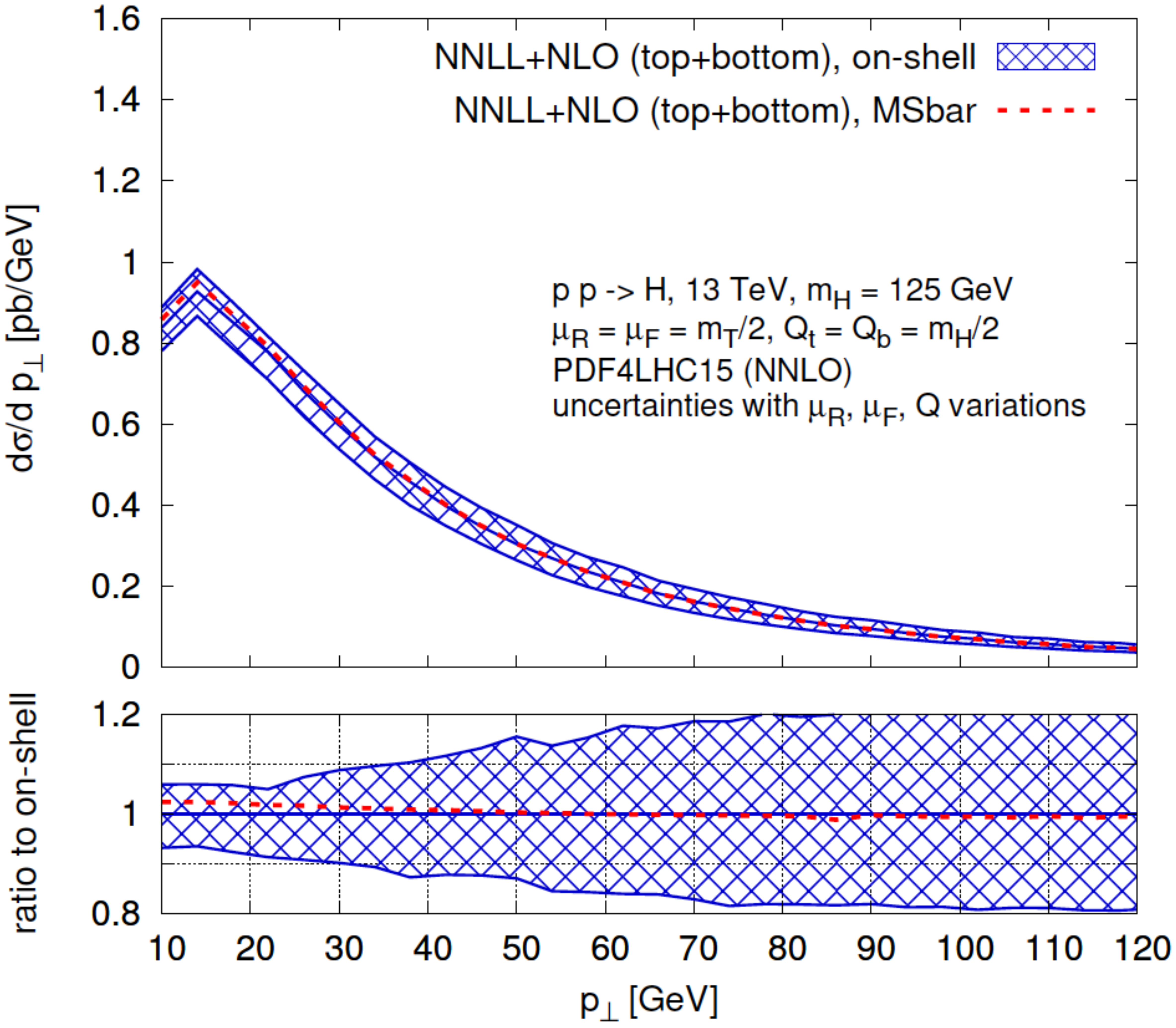
Higgs p_T distribution: quark masses



[Caola, Lindert, Melnikov, PM, Tancredi, Wever ’18]

Higgs p_T distribution: quark masses

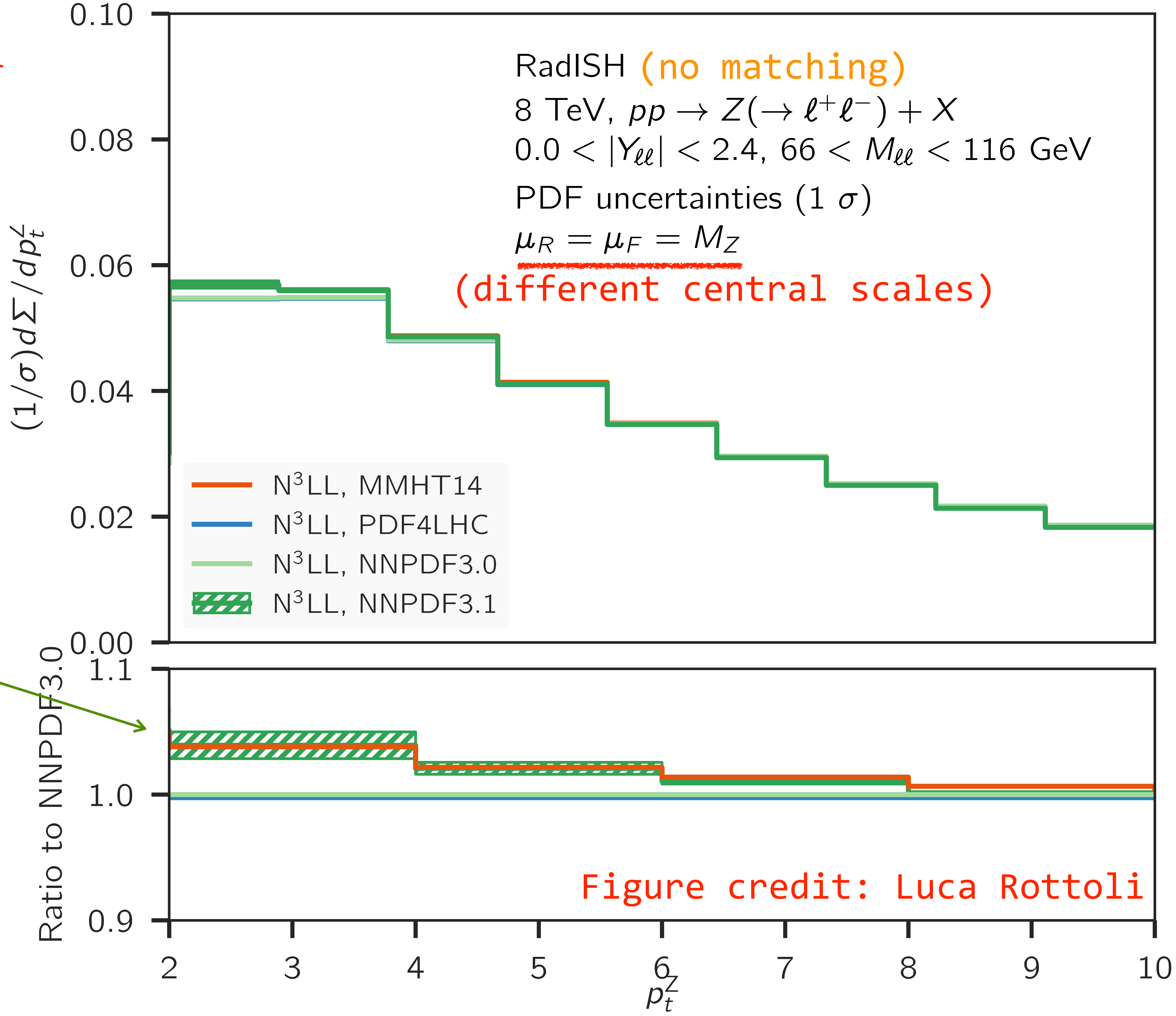




PDF uncertainty (Z @ LHC8)

- Data and fiducial cuts from [**ATLAS 1512.02192**]
- **PDF errors at the 1% level, but difference between sets can be as large as 3.5%**
  - Spectrum slightly harder with latest sets
  - Theory uncertainties in PDFs become relevant
    - see also Juan Rojo’s talk (this morning)

$p_t^{\ell^\pm} > 20\ \mathrm{GeV}, \qquad |\eta^{\ell^\pm}| < 2.4,$



(different central scales)

Envelope of NNPDF3.1 sets

Figure credit: Luca Rottoli

More predictions at LHC8 (phi*)