The role of q_T resummation in fiducial cross sections at the LHC

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Based on
[PRL 127 (2021) 7, 072001; arXiv:2102.08039]
[JHEP 04 (2021) 102; arXiv:2006.11382]
[JHEP 03 (2020) 158; arXiv:1911.08486]

in collaboration with

G. Billis, B. Dehnadi, J. Michel, I. Stewart, F. Tackmann

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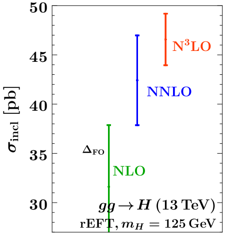
Motivation: Higgs production at the LHC

- $gg \to H \to \gamma\gamma$ a key benchmark of the SM
- Can only measure *fiducial* cross sections in experiment, i.e. necessarily apply kinematic selection cuts
- Example: [ATLAS-CONF-2019-029]

$$p_T^{\gamma 1} \geq 0.35\, m_H, \quad p_T^{\gamma 2} \geq 0.25\, m_H, \qquad |\eta_\gamma| \leq 1.37 \quad \text{or} \quad 1.52 \leq |\eta_\gamma| \leq 2.37$$

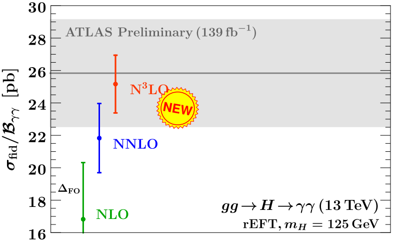
Inclusive Higgs production

- N^{3}LO result calculated in [Anastasiou et al '15, Mistlberger '18]
- Perturbation theory stable at N^{3}LO



Fiducial Higgs production (ATLAS $\gamma\gamma$ cuts)

- Calculated at N^{3}LO in [Billis, Dehnadi, ME, Michel, Tackmann '21]
- Apparent loss of convergence



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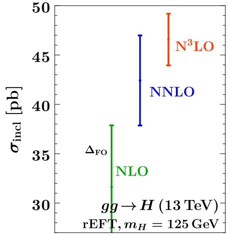

Fiducial Higgs production (ATLAS $\gamma\gamma$ cuts)

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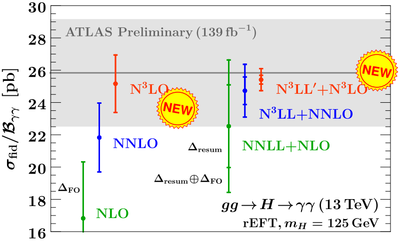
- q_T-Resummation restores convergence



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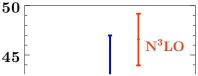

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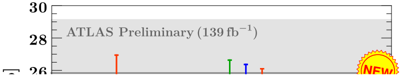


Goal of this talk:

1. Understand how q_T resummation impacts the *total fiducial* cross section
2. How to calculate fiducial cross sections with q_T resummation

Resummation effects in the total cross section

Resummation effects in the total cross section

- Starting point: factorize cross section into decay and production:

$$\sigma(\Theta) = \int \mathrm{d}Y\,\mathrm{d}q_T\, A(q_T, Y; \Theta) W(q_T, Y)$$

  - q is Higgs momentum
  - Cuts Θ only enter the acceptance A
  - $W(q_T, Y)$ is the hadronic structure function

- n.b.: For Drell-Yan, replace $A\,W \to A^{\mu\nu} W_{\mu\nu} = \sum_{i=-1}^{7} A_i W_i$
  - A_i are the angular coefficients (depend on CS angles (θ, ϕ))
  - Same conclusions as for Higgs when integrating over (θ, ϕ)

    [ME, Michel, Stewart, Tackmann '20] $\to$ in this talk, consider only Higgs production

- *Inclusive* case: $A_{\mathrm{incl}} = 1 \quad \Rightarrow \quad \sigma_{\mathrm{incl}} = \int \mathrm{d}Y\,\mathrm{d}q_T W(q_T, Y)$

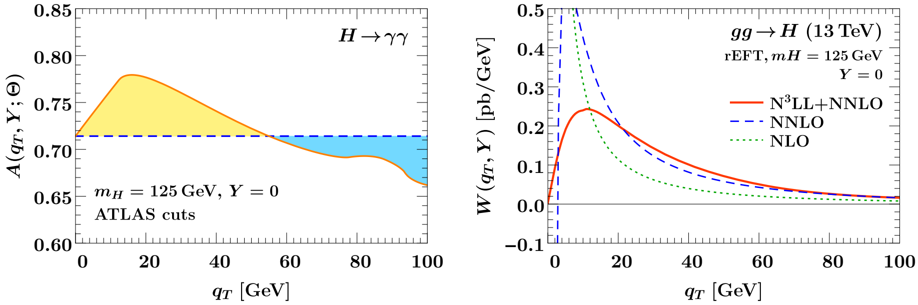
- *Fiducial* case: $A(q_T, Y; \Theta)$ acquires nontrivial dependence on q_T
  - Typically induces sensitivity to small-q_T region
  - which makes cross section sensitive to q_T resummation

Illustration of acceptance

- Fiducial corrections from q_T-dependence of A induce resummation effects in

$$\sigma(\Theta) = \int \mathrm{d}Y\, \mathrm{d}q_T\, A(q_T, Y; \Theta) W(q_T, Y)$$

- Acceptance acts as a weight under the q_T integral
  - Strong q_T-dependence of $A(q_T, Y; \Theta)$ in resummation regime $q_T \ll m_H$



- Effect is *predicted* by resummed perturbation theory

Relation to q_T factorization

- Generic structure of the q_T spectrum:

$$\frac{d\sigma}{dq_T} = \frac{d\sigma^{(0)}}{dq_T} + \frac{d\sigma^{(1)}}{dq_T} + \frac{d\sigma^{(2)}}{dq_T} + \cdots$$
$$= \frac{1}{q_T}\left[\mathcal{O}(1) + \mathcal{O}\left(\frac{q_T}{m_H}\right) + \mathcal{O}\left(\frac{q_T^2}{m_H^2}\right) + \cdots\right]$$

- $\sigma^{(0)}$: Described by well-known TMD factorization theorem

$$\frac{d\sigma^{(0)}}{dq_T} \sim \frac{1}{q_T}\sum_{n,m}\alpha_s^n \ln^m \frac{q_T}{m_H}$$

  - Divergent as $q_T \to 0$ and requires resummation (well known)

- $\sigma^{(1)}$: Linear power corrections from fiducial cuts [ME, Michel, Stewart, Tackmann '20]

$$\frac{d\sigma^{(1)}}{dq_T} \sim \frac{1}{m_H}\sum_{n,m}\alpha_s^n \ln^m \frac{q_T}{m_H}$$

  - Still logarithmically divergent as $q_T \to 0$

- $\sigma^{(2)}$: Arise from fiducial cuts *and* corrections to hadronic tensor
  - Truly suppressed as $q_T \to 0$ $\quad\to\quad$ extracted from fixed order

Relation to q_T factorization

- Recall: $$\sigma(\Theta) = \int \mathrm{d}Y\, \mathrm{d}q_T\, A(q_T, Y; \Theta) W(q_T, Y)$$
- Expand acceptance and hadronic structure function as

$$A(q_T, Y; \Theta) = A^{(0)}(Y; \Theta) \quad \times \left[1 + \mathcal{O}\left(\frac{q_T}{m_H}\right)\right]$$
$$W(q_T, Y) = W^{(0)}(q_T, Y) \times \left[1 + \mathcal{O}\left(\frac{q_T^2}{m_H^2}\right)\right]$$

  - Presence of linear terms first pointed out in [ME, Tackmann '19]
- Strict TMD factorization:

$$\frac{\mathrm{d}\sigma^{(0)}}{\mathrm{d}q_T} = \int \mathrm{d}Y\, A^{(0)}(Y; \Theta) W^{(0)}(q_T, Y)$$

- Isolate linear fiducial power corrections:

$$\frac{\mathrm{d}\sigma^{\mathrm{fpc}}}{\mathrm{d}q_T} = \int \mathrm{d}Y \left[A(q_T, Y; \Theta) - A^{(0)}(Y; \Theta)\right] W^{(0)}(q_T, Y)$$

  - Contains *all* linear (and more) power corrections [ME, Michel, Stewart, Tackmann '20]

Numerical illustration

- Isolate linear fiducial power corrections:

$$\frac{d\sigma^{\text{fpc}}}{dq_T} = \int dY \left[A(q_T, Y; \Theta) - A^{(0)}(Y; \Theta)\right] W^{(0)}(q_T, Y)$$

- Isolate their effect in the fixed-order expansion of $\sigma(\Theta)$ and compare to inclusive cross section σ

$$\sigma^{\text{FO}}_{\text{incl}} = 13.80\,[1 + 1.291 + 0.783 + 0.299]\,\text{pb}$$

$$\sigma^{\text{FO}}_{\text{fid}} = 6.928\,[1 + 1.429 + 0.723 + 0.481]\,\text{pb}$$

$$= 6.928\,[1 + (1.300 + 0.129_{\text{fpc}}) + (0.784 - 0.061_{\text{fpc}}) + (0.331 + 0.150_{\text{fpc}})]\,\text{pb}$$

- Fiducial power corrections show no convergence, while remainder is very similar to inclusive case
  - See also [Alekhin, Kardos, Moch, Trócsányi '21] for detailed numerical study for Drell-Yan

q_T resummation and total cross section

- Isolate linear fiducial power corrections:

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- Fiducial power corrections show no convergence,
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- Good news: fiducial corrections can be resummed in the standard fashion
  - Only requires standard TMD resummation of $W^{(0)}(q_T, Y)$
- Total cross section becomes derived quantity from resummed q_T spectrum

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Remark on [Salam, Slade '21]:

- By using DDT formula $W^{(0)}(q) \sim \frac{4\alpha_s C_A L}{\pi q_T} e^{-2\alpha_s C_A L^2/\pi}$, can show that

$$\sigma^{\rm fpc} \sim \sum_n (-1)^{n+1} \frac{(2n!)}{2(n!)} \left(\frac{2\alpha_s C_A}{\pi}\right)^n$$

  - Fixed-order is factorially divergent and *requires* resummation
- Alternative approach: employ cuts that avoid linear corrections
  $\to$ requires agreement with experimentalists on suitable cuts

Higgs q_T spectrum and total cross section at N^{3}LO+N^{3}LL$'$

Setup

Resummed q_T spectrum:

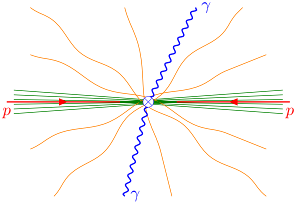
- Split q_T spectrum as $$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\text{sing}}}{dq_T} + \frac{d\sigma^{\text{nons}}}{dq_T}$$
- Singular cross section captures LP *and* fiducial corrections:

$$\frac{d\sigma^{\text{sing}}}{dq_T} = \frac{d\sigma^{(0)}}{dq_T} + \frac{d\sigma^{\text{fpc}}}{dq_T} = \int dY\, A(q_T, Y; \Theta) W^{(0)}(q_T, Y)$$

- Standard TMD factorization [Collins, Soper, Sterman '85; Becher, Neubert '10; Collins '11; Echevarria, Idilbi, Scimemi '11, Chiu, Jain, Neill, Rothstein '12]

$$W^{(0)}(q_T, Y) = H(m_H^2, \mu) \int d^2\vec{b}_T\, e^{i\vec{q}_T \cdot \vec{b}_T} B_g^{\mu\nu}(x_a, \vec{b}_T, \mu, \nu) B_{g\,\mu\nu}(x_b, \vec{b}_T, \mu, \nu) S(b_T, \mu, \nu)$$

- Implement N^{3}LL evolution of virtuality (μ) and rapidity (ν) RGE in b_T space
  - Hybrid profile scales to turn off resummation [Lustermans, JM, Tackmann, Waalewijn '19]



- Three-loop ingredients for N^{3}LL$'$ accuracy:
  - Form factor [Baikov et al. '09; Lee et al., Gehrmann et al. '10]
  - Beam function [ME, Mistlberger, Vita; Luo, Yang, Zhu, Zhu '20] $\rightarrow$ see G. Vita's talk
  - Soft function [Li, Zhu '16]

Setup

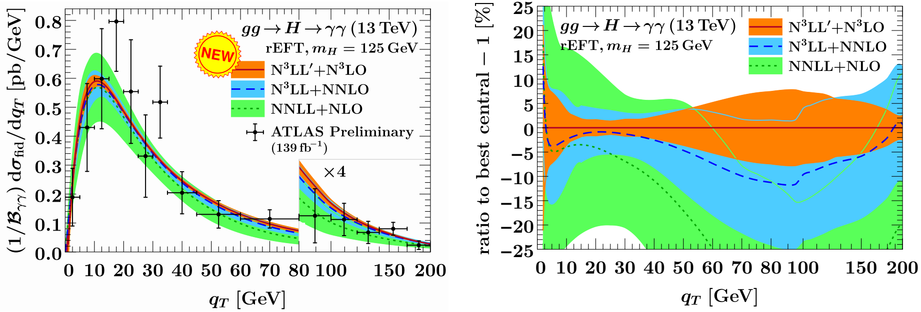
Nonsingular corrections

- Split q_T spectrum as $$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\rm sing}}{dq_T} + \frac{d\sigma^{\rm nons}}{dq_T}$$
- Nonsingular terms from fixed order:

$$\frac{d\sigma^{\rm nons}}{dq_T} = \int dY\, A(q_T, Y; \Theta)\left[W^{(2)}(q_T, Y) + \cdots\right] = \left[\frac{d\sigma_{\rm FO}}{dq_T} - \frac{d\sigma^{\rm sing}_{\rm FO}}{dq_T}\right]_{q_T>0}$$

- $\sigma_{\rm FO}$ obtained from $H+1j$ at NNLO
  - Obtaining stable results is hard (particularly at NNLO)
  - At NLO: renormalize & implement bare analytic results
    [Dulat, Lionetti, Mistlberger, Pelloni, Specchia '17]
  - At NNLO: fit `NNLOjet` data to known functional form of nonsingular terms
    [Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '15-16; as used in Chen et al; Bizoń et al. '18]
- Fitted results allow us to apply nonsingular correction down to $q_T \to 0$
  - Crucial for integrating over q_T to obtain total cross section
  - n.b. for the experts: we use differential q_T subtractions,
    not a q_T slicing which suffers from huge corrections

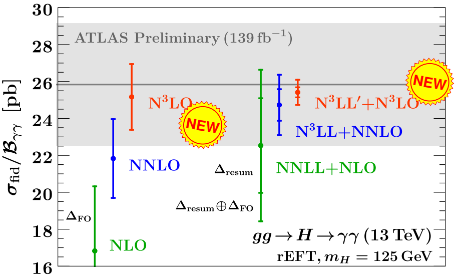
Results: fiducial q_T spectrum at N^{3}LL′+N^{3}LO



- Total uncertainty is $\Delta_{\rm tot} = \Delta_{q_T} \oplus \Delta_{\varphi} \oplus \Delta_{\rm match} \oplus \Delta_{\rm FO} \oplus \Delta_{\rm nons}$
  [See also ME, Michel, Stewart, Tackmann, 2006.11382 for details]
- Observe excellent perturbative convergence & uncertainty coverage
  - Crucial to consider *every* variation to probe all parts of the prediction
- Divide $H \to \gamma\gamma$ branching ratio $\mathcal{B}_{\gamma\gamma}$ out of data [LHC Higgs Cross Section WG, 1610.07922]
- Data are corrected for other production channels, photon isolation efficiency
  [ATLAS, 1802.04146]

Results: fiducial cross section at N^{3}LL$'$+N^{3}LO

- Integrating the (un-)resummed q_T spectrum yields total cross section:



- Larger N^{3}LO corrections to fiducial than to inclusive cross section
  - Caused by fiducial power corrections & must be resummed
- Resummation restores convergence
  - Dedicated estimate of resummation uncertainty $\Delta_{\rm resum}$
- First direct comparison to experimentally measured total Higgs cross section at genuine three-loop order

Conclusion

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Resummation effects in the total cross section

- Showed that fiducial cuts generically induce linear power corrections
- These are logarithmically divergent as $q_T \to 0$ and *must* be resummed
  - Easily understood as q_T-dependent shape of acceptance
  - Total cross section becomes derived quantity from q_T spectrum
- Standard TMD resummation sufficient: $\sigma(\Theta) = \int \mathrm{d}^4 q \, A(q;\Theta) W^{(0)}(q) + \cdots$
- Outlook: Also applies to other leptonic observables (e.g. p_T^γ) and fiducial Drell-Yan production

Higgs production at N^{3}LO+N^{3}LL′:

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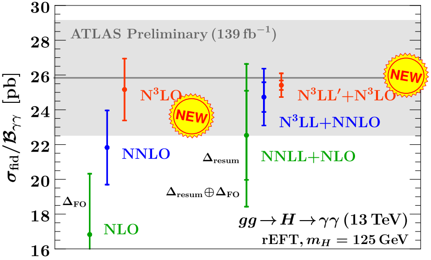
- First direct comparison to LHC data at genuine three-loop order



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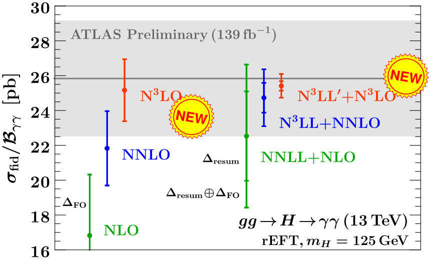
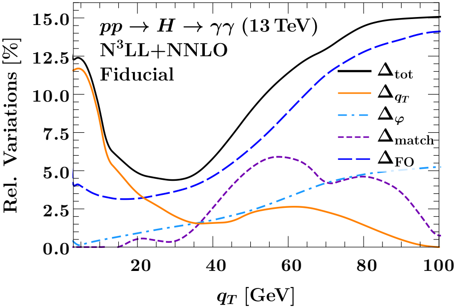
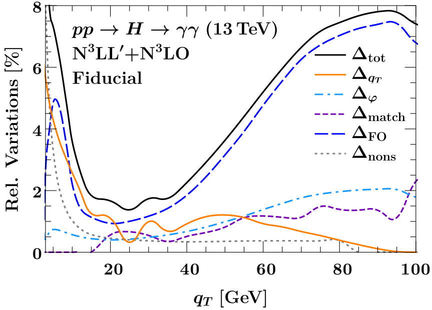


Backup slides

Uncertainty breakdown



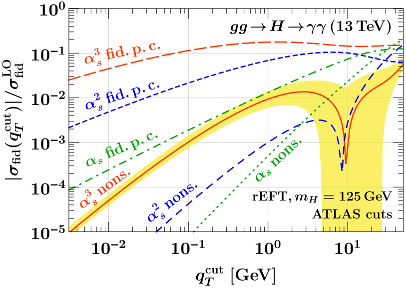


N^{3}LO: $\sigma_{\rm fid}/\mathcal{B}_{\gamma\gamma} = (25.16 \pm 1.78_{\rm FO} \pm 0.12_{\rm nons})$ pb

N^{3}LL$'$+N^{3}LO: $\sigma_{\rm fid}/\mathcal{B}_{\gamma\gamma} = (25.41 \pm 0.59_{\rm FO} \pm 0.21_{q_T} \pm 0.17_{\varphi} \pm 0.06_{\rm match} \pm 0.20_{\rm nons})$ pb

- Δ_{q_T} 36 independent scale variations in $W^{(0)}$ factorization
- Δ_{φ} Vary phase of hard scale over $\arg \mu_H \in \{\pi/4, 3\pi/4\}$
- $\Delta_{\rm match}$ Vary transition points governing resummation turn-off
- $\Delta_{\rm FO}$ Vary $\mu_R/m_H \in \{1/2, 2\}$ (dominates over μ_F due to overall α_s^2)
- $\Delta_{\rm nons}$ Uncertainty on nonsingular extraction

Comparison to other methods: q_T slicing



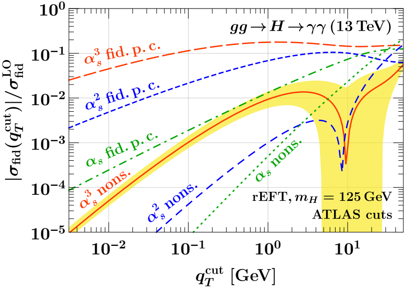
Slicing approach to q_T subtractions:

[used e.g. in Cieri, Chen, Gehrmann, Glover, Huss, 1807.11501; Camarda, Cieri, Ferrera, 2103.04974]

$$\sigma = \underbrace{\sigma^{(0)}(q_T^{\rm cut}) + \sigma^{\rm fpc}(q_T^{\rm cut})}_{=\sigma^{\rm sing}(q_T^{\rm cut})} + \sigma^{\rm nons}(q_T^{\rm cut}) + \int_{q_T^{\rm cut}} {\rm d}q_T \, \frac{{\rm d}\sigma_{\rm FO_1}}{{\rm d}q_T}$$

- Slicing uses finite $q_T^{\rm cut} \sim 2\,{\rm GeV}$ and neglects *both* $\sigma^{\rm fpc}(q_T^{\rm cut}), \sigma^{\rm nons}(q_T^{\rm cut}) \approx 0$
- This is a catastrophic approximation even at α_s^2, and definitely at α_s^3
- Even without $\sigma^{\rm fpc}$ (e.g., without cuts), this is a bad approximation at α_s^3
  - $q_T^{\rm cut}$ variations only scan local maximum around $2\,{\rm GeV}$ ...

Comparison to other methods: Projection to Born



Projection-to-Born method:

[used e.g. in Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607]

$$\frac{d\sigma}{dY} = A(0,Y)\,\frac{d\sigma_{\rm incl}}{dY} + \int_{\approx q_T^{\rm cut}} dq_T\,\big[A(q_T,Y) - A(0,Y)\big]\,W(q_T,Y)$$

- First term from analytic (threshold expansion of) inclusive rapidity spectrum
- Second term numerically from $H + 1j$ MC, dominated by $\sigma^{\rm fpc}$ at small q_T
- Need to integrate down to $q_T^{\rm cut} \ll 0.1\,{\rm GeV}$ to get error below 10% of $\sigma_{\rm LO}^{\rm fid}$!
  [See also Salam, Slade, 2106.08329 for an explicit/analytic estimate at double-logarithmic level]

Fitting nonsingular corrections

- Split q_T spectrum as $$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\rm sing}}{dq_T} + \frac{d\sigma^{\rm nons}}{dq_T}$$
- Nonsingular terms from fixed order:

$$\frac{d\sigma^{\rm nons}}{dq_T} = \int dY\, A(q_T, Y; \Theta)\big[W^{(2)}(q_T, Y) + \cdots\big] = \left[\frac{d\sigma_{\rm FO}}{dq_T} - \frac{d\sigma^{\rm sing}_{\rm FO}}{dq_T}\right]_{q_T > 0}$$

- Obtaining stable results is hard (particularly at NNLO)

Key idea

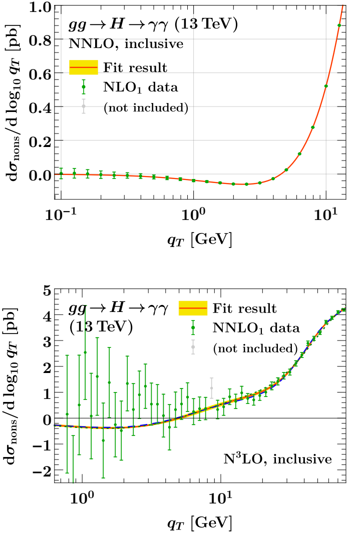
Fit nonsingular data to known form at subleading power and integrate *analytically*:

$$q_T \frac{d\sigma^{\rm nons}_{\rm FO}}{dq_T}\bigg|_{\alpha_s^n} = \frac{q_T^2}{m_H^2} \sum_{k=0}^{2n-1} \left(a_k + b_k \frac{q_T}{m_H} + c_k \frac{q_T^2}{m_H^2} + \cdots\right) \ln^k \frac{q_T^2}{m_H^2}$$

- Include higher-power b_k, c_k to get unbiased a_k
- Allows us to use more precise data at higher q_T as lever arm in the fit
- Include dedicated fit uncertainty
- Fit procedure tested extensively in [Moult, Rothen, Stewart, Tackmann, Zhu '15-'16]

Fit results

Inclusive:



Fiducial: