Higgs p_T Spectrum and Total Cross Section with Fiducial Cuts

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[based on 2102.08039]

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE
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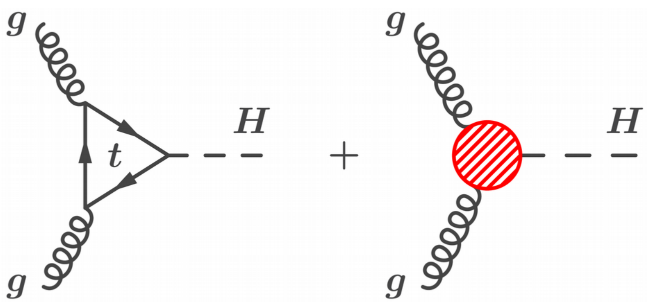
DESY.

LHC Physics Meeting, October 25th 2021, DESY

Motivation

- Precise measurements of the Higgs boson properties are crucial part of the physics program at LCH

- Differential cross sections such as Higgs p_T spectrum are of prime interest
  - Serves as bench mark spectrum in various experimental analyses
  - Provides a model independent way to search for BSM in the Higgs sector



$$= \left(\frac{\alpha_s}{12\pi v} C_t + \frac{v}{\Lambda^2} C_{HG}\right) H\, G^a_{\mu\nu} G^{a,\mu\nu}$$

Motivation

Challenges for theory:

- QCD corrections to $gg \to H$ are large: $\sigma/\sigma_{\rm LO} \sim 3$
- Calculation of the inclusive cross sections has been pushed up to N^{3}LO

[Anastasiou, Duhr, Dulta, Furlan, Gerhmann, Herzog, Lazopoulos, Mistlberger ‘15-’18]

- However experimental measurements at LHC apply kinematic selection cuts on Higgs decay products

ATLAS fiducial cuts for $H \to \gamma\gamma$

$$p_T^{\gamma 1} \geq 0.35\, m_H\,, \quad p_T^{\gamma 2} \geq 0.25\, m_H\,, \quad |\eta^\gamma| \leq 2.37\,, \quad |\eta^\gamma| \notin [1.37, 1.52]$$

Needs to account properly for the complete interplay of QCD and *O(1)* fiducial effects

Goal

Consider $gg \to H \to \gamma\gamma$ with ATLAS fiducial cuts: [Billis, BD, Ebert, Michel, Tackmann, '21]

$$p_T^{\gamma 1} \geq 0.35\, m_H\,, \quad p_T^{\gamma 2} \geq 0.25\, m_H\,, \quad |\eta^\gamma| \leq 2.37\,, \quad |\eta^\gamma| \notin [1.37, 1.52]$$

Goal:

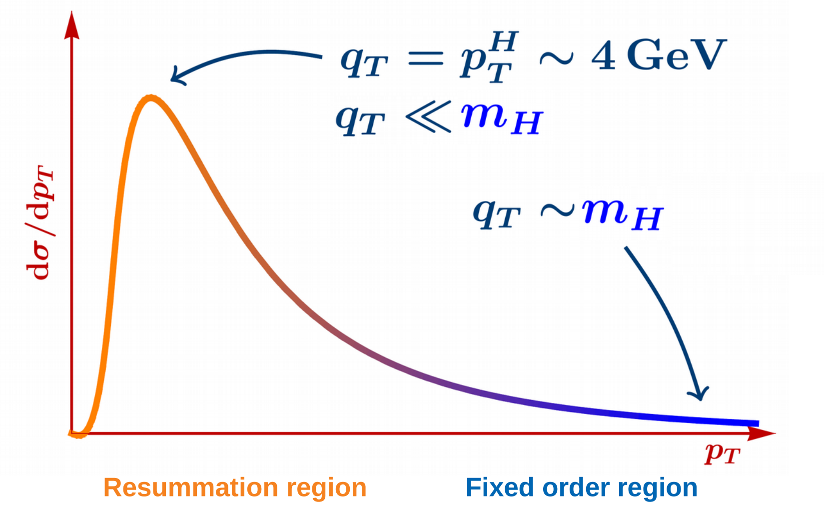
Compute fiducial spectrum in $q_T = p_T^H = p_T^{\gamma\gamma}$ at $\mathrm{N^3LL'{+}N^3LO}$

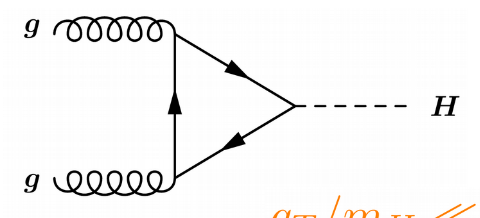
Compute total fiducial cross section at $\mathrm{N^3LL'{+}N^3LO}$

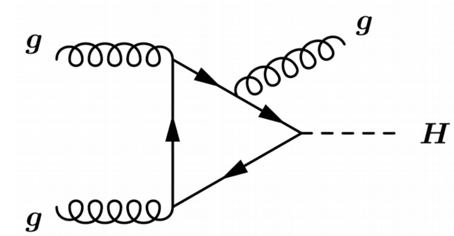
Previous state of the art was $\mathrm{N^3LL + NNLO}$ and NNLO, respectively
[Chen et al.'18, Bizon et al. '18, Gutierre-Reyes et al. '19, Becher, Neumann '20]

Theory overview

Higgs p_T Spectrum







$q_T/m_H \ll 1$

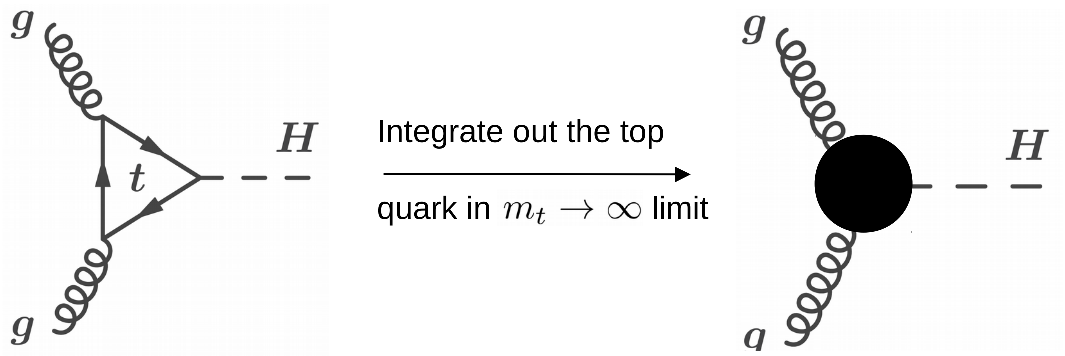
$q_T/m_H \sim 1$

- Close to Born kinematics dressed with soft and collinear emissions
- Use EFT approaches (SCET):
  - ✓ Systematic expansion in power of q_T
  - ✓ Cross section factorizes
  - ✓ Resumes large logarithms for dominant singular corrections

- Described by H + (1-jet) kinematics
- Perturbative fixed order (FO) calculation

Theory: Framework

$$g(p_a)\, g(p_q) \rightarrow H(q) + X(p_X) \rightarrow \gamma(p_1)\gamma(p_2) + X(p_X)$$



✓ QCD current in EFT:

$$J_{\mathrm{EFT}} = \frac{\alpha_s}{12\,\pi\,v}\, C_t(m_t)\, F_{\mu\nu}\, F^{\mu\nu}$$

✓ Dominant top mass dependence → rescale with the exact leading order (rEFT):

$$J_{\mathrm{rEFT}} = \frac{\alpha_s}{12\,\pi\,v}\, F_0(m_t)\, C_t(m_t)\, F_{\mu\nu}\, F^{\mu\nu}$$

Theory: Framework

$\Gamma_H \ll m_H$ ➡ Production and decay of the Higgs factorize

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

$W(q_T, Y)$ → **hadronic structure** function encoding the $gg \to H$ production process

✓ **Only** depends on the **higgs rapidity** (Y) and **transverse momentum** (q_T)

$$W(q_T, Y) = \frac{\mathrm{d}\sigma_{\mathrm{incl}}}{\mathrm{d}q_T \mathrm{d}Y} = \frac{\pi^2}{2E_{\mathrm{cm}}^2} \sum\!\!\!\!\!\!\int_X \langle gg|J_{\mathrm{rEFT}}^\dagger|X\rangle\langle X|J_{\mathrm{rEFT}}|gg\rangle \delta^4(p_a + p_b - q - p_X)$$

$A(q_T, Y; \Theta)$ → **acceptance factor** encoding the **higgs decay and fiducial cuts (** Θ **)**

✓ $A_{\mathrm{incl}} = 1$

Higgs p_T Spectrum

Expand the cross section in powers of q_T

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} = \frac{\mathrm{d}\sigma^{(0)}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{(1)}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{(2)}}{\mathrm{d}q_T} + \cdots$$

$$\sim \frac{1}{q_T}\left[\mathcal{O}(1) + \mathcal{O}\left(\frac{q_T}{m_H}\right) + \mathcal{O}\left(\frac{q_T^2}{m_H^2}\right) + \cdots\right]$$

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

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

$$\frac{\mathrm{d}\sigma^{\mathrm{nons}}}{\mathrm{d}q_T} = \int \mathrm{d}Y\, A(q_T, Y; \Theta) \left[W^{(2)}(q_T, Y) + \cdots\right]$$

same hadronic structure enters the leading power and fiducial power corrections

Higgs p_T Spectrum

Expand the cross section in powers of q_T

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

Leading Power:

$$\frac{d\sigma^{(0)}}{dq_T} = \sigma_{\mathrm{LO}}\,\delta(q_T) + \sum_{n=1} \alpha_s^n \left\{ \sigma_n^{\mathrm{V}}\,\delta(q_T) + \sum_{m=0}^{2n-1} \sigma_{nm}^{(0)} \left[\frac{\ln^m(q_T/m_H)}{q_T}\right]_+ \right\}$$

- Leading order + α_s { virtual corrections + real radiation (log enhanced / singular) }
- Predicted by factorization theorem in SCET: $W^0 = H \times B \otimes B \otimes S$

  Hard function: includes the Wilson coefficient from matching SCET onto rEFT

  $$H = \left|\alpha_s\, F_0(m_t)\, C_t(m_t) C_{gg}(m_H)\right|^2$$

  Beam functions: collinear initial state radiations

  Soft function: isotropic soft radiations

✓ systematically resumes log-enhanced singular terms to all order in perturbation theory

✓ all ingredients are know for analysis at $\mathrm{N^3LL'}+\mathrm{N^3LO}$ [see 2102.08039 for all references]

Higgs p_T Spectrum

Expand the cross section in powers of q_T

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

Linear (fiducial) power corrections:

$$\frac{d\sigma^{\rm fpc}}{dq_T} = \sum_{n=1} \alpha_s^n \sum_{m=0}^{2n-1} \sigma^{\rm fpc}_{nm} \frac{1}{m_H} \ln^m(q_T/m_H)$$

- Still logarithmic divergent (but integrable for $q_T \to 0$)
- Also predicted by the factorization theorem for W^0 [Ebert, Michel, Stewart, Tackmann '20]
  - ✓ Can be resummed to the same order as leading power corrections
  - ✓ Can be included in the q_T-subtraction techniques (i.e. total cross section)

Higgs p_T Spectrum

Expand the cross section in powers of q_T

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

Quadratic and higher order power corrections:

$$\frac{d\sigma^{\rm nons}}{dq_T} = \sum_{n=1} \alpha_s^n \sum_{m=0}^{2n-1} \sigma^{\rm nons}_{nm} \frac{q_T}{m_H^2} \ln^m(q_T/m_H) + \cdots$$

- **Non-singular** (vanishes for $q_T \to 0$)
- Extracted from **H + (*1-jet*)** calculations in fixed order perturbation theory

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

$$\frac{d\sigma^{\rm nons}}{dq_T} = \frac{d\sigma^{(\rm full)}_{\rm FO}}{dq_T} - \frac{d\sigma^{(0)}_{\rm FO}}{dq_T} - \frac{d\sigma^{\rm fpc}_{\rm FO}}{dq_T}$$

Higgs p_T Spectrum

Expand the cross section in powers of q_T

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} = \frac{\mathrm{d}\sigma^{(0)}_{\mathrm{res}}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{\mathrm{fpc}}_{\mathrm{res}}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{\mathrm{nons}}}{\mathrm{d}q_T}$$

$$\sim \frac{1}{q_T}\left[\mathcal{O}(1) + \mathcal{O}\left(\frac{q_T}{m_H}\right) + \mathcal{O}\left(\frac{q_T^2}{m_H^2}\right) + \cdots\right]$$

Quadratic and higher order power corrections:

$$\frac{\mathrm{d}\sigma^{\mathrm{nons}}}{\mathrm{d}q_T} = \sum_{n=1} \alpha_s^n \sum_{m=0}^{2n-1} \sigma^{\mathrm{nons}}_{nm} \frac{q_T}{m_H^2} \ln^m(q_T/m_H)$$

- **Non-singular** (vanishes for $q_T \rightarrow 0$)
- Extracted from **H + (*1-jet*)** calculations in fixed order perturbation theory

  fixed order input:

  NLO and NNLO results are well known [Dulat, Lionetti,Mistlberger, Pelloni, Specchia ‘17]

  At N³LLO, used the existing binned results from NNLOjet (not precise enough towards small q_T)
  [Chen et al ‘15-’16-’18 , Bizon et al ‘18]

A priori not a problem for determining q_T spectrum where $q_T > 2\,\mathrm{GeV}$
However we need a better control on the spectrum for $q_T < 2\,\mathrm{GeV}$ to have a reliable determination for the total cross section (to integrate over the spectrum)

Higgs p_T Spectrum

Expand the cross section in powers of q_T

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} = \frac{\mathrm{d}\sigma^{(0)}_{\mathrm{res}}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{\mathrm{fpc}}_{\mathrm{res}}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{\mathrm{nons}}}{\mathrm{d}q_T}$$
$$\sim \frac{1}{q_T}\Big[\mathcal{O}(1) + \mathcal{O}\Big(\frac{q_T}{m_H}\Big) + \mathcal{O}\Big(\frac{q_T^2}{m_H^2}\Big) + \cdots\Big]$$

Quadratic and higher order power corrections:

$$\frac{\mathrm{d}\sigma^{\mathrm{nons}}}{\mathrm{d}q_T} = \sum_{n=1}\alpha_s^n \sum_{m=0}^{2n-1} \sigma^{\mathrm{nons}}_{nm} \frac{q_T}{m_H^2} \ln^m(q_T/m_H)$$

- **Non-singular** (vanishes for $q_T \to 0$)
- Extracted from **H + (*1-jet*)** calculations in fixed order perturbation theory

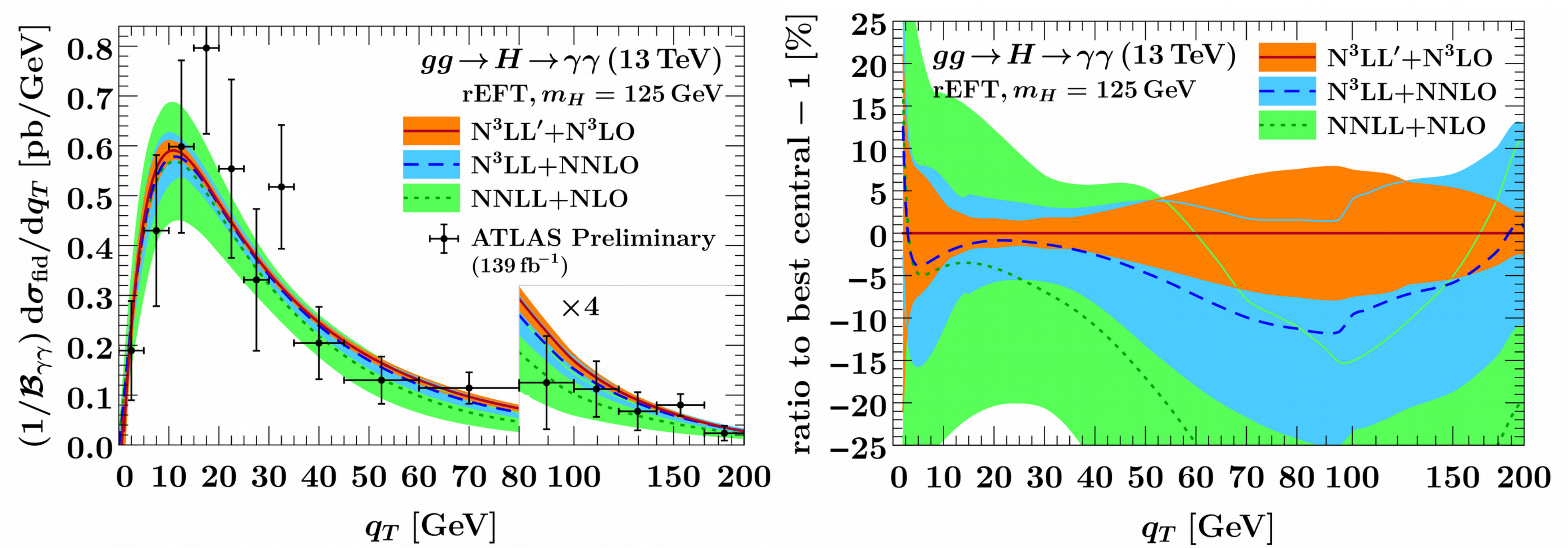
Key Idea: fit non-singular data to well known form at subleading powers

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

✓ more precise data at higher q_T to control the non-singular in the deep IR limit $q_T \to 0$
✓ allows an analytic integration over the spectrum down to $q_T = 0$ to determine total cross section

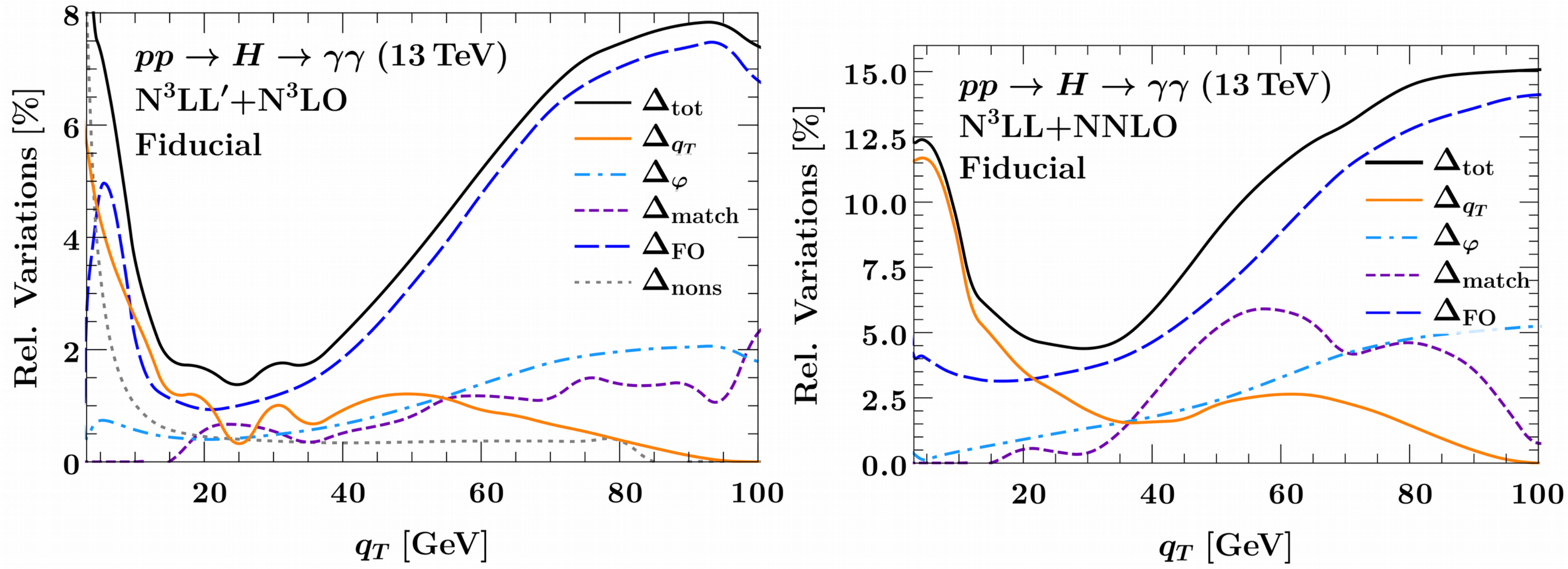
Numerical results

Fiducial p_T Spectrum



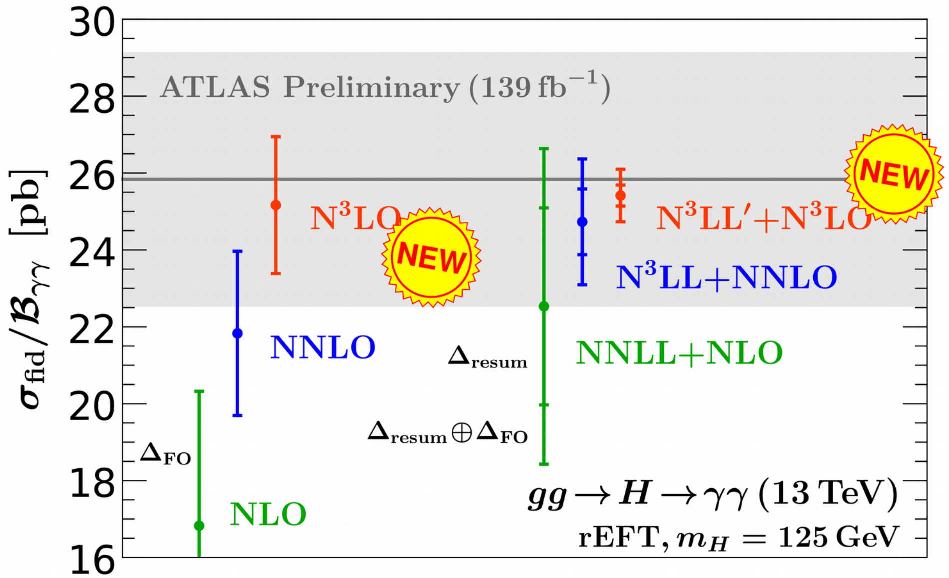
- Total uncertainty is $\Delta_{tot} = \Delta_{q_T} \oplus \Delta_{\varphi} \oplus \Delta_{match} \oplus \Delta_{FO} \oplus \Delta_{nons}$
- Observe excellent perturbative convergence and uncertainty coverage
- Devided the branching ratio out of data [LHC Higgs Cross Section WG, 1610.07922]
- Data are corrected for other production channels, photon isolation efficiency [ATLAS, 1802.04146]

Error Budget



✓ Major reductions in the resummation and fixed order uncertainties (**note the y axis scales**)

Total Cross Section



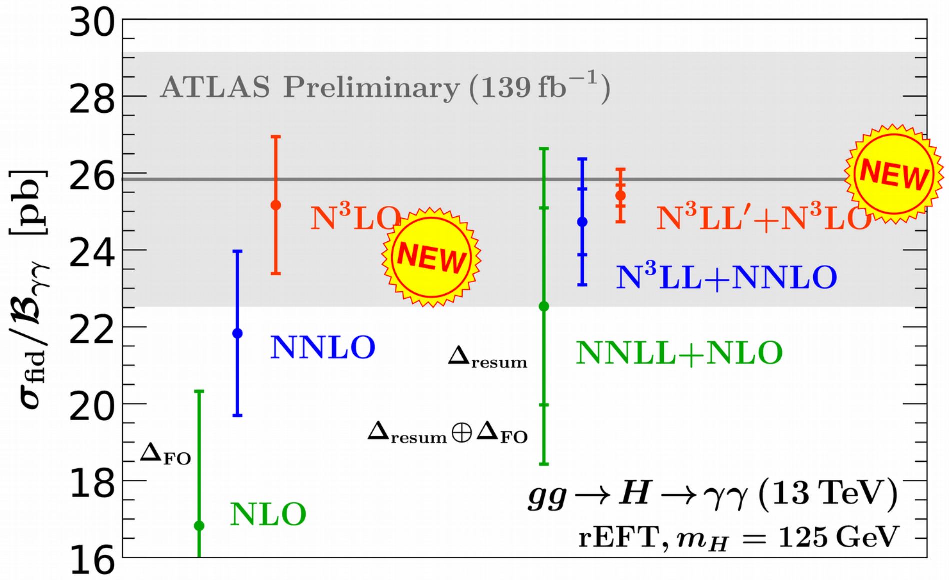
- ✓ Total cross section: $\sigma = \int_0 \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$
- ✓ Fiducial power corrections induce resummation effects in the total cross section

Compare fixed-order series, isolating effect of $\int \mathrm{d}q_T \, \frac{\mathrm{d}\sigma^{\rm fpc}}{\mathrm{d}q_T}$:

$$
\begin{aligned}
& \qquad\qquad\qquad \alpha_s \qquad\qquad\qquad\qquad \alpha_s^2 \qquad\qquad\qquad\qquad \alpha_s^3 \\
\sigma_{\rm incl}^{\rm FO} &= 13.80\,[1 + 1.291 \quad + 0.783 \quad + 0.299]\,\mathrm{pb} \\
\sigma_{\rm fid}^{\rm FO} &= 6.928\,[1 + 1.429 \quad + 0.723 \quad + 0.481]\,\mathrm{pb} \\
&= 6.928\,[1 + (1.300 + 0.129_{\rm fpc}) + (0.784 - 0.061_{\rm fpc}) + (0.331 + 0.150_{\rm fpc})]\,\mathrm{pb}
\end{aligned}
$$

► Fiducial power corrections show no convergence, remainder is similar to inclusive

Total Cross Section



- ✓ Total cross section: $\sigma = \int_0 \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$
- ✓ Fiducial power corrections induce resummation effects in the total cross section

After resummation of $\sigma^{(0)} + \sigma^{\rm fpc}$, at successive matched orders:

$$\sigma^{\rm res}_{\rm incl} = 24.16\,[1 + 0.756 + 0.207 + 0.024]\,\mathrm{pb}$$
$$\sigma^{\rm res}_{\rm fid} = 12.89\,[1 + 0.749 + 0.171 + 0.053]\,\mathrm{pb}$$

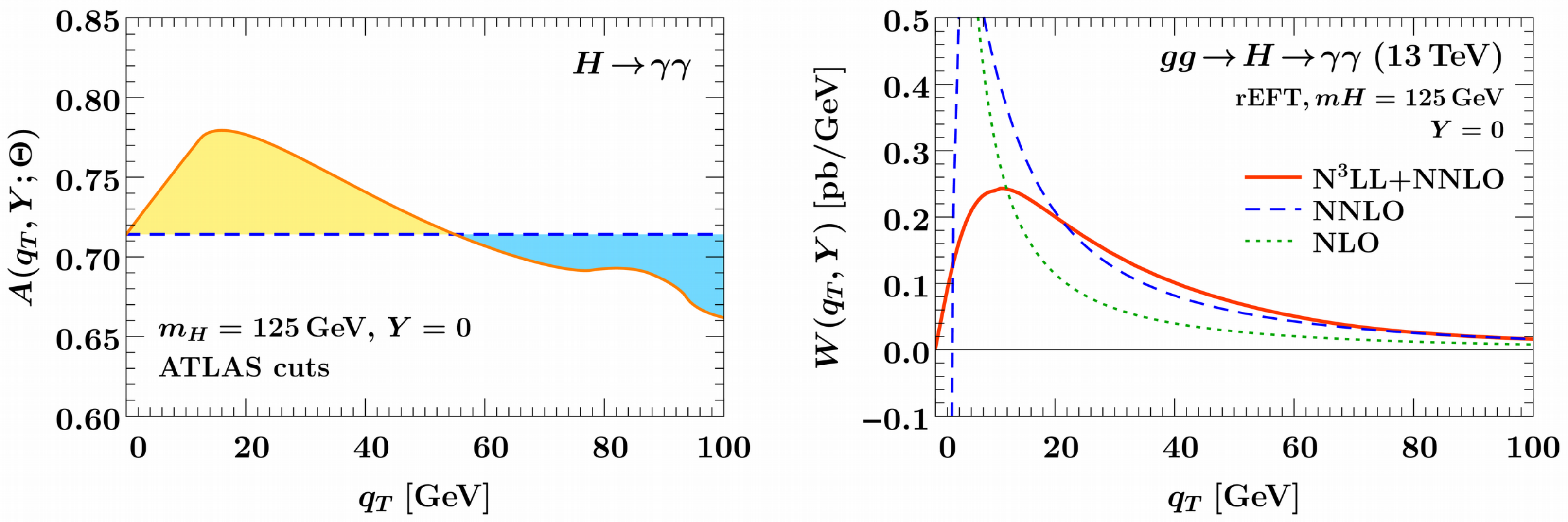
- ➢ Inclusive cross section: resummation effects formally cancel (computable in FO)
- ➢ fiducial cross section: fiducial cuts resolve the resummation effects (derived quantity)

Total XS: Resummation Effects

Key point

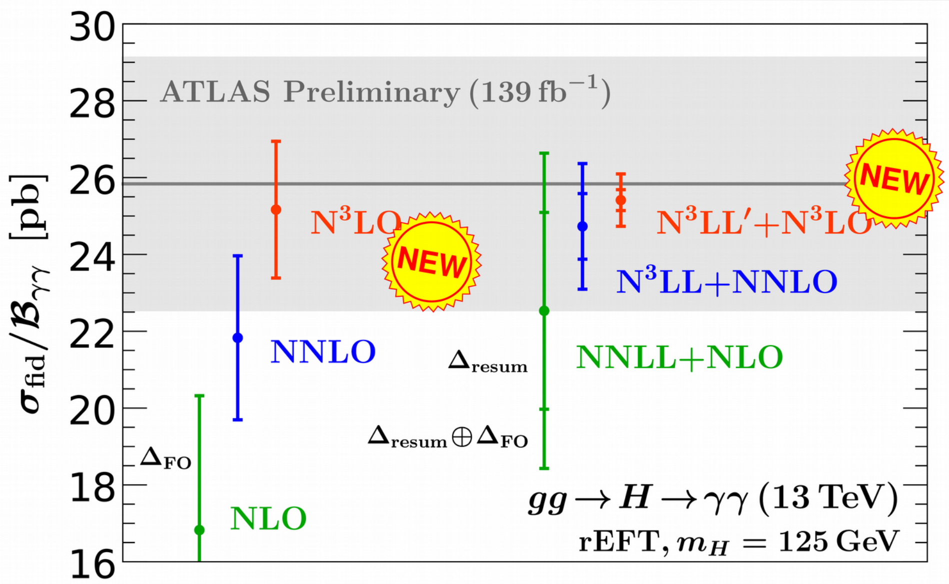
Fiducial power corrections induce resummation effects *in the total xsec.*

Acceptance acts as a weight in the q_T integral.



$$\sigma_{\mathrm{incl}} = \int \mathrm{d}q_T\, W(q_T) \qquad \sigma_{\mathrm{fid}} = \int \mathrm{d}q_T\, A(q_T)\, W(q_T)$$

Total Cross Section

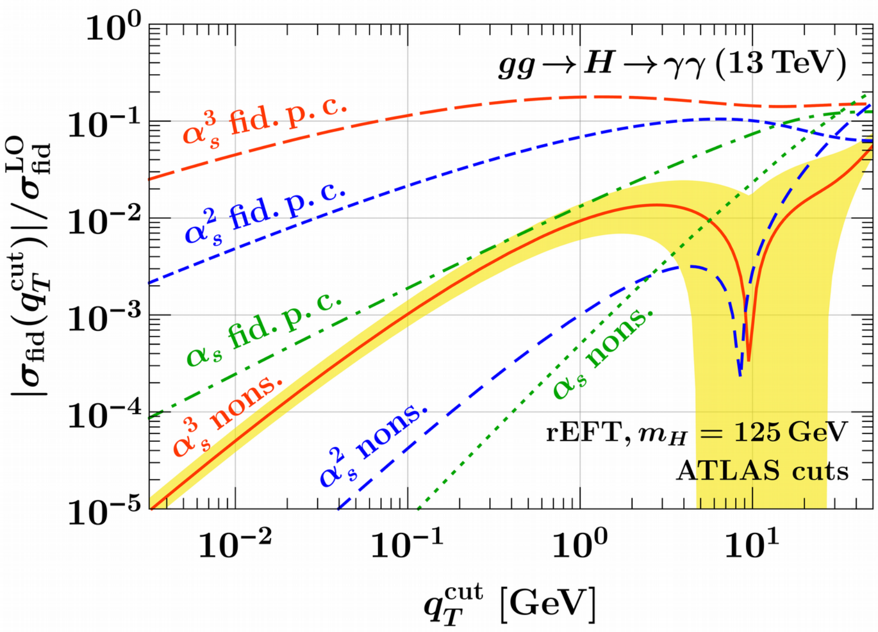


✓ Total cross section: $\sigma = \int_0 \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$

Final results for total fiducial Higgs cross section at N^{3}LL$'$+N^{3}LO

$$\sigma_{\rm fid}/\mathcal{B}_{\gamma\gamma} = (25.41 \pm 0.59_{\rm FO} \pm 0.21_{q_T} \pm 0.17_{\varphi} \pm 0.06_{\rm match} \pm 0.20_{\rm nons})\,\mathrm{pb}$$

Comparison to q_T slicing



Usual slicing approach to q_T subtractions:

$$\sigma = \int_0^{q_T^{\rm cut}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T} + \int_{q_T^{\rm cut}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$$

$$= \int_0^{q_T^{\rm cut}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma^{(0)}}{\mathrm{d}q_T} + \int_0^{q_T^{\rm cut}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma^{\rm fpc}}{\mathrm{d}q_T} + \int_0^{q_T^{\rm cut}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma^{\rm nons}}{\mathrm{d}q_T} + \int_{q_T^{\rm cut}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$$

Uses $q_T^{\rm cut} \sim 1\mathrm{GeV}$ and **neglects the fiducial and nonsingular corrections!**

Very bad approximation **(unfeasible)** already at α_s and α_s^2 (α_s^3)

Summary

- Results for **fiducial p_T spectrum** for $H \to \gamma\gamma$ at $\mathrm{N^3LL'{+}N^3LO}$
  - Significant reduction in perturbative uncertainties
  - Good agreement with ATLAS preliminary data

- **Total fiducial cross section** at $\mathrm{N^3LL'{+}N^3LO}$
  - Poor convergence in FO due to fiducial power corrections induced by the experimental acceptance factor
  - Improved convergence by resumming all linear power corrections

Thank you for your attention!

Backup slides

Linear fiducial power correction

Consider $p(P_a)\,p(P_b) \to H(q) + X(p_X) \to \gamma(p_1)\,\gamma(p_2) + X(p_X)$

$$
\begin{aligned}
q^\mu &= \Big(\sqrt{m_H^2 + q_T^2}\cosh Y, q_T, 0, \sqrt{m_H^2 + q_T^2}\sinh Y\Big)\,,\\
p_1^\mu &= p_{T_1}(\cosh\eta_1, \cos\phi, \sin\phi, \sinh\eta_1)\,,\\
p_2^\mu &= q^\mu - p_1^\mu\,,
\end{aligned}
$$

ϕ Is the azimuthal angle between $\vec{q}_T$ and $\vec{p}_{T_1}$

$$
\begin{aligned}
A(q;\Theta) &= 8\pi \int \mathrm{d}\Phi_{\gamma\gamma}(q)\,\theta\big(p_{T_1}^2 - p_T^{\min 2}\big)\theta\big(p_{T_2}^2 - p_T^{\min 2}\big)\\
&= \frac{4}{\pi}\int_0^\pi \mathrm{d}\phi \int_0^\infty \mathrm{d}\Delta\eta\, \frac{p_{T_1}^2}{m_H^2}\,\theta\big(p_{T_1}^2 - p_T^{\min 2}\big)\,\theta\big(p_{T_1}^2 - p_T^{\min 2} - 2p_{T_1}q_T\cos\phi + q_T^2\big)
\end{aligned}
$$

The linear term breaks the azimuthal symmetry (one can not expand and average it out)

$$
\begin{aligned}
&\theta\big(p_{T_1}^2 - p_T^{\min 2}\big)\,\theta\big(p_{T_1}^2 - p_T^{\min 2} - 2q_T p_{T_1}\cos\phi\big) \times [1 + \mathcal{O}(q_T^2)]\\
&= \begin{cases} \theta\big(p_{T_1}^2 - p_T^{\min 2}\big) & \cos\phi < 0\,,\\ \theta\big(p_{T_1}^2 - p_T^{\min 2} - 2q_T p_{T_1}\cos\phi\big) & \cos\phi \geq 0\,. \end{cases}
\end{aligned}
$$

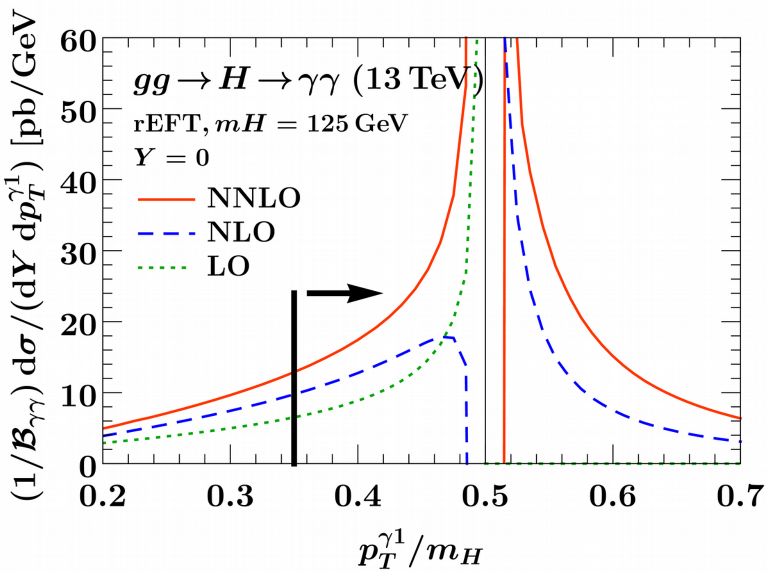
Total XS: Resummation Effects

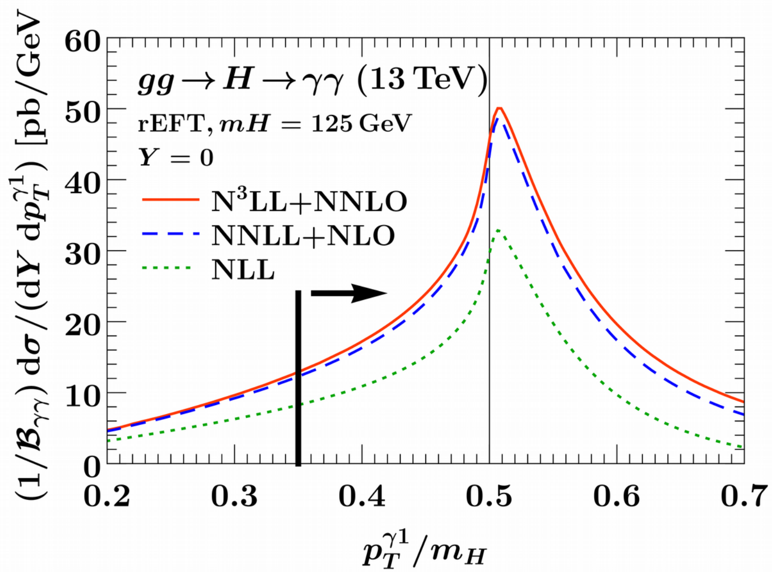
Key point

Fiducial power corrections induce resummation effects *in the total xsec.*

Two ways to understand this:

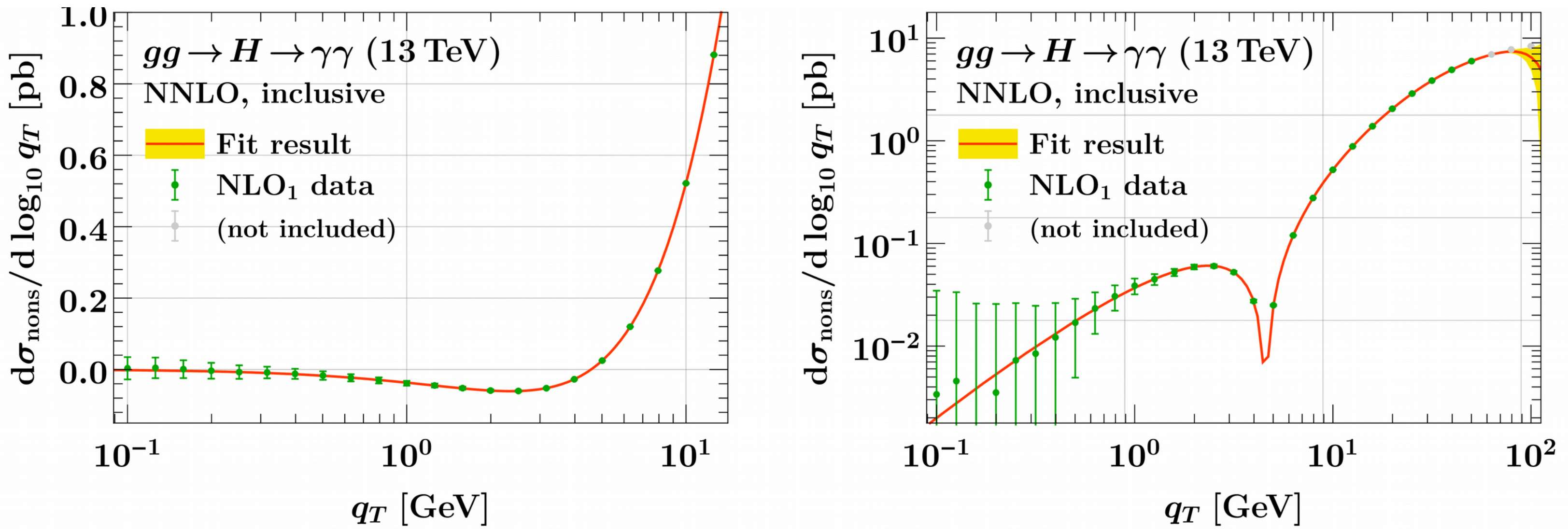
1. Acceptance acts as a weight in the q_T integral.
2. We're cutting on the resummation-sensitive photon p_T.





- Leaves behind logarithms of $\frac{p_L}{m_H} = \frac{p_T^{\text{cut}} - m_H/2}{m_H} = 0.15$

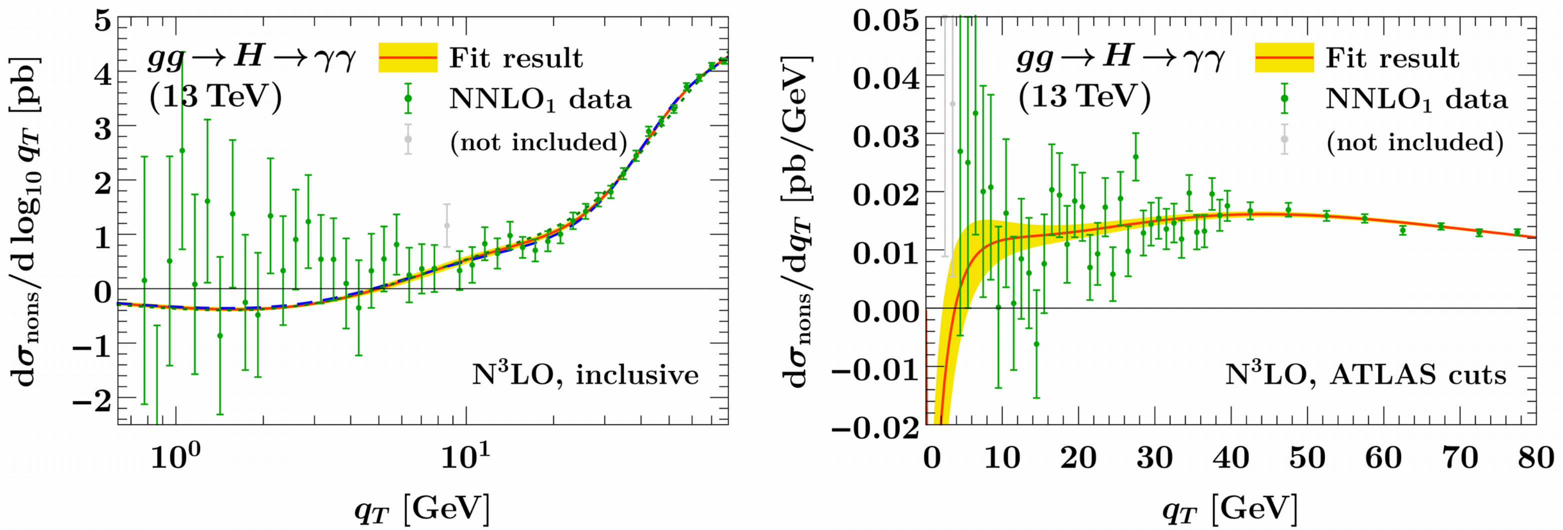
Fit results at NNLO



Fit procedure:

- Perform separate χ^2 fits of $\{a_k^{\text{incl,fid}}\}$ to inclusive and fiducial nonsingular data
  [generated by our analytic implementation]
- Increase fit window to larger q_T until p value decreases
- Include subleading log coefficients at next higher power until p value decreases
- Also test intermediate combination to ensure fit is stable
  [procedure follows Moult, Rothen, Stewart, Tackmann, Zhu '15-'16]

Fit results at N³LO



Setup:

- Perform a combined fit to all inclusive and fiducial data
  [NNLO$_1$: Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '15-16; as used in Chen et al. '18; Bizoń et al. '18]
  [Incl. N^{3}LO: Mistlberger '18]
- Empirically find $0.4 \leq a_k^{\rm fid}/a_k^{\rm incl} \leq 0.55$ at (N)NLO $\Rightarrow$ use as weak 1σ constraint
  - Makes sense, $a_k^{\rm fid,incl}$ are same underlying $W^{(2)}$ in slightly different Y range
  - Note that we are *not* just rescaling any part of the cross section by an acceptance