# Precision Computations for Higgs Production

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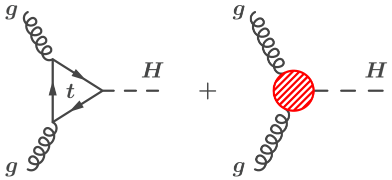
Room for Coffee Break Discussion: `https://mit.zoom.us/s/95962370657`
(open from 15:45 CET, passcode same as for this session)

# Motivation

- Measure fiducial & differential Higgs cross sections at the LHC
  - Most model-independent way we have to search for BSM in the Higgs sector
- Total fiducial cross section measures deviations from SM gluon-fusion rate




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

- $p_T^H$ spectrum is the most important differential quantity
- High $p_T^H \sim \sqrt{\hat{s}} \gg m_H$ increases sensitivity to new operators

  [...for SM precision theory, see next talk by R. Röntsch]

- Focus of this talk: $p_T^H \lesssim m_H \sim \sqrt{\hat{s}} \ll 2m_t$ (or $p_T^H$ integrated over)
  - Measure or put bounds on anomalous $b$, $c$, and light quark Yukawa couplings

    [Bishara, Haisch, Monni, Re '16; Soreq, Zhu, Zupan '16; see e.g. ATLAS-CONF-2019-029]

- Uncertainty $\Delta\sigma$ on SM prediction translates into discovery reach:

$$\frac{\Delta\sigma}{\sigma} \sim \frac{v^2}{\Lambda_{\mathrm{BSM}}^2} \quad \Leftrightarrow \quad \Lambda_{\mathrm{BSM}} \sim v\sqrt{\frac{\sigma}{\Delta\sigma}}$$

## Challenges for theory

- QCD corrections to $gg \to H$ are large: $\sigma/\sigma_{\mathrm{LO}} \approx 3$
  - Calculation of inclusive cross section has been pushed to N$^3$LO [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger '15-'18]
- But LHC experiments apply kinematic selection cuts on Higgs decay products
  - Need complete interplay of QCD corrections and $\mathcal{O}(1)$ fiducial acceptance

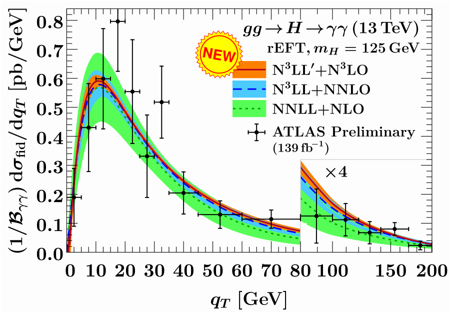
Consider $gg \to H \to \gamma\gamma$ with ATLAS fiducial cuts:

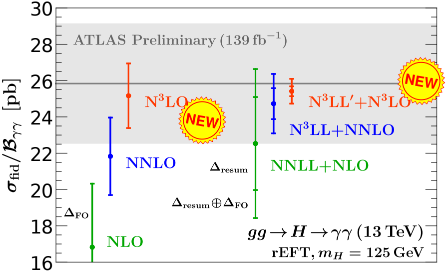
$$p_T^{\gamma 1} \geq 0.35\, m_H\,, \quad p_T^{\gamma 2} \geq 0.25\, m_H\,, \quad |\eta^\gamma| \leq 2.37\,, \quad |\eta^\gamma| \notin [1.37, 1.52]$$

## Focus of this talk

[Billis, Dehnadi, Ebert, JM, Tackmann, 2102.08039]

- Compute fiducial spectrum for $q_T \equiv p_T^H = p_T^{\gamma\gamma}$ at N$^3$LL$'$+N$^3$LO
- Compute total fiducial cross section at N$^3$LO, and improved by resummation



# Fiducial predictions for $gg \to H \to \gamma\gamma$ at three loops

Consider $gg \to H \to \gamma\gamma$ with ATLAS fiducial cuts:

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- Compute total fiducial cross section at N$^3$LO, and improved by resummation

- Previous state of the art was N$^3$LL(+NNLO$_1$) and NNLO, respectively
  [Chen et al. ’18; Bizoń et al. ’18; Gutierrez-Reyes et al. ’19; Becher, Neumann ’20]

Kicked off a recent push for fiducial color singlet at complete three-loop accuracy:

- Complementary N$^3$LO results for fiducial $Y_{\gamma\gamma}, \eta_{\gamma 1}, \Delta\eta_{\gamma\gamma}$ (with different method)
  [Chen, Gehrmann, Glover, Huss, Mistlberger, 2102.07607; see plenary talk by B. Mistlberger later today]
- Fiducial N$^3$LL′ results for Higgs (and Drell-Yan) $q_T$ spectrum
  [Re, Rottoli, Torrielli, 2104.07509; see also Camarda, Cieri, Ferrera, 2103.04974]

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$p_T^{\gamma 1}$ ... , ... 52]

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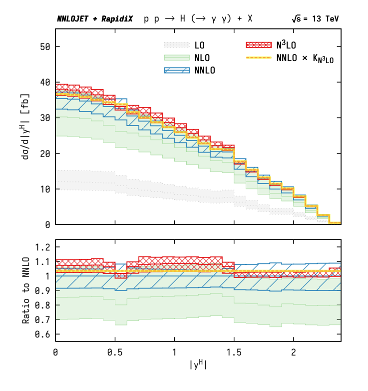


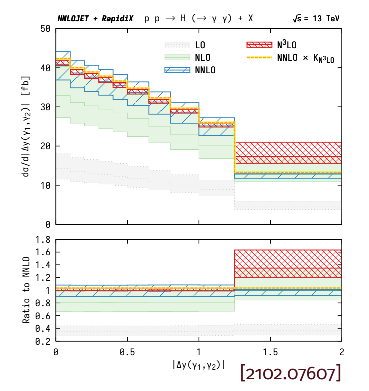


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Consider $gg$

$p_T^{\gamma 1} \geq 0$ ... $.37, 1.52]$

## Focus of th

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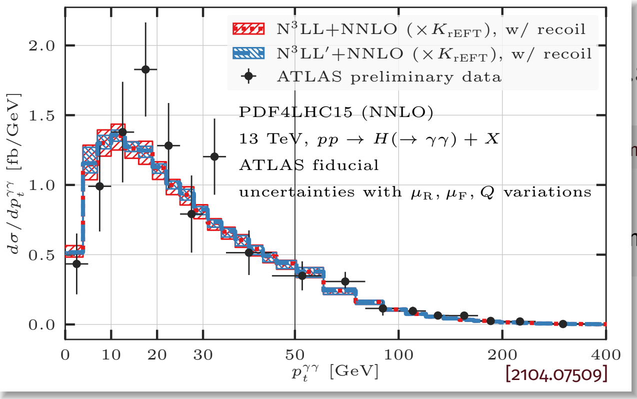
- Compute
- Compute ... mmation

- Previous
  [Chen et al.

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# Method

Compute cross section from $\sigma = \int \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$ and *power expand* around IR, $q_T \to 0$:

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} &= \frac{\mathrm{d}\sigma^{(0)}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{(1)}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{(2)}}{\mathrm{d}q_T} + \cdots \\
&\sim \frac{1}{q_T}\left[ \mathcal{O}(1) + \mathcal{O}\Big(\frac{q_T}{m_H}\Big) + \mathcal{O}\Big(\frac{q_T^2}{m_H^2}\Big) + \cdots \right]
\end{aligned}
$$

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

- Contains LO contribution, virtual corrections, and log-enhanced singular terms
- Predicted by factorization $\Rightarrow$ $q_T$ subtractions [Catani, Grazzini '07]

$$
\frac{\mathrm{d}\sigma^{(1)}}{\mathrm{d}q_T} = \sum_n \alpha_s^n \sum_m \sigma_{n,m}^{(1)} \frac{1}{m_H} \ln^m(q_T/m_H)
$$

- Still logarithmically divergent, only present if decay products are resolved
- *Also* predicted by factorization [Ebert, JM, Stewart, Tackmann '20]

# $q_T$ subtractions

Compute cross section from $\sigma = \int \mathrm{d}q_T \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$ and *power expand* around IR, $q_T \to 0$:

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

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

$$\frac{\mathrm{d}\sigma^{(2)}}{\mathrm{d}q_T} = \sum_n \alpha_s^n \sum_m \sigma_{n,m}^{(2)} \frac{q_T}{m_H^2} \ln^m(q_T/m_H) + \cdots$$

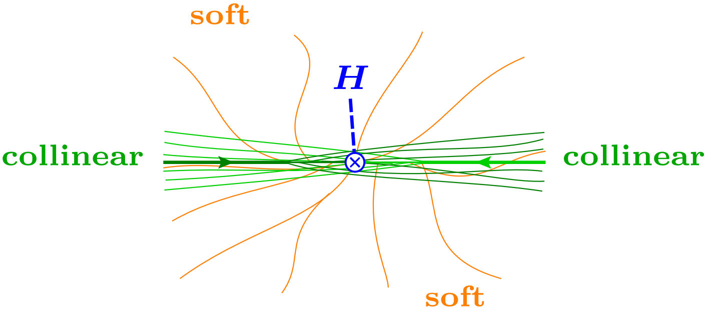
- Finite as $q_T \to 0$, extract from $H + 1j$ calculation

Set up some notation, use that production and decay (acceptance) factorize:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} = \int \mathrm{d}Y\, A(q_T, Y; \Theta)\, W(q_T, Y)\,, \quad A_{\mathrm{incl}} = 1\,, \quad W(q_T, Y) = \frac{\mathrm{d}\sigma_{\mathrm{incl}}}{\mathrm{d}q_T\, \mathrm{d}Y}$$

At leading power in $q_T \ll m_H$, the hadronic dynamics factorize as:

$$W^{(0)}(q_T, Y) = H(m_H^2, \mu) \int \mathrm{d}^2\vec{k}_a\, \mathrm{d}^2\vec{k}_b\, \mathrm{d}^2\vec{k}_s\, \delta\big(q_T - |\vec{k}_a + \vec{k}_b + \vec{k}_s|\big)$$
$$\times\, B_g^{\mu\nu}(x_a, \vec{k}_a, \mu, \nu)\, B_{g\,\mu\nu}(x_b, \vec{k}_b, \mu, \nu)\, S(\vec{k}_s, \mu, \nu)$$




- Predicts singular structure of $\dfrac{\mathrm{d}\sigma}{\mathrm{d}q_T}$ as $q_T \to 0$
- Enables all-order resummation $\Rightarrow$ Sudakov peak

# Leading-power factorization & resummation to N$^3$LL$'$

At leading power in $q_T \ll m_H$, the hadronic dynamics factorize as:

$$W^{(0)}(q_T, Y) = H(m_H^2, \mu) \int \mathrm{d}^2\vec{k}_a\, \mathrm{d}^2\vec{k}_b\, \mathrm{d}^2\vec{k}_s\, \delta\big(q_T - |\vec{k}_a + \vec{k}_b + \vec{k}_s|\big)$$
$$\times\, B_g^{\mu\nu}(x_a, \vec{k}_a, \mu, \nu)\, B_{g\,\mu\nu}(x_b, \vec{k}_b, \mu, \nu)\, S(\vec{k}_s, \mu, \nu)$$

To reach N$^3$LL$'$ for $W^{(0)}$, implemented in `SCETlib`:

- Three-loop soft and hard function …includes in particular the three-loop virtual form factor
  [Li, Zhu, '16] [Baikov et al. '09; Lee et al. '10; Gehrmann et al. '10]
- Three-loop unpolarized and two-loop polarized beam functions
  [Ebert, Mistlberger, Vita '20; Luo, Yang, Zhu, Zhu '20]
  [Luo, Yang, Zhu, Zhu '19; Gutierrez-Reyes, Leal-Gomez, Scimemi, Vladimirov '19]
- Four-loop cusp, three-loop noncusp anomalous dimensions
  [Brüser, Grozin, Henn, Stahlhofen '19; Henn, Korchemsky, Mistlberger '20; v. Manteuffel, Panzer, Schabinger '20] [Li, Zhu, '16; Moch, Vermaseren, Vogt '05; Idilbi, Ma, Yuan '06; Vladimirov '16]
- N$^3$LL solutions to virtuality/rapidity RGEs in $b_T$ space
- Hybrid profile scales for fixed-order matching
  [Lustermans, JM, Tackmann, Waalewijn '19]

# Fiducial power corrections (in this case)

... are the power corrections coming from the $q_T$-dependent acceptance:

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

- Uniquely predict all linear power corrections $\mathrm{d}\sigma^{(1)}$ because

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

- Resummed to the same N$^3$LL$'$ accuracy as leading-power terms by resumming $W^{(0)}$ and keeping *exact* $A(q_T, Y; \Theta)$

[Presence of linear terms pointed out in Ebert, Tackmann '20]
[Factorization demonstrated in Ebert, JM, Stewart, Tackmann '20]

## Key point

Fiducial power corrections induce resummation effects *in the total cross section*

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

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

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

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

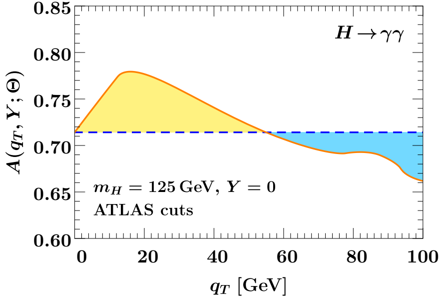
- Fiducial power corrections show no convergence, remainder is similar to inclusive

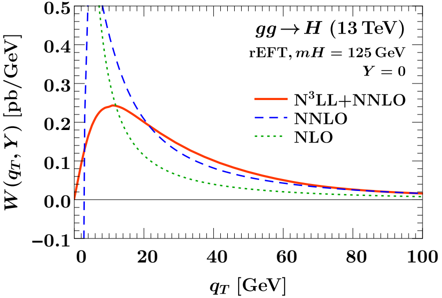
## Key point

Fiducial power corrections induce resummation effects *in the total cross section*

Two ways to understand this:

1. Acceptance acts as a weight under the $q_T$ integral



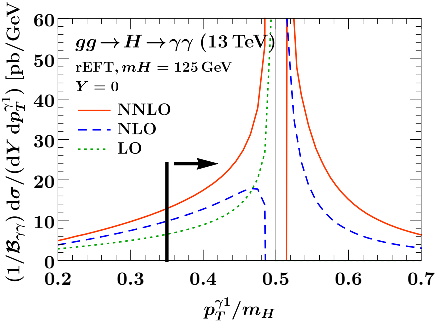

$$\sigma_{\mathrm{incl}} = \int \mathrm{d}q_T\, W(q_T) \qquad \sigma_{\mathrm{fid}} = \int \mathrm{d}q_T\, A(q_T)\, W(q_T)$$

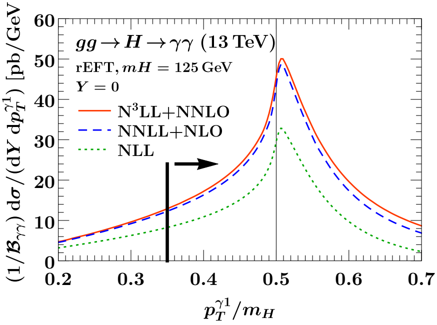
## Key point

Fiducial power corrections induce resummation effects *in the total cross section*

Two ways to understand this:

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



$$\sigma = \int_0^{q_T^{\mathrm{off}}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma^{\mathrm{sing}}}{\mathrm{d}q_T} + \int_0^{q_T^{\mathrm{off}}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma_{\mathrm{FO}}^{\mathrm{nons}}}{\mathrm{d}q_T} + \int_{q_T^{\mathrm{off}}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma_{\mathrm{FO}_1}}{\mathrm{d}q_T}$$

Include $\mathrm{d}\sigma^{\mathrm{fpc}}$ in differential subtraction:

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

Remaining (nonsingular) terms:

$$\frac{\mathrm{d}\sigma_{\mathrm{FO}}^{\mathrm{nons}}}{\mathrm{d}q_T} = \int \mathrm{d}Y \, A(q_T, Y; \Theta) \left[W_{\mathrm{FO}}^{(2)}(q_T, Y) + \cdots\right] = \left[\frac{\mathrm{d}\sigma_{\mathrm{FO}_1}}{\mathrm{d}q_T} - \frac{\mathrm{d}\sigma_{\mathrm{FO}}^{\mathrm{sing}}}{\mathrm{d}q_T}\right]_{q_T > 0}$$

Challenges:

- Obtaining stable $H + 1j$ results for $q_T \to 0$ is *hard* …in particular at NNLO$_1$
- Dropping the nonsingular below $q_T \leq q_T^{\mathrm{cut}}$ is not viable, either …as we'll see shortly
  - Crucial to use differential subtraction, not slicing

$$\sigma = \int_0^{q_T^{\rm off}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma^{\rm sing}}{\mathrm{d}q_T} + \int_0^{q_T^{\rm off}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma_{\rm FO}^{\rm nons}}{\mathrm{d}q_T} + \int_{q_T^{\rm off}} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma_{\rm FO_1}}{\mathrm{d}q_T}$$

Include $\mathrm{d}\sigma^{\rm fpc}$ in differential subtraction:

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Remaining (nonsingular) terms:

$$\frac{\mathrm{d}\sigma_{\rm FO}^{\rm nons}}{\mathrm{d}q_T} = \int \mathrm{d}Y \, A(q_T, Y; \Theta) \left[ W_{\rm FO}^{(2)}(q_T, Y) + \cdots \right] = \left[ \frac{\mathrm{d}\sigma_{\rm FO_1}}{\mathrm{d}q_T} - \frac{\mathrm{d}\sigma_{\rm FO}^{\rm sing}}{\mathrm{d}q_T} \right]_{q_T > 0}$$

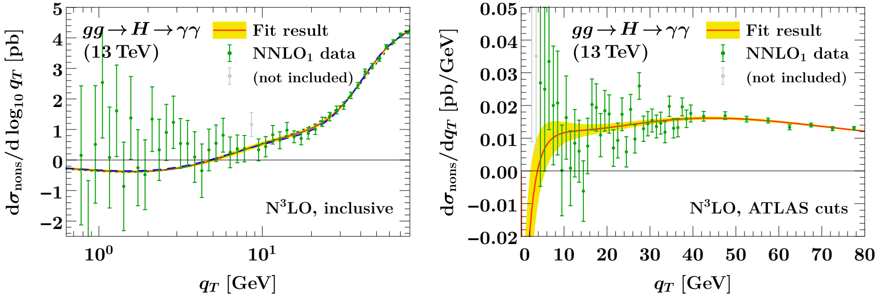
## Key idea

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

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

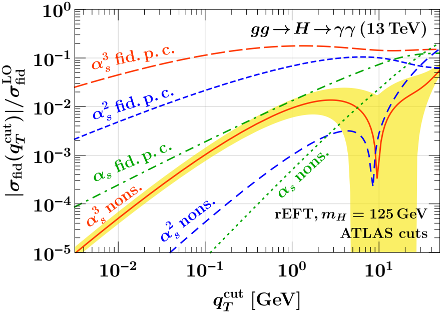
- Include higher-power $b_k, c_k$ to get unbiased $a_k$
  - Allows us to use more precise data at higher $q_T$ as lever arm in the fit

# Fit results at N$^3$LO




## Setup:

- Combined fit to existing binned inclusive and fiducial NNLO$_1$ data from `NNLOjet` [Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '15-16; as used in Chen et al. '18; Bizoń et al. '18]
- Empirically find $0.4 \leq a_k^{\mathrm{fid}}/a_k^{\mathrm{incl}} \leq 0.55$ at (N)NLO $\Rightarrow$ use as weak $1\sigma$ constraint
- Add $\sigma_{\mathrm{incl}}(q_T \leq q_T^{\mathrm{cut}}) = \sigma_{\mathrm{incl}}^{\mathrm{N^3LO}} - \sigma_{\mathrm{incl}}(q_T > q_T^{\mathrm{cut}})$ as additional incl. data point [Mistlberger '18]

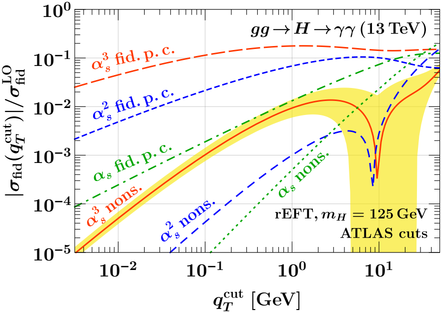



## Slicing approach to $q_T$ subtractions:

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

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

- Slicing uses finite $q_T^{\rm cut} \sim 2\,\mathrm{GeV}$ 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 $\alpha_s^2$, and definitely at $\alpha_s^3$
- Even without $\sigma^{\rm fpc}$ (incl. cross section), this is a bad approximation at $\alpha_s^3$
    - $q_T^{\rm cut}$ variations only scan local maximum around $2\mathrm{GeV}$ …




## Projection-to-Born method:

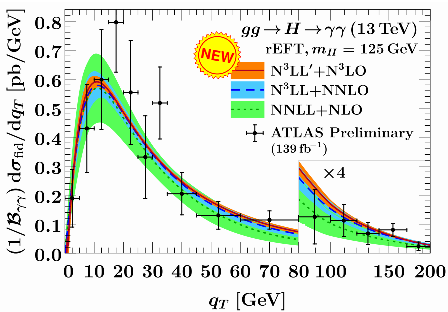
[used e.g. in Chen, Gehrmann, Glover, Huss, Mistlberger, 2102.07607]

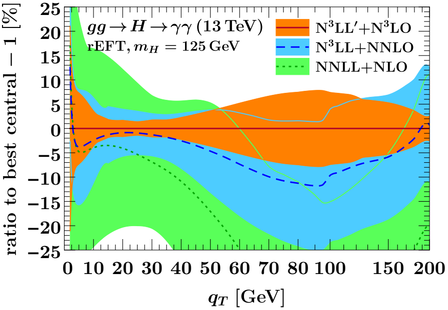
$$\frac{\mathrm{d}\sigma}{\mathrm{d}Y} = A(0,Y)\,\frac{\mathrm{d}\sigma_{\rm incl}}{\mathrm{d}Y} + \int_{\approx q_T^{\rm cut}} \mathrm{d}q_T \left[A(q_T,Y) - A(0,Y)\right] W(q_T,Y)$$

- 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 $q_T^{\rm cut} \ll 0.1\,\mathrm{GeV}$!

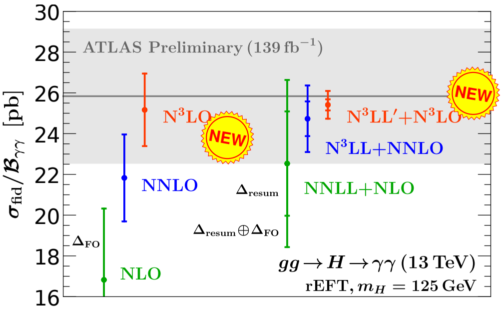
# Results and future directions

# The 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 Ebert, JM, 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]

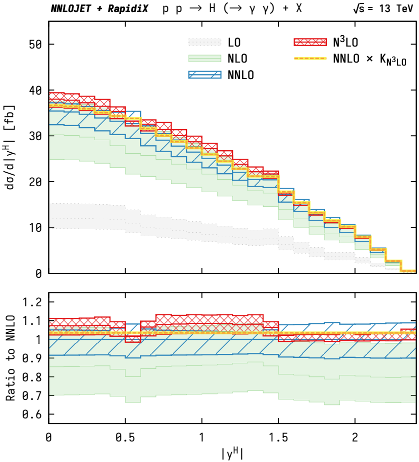


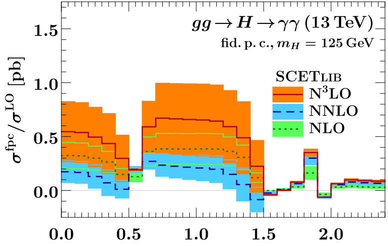

- Large N$^3$LO correction to fiducial cross section (worse than inclusive)
  - Caused by fiducial power corrections, *not* captured by rescaling inclusive N$^3$LO result
- Resummation restores convergence

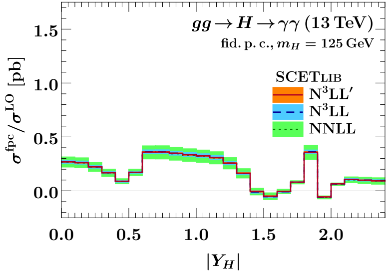
▶ Allows for the first direct comparison to experimentally measured total Higgs cross section at genuine three-loop order

- "Infrared sensitivity" observed also in other Higgs observables at N$^3$LO
  [Chen, Gehrmann, Glover, Huss, Mistlberger, 2102.07607]

$\Leftrightarrow$ Precisely the fiducial power corrections we can analytically deal with and resum



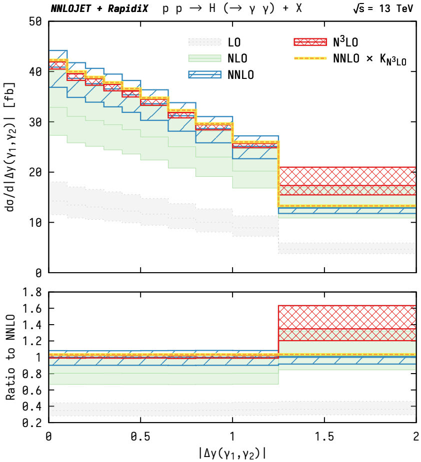



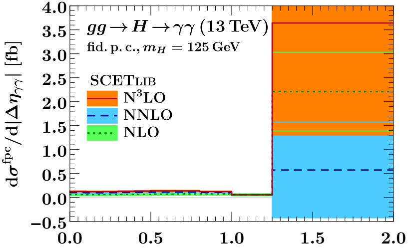

Note: Plots on the right show *only* $\sigma^{\mathrm{fpc}}$.

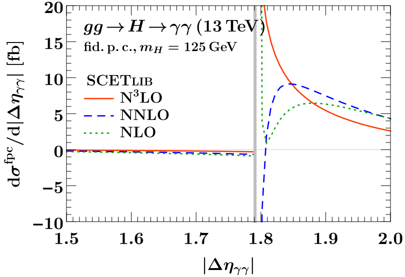
# Outlook: Resummation effects in other $H \to \gamma\gamma$ observables

- "Infrared sensitivity" observed also in other Higgs observables at N$^3$LO
  [Chen, Gehrmann, Glover, Huss, Mistlberger, 2102.07607]

⇔ Precisely the fiducial power corrections we can analytically deal with and resum

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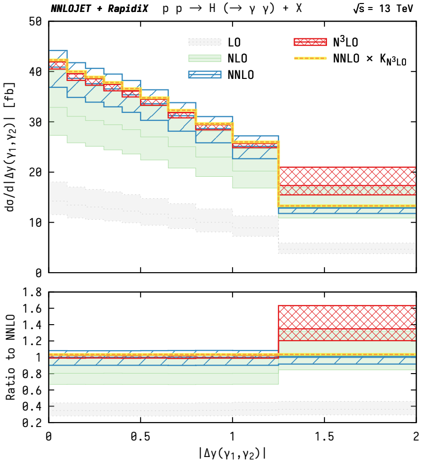


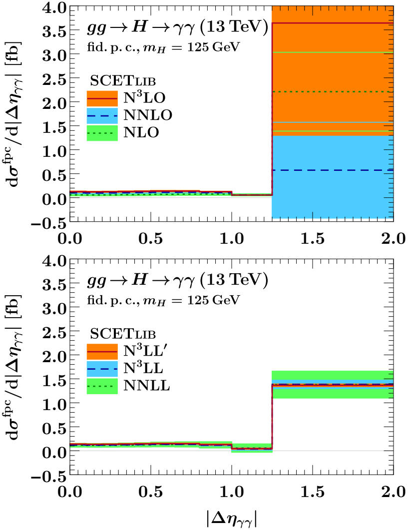


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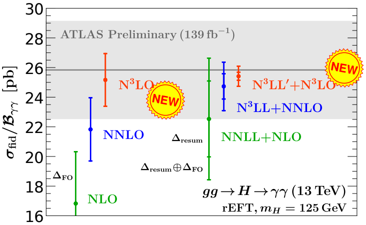
- Presented N$^3$LL′+N$^3$LO and N$^3$LO predictions for fiducial $p_T^H$ spectrum and total fiducial cross section for $gg \to H \to \gamma\gamma$ at the LHC
  - First direct comparison to LHC data at this order and level of precision




- Resummed large fiducial power corrections induced by experimental acceptance
  - Even *total* fiducial cross sections are sensitive to $q_T$ resummation effects
  - Enables best-possible combined predictions for other $H \to \gamma\gamma$ observables

- Nonsingular extraction and matching to total cross section made possible by combining all information from N$^3$LO $\sigma_{\rm incl}$, fixed-order `NNLOjet` data, fiducial power corrections, and known functional form at subleading power

- N$^3$LL′ fiducial power corrections to be part of upcoming public `SCETlib` release

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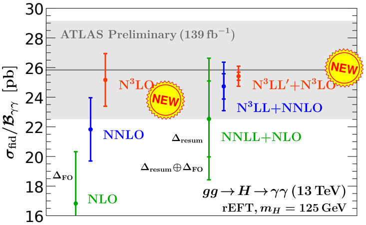


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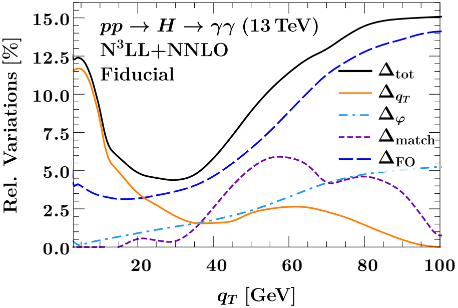
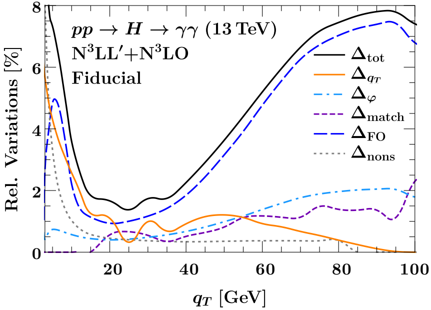
Thank you for your attention!

# Backup

# Uncertainty breakdown




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

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

- $\Delta_{q_T}$ 36 independent scale variations in $W^{(0)}$ factorization
- $\Delta_{\varphi}$ 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 $\mu_F$ due to overall $\alpha_s^2$)
- $\Delta_{\rm nons}$ Uncertainty on nonsingular extraction

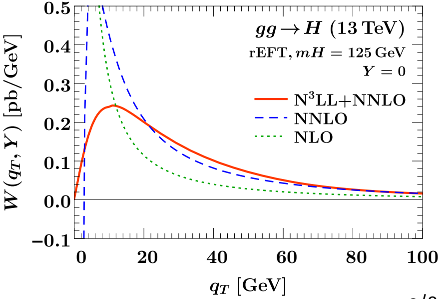
At leading power in $q_T \ll m_H$, the hadronic dynamics factorize as:

$$W^{(0)}(q_T, Y) = H(m_H^2, \mu) \int \mathrm{d}^2\vec{k}_a\, \mathrm{d}^2\vec{k}_b\, \mathrm{d}^2\vec{k}_s\, \delta\big(q_T - |\vec{k}_a + \vec{k}_b + \vec{k}_s|\big)$$
$$\times\, B_g^{\mu\nu}(x_a, \vec{k}_a, \mu, \nu)\, B_{g\,\mu\nu}(x_b, \vec{k}_b, \mu, \nu)\, S(\vec{k}_s, \mu, \nu)$$

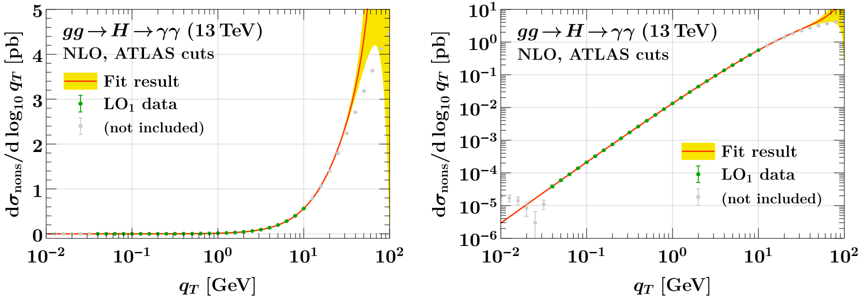
Ingredients satisfy 2D renormalization group equations, e.g. soft function:

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \ln \tilde{S}(\vec{b}_T, \mu, \nu) = \tilde{\gamma}_S^g(\mu, \nu) \qquad \nu \frac{\mathrm{d}}{\mathrm{d}\nu} \ln \tilde{S}(\vec{b}_T, \mu, \nu) = \tilde{\gamma}_\nu^g(b_T, \mu)$$

- Solve recursively at fixed order
  - Complete log structure of $\mathrm{d}\sigma^{(0)}$
- Closed-form all-order solution
  - Resummed Sudakov peak
- Resummation order specified by perturbative order of anom. dims. and boundary conditions



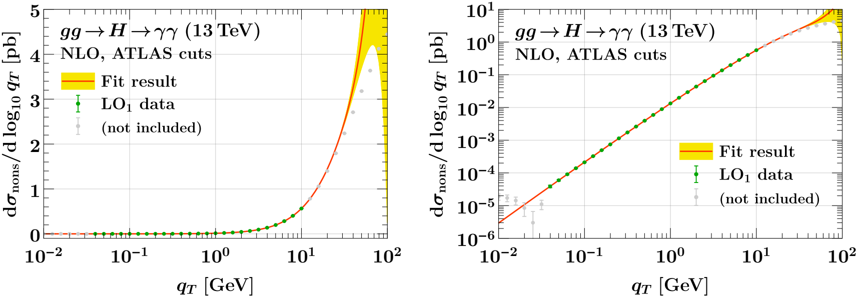
# Fit results at (N)NLO




Fixed-order inputs:

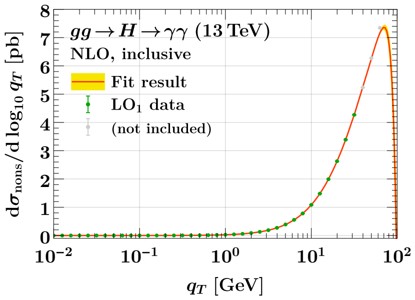
- NLO contribution to $W(q_T, Y)$ at $q_T > 0$ is easy
- At NNLO, renormalize & implement bare analytic results for $W(q_T, Y)$
  [Dulat, Lionetti, Mistlberger, Pelloni, Specchia ’17]

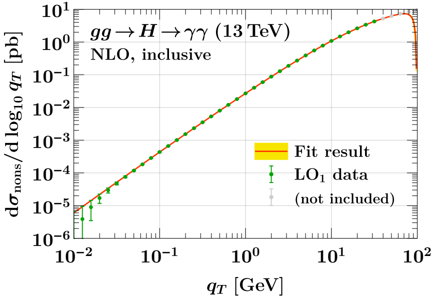
# Fit results at (N)NLO




## Fit procedure:

- Perform separate $\chi^2$ fits of $\{a_k^{\rm incl,fid}\}$ 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]

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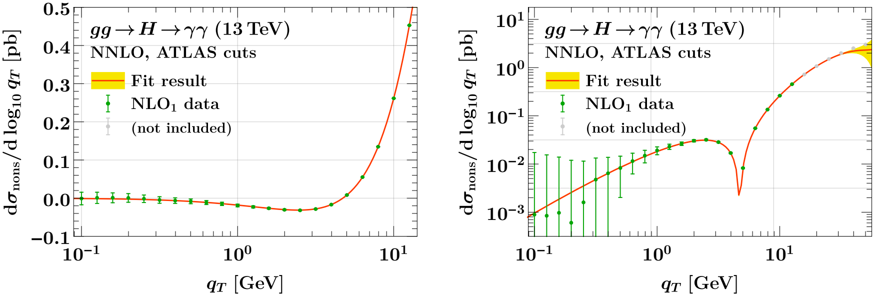


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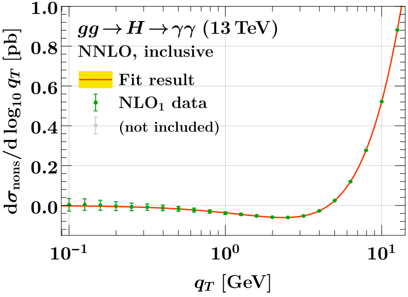


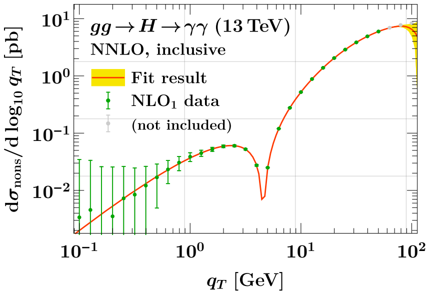


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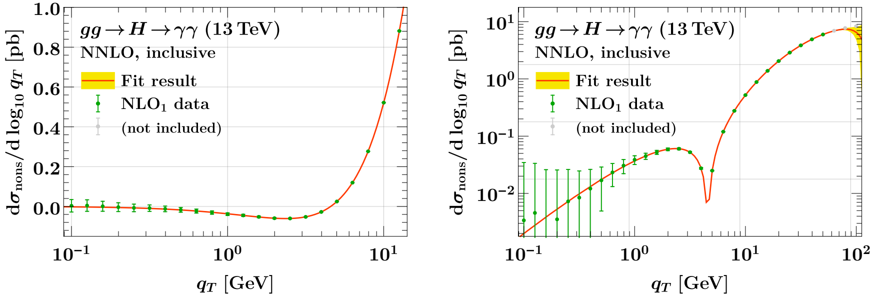


- Check the purely hadronic $a_k^{\mathrm{fid}}$ by directly fitting them to

$$q_T \int \mathrm{d}Y\, A^{(0)}(Y;\Theta)\big[W - W^{(0)}\big] = \frac{q_T^2}{m_H^2} \sum_{k=0}^{2n-1} \Big(a_k^{\mathrm{fid}} + c_k' \frac{q_T^2}{m_H^2} + \cdots\Big) \ln^k \frac{q_T^2}{m_H^2} \quad \checkmark$$

- Recover analytic (N)NLO coefficient of $\sigma_{\mathrm{incl}}$ at $10^{-5}$ ($10^{-4}$) ✓
- Analytic implementation gives us awesome precision on *all* NLP coefficients
  (all logs at NLO *and* NNLO, also differential in $Y$, broken down by color structure, ...)
  - Can serve as benchmark for $q_T$ resummation at subleading power