Resummation improved rapidity spectrum for gluon fusion Higgs production.

Markus Ebert
Deutsches Elektronen-Synchrotron

In collaboration with Johannes Michel & Frank Tackmann

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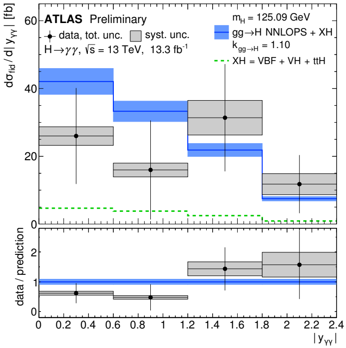
Outline

1. Motivation
2. Resummation of timelike logarithms
3. Total cross section
4. Higgs rapidity spectrum
5. Outlook: bbH and Drell-Yan
6. Summary

Motivation.

Higgs rapidity spectrum.

- Important observable of the LHC Higgs program:
  - Spectrum interesting in itself
  - Analyses need fiducial xsection
  - STXS: $\sigma(Y_{\rm cut} = 2.5)$
- Rapidity spectrum known to NNLO
  [Anastasiou, Melnikov, Petriello ’04, ’05]
  [Catani, Grazzini ’07]
  [Dulat, Lionetti, Mistlberger, Pelloni, Specchia ’17]
  - First step towards $\mathbf{N^3LO}$
- Total production cross section known to N^3LO
  [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger ’15, ’16]



[ATLAS-CONF-2016-067]

Goal:

Obtain Higgs rapidity spectrum with accuracy comparable to N^3LO.

Higgs fiducial measurement.

Example: ATLAS $H \to \gamma\gamma$ measurement [ATLAS-CONF-2016-067]

- Require two photons with
  - $0 \leq |Y| < 2.37$, excluding $1.37 < |Y| < 1.52$
  - $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$
  - $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$
  - Photon isolation...

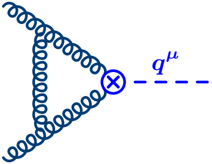
- Measured observables:
  - $\cos\theta^* = \dfrac{(E^{\gamma_1} + p_z^{\gamma_1})(E^{\gamma_2} - p_z^{\gamma_2}) - (E^{\gamma_1} - p_z^{\gamma_1})(E^{\gamma_2} + p_z^{\gamma_2})}{m_{\gamma\gamma}\sqrt{m_{\gamma\gamma}^2 + p_{T\,\gamma\gamma}^2}}$
  - $\Delta Y = |Y_1 - Y_2|$
  - $Y_{\gamma\gamma}$
  - ...

- Observables are very sensitive to fiducial cuts
  - Can't simply rescale by $\mathrm{N^3LO}$ cross section
    $\Leftrightarrow$ Require differential distribution at $\mathrm{N^3LO}$ accuracy

Higgs rapidity spectrum.

Timelike logarithms:

- Originate in the form factor at timelike momentum transfer:



$$F_{gg}^{(1)} = \frac{\alpha_s(\mu)}{4\pi} C_A \left(\text{IR-poles} - \ln^2 \frac{-q^2 - \mathrm{i}0}{\mu^2} + \cdots \right)$$

  - spacelike: $q^2 = -Q^2 < 0: \quad L^2\big|_{\mu=Q} = 0$
  - timelike: $q^2 = +Q^2 > 0: \quad L^2\big|_{\mu=Q} = -\pi^2$

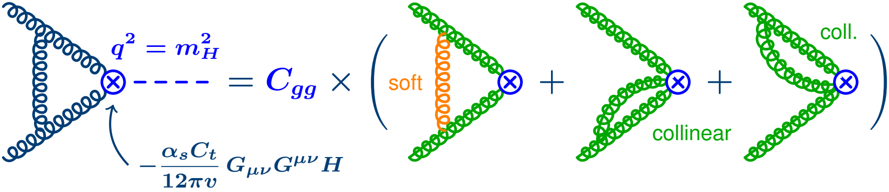
- Exponentiation well understood in Drell-Yan
  [Altarelli, Ellis, Martinelli '79; Parisi '80; Sterman '87; Magnea, Sterman '90]
  (but much smaller effect on K factor than in gluon fusion)
  and in the pion form factor [Bakulev, Radyushkin, Stefanis '00]
- Constitute a dominant source of higher-order corrections
  [Ahrens, Becher, Neubert '08]
  - Dominates K factor beyond NLO

Goal:

Resum timelike logarithms in $gg \to H$ rapidity spectrum
$\to$ Take care of dominant contribution beyond NNLO

Resummation of timelike logarithms.

Hard function.



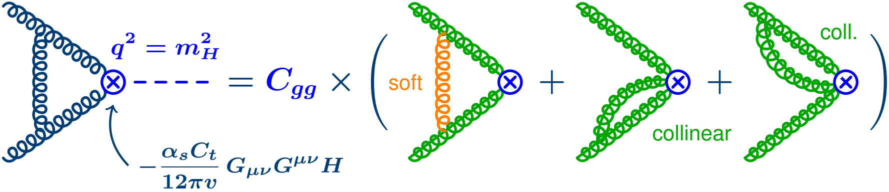
- Form factor contains hard virtual $(\mu \sim m_H)$ corrections
- Match QCD onto SCET $\rightarrow$ IR poles cancel in Wilson coefficient C_{gg}
  $\rightarrow C_{gg} \approx$ IR-finite form factor
  [N^{3}LO: Gehrmann, Glover, Huber, Ikizlerli, Studerus '10]
- Renormalized Wilson coefficient obeys RGE

$$\frac{\mathrm{d} \ln C_{gg}(m_H^2, \mu)}{\mathrm{d} \ln \mu} = \Gamma^g_{\mathrm{cusp}}[\alpha_s(\mu)] \ln \frac{-m_H^2 - \mathrm{i}0}{\mu^2} + \gamma_H[\alpha_s(\mu)] \equiv \gamma_H(m_H, \mu)$$

- Hard function $H = |C_{gg}|^2$ at arbitrary scale:

$$H(m_H^2, \mu_{\mathrm{FO}}) = \underbrace{H(m_H^2, \mu_H)}_{\text{boundary term}} \underbrace{\left| \exp\left[\int_{\mu_H}^{\mu_{\mathrm{FO}}} \frac{\mathrm{d}\mu'}{\mu'} \gamma_H(m_H, \mu') \right] \right|^2}_{\text{resummed logarithms } \ln(\mu_{\mathrm{FO}}/\mu_H)}$$

Hard function.



- Hard function $H = |C_{gg}|^2$ at arbitrary scale:

$$H(m_H^2, \mu_{\rm FO}) = H(m_H^2, \mu_H) \left| \exp\left[\int_{\mu_H}^{\mu_{\rm FO}} \frac{d\mu'}{\mu'} \gamma_H(m_H, \mu') \right] \right|^2$$

- Overall scale choice typically $\mu_{\rm FO} \approx m_H, m_H/2$
- Fixed-order boundary term:

$$\begin{aligned} H(\mu_H = m_H) &= 1 + 0.619 + 0.219 + 0.045 \\ H(\mu_H = m_H/2) &= 1 + 0.573 + 0.124 - 0.008 \\ H(\mu_H = -\mathrm{i} m_H) &= 1 + 0.084 - 0.001 - 0.004 \\ H(\mu_H = -\mathrm{i} m_H/2) &= 1 - 0.016 - 0.015 - 0.002 \end{aligned}$$

- Slow convergence of FO hard function part of large K factor
  [Ahrens, Becher, Neubert '08]

Factorization.

- Hard function is explicit in exclusive cross sections:

$$\frac{d\sigma}{d\mathcal{T}} = \sigma_B \times H(m_H^2, \mu) \times SC(\mathcal{T}, \mu) \times [1 + \mathcal{O}(\mathcal{T}/m_H)]$$

- $\mathcal{T}$ resolves additional emissions: $\mathcal{T} \to 0 \Leftrightarrow$ soft-collinear limit

  e.g. 1 0-jettiness (beam thrust) $\mathcal{T}_0 \ll m_H$

  e.g. 2 Higgs $\vec{p}_T \ll m_H$, leading $p_T^{\text{jet}} \ll m_H$

  e.g. 3 Partonic threshold $1 - z = 1 - m_H^2/\hat{s} \to 0$

- For the cross section inclusive in additional QCD emissions, define

$$\sigma(X) = H(m_H^2, \mu_{\mathrm{FO}}) \times R(X, \mu_{\mathrm{FO}})$$

Born kinematics/cuts

Formally justified if $\sigma(X)$ dominated by soft-collinear limit

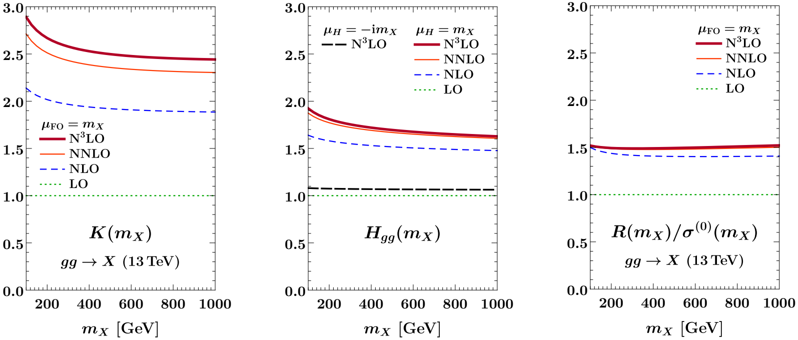
$$R^{(1)} = \sigma^{(1)} - H^{(1)}$$
$$R^{(2)} = \sigma^{(2)} - H^{(2)} - R^{(1)} H^{(1)}$$
$$\vdots$$

Validity of the method.

- Is splitting off the hard function justified?

$$\sigma(X) = H(m_H^2, \mu_{\rm FO}) \times R(X, \mu_{\rm FO})$$

- Possible flaw: Cancellations of $\ln^2(-1) = -\pi^2$ between H and R
- Illustration: Production of generic color-singlet resonance
  - Large perturbative corrections clearly mostly from H
  - Independent of the mass m_X (no accidental feature)



Resummed cross section & uncertainties.

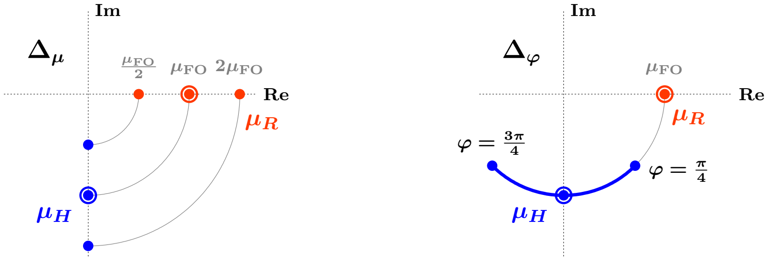
- Resum timelike logarithms by evolving H from $\mu_H = -\mathrm{i}m_H$:

$$\sigma_{\rm res} = H(m_H^2, \mu_H)\, U_H(\mu_H, \mu_{\rm FO})\, R(\mu_{\rm FO})$$
$$= U_H(\mu_H, \mu_{\rm FO}) \left[\sigma_{\rm FO} \frac{H(m_H^2, \mu_H)}{H(m_H^2, \mu_{\rm FO})} \right]_{\rm FO}$$

  - Reproduces fixed order at $\mu_H = \mu_{\rm FO}$

- N^{n}LO+N^{n}LL$'_\varphi$: N^{n}LO xsection + N^{n}LO hard function + N^{n}LL running

- Seven-point variation of (μ_R, μ_F), $\mu_H = \mu_R e^{-\mathrm{i}\pi/2}$: $\rightarrow \Delta_\mu$
- Vary phase of hard scale, $\mu_H = \mu_R\, e^{-\mathrm{i}\varphi}$: $\rightarrow \Delta_\varphi$



Total cross section.

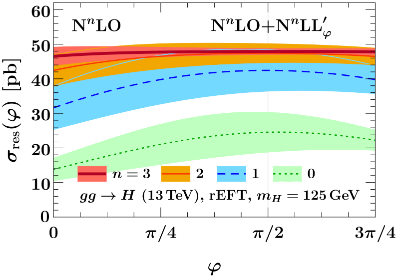
Higgs production in gluon fusion.

- Rescaled EFT scheme: $\sigma^{\mathrm{rEFT}} = |F_0|^2 \sigma^{\mathrm{EFT}}$
- Perturbative convergence:

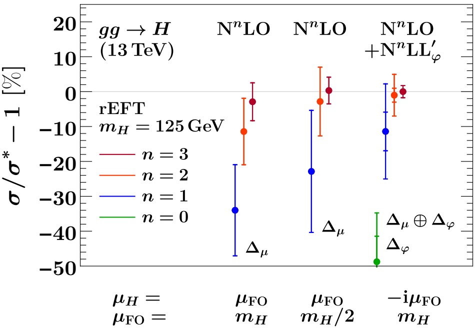
$$\sigma_{\mathrm{FO}}^{\mathrm{rEFT}} = (1 + 1.291 + 0.783 + 0.296) \times 13.80\,\mathrm{pb}$$
$$H(m_H^2, \mu_H = m_H) = 1 + 0.619 + 0.219 + 0.045$$
$$R(\mu_{\mathrm{FO}} = m_H) = (1 + 0.672 + 0.148 + 0.012) \times 13.80\,\mathrm{pb}$$

  - Perturbative corrections beyond NLO dominated by hard function

- Compare: $H(m_H^2, \mu_H = -\mathrm{i} m_H) = 1 + 0.084 - 0.001 - 0.004$
- Study phase dependence $\mu_H = m_H e^{-\mathrm{i}\varphi}$ of resummed xsection:
  - $\varphi = 0$: Fixed order
  - $\varphi = \pi/2$: Resummation
- Convergence significantly improves at $\varphi \to \pi/2$



- Perturbative convergence (relative to N^{3}LO+N^{3}LL$'_\varphi$)



- Compare FO and resummed prediction at N^{3}LO:

$$\sigma^{\rm rEFT}_{\rm FO} = (46.51 \pm 2.60_\mu)\,\text{pb} \qquad (5.59\%) \quad (\mu_{\rm FO} = m_H)$$

$$\sigma^{\rm rEFT}_{\rm FO} = (48.06 \pm 1.83_\mu)\,\text{pb} \qquad (3.82\%) \quad (\mu_{\rm FO} = m_H/2)$$

$$\sigma^{\rm rEFT}_{\rm res} = (47.90 \pm 0.82_\mu \pm 0.18_\varphi)\,\text{pb} \; (1.75\%) \quad (\mu_{\rm FO} = m_H)$$

How to assess theory uncertainties?

Scale variations (or: how to start a religious war)

- Different assessment of uncertainties in [Anastasiou et al, '16; YR4]
  1. Vary $\mu_F = \mu_R \equiv \mu_{\rm FO}$ simultaneously
  2. Evaluate $F_0(m_t, m_H)$ at $\overline{m}_t(\mu_{\rm FO})$
  3. Asymmetric uncertainties
- Example: ($\mu_{\rm FO} = m_H/2$)

$$\begin{aligned}\sigma_{\rm FO}^{\rm rEFT} &= (48.06 \pm 1.83_\mu)\,{\rm pb}\ \ (3.82\%)\\ &\overset{(1)}{\to} (48.06 \pm 1.54_\mu)\,{\rm pb}\ \ (3.21\%)\\ &\overset{(2)}{\to} (48.06 \pm 1.15_\mu)\,{\rm pb}\ \ (2.4\%)\\ &\overset{(3)}{\to} 48.06\,{\rm pb}^{+0.10\ {\rm pb}\ \ (0.2\%)}_{-1.15\ {\rm pb}\ \ (2.4\%)}\end{aligned}$$

Threshold effects

- N^{3}LO obtained in threshold expansion
  - Employ threshold-expanded running in μ_R, μ_F ($\to$ `SusHi`)?

$$\sigma_{\rm FO}^{\rm rEFT} = (48.17 \pm 1.99_\mu)\,{\rm pb}\ \ (4.14\%)$$

- Consider this as an additional/alternative uncertainty?

Gluon fusion beyond rEFT.

- Resummation + corrections beyond rEFT possible: m_t, m_b, m_c, EW, ...
  (→ see also M. Wiesemann's talk)
  - Most relevant & least straightforward: finite m_t-corrections at NLO

Option 1 Simply add them: $\sigma^{\text{rEFT}}_{\text{res}} + \delta\sigma^t_{\text{NLO}}$

Option 2 Use full $t\bar{t}H$-induced form factor at NLO, $\rho = \dfrac{m_H^2}{4m_t^2}$:

$$H^t = |F_0(\rho)|^2 |\alpha_s(\mu)|^2 \left\{ \left|C_t\, C_{gg}\right|^2 + 2\,\mathrm{Re}\left[\frac{\alpha_s(\mu)}{4\pi} \Delta F_1(\rho)\right] + \mathcal{O}(\rho\,\alpha_s^2) \right\}$$

- Compare both approaches:

n	$\sigma^{\text{rEFT}}_{\text{res}} + \delta\sigma^t_{\text{nlo}}$	$(\sigma^{\text{rEFT}} + \delta\sigma^t_{\text{nlo}})_{\text{res}}$
0	$24.5 \pm 5.7_\mu \pm 3.5_\varphi$ (27%)	$23.3 \pm 5.1_\mu \pm 3.4_\varphi$ (26%)
1	$42.2 \pm 5.9_\mu \pm 2.7_\varphi$ (15%)	$41.8 \pm 5.7_\mu \pm 2.8_\varphi$ (15%)
2	$47.2 \pm 2.6_\mu \pm 1.0_\varphi$ (6.0%)	$47.3 \pm 2.7_\mu \pm 1.0_\varphi$ (6.1%)
3	$47.7 \pm 0.8_\mu \pm 0.18_\varphi$ (1.7%)	$47.8 \pm 0.8_\mu \pm 0.25_\varphi$ (1.8%)

- Differences negligible beyond NLO

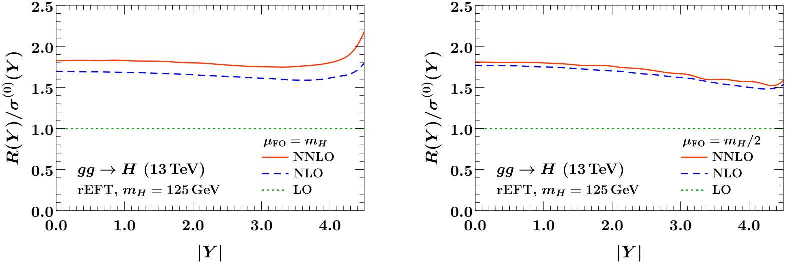
Higgs rapidity spectrum.

Higgs rapidity spectrum in gluon fusion.

- As before: split cross section into hard function $\boldsymbol{H}$ and remainder $\boldsymbol{R}$:

$$\frac{\mathrm{d}\sigma(Y)}{\mathrm{d}Y} = H(m_H^2, \mu_{\mathrm{FO}}) \times R(Y, \mu_{\mathrm{FO}})$$

  - $\boldsymbol{Y}$ dependence fully contained in $\boldsymbol{R}$
- Perturbative convergence of $\boldsymbol{R}$:



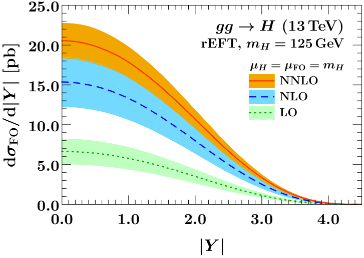
- Compare to inclusive cross section:

$$R(\mu_{\mathrm{FO}} = m_H) = (1 + 0.672 + 0.148 + 0.012) \times 13.80\,\mathrm{pb}$$

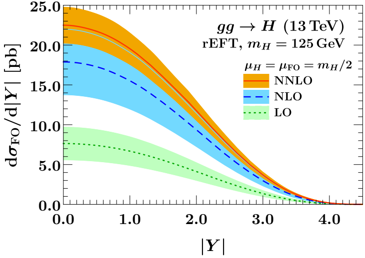
  - $\boldsymbol{R(Y)}$ essentially flat in $\boldsymbol{Y}$
  - Similar size as $\boldsymbol{R_{\mathrm{tot}}}$: Expect similar improvement

Resummed rapidity spectrum.

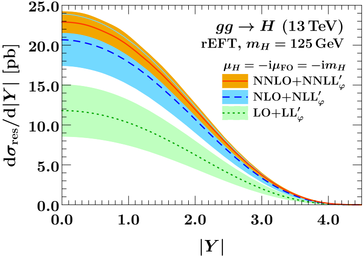
FO, $\mu_{FO} = m_H$



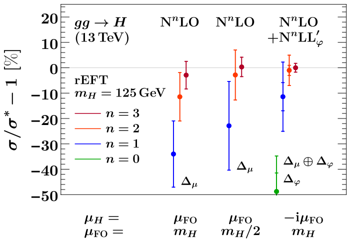
FO, $\mu_{FO} = m_H/2$



Resummed



Inclusive xsection



Higgs production with rapidity cut.

- Fiducial measurements require $\sigma(Y_{\rm cut}) = \int_0^{Y_{\rm cut}} \mathrm{d}|Y| \, \frac{\mathrm{d}\sigma}{\mathrm{d}|Y|}$
- Example: $Y_{\rm cut} = 2.5$ (for STXS)
- Fixed-order results:

n	$\sigma_{\rm FO}^{\rm rEFT} + \delta\sigma_{\rm NLO}^t$ N^{n}LO, $\mu_{\rm FO} = m_H$	N^{n}LO, $\mu_{\rm FO} = \frac{m_H}{2}$
0	$12.5 \pm 2.9_\mu$ (23%)	$14.5 \pm 3.9_\mu$ (27%)
1	$28.5 \pm 5.6_\mu$ (20%)	$33.3 \pm 7.5_\mu$ (23%)
2	$38.3 \pm 4.0_\mu$ (11%)	$41.9 \pm 4.2_\mu$ (10%)
3*	≈ 42.0	≈ 43.2

- Resummed result:

n	$\sigma_{\rm res}^{\rm rEFT} + \delta\sigma_{\rm NLO}^t$ N^{n}LO+N^{n}LL$'_\varphi$ (H)	$(\sigma^{\rm rEFT} + \delta\sigma_{\rm NLO}^t)_{\rm res}$ N^{n}LO+N^{n}LL$'_\varphi$ (H^t)
0	$22.2 \pm 5.2_\mu \pm 3.2_\varphi$ (27%)	$21.1 \pm 4.6_\mu \pm 3.1_\varphi$ (26%)
1	$38.4 \pm 5.4_\mu \pm 2.4_\varphi$ (15%)	$38.0 \pm 5.2_\mu \pm 2.6_\varphi$ (15%)
2	$42.8 \pm 2.3_\mu \pm 0.9_\varphi$ (5.8%)	$42.9 \pm 2.4_\mu \pm 0.9_\varphi$ (6.0%)
3*	≈ 43.2	≈ 43.3

Approximating the N^{3}LO rapidity spectrum.

- Approximate N^{3}LO rapidity spectrum through rescaling (?)

$$\sigma_{\text{N}^3\text{LO}}(Y_{\text{cut}}) \approx \frac{\sigma_{\text{N}^3\text{LO}}}{\sigma_{\text{NNLO}}} \times \sigma_{\text{NNLO}}(Y_{\text{cut}})$$

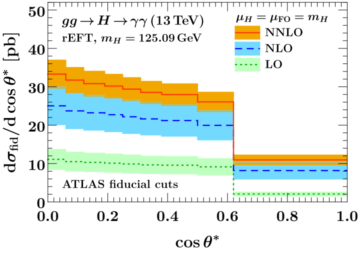
  - How to assign uncertainties?
- Cleaner approach: $\sigma(Y_{\text{cut}})$ at NNLO+NNLL$'_\varphi$
  - Contains dominant contribution to N^{3}LO K factor
  - Incorporates reliable uncertainties
- Illustration: Assume N^{3}LO contribution to R is flat in Y
  - Approximate $R^{(3)}(Y) \approx R^{(3)} \dfrac{\sigma^{(0)}(Y)}{\sigma^{(0)}}$

n	$\sigma_{\text{FO}} + \delta\sigma^t$ $(\mu = m_H/2)$	$\sigma_{\text{res}} + \delta\sigma^t$	$(\sigma + \delta\sigma^t)_{\text{res}}$
1	$33.3 \pm 7.5_\mu$ (23%)	$38.4 \pm 5.4_\mu \pm 2.4_\varphi$ (15%)	$38.0 \pm 5.2_\mu \pm 2.6_\varphi$ (15%)
2	$41.9 \pm 4.2_\mu$ (10%)	$42.8 \pm 2.3_\mu \pm 0.9_\varphi$ (5.8%)	$42.9 \pm 2.4_\mu \pm 0.9_\varphi$ (6.0%)
3*	≈ 43.2	≈ 43.2	≈ 43.3

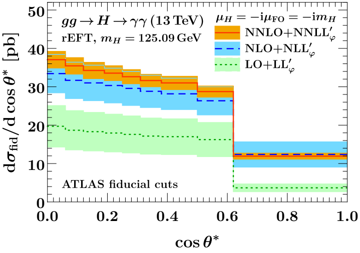
Fiducial observables in $gg \to H \to \gamma\gamma$.

- Recall fiducial photon cuts:
  - $0 \le |Y| < 2.37$, excluding $1.37 < |Y| < 1.52$
  - $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}\,,\ p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$
- Recall $\cos\theta^* = \dfrac{(E^{\gamma_1} + p_z^{\gamma_1})(E^{\gamma_2} - p_z^{\gamma_2}) - (E^{\gamma_1} - p_z^{\gamma_1})(E^{\gamma_2} + p_z^{\gamma_2})}{m_{\gamma\gamma}\sqrt{m_{\gamma\gamma}^2 + p_{T\,\gamma\gamma}^2}}$
  - Without cuts: completely flat for spin-0
  - Shape fully given by fiducial cuts

$\cos(\theta^*)$, fixed order

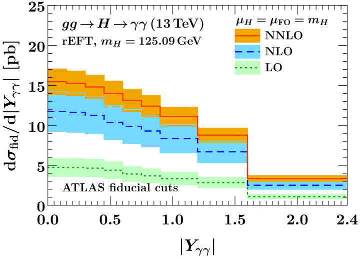


$\cos(\theta^*)$, resummed

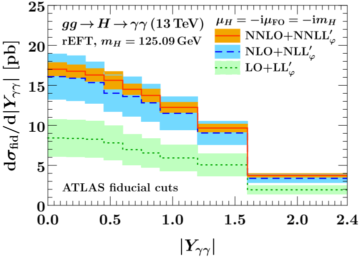


Fiducial observables in $gg \to H \to \gamma\gamma$.

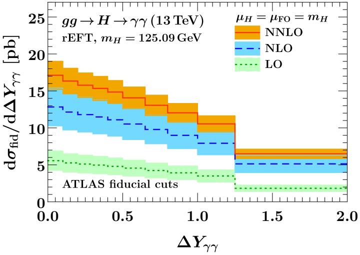
$|Y_H| = |Y_{\gamma\gamma}|$, fixed order



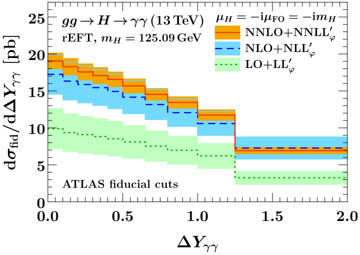
$|Y_H| = |Y_{\gamma\gamma}|$, resummed



$|\Delta Y_{\gamma\gamma}| = |Y_{\gamma_1} - Y_{\gamma_2}|$, fixed order



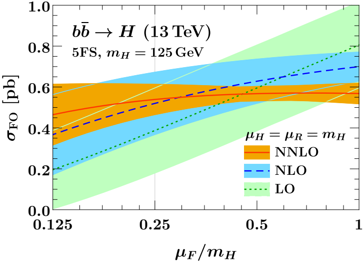
$|\Delta Y_{\gamma\gamma}| = |Y_{\gamma_1} - Y_{\gamma_2}|$, resummed

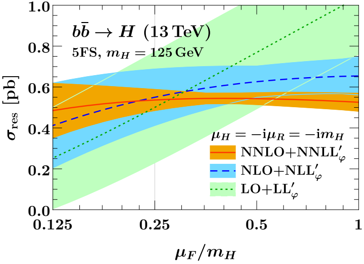


Outlook: $b\bar{b} \to H$ and Drell-Yan production.

μ_F dependence of $b\bar{b} \to H$

- $b\bar{b} \to H$ treated in 5-flavor scheme (5FS)
- Choice of factorization scale μ_F more important than μ_R
- Commonly adopted: $\mu_F = m_H/4$





- Perturbative convergence of R best at $\mu_F = m_H/4$:

$$R(\mu_R = m_H, \mu_F = m_H/4) = \sigma^{(0)} \times (1 + 0.115 - 0.031)$$

$$R(\mu_R = \mu_F = m_H) = \sigma^{(0)} \times (1 - 0.359 - 0.136)$$

  - μ_F captures collinear logarithms
  - μ_R captures virtual corrections

Resummed $b\bar{b} \to H$ cross section.

- Decompose $\sigma = H^S_{q\bar{q}} \times R$ (at $\mu_F = m_H/4, \mu_R = m_H$):

$$\sigma_{\mathrm{FO}} = (1 + 0.342 + 0.050) \times 0.387\,\mathrm{pb}$$
$$H^S_{q\bar{q}} = \; 1 + 0.227 + 0.054$$
$$R = (1 + 0.115 - 0.031) \times 0.387\,\mathrm{pb}$$

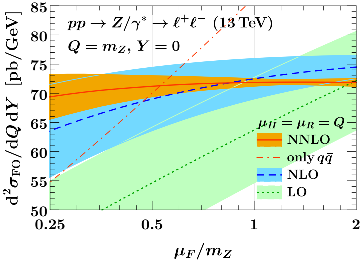
- K factor again dominated by hard function, but less dramatic than for $gg \to H$
- Resummed cross section:

n	σ_{FO} at N^{n}LO	σ_{res} at N^{n}LO+N^{n}LL$'_\varphi$
0	$0.387 \pm 0.208_\mu \pm 0.020_b$ (54%)	$0.500 \pm 0.269_\mu \pm 0.026_b \pm 0.033_\varphi$ (54%)
1	$0.520 \pm 0.153_\mu \pm 0.027_b$ (30%)	$0.550 \pm 0.138_\mu \pm 0.028_b \pm 0.006_\varphi$ (26%)
2	$0.539 \pm 0.074_\mu \pm 0.028_b$ (15%)	$0.537 \pm 0.052_\mu \pm 0.028_b \pm 0.002_\varphi$ (11%)

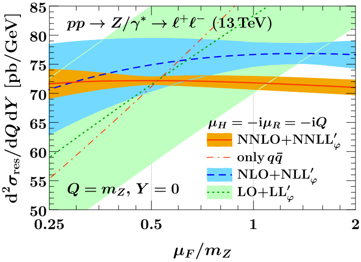
- Resummation slightly improves uncertainties
- Good agreement with fixed order gives confidence in central value
- Uncertainty can be further reduced by matched 4FS/5FS computation, see [Bonvini, Papanastasiou, Tackmann '16]

μ_F dependence of Drell-Yan $pp \to Z/\gamma^* \to l^+l^-$.

Fixed order

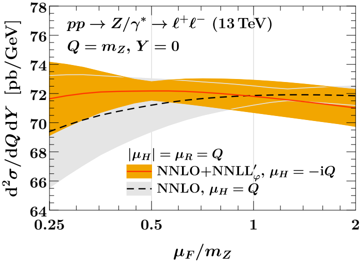


resummed



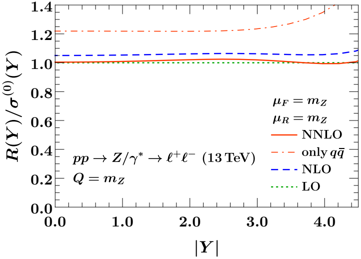
- FO: use $\mu_F = m_H$
- Resummed: use $\mu_F = m_H/2$
  - Good coverage of higher orders
  - Stable under μ_F variation
- $\mu_F = m_H/2$ minimizes impact of gluon channels (red line)

NNLO vs. NNLO+NNLL$'_\varphi$

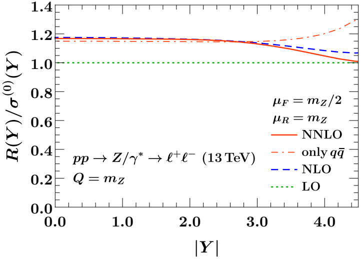


Resummed of Drell-Yan rapidity spectrum.

Fixed order, $\mu_{\mathrm{FO}} = m_H$

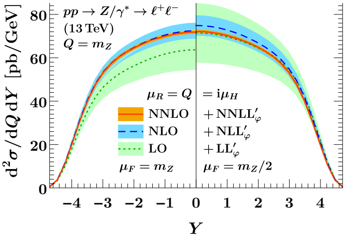


Fixed order, $\mu_{\mathrm{FO}} = m_H/2$



- Very good agreement of resummed / fixed order result
- Confidence in both central values and uncertainties

NNLO vs. NNLO+NNLL$'_\varphi$



Resummed of Drell-Yan rapidity spectrum.

- For illustration: $\dfrac{\mathrm{d}^2\sigma}{\mathrm{d}Q\mathrm{d}Y}$ at $Q = m_Z, Y = 0$
- Decomposition into hard function and remainder:

$$
\begin{aligned}
\mathrm{d}^2\sigma_{\mathrm{FO}}(\mu_R = m_Z, \mu_F = m_Z) &= (1 + 0.138 - 0.010) \times 63.7\,\mathrm{pb/GeV} \\
H^V_{q\bar q}(m_Z^2, \mu_H = m_Z) &= \ 1 + 0.088 + 0.0317 \\
R(\mu_R = m_Z, \mu_F = m_Z) &= (1 + 0.050 - 0.046) \times 63.7\,\mathrm{pb/GeV} \\
\mathrm{d}^2\sigma_{\mathrm{FO}}(\mu_R = m_Z, \mu_F = m_Z/2) &= (1 + 0.263 + 0.040) \times 54.6\,\mathrm{pb/GeV} \\
H^V_{q\bar q}(m_Z^2, \mu_H = m_Z) &= \ 1 + 0.088 + 0.0317 \\
R(\mu_R = m_Z, \mu_F = m_Z/2) &= (1 + 0.175 - 0.007) \times 54.6\,\mathrm{pb/GeV}\,.
\end{aligned}
$$

- Compare: $H^V_{q\bar q}(m_Z, \mu_H = -\mathrm{i}m_Z) = 1 - 0.150 - 0.001 - 0.001$
- Comparison of FO / resummed predictions:

n	σ_{FO} at $\mu_F = m_Z$	σ_{FO} at $\mu_F = m_Z/2$	σ_{res} at $\mu_F = m_Z/2$
0	$63.7\pm9.1_\mu$ (14%)	$54.6\pm9.6_\mu$ (17%)	$71.5\pm12.6_\mu\pm5.0_\varphi$ (19%)
1	$72.5\pm3.5_\mu$ (4.8%)	$69.0\pm5.4_\mu$ (7.9%)	$74.9\pm4.2_\mu\pm1.6_\varphi$ (6.1%)
2	$71.9\pm0.7_\mu$ (0.9%)	$71.2\pm1.8_\mu$ (2.5%)	$72.2\pm0.6_\mu\pm0.2_\varphi$ (0.9%)

Summary.

Summary.

- Rapidity distribution is an important Higgs observable:
  - Spectrum interesting in itself
  - Analyses need fiducial xsection with complicated cuts on final state
  - STXS: $\sigma(Y_{\rm cut} = 2.5)$
- Rapidity spectrum known to NNLO
  [Anastasiou, Melnikov, Petriello '04, '05; Catani, Grazzini '07]
- $\mathbf{N^3LO}$ on the way [Dulat, Lionetti, Mistlberger, Pelloni, Specchia '17]
- First step towards $\mathbf{N^3LO}$ accuracy: resummation of timelike logarithms
  - Well known in inclusive cross section:
    reduces FO uncertainty from 3.8% to 1.8%
  - Works nicely also for differential spectrum:
    uncertainties reduced from $\approx 10\%$ to $\approx 6\%$
  - Method was also validated for $b\bar{b} \to H$ and Drell-Yan
- Will be useful to further improve $\mathbf{N^3LO}$ once available

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Thank you for your attention!

Backup slides.

Assessing validity of resummation in threshold limit.

Validation in threshold limit [Anastasiou et al, '16]:

- Threshold limit $z = m_H^2/\hat{s} \to 1$ exactly factorizes: $\sigma_{\rm thr} = H \times S$
- Expand as

$$C_\delta \delta(1-z)\,, \qquad C_n \left[\frac{1}{1-z} \ln^n(1-z)\right]_+ \qquad (n \geq 0)$$

- Effect of timelike logarithms on C_δ:

$$C_{\delta\,\rm appr}^{(n+1)} = H^{(n+1)} + H^{(n)}\, S_\delta^{(1)} + \cdots + H^{(1)}\, S_\delta^{(n)}$$

- Result: [Anastasiou et al, '16]

LO+LL$'_\varphi$: $\quad C_\delta = 1 + 14.80\left(\frac{\alpha_s}{\pi}\right) + \cdots$

NLO+NLL$'_\varphi$: $\quad C_\delta = 1 + 9.87\left(\frac{\alpha_s}{\pi}\right) + 45.35\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots$

NNLO+NNLL$'_\varphi$: $\quad C_\delta = 1 + 9.87\left(\frac{\alpha_s}{\pi}\right) + 13.61\left(\frac{\alpha_s}{\pi}\right)^2 - 644.26\left(\frac{\alpha_s}{\pi}\right)^3 + \cdots$

N^{3}LO: $\quad C_\delta = 1 + 9.87\left(\frac{\alpha_s}{\pi}\right) + 13.61\left(\frac{\alpha_s}{\pi}\right)^2 + 1124.31\left(\frac{\alpha_s}{\pi}\right)^3$

- Bad estimate of higher-order terms by timelike logarithms ✗

Assessing validity of resummation in threshold limit.

Validation in threshold limit [Anastasiou et al, '16]:

- Threshold limit $z = m_H^2/\hat{s} \to 1$ exactly factorizes: $\sigma_{\rm thr} = H \times S$
- Expand as [Becher, Neubert '09]

$$\tilde{C}_\delta \delta(1-z)\,, \qquad \tilde{C}_n \left[\frac{1}{1-z} \ln^n \frac{(1-z)^2}{z}\right]_+ \qquad (n \geq 0)$$

- Effect of timelike logarithms on C_δ:

$$\tilde{C}^{(n+1)}_{\delta\,\rm appr} = H^{(n+1)} + H^{(n)}\,\tilde{S}^{(1)}_\delta + \cdots + H^{(1)}\,\tilde{S}^{(n)}_\delta$$

- Result:

LO+LL$'_\varphi$: $\tilde{C}_\delta = 1 + 14.80\left(\frac{\alpha_s}{\pi}\right) + \cdots$

NLO+NLL$'_\varphi$: $\tilde{C}_\delta = 1 + 19.74\left(\frac{\alpha_s}{\pi}\right) + 215.82\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots$

NNLO+NNLL$'_\varphi$: $\tilde{C}_\delta = 1 + 19.74\left(\frac{\alpha_s}{\pi}\right) + 210.07\left(\frac{\alpha_s}{\pi}\right)^2 + 1484.58\left(\frac{\alpha_s}{\pi}\right)^3 +$

N^{3}LO: $\tilde{C}_\delta = 1 + 19.74\left(\frac{\alpha_s}{\pi}\right) + 210.07\left(\frac{\alpha_s}{\pi}\right)^2 + 1372.11\left(\frac{\alpha_s}{\pi}\right)^3$

- Good estimate of higher-order terms by timelike logarithms ✓

Assessing validity of resummation in threshold limit.

Validation through K factor:

- Coefficient of $\delta(1-z)$ is scheme dependent & *unphysical*
- Consider a physical observable:

$$K = \frac{\sigma}{\sigma^{(0)}} = \frac{H \times R}{\sigma^{(0)}}$$

- Effect of timelike logarithms on K:

$$K_{\text{appr}}^{(n+1)} = H^{(n+1)} + H^{(n)}\, R_\delta^{(1)} + \cdots + H^{(1)}\, R_\delta^{(n)}$$

- Result:

LO+LL$'_\varphi$: $K = 1 + 14.80\left(\frac{\alpha_s}{\pi}\right) + \cdots$

NLO+NLL$'_\varphi$: $K = 1 + 30.52\left(\frac{\alpha_s}{\pi}\right) + 402.00\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots$

NNLO+NNLL$'_\varphi$: $K = 1 + 30.52\left(\frac{\alpha_s}{\pi}\right) + 425.27\left(\frac{\alpha_s}{\pi}\right)^2 + 3820.46\left(\frac{\alpha_s}{\pi}\right)^3 +$

N^{3}LO: $K = 1 + 30.52\left(\frac{\alpha_s}{\pi}\right) + 425.27\left(\frac{\alpha_s}{\pi}\right)^2 + 3576.94\left(\frac{\alpha_s}{\pi}\right)^3$

- Timelike logarithms predict K very well beyond NLO ✓