Higgs pT

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Karlsruher Institut für Technologie

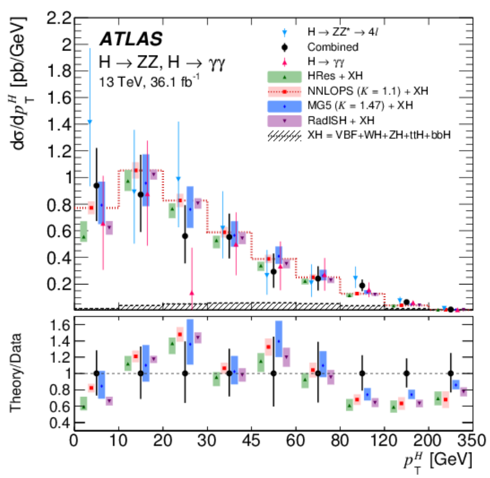
Higgs Hunting, Paris, 23-25 July, 2018

Higgs couplings

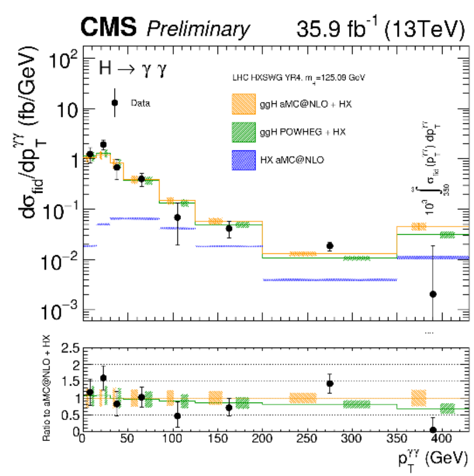
- *New scalar boson* discovered in 2012
- *Questions:* is it the SM Higgs? Does it couple to other particles outside the SM picture or can we use it as a probe of BSM?
- To answer: we need to measure Higgs couplings and compare with accurate SM prediction
- Higgs-W/Z constrained to about 20% of SM prediction, while top-Yukawa coupling constrained to ~50-100%
- Inclusive (gg-fusion) cross sections are known to impressive N3LO order already [Anastasiou et al. '16]

Going beyong inclusive rates:

- As more Run II data enters and luminosity increases, we will gain more experimental access to Higgs transverse momentum ($p_{T,H}$) distribution



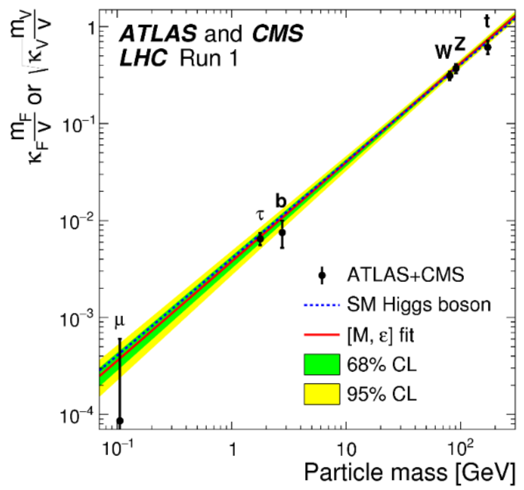
[CERN-EP-2018-080]



[CMS-PAS-HIG-17-015]

Relevance of $p_{T,H}$-distribution

- Theoretical knowledge of $p_{T,H}$ distributions is used to ***compute fiducial cross sections***, that are then used to determine Higgs couplings
- Can be used to ***constrain light-quark Yukawa couplings***
- Alternative pathway to ***distinguish top-Yukawa from point-like ggH coupling***



[arXiv:1606.02266]

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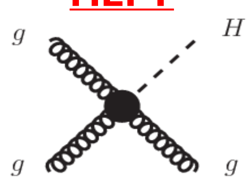
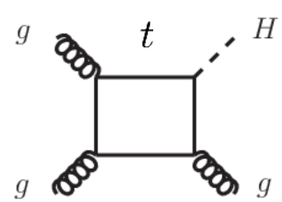
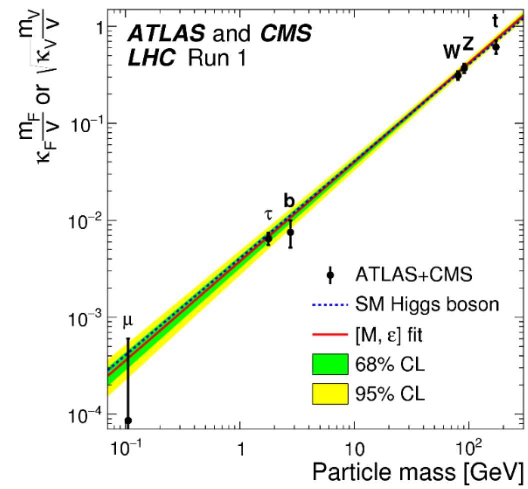
- Alternative pathway to ***distinguish top-Yukawa from point-like ggH coupling***
- Higgs production at LHC proceeds largely through quark loops, historically computed in HEFT limit $m_t \to \infty$
- Top quark loop ~ 90% and bottom loop ~ 5-10%

below top threshold	close to threshold	above top threshold
HEFT 	increasing $p_{T,H}$	
$m_t \to \infty$	$1 - \frac{4m_t^2}{\hat{s}} \ll 1$	$\frac{m_h^2}{4m_t^2}, \frac{4m_t^2}{p_\perp^2} \ll 1$



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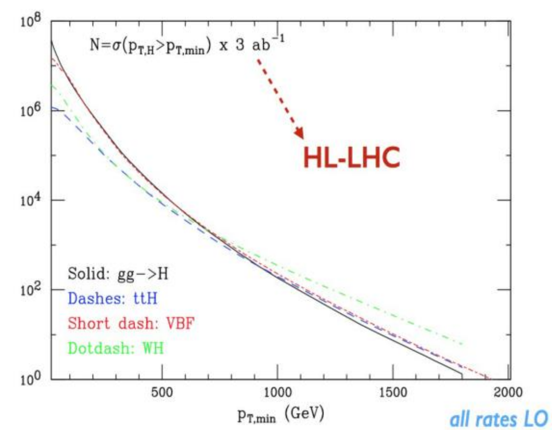
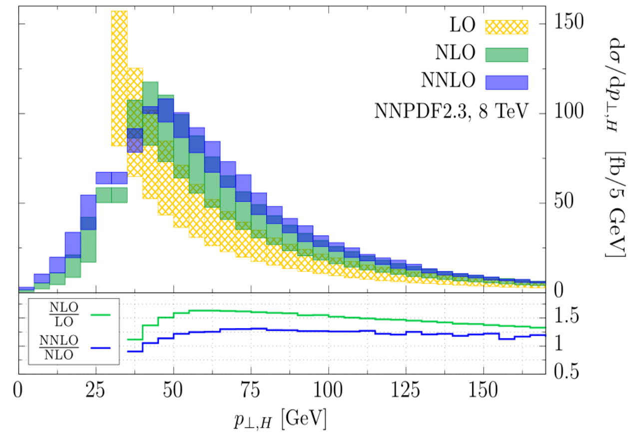


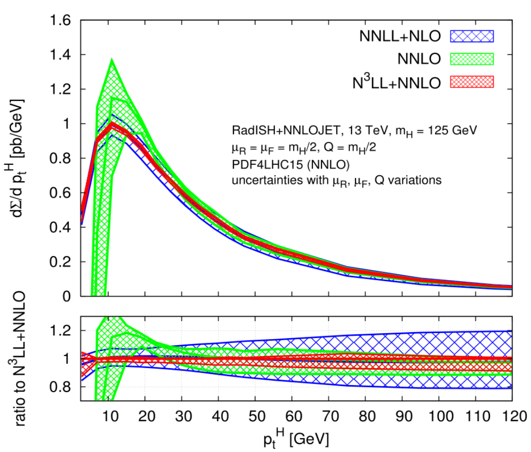
[Mangano talk at Higgs Couplings 2016]

Recent gg-fusion theory progress

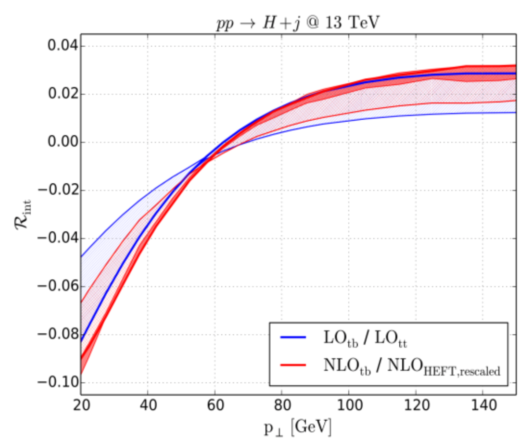
- Fixed order at NNLO QCD in HEFT: Boughezal, Caola et al. '15, Chen et al.' 16, Dulat et al. '17
- Low $p_{T,H}$ resummation at N3LL+NNLO QCD in HEFT: Bizon et al., Chen et al. '17-'18
- Bottom mass corrections at NLO QCD: Lindert et al. '17
- High $p_{T,H}$ region at NLO QCD with full top mass: Lindert et al., Jones et al., Neumann et al. '18
- Parton shower NLOPS: Frederix et al., Jadach et al. '16, ….



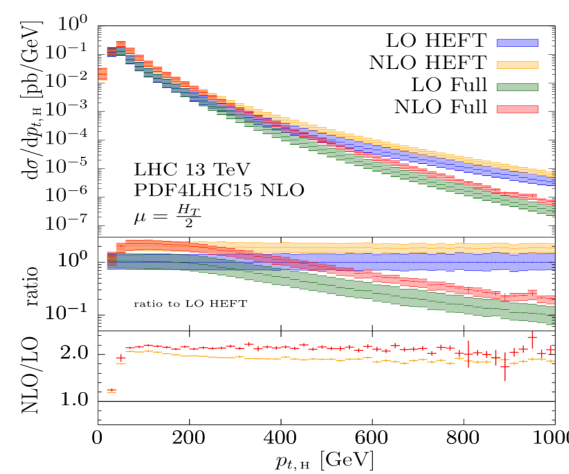
[Boughezal, Caola et al., arXiv: 1504.07922]



[Bizon, Chen et al., arXiv: 1805.0591]



[Lindert et al., arXiv: 1703.03886]



[Jones et al., arXiv: 1802.00349]

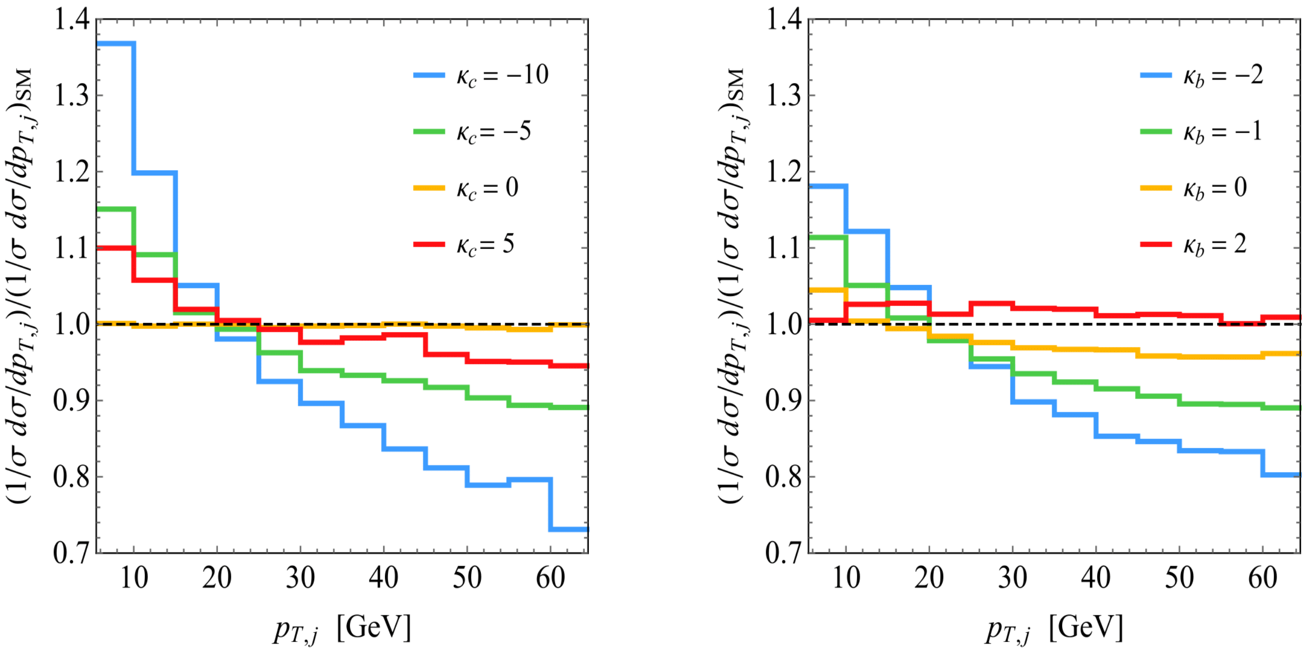
Below top threshold

- <u>Constrain bottom- and charm-quark Yukawa couplings</u>

- Light quark contributions appear pre-dominantly through interference with top. However relative contribution of direct $q\bar{q} \to Hg, qg \to Hq$ contribution increases with light Yukawa coupling

- Shape of $p_{T,H}$ distribution may put strong constraints on light-quark Yukawa couplings

[Bishara, Monni et al '16; Soreq et al '16]



$$\kappa_j = y_j / y_{j,SM}$$

- Bounds expected from HL-LHC $\kappa_c \in [-0.6, 3.0]$ $\kappa_b \in [0.7, 1.6]$

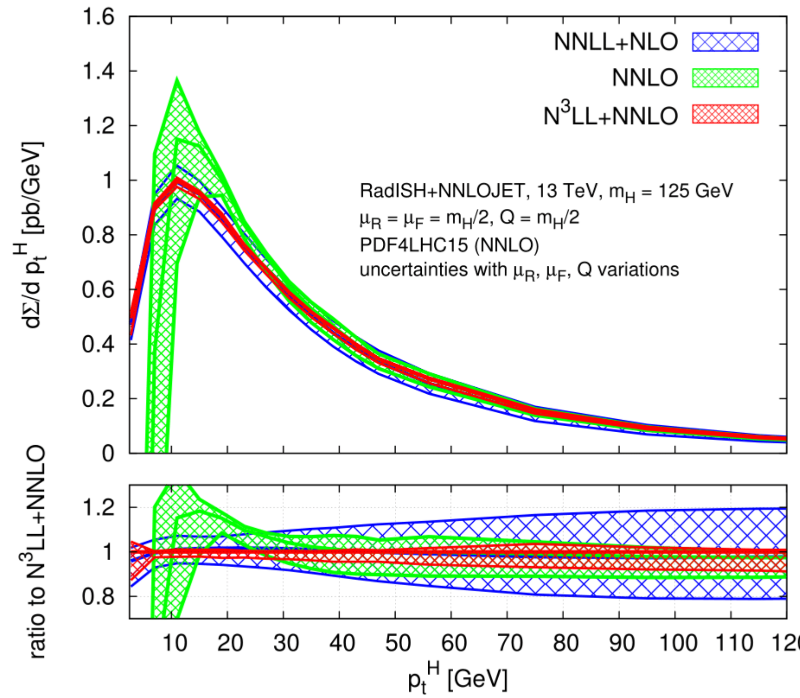
[Bishara, Monni et al '16]

Below top threshold $p_{T,H} \leq 350$ GeV: top contribution

- HEFT approximation good enough for top contribution
- Large Sudakov logarithms at very low $p_{T,H} \leq 30$ GeV

$$\frac{d\sigma}{dp_{T,H}} \sim \exp\{\alpha_s \log^2\left(\frac{p_{T,H}}{m_h}\right) + \alpha_s \log\left(\frac{p_{T,H}}{m_h}\right) + \cdots\}$$

- Higgs distribution at low $p_{T,H} \leq 30$ GeV requires resumming these logarithms. Perturbative expansion good at higher $p_{T,H} > 30$ GeV
- Resummation reduces scale error: top contribution now understood well to within few percent error



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Below top threshold $p_{T,H} \leq 350$ GeV: top contribution

- HEFT approximation good enough for top contribution
- Large Sudakov logarithms at very low $p_{T,H} \lesssim 30$ GeV

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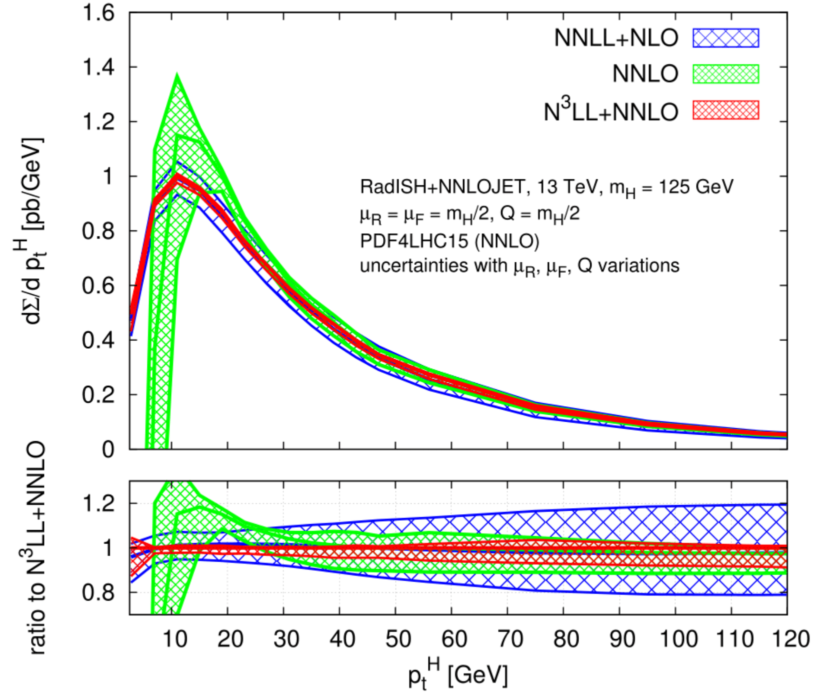
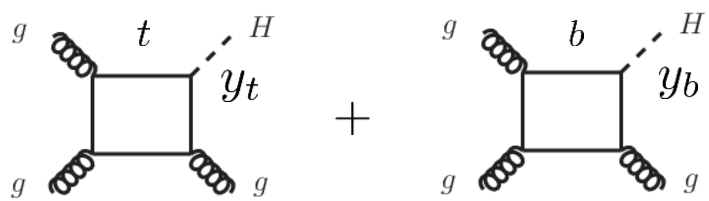
- Higgs distribution at low $p_{T,H} \lesssim 30$ GeV requires resumming these logarithms. Perturbative expansion good at higher $p_{T,H} > 30$ GeV
- Resummation reduces scale error: top contribution now understood well to within few percent error
- What about bottom mass corrections in ggF?



[Bizon, Chen et al., arXiv: 1805.0591]

$$\mathcal{A}^{LO}_{gg\to gH} \sim$$



dominant bottom correction

- Differential cross section $\mathrm{d}\sigma \sim |\mathcal{A}|^2 \to \mathrm{d}\sigma = \mathrm{d}\sigma_{tt} + \mathrm{d}\sigma_{tb} + \mathrm{d}\sigma_{bb}, \quad \mathrm{d}\sigma_{ij} \sim \mathcal{O}(y_i y_j)$

Below top threshold $p_{T,H} \leq 350$ GeV: including bottom

- <u>Theoretical complication</u>: $p_{T,H}$ above bottom threshold and thus bottom loop ***<u>does not factorize</u>***

$$p_{\mathrm{T,H}} > 2m_b \sim 10\,\mathrm{GeV} \;: \qquad \mathcal{A}_{gg\to Hg}^{\text{bottom-loop}} \sim \frac{y_b m_b}{p_{\mathrm{T,H}}} \log^2\left(\frac{4m_b^2}{p_{\mathrm{T,H}}^2}\right)$$

- Bottom contribution to $p_{T,H}$ computed recently at NLO [Lindert et al '17]
- Previous N2LL resummed predictions can now be matched to full NLO with bottom [Caola et al. '18]

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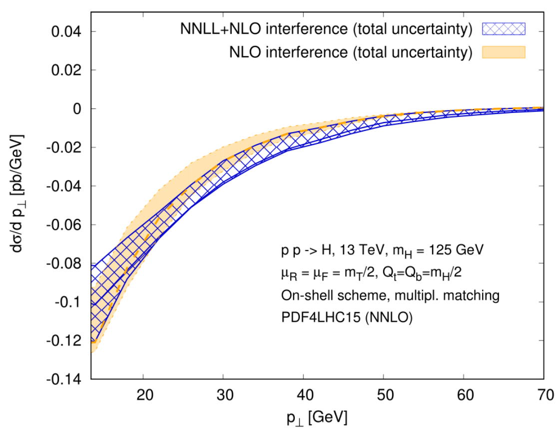
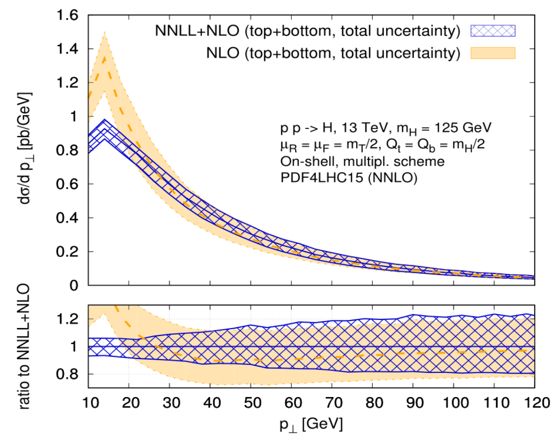
- Bottom contribution to $p_{T,H}$ computed recently at NLO [Lindert et al '17]
- Previous N2LL resummed predictions can now be matched to full NLO with bottom [Caola et al. '18]
- Resummation of Sudakov-logarithms $\log\left(p_{\mathrm{T,H}}/m_h\right)$ strictly speaking only possible when quark loop factorizes. At small $p_{T,H}$~10 GeV logs still large so best we can do is to resum and gauge error of different resummation scales and schemes

[Caola et al., ArXiv: 1804.07632]

- Interference contribution error~20%, translates to ~1-2% error on total
- Largest uncertainty of the top-bottom interference contribution from bottom mass scheme choice





- Open question: can we resum the bottom mass logarithms $\log\left(\frac{4m_b^2}{p_{\mathrm{T,H}}^2}\right)$? [Penin, Melnikov '16]

Above top threshold: $p_{T,H} \geq 400$ GeV

- <u>Constrain top Yukawa and point-like ggH coupling</u>

- Higgs couplings to top-partners induce effective ggH coupling

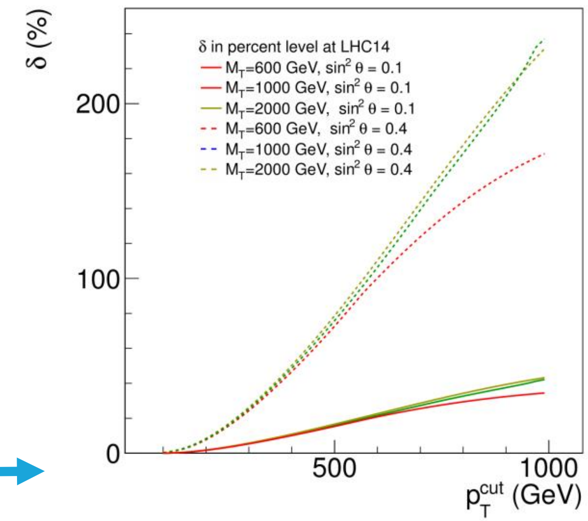
$$\frac{m_t}{v}\bar{t}tH \to -\kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{\mu\nu,a} H + \kappa_t \frac{m_t}{v}\bar{t}tH$$

- Inclusive rate only constrains sum $k_g + k_t$, while Higgs distribution at large $\boldsymbol{p_{T,H}}$ can disentangle the two contributions

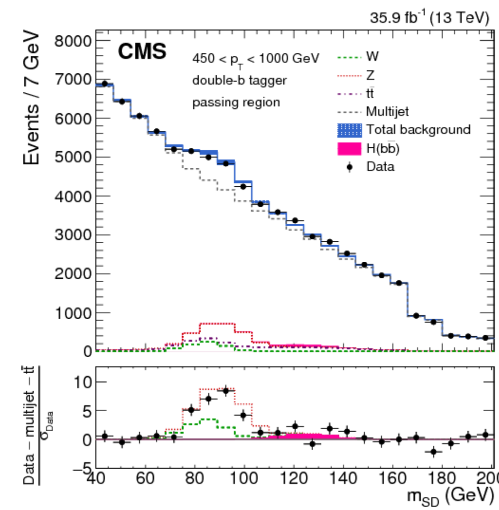
- CMS has <u>already</u> begun searching for boosted $H \to b\bar{b}$ decay

- At HL-LHC enough statistics for differential at $p_{T,H} \geq 400$ GeV

- <u>Theoretical complication</u>: usual HEFT approach breaks down starting at large $\boldsymbol{p_{T,H}}$ and top mass corrections cannot be neglected



[Banfi, Martin, Sanz, arXiv:1308.4771]



[CMS-HIG-17-010-003]

High $p_{T,H}$: boosted regime

- At $\boldsymbol{p_{T,H}}$ larger than twice the top mass, **not even the top loop is point-like**

- HEFT ($m_t \to \infty$) breakdown

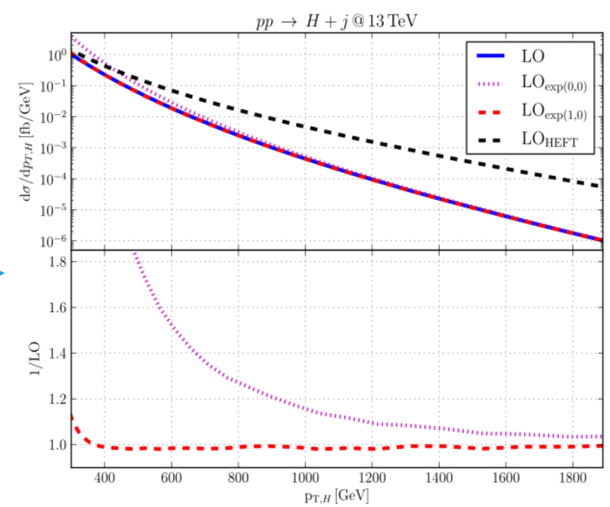
- Top amplitude *contains enhanced Sudakov-like logarithms* above top threshold

$$p_{\mathrm{T,H}} > 2m_t \sim 350\,\mathrm{GeV} \;: \qquad \mathcal{A}^{\text{top-loop}}_{gg\to Hg} = \frac{y_t m_t}{p_{\mathrm{T,H}}}\left\{\log^2\left(\frac{4m_t^2}{p_{\mathrm{T,H}}^2}\right) + \mathcal{O}\left(\frac{4m_t^2}{p_{\mathrm{T,H}}^2}\right)\right\}$$

- Use scale hierarchy, $\boldsymbol{p_{T,H} > 2m_t}$ to expand result in top mass

- Expansion in Higgs and top mass converges quickly

- In practice first top-mass correction is enough for approximating exact result within 1%

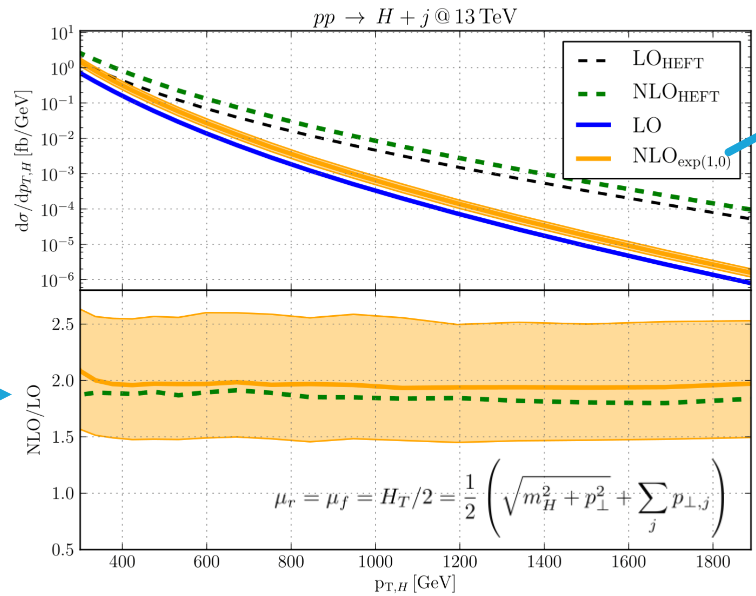


[Kudashkin et al., arXiv: 1801.08226]

High $p_{T,H}$: NLO results

[Kudashkin et al., arXiv: 1801.08226]

- NLO results
- HEFT K-factor close to exact



Expansion in top and Higgs mass approximation

PDF: NNPDF3.0

$$m_t = 173.2\,\mathrm{GeV}$$

$$m_H = 125\,\mathrm{GeV}$$

$$\mu = \{1/2, 2\} * \mu_0$$

$$\sigma^{\mathrm{theory,NLO}}_{p_{T,H} \geq 450\,\mathrm{GeV}}(gg \to H(\to b\bar{b})) \sim 7\,\mathrm{fb} \pm 20\%$$

$$\sigma^{\mathrm{CMS}}_{p_{T,H} \geq 450\,\mathrm{GeV}}(gg \to H(\to b\bar{b})) \sim 74 \pm 48(\mathrm{stat}) \pm 17(\mathrm{syst})\,\mathrm{fb}$$

- NLO predictions including full top mass dependence with numerical methods (see G. Heinrich's talk)
- NLO theory result should be multiplied with $\frac{NNLO_{HEFT}}{NLO_{HEFT}} \sim 1.2$ if proximity of HEFT and SM K-factors postulated to occur at NNLO as well

Summary and Outlook

- As luminosity increases at the LHC, we will have access to Higgs transverse momentum distribution with improving precision

- Higgs $\boldsymbol{p_{T,H}}$ distribution provides us rich information: 1. computation of fiducial cross sections; 2. fixing of light-Yukawa couplings; 3. alternative to measuring top-Yukawa coupling and point-like ggH couplings (CMS measurements underway)

- The past few years has seen remarkable theoretical progress that have important implications for predictions of $\boldsymbol{p_{T,H}}$ distribution, among others:

  Fixed order as well as N3LL resummed predictions in HEFT achieved

  Combined N2LL matched to NLO including bottom mass corrections now available, with as a result QCD corrections controlled to few percent in low to moderate $\boldsymbol{p_{T,H}}$ region

  High-$\boldsymbol{p_{T,H}}$ predictions including top mass available at NLO

- Much more progress and pheno implications to be expected

Backup slides

Real corrections with Openloops

- Channels for real contribution to Higgs plus jet at NLO

$$gg \to Hgg,\; gg \to Hq\bar{q},\; qg \to Hqg,\; q\bar{q} \to Hgg,\; \cdots$$

- Receives contributions from kinematical regions where one parton become soft or collinear to another parton
- This requires a delicate approach of these regions in phase space integral
- Openloops algorithm is publicly available program which is capable of dealing with these singular regions in a numerically stable way
- Crucial ingredient is tensor integral reduction performed via expansions in small Gram determinants: Collier

[Cascioli et al ’12, Denner et al ’03-’17]

- Exact top and bottom mass dependence kept throughout for one-loop computations