The Higgs pT distribution

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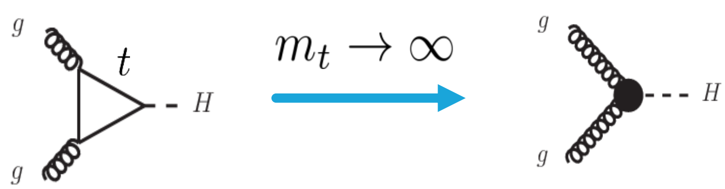
GGI: Amplitudes in the LHC era,
Florence 16 Oktober, 2018

Outline

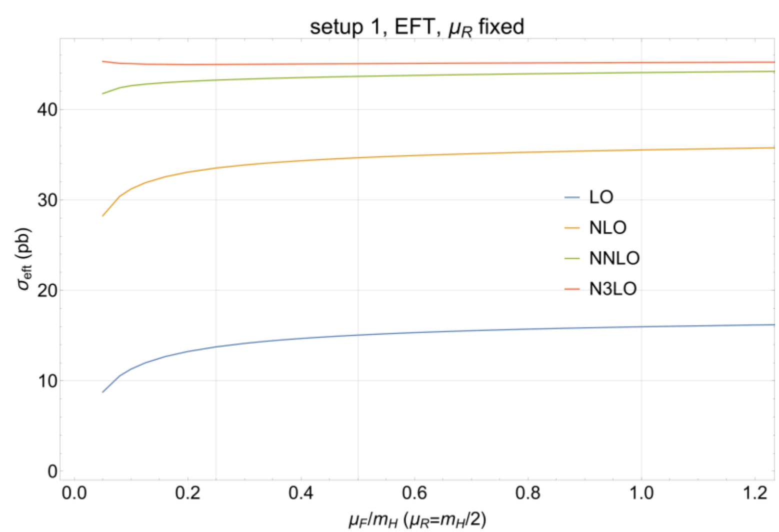
- Introduction
- Ingredients for NLO computation
- Pheno results: below top threshold
- Pheno results: above top threshold
- Summary and outlook

Higgs couplings

- *Questions:* is the scalar discovered in 2012 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 ~20-50%
- Higgs production at LHC proceeds largely through quark loops, historically computed in HEFT limit $m_t \to \infty$



- Inclusive (gg-fusion) cross sections are known to impressive N3LO order already

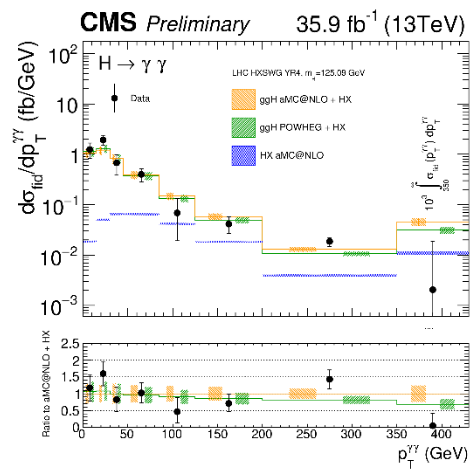


[Anastasiou et al '16, Mistlberger ' 18]

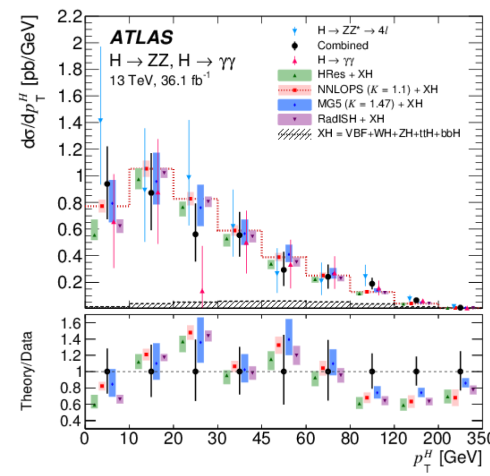
Going beyond inclusive rates: Higgs $p_{T,H}$

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

- Picturesque description of Higgs production at LHC:



[CMS-PAS-HIG-17-015]



[CERN-EP-2018-080]

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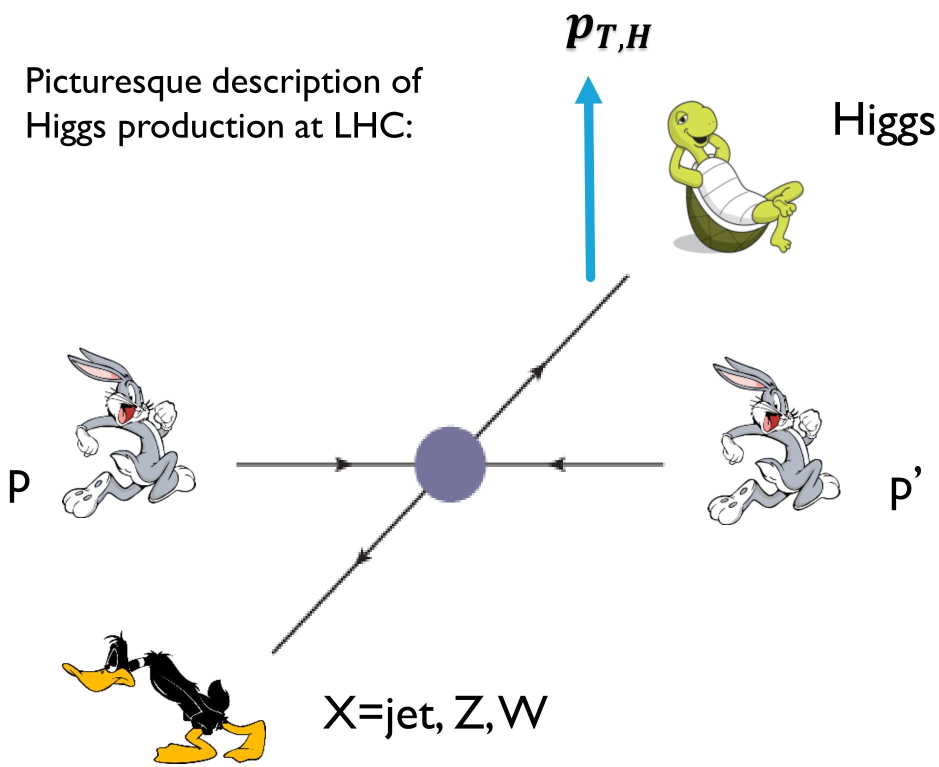

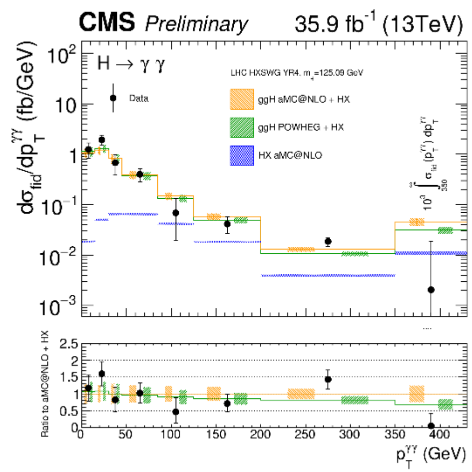

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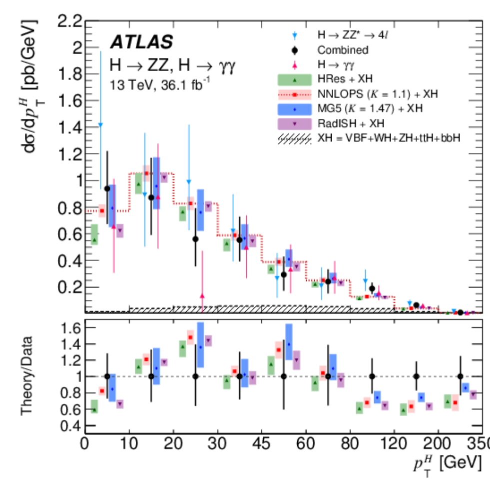
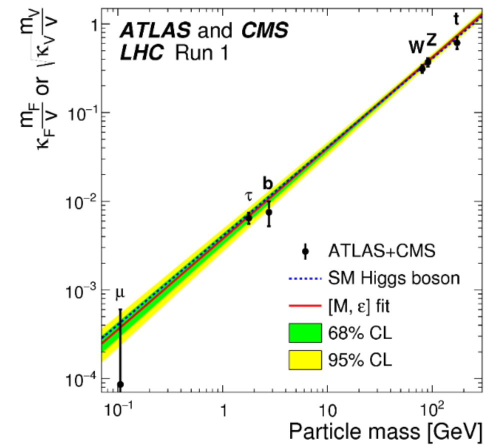


[CERN-EP-2018-080]

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*** (Top quark loop ~ 90% and bottom loop ~ 5-10%)
- Alternative pathway to ***distinguish top-Yukawa from point-like ggH coupling***



[arXiv: 1606.02266]

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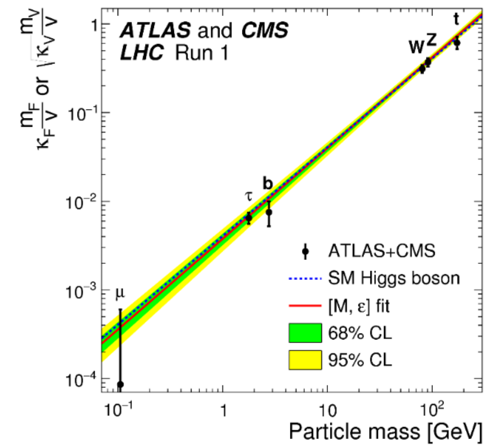

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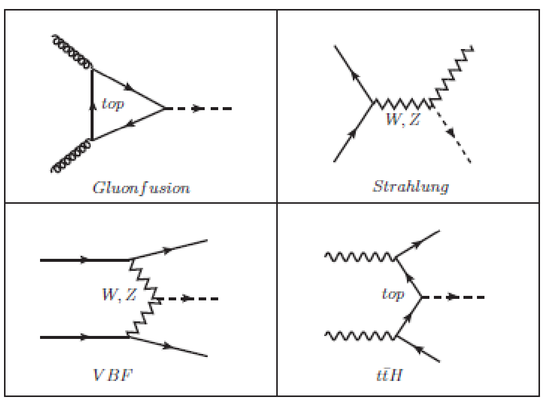
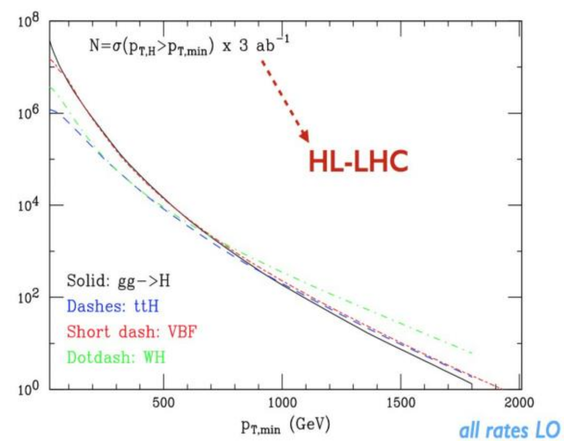


Main channels

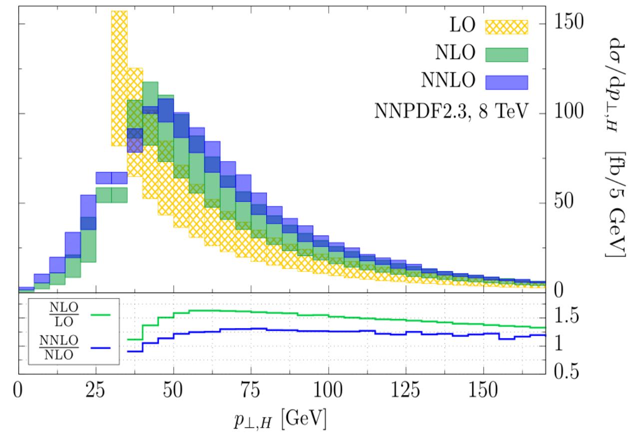


[Mangano talk at Higgs Couplings 2016]

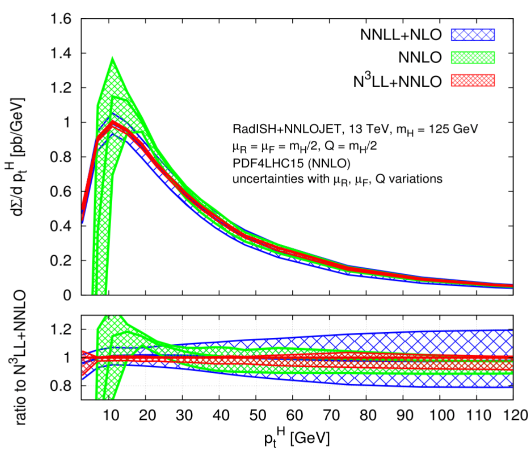
- gg-fusion dominates at low pT, where most Higgses are produced
- At very high pT ~ 1 TeV the electroweak channels start playing a bigger role

Recent gg-fusion theory progress

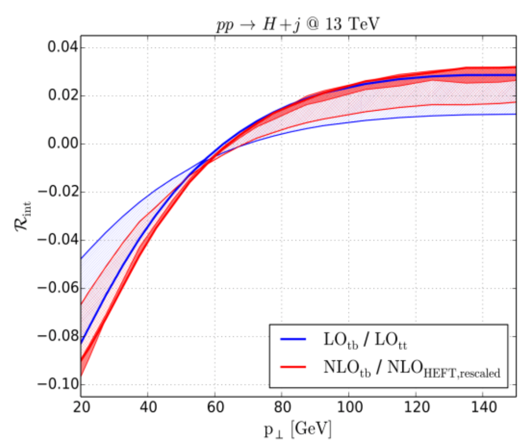
- Fixed order at NNLO QCD in HEFT: Boughezal, Caola et al. '15, Chen et al.' 16, Dulat et al. '17
- Low $p_{T,H}$ resummation at N3LL+NNLO QCD in HEFT: Bizon et al., Chen et al. '17-'18
- Bottom mass corrections at NLO QCD: Lindert et al. '17
- High $p_{T,H}$ region at NLO QCD with full top mass: Lindert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



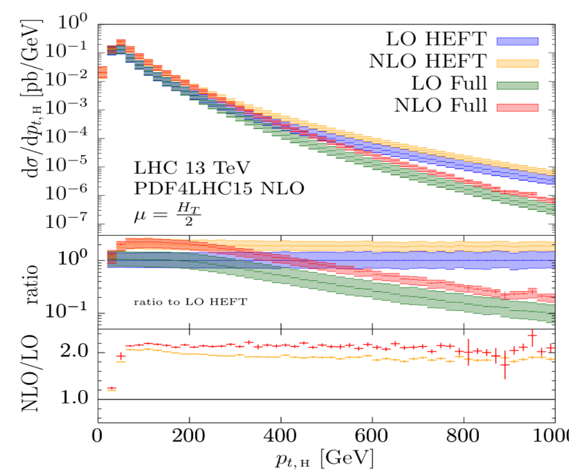
[Boughezal, Caola et al., arXiv: 1504.07922]



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



[Lindert et al., arXiv: 1703.03886]



[Jones et al., arXiv: 1802.00349]

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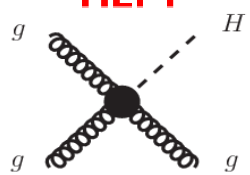
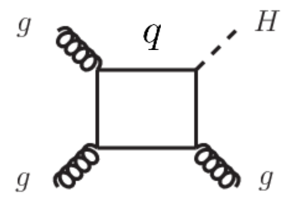
Gluon-fused H+j production at LHC

below quark thr.	close to threshold	above quark thr.
HEFT 	increasing $p_{T,H}$	
$m_q \to \infty$	$1 - \frac{4m_q^2}{\hat{s}} \ll 1$	$\frac{4m_q^2}{p_\perp^2} \ll 1$

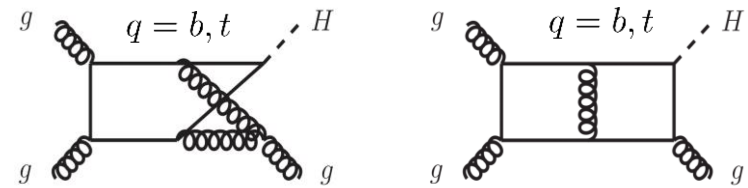
- Computation of bottom contribution starts at 1-loop for moderate $p_{T,H} > 10$ GeV
- Top quark loop resolved at high $p_{T,H} > 350$ GeV

NLO:

- Real corrections can be computed with exact mass dependence (MCFM, Openloops, Recola…)
- New required ingredients are two-loop virtual corrections

Virtual amplitude

- Typical two-loop Feynman diagrams are:



- Project onto form factors

$$\mathcal{A}_{H\to ggg}(p_1^{a_1}, p_2^{a_2}, p_3^{a_3}) = f^{a_1 a_2 a_3}\, \epsilon_1^\mu\, \epsilon_2^\nu\, \epsilon_3^\rho\, (F_1\, g^{\mu\nu}\, p_2^\rho + F_2\, g^{\mu\rho}\, p_1^\nu + F_3\, g^{\nu\rho}\, p_3^\mu + F_4\, p_3^\mu p_1^\nu p_2^\rho)$$

- Reduce with *Integration by parts* (IBP)

$$\mathcal{I}(s) = \sum \mathrm{Rational}(s,d) \times (\mathrm{Master\ Integrals})(s,d)$$

- Exact mass dependence in two-loop Feynman Integrals very difficult and currently out of reach [planar diagrams: Bonciani et al '16]

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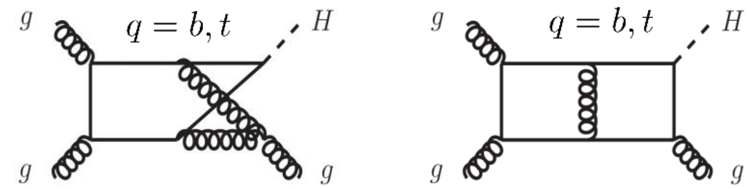

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- Use expansion approximation

Scale hierarchy below top threshold: $m_b \ll p_\perp, m_h \ll m_t$

Scale hierarchy above top threshold: $m_h \ll 2m_t \ll p_\perp$

Expand in <u>small quark mass</u> approach →

Two-loop *<u>amplitudes</u>* expanded in *<u>quark mass</u>* with differential equation method

[Mueller & Ozturk '15; Melnikov, Tancredi, CW '16, Kudashkin et al '17]

How useful and valid is m_q expansion?

- Integrals with massive quark loops computed exactly are complicated

Usefullness:

$$
\begin{aligned}
&\log\left(x_3x_1^2 - x_1^2 + x_2x_1 - 4x_3x_1 + R_1(x_1)R_2(x_1)R_7(x)\right),\\
&\log\left(-x_2^2 + x_1x_2 - x_1x_3x_2 + 2x_3x_2 + 2x_1x_3 + R_1(x_2)R_2(x_2)R_7(x)\right),\\
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&\log\left(x_3R_1(x_2)R_2(x_2) + x_2R_1(x_3)R_2(x_3)\right),\\
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[planar diagrams: Bonciani et al '16]

- Some sectors not known how to express in terms of GPL's anymore plus genuine elliptic sectors
- *Expanding* in small quark mass results in simple *2-dimensional harmonic polylogs*

Mass expansion

7

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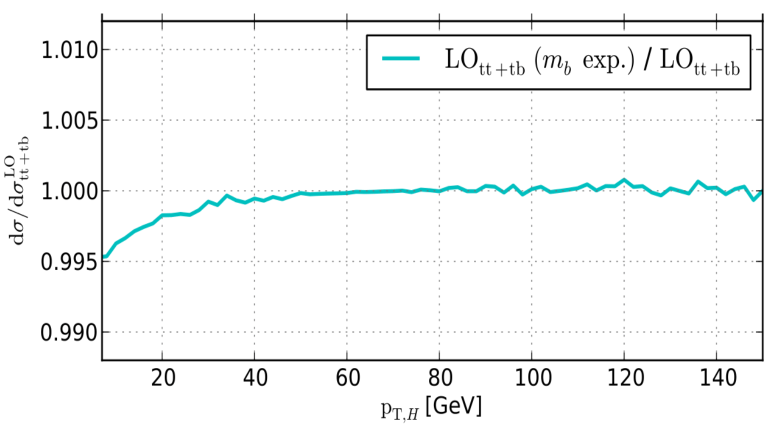
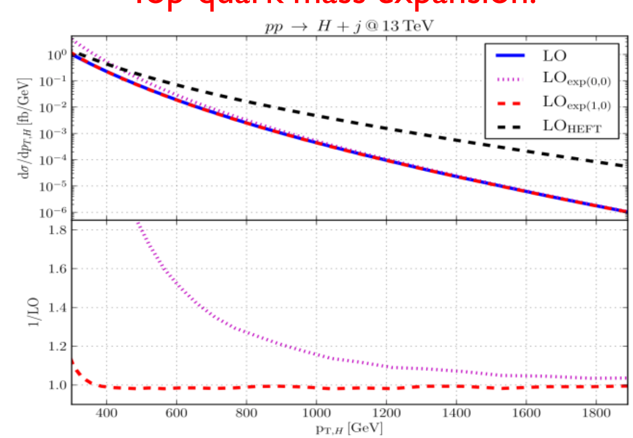
Validity:

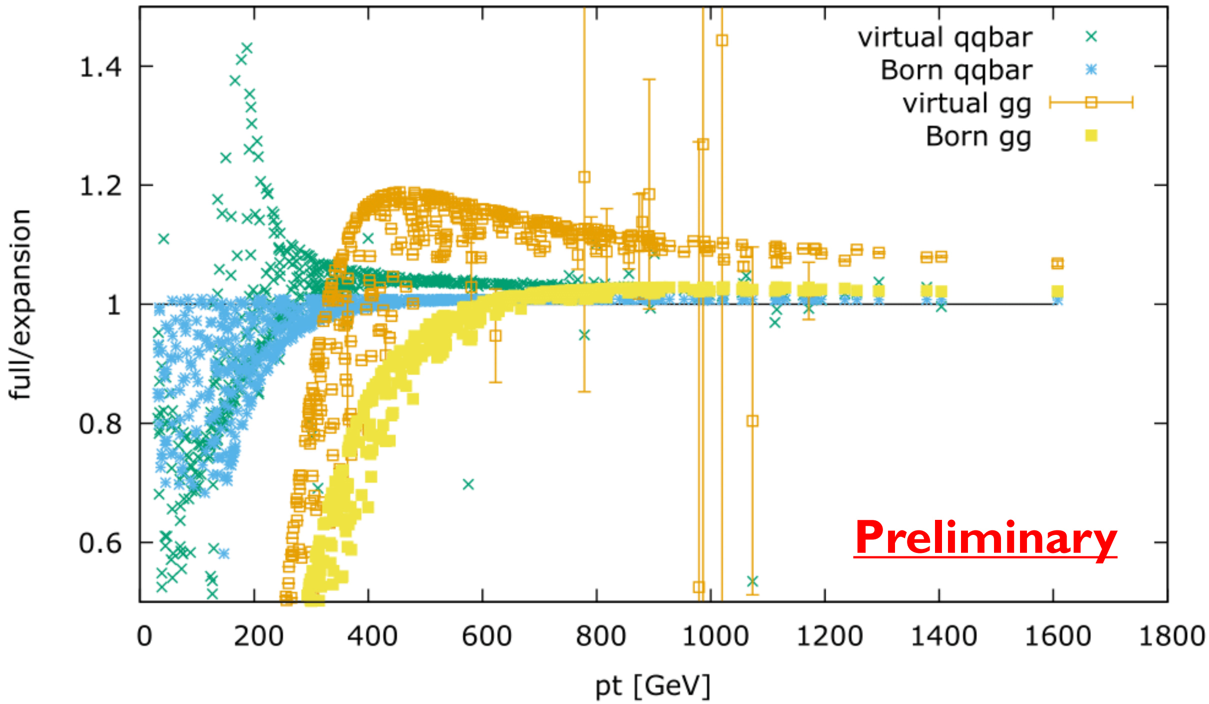
Bottom-quark mass expansion:



Top-quark mass expansion:



High-pT expansion comparison at NLO



[Plot from Matthias Kerner '18]

- Comparison of full (Secdec) and high-pT expanded virtual contributions

[Kudashkin et al, Jones et al '18]

- Agreement is good, within 20% difference down to 400 GeV
- Virtual piece contributes ~10-20%. Dominant real can be computed exactly w. Openloops

IBP reduction difficulties

[Melnikov, Tancredi, CW '16-'17]

- IBP reduction to Master Integrals $\mathcal{I}(s) = \sum \mathrm{Rational}(s,d) \times (\mathrm{Master\ Integrals})(s,d)$

- *Reduction very non-trivial*: we were not able to reduce top non-planar integrals with $t=7$ denominators with FIRE5/Reduze → coefficients become too large to simplify ~ hundreds of Mb of text

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- *Reduction for complicated t=7 non-planar integrals performed in two steps*:

1) FORM code reduction: $\mathcal{I}^{\text{NPL}}_{t=7} = \sum c_i \text{MI}^i_{t=7} + \sum d_i \mathcal{I}^i_{t=6}$

2) Plug reduced integrals into amplitude, expand coefficients c_i, d_i in m_q

3) Reduce with FIRE/Reduze: $t=6$ denominator integrals $\mathcal{I}_{t=6}$

- Exact m_q dependence kept at intermediate stages. Algorithm for *solving IBP identities directly expanded in small parameter is still an open problem*

MI with DE method for small m_q (1/2)

- System of partial differential equations (**DE**) in $\boldsymbol{m_q, s, t, m_h^2}$ with IBP relations

$$\frac{\partial}{\partial \tilde{s}_k} \vec{\mathcal{I}}^{MI}(\tilde{s}, \epsilon) \overset{\text{IBP}}{=} \overline{\overline{M}}_k(\tilde{s}, \epsilon).\vec{\mathcal{I}}^{MI}(\tilde{s}, \epsilon)$$

- Interested in m_q expansion of <u>Master integrals</u> I^{MI}

→ expand homogeneous matrix M_k in small m_q

<u>Step 1</u>: solve DE in m_q

- Solve m_q DE with following ansatz

$$\mathcal{I}_i^{MI}(m_q^2, s, t, m_h^2, \epsilon) = \sum_{ijkn} c_{ijkn}(s, t, m_h^2, \epsilon) \left(\frac{m_q^2}{s}\right)^{j-k\epsilon} \log^n\left(\frac{m_q^2}{s}\right)$$

- **<u>Peculiarity</u>**: half-integer powers of (squared) quark mass also in Ansatz, contributing momentum region unknown
- Plug into m_q DE and get constraints on coefficients c_{ijkn}
- c_{i000} is $m_q = 0$ solution (hard region) and has been computed before

[Gehrmann & Remiddi '00, Tausk, Anastasiou et al '99, Argeri et al. '14]

MI with DE method for small m_q (2/2)

- Ansatz $$\mathcal{I}_i^{MI}(m_q^2, s, t, m_h^2, \epsilon) = \sum_{ijkn} c_{ijkn}(s, t, m_h^2, \epsilon) \left(\frac{m_q^2}{s}\right)^{j-k\epsilon} \log^n\left(\frac{m_q^2}{s}\right)$$

Step 2: solve s, t, m_h^2 DE for $c_{ijkn}(s, t, m_h^2)$

- Solution expressed in extensions of usual polylogarithms: *Goncharov Polylogarithms*
- After solving DE for unknown c_{ijkn}, we are left with *unknown boundary constants* that only depend on ε

Step 3: fix ε dependence

- Determination of most boundary constants in ε by *imposing that unphysical cut singularities in solution* vanish
- Other constants in ε fixed by matching solution of DE to Master integrals computed via various methods (Mellin-Barnes, expansion by regions, numerical fits) in a specific point of s, t, m_h^2

Step 4: numerical checks with FIESTA

[A. Smirnov '14]

Constants: Mellin-Barnes method

- Let's say $(m_q^2)^{-1-2\epsilon}$ branch required of

$$\mathcal{I}^{MI} = c_0\,(m_q^2)^{-3/2-2\epsilon} + c_1\,(m_q^2)^{-1-\epsilon} + c_2 (m_q^2)^{-1-2\epsilon} + \mathcal{O}((m_q^2)^0)$$

$$\mathcal{I}^{MI} = \int \frac{D^d k D^d l}{((k_1+p_1)^2 - m_q^2)((k_1 - p_{23})^2 - m_q^2)(k_2^2 - m_q^2)((k_2+p_1)^2 - m_q^2)^2((k_1-k_2)^2)^{1+\delta}((k_1-k_2-p_2)^2)^{1-\delta}}$$

- Mellin-Barnes integration in complex plane

$$\frac{1}{(x+y)^\lambda} = \frac{1}{2\pi i}\int_{-i\infty}^{+i\infty} dz\, \frac{y^z}{x^{z+\lambda}}\frac{\Gamma(-z)\Gamma(\lambda+z)}{\Gamma(\lambda)} \longrightarrow$$

- Mellin-Barnes representation in s=u=-1

$$\mathcal{I}^{MI} = -\int_{-i\infty}^{+i\infty}\left(\prod_{i=1}^{4} dz_i\right)(-2-i0)^{-2\epsilon-z_1-z_2-z_3-3}(m_q^2)^{z_1}\Gamma(-z_1)\Gamma(-z_2)\Gamma(z_2+1)\Gamma(-z_3)$$
$$\times \frac{\Gamma(-z_4)\Gamma(-\epsilon-z_1-1)\Gamma(z_4-\epsilon)\Gamma(z_3-\delta+1)\Gamma(-2\epsilon-z_1-z_2-2)\Gamma(z_2+z_3+z_4+1)}{\Gamma(1-\delta)\Gamma(\delta+1)\Gamma(\epsilon+1)^2\Gamma(-2\epsilon-2z_1-1)\Gamma(-3\epsilon-z_1-1)\Gamma(-2\epsilon-z_1-1)}$$
$$\times\, \Gamma(2\epsilon+z_1+z_2+z_3+3)\Gamma(-2\epsilon-z_1-z_3+\delta-2)\Gamma(-\epsilon-z_1-z_2-z_3-z_4-1).$$

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- Require the pole at $z_1 = -1-2\epsilon \longrightarrow$ result is coefficient c_2

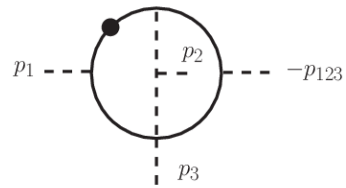
- After picking up pole, we expand in epsilon and apply Barnes-Lemma's, which reduces the amount of integrations to <u>one</u> (completely automatized steps)

- Fit numerically (integrals converge fastly) the constant or compute analytically by closing contours in complex plane of Mellin-Barnes integration

Square-root branches

- Expansion in m_q^2 $$\mathcal{I}^{MI} = c_0 \left(m_q^2\right)^{-3/2-2\epsilon} + c_1 \left(m_q^2\right)^{-1-\epsilon} + c_2 \left(m_q^2\right)^{-1-2\epsilon} + \mathcal{O}((m_q^2)^0)$$

- Normal integer power regions can be attributed to common soft, collinear and hard type regions, but **<u>what about square-root powers</u>**?

$$\mathcal{I}^{MI} =$$ 

- Mellin-Barnes result: $$c_0 \sim \frac{\pi^3}{4\sqrt{-s_{12}s_{13}s_{23}}}\left(\frac{1}{2\epsilon} + 2 - 5\log(2)\right)$$

- This diagram only appears in gg channel

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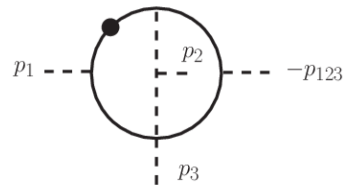

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- These branches do not contribute to the amplitude up to m_q^2, but what happens at higher orders? What if they reappear? Would it be possible to resum their corresponding logarithms? [Penin et al. '18]

- Which momentum regions contribute to these type of branches? **<u>If known, please visit: GGI, office 60, between 15-26 Oktober 2018 (ask for Wever)</u>**

- Do they contribute to other processes, such as HH for example? [Bonciani et al, Steinhauser et al. '18]

Outline

- Introduction
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- Pheno results: below top threshold
- Pheno results: above top threshold
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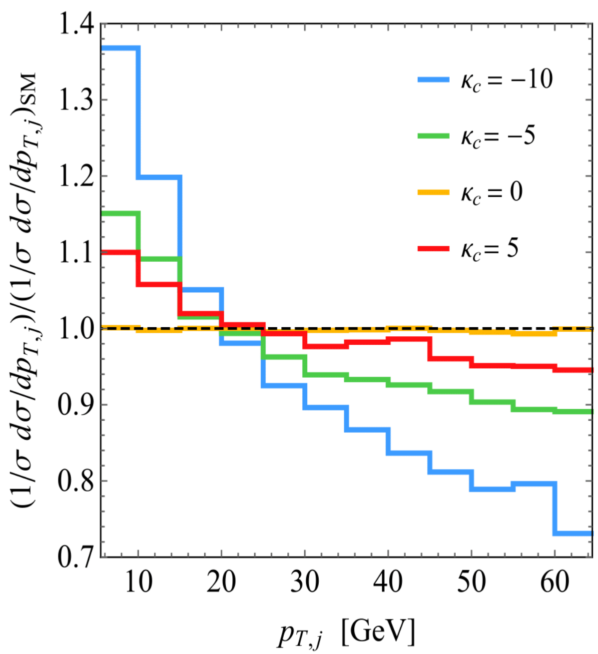
Below top threshold

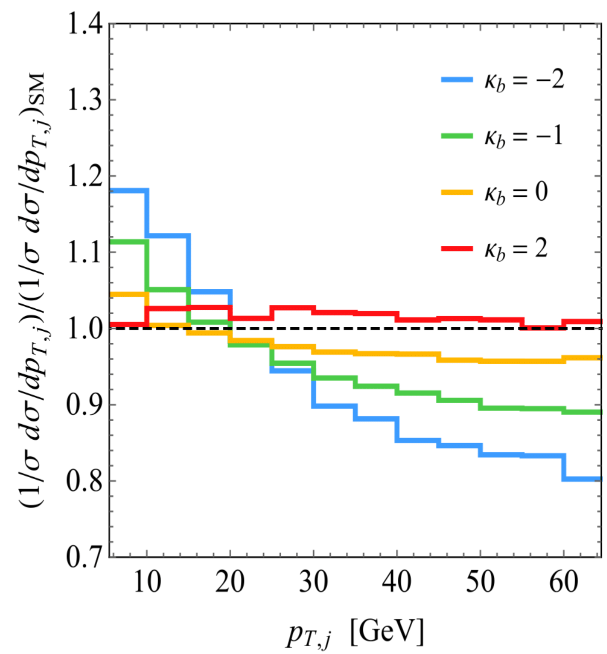
- <u>Constrain bottom- and charm-quark Yukawa couplings</u>

- 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 $\boldsymbol{p_{T,H}}$ 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 $\kappa_c \in [-0.6, 3.0]$ $\kappa_b \in [0.7, 1.6]$

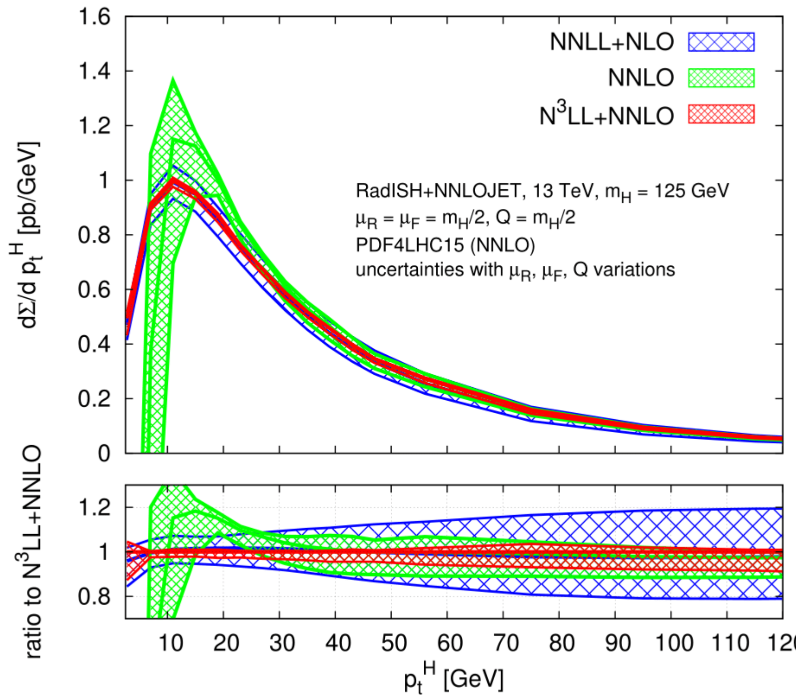
[Bishara, Monni et al '16]

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



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

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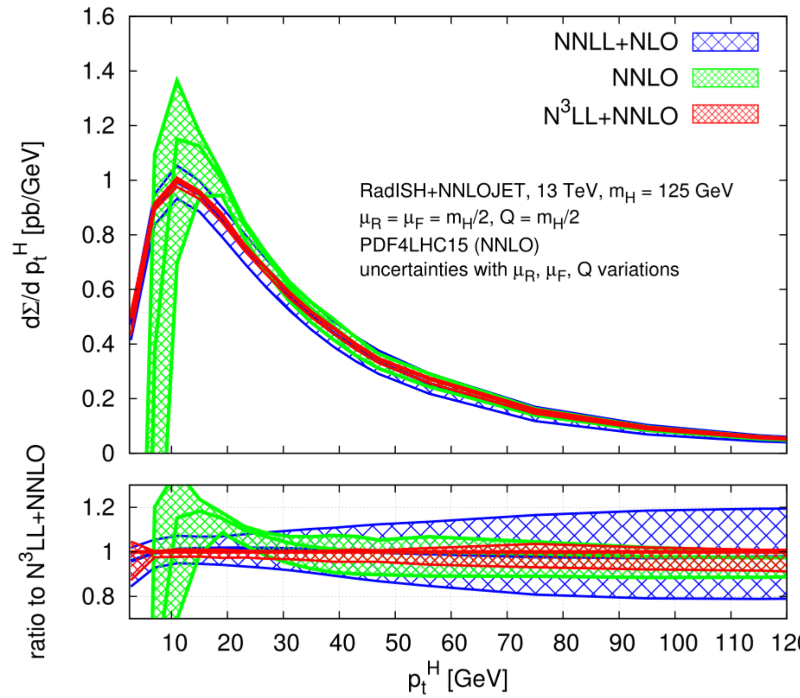
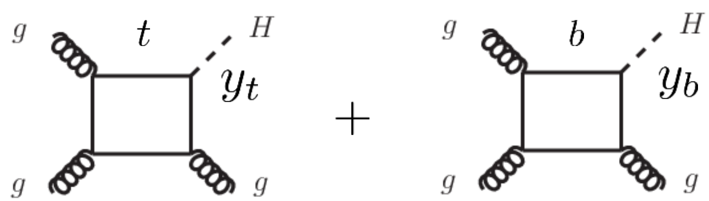
- What about bottom mass corrections in ggF?



[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

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

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

$$\longrightarrow \qquad d\sigma_{tb} \sim y_t\, y_b\, m_b \sim y_t\, m_b^2$$

- Top-bottom interference *naively suppressed* compared to top-top contribution by

$$m_b^2/m_h^2 \sim 10^{-3}$$

- However, logs enhance contribution such that suppressed by ~ $m_b^2/m_h^2 \log^2(m_h^2/m_b^2) \sim 10^{-1}$

- Every extra loop adds extra factor of $\log^2(p_\perp^2/m_b^2),\ \log^2(m_h^2/m_b^2)$

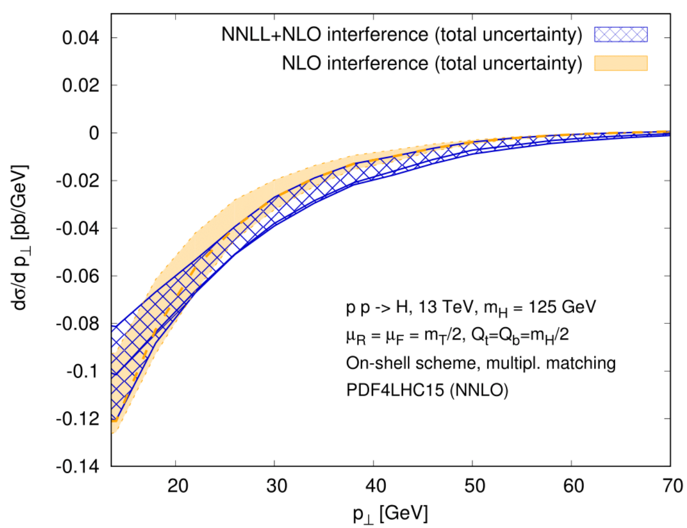
- Bottom contribution to $p_{T,H}$ computed recently at NLO [Lindert et al '17]

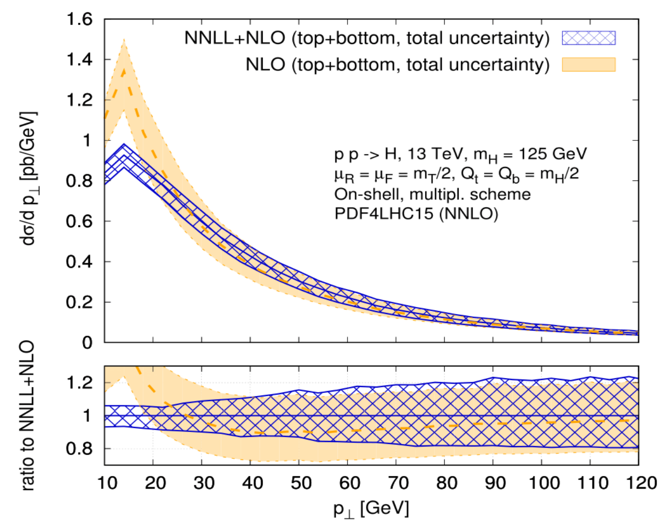
- Previous N2LL resummed predictions can now be matched to full NLO with bottom [Caola et al. '18]

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

[Caola et al., ArXiv: 1804.07632]

- Resummation of Sudakov-logarithms $\log\left(p_{\mathrm{T,H}}/m_h\right)$ strictly speaking only possible when quark loop factorizes
- At small $p_{T,H}{\sim}10$ GeV logs still large so best we can do is to resum and gauge error of different resummation scales and schemes





- 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]

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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

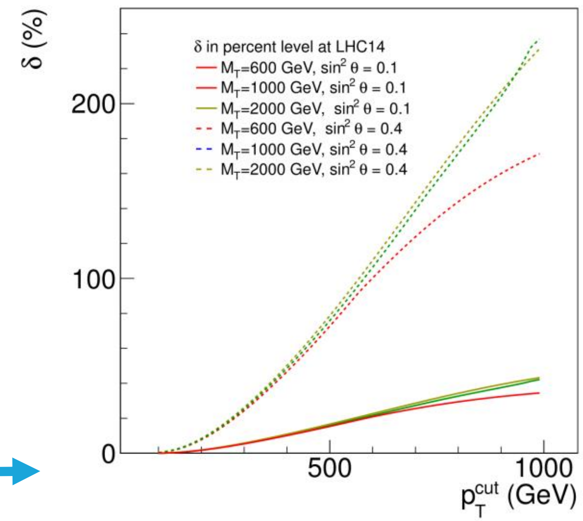
$$\frac{m_t}{v}\bar{t}tH \to -\kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{\mu\nu,a} H + \kappa_t \frac{m_t}{v}\bar{t}tH$$

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

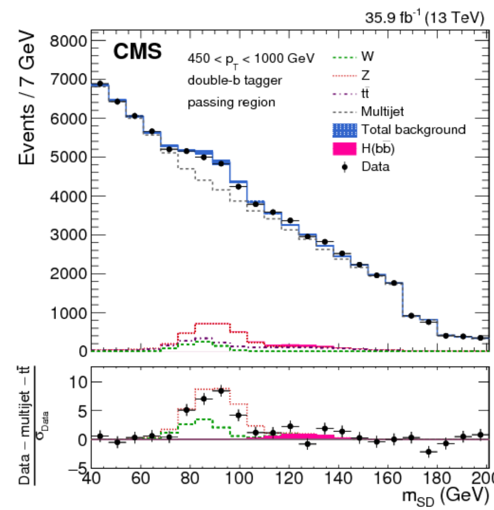
- CMS has <u>already</u> begun searching for boosted $H \to b\bar{b}$ decay

- 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]



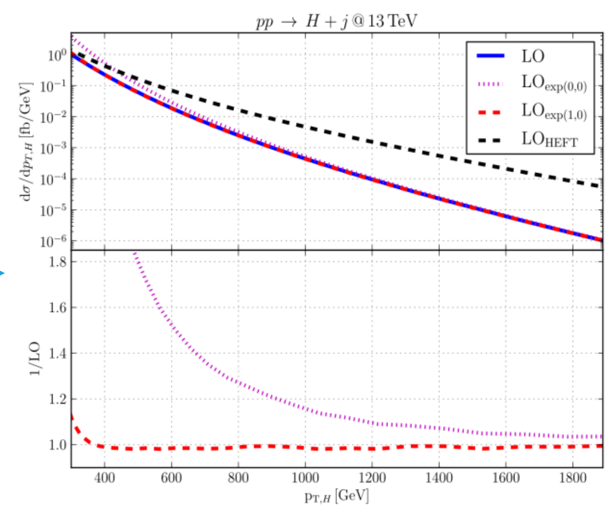
[CMS-HIG-17-010-003]

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

- At $p_{T,H}$ 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

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

- Use scale hierarchy, $p_{T,H} > 2m_t$ 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%



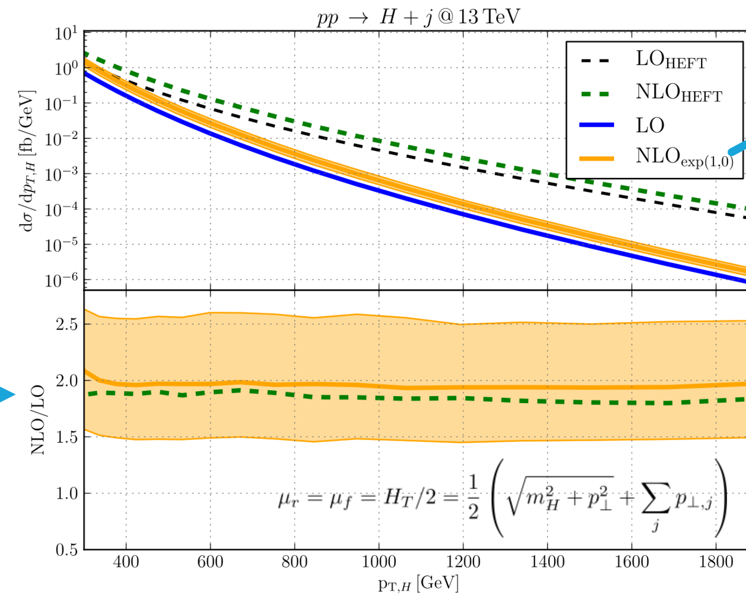
[Kudashkin et al., arXiv: 1801.08226]

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

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

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

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

	LO(HEFT)	LO(full)	NLO(HEFT)	NLO(full)	K(HEFT)	K(full)
≥ 450	22.00	6.75	41.71	13.25	1.90	1.96

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

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

- NLO 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

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Summary

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

- Higgs $p_{T,H}$ 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 $p_{T,H}$ distribution, among others:

  Fixed order as well as N3LL resummed predictions in HEFT achieved

  Bottom mass corrections have been computed at NLO

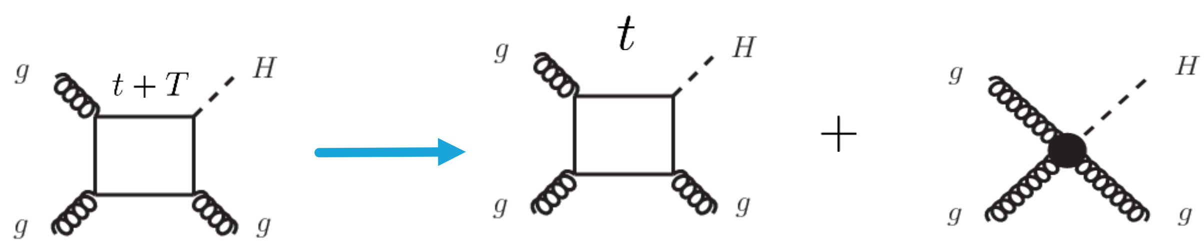
  Combined N2LL matched to NLO including bottom mass corrections now available, with as a result QCD corrections controlled to few percent in low to moderate $p_{T,H}$ region

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

Outlook and Open Questions

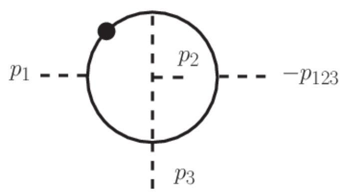
- How large are the mixed QCD-Electroweak corrections to the Higgs pT distribution? The planar MI for $H + jet$ recently computed [Becchetti et al. '18]

- Hgg point-like coupling: perform point-like and top-Yukawa analysis using recently computed higher order theory predictions for top contribution at high pT



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

- Momentum-space origin of square-root branches at high-pT?



$$\sim \overset{?}{c_0} \left(\frac{m_q^2}{s}\right)^{-3/2-2\epsilon} + c_1 \left(\frac{m_q^2}{s}\right)^{-1-\epsilon} + c_2 \left(\frac{m_q^2}{s}\right)^{-1-2\epsilon} + \mathcal{O}((m_q^2)^0)$$

- Resummation of logarithms in m_q? $\quad \log^2(p_\perp^2/m_b^2),\ \log^2(m_h^2/m_b^2)$ [Penin et al. '18]

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