Top-bottom interference effects in Higgs plus jet production at the LHC

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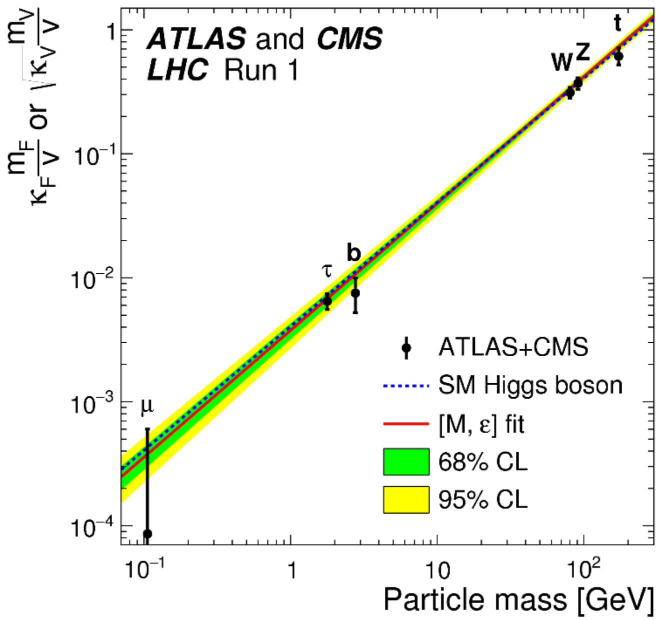
Introduction

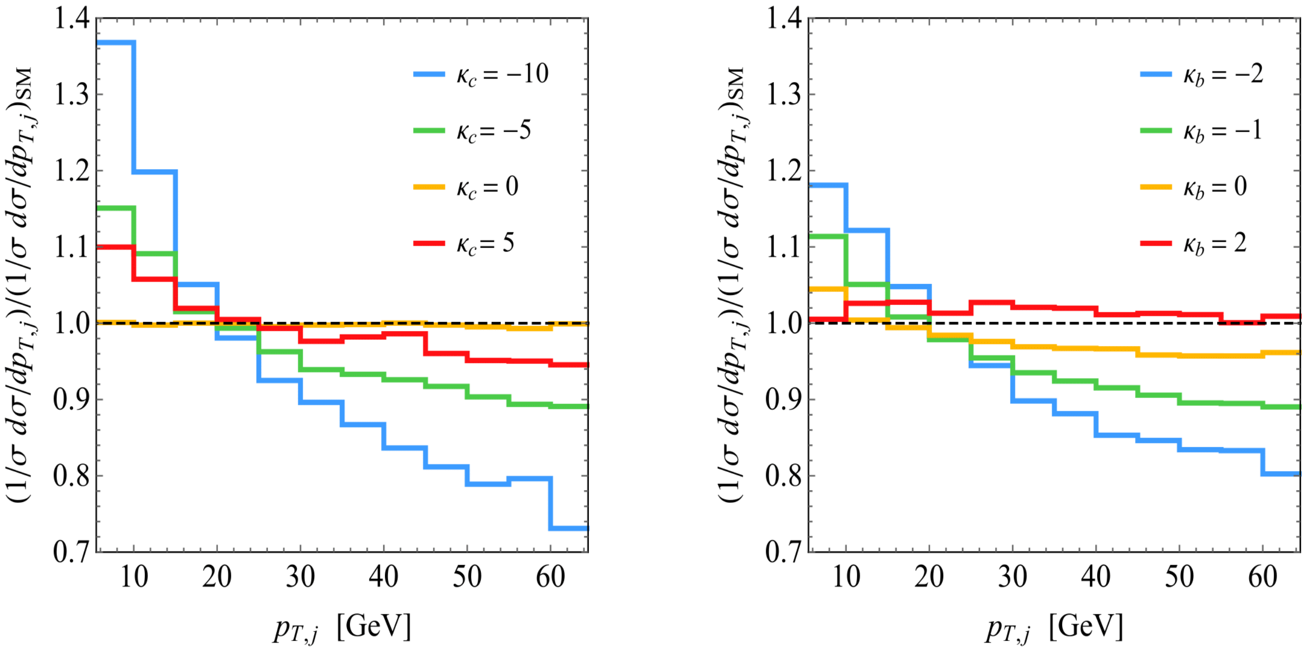
- One important focus of the LHC physics program is the study of *Higgs couplings* to other particles
- After high-luminosity run it is expected that major Higgs couplings can be constrained to few percent level
- Higgs couplings to light generation quarks practically unconstrained
- Current bounds from global fits to inclusive Higgs production cross section and exclusive Higgs decays



[arXiv:1606.02266]

Introduction: $H + j$ production

- Non-trivial Higgs transverse momentum ($\boldsymbol{p_{T,H}}$) distribution generated when extra jet is radiated: $\boldsymbol{H + j}$
- Shape of $\boldsymbol{p_{T,H}}$ distribution may put stronger constraints on light-quark Yukawa couplings [Bishara, Monni et al '16; Soreq et al '16]



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

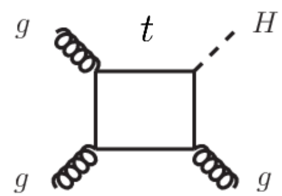
- Bounds expected from HL-LHC $\kappa_c \in [-0.6, 3.0]$ $\kappa_b \in [0.7, 1.6]$ [Bishara, Monni et al '16]

→ Reliable theoretical predictions for $H + j$ differential cross section required

Top-bottom interference

- Higgs plus jet production at LHC proceeds largely through quark loops

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



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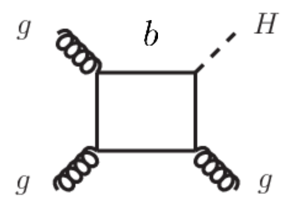


$\wr \qquad\qquad \wr$

$y_t \qquad\qquad y_b$

dominant bottom correction

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

$$y_j \sim m_j \qquad m_b = 4.5\,\mathrm{GeV} \qquad m_t = 173\,\mathrm{GeV}$$

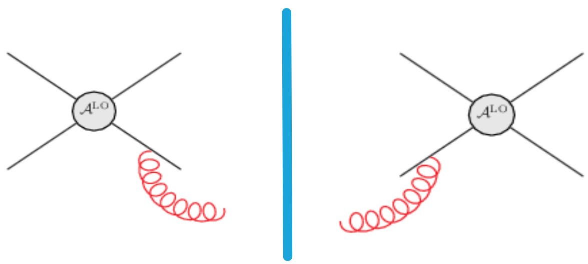
- Bottom amplitude *contains large Sudakov-like logarithms,* suppressed compared to top by $\quad m_b^2/m_h^2\left(\log^2(m_h^2/m_b^2), \log^2(p_\perp^2/m_b^2)\right) \sim 10^{-1}$

- In fact, LO bottom contribution ~ 5-10% of LO top contribution at $p_\perp \in [10, 40]\,\mathrm{GeV}$

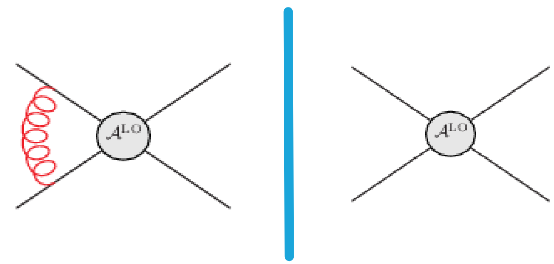
- Top loop receives large NLO corrections $\longrightarrow$ what about bottom loop at NLO?

Calculation at NLO

- Real (2 to 3) and virtual (2 to 2) contributions need to be combined, very well understood at NLO



Real corrections

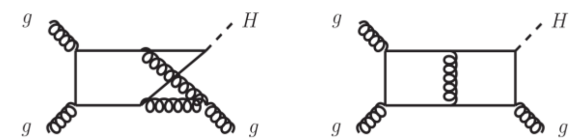


Virtual corrections

- Real corrections computed in Openloops with exact top, bottom mass

[Cascioli et al '12-17; Denner, Dittmaier et al '03-'17]

- One new ingredient are two-loop virtual corrections



- Exact mass dependence in two-loop Feynman Integrals currently out of reach

[planar: Bonciani et al '16]

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

Top: *Infinite top mass limit*, well known how to be treated, shrink top loop (HEFT)

Bottom: Expand two-loop amplitude in *bottom mass* with differential equation method

[Mueller & Ozturk '15; Melnikov, Tancredi, CW '16-'17]

Computing virtual bottom amplitudes

- Virtual amplitude made up of *complicated two-loop tensor Feynman integrals*

→ project amplitude onto form factors

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

- Form factors F_i expressed in terms of *scalar integrals*
- *Integration by parts* (IBP) identities $$\int \Big(\prod_i d^d k_i\Big) \frac{\partial}{\partial k_j^\mu}\Big(v^\mu I\Big) = \text{Boundary term} \overset{DR}{=} 0$$
- Reduce form factors to *Master Integrals* (**MI**) $$F_i(s,\epsilon) = \sum_j \text{Rational}_{ij}(s,\epsilon)\mathcal{I}_j^{MI}(s,\epsilon)$$

Compute Master Integrals with differential equations

- Setup and solve differential equations (**DE**) perturbatively in small $\boldsymbol{m_b}$ $$\frac{\partial}{\partial \tilde{s}_k}\vec{\mathcal{I}}^{MI}(\tilde{s},\epsilon) \overset{\text{IBP}}{=} \overline{\overline{M}}_k(\tilde{s},\epsilon).\vec{\mathcal{I}}^{MI}(\tilde{s},\epsilon)$$

Numerical setup

[Lindert, Melnikov, Tancredi, CW '17]

- LHC 13 TeV
- PDF set and associated strong coupling constant: NNPDF3.0_lo for LO and NNPDF3.0_nlo for NLO
- Central scale is dynamical:

$$\mu_r = \mu_f = \mu_0 = H_T/2, \quad H_T = \sqrt{m_H^2 + p_\perp^2} + \sum_j p_{\perp,j}$$

$$m_H = 125\,\mathrm{GeV}, \quad m_t = 173.2\,\mathrm{GeV}$$

Theory uncertainties considered

- Scale variation: $\mu = \{1/2, 2\} * \mu_0$

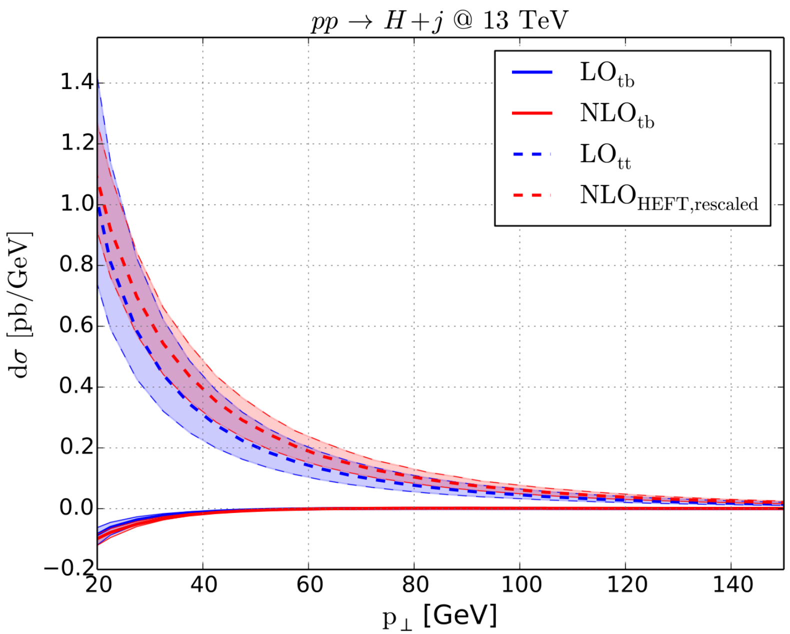
- Large ambiguity in bottom mass scheme: appropriate renormalization scheme for m_b from Yukawa coupling is MSbar scheme at $\mu \sim m_h$, while scheme for m_b from helicity flip might require on-shell bottom mass scheme instead. Two bottom mass schemes considered:

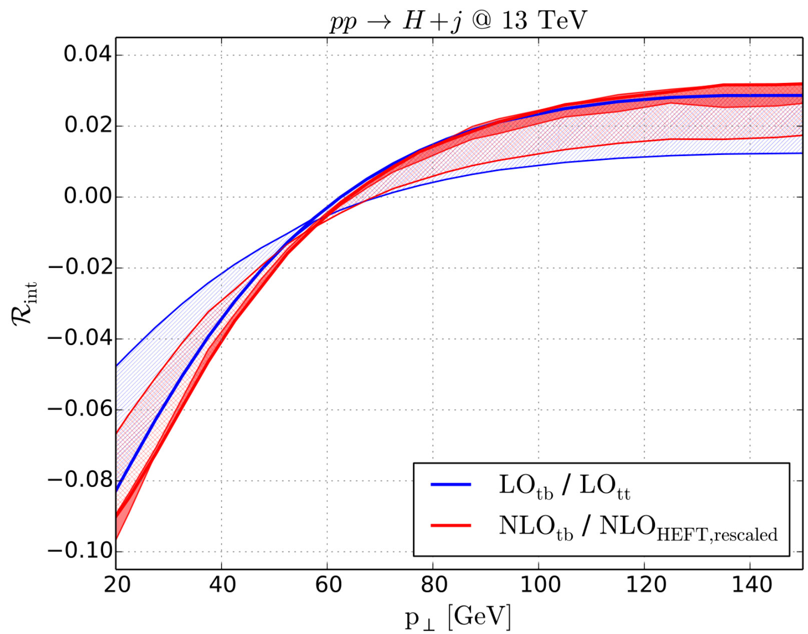
$$m_b^{\mathrm{OS}} = 4.75\,\mathrm{GeV}$$

$$m_b^{\overline{\mathrm{MS}}}(\mu = 100) = 3.07\,\mathrm{GeV}$$

Higgs transverse momentum distribution

[Lindert, Melnikov, Tancredi, CW '17]



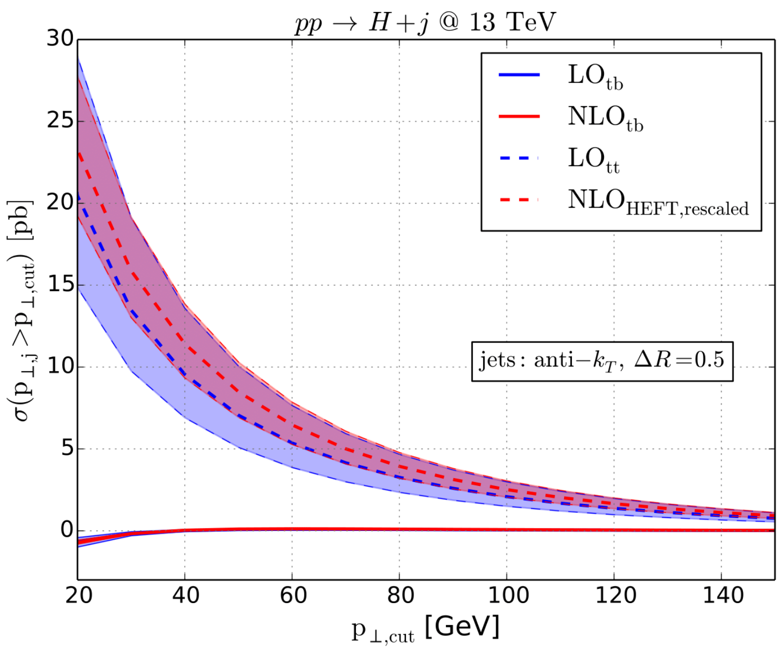


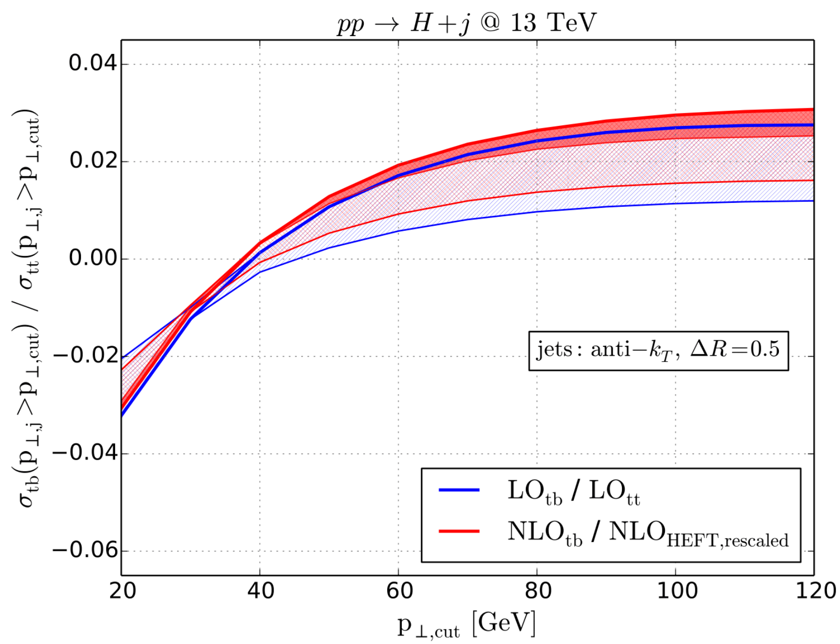
- Top-bottom interference at $p_{T,H}$=30 GeV: -6% at LO and -7% at NLO
- Large relative corrections to top-bottom interference ~ relative corrections to top-top ~ 40%
- Large mass renormalization-scheme ambiguity
- At small $p_{T,H}$ the ambiguity is reduced by a factor of two at NLO; less pronounced at larger $p_{T,H}$

Total Higgs plus jet cross section

[Lindert, Melnikov, Tancredi, CW ’17]

- Total integrated cross section as function of threshold on jet $p_{T,j}$





$$\sigma_{tb}/\sigma_{tt}(p_{T,j} > 20, 30, 40, 50)_{\mathrm{LO}} = -3.2, -1.2, +0.1, 1.1\%$$

$$\sigma_{tb}/\sigma_{tt}(p_{T,j} > 20, 30, 40, 50)_{\mathrm{NLO}} = -3.1, -1.1, +0.3, 1.3\%$$

- Total integrated NLO top-bottom interference contributes [-3% , 3%] of NLO top-top contribution
- Strong dependence on jet $p_{T,j}$ cut

Summary

- Fully differential NLO QCD corrections to top-bottom interference first time computed
- Two-loop integrals computed at first order in bottom mass expansion with DE method
- NLO bottom contribution ~ [-10, -4] % of NLO top contribution at lower range of Higgs $\boldsymbol{p_{T,H}}$
- On-shell vs MSbar bottom mass: large renormalization scheme ambiguity. Reduced at small $\boldsymbol{p_{T,H}}$ ~ 20-40 GeV, but unchanged at larger $\boldsymbol{p_{T,H}}$ ~ 60-100 GeV

Outlook

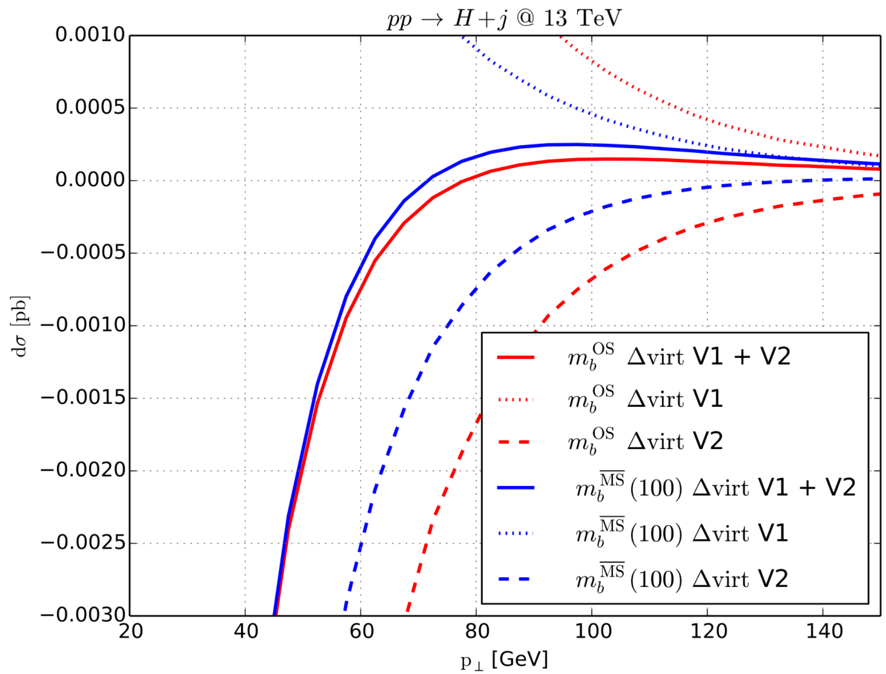
Combine various contributions to get best $H + j$ prediction:

- Low $\boldsymbol{p_{T,H}}$-resummation [Grazzini et al '13; Banfi et al '14,16; Bagnaschi et al '15]
- NNLO HEFT corrections [Boughezal et al '14,15; Gehrmann et al '15,16]
- NLO top-bottom interference [Lindert et al '17]

Backup slides

V1:NLO(t)xLO(b) vs V2:LO(t)xNLO(b)

[Lindert, Melnikov, Tancredi, CW '17]



$$d\sigma_{tb}^{\rm virt} \sim {\rm Re}\left[A_t^{\rm LO} A_b^{\rm LO*} + \frac{\alpha_s}{2\pi}\left(\underbrace{A_t^{\rm NLO} A_b^{\rm LO*}}_{\rm V1} + \underbrace{A_t^{\rm LO} A_b^{\rm NLO*}}_{\rm V2}\right)\right]$$

- Two contributions enter with opposite signs
- V2 is dominant at low $p_{T,H}$ ~ 20-50 GeV which reduces mass scheme ambiguity
- At large $p_{T,H}$ V1~V2 and V1 represents LO bottom mass scheme ambiguity

Three families flashing by

$$\mathcal{I}_{\text{top}}(a_1, a_2, ..., a_8, a_9) = \int \frac{\mathfrak{D}^d k \mathfrak{D}^d l}{[1]^{a_1}[2]^{a_2}[3]^{a_3}[4]^{a_4}[5]^{a_5}[6]^{a_6}[7]^{a_7}[8]^{a_8}[9]^{a_9}}$$

Prop.	Topology PL1	Topology PL2	Topology NPL
[1]	k^2	$k^2 - m_b^2$	$k^2 - m_b^2$
[2]	$(k-p_1)^2$	$(k-p_1)^2 - m_b^2$	$(k+p_1)^2 - m_b^2$
[3]	$(k-p_1-p_2)^2$	$(k-p_1-p_2)^2 - m_b^2$	$(k-p_2-p_3)^2 - m_b^2$
[4]	$(k-p_1-p_2-p_3)^2$	$(k-p_1-p_2-p_3)^2 - m_b^2$	$l^2 - m_b^2$
[5]	$l^2 - m_b^2$	$l^2 - m_b^2$	$(l+p_1)^2 - m_b^2$
[6]	$(l-p_1)^2 - m_b^2$	$(l-p_1)^2 - m_b^2$	$(l-p_3)^2 - m_b^2$
[7]	$(l-p_1-p_2)^2 - m_b^2$	$(l-p_1-p_2)^2 - m_b^2$	$(k-l)^2$
[8]	$(l-p_1-p_2-p_3)^2 - m_b^2$	$(l-p_1-p_2-p_3)^2 - m_b^2$	$(k-l-p_2)^2$
[9]	$(k-l)^2 - m_b^2$	$(k-l)^2$	$(k-l-p_2-p_3)^2$

IBP reduction

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

- IBP reduction to Master Integrals

$$\mathcal{I}_{a_1\cdots a_n}(s) = \sum_{(b_1\cdots b_n)\in\text{Master Integrals}} \text{Rational}_{a_1\cdots a_n}^{b_1\cdots b_n}(s,d)\text{MI}_{b_1\cdots b_n}(s)$$

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

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

1) FORM code reduction:

$$\mathcal{I}_{t=7}^{\text{NPL}} = \sum c_i \text{MI}_{t=7}^i + \sum d_i \mathcal{I}_{t=6}^i$$

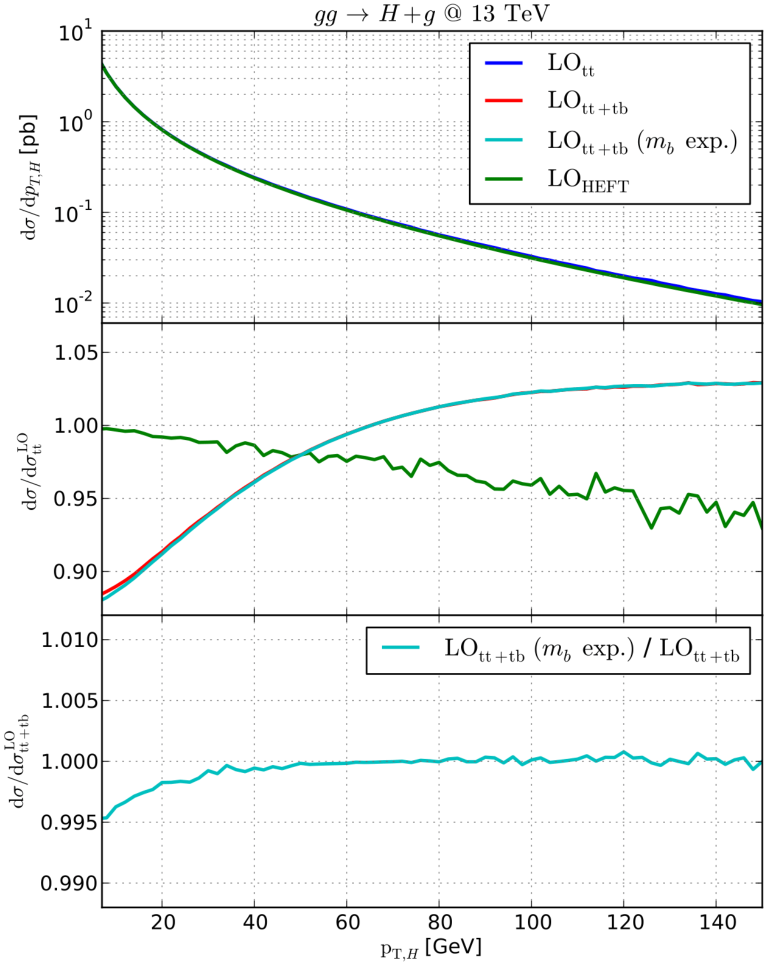
2) Plug reduced integrals into amplitude, expand coefficients c_i, d_i in m_b

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

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

- *Expansion in m_b occurs at last step*: solving with Master integrals with *differential equation method*

LO contributions



How useful is m_b expansion?

- NLO amplitudes require computing 2-loop Feynman integrals with massive quark loop
- If these integral are computed exactly in quark mass, results in *very complicated functions*

[planar diagrams: Bonciani et al '16]

$$
\begin{aligned}
&\log\left(x_3x_1^2 - x_1^2 + x_2x_1 - 4x_3x_1 + R_1(x_1)R_2(x_1)R_7(x)\right),\\
&\log\left(-x_2^2 + x_1x_2 - x_1x_3x_2 + 2x_3x_2 + 2x_1x_3 + R_1(x_2)R_2(x_2)R_7(x)\right),\\
&\log\left(-x_3^2x_1^2 + 3x_3x_1^2 + 4x_3^2x_1 - 4x_2x_3x_1 + R_1(x_3)R_5(x)R_6(x)x_1\right),\\
&\log\left(x_3R_1(x_2)R_2(x_2) + x_2R_1(x_3)R_2(x_3)\right),\\
&\log\left(x_1R_1(x_2)R_2(x_2) + x_2R_1(x_1)R_2(x_1)\right),\\
&\log\left(x_1R_1(x_3)R_2(x_3) - R_1(x_1)R_1(x_3)R_5(x)\right),\\
&\log\left(x_3R_1(x_1)R_2(x_1) - R_1(x_1)R_1(x_3)R_5(x)\right),\\
&\log\left(-x_2R_1(x_1)R_2(x_1) + x_3R_1(x_1)R_2(x_1) + x_1R_3(x_3)R_4(x_3)\right),\\
&\log\left(-x_2R_1(x_2)R_2(x_2) + x_3R_1(x_2)R_2(x_2) + x_2R_3(x_3)R_4(x_3)\right),\\
&\log\left(-x_2R_1(x_3)R_2(x_3) + x_1R_1(x_3)R_2(x_3) + x_3R_3(x_1)R_4(x_1)\right),\\
&\log\left(-x_2R_1(x_2)R_2(x_2) + x_1R_1(x_2)R_2(x_2) + x_2R_3(x_1)R_4(x_1)\right),\\
&\log\left(-x_3^2x_1^2 + 3x_3x_1^2 + 4x_3^2x_1 - 3x_2x_3x_1 + R_1(x_1)R_1(x_3)R_5(x)R_7(x)\right),\\
&\log\left(x_2R_1(x_1)R_1(x_3)R_5(x) - x_1x_3R_1(x_2)R_2(x_2)\right),\\
&\log\left(-x_2x_3 + x_1x_3 + R_1(x_2)R_2(x_2)x_3 - R_1(x_1)R_1(x_3)R_5(x)\right).
\end{aligned}
$$

$$
\begin{aligned}
&R_1(x_1) = \sqrt{-x_1}\,,\ R_1(x_3) = \sqrt{-x_3}\,,\ R_1(x_2) = \sqrt{-x_2}\,,\\
&R_2(x_1) = \sqrt{4-x_1}\,,\ R_2(x_3) = \sqrt{4-x_3}\,,\ R_2(x_2) = \sqrt{4-x_2}\,,\\
&R_3(x_1) = \sqrt{x_2-x_1}\,,\ R_3(x_3) = \sqrt{x_2-x_3}\,,\\
&R_4(x_1) = \sqrt{x_2-x_1-4}\,,\ R_4(x_3) = \sqrt{x_2-x_3-4}\,,\\
&R_5(x) = \sqrt{4x_2 + x_1x_3 - 4(x_1+x_3)}\,,\\
&R_6(x) = \sqrt{2x_3(-2x_2+x_1+2x_3) - x_1x_3^2 - x_1}\,,\\
&R_7(x) = \sqrt{2x_1x_3(x_2-x_1) + (x_2-x_1)^2 + (x_1-4)x_1x_3^2}\,.
\end{aligned}
$$

- Starting from weight three not possible to express in terms of usual GPL's anymore
- *Expanding* in small bottom quark mass results in simple *2-dimensional harmonic polylogs*

[Vermaseren, Remiddi, Gehrmann]

Real corrections with Openloops

- Channels for real contribution to Higgs plus jet at NLO

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

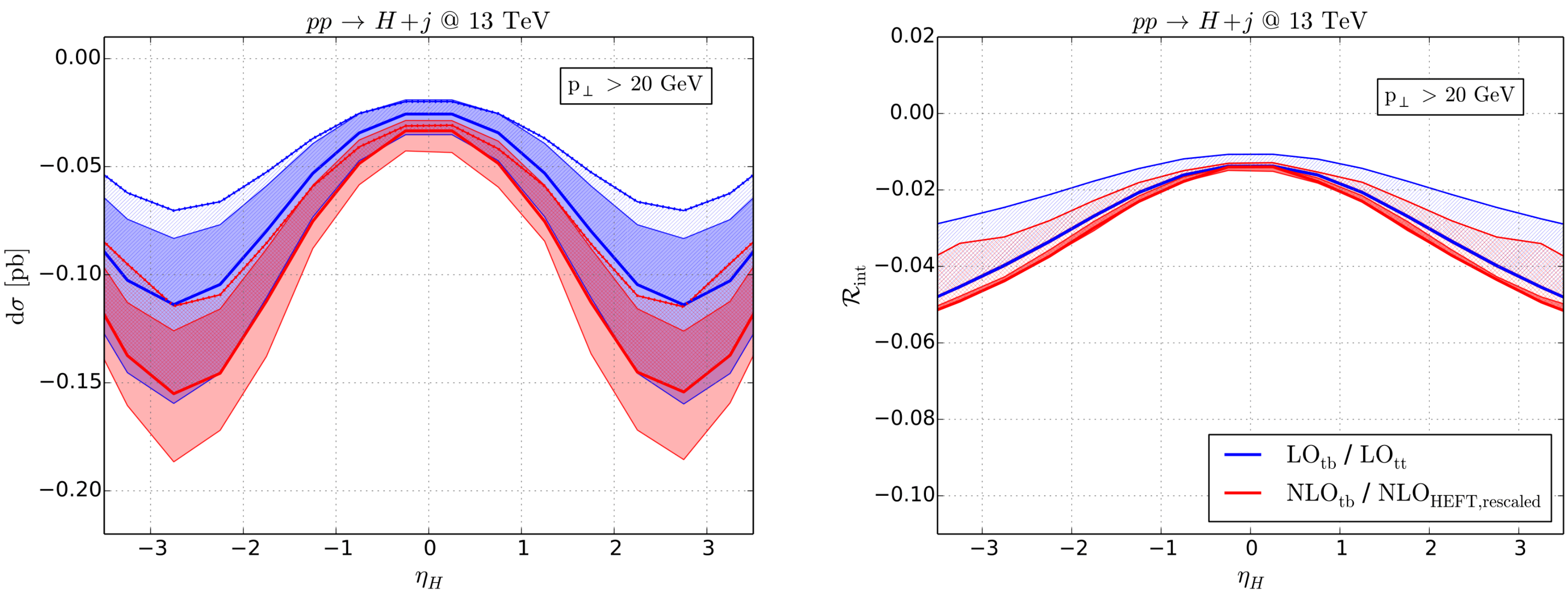
- Receives contributions from kinematical regions where one parton become soft or collinear to another parton
- This requires a delicate approach of these regions in phase space integral
- Openloops algorithm is publicly available program which is capable of dealing with these singular regions in a numerically 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 both top-top and top-bottom contribution to differential cross section

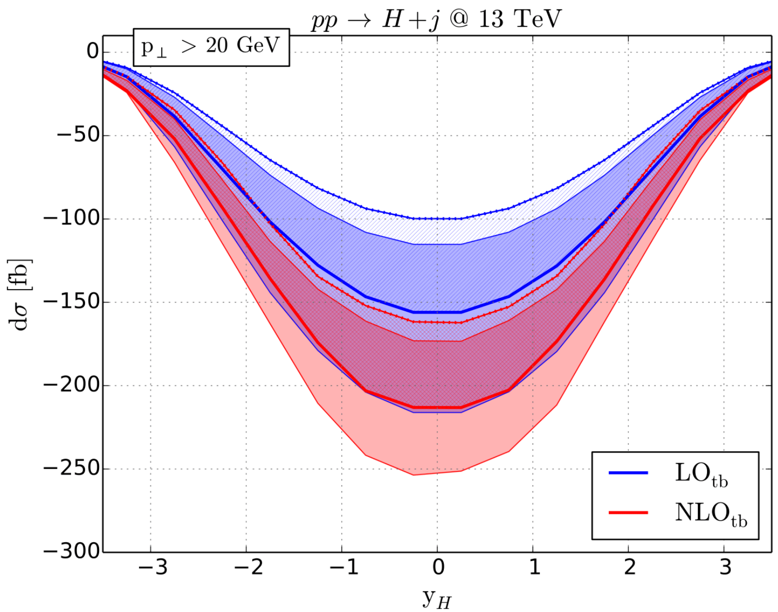
Higgs pseudo-rapidity distribution

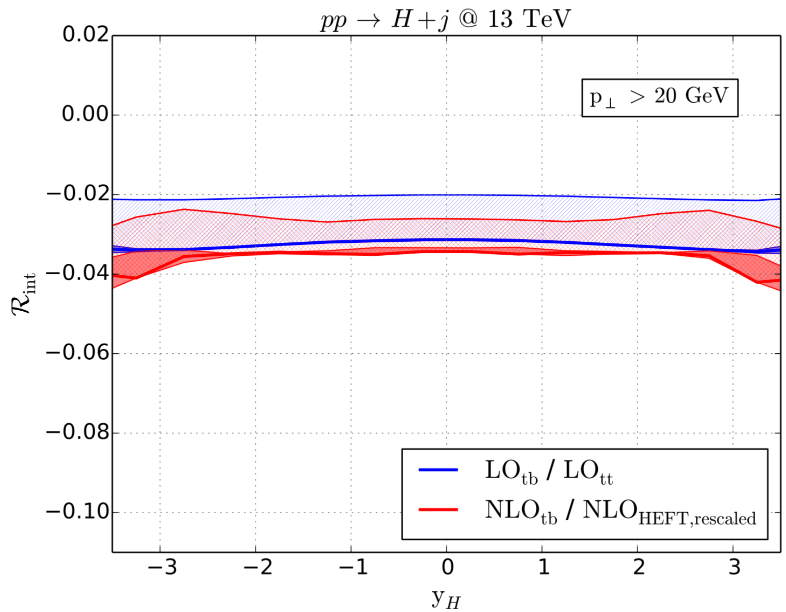
[Lindert, Melnikov, Tancredi, CW '17]



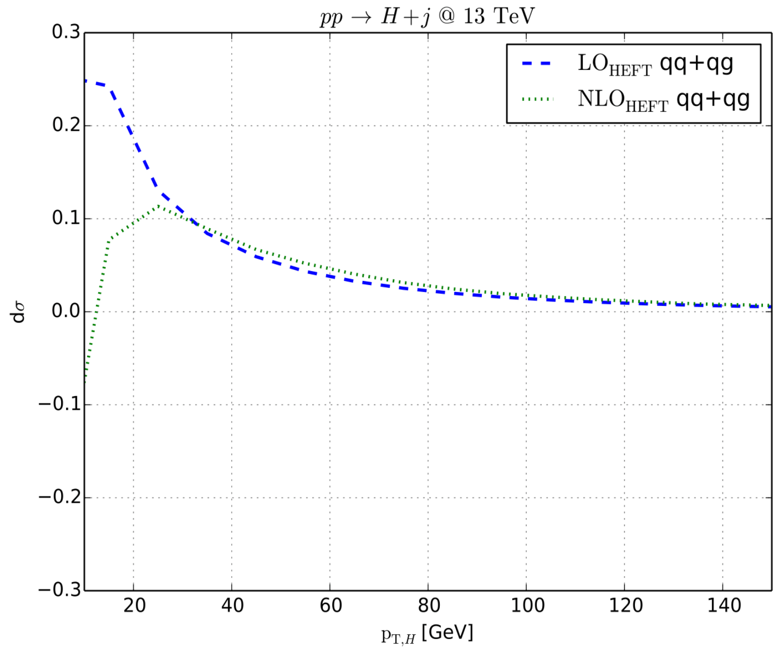
- Relative corrections to top-bottom interference ~ relative corrections to top-top
- At central rapidity (dominated by large $p_{T,H}$) mass scheme ambiguity similar between LO and NLO
- At larger absolute rapidity (dominated by small $p_{T,H}$) the mass scheme variation band is smaller for NLO

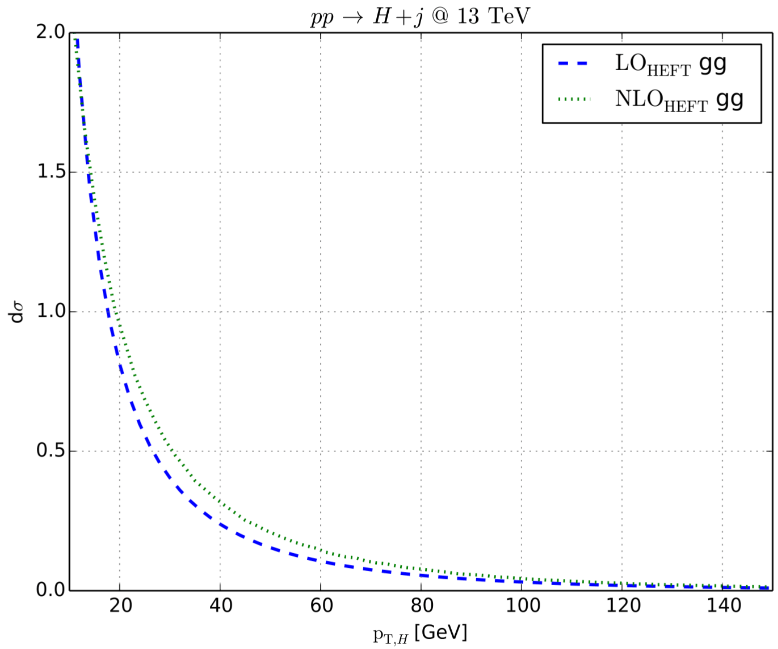
Higgs rapidity distribution





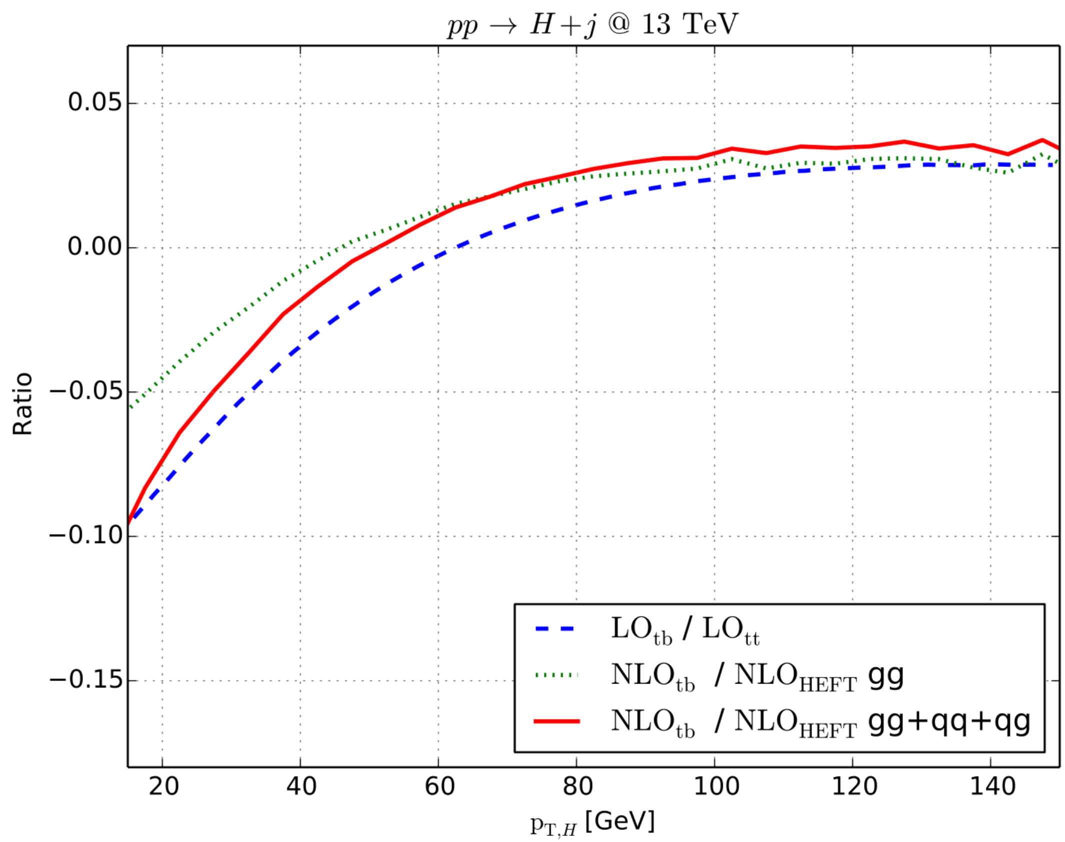
Channel contribution: tt





- gg fusion channel dominates

Channel contribution: tb



- gg fusion channel dominates