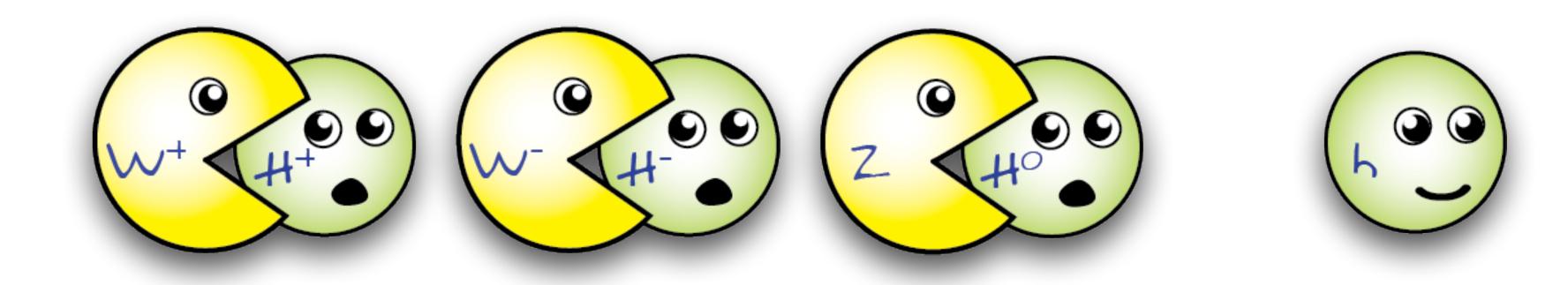
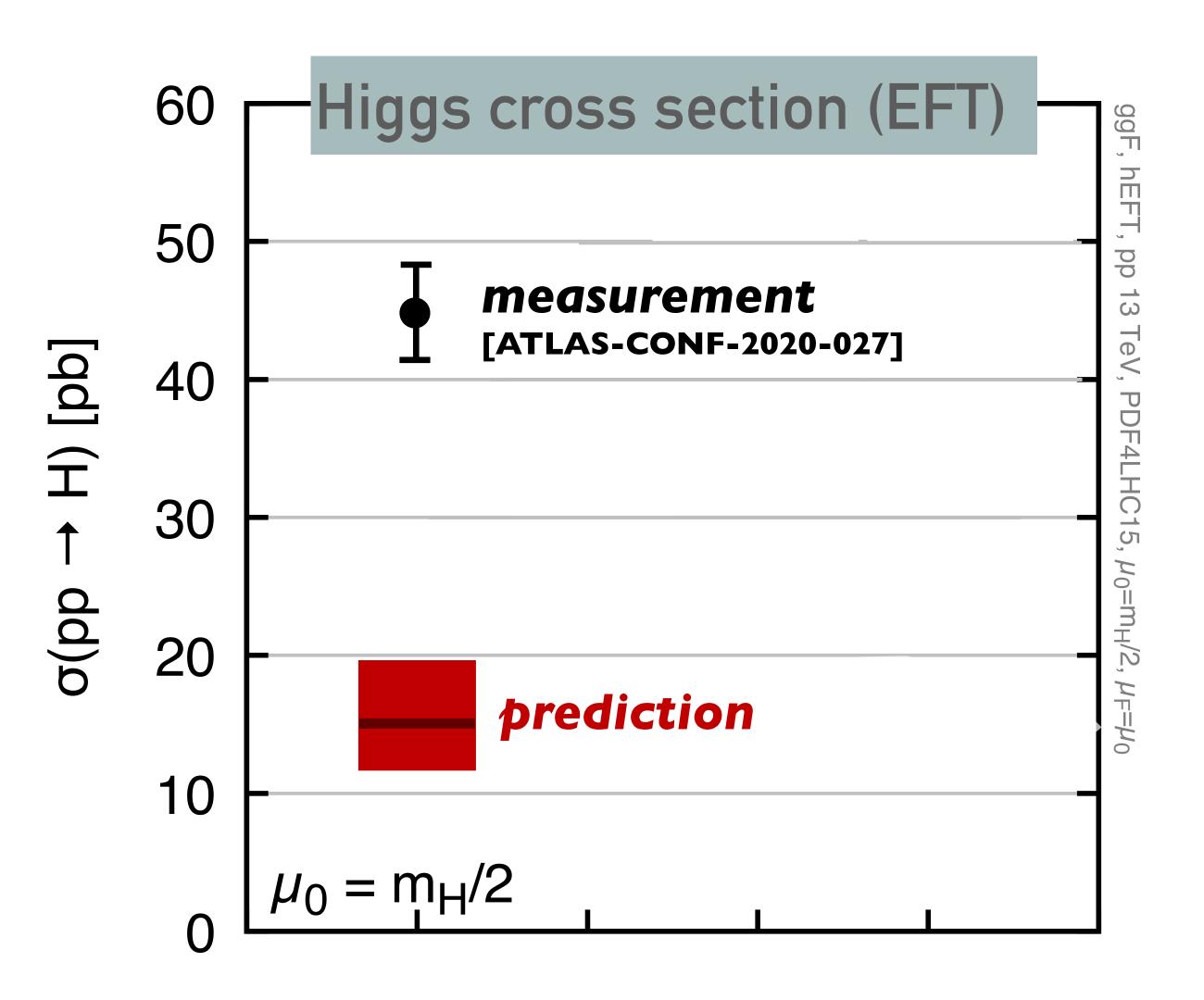
Higgs differential cross sections

Max-Planck-Institut für Physik

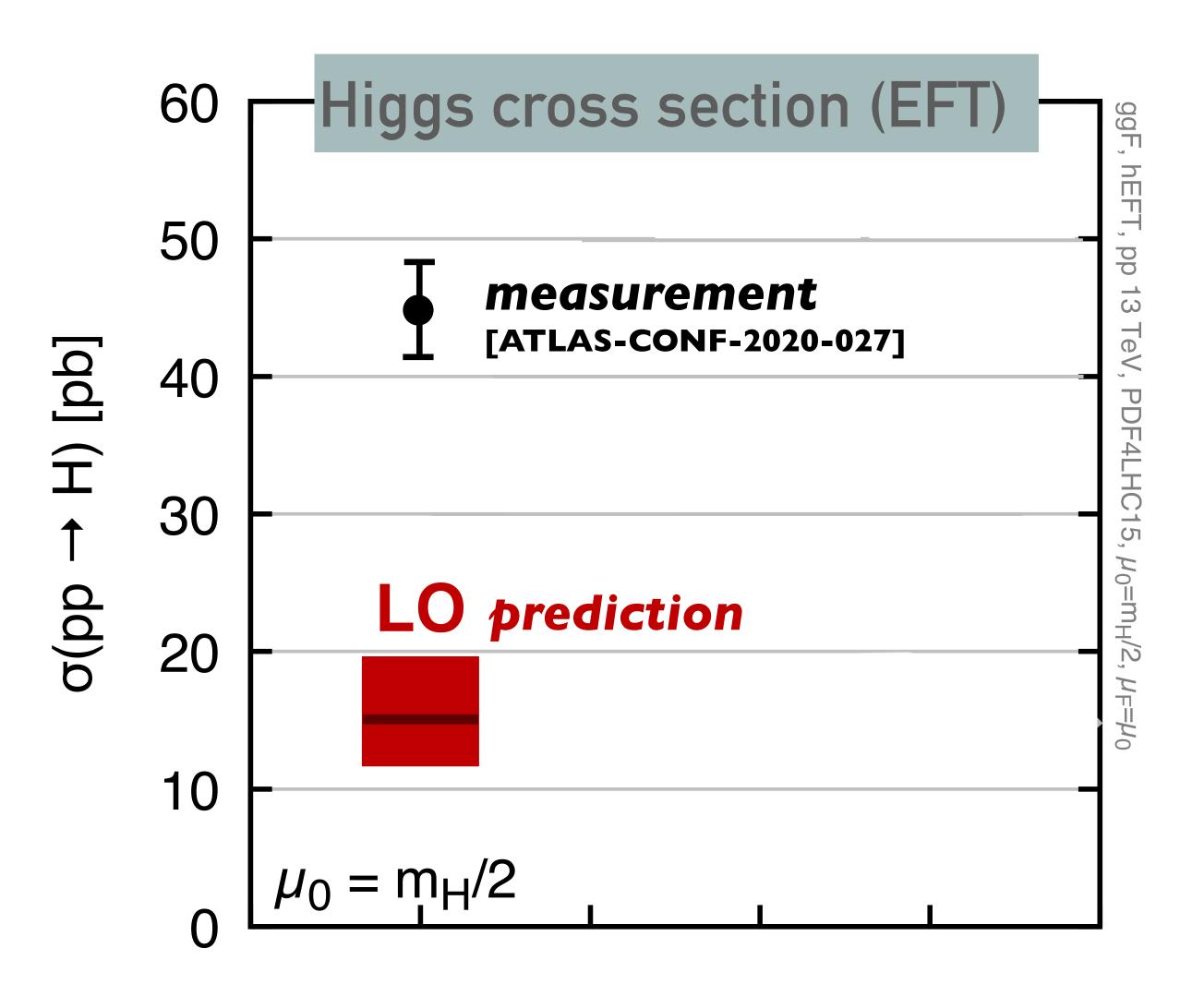


Standard Model at the LHC 2022 CERN (Geneva, Switzerland), April 11-14, 2022

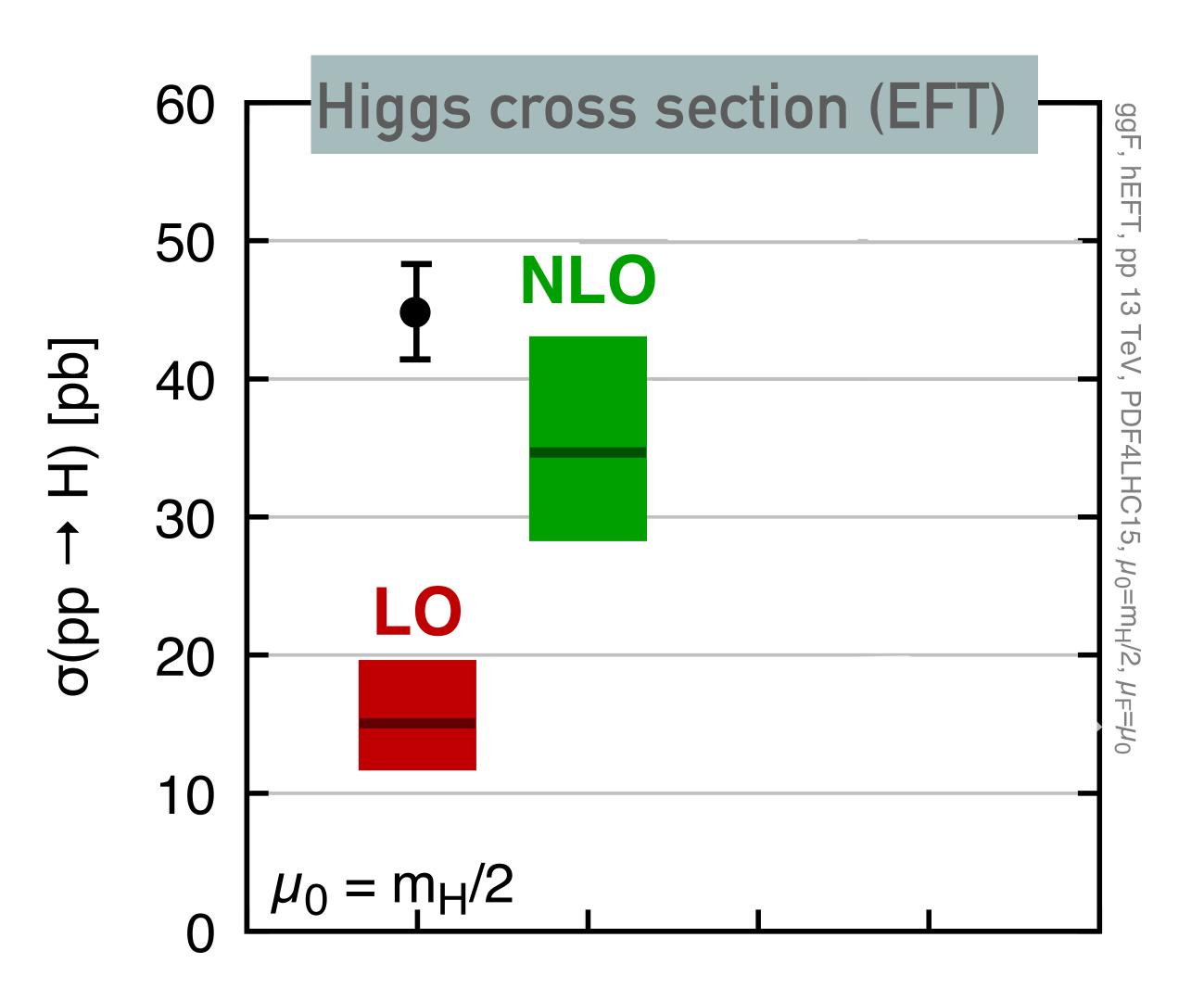
Marius Wiesemann



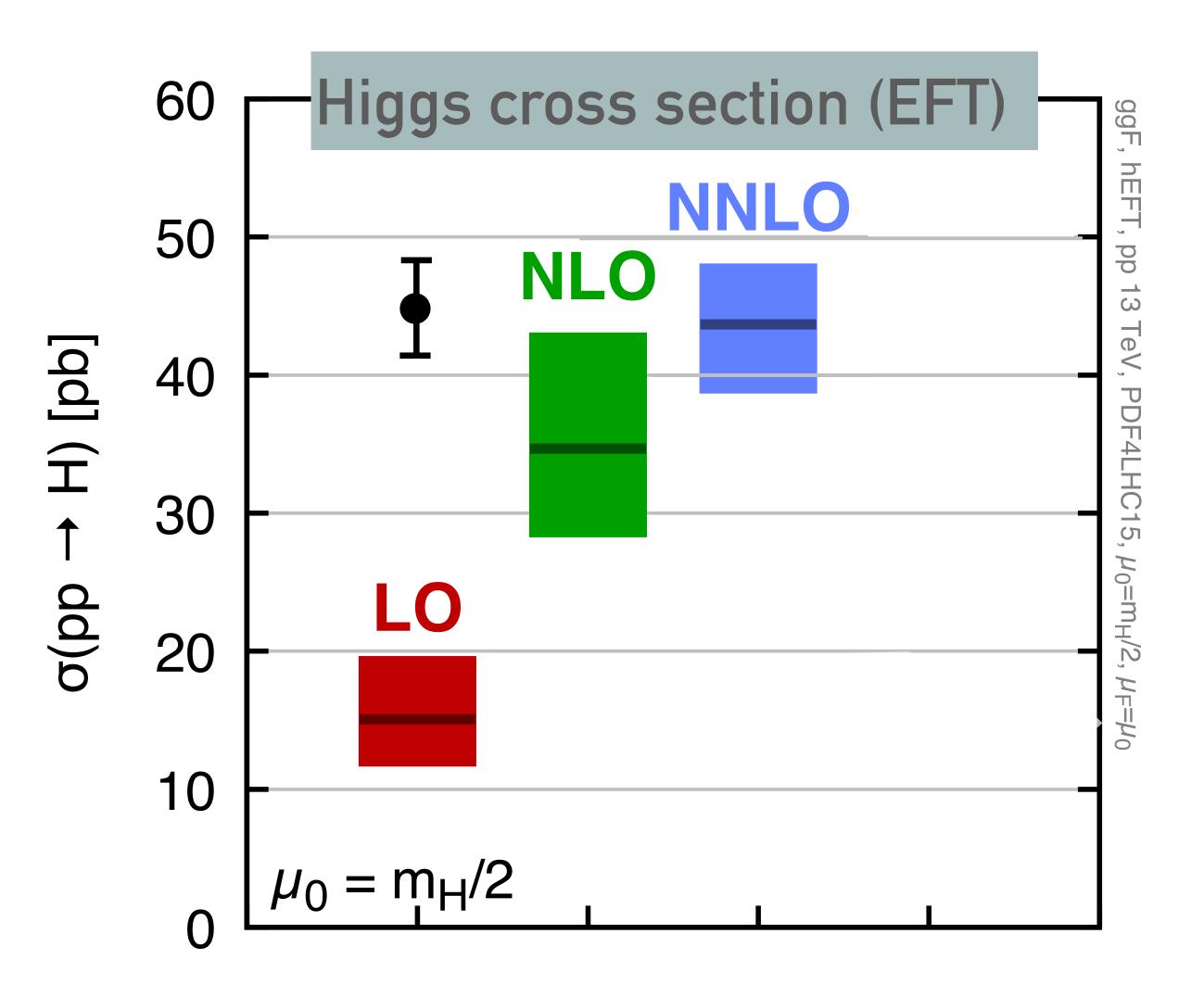




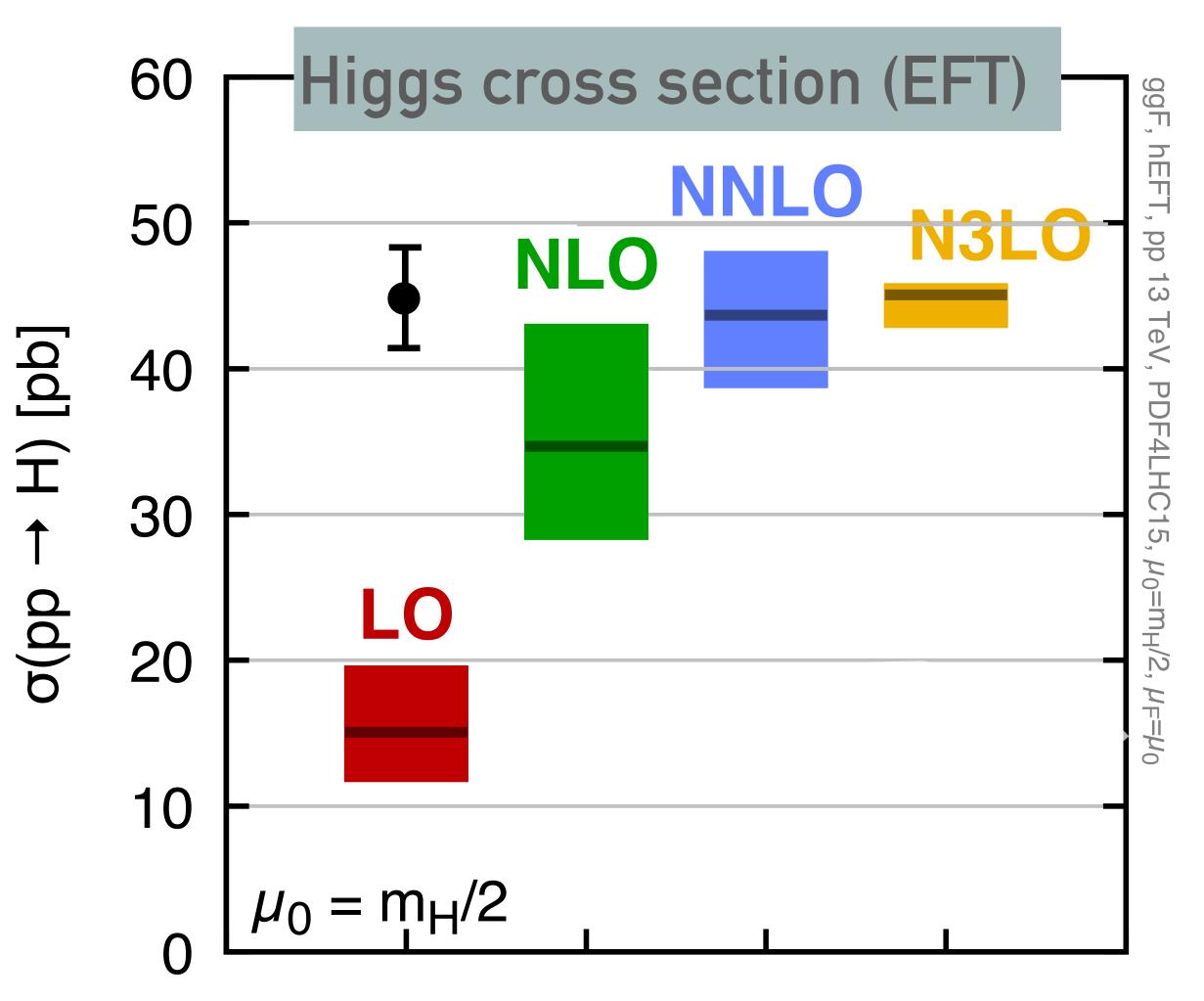






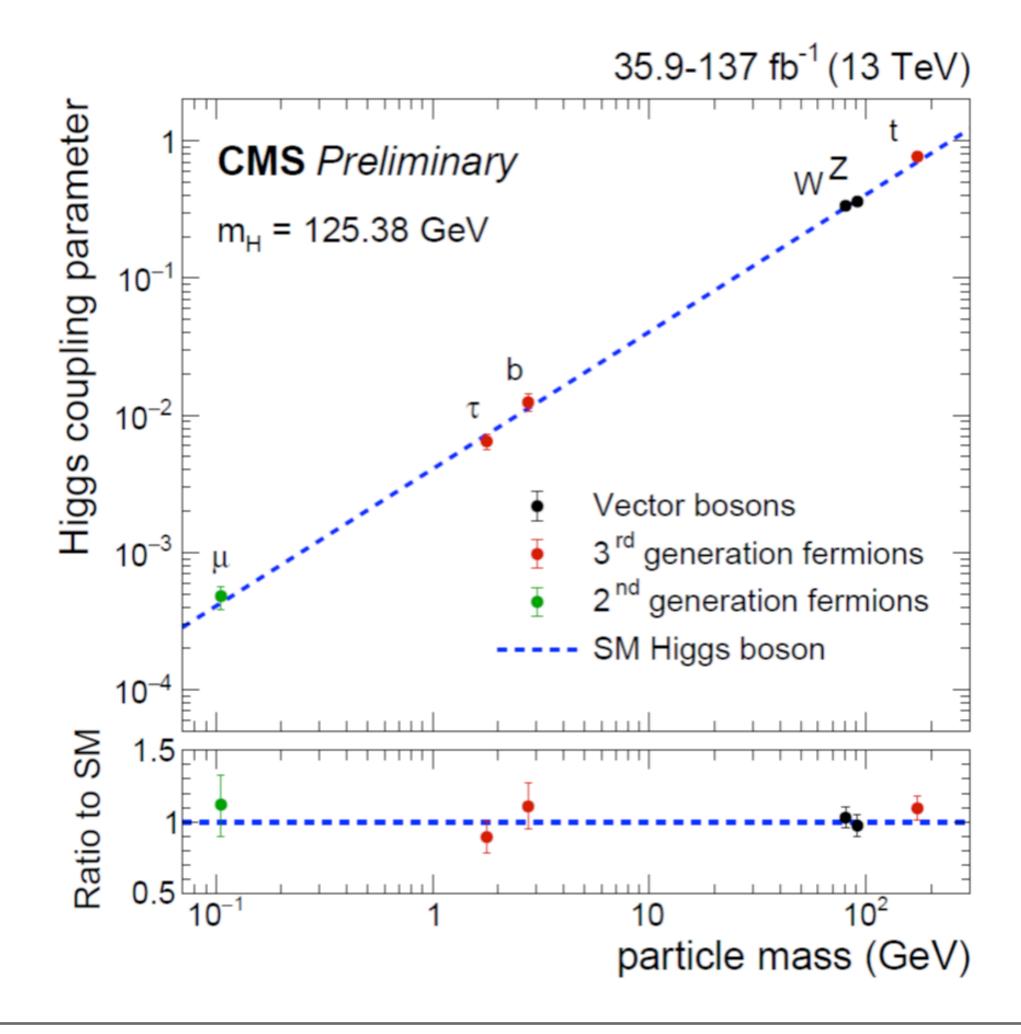






[Anastasiou et al. '15], [Mistlberger '18]



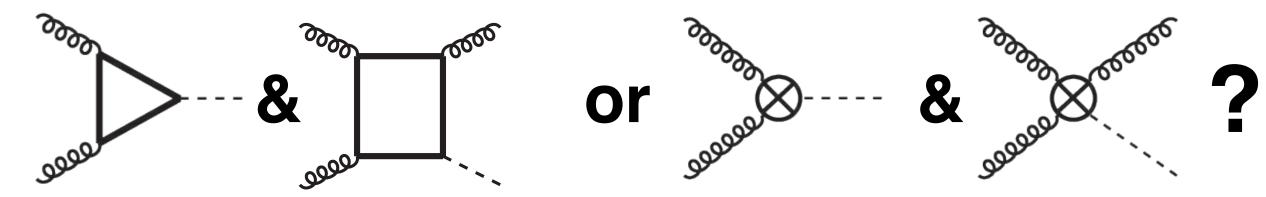


Higgs couplings

Higgs differential cross sections

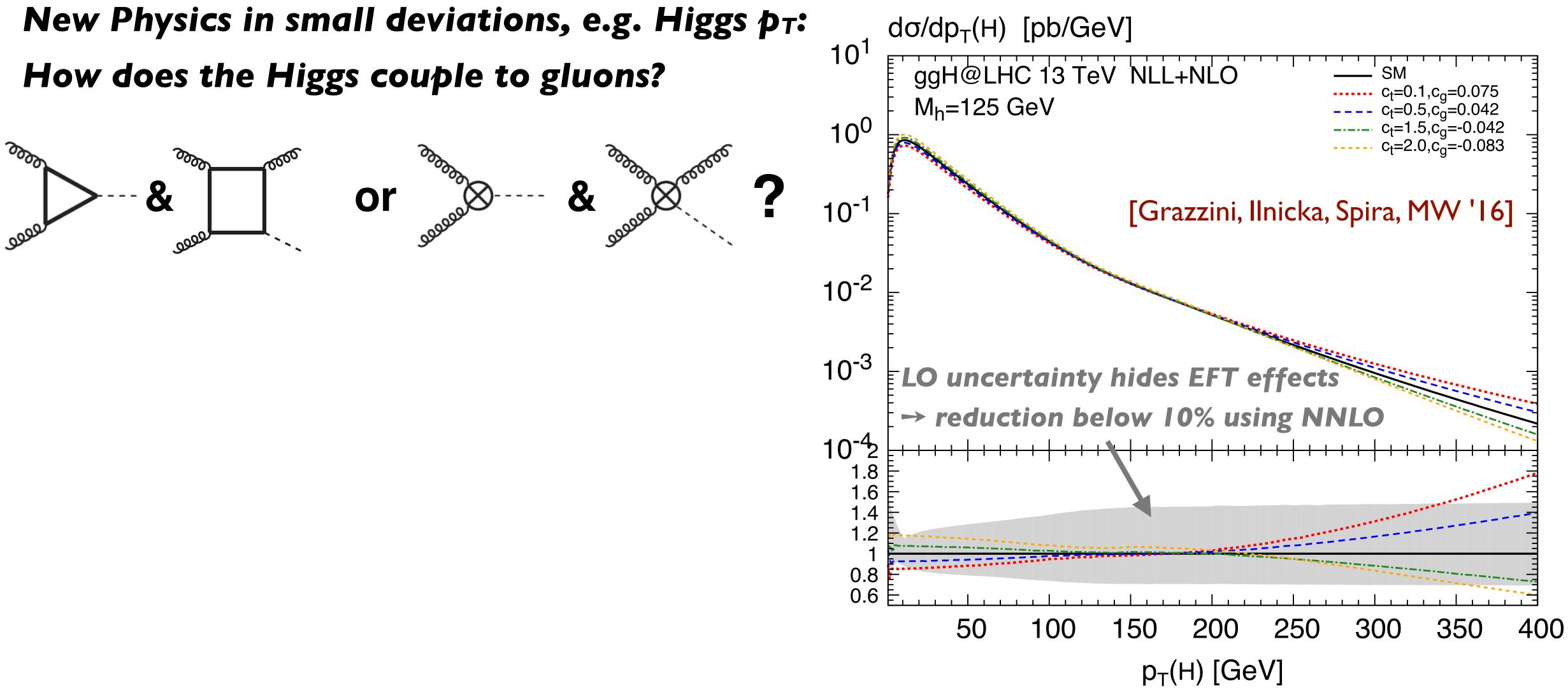


New Physics in small deviations, e.g. Higgs pT: How does the Higgs couple to gluons?



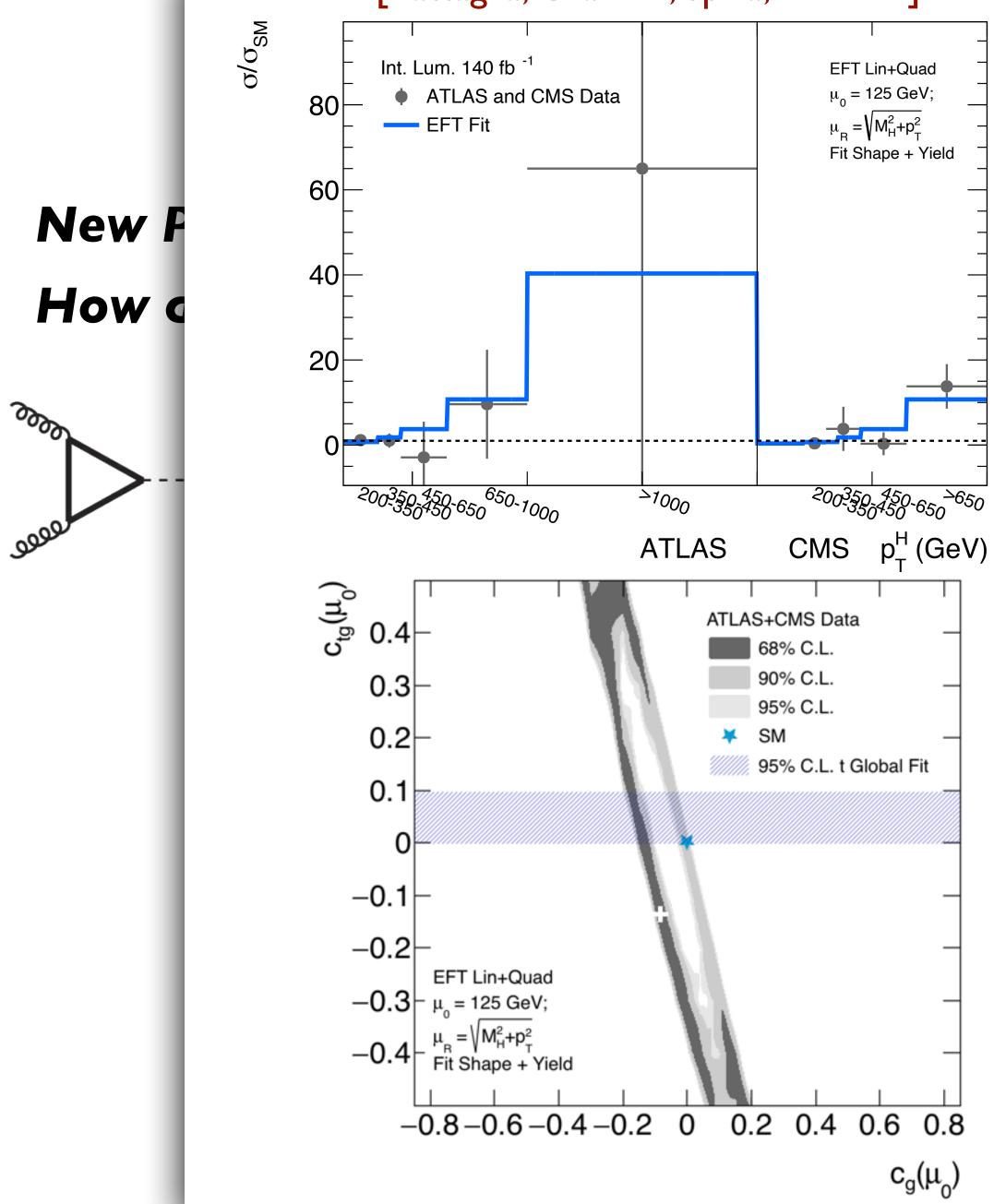
Higgs differential cross sections



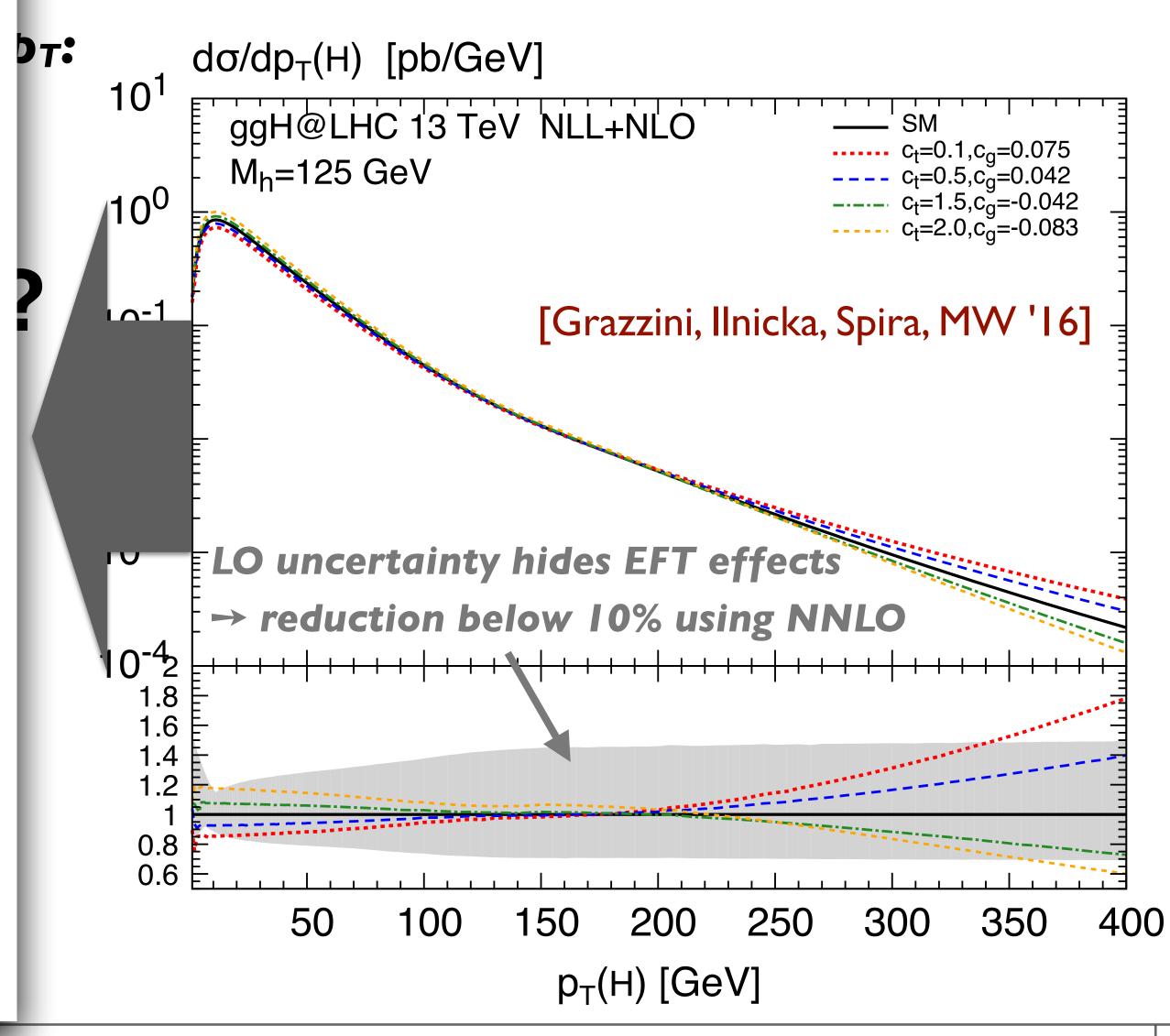




[Battaglia, Grazzini, Spira, MW '21]



recision?

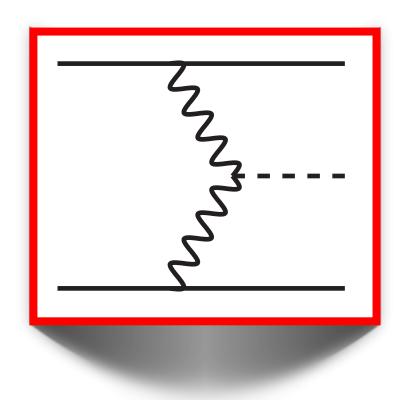


Higgs differential cross sections

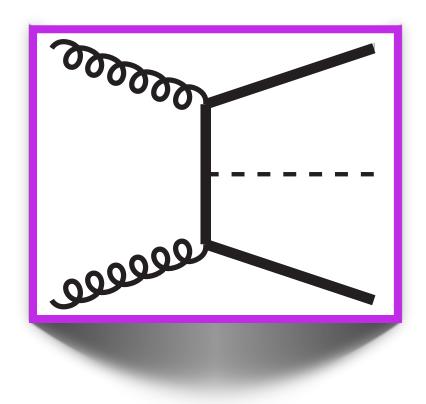


Higgs production

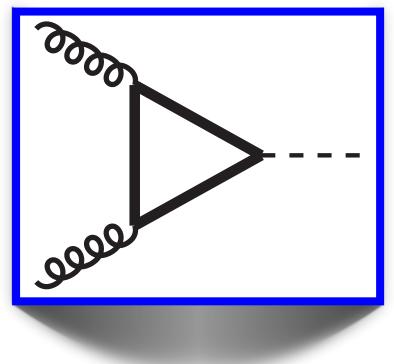
 $\mathsf{VBF} \sim 7\,\%$



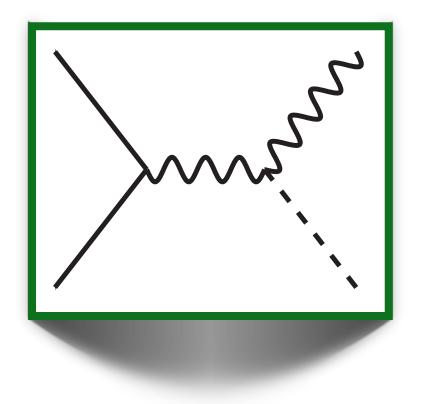
bbH, ttH $\sim 1~\%$

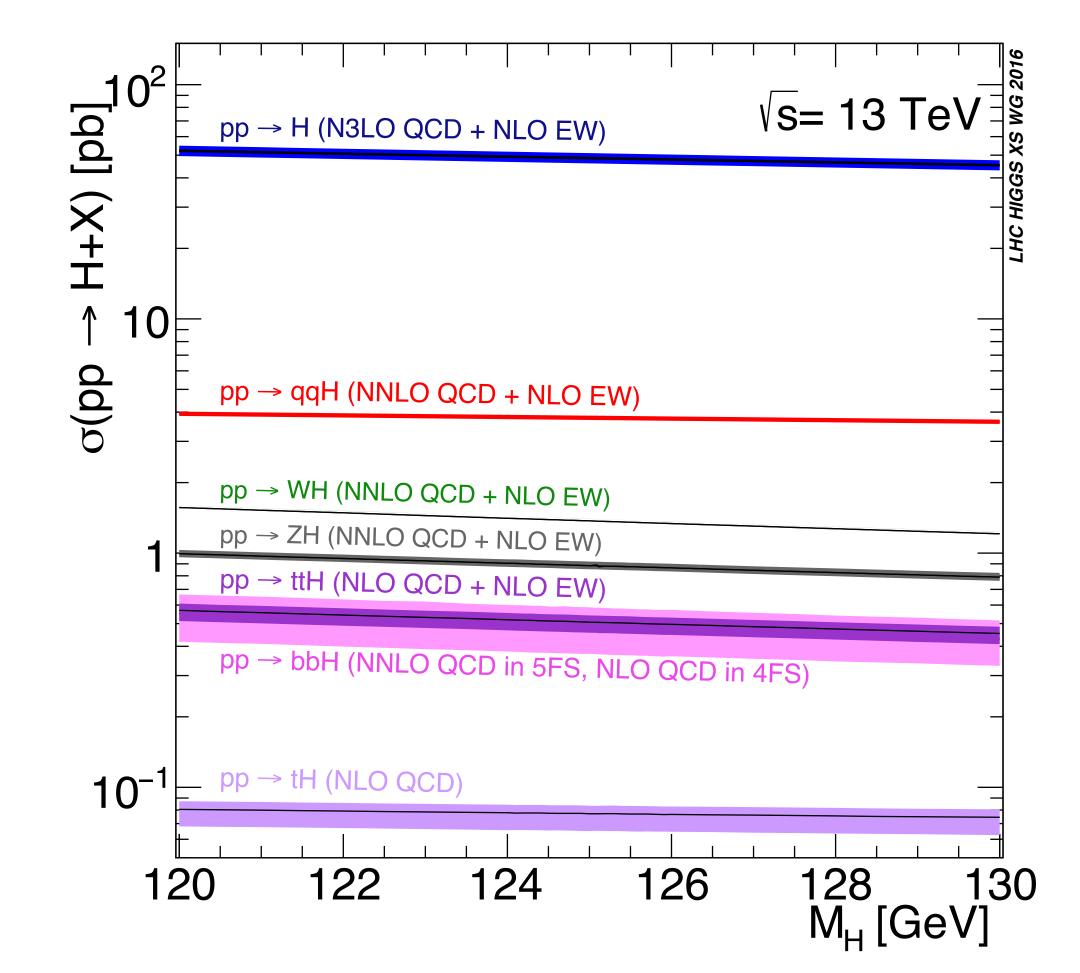


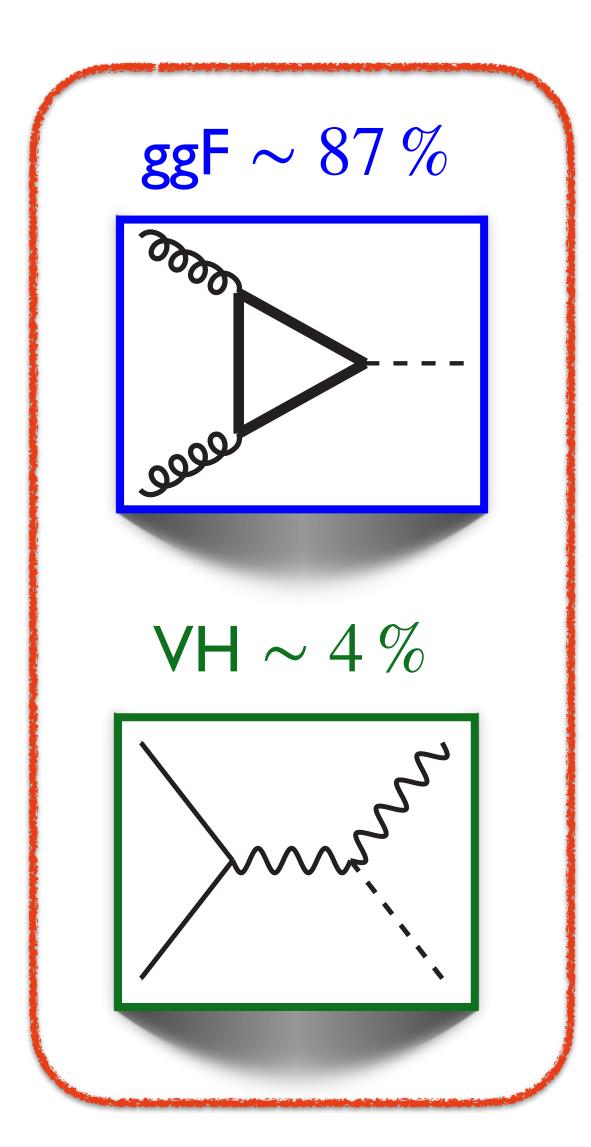
ggF ~ 87 %



 $VH \sim 4\%$



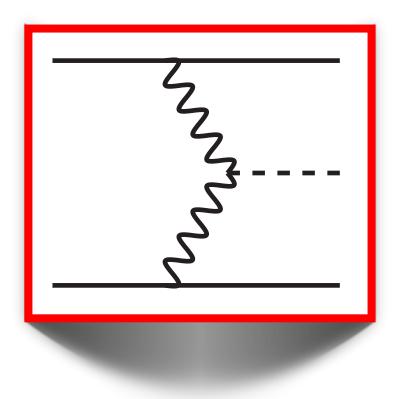




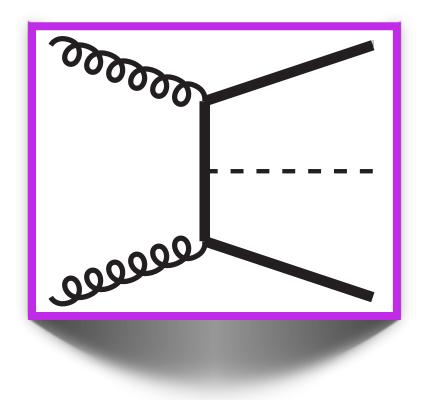
focus of this talk

Higgs production

VBF $\sim 7\%$

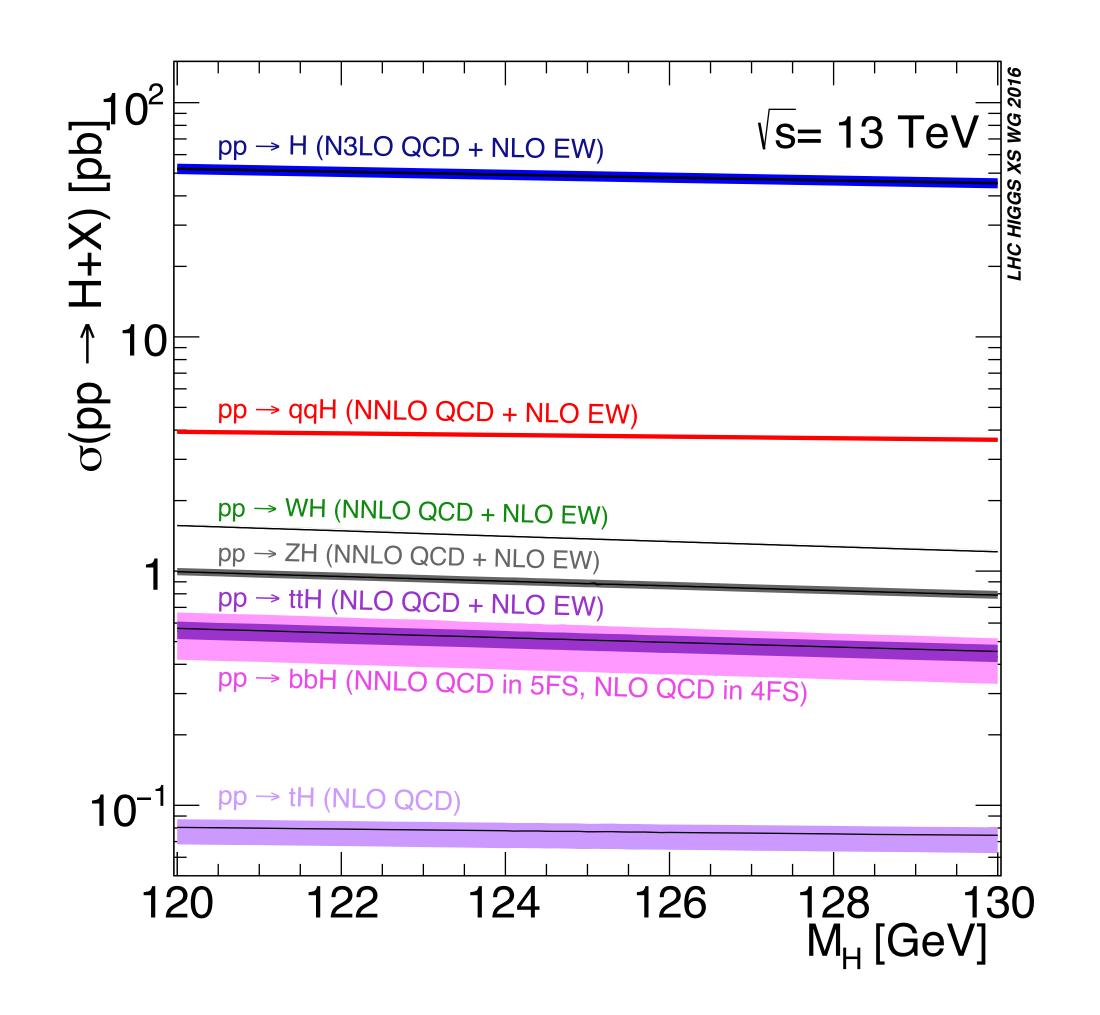


bbH, ttH $\sim 1\%$





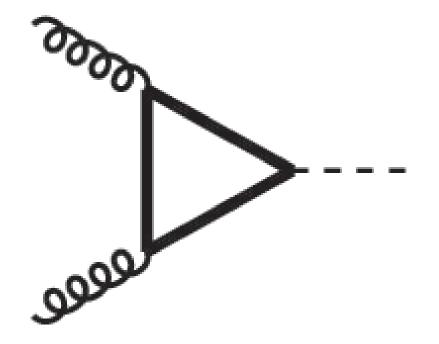
Higgs differential cross sections



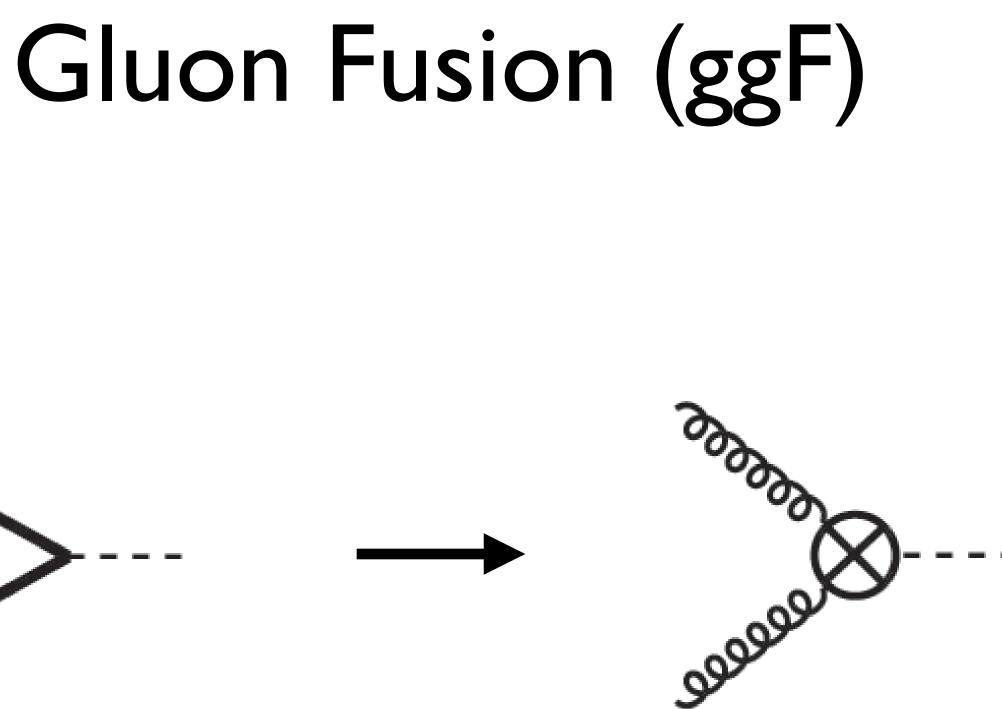
Disclaimer: will present a very incomplete and personal selection of results

April 12th, 2022

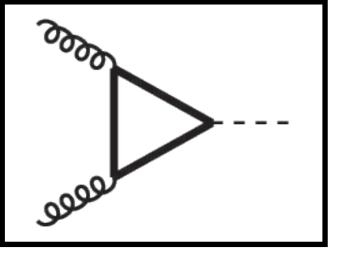




Widely assumed EFT approximation "heavy-top limit" (HTL), by integrating out the top quark, for higher-order corrections. $(\rightarrow$ need to compute effectively one loop less)









inclusive XS known for a while:

- soft expansion [Anastasiou et al. '15]
- full [Mistlberger '18]

differential:

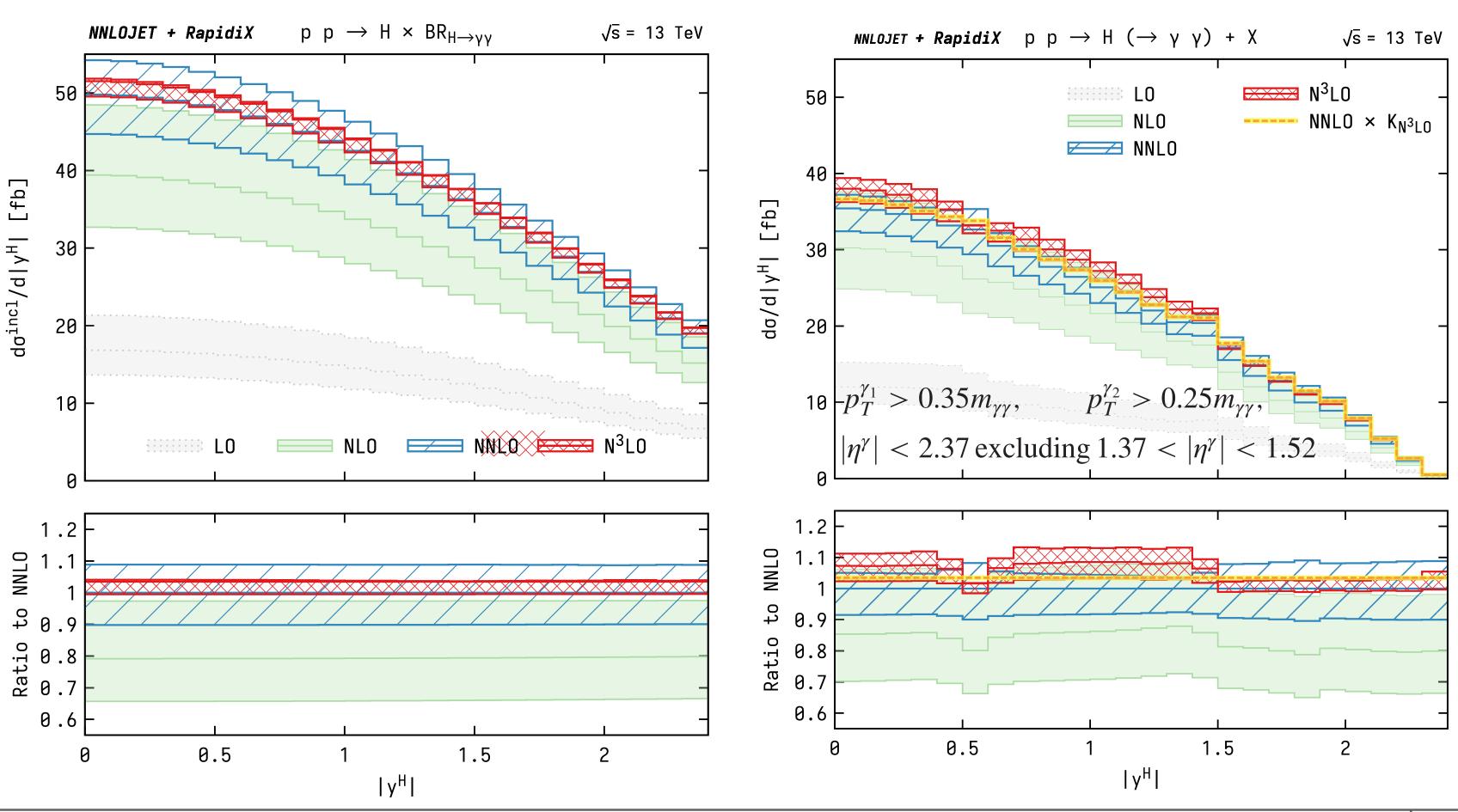
- H+jet at NNLO [Chen, Gehrmann, Glover, Jaquier '14]
- Higgs rapidity at N³LO [Dulat, Mistlberger, Pelloni '18]

Projection-to-Born [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

N³**LO** for $gg \rightarrow H \rightarrow \gamma\gamma$ (fully differential)

Marius Wiesemann (MPP Munich)

no cuts (inclusive)



Higgs differential cross sections

ggF @ N³LO differential

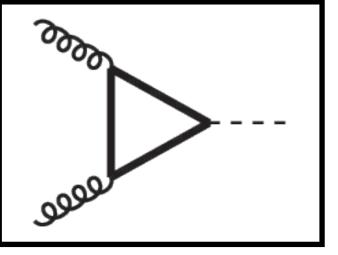
[Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni '21]

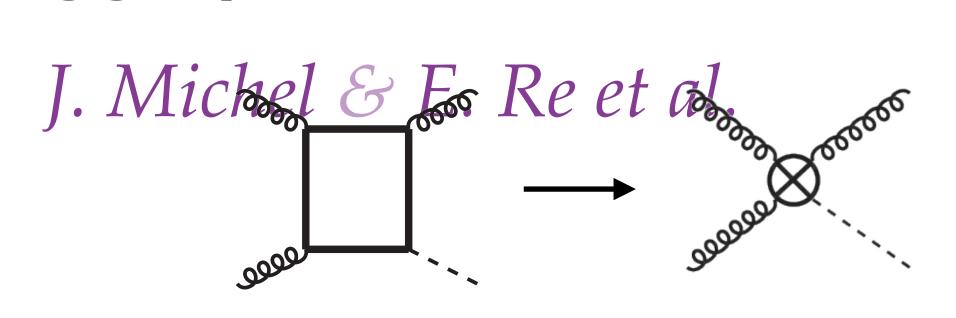
Higgs rapidity

fiducial cuts (ATLAS)

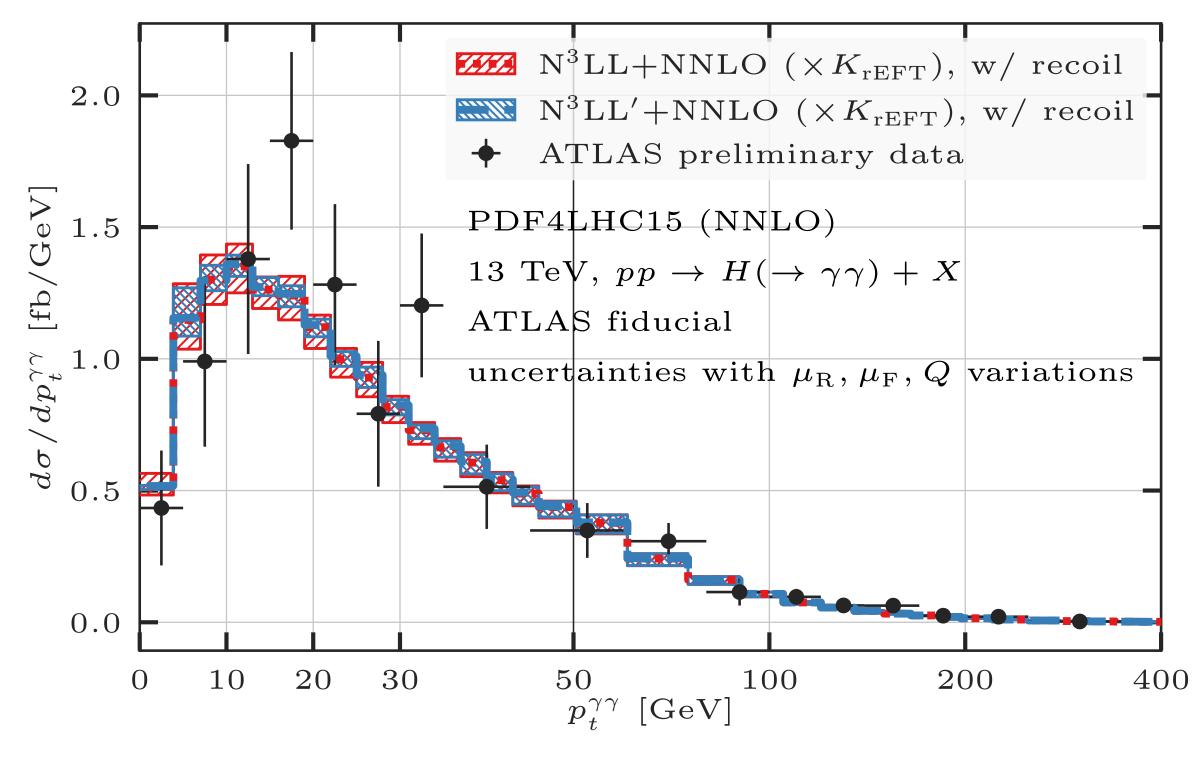
April 12th, 2022



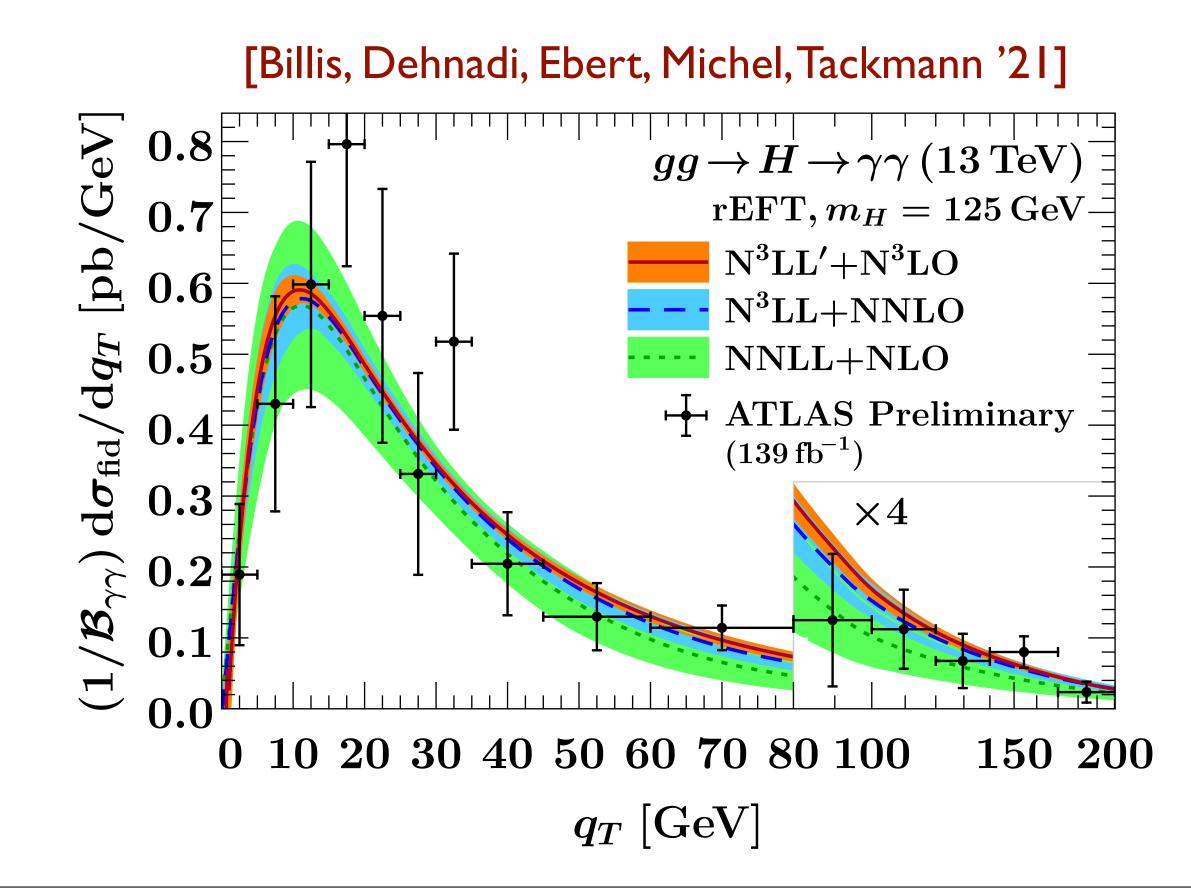




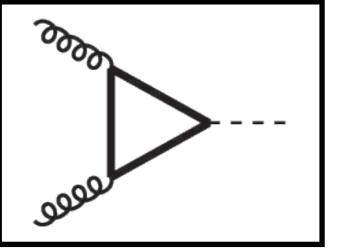
[Re, Rottoli, Torrieli '21]

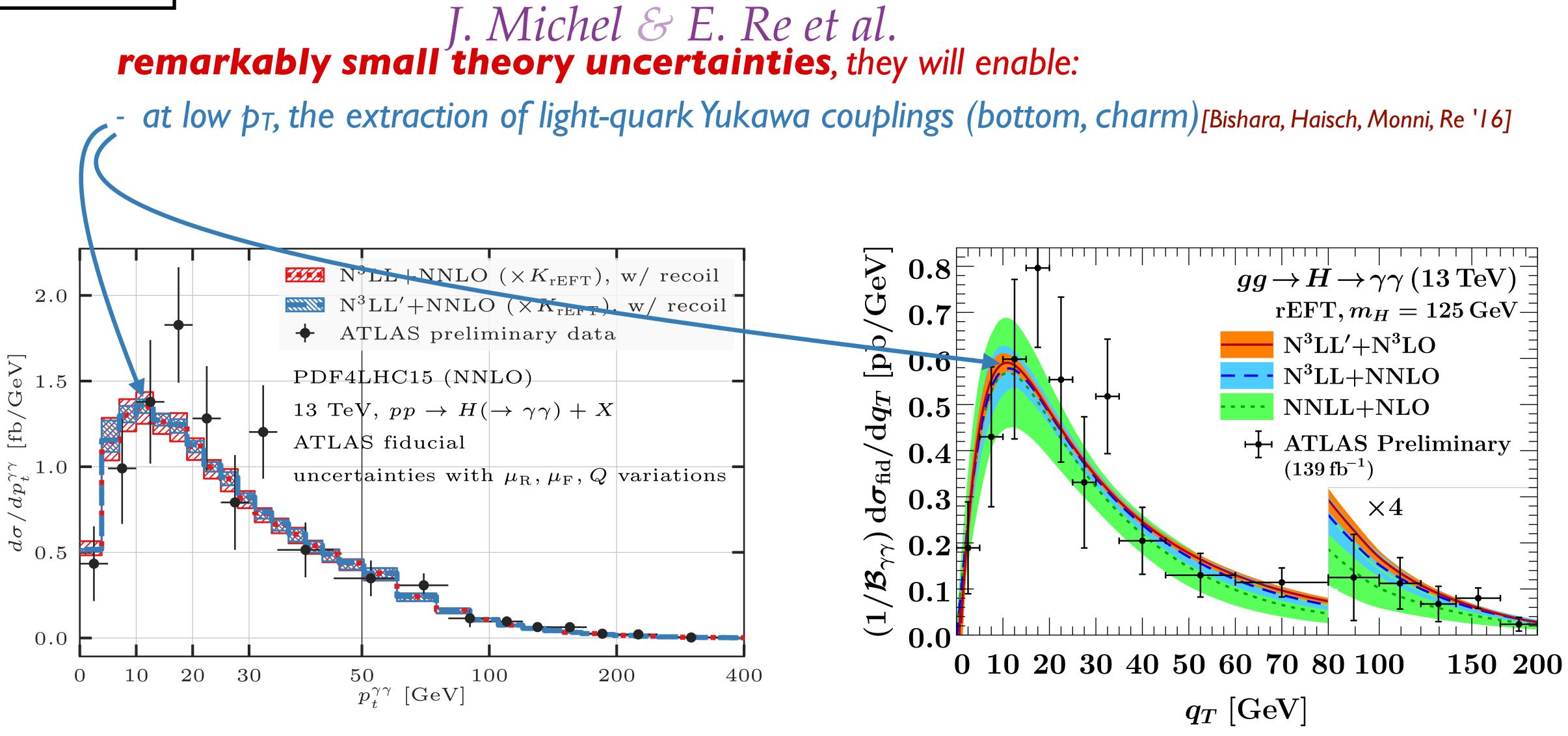


Higgs pt @ N³LL'+NNLO





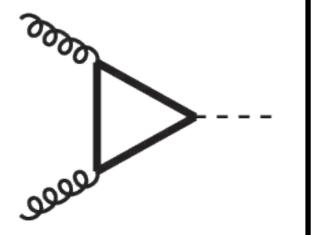




Higgs pt @ N³LL'+NNLO

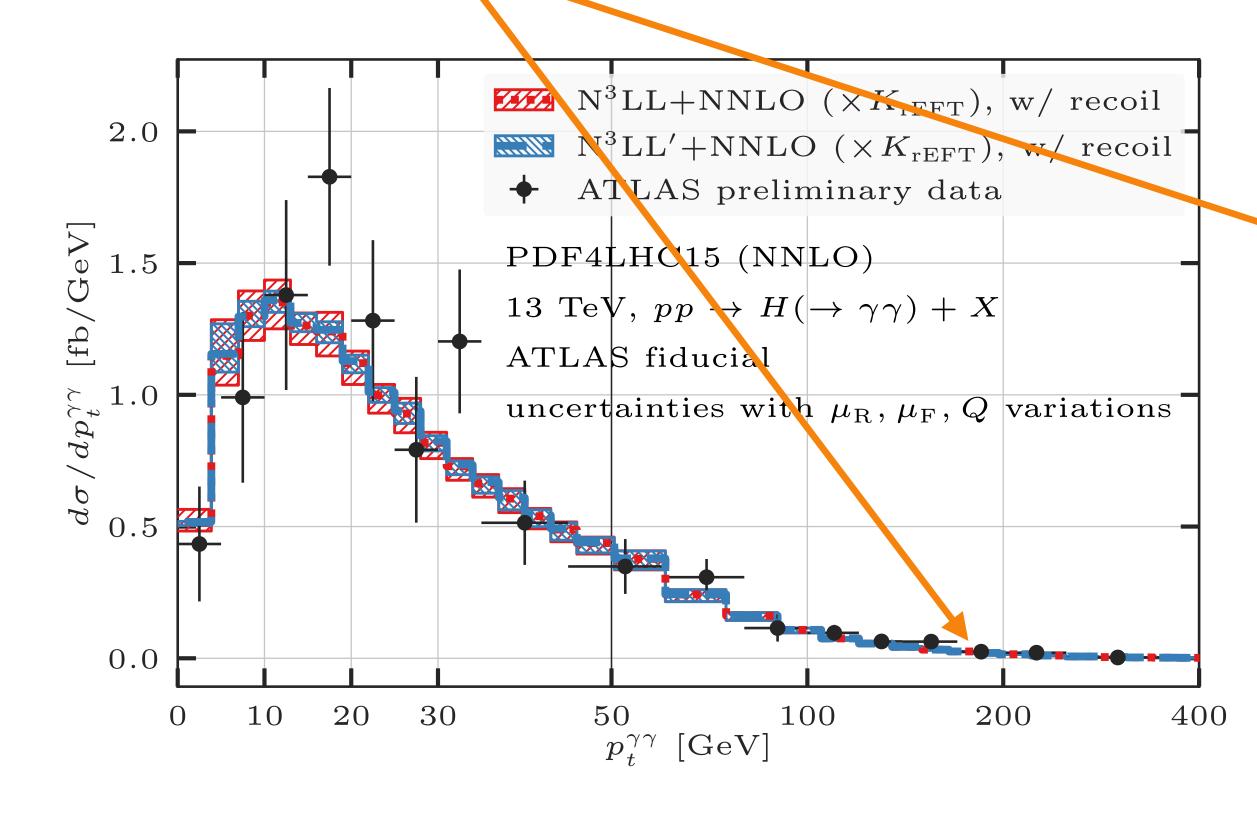




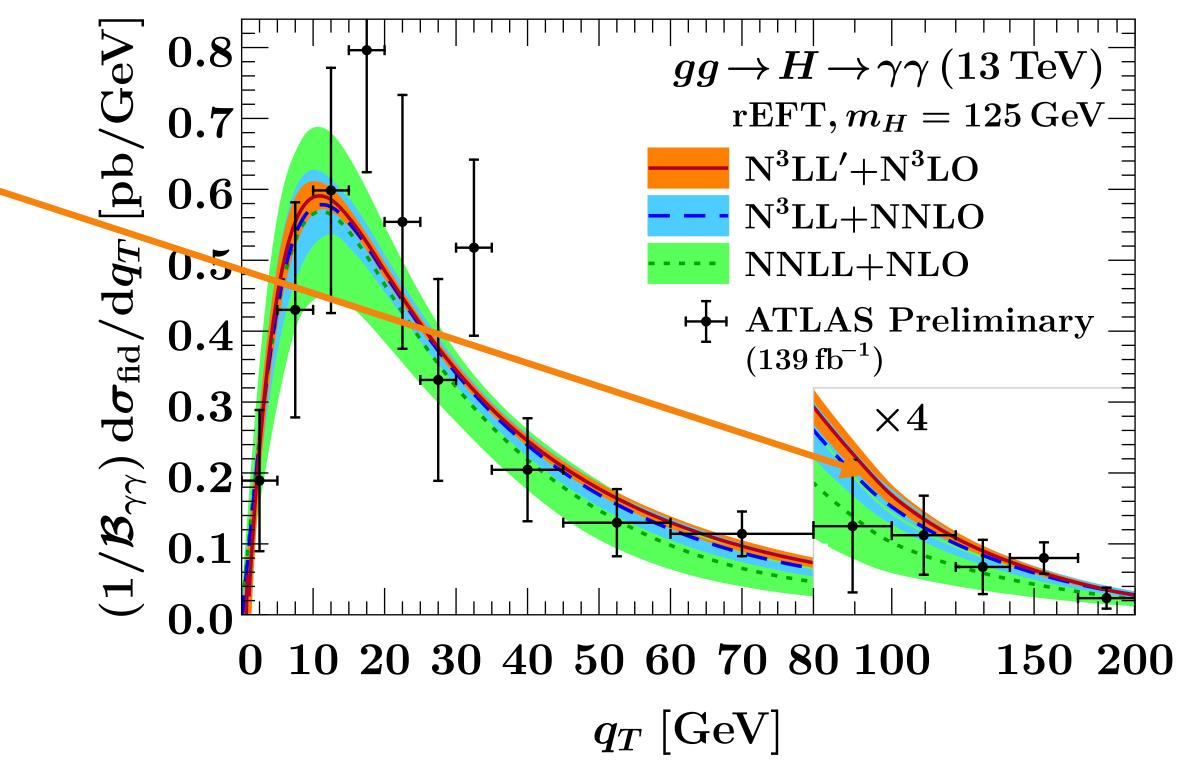


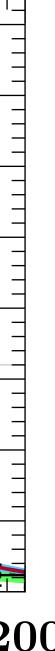
J. Michel & E. Re et al. remarkably small theory uncertainties, they will enable: - at low p_T, the extraction of light-quark Yukawa couplings (bottom, charm)[Bishara, Haisch, Monni, Re '16]

- at high p_T, the extraction of the Higgs coupling to gluons, see e.g. [Battaglia, Grazzini, Spira, MW '21]

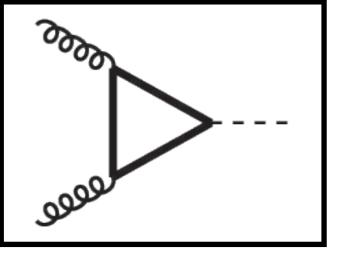


Higgs pt @ N³LL'+NNLO

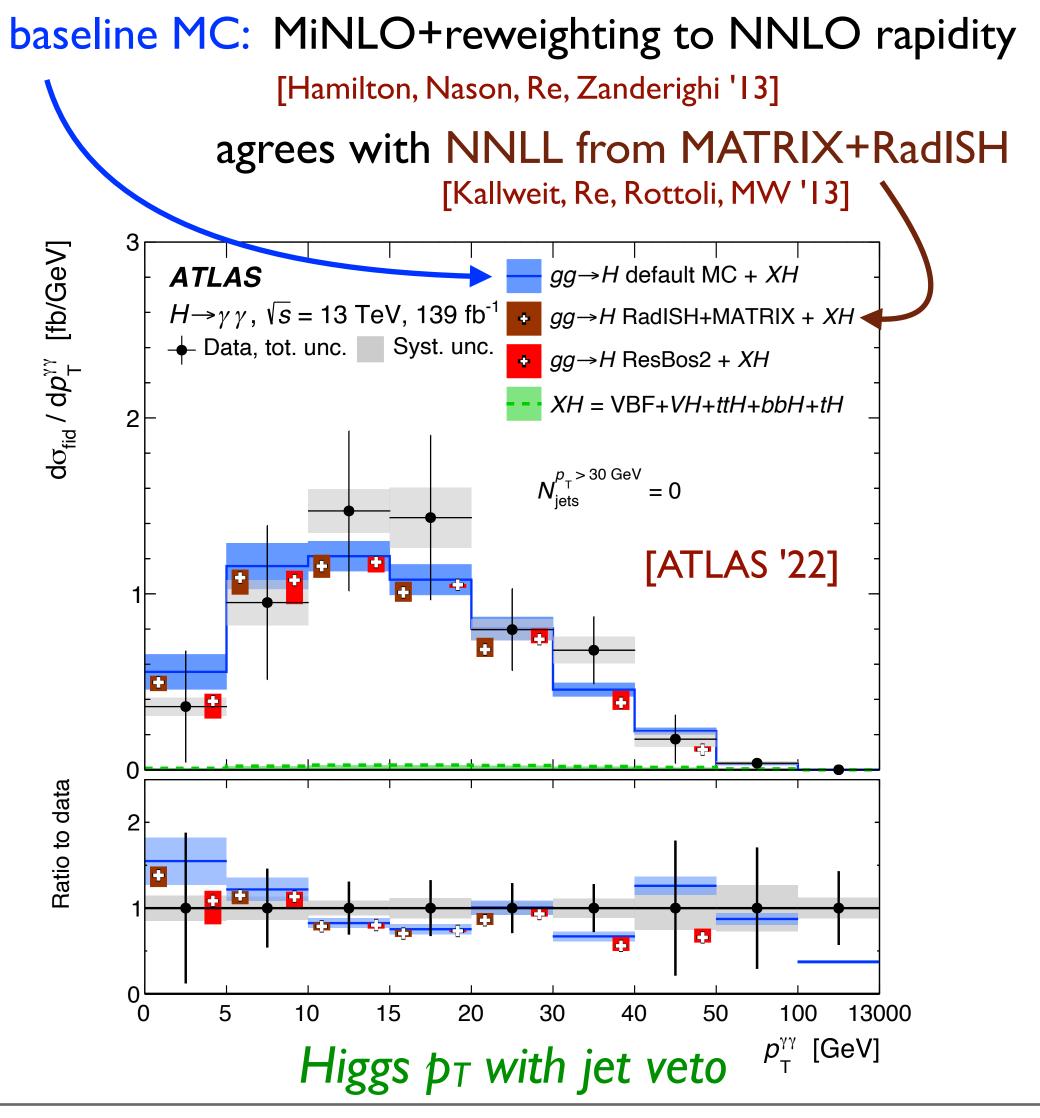






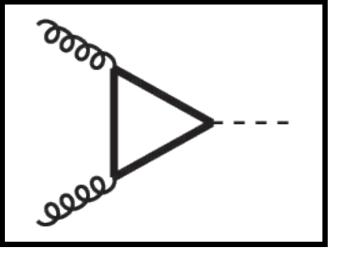




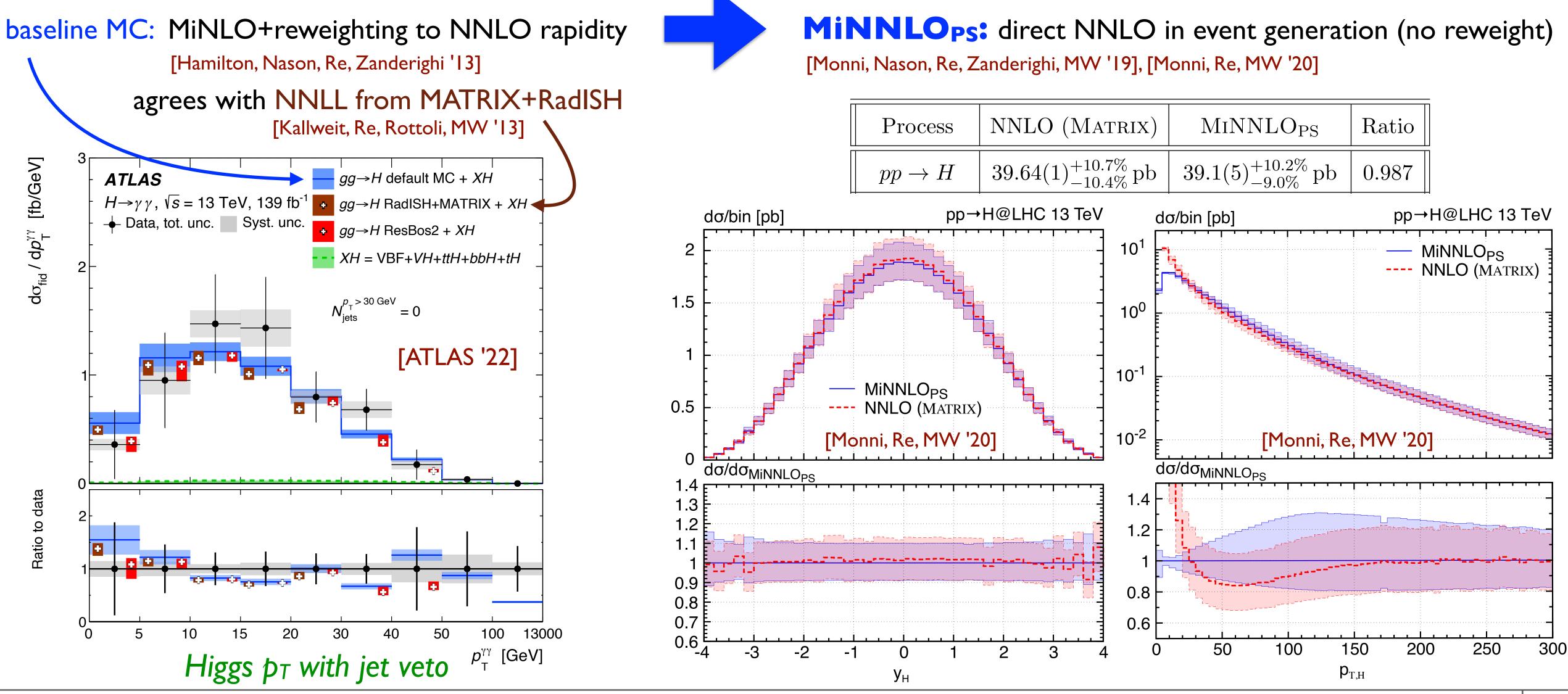


ggF @ NNLO+PS





ggF @ NNLO+PS



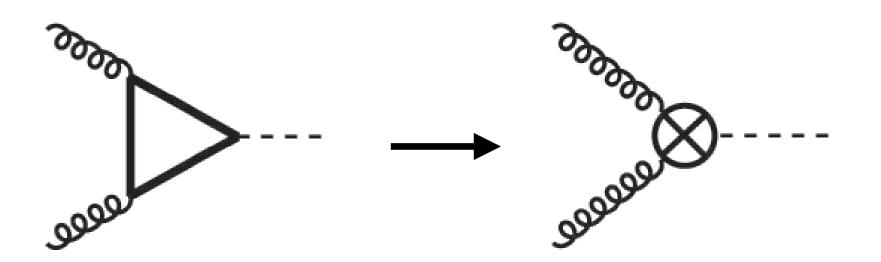
Marius Wiesemann (MPP Munich)



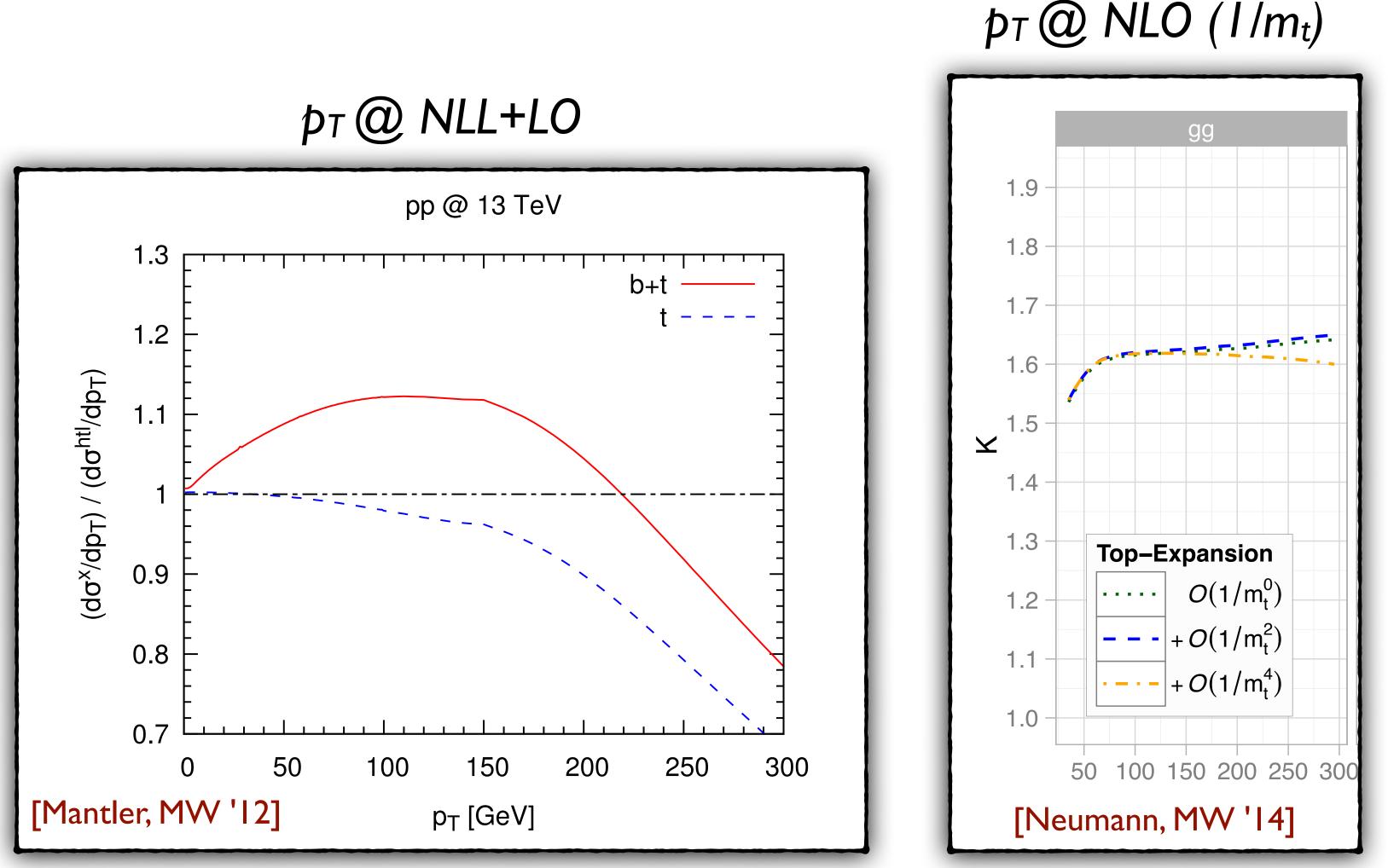
Higgs differential cross sections

April 12th, 2022

All based on HTL approximation



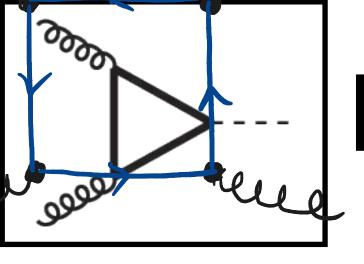
top and bottom mass effects?



Higgs differential cross sections

April 12th, 2022





 $\frac{10^{-2}}{10^{-3}}$ $\frac{10^{-3}}{10^{-4}}$

 $b 10^{-5}$

 10^{-6}

 10^{-7}

2.0

0

 $\frac{10^{-1}}{10^{-1}}$

/LO

NLO

LHC 13 TeV

200

 $\mu = \frac{H_T}{2}$

the full matrix elements respective the virtual contributions of H + 2 jets production are currently not available, nevertheless, their explicit infrared divergence at NLO can be predicted by the Catani Massdirected Structure (μ_R^2 ; p_1^2) and μ_R^2 ; p_2^2) and μ_R^2 ; p_2^2 , μ_R^2 ; $\mu_$

NLO Full

PDF4LHC15 NLO

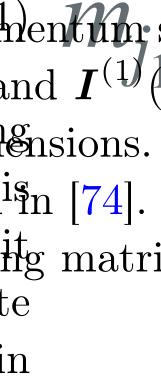
400

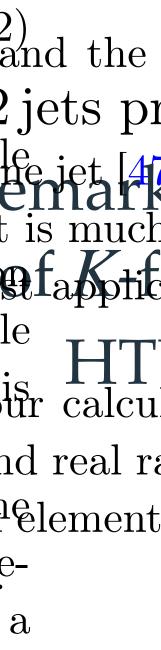
Marius Wiesemann (MPP Munifinite top-quark mass for progestifferential jrarecomputed exactly using SECDECA3ril 12th, 2022

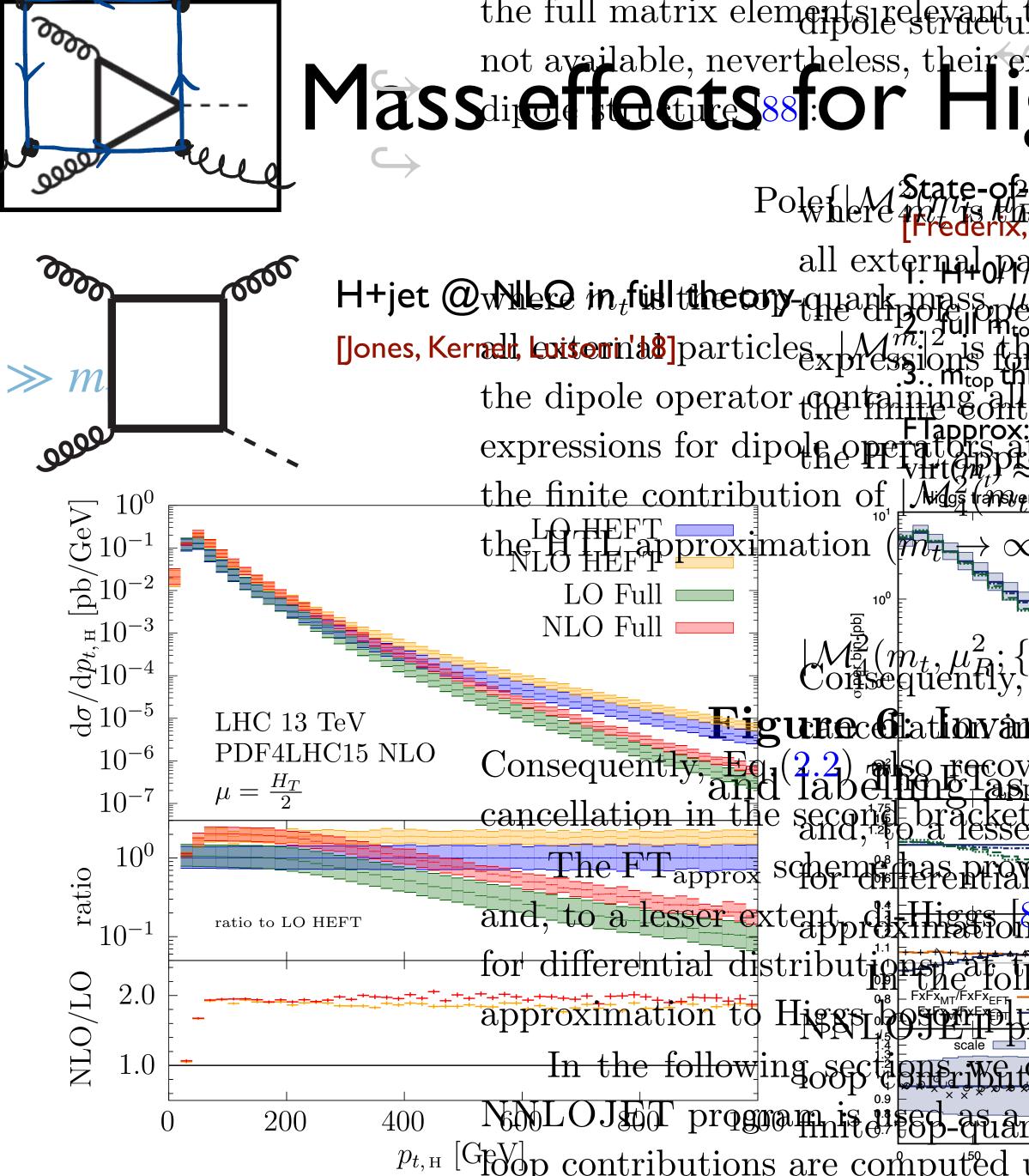
Pole $here 4 \pi \eta$ is the top) $|\eta\rangle$ ark mass, μ_R^2 , is the pole horizontal satisfies $|\theta\rangle$ is the momentum. all external particles, $|\mathcal{M}_n^m|^2$ is the matrix element with n legs and m loops and $I^{(1)}$ H+jet @while@in_fieldtheory-quarkpores.perator the renormalization scale R{Plviergences mentup set regardingnisms. [Jones, Kernald, Luisoni' 18] particles M_{ssions}^{m} [2 is the instrict sleafed by the difference with a less matrix elements with a less matrix element with a less matrix element [1]. the dipole operator f_{1} f_{1} f_{1} f_{2} f_{1} f_{2} f_{2} expressions for dipole operators at samated matrix element level can be found in [74]. We estimate the finite contribution of $|\mathcal{M}_4^2(m_t, \mu_R^2; \{p\})|^2$ by re-weighting the corresponding matrix element in $\begin{array}{c} \text{the LG HEFT}_{\text{NLO HEFT}} \text{provimation } (m_t \to \infty) \text{ using:} \\ \text{LO Full} \end{array} \\ \begin{array}{c} \mathcal{M}_4^2(m_t, \mu_R^2; \{p\})|^2 \to |\mathcal{M}_4^1(\infty, \mu_R^2; \{p\})|^2 \frac{|\mathcal{M}_4^1(m_t; \{p\})|^2}{|\mathcal{M}_4^0(\infty; \{p\})|^2}. \end{array}$

 $\left| \mathcal{M}_{4}^{2}(m_{t}, \mu_{R}^{2}; \{p\}) \right|^{2} \xrightarrow{} |\mathcal{M}_{4}^{1}(\infty, \mu_{R}^{2}; \{p\})|^{2} \frac{|\mathcal{M}_{4}^{1}(m_{t}; \{p\})|^{2}}{|\mathcal{M}_{4}^{1}(\mathfrak{st}; p)|^{2}} \frac{|\mathcal{M}_{4}^{1}(m_{t}; \{p\})|^{2}}{|\mathcal{M}_{4}^{1}(\mathfrak{st}; p)|^{2}} \right|^{2} \xrightarrow{} |\mathcal{M}_{4}^{1}(\mathfrak{st}; p)|^{2} \frac{|\mathcal{M}_{4}^{1}(m_{t}; \{p\})|^{2}}{|\mathcal{M}_{4}^{1}(\mathfrak{st}; p)|^{2}}$ Figure 6 Lation variable temperate bilisteril but Eq. (2.0) the objectically strengined $\mathrm{H}+2\,\mathrm{jets}$ pi Consequently, Eq. (2.2) also recovers the explicit pole structure in Eq. (2.1) and the explicit pole iet [4] cancellation in the second bracket of Eq. 3. is automatically retained wever in the latter case, it is much The FT approx schementere prave is for a kapting the time for Higgs phier on it present the first of the firs and, to a lesser extent dia Higgs of the production of the wey for the latter case at it is out choices reliable for differential distributions) at the LHC sections we document and present the first application of this calcu approximation to Higgs bogen phis two jet areduction at NLOvin event generator and all Born and real ra In the following sections we document the details himple net of 92.2. The calculations at The lement NALOJET program is used as a range level seen generater and all Bernand usal reliation one $p_{t,H}$ [GROP contributions are computed using OPENLOOPS2.2. The two-loop matrix elements involving a







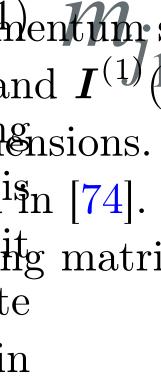


Marius Wiesemann (MPP Munifinite top-quark mass for progestifferential jrarecomputed exactly using SECDECA3ril 12th, 2022

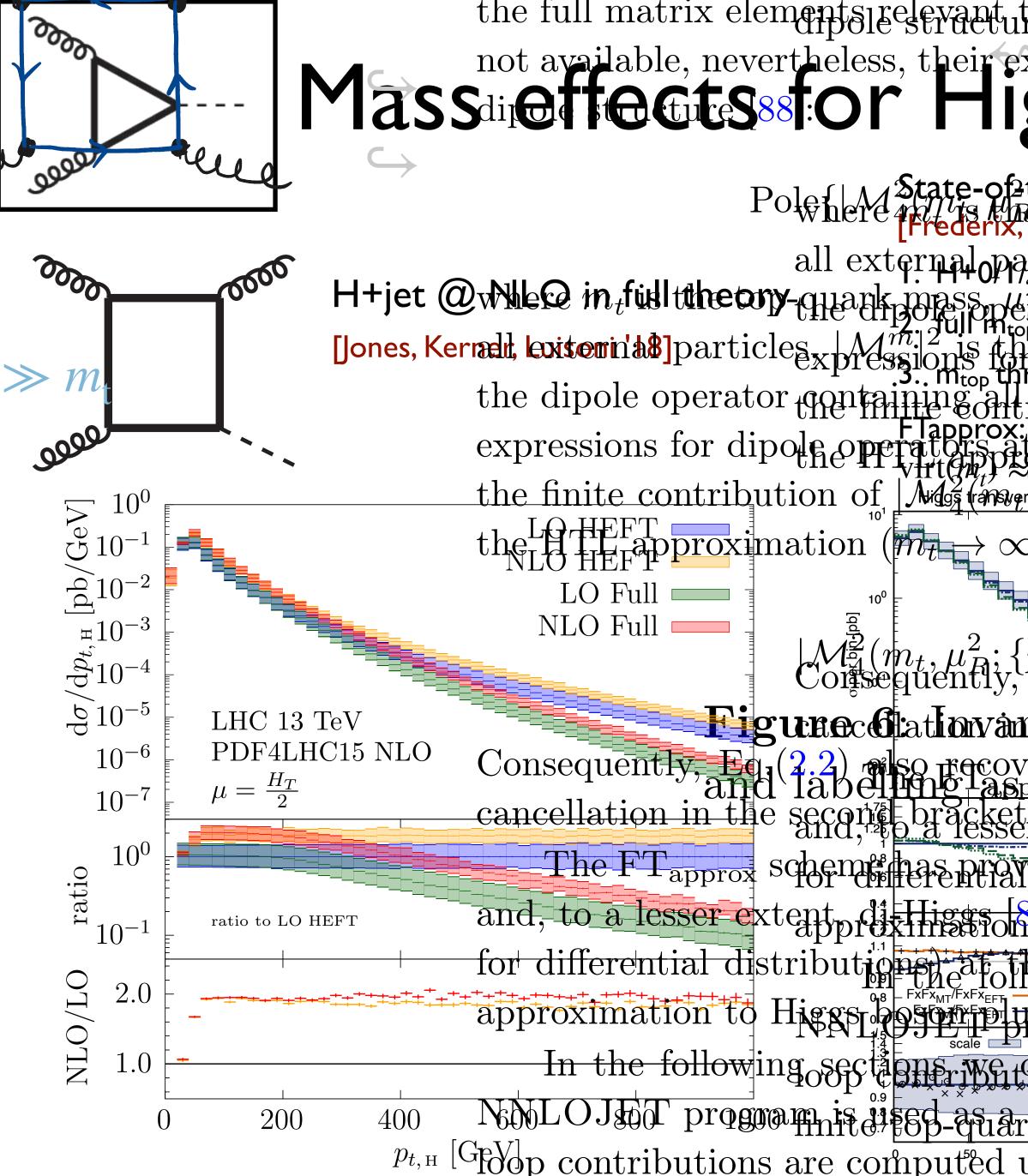
the full matrix elements respective the virtual contributions of H + 2 jets production are currently not available, nevertheless, their explicit infrared divergence at NLO can be predicted by the Catani Massdirected Structure (μ_R^2 ; μ Pole here $\frac{\text{State-of-the-art mass offects}}{\text{Model}} = \frac{1}{2} \frac{$ all external particles MO+PS is the matrix element with n legs and m loops and $I^{(1)}$ H+jet @while@in_fieldtheony-quark mass neration for H=0-jet explication for H= [Jones, Kernelit, kvistorin'a8] particles $M_{sion}^{\hat{m}}$ is the matrix element with n less and $M_{sion}^{\hat{m}}$ and $M_{sion}^{$ the dipole operator containing antrespicit by divergences in despace-time dimensions corresponding matrix elements in the divergences in despace-time dimensions corresponding matrix elements in the divergences in despace-time dimensions corresponding matrix elements in the divergences in despace-time dimensions corresponding matrix elements in the divergences in despace-time dimensions corresponding matrix elements in the divergences in despace-time dimensions corresponding matrix elements in the divergences in despace-time dimensions corresponding matrix elements in the divergences in despace-time dimensions in the divergences in despace-time dimensions in the dimensions of the despace of the divergences in the dimensions of the despace of the d the finite contribution of $|M_{p}|$ (answerse $|t_{p}|$) $|^{2}$ by re-weighting the corresponding matrix element in $the \overset{\text{LEFT}}{\text{HEFT}} \underset{\text{HEFT}}{\text{HEFT}} \underset{\text{Freed}}{\text{proving}} \underset{\text{HEFT}}{\text{heft}} \underset{\text{Freed}}{\text{heft}} \underset{\text{HEFT}}{\text{heft}} \underset{\text{HEFT}}{\overset{\text{Freed}}{\text{heft}}} \underset{\text{HEFT}}{\overset{\text{HEFT}}{\overset{\text{HEFT}}}} \underset{\text{HEFT}}{\overset{\text{HEFT}}{\overset{\text{HEFT}}{\text{heft}}}} \underset{\text{HEFT}}{\overset{\text{HEFT}}}{\overset{\text{HEFT}}{\overset{\text{HEFT}}{\overset{\text{HEFT}}}{\overset{\text{HEF$ $\overline{|\mathcal{M}_4^0(\infty;\{p\})|^2}$. $\mathcal{M}_{\mathcal{A}}^{\overline{\mathbf{a}}}(m_t,\mu_R^2;\{p\})|^2 \xrightarrow{\mathcal{M}_{\mathcal{A}}} \mathcal{M}_{\mathcal{A}}^1(\infty,\mu_R^2;\{p\})|^2 \frac{|\mathcal{M}_{\mathcal{A}}^1(m_t;\{p\})|^2}{|\mathcal{M}_{\mathcal{A}}^1(m_t;\{p\})|^2} \xrightarrow{\mathcal{M}_{\mathcal{A}}^1(m_t;\{p\})|^2}{|\mathcal{M}_{\mathcal{A}}^1(\mathbf{cit};\mathbf{p})|^2}$ Figure 6 at invariants mass base to the top of the thin set is tending the H + 2 jets p Consequently, Eq. (2.2) also recovers the explicit pole structure in Eq. (2.1) and the explicit pole jet [4] cancellation in the second bracket of Eq. 2.3) is automatically retained wever in the latter case, it is much The FT approx scheme has pray of the parkably reliable we Higgs phene and present other the factor factor and, to a lesser extent of Higgs 189 bridges besch prever in the platter case at it is out choices reliable for differential distribution of the fill sections we document and present the first application of this calcu

In the following sections were as the detailed in plenetation 2.2. The calculations at The lement NALOJEOT program is is sed as a rearrant for povent generater and alle Bernaud usal gestietion one $p_{t,H}$ [Group contributions are computed using 'OPENLOOPS2".2_{p-(H)} two-loop matrix elements involving a



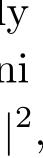


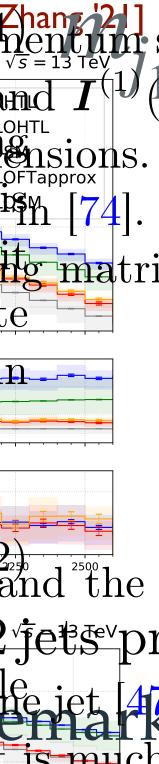


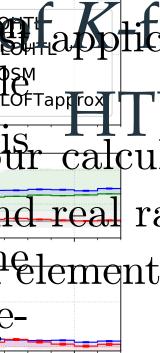


Marius Wiesemann (MPP Munifinite top-quark mass for progestiffential jnare computed exactly using SECDECA3 il 12th, 2022

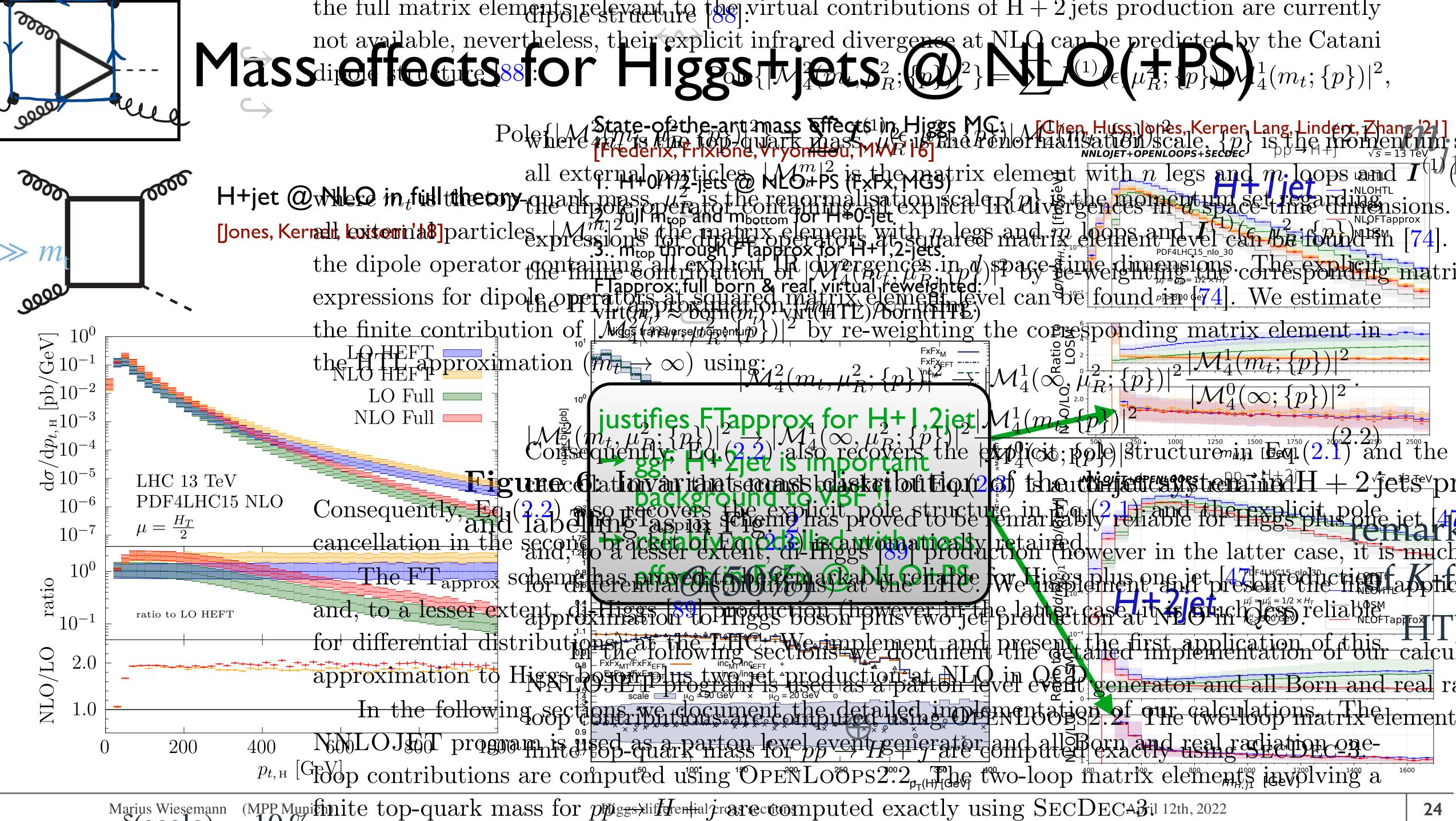
the full matrix elements represented the two virtual contributions of H + 2 jets production are currently not available, nevertheless, their explicit infrared divergence at NLO can be predicted by the Catani Massdiette fields and the field of the field State-of-the-art mass affects in Higgs MC: (Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang 21) And is the top-quark mass with the station scale. { p} is the mornalisation scale. { p} is the morner uni-frederix, Frixione, Vryonidou, MWR 16 all external particles MO+PS is the matrix element with n legs and η loops and $I^{(1)}$ H+jet @while@in_fuil theony-quark mass derais the renormalisation is all the renormalisation is all the renormalisation is the renormalized is the renormalisation is the renormalisati [Jones, Kernedit, Lexistorin'a8] particles [Mail 2] is the matrix element, with nales and \bar{n}_{\pm} [ones, Kernedit, Lexistorin'a8] particles [Mail 2] is the matrix element, with nales and \bar{n}_{\pm} [ones matrix of the matrix element with nales and \bar{n}_{\pm} [ones matrix of the matrix element with nales and \bar{n}_{\pm} [ones matrix element]. [74] the dipole operator (operating and reversed) of the divergences in a) space fine dimensions. The point in a matrix elements in a) space fine dimensions. The point is corresponding matrix elements in a real, virtual reverse for the found reverse of the found of the operators at some of the matrix elements in the found of the operators at some of the matrix elements in the found of the operators at some of the operators at some of the operators o the finite contribution of [Adag (analy self on equip)]² by re-weighting the corresponding matrix element in $\begin{array}{c} \text{the}_{\text{LO}} \stackrel{\text{FEFT}}{\text{HEFT}} \text{provimation} & (\overrightarrow{m_t} \rightarrow \infty) \text{ using:} \\ \mathcal{M}_4^2(m_t, \mu_R^2; \{p\}) \stackrel{\text{FEFX}}{\xrightarrow{\text{FXFX}}} = \left[\mathcal{M}_4^1(\infty, \mu_R^2; \{p\}) | 2 + \mathcal{M}_4^1(m_t; \{p\}) | 2 + \mathcal{$ $|\mathcal{M}_4^0(\infty;\{p\})|^2$ $\mathcal{M}_{4}^{\overline{2}}(m_{t},\mu_{t}^{2};\{p\})^{2} \rightarrow \mathcal{M}_{4}^{1}(\infty,\mu_{t}^{2};\{p\})^{2} \rightarrow \mathcal{M}_{4}^{1}(m_{t}^{2};\{p\})^{2} \rightarrow \mathcal{M}_{4}^{1}(m_{t}^{2};\{p\})$ Figure dation in the second state of the difference of the term H + 2fetsConsequently, Eq.(2.2) also recovers the explicit pole structure in Eq.(2.1) and the explicit pole iet 4 cancellation in the second bracket of Eq. 2.3. is automatically retained wever in the latter case, it is much The FT approx scheme has pray of the parkably reliable we Higgs phene of the resent of the riggs and the sent of the riggs and the riggs and the riggs and the riggs and the riggs are riggs and the riggs and the riggs are riggs and the riggs and the riggs are riggs and the riggs are riggs and, to a lesser extent of Higgs 189 bridges bason provided productions at the start of the star for differential distribution of the following sections we document and present the first application of this calcu approximation to Hissiphies two internet approximation is all Born and real rate of the production of the In the following sections were of the detailed in plenetoties 2.2. The calculations at The lement NALOJET program is is fold as a rearrant level over generater and all part is a station one $p_{t,H}$ [GEV] contributions are computed using OPENLOOPS2.2 two-loop matrix elements involving a

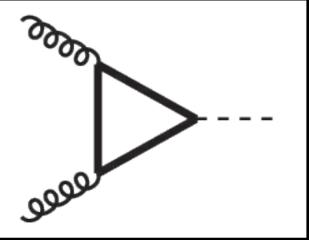












rather than (Kezekos, sectioder, Keappelve Niggetiedte 20] This qqhas the additional advantage that ultraviolet and infrared divergences in the form of $1/\epsilon^w$ poles in the dimensional 3 the NNLO level. Hence, for $\frac{\sigma_{\text{NNLO}}}{\sigma_{\text{HEFT}}} = \frac{\sigma_{\text{HEFT}}}{\sigma_{\text{HEFT}}} = \frac{\sigma_{\text{NNLO}}}{\sigma_{\text{HEFT}}} = \frac{\sigma_$ egrate them in order to obtain ASTER Smannes as the state of the +0.62-181397 heavy-top. 1921 t=ig. expected total date: the volume of -4the $.0667 \pm 0.0007$ -0.10s = 13 TeV. +0.62-16(5)termoin2thenspuare brackets of 25q. (2) HEF Ender to cancel 6 -1516.30 he 1R16 ivegreences with the 3029 ble real emoission ± 810023 -0.26stable Monte Carlehates ration 17 de phase space interrensional in the fundre Dextension to differential & Maganda NAL Other possible April 12th, 2022

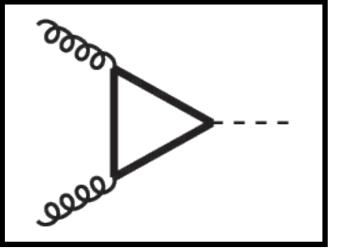
inclusive ggF^{σ} in full theory includes full mt lr, 29, 3140000 ton here onet, of ult, may hy 2140000 for 444 jet land full mt 1-loop for H+2jet he regulated $\mathfrak{gg}_{nplitudes, 16.30}$ + 19.64 + 8,76 \mathfrak{f}_{κ} / \mathfrak{h}_{κ} + 0.0345 in the C++ library + 0.0020 n) threshold for interme this intraction the mathematical and the second parameters of the second parameters is the second parameters is the second parameters of the second parameters of the second parameters is the second parameters of the seco inematics is parameterized Munich separately it Adding it at the out put the Stripper Hence. for

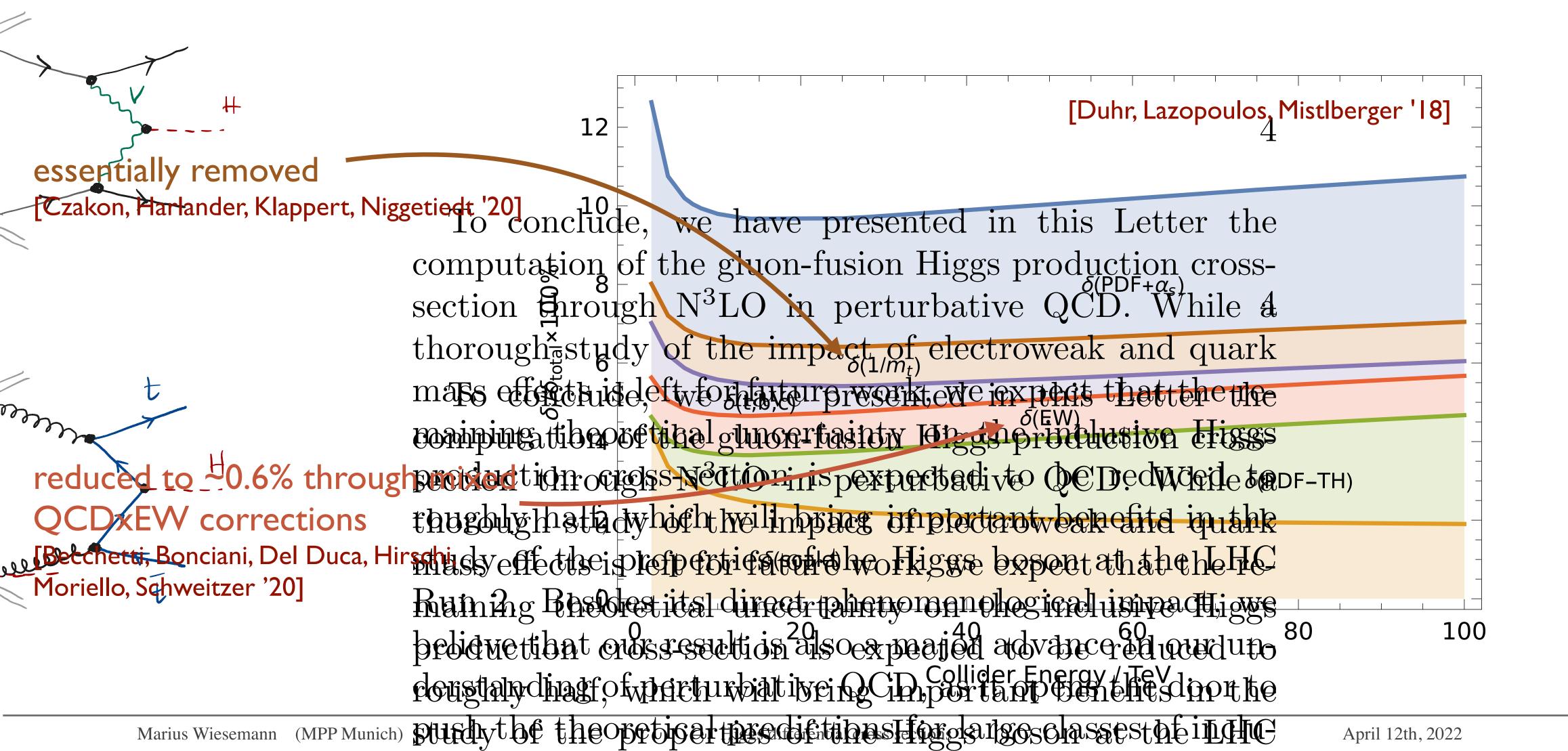
	singularities first appear at
channel	$\sigma_{\text{Hexam}}^{\text{NNDON}}$ the NLO contribute
	$\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s^3) + $
	This necessary to actually in This delay of the appearance
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qq	10.01 ± 0.04 troution small Fwe source the
total	7.39 + 9.15 + 4.18 - 0.0000000000000000000000000000000000
	methodiseusings anecased of

ed in Eq. (2), for the pro- $\rightarrow qH$ (second row) and nto the region below (left ggs-field vacuum expecta-The renormalization scale

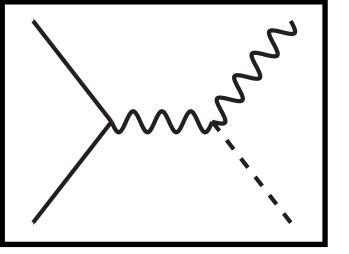


ggF error budget of inclusive XS







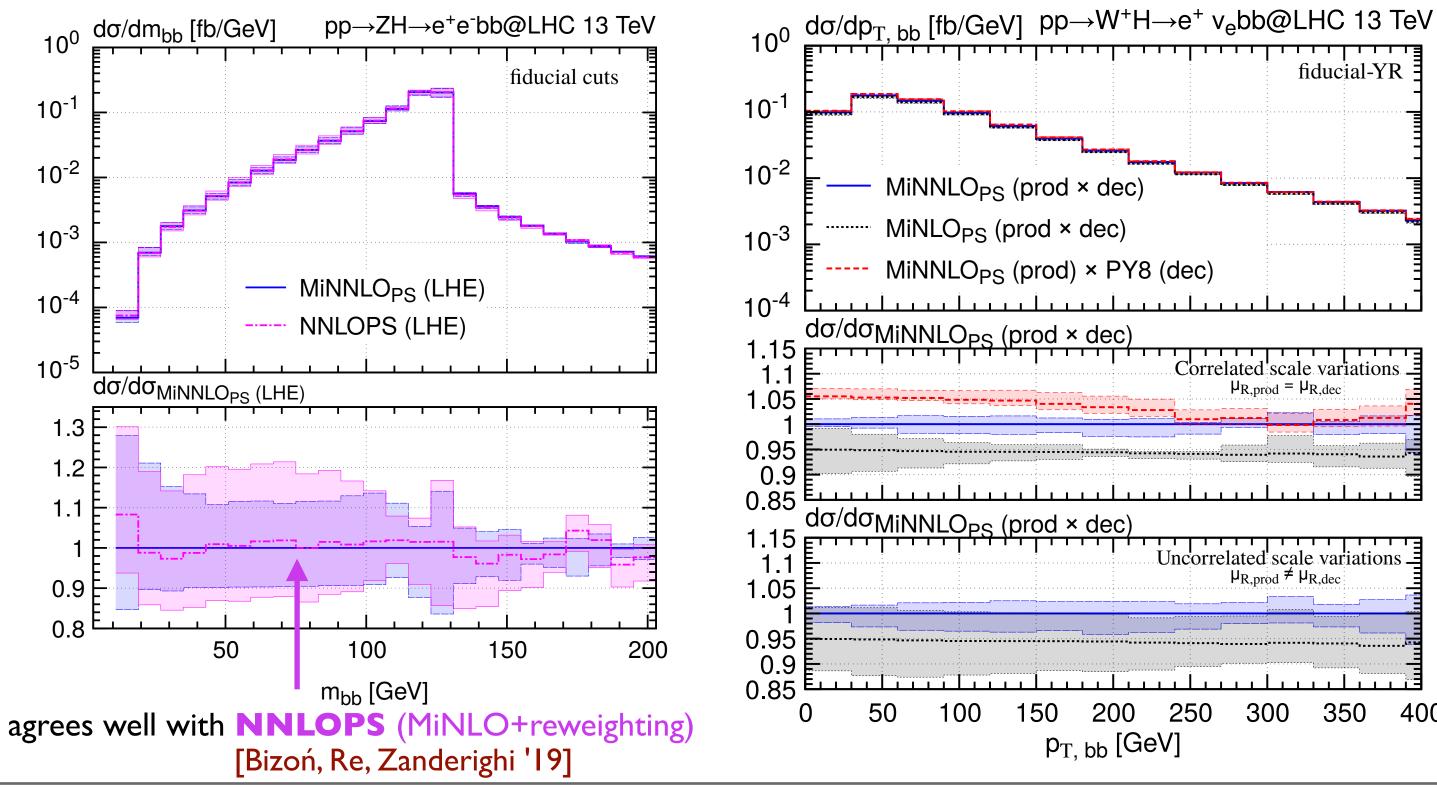


$VH \times H \rightarrow bb @ NNLO+PS$

* NNLO+PS accuracy in both production and decay see also [Alioli et al. '19] see also [Alioli et al. '20]

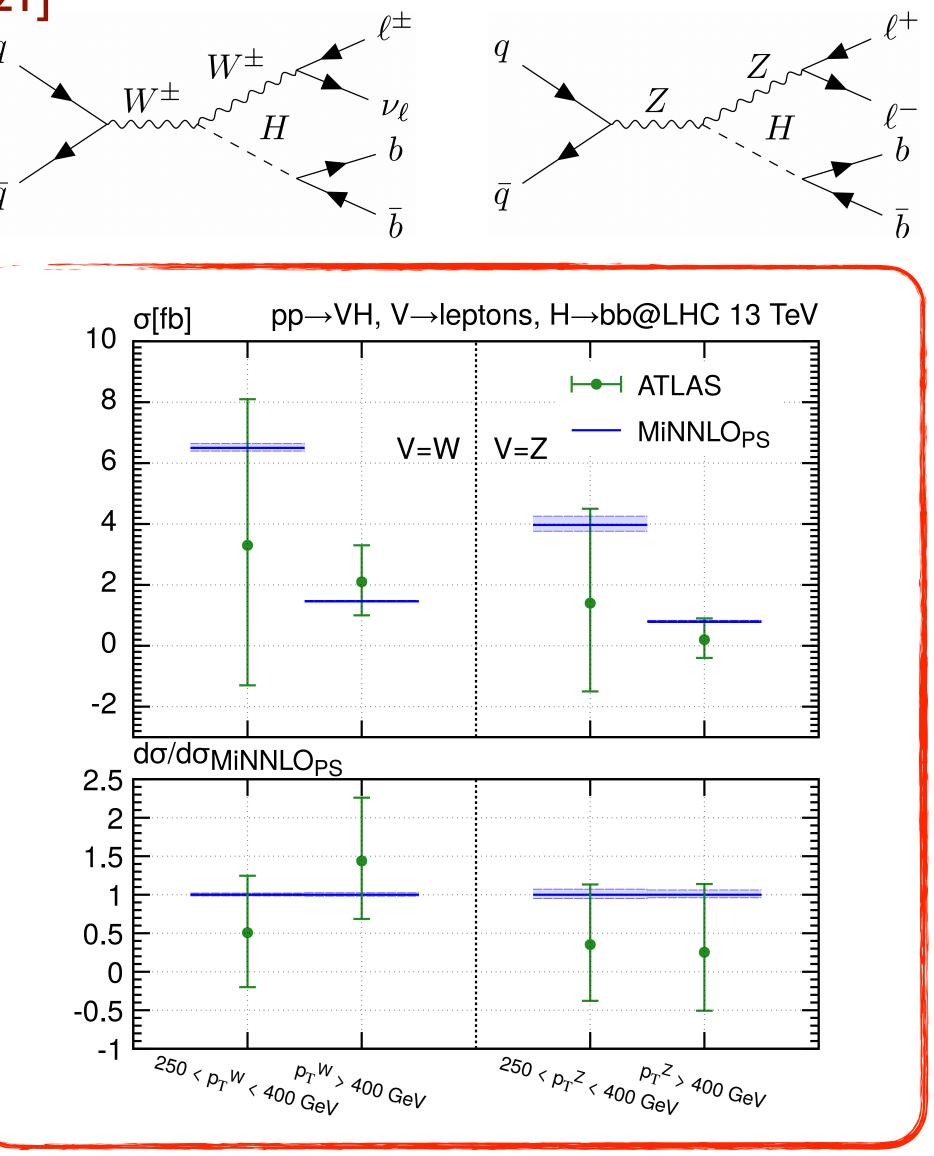
* includes NNLO directly in event generation through **MiNNLO_{PS} method** [Monni, Nason, Re, Zanderighi, MW '19], [Monni, Re, MW '20]

 \bigstar main production channel to observe $H \rightarrow bb$ (largest branching fraction)



[Zanoli, Chiesa, Re, MW, Zanderighi '21]

fiducial-YR $\mu_{R,prod} = \mu_{R,dec}$ $\mu_{R,prod} \neq \mu_{R,dec}$

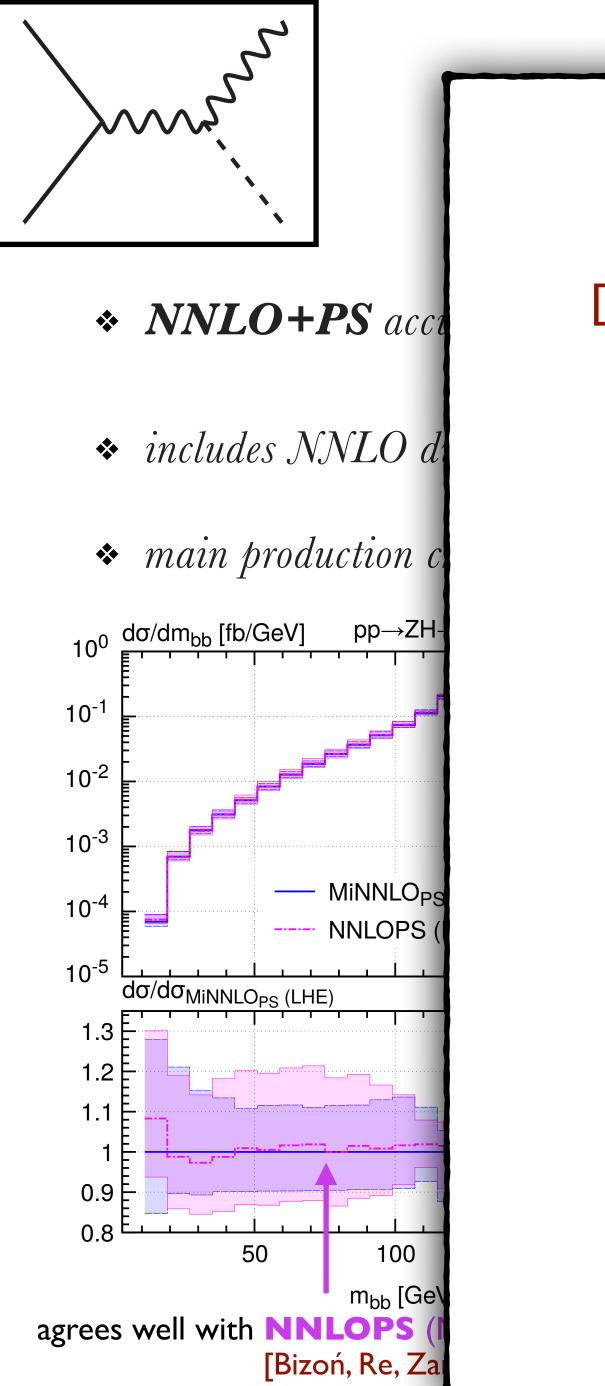


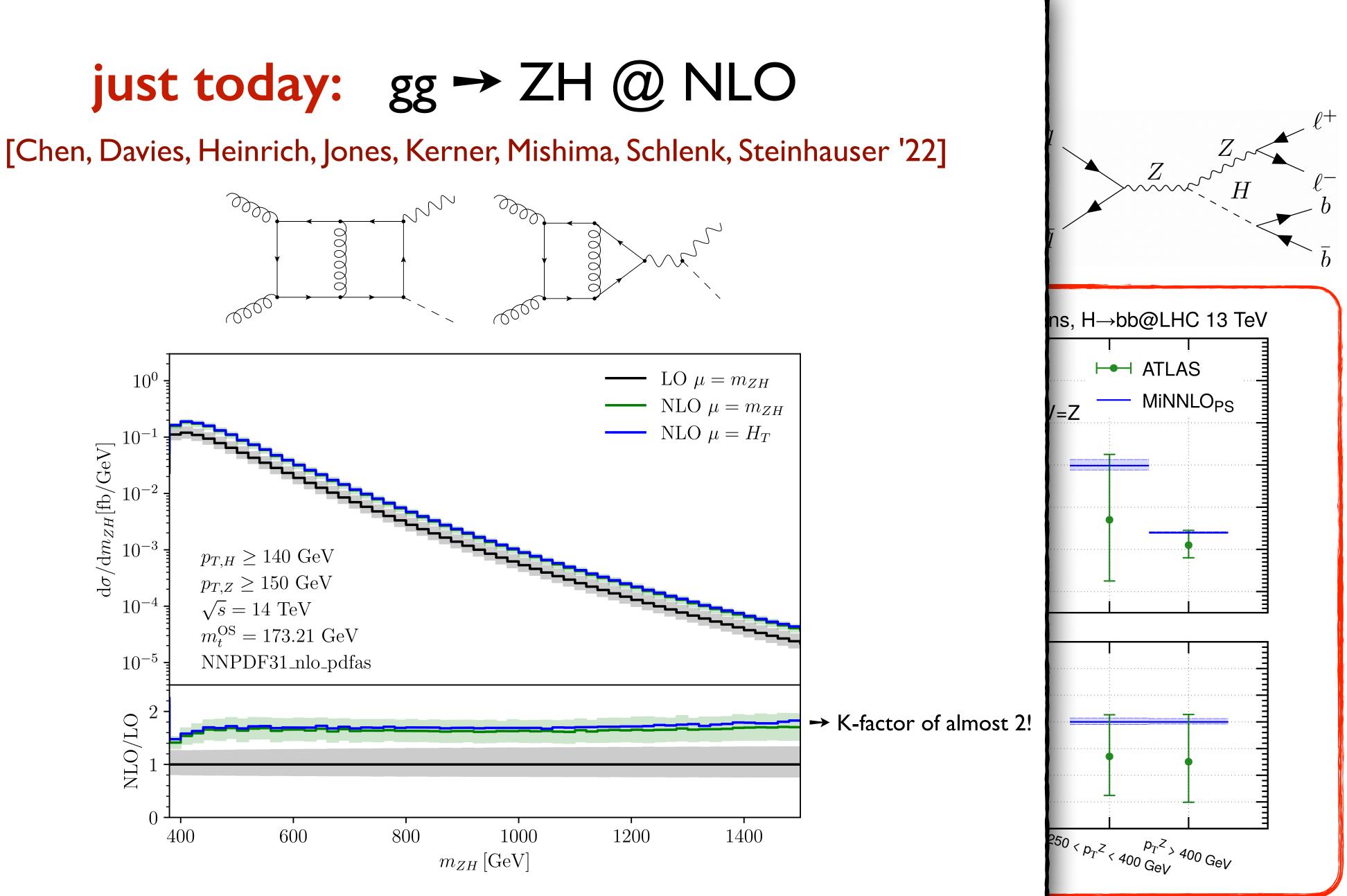
Higgs differential cross sections

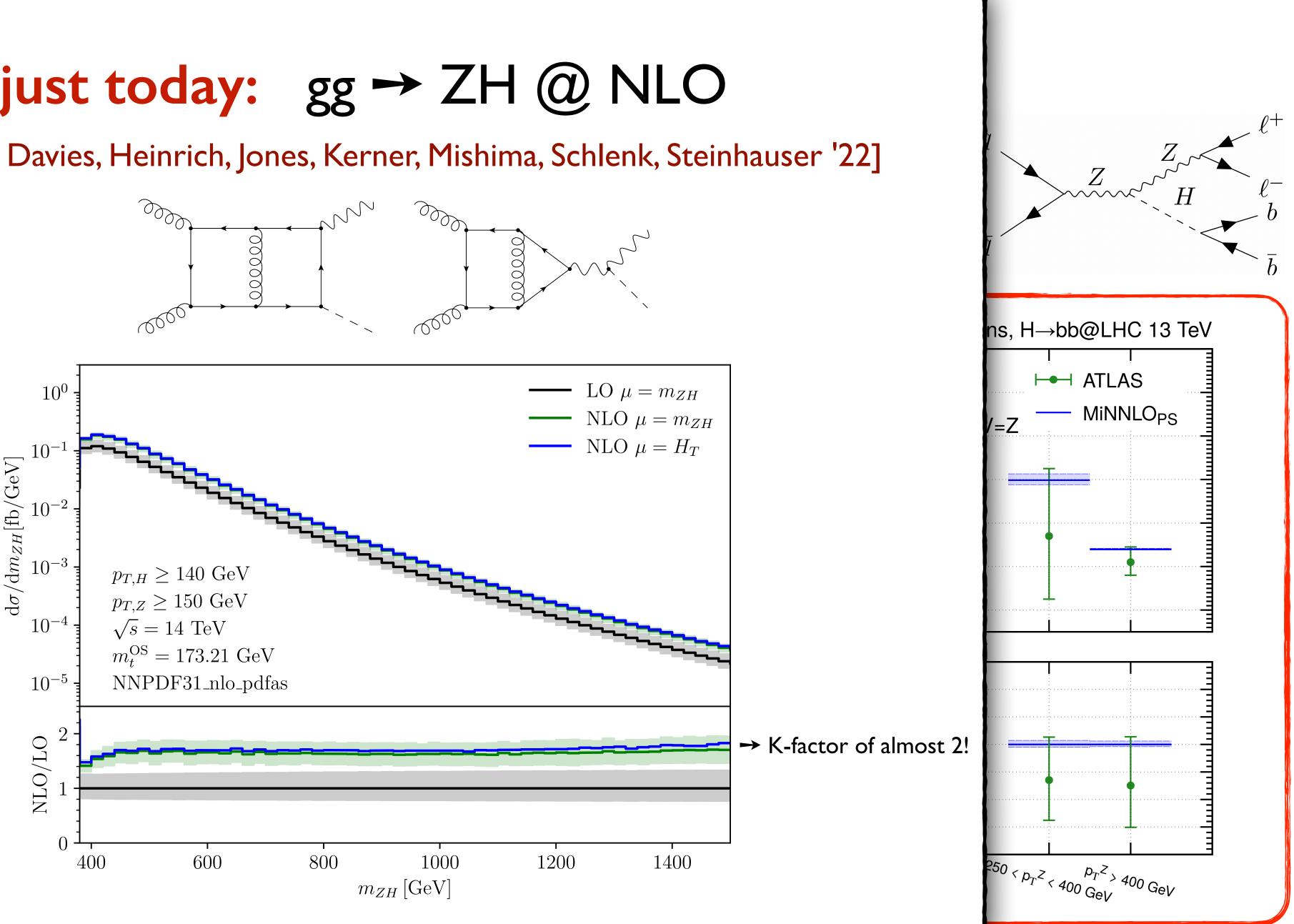
300

350

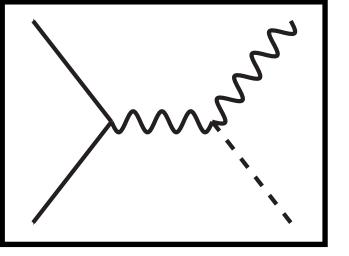
400









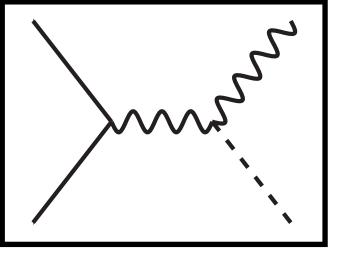


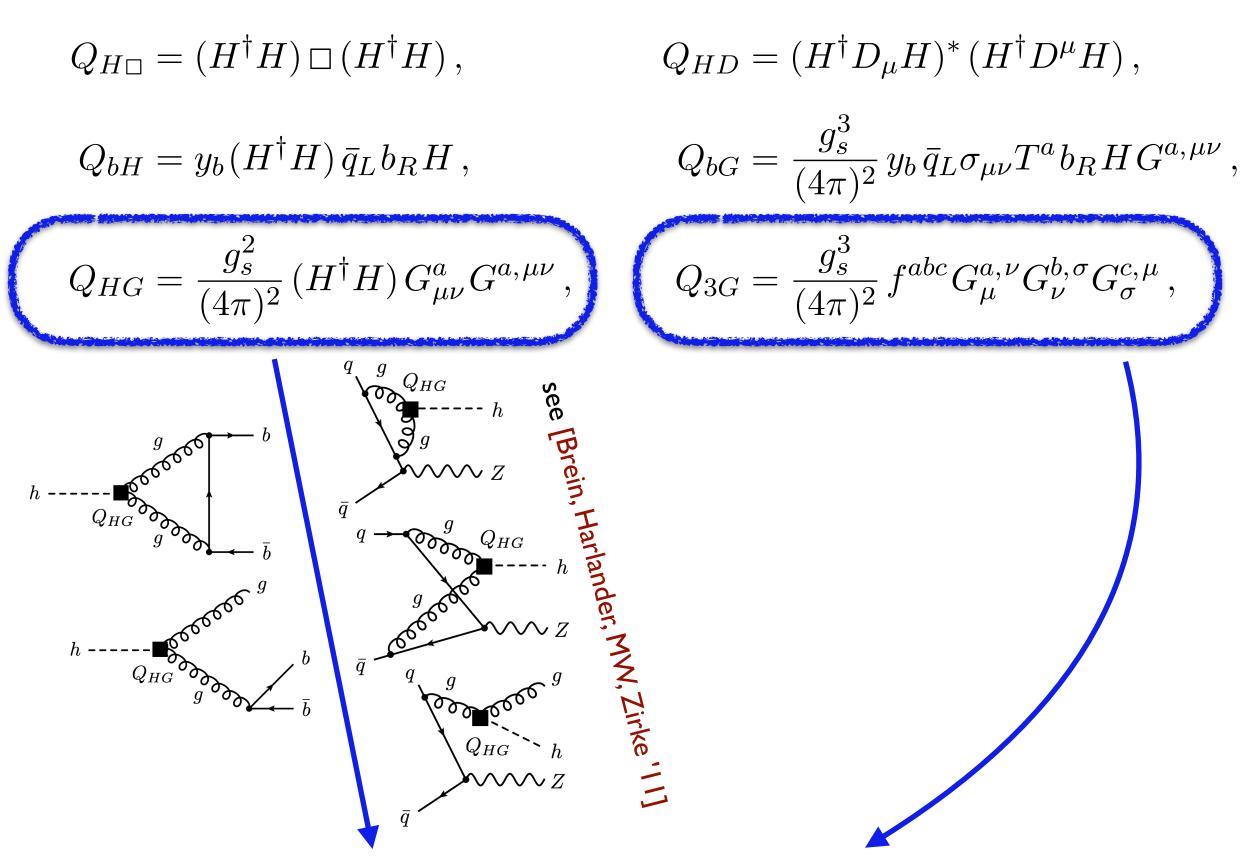
[Haisch, Scott, MW, Zanderighi, Zanoli '22]

$$Q_{H\Box} = (H^{\dagger}H) \Box (H^{\dagger}H),$$
$$Q_{bH} = y_b (H^{\dagger}H) \bar{q}_L b_R H,$$
$$Q_{HG} = \frac{g_s^2}{(4\pi)^2} (H^{\dagger}H) G^a_{\mu\nu} G^{a,\mu\nu}$$

 $Q_{HD} = (H^{\dagger}D_{\mu}H)^* (H^{\dagger}D^{\mu}H) ,$ $Q_{bG} = \frac{g_s^3}{(4\pi)^2} y_b \bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu} ,$ $^{\mu\nu}, \qquad Q_{3G} = \frac{g_s^3}{(4\pi)^2} f^{abc} G^{a,\nu}_{\mu} G^{b,\sigma}_{\nu} G^{c,\mu}_{\sigma},$







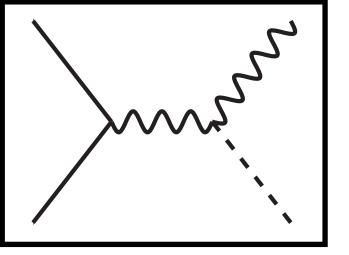
negligible impact already with current constraints

[Haisch, Scott, MW, Zanderighi, Zanoli '22]

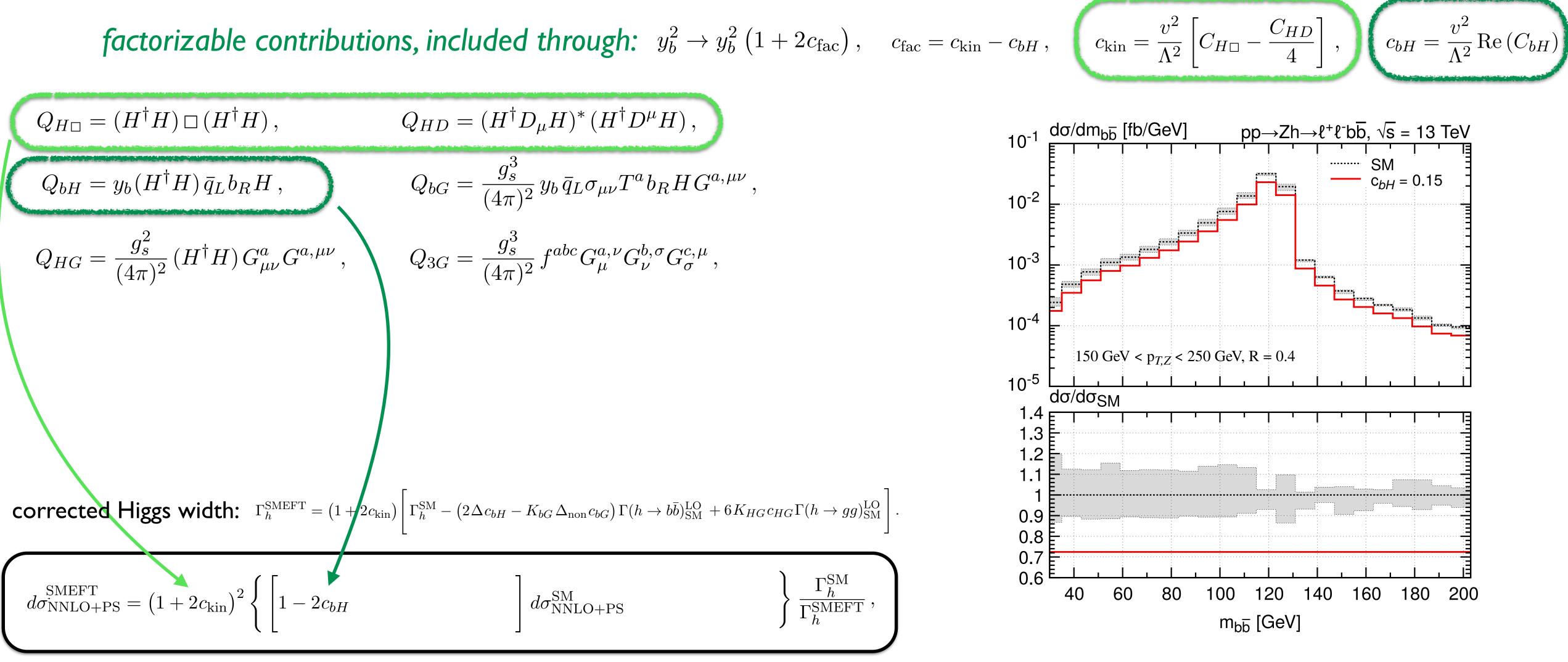


Higgs differential cross sections

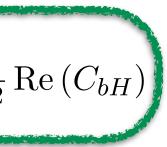




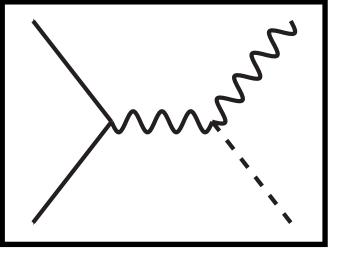
[Haisch, Scott, MW, Zanderighi, Zanoli '22]



Higgs differential cross sections

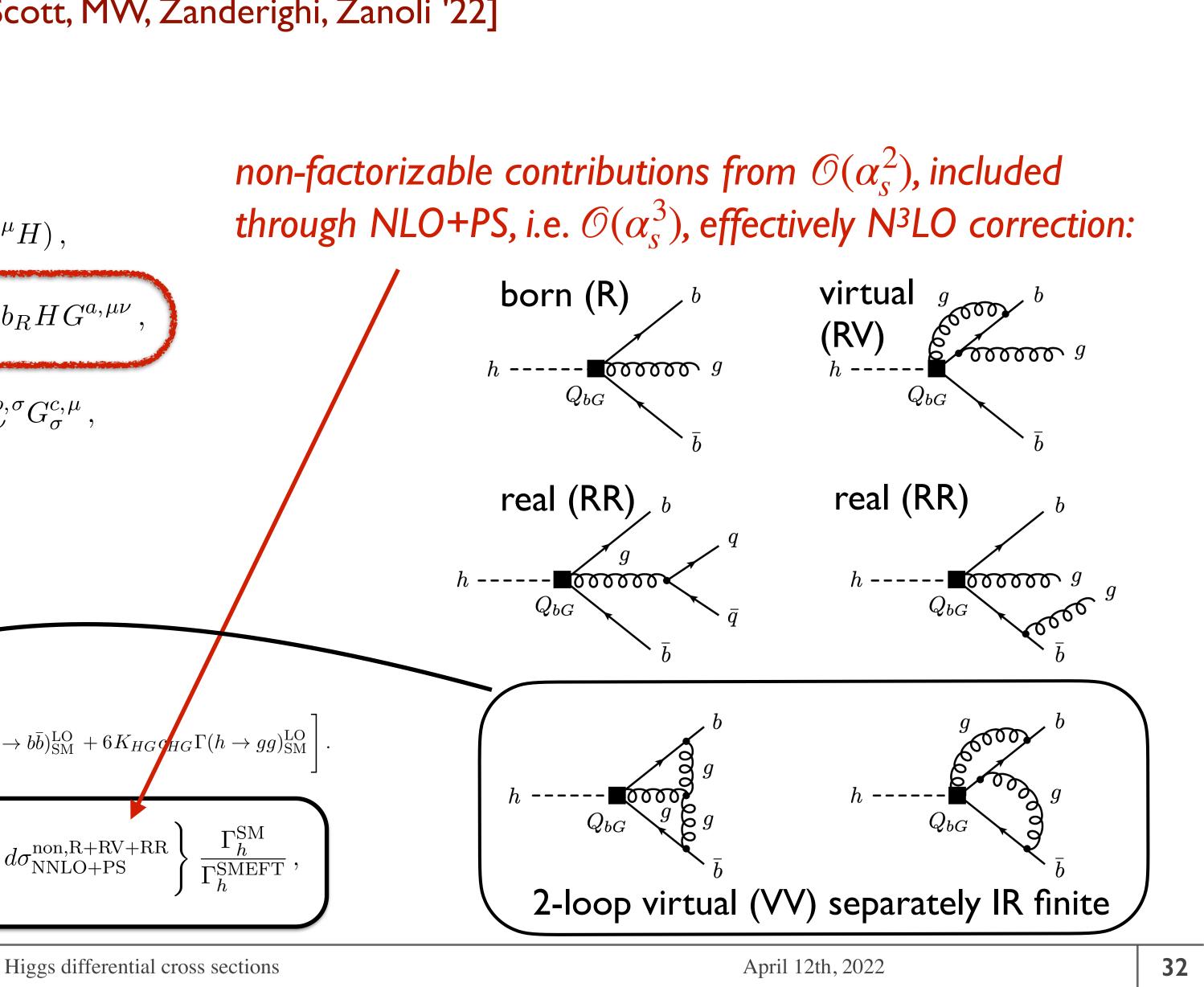


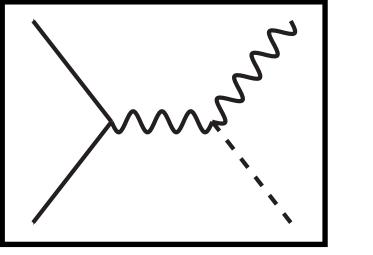




[Haisch, Scott, MW, Zanderighi, Zanoli '22]

$$Q_{H\Box} = (H^{\dagger}H) \Box (H^{\dagger}H), \qquad Q_{HD} = (H^{\dagger}D_{\mu}H)^{*} (H^{\dagger}D^{\mu}H), \qquad Q_{bH} = y_{b}(H^{\dagger}H) \bar{q}_{L}b_{R}H, \qquad Q_{bG} = \frac{g_{s}^{3}}{(4\pi)^{2}} y_{b} \bar{q}_{L}\sigma_{\mu\nu}T^{a}b_{R}HG^{a,\mu}, \qquad Q_{BG} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{abc}G^{a,\nu}_{\mu}G^{b,\sigma}G^{c,\mu}, \qquad Q_{3G} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{abc}G^{a,\nu}_{\mu}G^{b,\sigma}_{\nu}G^{c,\mu}, \qquad Q_{3G} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{abc}G^{a,\nu}_{\mu}G^{b,\sigma}_{\nu}G^{c,\mu}_{\nu}, \qquad Q_{3G} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{abc}G^{a,\mu}_{\mu}G^{b,\sigma}_{\nu}G^{c,\mu}_{\nu}, \qquad Q_{3G} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{abc}G^{a,\mu}_{\mu}G^{b,\sigma}_{\nu}G^{c,\mu}_{\nu}, \qquad Q_{3G} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{abc}G^{a,\mu}_{\mu}G^{b,\sigma}_{\nu}G^{c,\mu}_{\nu}, \qquad Q_{3G} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{a,\mu}_{\mu}G^{b,\sigma}_{\nu}G^{c,\mu}_{\mu}G^{c,\mu}_{\mu}G^{c,\mu}_{$$



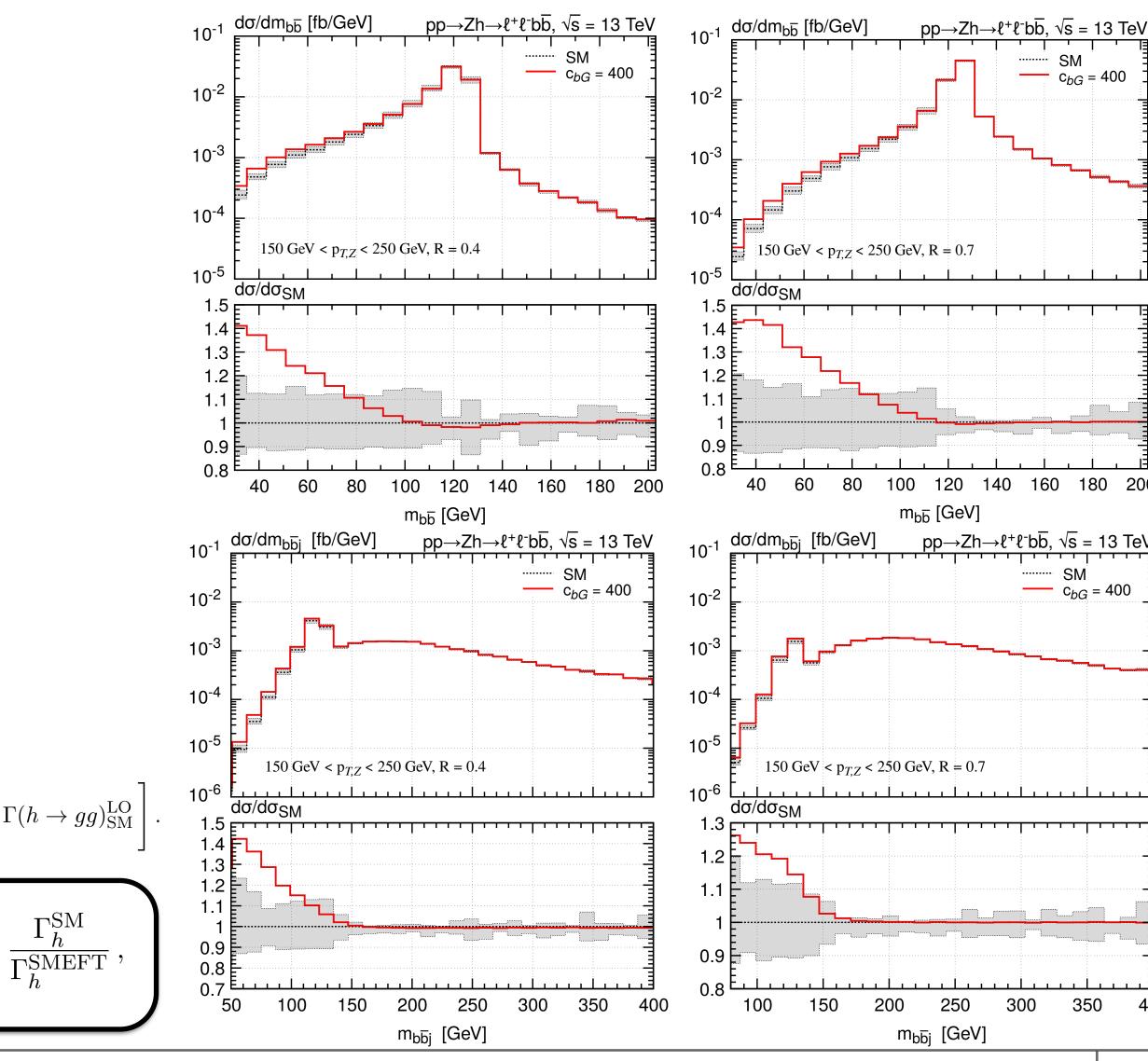


$$\begin{aligned} Q_{H\Box} &= (H^{\dagger}H) \Box (H^{\dagger}H) \,, \\ Q_{bH} &= y_b (H^{\dagger}H) \,\bar{q}_L b_R H \,, \\ Q_{bG} &= \frac{g_s^3}{(4\pi)^2} \, y_b \, \bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu} \\ Q_{HG} &= \frac{g_s^2}{(4\pi)^2} \, (H^{\dagger}H) \, G^a_{\mu\nu} G^{a,\mu\nu} \,, \end{aligned} \qquad \begin{aligned} Q_{HD} &= (H^{\dagger}D_{\mu}H)^* \, (H^{\dagger}D^{\mu}H) \,, \\ Q_{bG} &= \frac{g_s^3}{(4\pi)^2} \, y_b \, \bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu} \\ Q_{3G} &= \frac{g_s^3}{(4\pi)^2} \, f^{abc} \, G^{a,\nu}_{\mu} G^{b,\sigma}_{\nu} G^{c,\mu}_{\sigma} \,, \end{aligned}$$

corrected Higgs width: $\Gamma_h^{\text{SMEFT}} = (1 + 2c_{\text{kin}})$ $\left| \Gamma_h^{\rm SM} - \left(2\Delta c_{bH} - K_{bG}\Delta_{\rm non}c_{bG} \right) \Gamma(h \to b\bar{b})_{\rm SM}^{\rm LO} + 6K_{HG}c_{HG}\Gamma(h \to gg)_{\rm SM}^{\rm LO} \right|$

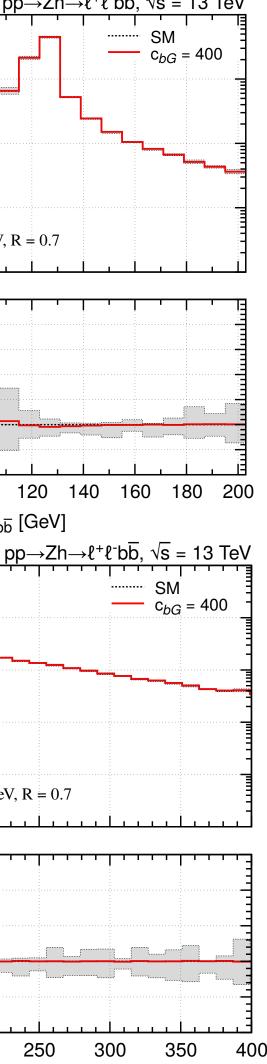
 $d\sigma_{\rm NNLO+PS}^{\rm SMEFT} = \left(1 + 2c_{\rm kin}\right)^2 \left\{ \left[1 - 2c_{bH} + \frac{\Gamma(h \to b\bar{b})_{\rm SMEFT}^{\rm non,VV}}{\Gamma(h \to b\bar{b})_{\rm SM}^{\rm NNLO}}\right] d\sigma_{\rm NNLO+PS}^{\rm SM} + d\sigma_{\rm NNLO+PS}^{\rm non,R+RV+RR} \right\}$

[Haisch, Scott, MW, Zanderighi, Zanoli '22]



Higgs differential cross sections

April 12th, 2022



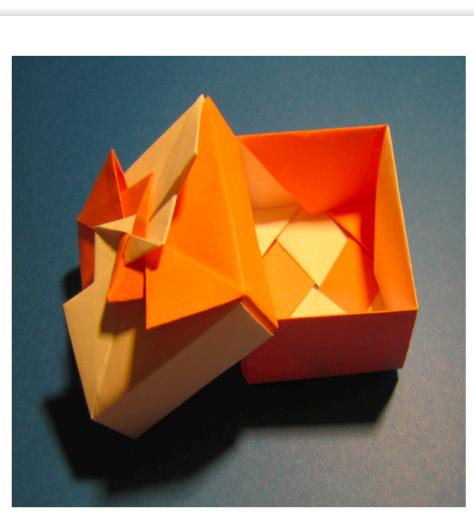


H production & background generators @ NNLO+PS

The POWHEG BOX

Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.





Index:

- Available NLO+PS processes
- NNLOps using MiNNLOps
- Proper references
- Downloads
- Version 2
- Version RES
- <u>Bugs</u>
- Licence
- Contributing Authors



ggF Higgs production in POWHEG-BOX-V2

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

Top-quark pair generator now available [Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

 $MiNNLO_{PS}$ has been extended to $2 \rightarrow 2$ colour-singlet processes (built in POWHEG-BOX-RES).

[Lombardi, MW, Zanderighi '20]

WW generator [Lombardi, MW, Zanderighi '21]

ZZ generator with incoherent combination of $q\bar{q}$ and gg channels [Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]

VH generator interfaced with $H \rightarrow bb$ decay (t.b.a.) [Zanoli, Chiesa, Re, MW, Zanderighi '21]

pp generator (t.b.a.) [Gavardi, Oleari, Re 'to appear]

More to come

Higgs differential cross sections









Summary

- + enormous progress on Higgs predictions in past years
- ★ in HTL: N³LO inclusive and fully differential; NNLO+PS and merged NLO+PS MCs
- **X** NNLO cross section in full theory; quark-mass dependence in distributions at NLO(+PS)
- \bigstar VH production and H \rightarrow bb decay at NNLO+PS in SM and SMEFT

Outlook

- differential NNLO(+PS) in full theory $\mathbf{\star}$
- beyond NLO(+PS) for ttH and bbH

* N³LO for Higgsstrahlung (similar to Drell Yan), inclusive & differential? (VH+jet at NNLO known)



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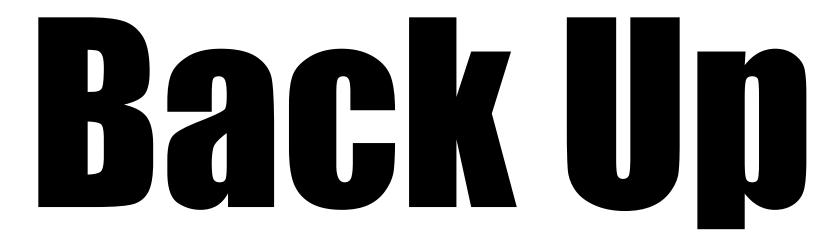
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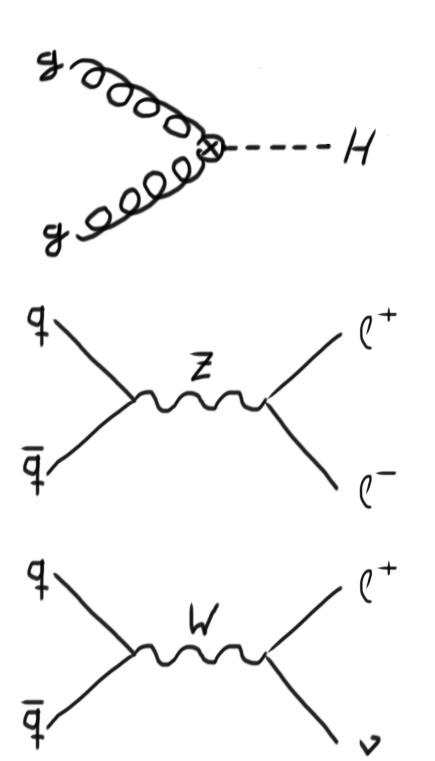


Outlook

* N³LO for Higgsstrahlung (similar to Drell Yan), inclusive & differential? (VH+jet at NNLO known)







Process	NNLO (MATRIX)	MINNLO _{PS}	Ratio
$pp \to H$	$39.64(1)^{+10.7\%}_{-10.4\%} \mathrm{pb}$	$39.1(5)^{+10.2\%}_{-9.0\%} \mathrm{pb}$	0.987
$pp \to \ell^+ \ell^-$	$1919(1)^{+0.8\%}_{-1.1\%}\mathrm{pb}$	$1917(1)^{+1.4\%}_{-1.1\%}\mathrm{pb}$	0.999
$pp \to \ell^- \bar{\nu}_\ell$	$8626(4)^{+1.0\%}_{-1.2\%} \mathrm{pb}$	$8643(4)^{+1.7\%}_{-1.5\%} \mathrm{pb}$	1.002
$pp \to \ell^+ \nu_\ell$	$11677(5)^{+0.9\%}_{-1.3\%} \mathrm{pb}$	$11693(5)^{+1.5\%}_{-1.6\%} \mathrm{pb}$	1.001

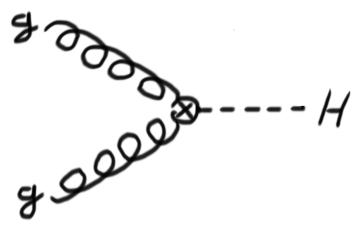
MiNNLO_{PS}: $2 \rightarrow 1$ colour-singlet processes

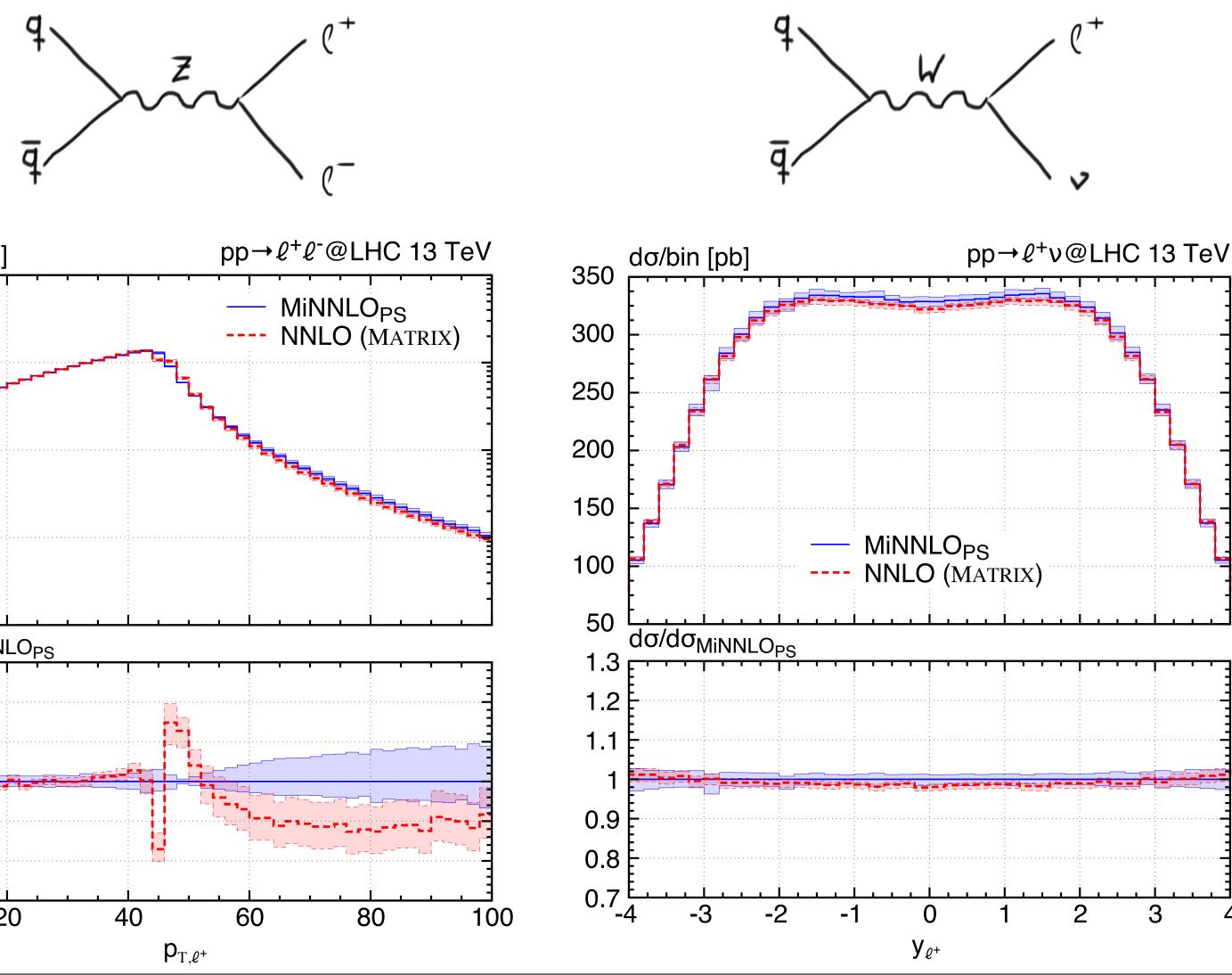
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

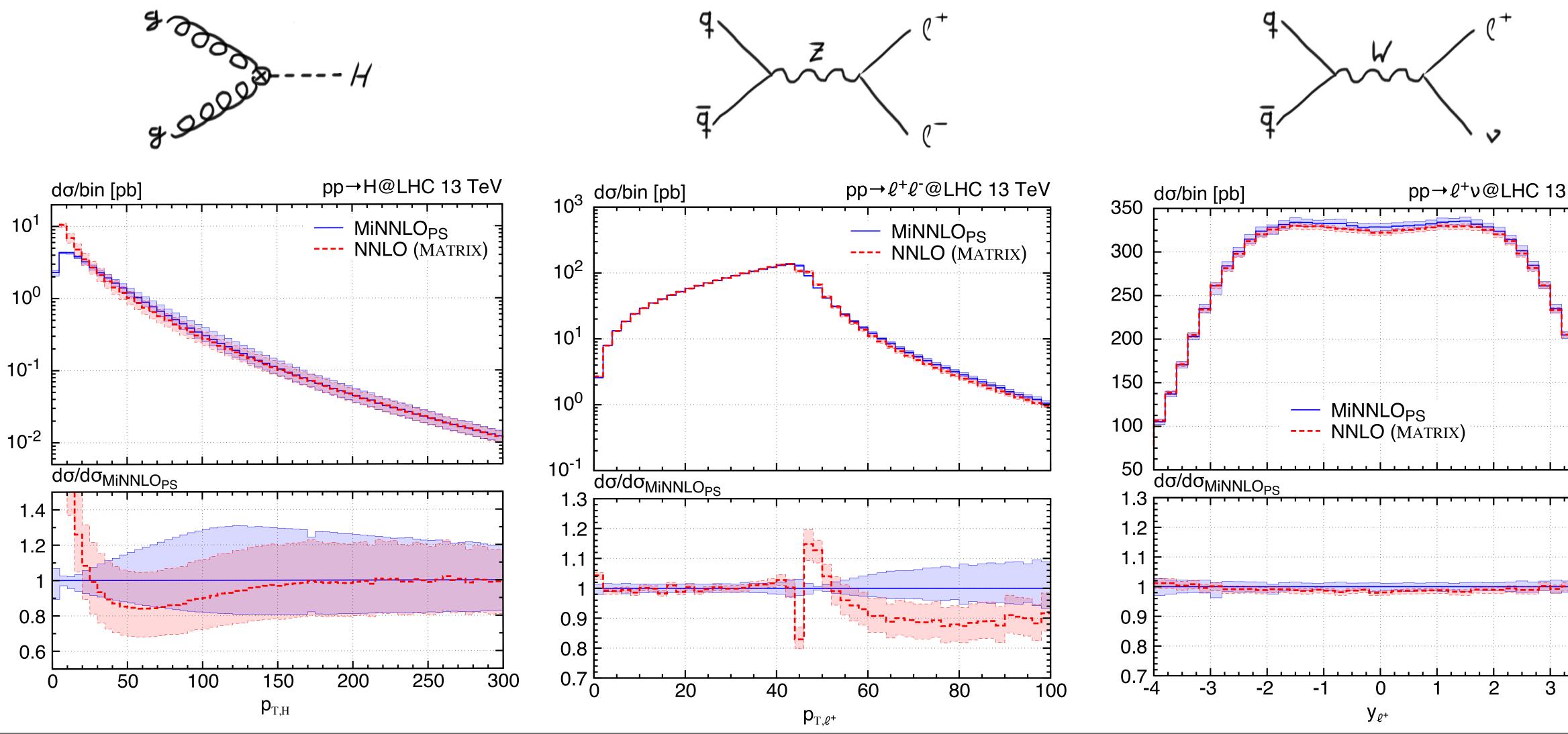












MiNNLO_{PS}: $2 \rightarrow 1$ colour-singlet processes

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

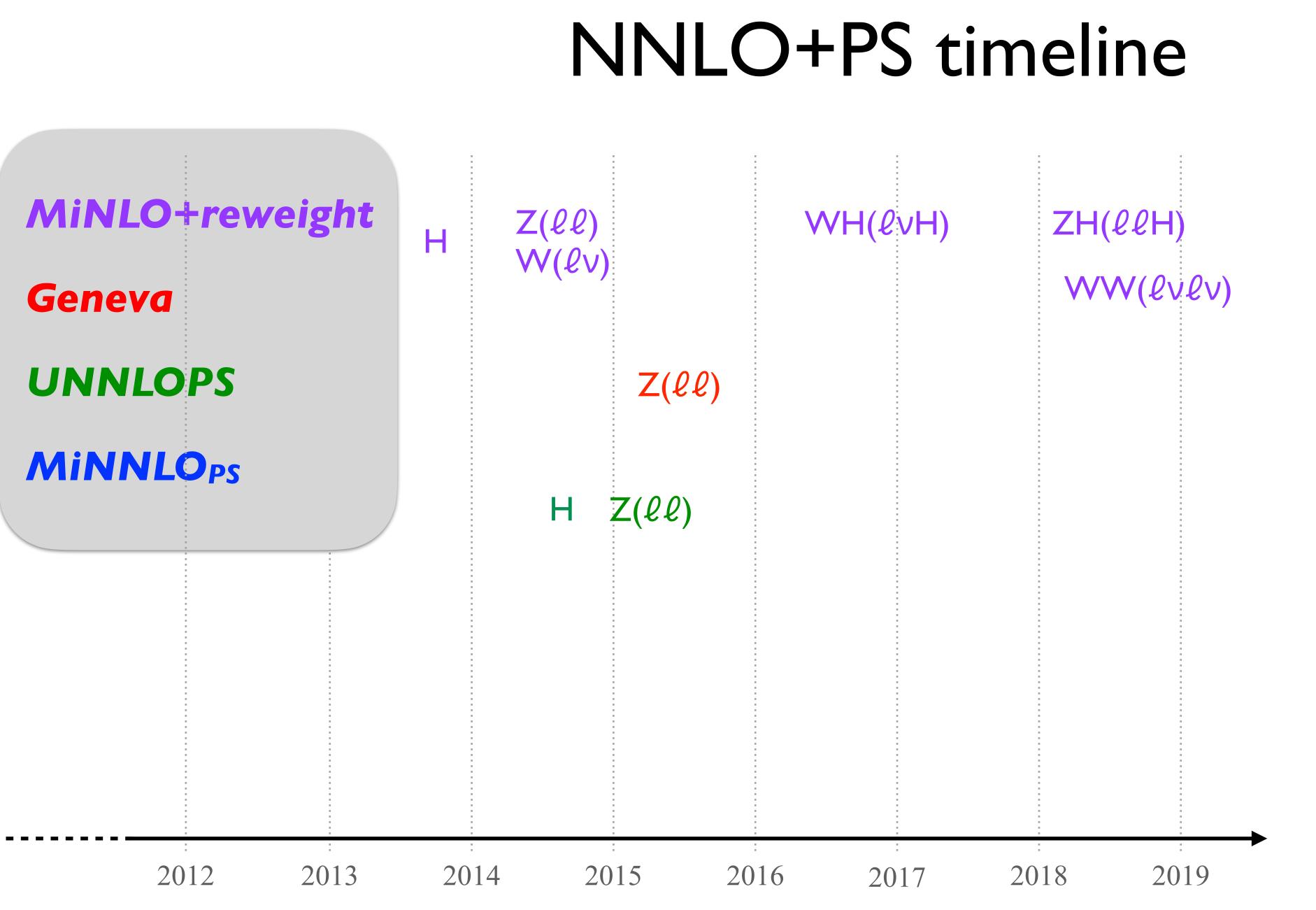
Higgs differential cross sections

April 12th, 2022



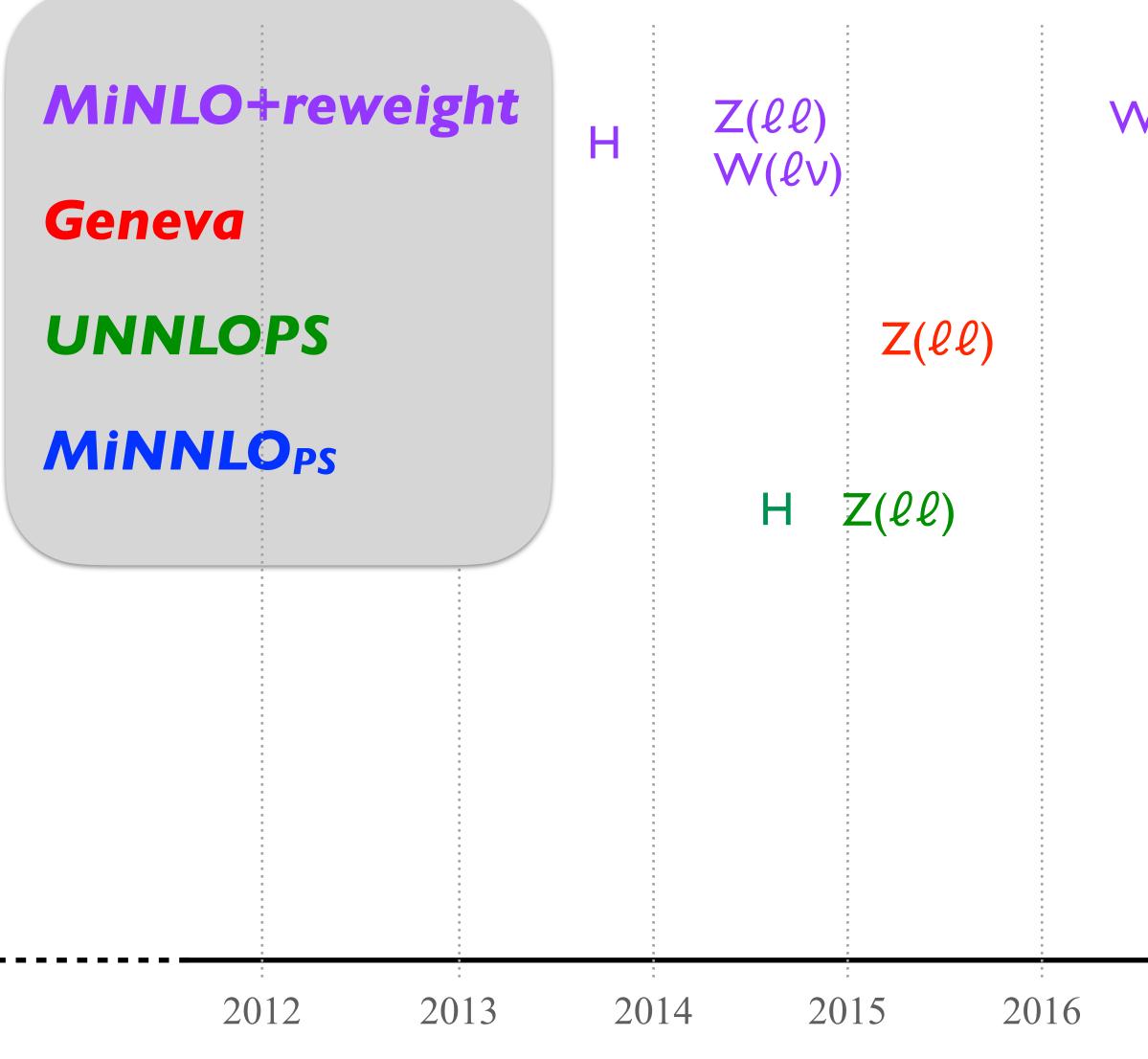








NNLO+PS timeline

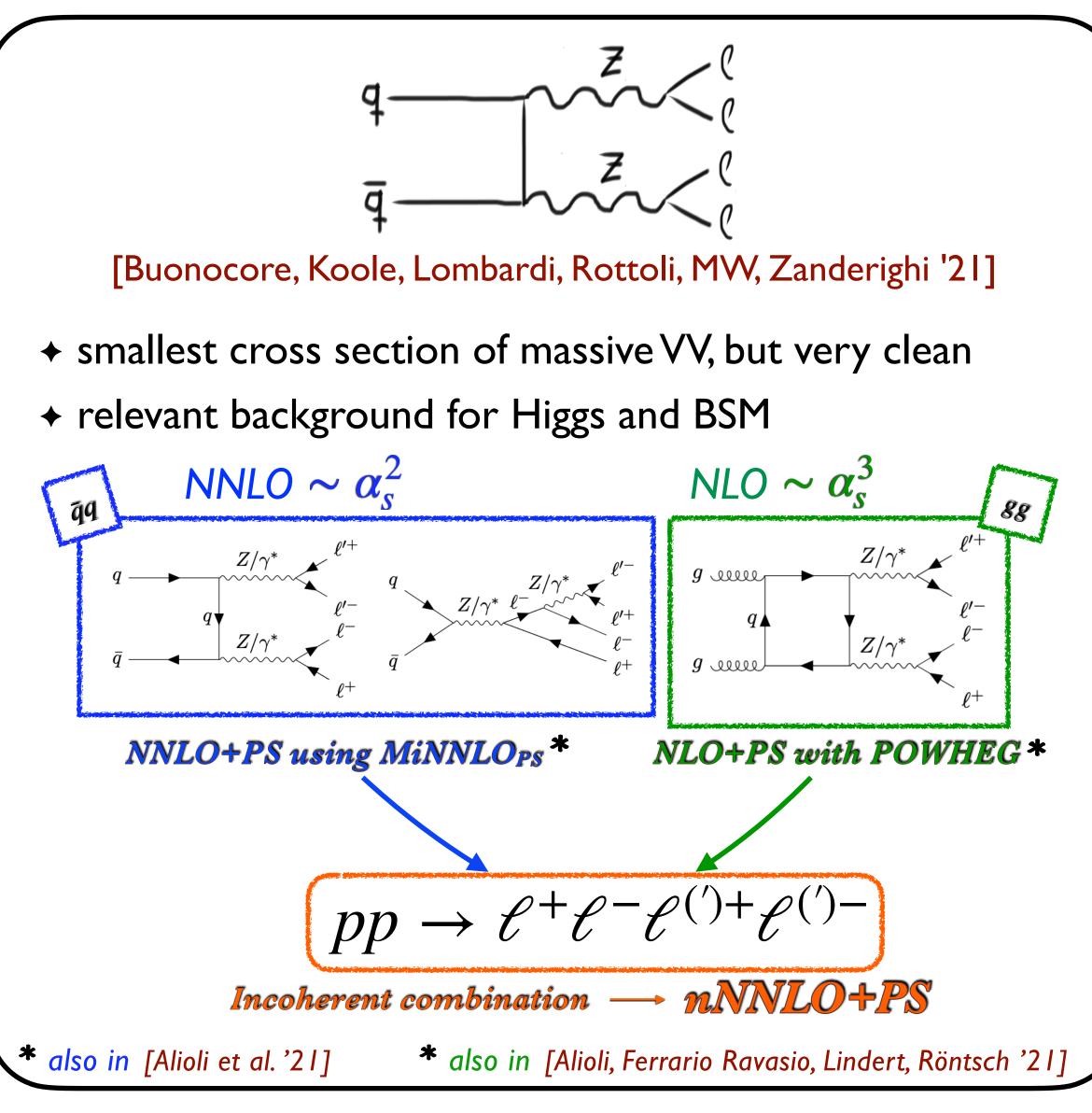


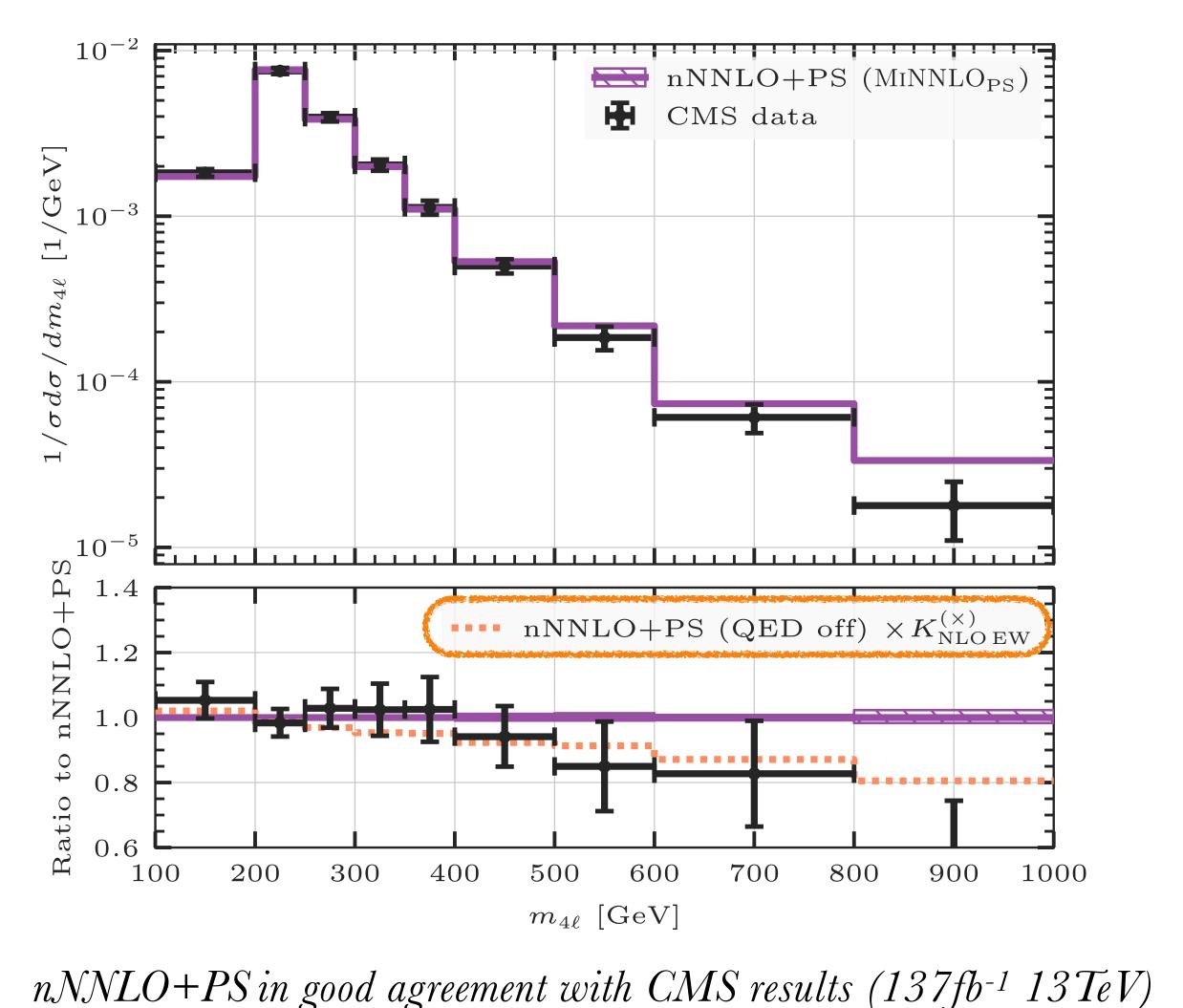
VH(ℓvH)	ZH(ℓℓH)	H	I→ bb		
	WW(lvl		Ή(ℓℓΗ) VH(ℓνΗ)	Wγ(.	θνγ)
				→bb →gg	
			Y	Υ ΖΖ(ℓℓ	<i>ll</i>)
			Z	γ(ℓℓγ)	
				WW(lvl	?∨)
		н		ZZ(ℓ	<u>eee)</u>
		Z(ℓℓ)	$W(\ell v)$) Ζγ(ν	νγ)
			t		ℓH)xH→bb vH)xH→bb
2017	2018 2019	9 202	20 20	20	22



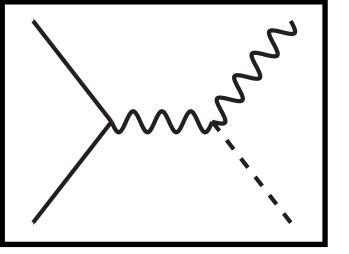


MiNNLO_{PS}: nNNLO+PS (x EW) for $ZZ(\ell\ell\ell'\ell')$





✓ nNNLO+PS in good agreement with CMS results (137fb⁻¹) ✓ EW corrections (through NLO K factor) to describe tails

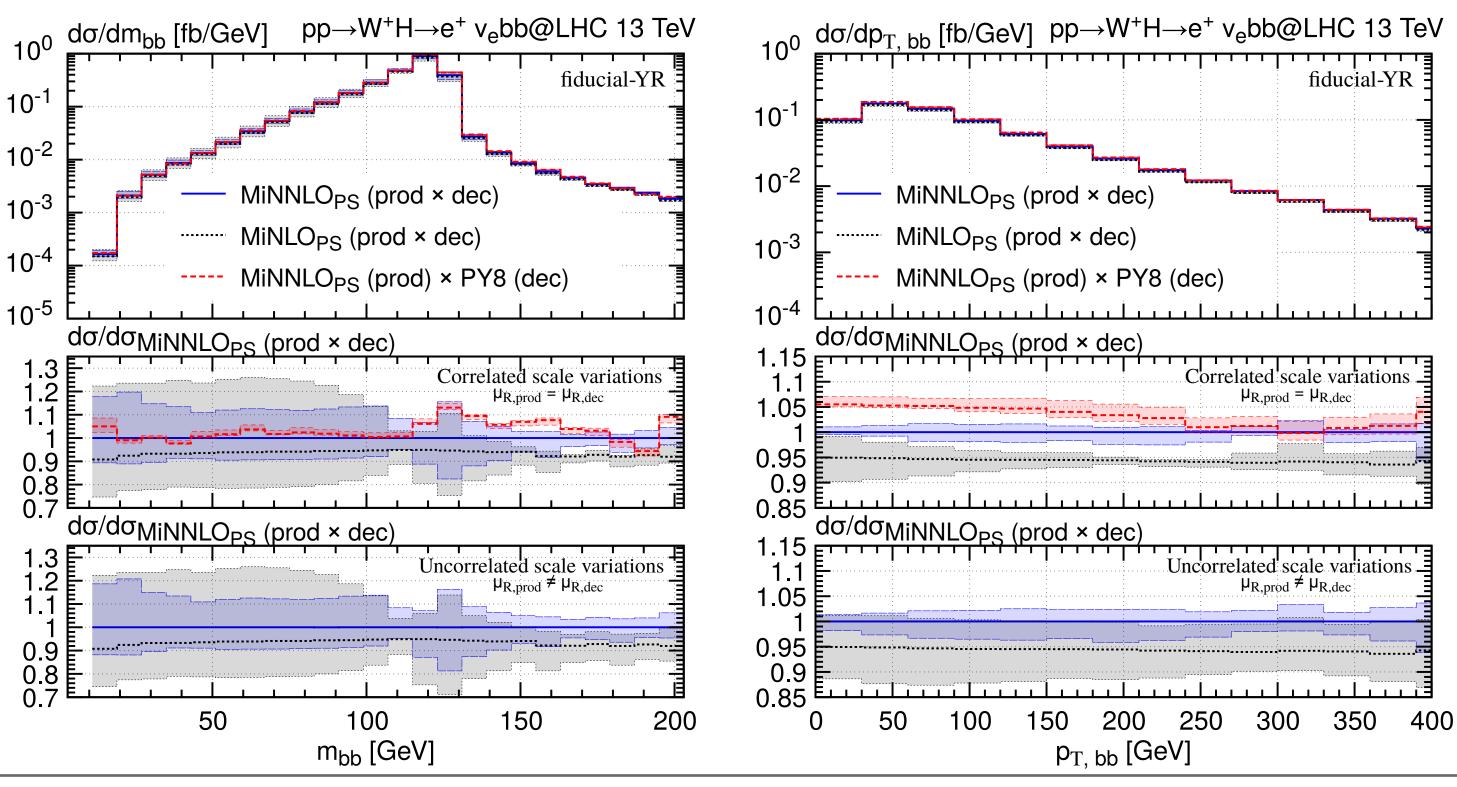


$VH \times H \rightarrow bb @ NNLO+PS$

* NNLO+PS accuracy in both production and decay see also [Alioli et al. '19] see also [Alioli et al. '20]

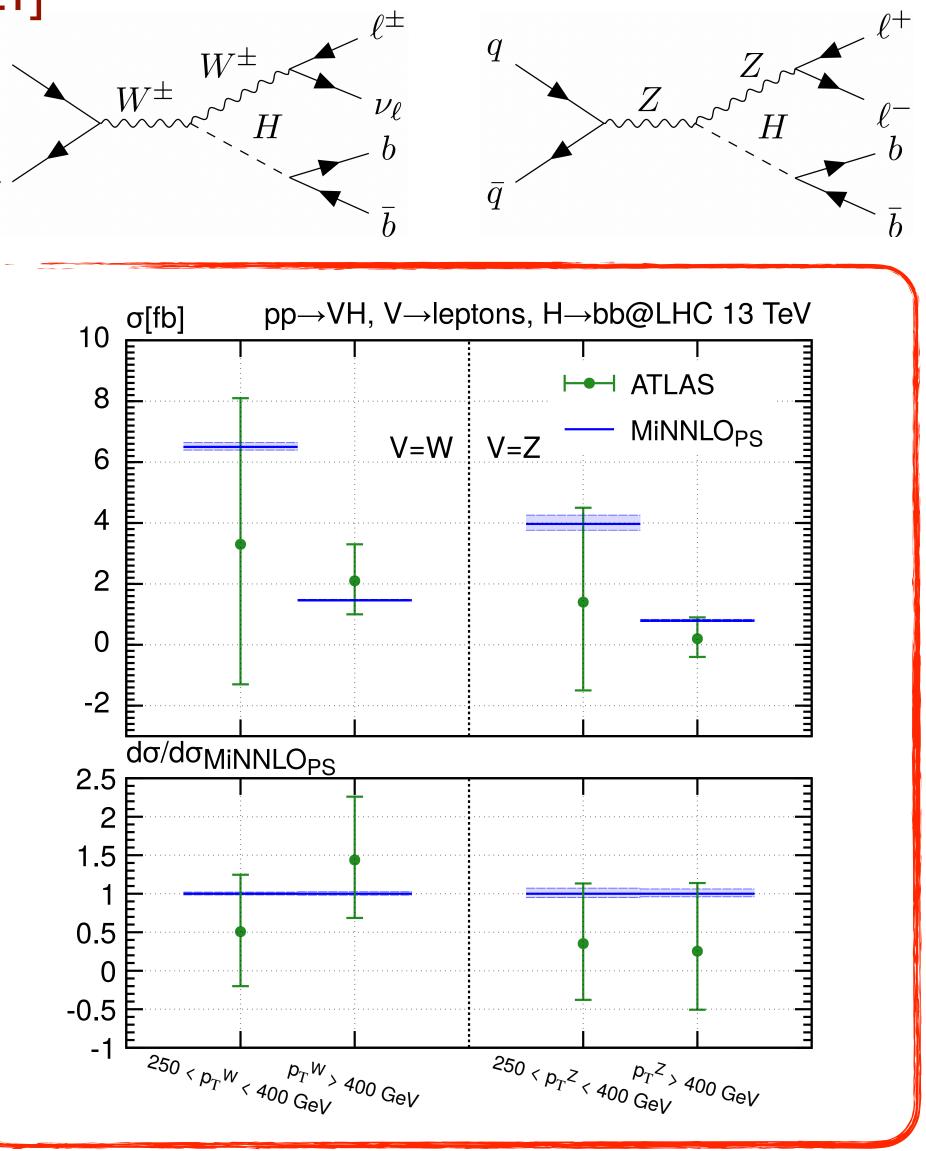
* includes NNLO directly in event generation through **MiNNLO_{PS} method** [Monni, Nason, Re, Zanderighi, MW '19], [Monni, Re, MW '20]

 \bullet main production channel to observe $H \rightarrow bb$ (largest branching fraction)



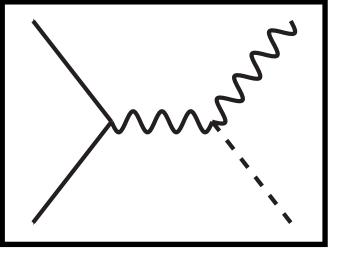
Marius Wiesemann (MPP Munich)

[Zanoli, Chiesa, Re, MW, Zanderighi '21]



Higgs differential cross sections

April 12th, 2022



$$Q_{H\Box} = (H^{\dagger}H) \Box (H^{\dagger}H), \qquad Q_{HD} = (H^{\dagger}D_{\mu}H)^{*} (H^{\dagger}D^{\mu}H),$$
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$$Q_{HG} = \frac{g_{s}^{2}}{(4\pi)^{2}} (H^{\dagger}H) G^{a}_{\mu\nu}G^{a,\mu\nu}, \qquad Q_{3G} = \frac{g_{s}^{3}}{(4\pi)^{2}} f^{abc}G^{a,\nu}G^{b,\sigma}G^{c,\mu}_{\sigma},$$
$$N^{3}LO \ QCD \ inclusive \ H \twoheadrightarrow bb \ decay \ width:$$

$$\Gamma(h \to b\bar{b})_{\rm SMEFT}^{\rm N^3LO} = \left\{ \left(1 + 2c_{\rm fac}\right) \left[1 + \frac{\alpha_s}{\pi} 5.67 + \left(\frac{\alpha_s}{\pi}\right)^2 29.15 + \left(\frac{\alpha_s}{\pi}\right)^3 41.76\right] + \left(\frac{\alpha_s}{\pi}\right)^2 \frac{m_h^2}{3v^2} \left[1 + \frac{\alpha_s}{\pi} 17.32\right] c_{bG} \right\} \Gamma(h \to b\bar{b})_{\rm SM}^{\rm LO},$$

corrected Higgs width: $\Gamma_h^{\text{SMEFT}} = (1 + 2c_{\text{kin}}) \left[\Gamma_h^{\text{SM}} - (2\Delta c_{bH} - K_{bG}\Delta_{\text{non}}c_{bG})\Gamma(h \to b\bar{b})_{\text{SM}}^{\text{LO}} + 6K_{HG}c_{HG}\Gamma(h \to gg)_{\text{SM}}^{\text{LO}} \right].$

 $d\sigma_{\rm NNLO+PS}^{\rm SMEFT} = \left(1 + 2c_{\rm kin}\right)^2 \left\{ \left[1 - 2c_{bH} + \frac{\Gamma(h \to b\bar{b})_{\rm SMEFT}^{\rm non,VV}}{\Gamma(h \to b\bar{b})_{\rm SM}^{\rm NNLO}}\right] d\sigma_{\rm NNLO+PS}^{\rm SM} + d\sigma_{\rm NNLO+PS}^{\rm non,R+RV+RR} \right\} \frac{\Gamma_h^{\rm SM}}{\Gamma_h^{\rm SMEFT}},$

[Haisch, Scott, MW, Zanderighi, Zanoli '22]

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u$

Higgs differential cross sections

