Higgs Theory

Conveners:
(TH) Fabrizio Caola, Stephen Jones

Outline

Overview

Truly impressive progress since last meeting

Pushing more channels one ``N'' higher

Increasingly, differential & fiducial predictions produced at high-orders

Very important progress understanding mixed EW-QCD, quark mass effects

Selected Examples

ggH: Fully differential + fiducial cross-section @ N^{3}LO QCD, mixed QCD-EW, top-quark mass effects @ NNLO QCD

VBF: Les Houches 2019 study, non-factorisable contributions

WH @ NNLO QCD with bottom-quark mass effects, WHj @ NNLO QCD

$b\bar{b}H$ @ N^{3}LO QCD with 4FS/5FS matching

$Hb\bar{b}$ QCD + EW corrections

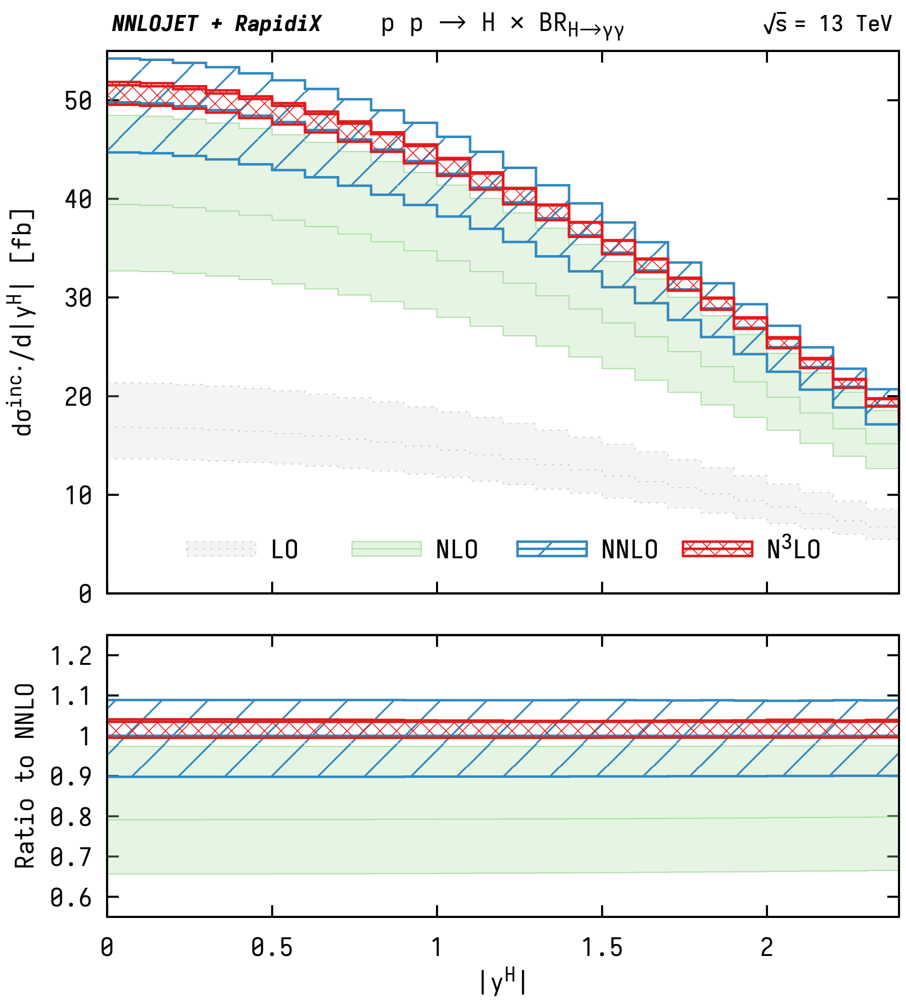
$t\bar{t}H$ off-diagonal channels @ NNLO QCD, tHj QCD + EW corrections

Progress in global EFT fits

I had to make a very unfair selection and I skip several very interesting and important topics, please feel free to bring them up during questions/discussion!

ggF: N^{3}LO Differential (Part 1)

Inclusive



ATLAS cuts

$p_T^{\gamma_1} > 0.35\ m_{\gamma\gamma}$

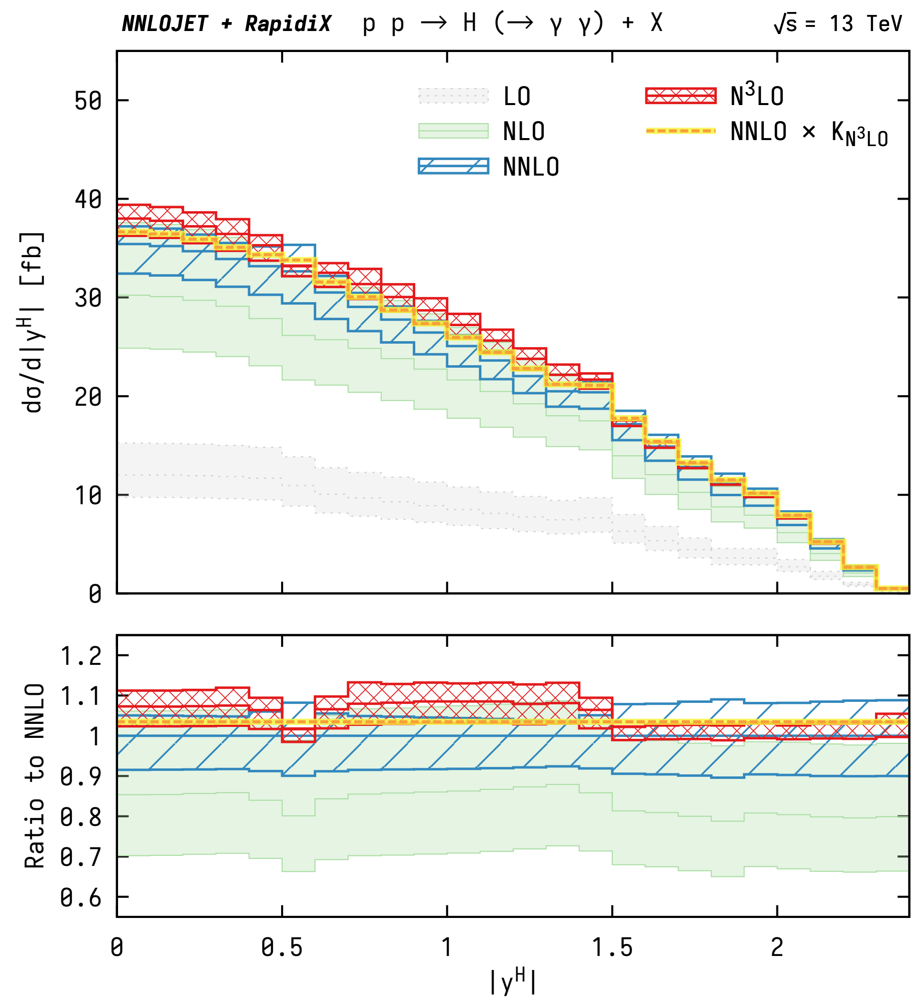
$p_T^{\gamma_2} > 0.25\ m_{\gamma\gamma}$

$|y^\gamma| < 2.37$

$1.37 < |y^\gamma| < 1.52$ (reject)

$\Delta R < 0.2$

Fully Differential



Chen, Gehrmann, Glover, Huss , Mistlberger , Pelloni 21

Used projection-to-born method, presented: $y^H, y^{\gamma_1}, \Delta y^{\gamma_1\gamma_2}$

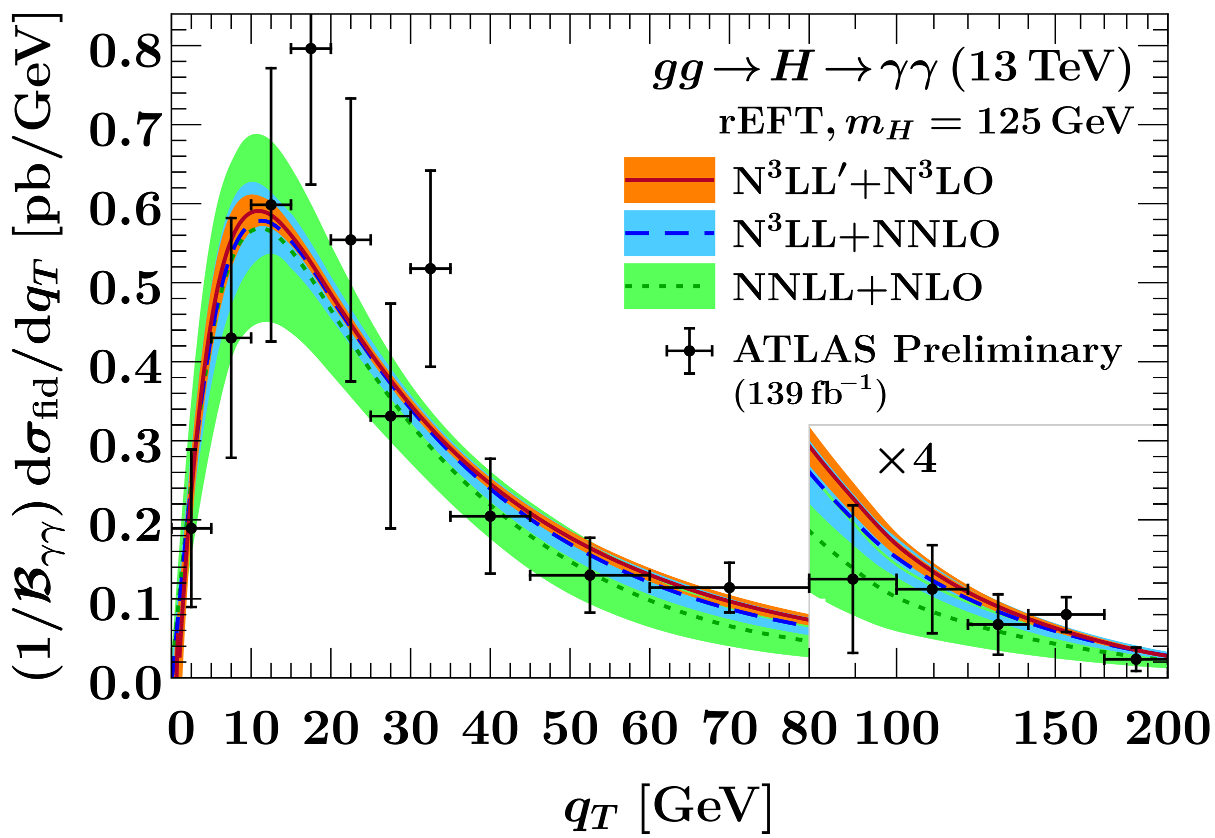
Perturbative expansion looks reasonable (reduced uncertainties, stable)

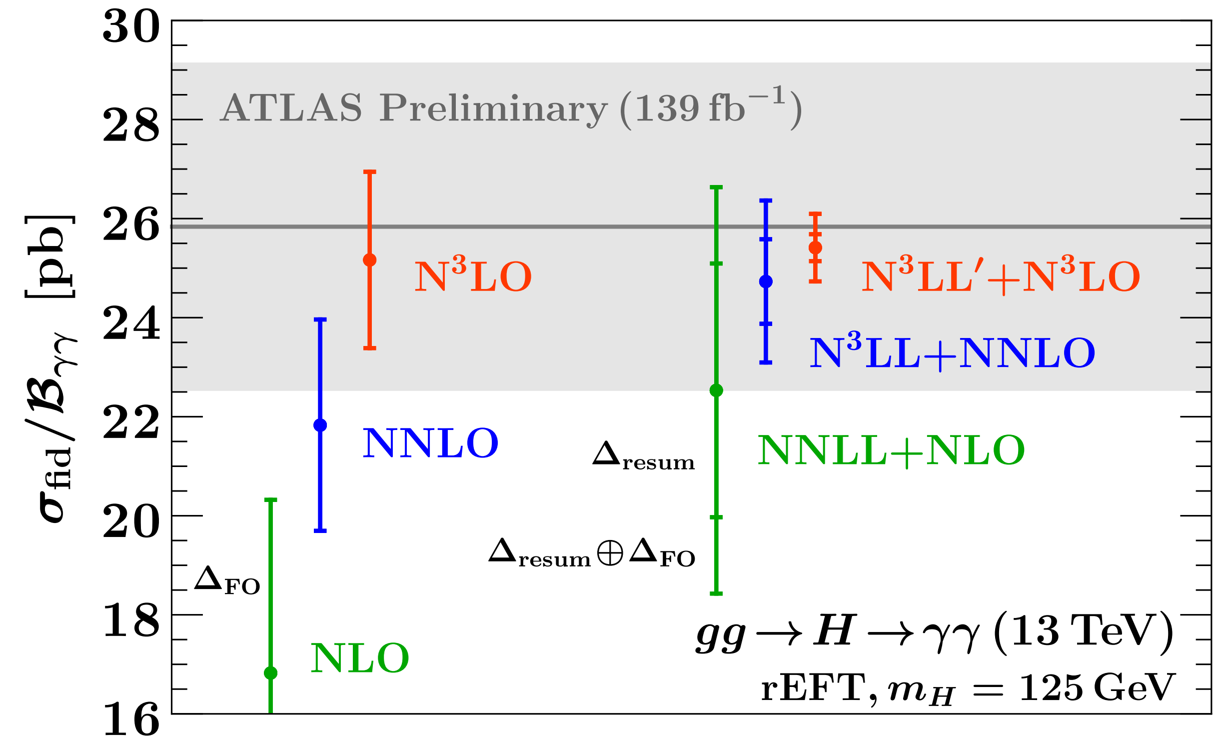
Inclusive: remarkably flat K-factor (as expected)

Differential: naïve rescaling fails for $|y^H| < 1.5$, IR sensitivity @ $|y^H| \sim 0.5$

ggF: N^3LO Differential (Part 2)

With Fiducial Cuts





Billis, Dehnadi, Ebert, Michel, Tackmann 21

Resummed large fiducial power corrections induced by fiducial cuts (even in σ_{fid})

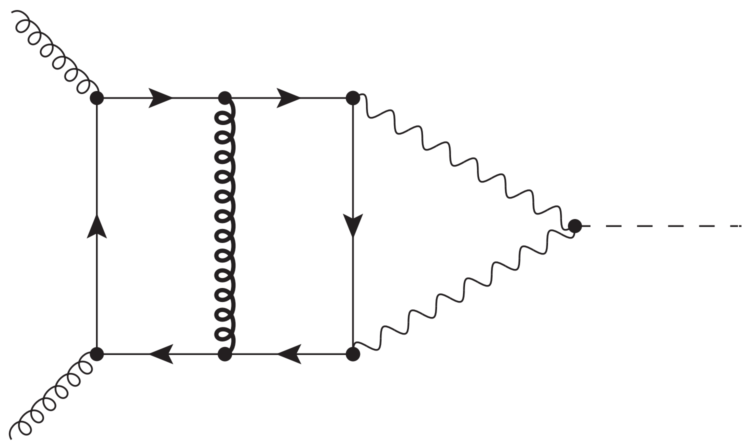
$$\sigma_{fid} = 57.69\,(1 \pm 2.7\%_{pert} \pm 2.1\%_{BR} \pm 3.2\%_{PDF+\alpha_s} \pm 2\%_{EW} \pm 2\%_{t,b,c})\ \text{fb}$$

Future:

Include fiducial power corrections also in $y^H, \Delta y^{\gamma_1\gamma_2}$? (J. Michel talk @ LHCP2021)

Explore different fiducial cuts which suppress these effects?

ggF: Mixed QCD-EW Corrections

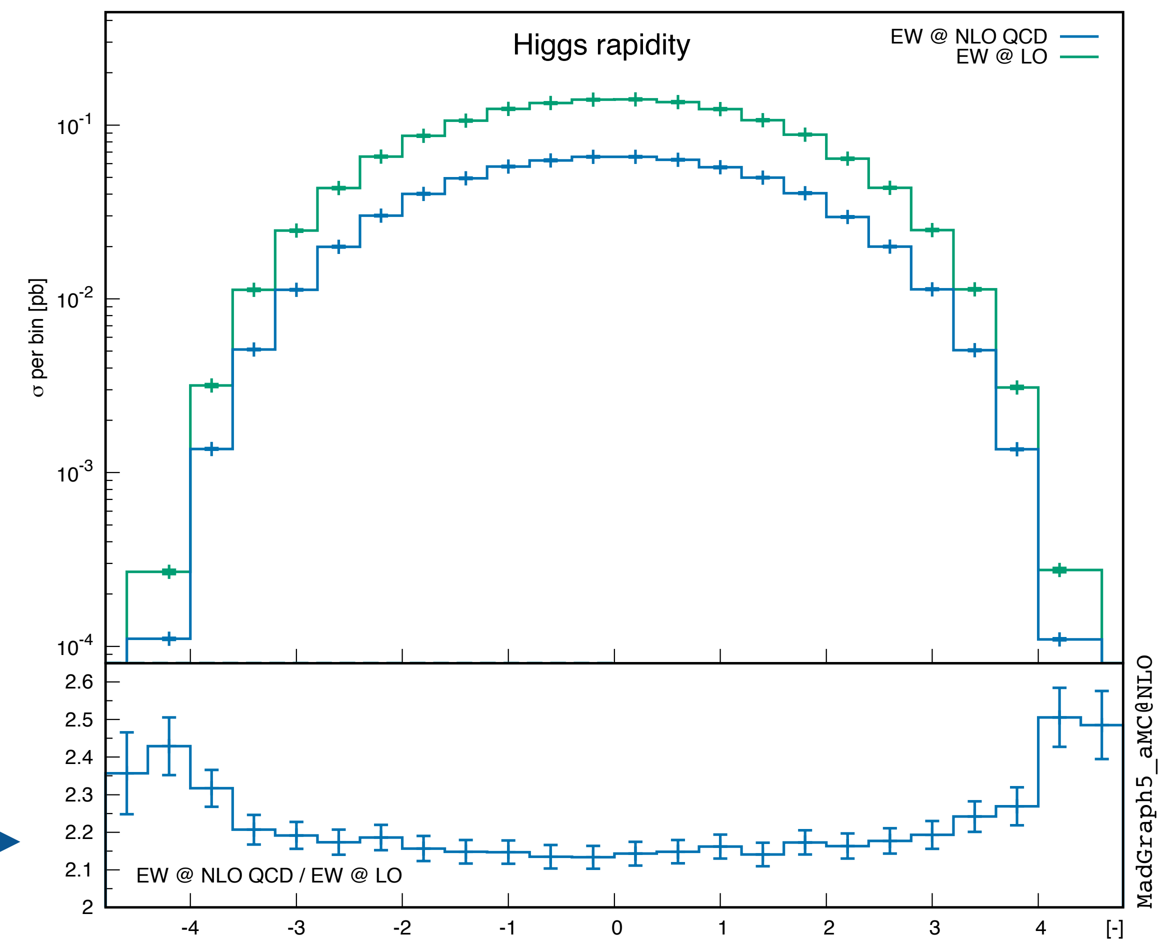


Challenging computations

Bonetti, Melnikov, Tancredi 17

Bonetti, Panzer, Smirnov, Tancredi 20

Dominant light-quark contributions computed, rather flat K-factor (at least for rapidity distribution)



Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20

Increases σ_{tot} by $+5.1\,\%$, reduces residual uncertainty $\delta(\text{EW}) \sim 0.6\,\%$

Favouring factorisation of EW corrections: $\sigma = \sigma_{\text{LO}}\,(1+\delta_{\text{QCD}}) \times (1+\delta_{\text{EWK}})$

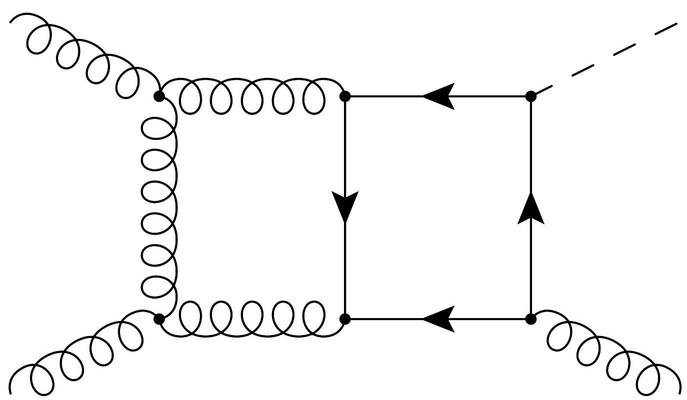
Compatible with previous estimates e.g. Bonetti, et al. 18; Anastasiou et al. 18, Anastasiou, et al. 08

Future:

Corrections at large p_T? Without heavy top-quark approximation?

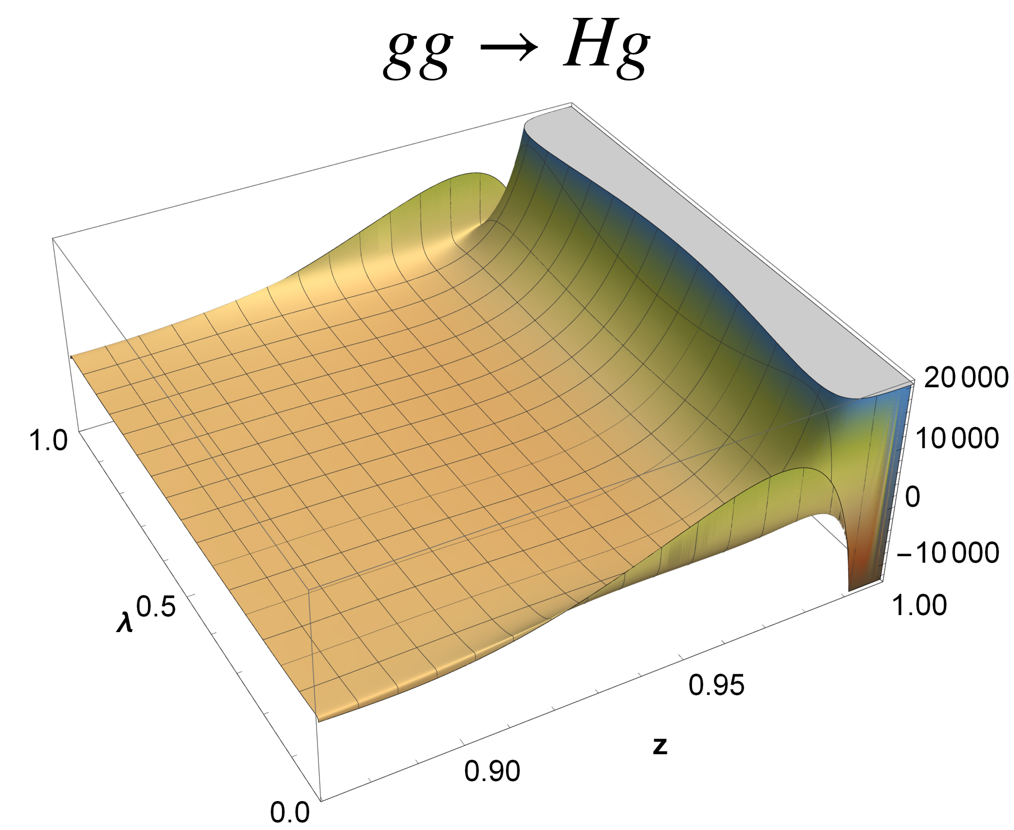
LO and NLO quark-induced EW contribution

ggF: NNLO with full top-quark mass



H+1jet @ 2-loop & H @ 3-loop using numerical solution of differential equations

Czakon, Niggetiedt 20;
Czakon, Harlander, Klappert, Niggetiedt 21



Czakon, Harlander, Klappert, Niggetiedt 21

Decreases σ_{tot} by $-0.26\,\%$

Intricate interplay between mass effects: $gg\ (+0.62\%), qg\ (-16\%), qq\ (-15\%)$

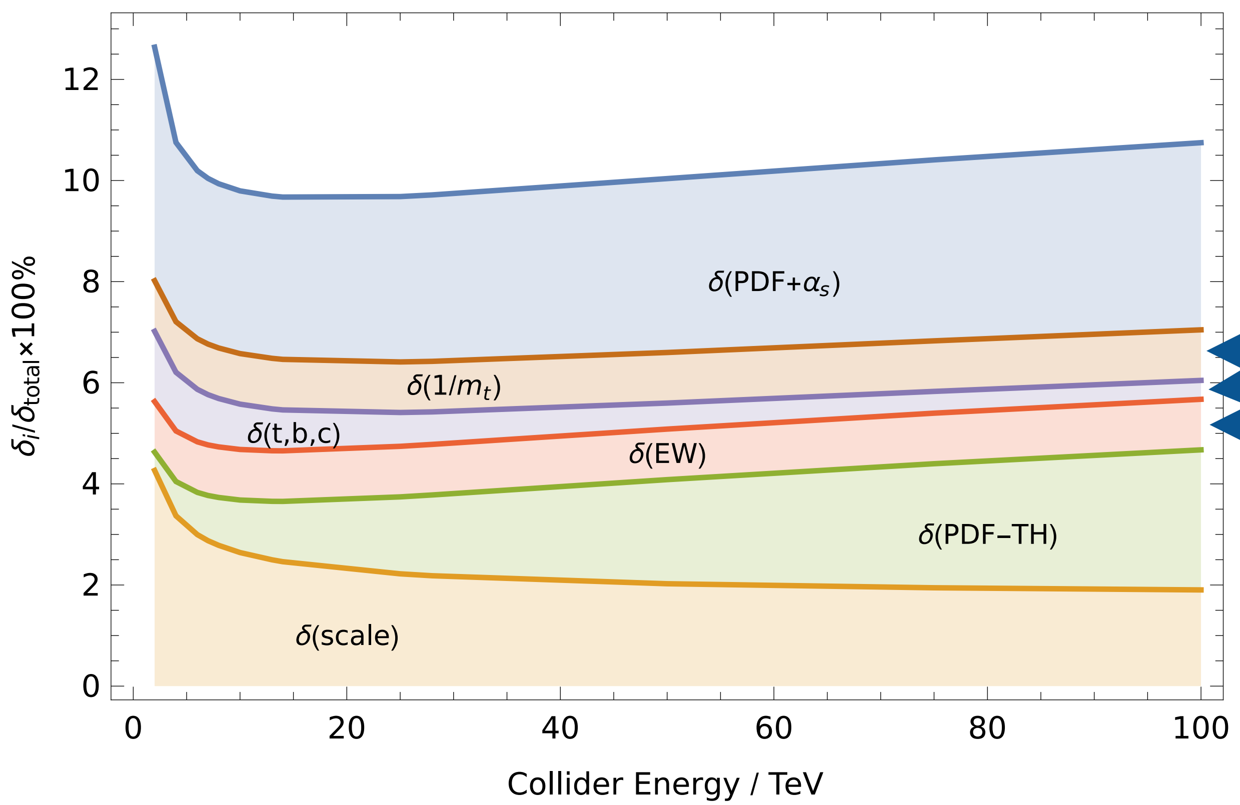
Complete NNLO results obtained using STRIPPER framework

Future:

Use technology to include light quark mass effects (large logs/need to resum?)

Impact on differential distributions/ fiducial cross sections

ggF: Taking Stock



iHixs2: Dulat, Lazopoulos, Mistlberger 18

Progress is steadily beating down sources of TH uncertainty

Czakon, Harlander, Klappert, Niggetiedt 21

Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20; + Bonetti, Panzer, Smirnov, Tancredi, Melnikov, …

Also exposing new sources of uncertainty/ areas where we can do better:

Fiducial power corrections (covered previously)

Next-to-leading power corrections @ threshold Beneke, Garny, Jaskiewicz, Szafron, Vernazza, Wang 19; van Beekveld, Laenen, Sinninghe Damsté, Vernazza 21;

The precision era mantra:

TH: Do we miss sources of uncertainty? (PDF MHOU, Schemes, NLP, …)

EXP: Do we use the most accurate results? (PS validation, Match/ Merge)

Elephant in the room PDF (+PDF TH) uncertainties

VBF: LH2019 Study

Extensive study of VBF (started at LH2019) published!

Buckley, Chen, Cruz-Martinez, Ferrario Ravasio, Gehrmann, Glover, Höche, Huss, Huston, Lindert, Plätzer, Schönherr 21

Input from NNLOjet, POWHEG, Herwig, Sherpa

Important work getting a handle on this:

- NLOPS vs NNLO
- Detailed PS comparisons
- Additive/Multiplicative matching
- Jet-radius dependence
- High-$p_{T,H}$ region

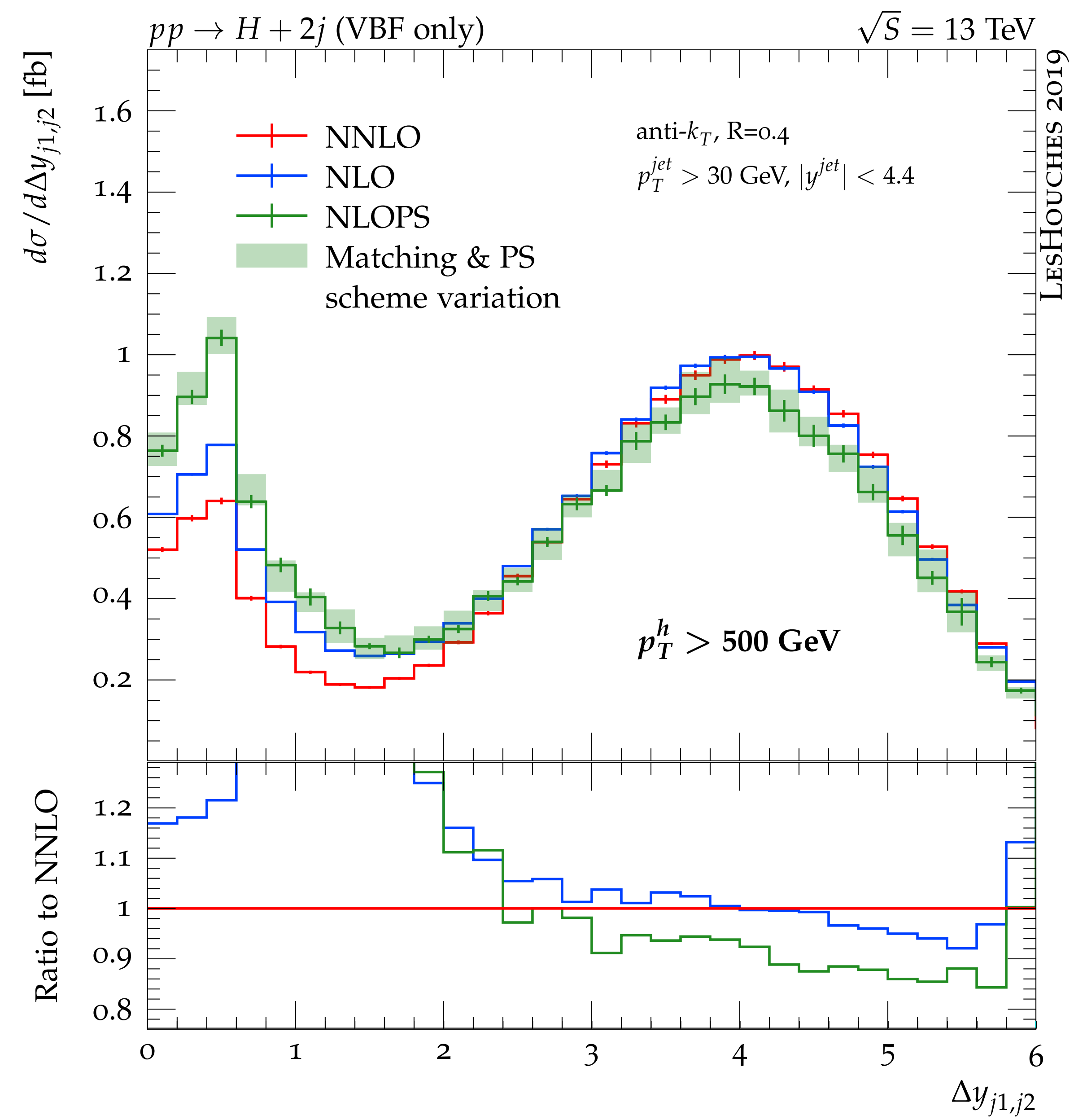
Many Lessons:

At large $p_{T,H}$ disentangling VH/VBF more difficult

Mostly(!) reasonable NNLO vs NLOPS

EW $H + 2$ jet $\approx$ VBF + VH

...



VBF ($H \to ZZ$): NLO QCD + EW

Process $pp \to e^+e^-\mu^+\mu^- jj + X$ at $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_s\alpha^6)$

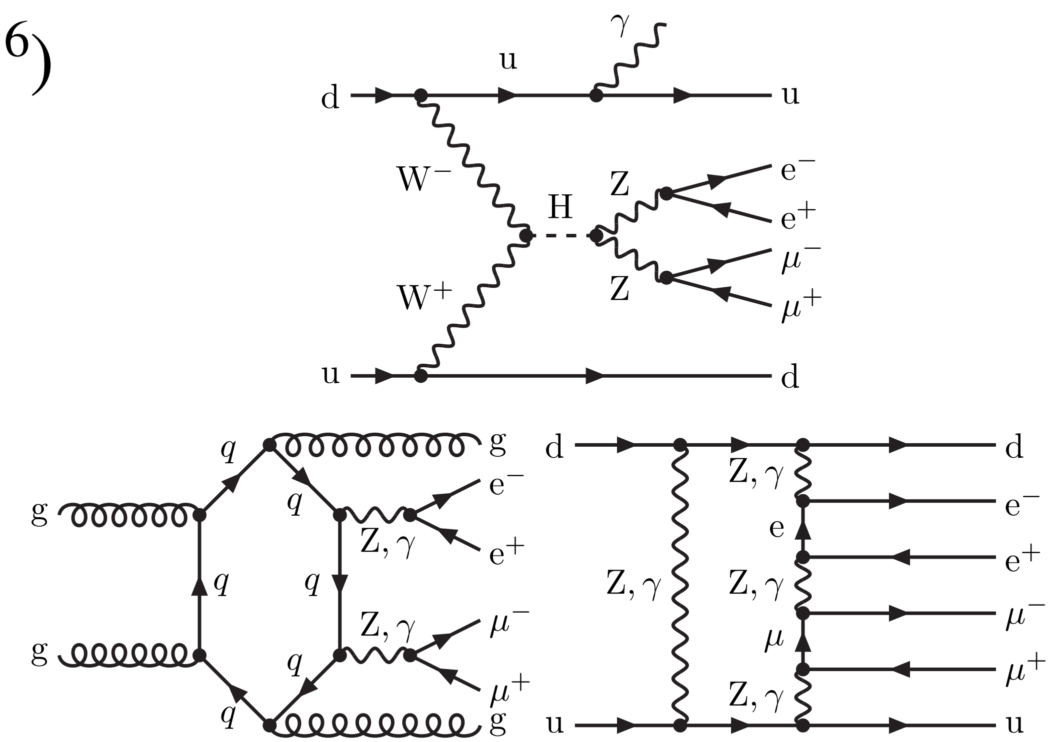
Denner, Franken, Pellen, Schmidt 20

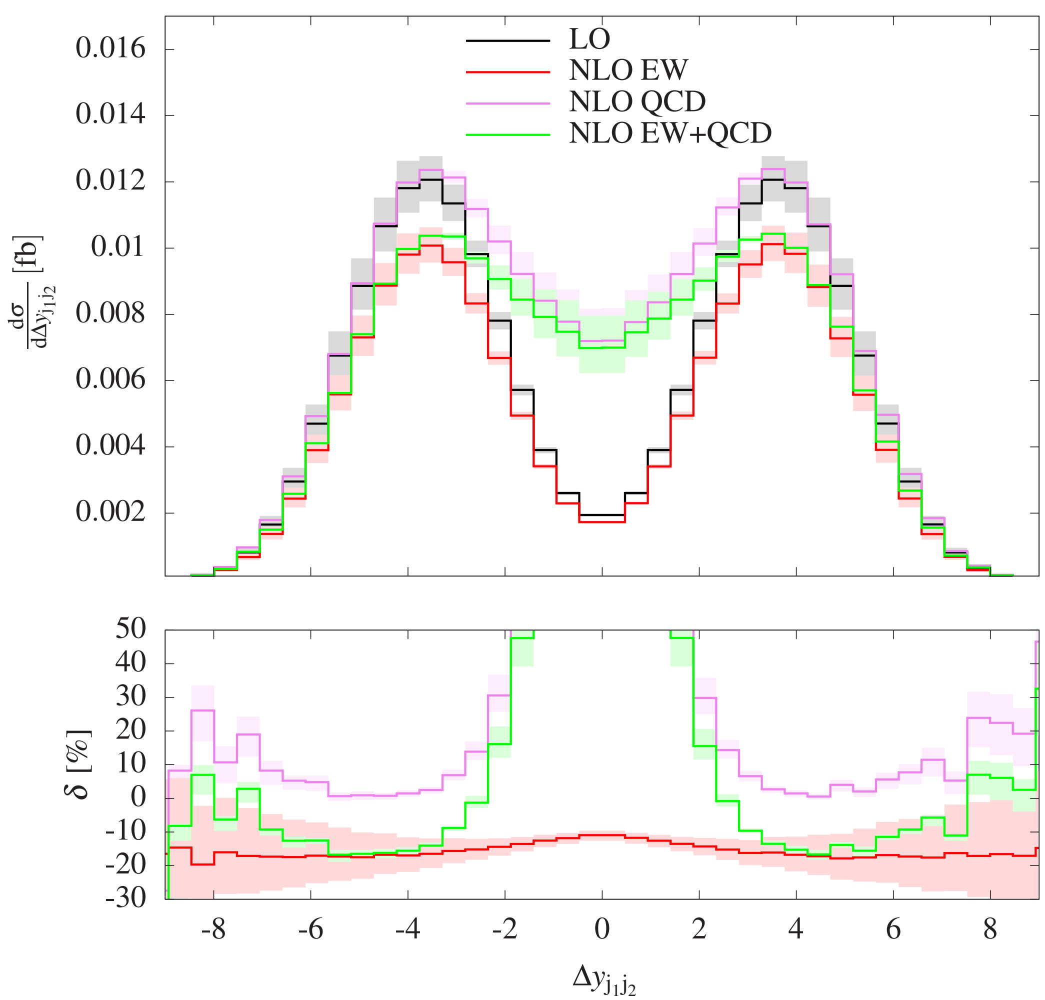
Includes all off-shell, non-resonant & interf. effects

Decreases σ_{fid} by $-16\,\%$, mostly due to EW

Sudakov logs: $\ln^2(Q^2/M_W^2),\ \ln(Q^2/M_W^2)$

EW corrections can reach $-40\,\%$ at high energy





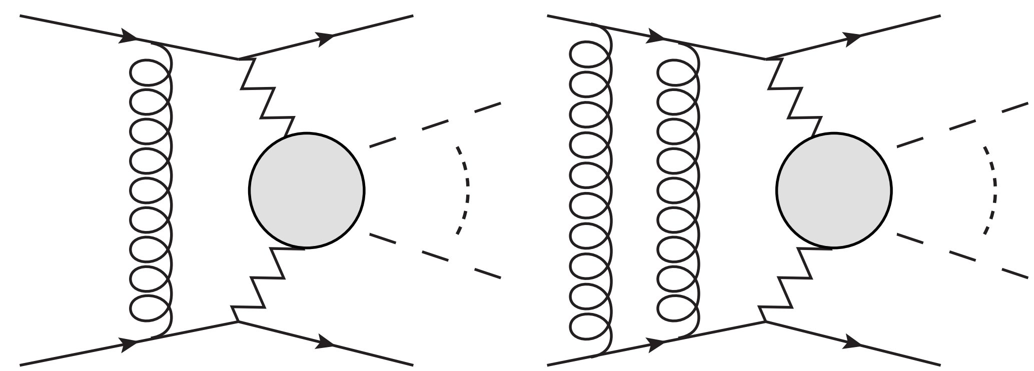
Lessons:

Authors advocate proper inclusion of tri-boson contributions, not subtracting from signal

Care when using MC relying on VBS to extrapolate inclusive measurements

VBF HH: Non-factorisable contribution

VBF Approximation/structure function approach: neglect the (colour suppressed) exchange of particles between the quark lines

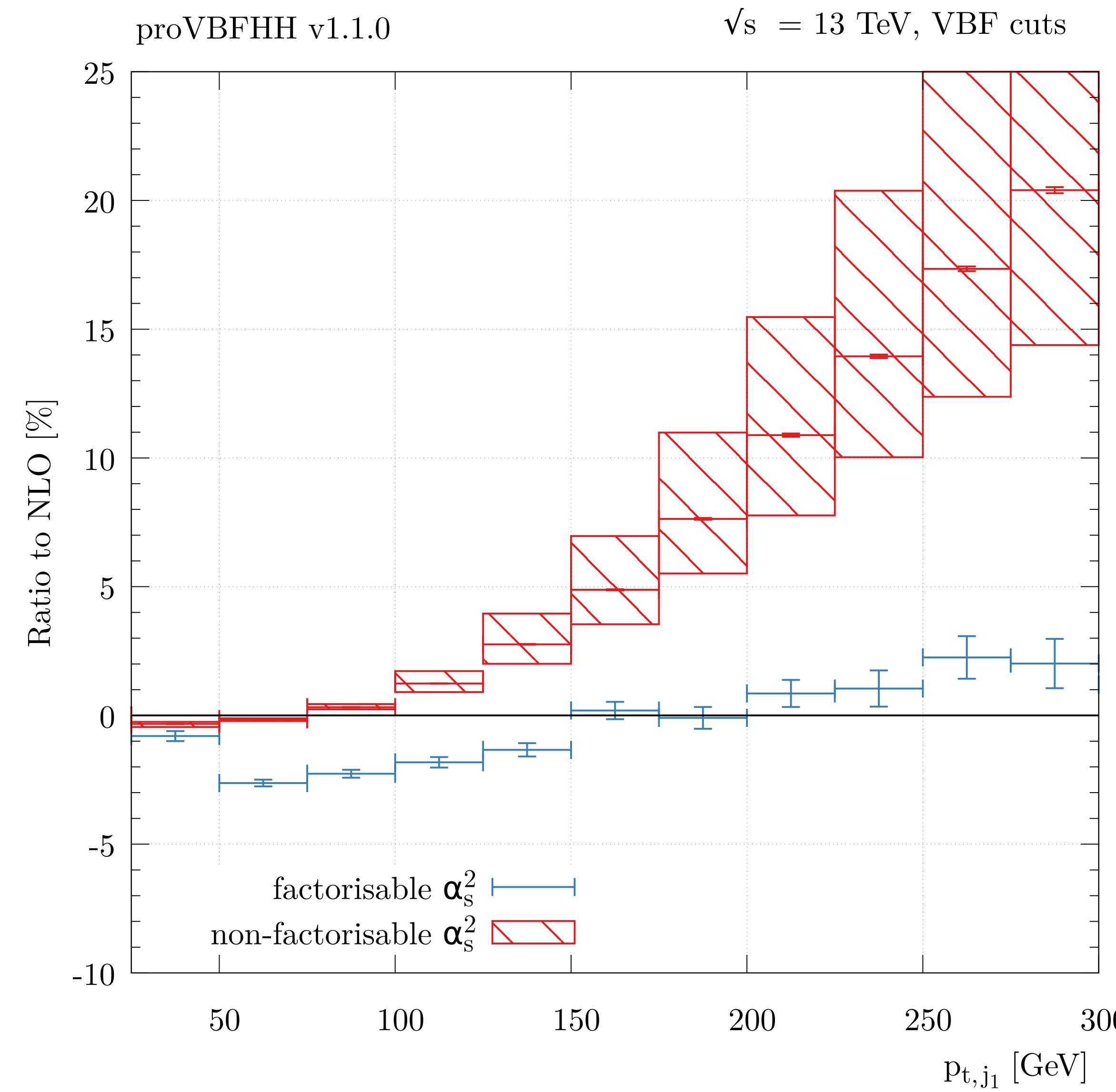


Non-factorisable contributions recently studied using the eikonal approximation
Liu, Melnikov, Penin 19
Dreyer, Karlberg, Tancredi 20

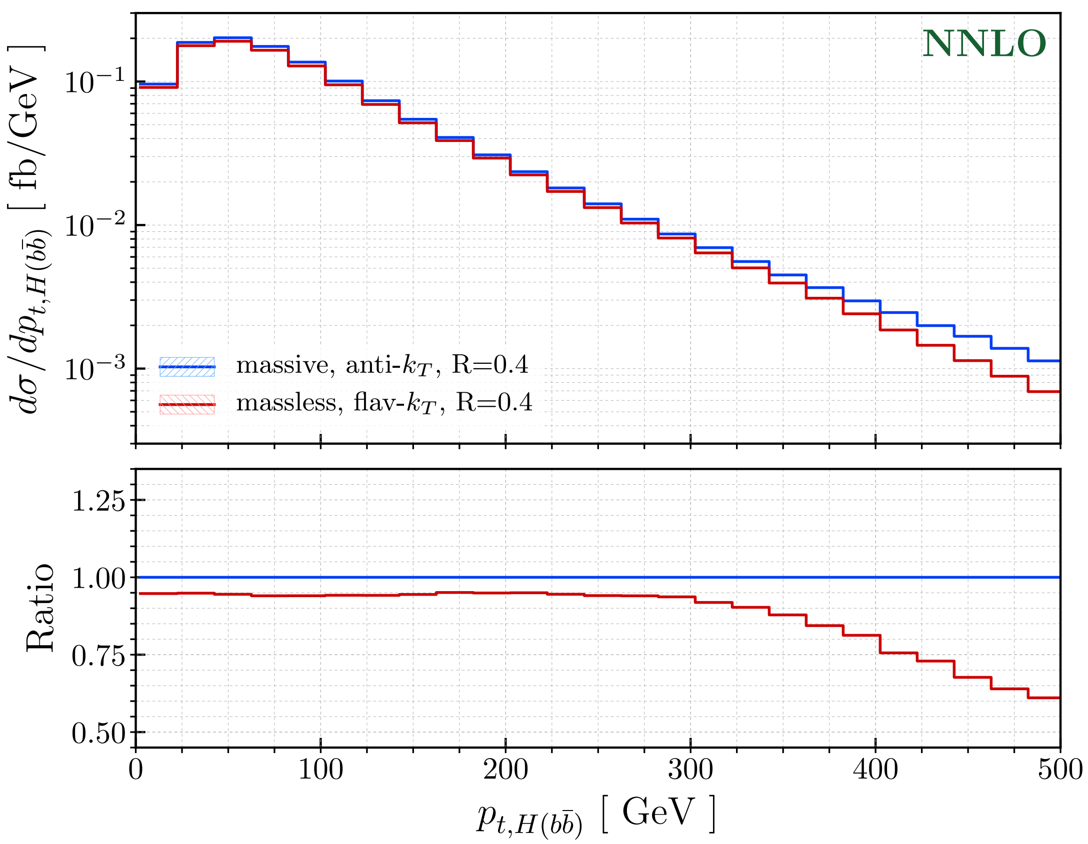
H - Small corrections, but shape can differ from structure function approximation
HH - Delicate cancellations between diagrams spoiled, giving rise to a large corrections

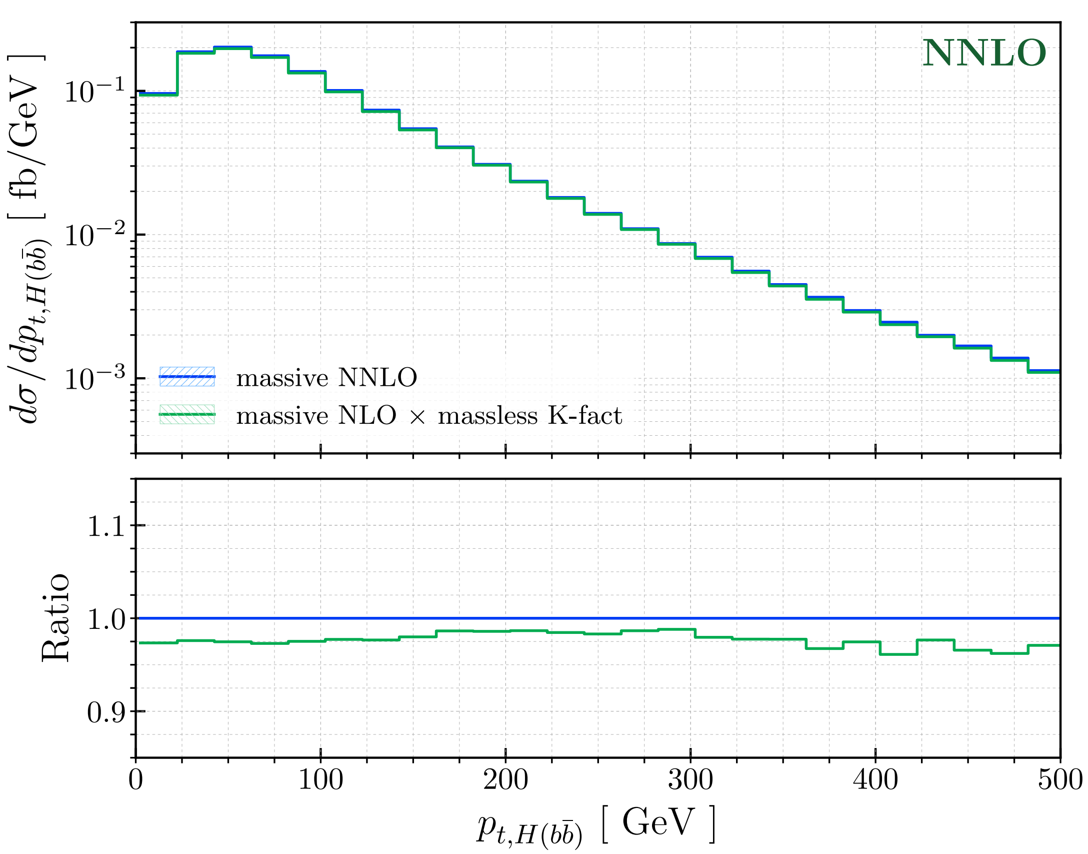
$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{HH,\mathrm{nf}} \sim \widetilde{\alpha}_s^2 \Big[\left(1 - \frac{\pi^2}{3}\right) \left(\mathrm{d}\sigma^{\mathrm{LO}}_{TT} + \mathrm{d}\sigma^{\mathrm{LO}}_{TB}\right) + \left(\frac{5}{4} - \frac{\pi^2}{3}\right) \mathrm{d}\sigma^{\mathrm{LO}}_{BB} \Big] .$$

(As pointed out by authors) Eikonal approximation not trustworthy for too high $p_{t,j}$



VH: NNLO WH with b mass effects





WH production with $H \to b\bar{b}$ now known at NNLO QCD including bottom mass effects
Behring, Bizon, Caola, Melnikov, Röntsch 20

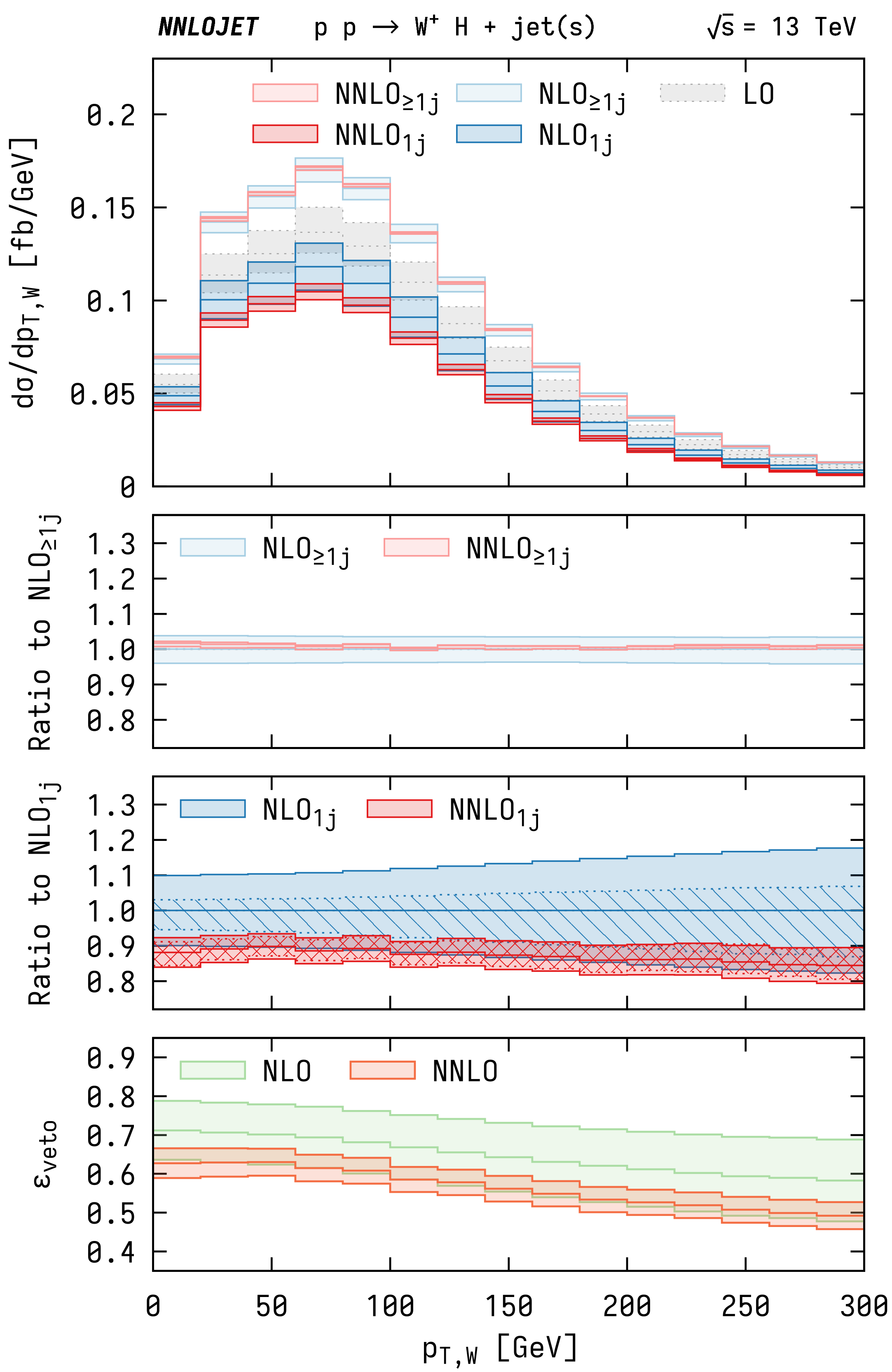
Allows application of realistic jet algorithms for b jets (important for TH vs EXP)

Including b mass increases σ_{tot} by $+6.3\,\%$ ($+7.7\,\%$ for boosted σ_{fid})

Rescaling massive NLO works for some distributions (e.g. $p_{t,H(b\bar{b})}$ but not $m_{H(b\bar{b})}$)

New paper today:
Anomalous couplings in WH and ZH @ NNLO QCD with massive b quarks
Bizon, Caola, Melnikov, Röntsch 21

VHj: NNLO WH + jet(s)



NNLO QCD including Drell-Yan type and top-loop induced contributions

Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 20

Flat K-factors ~1 for inclusive jet production

Corrections $\mathcal{O}(-10\%)$ for exclusive jet production (residual TH uncertainty $\mathcal{O}(5\%)$)

NLO/NNLO predictions consistent only when **uncorrelated** prescription for evaluating TH uncertainty is used

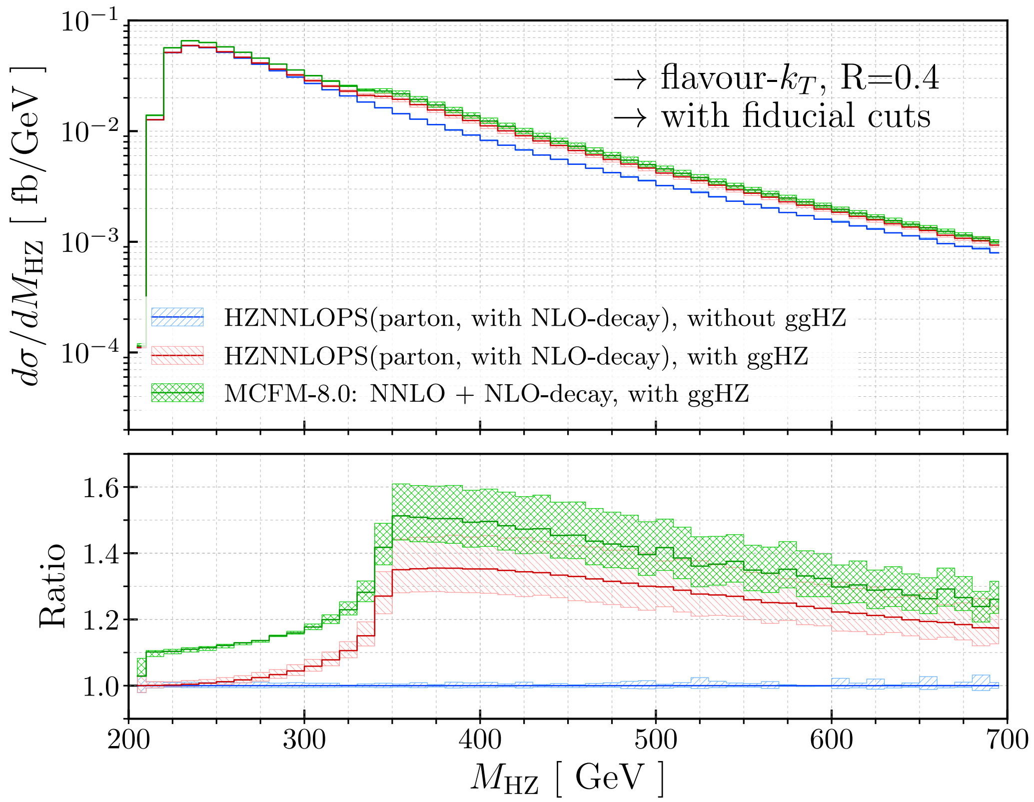
$$\sigma_{1j} \equiv \sigma_{\geq 1j} - \sigma_{\geq 2j} \,, \qquad \Delta^2_{1j} = \Delta^2_{\geq 1j} + \Delta^2_{\geq 2j}$$

Stewart, Tackmann 11

Future:

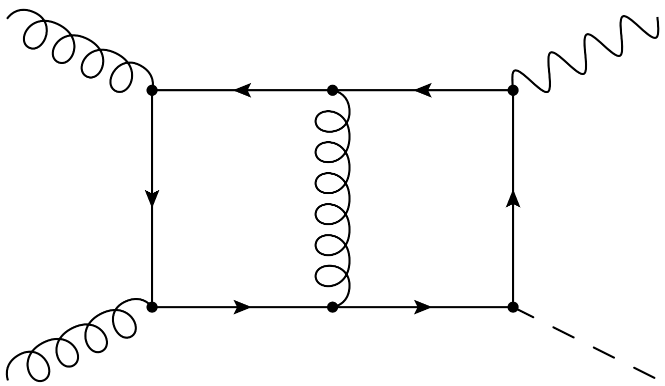
What should we be doing with b-jets in general? Want a procedure close to EXP but which we can handle theoretically (correct treatment of $g \to b\bar{b}$)

$ZH/ZZ/WW$: Gluon fusion virtuals



Astill, Bizon, Re, Zanderighi 18

Sizeable impact of $gg \to ZH$ above top-quark threshold, desirable to have to NLO



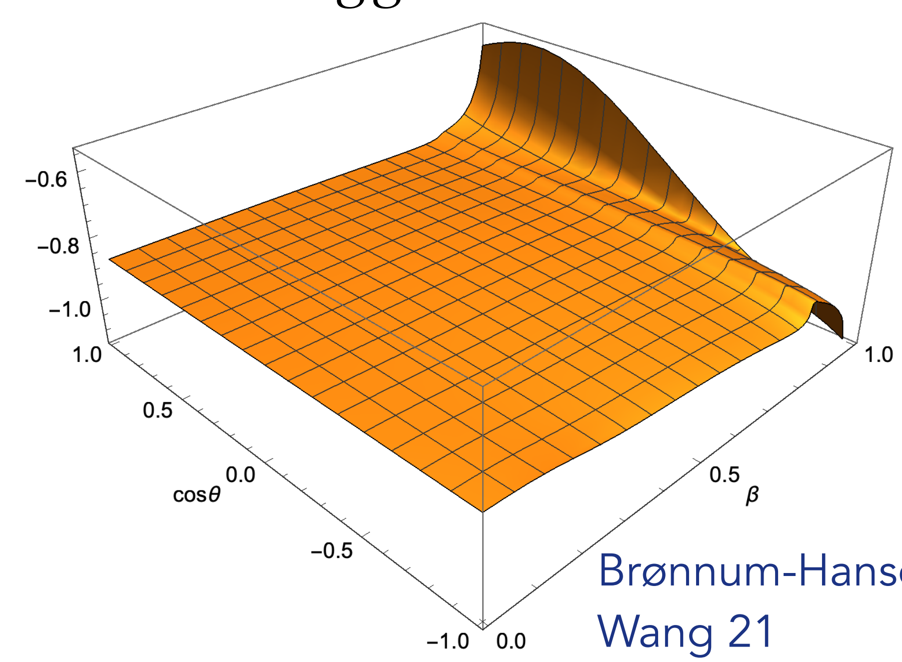
TH progress: virtuals complete

Davies, Mishima, Steinhauser 20;
Chen, Heinrich, Jones, Kerner, Klappert, Schlenk 20;

Virtuals complete also for $gg \to WW$ and $gg \to ZZ$

Davies, Mishima, Steinhauser, Wellmann 20; Brønnum-Hansen, Wang 20, 21;
Agarwal, Jones, von Manteuffel 20;

$gg \to ZZ$



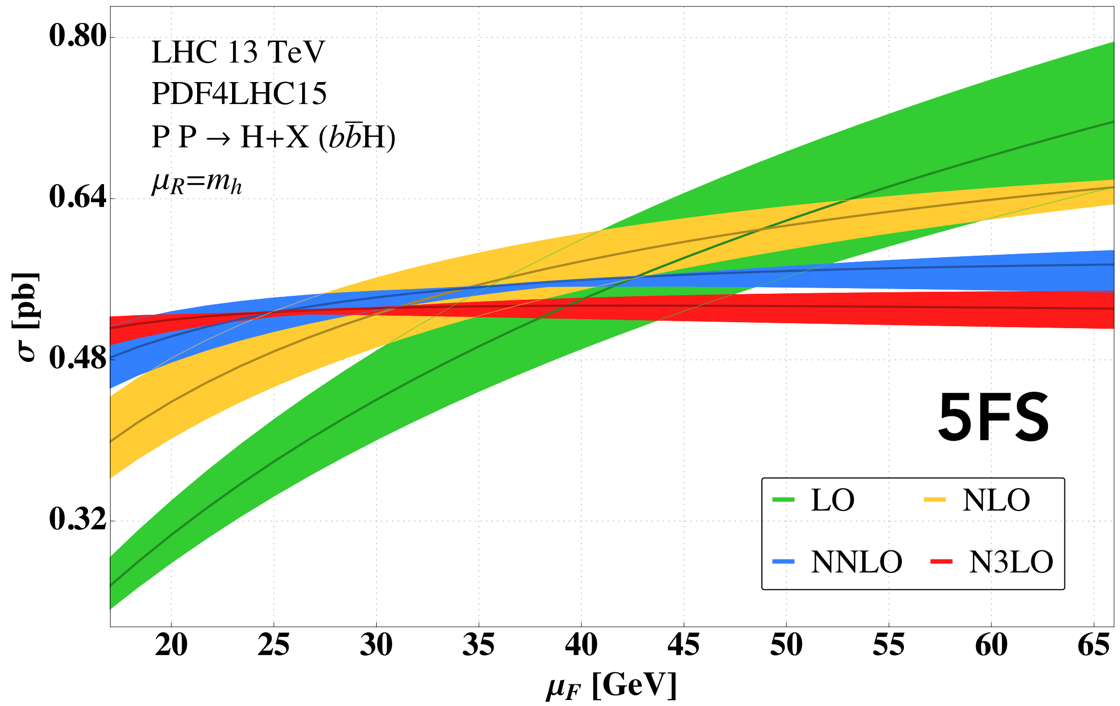
Brønnum-Hansen, Wang 21

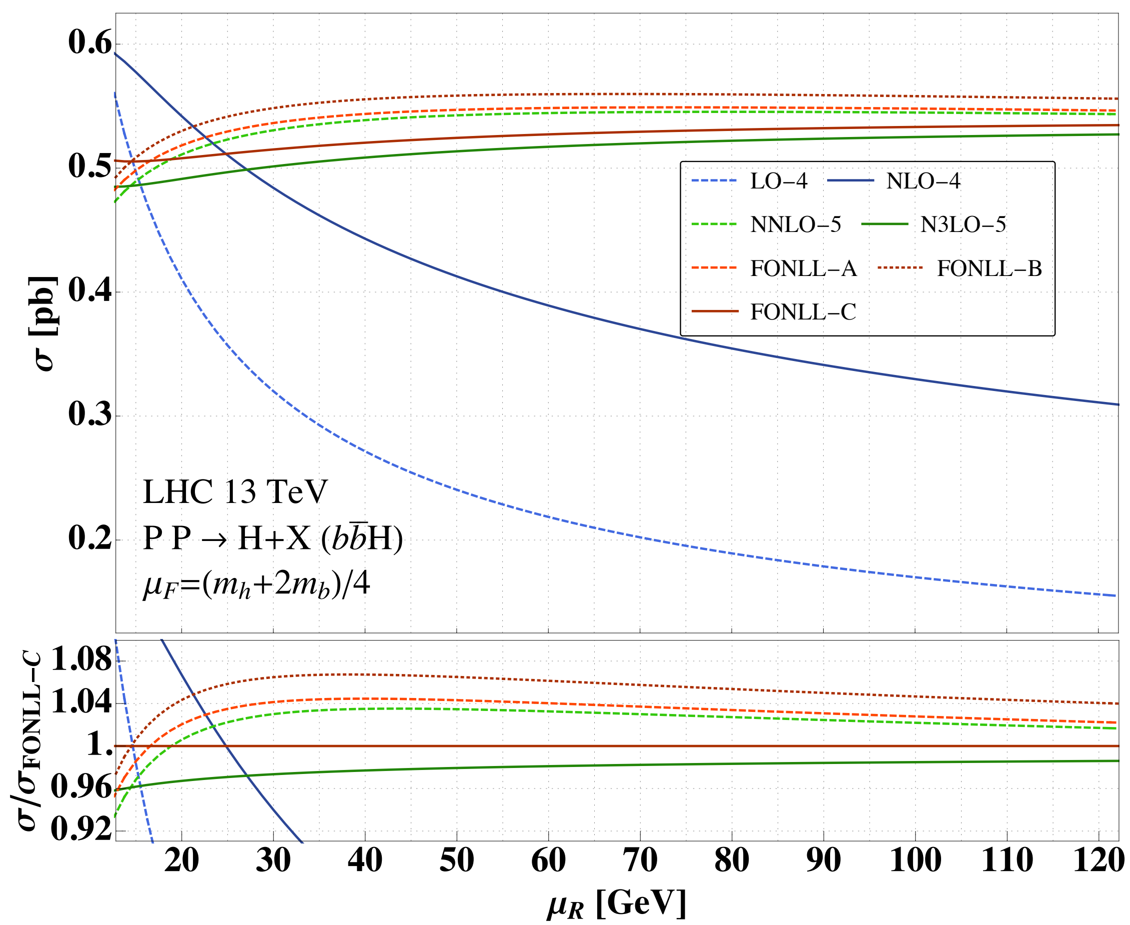
Future:

Interesting to see impact of these corrections above/around top-quark

Must not forget mass-scheme uncertainty

$b\bar{b} \to H$: N³LO QCD





N³LO QCD corrections to $b\bar{b} \to H$

Duhr, Dulat, Hirschi, Mistlberger 20

Supports choice of a rather small value for μ_F

Examined 3 matching procedures for 4FS/5FS

$$\sigma^{\rm matched} = \sigma^{(4)} + \sigma^{(5)} - \sigma^{(4-5)}$$

FONLL-A: All ingredients $\mathcal{O}(\alpha_s^2)$

NNLO 5FS matched to LO 4FS

FONLL-B: All ingredients $\mathcal{O}(\alpha_s^3)$ except parts of $\sigma^{(5)}$ with a b-quark in the initial state, kept to $\mathcal{O}(\alpha_s^2)$

Retains NLO accuracy of 4FS

FONLL-C: All ingredients $\mathcal{O}(\alpha_s^3)$

N³LO 5FS matched to NLO 4FS

Matching increases $\sigma_{\rm tot}$ by $+2\,\%$

New b-initiated channels give a **large negative** contribution

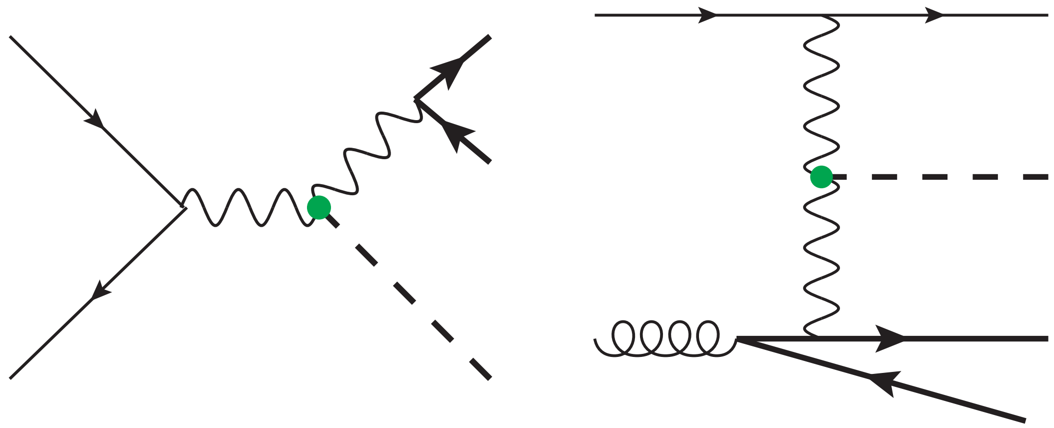
Questions: Anything general to learn about 4FS/5FS from this?

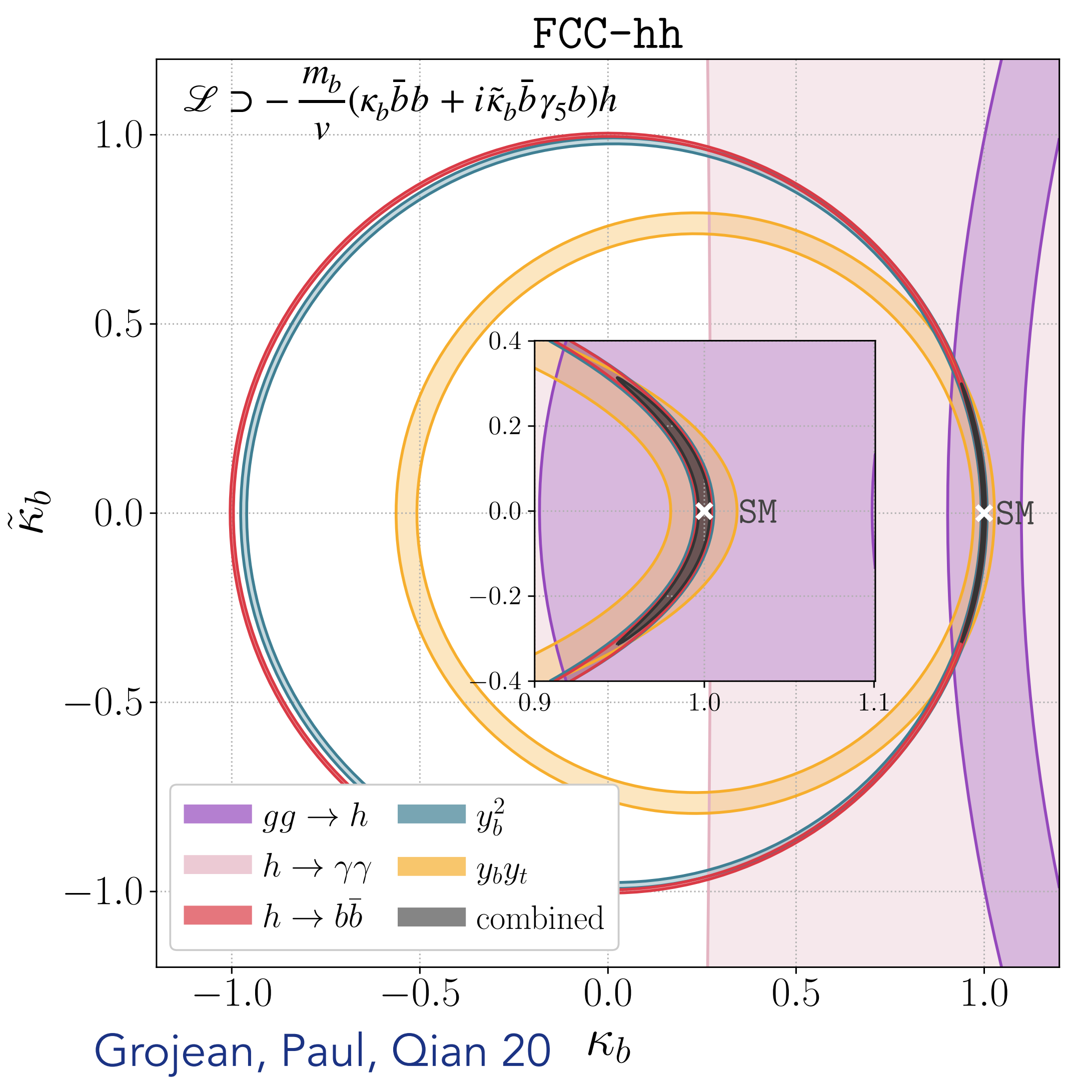
RIP $Hb\bar{b}$?

$Hb\bar{b}$ studied accounting for all 1-loop and real-emission corrections of QCD and EW origin $\mathcal{O}(\alpha_s^m \alpha^{n+1})$ with $m+n=2,3$

Challenging to extract genuine y_b^2 signal due to huge ZH, VBF backgrounds (even differentially)

Pagani, Shao, Zaro 20





Grojean, Paul, Qian 20

But BDTs can still separate the hidden signal?

Grojean, Paul, Qian 20

Authors applied a variety of techniques: interpretable machine learning, kinematic shapes, Shapley values,…

Still @ HL-LHC $h \to b\bar{b}$, $gg \to h$ very constraining

@ FCC-hh $Hb\bar{b}$improves bounds on phase by $15\,\%$

Future:

Clearly a challenging measurement

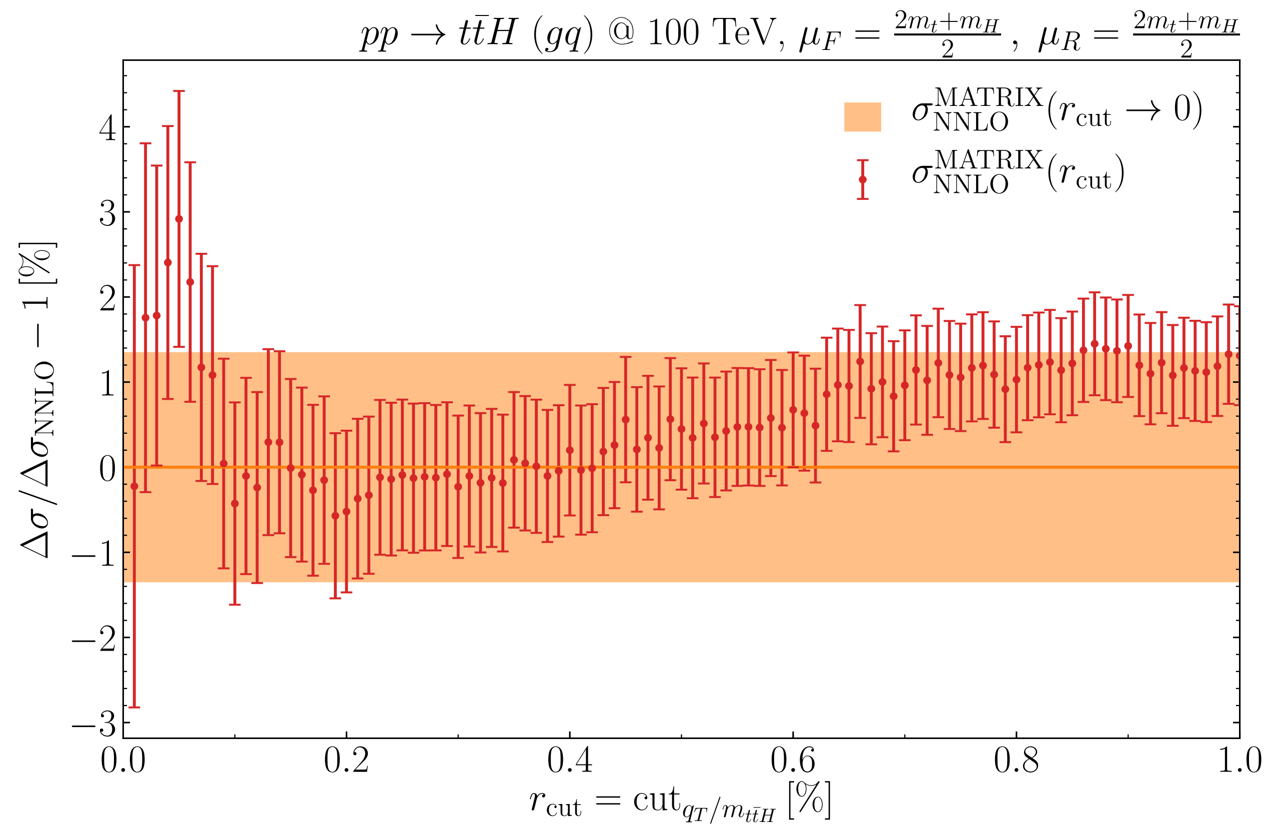
A good testing ground for separating S/B

$t\bar{t}H$: NNLO QCD Off-Diagonal Contributions

$ab \to t\bar{t}H + X$, off-diagonal contributions $(qg, qq, qq', q\bar{q}' \quad (q \neq q'))$ obtained @ NNLO

Catani, Fabre, Grazzini, Kallweit 21

Fully differential results obtained using the q_T subtraction method, can be applied generally to $Q\bar{Q}F$ (where F is a colourless final state system)



σ [fb]	13 TeV	100 TeV
LO	394.987(3)	28228.2(2)
NLO (MADGRAPH5_AMC@NLO)	499.76(4)	36948(3)
NLO (MATRIX)	499.73(1)	36947(1)
NLO (q_T)	499.79(4)	36947(3)
$\mathcal{O}(\alpha_S^4)_{qg}$	−0.796(27)	214.7(2.9)
$\mathcal{O}(\alpha_S^4)_{q(\bar{q})q'}$	0.62694(82)	95.307(56)

No big surprises, $\mathcal{O}(\alpha_s^4)$ contribution of off-diagonal channels found to contribute at few per mille level

Future:
Clearly, interesting to see the impact of diagonal channels @ NNLO

New paper today: Higgs-boson production in top-quark fragmentation, can obtain top-quark/Higgs boson mass dependence from massless calculations

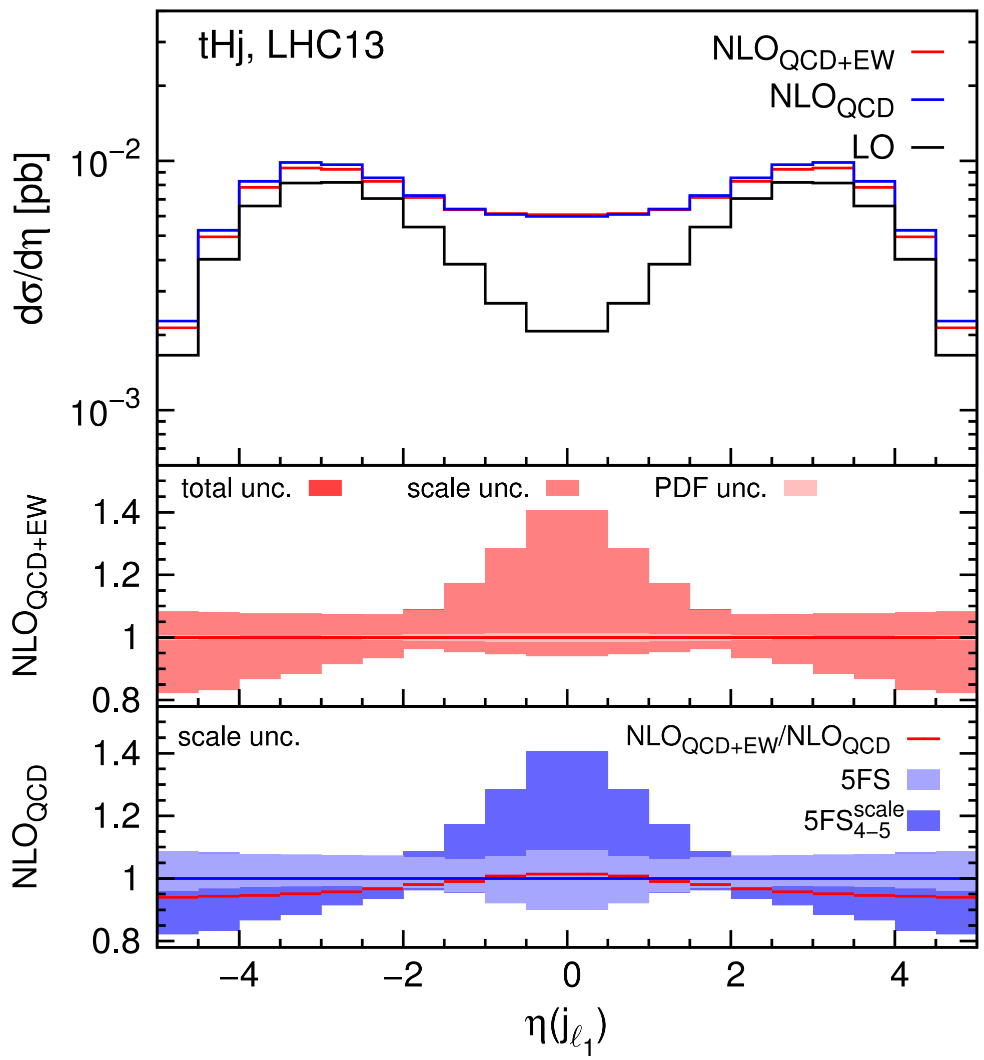
Brancaccio, Czakon, Generet, Krämer 21

tHj and *tZj*: NLO QCD+EW predictions

tHj and *tZj* computed at NLO QCD+EW accuracy in 5FS, ``matching'' to 4FS proposed
Pagani, Tsinikos, Vryonidou 20

NLO EW corrections found to be within NLO QCD theory uncertainties only if 4FS/5FS uncertainty taken into account ($5\mathrm{FS}^{\mathrm{scale}}_{4-5}$)

Accuracy	Channel	FS	tHj
$\mathrm{NLO_{QCD}}$	t-ch.	4FS	$68.1(1)^{+2.7(+4.0\%)}_{-4.5(-6.6\%)}\ ^{+0.4(+0.5\%)}_{-0.4(-0.5\%)}$
		5FS	$71.3(1)^{+5.2(+7.2\%)}_{-1.7(-2.4\%)}\ ^{+0.3(+0.5\%)}_{-0.3(-0.5\%)}$
		$5\mathrm{FS}^{\mathrm{scale}}_{4-5}$	$71.3(1)^{+5.2(+7.2\%)}_{-7.7(-10.9\%)}\ ^{+0.3(+0.5\%)}_{-0.3(-0.5\%)}$
$\mathrm{NLO_{QCD}}$	t-ch., s-ch., tW_h	5FS	$85.1(2)^{+5.4(+6.4\%)}_{-2.3(-2.7\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$
		$5\mathrm{FS}^{\mathrm{scale}}_{4-5}$	$85.1(2)^{+6.2(+7.2\%)}_{-9.2(-10.9\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$
$\mathrm{NLO_{QCD+EW}}$	t-ch., s-ch., tW_h	5FS	$82.2(2)^{+5.6(+6.8\%)}_{-2.4(-2.9\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$
		$5\mathrm{FS}^{\mathrm{scale}}_{4-5}$	$82.2(2)^{+5.9(+7.2\%)}_{-8.9(-10.9\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$



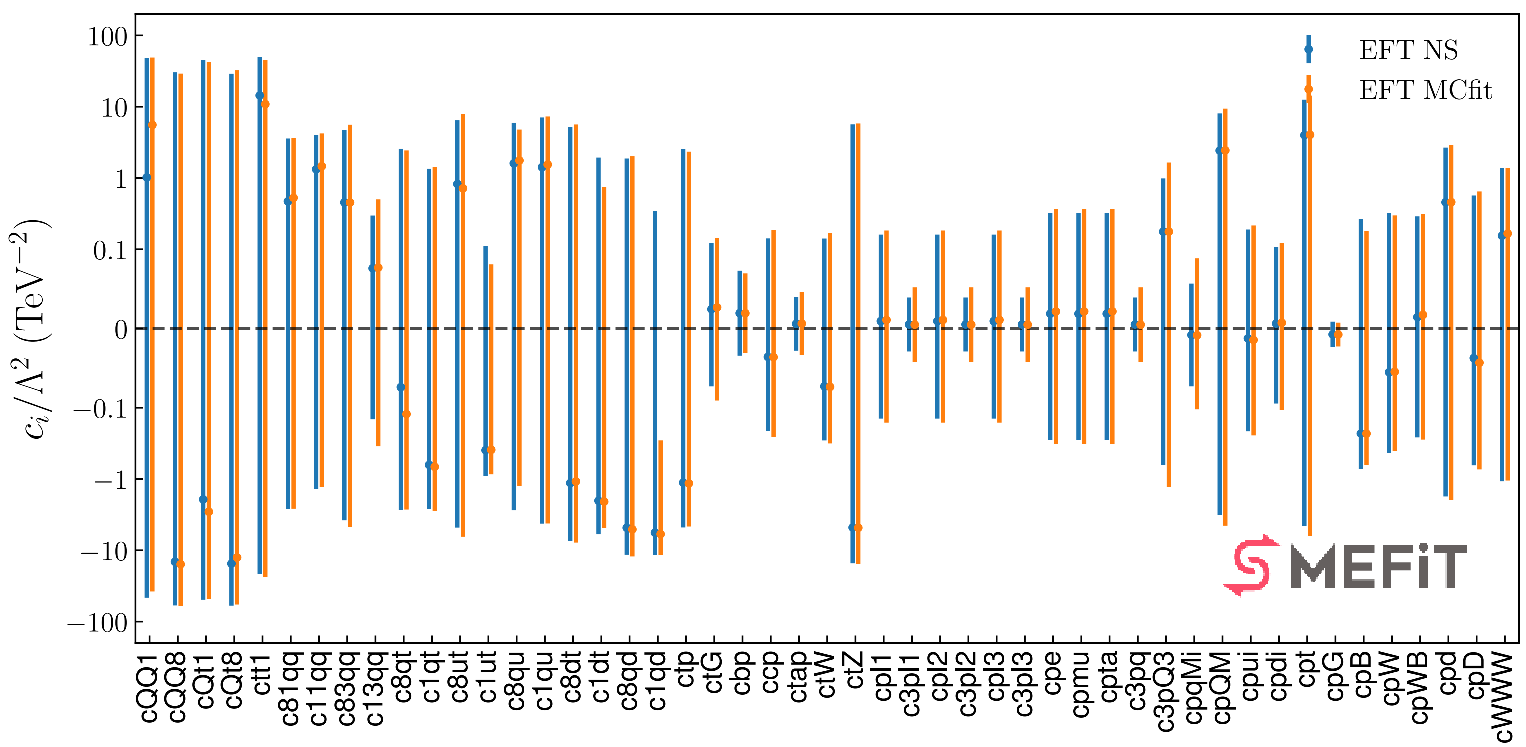
EW corrections reduce σ_{tot} by $-3.4\ \%$, also slightly alter shape

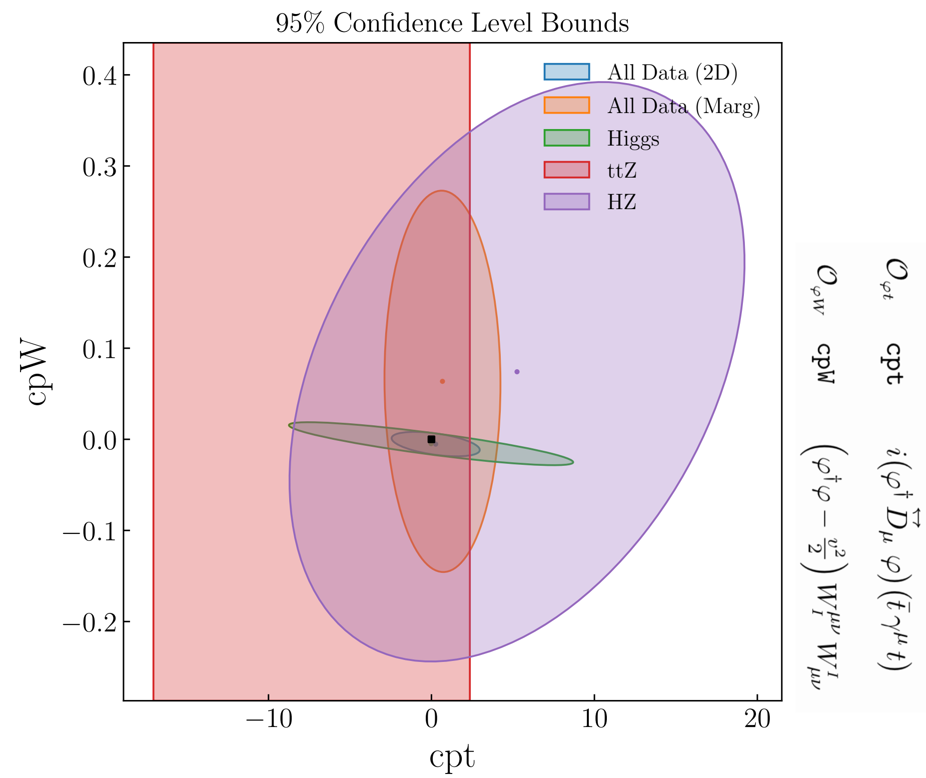
Note: Separation of $t-$channel, $s-$channel or tW production modes not properly defined at NLO EW accuracy, estimation of FS uncertainty not trivial

EFT: top+higgs global fits

Significant advances in global EFT fits to Higgs, diboson, top and EW data,
Also accounting for linear and quadratic corrections in the $1/\Lambda^2$ expansion

Several mature codes now publicly available e.g. SMEFIT, Fitmaker
Ellis, Madigan, Mimasu, Sanz, You 20; Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang 21





NLO QCD corrections to EFT cross-sections automated and an have non-trivial impact on fit (best-fit, CL intervals)

Future:

Data from high-p_T VBS, Z-production in VBF, DY, multi-jet?
Flavour data from LHCb, Belle…
Low energy e.g. neutrino data, electric dipole moment…
Develop ``statistically optimal'' observables for EFT

Conclusion

Strange times, strange location, strange talk…

Really incredible progress has been made since the last LH:

- Wish-list has been thoroughly attacked from all sides
- Many interesting topics have (re-)emerged (fiducial cuts and IR sensitivity, QCD-EW corrections, b-jets, 4FS/5FS, non-factorisable contributions to VBF)
- Much, much, more… (please bring them up during the discussion!)

Very hard to capture the spirit of Les Houches in a Zoom talk

This year we will miss the mountains, but hopefully not the discussion…

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ (incl.) $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$ $\mathrm{NNLO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{N^3LO_{HTL}}$ (partial results available) $\mathrm{NNLO_{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO^{(VBF)}_{QCD} + NLO^{(VBF)}_{EW}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to H + V$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{NLO^{(t,b)}_{gg \to HZ}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$

LH2019 Wishlist


Thank you for listening!