# Higgs Theory

Conveners:
(TH) Daniel de Florian, Stephen Jones

# Outline

**Precision Theory Challenges**

Theory uncertainties becoming increasingly important

Experiments increasingly able to provide precise differential measurements

\+ Excellent from new physics perspective

\- New challenges for theory precision

Results in next year(s) will serve as legacy: we must think carefully what we do

**Higgs State of the Art**

Gluon-fusion: Inclusive + Rapidity distribution

VBF, VH, ttH

Higgs pt: small/intermediate/boosted

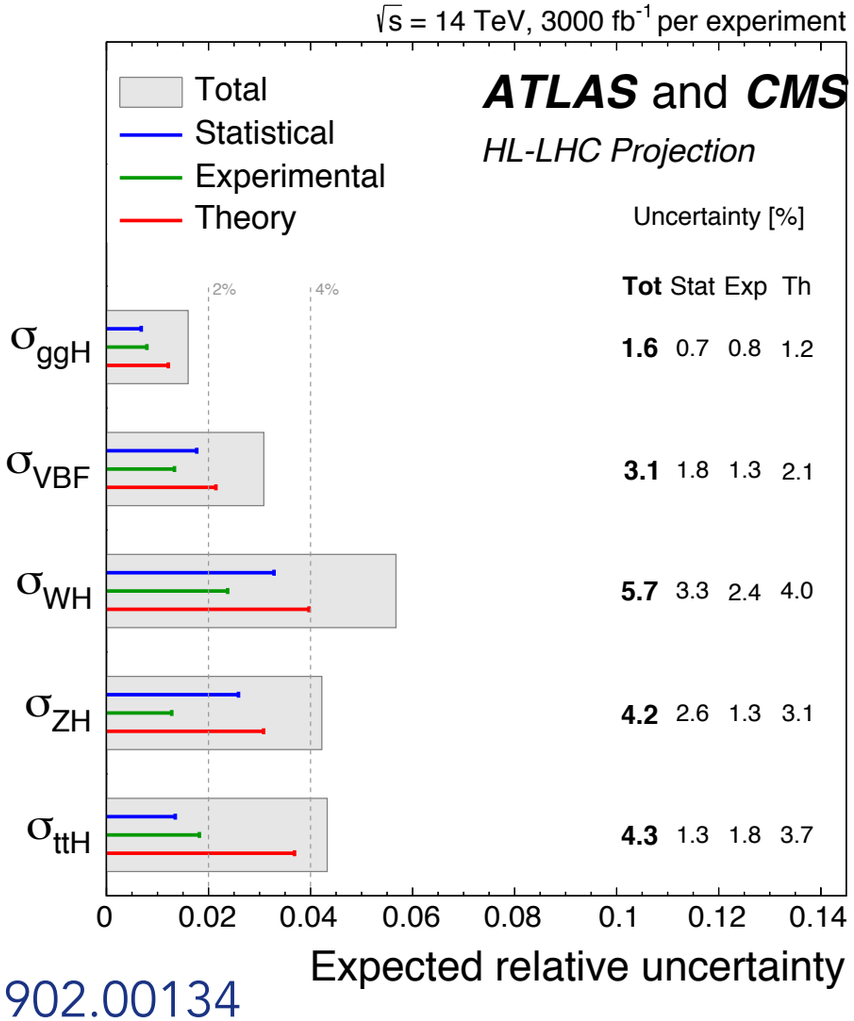
Higgs pair production

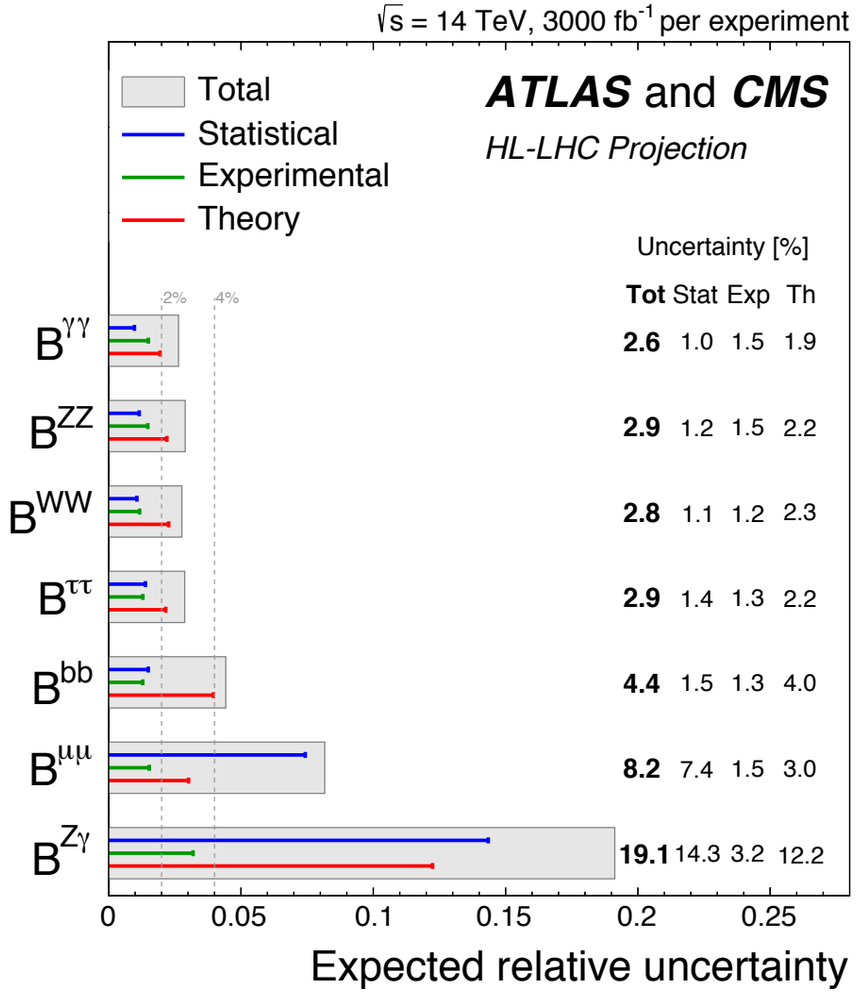
**EFTs for interpreting Higgs Measurements**

# Precision Theory Challenges

HL-LHC Projections

(S2) TH uncertainties scaled down by factor 2, EXP scaled according to $\sqrt{\mathscr{L}}$




**TH errors may dominate**

1902.00134

**Precision becomes even more critical**

TH: Do we miss sources of uncertainty? (HTL, EW corr., PDF MHOU, Schemes, …)

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

# Higgs - Gluon-Fusion

| | | | | |
|---|---|---|---|---|
| $\sigma_{PP\to H+X}$ | = | 16.00 pb | (+32.87%) | LO, rEFT |
| | + | 20.84 pb | (+42.82%) | NLO, rEFT |
| | + | 9.56 pb | (+19.64%) | NNLO, rEFT |
| | + | 1.62 pb | (+3.32%) | N$^3$LO, rEFT |
| | − | 2.07 pb | (−4.25%) | (t,b,c) corr. to exact NLO |
| | + | 0.34 pb | (+0.70%) | $1/m_t$ corr. to NNLO |
| | + | 2.37 pb | (+4.87%) | EWK corr. |
| | = | 48.67 pb . | | |

| | | | | |
|---|---|---|---|---|
| $\delta$(theory) | = | $^{+0.13pb}_{-1.20pb}$ | $(^{+0.28\%}_{-2.50\%})$ | $\delta$(scale) |
| | + | $\pm 0.56pb$ | $(\pm 1.16\%)$ | $\delta$(PDF-TH) |
| | + | $\pm 0.49pb$ | $(\pm 1.00\%)$ | $\delta$(EWK) |
| | + | $\pm 0.41pb$ | $(\pm 0.85\%)$ | $\delta$(t,b,c) |
| | + | $\pm 0.49pb$ | $(\pm 1.00\%)$ | $\delta(1/m_t)$ |
| | = | $^{+2.08pb}_{-3.16pb}$ | $(^{+4.28\%}_{-6.5\%})$ , | |
| $\delta$(PDF) | = | $\pm 0.89$pb | $(\pm 1.85\%)$, | |
| $\delta(\alpha_S)$ | = | $^{+1.25pb}_{-1.26pb}$ | $(^{+2.59\%}_{-2.62\%})$ . | |

**Need to attack on many fronts to further improve**

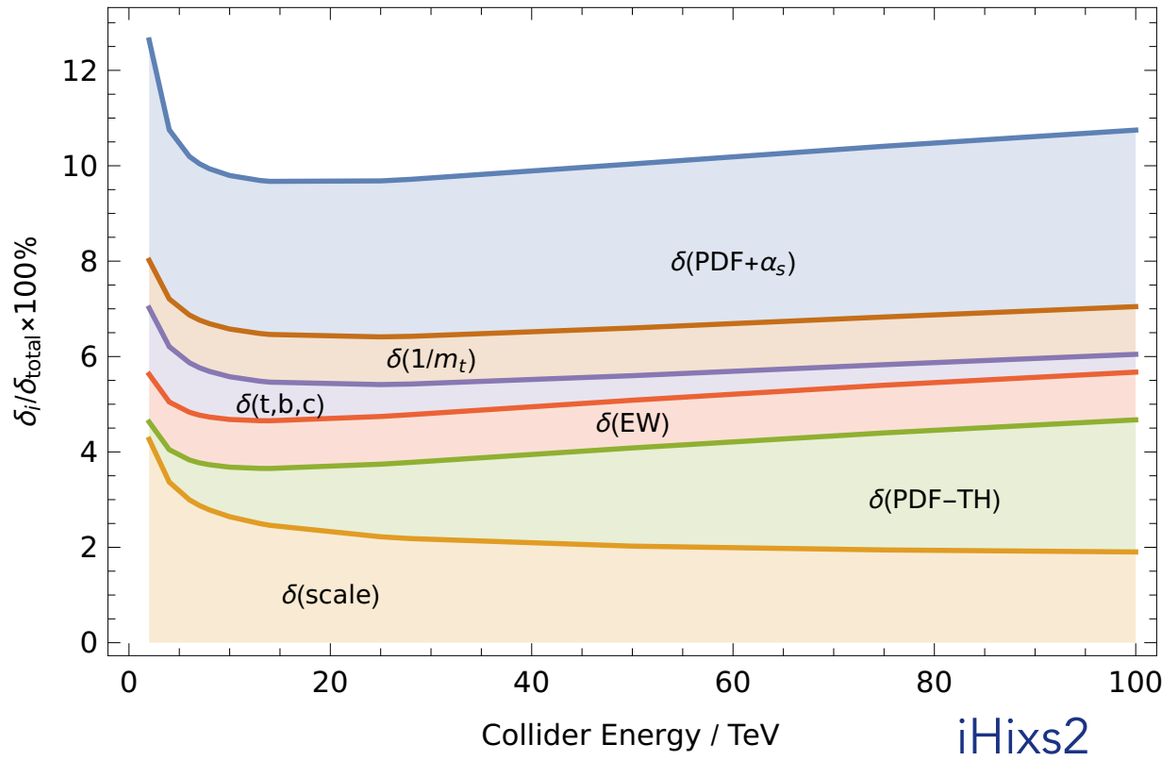
- N$^3$LO PDFS
- Full Mass dependence at NNLO
- EW corrections Bonetti, Melnikov, Tancredi 17,18
- …

**Exact** N$^3$LO Higgs boson production without threshold expansion
Mistlberger 18

Included in a handy code iHixs2
Dulat, Lazopoulos, Mistlberger 18

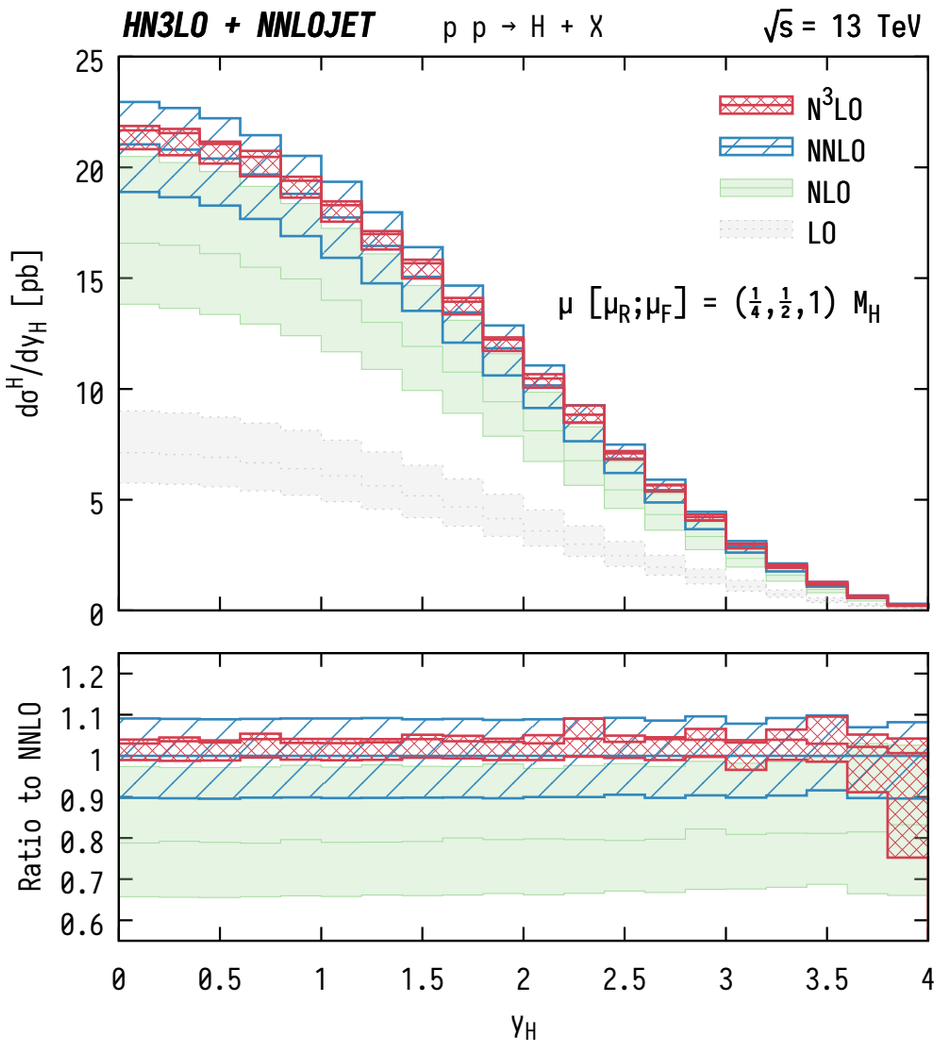
Excellent agreement with threshold expansion for dominant gg channel

Top-quark mass effects known at 3-loop (virtual piece) Davies, Groeber, Maier, Rauh, Steinhauser 19

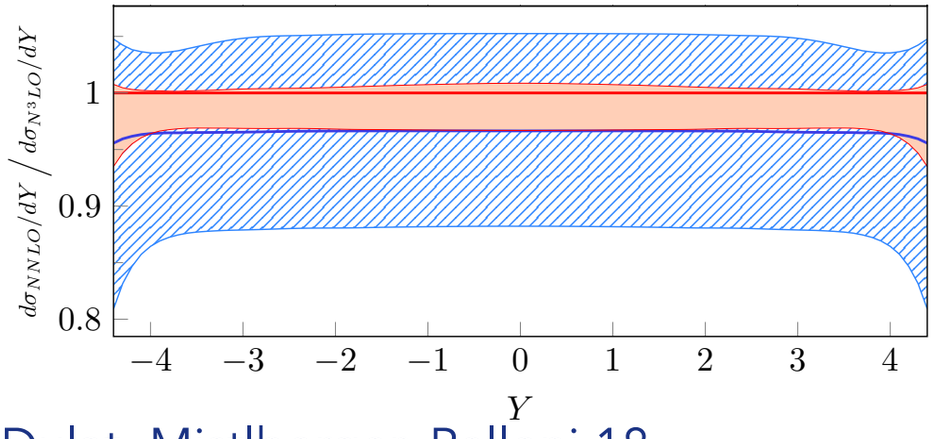


iHixs2

# N³LO Higgs Rapidity




Cieri, Chen, Gehrmann, Glover, Huss 18




Dulat, Mistlberger, Pelloni 18

Both computations at N³LO in good agreement:
1) Cieri et al. - Assumes 3rd order collinear function uniform in rapidity
2) Dulat et al. - Soft expansion

**Remarkably flat K-factor (as expected)**

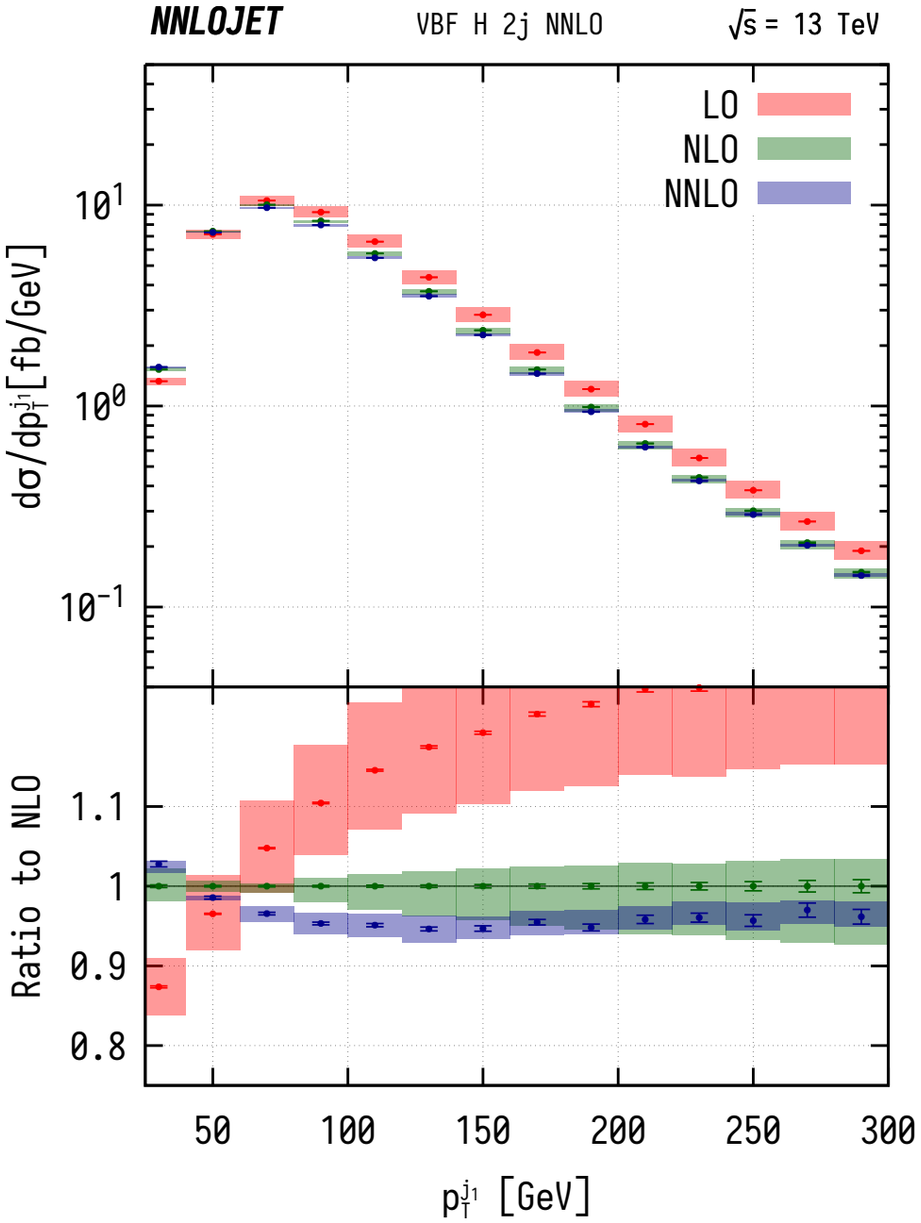
Cieri et al. relies on $q_T$ subtraction, calculation rather time consuming (~7M CPU h)

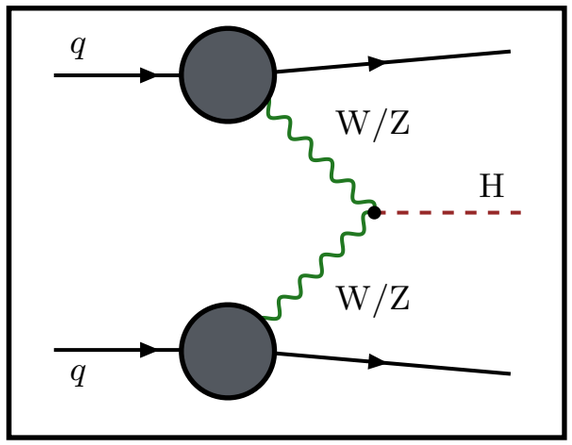
**Future: with decays & in fiducial region**
How good are predictions currently used by EXP?
Best way to use improved TH predictions…

# VBF Higgs production

NNLO QCD corrections to VBF-2j production and NLO QCD corrections to VBF-3j production using structure function approach Cruz-Martinez, Gehrmann, Glover, Huss 18

Uncovered error in earlier calculation stemming from VBF-3j piece (now fixed)
Cacciari, Dreyer, Karlberg, Salam, Zanderighi 15; Figy, Hankele, Zeppenfeld 07




NNLO Cross section ~4% smaller than NLO (with VBF cuts)

VBF di-Higgs production now also known at N³LO and NNLO (fully differential)
Dreyer, Karlberg 18, 18

**Common project with Jets group:**
Prospects for quark/gluon jet tagging for VBF?

# Higgs - VH

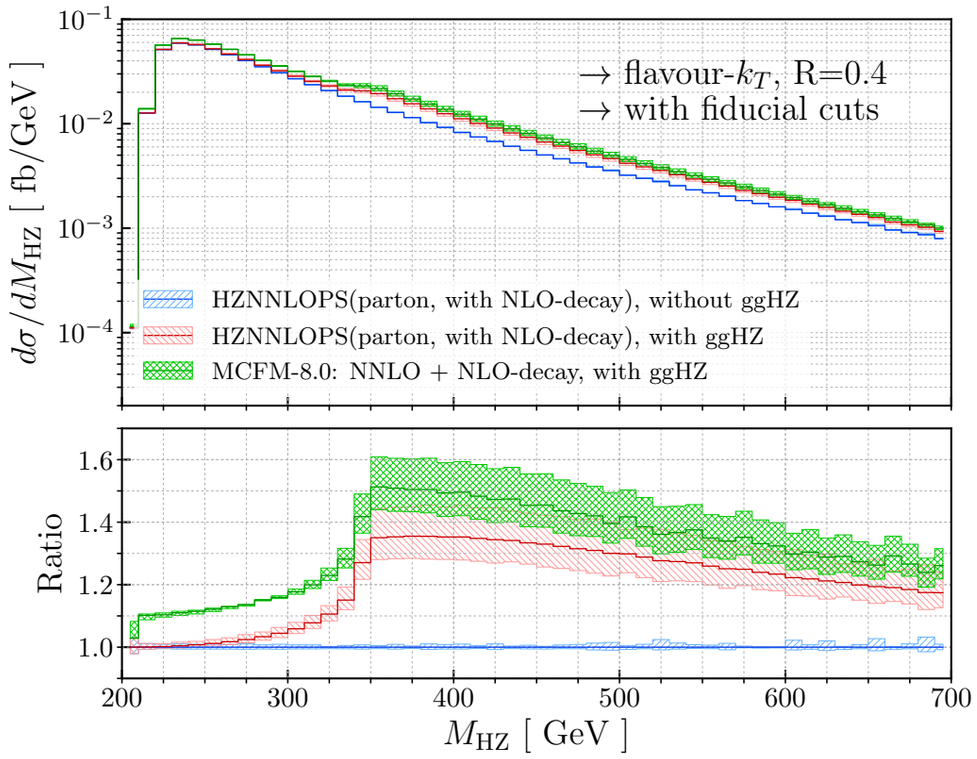
NNLO QCD corrections (both production and decay) to $pp \to W(l\nu)H(b\bar{b})$ using NWA and $m_b = 0$* Ferrera, Somogyi, Tramantano 17; Caola, Luisoni, Melnikov, Röntsch 17

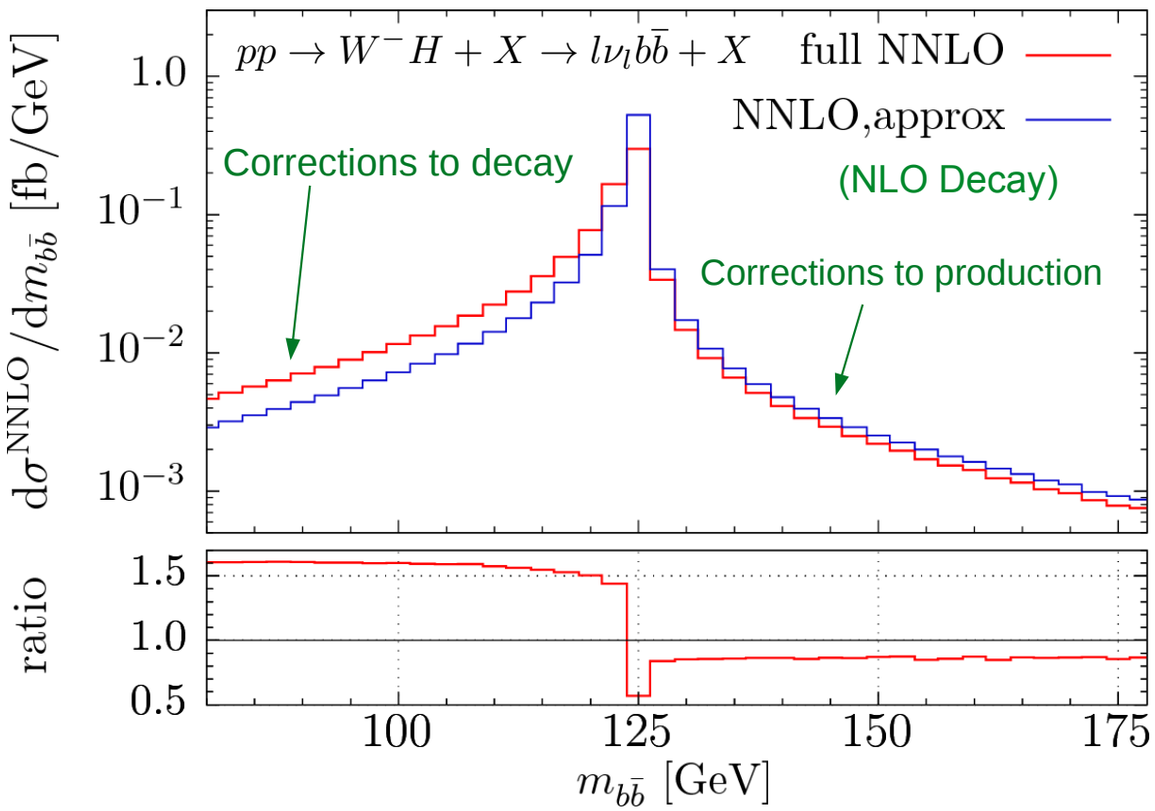
Significant corrections to some distributions (those trivial at LO)

PS captures some of the effect

Include NNLO calculation of $H \to b\bar{b}$ with massive bottom quark?

Bernreuther, Chen, Si 18; Primo, Sasso, Somogyi, Tramontano 18




NNLOPS accurate $pp \to H(b\bar{b})Z(l^+l^-)$

Astill, Bizon, Re, Zanderighi 18

Sizeable impact of $gg \to HZ$ above top- quark threshold (note: beyond LO ``gluon induced'' reals interfere with $q\bar{q}$, $qg$ channel)

# Higgs - ttH

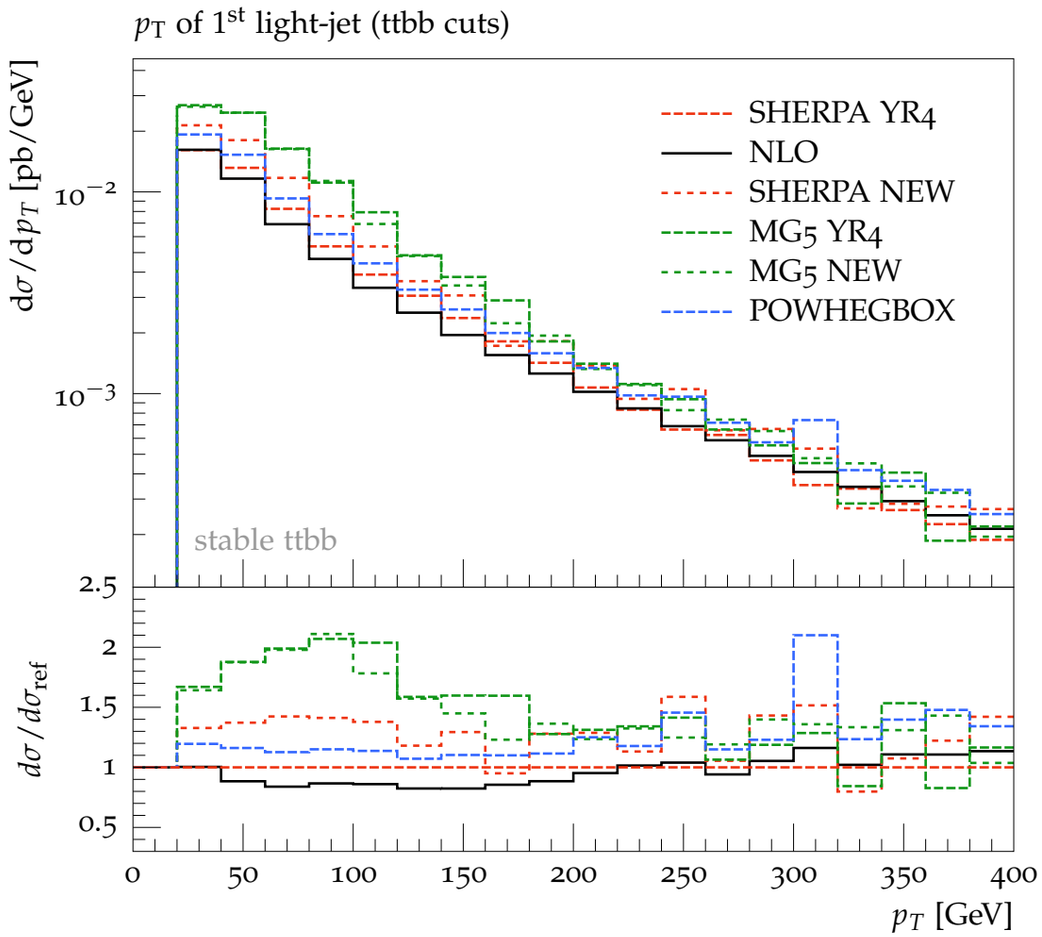
Discovered in Run II CMS-HIG-17-035; CERN-EP-2018-138

Considerable theory uncertainty for $t\bar{t}H$ backgrounds
Experiments use MC modelling for irreducible $t\bar{t}b\bar{b}$ background (NLO+PS+re-weight)

Significant discussion of background within LHCXSWG ttH subgroup:

- Tuned comparison of various PS tools
- Scale tuning using NLO $t\bar{t}b\bar{b}j$
- Finding origin of discrepancy (b-jet bin migrations, large K-factor + spuriously large $R_{PS}$,…?)
- NLO merging of $X + b\bar{b}$ & $X + jj$

  Höche, Krause, Siegert 19




**Room for TH/EXP interaction**

Experiments primarily need guidance for transfer from control to signal regions
How to transfer findings from V+HF to tt+HF?
Can we constrain tt+HF using tt+jets data?

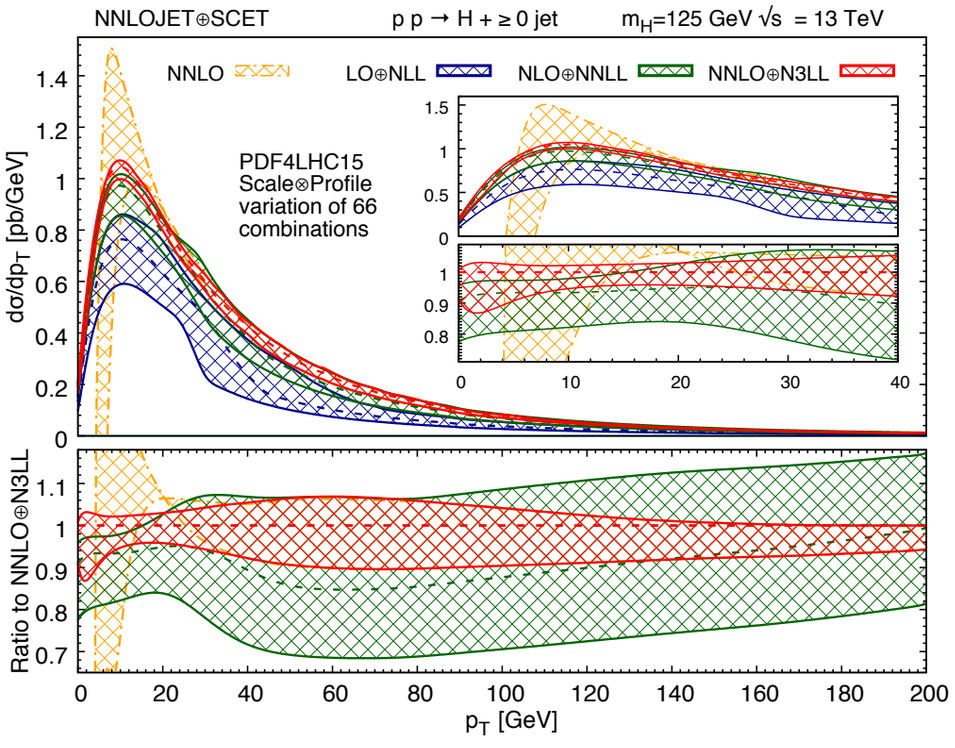
Points taken from:
Frank Siegert (SM@LHC19)

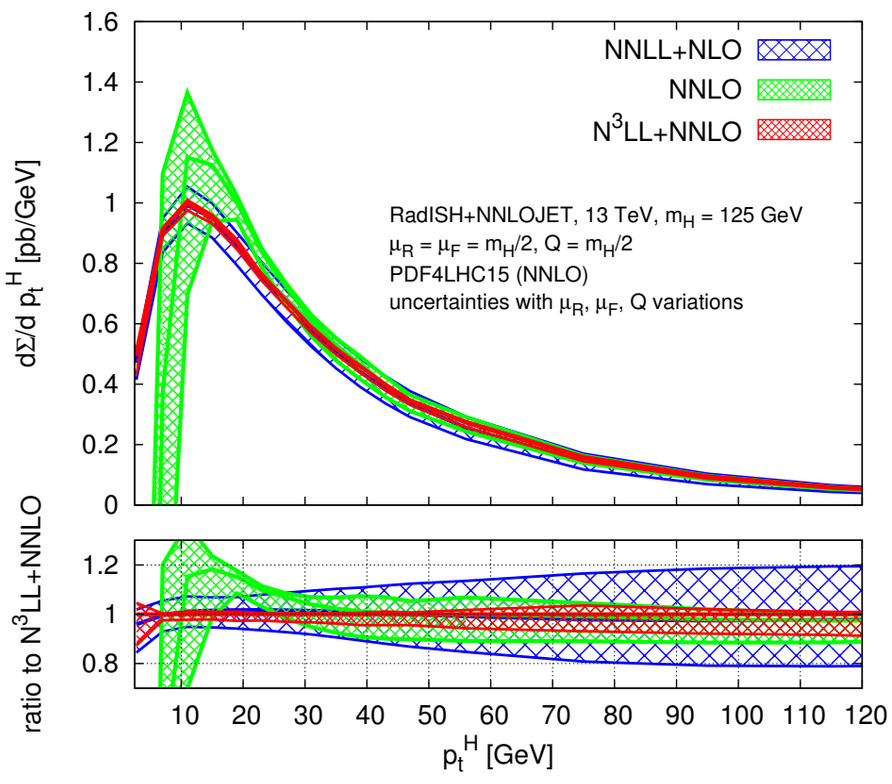
# Higgs - Small pt

Higgs Boson transverse momentum spectrum at small $p_T$ known at NNLO + N$^3$LL

1) SCET based approach Chen, Gehrmann, Glover, Huss, Li, Neill, Schulze, Stewart, Zhu 18
2) Direct QCD Bizoń, Chen, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli 18

Resum $\ln(p_T/m_H)$: remaining perturbative uncertainties ~6% for $5 < p_T < 35$ GeV




Impact of resummation also studied for $H \to \gamma\gamma$ (fiducial)

Found to be rather similar to inclusive case

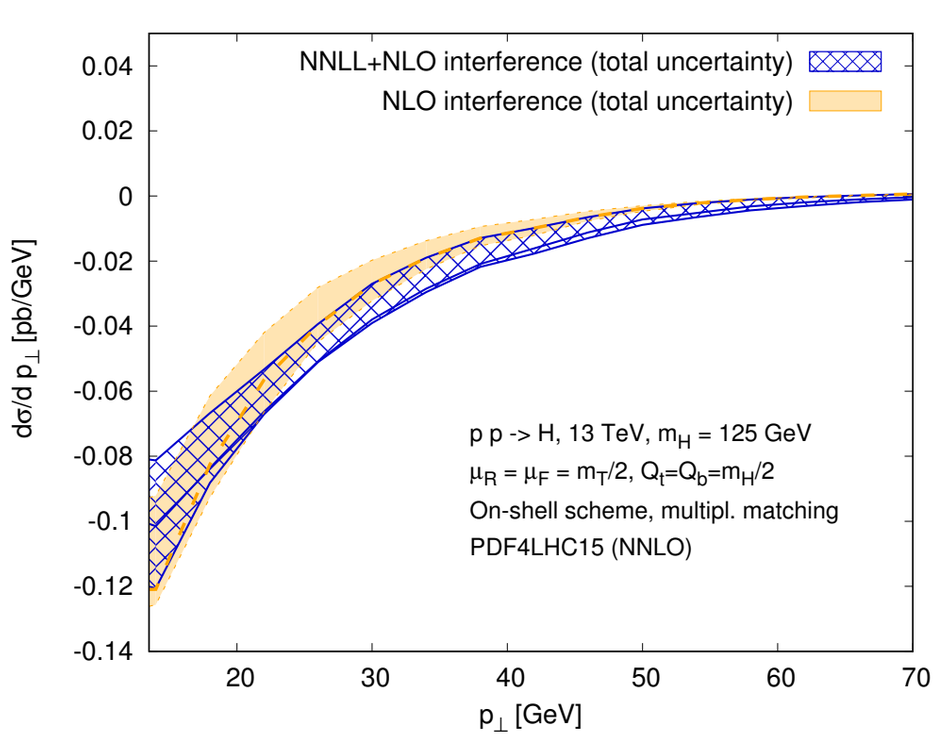
Extremely small scale uncertainty due to accidental cancellation for central scale choice $\mu_F = \mu_R = m_H/2$

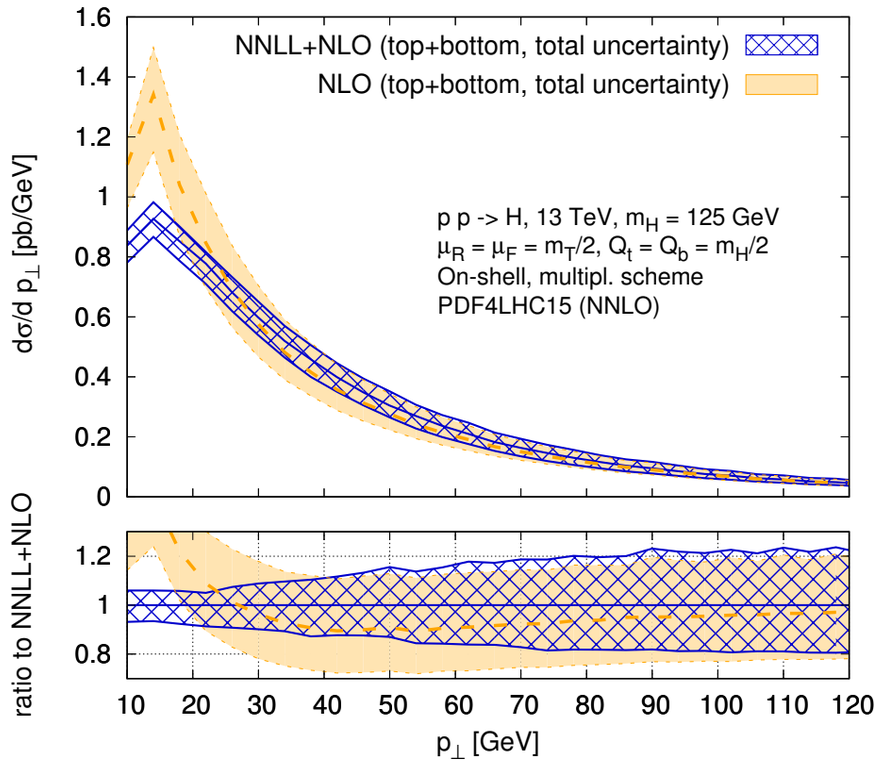
# Higgs - Top/Bottom Interference

Interference studied at NLO+NNLL (for $m_B < p_T < m_T$ )

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

Can combine $m_B^2 \ll |s|, |t|, |u|, m_H^2$ with $m_T \to \infty$ approximation for NLO pieces to compute this effect Melnikov, Tancredi, Wever 17; Lindert, Melnikov, Tancredi, Wever 17




Caola, Lindert, Melnikov, Monni, Tancredi, Wever 18

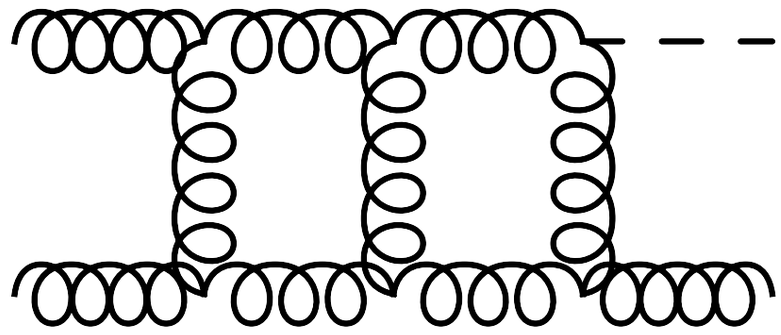
Sizable (~20%) uncertainty from bottom-quark mass scheme choice at small $p_T$ (assessed by comparing $\rm OS$ scheme to $\overline{\rm MS}$ ) - hard to reduce this uncertainty

Does not yet include NNLO+N$^3$LL top-quark only (HTL) result Bizon, Monni, Re, Rottoli, Torrielli 17

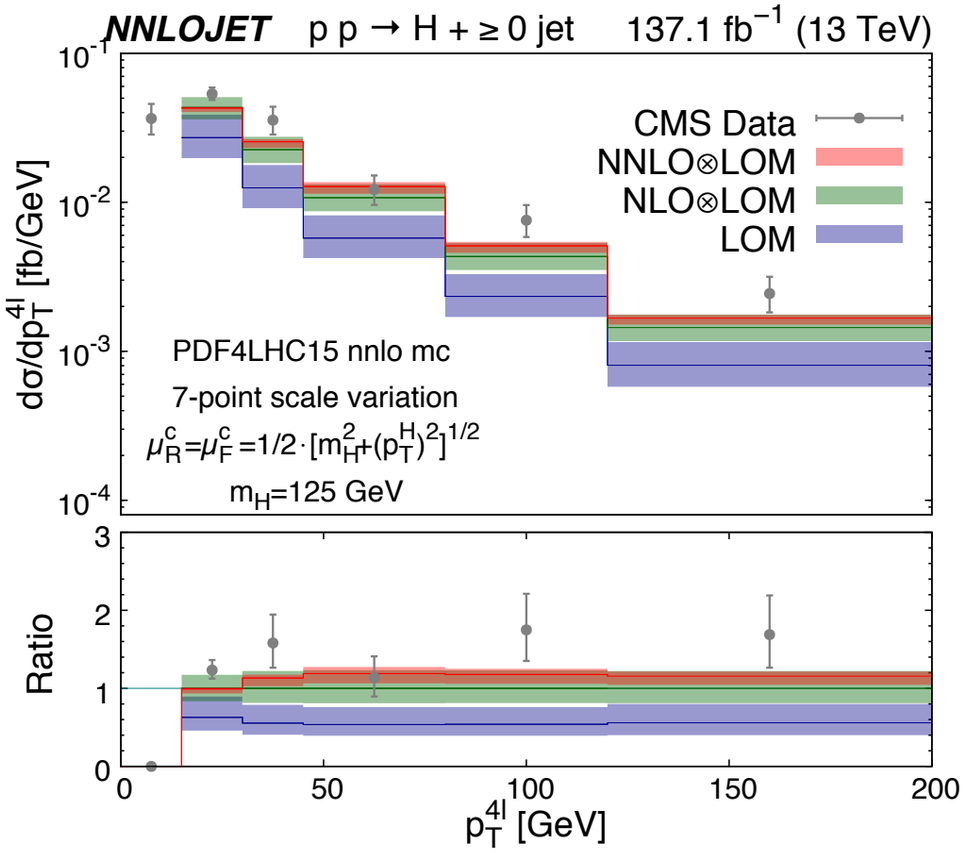
# Higgs - Moderate pt & HTL

H+Jet Computed at NNLO QCD (HTL) by 3 groups

1) Antenna subtraction
   Chen, Gehrmann, Glover, Jaquier 14
2) Sector improved residue subtraction
   Boughezal, Caola, Melnikov, Petriello, Schulze 15
3) N-Jetiness
   Boughezal, Focke, Giele, Liu, Petriello 15



Long standing discrepancy between 1/2 and 3 finally seems to have been resolved (issue with implementations of H+2j, too large $\tau_{\text{cut}}$ ) Campbell, Ellis, Seth 19




Fiducial cross sections for H+Jet now known at NNLO QCD for:

- $H \to \gamma\gamma$
- $H \to WW^* \to (2l,2\nu)$ Caola, Melnikov, Schulze 15
- $H \to ZZ^* \to 4l$ Chen, Gehrmann, Glover, Huss 19

Discussion of acceptance factors for STXS at LO, NLO, NNLO (stability impacted by choice of EXP cuts), Comparison with what EXP are doing?

# Large pt - Boosted Higgs

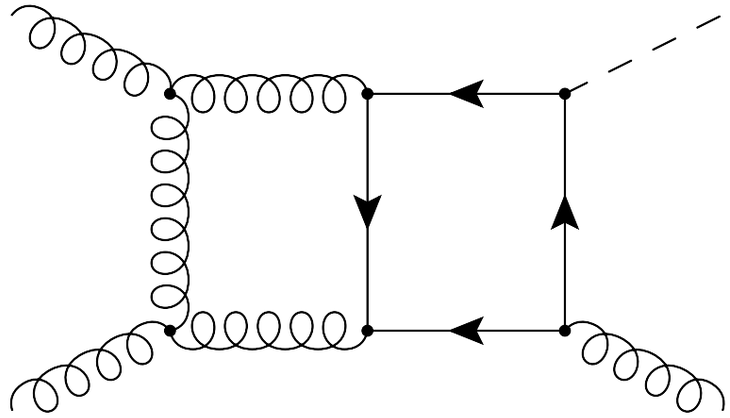
Expect $m_T \to \infty$ approximation to fail, resolve loop

Known at NLO in 2 approaches:

1) Expansion valid for $m_H^2, m_T^2 \ll |s| \sim |t| \sim |u|$

   (Lindert), Kudashkin, Melnikov, Wever 17,18; Neumann 18

2) Exact result (numerical) SPJ, Kerner, Luisoni 18



Large K-factor ~ 2

For the scale choice $\mu = H_T/2$ :

- K-factor very similar to HTL
- K-factor nearly flat at large $p_T$
- ~8% increase from including $m_T$ in virtuals

**Several open questions…**

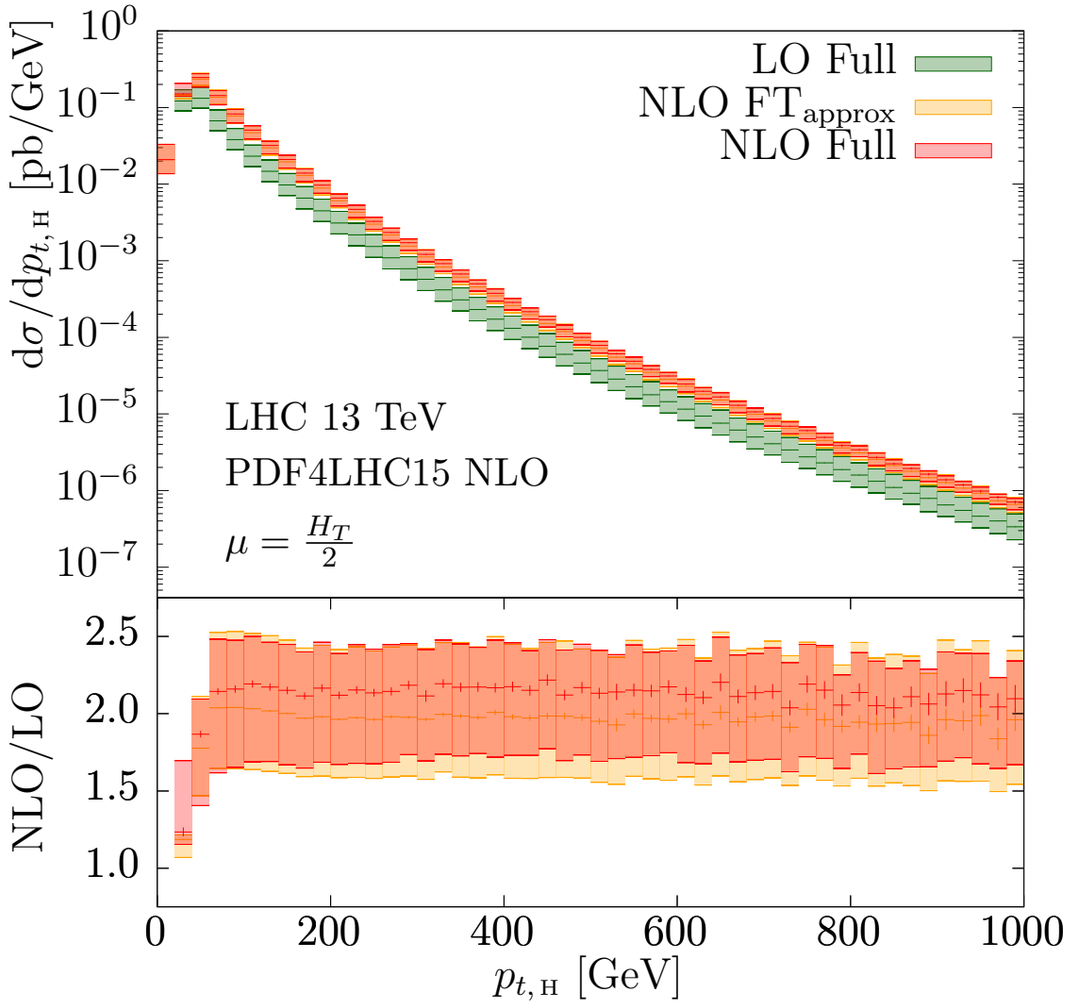
Combination with NNLO HTL

Top-quark mass scheme uncertainty $\mathrm{OS}/\overline{\mathrm{MS}}$

Background processes (V+jets,…)

Electroweak corrections

How well do PS really do (esp. for LO accurate variables)?

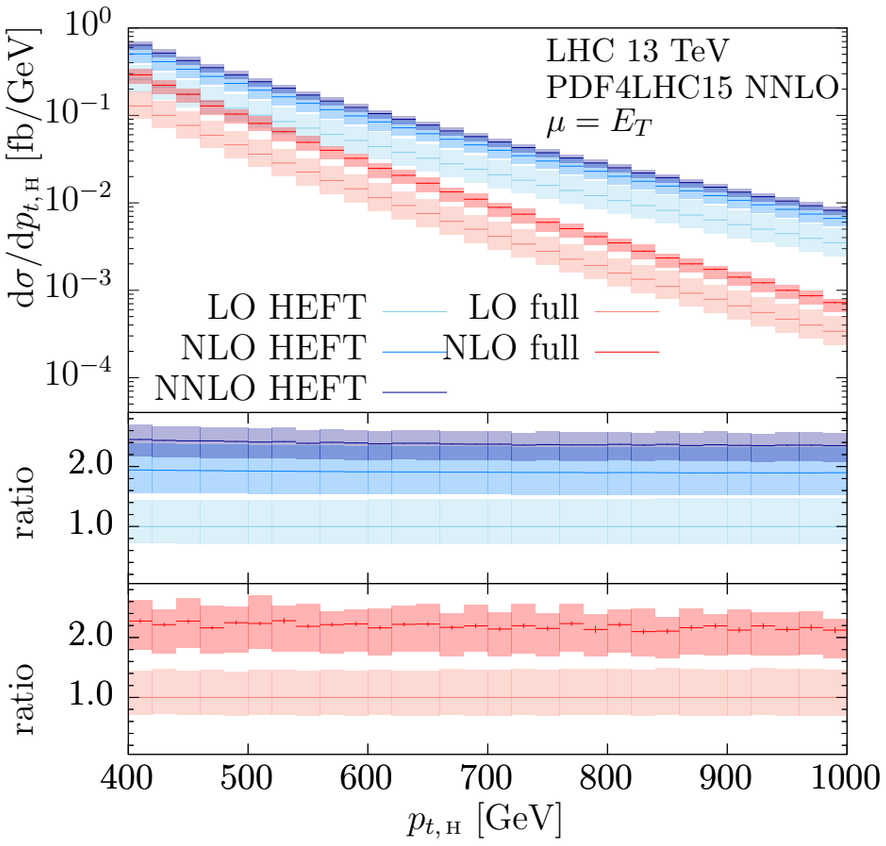


# Large pt - Boosted Higgs (II)

Poor man's NNLO EFT/NLO full combination is available for boosted Higgs:

Rescale NLO by $K_{NNLO} = NNLO_{HTL}/NLO_{HTL}$
Assumes SM/HTL K-factors similar

$$\frac{d\sigma^{\text{EFT-improved (1), NNLO}}}{dp_\perp} = \frac{\frac{d\sigma^{\text{QCD, NLO}}}{dp_\perp}}{\frac{d\sigma^{\text{EFT, NLO}}}{dp_\perp}} \frac{d\sigma^{\text{EFT, NNLO}}}{dp_\perp}$$



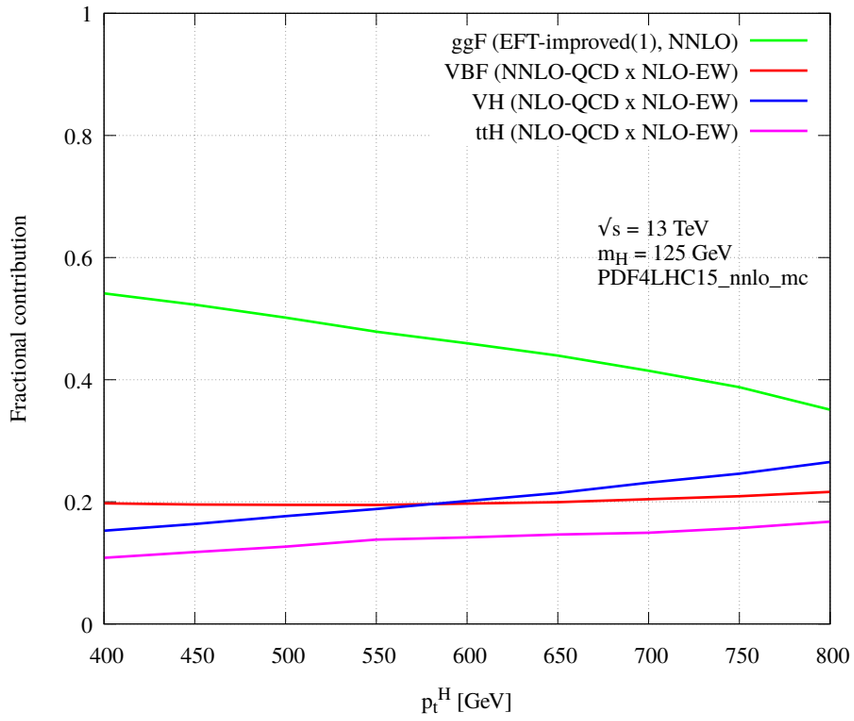

| $p_T^{\text{cut}}$ | $\text{LO}_{\text{full}}$ | $\text{NLO}_{\text{full}}$ | $K_{\text{full}}^{\text{NLO}}$ | $\text{LO}_{\text{EFT}}$ | $\text{NLO}_{\text{EFT}}$ | $\text{NNLO}_{\text{EFT}}$ | $K_{\text{EFT}}^{\text{NLO}}$ | $K_{\text{EFT}}^{\text{NNLO}}$ |
|---|---|---|---|---|---|---|---|---|
| 400 | $11.9^{+45\%}_{-29\%}$ | $27^{+15\%}_{-20\%}$ | 2.23 | $32^{+44\%}_{-29\%}$ | $63^{+23\%}_{-19\%}$ | $78^{+9.2\%}_{-12\%}$ | 1.93 | 1.25 |
| 430 | $8.2^{+45\%}_{-29\%}$ | $18.3^{+14\%}_{-21\%}$ | 2.22 | $25^{+44\%}_{-29\%}$ | $48^{+22\%}_{-19\%}$ | $60^{+9.1\%}_{-11\%}$ | 1.92 | 1.25 |
| 450 | $6.5^{+45\%}_{-29\%}$ | $14.5^{+14\%}_{-21\%}$ | 2.22 | $21^{+45\%}_{-29\%}$ | $41^{+22\%}_{-19\%}$ | $51^{+9.1\%}_{-11\%}$ | 1.92 | 1.25 |
| 500 | $3.7^{+45\%}_{-29\%}$ | $8.1^{+14\%}_{-21\%}$ | 2.22 | $14.2^{+45\%}_{-29\%}$ | $27^{+22\%}_{-20\%}$ | $34^{+9\%}_{-11\%}$ | 1.91 | 1.25 |
| 550 | $2.1^{+45\%}_{-30\%}$ | $4.7^{+13\%}_{-21\%}$ | 2.19 | $9.8^{+45\%}_{-29\%}$ | $18.6^{+22\%}_{-20\%}$ | $23^{+8.9\%}_{-11\%}$ | 1.91 | 1.25 |
| 600 | $1.28^{+46\%}_{-30\%}$ | $2.8^{+14\%}_{-21\%}$ | 2.18 | $6.8^{+45\%}_{-29\%}$ | $13.0^{+22\%}_{-20\%}$ | $16.2^{+8.8\%}_{-11\%}$ | 1.90 | 1.25 |
| 650 | $0.79^{+46\%}_{-30\%}$ | $1.71^{+14\%}_{-21\%}$ | 2.17 | $4.9^{+46\%}_{-29\%}$ | $9.3^{+22\%}_{-20\%}$ | $11.5^{+8.7\%}_{-11\%}$ | 1.90 | 1.24 |
| 700 | $0.49^{+47\%}_{-30\%}$ | $1.06^{+14\%}_{-21\%}$ | 2.15 | $3.5^{+46\%}_{-29\%}$ | $6.7^{+22\%}_{-20\%}$ | $8.3^{+8.7\%}_{-11\%}$ | 1.90 | 1.24 |
| 750 | $0.32^{+47\%}_{-30\%}$ | $0.67^{+13\%}_{-21\%}$ | 2.14 | $2.6^{+46\%}_{-30\%}$ | $4.9^{+22\%}_{-20\%}$ | $6.1^{+8.6\%}_{-11\%}$ | 1.90 | 1.24 |
| 800 | $0.20^{+47\%}_{-30\%}$ | $0.43^{+13\%}_{-21\%}$ | 2.12 | $1.90^{+46\%}_{-30\%}$ | $3.6^{+22\%}_{-20\%}$ | $4.5^{+8.6\%}_{-11\%}$ | 1.90 | 1.24 |
| 850 | $0.135^{+47\%}_{-30\%}$ | $0.28^{+13\%}_{-21\%}$ | 2.10 | $1.42^{+47\%}_{-30\%}$ | $2.7^{+22\%}_{-20\%}$ | $3.3^{+8.6\%}_{-11\%}$ | 1.89 | 1.24 |

LHCHXSWG-2019-002 (V2)

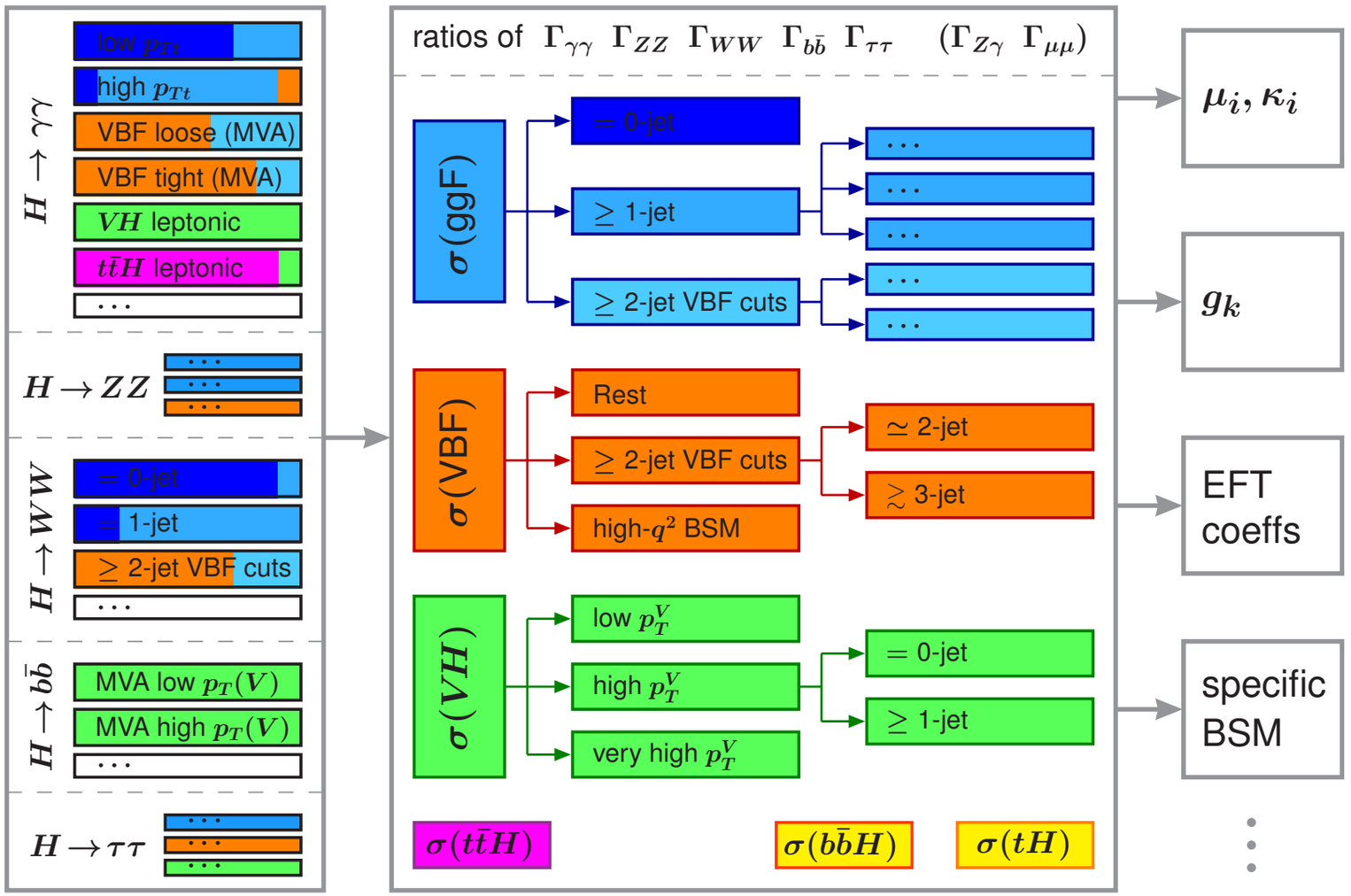
Find reasonable agreement with state of the art showered predictions

At high-$p_T$ considerable contribution from VH,VBF,ttH

LHCHXSWG-2019-001



# Simplified Template Cross Sections




Stage 1.1 update recently released LHCHXSWG-2019-003

**Combined Meeting with LHCXSWG Fiducial/STXS Subgroup Scheduled:**

``STXS in production and ideas for STXS in decays''

Wednesday 12 June 14h00-18h00 Auditorium

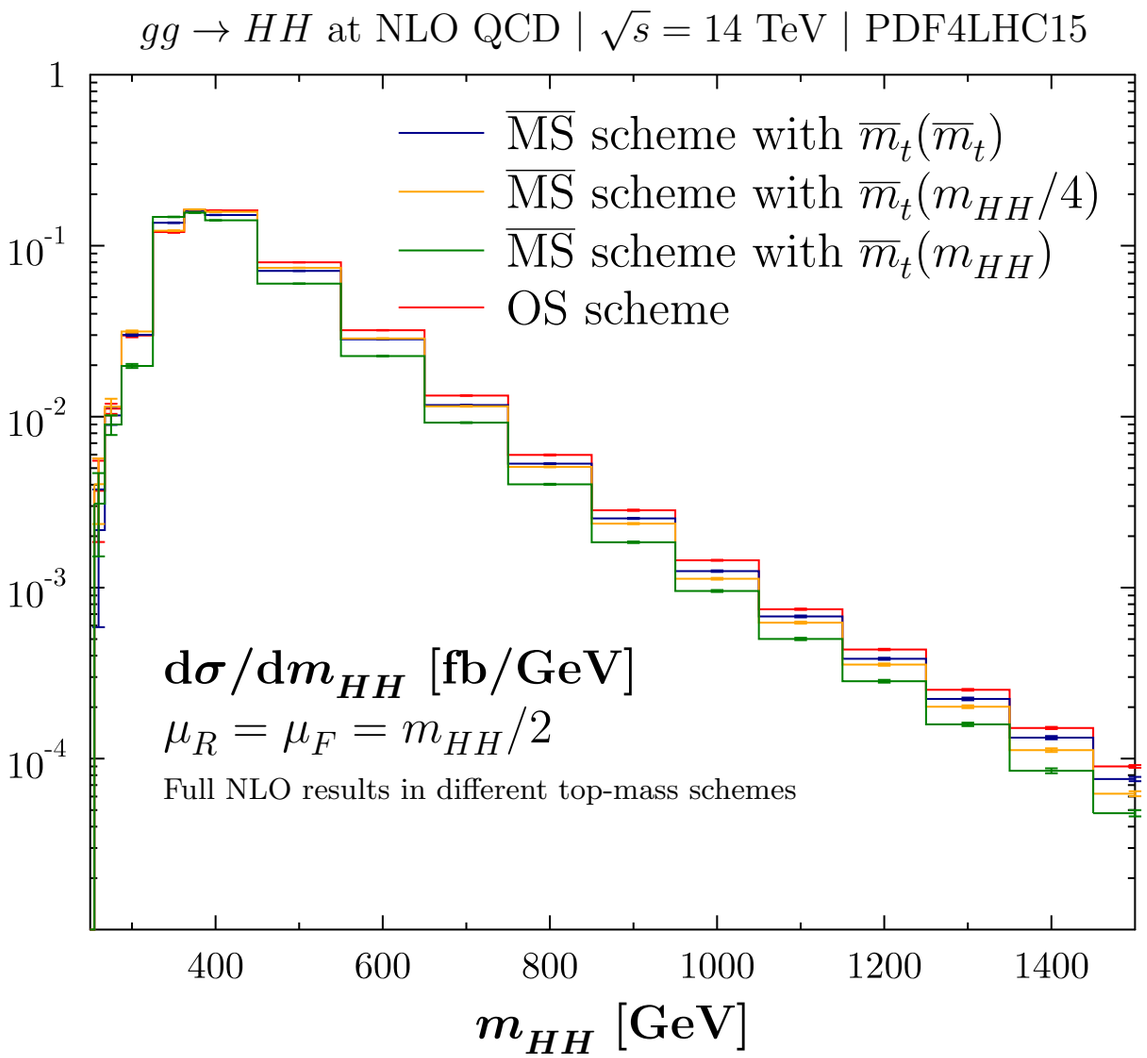
**→Talk of Michael**

# Higgs Pair Production

Now have two independent computations of HH at NLO QCD (both numerical)

Good agreement between two groups

Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16;
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18




Recent calculation allows $m_T$ to be varied

Large top-quark mass scheme uncertainty

**Questions:**

How exactly should we assess this uncertainty?

How does this impact results at NNLO?

Can we learn anything more from the analytic high-energy limit results?

Davies, Mishima, Steinhauser, Wellmann 18
Davies, Herren, Mishima, Steinhauser 19

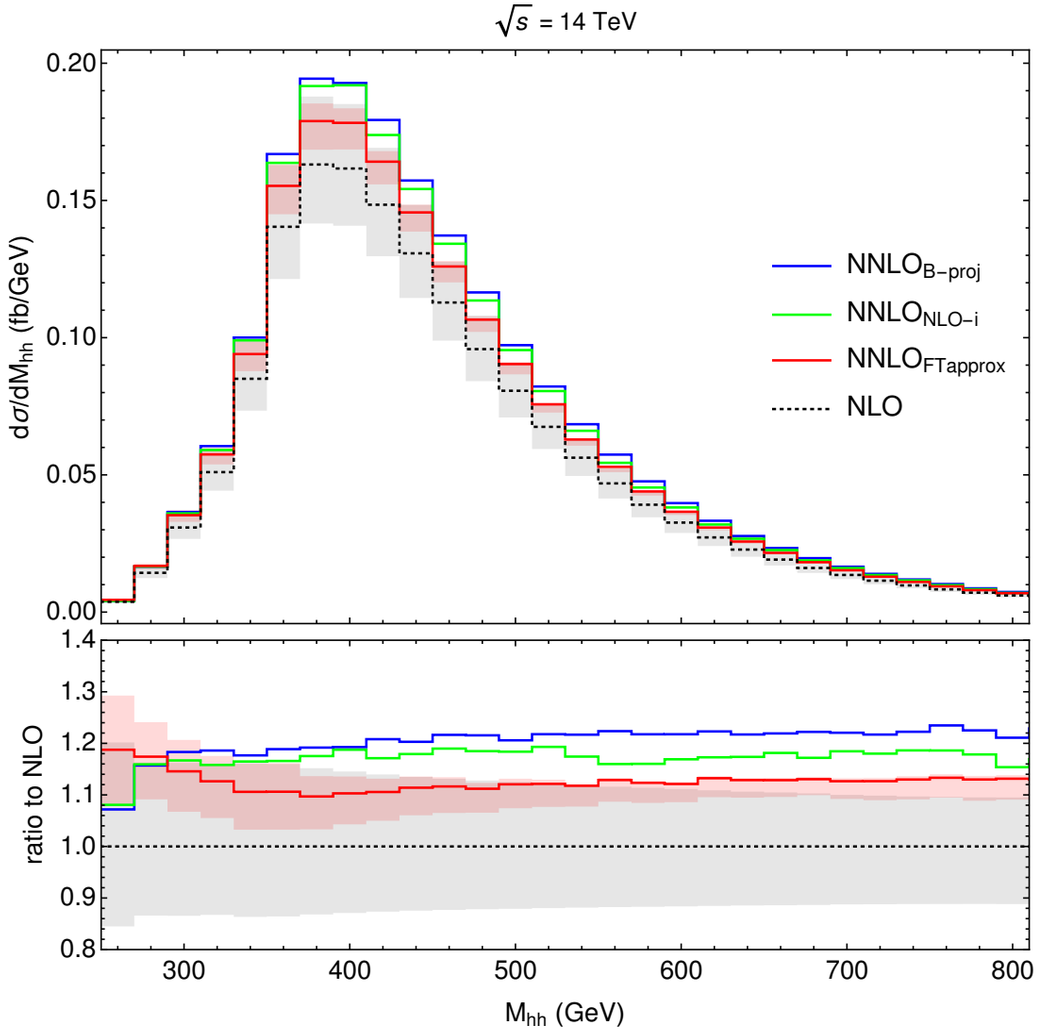
Towards resummation? Liu, Penin 17, 18

Partial EW results now known Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao 18

# Higgs Pair - NNLO HTL Combined with NLO SM

Differential NNLO HTL + NLO SM

Top quark mass effects studied using 3 different approximations




Grazzini, Heinrich, SJ, Kallweit, Kerner, Lindert, Mazzitelli 18; (+NNLL) de Florian, Mazzitelli 18;

| $\sqrt{s}$ | 13 TeV | 14 TeV | 27 TeV | 100 TeV |
|---|---|---|---|---|
| NLO [fb] | $27.78\,^{+13.8\%}_{-12.8\%}$ | $32.88\,^{+13.5\%}_{-12.5\%}$ | $127.7\,^{+11.5\%}_{-10.4\%}$ | $1147\,^{+10.7\%}_{-9.9\%}$ |
| $\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb] | $28.91\,^{+15.0\%}_{-13.4\%}$ | $34.25\,^{+14.7\%}_{-13.2\%}$ | $134.1\,^{+12.7\%}_{-11.1\%}$ | $1220\,^{+11.9\%}_{-10.6\%}$ |
| $\mathrm{NNLO}_{\mathrm{NLO-i}}$ [fb] | $32.69\,^{+5.3\%}_{-7.7\%}$ | $38.66\,^{+5.3\%}_{-7.7\%}$ | $149.3\,^{+4.8\%}_{-6.7\%}$ | $1337\,^{+4.1\%}_{-5.4\%}$ |
| $\mathrm{NNLO}_{\mathrm{B-proj}}$ [fb] | $33.42\,^{+1.5\%}_{-4.8\%}$ | $39.58\,^{+1.4\%}_{-4.7\%}$ | $154.2\,^{+0.7\%}_{-3.8\%}$ | $1406\,^{+0.5\%}_{-2.8\%}$ |
| $\mathrm{NNLO}_{\mathrm{FTapprox}}$ [fb] | $31.05\,^{+2.2\%}_{-5.0\%}$ | $36.69\,^{+2.1\%}_{-4.9\%}$ | $139.9\,^{+1.3\%}_{-3.9\%}$ | $1224\,^{+0.9\%}_{-3.2\%}$ |
| $M_t$ unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$ | $\pm 2.6\%$ | $\pm 2.7\%$ | $\pm 3.4\%$ | $\pm 4.6\%$ |
| $\mathrm{NNLO}_{\mathrm{FTapprox}}/\mathrm{NLO}$ | 1.118 | 1.116 | 1.096 | 1.067 |

**1) $\mathrm{NNLO}_{\mathrm{NLO\text{-}i}}$**

Rescale NLO by $K_{NNLO} = \mathrm{NNLO}_{HTL}/\mathrm{NLO}_{HTL}$

**2) $\mathrm{NNLO}_{\mathrm{B\text{-}proj}}$**

Project real radiation contributions to Born configurations, rescale by $\mathrm{LO}/\mathrm{LO}_{HTL}$

**3) $\mathrm{NNLO}_{\mathrm{FTapprox}}$**

NNLO HTL correction rescaled for each multiplicity by:

$$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\mathrm{Born}}_{\mathrm{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\mathrm{HEFT}}(ij \to HH + X)}$$

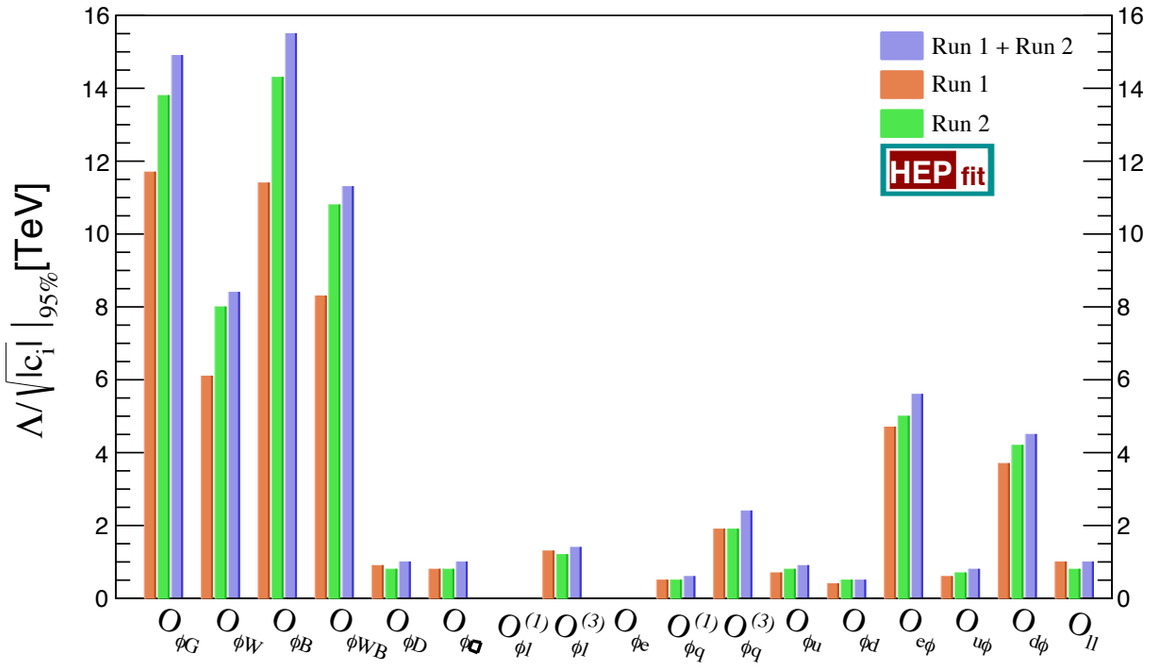
# EFTs - Interpretation of Higgs Measurements

EFTs allow us to make model-independent statements about constraints on new interactions and on the scale of new physics

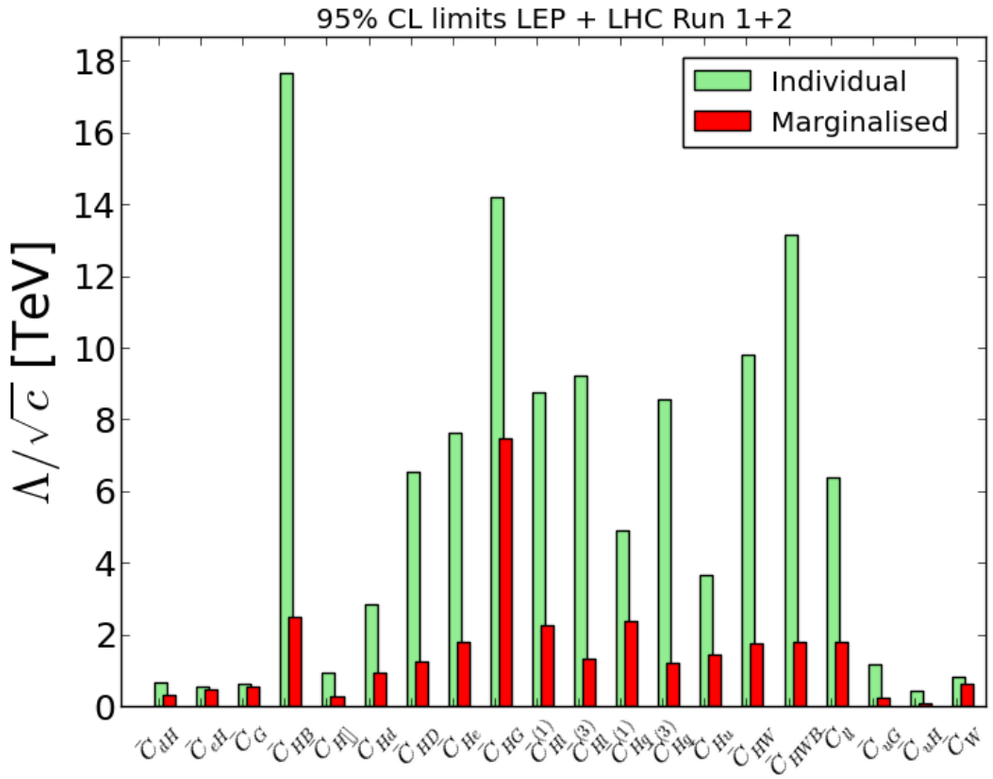
Higher-order results including dim-6 operators known for:

VH, VBF, ttH, ggF Maltoni, Mawatari, Zaro 13; Degrande, Fuks, Mawatari, Mimasu, Sanz 16; Maltoni, Vryonidou, Zhang 16; Deutschmann, Duhr, Maltoni, Vryonidou 17; …

Significant progress made in automating NLO calculations for EFTs




de Blas, Ciuchini, Franco, Mishima, Pierini, Reina, Silvestrini 17




Ellis, Murphy, Sanz, You 18

**Meeting Scheduled:**

``EFT interpretation of Higgs measurements''

Thursday 13 June 10h00-12h00 Library

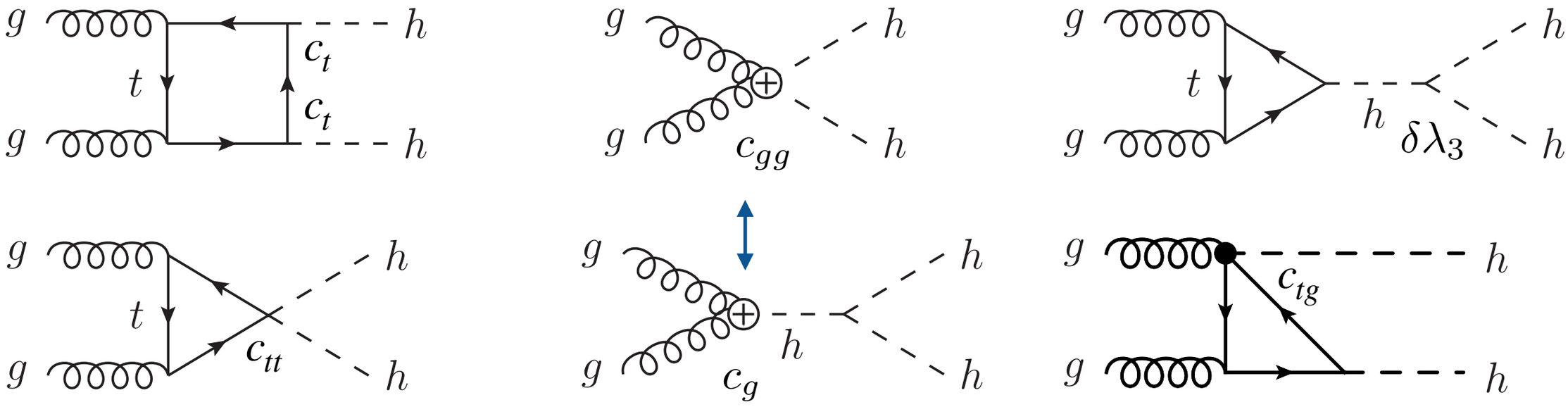
**→Talk of Michael**

# EFTs - Application to Higgs Pair Production

Full NLO QCD result with variable $y_T, \lambda$ available in POWHEG Heinrich, SPJ, Kerner, Luisoni, Scyboz 19

Constraints on $\lambda$ also from EW-corrections to H, EW precision

Bizoń, Gorbahn, Haisch, Zanderighi, Degrassi, Giardino, Maltoni, Pagani, Shivaji, Zhao, Di Vita, Grojean, Panico, Riembau, Vantalon, Fedele, Kribs, Maier, Rzehak, Spannowsky, Waite 16,17,18




(not included in NLO analysis)

NLO result w/ top mass including EFT couplings Buchalla, Capozi, Celis, Heinrich, Scyboz 18

NNLO result in HTL known including EFT couplings de Florian, Fabre, Mazzitelli 18

All pieces in principle within reach for NLO-improved NNLO result including EFTs

Would this be useful to have? Linear/non-linear basis? Chromomagnetic operator?

**Combined Meeting with LHCXSWG HH Subgroup Scheduled:**

``SM Uncertainties & EFTs'' Monday 17 June 14h00-18h00 Auditorium

**Thank you for listening and enjoy Les Houches!**