Working Group 1: ggF Update

Conveners:
(EXP) Jonathon Langford, Haider Abidi
(TH) Stephen Jones, Alexander Huss

Current Sub-Group Conveners

Experiment

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Theory

Alexander Huss: alexander.huss@cern.ch **(NEW 09/22 - Welcome!)**

Stephen Jones: s.jones@cern.ch

Please do feel free to reach out to any/all of us

Outline

Current Status

Overview of Recent Progress

- Top-quark mass effects @ NNLO QCD
- Mixed EW-QCD corrections
- H+j @ NLO QCD
- H+2j production @ NLO QCD
- Experimental update

Ongoing Tasks/ Future Directions for the Working Group

- Update ggF cross section & boosted Higgs recommendations
- Parton shower uncertainties / systematics (needs interested TH)

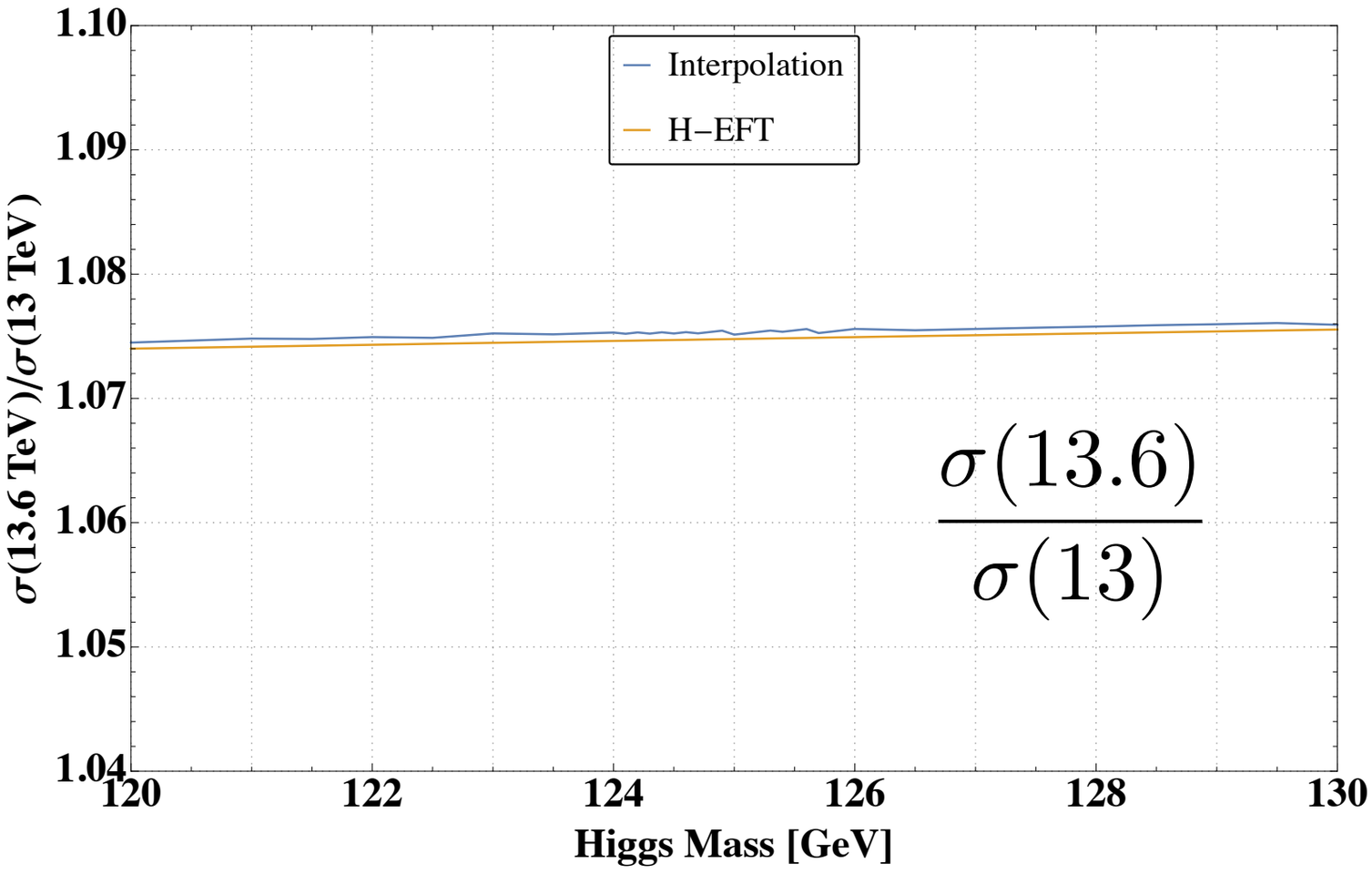
Current ``Run 2'' Recommendation

Based on Yellow Report 4 (2016), HL-HE Report (2019) & LHCHXSWG-2019-001

Numbers produced for:
$\sqrt{s} = 13,\ 14,\ 27\ \text{TeV}$

Interpolated numbers for:
$\sqrt{s} = 13.6\ \text{TeV}$

Uncertainties carried over from YR4 prescription



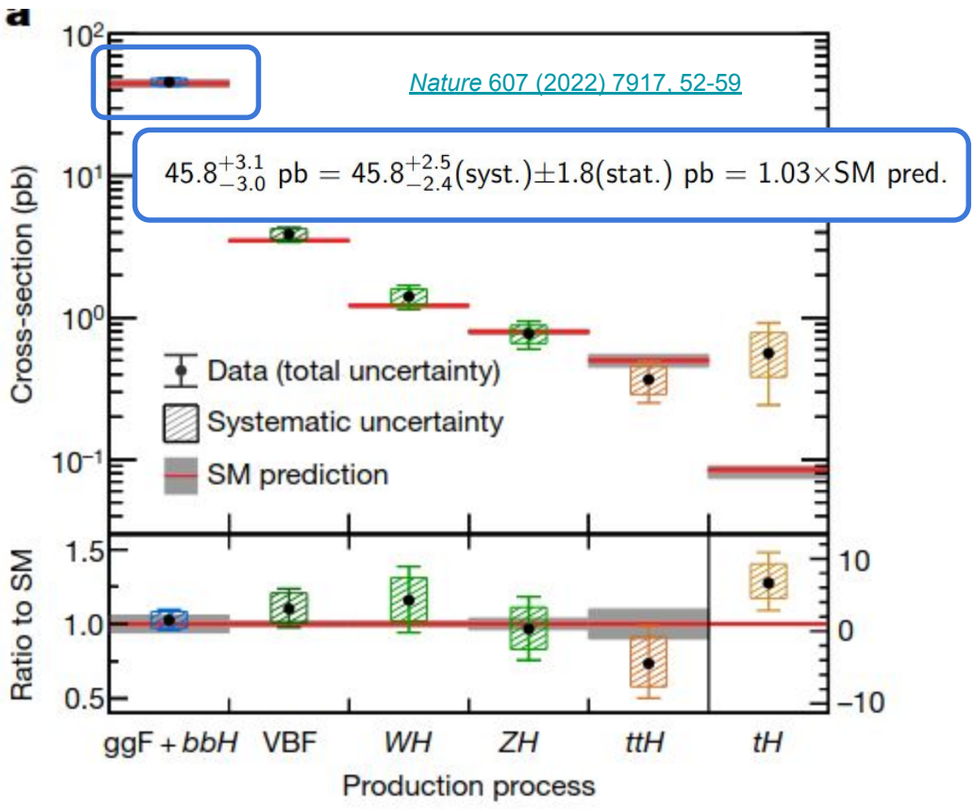
Plot: Mistlberger (WG1 Meeting 03.02.22)

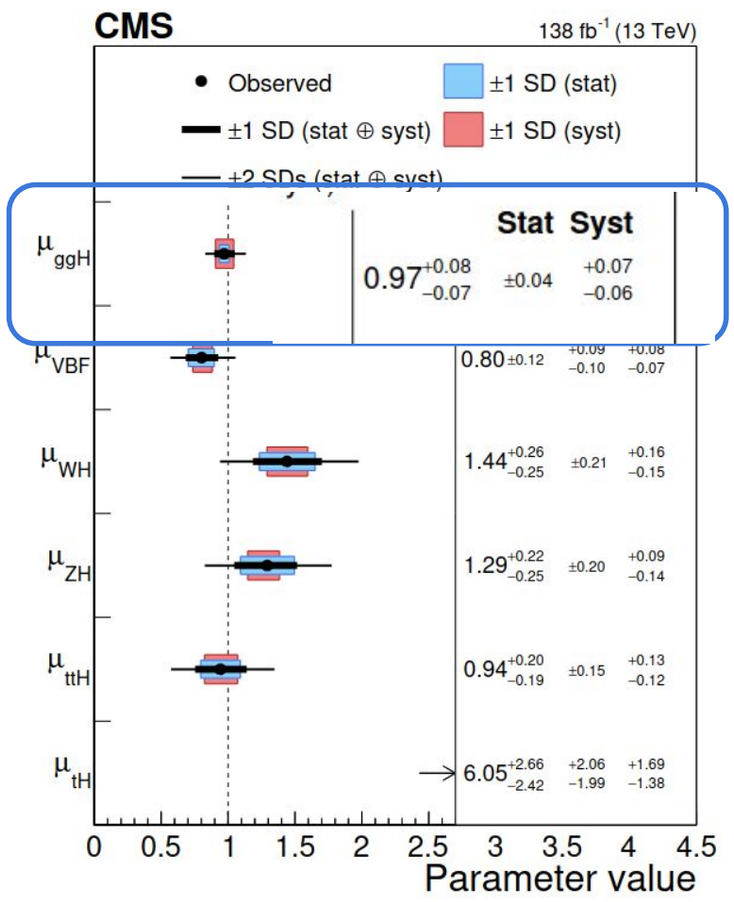
Note: The (interpolated) numbers are available from the spreadsheet on the twiki

Recent inclusive measurements

- Highest precision achieved by combining decay channels

Nature 607 (2022) 7917 60-68





- ATLAS present result as cross-section, CMS as signal strength (relative to SM, with theory unc folded in)
- Inclusive ggF is now **syst-limited**: requires analysis/theory improvements to gain here

Update Needed

Many new/improved results since last major update (YR4/YR2019)

process	known	desired
$pp \to H$	**$\mathrm{N^3LO_{HTL}}$** **$\mathrm{NNLO}^{(t)}_{\mathrm{QCD}}$** $\mathrm{N}^{(1,1)}\mathrm{LO}^{(\mathrm{HTL})}_{\mathrm{QCD}\otimes\mathrm{EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) $\mathrm{NNLO}^{(b,c)}_{\mathrm{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ **$\mathrm{NLO_{QCD}}$** **$\mathrm{N}^{(1,1)}\mathrm{LO_{QCD\otimes EW}}$**	$\mathrm{NNLO_{HTL}}\otimes\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$
$pp \to H + 2j$	**$\mathrm{NLO_{HTL}}\otimes\mathrm{LO_{QCD}}$** $\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ (incl.) **$\mathrm{NNLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$** $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{EW}}$	$\mathrm{NNLO_{HTL}}\otimes\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$ $\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NNLO}^{(\mathrm{VBF})}_{\mathrm{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{QCD}}$	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$

Les Houches 2021 (**RED** = new results/updates since LH2019)

+ PDFs

Including PDF4LHC21

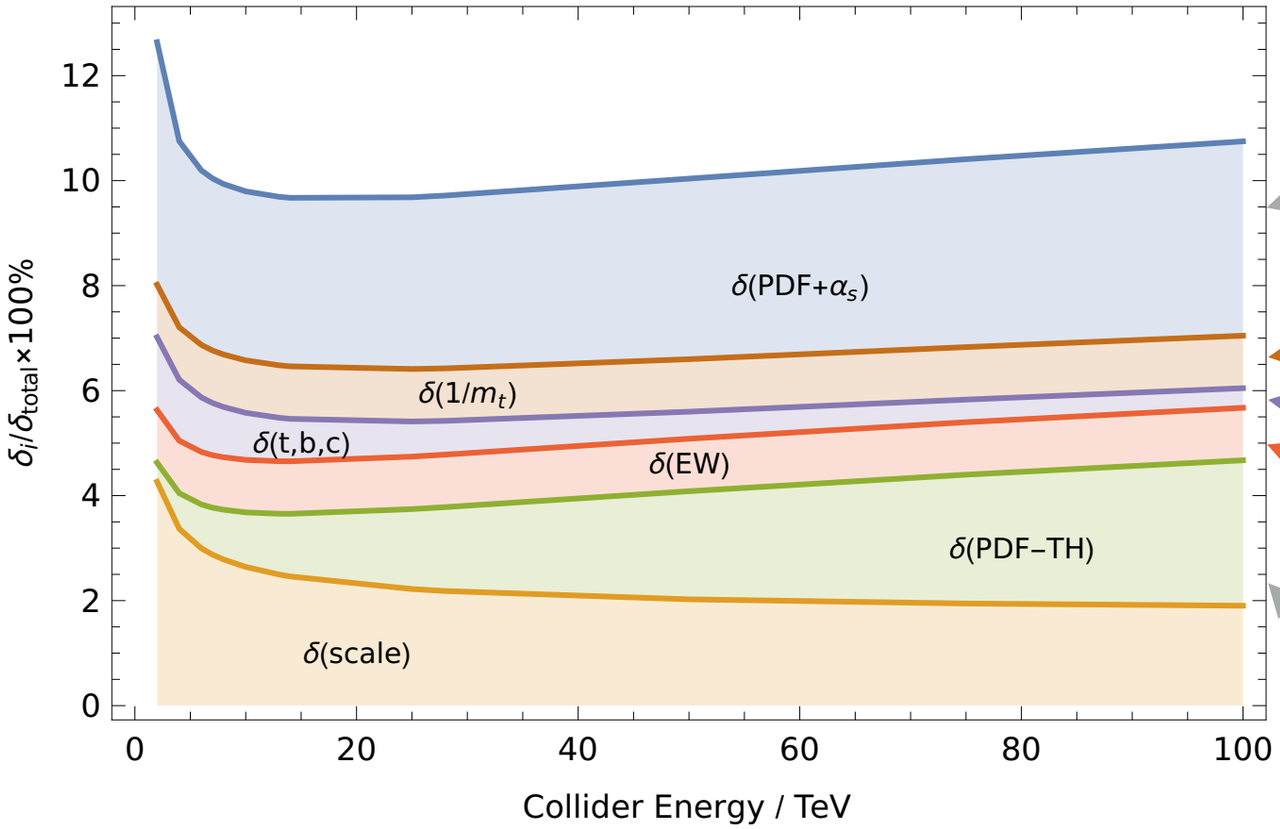
PDF4LHC WG 22

Our view is that this justifies an update of the ggF recommendations for:

1) total cross-section and **2) boosted Higgs**

Error Budget

Goal: accurately reflect changes in TH uncertainty since YR4



iHixs2: Dulat, Lazopoulos, Mistlberger 18

Update to PDF4LHC21
PDF4LHC WG 22

Removed
Czakon, Harlander, Klappert, Niggetiedt 21

Can be removed (?)

Reduced from ~1% to 0.6%
Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20; + Bonetti, Panzer, Smirnov, Tancredi, Melnikov, …

Missing $\mathrm{N^3LO}$ PDFs
McGowan, Cridge, Harland-Lang, Thorne 22

Our Ingredient List (so far):

$\mathrm{N^3LO_{HTL}}$ - iHixs2 & n3loxs Baglio, Duhr, Mistlberger, Szafron 22

$\delta(1/m_t)$ - NNLO full top-quark mass dependence (include mass-scheme uncert. estimate)

$\delta(t,b,c)$ - similar techniques to full top-quark mass dependence (very challenging $m_q \sim 0$, m_b & m_t)

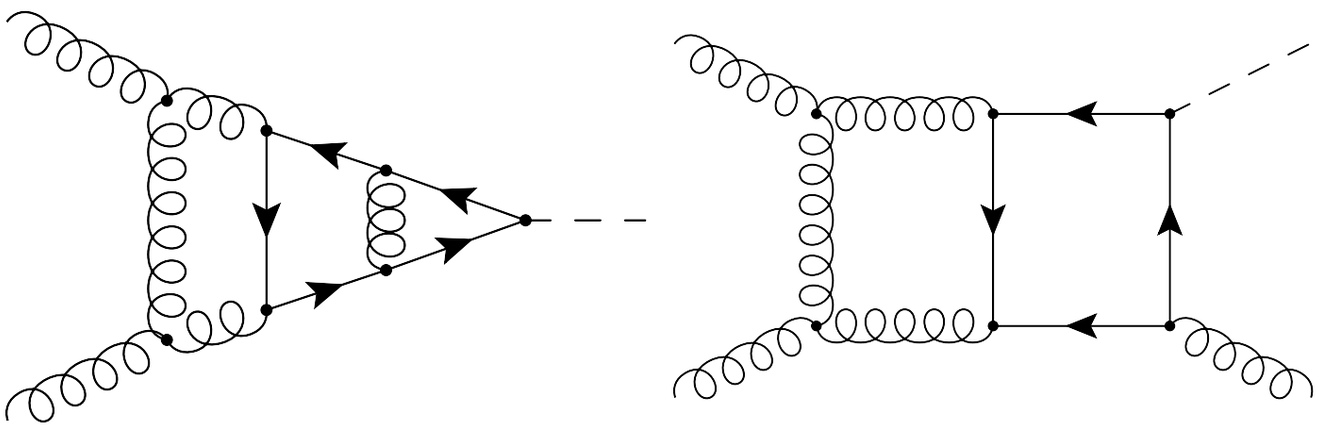
$\delta(\mathrm{EW})$ - light-quark contributions: gg-channel fully known, quark channel amplitudes known

$\delta(\mathrm{PDF-TH})$ - estimate with individual sets (PDF4LHC21 has no NLO set), compare to $\mathrm{aN^3LO}$

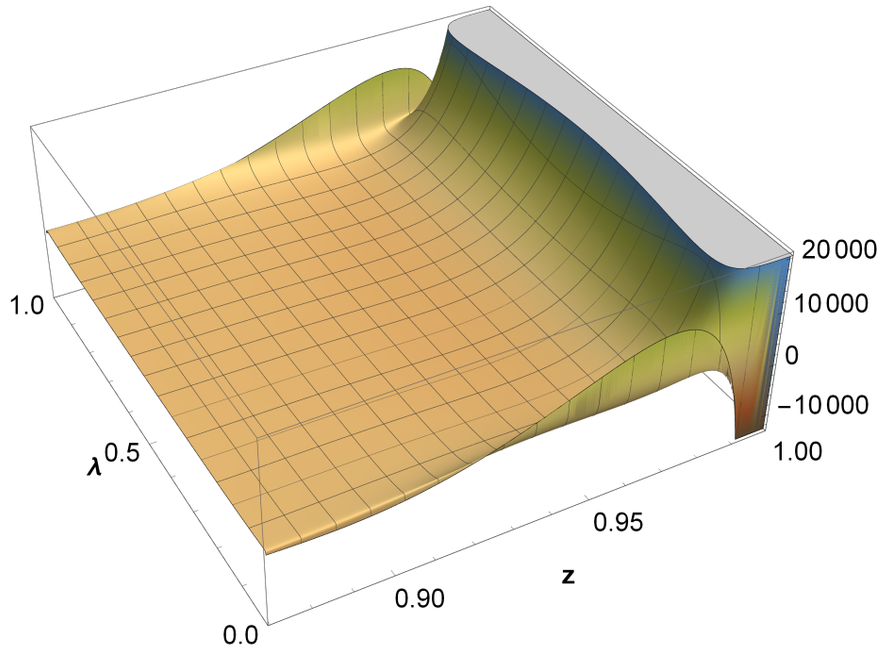
Some Relevant Highlights

NNLO with full top-quark mass

→ **See: Marco's Talk (Monday)**



$gg \to Hg$



$2\mathrm{Re}\langle M^{(1)}_{\text{exact}} | M^{(2)}_{\text{exact}} \rangle |_{\text{regulated}}$

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

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

Decreases σ_{tot} by $-0.26\,\%$ @ 13 TeV compared to heavy top limit (HTL)

Intricate interplay between mass effects $gg\ (+0.62\%), qg\ (-16\%), qq\ (-15\%)$
Complete NNLO results obtained using STRIPPER framework

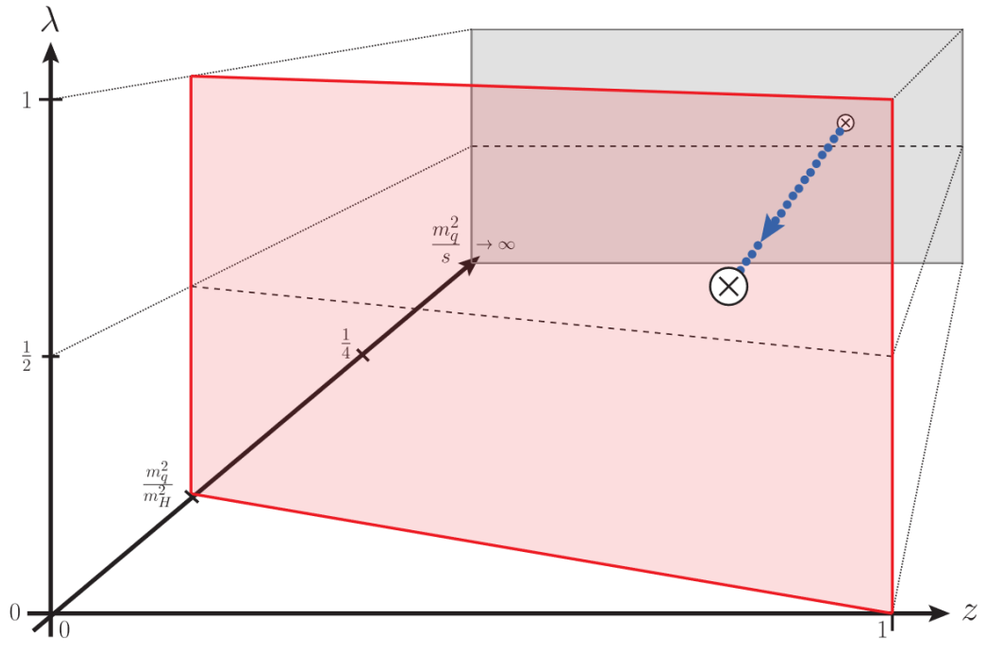
What to do with bottom/charm quarks?

Would be very useful to know bottom/charm effects @ NNLO (reduce $\delta(t, b, c)$)

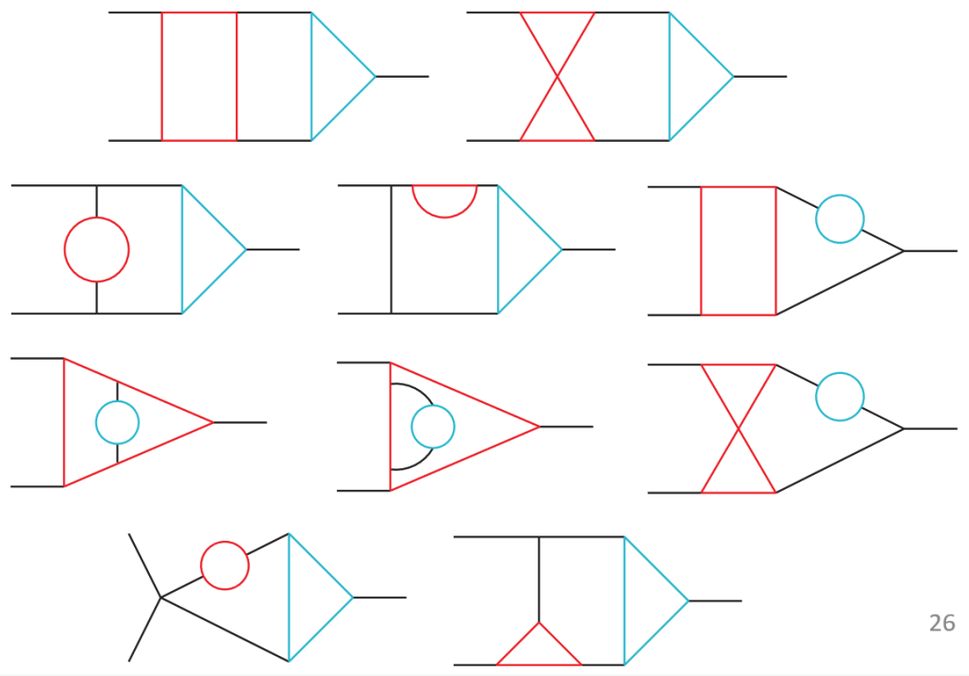
However, technically very challenging to get NNLO results

Summary

- Same techniques can be applied to compute bottom quark mass effects…
- Large hierarchy between m_b^2 and m_H^2 can lead to numerical instabilities when solving the differential equations
- Boundaries at $m_q^2 \to \infty$ not optimal



Corrections to $gg \to H$ at three loops for two different massive quark flavors unknown



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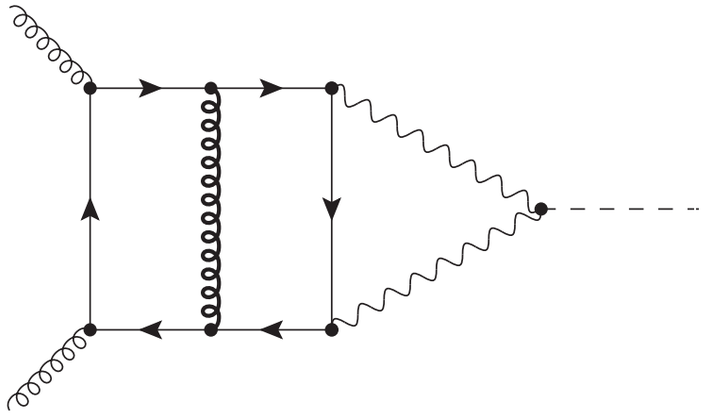
Slide: Marco (Monday)

Mixed QCD-EW Corrections @ $\mathrm{NLO}_{\mathrm{QCD}}$

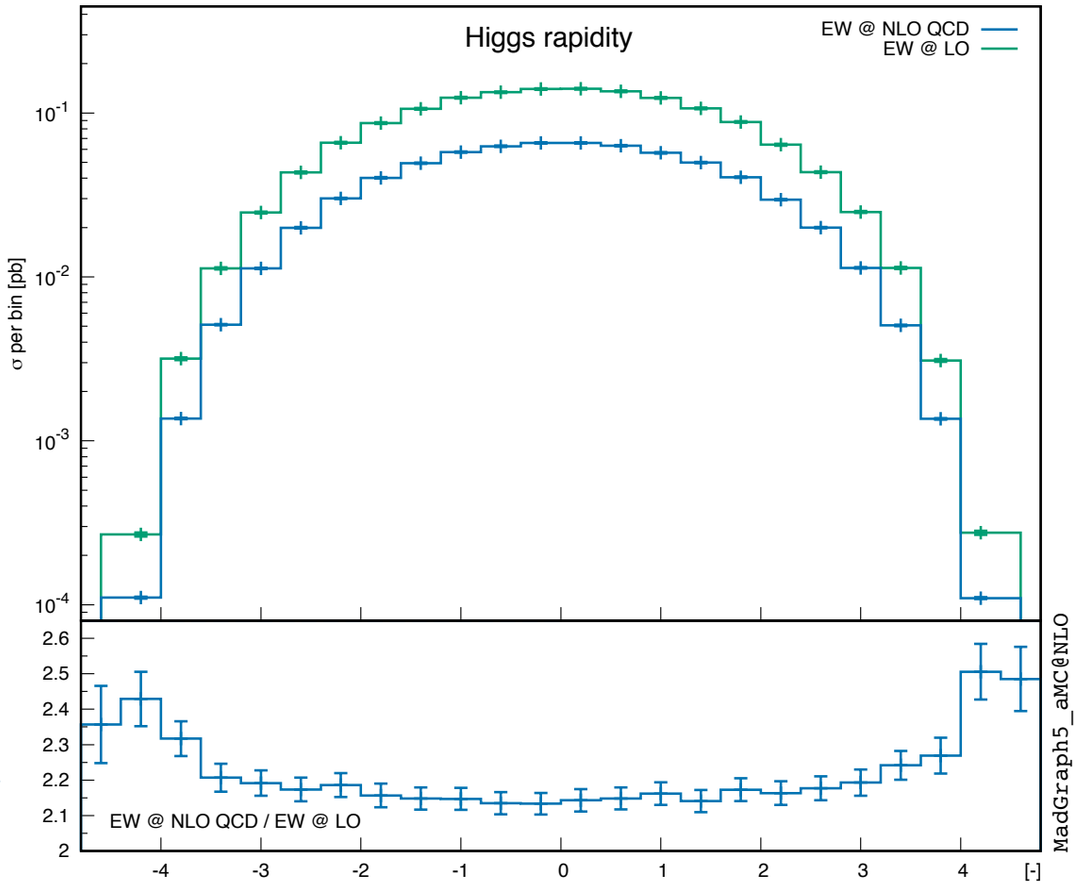


Challenging calculations

Bonetti, Melnikov, Tancredi 17

Bonetti, Panzer, Smirnov, Tancredi 20

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



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

Increases σ_{tot} by $+5.1\,\%$ @ 13 TeV, reduces residual uncertainty $\delta(\mathrm{EW}) \sim 0.6\,\%$

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

Compatible with previous estimates:

Soft approx: $+5.4\,\%$,
Bonetti, Melnikov, Tancredi 18;

$M_H \ll M_V : +5.2\,\%$,
Anastasiou, Boughezal, Petriello 09;

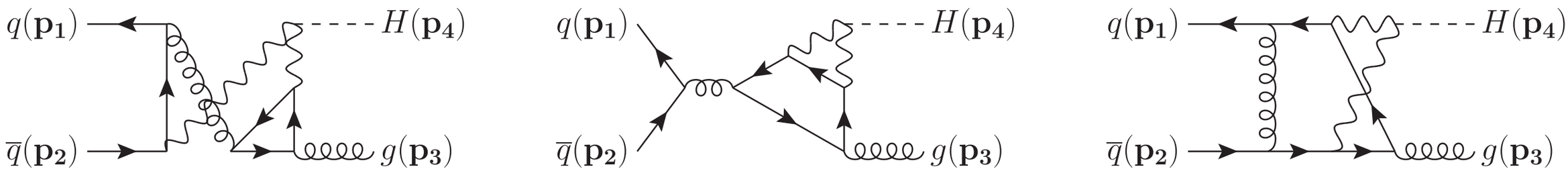
$M_H \gg M_V : +5.4\,\%$
Anastasiou, Del Duca, Furlan, Mistlberger, Moriello, Schweitzer, Specchia 19

What to do with the $qg, \bar{q}g, q\bar{q}$ channels?

Previous calculation of QCD-EW corrections only considers dominant gg channel

Impact of the quark channels expected to be relatively suppressed (due to large gg lumi), primary impact likely to be $\mathcal{O}(-2\%)$ shift at large/moderate p_T

But: 2-loop $q\bar{q}Hg$ amplitudes known



Bonetti, Panzer, Tancredi 22

Presumably, all-channel QCD-EW estimate is within reach

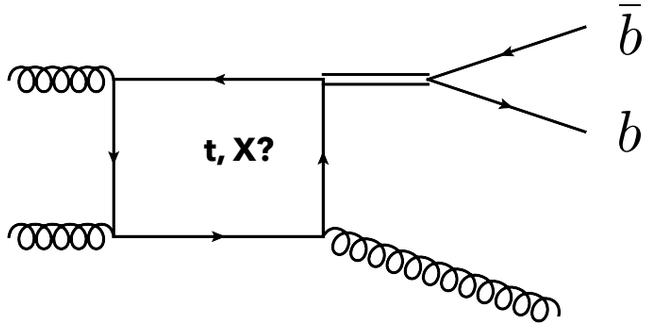
Proposal:
The sub-group should continue assembling the ingredients required for an update (including the existing QCD-EW corrections), iron out any issues, keep in touch with authors who may produce an improved QCD-EW estimate.

Summary: Boosted Higgs Meeting 2.03.22

Subgroup meeting in March 2022 to discuss potential Boosted Higgs update

FUTURE UPDATED NOTE

PROPOSED UPDATES: SUMMARY



- 13.6 TeV
- PDF4LHC21
- Extend pT range to 1.25 TeV
- QCD / Electroweak corrections for ggF
- Mass scheme uncertainty for NLO QCD ggF
- Parton Showers: HJ and HJJ
- Non-factorizable corrections in VBF
- …

Predictions and measurements for a Higgs boson at large transverse momentum are difficult but very interesting. Due to the particular complexity and not publicly accessible inputs providing explicit information in a combined effort from the theory community is useful.

We would like to propose an extension of the current public note to include several updates useful for the next years of LHC studies.

To make this a reality a concerted effort and support will be necessary.

Slide: Mistlberger (Predictions for Boosted Higgs Production 22)

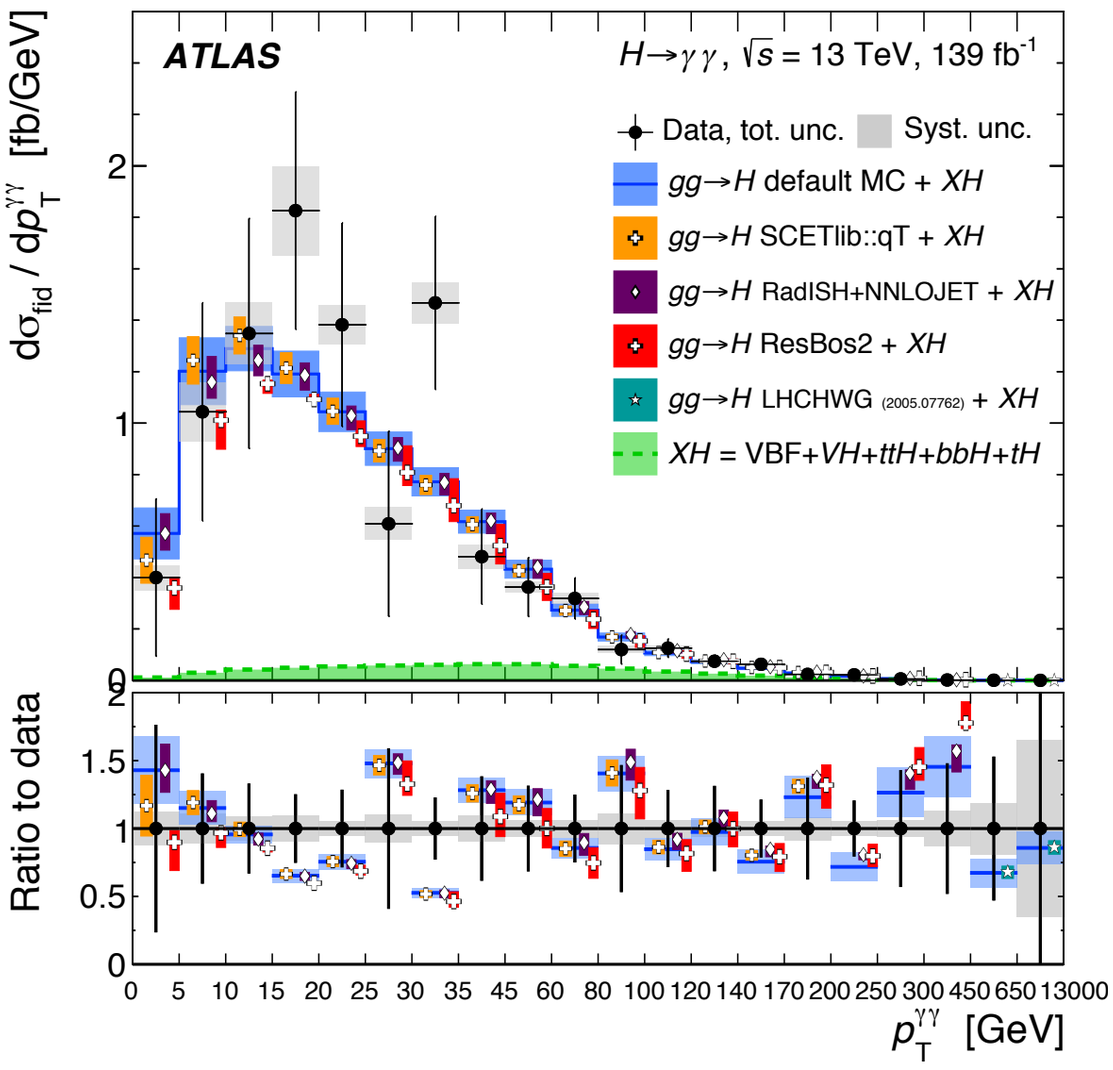
Many of these points can now be meaningfully addressed

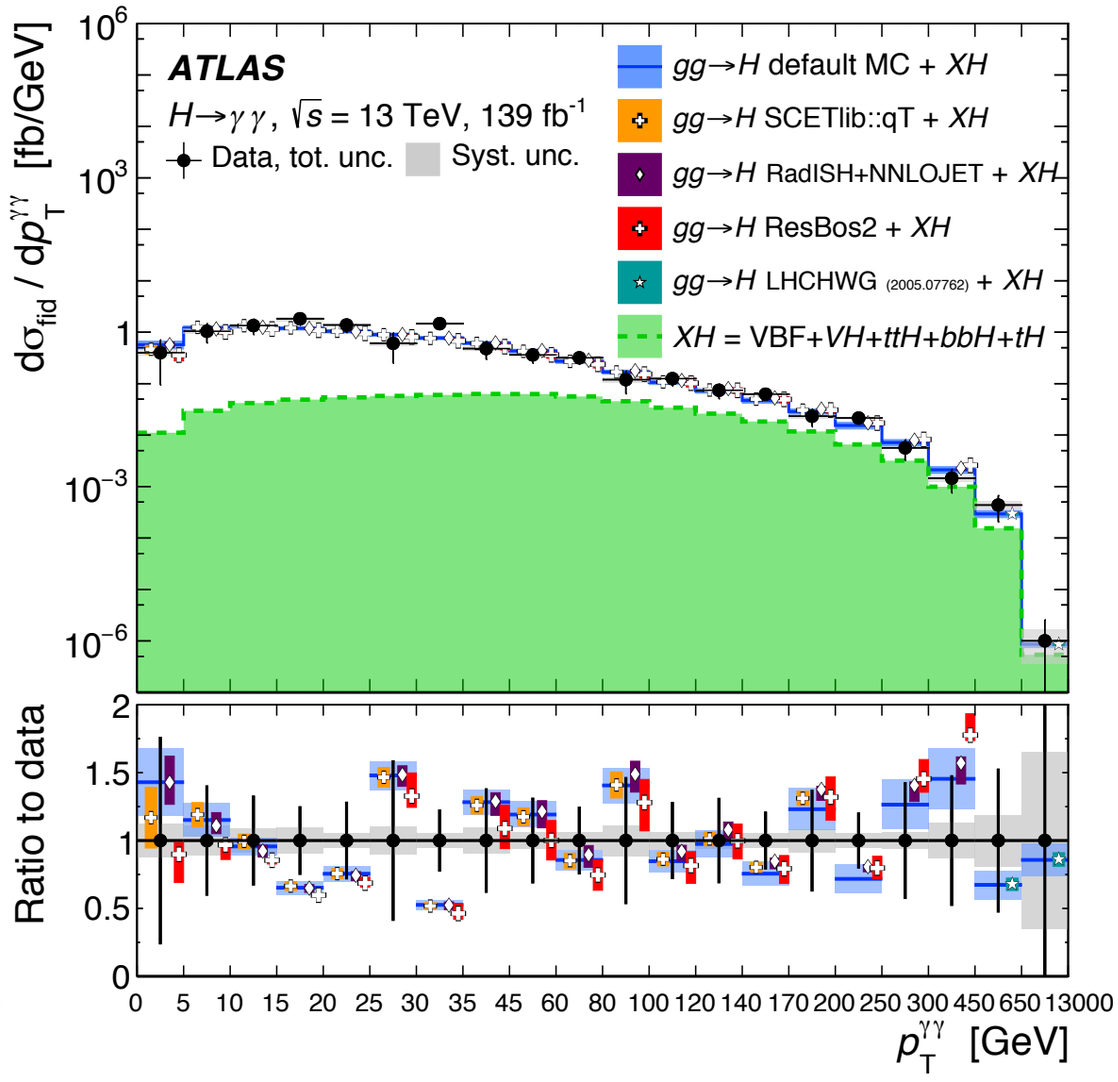
At high p_T all channels (i.e. non-ggF) are contributing significantly

Will require considerable input from the community & other WGs

Summary: Boosted Higgs Meeting 2.03.22

Subgroup meeting in March 2022 to discuss potential Boosted Higgs update





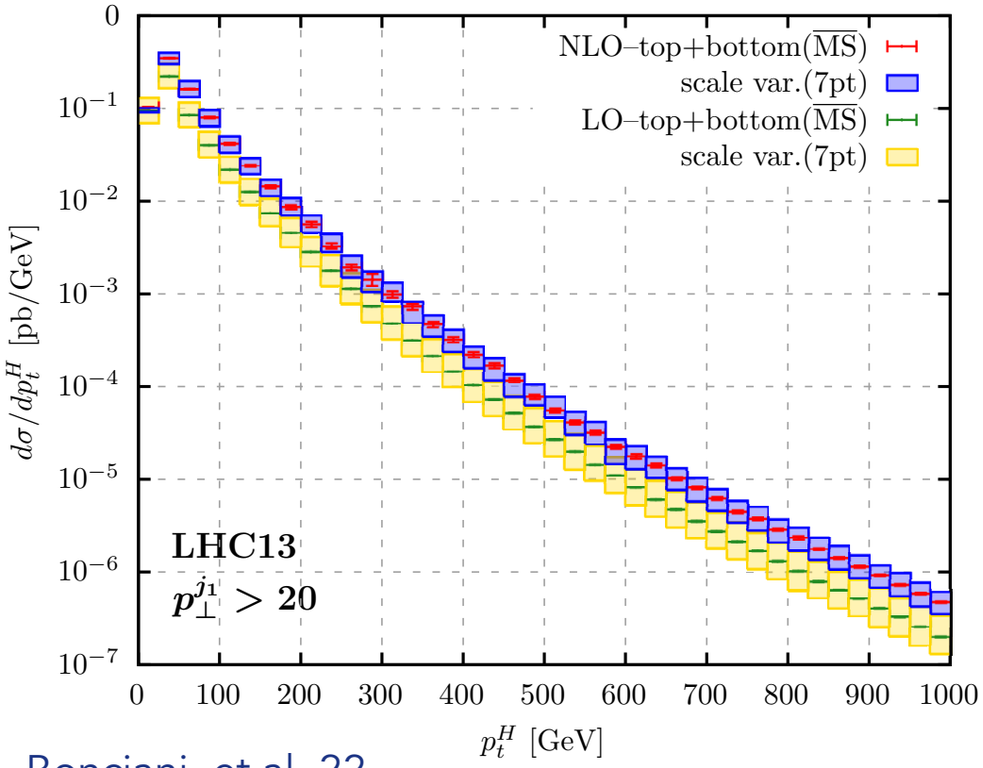
ATLAS 2202.00487

Boosted Higgs: NLO H+j

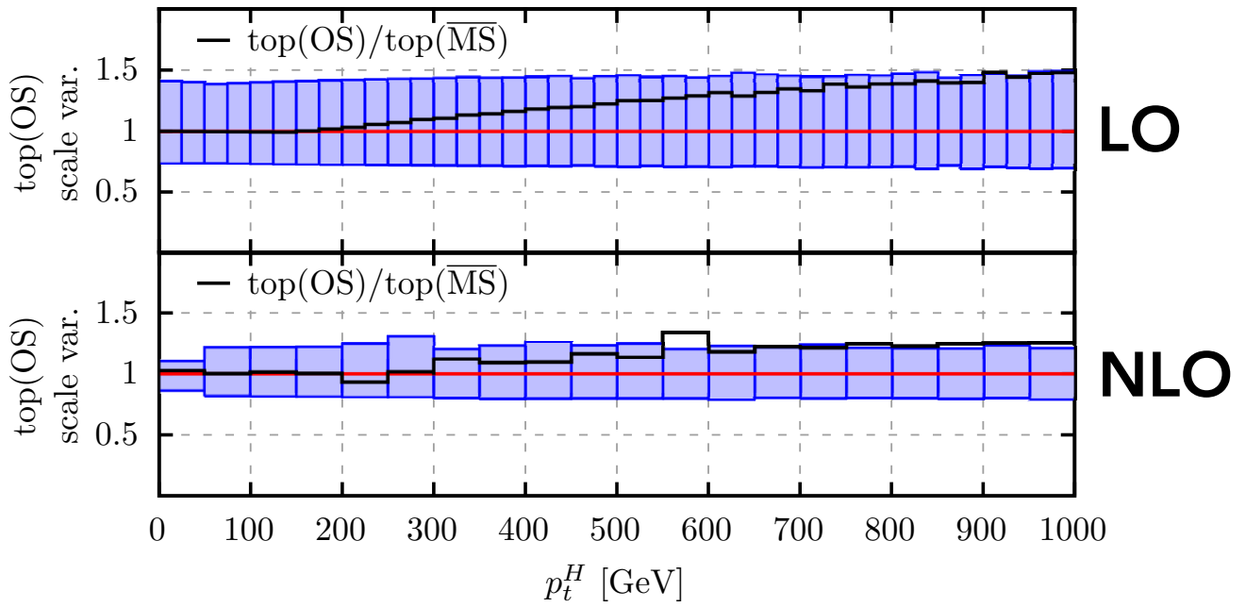
→ **See: Vittorio's Talk (Monday)**

HTL not valid for $p_T \gtrsim m_t$: (b,t)-quark mass effects now known for H+j at NLO

Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano 22;
Kudashkin, Melnikov, Wever, Lindert/ Neumann/ Chen, Huss, SPJ, Kerner, Lang, Luisoni, Zhang 18-21



Bonciani, et al. 22



Bottom and top/bottom interference effects relevant only for low-p_T

Mass scheme uncertainty now known:

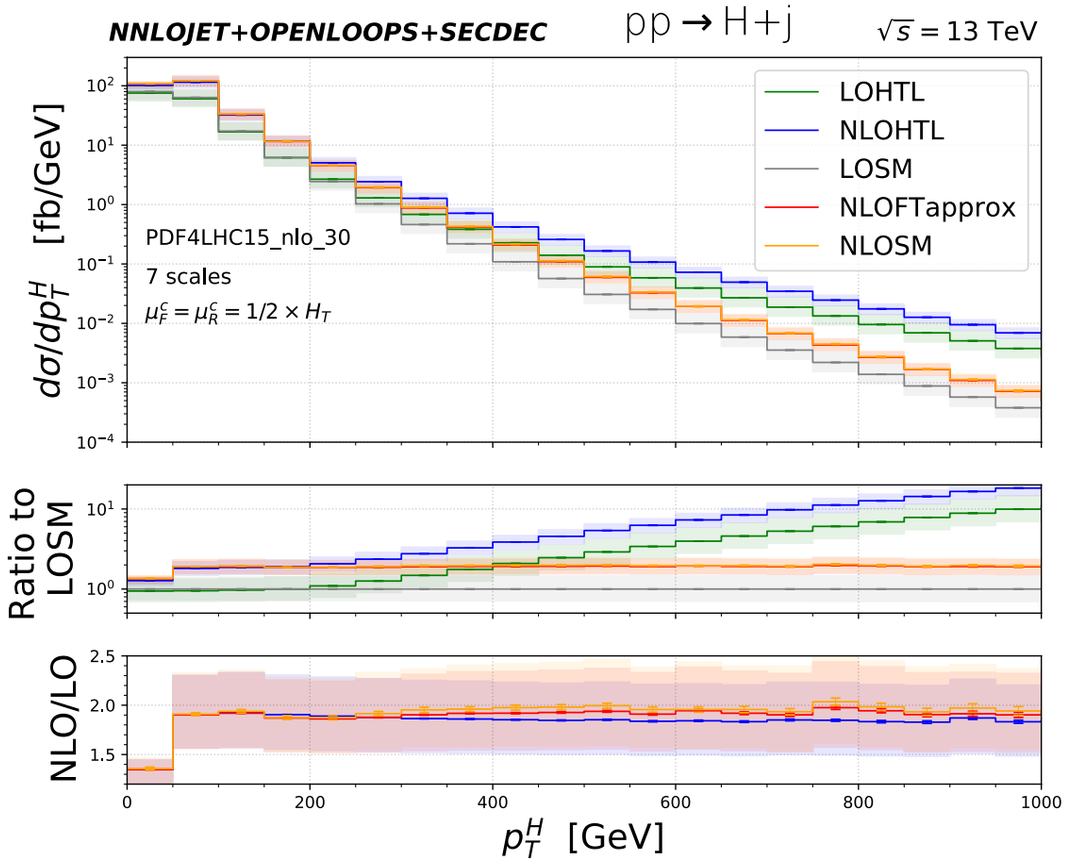
Reduced @ NLO but still comparable to scale uncertainty

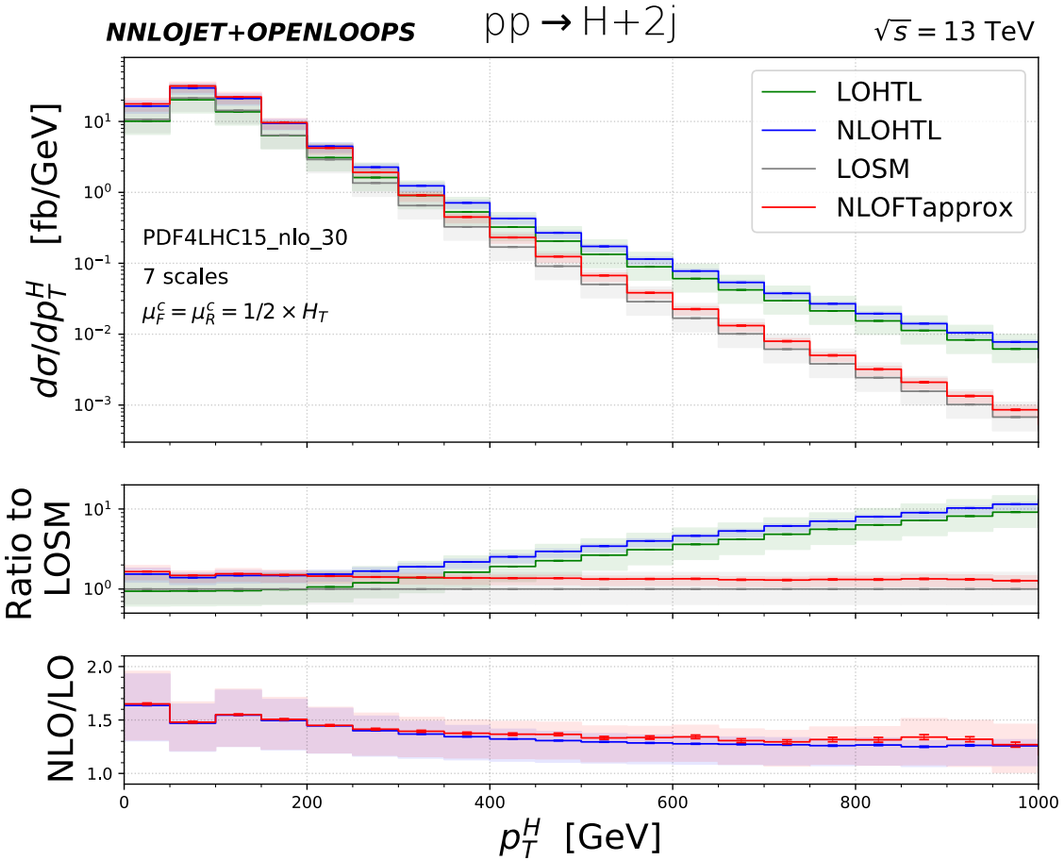
Boosted Higgs: H+2j at High p_T

Approximation $\mathrm{FT}_{\mathrm{approx}}$ Maltoni, Vryonidou, Zaro 14 **works surprisingly well for H+j**

Use exact Born + Reals

Approximate 2-loop Virtuals with $|\mathscr{M}_4^2(m_t,\mu_R^2;\{p\})|^2 \to |\mathscr{M}_4^1(\infty,\mu_R^2;\{p\})|^2 \dfrac{|\mathscr{M}_4^1(m_t;\{p\})|^2}{|\mathscr{M}_4^0(\infty;\{p\})|^2}$



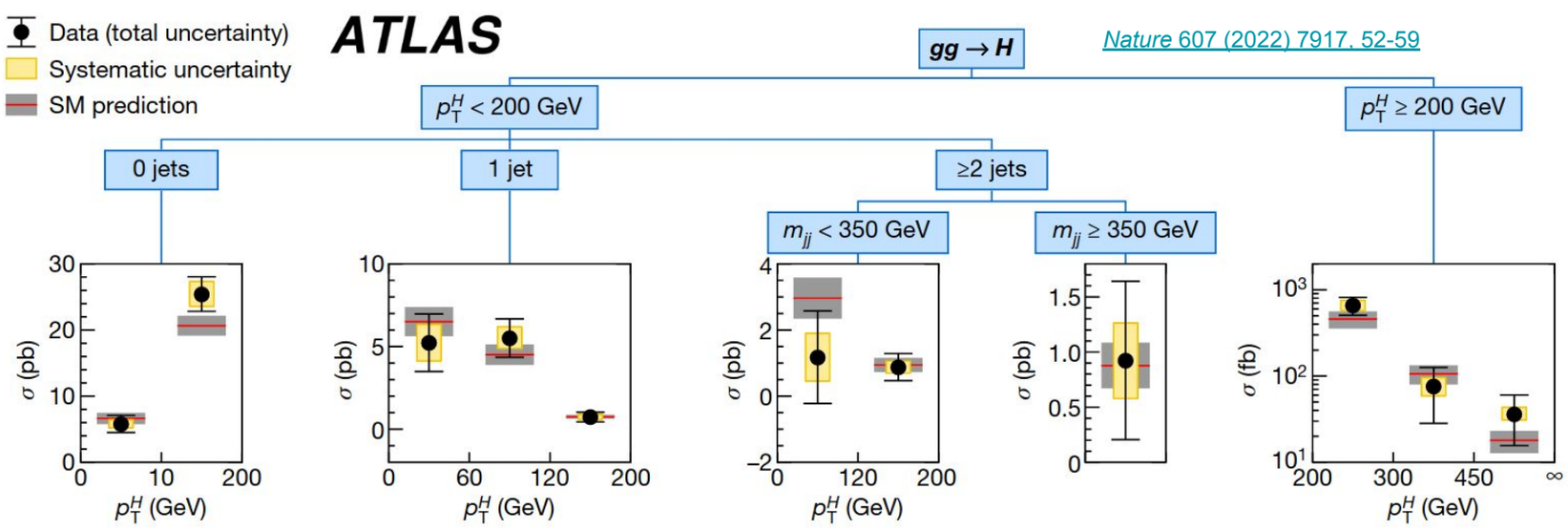


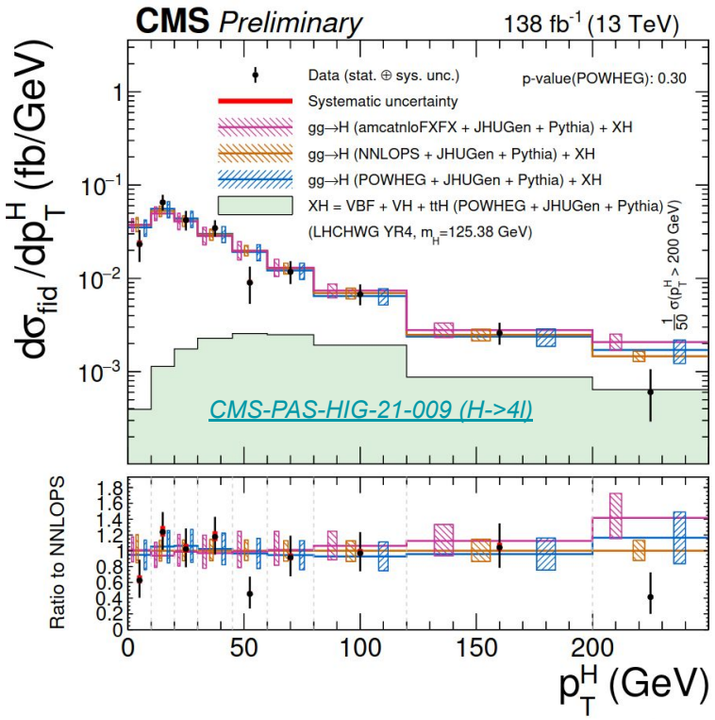
Chen, Huss, SPJ, Kerner, Lang, Lindert, Zhang 21

Assuming approximation works similarly well for higher jet multiplicity, can produce improved H+2j predictions just by computing full reals

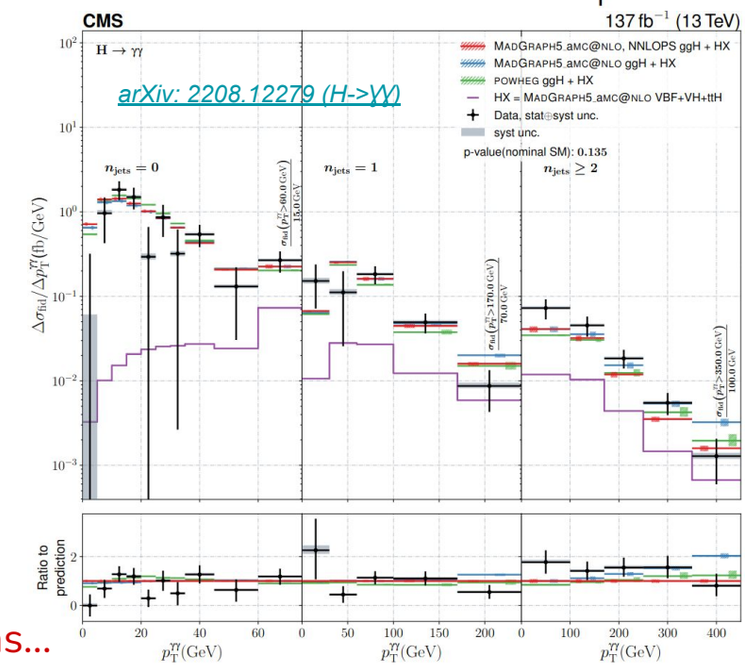
Experimental Summary

Recent STXS and differential





- Throughout Run 2, experiments have built up accurate + granular description of ggF
- STXS: many ggF stage 1.2 bins measured e.g. ATLAS combination above
  - Defined by kinematic splittings in pTH, Njets, mjj (ptHjj)
  - Good precision in rare regions of phase space e.g. Njets > 2
  - SM holds true (for now)
- Also fiducial differential measurements in many decay channels
  - More model-independent than STXS
  - Sufficient statistics to measure double-differential XS
  - Distributions used to probe BSM physics, CP structure, precision SM calculations…



Future plans and wishlist

- Both experiments will perform ggF cross section measurements at 13.6 TeV
  - Use updated theoretical predictions/tools, at new c.o.m. energy
- STXS/differential measurements will continue throughout Run 3
  - Extra statistics to target increasingly difficult to model regions of phase space e.g. H+2 jets
  - Experiments will use state-of-the-art tools for simulation e.g. MiNNLOps
  - Will converge on STXS uncertainty scheme before Run 3 analyses
- Parton shower modelling has become a dominant theory uncertainty for ggF cross sections
  - Worth investing time + effort in defining consistent scheme for PS uncertainties
  - And hopefully reduce their impact

	ggF + $b\bar{b}$H	VBF	WH	ZH	$t\bar{t}H$	tH
Uncertainty source	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]
Theory uncertainties						
Higher-order QCD terms	±1.4	±4.1	±4.1	±12	±2.8	±16
Underlying event and parton shower	±2.5	±16	±2.5	±4.0	±3.6	±48
PDF and α_s	< ±1	±2.0	±1.4	±2.3	< ±1	±5.8
Matrix element	< ±1	±3.2	< ±1	±1.2	±2.5	±8.2
Heavy-flavour jet modelling in non-$t\bar{t}H$ processes	< ±1	< ±1	< ±1	< ±1	< ±1	±13

Working Group 1: ggF Summary

In Progress & Upcoming

Publishing Boosted Higgs Note

Update of Boosted Higgs Recommendation

Full Update of Inclusive ggF Cross Section Recommendation

- N^{3}LO QCD Corrections (without threshold expansion)
- Top Quark Mass Effects @ NNLO (Missing: b & c quark mass effects)
- Mixed QCD-EW Corrections (Missing: $qg, q\bar{q}$ channels)
- PDF4LHC21 & PDF-TH uncertainty

Request for Input

Parton shower uncertainties and associated systematics

Want to get involved or have comments /questions to any item?
Please get in touch