Standard Model Higgs

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Les Houches 2023

Thanks to the many people who provided input!

Introduction

The list of topics for possible exercises can be found at:

https://phystev.cnrs.fr/wiki/2023:topics#session_1 → **Standard Model Higgs:**

These topics also overlap with the activities of the LHCHWGs.

In particular you can find the WG2 list at:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG2#Topics

and a LH style list of topics on CP:

https://docs.google.com/document/d/1qX5Ypq0Frw47HzltEqtxEt8PG9NM3Z5vkl8BGT2OZtk/edit#

Many topics also shared with other Les Houches groups – we focus on their impact on Higgs phenomenology.

Outline

- aN3LO pdfs for *gg -> H*
- Cell resampling for negative weight reduction.
- Gluon fusion as background for VBF
- VH(->bb) with flavour-sensitive jet algorithms
- PS & UE development
- Theory/Experiment Information Exchange
- Generators & GPU
- STXS and CP
- STXS and HHH couplings

Impact of aN3LO PDFs on ggF XS

Thanks: Thomas C, Giacomo M, Stefano F, Alex H

MSHT approximate N3LO PDFs (2207.04739) have a significant impact on Higgs ggF XS prediction

σ order	PDF order	$\sigma + \Delta\sigma_+ - \Delta\sigma_-$ (pb)	σ (pb) $+ \Delta\sigma_+ - \Delta\sigma_-$ (%)
PDF uncertainties			
N^3LO	aN^3LO (no theory unc.)	$45.296 + 0.723 - 0.545$	$45.296 + 1.60\% - 1.22\%$
	aN^3LO $(H_{ij} + K_{ij})$	$45.296 + 0.832 - 0.755$	$45.296 + 1.84\% - 1.67\%$
	aN^3LO (H'_{ij})	$45.296 + 0.821 - 0.761$	$45.296 + 1.81\% - 1.68\%$
	NNLO	$47.817 + 0.558 - 0.581$	$47.817 + 1.17\% - 1.22\%$
NNLO	NNLO	$46.206 + 0.541 - 0.564$	$46.206 + 1.17\% - 1.22\%$

NNLO with NNLO pdf → N3LO with NNLO pdf: +1.6 pb

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NNLO with NNLO pdf → N3LO with NNLO pdf: -0.9 pb

Talk: Tom Cridge (Friday)

Impact of aN3LO PDFs on ggF XS

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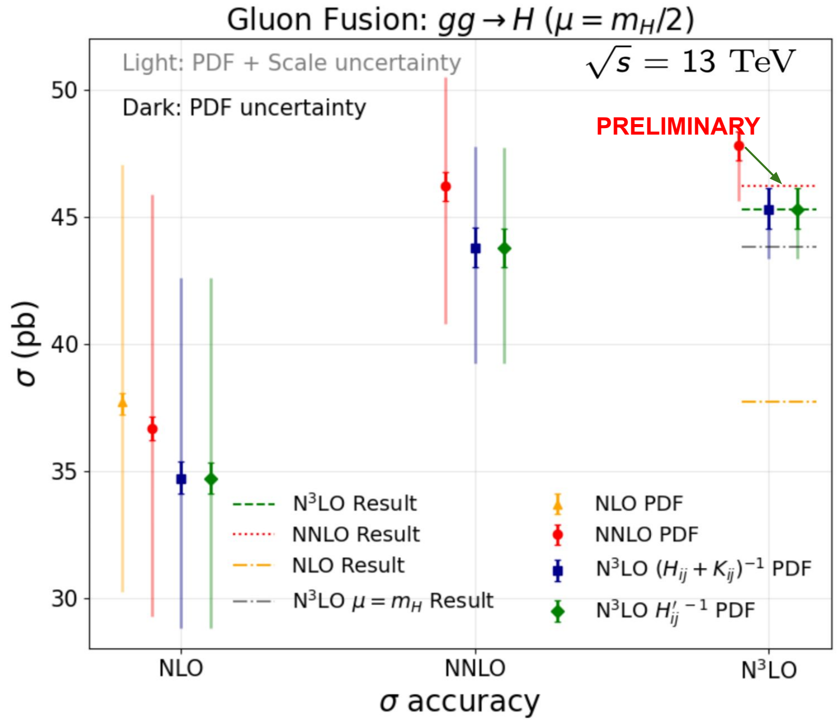

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Impact of aN3LO PDFs on ggF XS

Thanks: Thomas C, Giacomo M, Stefano F, Alex H

NNPDF: (**PRELIMINARY**) set that can be used for further study (subject to internal validation in the coming weeks)

Defined settings + comparisons that will provide useful input to the LHCHWG discussion

Project page:
https://phystev.cnrs.fr/wiki/2023:groups:smhiggs:ggf-an3lo:start

Main questions:

1. How does the NNLO δ(PDF) + δ(PDF-TH) uncert compare to the combined aN3LO δ (PDF+PDF-TH) uncert?
2. How do the MSHT aN3LO results compare to the NNPDF aN3LO results (both XS and uncertainties)?
3. Does adding a Higgs rapidity cut $|yX| < 2.5$ have a significant impact on the conclusions?

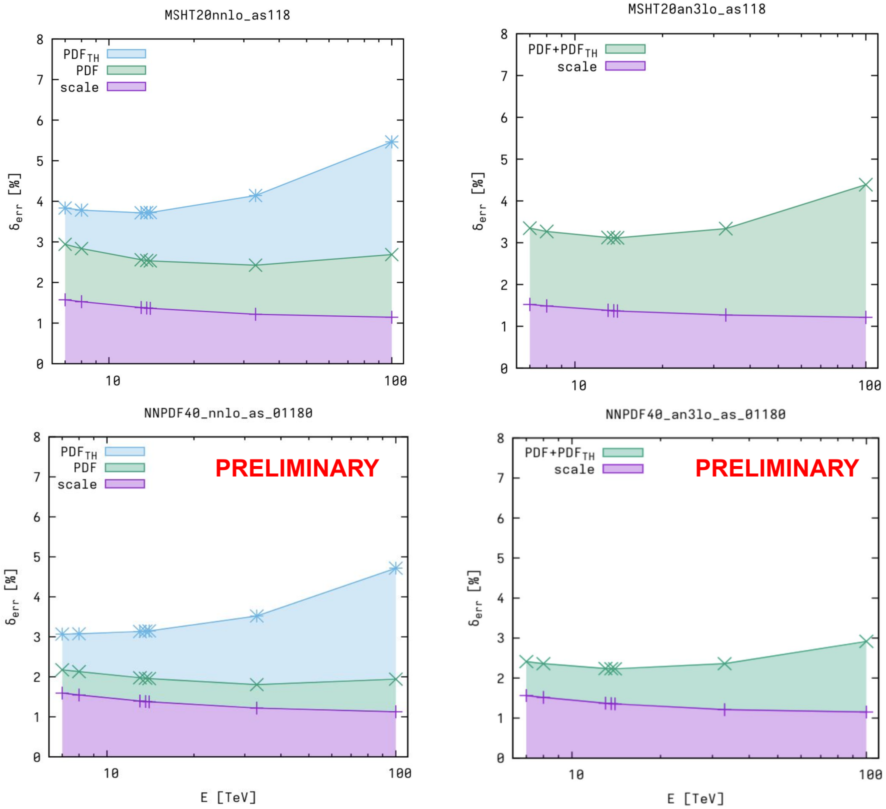
Note: All results to follow are **PRELIMINARY** and are subject to change after PDF sets are published!

See Alex's talk for further details

Impact of aN3LO PDFs on ggF XS

Thanks: Thomas C, Giacomo M, Stefano F, Alex H

The ad-hoc prescription $\delta(\text{PDF-TH}) = \pm\frac{1}{2}\left|\sigma^{(2)}(\text{PDF}_{\text{NNLO}}) - \sigma^{(2)}(\text{PDF}_{\text{NLO}})\right|$ is replaced by PDF+PDF-TH/MHOU built into the sets



Initial hints (**PRELIMINARY**):

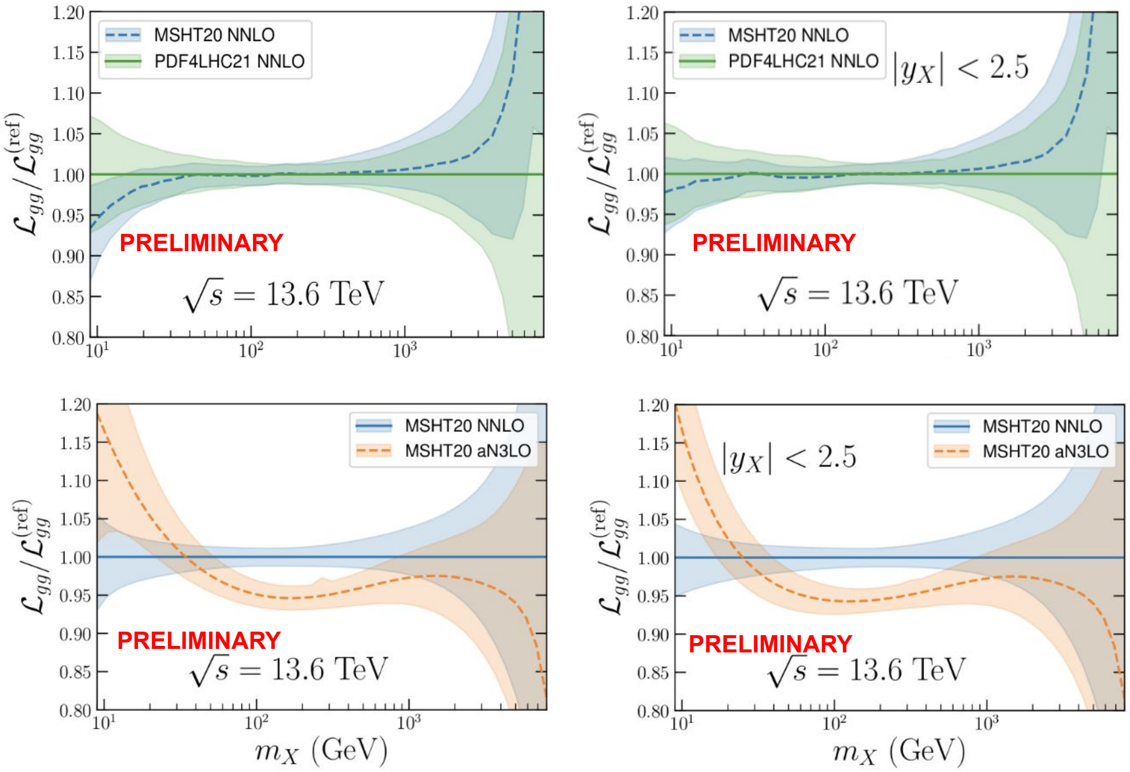
- Both sets see a reduction in PDF+PDF-TH uncertainty at aN3LO.
- At larger energies, both sets see a growth in PDF+PDF-TH uncertainty (sensitivity to smaller-x).
- MSHT20 error is slightly larger (~1%) than NNPDF4.0 at both NNLO and aN3LO.

Will be interesting to revisit this once NNPDF sets are finalised!

Impact of aN3LO PDFs on ggF XS

Thanks: Thomas C, Giacomo M, Stefano F, Alex H

Looking at the gg-lumi: |yX| < 2.5 rapidity cut does not seem to have a big impact around the Higgs boson mass



Cell Resampling for Negative Weight Reduction

Thanks: Ana C, Jeppe A, Andreas M

CRES (Cell Resampler) presented by Jeppe
Code publicly available:
https://github.com/a-maier/cres

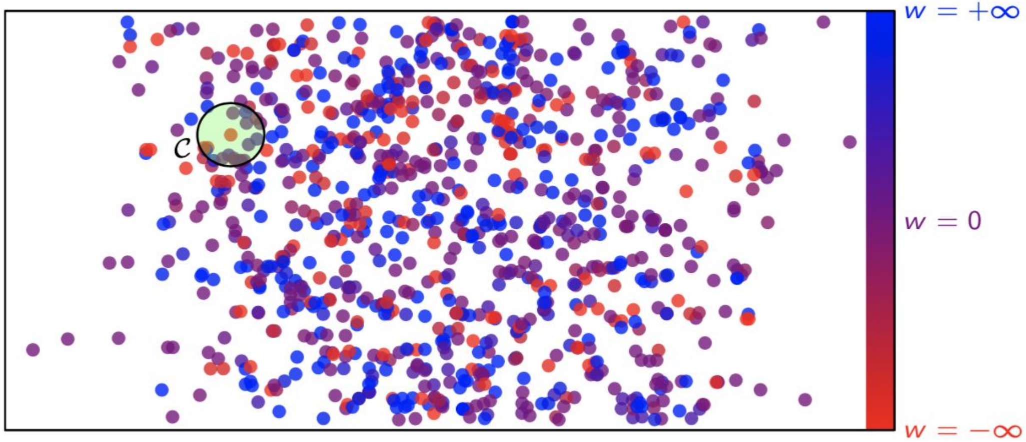
LH Study:

- Apply cell resampling to Higgs signal or background events similar to those used by the experiments
- Perform closure tests and measure degree of of simplification e.g. neg wgt event reduction

Several avenues to pursue for proceedings:

- Try different metrics for what constitutes “close” events?
- Try e.g. J/psi→leptons (something very narrow): check for technical issues regarding IR sensitivity, modifying distributions…
- Plots of mean/median/width of the cell resampling bins, studying these distributions and their potential impact

Aside: Jeppe surely wins the “most questions per talk” medal for this LH!



Talk: Jeppe Andersen (Friday)

Cell Resampling for Negative Weight Reduction

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Project page:
https://phystev.cnrs.fr/wiki/2023:groups:smhiggs:higgs-cell-resample:start

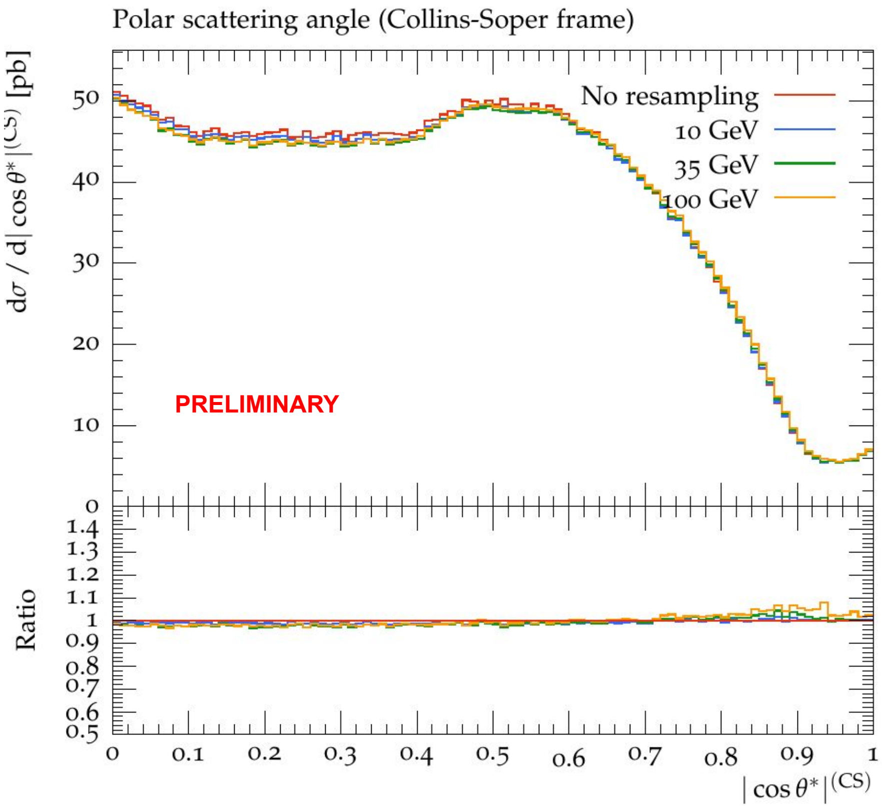
Applied Cell resampling to fixed-order event sample relevant for Higgs background:
pp→γγ(+2) @ NLO
90 < mγγ < 175 GeV
ptγ > 17 GeV
|ηγ| < 2.7
Fixione isolation (R0=0.1, n=2, ε=0.1)

First run with photons!

Negative Event Fraction (25M events)
Initial: 0.310
10 GeV Cell: 0.267
35 GeV Cell: 0.186
100 GeV Cell: 0.067

Interesting to see what happens with more events – stay tuned!

LHEF support added to CRES to enable this study (special thanks to Andreas!)



ggF VBF Background @ NLO FTApprox

Thanks: Xuan C, Alex H, Mathieu P

Fixed order results known for:
pp→H+2j @ NLO (FTApprox)

Amplitudes:
B: H+2j @ 1-loop w/ full mt
R: H+3j @ 1-loop w/ full mt
V: H+2j w/ full mt x HTL K-factor

However, above result was never run with VBF cuts.

LH Study:

- Produce a ggF background to VBF @ NLO FTApprox
- Compare to HEJ result
- Compare to other existing results for the ggF background (feel free to contact us if you want to be included in the comparison!)

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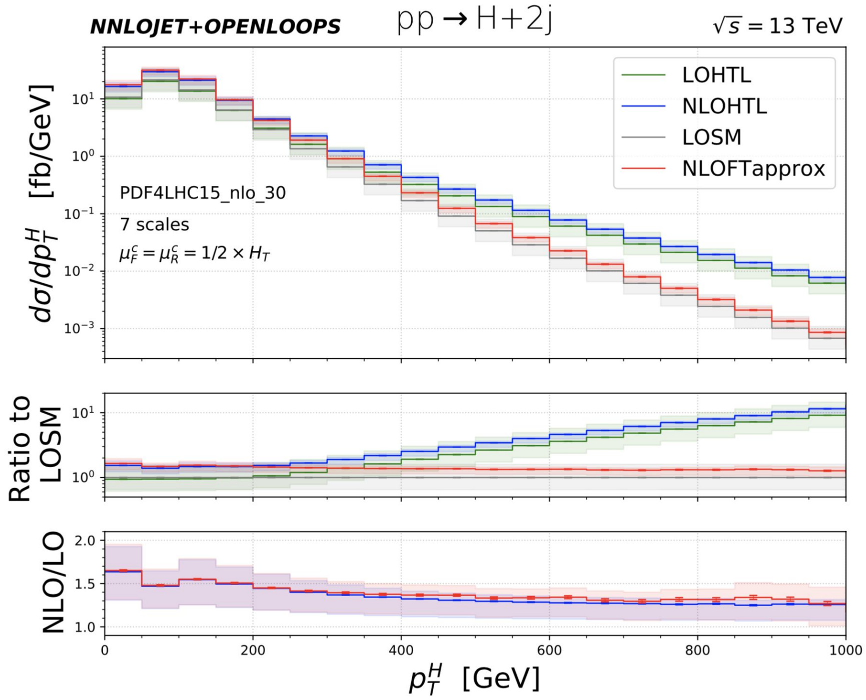

[Chen et al, '21]

ggF VBF Background @ NLO FTApprox

Thanks: Xuan C, Alex H, Mathieu P

Desired Cuts/Binning clarified for non-STXS runs

Codes currently running:

- pp→H+2j @ NLO (FTApprox)
- HEJ

Setup

Input parameters and settings

- $\sqrt{s} = 13.6\,\mathrm{TeV}$
- PDF set: `PDF4LHC21_40`
- $M_{\mathrm{H}} = 125.09\,\mathrm{GeV}$
- $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$
- $M_{\mathrm{Z}} = 91.1876\,\mathrm{GeV}, \Gamma_{\mathrm{Z}} = 2.4952\,\mathrm{GeV}$
- $M_{\mathrm{W}} = 80.379\,\mathrm{GeV}, \Gamma_{\mathrm{W}} = 2.085\,\mathrm{GeV}$
- G-mu scheme with $\alpha_{G_\mu} = 0.75652103079904\ldots \times 10^{-2}$ (from $G_\mu = 1.16638 \times 10^{-5}\,\mathrm{GeV}^{-2}$)
- central scale choice: $\mu_0^2 = (M_{\mathrm{H}}/2)\sqrt{(M_{\mathrm{H}}/2)^2 + p_{\mathrm{T,H}}^2}$ (Eq.(2) of 1506.02660)

Cuts/Binning

Event definition/selection:

- jets: anti-kT with $R = 0.4$
- $p_{\mathrm{T},j} > 30\,\mathrm{GeV}$
- $|\eta_j| < 4.7$
- $m_{jj} > 300\,\mathrm{GeV}$
- $|\Delta y_{jj}| > 2$
- no rapidity selection on Higgs

Histograms and binning:

- double-differential ($m_{jj} \times p_{\mathrm{T,H}}$): `[300, 500, 700, 900, 1100, ∞] × [0, 80, 120 ,260, 500, 850, ∞]`
- double-differential ($m_{jj} \times \Delta\phi_{jj}$): `[300, 500, 700, 900, 1100, ∞] × [0, π/4, π/2, 3π/4, π]`
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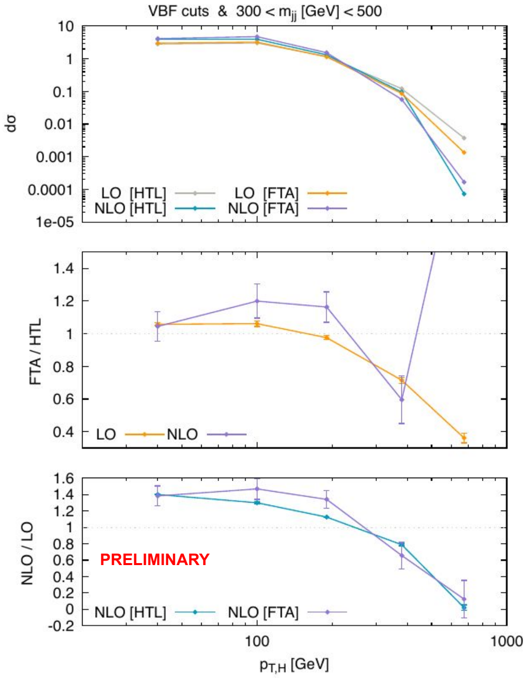

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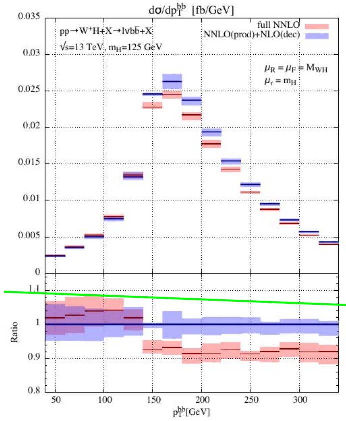
Flavour tagging in VH(-> bb)

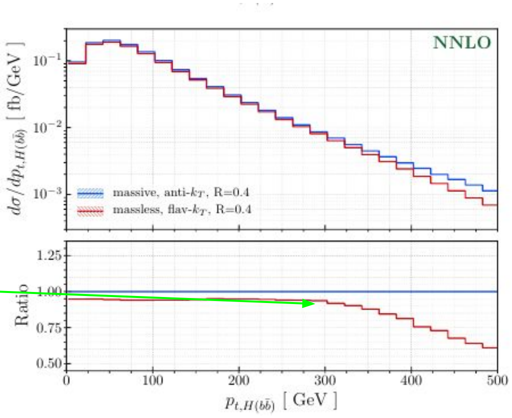
Earlier studies of VH(->bb) at NNLO used:

- flavour-kT with massless b-quarks (IR safe)
- anti-kT using massive b-quarks (IR safe)

Comparison shows discrepancy starting at pTH ~ 300 GeV.



[Ferrera, Somogyi, Tramontano '17]



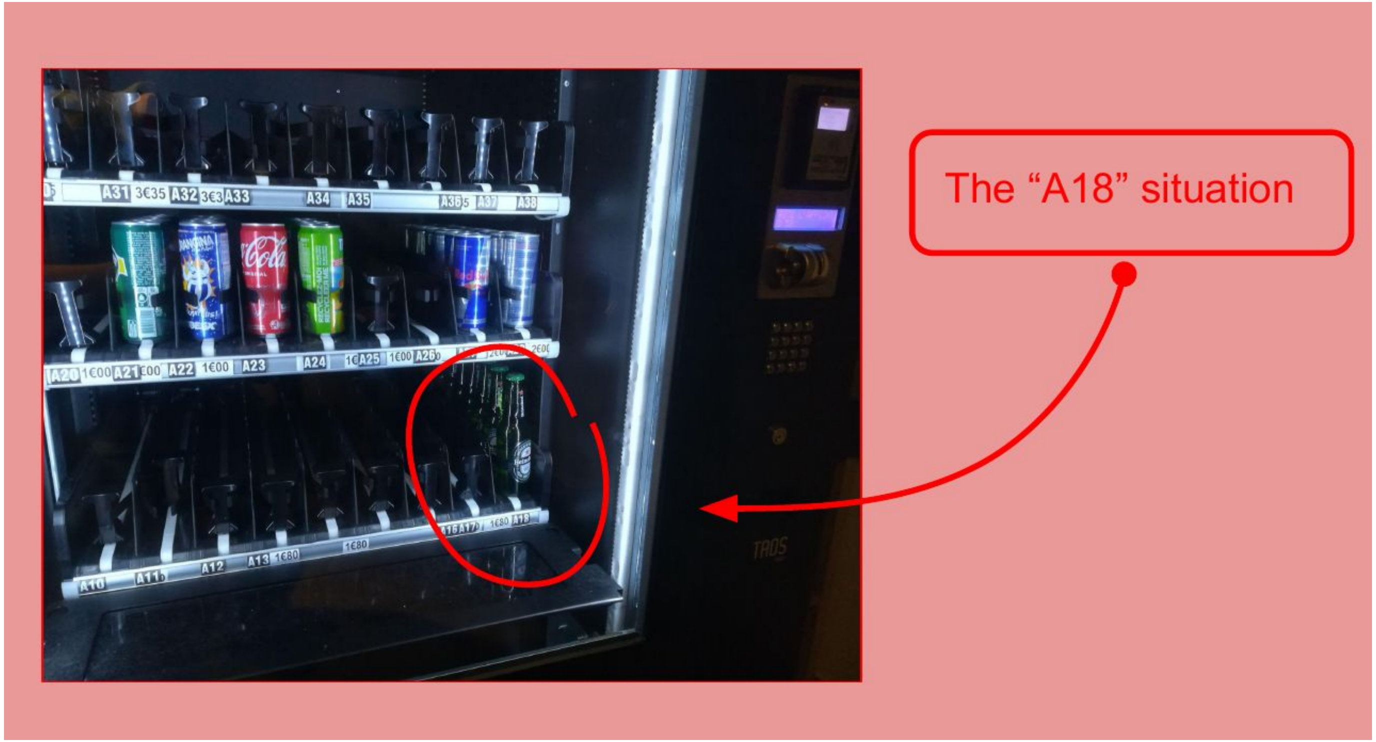
[Behring et al, '20]

Problem:

- Flavour-kT does not correspond with experimental setups
- Massive calculation (in general) is more complicated

So if you had an NNLO calculation for massless b quarks…

Flavour tagging in VH(-> bb)



Flavour tagging in VH(-> bb)

Thanks: Daniel R, Rene P, Giovanni S, Ludo S, Arnd B

New generation of flavour-sensitive algorithms allows flavour tagging with massless FO calculations using anti-kT jet definition

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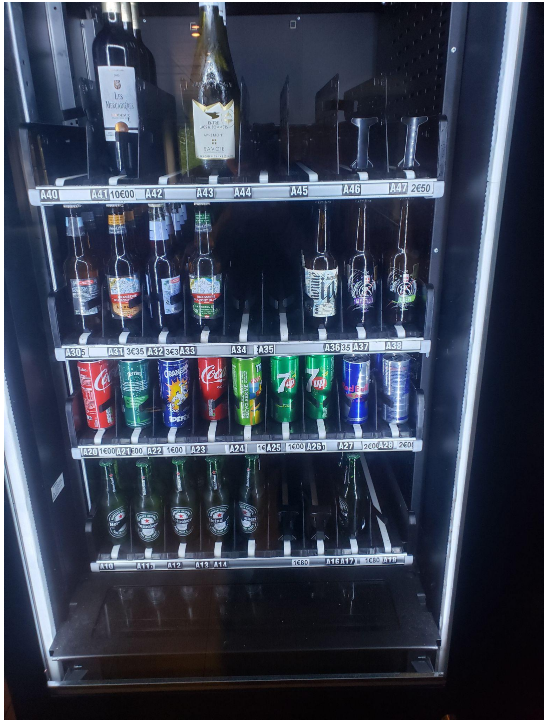
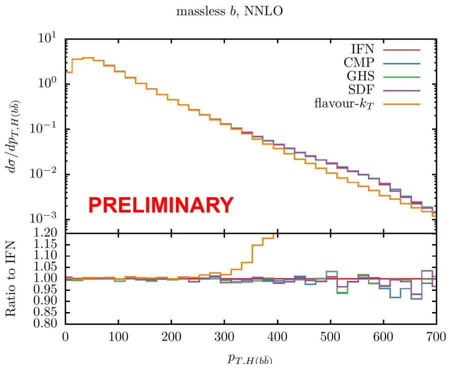
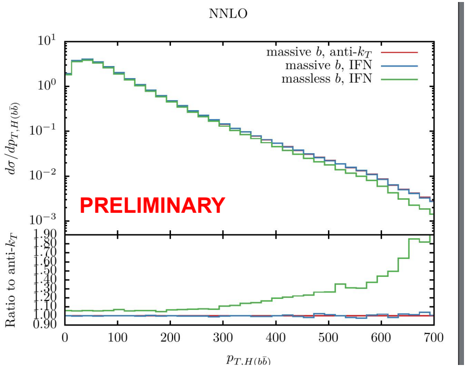


Flavour tagging in VH(-> bb)

Thanks: Daniel R, Rene P, Giovanni S, Ludo S, Arnd B

How do these impact WH(->bb) at NNLO?





- Good agreement between SDF, IFN, CMP, GHS
- Difference with respect to flavour-kT starting at pTH ~ 300 GeV
  - Similar to what was seen in comparison of flavour-kT (massless b quarks) vs anti-kT (massive b-quarks)

- Use flavour-sensitive jet algorithms with **massive** b quarks:
  - Compare against “vanilla” anti-kT
  - Compare massless b quarks vs massive b quarks with same jet algorithm.
- *Caveat:* Results with massive b-quarks use nf=4 in pdfs, with massless use nf=5.
- Stay tuned…

Flavour algorithms

IRC safe flavour-aware algorithms in experimental measurements:

Jets

q/g jet tagging

- Lots of studies for different flavor-aware algorithms and q/g tagging happened/ongoing/planned

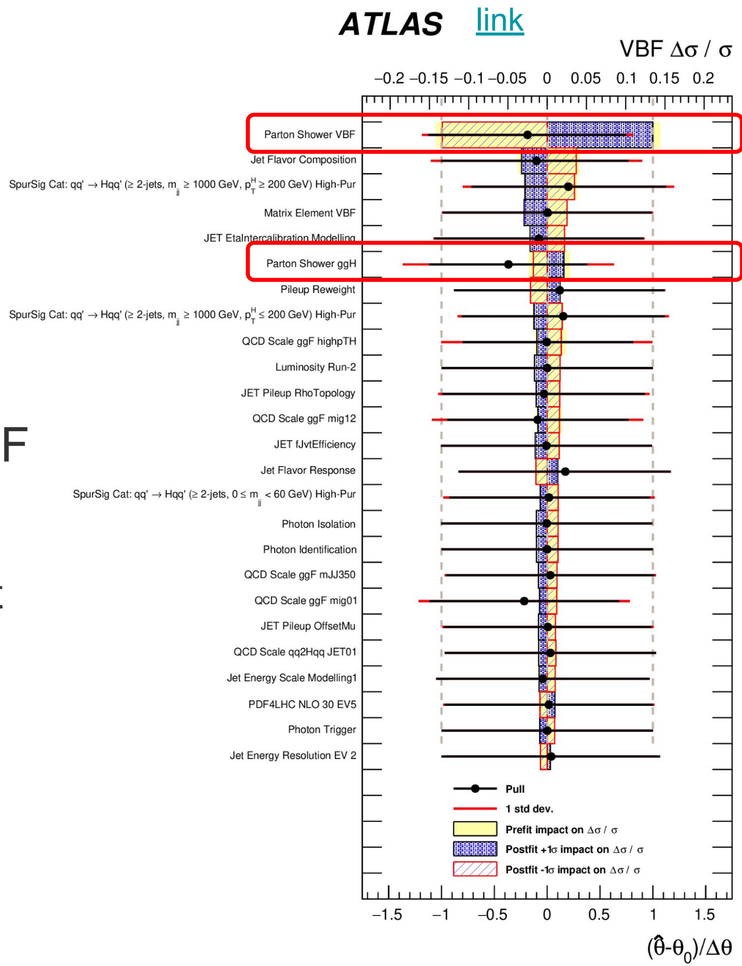
⇒ See more in Jets summary & closeout talk

Parton Shower & underlying event issues and developments

The limiting systematic on VBF
(and very significant for other Higgs processes)

Big efforts started to do comprehensive studies in VBF

- Define phase spaces and observables
- Include parton shower, hadronization, underlying event
  - Use tunes from ATLAS & CMS directly
- And much more…



⇒ See more in Techniques & Calculations summary & closeout talk

Experiment/Theory efficient information exchange

Theory colleagues expressed wish to have exact setups of generators available

- Maybe experiments can make this available (for main samples)??
  - Have a Zenodo reference for each (main) sample, pointing to the precise setup?
- Could ATLAS+CMS experiments generate the big samples together?

Experiment/Theory efficient information exchange

Vinicius Mikuni is working with Omnifold, a way to unfold on an event-by-event basis (see slides)

- Philippe Gras provided a CMS H→4l sample
  - Containing reco and truth particle level
- Use this to exercise:
  - Event-wise unfolding with signal only
  - In second step: add background
  - Try also H→γγ sample/analysis

Questions:

- How to treat the negative weights in the sample?
  - Could use *Cell Resampler* to reweight sample
    (see Jeppe Andersen's talk on Friday, and earlier slides)

Generators - negative weights

Generators take ~10% of the experiments computing resources. With more precision (gen) and larger datasets (exp), the time required for generation is expected to increase significantly.

- Very important for experiments; lots of money involved!
- A patch could be *Cell Resampler*
  (see Jeppe Andersen's talk on Friday, and earlier slides)
  - But better would be to improve this in generators directly

Generators - GPU

Generation on GPU

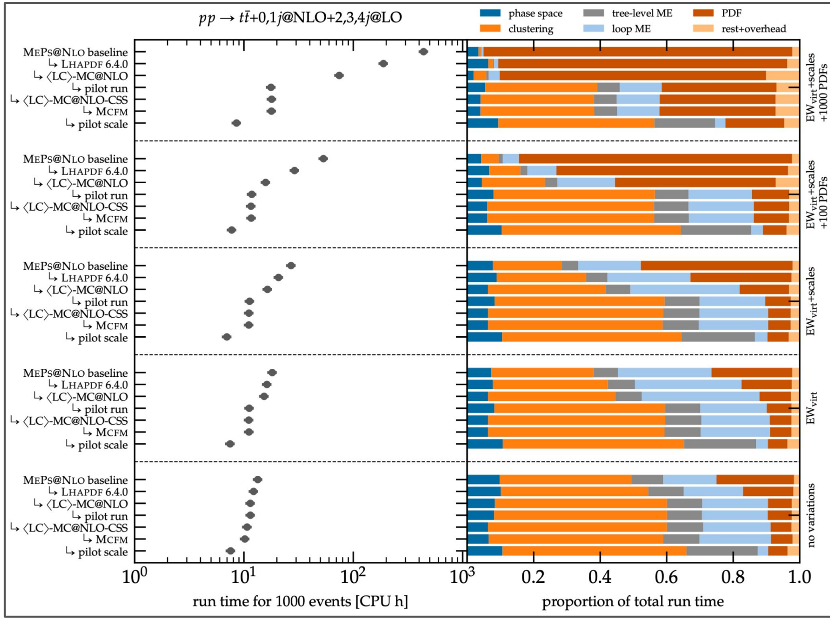
Andrea Valassi presented work with MadGraph:

- Good speedups seen with SIMD and CUDA
  - LO-only
- Need to approach MG libraries to also port accordingly

Max Knobbe presented work with Sherpa:

- Focus on processes with many legs/logs and high cross-section
- Hadronization & parton shower have lots of *if/else* → terrible for GPU
  - Write out events from GPU to HDF5 file and shower + hadronize with Sherpa afterwards

⇒ See more in Tools summary & closeout talk



Very large speedups (**x2-78**) demonstrated when running ATLAS setup with >100 weights (EW, PDF,...) using *simplified pilot runs and fast PDFs* [https://arxiv.org/abs/2209.00843]

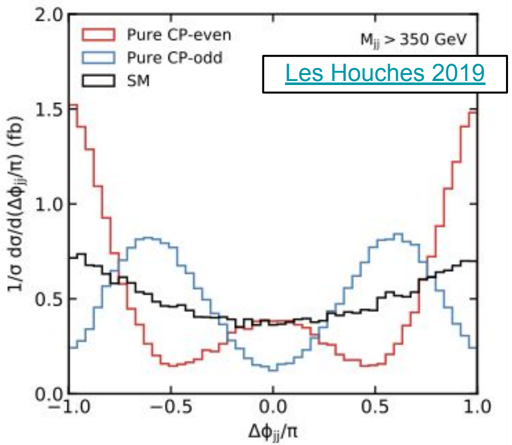
CMS use the MG reweighting module as standalone to perform the reweighting on the final data format

STXS and CP - setting the scene

Current STXS without dedicated sensitivity to CP (in production)

Integrate this in the next version of STXS (optionally?)

Several dedicated individual measurements exist, e.g., exploiting signed $\Delta\varphi_{jj}$ in ≥ 2-jet topology



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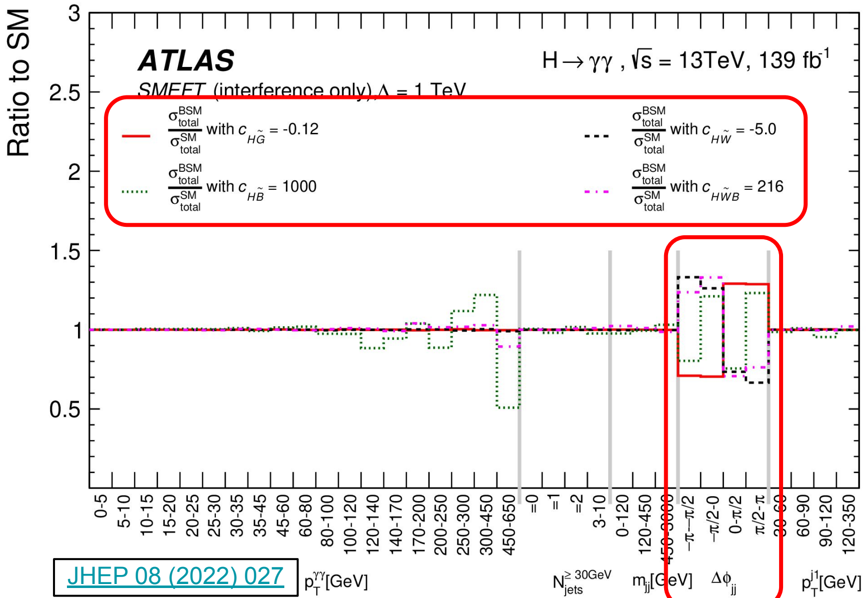

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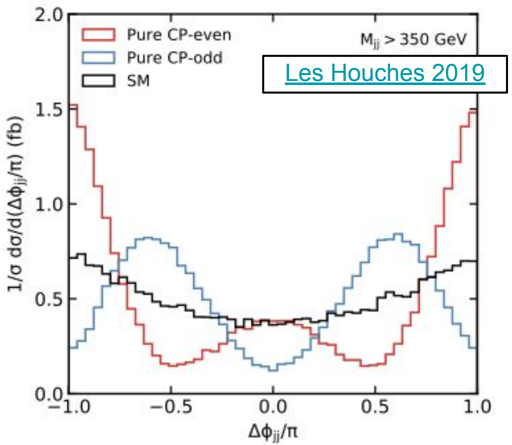

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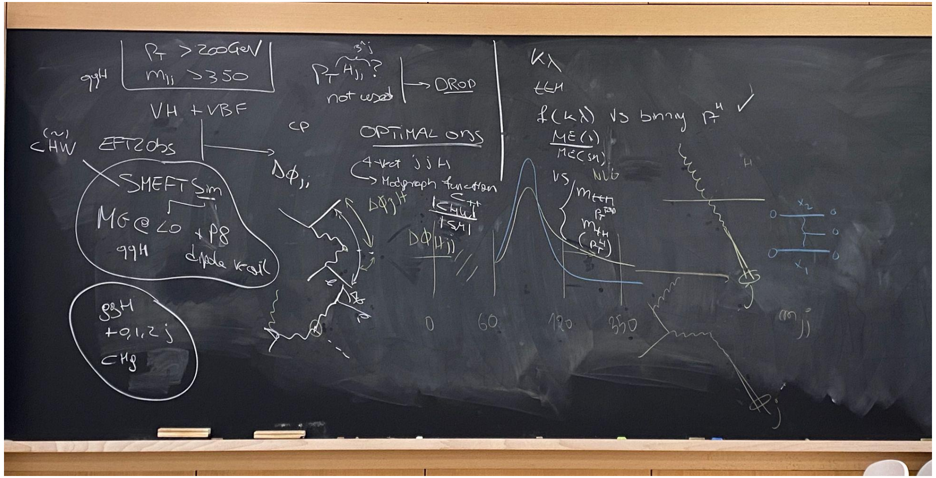

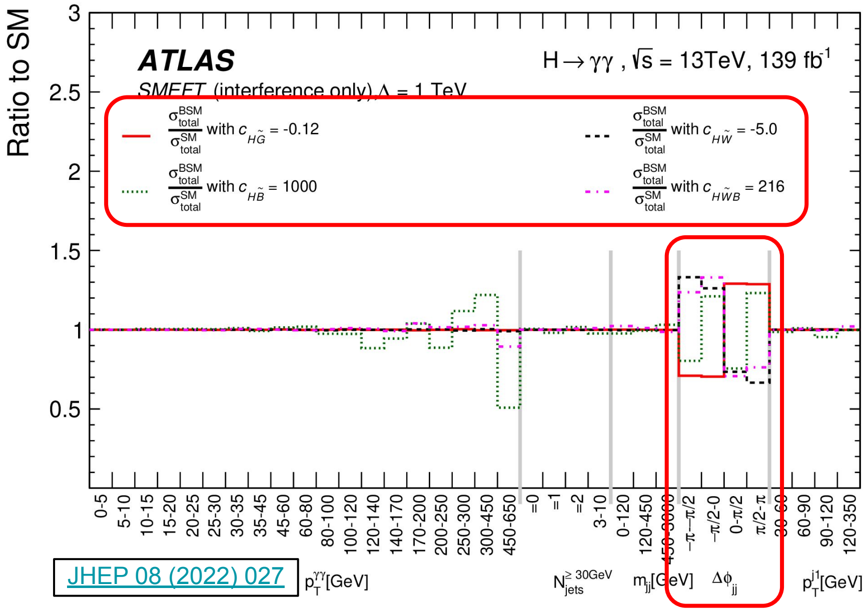

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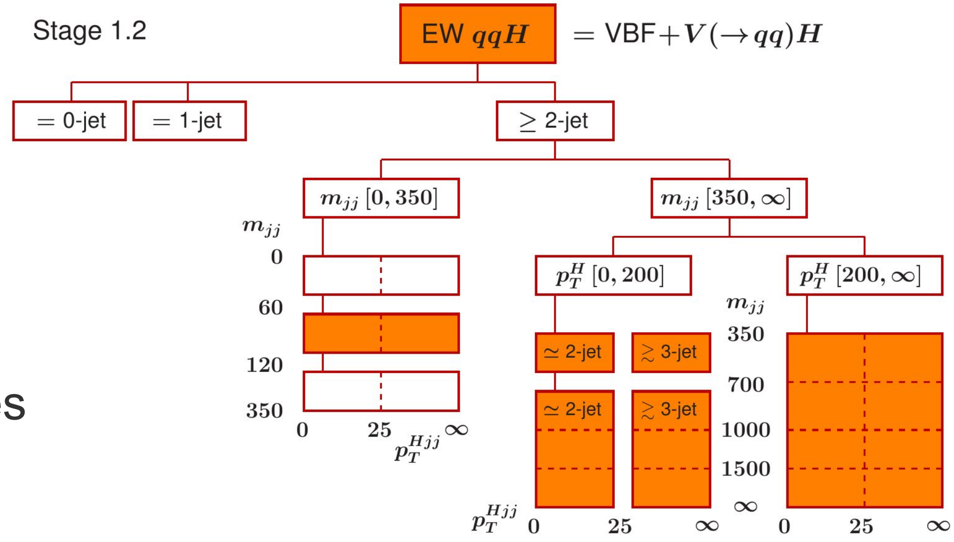
STXS and CP - EW qqH



Start with EW qqH ≥ 2-jet topology and split in signed $\Delta\varphi_{jj}$

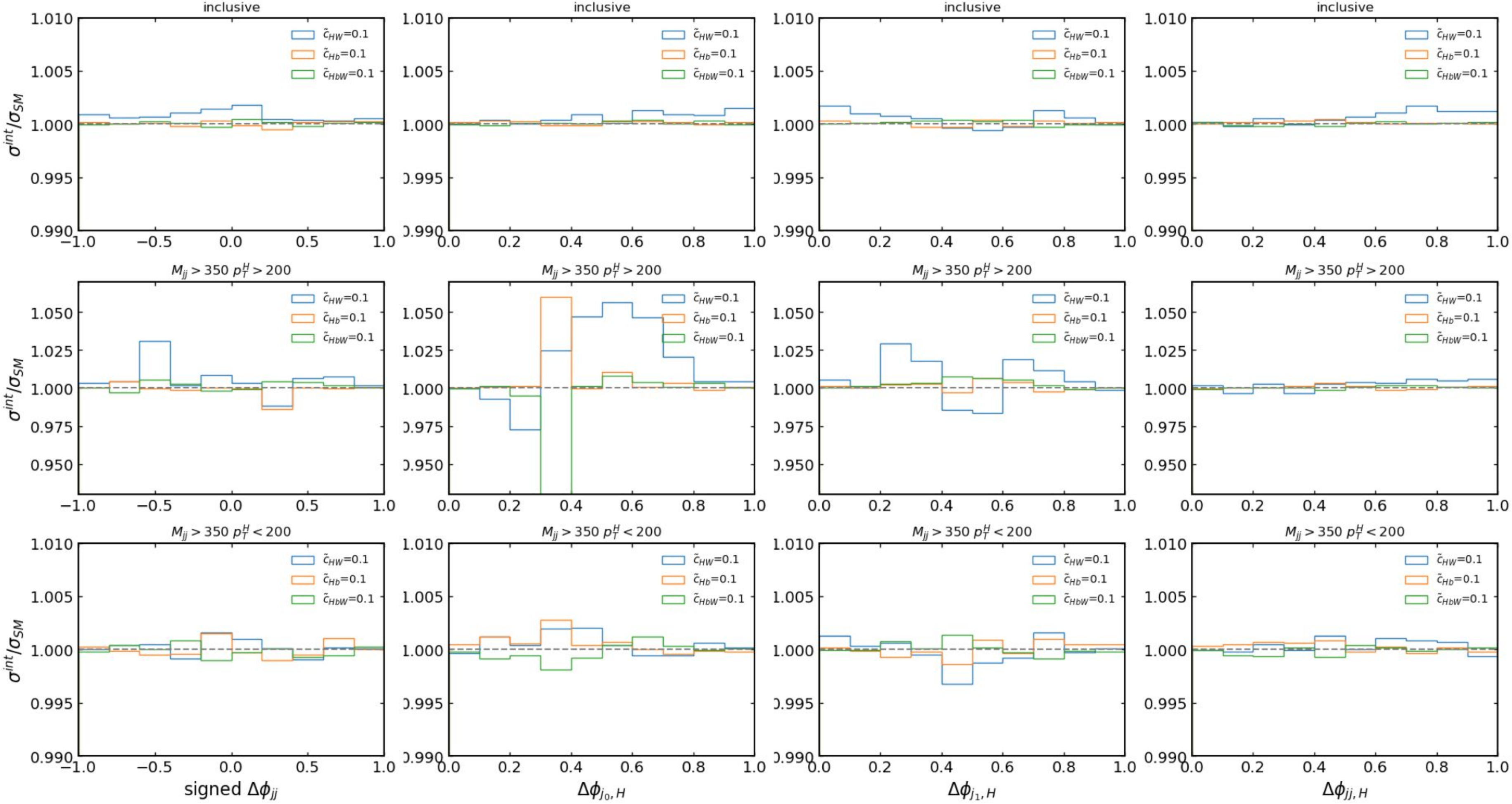
- Check also low m_{jj}, i.e., V(had)H region
  - Explore other CP-sensitive variables
- Remove p_T(Hjj) splits(?)

Preliminary study by Yacine Haddad:

- Test CP-odd operators $\check{C}_{HW}$, $\check{C}_{HB}$, $\check{C}_{HWB}$ (set them all to 0.1 as first try)
- Try out different CP-sensitive variables in different phase-space regions:
  - Inclusive
  - m_{jj} > 350 GeV and p_T(H) > 200 GeV
  - m_{jj} > 350 GeV and p_T(H) < 200 GeV

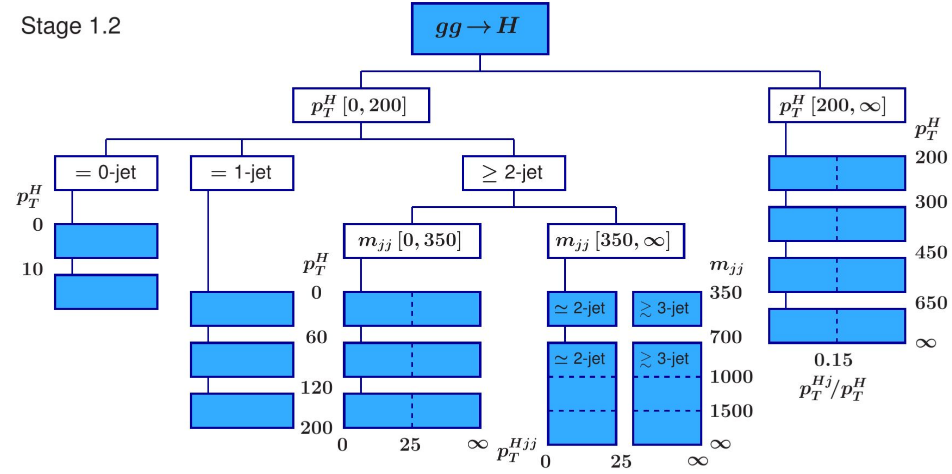
STXS and CP

Preliminary study by Yacine Haddad:



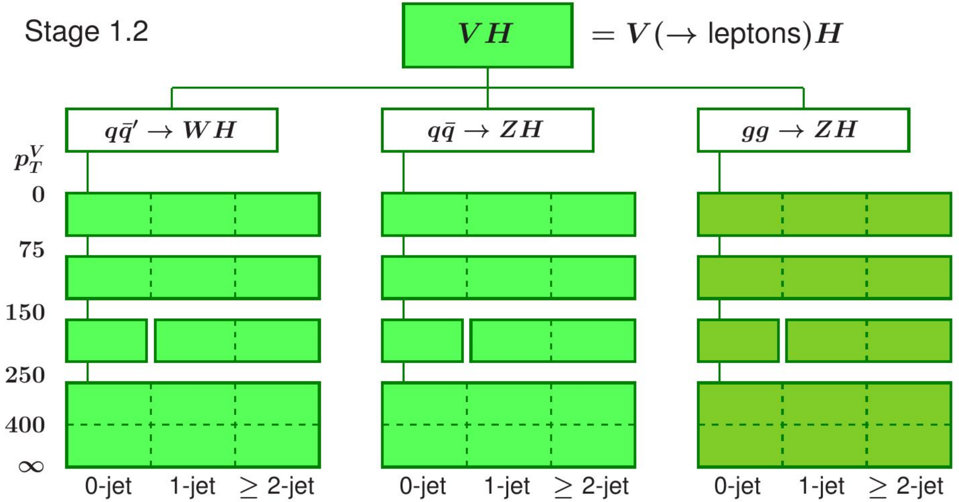
STXS and CP - others

Repeat study for ggF in ≥ 2-jet topology



Explore also V(lep)H bins eventually as well

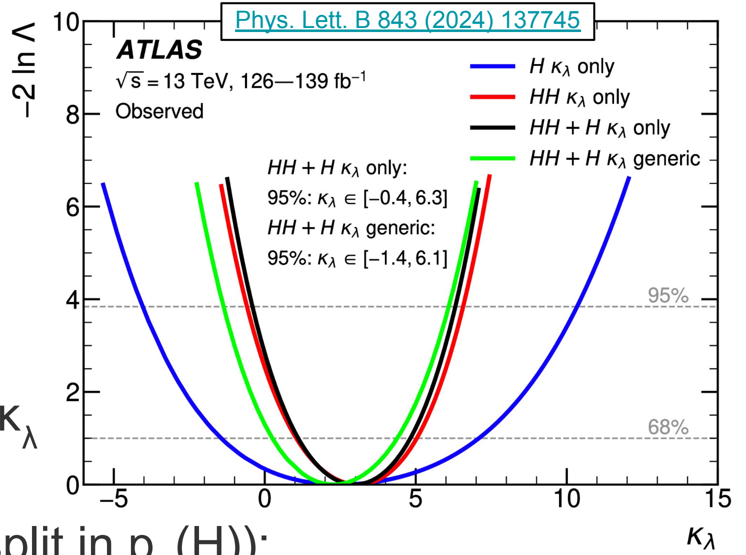
- Including checking other variables



Longer term and ideas

- Split using Optimal Observables?
  - One for VBF
  - and two for VH (WH and ZH)

STXS and κ_λ HHH coupling



H+HH combination to extract HHH coupling

- κ_λ modifier w.r.t. SM λ_{HHH}
- Use single-H STXS measurements with κ_λ parametrization (no shape for ggF used)
- But STXS was never designed to be sensitive to κ_λ

Preliminary study by Gianna Mönig using ttH STXS (split in p_T(H)):

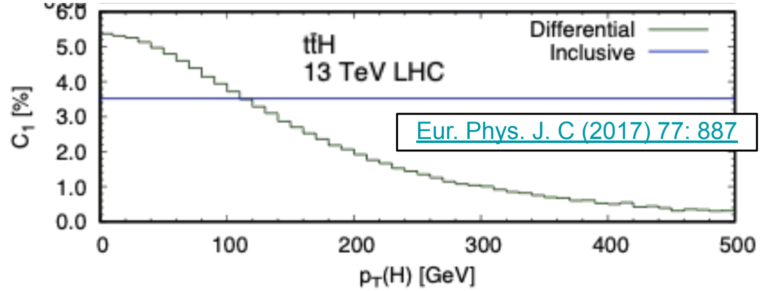
- C_1 obtained by ratio between LO and NLO cross-section in κ_λ expansion
- Use Fisher information as measure:
  - C_1 / (1+δZ) (from Eq. 5 of arXiv:1709.08649)
- Maximize sum of C_1 of all bins:
- No information about statistics in bins included
  → more bins lead to higher values of measure

bin edges	Sum of C1
0,60,120,200,300,450	0.150
0,60,100,200,300,450	0.155
0,50,100,200,300,450	0.156
0,40,100,200,300,450	0.159
60 bins between 0&500	1.347

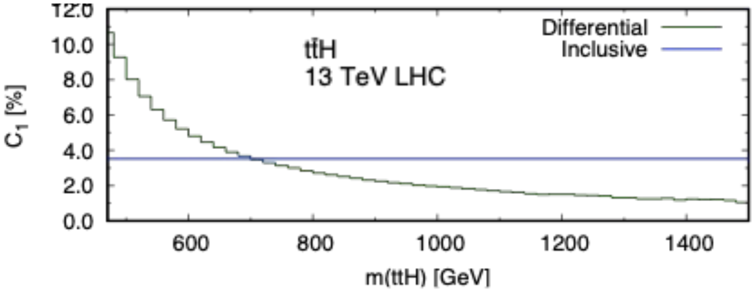
STXS and κ_λ HHH coupling

Investigate other observables?

- ttH STXS is split in $p_T(H)$
  - but ttH multilepton cannot reconstruct $p_T(H)$ well
  - Maybe study e.g., $m_{(T)}(ttH)$ instead?

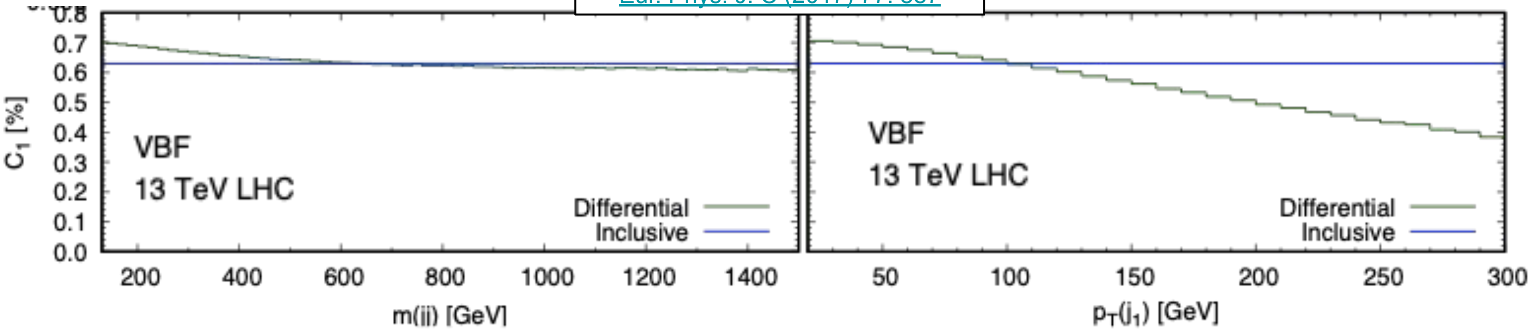


Eur. Phys. J. C (2017) 77: 887



- EW qqH (in VBF-like phase space) is split mostly in m_{jj}, plus one split in $p_T(H)$
  - Maybe study $p_T(j_1)$ instead?

Eur. Phys. J. C (2017) 77: 887



STXS and κ_λ HHH coupling

Preliminary study using ttH by Gianna Mönig:

- Signal-only STXS fit using pseudo-data with $\kappa_\lambda = 2$
  - Vary $p_T(H)$ bin boundaries
  - Assume same exp. efficiency in all bins
  - Fit κ_λ directly
    - Assume quadratic dependence of cross-section variation with κ_λ (good approximation for small κ_λ)
  - Exact binning has no impact on κ_λ uncertainty

bin edges	uncertainty
ptH: 0,60,120,200,300,450	-0.53,0,57
ptH: 0,60,100,200,300,450	-0.53,0,57
ptH: 0,50,100,200,300,450	-0.53,0,57
ptH: 0,40,100,200,300,450	-0.53,0,57

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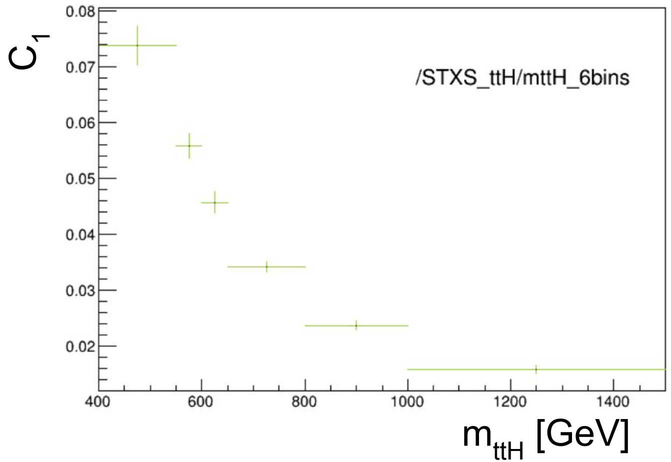
ptH: 0,50,100,200,300,450	-0.53,0,57
ptH: 0,40,100,200,300,450	-0.53,0,57
mttH: 400,550,600,650,800,1000,1500	-0.51,0,54

- **Try using m_{ttH} instead of $p_T(H)$:**
  - 6 bins [GeV]: 400, 550, 600, 650, 800, 1000, 1500
  - 5 bins [GeV]: 400, 550, 650, 800, 1000, 1500
  - Sensitivity slightly better than with $p_T(H)$
    - At reco-level, can reconstruct these two better or worse, depending on channel



STXS and κ_λ HHH coupling

Preliminary study using ttH by Gianna Mönig:

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bin edges	uncertainty
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ptH: 0,40,100,200,300,450	-0.53,0,57
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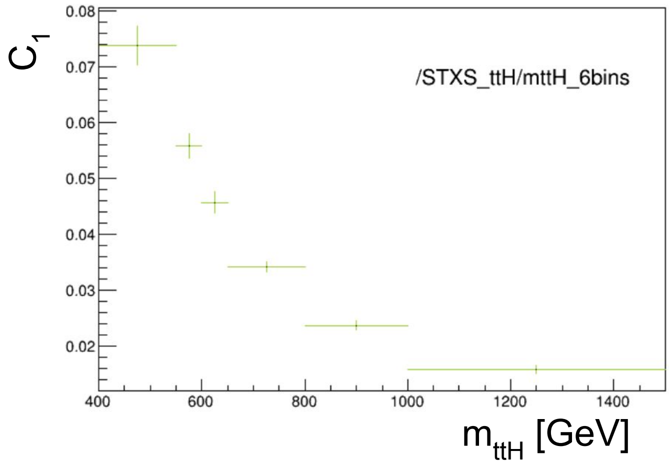


- Great start… more detailed studies needed…

A wishlist of another kind

Collected wishes from the experimental community (not exhaustive), other than the wishlist discussed on Monday:

- Narrower weight distribution in generators
- Parton shower + underlying event for VBF and ggF+2jet: better predictions and move away from 2-point systematics ⇒ some progress here, see Les Houches summaries…
- NLO generator for $gg \to ZH$
- Include κ_c in the parameterization of the $gg \to ZH$ production
- $H \to 4\ell$ decay: EW modelling will become important w/ more data. Leading theory systematic for $m_{4\ell}$ mass measurement, and it impacts CP-sensitive models
- STXS:
  - Add 1 bin for tH
  - Add higher $p_T(V)$ splits, e.g., 400-600 GeV
  - Many dashed bin boundaries in v1.2 should go. Experiments cannot target them.
  - Add decay-STXS where it matters

A wishlist of another kind

Collected wishes from the experimental community (not exhaustive), other than the wishlist discussed yesterday:

- Backgrounds:
  - V + heavy flavor:
    - Different strategies in place for ATLAS and CMS, but in the end still large data/MC discrepancies
    - Severe mismodelling of $p_T(V)$ seen in Sherpa
    - aMC@NLO FxFx very different w.r.t. Sherpa 2.2.11 in N_{jets} at high $p_T(V)$
  - ttW:
    - Multileg setup w/ EW NLO3 contributions
    - Compare Sherpa and aMC@NLO multileg w/ RIVET routine
  - ttbb & ttcc with full systematics model
  - tHjb, tWH: 5FS vs 4FS

Summary

A lot of activities got kickstarted here!

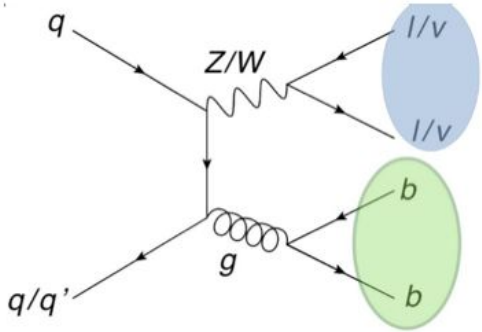
Remember to always respect the living ghost of Les Houches…

Backgrounds - V+HF for VH→bb

https://indico.cern.ch/event/1207058/

V+heavy-flavour represents the main irreducible background of the VHbb analysis

- Signal extracted from the fit to a NN where the bkg is from MC (starting sample 10^9 evts)
- theory prediction extremely important for accurate signal extraction
- data constrains prediction of V+jets processes very precisely ⇒ MC modelling and choice of systematics variations can impact the measurement significantly



Different strategies in place for ATLAS and CMS, but in the end still large data/MC discrepancies

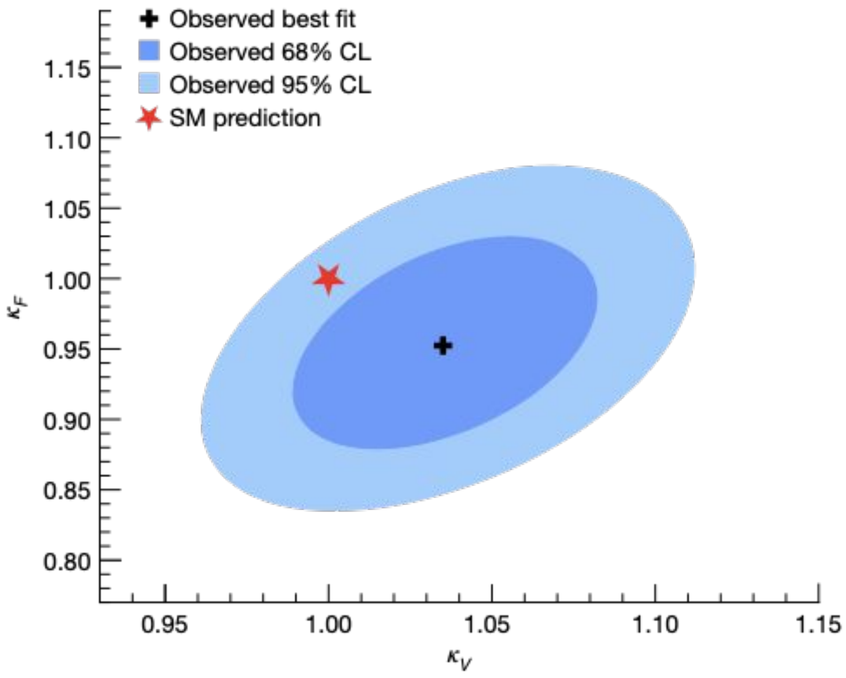
CMS

- (2016) LO MadGraph with MLM matching: reweighted to NLO in etabb + Xsec reweighted to NNLO QCD + NLO EWK in $p_T(V)$
- (2017/18) NLO MadGraph with FxFx matching: Xsec reweighted to NNLO QCD + NLO EWK in $p_T(V)$
    - Still o(30-40%) scale factor on the normalization

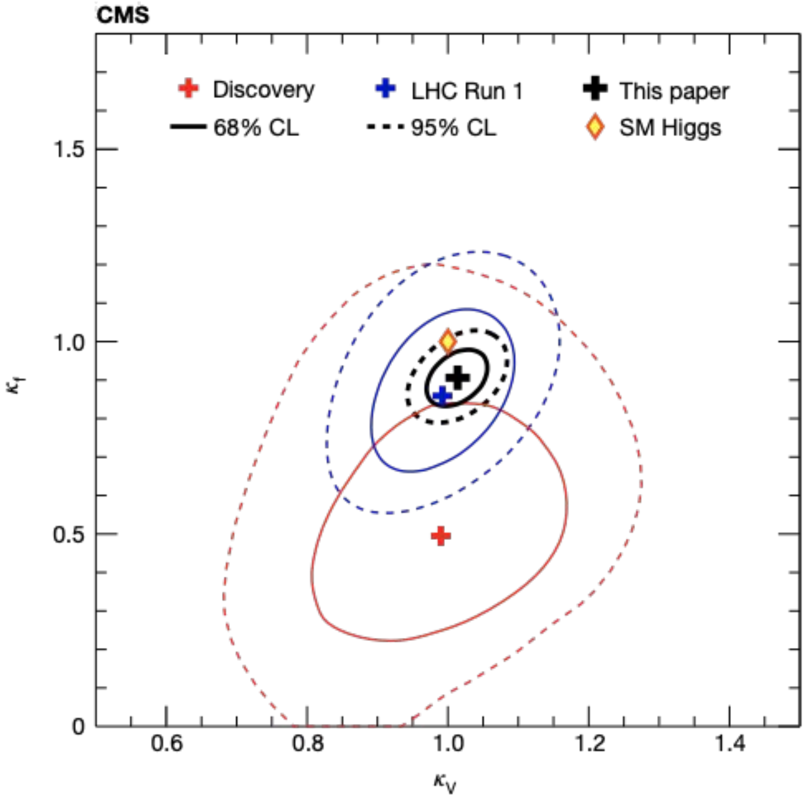
ATLAS

V+hf modelled with Sherpa 2.2.1 and now Sherpa 2.2.11.

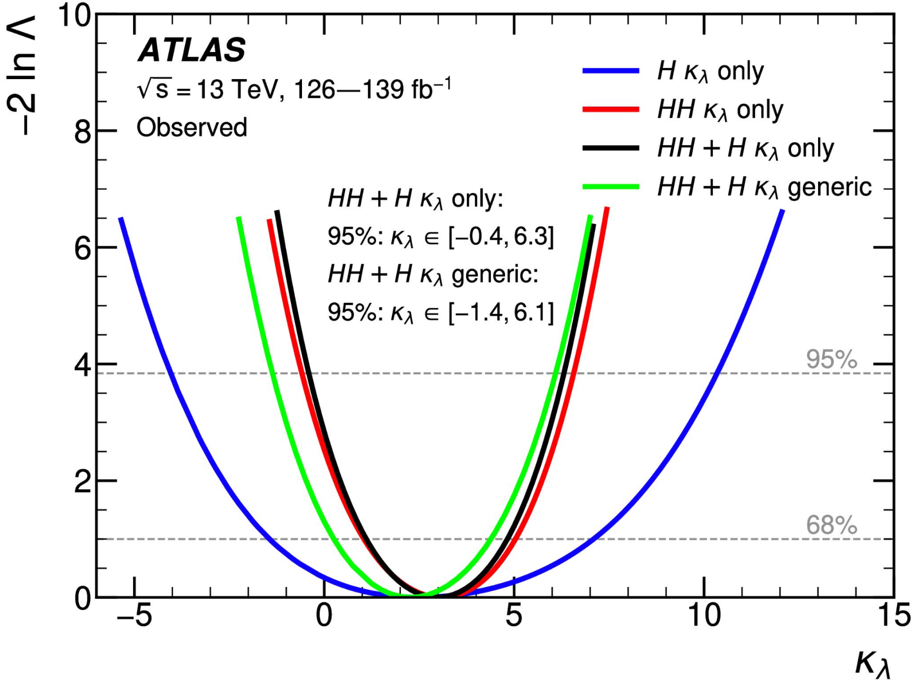
- underestimation of the overall yield and Sherpa 2.2.11 shows a severe mismodelling of the vector boson pT in the relevant range of 75-400 GeV requiring correction factors of up to 1.5-2 at high $p_T(V)$
- enabling NLO electroweak corrections worsens the agreement further
- the alternative MC sample currently under study, MG_aMC@NLO+Pythia8 with FxFx merging, shows very large differences to Sherpa 2.2.11 in the prediction of number of jets at high $p_T(V)$

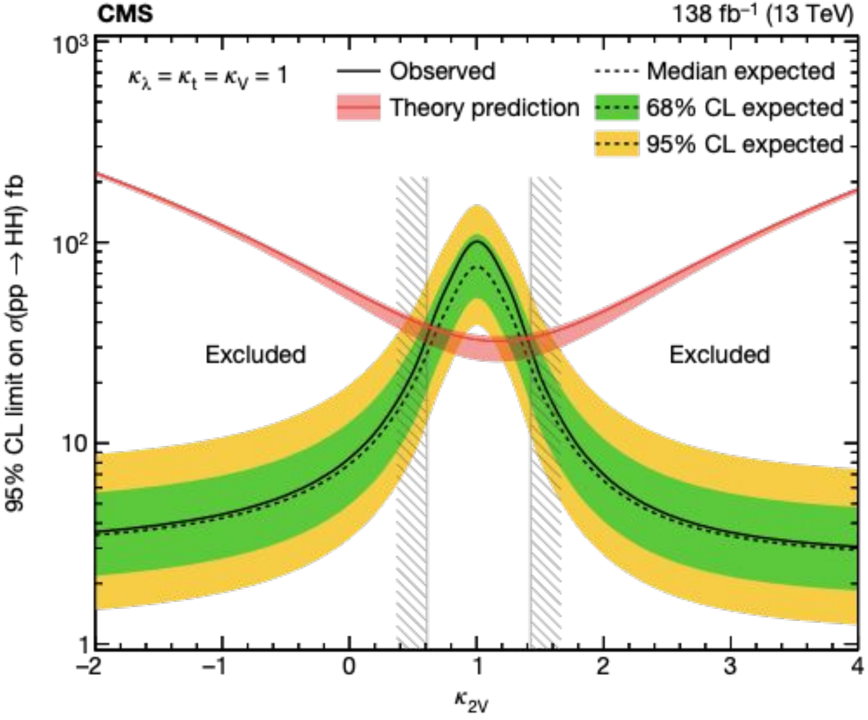


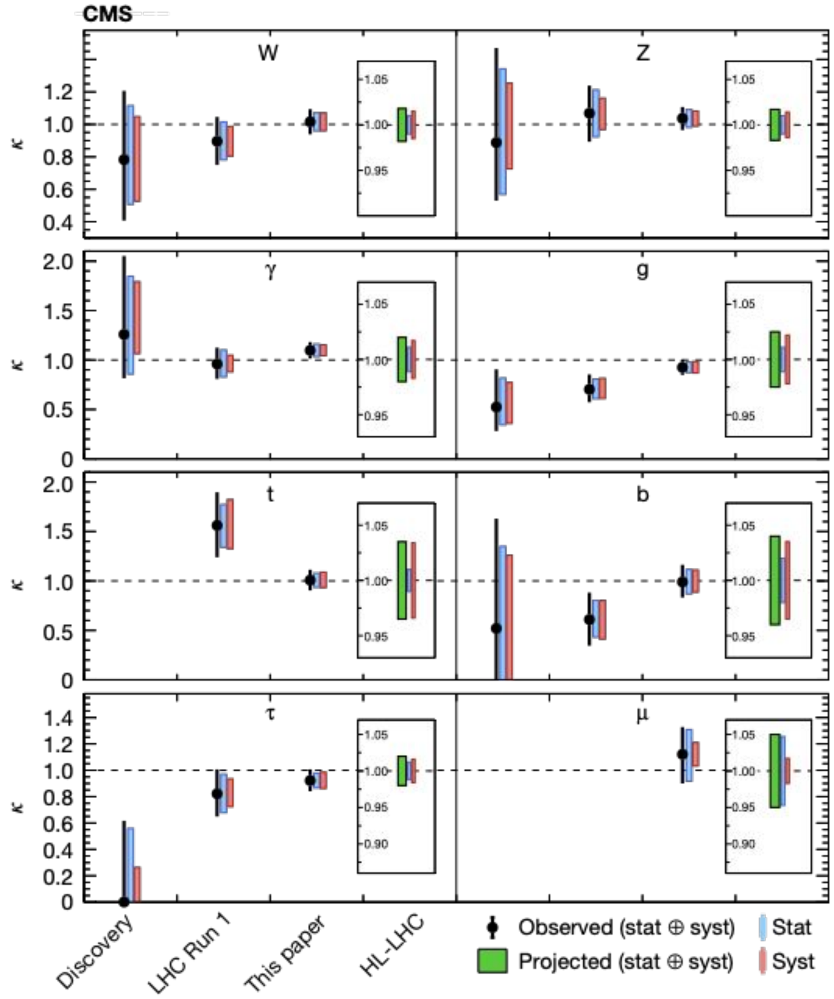
Observed best fit
Observed 68% CL
Observed 95% CL
SM prediction
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.95
1.00
1.05
1.10
1.15
κ_V
κ_F



CMS
Discovery
LHC Run 1
This paper
68% CL
95% CL
SM Higgs
1.5
1.0
0.5
0
0.6
0.8
1.0
1.2
1.4
κ_V
κ_f


ATLAS
$\sqrt{s}$ = 13 TeV, 126—139 fb^{-1}
Observed
$H\ \kappa_\lambda$ only
$HH\ \kappa_\lambda$ only
$HH + H\ \kappa_\lambda$ only
$HH + H\ \kappa_\lambda$ generic
$HH + H\ \kappa_\lambda$ only:
95%: $\kappa_\lambda \in [-0.4, 6.3]$
$HH + H\ \kappa_\lambda$ generic:
95%: $\kappa_\lambda \in [-1.4, 6.1]$
95%
68%
$-2 \ln \Lambda$
κ_λ


CMS
138 fb^{-1} (13 TeV)
$\kappa_\lambda = \kappa_t = \kappa_V = 1$
Observed
Median expected
Theory prediction
68% CL expected
95% CL expected
Excluded
Excluded
95% CL limit on σ(pp → HH) fb
κ_{2V}


CMS
W
Z
γ
g
t
b
τ
μ
κ
Discovery
LHC Run 1
This paper
HL-LHC
Observed (stat ⊕ syst)
Projected (stat ⊕ syst)
Stat
Syst

Yukawa couplings

top: ttH/tttt

Extracting Higgs couplings without cross-section assumptions:

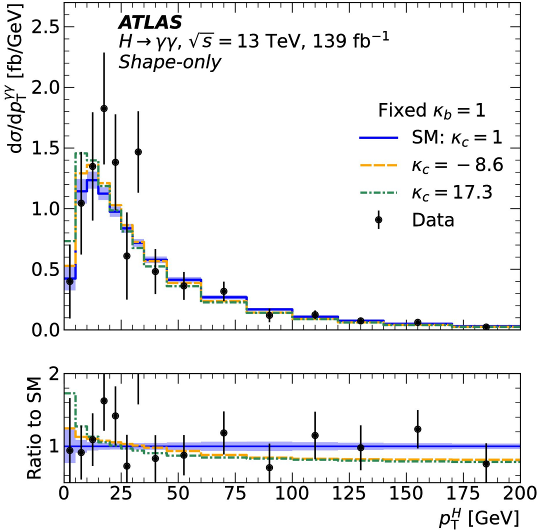
- Breaking degeneracies (e.g. total width or on BR) using 4top
- CMS ttbar angular → top-Yukawa

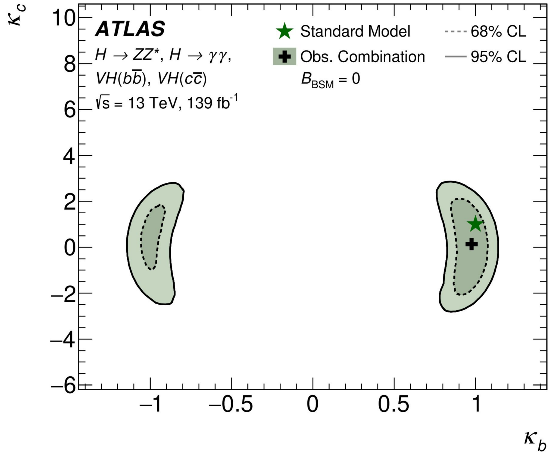
charm: VH, H → cc (a la VH(bb)), and indirect measurements via $p_T(H)$

Combining direct (VH(cc/bb), VBF, ggH) and indirect ($p_T(H)$) measurements;

Like to have:

- Including κ_c in the parameterization of the gg→ZH production





ATLAS Hyy+H4l+VHbb+VHcc:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2022-04/

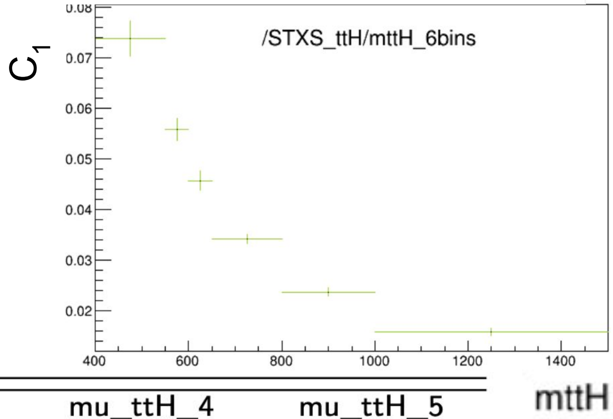
STXS and κ_λ HHH coupling

Preliminary study by Gianna Mönig:

- Signal-only STXS fit using pseudo-data with $\kappa_\lambda = 2$
  - Assume same exp. efficiency in all bins

bin edges	mu_ttH_0	mu_ttH_1	mu_ttH_2	mu_ttH_3	mu_ttH_4	mu_ttH_5
0,60,120,200,300,450	-4.6 %,4.9 %	-3.9 %,4.0 %	-4.6 %,4.8 %	-7.2 %,7.6 %	-11.9 %,13.4 %	-21.9 %,28.0 %
0,60,100,200,300,450	-4.6 %,4.9 %	-4.6 %,4.8 %	-3.9 %,4.0 %	-7.2 %,7.6 %	-11.9 %,13.4 %	-21.9 %,28.0 %
0,50,100,200,300,450	-5.3 %,5.6 %	-4.1 %,4.3 %	-3.9 %,4.0 %	-7.2 %,7.6 %	-11.9 %,13.4 %	-21.9 %,28.0 %
0,40,100,200,300,450	-6.4 %,6.8 %	-3.8 %,3.9 %	-3.9 %,4.0 %	-7.2 %,7.6 %	-11.9 %,13.4 %	-21.9 %,28.0 %

  - Mainly move sensitivity to different bins



- **Try m_{ttH}:**
  - 6 bins [GeV]: 400, 550, 600, 650, 800, 1000, 1500
  - 5 bins [GeV]: 400, 550, 650, 800, 1000, 1500
  - Sensitivity not that much worse than for $p_T(H)$

bin edges	mu_ttH_0	mu_ttH_1	mu_ttH_2	mu_ttH_3	mu_ttH_4	mu_ttH_5
6bins	-7.3 %,8.0 %	-6.2 %,6.7 %	-6.3 %,6.7 %	-4.2 %,4.4 %	-5.3 %,5.5 %	-6.4 %,6.8 %
5bins	-7.3 %,8.0 %	-4.5 %,4.7 %		-4.2 %,4.4 %	-5.3 %,5.5 %	-6.4 %,6.8 %

- Great start… more detailed studies needed…

Flavour algorithms

IRC safe flavour-aware algorithms in experimental measurements:

- What can we do with these tools ?
- Comparison with anti-kt in unfolding ?
- VHbb (or cc): g→bb effect on Data/MC scale factors for merged (non merged) jets ?
- Can these algorithms help in the calibration procedures of boosted taggers ? g→bb vs Hbb
  → see also Andreas/Simone talk on single b-jet
- FCCee: what is the effect of these algorithms in strange tagging ? link

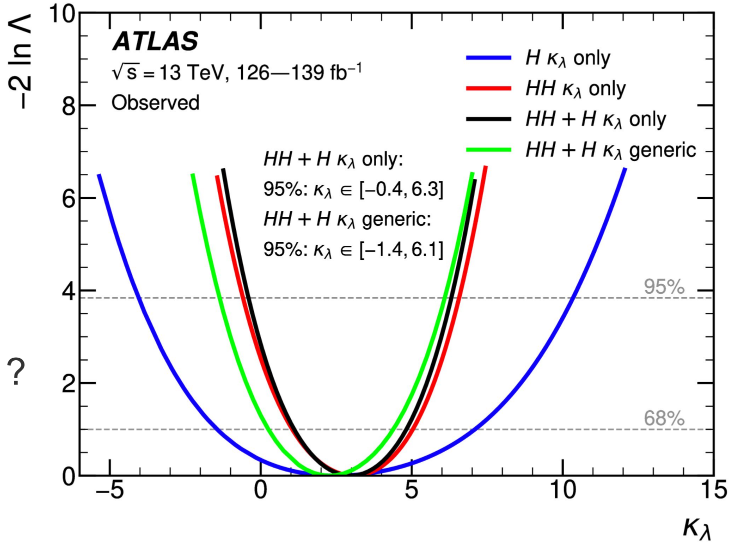
Jets

q/g jet tagging

- More and more complex NN approaches (ParticleNets) working with basic events objects (PFcandidate - tracks, clusters). Indicative performance: reject x5 for a signal efficiency of 80%
- Can we convince ourselves that the features they're learning are reliable ?
  Are we sure we're not getting better discrimination from unsound / theory uncertain features?
- Study with Delphes + ParticleNet

→ See Andreas/Simone talk on ParticleNet

Double Higgs



Constraining the Higgs self coupling

- Exploited the sensitivity of single H in constraining k_λ
- Are there other observables that we can use beside p_T?
- Channels beyond ggHH are being explored,
  any more promising process ?
- Can the (very weak) constraints on k_4 help constraining k_3 ?

STXS binning for self-coupling interpretation

- It was not optimised for k_λ, is there something better we can do ?
- Can we optimise some fiducial differential measurement for k_λ ?
- Is there any observable to bin on, that would increase sensitivity to k_λ?
  - “Brute force approach”: study a LR: ME(λ)/ME(SM) as a function of the H kinematics ?

Experiment/Theory efficient information exchange

Publishing Likelihoods: information exchange

- What is the use case ? Re-interpretation ? Combinations ? e.g. HEP / Low E ?
- When is the full likelihood needed ? when are cov mtx enough ?
- ...what do we mean by full likelihood? Are “Simplified Likelihoods” good enough ? (e.g. link)

Publishing Likelihoods: tools

- CMS → plan to release the “combine” package as a generic tool. CMS papers could then appear with a record in HEPDATA containing datacards/workspaces
- ATLAS → work on pyhf json format. Only binned distributions
- Common (human readable) format for datacards
  - effort started in the ROOT group + experiments
  - HS3 (High Energy Physics Statistics Serialization Standard) as emerging community standard?
    - Subscribe to hep-statistics-serialization-standard@cern.ch
    - Discussion in github issue tracker: https://github.com/hep-statistics-serialization-standard/hep-statistics-serialization-standard/issues
  - Common LH2 (Les Houche LikeliHood) format defining the content ?

Experiment/Theory efficient information exchange

"RIVET with efficiencies"

- Add to RIVET the possibility to import weight (xgboost, tensorflow, …)
- It would have some applications:
  - Particle level → "smearing module / Delphes" → Classifier → Analysis category
  - Particle level → Analysis Category
    - (proof of principle trained on ggF $H\rightarrow\gamma\gamma$ sample then used to predict analysis category for different input kinematics)

Something along these lines was done on the VBF-W cross section in 2019 (link)

Precision

Requirements and goals for measuring Higgs processes and properties @ HL-LHC / 14 TeV, 100 TeV, and e+e- Higgs Factories

→ Karsten

Experiment/Theory efficient information exchange

Can unbinned reweighting with machine learning be useful?

- Move away from the 1D scale factors, which can damage correlations among variables
- “Gain statistics” Morph a low stat alternative sample to a high stats nominal https://arxiv.org/pdf/2007.02873.pdf

Unfolded unbinned cross sections ? How sensitive are they on hyperparameters ?

- Multifold (list of observables all unfolded at the same time) and Omnifold (unfolding at the event level that can be re-binned in any observable).
- Does it work both in simple cases (resonance) and in more complex multiple-scale processes (ttHbb) ? (take two MC and unfold one to the other)

Likelihood free inference beyond arXiv-like examples ? Try some complex case ? (again ttHbb?)

Experiment/Theory efficient information exchange

Generation on GPU

Theorists + ATLAS & CMS generators groups + CERN computing to take advantage of a GPU based version of Madgraph

ME calculations offloaded to GPUs

Overall execution is still dominated by the Fortran part of the computation

ATLAS & CMS working on implementing a GPU-based event generation in central workflows

ATLAS also in contact with Sherpa to test their GPU-based code, when it will be available

Benchmarking ?

Also recent very large speedups (**x2-78**) demonstrated when running ATLAS setup with >100 weights (EW, PDF,...) using simplified pilot runs and fast PDFs [https://arxiv.org/abs/2209.00843]

		madevent		
CUDA grid size		8192		
$gg \to t\bar{t}gg$	MEs precision	$t_{TOT} = t_{Mad} + t_{MEs}$ [sec]	N_{events}/t_{TOT} [events/sec]	N_{events}/t_{MEs} [MEs/sec]
Fortran	double	55.4 = 2.4 + 53.0	1.63E3 (=1.0)	1.70E3 (=1.0)
CUDA	double	2.9 = 2.6 + 0.35	3.06E4 (x18.8)	2.60E5 (x152)
CUDA	float	2.8 = 2.6 + 0.24	3.24E4 (x19.9)	3.83E5 (x225)

NVidia V100, Cuda 11.7, gcc 11.2

		madevent		
CUDA grid size		8192		
$gg \to t\bar{t}ggg$	MEs precision	$t_{TOT} = t_{Mad} + t_{MEs}$ [sec]	N_{events}/t_{TOT} [events/sec]	N_{events}/t_{MEs} [MEs/sec]
Fortran	double	1228.2 = 5.0 + 1223.2	7.34E1 (=1.0)	7.37E1 (=1.0)
CUDA	double	19.6 = 7.4 + 12.1	4.61E3 (x63)	7.44E3 (x100)
CUDA	float	11.7 = 6.2 + 5.4	7.73E3 (x105)	1.66E4 (x224)
CUDA	mixed	16.5 = 7.0 + 9.6	5.45E3 (x74)	9.43E3 (x128)

NVidia V100, Cuda 11.7, gcc 11.2

Stephan Hageboeck, Stefan Roiser, Andrea Valassi, Olivier Mattelaer

Generators - negative weights

Generators take ~10% of the experiments computing resources. With more precision (gen) and larger datasets (exp), the time required for generation is expected to increase significantly.

- Origin of negatively weighted events: NLO cross sections are not positive definite in local phase space
  - Some events arising from the hard scatter acquire negative weights
- CMS exploring two different strategies for the mitigation of negative weights:
  - MC@NLO-Δ scheme based on dealing with over estimation of MC counter terms in aMC@NLO (arXiv:2002.12716)
  - *Positive resampling*: eliminates negative weights locally in phase space (arXiv:2109.07851)
    - Process independent, preserves physical observables
    - Can we prove that methods like positive reweighting works on the full analysis phase space ?
- The negative weight reduction scheme implemented in Sherpa, based on color correction approximations is implemented in CMS
  - up to 50% reduction observed in various processes, ttV, ttbar, V+jets
  - cross sections and distributions of observables remain unchanged

Double Higgs

Constraining the Higgs self coupling

Exploited the sensitivity of single H in constraining k_λ

Channels beyond ggHH are being explored, are there other promising processes ?

Show results from VBFHH , VHH → ATLAS split W/Z, ttHH
HHbbbb in ggF+VBF ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-29/
HHbbγγ ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-34/
VHH ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-31/

STXS binning for self-coupling interpretation

It was not optimised for this, is there something better we can do ?

Any fiducial differential measurements optimised for k_λ ?

Any obvious observable to bin on ? Otherwise study a LR: ME(λ)/ME(SM) as a function of the H kinematics ?

Combined HHH + HH + H improve quartic but maybe also lambda ?

https://indico.cern.ch/event/1283461/contributions/5392831/attachments/2657965/4603533/20230601_HHH_CMS_WGM.pdf

Show results from VBFHH, VHH ttHH
ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-03/

Generators - GPU

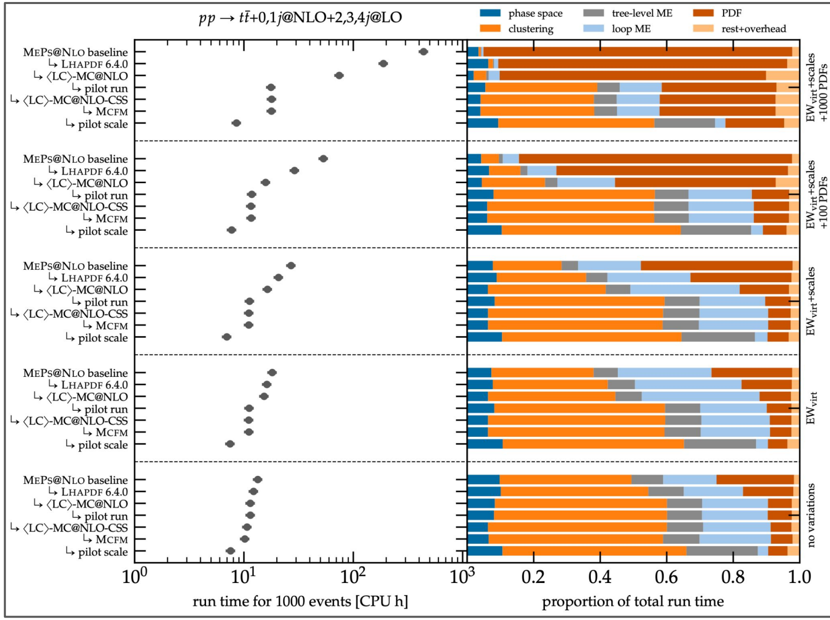
Generation on GPU

MadGraph Authors + ATLAS & CMS generators groups + CERN computing to take advantage of MadGraphGPU:

- MadgraphGPU for users: hands on on how to set it up and run
- MadgraphGPU internals for other MCs: compare what learnt with MadGraph (moving from single to multi event APIs, vectorization and GPUs) to what people in other MCs plan to do (eg SHERPA). Some components may become interchangeable across different MC generators through well defined software APIs.

ATLAS & CMS working on implementing GPU-based event generation in central workflows

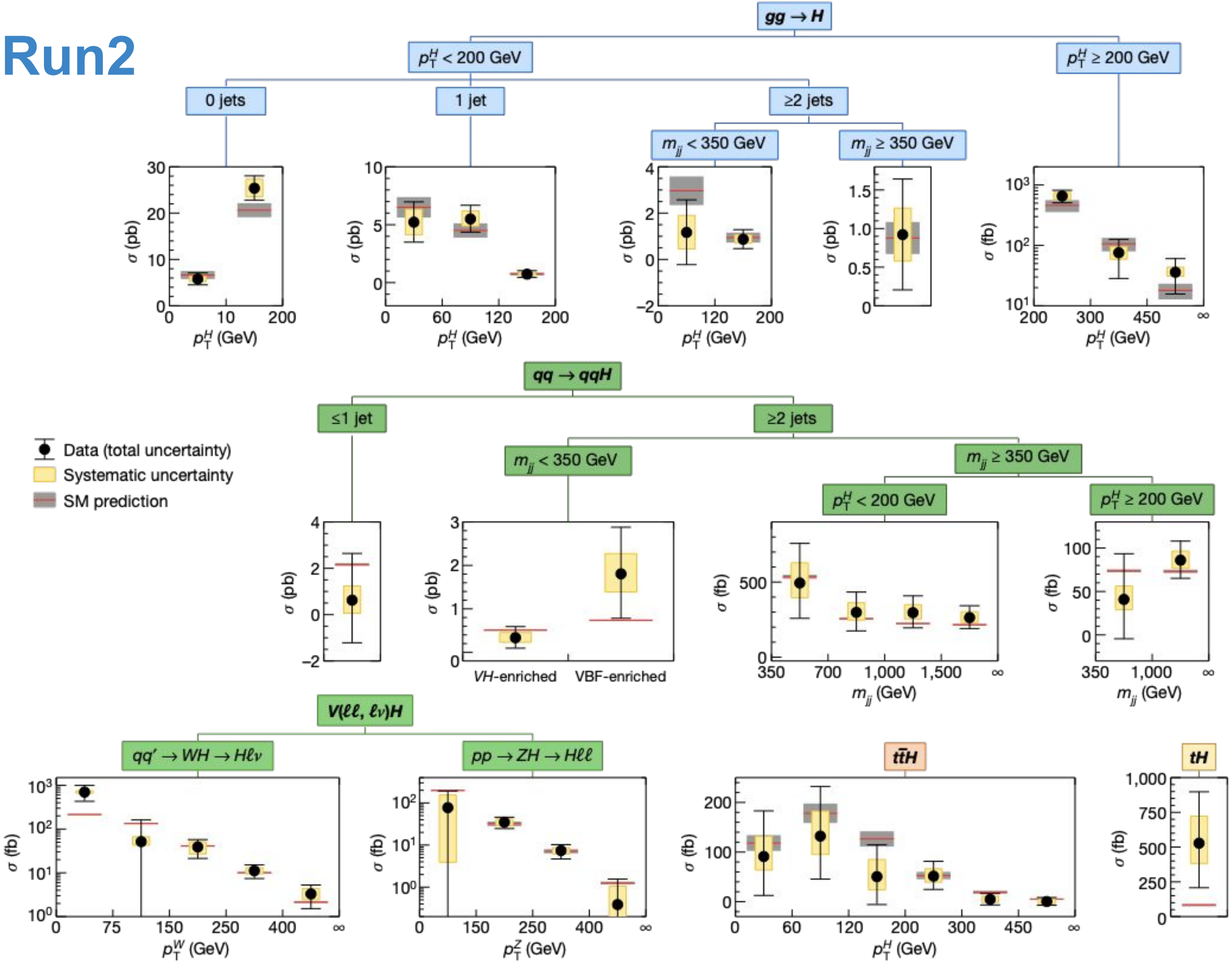
ATLAS also in contact with Sherpa to test their GPU-based code, when it will be available.



Very large speedups (**x2-78**) demonstrated when running ATLAS setup with >100 weights (EW, PDF,...) using *simplified pilot runs and fast PDFs* [https://arxiv.org/abs/2209.00843]

CMS use the MG reweighting module as standalone to perform the reweighting on the final data format

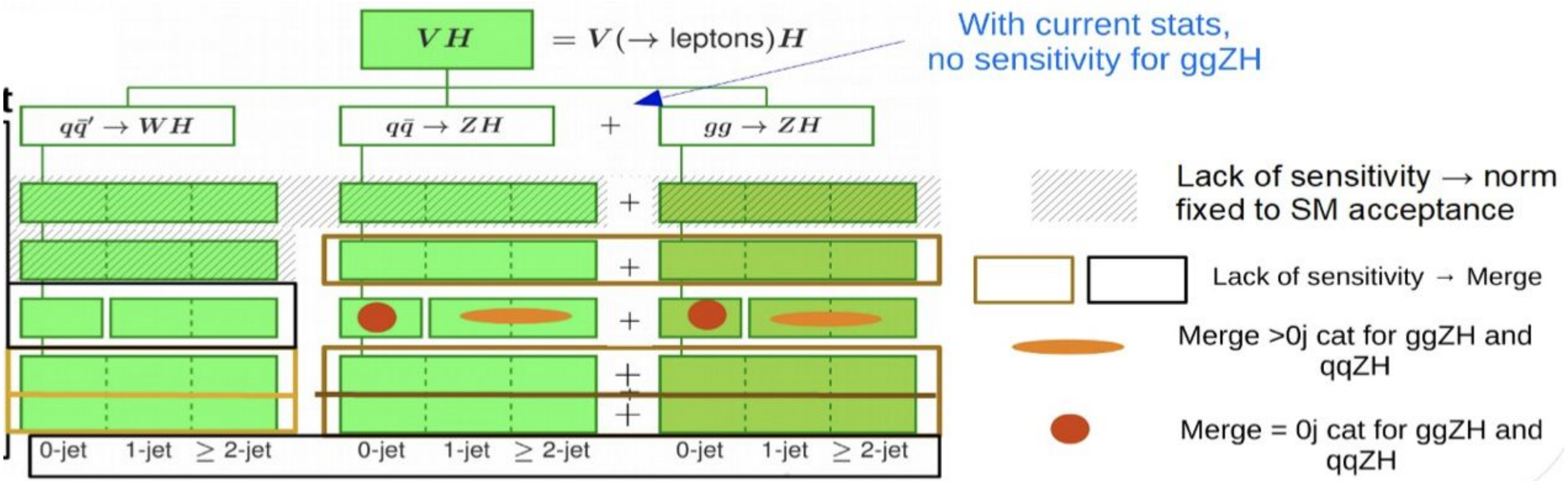
STXS in Run2



gg → H
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
0 jets
1 jet
≥2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
qq → qqH
≤1 jet
≥2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
Data (total uncertainty)
Systematic uncertainty
SM prediction
VH-enriched
VBF-enriched
V(ℓℓ, ℓν)H
qq′ → WH → Hℓν
pp → ZH → Hℓℓ
tt̄H
tH
σ (pb)
σ (fb)
p_T^H (GeV)
m_{jj} (GeV)
p_T^W (GeV)
p_T^Z (GeV)

STXS for Run3

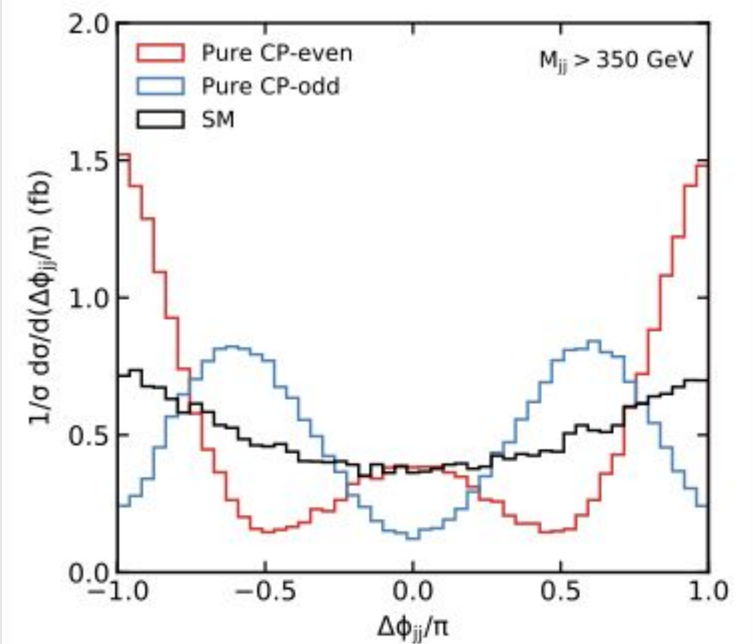
v1.2 too aggressive binning (required merging bins for lack of sensitivity)



STXS for Run3

v1.3 strategy could be less aggressive: just add more bins at high $p_T(V)$, e.g. 400-600 GeV, and split more $p_T(V)$ bins also in n_{Jet} ?

Add bins to highlight specific observables ? (e.g. CP-sensitive binning)



Extension of stage 1.1 with a binning of [−π, −π/2, 0, π/2, π] in Δϕjj for Mjj >350 GeV (pT >100GeV) in both high and low pHT branches.

See LS2019: arxiv.org:2003.01700 and recent summary at VBF workshop: link

Try new observables ?

What about VH ?

STXS for Run3

Integrating decays in STXS

Example: a generator produces a Higgs decay with a bb-pair of 110 GeV and an e+e- pair of 5 GeV. What process is this? If we want to define decay bins, we should be able to tell for each event where it belongs:

- $H \to ZZ^* \to (Z \to bb)(Z \to ee)$?
- $H \to Z\gamma^* \to (Z \to bb)(\gamma^* \to ee)$?
- $H \to bb$+EW correction$\to bb\gamma^* \to bb(\gamma^* \to ee)$

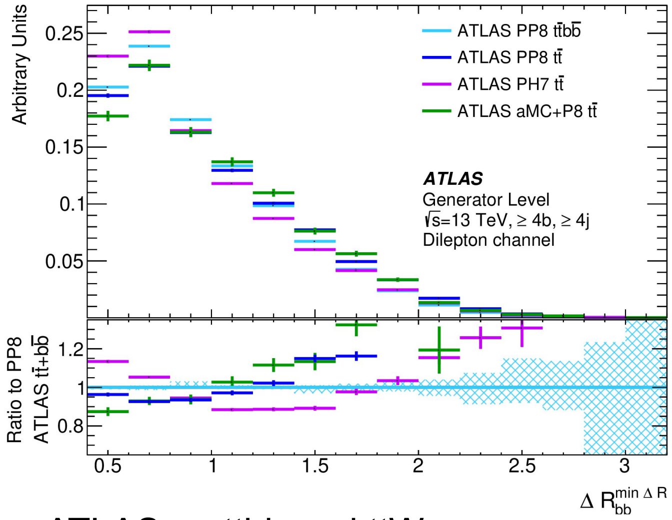
Some avenues have already been tried :

- 0 st edition: informal discussion, Les Houches 2017
- 1 st edition: STXS/fiducial meeting, 17th May 2018
- 2 nd edition: Les Houches, 12th June 2019
- 3 rd edition: LHC Higgs XS WG workshop, 17th October 2019
- 4 th edition: LHC Higgs XS WG2 STXS/fid meeting, 1st July 2020
- 5 th edition: LHC Higgs XS WG workshop, 9th Nov 2020

Michael Duehrssen had a concrete set of cuts to be tried (talk - WG2).

Check them out ? New ideas ?

b-quark issues: Backgrounds for Higgs processes ttbb/ttH



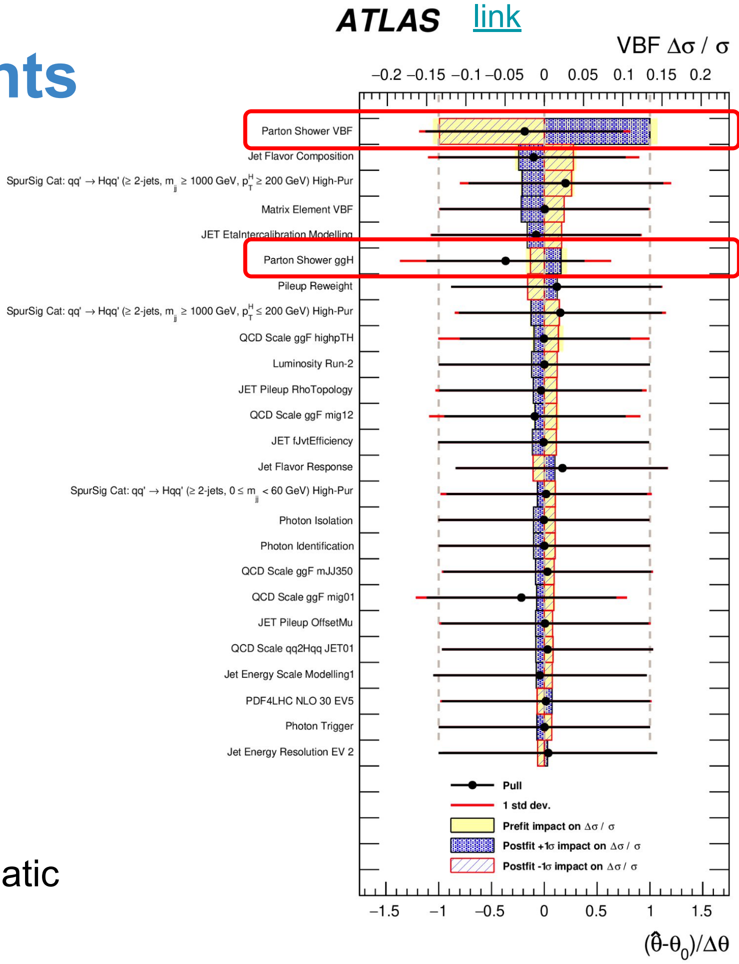
Pub note from ATLAS on ttbb and ttW

[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-026/]

Parton Shower issues and develoments

The limiting systematic on VBF
(and very significant for other Higgs processes):

- Predictions for VBF/VBS processes highly sensitive to PS description, particularly (but not only) for third-jet observables
- Two-point PS uncertainty bands currently used by experiments is a limiting factor in VBF precision measurements
- A clear VBF process PS uncertainty prescription is important for Run-3 measurements and beyond
- What can new showers say on this right now?
- See more in Raoul/Stephen talk



Main experimental combinations start seeing more and more systematic limitations, from PDFs in other phase spaces.

- See approximate-N3LO PDFs in Raoul/Stephen talk

Parton Shower issues and develoments

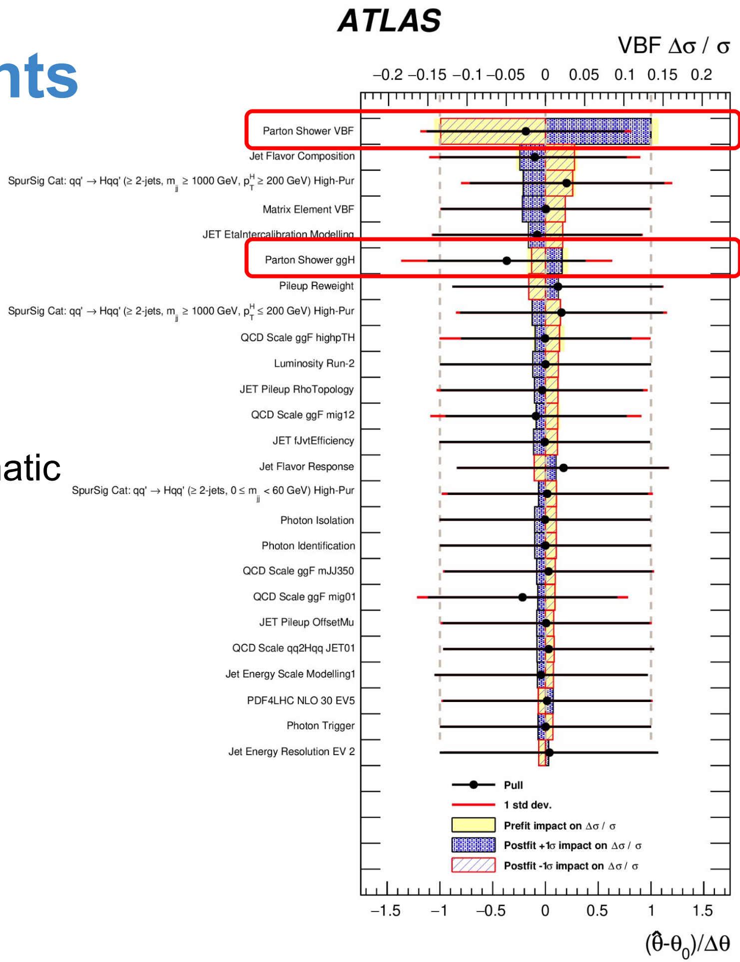
The limiting systematic on VBF

(and very significant for other Higgs processes):

- What can we do with this?
- What can new showers say on this right now?

Main experimental combinations start seeing more and more systematic limitations, from PDFs in other phase spaces.

- Will N3LO PDFs help?



From an ATLAS person: "*I personally believe this is single most important issue we need to solve. PS are the largest source of uncertainty, we need to benchmarks this, and I think we need to have recommendations on how to move away from a 2 point systematic for PS*"

ATLAS $H \rightarrow \gamma\gamma$:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2020-16/

Generators

Generators take ~10% of the experiments computing resources, with more precision (gen) and larger datasets (exp), the time required for generation is expected to increase significantly.

Typical comment: "*I think this is one of the main issues we have to solve. Not just the usual problems with dilution of MC stats, if we have to do statistics test, this requires sampling of toys from MC. Negative weights make this an issue. We have various mitigation strategies, but they all are an approximation*"

Event generators:

Reduction of negative weights using NN resampling ?

Can you prove that methods like positive reweighting works on the full phase space ?

Compare different generators ?

arxiv:2002.12716

Rate of negative events

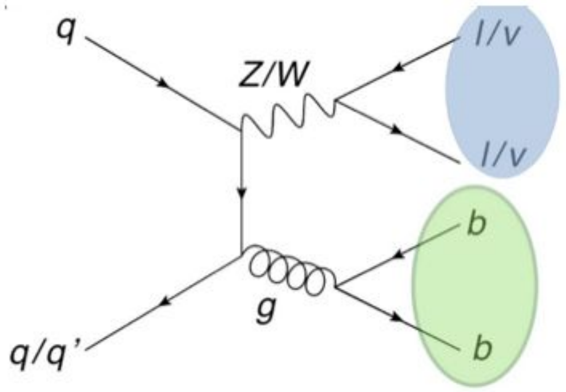
$pp \to e^+e^-$	6.9%	(1.3)
$pp \to e^+\nu_e$	7.2%	(1.4)
$pp \to H$	10.4%	(1.6)
$pp \to Hb\bar{b}$	40.3%	(27)
$pp \to W^+j$	21.7%	(3.1)
$pp \to W^+t\bar{t}$	16.2%	(2.2)
$pp \to t\bar{t}$	23.0%	(3.4)

Cost In sample size

$$c(f) = \frac{1}{(1-2f)^2}$$

b-quark issues: Backgrounds for Higgs processes V+HF/VH

V+Jets



LO MadGraph With MLM matching	LO	LO reweighted to NLO in etabb + XSec reweighted to NNLO QCD + NLO EWK in $p_T(V)$
aMC@NLO with FXFX merging	NLO	XSec reweighted to NNLO QCD + NLO EWK in $p_T(V)$

From an ATLAS person: "*For VH, H->bb/cc, V+hf is a major background that has been modelled by Sherpa 2.2.1 and now Sherpa 2.2.11. Beyond underestimation of the overall yield, Sh 2.2.11 shows a severe mismodelling of the vector boson pT in the relevant range of 75-400 GeV requiring correction factors of up to 1.5-2 at high pTV; enabling NLO electroweak corrections worsens the agreement further. Furthermore, the alternative MC sample currently under study, MG_aMC@NLO+Pythia8 with FxFx merging, shows very large differences to Sherpa 2.2.11 in the prediction of number of jets at high pTV.* "

Backgrounds

ggF + 2-jet predictions with VBF-like selections:

CMS: I think the main point is that we typically use POWHEG for ggF, which is LO for ggF + 2-jet, while there are a variety of NLO predictions available that would work well for a VBF-enriched region/analysis.

Slide 20 here gives an overviewhttps://indico.cern.ch/event/1169286/contributions/5126673/attachments/2555330/4404452/cooperstein_LHCVBFHSummary_29112022.pdf. In short, here is a probably non-exhaustive list of the “latest-and-greatest” predictions (last bullet)

- “ggF+2-jet at NLO via amc@NLO, HJMiNNLO, HERWIG with NLO matching + multijet merging”

There are also dedicated comparative studies like the one I reference on the slide, also at high-pT where things can be a bit different. I would not necessarily reference that single publication, since there are probably a variety of relevant publications.

As we discussed, the point is that further development on the theory side is great but we should also make sure to take advantage with our experimental measurements probing VBF topologies.