Overview of VBF activities

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Overview

- Summary of October VBF workshop at CERN and review of the field.

- Updated predictions:
  - Inclusive cross sections @13.6 TeV
  - Follow-up study on differential distributions (fixed order, maybe NLO+PS)

- Future near-term projects:
  - Parton shower modeling and uncertainties
  - Overlap with ggF
  - Prescription to apply NNLO QCD and NLO EW to event generators
  - …

Workshop overview

- Three-day workshop at CERN Oct. 19-21 (link to indico), aiming to foster exchanges/ projects between theorists and experimentalists related to VBF.
  - 59 registered participants, ~half in person.
  - A big thank you to Alexander Karlberg for helping to organize along with VBF conveners.
  - And the theory department in general for their support (coffee breaks and hotel pre-booking).

- Three sessions with invited speakers:
  - *State of the art*: Run-2 measurements and progress in theory
  - *Parton shower*: limitations for measurements and overview from theory perspective
  - *Future*: looking towards the next years (experiment and theory)

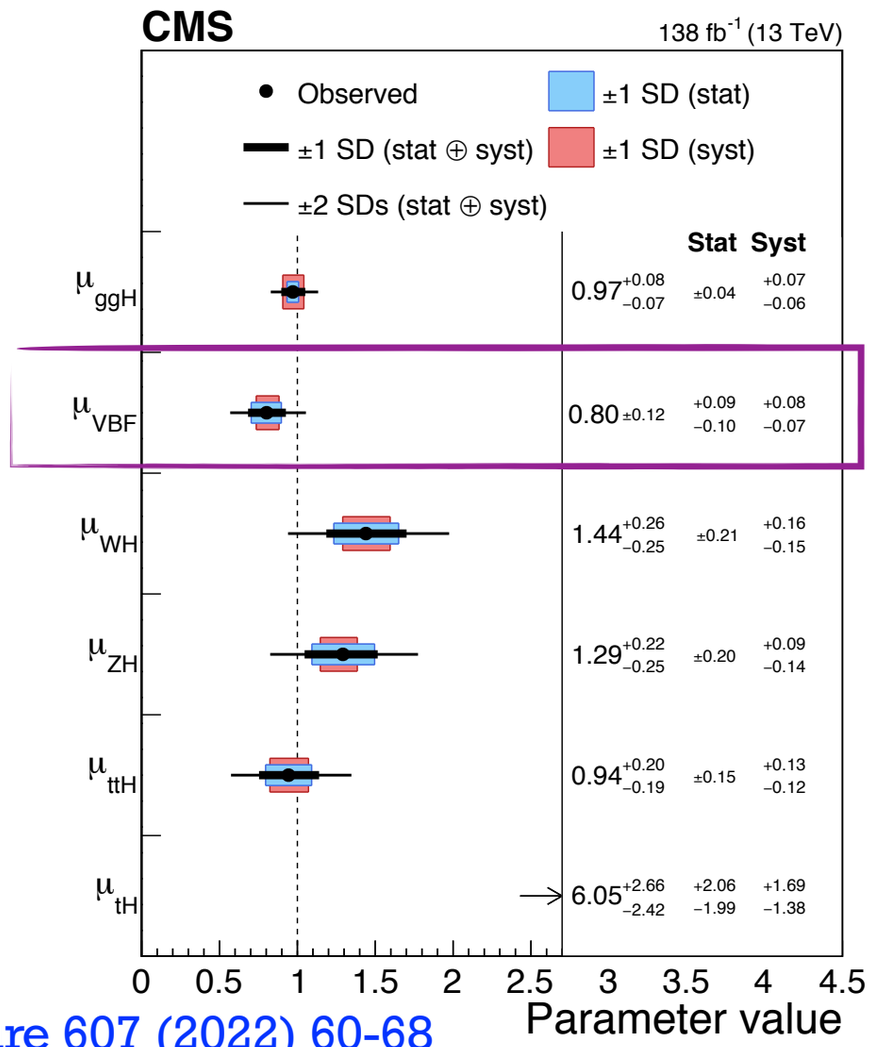
- Additional session featuring submitted abstracts

- Many fruitful discussions! I will try to briefly summarize here…

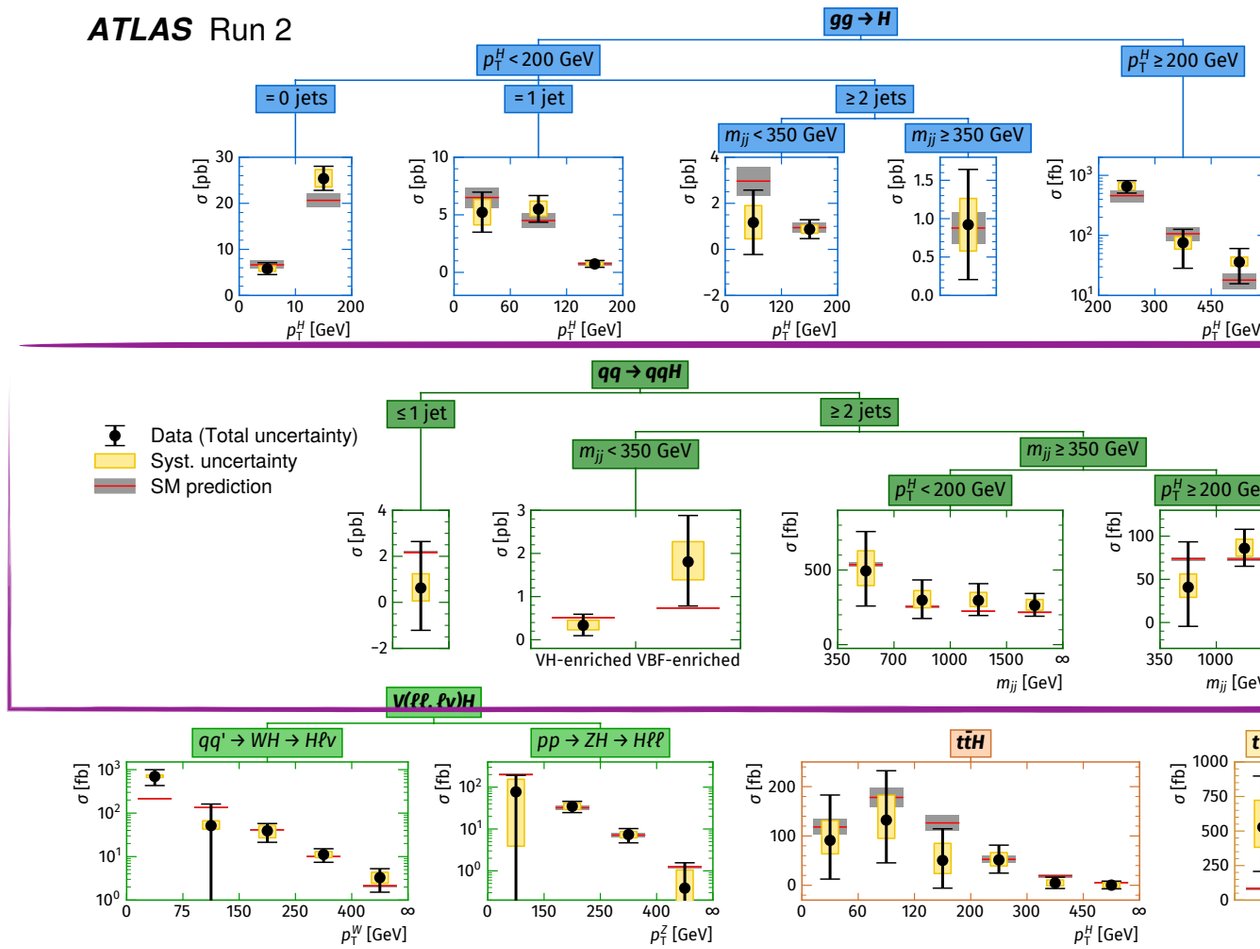
State of the art

- Both experiments nearing ~10% precision on inclusive VBF H cross section
  - ⇒ first years of precision era for VBF H measurements.

- Statistical and systematic uncertainties similar in magnitude, with substantial uncertainty contribution from theory
  - ⇒ to make the most of the data in the years to come, we need innovation on multiple fronts.



Nature 607 (2022) 60-68



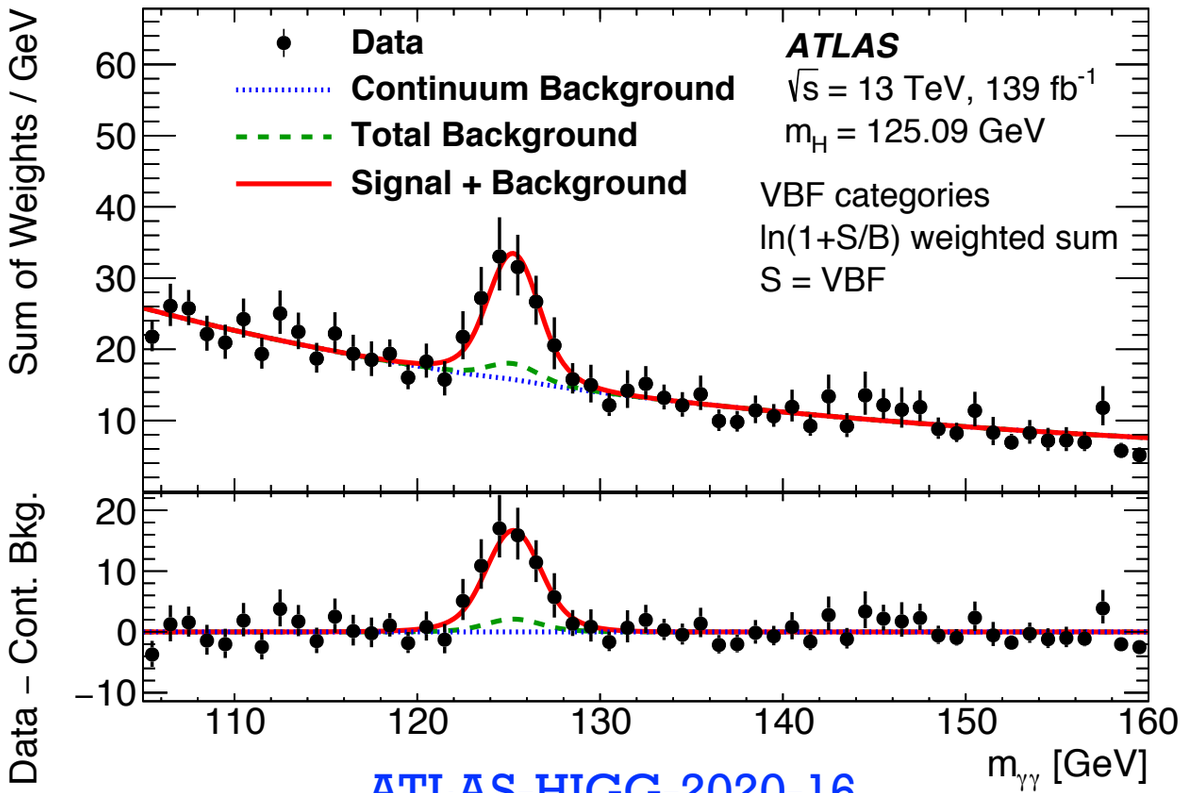
Nature 607, pages 52-59 (2022)

VBF measurements by channel

- VBF measurements by channel are highly varied:
  - Different $p_T(H)$, m_{jj} regions depending on background
  - Different analysis strategies depending on main deliverables, primary uncertainties.

- Theory uncertainties impact some channels more than others, but systematic uncertainties in general will eventually limit most of the main VBF measurement channels at the LHC.

	$\mu_{VBF} = \sigma/\sigma_{SM}$	$\Delta\mu_{STAT}$	$\Delta\mu_{SYST}$
H→ττ	$0.81^{+0.17}_{-0.16}$	±0.14	±0.10
H→WW	$0.71^{+0.28}_{-0.35}$	±0.20	±0.16
H→γγ	$1.04^{+0.34}_{-0.31}$	±0.31	$^{+0.16}_{-0.09}$
H→ZZ	$0.48^{+0.48}_{-0.38}$	$^{+0.46}_{-0.37}$	$^{+0.14}_{-0.10}$
H→bb	$0.92^{+0.45}_{-0.39}$	±0.32	$^{+0.31}_{-0.22}$
H→μμ	$1.36^{+0.69}_{-0.61}$	(dominant)	



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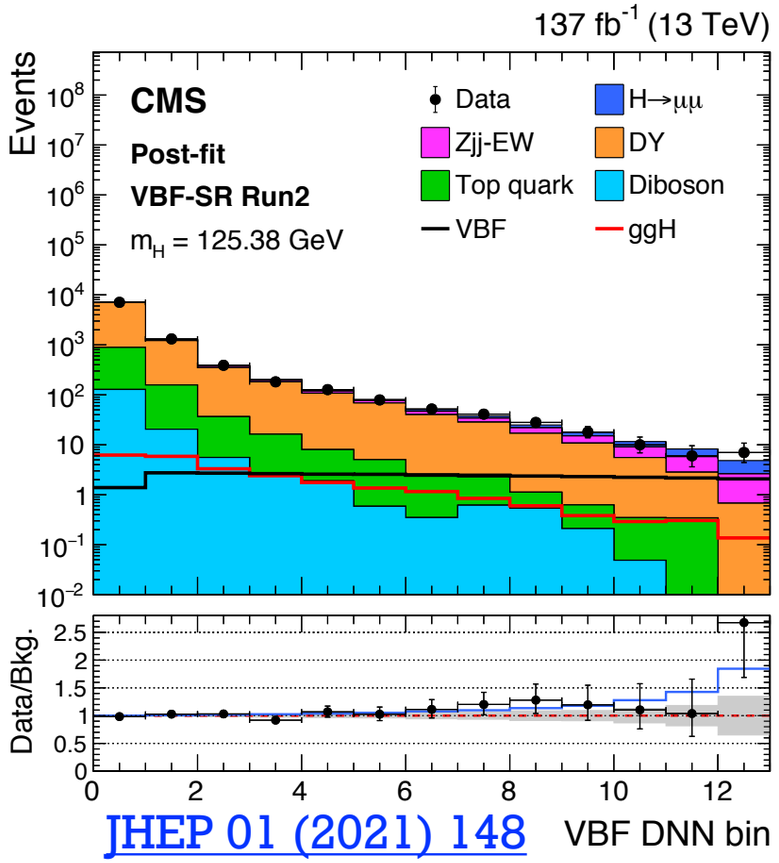

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Typical VBF uncertainties

- Primary theory uncertainties impacting VBF measurements are:
  - Parton shower: leading impact, focus of next slides
  - ggF contribution in VBF-enriched region.
- Other theory uncertainties (PDF, QCD scale for VBF signal, …) are largely negligible.

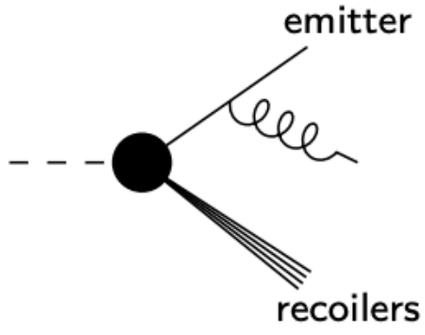
General overview of VBF theory uncertainty sizes in typical VBF measurements*

	VBF H	**ggH (in VBF-enriched region)**
PDF	<1%	<3%
QCD scale	<1%	2-20%
UE	<1.5%	<2-3%
Parton shower	2-15%	4-10%

*numbers borrowed from workshop (R. Gerosa)

Parton shower descriptions

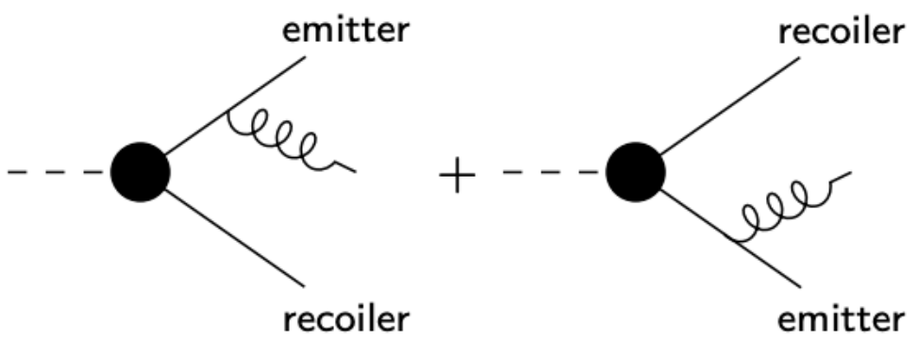
Slide borrowed from workshop (C. Preuss)



PYTHIA simple shower, HERWIG $\tilde{q}$

- recoil **independent** of colour partners
- coherent upon **angular ordering**

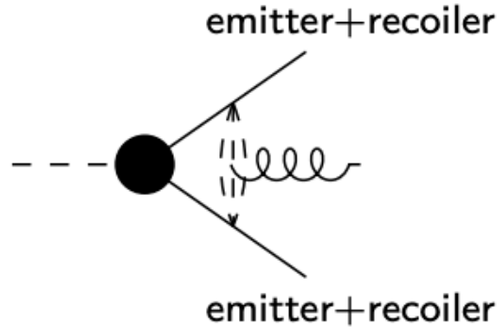
Dipoles



e.g. SHERPA CSS, HERWIG dipole, DIRE

- recoil taken by **opposite dipole end**
- **intrinsically** coherent

Antennae

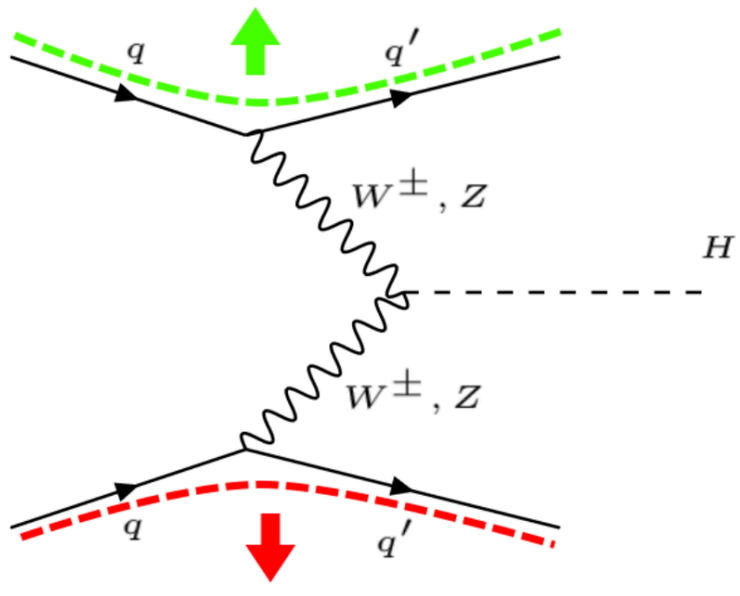


e.g. ARIADNE, VINCIA

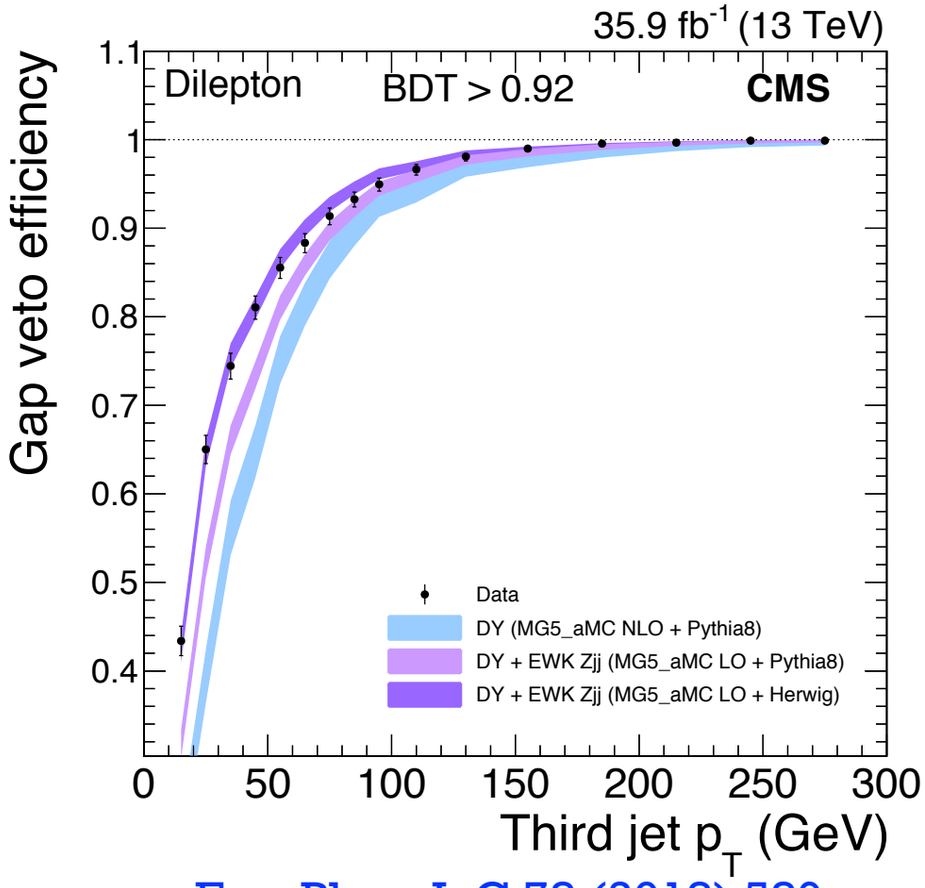
- **both parents** absorb transverse recoil
- **intrinsically** coherent

Parton shower in VBF

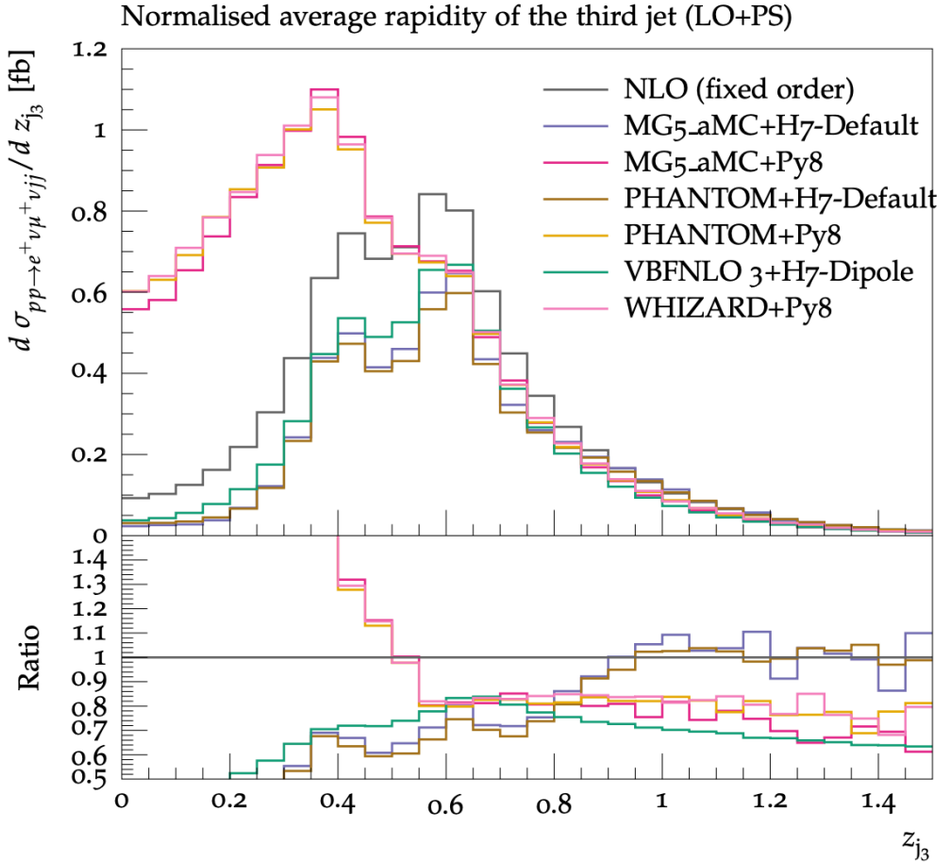
- Understood during Run-2 that *PYTHIA default does not accurately model VBF processes, with large effects*:
  - Experimentally confirmed by CMS EW [W/Z]jj measurements with 2016 data.
  - "dipole recoil" scheme implemented in PYTHIA with more theoretically accurate description.



- Very active area of discussion in the last years - where do we stand today?



Eur. Phys. J. C 78 (2018) 589



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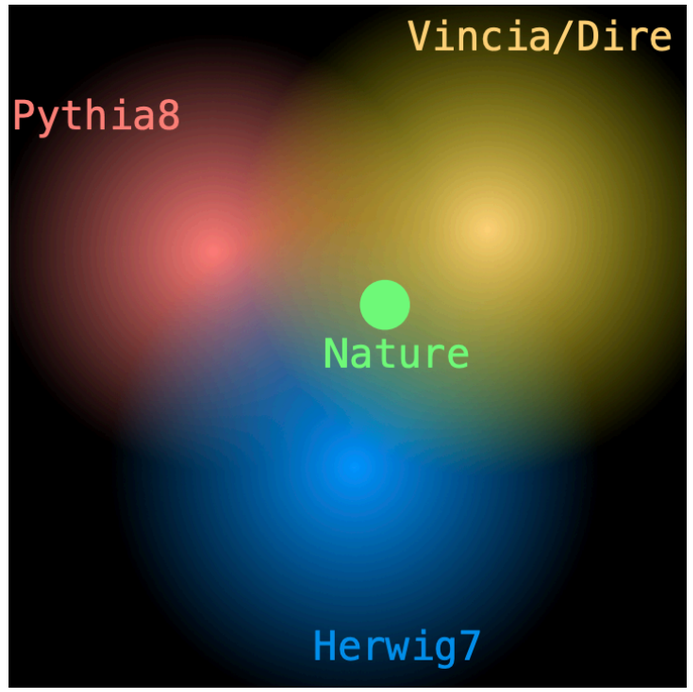
VBF PS algorithms on the market today

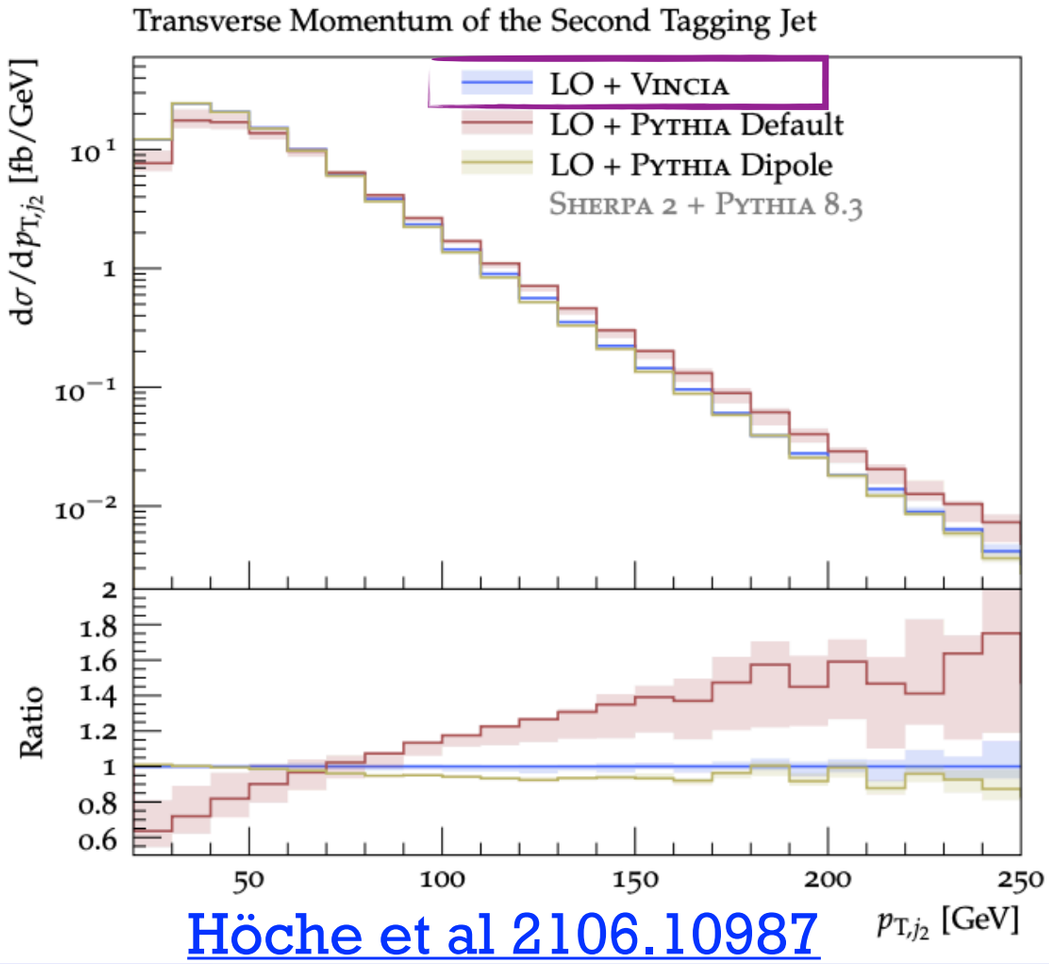
- Run-2 consensus: derive PS uncertainty from two-point comparison of PYTHIA with dipole recoil and HERWIG.
  - Both give similar level of agreement to fixed order NNLO prediction.

- Antenna shower available in VINCIA, which can be interfaced with PYTHIA.
  - Shown to agree quite well with dipole shower.

- Multiple VBF H PS options available today, with no clear consensus from theory on best way to assess the uncertainty:
  - Each algorithm has its limitations, but a priori each is similarly accurate, closes with fixed order.



Tomorrow's PS description?



Höche et al 2106.10987

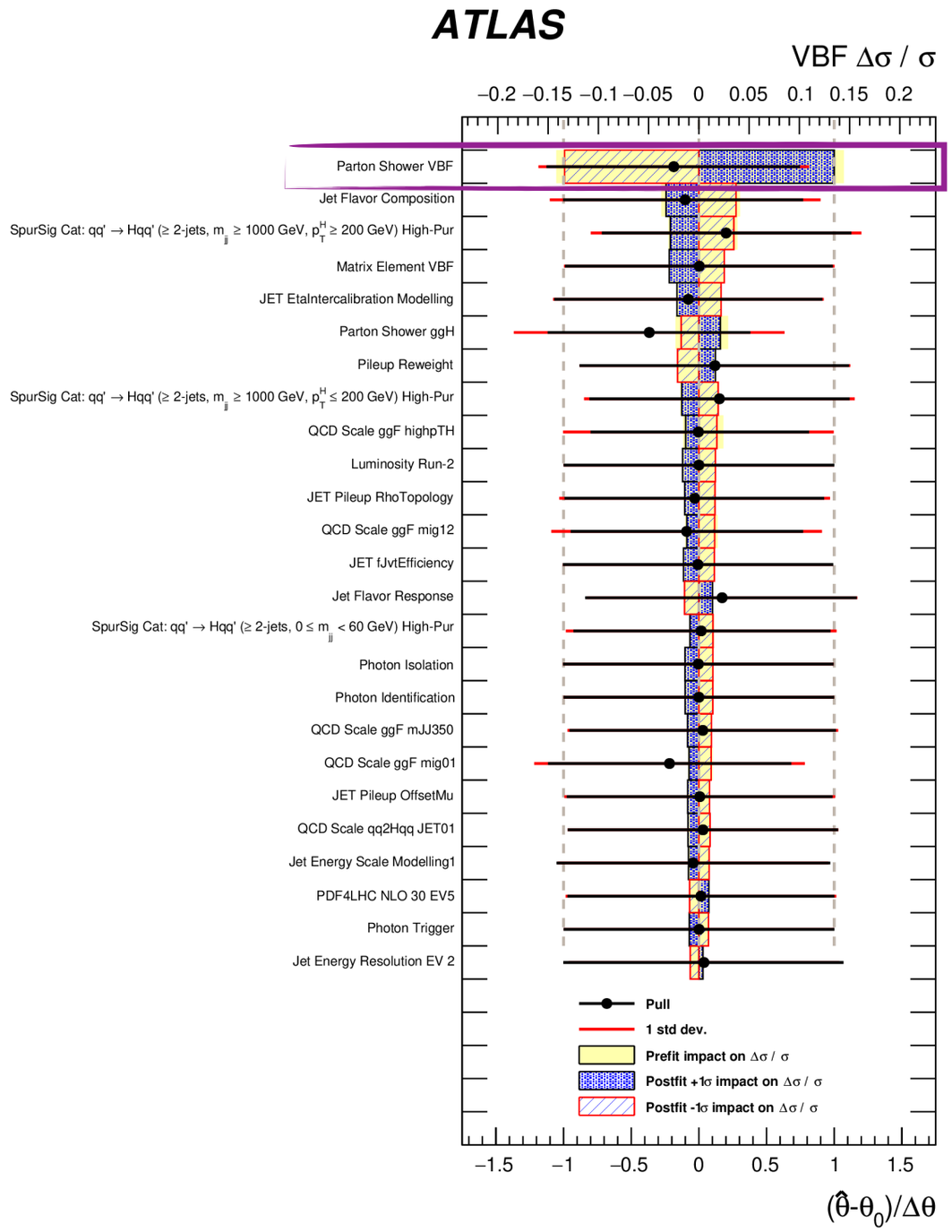
Why it matters

- PS uncertainty derived from symmetrized two-point Pythia dipole vs. Herwig7 can impact VBF measurement by as much as 15%.

- The PS uncertainty for VBF H seems likely to dominate theory (and total systematic?) uncertainty for the years to come.

- *Depending on the developments in the next years, we may soon be limiting the reach of our VBF H measurements.*
  - Not only in terms of the theoretical precision, but also in how best to implement the PS uncertainty.

Impacts from ATLAS Run-2 STXS H→γγ: link



Contributed talks

- Variety of topical contributions highlighting various developments in the field:
  - Deep learning techniques in VBFH searches in H→inv (*Vishal Singh Ngairangbam*)
  - Experimental falsification of SMEFT (*Alexandre Salas-Bernárdez*)
  - Looking at VBF processes from a polarisation perspective (*Giovanni Pelliccioli*)
  - Towards WBF with realistic final states and anomalous couplings at NLO (*Konstantin Asteriadis*)
  - High Energy Jets (HEJ) applied to inclusive Higgs+jets production (*Jérémy Paltrinieri*)
  - A sensitivity study of VBF-V to dimension-6 EFT operators at the LHC (*Flavia Cetorelli*)
  - Experimental potential on CP sensitive STXS splitting. (*Benedict Tobias Winter*)
  - Electroweak corrections and shower effects to Higgs production in association with two jets at the LHC (*Johannes Scheller*)

- I will highlight a couple examples…

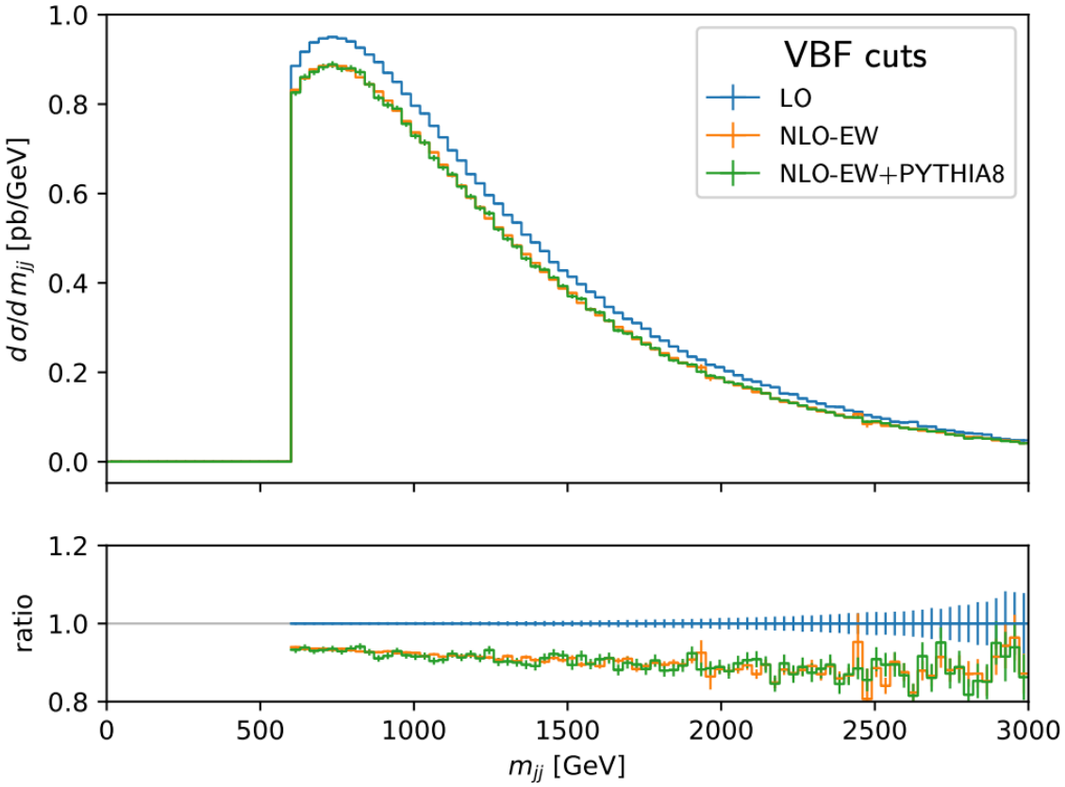
NLO-EW differential corrections

- *New NLO EW* differential corrections available this year.
  - Prescription to use NLO EW and NLO QCD corrections with PS.

- An important development towards Run-3 measurements and beyond, as we further probe VBF at higher p_T/ large m_{jj}..

Implementation of the POWHEG Process

- Based on `POWHEG BOX RES`
- Full EW production process of $H + 2J$
- Either NLO-QCD or NLO-EW corrections
- Resonance-aware formalism allows for multi-channel phase space
- `RECOLA` amplitudes
- Interface for matching to `PYTHIA8` (8.240)
  - QCD shower with NLO-QCD corrections
  - QED shower with NLO-EW corrections



*borrowed from workshop (J. Scheller)

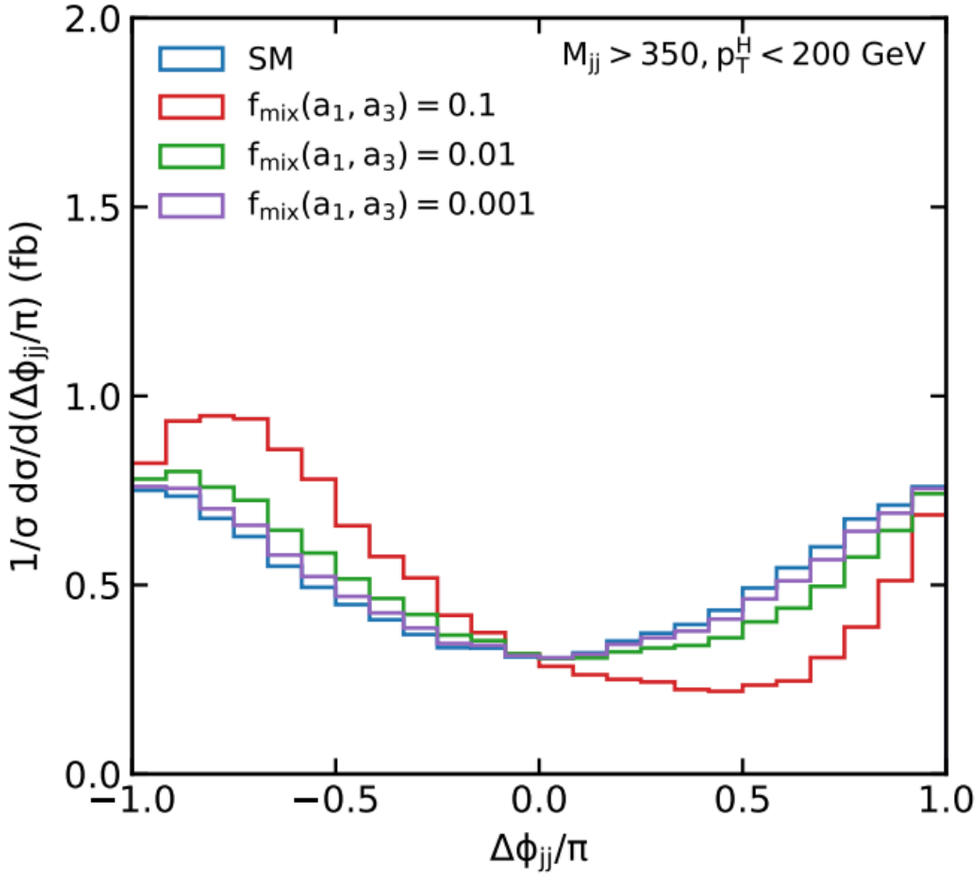
JHEP09(2022)191

Probing CP in VBF production

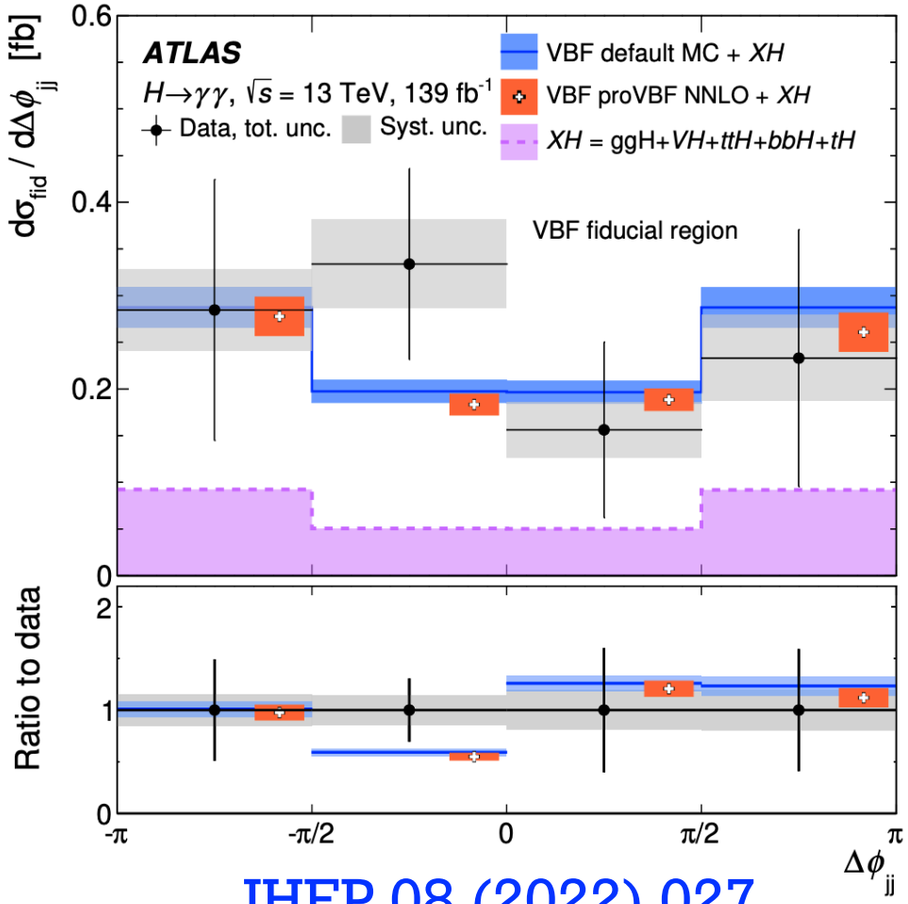
- Angular separation between the VBF-tagged jets is affected by modifications to the H-VV vertex CP structure.
  - An alternative production-side CP probe in addition to H→ZZ (from decay).

- ATLAS Run-2 H→γγ measured unfolded Δφ(jj) distribution in VBF-enriched region, following initial proposals from Les Houches 2019.

- For Run-3 (and beyond), likely to include coarse binning in Δφ(jj) to probe asymmetries/CP.



arXiv:2003.01700



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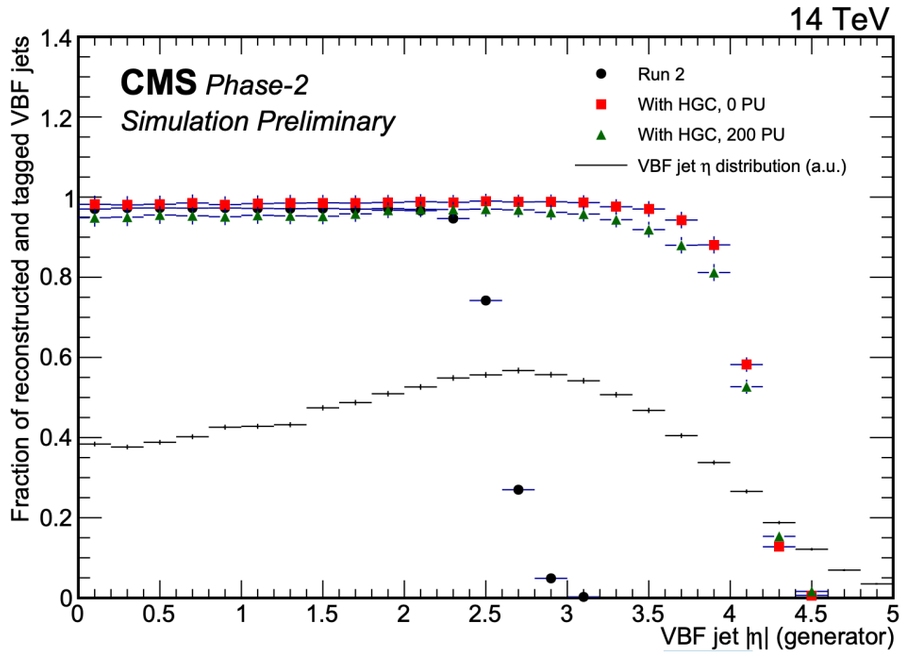
Looking towards the future: experiment

- Beyond factor 2-3 improvement in statistics from Run-3, HL-LHC will reduce VBF measurement uncertainties to the level of a few to 5%.

- To fully take advantage of these datasets, we have plenty of work to do in:
  - Understanding and calibrating new highly complex detectors in a very high pileup environment.
  - Reducing experimental uncertainties.



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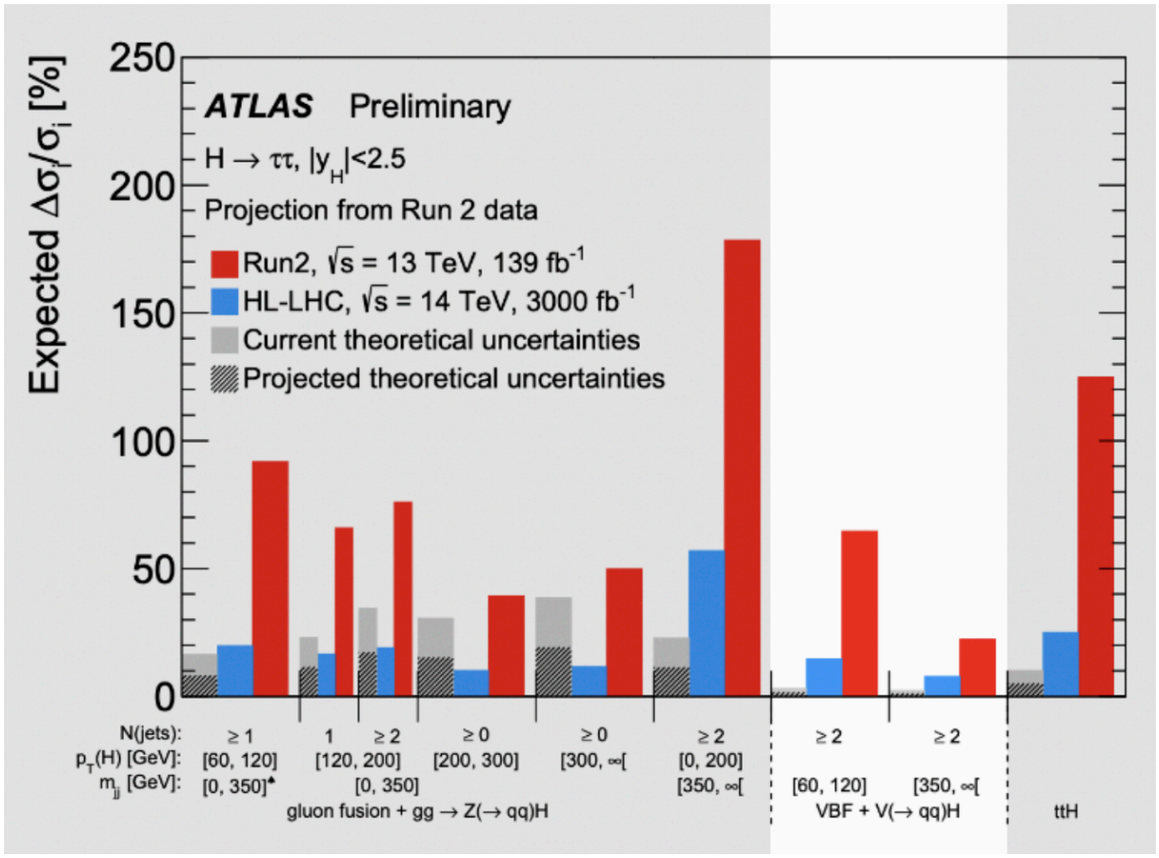

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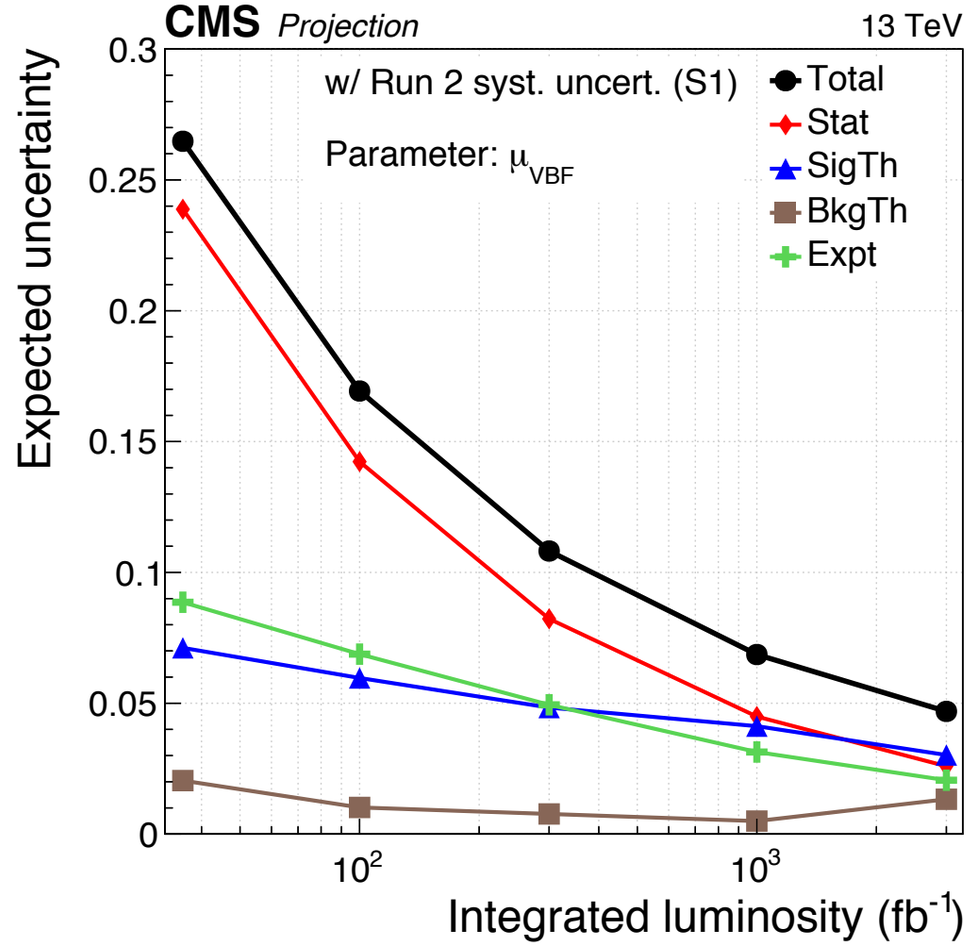

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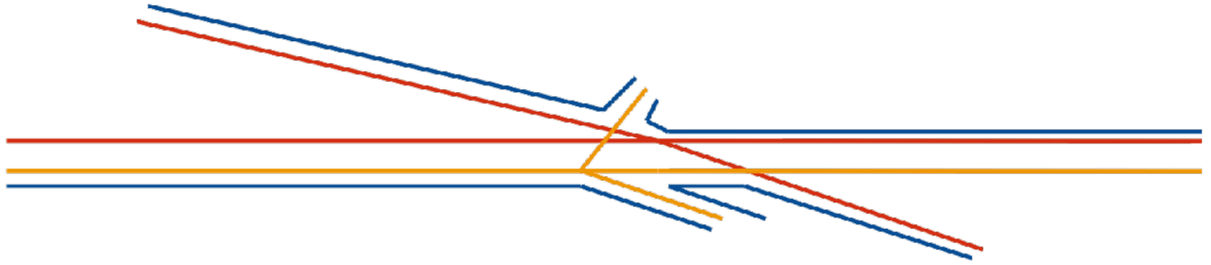
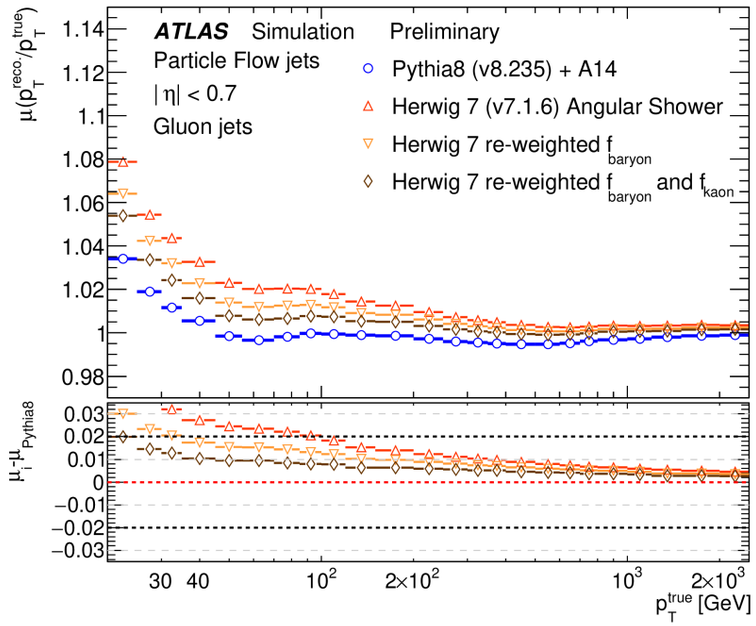
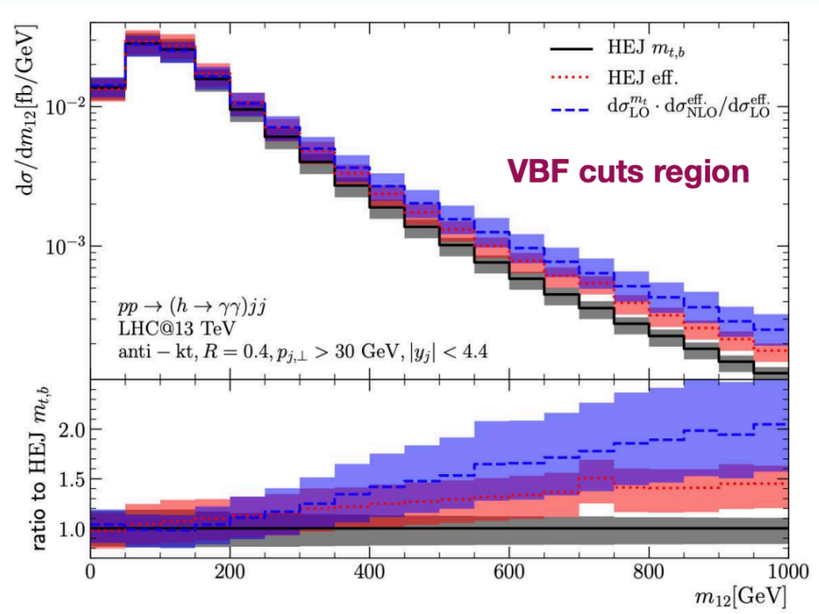
Looking towards the future: theory

- "VBF is among those processes which challenge predictions at all scales and all levels of detail"
  - From Simon's talk at the workshop



- Avenues for development on many fronts:
  - Accuracy of parton showers
  - Challenges in matching and merging
  - Jet vetos & non-global observables
  - High-energy effects
  - Soft QCD effects.
  - …





- Making progress, but still plenty to do to understand effects at the ~percent level.

Updated predictions: inclusive cross section

- Finishing calculation of VBF H inclusive cross section @13.6 TeV.
  - N3LO QCD from proVBFH (update by Karlberg)
  - NLO EW from HAWK (update by Denner, Dittmaier, Mück)

- Today we show just the N3LO QCD, but NLO EW corrections are ready too and just need to be combined.

VBF (N3LO QCD)							
MH	Cross Section	Uncertainty					
		Scale		TU	PDF+αs	PDF	αs
[GeV]	[pb]	pos [%]	neg [%]	[%]	[%]	[%]	[%]
120.00	4.473	0.1	-0.1		±2.2	±2.1	±0.4
122.00	4.402	0.1	-0.1		±2.2	±2.1	±0.4
124.00	4.333	0.1	-0.1		±2.2	±2.1	±0.4
124.60	4.313	0.1	-0.1		±2.2	±2.1	±0.4
124.80	4.306	0.1	-0.1		±2.2	±2.1	±0.4
125.00	4.299	0.1	-0.1		±2.2	±2.1	±0.4
125.09	4.296	0.1	-0.1		±2.2	±2.1	±0.4
125.20	4.292	0.1	-0.1		±2.2	±2.1	±0.4
125.30	4.289	0.1	-0.1		±2.2	±2.1	±0.4
125.38	4.286	0.1	-0.1		±2.2	±2.1	±0.4
125.60	4.279	0.1	-0.1		±2.2	±2.1	±0.4
126.00	4.265	0.1	-0.1		±2.2	±2.1	±0.4
128.00	4.199	0.1	-0.1		±2.2	±2.1	±0.4
130.00	4.135	0.1	-0.1		±2.2	±2.1	±0.4

Differential cross sections

- Important to calculate differential/fiducial VBF cross sections as well:
  - VBF measurement regions include selections on m_{jj}, $p_T(j)$, $|\Delta Y(jj)|$, …
  - Large overlap with VH at low m_{jj}, validity of VBF approximation, etc.

- *Calculate variety of N-dimensional differential distributions*:
  - Single-differential distribution for $p_T(H)$
  - Double differential:
    - m_{jj} vs. $p_T(H)$
    - m_{jj} vs. $|\Delta\varphi(jj)|$
    - m_{jj} vs. $|\Delta Y(jj)|$
    - $p_T(H)$ vs. $|\Delta Y(jj)|$
    - $p_T(H)$ vs. N_{jet}
  - Triple differential:
    - m_{jj} vs. $p_T(H)$ binning of STXS x 2 bins in$|\Delta\varphi(jj)|$ $(0,\pi/2,\pi)$
  - STXS binning for m_{jj} and $p_T(H)$, 4-6 bins for other distributions.

- Calculations provided for two selection regions:
  - STXS selections: $|\eta(j)|<4.7$, $p_T(j)>25/30$ GeV.
  - STXS selections + $m_{jj}>300$ GeV, $|\Delta Y(jj)|>2.0$

- Work in progress…

Parton shower description and uncertainties

- First of all, need to make sure that experiments follow correct prescriptions:
  - PYTHIA this year released a set of PS for VBF instructions here, would be nice to have for other PS algorithms as well.

- Both experiments currently plan to implement VBF PS uncertainty for Run-3 analyses as symmetrized two-point Pythia dipole vs. Herwig7 difference.
  - Resulting uncertainty can impact the VBF measurement by as much as 10-15%, and can have a significant impact on the measurement(s).

- Any ideas welcome for how to better define this uncertainty band
  - An active discussion point going forward
  - Keep in mind that if we want to update the prescription for the Run-3 measurements we need to act soon (things take time!).

Applying NNLO QCD and NLO EW to event generators

- Current state of the art for VBF H:
  - NLO EW + PS: JHEP09(2022)191
  - NNLO QCD: PRL.115.082002, Phys.Lett.B 781 (2018) 672-677, JHEP02 (2022) 046
  - NLO QCD + PS (any general MC)

- But no prescription yet for NLO QCD + NLO EW with PS for VBF.
  - Possibly coming soon, would be great to have a recipe for approximating NNLO QCD corrections as well.
  - NNLO QCD + NLO EW with PS is a longer-term challenge.

- Must in parallel continue to work on improving description of parton shower.
  - Can first be studied in the strict VBF approximation without need for cuts, and then go beyond.

Reducing ggF uncertainties in VBF

- Sub-leading theory uncertainties from ggF contribution to VBF-enriched region
  - Typically large theory uncertainties on the ggF prediction in this phase space
  - Typical ggF contribution in VBF-enriched measurement region is 10-20%.

- Active area of development in theory:
  - See for example recent comparative study of predictions in VBF-like regions, including at high-$p_T(H)$[1].
    - Further work is needed to better disentangle and understand ggF contamination.
      - See for example J. Paltrinieri's dedicated talk on HEJ at the workshop

- On the experimental side, important to rely on predictions at highest possible precision in ggF+2-jet region and not only inclusively.
  - i.e. ggF+2-jet at NLO via amc@NLO, HJMiNNLO, HERWIG with NLO matching + multijet merging, …

[1] JHEP11(2021)108

Summary

- *We are entering the precision era for VBF H*, with STXS/differential measurement possible in multiple decay channels.

- *Systematic uncertainties, which include a substantial theory component, are approaching the size of statistical uncertainties* in many of the main VBF measurement channels.
  - *The parton shower description and uncertainty are the most important issue* going forward, and any ideas/development there will have a clear impact towards Run-3 and beyond.
  - Now is the time to make the developments that can/will be used for the Run-3 legacy measurements.

- Improving the predictions for VBF requires developments on multiple fronts.
  - Important to make sure that experiments are also aware and able to implement the latest improvements.

- Clear interplay between developments in theory and experiment:
  - It's not only a matter of reducing the final measurement uncertainty, analysis strategies are to an extent designed because of limitations from uncertainties.

Additional information

- Welcome to Silvia Ferrario Ravasio replacing Simon Plätzer.
  - And a big thank you to Simon!

- e-group: lhc-higgs-vbf ⇒ please subscribe!

- A twiki page is available summarizing the main activities.

- Email us at lhc-higgs-vbf-convener@cernNOSPAMPLEASE.ch

Additional Material