19th LHCHWG Workshop
28/11/2022

Towards STXS 1.3

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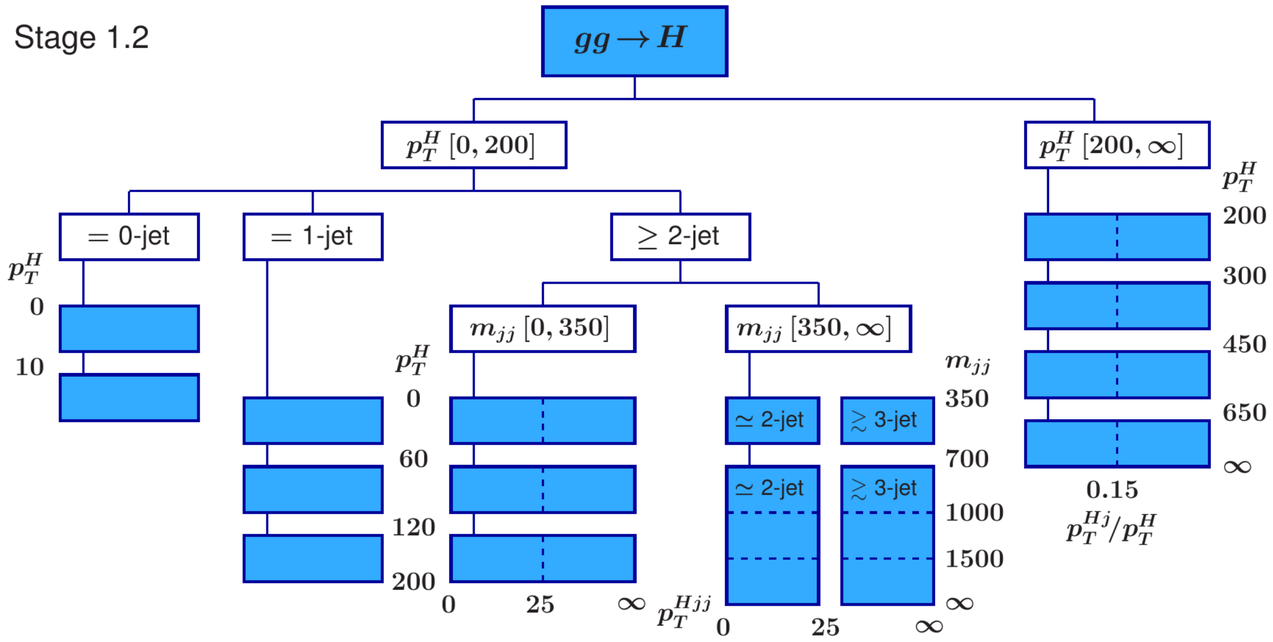
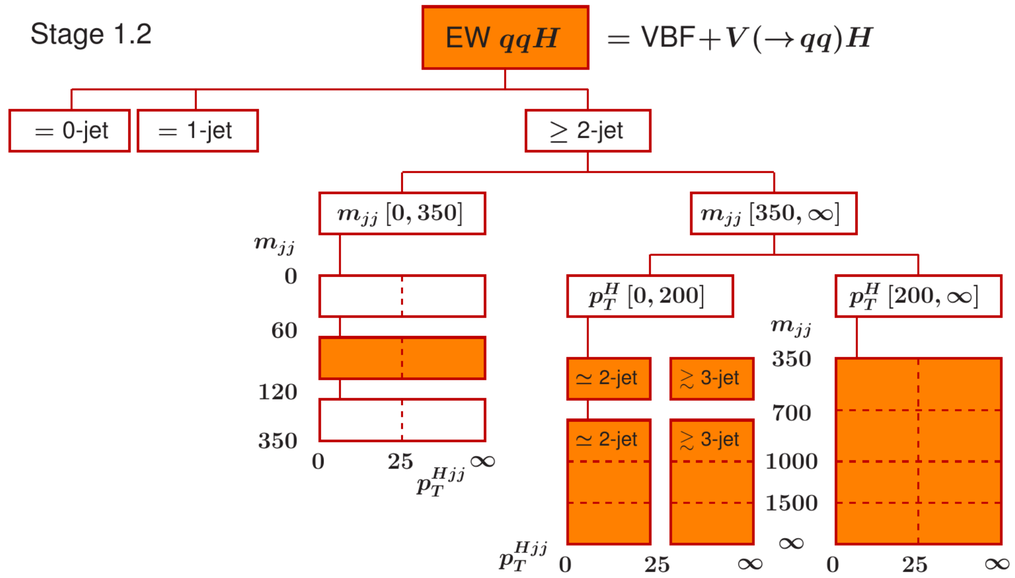
On behalf of LHCHWG2 & STXS/Differential Sub-group

STXS in a nutshell

The primary goal of STXS framework is to minimise the measurement dependence on theory predictions without losing sensitivity

Coverage of the entire phase space and **specific regions** designed **to detect BSM effects**





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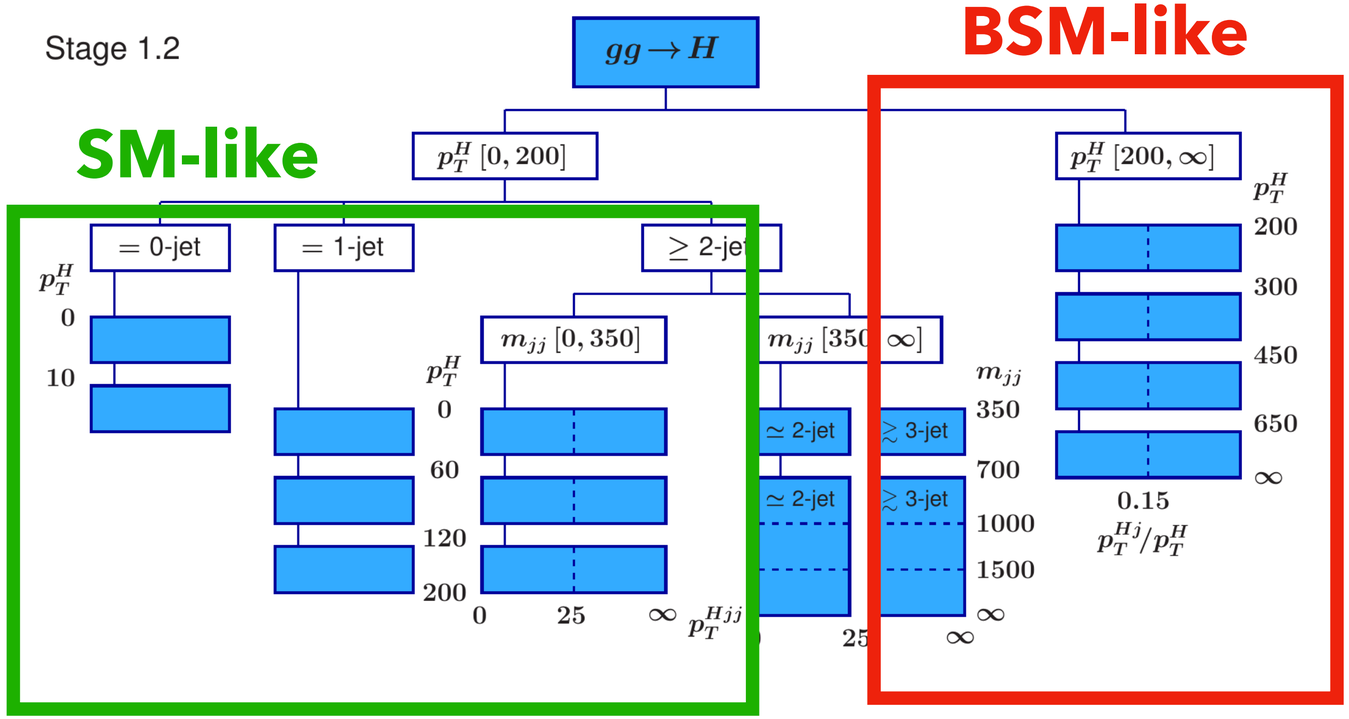
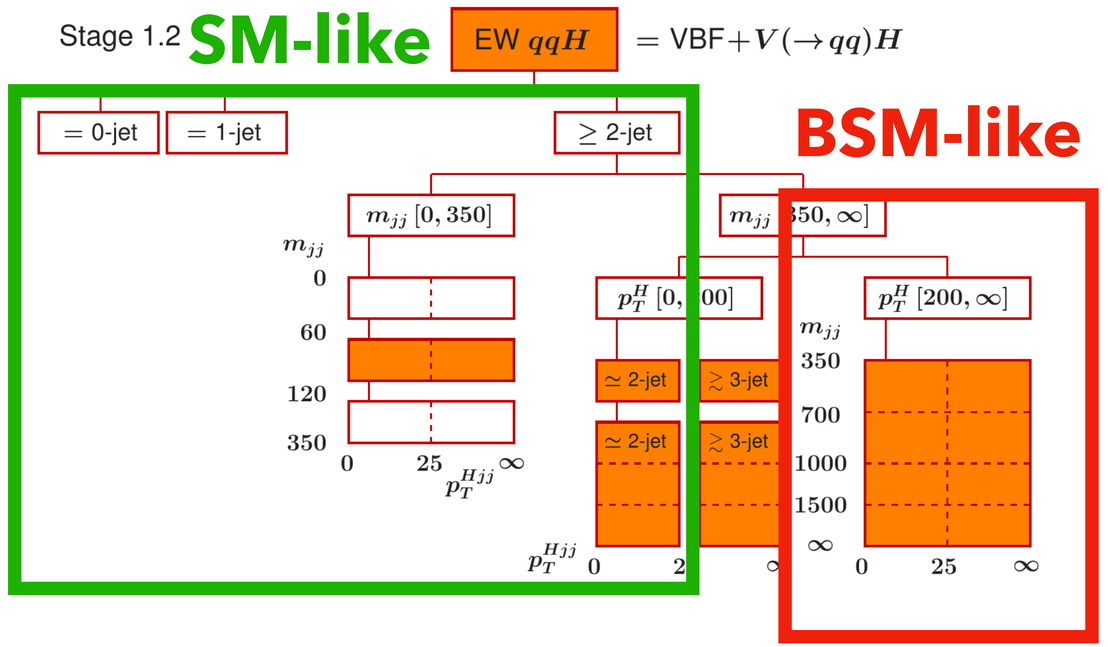




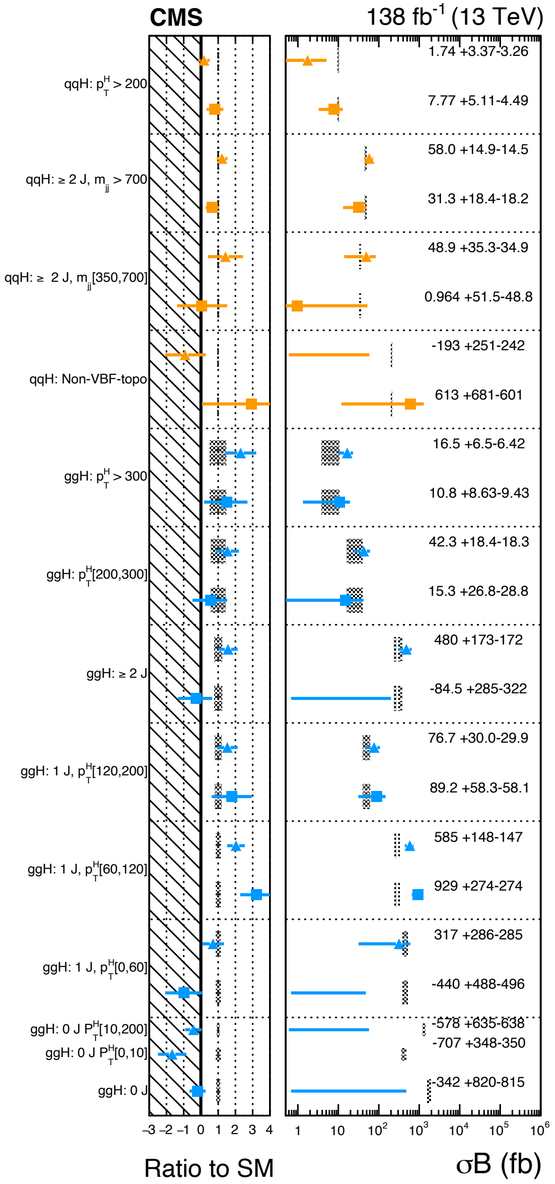
STXS in a nutshell

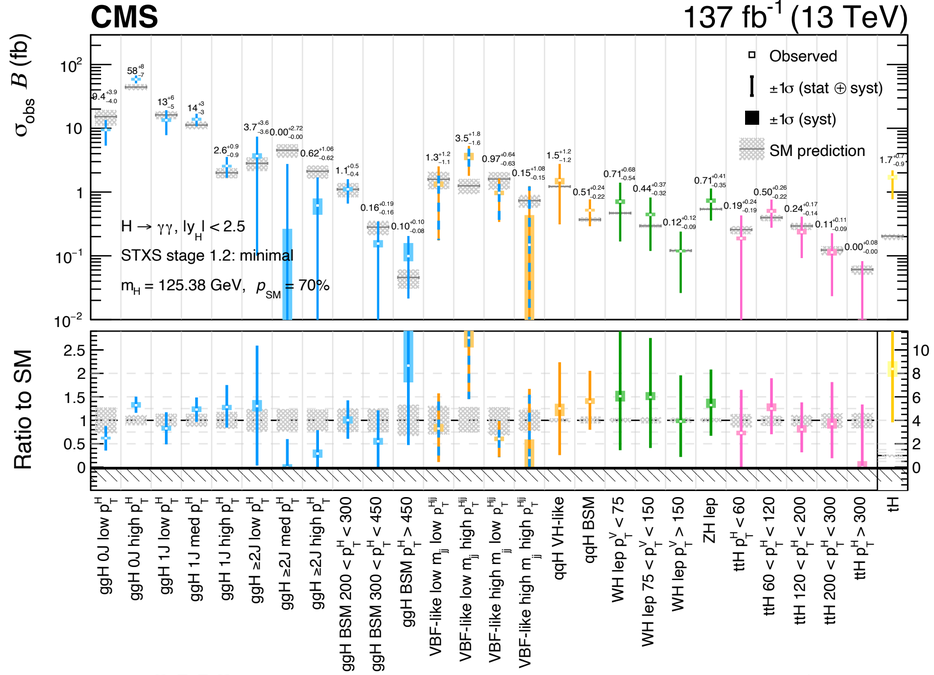
- **Constant evolution throughout LHC Run-II**: **increasing** the bins **granularity for all** the **production modes**
- **Currently** we are at **STXS Stage 1.2**
  - Well documented in the LHCPhysics TWiki (possibly to follow up with a public document)
  - Rivet routine for STXS 1.2 classification available on the LHCHWG2 gitlab page
  - **Pros:** good coverage of the whole phase space through highly granular binning
  - **Cons:** even with full Run-II statistics, analyses end up merging bins in some phase space regions
- **Today: going beyond STXS Stage 1.2**
  - Where do we stand with Stage 1.2 in terms of results & recommendations
  - Considerations and ideas for STXS 1.3: feedbacks and discussions are warmly welcomed!

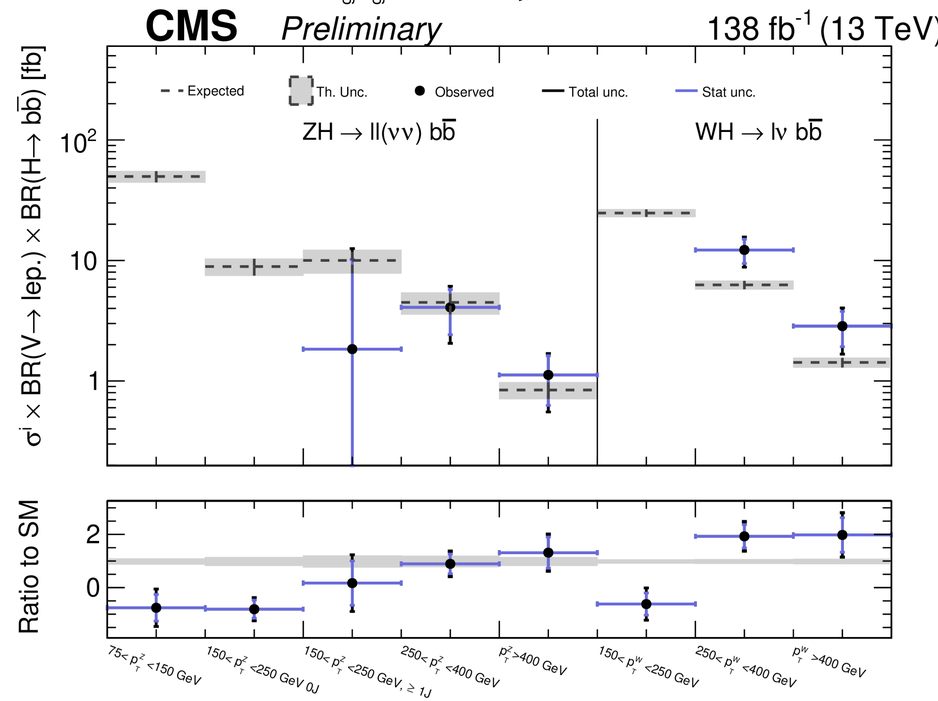
Current status

Highly granular characterisation of **ggF**, **VBF**, **VH**, and **ttH production** modes

Run-II dataset exploited **in all final states**: **access to** various phase space regions (e.g. **high pT ggH**, **tH in $H\gamma\gamma$**), but many **results** are **still stat.-dominated**







Hyy: arXiv:2103.06956

Htt: arXiv:2204.12957

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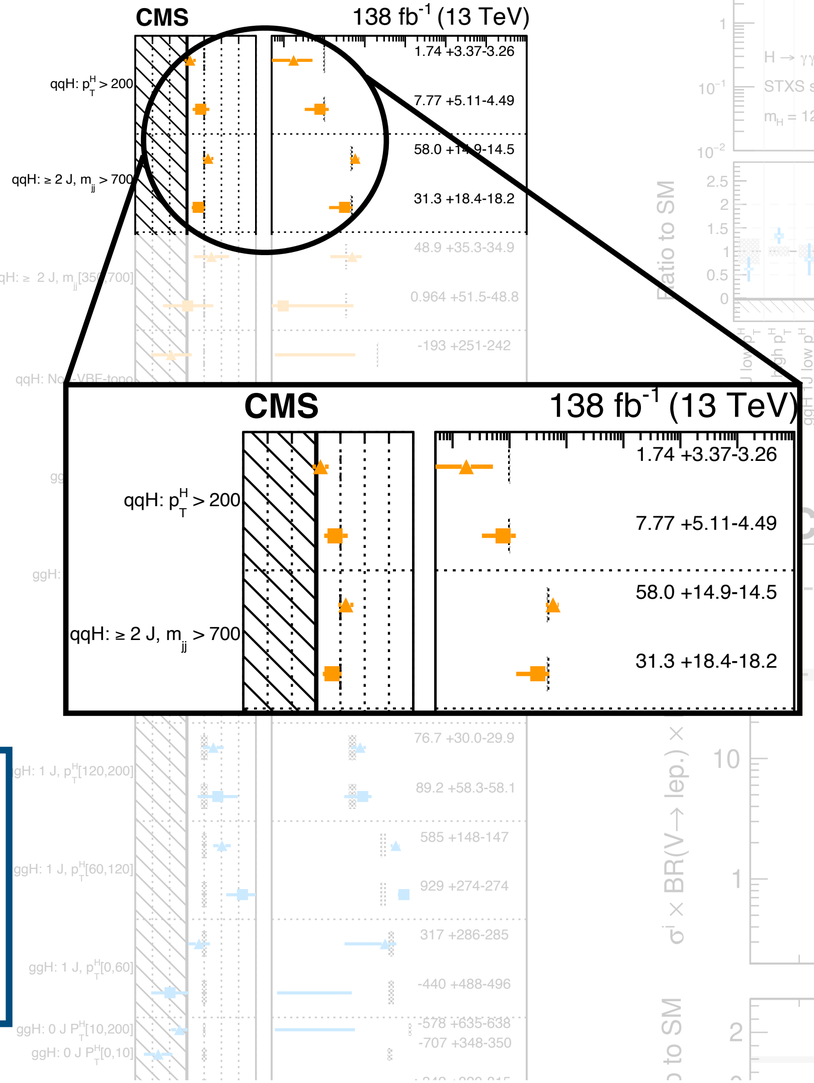
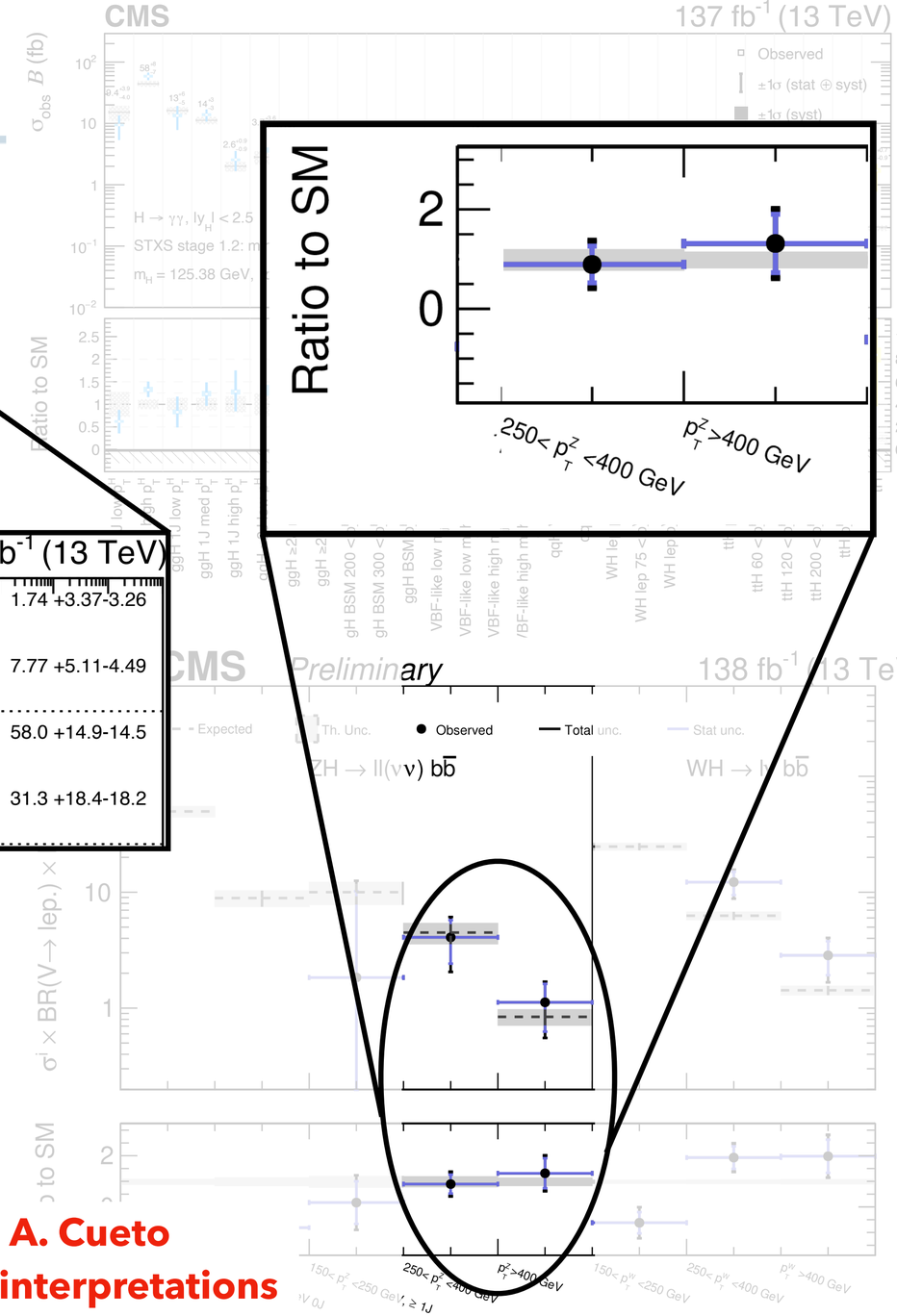
Precious measurements to test SM predictions (theory uncertainties) **and probe possible BSM effects: qqH high pT and VH high pTV regions**





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See talks from M. Knight and A. Cueto for more on STXS results and their interpretations

STXS 1.2 Uncertainties

Run-II has seen the surge of STXS (1.2) measurements and their subsequent interpretations.
In this context, lot of work has been done in the LHCHWG to define central recommendations for theory uncertainties

- **Acceptance uncertainties:**
  - Define migration within STXS bins
  - Required for STXS measurements
- **Normalisation + migration uncertainties:**
  - Define migrations across STXS bin boundaries
  - Required for STXS interpretations and bins merging

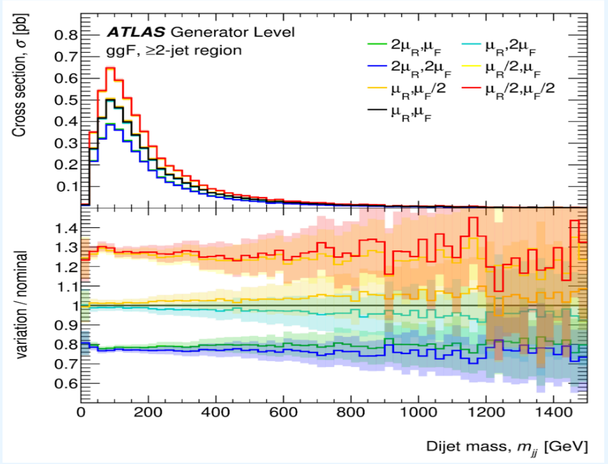
Several discussions within the LHCHWG to converge on a common uncertainty scheme (ATLAS+CMS+Theory):

- **ATLAS:** final derivation of **ggH** and **ttH** uncertainties
- **CMS:** final derivation of **VH** and **qqH** uncertainties
- We will **document** the outcome of these studies **in a LHC-wide note** (currently WIP) to be used as a reference for analyses and for the derivation of uncertainties in future Stages of STXS

STXS 1.2 Uncertainties - cnt'd

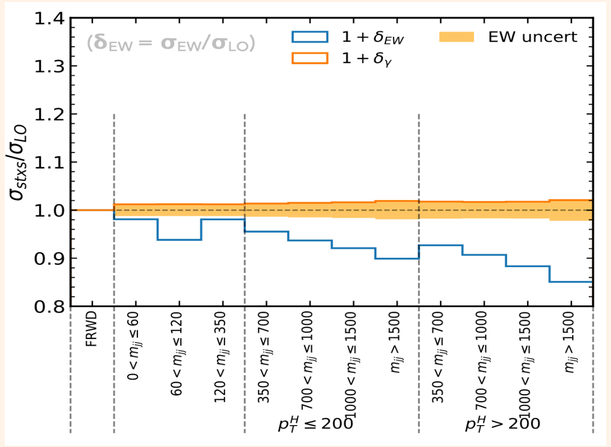
ggH

- Uncertainties derived from POWHEG with NNLOPS reweighing
- Long range ST method evolving from Stage 1
- Variations of $\mu_{R(F)}$ scales + overall yield and jet-bins migration



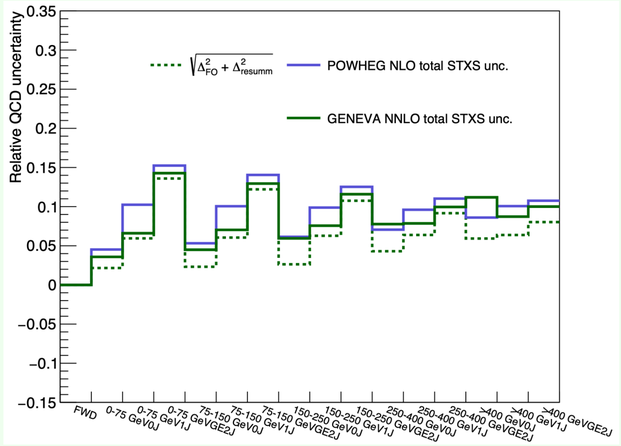
qqH

- Uncertainties derived from POWHEG VBFH, HAWK, and Herwig7 generators
- 4 inclusive NPs (Δ_y, Δ_{2j}, Δ_{25}, Δ_{200}) + 6 NPs from ST method
- Inclusion of VH-had mode and EWK corrections



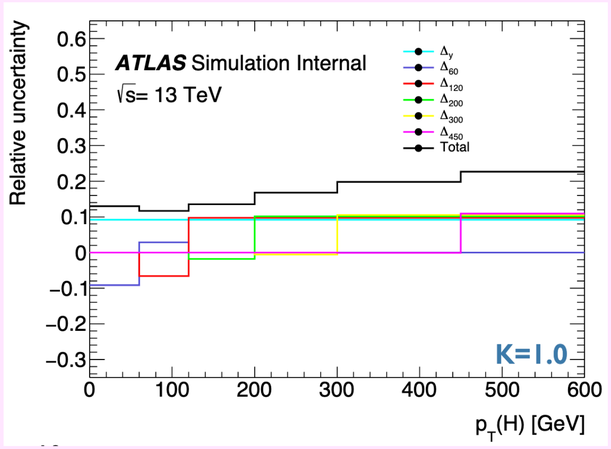
VH

- Uncertainties derived from POWHEG MiNLO and GENEVA NNLO+NNLL: results in agreement
- Maximum split scheme in STXS Stage 1.2 used
- Variations of $\mu_{R(F)}$ and FO scales in GENEVA are used



ttH

- ST method to account for uncertainties around the 6 ttH bin boundaries
- Factor out the effect on the total xsec, which is kept constant
- Leading contributions from QCD (ISR dn), smaller effect from PS and NLO matching



How to move forward?

- **At the end of Run-II most of the analyses have measured STXS 1.2 cross sections, but we have still some open points:**
  - Converge on LHCHWG note for STXS 1.2 uncertainties as soon as possible (all the inputs in place now)
  - ATLAS and CMS will perform STXS 1.2 combinations and EFT interpretations, setting the bases for future analyses and developments of the framework
  - Theory (re-)interpretation of the experimental results using correlation matrices as input (e.g. HiggsBounds, Lilith,…)
- **With the LHC Run-III just started we have to look forward and start the preparation of the next steps:**
  - Gather feedbacks from experiments on STXS 1.2 to understand its shortcomings (e.g. sensitivity of the analyses to different phase space regions)
  - Define timeline and goals for a possible STXS Stage 1.3: fundamental to get inputs from theory (e.g. what to expect on the evolution of theoretical predictions and uncertainties) but also to consider that LHC Run-III will not bring much more sensitivity to the different channels
  - There can be several directions (more in the next slides): further splitting of high pT regions? Decay-like bins? CP-sensitive bins in qqH (and VH)?

Towards STXS 1.3: decay bins

Possibility to define bins to discriminate different decay channels:

- Initial proposal presented during the 16th and 17th LHCHWG Workshop, but person power would be needed to resurrect the effort and progress with this proposal
- **Pros:** Complementary to fiducial differential measurements; the first "Stage" could be probed by all the analyses without issues of limited stat/sensitivity; probe decay-side to which current STXS is agnostic
- **Cons:** Person power to perform gen-level studies; need a clear definition of objects and cuts to discriminate different decay channels; resolve the interplay among different decay channels (e.g. tau decays, QCD emissions, etc)
- Work on this topic resumed few months ago (M. Duehrssen) on HZZ from the preliminary bins boundaries and objects definitions detailed in this note and in this presentation

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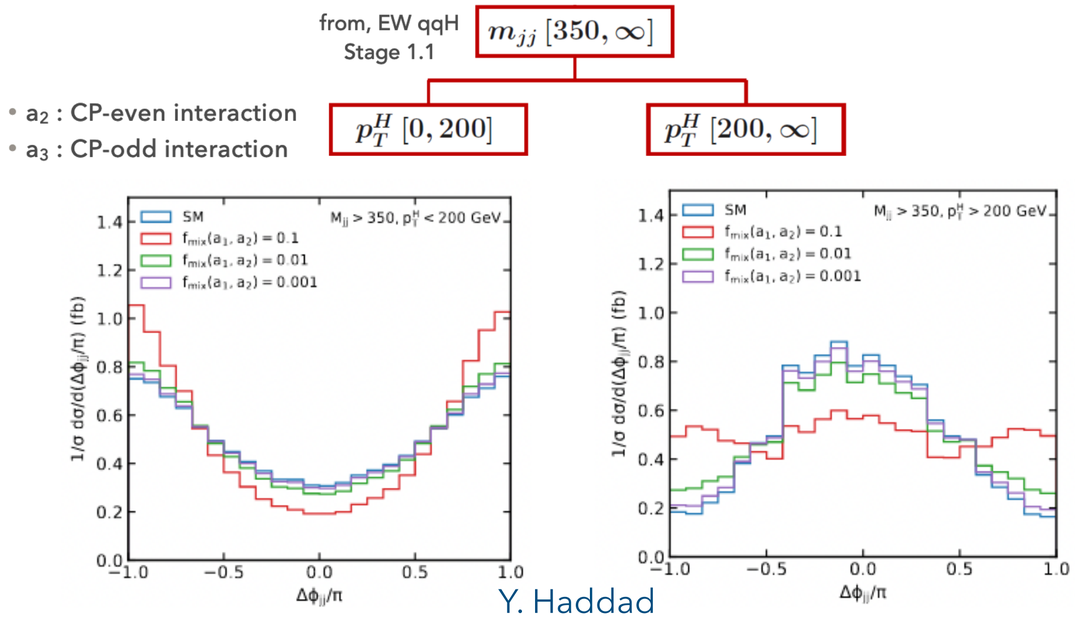
Label	Final state	Kinematic selection	Comment
$H \to ee$	$H \to ee + X$	$m_{ee} \geq 120$ GeV	Section 3.1
$H \to ff$	$H \to f\bar{f} + X$	$m_{ff} \geq 105$ GeV	Section 3.1
$H \to Z\gamma$	$H \to ee + \gamma + X$	$50 \leq m_{ff} < 120$ GeV, $m_{ff\gamma} \geq 120$ GeV	Section 3.1
$H \to Z\gamma$	$H \to ff + \gamma + X$	$50 \leq m_{ff} < 105$ GeV, $m_{ff\gamma} \geq 120$ GeV	Section 3.1
$H \to \gamma^*\gamma$	$H \to ff + \gamma + X$	$m_{ff} < 50$ GeV, $m_{ff\gamma} > 120$ GeV	Section 3.1
$H \to \gamma\gamma$	$H \to \gamma\gamma$	$m_{\gamma\gamma} = 125$ GeV	Section 3.1
$H \to 4\ell$	$H \to 4\ell + X$	$m_{34} \geq 10$ GeV, $m_{34} \leq m_{12} < 105$ GeV	Section 3.2
$H \to 2e2\mu$	$H \to 2e2\mu + X$	$m_{34} \geq 10$ GeV, $m_{34} \leq m_{12} < 105$ GeV	Section 3.2
$H \to 2\ell 2\nu$	$H \to \ell\ell\nu\nu + X$	$80 \leq m_{2\ell} < 105$ GeV	Section 3.3
$H \to 2\ell 2f$	$H \to \ell\ell ff + X$	$80 \leq m_{2\ell} < 105$ GeV, $ff! = ee, \mu\mu, \nu\nu$	Section 3.4
$H \to \ell\nu\ell\nu$	$H \to \ell\nu\ell\nu + X$	$10 < m_{\ell\ell} < 80$ GeV	Section 3.3
$H \to e\nu\mu\nu$	$H \to e\nu\mu\nu + X$	$10 < m_{e\mu} < 105$ GeV	Section 3.3
$H \to \ell\nu ff'$	$H \to \ell\nu ff' + X$	$10 < m_{\ell\nu} <?$ GeV	Section 3.4
$H \to fff'f'$	$H \to fff'f' + X$	$10 < m_{12} < 105$ GeV, $fff'f'! =$modes above	Section 3.5
$H \to f_1f_2f_3f_4$	$H \to f_1f_2f_3f_4 + X$	$f_1f_2f_3f_4! =$modes above	Section 3.5

Table 1: Kinematic definition of Higgs decay modes. Only particles originating from the Higgs decay are considered. Definitions: $4\ell = 4e, 4\mu$; $2\ell = ee, \mu\mu$

Towards STXS 1.3: CP in VBF

Rising interest in CP studies justifies the definition of CP-sensitive bins (in VBF and VH)

- General interest of LHCHWG on CP studies (not only in STXS) → strongly supports studies on this topic
- Several "non-STXS" analyses have already been published with results on Higgs CP (e.g. anomalous couplings in HZZ, HWW, and CP-sensitive measurements in H$\tau\tau$) → STXS-like analyses could bring additional sensitivity isolating different phase space regions
- Possibility to exploit $\Delta\phi_{jj}$ as a CP-sensitive observable in VBF and VH, as initially shown by Y. Haddad

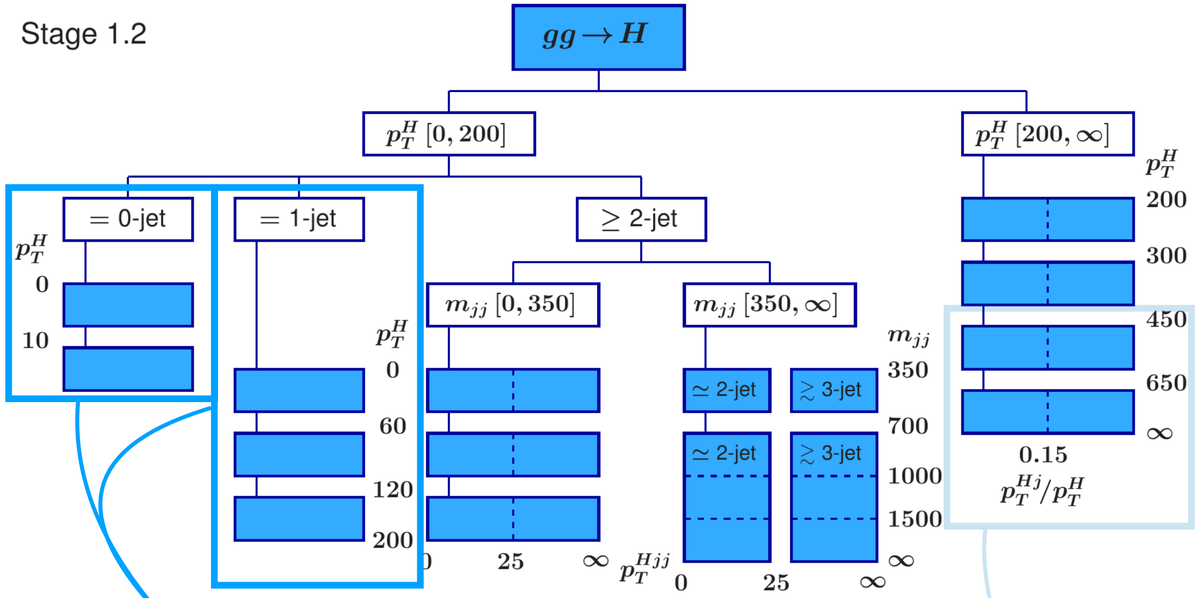


Y. Haddad

See talk from B. Winter

Towards STXS 1.3: more bins

Stage 1.2



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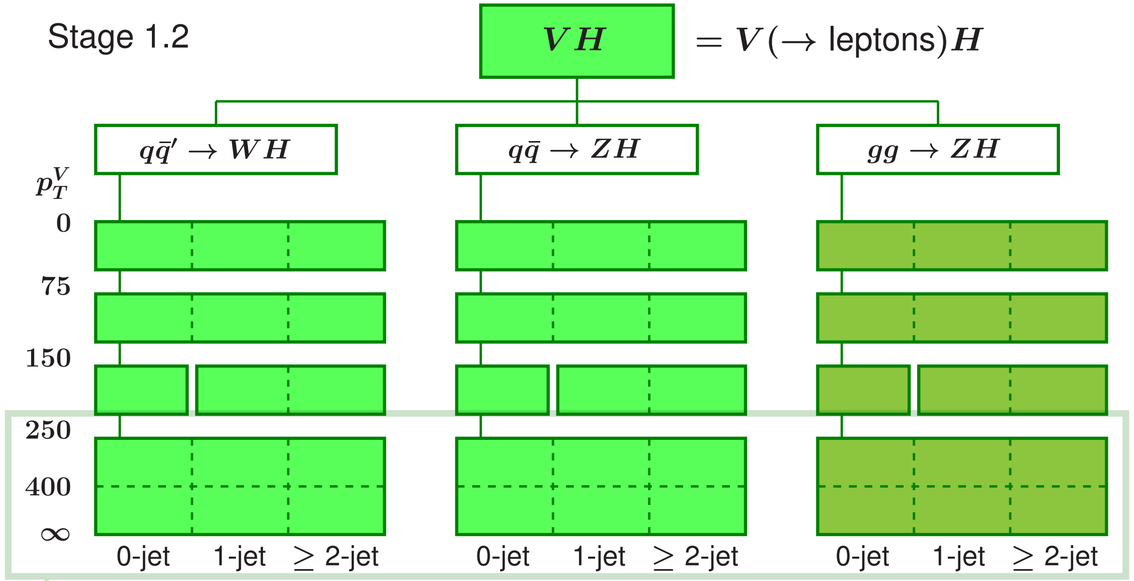


Low pT(H) bins in ggH have the **largest sensitivity** in many analyses

Consider **further fragmentation** of the low-pT region **to probe** even **in more detail SM** predictions **and** theoretical **calculations**

High pT(H) bins introduced with Stage 1.2

Can we go **more granular and/or redefine bins** to enhance sensitivity to BSM effects?

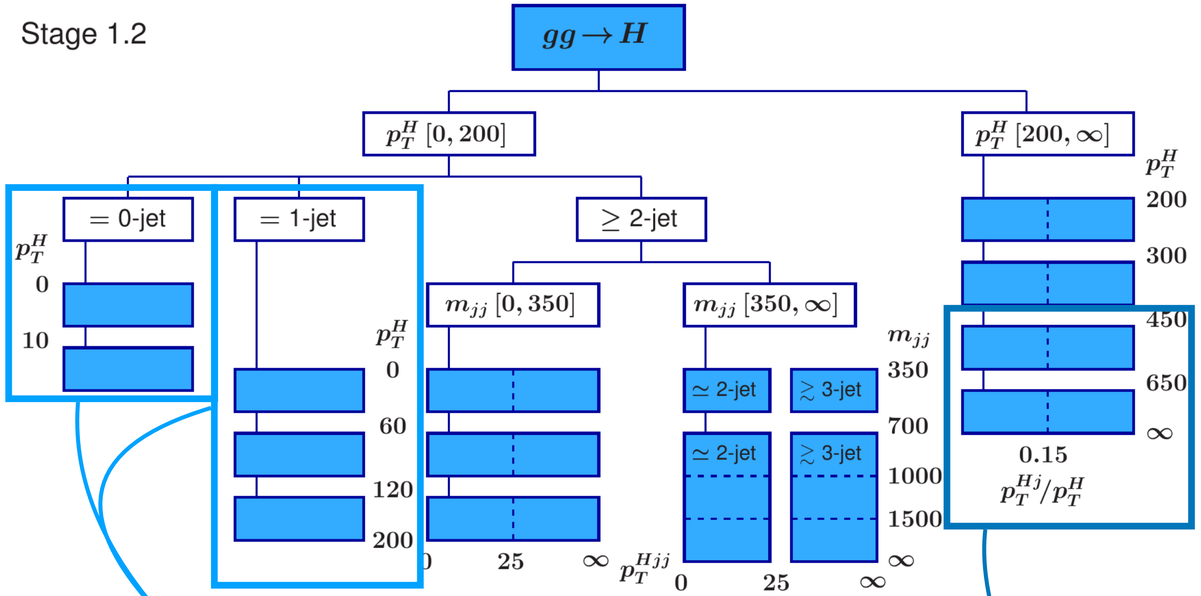
Inputs from theory (e.g. higher-order calculations using pT(H)/pT(Hj) and the STXS cuts) can be useful

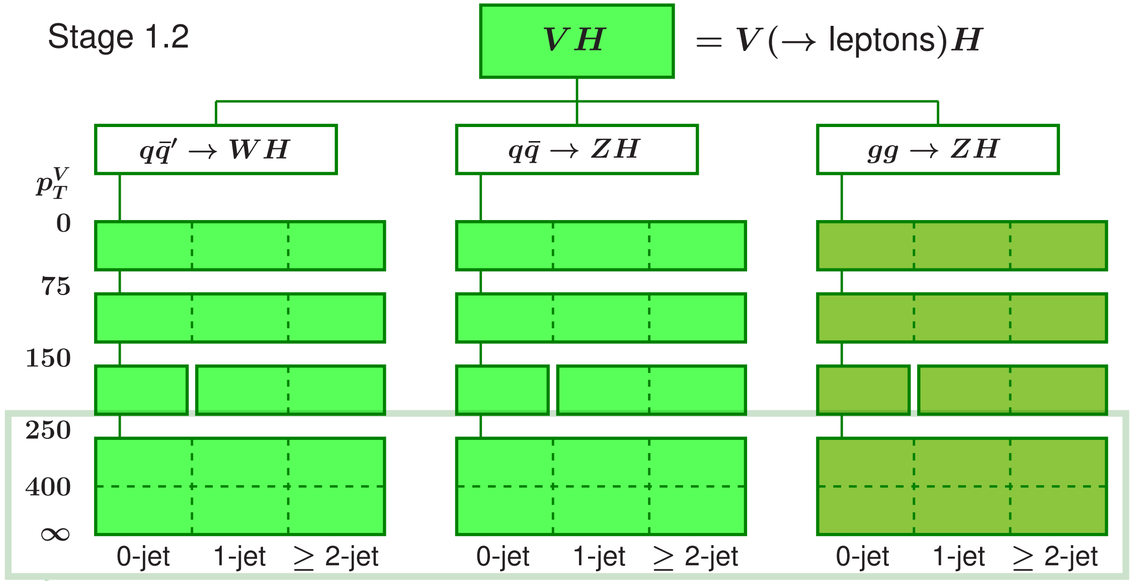
Possibly include **additional bins** at **pT(V) > 250/400 GeV** to enhance BMS sensitivity

CMS VH(bb) already **introduced pT(V)>400 GeV** boundary in the analysis

Start to **measure STXS** in **dashed** bin **boundaries**

Towards STXS 1.3: more bins





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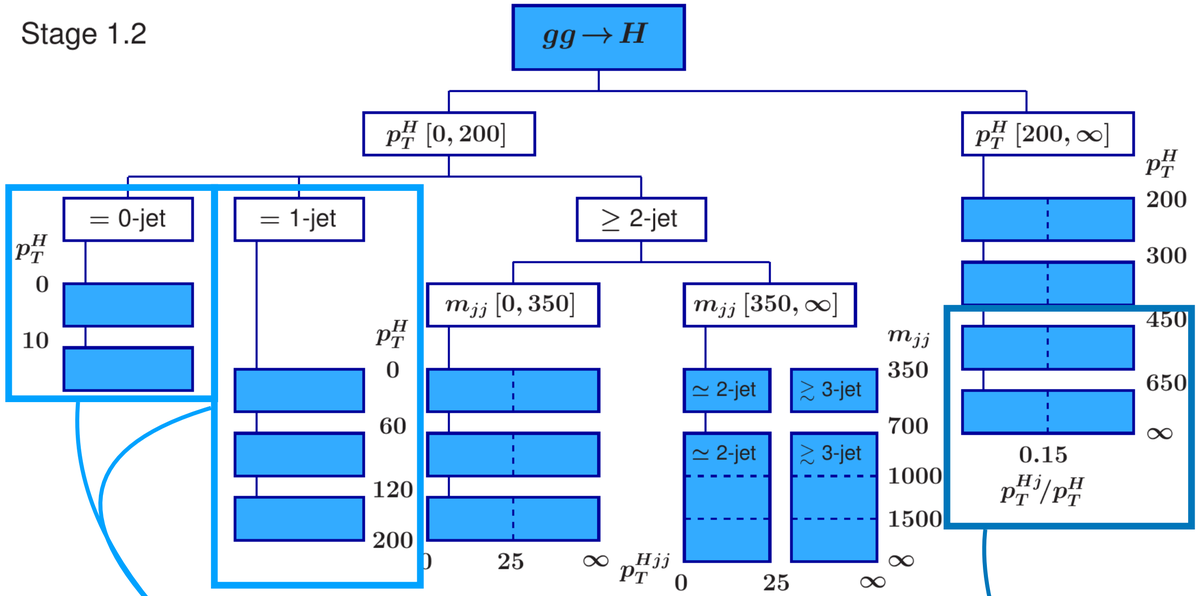

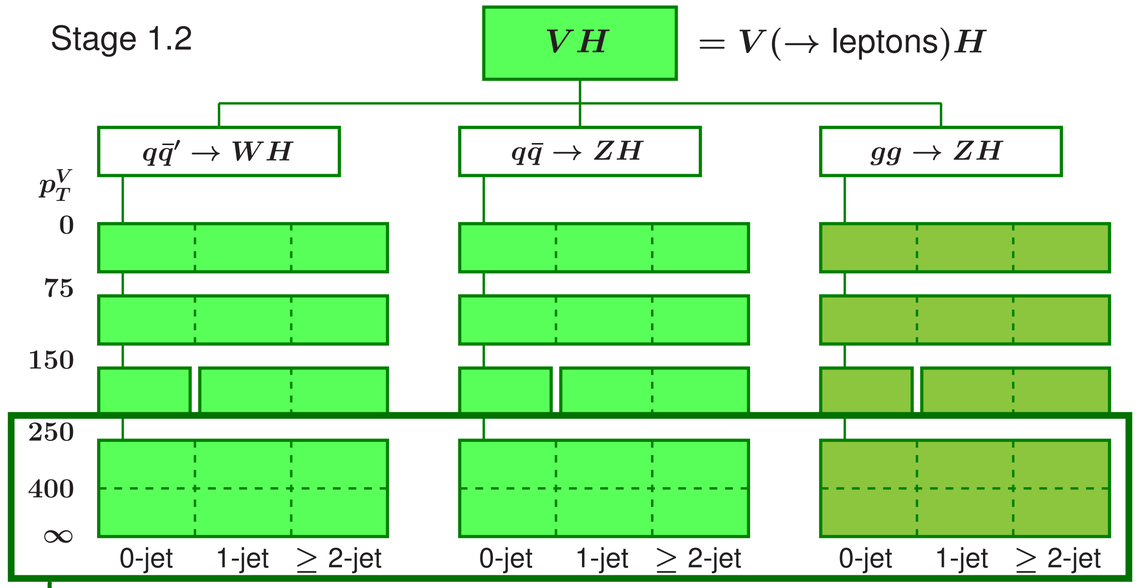

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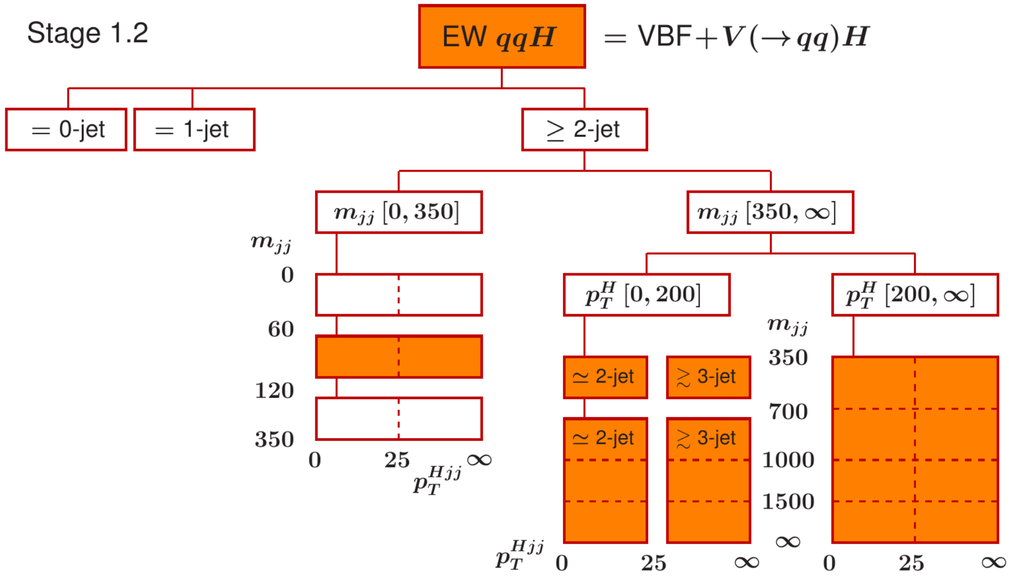
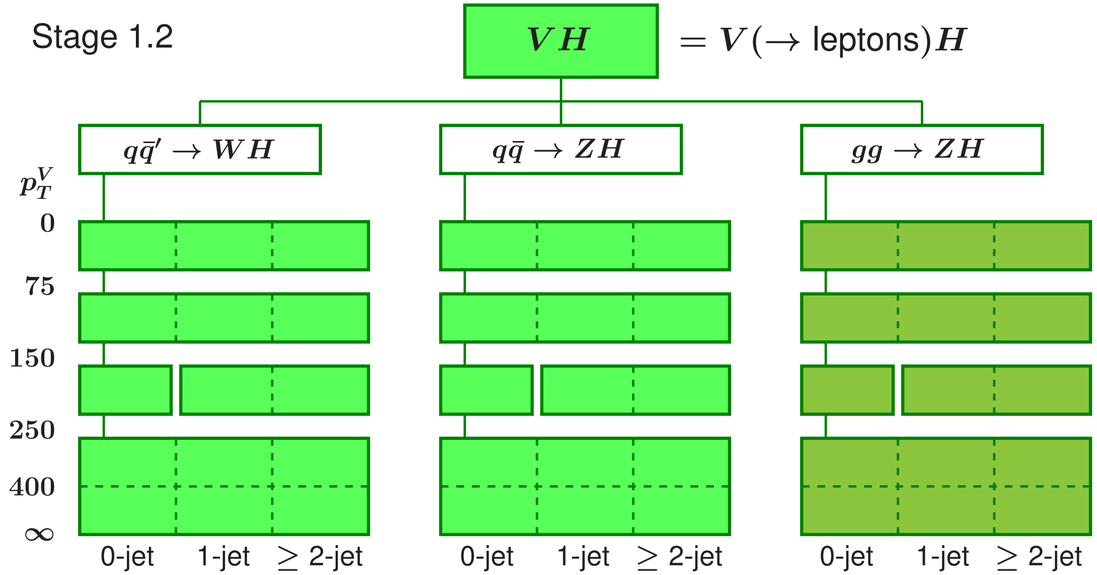
Food for thought





Instead of thinking in terms of:

- Is it worth to substitute pT(V) with pT(H) for the VH bins definition?
- Is pT(Hjj) the most efficient observable for the definition of bins in mJJ > 350 GeV region?
- Can we enhance the purity of VBF bins in qqH-like STXS regions?

⇒ This kind of observations can be made in view of Stage 2 (i.e. HL-LHC), where a possible restyling of STXS bins may be considered

We should instead be considering:

- STXS 1.3 is an evolution of 1.2 ⇒ no major change in observables!
- These observables have been chosen because they are the best compromise for all the analyses (e.g. pTHjj in VBF)

⇒ Given these observables and these STXS cuts (e.g. |y(H)|<2.5), what the higher-order calculations tell us? Which phase space regions are the most interesting and which boundaries?

Towards STXS 1.3: Theory inputs

STXS Stage 1.2 results are still limited by the statistical uncertainty and Run-III will enable improved measurements. However, STXS results can benefit also from improvements on the theory side(*):

- Usage of the latest MC generators (e.g. VBF: Herwig for PS, HAWK for EW corrections)
- Theory uncertainties: e.g. improvement on ggH+2j bkg reduction in VBF phase-space
- Improve accuracy of theory predictions: NLO_{QCD+EW}+PS and multi-jet merging in VBF, N^3LO differential predictions in ggH, new ggH+1/2j predictions
- Modelling (and isolation?) of ggZH@NLO effects and additional improvements in VH processes (e.g. MiNNLOPS)

→ the above are orthogonal to STXS (1.3) developments and the two will evolve in parallel

- **Higher order calculations:** new and improved HO calculations become extremely useful to STXS studies and development when they are performed using the same observables adopted in the STXS framework (e.g. pT(V), pT(Hjj), mjj…) and the same acceptance ($|y(H)| < 2.5$)

(*): some of the inputs taken from the recent VBF workshop

Conclusion & discussion

- **What have we learnt from Run-II analyses?**
  - Many analyses still have limited sensitivity to STXS 1.2 bins → bins merging in several analyses
  - Finalised the definition of STXS 1.2 uncertainties: acceptance (measurements) and normalisation (interpretation)
  - Resumed work on LHCHWG Note with description of STXS 1.2 uncertainties → publish as soon as possible
  - Substantial efforts in deriving (SM)EFT parametrisation in STXS bins and perform EFT interpretations (both inter-experiment and from Theory side using published results and correlation matrices)
- **It is now time to look beyond STXS 1.2**:
  - What are the lessons learnt and the feedbacks from theory and experimental communities?
  - Several possibilities to move towards STXS 1.3: further splitting of high/low pT regions; decay-like bins; CP-sensitive bins
  - **Timeline for STXS 1.3**: measurements with **Run-III** statistics.
    What is more realistic (splitting, CP bins …) and on which timeline?
  - STXS stages are thought for a given luminosity. **LHC Run-III ↔ STXS 1.3**: in the definition of the bins consider experimental sensitivities. Minimise bin merging, which should be done iff uncertainty in a given bin is larger than 100 %