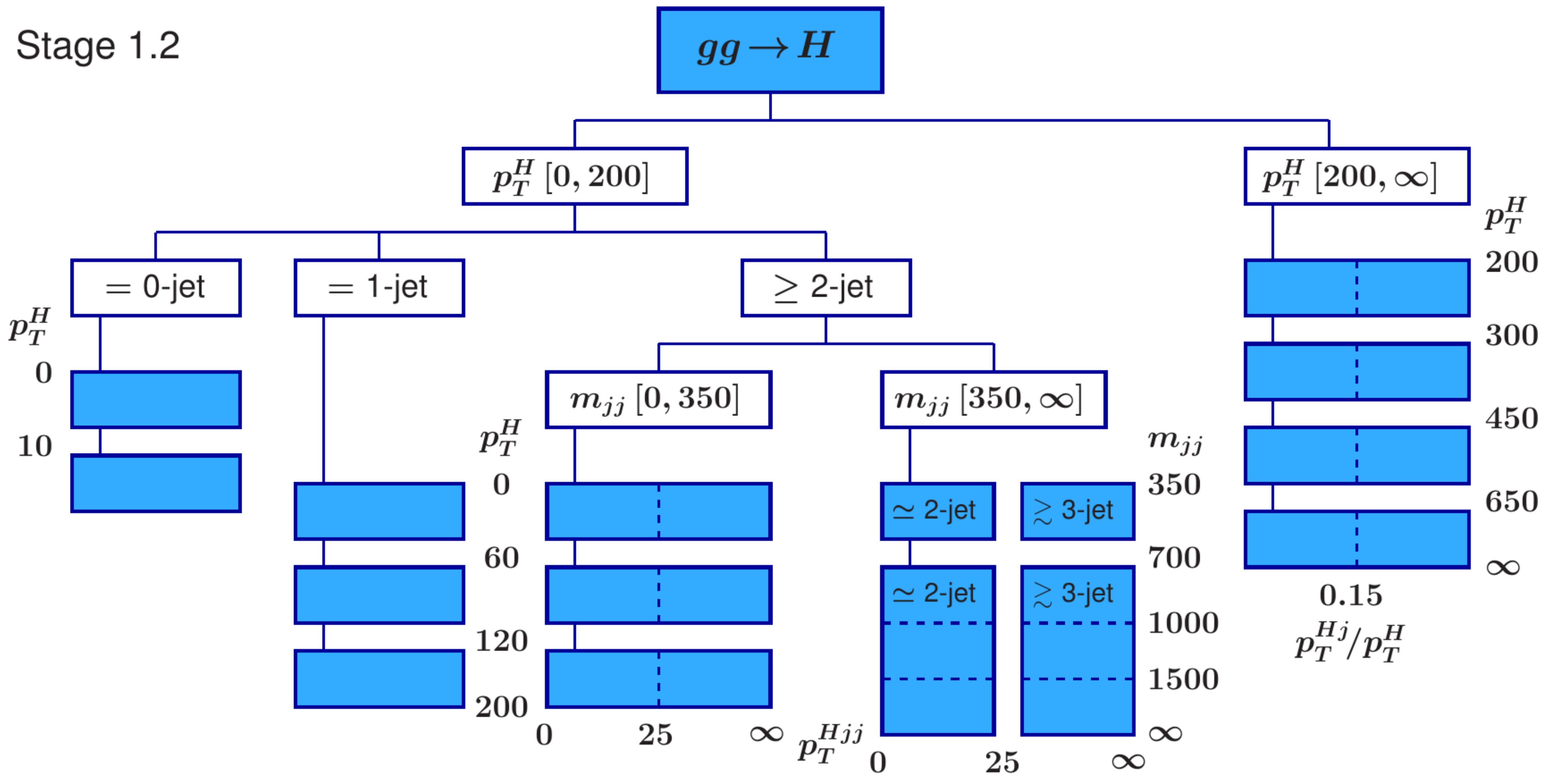
LHCHWG Workshop
STXS 1p3 proposal

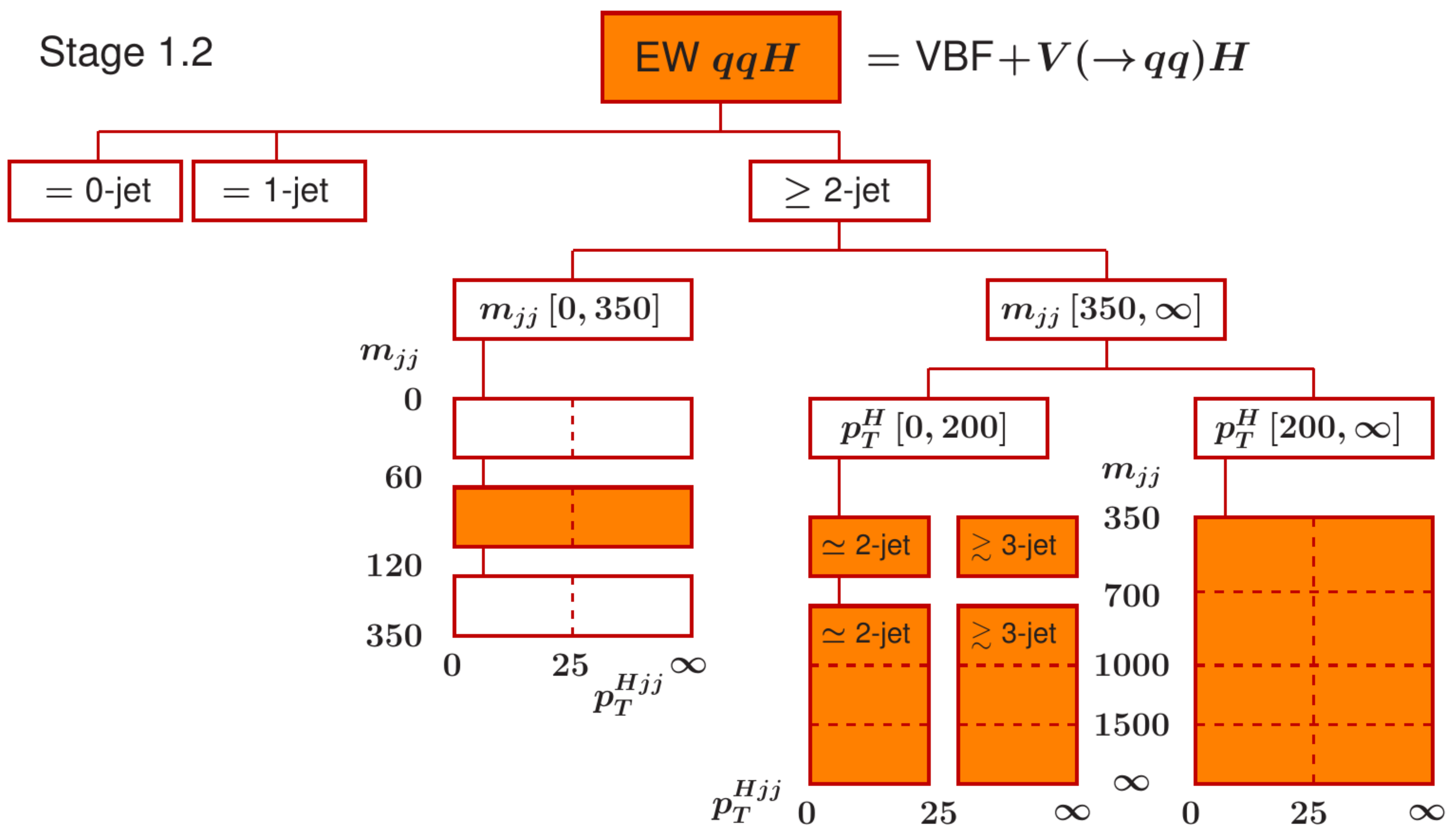
Matteo Bonanomi
(University of Hamburg)
On behalf of WG2

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, expected in the tails of the pT distribution, at higher pT, where less stat is available**

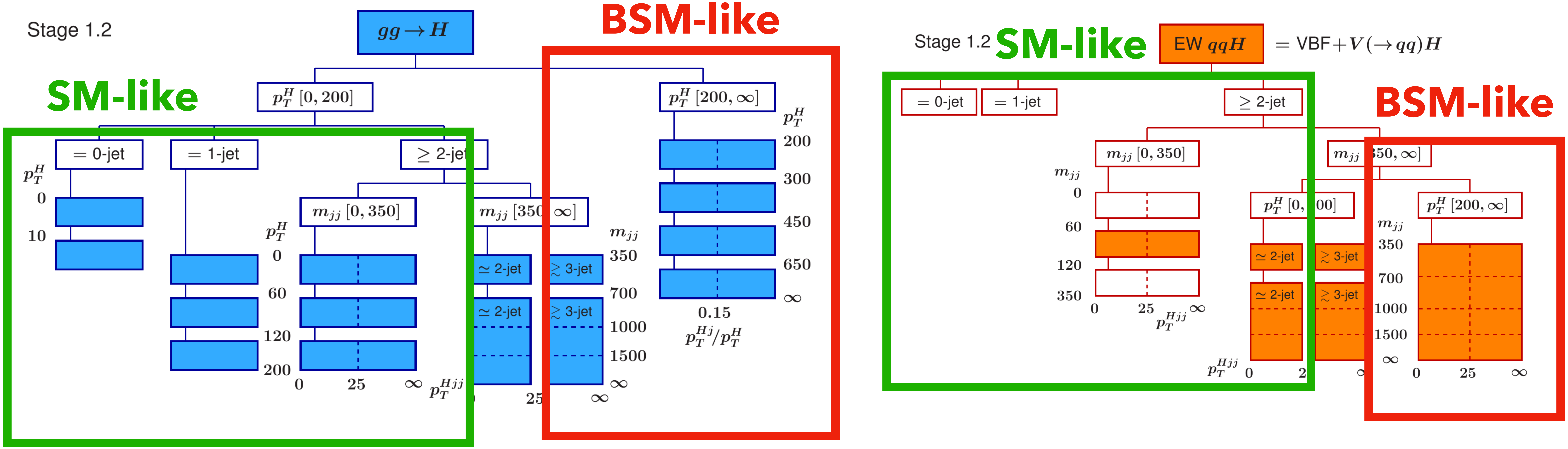




STXS in a nutshell

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

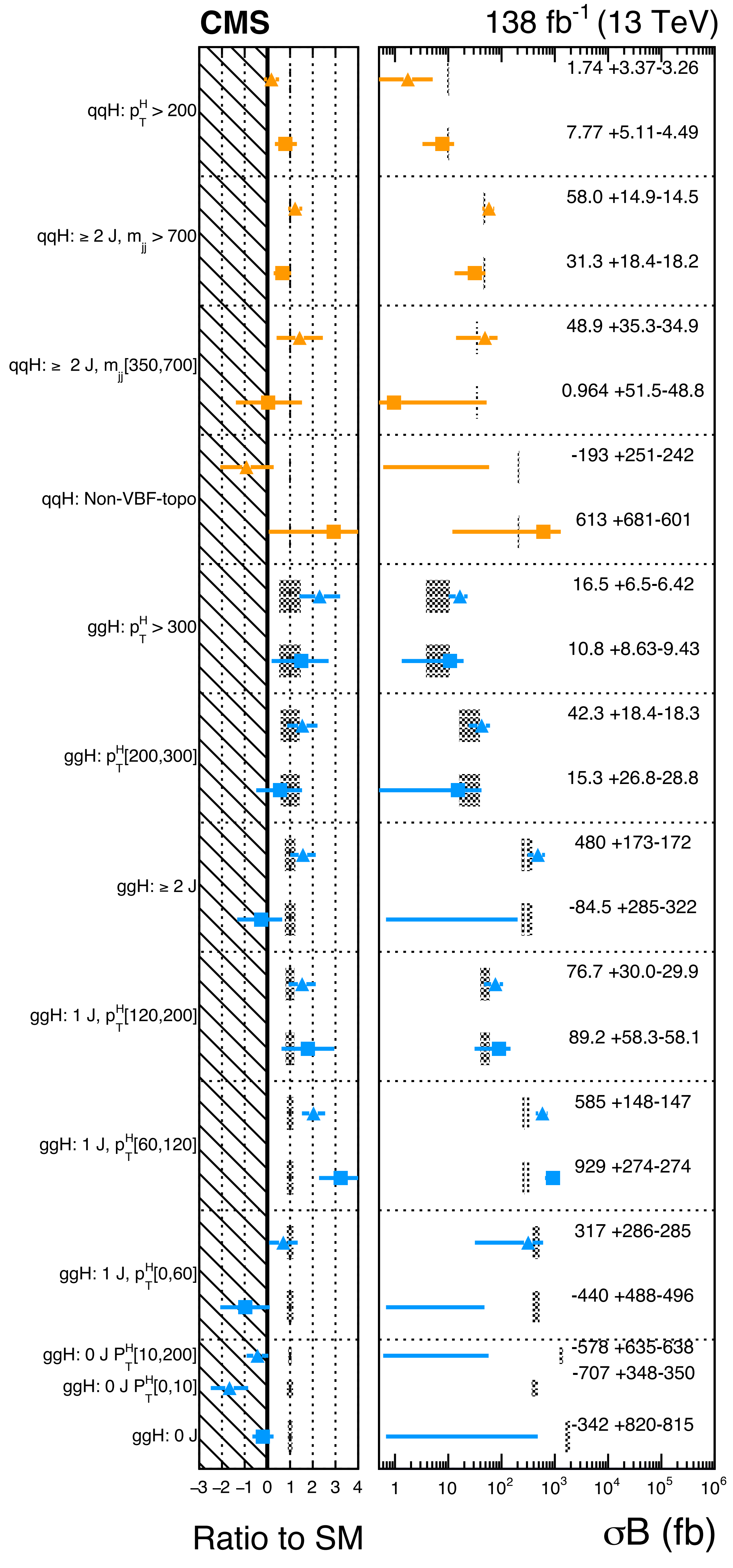
Coverage of the entire phase space and **specific regions** designed **to detect BSM effects, expected in the tails of the pT distribution, at higher pT, where less stat is available**



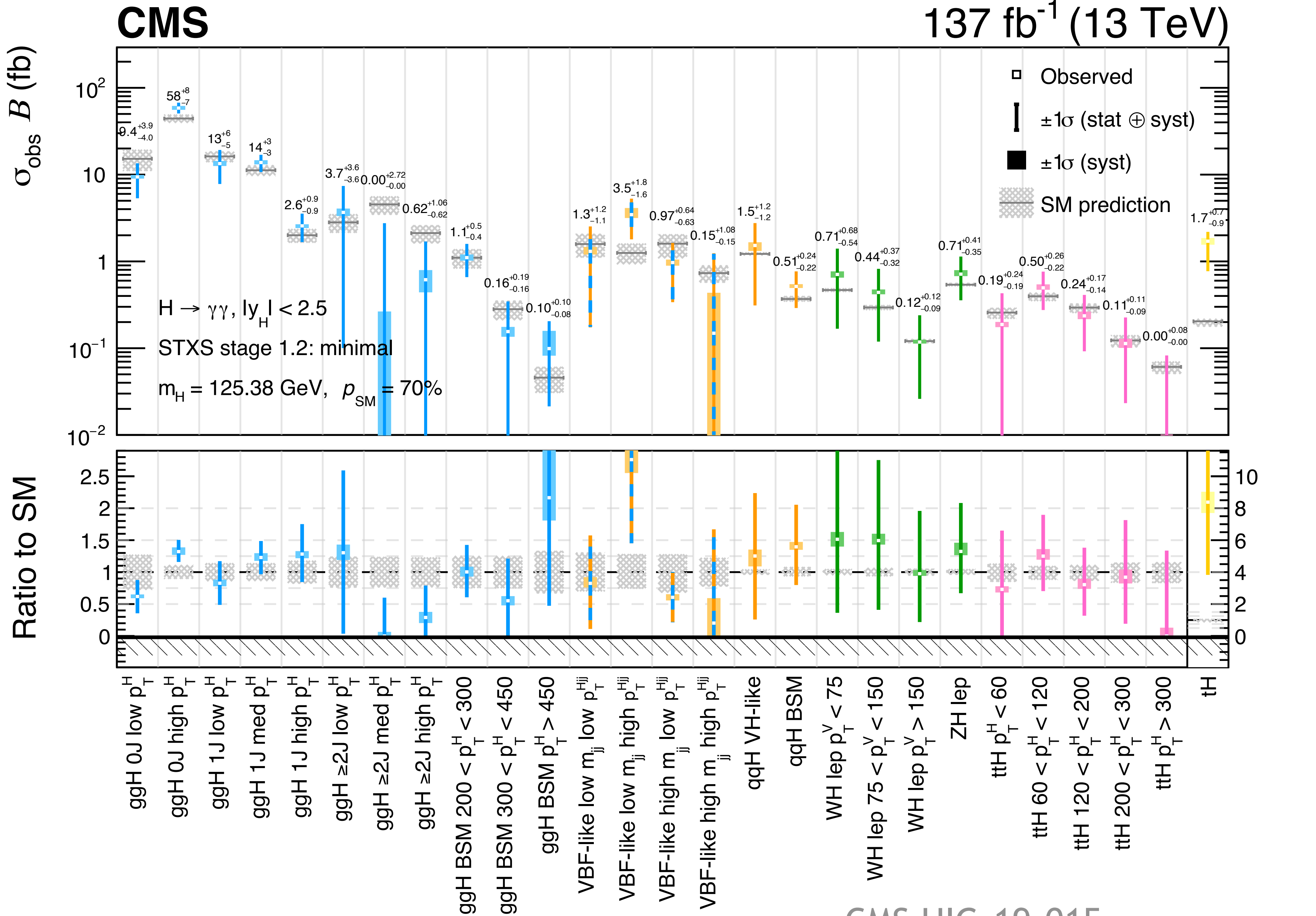
Stage 1.2 in 1 slide

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

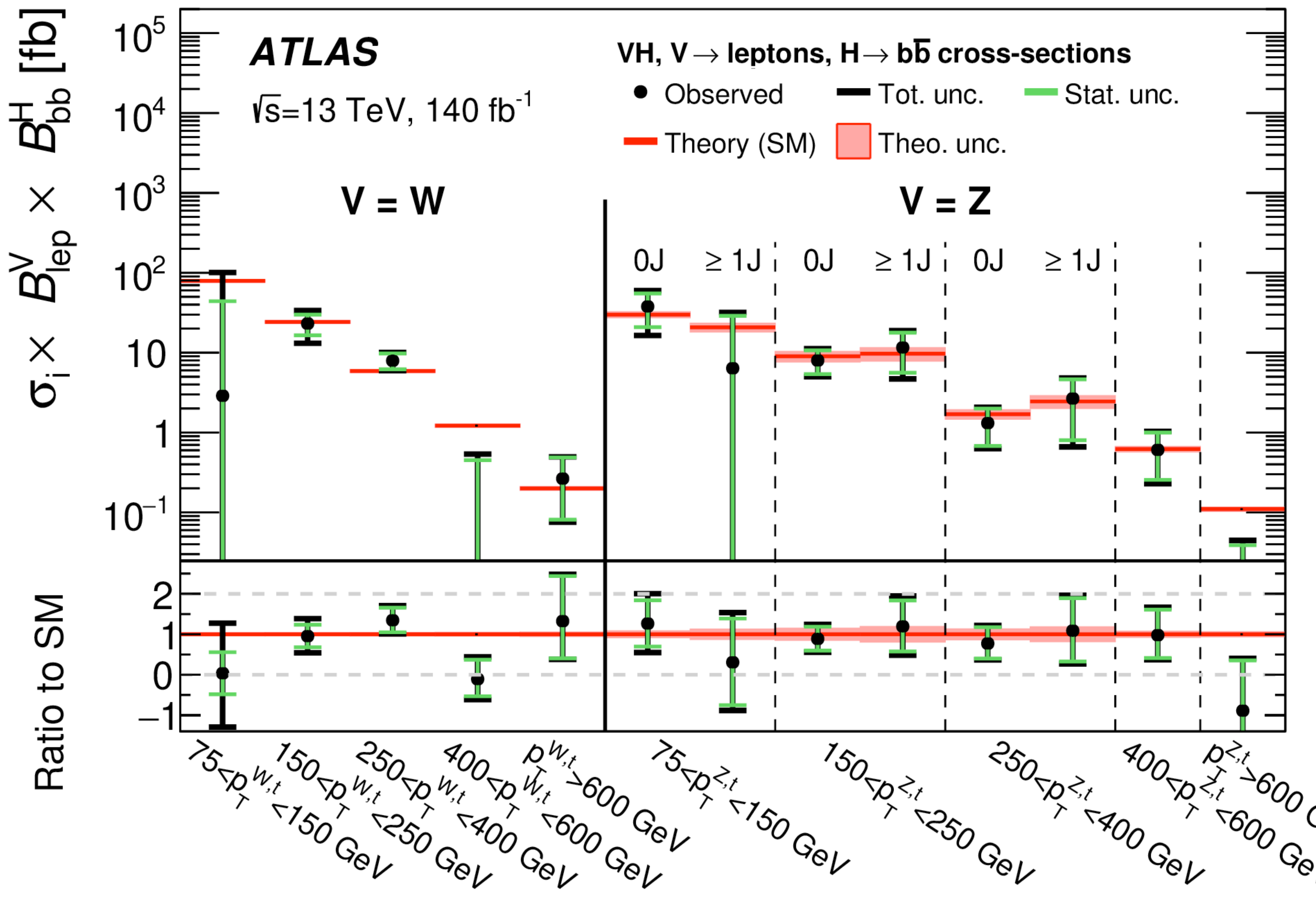
Run-II dataset exploited **in all final states: access to** various phase space regions (e.g. **high pT ggH**, **tH in $H\gamma\gamma$**)



CMS HIG-19-010



CMS HIG-19-015



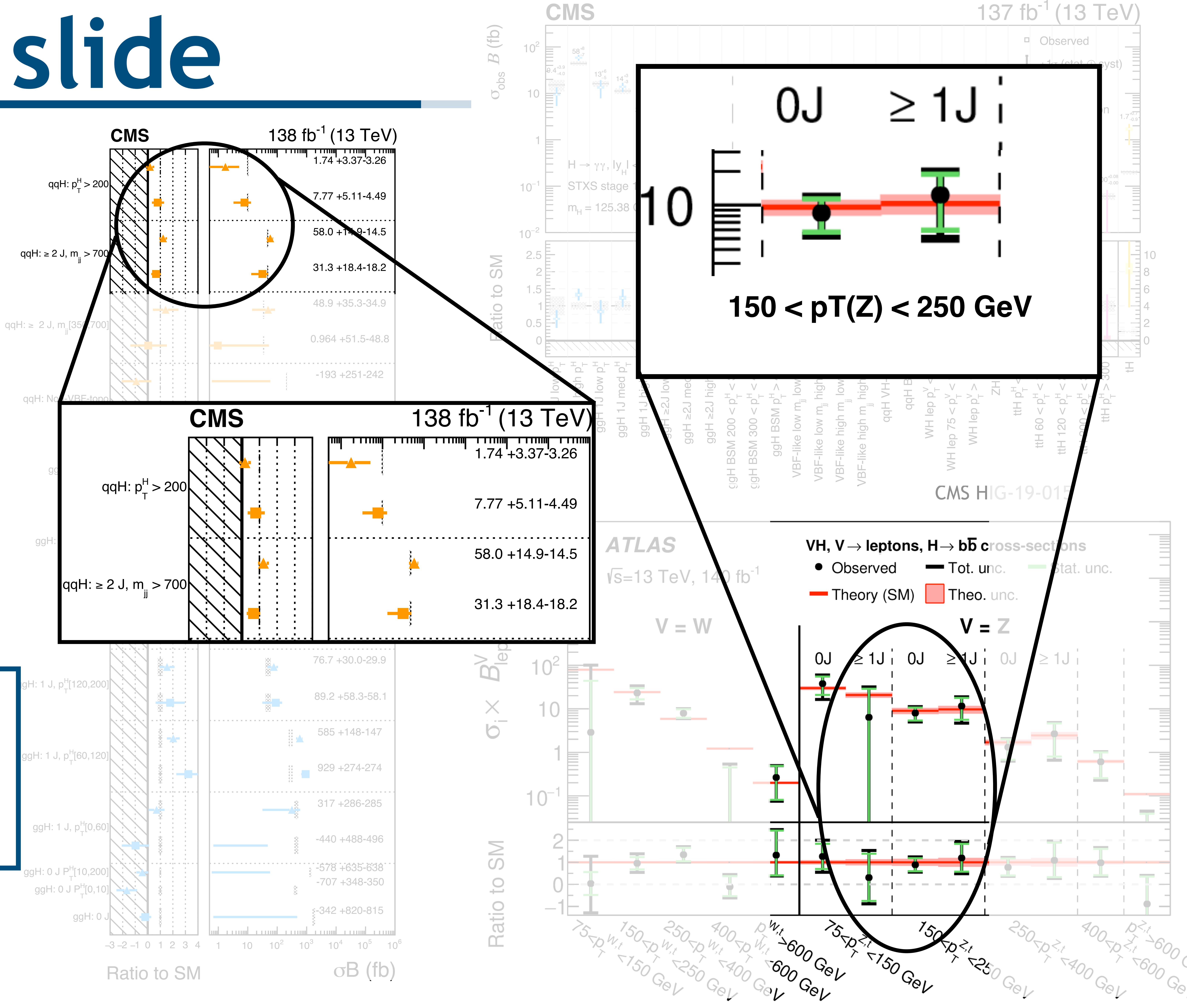
ATLAS HIGG-2020-20

Stage 1.2 in 1 slide

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** $H\gamma\gamma$)

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

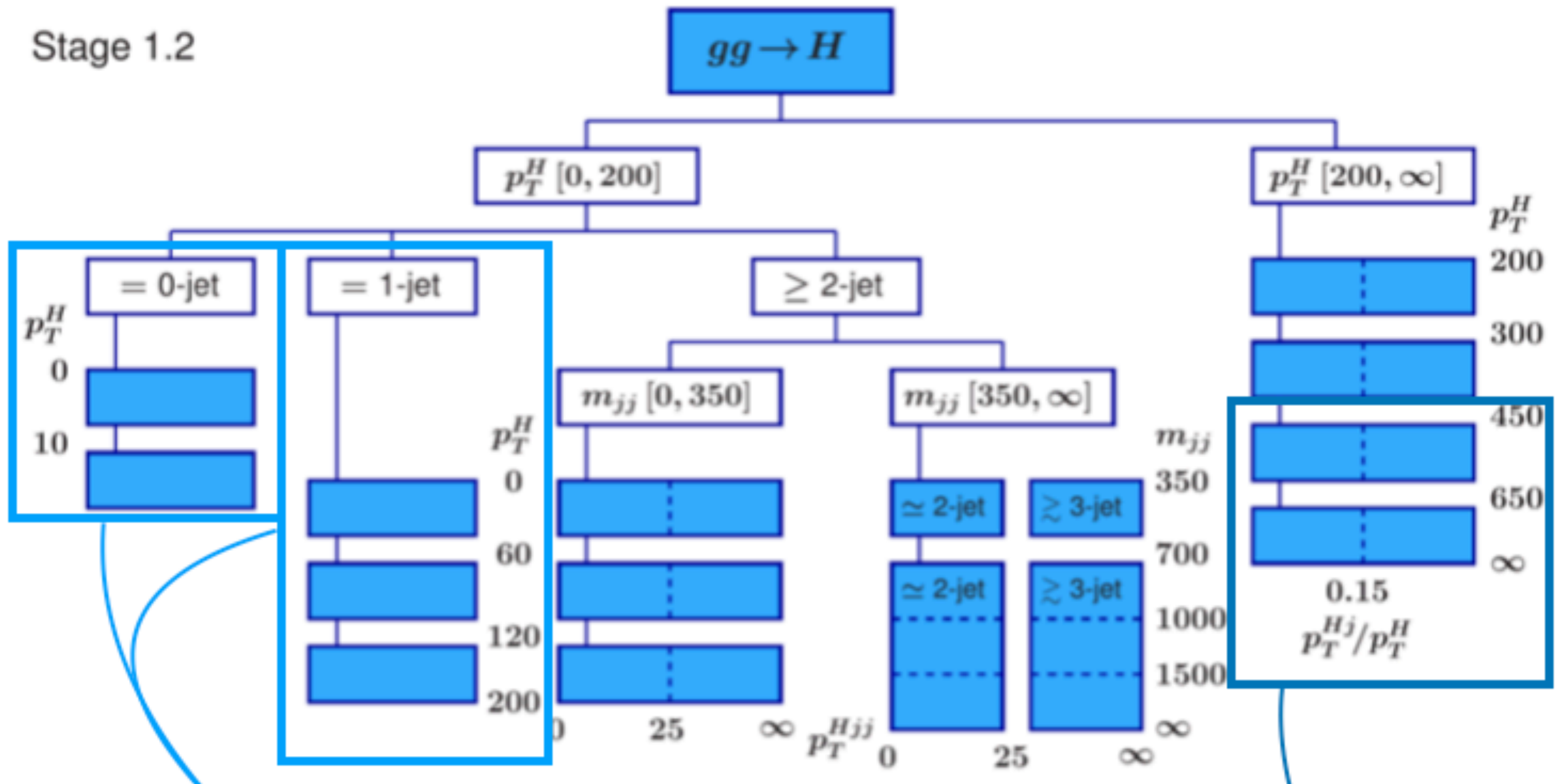


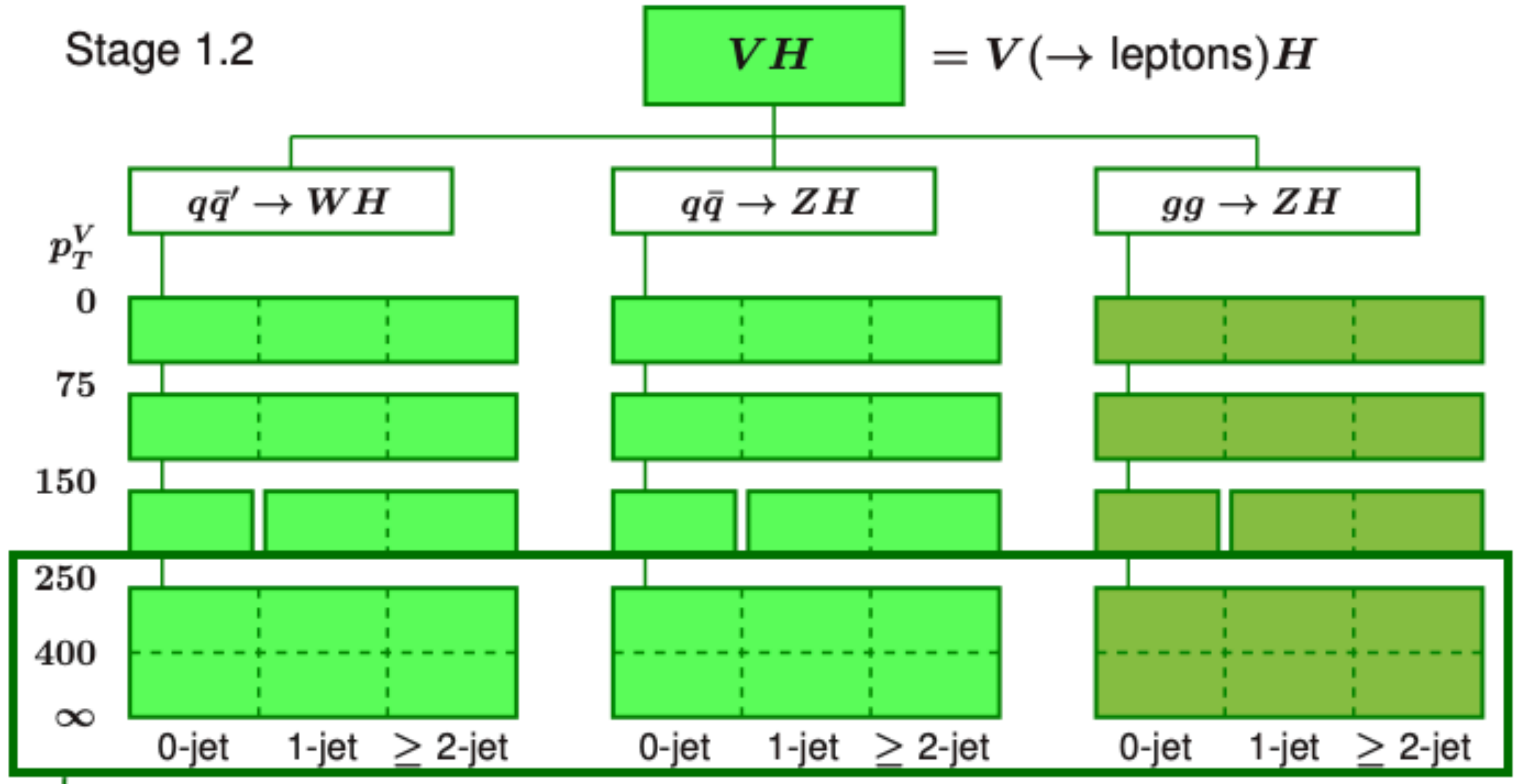
CMS HIG-19-010

ATLAS HIGG-2020-20

It has been a long road until now

Towards STXS 1.3: more bins





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

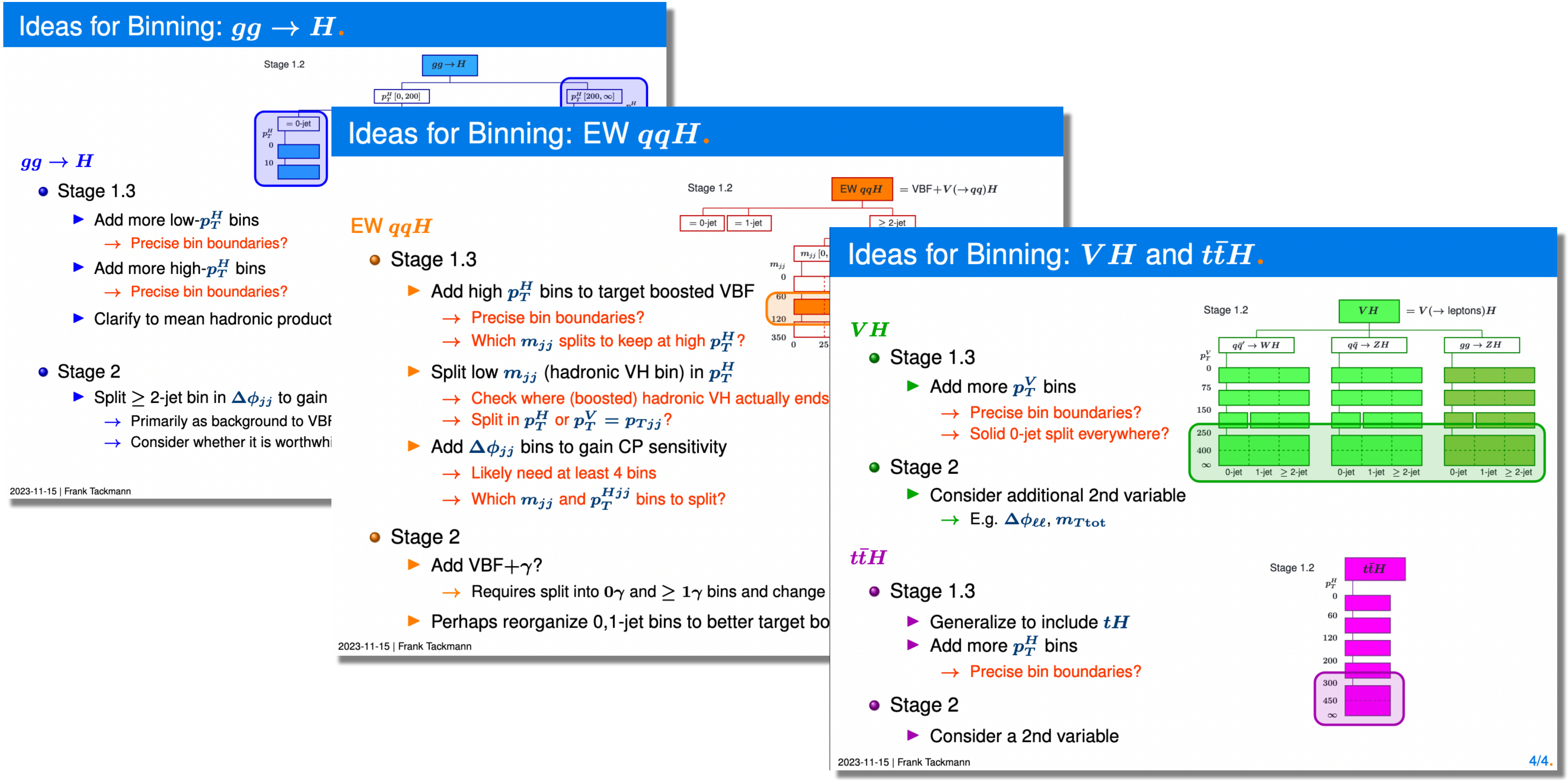
Possibly include **additional bins** at **pT(V) > 250/400 GeV** to enhance BMS sensitivity

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

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

19th LHCHWG Workshop, 28/11/22 - M. Bonanomi **15**

What we had in mind



What we had in mind

Ideas for Binning:

$gg \to H$

- Stage 1.3
  - Add more low-p_T^H
    - → Precise bin bou
  - Add more high-p_T^H
    - → Precise bin bou
  - Clarify to mean ha
- Stage 2
  - Split $\geq$ 2-jet bin in
    - → Primarily as ba
    - → Consider wheth

2023-11-15 | Frank Tackmann

WG2: Higgs Properties subgroup meetings

June 2024

10 Jun STXS 1.3 finalization - additional studies

March 2024

27 Mar STXS 1.3 finalization - additional studies

February 2024

29 Feb STXS 1.3 finalization (take 2)

15 Feb [postponed] STXS 1.3 finalization (take 2)

December 2023

14 Dec STXS 1.3 finalization

September 2023

27 Sept WG2: CP violation in ttH interactions

26 Sept WG2 WG3 joint meeting on CP violation in extended Higgs sector

25 Sept WG2 STXS in Decay discussion

Where do we stand now

Why STXS Stage 1.3?

- STXS Stage 1.2 was specifically designed for Run-II. When looking at the current status of experimental results (especially combinations of different channels), it is clear that higher granularity is needed
- Need to move to a solid base for Run-III, increasing granularity of Stage 1.2
- Need to target EFT and CPV with more specific bins and observables

On which basis to build?

- Increase granularity, but baring in mind that Run-III stat ~ Run-II stat
- STXS 1.3 should be an incremental change, ideally backward compatible, and not pose a large workload on the analyses that use it
- Backward compatibility to make possible combination of results (thinking about the different c.o.m energies) and/or interpretations if the experiments wish to do so. More drastic changes to be introduced in Stage 2 (for HL-LHC era)

From STXS 1.2: ttH

Increase granularity and start measuring all STXS bins in ttH

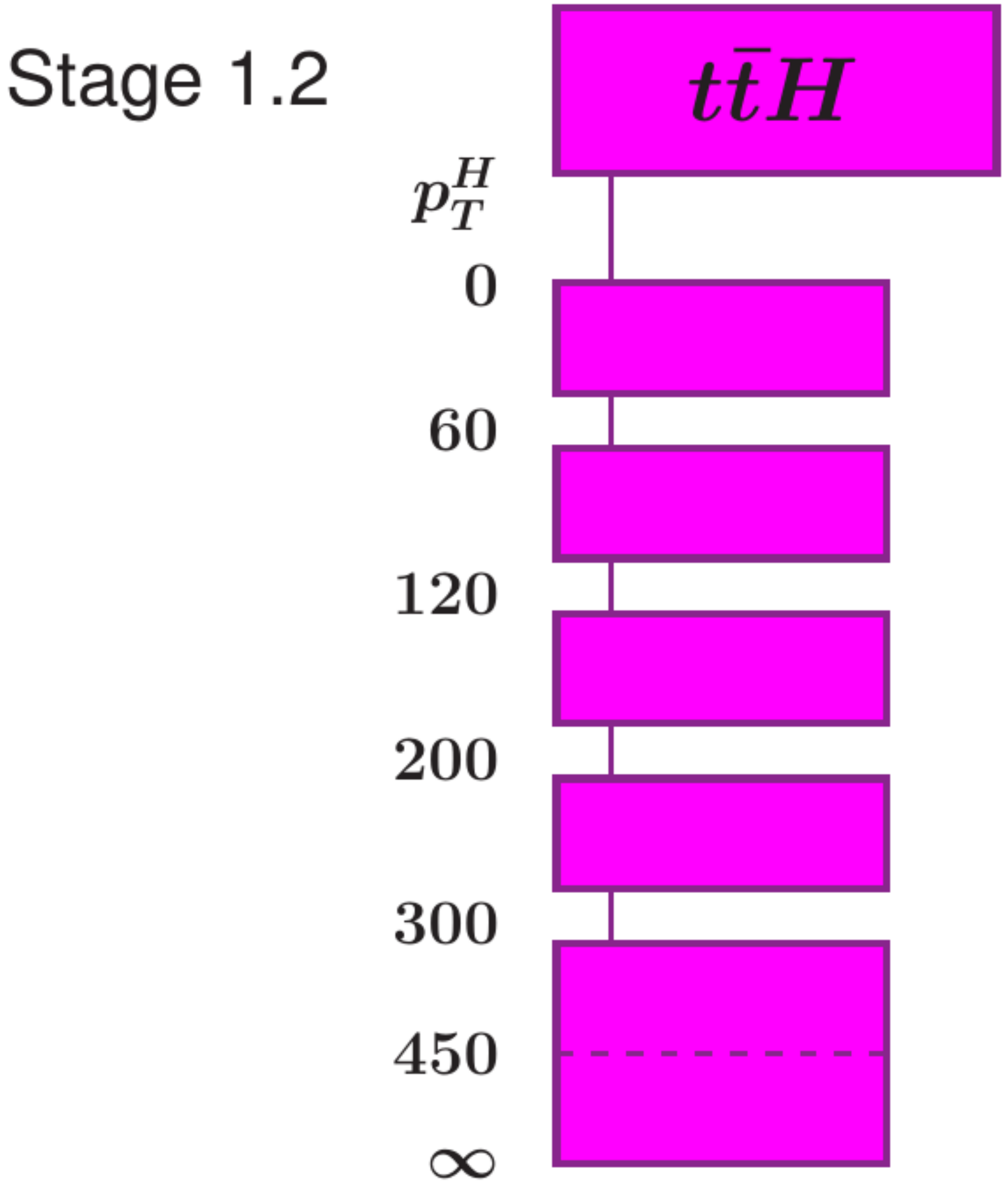
- Enough statistics available
- Solid splittings at pT(H) = 450 GeV
- Additional bin at pT(H) = 650 GeV

Start measuring tH independently

- Independent (inclusive) tH bins, dashed tWH, tHq

For STXS Stage 2:

- Introduce splitting in CP-sensitive observables



To STXS 1.3: ttH

Increase granularity and start measuring all STXS bins in ttH

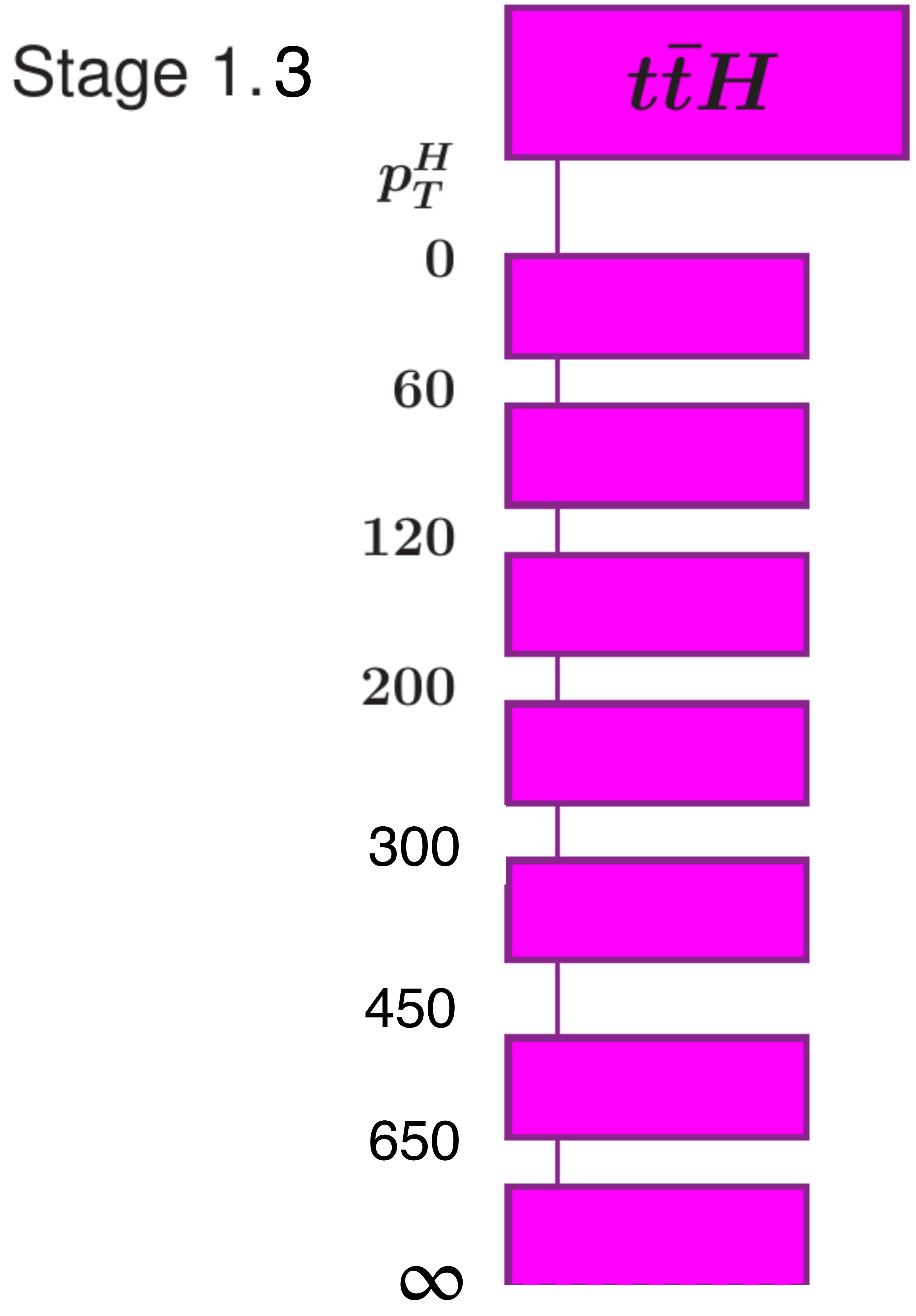
- Enough statistics available
- Solid splittings at pT(H) = 450 GeV
- Additional bin at pT(H) = 650 GeV

Start measuring tH independently

- Independent (inclusive) tH bins, dashed tWH, tHq

For STXS Stage 2:

- Introduce splitting in CP-sensitive observables



From STXS 1.2: V(lep)H

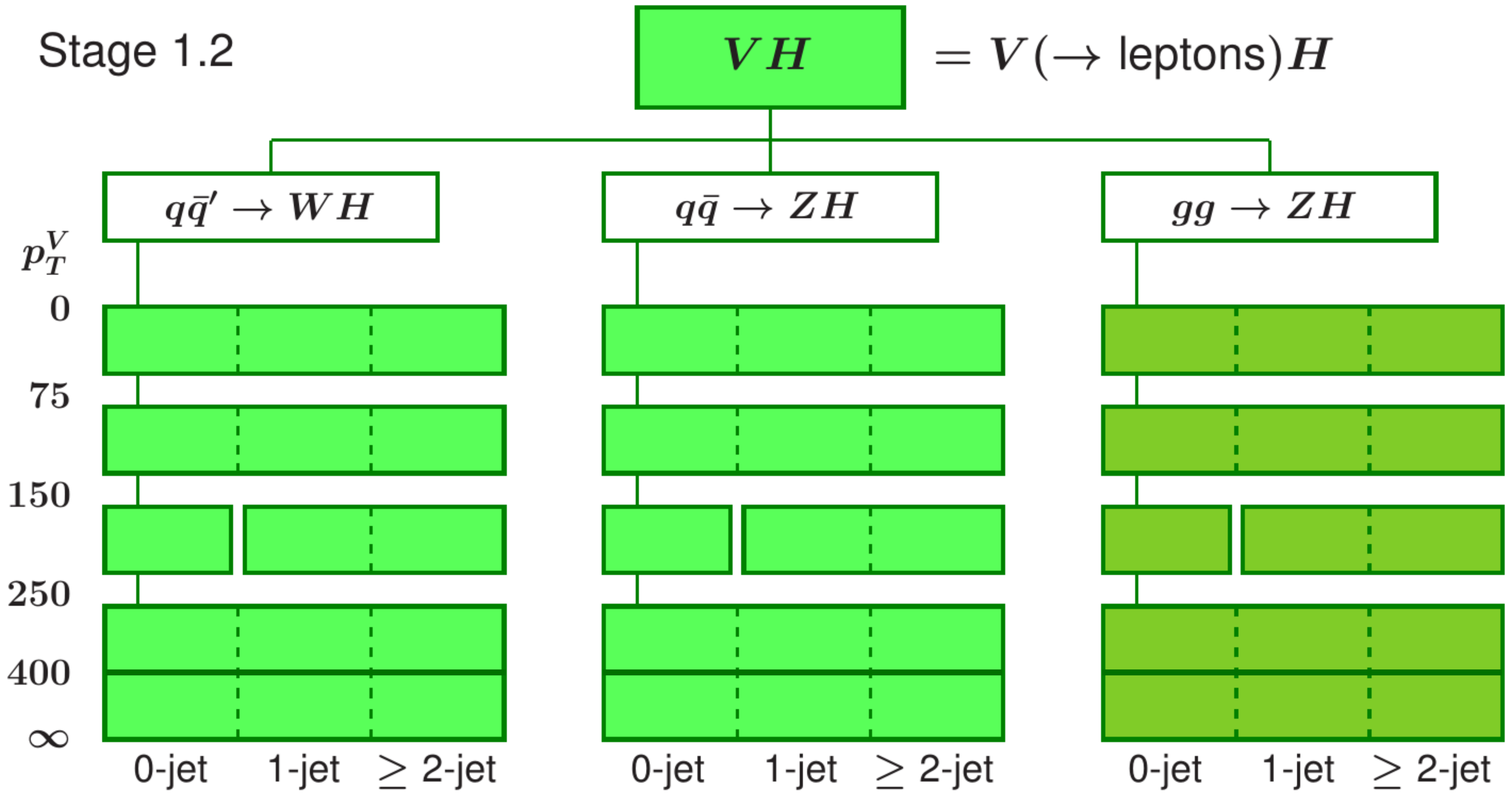
Increase granularity and measure all bins

- Enough statistics available
- Solid splittings at pT(H) = 400 GeV
- Additional bin at pT(H) = 600 GeV

Start measuring dashed bins

For STXS Stage 2:

- Introduce splitting in CP-sensitive observables



To STXS 1.3: V(lep)H

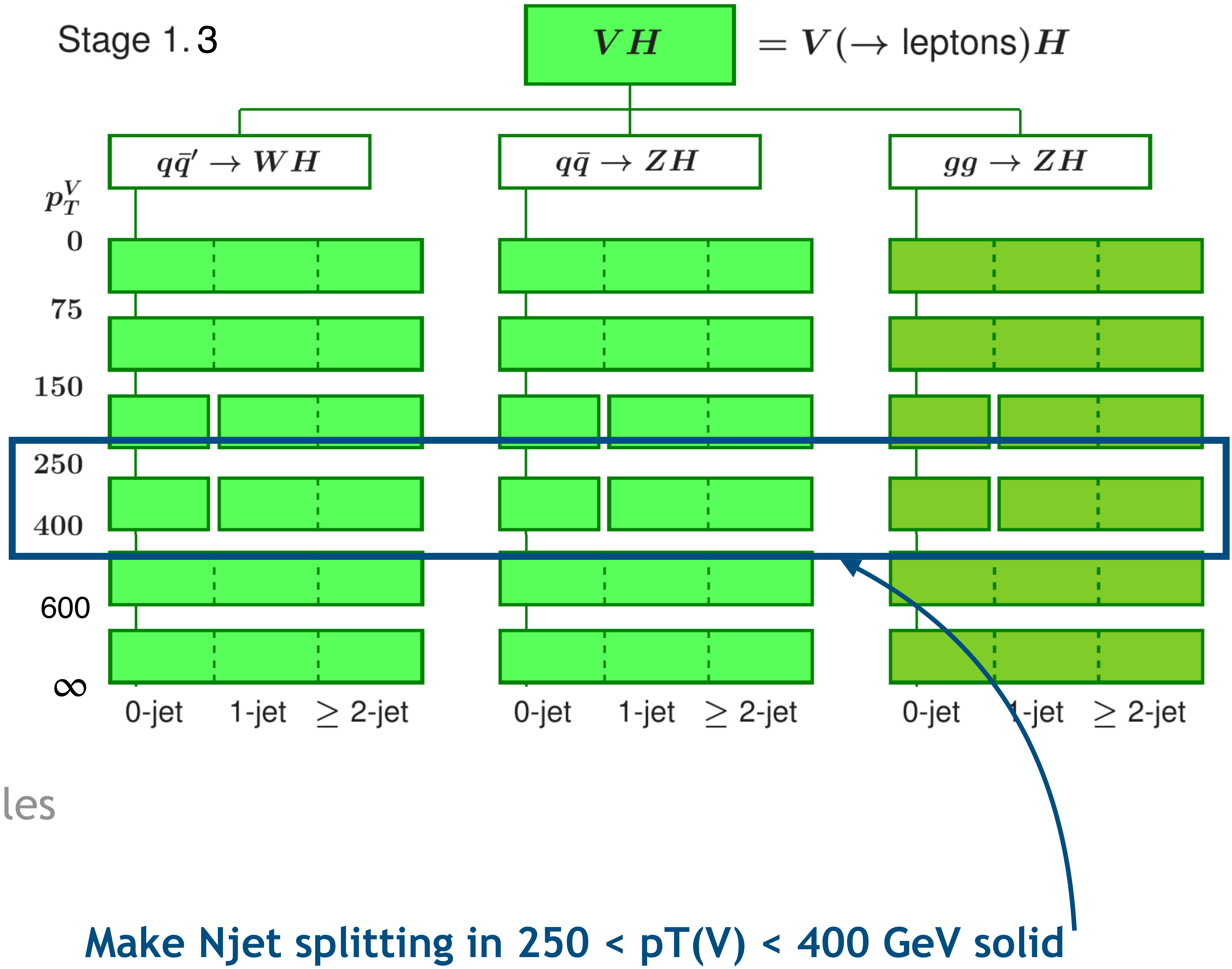
Increase granularity and measure all bins

- Enough statistics available
- Solid splittings at pT(H) = 400 GeV
- Additional bin at pT(H) = 600 GeV

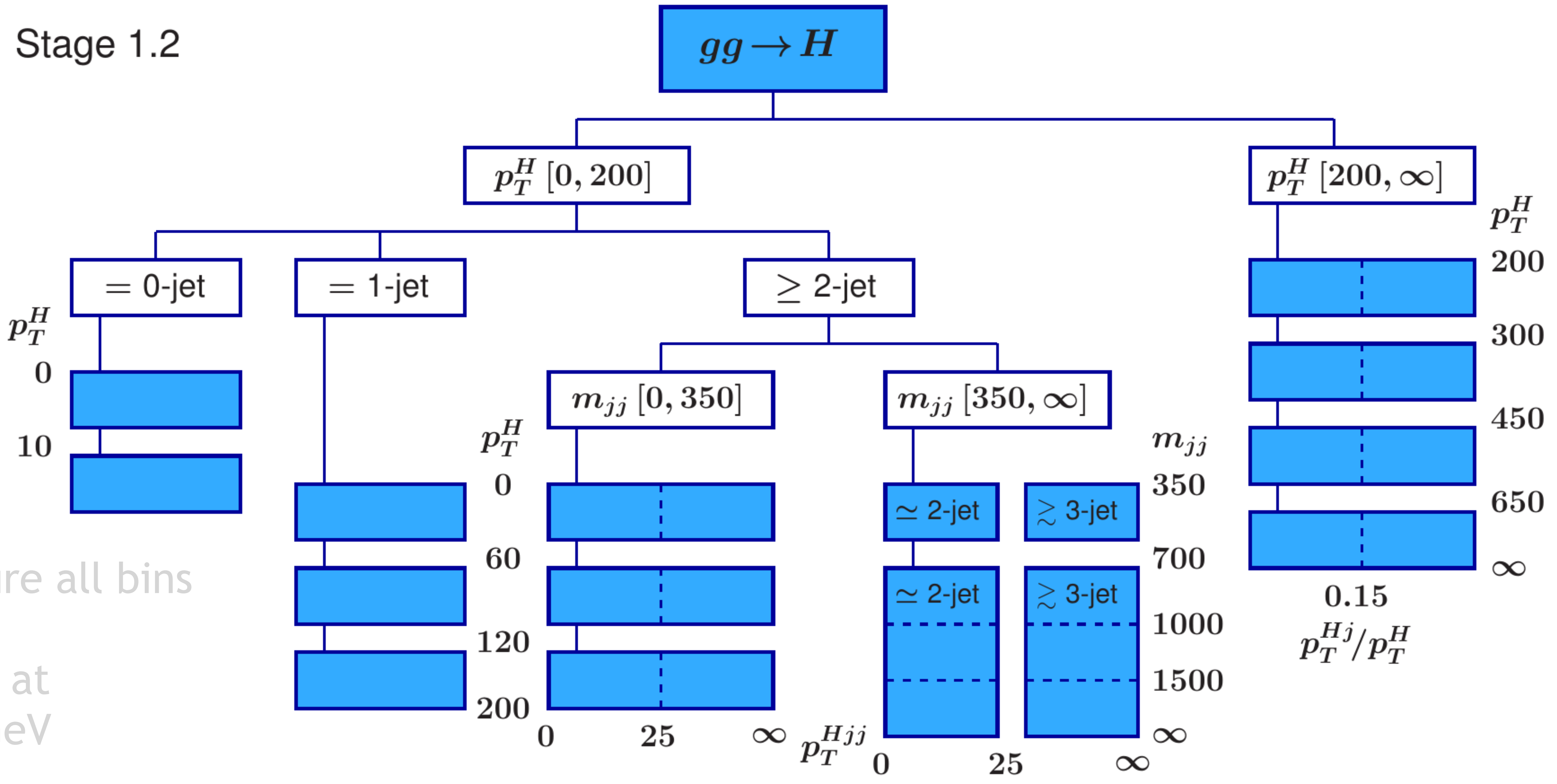
Start measuring dashed bins

For STXS Stage 2:

- Introduce splitting in CP-sensitive observables



From STXS 1.2: ggH



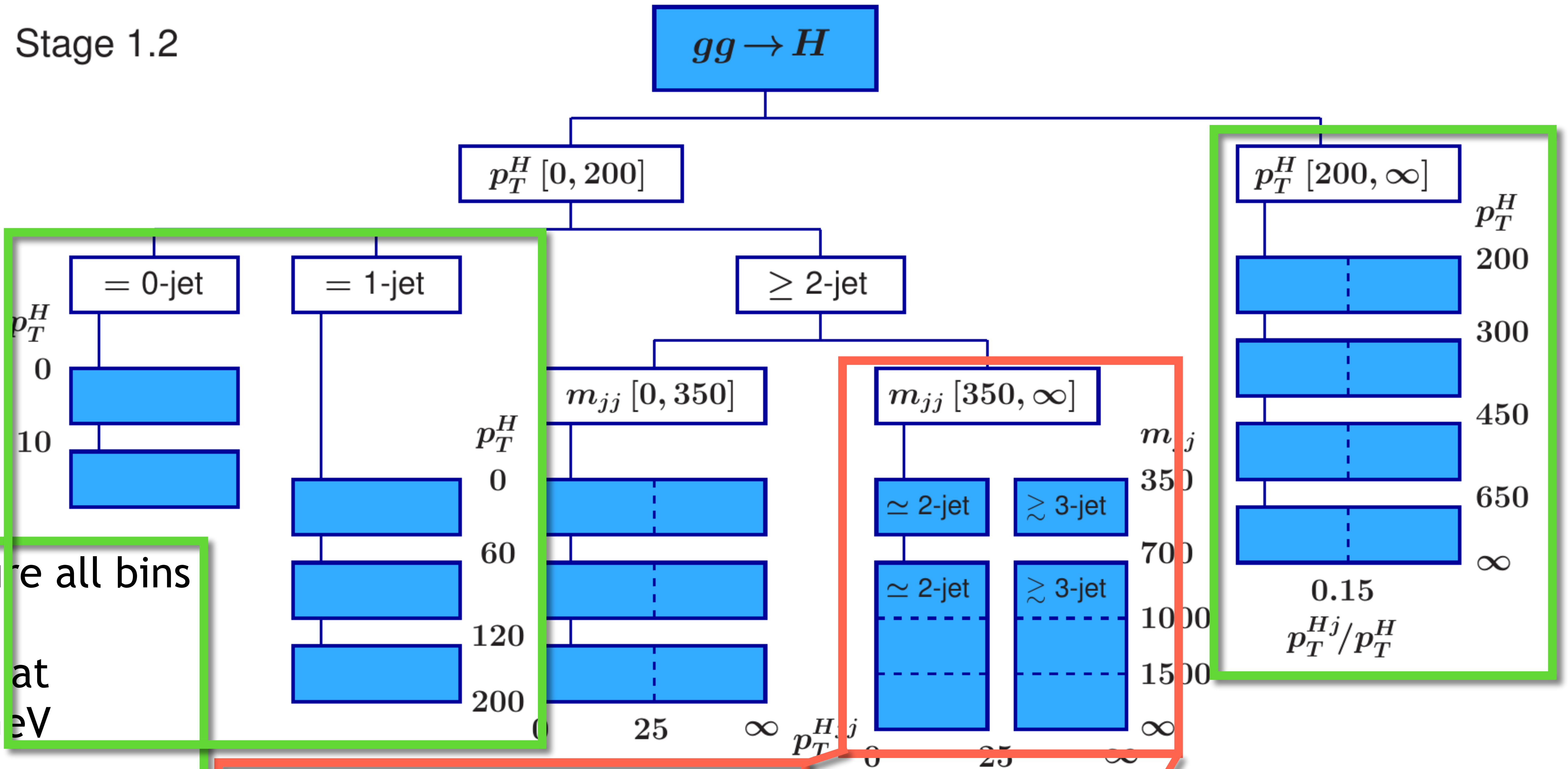
Increase granularity and measure all bins

- **0 jet bin:** pT(H) splitting at 0, 5, 10, 15, 20, 25, 30 GeV
- **1 jet bin:** add splitting at pT(H) = 30 GeV
- **pT(H) > 200 Gev:** add splitting at 1 TeV

Start probing CP-sensitive observables

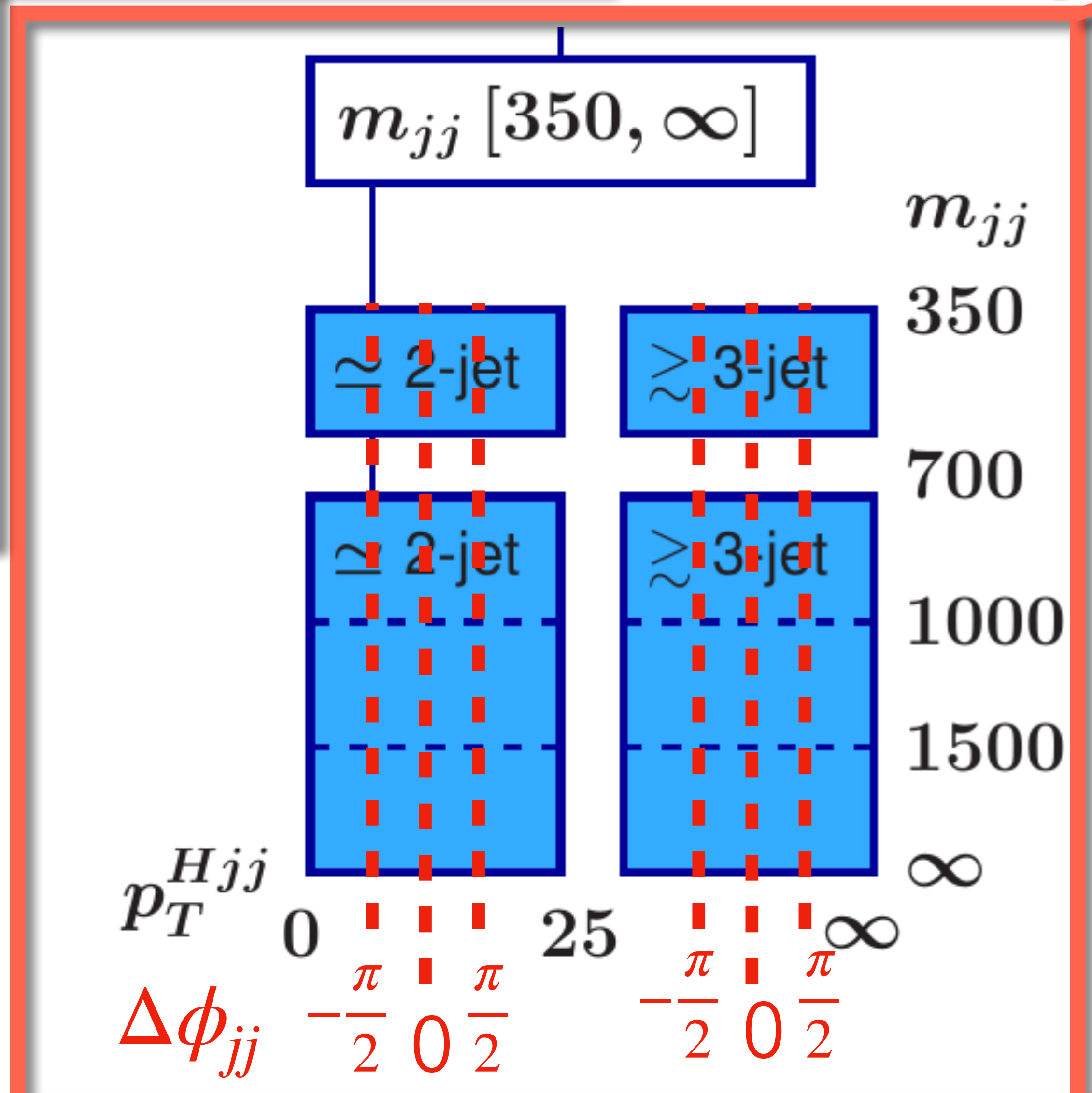
- **Dashed boundaries in $\Delta\phi_{jj}$** at $[-\pi, \frac{\pi}{2}, 0, \frac{\pi}{2}, \pi]$
- Leave p_T^{Hjj} **and nJet bins**

To STXS 1.3: ggH



Increase granularity and measure all bins

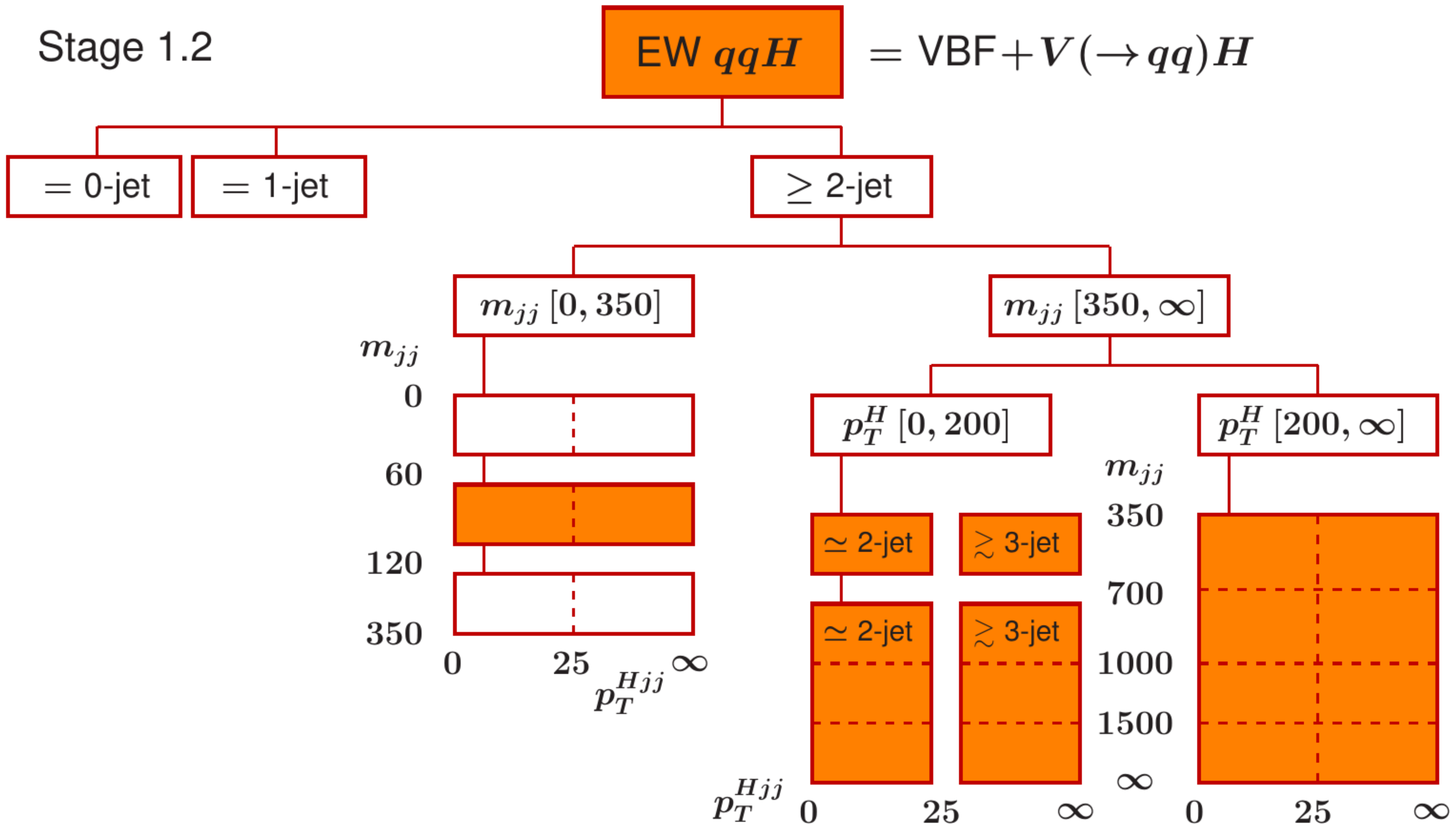
- **0 jet bin:** pT(H) splitting at 0, 5, 10, 15, 20, 25, 30 GeV
- **1 jet bin:** add splitting at pT(H) = 30 GeV
- **pT(H) > 200 Gev:** add splitting at 1 TeV



Start probing CP-sensitive observables

- **Dashed boundaries in $\Delta\phi_{jj}$** at $[-\pi, \frac{\pi}{2}, 0, \frac{\pi}{2}, \pi]$
- **Leave $p_T^{H_{jj}}$ and nJet bins**

From STXS 1.2: qqH



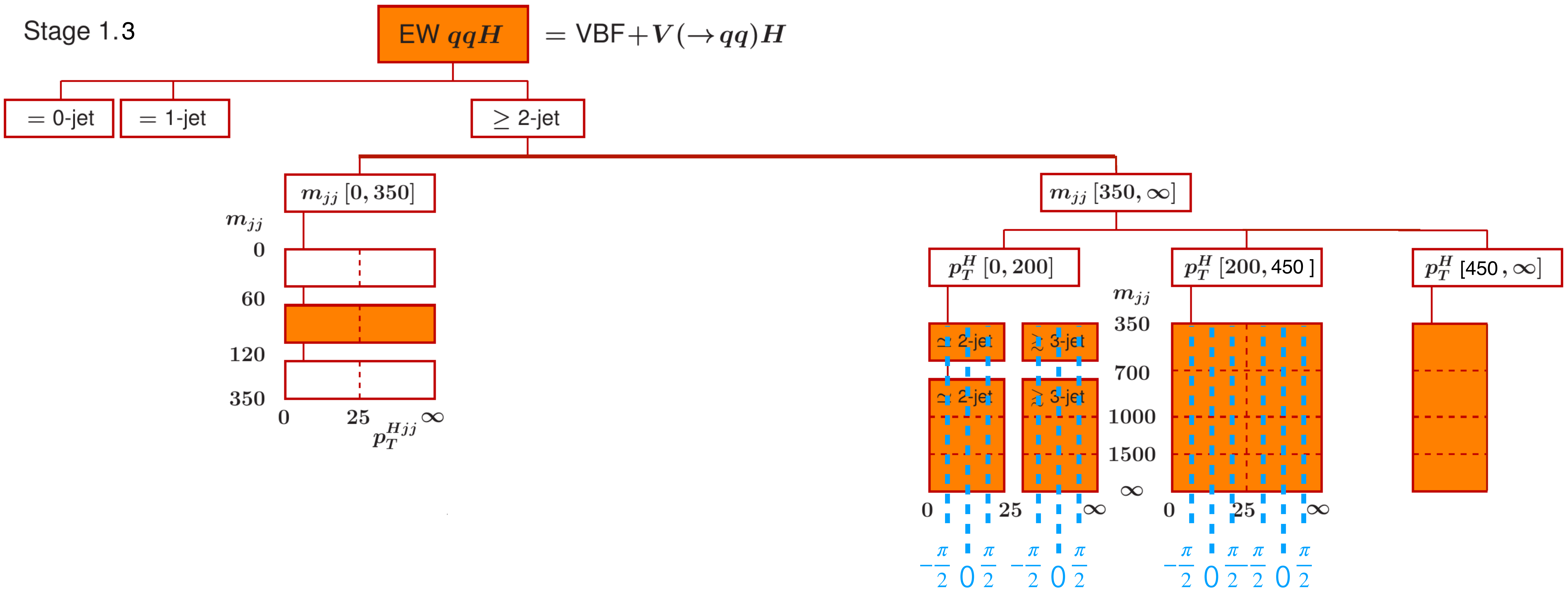
Extend granularity at high pT in $m_{jj} > 350$ GeV

- Introduce a bin splitting at pT(H) = 450 GeV
- In the bin at pT(H) > 450 GeV, leave dashed m_{jj} bins without any p_T^{Hjj} splitting

Start probing CP-sensitive observables up to 450 GeV

- Dashed boundaries in $\Delta\phi_{jj}$ at $[-\pi, \frac{\pi}{2}, 0, \frac{\pi}{2}, \pi]$

To STXS 1.3: qqH



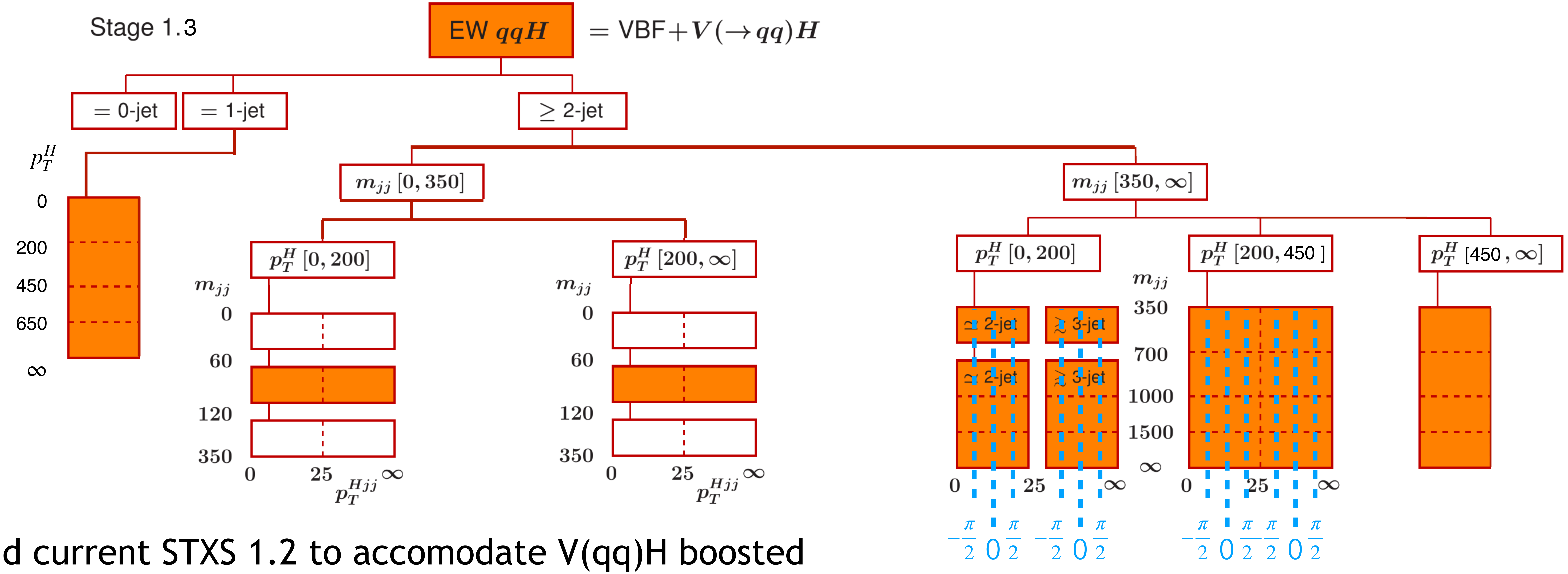
Extend granularity at high pT in $m_{jj} > 350$ GeV

- **Introduce a bin splitting at pT(H) = 450 GeV**
- **In the bin at pT(H) > 450 GeV, leave dashed m_{jj} bins without any p_T^{Hjj} splitting**

Start probing CP-sensitive observables up to 450 GeV

- **Dashed boundaries in $\Delta\phi_{jj}$ at $[-\pi, \frac{\pi}{2}, 0, \frac{\pi}{2}, \pi]$**

STXS 1.3: qqH - boosted topology



Extend current STXS 1.2 to accomodate V(qq)H boosted

- **1 jet bin:** split in pT(H) at [0, 200, 450, 650] GeV
- m_{jj} [0,350] **bin:** split in pT(H) [0,200] and [200,∞]
  (Maintain the current p_T^{Hjj} and m_{jj} dashed bins)

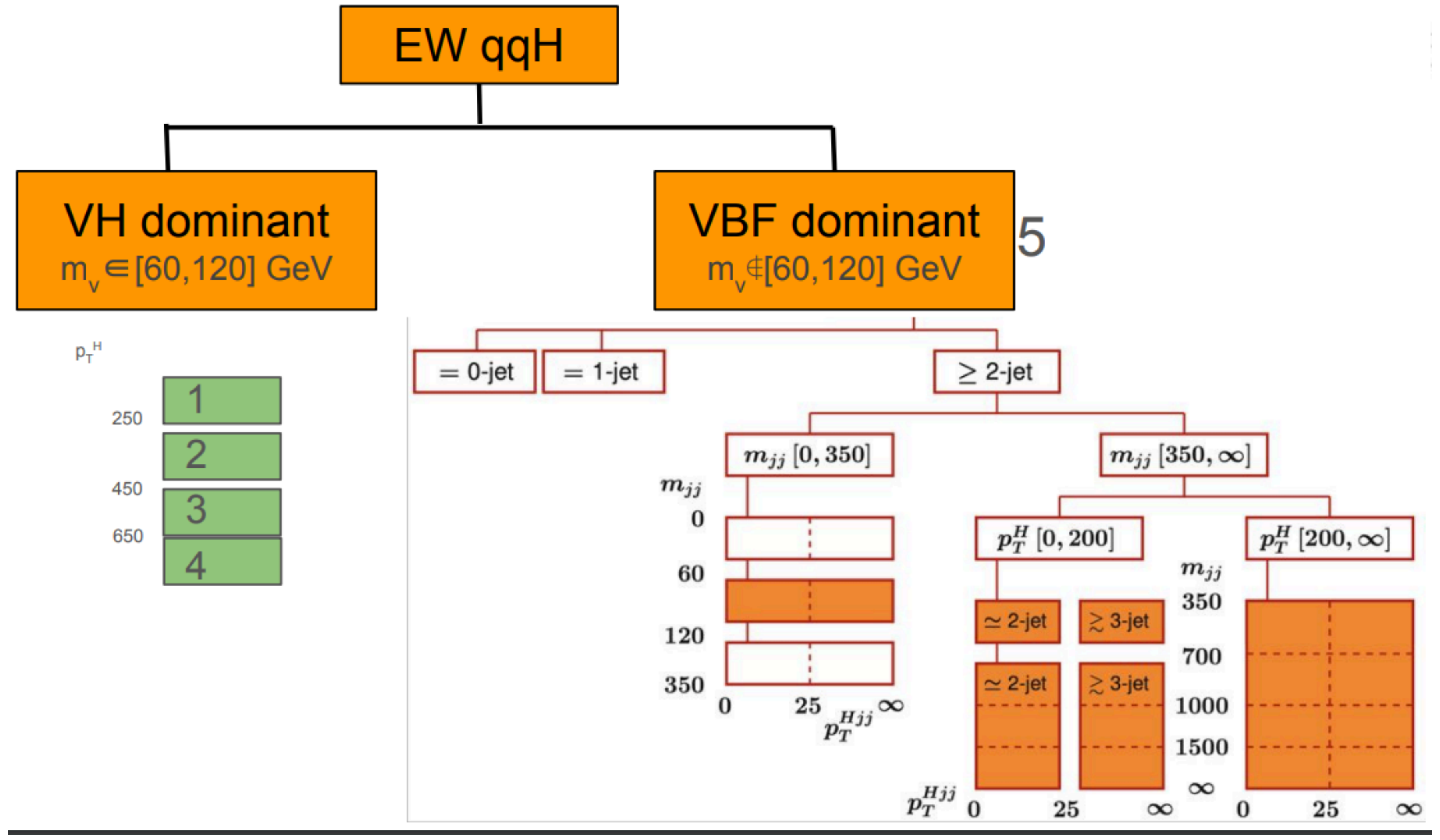
Pros: Still backwards compatible with Stage 1.2, essentially no impact on VBF

Cons: Only captures ~ 50% of boosted V(qq)H

STXS 1.3: qqH - boosted topology

Alternative proposal to capture events with large-radius jets

- Split qqH STXS into two bins, targeting V(qq)H and VBF
- Split as a function of m_V, thus enhancing sensitivity to fat jets



$$m_V = \begin{cases} m(j_1), & \text{No. jet} = 1 \\ \max(m(j_1), m(j_2)), & \text{No. jet} > 1,\ \max(m(j_1), m(j_2)) > 60\ \text{GeV} \\ m(j_1 j_2), & \text{No. jet} > 1,\ \max(m(j_1), m(j_2)) < 60\ \text{GeV} \end{cases}$$

Pros:

- Captures > 95% of the V(qq)H boosted topology
- More cumbersome, but still backwards compatible, since VBF contamination in VH-dominant bins is less than 10%

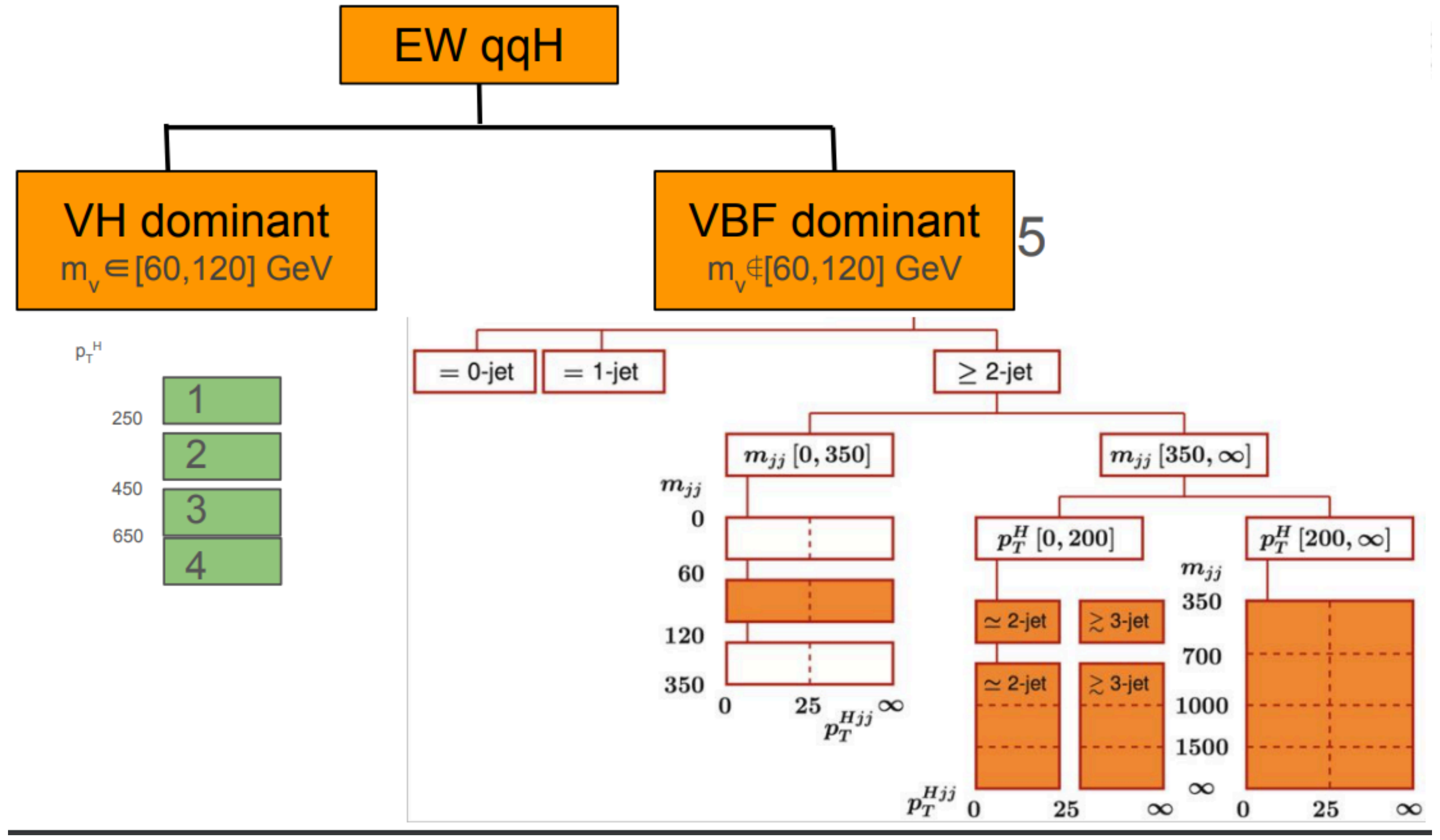
Cons:

- Introduction of a new (and composite) observable
- Top-level splitting of the qqH bin could (needlessly) increase complexity for non-boosted analyses

STXS 1.3: qqH - boosted topology

Alternative proposal to capture events with large-radius jets

- Split qqH STXS into two bins, targeting V(qq)H and VBF
- Split as a function of m_V, thus enhancing sensitivity to fat jets



$$m_V = \begin{cases} m(j_1), \text{ No. jet} = 1 \\ \max(m(j_1), m(j_2)), \text{ No. jet} > 1, \max(m(j_1), m(j_2)) > 60 \text{ GeV} \\ m(j_1 j_2), \text{ No. jet} > 1, \max(m(j_1), m(j_2)) < 60 \text{ GeV} \end{cases}$$

Pros:

- Captures > 95% of the V(qq)H boosted topology
- More cumbersome, but still backwards compatible, since VBF contamination in VH-dominant bins is less than 10%

Cons:

- Introduction of a new (and composite) observable
- Top-level splitting of the qqH bin could (needlessly) increase complexity for non-boosted analyses

Final proposal

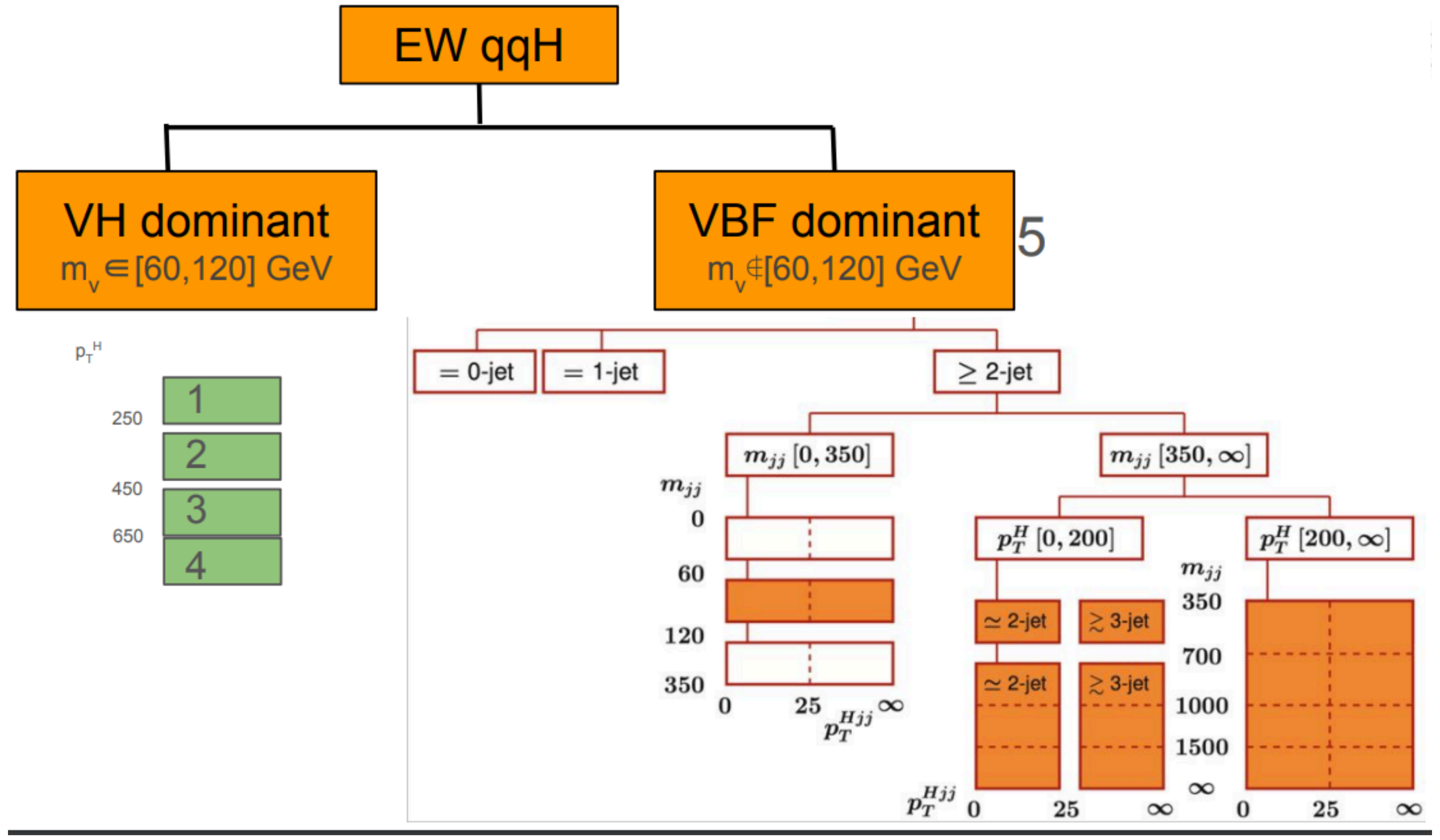
Use Option 1 (cf. Slide 15) for STXS Stage 1.3

Adopt Option 2 (this slide) for STXS Stage 2.0

Beyond STXS 1.3

Target V(qq)H boosted topology

- Split qqH STXS into two bins, targeting V(qq)H and VBF
- Split as a function of m_V, thus enhancing sensitivity to fat jets



$$m_V = \begin{cases} m(j_1), \text{ No. jet} = 1 \\ \max(m(j_1), m(j_2)), \text{ No. jet} > 1, \max(m(j_1), m(j_2)) > 60 \text{ GeV} \\ m(j_1 j_2), \text{ No. jet} > 1, \max(m(j_1), m(j_2)) < 60 \text{ GeV} \end{cases}$$

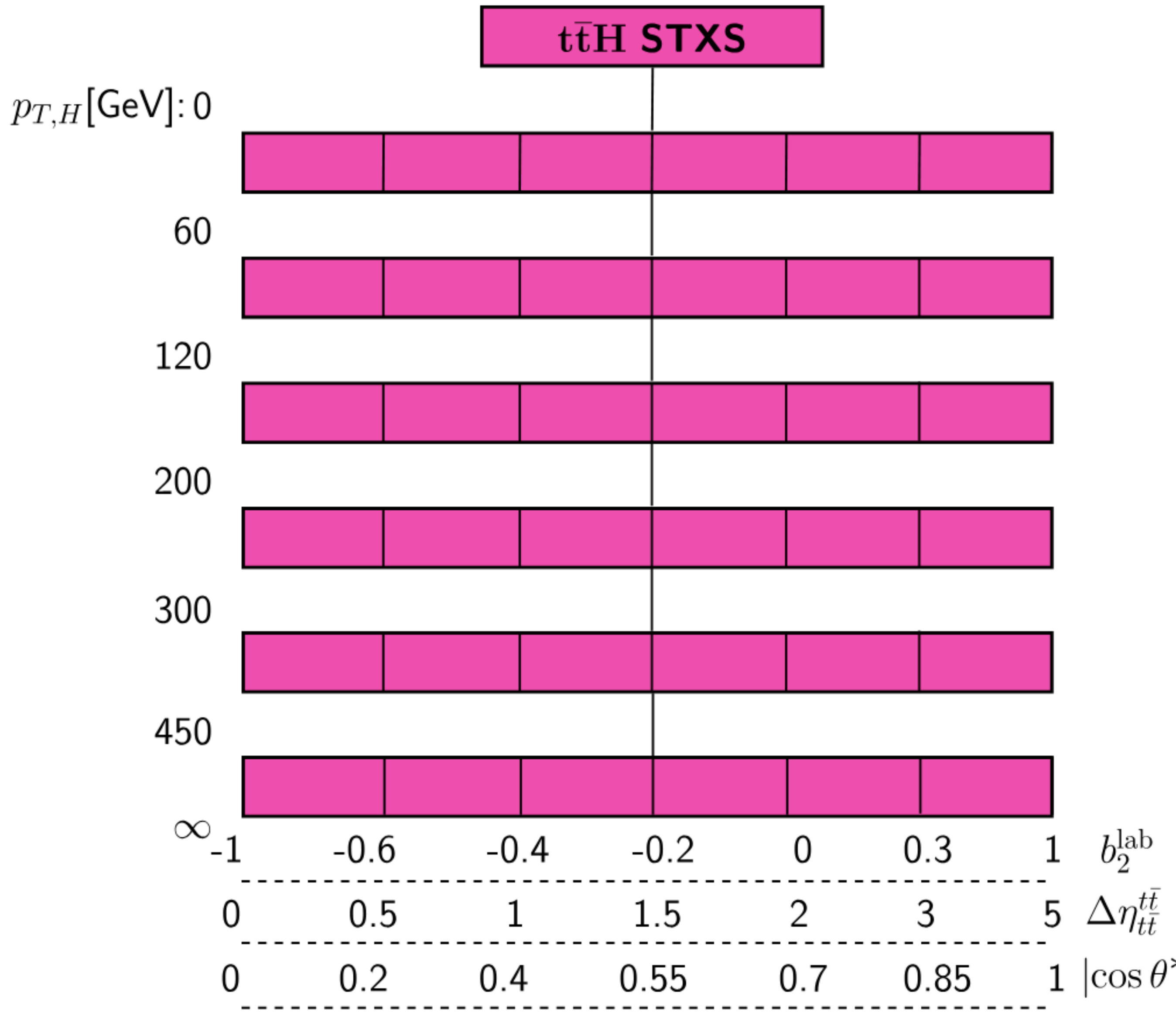


Figure 12: Proposal for an extension of the current STXS binning for the $t\bar{t}H$ production mode. Each bin in $p_{T,H}$ is further split in bins of either $b_2^{\rm lab}$, $\Delta\eta_{t\bar{t}}^{t\bar{t}}$, or $|\cos\theta^*|$.

arXiv:2406.03950

Explore ttH CPV potential

- Extend STXS Stage 1.2 binning with more pT(H) splits
- Include splitting in CP-sensitive observables (e.g. $|\cos(\theta^*)|$, $\Delta\eta_{t\bar{t}}$, b_2^{lab})

Conclusion

After a (more than) year-long of discussions, we are now proposing STXS Stage 1.3 binning!

- Many thanks to all the people involved in the discussions and to those who provided inputs and contributed to the studies
- We would like to make this proposal official and document it in a LHCHWG note
- If agreed upon, the proposal should be followed up by the experiments for the calculation of the uncertainties
- The studies for Stage 1.3 (LHC Run-III) already set the bases for the future developments of Stage 2.0 (HL-LHC), which are already ongoing

In parallel, we are working on the finalisation of the uncertainty note for STXS Stage 1.2, which will used as the official reference for the method to compute Stage 1.3 uncertainties

BACKUP SLIDES

Beyond STXS 1.3

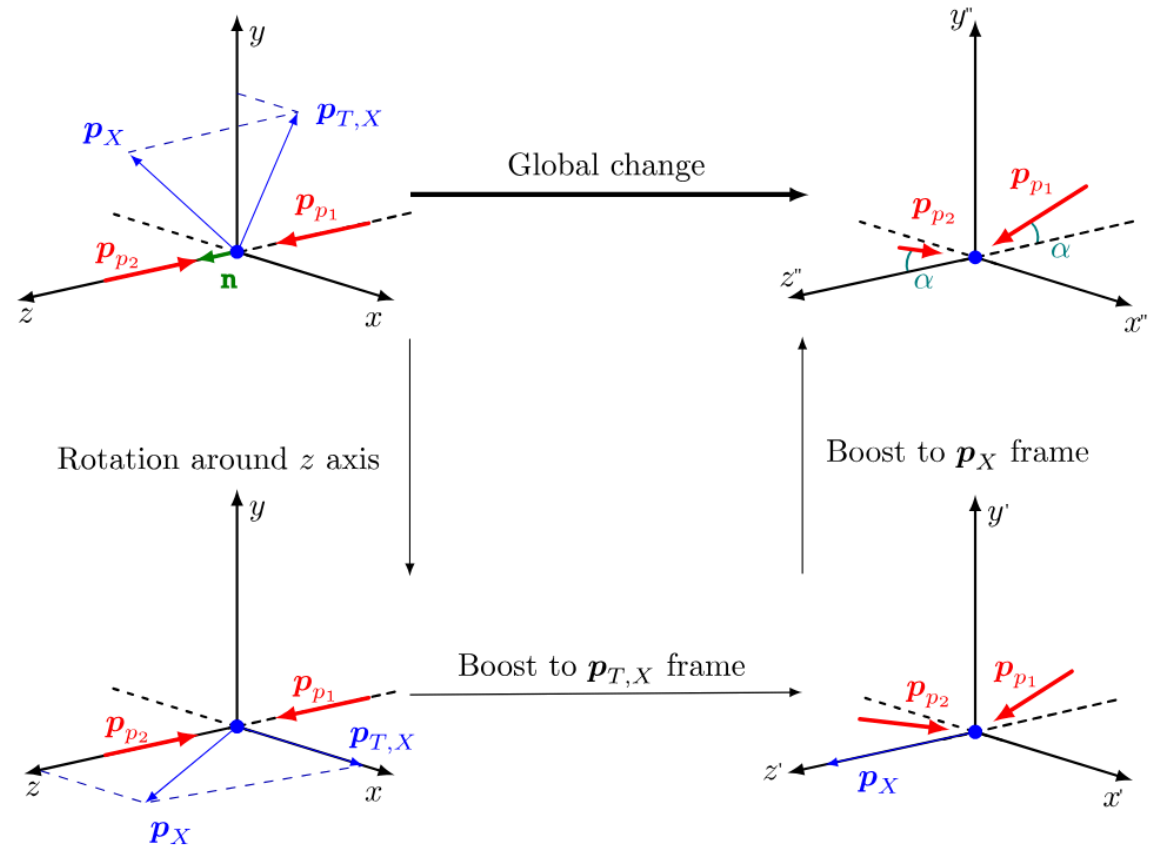


Figure 1: Sketch illustrating the rest frame definition adopted in this work. The rest frame X is shown here, defined by $\boldsymbol{p}_X = \boldsymbol{0}$, where $X = H,\, t\bar{t},\, t\bar{t}H$.

observable	definition	frame	reference
$p_{T,H}$	-	lab, $t\bar{t}$, $t\bar{t}H$	-
$\Delta\eta_{t\bar{t}}$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$	-
$\Delta\phi_{t\bar{t}}$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$	-
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	frame-invariant	-
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant	-
$\lvert\cos\theta^*\rvert$	$\frac{\lvert\boldsymbol{p}_t\cdot\boldsymbol{n}\rvert}{\lvert\boldsymbol{p}_t\rvert\cdot\lvert\boldsymbol{n}\rvert}$	$t\bar{t}$	[74, 91]
b_1	$\frac{(\boldsymbol{p}_t\times\boldsymbol{n})\cdot(\boldsymbol{p}_{\bar{t}}\times\boldsymbol{n})}{p_{T,t}p_{T,\bar{t}}}$	all	[82]
b_2	$\frac{(\boldsymbol{p}_t\times\boldsymbol{n})\cdot(\boldsymbol{p}_{\bar{t}}\times\boldsymbol{n})}{\lvert\boldsymbol{p}_t\rvert\;\lvert\boldsymbol{p}_{\bar{t}}\rvert}$	all	[82]
b_3	$\frac{p_t^x\;p_{\bar{t}}^x}{p_{T,t}p_{T,\bar{t}}}$	all	[82]
b_4	$\frac{p_t^z\;p_{\bar{t}}^z}{\lvert\boldsymbol{p}_t\rvert\;\lvert\boldsymbol{p}_{\bar{t}}\rvert}$	all	[82]
ϕ_C	$\arccos\left(\frac{\lvert(\boldsymbol{p}_{p_1}\times\boldsymbol{p}_{p_2})\cdot(\boldsymbol{p}_t\times\boldsymbol{p}_{\bar{t}})\rvert}{\lvert\boldsymbol{p}_{p_1}\times\boldsymbol{p}_{p_2}\rvert\;\lvert\boldsymbol{p}_t\times\boldsymbol{p}_{\bar{t}}\rvert}\right)$	H	[84]

Table 1: Overview of the $\mathcal{CP}$-sensitive observables considered in this work, including their definition, the rest frames in which they are analysed, and references where they are discussed in more detail.

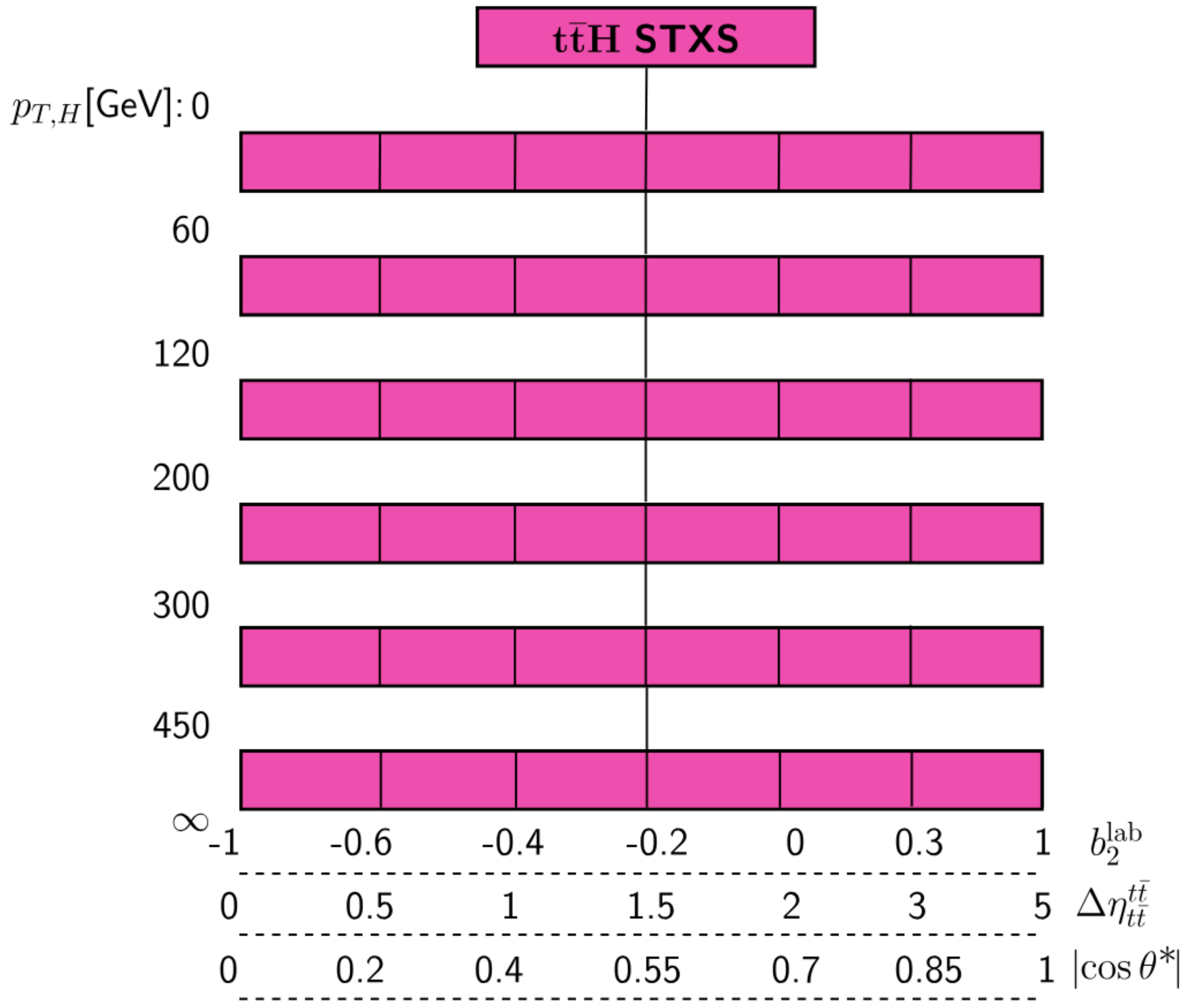


Figure 12: Proposal for an extension of the current STXS binning for the $t\bar{t}H$ production mode. Each bin in $p_{T,H}$ is further split in bins of either $b_2^{\rm lab}, \Delta\eta_{t\bar{t}}^{t\bar{t}}$, or $\lvert\cos\theta^*\rvert$.

arXiv:2406.03950

Explore ttH CPV potential

- Extend STXS Stage 1.2 binning with more pT(H) splits
- Include splitting in CP-sensitive observables (e.g. $\lvert\cos(\theta^*)\rvert$, $\Delta\eta_{t\bar{t}}$, b_2^{lab})