Higgs boson differential and STXS measurements

Bosonic channels

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On behalf of the **CMS collaboration**

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Laboratoire Leprince-Ringuet

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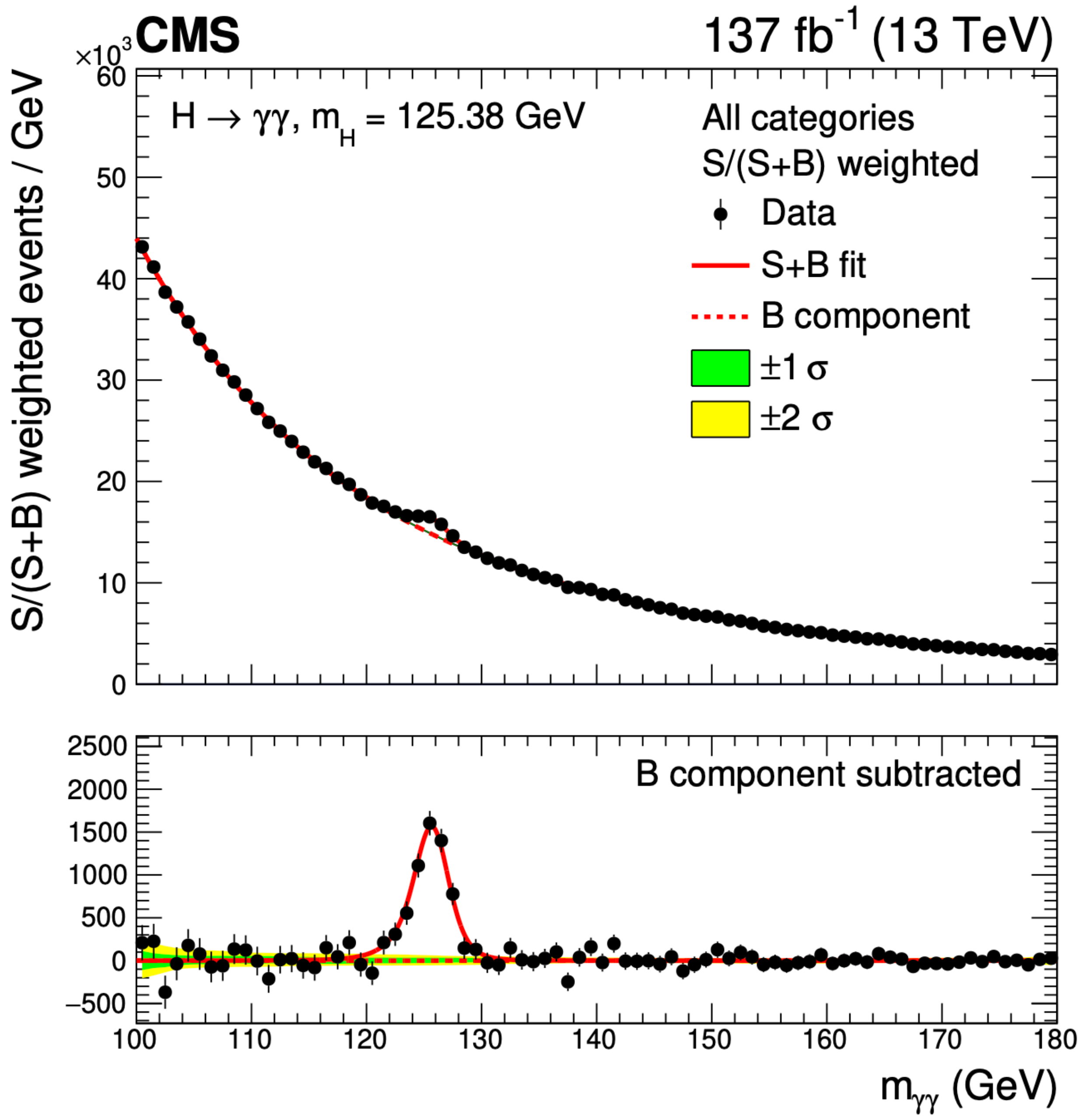
Decay channels

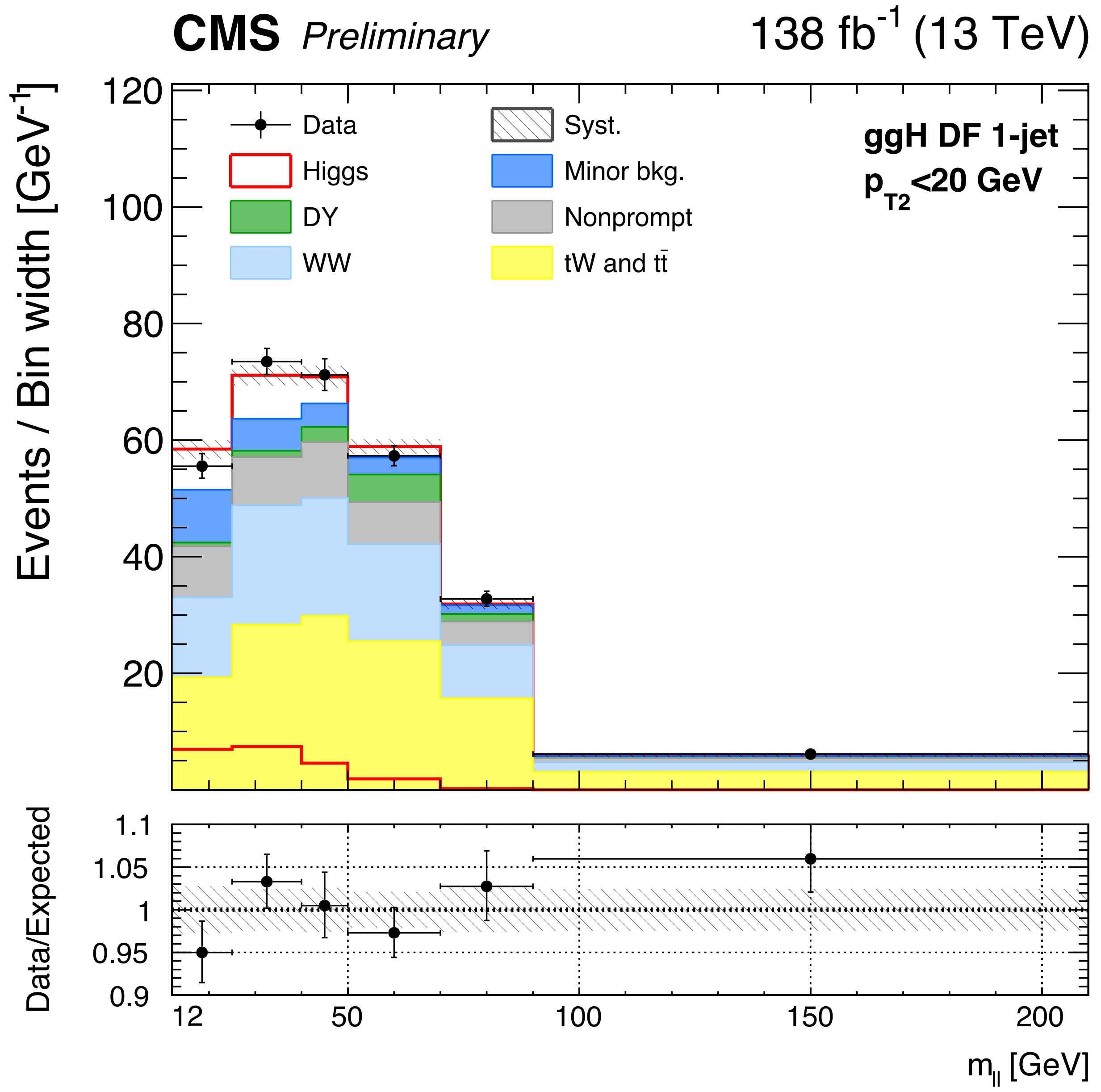
$H \rightarrow \gamma\gamma$

- **Clean and clear signal signature**: two reconstructed isolated photons
- **Narrow peak** over **smoothly falling background** (excellent photon energy resolution)
- *Backgrounds: QCD $\gamma\gamma$ production, γ+jet, jet-jet*



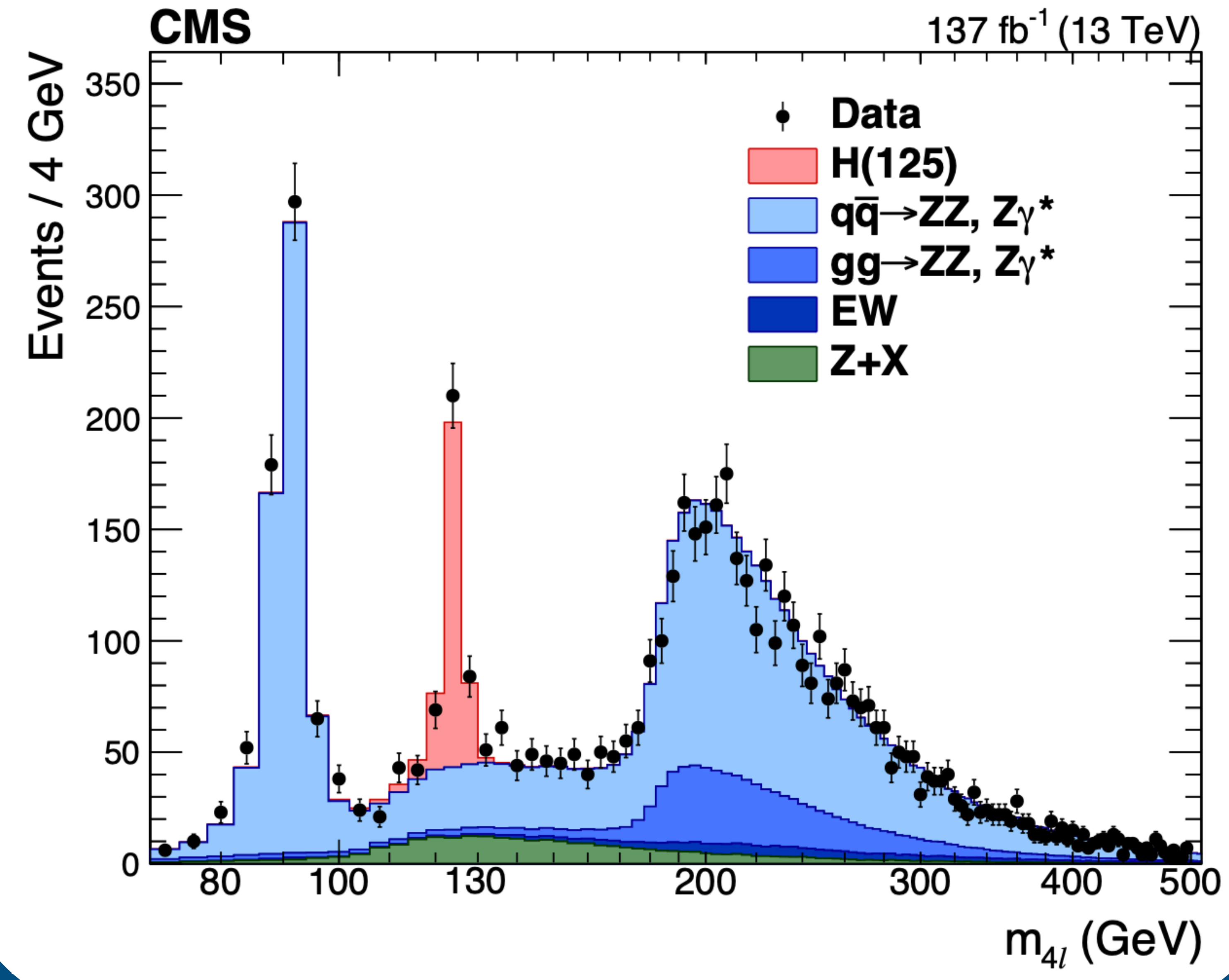
$H \rightarrow WW$

- **Second highest BR** (~ 21.5%)
- Reconstruction of the Higgs boson mass from visible decay products is impossible due to **neutrinos**
- *Backgrounds: W^+W^-, $t\bar{t} + tW$, $\tau^+\tau^-$, minor bkgs ($W\gamma$, diboson, W^+W^-+2jets, …), and non-prompt leptons*



$H \rightarrow ZZ^* \rightarrow 4\ell$

- **Narrow peak** over **flat background**
- **Small BR** (~0.028%)
- Three different final states: 2e2μ, 4e, 4μ
- *Backgrounds: non-resonant ZZ production ($q\bar{q} \rightarrow ZZ$, $gg \rightarrow ZZ$), EW processes (ZZZ, WZZ, WWZ, $t\bar{t}Z$, …), and Z+X (Z+jets, $t\bar{t}$+jets, …)*



$H \to \gamma\gamma$

- **Clean and clear signal signature**: two reconstructed isolated photons
- **Narrow peak** over **smoothly falling background** (excellent photon energy resolution)
- Backgrounds: QCD $\gamma\gamma$ production, γ+jet, jet-jet

$H \to WW$

- **Second highest BR** (~ 21.5%) among decay modes of the Higgs boson
- Presence of **neutrinos** in the final state makes it impossible reconstruct the Higgs boson mass from the visible decay products
- Backgrounds: W^+W^-, $t\bar{t} + tW$, $\tau^+\tau^-$, minor bkgs ($W\gamma$, diboson, W^+W^-+2jets, …), and non-prompt leptons

$H \to ZZ^* \to 4\ell$

- **High S/B** (~2)
- **Narrow peak** over **flat background**
- **Small BR** (~0.028%)
- Three different final states: 2e2μ, 4e, 4μ
- Backgrounds: non-resonant ZZ production ($q\bar{q} \to ZZ$, $gg \to ZZ$), EW processes (ZZZ, WZZ, WWZ, $t\bar{t}Z$, …), and Z+X (Z+jets, $t\bar{t}$+jets, $Z\gamma$+jets, …)

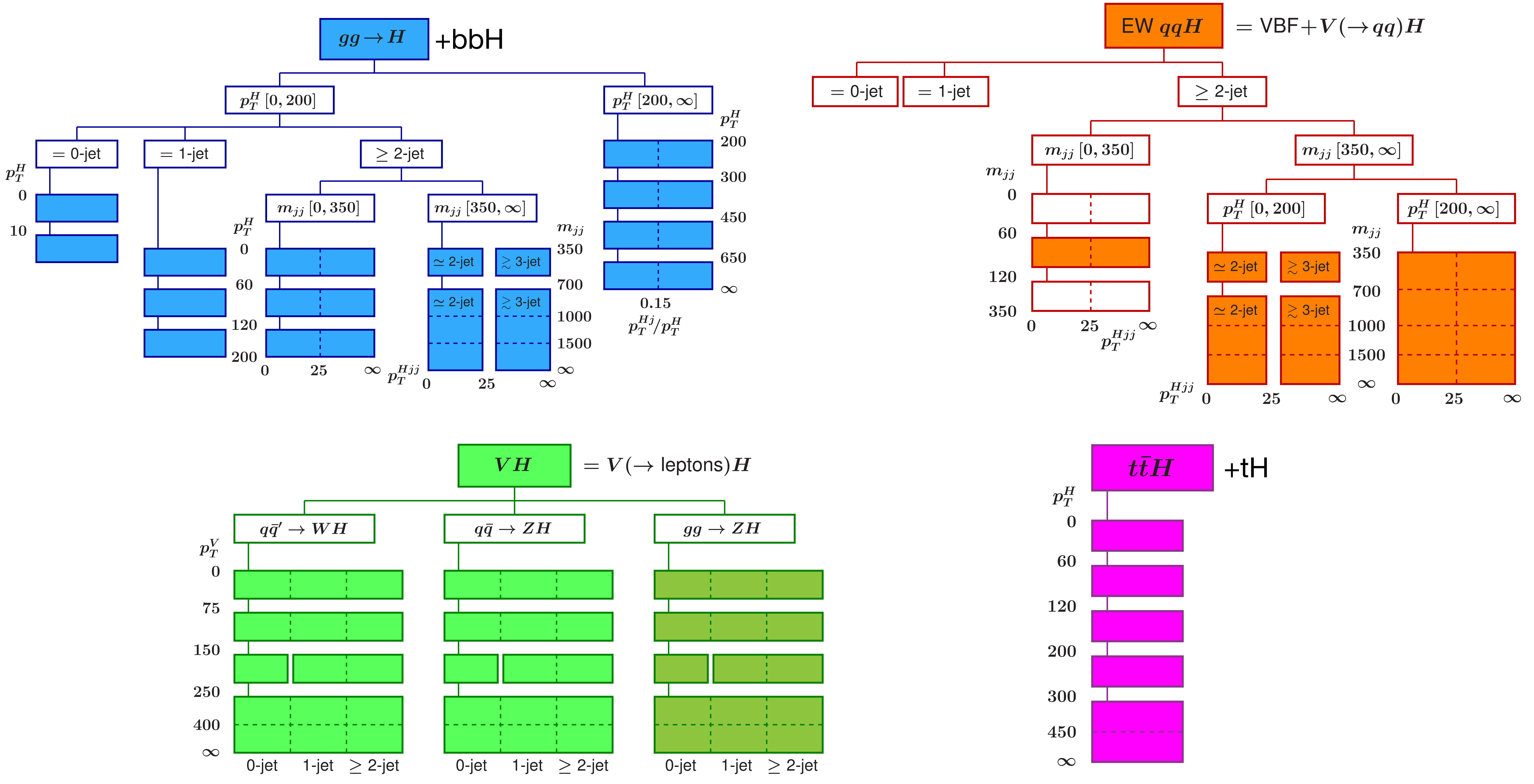
All results in today's presentation are based on Run 2 statistics

Going differential: STXS

Simplified Template Cross Sections

Maximise sensitivity to isolate BSM effects while reducing theory dependence

- All presented results are based on **stage 1.2** of the STXS framework
- Central recommendation from LHC Higgs Working Group
- Each analysis, depending on its sensitivity and features, has to **merge some STXS bins to avoid large uncertainties or high correlations**
- However, **merging bins reduces the model-independence**



STXS in $H \to \gamma\gamma$

10.1007/JHEP07(2021)027

- Extensive use of **BDT** and **DNN** to build categories targeting STXS bins
- Two sets of results are presented for Hgg with two levels of granularity:
  - **Maximal merging scenario**: STXS bins are merged until their expected uncertainty is less than 150%
  - **Minimal merging scenario**: Merge as few bins as possible whilst ensuring that parameters do not become too anti-correlated

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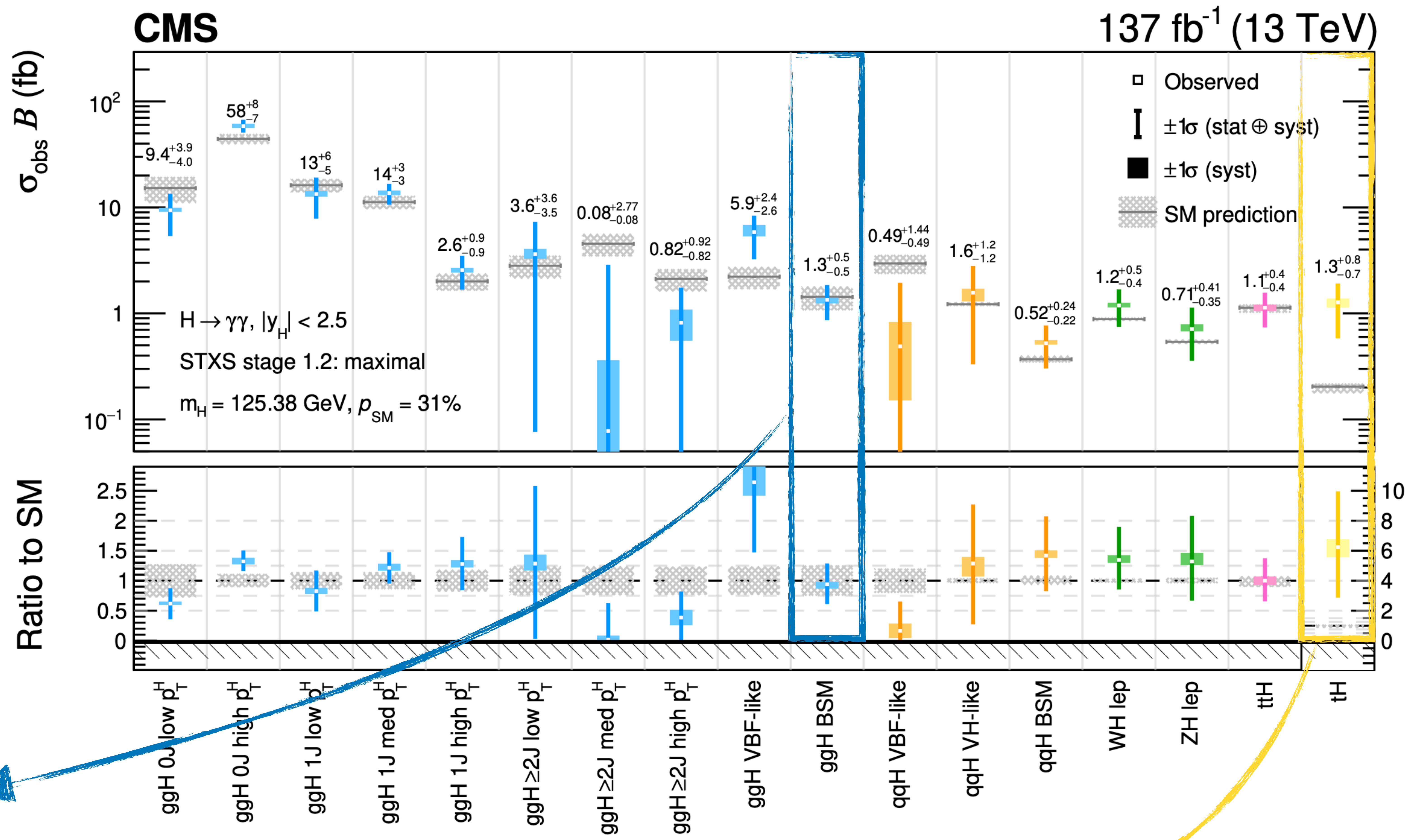

- Sensitive to BSM physics entering the ggH loop
- $p_T(H) > 200$ GeV
- Precision less than 40%
- Consistent with SM

- tH production mode measured separately from ttH
- Best tH measurement up to date
- Observed (expected) 95% CL limit is 14 (8) x SM value

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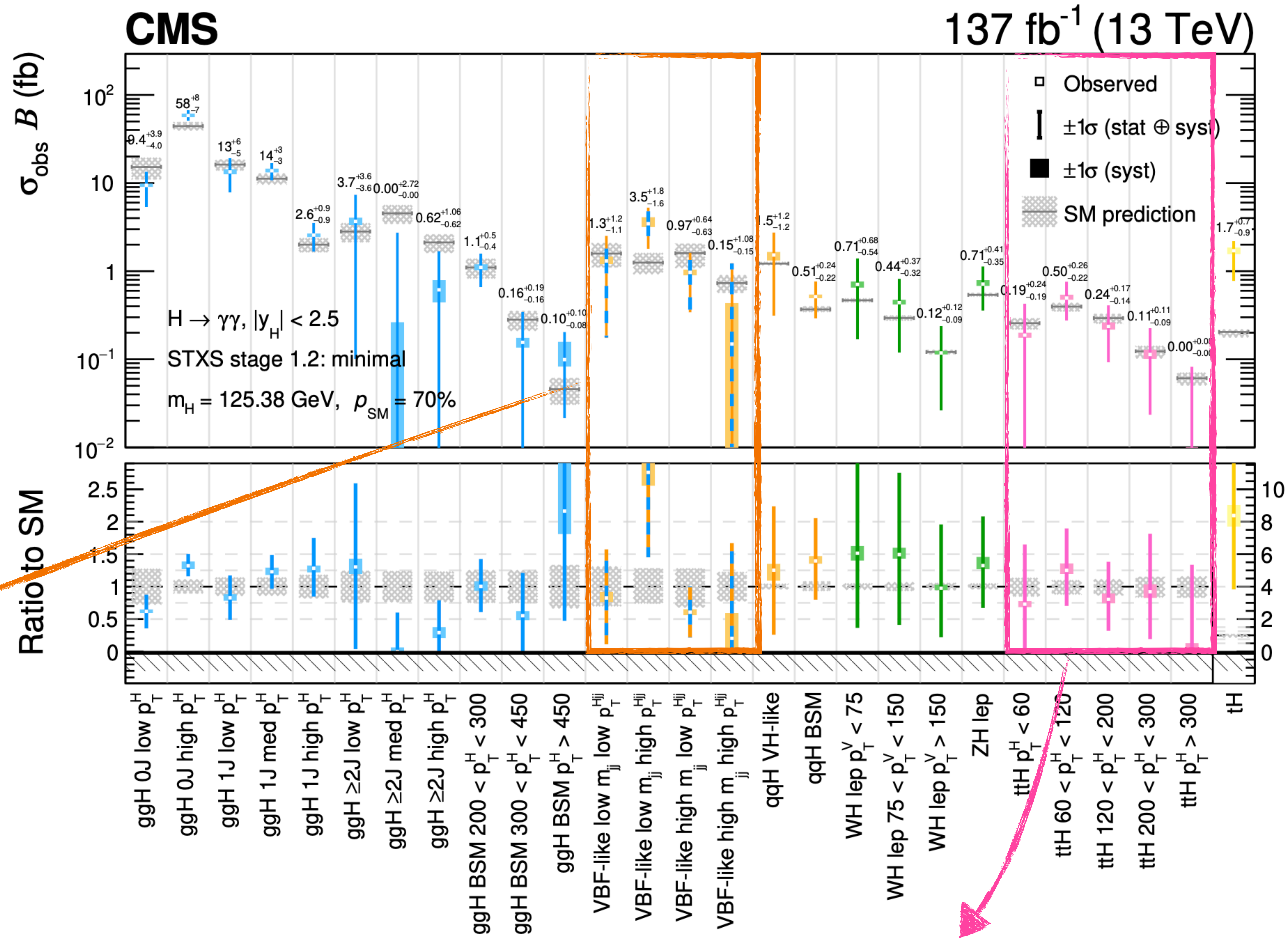


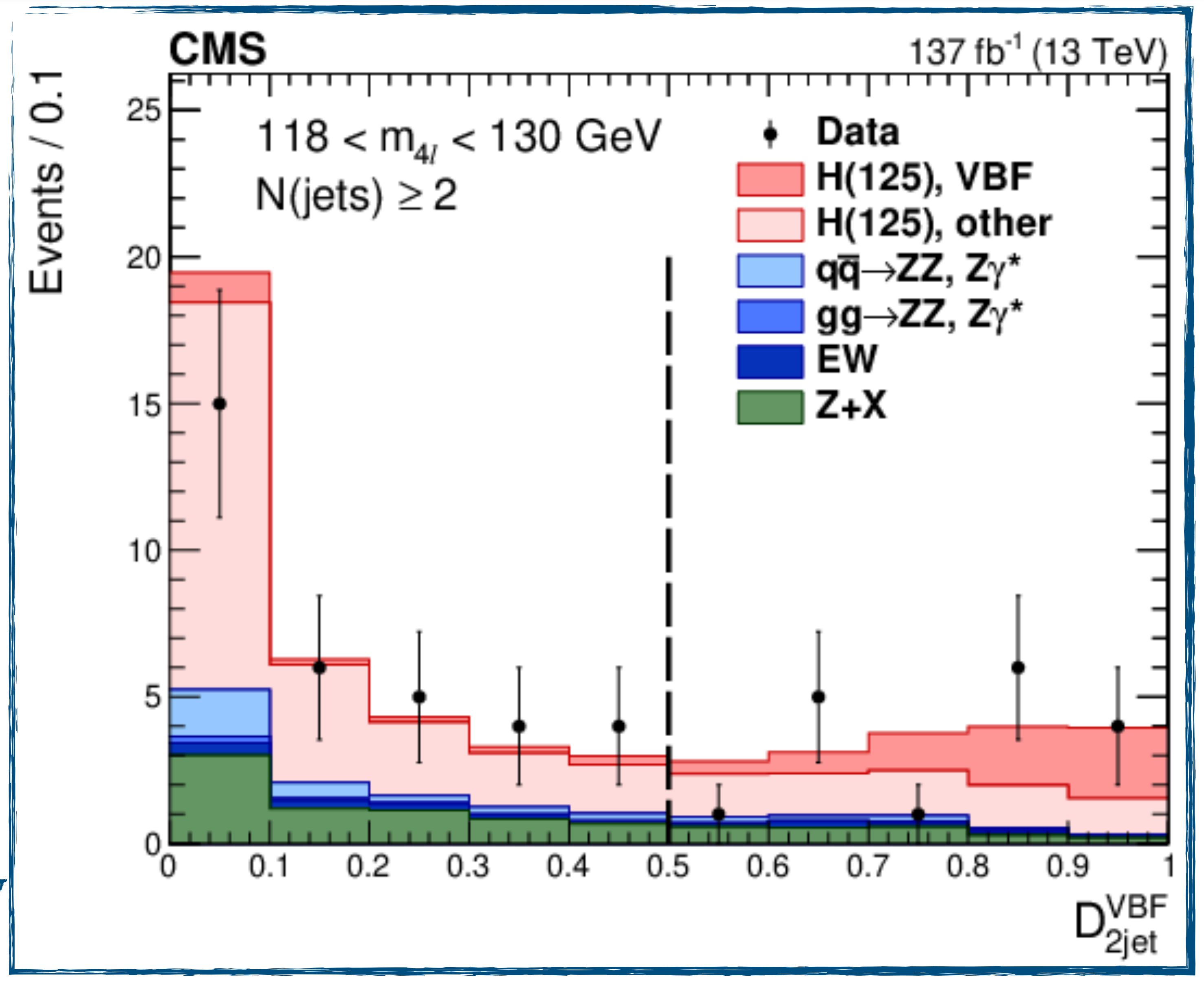
To avoid large correlations all VBF-like bins (in ggH and qqH) are merged together

Differential measurement of ttH production in pT bins

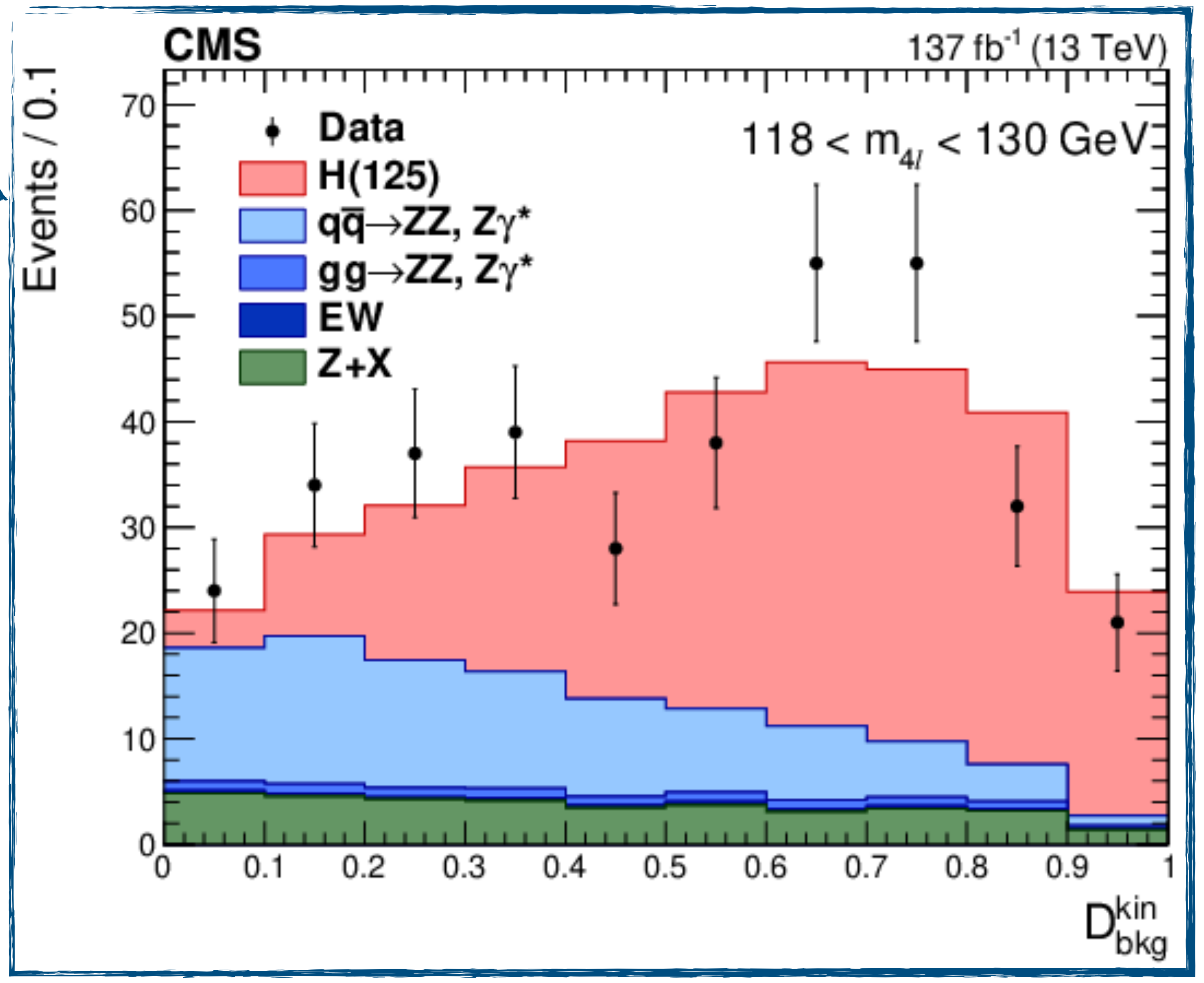
STXS in $H \to ZZ^* \to 4\ell$

10.1140/epjc/s10052-021-09200-x

- Extensive use of **kinematic discriminants** based on **matrix-element probabilities**
- Categories are defined on the multiplicity of jets, b-tagged jets, additional leptons, invariant mass of the two leading jets, transverse momentum of the ZZ candidate, and **kinematic discriminants**
- **2D likelihood fit in** $(m_{4\ell}, \mathscr{D})$ in [105,140] GeV, where $\mathscr{D}$ is a kinematic discriminant to separate signal from backgrounds depending on the category



Example of kinematic discriminants used for categorisation of the VBF-2jet-tagged ($\mathscr{D}_{2jet}^{VBF} > 0.5$)

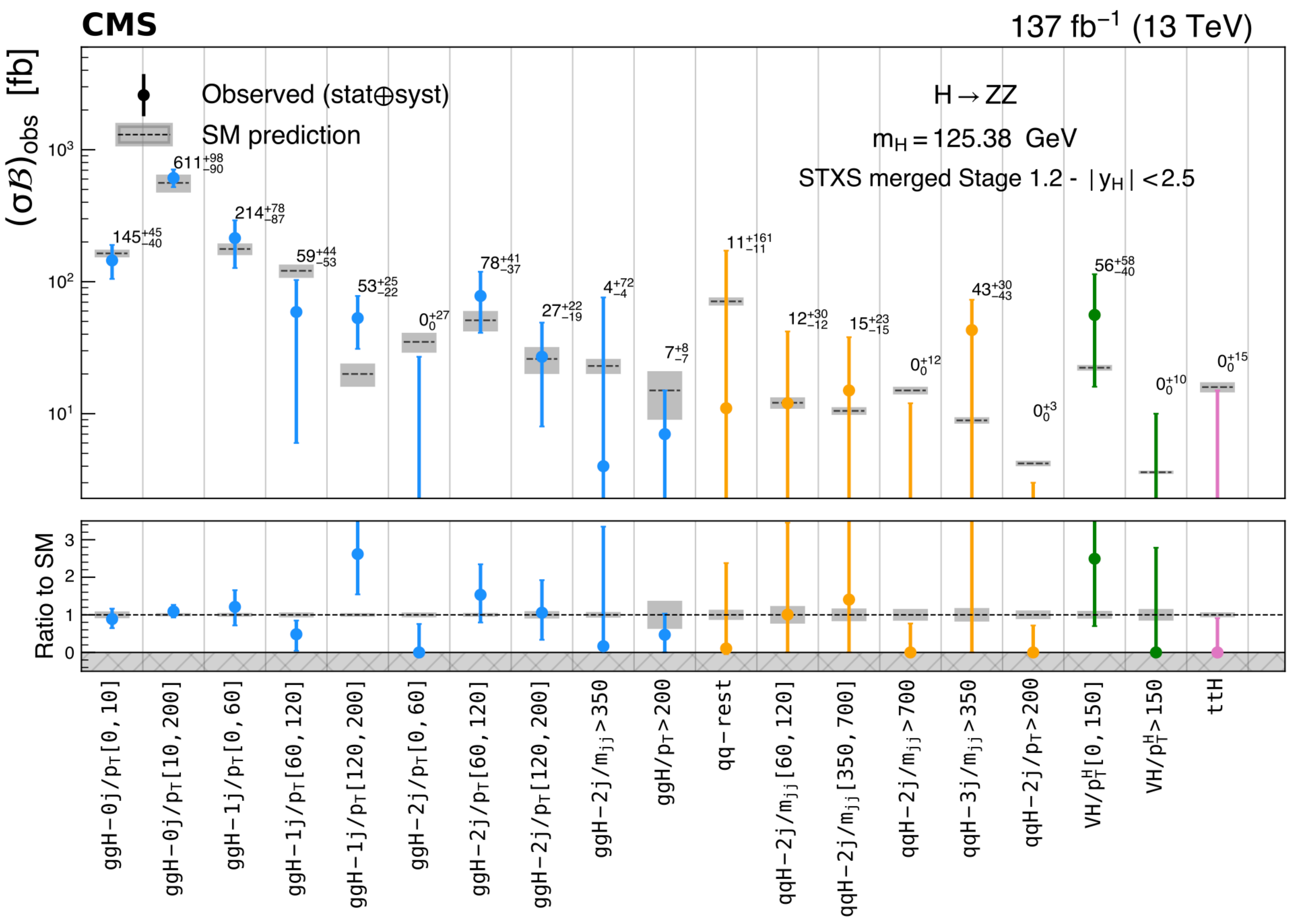


Example of kinematic discriminants used for the 2D fit

STXS in $H \to ZZ^* \to 4\ell$

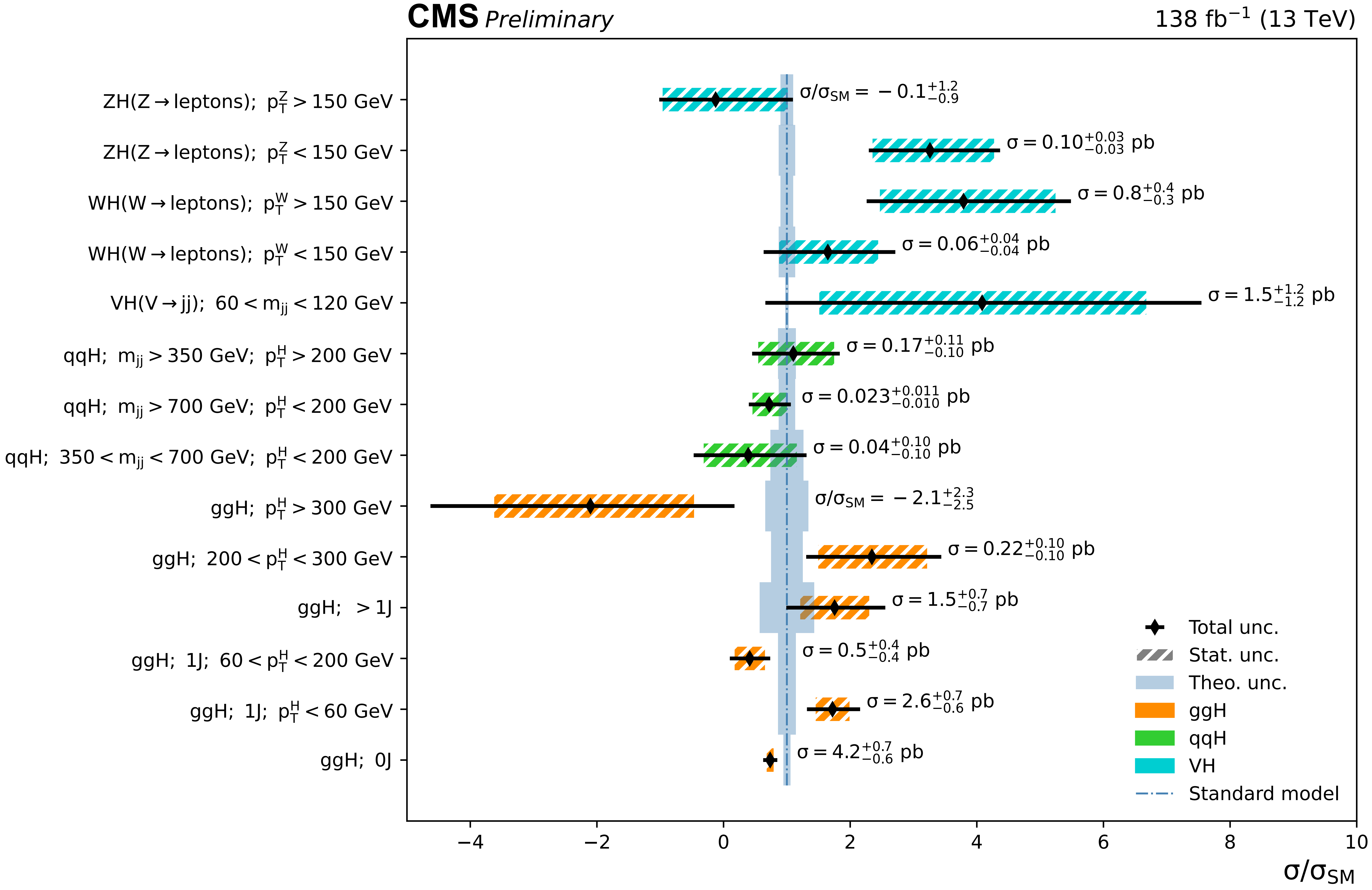
10.1140/epjc/s10052-021-09200-x

- Good sensitivity to **ggH** process
- Because of low statistics many bins have been merged together and some of them resulted to be fit to zero



STXS in $H \to WW$

- Both **same-flavour** $H \to W^+W^- \to e^{\pm}\mu^{\mp}\nu\bar{\nu}$ and **different-flavour** $H \to W^+W^- \to e^+e^-\nu\bar{\nu}$ $(\mu^+\mu^-\nu\bar{\nu})$ final states are used
- Extensive use of **DNN** for categorisation
- Analysis targets only **ggH**, **qqH**, and **VH**
- Good sensitivity to **ggH** process

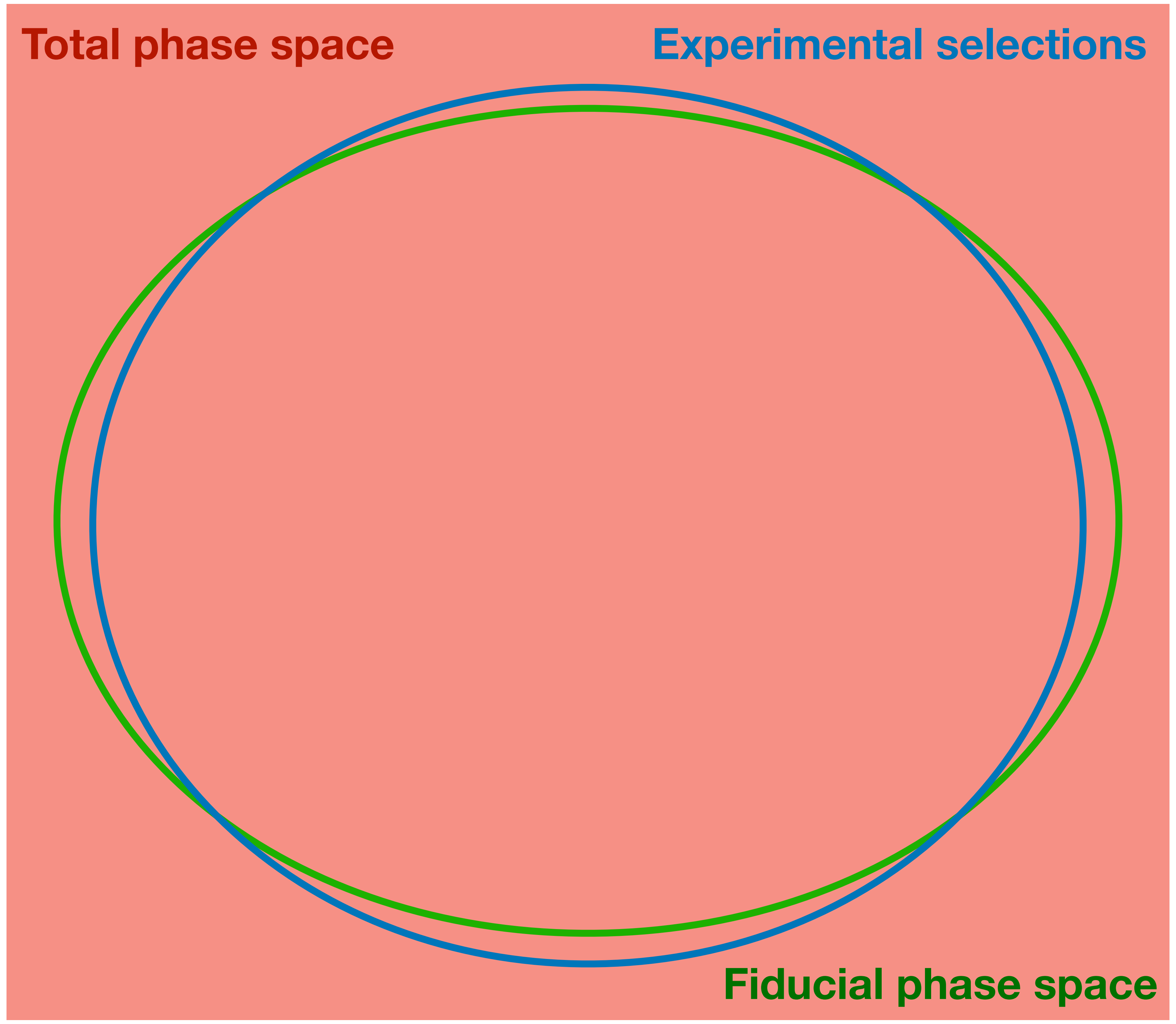


Going differential: fiducial

Fiducial differential cross sections

Optimised for maximal theory independence

- Fiducial volume is analysis-dependent and defined **to match as closely as possible experimental selections** to attain **model-independence**
- Thanks to Run2 statistics the number of observables is growing as well as their granularity
- Choice of bin-boundaries:
  - **Bins aligned** to ease the upcoming combination that will include $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$, $H \to \tau\tau$, and $H \to bb$
  - Having enough statistics to have a **low expected uncertainty** on the cross-section
  - Ensuring a good level of **S/B** value



Differential in $H \to \gamma\gamma$

CMS-PAS-HIG-19-016

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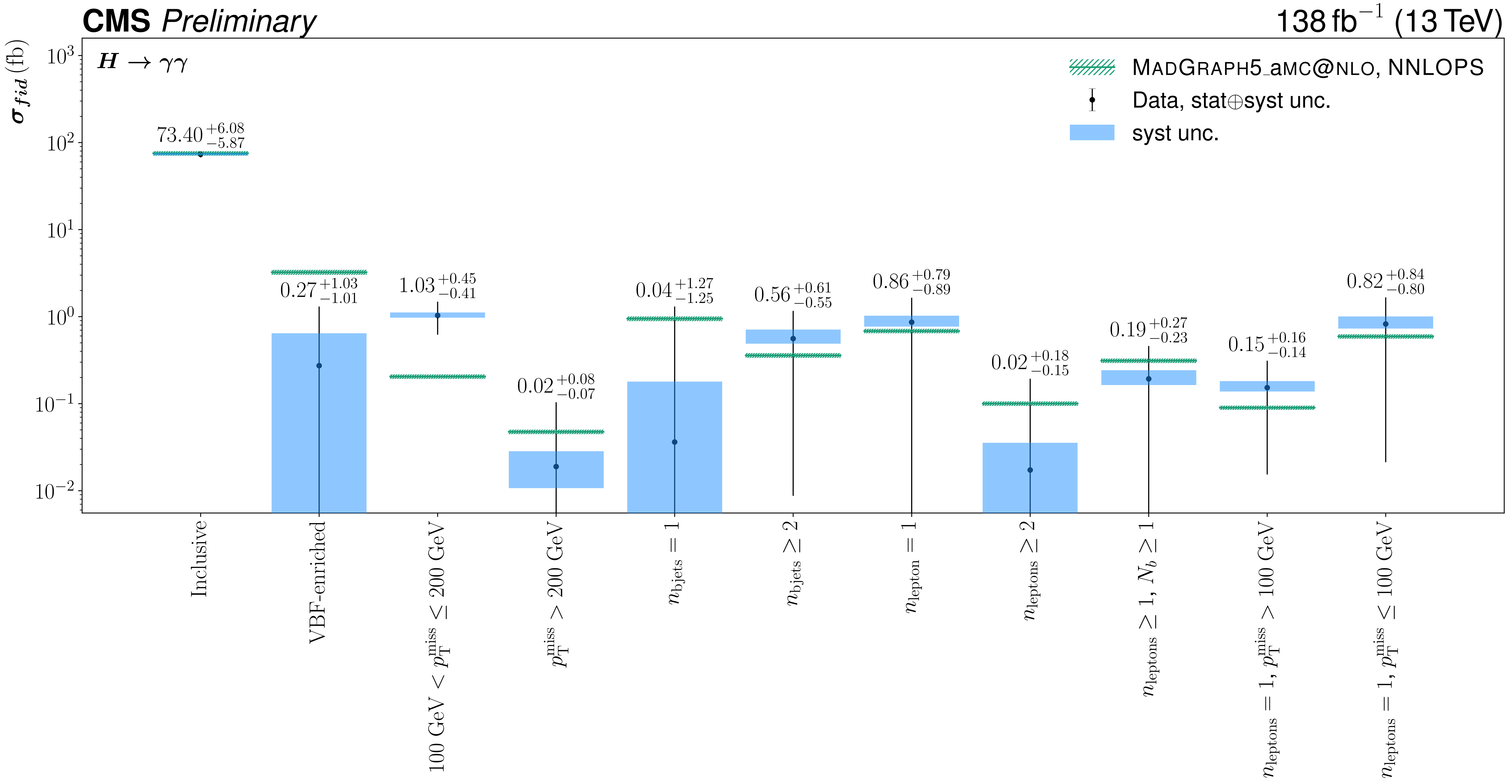
First-time presentation in a conference

- Extensive collection of results both inclusive and differential
- Some observables measured in **VBF-enriched** phase-space ($N_{jets} \geq 2$, $\Delta\eta_{jj} > 3.5$, $m_{jj} > 200$ GeV)
- Inclusive fiducial cross sections measured in **dedicated phase-space regions** designed to loosely **target specific production modes**:
  - **ttH-like** phase space: $N_{lep} \geq 1, N_{bjet} \geq 1$
  - **VH-like** phase space: $N_{lep} = 1, p_{T,miss} < 100$ GeV
  - **WH-like** phase space: $N_{lep} = 1, p_{T,miss} > 100$ GeV
- First-time measurement of a **rapidity-weighed jet observables**
- **Double-differential observables**



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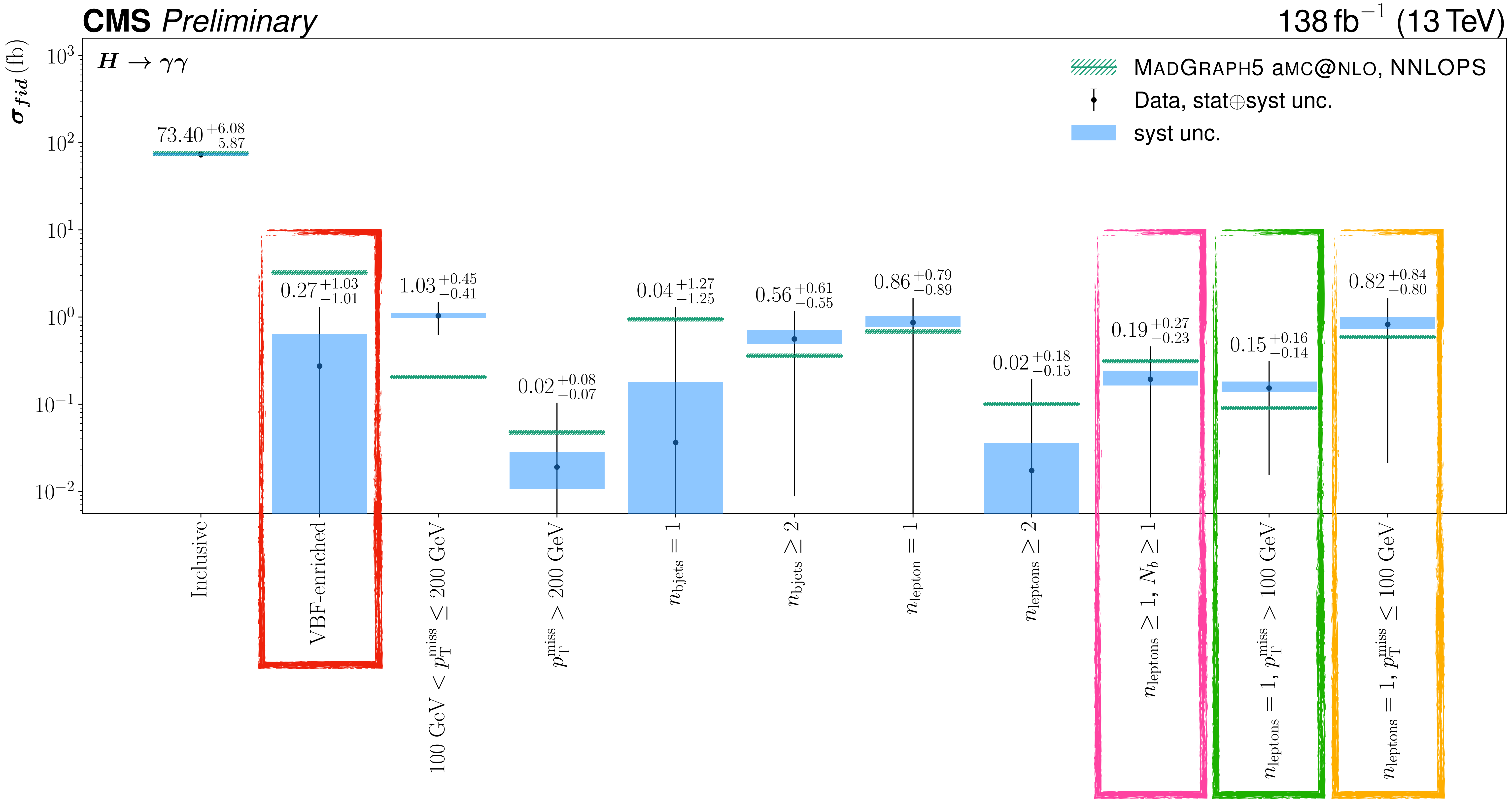

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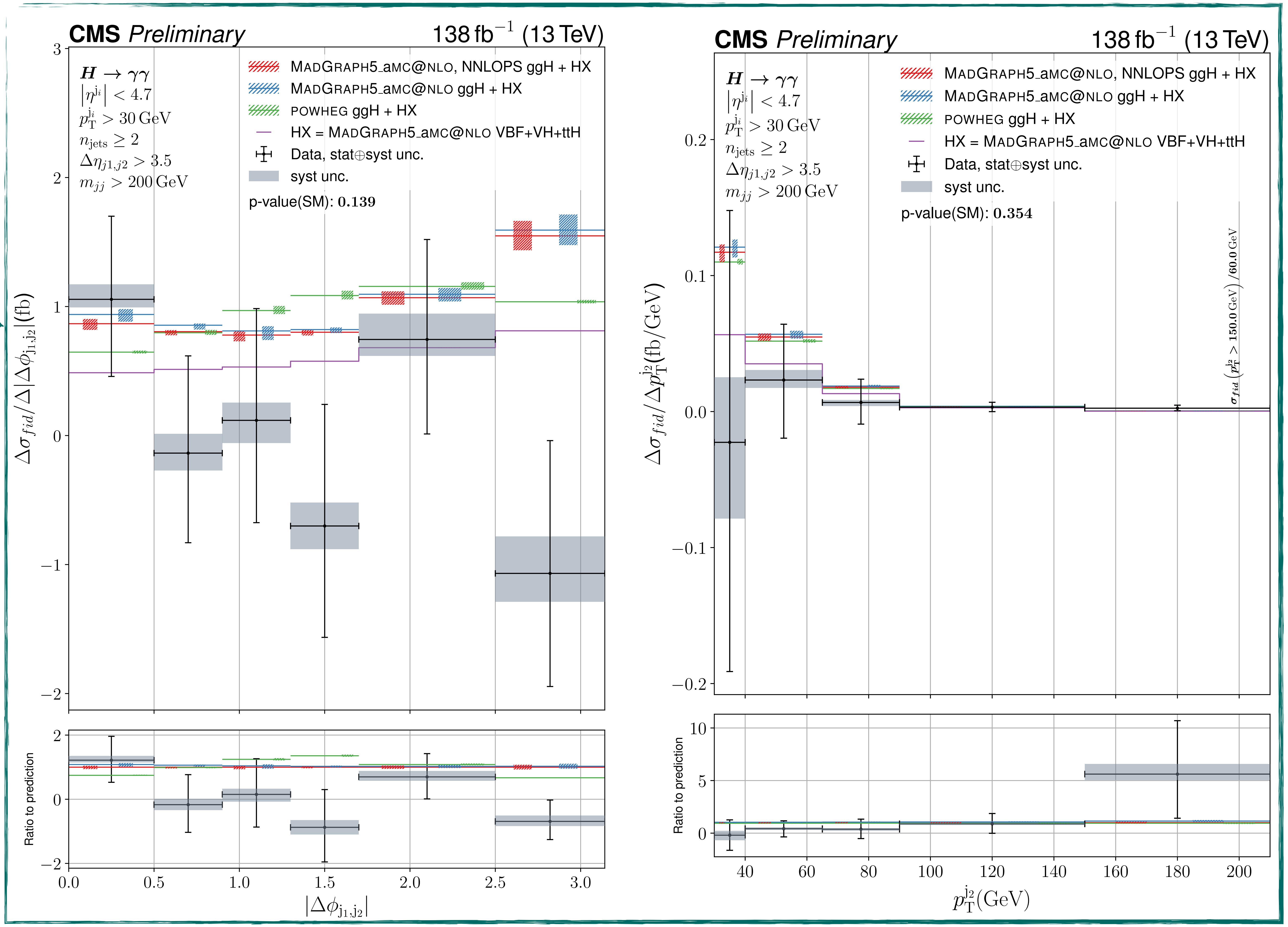

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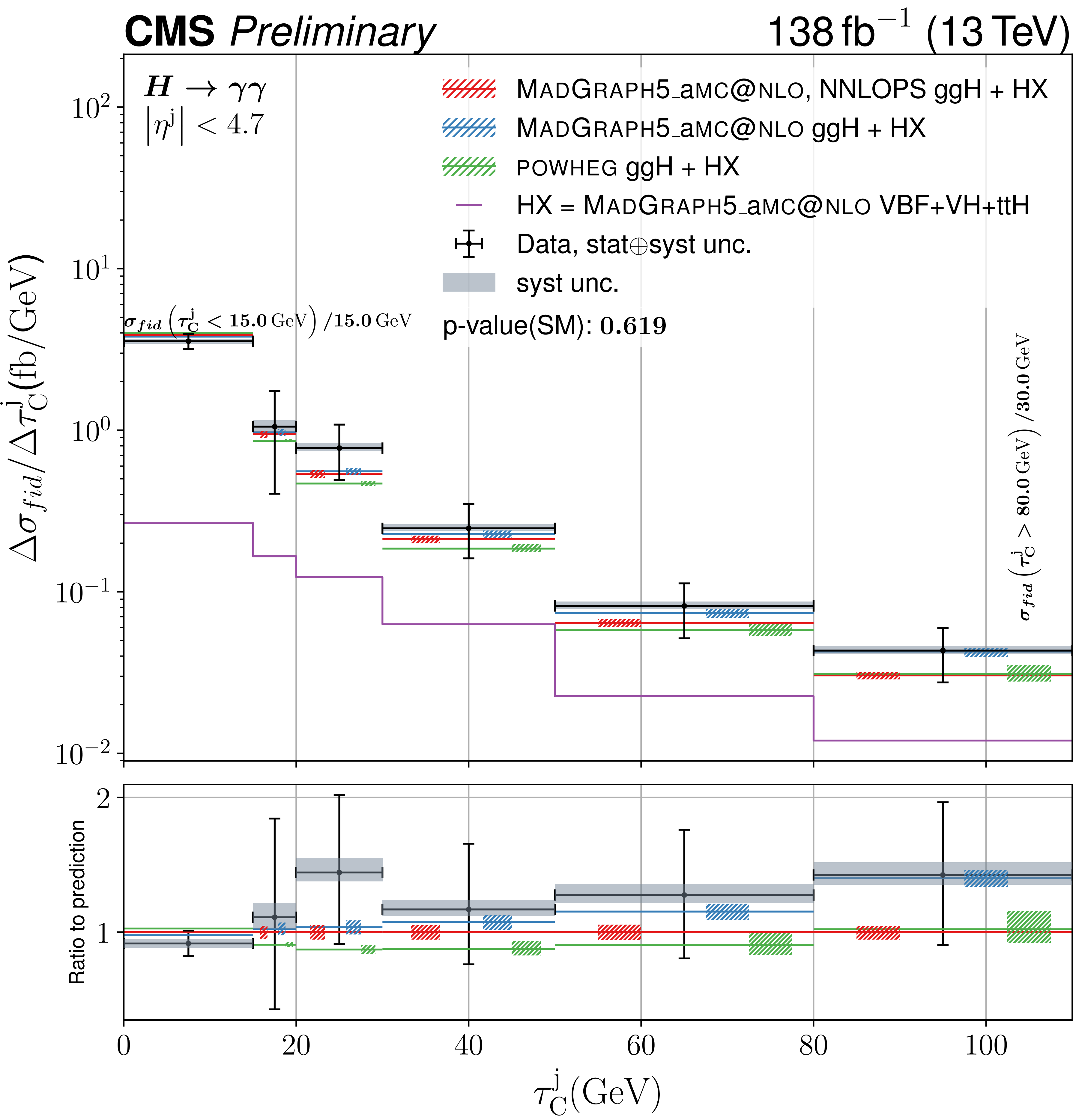

$$\tau_C^j = \max_j \left(\frac{\sqrt{E_j^2 - p_{z,j}^2}}{2\cosh\left(Y_j - Y_H\right)} \right)$$

Binning in such observables rather than in p_T^j does not introduce extra logarithms (or minimises their contribution) in the resummation region (low-pT) of ggH XS calculations leading to **precise theoretical computations and test of QCD resummation**

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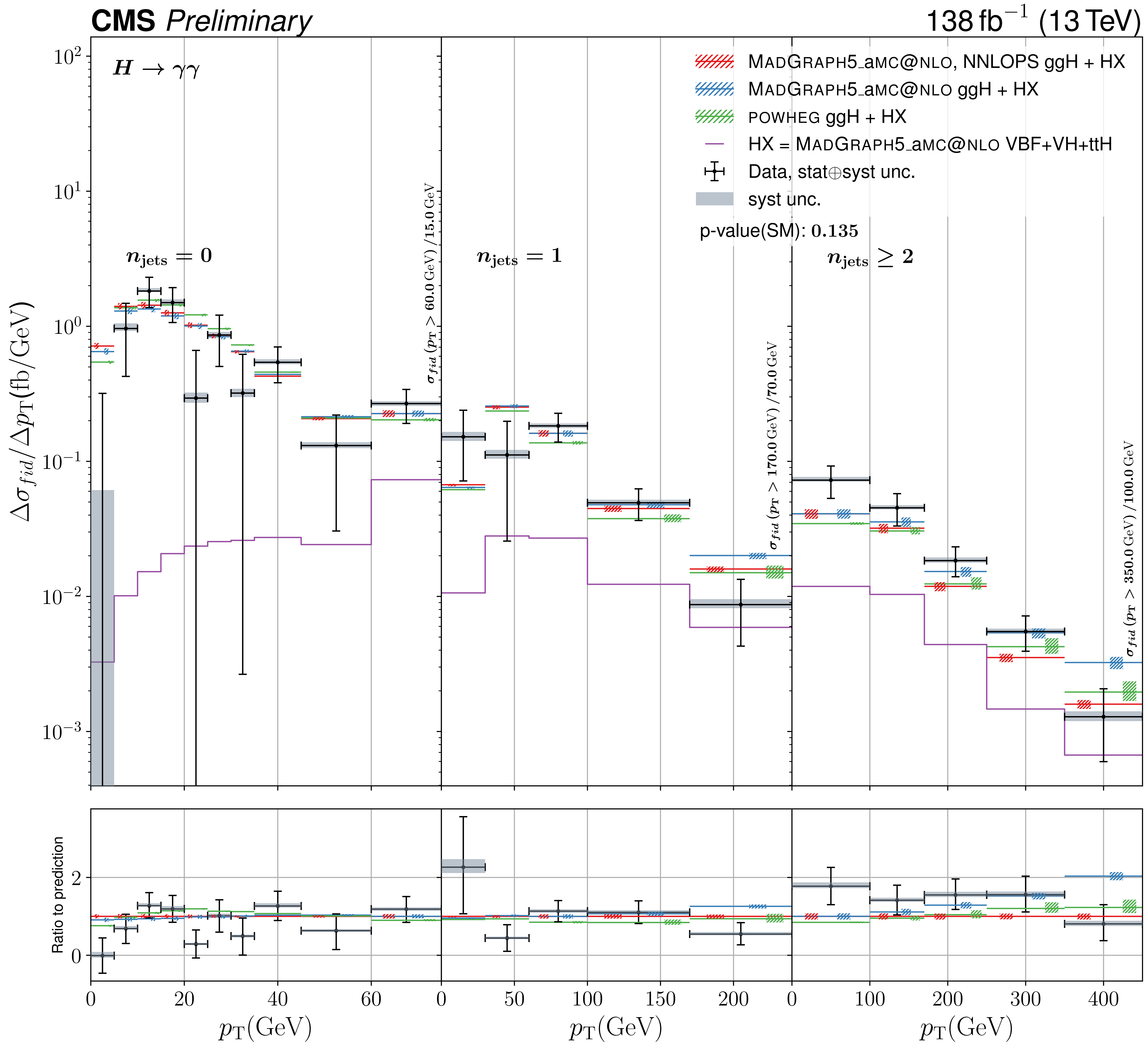
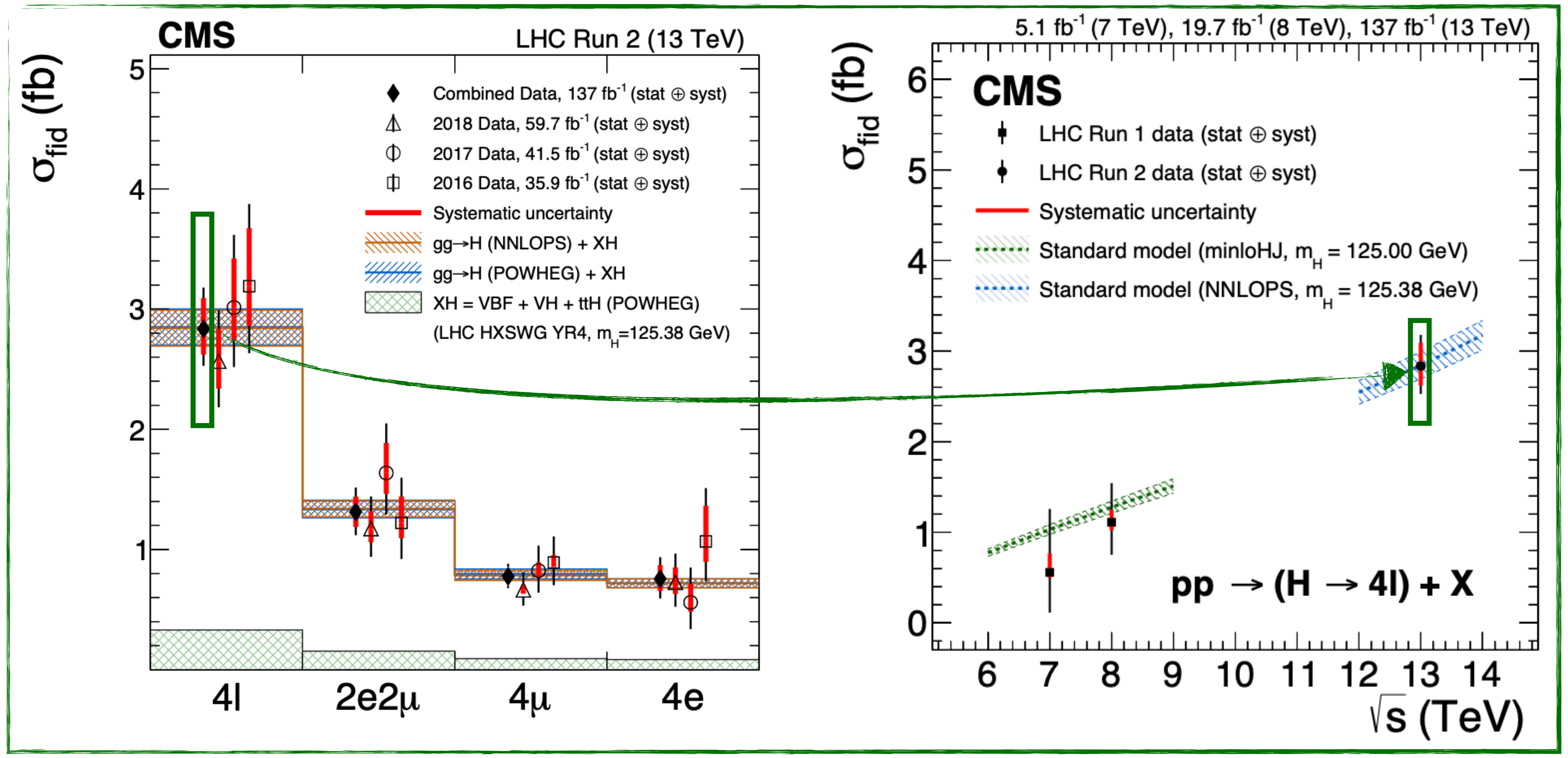


Differential in $H \to ZZ^* \to 4\ell$ 10.1140/epjc/s10052-021-09200-x

- **Inclusive result** quoted both **inclusive** and **separately in the three final states**



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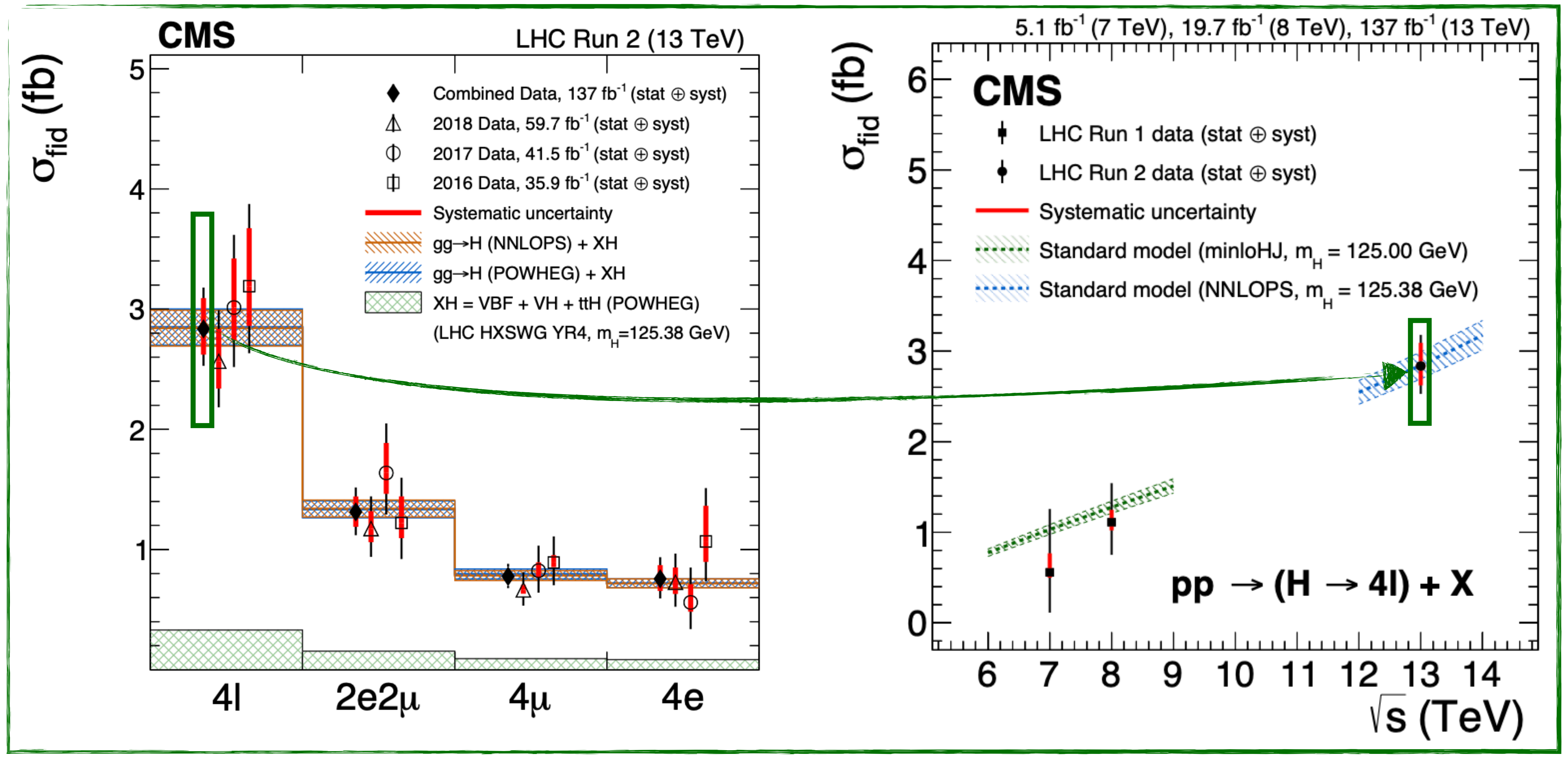
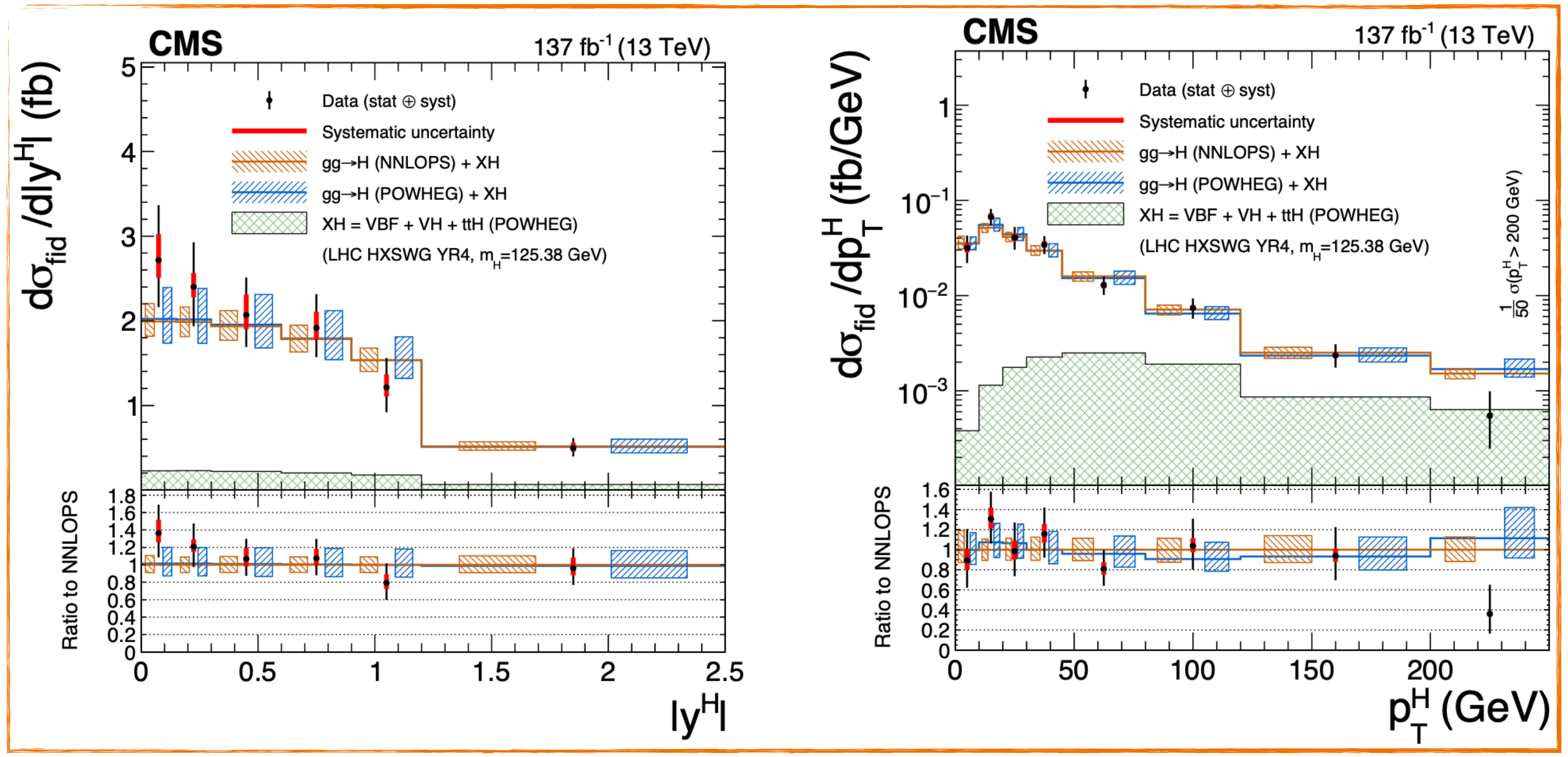
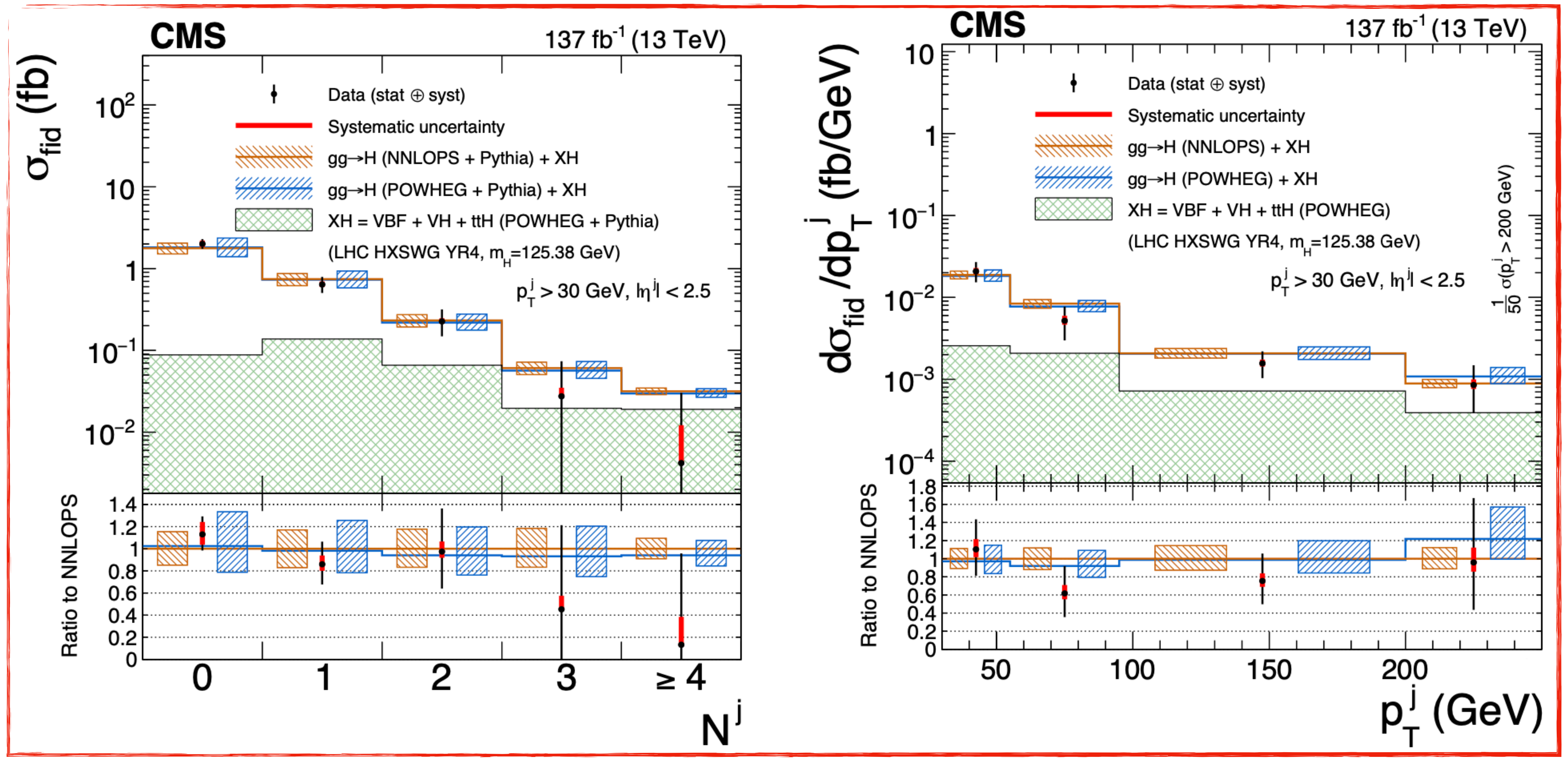
- Measurement of differential **jet observables** and observables targeting **production**

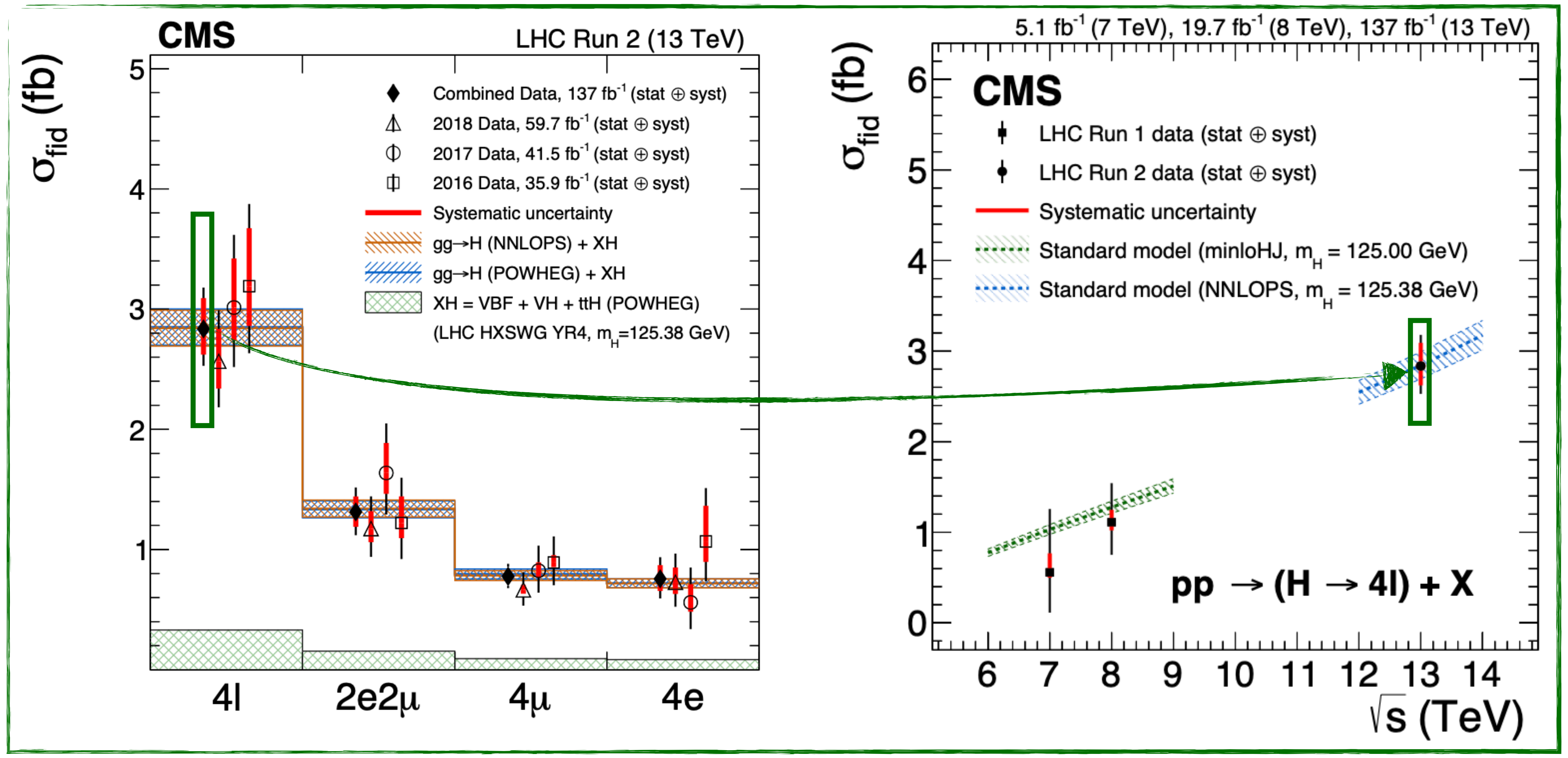


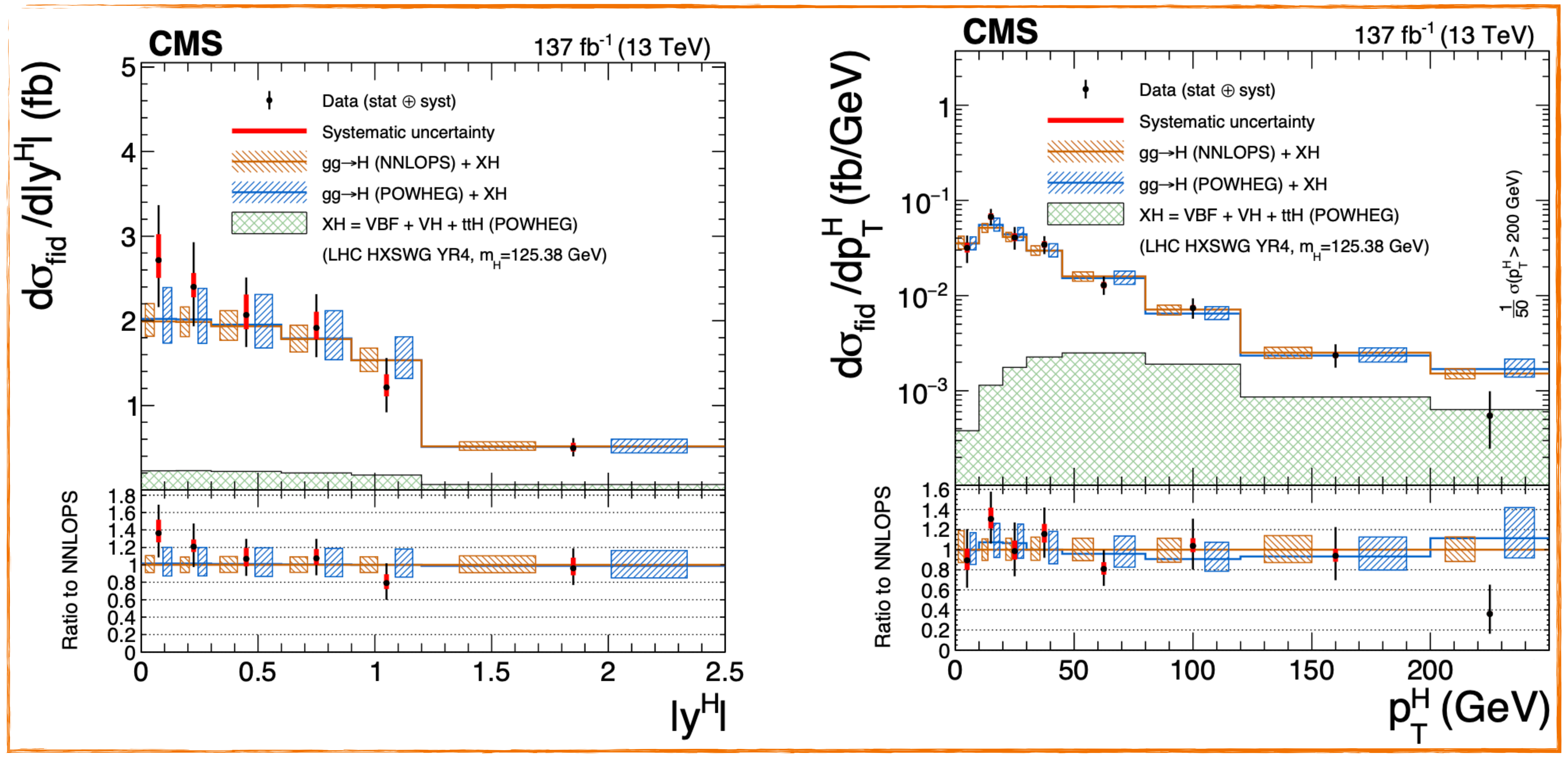


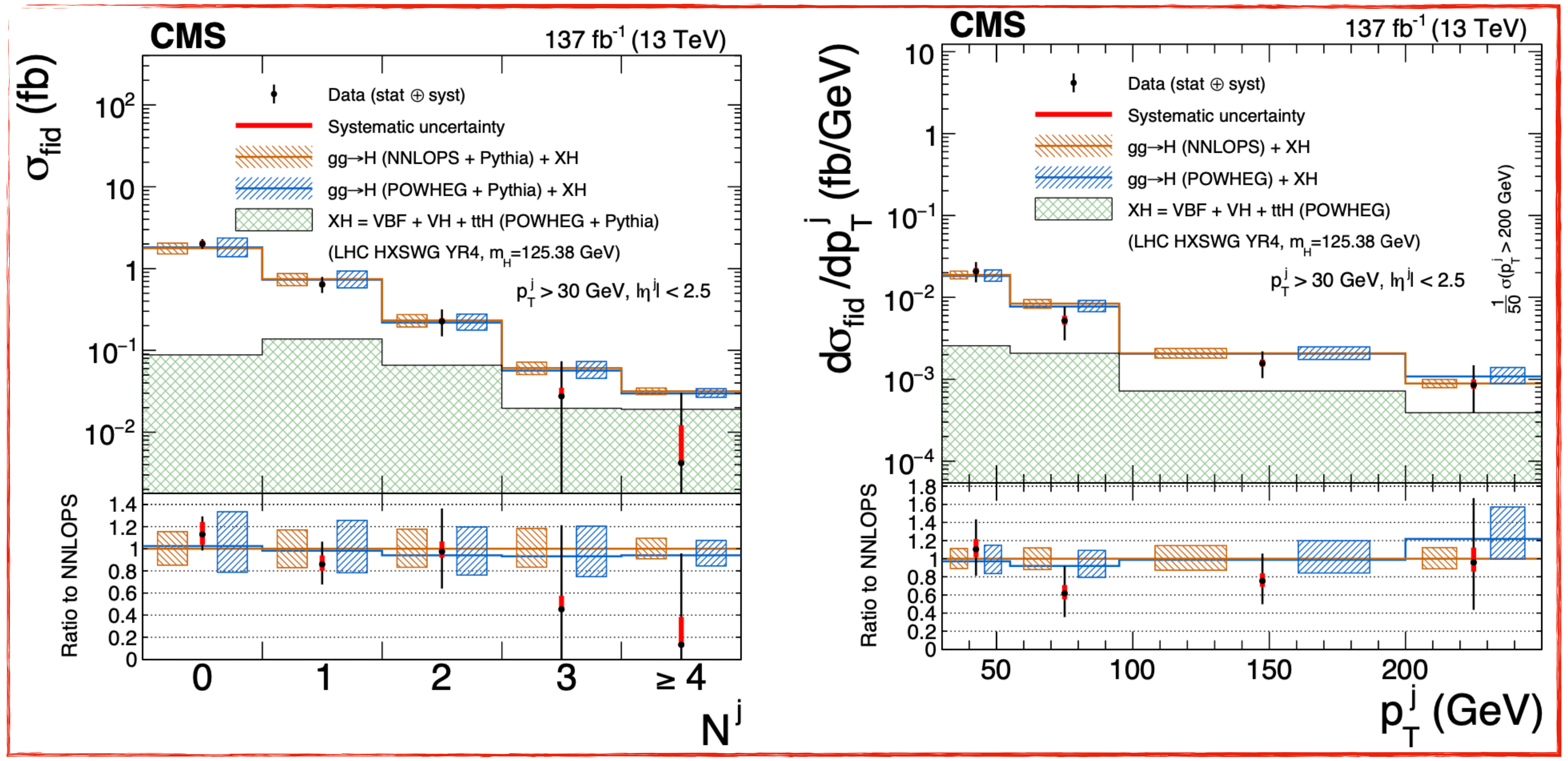


Differential in $H \to ZZ^* \to 4\ell$ [10.1140/epjc/s10052-021-09200-x](https://doi.org/10.1140/epjc/s10052-021-09200-x)

- **Inclusive result** quoted both **inclusive** and **separately in the three final states**
- Measurement of differential **jet observables** and observables targeting **production**
- **Floating BR** of the H boson to different final states







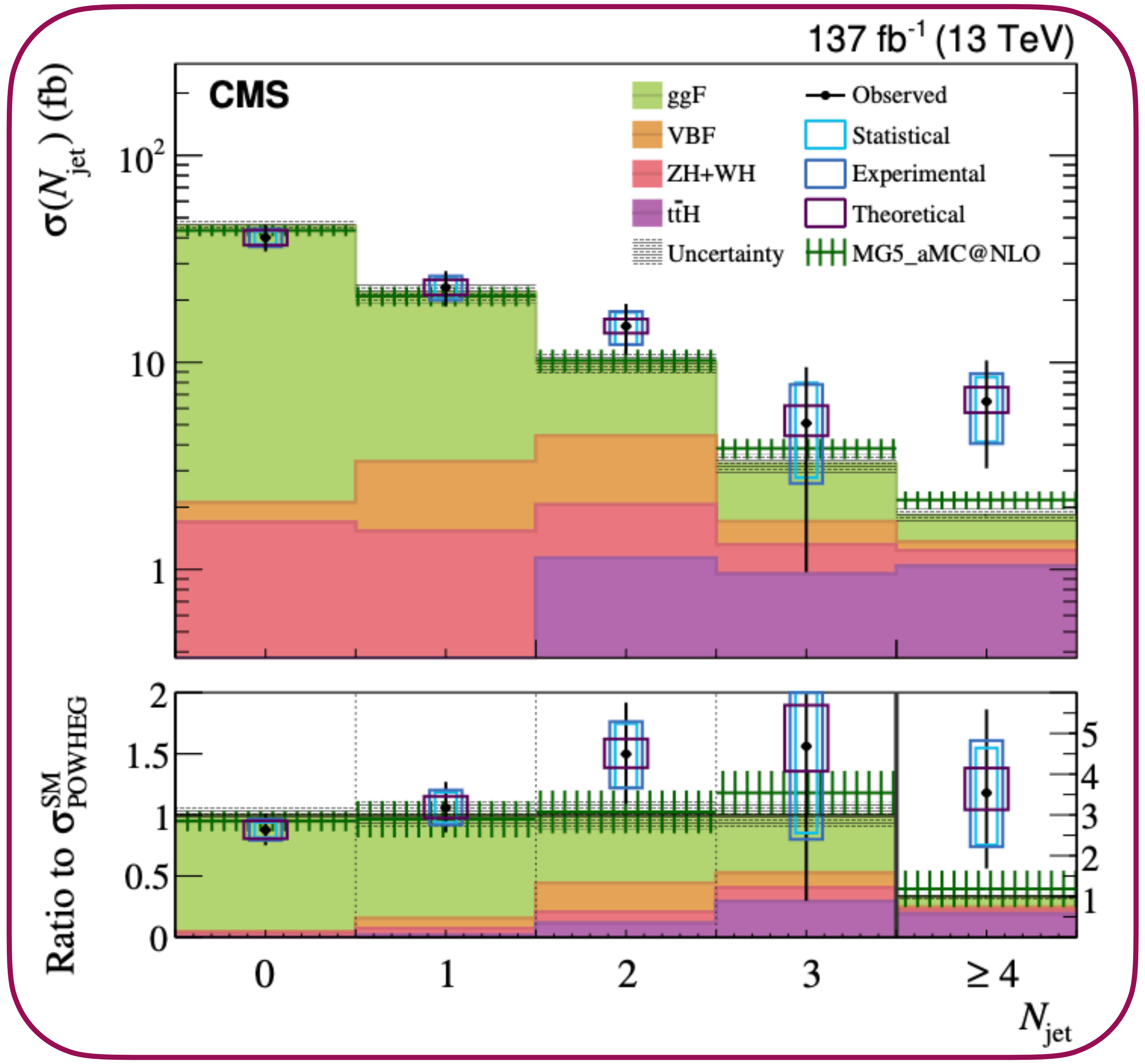
Differential in $H \to WW$

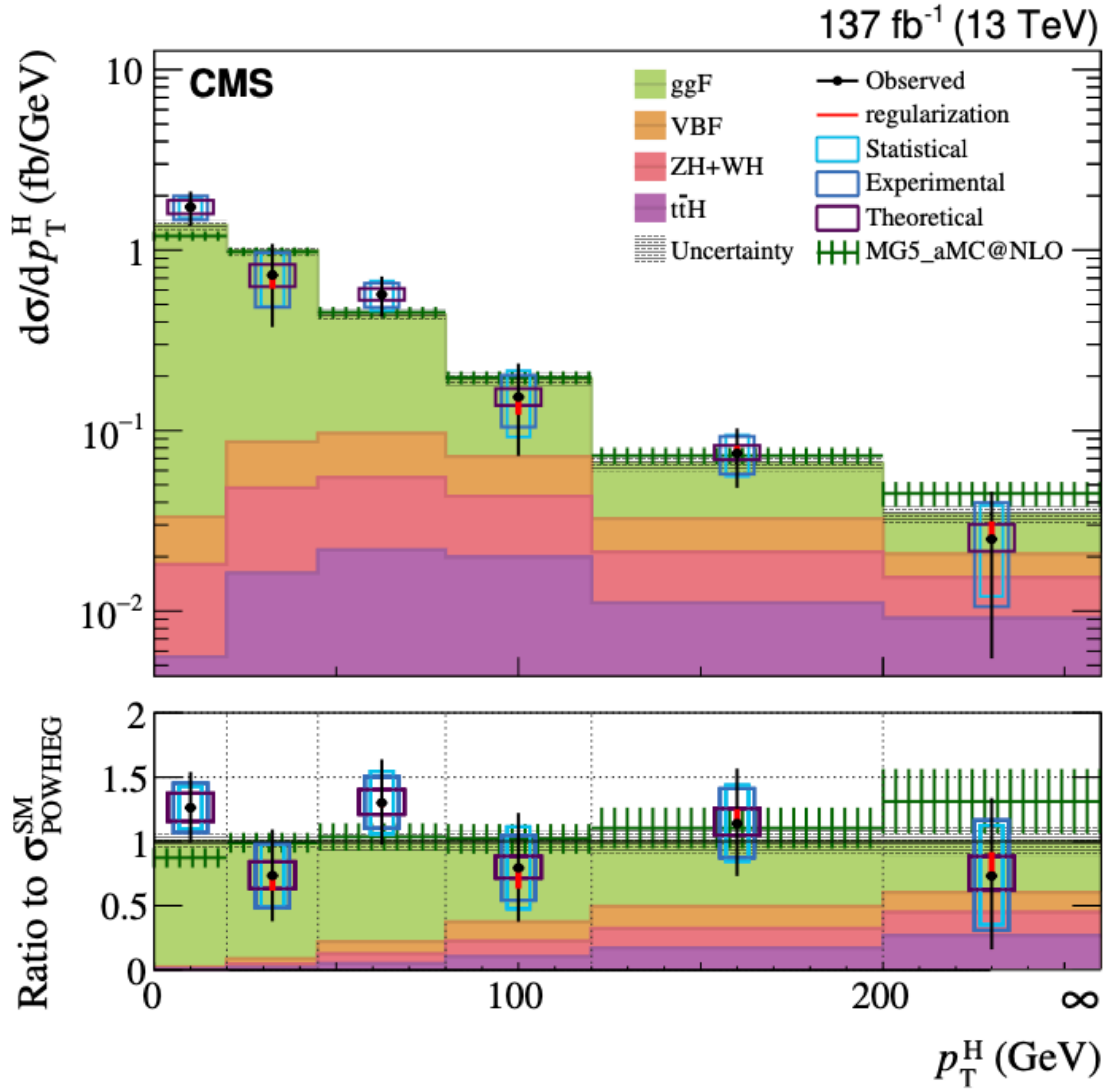
10.1007/JHEP03(2021)003

Unlike the STXS analysis, only $H \to W^+W^- \to e^{\pm}\mu^{\mp}\nu\bar{\nu}$ is considered to suppress DY bkg

Inclusive fiducial cross section

$\sigma^{fid} = 86.5 \pm 9.5$ fb $\qquad \sigma^{fid}_{SM} = 82.5 \pm 4.2$ fb





- Choice of bin boundaries
  - **Larger than the p_T^H resolution** ($\simeq p_T^{miss}$ resolution $\simeq$ 20 GeV)
  - At high p_T^H to have an **expected uncertainty less than 100%**
- **Regularised unfolding**
  - Large off-diagonal elements in the unfolding matrix
  - Tikhonov regularisation

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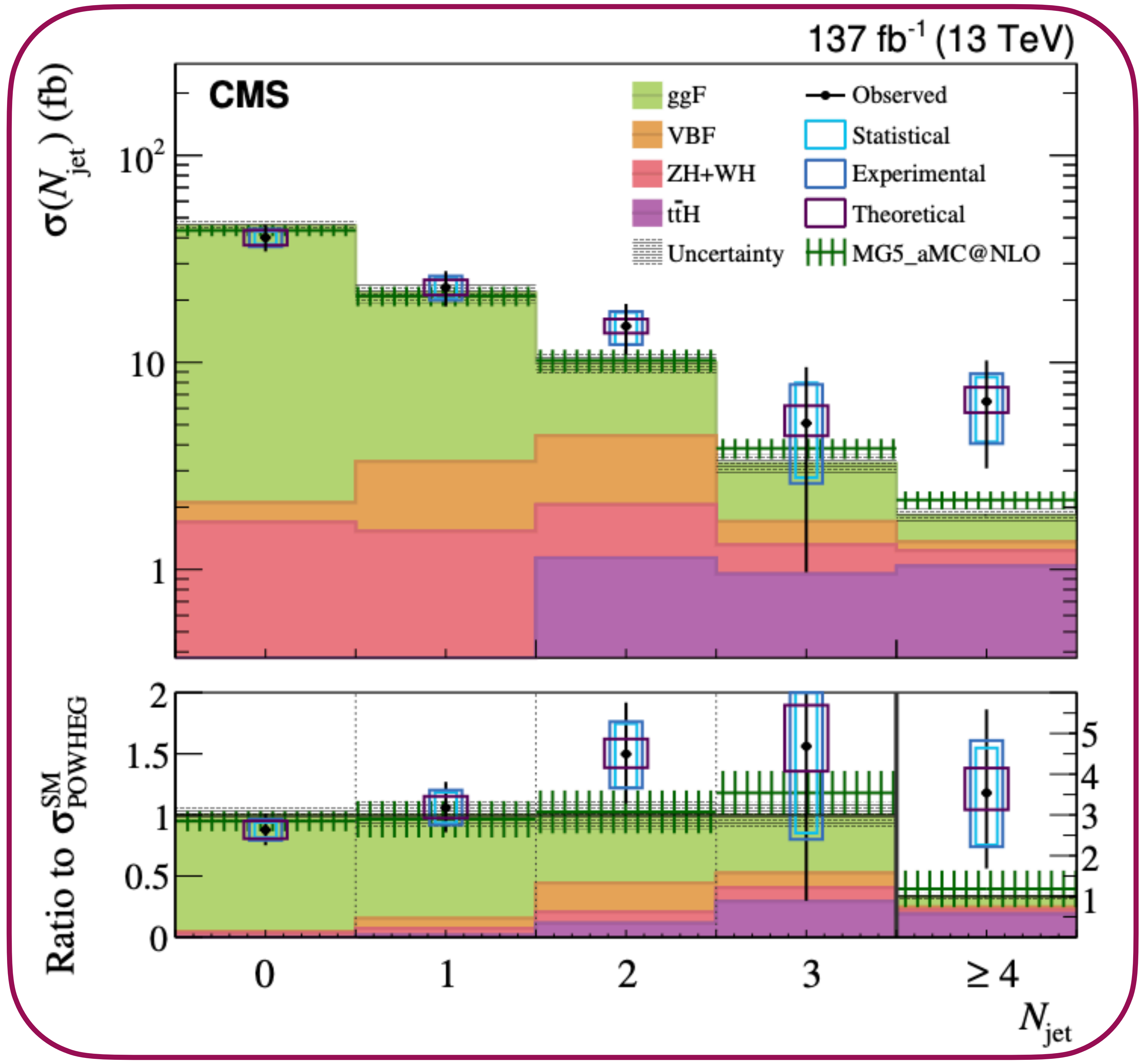

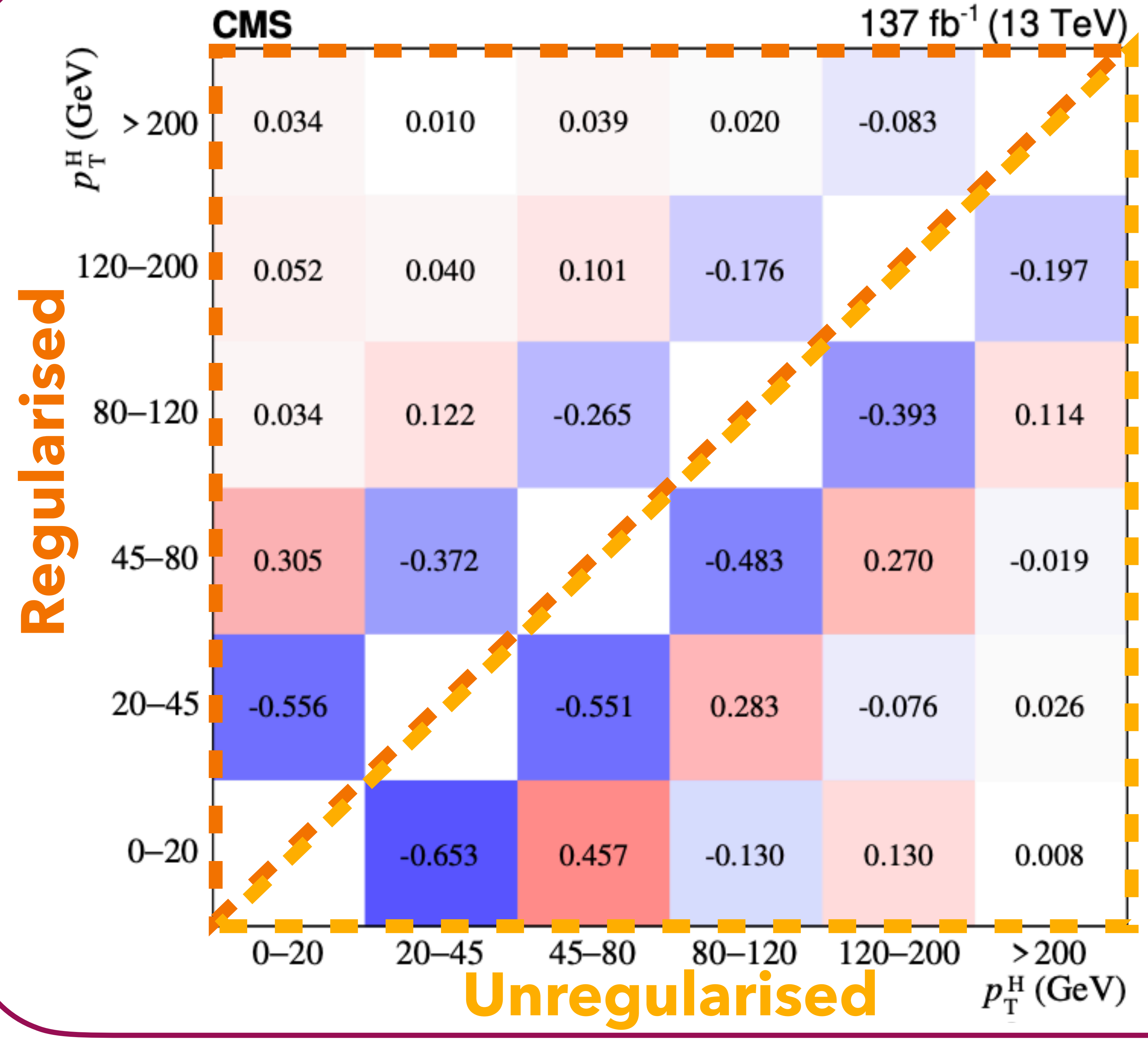

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- **Regularised unfolding**
  - Large off-diagonal elements in the unfolding matrix
  - Tikhonov regularisation
  - It **counters negative correlations**

Conclusions

Fiducial Cross Sections and **Simplified Template Cross Sections** provide two complementary ways to measure the Higgs boson properties and **CMS Run2 results** have been presented in the bosonic decay channels

Overall **good agreement with SM**

Where do we stand on uncertainty?

$H \to \gamma\gamma$

$\sigma_{fid} = 73.4^{+6.1\ (8.3\%)}_{-5.3\ (7.2\%)}$ fb

$\sigma_{fid} = 73.4^{+5.4\ (7.4\%)}_{-5.3\ (7.2\%)}$ (stat.)$^{+2.4\ (3.3\%)}_{-2.2\ (2.3\%)}$ (sys.) fb

$H \to WW$

$\mu_{fid} = 1.05 \pm 0.12\ (11.4\%)$

$\mu_{fid} = 1.05 \pm 0.05\ (4.8\%)$ (stat.) $\pm\, 0.10\ (9.5\%)$ (sys.)

$H \to ZZ^* \to 4\ell$

$\sigma_{fid} = 2.84^{+0.34\ (12.0\%)}_{-0.31\ (10.9\%)}$ fb

$\sigma_{fid} = 2.84^{+0.23\ (8.1\%)}_{-0.22\ (7.7\%)}$ (stat.)$^{+0.26\ (9.2\%)}_{-0.21\ (7.4\%)}$ (sys.) fb

The current uncertainty on the ggH XS is about 6%

$H \to \gamma\gamma$ is very close to measure the fiducial cross section **at the same level of precision** of the leading production mode

$H \to \gamma\gamma$ systematic uncertainty is well below the ggH theoretical precision

$H \to WW$ is **dominated by systematics**

Systematic and statistical uncertainty in $H \to ZZ$ are of the **same magnitude**

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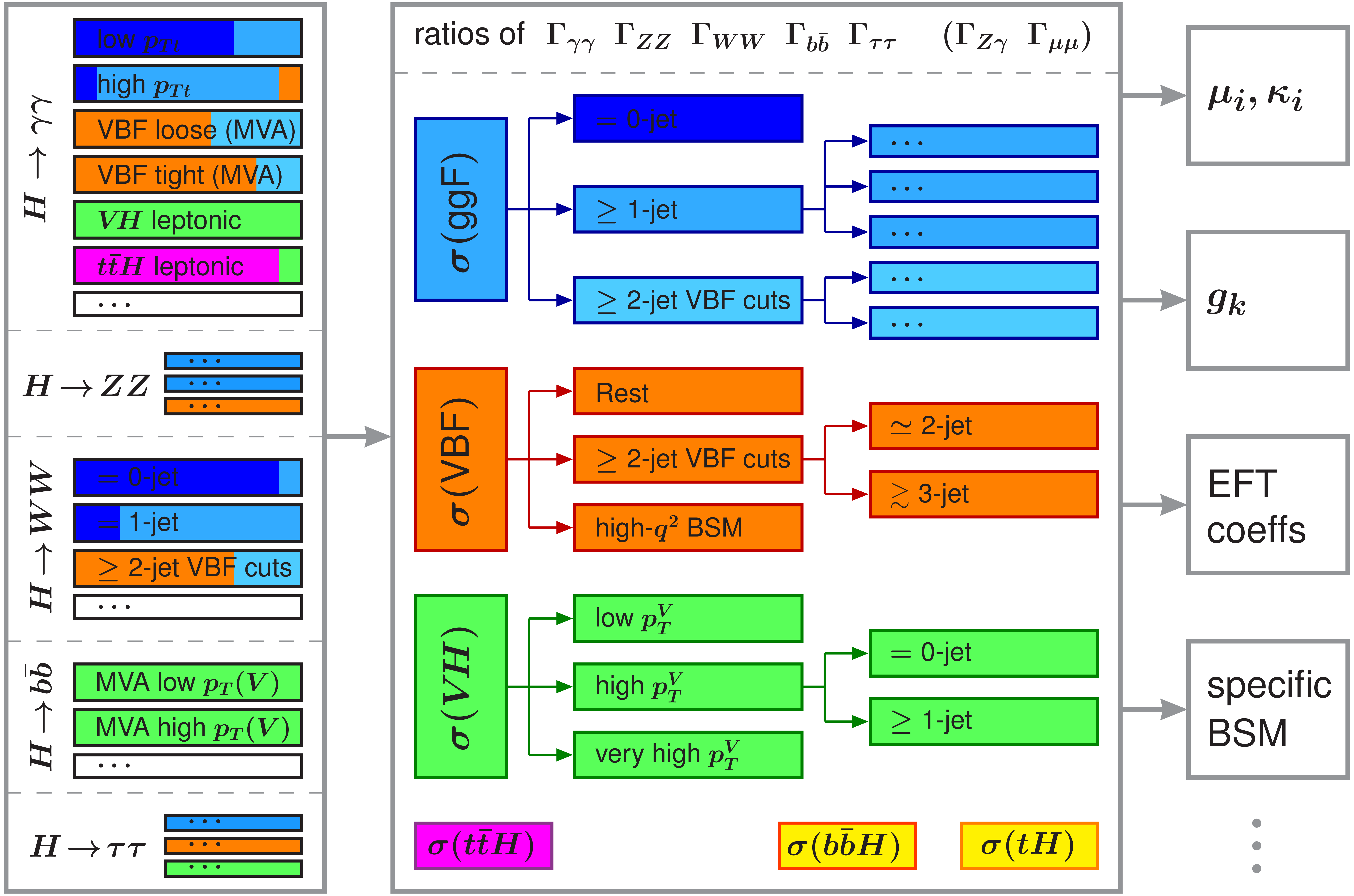
We are officially entering in the **precision era of the Higgs physics**

Looking forward to see results from Run3

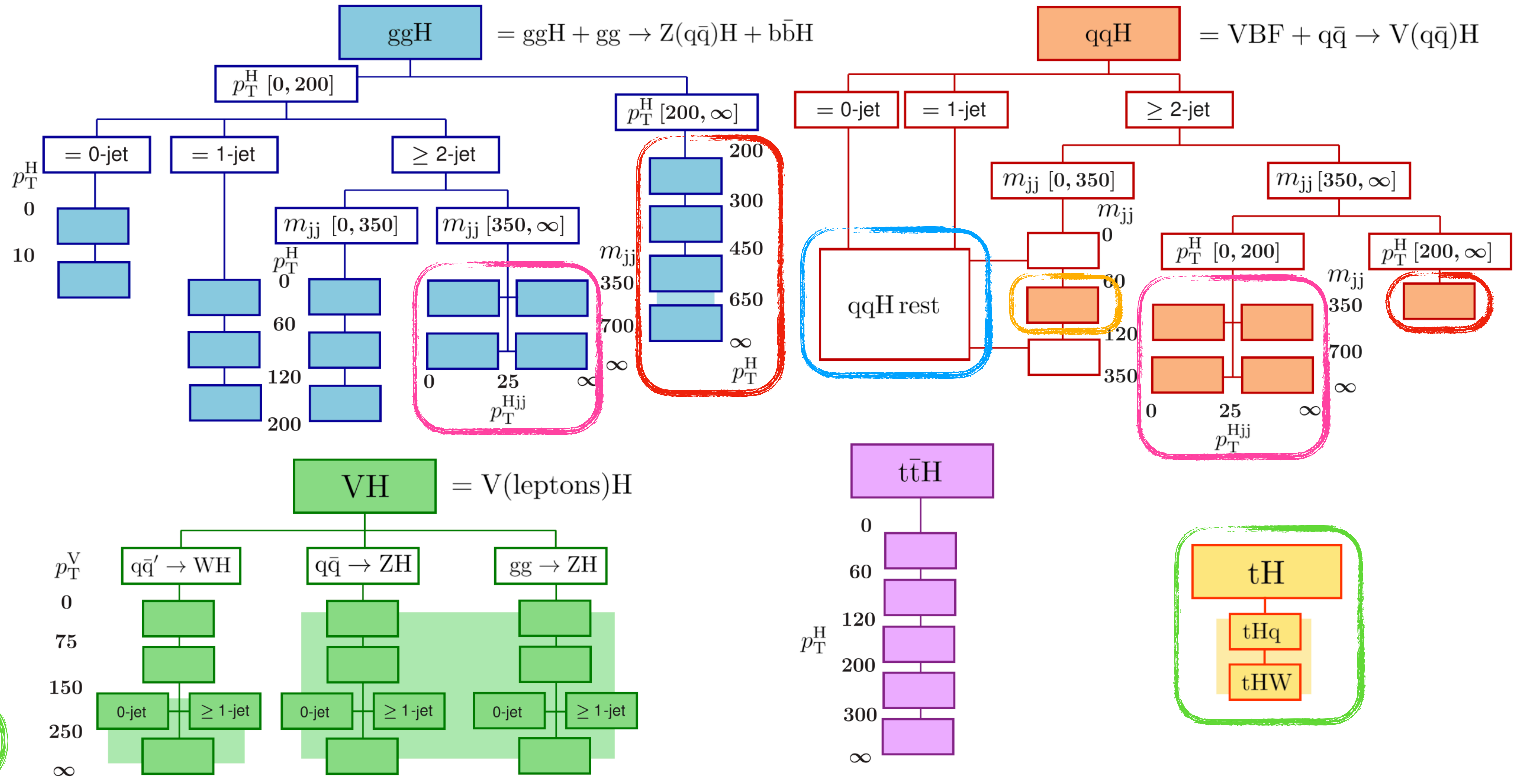
Backup

STXS workflow

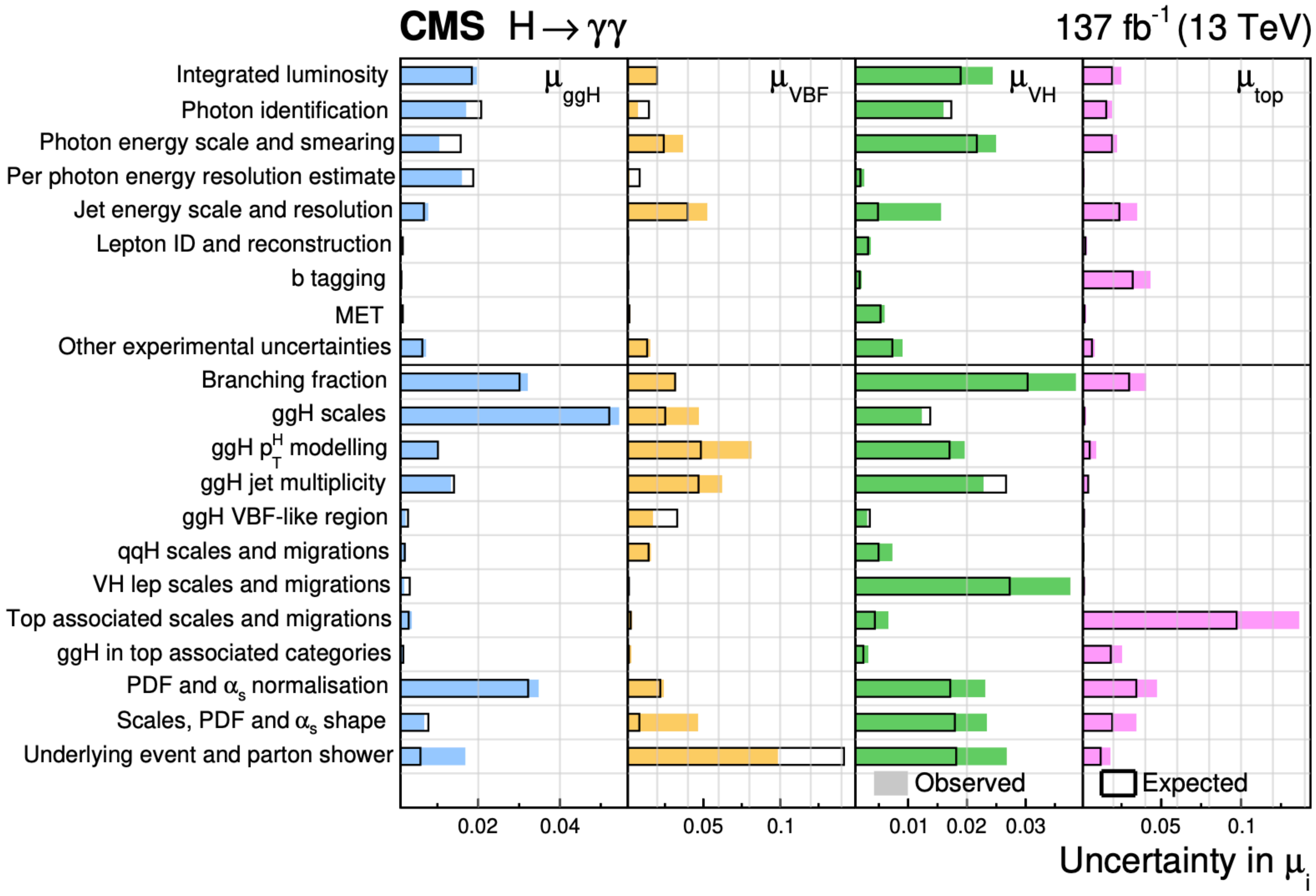


STXS scheme in $H \rightarrow \gamma\gamma$

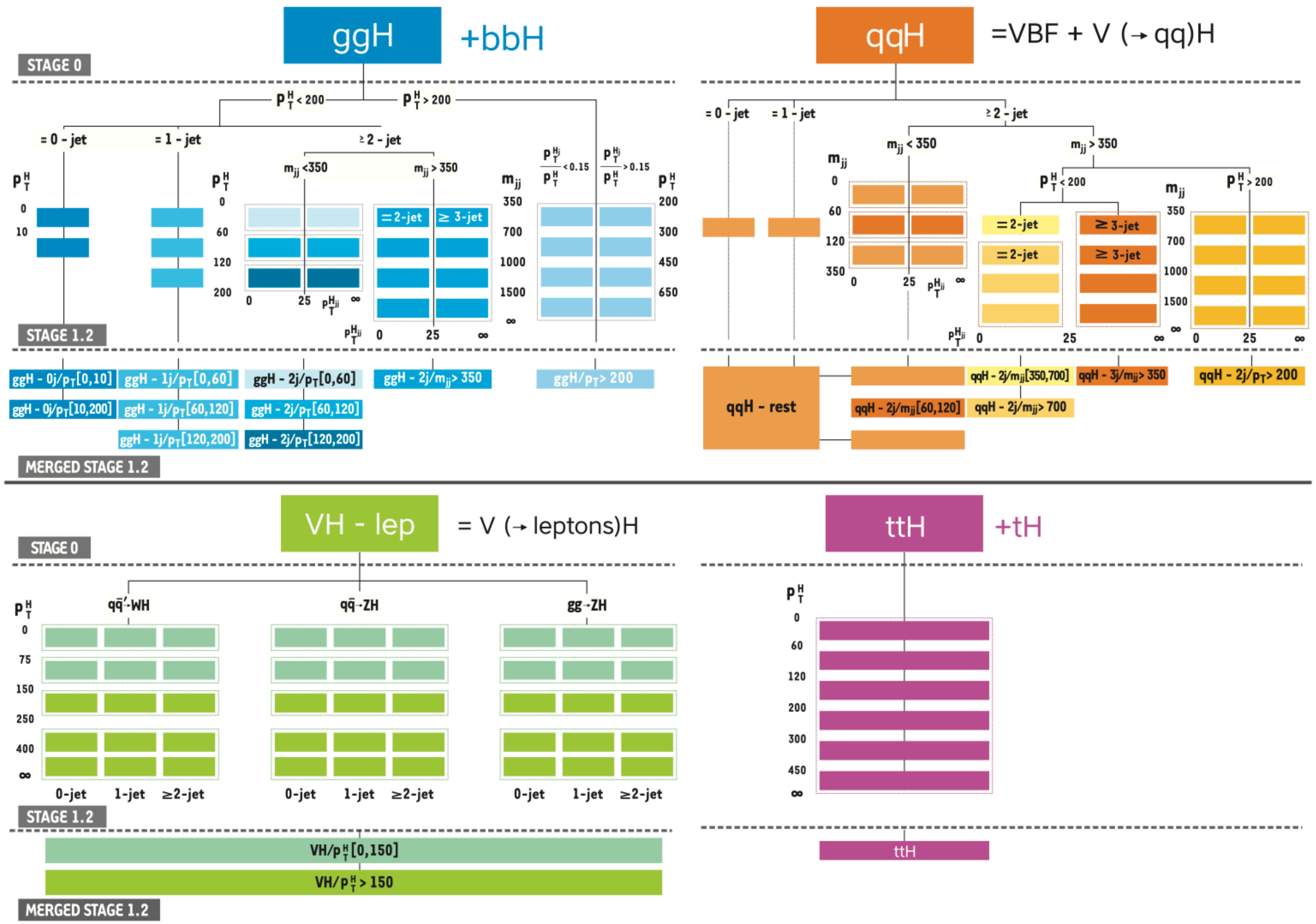
- Bins referred to as BSM: low XS in the SM that could be enhanced by the presence of additional BSM particles
- No analysis categories to target qqH rest: fixed to SM value
- VBF-like bins are categorised together in VBF categorisation
- VH hadronic bins
- tH production mode measured separately from ttH



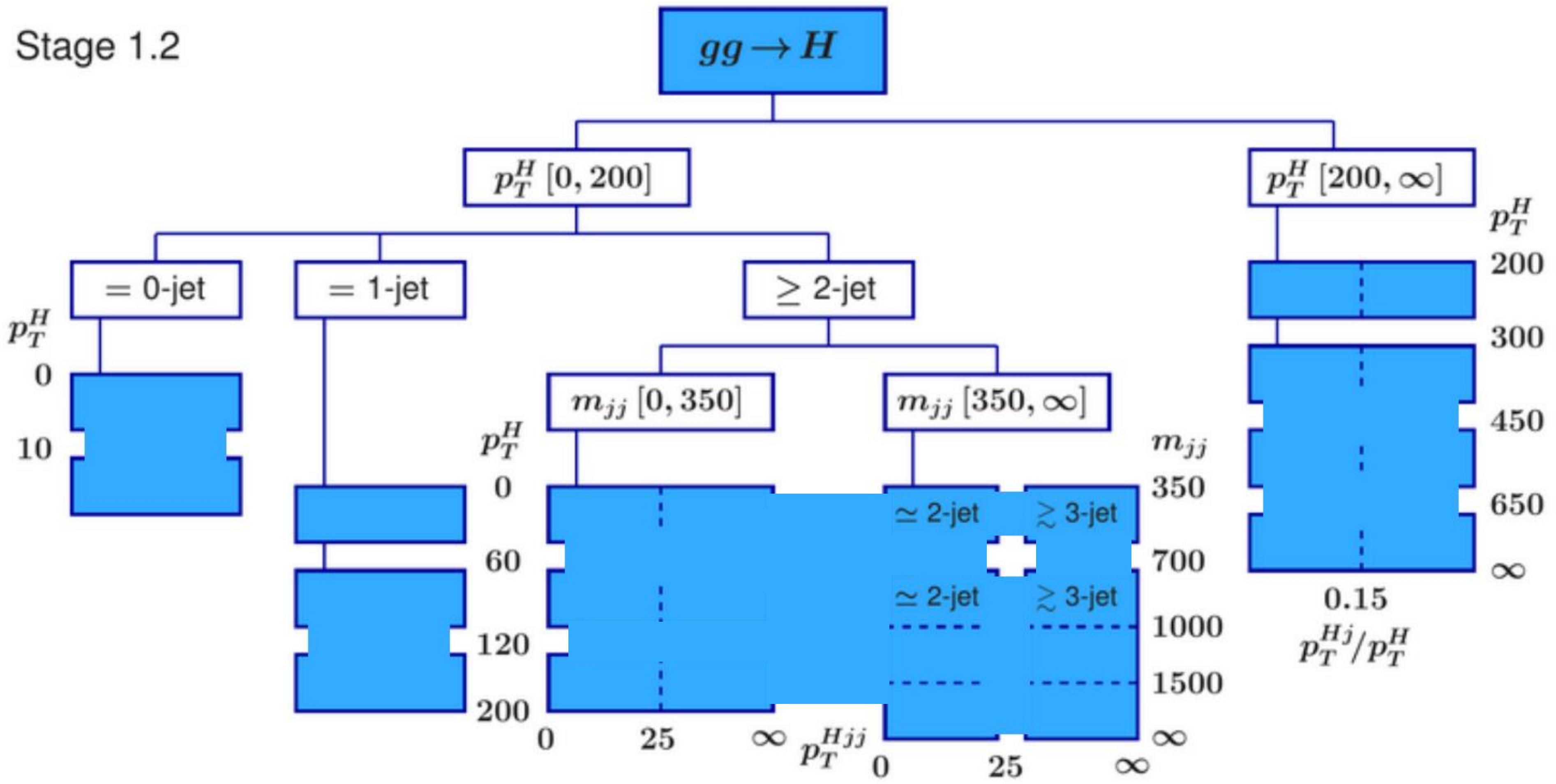
STXS impacts in $H \to \gamma\gamma$

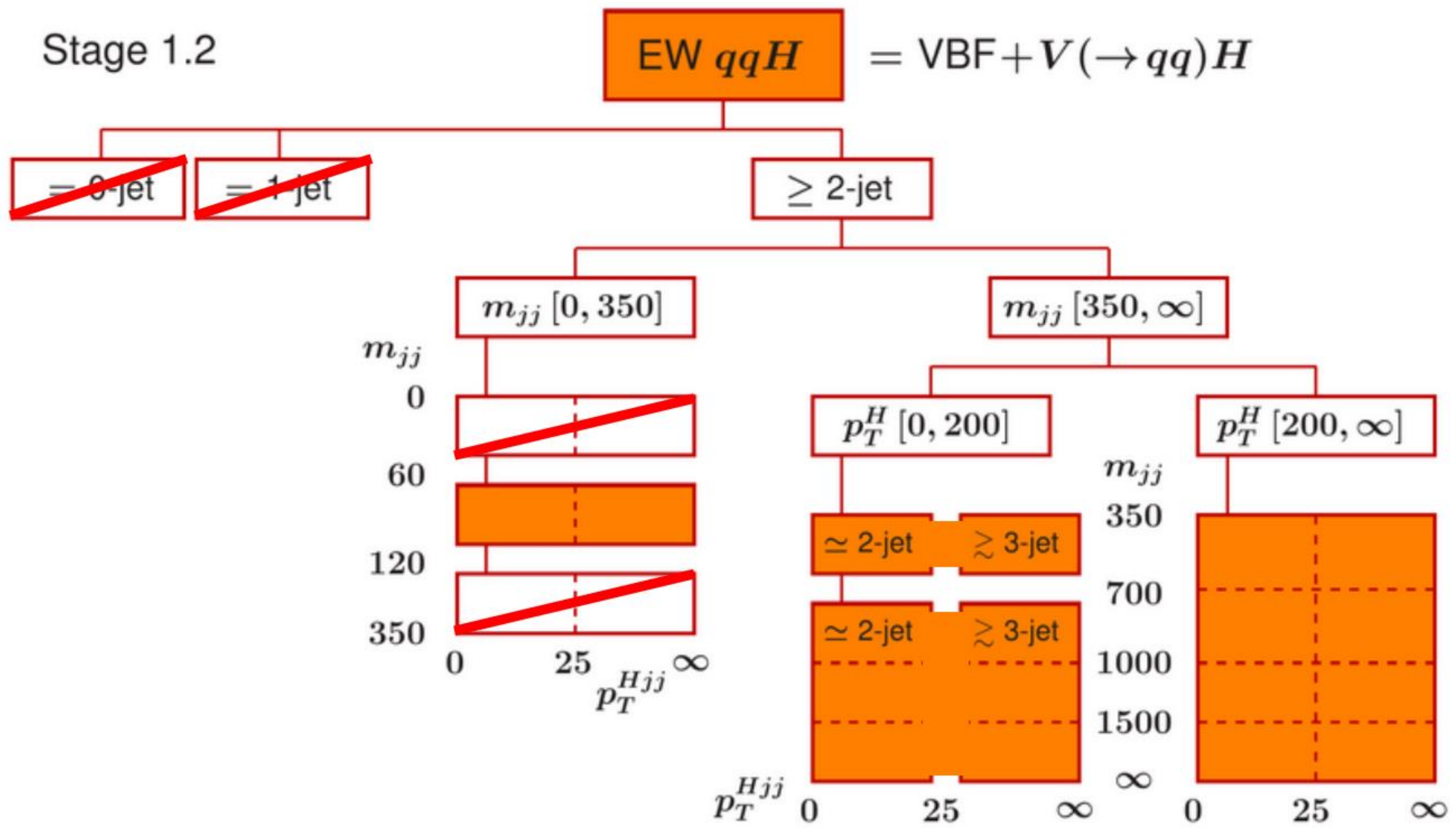


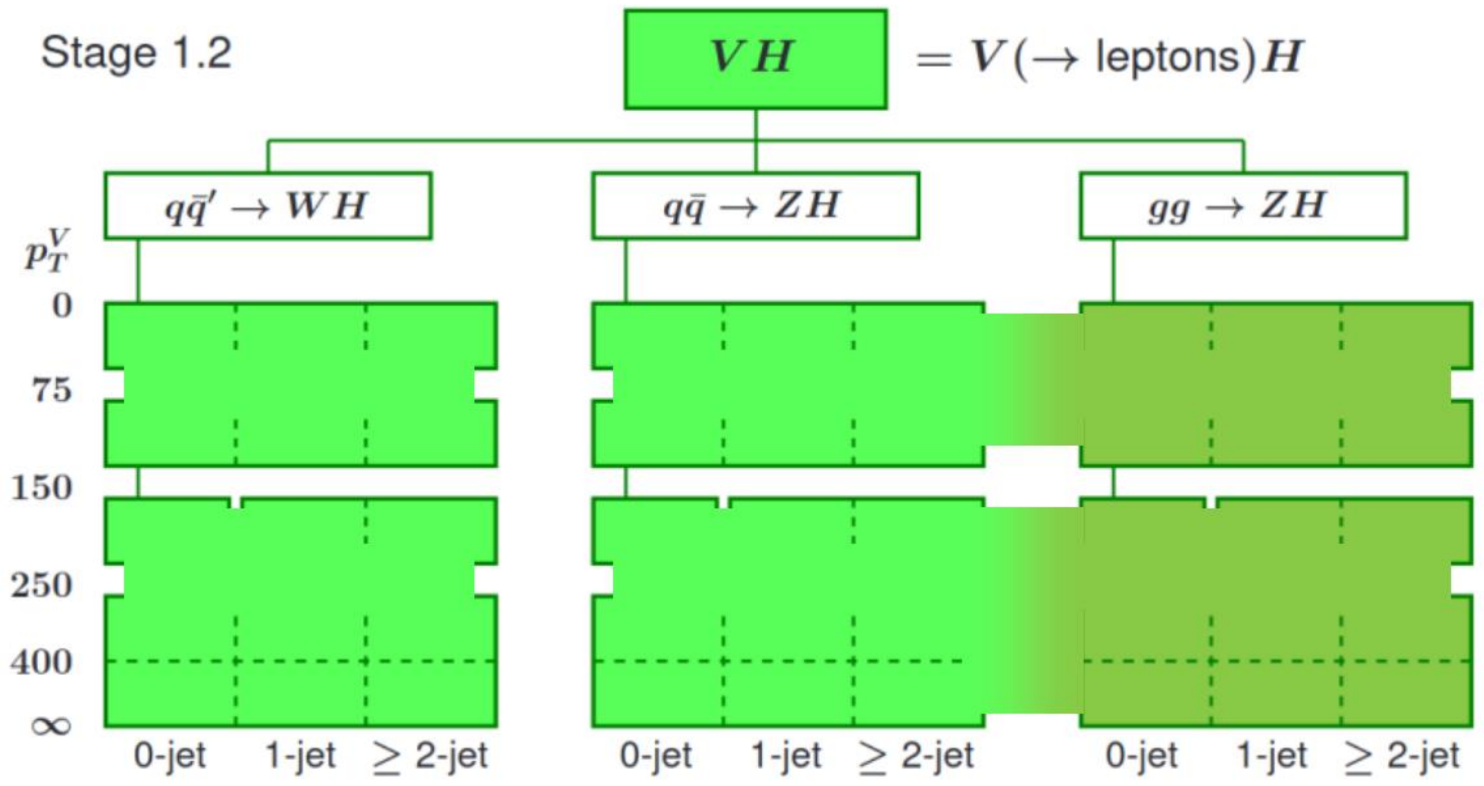
STXS in $H \to ZZ^* \to 4\ell$



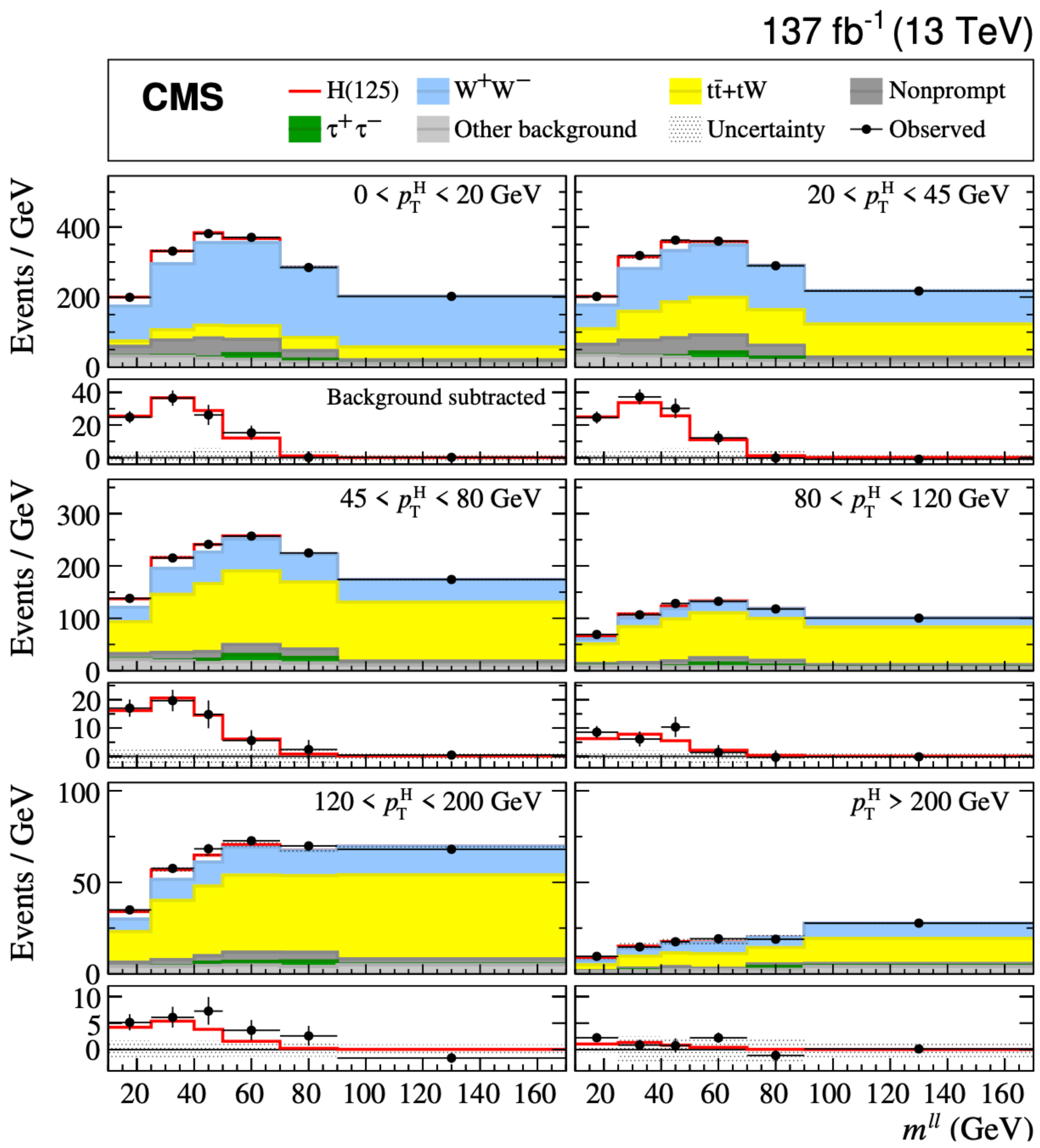
STXS in $H \rightarrow WW$

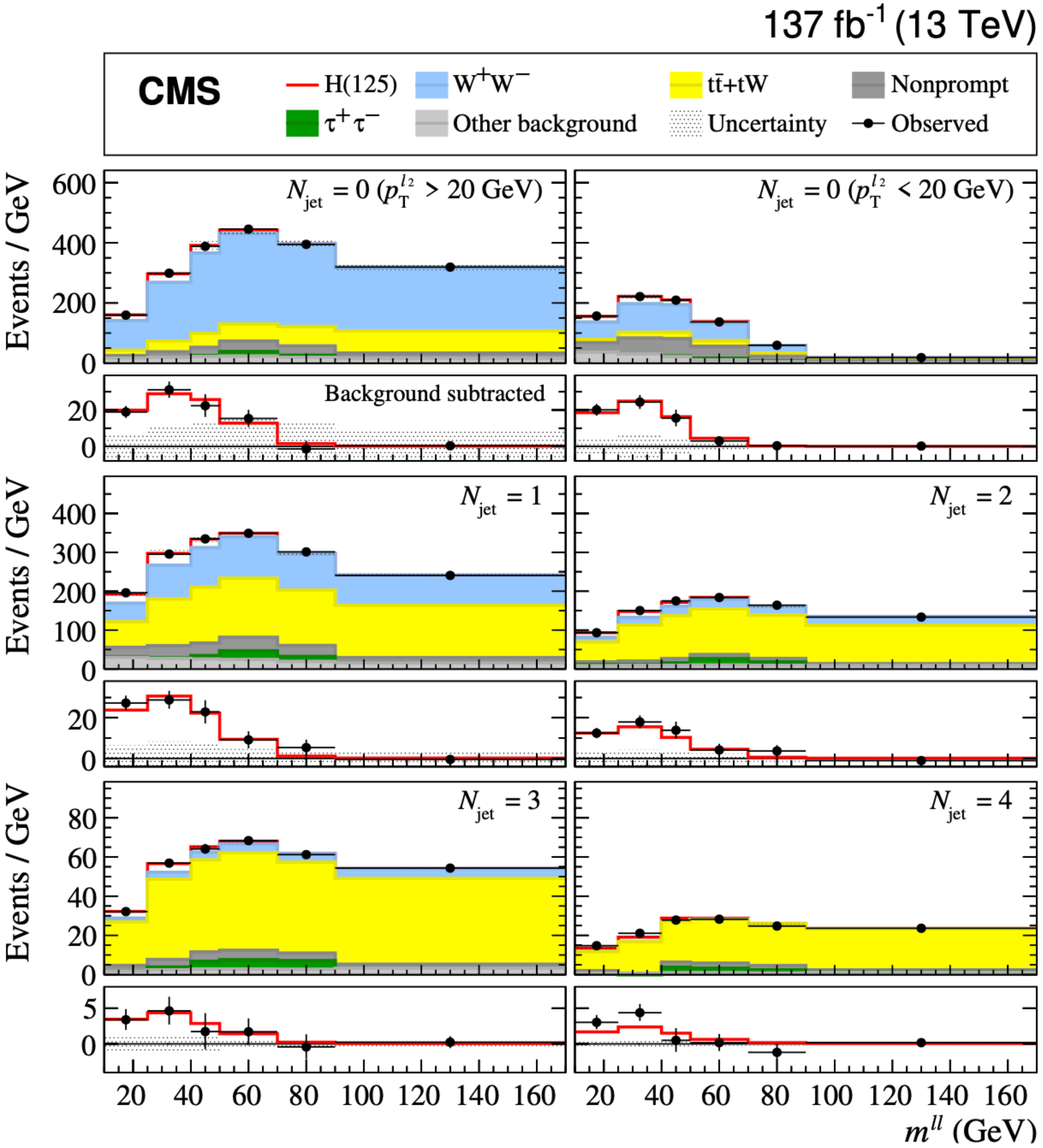






Reco-level differential distributions $H \to WW$





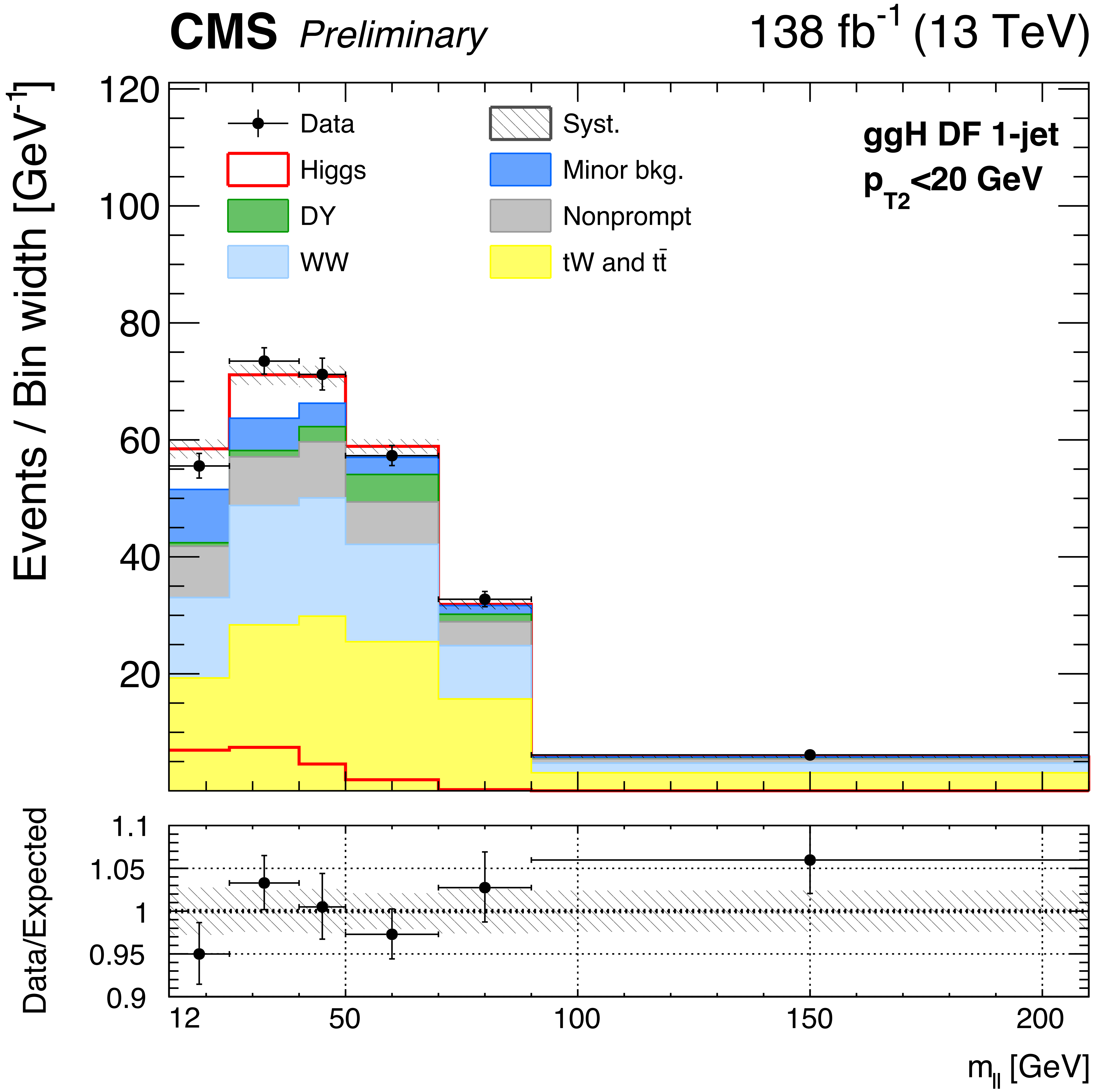
$H \to WW$ backgrounds

- Backgrounds
  - Floating bkg normalisation
    - W^+W^-
    - $t\bar{t} + tW$
    - $\tau^+\tau^-$

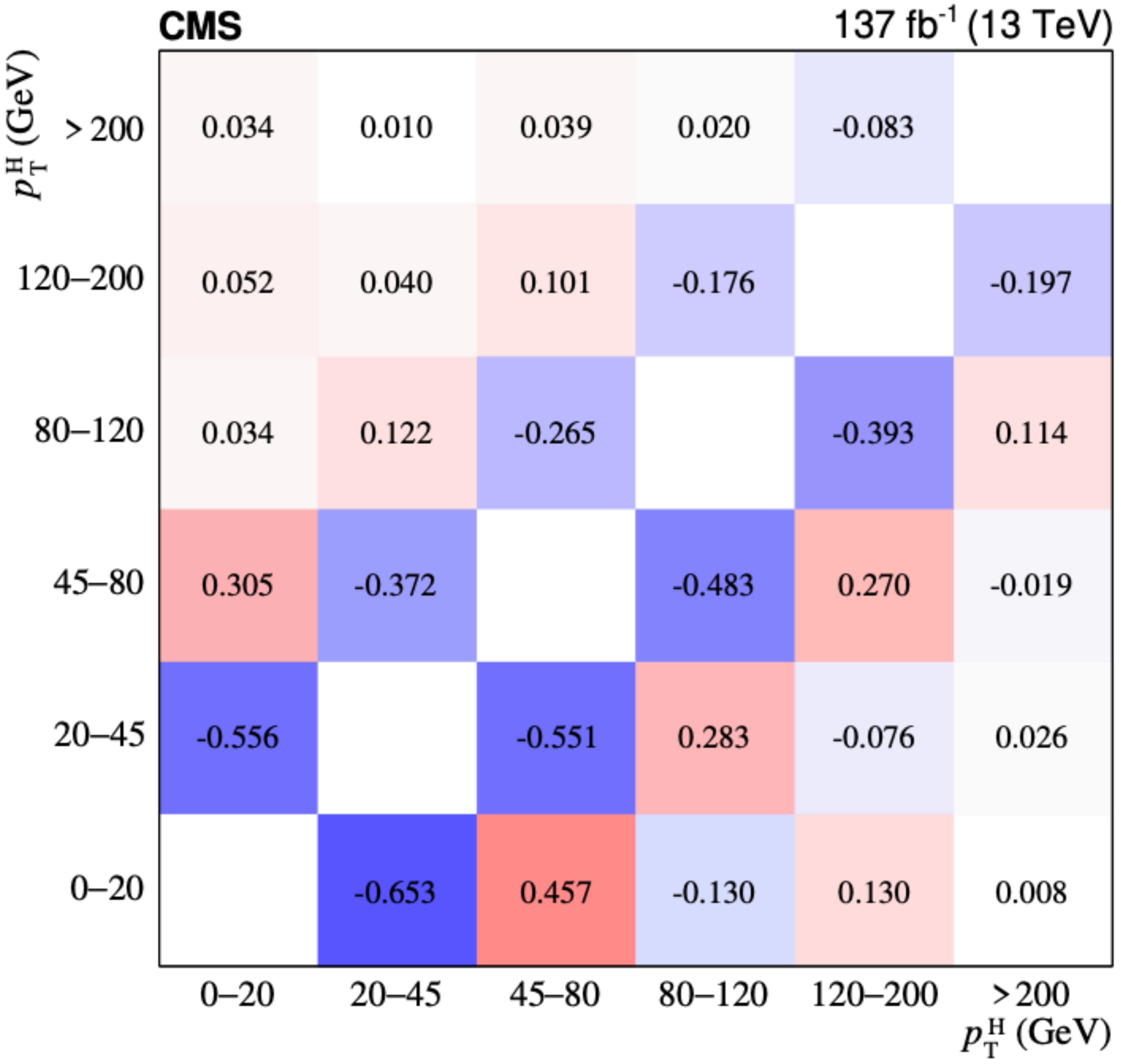
No CR, mostly contained by the high $m^{\ell\ell}$ region

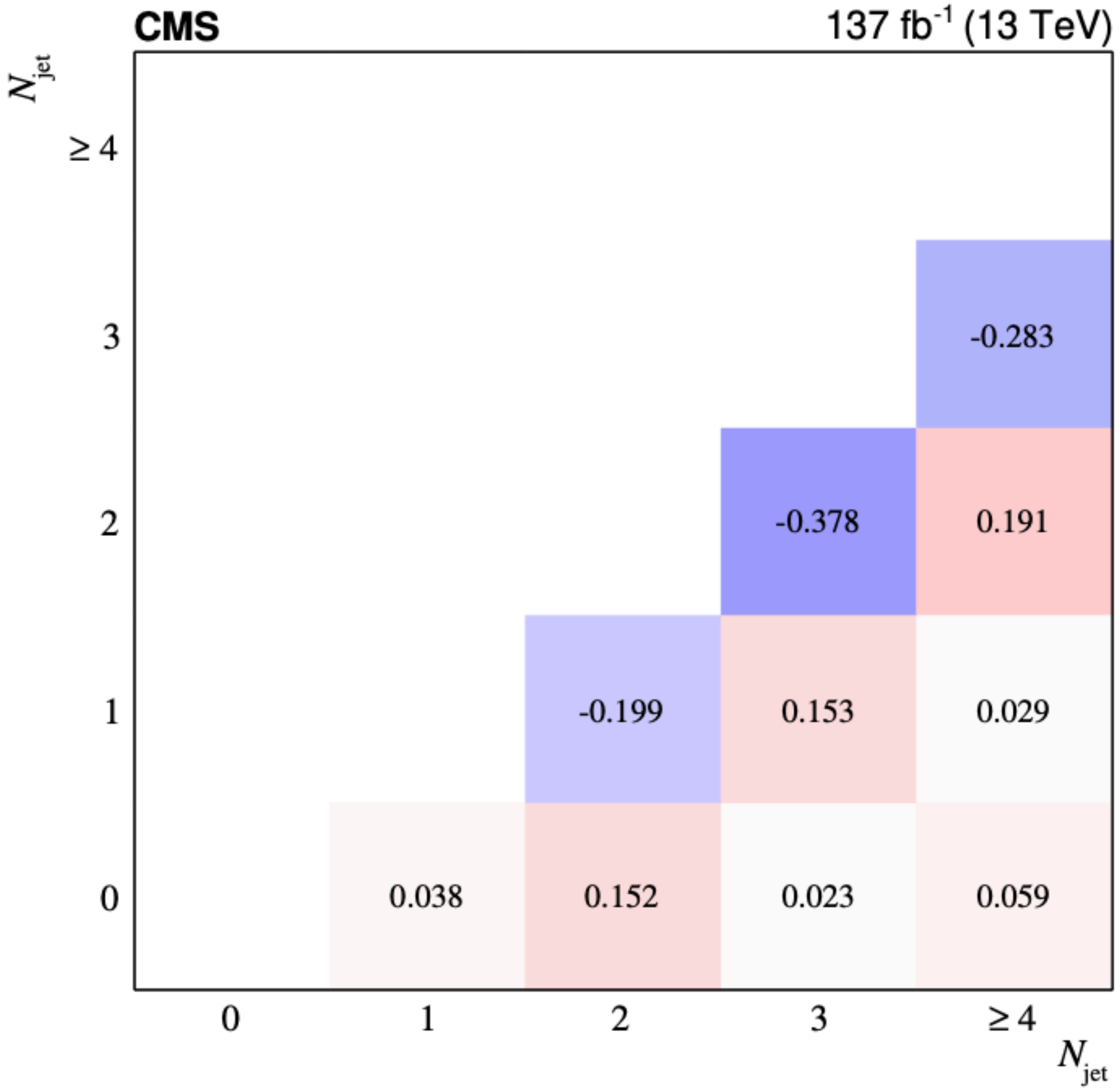
CRs to help the fit

  - MC estimation
    - Minor bkg: $W\gamma$, diboson, W^+W^-+2jets, etc.
  - Data-driven method
    - Non-prompt leptons



Correlations matrices for fiducial $H \to WW$





$H \to ZZ^* \to 4\ell$ mus impacts