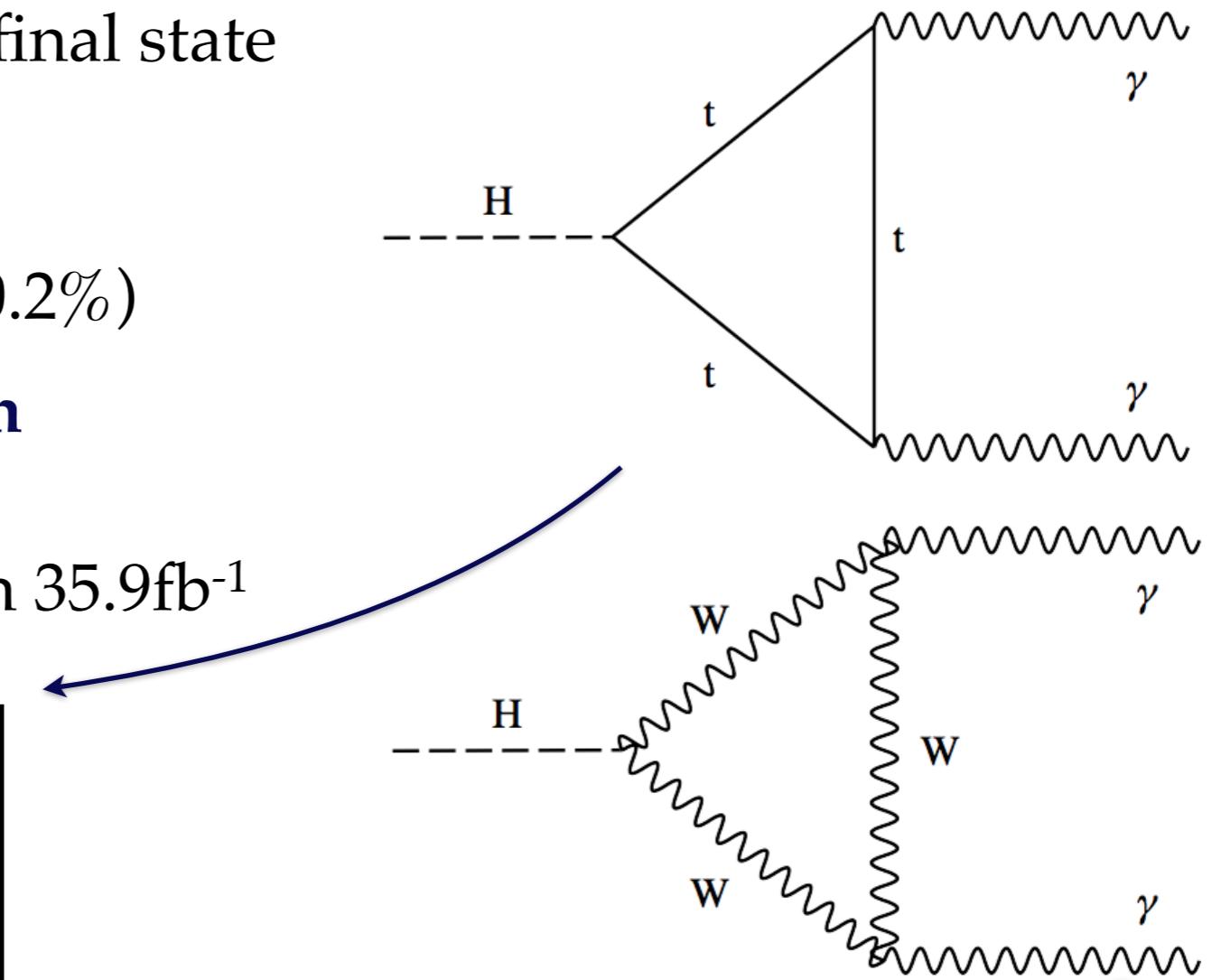
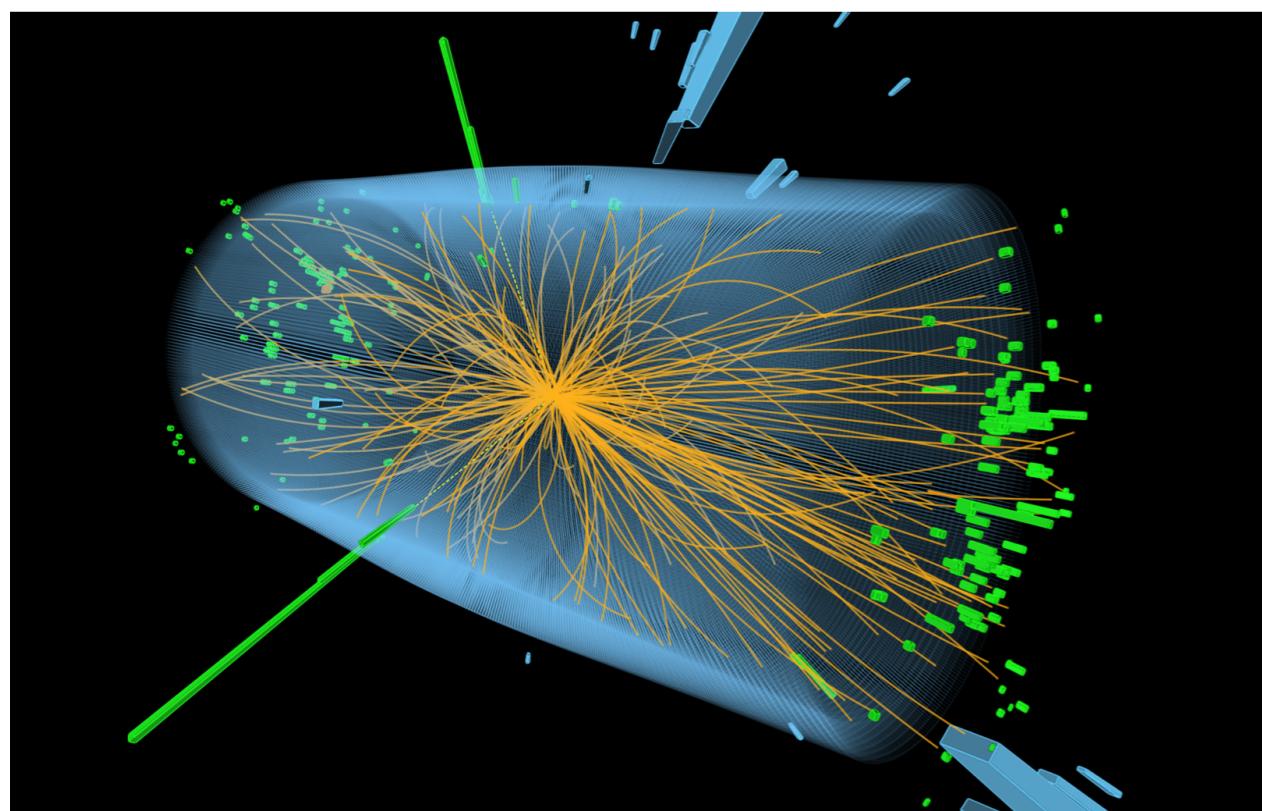


Measurements of the Higgs boson decaying into two photons at CMS

Ed Scott, on behalf of the CMS Collaboration

ICHEP, Seoul, 6th July 2018

- High resolution channel with clean final state containing two energetic photons
- Key to discovery despite low BR ($\sim 0.2\%$)
- **Now ideal for performing precision measurements of Higgs properties:**
select almost 2000 signal events with 35.9fb^{-1}



- CMS has analysed the full 2016 dataset of 35.9fb^{-1}
- Submitted to JHEP in April

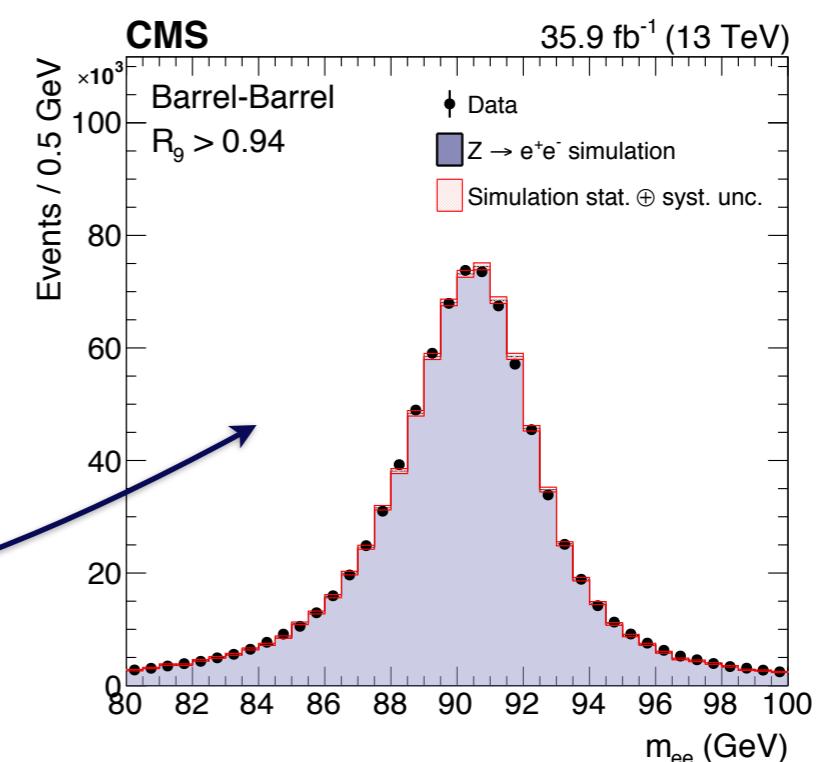
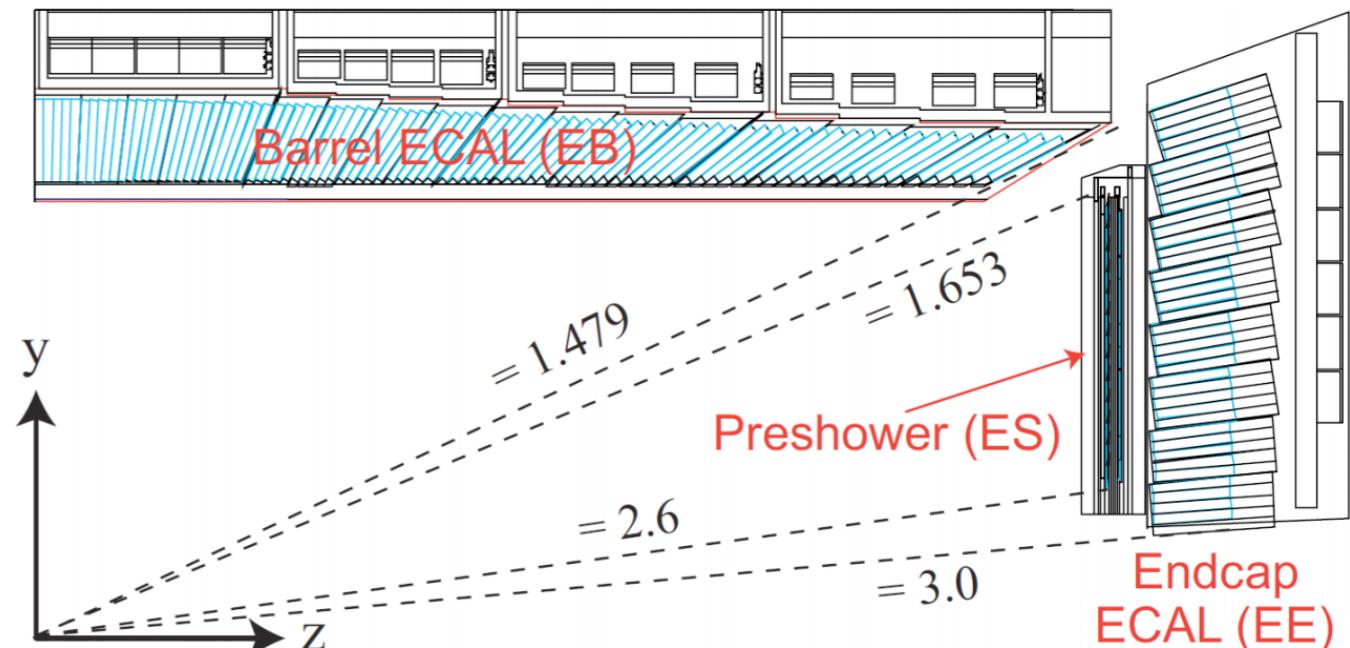
- Construct categories **targeting different Higgs production mechanisms**
 - ◆ achieved by using several multivariate discriminators at various levels
- And further split by signal-to-background ratio if beneficial
- Extract signal strength by performing a simultaneous fit to the $m_{\gamma\gamma}$ distribution in each category
- Now have enough $\gamma\gamma$ events to measure rare Higgs production processes, along with precision measurements of other quantities
 - ◆ cross-sections: inclusive, different production modes, and differential
 - see [talk from V. Tavolaro](#) for **new $\gamma\gamma$ differential results**
 - ◆ Higgs mass: this requires detailed knowledge of the energy scale systematics
 - produced result with full Run 1 dataset: $m_H = 124.70 \pm 0.34$ GeV
 - **update with Run 2 data is in progress**

Photon energy scale

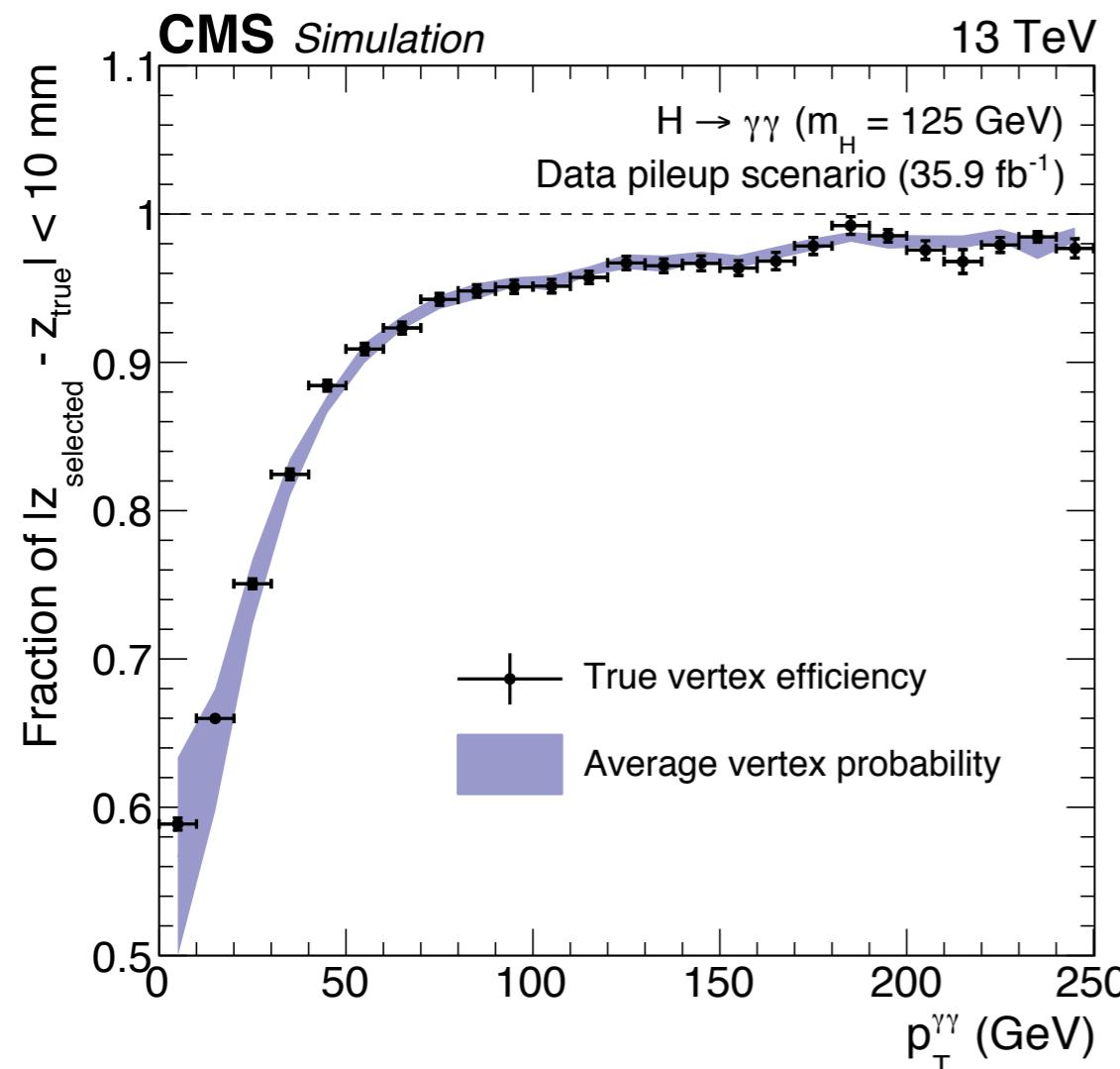


$$m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos \theta)}$$

- Electromagnetic calorimeter formed of lead tungstate crystals
- Response calibrated and corrected for changes over time
- **Photon energy and its uncertainty estimated using multivariate regression**
 - ◆ inputs: shower shape & position
- Data energy scale & MC resolution corrected using $Z \rightarrow ee$ events

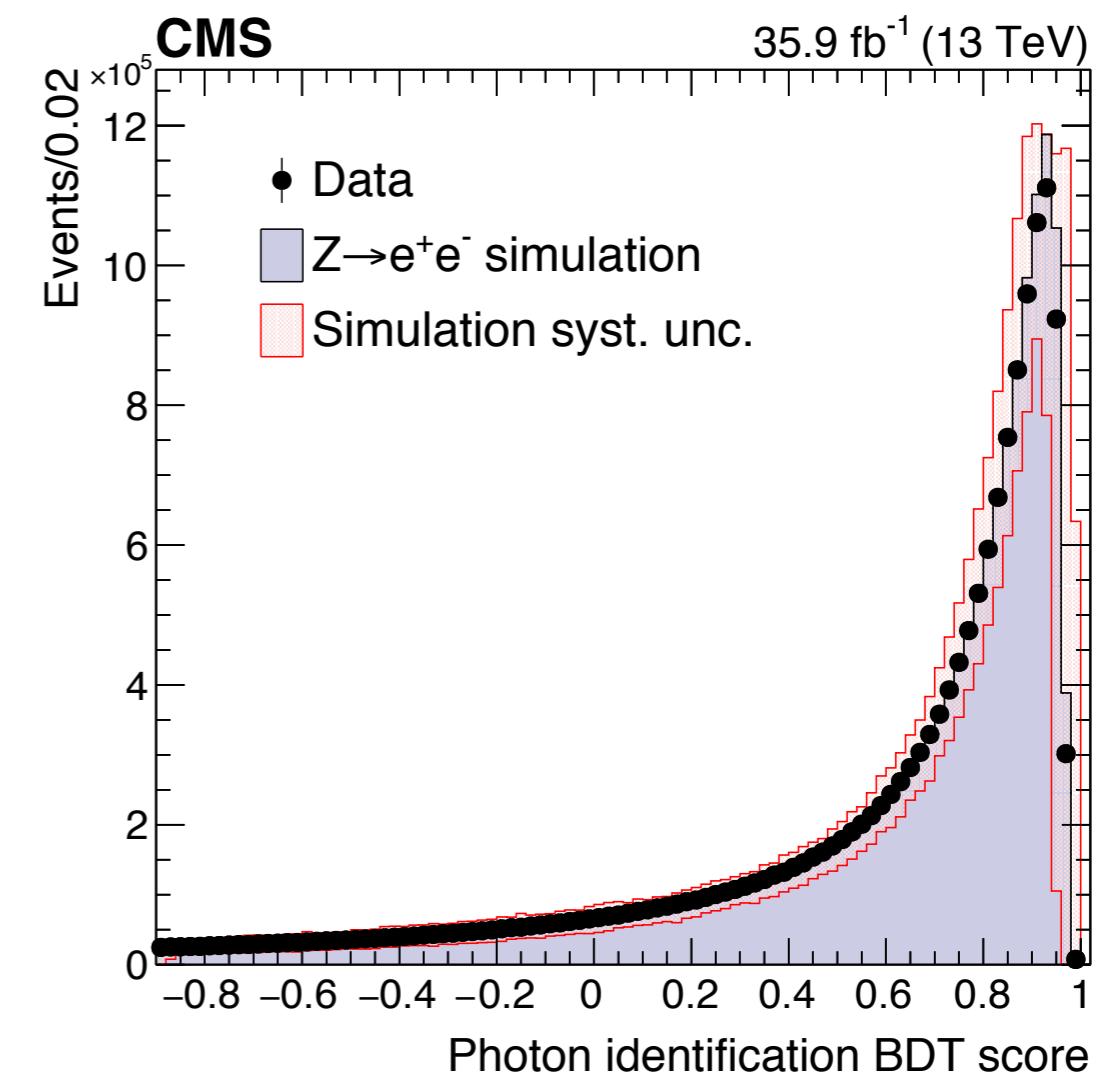
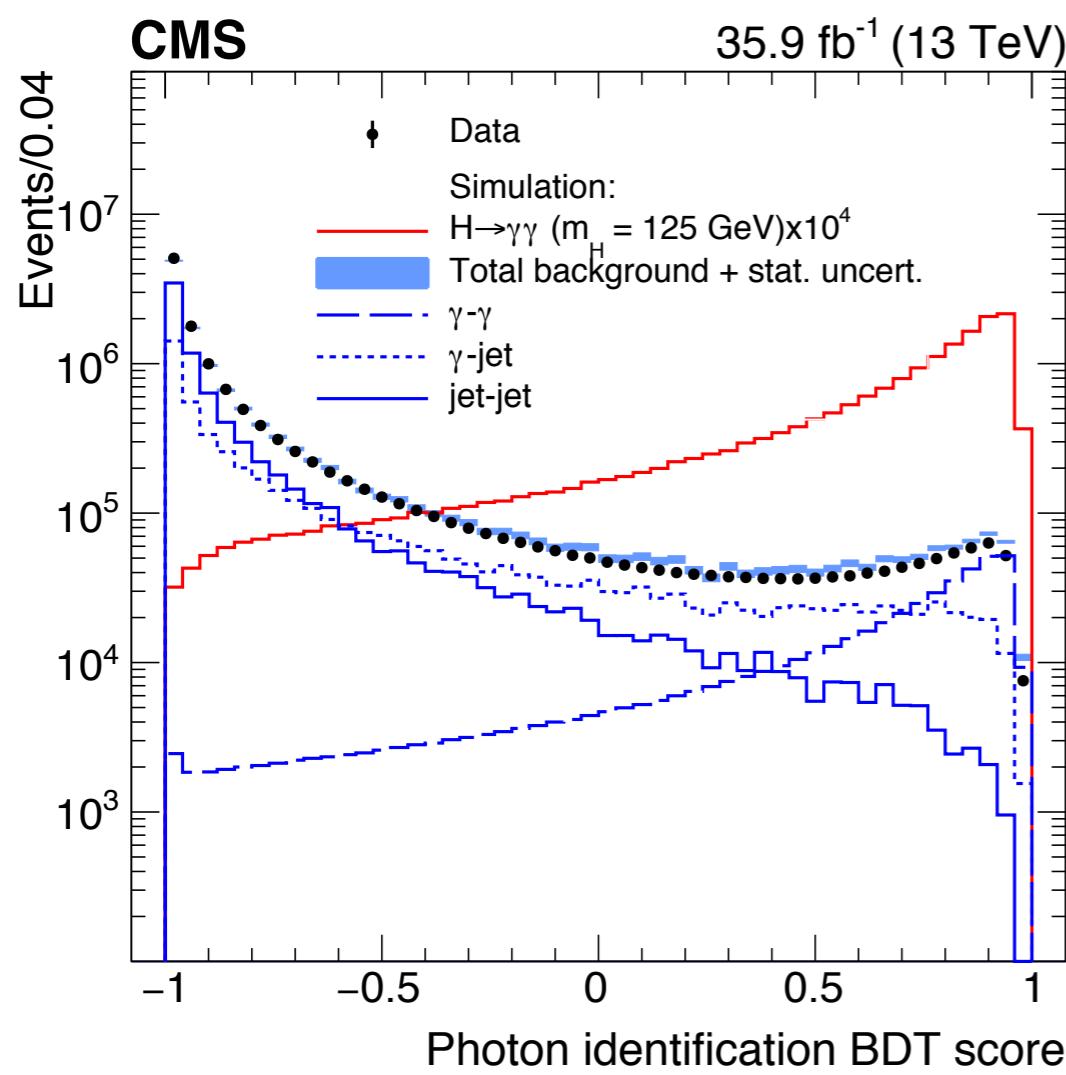


$$m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos \theta)}$$

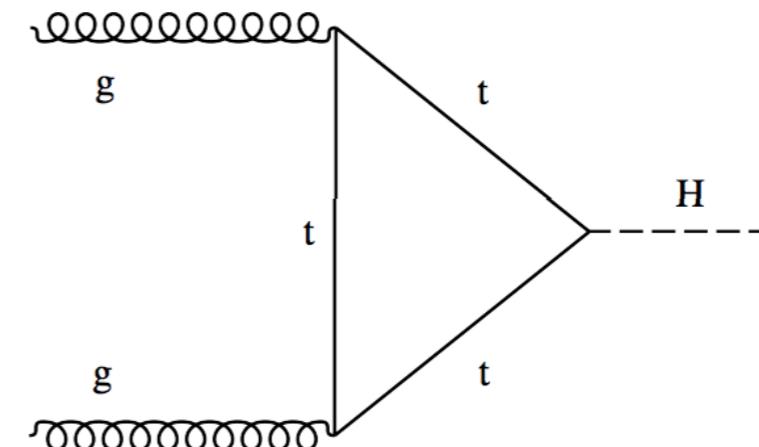
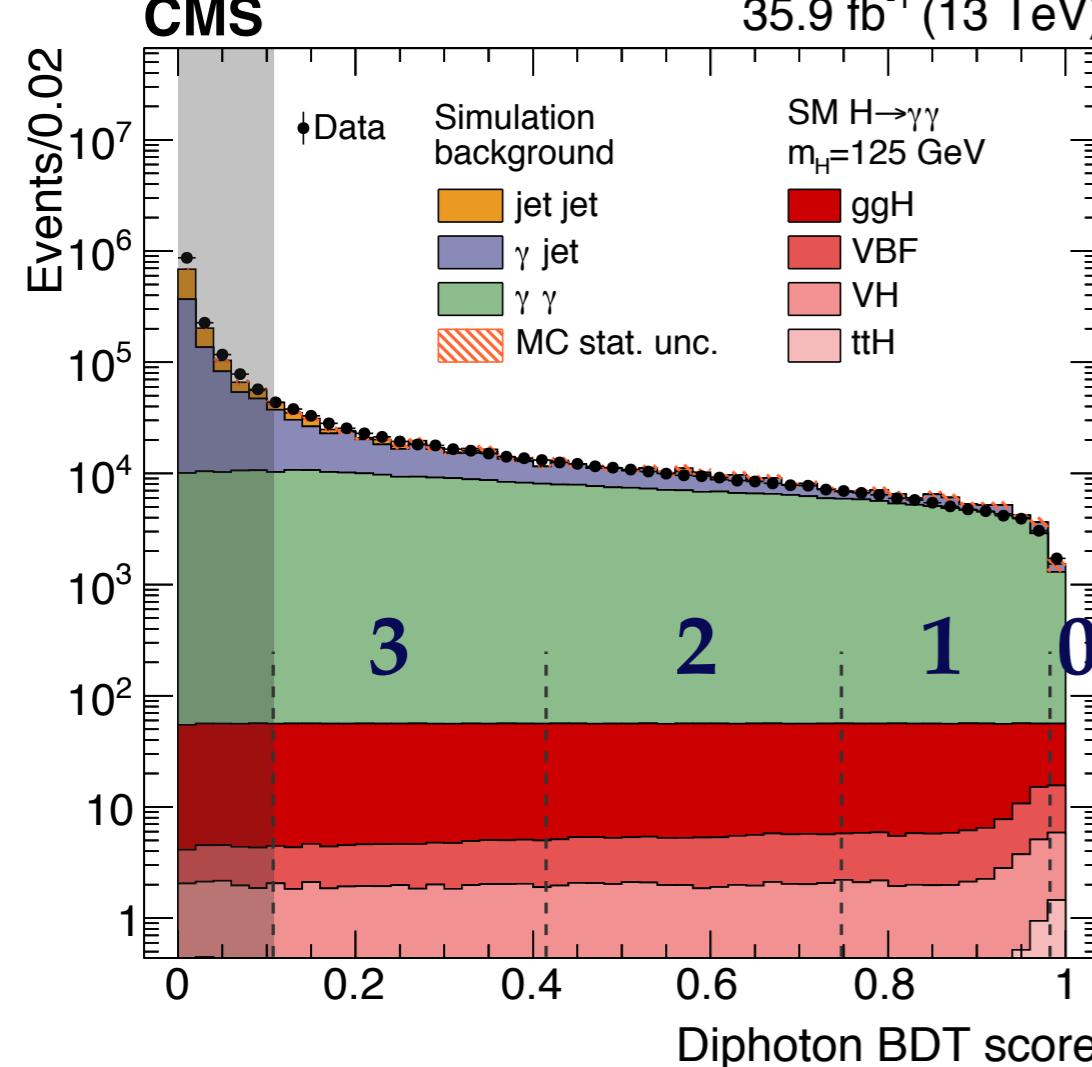


- Choosing a vertex **within 1cm of true interaction** → no impact on resolution
- Use boosted decision tree (BDT) to select diphoton vertex
 - ◆ inputs relate to p_T of tracks recoiling against the diphoton system
- Efficiency improves with Higgs p_T ; **integrated efficiency ~80%**
- Second BDT estimates probability the vertex choice is correct

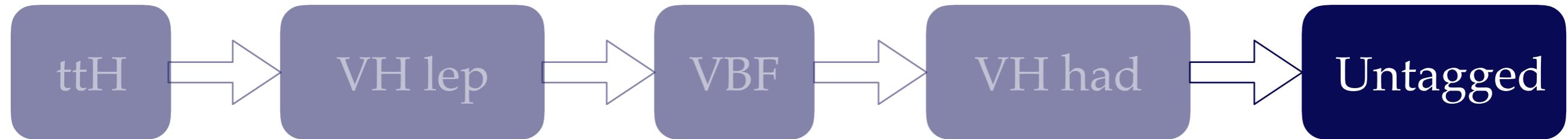
- A photon identification BDT is used to preferentially select prompt photons
- **Shower shape, isolation, and kinematic variables** are included as inputs
- Validate by checking data/MC agreement in $Z \rightarrow ee$ events



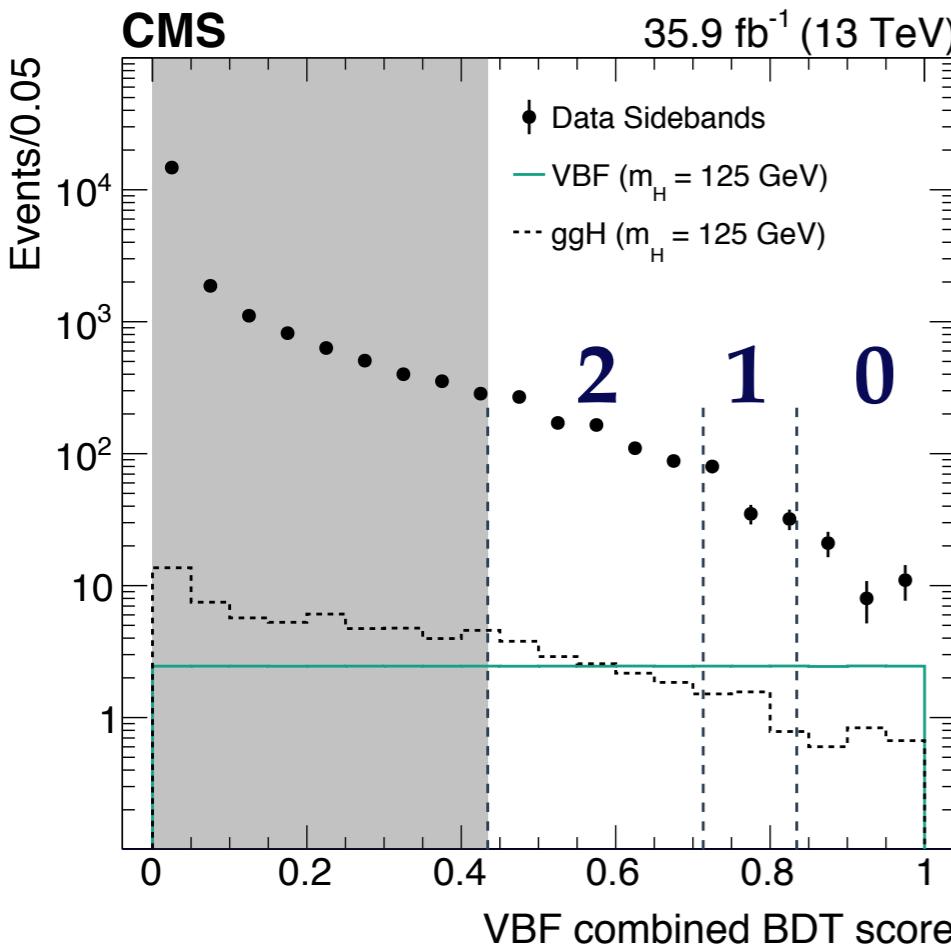
Untagged categories



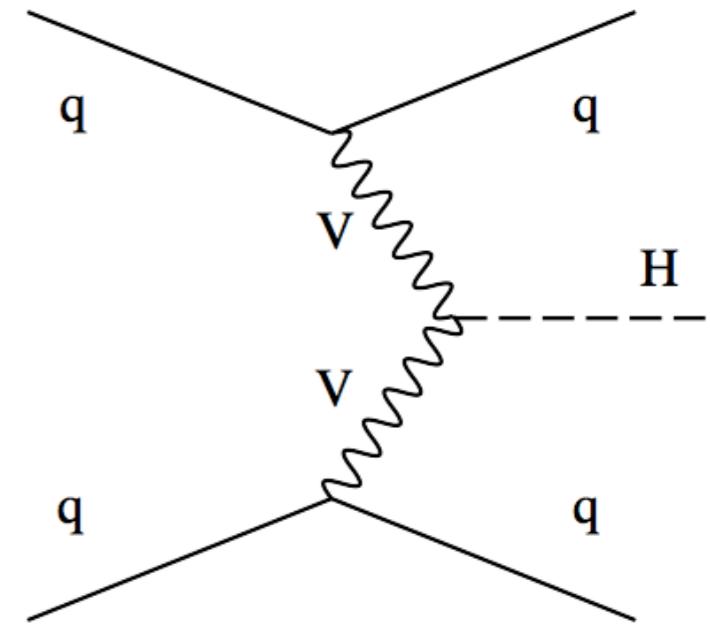
- Untagged events are split using a diphoton BDT
- **Photon kinematics & identification score, with mass resolution vertex probability estimates, are used as inputs**
- Defines four categories with decreasing S/B
- Also used in tags targeting specific modes



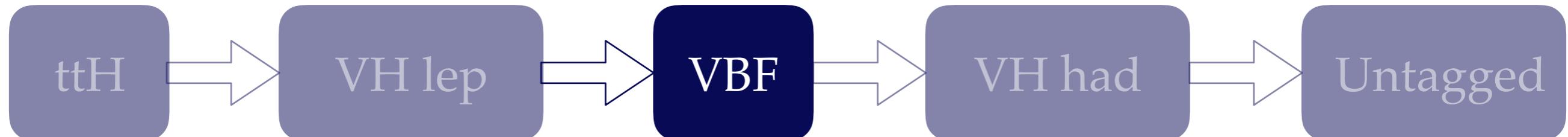
VBF categories



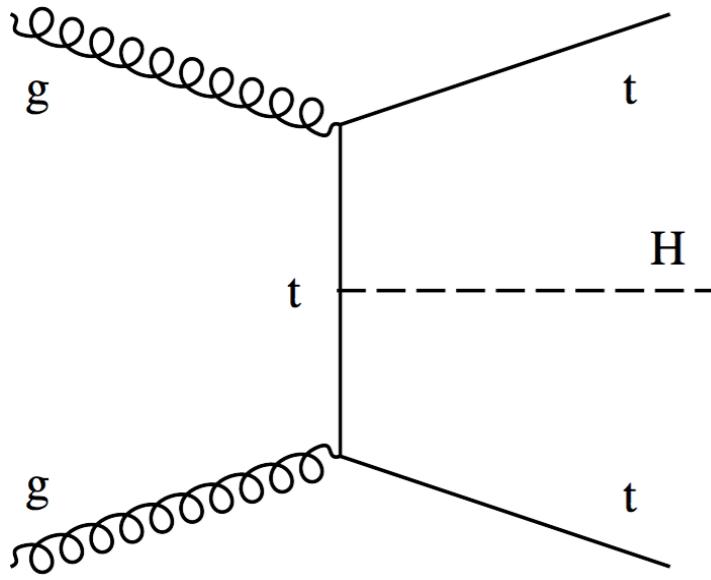
- Dijet preselection:
 - jet $p_T > 40$ (30) GeV
 - $|\eta| < 4.7$
 - tight pileup ID
 - $m_{jj} > 250$ GeV
- BDT strategy:
 1. construct dijet BDT
 2. construct “combined” BDT with diphoton + dijet info



- Inputs to dijet BDT include jet + dijet kinematics, plus angular variables
- The combined BDT then uses the diphoton + dijet BDTs, along with $p_{T,\gamma}/m_{\gamma\gamma}$
- Combined BDT defines three categories; other events pass to untagged

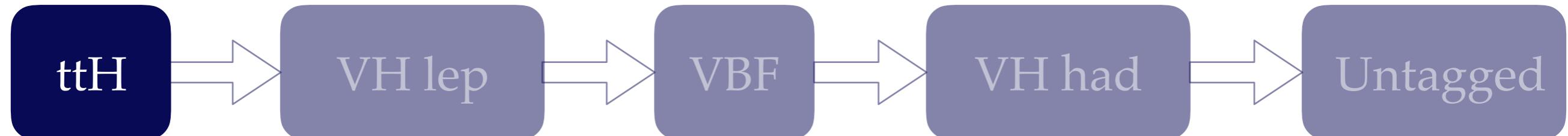
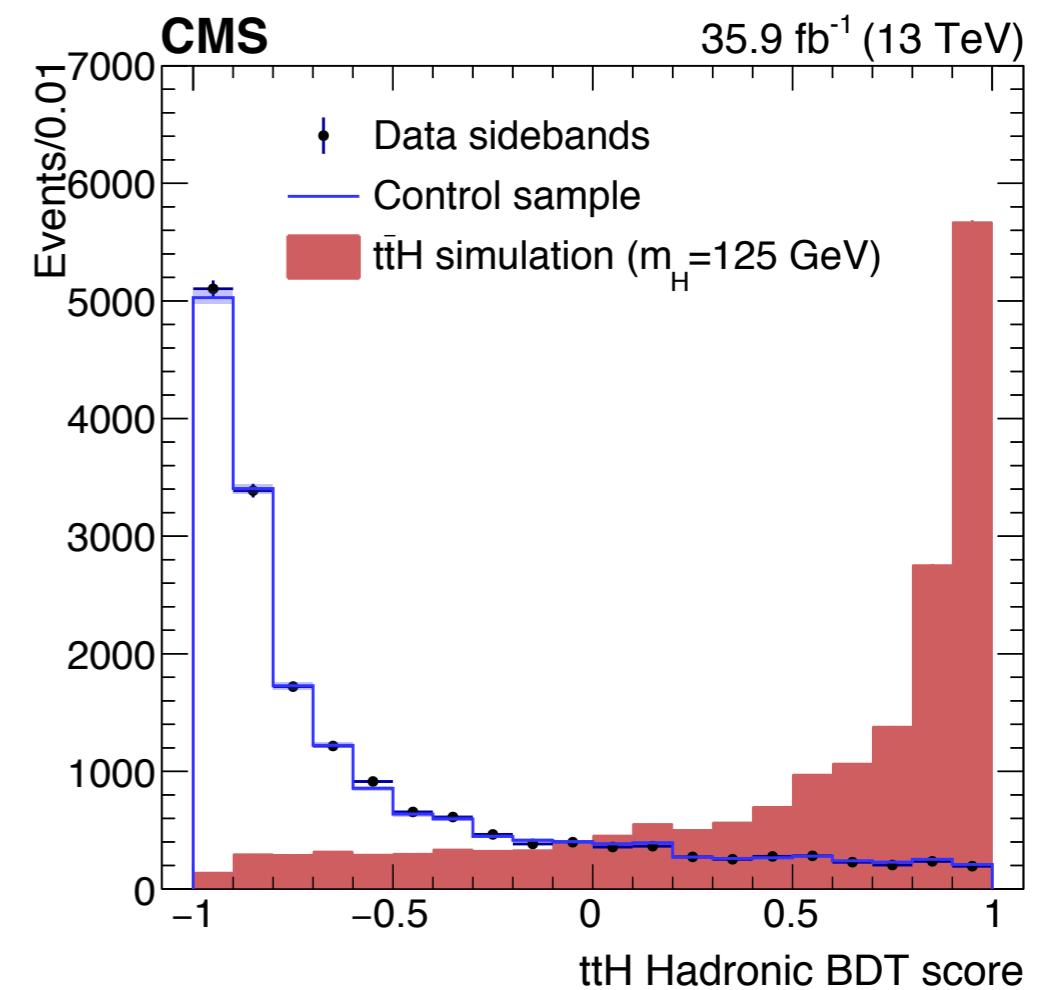


ttH categories

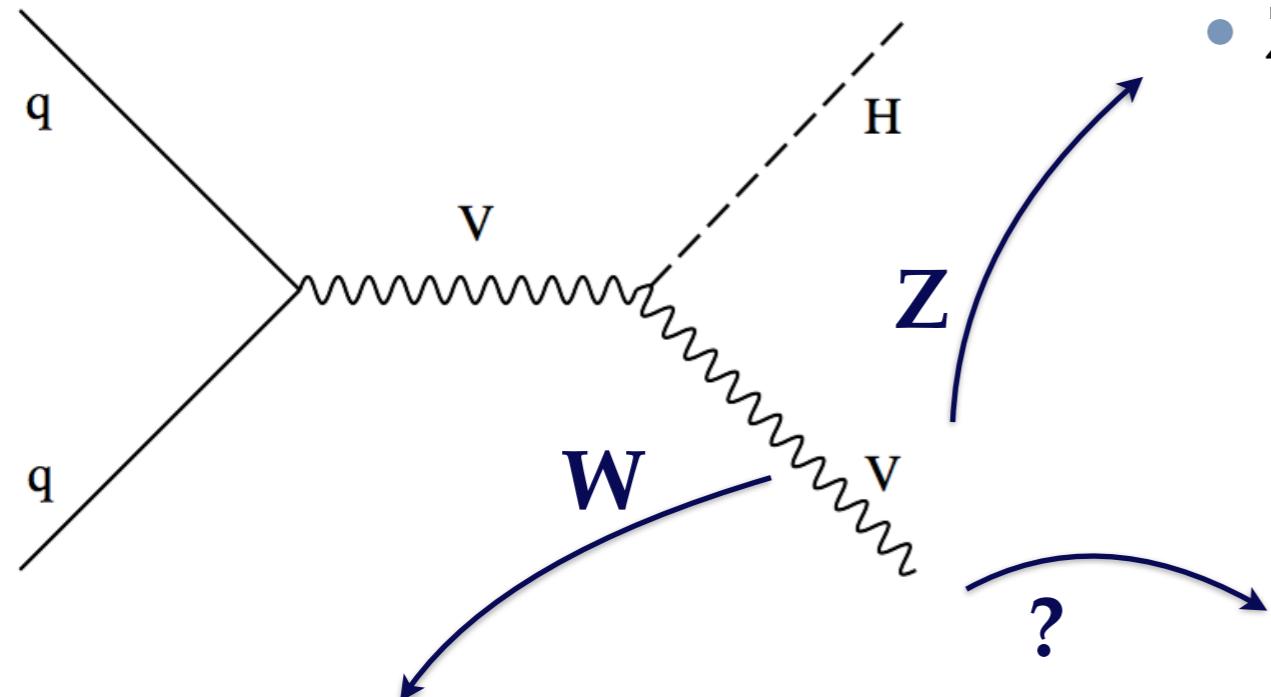


- Leptonic tag:
 - ◆ ≥ 1 lepton (well-separated from jets, photons)
 - ◆ ≥ 2 jets (well-separated), with at least one b-tagged

- Hadronic tag: 0 leptons, ≥ 3 jets, ≥ 1 b-jet, plus a **requirement on dedicated BDT**
 - ◆ just three inputs: number of jets, leading jet p_T , and two highest b-tag scores
 - ◆ good agreement between data sidebands and control region



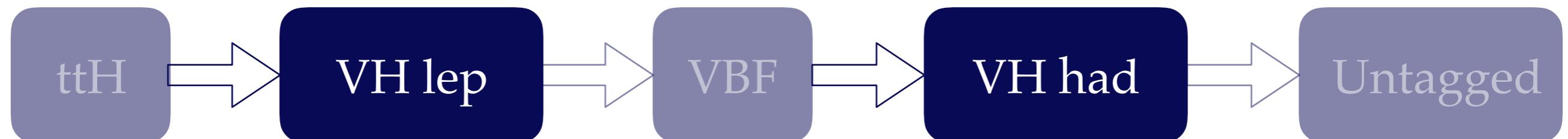
VH categories



- WH leptonic tag:
 - ◆ ≥ 1 lepton, $p_T > 20$ GeV
 - ◆ conversion veto for electrons
 - ◆ $p_T^{\text{miss}} > 45$ GeV
 - ◆ ≤ 2 jets

- ZH leptonic tag:
 - ◆ two same-flavour, opposite sign leptons
 - ◆ $70 < m_{ll} < 110$ GeV
 - ◆ conversion veto for electrons

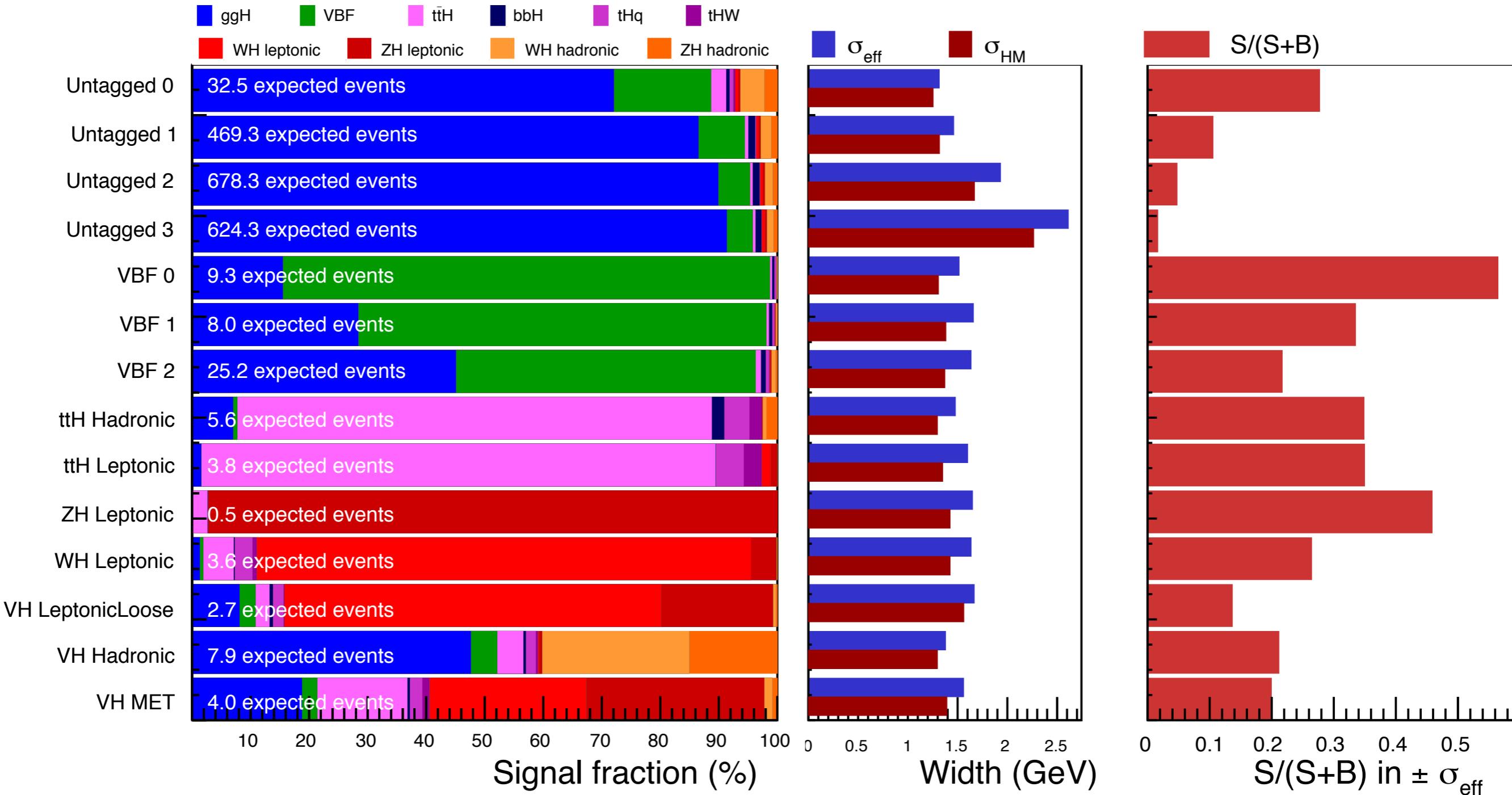
- VH leptonic loose tag: identical to WH leptonic but $p_T^{\text{miss}} < 45$ GeV
- VH MET tag:
 - ◆ $p_T^{\text{miss}} > 85$ GeV, $\Delta\phi(\gamma\gamma, p_T^{\text{miss}}) > 2.4$
- VH hadronic tag:
 - ◆ two jets with $p_T > 40$ GeV, $|\eta| < 2.4$
 - ◆ $70 < m_{jj} < 110$ GeV, $|\cos\theta^*| < 0.5$



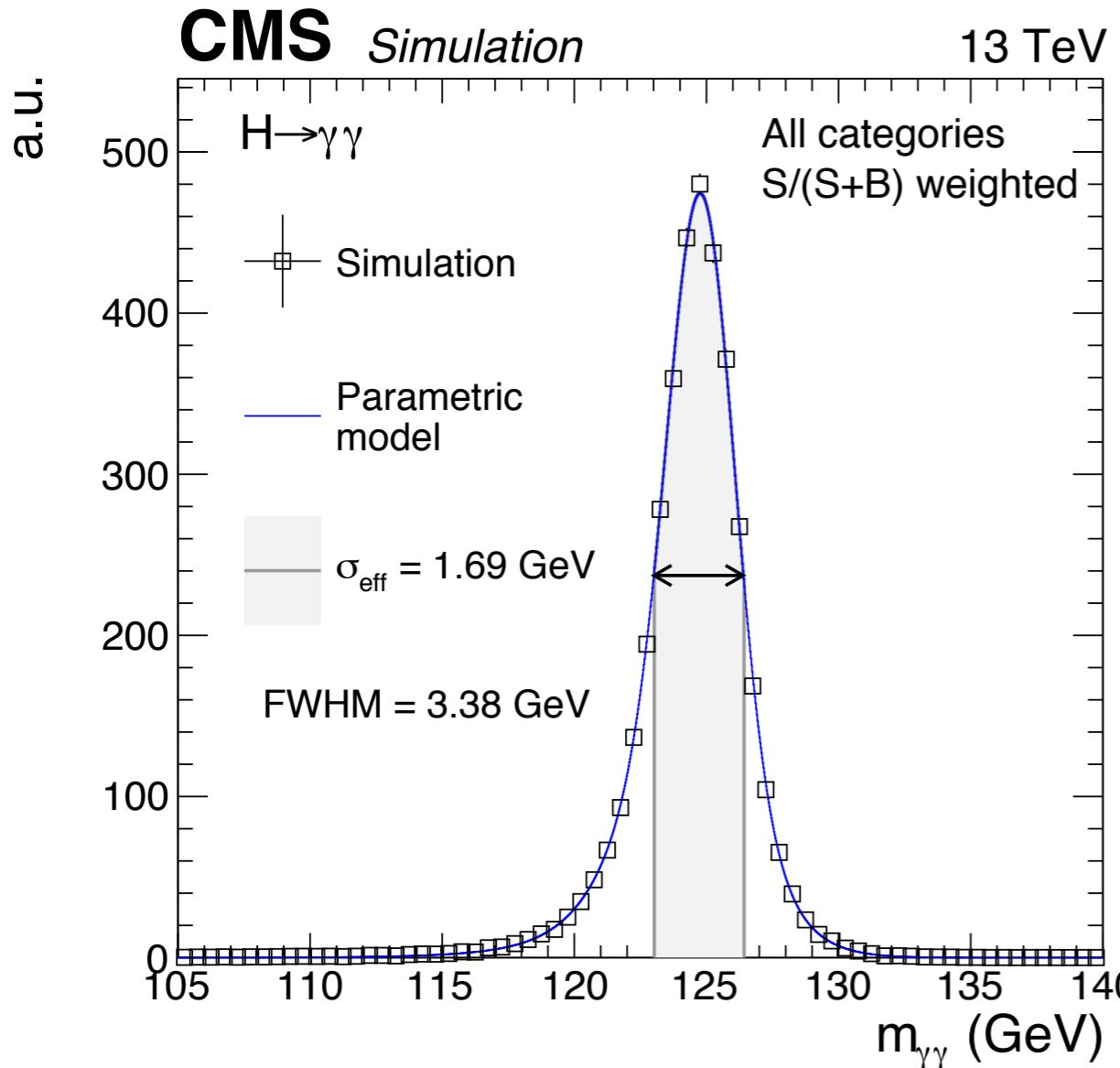
Signal composition

CMS Simulation $H \rightarrow \gamma\gamma$

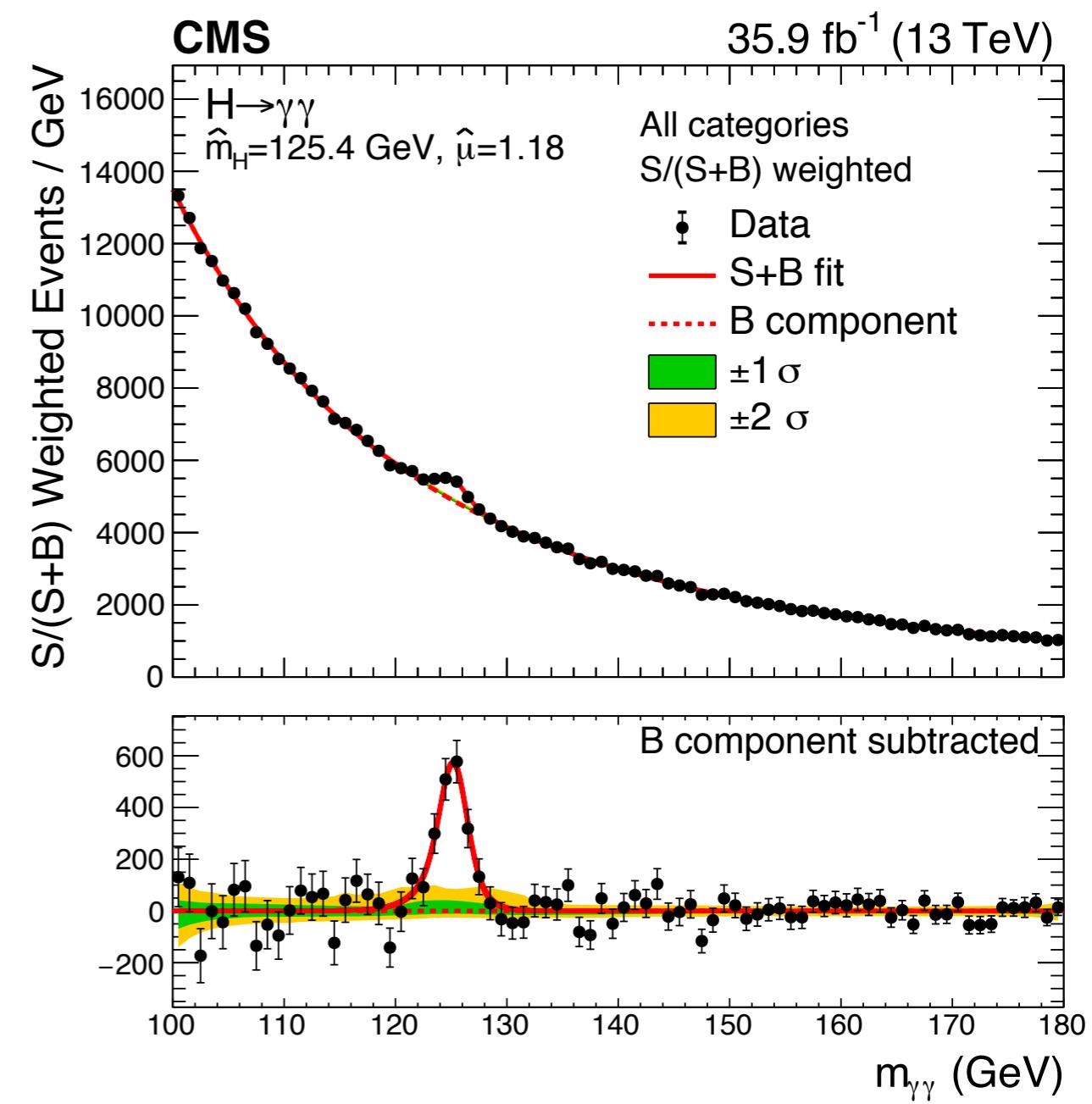
35.9 fb^{-1} (13 TeV)



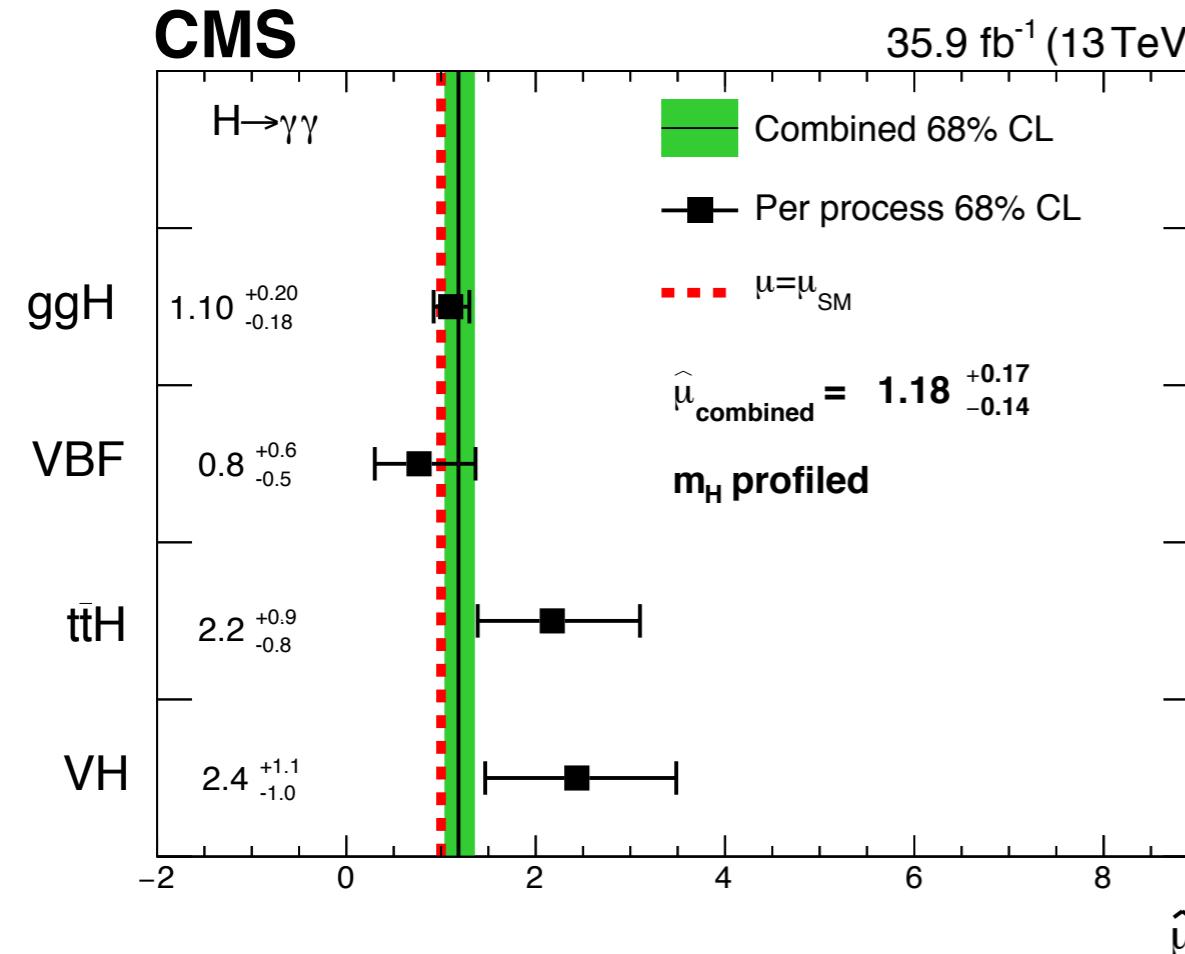
Imperial College London Signal & background model CMS



- Signal model parametric in m_H



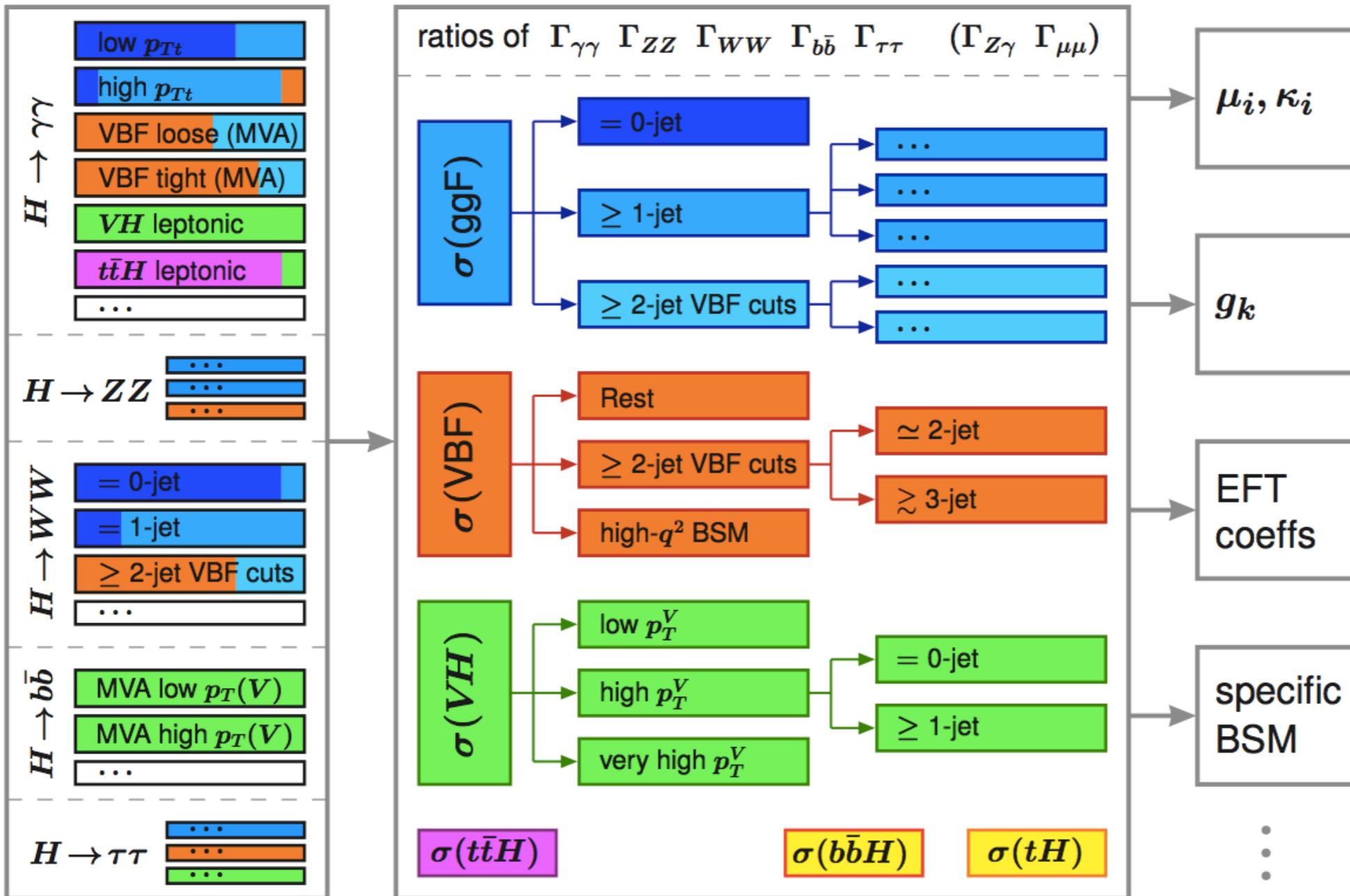
- Background fitted from data
- Choice of function treated as discrete nuisance parameter in the final fit



- Two types of per-process signal strength measurement
 - ◆ traditional signal strengths: theory uncertainty included in the measurement

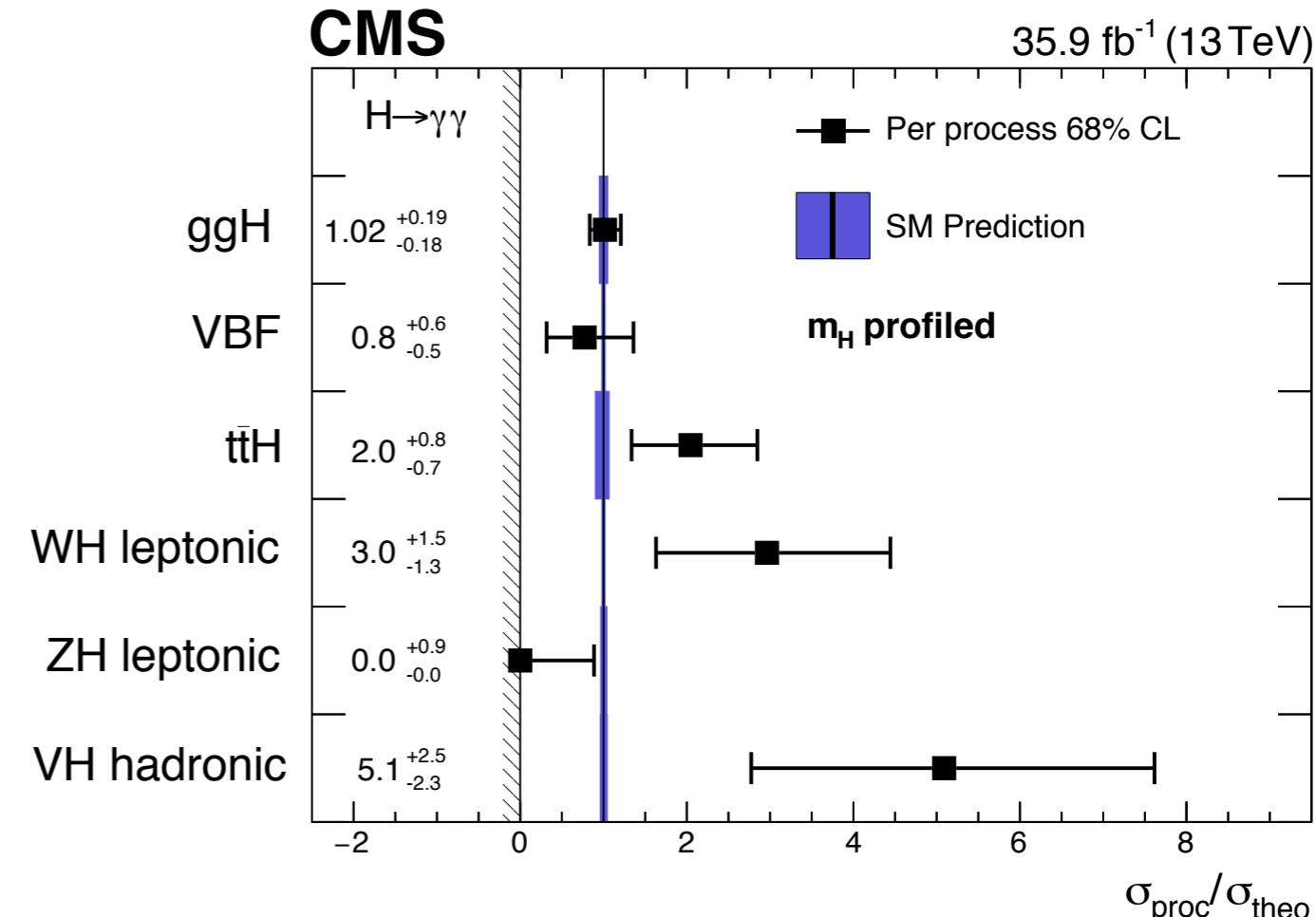
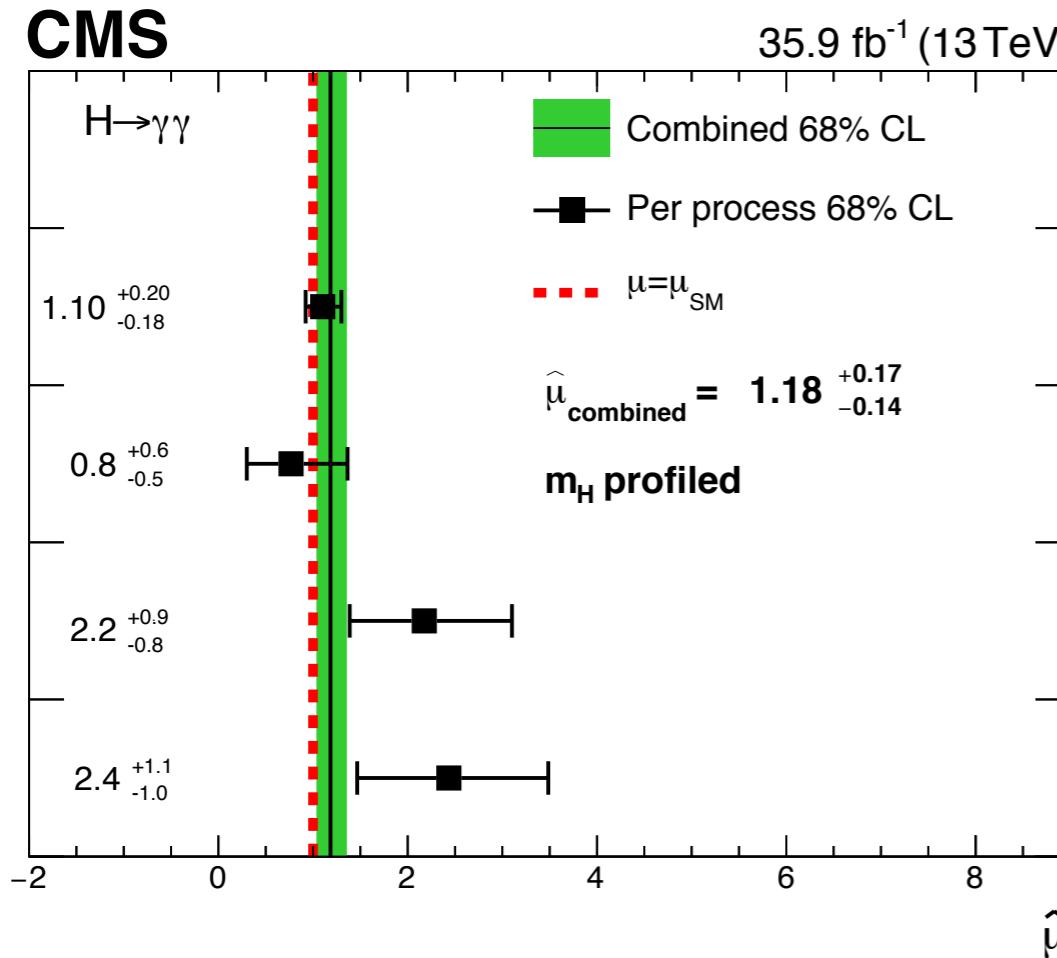
$$\hat{\mu} = 1.18^{+0.17}_{-0.14} = 1.18^{+0.12}_{-0.11} \text{ (stat)}^{+0.09}_{-0.07} \text{ (syst)}^{+0.07}_{-0.06} \text{ (theo)}$$

Results

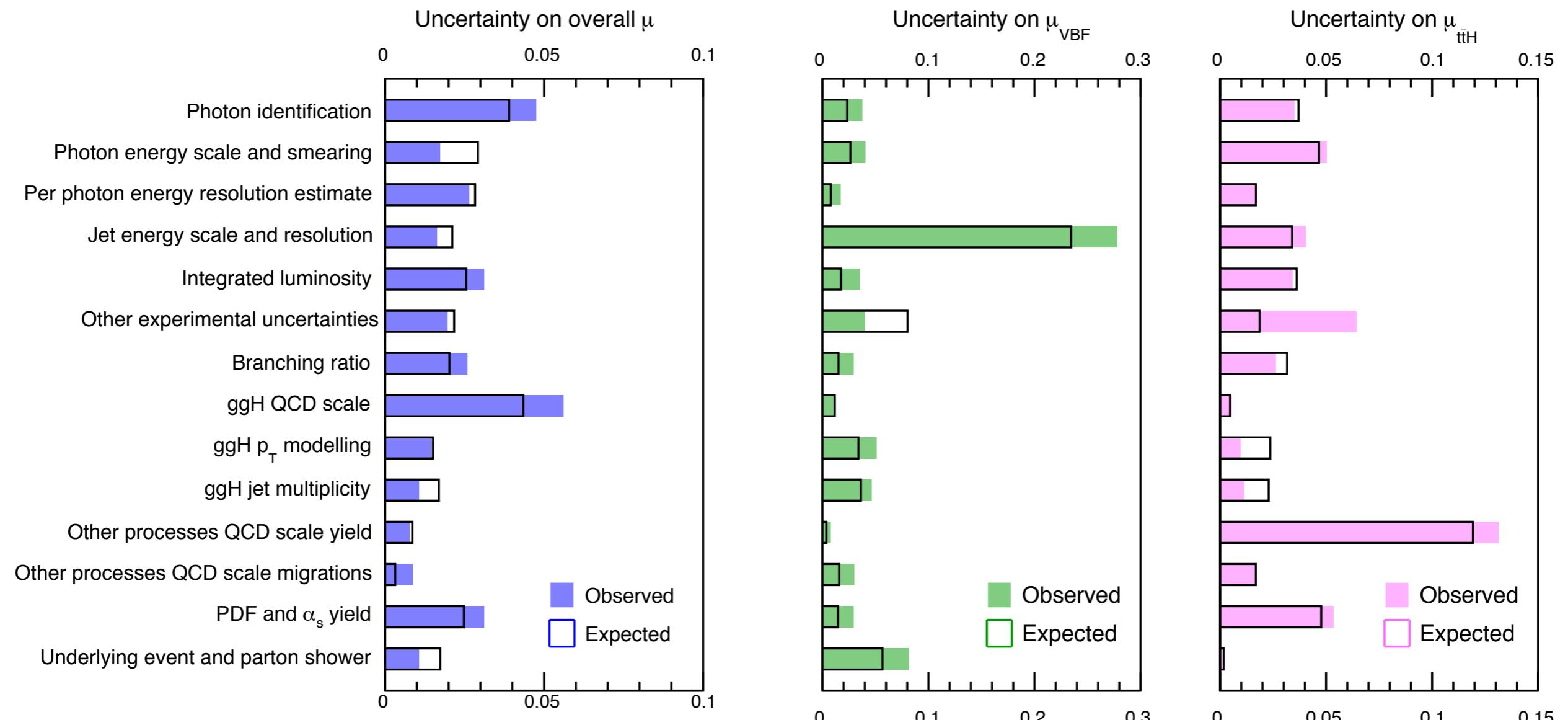


- Simplified Template Cross-section (STXS) framework aims to minimise measurements' dependence on theory

- Results can then be re-interpreted with new theories
- Kinematic regions isolate BSM effects
- And provide coherent framework for combination of channels & experiments

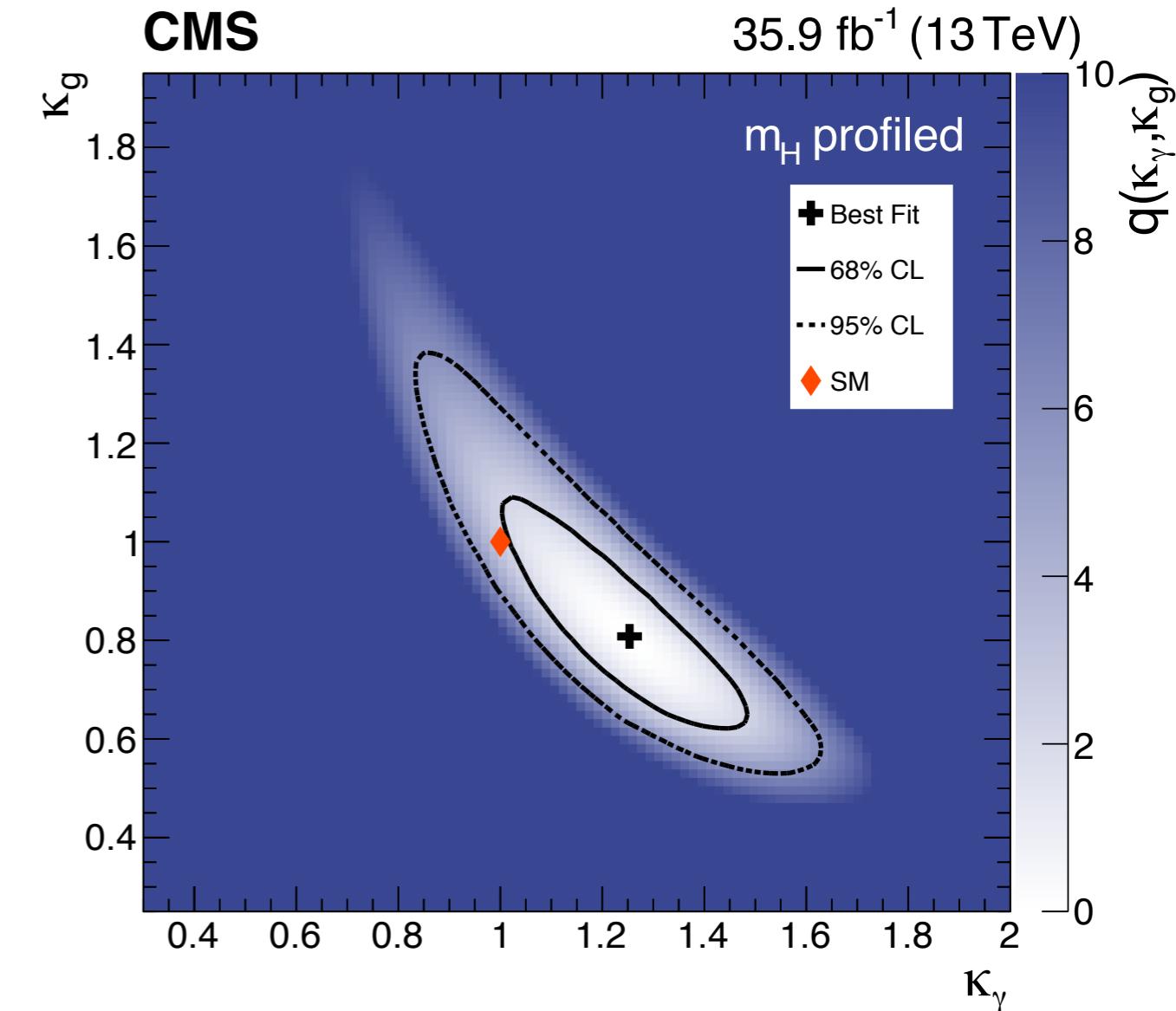
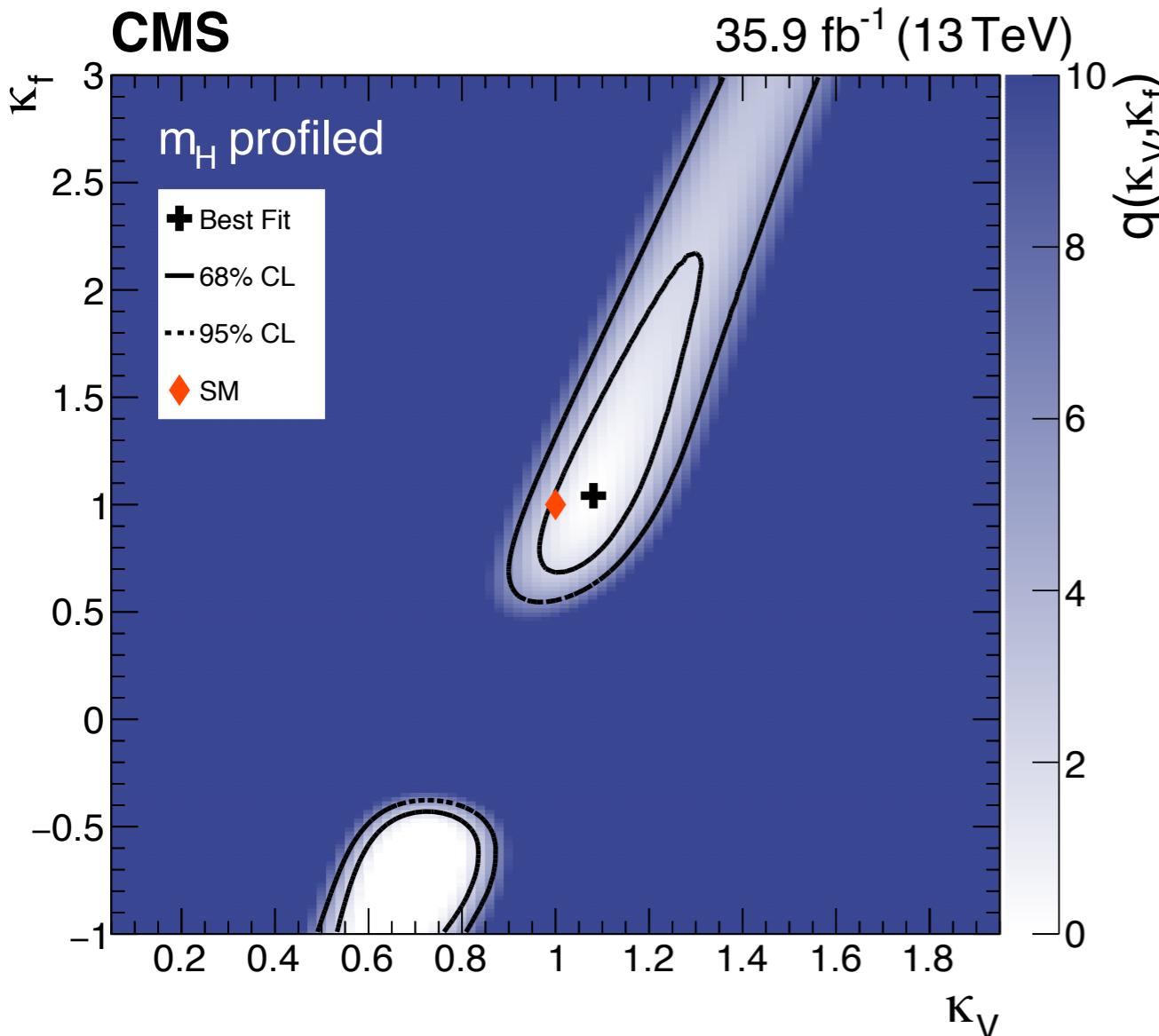


- Two types of per-process signal strength measurement
 - ◆ traditional signal strengths: theory uncertainty included in the measurement
 - ◆ Stage 0 STXS: factorise theory uncertainty on overall yield
- Significance of ttH observed to be 3.3σ (1.5σ expected)
 - ◆ see [talk by C. Diez Pardos](#) for details on CMS ttH measurements

CMS $H \rightarrow \gamma\gamma$ 35.9 fb^{-1} (13 TeV)

- Inclusive signal strength on point of becoming systematics-limited
- Important contributions from both theoretical and experimental uncertainties

Results



- Fits with loops resolved (LHS) and unresolved (RHS)
- All consistent with SM so far
- See [N. Wardle's talk](#) for latest and greatest results on Higgs couplings

$$\kappa_j^2 = \Gamma^j / \Gamma_{\text{SM}}^j$$

$H \rightarrow \gamma\gamma$ analysis of the 35.9fb^{-1} collected by CMS in 2016 is complete

- ◆ inclusive signal strength $\mu = 1.18^{+0.17}_{-0.14}$
- ◆ per-process signal strengths and coupling measurements all consistent with the standard model
- ◆ also report Simplified Template Cross-Section measurements at Stage 0
- ◆ important input to ttH and grand combinations

Higgs physics now in the era of precision measurements

- ◆ inclusive measurements becoming systematics-limited
- ◆ aim to make measurements as re-interpretable as possible going forward

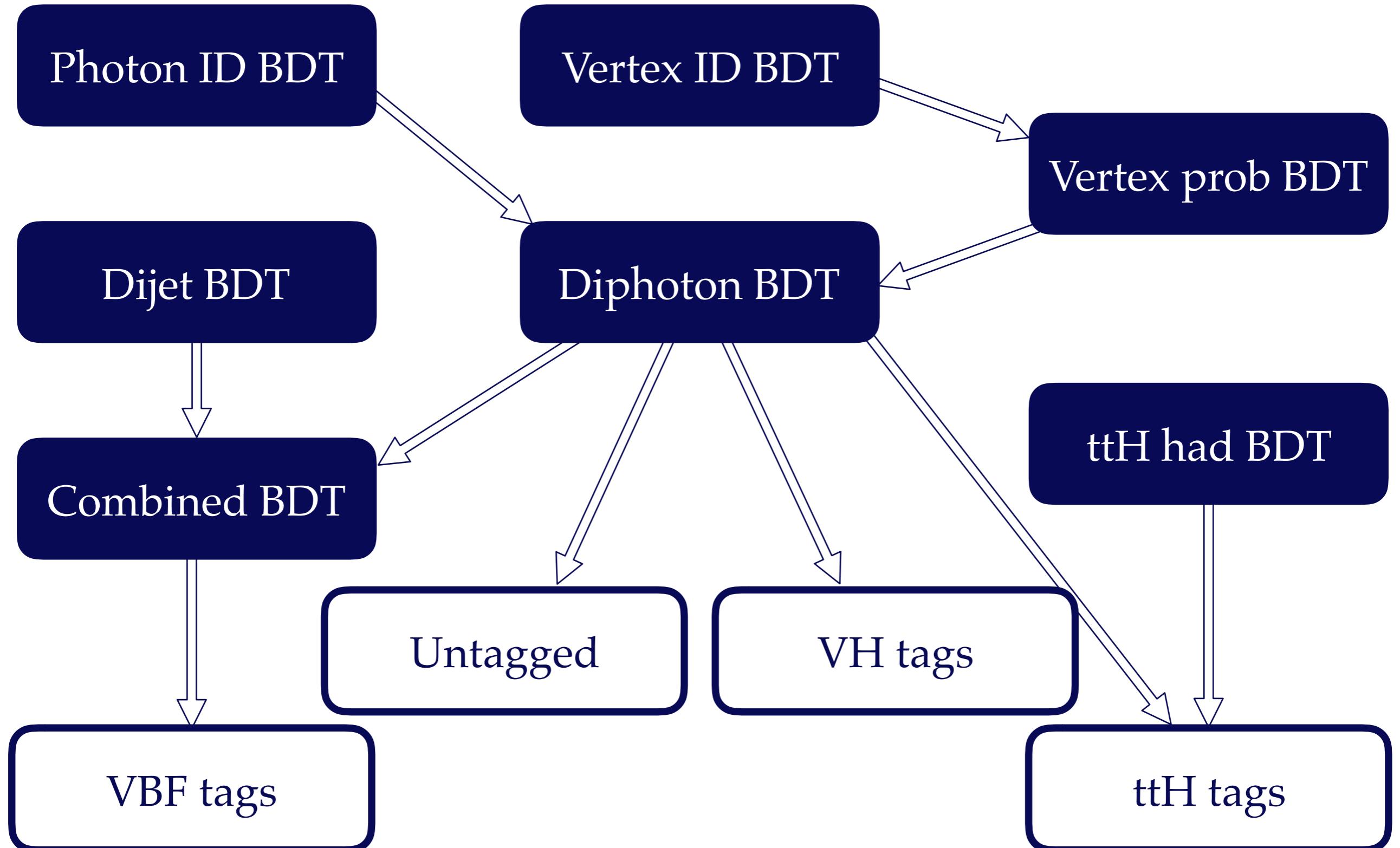
Now working to maximise performance for Run 2 legacy results

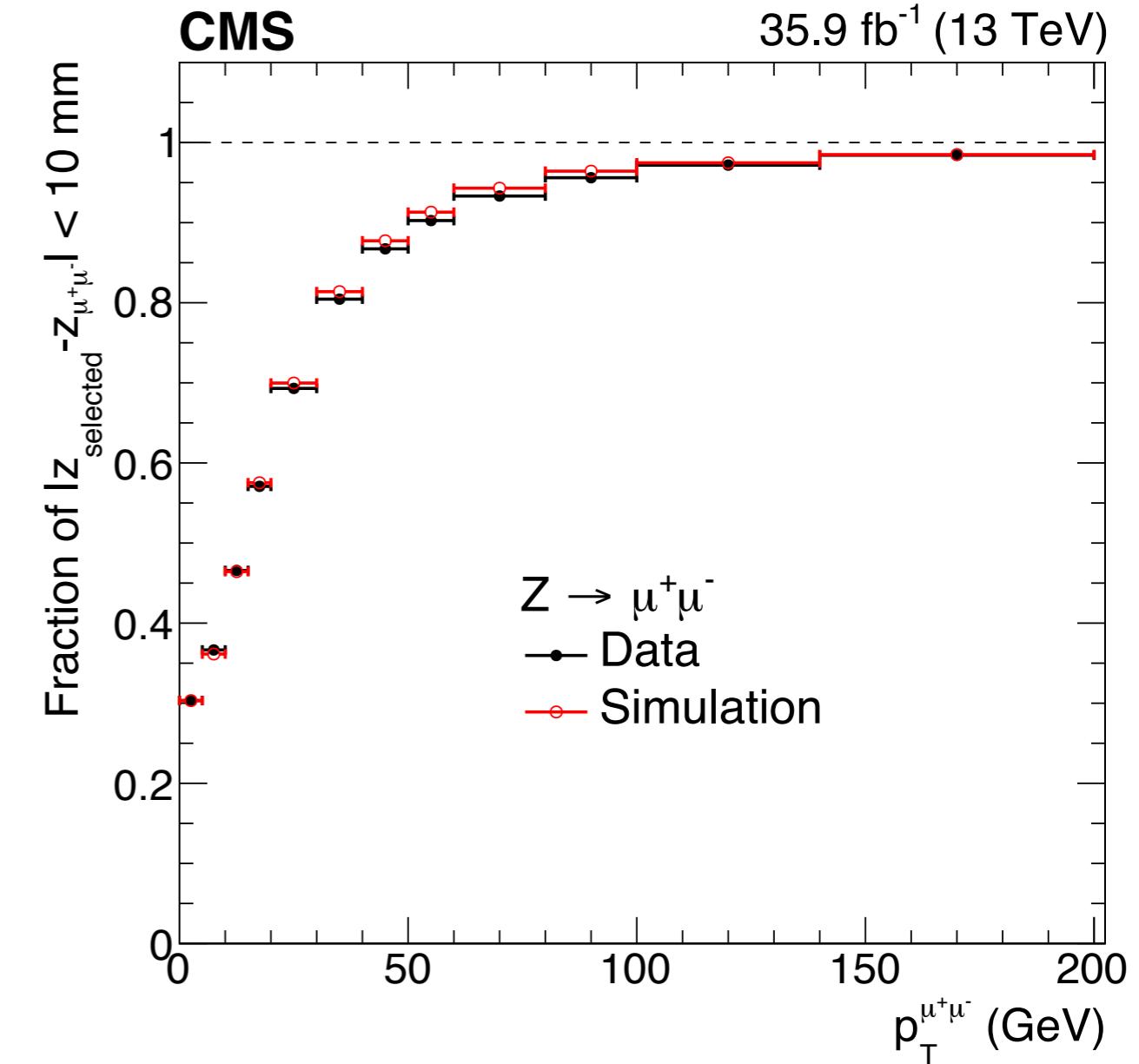
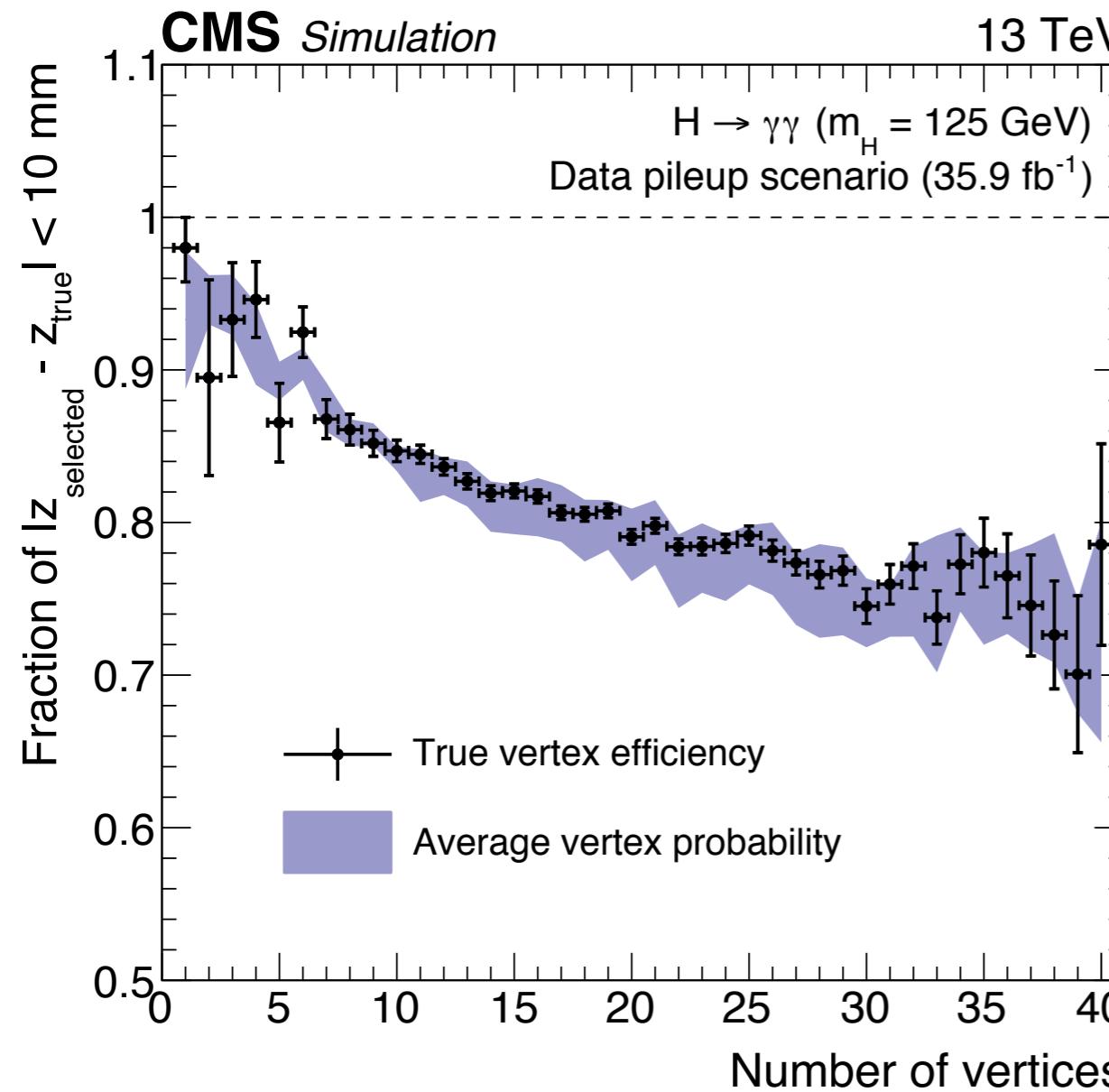
The background of the slide is a wide-angle, aerial photograph of the Seoul city skyline at dusk or night. The sky is filled with warm orange and yellow hues from the setting sun. In the foreground, numerous buildings are illuminated with their lights reflecting off the water. A prominent skyscraper, likely the Lotte World Tower, stands tall in the center-right, its upper portion still under construction with visible cranes. To the left, the N Seoul Tower is visible against the horizon. The Han River flows through the city, with several bridges spanning it, their structures also glowing with lights.

Thank you

BACKUP

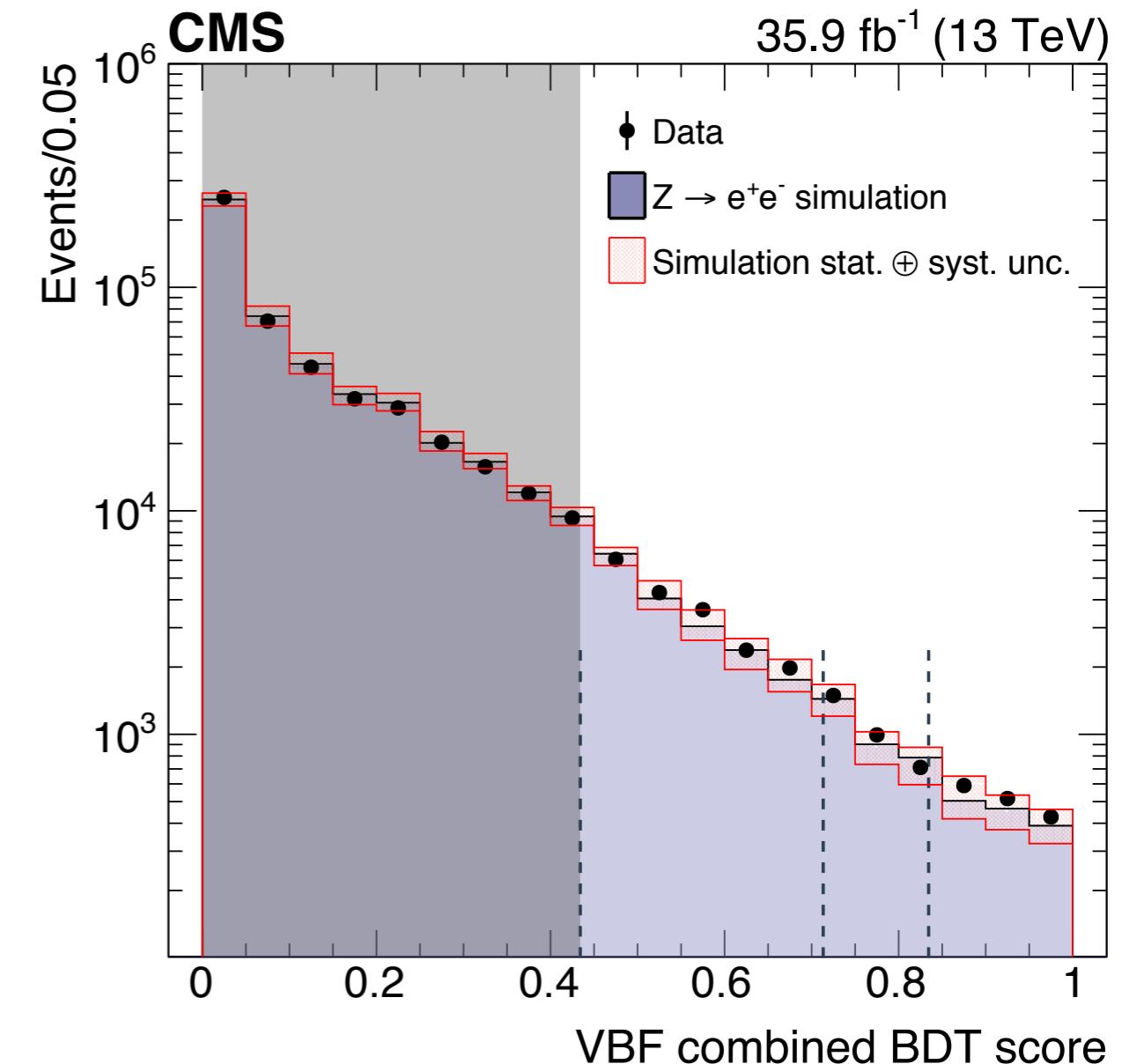
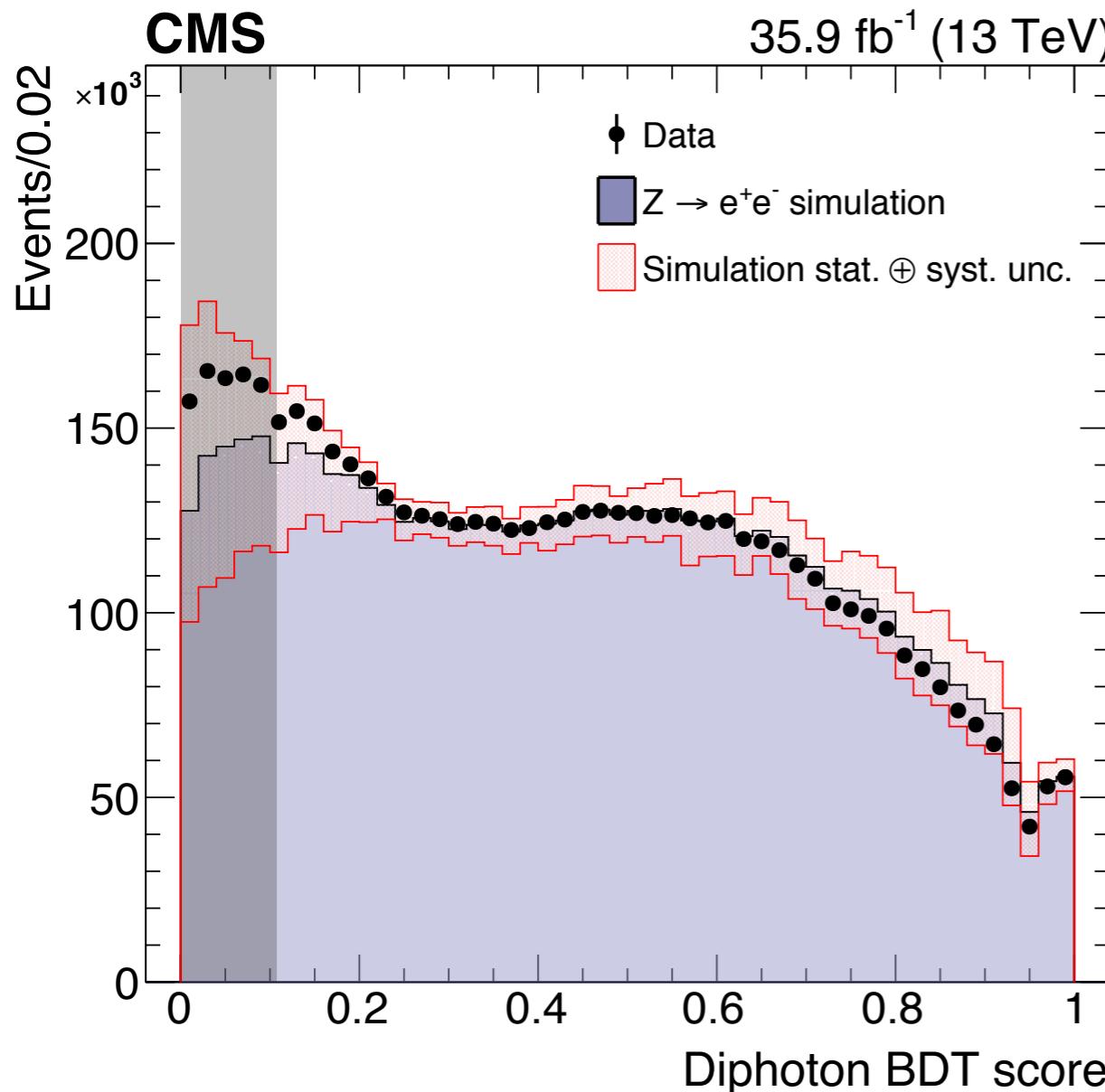
Analysis schematic





- LHS: the vertex identification efficiency as a function of number of vertices
- RHS: data and MC comparison of the identification in the $Z \rightarrow \mu\mu$ control region, as a function of the dimuon p_T

Classifier validation

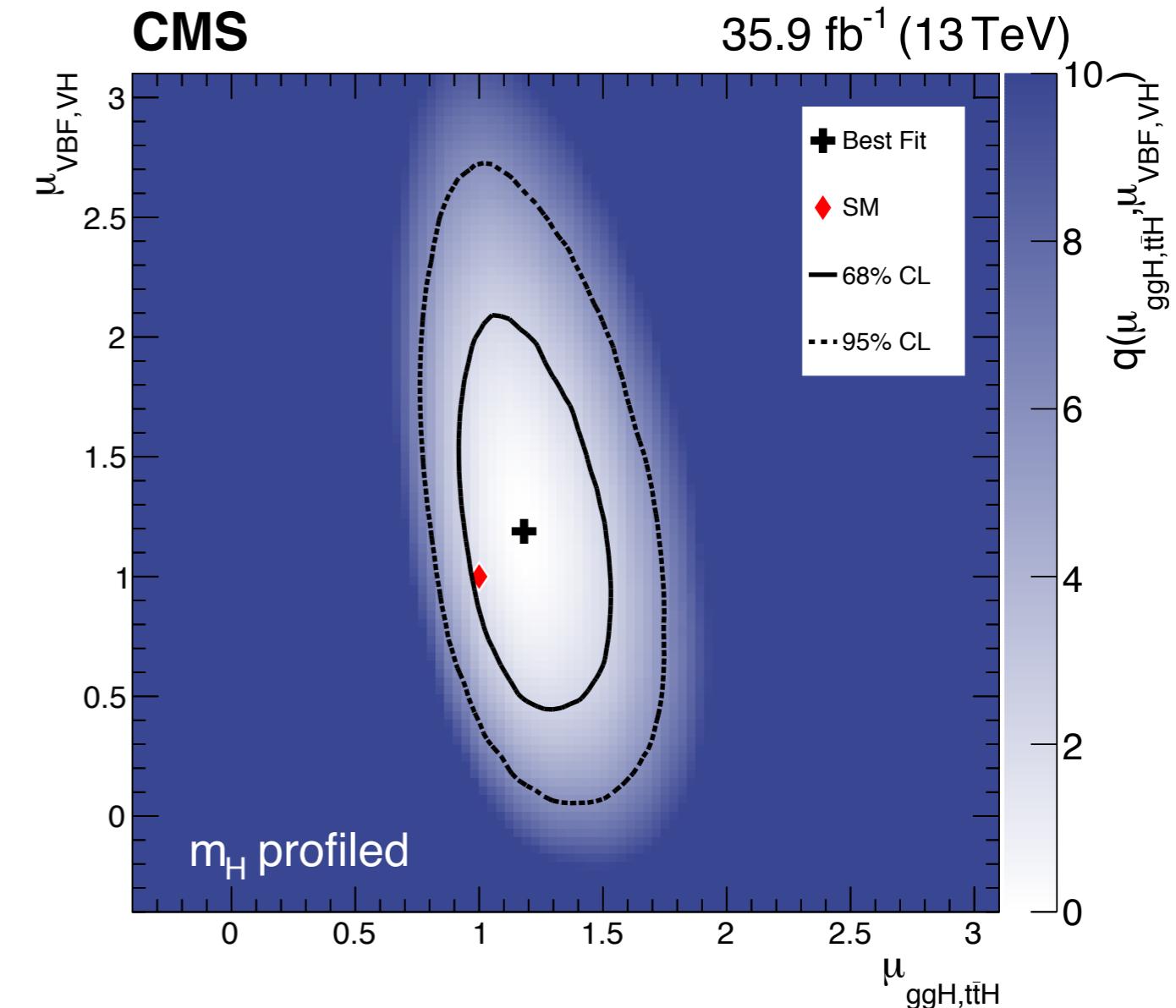
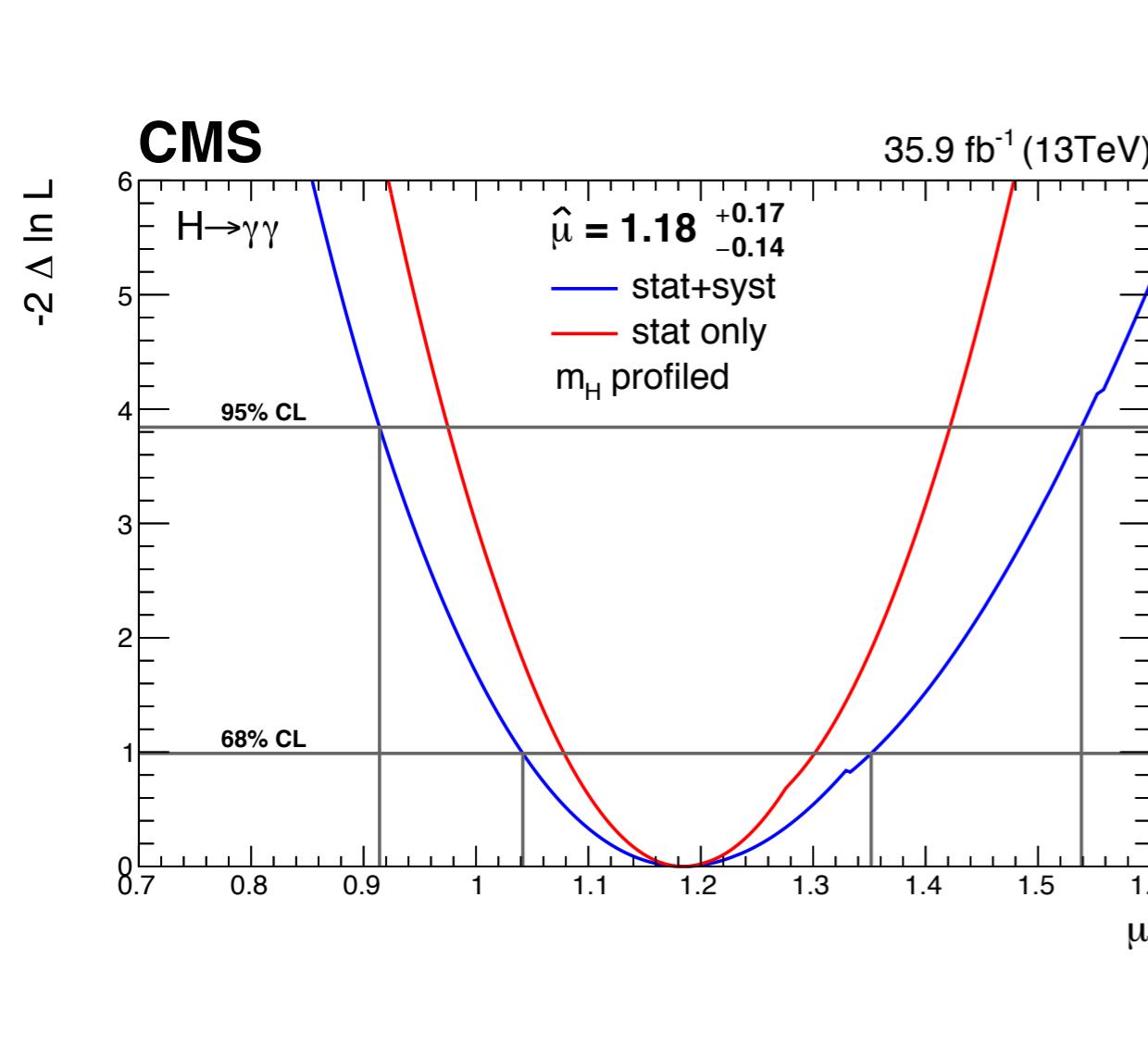


- Comparison of data and MC in $Z \rightarrow ee$ control regions for the diphoton BDT (classifying untagged events) and the VBF combined BDT (classifying the categories targeting VBF production)

Categorisation

Event categories	Expected SM 125 GeV Higgs boson signal											σ_{eff} (GeV)	σ_{HM} (GeV)	Bkg (GeV $^{-1}$)
	Total	ggH	VBF	ttH	bbH	tHq	tHW	WH lep	ZH lep	WH had	ZH had			
Untagged 0	32.5	72.0 %	16.6 %	2.6 %	0.6 %	0.7 %	0.3 %	0.6 %	0.3 %	4.2 %	2.2 %	1.32	1.26	21.8
Untagged 1	469.3	86.5 %	7.9 %	0.6 %	1.2 %	0.1 %	<0.05 %	0.5 %	0.3 %	1.9 %	1.1 %	1.46	1.32	925.1
Untagged 2	678.3	89.9 %	5.4 %	0.4 %	1.2 %	0.1 %	<0.05 %	0.5 %	0.3 %	1.4 %	0.8 %	1.93	1.67	2391.7
Untagged 3	624.3	91.3 %	4.4 %	0.5 %	1.0 %	0.1 %	<0.05 %	0.5 %	0.3 %	1.2 %	0.7 %	2.61	2.27	4855.1
VBF 0	9.3	15.5 %	83.2 %	0.4 %	0.4 %	0.3 %	<0.05 %	<0.05 %	<0.05 %	0.2 %	<0.05 %	1.52	1.31	1.6
VBF 1	8.0	28.4 %	69.7 %	0.4 %	0.6 %	0.4 %	<0.05 %	0.1 %	<0.05 %	0.3 %	0.1 %	1.66	1.38	3.3
VBF 2	25.2	45.1 %	51.2 %	0.9 %	0.8 %	0.6 %	0.1 %	0.2 %	0.1 %	0.8 %	0.3 %	1.64	1.37	18.9
ttH Hadronic	5.6	7.0 %	0.7 %	81.1 %	2.1 %	4.3 %	2.1 %	0.1 %	0.1 %	0.7 %	1.9 %	1.48	1.30	2.4
ttH Leptonic	3.8	1.5 %	<0.05 %	87.8 %	0.1 %	4.7 %	3.1 %	1.5 %	1.2 %	<0.05 %	<0.05 %	1.60	1.35	1.5
ZH Leptonic	0.5	<0.05 %	<0.05 %	2.6 %	<0.05 %	<0.05 %	0.1 %	<0.05 %	97.3 %	<0.05 %	<0.05 %	1.65	1.43	0.1
WH Leptonic	3.6	1.3 %	0.6 %	5.2 %	0.2 %	3.0 %	0.7 %	84.5 %	4.3 %	0.1 %	0.1 %	1.64	1.43	2.1
VH LeptonicLoose	2.7	8.1 %	2.7 %	2.4 %	0.6 %	1.8 %	0.1 %	64.4 %	19.1 %	0.6 %	0.2 %	1.67	1.56	3.5
VH Hadronic	7.9	47.6 %	4.5 %	4.4 %	0.4 %	1.7 %	0.3 %	0.2 %	0.5 %	25.2 %	15.1 %	1.38	1.30	7.2
VH MET	4.0	18.7 %	2.6 %	15.4 %	0.4 %	2.1 %	1.2 %	26.8 %	30.4 %	1.4 %	0.9 %	1.56	1.39	3.5
Total	1875.0	86.9 %	7.1 %	1.0 %	1.1 %	0.2 %	<0.05 %	0.8 %	0.4 %	1.6 %	0.9 %	1.96	1.62	8237.8

- The expected number of signal events and the breakdown of the composition per production mode for each category used in the analysis



- Overall signal strength scan (LHS) and 2D scan of the signal strengths of fermionic ($\text{ggH}+\bar{\text{t}}\text{tH}$) and bosonic ($\text{VBF}+\text{VH}$) production modes
- Both are compatible with the SM to within $\sim 1\sigma$