Measurement of the transverse momentum spectrum of the Higgs boson decaying into WW with the CMS experiment

LaThuile 2016: Les Rencontres de Physique de la Vallée d'Aoste

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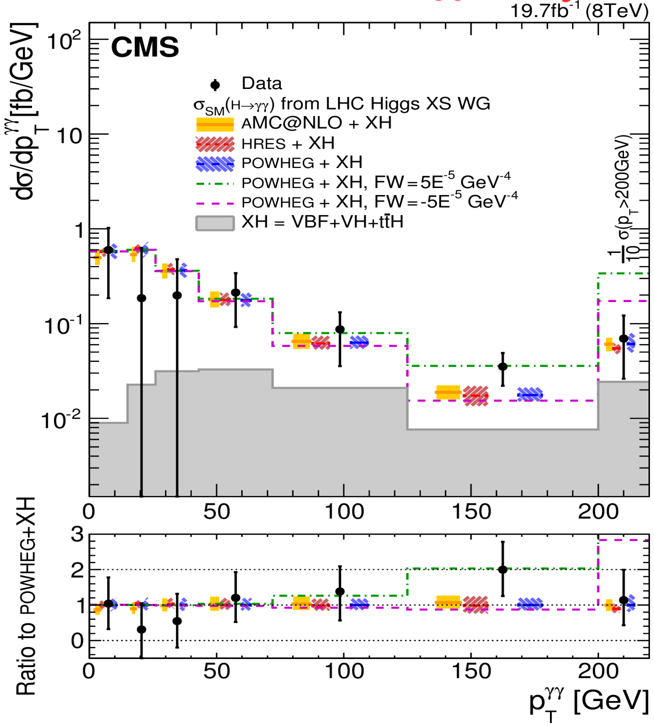
Reference: CMS-HIG-PAS-15-010

State of the art

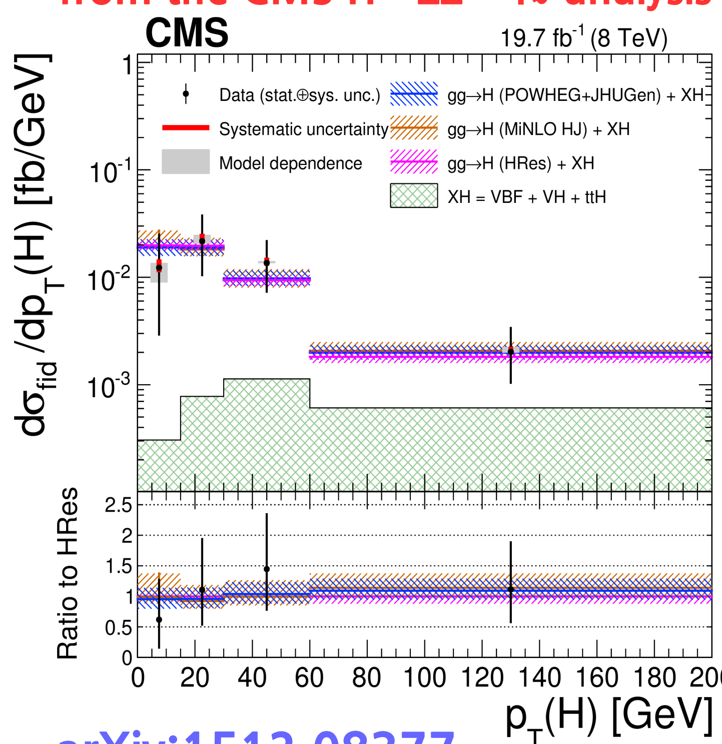
- The Higgs boson transverse momentum (p_T^H) spectrum can be affected by the presence of new physics and its measurement allows **testing the existing theoretical calculations in the SM Higgs sector.**
- Higgs p_T differential and fiducial measurements at 8 TeV have been reported by ATLAS and CMS.

Higgs transverse momentum spectrum from the CMS H→γγ analysis



EPJC 76 (2016) 13

Higgs transverse momentum spectrum from the CMS H→ZZ→4ℓ analysis

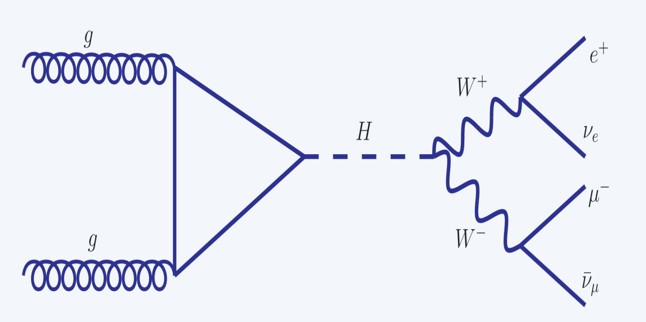


arXiv:1512.08377
Submitted to JHEP

Measurement basics

- The measurement of the **fiducial integrated cross section and transverse momentum spectrum for the Higgs boson** production in H→WW→2ℓ2ν decays is performed.

- **H→WW→2l2υ signature**:
  - Two isolated high p_T electrons or muons with opposite charge;
  - Moderate MET.



- **With respect to H→ZZ→4ℓ or H→γγ**:
  - Significantly higher σ×BR;
  - Worst p_T^H resolution due to the presence of neutrinos.

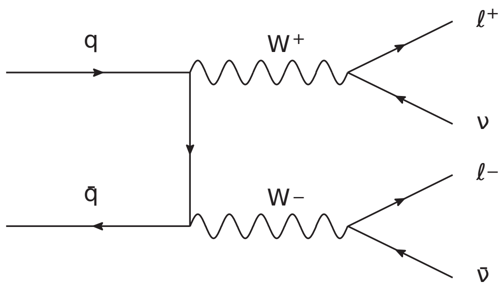
- Analysis performed looking at **different flavour leptons (*eμ*)**.

p_T^H can be reconstructed using transverse observables

$$\boxed{p_T^H = |\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}|}$$

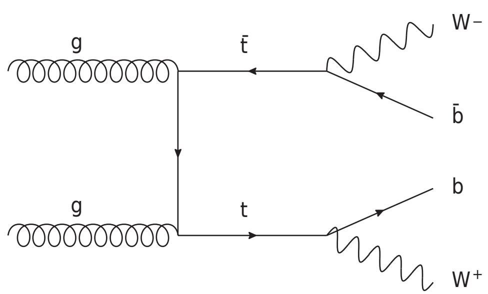
Main backgrounds

Non resonant WW



- Sizeable at small values of p_T^H.
- Same final state as signal but slightly different kinematics.

$t\bar{t}$ background



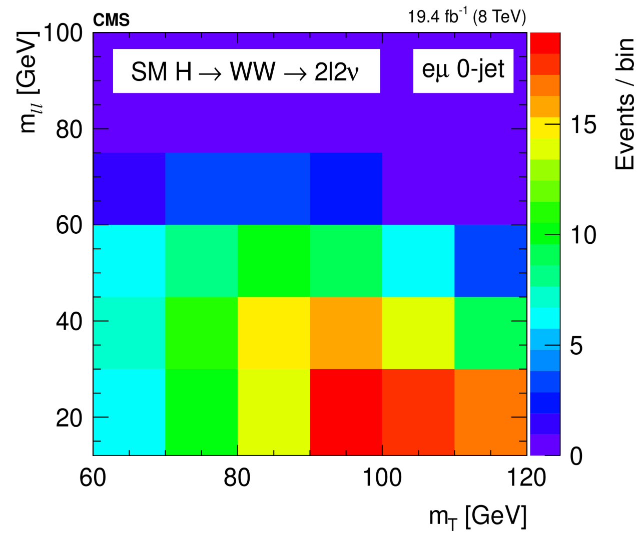
- Dominant at large values of p_T^H.
- Characterized by 2 b-jets.
- Suppressed using a b-jet veto.

- **Other backgrounds**: DY→$\tau^+\tau^-$, W+jets, $W\gamma^{(*)}$, WZ, ZZ, VVV (V=W,Z)

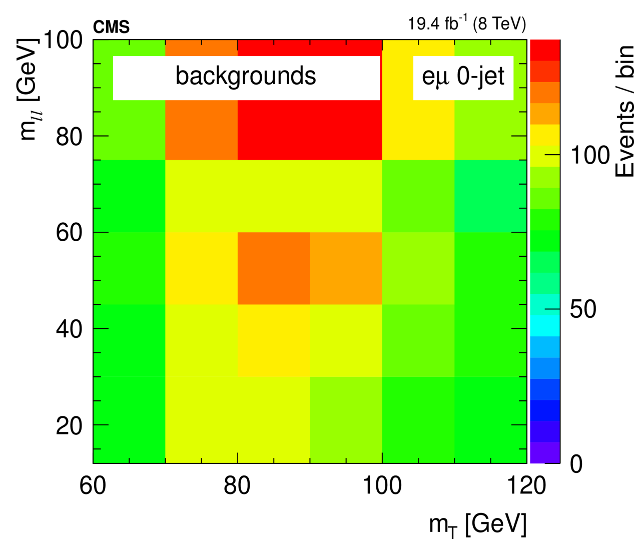
- Main backgrounds estimated using data driven techniques.

Analysis strategy

- Event selection based on the previously published H→WW→2ℓ2ν measurements (JHEP01(2014)096).
  - Important difference: **inclusive in jets multiplicity**.



- The p_T^H spectrum is binned.
  - accurate binning needed to avoid large bin migration effects.



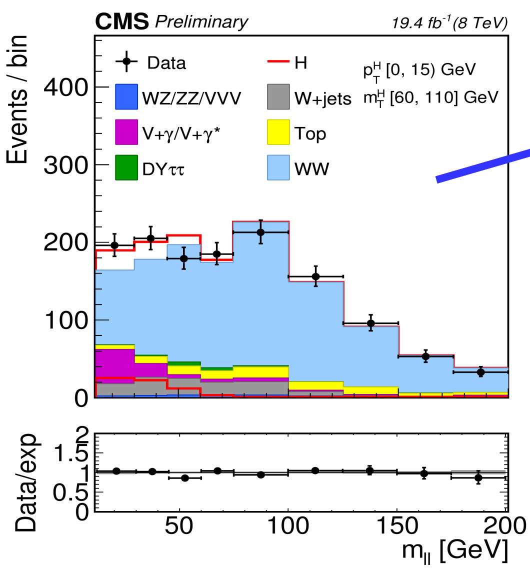
- 2D template fit used to measure the signal strength in each bin:
  - **di-lepton mass ($m_{\ell\ell}$)** and **transverse mass (m_T)** used to discriminate signal and backgrounds.

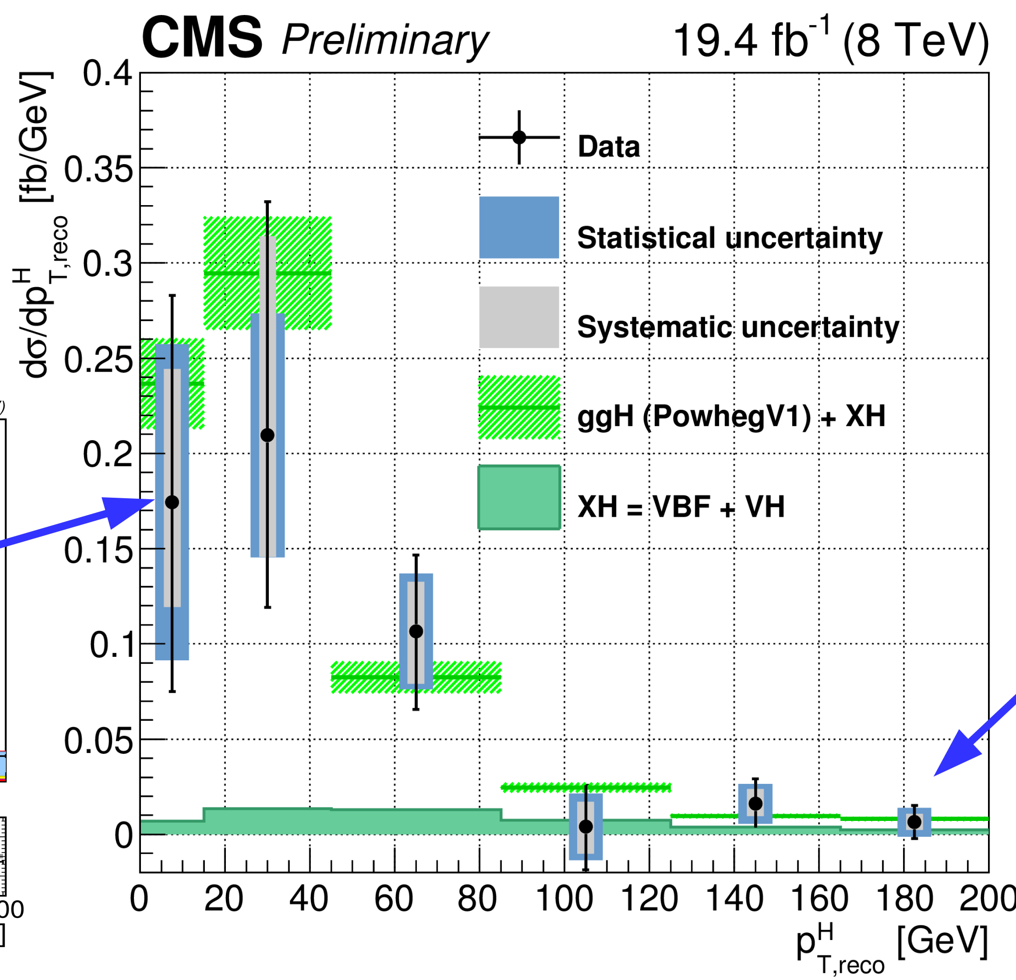
$$m_T = \sqrt{2p_T^{\ell\ell}E_T^{\text{miss}}(1-\cos\Delta\phi(\ell\ell, E_T^{\text{miss}}))}$$

Reconstructed Higgs p_T spectrum

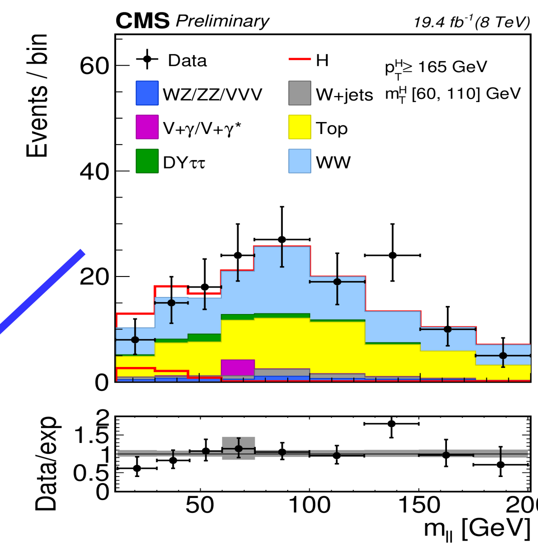
- Backgrounds are subtracted and the signal strength is obtained in each bin using a Maximum Likelihood fit.
- Good agreement between data and theory (after the simulation of the detector).

$m_{\ell\ell}$ shape in the first p_T^H bin



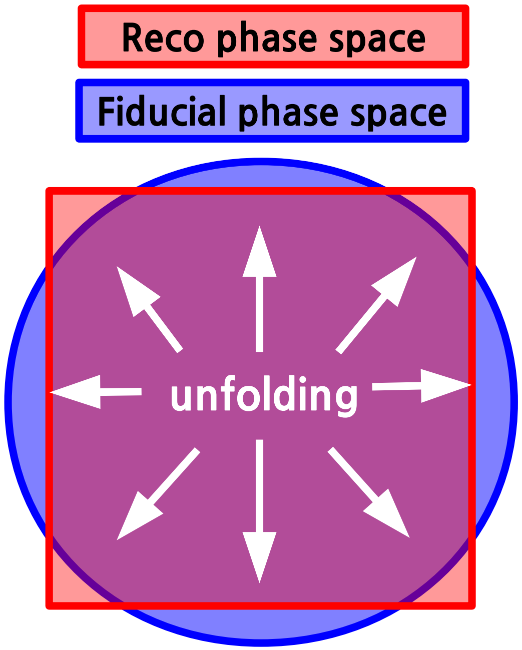


$m_{\ell\ell}$ shape in the last p_T^H bin



Fiducial phase space

- **Results extrapolated to a fiducial phase space** with a regularized unfolding procedure.
- Direct comparison with theoretical predictions and other experimental results.



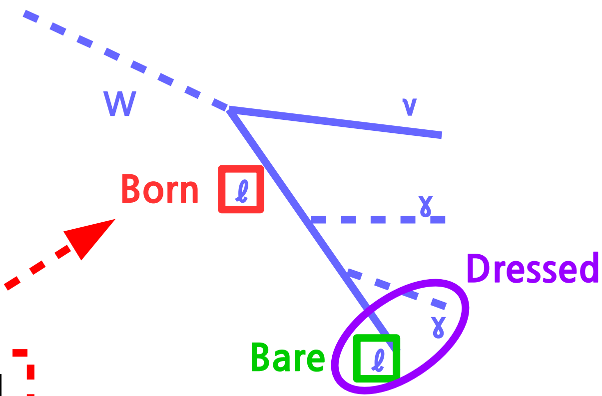
Fiducial & reconstructed

Fiducial & non-reconstructed

Non-fiducial & reconstructed

Kinematic requirements closely matching the analysis selection.

Born level leptons



Kinematic requirements for the fiducial phase space	
Leading lepton transverse momentum	$p_{\mathrm{T}} > 20$ GeV
Sub-leading lepton transverse momentum	$p_{\mathrm{T}} > 10$ GeV
Pseudorapidity of electrons and muons	$\lvert\eta\rvert < 2.5$
Invariant mass of the two leptons	$m_{\ell\ell} > 12$ GeV
Transverse momentum of the lepton pair	$p_{\mathrm{T}}^{\ell\ell} > 30$ GeV
Invariant mass of the leptonic system in the transverse plane	$m_{\mathrm{T}}^{\mathrm{H}} > 50$ GeV
No MET cut applied	

Unfolding

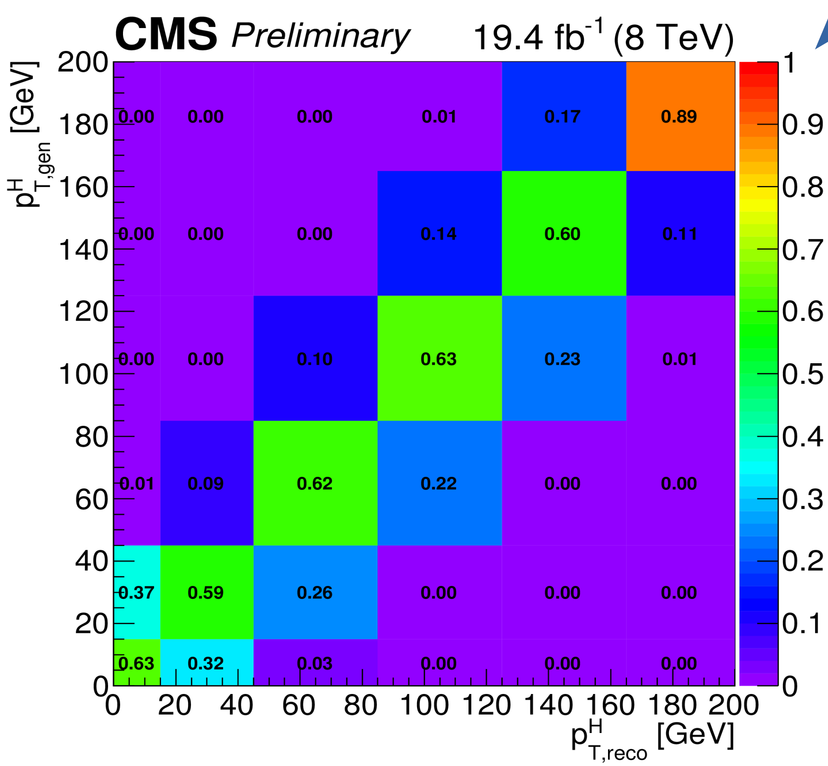
- **Basic principle**: use the MC signal samples to make the distribution of the variable of interest before and after the full GEANT4 simulation of the CMS detector and the event reconstruction.

Distribution at reconstructed level (after the full CMS simulation)

$$R_i^{MC} = M_{ij} \, T_j^{MC}$$

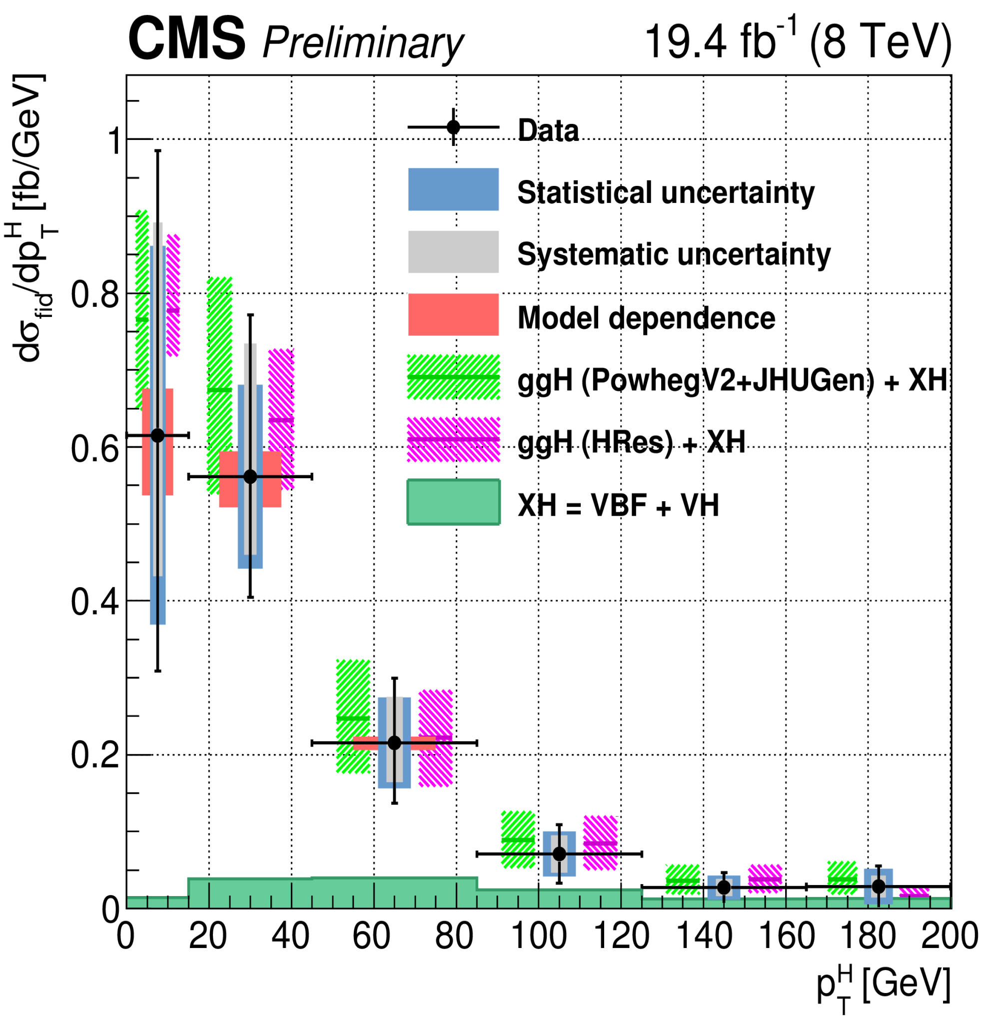
Distribution at MC generator level

Response matrix



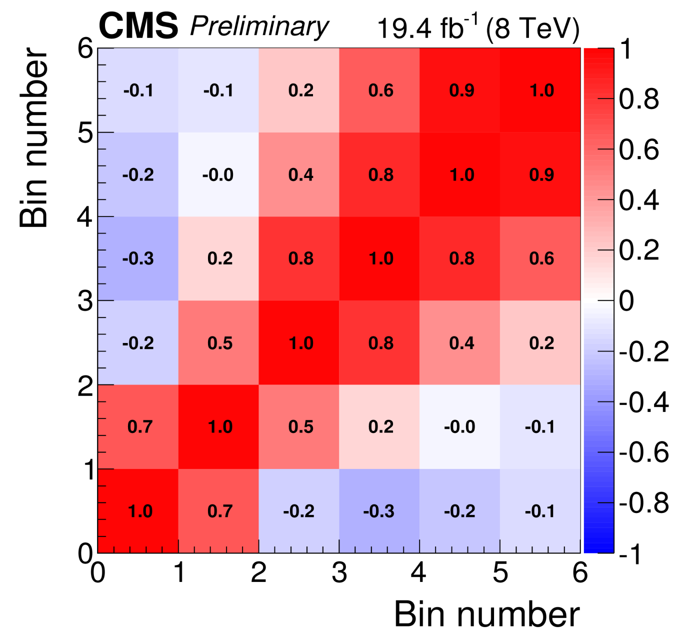
- Large **off-diagonal contributions** in the response matrix
  - due to detector resolution effects.
- Unfolding with **SVD method** and Tikhonov **regularization function**.

- The **unfolded spectrum** is compared with two SM-based theory predictions:
  - ggH production simulated using the **HRes** or **PowhegV2** programs.



Good data/theory agreement within uncertainties

Correlation matrix



$$\sigma_{\text{fid}} = 39 \pm 8\ (\text{stat}) \pm 9\ (\text{syst})\ \text{fb}$$

$$\sigma_{theory} = 48 \pm 8\ \text{fb}$$

Perspectives with 13 TeV data

- Large **increase of ggH cross section** with respect to 8 TeV (~2.2).
  - Backgrounds also increase (especially $t\bar{t}$).

process	$\sigma_{13\ \mathrm{TeV}}/\sigma_{8\ \mathrm{TeV}}$
$Z/\gamma^* \to \ell^+\ell^-$	1.7
$WW \to 2\ell 2\nu$	1.8
W+jets	1.6
$V\gamma^*$	2
ZZ	2
$t\bar{t}$	3.5
VVV	2.5

- With ~30 fb^{-1} at the end of 2016 we expect ~3.3 times the current number of signal events.
  - **Reduction to ~55% of the statistical uncertainty.**
  - Considerable improvement in the p_T^H shape constraint.
- Improvement of systematic uncertainties.
  - More statistics for data driven estimations.

Conclusions

- The first Higgs boson differential measurement performed at LHC in the $H \to WW \to 2\ell 2\nu$ decay channel.
- p_T^H spectrum reported in a fiducial phase space using a regularized unfolding procedure.
- Results show a good agreement with theoretical expectations within experimental uncertainties.
- Results competitive with existing measurements.
- Large improvement expected with new 13 TeV data.

BACKUP

Background estimation

Process	Normalization	Shape	Control/template sample
WW	data	simulation	events at high $m_{\ell\ell}$ and $m_{\mathrm{T}}^{\mathrm{H}}$
Top	data	simulation	top-enriched control region
W+jets	data	data	events with loosely identified leptons
Wγ	simulation	data	events with an identified γ
Wγ^*	data	simulation	W$\gamma^* \rightarrow 3\mu$ sample
$Z/\gamma^* \rightarrow \tau\tau$	data	data	τ embedded sample

Systematic uncertainties

- **Experimental uncertainties**:
  - luminosity, lepton momentum scale and resolution, **MET scale and resolution**, jet energy scale, b tagging uncertainty.
- **Background estimation uncertainties**:
  - related to the normalization estimation of each background, *e.g.* **$t\bar{t}$ background**.
- **Theoretical uncertainties**:
  - related to the theoretical models used for simulating signal and background events.

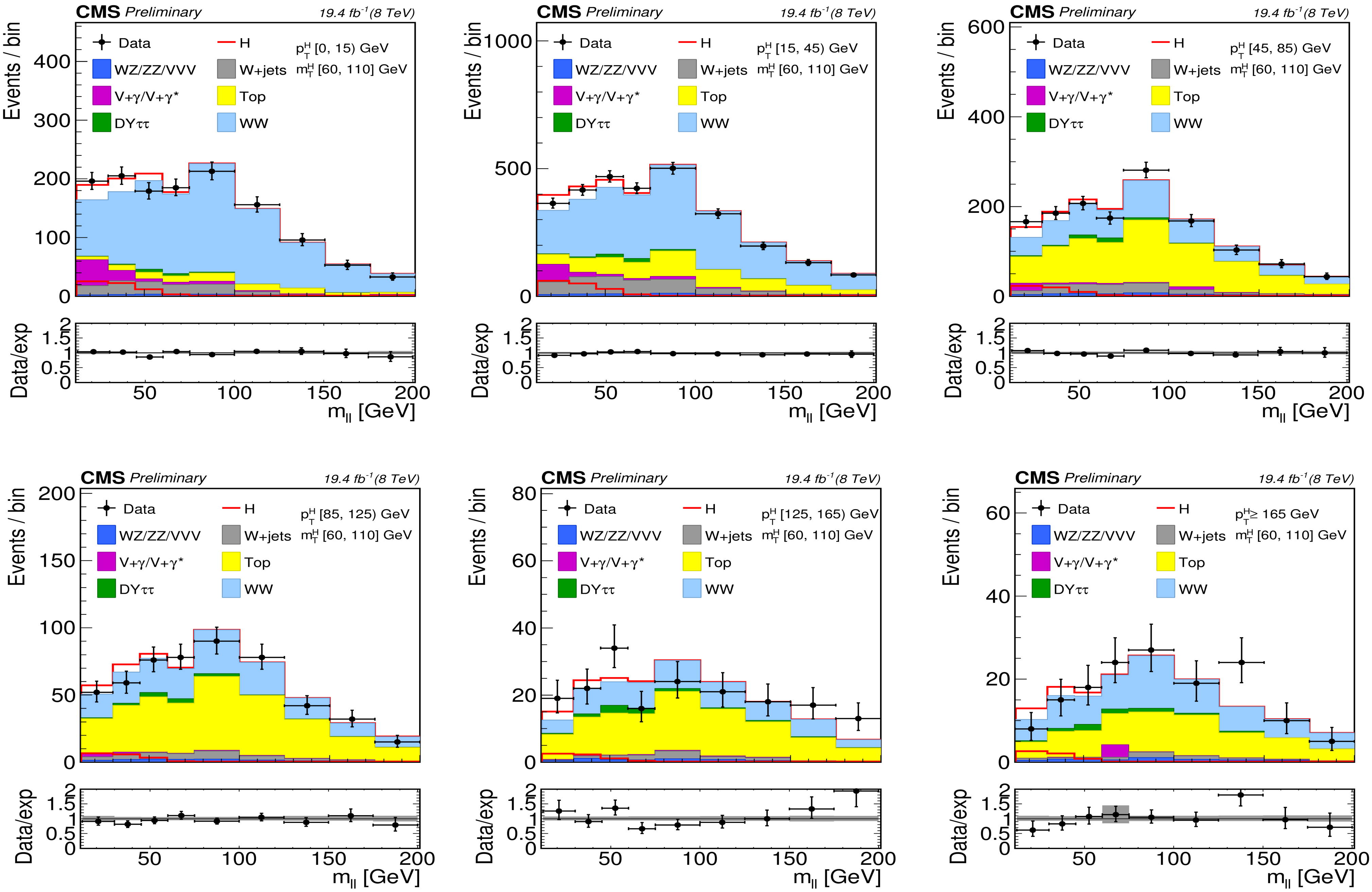
Uncertainties on backgrounds contributions	
Source	Uncertainty
$t\bar{t}$, tW	$\sim 20-50\%$
W+ jet	$\sim 40\%$
WZ, ZZ	$\sim 4\%$
$V\gamma/\gamma^*$	$\sim 30\%$

Experimental uncertainties	
Source	Uncertainty
Luminosity	2.6%
Trigger efficiency	$1-2\%$
Lepton reconstruction and ID	$3-4\%$
Lepton energy scale	$2-4\%$
E_T^{miss} modeling	2%
Jet energy scale	10%
Pileup multiplicity	2%
B-mistag modeling	$\sim 3\%$

Theoretical uncertainties	
Source	Uncertainty
b-veto jet binning	$\sim 1-2\%$
PDF	$\sim 1\%$
WW shape	$\sim 1\%$

- Each source of uncertainty is propagated as a nuisance parameter through the fit.

$m_{\ell\ell}$ shapes



Signal and background yields

Process	Yields					
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
ggH	54 ± 4	126 ± 7	78 ± 7	2.5 ± 0.3	9 ± 2	4.0 ± 0.9
qqH	0.78 ± 0.11	4.4 ± 0.3	11.3 ± 0.9	0.87 ± 0.08	4.6 ± 0.5	1.7 ± 0.2
WH	1.4 ± 1.1	5.1 ± 1.5	6.5 ± 2.7	0.31 ± 0.15	1.4 ± 1.0	0.5 ± 0.3
ZH	0.6 ± 0.5	1.6 ± 0.7	2.2 ± 1.3	0.13 ± 0.10	0.45 ± 0.15	0.19 ± 0.11
Total signal	318 ± 12					
qqWW	1496 ± 100	2829 ± 233	751 ± 221	413 ± 121	135 ± 62	161 ± 55
ggWW	586 ± 163					
Top 0 jets	573 ± 160					
Top $\geq$1 jet	137 ± 34	906 ± 154	1532 ± 190	714 ± 126	241 ± 53	139 ± 50
W+jets	835 ± 195					
DY$\tau\tau$	181 ± 58					
VV	236 ± 25					
Vγ^*	215 ± 77					
Vγ	154 ± 115					
VVV	31 ± 18					
Total background	12264 ± 575					
Data	12566 ± 112					

Differential cross section table

Bin i [GeV]	$d\sigma_i / dp_{T,i}^{H}$ [fb/GeV]	Total uncertainty (up/down) [fb/GeV]	Statistical uncertainty [fb/GeV]	Type A uncertainty [fb/GeV]	Type B uncertainty (up/down) [fb/GeV]	Type C uncertainty (up/down) [fb/GeV]
0-15	0.615	+0.370/-0.307	$\pm$0.246	$\pm$0.179	+0.211/-0.038	+0.0782/-0.0608
15-45	0.561	+0.210/-0.157	$\pm$0.120	$\pm$0.093	+0.146/-0.041	+0.0395/-0.0327
45-85	0.215	+0.084/-0.078	$\pm$0.059	$\pm$0.037	+0.047/-0.034	+0.0089/-0.0084
85-125	0.071	+0.038/-0.038	$\pm$0.029	$\pm$0.017	+0.018/-0.017	+0.0018/-0.0022
125-165	0.027	+0.020/-0.019	$\pm$0.016	$\pm$0.009	+0.007/-0.007	+0.0003/-0.0006
165-∞	0.028	+0.027/-0.027	$\pm$0.023	$\pm$0.012	+0.008/-0.007	+0.0002/-0.0006