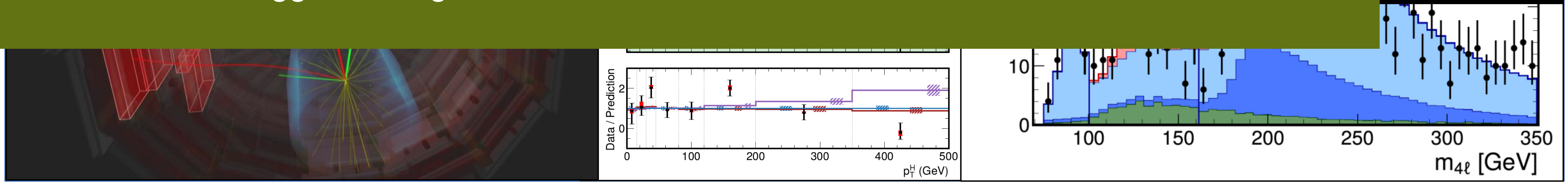
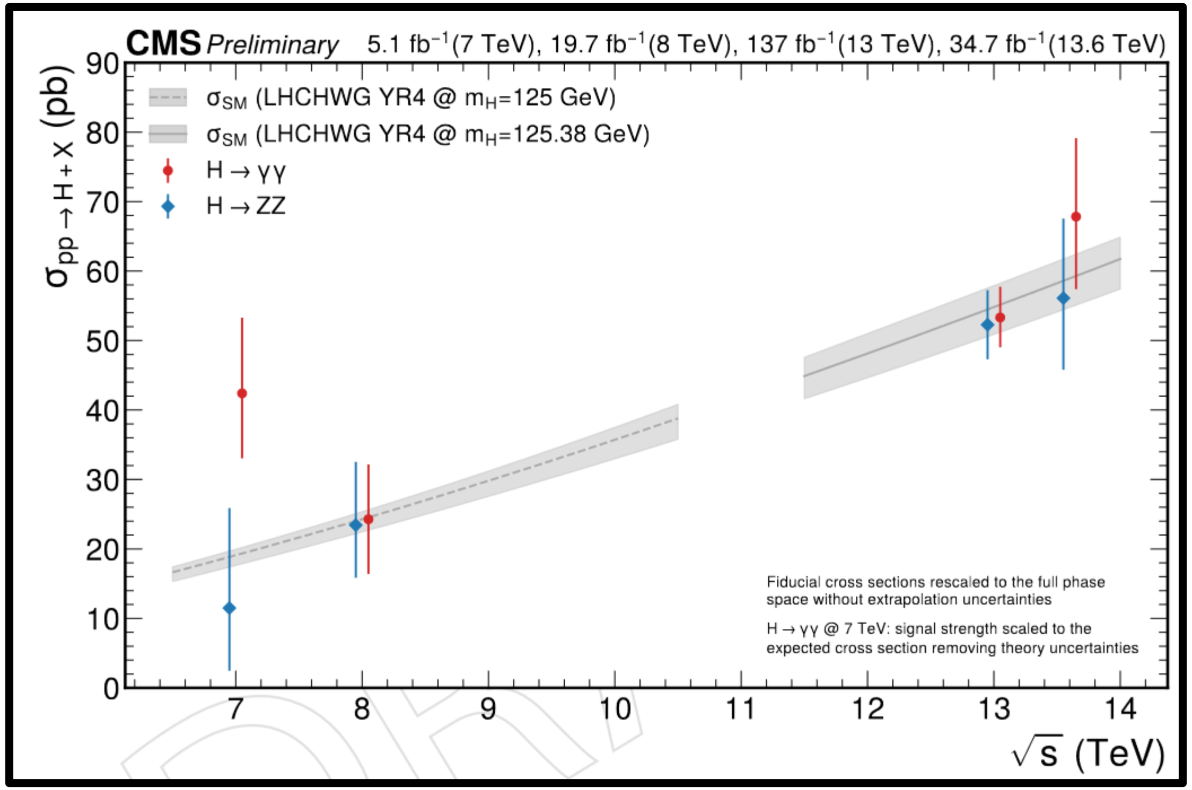
Higgs boson fiducial cross section at √s=13.6 TeV with the CMS detector

Nico Härringer
On behalf of the CMS collaboration
23.09.2024, Higgs Hunting 2024

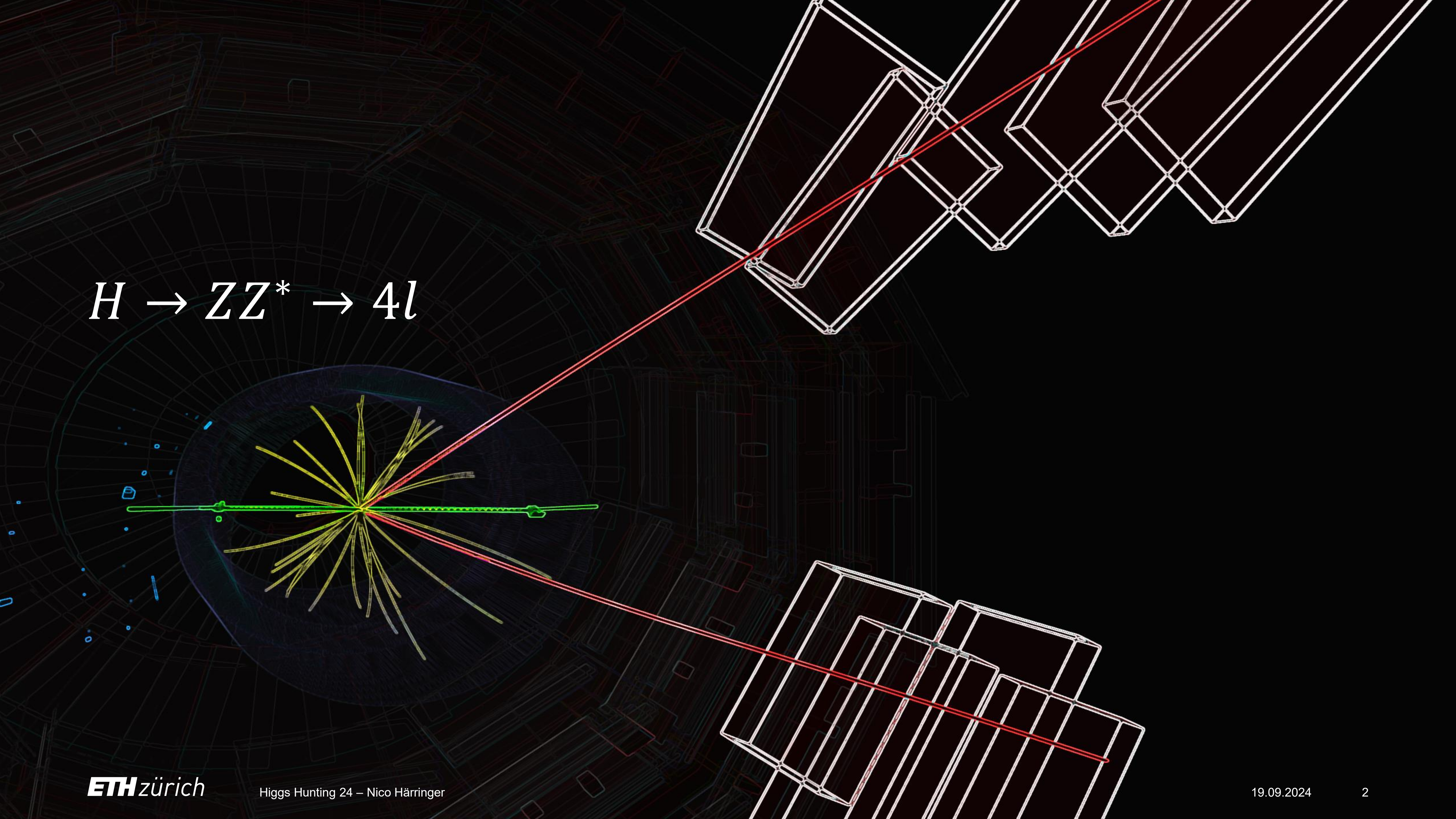


Introduction

- Inclusive and differential fiducial cross section
  - $H \rightarrow ZZ^* \rightarrow 4l$ (CMS PAS HIG-24-013)
  - $H \rightarrow \gamma\gamma$ (CMS PAS HIG-23-014)
- Dataset
  - Early Run 3 @ 13.6 TeV (2022, 34.7 fb^{-1})
    - ReReco: 13.8 fb^{-1}
    - Prompt: 20.9 fb^{-1}
- Using new data format
  - Very lightweight (1-2 kB/Event)

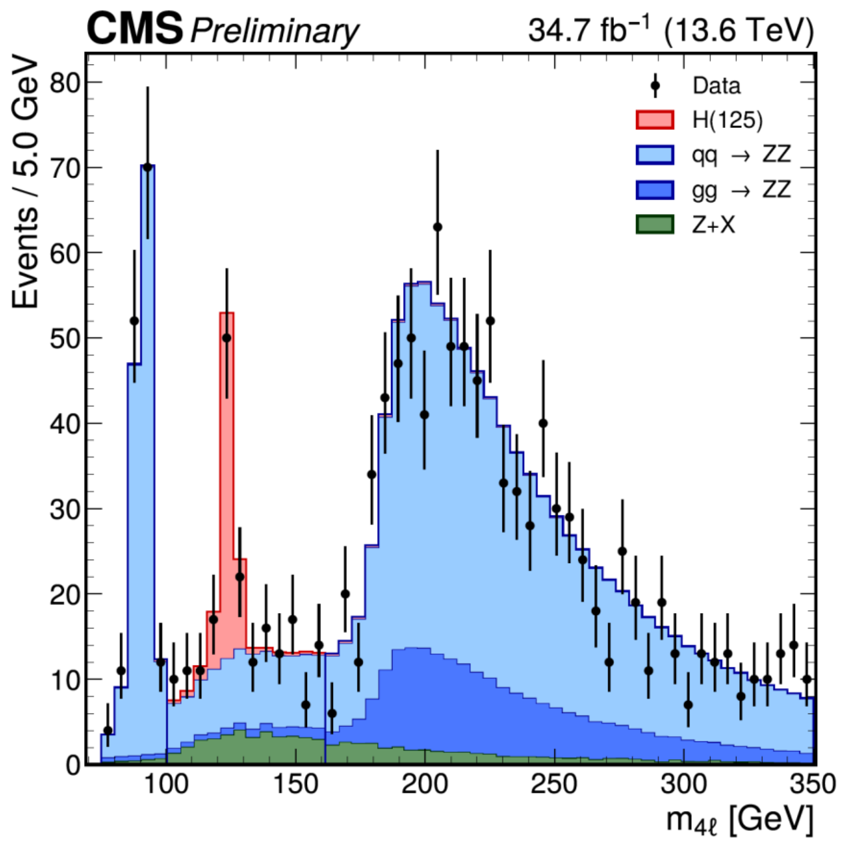


$$H \to ZZ^* \to 4l$$



$H \rightarrow ZZ^* \rightarrow 4l$: Description

- Large $S/\sqrt{S+B}$ (golden channel)



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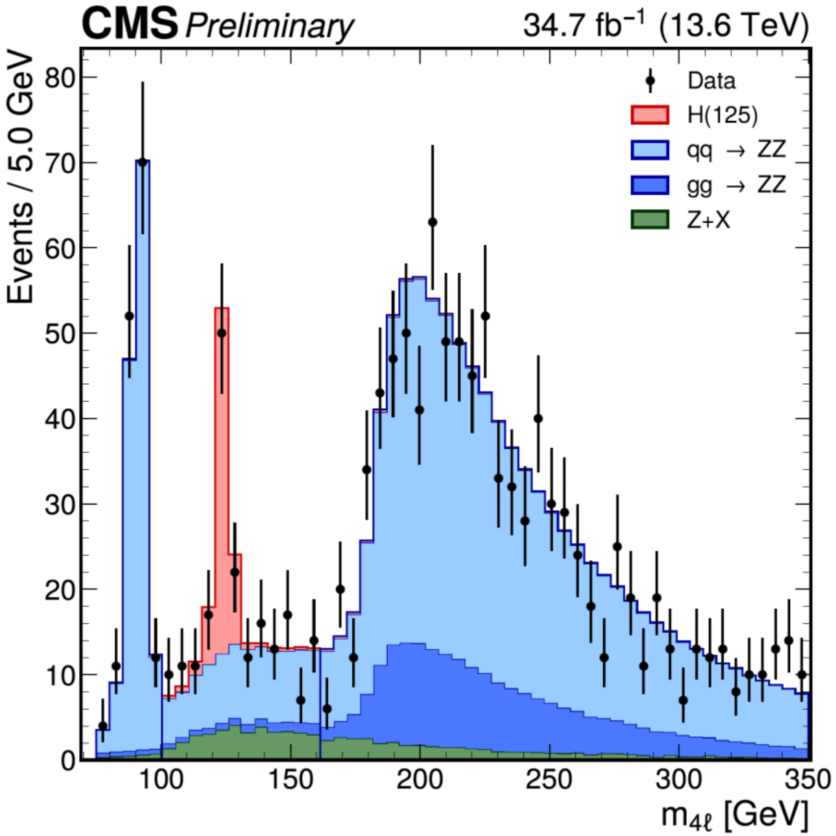

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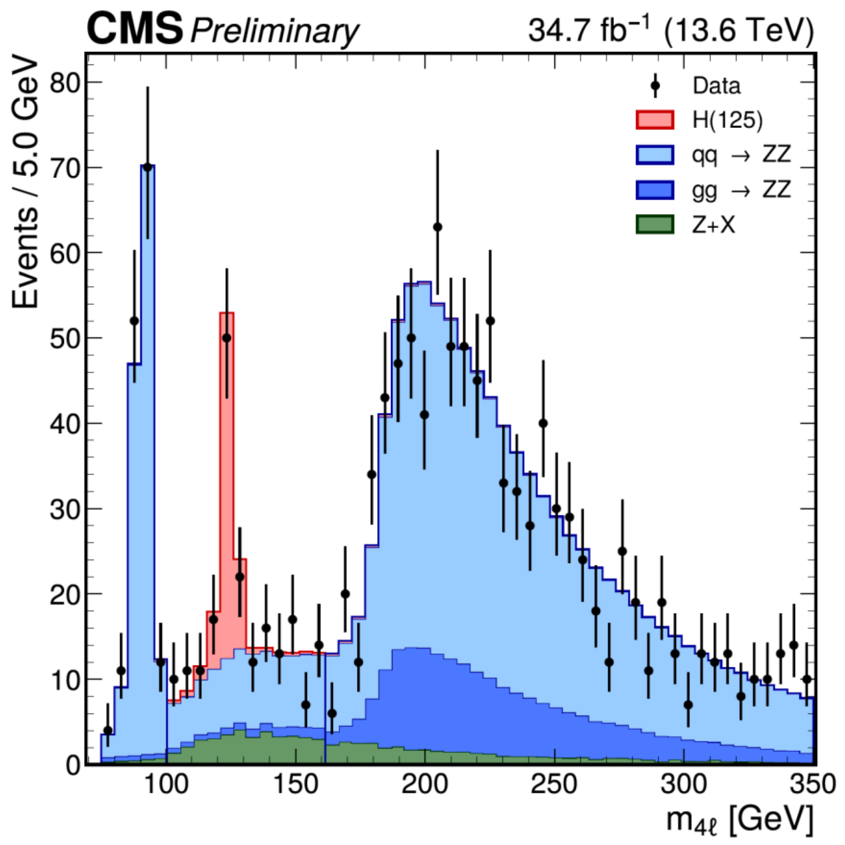

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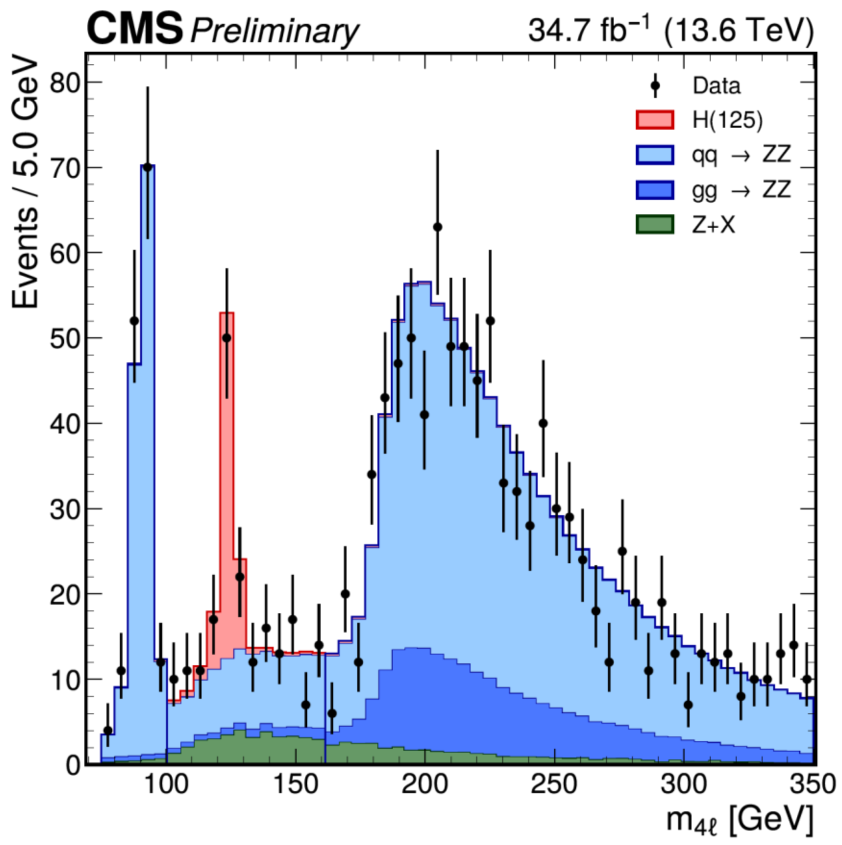

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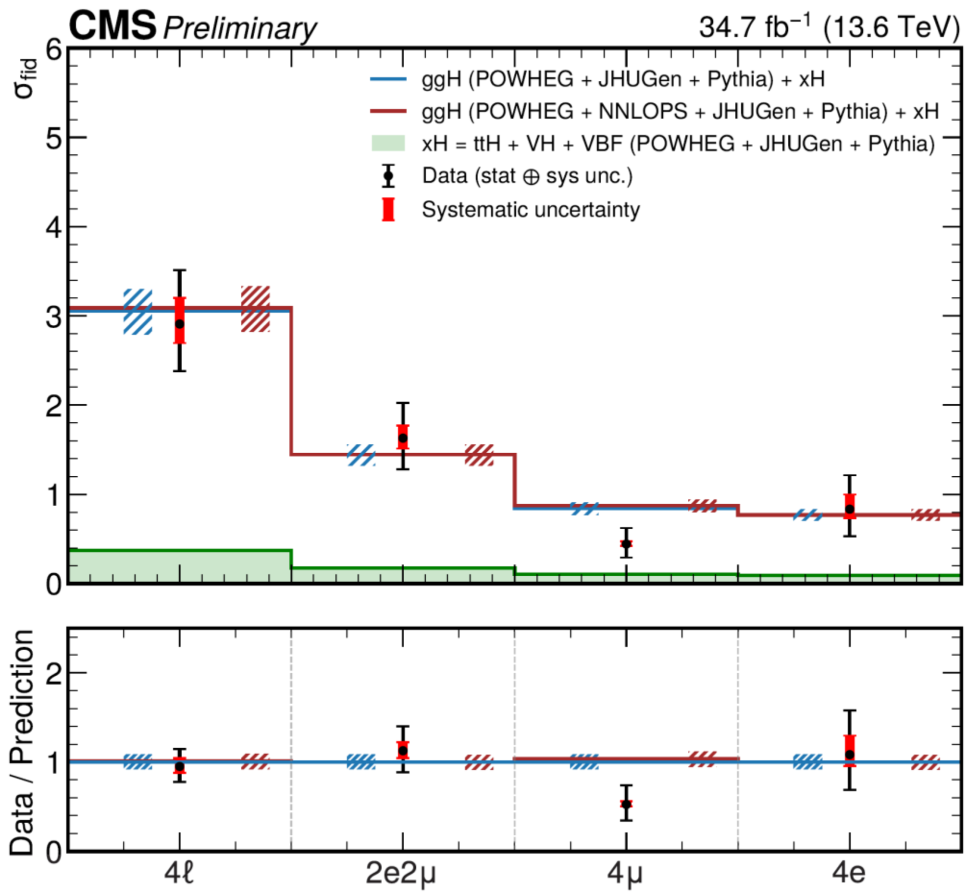
  - All decay modes combined



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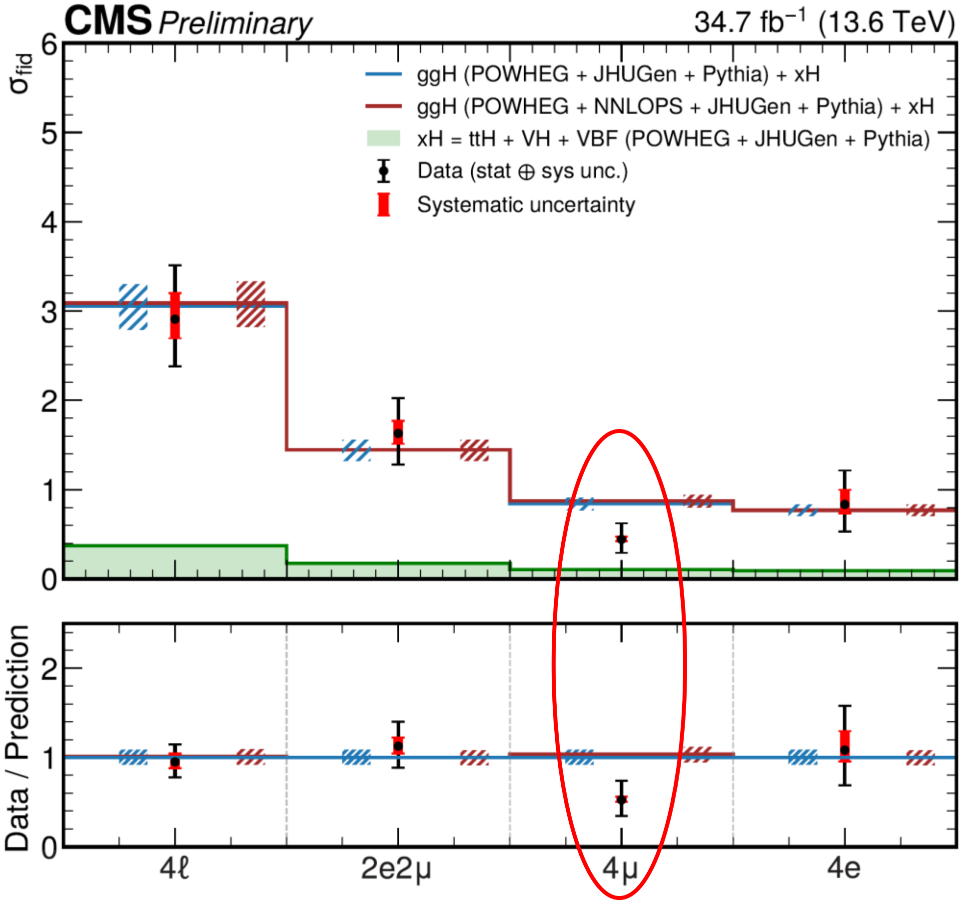
  - Smallest systematic uncertainty for 4μ



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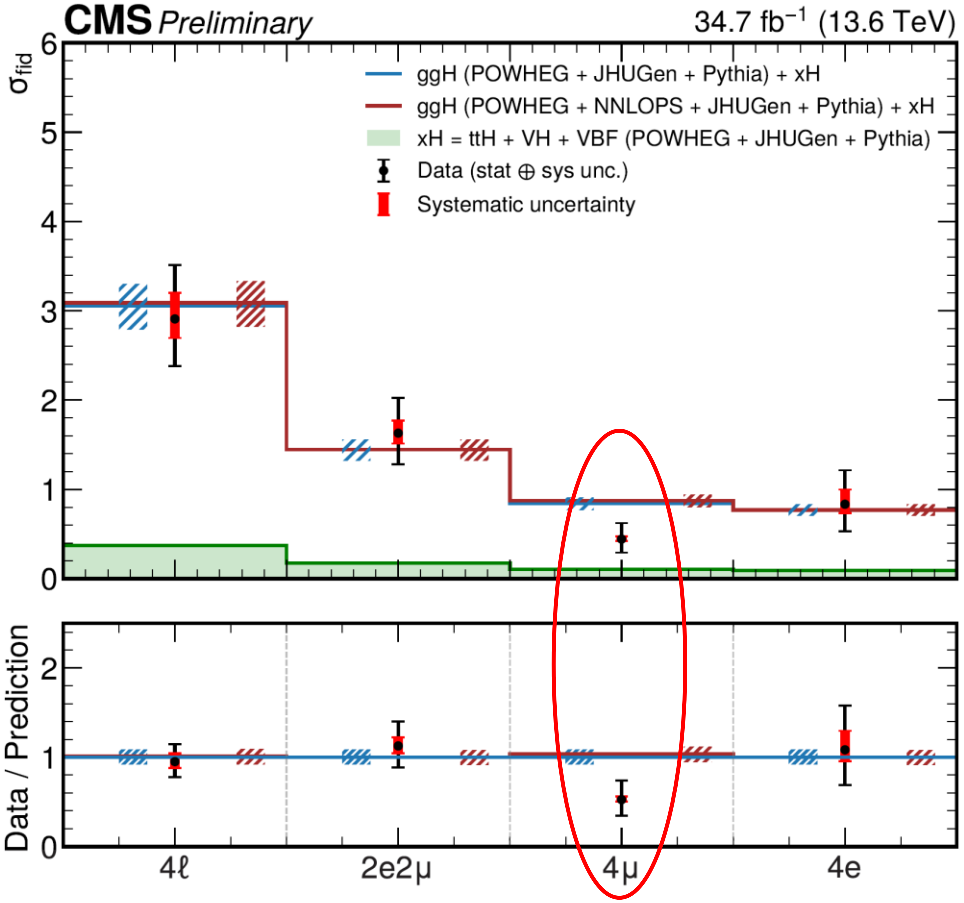

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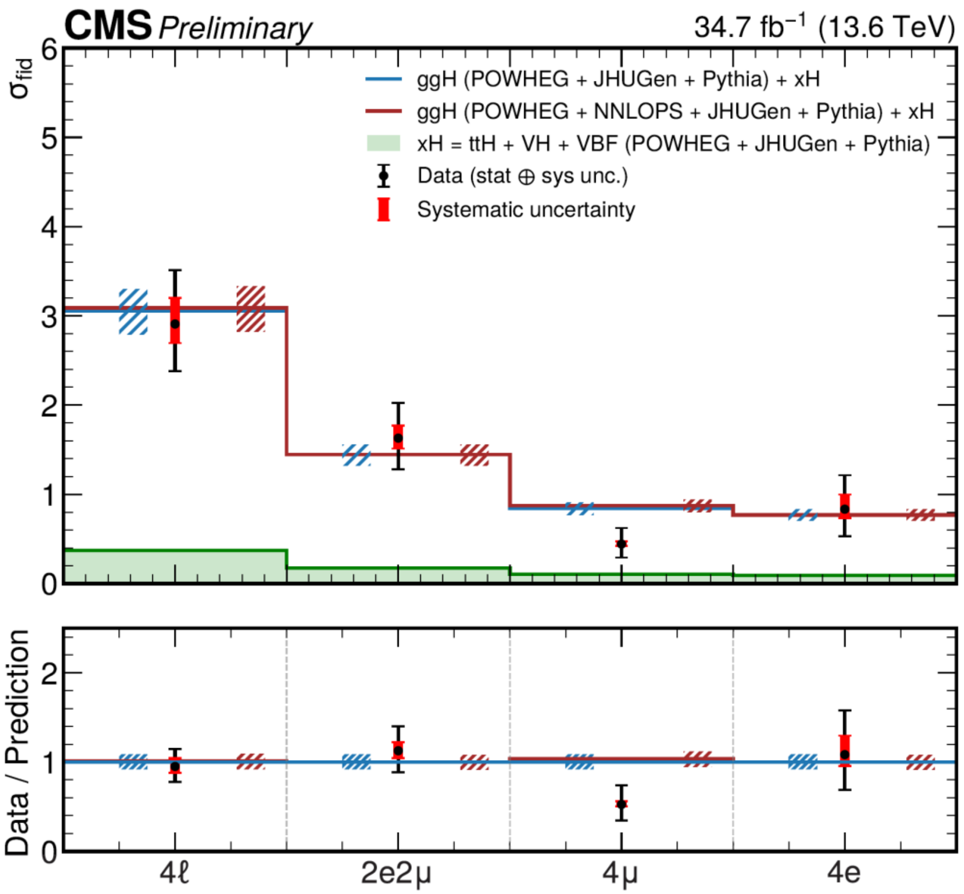

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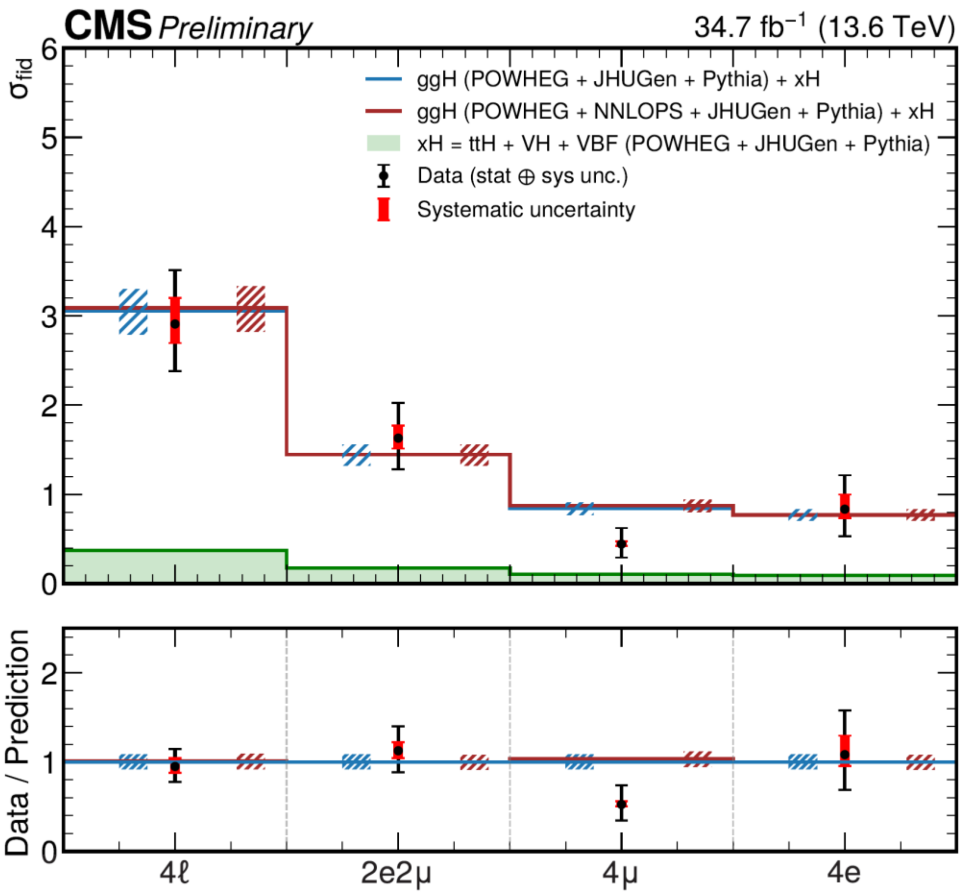
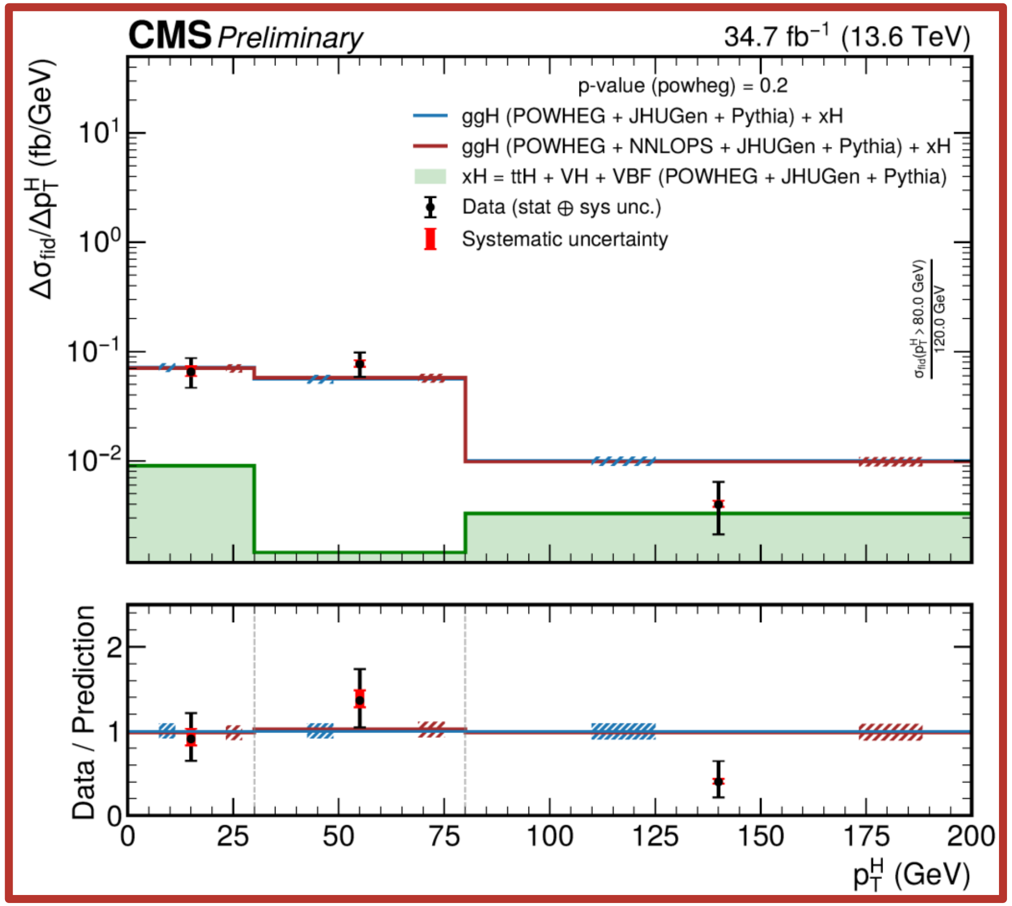
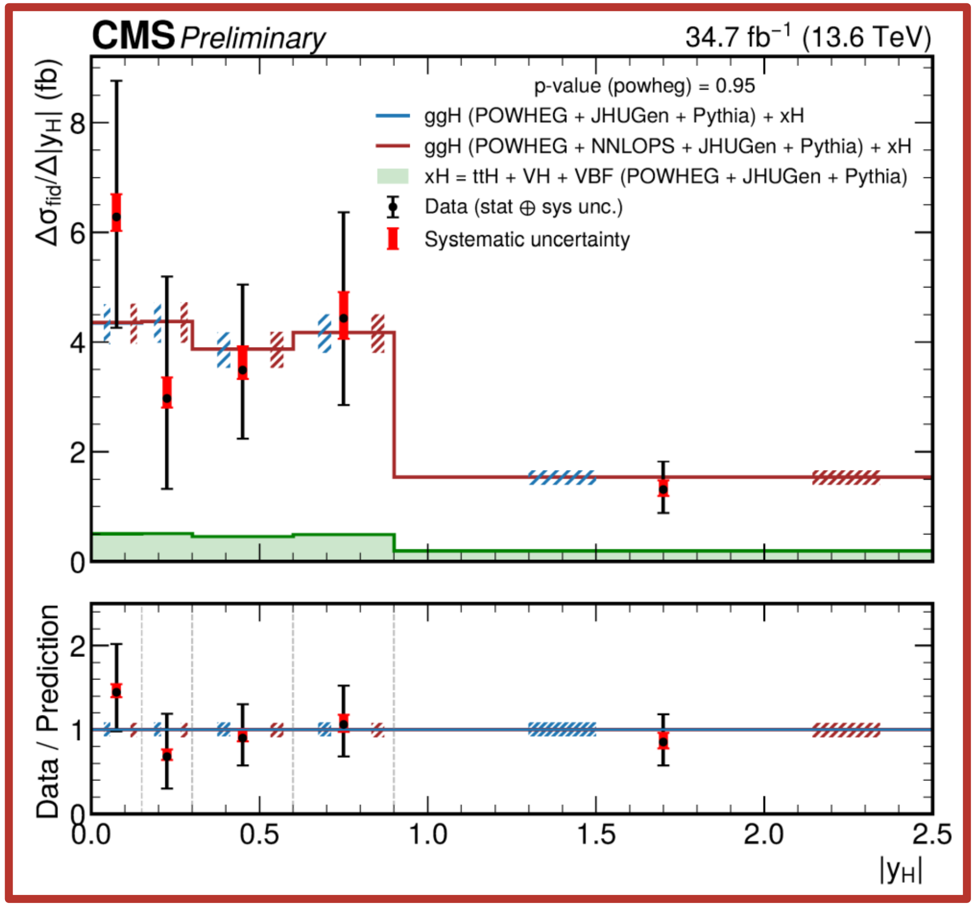
$$\sigma^{4l}_{fid} = 2.94^{+0.53}_{-0.49}\,(\text{stat.})^{+0.29}_{-0.22}\,(\text{syst.})\text{ fb}$$



$H \to ZZ^* \to 4l$: Differential fiducial cross section

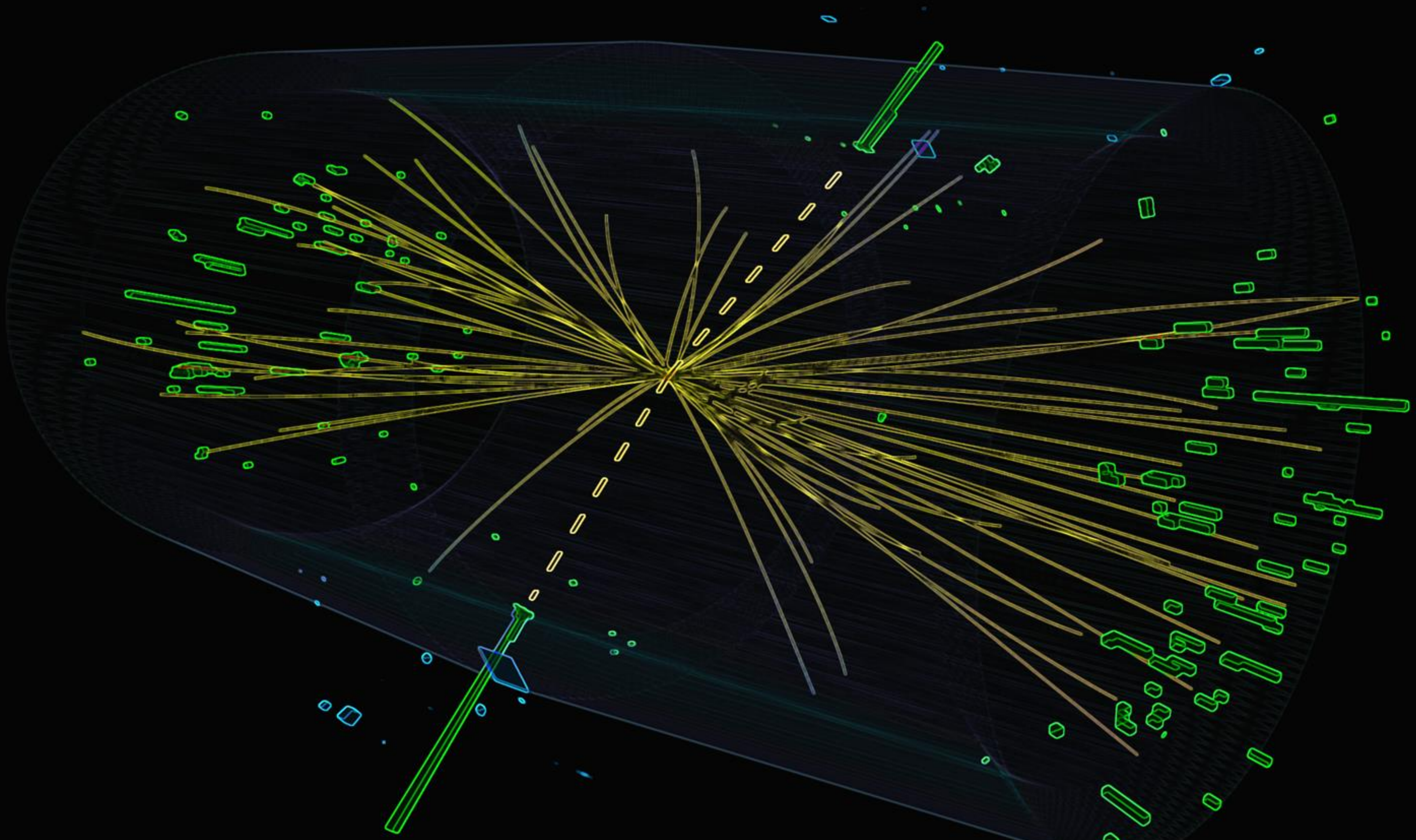




p_T^H

$|y_H|$

$H \to \gamma\gamma$



$H \to \gamma\gamma$: Description

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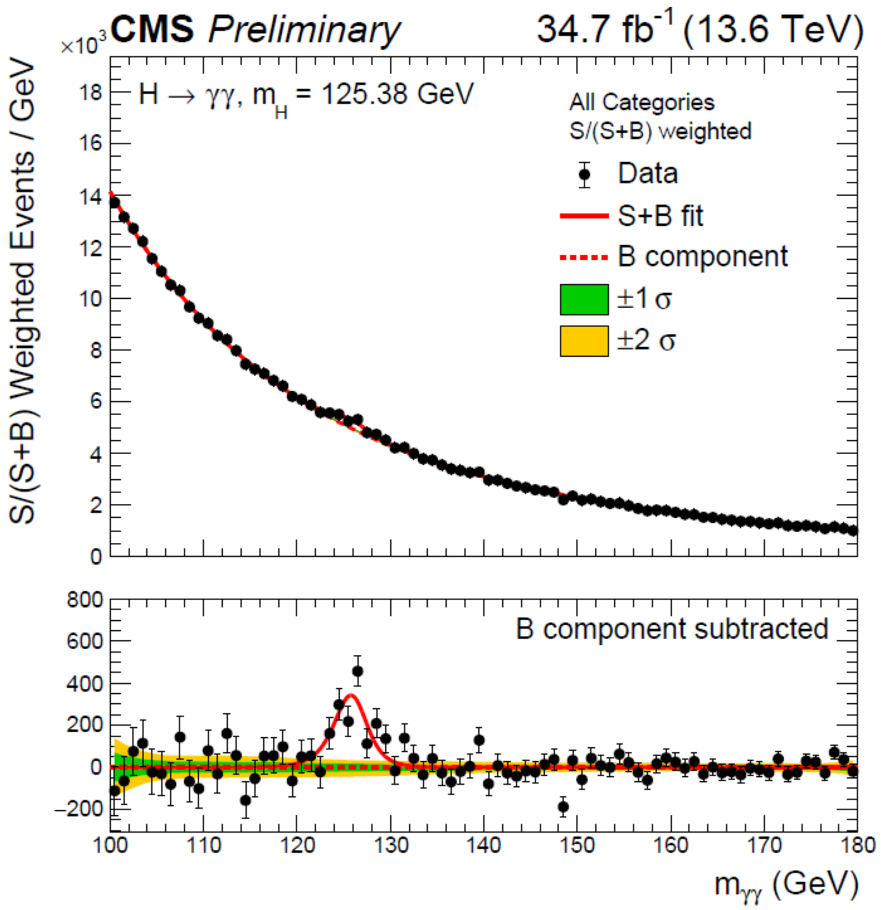

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- Large background, small $S/\sqrt{S+B}$
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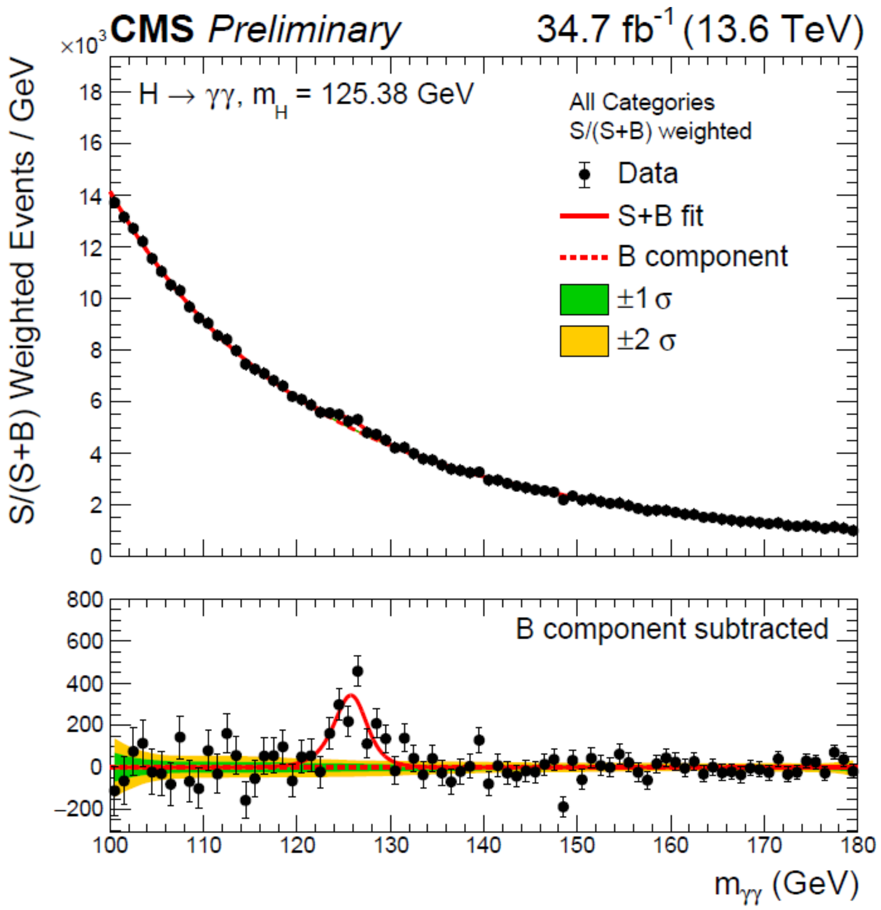

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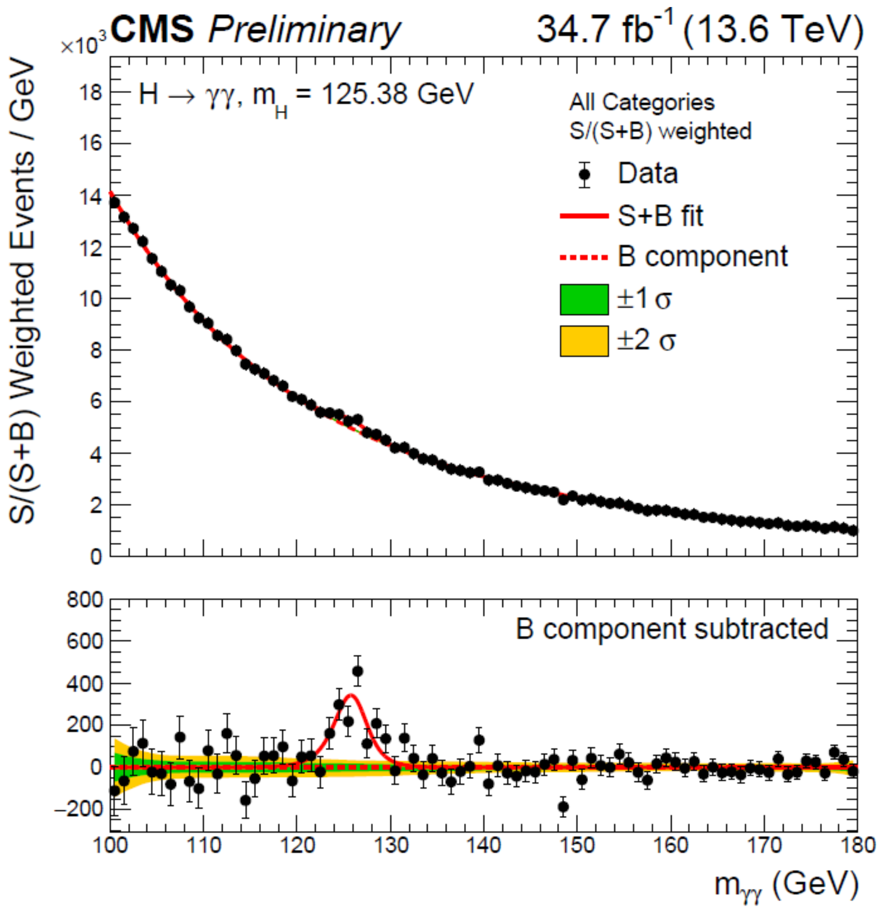
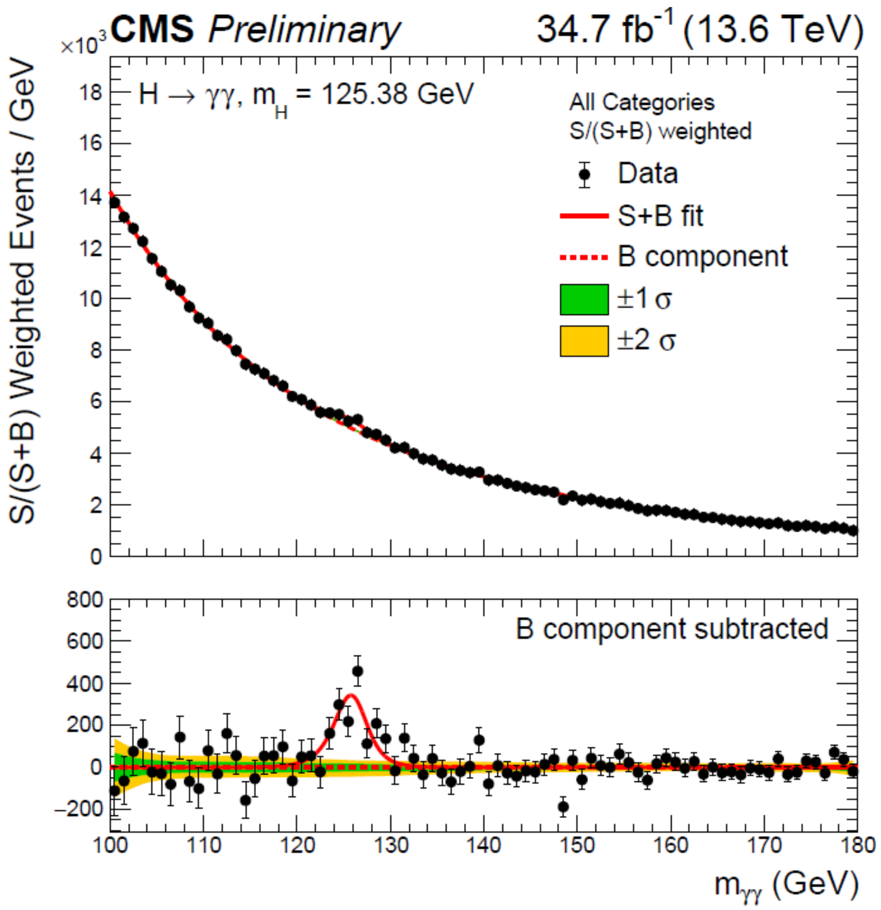


$H \to \gamma\gamma$: Description

- Large background, small $S/\sqrt{S+B}$
- Novelties compared to Run 2 (CMS PAPER HIG-17-025)
  - Data/MC corrections
  - Updated fiducial phase space



$H \rightarrow \gamma\gamma$: Normalizing Flows

- ⚠️ Non-negligible differences between Data and Simulation → large systematic uncertainty
  - Solution: Bring data and simulation closer together, but how?

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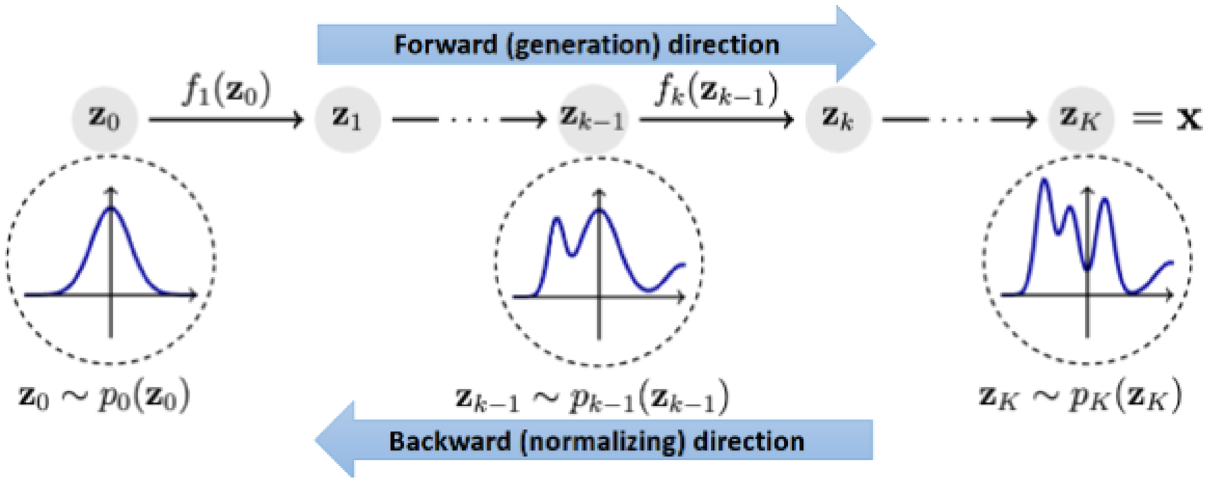

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- 🆕 Novelty in this analysis cycle: Normalizing Flows
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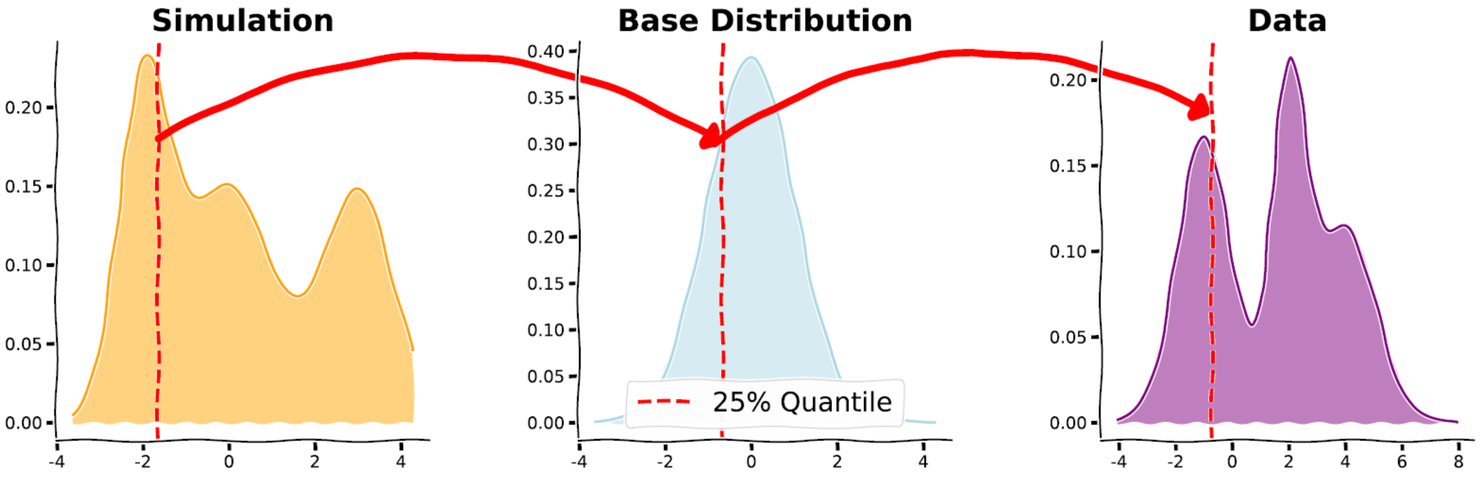
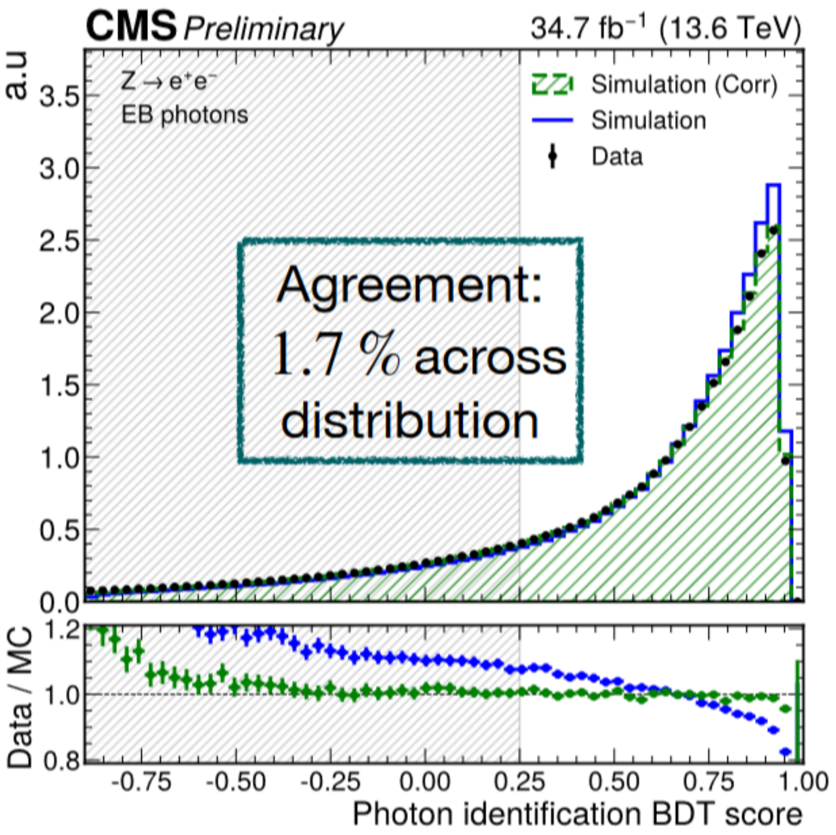
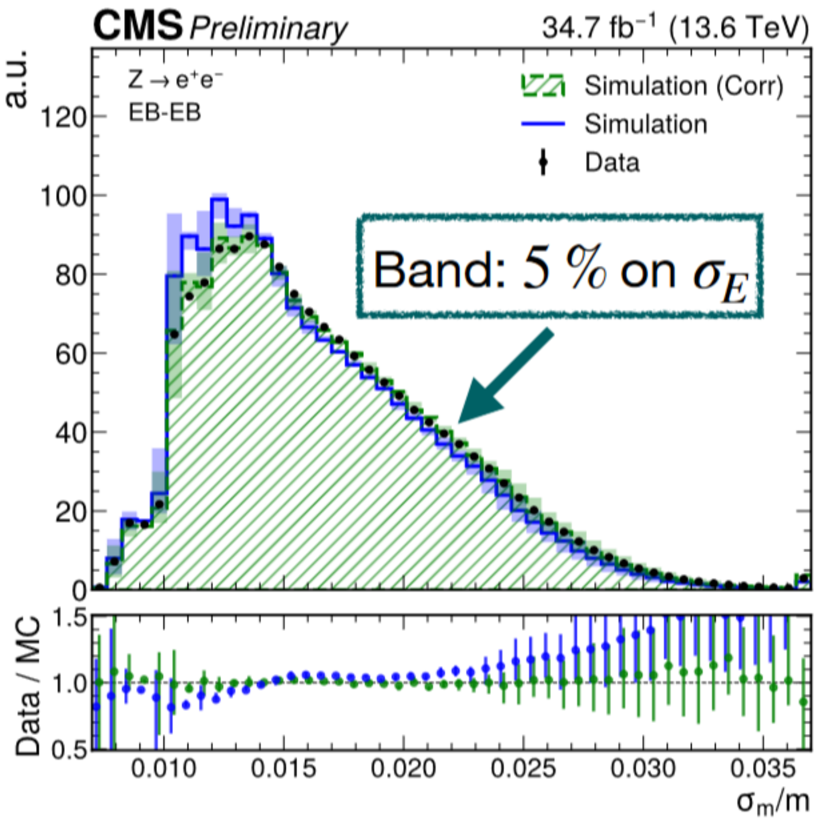
    - One flow (paper)



$H \to \gamma\gamma$: Normalizing Flows

- Drastically improved agreement after correction





$H \to \gamma\gamma$: Fiducial phase space and jet definition

- Use relative isolation

$$\mathcal{I} = \sum_i^{\Delta R<0.3} \frac{p_{T,i}}{p_T}$$

Fiducial phase space

$$\mathcal{I} \times p_T^{\gamma} < 10 \text{ GeV}$$
$$\sqrt{p_T^{\gamma_1} p_T^{\gamma_2}}/m_{\gamma\gamma} > 1/3$$
$$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$$
$$|\eta^{\gamma_{1,2}}| \notin (1.4442, 1.566)$$
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New geometric cut [1], improves perturbative convergence in fiducial region

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- Jet definition @ particle level:
  - Anti-k_T clustering of stable particles
  - Distance parameter: $\Delta R < 0.4$
  - Jets removed if overlap with $\mathrm{e}\ (\mu)$ within $\Delta R < 0.4$
    - $p_T > 15\ (10)$ GeV, $|\eta| < 2.5\ (2.4)$, $I < 0.2$

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Matches jet definition @ RECO level

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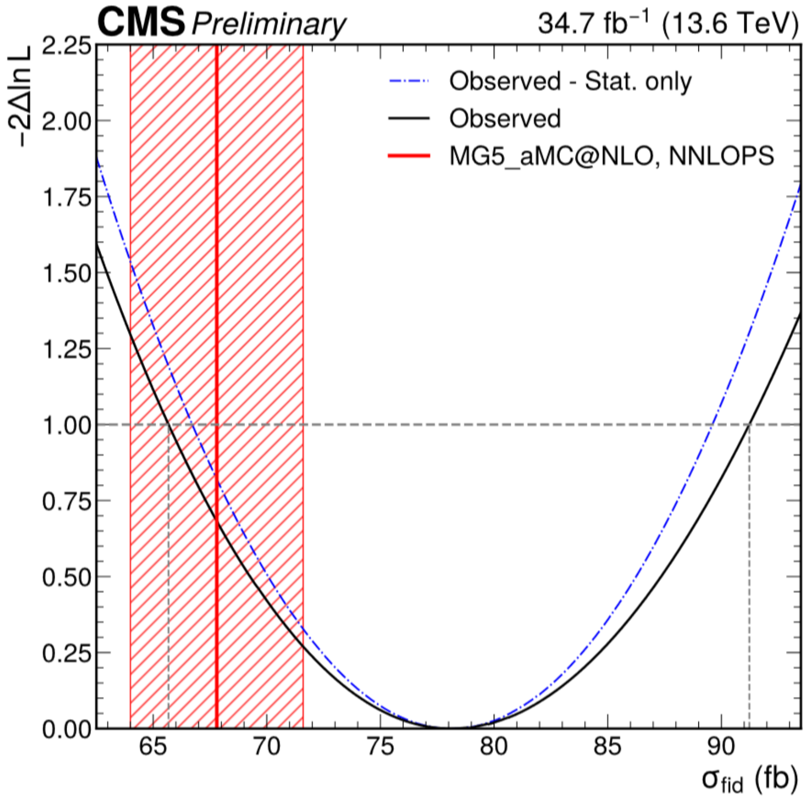
- Inclusive result
  - $\sigma_{fid} = 78 \pm 11(\text{stat.})\,^{+6}_{-5}(\text{syst.})\text{ fb} = 78^{+13}_{-12}\text{ fb}$



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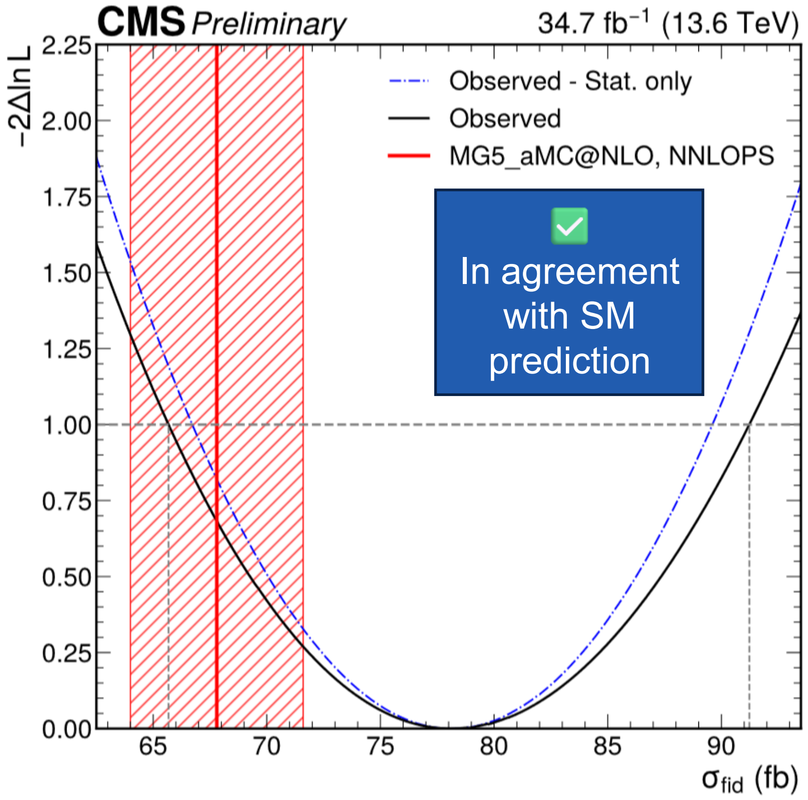

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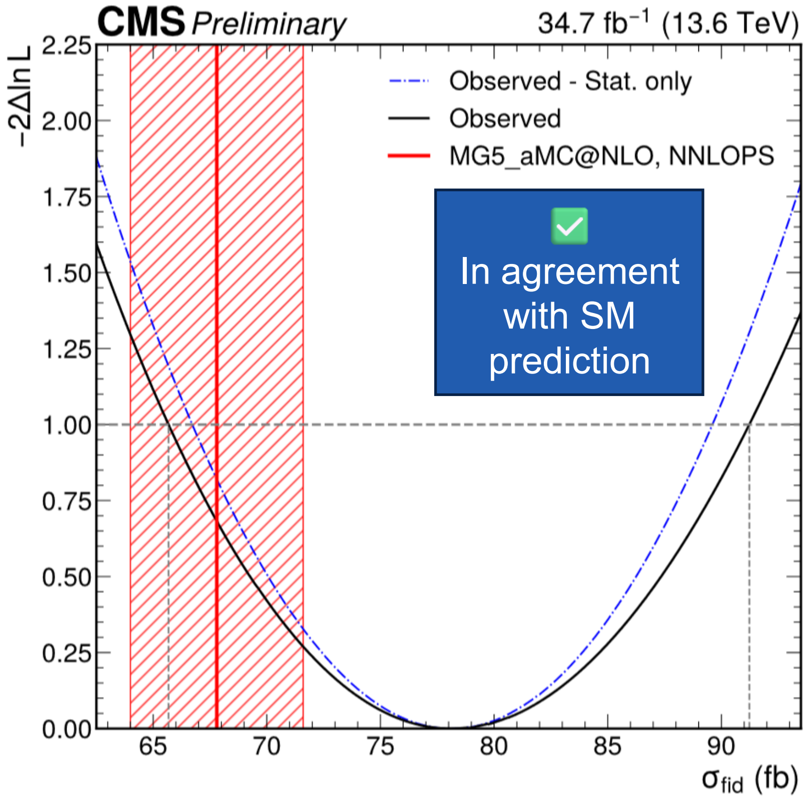
  - Systematic uncertainties
    - Dominated by energy scale and resolution

Systematic uncertainty	Magnitude
Photon energy scale and resolution group	$+5.8\% / -4.9\%$
Category migration from energy resolution	$+3.5\% / -3.9\%$
Integrated luminosity	$\pm 1.4\%$
Photon preselection efficiency	$\pm 1.4\%$
Energy scale non-linearity	$+0.8\% / -1.6\%$
Photon identification efficiency	$\pm 1.0\%$
Pileup reweighting	$\pm 0.8\%$



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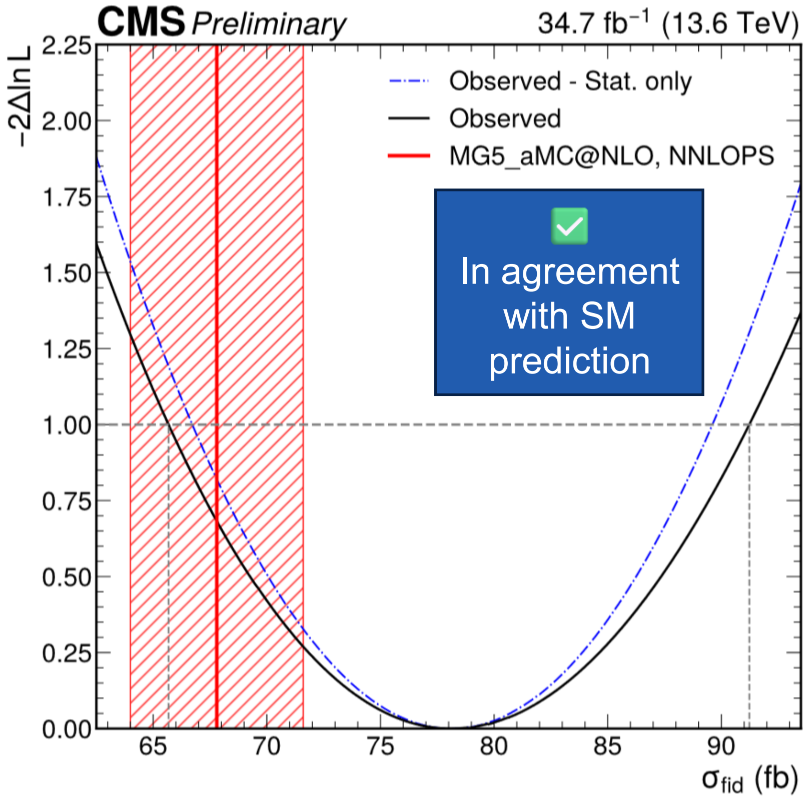
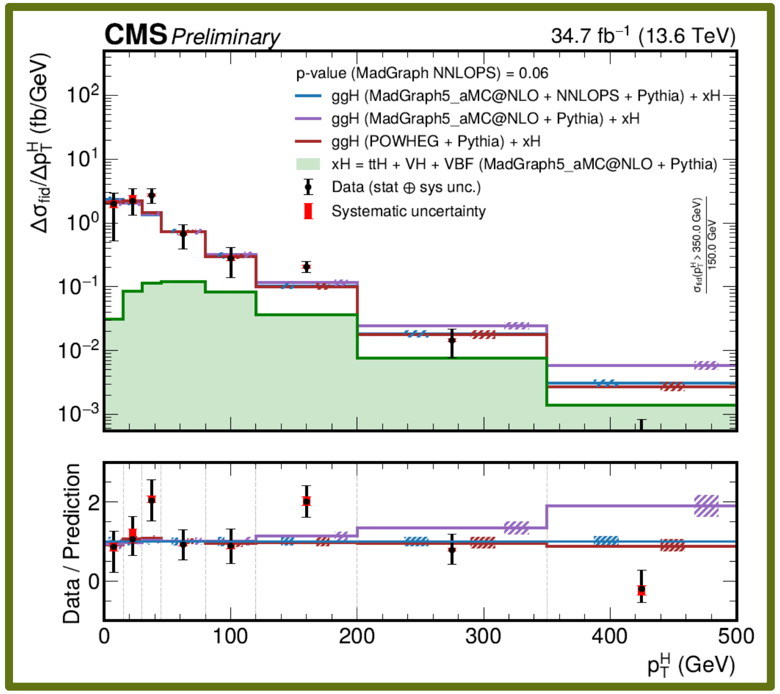
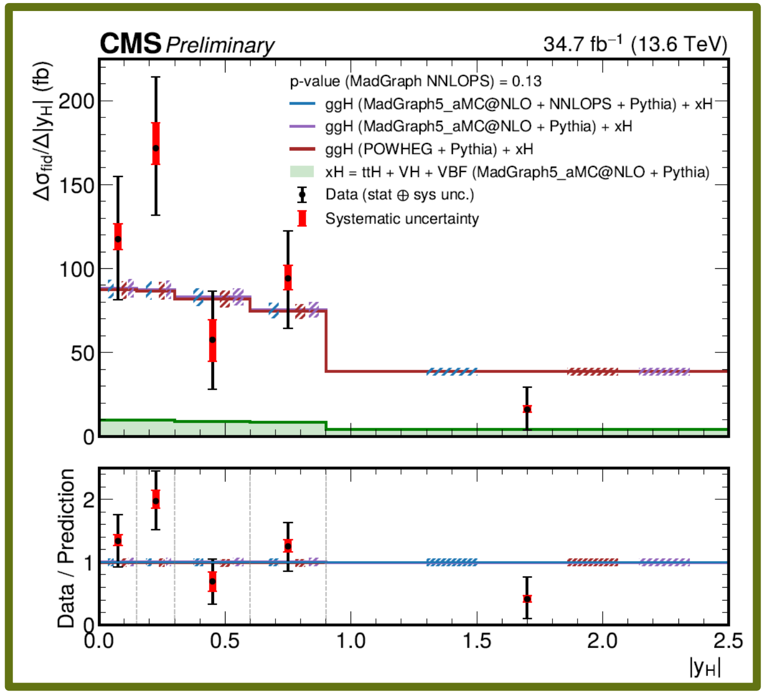
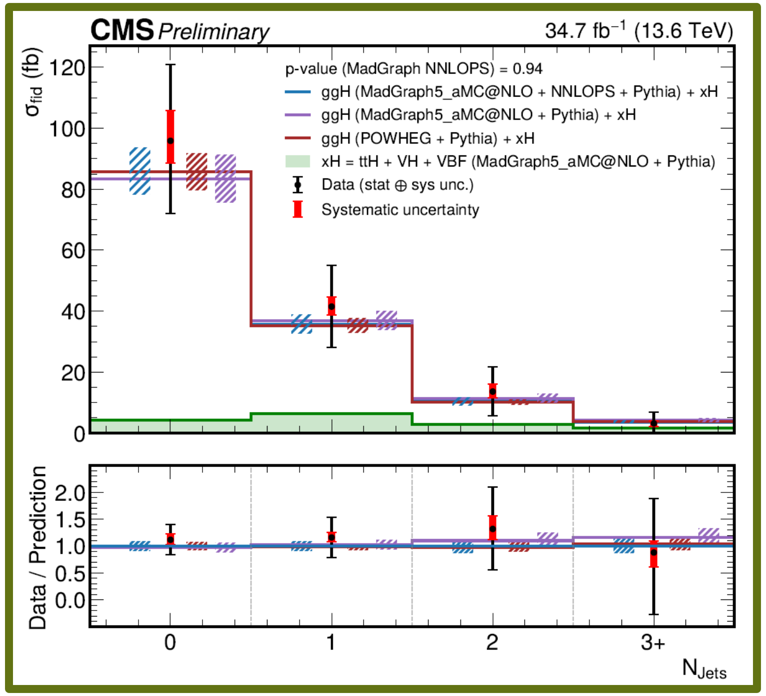


$H \to \gamma\gamma$: Differential fiducial cross section







p_T^H

$|y_H|$

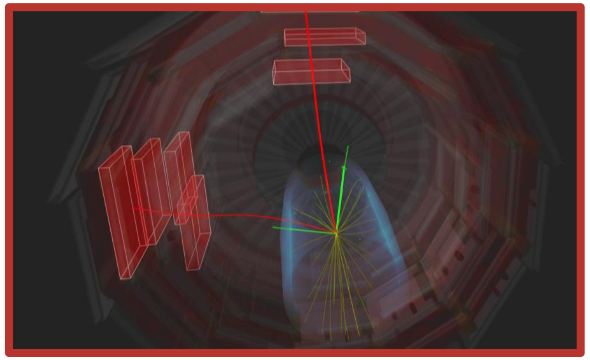
N_{Jets}

$p_{\mathrm{T}}^{\mathrm{H}}$ [GeV]	0	15	30	45	80	120	200	350	∞
y^{H}	0	0.15	0.3	0.6	0.9	2.5			
N_{jets}	0	1	2	3	∞				

Conclusion

Summary

- Presented the <u>first</u> Higgs results using CMS data collected during the ongoing Run 3
- $H \rightarrow ZZ^* \rightarrow 4l$:
  - Inclusive & differential cross sections
    - ✅ In agreement with prediction



- $H \rightarrow \gamma\gamma$:
  - Normalizing Flow
    - One flow to correct all ingredients for BDT and mass resolution
  - New geometric cut: Improves perturbative convergence in fiducial region
  - Inclusive & differential cross sections
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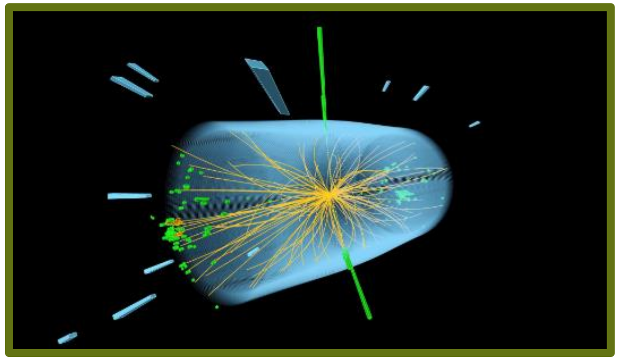
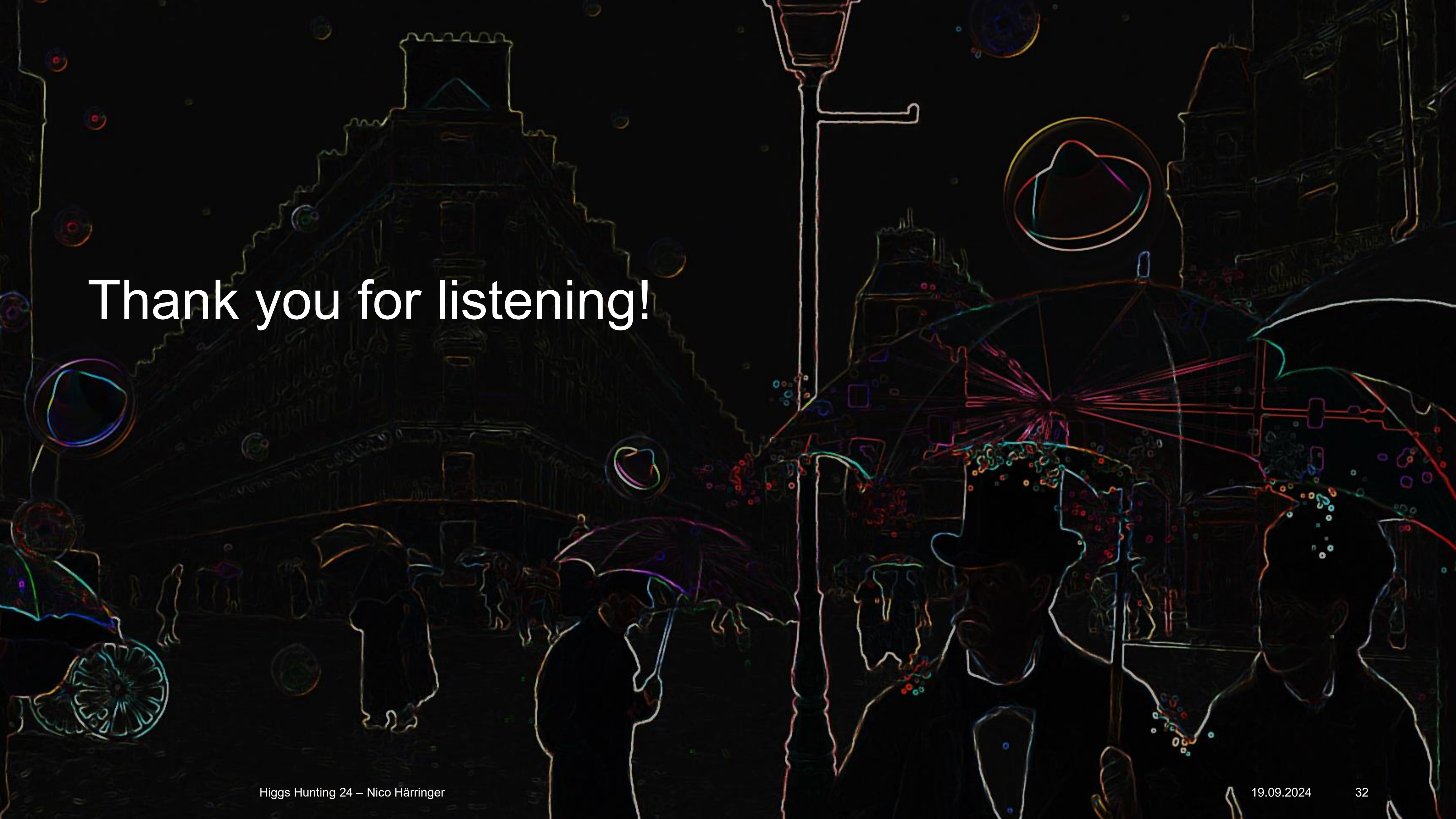




Thank you for listening!

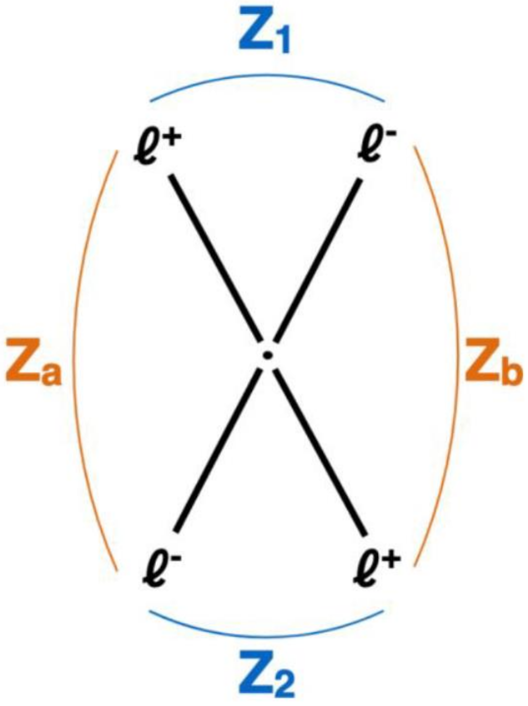
$H \rightarrow ZZ^* \rightarrow 4l$: Backup

Event selection

Z Candidates: OS SF lepton pairs, with $12<m_{ll}<120$ GeV

ZZ Candidates: pairs of non-overlapping Z cand, Z_1 is the candidate with mass closest to m_Z nominal

- $m_{Z1} > 40$ GeV
- $pT_{l1} > 20$ GeV, $pT_{l2} > 10$ GeV
- $\Delta R > 0.02$ between each of the 4 leptons
- $m_{ll} > 4$ GeV for OS pairs
- reject 4e and 4μ candidates where the alternative pairing satisfies $|m_{Za} - m_Z| < |m_{Z1} - m_Z|$ AND $m_{Zb} < 12$ GeV
- $m_{4l} > 70$ GeV



If more than 1 ZZ Candidate passes the selection, the one with the **highest Z_2 pT is retained**

Signal region: $105 < m_{4l} < 160$ GeV

Fiducial Phase Space

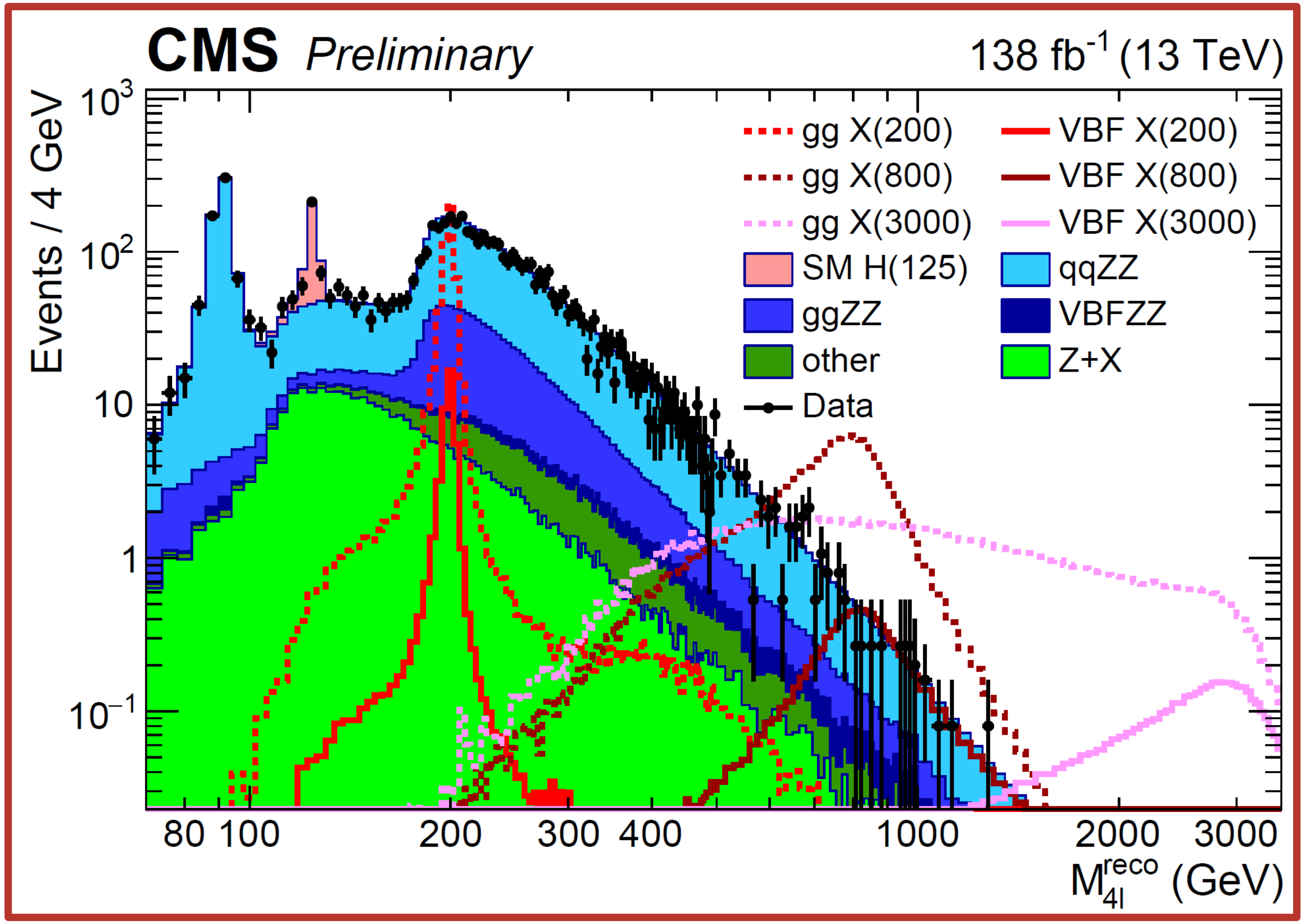
Defined at GEN-level to match the experimental selection at reco-level
→ ensure model independence of the results and ease the reinterpretability

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_T	$p_T > 20$ GeV
next-to-leading lepton p_T	$p_T > 10$ GeV
additional electrons (muons) p_T	$p_T > 7(5)$ GeV
pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
p_T sum of all stable particles within $\Delta R < 0.3$ from lepton	less than $0.35 \cdot p_T$
Event topology	
existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
inv. mass of the Z_1 candidate	$40\,\text{GeV} < m(Z_1) < 120\,\text{GeV}$
inv. mass of the Z_2 candidate	$12\,\text{GeV} < m(Z_2) < 120\,\text{GeV}$
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$m(\ell^+\ell'^-) > 4\,\text{GeV}$
inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 160\,\text{GeV}$
the selected four leptons must originate from the $H \to 4\ell$ decay	

Gen-level isolation included to reduce model dependence on efficiency

PAPER

$H \to ZZ^* \to 4l$: High mass spectrum



HIG-24-002

$H \to ZZ^* \to 4l$: Run 2 Strategy

- Trigger efficiencies:
  - Derived using TnP with applied Scale Factors
- Electrons
  - pT>7GeV, $|\eta|$<2.5, SIP<4, d_xy<0.5cm, d_z<1cm
  - ID and Isolation: HZZ MVA, training with 2018 data
- Muons
  - pT>5GeV, $|\eta|$<2.4, SIP<4, d_xy<0.5cm, d_z<1cm
- Statistical Normalization

$$
\begin{aligned}
N^{f,i}_{\text{obs}}(m_{4\ell}) &= N^{f,i}_{\text{fid}}(m_{4\ell}) + N^{f,i}_{\text{nonfid}}(m_{4\ell}) + N^{f,i}_{\text{nonres}}(m_{4\ell}) + N^{f,i}_{\text{bkg}}(m_{4\ell}) \\
&= \epsilon^{f}_{i,j} \cdot \left(1 + f^{f,i}_{\text{nonfid}}\right) \cdot \sigma^{f,j}_{\text{fid}} \cdot \mathcal{L} \cdot \mathcal{P}_{\text{res}}(m_{4\ell}) \\
&\quad + N^{f,i}_{\text{nonres}} \cdot \mathcal{P}_{\text{nonres}}(m_{4\ell}) + N^{f,i}_{\text{bkg}} \cdot \mathcal{P}_{\text{bkg}}(m_{4\ell})
\end{aligned}
$$

$H \to \gamma\gamma$: Backup

From MiniAOD to NanoAOD: the vertex

The mass resolution in $\mathrm{H} \rightarrow \gamma\gamma$ is driven by:

- photon energy resolution –> ECAL;
- precision in measuring the opening angle between the two photons –> **vertex choice**.

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\alpha)}$$

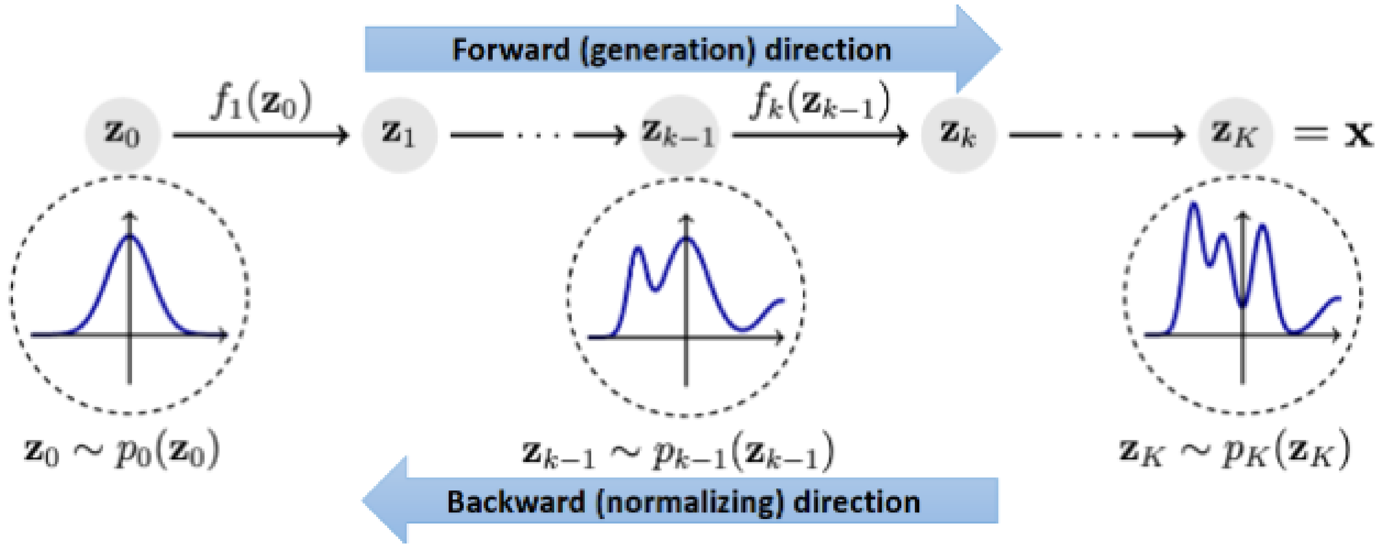
$\mathrm{H} \rightarrow \gamma\gamma$ vertex previously assigned by means of a BDT and all MiniAOD variables, which are computed wrt the 0th vertex $\left(\max \sum p_{\mathrm{T}}^2\right)$, were recomputed wrt to the chosen diphoton vertex

Run2 workflow

❌ **Hgg vertex cannot be used with central NanoAOD**

Alessandro Tarabini

$H \to \gamma\gamma$: Normalizing Flows



Setting up the problem

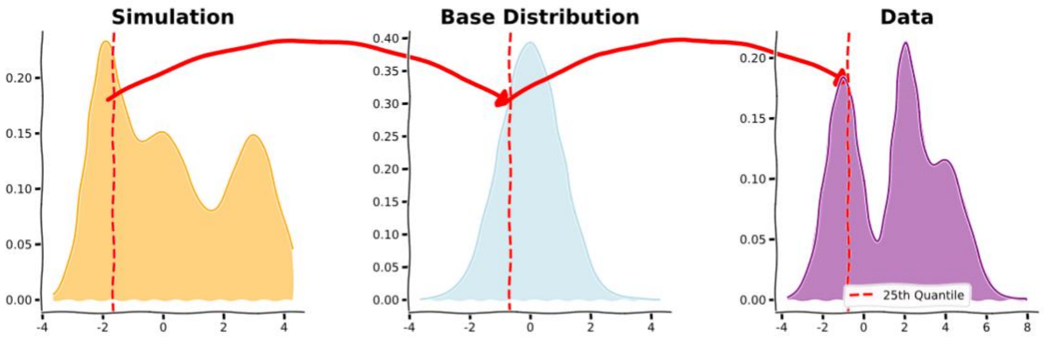
- The objective is to perform single-object (photon) corrections
- This can be achieved by choosing a high-purity region and adjusting your simulated distribution to match the data distributions
- We study electrons from $Z \rightarrow ee$ which are reconstructed as photons (only Ecal, no tracking information)
- Using the tag and probe framework to obtain an unbiased sample of probe electrons
- Sample has a negligible background contribution
- Perform the correction of the inputs to the mvaID (Run 3 EGM photon ID)
  - But, condition these corrections on the kinematics (p_T, η, ϕ, ρ)
  - A reweighting is performed on those variables
  - With this we can apply the correction to $H \rightarrow \gamma\gamma$ for example

- R_9
- $\sigma_{i\eta i\eta}$
- η_{Width}
- ϕ_{Width}
- $\sigma_{i\eta i\phi}$
- S_4
- $\frac{H}{E}$
- $ecalPFClusterIso$
- $trkSumPtHollowConeDR03$
- $trkSumPtSolidConeDR04$
- $pfChargedIso$
- $pfChargedIsoWorstVtx$
- $esEffSigmaRR$
- $esEnergyOverRawE$
- $hcalPFClusterIso$
- σ_E/E

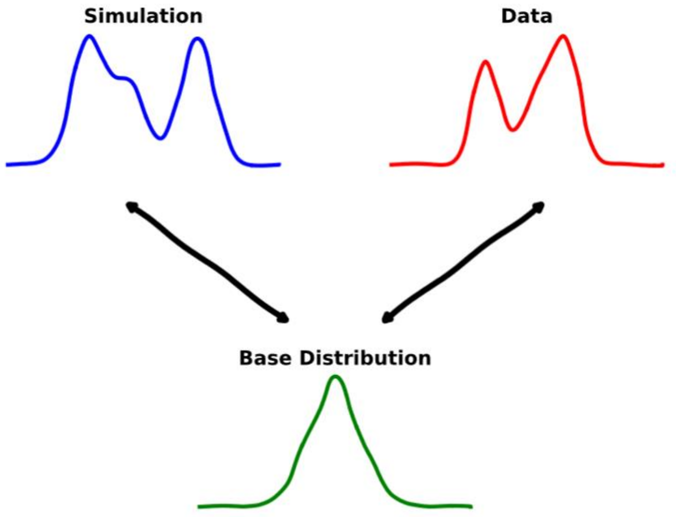
Slide by C. Daumann

Normalizing flows for simulation corrections

- How can flows be used to perform morphing?
- The key is the monotonically increasing property of f
- This means that quantiles are conserved after f(y)
- We train a single normalizing flow on both MC and data
- Events are conditioned on an IsData boolean, which allows the flow to learn both distributions
- The methods is documented in our paper (2403.18582)



(2403.18582)



(2403.18582)

Other methods also explore the use of flows for corrections like the flow4flows (2211.02487) or the CQR with flows (2309.15912)

$H \rightarrow \gamma\gamma$: Backup

$$\mathscr{L}(\vec{\mu}, \vec{\theta}, m_{\mathrm{H}}) = \prod_{c}^{\mathrm{cat}} \prod_{b}^{\mathrm{kinBins}} \mathrm{Pois}\left[n_{\mathrm{obs}} \,\middle|\, \sum_{j}^{\mathrm{genBin}} \mu_j^{\mathrm{fid}} \, S_j(\vec{\theta}, m_{\mathrm{H}}) \, f_S(\vec{\theta}, m_{\mathrm{H}}) + N^{\mathrm{out}}(\vec{\theta}) \, f_{\mathrm{S}}^{\mathrm{out}}(\vec{\theta}, m_{\mathrm{H}}) + B(\vec{\theta}) \, f_B(\vec{\theta}) \right] \times \prod_{k=1}^{n_k} p_k(\tilde{\theta}_k \,|\, \theta_k)$$

Contribution from events **outside of the fiducial phase space**

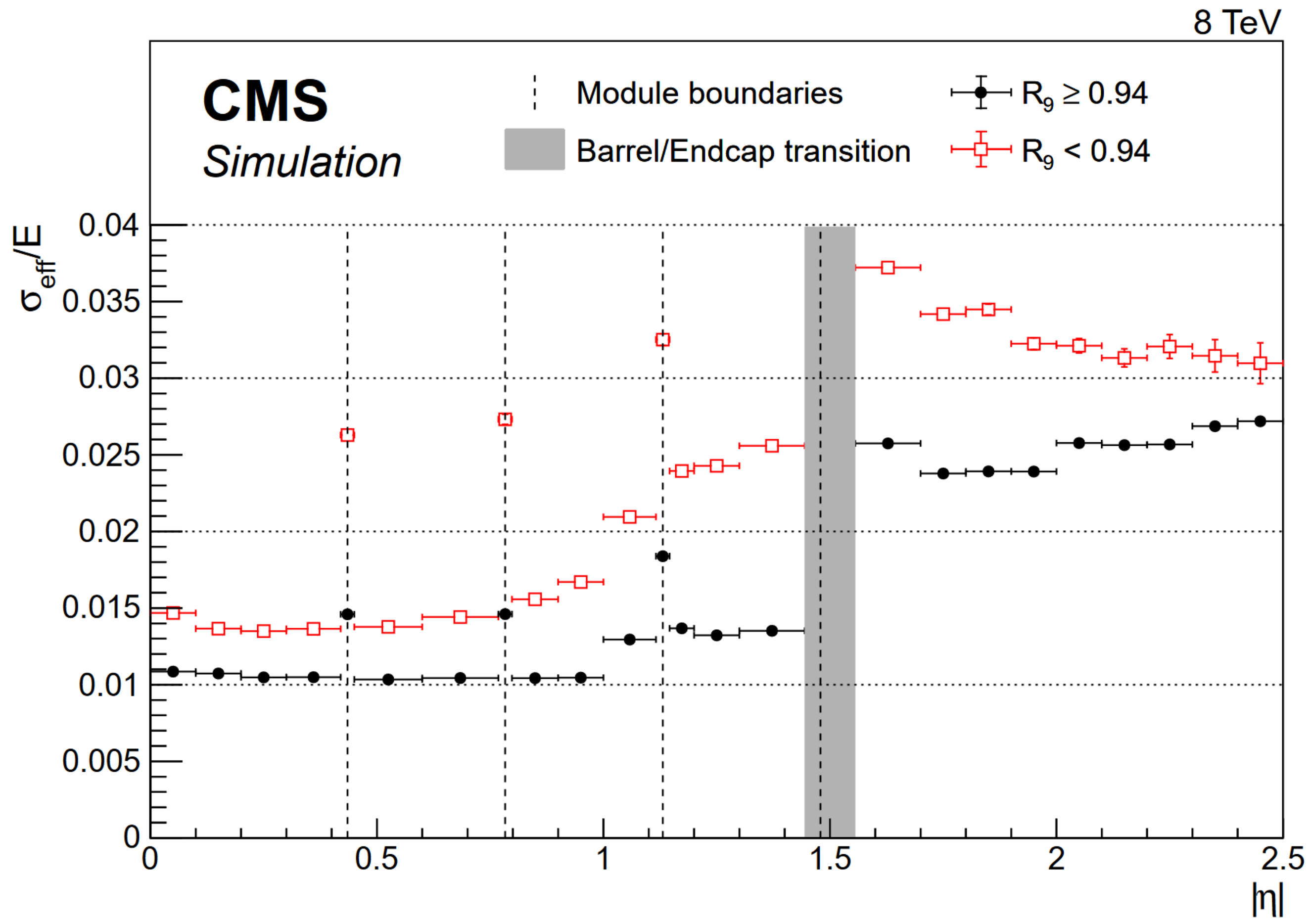
Same implementation as events originating from inside the fiducial phase space

Fraction of out-of-fiducial events

	Best resolution	**Medium resolution**	**Worst resolution**
ggH	0.06%	0.19%	1.62%
VBF	0.17%	0.50%	1.97%
VH	0.31%	0.57%	2.16%
ttH	0.57%	0.83%	2.30%

$H \rightarrow \gamma\gamma$: Backup

- CMS ECAL Energy resolution



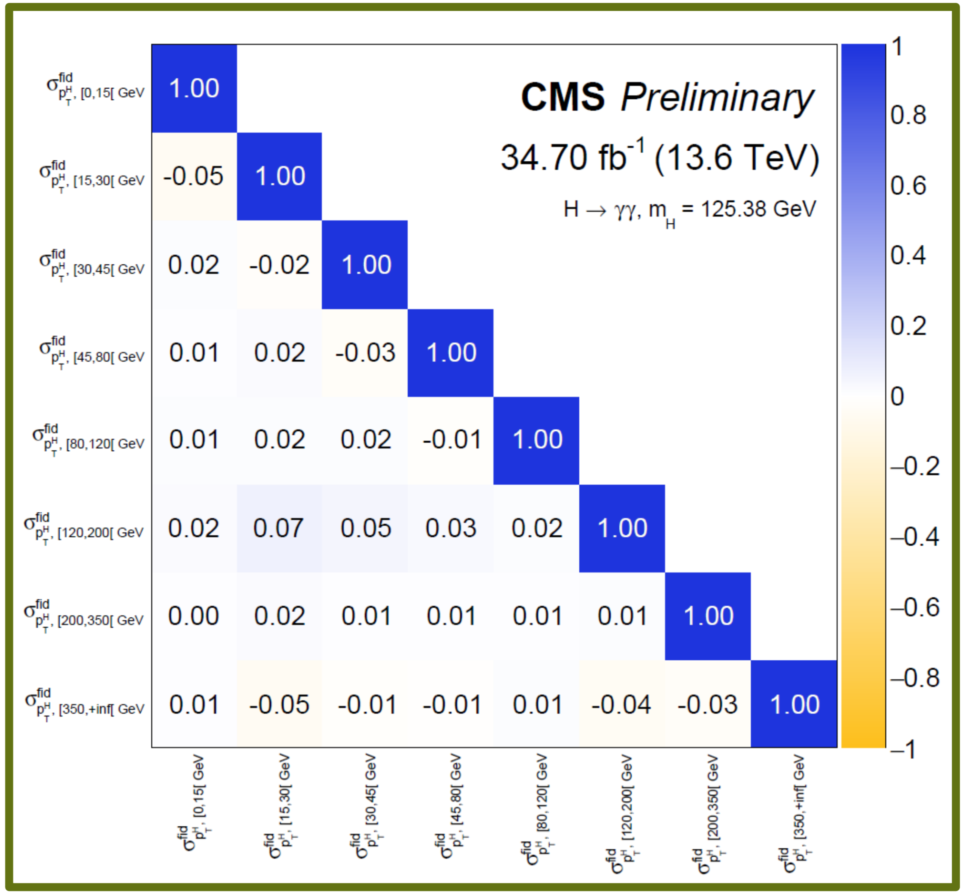
$H \to \gamma\gamma$: Backup

- Consider photons in acceptance ($p_T > 25$ GeV)
- Apply BDT cut to reduce background.
- Keep $p_T^{\gamma\gamma}$-leading diphoton system satisfying $p_T^{\gamma_1} > 35$ GeV

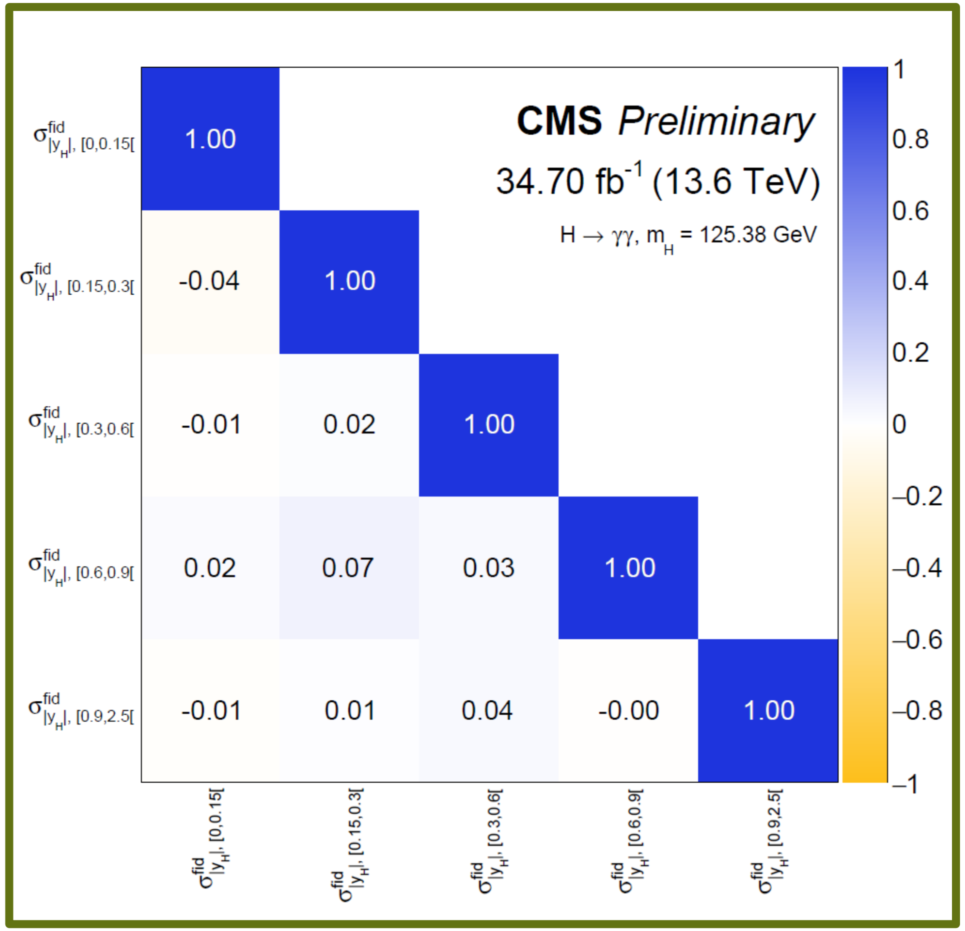
Category	R9	H / E	sieie	Hollow cone track isolation	PF photon isolation
Barrel, high R9	> 0.85	< 0.08	–	–	–
Barrel, low R9	[0.5, 0.85]	< 0.08	< 0.015	< 6 GeV	< 4 GeV
Endcap, high R9	> 0.9	< 0.08	–	–	–
Endcap, low R9	[0.8, 0.9]	< 0.08	< 0.035	< 6 GeV	< 4 GeV

In addition: Logical OR of $R_9 > 0.8$ | $I_{\text{ch,quadr}} < 20\,\text{GeV}$ | $I_{\text{ch,quadr,rel}} < 0.3$ } resembling miniAOD requirements

$H \to \gamma\gamma$: Correlation Matrices

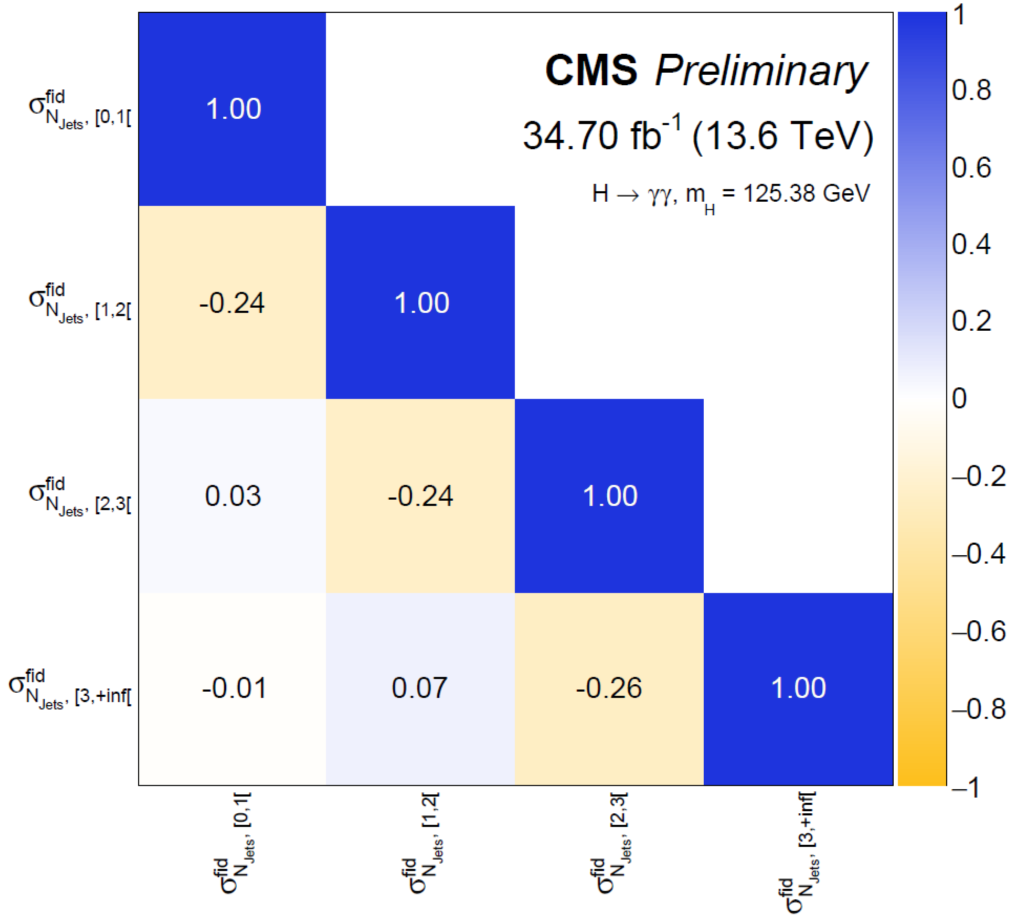


p_T^H



$|y_H|$

$H \to \gamma\gamma$: Correlation Matrices



N_{Jets}