Status of H→Zγ search

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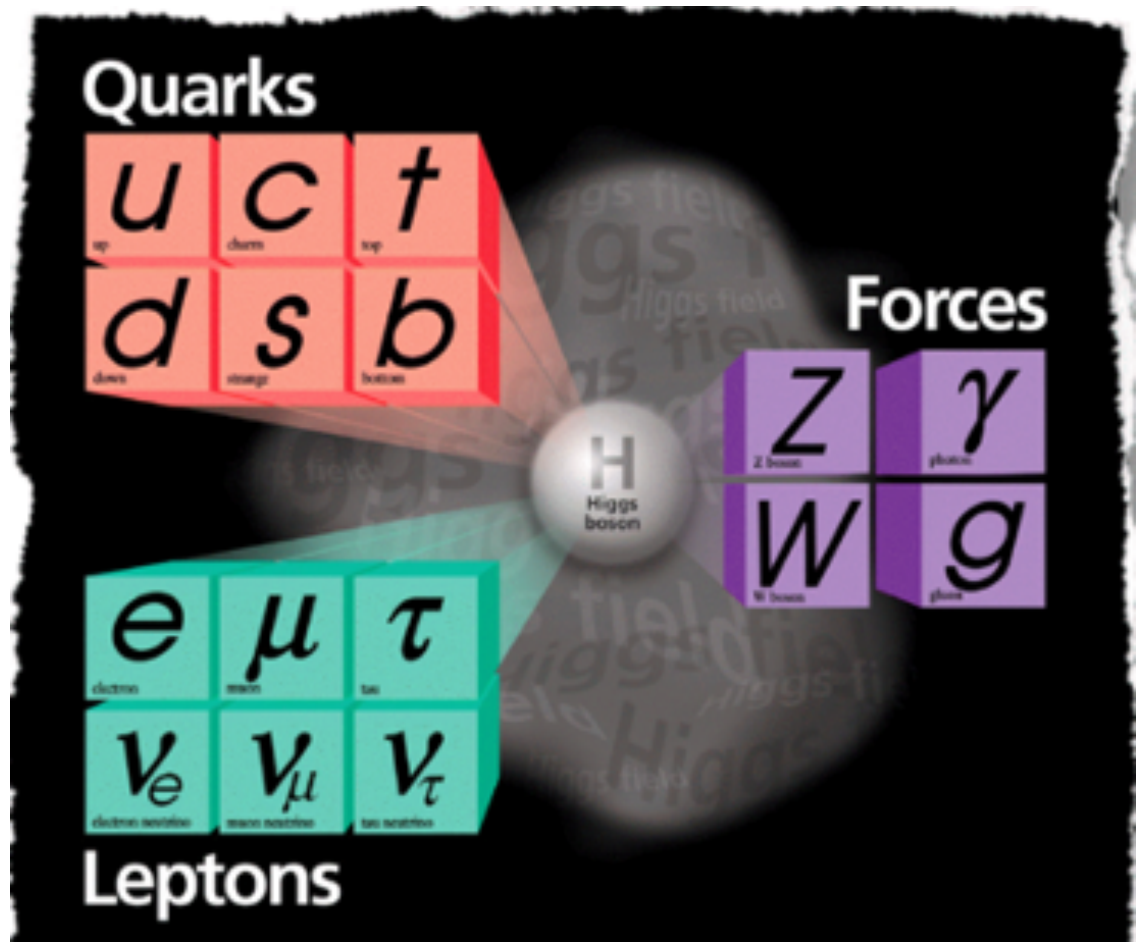
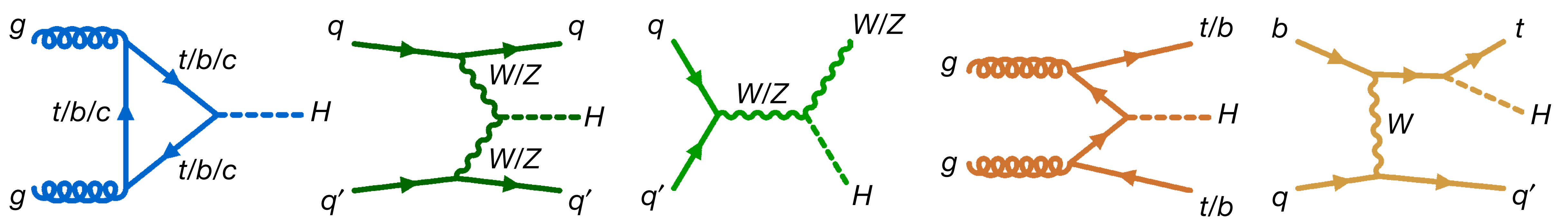
Introduction

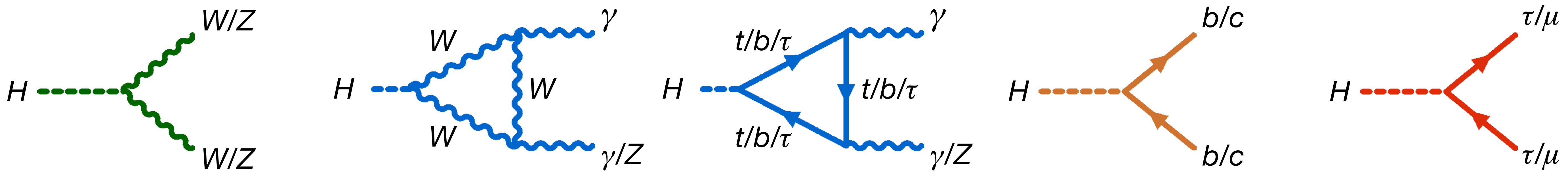
The Higgs particle is responsible for the masses of elementary particles.

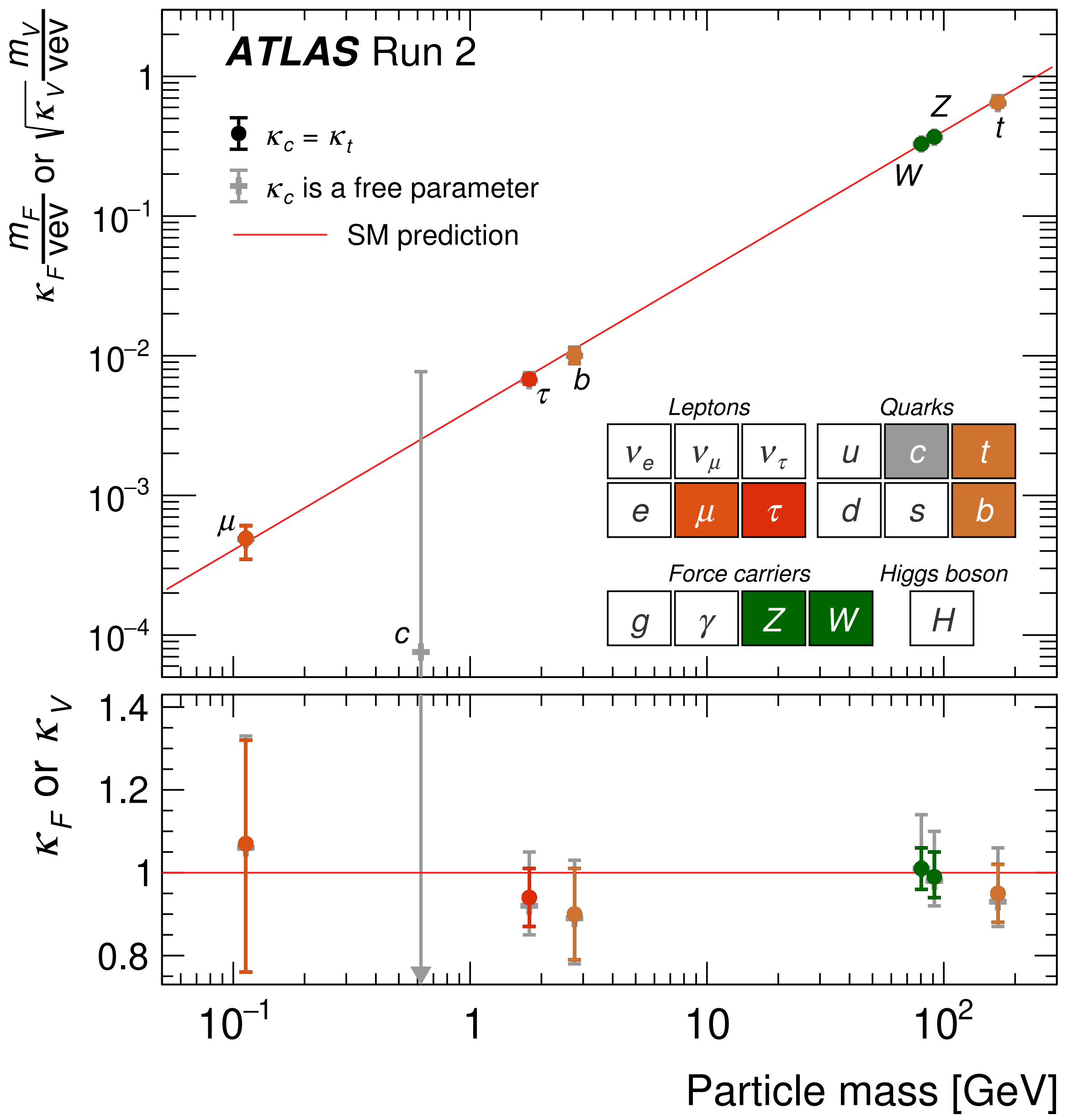


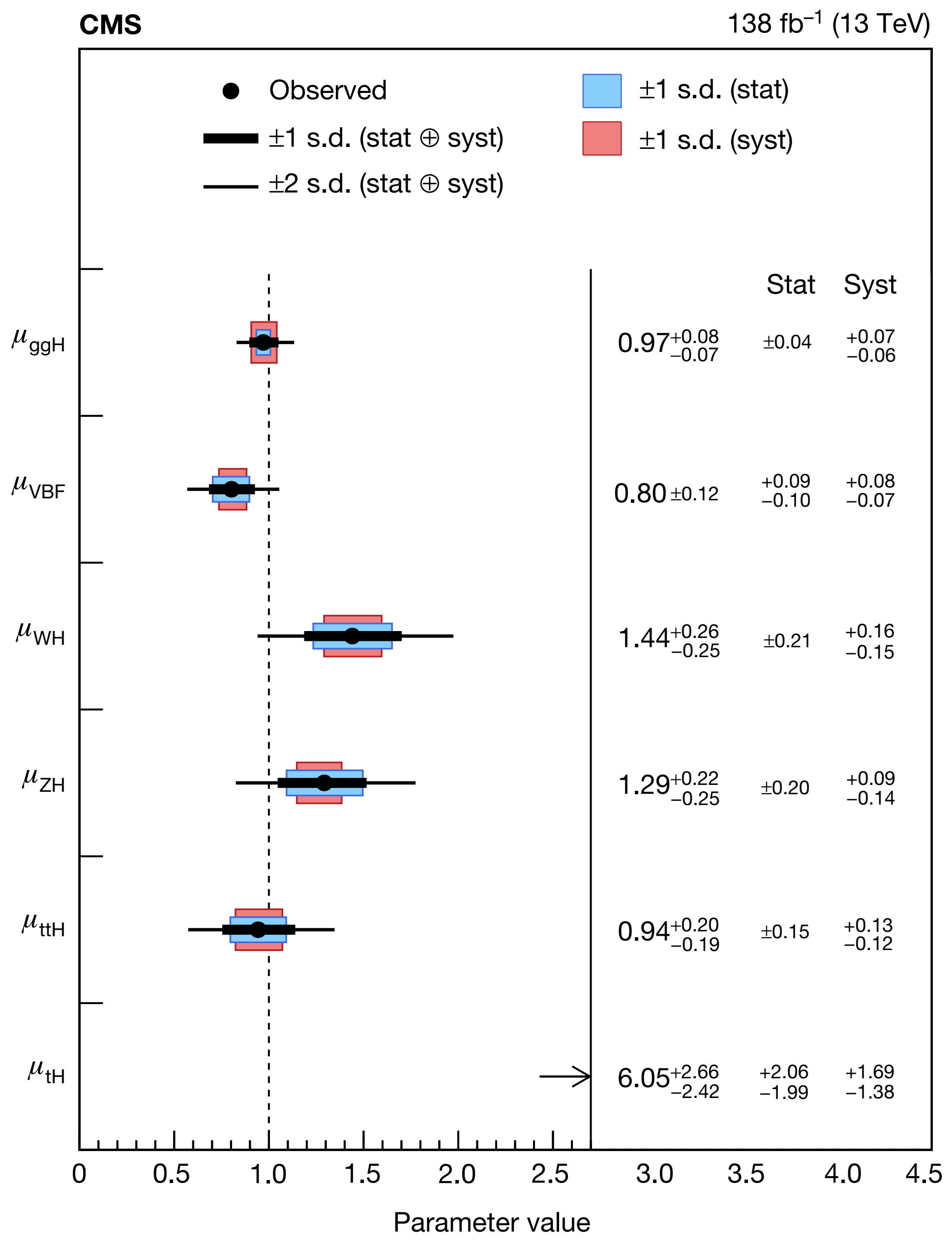
Main Higgs production modes @ LHC

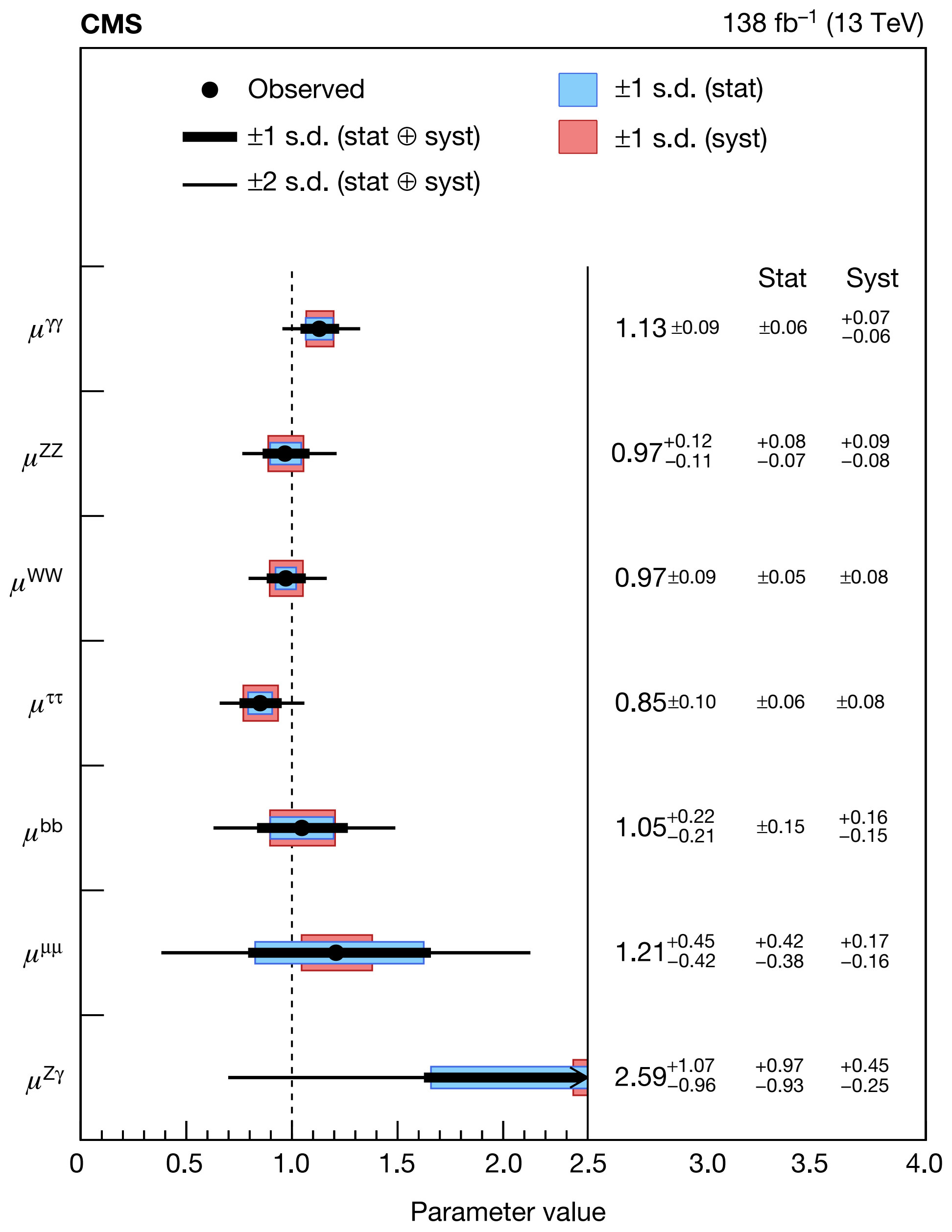


Main Higgs decay modes

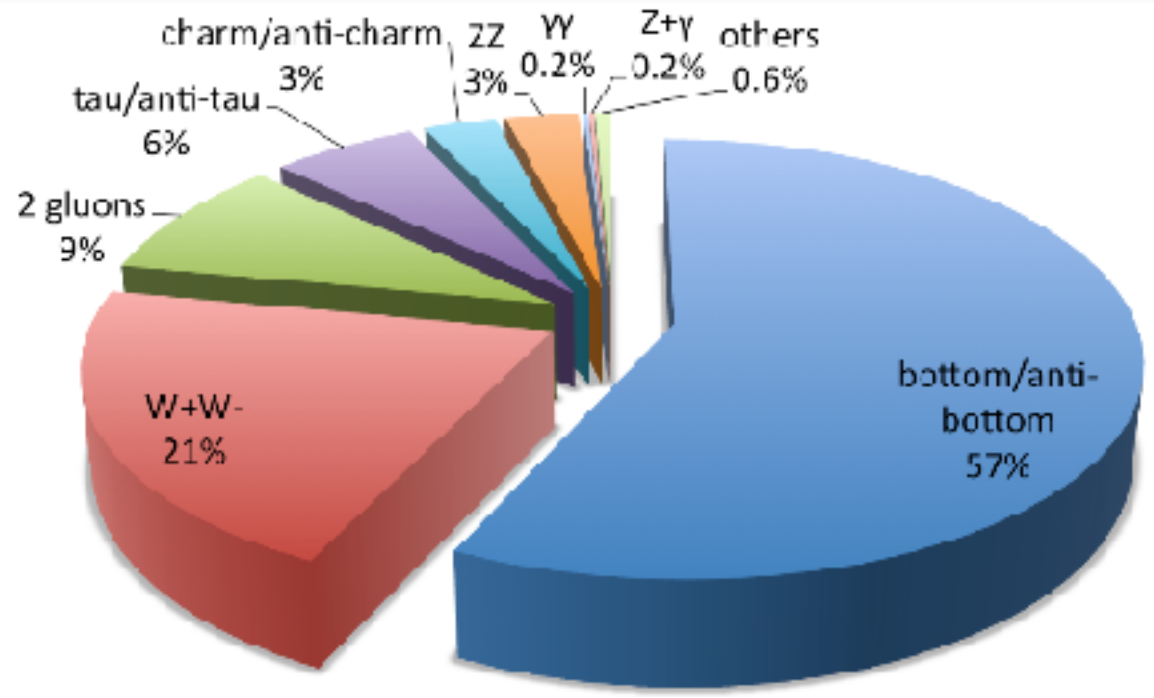


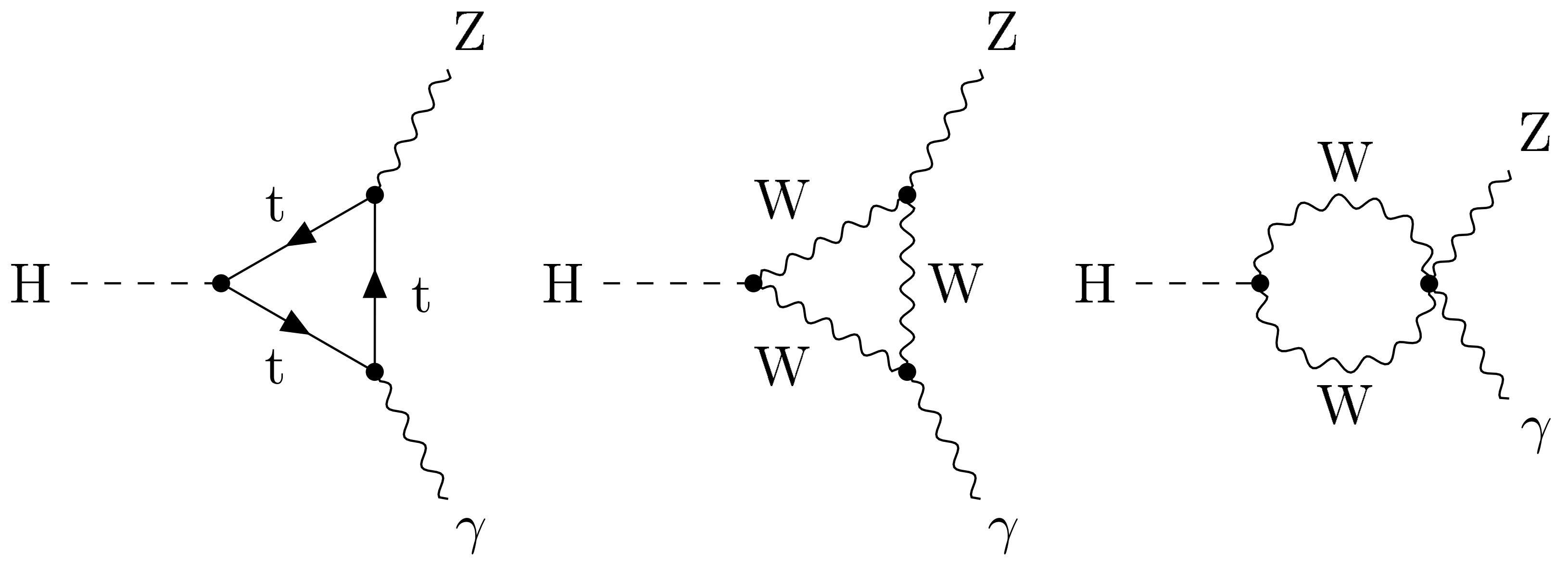






H→Zγ rare decays





H→Zγ loop decay

ZZ* and γγ: high resolution and precise differential measurements

WW*: high BR but low mass resolution

ττ and bb: high BR but low S/B, important to directly probe Yukawa coupling with 3rd generation

μμ: very small BR but access to Yukawa coupling with 2nd generation fermions

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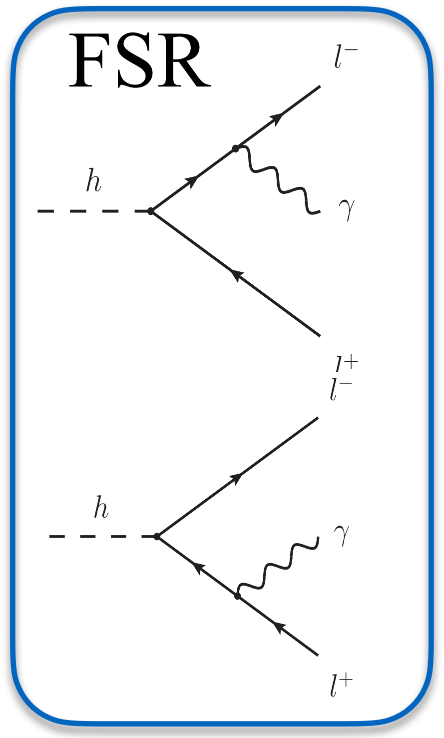
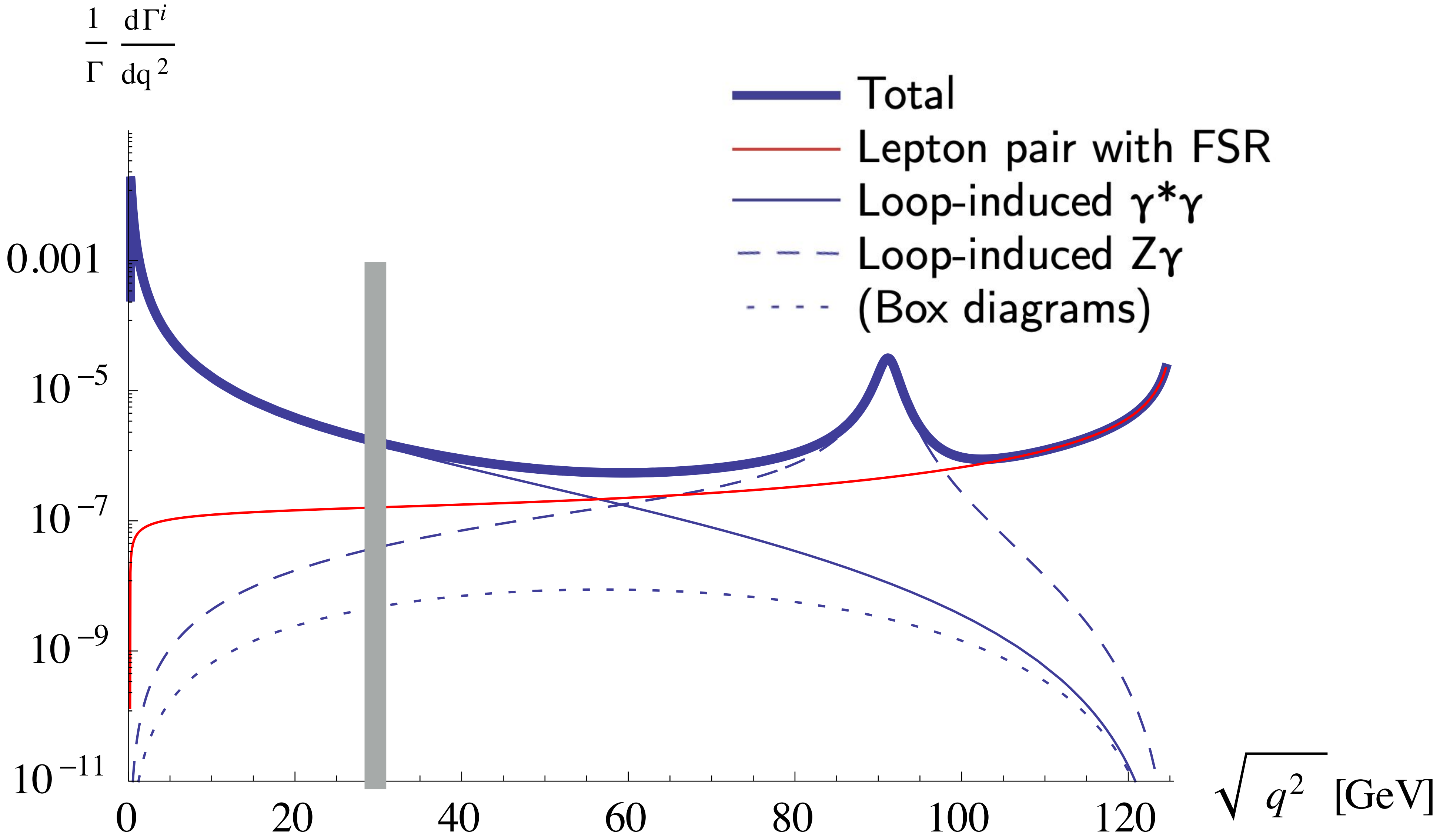
Probe for Higgs rare decay to complement the Higgs property in SM and new physics search

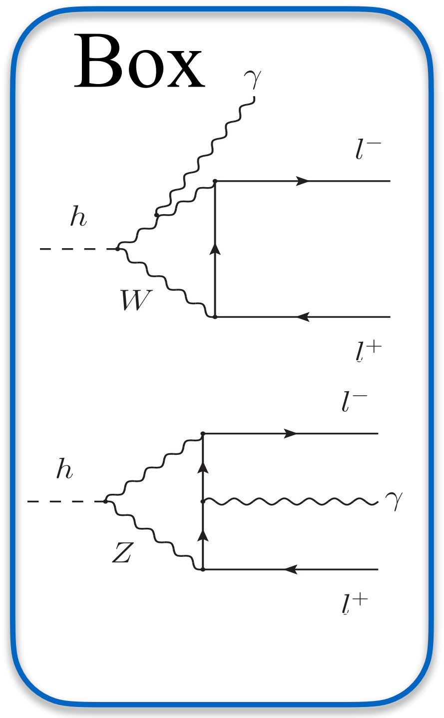
- In SM, $Br(H\to Z\gamma) = (1.57\pm0.09)\times10^{-3}$, comparable with $Br(H\to\gamma\gamma) = (2.27\pm0.04)\times10^{-3}$
- In current LHC study, focus on $Z\to ee/\mu\mu$ only with the $ll\gamma$ final state
  - Good resolution, efficiency and S/B separation
  - Low fraction of 6%

H→llγ

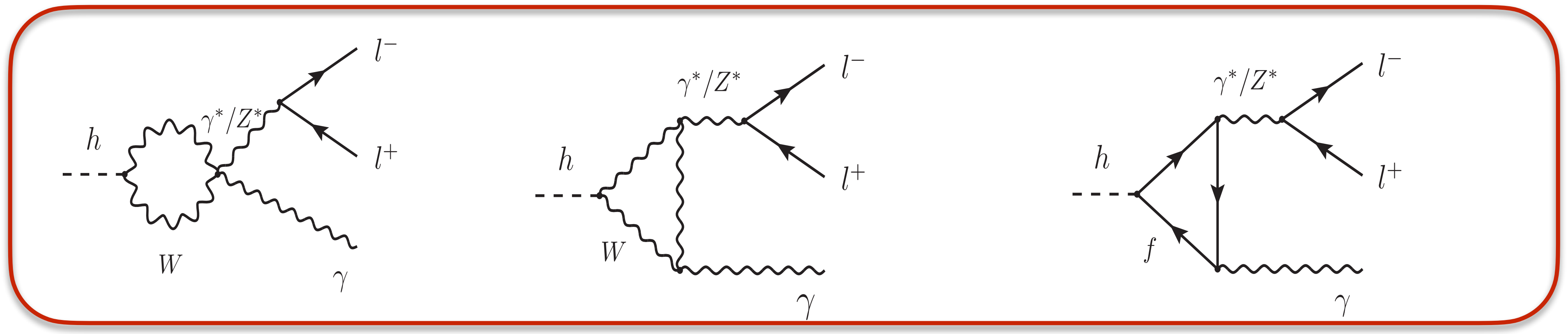
In the H→llγ decay mode, Zγ and γ*γ and llγ are technically not distinguishable







$$\frac{\Gamma(h \to \gamma\mu^+\mu^-)}{\Gamma(h \to \gamma\gamma)} = 5.8\%$$



Separated optimization for on-shell H→Zγ with mll>40GeV and off-shell H→γ*γ with mll<30GeV

Search for H→Zγ @Run2 (ATLAS)

- Decay rate is quite low for the e/μ channel only
- Major in low pt region: ~20GeV for photon, ~50GeV and 30GeV for leading lepton and subleading lepton
  - Single-/Di-lepton triggers: High efficiency achieved with 95.6% for e channel and 92.2% for μ channel
- Higgs mass resolution improvement
  - 3% gain from FSR and 7%(13%) gain from Z-mass constraint for e(μ) channel

candidates	channel	single/di-lepton	trigger name
2015 data	$Z(\to ee)\gamma$	single electron	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium, HLT_e120_lhloose
2015 data	$Z(\to ee)\gamma$	di-electron	HLT_2e12_lhloose_L12EM10VH
2016 data	$Z(\to ee)\gamma$	single electron	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0, HLT_e140_lhloose_nod0
2016 data	$Z(\to ee)\gamma$	di-electron	HLT_2e17_lhvloose_nod0
2017-2018 data	$Z(\to ee)\gamma$	single electron	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0, HLT_e140_lhloose_nod0
2017-2018 data	$Z(\to ee)\gamma$	di-electron	HLT_2e24_lhvloose_nod0
2015 data	$Z(\to \mu\mu)\gamma$	single muon	HLT_mu26_imedium, HLT_mu50
2015 data	$Z(\to \mu\mu)\gamma$	di-muon	HLT_mu22_mu8noL1
2016 data	$Z(\to \mu\mu)\gamma$	single muon	HLT_mu26_imedium HLT_mu26_ivarmedium, HLT_mu50
2016 data	$Z(\to \mu\mu)\gamma$	di-muon	HLT_mu22_mu8noL1
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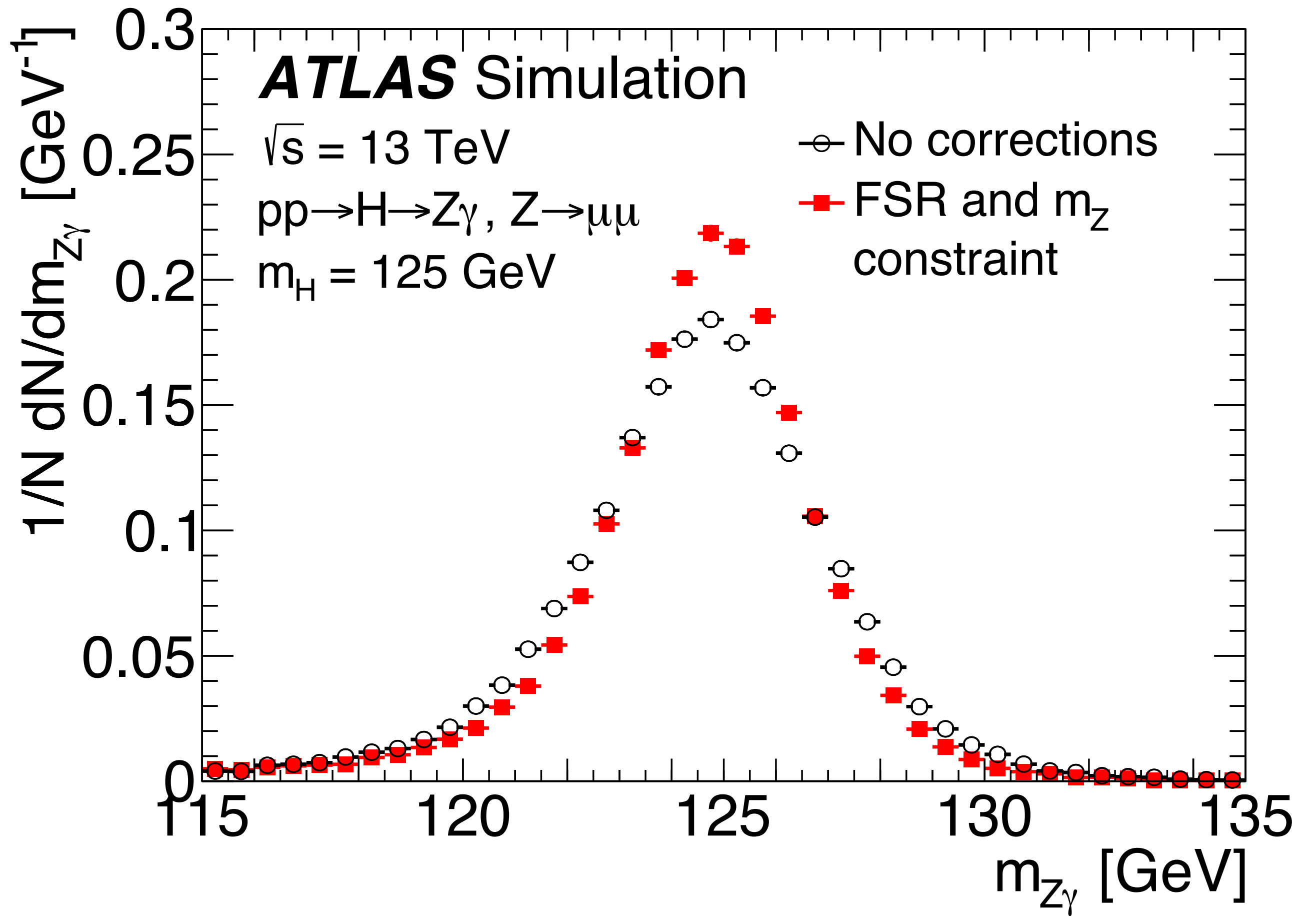
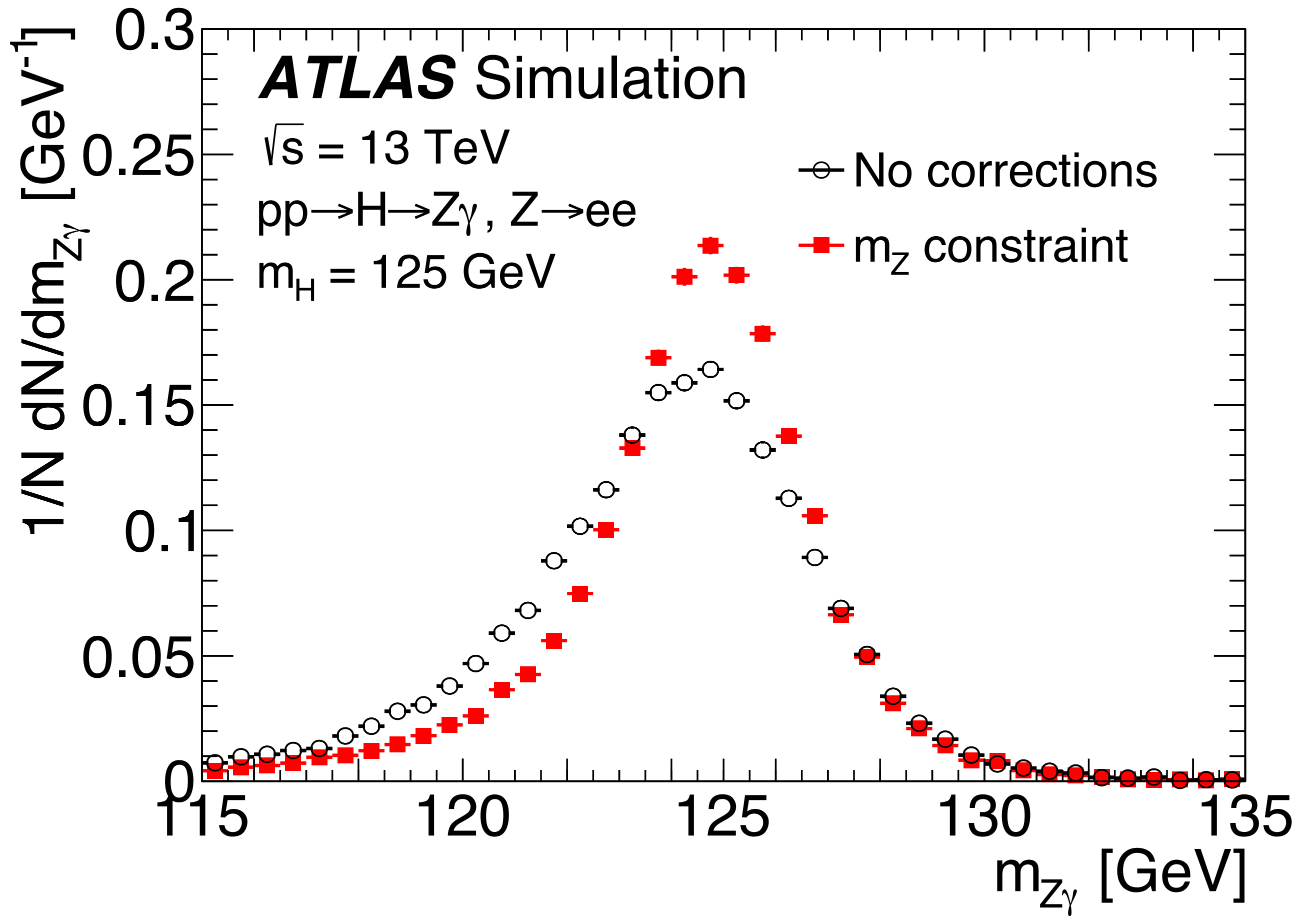
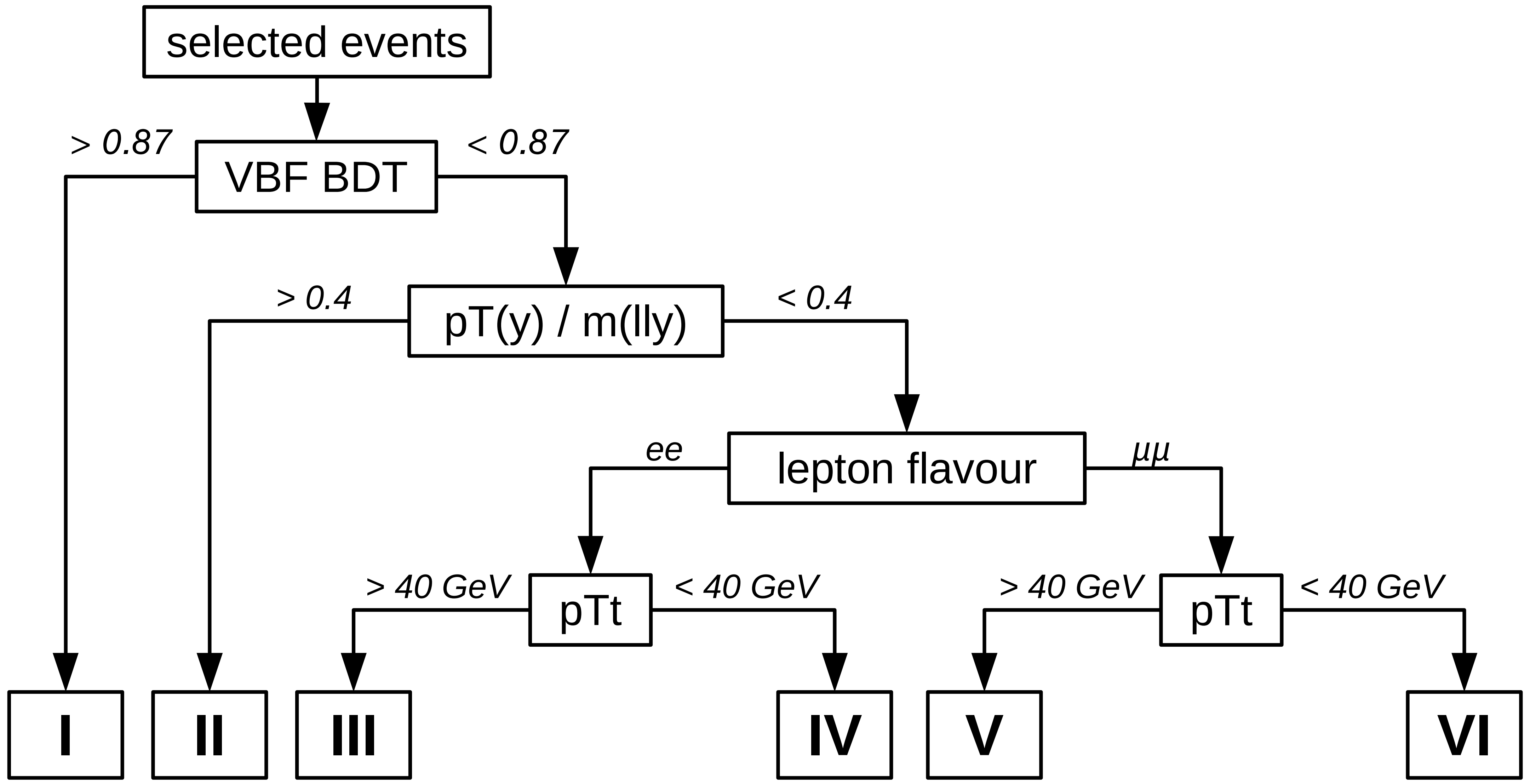




Search for H→Zγ @Run2 (ATLAS)

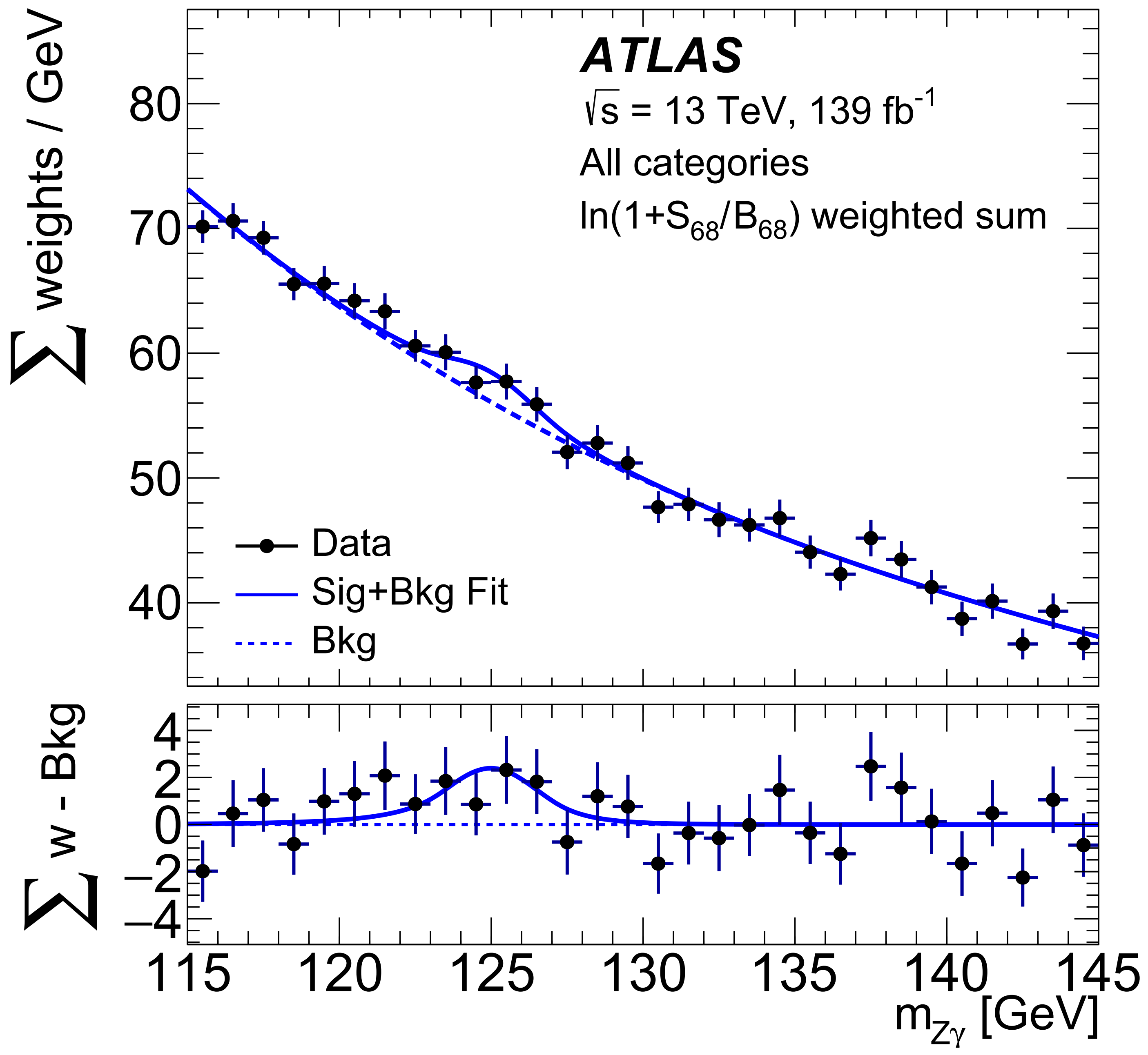


Category	$S_{68}/B_{68}\ [10^{-2}]$	$S_{68}/\sqrt{S_{68}+B_{68}}$
VBF-enriched	16.2	0.60
High relative p_{T}	7.0	0.70
High p_{Tt} ee	2.1	0.45
Low p_{Tt} ee	0.5	0.43
High p_{Tt} $\mu\mu$	1.9	0.47
Low p_{Tt} $\mu\mu$	0.5	0.47
Inclusive	0.7	0.86

- Higgs signal mode include: ggH, VBF, VH, ttH.
- Dedicated optimization only for the VBF and ggF production modes

Results

Simultaneous fit performed on $m_{Z\gamma}$ spectra of the mutual categories



Uncertainty	$\Delta\mu/\mu$ (obs.)	$\Delta\mu/\mu$ (exp.)
Statistical uncertainty	43.1%	82.8%
Spurious signal	14.7%	28.4%
e/γ scale, resolution	2.0%	2.4%
Luminosity	1.7%	1.6%
Photon efficiency	1.6%	1.8%
Jet	1.5%	1.1%
Electron, Higgs mass, Muon, $H \to \mu\mu$ normalization, PRW	2.0%	2.1%
QCD scale	6.9%	6.1%
BR($H \to Z\gamma$) uncertainty	5.7%	5.9%
UEPS	2.4%	2.1%
PDF, α_s	2.2%	2.8%
Total	46.7%	88.1%

- **SM prediction (m_H = 125.09GeV):**
  - Br(H→Zγ)=1.54×10^{-3}
  - σ(pp→H)×Br(H→Zγ)=83.1fb
- Obs (Exp) μ: 3.6 (1.7)×SM @95% CL

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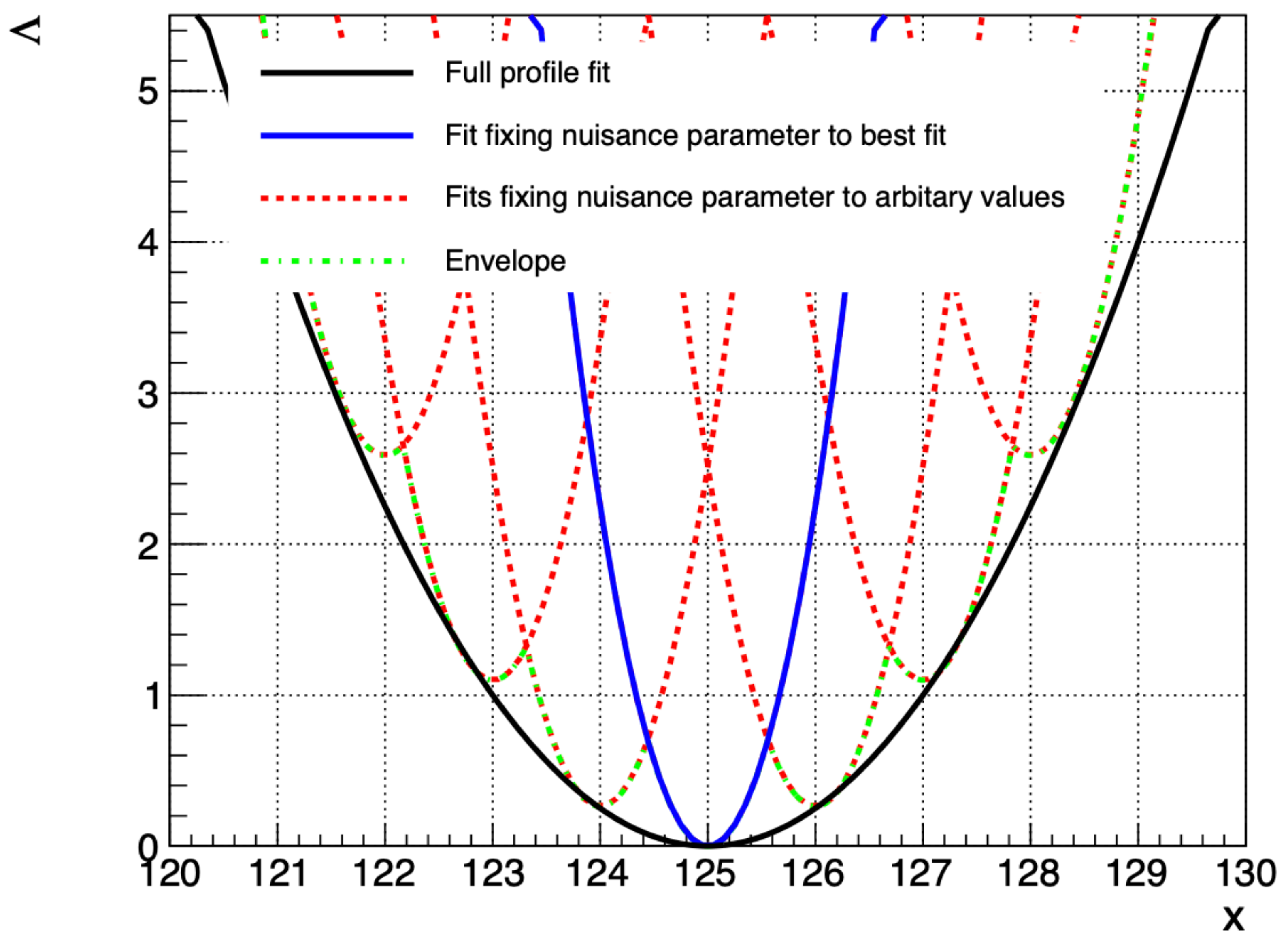
- The analysis is still statistical dominantly
- Major systematic uncertainty is spurious signal due to the decision from background function form

Search for H→Zγ @Run2 (CMS)

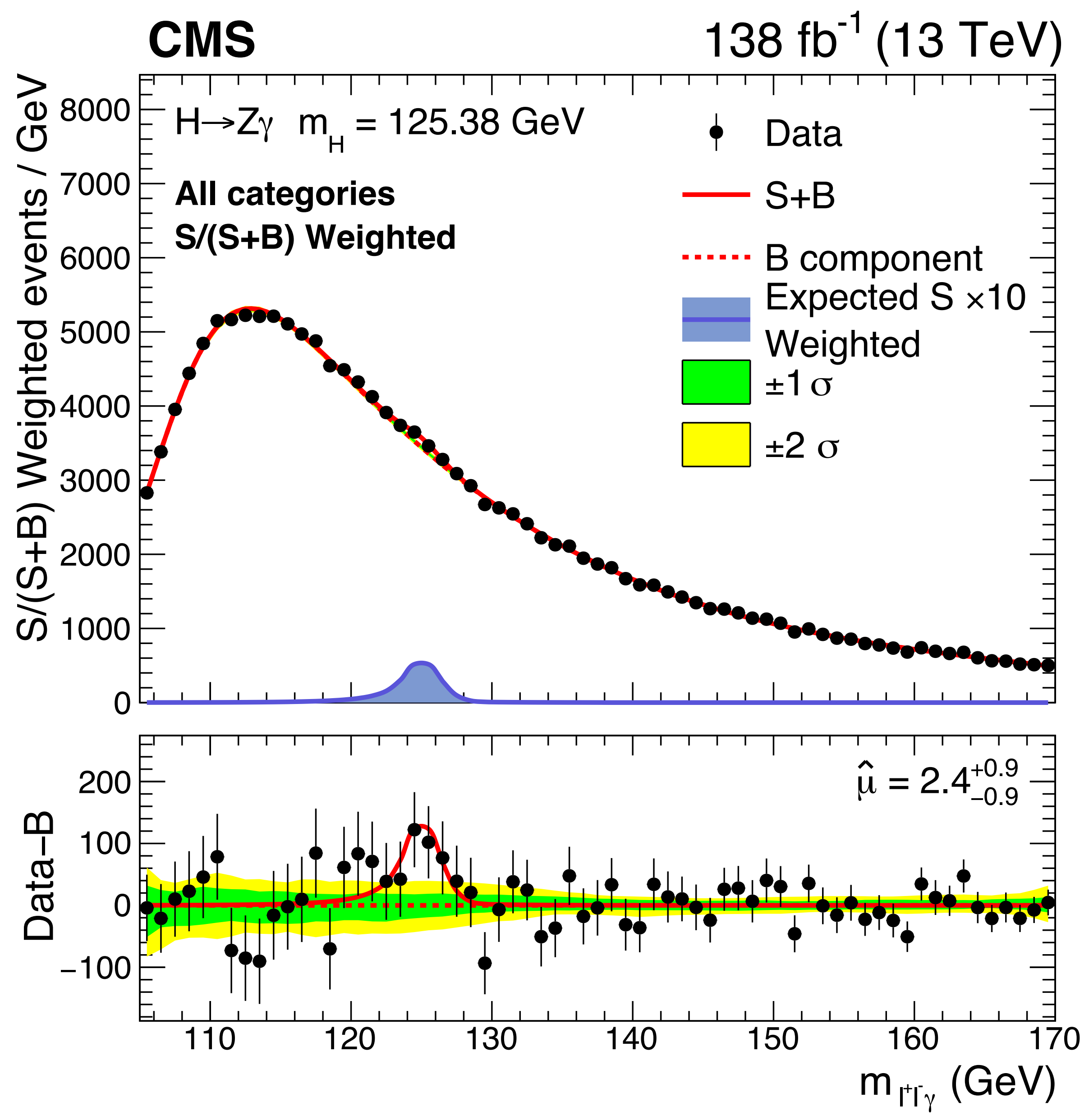
$138\ \mathrm{fb}^{-1}$	Lepton		Dijet 1	Dijet 2	Dijet 3	Untagged 1	Untagged 2	Untagged 3	Untagged 4
SM signal yield									
ggH	0.51	e^+e^-	1.10	1.62	9.44	6.89	7.35	29.8	22.5
		$\mu^+\mu^-$	1.41	2.05	12.1	8.52	9.17	38.0	29.0
VBF	0.09	e^+e^-	1.94	0.76	1.13	0.71	0.35	0.92	0.51
		$\mu^+\mu^-$	2.40	0.97	1.43	0.89	0.43	1.18	0.65
$VH + t\bar{t}H$	1.84	e^+e^-	0.04	0.13	1.89	0.31	0.17	0.45	0.27
		$\mu^+\mu^-$	0.05	0.16	2.36	0.39	0.21	0.57	0.33
SM resonant background $H \to \mu^+\mu^-$	0.14	$\mu^+\mu^-$	0.27	0.27	0.43	0.62	0.49	2.02	1.78
Mass resolution (GeV)	2.12	e^+e^-	1.91	2.06	2.15	1.80	1.97	2.12	2.33
		$\mu^+\mu^-$	1.52	1.61	1.72	1.37	1.42	1.62	1.83
Data yield	1485		168	589	11596	1485	1541	2559	17608
$S/\sqrt{B}$	0.06		0.54	0.24	0.26	0.45	0.35	0.53	0.30

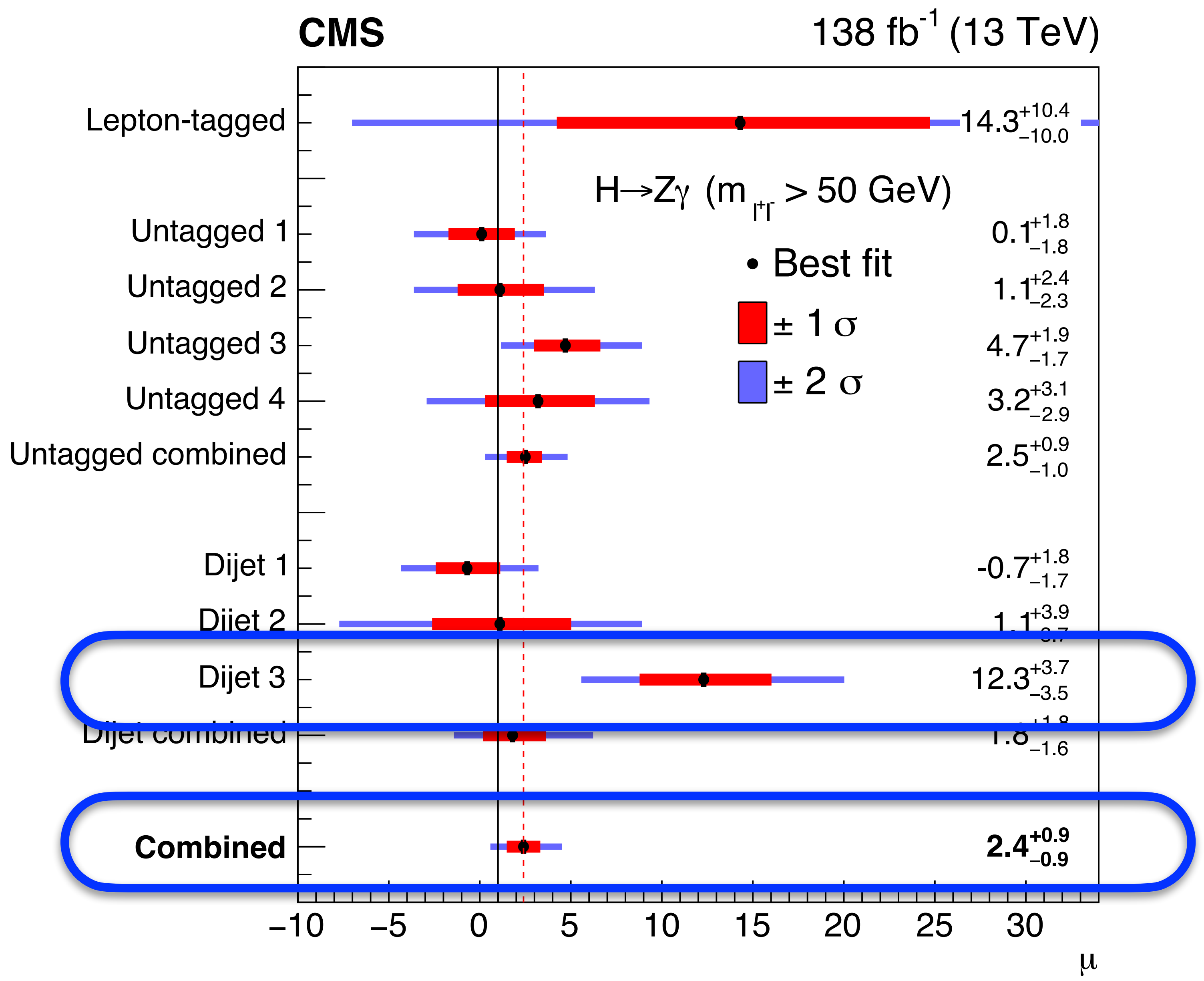


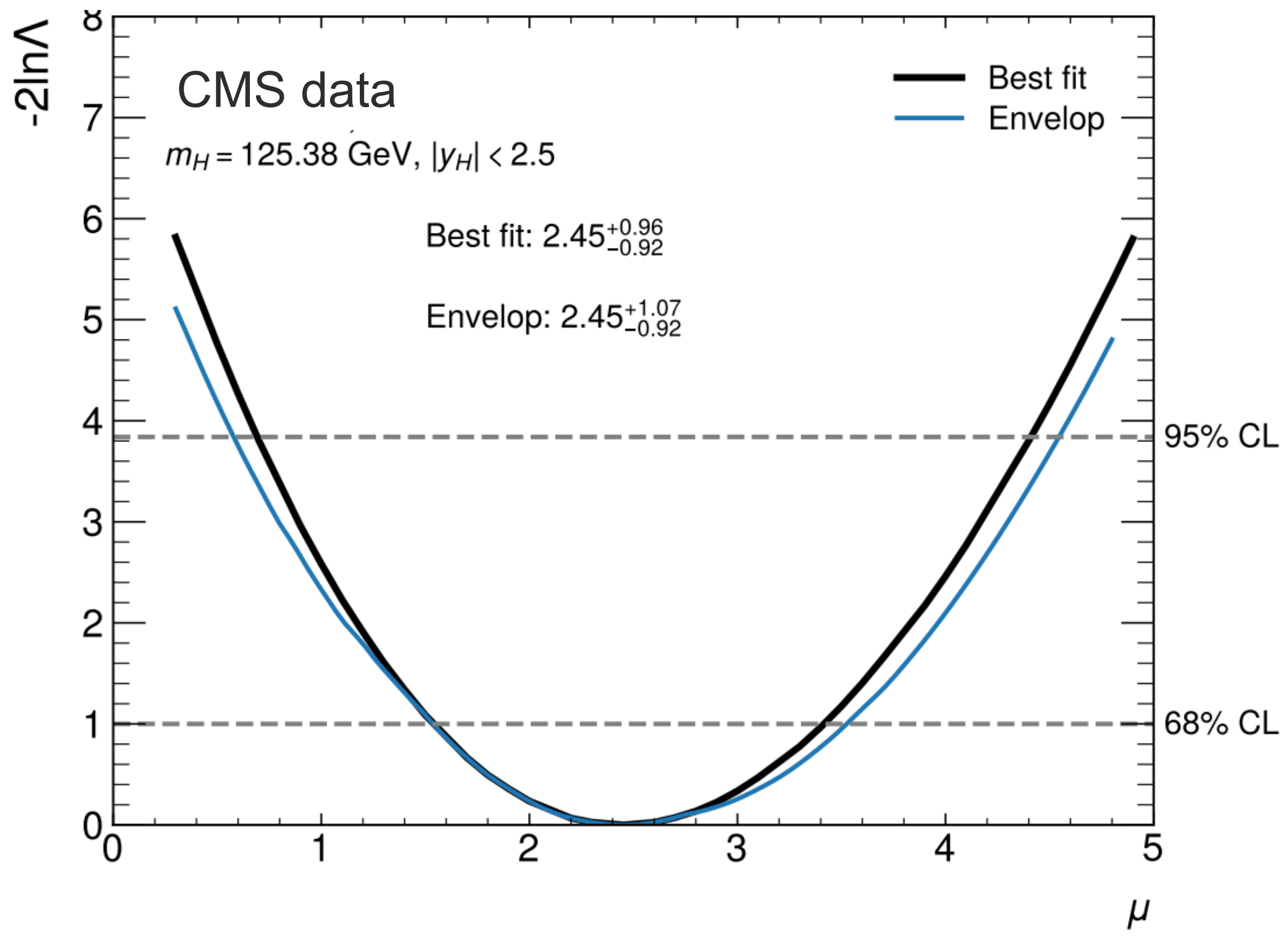
arxiv: 2204.12945

- ◈ Higgs signal mode include: **ggH, VBF, VH, ttH**
- ◈ Dedicated categorization optimization: **VH-rich, VBF-rich, ggH-rich**
- ◈ Discrete profiling method for the background function decision:
  - ✦ float the background function form in each category
  - ✦ take into account the n.d.f. difference of background functions

Search for H→Zγ @Run2 (CMS)



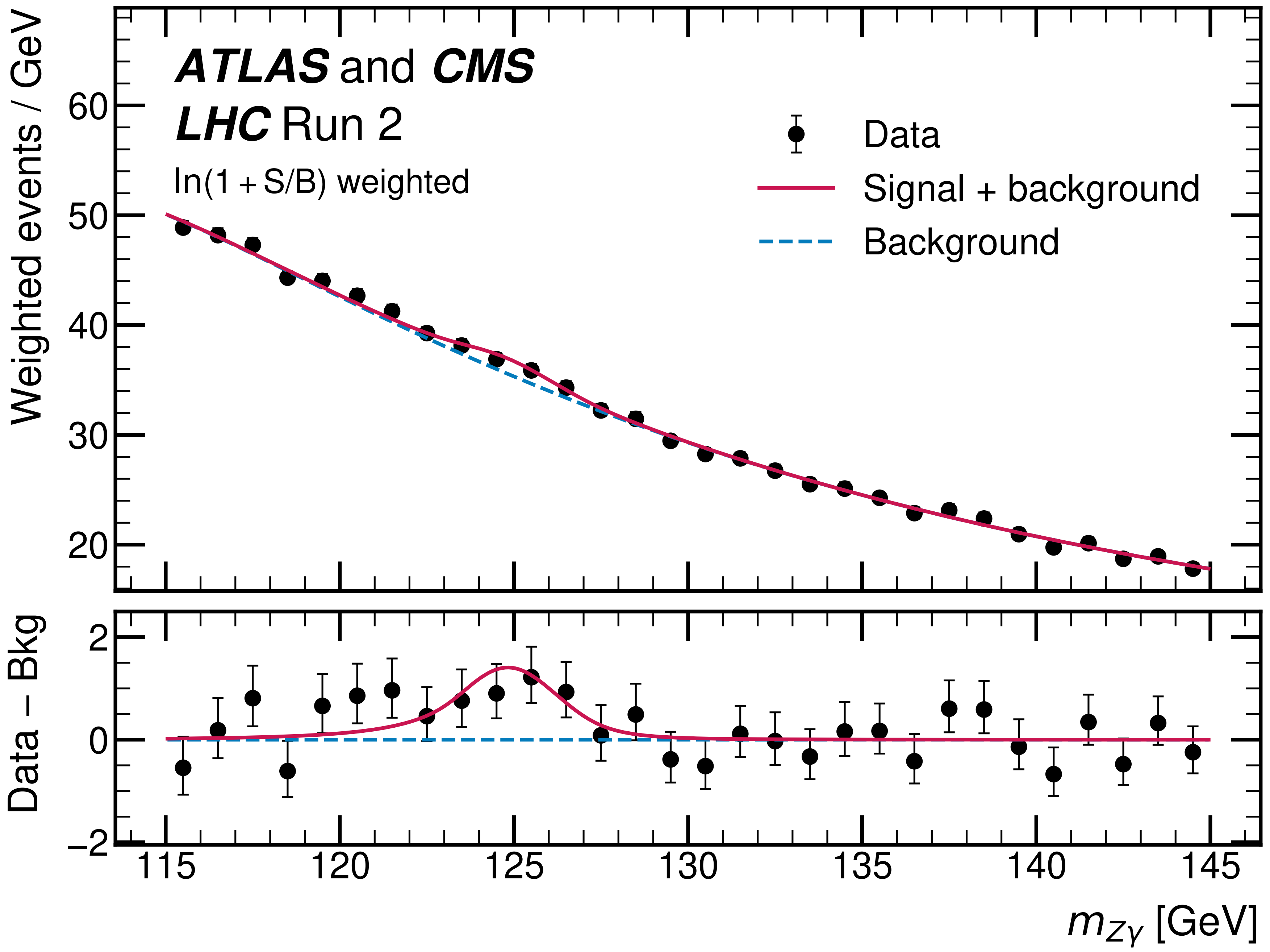


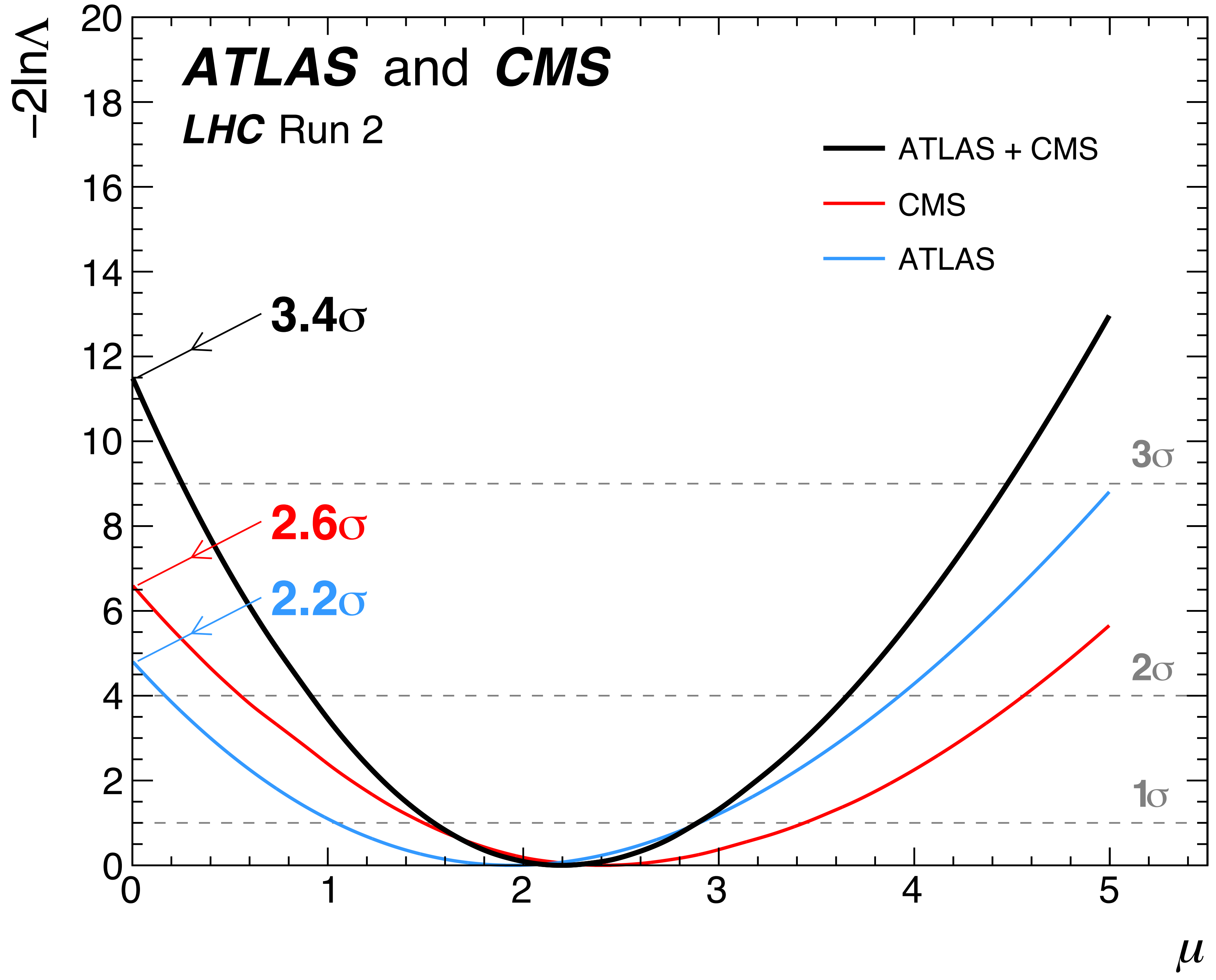


arxiv: 2204.12945

- **Different Higgs mass (m_H = 125.38GeV)**
- Observed (expected) significance： 2.7 (1.2) σ
- Observed (expected) signal strength: 2.4 $^{+0.8}_{-0.9}$ (stat)$^{+0.3}_{-0.2}$(syst) (1.0±0.9)

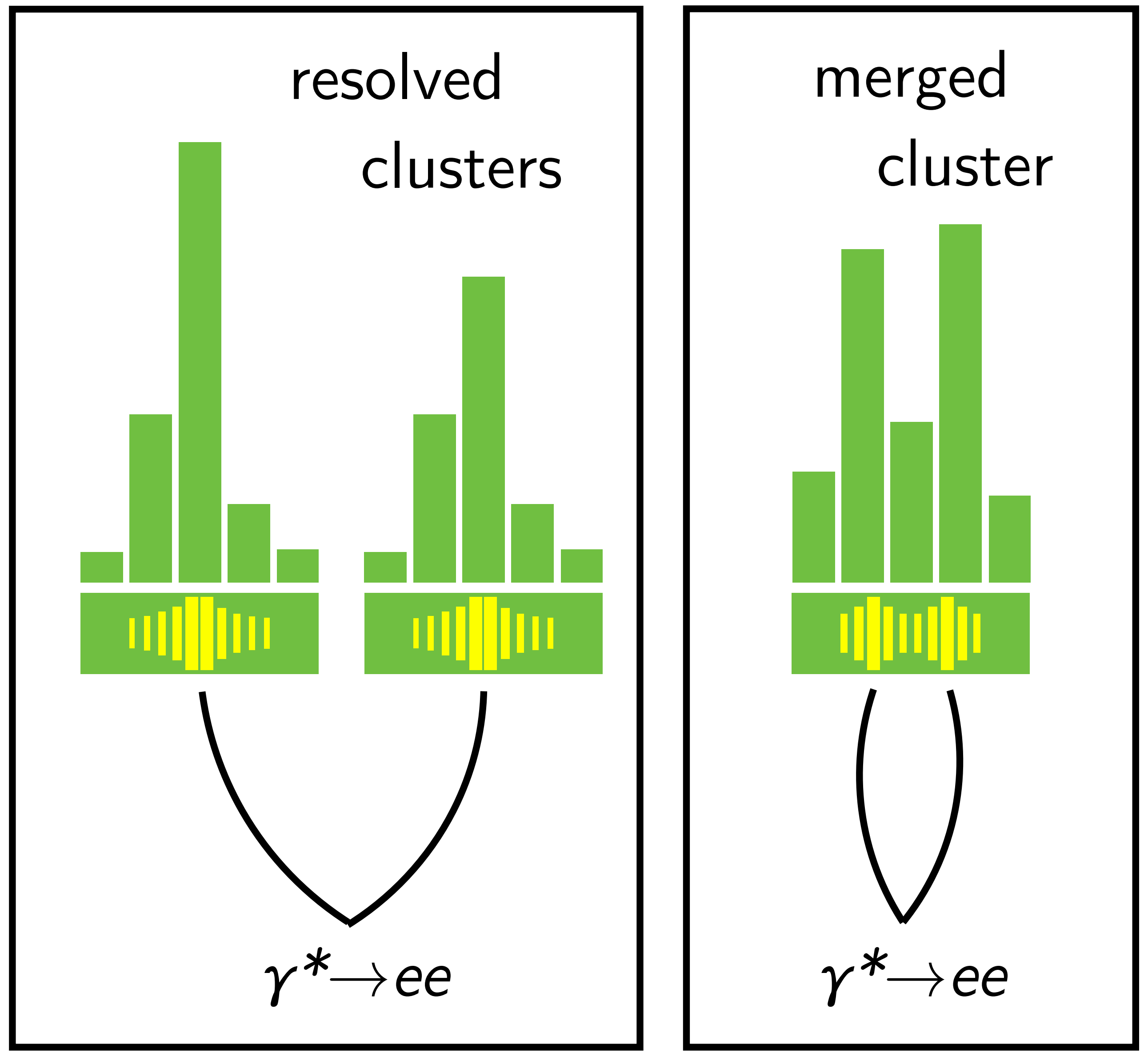
First evidence of H→Zγ with ATLAS-CMS combination





	ATLAS	CMS	ATLAS+CMS
μ	$2.0^{+1.0}_{-0.9}$	$2.4^{+1.0}_{-0.9}$	$2.2\pm0.6^{+0.3}_{-0.2}$
Obs. Z	2.2σ	2.6σ	3.4σ
Exp. Z	1.2σ	1.1σ	1.6σ

H→γ*γ @ ATLAS



Resolved Electrons:

$p_T > 4.5$ GeV

Both tracks require innermost pixel hit

E–γ Ambiguity: unambiguous ele (bit=0)

Medium ID

FCLoose* *applied only to the leading e*

$d_0/\sigma_{d0} < 3$, $|z_0 \sin\theta| < 0.5$

Merged Electrons

$p_T > 20$ GeV

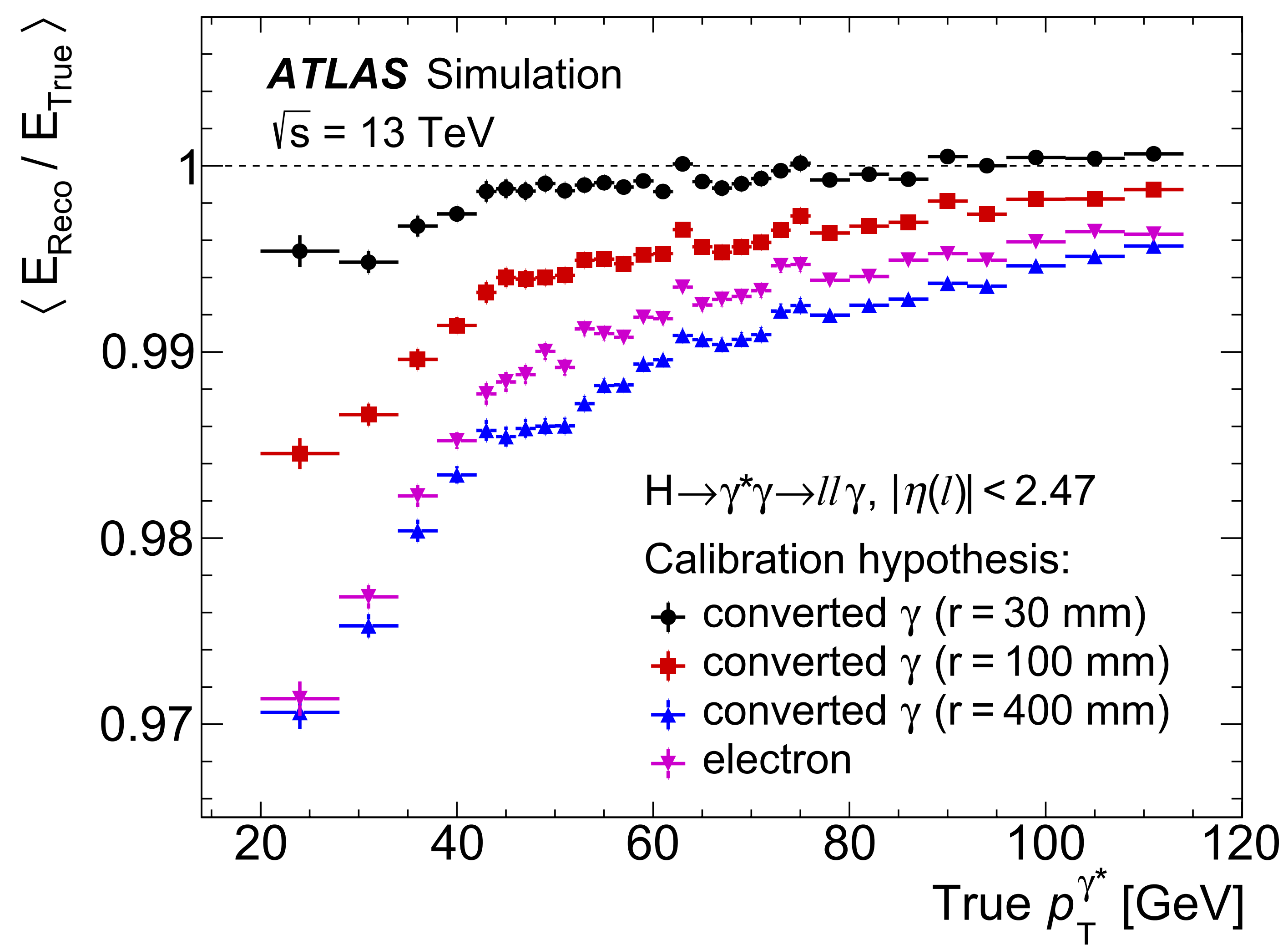
Both tracks require innermost pixel hit

E–γ Ambiguity: reject Ambiguity=5

Custom ID (TMVA)

FCTight Isolation

$d_0/\sigma_{d0} < 3$, $|z_0 \sin\theta| < 0.5$



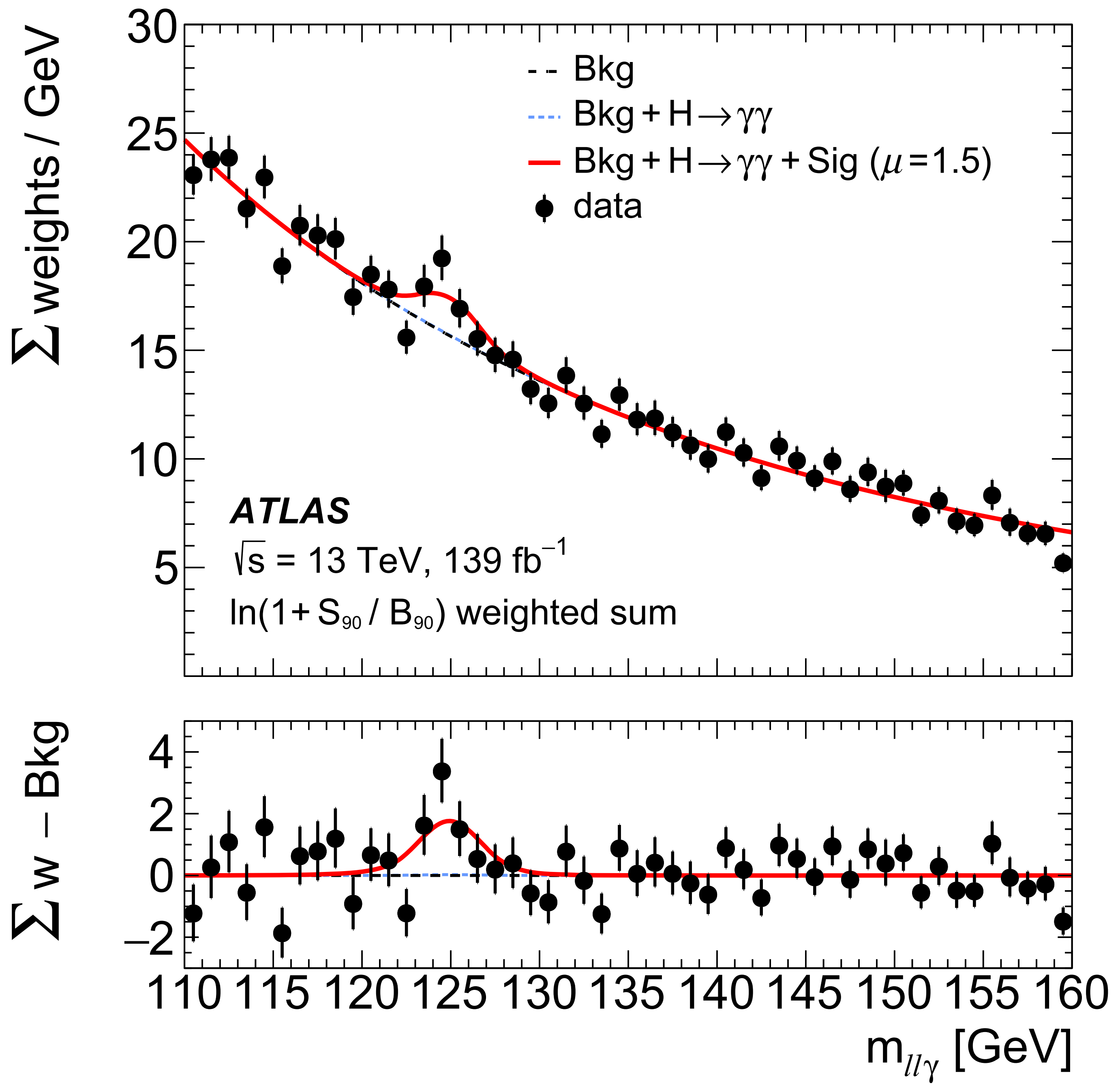
- **Custom ID for Merged Electrons** (with the efficiency of 50 - 70%)
- **Dedicated calibration for merged electron as converted photon with radius 30mm**

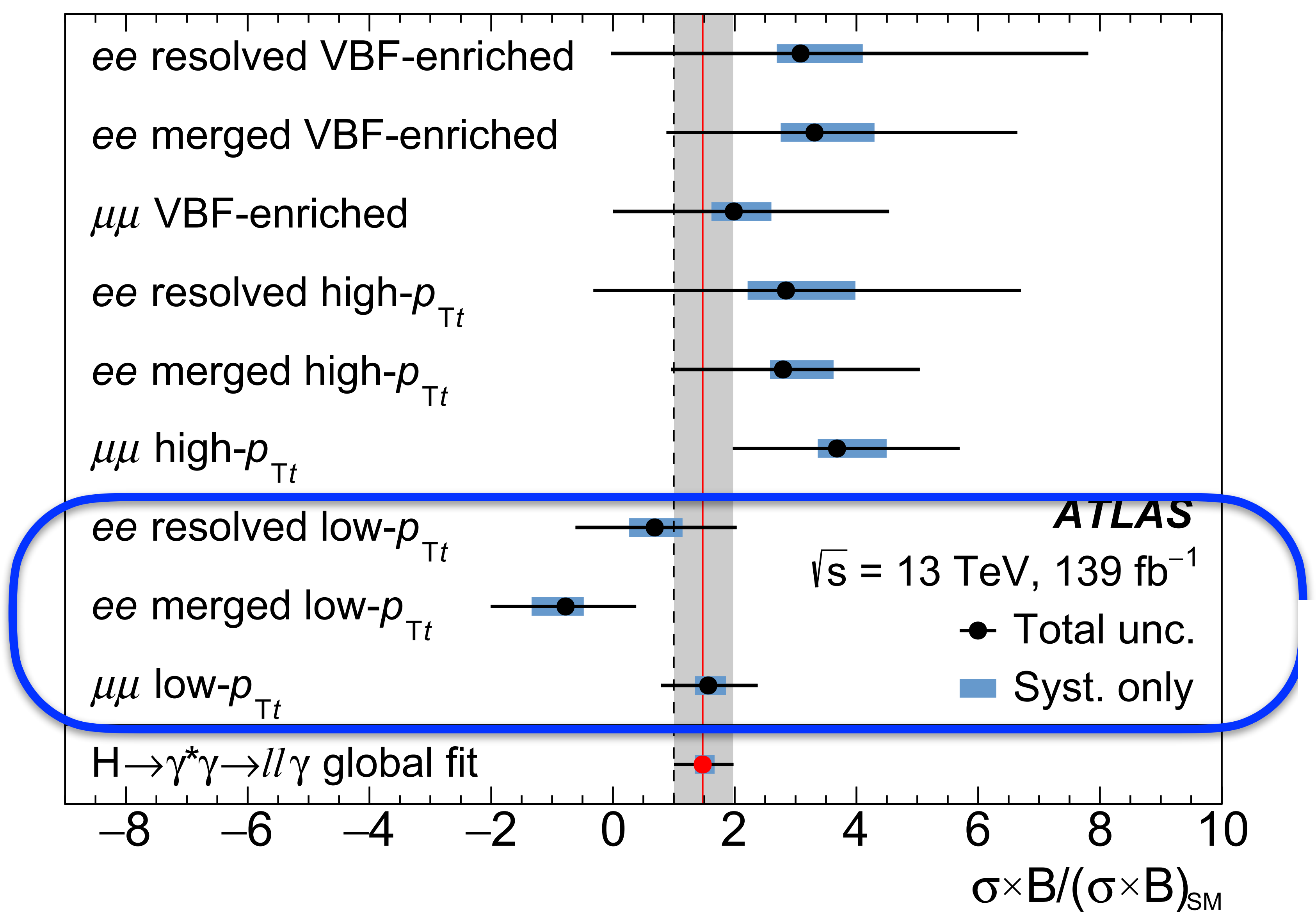
Categorization

Category	Definition
VBF Category	2 jets >25 GeV 2 selected jets must be >30 GeV if forward ($\|\eta\| > 2.5$) $m_{jj} > 500$ GeV • $\|\eta_{Zepp}\| < 2.0$ • $\Delta\eta_{jj} > 2.7$ $\Delta\varphi(\ell\ell\gamma, jj) > 2.8$ $\min(\Delta R(obj, j_i)) > 1.5$ for $j_i = 0,1$ and obj $= \gamma, \ell_0, \ell_1$
High-$p_{TThrust}$ Category	Fails VBF Category selection $\ell\ell\gamma$ $p_{TThrust} > 100$ GeV
Low-$p_{TThrust}$ Category	All remaining events

Category	Events	S_{90}	B^N_{90}	$B_{H\to\gamma\gamma}$	f_{90} [%]	Z_{90}
ee resolved VBF-enriched	10	0.4	1.6	0.009	20	0.3
ee merged VBF-enriched	15	0.8	2.0	0.07	27	0.5
$\mu\mu$ VBF-enriched	33	1.3	5.9	–	18	0.5
ee resolved high-p_{Tt}	86	1.1	12	0.02	9	0.3
ee merged high-p_{Tt}	162	2.5	18	0.2	12	0.6
$\mu\mu$ high-p_{Tt}	210	4.0	34	–	11	0.7
ee resolved low-p_{Tt}	3713	22	729	0.5	2.9	0.8
ee merged low-p_{Tt}	5103	29	942	2	3.0	1.0
$\mu\mu$ low-p_{Tt}	9813	61	1750	–	3.4	1.4

9 categories in total: (μμ, merged-e, resolve-e) × (VBF, high-Pt, low-Pt)





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- Observed (expected) significance for mH=125.09GeV is **3.2σ (2.1σ)**
- **Dominated by the statistical uncertainty**
  - μ_{obs} = 1.5±0.5 = 1.5±0.5(stat.)$^{+0.2}_{-0.1}$(syst.)
  - μ_{exp} = 1.0±0.5 = 1.0±0.5(stat.)$^{+0.2}_{-0.1}$(syst.)

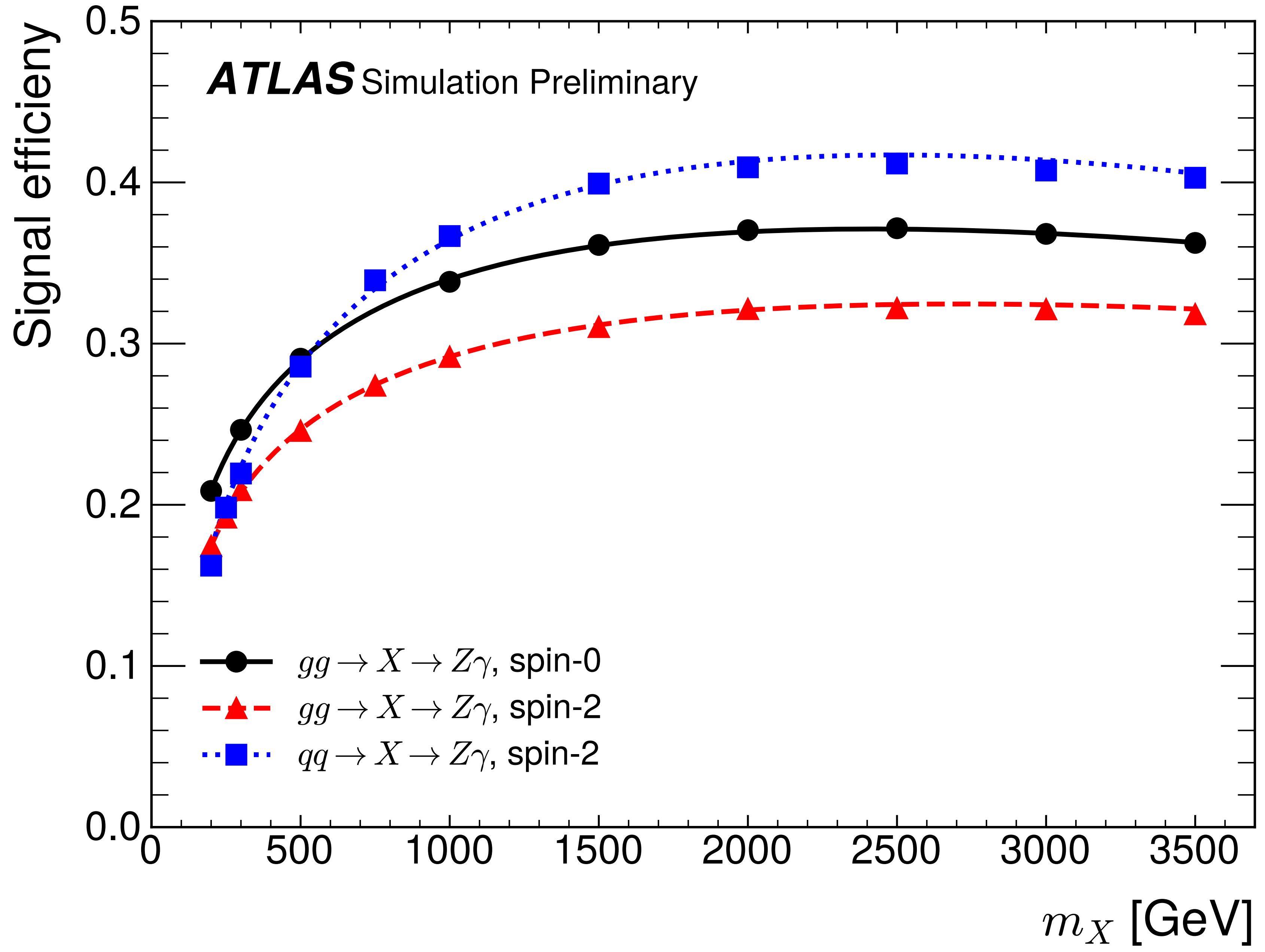
Zγ high mass search

- Focus on the Z→ee/μμ decay modes: high efficiency, good resolution and low s/b ratio
- **Challenge for Merged electron identification:** due to boost effect for the very high resonance mass, the di-leptons are quite collimated, out of detector granularity for electron pairs.

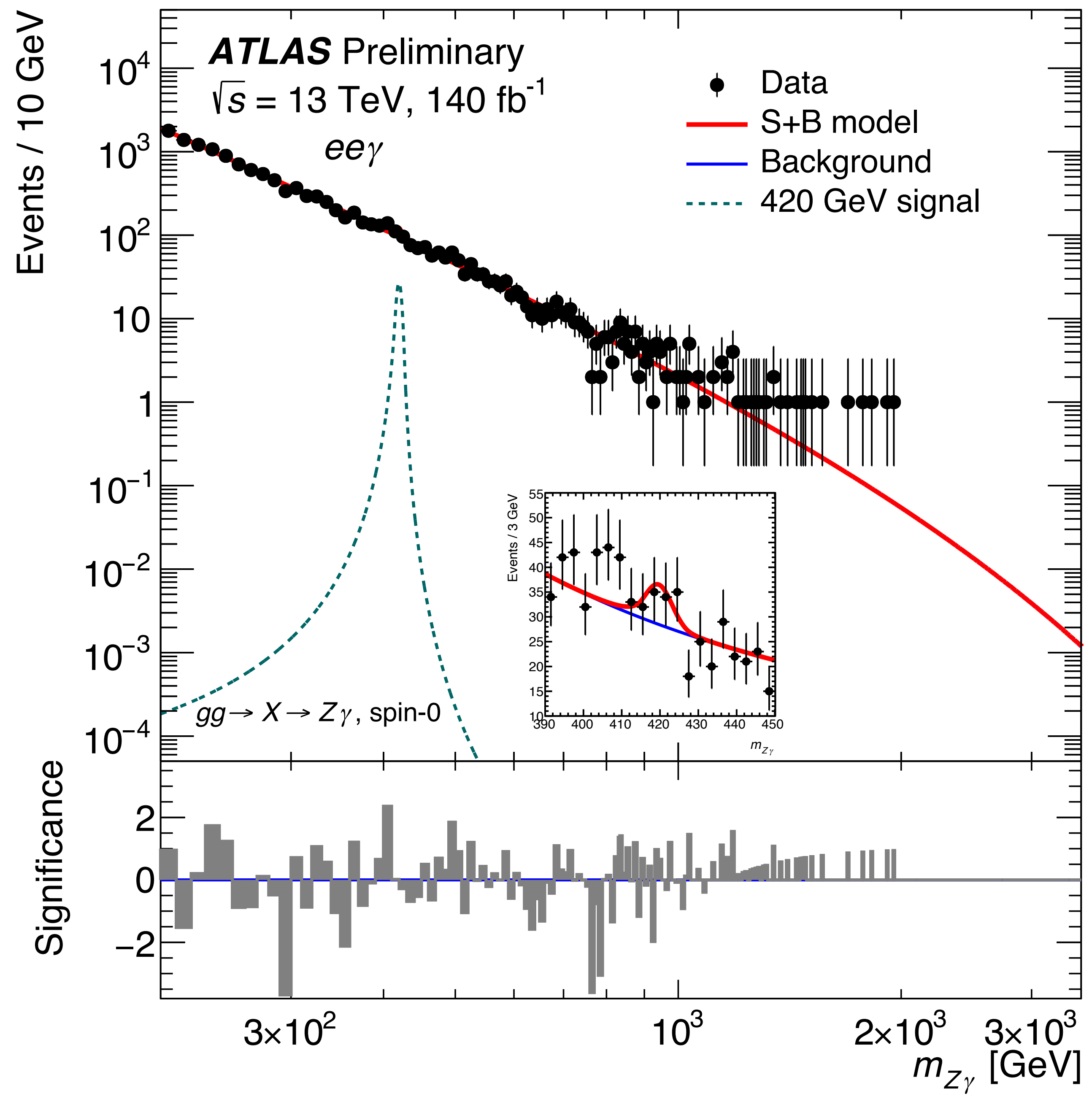
- **Customized electron ID (MVA ID):**
  - MVA (XGBoost) using **shower shape variables** and **track-related variables** with **a signal efficiency of 99% @ 5TeV**
- **Mix-ID**: combine standard loose ID and MVA ID with a logical OR which improve the efficiency by 6.2% - 12.7%
- **eγ pair selection:** one of electrons is misreconstructed as a photon, and retrieve via tracking matching

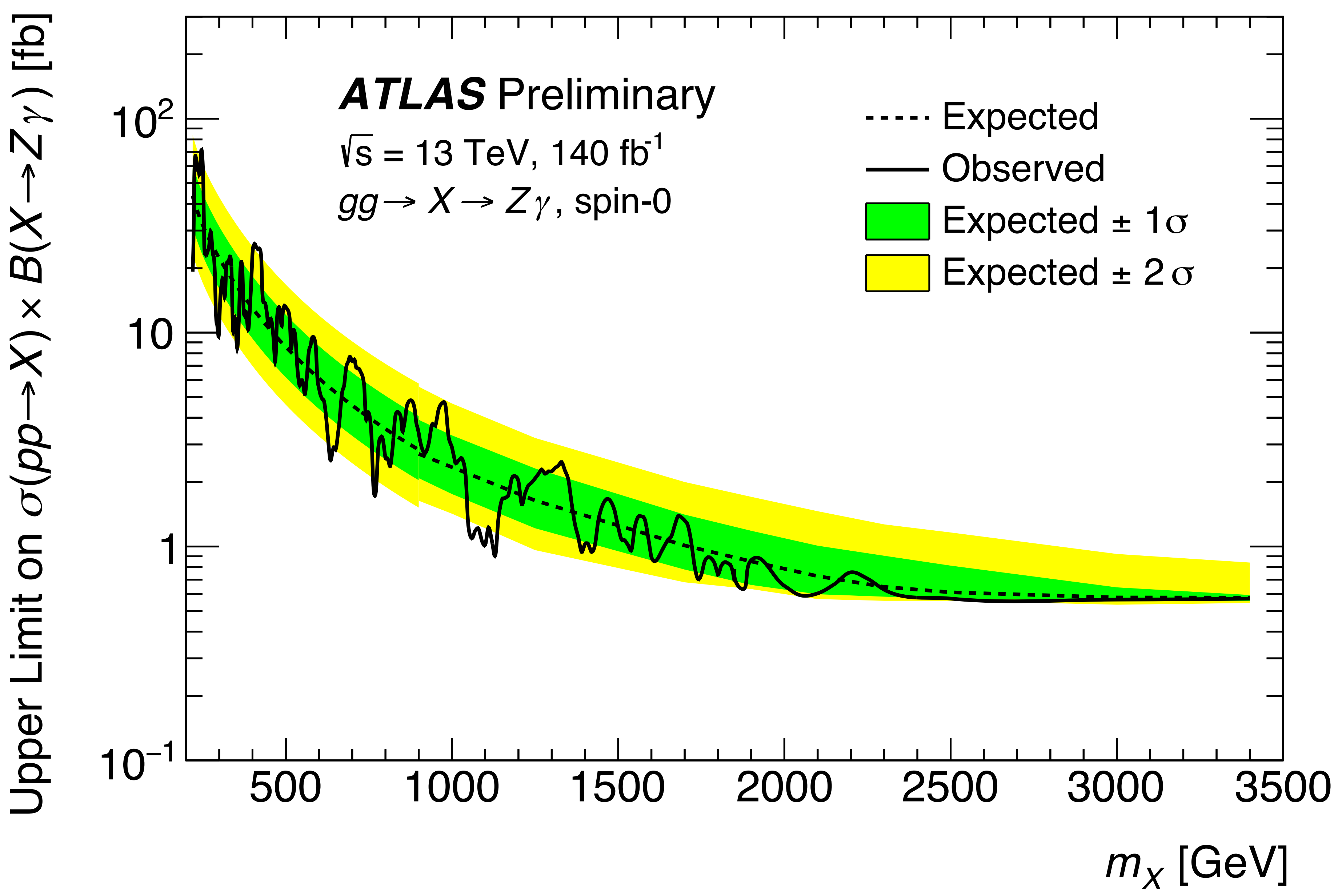
R_η, R_{had}, R_ϕ, $\Delta\mathrm{E}_s$ and $\mathrm{E}_{\mathrm{ratio}}$

E/p, eProbabilityHT, $\Delta\eta_1$, d_0, $n_{\mathrm{innermost}}$, n_{Pixel} and n_{Si}



New resonance search in Zγ decay mode





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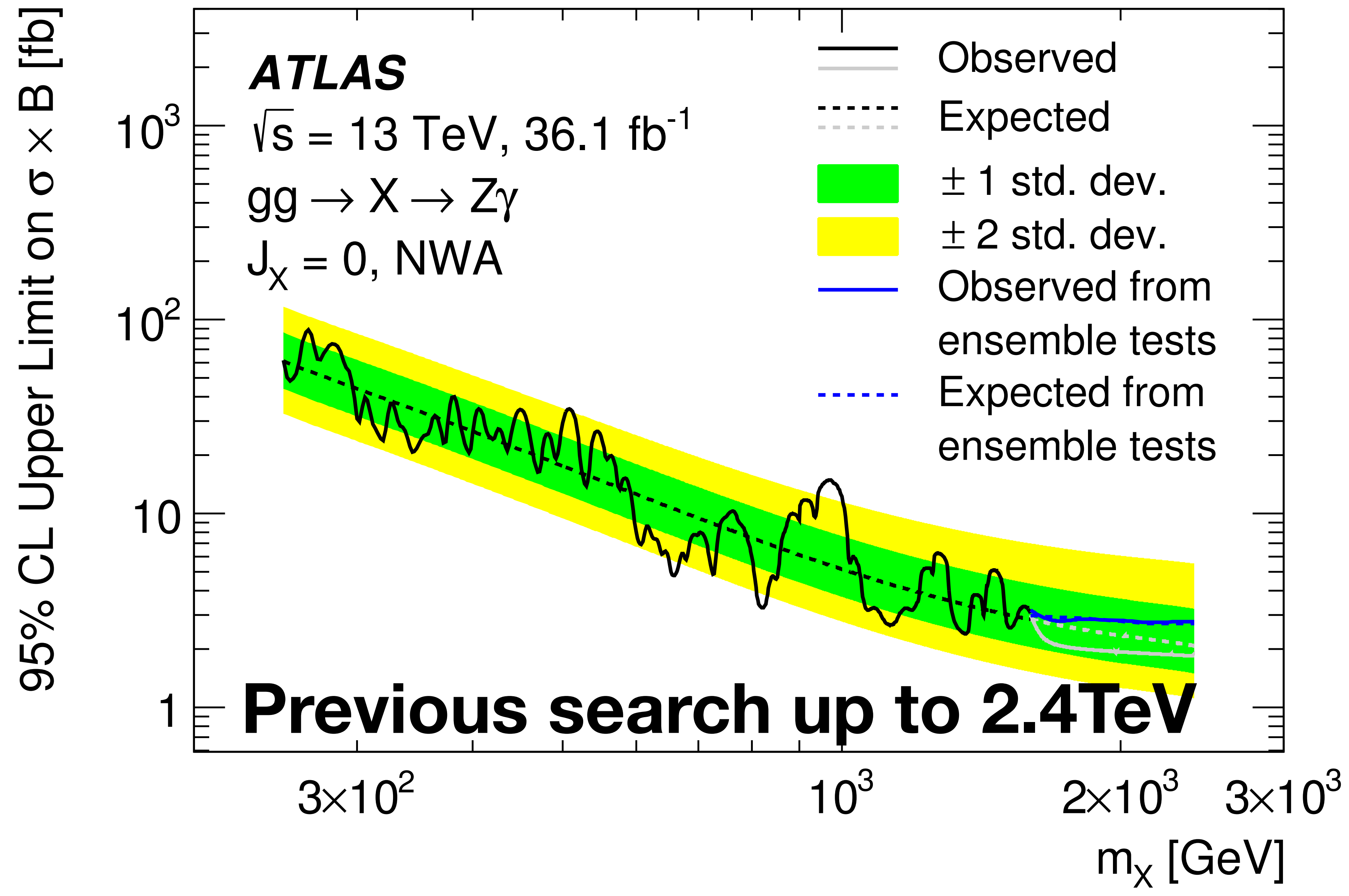

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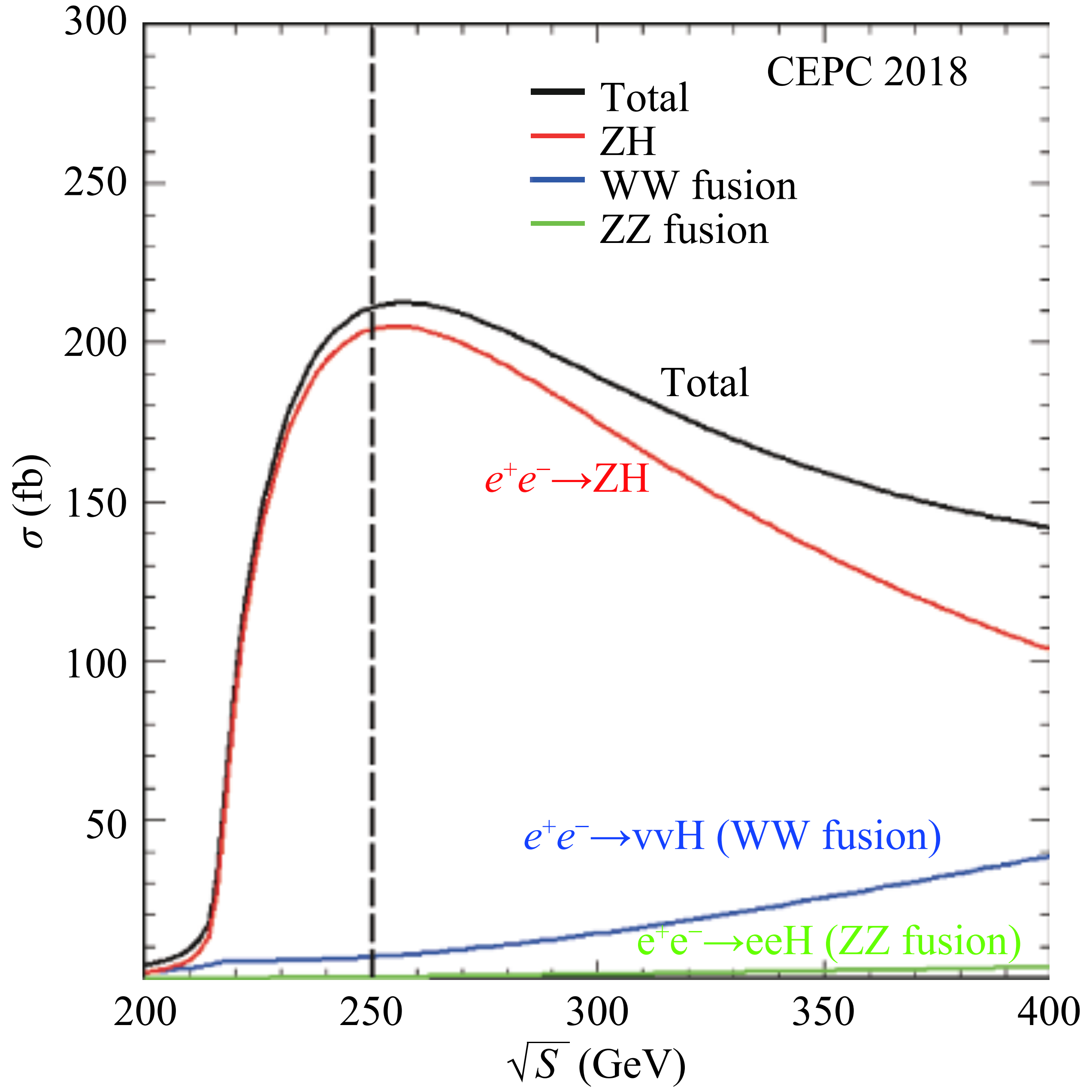
◈ Due to the dedicated identification for boost di-electron pair：

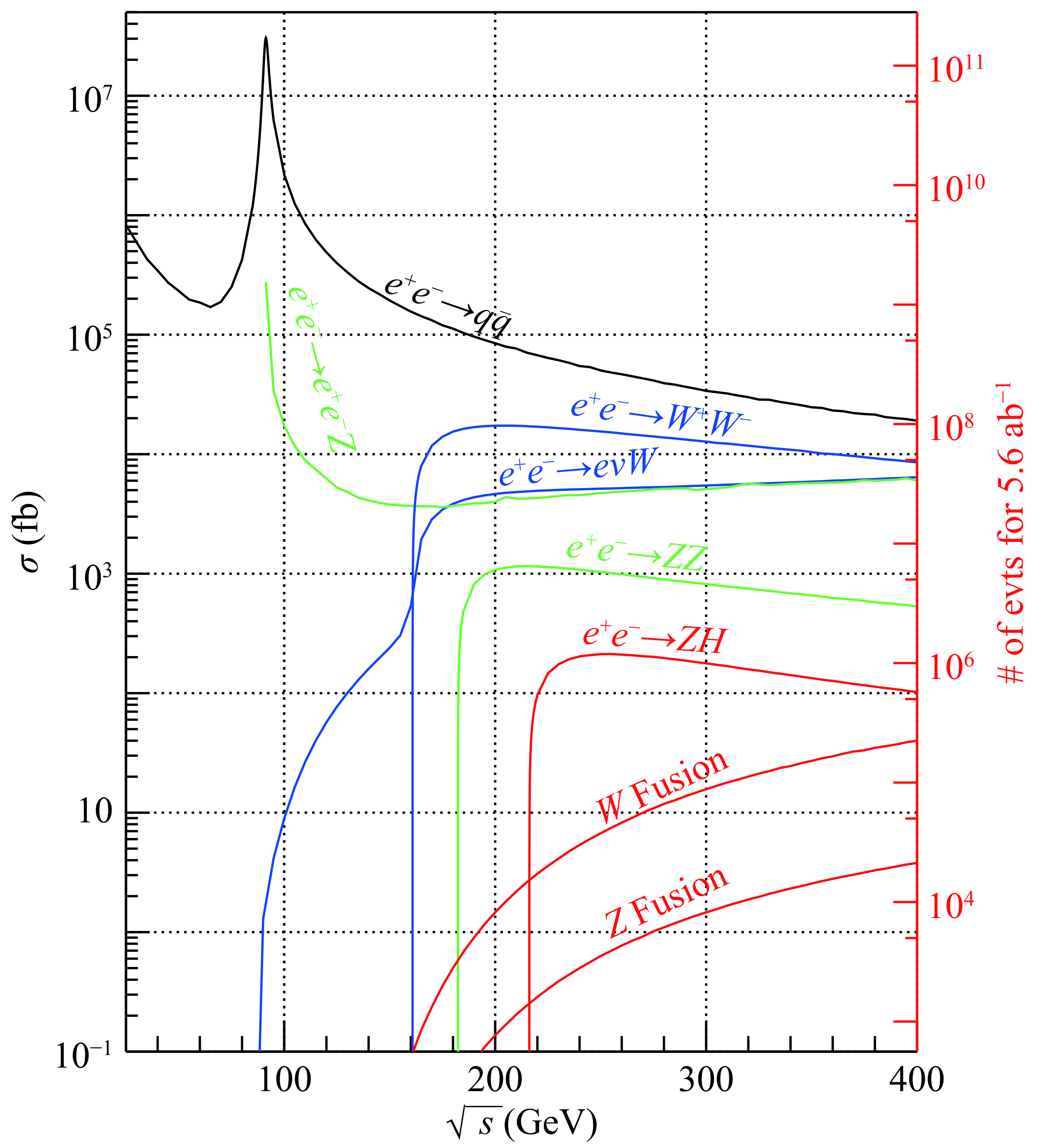
- ✦ Search range extends up to 3.4TeV
- ✦ Sensitivity improved with a factor of 1.9 - 4
- ✦ Available for further search extension in future

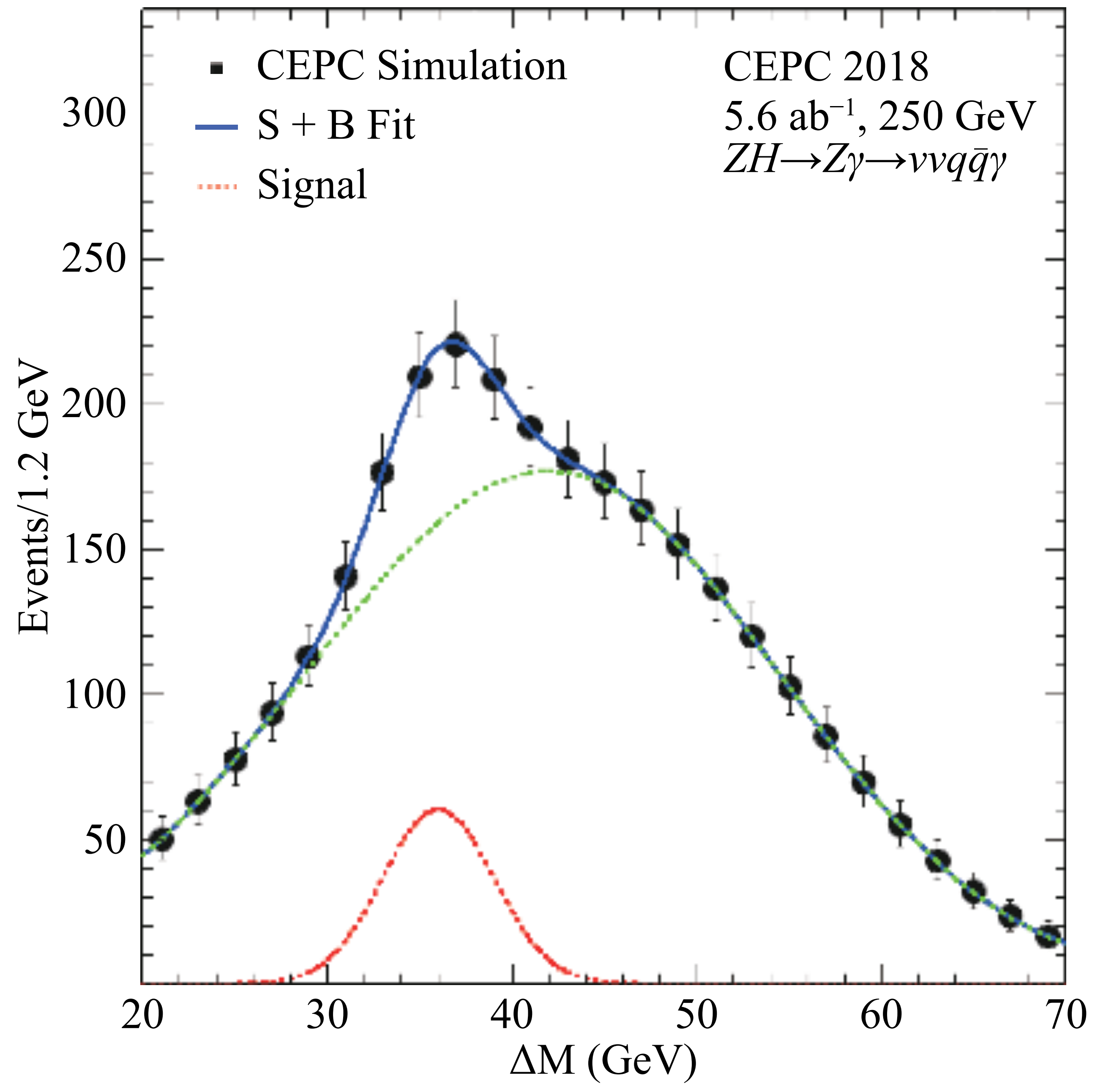
Recap of H→Zγ search @ LHC

- Run2 studies have been finished: due to the high efficiency, good resolution and signal-background rate, current results are focused on e/μ channel:
  - First observed evidence of 3.4σ with ATLAS-CMS combination
  - With dedicated merge di-electron identification for the low-pt case and boost case, achieve the evidences of $H \to \gamma^* \gamma$ and extend search range to 3.5TeV
- Room for possible improvement:
  - Optimization for the reconstruction and identification of low pt photon and lepton
  - Explore the Z hadronic decays and invisible decays: challenge trigger selection due to the soft final particles. (15GeV Jet threshold @ L1 corresponds to ~50GeV Jet @ HLT)

H→Zγ @ CEPC







- H→Zγ targets the signal process of ZH→ZZγ→υυqqγ
- Mass difference used as final distinguish observable: $\Delta M = M_{qq\gamma} - M_{qq}$, $\Delta M = M_{\upsilon\upsilon\gamma} - M_{\upsilon\upsilon}$
- With the integrated luminosity of 5.6ab-1 @250GeV, 13% precision on σ(ZH)×BR(H→Zγ)

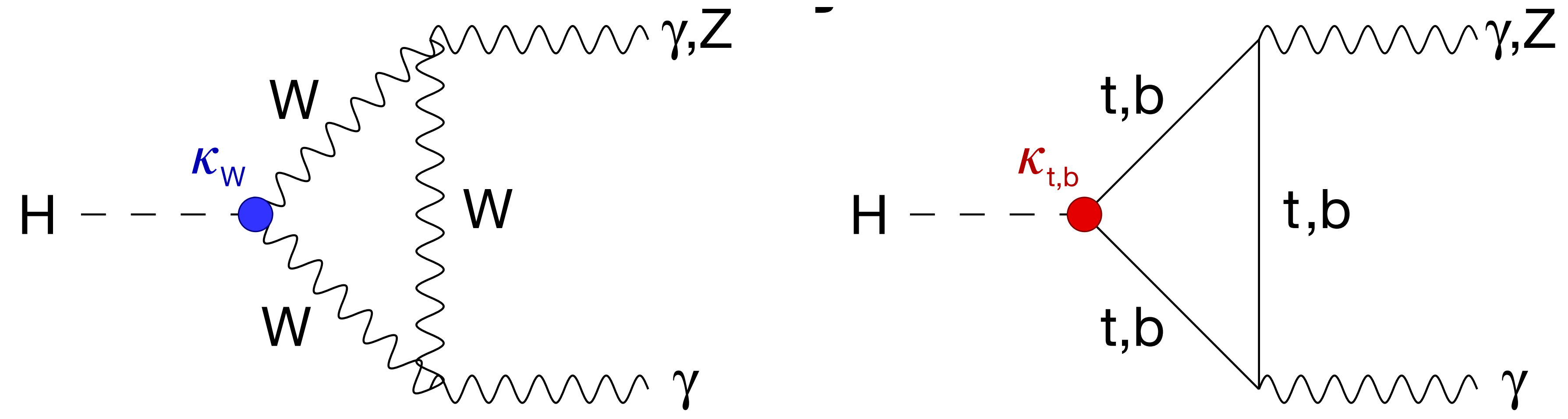
Coupling measurement

$$(\sigma\cdot\mathrm{BR})(i\to\mathrm{H}\to f)=\frac{\sigma_i^{SM}\kappa_i^2\cdot\Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2}\quad\rightarrow\quad \mu_i^f\equiv\frac{\sigma\cdot\mathrm{BR}}{\sigma_{\mathrm{SM}}\cdot\mathrm{BR}_{\mathrm{SM}}}=\frac{\kappa_i^2\cdot\kappa_f^2}{\kappa_H^2}$$

$$\Gamma_H=\frac{\Gamma_H^{\mathrm{SM}}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

$$\mathcal{L}_{\mathrm{EFT}}=\mathcal{L}_{\mathrm{SM}}+\sum_i\frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}+\sum_j\frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)}+\cdots$$

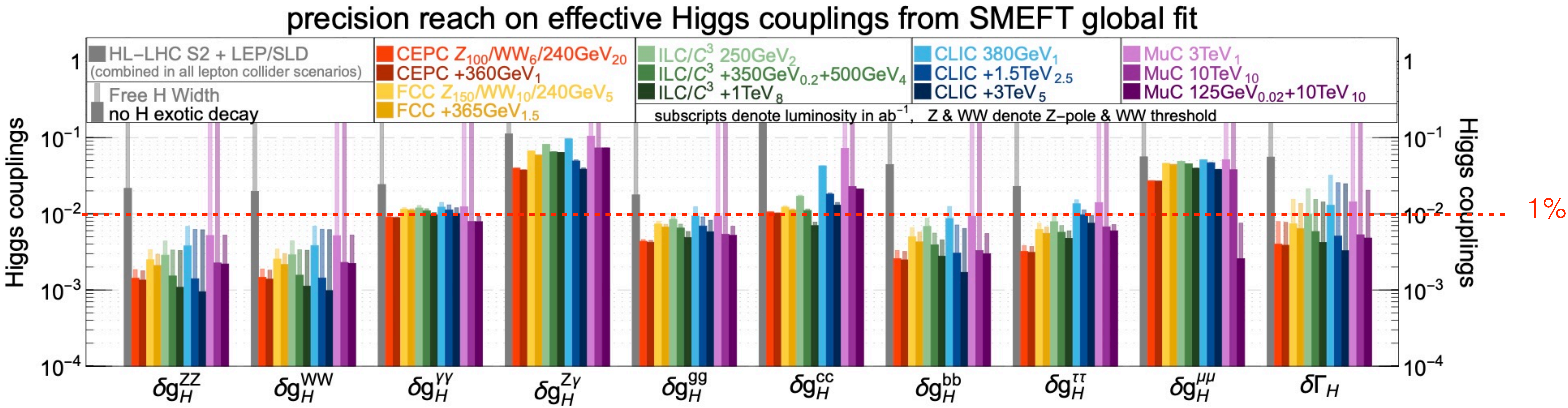
Loop interaction



$$\kappa_{Z\gamma}^2\sim\quad 1.12\cdot\kappa_W^2+0.00035\cdot\kappa_t^2-0.12\cdot\kappa_W\kappa_t$$

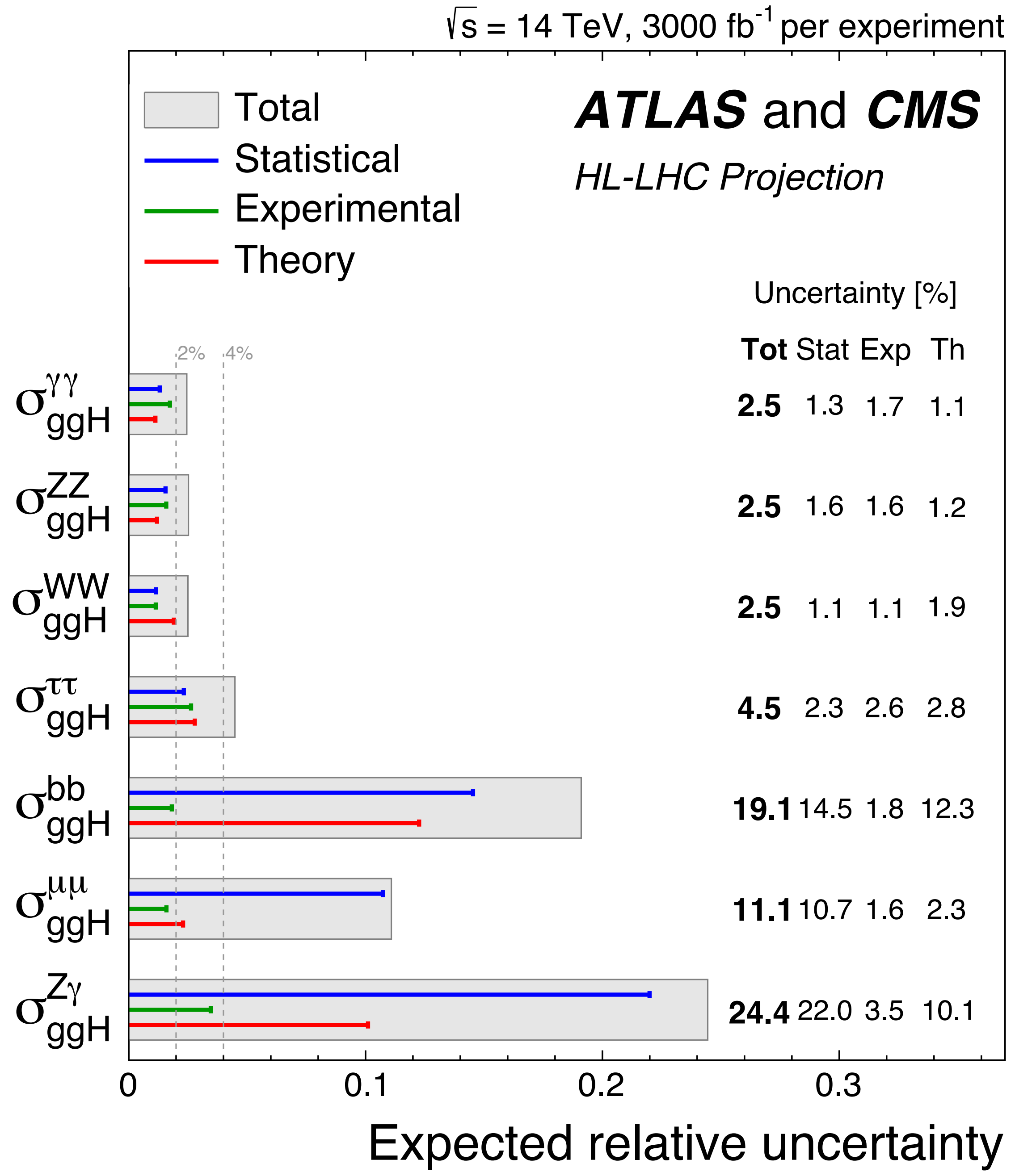
- **Assumptions:**
  - Single state, spin 0 and CP-even, Narrow-width approximation
- **κ-framework Methodology:** parametrize deviations with coupling scale factors {κ_X}
  - A simple and intuitive parametrization of the potential derivation with the limitation for its understanding
  - BSM decays parametrized including invisible decays and untagged decays
  - CEPC has a clear advantage on κ_Z measurement and BR_{inv} constraint
- **EFT:**
  - Directly introduce the new physics effect with the higher dimension operators

Prospect



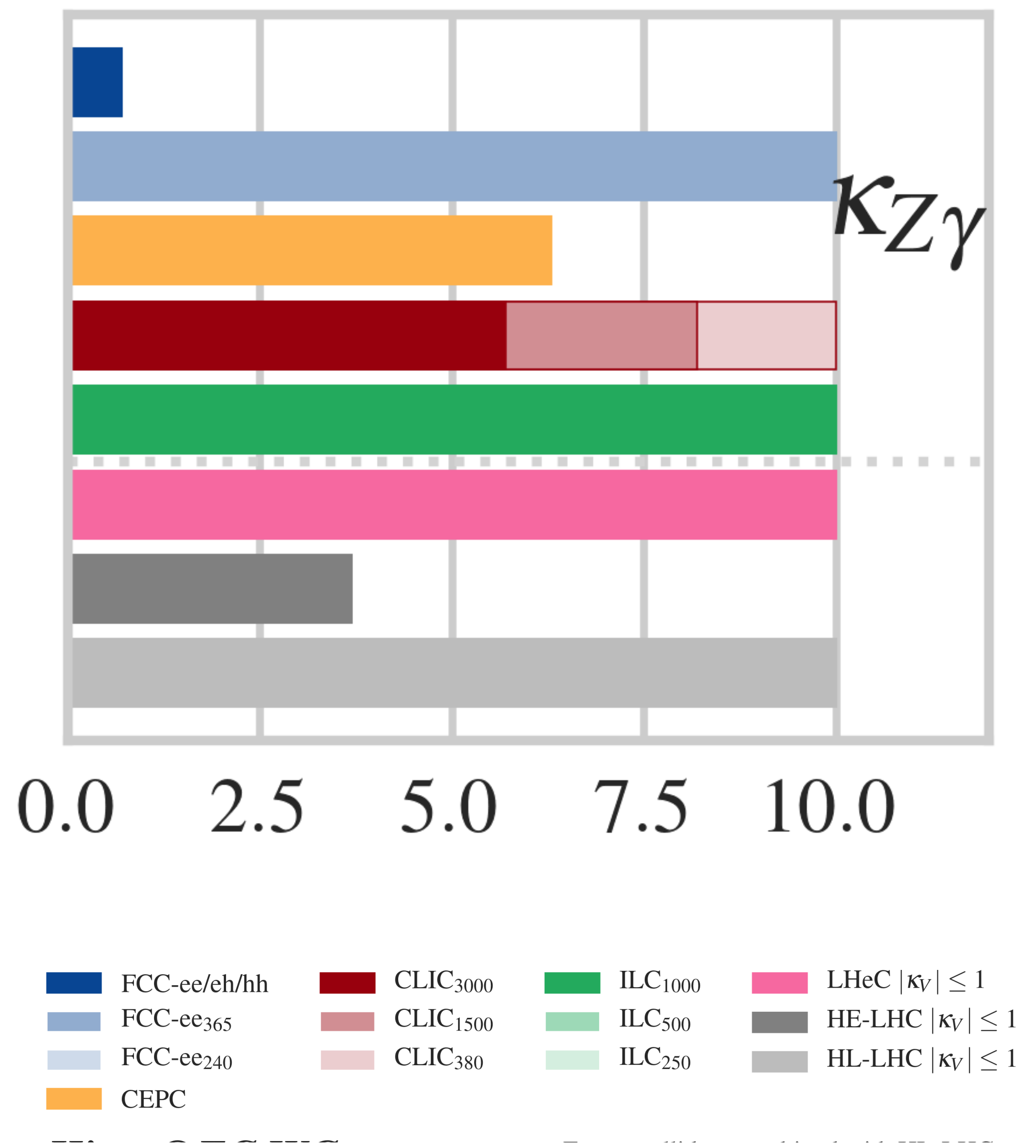
- Most of parameters can reach the precision of ~1%
- For the rare decays, HZγ and Hμμ have comparable sensitivities among different colliders

Prospect of HZγ coupling



kappa-0	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 15000	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69

kappa-3 scenario	HL-LHC+ ILC$_{250}$	ILC$_{500}$	ILC$_{1000}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
$\kappa_{Z\gamma}$ [%]	10.∗	10.∗	10.∗	10.∗	8.2	5.7	6.3	10.∗	10.∗	0.7



- With 3000fb^{-1} @ HL-LHC, ATLAS expected significance is 4.9σ with the uncertainty of 24%
- With the combination of HL-LHC + CEPC, the precision can reach ~6.3%
  - ~20% anti-correlation between HZγ and untagged branching fraction
- The best precision from FCC-hh: 0.7%

Summary

- ◈ Search for $H \rightarrow Z\gamma$ rare decay can probe the Higgs loop interaction in SM and BSM physics
- ◈ All the $H/X \rightarrow Z\gamma$ studies with full-Run2 data done：
  - ✦ First observed evidence of 3.4σ was achieved with ATLAS-CMS combination
  - ✦ Evidence of $H \rightarrow \gamma^*\gamma$ search with a significance of 3.2σ
  - ✦ $Z\gamma$ high mass search successfully extend to 3.4TeV
- ◈ More promising results with higher statistics of Run3 and more sensitivity optimization