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Searches for Higgs boson rare decays

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On behalf of the CMS Collaboration

ICHEP2018 SEOUL
XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS
JULY 4 - 11, 2018 COEX, SEOUL

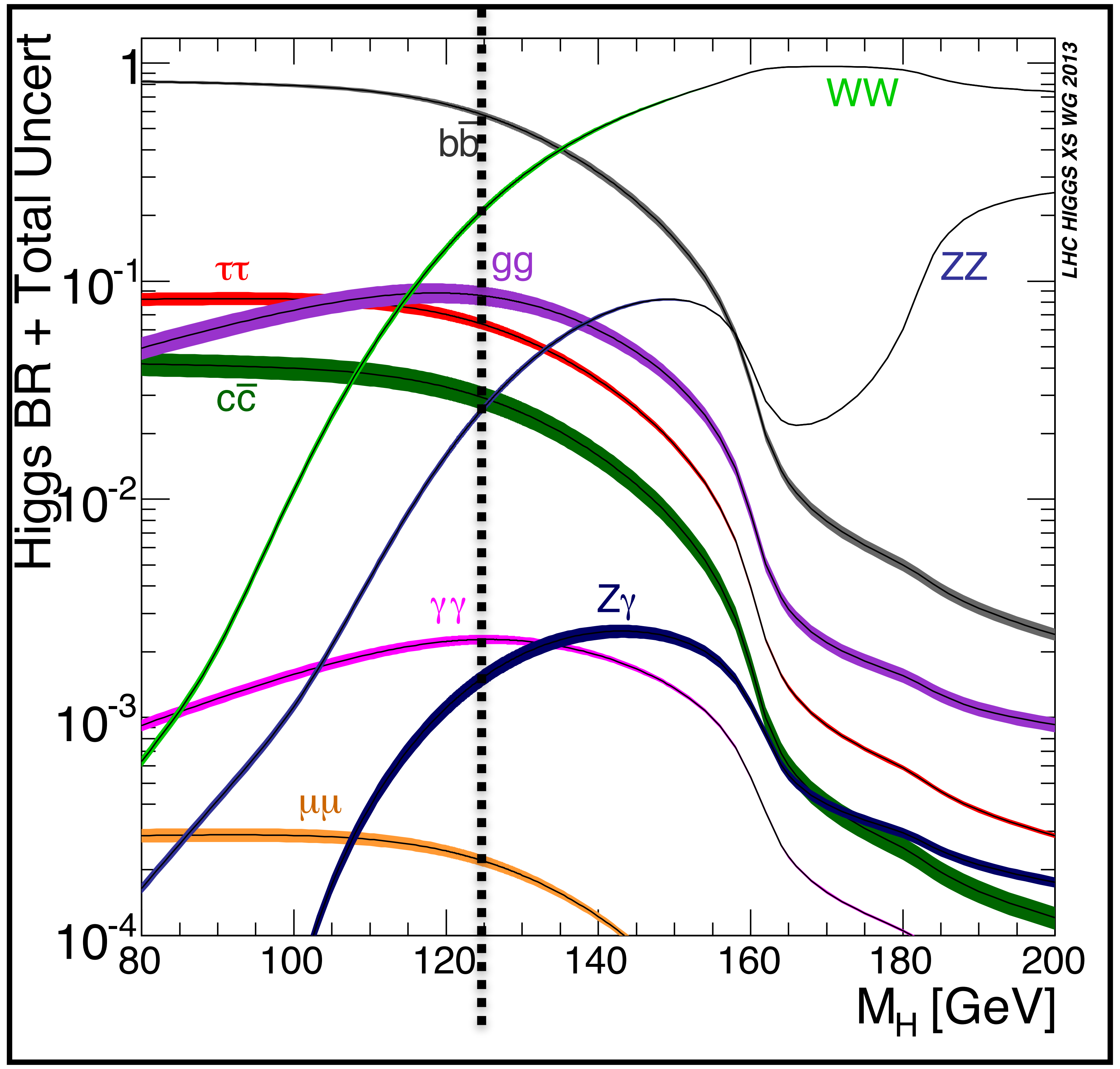
Higgs boson rare decays

- Measurements of Higgs couplings and properties in the main decay channel shows good compatibility with the SM predictions

CMS-HIG-17-031

H_{125} branching ratio as in the SM → ***Searches for rare decays based on 2016 data*** → ***Why looking for such rare decays?***

Do we expect to have sensitivity for them?



Channel	BR
$\mathrm{H} \rightarrow \text{invisible}$	$\geq 1 \times 10^{-3}$
$\mathrm{H} \rightarrow \mu\mu$	2.17×10^{-4}
$\mathrm{H} \rightarrow \mathrm{Z}\gamma \rightarrow \ell\ell\gamma$	1.01×10^{-4}
$\mathrm{H} \rightarrow \mathrm{J}/\psi\gamma$	3.0×10^{-6}

- Rare decay rates can deviate from the SM predictions and be enhanced as predicted in several BSM models

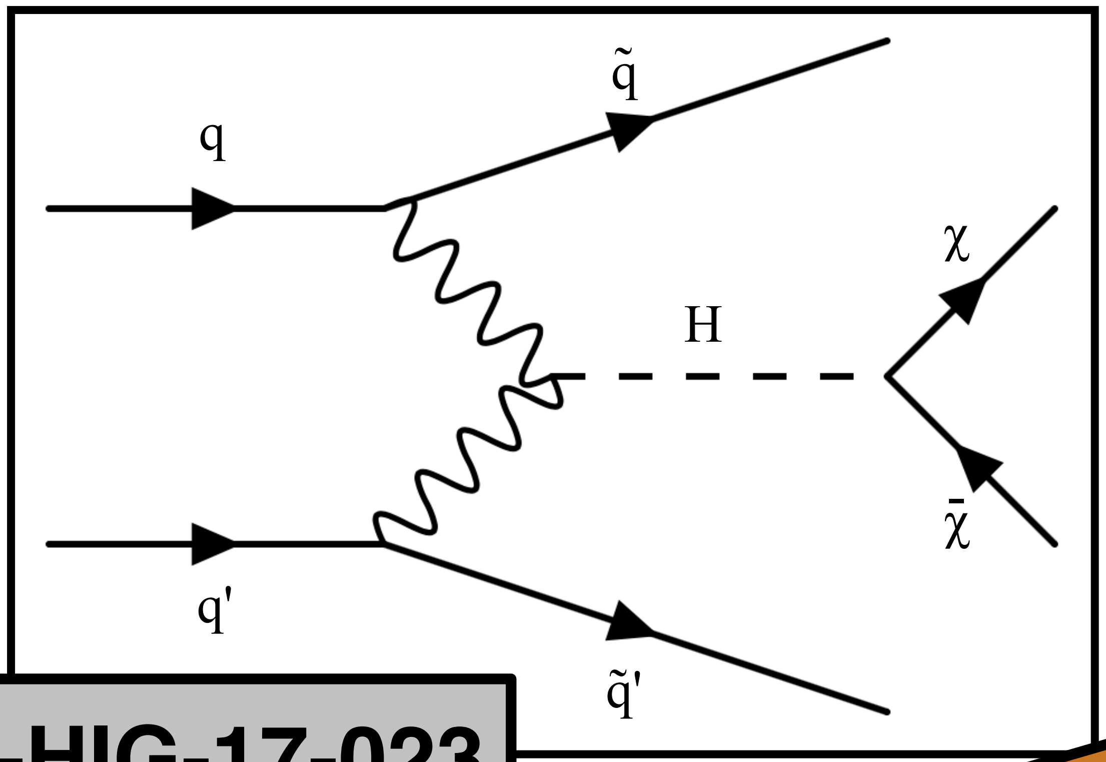
- B(H → BSM) < 34% from Run-I as in ***JHEP 08 (2016) 045***

Higgs to invisible searches

- In the SM, Higgs decays to invisible particles (neutrinos) only via H → ZZ* → 4ν with BR of 0.1%
- We don't know enough about the SM Higgs → plenty of room for couplings to a new hidden dark sector

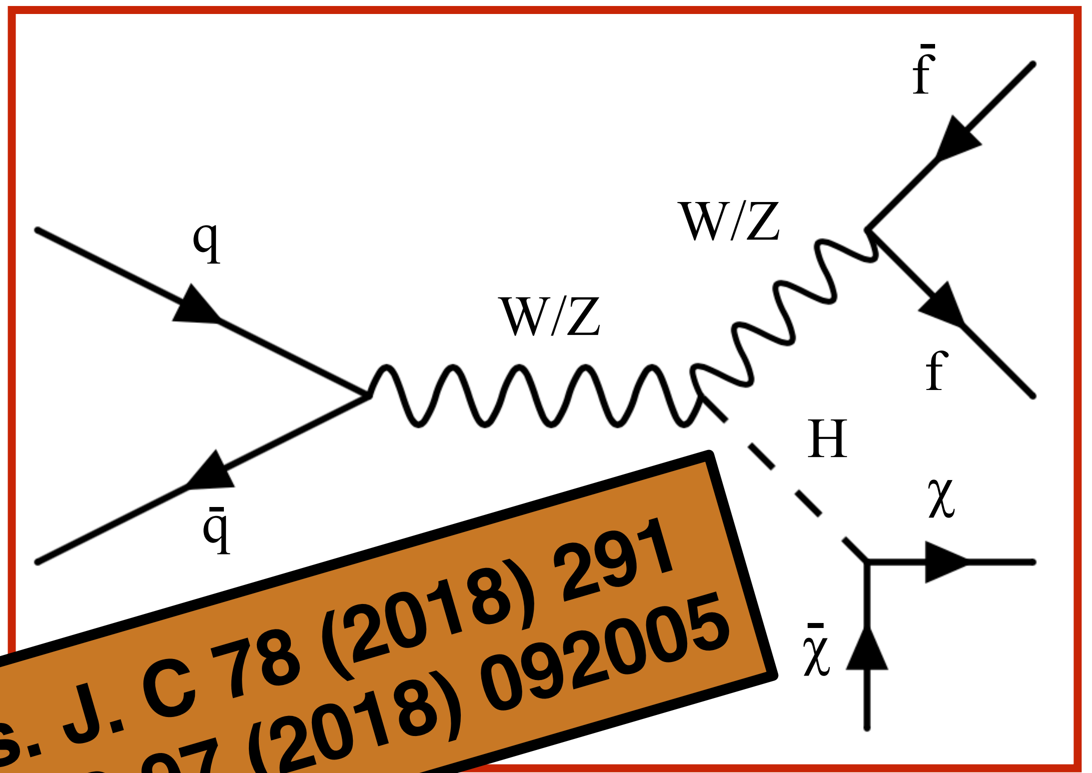
All the Higgs production modes can be used to probe its coupling with "invisible" particles

VBF-tag



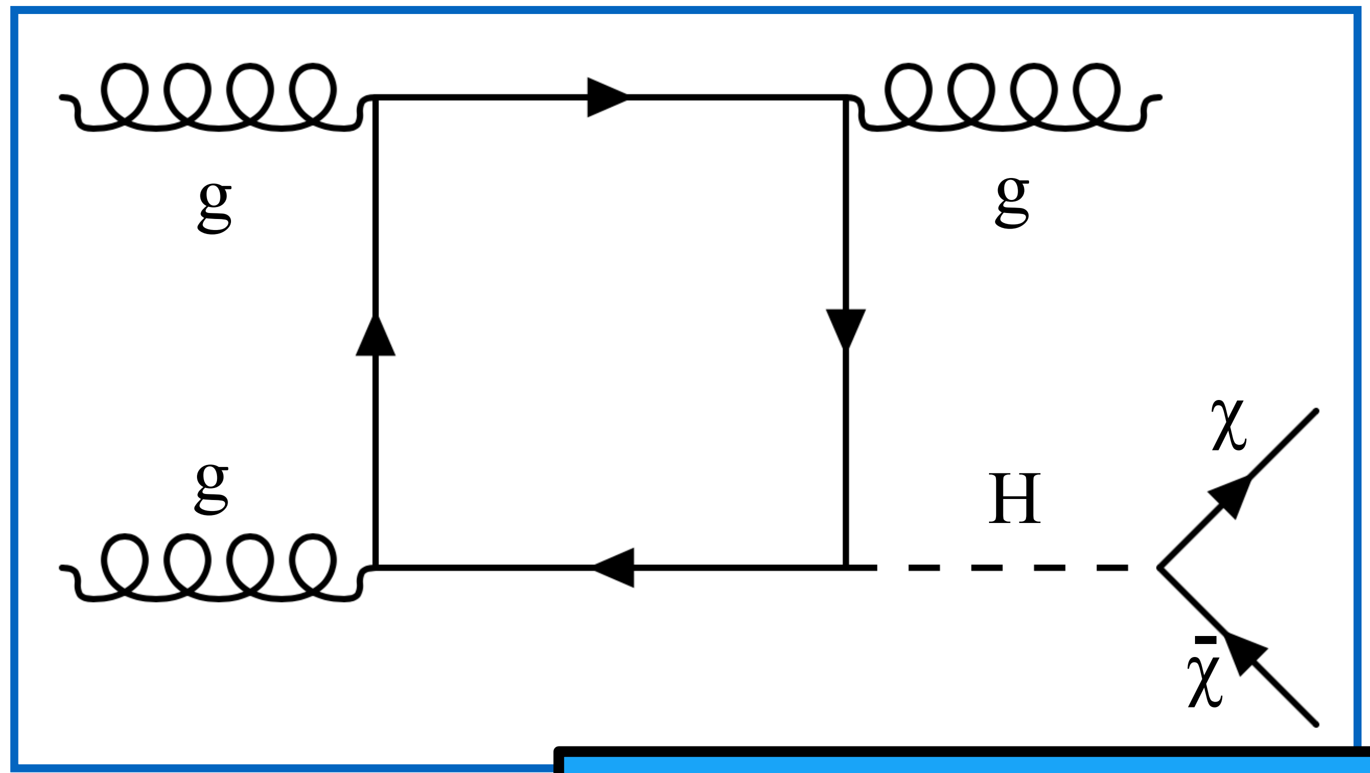
CMS-HIG-17-023

VH-tag, V → ℓℓ or qq'



Eur. Phys. J. C 78 (2018) 291
Phys. Rev. D 97 (2018) 092005

ggH + jets tag

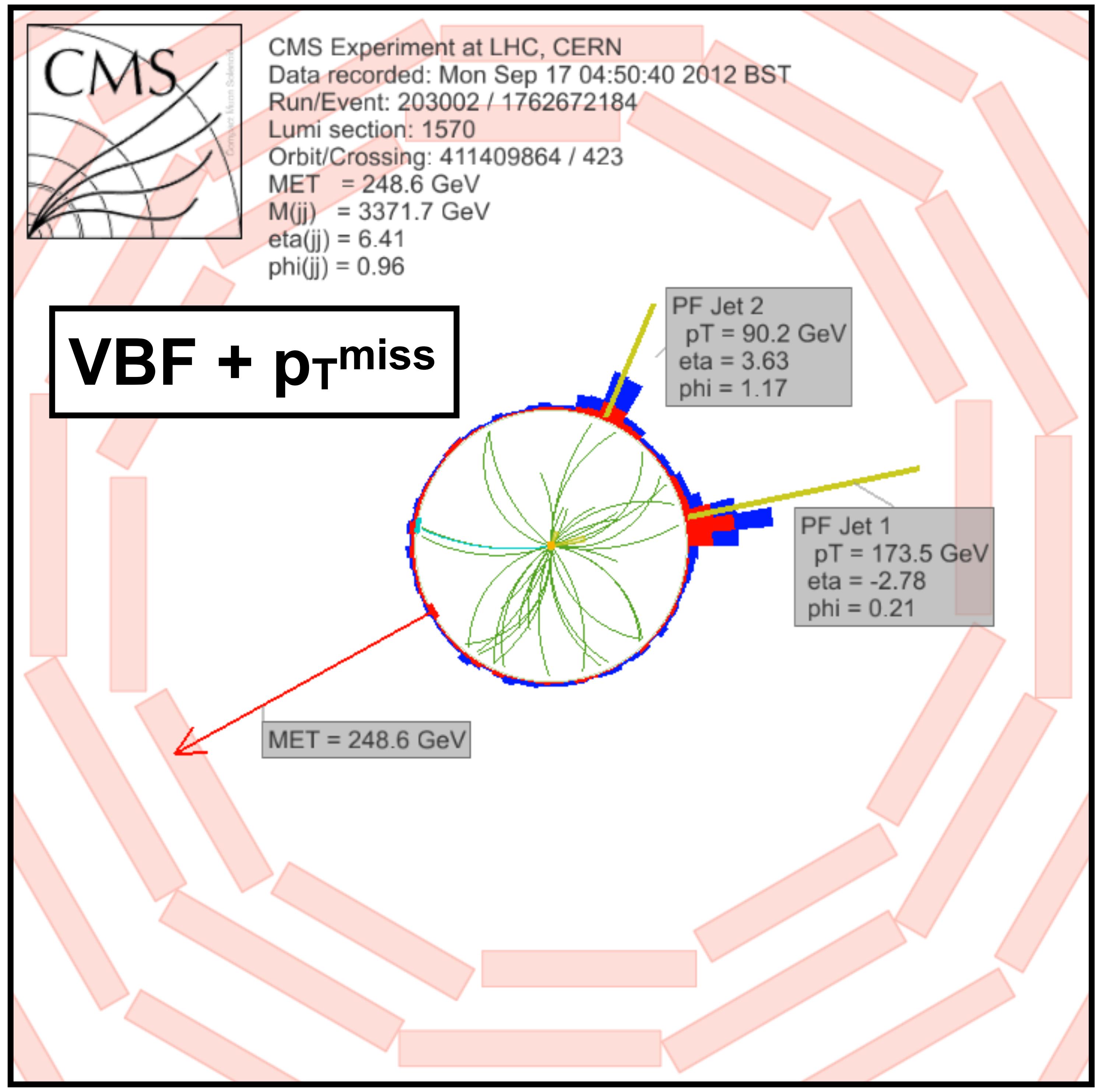


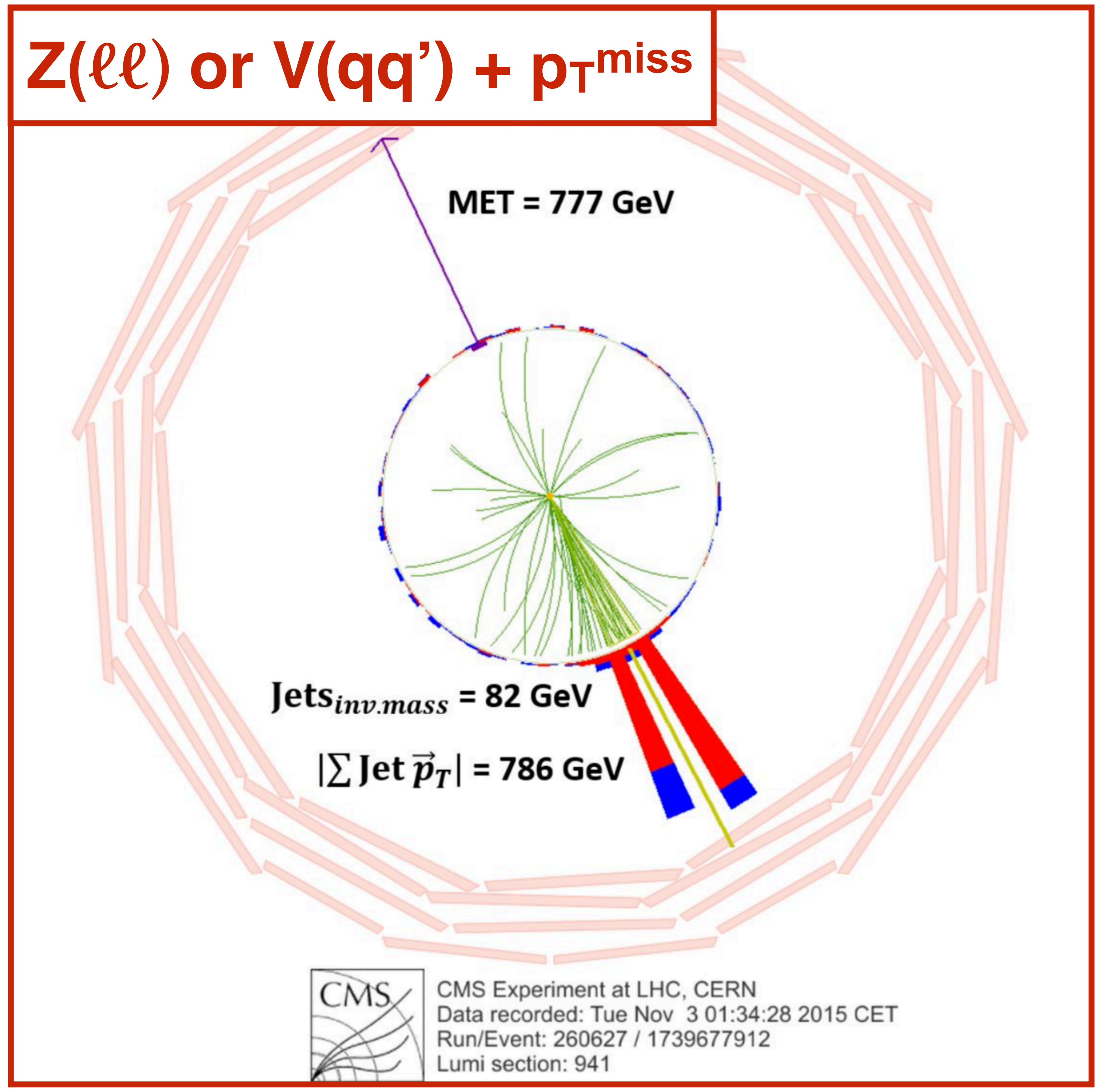
Phys. Rev. D 97 (2018) 092005

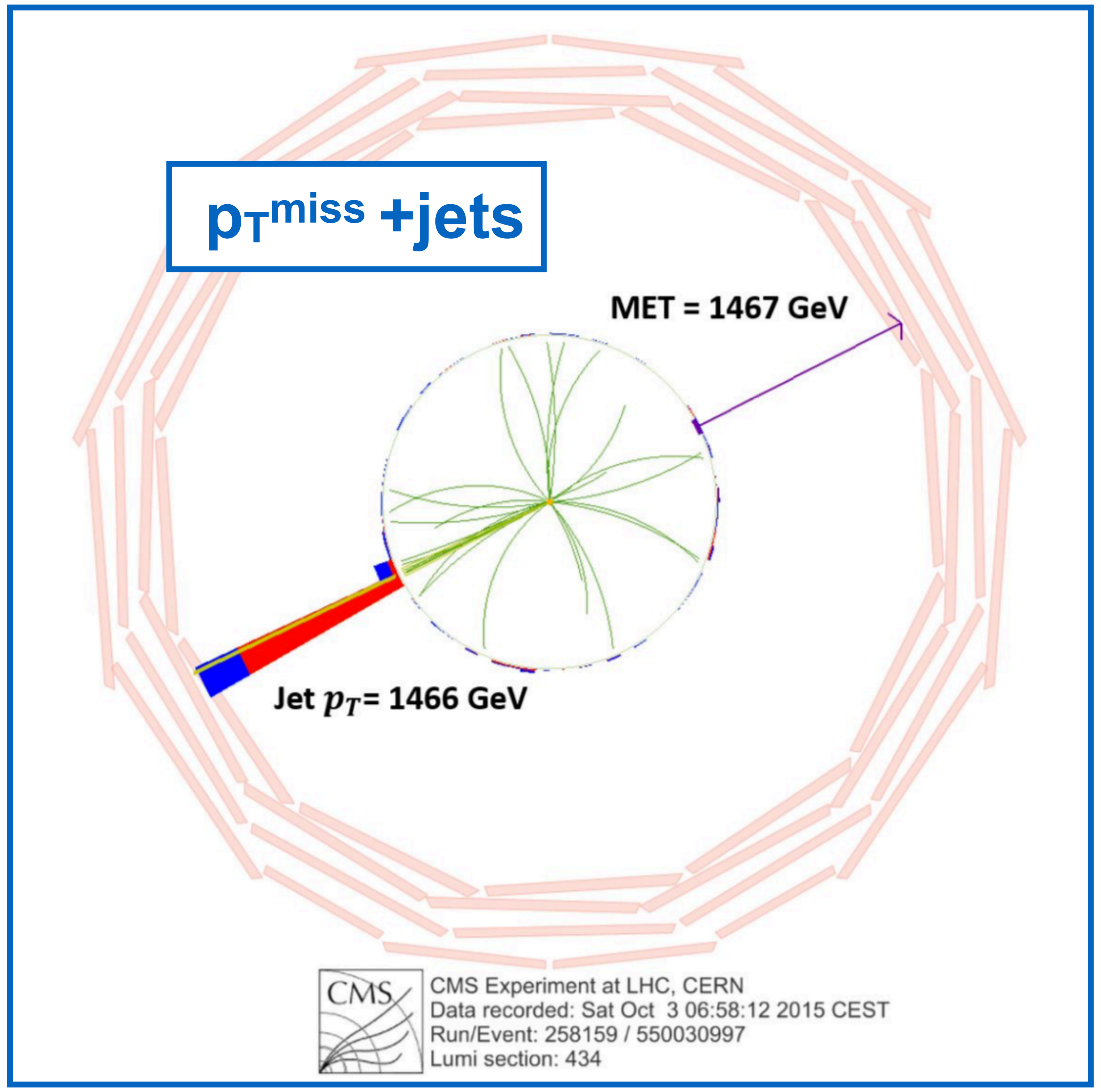
All searches characterized by large p_T^{miss}

The Higgs boson recoils against a visible system used to distinguish between production modes

Higgs → inv. signatures







Signature: 2-jets with large Δη and m(jj)

- Large E_T^{miss} > 250 GeV
- $p_T(j_1)$ > 80 GeV, $p_T(j_2)$ > 40 GeV,
- |Δη(jj)| > 1 and Δφ(jj) < 1.5
- Veto leptons and b-tagged jets

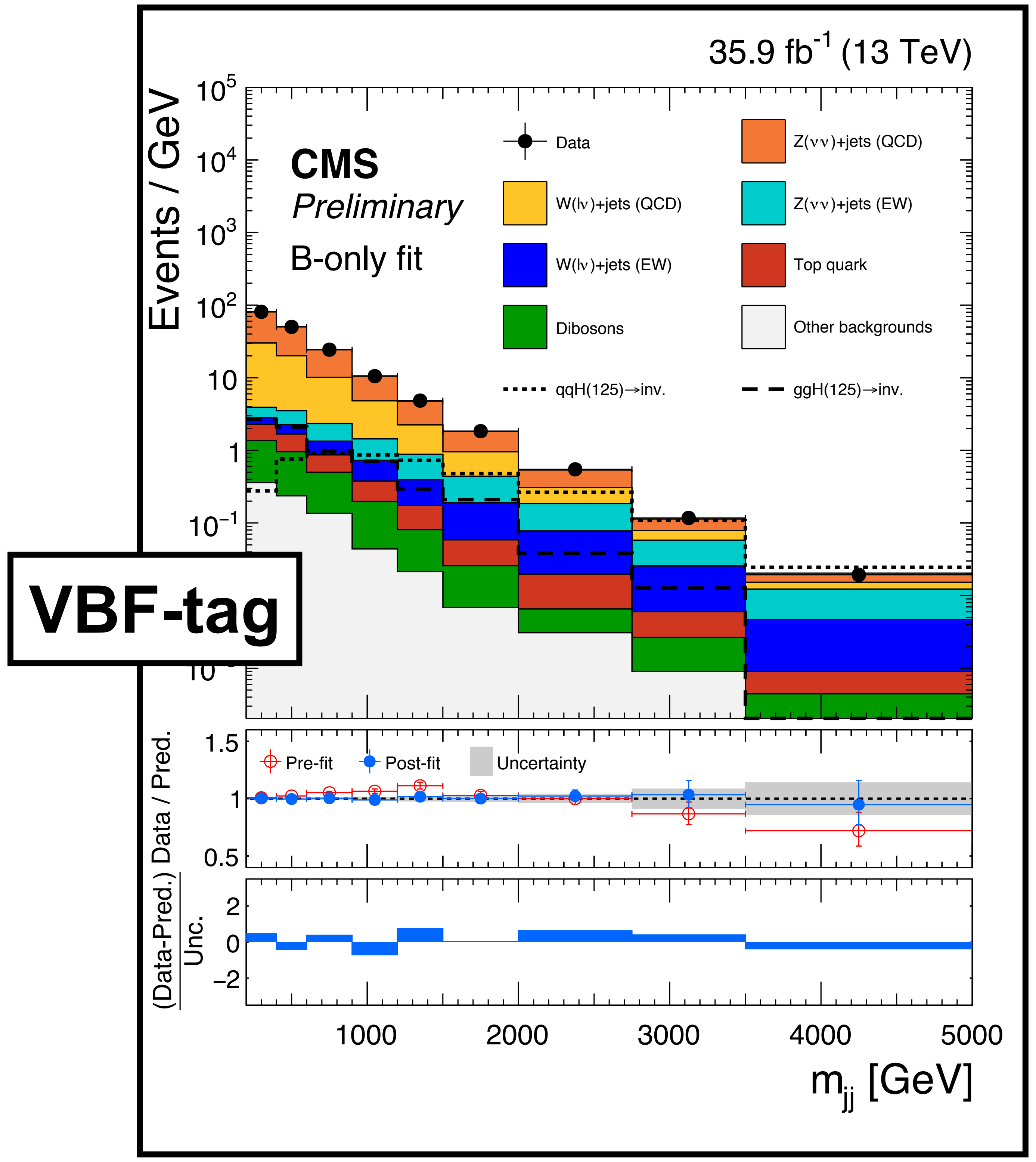
Signature: p_T^{miss} + 2-leptons from Z-boson or high p_T jets from V(qq')

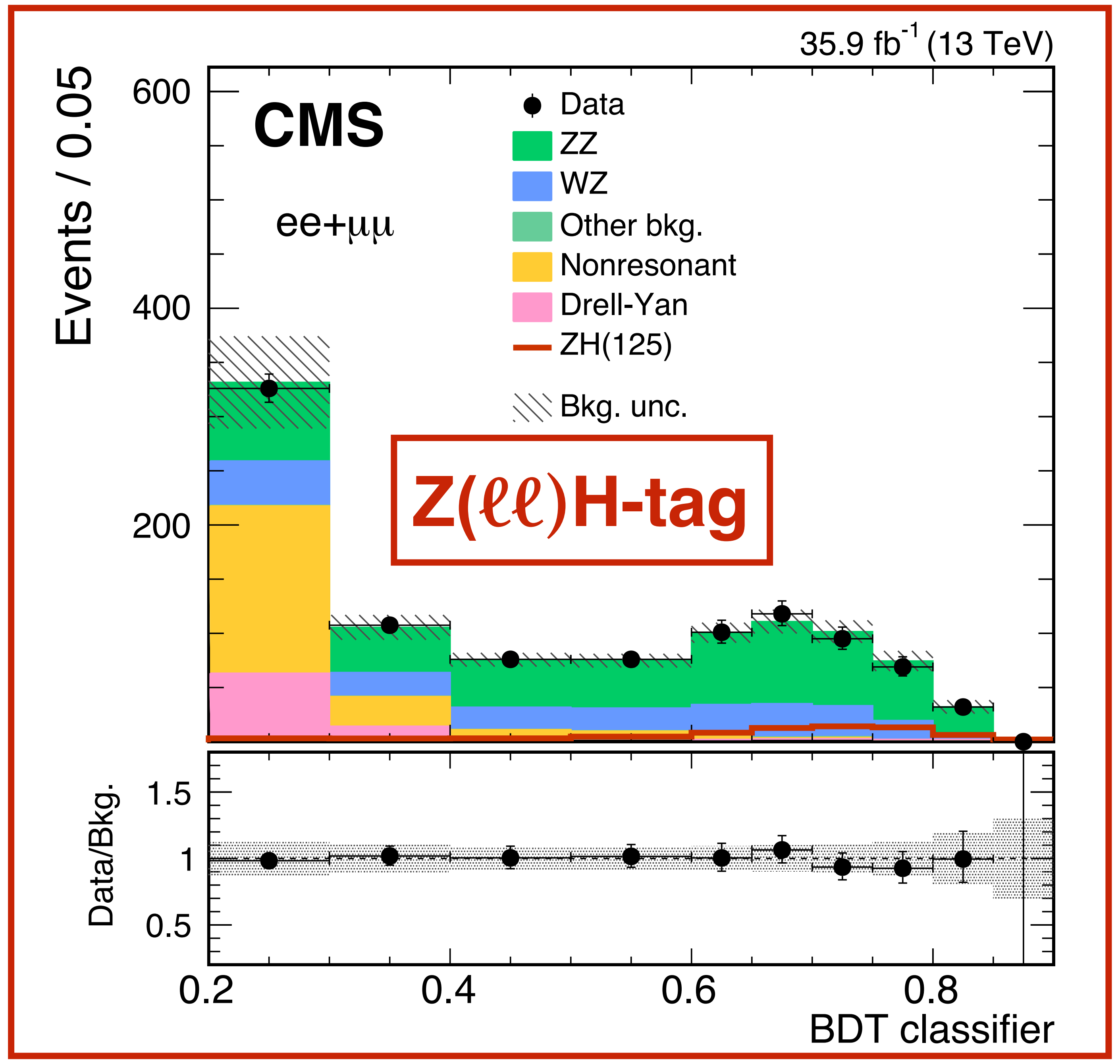
- V(qq') identified via substructure techniques from AK8 jet p_T > 250 GeV
- Z(ℓℓ)H search uses a BDT to increase the sensitivity against ZZ and WZ

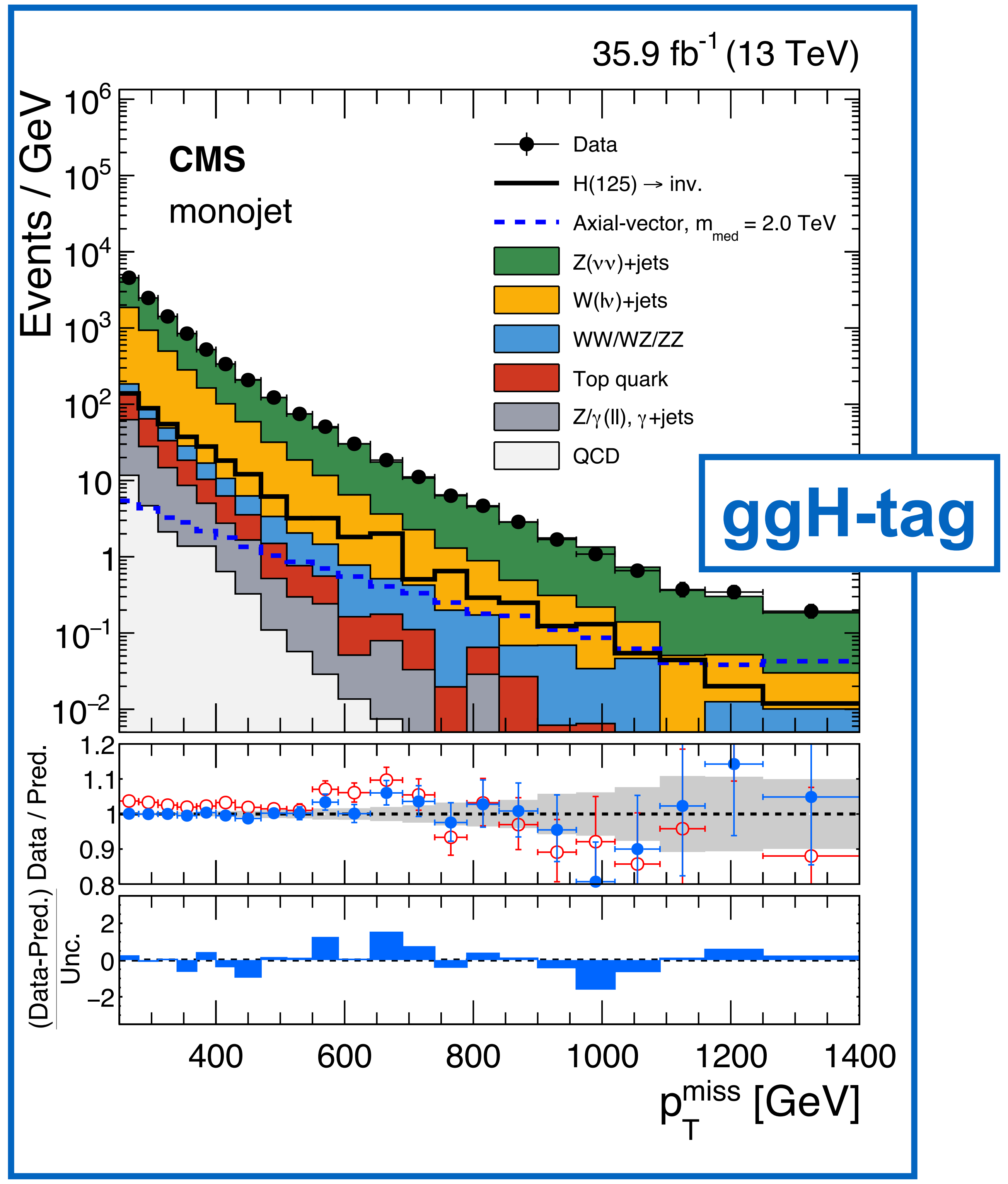
Signature: large p_T^{miss} + high p_T central jet

- Large E_T^{miss} > 250 GeV
- At least one jet p_T > 100 GeV, |η| < 2.4
- Veto leptons and b-tagged jets
- Overlap with VBF and V(qq)H removed

Higgs → inv. signal extraction







- Signal extracted by fitting the m(jj) spectrum
- **Main bkg**: Z(νν)+jets and W+jets from both QCD and EW productions
- **Bkg estimation:** via dedicated control samples i.e. Z(μμ), Z(ee), W(μν) and W(eν)

- Signal extracted by fitting the output of a BDT classifier
- **Main bkg**: ZZ, WZ and residuals from WW and top backgrounds
- **Bkg estimation:** via dedicated control samples i.e. ZZ(4l), WZ(3lν)

- Signal extracted by fitting the p_T^{miss} spectrum
- **Main bkg**: Z(νν)+jets and W+jets
- **Bkg estimation**: via dedicated control samples i.e. Z(μμ), Z(ee), W(μν), W(eν) and γ+jets

Upper limits on BR(H→inv)

CMS-HIG-17-023

exclusion sensitivity

VBF-tag

95% CL limits on BR(H→inv)

Obs (Exp) < 28 (21) %

VH-tag, V → ℓℓ or qq'

95% CL limits on BR(H→inv)

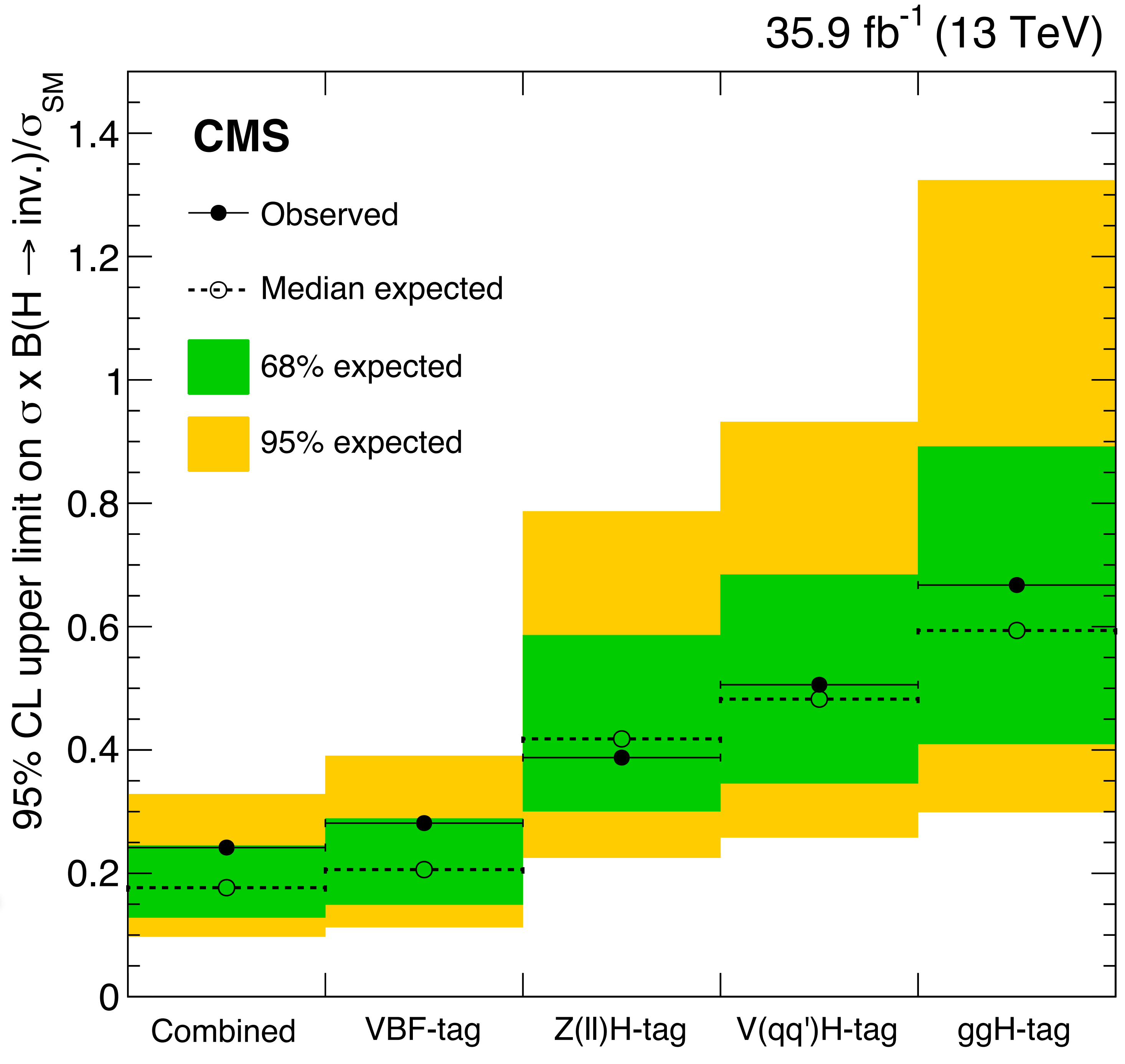
Z(ℓℓ)H → Obs (Exp) < 40 (42) %

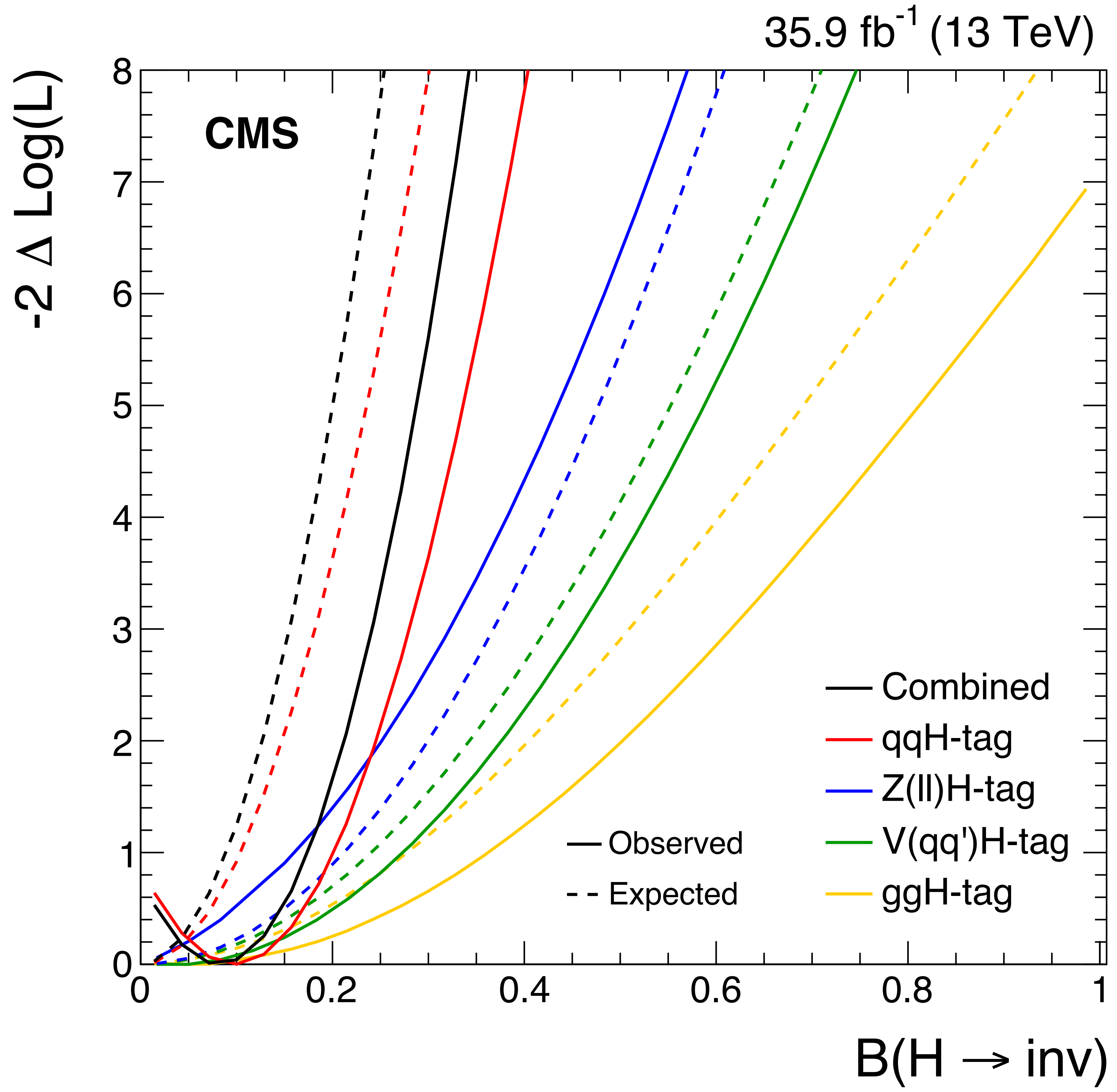
V(qq')H → Obs (Exp) < 50 (48) %

ggH-tag

95% CL limits on BR(H→inv)

Obs (Exp) < 64 (58) %





The observed (exp.) 95% CL limit on BR(H→inv) (assuming SM production rate) is < 0.24 (0.18)

Data are compatible with the SM predictions

From Higgs coupling measurements: BR(H→inv) < 0.22 driven by μ_H = 1.17

Limits still two-order of magnitude weaker than BR(H→ZZ*→4ν)

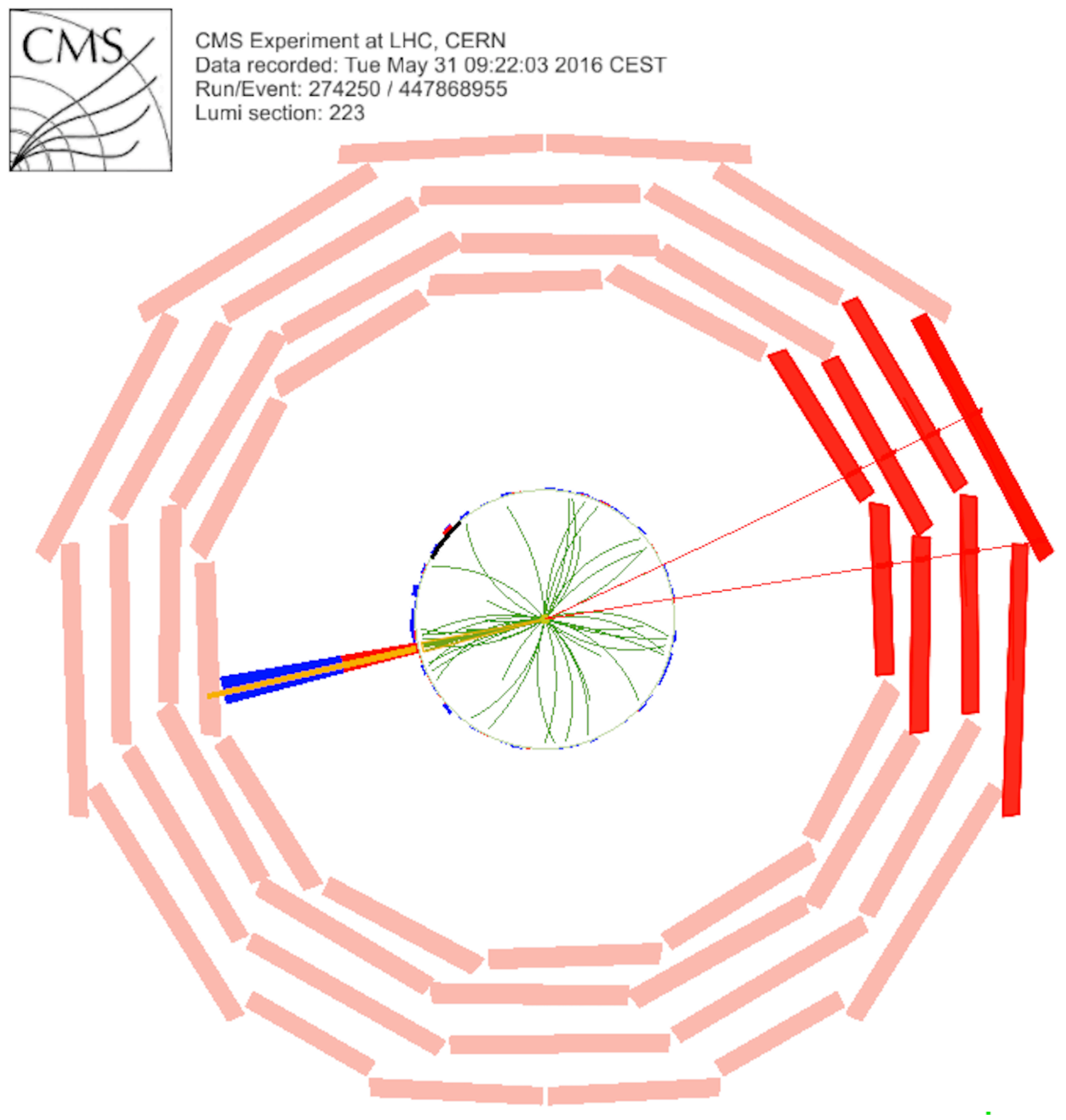
Search for H → $\mu^+\mu^-$

CMS-HIG-17-019

- First channel that will provide evidence for coupling of the Higgs to the 2nd fermion generation

Experimental signature

- **Clean**: two oppositely charged and isolated muons
- Additional jet activity, b-jets and p_T^{miss} used to distinguish between production modes



→

Expected backgrounds

- $Z/\gamma^* \to \mu\mu$
- ZZ, WZ and WW
- ttbar and single-top

→

Why is challenging?

- SM backgrounds are very large in cross section compared to the signal
- S/B around 0.01 @ 125 GeV

Analysis strategy

- Signal extracted by fitting the $m_{\mu\mu}$ spectrum → tiny peak above a falling background
- ***To increase S/B:***
  - Exploit at best kinematic differences between S and B
  - Exploit at best the evolution of the $m_{\mu\mu}$ resolution in the detector

Event classification

CMS-HIG-17-019

Events are first categorized according to kinematic properties:

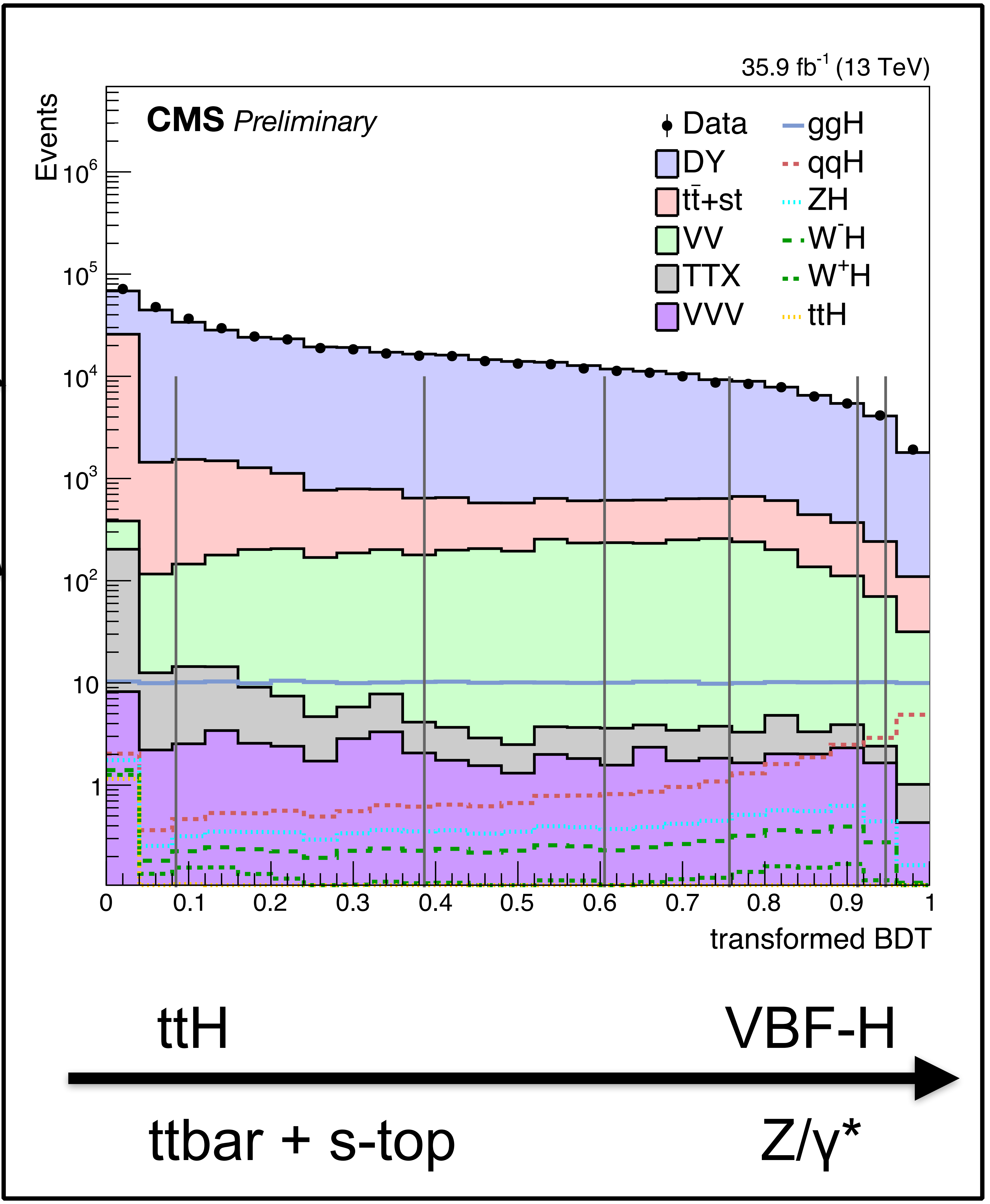
BDT discriminant

- **Input observables mostly uncorrelated with $m_{\mu\mu}$**
- Di-muon system: p_T, $\Delta\eta$, $\Delta\varphi$ → **separate ggH vs Z/γ***
- If at least two jets: **$\Delta\eta(jj)$** and **m_{jj}** → **VBF-tag**
- Other properties: N_{jets}, N_{bjets}, p_T^{miss} → **suppress top bkg**

7-BDT categories used to **distinguish** between **production modes** → **VBF** is the **most sensitive category**

BDT categories are further breakdown according to the η of the forward muon to gauge the peak resolution

- Muon p_T resolution mostly evolve with η
- 3 η-regions: $|\eta| < 0.9$, $0.9 < |\eta| < 1.9$ and $1.9 < |\eta| < 2.4$

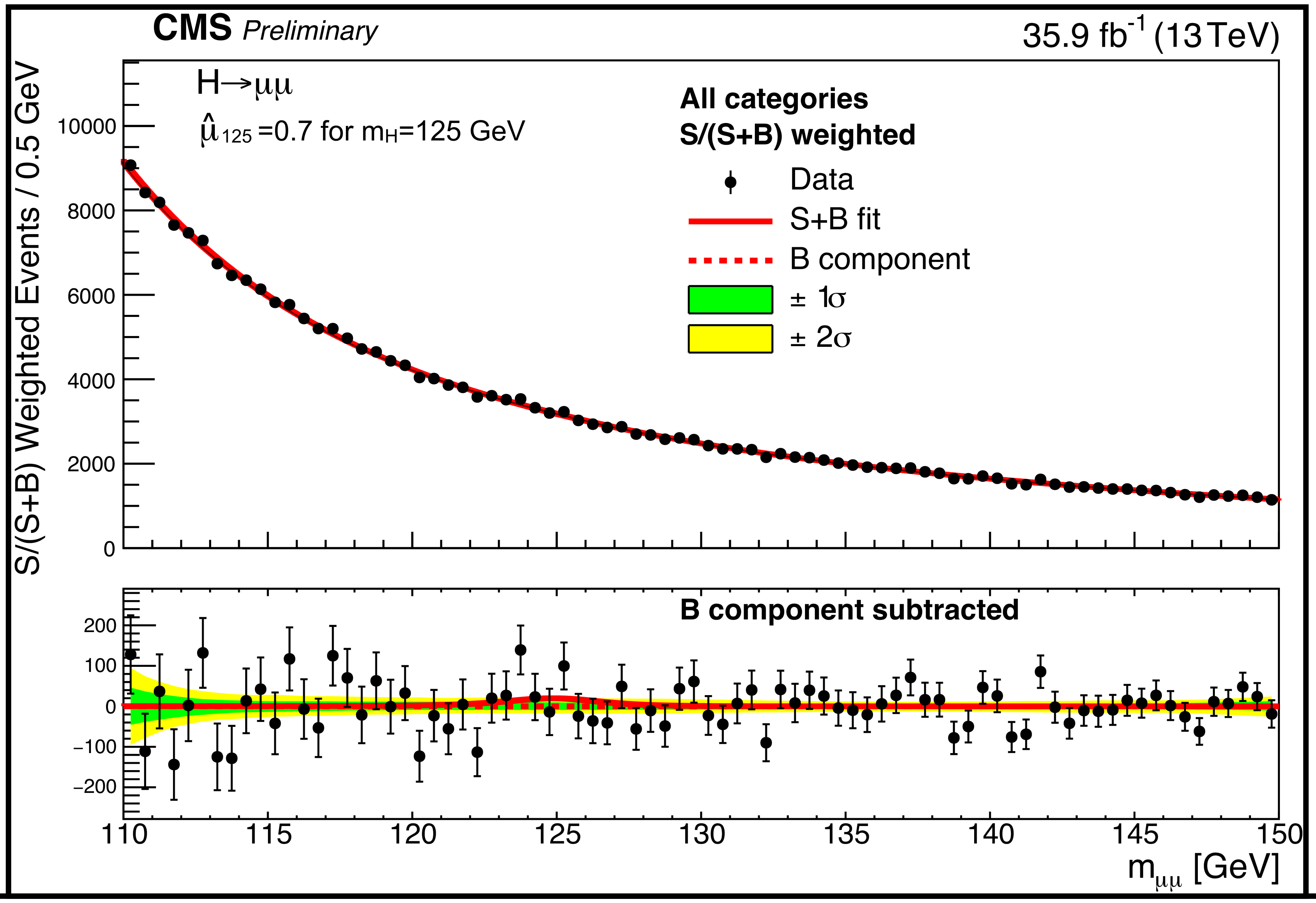


Upper limits on BR(H→μμ)

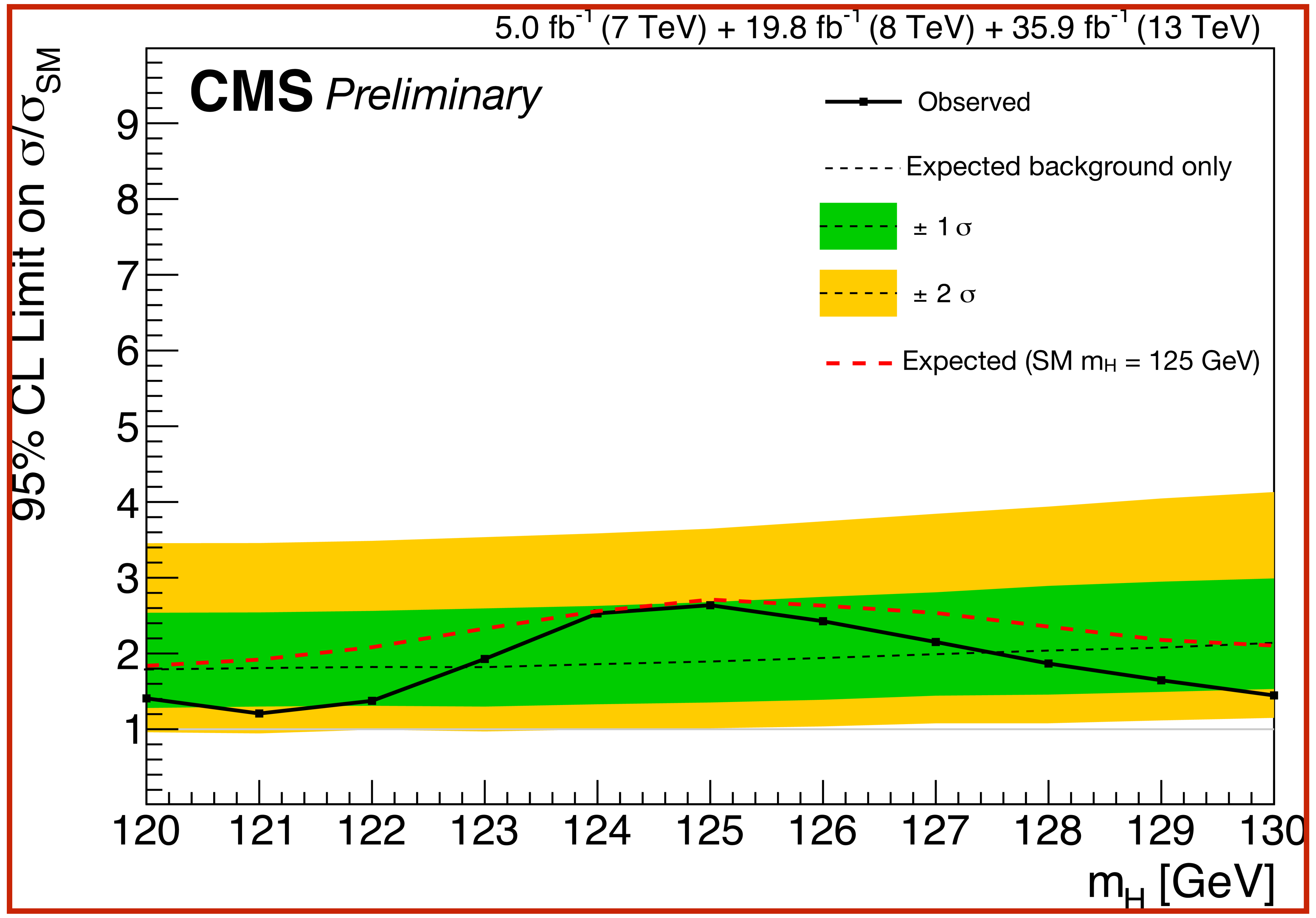
CMS-HIG-17-019

In each of the 15 event categories

- ***Signal is extracted by fitting the $m_{\mu\mu}$ spectrum***
- Background fit functions vary per-category
- ***True form for the background is unknown***
- Functional form chosen in each category to minimise the bias on the signal strength



- No significant excess observed
- Combination of 7+8+13 TeV analyses performed



Obs. (Exp.) 95% CL limit on B(H→μμ) (assuming SM) is < 5.7 (5.1) x 10^{-4}, 2.6 (1.9) x SM

Higgs → Zγ, γ*γ

arXiv:1806.05996, submitted to JHEP

- ***H* → *Zγ*** decays are very **similar** to ***H* → *γγ*** ones: BR(H → Zγ) = 0.15%, BR(H → γγ) = 0.22%
- ***Motivation:*** these rare decays can probe coupling to BSM particles in loops

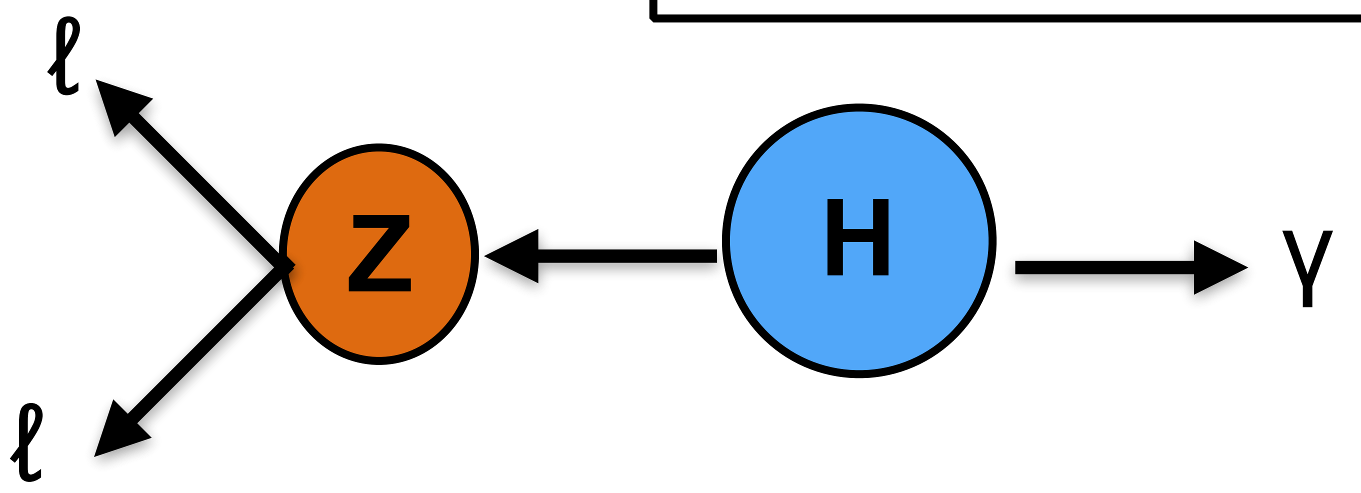
Search performed *in* ***leptonic channels*** → ***μμγ*** or ***eeγ*** final states

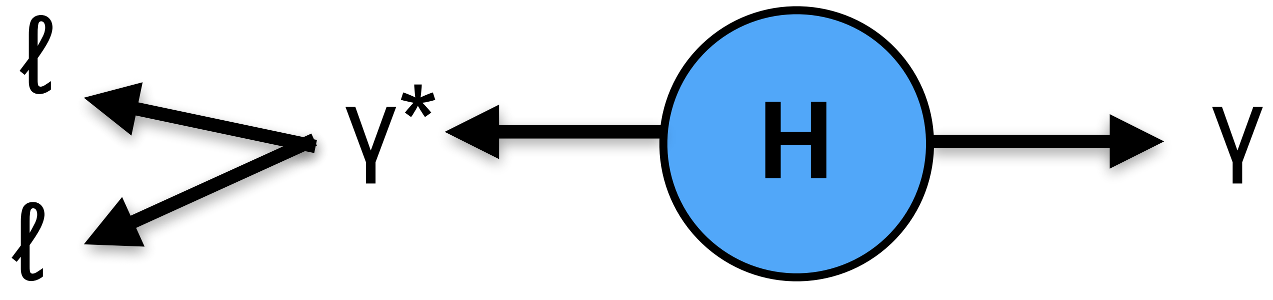
Contribution from ***H* → *γ*γ*** is ***irreducible*** and ***interfere*** *with* ***H→Zγ***

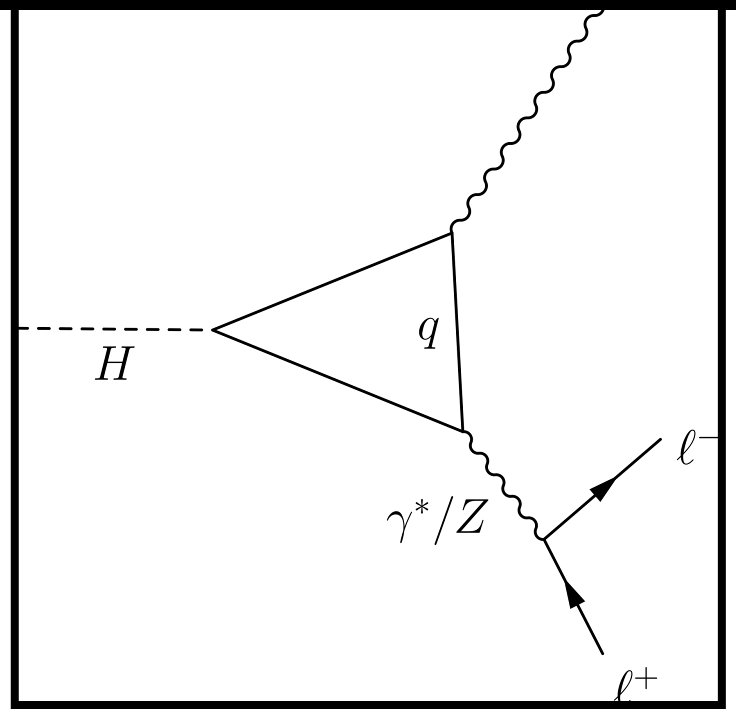
Separated via m(ℓℓ) selection
H → Zγ → ℓℓγ for m(ℓℓ) > 50 GeV
H → γ*γ → ℓℓγ for m(ℓℓ) < 50 GeV

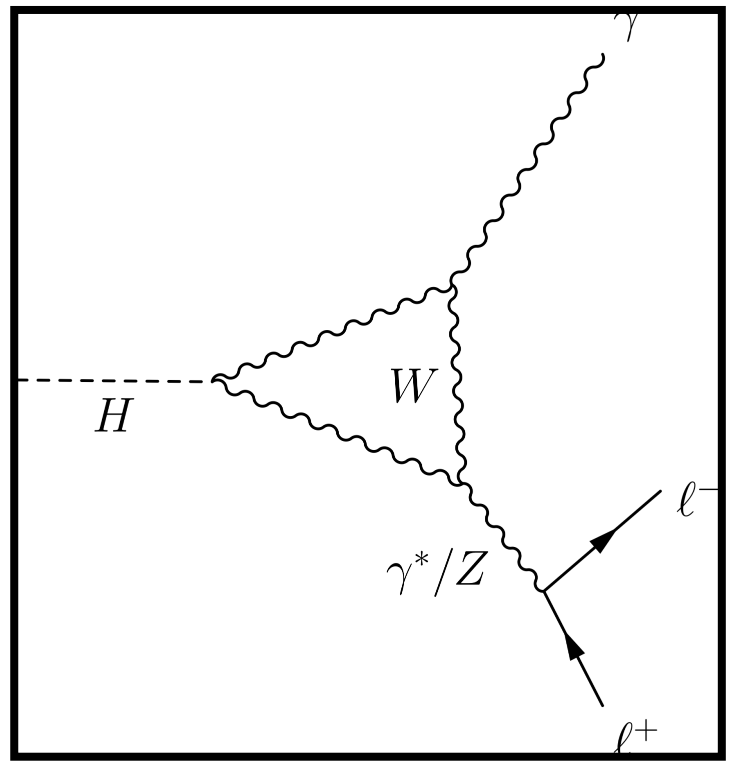
At low m(ℓℓ) only μμγ channel considered because decay products are collimated

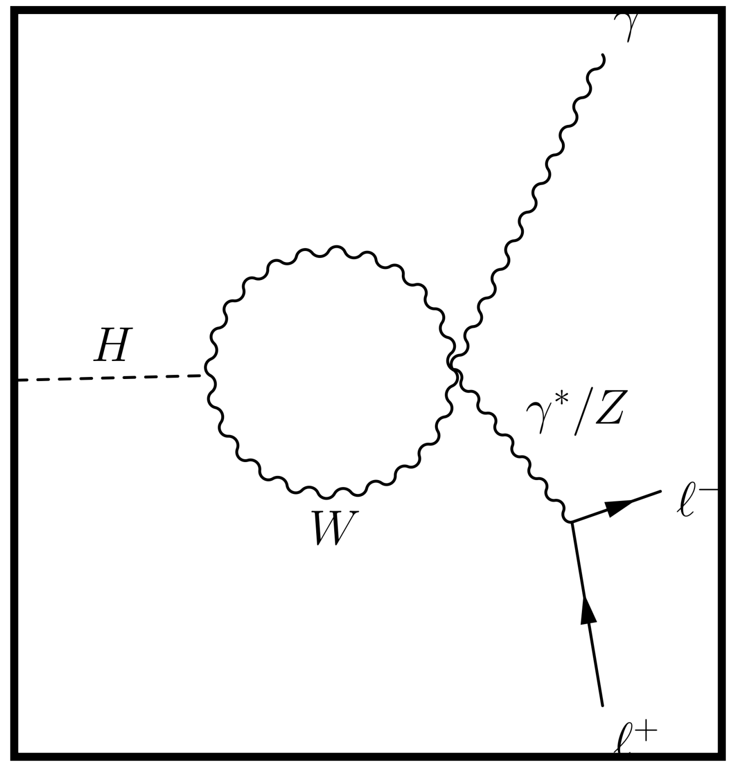
Both J/ψ and Υ regions are excluded











- ***Analysis strategy:*** signal extracted by fitting the m(ℓℓγ) spectrum → tiny peak above a falling background

Event selection

arXiv:1806.05996, submitted to JHEP

- Events classified to distinguish between production modes and to follow the evolution of the peak resolution

$H \to \gamma^*\gamma \to \ell\ell\gamma$ for $m(\ell\ell) < 50$ GeV

- ***VBF category:*** $N_{jets} \geq 2$, $\Delta\eta_{jj} > 3.5$, $m_{jj} > 500$ GeV, $\Delta\phi(jj, \ell\ell\gamma) > 2.4$
- ***Untagged categories:*** defined according to the photon energy resolution evolution

H_{125} acceptance x efficiency ~ 26%

$H \to Z\gamma \to \ell\ell\gamma$ for $m(\ell\ell) > 50$ GeV

- ***VH categories:*** additional leptons to target leptonic decays of W or Z boson
- ***VBF category:*** $N_{jets} \geq 2$, $\Delta\eta_{jj} > 3.5$, $m_{jj} > 500$ GeV, $\Delta\phi(jj, \ell\ell\gamma) > 2.4$, no additional leptons
- ***Boosted category:*** $p_T(\ell\ell\gamma) > 60$ GeV
- ***Untagged categories:*** defined according to the evolution of the photon, muon and electron energy resolution

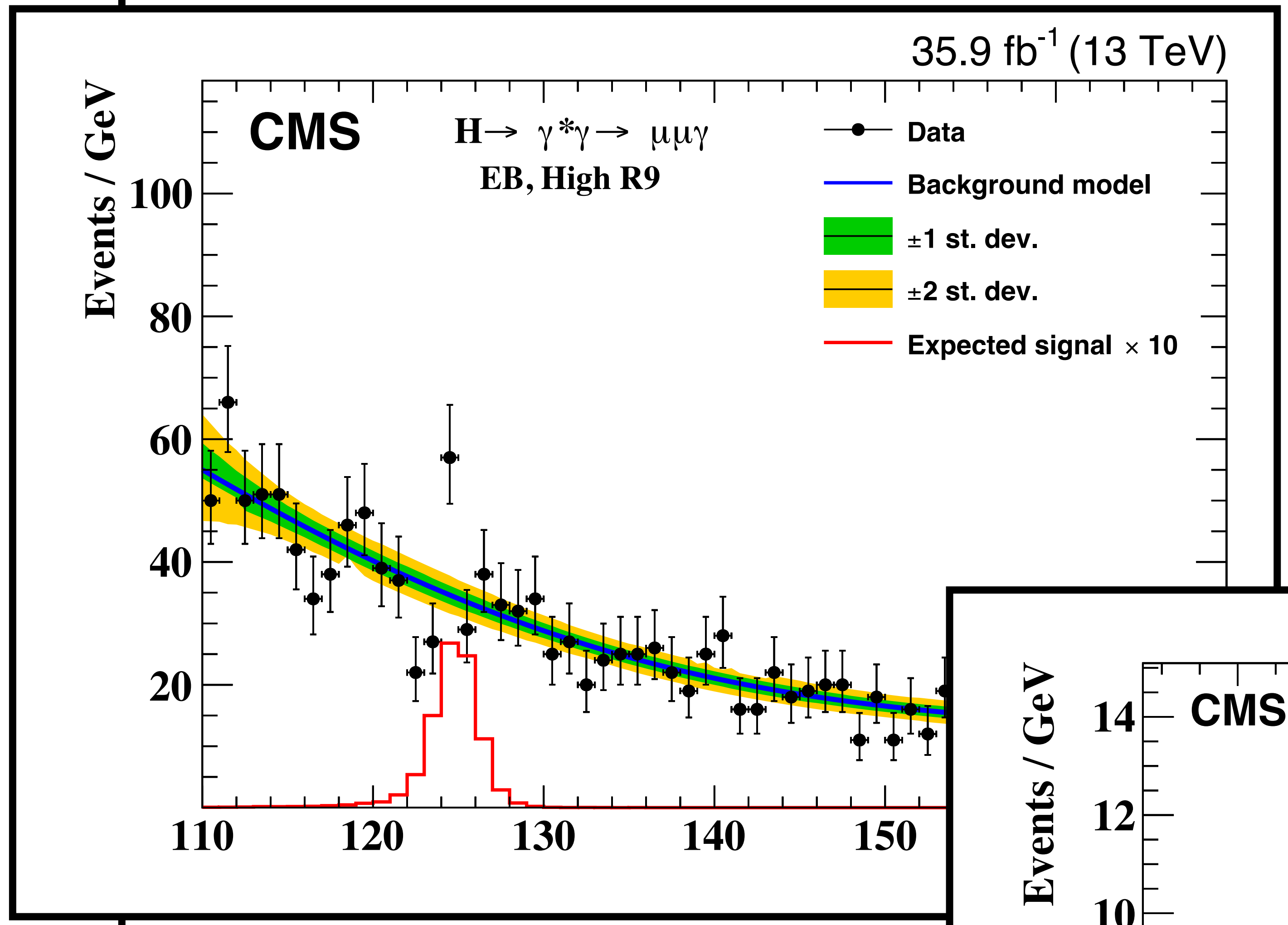
H_{125} acceptance x efficiency 22-29%

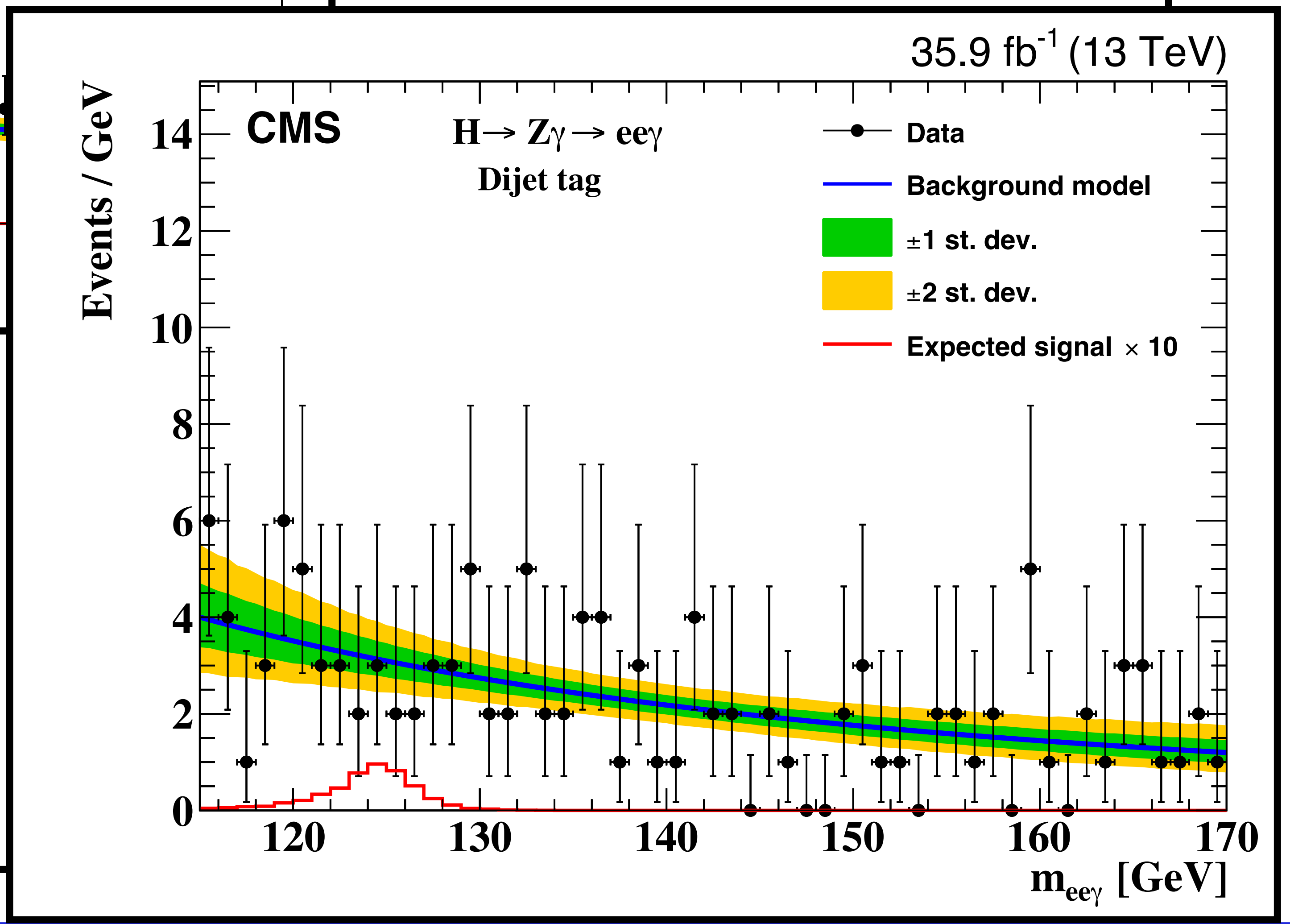
Gain in sensitivity from categorisation ~ 18%

Upper limits on BR(H→ℓℓγ)

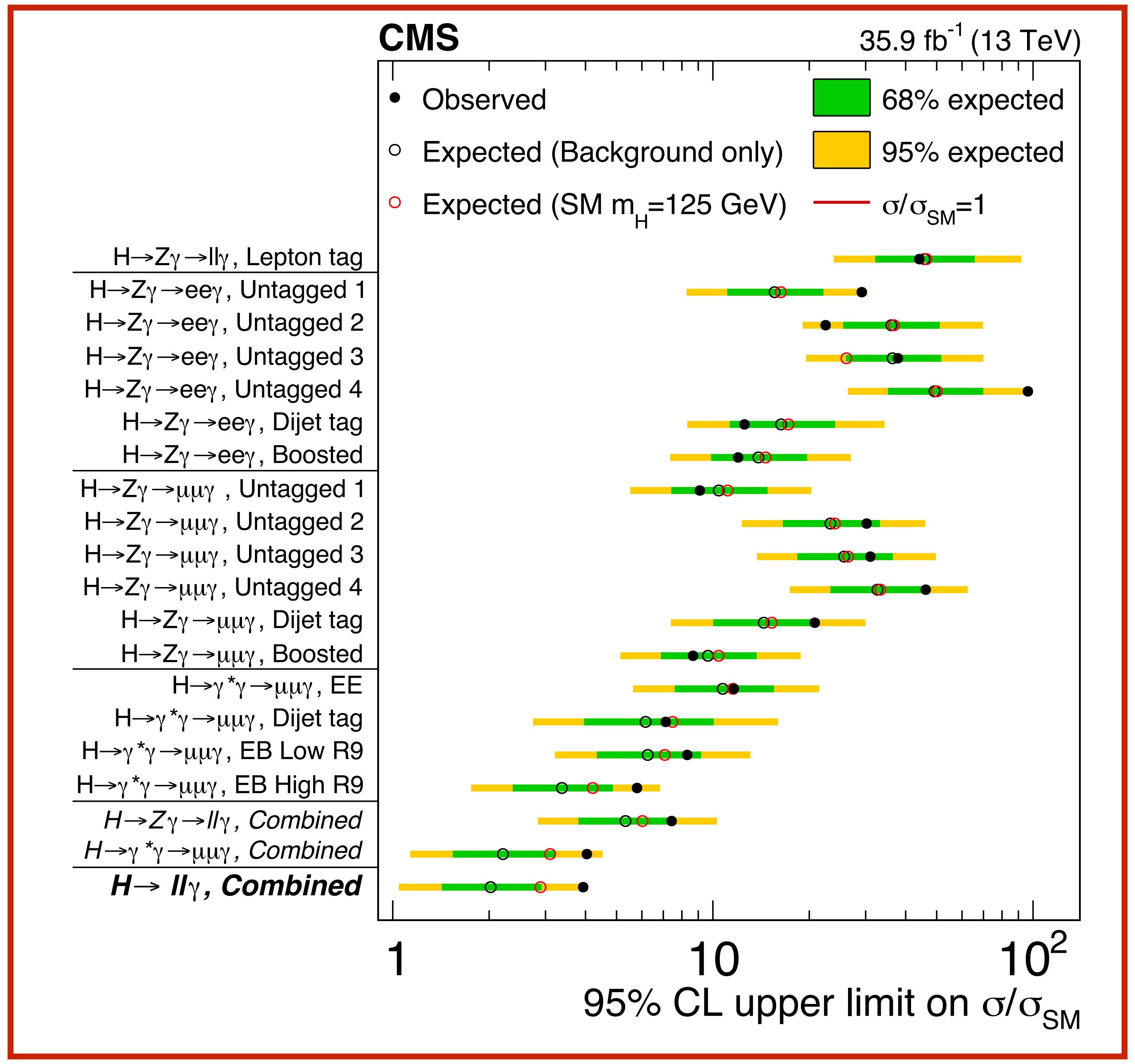
arXiv:1806.05996, submitted to JHEP

- ***Signal is extracted by fitting the $m_{\ell\ell\gamma}$ spectrum***
- Background fit functions vary per-category
- ***True form for the background is unknown***
- Functional form chosen to minimise the bias on the signal strength





- No significant deviations from b-only expectation
- Results obtained assuming m_H = 125 GeV



Obs. (Exp.) 95% CL limit

BR(H → Zγ → ℓℓγ) < 8.0 (5.8) x SM

BR(H → γ*γ → ℓℓγ) < 4.0 (2.2) x SM

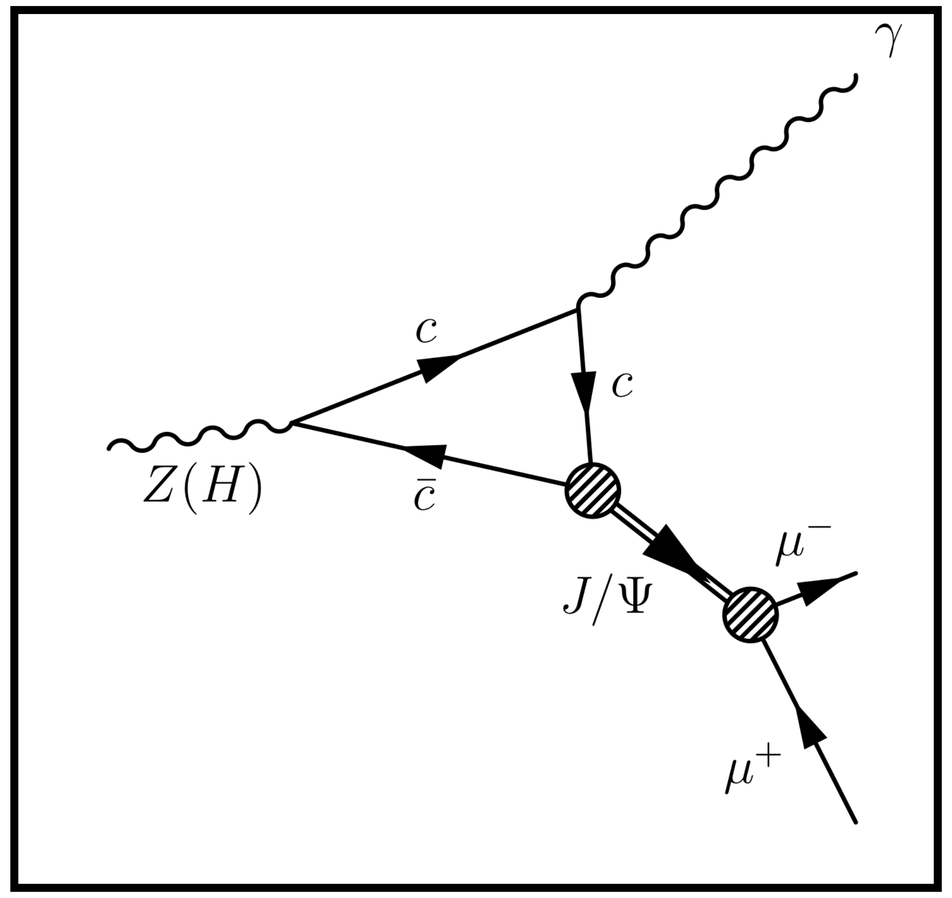
Higgs → $J/\psi\gamma$

CMS-SMP-17-012

NEW

- ***Motivation:*** search for H → $J/\psi\gamma$ decays used to couplings to the second generation of quarks

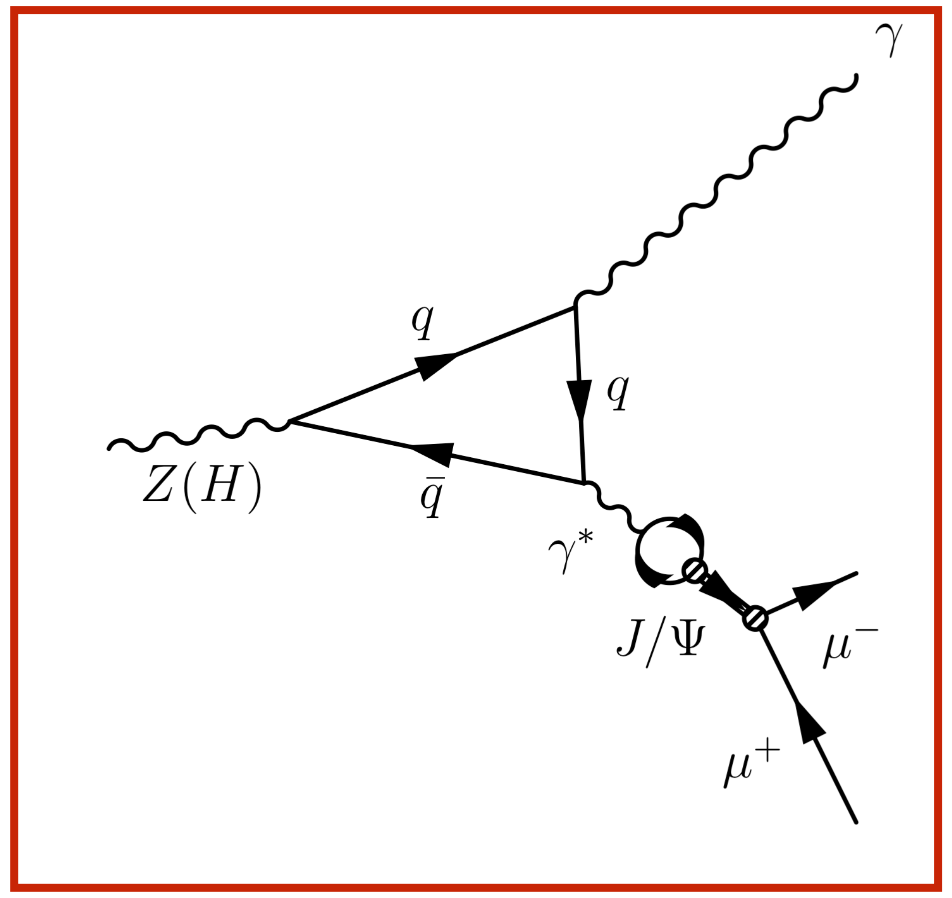
Direct mechanism: Higgs coupled to c-quarks



interference

$$\mathcal{B}_{SM}(\mathrm{H} \to \mathrm{J}/\psi\ \gamma) = (3.0^{+0.2}_{-0.2}) \times 10^{-6}$$

Indirect mechanism: J/ψ produced by γ^* conversion



- **Cons:** very small decay rate → few signal events expected given Run-II statistics
- **Pros:** looking at $J/\psi \to \mu\mu$ provides clean signature w.r.t. searches for H → cc

Complementary with "standard" H→cc searches

- **Main backgrounds:** $Z/\gamma^* \to \mu\mu\gamma$ and $H \to \gamma^*\gamma \to \mu\mu\gamma$

NEW

Analysis strategy and results

CMS-SMP-17-012

- ***Selections:*** $\Delta R(\mu,\gamma) > 1$, $\Delta R(\mu\mu,\gamma) > 2$, $|\Delta\phi(\mu\mu,\gamma)| > 1.5$ and **$3.0 < m(\mu\mu) < 3.2$ GeV**
- ***Analysis strategy:*** despite the m(μμ) requirement, very similar to those of the $H\to\gamma^*\gamma\to\mu\mu\gamma$ search

Event classification

Very low signal rate → production-mode or resolution based categories are not introduced

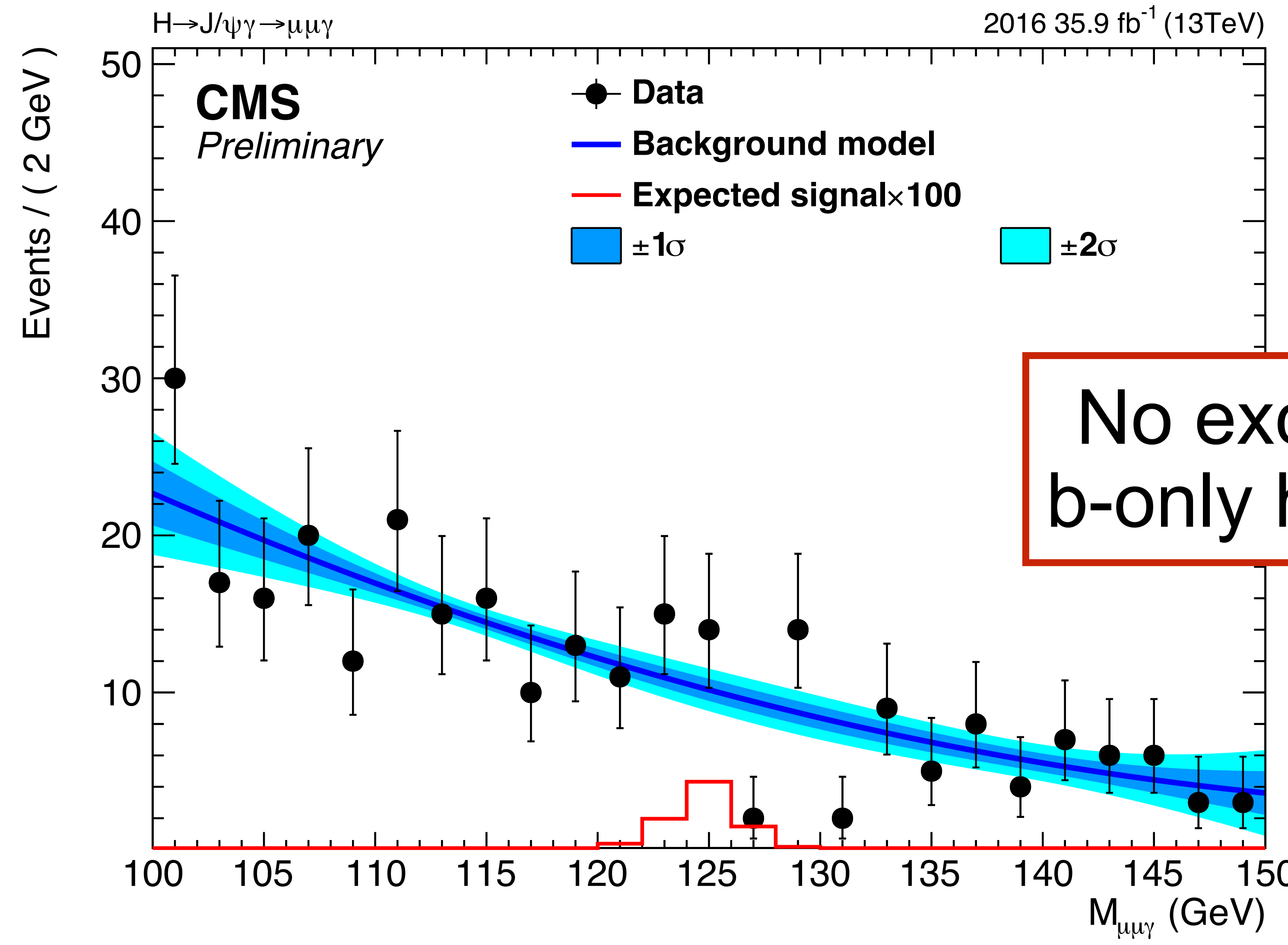
H_{125} acceptance x efficiency ~ 22%

Decay	Category Production	Data	Signal	Background
$H\to J/\psi\,\gamma$	ggF	279	7.1×10^{-2}	0.2
	VBF		3.5×10^{-3}	9.4×10^{-3}
	ZH		7.1×10^{-4}	2.3×10^{-3}
	W^+H		6.0×10^{-4}	1.0×10^{-3}
	W^-H		4.5×10^{-4}	1.3×10^{-3}
	ttH		2.7×10^{-4}	1.3×10^{-3}

Background refers to only $H\to\gamma^*\gamma\to\mu\mu\gamma$ contribution

Signal is extracted by fitting the $m_{\ell\ell\gamma}$ distribution

- Bernstein polynomial used to model the continuum bkg



No excess w.r.t. b-only hypothesis

Obs. (Exp.) limit from 13 + 8 TeV combination

$B(H\to J/\psi\gamma) <$ 220 (160) x SM

Summary

- Extensive, on-going program at CMS searching for Higgs rare decays:
  - Probing couplings of the Higgs boson to 2nd generation of leptons and quarks
  - Searching for couplings of the Higgs boson to invisible particles
  - Searching for sign of BSM physics in loops (Z/γ and J/ψγ decays)

No significant deviations from SM predictions observed

$H \rightarrow$ invisible

- VBF H_{inv} is the most sensitive channel
- Upper limits aligned with Run-I sensitivity
- ***$BR(H_{inv}) < 24\%\ (18\%)$***

$H \rightarrow \mu\mu$

- Approaching SM sensitivity, which should be reached by end of Run-II
- ***$BR(H_{\mu\mu}) < 2.6\ (1.9)$ x SM***

$H \rightarrow Z\gamma$ $H \rightarrow J/\psi\ \gamma$

- Sensitivity far from SM predictions, wont' be reached with Run-II data
- ***$BR(H_{Z\gamma}) < 8.0\ (5.8)$ x SM***
- ***$BR(H_{J/\psi\gamma}) < 220\ (160)$ x SM***

Backup slides

LFV in Higgs decays

JHEP 06 (2018) 001

- Search for lepton-flavour-violation in Higgs decays in the $e\tau$, $\mu\tau$ channels
- Physics scenarios for LFV decays: composite Higgs, supers-symmetry, RS models, 2HDM ..etc..

- BR of τ-lepton to muons and electrons may be modified if LFV Higgs decays are predicted
  - Present τ-lepton decays measurements provide bounds on $B(H\to\mu\tau)$ and $B(H\to e\tau)$ to be < 10%
  - $H\to\mu e$ not interesting because constrained by $BR(\mu\to e\gamma)$ to be $< 10^{-9}$

- **Final states explored:** $H\to\mu\tau_h$, $H\to e\tau_h$, $H\to\mu\tau_e$ and $H\to e\tau_\mu$. Same flavour lepton final-states are overwhelmed by Z+jets
- **Event classification:** according to the number of jets to distinguish between production modes

0-jet category | ***1-jet category*** | ***2-jet category m(jj) < 550 GeV*** | ***2-jet category m(jj) > 550 GeV***

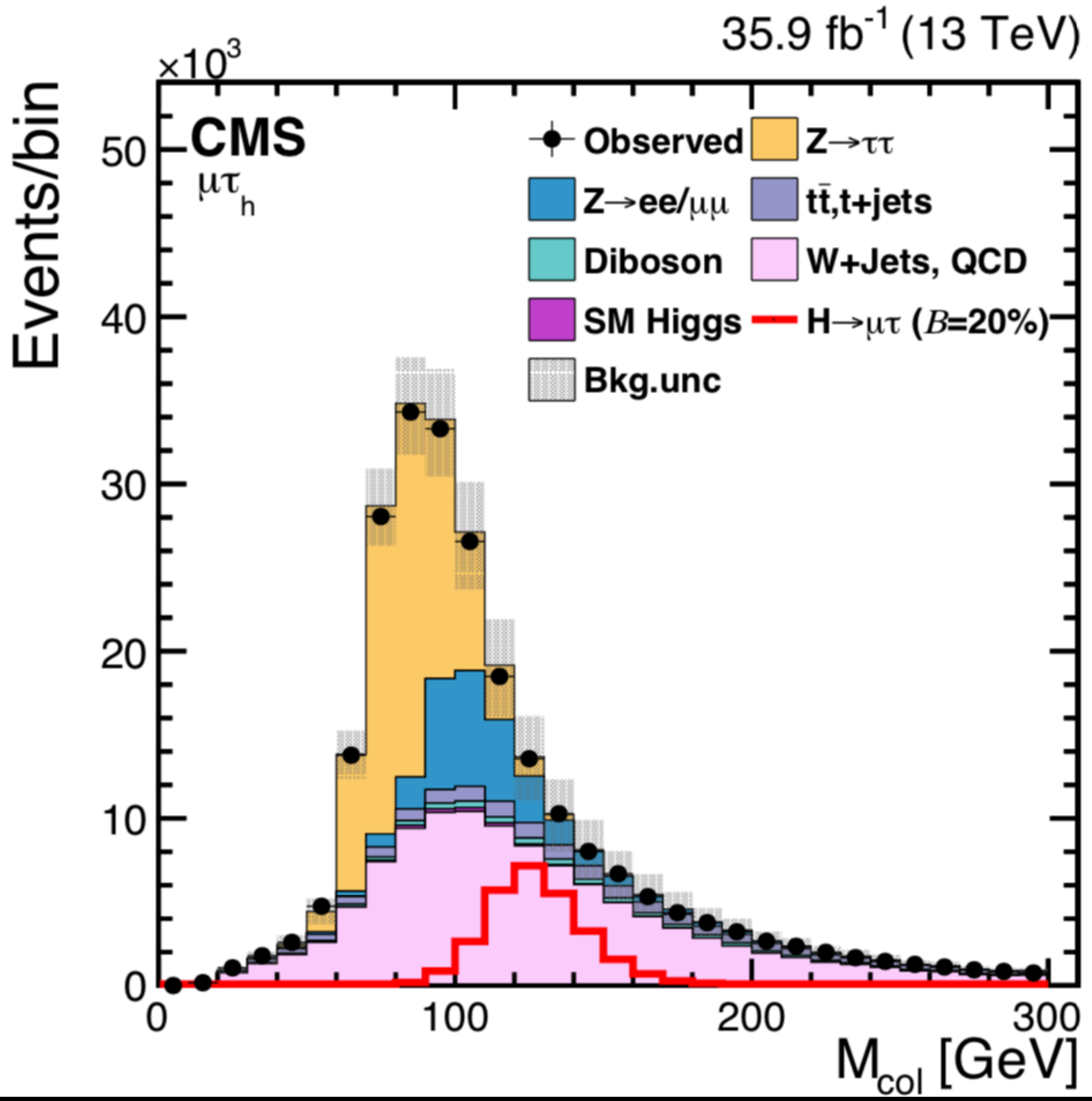
Signal extraction: fit a BDT discriminant in each category trained to maximise the separation between signal and backgrounds. The BDT includes also the collinear mass

Higgs LFV: final states

JHEP 06 (2018) 001

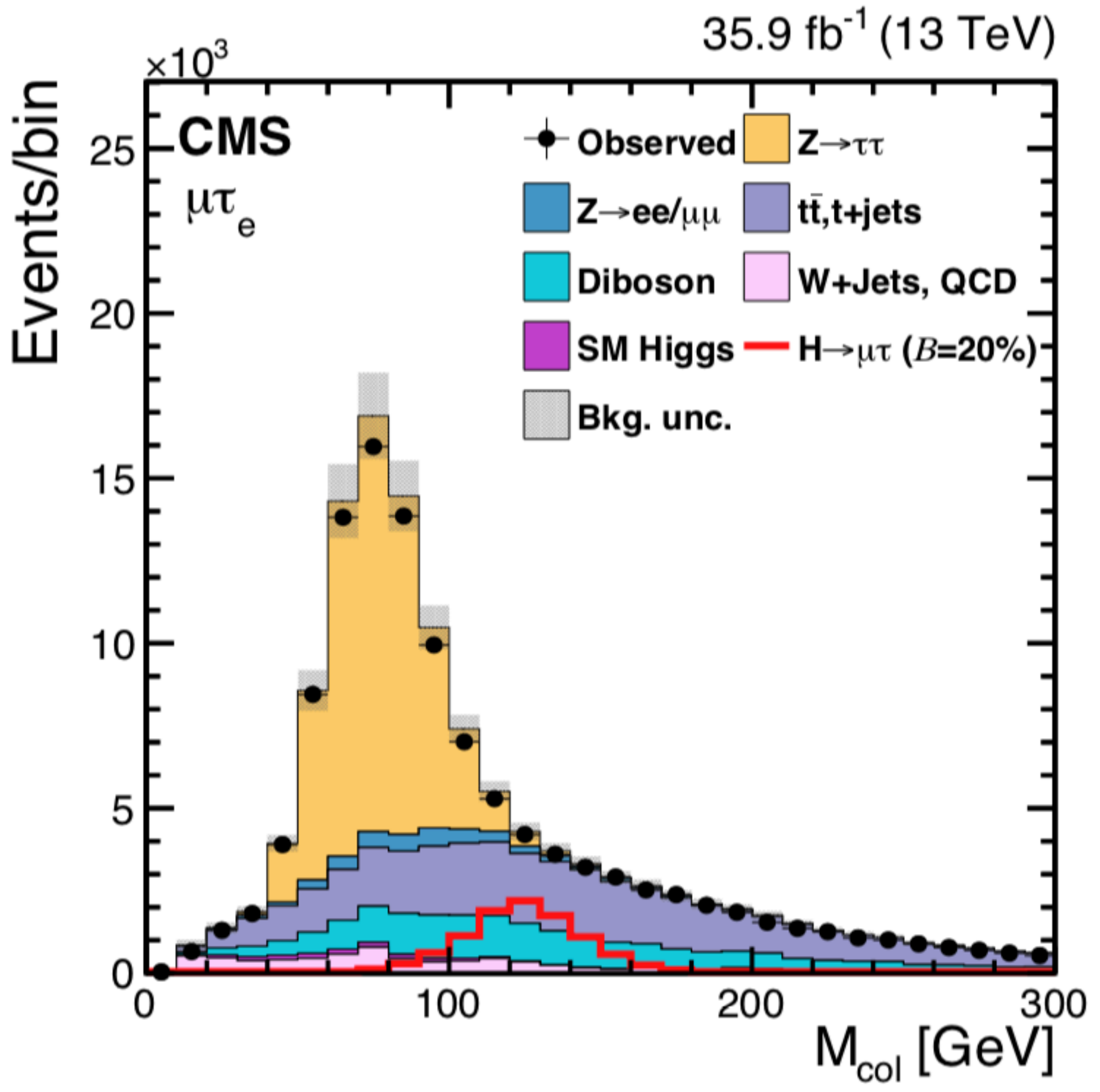
$H \rightarrow \mu\tau_h$

Main bkgs: Z($\tau\tau$) as well as W+jets and Z($\ell\ell$) where a jet is mis-identified as a τ_h



$H \rightarrow \mu\tau_e$

Main bkgs: Z(ττ) and top backgrounds



$H \rightarrow e\tau_h$

Main bkgs: Z(ττ) as well as W+jets and Z($\ell\ell$) where a jet is mis-identified as a τ_h

$H \rightarrow e\tau_\mu$

Main bkgs: Z(ττ) and top backgrounds

Higgs LFV: uncertainties

JHEP 06 (2018) 001

Systematic uncertainty	$H \to \mu\tau_h$	$H \to \mu\tau_e$	$H \to e\tau_h$	$H \to e\tau_\mu$
Muon trigger/identification/isolation	2%	2%	—	2%
Electron trigger/identification/isolation	—	2%	2%	2%
Hadronic tau lepton efficiency	5%	—	5%	—
b tagging veto	2.0–4.5%	2.0–4.5%	—	2.0–4.5%
$Z \to \mu\mu$, ee + jets background	—	10%⊕5%	—	10%⊕5%
$Z \to \tau\tau$ + jets background	10%⊕5%	10%⊕5%	10%⊕5%	10%⊕5%
W + jets background	—	10%	—	10%
QCD multijet background	—	30%	—	30%
WW, ZZ background	5%⊕5%	5%⊕5%	5%⊕5%	5%⊕5%
$t\bar{t}$ background	10%⊕5%	10%⊕5%	10%⊕5%	10%⊕5%
$W\gamma$ background	—	10%⊕5%	—	10%⊕5%
Single top quark background	5%⊕5%	5%⊕5%	5%⊕5%	5%⊕5%
$\mu \to \tau_h$ background	25%	—	—	—
$e \to \tau_h$ background	—	—	12%	—
Jet $\to \tau_h, \mu, e$ background	30%⊕10%	—	30%⊕10%	—
Jet energy scale	3–20%	3–20%	3-20%	3–20%
τ_h energy scale	1.2%	—	1.2%	—
$\mu, e \to \tau_h$ energy scale	1.5%	—	3%	—
e energy scale	—	0.1 – 0.5%	0.1 – 0.5%	0.1 – 0.5%
μ energy scale	0.2%	0.2%	—	0.2%
Unclustered energy scale	$\pm1\sigma$	$\pm1\sigma$	$\pm1\sigma$	$\pm1\sigma$
Renorm./fact. scales (ggH) [?]	3.9%			
Renorm./fact. scales (VBF and VH) [?]	0.4%			
PDF + α_s (ggH) [?]	3.2%			
PDF + α_s (VBF and VH) [?]	2.1%			
Renorm./fact. acceptance (ggH)	−3.0% – +2.0%			
Renorm./fact. acceptance (VBF and VH)	−0.3% – +1.0%			
PDF + α_s acceptance (ggH)	−1.5% – +0.5%			
PDF + α_s acceptance (VBF and VH)	−1.5% – +1.0%			
Integrated luminosity	2.5%			

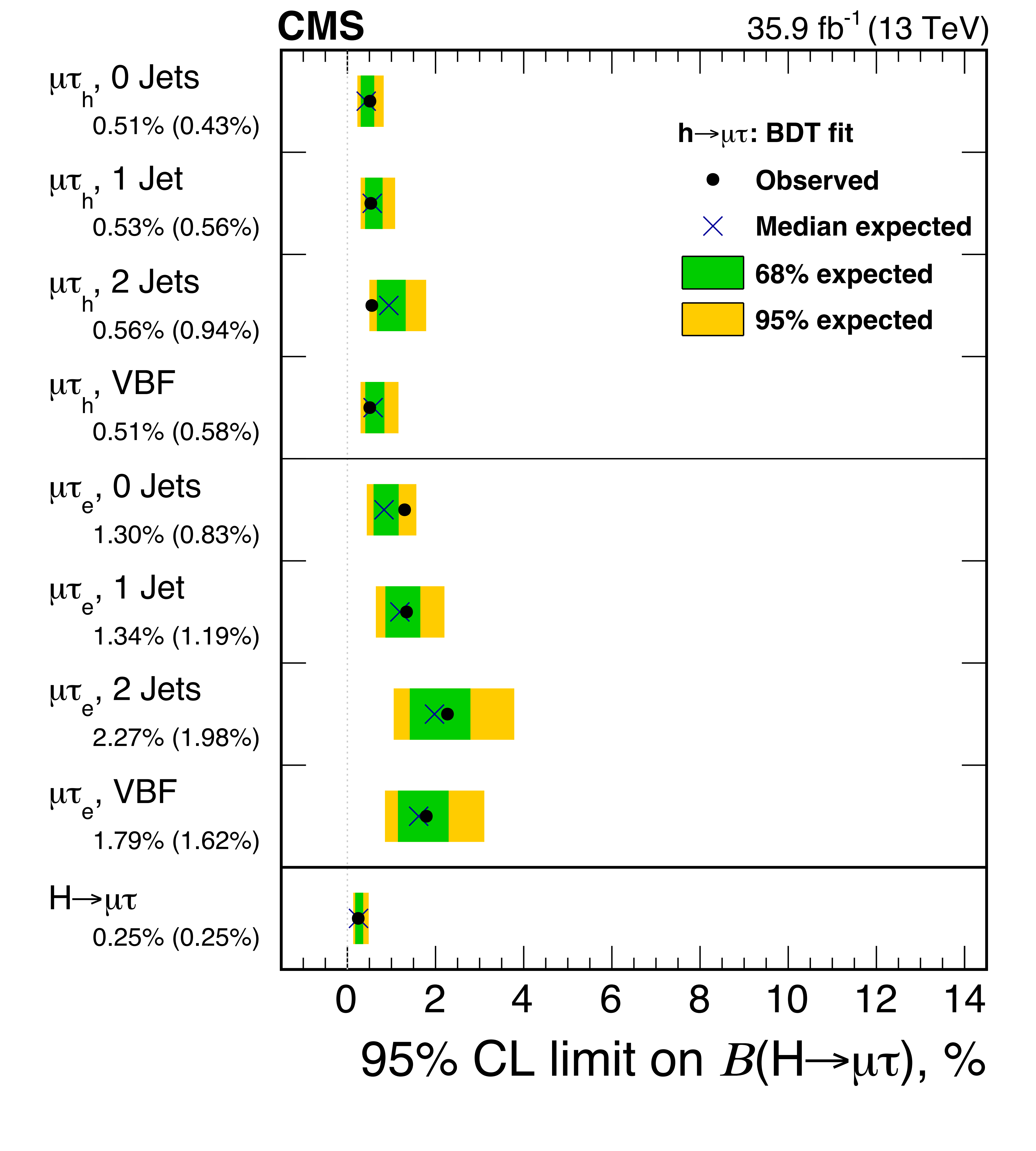
$H \rightarrow \mu\tau_h, \mu\tau_e$ results

JHEP 06 (2018) 001

$H \to \mu\tau_h, \mu\tau_e$ results

JHEP 06 (2018) 001

	Expected limits (%)				
	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	<0.83	<1.19	<1.98	<1.62	<0.59
$\mu\tau_h$	<0.43	<0.56	<0.94	<0.58	<0.29
$\mu\tau$			<0.25		
	Observed limits (%)				
	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	<1.30	<1.34	<2.27	<1.79	<0.86
$\mu\tau_h$	<0.51	<0.53	<0.56	<0.51	<0.27
$\mu\tau$			<0.25		
	Best fit branching fractions (%)				
	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	0.61 ± 0.36	0.22 ± 0.46	0.39 ± 0.83	0.10 ± 1.37	0.35 ± 0.26
$\mu\tau_h$	0.12 ± 0.20	-0.05 ± 0.25	-0.72 ± 0.43	-0.22 ± 0.31	-0.04 ± 0.14
$\mu\tau$			0.00 ± 0.12		



H → $e\tau_h$, $e\tau_e$ results

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$H \to e\tau_h, e\tau_e$ results

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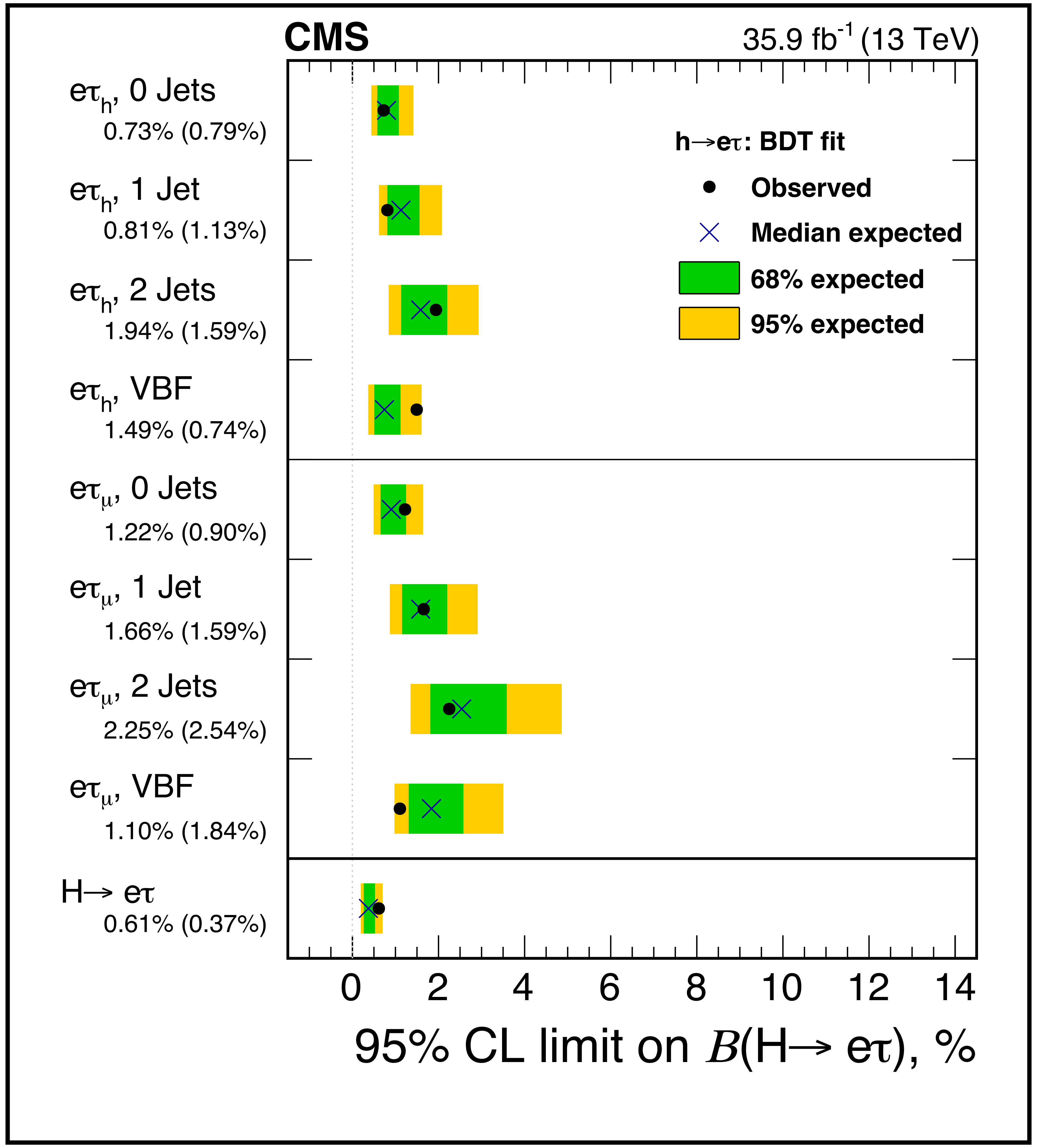
	Expected limits (%)				
	0-jet	1-jet	2-jets	VBF	Combined
$e\tau_\mu$	<0.90	<1.59	<2.54	<1.84	<0.64
$e\tau_h$	<0.79	<1.13	<1.59	<0.74	<0.49
$e\tau$			<0.37		
	Observed limits (%)				
	0-jet	1-jet	2-jets	VBF	Combined
$e\tau_\mu$	<1.22	<1.66	<2.25	<1.10	<0.78
$e\tau_h$	<0.73	<0.81	<1.94	<1.49	<0.72
$e\tau$			<0.61		
	Best fit branching fractions (%)				
	0-jet	1-jet	2-jets	VBF	Combined
$e\tau_\mu$	0.47 ± 0.42	0.17 ± 0.79	−0.42 ± 1.01	−1.54 ± 0.44	0.18 ± 0.32
$e\tau_h$	−0.13 ± 0.39	−0.63 ± 0.40	0.54 ± 0.53	0.70 ± 0.38	0.33 ± 0.24
$e\tau$			0.30 ± 0.18		



Higgs LFV: final result

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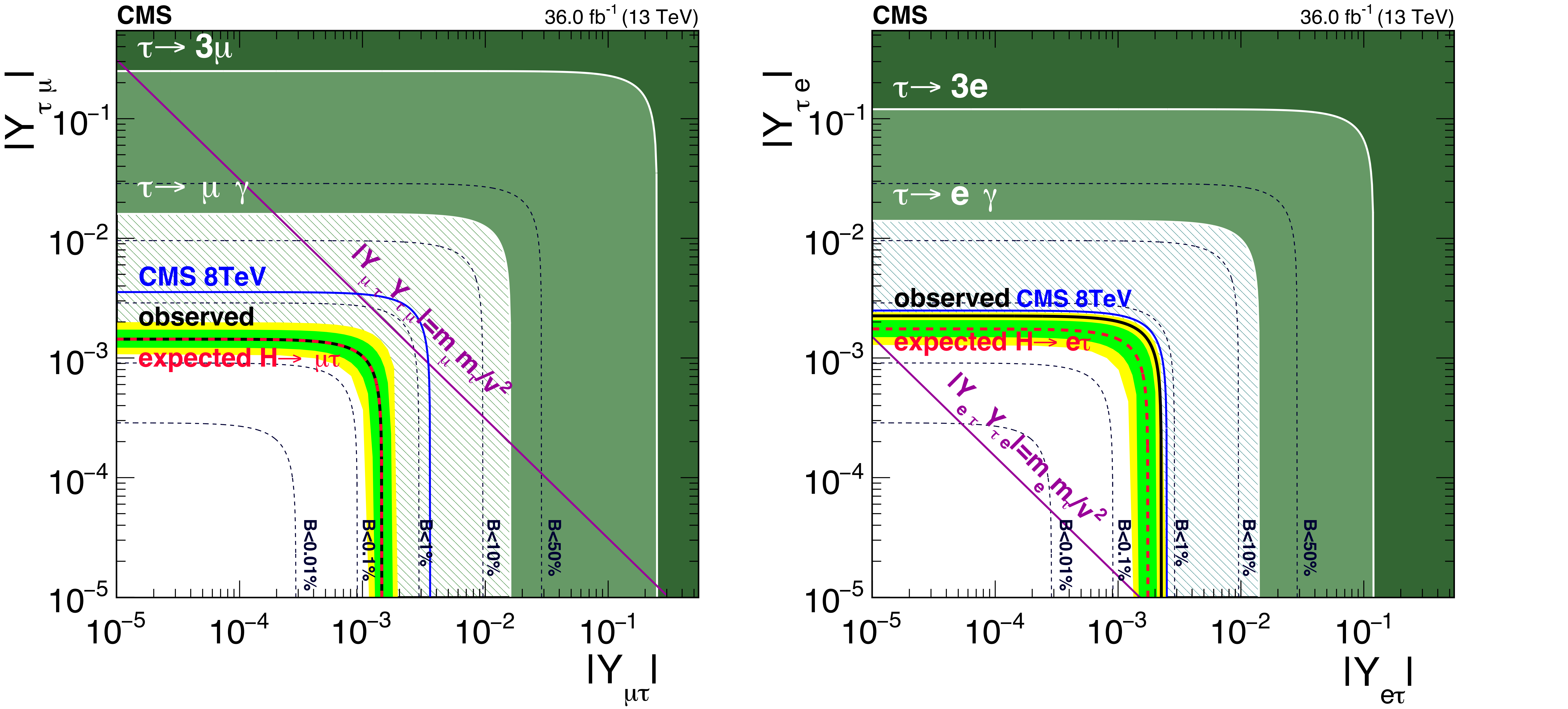
Upper limits on BR(H→μτ) and BR(H→eτ)

	Observed (expected) limits (%)		Best fit branching fraction (%)	
	BDT fit	M_{col} fit	BDT fit	M_{col} fit
$H \to \mu\tau$	<0.25 (0.25)%	<0.51 (0.49) %	0.00 ± 0.12 %	0.02 ± 0.20 %
$H \to e\tau$	<0.61 (0.37) %	<0.72 (0.56) %	0.30 ± 0.18 %	0.23 ± 0.24 %

Translation on sounds for LFV Yukawa couplings

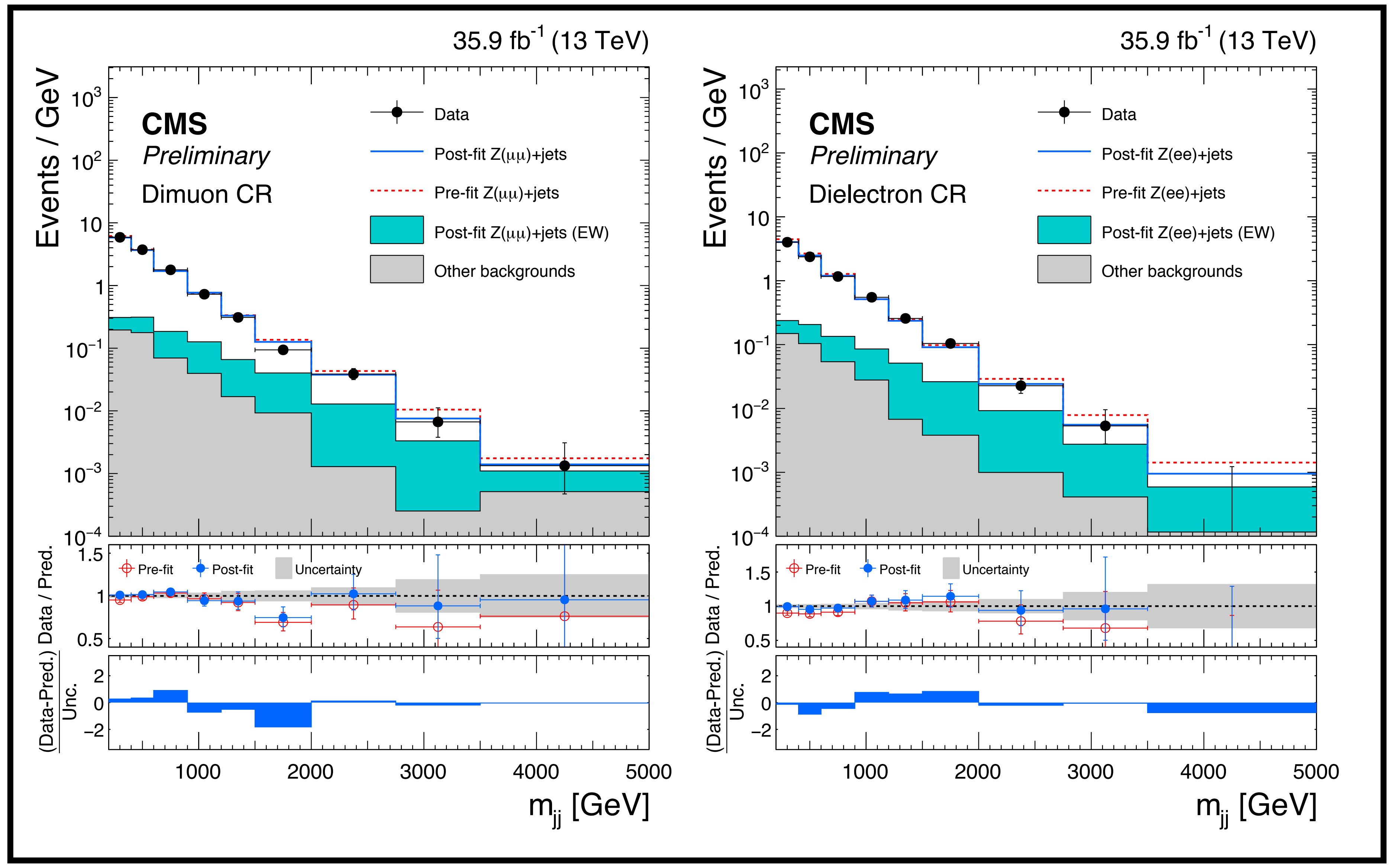
	BDT fit	M_{col} fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 1.43 \times 10^{-3}$	$< 2.05 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.26 \times 10^{-3}$	$< 2.45 \times 10^{-3}$

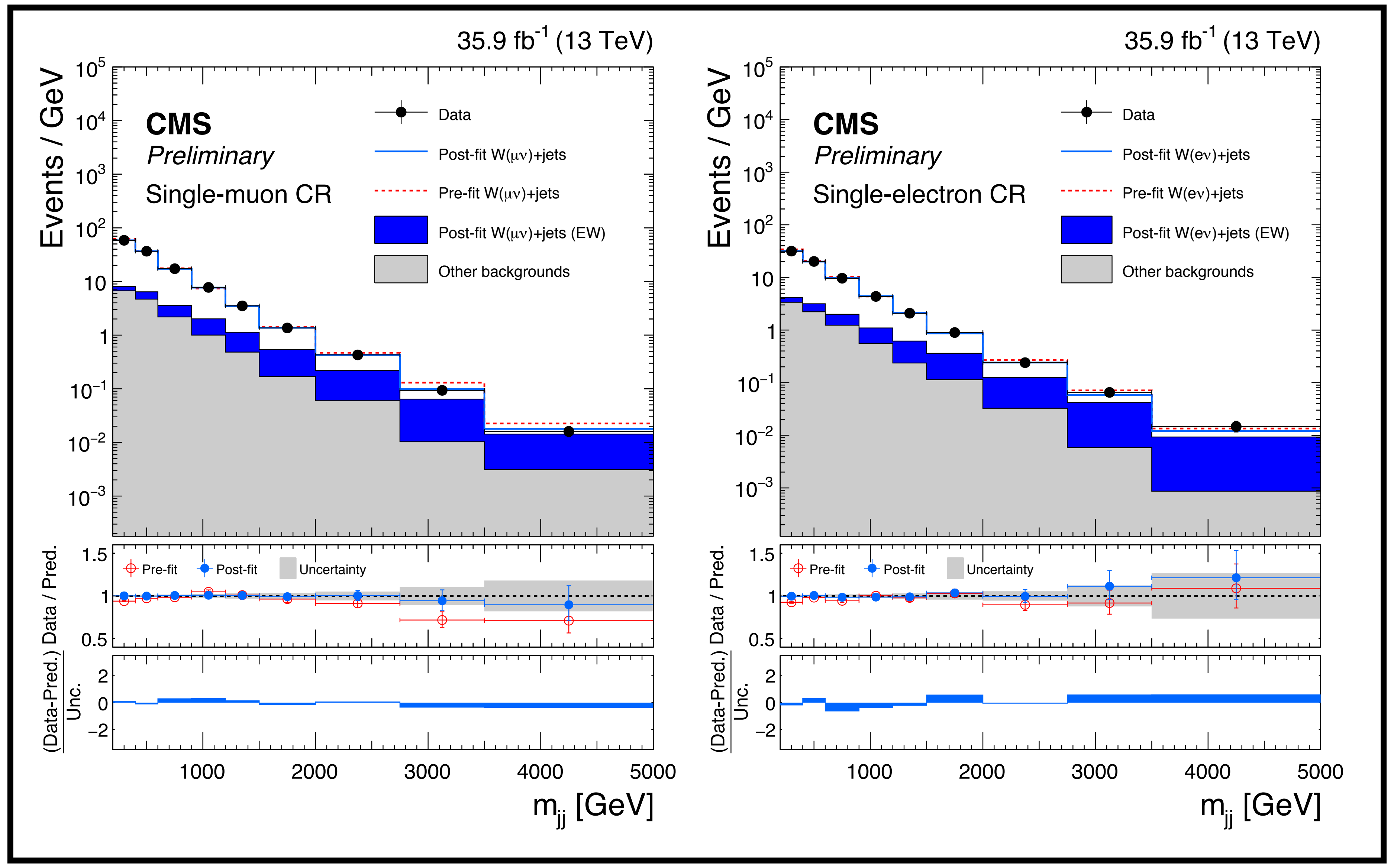
No excess compared to b-only prediction from SM

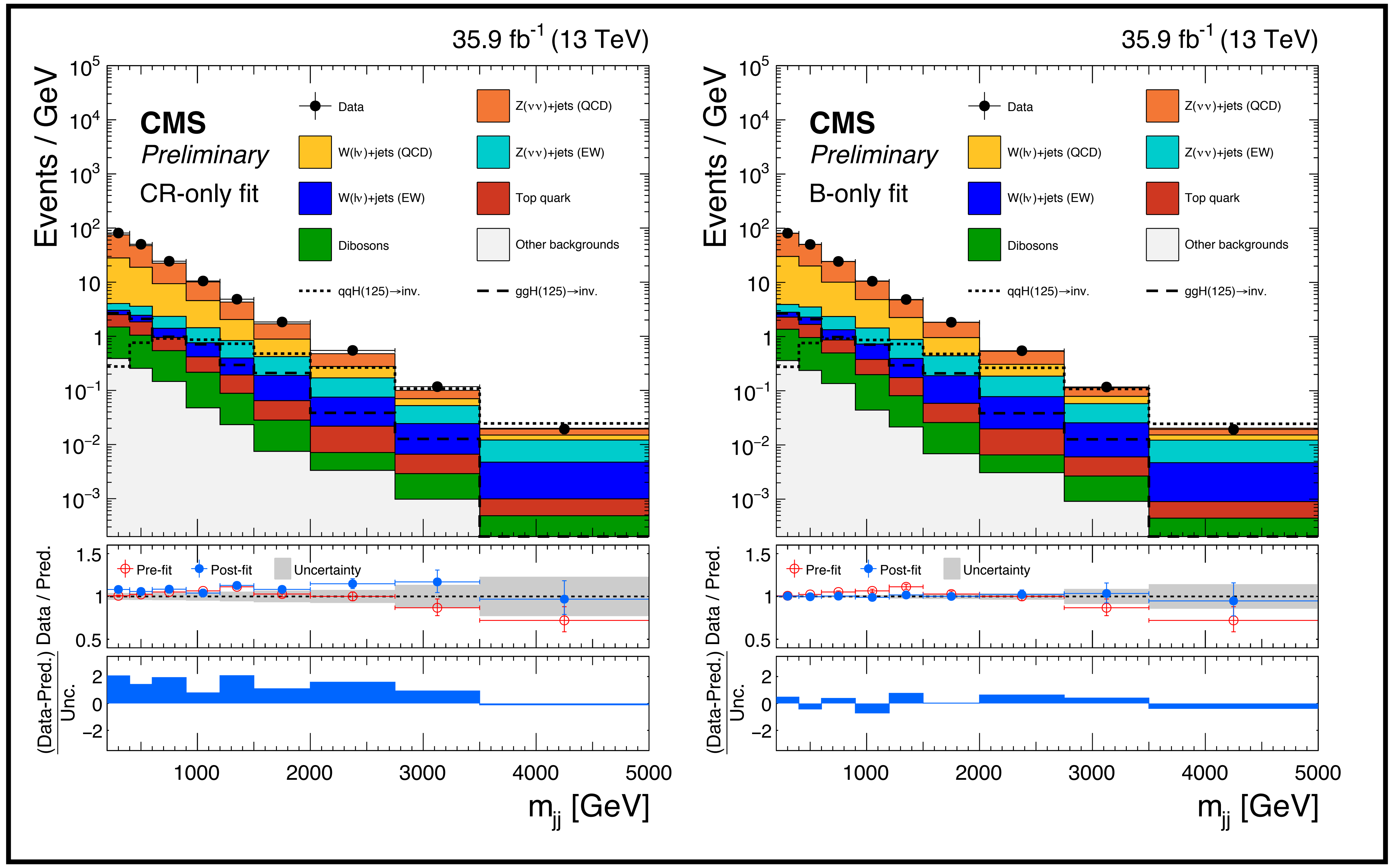


VBF H_{inv} : additional material

CMS-HIG-17-023







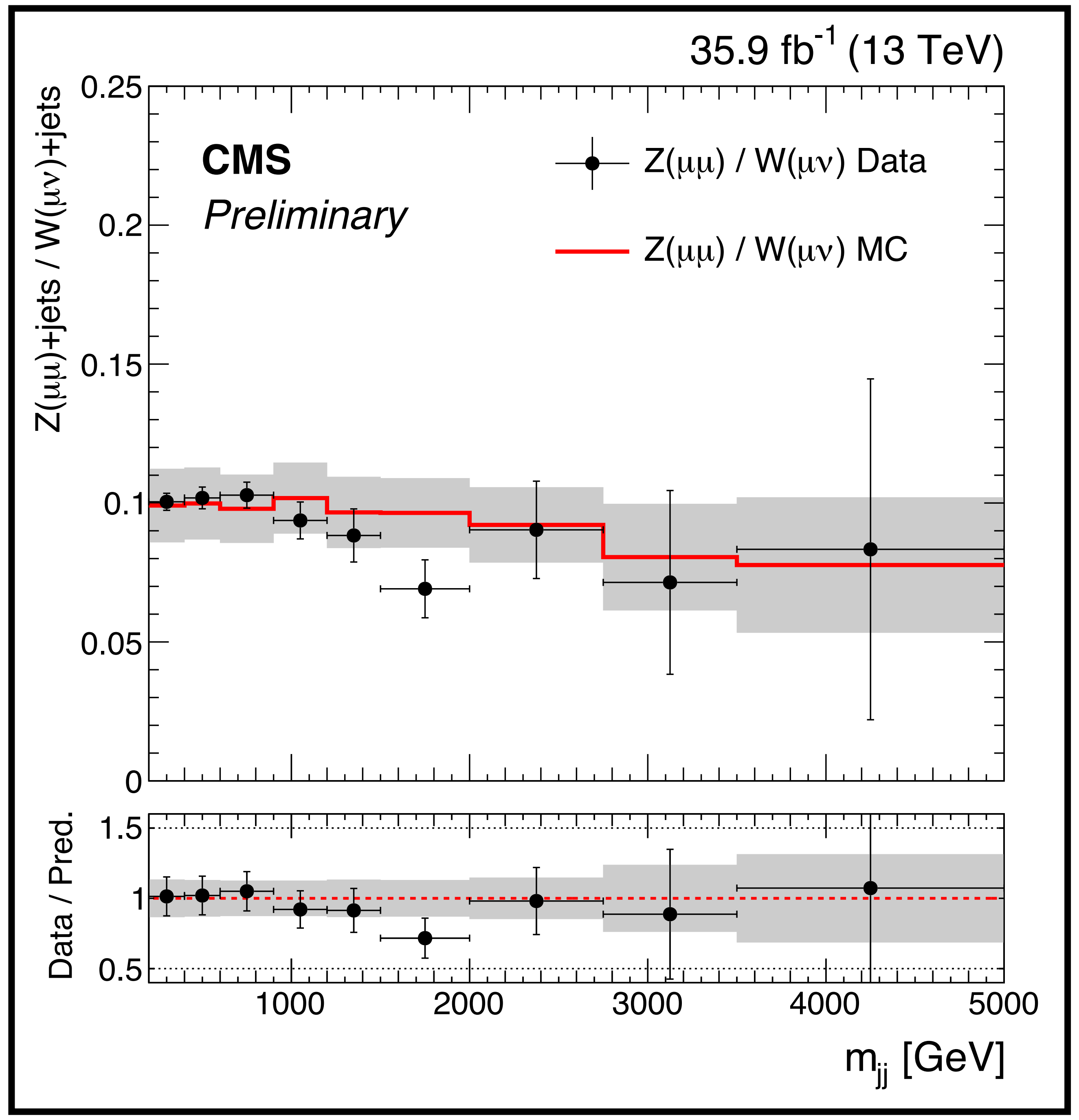
Background prediction from control-regions

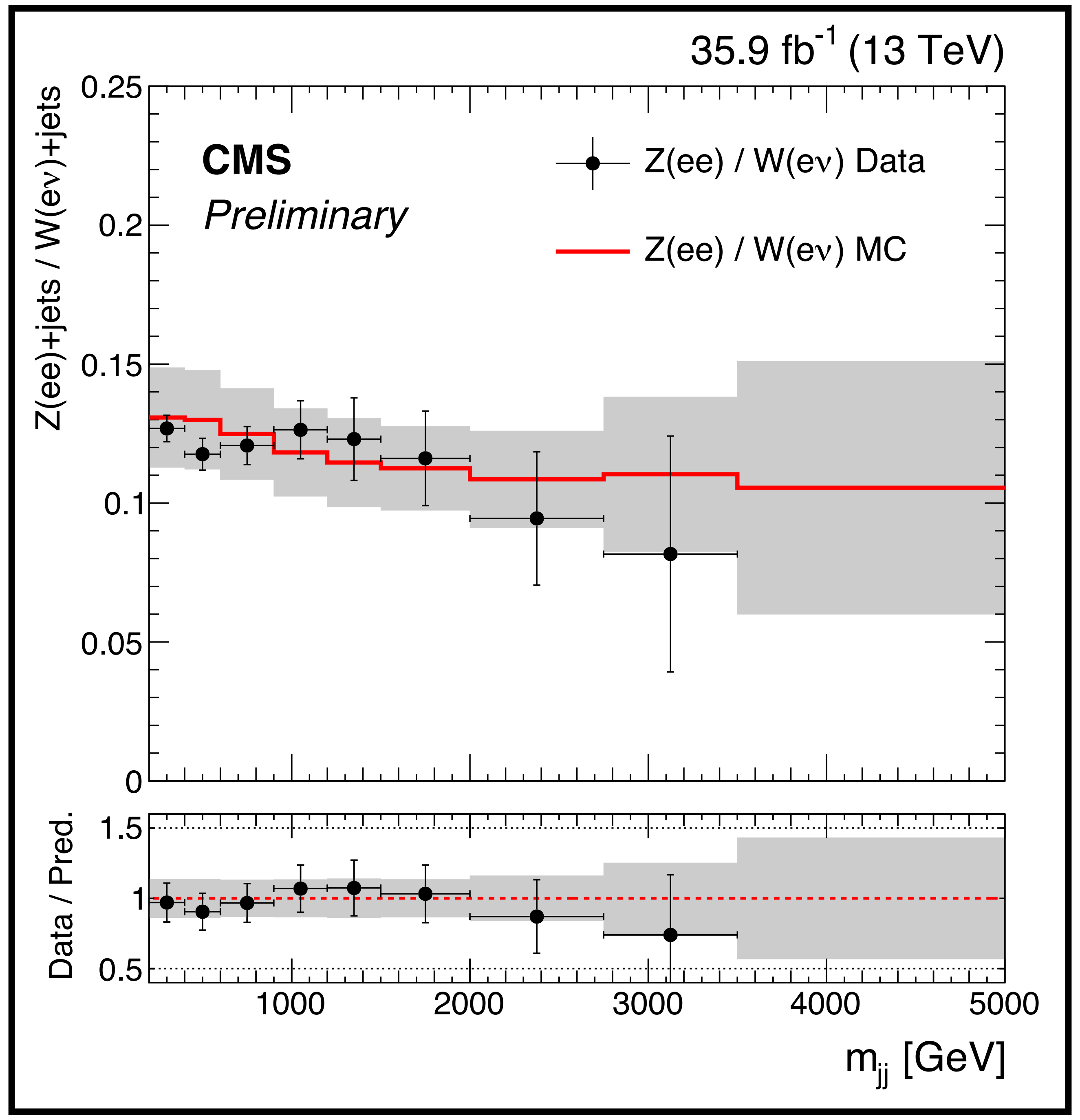
Background prediction performing a full b-only fit including also the SR

VBF H_{inv} : additional material

CMS-HIG-17-023

Validation of the systematic uncertainties on the Z/W ratio





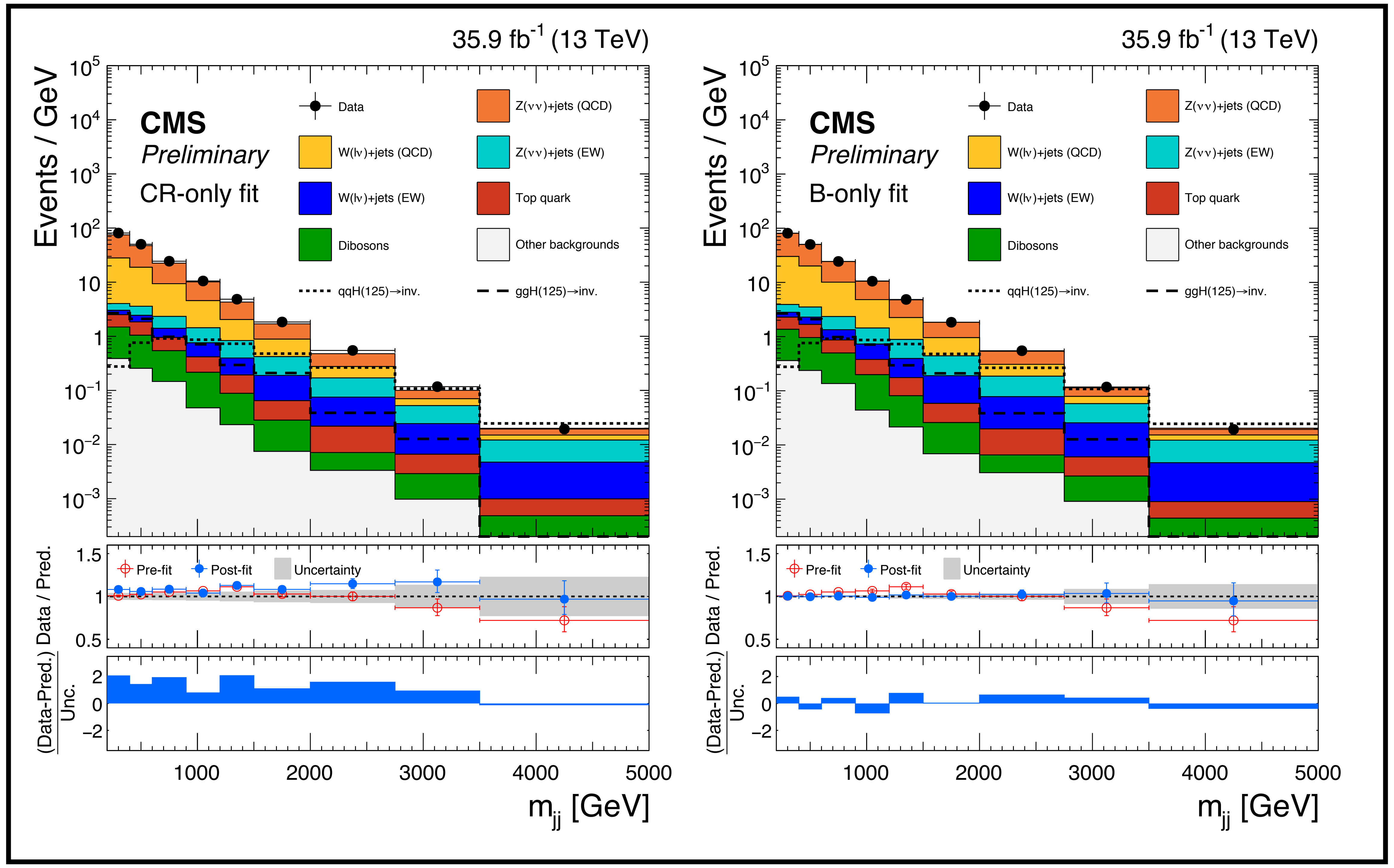
Impact on the BR(H_{inv}) measurement

Source of uncertainty	Ratios	Uncertainty vs m_{jj}	Impact on $\mathcal{B}(H \to inv)$
		Theoretical uncertainties	
Ren. scale V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	9–12%	48%
Ren. scale V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	9–12%	23%
Fac. scale V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	2–7%	4%
Fac. scale V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	2–7%	2%
PDF V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	0.5–1%	< 1%
PDF V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	0.5–1%	< 1%
NLO EW corr.	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	1–2%	< 1%
		Experimental uncertainties	
Muon reco. eff.	$W(\mu\nu)/W(\ell\nu)$, $Z(\mu\mu)/Z(\nu\nu)$	≈ 1% (per leg)	8%
Ele. reco. eff.	$W(e\nu)/W(\ell\nu)$, $Z(ee)/Z(\nu\nu)$	≈ 1% (per leg)	3%
Muon id. eff.	$W(\mu\nu)/W(\ell\nu)$, $Z(\mu\mu)/Z(\nu\nu)$	≈ 1% (per leg)	8%
Ele. id. eff.	$W(e\nu)/W(\ell\nu)$, $Z(ee)/Z(\nu\nu)$	≈ 1.5% (per leg)	4%
Muon veto	$W(CRs)/W(\ell\nu)$, $Z(\nu\nu)/W(\ell\nu)$	≈ 2.5 (2)% for EW (QCD)	7%
Ele. veto	$W(CRs)/W(\ell\nu)$, $Z(\nu\nu)/W(\ell\nu)$	≈ 1.5 (1)% for EW (QCD)	5%
τ veto	$W(CRs)/W(\ell\nu)$, $Z(\nu\nu)/W(\ell\nu)$	≈ 3.5 (3)% for EW (QCD)	13%
Jet energy scale	$Z(CRs)/Z(\nu\nu)$, $W(CRs)/W(\ell\nu)$	≈ 1 (2)% for Z/Z (W/W)	2%
Ele. trigger	$W(e\nu)/W(\ell\nu)$, $Z(ee)/Z(\nu\nu)$	≈ 1%	< 1%
p_T^{miss} trigger	All ratios	≈ 2%	18%

VBF H_{inv} : additional material

CMS-HIG-17-023

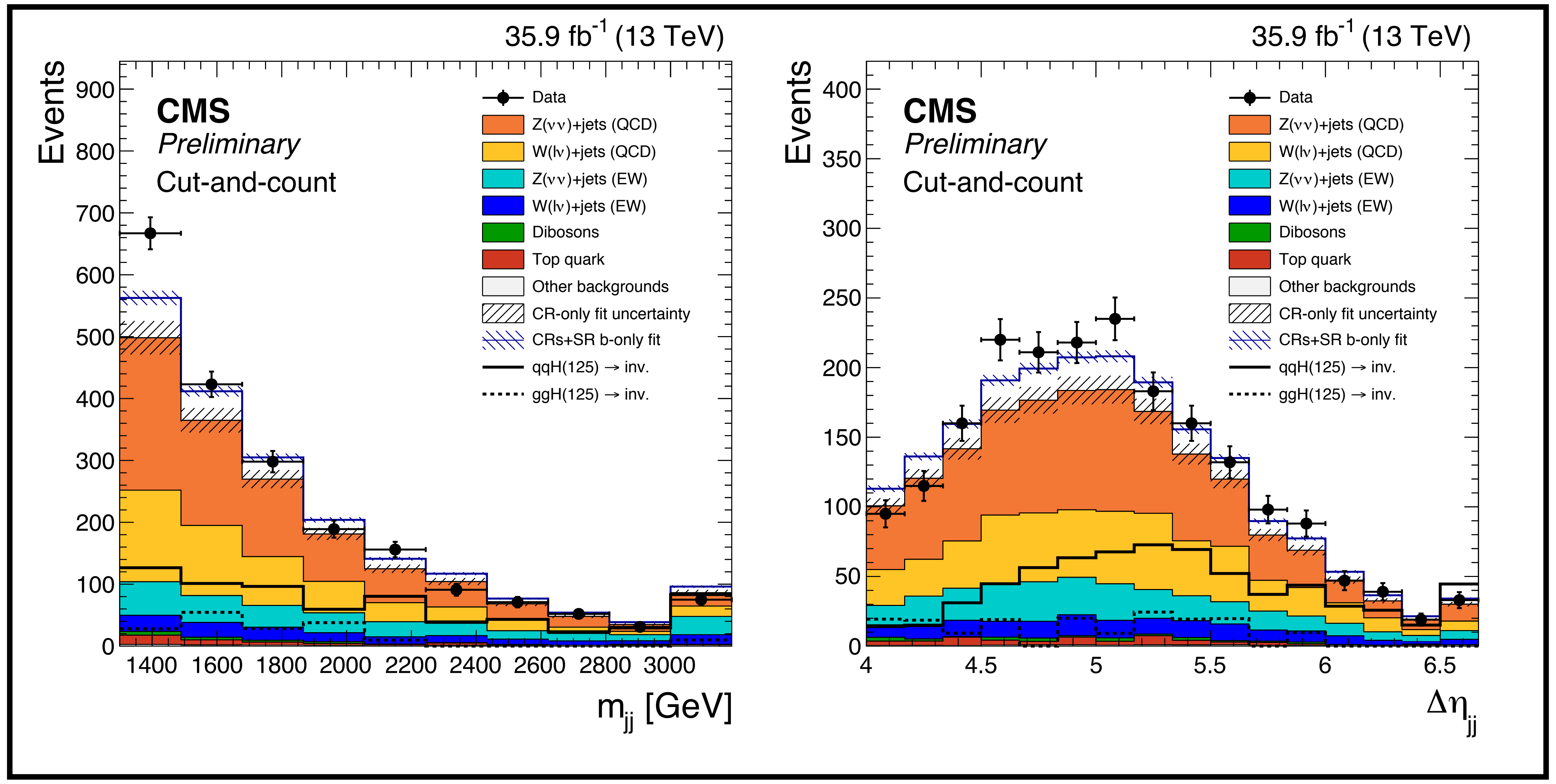
Shape analysis based fitting the m(jj) spectrum



Background prediction from control-regions

Background prediction performing a full b-only fit including also the SR

Counting experiment + shapes from MC



Total background yields from control-regions, while shapes are from MC

VBF H_{inv} : additional material

CMS-HIG-17-023

Shape analysis: background prediction from control-regions

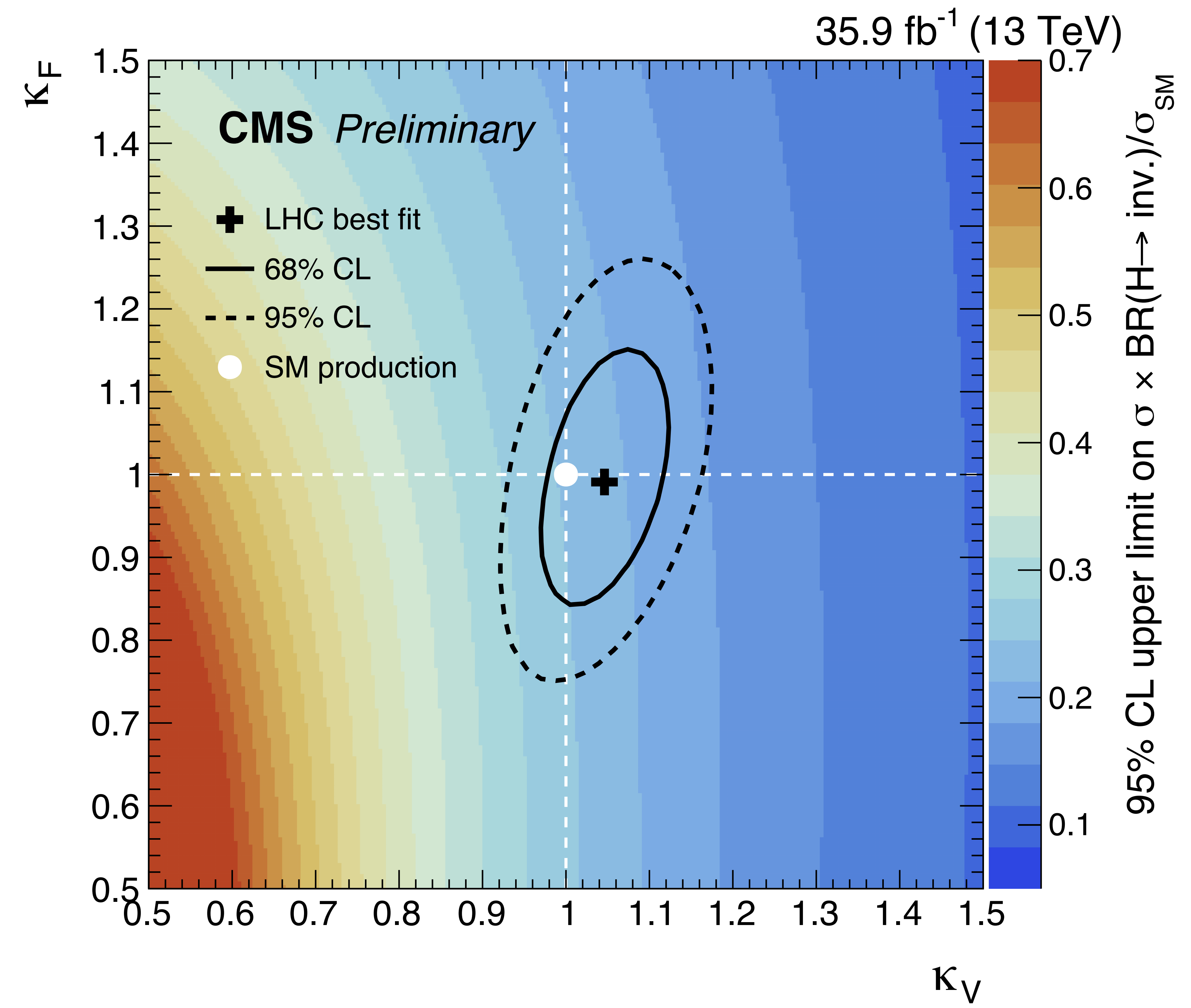
Process	m_{jj} range in TeV								
	0.2–0.4	0.4–0.6	0.6–0.9	0.9–1.2	1.2–1.5	1.5–2.0	2.0–2.75	2.75–3.5	> 3.5
$Z(\nu\nu)$ (QCD)	9367 ± 394	5716 ± 256	3925 ± 184	1665 ± 84	675 ± 43	406 ± 26	151 ± 14	22.6 ± 3.6	7.5 ± 2.1
$Z(\nu\nu)$ (EW)	202 ± 8	230 ± 10	278 ± 13	203 ± 10	131 ± 8	115 ± 8	71.3 ± 6.6	20.9 ± 3.4	11.6 ± 3.1
$W(\ell\nu)$ (QCD)	4786 ± 252	3046 ± 165	2122 ± 125	936 ± 58	361 ± 29	232 ± 19	79.3 ± 8.9	13.4 ± 2.8	4.3 ± 1.5
$W(\ell\nu)$ (EW)	101 ± 15	118 ± 16	135 ± 18	102 ± 13	61.4 ± 7.9	62.2 ± 7.9	39.9 ± 4.8	13.3 ± 1.8	5.6 ± 1.4
Top-quark	206 ± 32	161 ± 25	124 ± 19	60.7 ± 9.3	31.6 ± 6.1	18.3 ± 2.9	11.1 ± 1.8	2.8 ± 0.5	0.9 ± 0.2
Dibosons	219 ± 39	158 ± 28	119 ± 21	50.9 ± 9.1	19.5 ± 3.5	10.4 ± 1.8	2.8 ± 0.5	1.4 ± 0.3	0.4 ± 0.1
Others	77.5 ± 19.5	51.5 ± 11.5	43.8 ± 10.7	14.3 ± 2.9	6.9 ± 1.5	3.7 ± 0.8	2.5 ± 0.6	0.7 ± 0.3	0.3 ± 0.4
Total Bkg.	14960 ± 563	9482 ± 378	6738 ± 281	3032 ± 135	1286 ± 73	849 ± 48	358 ± 28	75.3 ± 9.8	29.9 ± 7.2
Data	16181	10035	7312	3154	1453	919	411	88	29
Signal	591 ± 285	571 ± 232	566 ± 172	472 ± 131	307 ± 64	344 ± 83	228 ± 40	90.3 ± 18.8	37.4 ± 9.1

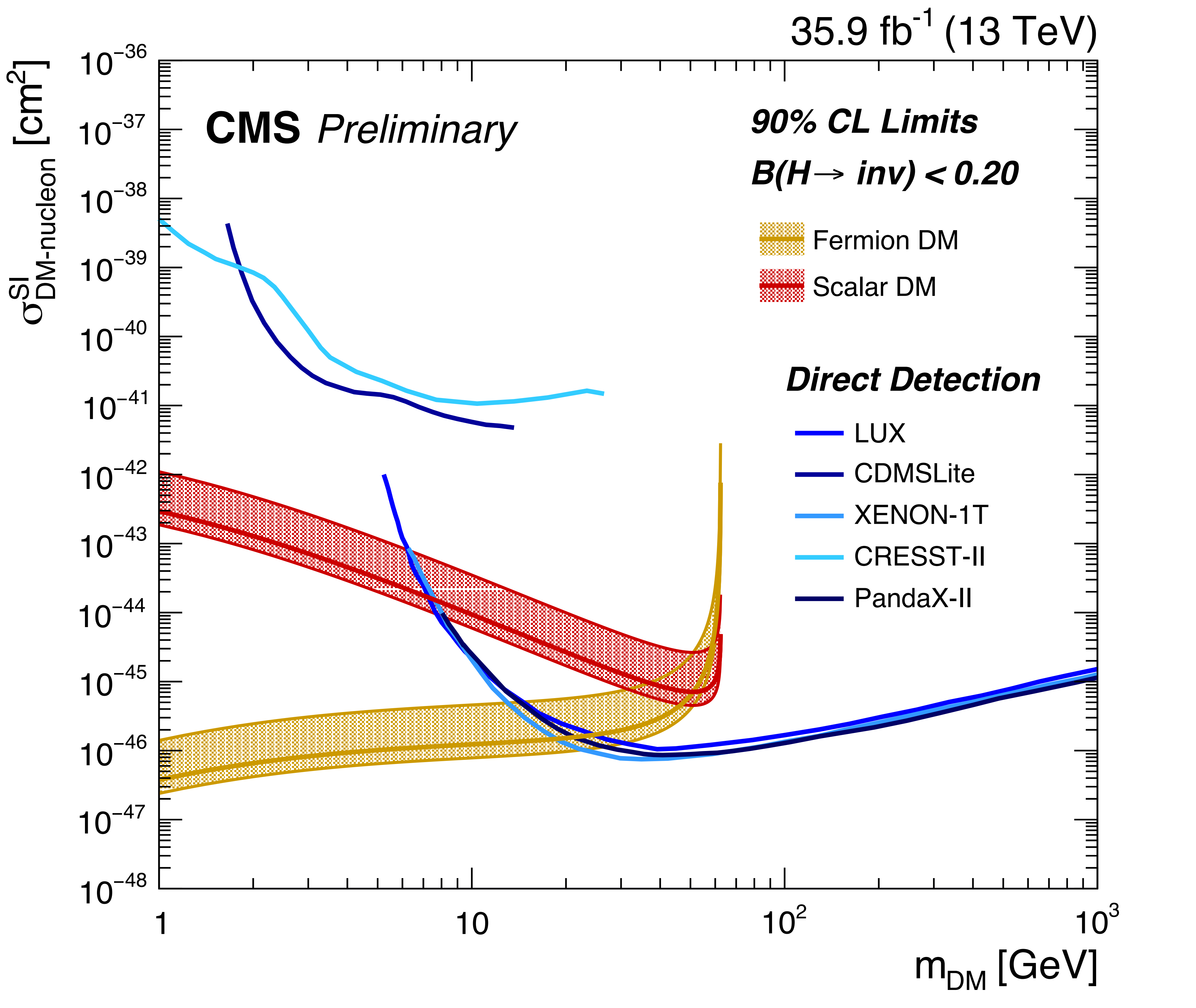
Cut-and-count analysis: background prediction from control-regions

Process	Signal Region	Dimuon CR	Dielectron CR	Single-Muon CR	Single-Electron CR
$Z(\nu\nu)$ (QCD)	799 ± 72	-	-	-	-
$Z(\nu\nu)$ (EW)	275 ± 34	-	-	-	-
$Z(\ell\ell)$ (QCD)	-	90.1 ± 7.9	64.7 ± 5.8	26.8 ± 1.2	4.9 ± 0.2
$Z(\ell\ell)$ (EW)	-	32.7 ± 4.3	25.0 ± 3.4	5.9 ± 0.3	2.4 ± 0.2
$W(\ell\nu)$ (QCD)	497 ± 33	0.2 ± 0.2	0.8 ± 0.6	891 ± 31	533 ± 21
$W(\ell\nu)$ (EW)	145 ± 11	0.1 ± 0.1	-	416 ± 16	260 ± 11
Top-quark	43.7 ± 9.8	5.3 ± 1.6	3.7 ± 1.1	126 ± 22	83.1 ± 15.4
Dibosons	19.9 ± 6.1	2.6 ± 1.3	0.9 ± 0.5	23.5 ± 4.9	16.1 ± 4.1
Others	3.3 ± 2.6	-	-	25.6 ± 20.7	2.9 ± 2.9
Total Bkg.	1784 ± 97	131 ± 8	95.2 ± 5.9	1515 ± 34	902 ± 24
Data	2053	114	104	1512	914
Signal $m_H = 125$ GeV	851 ± 148	-	-	-	-

VBF H_{inv} : additional material

CMS-HIG-17-023





Hinv limits in case of deviations from SM couplings → with 95% CL region, BR(H_{inv}) limit moves from 0.17 to 0.29 (observed limit)

Higgs portal of DM interactions: limit on the spin-independent DM-nucleon scattering cross section given $m_{DM} < m_H / 2$

ZH_{inv}: additional material

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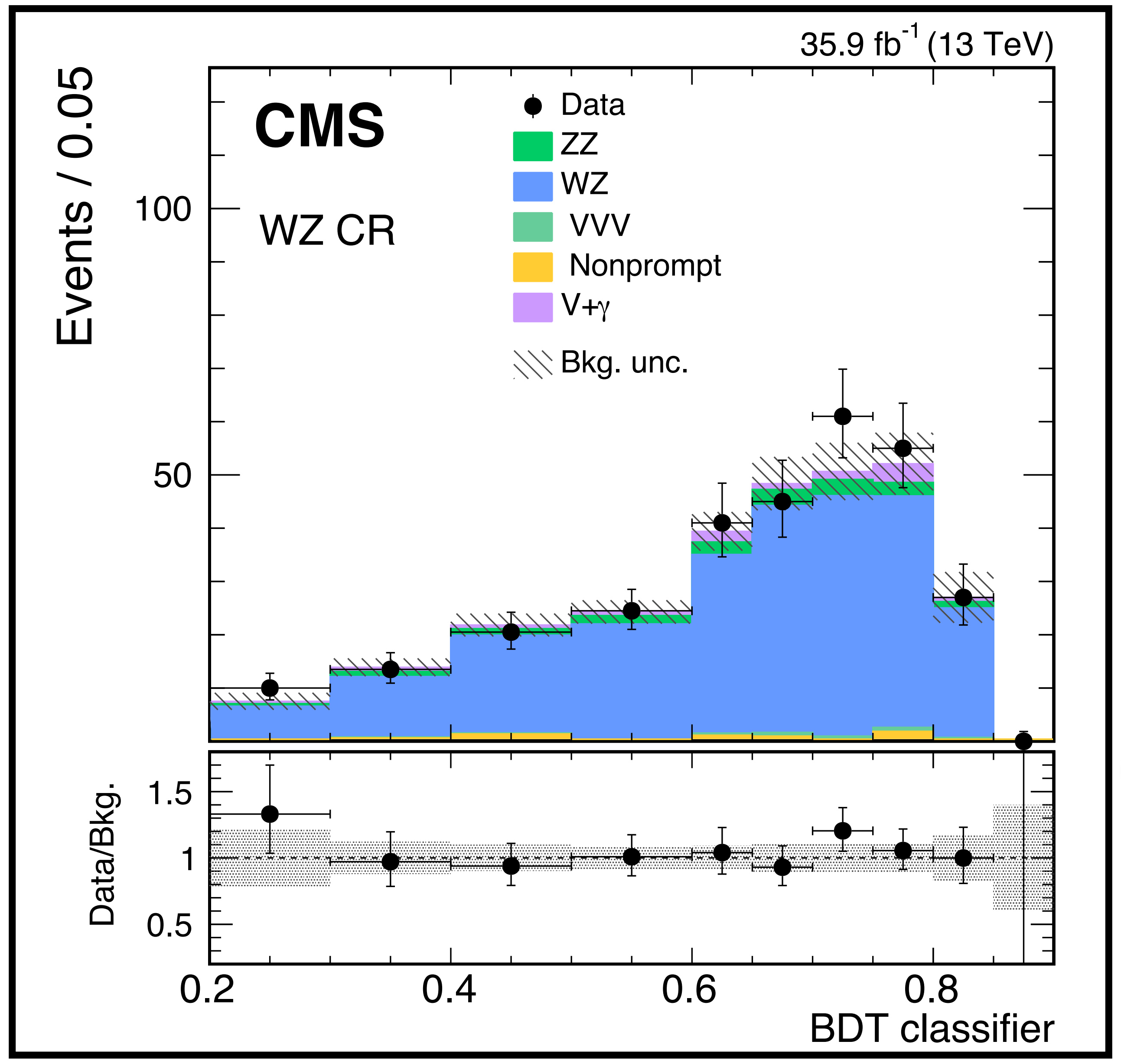
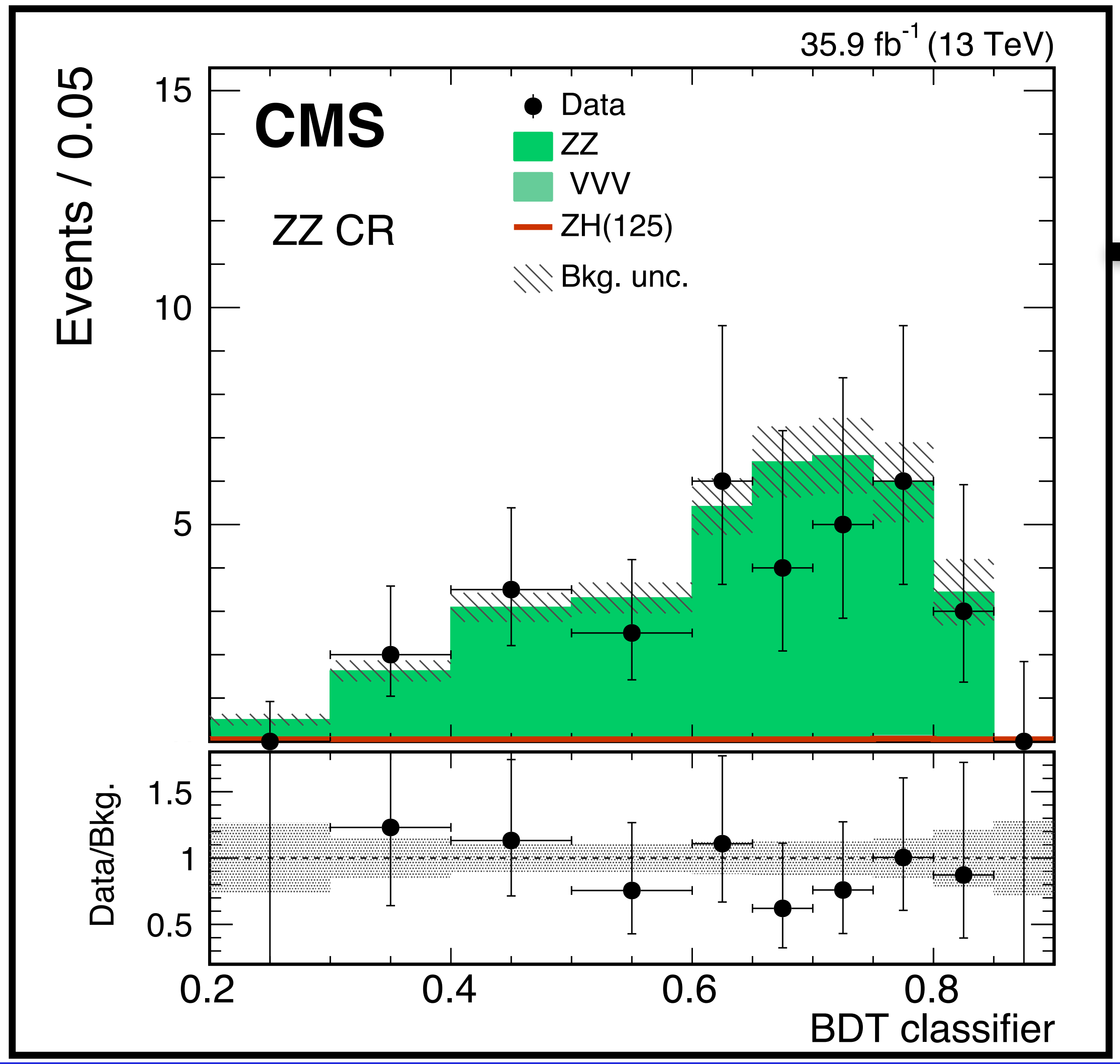
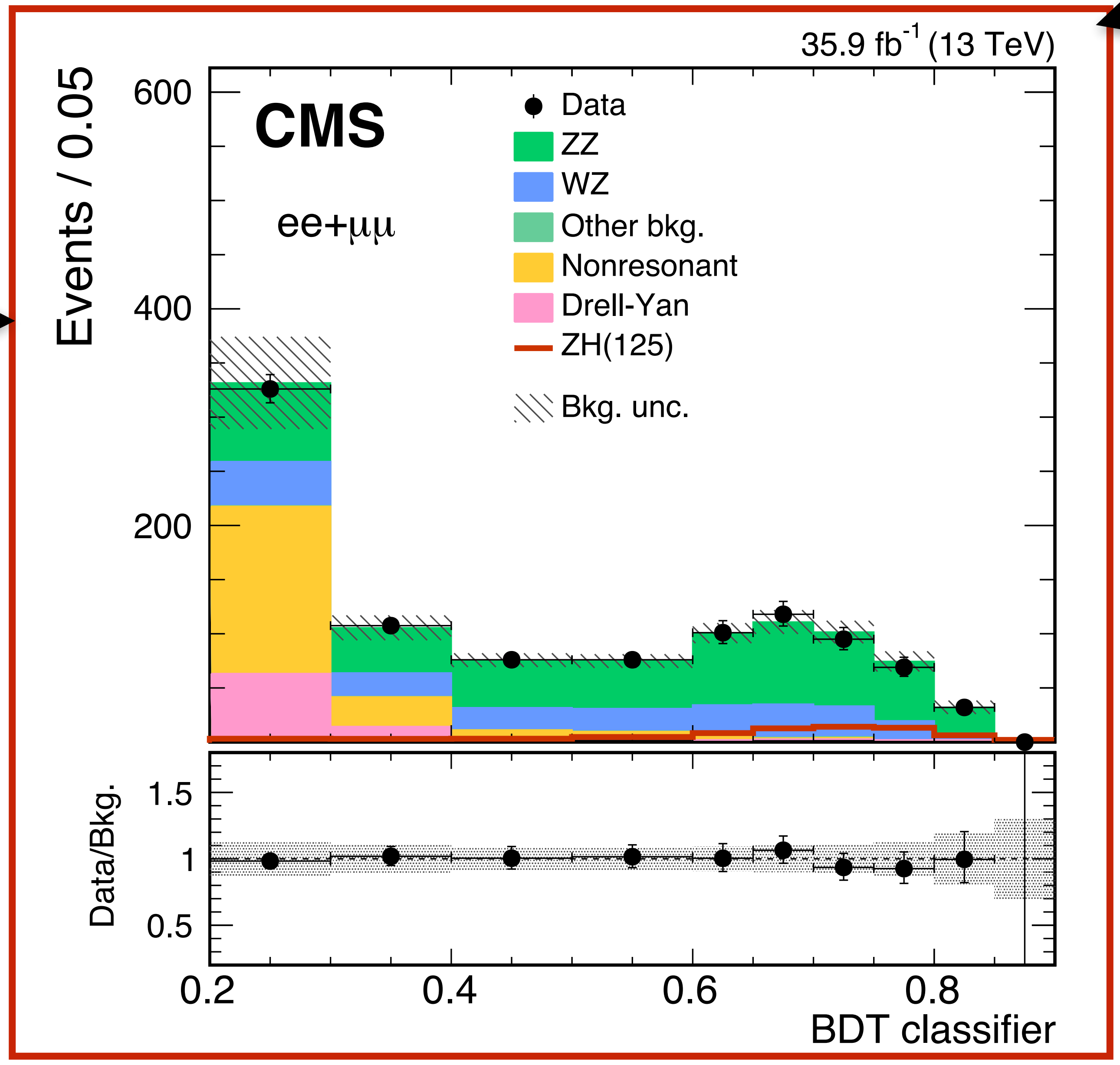




Selection	Requirement	Reject
N_ℓ	$=2$	WZ, VVV
p_T^ℓ	$>25/20$ GeV for electrons >20 GeV for muons	QCD
Z boson mass requirement	$\lvert m_{\ell\ell} - m_Z \rvert < 15$ (30) GeV	WW, top quark
Jet counting	≤ 1 jet with $p_T^j > 30$ GeV	$Z/\gamma^* \to \ell\ell$, top quark, VVV
$p_T^{\ell\ell}$	>60 GeV	$Z/\gamma^* \to \ell\ell$
b tagging veto	CSVv2 < 0.8484	Top quark, VVV
τ lepton veto	0 τ_h cand. with $p_T^\tau > 18$ GeV	WZ
p_T^{miss}	>100 GeV (130 GeV, training only)	$Z/\gamma^* \to \ell\ell$, WW, top quark
$\Delta\phi(\vec{p}_T^{\,j}, \vec{p}_T^{\,miss})$	>0.5 rad	$Z/\gamma^* \to \ell\ell$, WZ
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,miss})$	>2.6 rad (omitted)	$Z/\gamma^* \to \ell\ell$
$\lvert p_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	<0.4 (omitted)	$Z/\gamma^* \to \ell\ell$
$\Delta R_{\ell\ell}$	<1.8 (omitted)	WW, top quark



ZH$_{inv}$: additional material

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Source of uncertainty	Effect (%) Signal	ZZ	WZ	NRB	DY	Impact on the exp. limit (%)
* VV EW corrections	—	10	−4	—	—	14 (12)
* Renorm./fact. scales, VV	—	9	4	—	—	2 (1)
* Renorm./fact. scales, ZH	3.5	—	—	—	—	
* Renorm./fact. scales, DM	5	—	—	—	—	
* PDF, WZ background	—	—	1.5	—	—	
* PDF, ZZ background	—	1.5	—	—	—	
* PDF, Higgs boson signal	1.5	—	—	—	—	
* PDF, DM signal	1–2	—	—	—	—	
* MC sample size, NRB	—	—	—	5	—	1
* MC sample size, DY	—	—	—	—	30	
* MC sample size, ZZ	—	0.1	—	—	—	
* MC sample size, WZ	—	—	2	—	—	
* MC sample size, ZH	1	—	—	—	—	
* MC sample size, DM	3	—	—	—	—	
NRB extrapolation to the SR	—	—	—	20	—	<1
DY extrapolation to the SR	—	—	—	—	100	<1
Lepton efficiency (WZ CR)	—	—	3	—	—	<1
Nonprompt bkg. (WZ CR)	—	—	—	—	30	<1
Integrated luminosity	2.5					<1
* Electron efficiency	1.5					1 (<1)
* Muon efficiency	1					
* Electron energy scale	1–2					
* Muon energy scale	1–2					
* Jet energy scale	1–3 (typically anticorrelated w/ yield)					
* Jet energy resolution	1 (typically anticorr.)					
* Unclustered energy (p_T^{miss})	1–4 (typically anticorr.), strong in DY					
* Pileup	1 (typically anticorrelated)					
* b tagging eff. & mistag rate	1					
* BDT: electron energy scale	1.1	2.9	2.6	—	—	— (2)
* BDT: muon energy scale	1.5	4.3	2.7	—	—	
* BDT: p_T^{miss} scale	1.0	3.2	4.1	—	—	

ggH$_{inv}$ and V(qq)H$_{inv}$: additional material

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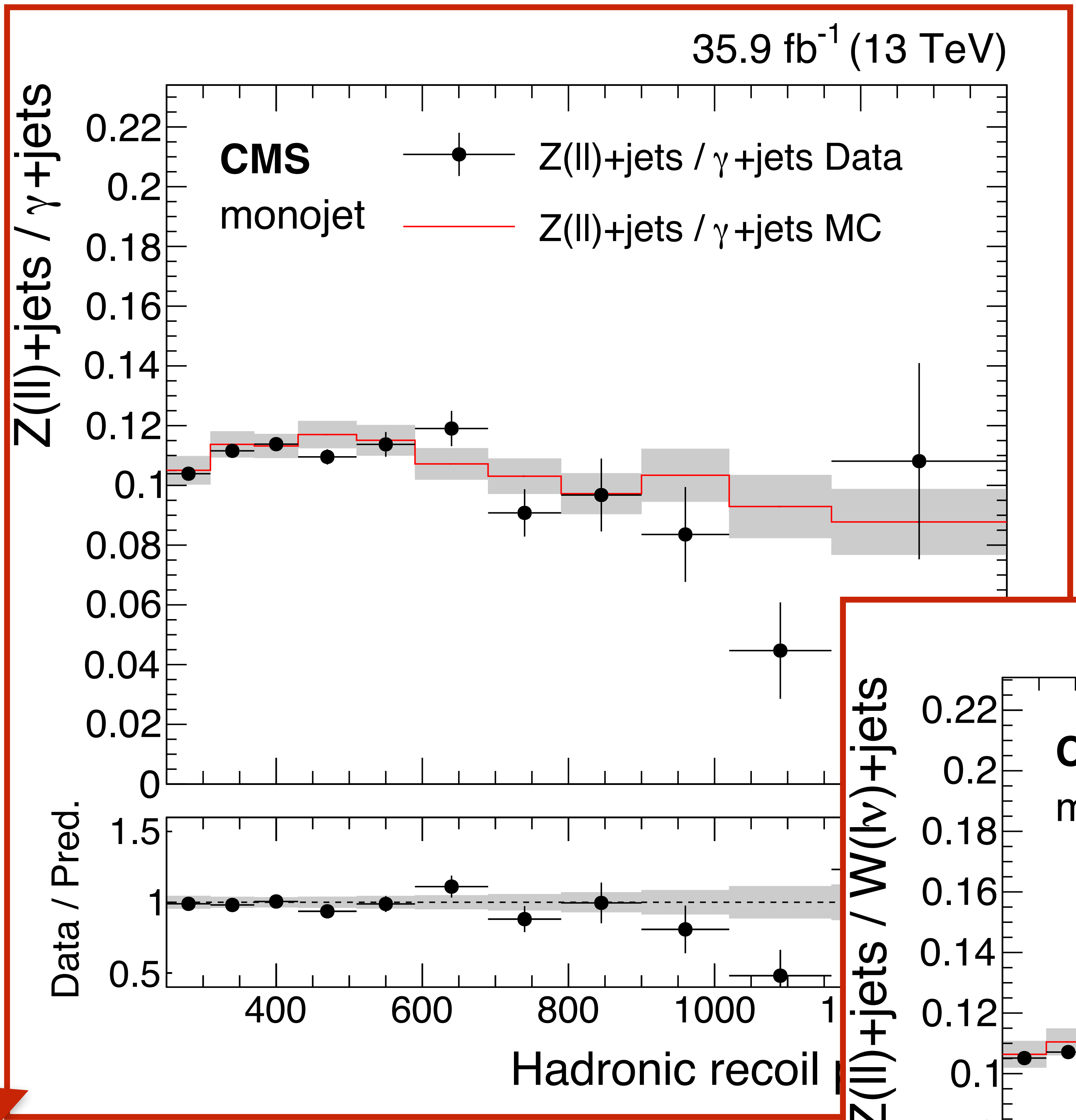
Signal region selections

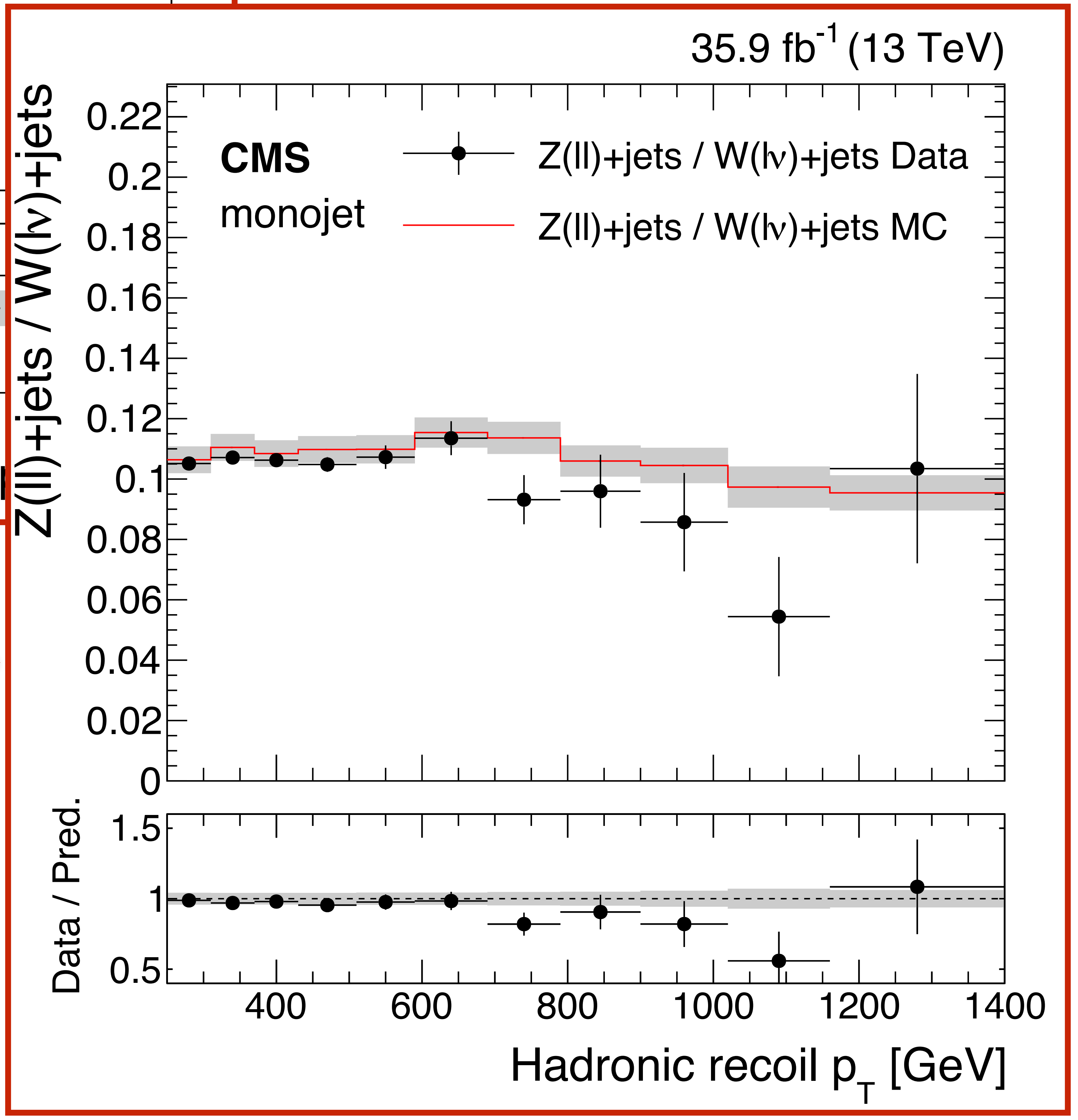
Variable	Selection	Target background
Muon (electron) veto	$p_T > 10\,\text{GeV}$, $\lvert\eta\rvert < 2.4(2.5)$	$Z(\ell\ell)$+jets, $W(\ell\nu)$+jets
τ lepton veto	$p_T > 18\,\text{GeV}$, $\lvert\eta\rvert < 2.3$	$Z(\ell\ell)$+jets, $W(\ell\nu)$+jets
Photon veto	$p_T > 15\,\text{GeV}$, $\lvert\eta\rvert < 2.5$	γ+jets
Bottom jet veto	CSVv2 < 0.8484, $p_T > 15\,\text{GeV}$, $\lvert\eta\rvert < 2.4$	Top quark
p_T^{miss}	$>250\,\text{GeV}$	QCD, top quark, $Z(\ell\ell)$+jets
$\Delta\phi(\vec{p}_T^{\,jet}, \vec{p}_T^{\,miss})$	>0.5 radians	QCD
Leading AK4 jet p_T and η	$>100\,\text{GeV}$ and $\lvert\eta\rvert < 2.4$	All

Leading AK8 jet	Mono-V selection
p_T and η	$>250\,\text{GeV}$ and $\lvert\eta\rvert < 2.4$
τ_2/τ_1	<0.6
Mass (m_{jet})	$65 < m_{jet} < 105\,\text{GeV}$

Z/γ and Z/W ratio theoretical uncertainties

Uncertainty source	Process (magnitude)	Correlation
Fact. & renorm. scales (QCD)	$Z\to\nu\nu/W\to\ell\nu$ (0.1 – 0.5%) $Z\to\nu\nu/\gamma$+jets (0.2 – 0.5%)	Correlated between processes; and in p_T
p_T shape dependence (QCD)	$Z\to\nu\nu/W\to\ell\nu$ (0.4 – 0.1%) $Z\to\nu\nu/\gamma$+jets (0.1 – 0.2%)	Correlated between processes; and in p_T
Process dependence (QCD)	$Z\to\nu\nu/W\to\ell\nu$ (0.4 – 1.5%) $Z\to\nu\nu/\gamma$+jets (1.5 – 3.0%)	Correlated between processes; and in p_T
Effects of unknown Sudakov logs (EW)	$Z\to\nu\nu/W\to\ell\nu$ (0 – 0.5%) $Z\to\nu\nu/\gamma$+jets (0.1 – 1.5%)	Correlated between processes; and in p_T
Missing NNLO effects (EW)	$Z\to\nu\nu$ (0.2 – 3.0%) $W\to\ell\nu$ (0.4 – 4.5%) γ+jets (0.1 – 1.0%)	Uncorrelated between processes; correlated in p_T
Effects of NLL Sudakov approx. (EW)	$Z\to\nu\nu$ (0.2 – 4.0%) $W\to\ell\nu$ (0 – 1.0%) γ+jets (0.1 – 3.0%)	Uncorrelated between processes; correlated in p_T
Unfactorized mixed QCD-EW corrections	$Z\to\nu\nu/W\to\ell\nu$ (0.15 – 0.3%) $Z\to\nu\nu/\gamma$+jets (<0.1%)	Correlated between processes; and in p_T
PDF	$Z\to\nu\nu/W\to\ell\nu$ (0 – 0.3%) $Z\to\nu\nu/\gamma$+jets (0 – 0.6%)	Correlated between processes; and in p_T





ggH_{inv} and $V(qq)H_{inv}$: additional material

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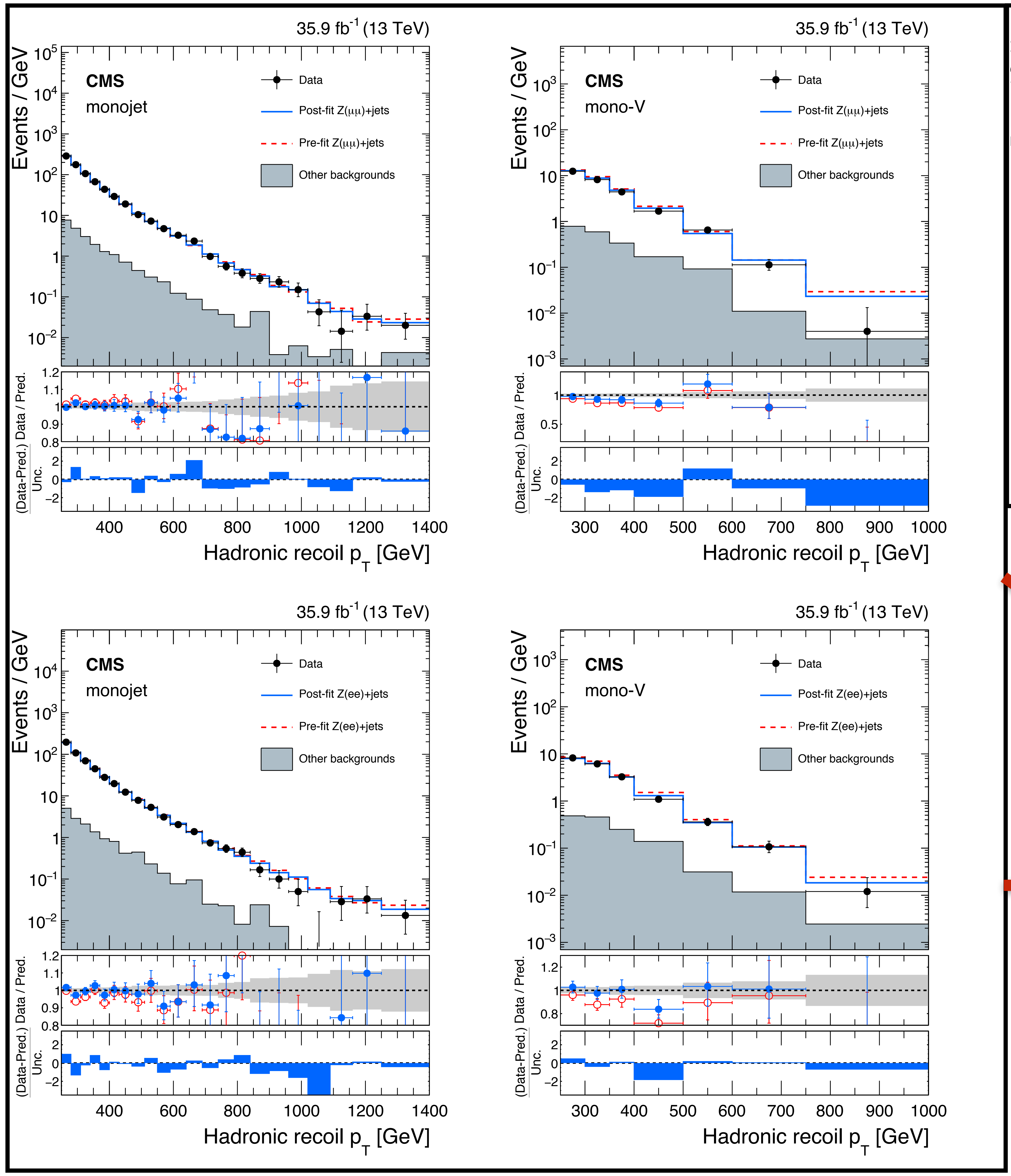
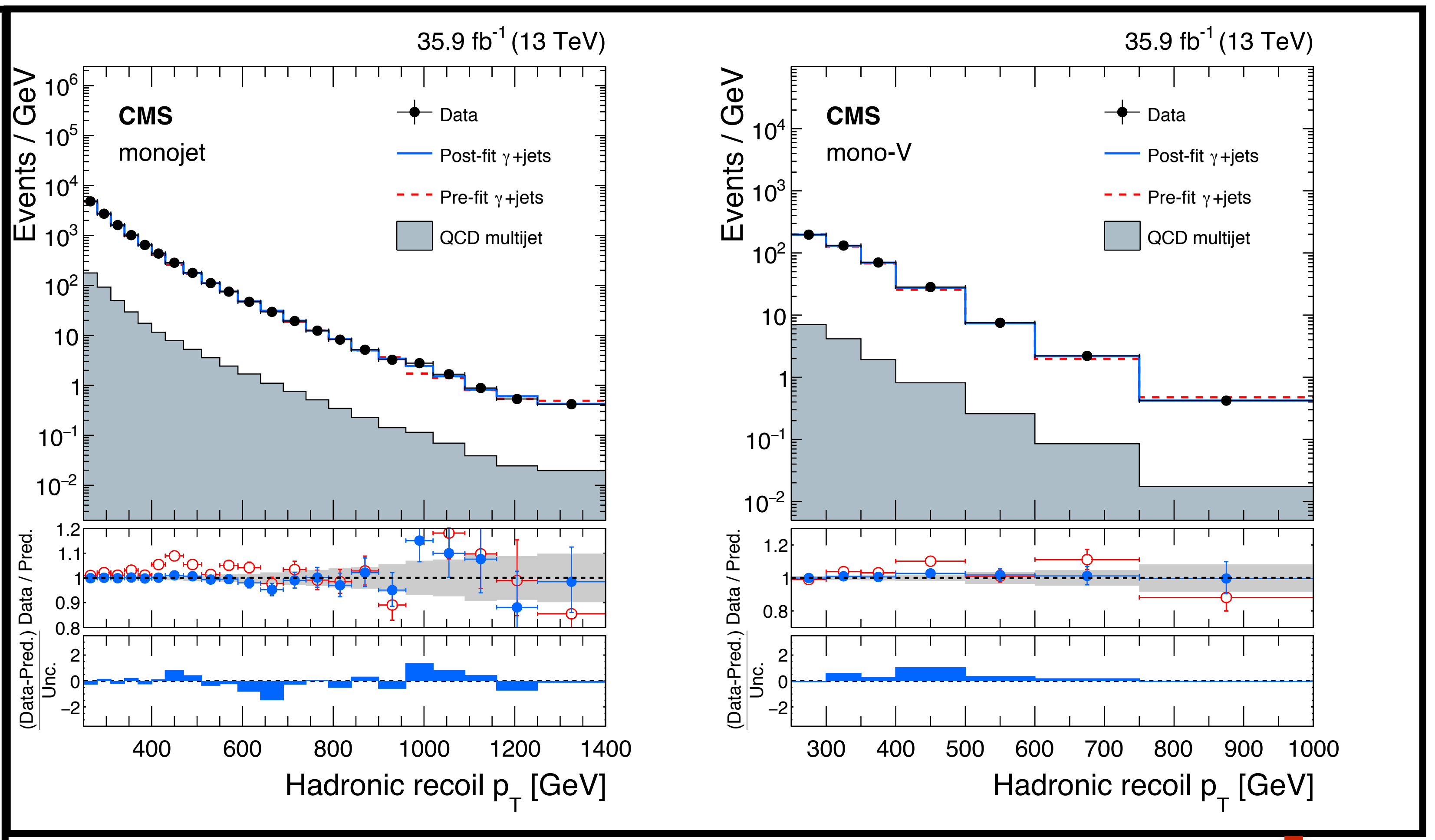
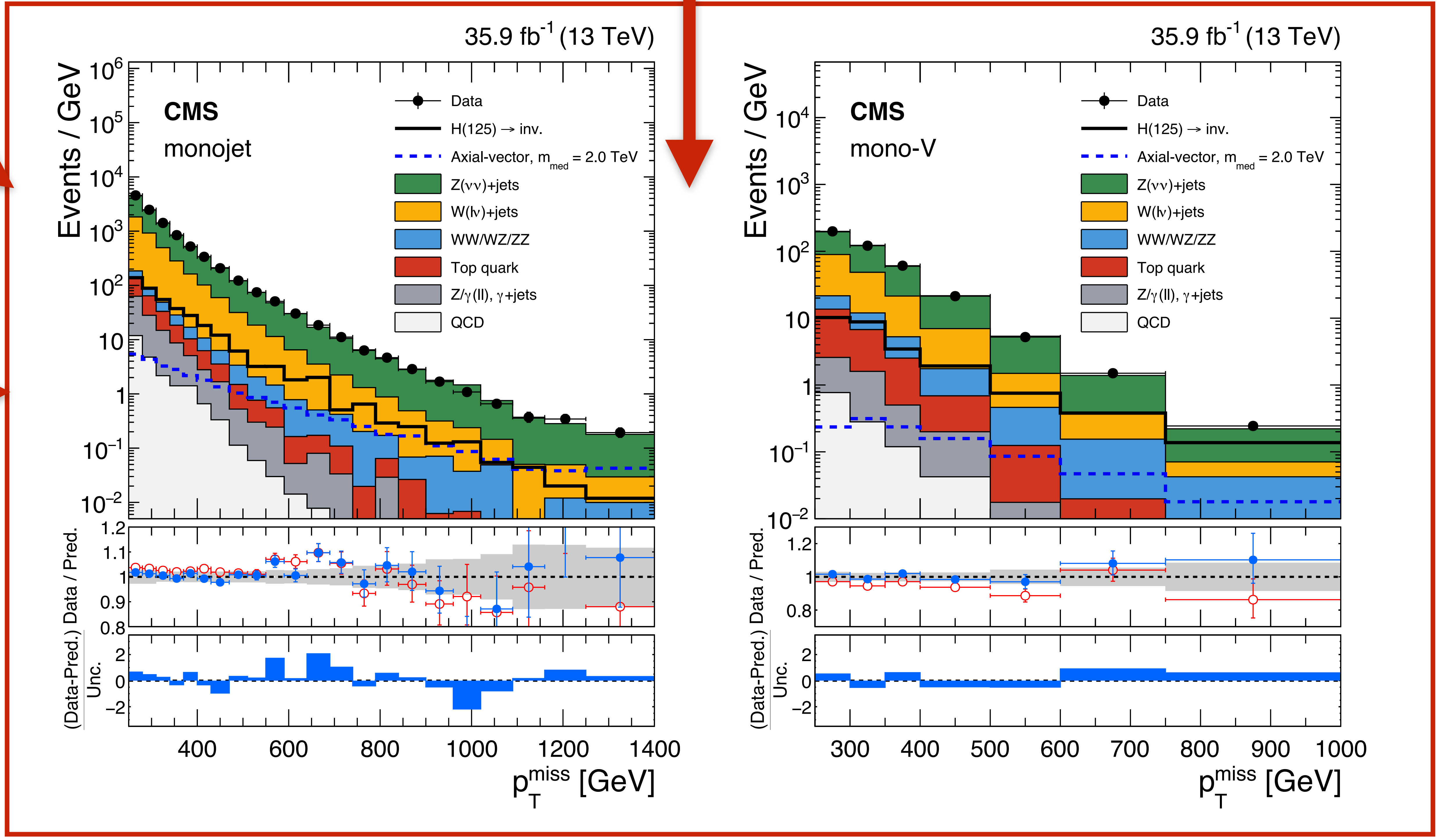




Background prediction from control-regions



ggH$_{inv}$ and V(qq)H$_{inv}$: additional material

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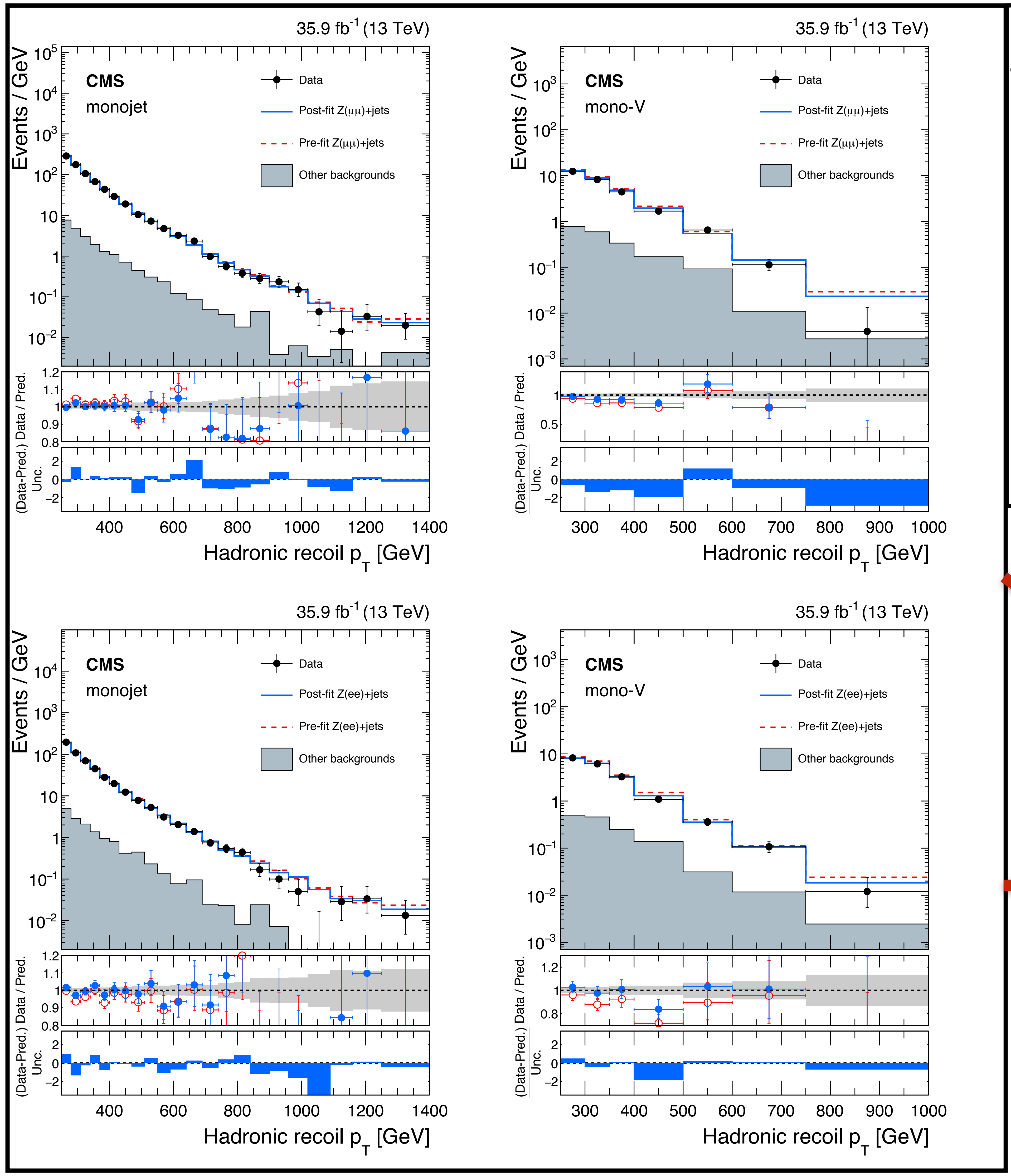
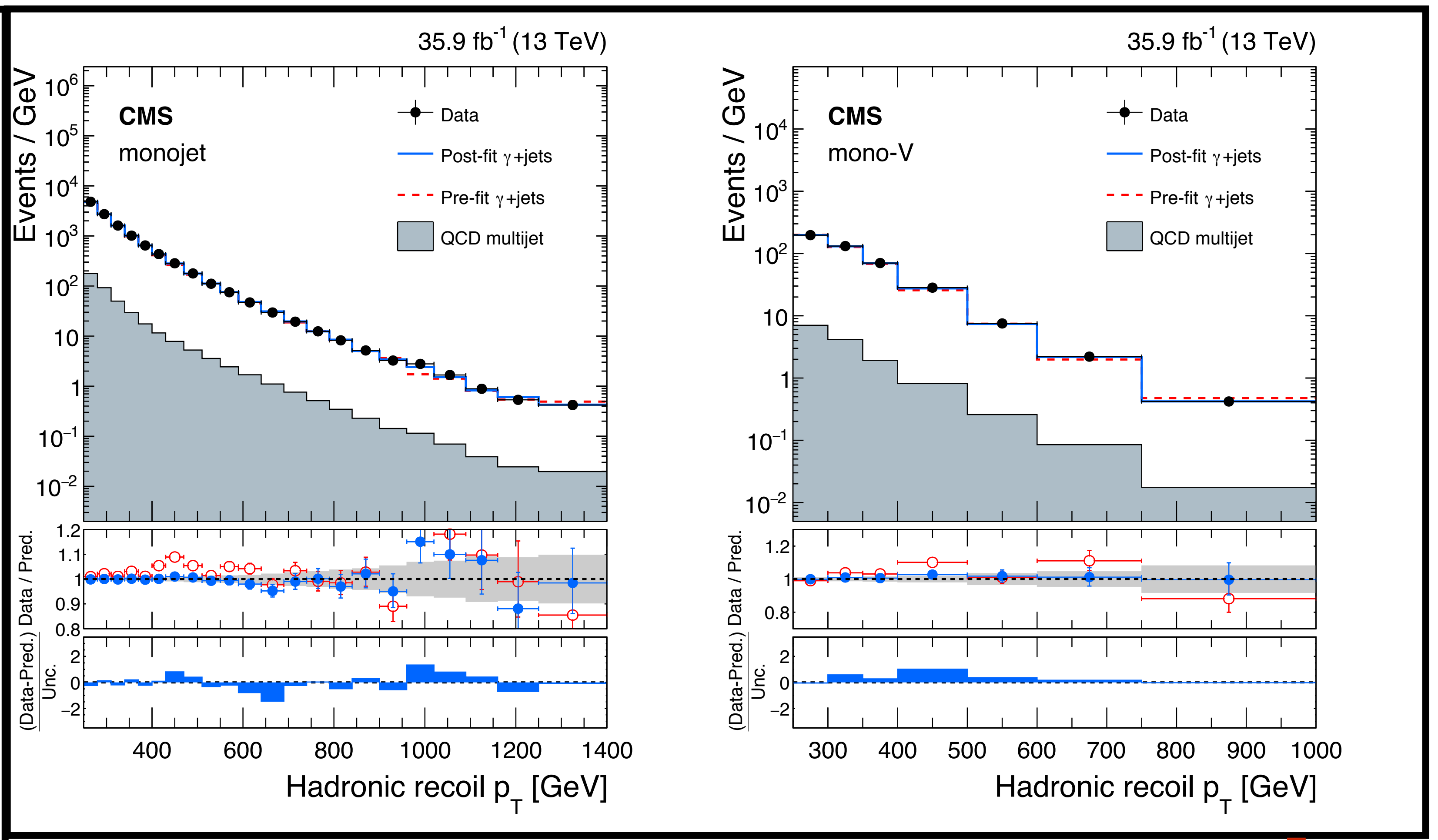
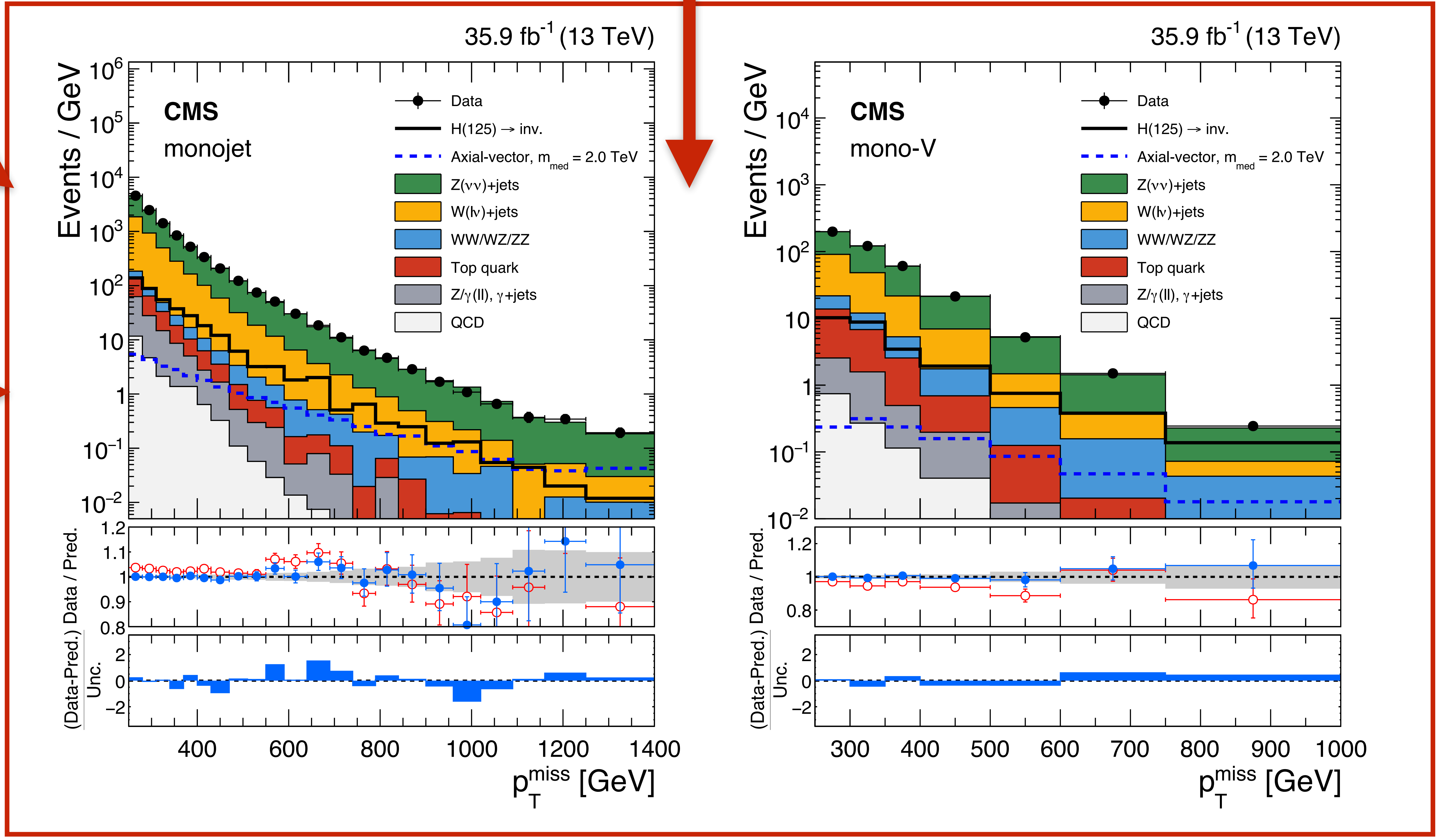




Background prediction performing a full b-only fit including also the SR



H→μμ: additional material

CMS-HIG-17-019

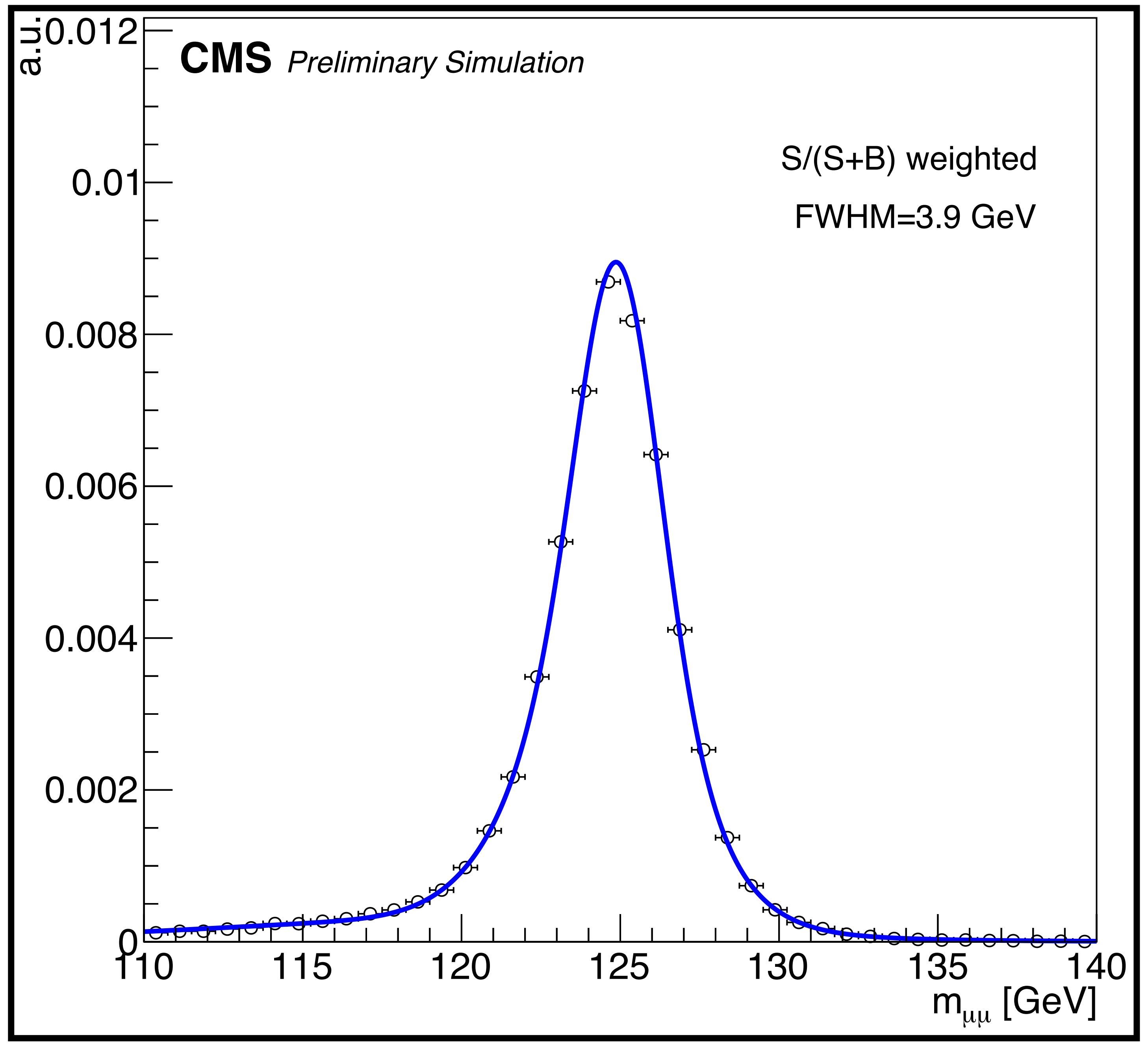
Index	BDT quantile	Max. muon $\|\eta\|$	ggH [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]	Signal	Bkg./GeV @125GeV	FWHM [GeV]	Bkg. functional fit form	$S/\sqrt{B}$ @ FWHM
0	0 – 8%	$\|\eta\| < 2.4$	4.9	1.3	3.3	6.3	31.9	21.2	3150.5	4.2	mBW $\cdot B_{deg4}$	0.12
1	8 – 39%	$1.9 < \|\eta\| < 2.4$	5.6	1.7	3.9	3.5	1.3	22.3	1327.5	7.3	mBW $\cdot B_{deg4}$	0.16
2	8 – 39%	$0.9 < \|\eta\| < 1.9$	10.3	2.8	6.5	6.4	5.2	41.1	2222.2	4.1	mBW $\cdot B_{deg4}$	0.29
3	8 – 39%	$\|\eta\| < 0.9$	3.2	0.8	1.9	2.1	3.5	12.7	775.9	2.9	mBW $\cdot B_{deg4}$	0.17
4	39 – 61%	$1.9 < \|\eta\| < 2.4$	2.9	1.7	2.7	2.7	0.3	11.8	435.0	7.0	mBW $\cdot B_{deg4}$	0.14
5	39 – 61%	$0.9 < \|\eta\| < 1.9$	7.2	3.3	6.1	5.2	1.3	29.2	955.9	4.1	mBW $\cdot B_{deg4}$	0.31
6	39 – 61%	$\|\eta\| < 0.9$	3.6	1.1	2.6	2.2	0.9	14.5	479.3	2.8	mBW $\cdot B_{deg4}$	0.26
7	61 – 76%	$1.9 < \|\eta\| < 2.4$	1.2	1.5	1.8	1.7	0.2	5.2	146.6	7.6	mBW $\cdot B_{deg4}$	0.11
8	61 – 76%	$0.9 < \|\eta\| < 1.9$	4.8	3.6	4.5	4.4	0.7	20.3	514.3	4.2	mBW $\cdot B_{deg4}$	0.29
9	61 – 76%	$\|\eta\| < 0.9$	3.2	1.6	2.3	2.1	0.6	13.1	319.7	3.0	mBW	0.28
10	76 – 91%	$1.9 < \|\eta\| < 2.4$	1.2	3.1	2.2	2.1	0.2	5.8	102.4	7.2	Sum Exp(n=2)	0.14
11	76 – 91%	$0.9 < \|\eta\| < 1.9$	4.4	8.7	6.2	6.0	1.1	20.3	363.3	4.2	mBW	0.34
12	76 – 91%	$\|\eta\| < 0.9$	3.1	4.0	3.8	3.6	0.9	13.7	230.0	3.2	mBW $\cdot B_{deg4}$	0.34
13	91 – 95%	$\|\eta\| < 2.4$	1.7	6.4	2.5	2.6	0.5	8.6	95.5	4.0	mBW	0.28
14	95 – 100%	$\|\eta\| < 2.4$	2.0	19.4	1.5	1.4	0.7	13.7	82.4	4.2	mBW	0.47
overall			59.1	61.1	51.8	52.3	49.2	253.3	12 961.5	3.9		

At low BDT score → best categories are those for which the peak resolution is better (central muons)

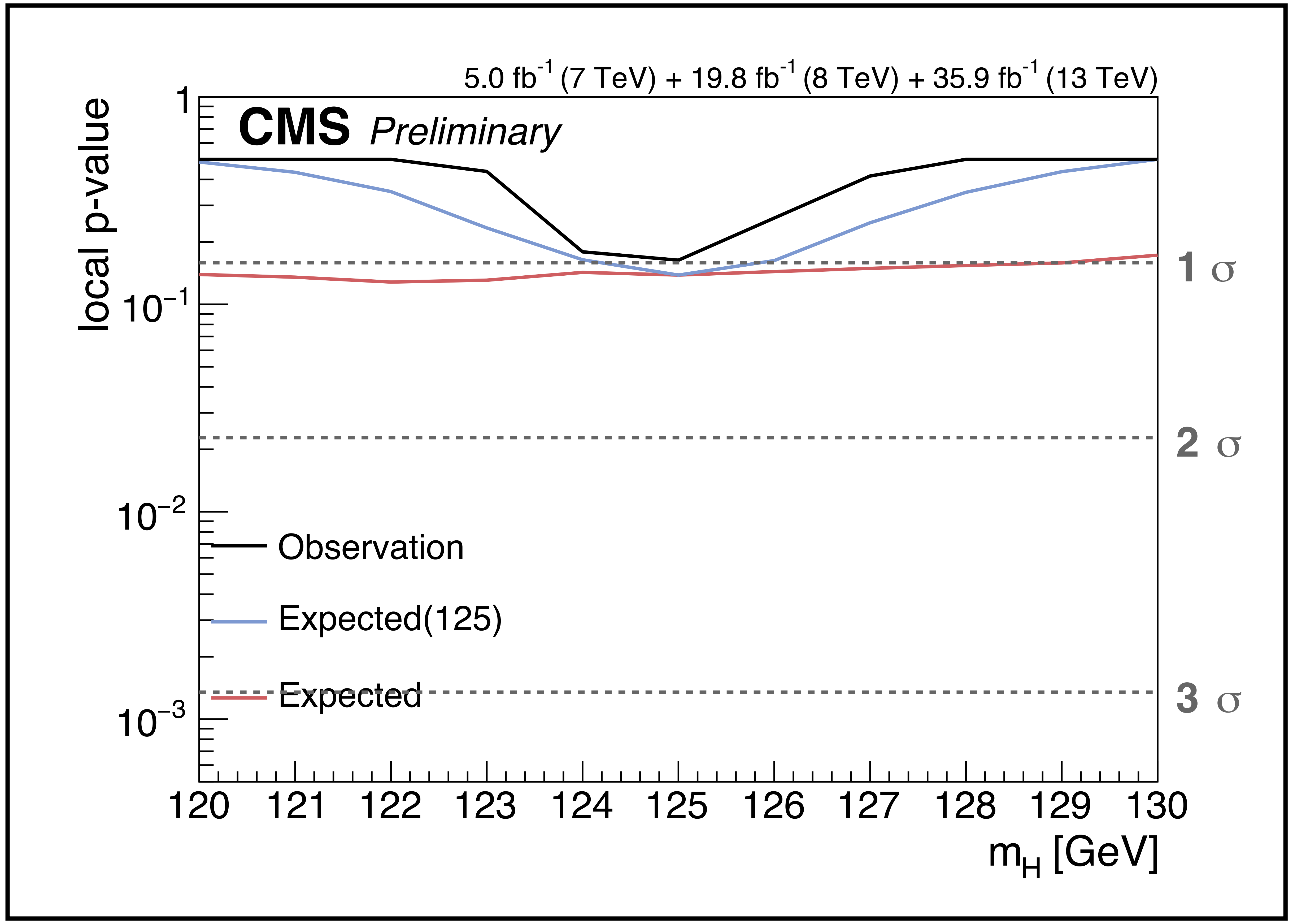
At high BDT score → not eta-categories but sensitivity larger because of smaller background (VBF-tag)

H→μμ: additional material

CMS-HIG-17-019



Modelled with a sum-of-three Gaussians
All categories summed by weighting for S/(S+B)

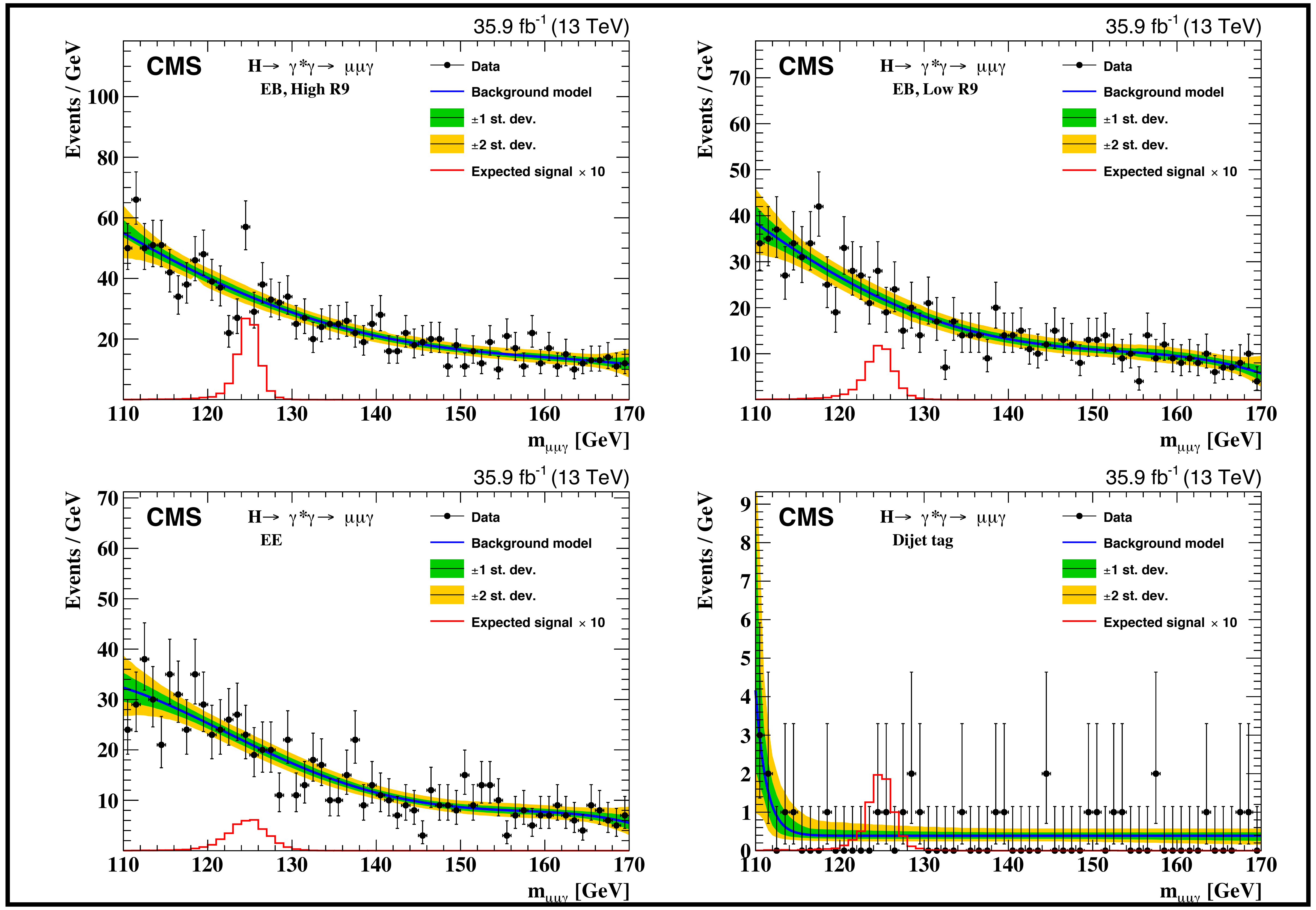


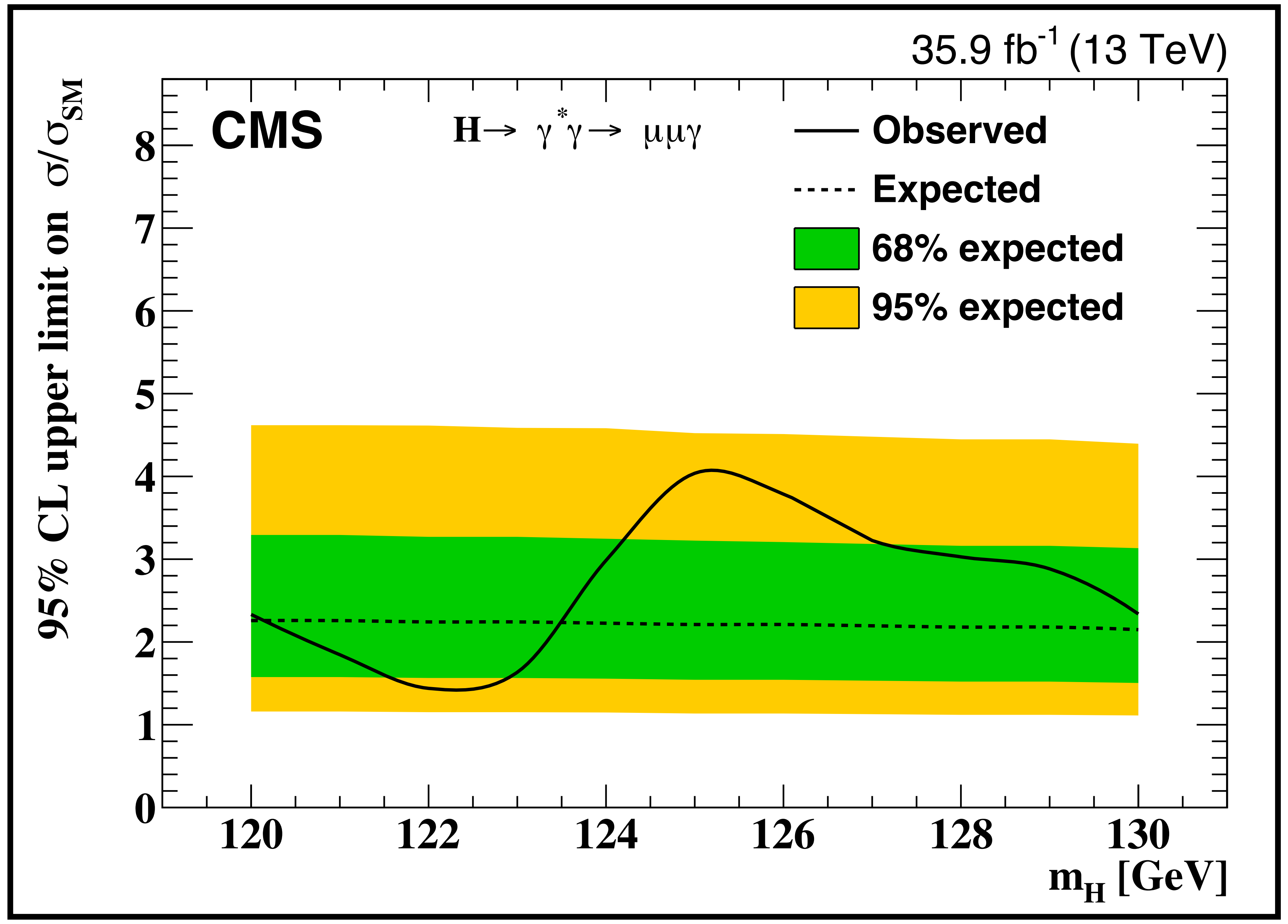
p-value of the b-only hypothesis given the observed data and the possible presence of a signal at a given m_H

p-value obs. (exp.) is about 1σ for m_H = 125 GeV

H→Zγ→ ℓℓγ: additional material

H → γ*γ → μμγ categories



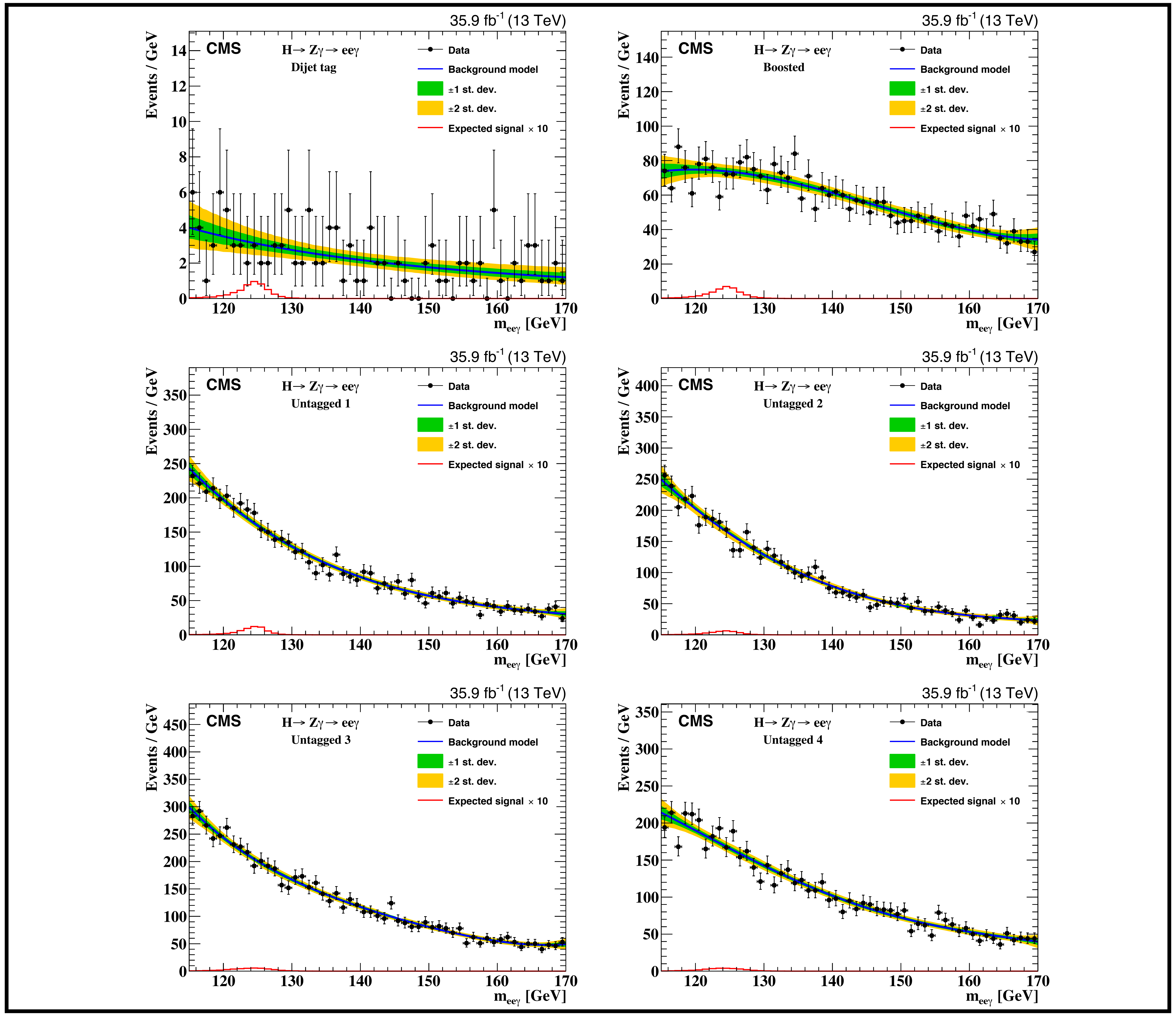


H→Zγ→ ℓℓγ: additional material

arXiv:1806.05996v1

H → Zγ → eeγ categories

Category	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
Lepton tag	Additional electron ($p_T > 7$ GeV) or muon ($p_T > 5$ GeV)	
Dijet tag	At least 2 jets required	At least 2 jets required
Boosted	$p_T(ee\gamma) > 60$ GeV	$p_T(\mu\mu\gamma) > 60$ GeV
Untagged 1	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 1.4442$ $R_9 > 0.94$	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 > 0.94$
Untagged 2	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 1.4442$ $R_9 < 0.94$	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 < 0.94$
Untagged 3	Photon $0 < \lvert\eta\rvert < 1.4442$ At least one lepton $1.4442 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons in $\lvert\eta\rvert > 0.9$ or one lepton in $2.1 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Untagged 4	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9



H→Zγ→ ℓℓγ: additional material

arXiv:1806.05996v1

H → Zγ → μμγ categories

Category	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
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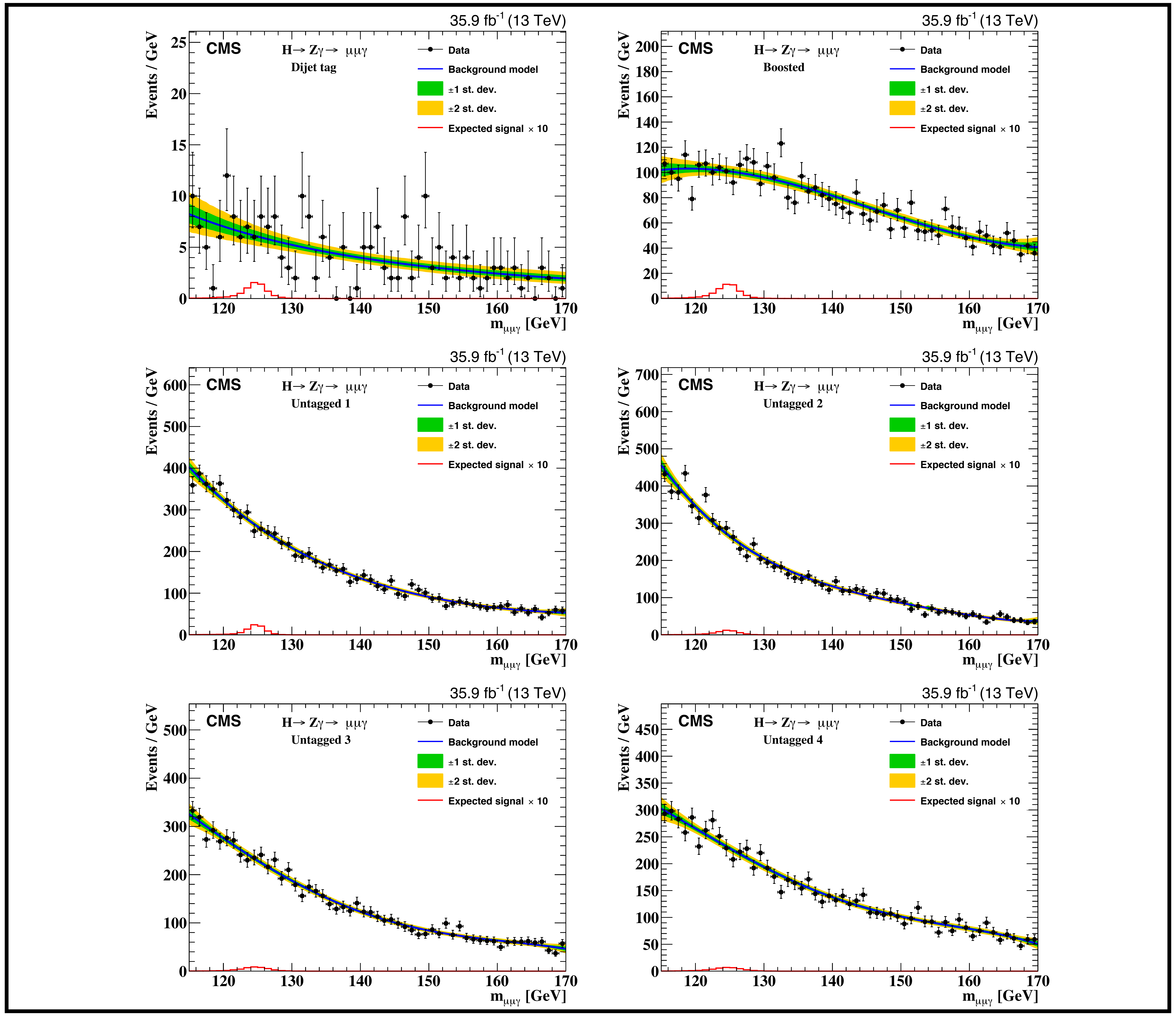
Untagged 2	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 1.4442$ $R_9 < 0.94$	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 < 0.94$
Untagged 3	Photon $0 < \lvert\eta\rvert < 1.4442$ At least one lepton $1.4442 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons in $\lvert\eta\rvert > 0.9$ or one lepton in $2.1 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Untagged 4	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9



H→Zγ→ ℓℓγ: additional material

arXiv:1806.05996v1

H → Zγ → eeγ and μμγ categories

Category	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
Lepton tag	Additional electron ($p_T > 7$ GeV) or muon ($p_T > 5$ GeV)	
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Untagged 1	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 > 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 > 0.94$
Untagged 2	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 < 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 < 0.94$
Untagged 3	Photon $0 < \|\eta\| < 1.4442$ At least one lepton $1.4442 < \|\eta\| < 2.5$ No requirement on R_9	Photon $0 < \|\eta\| < 1.4442$ Both leptons in $\|\eta\| > 0.9$ or one lepton in $2.1 < \|\eta\| < 2.4$ No requirement on R_9
Untagged 4	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.5$ No requirement on R_9	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.4$ No requirement on R_9