Searches for Higgs bosons beyond the Standard Model

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Higgs, as a gateway to BSM

- In a decade, the journey of the SM Higgs boson:
  - signal
  - background (e.g Rare SM measurements, eg. VVV)
  - **discovery tool**

- H serves as a “**standard candle**” in BSM analyses
  - known mass, known decays

    ex/ $\mathrm{H} \rightarrow \mathrm{bb}$ tagging

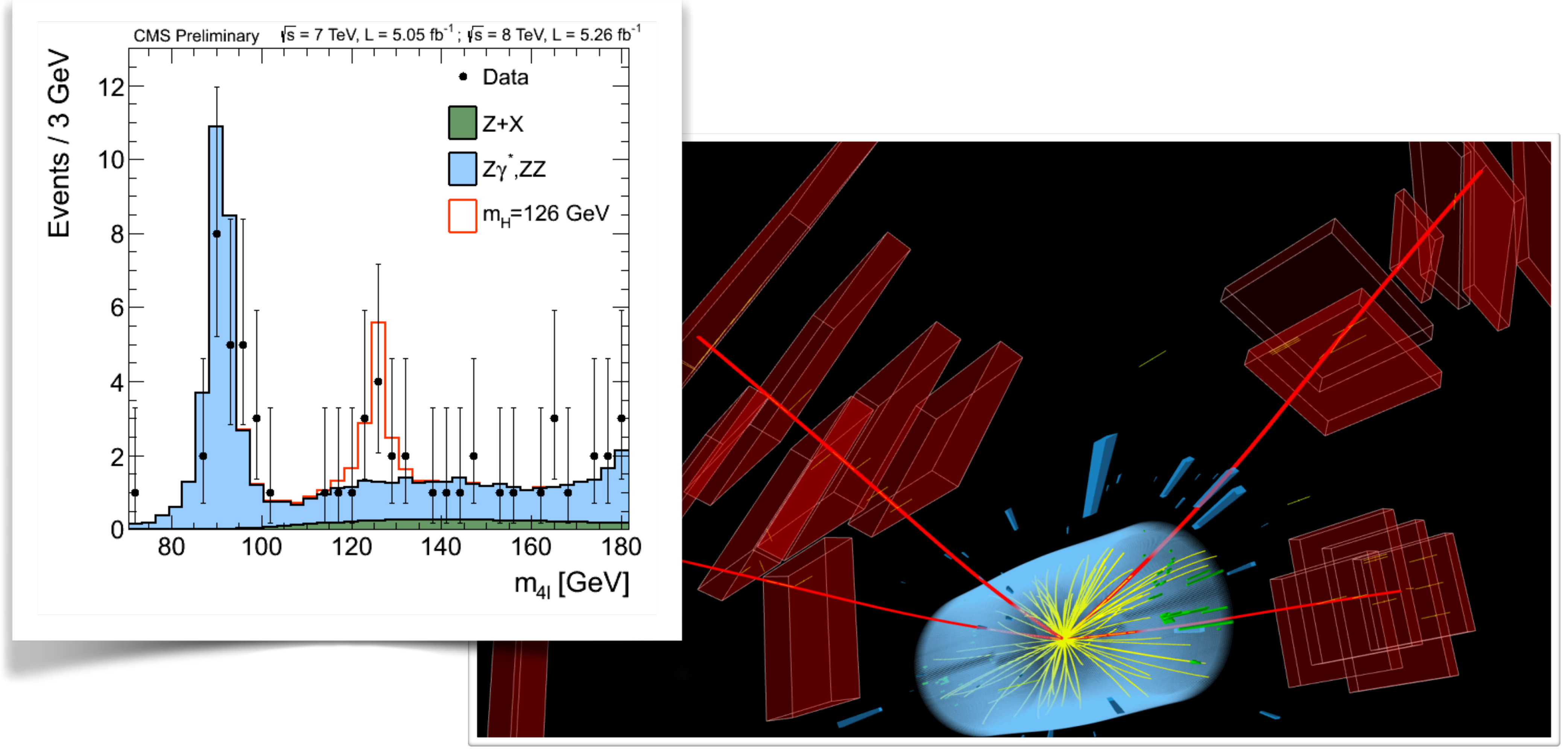
- Particles in an **extended scalar sector** (with hidden dynamics) could **mix** with the SM Higgs

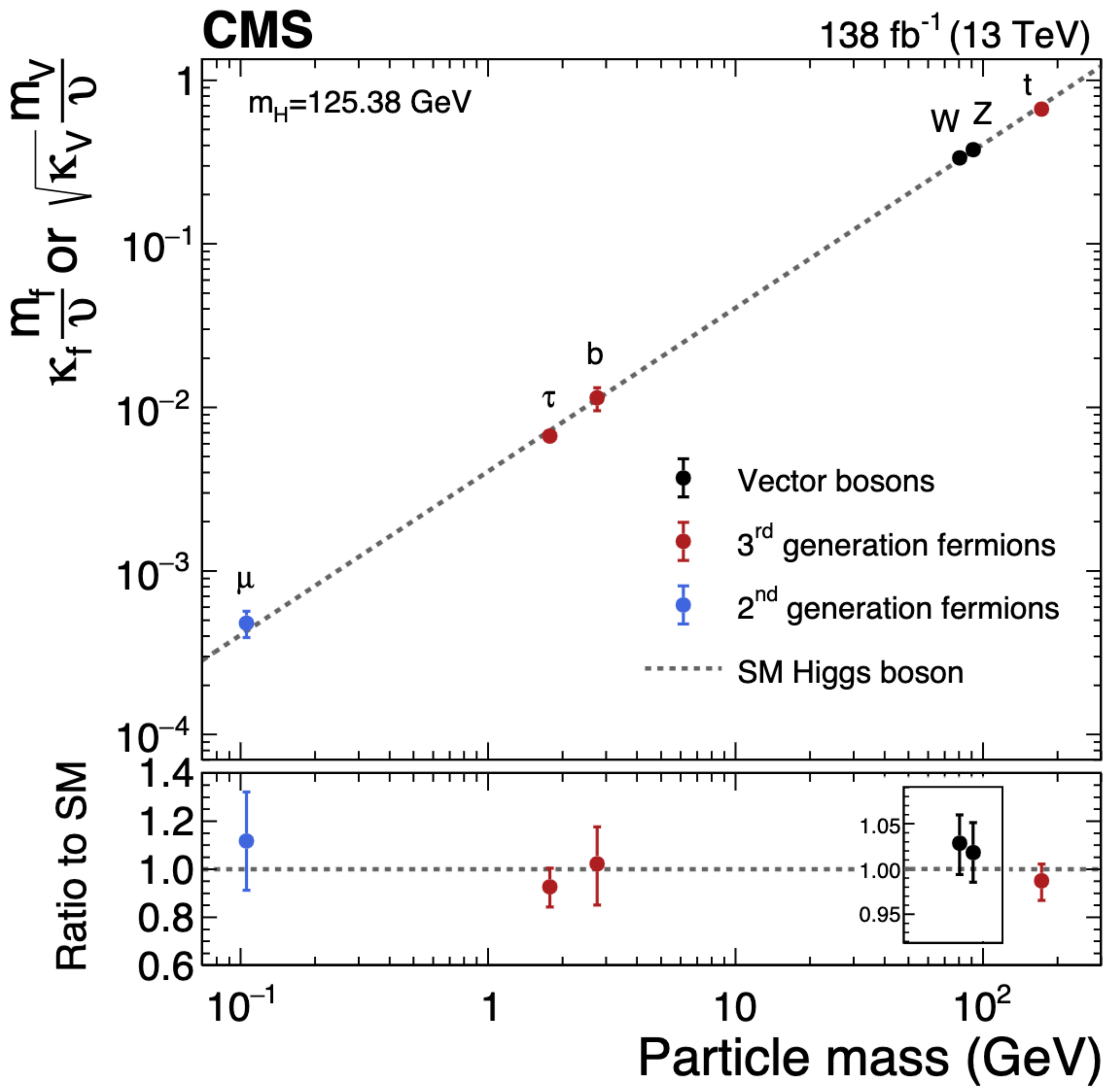
  → **Higgs-like decays of the new exotic particles**

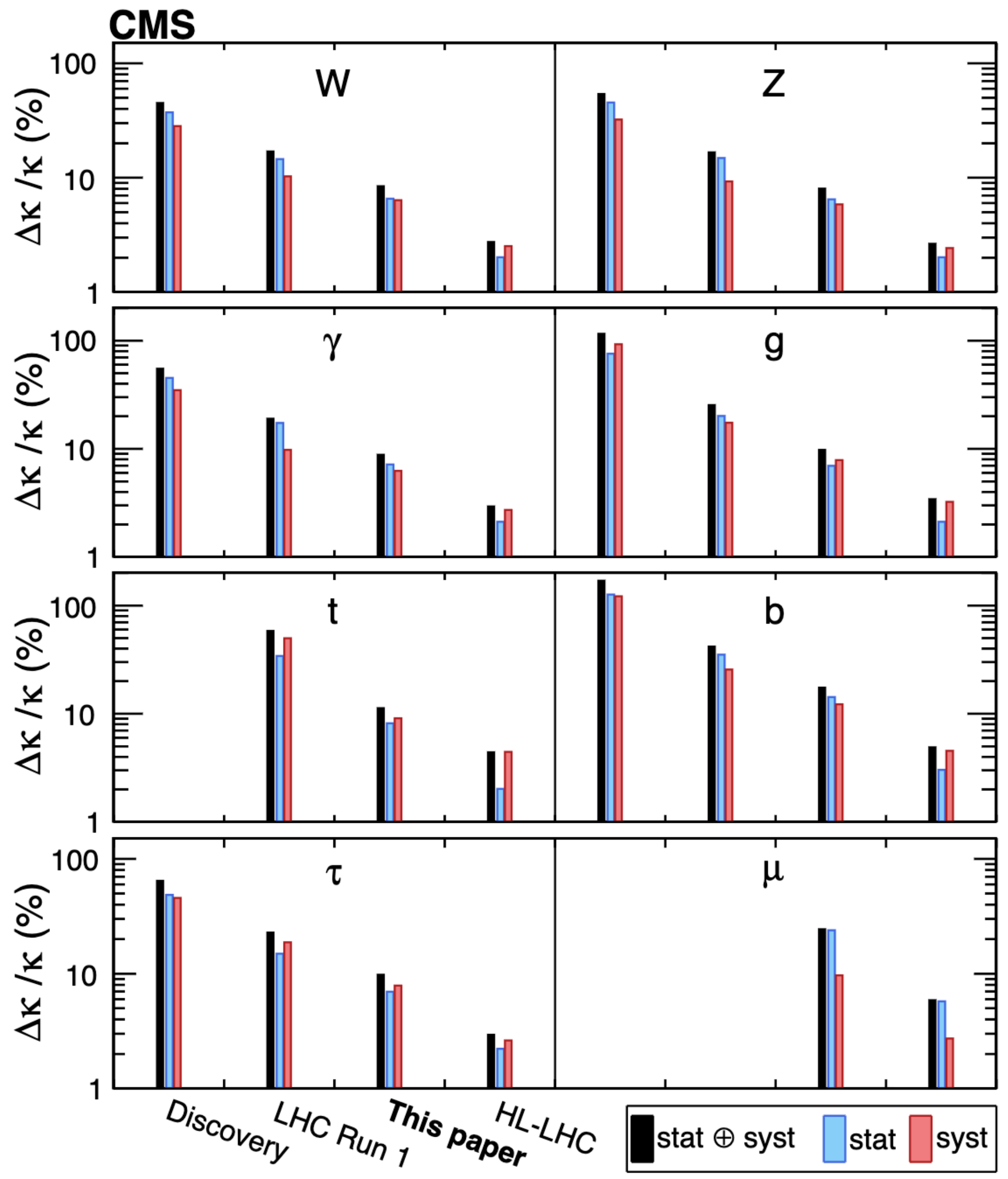
- **Higgs has** sufficient **freedom** for exotic couplings

  BR(H→non-SM) could be up to $\mathcal{O}(10)$ %

  → Can act as **portal to hidden sectors**





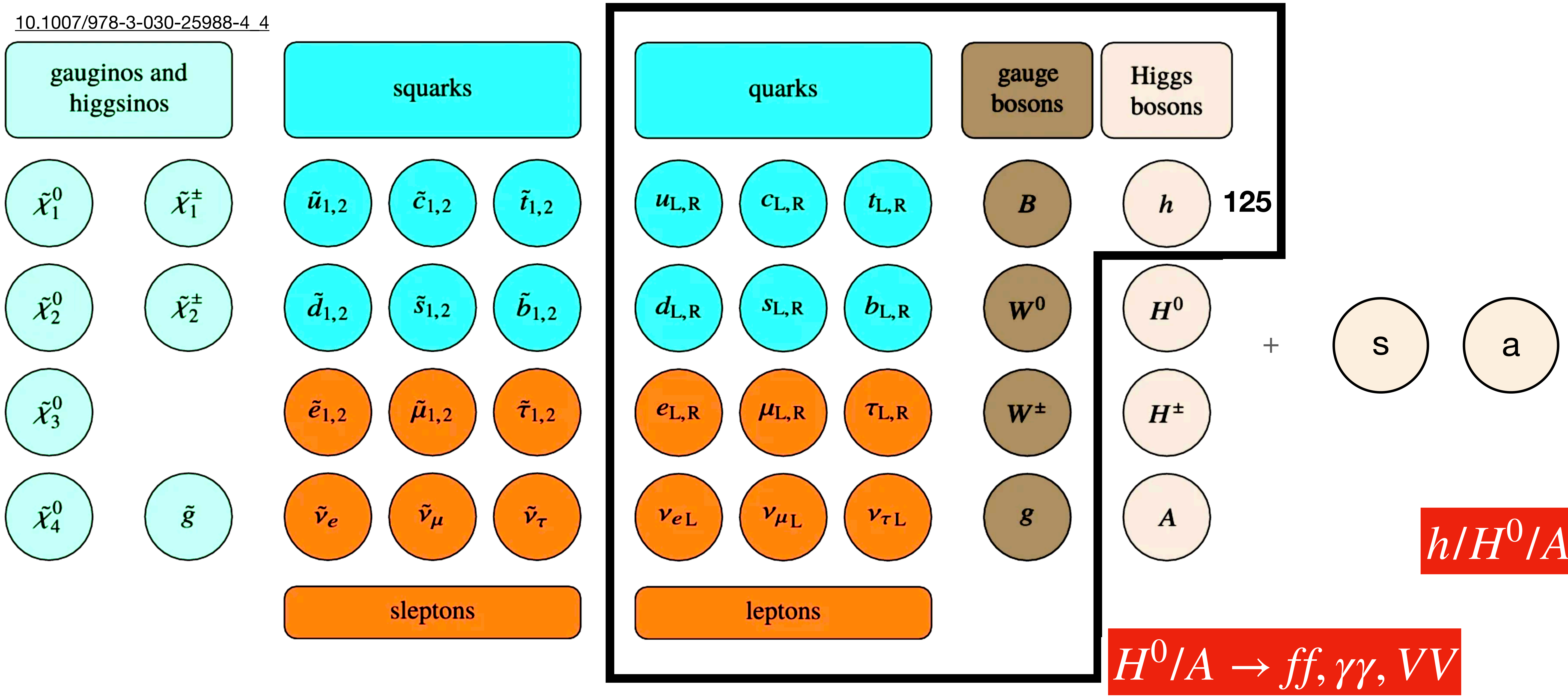


CMS-HIG-22-001

The extended scalar sector

(aka the many ways to add spin-0 states)

10.1007/978-3-030-25988-4_4



$h/H^0/A \rightarrow aa$

$a \rightarrow ff$

$H^0/A \rightarrow ff, \gamma\gamma, VV$

SM

$H^+ \rightarrow H^0/hW,\ tb, ..$

2HDM+S

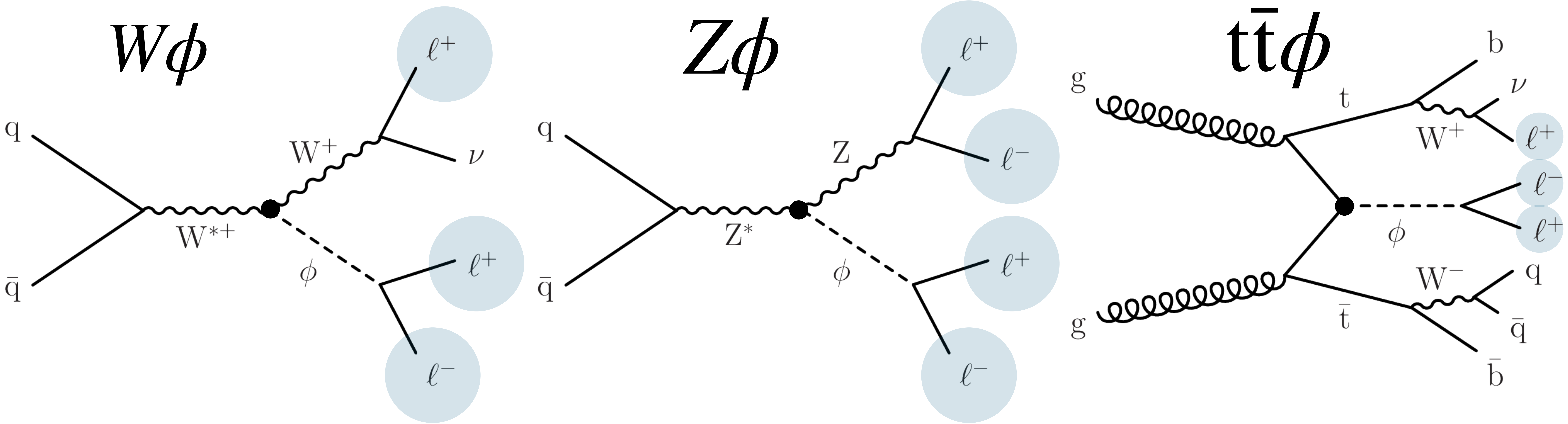
MSSM

2HDM

NMSSM

Search for Xϕ→ℓℓ

EXO-21-018



- Search for a new spin-0 particle in **associated production with a W/Z boson or a tt pair**
  - signal width is assumed to be smaller than detector resolution
  - **target mass range: 15-350 GeV**

- **Model independent** analysis:
  - all lepton **flavor** pairs $(\mathrm{ee}, \mu\mu, \tau\tau)$
  - all possible **coupling** types (scalar, pseudoscalar, Higgs-like production/decay) → **24 different scenarios**

$$\frac{1}{\Lambda_S}\phi_S F^{a\mu\nu}F^{a}_{\mu\nu} + \frac{1}{\Lambda_{PS}}\phi_{PS} F^{a\mu\nu}\tilde{F}^{a}_{\mu\nu} \qquad -\frac{g_{\psi S}}{\sqrt{2}}\phi_S\bar{\psi}\psi - \frac{g_{\psi PS}}{\sqrt{2}}\phi_{PS}\bar{\psi}i\gamma_5\psi \qquad -2\sin\theta\,\frac{\phi_H}{v}\left(m_W^2 W^{+\mu}W^{-}_{\mu} + \frac{1}{2}m_Z^2 Z^{\mu}Z_{\mu}\right)$$

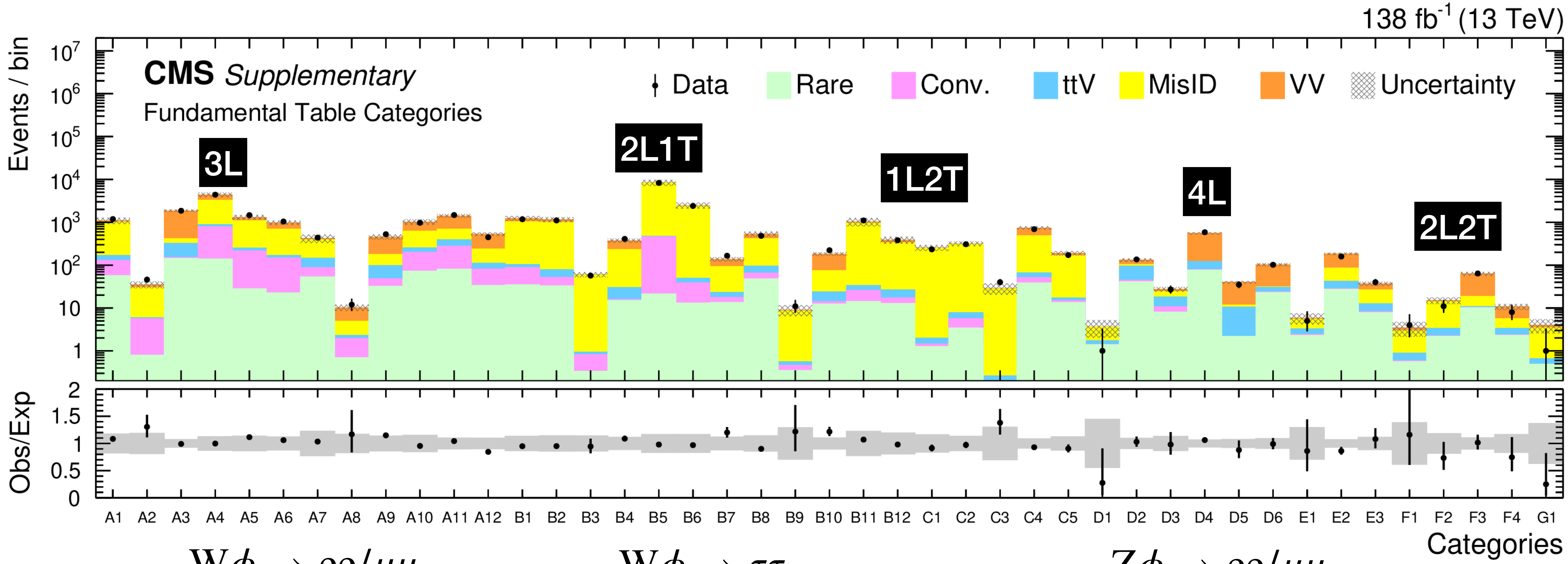
Search for $X\phi \to \ell\ell$

EXO-21-018
EXO-21-002

- Builds on an **inclusive multilepton analysis** with many categories
  - **3 and 4 lepton** final states (e, μ, τ) are used
  - **dilepton resonance** in multilepton events
  - first of its type “bump-hunt” at the LHC!
- A variety of SM backgrounds: WZ, ZZ, ttZ, ttW, Zγ, VVV, …
  - data driven estimation of backgrounds with $j \to e/\mu/\tau$

Charge/mass/flavor/…

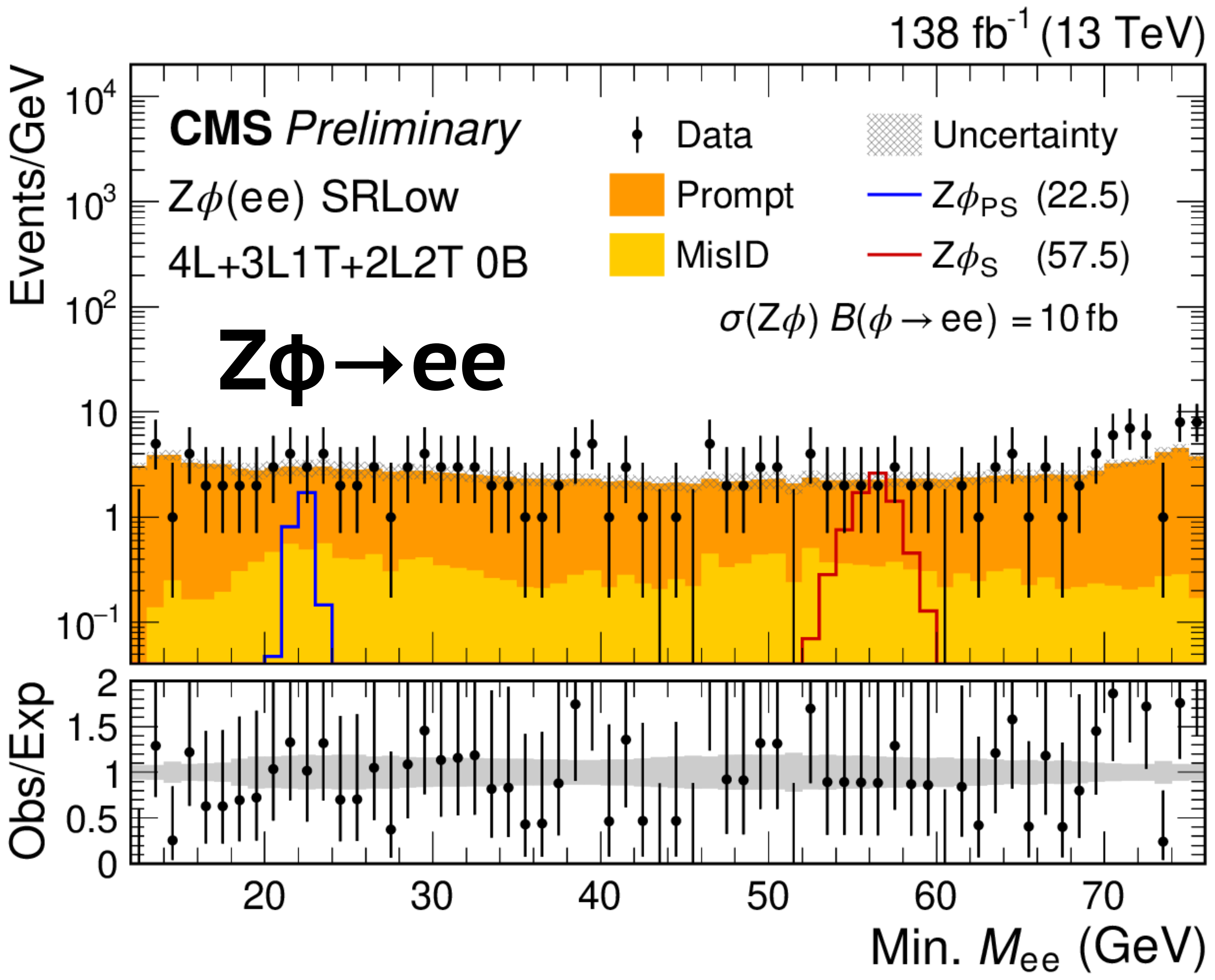
		OSSF0 BelowZ	OSSF0 AboveZ	SS	OSSF1 OnZ	OSSF1 BelowZ	OSSF1 AboveZ	OSSF1 MixedZ	OSSF2 Single-OnZ	OSSF2 Double-OnZ	OSSF2 OffZ
3L	Low p_T/M_T	A1	A1	A2	A3	A4	A5	A6	—	—	—
	High p_T/M_T	A7	A7	A8	A9	A10	A11	A12	—	—	—
2L1T	Low p_T	B1	B2	B3	B4	B5	B6	—	—	—	—
	High p_T	B7	B8	B9	B10	B11	B12	—	—	—	—
1L2T		C1	C2	C3	—	C4	C5	—	—	—	—
4L		D1	D1	D1	D2	D3	D3	D3	D4	D5	D6
3L1T		E1	E1	E1	E2	E3	E3	E3	—	—	—
2L2T		F1	F1	F1	F2	F2	F2	—	F3	—	F4
1L3T		G1	G1	G1	—	G1	G1	—	—	—	—

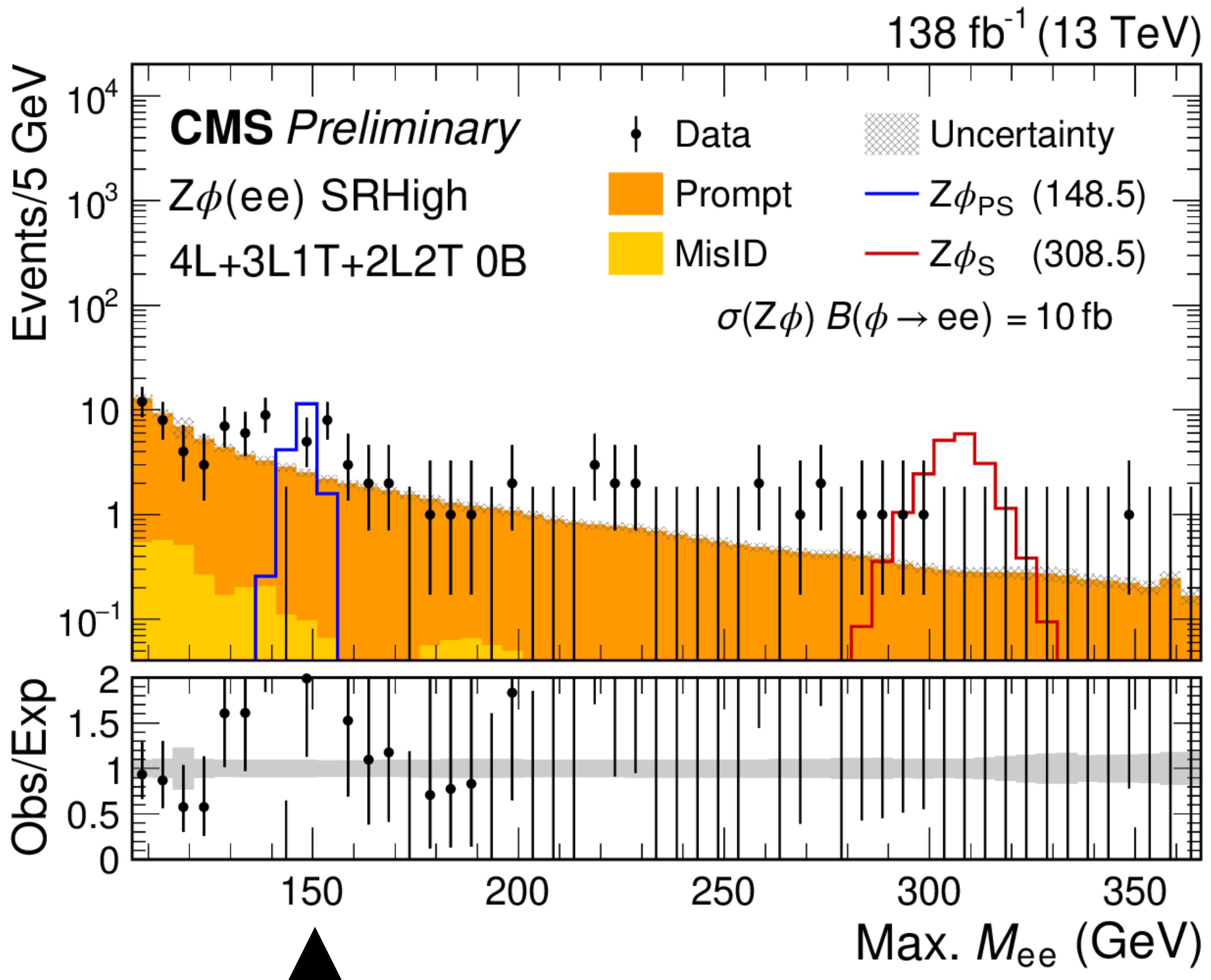


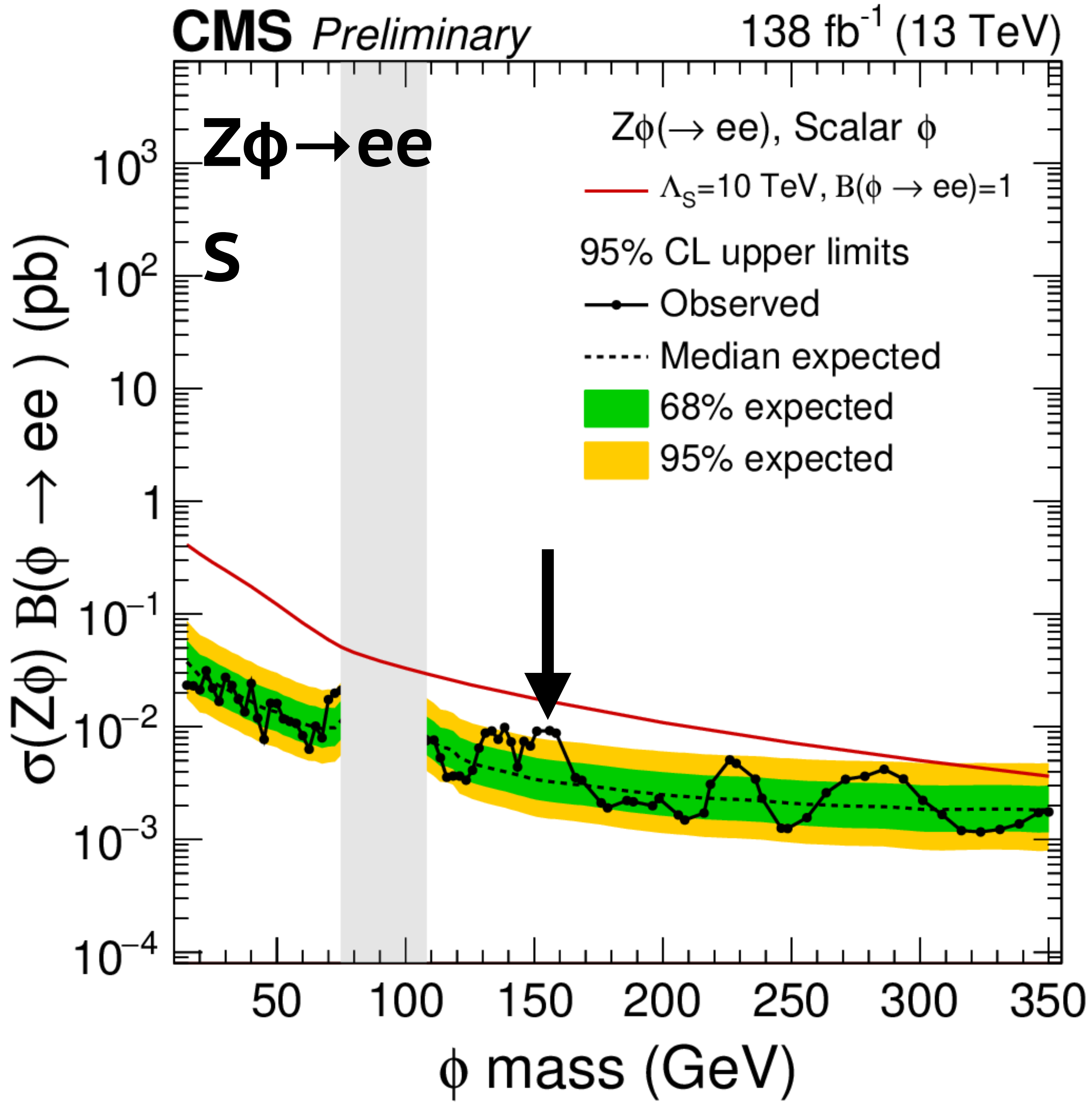
$W\phi \to ee/\mu\mu$
$t\bar{t}\phi \to ee/\mu\mu$
$W\phi \to \tau\tau$
$t\bar{t}\phi \to \tau\tau$
$Z\phi \to ee/\mu\mu$
$Z\phi \to \tau\tau$

Search for Zϕ→ℓℓ

EXO-21-018





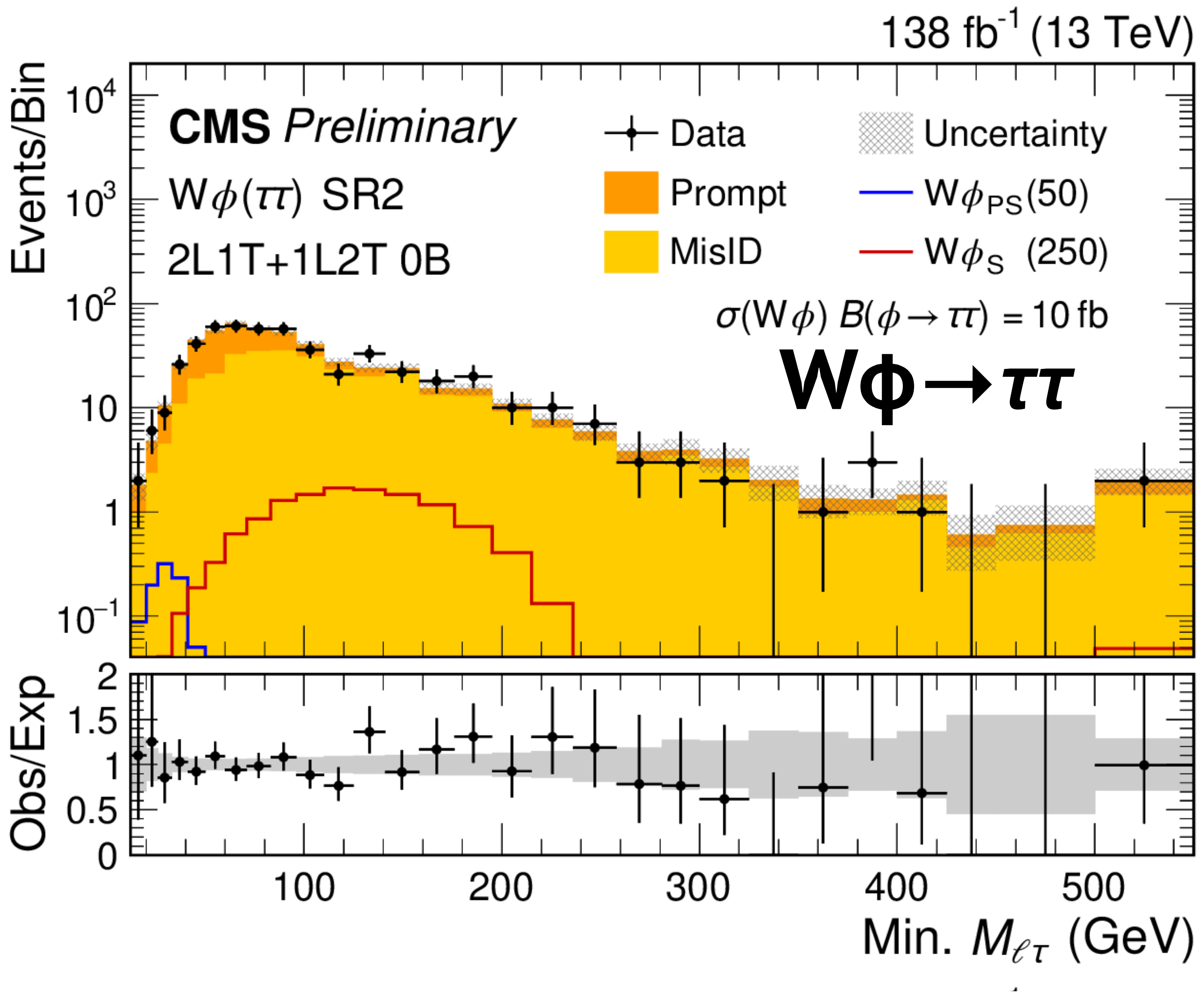


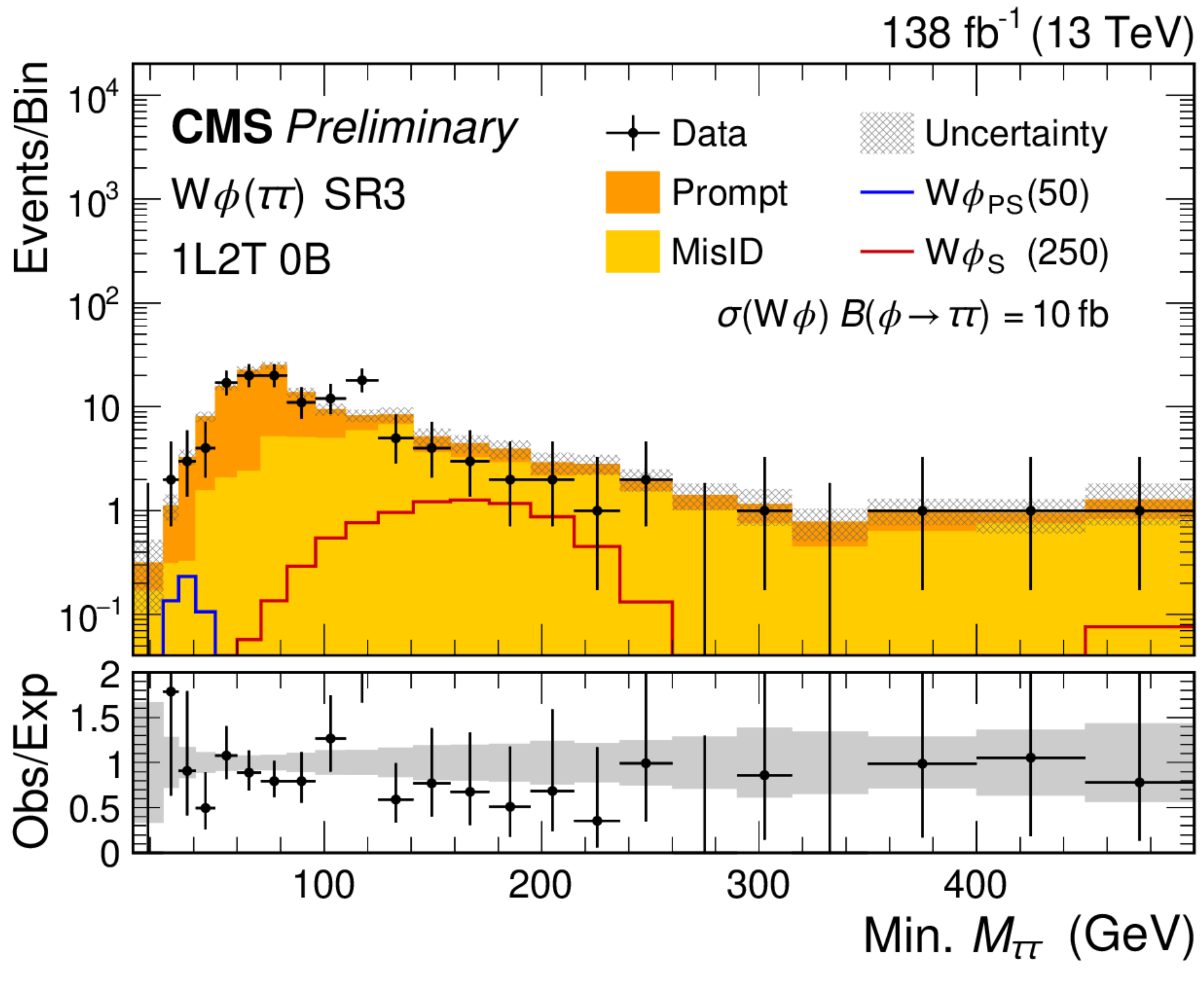
- Probes **9 different scenarios** (only $Z\phi \rightarrow$ ee **scalar** is shown)
- **4-lepton** channels dominate
- A binned maximum likelihood fit is performed on the dilepton mass

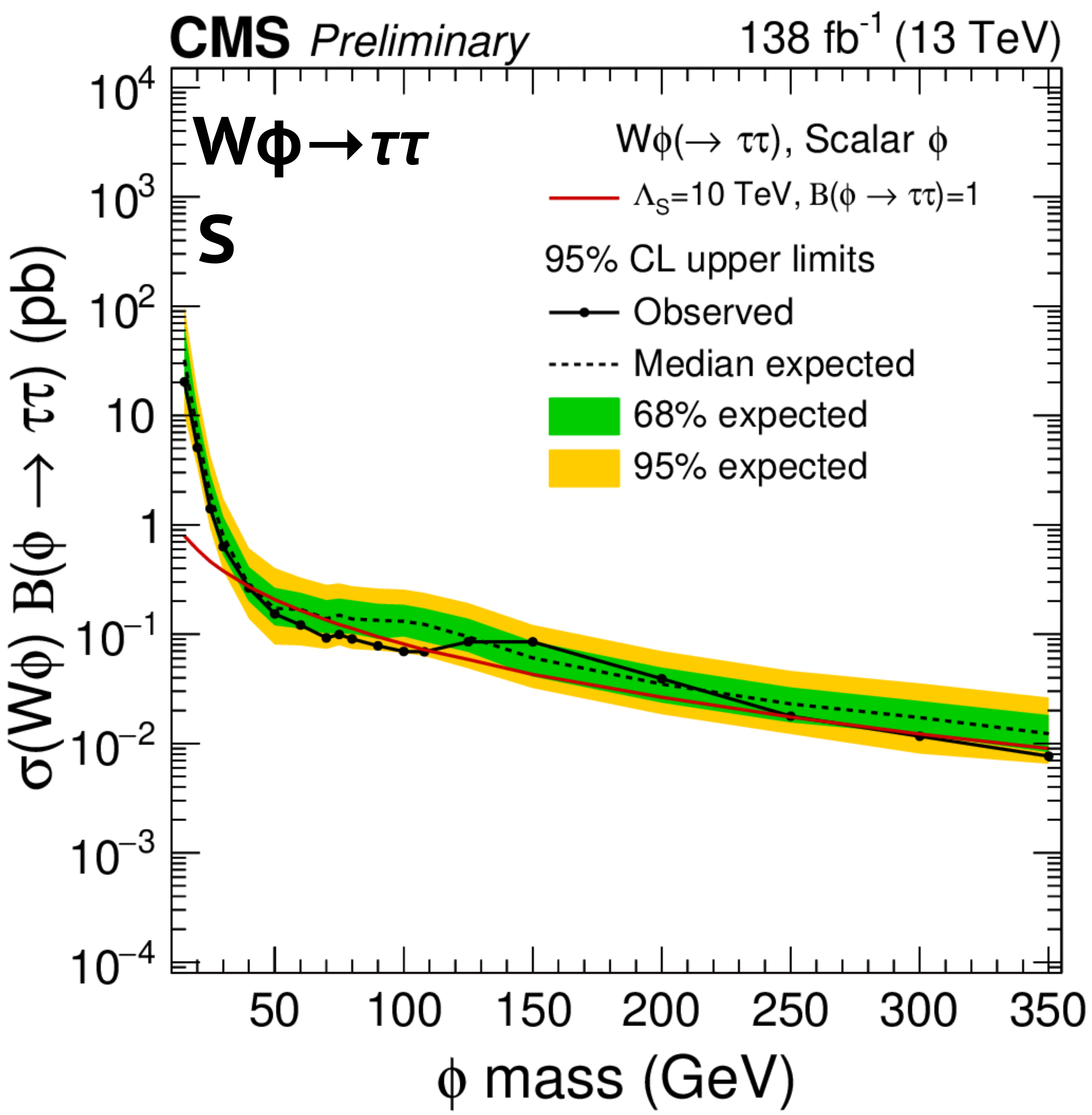
Excess at $m_\phi = 156$ GeV
2.9 (1.4) sigma local (global)

Search for Wϕ→ℓℓ

EXO-21-018



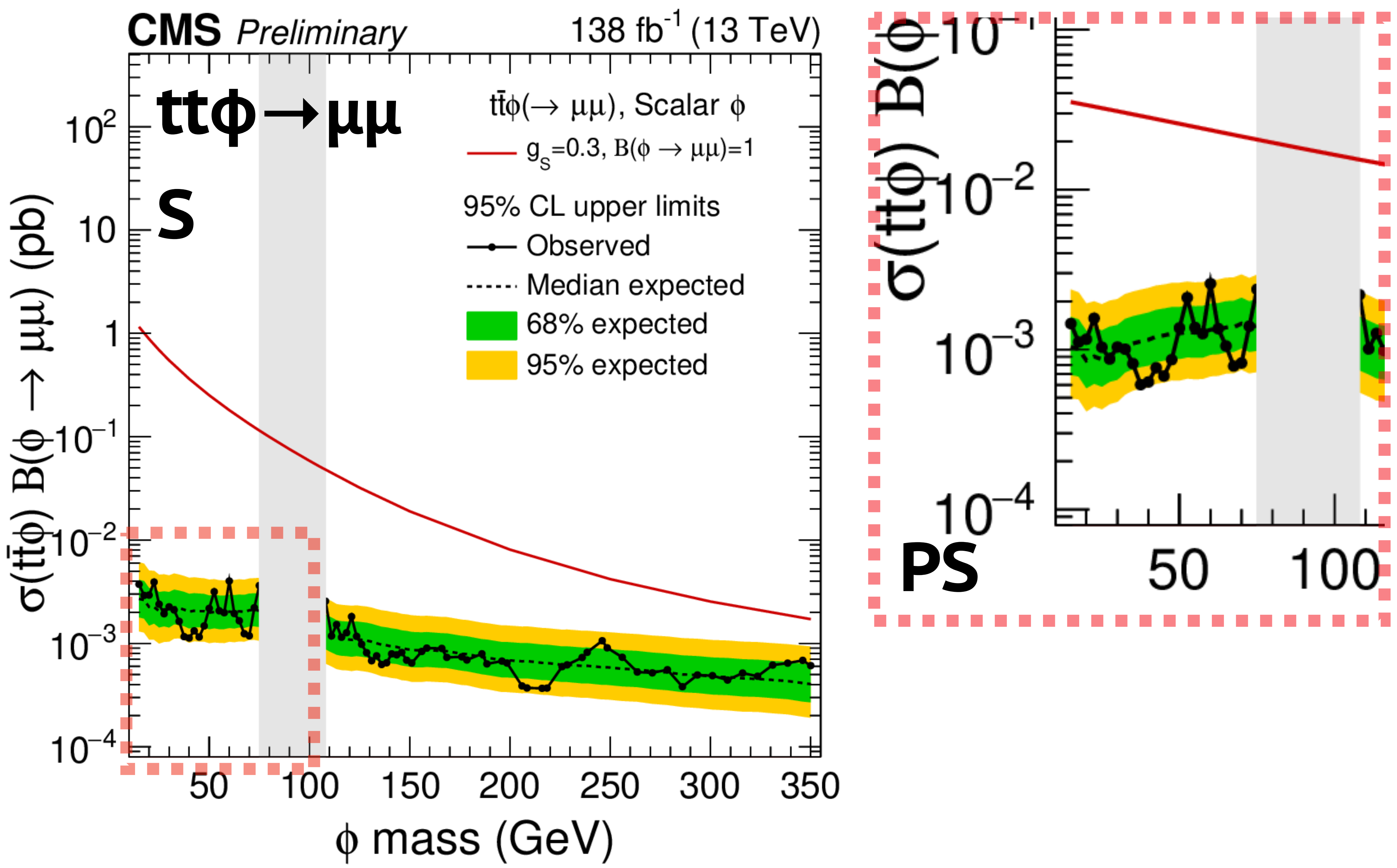


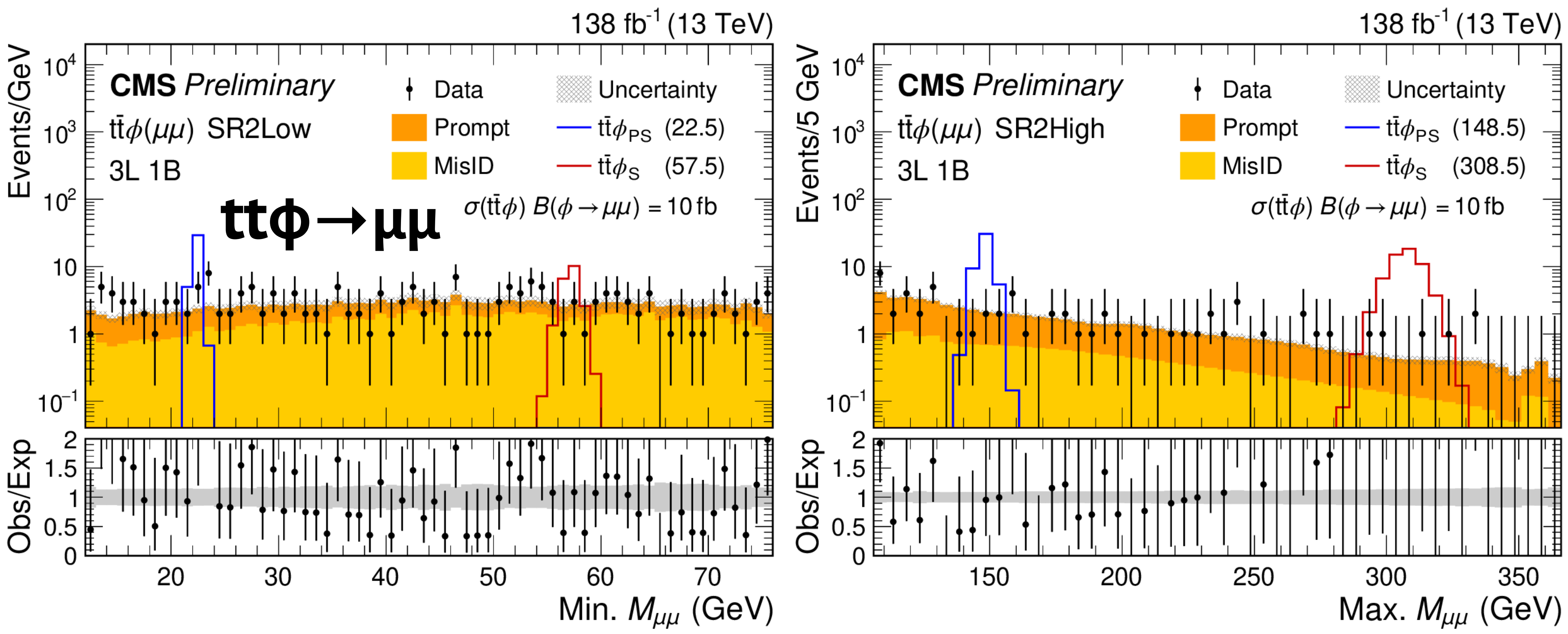


- **9 different scenarios** are probed (only $W\phi \rightarrow \tau\tau$ **scalar** is shown)
- **3 lepton channels** dominate (mostly with two hadronic tau candidates)
- $\phi \rightarrow \tau\tau$ decays produce **broad 'resonances'** $(e\mu, \ell\tau_h, \tau_h\tau_h)$
- τ_h reconstruction degrades at low p_T, **impacts sensitivity** at low mass

Search for ttϕ→ℓℓ

EXO-21-018





- **6 scenarios** are probed (only $\mu\mu$ **scalar/pseudoscalar** is shown)
- **Combination of 3 and 4 lepton channels** contribute
- Analysis sensitivity at low mass is **different between PS and S**:
  - fermionic couplings both in production and decay
  - **boosted ϕ decays** help in the PS scenario (esp. for e/μ)

Alternate bounds on couplings in various models are **coming soon (HEPData)**:

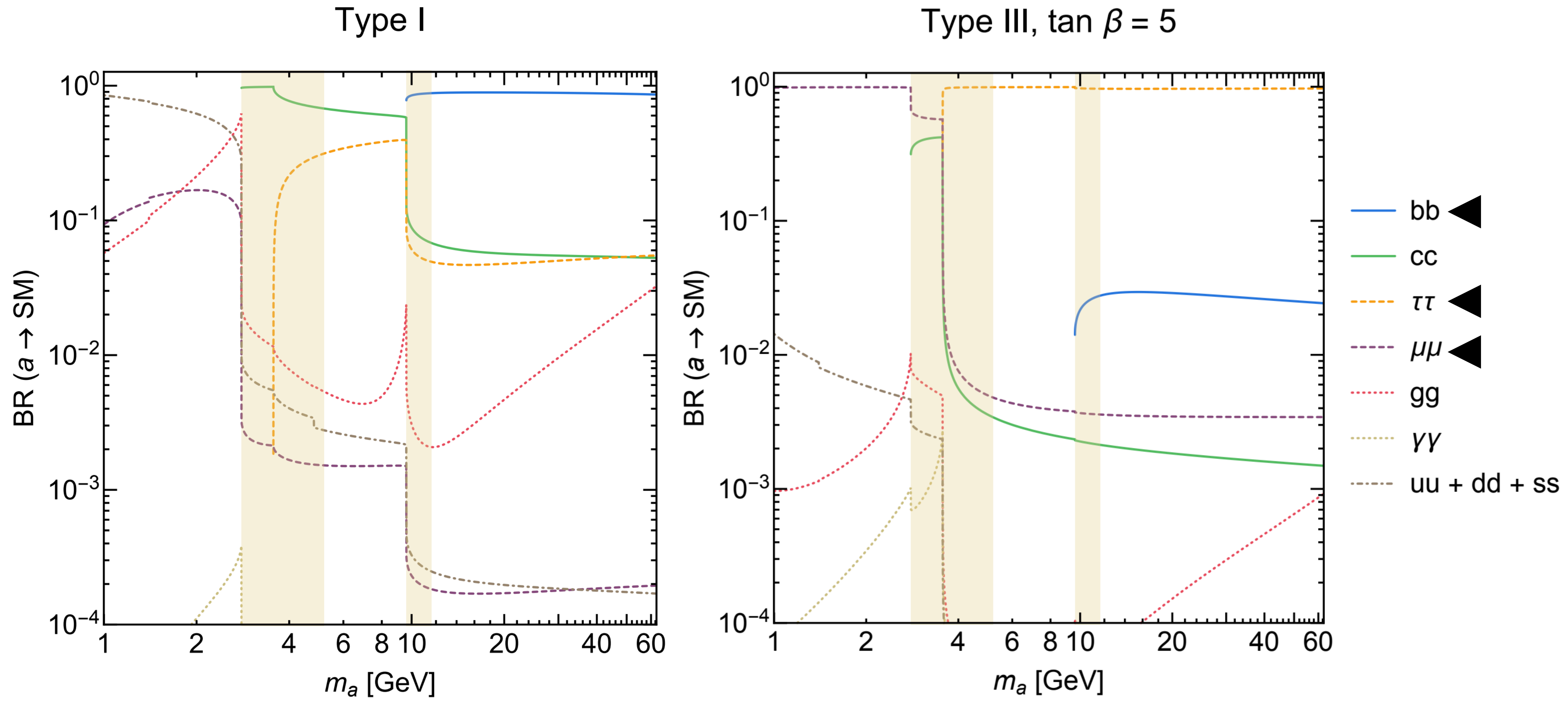
- Higgs-mixed scalar
- axion like particles
- dilaton like particles

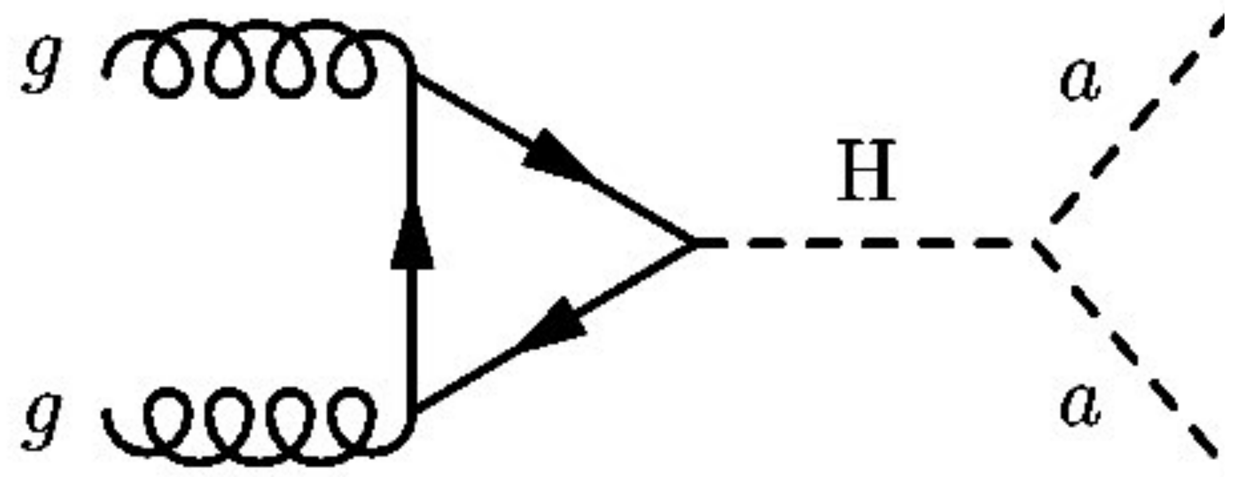
$$\sigma \sim g^2 \quad \text{or} \quad 1/\Lambda^2$$

Light pseudoscalars: H→aa

HIG-21-021
HIG-22-007

- Exotic Higgs boson decays to new lighter states are **still allowed**
- Probing a light pseudoscalar in the mass range **15 - 62.5 GeV** $(m_a < m_H/2)$
- Pseudoscalar-fermion couplings are **inherited via mixing** with the SM Higgs
  - bb, $\tau\tau$, $\mu\mu$ decay modes dominate at low masses





$\mathrm{H} \rightarrow \mathrm{aa} \rightarrow \mu\mu\mathrm{bb} \,/\, \tau\tau\mathrm{bb}$

Two complementary decay modes are targeted, leading to 4 distinct final states:

$\mu\mu\mathrm{bb}$ $\quad \tau_e\tau_\mu\mathrm{bb}$ $\quad \tau_e\tau_h\mathrm{bb}$ $\quad \tau_\mu\tau_h\mathrm{bb}$

High mass resolution ($\mu\mu$)

Large BR in large parts of parameter space (bb, $\tau\tau$)

Other CMS results: $\mu\mu\mu\mu$, $\tau\tau\tau\tau$, $\mu\mu\tau\tau$, $\gamma\gamma\gamma\gamma$ etc

Signal model includes ggF (~48 pb) and the VBF (~3.9 pb) contributions

Part 1: H→aa→μμbb

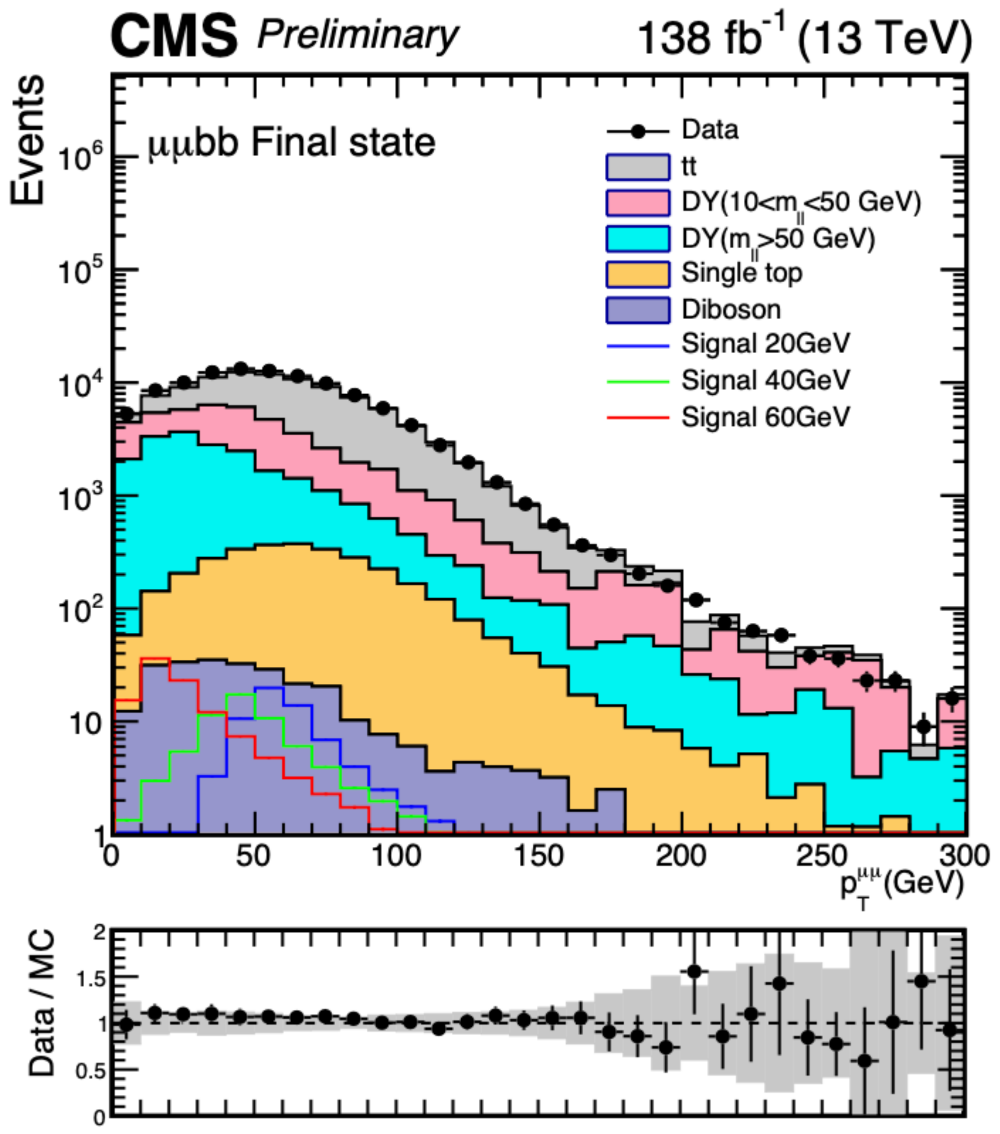
HIG-21-021
HIG-22-007

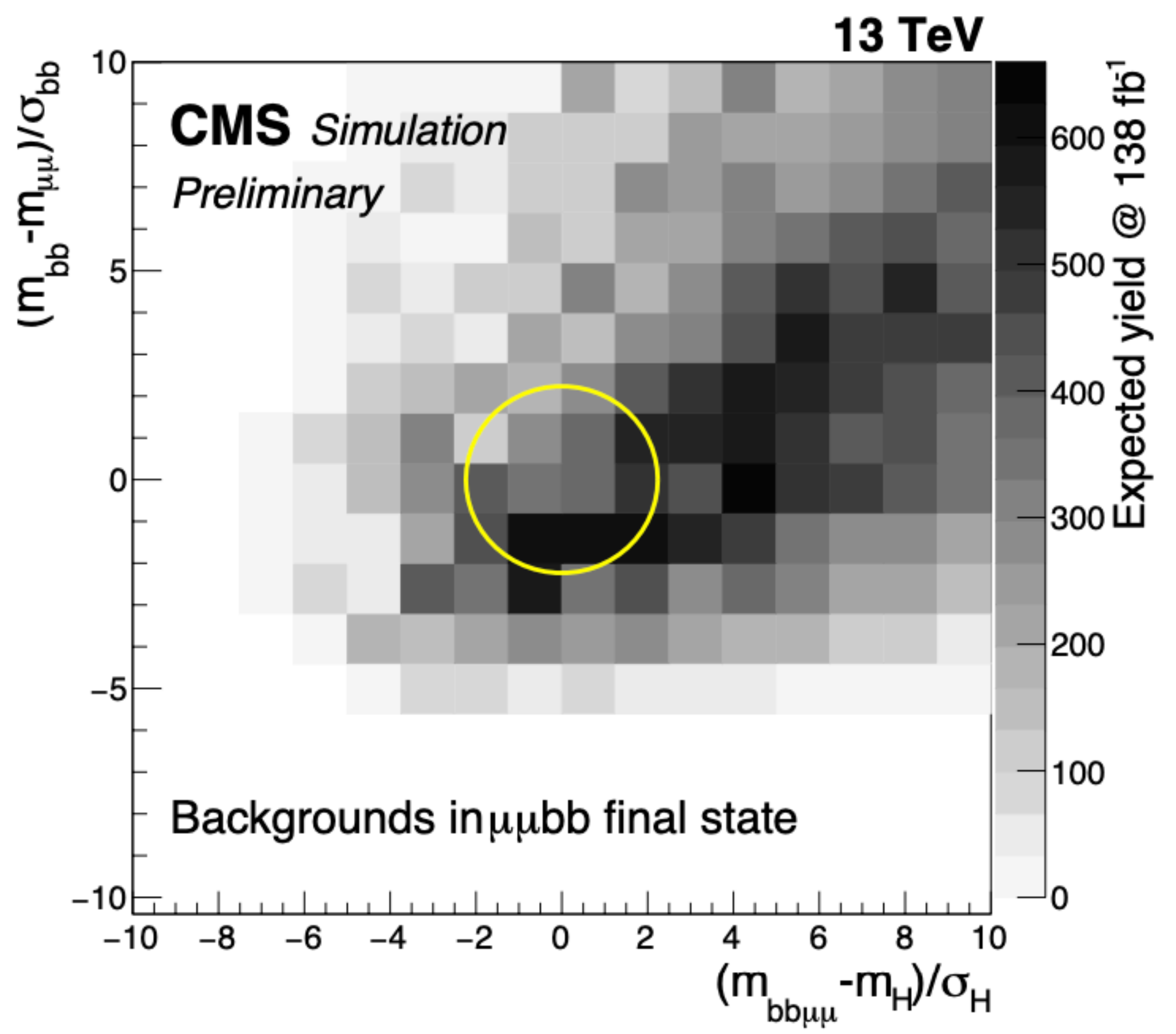
- Final state with 2 muons and 2 b-tagged jets
  - 5 distinct categories are defined, based on jet qualities
- Dominant SM **tt background** is reduced by MET<60 GeV requirement
- Mass resolution is used to define "**double resonance consistency cuts**"

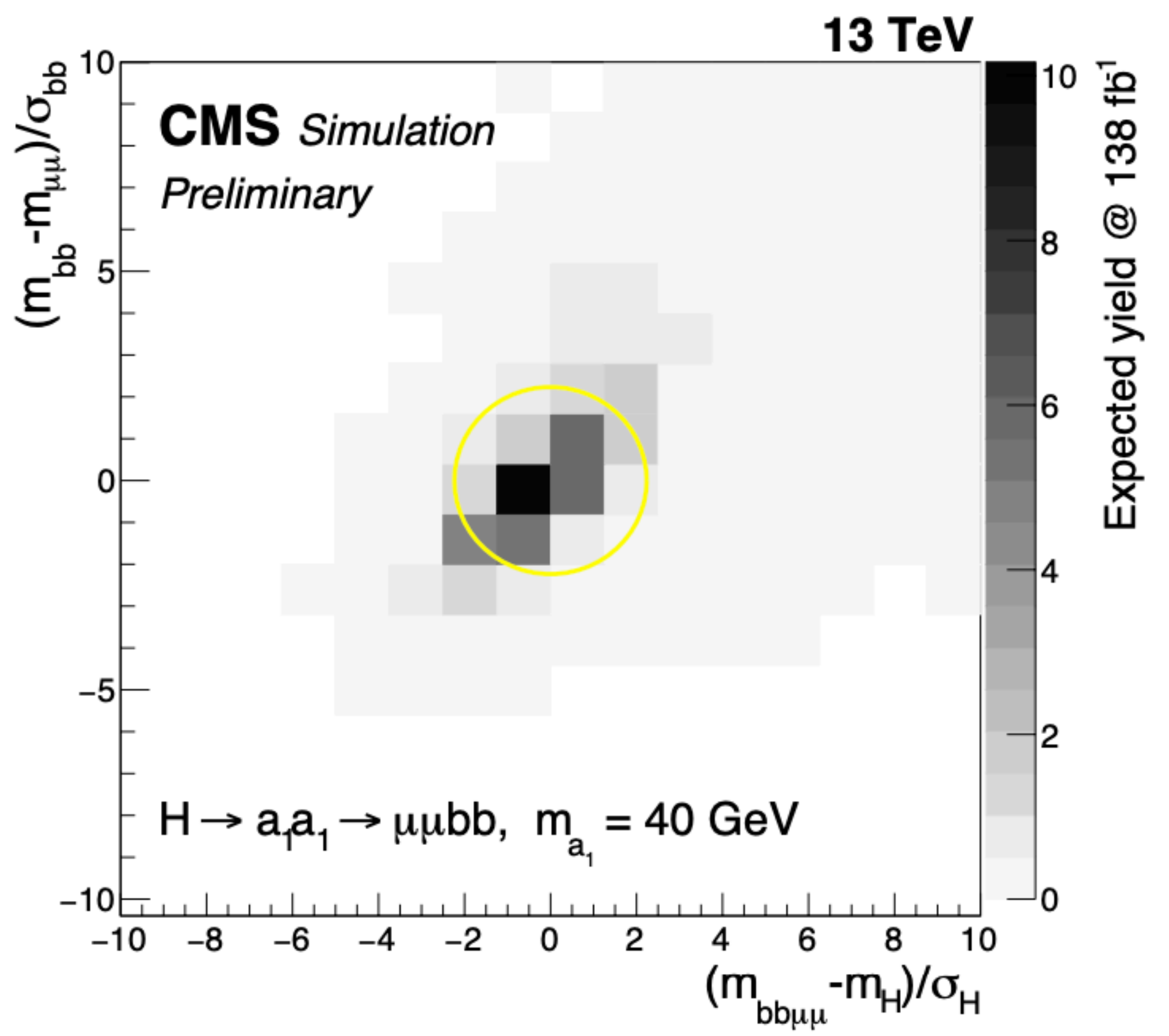
$$\chi^2_{tot} = \chi^2_{bb} + \chi^2_{H} \quad \text{where } \chi_{bb} = (m_{bb} - m_{\mu\mu})/\sigma_{bb} \quad \text{and} \quad \chi_{H} = (m_{\mu\mu bb} - 125)/\sigma_{H}$$

Categories for selected events	
Low p_T	at least one b-jet with $p_T < 20$ GeV
VBF	two add. jets with $p_T > 30$ GeV, $\lvert\eta\rvert < 4.7$, and $m_{jj} > 250$ GeV
TL	looser b jet passes L but fails M
TM	looser b jet passes M but fails T
TT	looser b jet passes T

Improves low mass sensitivity



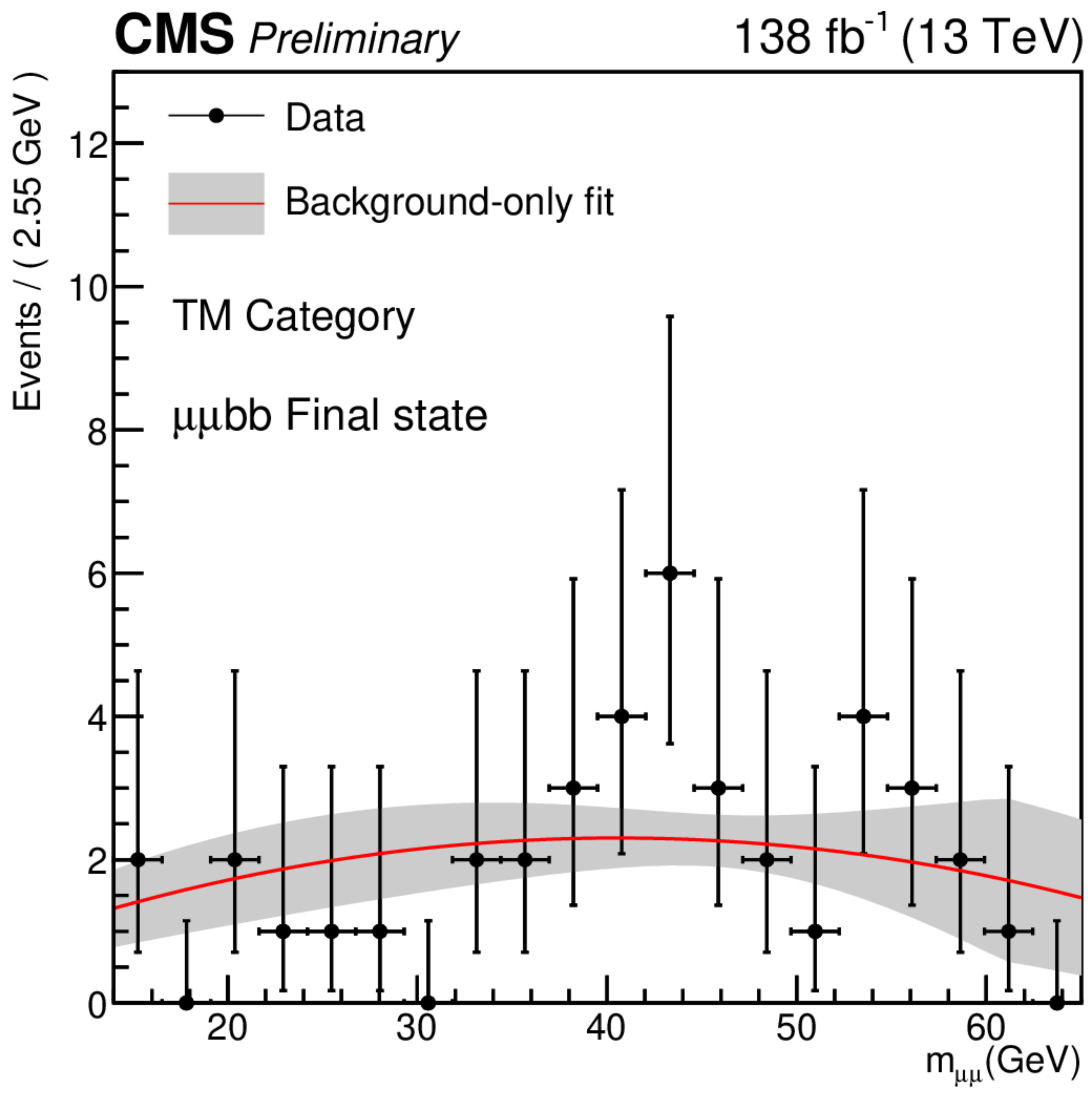


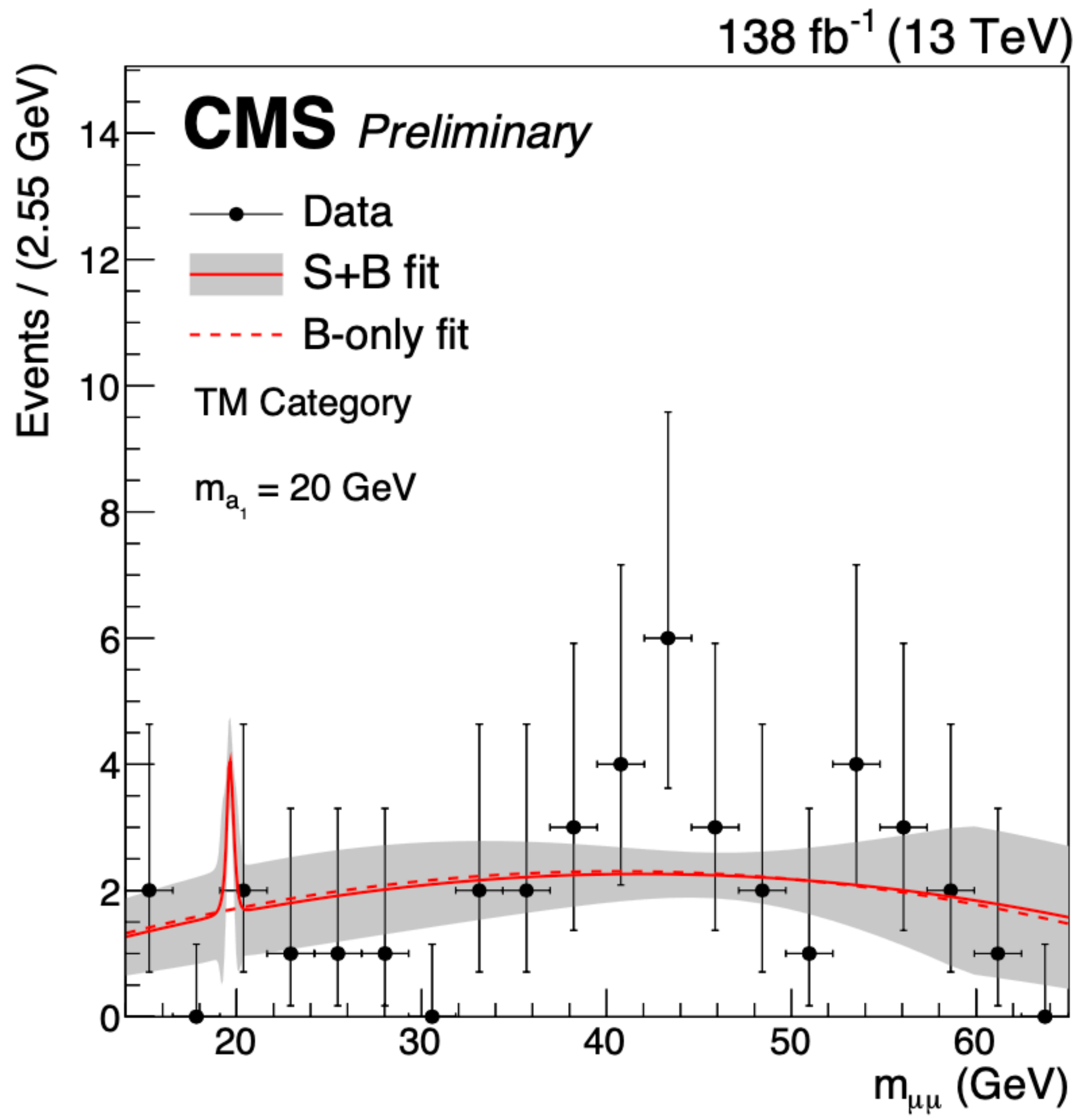


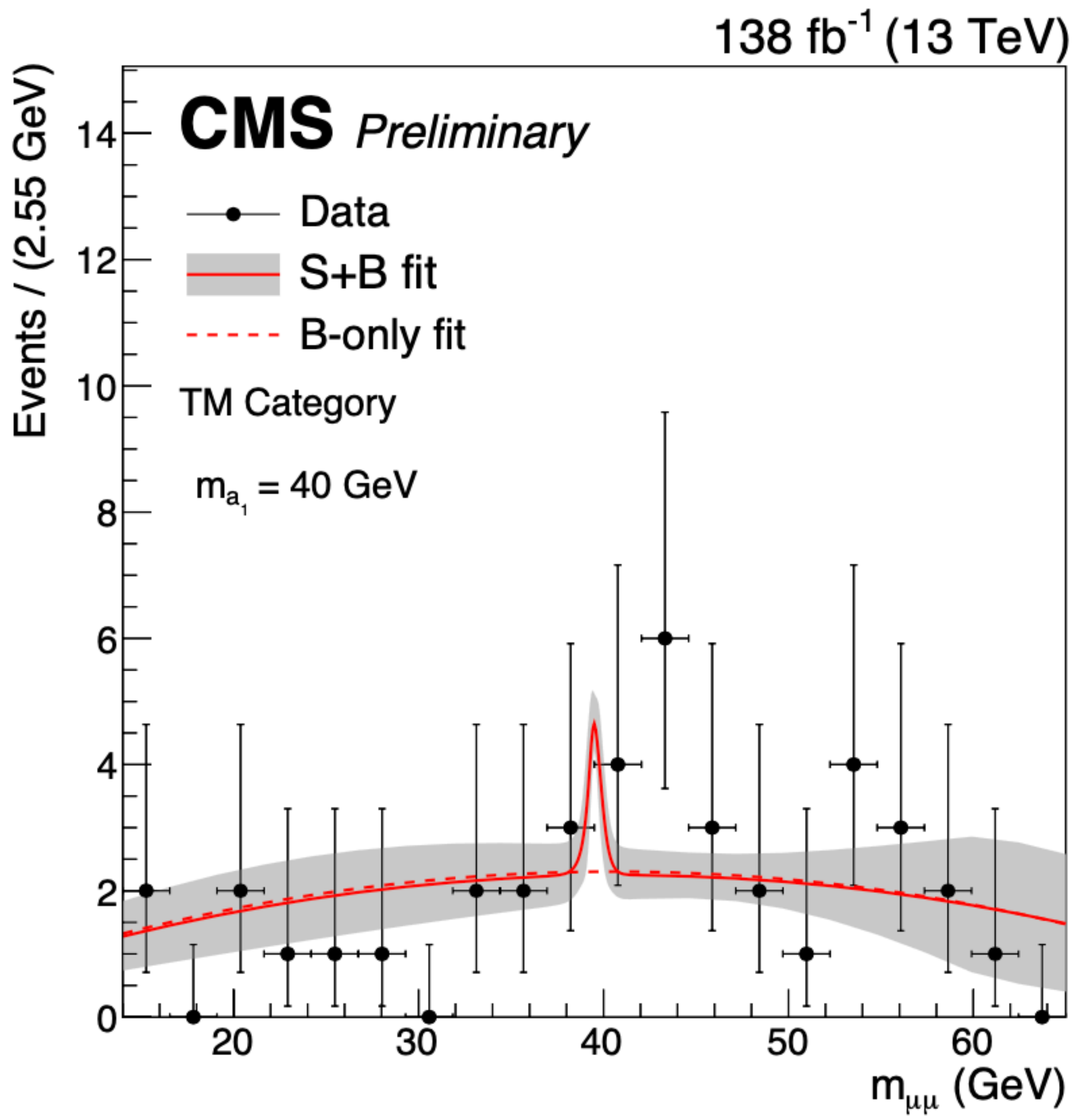
χ_H and χ_{bb} are corrected and decorrelated.

Part 1: H→aa→μμbb

HIG-21-021
HIG-22-007







Unbinned maximum likelihood fit is performed on the dimuon mass
- fully data driven background estimation!

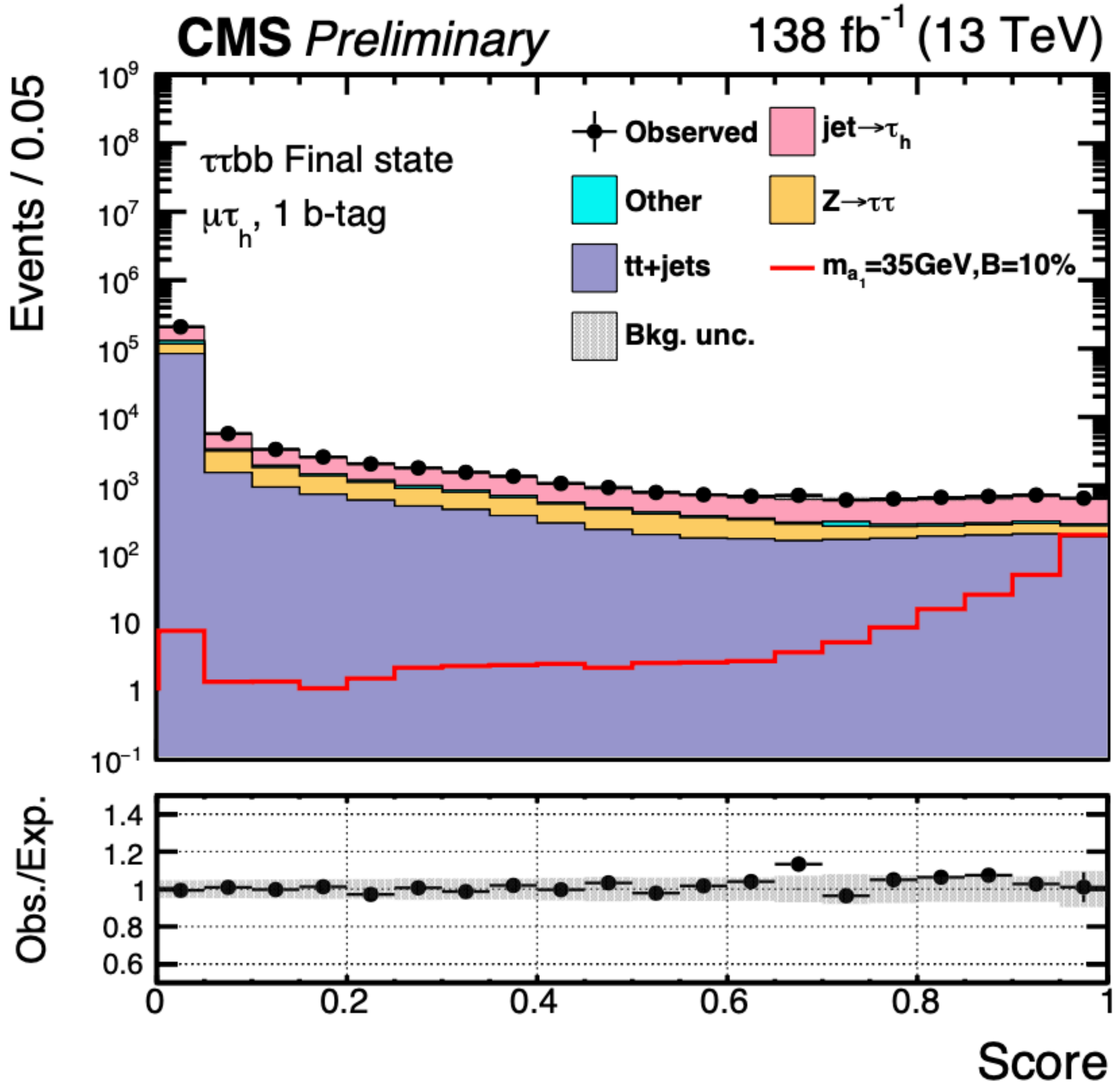
Part 2: $H \to aa \to \tau\tau bb$

HIG-21-021
HIG-22-007

- 6 categories, with one or two b-tagged jets
  - $\tau_e\tau_\mu b$ $\tau_e\tau_h b$ $\tau_\mu\tau_h b$
  - $\tau_e\tau_\mu bb$ $\tau_e\tau_h bb$ $\tau_\mu\tau_h bb$ (full signal reconstruction)

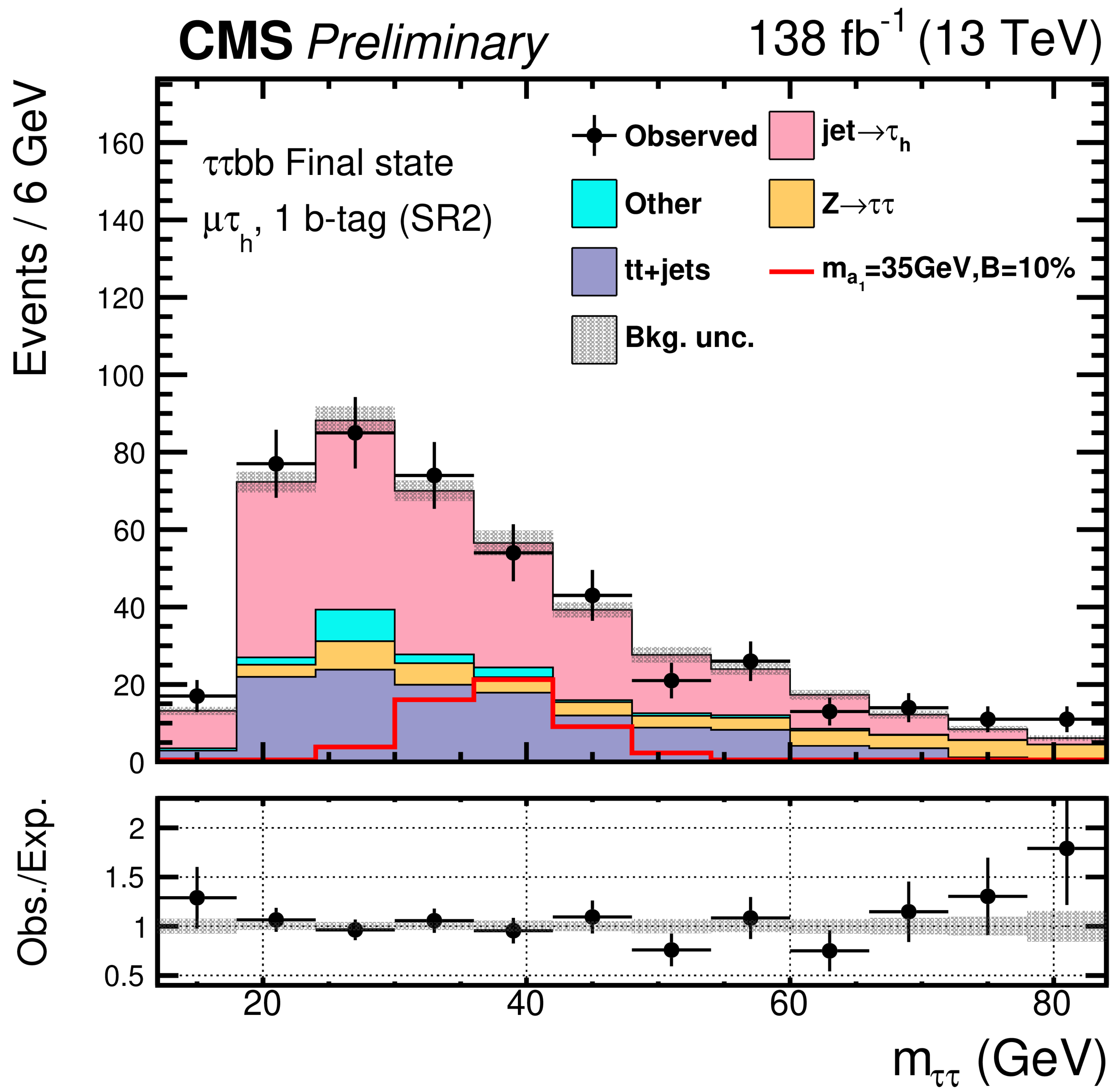
- A **DNN** is used to define multiple subcategories in each (**15 total**):
  - momentum vectors: p_T and η of leptons and jets
  - mass: $m(b\tau\tau)$, M_T ($W \to \ell\nu$ is at larger values)
    $\Delta m = (m_{bb} - m_{\tau\tau})/m_{\tau\tau}$
  - angular: ΔR, D_ζ ($Z \to \tau\tau$ is at large values, collinear MET and ditau)

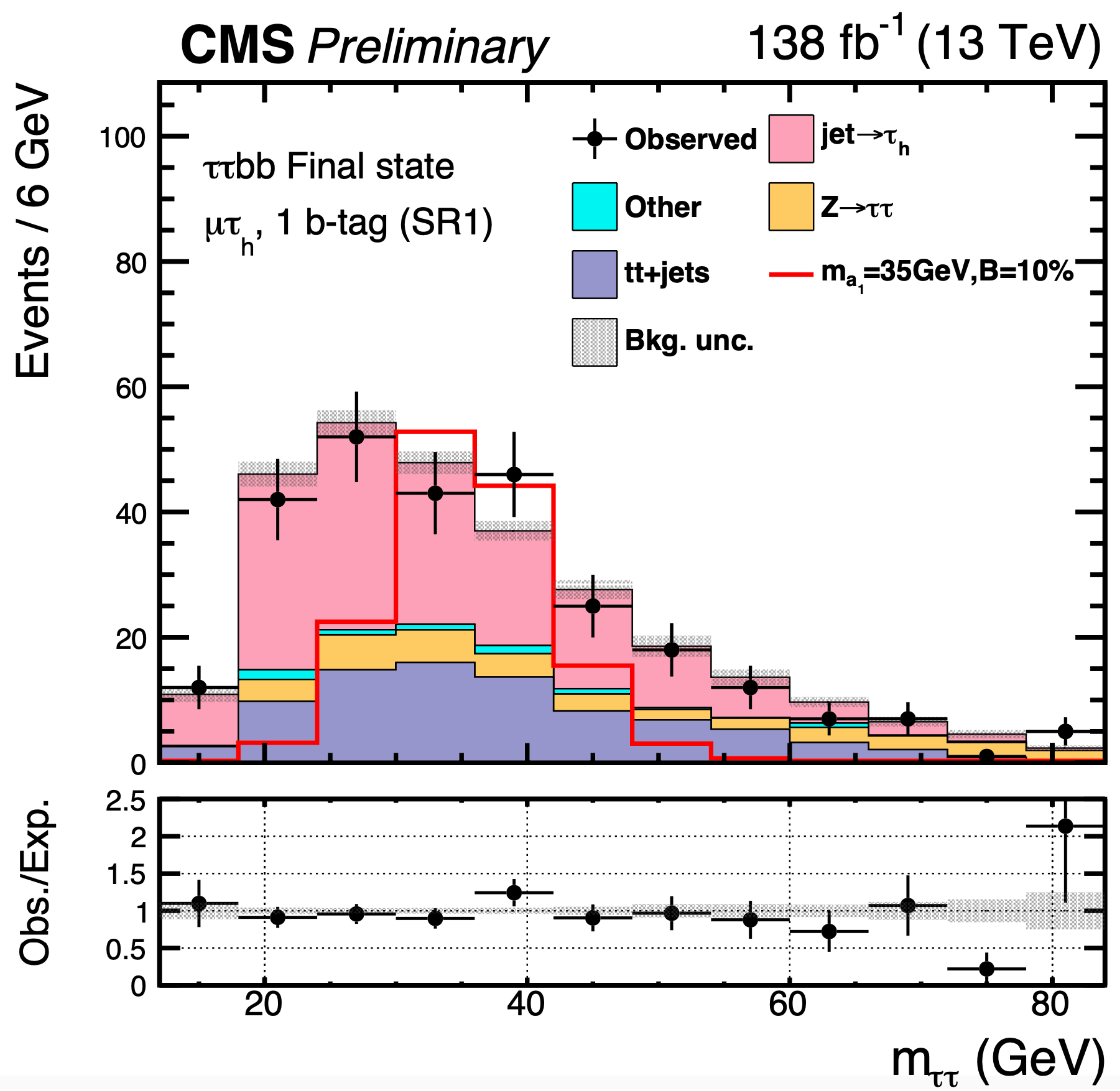
- Data driven "fake factor" method is used to estimate contributions from $j \to \tau_h$ processes (jets misidentified as hadronic taus).



Part 2: H→aa→ττbb

HIG-21-021
HIG-22-007

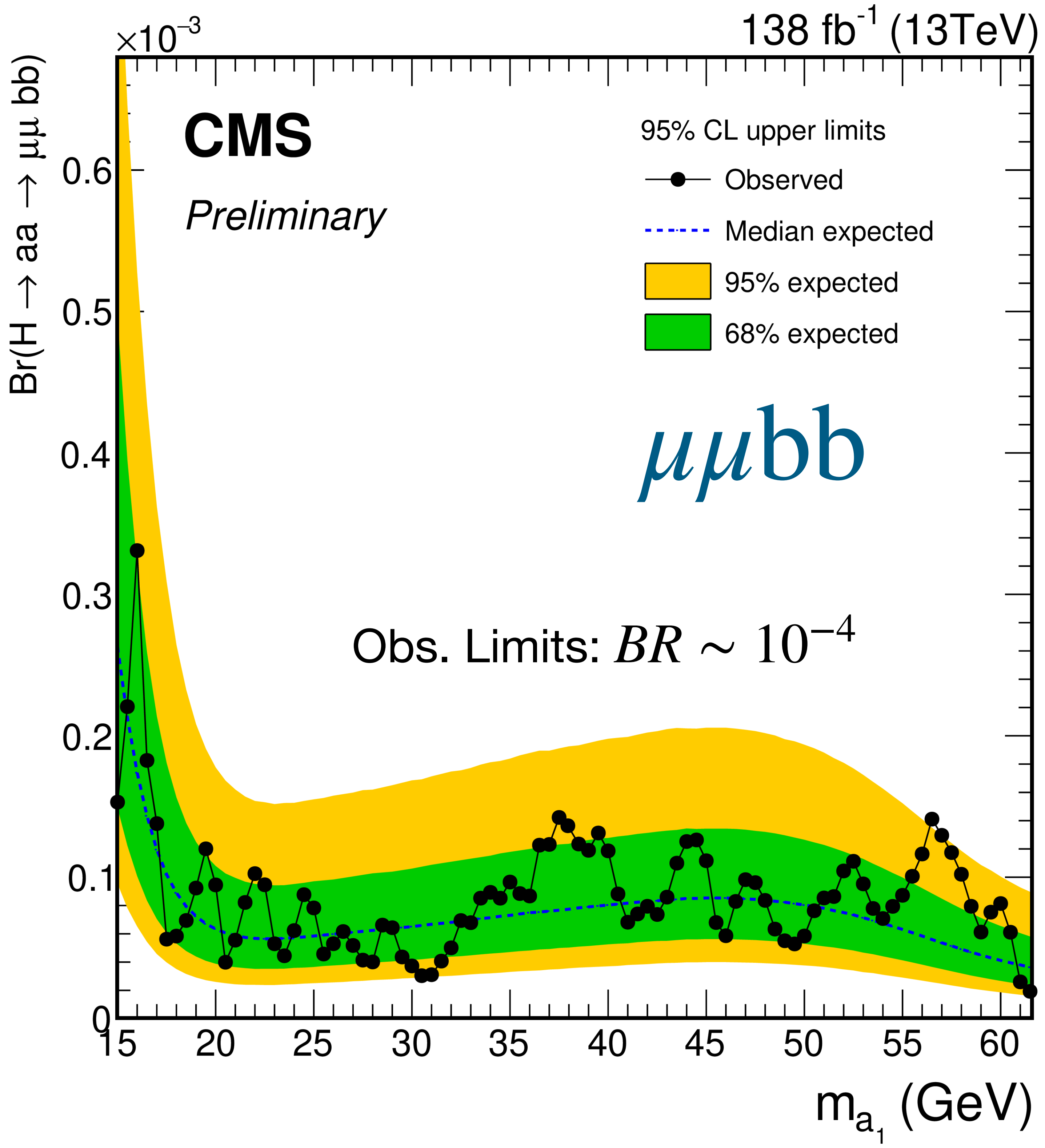


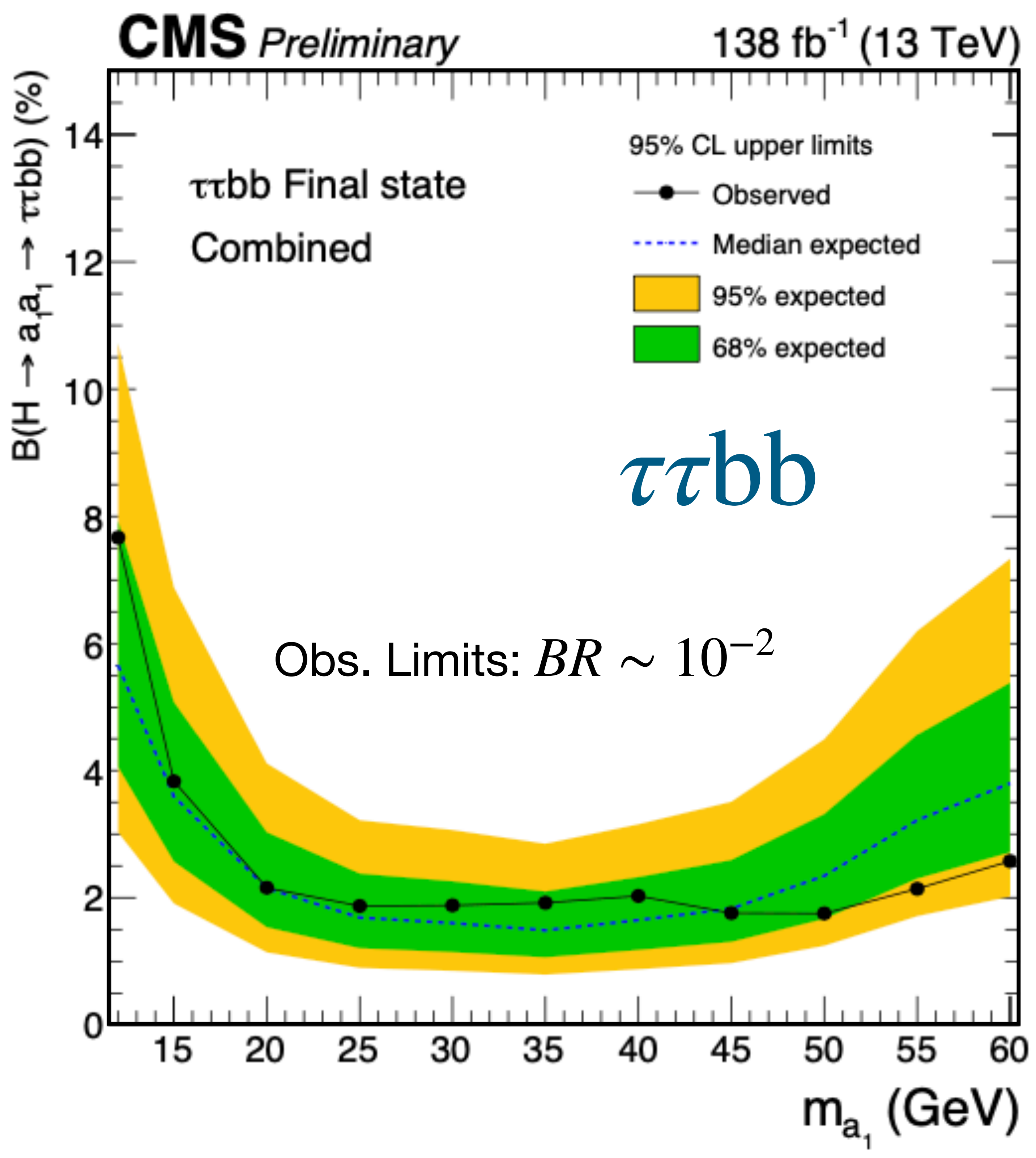


Binned maximum likelihood fit is performed on the ditau mass
- SVfit algorithm is used to improve sensitivity (~30%)

Light pseudoscalars: H→aa

HIG-21-021
HIG-22-007





two b-jets start to merge as a result of boosted $\mathrm{H} \rightarrow \mathrm{aa}$ decays

$e\mu$ ($\mu\tau$) final state drives sensitivity at low mass (overall)

- The results are obtained independent of the 2HDM type and $\tan\beta$ parameter.
  - SM H production is assumed
  - Statistical uncertainties dominate
  - Improvement of sensitivity over the earlier CMS results by a factor of ~2

- Model dependent limits are also available.

Light Higgs to diphotons

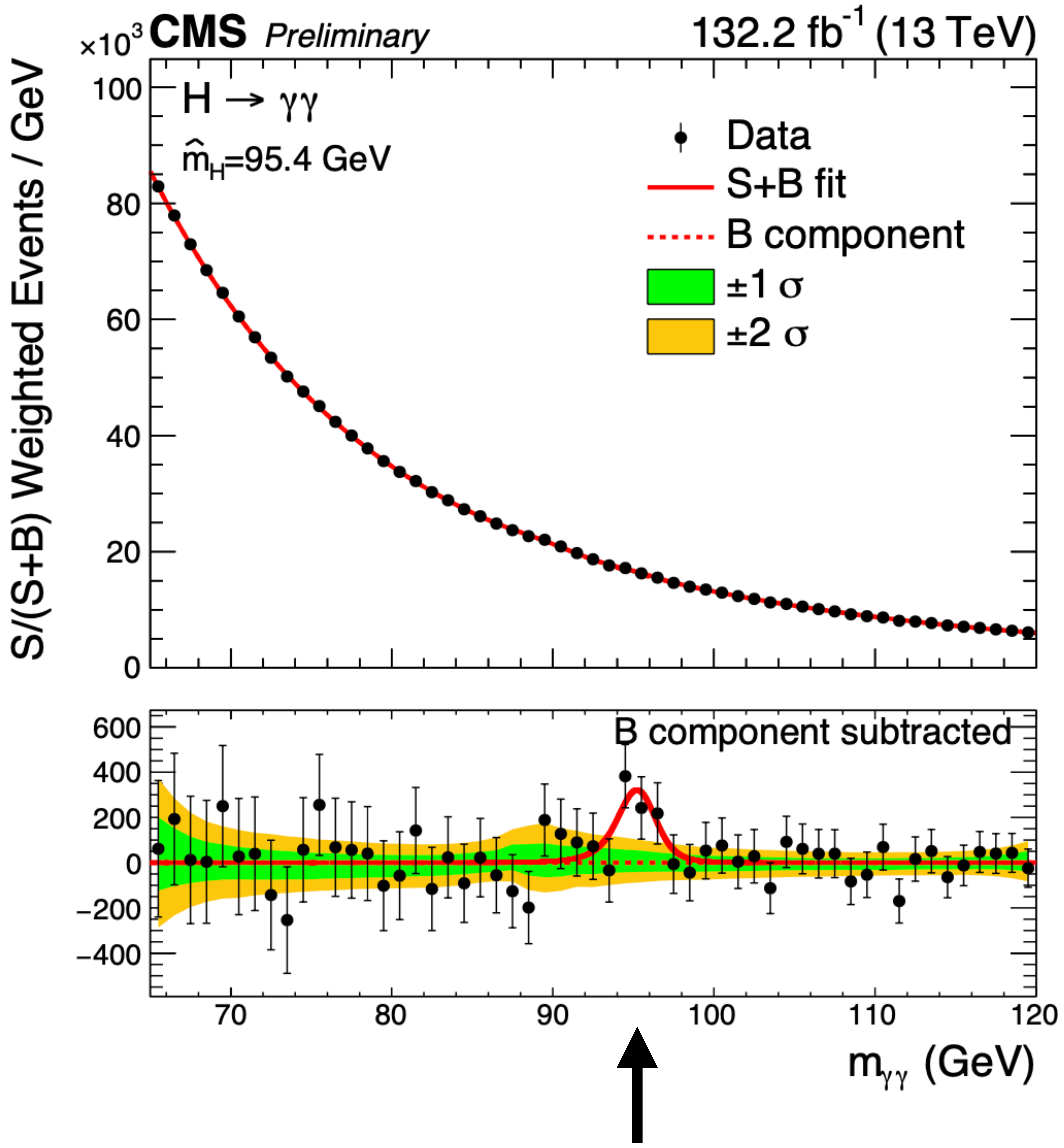
HIG-20-002

- Probing a "lighter" scalar state: $\mathrm{H} \rightarrow \gamma\gamma$
  - Assumes natural width is small compared to the detector resolution.
  - diphoton mass resolution is 1-3%

- Targets the mass range 70-110 GeV
  - lower mass bound is defined to **avoid trigger turn-on** effects.
  - higher masses are covered by the $\mathrm{H}(125) \rightarrow \gamma\gamma$ analyses

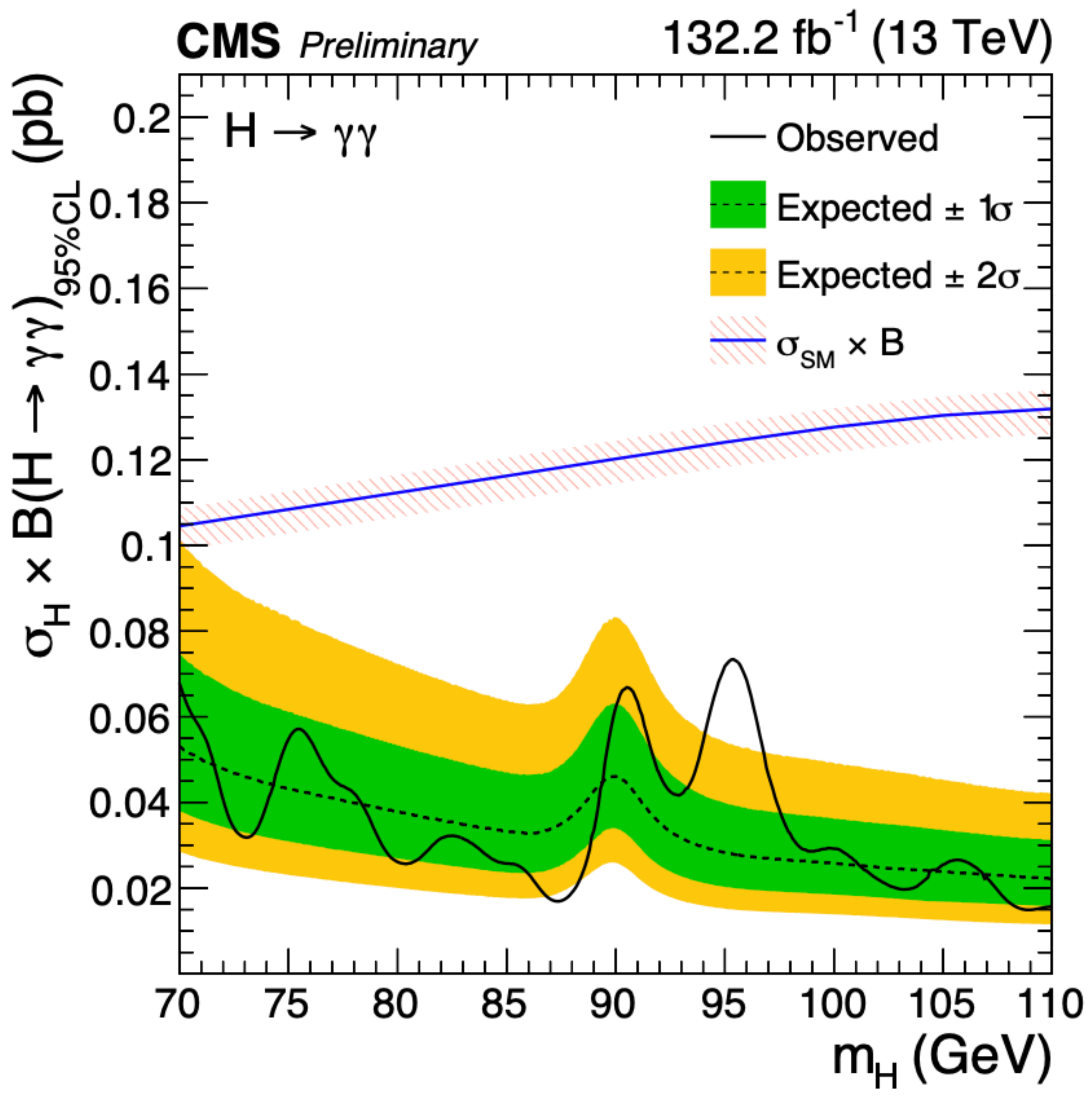
- MVA techniques are used both for photon ID and event classification.
  - Photon MVA: lateral shower shape, isolation, energy density, η related variables (prompt vs nonprompt)

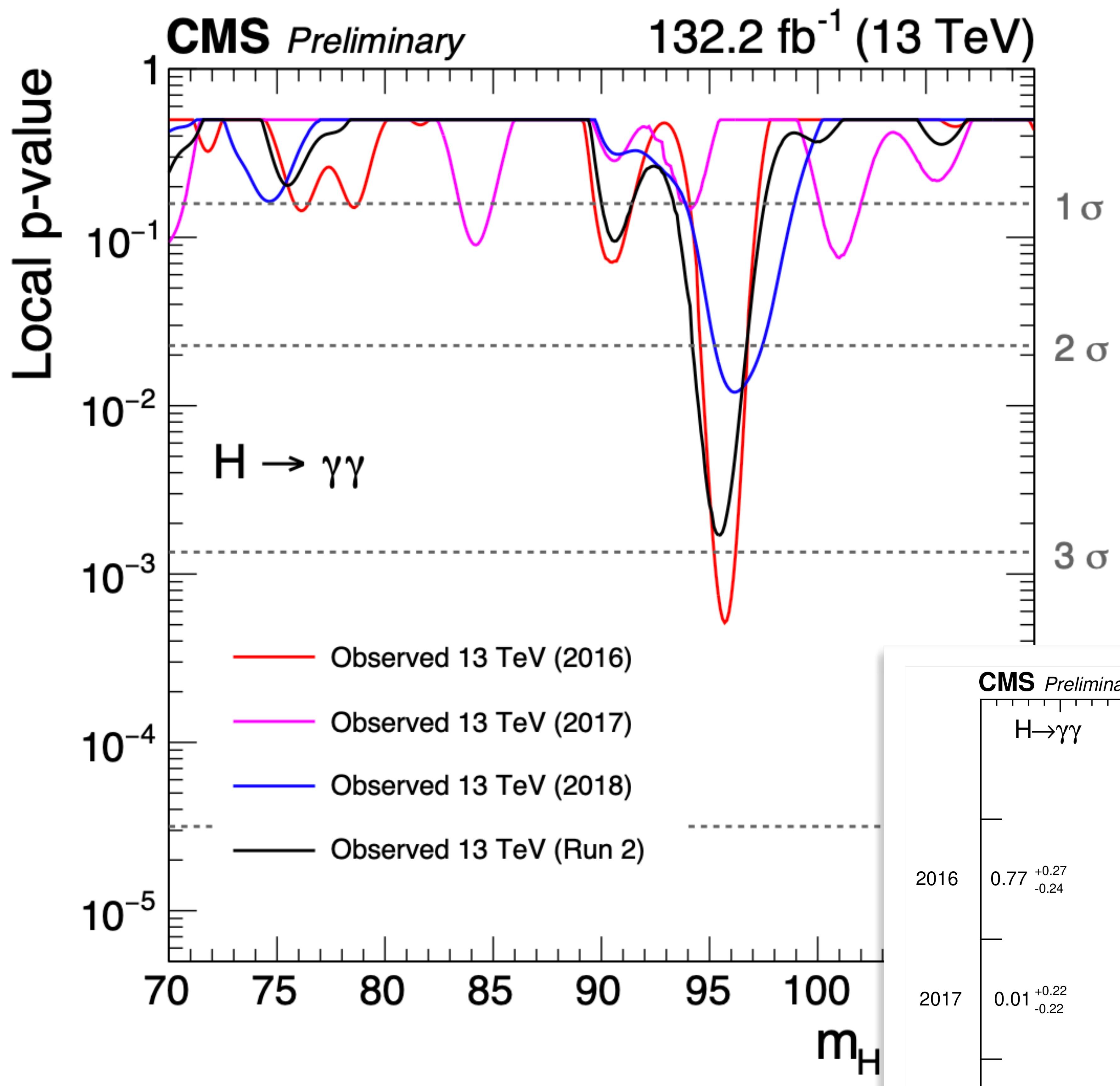
- Search for narrow signal peak over smoothly-falling background.
  - parametric fit to the diphoton mass spectrum is used



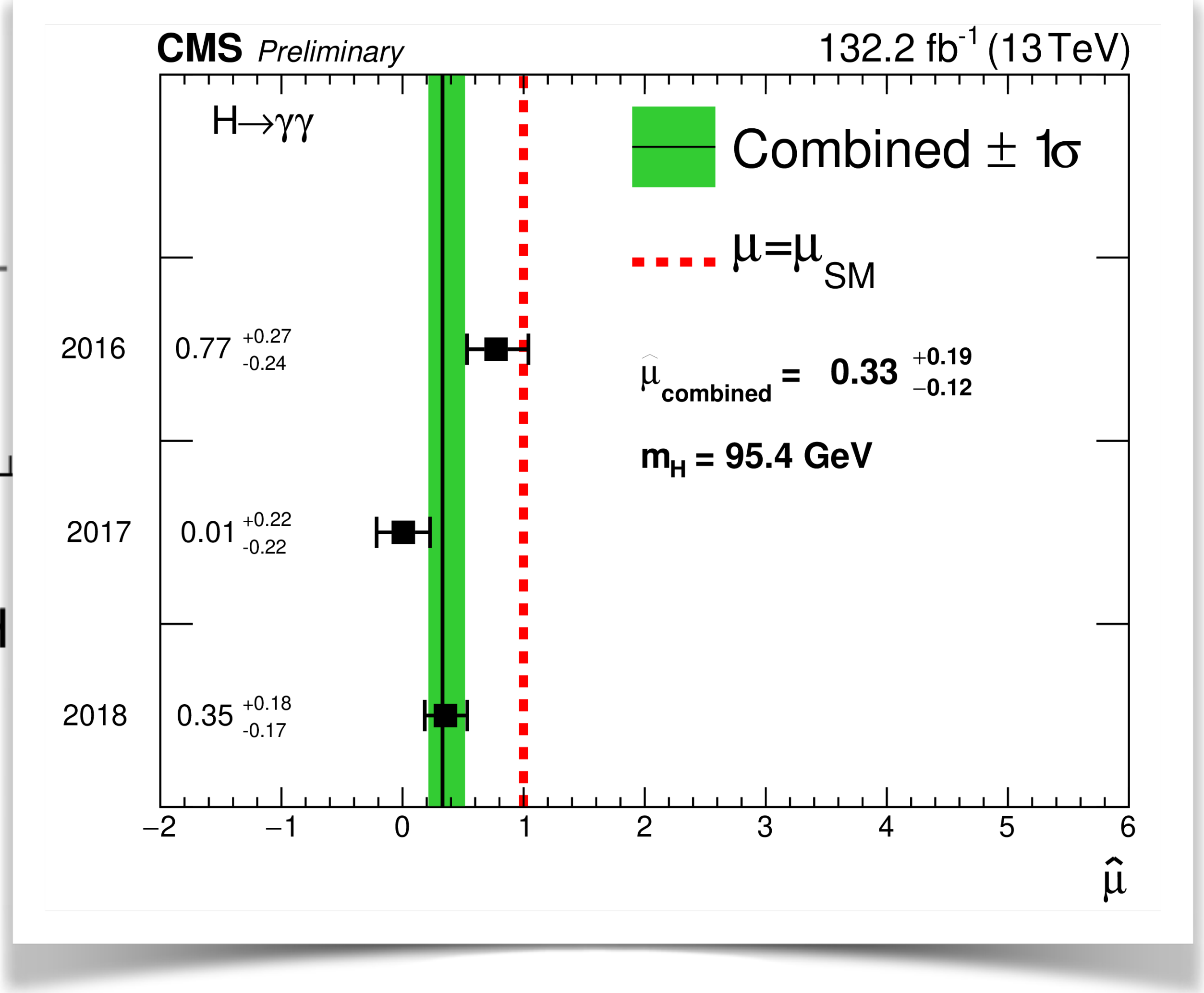
Light Higgs to diphotons

HIG-20-002





Run2:
excess at 95.4 GeV with a local (global) significance of 2.9 (1.3) standard deviations.



The first full Run2 search for such resonances in the diphoton final state!

Prompt low mass dimuons

EXO-21-005

- Probing **1.1-7.9 GeV mass range** with muon $p_T > 3$ GeV
  - events are directly reconstructed in the HLT
    The high-rate trigger stream: 4-8kB/event at ~ 2 kHz
    → **CMS scouting dataset**

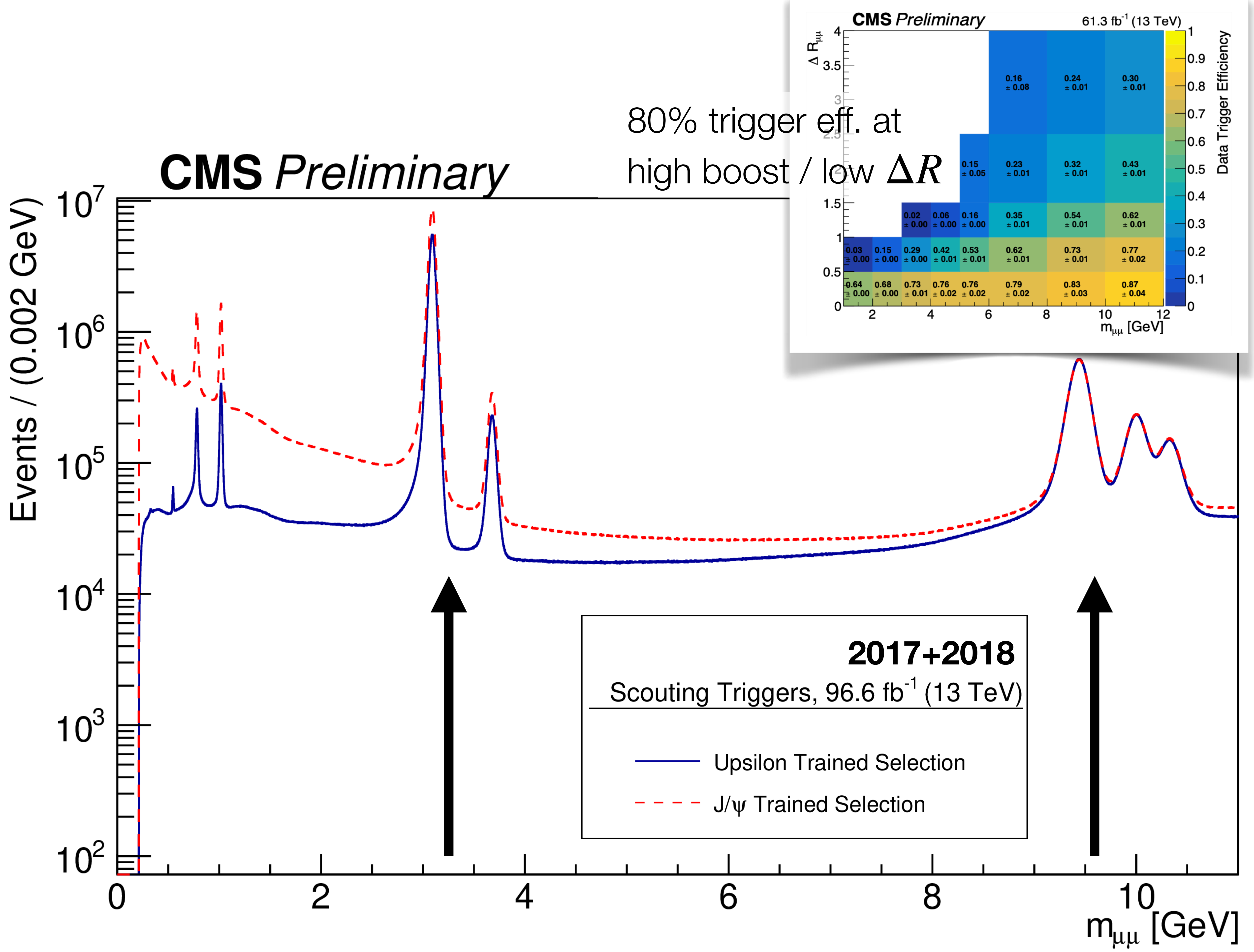
  **for comparison, regular dimuon trig. rate is <0.5 kHz*

- **Two custom MVA** selections are defined for low and "high" masses:
  - boost of dimuon pairs ↔ uncertainty on vertex position
  - improves sensitivity by ~30% w.r.t previous efforts

- Promptness cuts on the dimuon vertex - beam spot distance:
  - $L < 0.015 - 0.2$ cm and $L/\sigma_L < 3.5$ (depending on mass and p_T)

- Simultaneous **S+B fits** to the dimuon invariant mass distribution.
  - fully **data driven** background estimation!
  - assumes **narrow** resonance (CMS dimuon mass resolution ≈1.3%).
  - fit window ±5x the mass resolution around the resonance mass.

80% trigger eff. at high boost / low ΔR

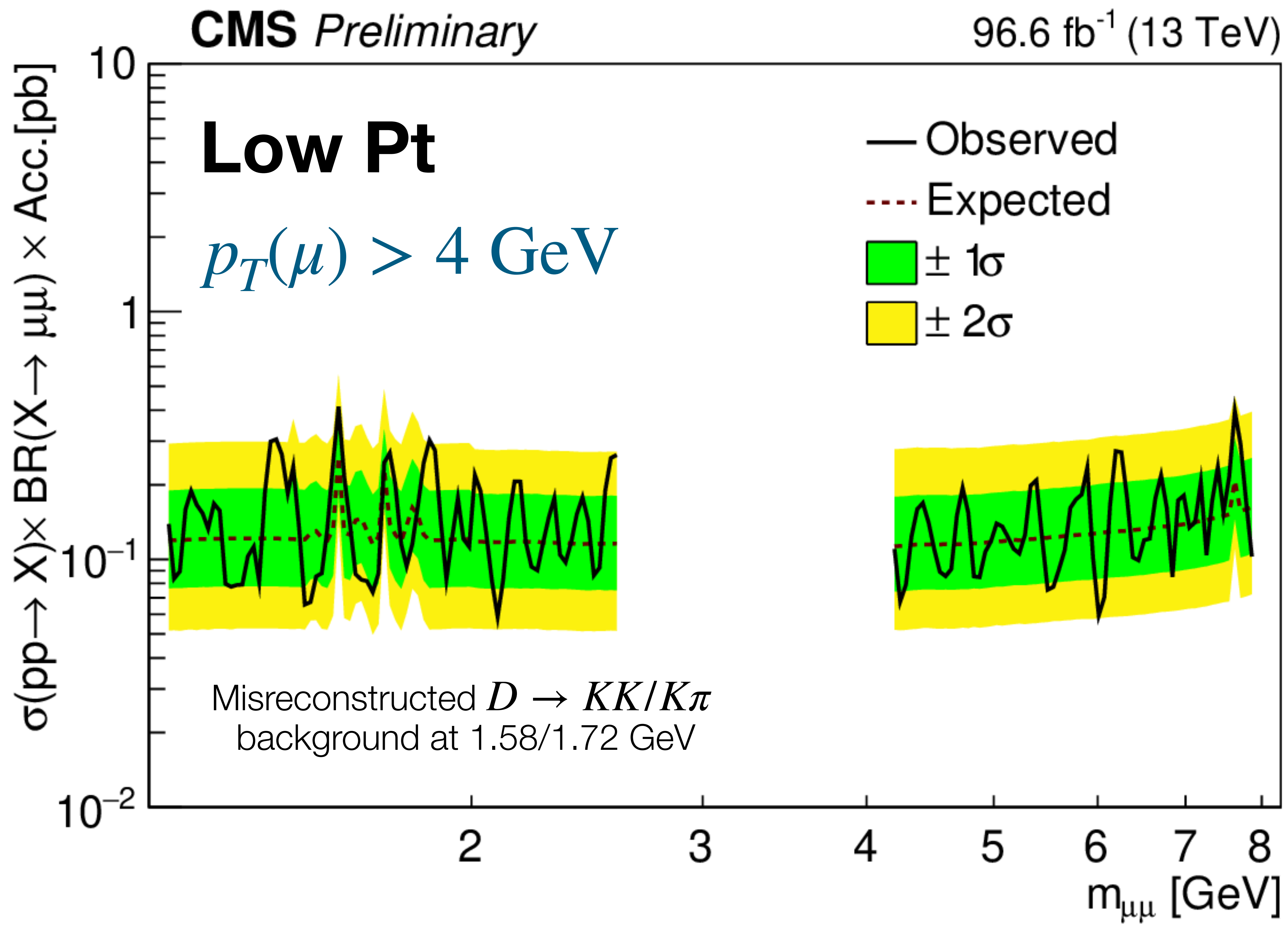


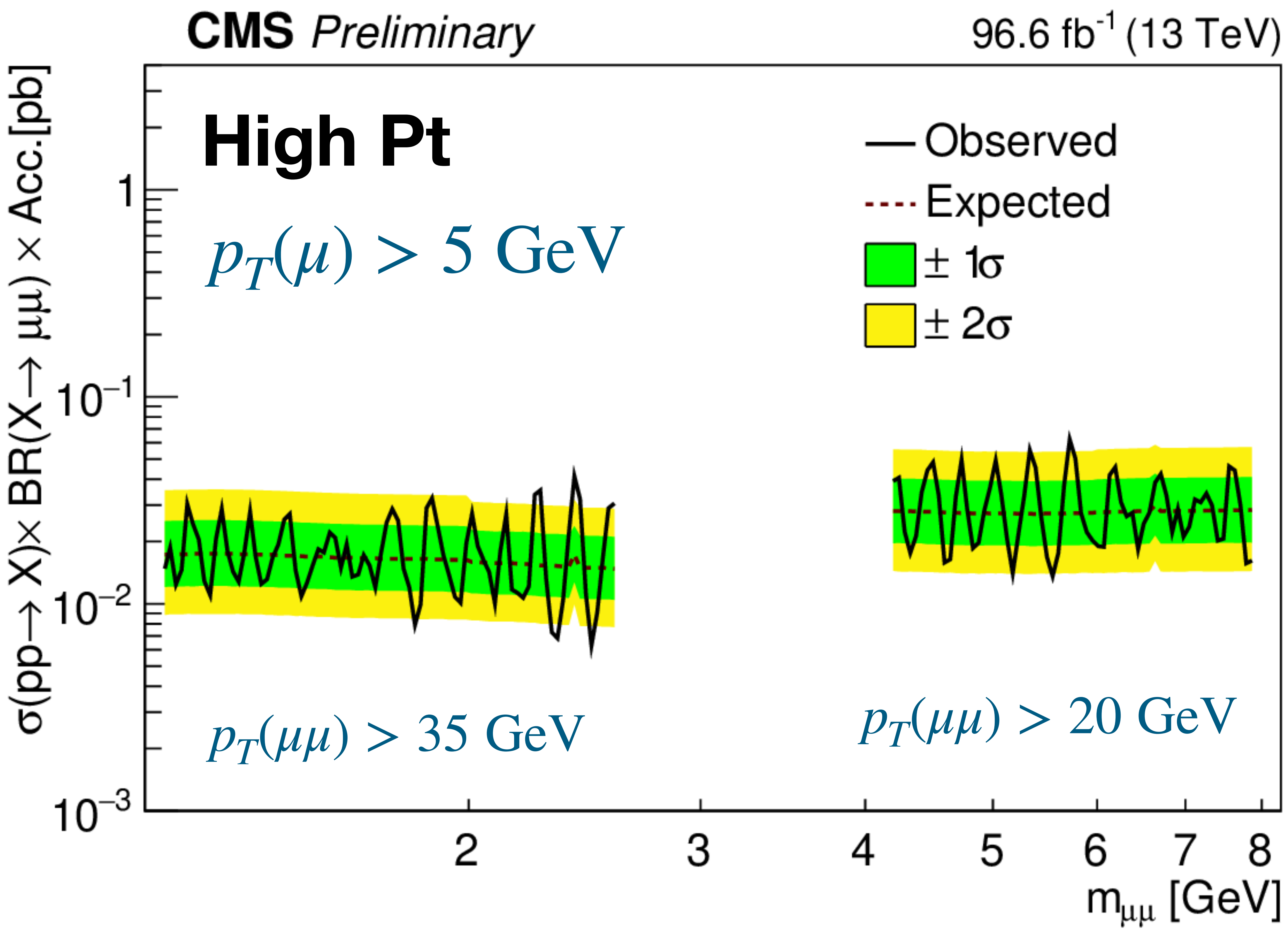
Dedicated MVAs for muon identification:
- quality of the muon tracks, the relative muon isolation and the vertex that the muons are associated with.

See EXO-20-014 for the CMS long-lived dimuon analysis

Prompt low mass dimuons

EXO-21-005



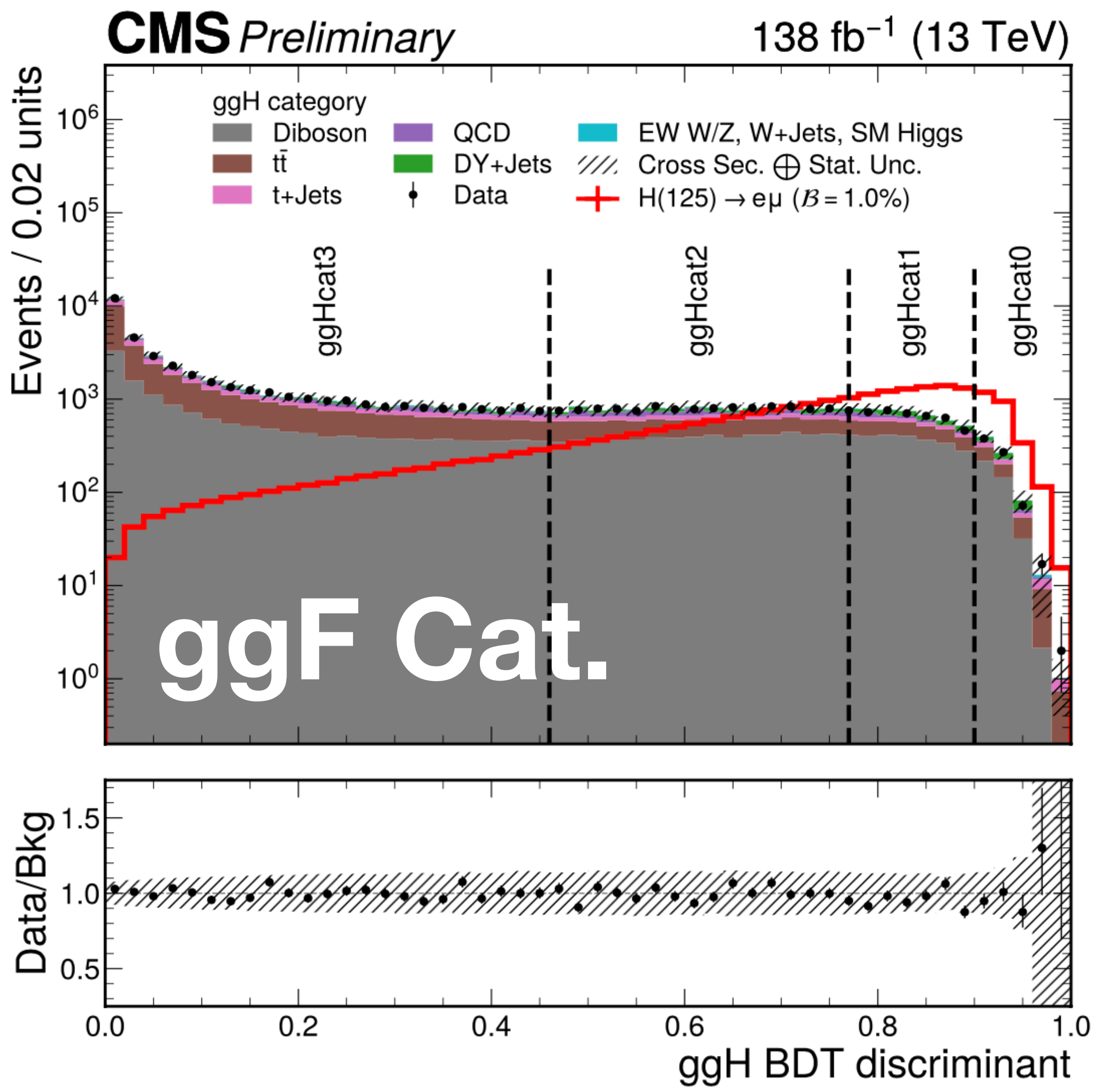


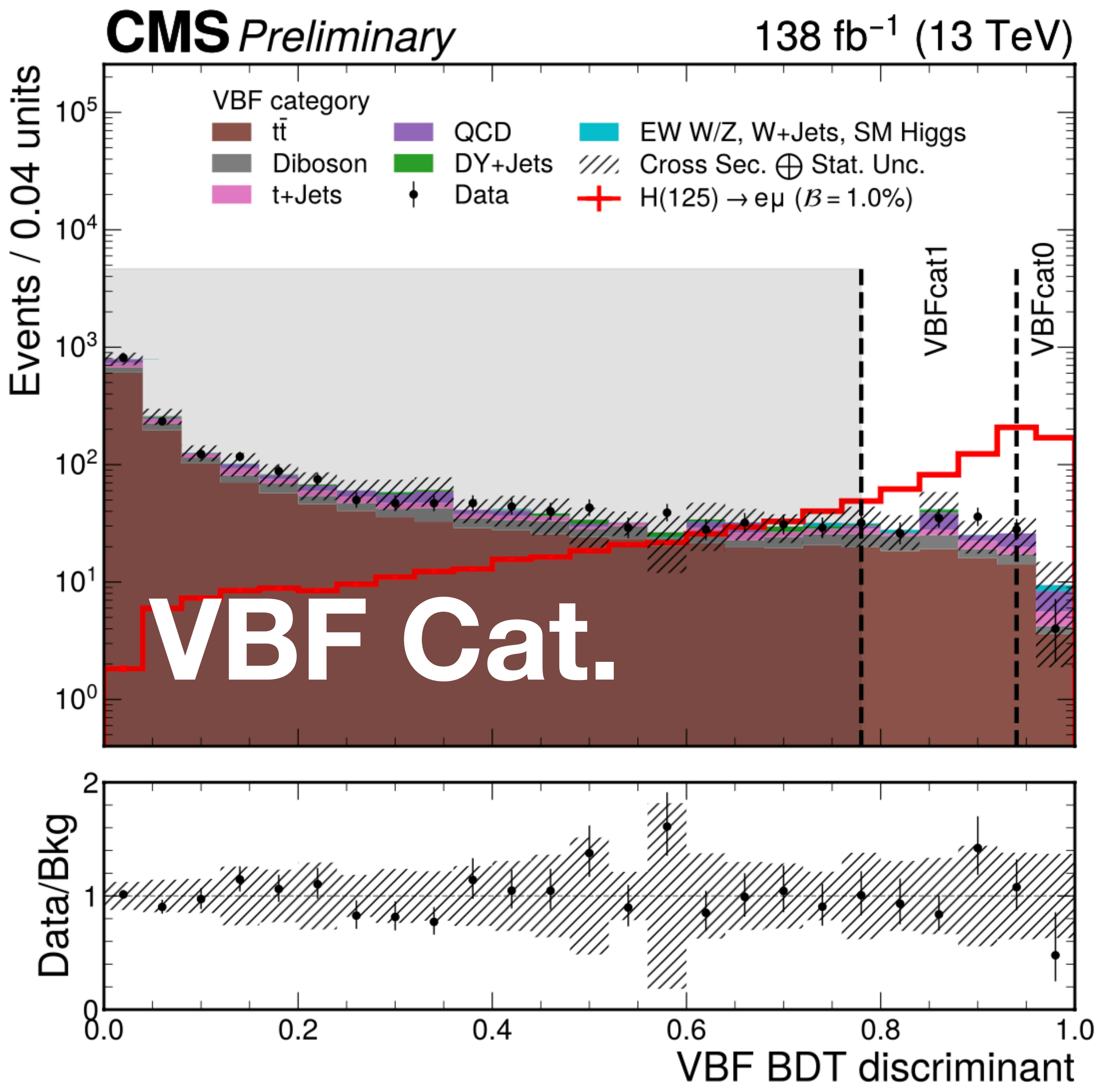
The background model fit on the mass continuum becomes unreliable over the J/ψ, ψ′ resonances, hence this region is omitted. Model dependent limits are also available.

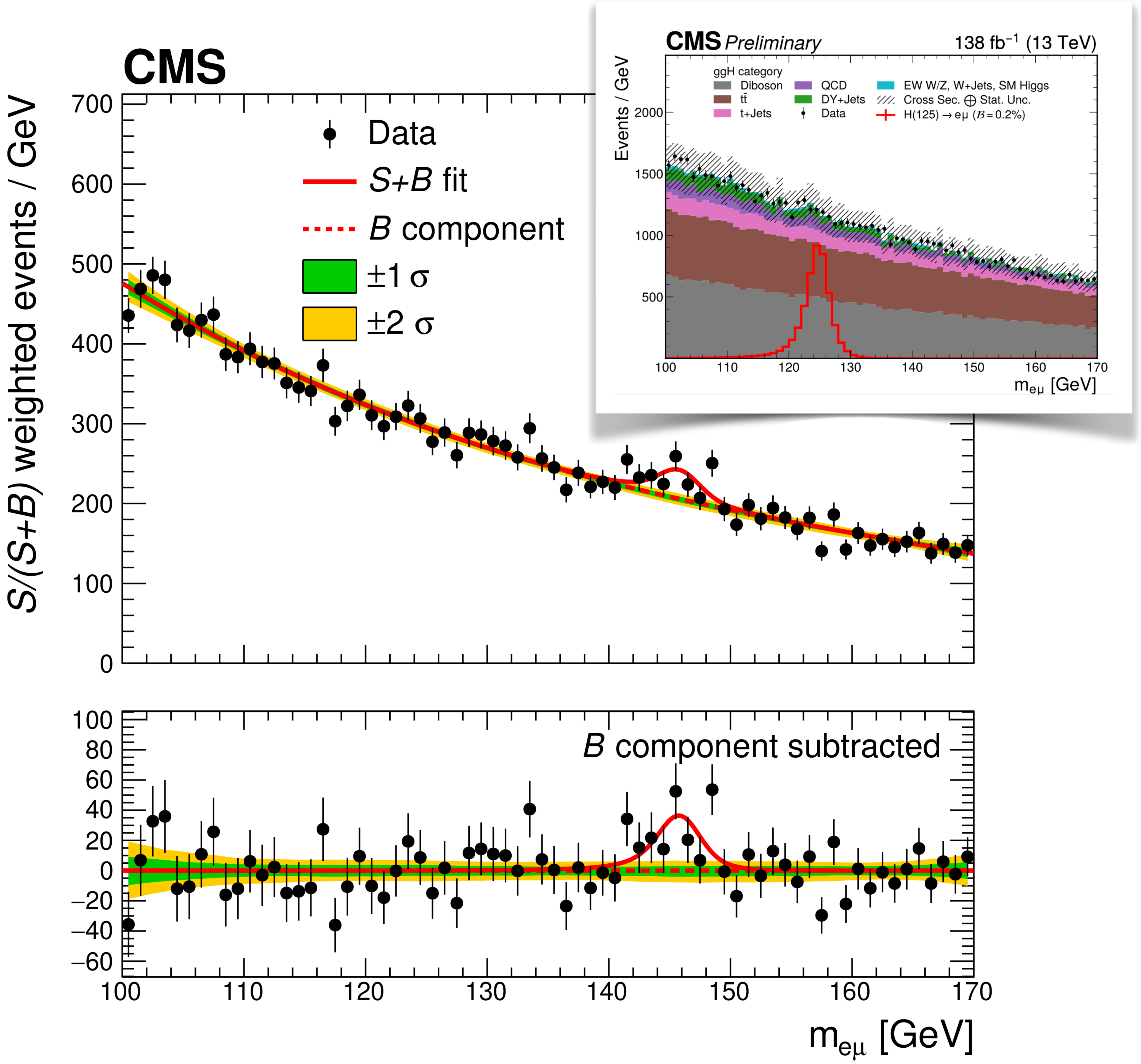
LFV decays of a new scalar

HIG-22-002

- Exotic decay: $H \to e\mu$
  - *can emerge in various BSM models with more than one Higgs boson doublet, composite Higgs models, MSSM, etc.*
- Targets both the ggF and VBF production modes.
  - these are targeted by 2 experimental categories, based on jets
- BDTs are used to further define subcategories in signal purity
  - MET, boost, angular variables of MET and dilepton system ($\Delta\eta$), N_j, p_T ratios, ..



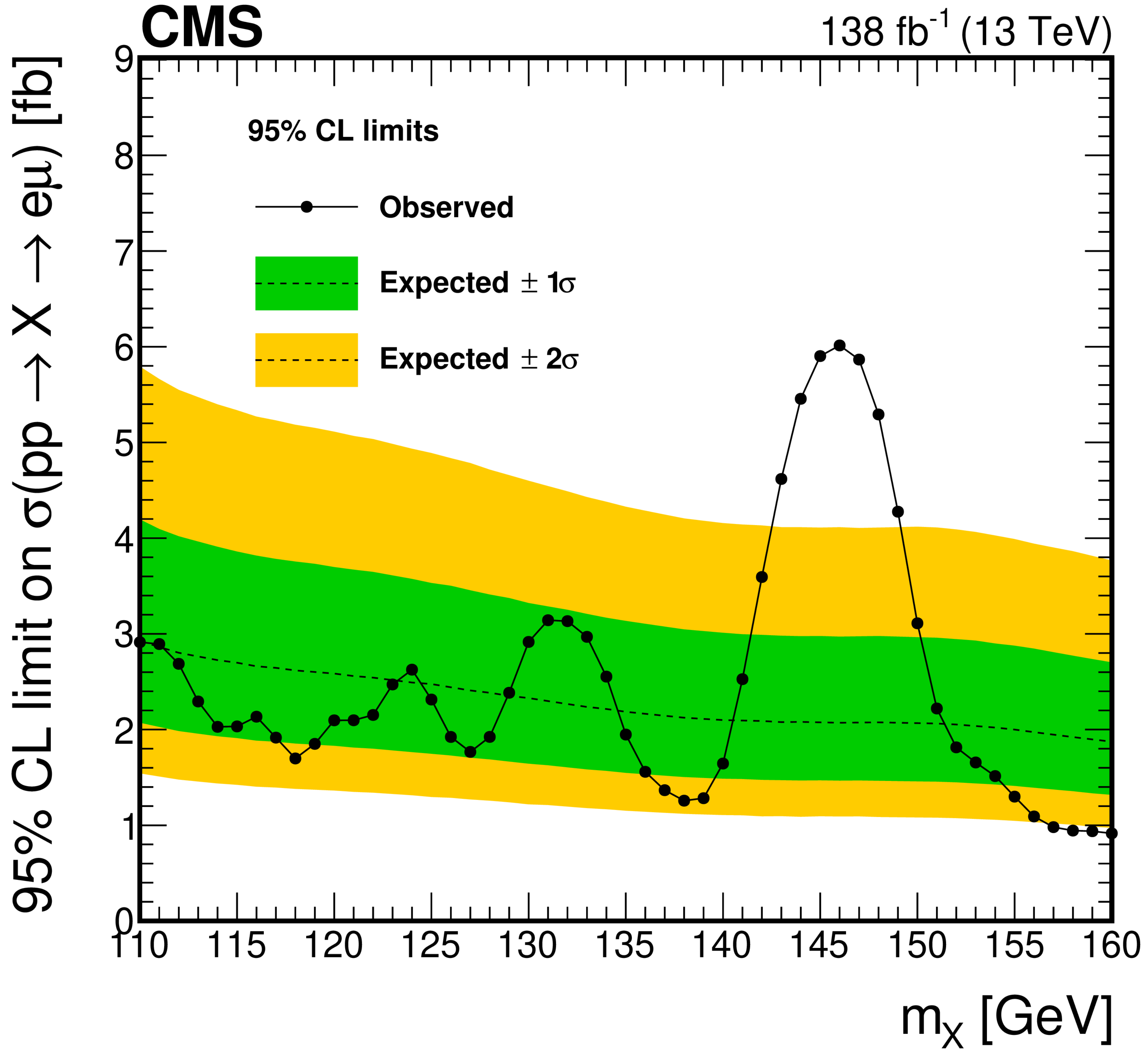


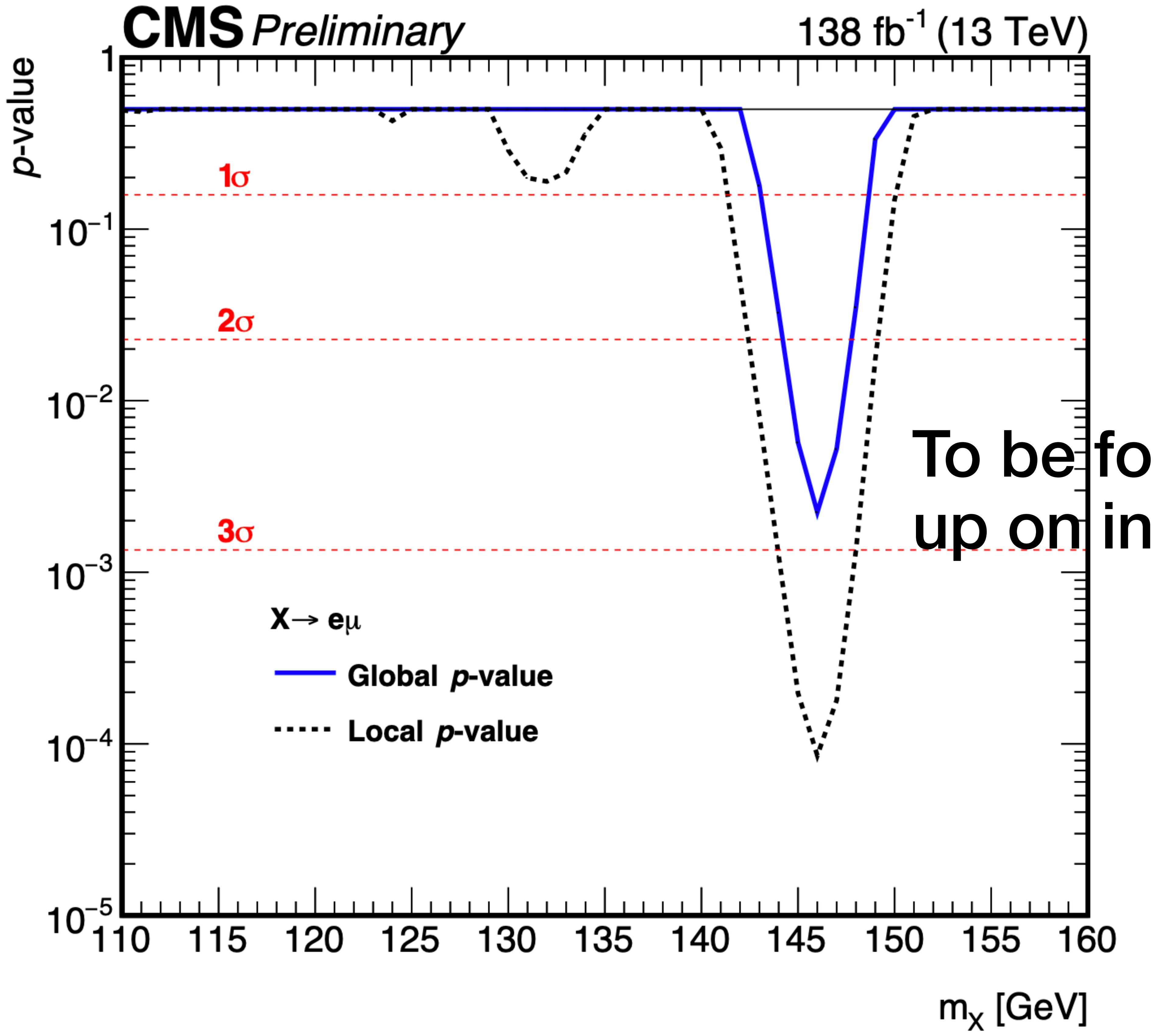


Completely data driven background estimation

LFV decays of a new scalar

HIG-22-002





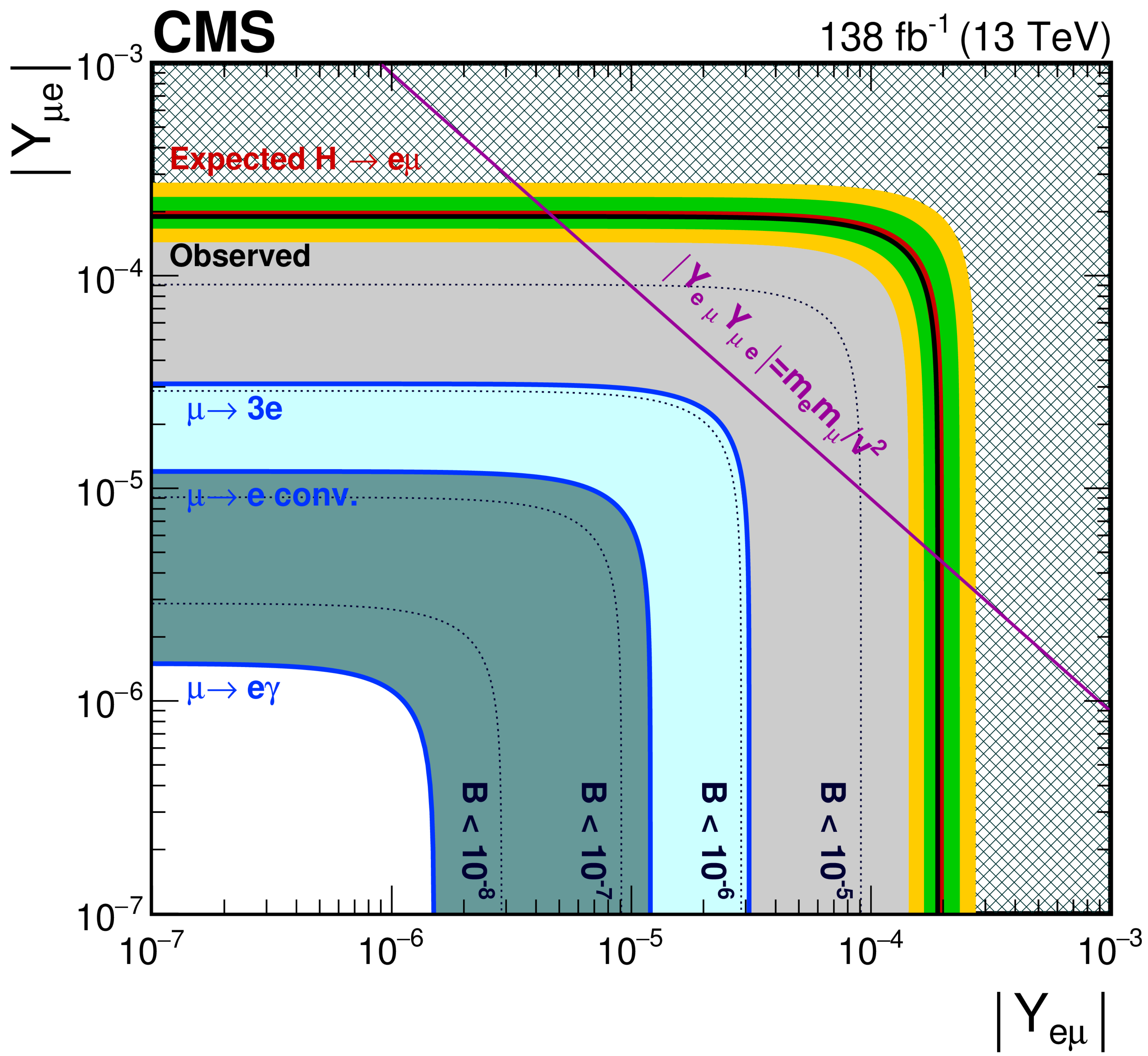
To be followed up on in Run 3!

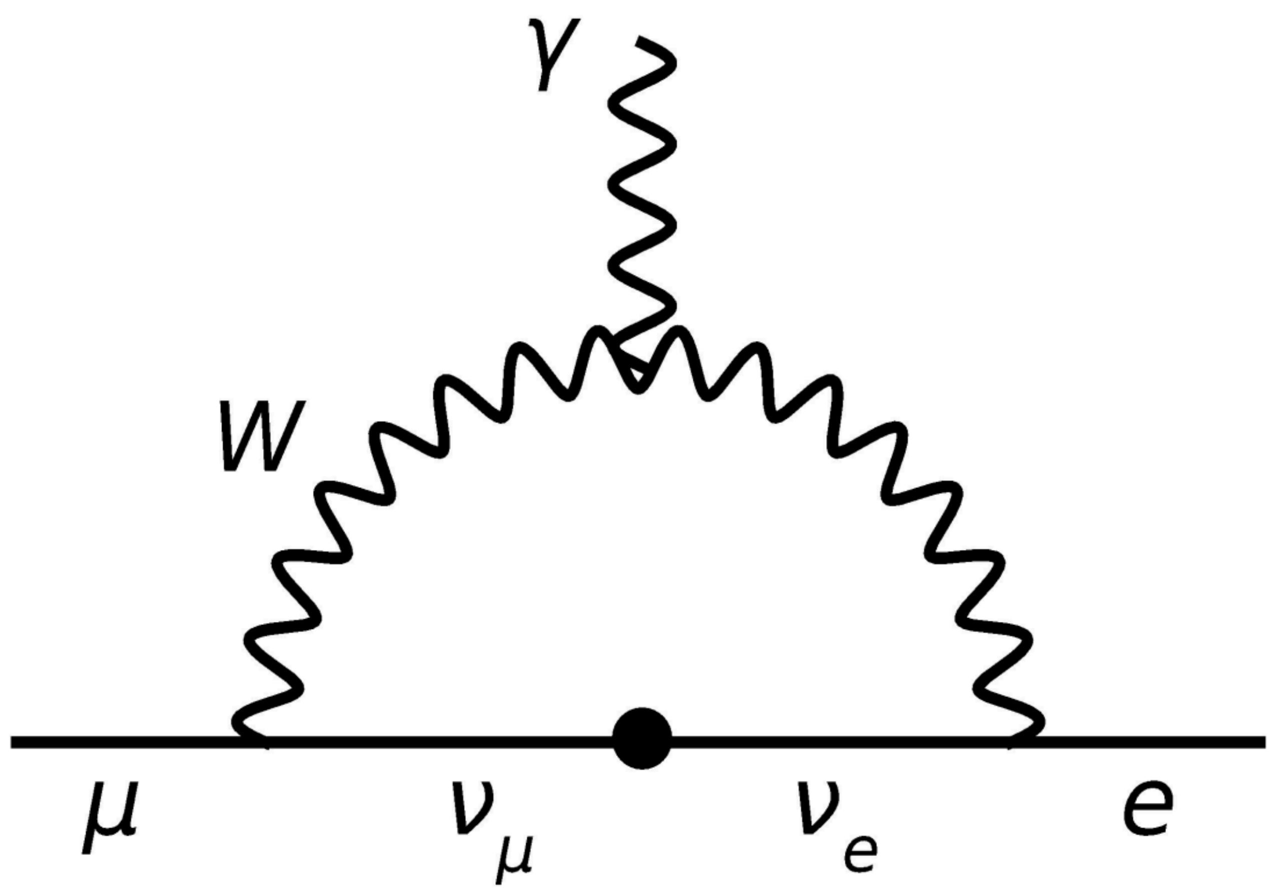
The first direct search for X → eμ in this mass range.

- i.e. with m_X below twice the W boson mass.

LFV decays of H(125)

HIG-22-002





μ→eγ bound BR($H \to e\mu$) $\lesssim 10^{-8}$

(with assumptions on the Higgs couplings Y_{ee}, $Y_{\mu\mu}$ and FCNC interactions)

Sets the **most stringent "direct" limit** on the LFV decay of SM Higgs:
BR($H \to e\mu$) $< 4.4 \cdot 10^{-5}$ at 95% CL

See CMS-HIG-20-009 for direct bounds on BR($H \to e\tau/\mu\tau$)

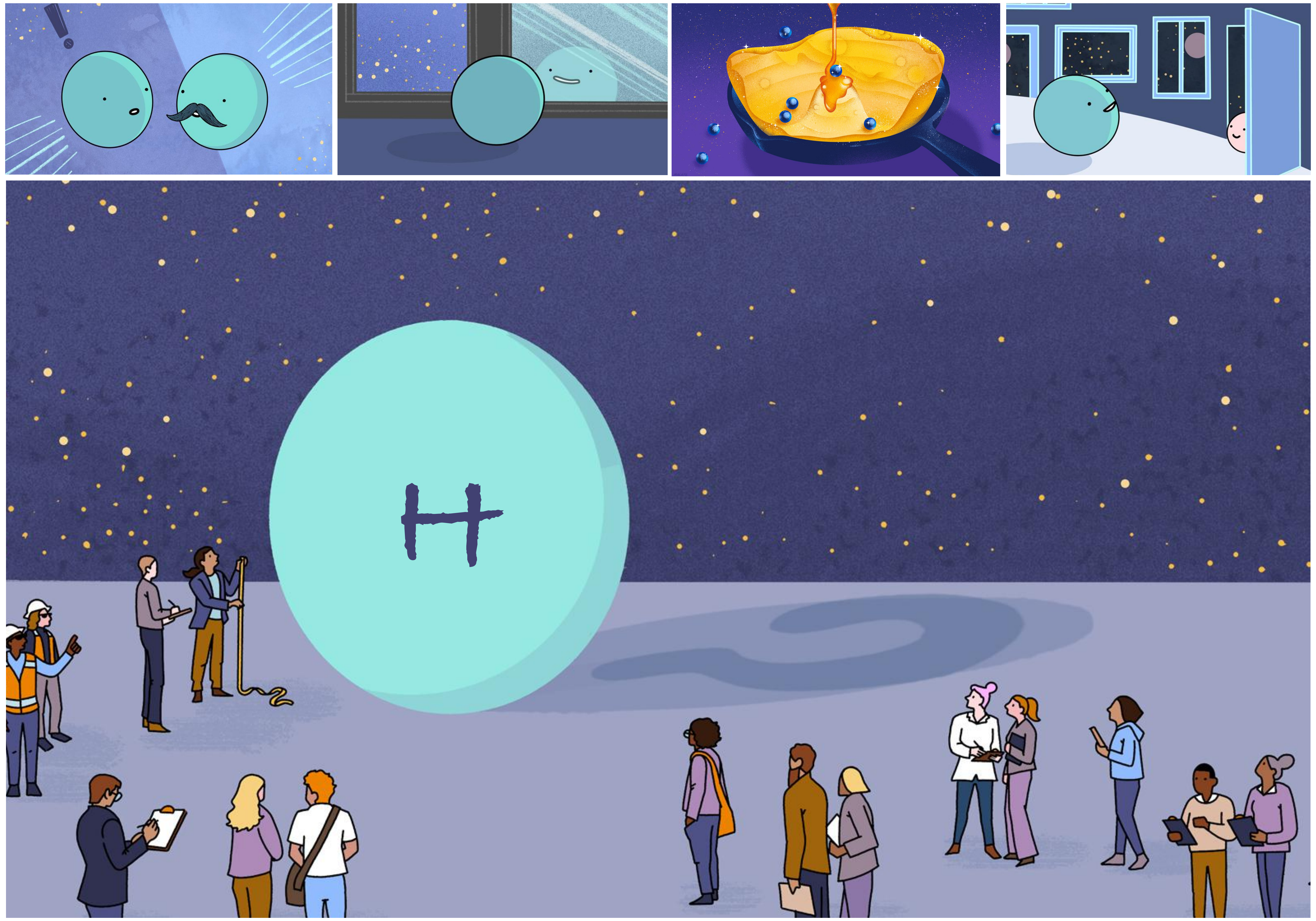
Conclusions

- Extensive BSM scalar sector program at CMS / LHC
  - $W\phi/Z\phi/tt\phi \to \ell\ell$
  - $h/H \to aa$
  - $H \to \gamma\gamma$
  - $h/H \to e\mu$
  - $X \to VV$
  - $X \to HH$
  - $H^+ \to H^0/hW,\, tb, ..$
  - …

- Focused on the recent searches from the CMS experiment

- Run3 is underway, at 13.6 TeV
  - expected to more than double the Run2 luminosity
  - BSM scalar sector is a **natural target** as the LHC dataset grows
    - Relatively low production rate
    - Next-to-minimal models significantly change detector phenomenology
    - Variety of final states from standard to very exotic/soft/collimated..

- *Stay tuned!*

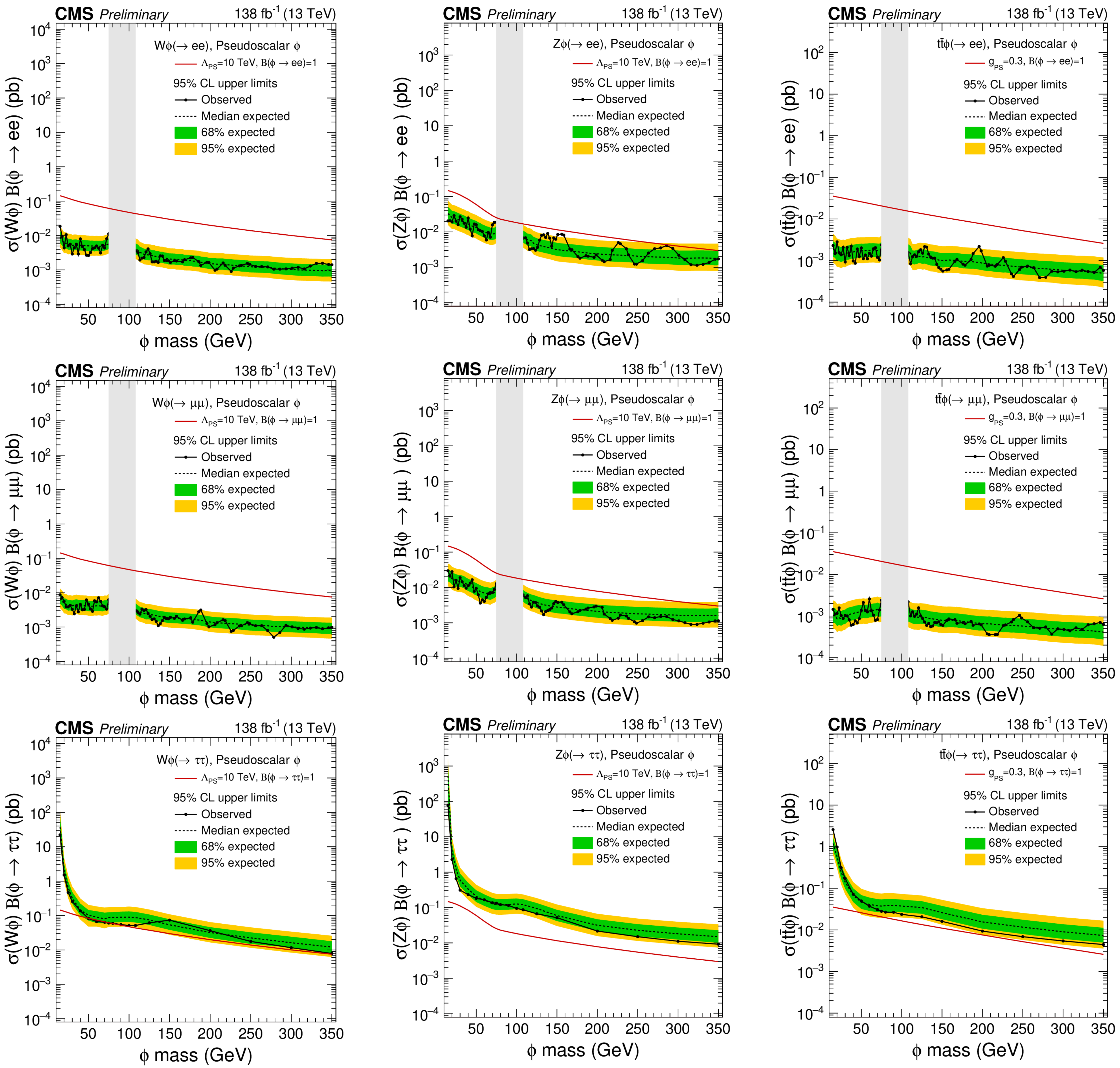


https://www.symmetrymagazine.org/article/four-things-physicists-still-wonder-about-the-higgs-boson
https://www.symmetrymagazine.org/article/what-the-higgs-boson-tells-us-about-the-universe

Backup

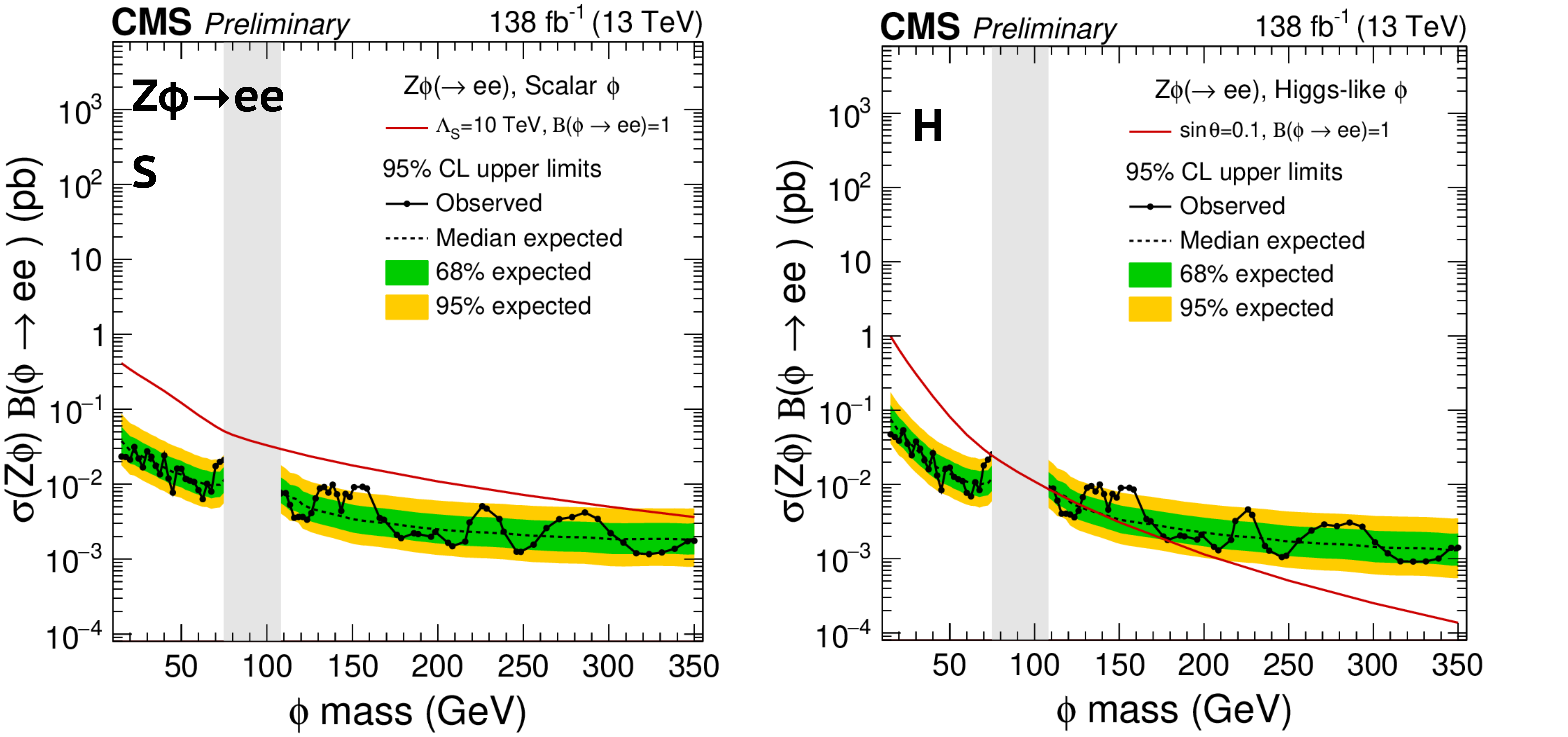
Search for Xϕ→ℓℓ (all PS results)

EXO-21-018



Search for Zϕ→ℓℓ

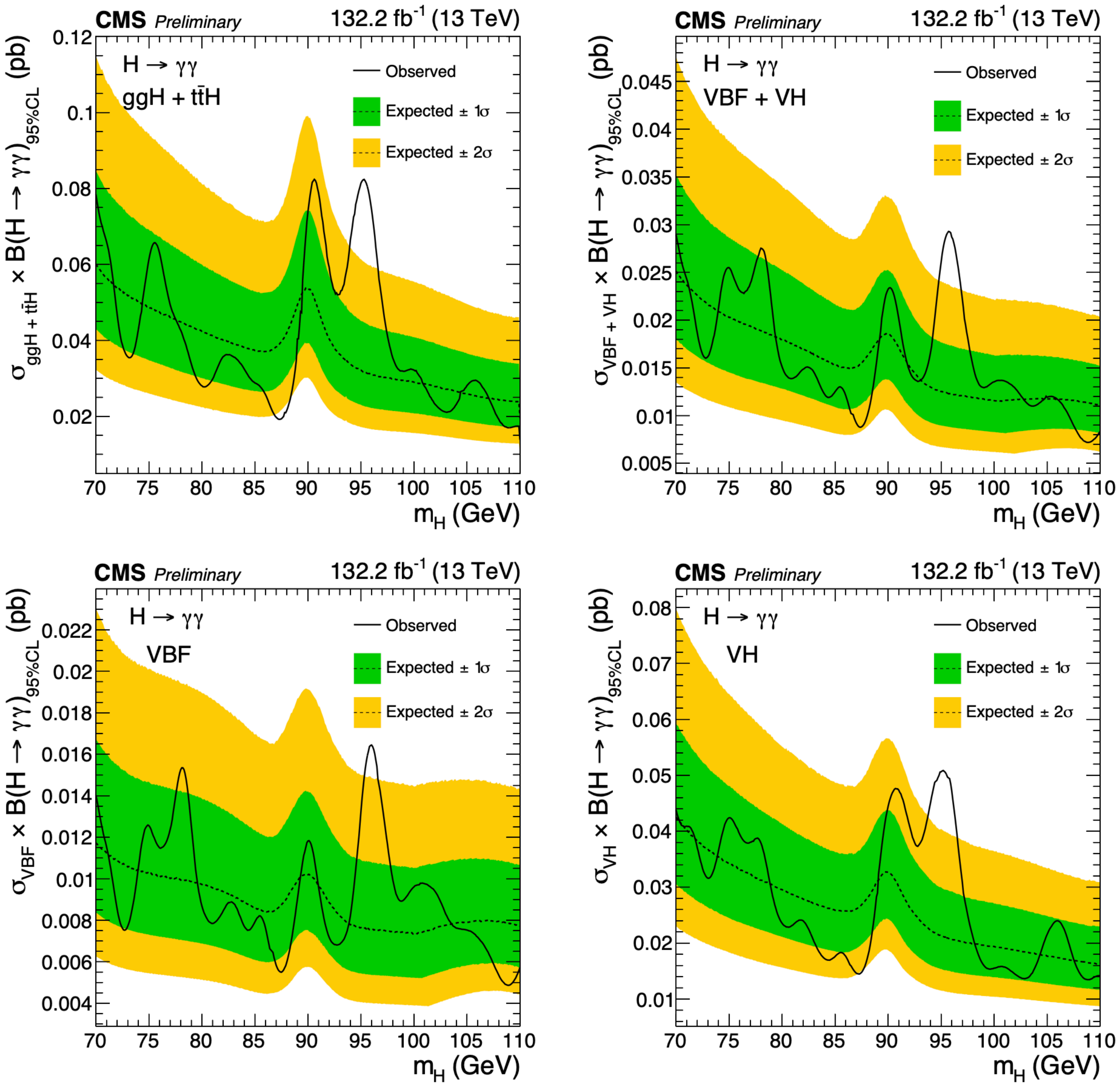
EXO-21-018



3-body decays of Z are more significant in the Higgs-like coupling

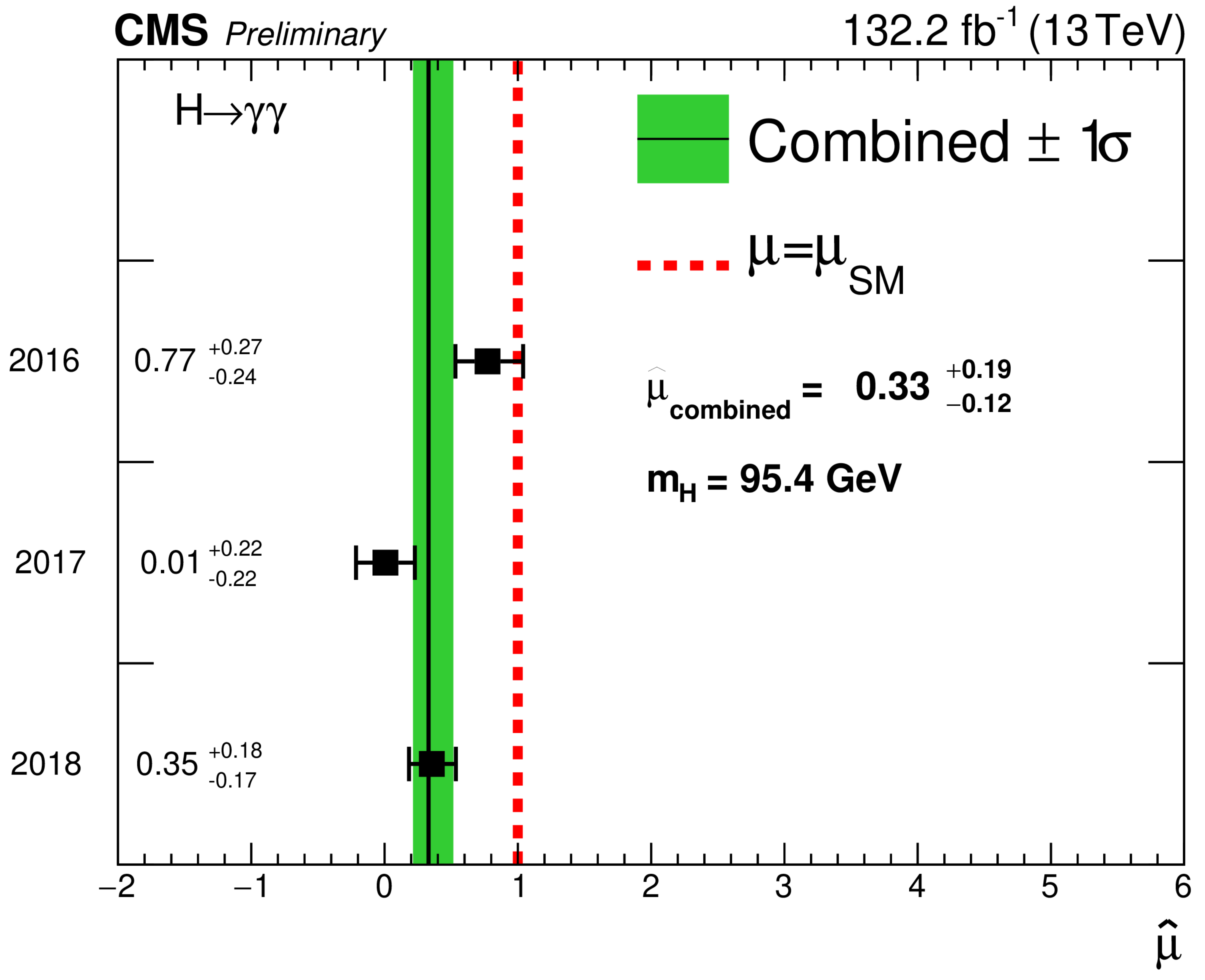
Light Higgs to diphotons

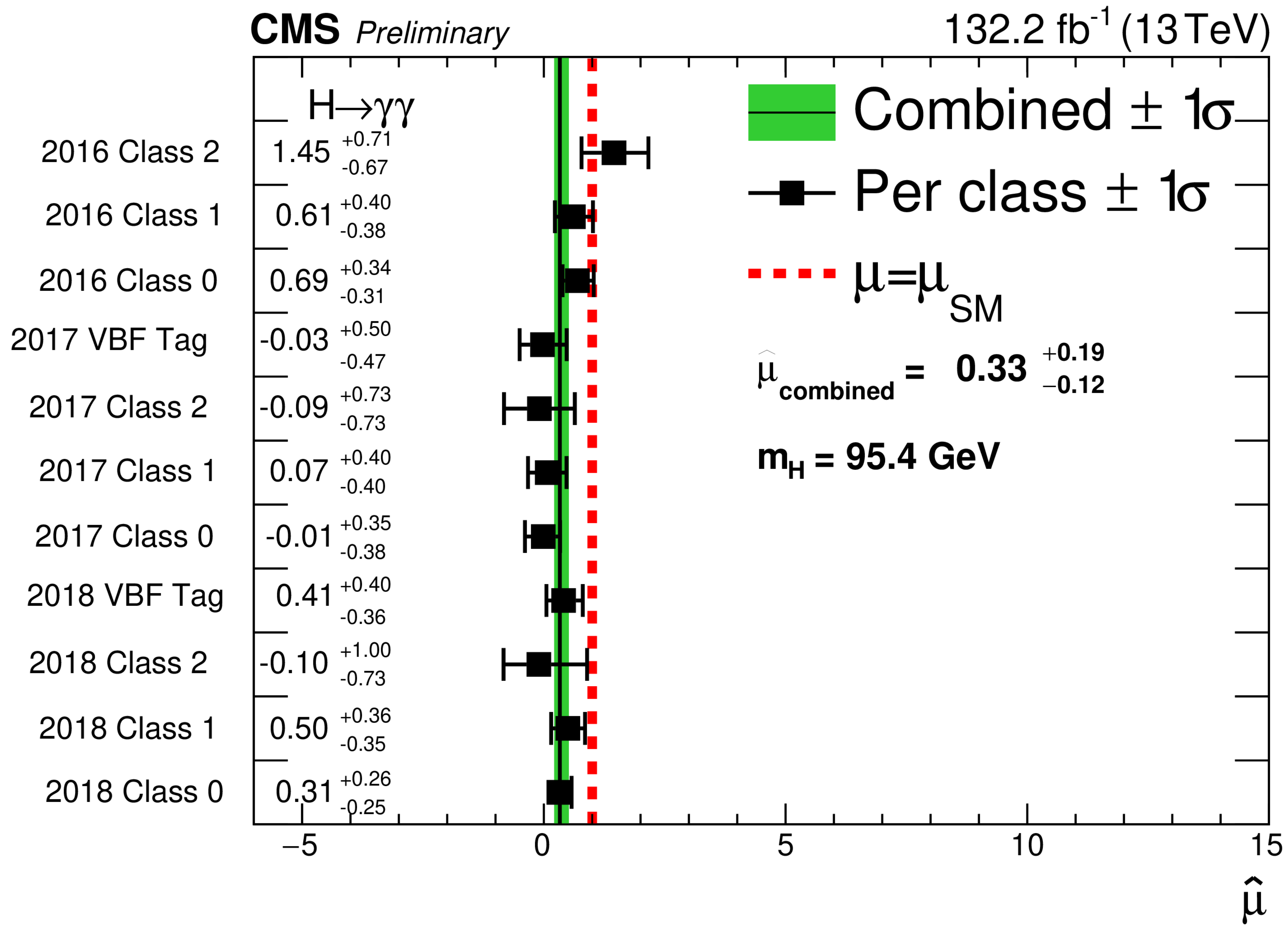
HIG-20-002



Light Higgs to diphotons

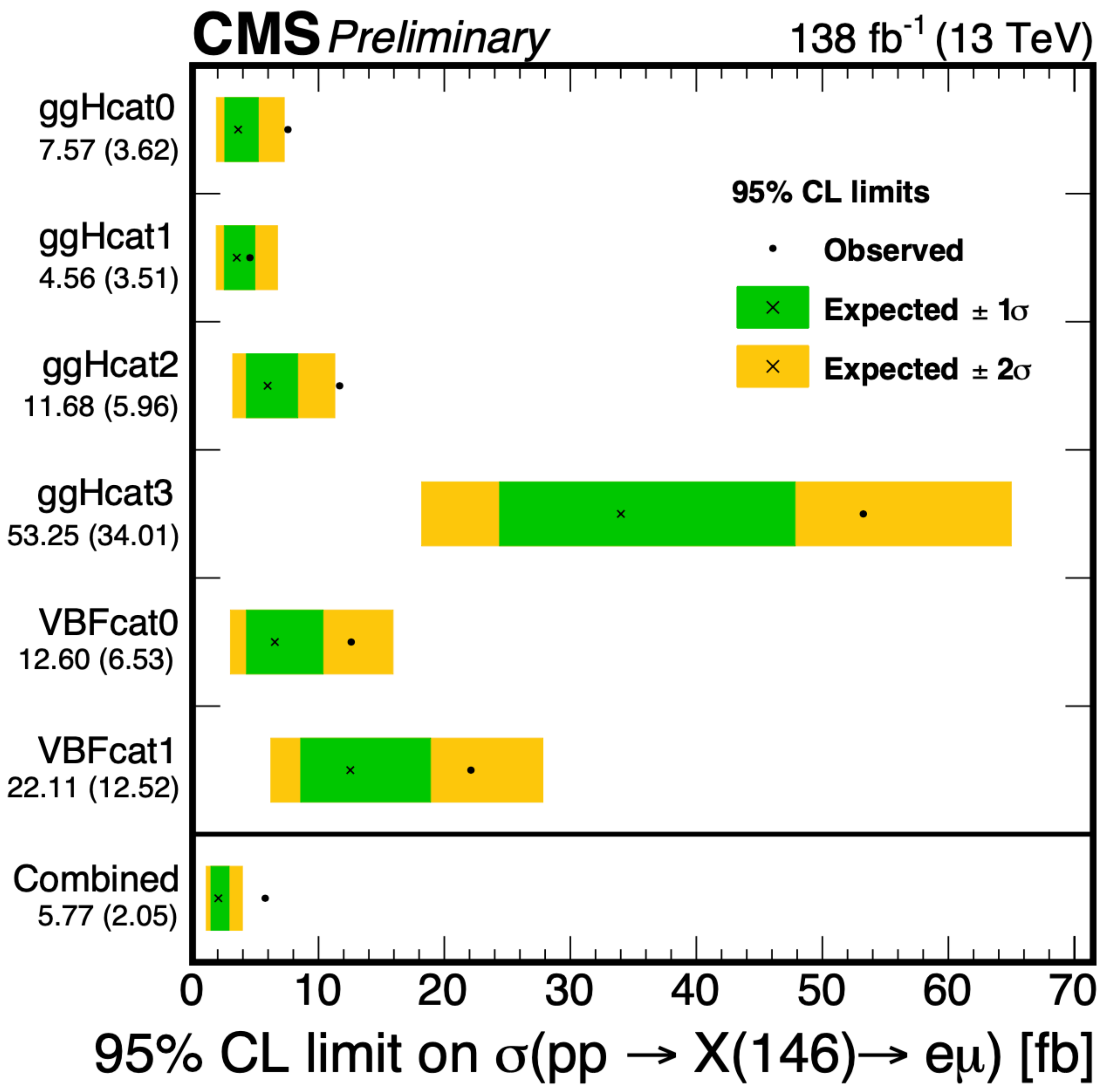
HIG-20-002

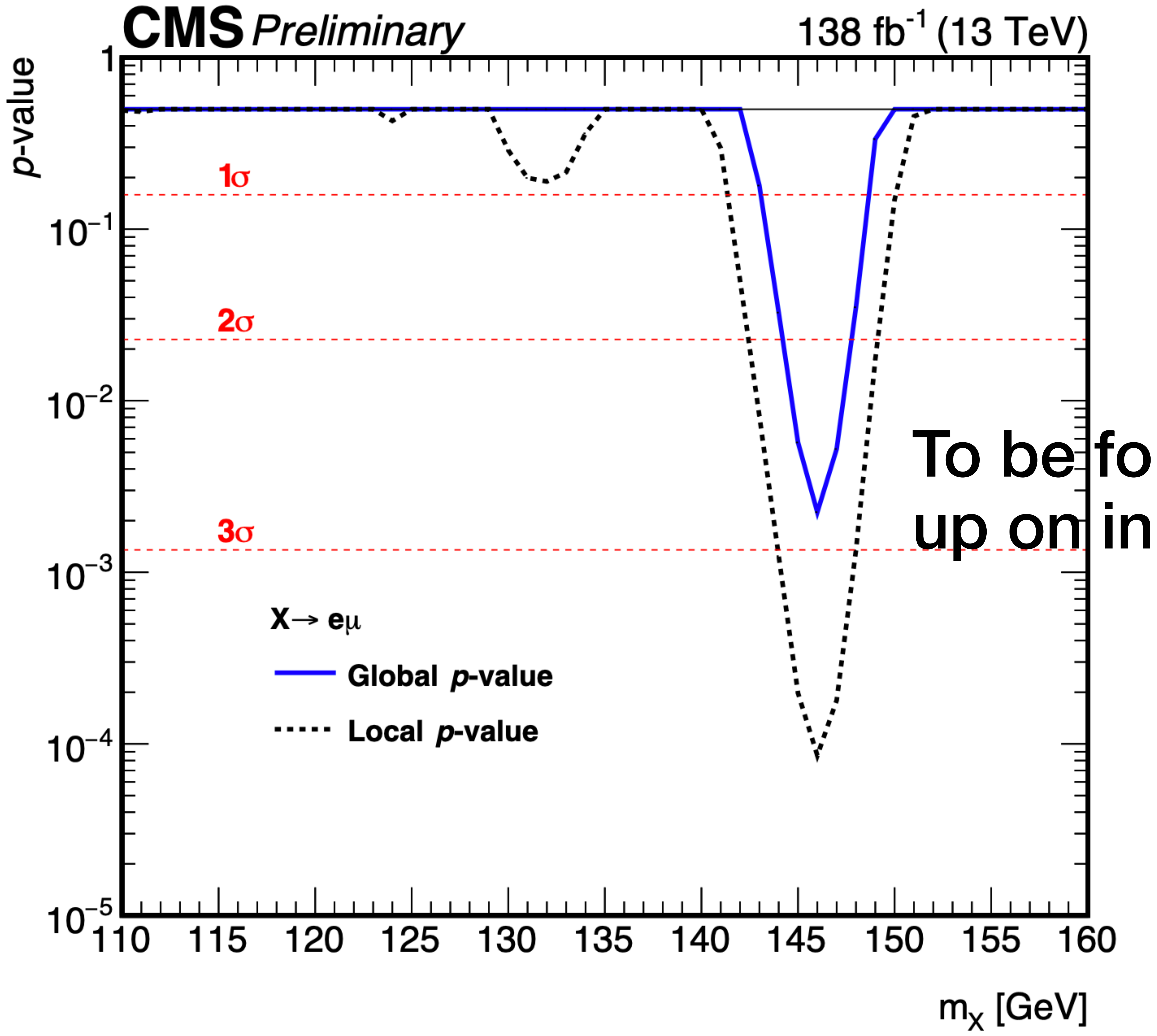




LFV decays of a new scalar

HIG-22-002





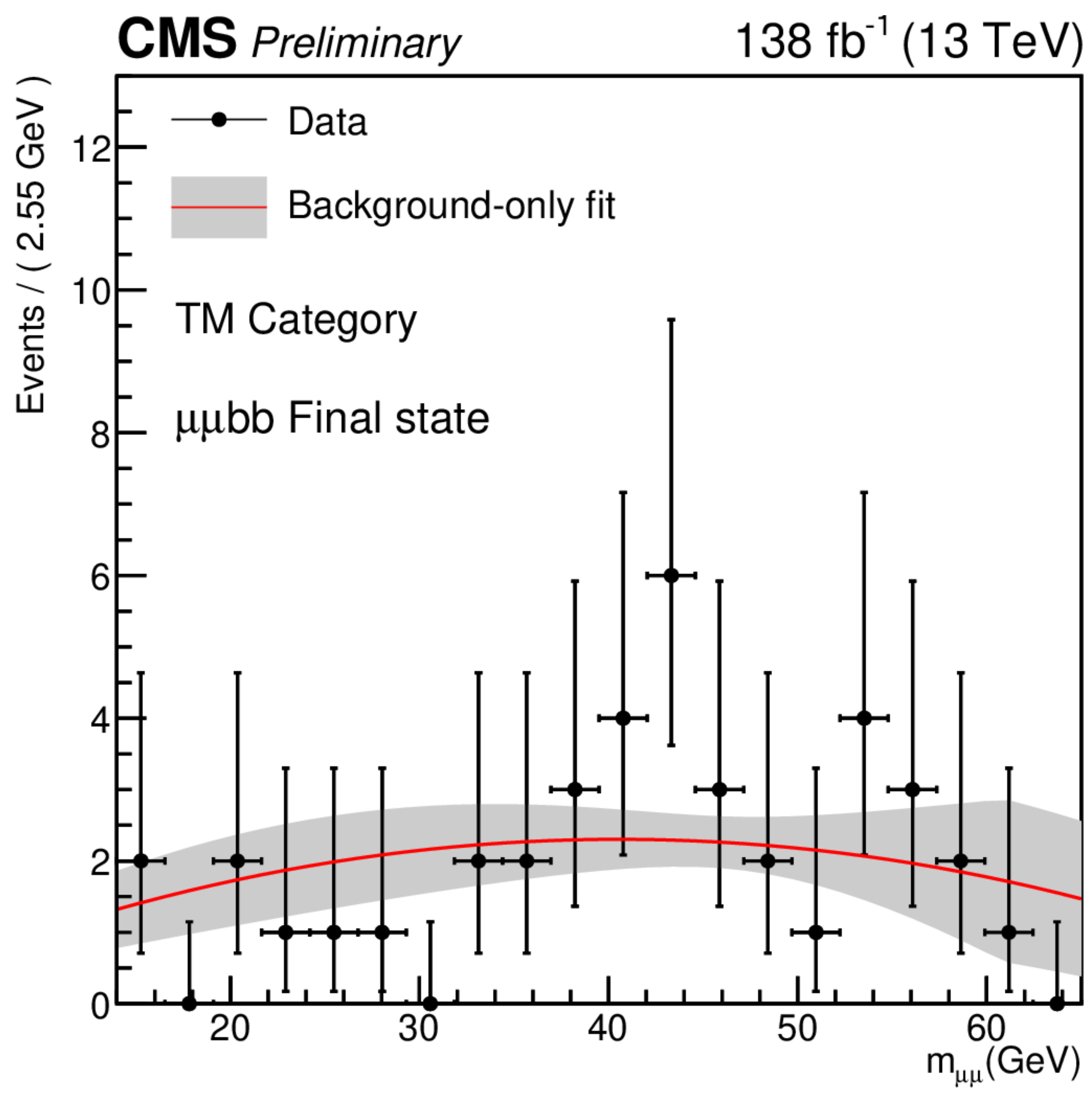
To be followed up on in Run 3!

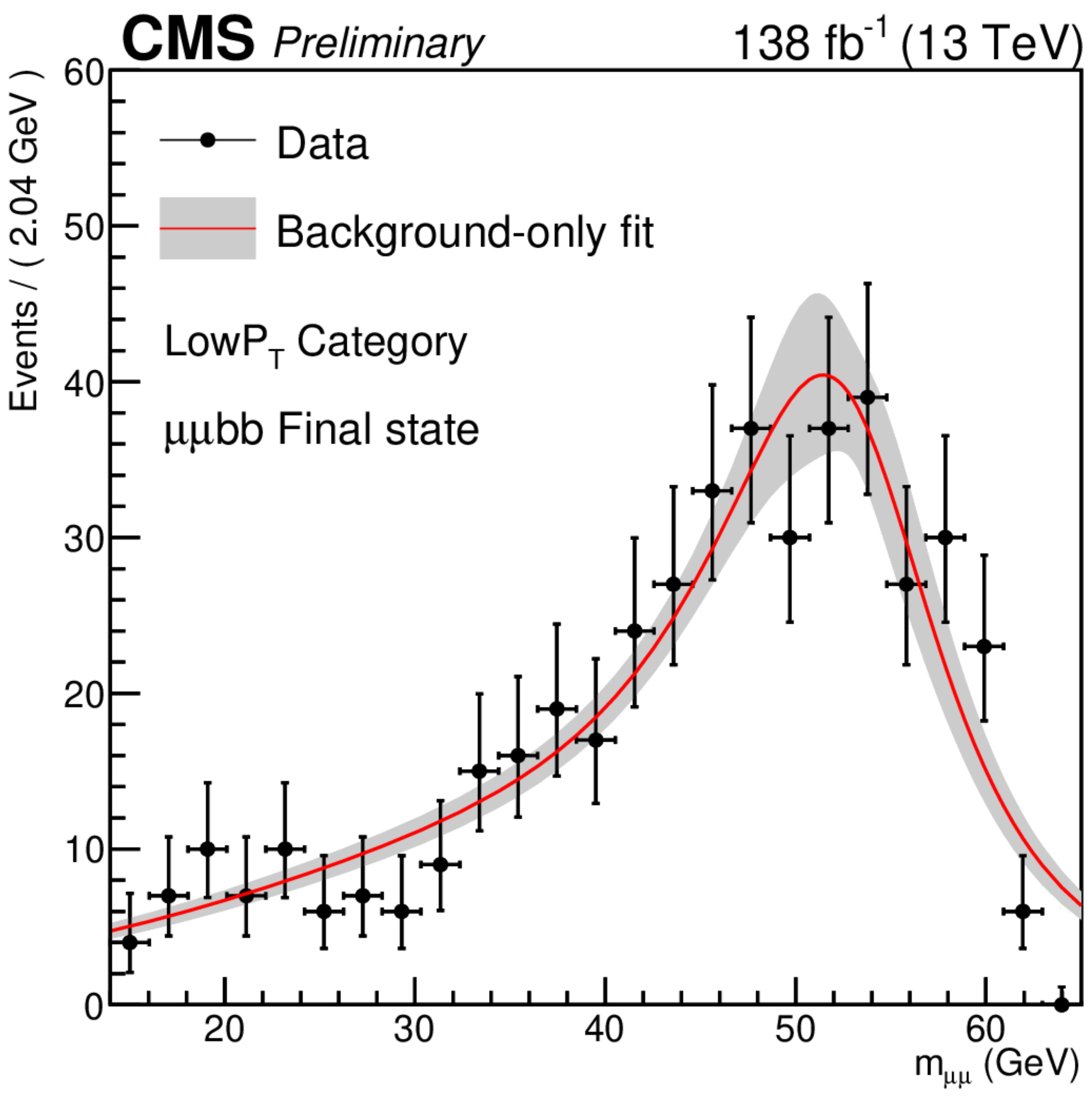
Relatively small excesses in multiple categories

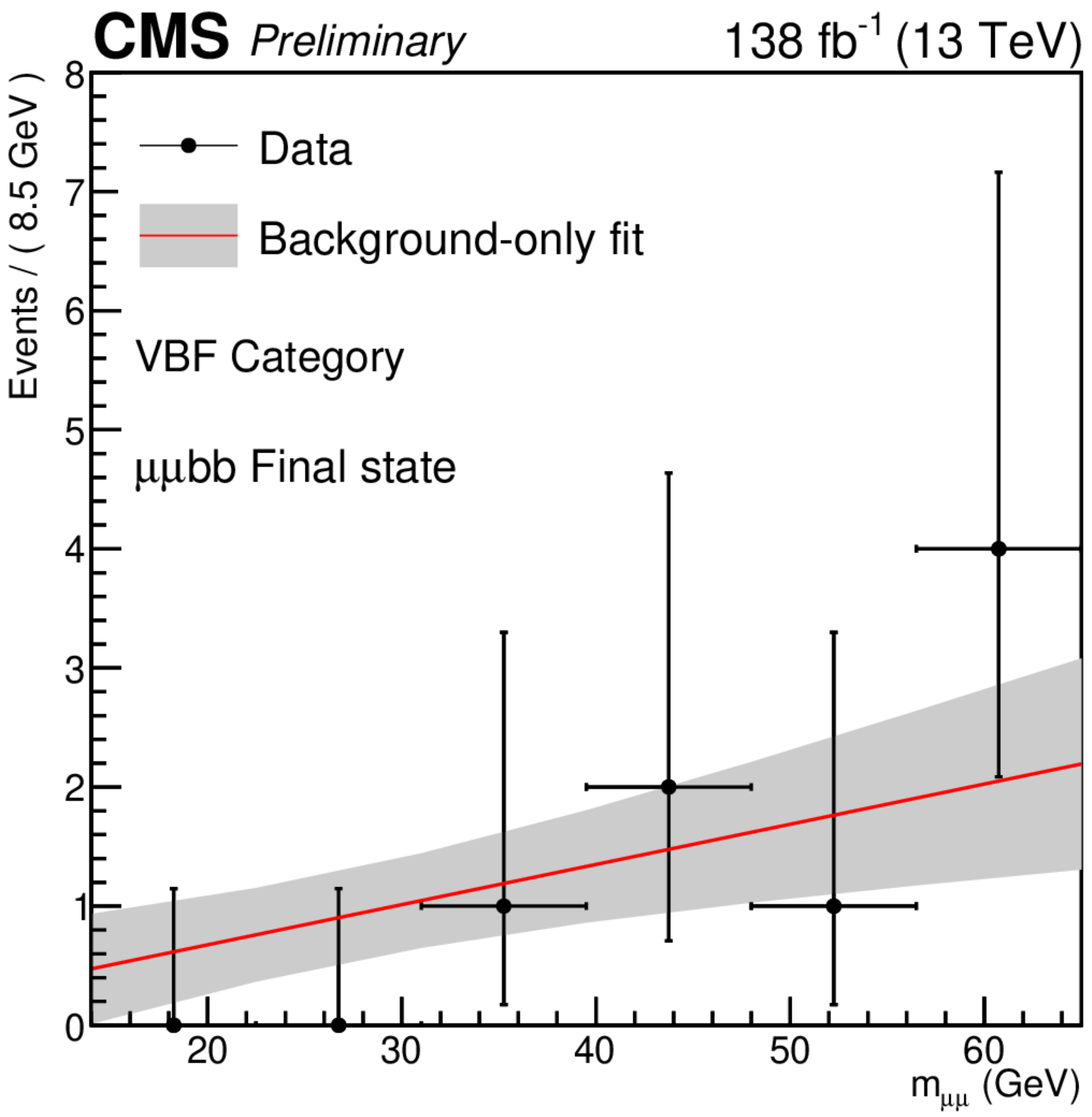
H→aa→μμbb

HIG-21-021

HIG-22-007



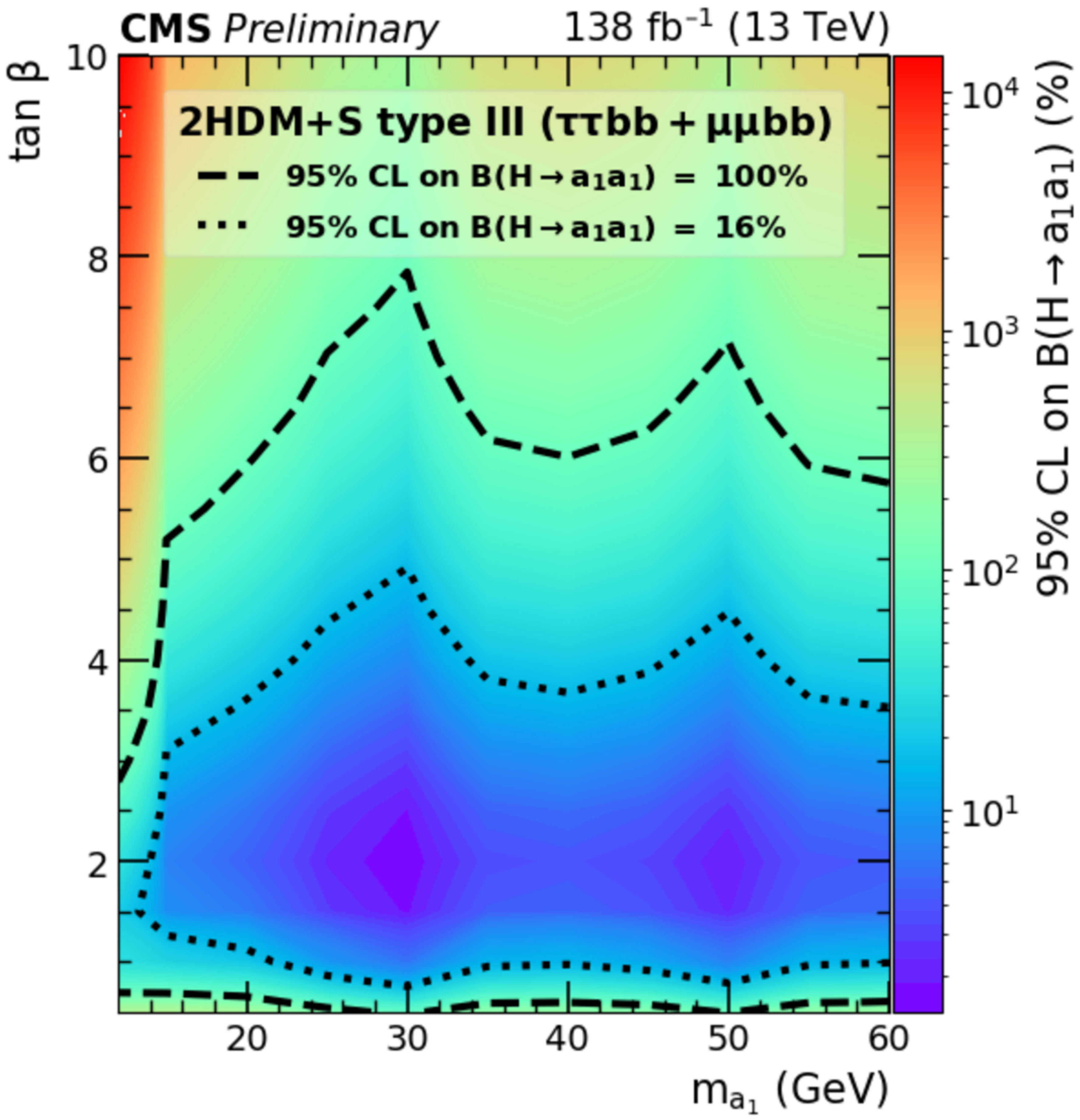


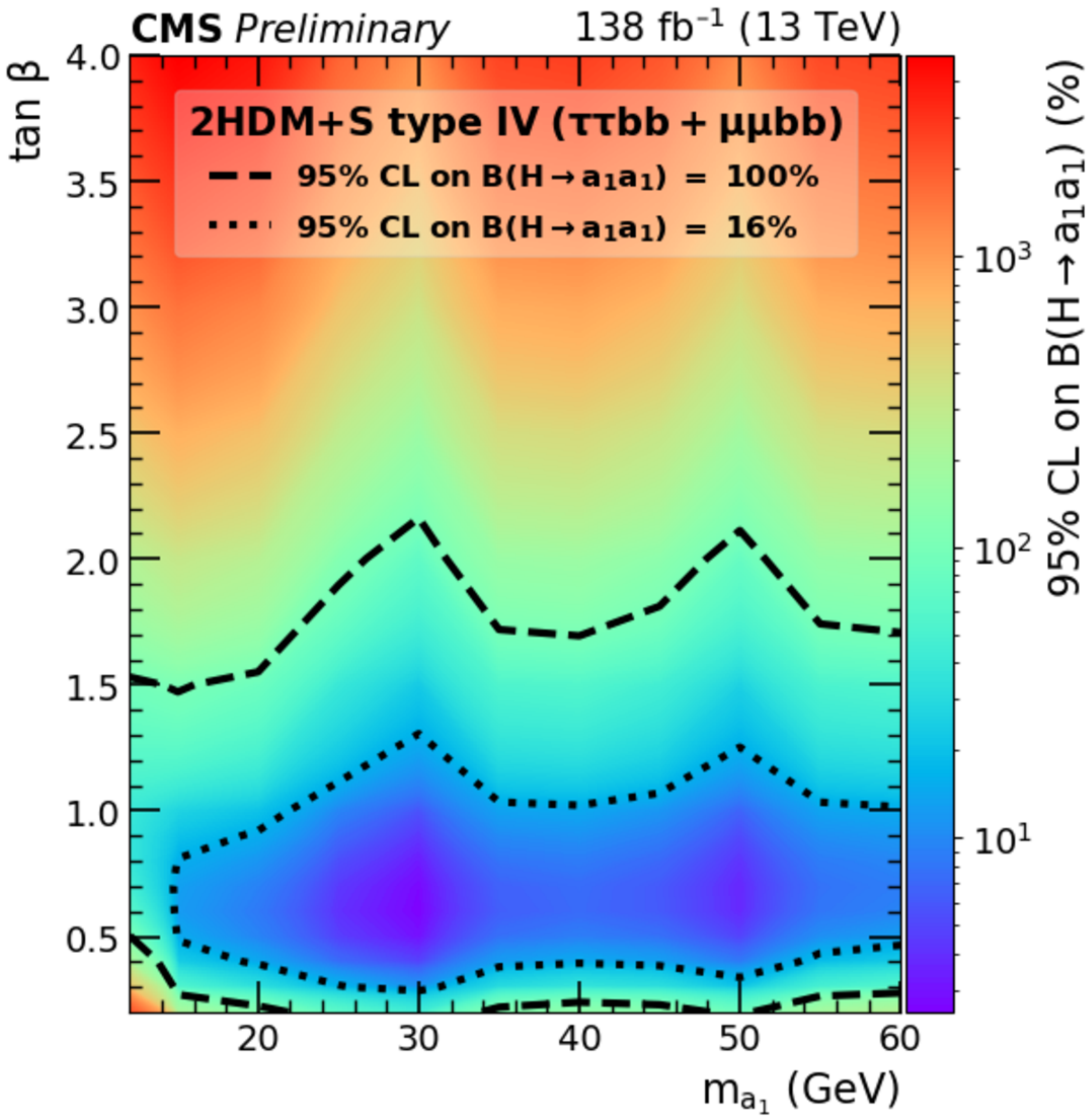


Unbinned maximum likelihood fit is performed on the dimuon mass in each of the categories

Light pseudoscalars: H→aa

HIG-21-021
HIG-22-007



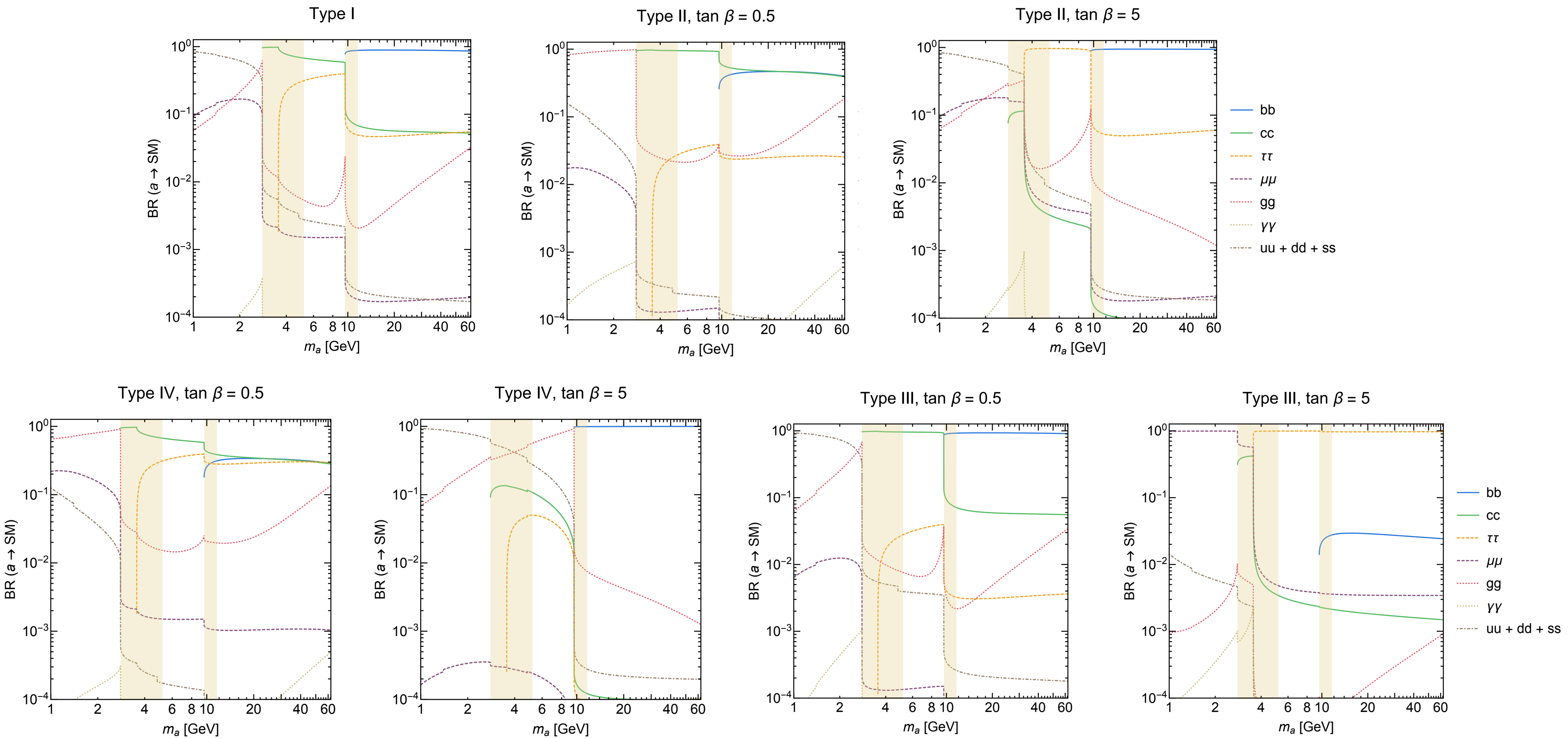


16% is the approx. upper limit on $H \to BSM$

Model dependent interpretations in 2HDM+S type III and IV scenarios.

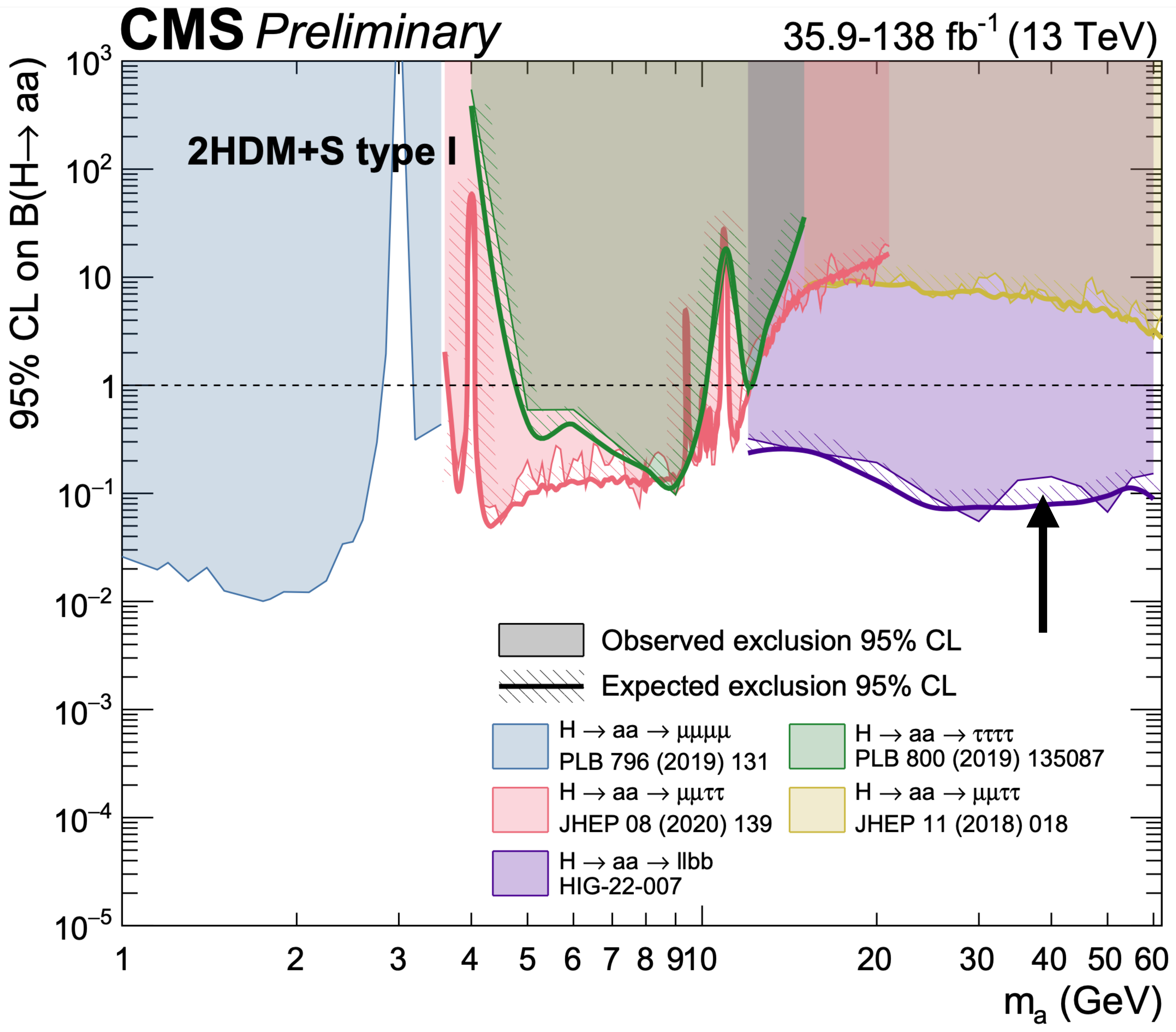
H2DM Pseudoscalar BRs

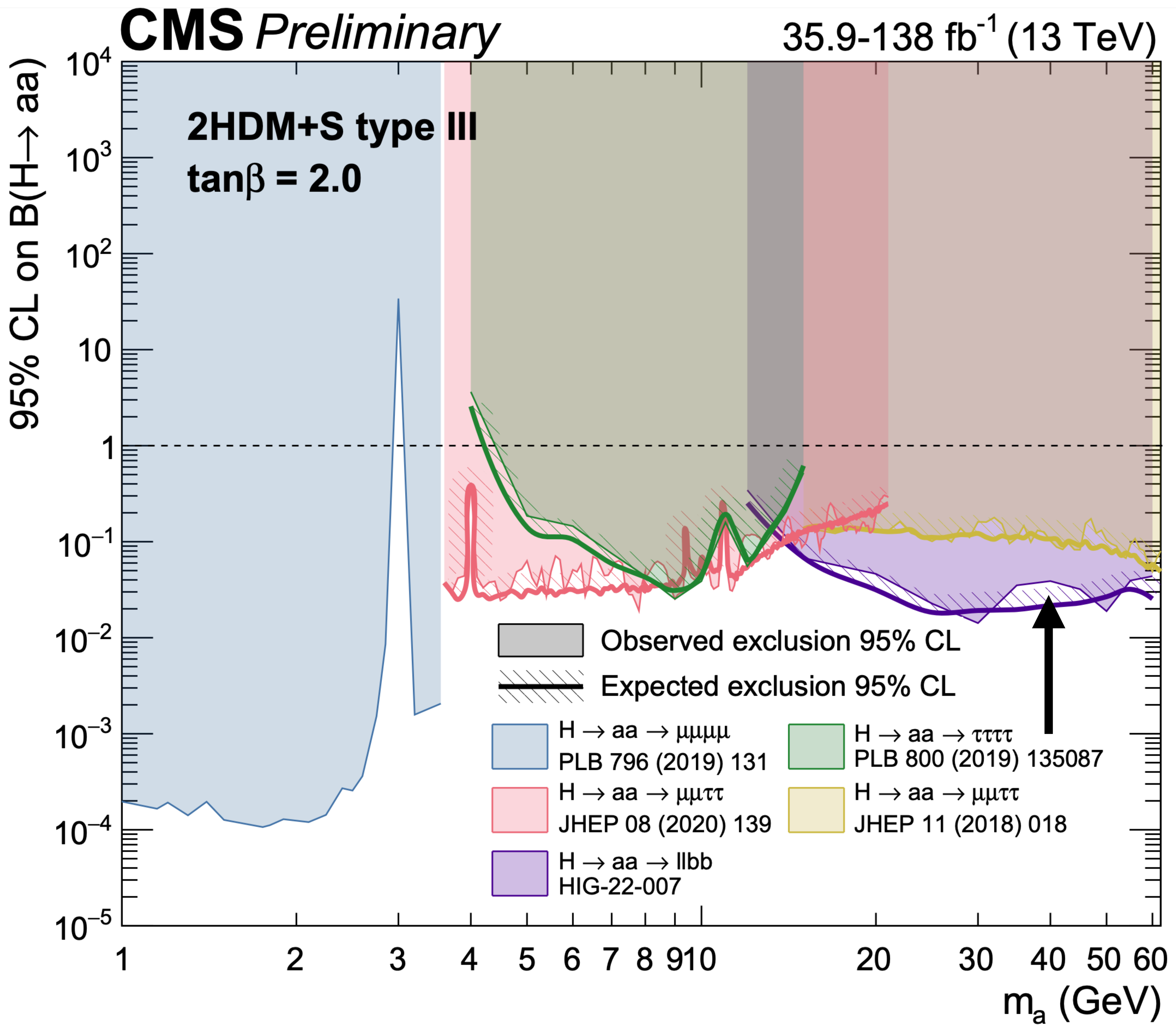
https://arxiv.org/abs/1312.4992



Light pseudoscalars: H→aa

HIG-21-021
HIG-22-007

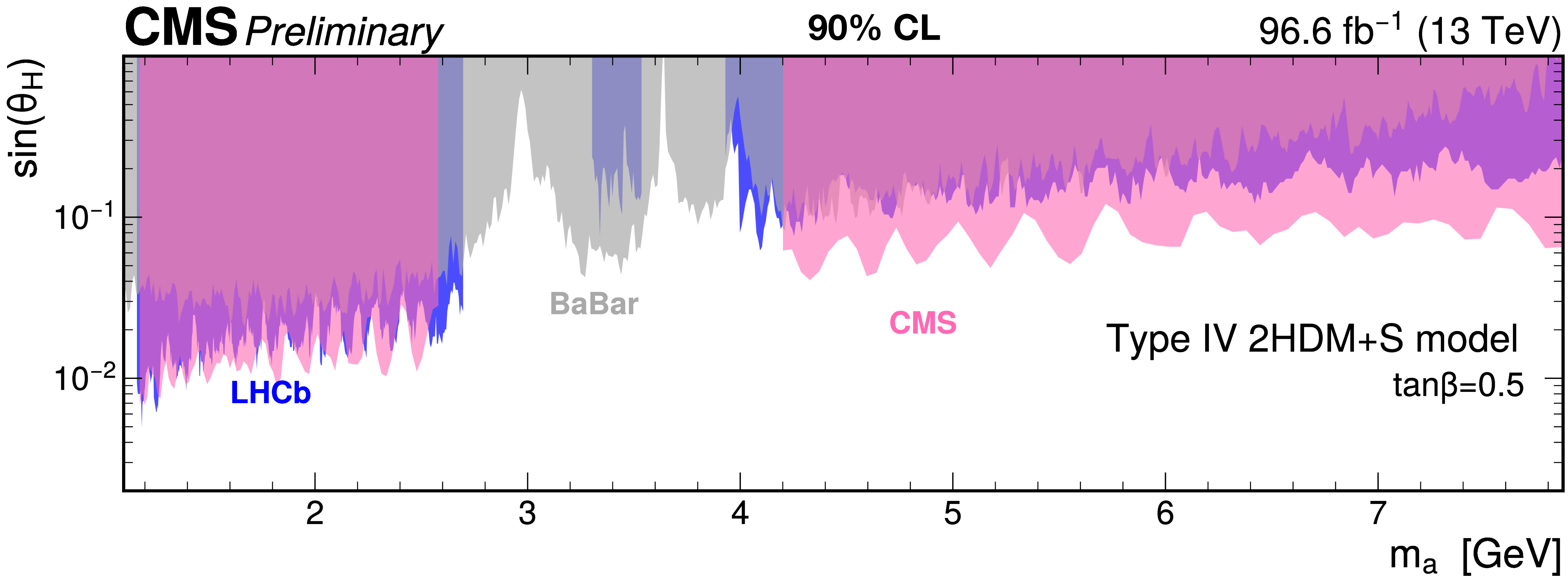




https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

Prompt low mass dimuons

EXO-21-005



Model specific Type-IV 2HDM+S reinterpretation of the high p_T limit
- ggF production mode yields higher boost than does the DY mode.

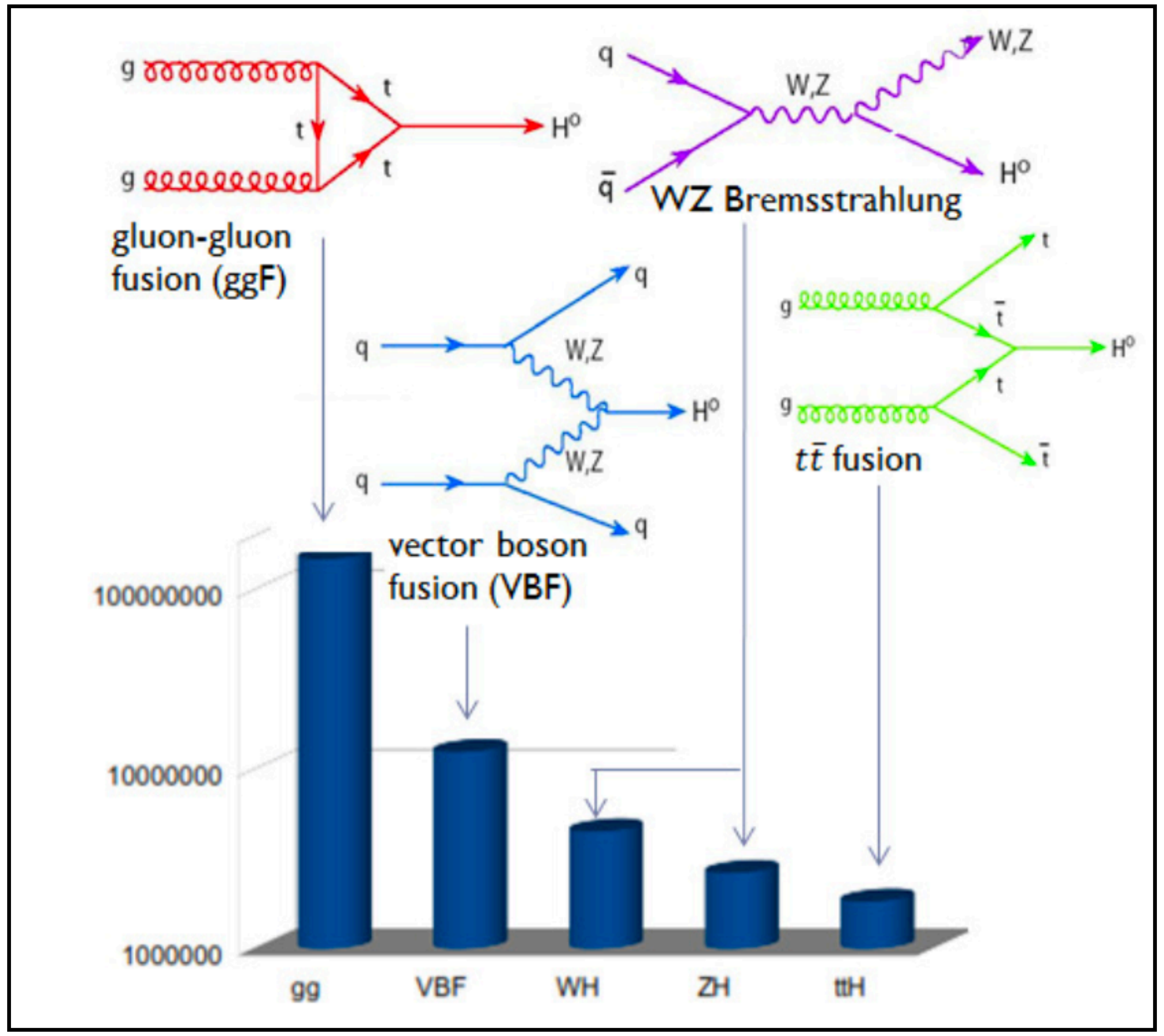
Search for $X\phi \rightarrow \ell\ell$

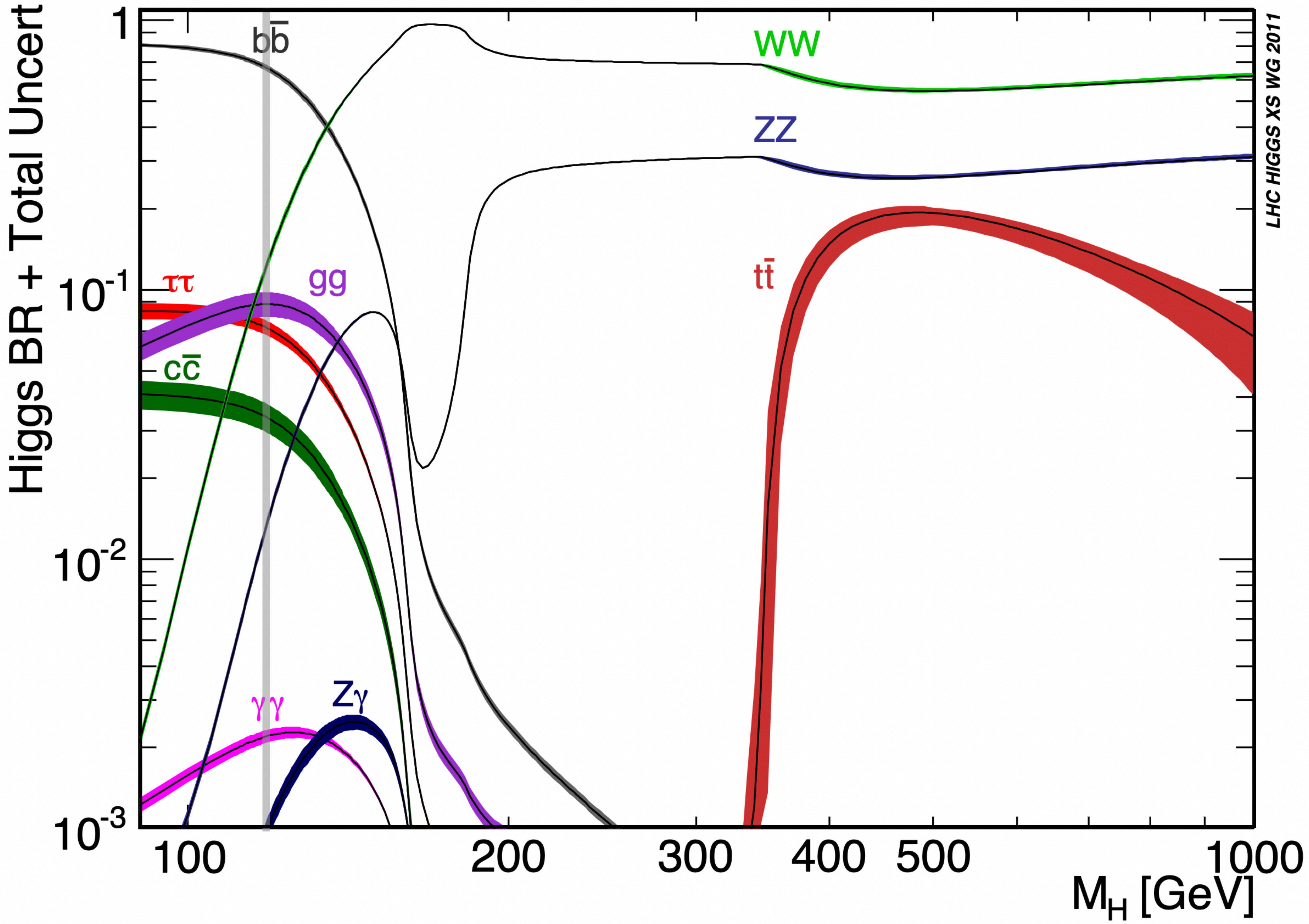
EXO-21-018

Label	Channels	Q_ℓ	OSSFn	M_{OSSF}	N_{b}	S_{T}	p_{T}^{3}	M_ℓ	Dilepton mass
$\mathrm{W}\phi(\mathrm{ee}/\mu\mu)$ SR1Low	$3\mathrm{L}(\mathrm{ee}\mu/\mathrm{e}\mu\mu)$	1	1	OffZ	0	–	–	$< 76, > 106$	M_{ee} / $M_{\mu\mu}$
$\mathrm{W}\phi(\mathrm{ee}/\mu\mu)$ SR2Low	$3\mathrm{L}(\mathrm{eee}/\mu\mu\mu)$	1	1	OffZ	0	–	–	$< 76, > 106$	$M_{\mathrm{ee}}^{\mathrm{min}}/M_{\mu\mu}^{\mathrm{min}}$
$\mathrm{W}\phi(\mathrm{ee}/\mu\mu)$ SR1High	$3\mathrm{L}(\mathrm{ee}\mu/\mathrm{e}\mu\mu)$	1	1	OffZ	0	> 200	> 15	> 150	M_{ee} / $M_{\mu\mu}$
$\mathrm{W}\phi(\mathrm{ee}/\mu\mu)$ SR2High	$3\mathrm{L}(\mathrm{eee}/\mu\mu\mu)$	1	1	OffZ	0	> 200	> 15	> 150	$M_{\mathrm{ee}}^{\mathrm{max}}/M_{\mu\mu}^{\mathrm{max}}$
$\mathrm{Z}\phi(\mathrm{ee}/\mu\mu)$ SRLow	4L+3L1T+2L2T	0	≥ 1	Not double-OnZ	0	–	–	–	$M_{\mathrm{ee}}^{\mathrm{min}}/M_{\mu\mu}^{\mathrm{min}}$
$\mathrm{Z}\phi(\mathrm{ee}/\mu\mu)$ SRHigh	4L+3L1T+2L2T	0	≥ 1	Not double-OnZ	0	> 200	–	> 150	$M_{\mathrm{ee}}^{\mathrm{max}}/M_{\mu\mu}^{\mathrm{max}}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR1Low	$3\mathrm{L}(\mathrm{ee}\mu/\mathrm{e}\mu\mu)$	1	1	OffZ	≥ 1	> 350	–	> 100	M_{ee} / $M_{\mu\mu}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR2Low	$3\mathrm{L}(\mathrm{eee}/\mu\mu\mu)$	1	1	OffZ	≥ 1	> 350	–	> 100	$M_{\mathrm{ee}}^{\mathrm{min}}/M_{\mu\mu}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR1High	$3\mathrm{L}(\mathrm{ee}\mu/\mathrm{e}\mu\mu)$	1	1	OffZ	≥ 1	> 400	> 15	> 100	M_{ee} / $M_{\mu\mu}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR2High	$3\mathrm{L}(\mathrm{eee}/\mu\mu\mu)$	1	1	OffZ	≥ 1	> 400	> 15	> 100	$M_{\mathrm{ee}}^{\mathrm{max}}/M_{\mu\mu}^{\mathrm{max}}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR3Low	4L+3L1T+2L2T	0	≥ 1	OffZ	–	> 350	–	–	$M_{\mathrm{ee}}^{\mathrm{min}}/M_{\mu\mu}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR3High	4L+3L1T+2L2T	0	≥ 1	OffZ	–	> 400	–	–	$M_{\mathrm{ee}}^{\mathrm{max}}/M_{\mu\mu}^{\mathrm{max}}$

Label	Channels	Q_ℓ	OSSFn	M_{OSSF}	N_{b}	S_{T}	N_{j}	p_{T}^{3}	M_ℓ	Dilepton mass
$\mathrm{W}\phi(\tau\tau)$ SR1	3L	1	0	–	0	> 200	–	> 15	> 150	$M_{\mathrm{e}\mu}^{\mathrm{min}}$
$\mathrm{W}\phi(\tau\tau)$ SR2	2L1T+1L2T	1	0	–	0	> 200	–	> 30	> 150	$M_{\ell\tau}^{\mathrm{min}}$
$\mathrm{W}\phi(\tau\tau)$ SR3	1L2T	1	1	–	0	> 200	–	> 30	> 150	$M_{\tau\tau}^{\mathrm{min}}$
$\mathrm{Z}\phi(\tau\tau)$ SR1	4L+2L2T	0	1	–	0	> 200	–	–	–	$M_{\mathrm{e}\mu}^{\mathrm{min}}$
$\mathrm{Z}\phi(\tau\tau)$ SR2	3L1T	0	1	–	0	> 200	–	–	–	$M_{\ell\tau}^{\mathrm{min}}$
$\mathrm{Z}\phi(\tau\tau)$ SR2	2L2T	0	0	–	0	> 200	–	–	–	$M_{\ell\tau}^{\mathrm{min}}$
$\mathrm{Z}\phi(\tau\tau)$ SR3	2L2T	0	2	–	0	> 200	–	–	–	$M_{\tau\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR1	3L	1	0	–	0	> 400	> 1	> 15	> 100	$M_{\mathrm{e}\mu}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR2	2L1T+1L2T	1	0	–	0	> 400	> 1	> 30	> 100	$M_{\ell\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR3	1L2T	1	1	–	0	> 400	> 1	> 30	> 100	$M_{\tau\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR4	3L	1	1	OffZ	> 0	> 400	> 1	> 15	> 100	$M_{\mathrm{e}\mu}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR4	3L	1	0	–	> 0	> 400	> 1	> 15	> 100	$M_{\mathrm{e}\mu}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR5	2L1T+1L2T	1	0	–	> 0	> 400	> 1	> 30	> 100	$M_{\ell\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR6	1L2T	1	1	–	> 0	> 400	> 1	> 30	> 100	$M_{\tau\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR7	3L1T	0	1	OffZ	–	> 400	–	–	–	$M_{\ell\tau/\tau\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR7	3L1T	0	0	–	–	> 400	–	–	–	$M_{\ell\tau/\tau\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR7	2L2T	0	2	OffZ	–	> 400	–	–	–	$M_{\ell\tau/\tau\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR7	2L2T	0	< 2	–	–	> 400	–	–	–	$M_{\ell\tau/\tau\tau}^{\mathrm{min}}$
$\mathrm{t\bar{t}}\phi(\tau\tau)$ SR7	1L3T	0	1	–	–	> 400	–	–	–	$M_{\ell\tau/\tau\tau}^{\mathrm{min}}$

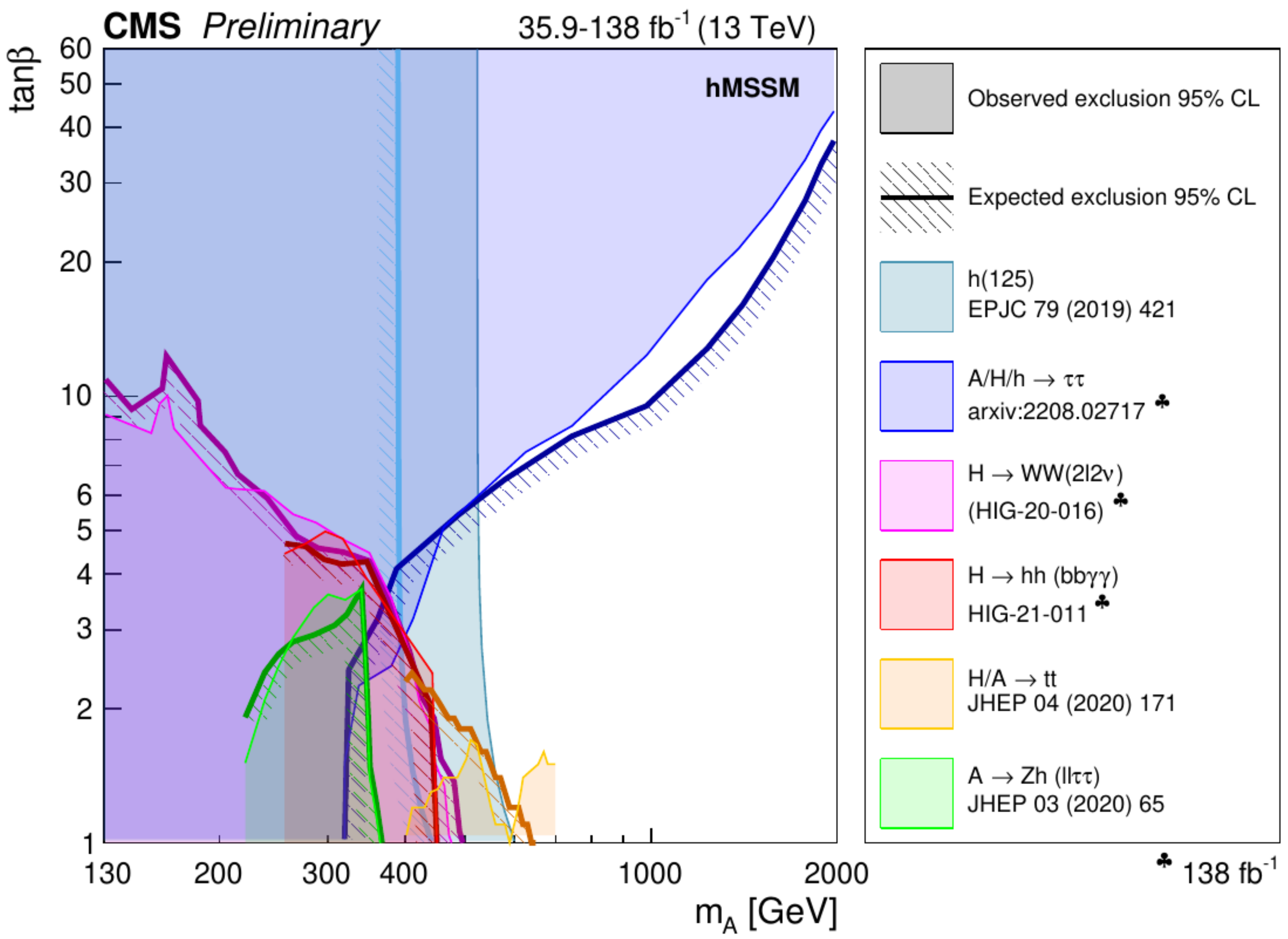
Higgs production and decay





ggF and VBF are the dominant production modes at the LHC.

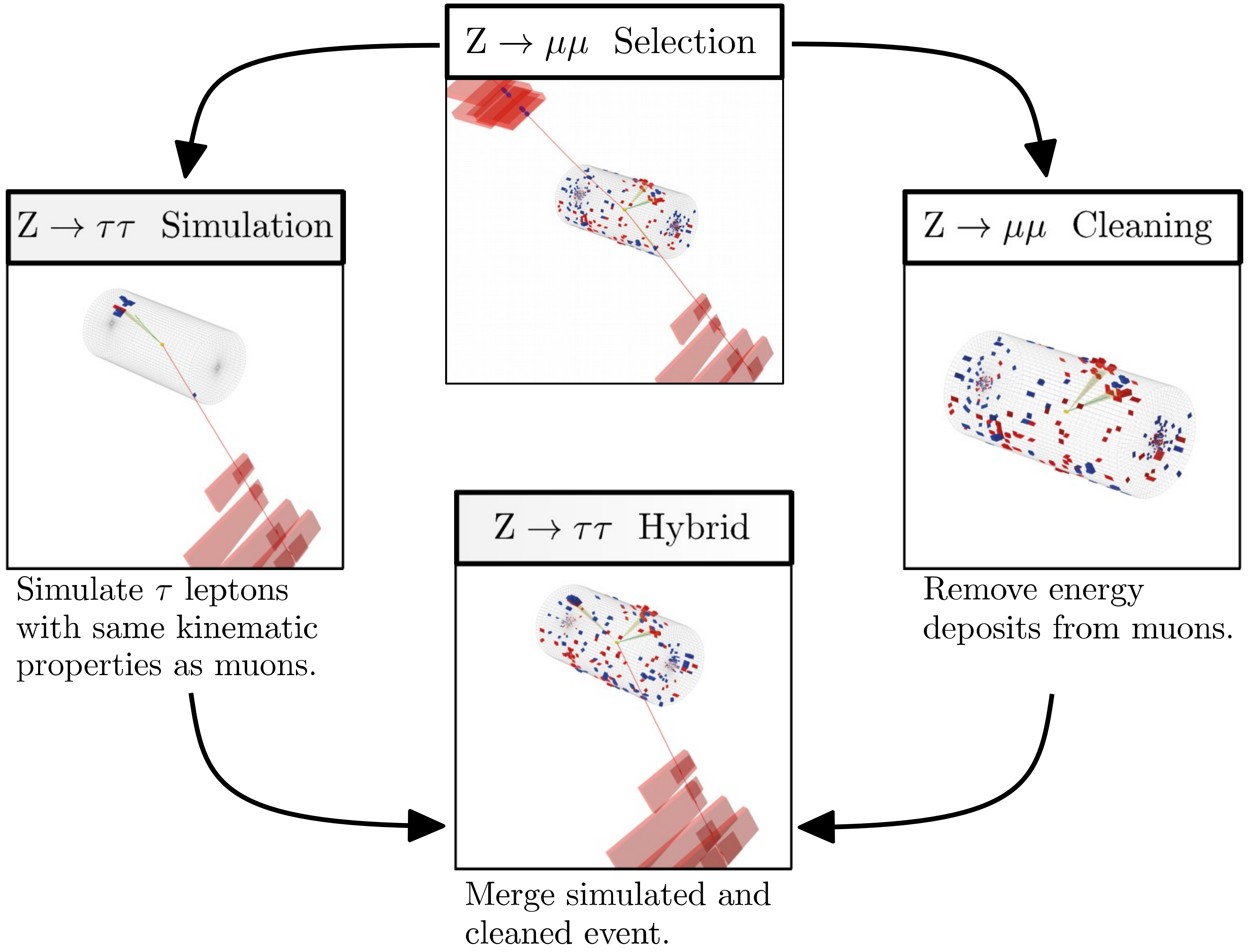
The scalar landscape in MSSM

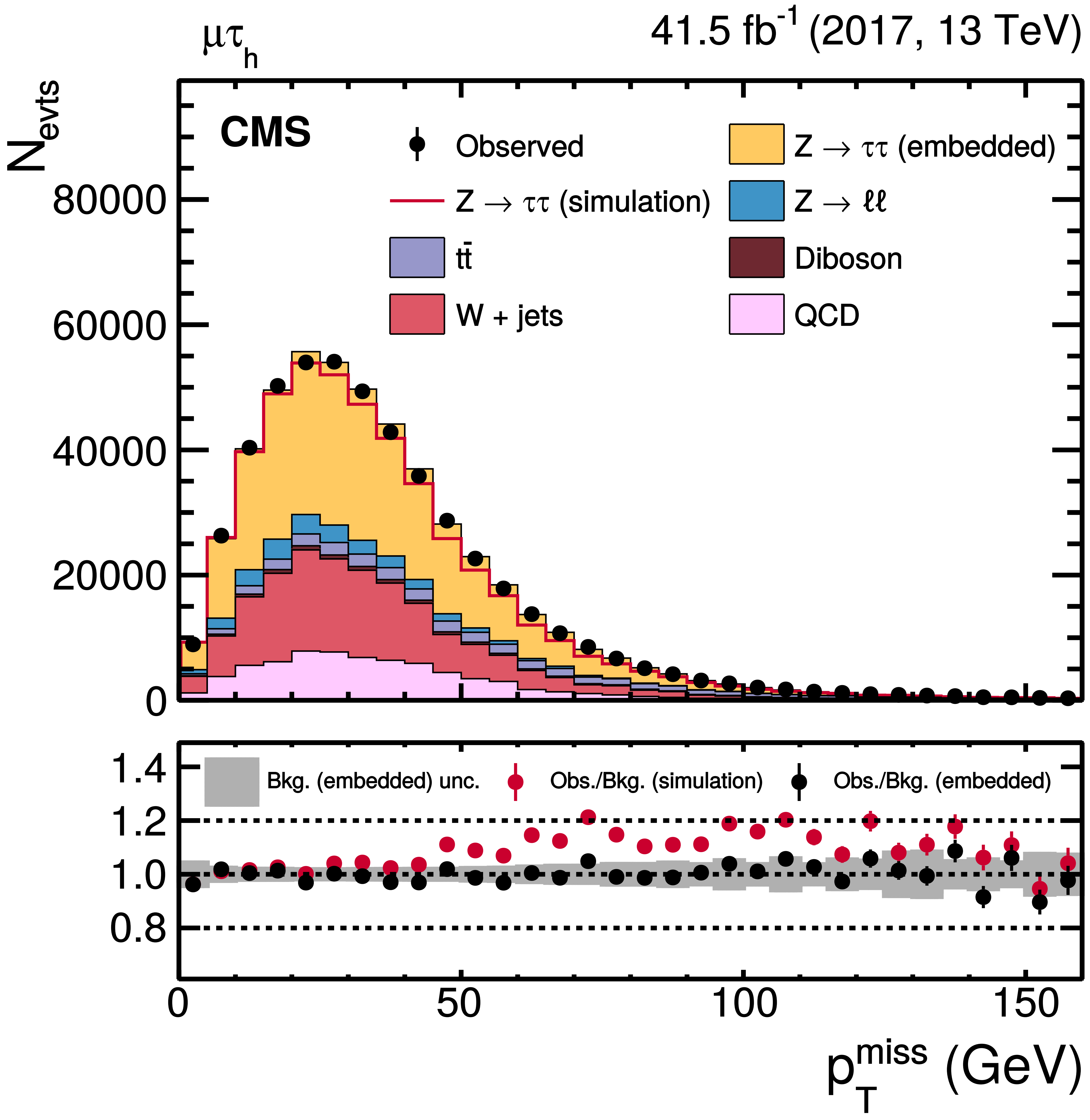


https://twiki.cern.ch/twiki/pub/CMSPublic/SummaryResultsHIG/MSSM_limits_hMSSM_Mar2023.png

Tau embedding

TAU-18-001





Embedding technique eliminates possible issues with underlying event description, pileup contributions, or production of associated jets .