Exotic tops anomalous interactions non-standard decays

The 12th Annual Large Hadron Collider Physics Conference

University of Cyprus

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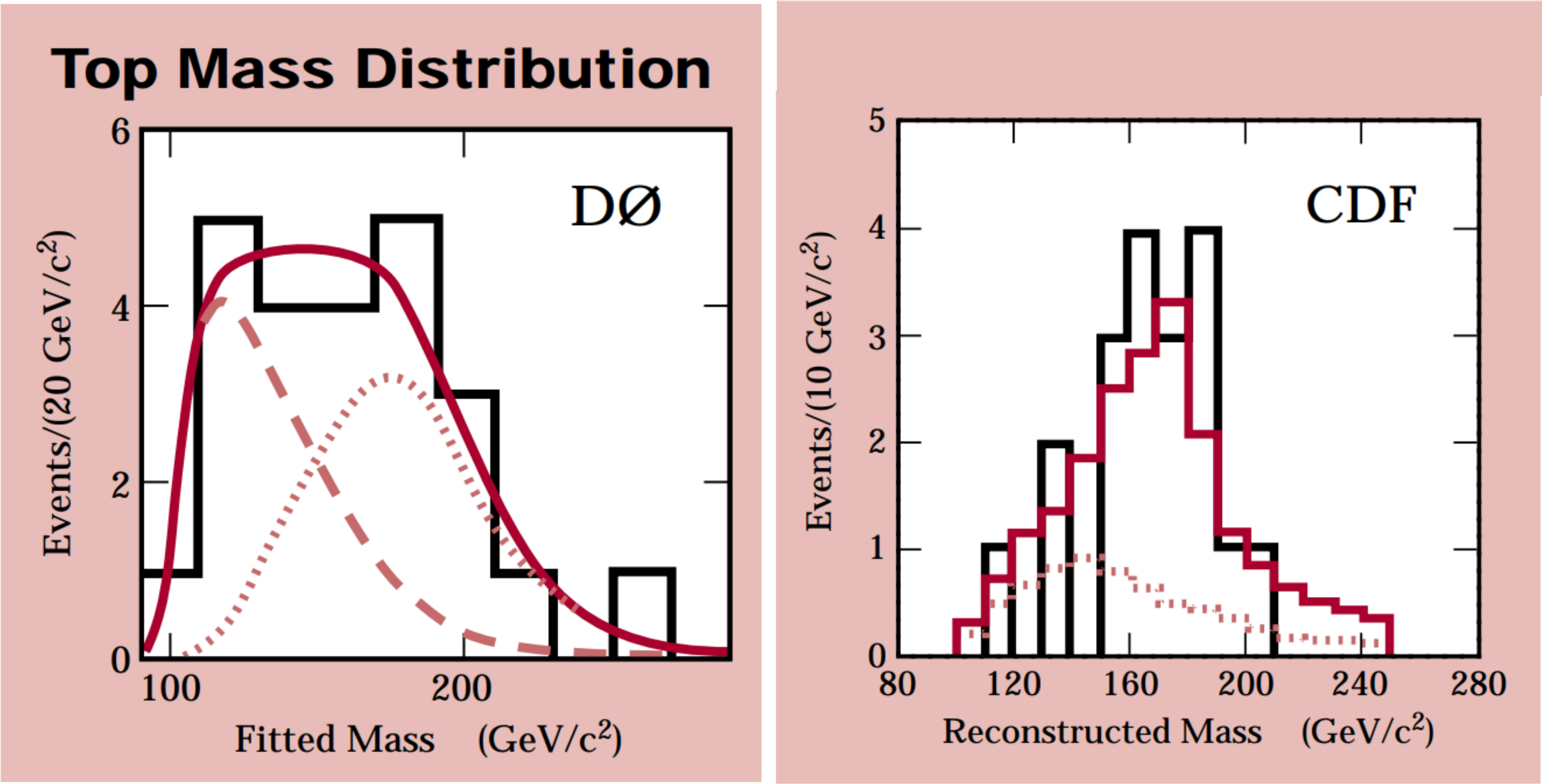
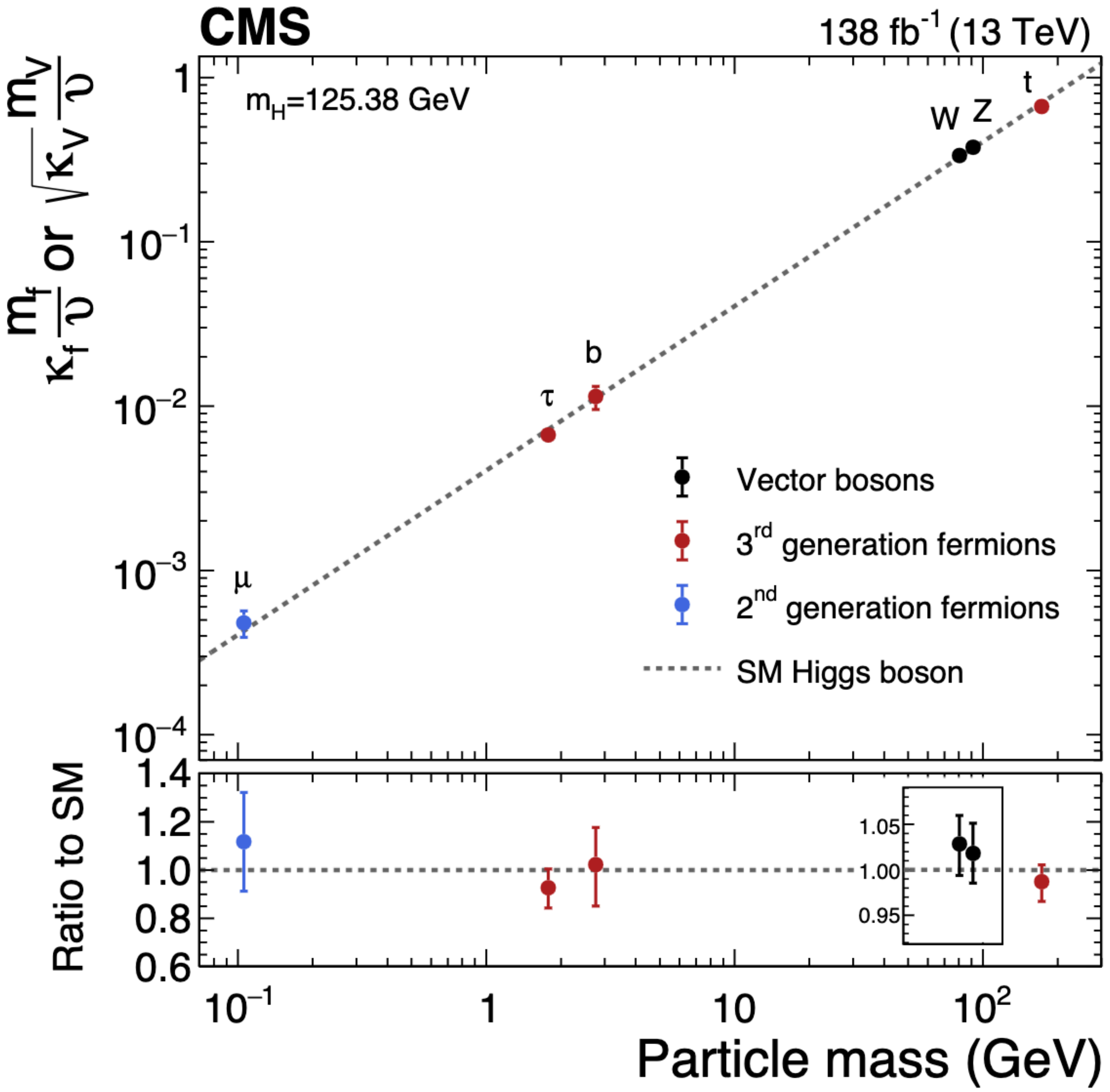
June 5, 2024

Top: late to party, first to BSM

https://inspirehep.net/literature/408027



$m_{top} \sim 173$ GeV



arXiv: 2207.00043

1995

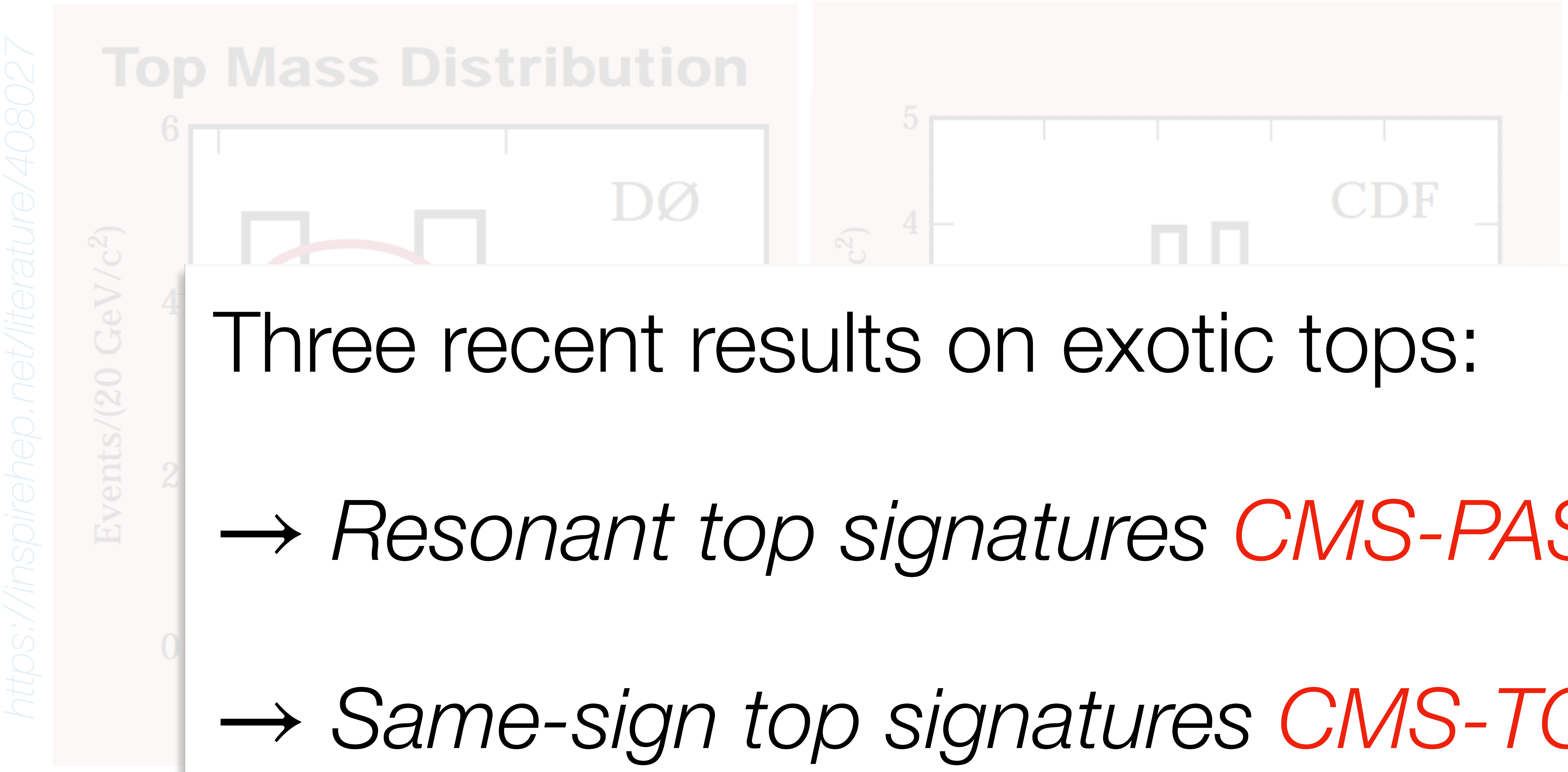
2020

Top quark is special:

→ the heaviest SM mass (least constrained by low-energy measurements)

→ strongly coupled to fields of the scalar sector

Top: late to party, first to BSM



Three recent results on exotic tops:

→ *Resonant top signatures CMS-PAS-B2G-23-006* ***(new result!)***

→ *Same-sign top signatures CMS-TOP-22-010 / arXiv:2311.03261*

→ *Top associated production CMS-EXO-21-018 / arXiv:2402.11098*

Top quark is special:

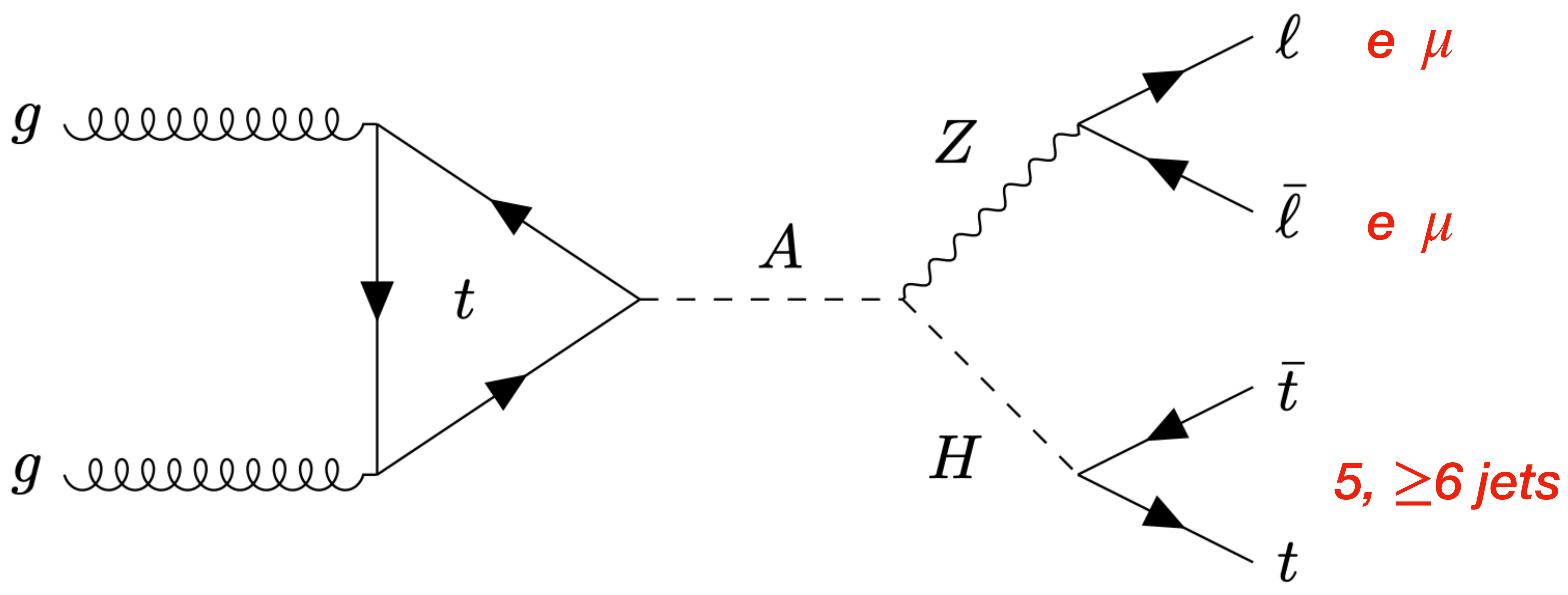
→ the heaviest SM mass (least constrained by low-energy measurements)

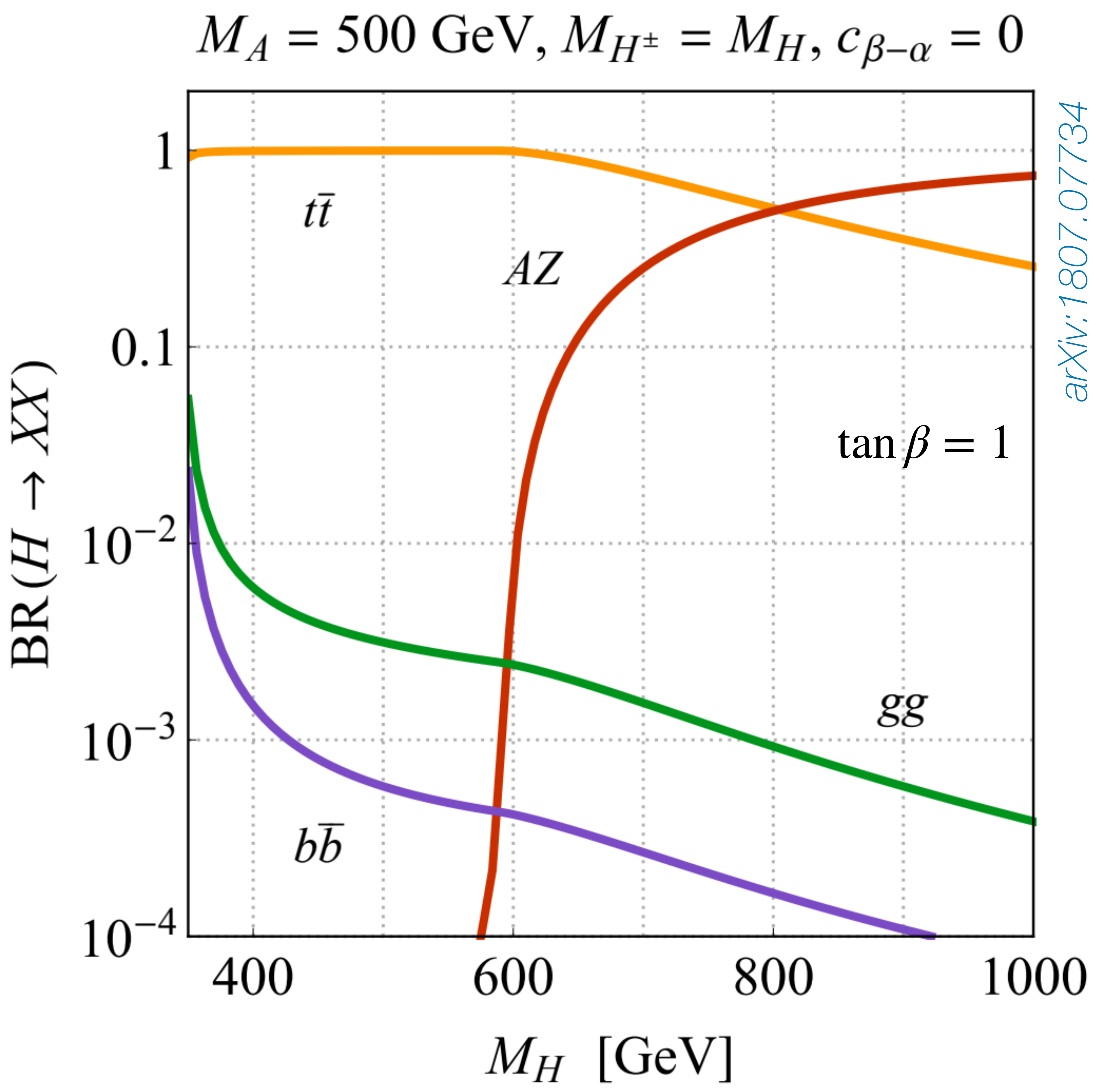
→ strongly coupled to fields of the scalar sector

Resonant tops: heavy scalars

CMS-PAS-B2G-23-006

- **2HDM inspired signature**: CP even (h,H), CP odd (A), charged ($H^{\pm}$)
  - → **A and H are taken to have a sizable mass splitting ($\gtrsim 100$ GeV)**
  - → In the alignment limit, A → Zh(125) is suppressed, **but A → ZH is not.**
  - → **H → $t\bar{t}$ decays** mostly dominate for small to moderate $\tan\beta$.



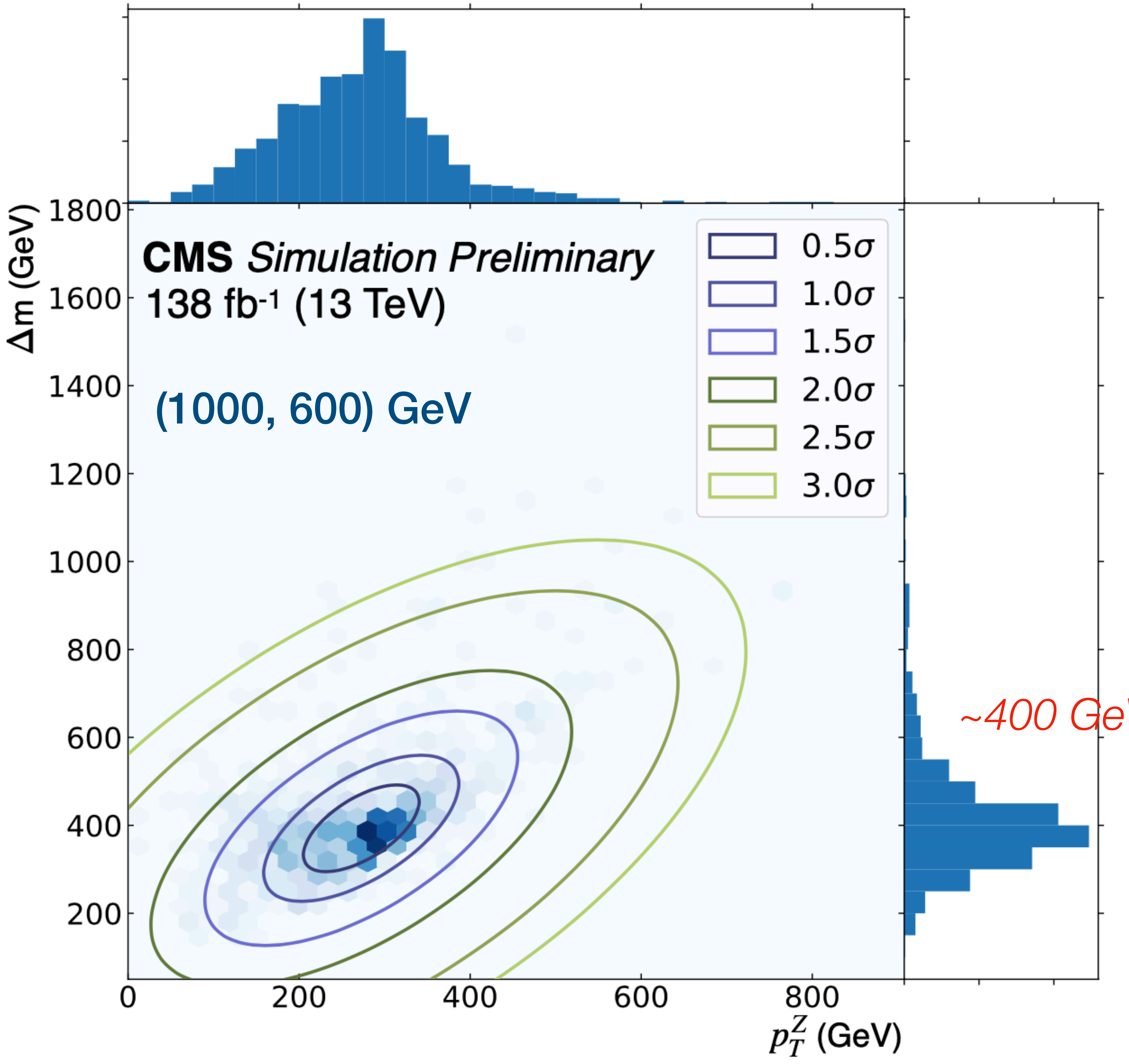


This is the first time this signature is targeted at the LHC

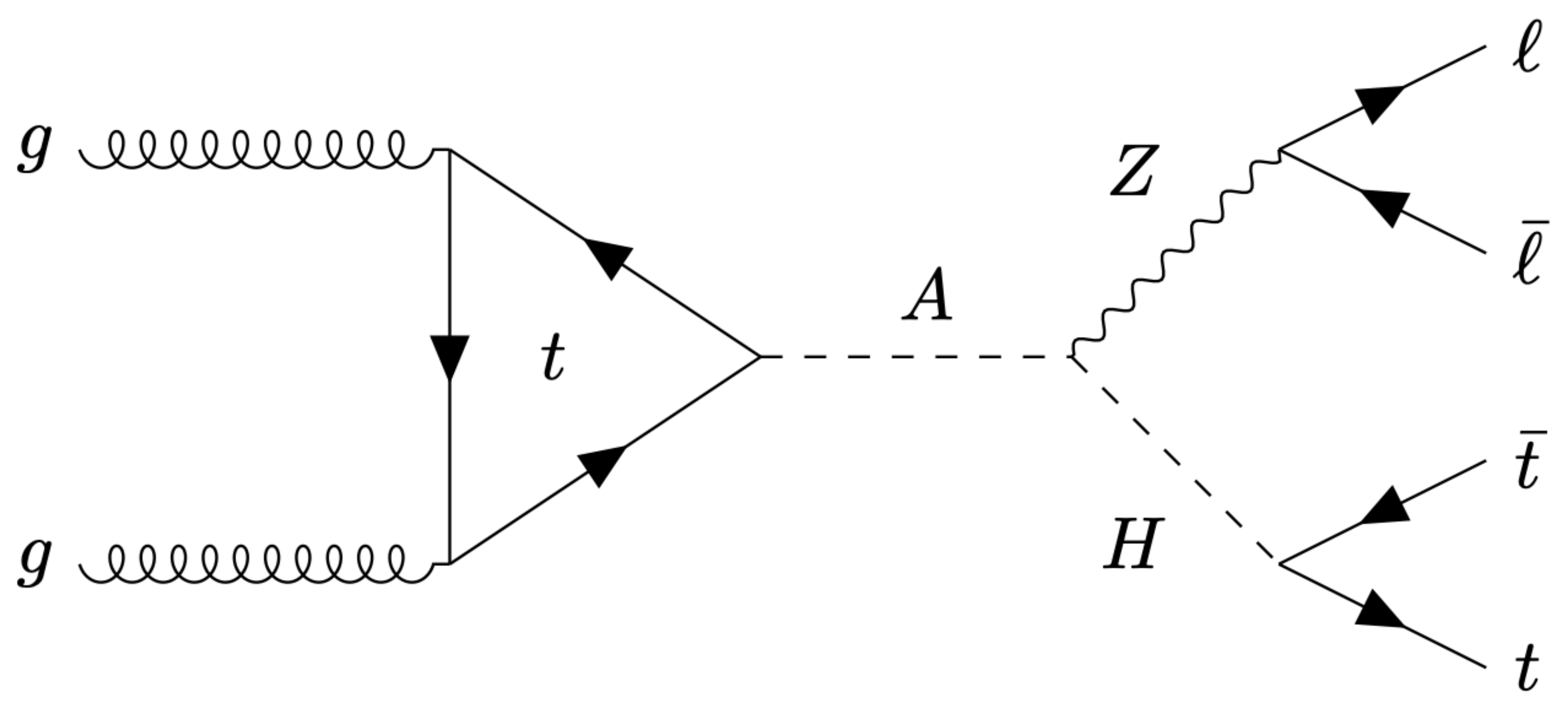
Resonant tops: heavy scalars

CMS-PAS-B2G-23-006

Max at ~300 GeV: ΔM - M(Z)



~400 GeV



- **Triple-resonance structure:** (dilepton), ($t\bar{t}$), and ($t\bar{t}$+dilepton)
- ΔM and Z p_{T} wins over m($t\bar{t}$) and m($t\bar{t}$Z), once jet energy uncertainties are taken into account:

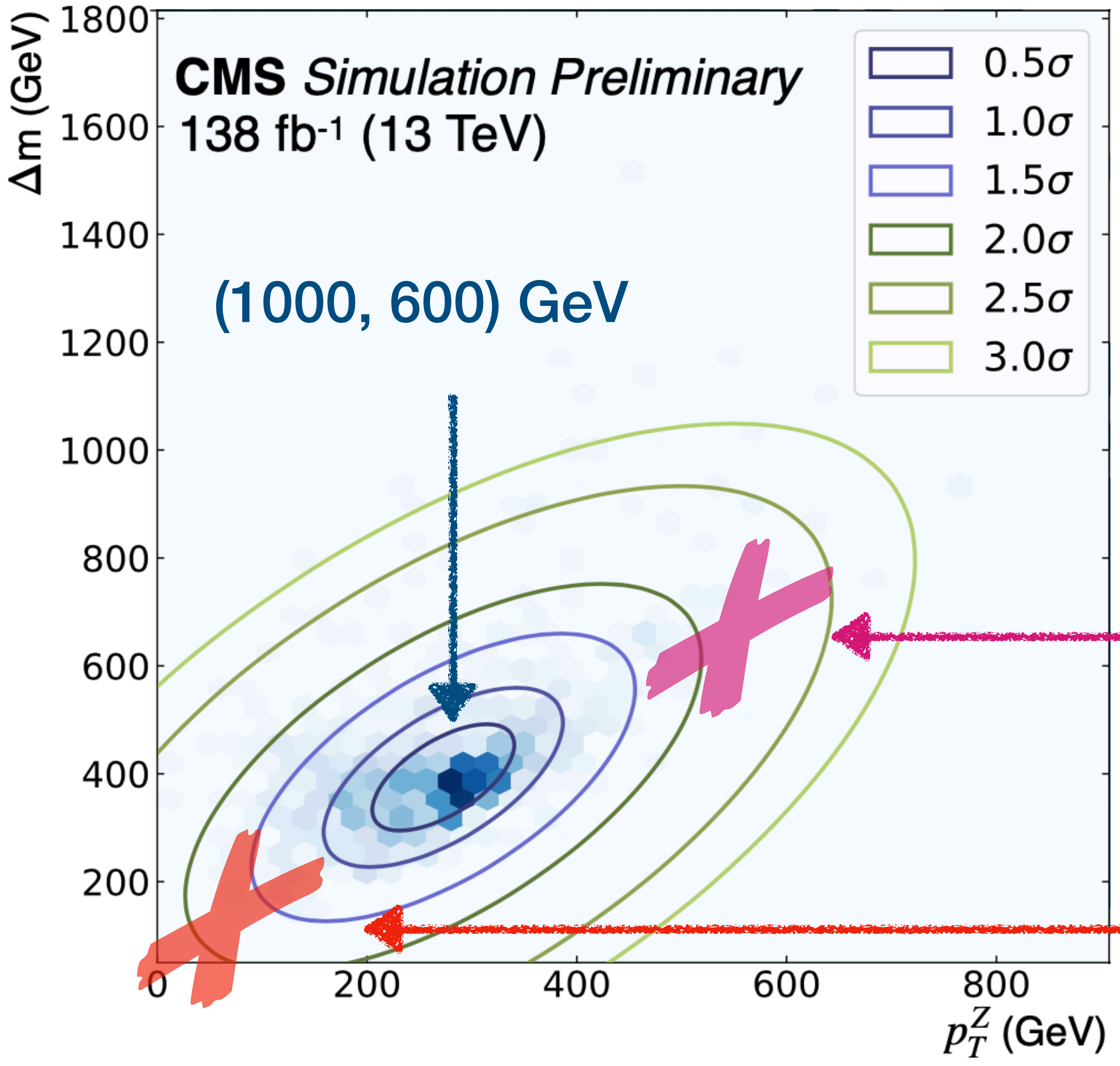
→ Z p_{T} is a **clean, leptonic quantity, cut-off defined by ΔM**

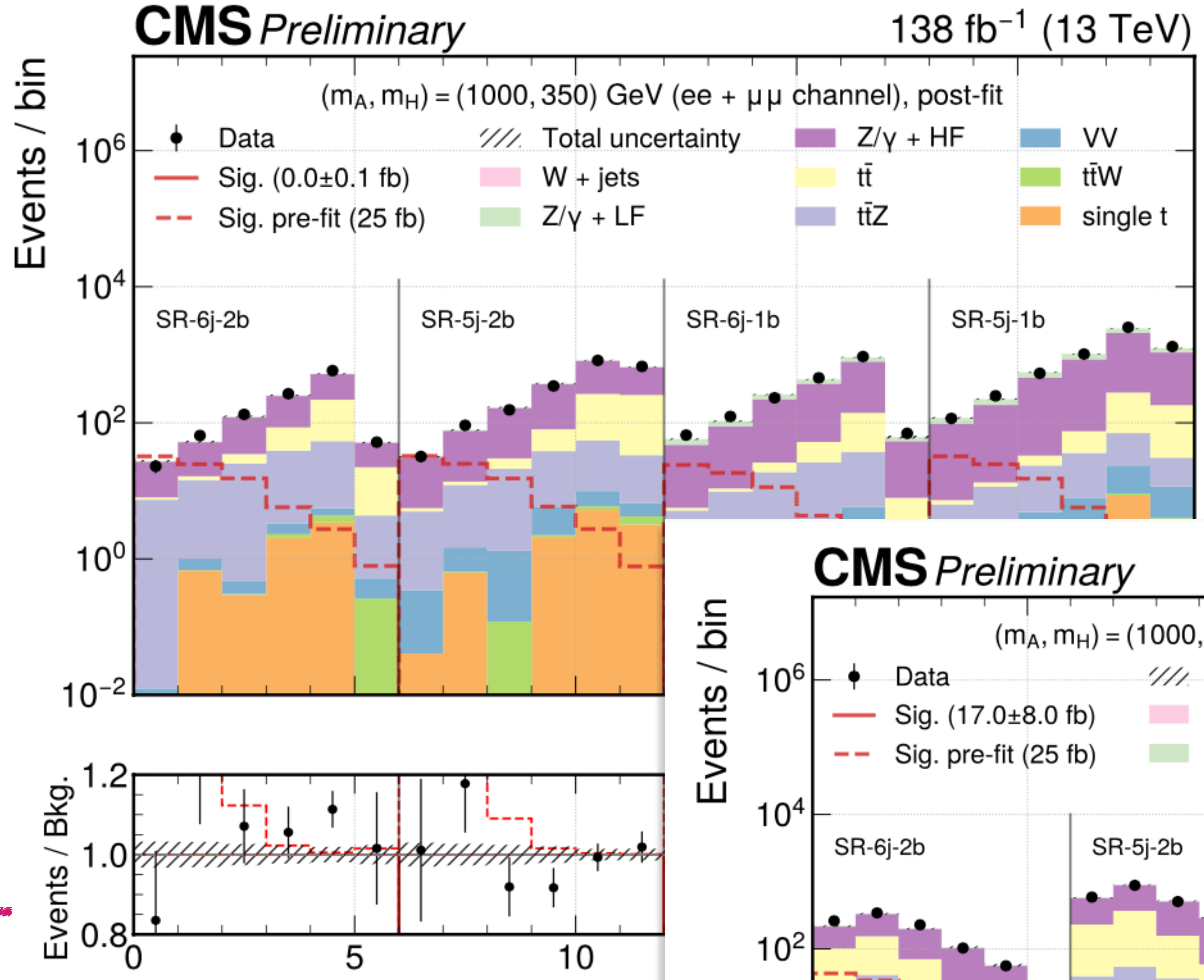
→ **Correlations** in m($t\bar{t}$) and m($t\bar{t}$Z) are used to **reduce uncertainties**

→ **Interference effects with SM ttZ is small** in these variables (in comparison to experimental resolution)

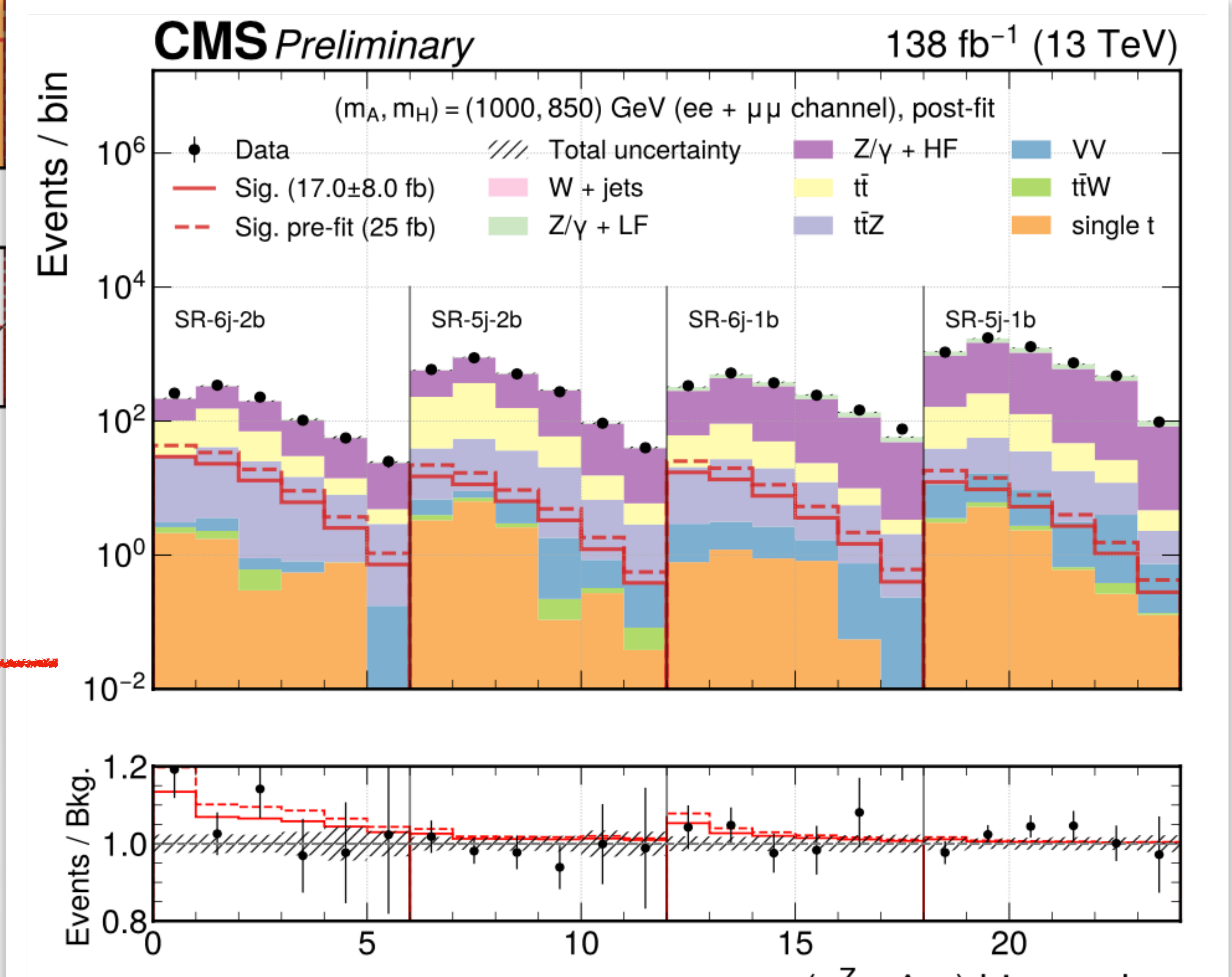
Resonant tops: heavy scalars

CMS-PAS-B2G-23-006





(1000,350) GeV

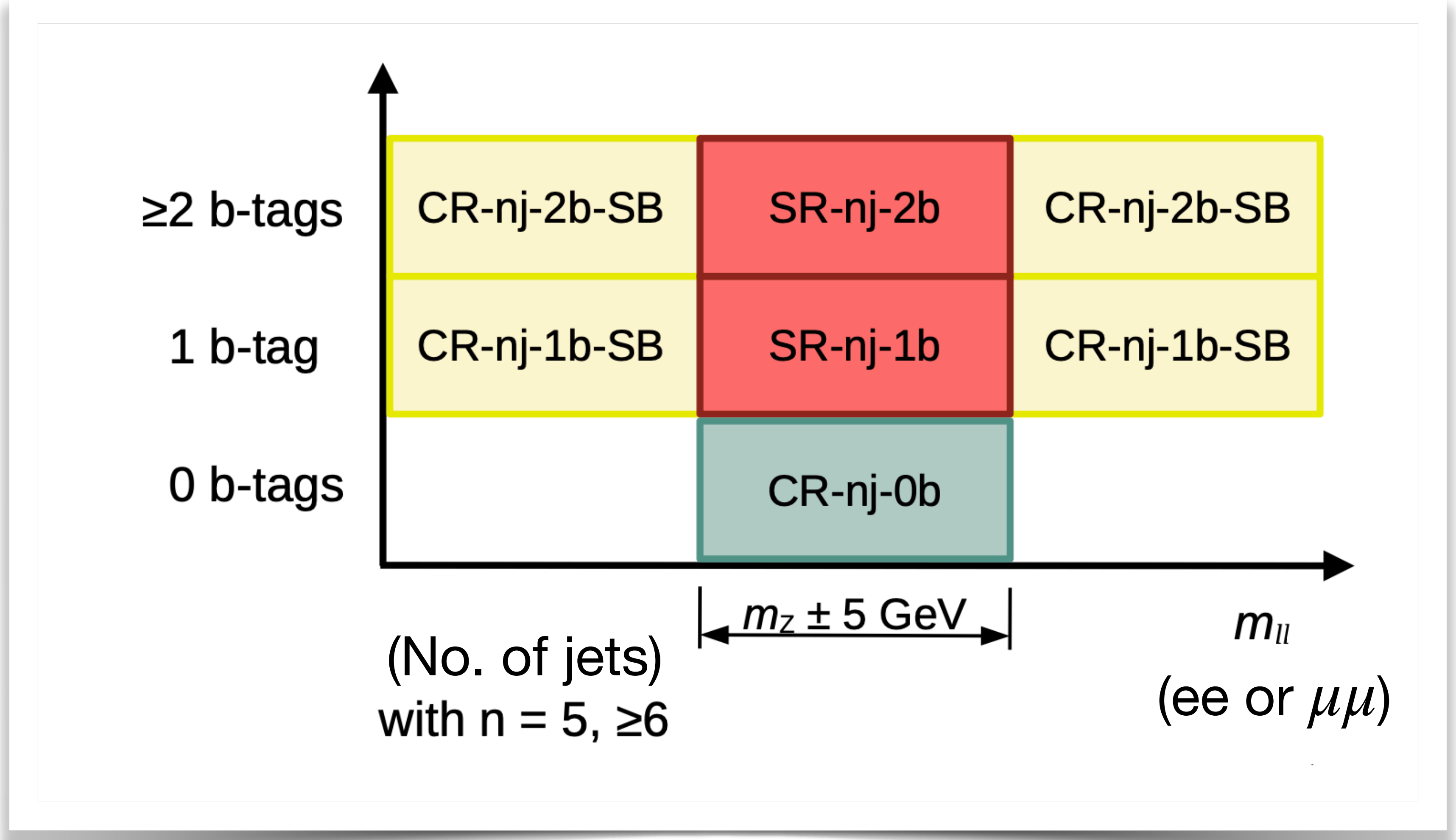


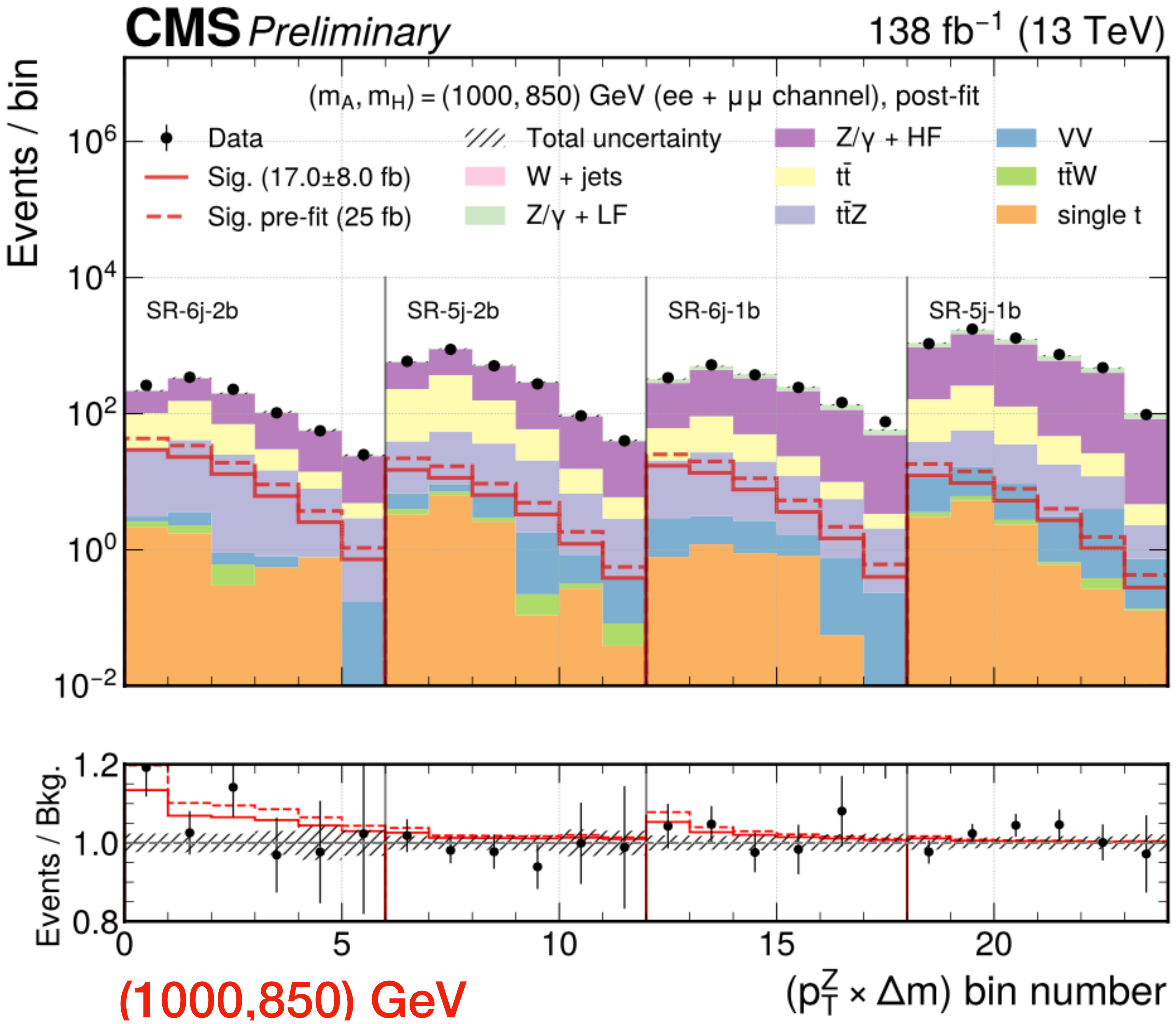
(1000,850) GeV

Signal regions are carved out in quantiles around the peak on the ΔM and Z p_{T} plane

Resonant tops: heavy scalars

CMS-PAS-B2G-23-006





(1000,850) GeV

Largest excess with local significance: ~2σ

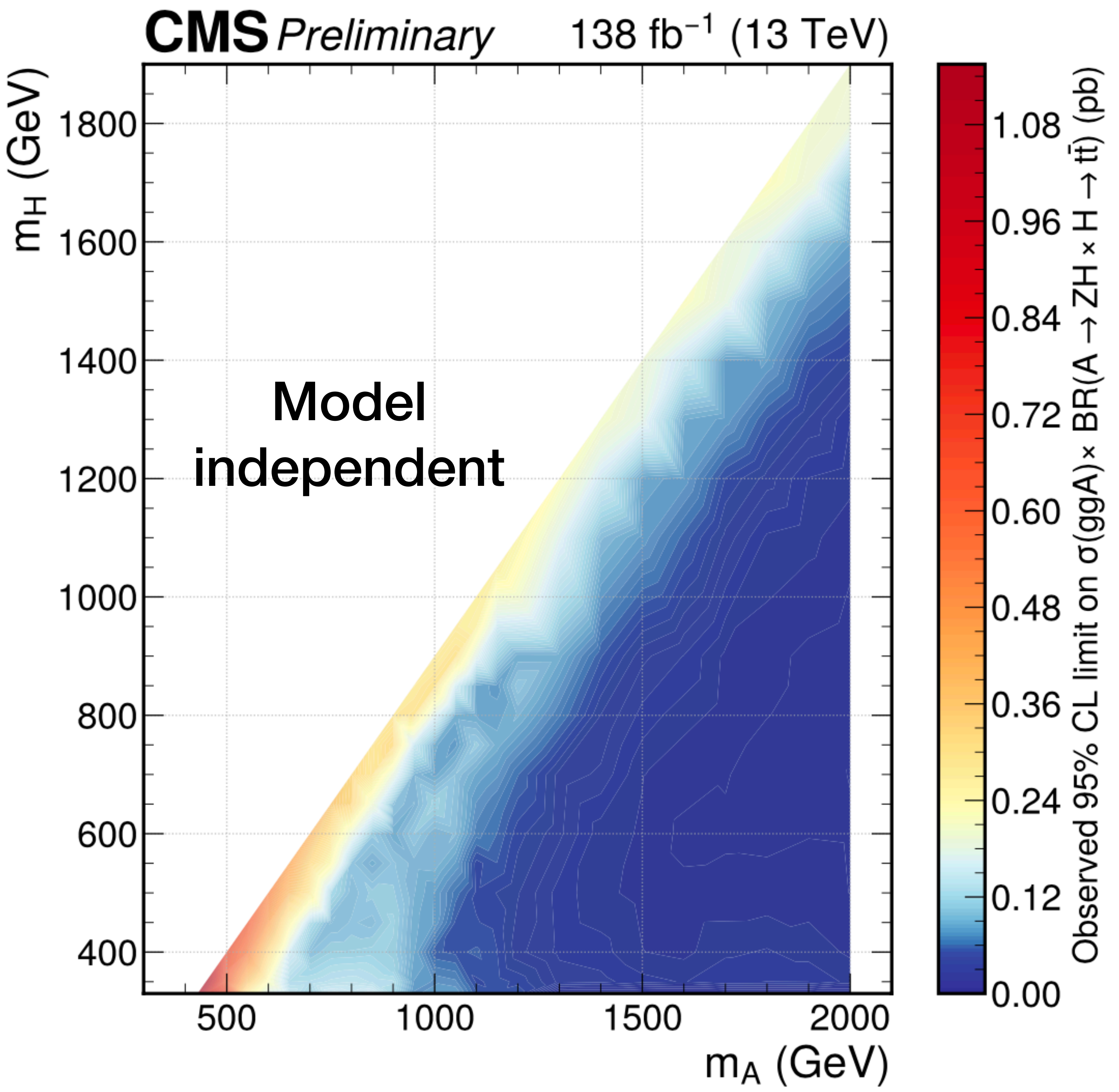
- Closer look at the signal region bins:

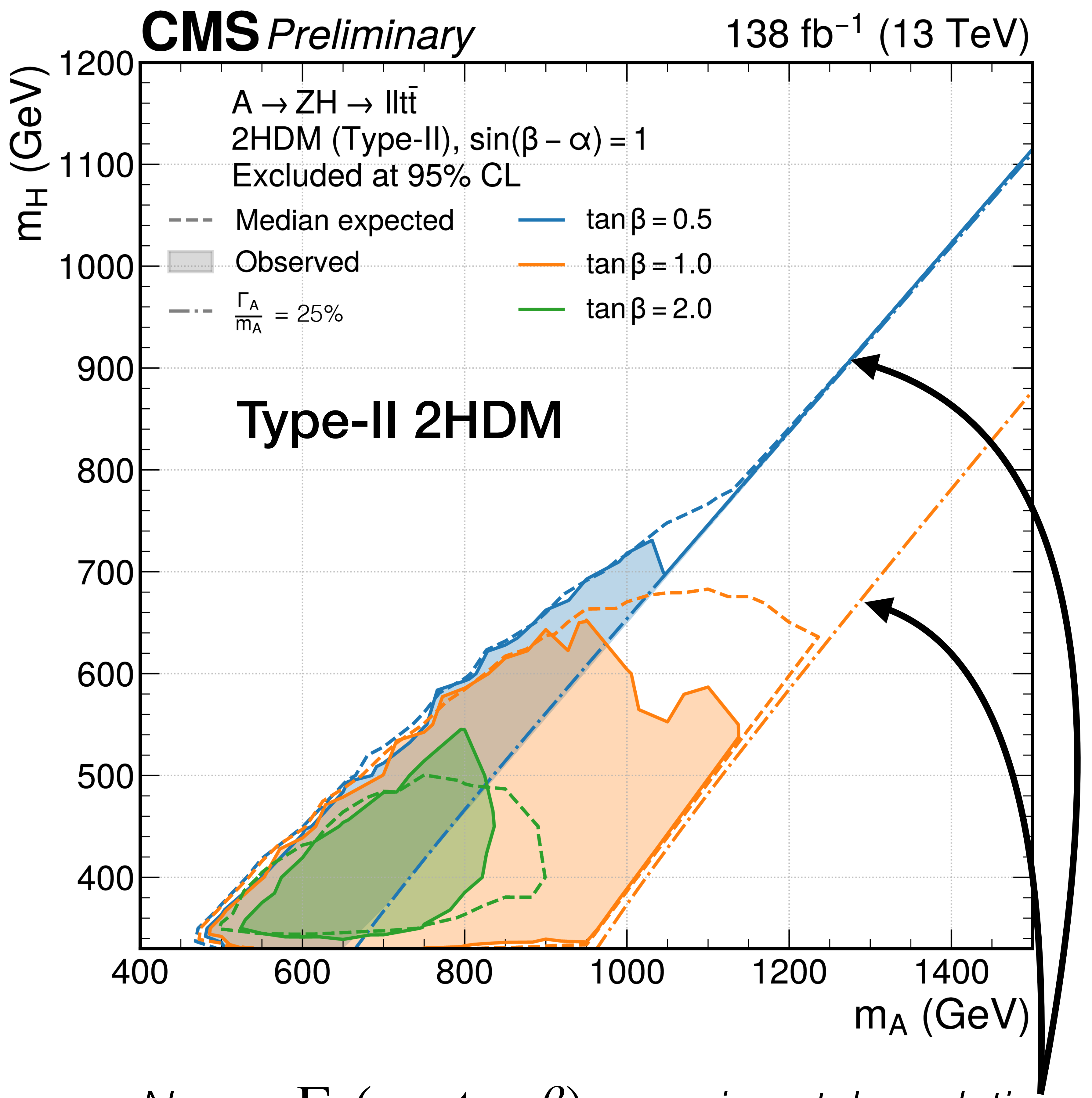
→ 2LOS signature is dominated by **irreducible** backgrounds.

→ Additional 40% on the **DY+heavy flavor component** (follows from 0/1 b-jet control region studies)

Resonant tops: heavy scalars

CMS-PAS-B2G-23-006





Limits on $\sigma \times BR$ *(pb)*

→ *Narrow* $\Gamma_A(m_A, \tan\beta)$*, experimental resolution of m(ttZ)~25%*

→ *(650, 450) GeV excess (~2.8*σ*) from ATLAS-CONF-2023-034 not confirmed*

Same-sign tops: non-diagonal coupling

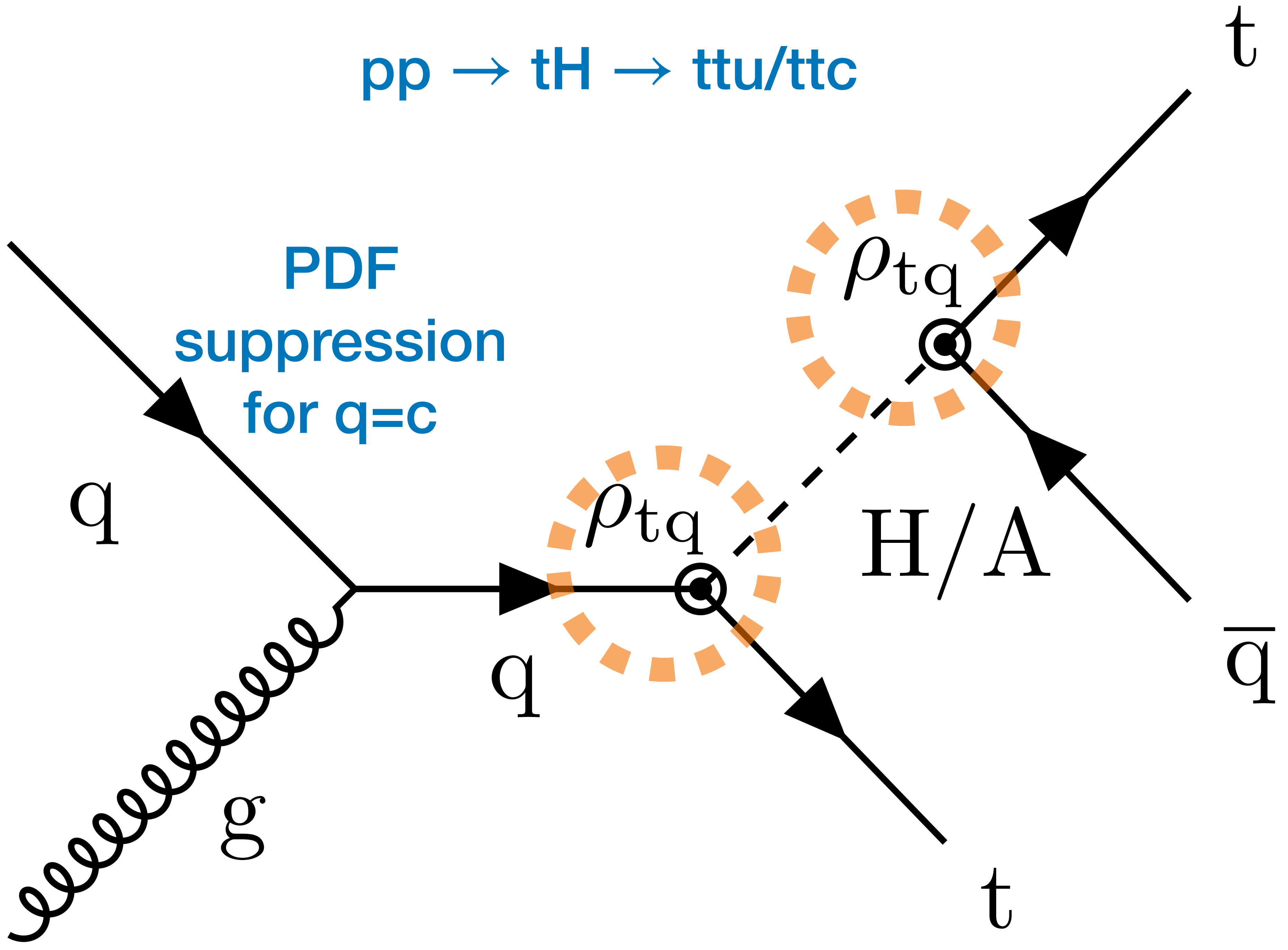
CMS-TOP-22-010
arXiv:2311.03261

- Search for **new Yukawa couplings of the top quark** in models with additional Higgs bosons.

- **Generalized 2HDM model**:
  → H/A are set to have sizable **non-diagonal Yukawa couplings to quarks.**
  → This analysis targets ρ_{tu} **or** ρ_{tc}**, one coupling at a time.**
  → Flavor changing neutral Higgs (**FCNH**) interactions are **absent for SM Higgs**, ex/ $t \rightarrow ch_{125}$ is **suppressed** ($BR \sim 10^{-15}$).

- **Same-sign top pair:** 2LSS signature with 3 jets (of which 2 are b-jets)

- **Three different** signal scenarios:
  → **H** is assumed to be **decoupled.**
  → **A** is assumed to be **decoupled.**
  → A and H are **near-mass-degenerate**, and accessible.



New "Higgs bosons" through same-sign top-quark production in association with an extra jet

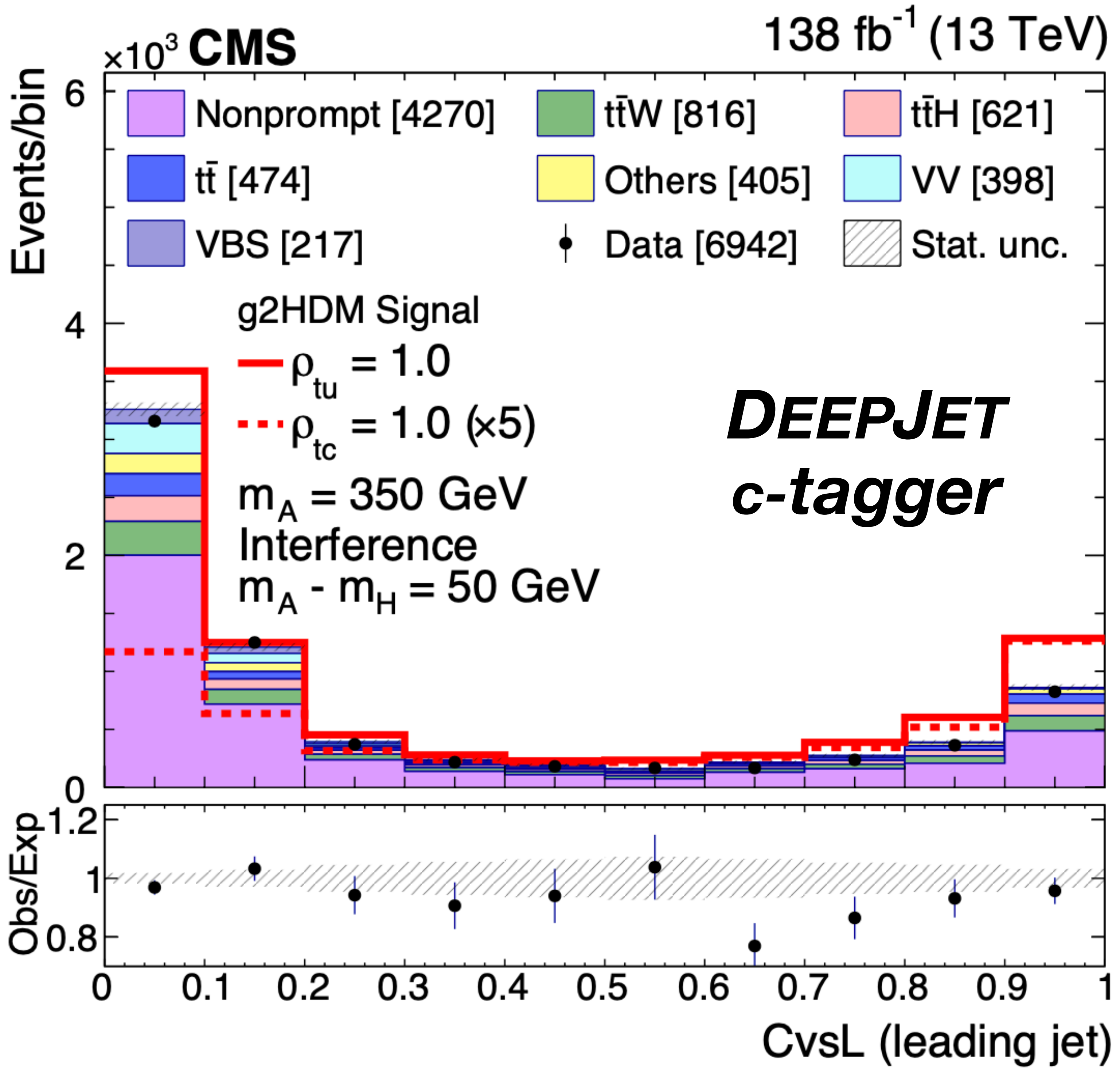
Same-sign tops: non-diagonal coupling

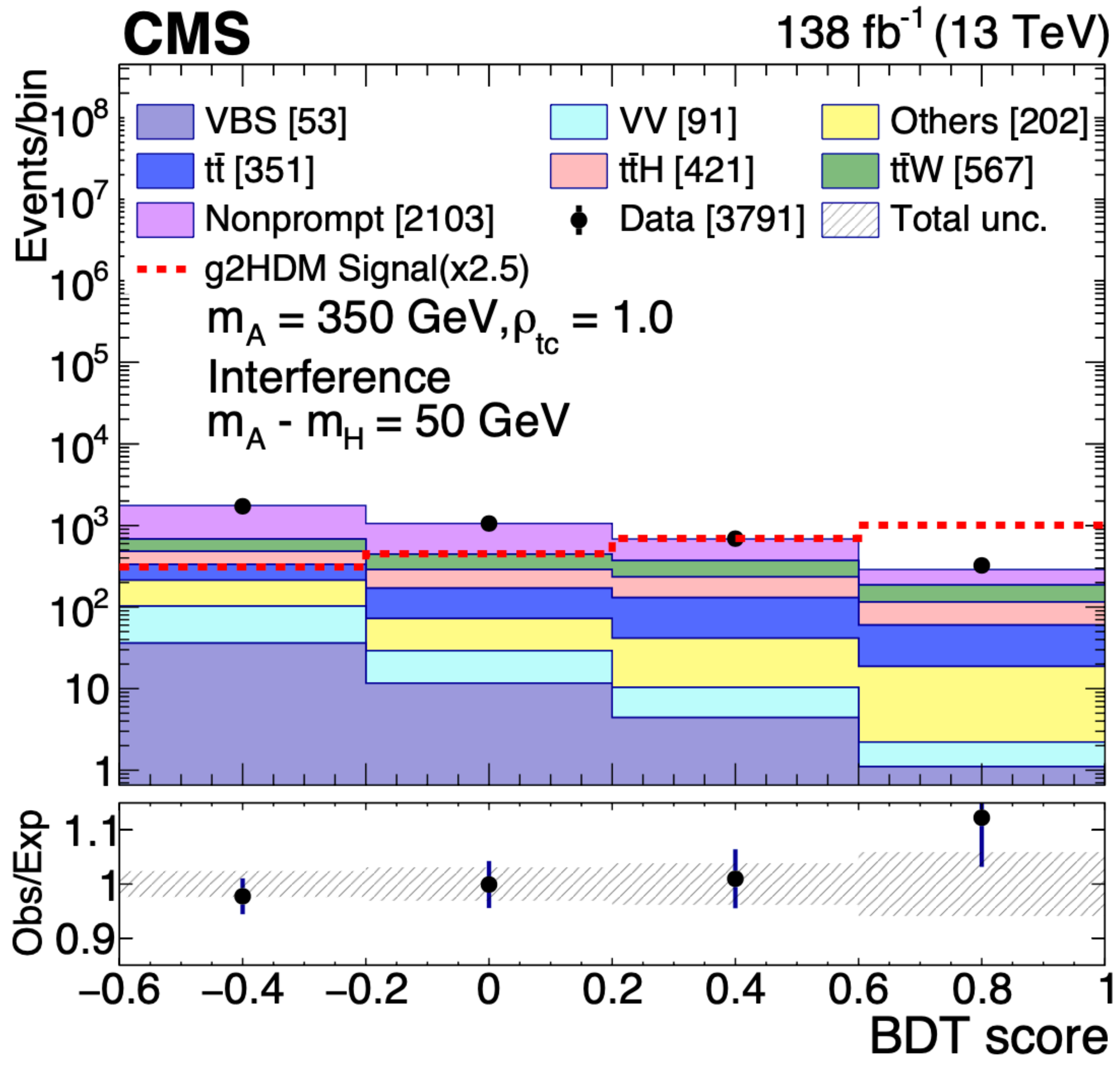
CMS-TOP-22-010
arXiv:2311.03261

- **2LSS is the target signature**, split by flavor, ee, $\mu\mu$, eμ.
  - → **ttW** is the largest irreducible background.
  - → $t\bar{t}$ contributions via **nonprompt / e charge misID background,** estimated via data driven methods.
- A dedicated **BDT training** is used to discriminate S from B.

Input variables

$\mathrm{CvsL}(j_a)$
$\mathrm{CvsB}(j_a)$
$\Delta R(j_a, j_b)$
$m(j_a, j_b)$
$\Delta R(j_a, l_b)$
$m(j_a, l_b)$
$p_\mathrm{T}(\ell_a)$
$m(\ell_1, \ell_2, j_a)$
$m(\ell_1, \ell_2)$
H_T
$p_\mathrm{T}^\mathrm{miss}$

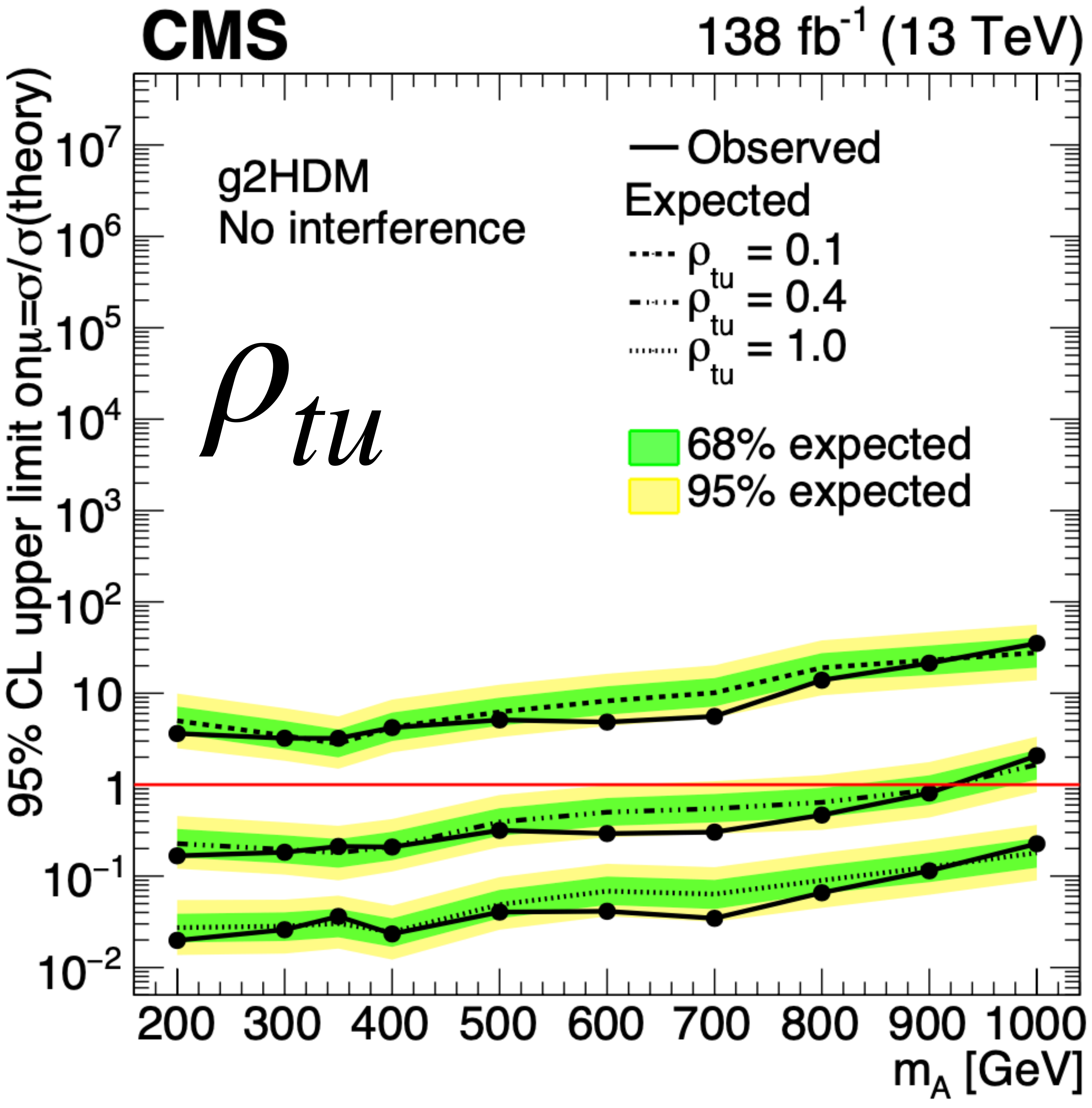




BDT distributions are ~independent of coupling values, only depend on mass.

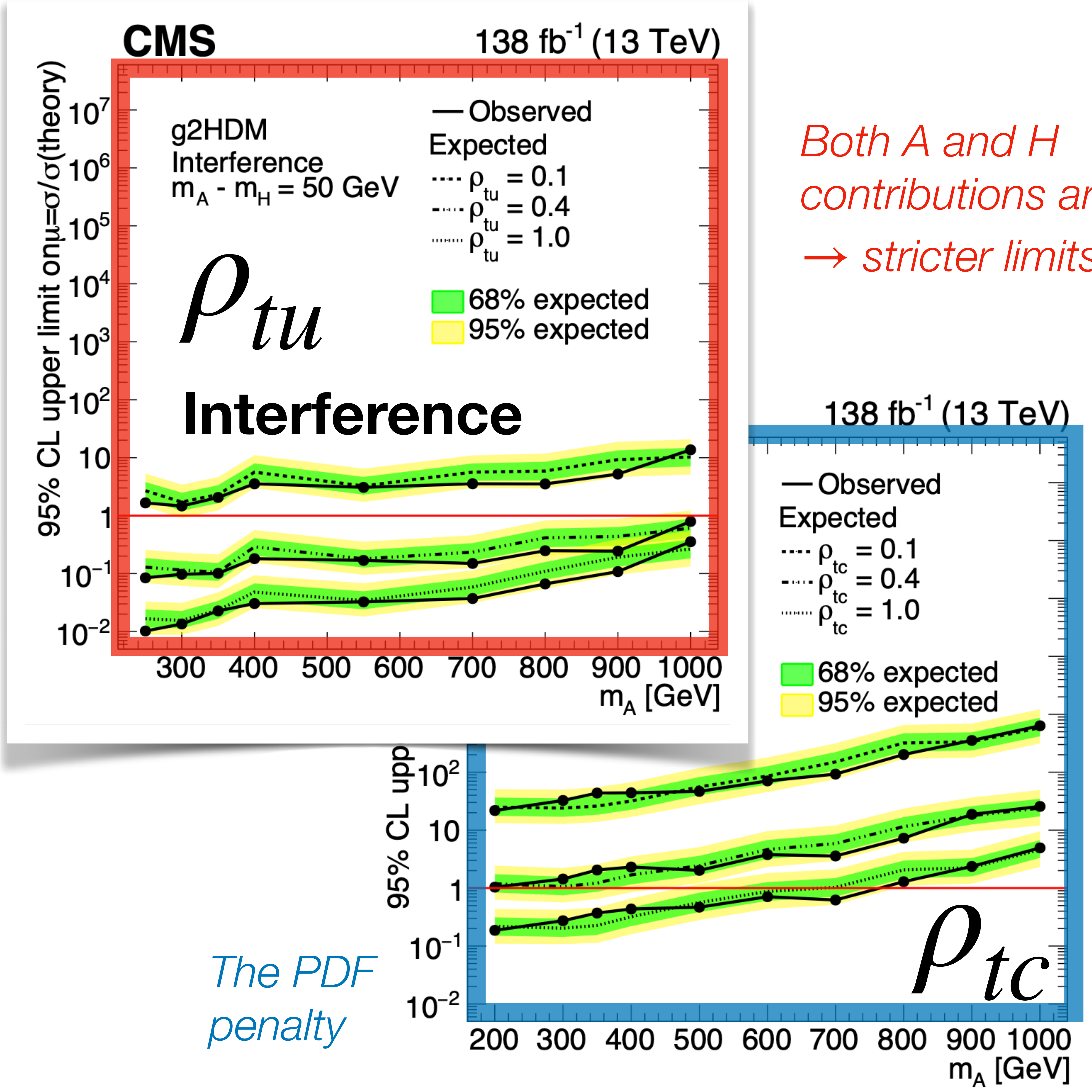
Same-sign tops: non-diagonal coupling

[CMS-TOP-22-010](#)
arXiv:2311.03261



Alternate scenario: **A and H is near-mass-degenerate**, ΔM=50 GeV.

→ *fully mass degenerate: interference effects suppress cross section .*

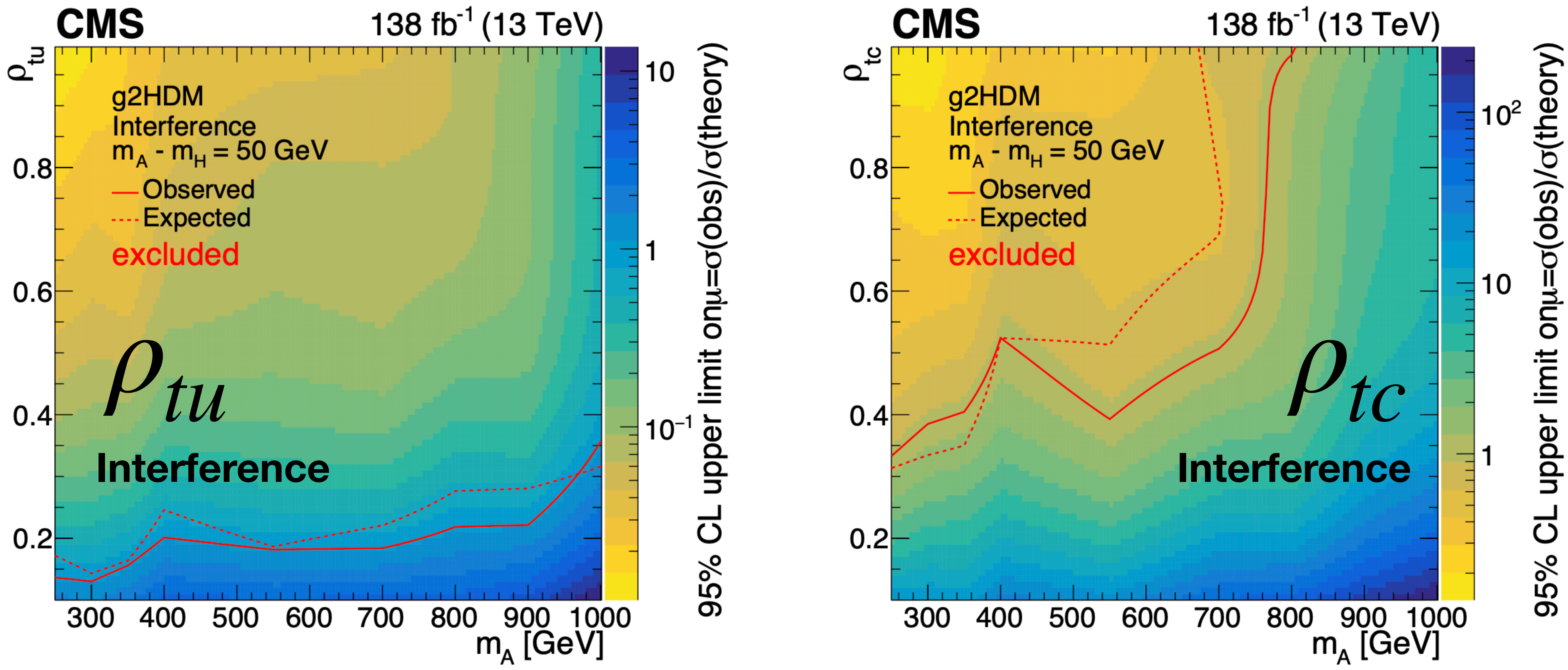


Both A and H contributions are present:
→ stricter limits

The PDF penalty

Same-sign tops: non-diagonal coupling

CMS-TOP-22-010
arXiv:2311.03261



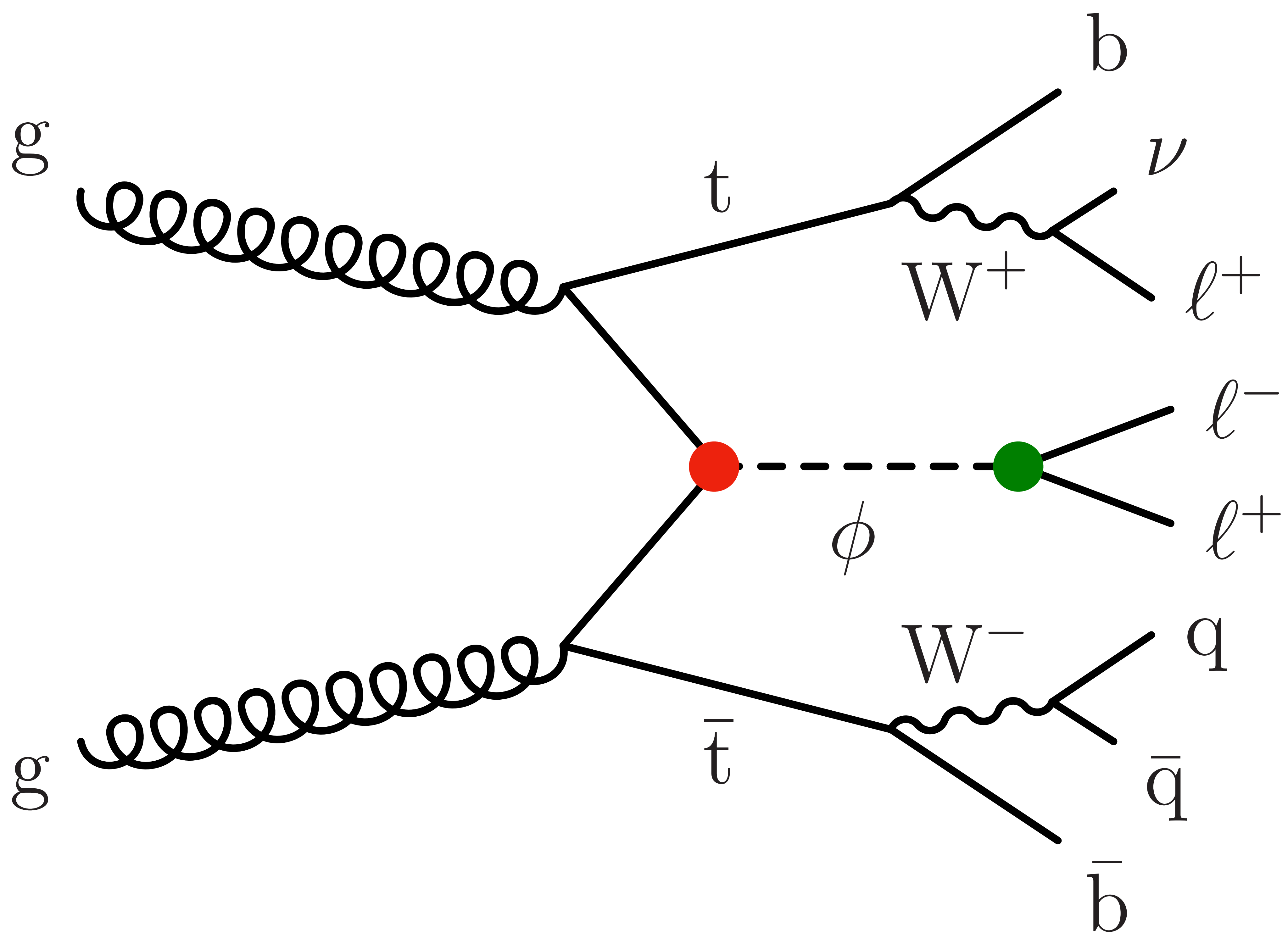
A ↔ H can be used interchangeably in the derived constraints.

(Similar 2D bounds are also set on scenarios without interference)

Tops: as gateway to new scalars

[CMS-EXO-21-018](#)
arXiv:2402.11098

- Extending SM with a **single spin-0 state ϕ,** with couplings to **top quark and charged leptons (e, μ, τ).**



Production: g_t $(\rightarrow \sigma)$

Decay: g_ℓ $(\rightarrow \text{BR})$

Associated production: $g_t > g_\ell > 0$, $m_\phi < 350$ GeV

$$\mathcal{L} \subset -\frac{g_{\psi S}}{\sqrt{2}} \phi_S \overline{\psi}\psi \quad \leftrightarrow \quad g_{\psi S} = \sqrt{2}\sin\theta m_\psi / v$$

Scalar

Scalar mixing with Higgs

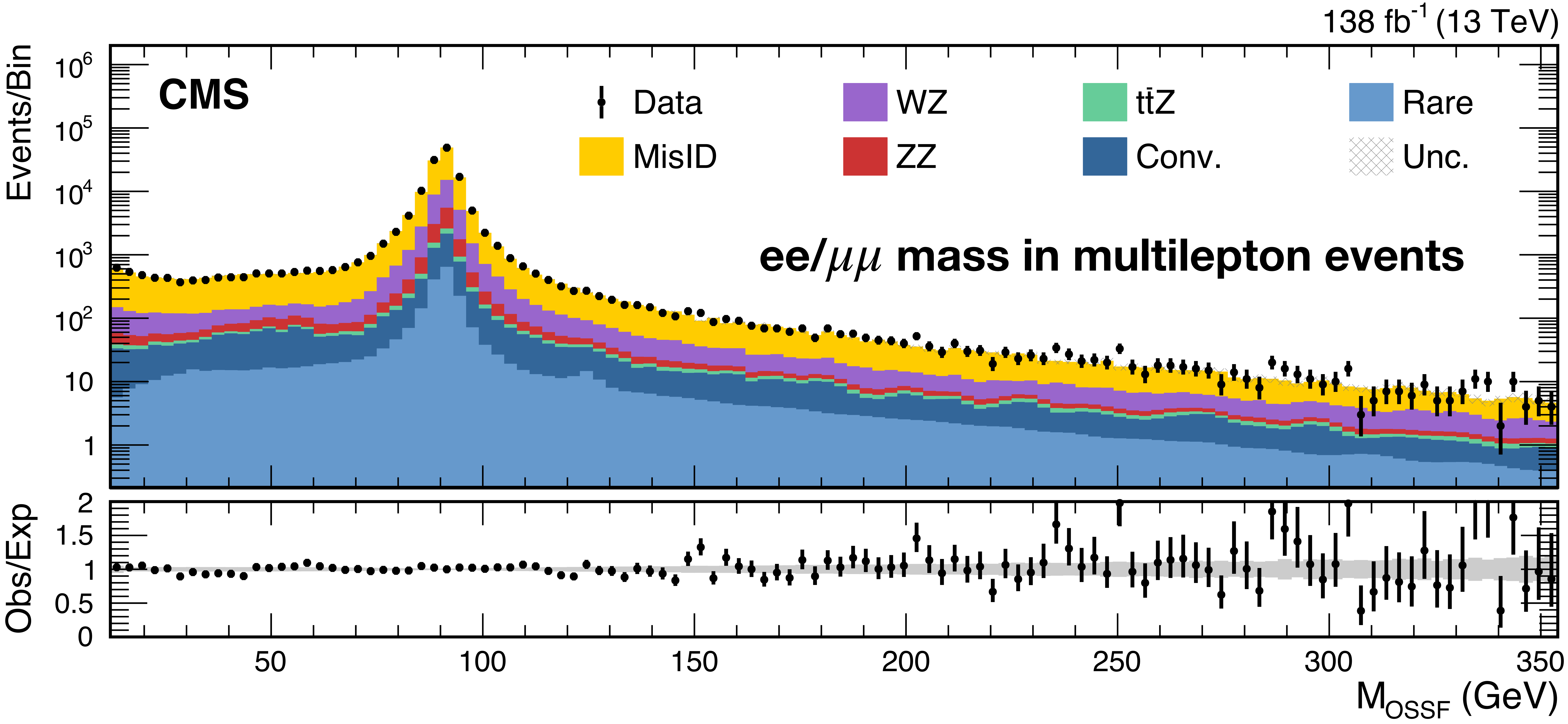
$$-\frac{g_{\psi PS}}{\sqrt{2}} \phi_{PS} \overline{\psi} i\gamma_5 \psi$$

Pseudoscalar

Tops: as gateway to new scalars

[CMS-EXO-21-018](#)
arXiv:2402.11098

Quarkonium resonances



$\sim 2m_{top}$

- Analysis targets **dilepton resonances** (ee/$\mu\mu/\tau\tau$) in the mass range **15-350 GeV in multilepton events**

  → Substantial **misID lepton backgrounds** (estimated via data-driven methods).

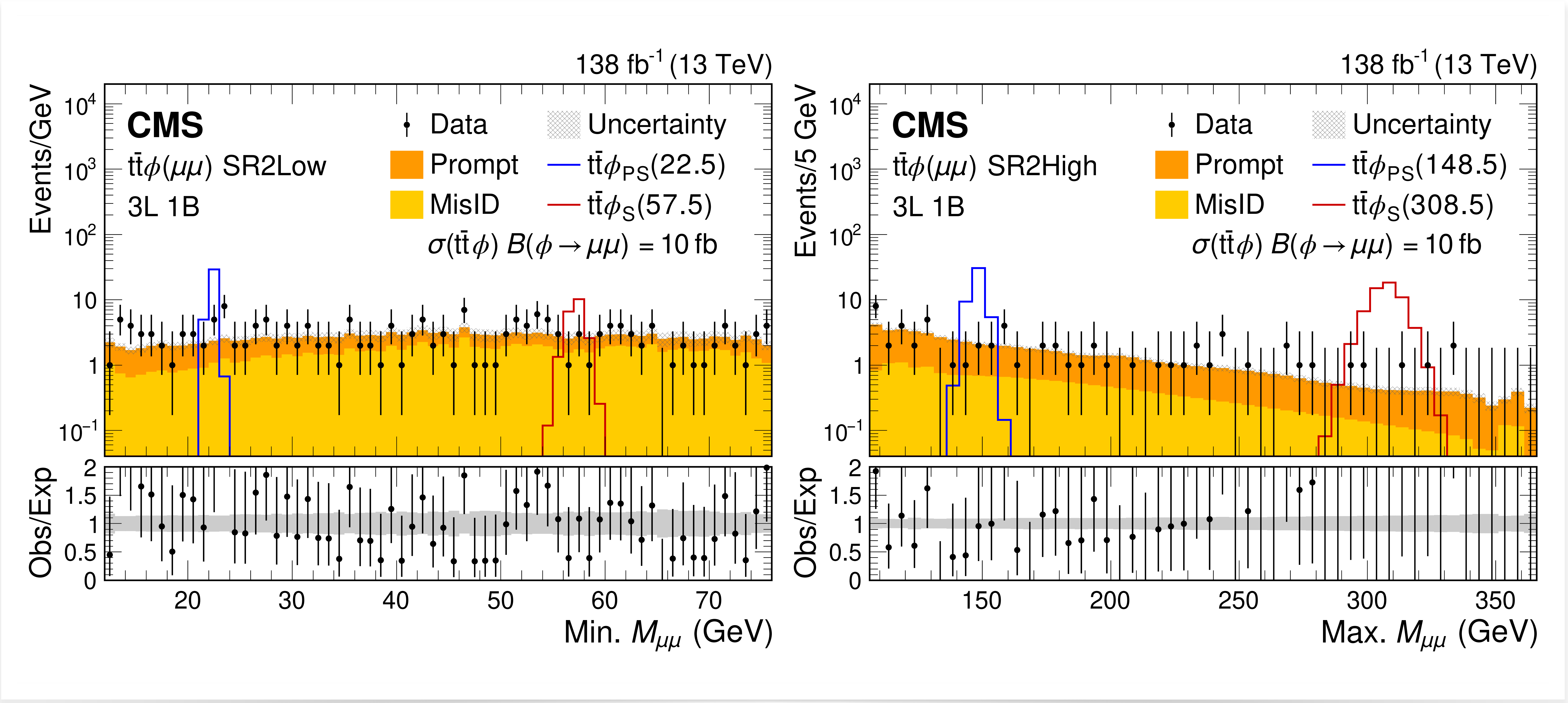
  → All lepton flavors are used (including **hadronic tau** leptons).

Tops: as gateway to new scalars

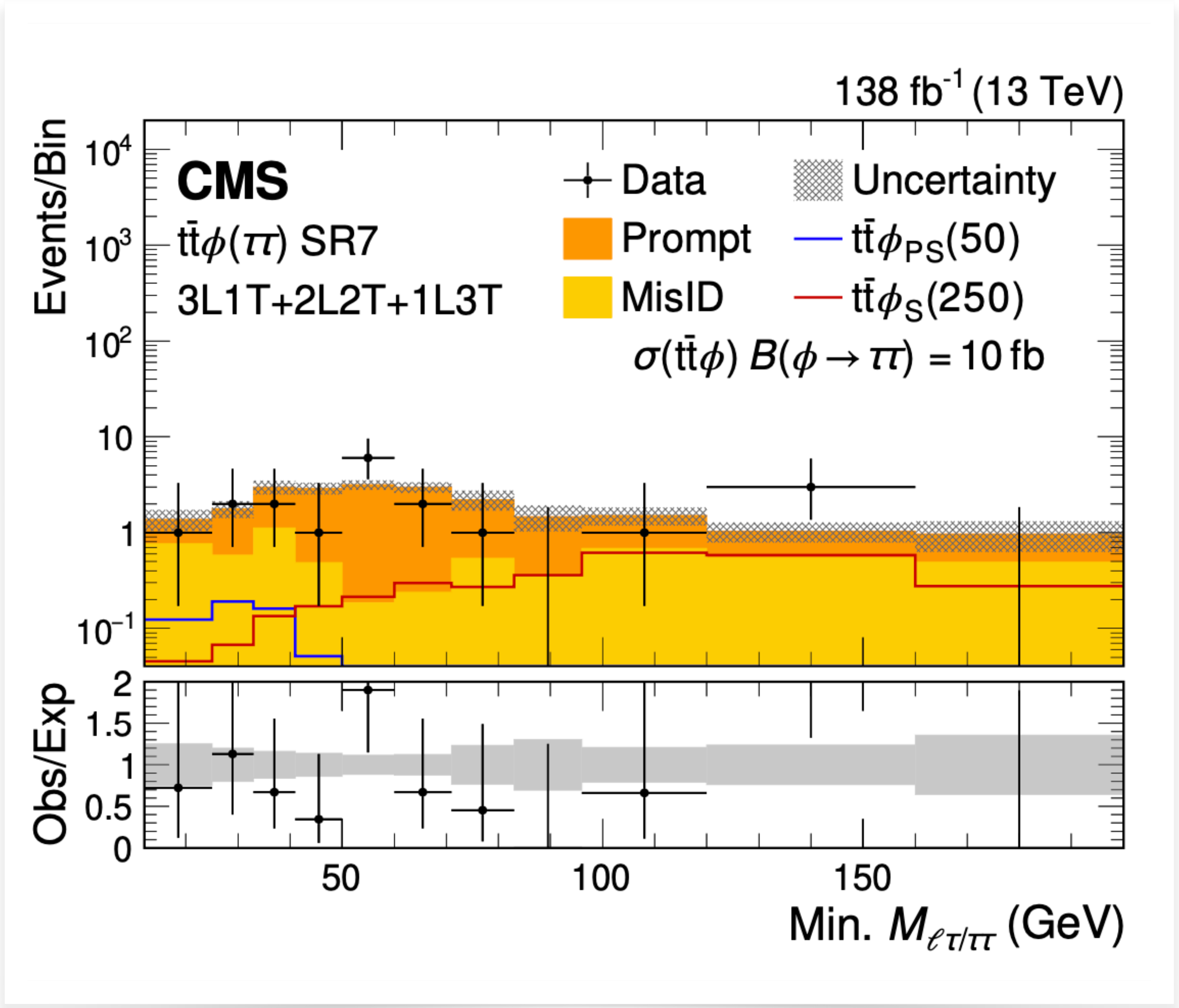
[CMS-EXO-21-018](https://cms-results.web.cern.ch/) *arXiv:2402.11098*

- Multi-category, cut based analysis targeting **3/4-lepton events of ~all flavor combinations** (lepton = e, μ, or hadronic τ)
  → Most sensitive bins for the $t\bar{t}\phi$ **signal: 3-lepton events with at least 1 b-tagged jet** (a combination of channels contribute!)

- **6 scenarios** are probed (ee/$\mu\mu/\tau\tau$ **scalar/pseudoscalar**) for the $t\bar{t}\phi$ signal.
  → Analysis also targets $W\phi$ and $Z\phi$ signals *(not shown, 18 additional scenarios)*.



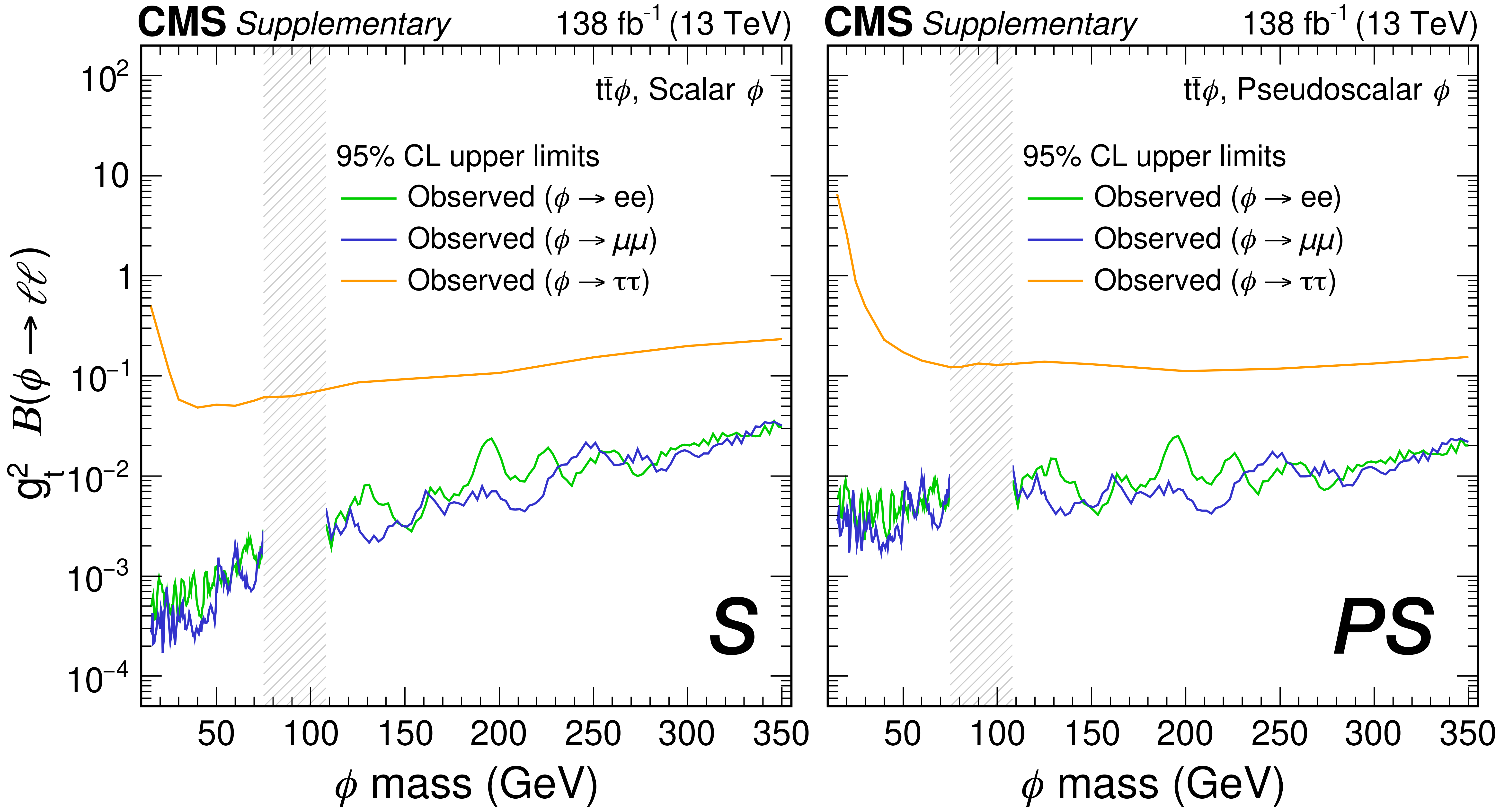
Narrow $\mu\mu$ resonance (ee behaves similarly)

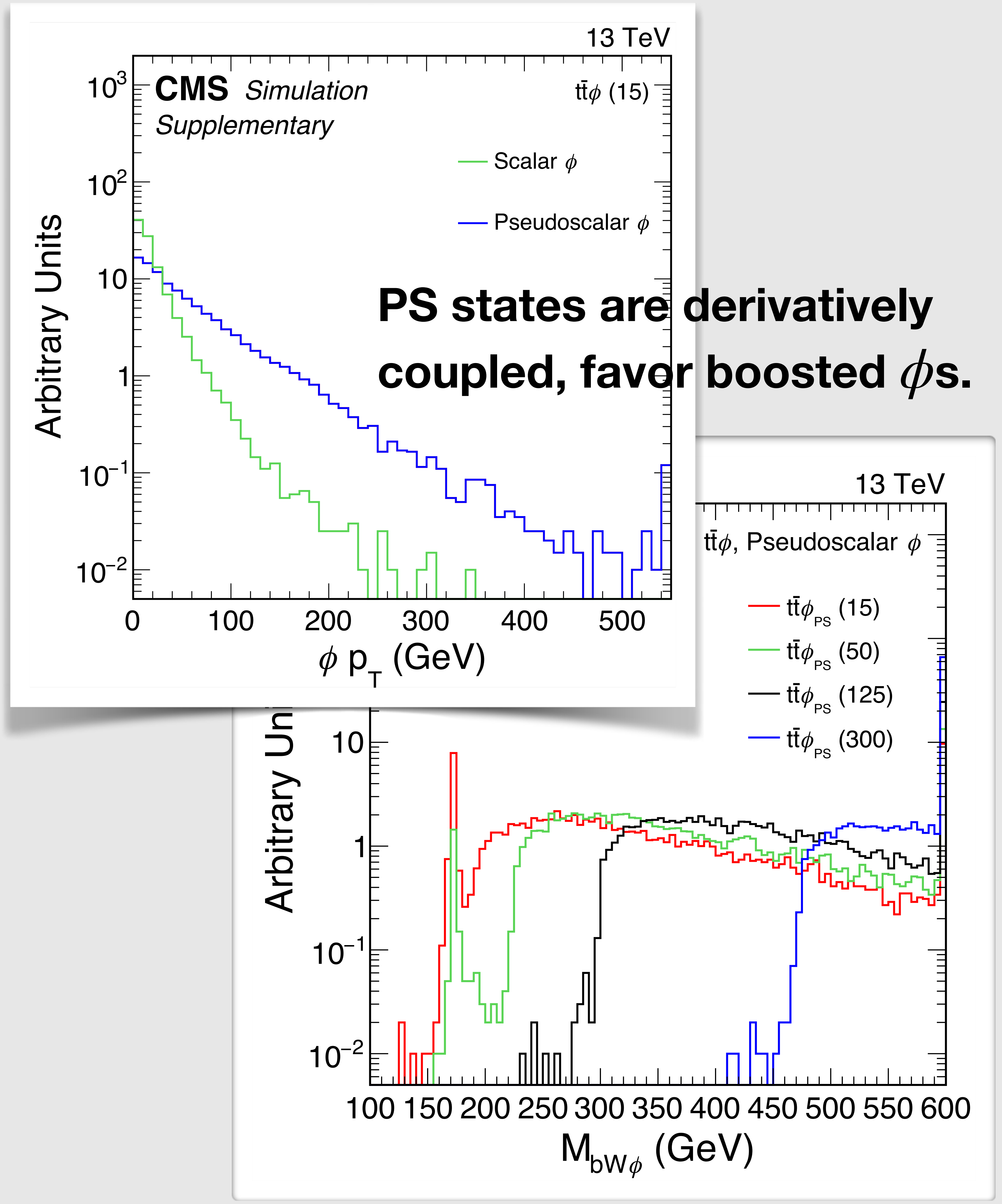


Wide $\ell\tau_h/\tau_h\tau_h$ resonance

Tops: as gateway to new scalars

CMS-EXO-21-018
arXiv:2402.11098





PS states are derivatively coupled, favor boosted ϕs.

- Bounds are set on $g^2 \times BR(\phi \to \ell\ell)$

  → $\sigma(pp \to t\bar{t}\phi)$ **is larger for Scalar ϕ, hence generally better bounds.**

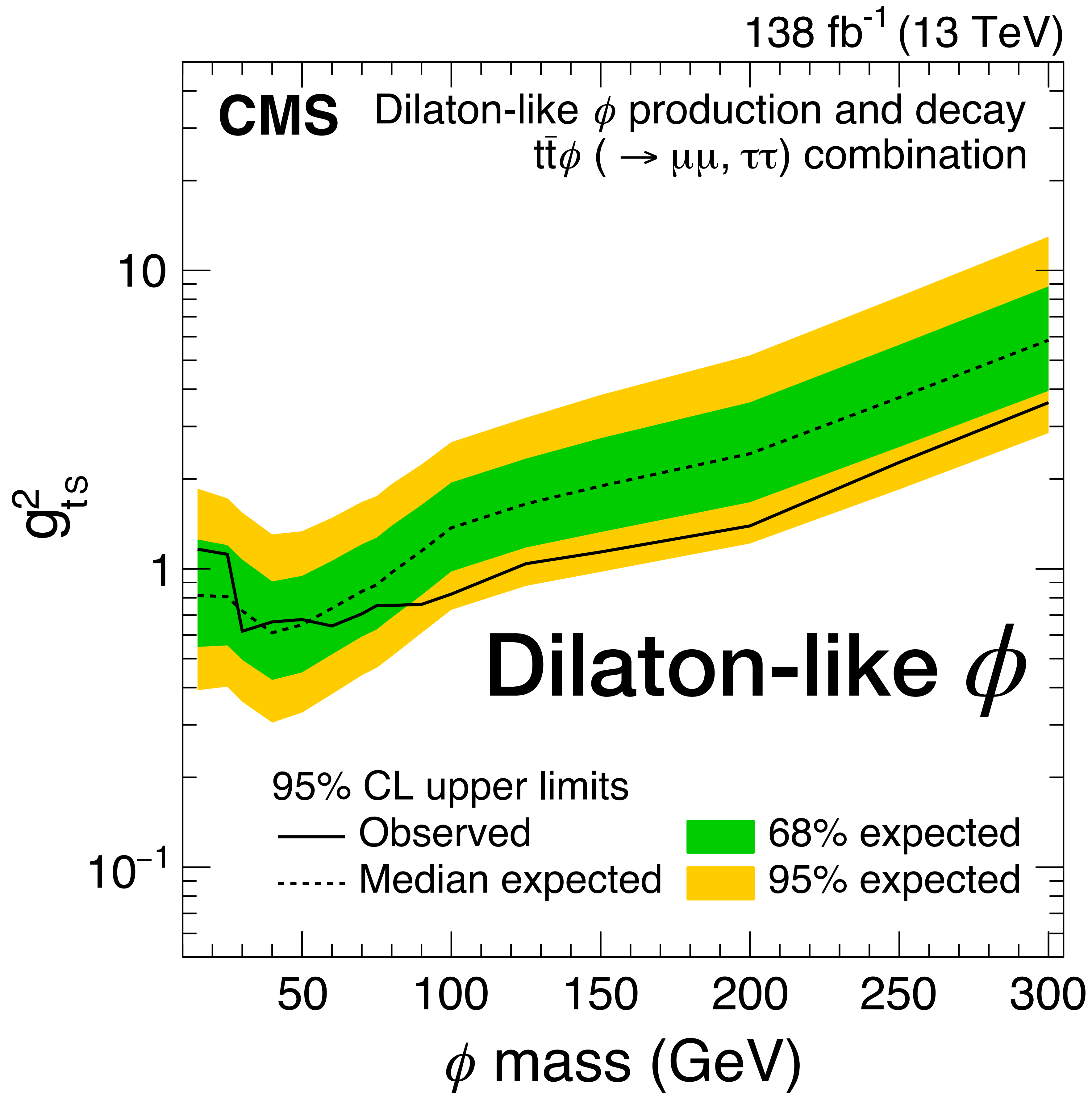
  → Signal acceptance x efficiency is **different between PS and S, esp. at low masses**

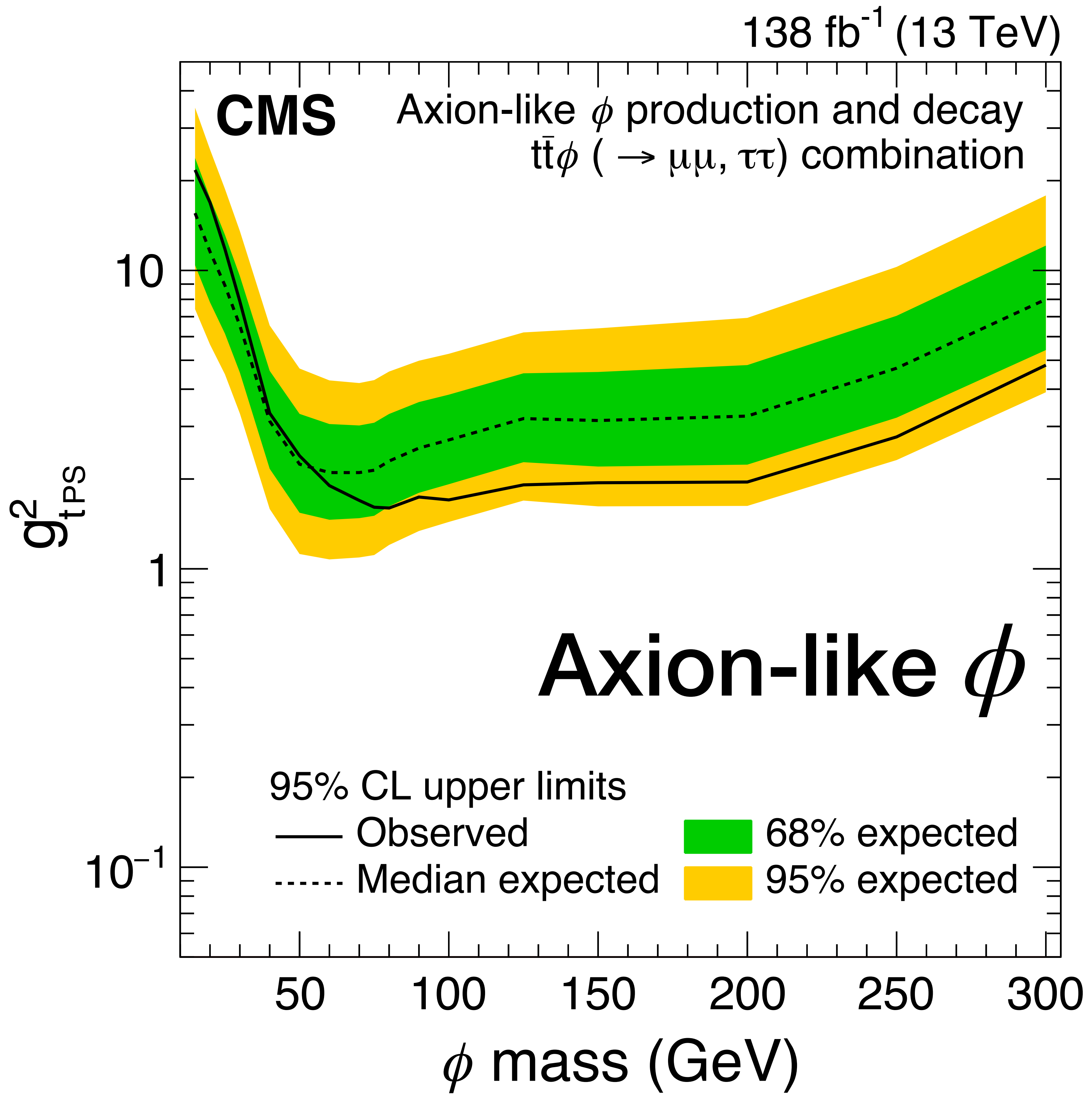
  → At low masses, analysis probes **3-body decays of the top: $t \to bW\phi$**

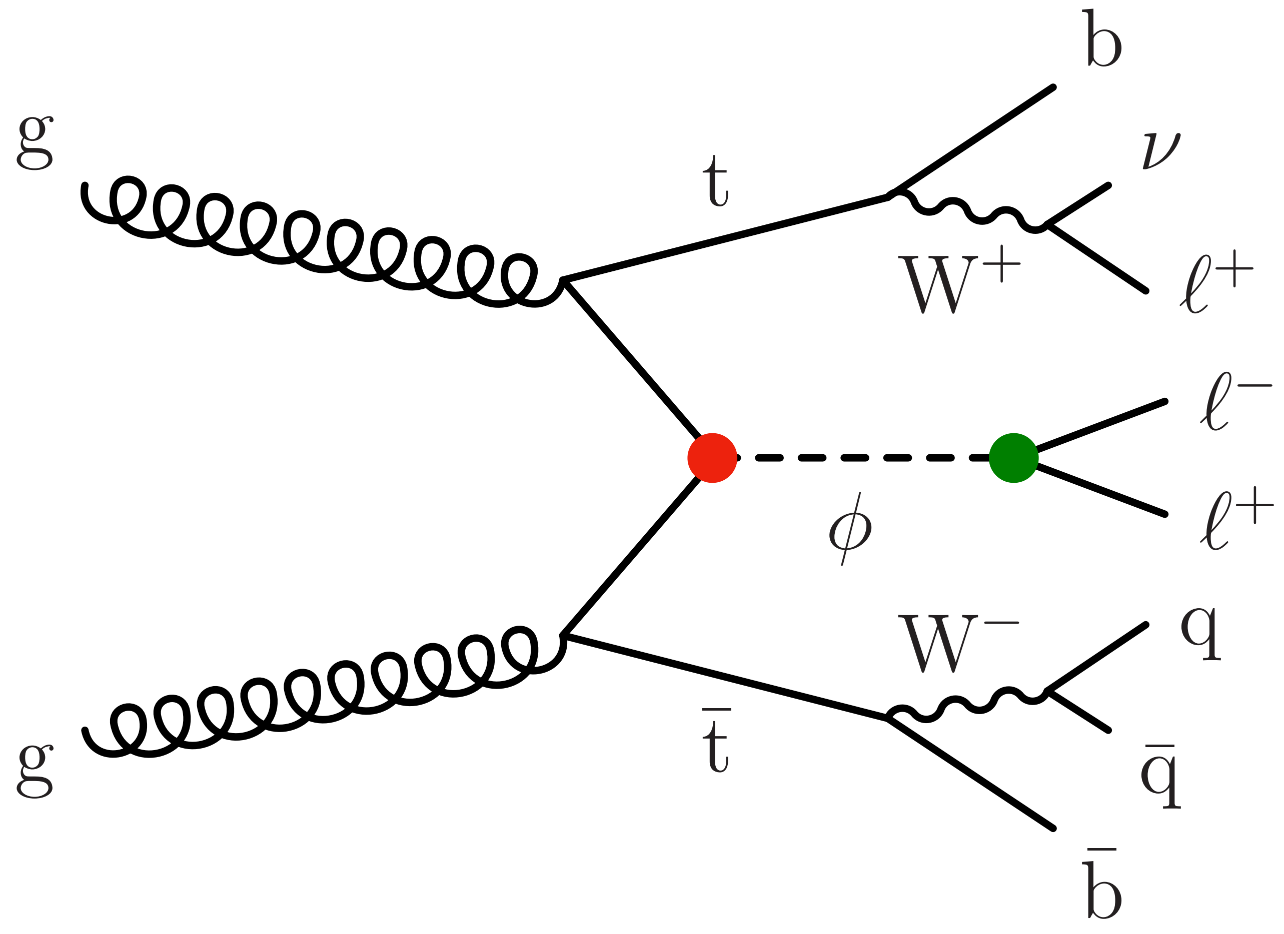
Tops: as gateway to new scalars

CMS-EXO-21-018

arXiv:2402.11098



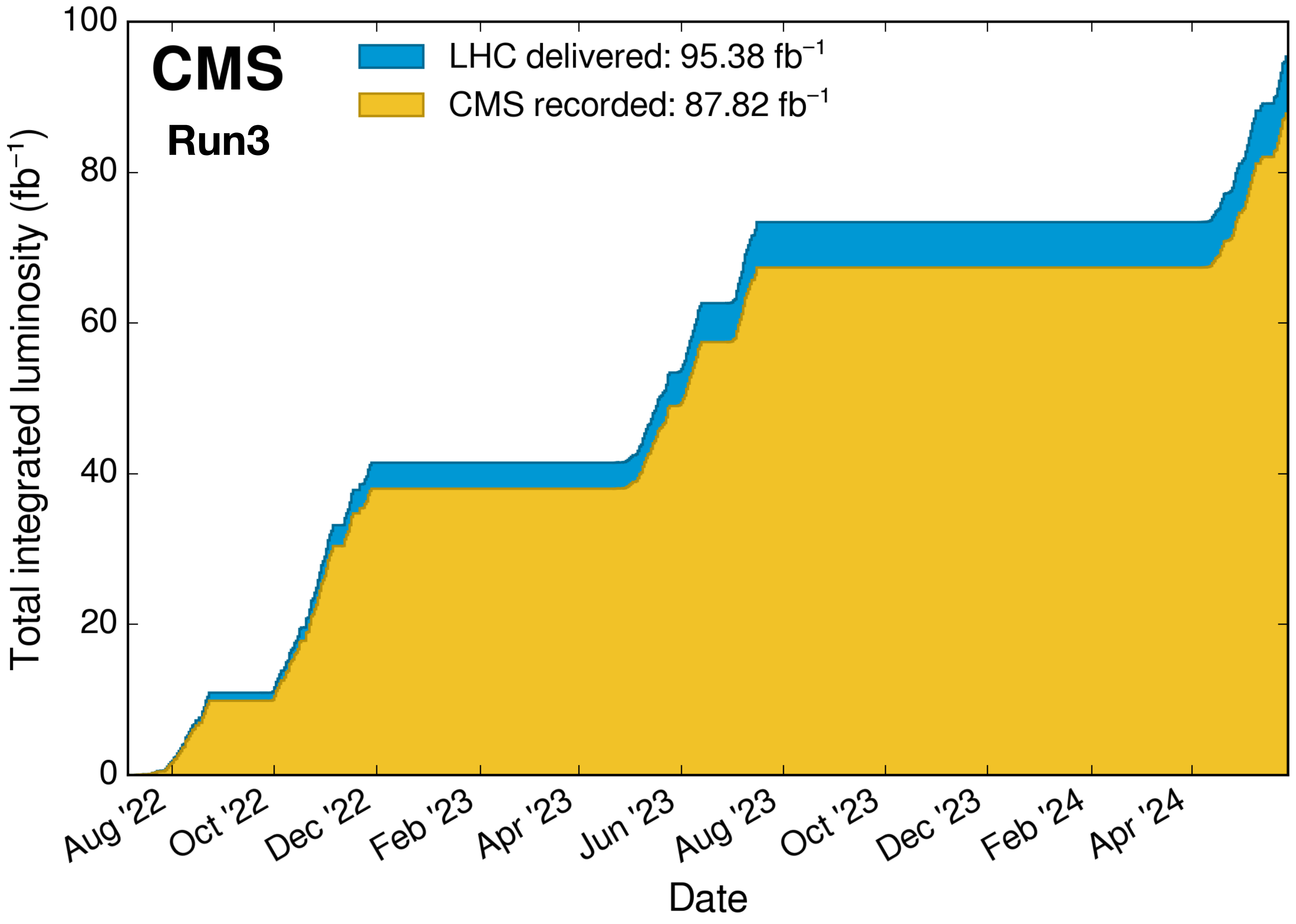




- **First direct bounds** on **dilaton-like (scalar) and axion-like (pseudoscalar)** fermiophilic states.
  → ϕ is assumed to couple to fermions only, proportional to their masses.
  → Sensitivity is dominated by $\tau\tau$ signal regions for masses above 30 GeV ($\mu\mu$ otherwise)

To conclude

- Three recent CMS results on "**exotic tops**":
  - *Resonant top signatures*
    CMS-PAS-B2G-23-006
    (03/2024)
  - *Same-sign top signatures*
    CMS-TOP-22-010 / arXiv:2311.03261
    (02/2024)
  - *Top associated production*
    CMS-EXO-21-018 / arXiv:2402.11098
    (02/2024)



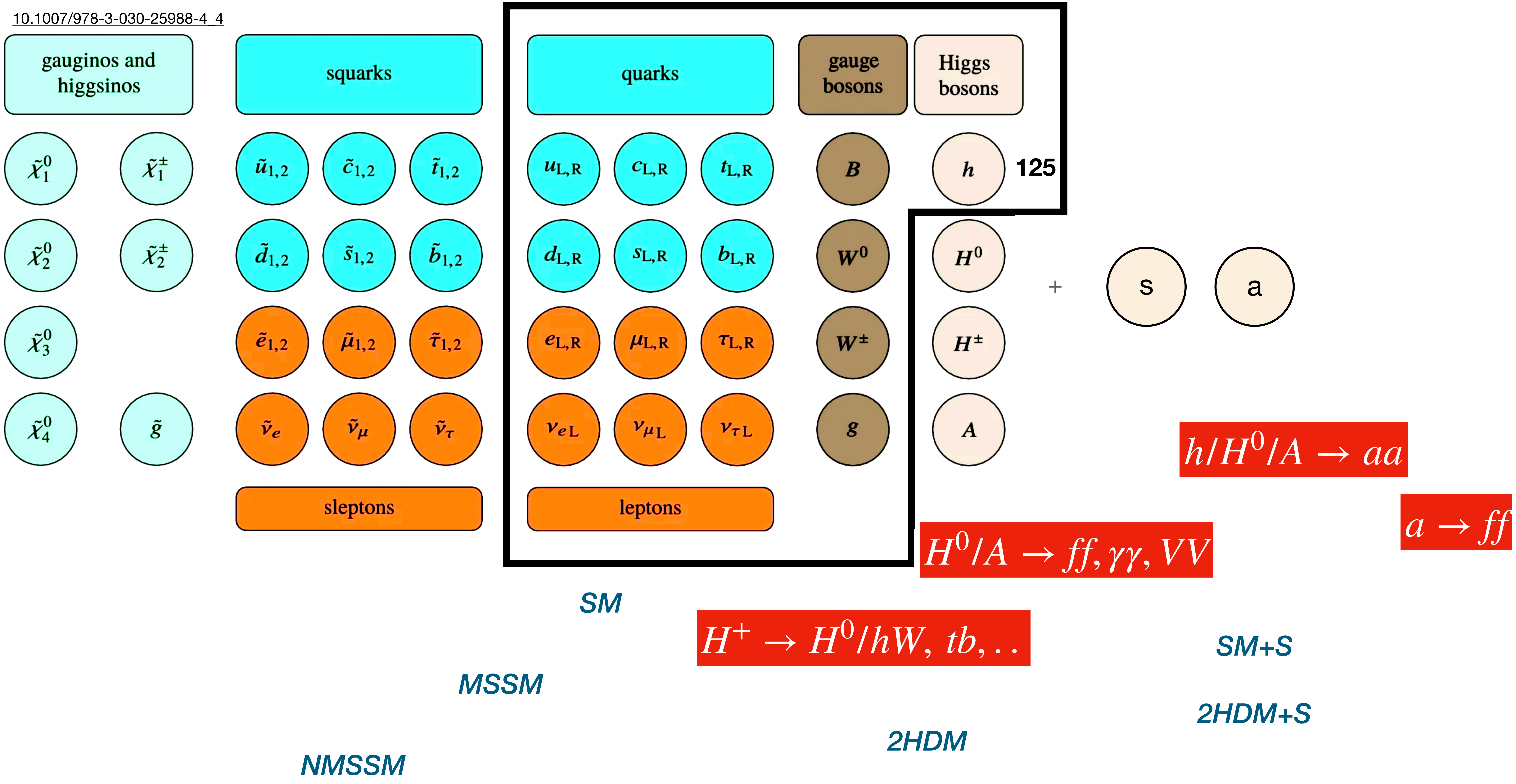
- **Challenging signals at EWK scale**
  → *Run2 dataset is still delivering.*
  → *Run3 efforts have started, stay tuned!*

Additional material

The extended scalar sector

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

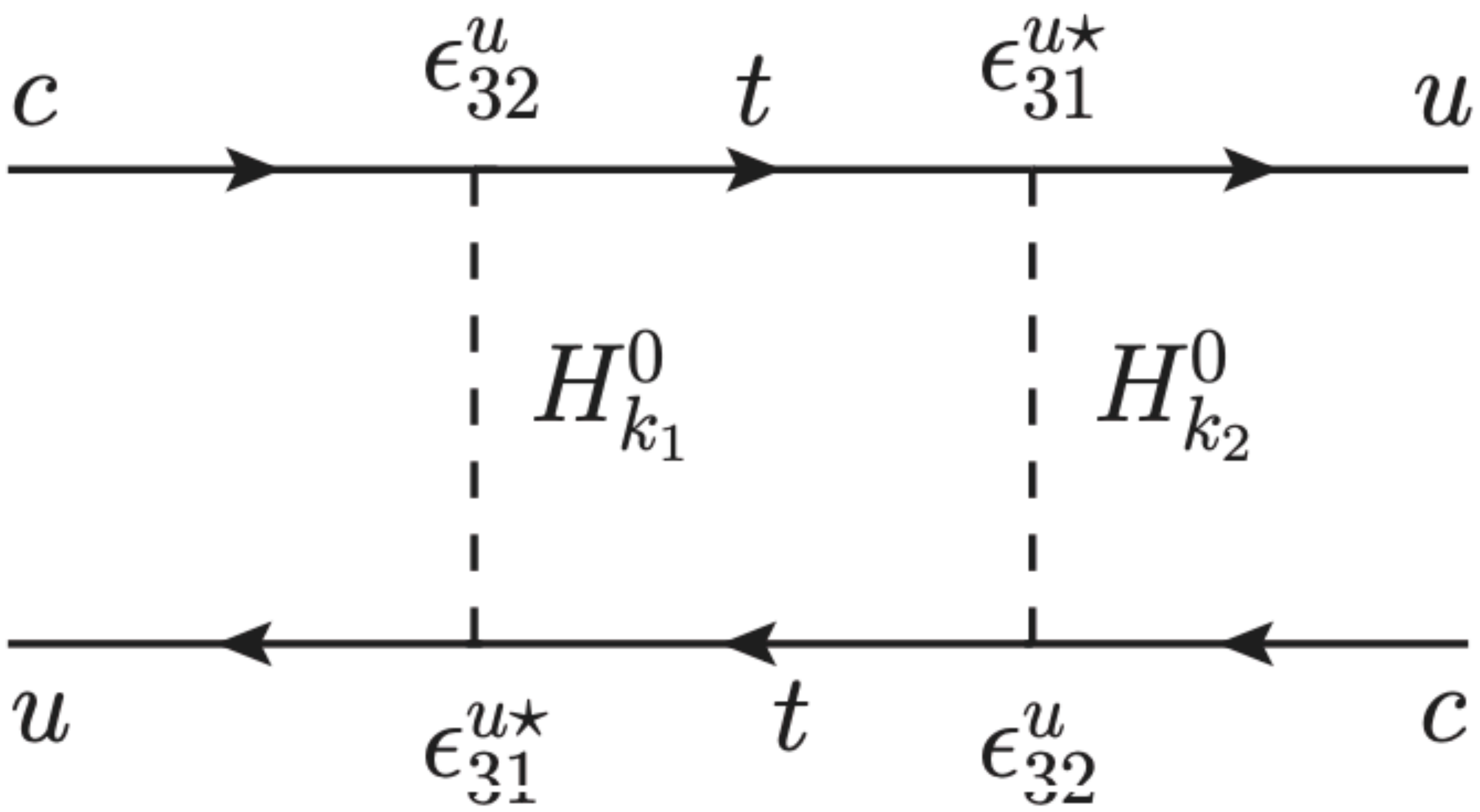
10.1007/978-3-030-25988-4_4



Bounds on off-diagonal couplings

CMS-TOP-22-010
arXiv:2311.03261

neutral Higgs box contribution to $D-\overline{D}$ mixing



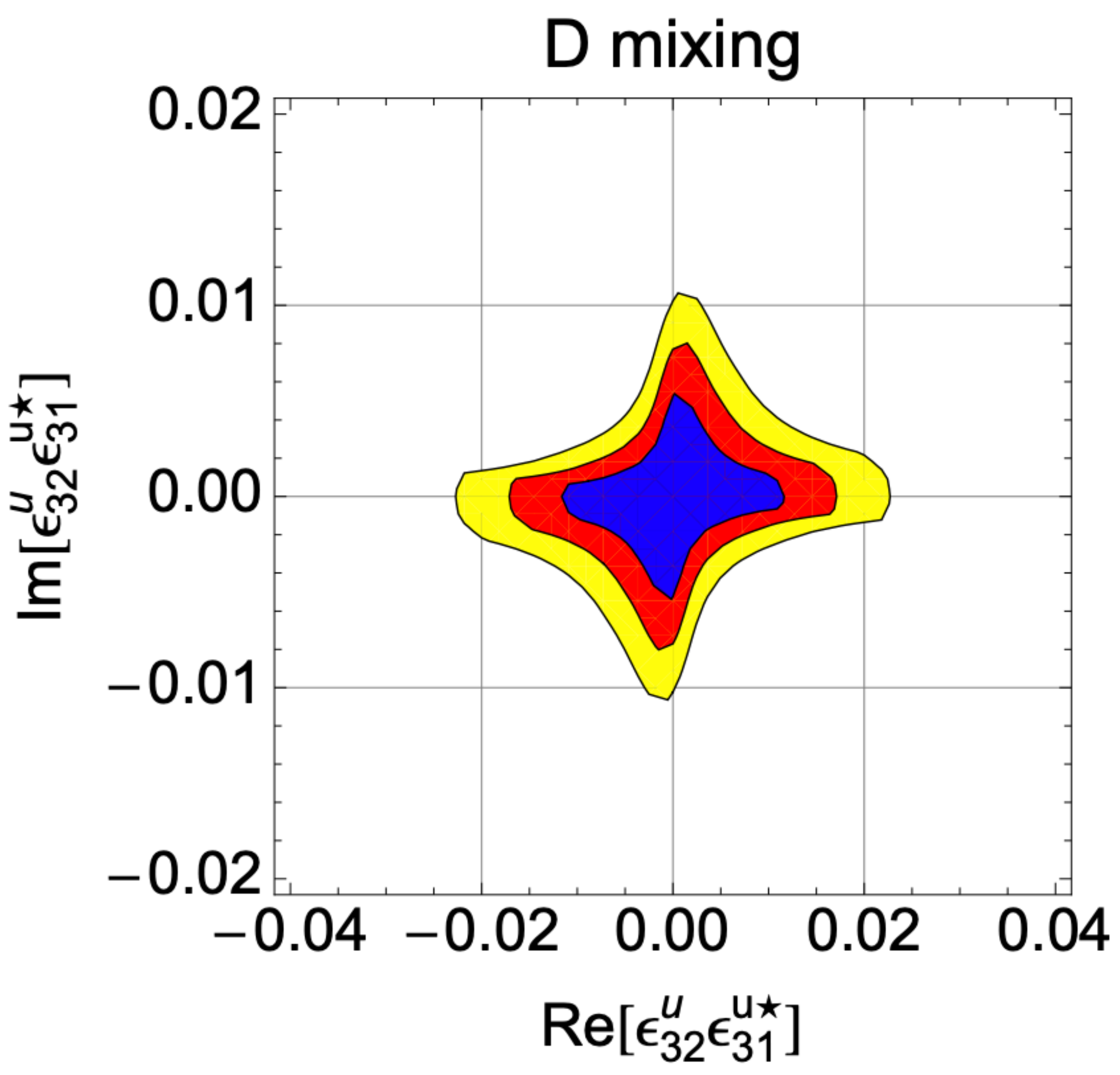


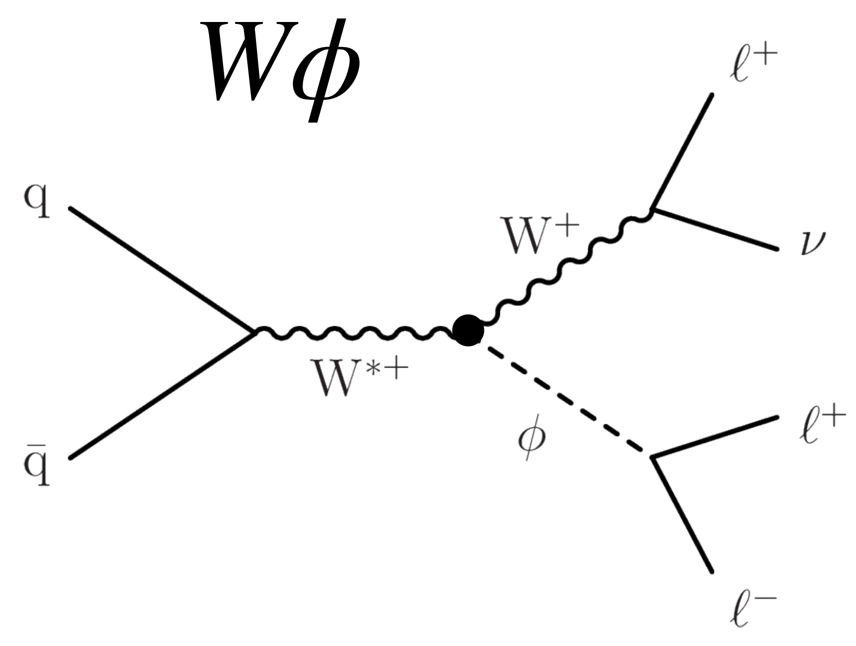
FIG. 19: Allowed region in the complex $\epsilon^u_{32}\epsilon^{u\star}_{31}$–plane obtained from neutral Higgs box contributions to $D-\overline{D}$ mixing for $\tan\beta = 50$ and $m_H = 700\,\mathrm{GeV}$ (yellow), $m_H = 500\,\mathrm{GeV}$ (red) and $m_H = 300\,\mathrm{GeV}$ (blue).

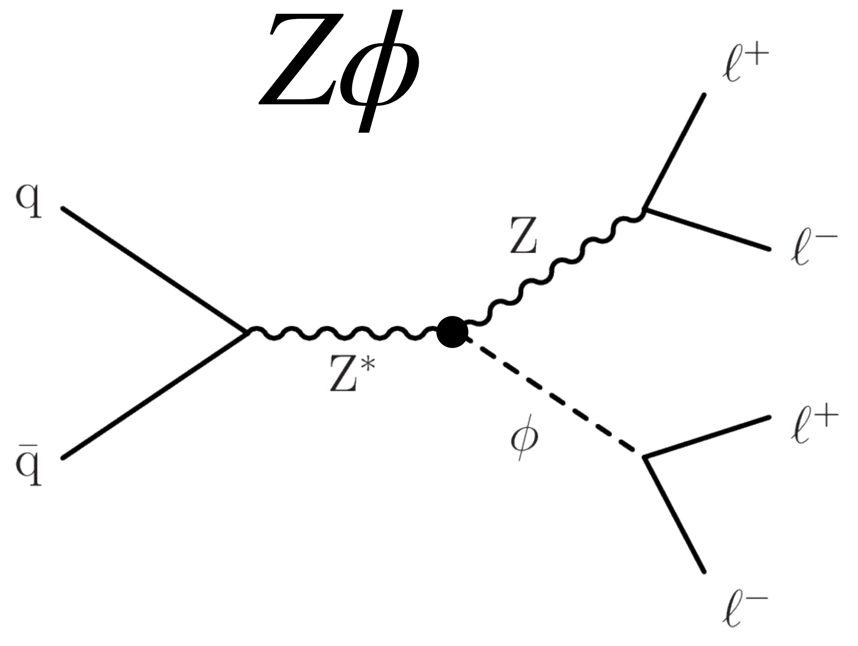
arXiv:1303.5877

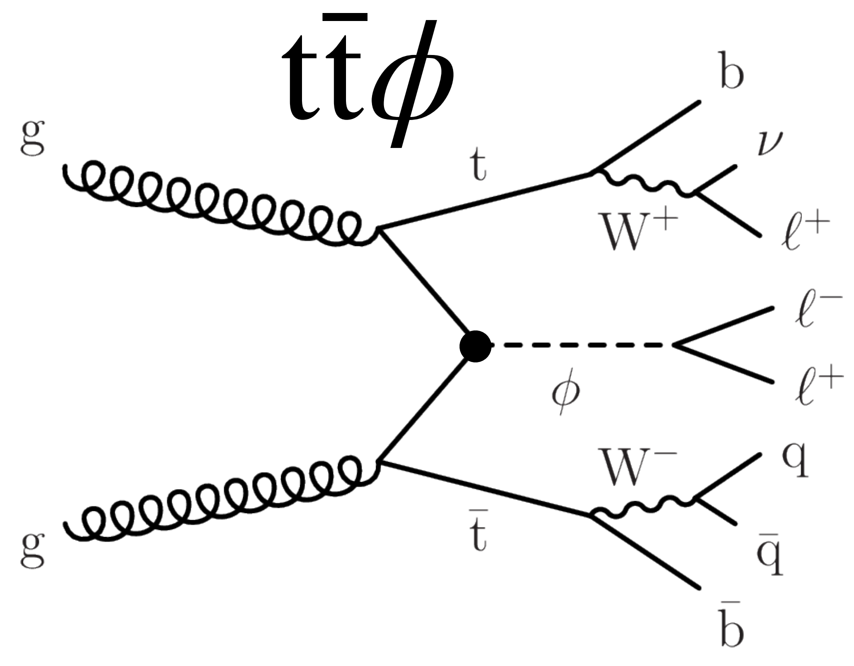
All signal regions: $X\phi$

CMS-EXO-21-018
arXiv:2402.11098

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	3L($\mathrm{ee}\mu/\mathrm{e}\mu\mu$)	1	1	OffZ	0	–	–	< 76, > 106	M_{ee} / $M_{\mu\mu}$
$\mathrm{W}\phi(\mathrm{ee}/\mu\mu)$ SR2Low	3L($\mathrm{eee}/\mu\mu\mu$)	1	1	OffZ	0	–	–	< 76, > 106	$M_{\mathrm{ee}}^{\mathrm{min}}$ / $M_{\mu\mu}^{\mathrm{min}}$
$\mathrm{W}\phi(\mathrm{ee}/\mu\mu)$ SR1High	3L($\mathrm{ee}\mu/\mathrm{e}\mu\mu$)	1	1	OffZ	0	> 200	> 15	> 150	M_{ee} / $M_{\mu\mu}$
$\mathrm{W}\phi(\mathrm{ee}/\mu\mu)$ SR2High	3L($\mathrm{eee}/\mu\mu\mu$)	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	3L($\mathrm{ee}\mu/\mathrm{e}\mu\mu$)	1	1	OffZ	≥ 1	> 350	–	> 100	M_{ee} / $M_{\mu\mu}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR2Low	3L($\mathrm{eee}/\mu\mu\mu$)	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	3L($\mathrm{ee}\mu/\mathrm{e}\mu\mu$)	1	1	OffZ	≥ 1	> 400	> 15	> 100	M_{ee} / $M_{\mu\mu}$
$\mathrm{t\bar{t}}\phi(\mathrm{ee}/\mu\mu)$ SR2High	3L($\mathrm{eee}/\mu\mu\mu$)	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	–	–	–	$M_{\ell\tau/\tau\tau}^{\mathrm{min}}$

$W\phi/Z\phi$ bounds

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