Christoph Englert

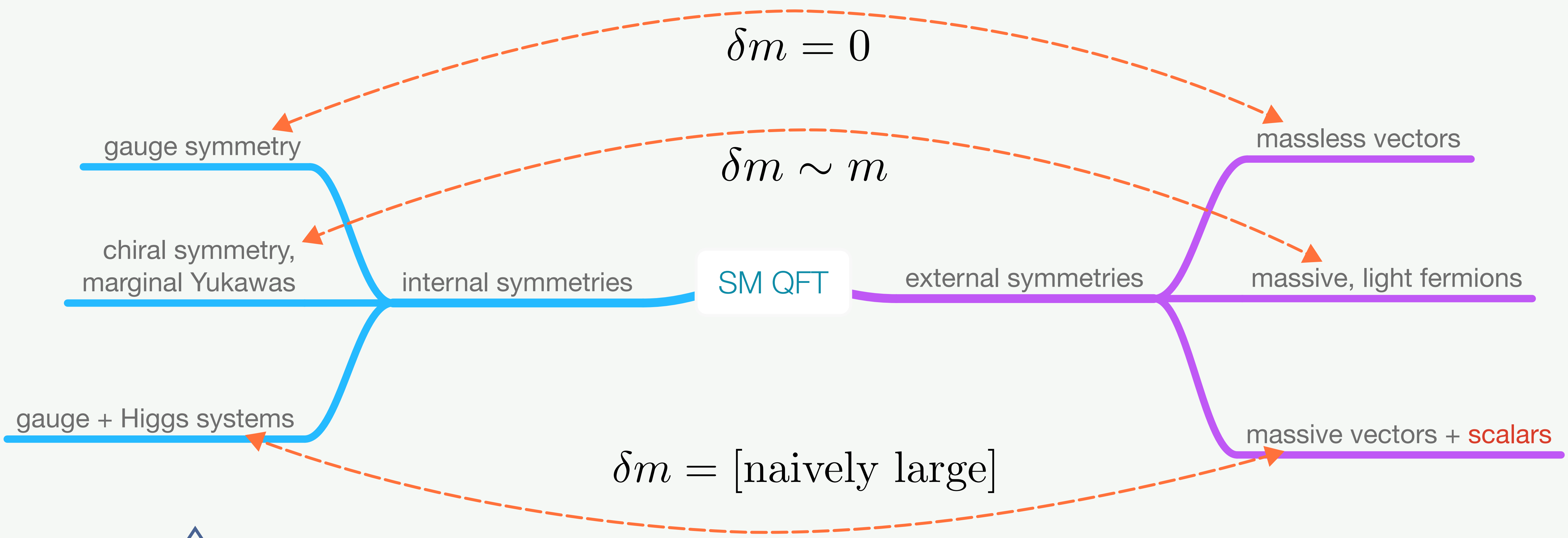
Theoretical outlook for LHC Run 3

UKHEP Forum

24/11/21

University of Glasgow

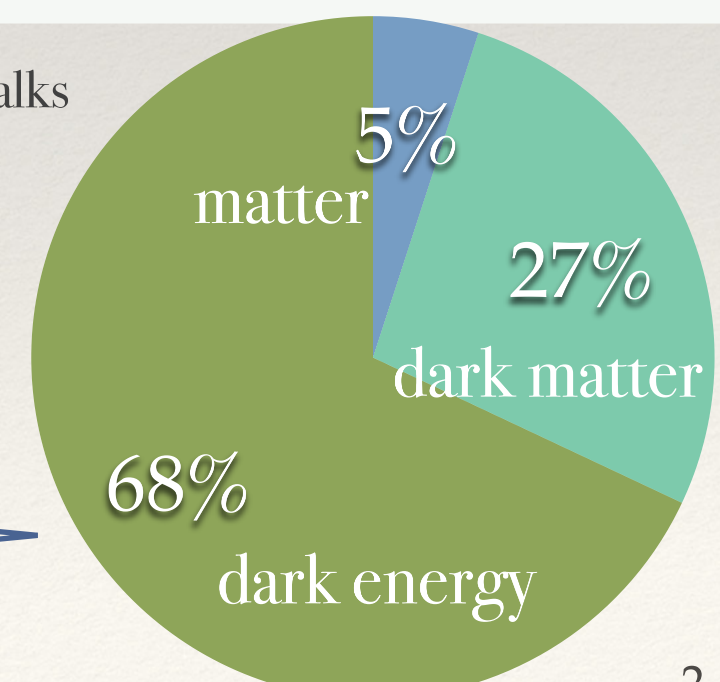
The Standard Model: a tale of symmetries



Theoretical reservation…

$\rightarrow$ Jocelyn's and David's talks

…pairs up with facts



era of experimental beacons and theoretical intuition

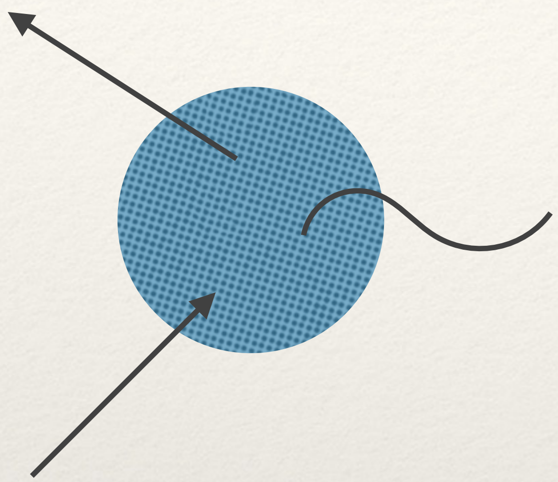
LHC RUN 3

- anomaly clarification: g-2, LFU and CP
- Higgs and top phenomenology
- precision vs anomaly detection

anomalous muon magnetic moment

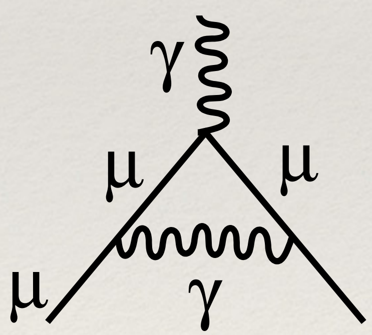
→ Alex's and Andreas' talks

- general decomposition of three-point QED vertex



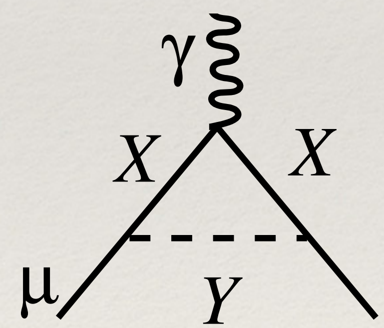
$$= -ie\bar{u}(p')\left[\gamma^\mu F_1(k^2) + \frac{i}{2M_\mu}\sigma^{\mu\nu}k_\nu F_2(k^2) + \dots\right]u(p)$$

- magnetic moment $\vec{\mu} = \dfrac{e}{2m}[2\overset{=1}{F_1(0)} + 2\overset{=a_\mu}{F_2(0)}]\vec{S}$ gives $g = 2 + 2F_2(0)$



$$\delta a_\mu^{\mathrm{QED}} = \frac{\alpha}{2\pi}$$

[Schwinger `48]
... [Ayoma et al. `15/`17]



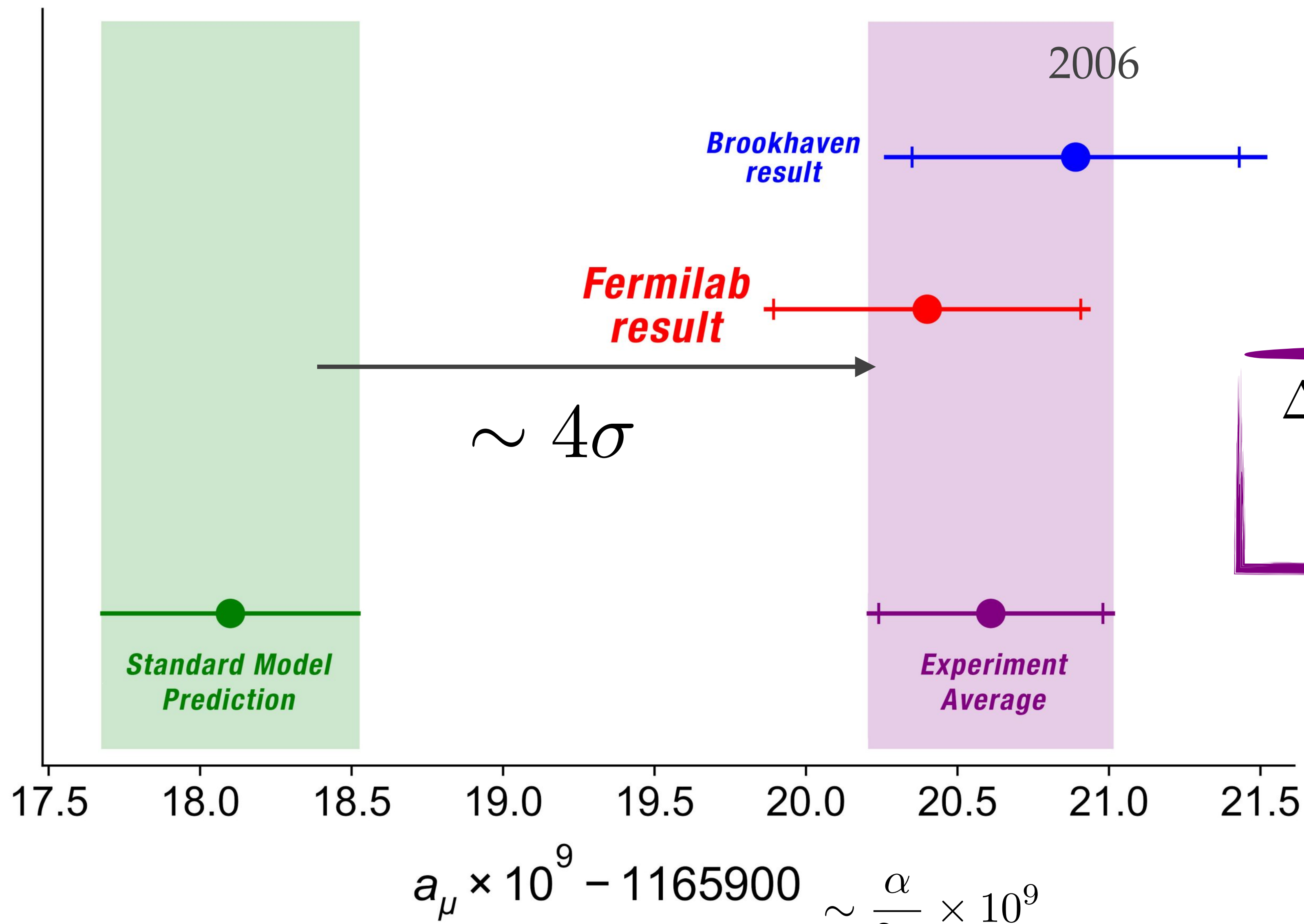
$$\delta a_\mu \sim g_{\mu XY}^2 \frac{m_\mu^2}{m_X^2}$$

new physics predominantly in muons, but large modification means either strong coupling or light states

→ Alex's and Andreas' talks

- combined experimental and theoretical effort

[Abi et al. (Muon g-2 collaboration) `21]



$\sim \frac{\alpha}{2\pi} \times 10^9$

Theory White Paper
[Aoyama et al. 2006.04822]

$$\boxed{\begin{aligned}\Delta a_\mu &= a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) \\ &= (25.1 \pm 5.9) \times 10^{-10}\end{aligned}}$$

5

- comprehensive investigation already after BNL

Single field SM extensions

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\rm BNL}$, Δa_μ^{2021}
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Excluded: $\Delta a_\mu < 0$
2	0	$(\mathbf{1}, \mathbf{1}, 2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -1/2)$	Updated in Sec. 3.2
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated Sec. 3.3.
6	0	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	Excluded: LHC searches
7	0	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated Sec. 3.3.
9	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Excluded: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1}, \mathbf{1}, -1)$	Excluded: Δa_μ too small
12	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$	Excluded: LEP lepton mixing
13	1/2	$(\mathbf{1}, \mathbf{2}, -3/2)$	Excluded: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
16	1	$(\mathbf{1}, \mathbf{1}, 0)$	Special cases viable
17	1	$(\mathbf{1}, \mathbf{2}, -3/2)$	UV completion problems
18	1	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: LHC searches
19	1	$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	UV completion problems
20	1	$(\overline{\mathbf{3}}, \mathbf{1}, -5/3)$	Excluded: LHC searches
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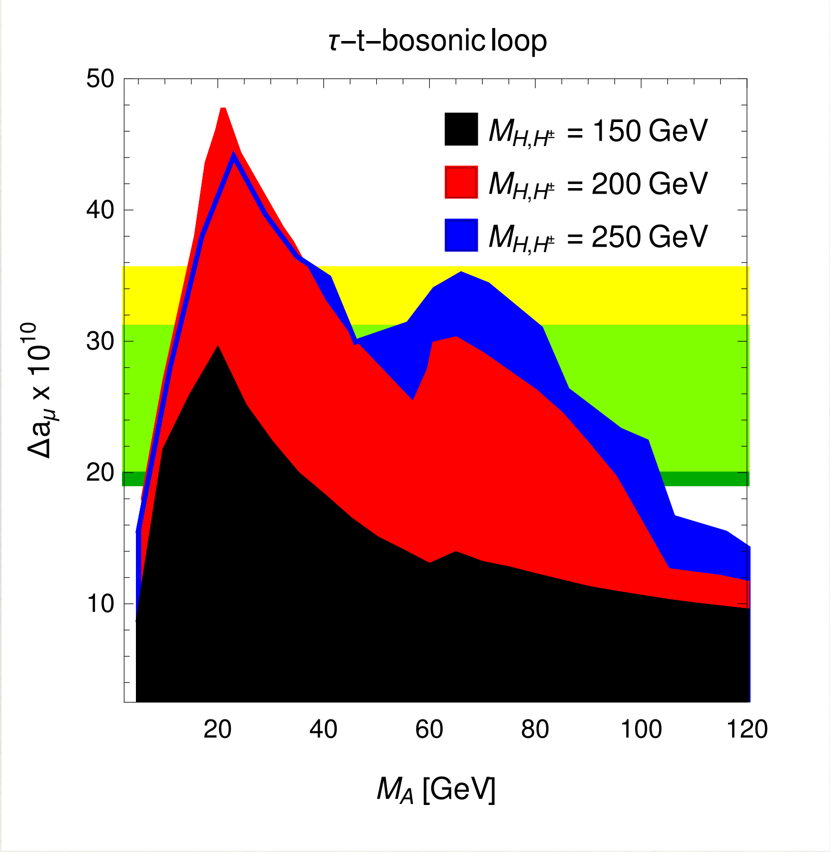
22	1	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: $\Delta a_\mu < 0$
23	1	$(\overline{\mathbf{3}}, \mathbf{3}, -2/3)$	Excluded: proton decay

[Athron et al. `21]

- difficult in good old type I/II models

[Cherchiglia et al. `16]
[Atkinson et al. `21]



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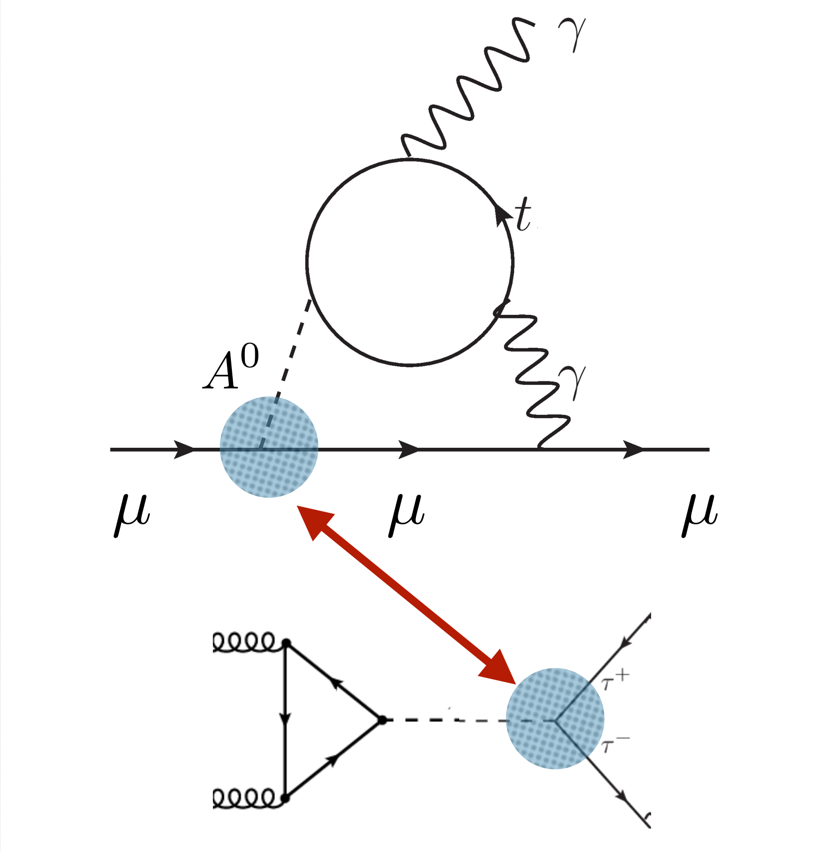

- lepton specific / flavour aligned possible: tau final states at run 3

multi-field SM extensions

$(SU(3)_C \times SU(2)_L \times U(1)_Y)_{\text{spin}}$	$+\mathbb{Z}_2$	Result for $\Delta a_\mu^{\text{BNL}}$, Δa_μ^{2021}
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Projected LHC 14 TeV exclusion, not confirmed
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	No	Excluded: LHC searches
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LEP contact interactions
	Yes	Viable with under abundant DM
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$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: LEP search
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{3},0)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{3},-1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
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[Athron et al. `21]

new physics?

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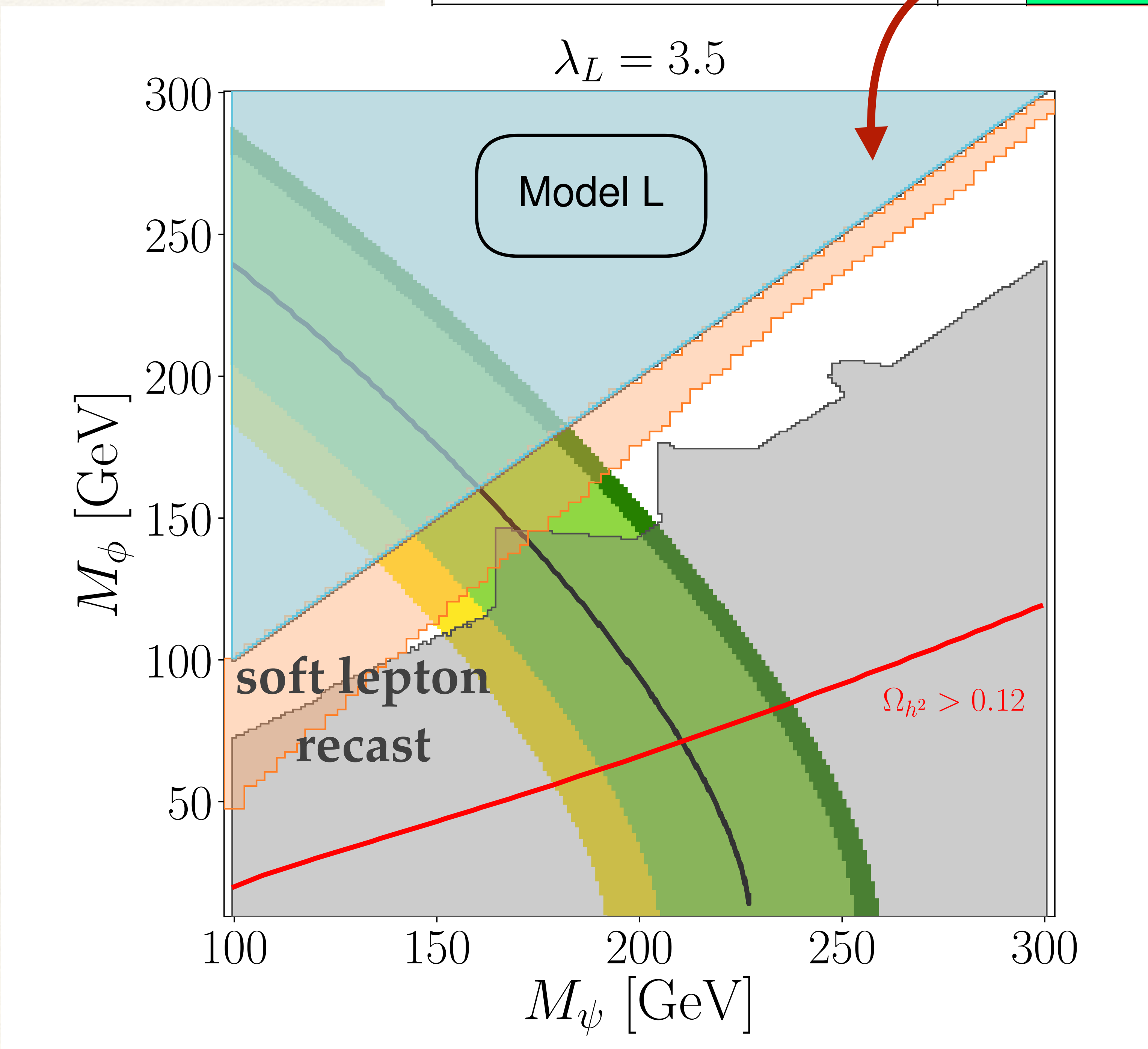
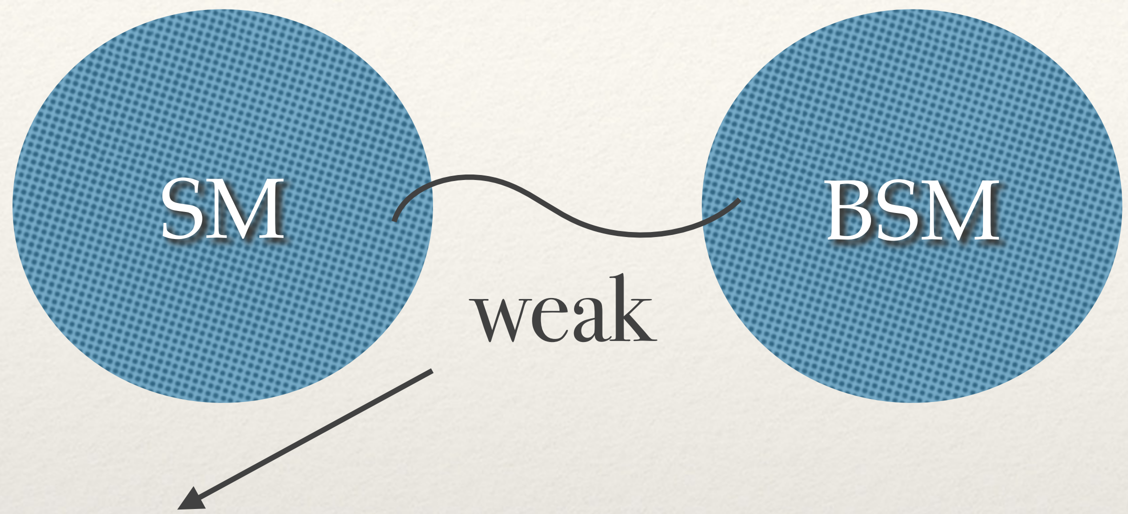


[Athron et al.`21]

new strongly coupled physics?

- way out of perturbative conundrum à la composite Higgs?



full (multi-)loop calculations

many examples in literature

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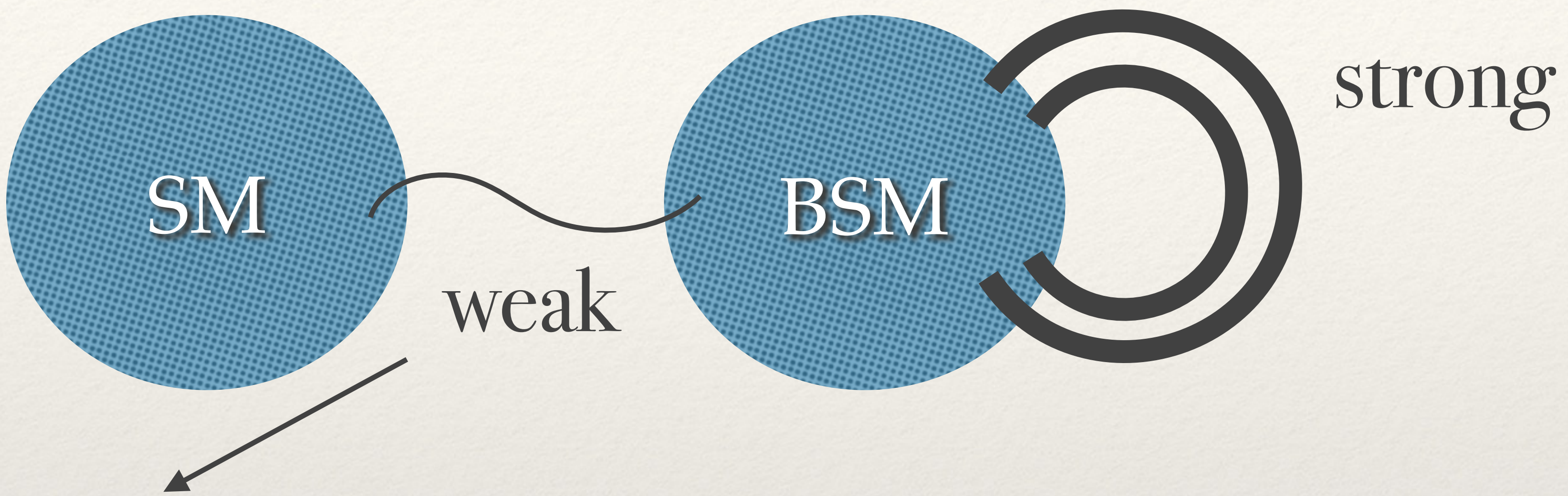

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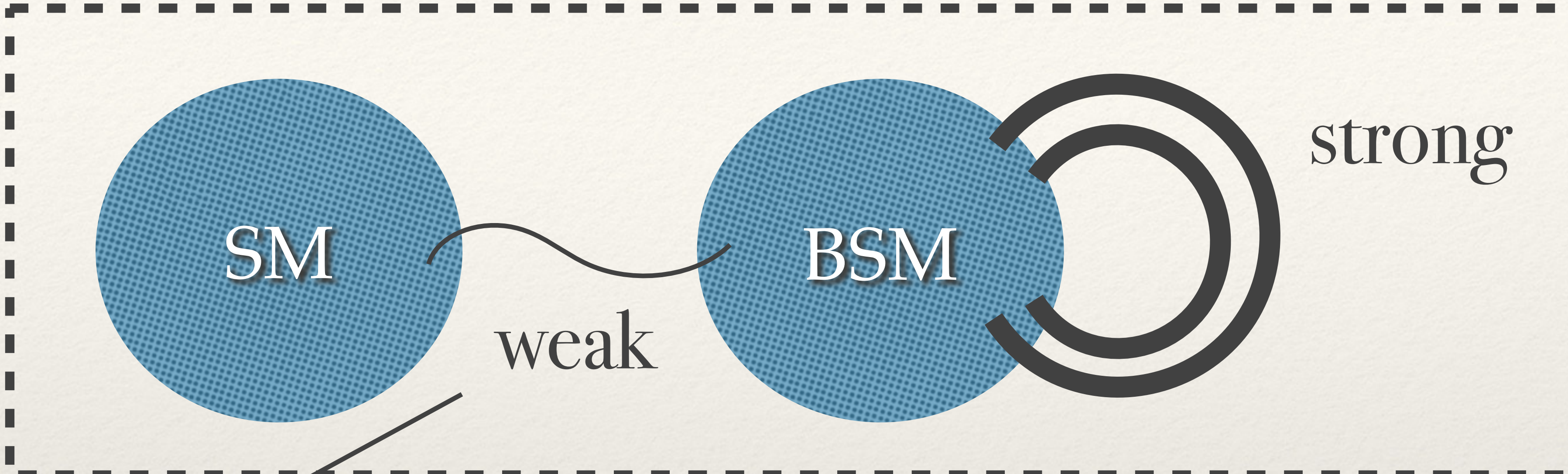


full (multi-)loop calculations

many examples in literature

e.g. CCWZ

Effective field theory of BSM states

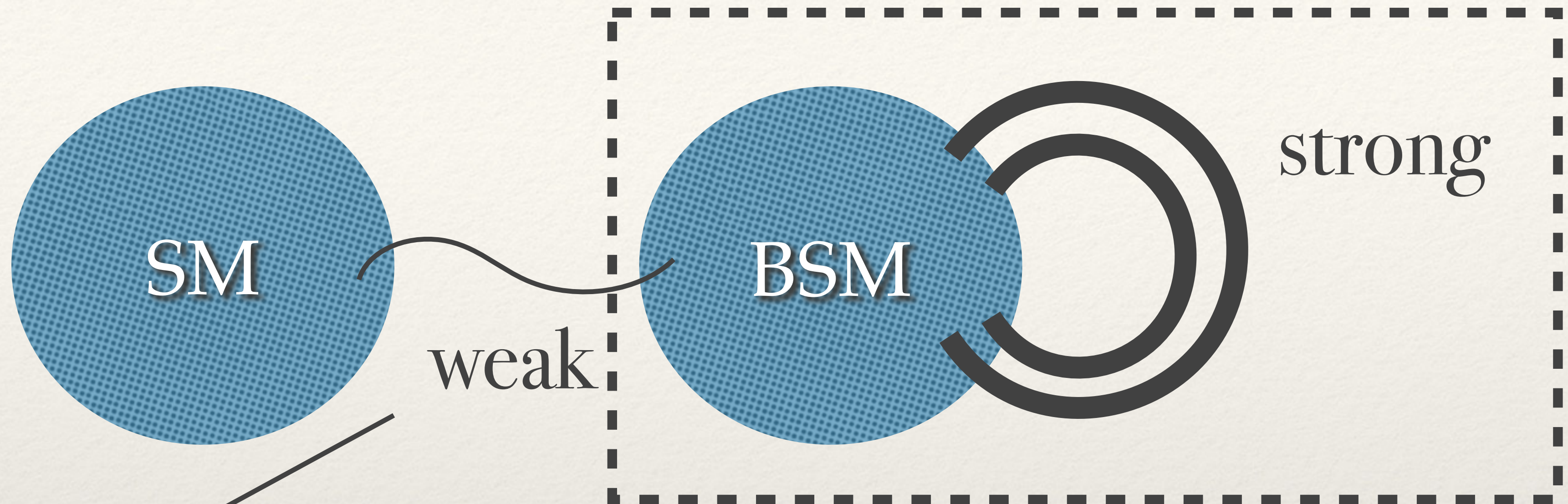
- elevate g-2 to input data (already for SMEFT) [Aebischer et al. `21]

New physics scale
in principle ~ 200 TeV
[Allwicher et al. `21]

mu/e Higgs
decays + CKM
[Cirigliano et al.`21]

new strongly coupled physics?

- way out of perturbative conundrum à la composite Higgs?



full (multi-)loop calculations

many examples in literature

e.g. CCWZ

Effective field theory of BSM states

- elevate g-2 to input data (already for SMEFT)
- address SM shortcomings beyond g-2
- reflect how *any* integrated out dynamics affects correlations

[Aebischer et al. `21]
[Allwicher et al. `21]
[Cirigliano et al.`21]

new strongly coupled physics?

- minimal example: Zee-Babu SM extension

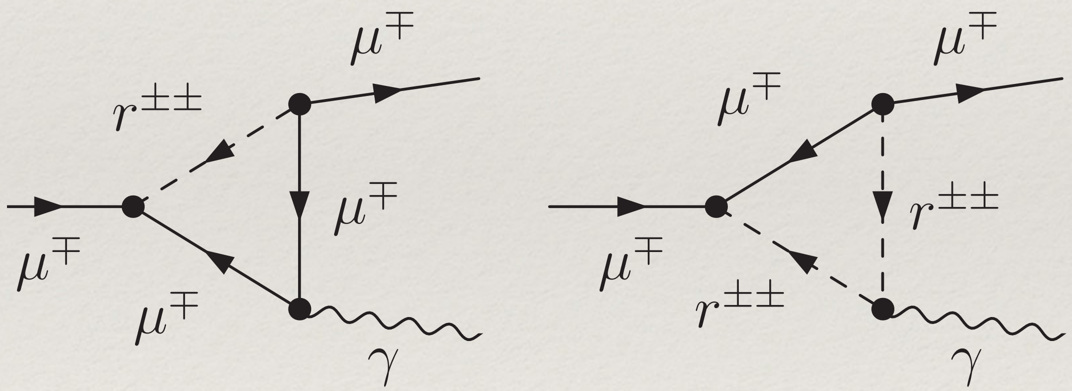
[Anisha et al. `21]

neutrino physics etc.

$$\mathcal{S} : (\mathbf{1}, \mathbf{1}, 1)$$
$$\mathcal{R} : (\mathbf{1}, \mathbf{1}, 2)$$

$$a_\mu^{\rm d4}(\text{Zee-Babu}) = -\frac{M_\mu^2}{24\pi^2}\left(\frac{(f_\mathcal{S}^\dagger f_\mathcal{S})_{\mu\mu}}{M_{h^\pm}^2} + 4\frac{(f_\mathcal{R}^\dagger f_\mathcal{R})_{\mu\mu}}{M_{r^{\pm\pm}}^2}\right)$$

e.g. [Leville et al. `78]
[Moore et al. `85]



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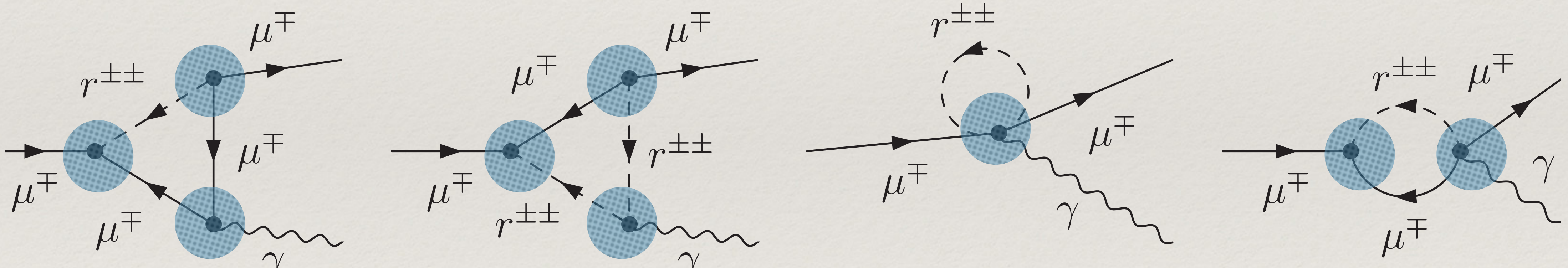

- negative result can be compensated by kinematically enhanced loop dynamics and/or strong couplings....

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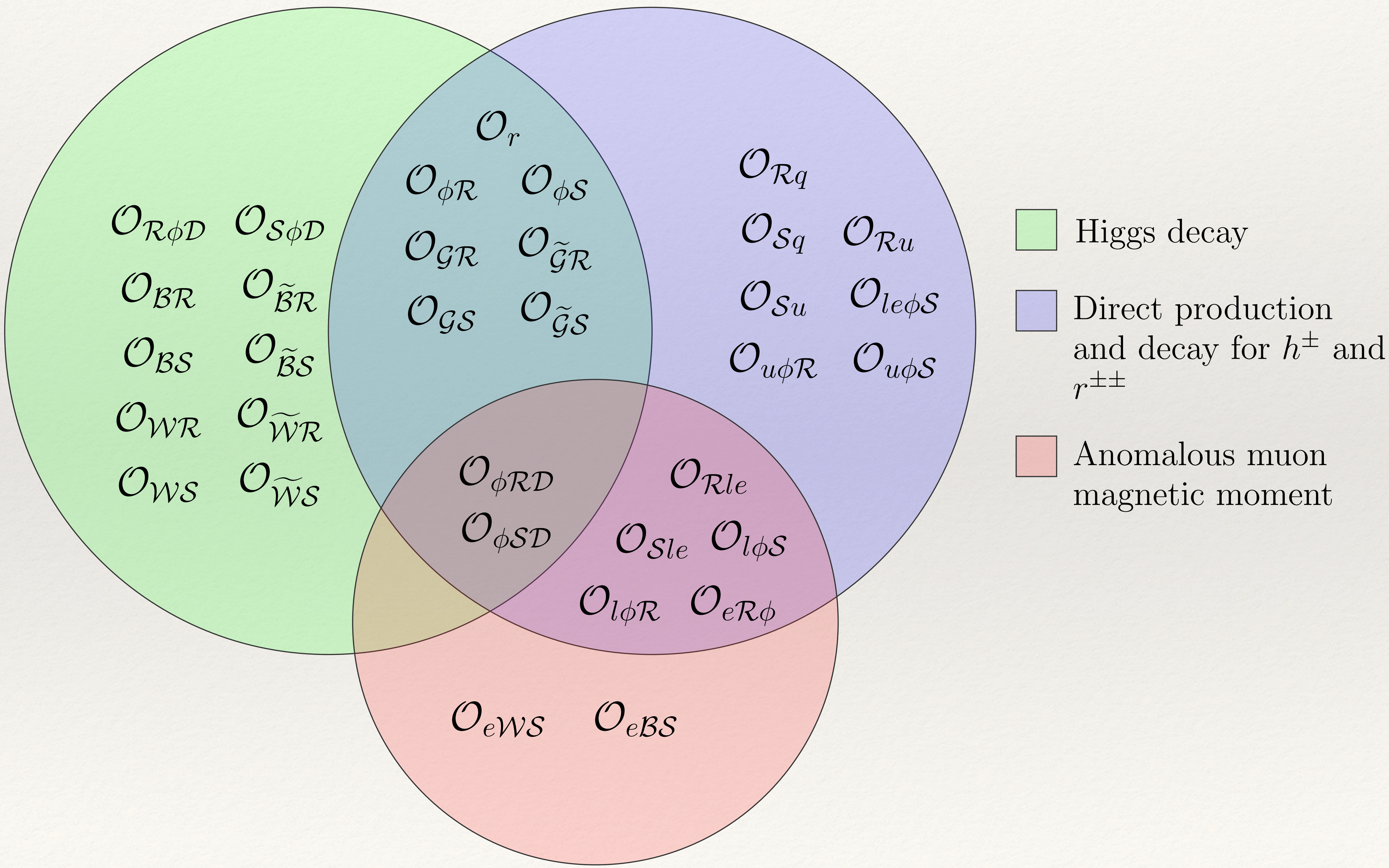
$$\Lambda^2 \times a_\mu^{{\rm d6},r^{\pm\pm}}(\text{Zee-Babu}) = \frac{f_\mathcal{R} M_\mu^2 v^2 (\mathcal{C}_{e\mathcal{R}\phi})_{\mu\mu}}{6\pi^2 M_{r^{\pm\pm}}^2} + \frac{f_\mathcal{R} M_\mu^2 v^2 (\mathcal{C}_{\ell\phi\mathcal{R}})_{\mu\mu}}{2\pi^2 M_{r^{\pm\pm}}^2} \left(\log\left(\frac{M_{r^{\pm\pm}}}{M_\mu}\right) - \frac{1}{4} \right)$$
$$+ \frac{f_\mathcal{R} M_\mu^3 v (\mathcal{C}_{\mathcal{R}\ell e})_{\mu\mu}}{\sqrt{2}\pi^2 M_{r^{\pm\pm}}^2} \left(\frac{7}{12} - \log\left(\frac{M_{r^{\pm\pm}}}{M_\mu}\right)\right) + \frac{f_\mathcal{R}^2 M_\mu^2 v^2 \mathcal{C}_{\phi\mathcal{R}\mathcal{D}}}{12\pi^2 M_{r^{\pm\pm}}^2}$$
$$+ \ldots..$$

- negative result can be compensated by kinematically enhanced loop dynamics and/or strong couplings....

- relatively low cut off can be consistent with TeV scale exotics
- many interactions! But muon-Higgs-exotics interplay **transparent**



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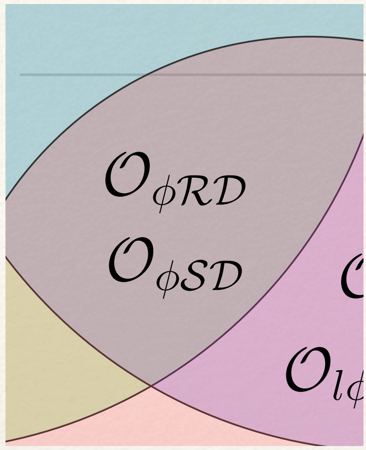
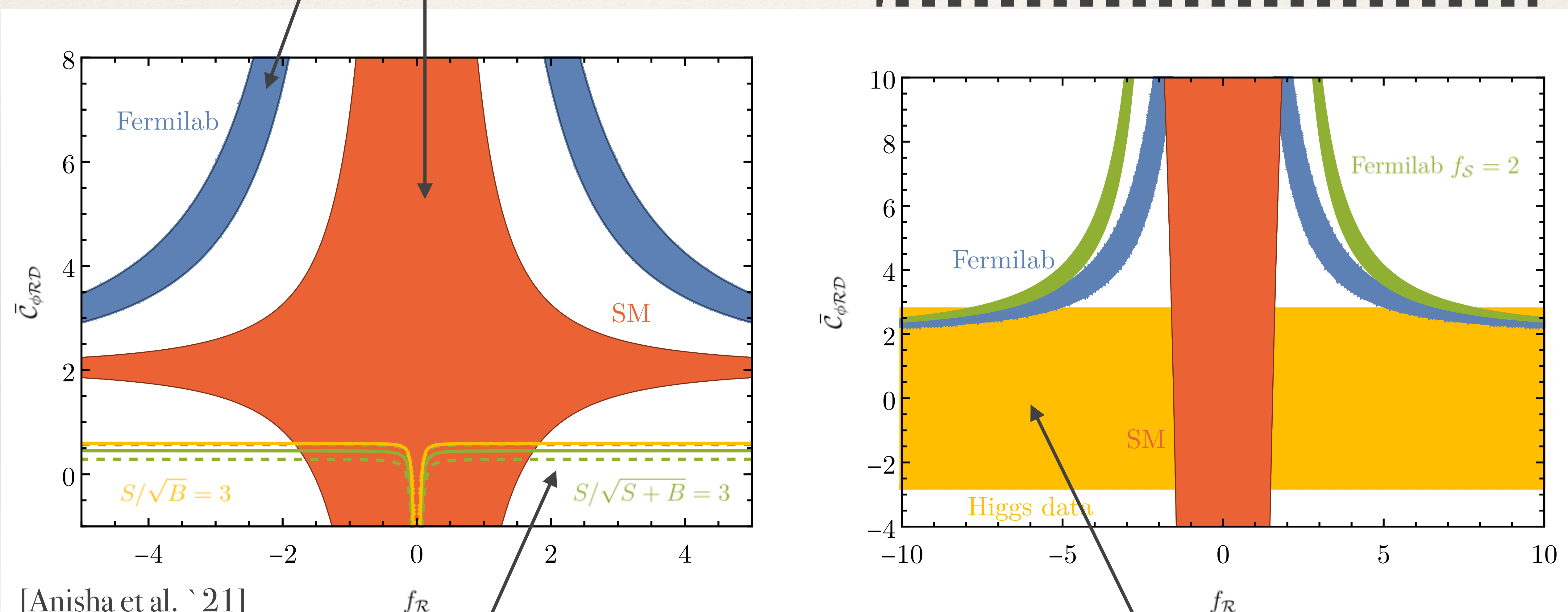


Excellent opportunity for HL-LHC to close sensitivity gaps!

blind direction $\mathcal{C}_{\phi\mathcal{SD}} \approx -4\mathcal{C}_{\phi\mathcal{RD}}$

$M_{r^{\pm\pm}} = M_{h^\pm}$

muon magnetic moment



ECFA Higgs signal strength @ 3/ab

doubly charged Higgs pair production @3/ab

coupling/scale separated BSM physics

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

concrete models

- extended SMEFT
- ($\mathbb{C}$) Higgs portals
- 2HDMs
- simplified models
- compositeness….

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rich kinematical structure

concrete models

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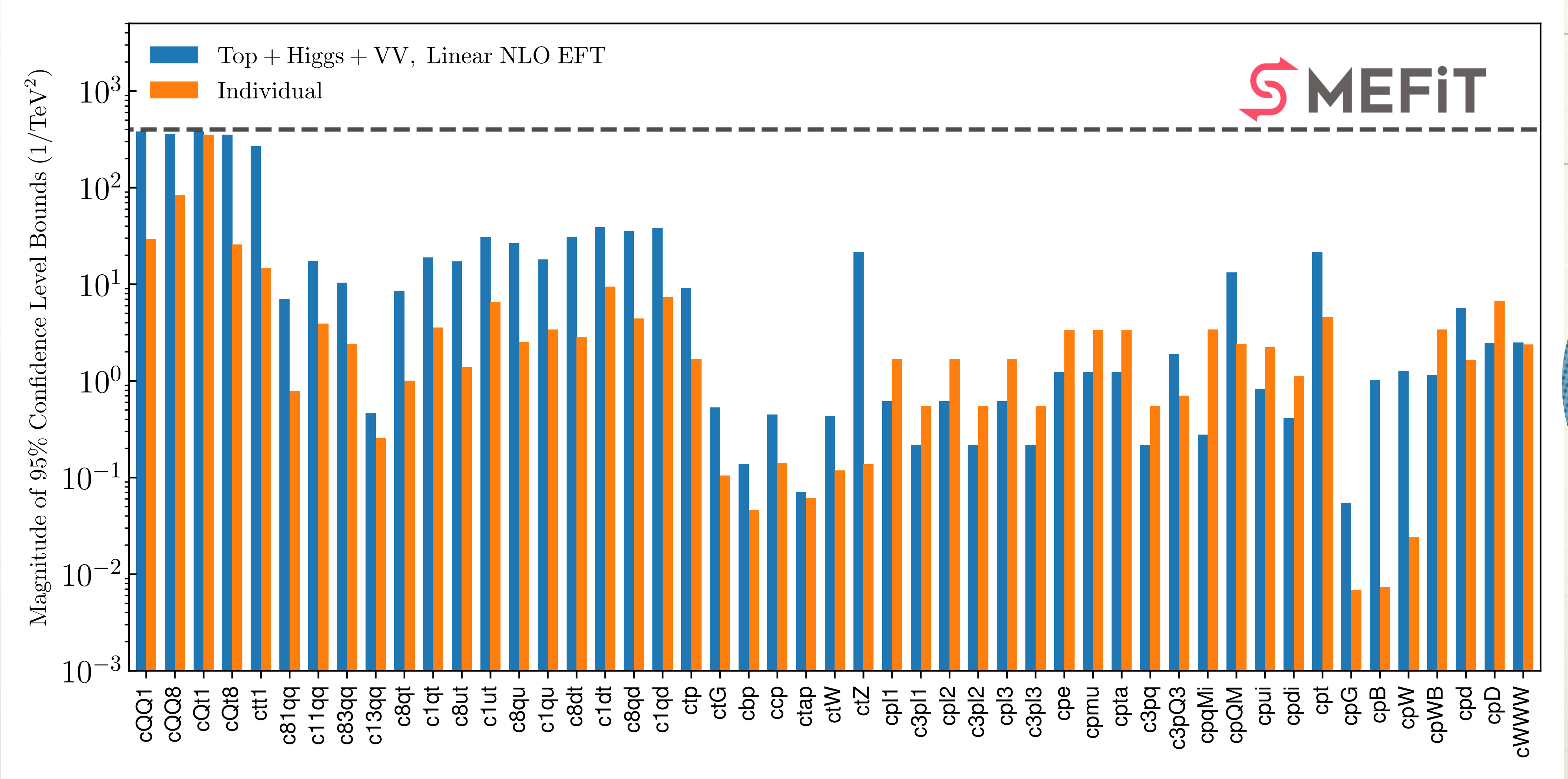
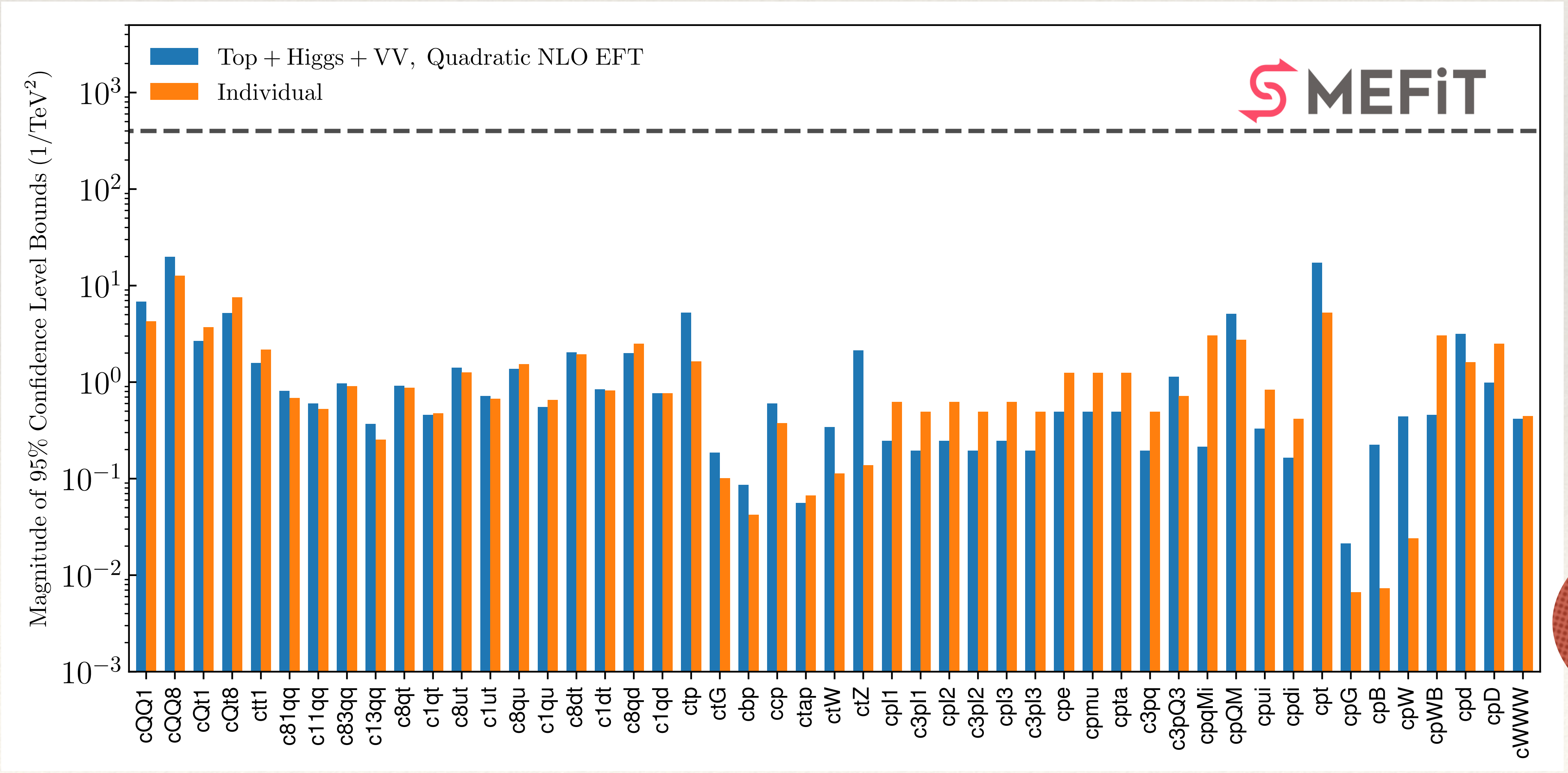
EFT@Run-3





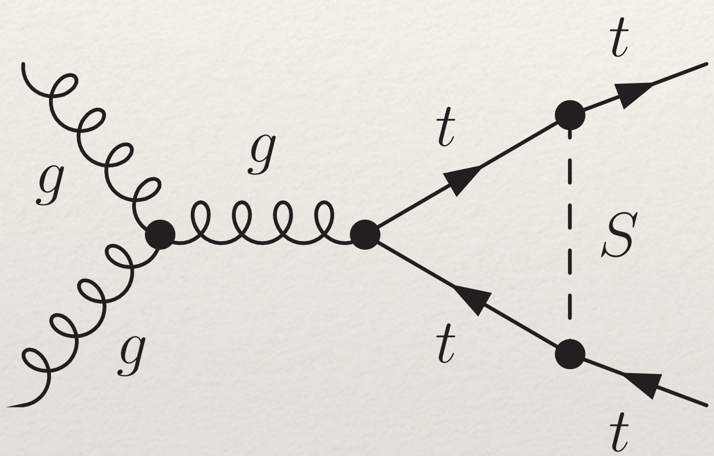
major theoretical focus post 2012

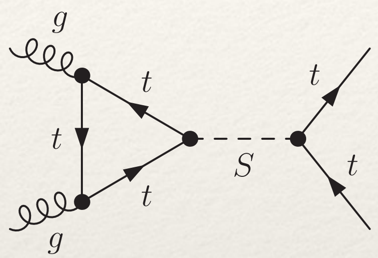
[Ellis, Sanz, You]
[TopFitter]
[Sfitter]
[GFitter]
[SMEFiT]
…

proof-of-principle case + NLO tools

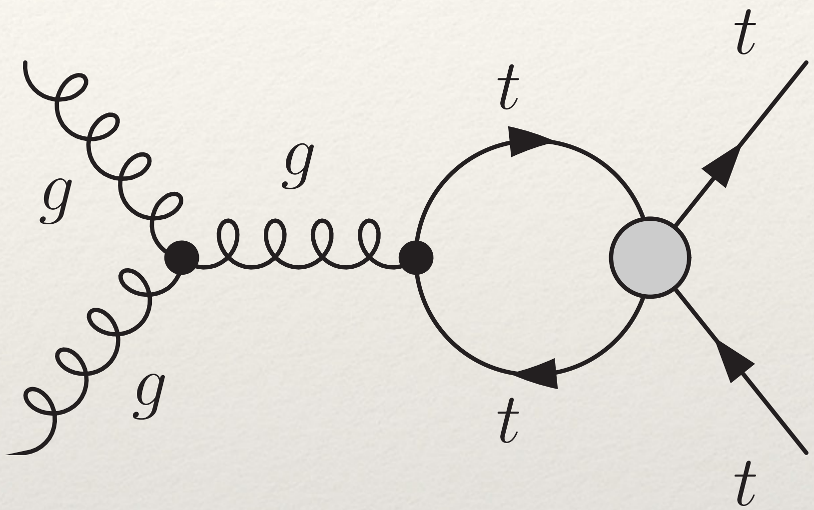
experimental ownership @ R3

- new top-philic states arise in many BSM theories: $-\left(c_S \bar{t}_L t_R S + \mathrm{h.c.}\right)$
- top pair production with large cross section could fingerprint such states





no resonance



3 relevant operators

EFT to inform theory

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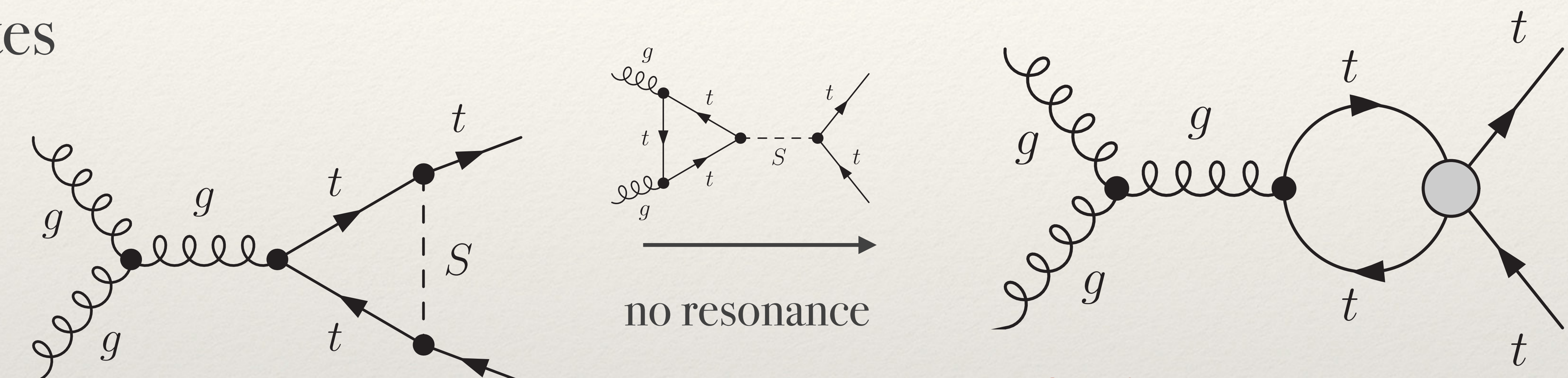
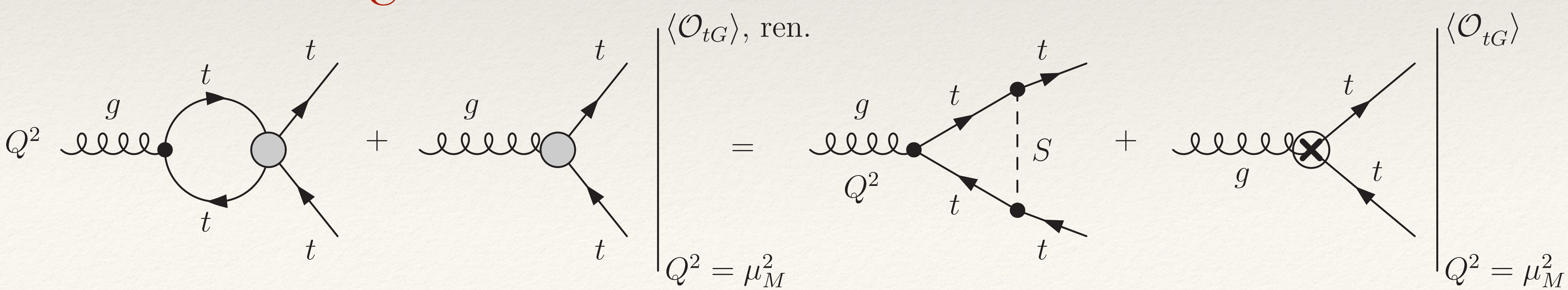
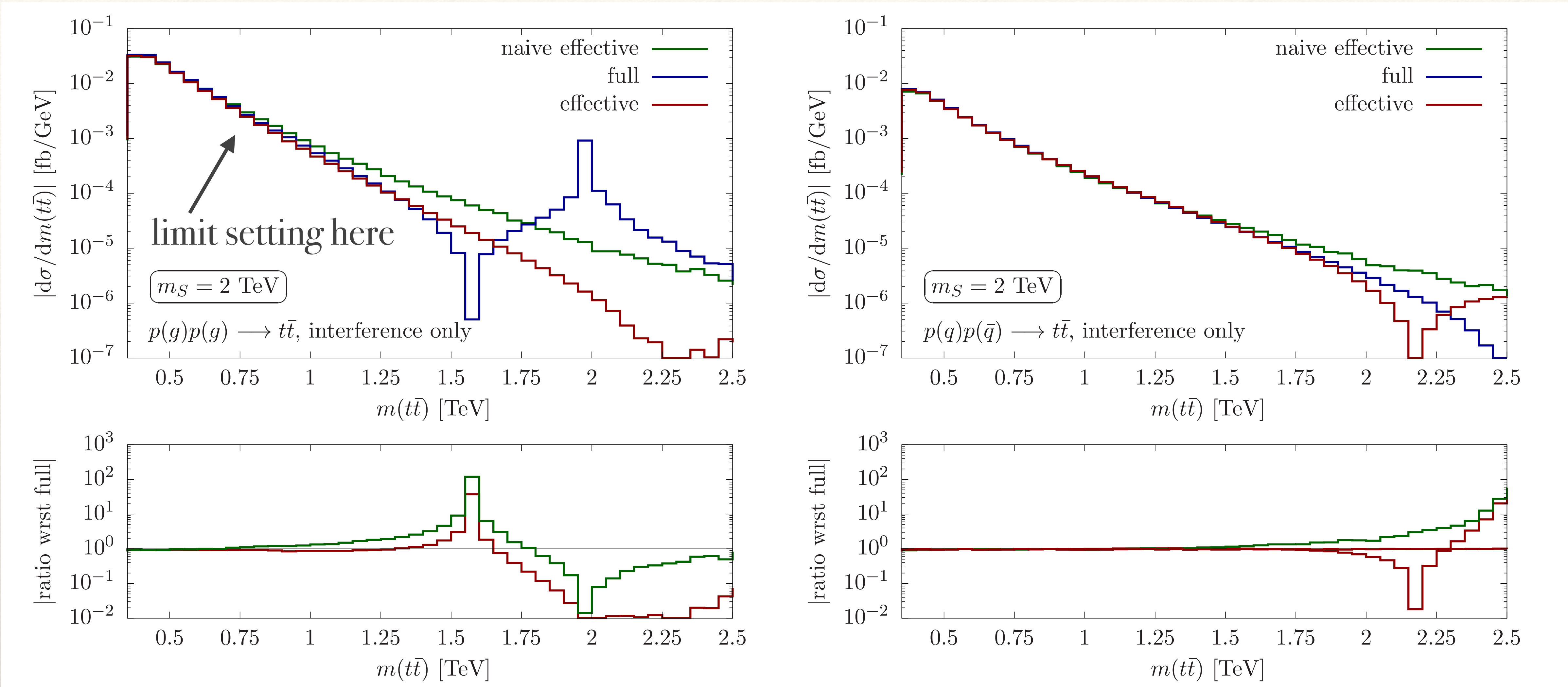


3 relevant operators

- EFT is suitable tool to constrain such states model-independently, *however matching is crucial!*



New physics in tops



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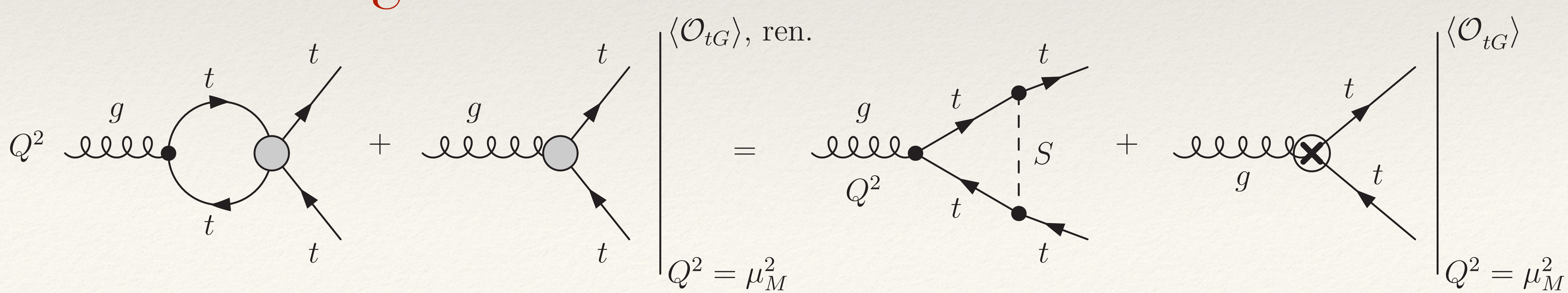
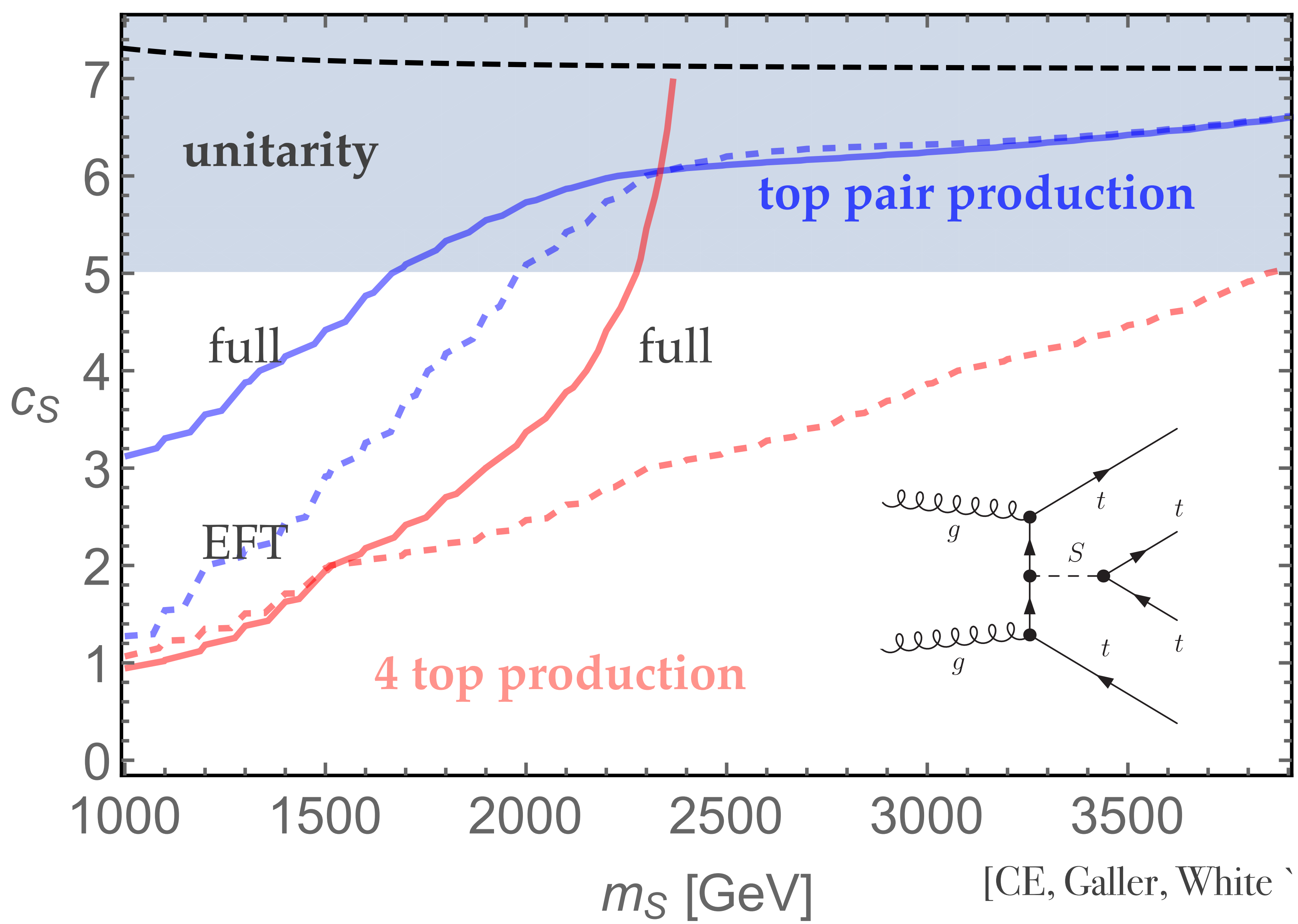


New physics in tops

- EFT is suitable tool to constrain such states model-independently, *however matching is crucial and so are expected uncertainties*



[CE, Galler, White ` 19]

New physics in tops

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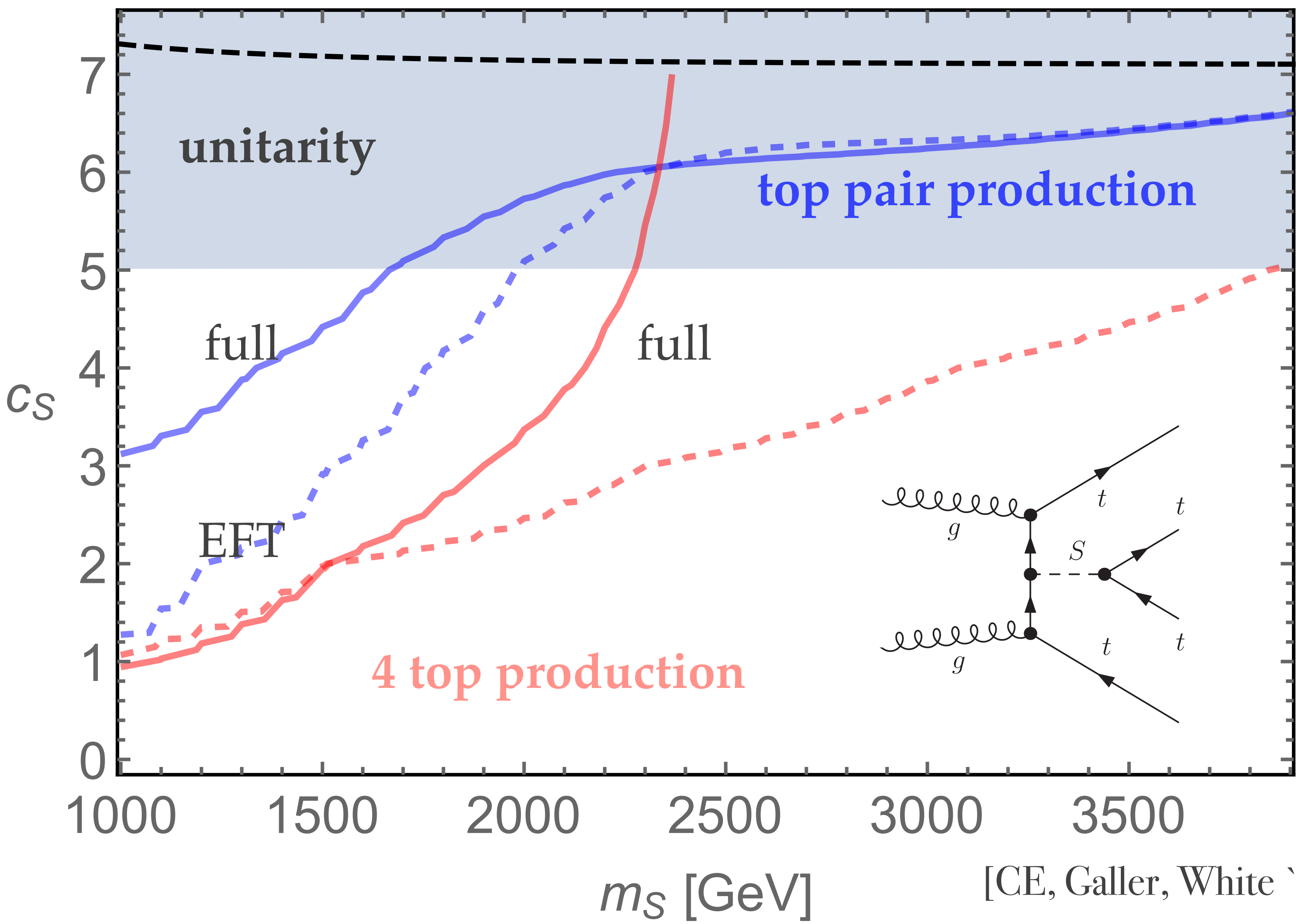


[CE, Galler, White ` 19]

reduction of uncertainty crucial for Run 3 precision

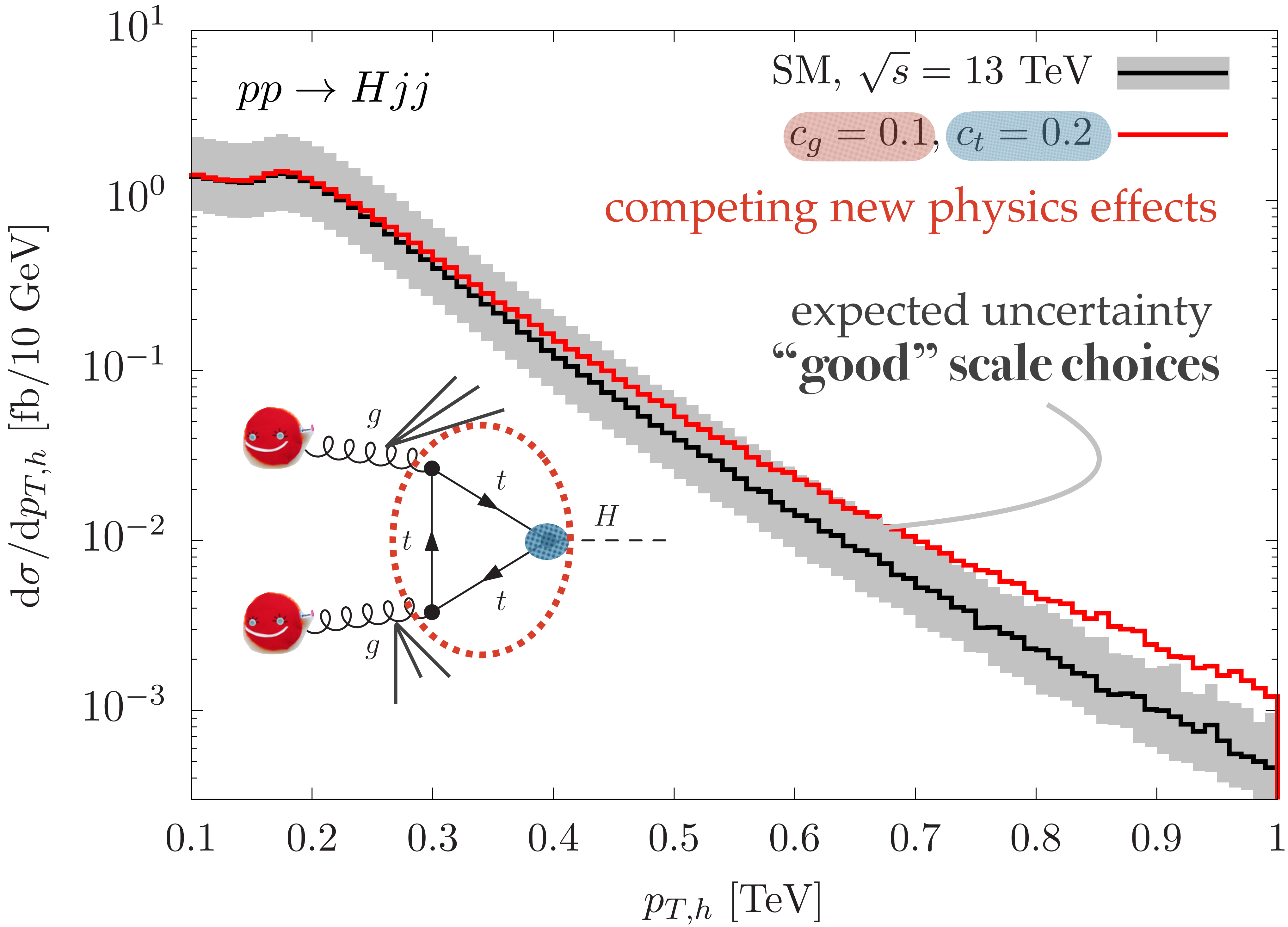
- *loops/legs/resummation*
- tops @N^{2}LO [Czakon, Mitov `13]…
- Higgs @ N^{3}LO [Anastasiou et al. `15]…
- Higgs pairs @NLO [Borowka et al. `16]…

- *robust BSM classification*
- data driven techniques
- machine learning
- anomaly detection

HL-LHC sensitivity

- prime example Higgs+2j, $m_t=\infty$ SM limit accidentally good, NLO in EFT limit

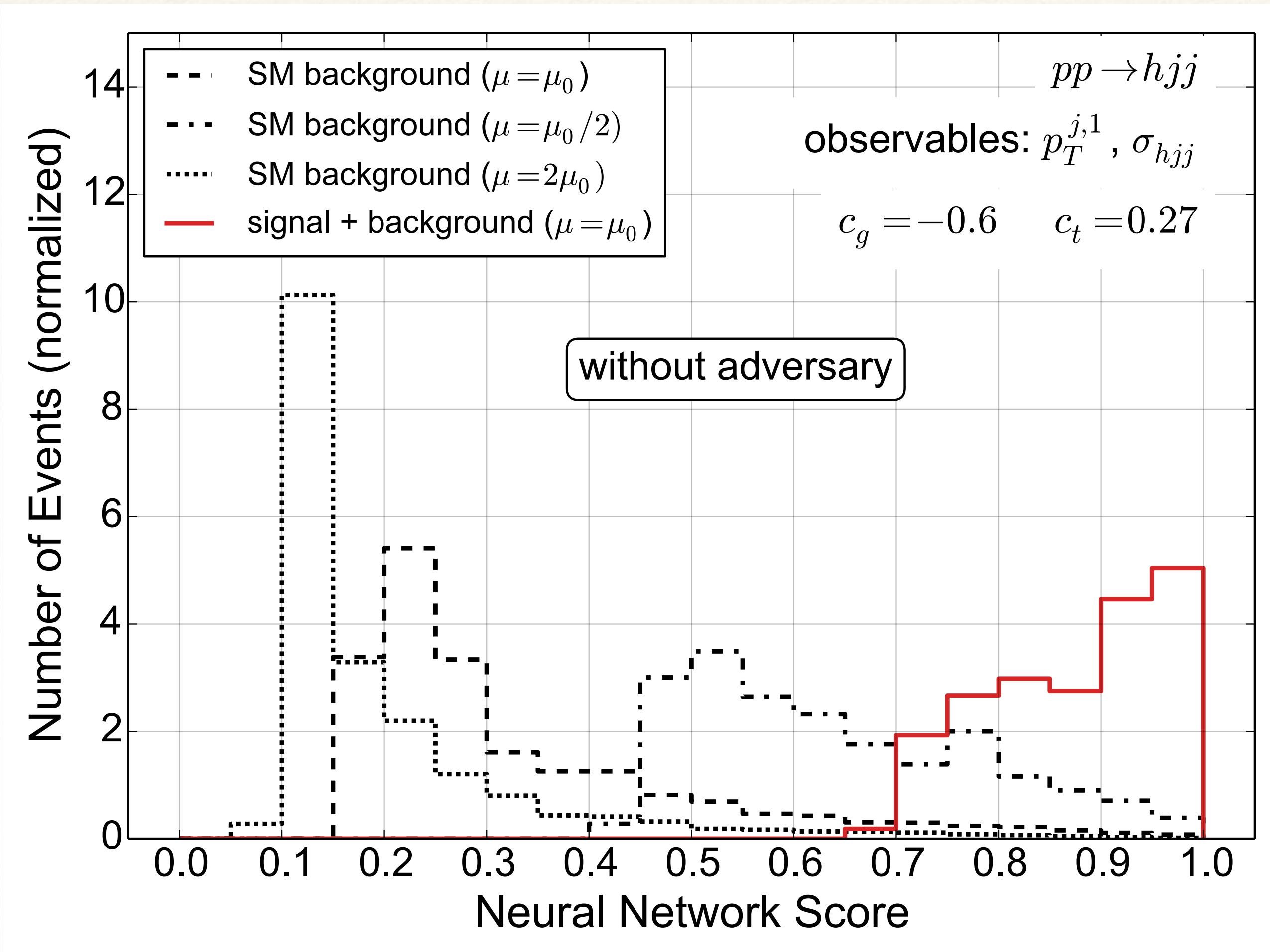
[Del Duca et al. `03]
[Campbell, Ellis, Zanderighi `06]

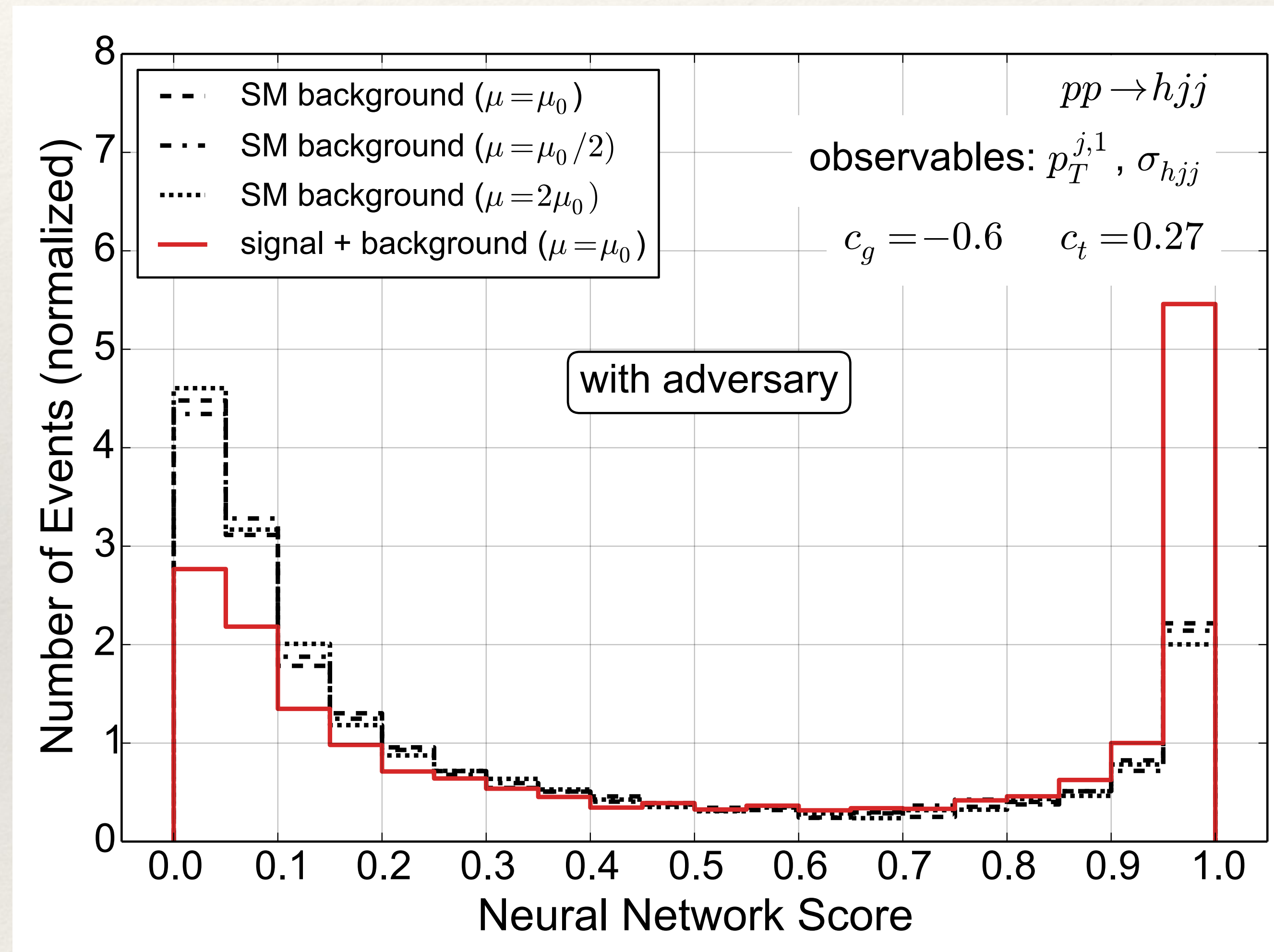


multi-scale processes to inform EFT fits

- prime example Higgs+2j, $m_t=\infty$ SM limit accidentally good, NLO in EFT limit

[Del Duca et al. `03]
[Campbell, Ellis, Zanderighi `06]





- include uncertainties to the selection of BSM-discriminating phase space regions: **most robust** sensitivity [Goodfellow et al. `14] [Louppe, Kagan, Cranmer `16] …

coupling/scale separated BSM physics

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

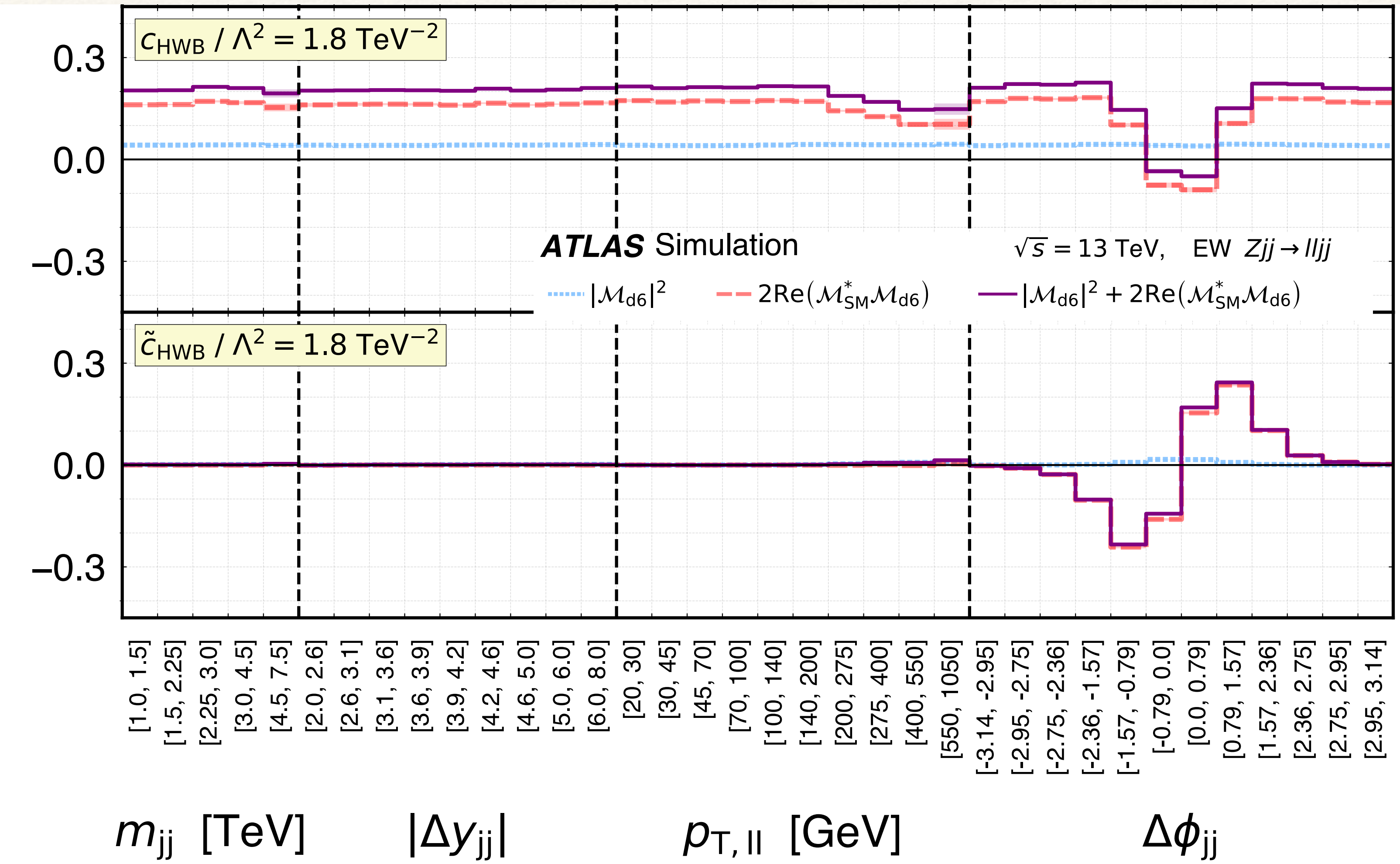
concrete models

- extended SMEFT
- ($\mathbb{C}$) Higgs portals
- 2HDMs
- simplified models
- compositeness….

model-independent
CP violation

[ATLAS, 2006.15458]

Higgs CP violation



- asymmetry-based measurement in elw Z+2jet production
- symmetric CP even effects cancel
- very challenging to combat fluctuations

- sign for hierarchical new physics beyond the SM ?

Wilson coefficient	Includes $|\mathcal{M}_{d6}|^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

CP violation in ATLAS

[ATLAS, 2006.15458]

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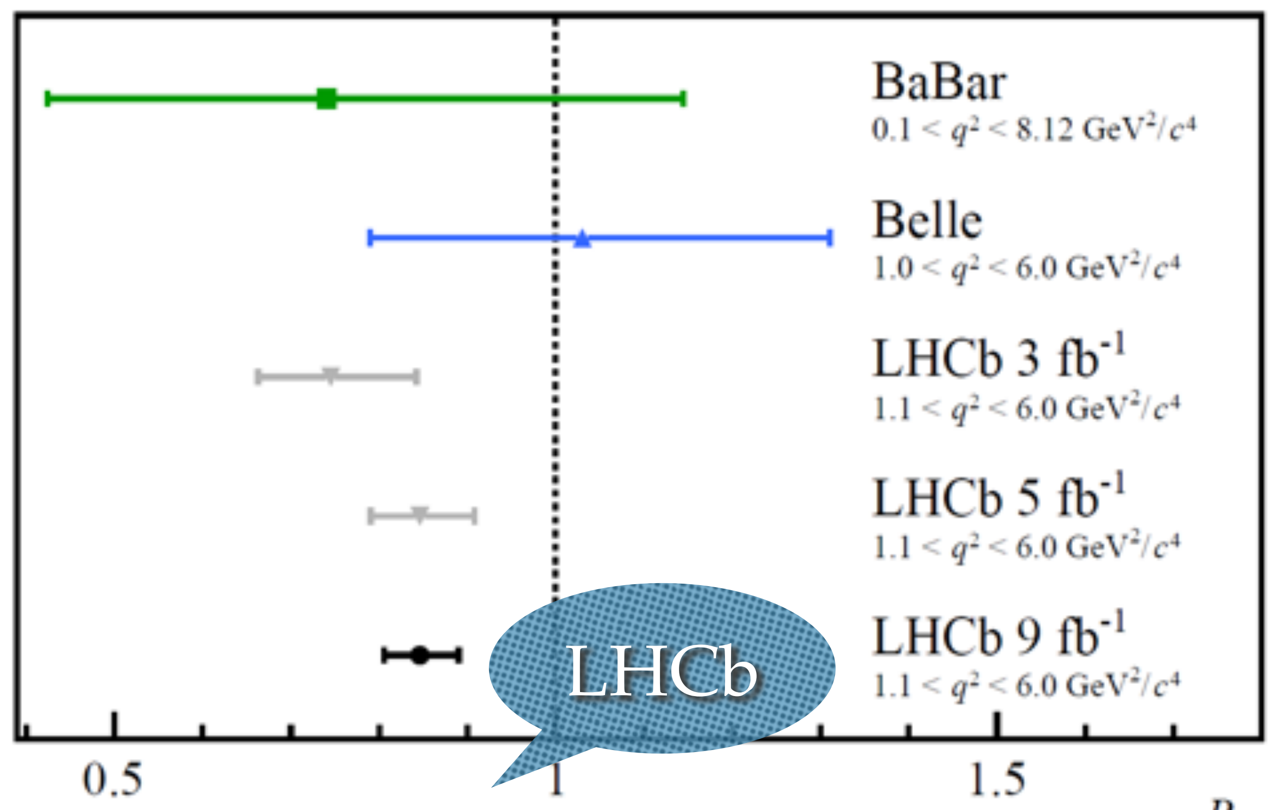
- ATLAS see a tension related to CP violation in WBF Z production
- sign for hierarchical new physics beyond the SM ?

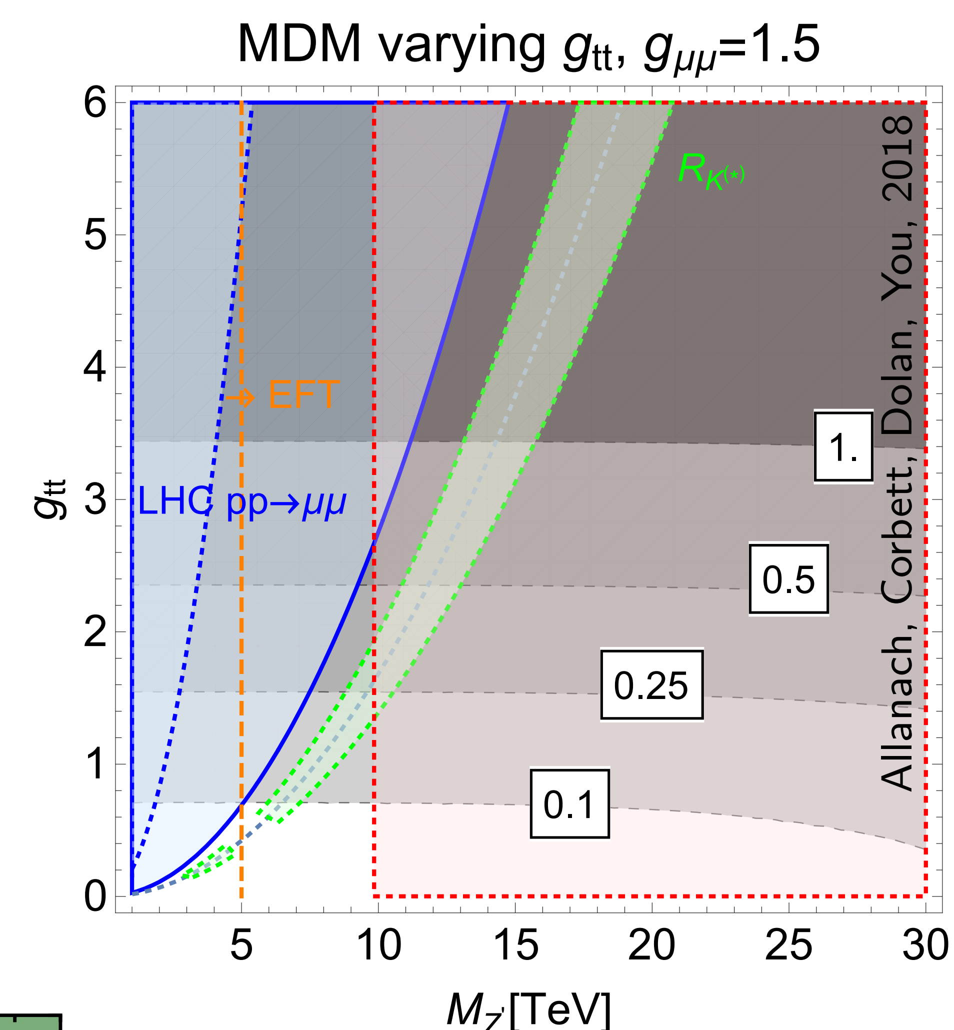
- what can be learned from this for Run 3? [Das Bakshi et al. `20]
  - Assumptions of two-parameter CP fits theoretically consistent in a wide class of vector-like leptons
  - Hierarchy $|C_{H\widetilde{W}B}|/\Lambda^2 > |C_{\widetilde{W}}|/\Lambda^2$ predicted in these scenarios
  - broad UV assumptions reduce complexity of fit whilst facilitating matching more straightforwardly

→ Andreas' and Ben's talks

LFU violation: non-trivial BSM flavour



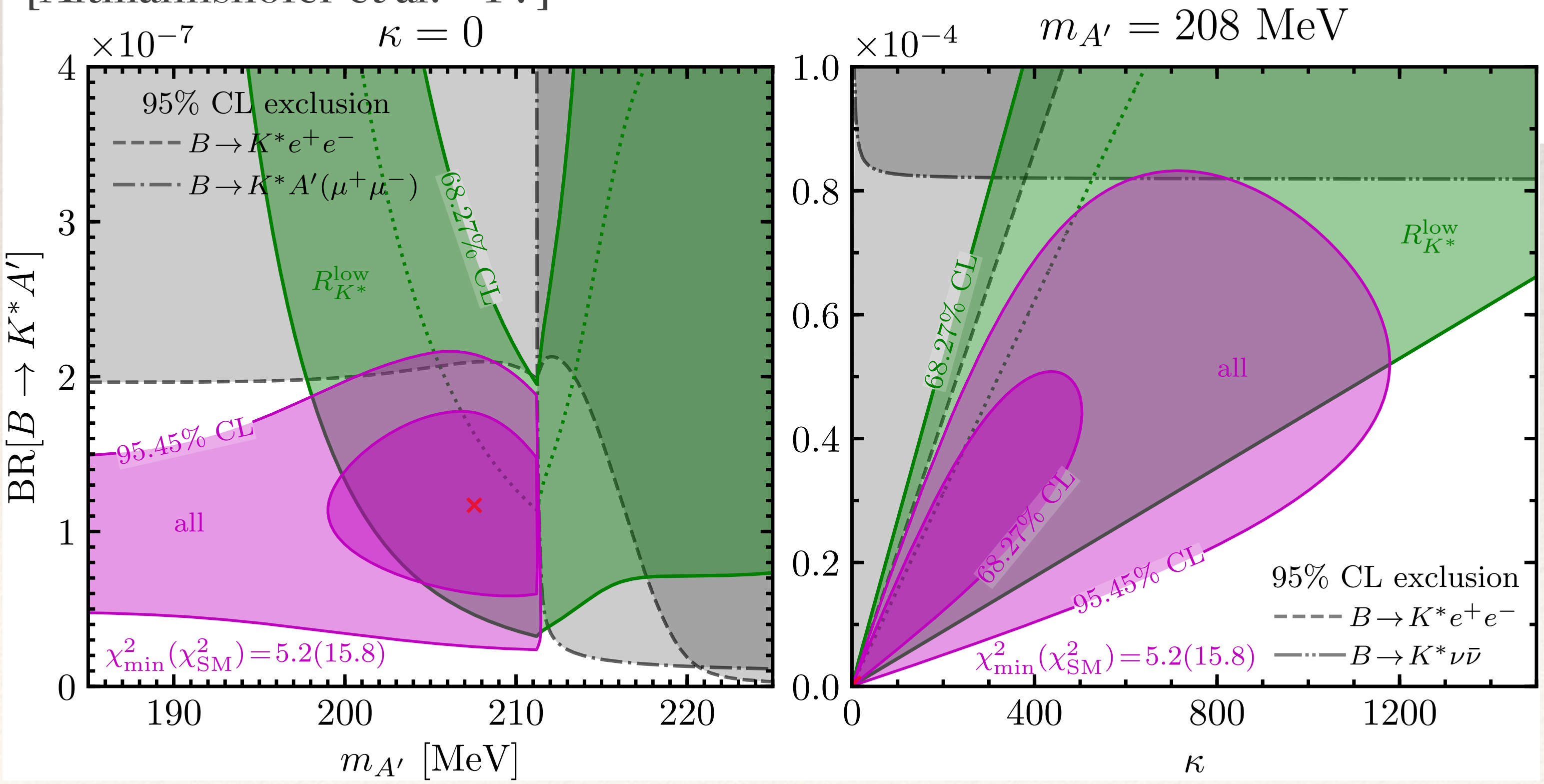
[LHCb, 2103.11769]



[Allanach et al. `18]

[Altmannshofer et al. `17]

Dark photon



- scenarios can be tested at LHC (and future high-energy colliders)

→ Andreas' and Ben's talks

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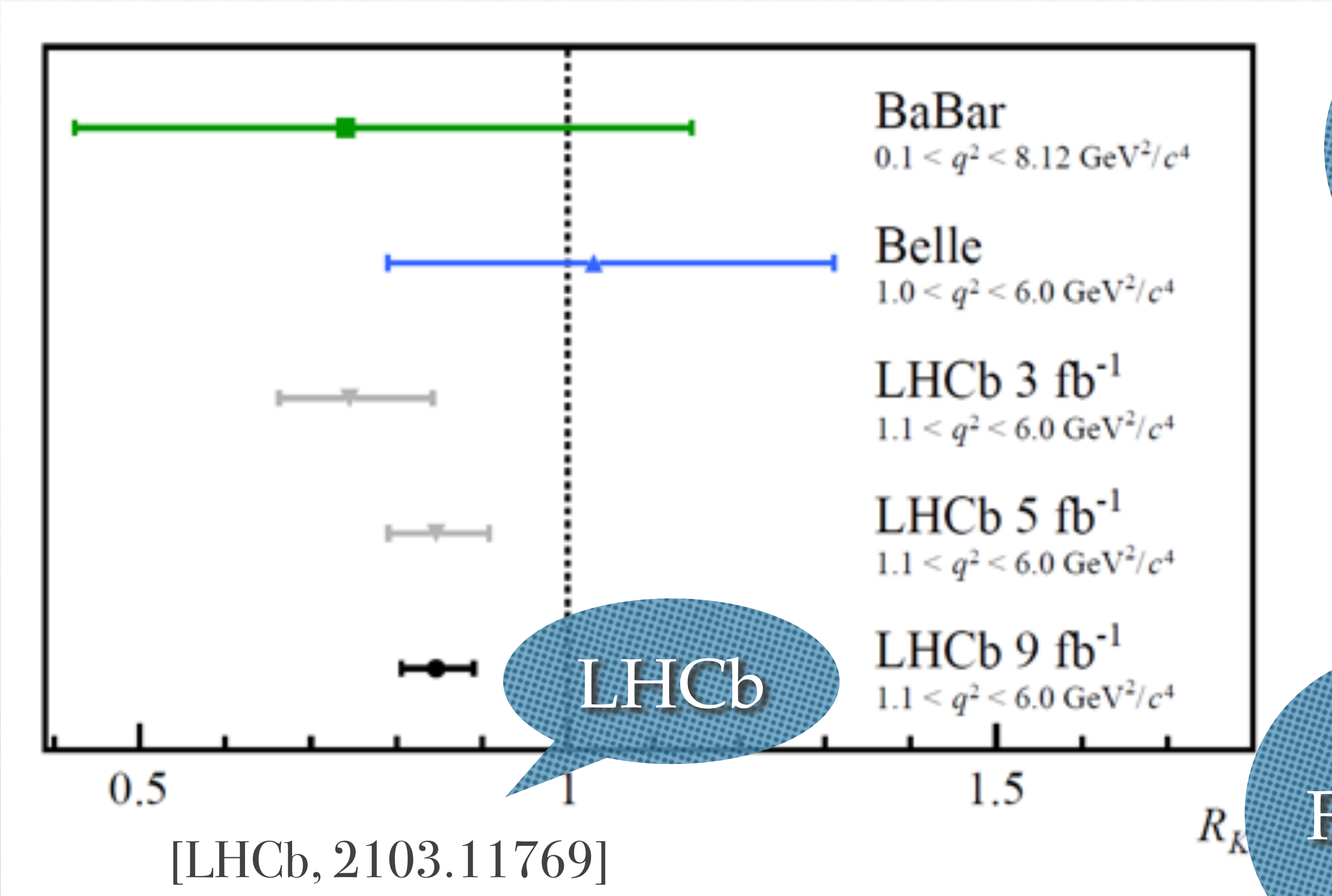

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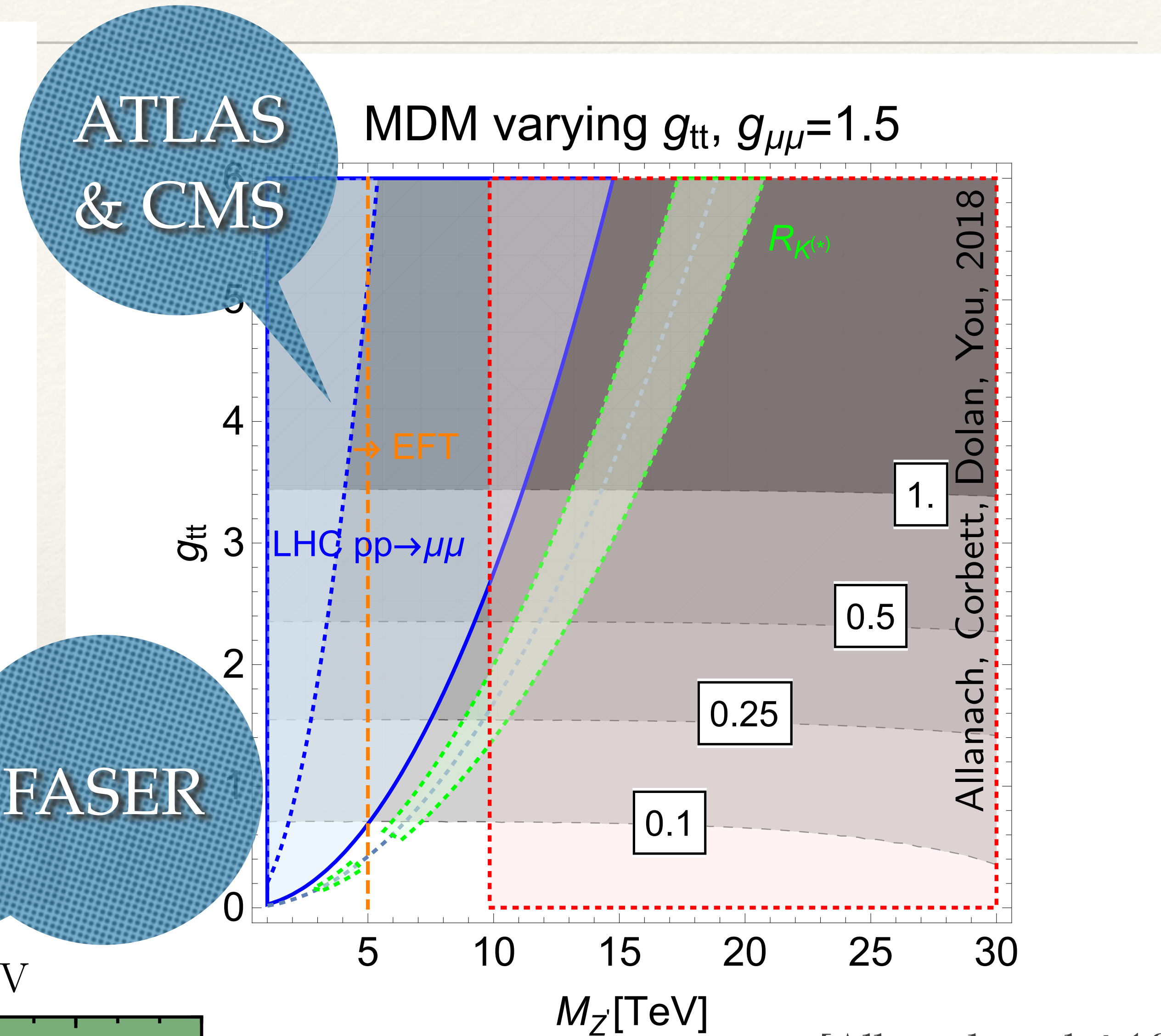
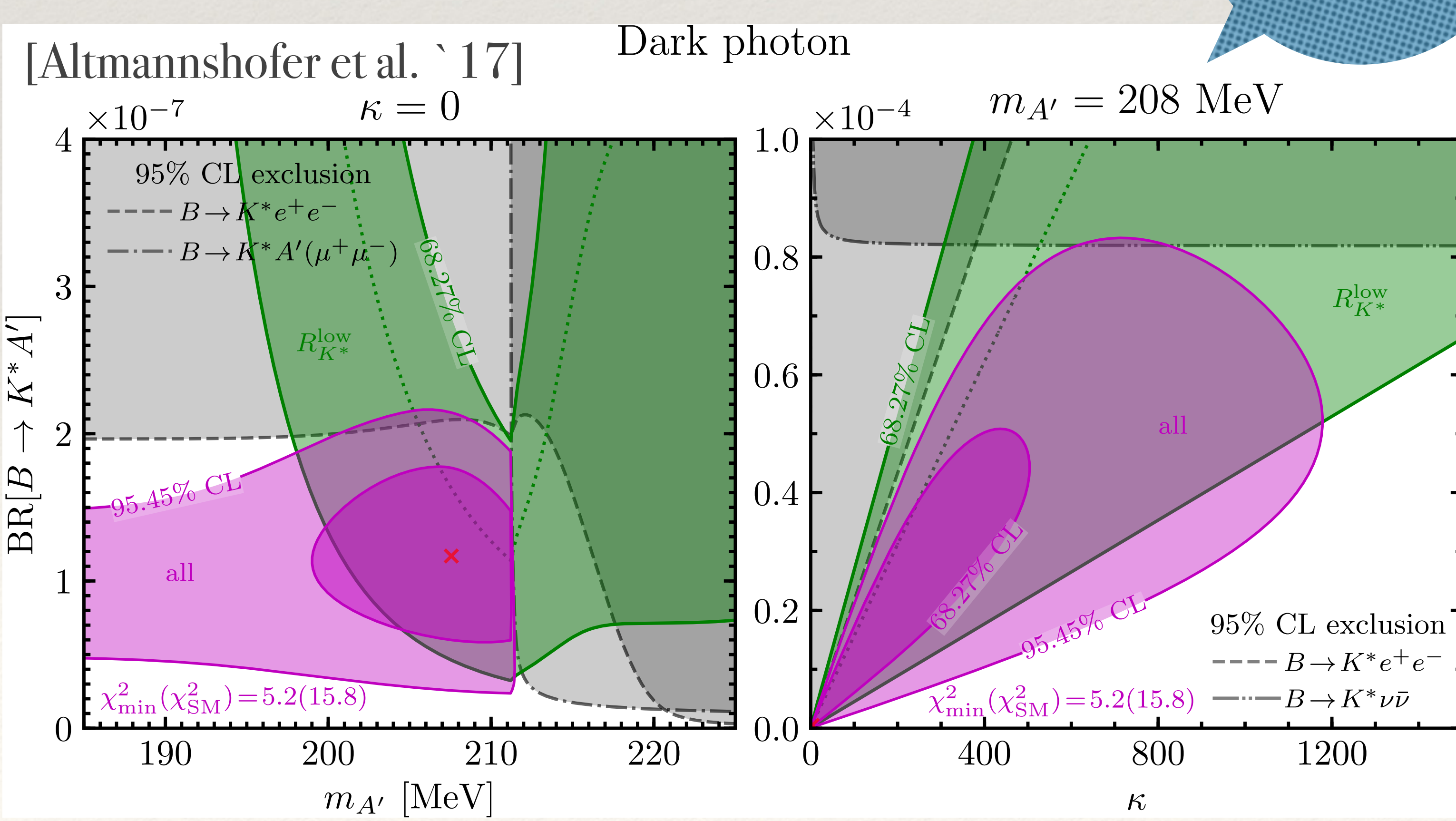


[Allanach et al. ` 18



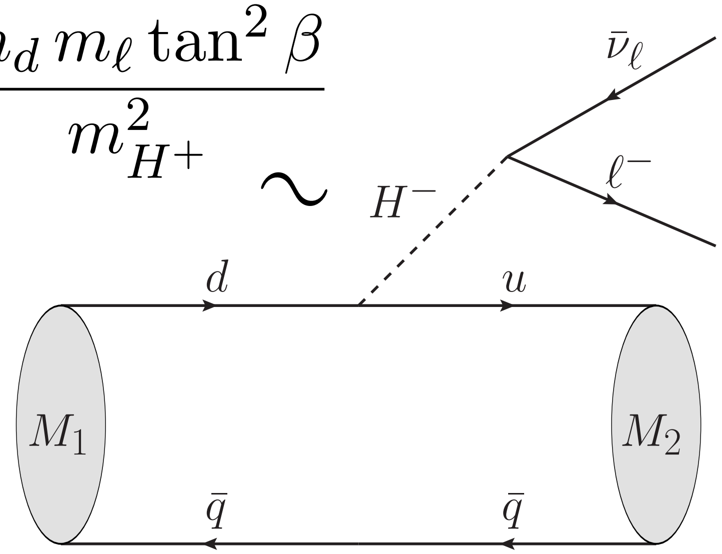
[Altmannshofer et al. ` 17]

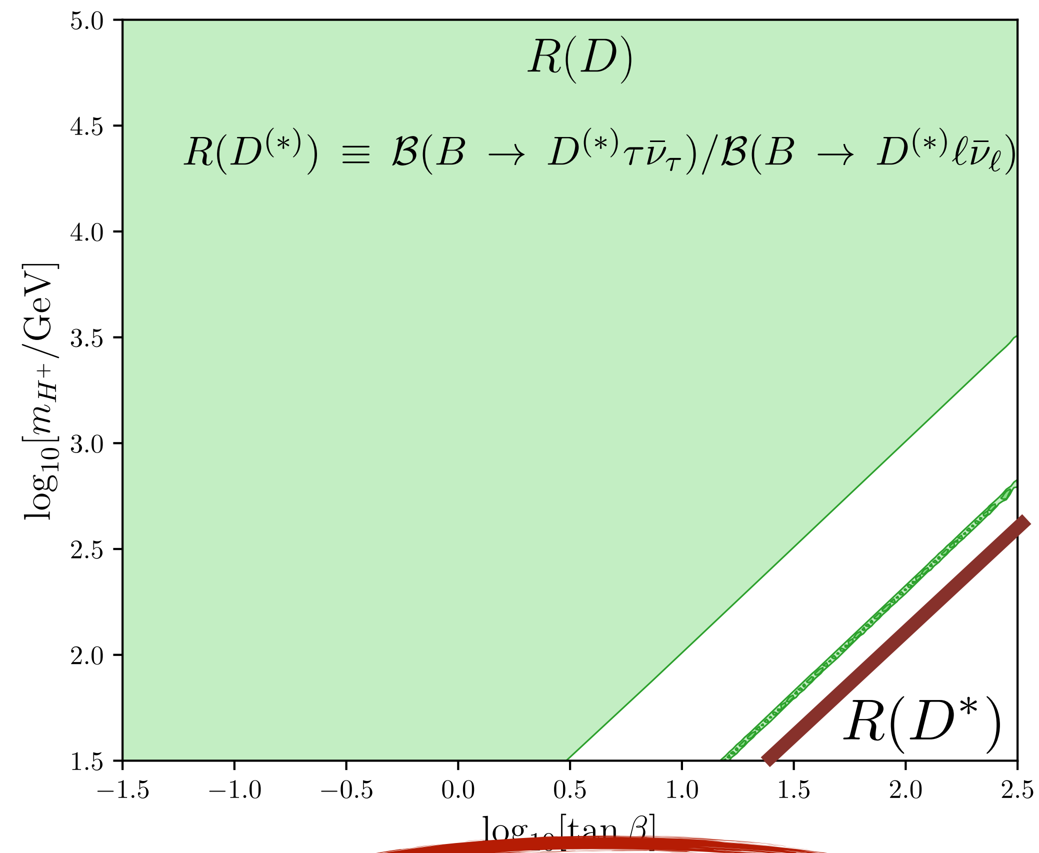
- scenarios can be tested at LHC (and future high-energy colliders)

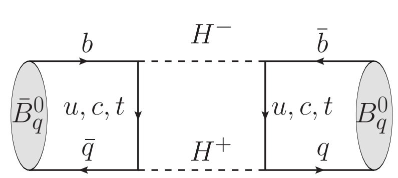
LFU and Higgs sector extensions

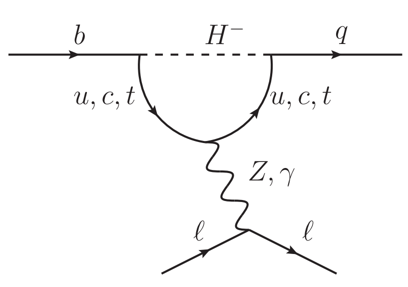
[Atkinson et al. `20]

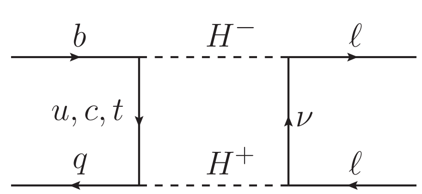
$$\frac{m_d\, m_\ell \tan^2\beta}{m_{H^+}^2} \sim$$

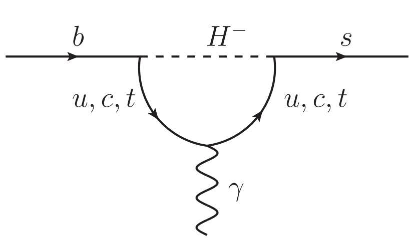




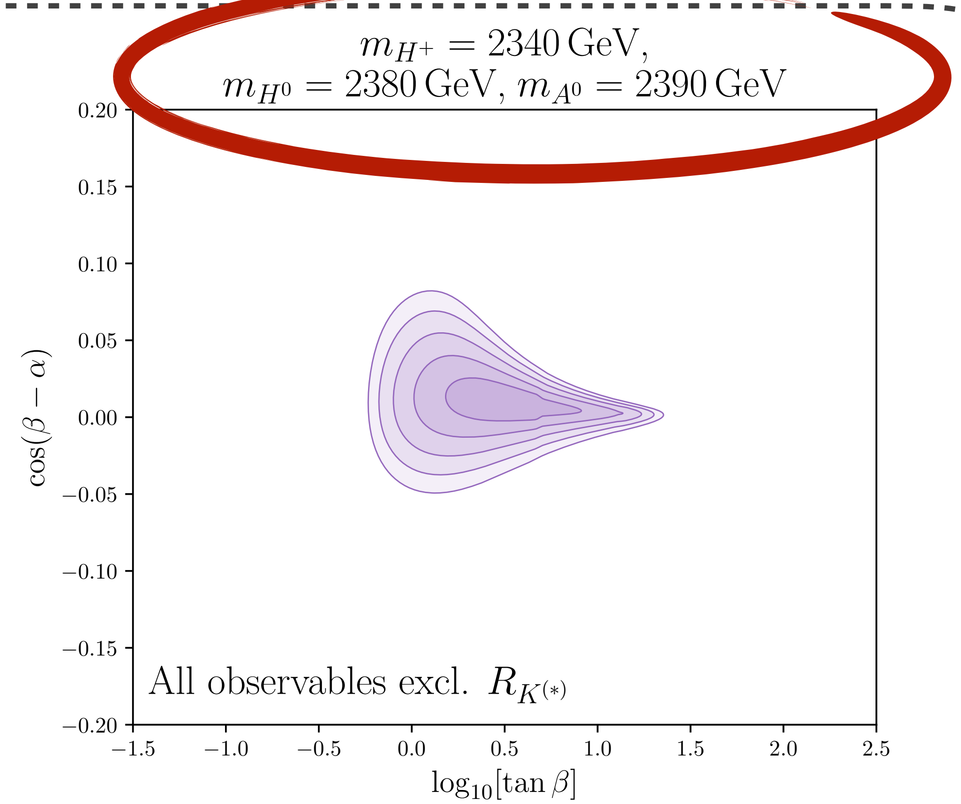








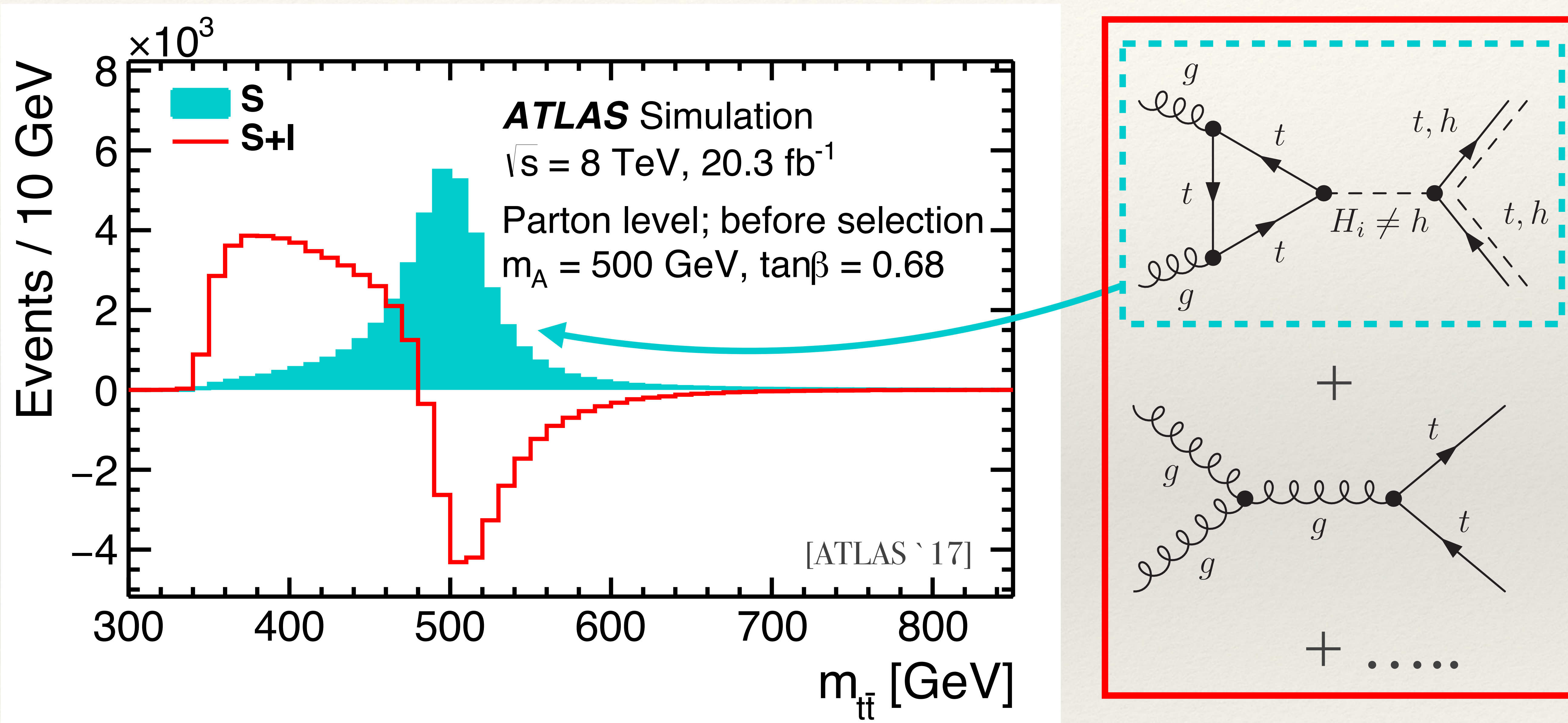
+125 GeV Higgs data



lowering Higgs masses for Run 3

- large interference effects of Higgs "signal" with QCD background

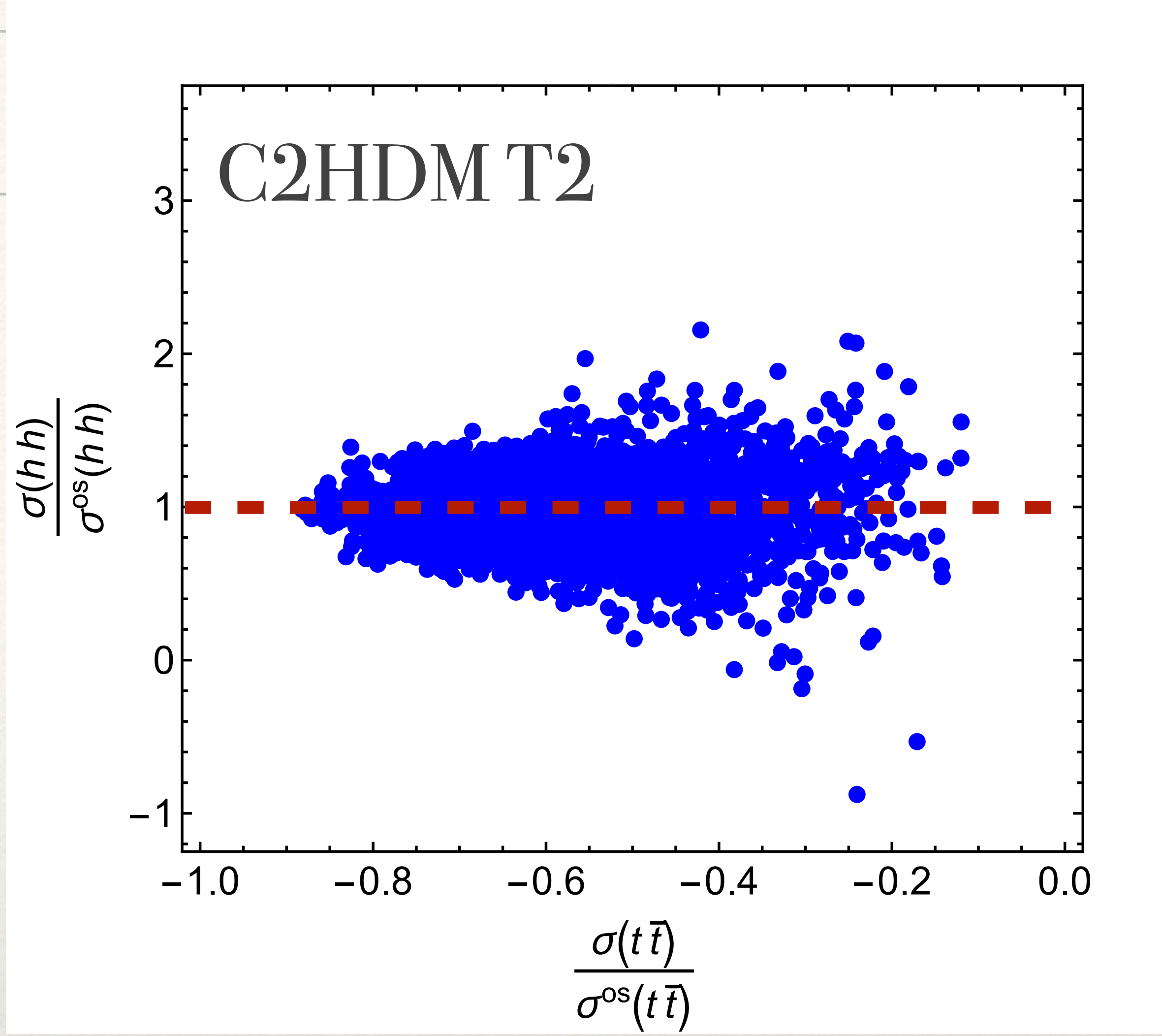
[Gaemers, Hoogeveen `84] [Dicus et al. `94] [Carena, Liu `16]…

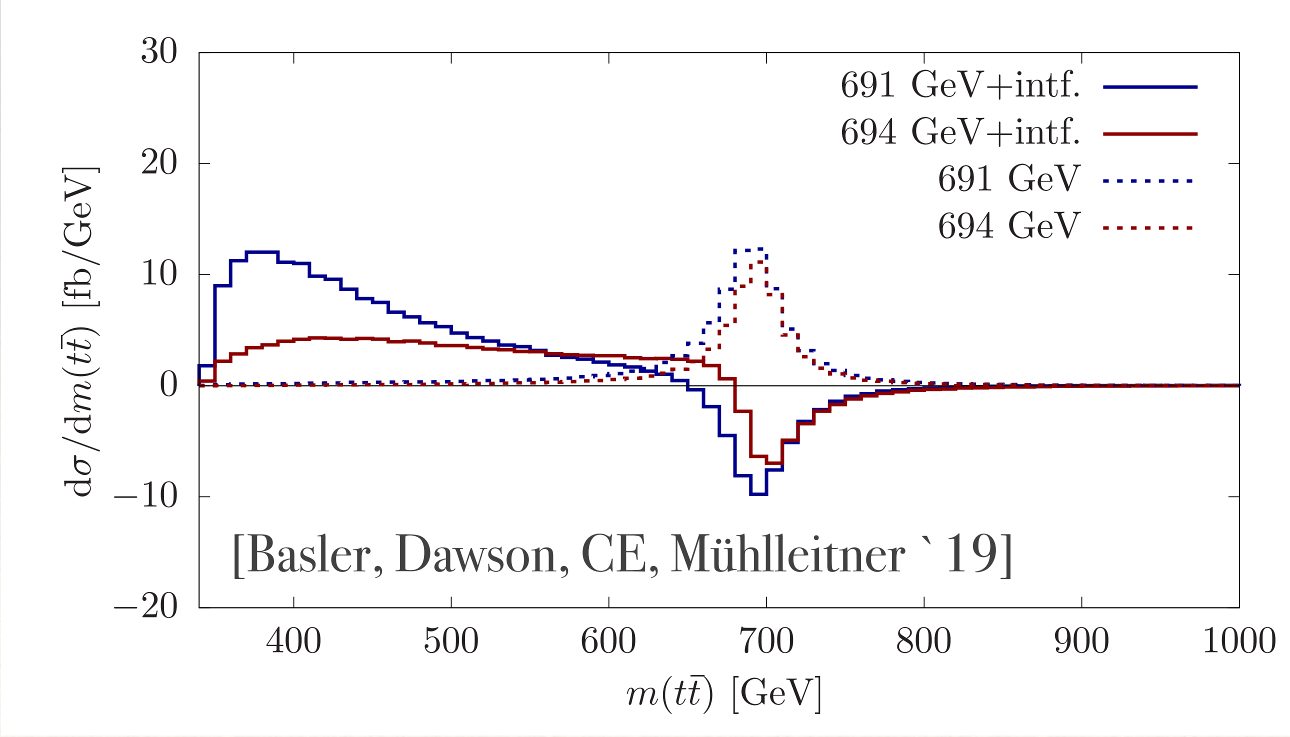


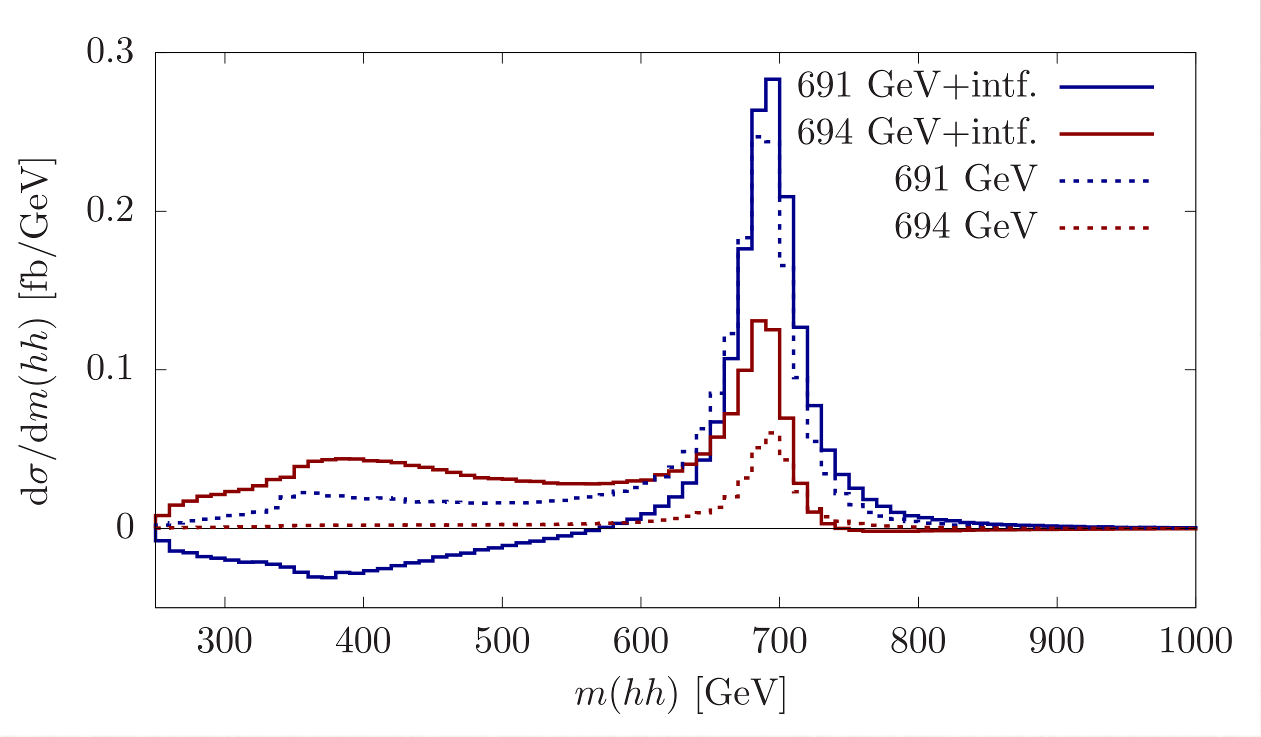
- top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!

special role of top quarks

- destructive interference in top final states can be correlated with HH enhancement
- phenomenologically viable regions with compressed spectra: **signal-signal interference**







era of experimental beacons and theoretical intuition

LHC
RUN
3

anomaly clarification: g-2, LFU and CP

- *more data*
- *complementary search strategies*

Higgs and top phenomenology

- *concrete UV extensions vs EFT*
- *fit strategies ready to go*
- *multi-Higgs final states in better reach*

precision vs anomaly detection

- *new strategies, machine learning,...*