

Christoph Englert

Highlights in Collider Phenomenology

Annual Theory Meeting

16/12/25

The overarching highlight to me...

...the emphasis is (back) on experimental data...

- ▶ unprecedented amount of data from the LHC and beyond
- ▶ robust understanding and validation of our null hypothesis

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...which should equip us with ambition and optimism.

→ ECFA

- ▶ full ‘monetisation’ of the LHC high-luminosity phase
- ▶ continued (UK) contributions to theoretical/exp. developments
- ▶ wedge the door open for large-scale progress in particle physics

Still null BSM results...

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$$

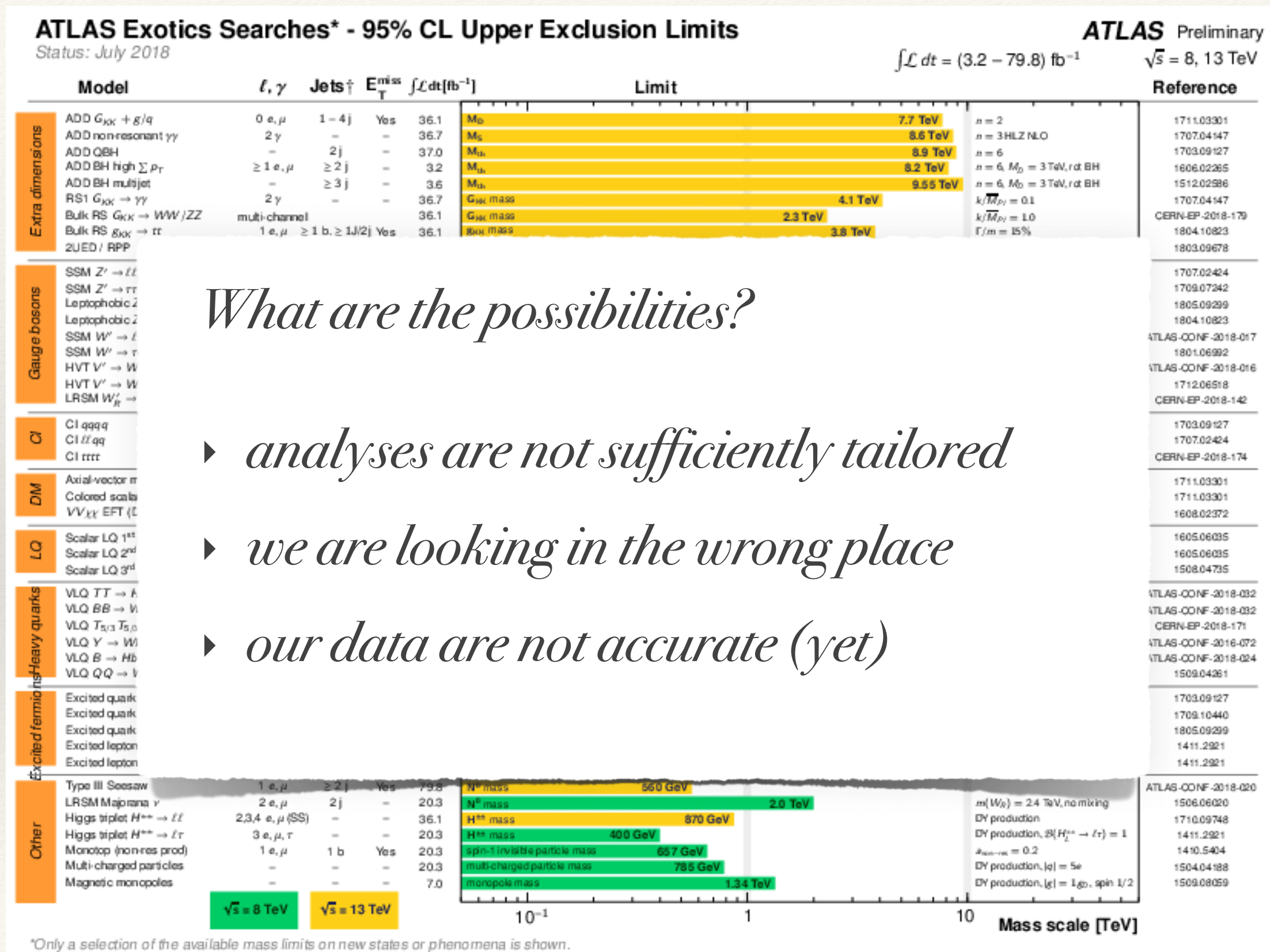
$$\sqrt{s} = 8, 13 \text{ TeV}$$

	Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1 - 4 j$	Yes	36.1	M_0 7.7 TeV	$n = 2$ 1711.03301	
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_0 8.6 TeV	$n = 3 \text{ HLZ NLO}$ 1707.04147	
	ADD QBH	-	$2 j$	-	37.0	M_{bh} 8.9 TeV	$n = 6$ 1703.09127	
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{bh} 8.2 TeV	$n = 6, M_0 = 3 \text{ TeV, rad BH}$ 1606.02265	
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{bh} 9.55 TeV	$n = 6, M_0 = 3 \text{ TeV, rad BH}$ 1512.02586	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	36.7	$G_{KK} \text{ mass}$ 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$ 1707.04147	
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK} \text{ mass}$ 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$ CERN-EP-2018-179	
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$g_{KK} \text{ mass}$ 3.8 TeV	$\Gamma/m = 15\%$ 1804.10823	
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	$KK \text{ mass}$ 1.8 TeV	$\text{Tier}(1,1), \mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$ 1803.09678	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	36.1	$Z' \text{ mass}$ 4.5 TeV	$\Gamma/m = 1\%$ 1707.02424	
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	$Z' \text{ mass}$ 2.42 TeV	1709.07242	
	Leptophobic $Z' \rightarrow b\bar{b}$	-	$2 b$	-	36.1	$Z' \text{ mass}$ 2.1 TeV	1805.09299	
	Leptophobic $Z' \rightarrow \tau\tau$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$Z' \text{ mass}$ 3.0 TeV	1804.10823	
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	79.8	$W' \text{ mass}$ 5.6 TeV	ATLAS-CONF-2018-017	
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	36.1	$W' \text{ mass}$ 3.7 TeV	1801.06992	
	HVT $V' \rightarrow WV \rightarrow qq\bar{q}\bar{q}$ model B	$0 e, \mu$	$2 j$	-	79.8	$V' \text{ mass}$ 4.15 TeV	$g_V = 3$ ATLAS-CONF-2018-016	
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V' \text{ mass}$ 2.93 TeV	$g_V = 3$ 1712.06518	
	LRSB $W'_R \rightarrow t\bar{b}$	multi-channel	-	-	36.1	$W' \text{ mass}$ 3.25 TeV	CERN-EP-2018-142	
CI	CI $qq\bar{q}\bar{q}$	-	$2 j$	-	37.0	A 21.8 TeV $\tilde{\eta}_{LL}$	1703.09127	
	CI $\ell\ell\bar{q}\bar{q}$	$2 e, \mu$	-	-	36.1	A 40.0 TeV $\tilde{\eta}_{LL}$	1707.02424	
	CI $t\bar{t}\bar{t}\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	A 2.57 TeV $ C_{4\ell} = 4\pi$	CERN-EP-2018-174	
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	m_{mediator} 1.55 TeV	$g_{\mu} = 0.25, g_{\tau} = 1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301	
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	m_{mediator} 1.67 TeV	$g_{\mu} = 1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301	
	VV $_{KK}$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	M_{χ} 700 GeV	$m(\chi) < 150 \text{ GeV}$ 1608.02372	
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$ 1605.06035	
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$ 1605.06035	
	Scalar LQ 3 rd gen	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$ 1508.04735	
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV	SU(2) doublet ATLAS-CONF-2018-032	
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet ATLAS-CONF-2018-032	
	VLQ $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3} \text{ mass}$ 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, \alpha(T_{5/3} Wt) = 1$ CERN-EP-2018-171		
	VLQ $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, \alpha(Y Wb) = 1/\sqrt{2}$ ATLAS-CONF-2016-072	
	VLQ $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$ ATLAS-CONF-2018-024	
	VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	1509.04261	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	37.0	$q^* \text{ mass}$ 6.0 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1703.09127	
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	$q^* \text{ mass}$ 5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440	
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	36.1	$b^* \text{ mass}$ 2.6 TeV	1805.09299	
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	$\ell^* \text{ mass}$ 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921	
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921	
Other	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	$N^0 \text{ mass}$ 560 GeV	$m(W_2) = 2.4 \text{ TeV, no mixing}$ ATLAS-CONF-2018-020	
	LRSB Majorana ν	$2 e, \mu$	$2 j$	-	20.3	$N^0 \text{ mass}$ 2.0 TeV	DY production 1506.06020	
	Higgs triplet $H^{++} \rightarrow \ell\ell$	$2, 3, 4 e, \mu (SS)$	-	-	36.1	$H^{++} \text{ mass}$ 870 GeV	DY production, $\mathcal{B}(H^{++} \rightarrow \ell\tau) = 1$ 1710.09748	
	Higgs triplet $H^{++} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{++} \text{ mass}$ 400 GeV	1411.2921	
	Monotop (non-res prod)	$1 e, \mu$	$1 b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$A_{\text{non-res}} = 0.2$ 1410.5404	
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ q = 5e$ 1504.04188	
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	DY production, $ g = 1 g_D, \text{ spin } 1/2$ 1509.08059	
	$\sqrt{s} = 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$			10^{-1}	1	10	Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

Still null BSM results...



What are the possibilities?

- analyses are not sufficiently tailored
- we are looking in the wrong place
- our data are not accurate (yet)

address BSM needs

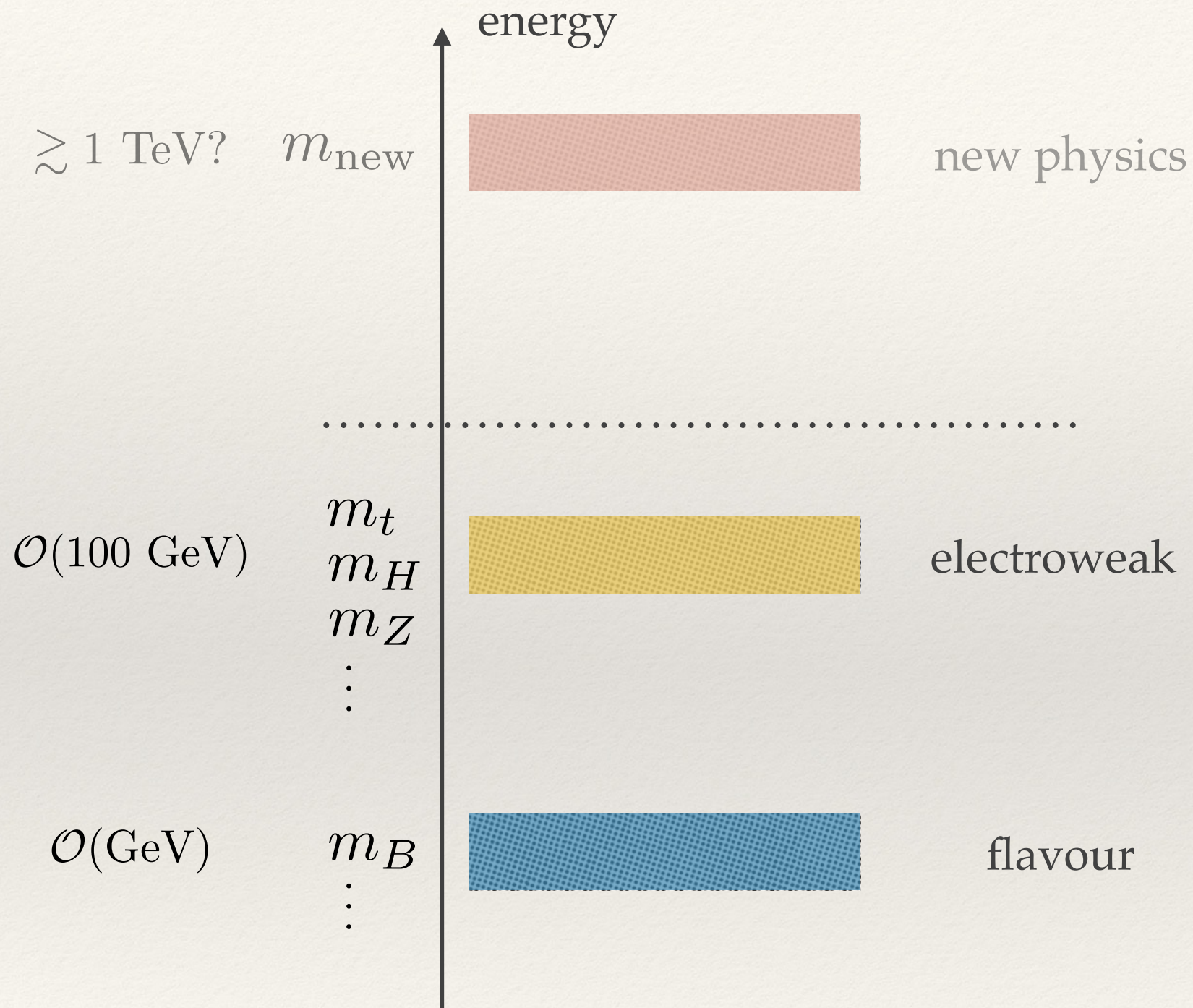
[Sakharov '67] ...

→ Georg's talk

address BSM needs
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bottom-up approach: EFT

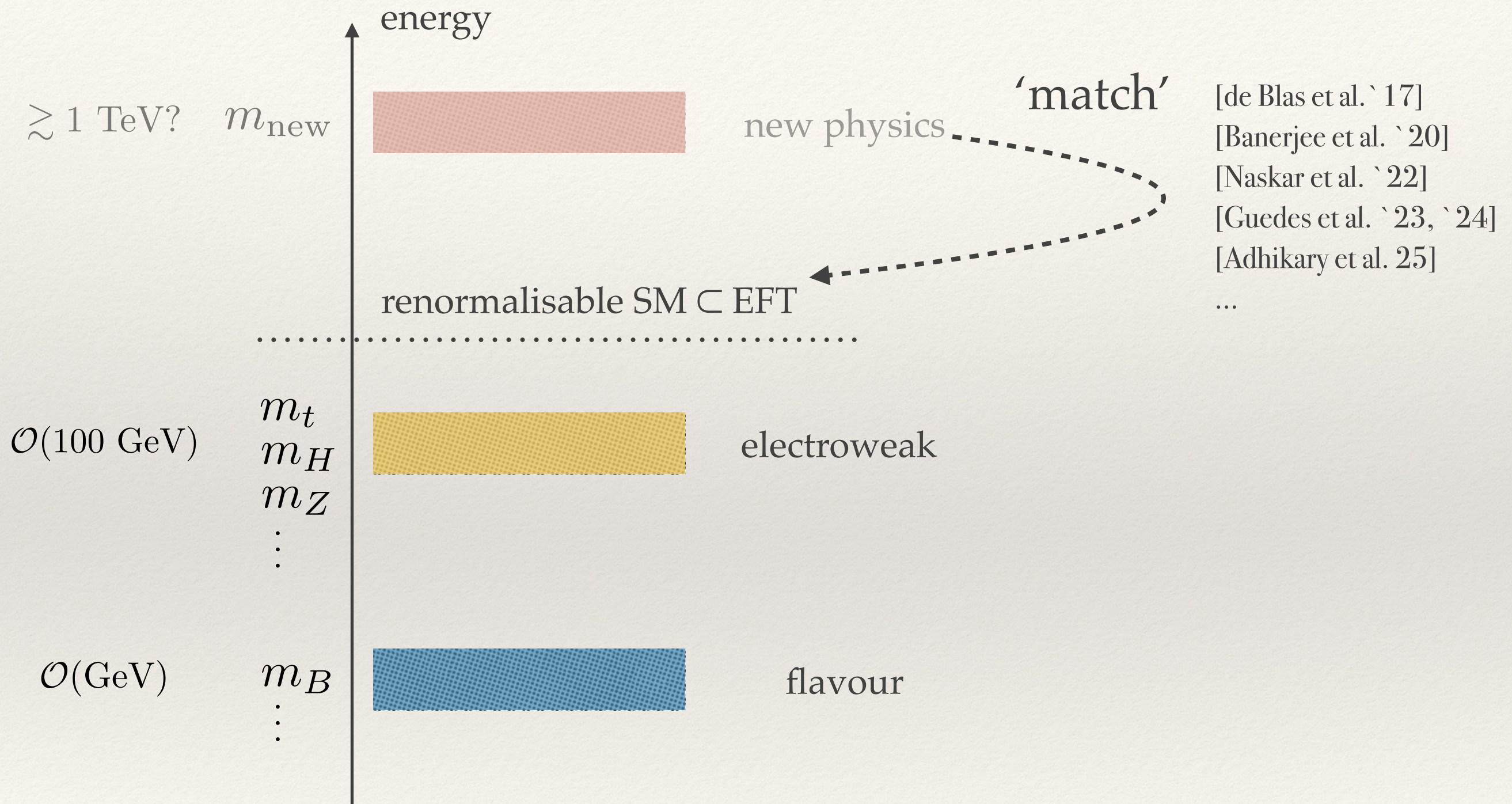


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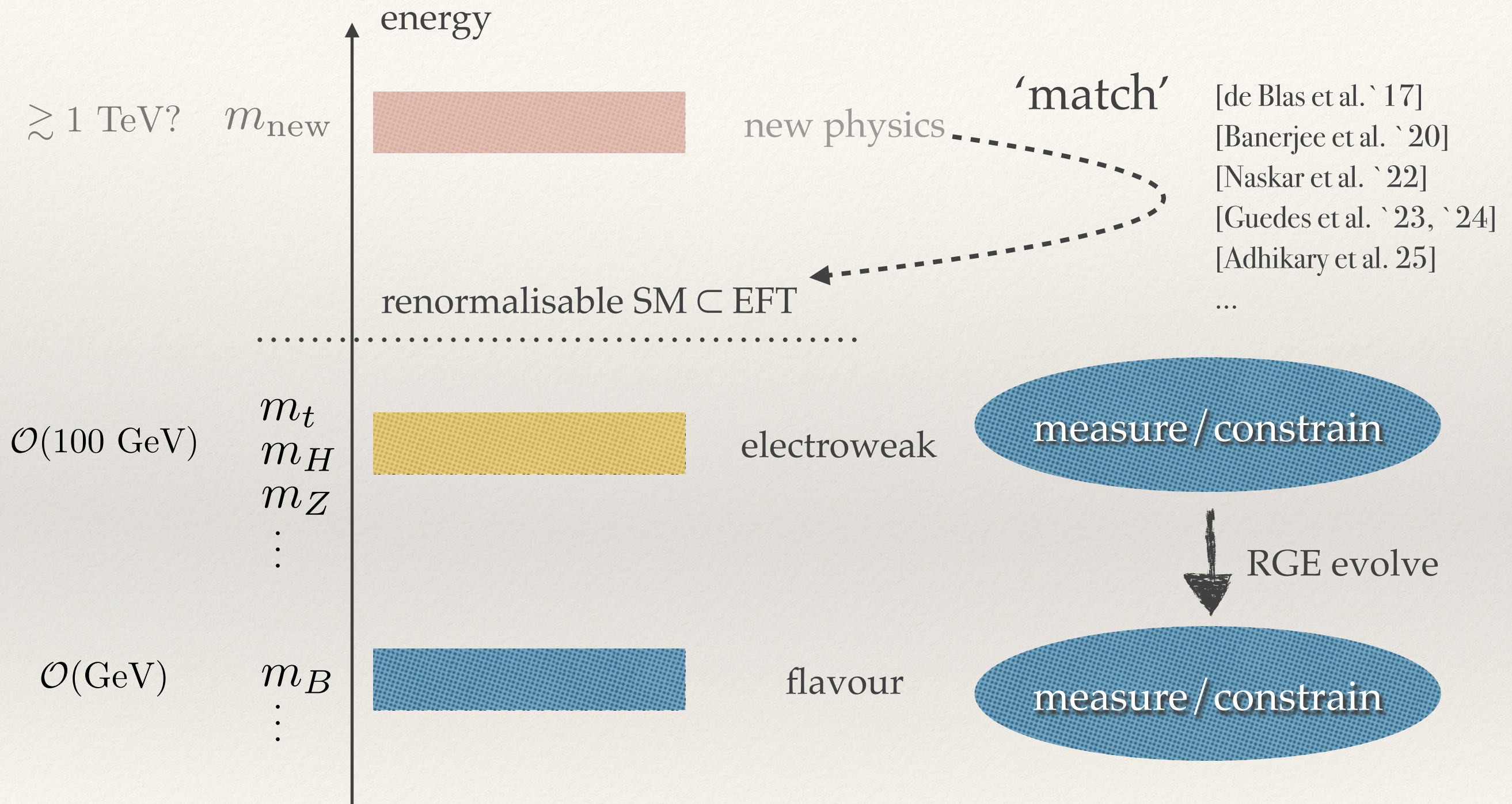
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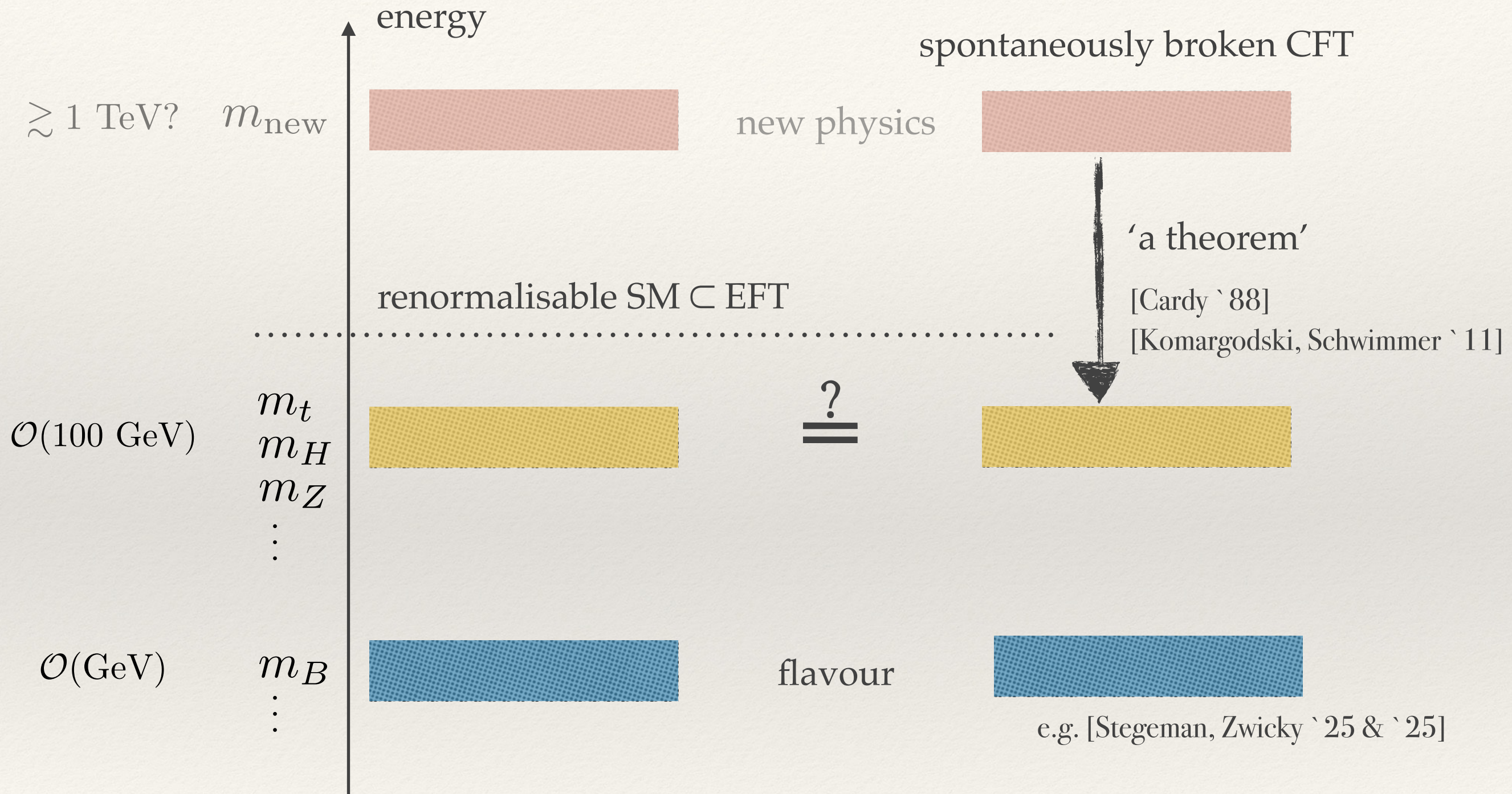
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theoretical ambition



(pert.) Quantum Field Theory = Prediction of Correlations

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SMEFT $SU(2)_C \times U(1)_Y / U(1)_{EM}$ (+ flavour)

- ▶ clear power counting: $\dim. 6 > \dim. 8 > \dots$
- ▶ comparably few (bosonic) parameters
- ▶ tight correlations across Higgs multiplicities
- ▶ non-linear elw vacuum: non-trivial technical implications...

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

[Buchmüller, Wyler '87]

[Hagiwara, Peccei, Zeppenfeld, Hikasa '87]

[Grzadkowski, Iskrzynski, Misiak, Rosiek '10]

...

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HEFT $SU(2)_C \times SU(2)_L / SU(2)_{EW}$ (+ flavour)

“technicolour” / χ PT + singlet scalar

- ▶ CCWZ construction of EW scale + observed states [Coleman, Wess, Zumino '69]
- ▶ large number of parameters cf. counting [Brivio et al. '25] [Callan, Coleman, Wess, Zumino '69]
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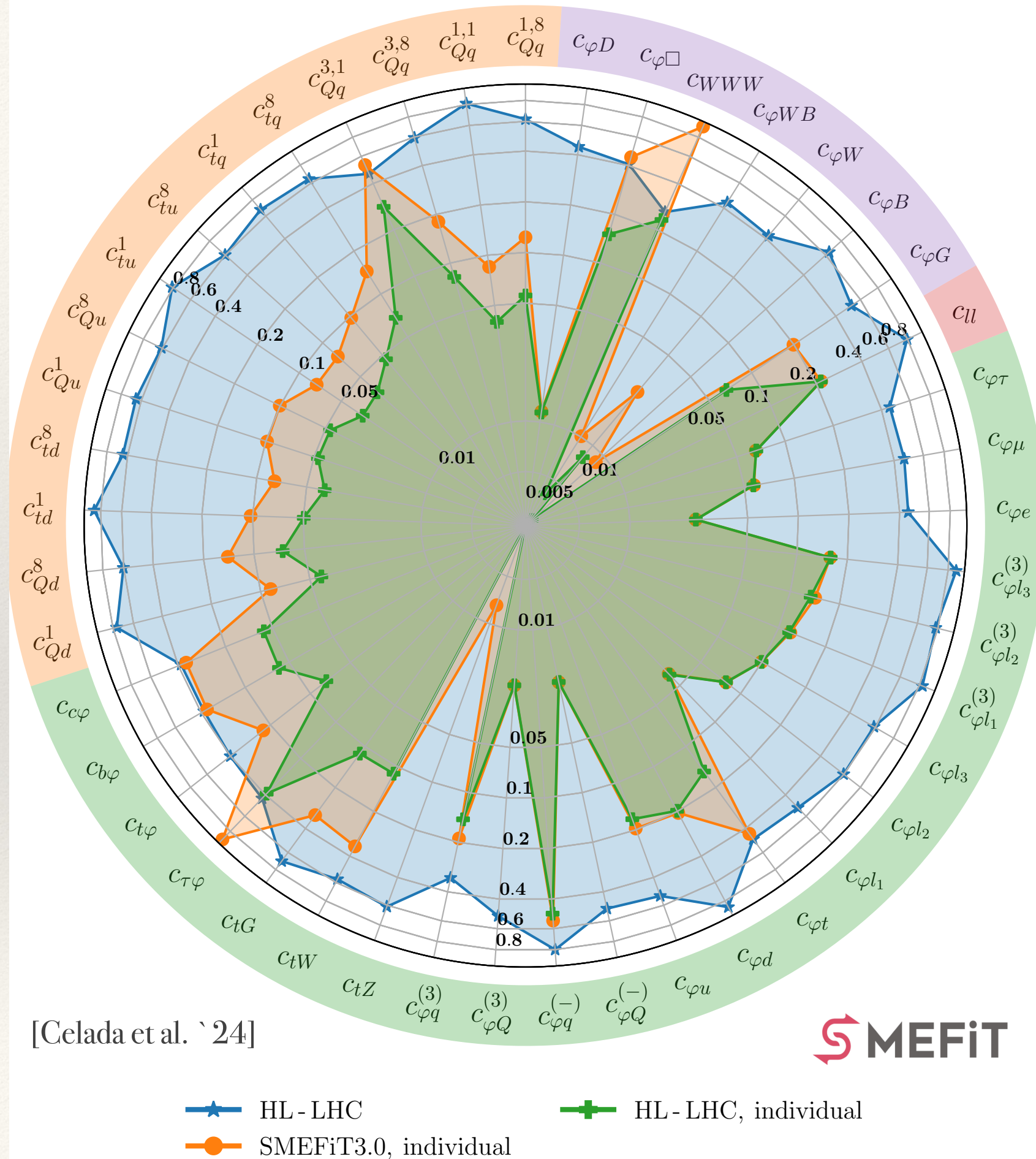
[Alonso et al. '16]

[Craig et al. '21]

[Anisha et al. '22]

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⋮



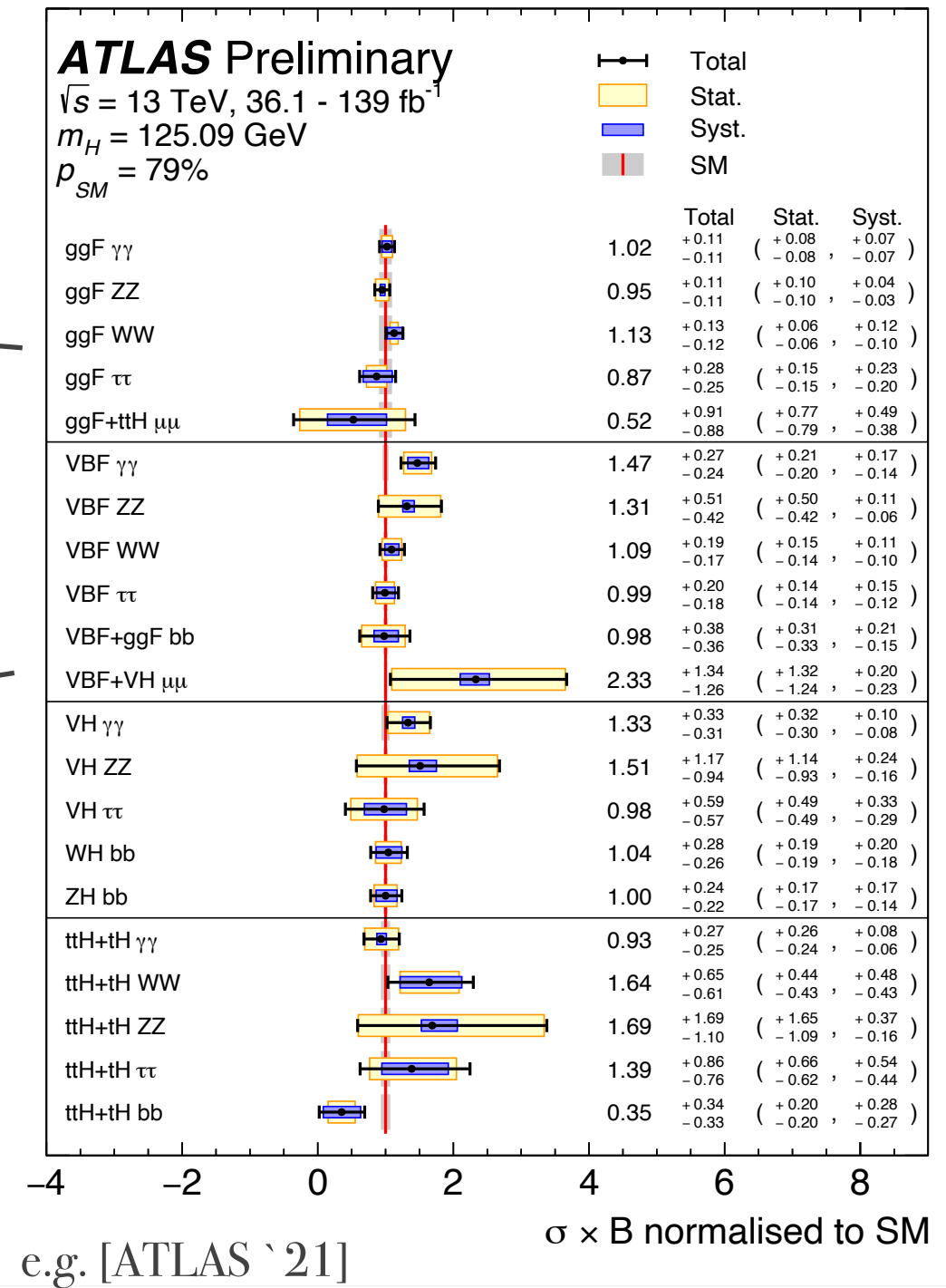
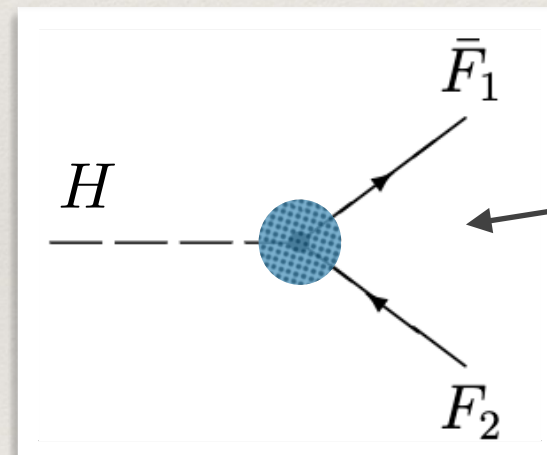
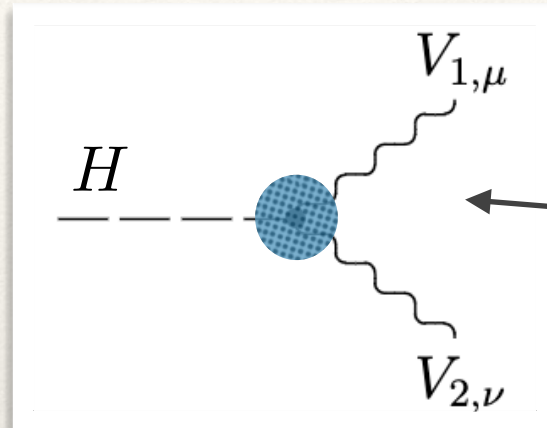
SMEFT analyses

- ▶ ...well underway...
- ▶ ...with exp. buy-in!
- ▶ plethora of parameters
- ▶ flavour-blind results:
0.1-1/TeV² sensitivity
- ▶ improvements towards HL-LHC possible via data...
- ▶ ...not a silver bullet for BSM discovery
- ▶ flavoured models as counterexamples

...[CE, Mayer, Naskar, Renner '24]

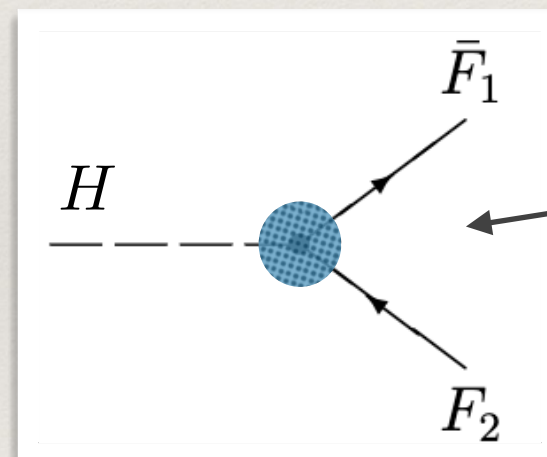
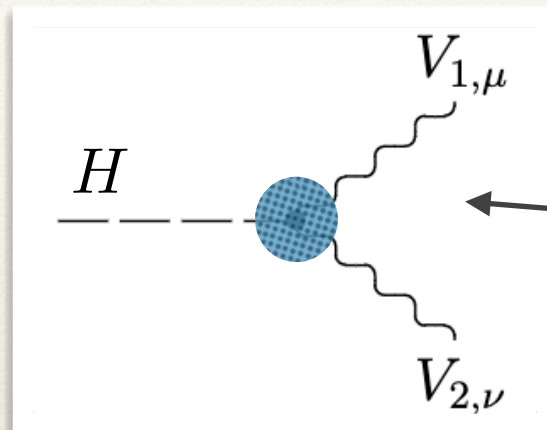
no reason to be so pessimistic at this point!

single Higgs physics seems to favour the SM

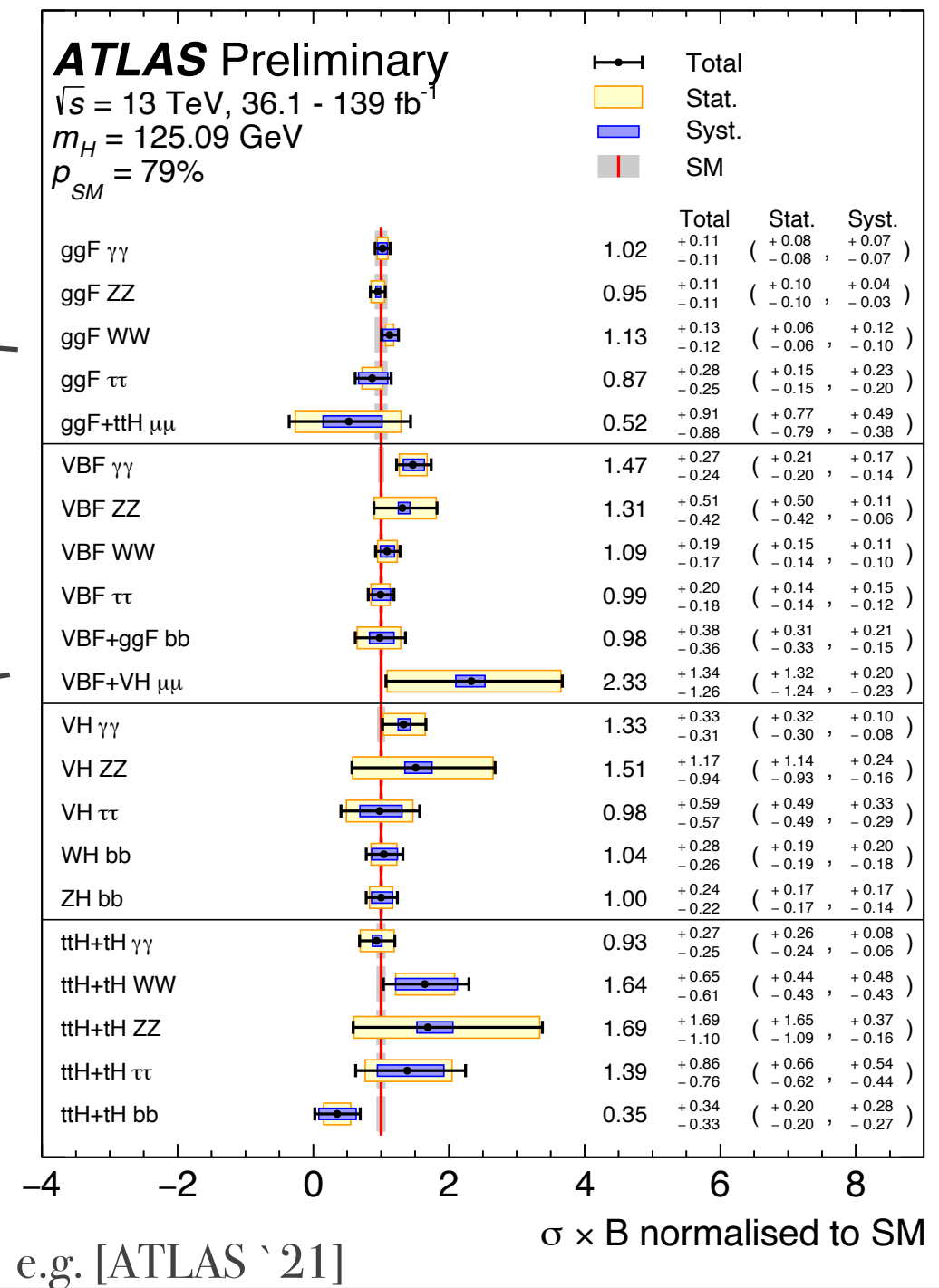


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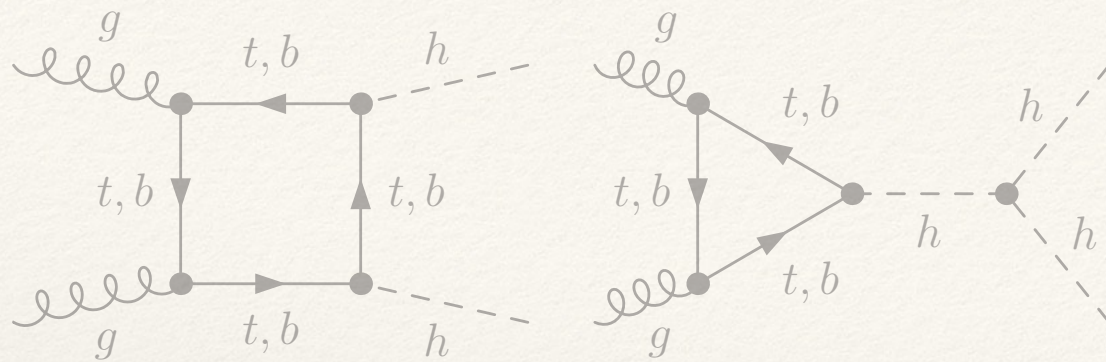
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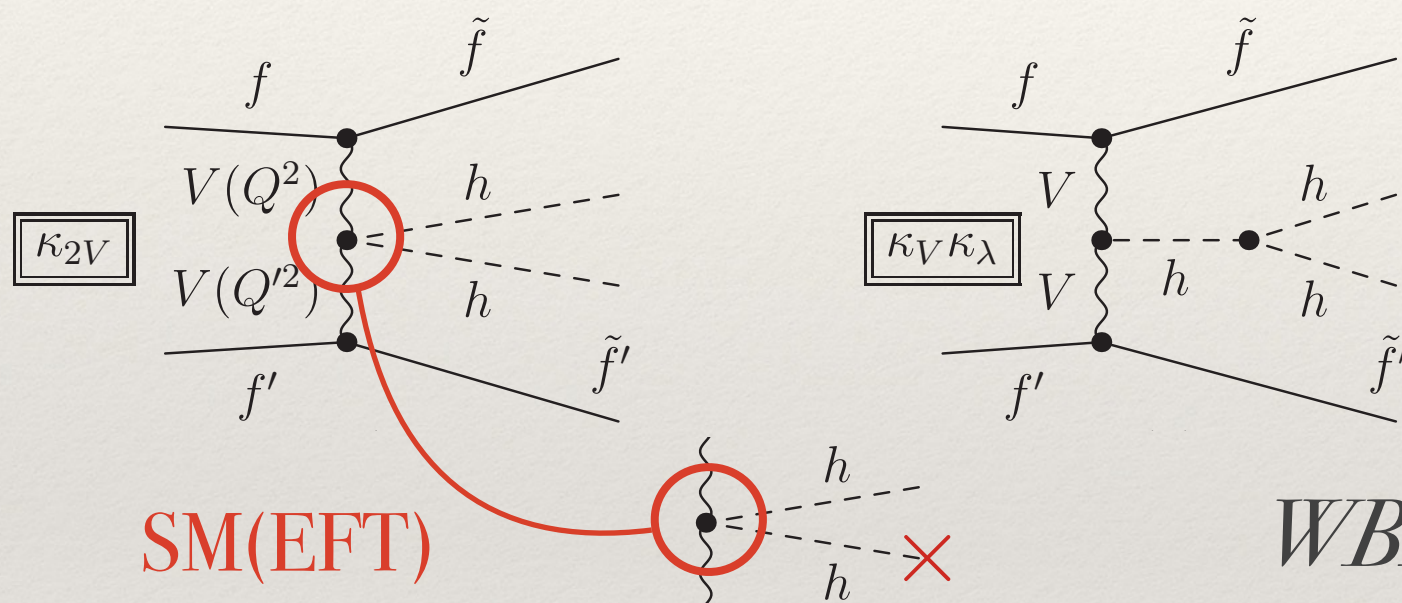
find glory in multi-Higgs final states?



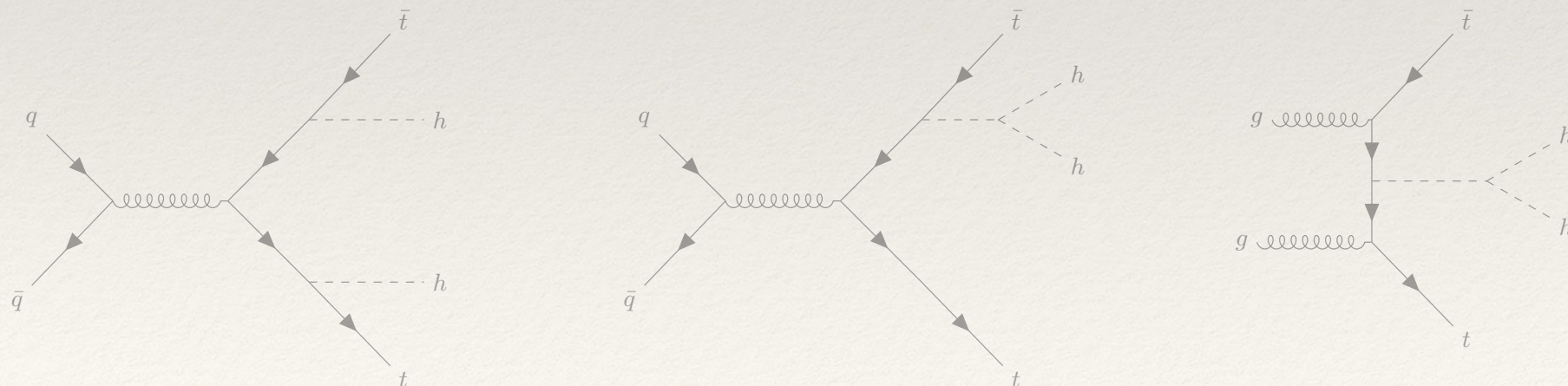
collider probes



GF Higgs pair production $\sim 30 \text{ fb}$



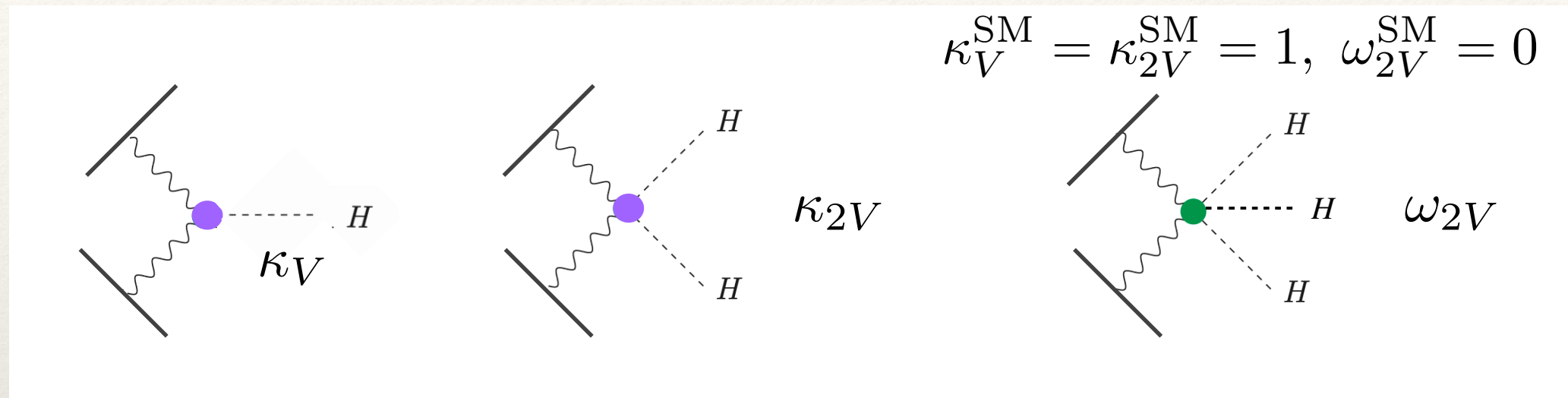
WBF Higgs pair production $\sim 1 \text{ fb}$



top-associated Higgs pair production $\approx 1 \text{ fb}$

beyond single Higgs bosons?

- ▶ pinpoint bosonic multi-Higgs interactions at hadron machines?



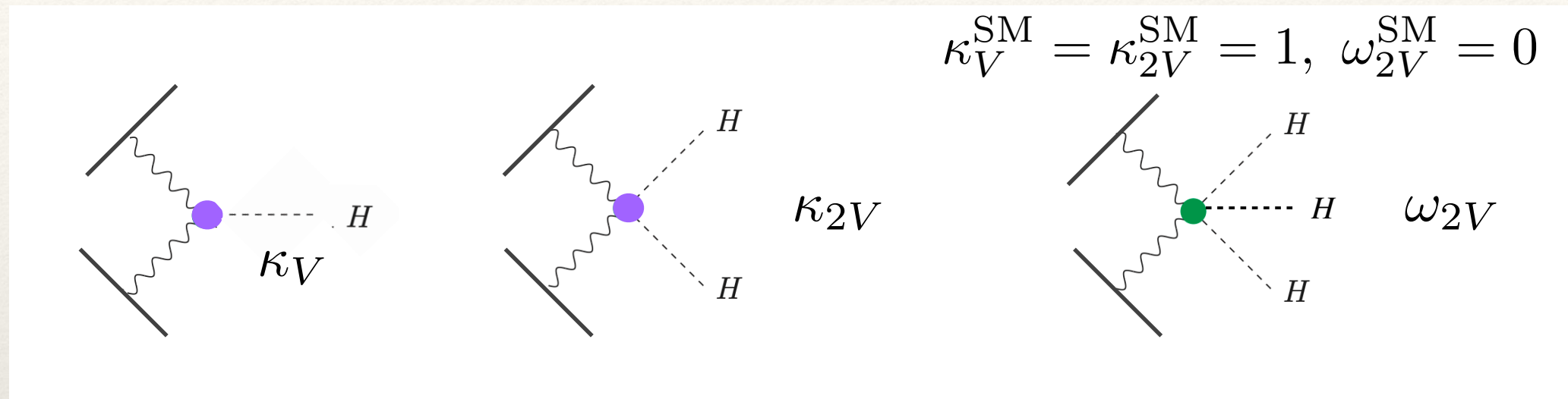
....[Braun et al. `25]

[Jäger et al. `25]
[Braun et al. `25]

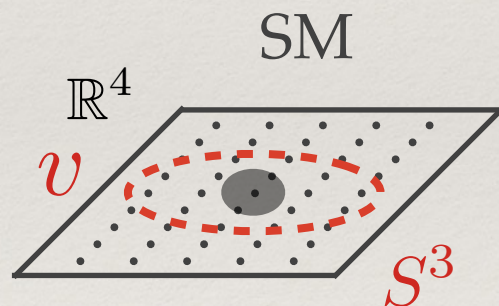
[Anisha et al. `25]
[Domenech et al. `25]

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geometrical probe of the ELWSB manifold



$$\kappa_V, \kappa_{2V} = 1, \omega_{2V} = 0$$

[Alonso et al. `16]

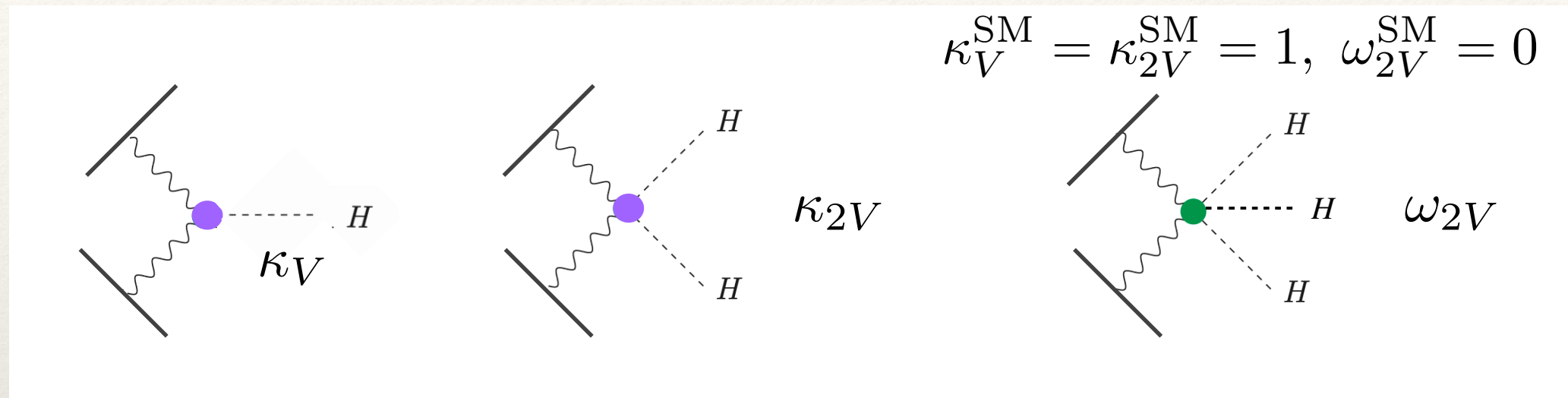
[Alonso, West `21]

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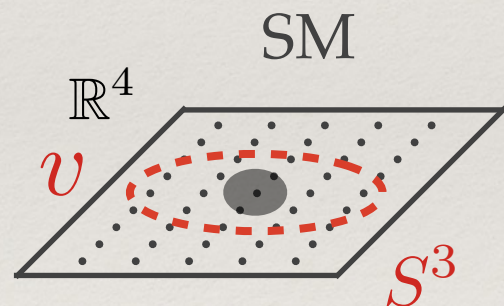
[Alonso, Chattopadhyay, Ingoldby `25]

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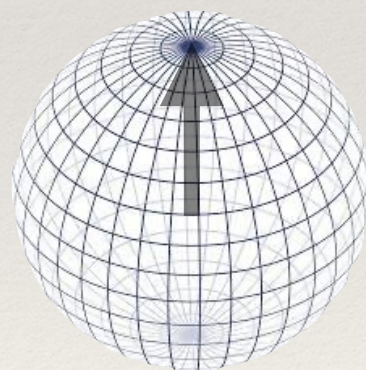
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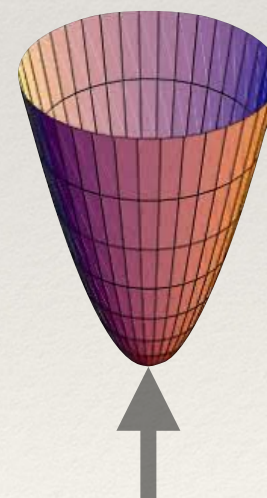
geometrical probe of the ELWSB manifold



$$\kappa_V, \kappa_{2V} = 1, \omega_{2V} = 0$$



$$\kappa_V, \kappa_{2V} \lesssim 1, \omega_{2V} \simeq 0$$



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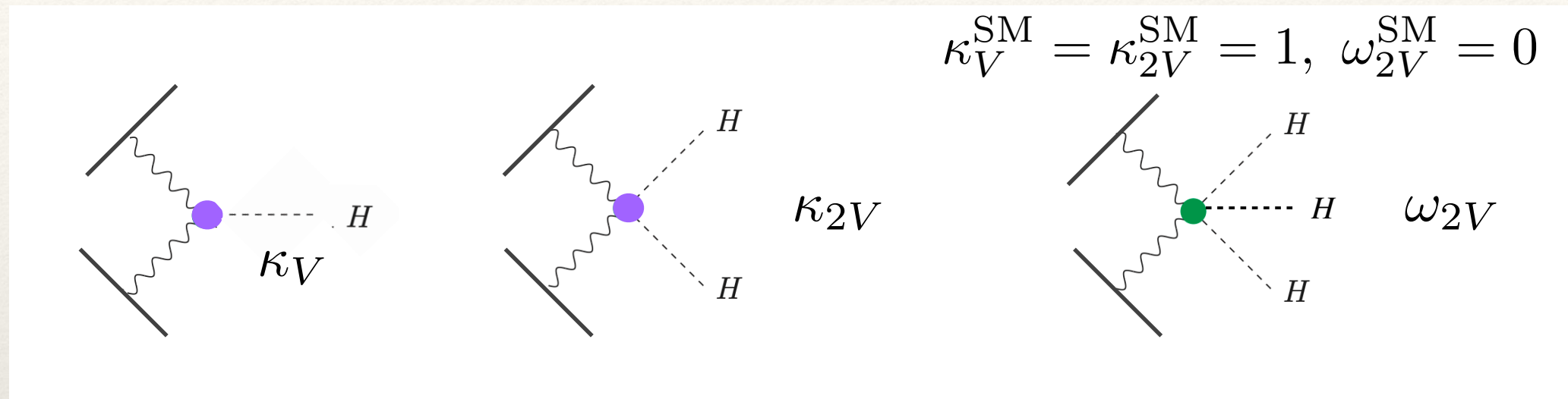
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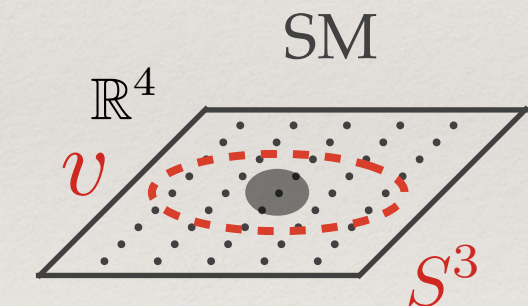
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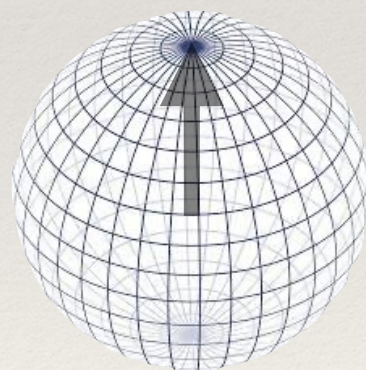
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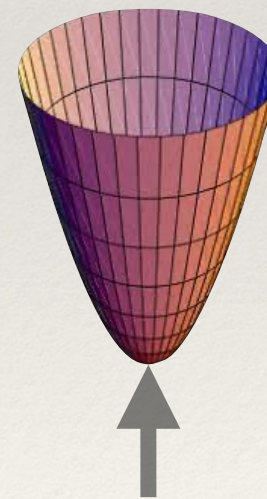
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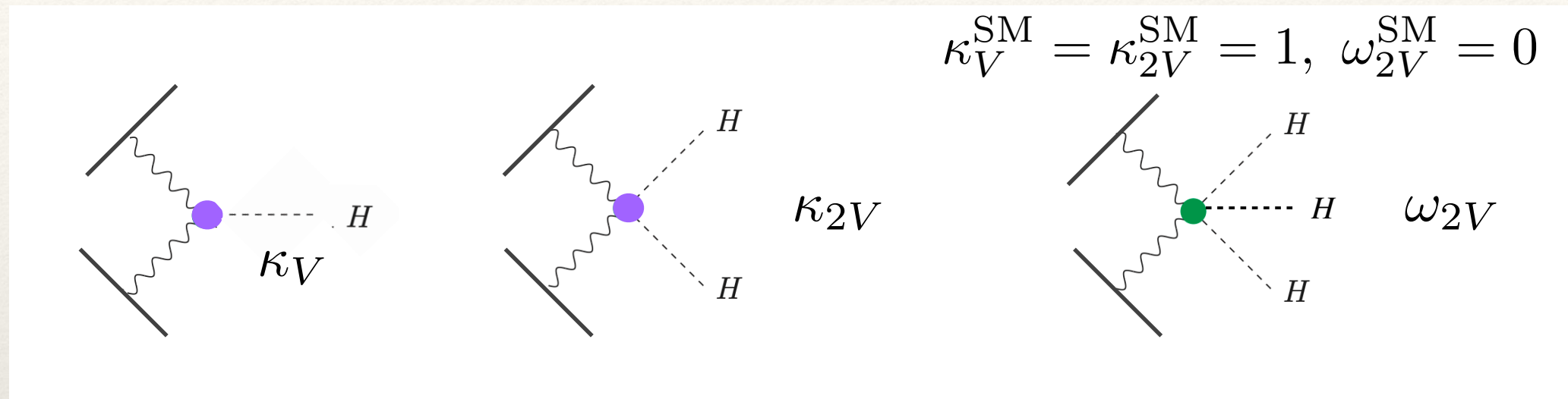
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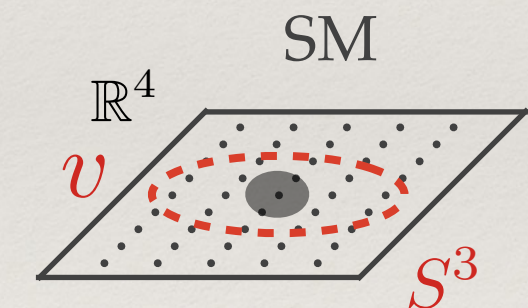
composite Higgs theories

beyond single Higgs bosons?

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geometrical probe of the ELWSB manifold



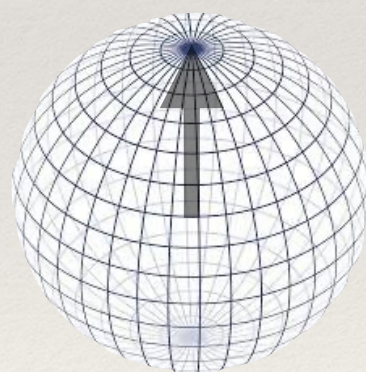
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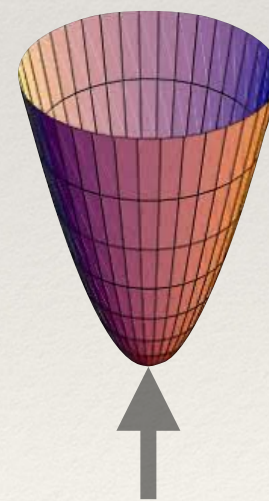
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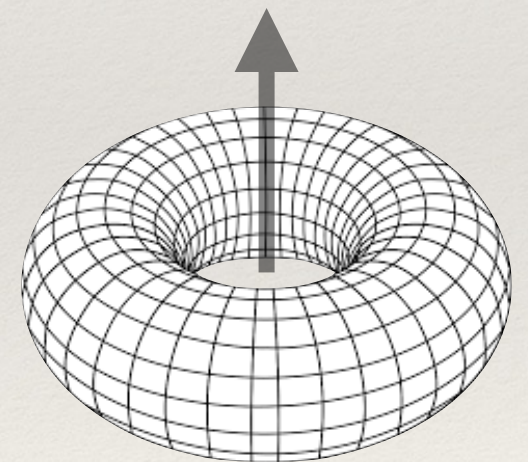
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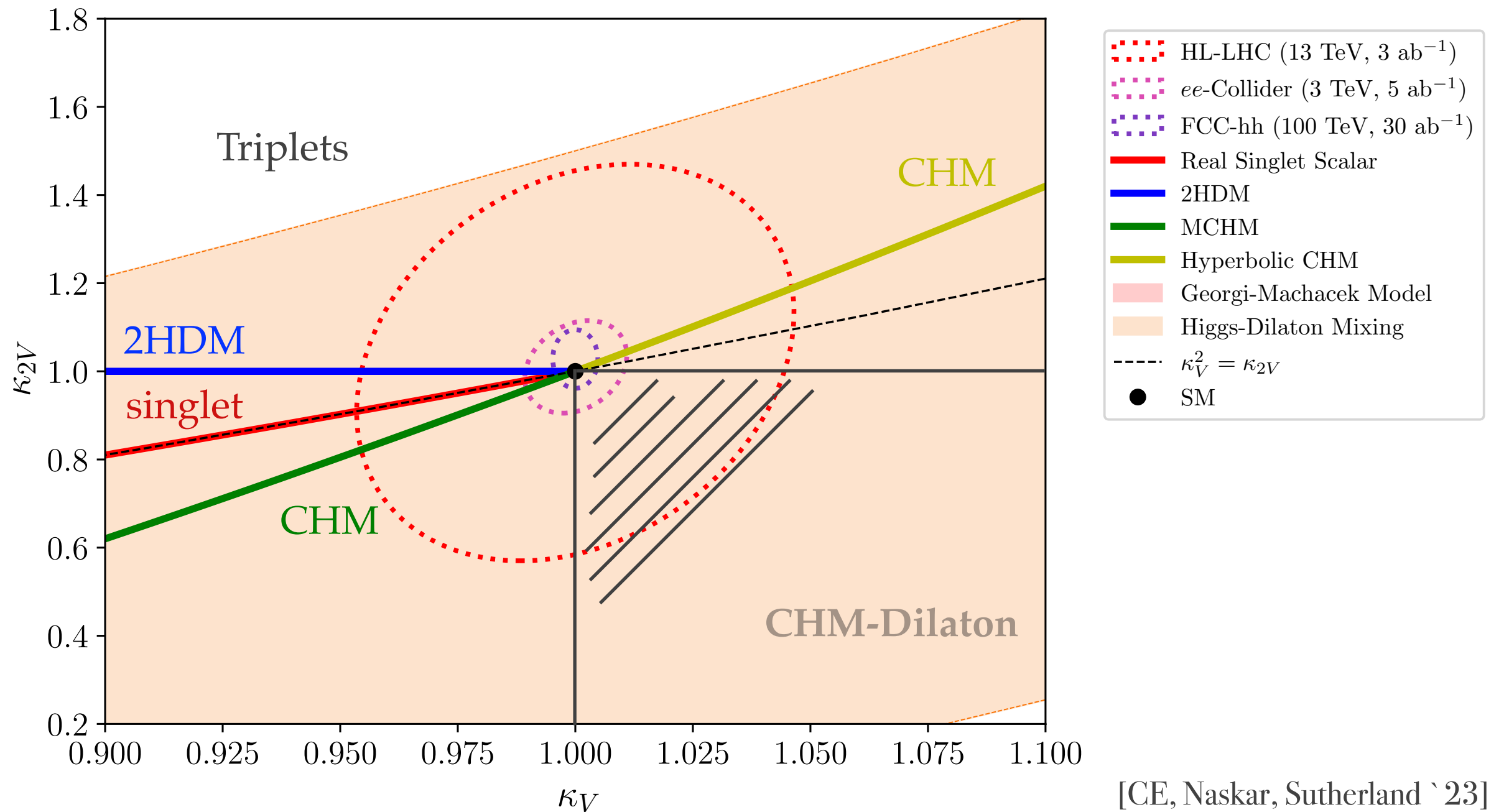


$$\kappa_V, \kappa_{2V} \simeq 1, \omega_{2V} \lesssim 1$$

composite Higgs theories

intrinsic HEFT

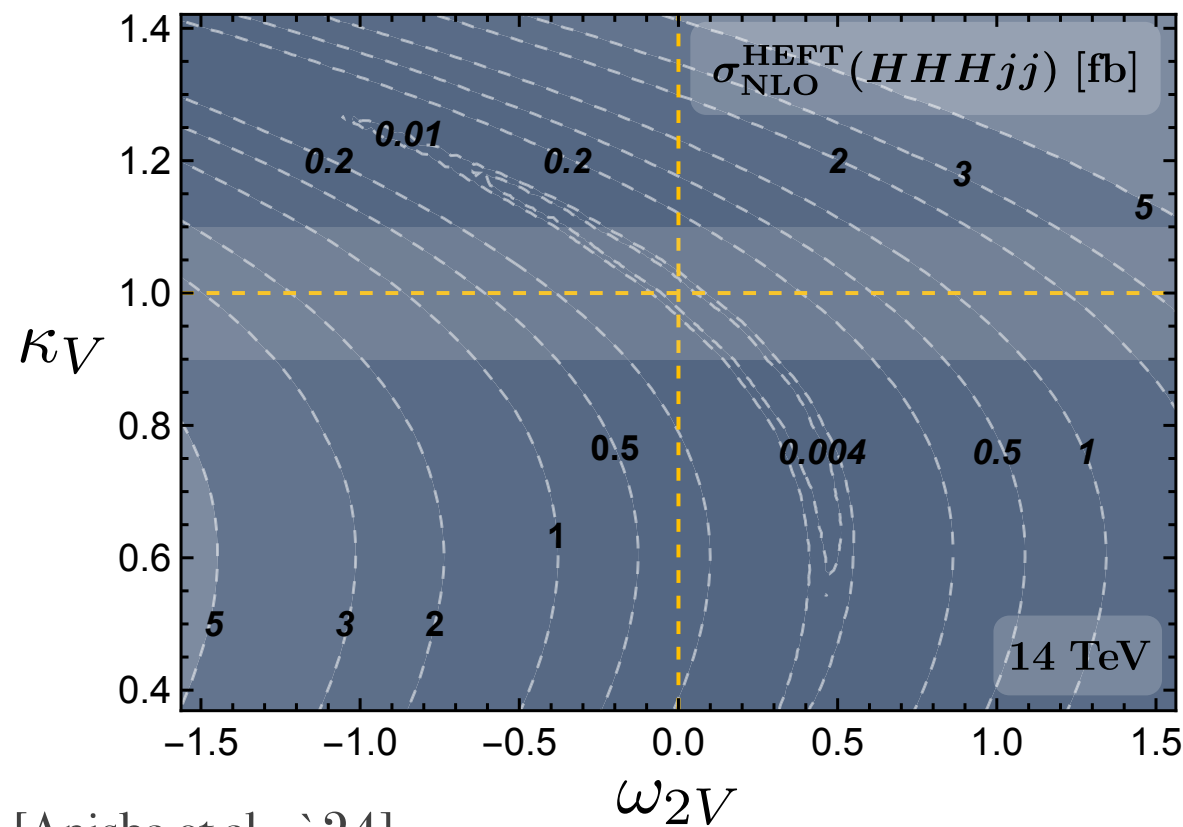
charting phenomenological possibilities



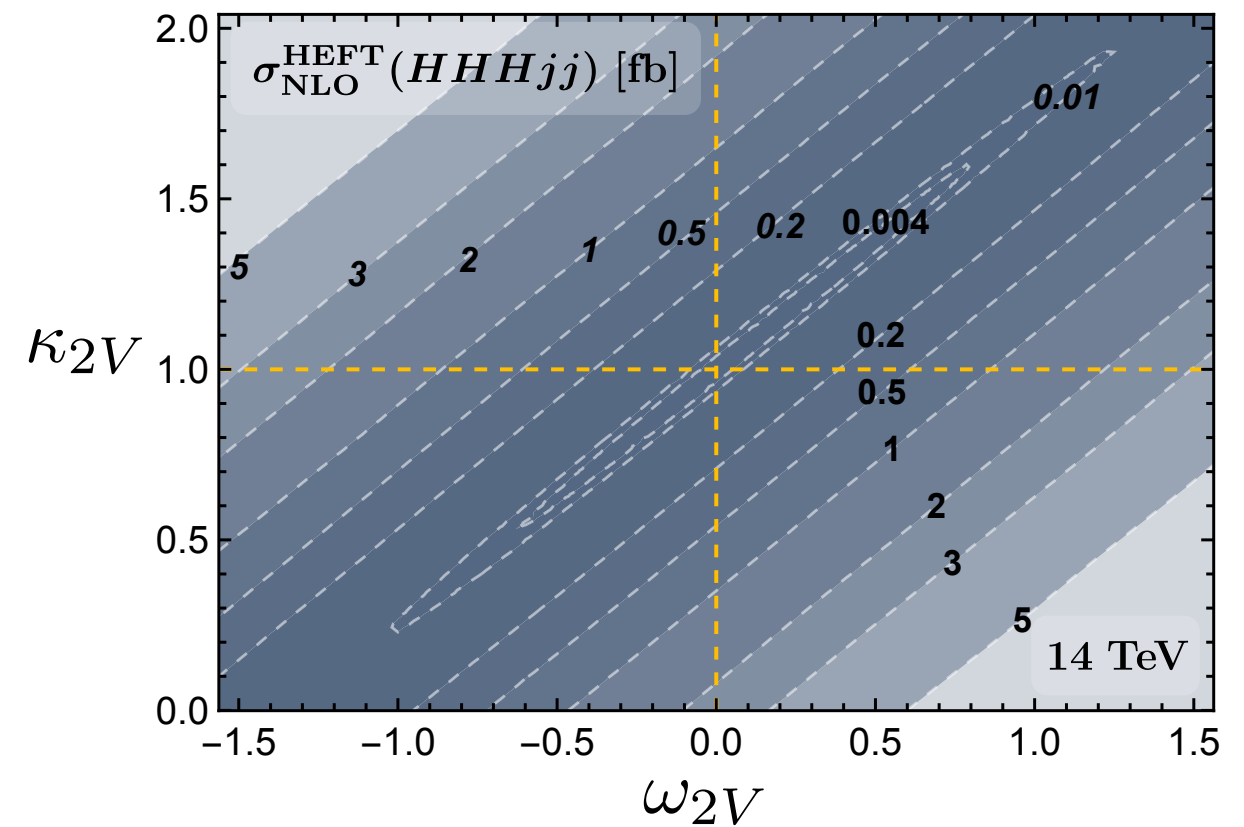
- big surprises a priori possible, but with TeV-relevant exotics

dilaton status see the recent [Brugisser et al. '22]

triple Higgs?



[Anisha et al., '24]



- ▶ stability under QCD corrections of WBF H/HH^n

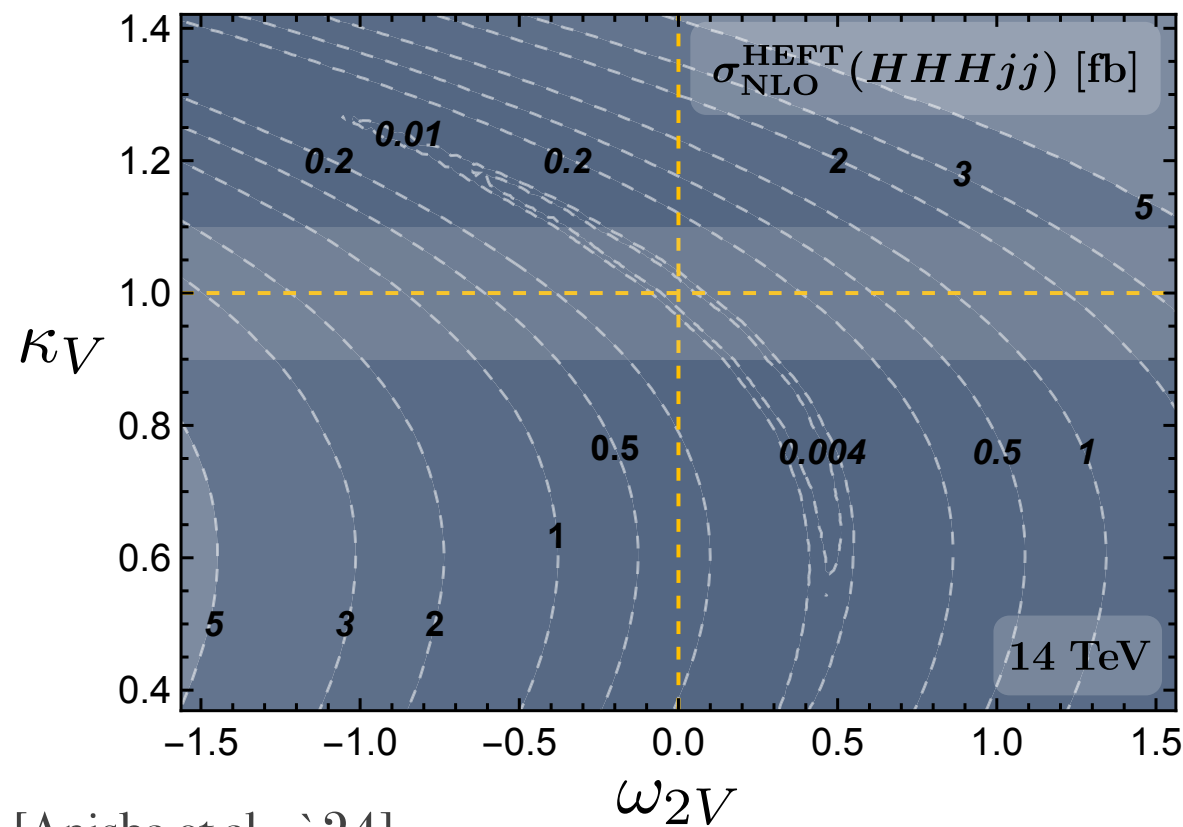
WBF is a clear window into (strong) ELW effects

- ▶ H easy, HH doable, HHH 😱

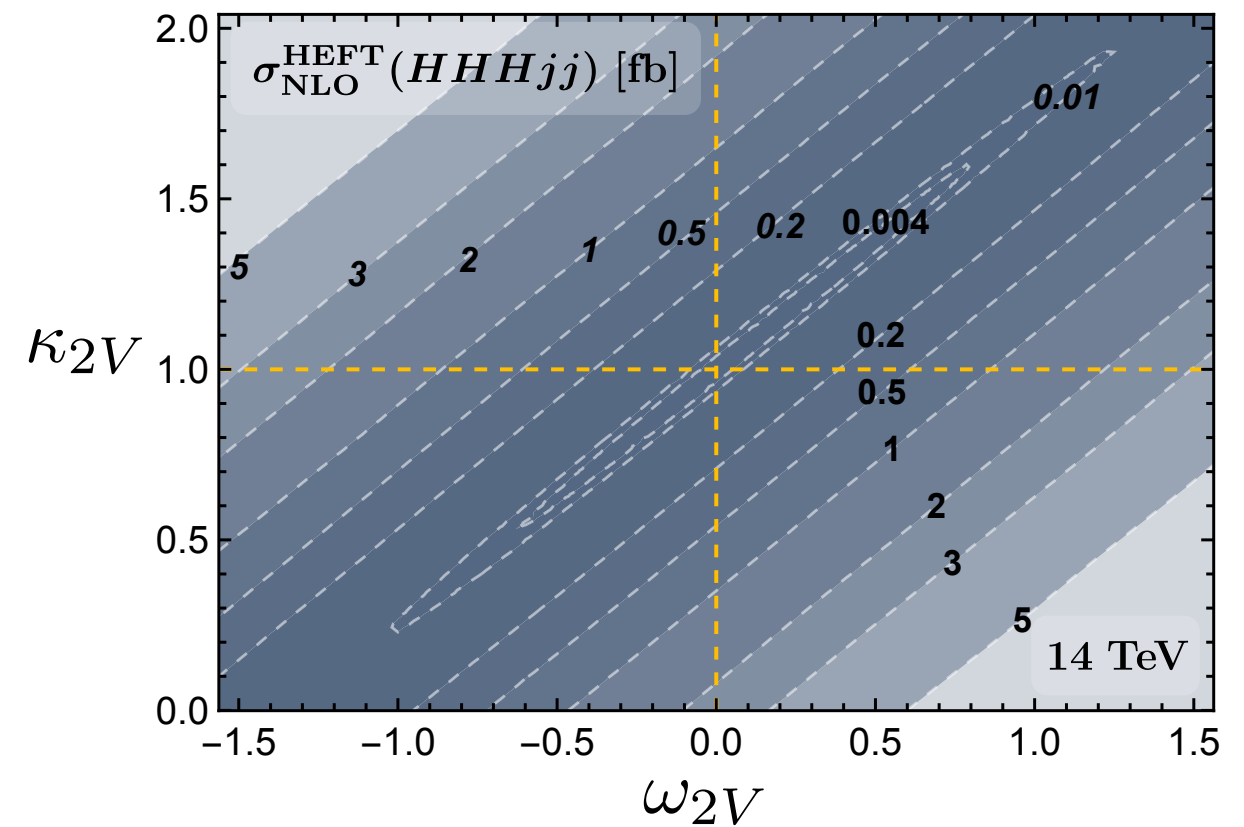
could be a muon collider target!

[Celada et al. '23]

triple Higgs?



[Anisha et al., '24]



- ▶ stability under QCD corrections of WBF H/HH^n

WBF is a clear window into (strong) ELW effects

- ▶ H easy, HH doable, HHH 😱

- ▶ context with fixed order perturbation theory

strongly
coupled modes
will show

$\omega_{2V} = 0.1 \rightarrow 85\%$ events in the non-perturbative

relevance & clarity of perturbative improvements

- ▶ in HEFT (Higgs = ‘custodial’ singlet) decorrelating multiplicities is technically consistent to all orders

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \mathcal{L}_{\text{ferm}} + \mathcal{L}_{\text{Yuk}} \\ & + \frac{v^2}{4}\mathcal{F}_H \text{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H) + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{FP}} \\ \mathcal{F}_H = & \left(1 + 2 \overbrace{(1 + \zeta_1)}^{\kappa_V} \frac{H}{v} + \overbrace{(1 + \zeta_2)}^{\kappa_{2V}} \left(\frac{H}{v}\right)^2 + \dots\right)\end{aligned}$$

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\mathcal{O}_0	$a_0(M_Z^2 - M_W^2)\text{Tr}[U\tau^3 U^\dagger \mathbf{v}_\mu]\text{Tr}[U\tau^3 U^\dagger \mathbf{v}_\mu]$
\mathcal{O}_1	$a_1 g' g_W \text{Tr}[U B_{\mu\nu} \frac{\tau^3}{2} U^\dagger W_{\mu\nu}^a \frac{\tau^a}{2}]$
\mathcal{O}_{HBB}	$-a_{HBB} g'^2 \frac{H}{v} \text{Tr}[B_{\mu\nu} B^{\mu\nu}]$
\mathcal{O}_{HWW}	$-a_{HWW} g_W^2 \frac{H}{v} \text{Tr}[W_{\mu\nu}^a W^{a\mu\nu}]$
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\mathcal{O}_{H1}	$a_{H1} g' g_W \frac{H}{v} \text{Tr}[U B_{\mu\nu} \frac{\tau^3}{2} U^\dagger W_{\mu\nu}^a \frac{\tau^a}{2}]$
\mathcal{O}_{H11}	$a_{H11} \frac{H}{v} \text{Tr}[\mathcal{D}_\mu \mathbf{v}^\mu \mathcal{D}_\nu \mathbf{v}^\nu]$
\mathcal{O}_{d1}	$i a_{d1} g' \frac{\partial^\nu H}{v} \text{Tr}[U B_{\mu\nu} \frac{\tau^3}{2} U^\dagger \mathbf{v}^\mu]$
\mathcal{O}_{d2}	$i a_{d2} g_W \frac{\partial^\nu H}{v} \text{Tr}[W_{\mu\nu}^a \frac{\tau^a}{2} \mathbf{v}^\mu]$
\mathcal{O}_{d3}	$a_{d3} \frac{\partial^\nu H}{v} \text{Tr}[\mathbf{v}^\mu \mathcal{D}_\mu \mathbf{v}^\mu]$
$\mathcal{O}_{\square \square}$	$a_{\square \square} \frac{\square H \square H}{v^2}$

$$\mathcal{F}_H = \left(1 + 2 \overbrace{\left(1 + \zeta_1\right)}^{\kappa_V} \frac{H}{v} + \overbrace{\left(1 + \zeta_2\right)}^{\kappa_{2V}} \left(\frac{H}{v}\right)^2 + \dots\right)$$

radiatively source ‘higher-dimensional’ interactions

[Weinberg ‘79] [Gasser, Leutwyler ‘84]...

[Espiru et al. ‘13] [Delgado et al. ‘13]

[Brivio et al. ‘14] [Buchala et al. ‘17] [Herrero, Morales ‘21]

...

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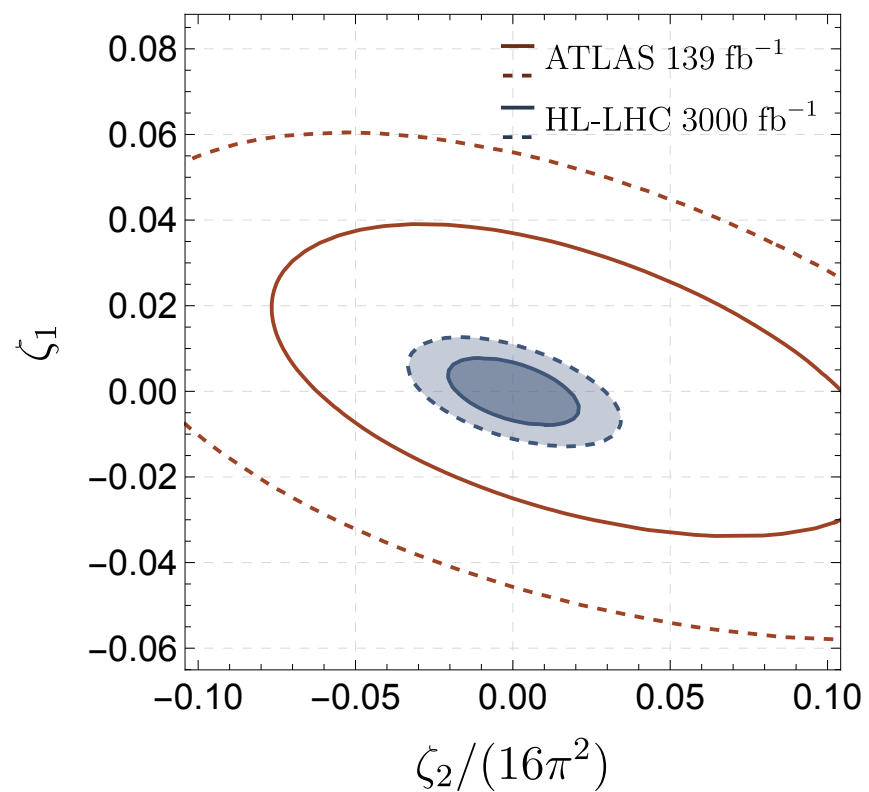
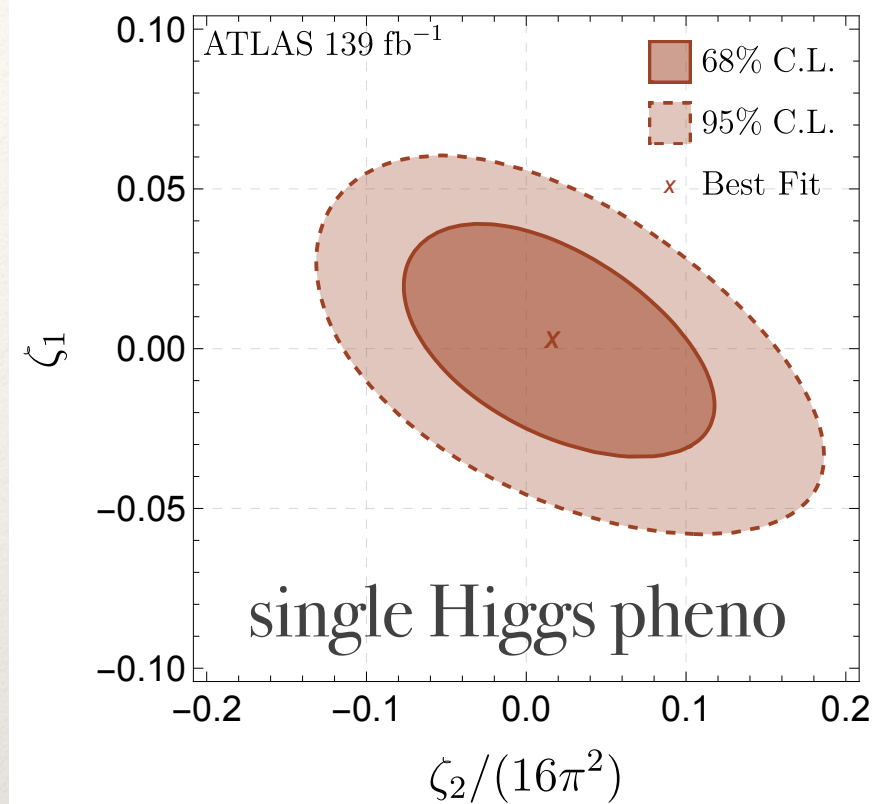
[Brivio et al. ‘14] [Buchala et al. ‘17] [Herrero, Morales ‘21]

...

lots of interesting physics/technical advantages

- ▶ Higgs physics is gauge-independent
- ▶ vacuum gauge-independent
- ▶ masses gauge-independent
- ▶

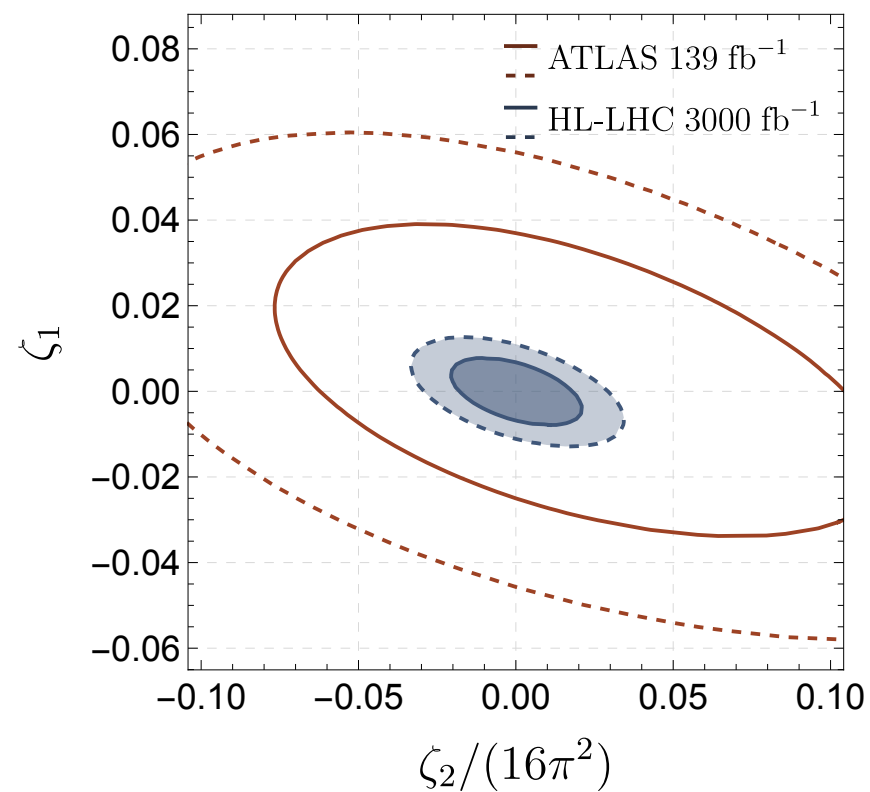
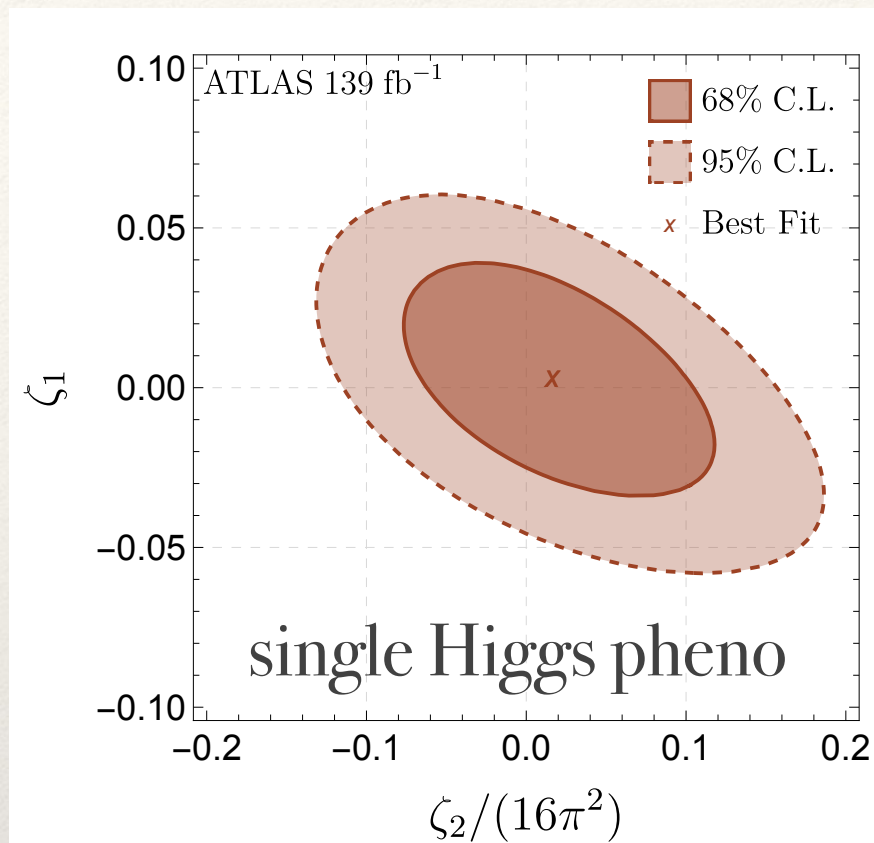
beyond leading order with flexibility



- radiative correlations perfectly consistent

...
[Herrero, Morales `21]
[Anisha et al. `22]
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beyond leading order with flexibility



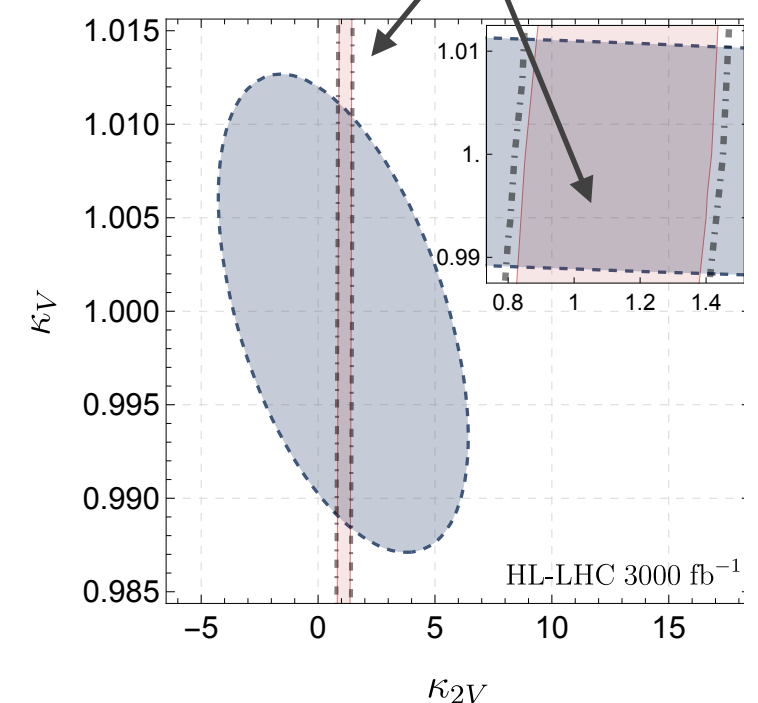
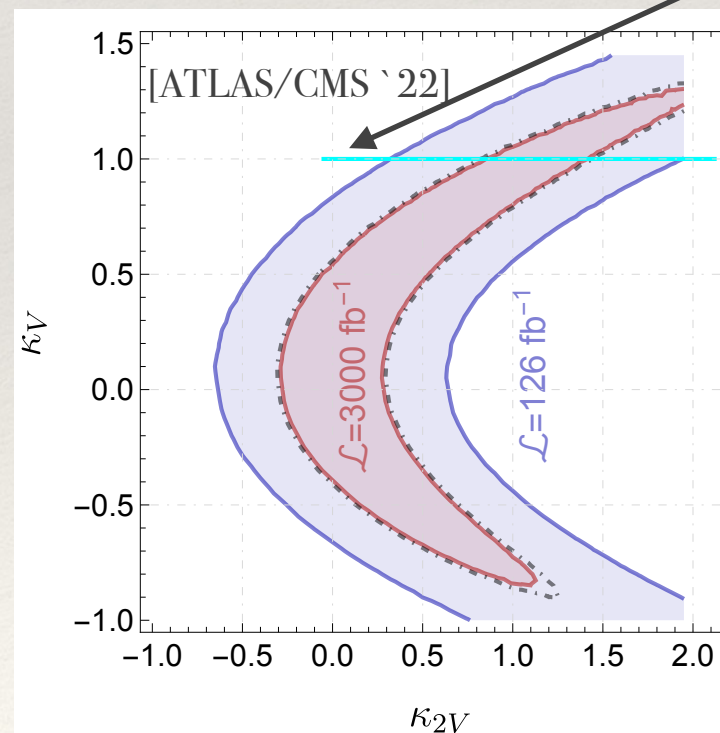
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...

GNN WBF HH analysis

► direct sensitivity likely more competitive at the LHC

correlation of a priori
free parameters in HEFT
happens through weak
interactions



- ▶ progress in highly-adapted new physics analysis optimisation
beyond classical machine learning, e.g. anomaly detection

[Araz, Spannowsky `22]

[Hammad, Nojiri, Yamazaki `24]

[Oleksiyuk et al. `25]

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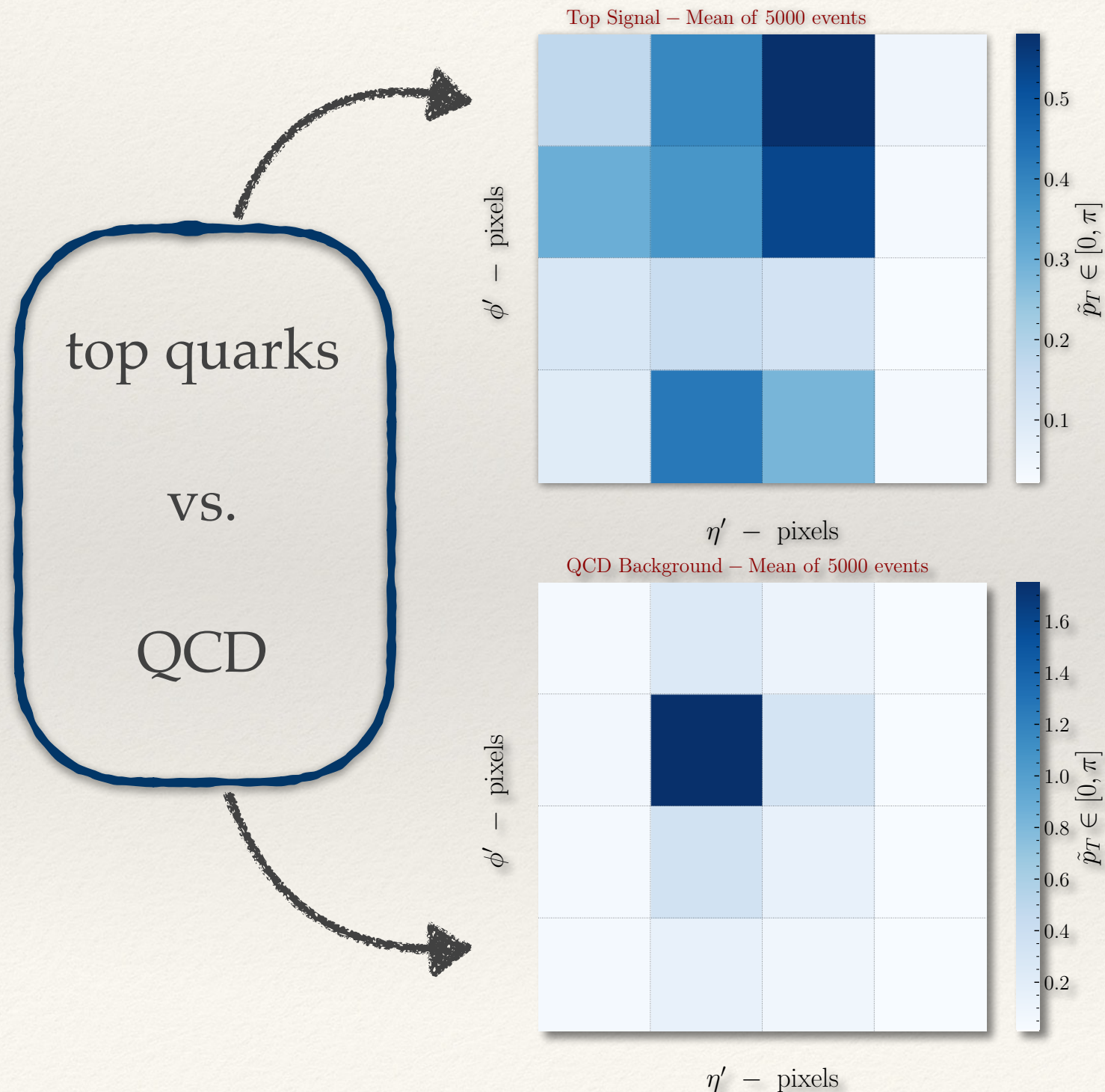
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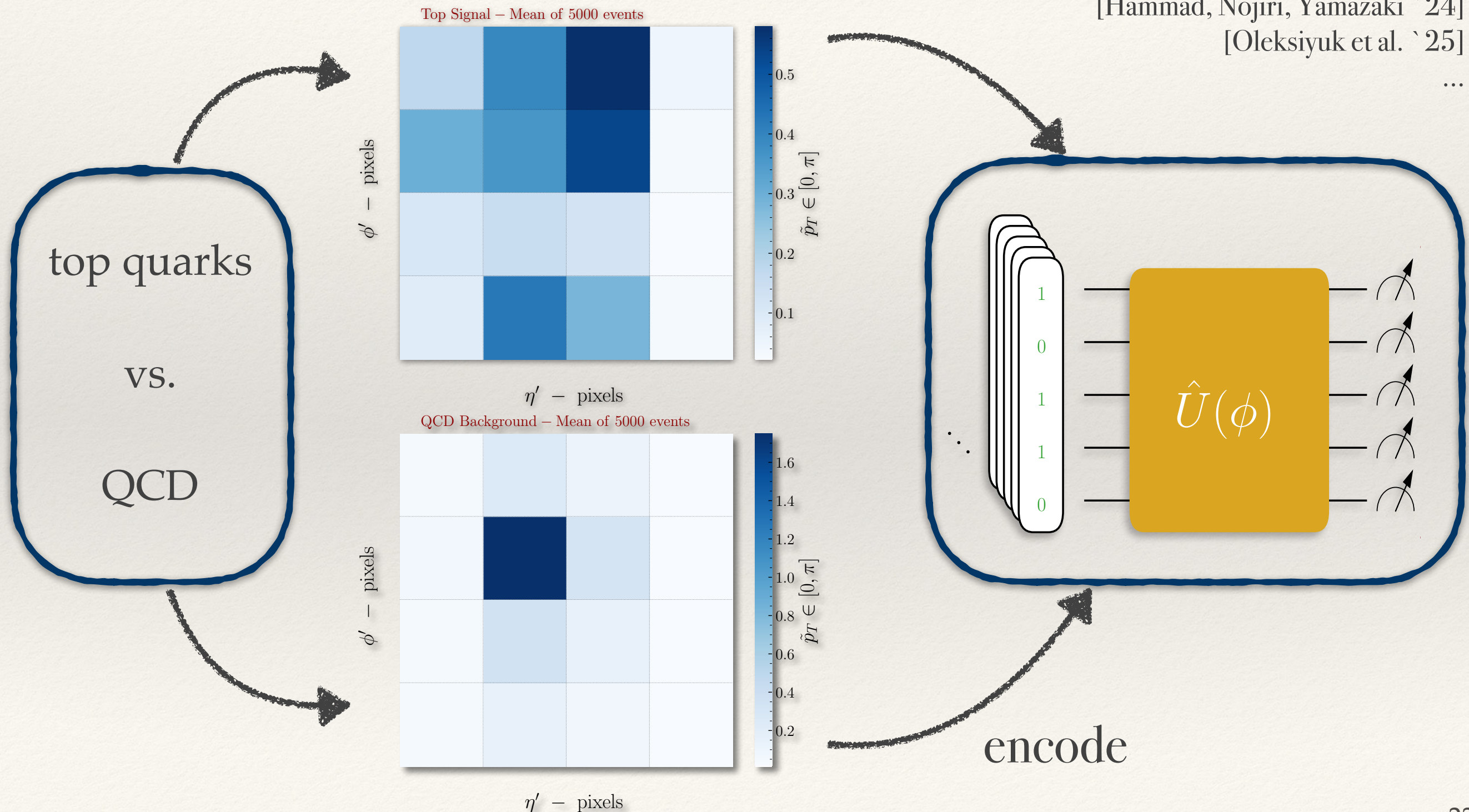
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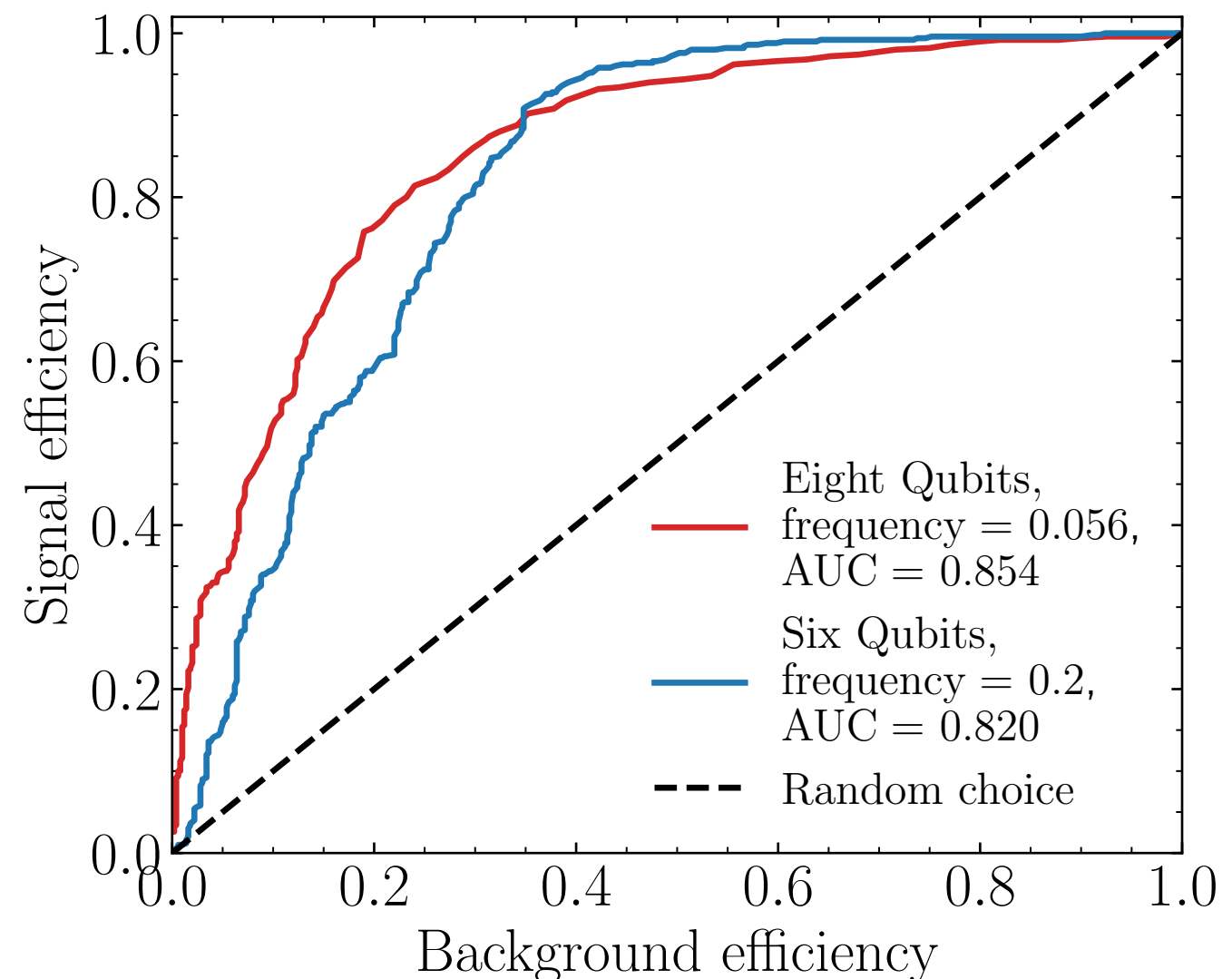
top quarks

vs.

QCD

opportunities
ahead!

Quantum-probabilistic Hamiltonian learning



[Araz, Spannowsky `22]

EFT data interpretation induces a source of uncertainty

[Haag '58]...[Criado, Perez-Victoria et al. '18]...

- ▶ use of EoMs to obtain ‘operator bases’ \neq QFT redundancy

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[Manohar `18]

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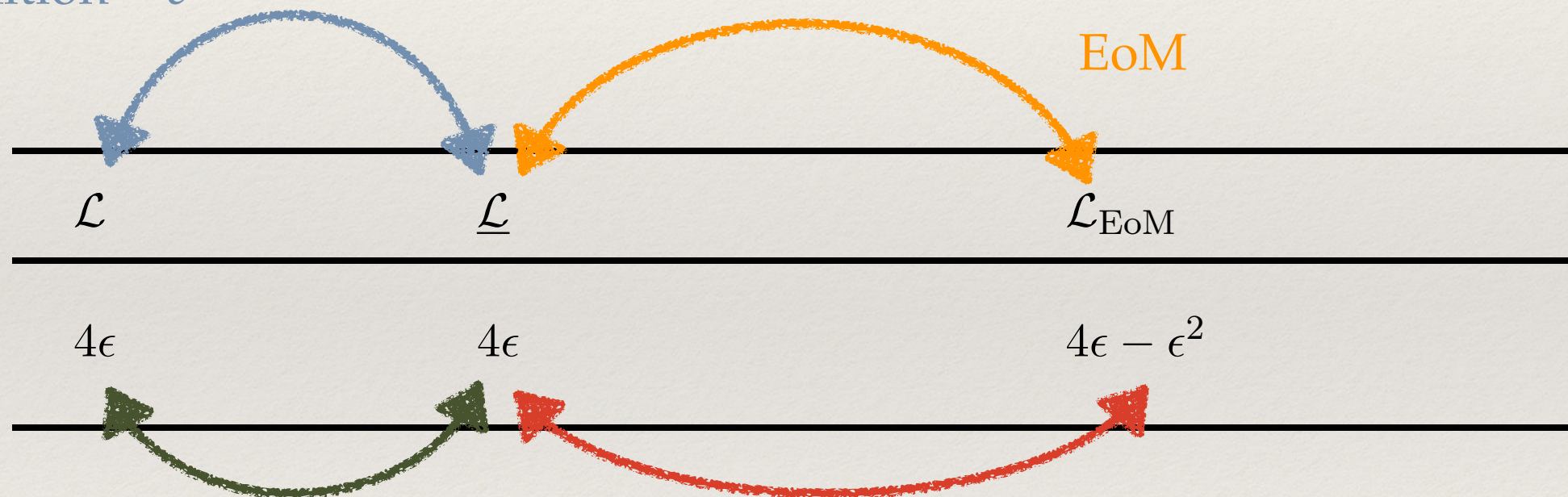
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field redefinition $\sim \epsilon$



S matrix

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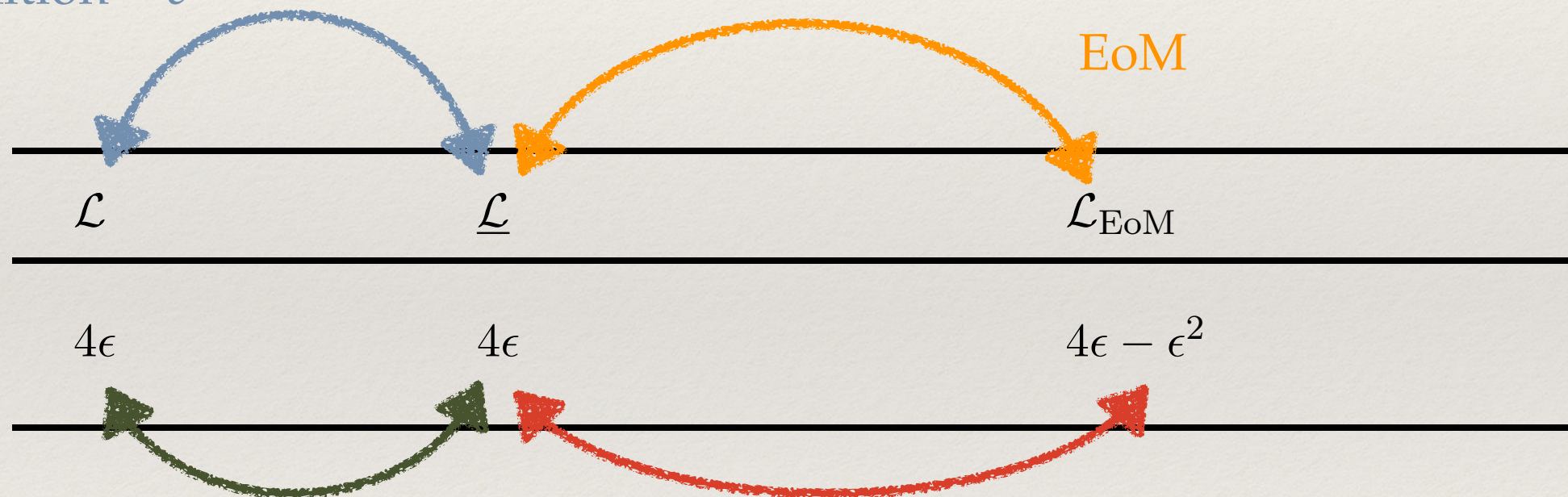
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field redefinition $\sim \epsilon$

$$\mathcal{L} = \mathcal{L}_0 + \epsilon \mathcal{L}_{\text{BSM}}$$



- ▶ EoM is only infinitesimally equivalent to a field redefinition
- ▶ juxtaposition of data quality (rare final states) informing tell-tale new physics effects (poor constraint $\epsilon \sim 4$ cannot be trusted)

...with additional sources of uncertainty!

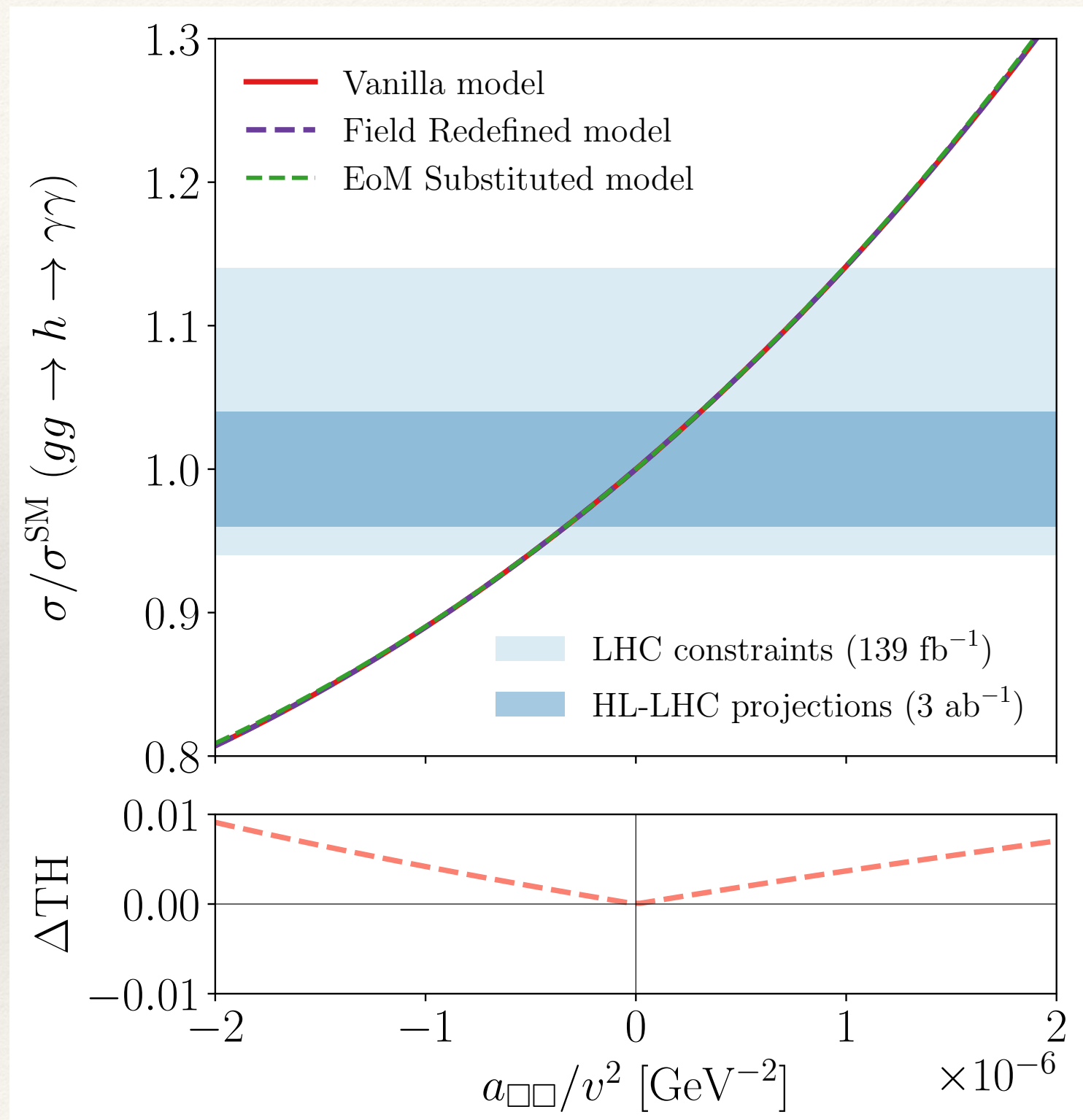
$\sim \epsilon$ SM limit well behaved

$$\Delta\text{TH} = \left| \frac{\sigma - \sigma_{\text{EoM}}}{\sigma - \sigma_{\text{SM}}} \right|$$

...with additional sources of uncertainty!

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...with additional sources of uncertainty!

$$\sim \epsilon \quad \text{SM limit well behaved}$$

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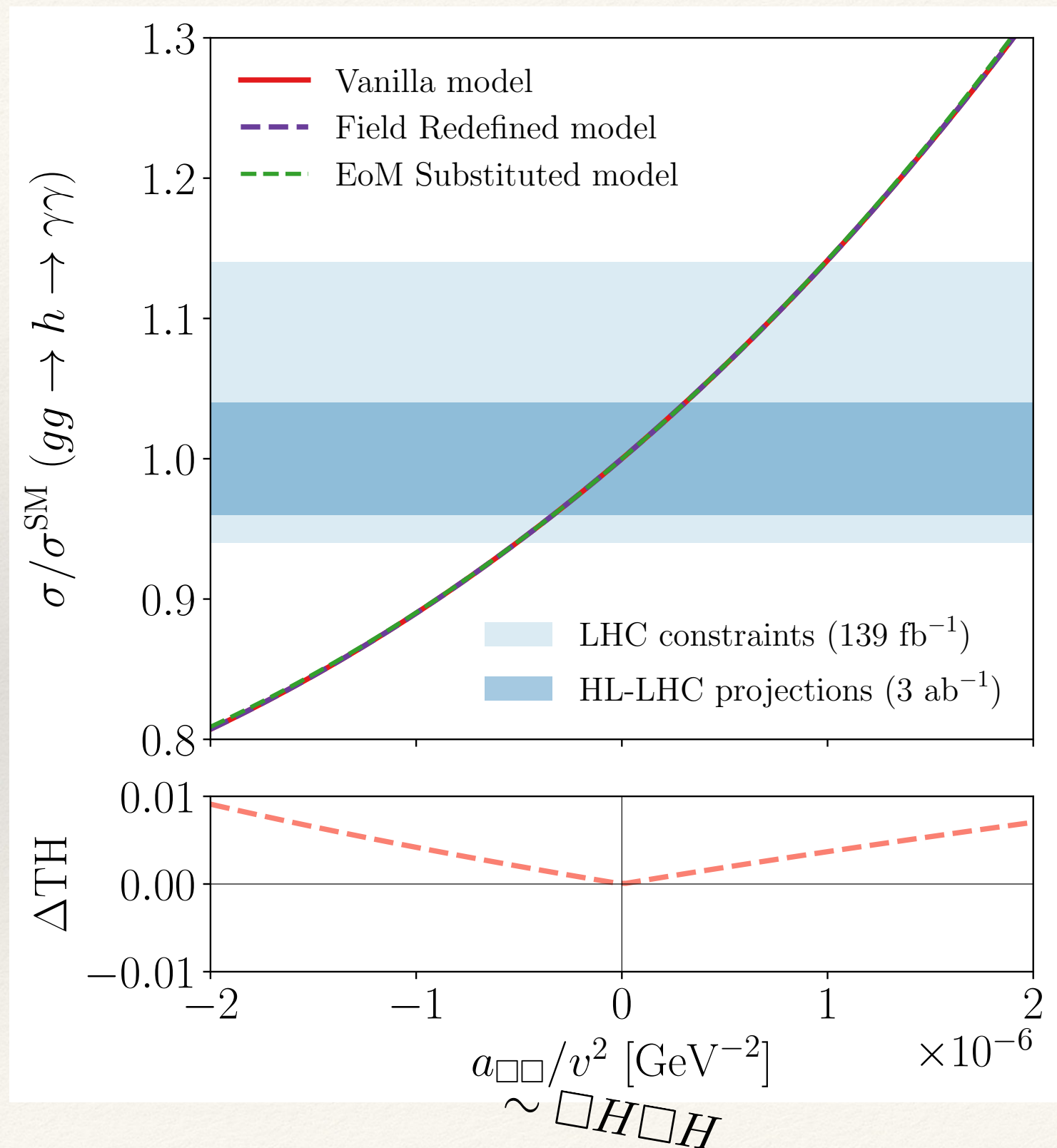
- ▶ good control over data (abundant final states) = good quality constraints
- ▶ no problem for inclusive Higgs boson production?

theoretical error negligible

(still important: unitarity/power counting)

[Alonso, CE, Naskar, Rahaman '25]

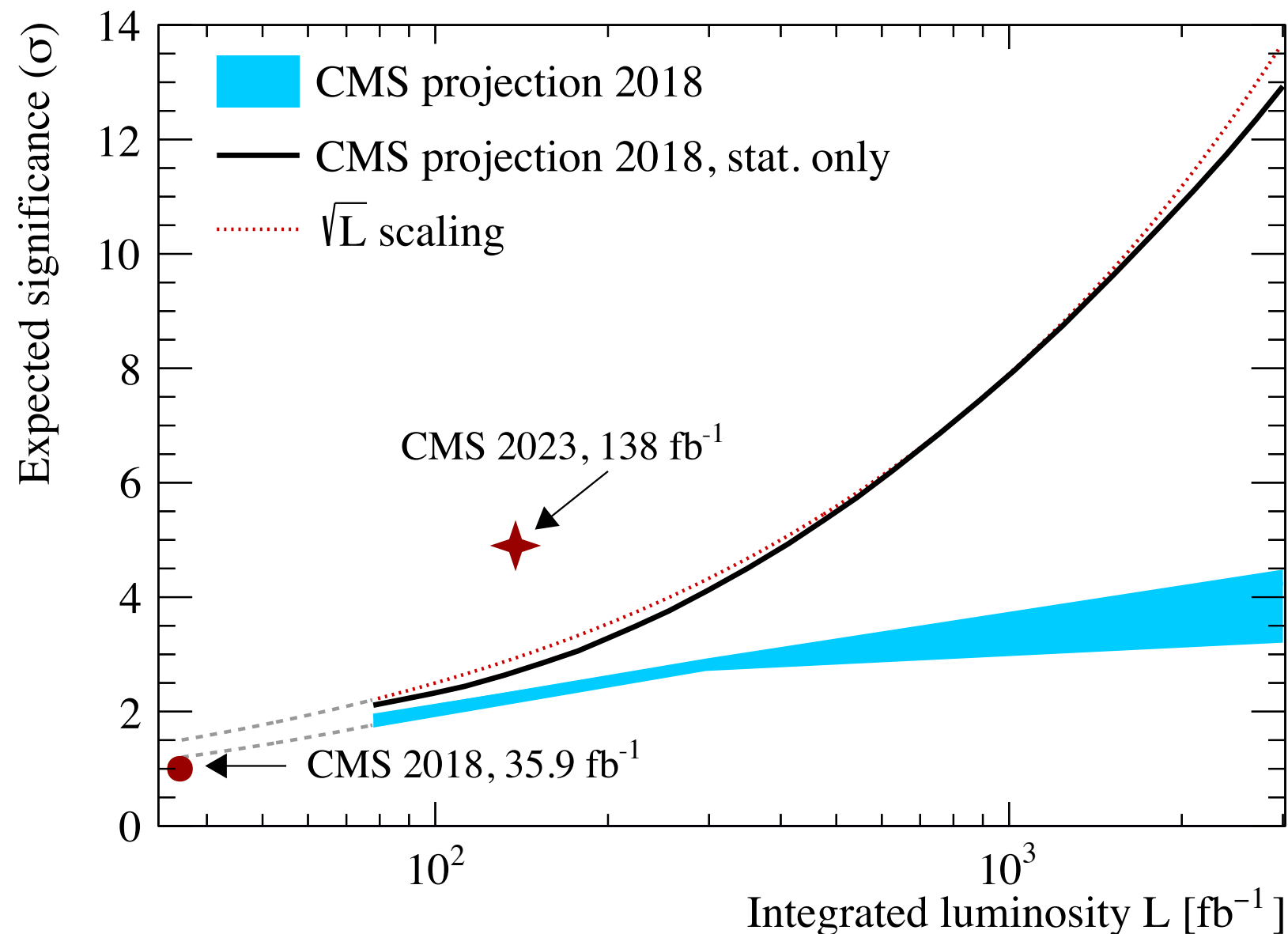
[Brivio et al. '25]



ghosts etc. [Brivio et al. '14]

robustness of rare final states?

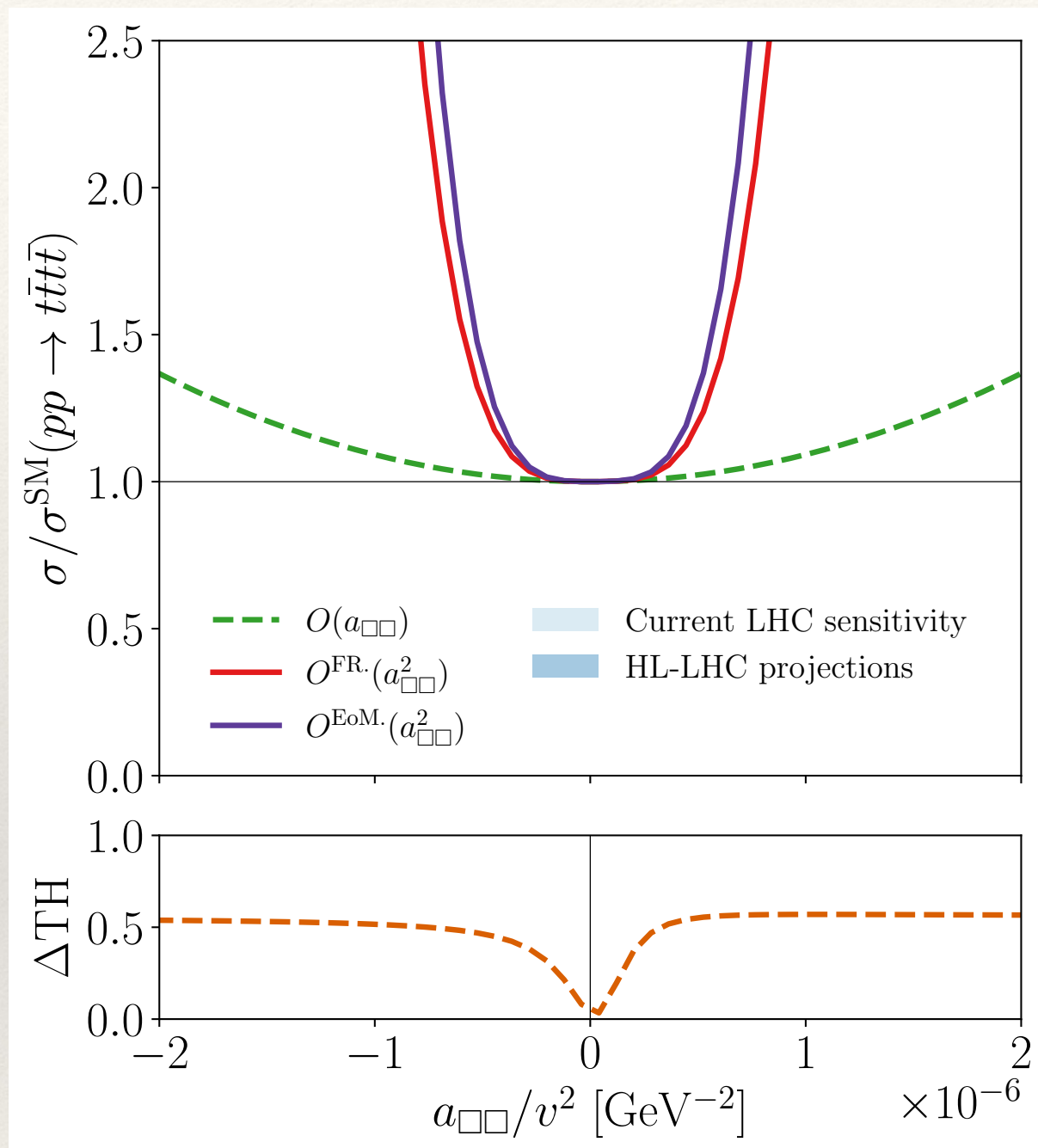
- ▶ four top quark production highly sensitive to electroweak interactions
[Alvarez et al. '16] [Frederix et al. '17] [Darme et al. '18]...
- ▶ increasing interest by the theory and experimental communities



- ▶ major sensitivity leaps by ATLAS and CMS !
- ▶ conservative estimates create an *unrealistically* pessimistic outlook of the HL-LHC capacity

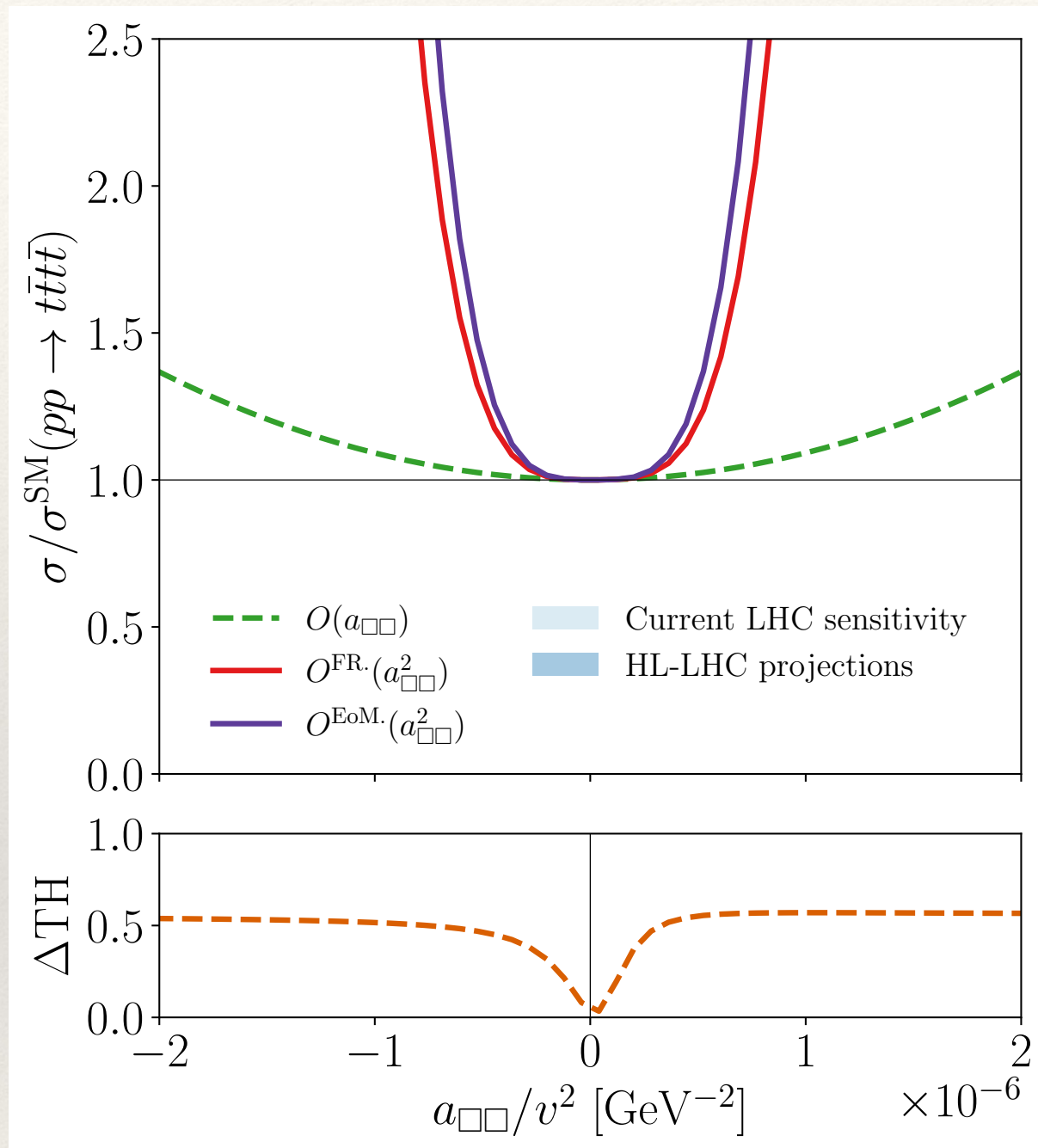
robustness of rare final states?

- significant *a priori* uncertainty for model-independent analysis strategies....



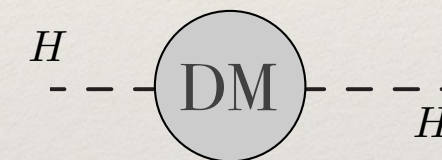
robustness of rare final states?

- ▶ significant *a priori* uncertainty for model-independent analysis strategies....
- ▶ but can be *misleading* when understood against concrete (strongly-coupled) new physics

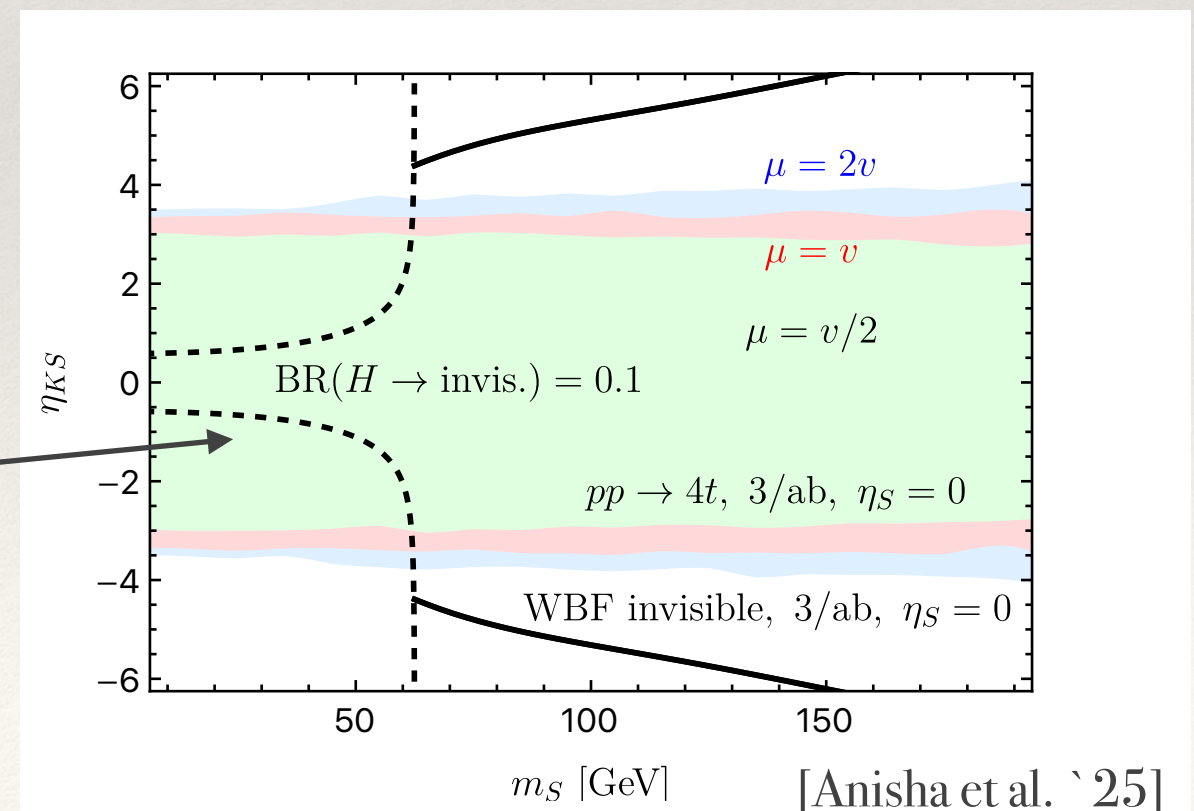


four top constraints on PNCB-type portal DM theories + uncertainty

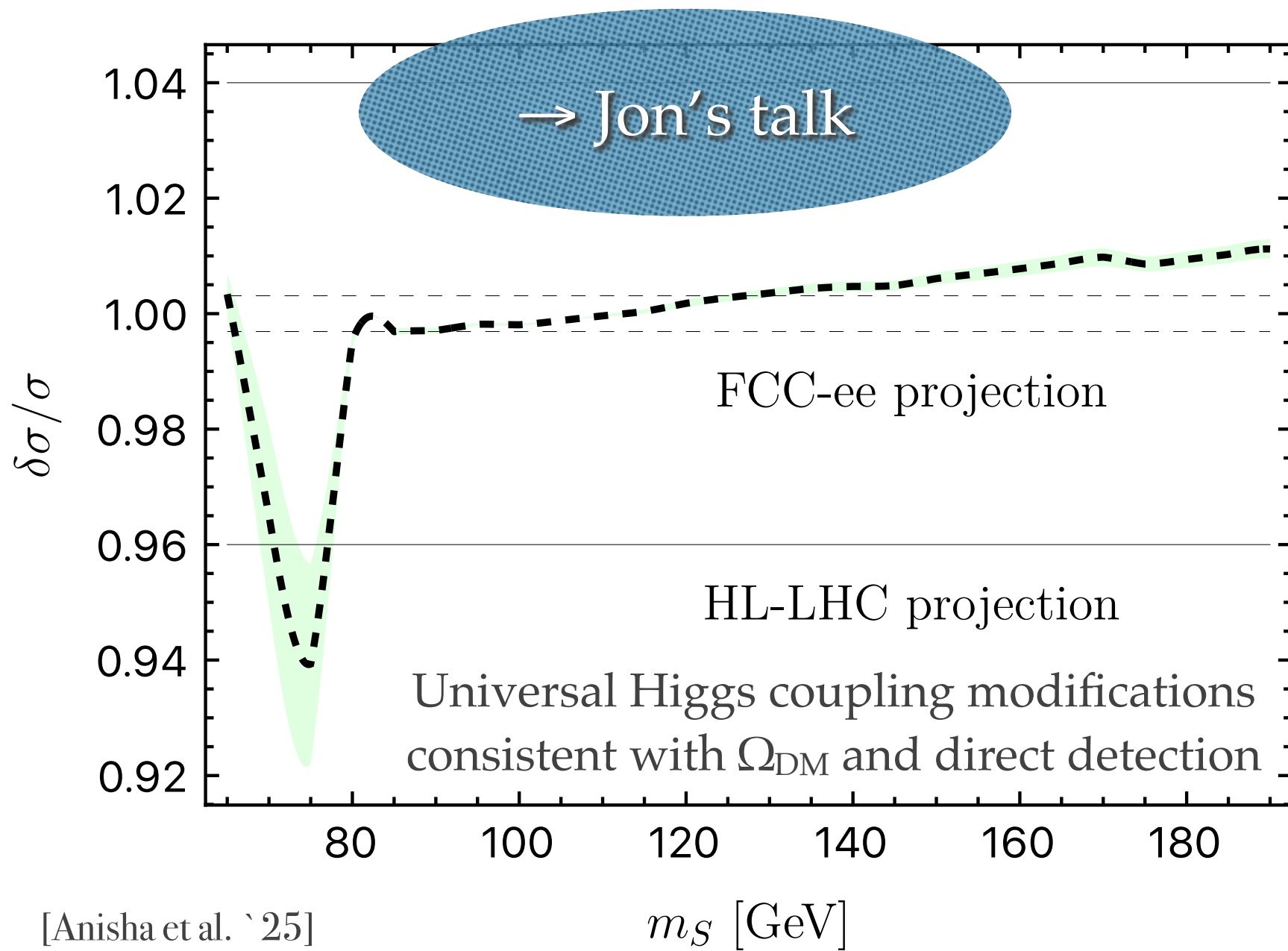
[Frigerio, Pomarol, Riva, Urbano `14], [Marzocca, Urbano `14]...



...but cancellations in gauge amplitudes!



robustness of rare final states?



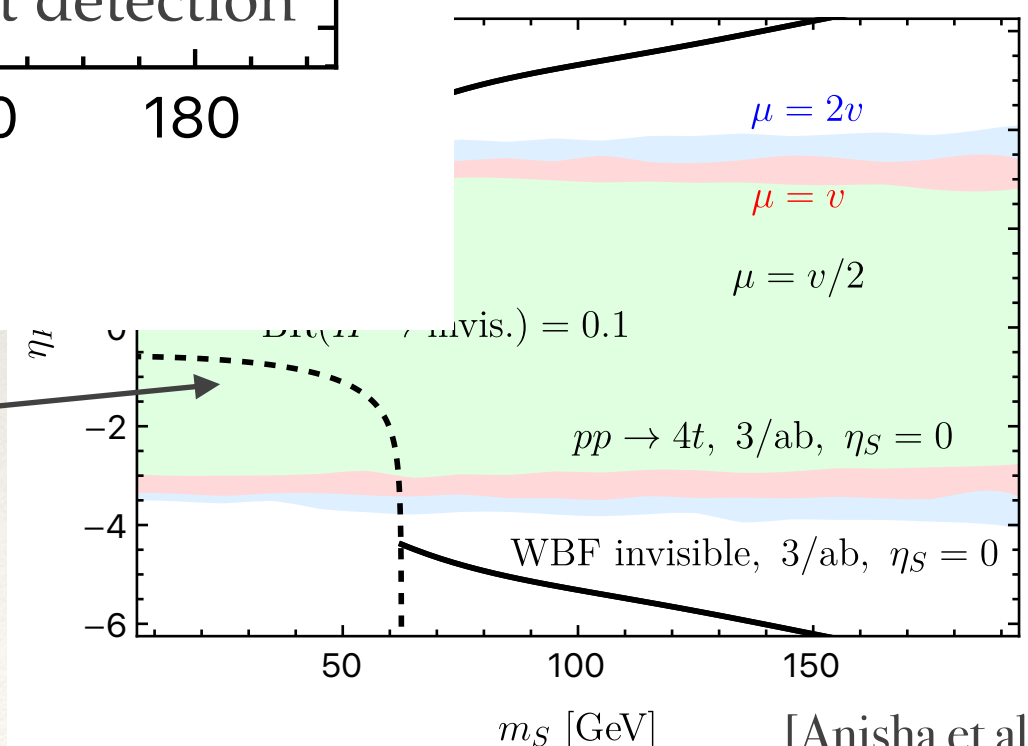
a priori uncertainty for independent analysis

misleading when against concrete (coupled) new physics

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four top constraints on PNGB-type portal DM theories + uncertainty

[Frigerio, Pomarol, Riva, Urbano '14], [Marzocca, Urbano '14]...



[Bordone, Gubernari, Huber, Jung, van Dyk `20]

- ▶ longstanding tension in non-leptonic B decays within QCDf

	Channel	Experiment	SM	Pull
R_K	$\bar{B}^0 \rightarrow D^+ K^-$	$0.058^{+0.004}_{-0.004}$	$0.082^{+0.002}_{-0.001}$	$\approx 5.6 \sigma$
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new physics?

power
corrections?

flavour / collider

[Bordone, Gubernari, Huber, Jung, van Dyk `20]

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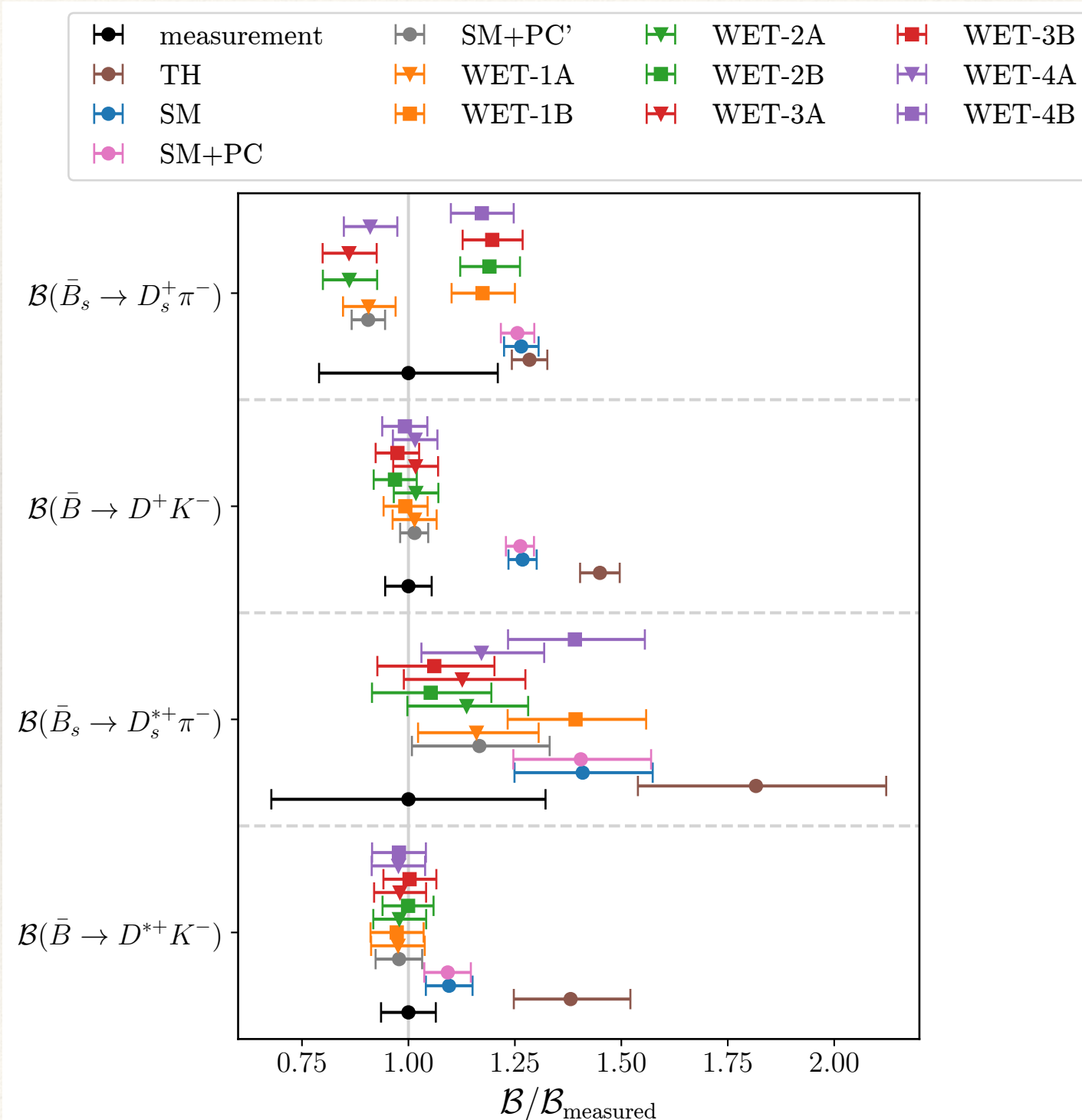
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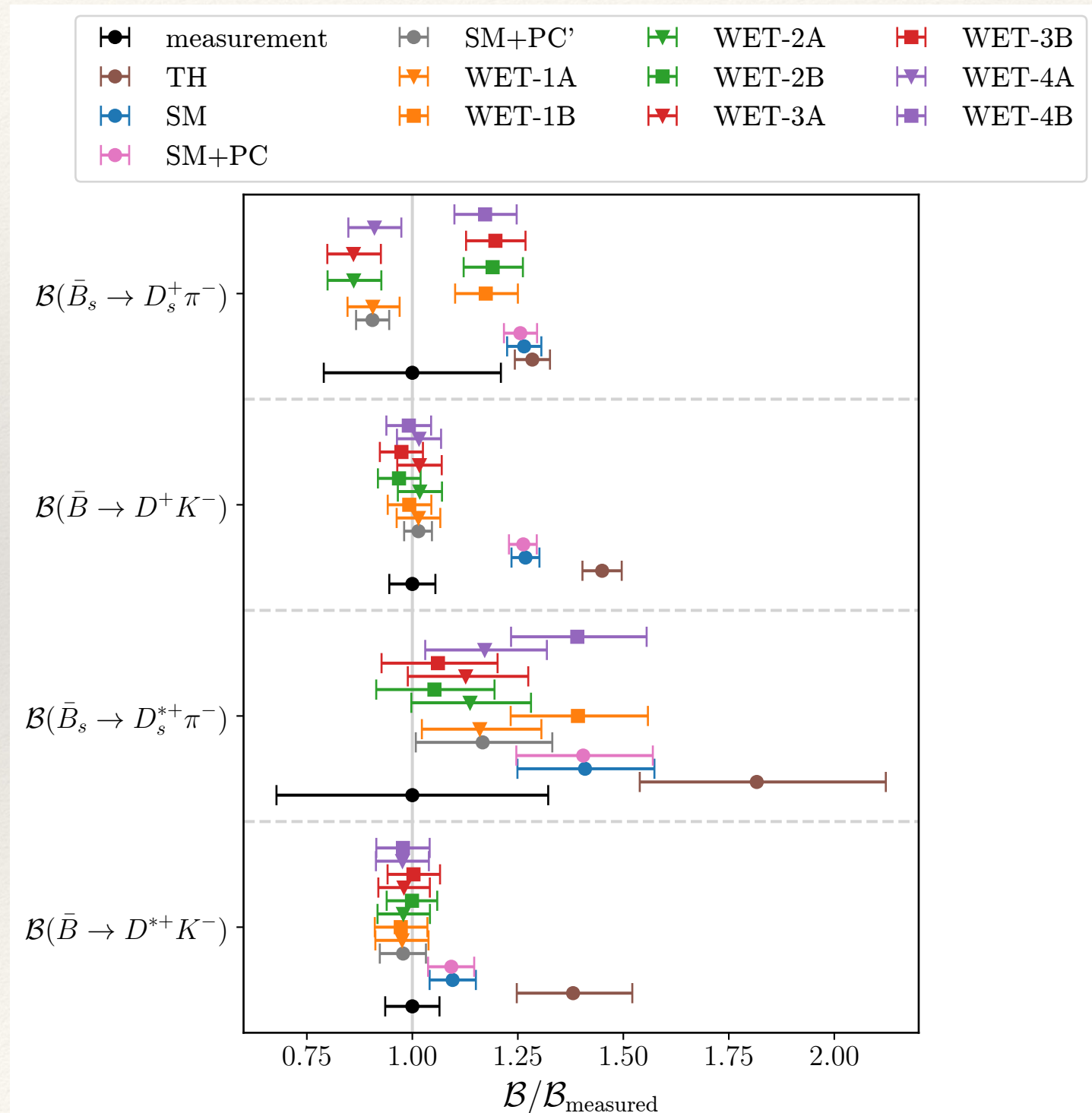
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- mounting tension with
(in)direct LHC searches ?

[Bordone, Greljo, Marzocca `21]

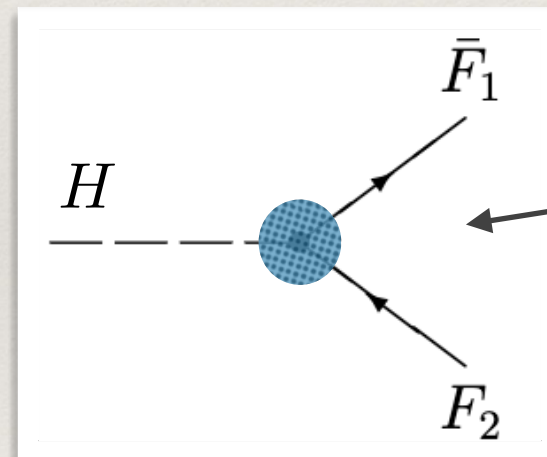
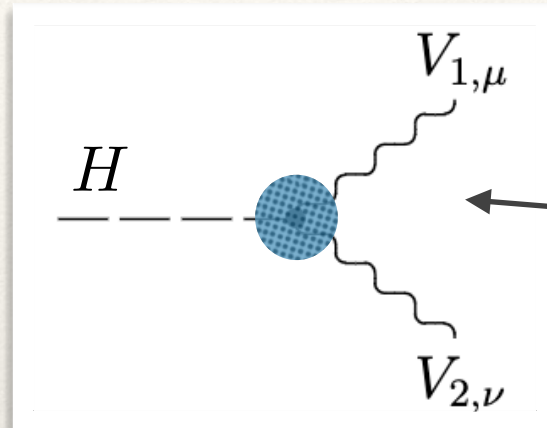
[Atkinson, CE, Tetlalmatzi-Xolocotzi, Kirk `24]

one to watch!

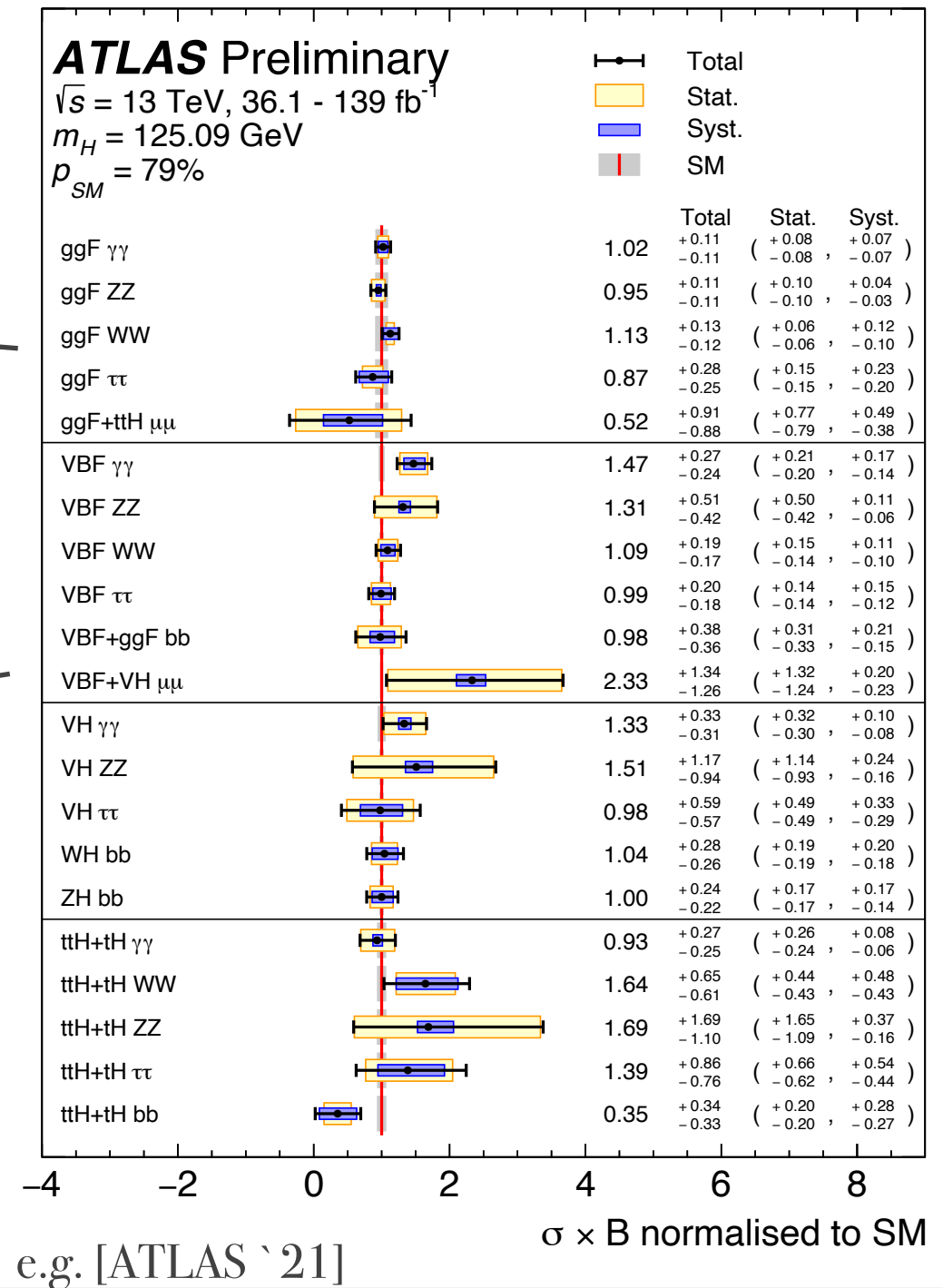


no reason to be so pessimistic at this point!

HL-LHC could reveal %-level Higgs coupling deviations (corroborated by e.g. FCC-ee)



reincarnation of the LHC
no lose theorem



unitarity for discovery

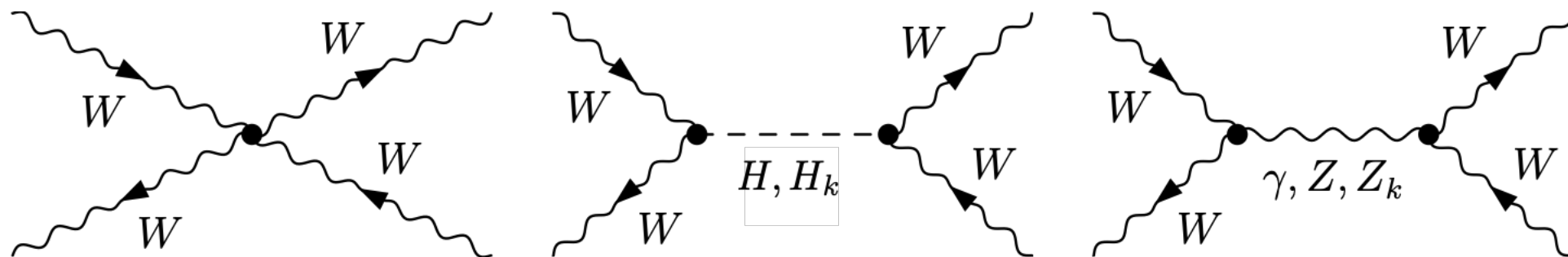
- ▶ unitarity restoration is only efficient with scalar and vector resonances
sum rules for longitudinal vector boson scattering

[Weinberg '67]...

...[Alboteanu et al. '08]

[Birkedal, Matchev, Perelstein '04]

[CE, Harris, Spannowsky, Takeuchi '15]



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$$4m_W^2 g_{WWWW} = \sum_k 3m_{Z_k}^2 g_{WWZ_k}^2 + \sum_k g_{WWH_k}^2$$

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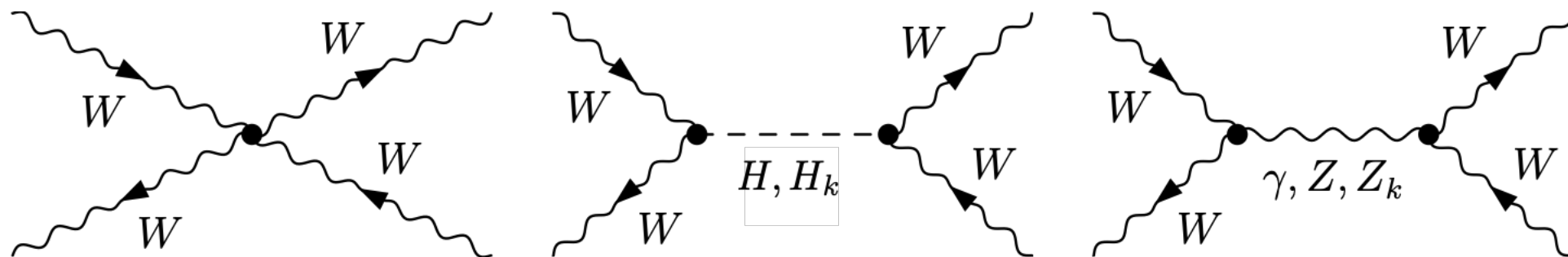
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Higgs deviation

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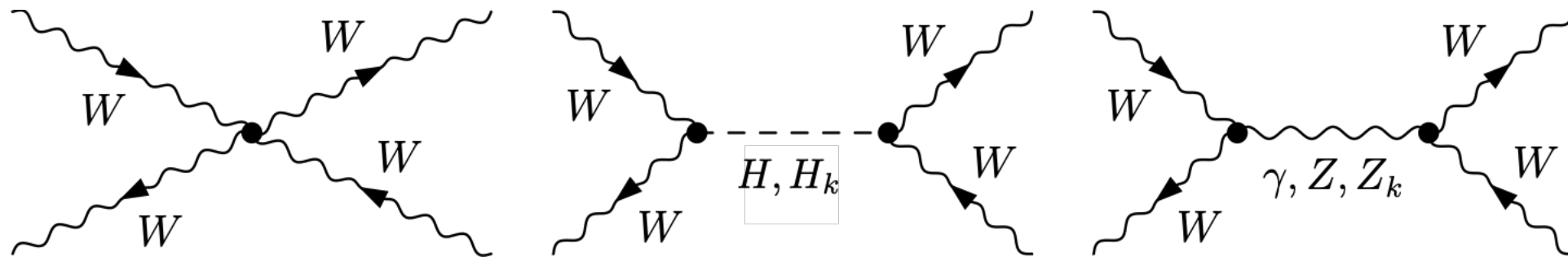
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prediction

Higgs deviation

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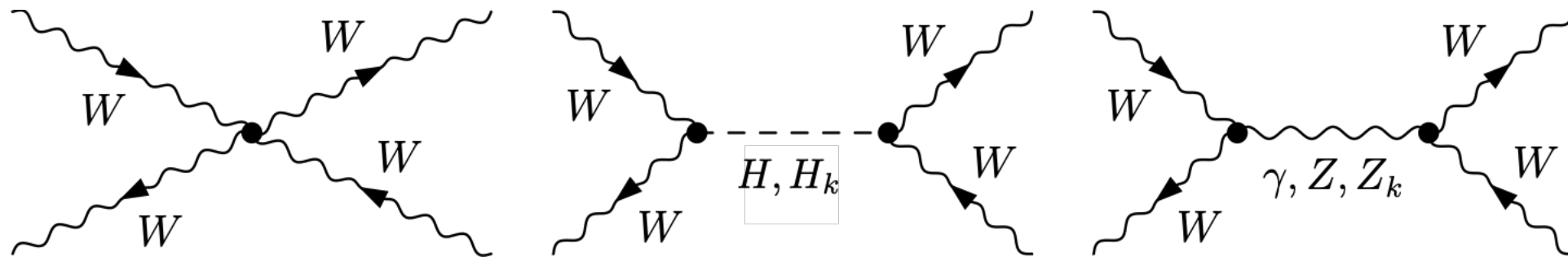
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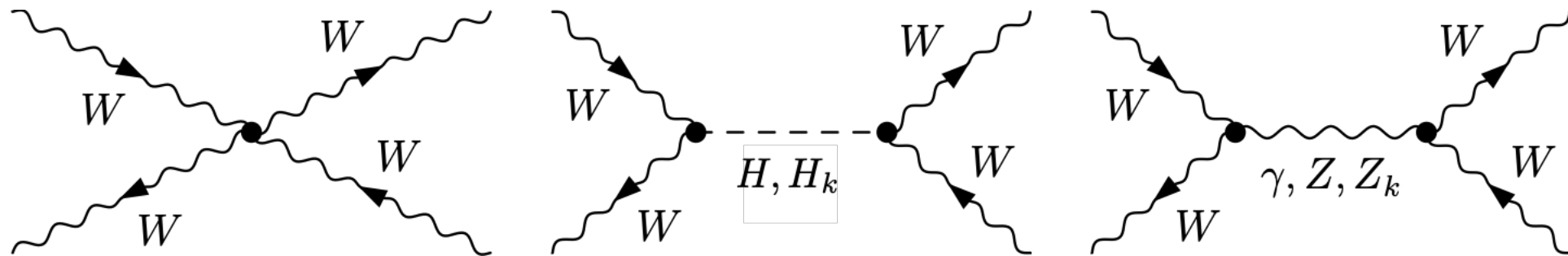
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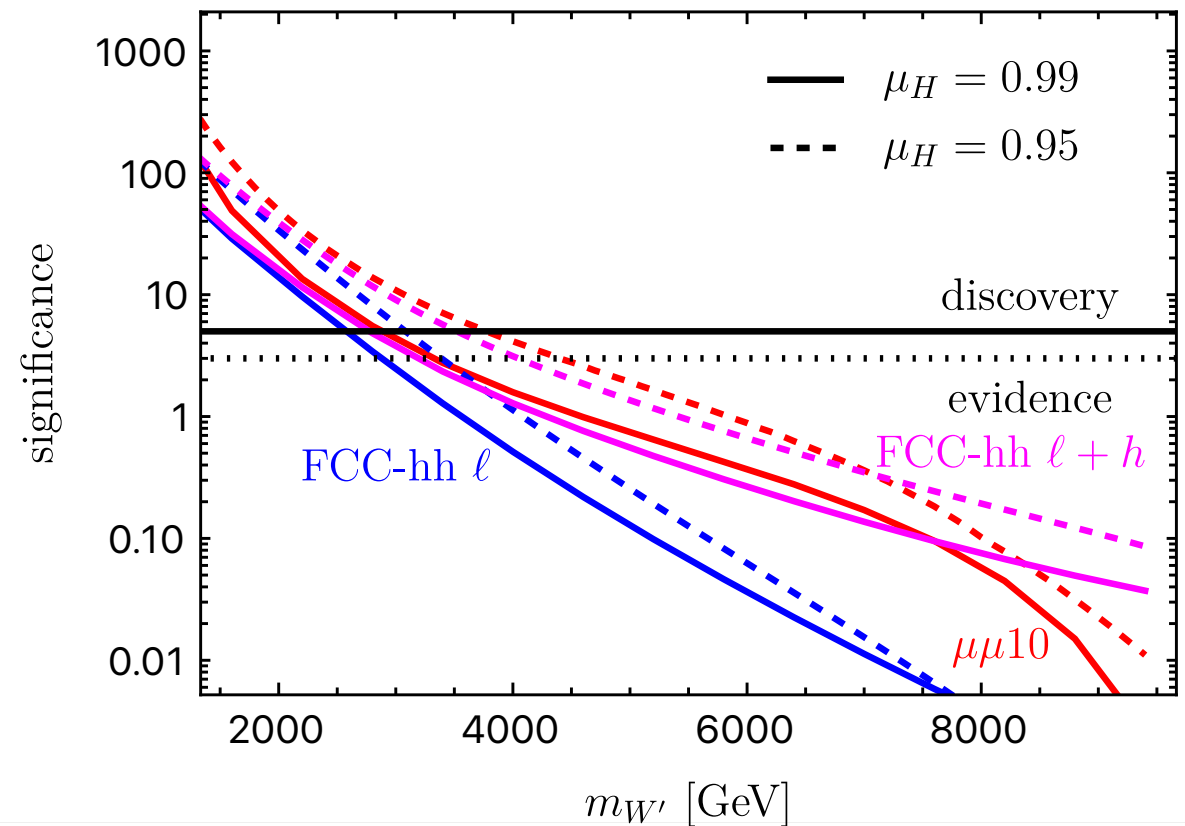
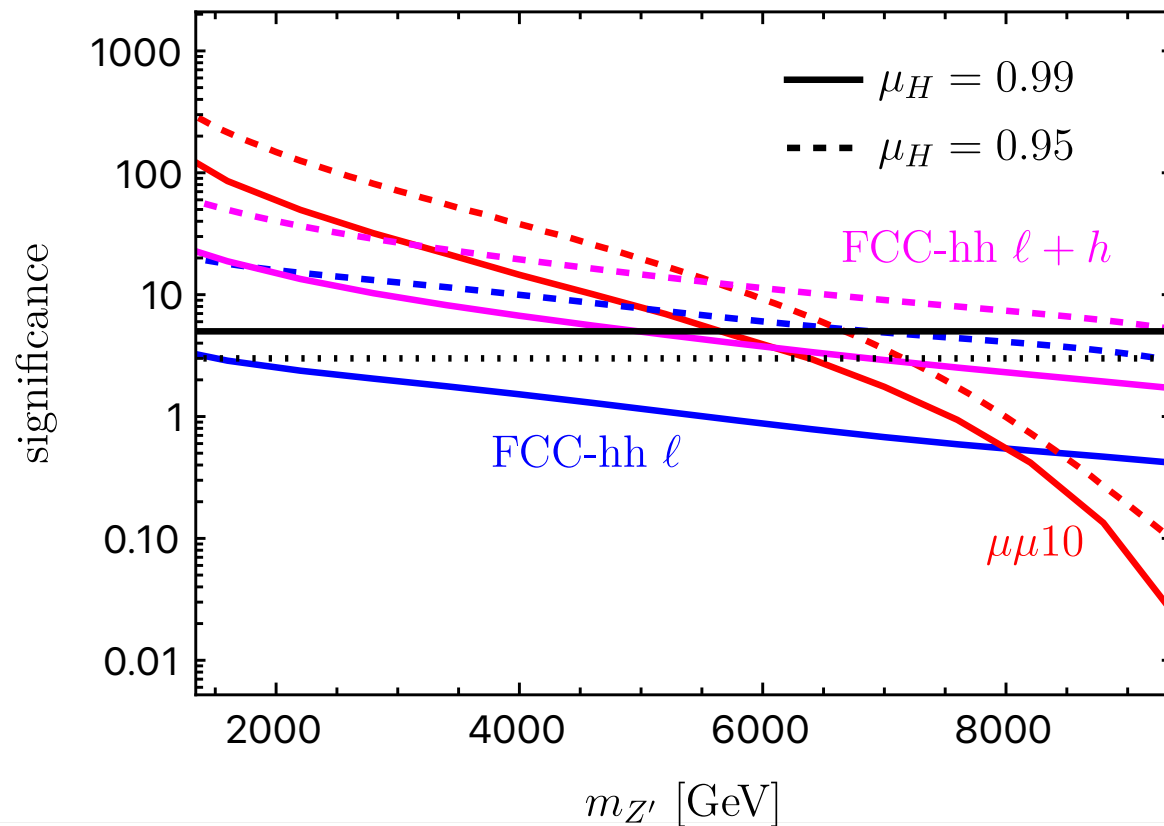
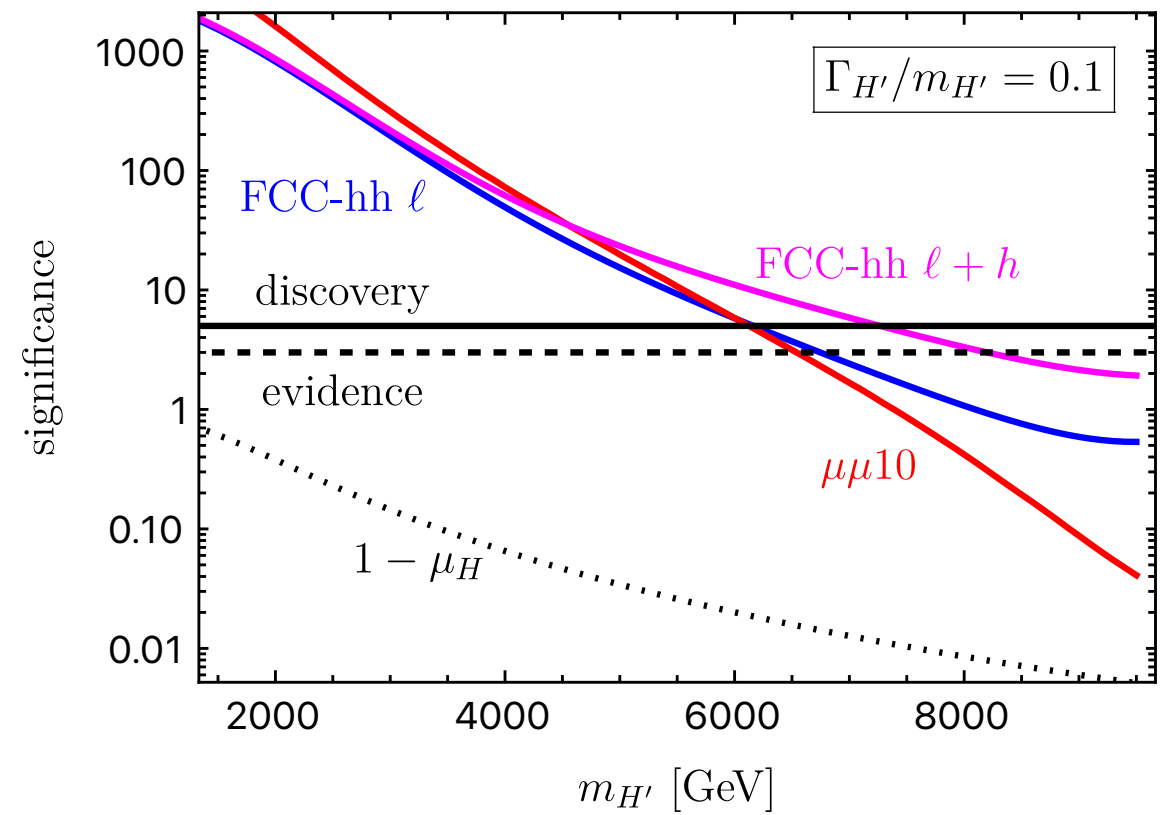
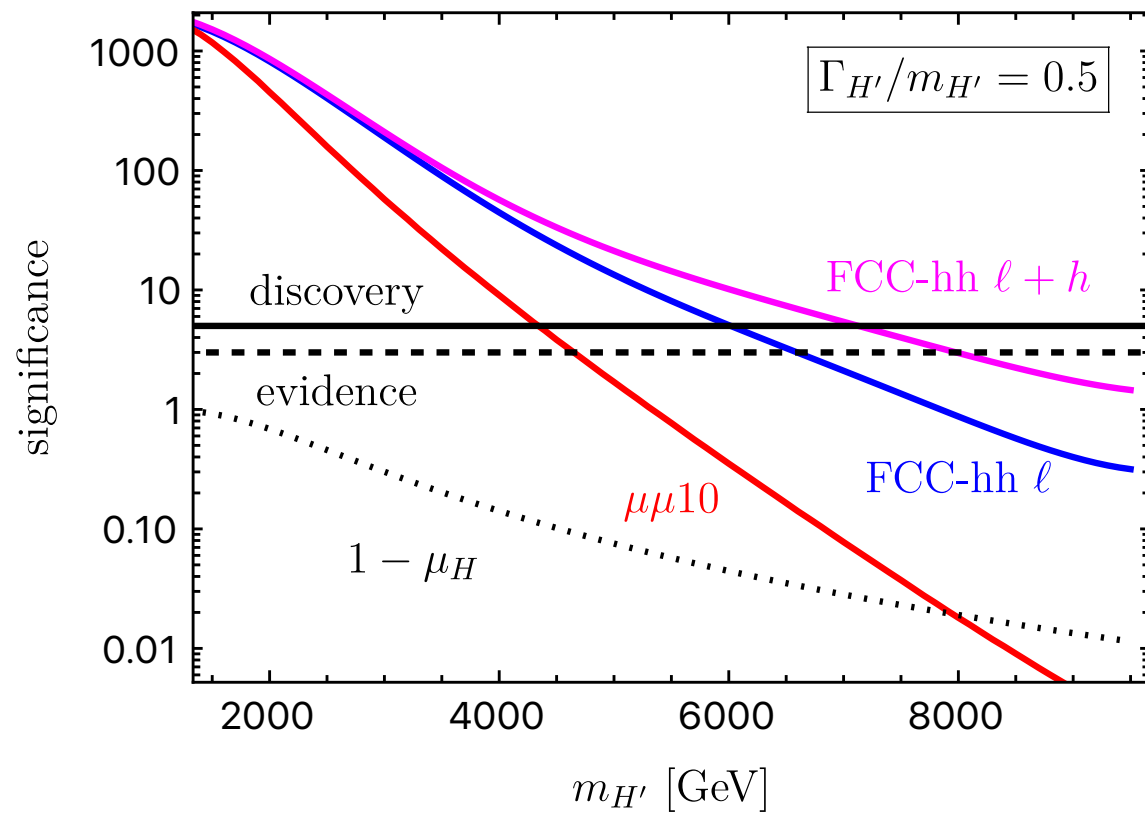
Higgs deviation

pheno determined by unitarity, gauge
symmetry ($d > 4$), and convergence

prediction

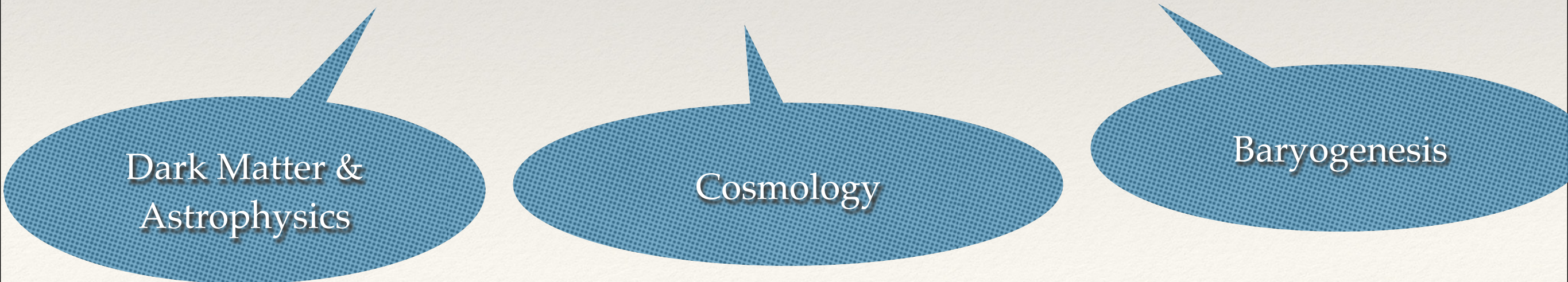
unitarity for discovery

[CE, Pilkington, Spannowsky, Naskar, hopefully in time for Xmas]



Summary

- ▶ no new physics so far; no shortage of progress, ideas, opportunities,...
- ▶ theoretical/experimental inconsistencies are clearer than ever
- ▶ holistically-informed & directed effort for discovery-led physics
first principles motivation & calculation, model-(in)dependent techniques, ML,
- ▶ only limited insights into the electroweak scale so far
 - ▮ margins get smaller, but are big enough for surprises
 - ▮ collider pheno directly relevant for other pheno arenas



Dark Matter &
Astrophysics

Cosmology

Baryogenesis