LEVERHULME TRUST

MANCHESTER 1824
The University of Manchester

Christoph Englert

Highlights in Collider Phenomenology

Annual Theory Meeting

16/12/25

The overaching 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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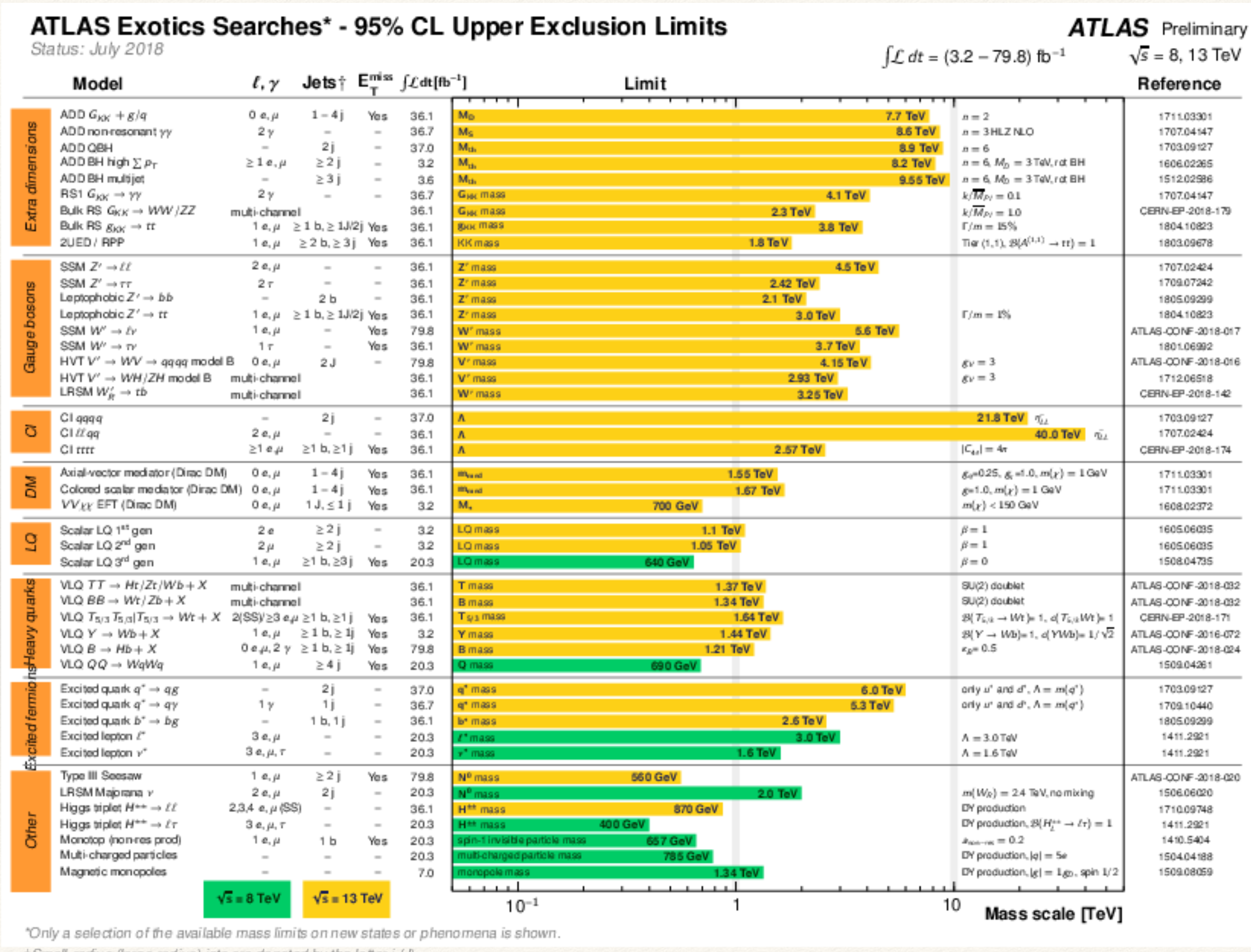
…which should equip us with ambition and optimism.

→ 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…



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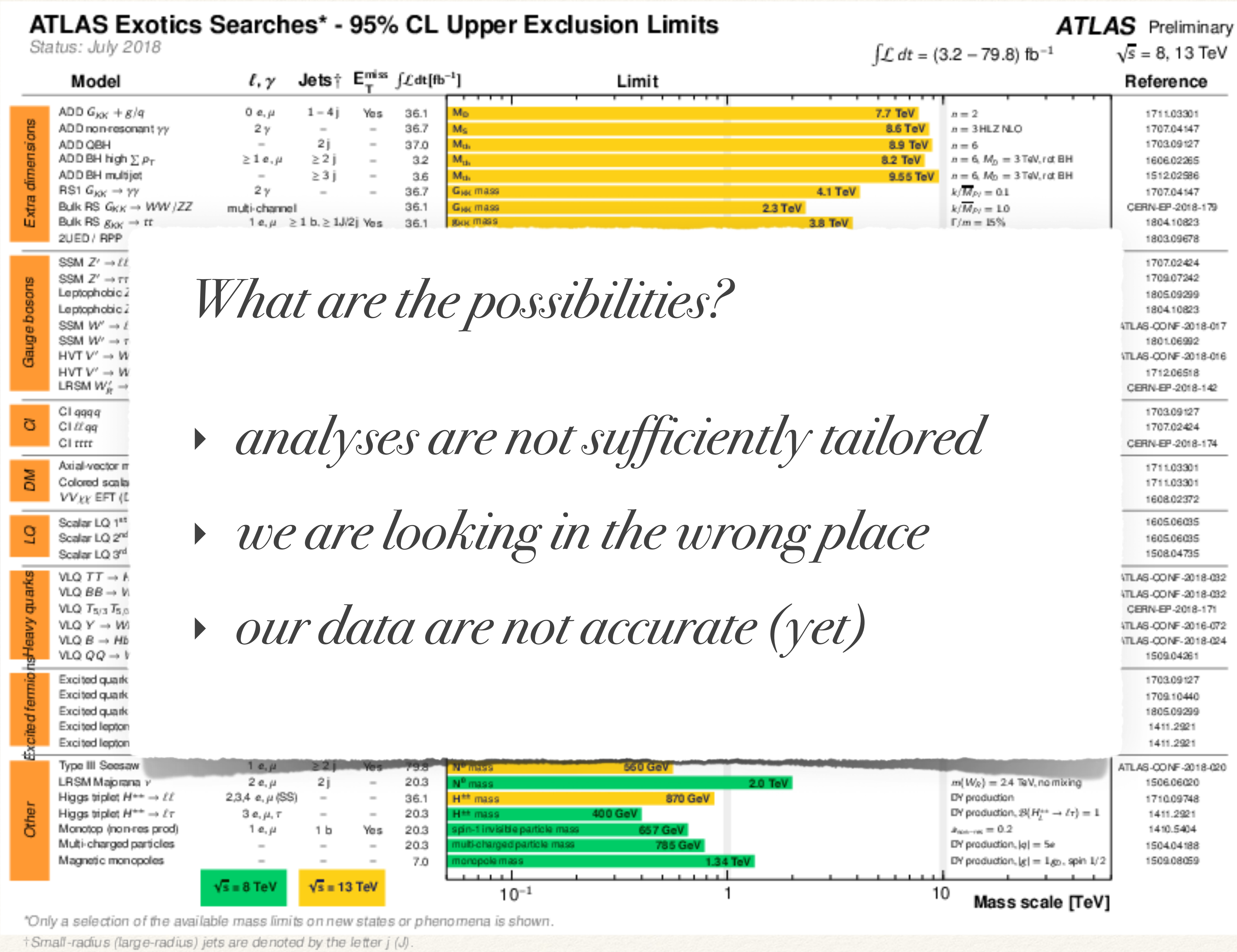

What are the possibilities?

- *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

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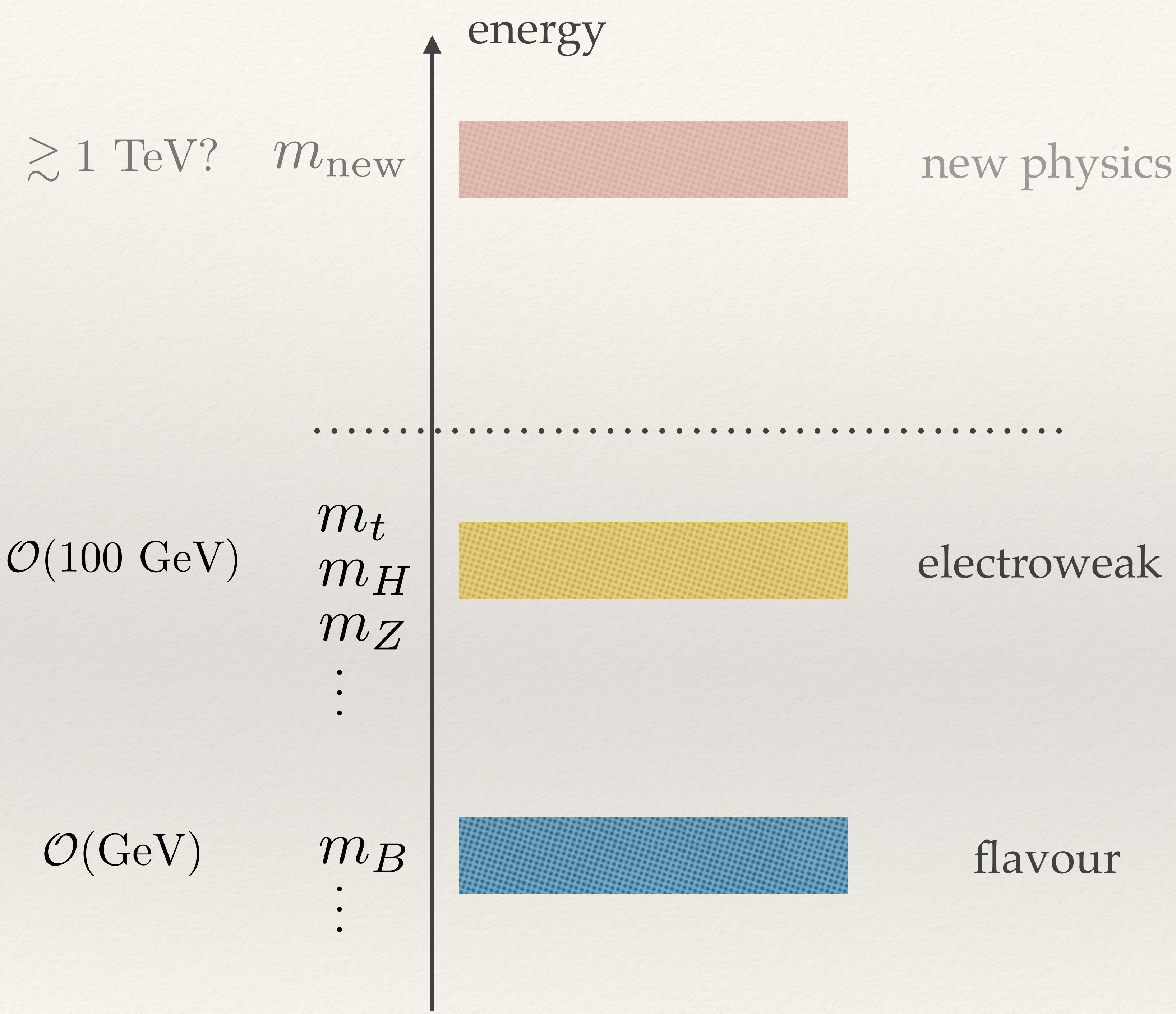
bottom-up approach: EFT



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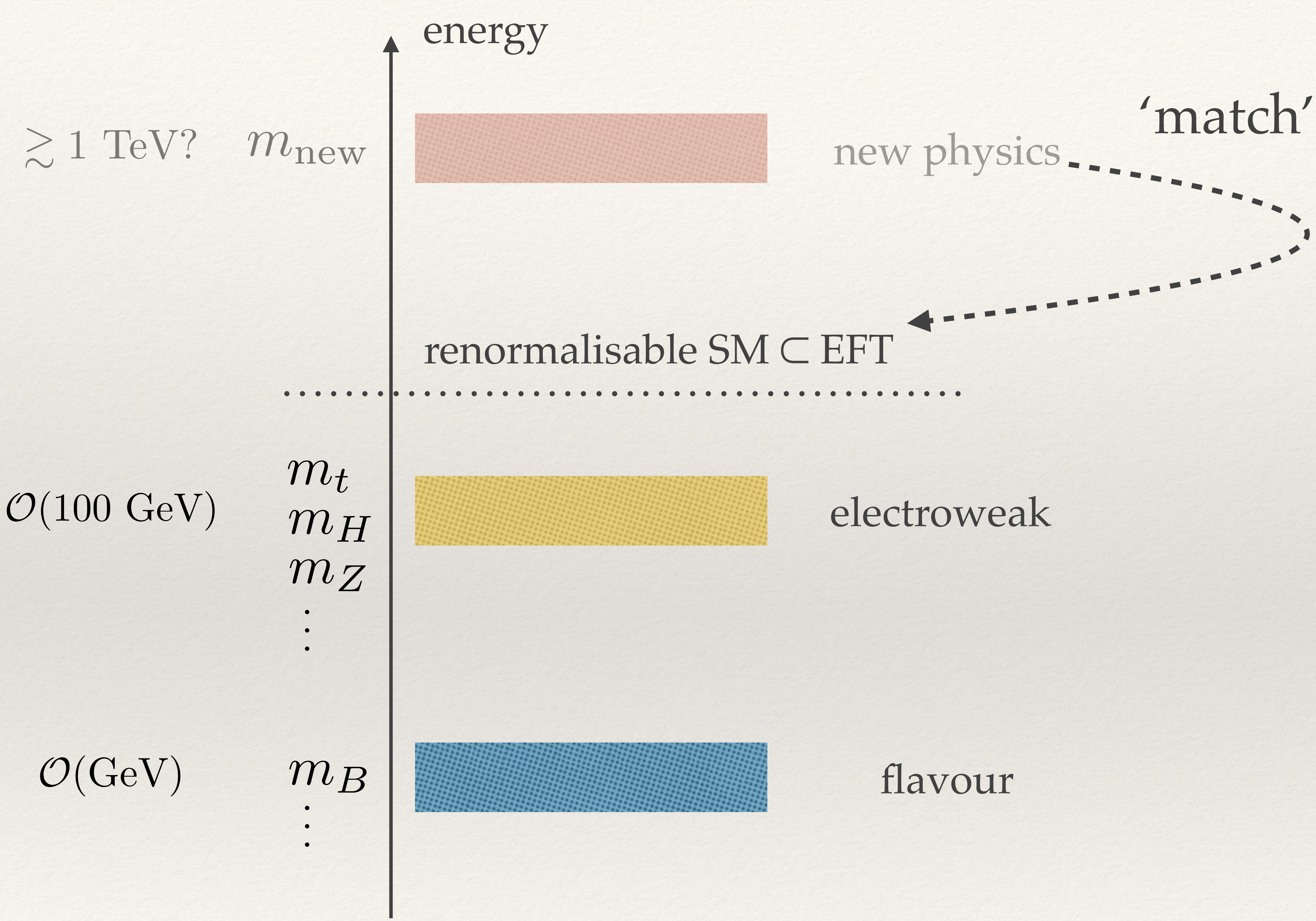

[de Blas et al. `17]
[Banerjee et al. `20]
[Naskar et al. `22]
[Guedes et al. `23, `24]
[Adhikary et al. 25]
…

bottom-up approach: EFT

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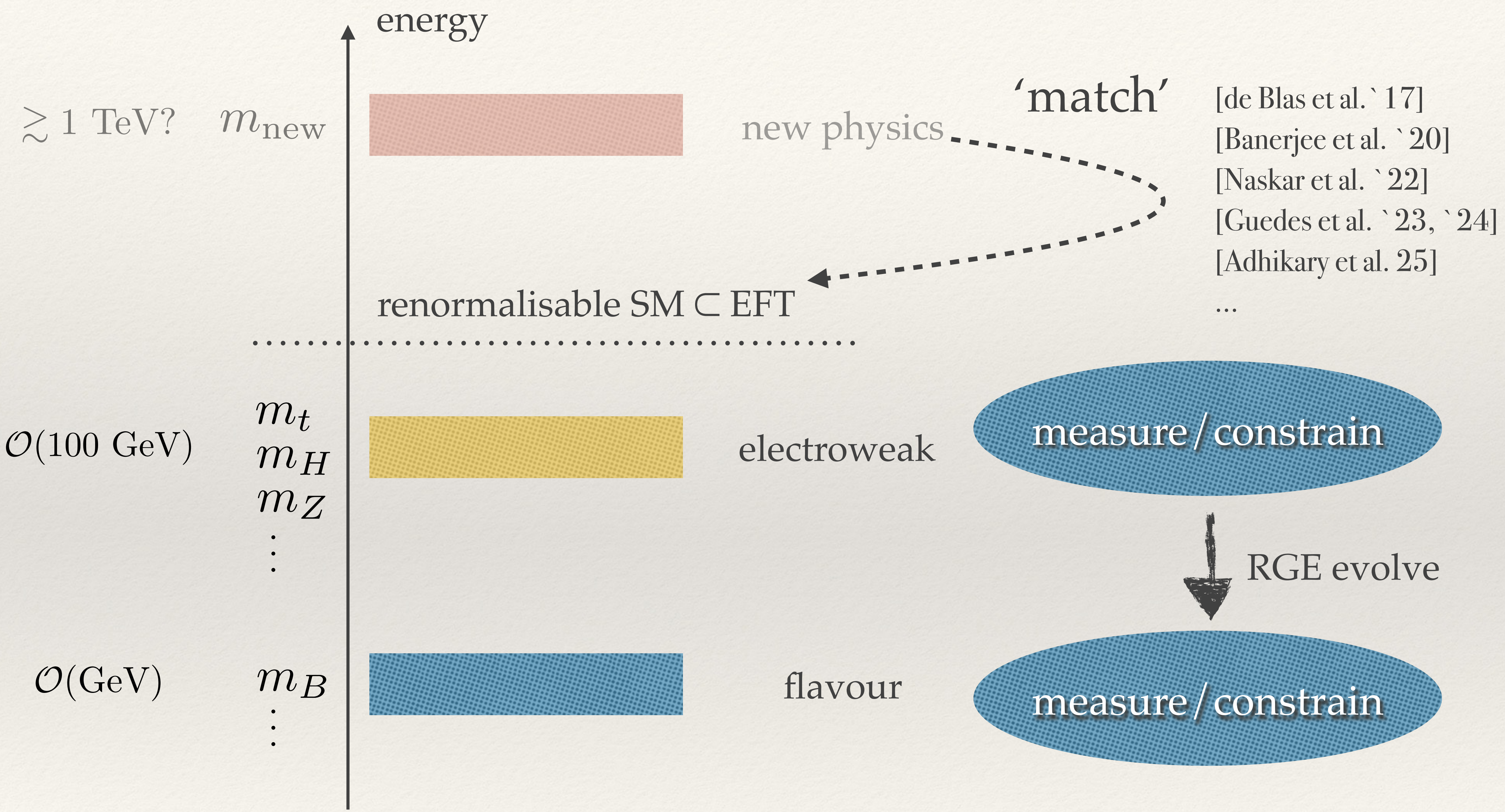
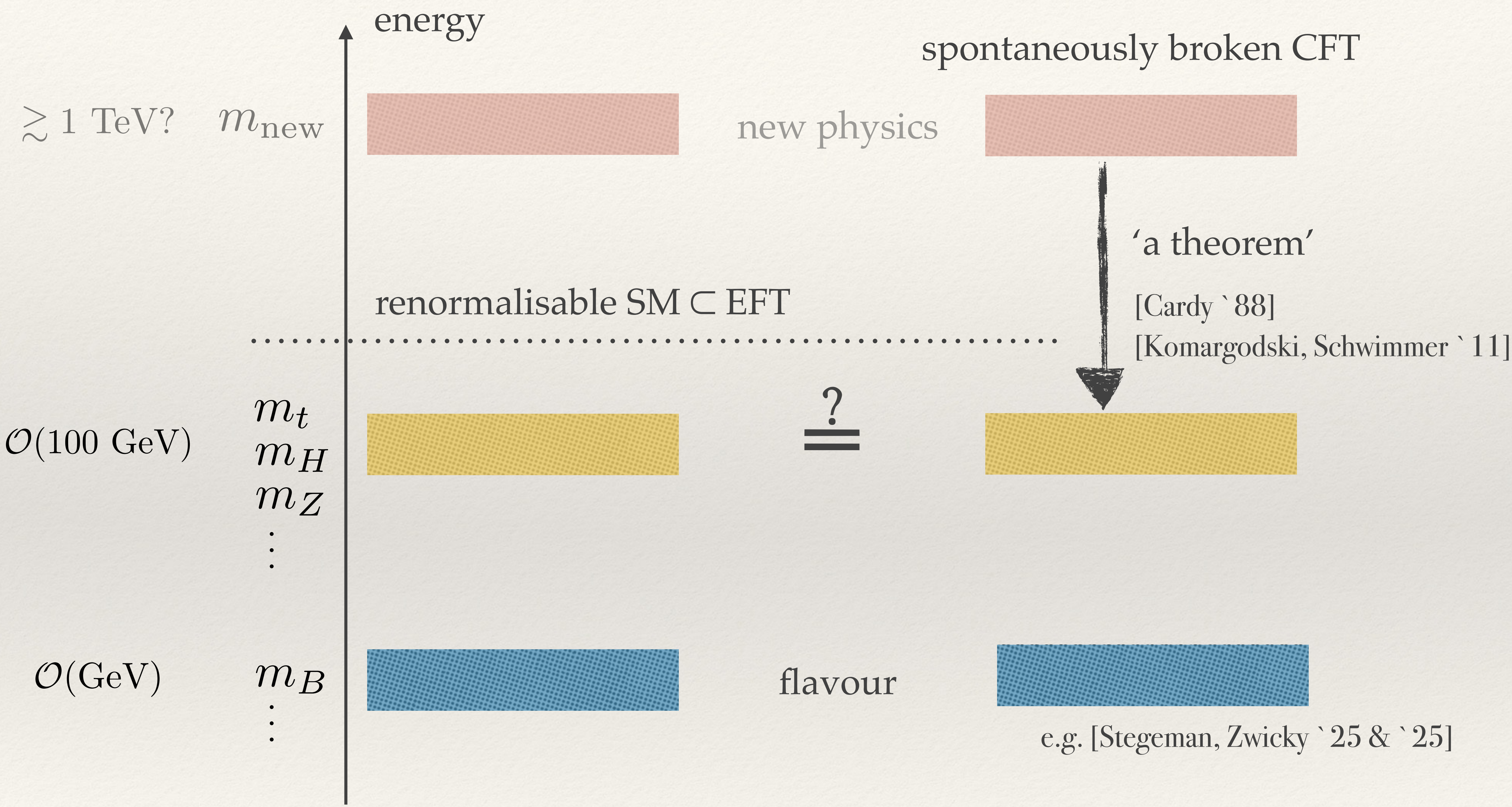


bottom-up approach: EFT

theoretical ambition



(pert.) Quantum Field Theory = Prediction of Correlations

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SMEFT SU(2)xU(1)/U(1) (+ flavour)

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

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

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]
...

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HEFT SU(2)xSU(2)/SU(2) (+ flavour)

"technicolour"/ χPT + singlet scalar

- CCWZ construction of EW scale + observed states [Coleman, Wess, Zumino `69] [Callan, Coleman, Wess, Zumino `69]
- large number of parameters cf. counting [Brivio et al. `25]
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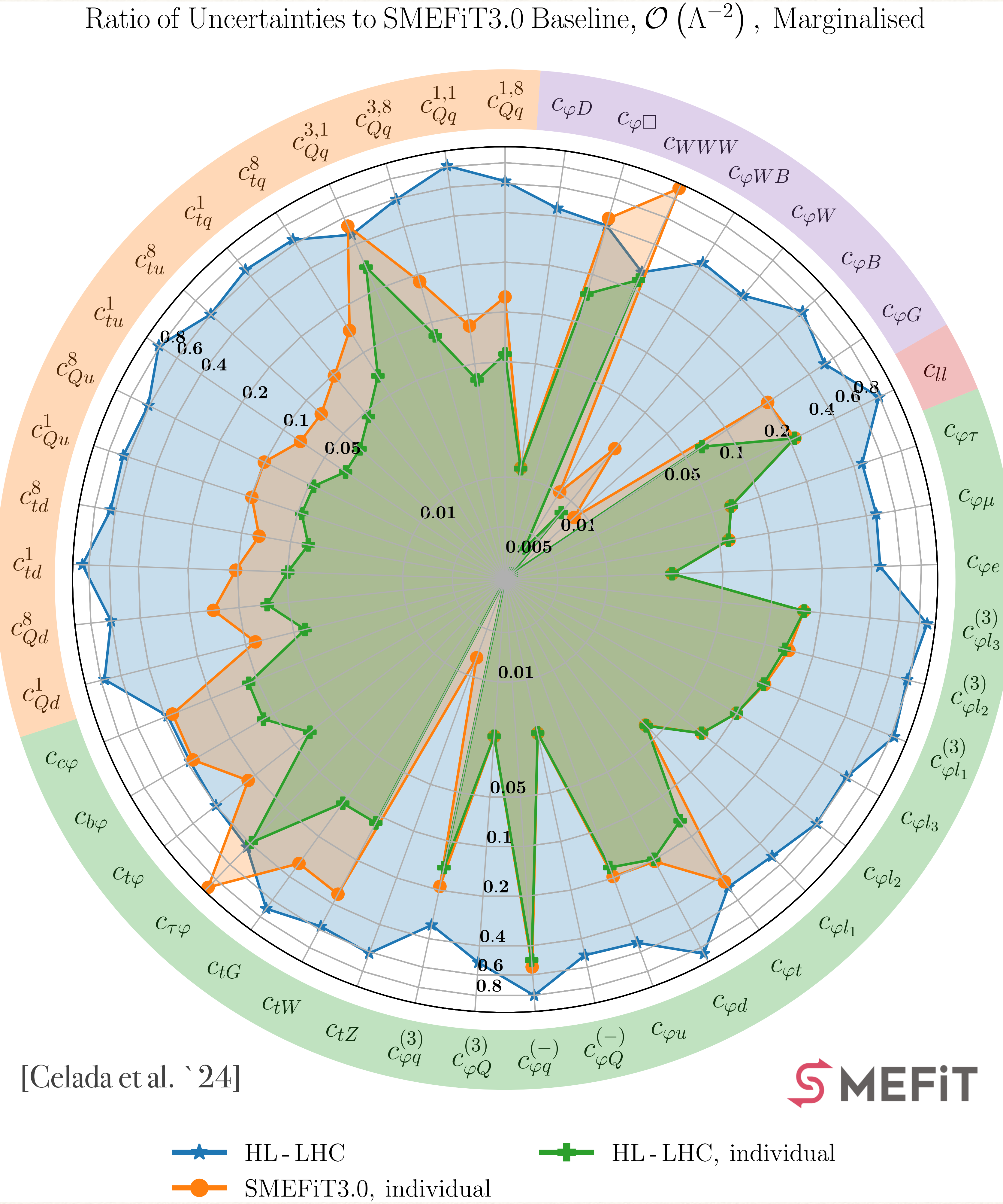
[Alonso et al. `16]
[Craig et al. `21]
[Anisha et al. `22]
[CE, Naskar, Sutherland `23]
⋮



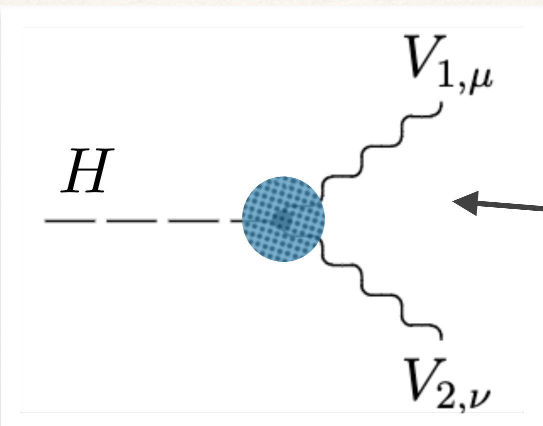
SMEFT analyses

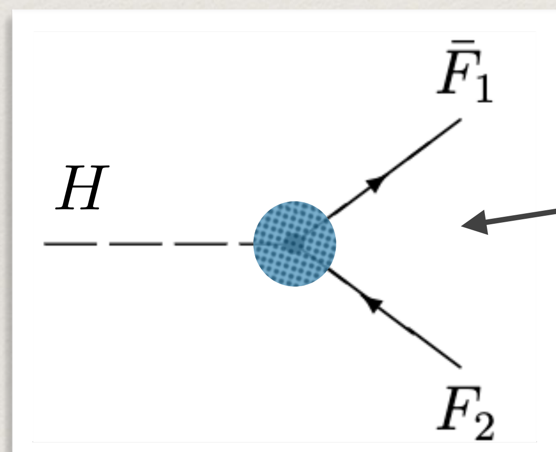
- …well underway…
- …with exp. buy-in!
- plethora of parameters
- <u>flavour-blind</u> results: 0.1-1/TeV^2 sensitivity
- improvements towards HL-LHC possible via data…
- …not a silver bullet for BSM discovery
- flavoured models as counterexamples

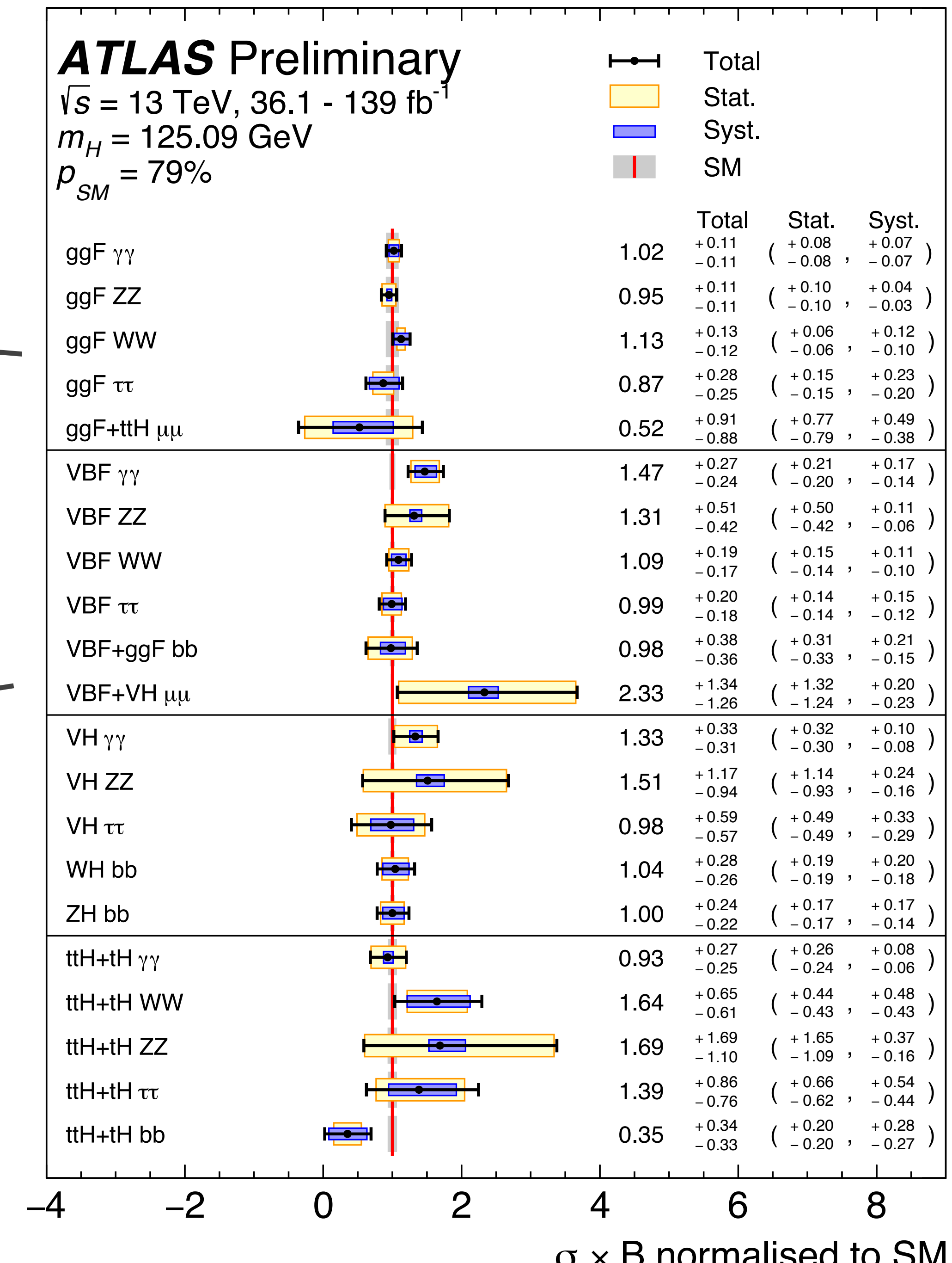
…[CE, Mayer, Naskar, Renner` 24]

no reason to be so pessimistic at this point!

single Higgs physics seems to favour the SM







e.g. [ATLAS `21]

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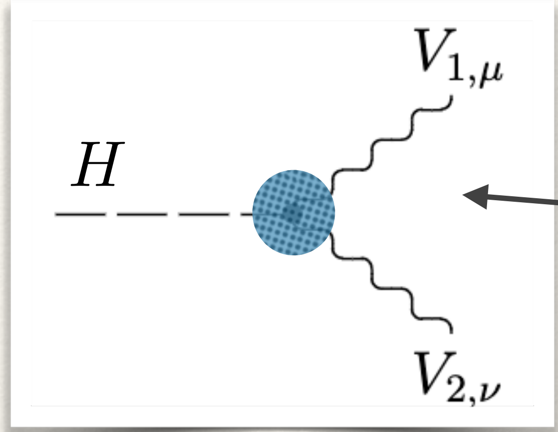
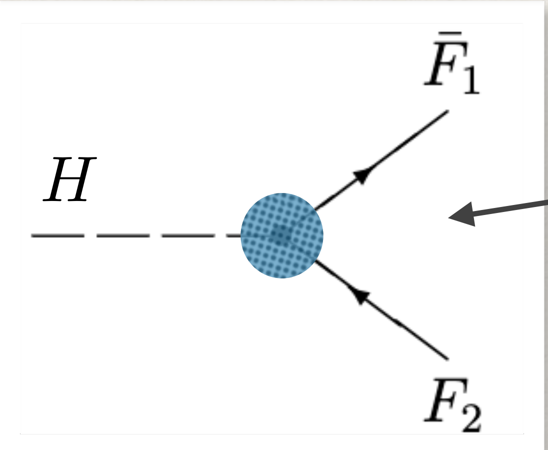
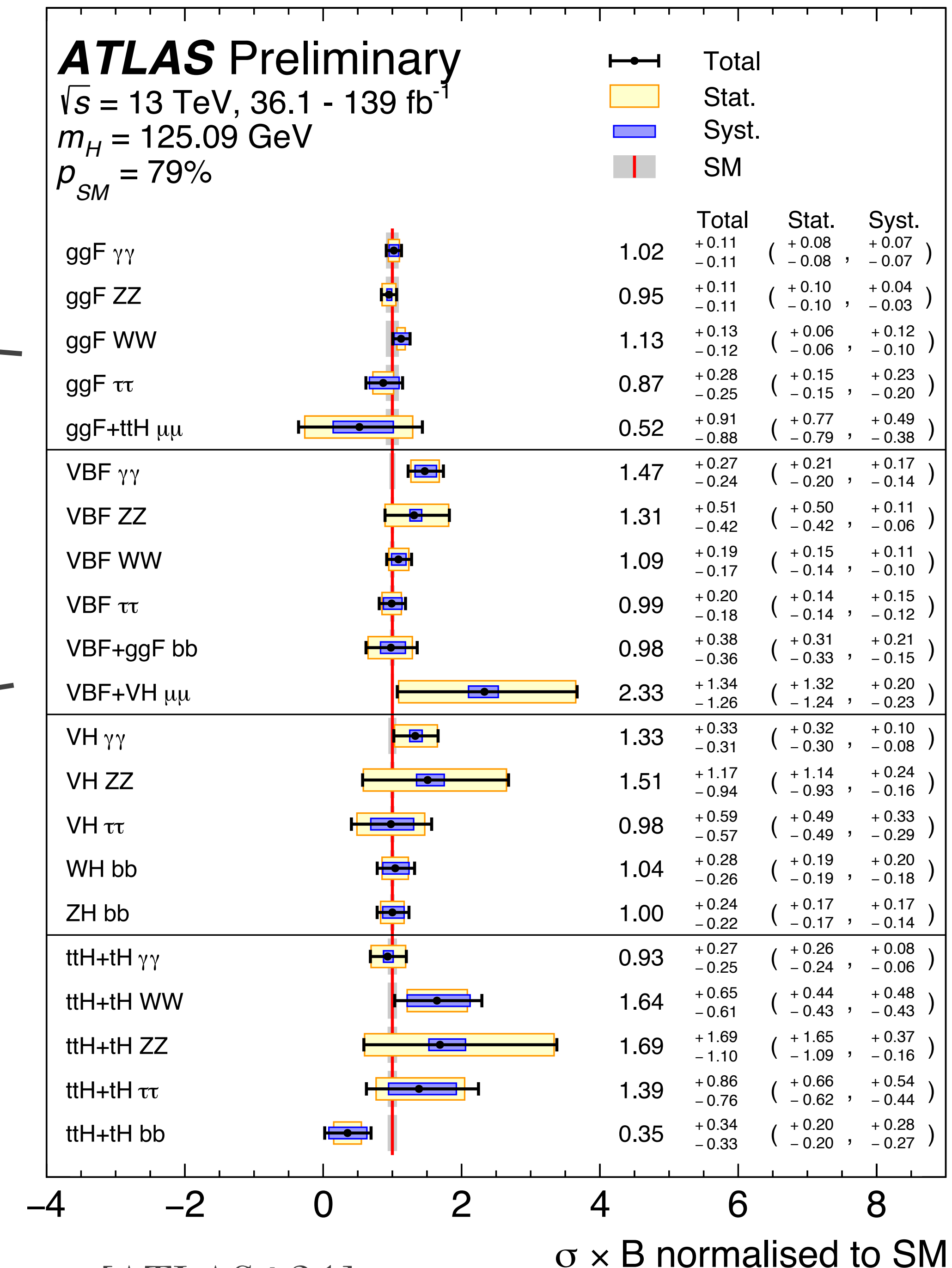




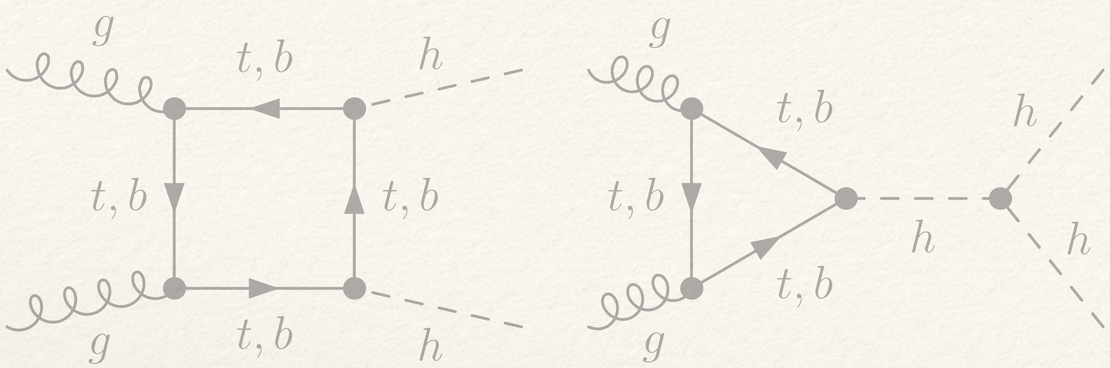


e.g. [ATLAS `21]

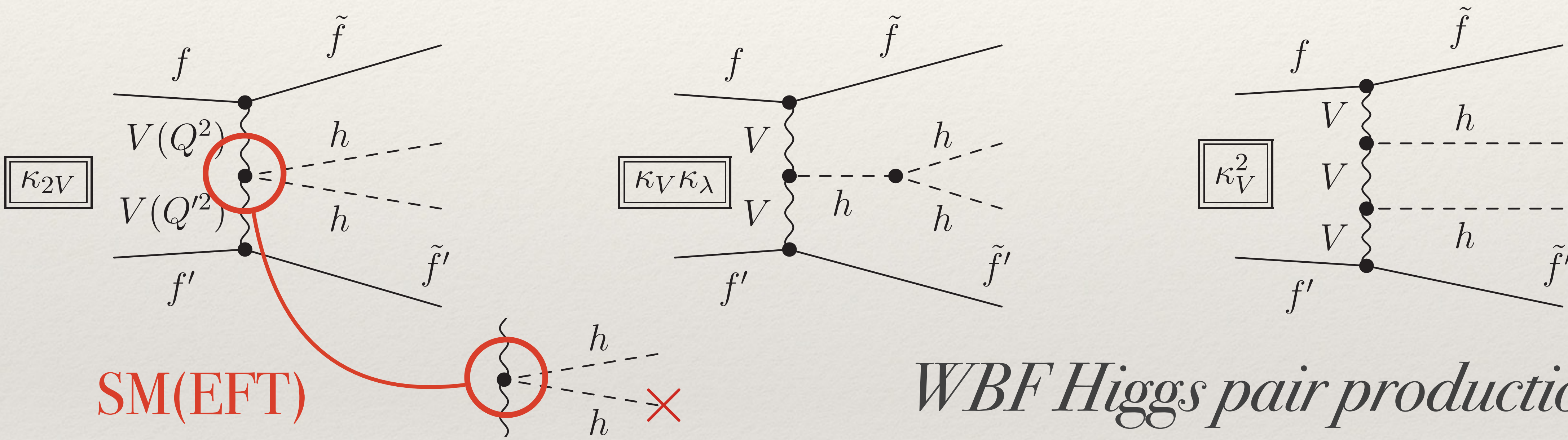
find glory in multi-Higgs final states?

...[Baur, Plehn, Rainwater `02] ... [CE, Carlson, Sjölin, Spannowsky `25] [Brivio et al `25] [Domenech et al. `25] [Dedes et al. `25]

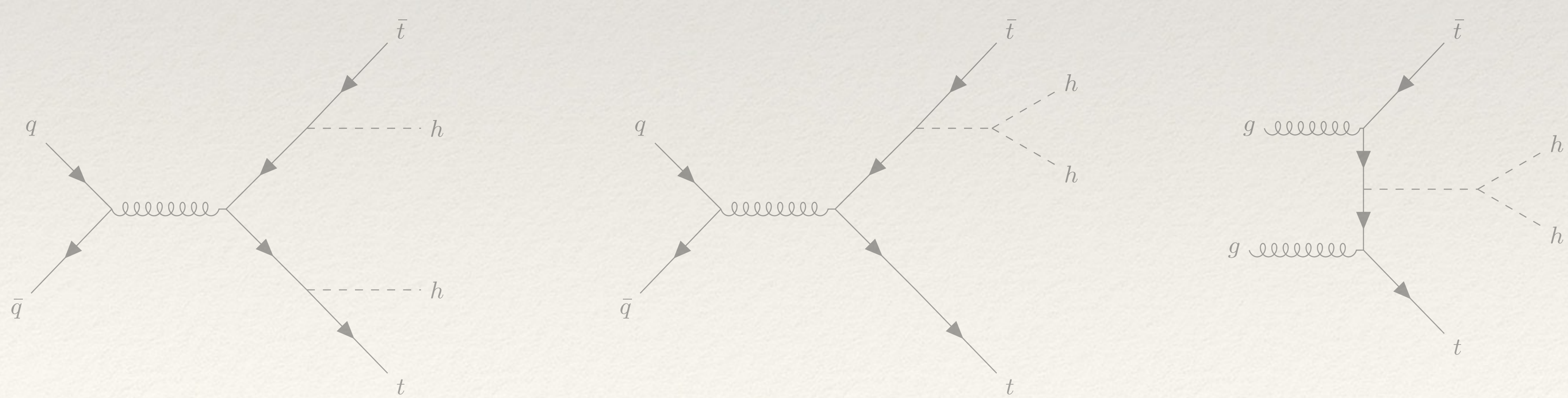
collider probes



GF Higgs pair production ~30 fb

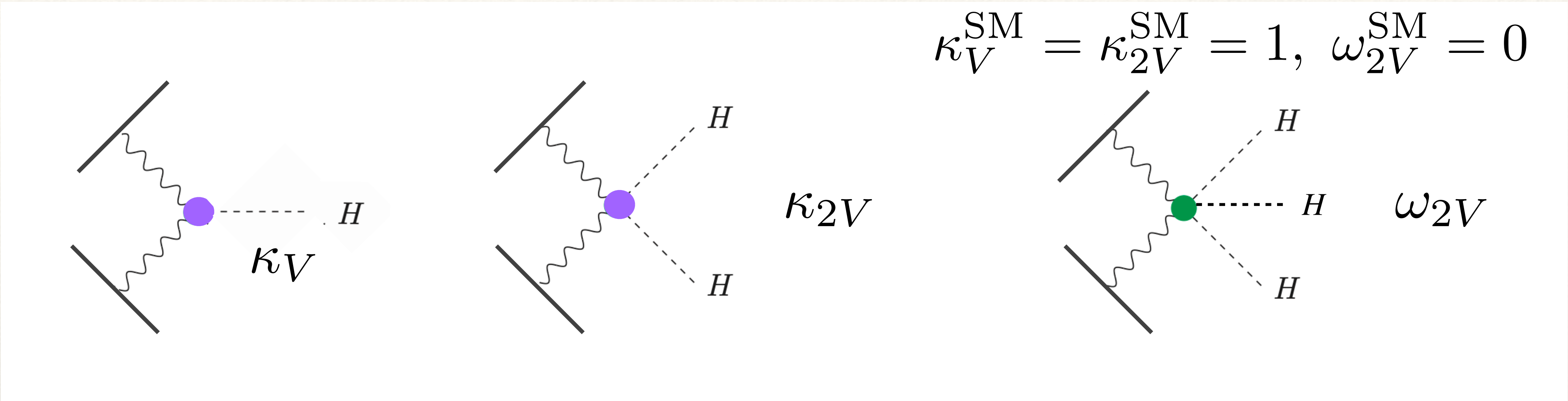


WBF Higgs pair production ~1 fb



top-associated Higgs pair production ≲1 fb

- 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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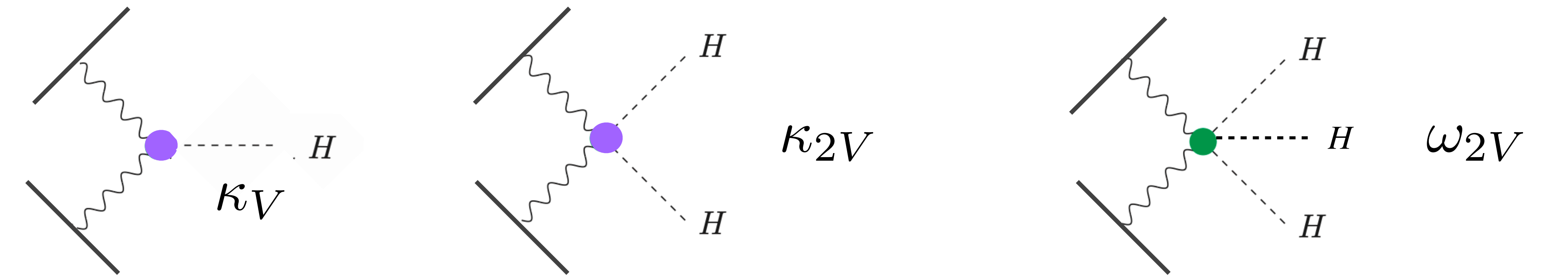
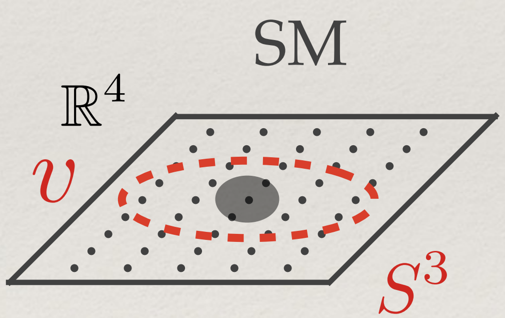


geometrical probe of the ELWSB manifold



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[Alonso et al. `16]
[Alonso, West `21]
[Anisha, Domenech et al. `22]
[Alonso, Chattopadhyay, Ingoldby `25]

beyond single Higgs bosons?

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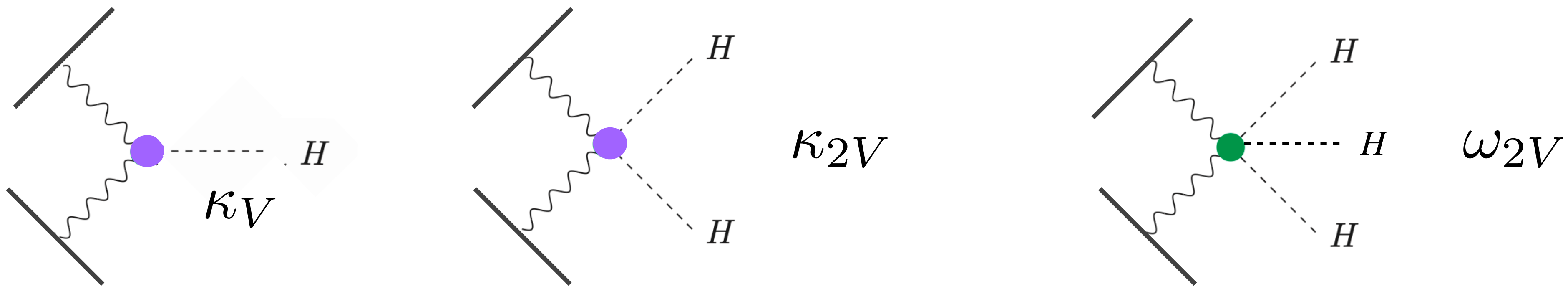

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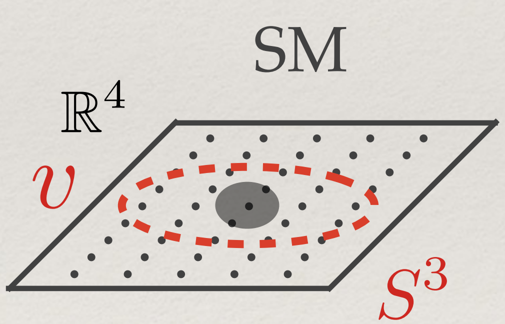

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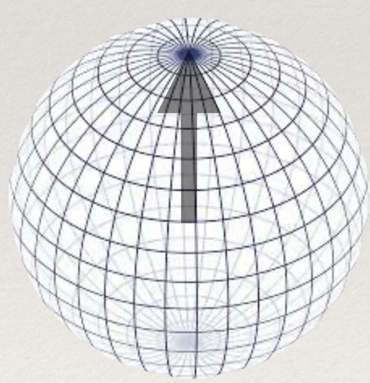

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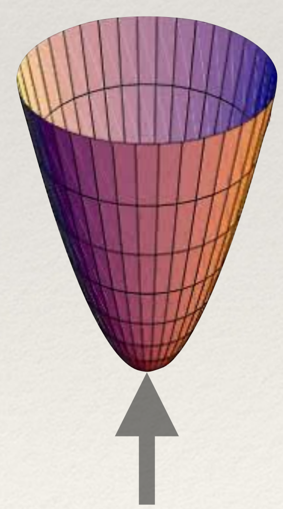

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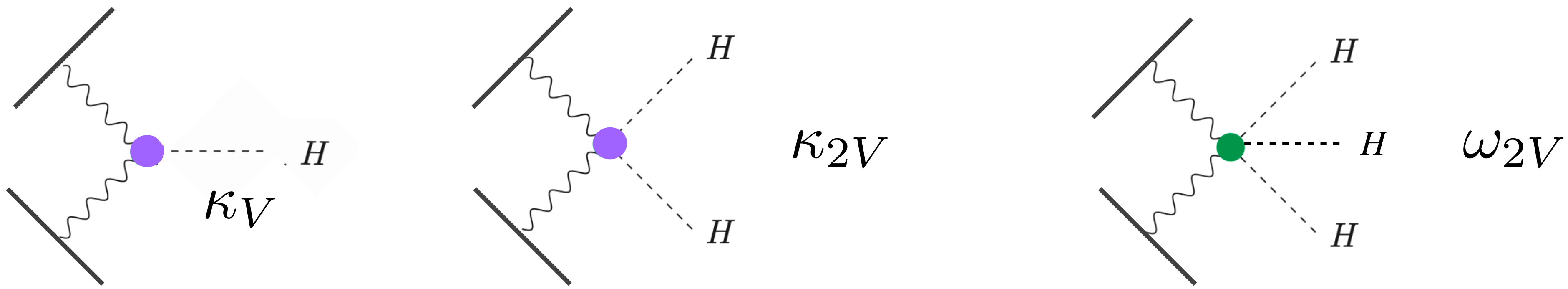
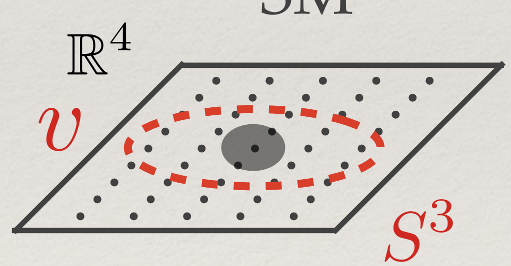


geometrical probe of the ELWSB manifold

SM



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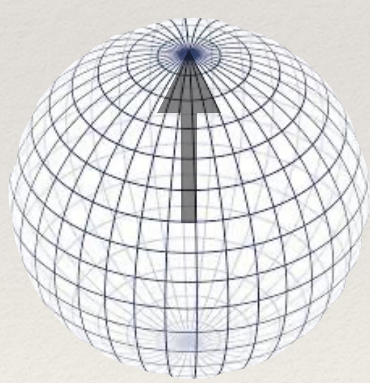

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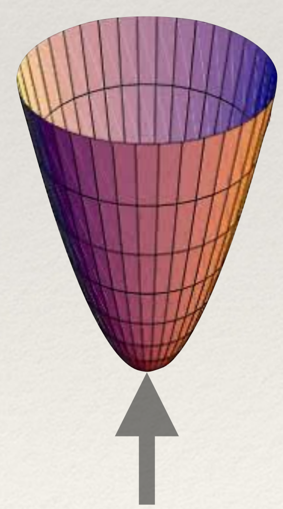

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composite Higgs theories

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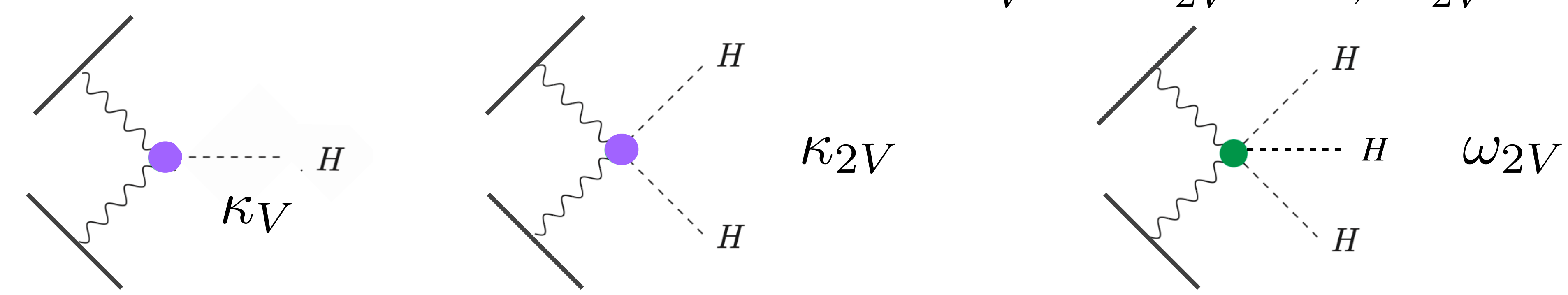

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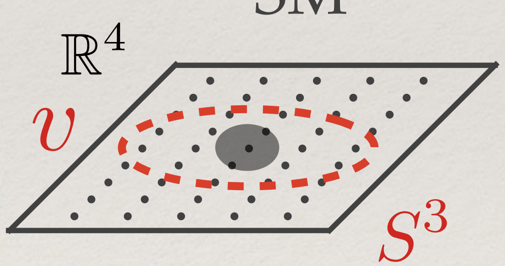

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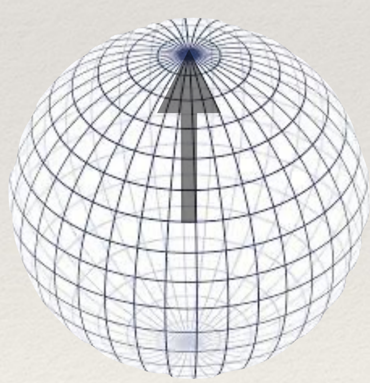

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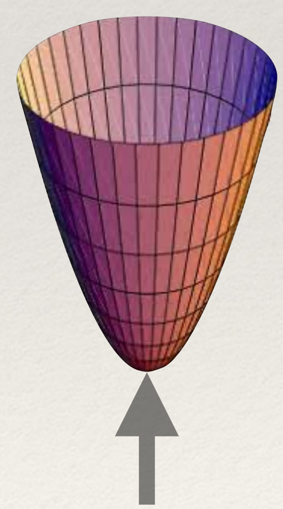

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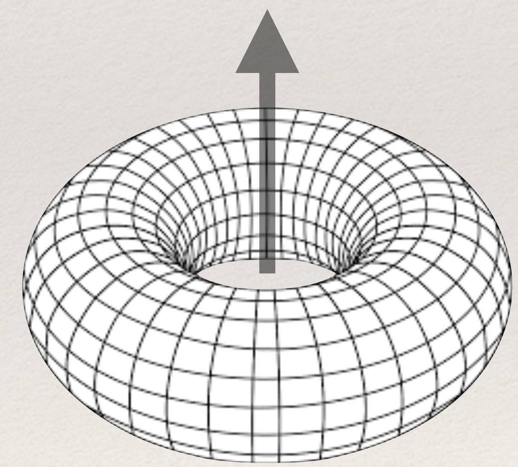

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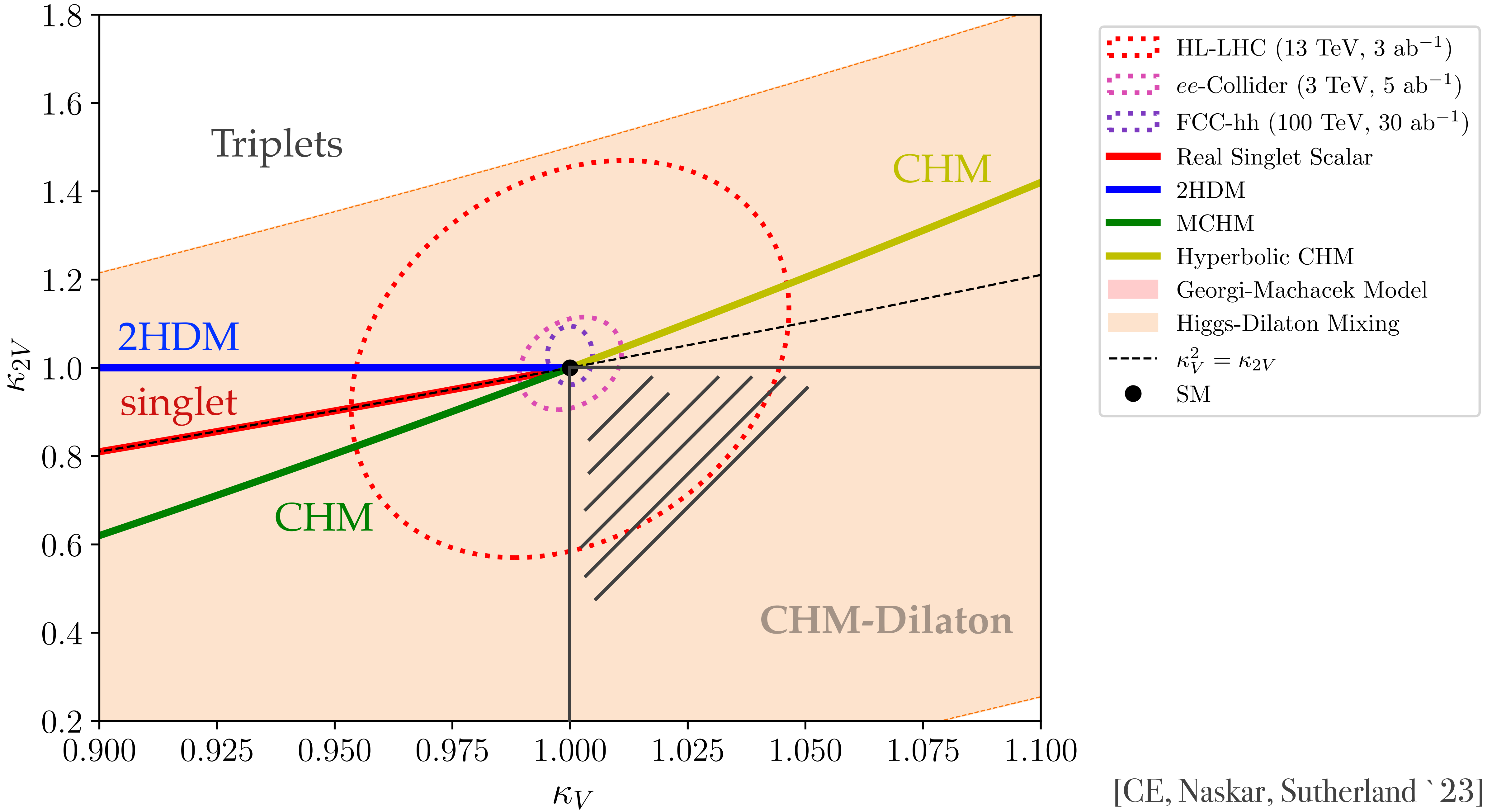
composite Higgs theories

intrinsic HEFT

charting phenomenological possibilities

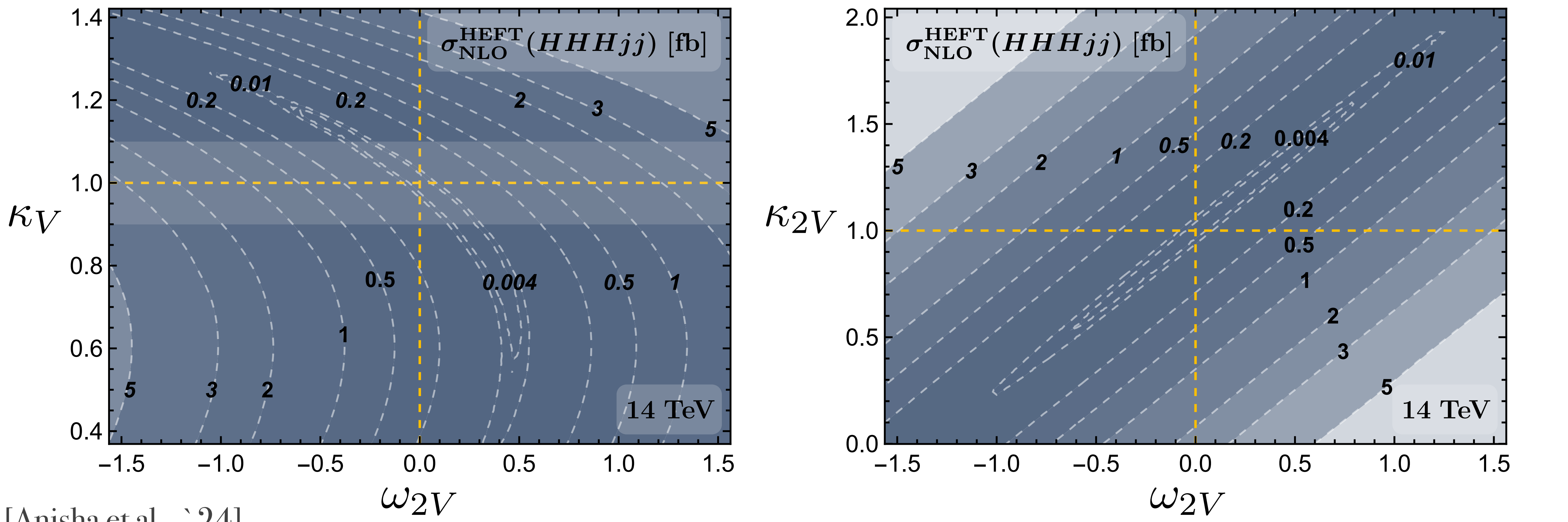


[CE, Naskar, Sutherland `23]

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

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

triple Higgs?



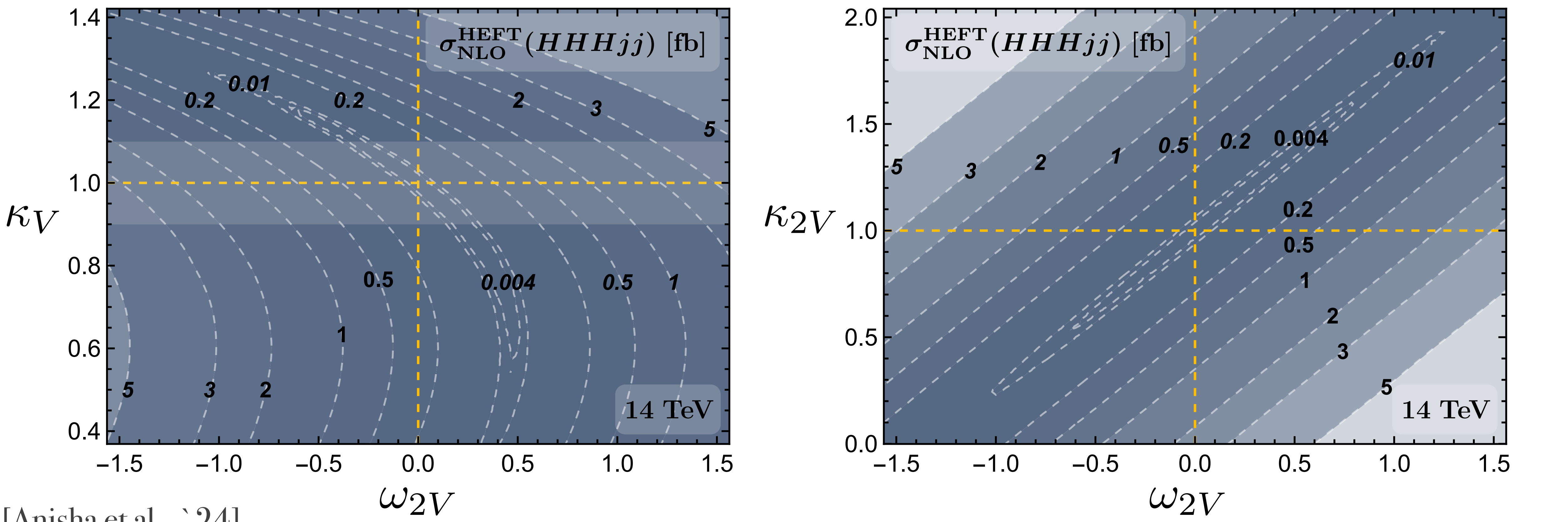
[Anisha et al., `24]

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

WBF is a clear window into (strong) ELW effects

- *H* easy, *HH* doable, *HHH* 😱

[Celada et al. `23]



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- 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

$$\mathcal{L} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \mathcal{L}_{\text{ferm}} + \mathcal{L}_{\text{Yuk}}$$

$$+ \frac{v^2}{4}\mathcal{F}_H \,\text{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H) + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{FP}}$$

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

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radiatively source `higher-dimensional` interactions

$\mathcal{O}_0$	$a_0(M_Z^2 - M_W^2)\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]$
$\mathcal{O}_1$	$a_1\, g' g_W\, \text{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$
$\mathcal{O}_{HBB}$	$-a_{HBB}\, g'^2\frac{H}{v}\text{Tr}\left[B_{\mu\nu}B^{\mu\nu}\right]$
$\mathcal{O}_{HWW}$	$-a_{HWW}\, g_W^2\frac{H}{v}\text{Tr}\left[W^a_{\mu\nu}W^{a\mu\nu}\right]$
$\mathcal{O}_{\Box\mathcal{V}\mathcal{V}}$	$a_{\Box\mathcal{V}\mathcal{V}}\frac{\Box H}{v}\text{Tr}\left[\boldsymbol{\mathcal{V}}_\mu\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{H0}$	$a_{H0}(M_Z^2 - M_W^2)\frac{H}{v}\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]$
$\mathcal{O}_{H1}$	$a_{H1}\, g' g_W\frac{H}{v}\text{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$
$\mathcal{O}_{H11}$	$a_{H11}\frac{H}{v}\text{Tr}\left[\mathcal{D}_\mu\boldsymbol{\mathcal{V}}^\mu\mathcal{D}_\nu\boldsymbol{\mathcal{V}}^\nu\right]$
$\mathcal{O}_{d1}$	$ia_{d1}\, g'\frac{\partial^\nu H}{v}\text{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{d2}$	$ia_{d2}\, g_W\frac{\partial^\nu H}{v}\text{Tr}\left[W^a_{\mu\nu}\frac{\tau^a}{2}\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{d3}$	$a_{d3}\frac{\partial^\nu H}{v}\text{Tr}\left[\boldsymbol{\mathcal{V}}^\mu\mathcal{D}_\mu\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{\Box\Box}$	$a_{\Box\Box}\frac{\Box H\Box H}{v^2}$

[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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$\mathcal{O}_0$	$a_0(M_Z^2 - M_W^2)\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]$
$\mathcal{O}_1$	$a_1\,g'g_W\,\text{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$
$\mathcal{O}_{HBB}$	$-a_{HBB}\,g'^2\frac{H}{v}\text{Tr}\left[B_{\mu\nu}B^{\mu\nu}\right]$
$\mathcal{O}_{HWW}$	$-a_{HWW}\,g_W^2\frac{H}{v}\text{Tr}\left[W^a_{\mu\nu}W^{a\mu\nu}\right]$
$\mathcal{O}_{\Box\mathcal{V}\mathcal{V}}$	$a_{\Box\mathcal{V}\mathcal{V}}\frac{\Box H}{v}\text{Tr}\left[\boldsymbol{\mathcal{V}}_\mu\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{H0}$	$a_{H0}(M_Z^2 - M_W^2)\frac{H}{v}\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]\text{Tr}\left[U\tau^3U^\dagger\boldsymbol{\mathcal{V}}_\mu\right]$
$\mathcal{O}_{H1}$	$a_{H1}\,g'g_W\frac{H}{v}\text{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$
$\mathcal{O}_{H11}$	$a_{H11}\frac{H}{v}\text{Tr}\left[\mathcal{D}_\mu\boldsymbol{\mathcal{V}}^\mu\mathcal{D}_\nu\boldsymbol{\mathcal{V}}^\nu\right]$
$\mathcal{O}_{d1}$	$ia_{d1}\,g'\frac{\partial^\nu H}{v}\text{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{d2}$	$ia_{d2}\,g_W\frac{\partial^\nu H}{v}\text{Tr}\left[W^a_{\mu\nu}\frac{\tau^a}{2}\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{d3}$	$a_{d3}\frac{\partial^\nu H}{v}\text{Tr}\left[\boldsymbol{\mathcal{V}}^\mu\mathcal{D}_\mu\boldsymbol{\mathcal{V}}^\mu\right]$
$\mathcal{O}_{\Box\Box}$	$a_{\Box\Box}\frac{\Box H\Box H}{v^2}$

κ_V κ_{2V}

$$\mathcal{F}_H = \left(1 + 2(1+\zeta_1)\frac{H}{v} + (1+\zeta_2)\left(\frac{H}{v}\right)^2 + \ldots\right)$$

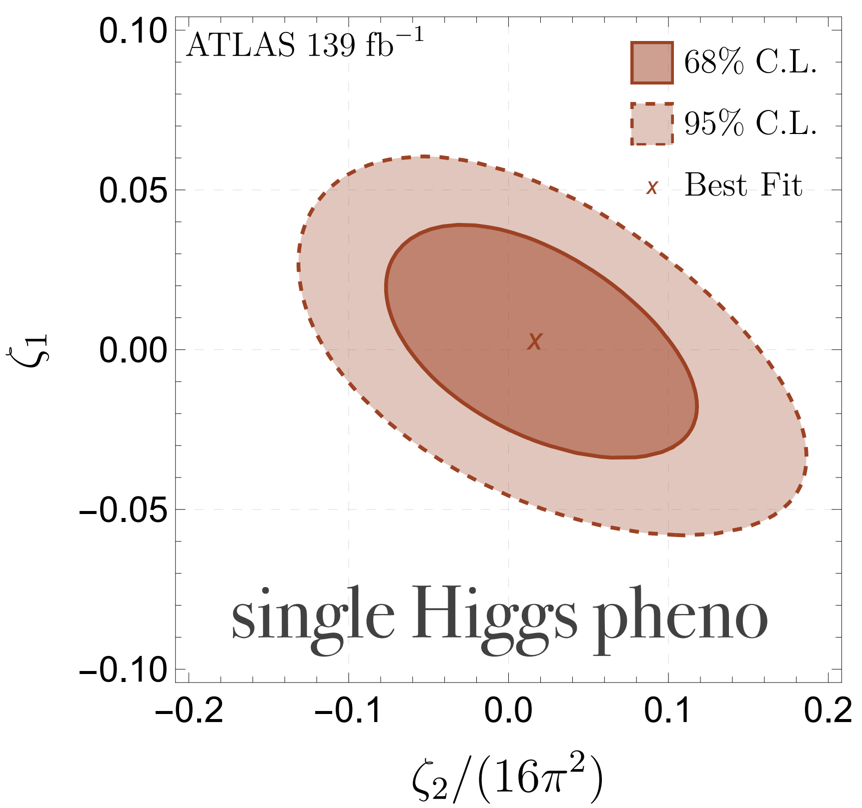
radiatively source `higher-dimensional` interactions

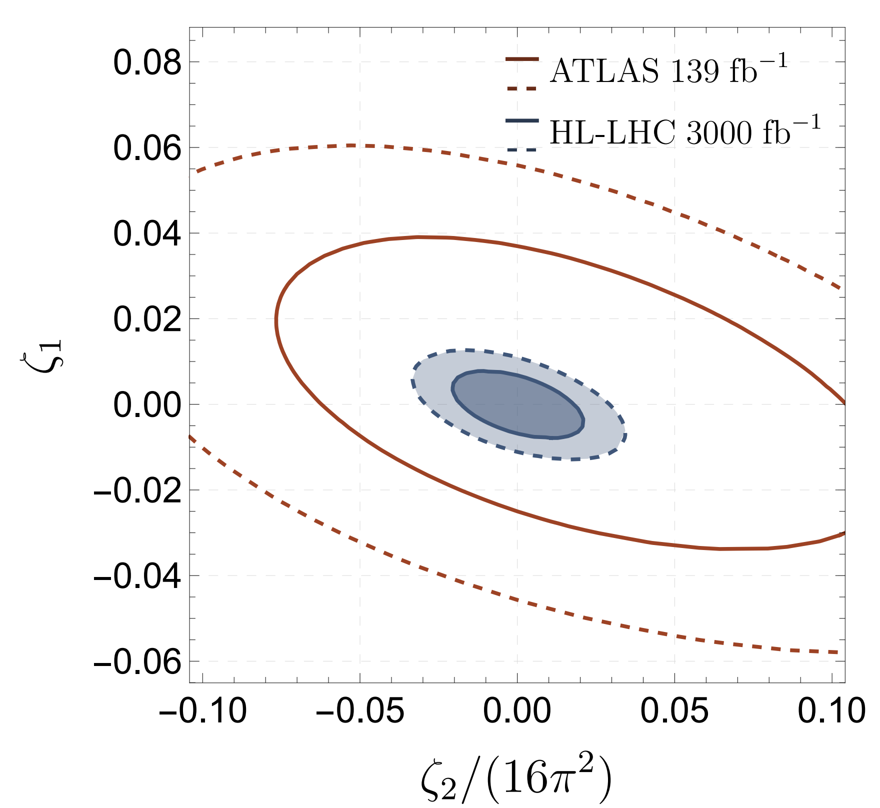
[Weinberg `79] [Gasser, Leutwyler `84]...
[Espiru et al. `13] [Delgado et al.`13]
[Brivio et al. `14] [Buchala et al. `17] [Herrero, Morales `21]
...

lots of interesting physics/technical advantages

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

beyond leading order with flexibility

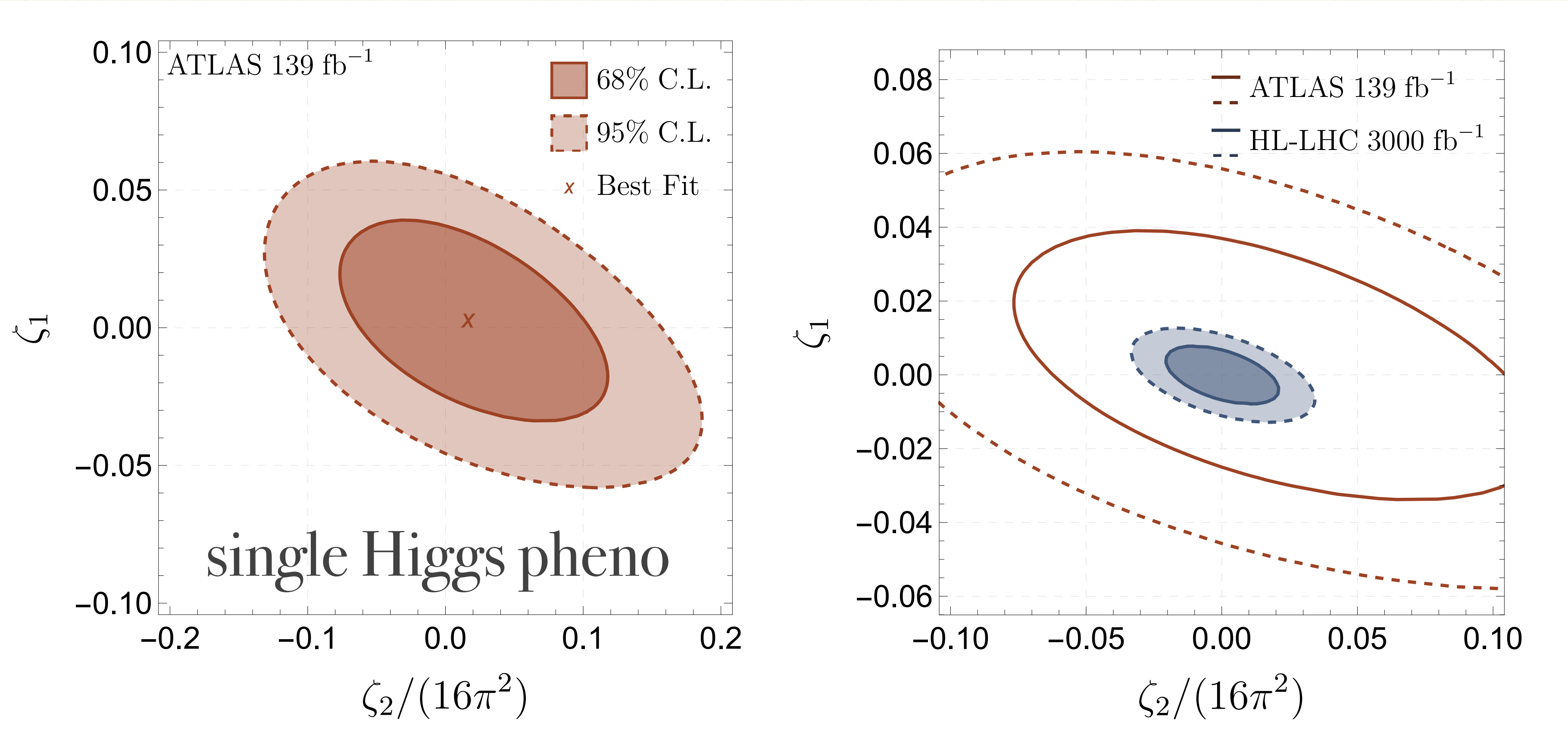




- radiative correlations perfectly consistent

…
[Herrero, Morales `21]
[Anisha et al. `22]
[Herrero, Morales `22]
…

beyond leading order with flexibility



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[Herrero, Morales `21]
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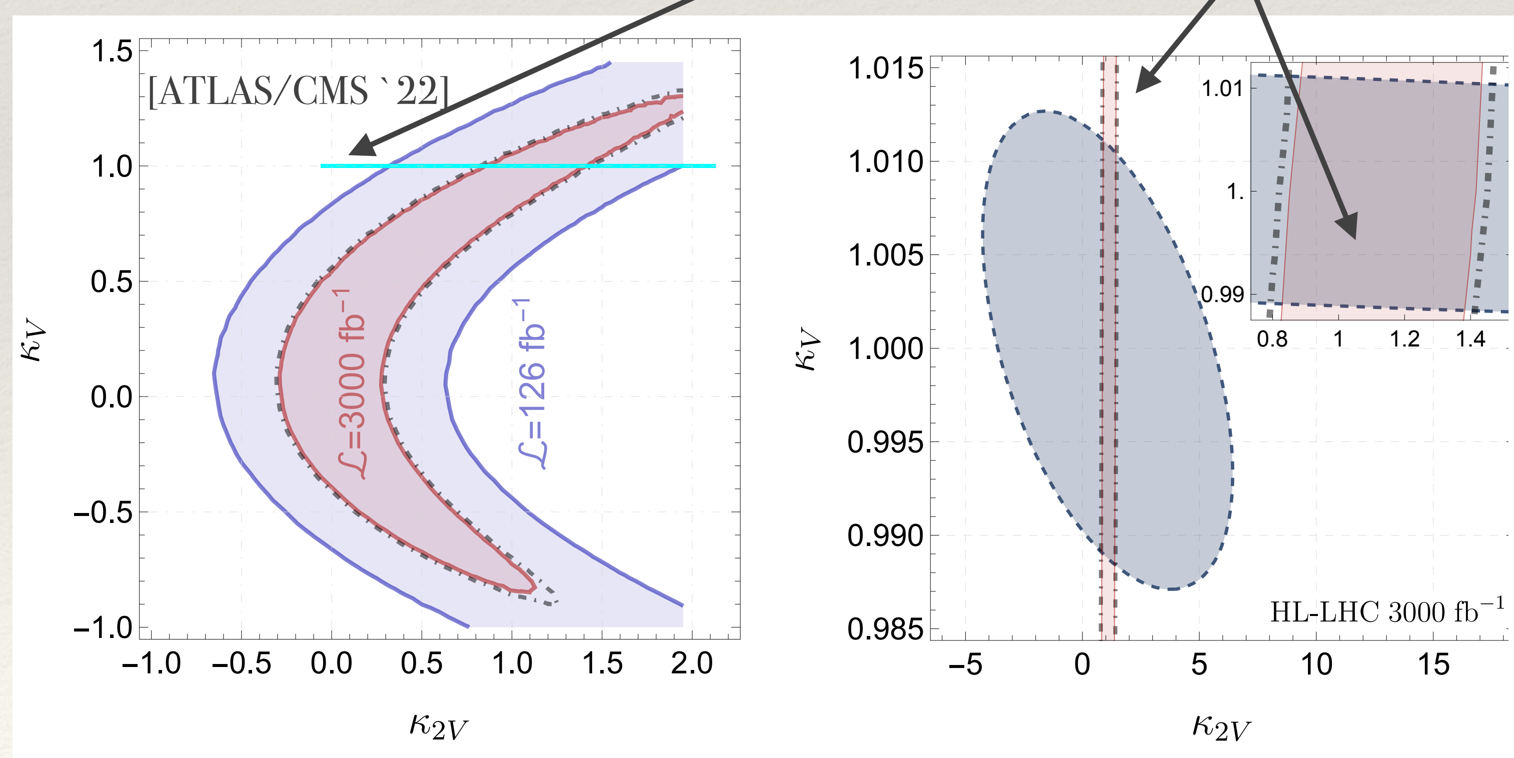
…

GNN WBF HH analysis

- direct sensitivity likely more competitive at the LHC

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



Sven’s talk←

- 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]
…

Sven's talk←

(Q)ML

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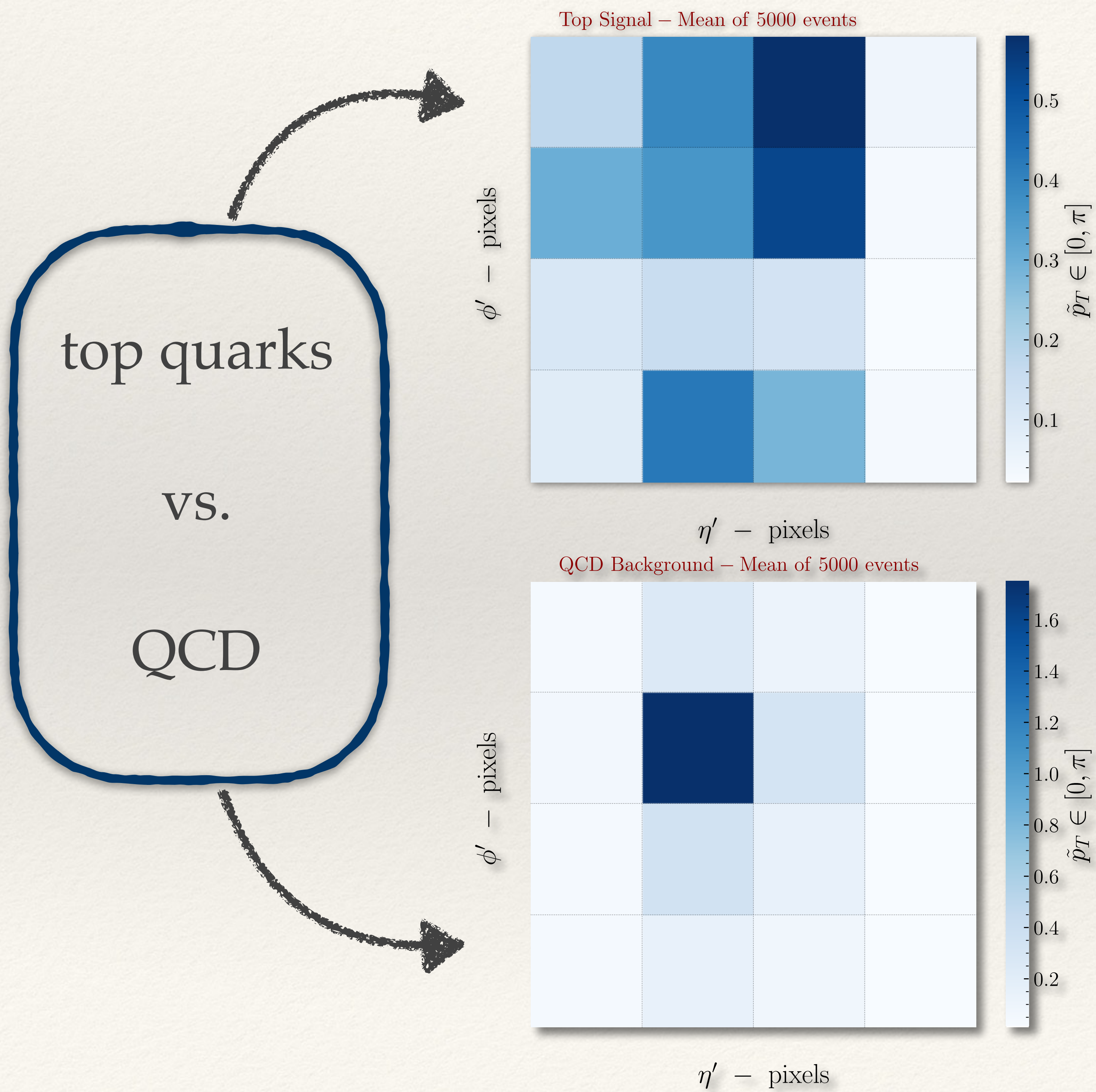

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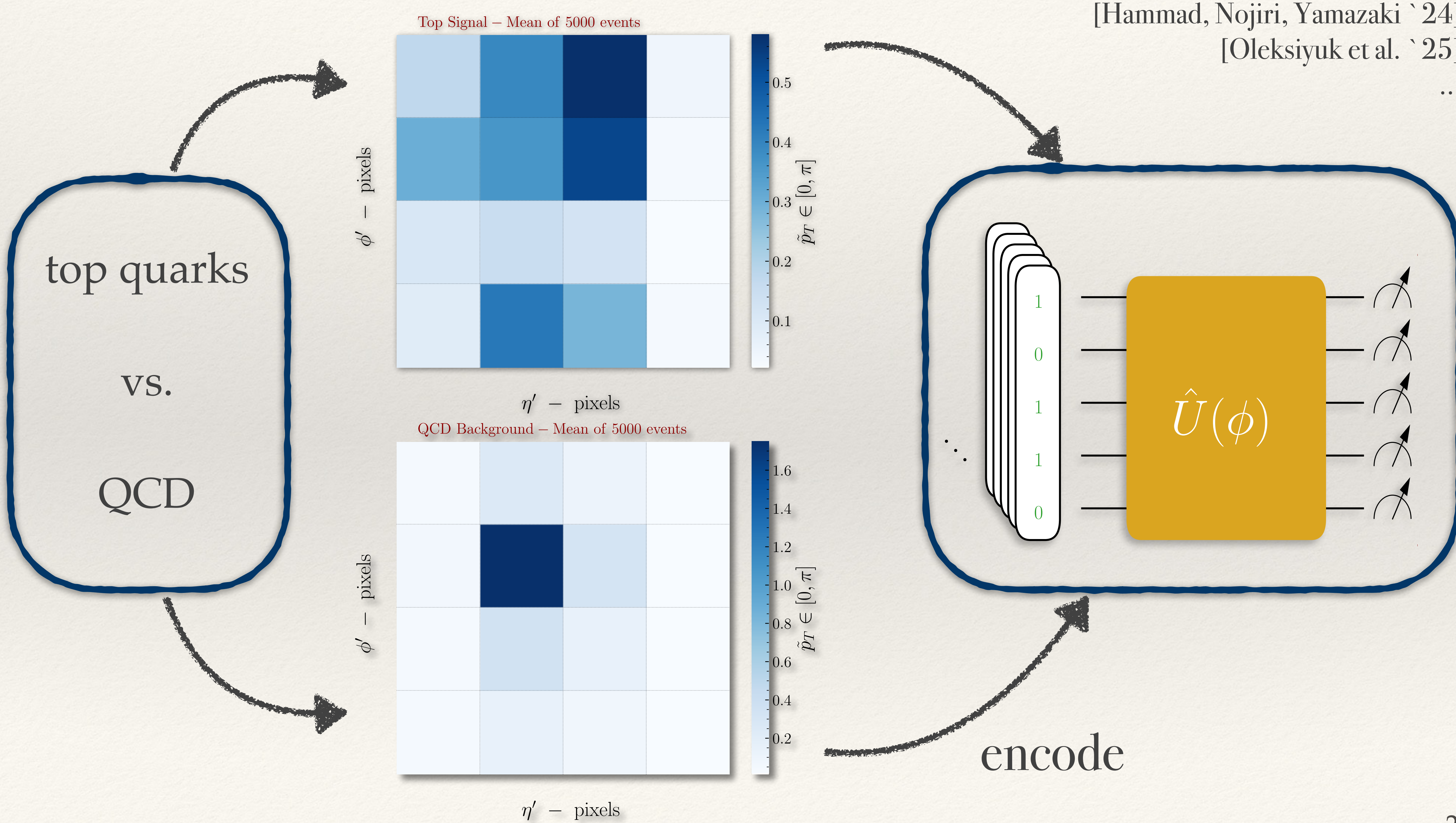

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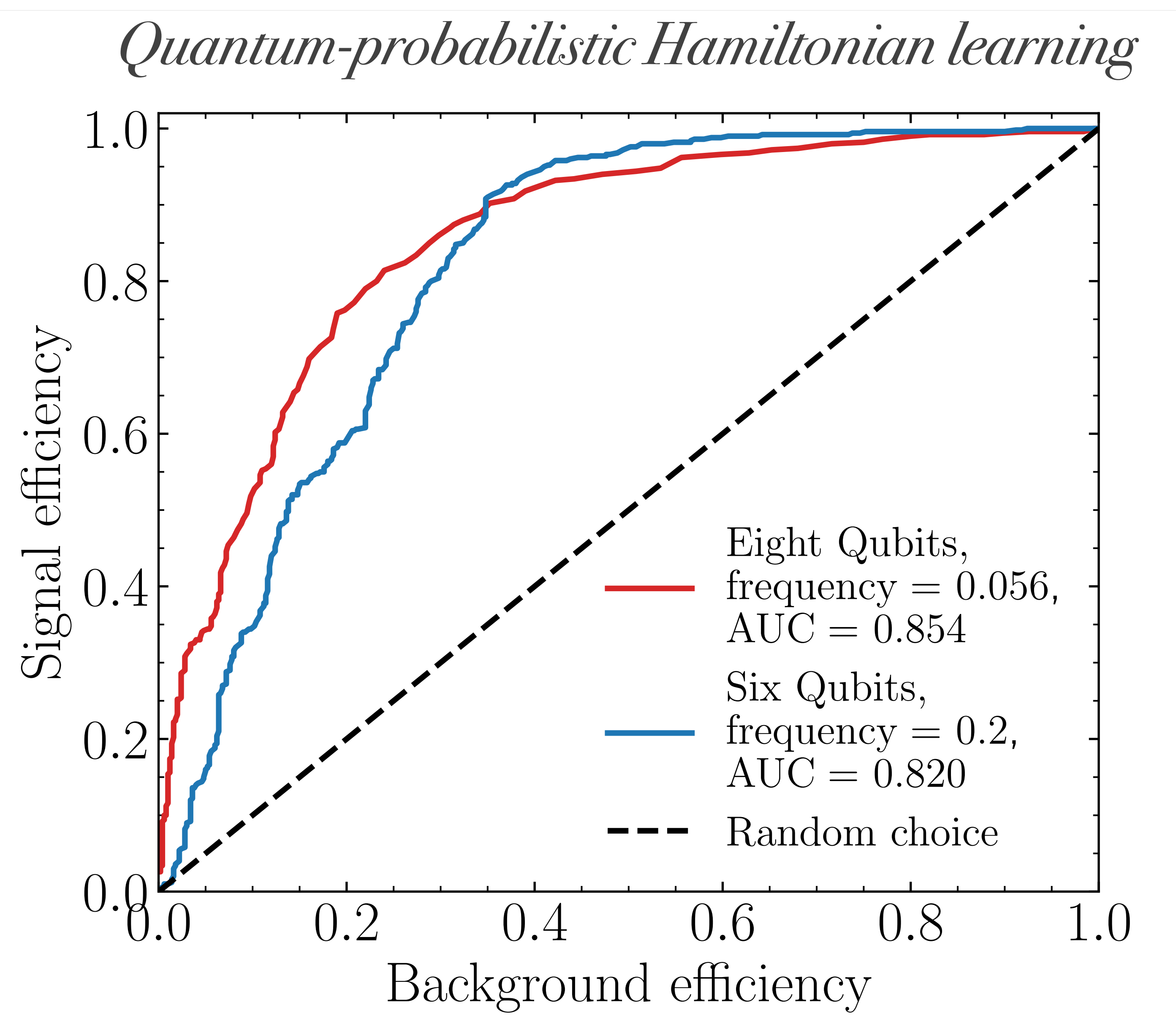
…

top quarks

vs.

QCD



[Araz, Spannowsky `22]

opportunities ahead!

EFT data interpretation induces a source of uncertainty

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

- use of EoMs to obtain 'operator bases' ≠ QFT reduandancy

  [Grzadkowski, Iskrzynski, Misiak, Rosiek ` 10]

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[Manohar `18]

[Criado, Jäckel, Spannowsky `24]

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

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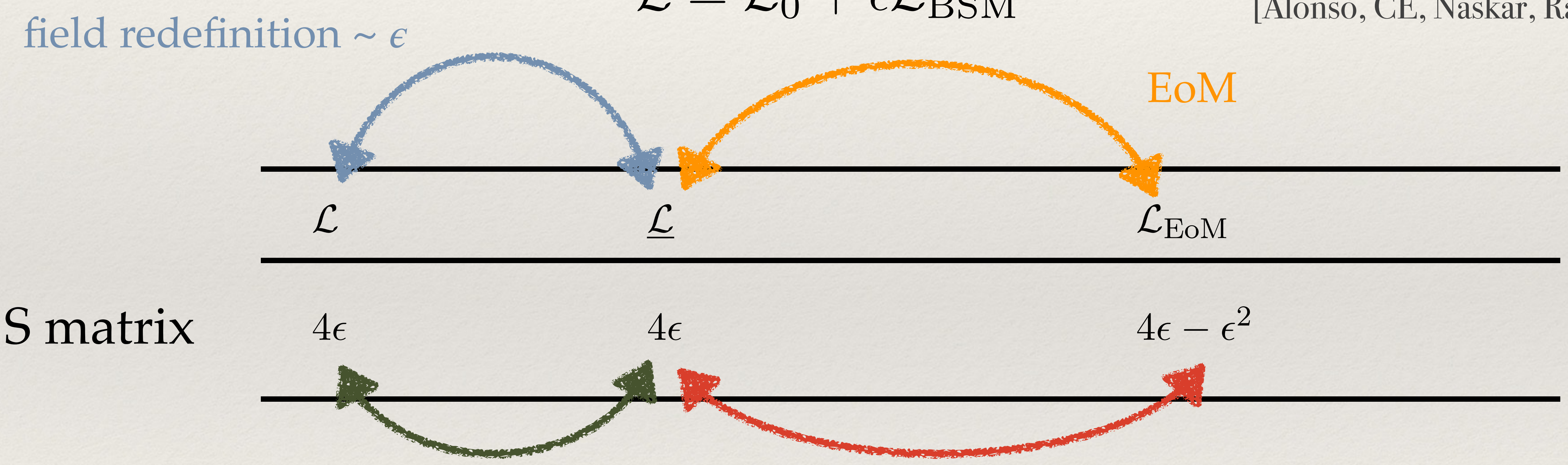

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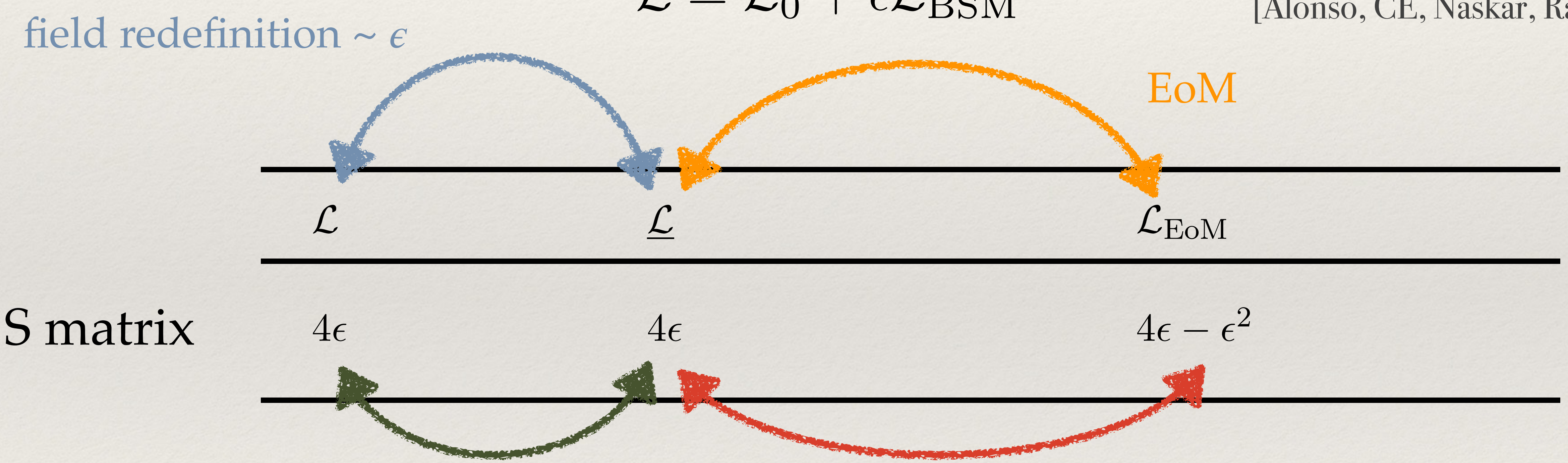

- EoM is only infinitessimally equivalent to a field redefinition
- juxtaposition of data quality (rare final states) informing tell-tale new physics effects (poor constraint $\epsilon \sim 4$ cannot be trusted)

…with additional sources of uncertainty!

$\sim \epsilon$ SM limit well behaved

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

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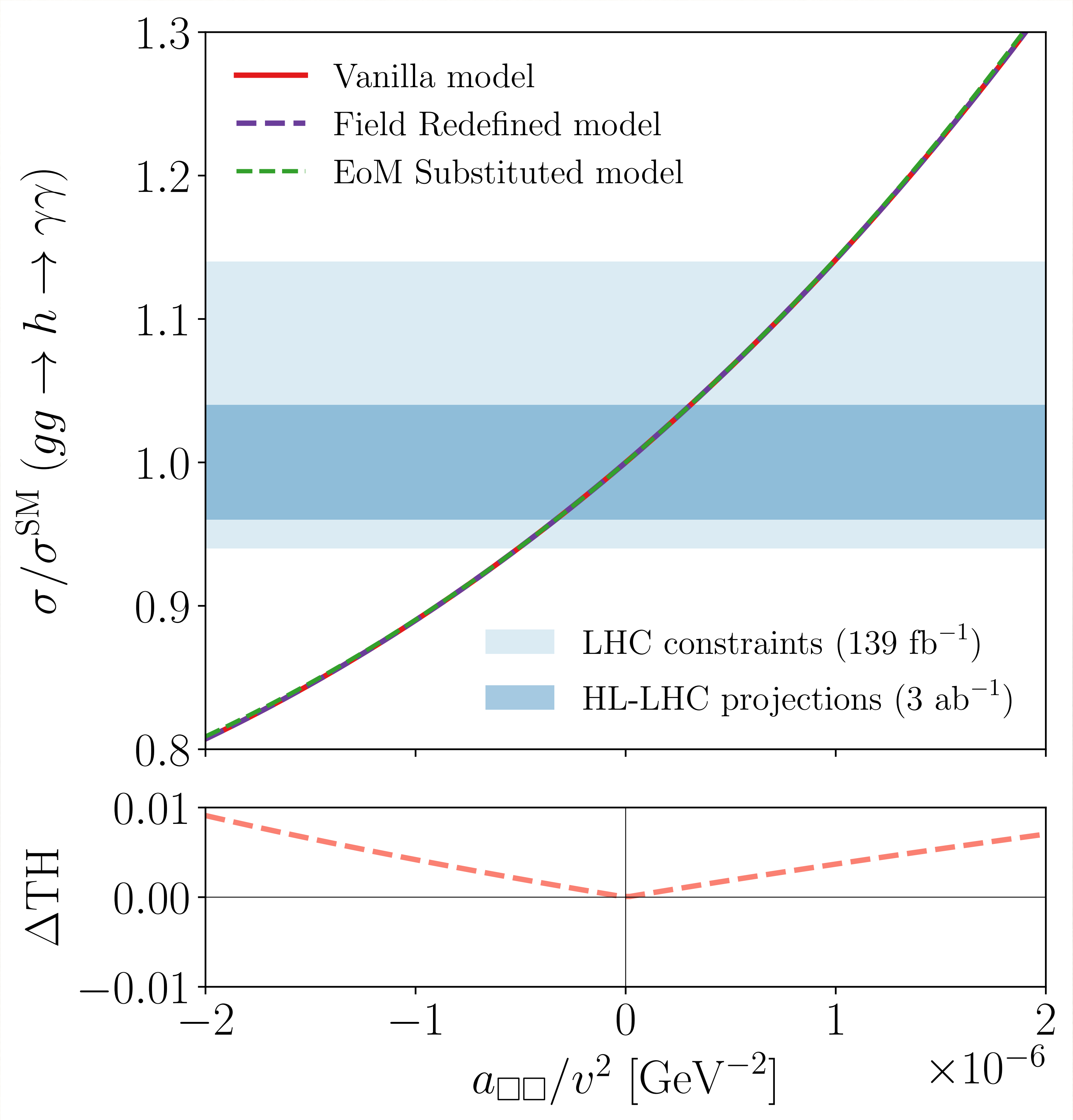


…with additional sources of uncertainty!

$\sim \epsilon$ SM limit well behaved

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

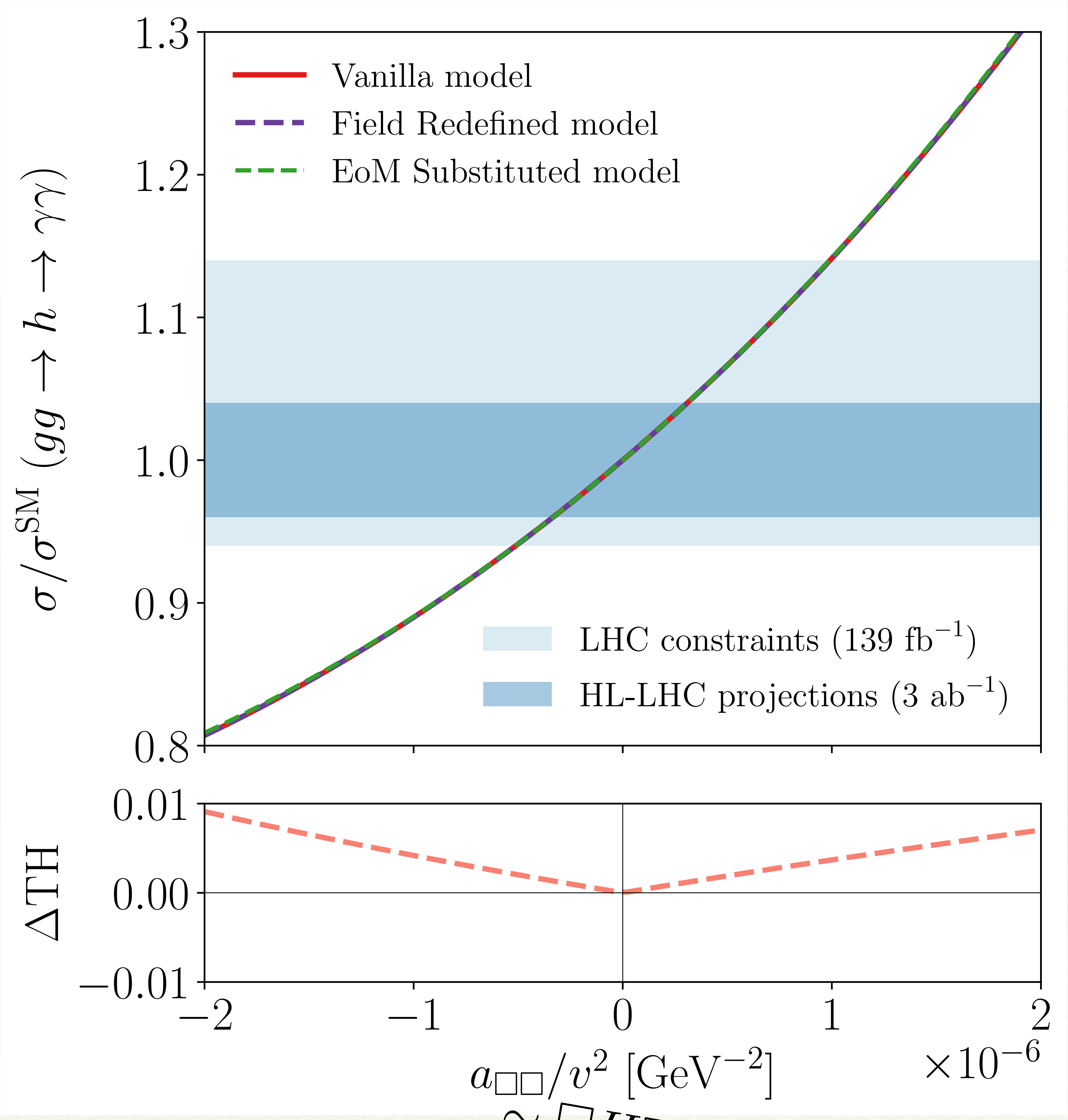
- good control over data (abundant final states) = good quality constraints
- no problem for inclusive Higgs boson production?

theoretical error negligible

(still important: unitarity/power counting)

[Alonso, CE, Naskar, Rahaman `25]

[Brivio et al. `25]



$\sim \Box H \Box H$

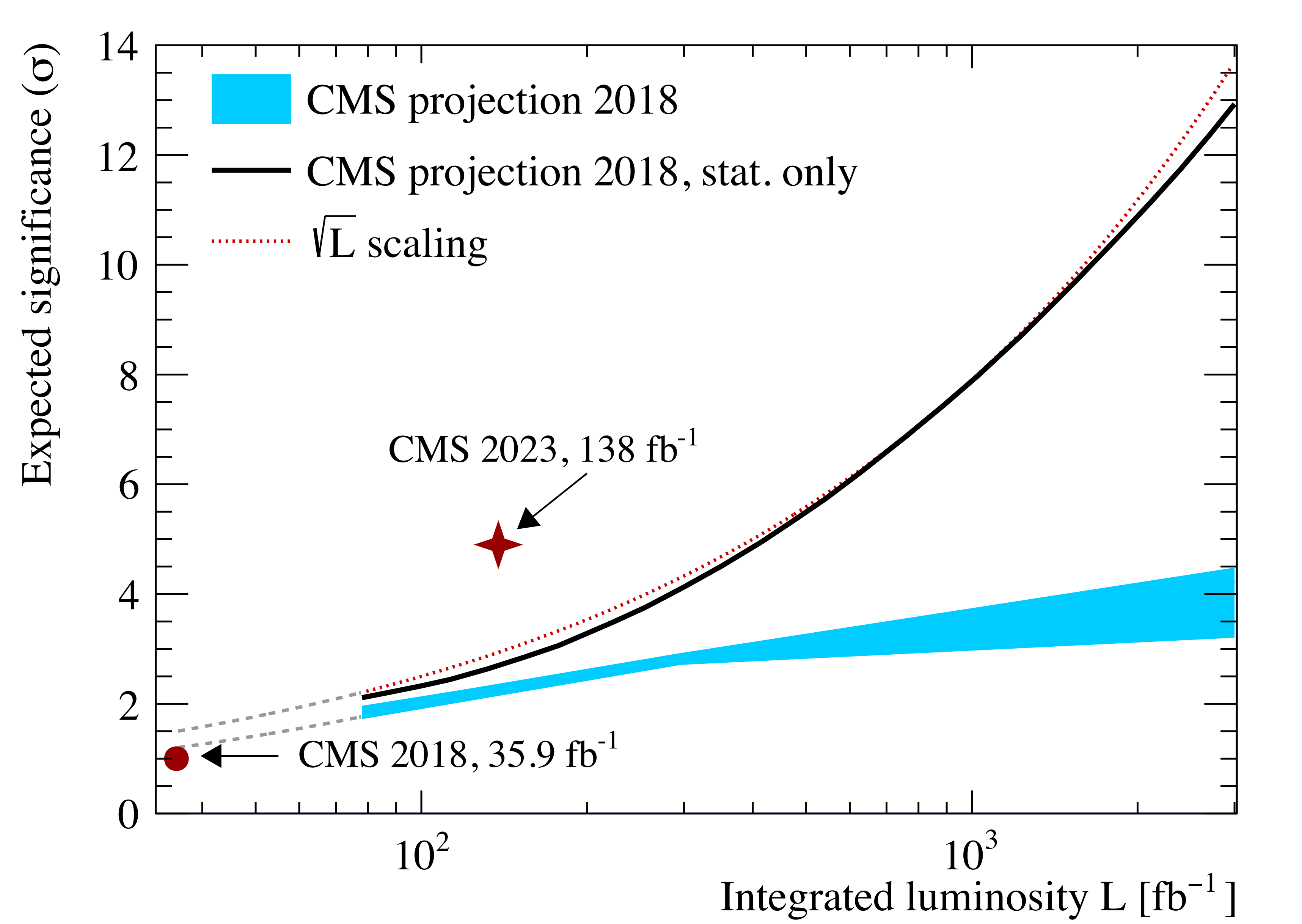
ghosts etc. [Brivio et al. `14]

robustness of rare final states?

- four top quark production highly sensitive to electroweak interactions

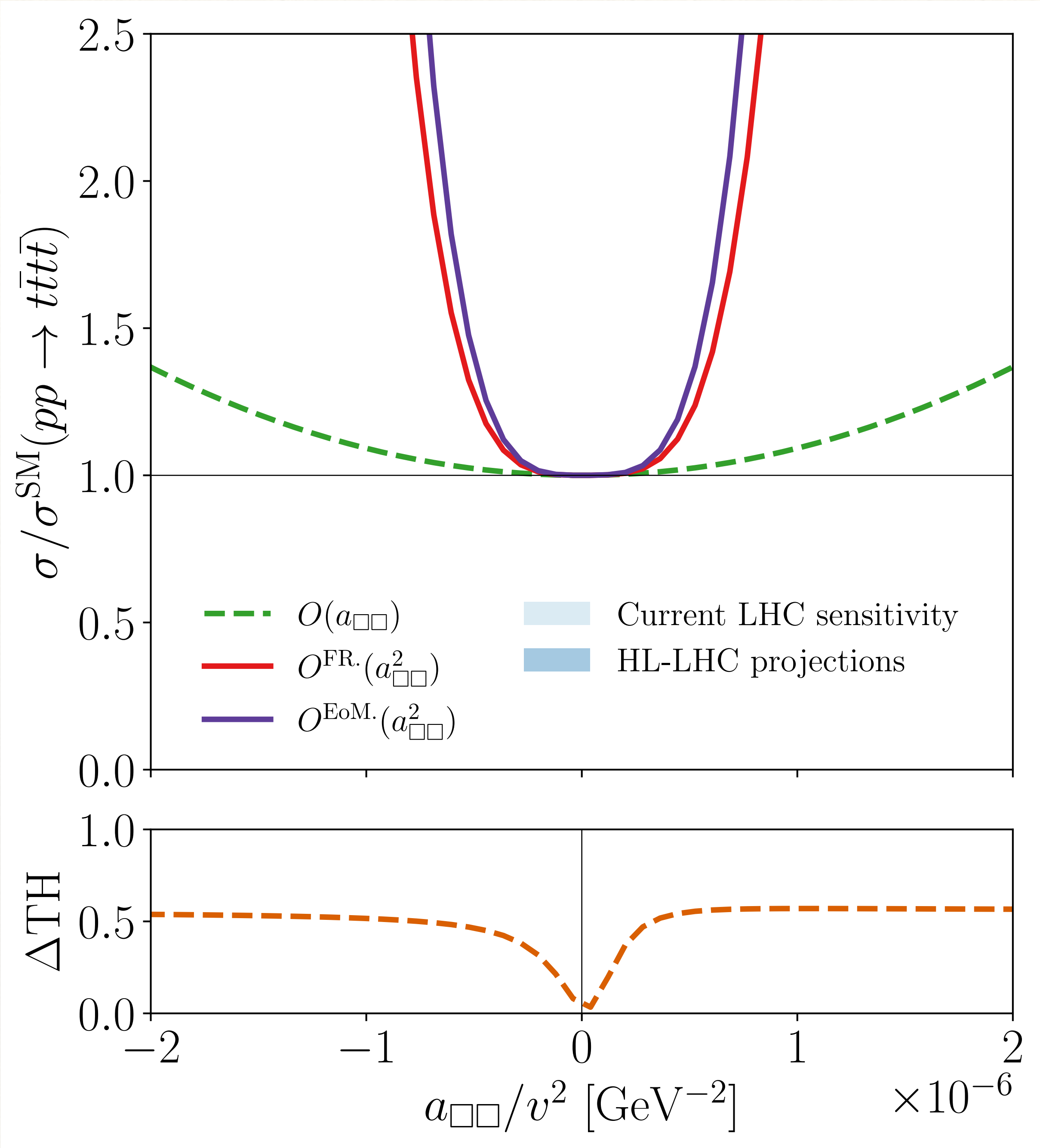
[Alvarez et al. `16] [Frederix et al. `17] [Darme et al. `18]...

- increasing interest by the theory and experimental communities



[CE, Kogler, Spannowsky `24]

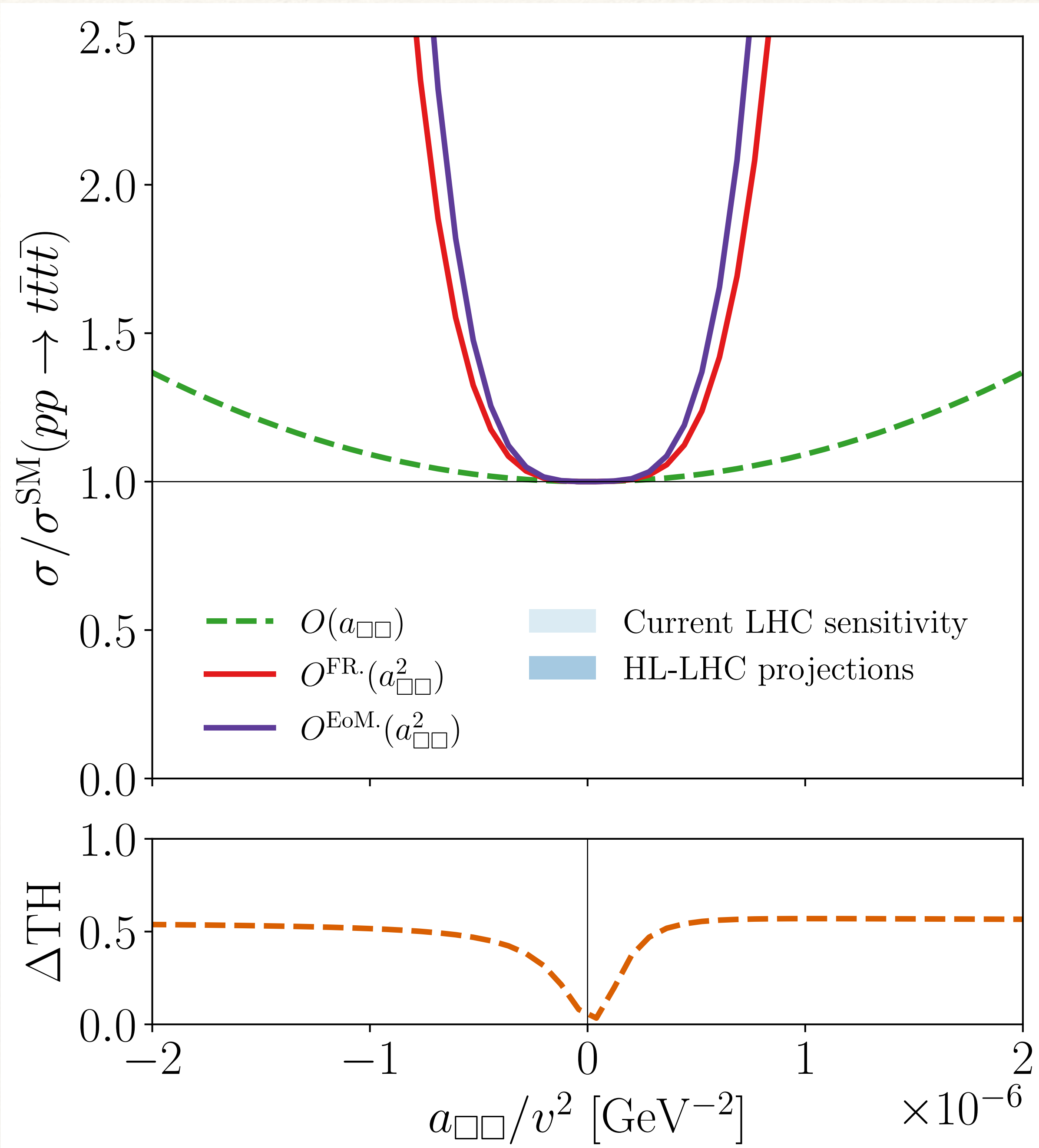
- major sensitivity leaps by ATLAS and CMS !
- conservative estimates create an *unrealistically* pessimistic outlook of the HL-LHC capacity

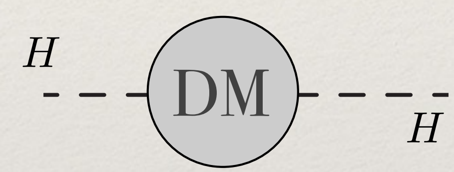


- significant *a priori* uncertainty for model-independent analysis strategies….

robustness of rare final states?

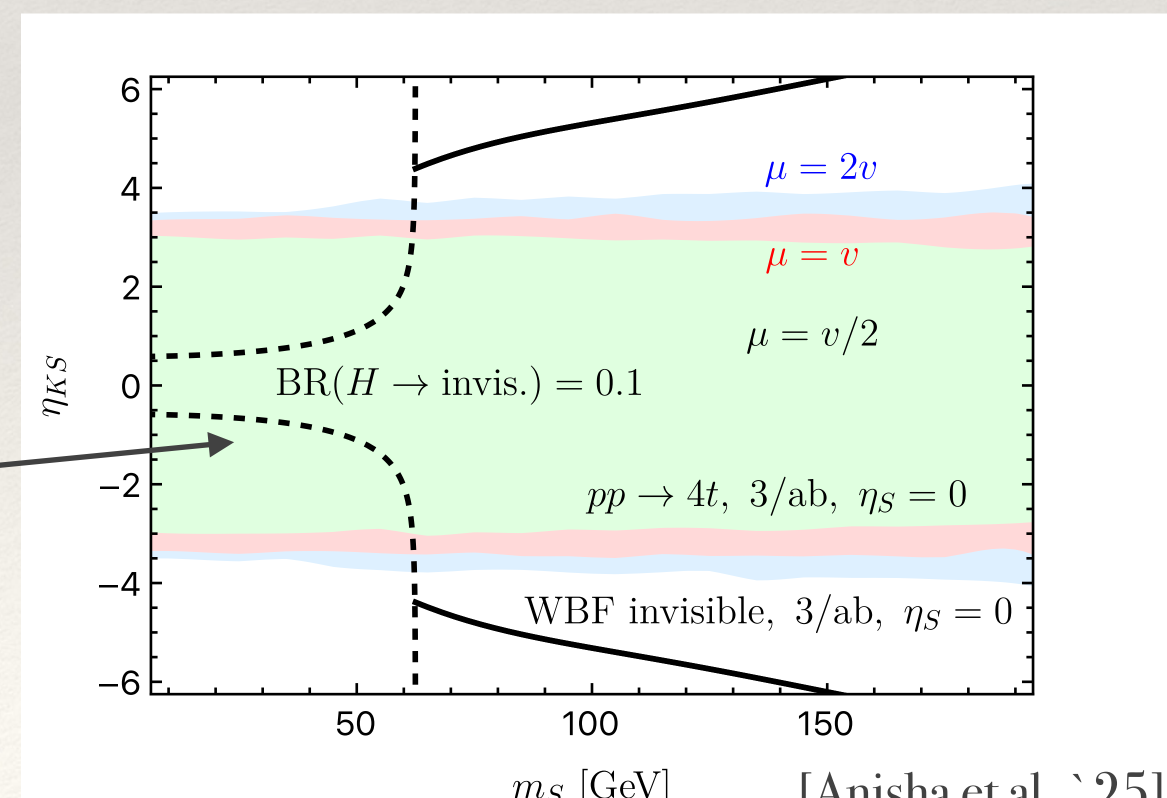
- significant *a priori* uncertainty for model-independent analysis strategies....
- but can be *misleading* when understood against concrete (strongly-coupled) new physics





...but cancellations in gauge amplitudes!

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



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

[Anisha et al. `25]

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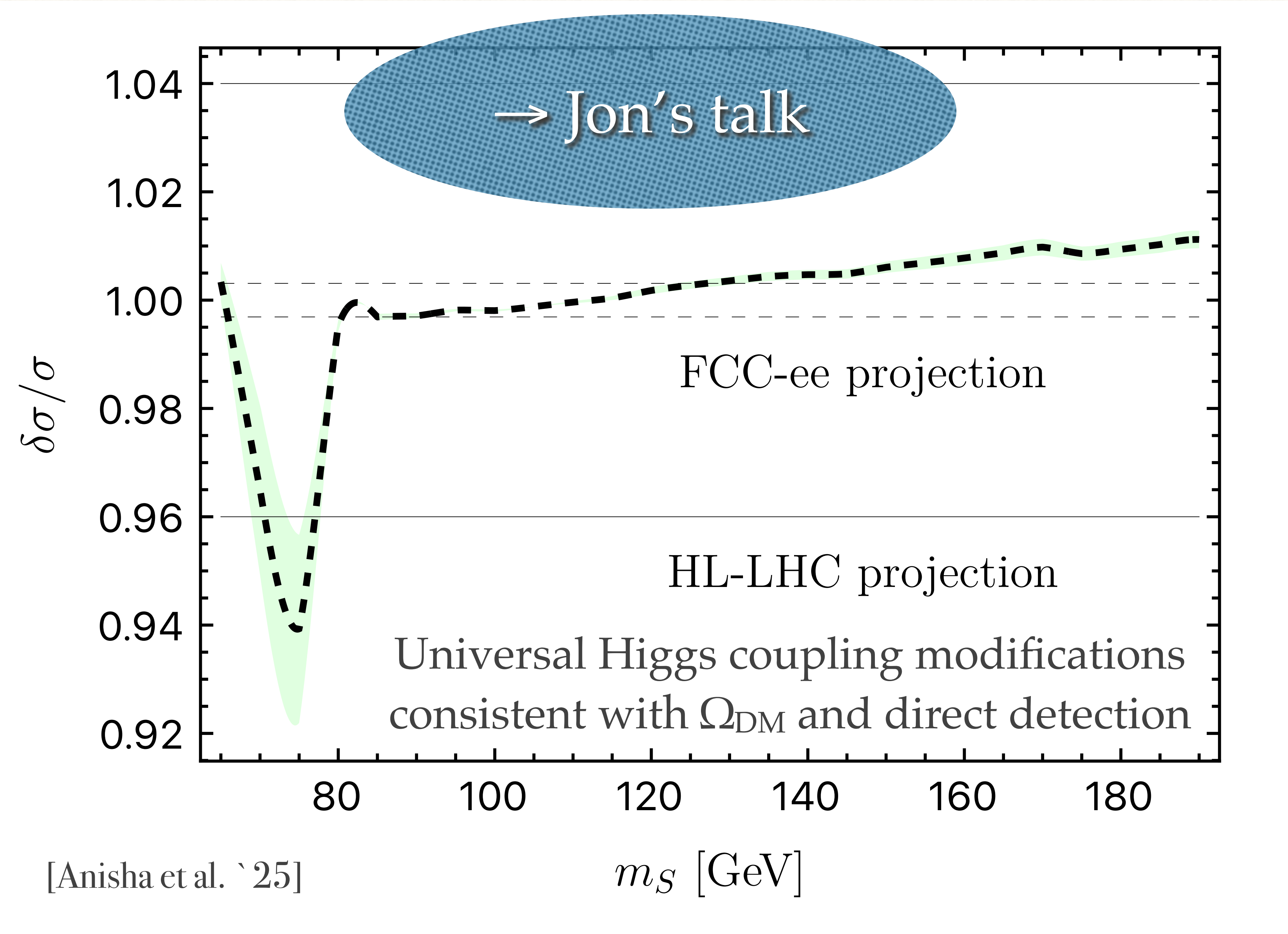

priori uncertainty for
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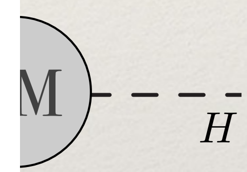

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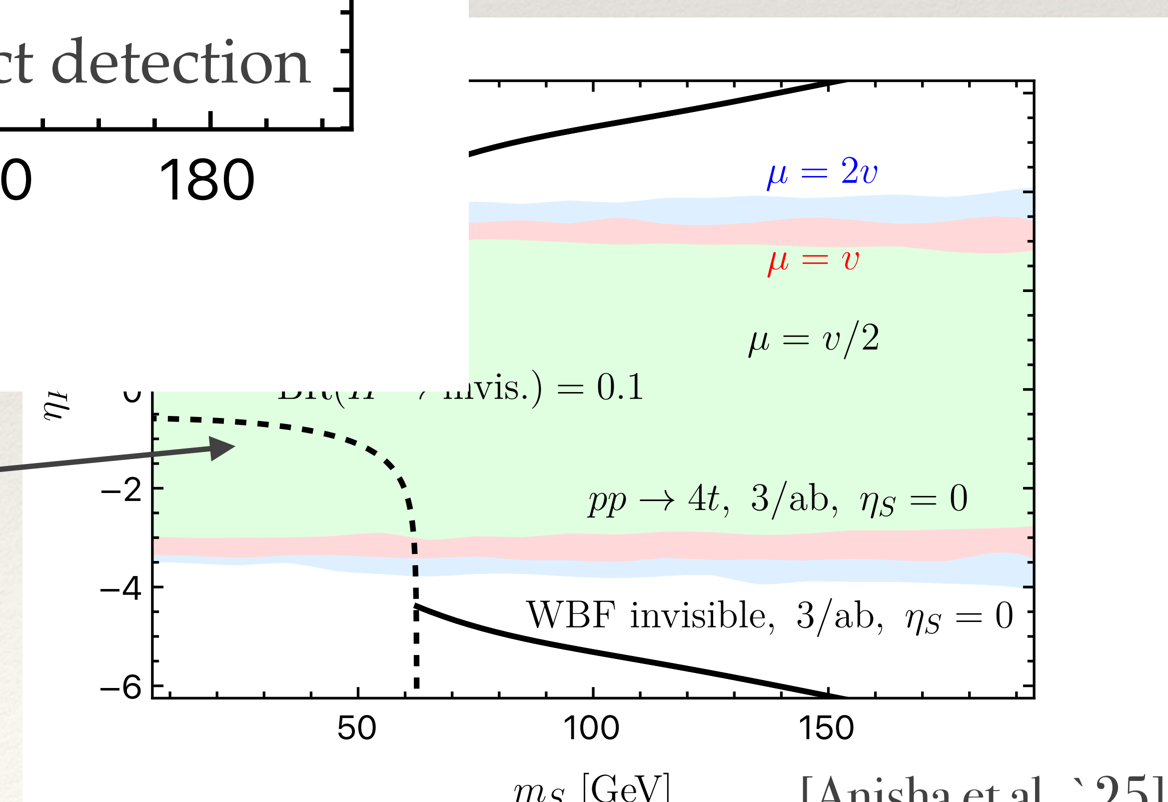

four top constraints on PNGB-type
portal DM theories + uncertainty

[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	$\bar{B}^0 \to D^+ K^-$	$0.058^{+0.004}_{-0.004}$	$0.082^{+0.002}_{-0.001}$	$\approx 5.6\,\sigma$
$R_{s\pi}$	$\bar{B}_s \to D_s^+ \pi^-$	0.71 ± 0.06	$1.06^{+0.04}_{-0.03}$	$\approx 5\,\sigma$
R_{K^*}	$\bar{B}^0 \to D^+ K^{*-}$	0.136 ± 0.023	$0.14^{+0.01}_{-0.01}$	$\approx 0.16\,\sigma$
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e.g. [Piscopo, Rusov `23]

flavour / collider

new physics?

power corrections?

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

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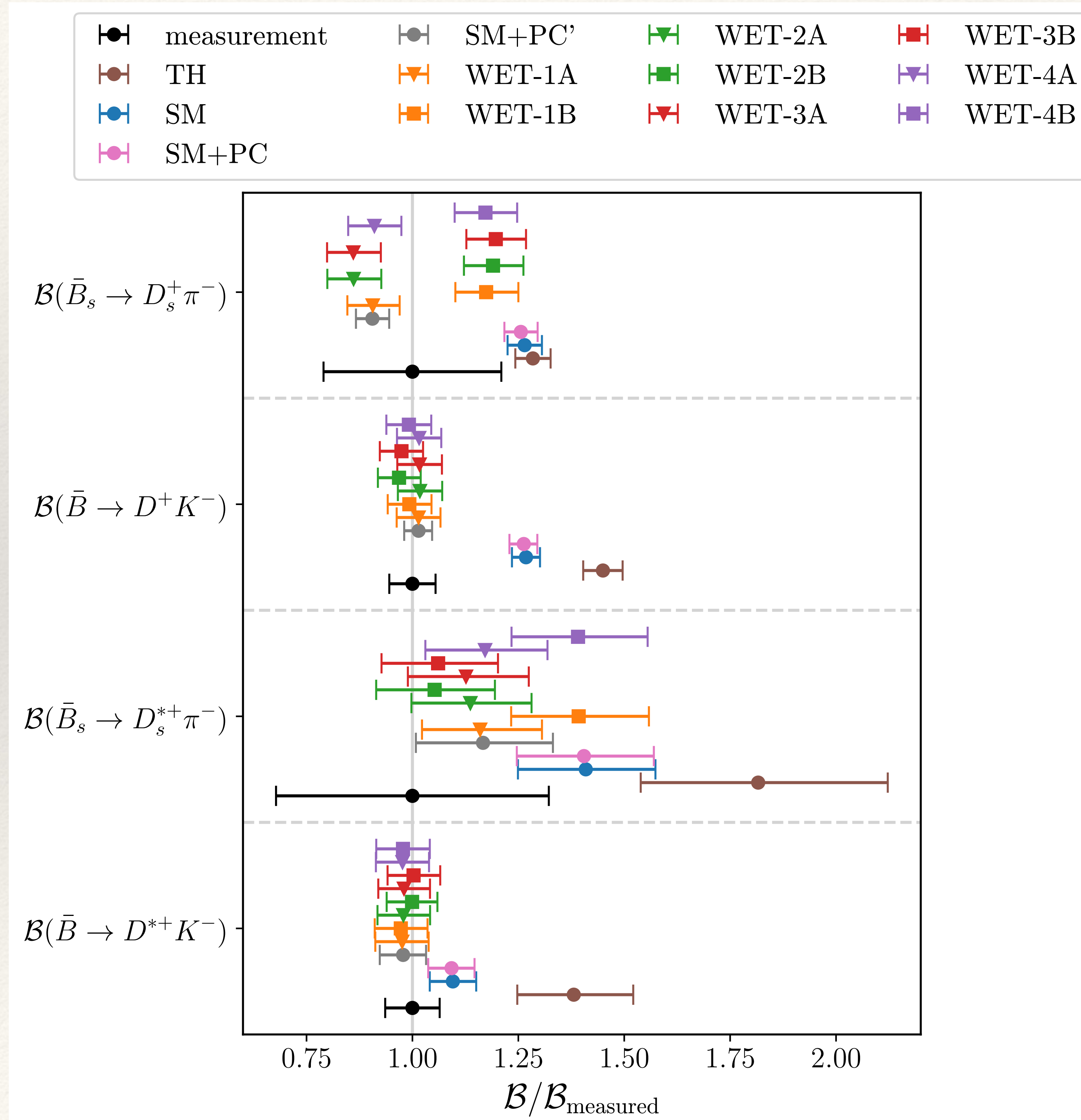

[Meiser, van Dyk, Virto `24]

e.g. [Piscopo, Rusov `23]

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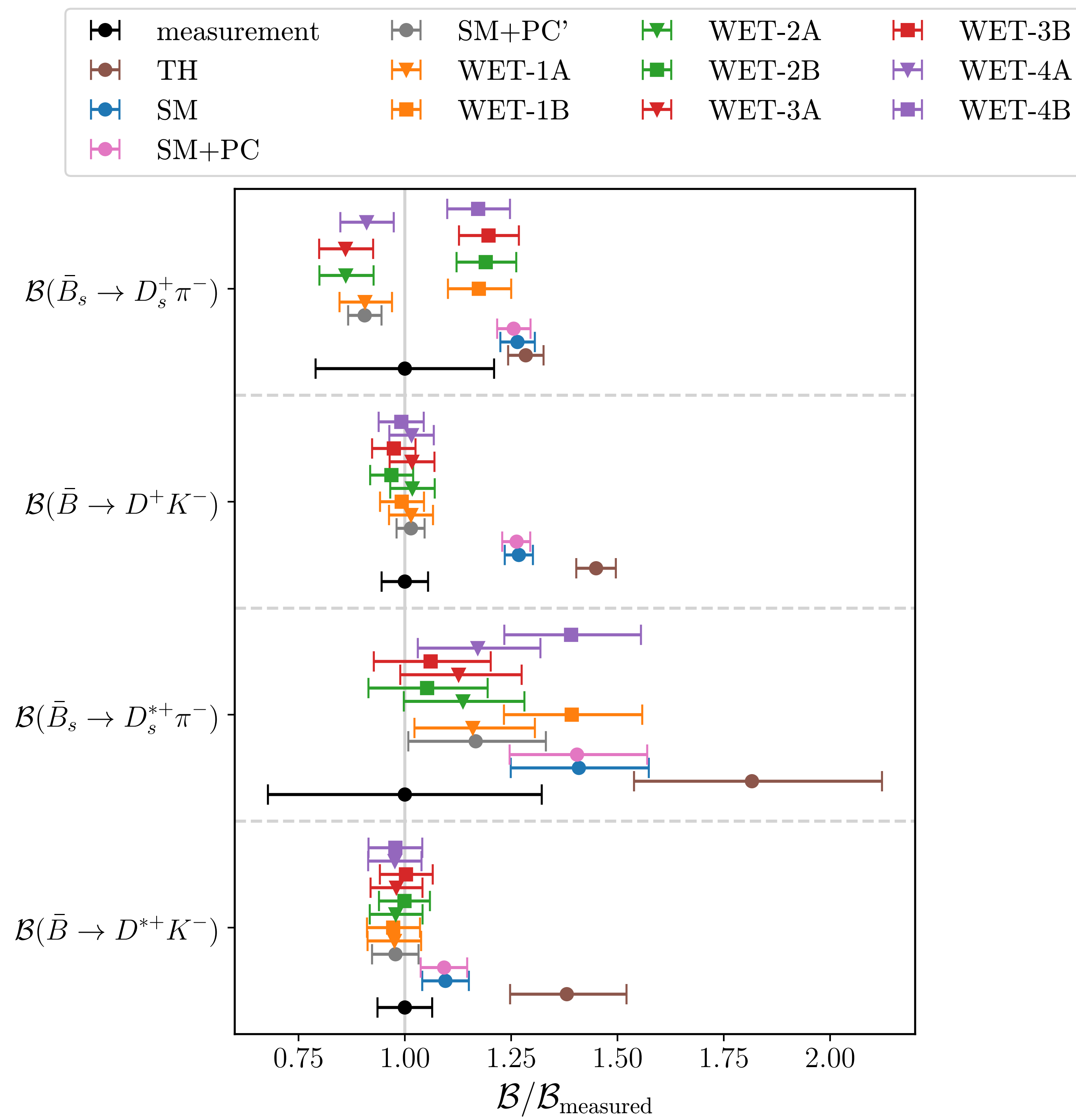


- mounting tension with (in)direct LHC searches ?

[Bordone, Greljo, Marzocca `21]

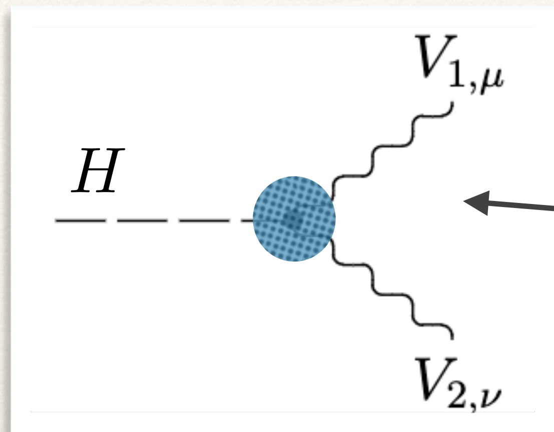
[Atkinson, CE, Tetlalmatzi-Xolocotzi, Kirk `24]

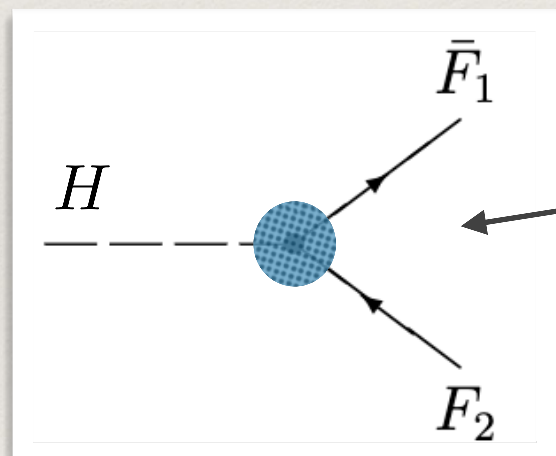
one to watch!

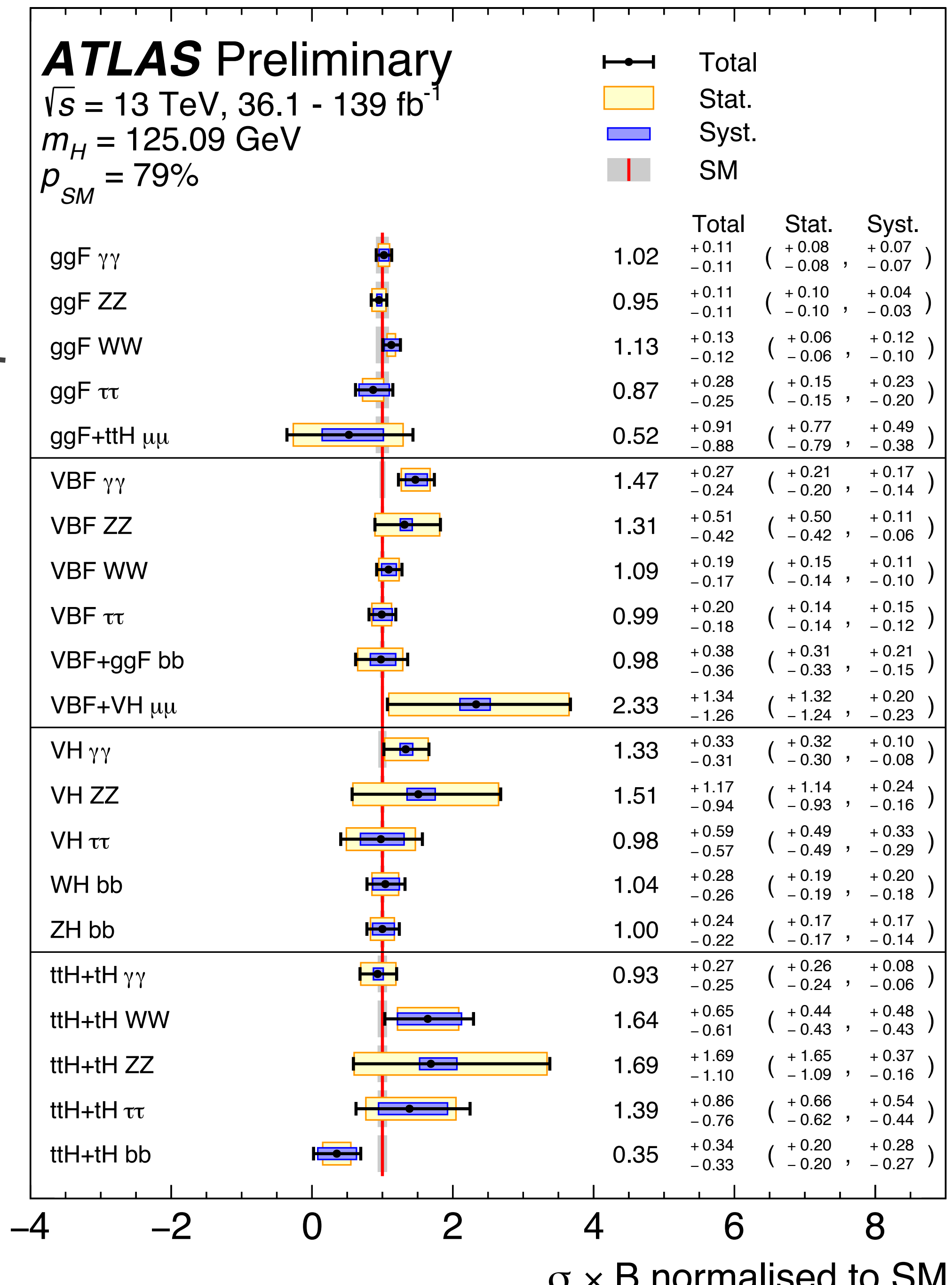
[Meiser, van Dyk, Virto `24]

no reason to be so pessimistic at this point!

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







e.g. [ATLAS `21]

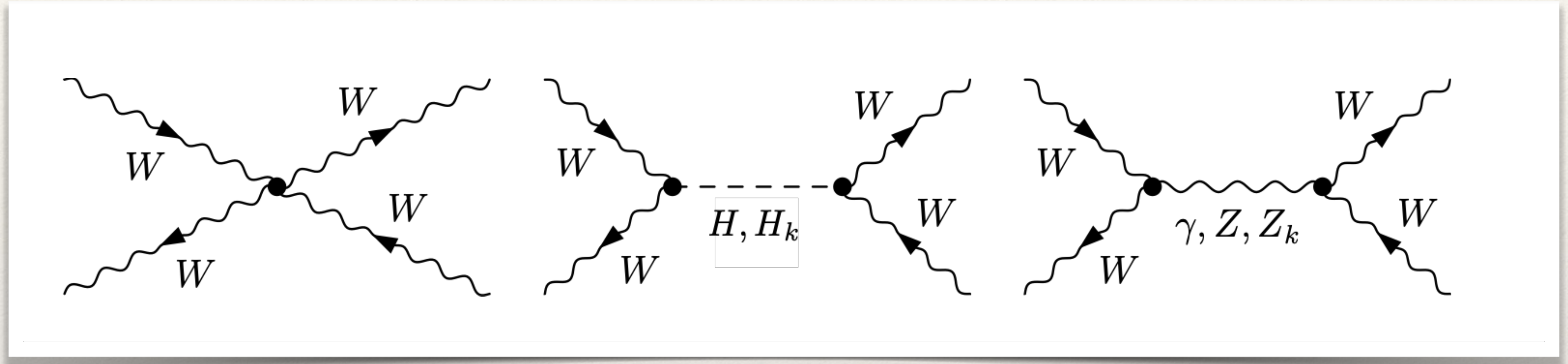
reincarnation of the LHC no lose theorem

[Cornwall et al. `75] [Lee et al. `77] [Chanowitz et al. `78]

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]



$$g_{WWWW} = g^2_{WW\gamma} + \sum_k g^2_{WWZ_k} \,,$$

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

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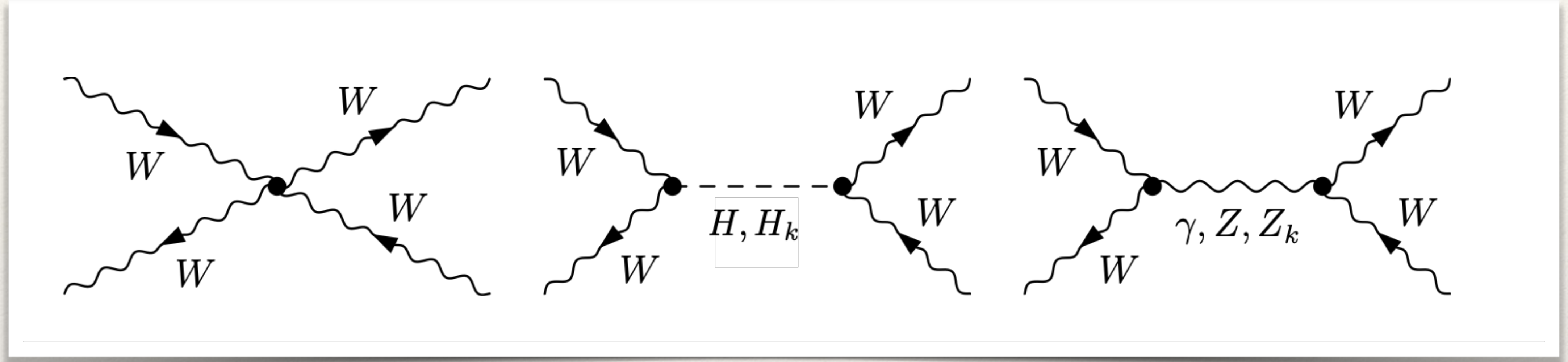

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Higgs deviation

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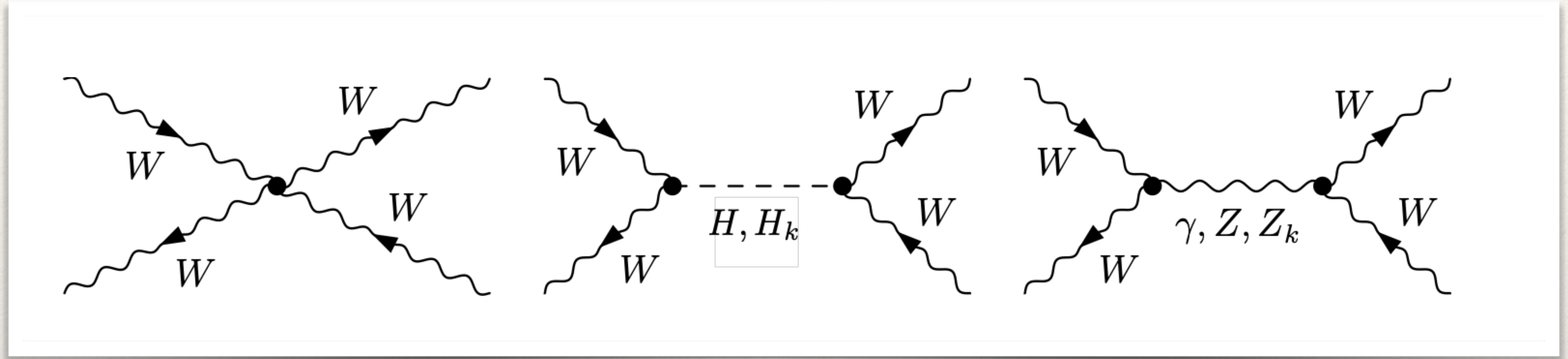

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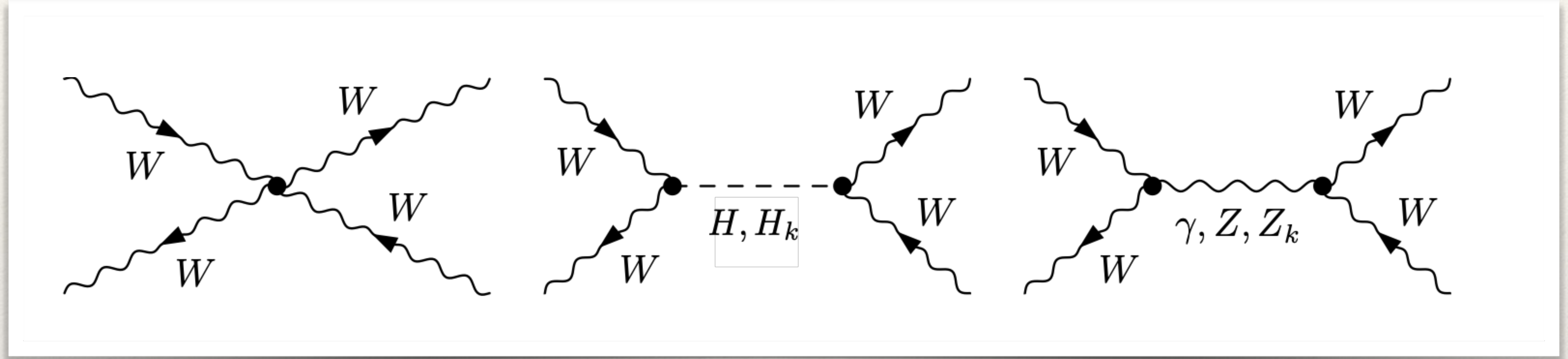

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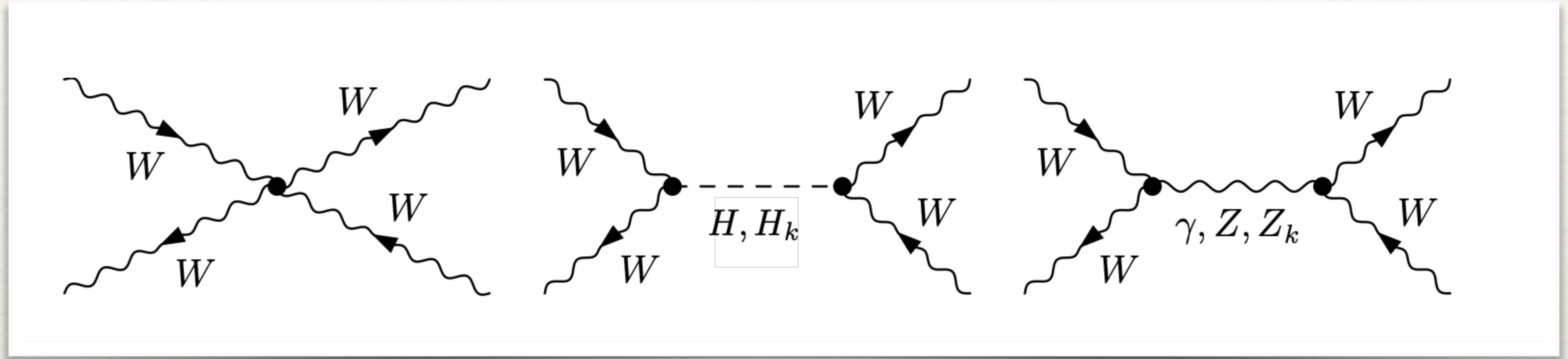
[Birkedal, Matchev, Perelstein `04]
[CE, Harris, Spannowsky, Takeuchi `15]



prediction

$$g_{WWWW} = g^2_{WW\gamma} + \sum_k g^2_{WWZ_k}\,,$$

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

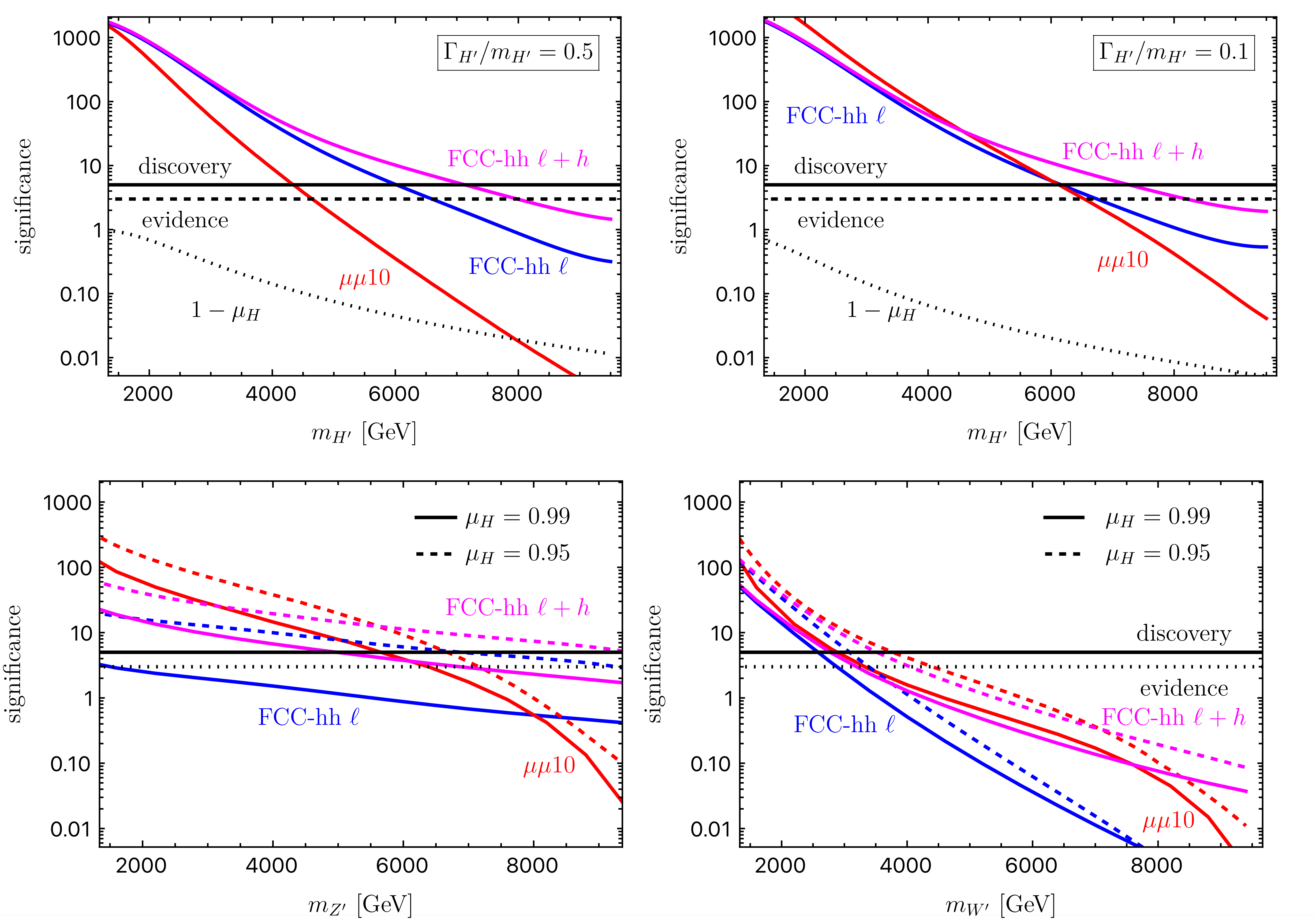
Higgs deviation

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 techniqes, 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