Christoph Englert

t-b Synergies for BSM

"precision flavour vs. high energy coverage"

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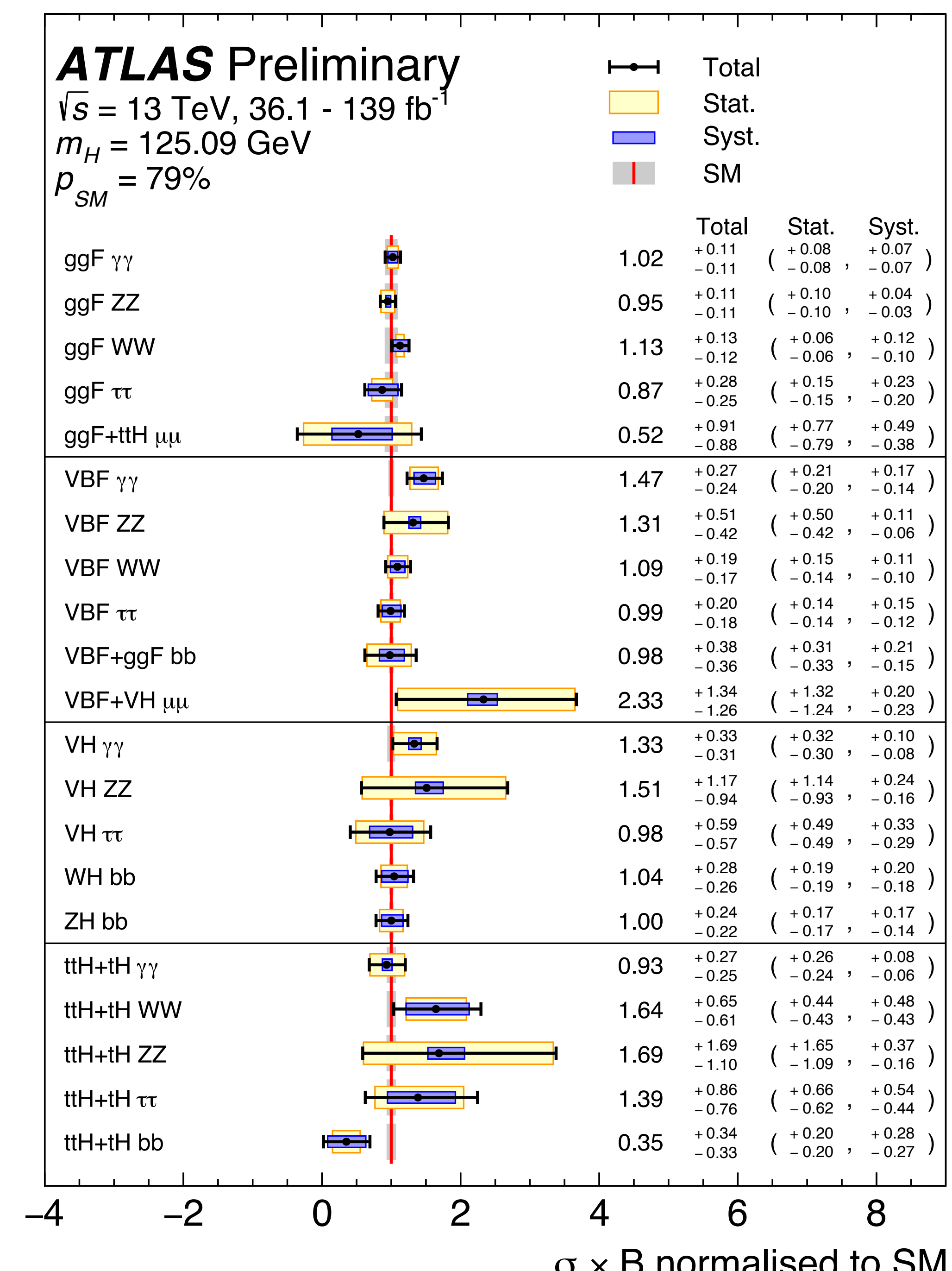
26/03/25

LEVERHULME TRUST

Science and Technology Facilities Council

University of Glasgow

- plethora of *serious* theoretical problems: tuning, CP, …
- somehow SM correlations at high energies (too!) accurate



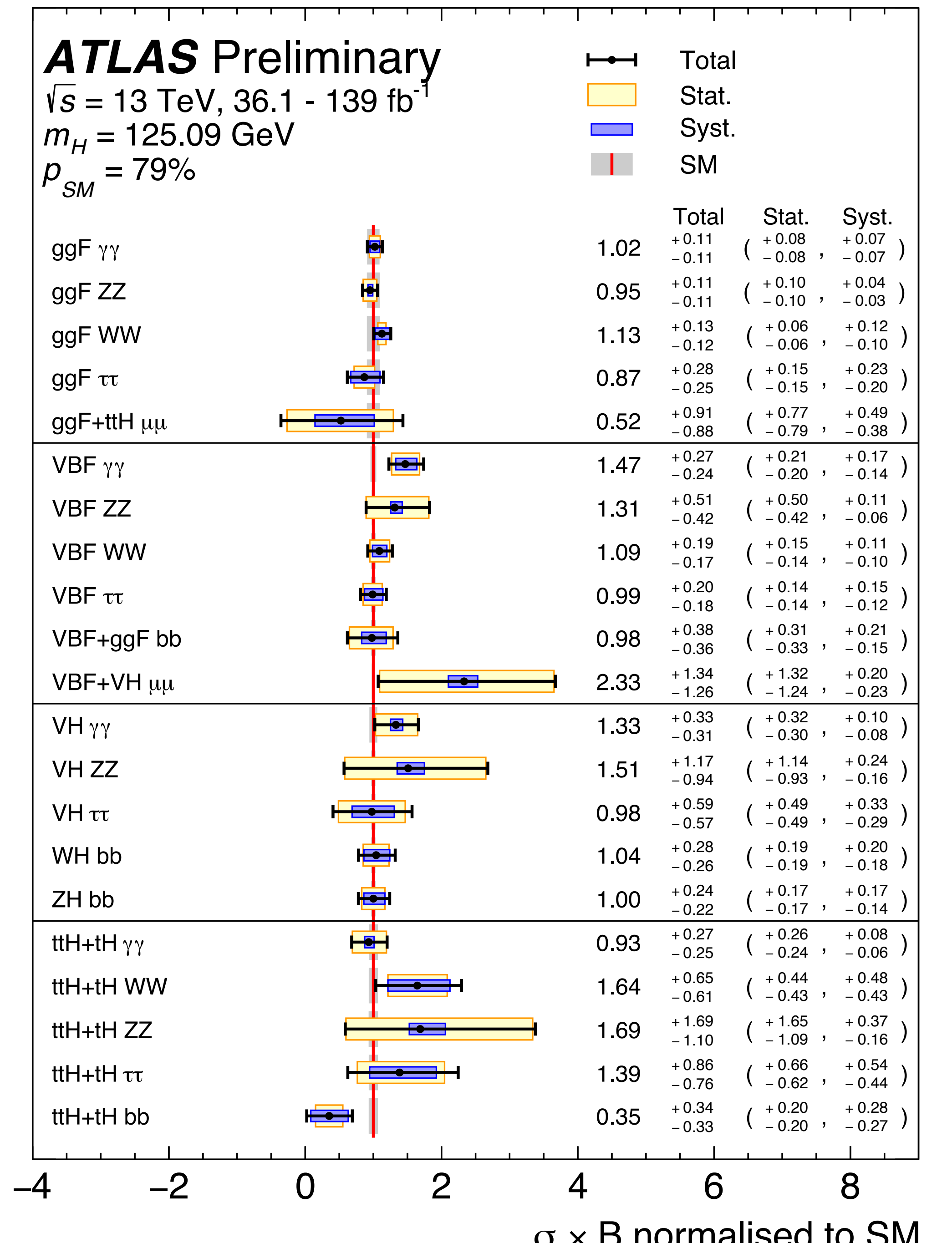
e.g. [ATLAS `21]

BSM ?

- plethora of *serious* theoretical problems: tuning, CP, …
- somehow SM correlations at high energies (too!) accurate

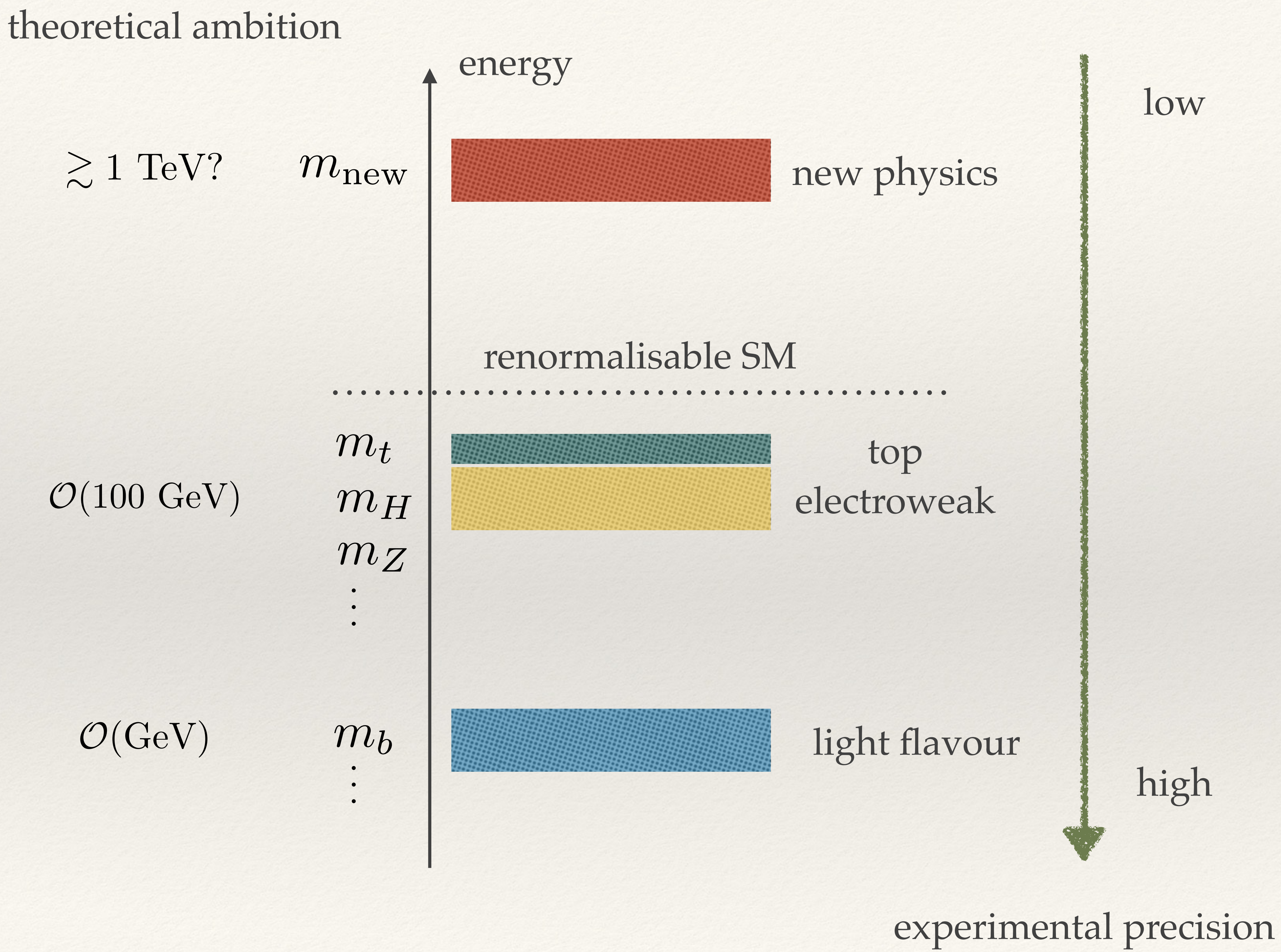
clues in data?

- *integrated approach across energy scales*
- *tension anomalies*
- *tension motivated approaches*
- *close loopholes*

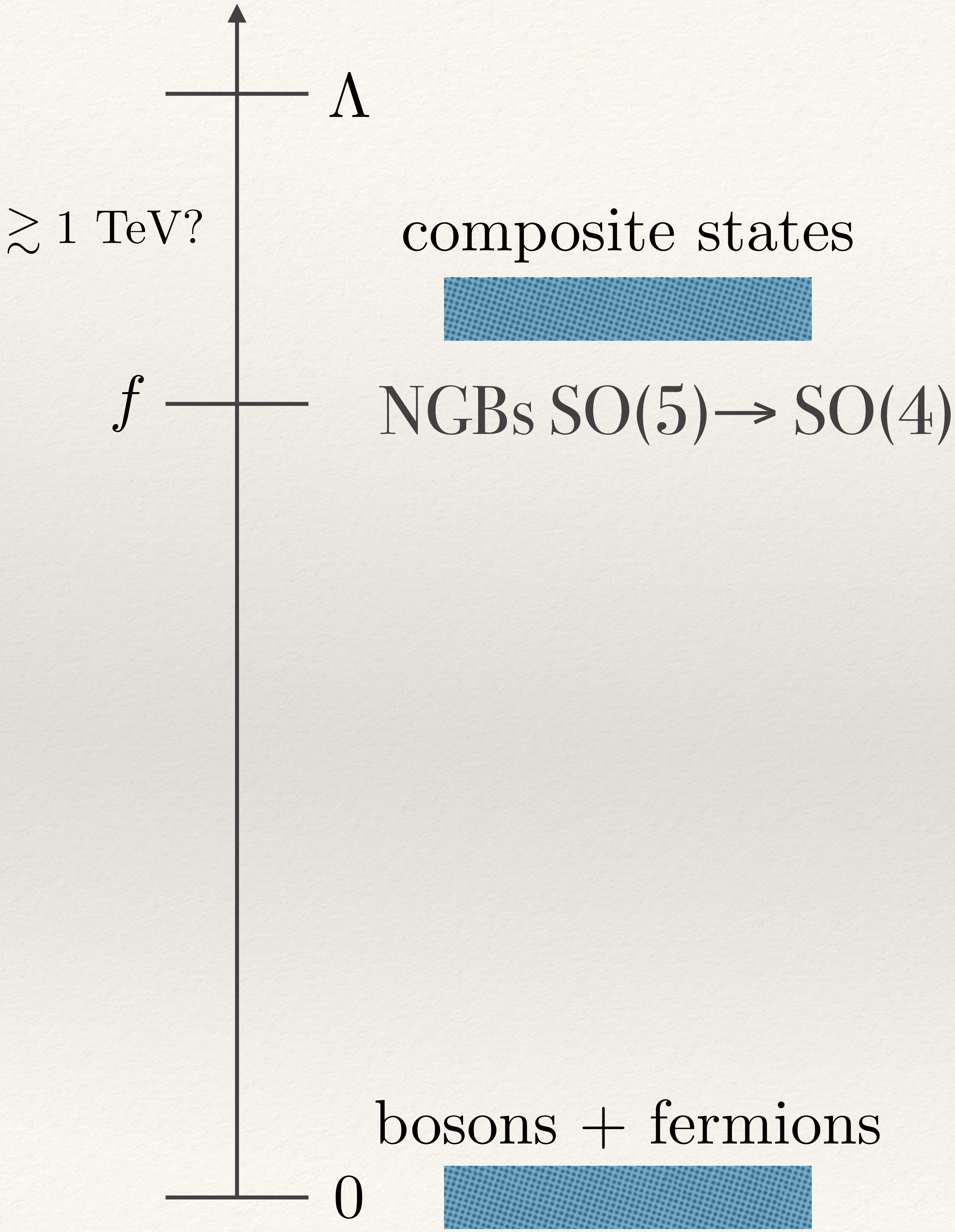


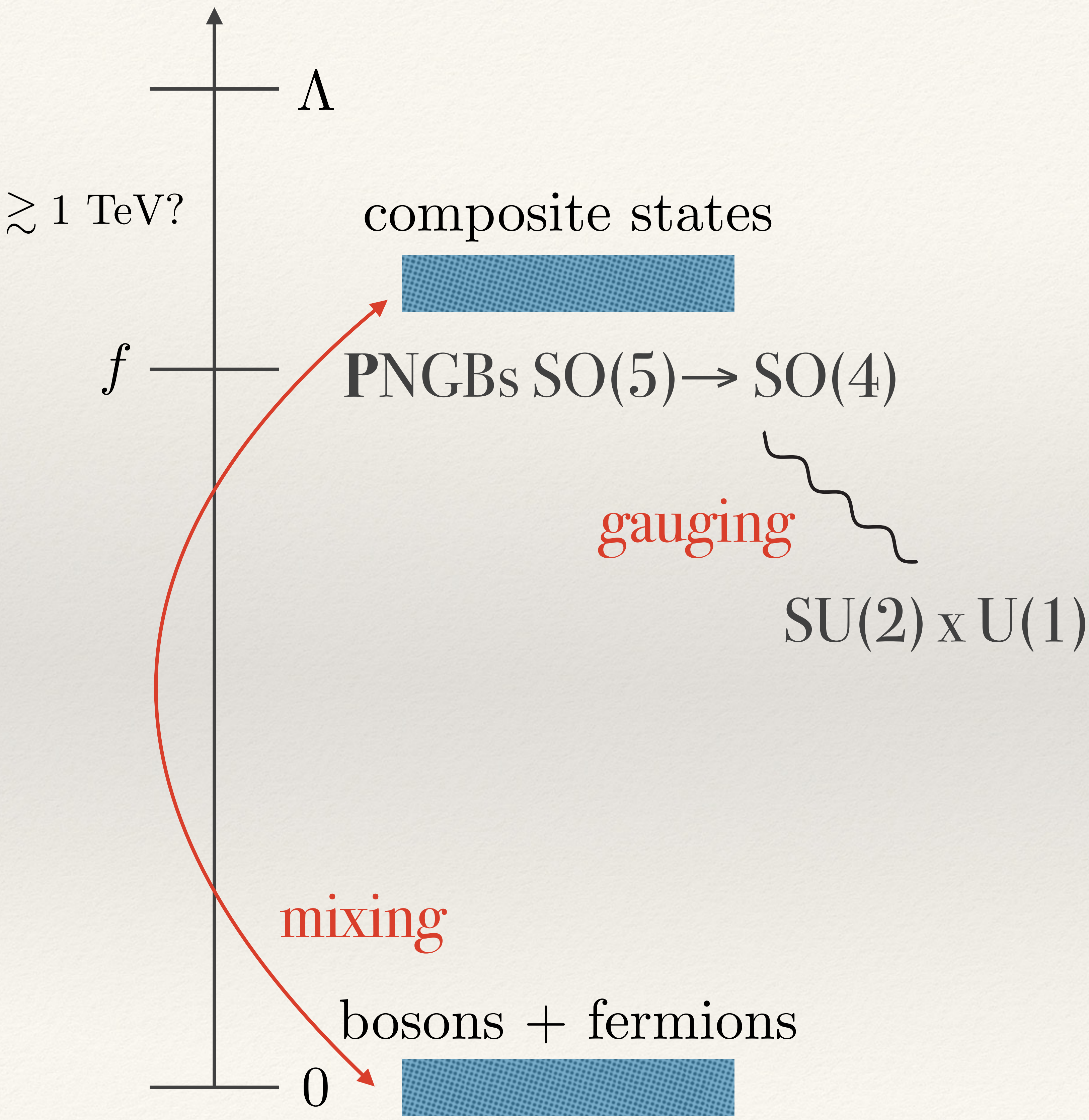
e.g. [ATLAS `21]

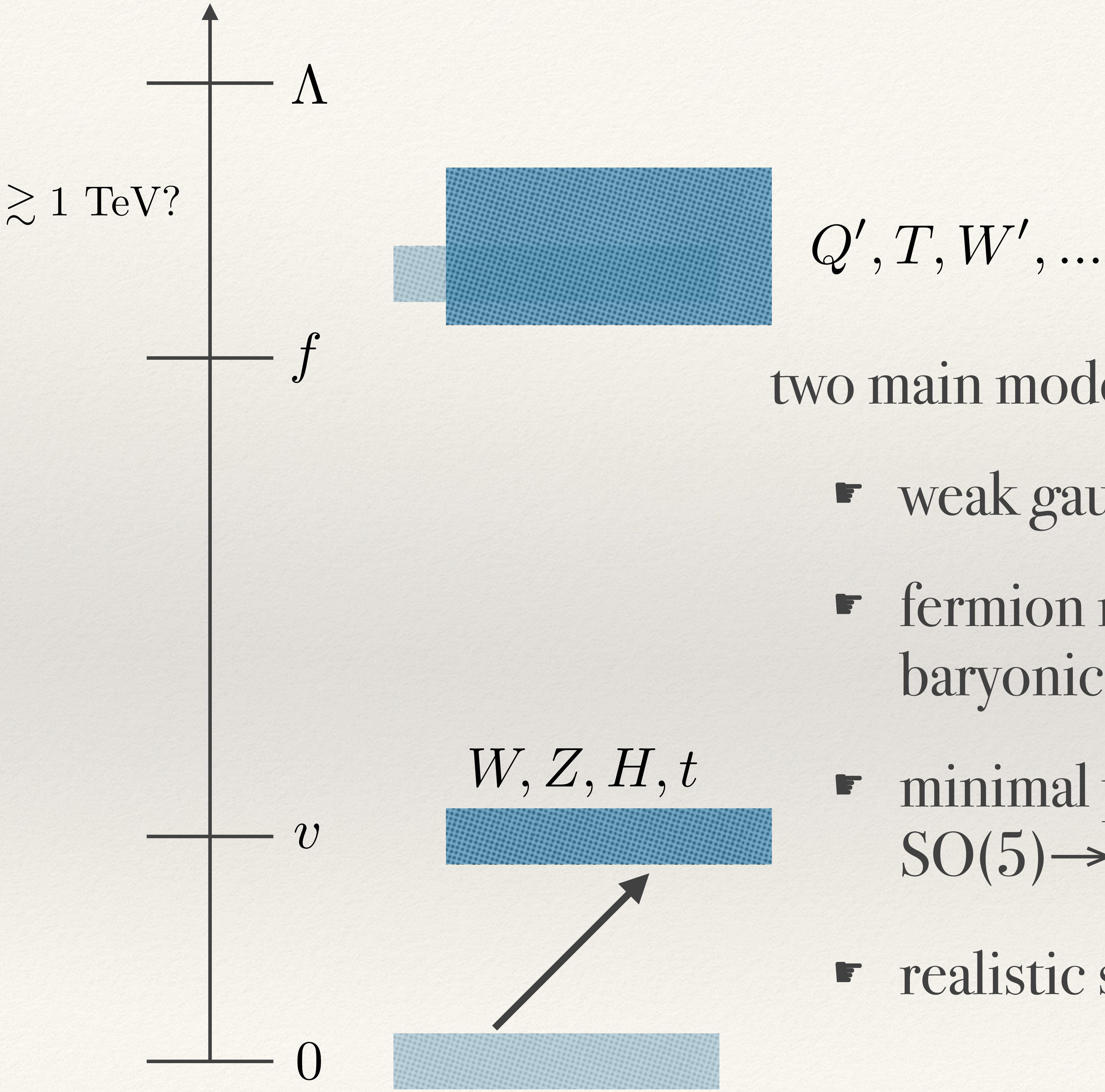
BSM ?


theoretical ambition
energy
$\gtrsim 1$ TeV?
m_{new}
new physics
renormalisable SM
m_t
top
$\mathcal{O}(100\text{ GeV})$
m_H
electroweak
m_Z
$\mathcal{O}(\text{GeV})$
m_b
light flavour
low
high
experimental precision

Strong interaction top flavour

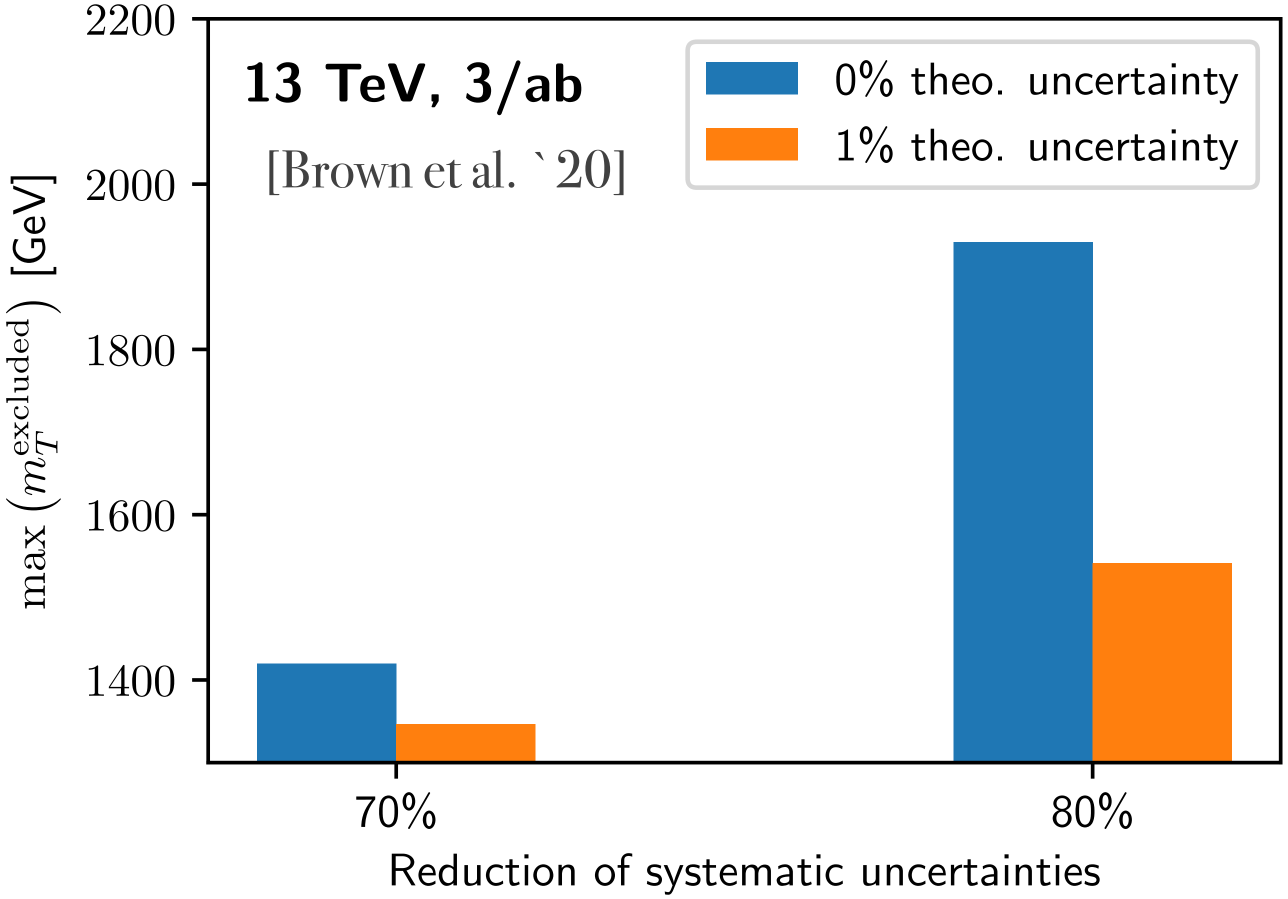



Λ
$\gtrsim 1$ TeV?
composite states
f
PNGBs SO(5)→ SO(4)
gauging
SU(2) x U(1)
mixing
bosons + fermions
0



two main model-building ingredients

- weak gauging of subgroup
- fermion masses through mixing with baryonic matter [Kaplan `91] [Agashe, Contino, Pomarol `04]...
- minimal phenomenological version SO(5)→ SO(4) ≃ $SU(2)^2$ e.g. [Contino `10]...
- realistic scenarios more complicated [Ferretti `14]...



$$\mathcal{L} \supset \bar{t}\gamma^\mu \left[g_L^t P_L + g_R^t P_R\right] t Z_\mu + \bar{b}\gamma^\mu \left[g_L^b P_L + g_R^b P_R\right] b Z_\mu + \left(\bar{b}\gamma^\mu \left[V_L P_L + V_R P_R\right] t W_\mu^+ + \text{h.c.}\right)$$

$$V_L = -\frac{g}{\sqrt{2}}\left[1 + \delta_{W,L}\right] \quad \text{etc.}$$

$$\delta_{W,L} \in [-0.029, 0.019]\,, \quad \delta_{W,R} \in [-0.009, 0.009]\,,$$
$$\delta^t_{Z,L} \in [-0.639, 0.277]\,, \quad \delta^t_{Z,R} \in [-1.566, 1.350]\,.$$

model correlations ↓

[Azatov et al.` 15]
[Sannino et al. ` 17]

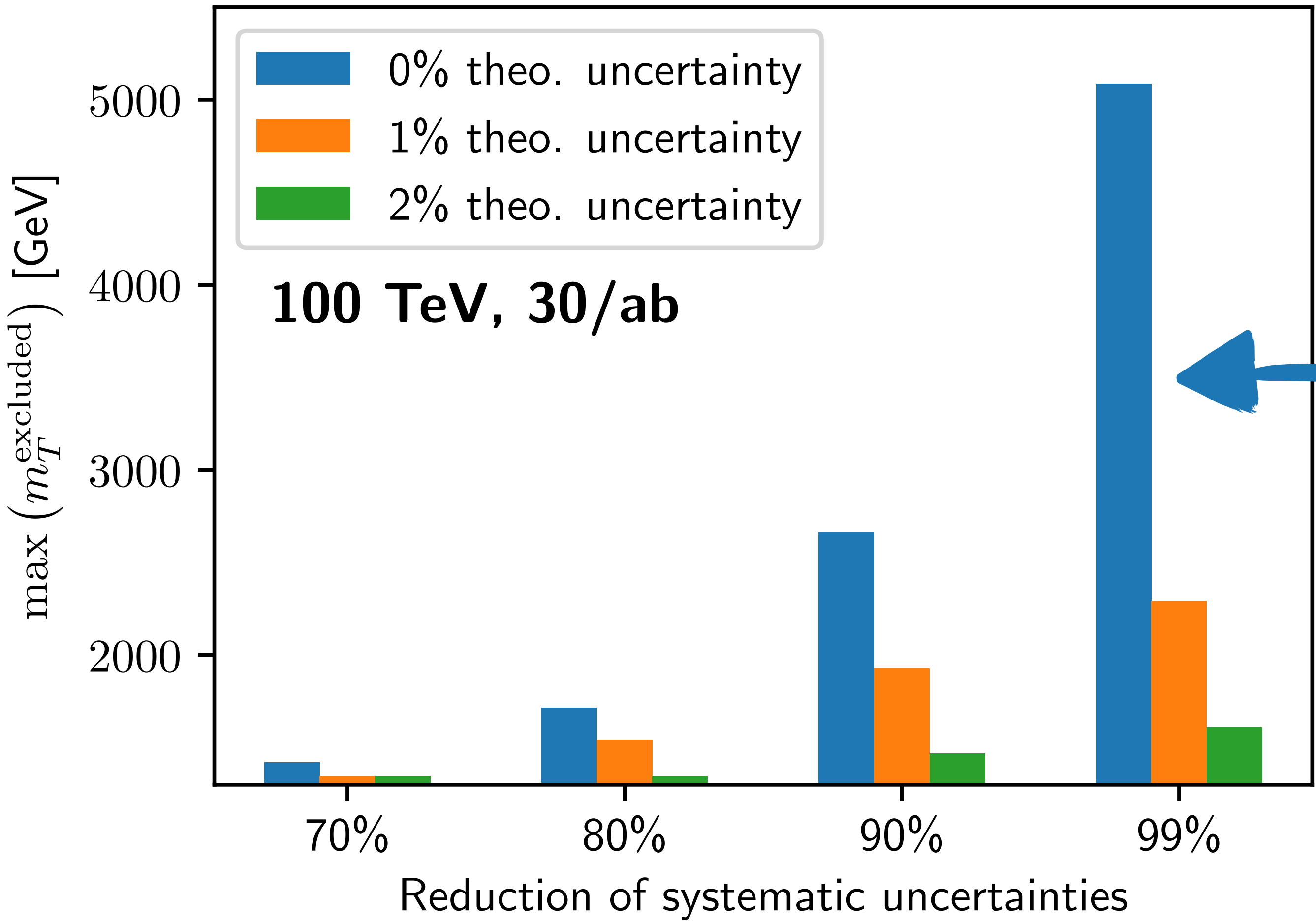
$$\delta_{W,L} \in [-0.025, 0.02]\,, \quad \delta_{W,R} \in [-0.0014, 0.0013]\,,$$
$$\delta^t_{Z,L} \in [-0.073, 0.06]\,, \quad \delta^t_{Z,R} \in [-0.33, 0.37]$$

- existing direct top partner constraints in the range of $\gtrsim 1.5$ TeV compatible

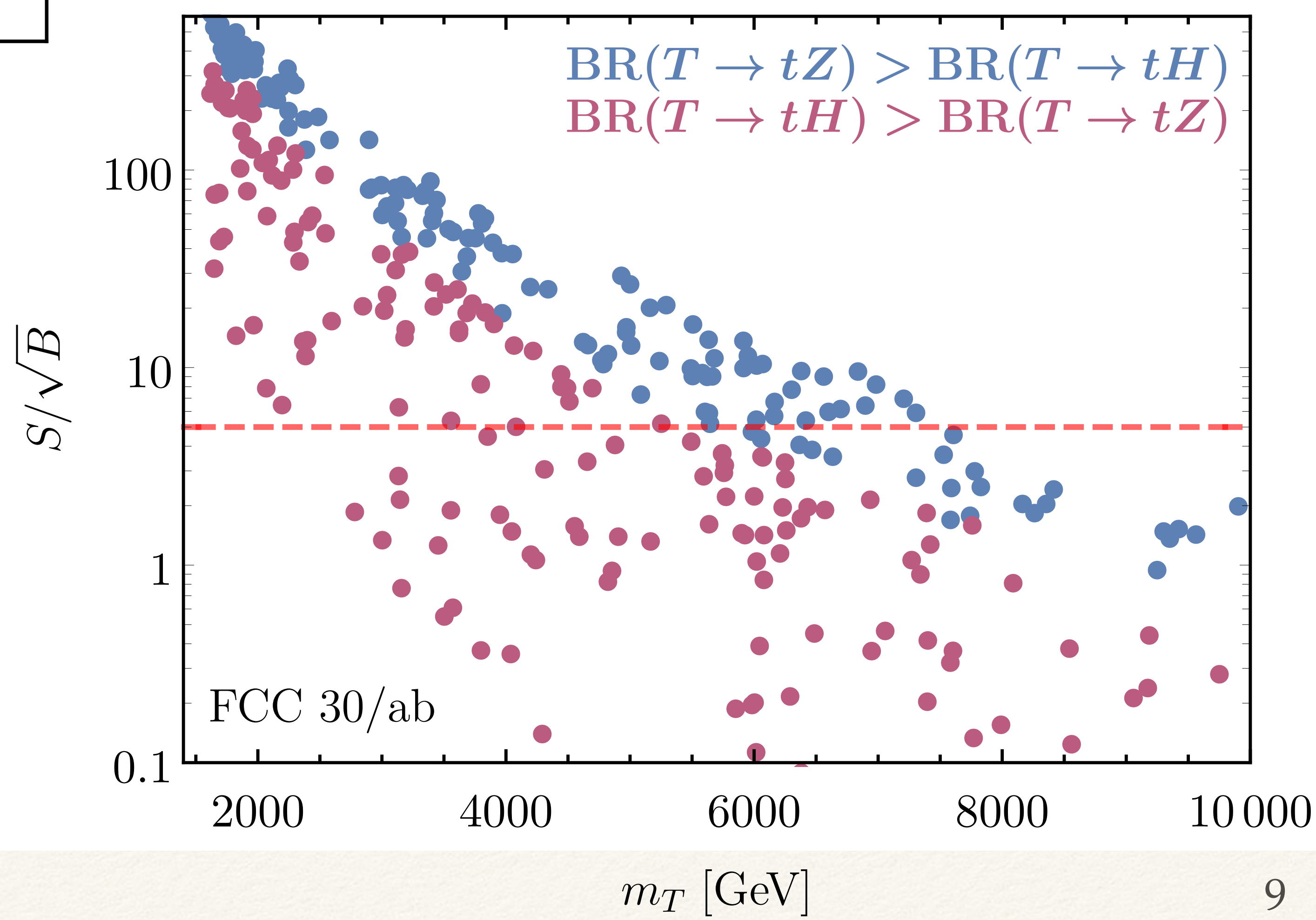
[Matsedonskyi, Panico, Wulzer ` 15]
[Li et al. ` 19]
...

- theoretical uncertainties are main sensitivity limitations, adding additional channels does not change this picture dramatically

the future of strongly-interacting top flavour



- optimistic extrapolations provide indirect sensitivity up to about 5 TeV

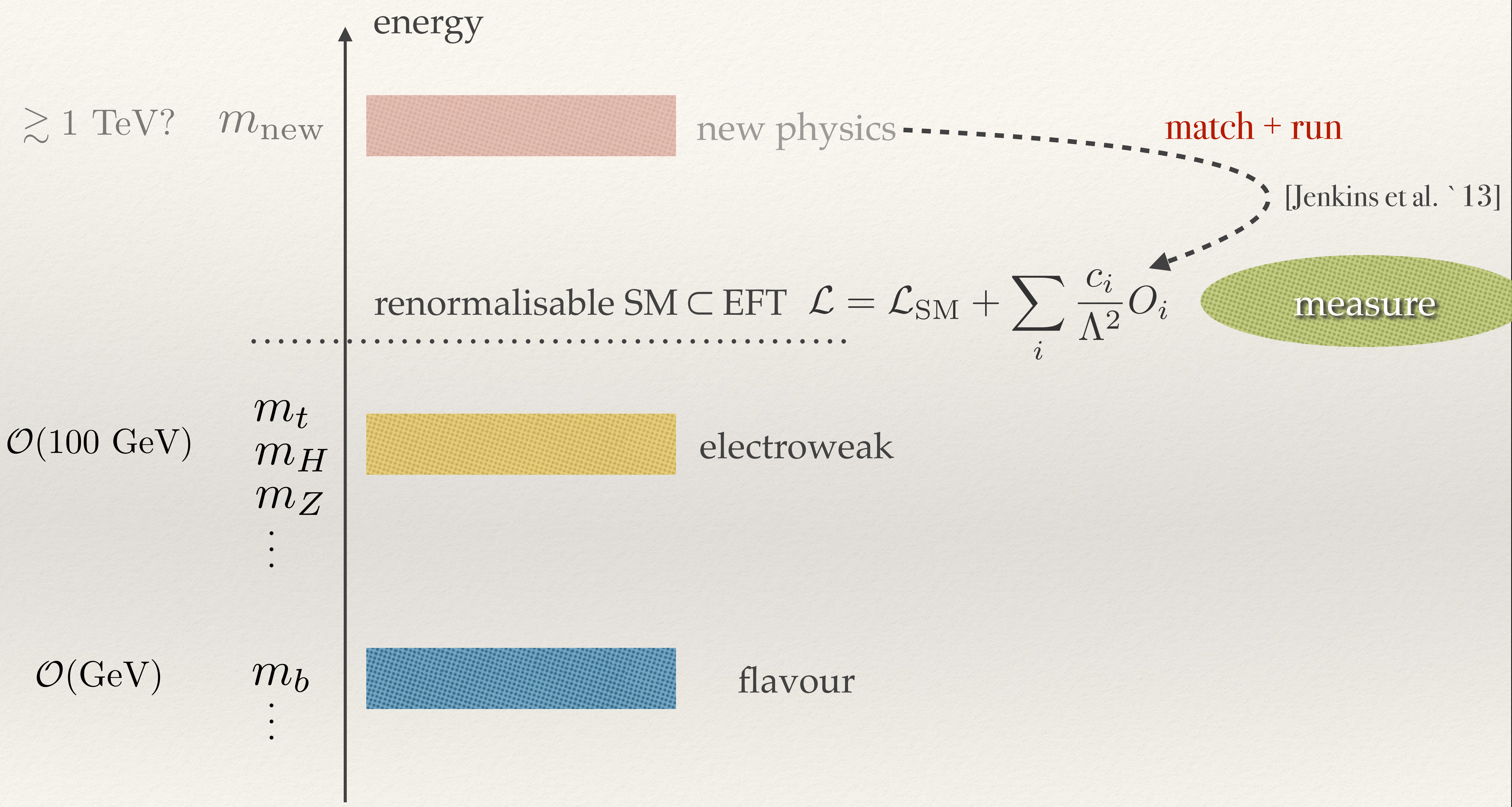


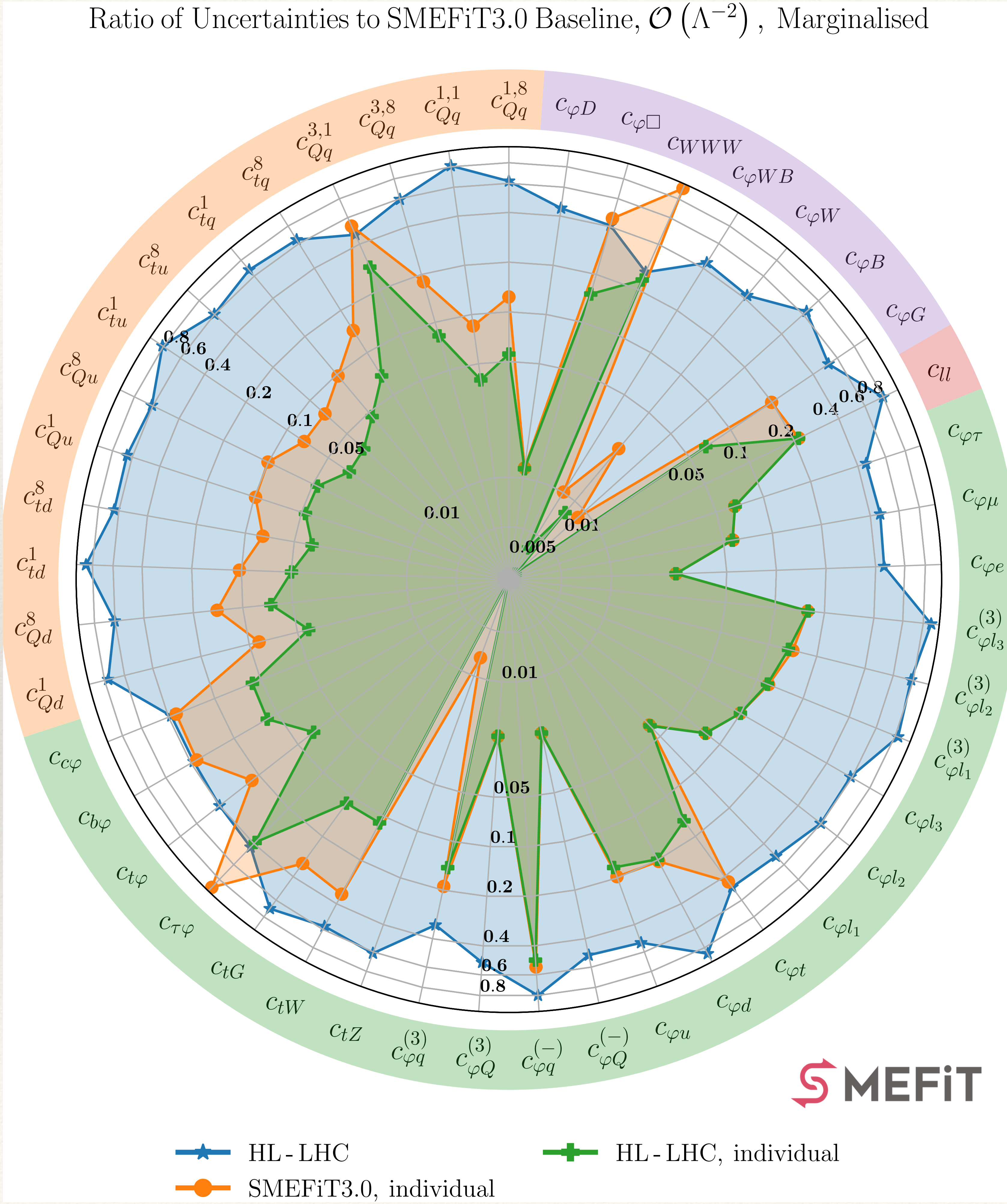
- direct top partner searches in electroweak channels providing direct sensitivity up to 8 TeV

[Barducci et al. `17]
[Li et al. `19]
...**[ECFA `25]**

bottom-up approach: EFT

theoretical ambition



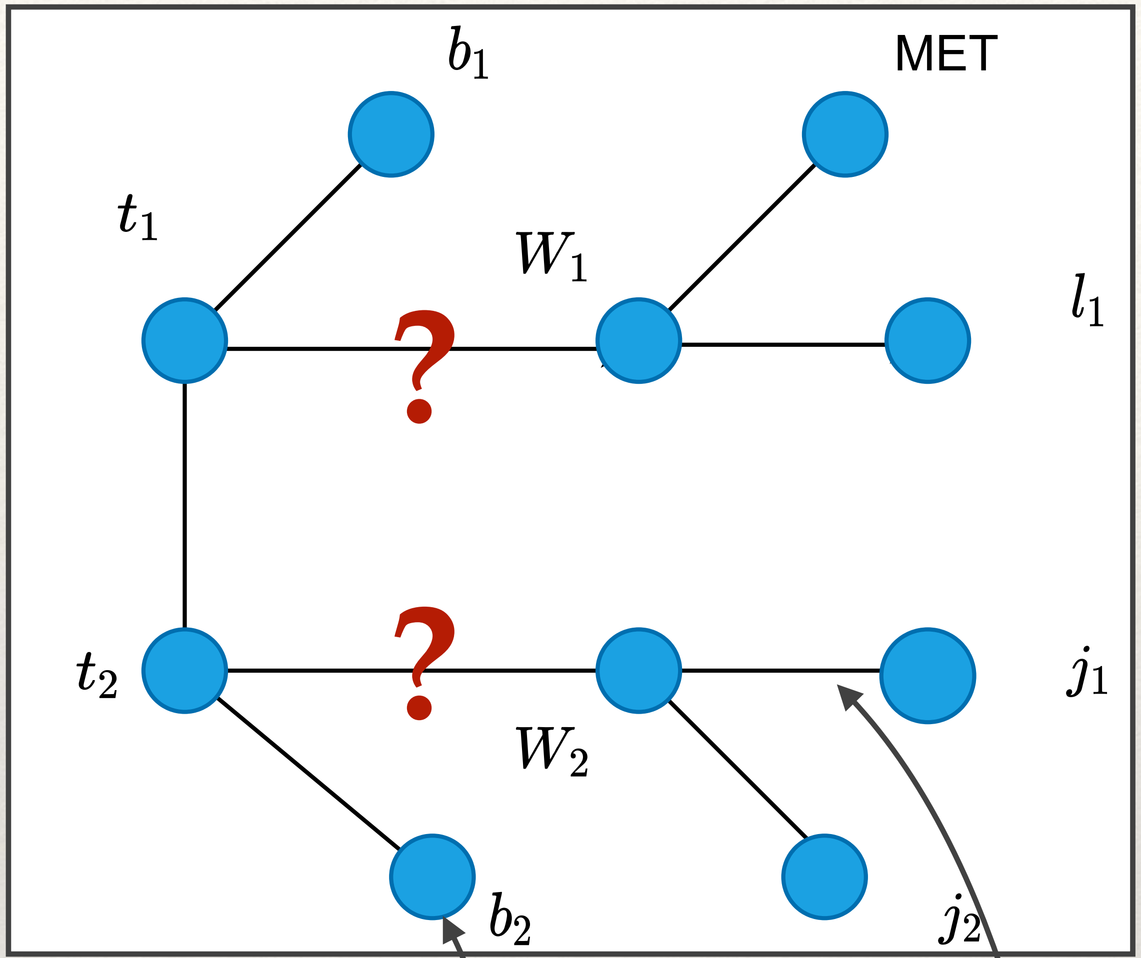


EFT approach

- ...well underway
- many parameters...
- flavour-agnostic results: 0.1-1/TeV^2 sensitivity
- improvements towards HL-LHC possible via data

[Celada et al. `24]

EFT approach



e.g. GNNs

edges for *feature correlation*

nodes with *features*
$[p_T, \eta, \phi, E, m, \mathrm{PID}]$

- …well underway
- many parameters…
- flavour-agnostic results: 0.1-1/TeV^2 sensitivity
- improvements towards HL-LHC possible via data
- but also through optimised new physics classifiers

EFT approach

top pair production + semi-leptonic decays

fractional improvement over collider observables

	[CMS `16] 2.3 fb^{-1}		3 ab^{-1}	
	Individual	Profiled	Individual	Profiled
$\bar{C}_G$	0.07%	14.12%	0.07%	11.09%
$\bar{C}_{\varphi q}^{(3)33}$	33.74%	34.19%	33.73%	33.48%
$\bar{C}_{uG}^{33}$	28.29%	32.18%	28.28%	30.74%
$\bar{C}_{uW}^{33}$	34.86%	35.35%	34.85%	35.53%
$\bar{C}_{qd}^{(8)33ii}$	4.71%	4.68%	4.71%	4.76%
$\bar{C}_{qq}^{(1)i33i}$	3.50%	3.45%	3.50%	4.73%
$\bar{C}_{qq}^{(3)i33i}$	4.35%	4.28%	4.35%	5.00%
$\bar{C}_{qq}^{(3)ii33}$	63.83%	–	63.83%	71.91%
$\bar{C}_{qu}^{(8)33ii}$	3.45%	3.51%	3.45%	3.48%
$\bar{C}_{qu}^{(8)ii33}$	3.74%	3.72%	3.74%	3.77%
$\bar{C}_{ud}^{(8)33ii}$	4.62%	4.46%	4.62%	4.79%
$\bar{C}_{uu}^{i33i}$	3.38%	3.35%	3.38%	1.95%
$\bar{C}_{lq}^{(3)ii33}$	–	–	10.57%	35.52%

- ...well underway
- many parameters...
- flavour-agnostic results: 0.1-1/TeV^2 sensitivity
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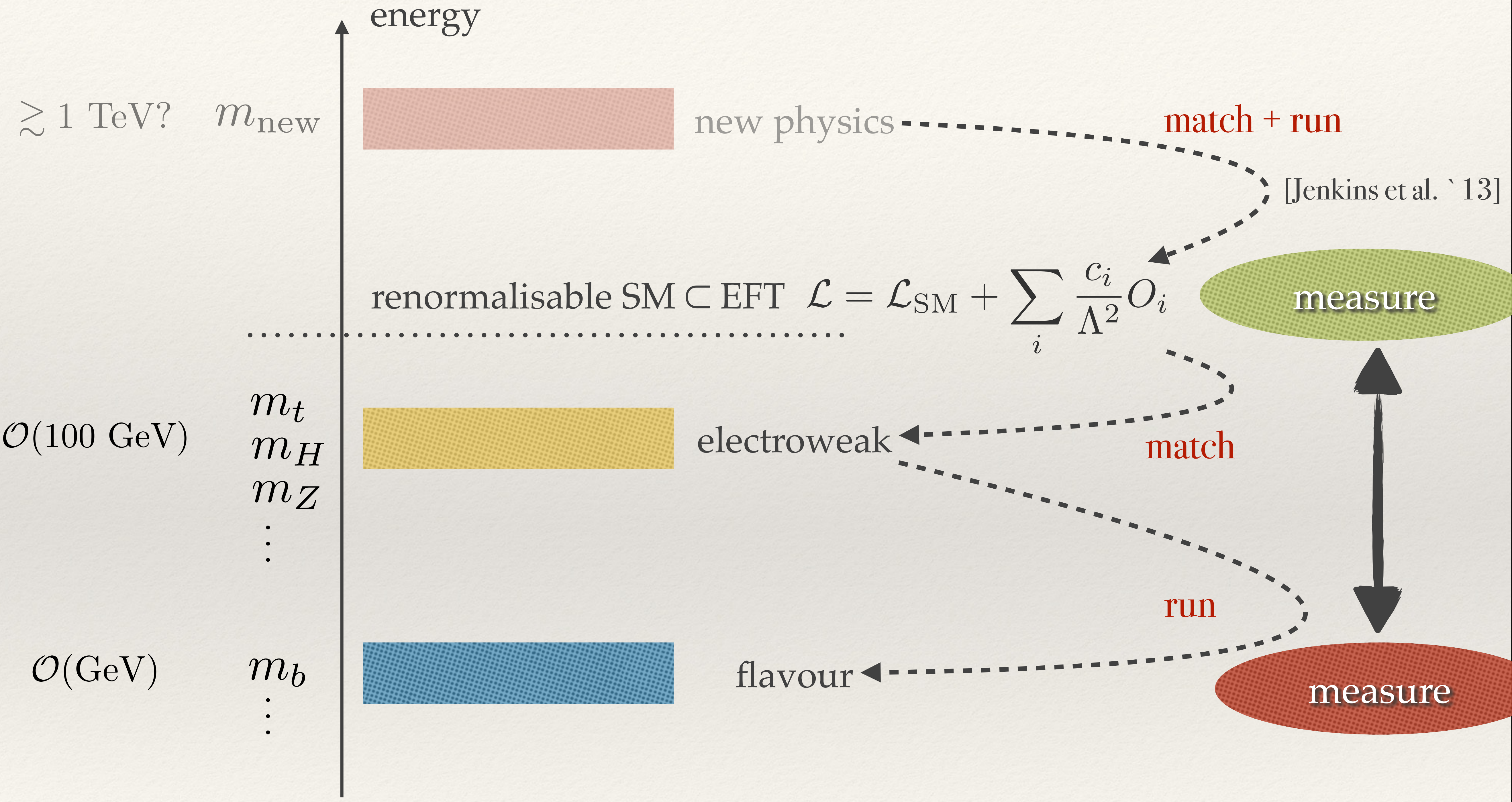
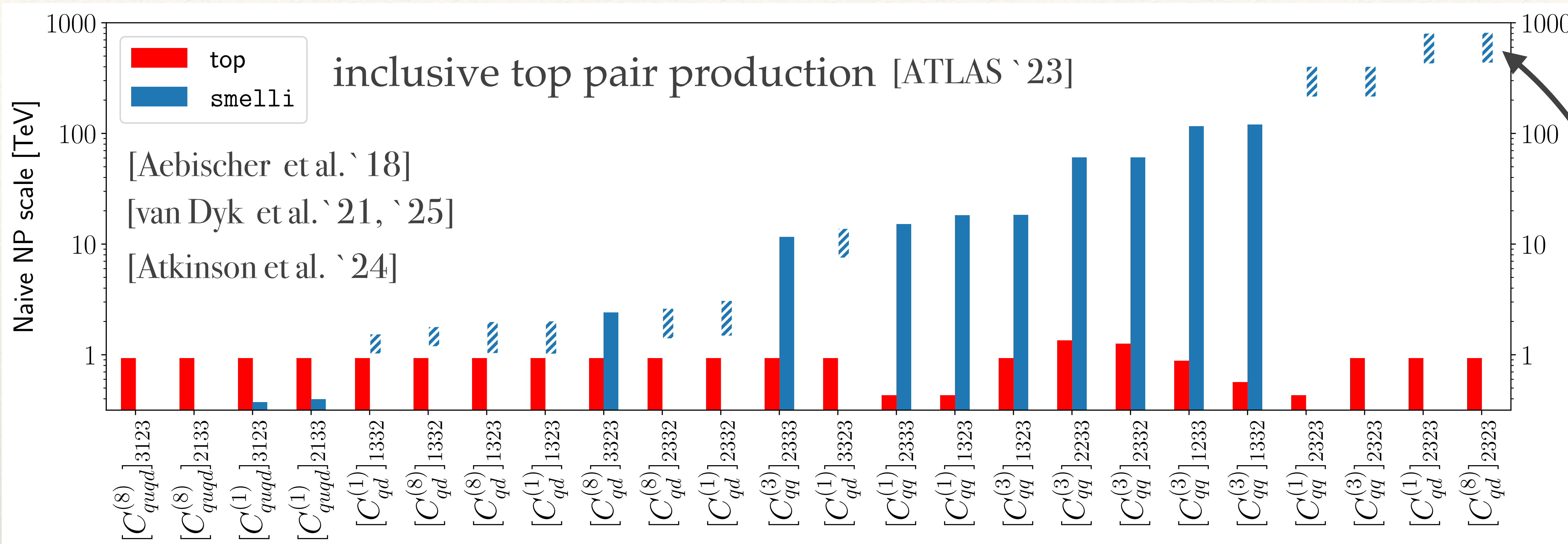
[Brown et al. `21]

bottom-up approach: EFT

theoretical ambition



bottom-up approaches: top vs bottom



- LHC measurements largely quark flavour-blind (with exceptions)
- top sector motivated to establish RGE-informed B/K analyses
- differential analyses to enhance tensions underway…

	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	$0.14^{+0.01}_{-0.01}$	$\approx 0.16\,\sigma$
R_K^*	$\bar{B}^0 \to D^{*+} K^-$	0.064 ± 0.003	$0.076^{+0.002}_{-0.001}$	$\approx 3.6\,\sigma$
$R_{s\pi}^*$	$\bar{B}_s \to D^{*+} \pi^-$	$0.52^{+0.18}_{-0.16}$	$1.05^{+0.04}_{-0.03}$	$\approx 3.1\,\sigma$

jets [Bordone, Greljo, Marzocca `21]

Drell Yan [Grunwald, Hiller, Kröniger, Nollen `24, `25]

- right-handed down sector…

$$O_{dd} = (\bar{d}^i_R \gamma^\mu d^j_R)(\bar{d}^k_R \gamma_\mu d^l_R).$$

loopholes?

- right-handed down sector…

$$O_{dd} = (\bar{d}^i_R \gamma^\mu d^j_R)(\bar{d}^k_R \gamma_\mu d^l_R).$$

no Higgs data sensitivity

no ELW data sensitivity

no top data sensitivity

- is this relevant in the UV model landscape? **YES!**

[Giudice, Gripaios, Sundrum `11]
…
[CE, Mayer, Naskar, Renner `24]

[de Blas et al. `18]

State	Spin	SM charges	Tree-level generated operators
$\Phi_{(3)}$	0	$(\mathbf{3},\mathbf{1})_{2/3}$	O_{dd}
$\Phi_{(6)}$	0	$(\bar{\mathbf{6}},\mathbf{1})_{2/3}$	O_{dd}
$\mathcal{B}$	1	$(\mathbf{1},\mathbf{1})_0$	$O_{ll},\ O^{(1)}_{qq},\ O^{(1)}_{lq},\ O_{ee},\ O_{dd},\ O_{uu},\ O^{(1)}_{ud},\ O_{le},\ O_{qe},\ O_{ld},\ O_{lu},\ O^{(1)}_{qd},$ $O^{(1)}_{qu},\ O_{HD},\ O_{H\Box},\ O_{eH},\ O_{dH},\ O_{uH},\ O^{(1)}_{Hl},\ O^{(1)}_{Hq},\ O_{He},\ O_{Hd},\ O_{Hu}$
$\mathcal{G}$	1	$(\mathbf{8},\mathbf{1})_0$	$O^{(1)}_{qq},\ O^{(3)}_{qq},\ O_{dd},\ O_{uu},\ O^{(8)}_{ud},\ O^{(8)}_{qu},\ O^{(8)}_{qd}$

loopholes?

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$$O_{dd} = (\bar{d}^i_R \gamma^\mu d^j_R)(\bar{d}^k_R \gamma_\mu d^l_R).$$

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State	Spin	SM charges
$\Phi_{(3)}$	0	$(\mathbf{3},\mathbf{1})_{2/3}$
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$$\frac{SO(6)\times SO(5)}{SU(3)_c \times U(1)_t \times SU(2)_L \times SU(2)_R}$$

$$\frac{Sp(6)\times SO(5)}{SU(3)_c \times U(1)_s \times SU(2)_L \times SU(2)_R}$$

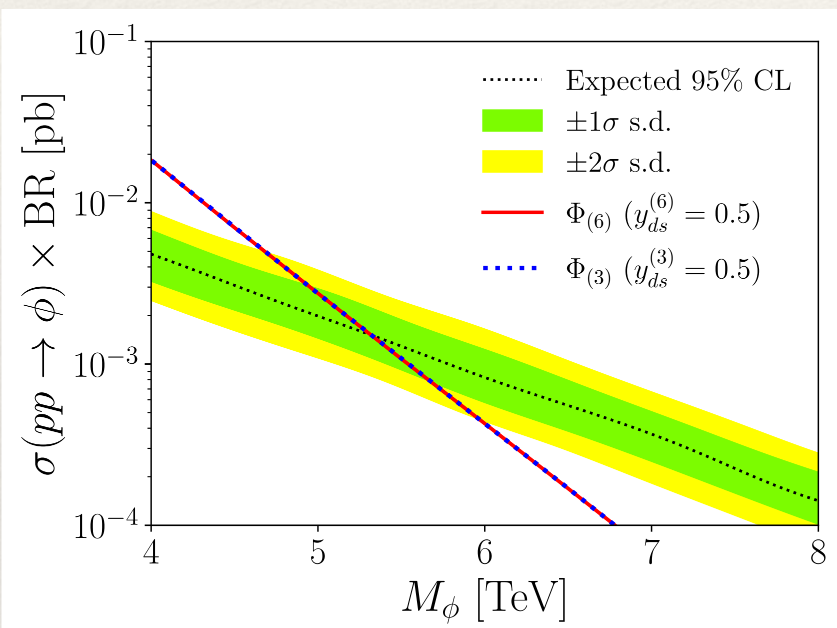
…scalar diquarks probe different partial composites scenarios!

coloured exotica vs lepton-specific

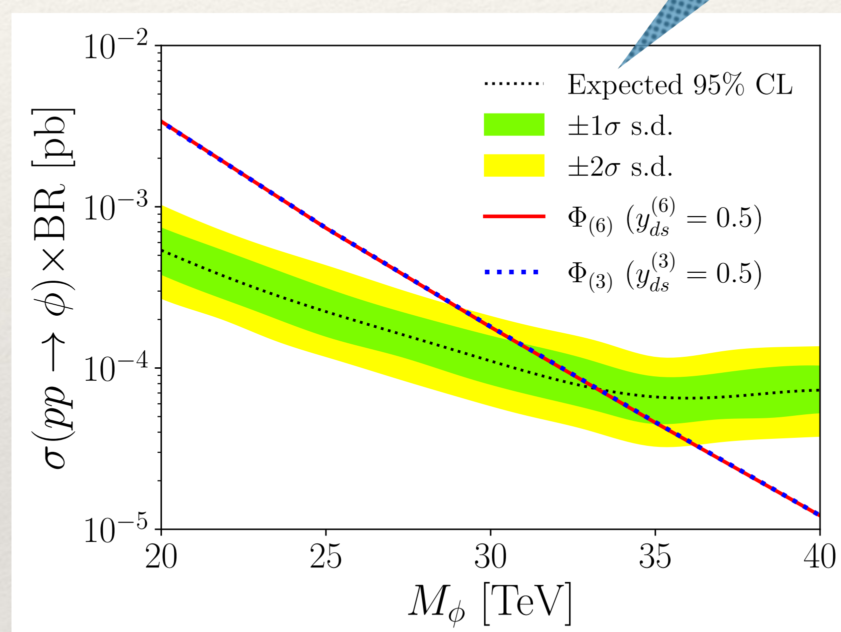
- direct production at hadron colliders, degenerate exclusion projections

$(\mathbf{3},\mathbf{1})_{2/3}$ vs. $(\bar{\mathbf{6}},\mathbf{1})_{2/3}$ ← UV flavour structures

down-type sector



HL-LHC



FCC-hh

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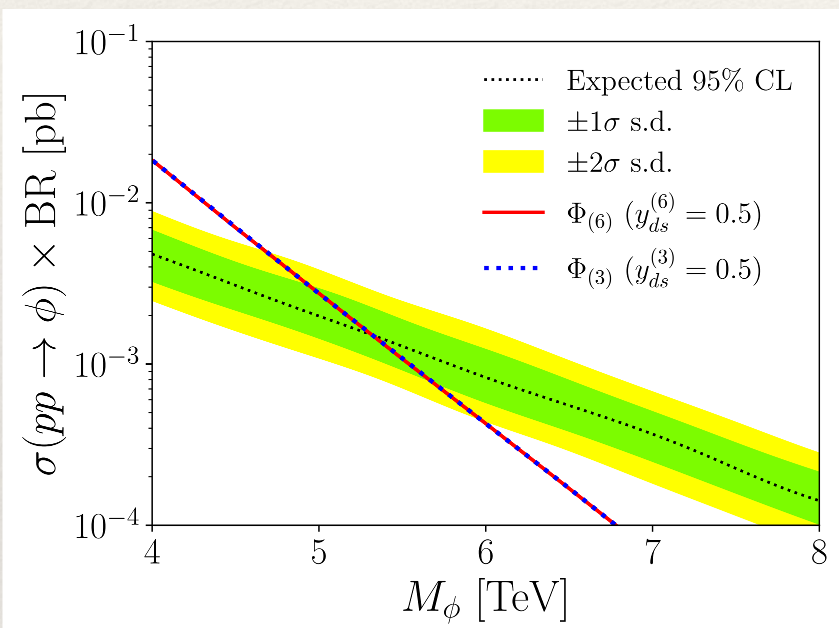

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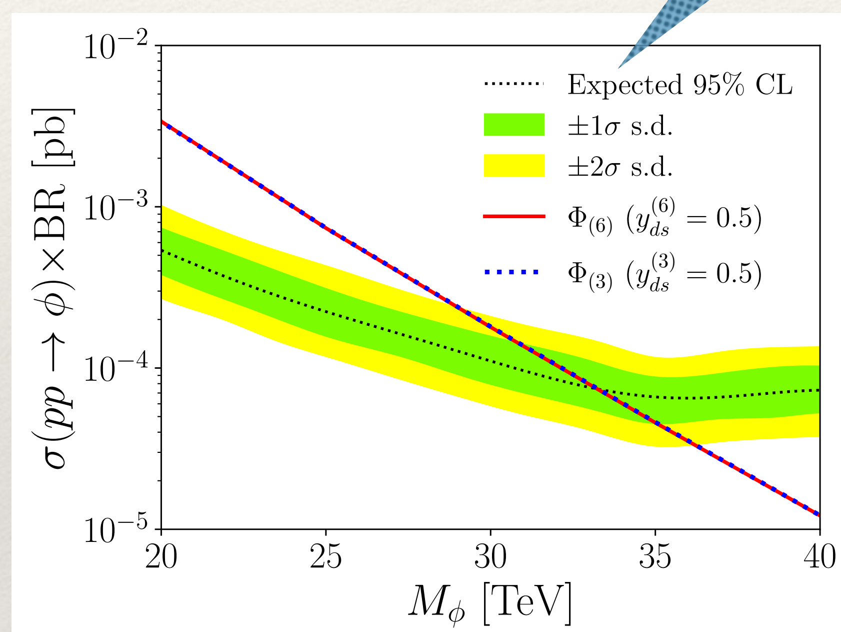

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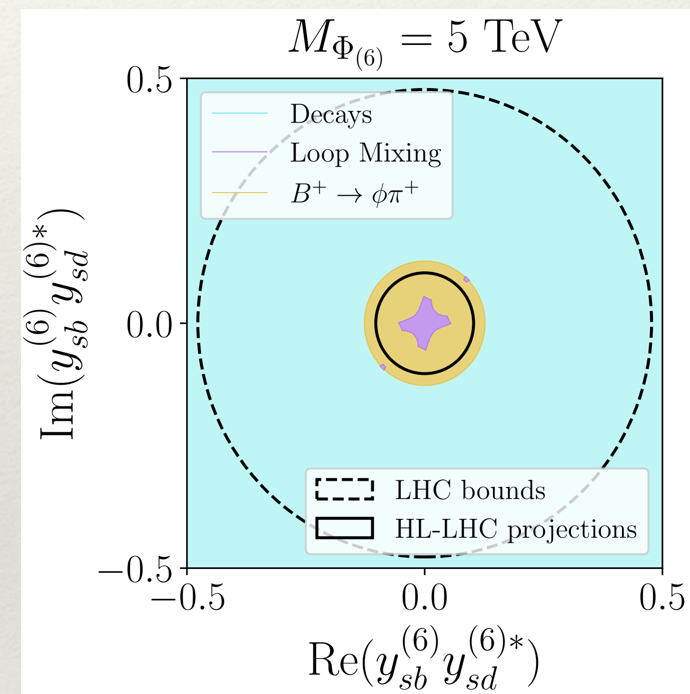

collider+flavour

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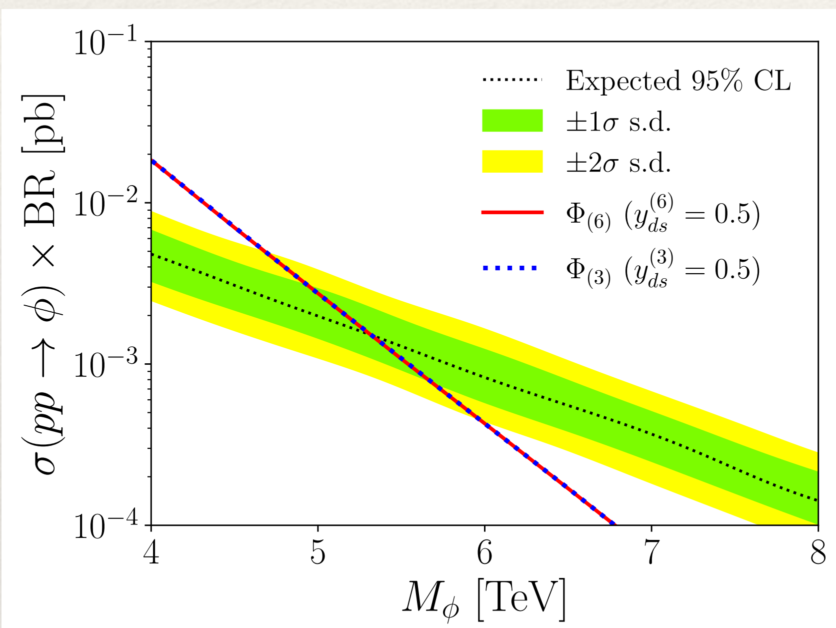
FCC-hh



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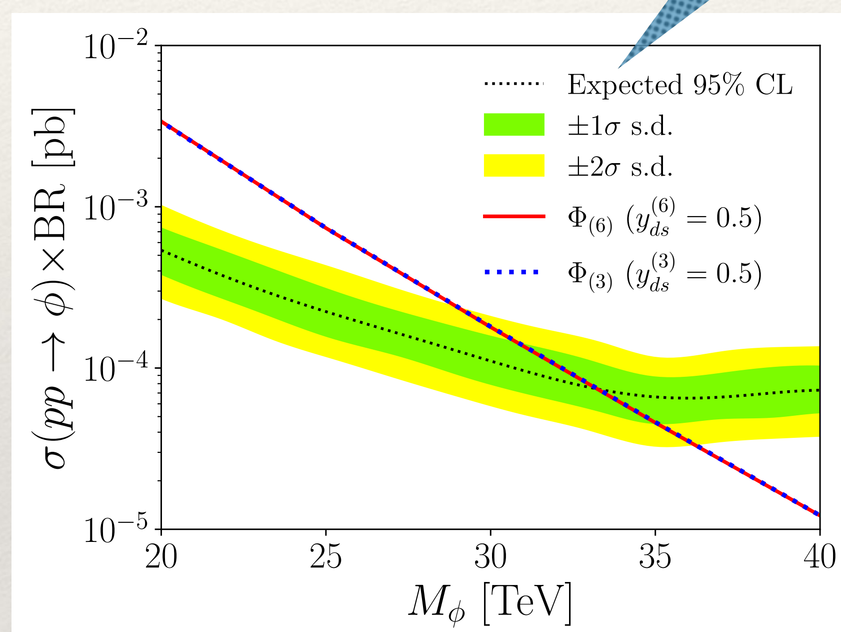

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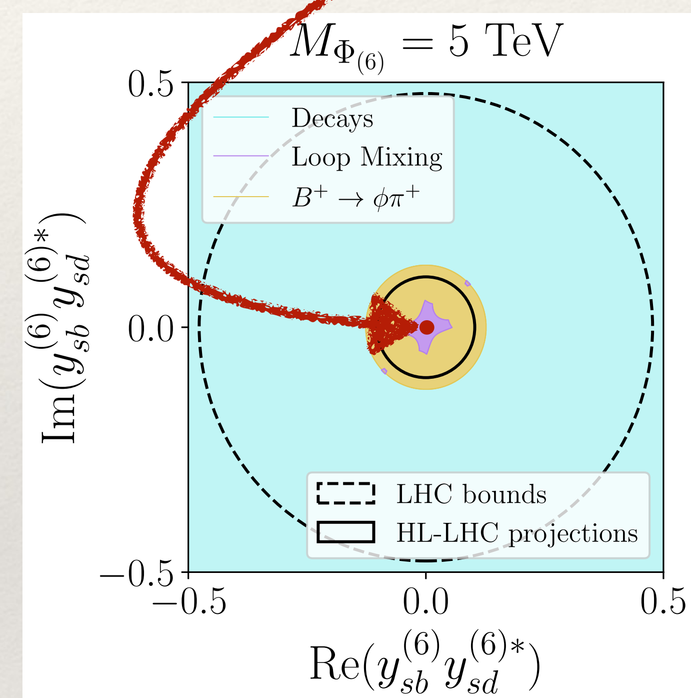

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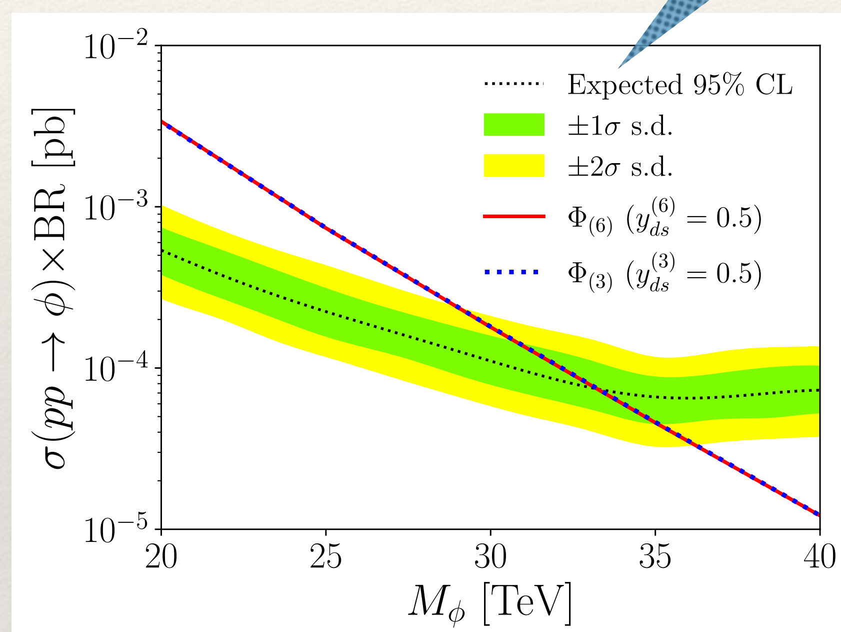

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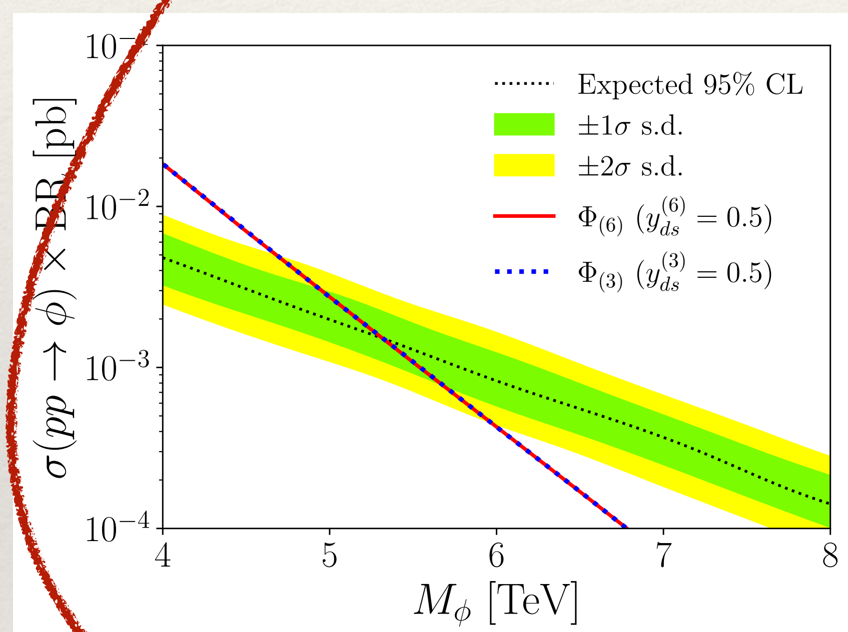

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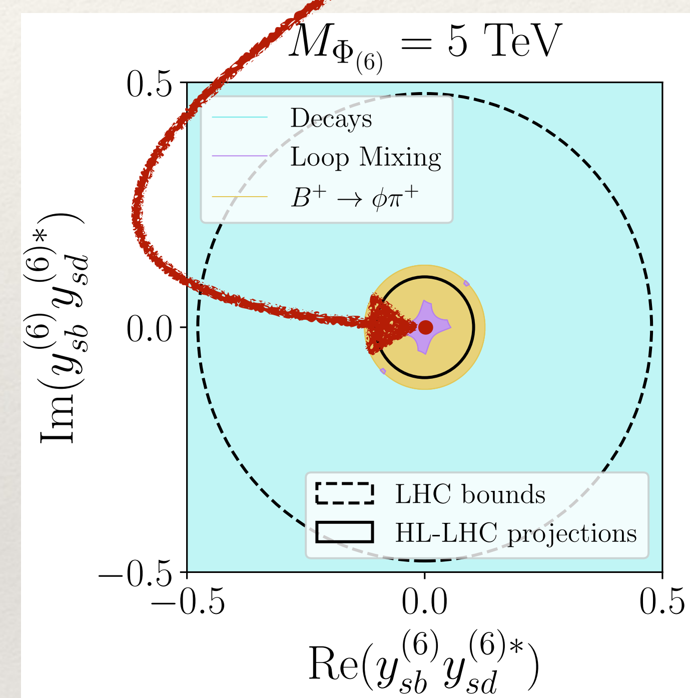


collider+flavour

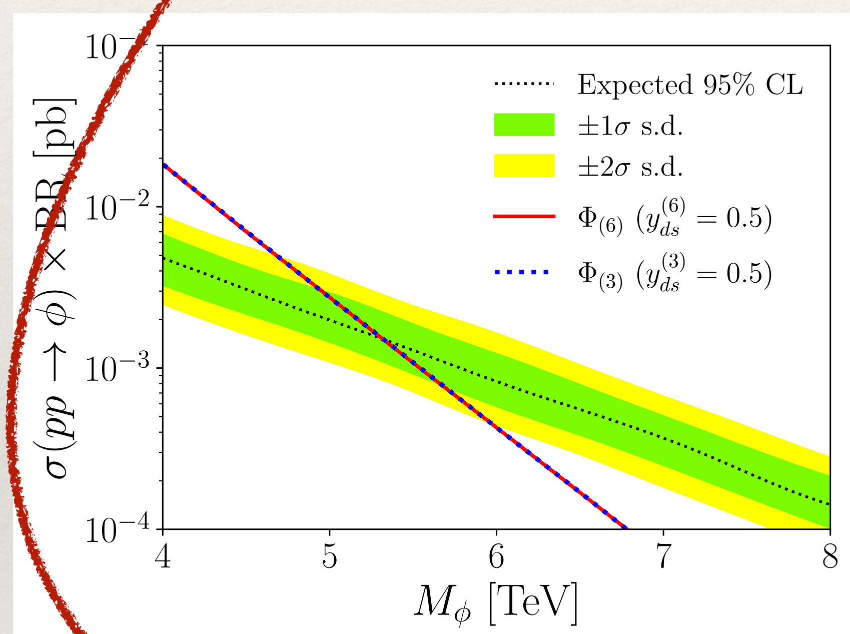
pair production at lepton colliders is $U(1)_Y$ gauge suppressed

coloured exotica vs lepton-specific

- direct production at hadron colliders, degenerate exclusion projections

$(\mathbf{3},\mathbf{1})_{2/3}$ vs. $(\bar{\mathbf{6}},\mathbf{1})_{2/3}$ ← UV flavour structures ← down-type sector

FCC-hh



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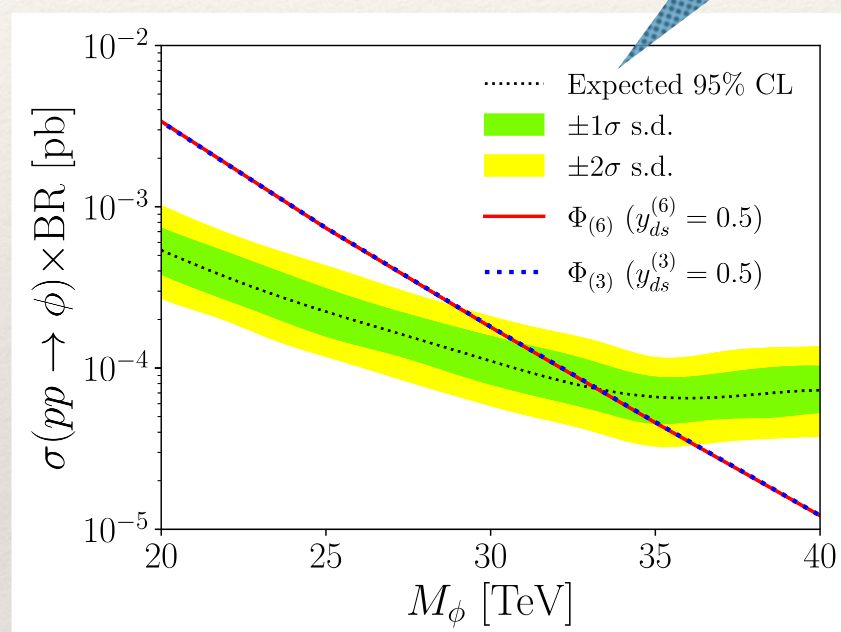

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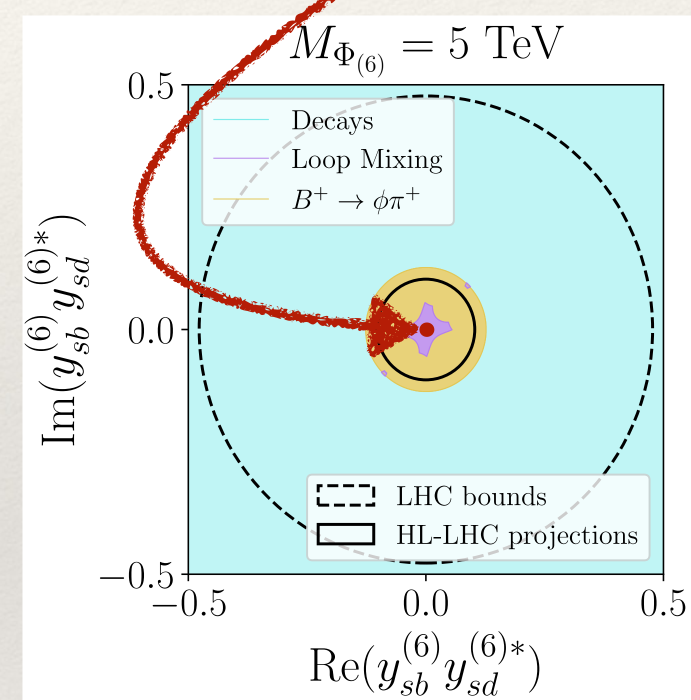

collider+flavour

pair production at lepton colliders is $U(1)_Y$ gauge suppressed

ee/μμ has no competitive discovery potential

coloured exotica vs lepton-specific

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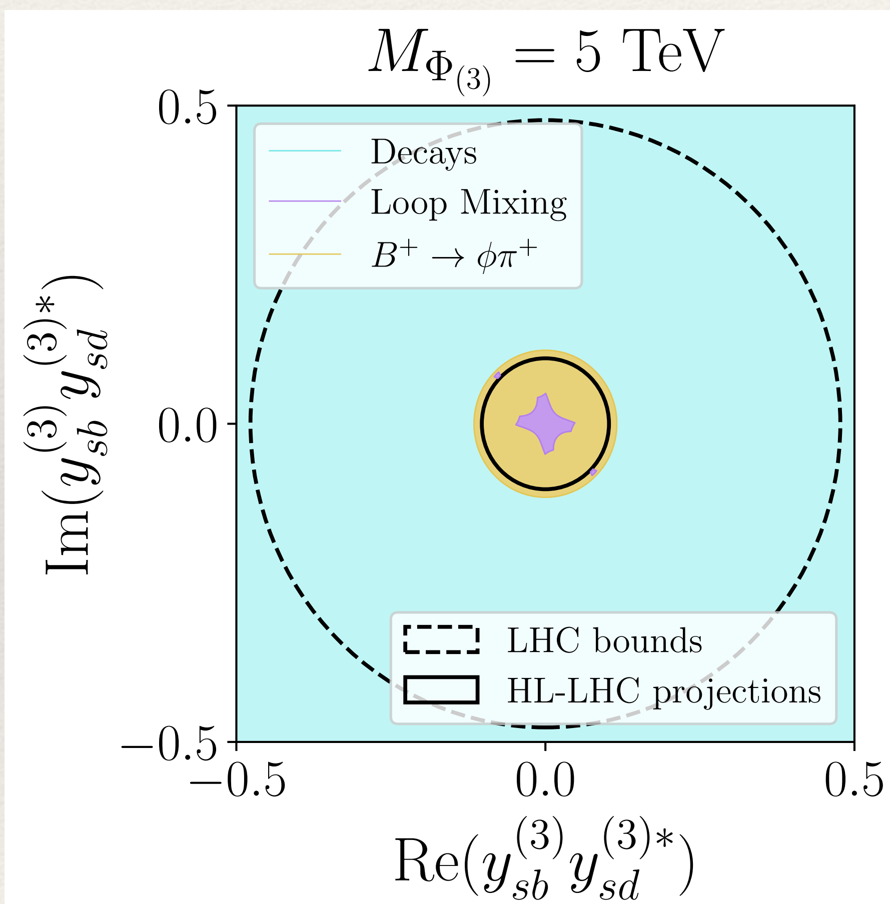

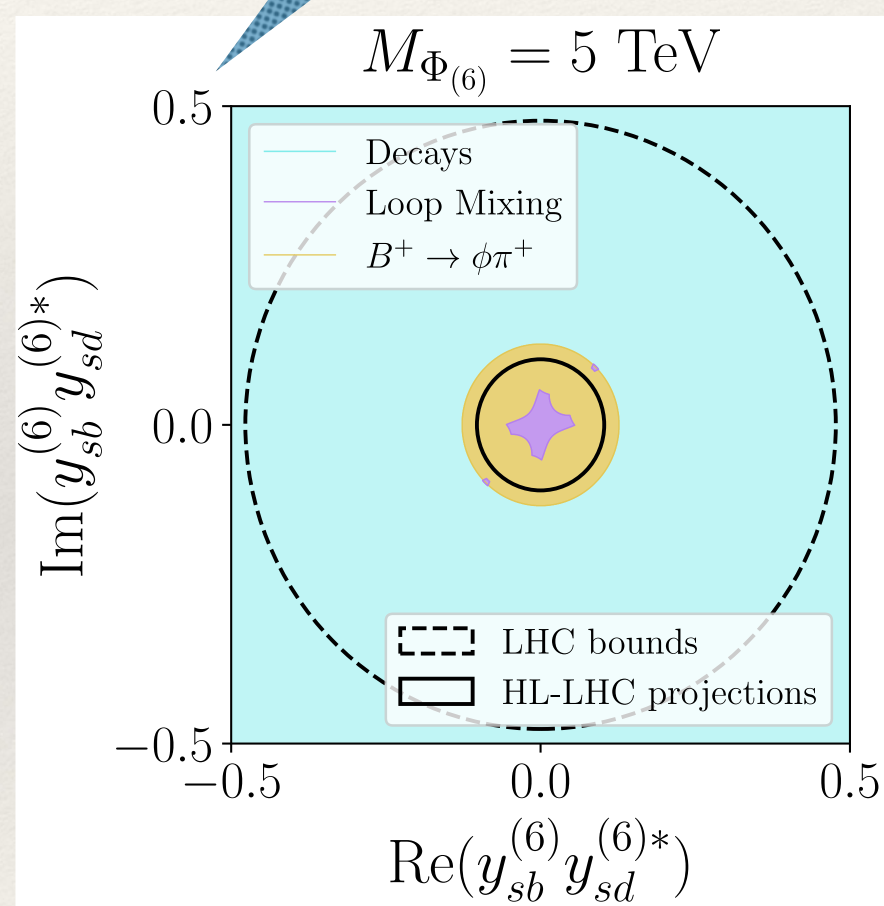

flavour observations/tagging necessary to complement hadron discovery potential!

Summary

- we have lots of puzzles but no substantiated answers

Summary

- we have lots of puzzles but no substantiated answers (yet)
- ...but data is coming – challenging our assumptions/methods/...
- combining the largest energy with the highest precision through theoretically robust methodology might hold answers to some Qs
- can expect good improvement towards HL-LHC
- FCC-ee prospects to go beyond the HL-LHC... (not discussed here)