Composite Higgs signatures at the LHC (and future)

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Snowmass EF08, 11 June 2020

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How to give mass to SM fermions?

- Partial compositeness is the most popular framework
- It predicts heavy spin-1/2 "top partners"
- Additional light "pions" are a must

How to give mass to SM fermions?

Replace the Higgs with a composite operator:

$$y_t \, \varphi_H^* \, \bar{q}_L t_R \longrightarrow \frac{\lambda_t}{\Lambda^{d-1}} \mathcal{O}_H \, \bar{q}_L t_R \qquad \left(\frac{\lambda_t}{\Lambda^2} \, \bar{\psi}\psi \, \bar{q}_L t_R \right)$$

High scale (flavour)

Unsuppressed coupling (top) requires $d \sim 1$,
i.e. the dimension of a scalar field!

It walks like a scalar,
it quacks like a scalar...
it is probably a scalar! →

Guess who's back?
Naturalness problem!

How to give mass to SM fermions?

Top partial compositeness:

$$\frac{\lambda_R}{\Lambda^{d_{\mathcal{B}}-5/2}}\,\mathcal{O}_{\mathcal{B}} t_R \qquad \left(\frac{\lambda_R}{\Lambda^2}\bar{\psi}\psi\bar{\psi}\, t_R\right)$$

Unsuppressed coupling (top) requires $d_{\mathcal{B}} \sim 5/2$!
Not related to a scalar dimension...

How to give mass to SM fermions?

Top partial compositeness:

$$\frac{\lambda_R}{\Lambda^{d_{\mathcal{B}}-5/2}}\,\mathcal{O}_{\mathcal{B}}t_R \qquad \left(\frac{\lambda_R}{\Lambda^2}\bar\psi\psi\bar\psi\;t_R\right)$$

$$\Big\downarrow$$

$$y_L f\;\bar q_L T_R\,,\;\; y_R f\;\overline{T}_L t_R \quad\longrightarrow\quad y_t \sim \frac{y_R y_L f}{M_T}$$

- Top partners emerge from the spin-1/2 composite operators.

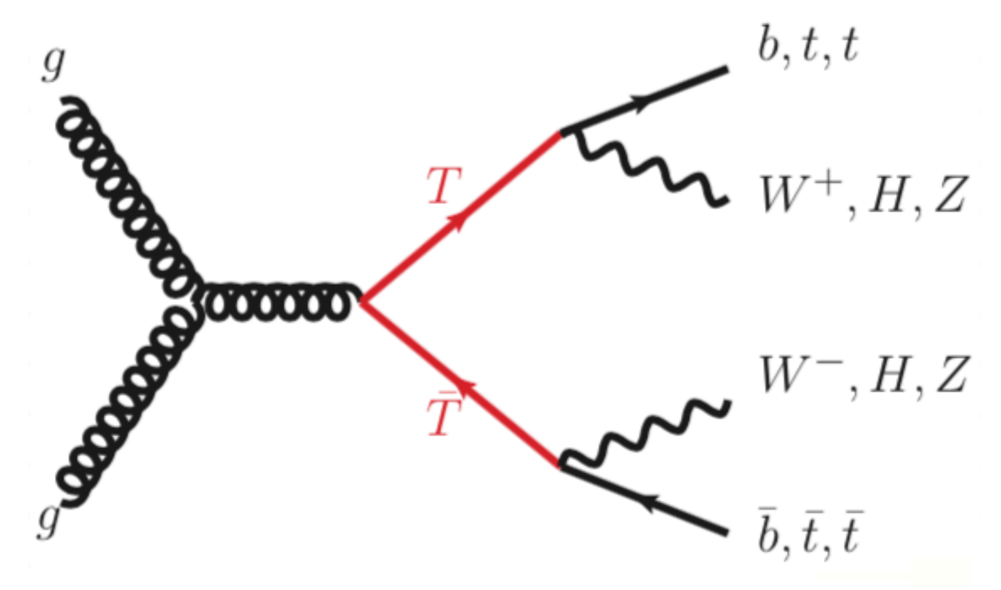
- They cannot be too heavy (multi-TeV range).

Generic properties

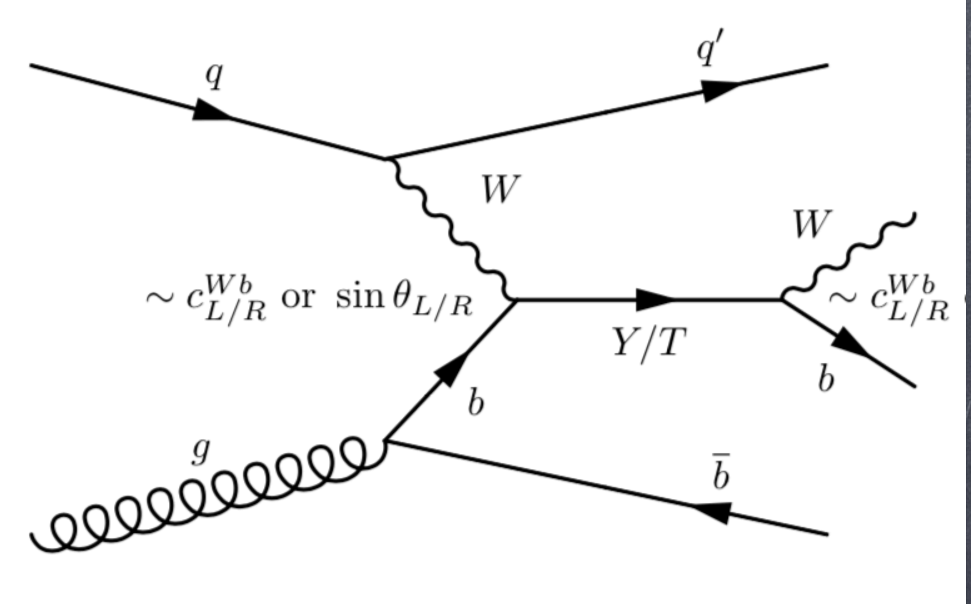
- They have QCD gauge interactions, leading to "model-independent" pair production (caveat: neutral naturalness, EW contr.)
- Coupling to W, Z and H are "chiral" (i.e., involve dominantly one chirality)
- Charges related to quarks: T(+2/3), B(-1/3)
- Exotic charges from custodial symmetry: X(+5/3), Y(-4/3)

Top partners at colliders

Pair production:



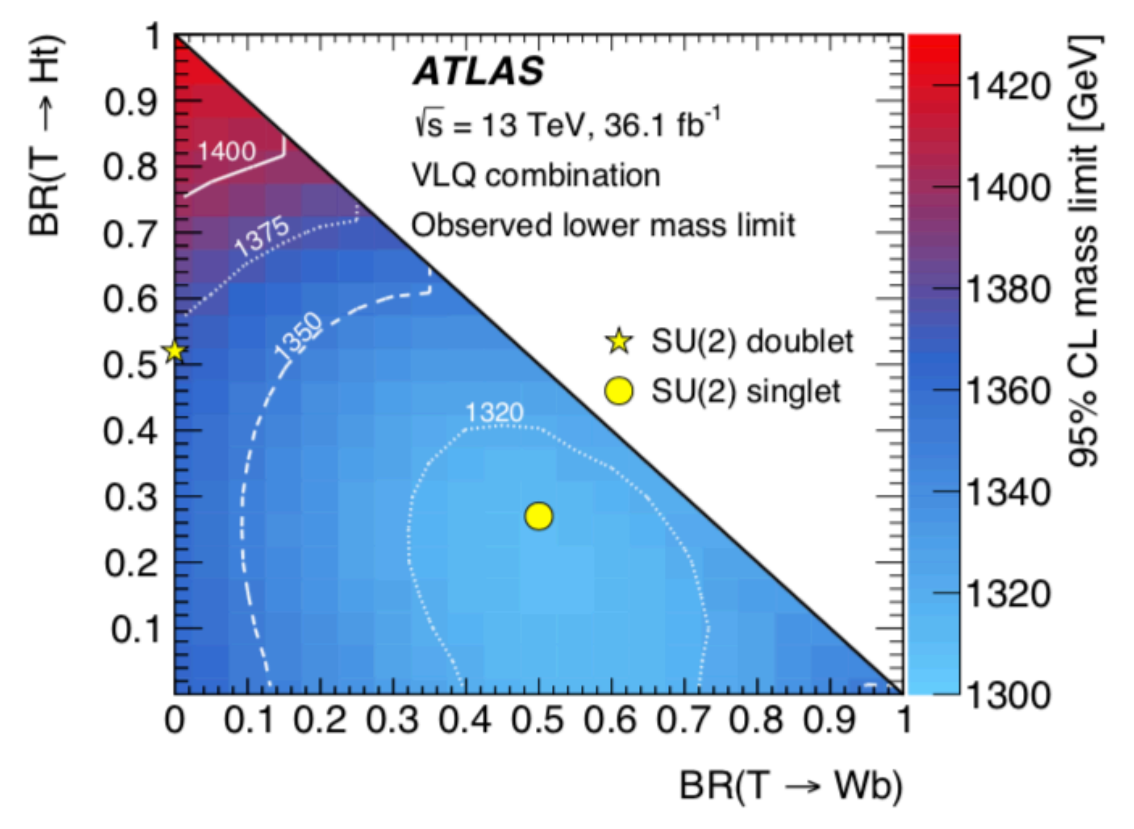
Single production:



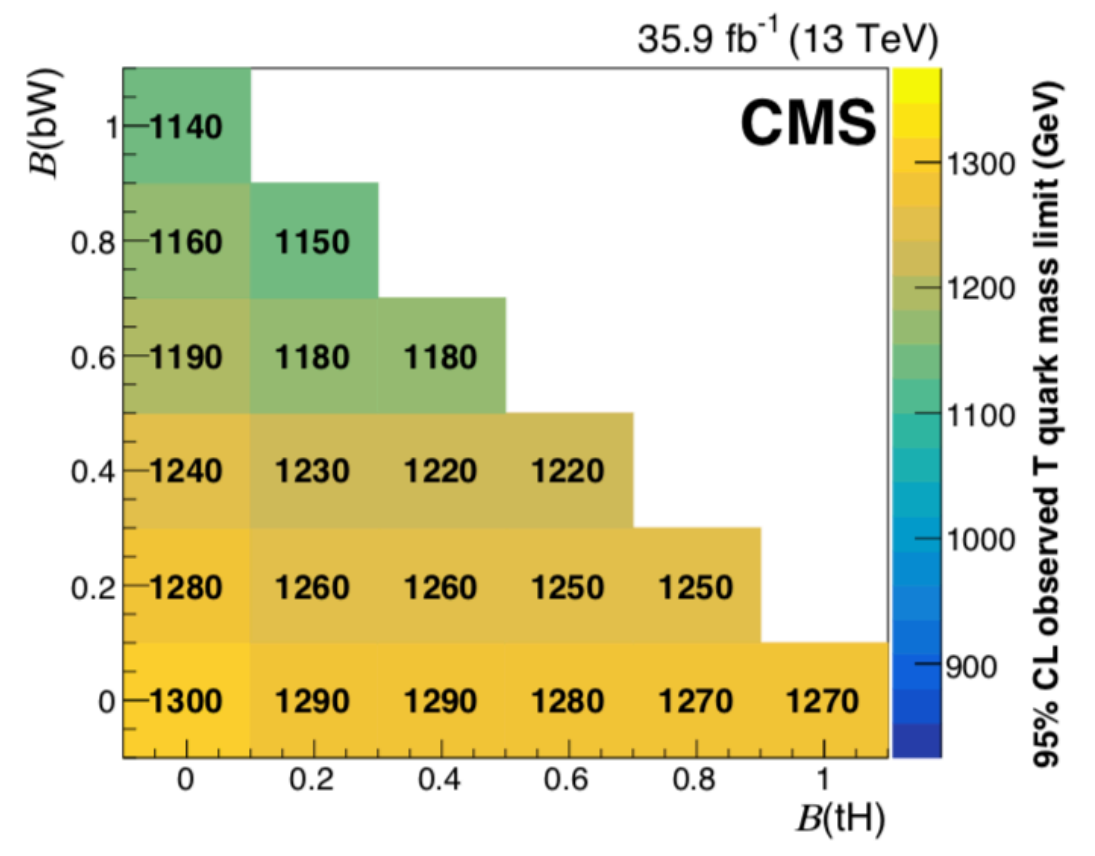
- Only depends on the mass (to first approximation)
- Can study as a function of the Branching Ratios
- Production depends on a coupling (model dependence)
- Becomes more relevant at high mass (new searches)

Other production channels: EW pair production, resonant production via heavier boson, ...

Top partners at colliders



Combination with many channels



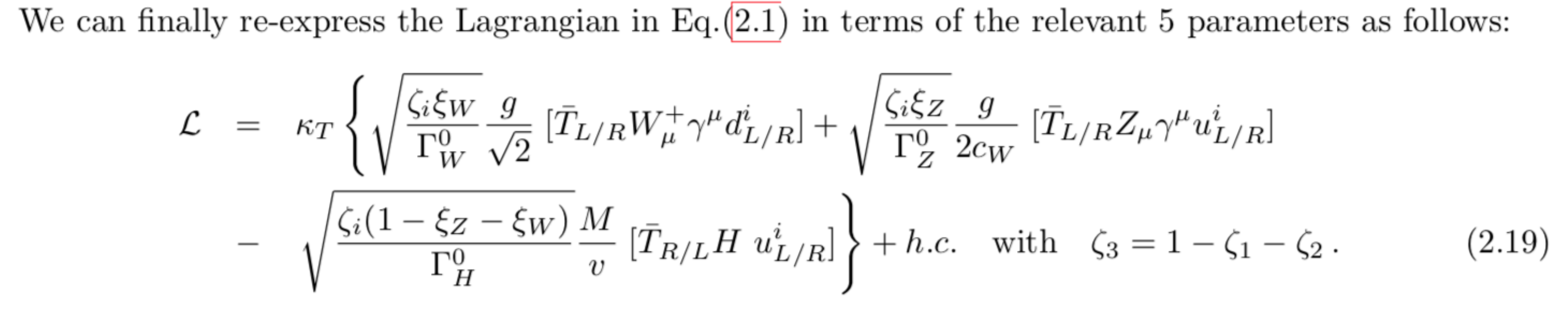
	0	0.2	0.4	0.6	0.8	1
1	1140					
0.8	1160	1150				
0.6	1190	1180	1180			
0.4	1240	1230	1220	1220		
0.2	1280	1260	1260	1250	1250	
0	1300	1290	1290	1280	1270	1270

Final states with 1 or 2 leptons

- Strategy: focus on a specific final state (bW, tH, tZ), design optimal searches
- Express a bound on the mass in the BR parameter space.

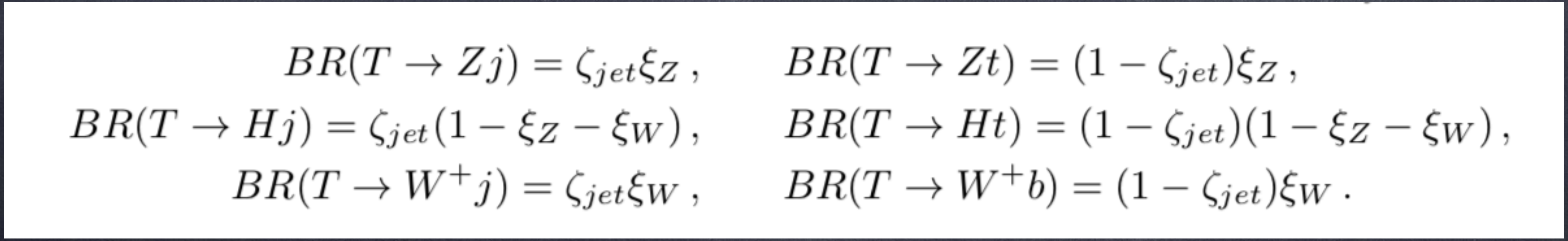
Top partners at colliders

For single production, one may adopt a similar strategy, with one additional parameter: a coupling



We can finally re-express the Lagrangian in Eq.(2.1) in terms of the relevant 5 parameters as follows:

$$\begin{aligned}\mathcal{L} \;=\;& \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W}{\Gamma_W^0}}\, \frac{g}{\sqrt{2}}\, [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d^i_{L/R}] + \sqrt{\frac{\zeta_i \xi_Z}{\Gamma_Z^0}}\, \frac{g}{2c_W}\, [\bar{T}_{L/R} Z_\mu \gamma^\mu u^i_{L/R}] \right. \\ & \left. -\; \sqrt{\frac{\zeta_i (1-\xi_Z-\xi_W)}{\Gamma_H^0}}\, \frac{M}{v}\, [\bar{T}_{R/L} H\, u^i_{L/R}] \right\} + h.c. \quad \text{with} \quad \zeta_3 = 1 - \zeta_1 - \zeta_2 \,. \end{aligned} \tag{2.19}$$



$$\begin{aligned} BR(T \to Zj) &= \zeta_{jet}\xi_Z\,, & BR(T \to Zt) &= (1-\zeta_{jet})\xi_Z\,, \\ BR(T \to Hj) &= \zeta_{jet}(1-\xi_Z-\xi_W)\,, & BR(T \to Ht) &= (1-\zeta_{jet})(1-\xi_Z-\xi_W)\,, \\ BR(T \to W^+ j) &= \zeta_{jet}\xi_W\,, & BR(T \to W^+ b) &= (1-\zeta_{jet})\xi_W\,. \end{aligned}$$

1305.4172

One of the many possible parameterisations...

Projections for 100 TeV collider:

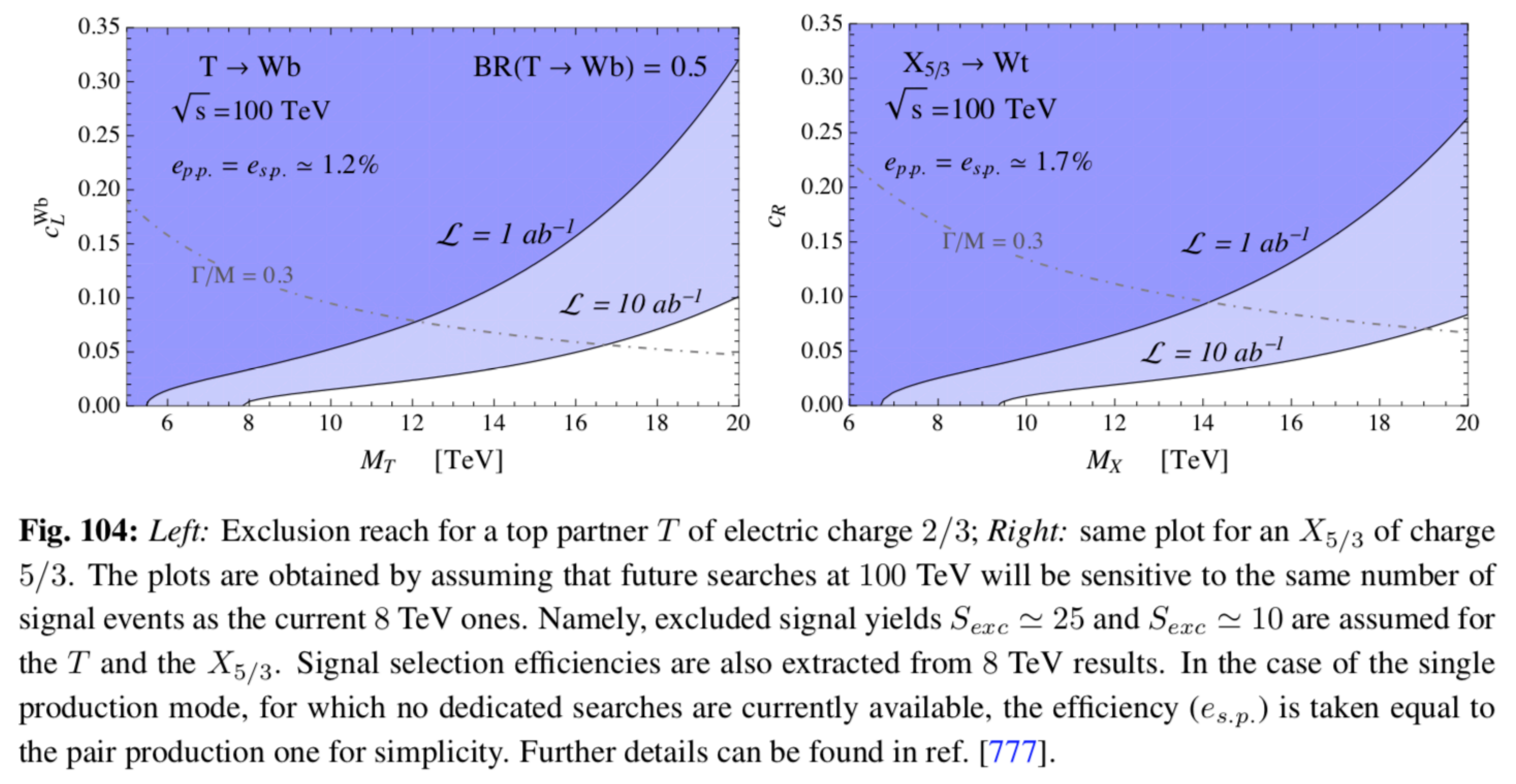


Fig. 104: *Left:* Exclusion reach for a top partner T of electric charge $2/3$; *Right:* same plot for an $X_{5/3}$ of charge $5/3$. The plots are obtained by assuming that future searches at 100 TeV will be sensitive to the same number of signal events as the current 8 TeV ones. Namely, excluded signal yields $S_{exc} \simeq 25$ and $S_{exc} \simeq 10$ are assumed for the T and the $X_{5/3}$. Signal selection efficiencies are also extracted from 8 TeV results. In the case of the single production mode, for which no dedicated searches are currently available, the efficiency ($e_{s.p.}$) is taken equal to the pair production one for simplicity. Further details can be found in ref. [777].

Matsedonskyi, Panico, Wulzer 1409.0100

This is the “standard” story,
can we go beyond?

Do we need to?

YES

Top partners as baryons

Gauge-fermion underlying theory

$$\frac{1}{\Lambda_{\text{fl.}}}\, q\underbrace{\sigma^{\mu\nu}\psi G_{\mu\nu}}_{T}$$

$$d_T^{\text{naive}} = 7/2$$

- typically loop-suppressed
- psi need to carry colour and flavour quantum numbers

$$\frac{1}{\Lambda_{\text{fl.}}^2}\, q\underbrace{\psi\psi\psi}_{T}$$

$$d_T^{\text{naive}} = 9/2$$

- higher dimension, but easier to generate
- Note: issue with other 4-Fermion interactions non avoided!!! Anomalous dimensions are crucial!

Sequestering QCD

G.Ferretti, D.Karateev
1312.5330, 1604.06467

$\mathcal{G}_{\mathrm{TC}}$: rep R rep R'

ψ χ

$T = \psi\psi\chi$ or $\psi\chi\chi$

SM : EW colour + hypercharge

global : $\langle\psi\psi\rangle \neq 0$

↓

pNGB Higgs
DM?

a) $\langle\chi\chi\rangle \neq 0$

coloured pNGBs
di-boson

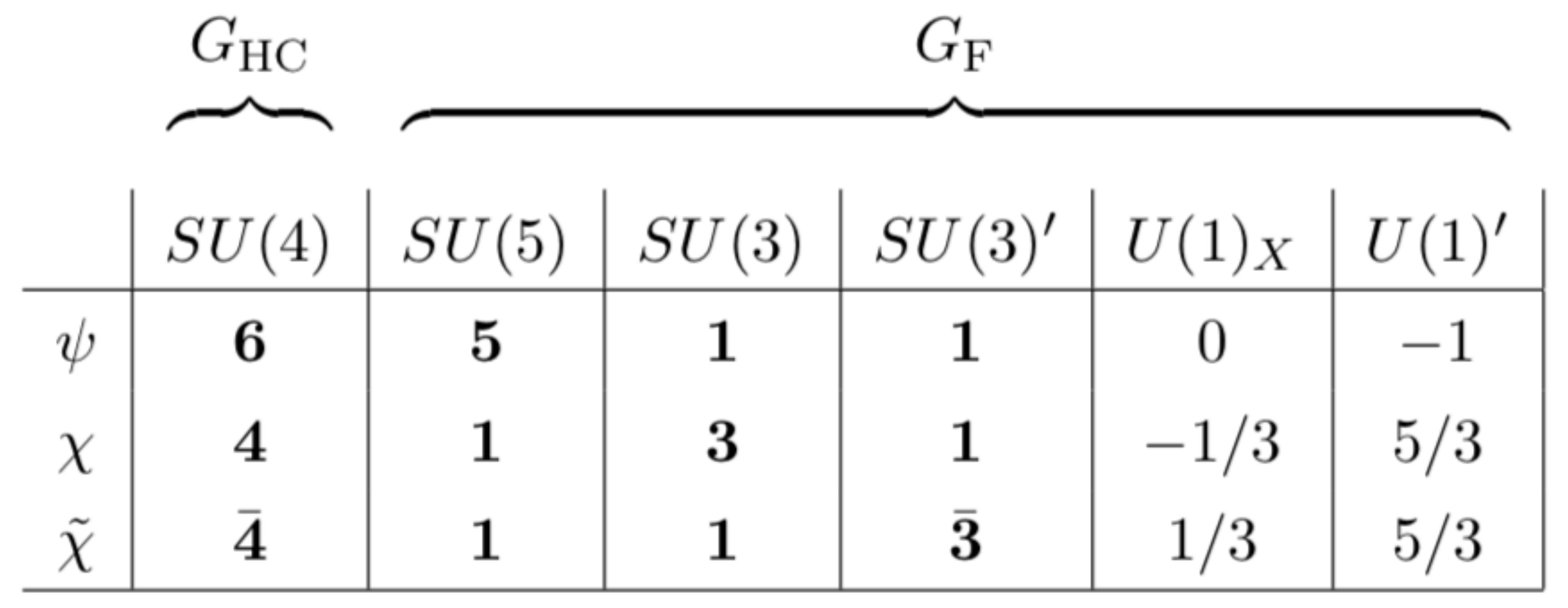
b) $\langle\chi\chi\rangle = 0$

light top partners
from t Hooft anomaly
conditions?

An example

Baryons: $\psi\chi\chi$

Ferretti 1404.7137



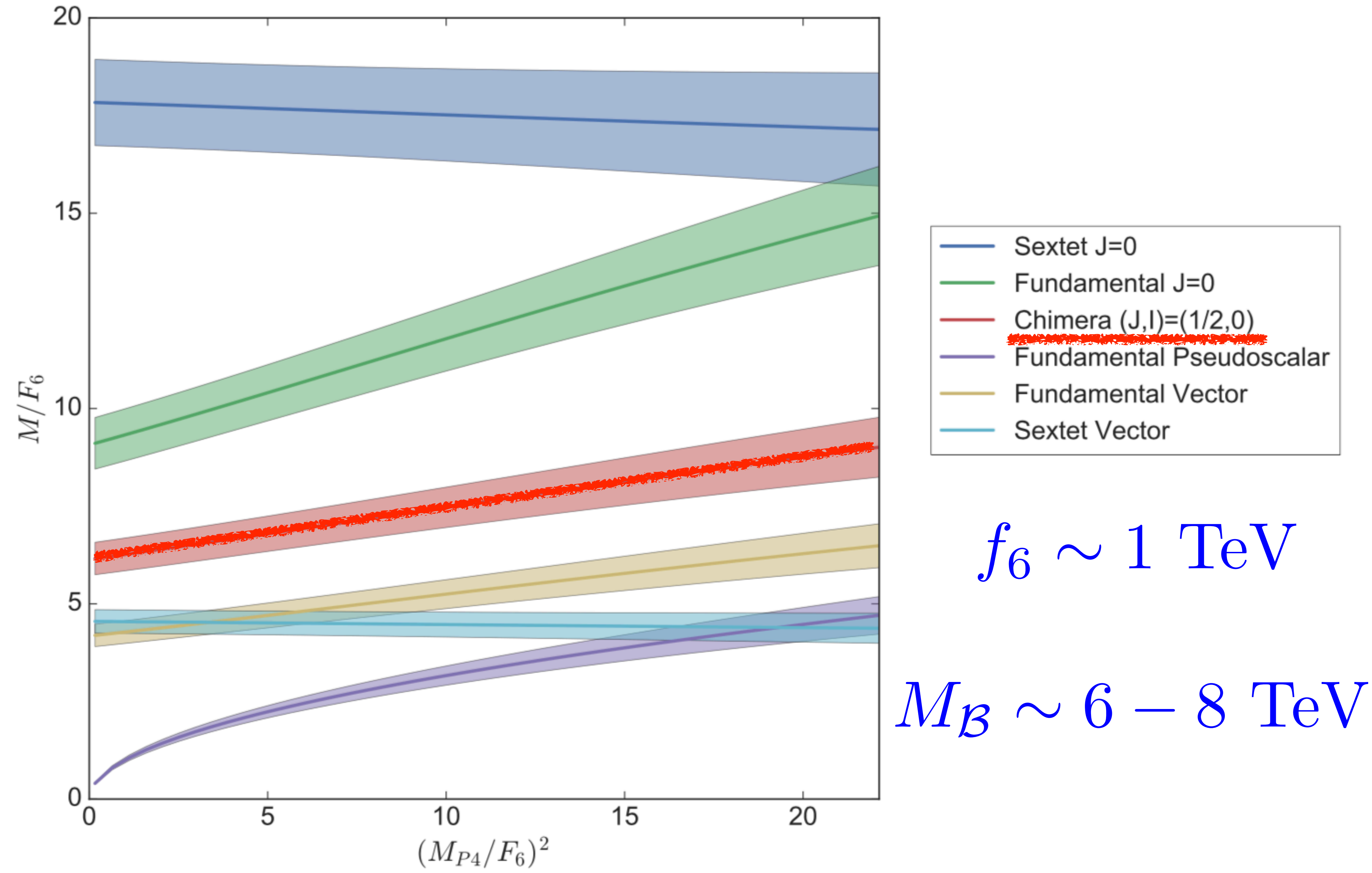
	$G_{\rm HC}$	$G_{\rm F}$				
	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
ψ	$\mathbf{6}$	$\mathbf{5}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
χ	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$5/3$
$\tilde{\chi}$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$1/3$	$5/3$

Preliminary lattice results are available!

An example

Baryons: $\psi\chi\chi$

Ayyar et al 1801.05809



$f_6 \sim 1$ TeV

$M_{\mathcal{B}} \sim 6 - 8$ TeV

Global symmetries

More precisely, the global symmetries are:

$$SU(N_Q) \times SU(N_\chi) \times U(1)_Q \times U(1)_\chi$$

WZW term:

$$\mathcal{L} \supset \frac{g_i^2}{32\pi^2} \frac{\kappa_i}{f_a}\, a\, \epsilon^{\mu\nu\alpha\beta} G^i_{\mu\nu} G^i_{\alpha\beta}\,,$$

Coefficients depend
on the underlying dynamics!

G = A, W, Z, g !!!

Cai, Flacke, Lespinasse 1512.04508

Anomalous U(1) -> heavy η'

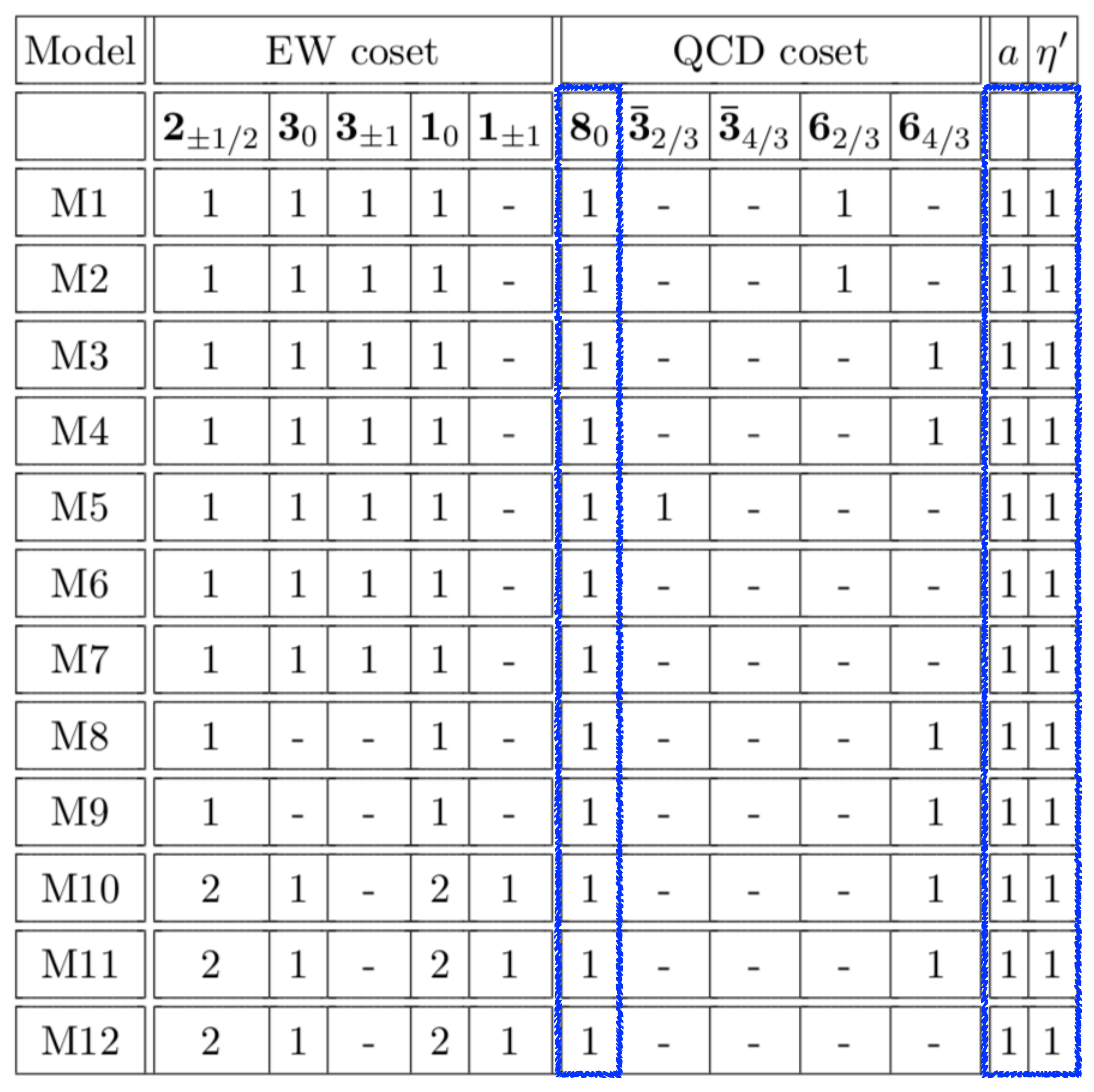
Orthogonal U(1) -> pNGB a

Decays and production
only via WZW anomaly.

Model zoology

Ferretti
1604.06467

GC, T.Flacke, G.Ferretti,
H.Serodio
1902.06890

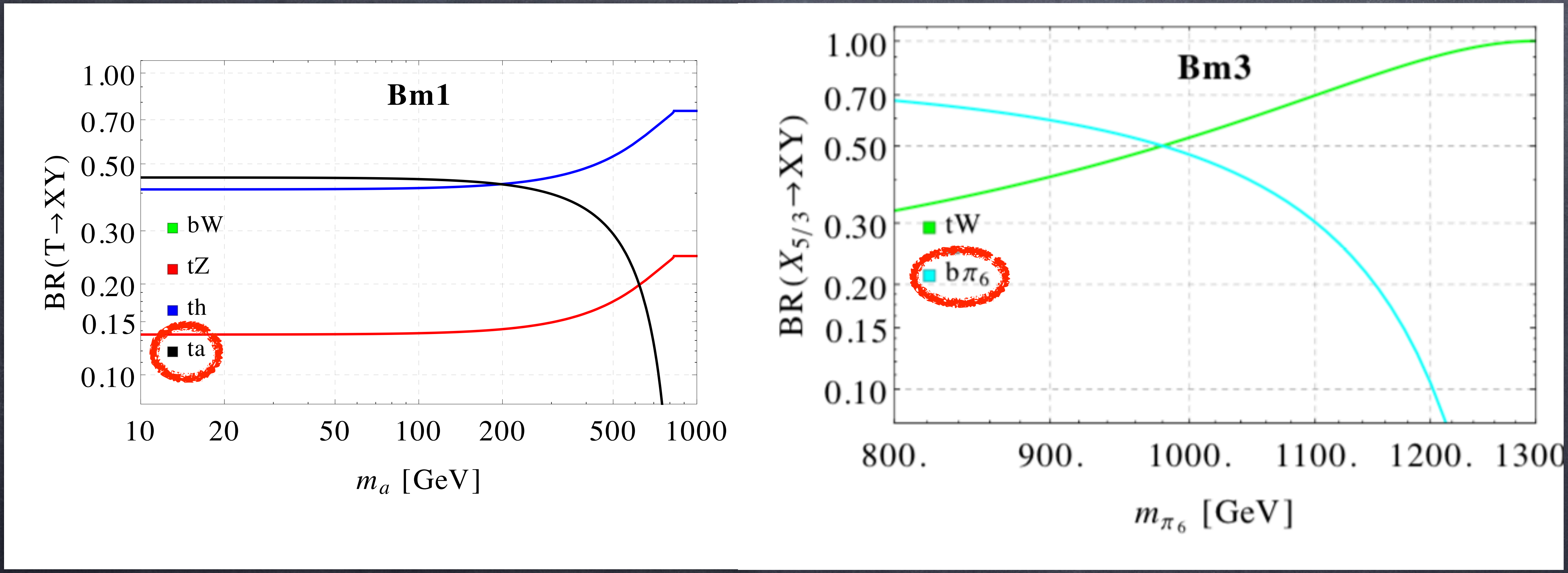


Model	EW coset					QCD coset					a	η'
	$\mathbf{2}_{\pm1/2}$	$\mathbf{3}_0$	$\mathbf{3}_{\pm1}$	$\mathbf{1}_0$	$\mathbf{1}_{\pm1}$	$\mathbf{8}_0$	$\bar{\mathbf{3}}_{2/3}$	$\bar{\mathbf{3}}_{4/3}$	$\mathbf{6}_{2/3}$	$\mathbf{6}_{4/3}$		
M1	1	1	1	1	-	1	-	-	1	-	1	1
M2	1	1	1	1	-	1	-	-	1	-	1	1
M3	1	1	1	1	-	1	-	-	-	1	1	1
M4	1	1	1	1	-	1	-	-	-	1	1	1
M5	1	1	1	1	-	1	1	-	-	-	1	1
M6	1	1	1	1	-	1	-	-	-	-	1	1
M7	1	1	1	1	-	1	-	-	-	-	1	1
M8	1	-	-	1	-	1	-	-	-	1	1	1
M9	1	-	-	1	-	1	-	-	-	1	1	1
M10	2	1	-	2	1	1	-	-	-	1	1	1
M11	2	1	-	2	1	1	-	-	-	1	1	1
M12	2	1	-	2	1	1	-	-	-	-	1	1

Exotic top partner decays

In realistic models:

N.Bizot et al, 1803.00021



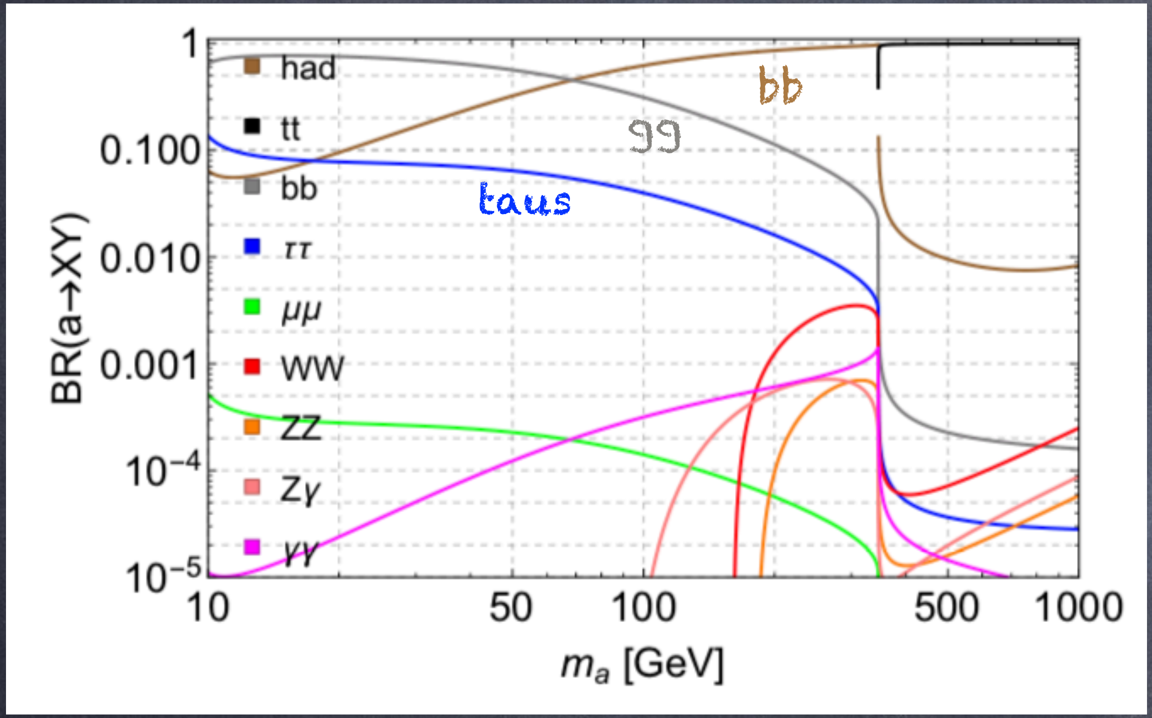
Phenomenology
studied in:

Benbrik et al, 1907.05029
Xie Ke-Pan et al, 1907.05894
Zhang Mengchao et al, 1908.07524

$T_{2/3}$ exotic decays

Zhang Mengchao et al, 1908.07524

T -> t a



Below tt threshold:

a-> gg

a-> bb

We recast:

- CMS excited top @ RunII

CERN-EP-2017-272

- ATLAS RPV SUSY @ RunI

CERN-PH-EP-2015-020

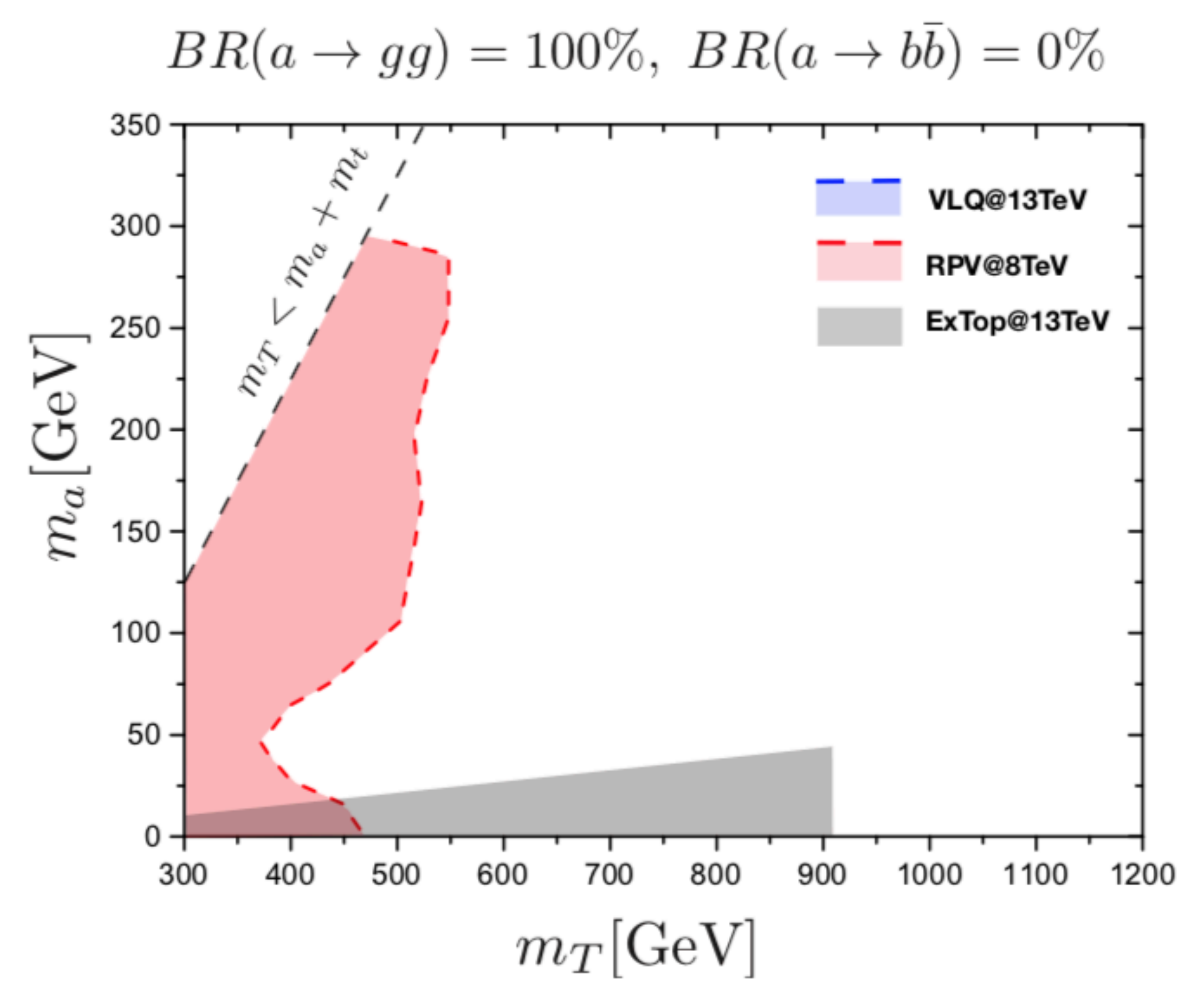
(RunII update has too high HT cut)

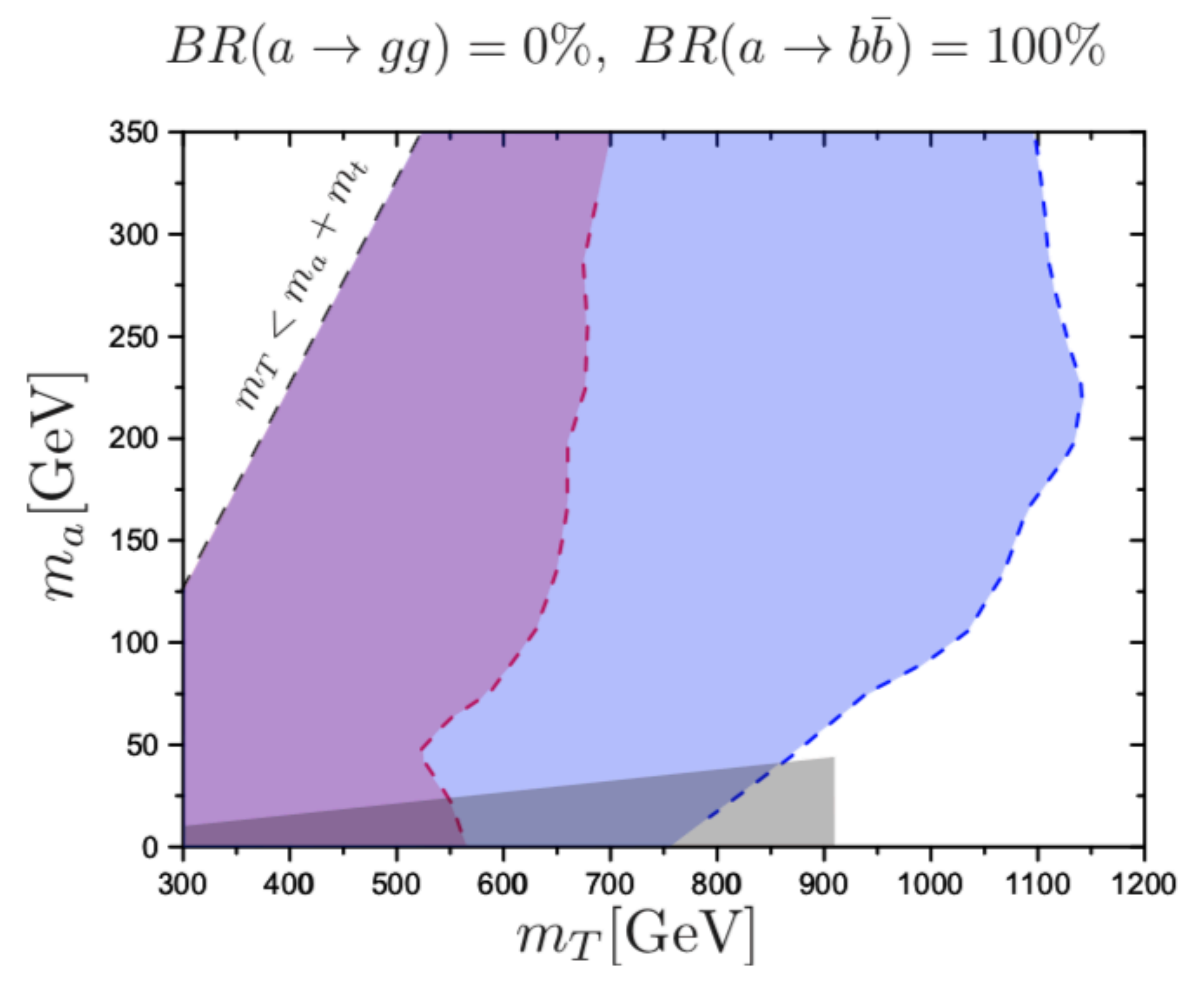
- ATLAS T->tHbb @ RunII

CERN-EP-2018-031

$T_{2/3}$ exotic decays

Zhang Mengchao et al, 1908.07524





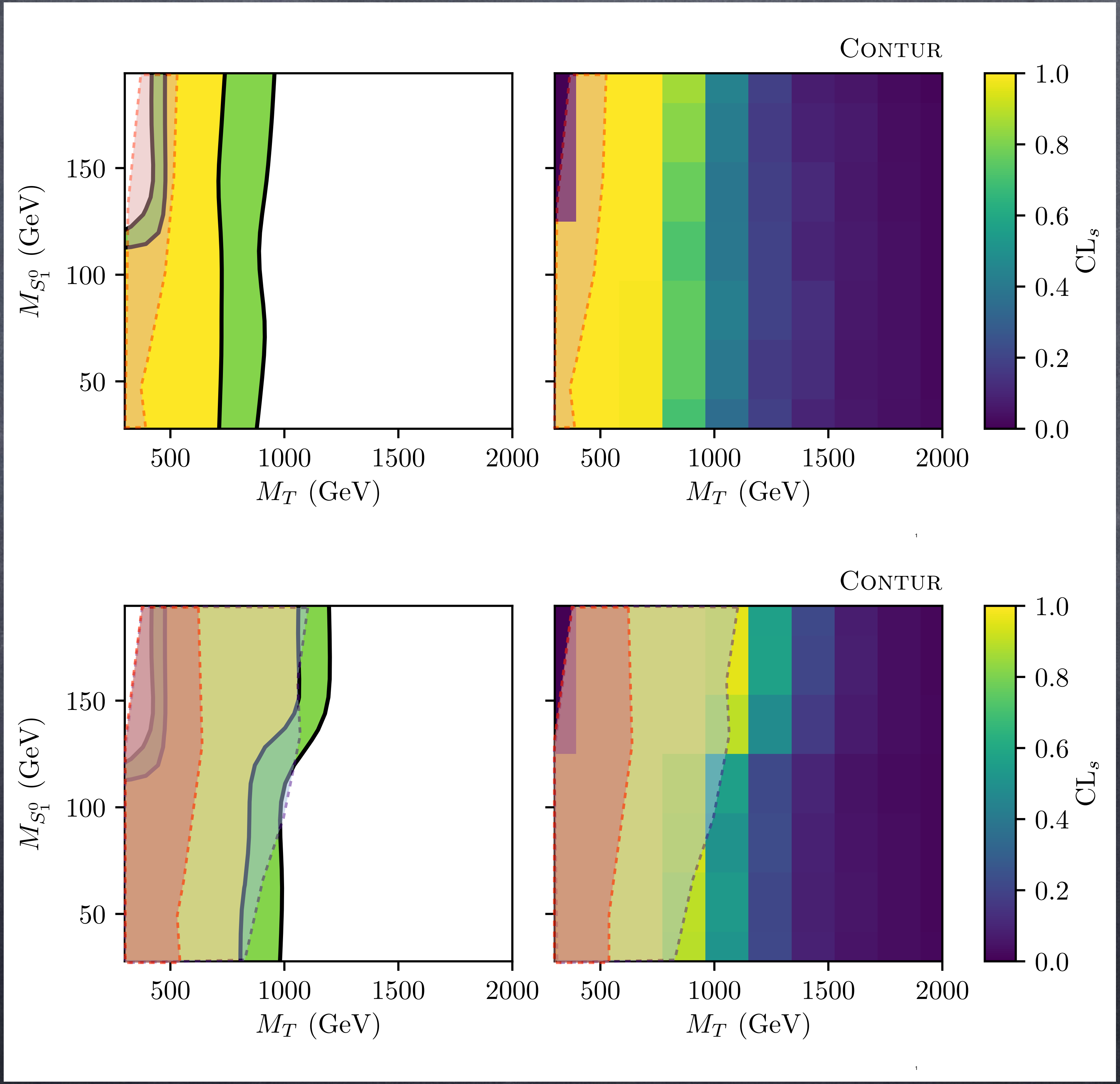
Bounds are substantially weakened for decays into jets!

$T_{2/3}$ exotic decays

T->ta->tjj

SM measurements can do better than BSM searches!

T->ta->tbb

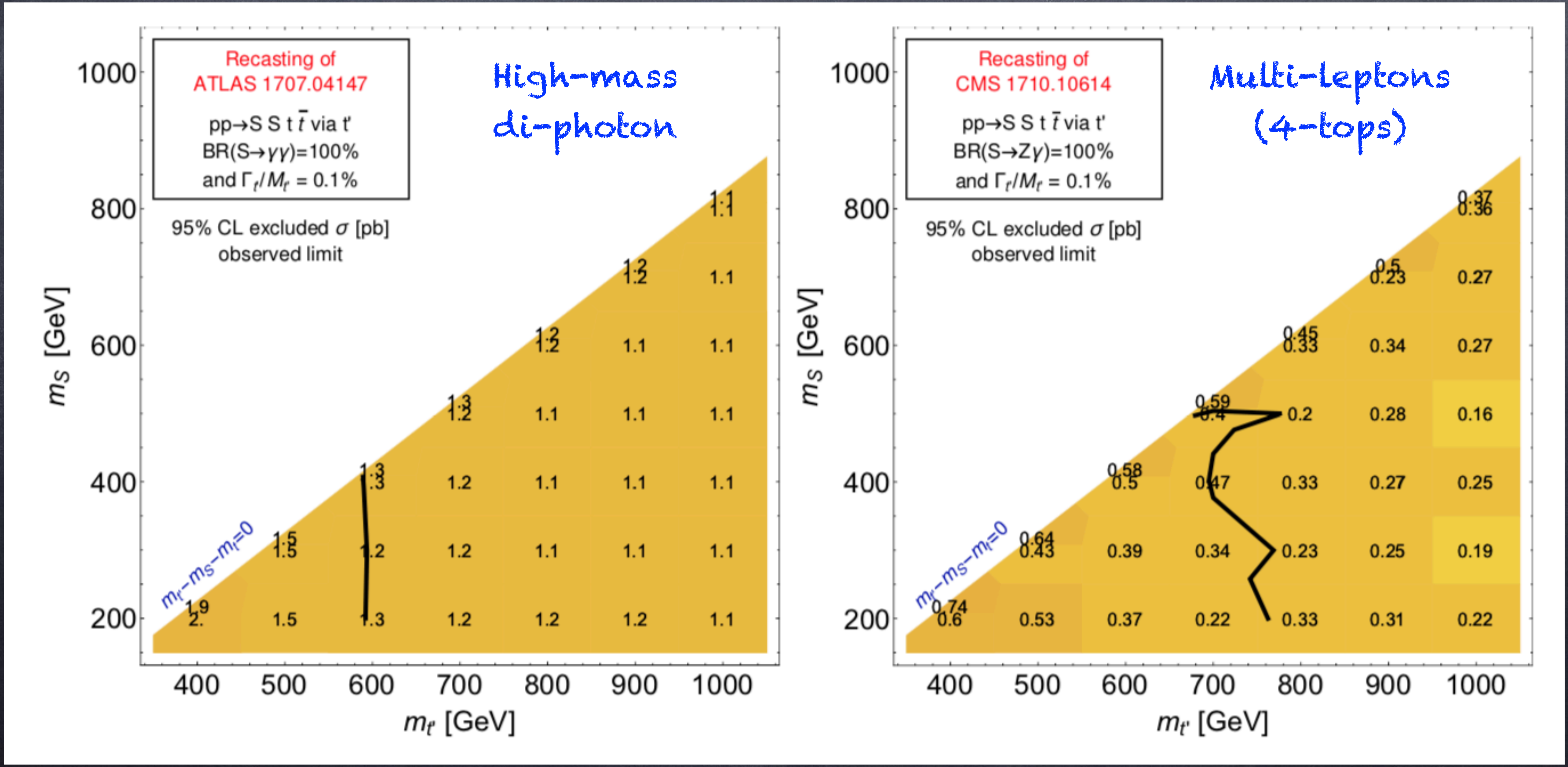


Les Houches 2019 proceedings, 2002.12220

$T_{2/3}$ exotic decays

Benbrik et al, 1907.05029

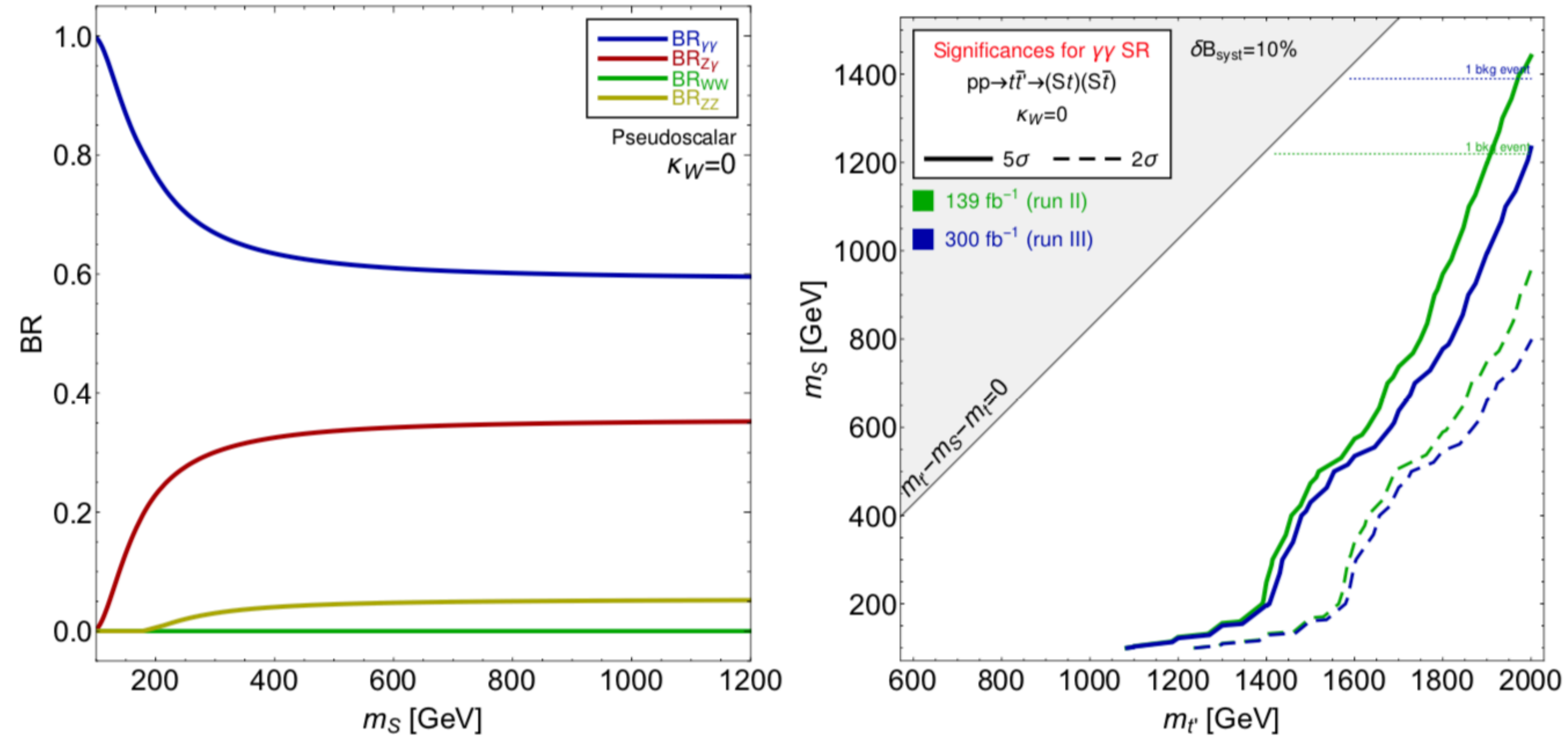
T -> t S, S -> VV'



$T_{2/3}$ exotic decays

Benbrik et al, 1907.05029

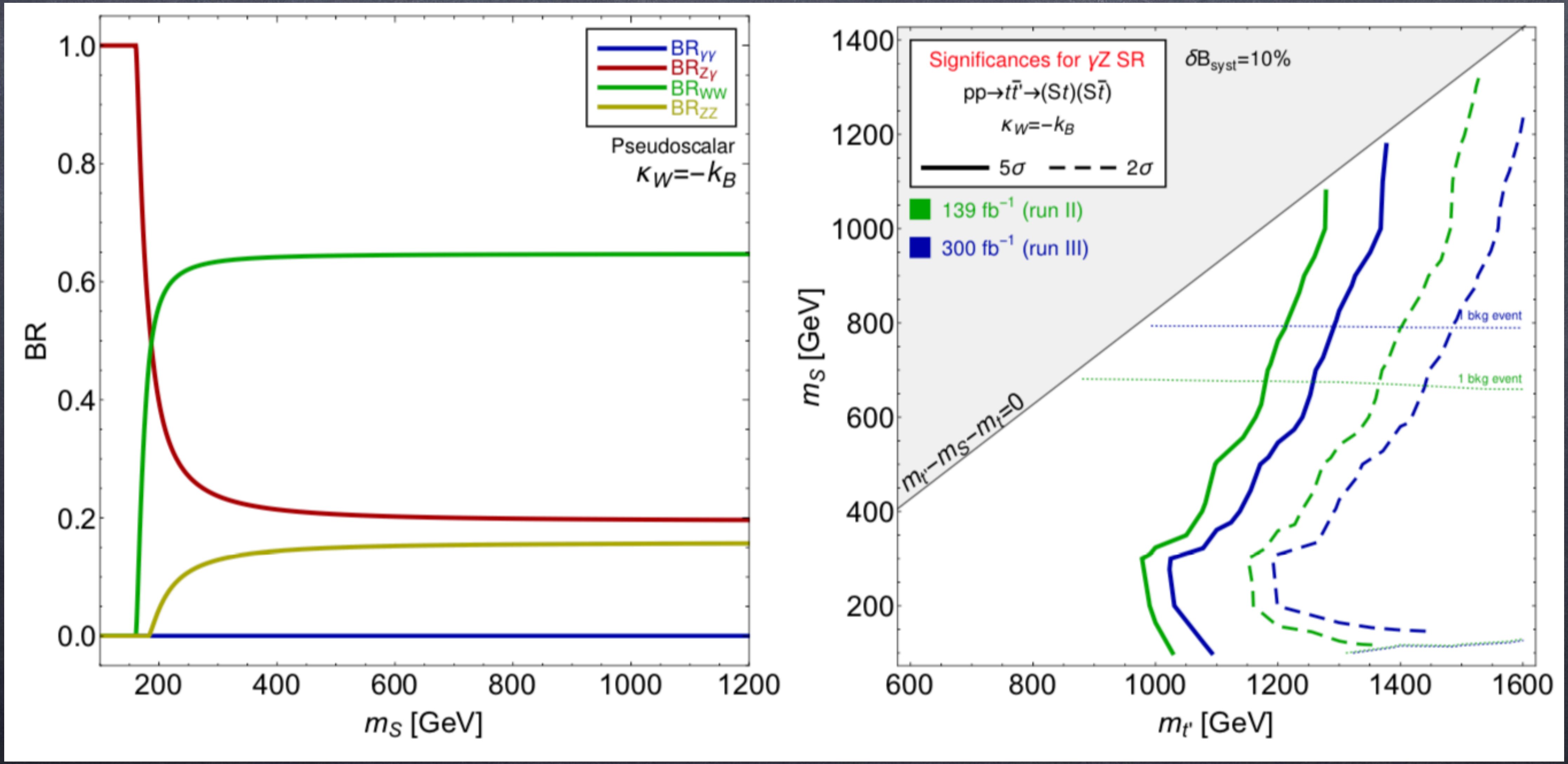
T -> t S, S -> VV'



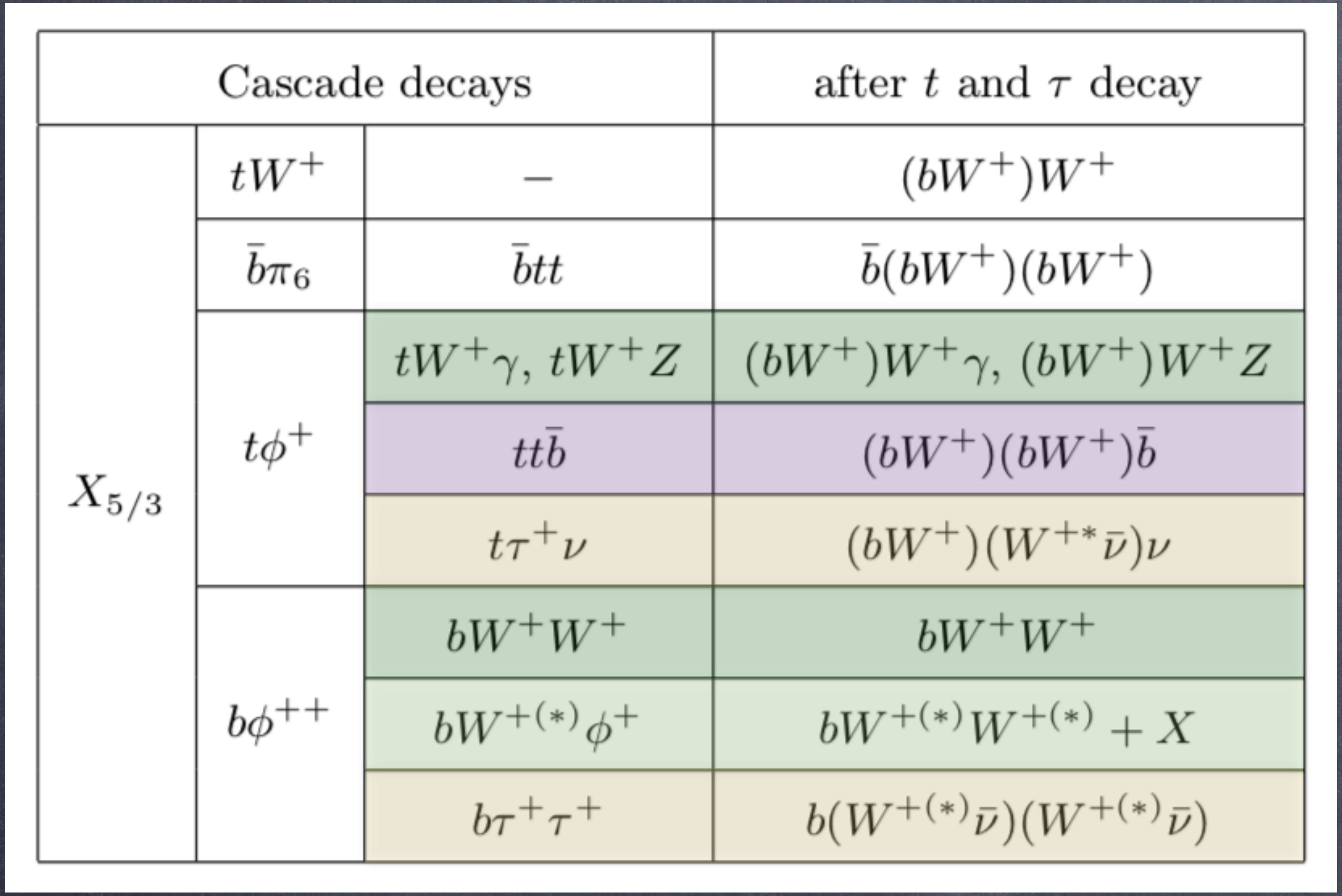
$T_{2/3}$ exotic decays

Benbrik et al, 1907.05029

$T \to t\ S,\ S \to VV'$



$X_{5/3}$ exotic decays



Cascade decays			after t and τ decay
$X_{5/3}$	tW^+	$-$	$(bW^+)W^+$
	$\bar{b}\pi_6$	$\bar{b}tt$	$\bar{b}(bW^+)(bW^+)$
	$t\phi^+$	$tW^+\gamma$, tW^+Z	$(bW^+)W^+\gamma$, $(bW^+)W^+Z$
		$tt\bar{b}$	$(bW^+)(bW^+)\bar{b}$
		$t\tau^+\nu$	$(bW^+)(W^{+*}\bar{\nu})\nu$
	$b\phi^{++}$	bW^+W^+	bW^+W^+
		$bW^{+(*)}\phi^+$	$bW^{+(*)}W^{+(*)} + X$
		$b\tau^+\tau^+$	$b(W^{+(*)}\bar{\nu})(W^{+(*)}\bar{\nu})$

All final states have SSL pairs.

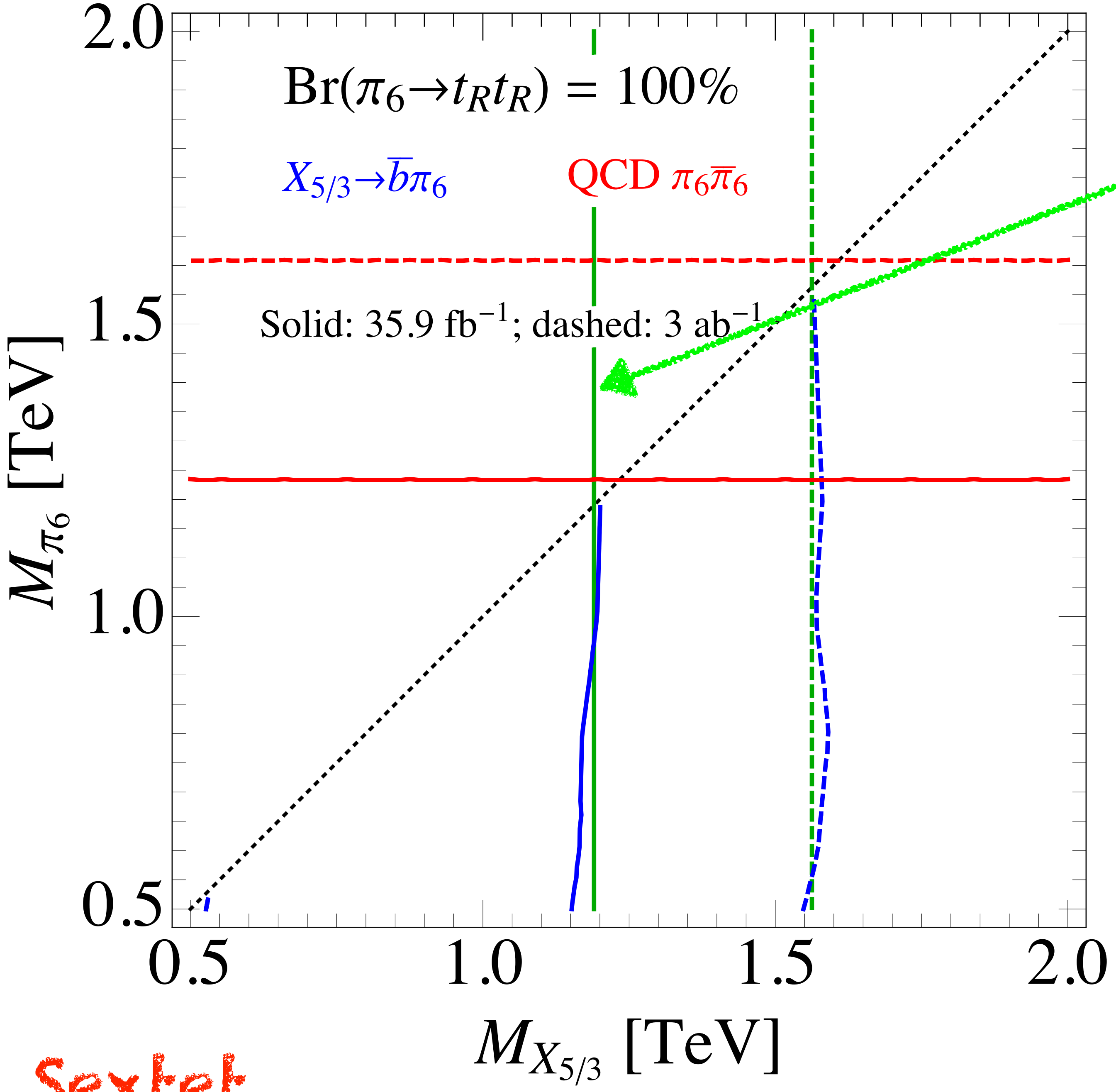
Decays of the scalars are exclusive (either one or the other)

We recast the SSL CMS search in

CERN-EP-2018-258

Xie Ke-Pan et al, 1907.05894

$X_{5/3}$ exotic decays

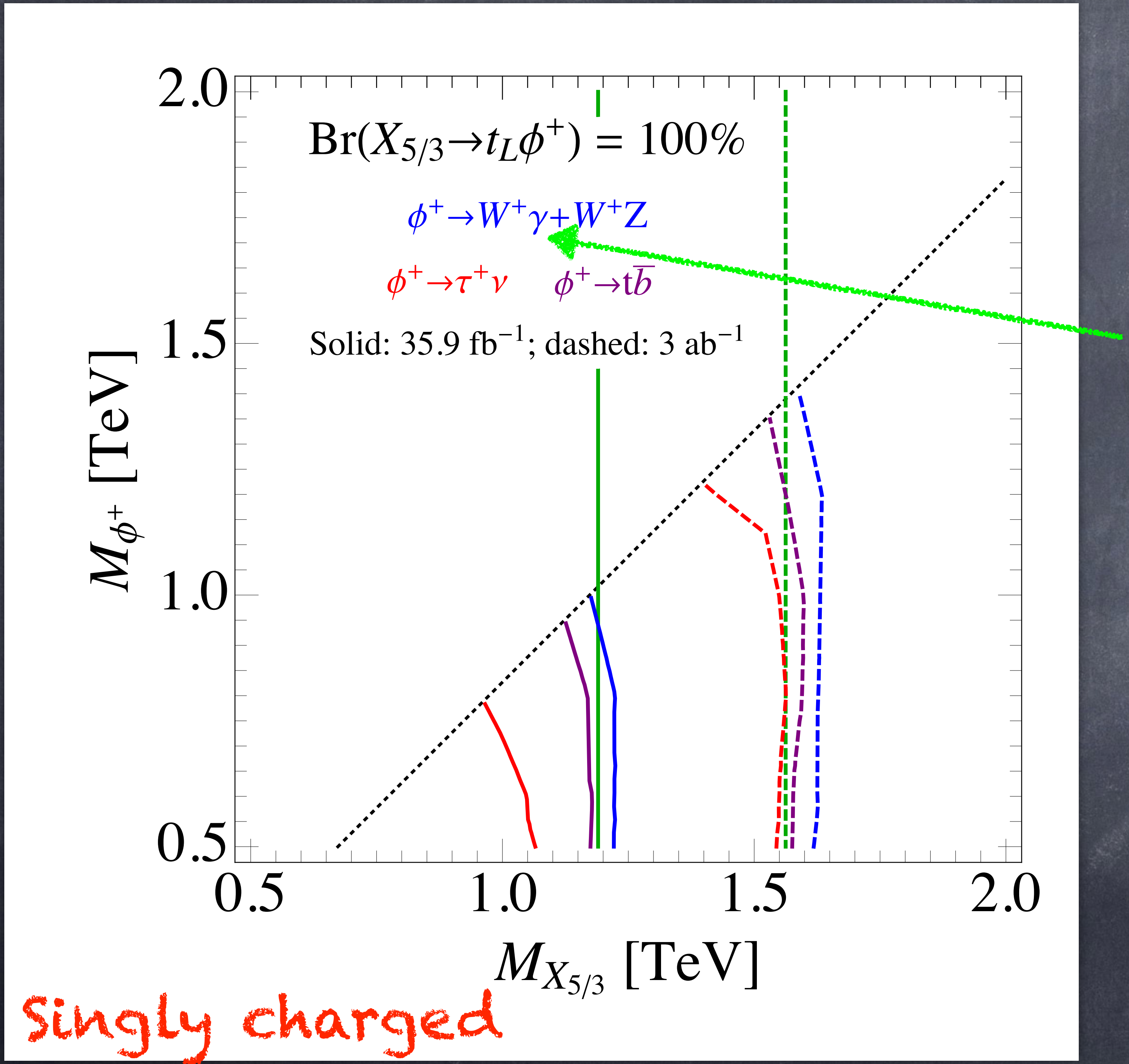


Sextet

Green: bound for standard decay X -> t W

Xie Ke-Pan et al, 1907.05894

$X_{5/3}$ exotic decays



Singly charged

The high-pT photon may be used to tag this decay mode!

Xie Ke-Pan et al, 1907.05894

Exotic top partner decays: other channels

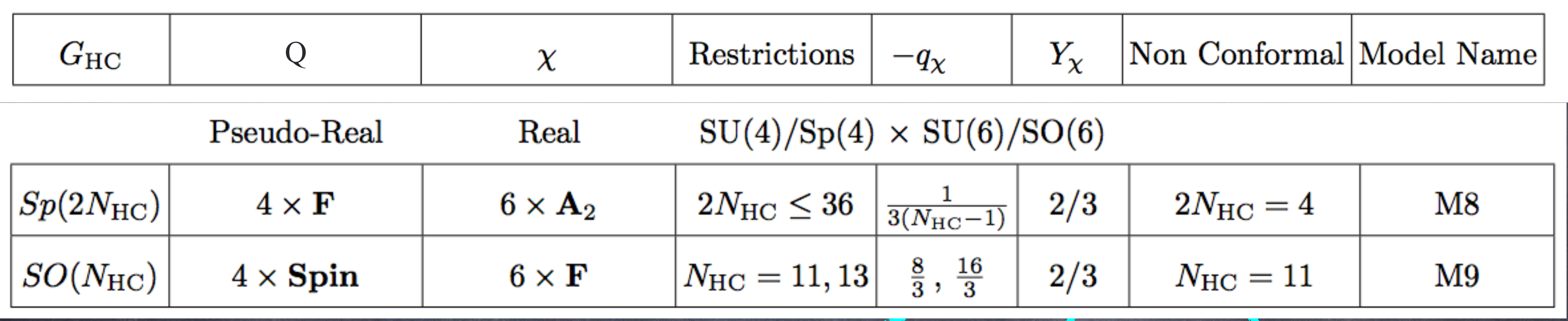
- Decays to a Dark Matter (collider stable) scalar.
- Decays to vectors.
- Top partners with exotic QCD charges: octets…

Outlook

- Light pseudo-scalars are ubiquitous: singlets + colour octet (+ charged ones)
- Partial Compositeness -> top partners at colliders
- Exotic decays are the norm!
- Projections and detailed studies for LHC and future colliders missing
- Direct production of the light pseudo-scalars/ vectors: See bonus track.

Bonus track

Model zoology



G_{HC}	Q	χ	Restrictions	$-q_\chi$	Y_χ	Non Conformal	Model Name
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\mathrm{HC}})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\mathrm{HC}} \leq 36$	$\frac{1}{3(N_{\mathrm{HC}}-1)}$	$2/3$	$2N_{\mathrm{HC}} = 4$	M8
$SO(N_{\mathrm{HC}})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} = 11, 13$	$\frac{8}{3}$, $\frac{16}{3}$	$2/3$	$N_{\mathrm{HC}} = 11$	M9

Defines $\tan\zeta$

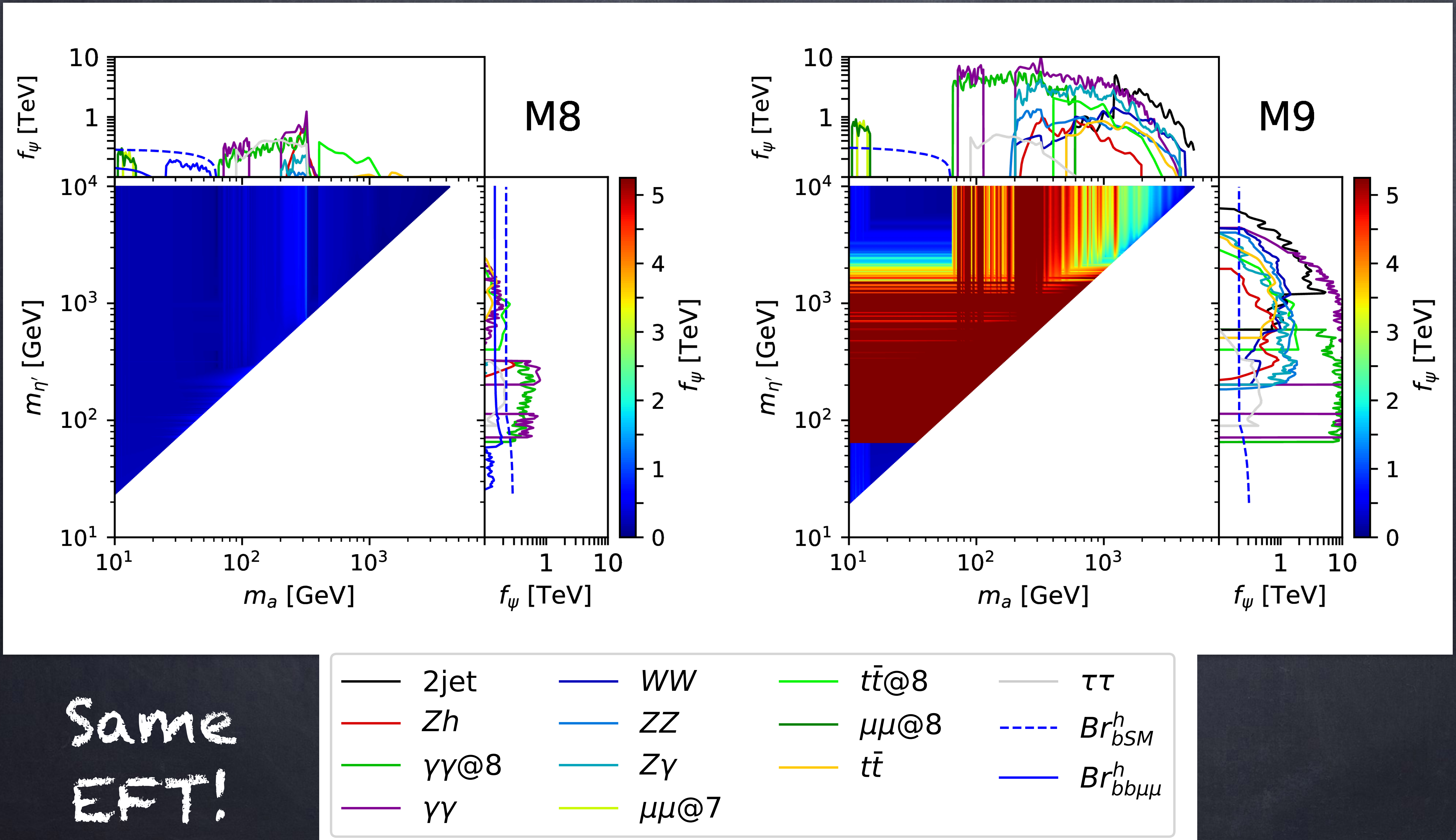
Theory confines!

$$T' = \langle QQ\chi \rangle$$

Note: there is enough baryons to give mass to the top (and bottom) only!

Singlets @ LHC:

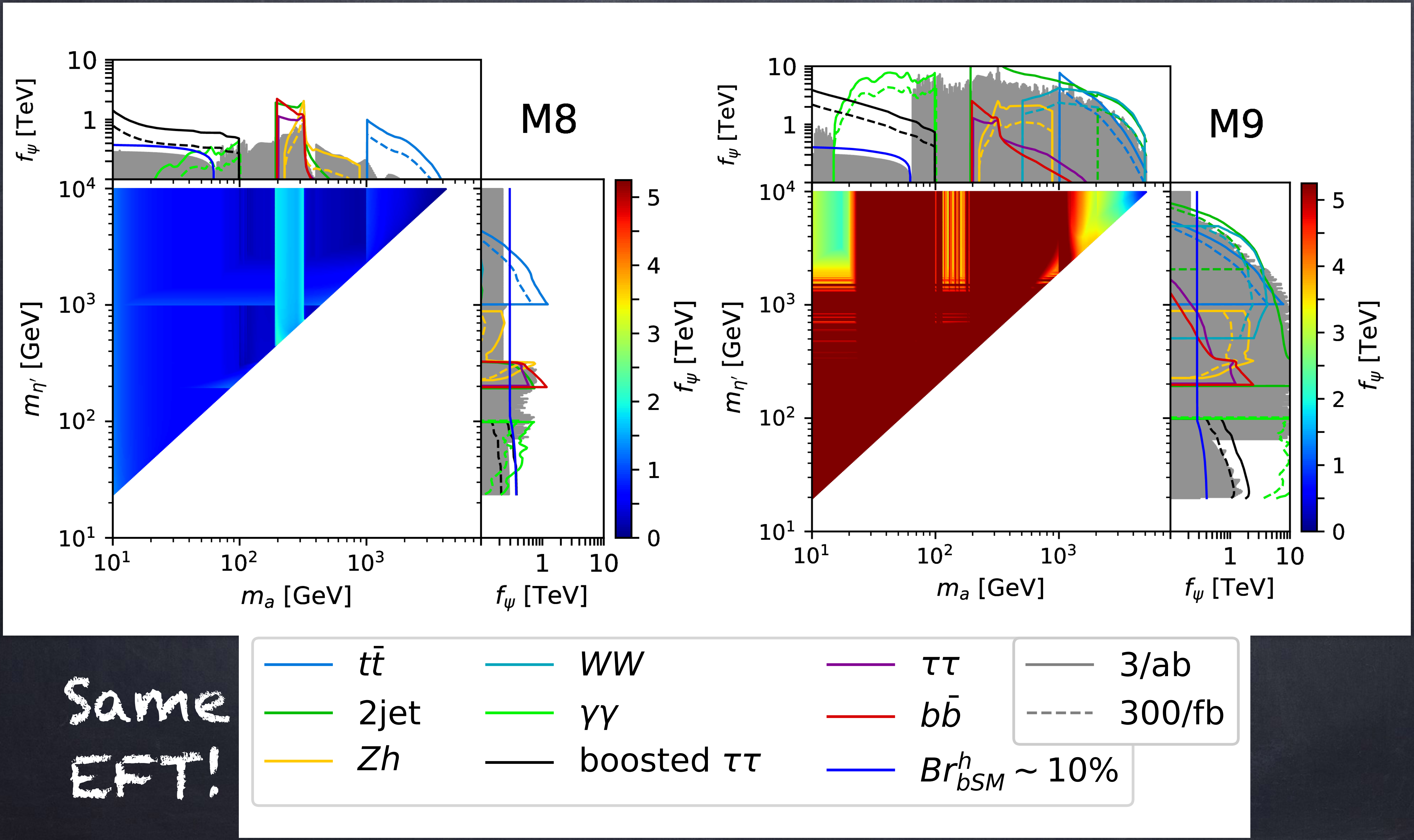
GC, T.Flacke, G.Ferretti,
H.Serodio
1902.06890



Same EFT!

Singlets @ HL-LHC:

GC, T.Flacke, G.Ferretti,
H.Serodio
1902.06890

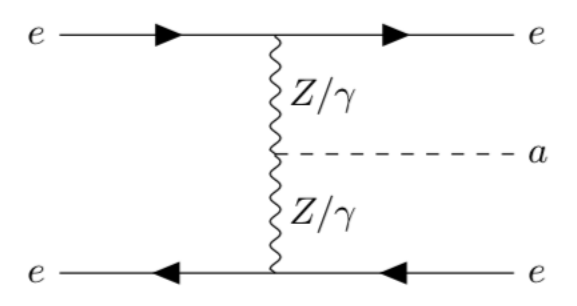


Same EFT!

Singlets @ FCC:

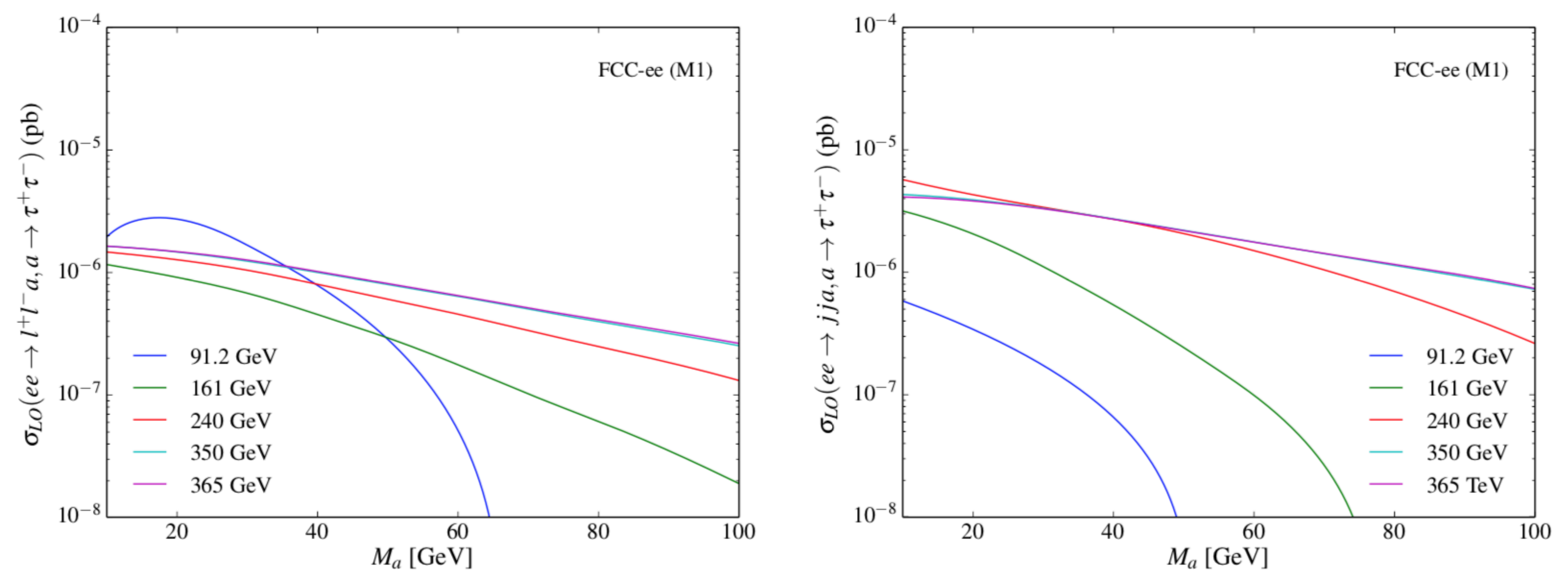
- Hadron option can probe higher mass values
- The open light-mass window (15-65 GeV) ideal for FCC-ee!

Singlets @ FCC:

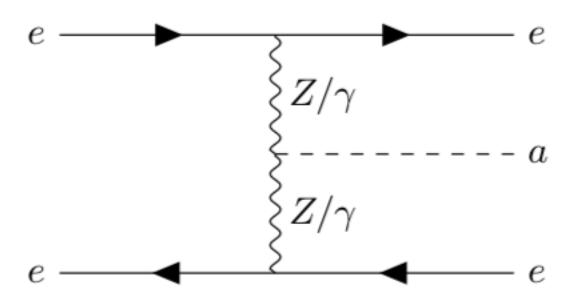


A.Cornell, A.Deandrea, B.Fuks, L.Mason
2004.09825

Small cross-sections:
high luminosity required!

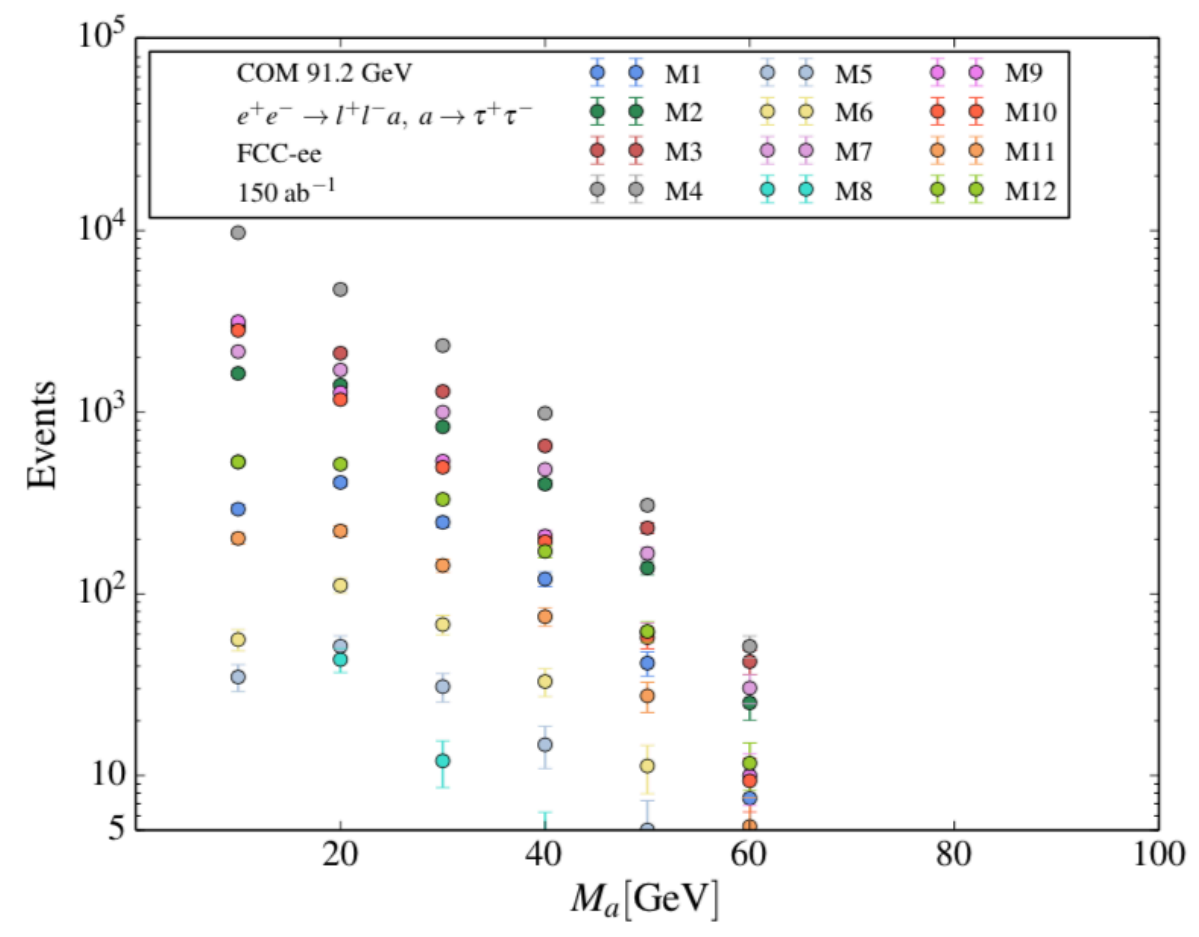


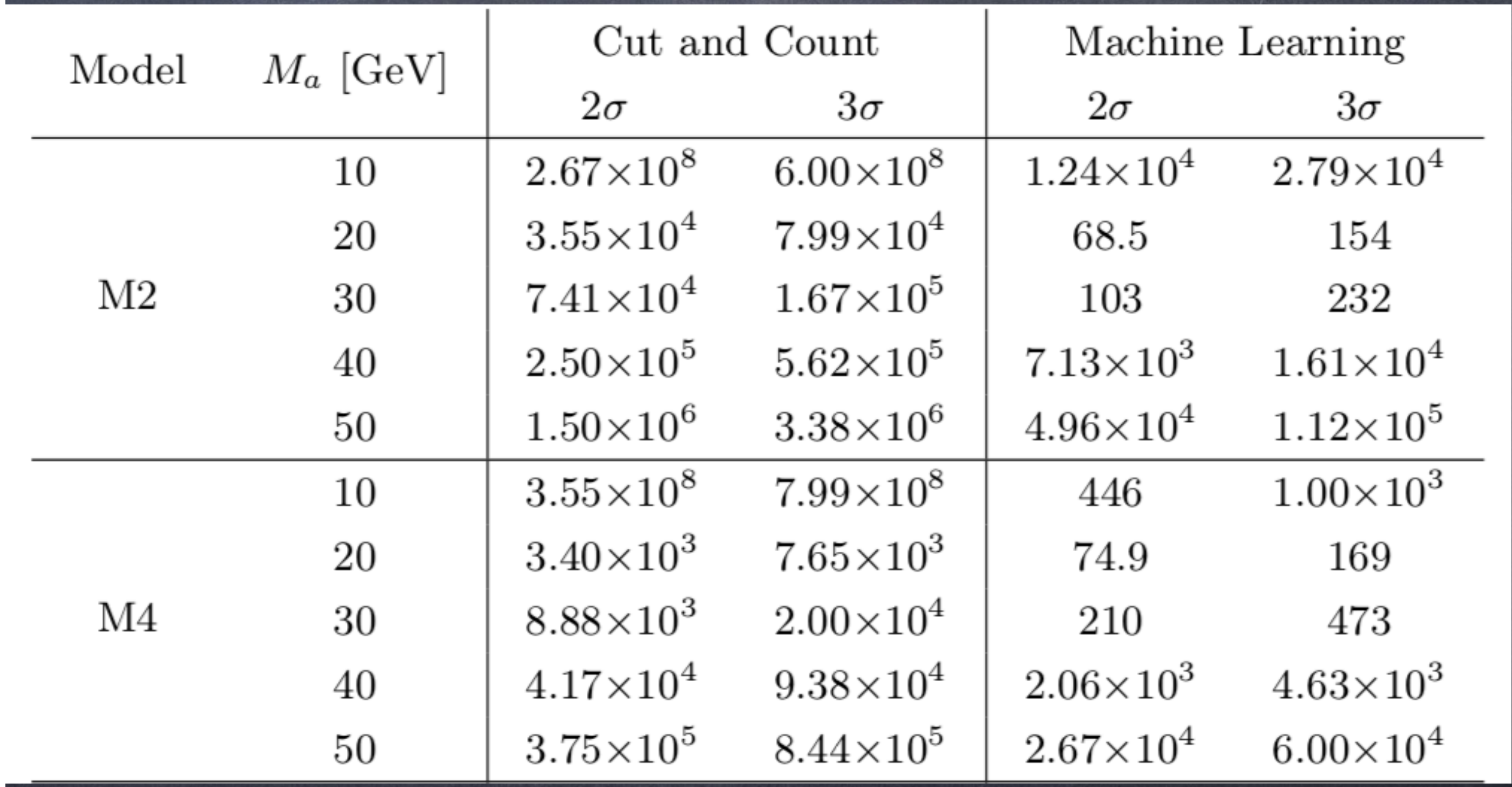
Singlets @ FCC:



A.Cornell, A.Deandrea, B.Fuks, L.Mason
2004.09825

Proposed search with di-tau decays, at the Z-pole.
Machine Learning used to improve sensitivity:





Model	M_a [GeV]	Cut and Count		Machine Learning	
		2σ	3σ	2σ	3σ
M2	10	2.67×10^8	6.00×10^8	1.24×10^4	2.79×10^4
	20	3.55×10^4	7.99×10^4	68.5	154
	30	7.41×10^4	1.67×10^5	103	232
	40	2.50×10^5	5.62×10^5	7.13×10^3	1.61×10^4
	50	1.50×10^6	3.38×10^6	4.96×10^4	1.12×10^5
M4	10	3.55×10^8	7.99×10^8	446	1.00×10^3
	20	3.40×10^3	7.65×10^3	74.9	169
	30	8.88×10^3	2.00×10^4	210	473
	40	4.17×10^4	9.38×10^4	2.06×10^3	4.63×10^3
	50	3.75×10^5	8.44×10^5	2.67×10^4	6.00×10^4

Required integrated Luminosity
in 1/ab

Colour octet

$$\Phi \to gg,\ g\gamma,\ gZ,\ (t\bar{t})$$

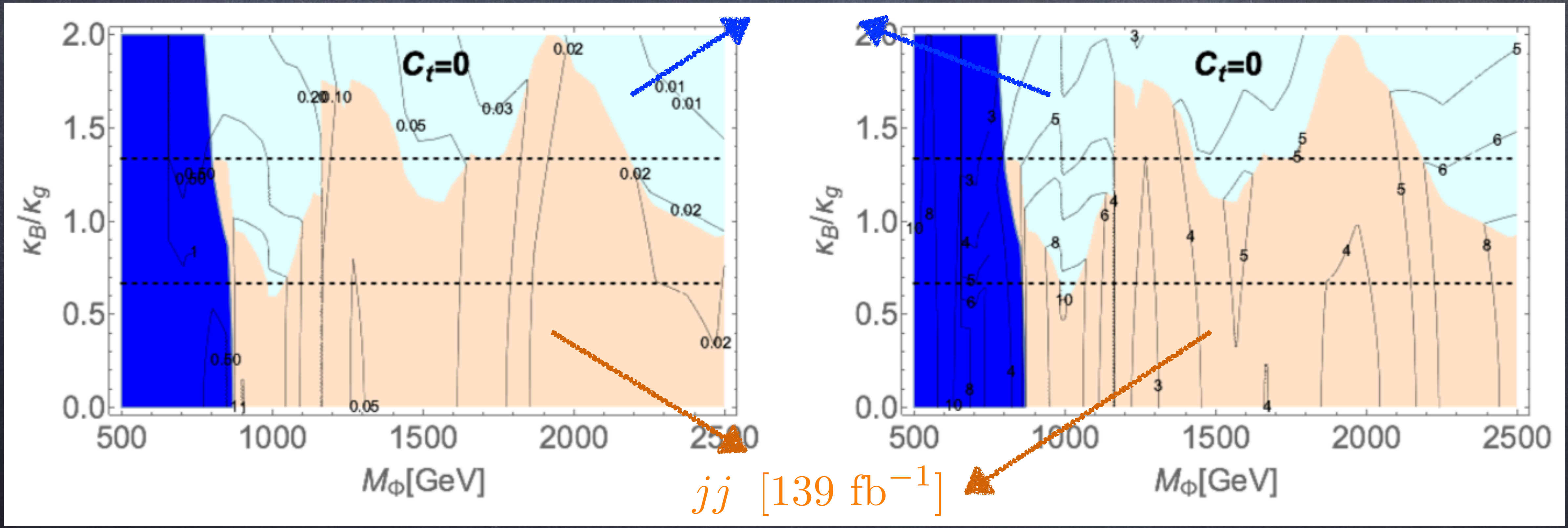
	$\frac{\mathrm{BR}(\Phi\to g\gamma)}{\mathrm{BR}(\Phi\to gg)}$	$\frac{\mathrm{BR}(\Phi\to gZ)}{\mathrm{BR}(\Phi\to gg)}$
$Y_\chi = 1/3$	0.048	0.014
$Y_\chi = 2/3$	0.19	0.058

Pair-production via QCD interactions

Single-production via gluon-fusion

GC, A.Deandrea, T.Flacke, A.Iyer
2002.01474

$j\gamma\ [36\ \mathrm{fb}^{-1}]$



$jj\ [139\ \mathrm{fb}^{-1}]$

Decays with photons are relevant!

Colour octet @ HL-LHC

Can we use photons in pair-production?

GC, A.Deandrea, T.Flacke, A.Iyer
2002.01474

- Strategy: same baseline as pair-dijet search, replacing one or two j with a photon

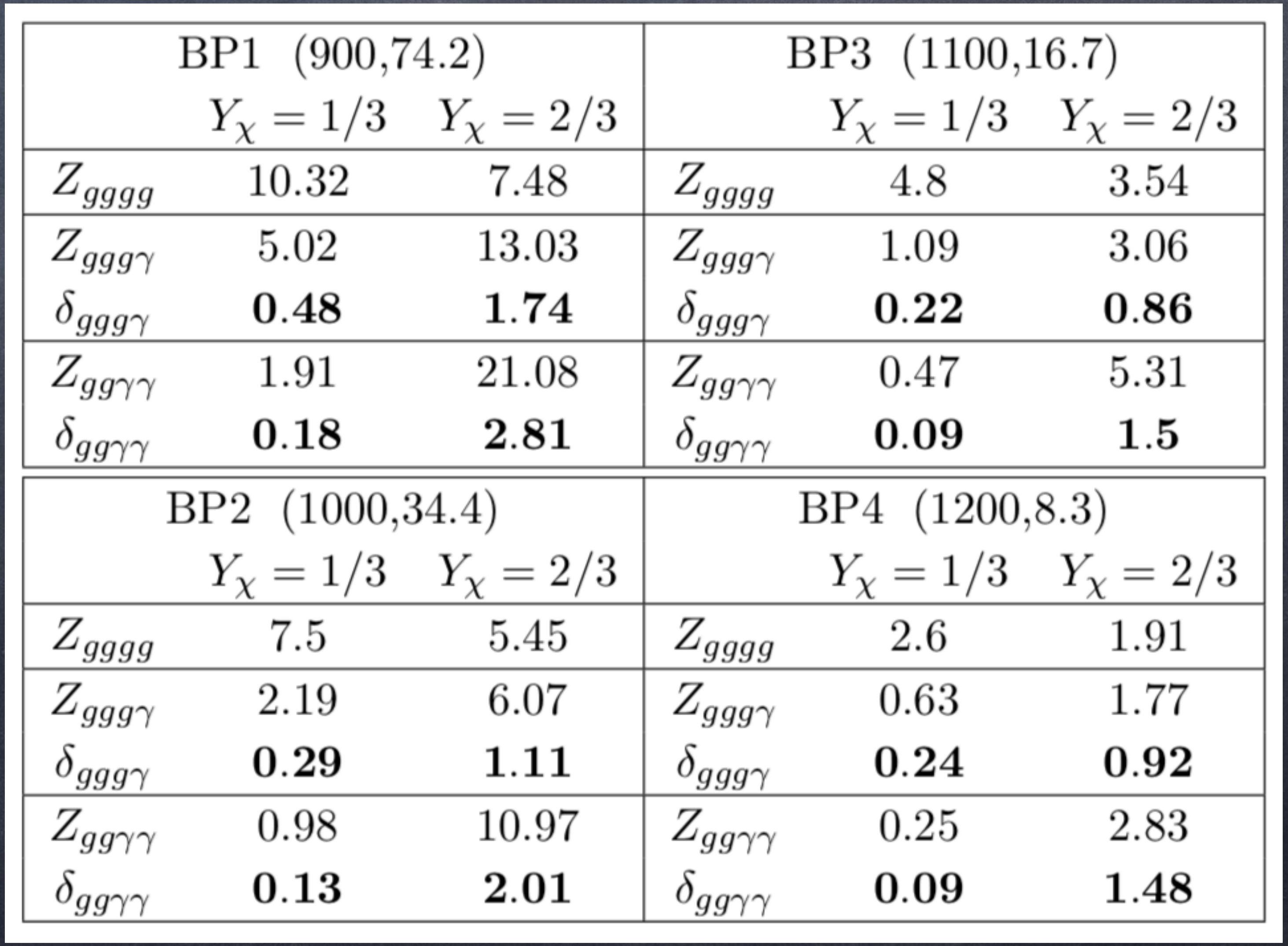
$L = 3\ \mathrm{ab}^{-1}$

Fake photon added:

$$\epsilon_{j\to\gamma} = 10^{-4}$$

$$Z = \frac{S}{\sqrt{B}}$$

HL-LHC can probe up to 1.2 TeV



BP1 (900,74.2)	$Y_\chi = 1/3$	$Y_\chi = 2/3$	BP3 (1100,16.7)	$Y_\chi = 1/3$	$Y_\chi = 2/3$
Z_{gggg}	10.32	7.48	Z_{gggg}	4.8	3.54
$Z_{ggg\gamma}$	5.02	13.03	$Z_{ggg\gamma}$	1.09	3.06
$\delta_{ggg\gamma}$	**0.48**	**1.74**	$\delta_{ggg\gamma}$	**0.22**	**0.86**
$Z_{gg\gamma\gamma}$	1.91	21.08	$Z_{gg\gamma\gamma}$	0.47	5.31
$\delta_{gg\gamma\gamma}$	**0.18**	**2.81**	$\delta_{gg\gamma\gamma}$	**0.09**	**1.5**

BP2 (1000,34.4)	$Y_\chi = 1/3$	$Y_\chi = 2/3$	BP4 (1200,8.3)	$Y_\chi = 1/3$	$Y_\chi = 2/3$
Z_{gggg}	7.5	5.45	Z_{gggg}	2.6	1.91
$Z_{ggg\gamma}$	2.19	6.07	$Z_{ggg\gamma}$	0.63	1.77
$\delta_{ggg\gamma}$	**0.29**	**1.11**	$\delta_{ggg\gamma}$	**0.24**	**0.92**
$Z_{gg\gamma\gamma}$	0.98	10.97	$Z_{gg\gamma\gamma}$	0.25	2.83
$\delta_{gg\gamma\gamma}$	**0.13**	**2.01**	$\delta_{gg\gamma\gamma}$	**0.09**	**1.48**

Colour octet @ FCC-hh

Can we use photons in pair-production?

GC, A.Deandrea, T.Flacke, A.Iyer
2002.01474

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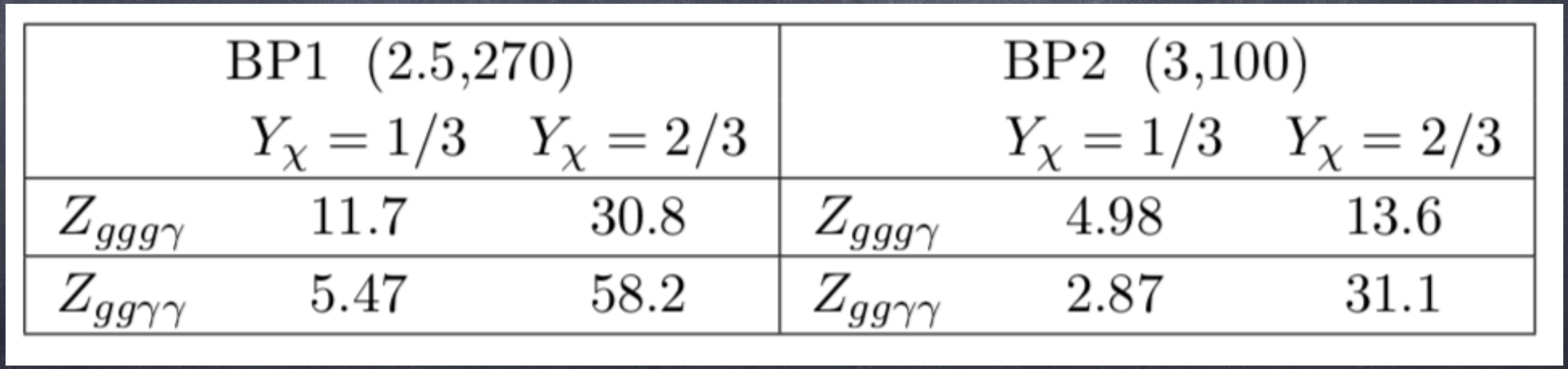
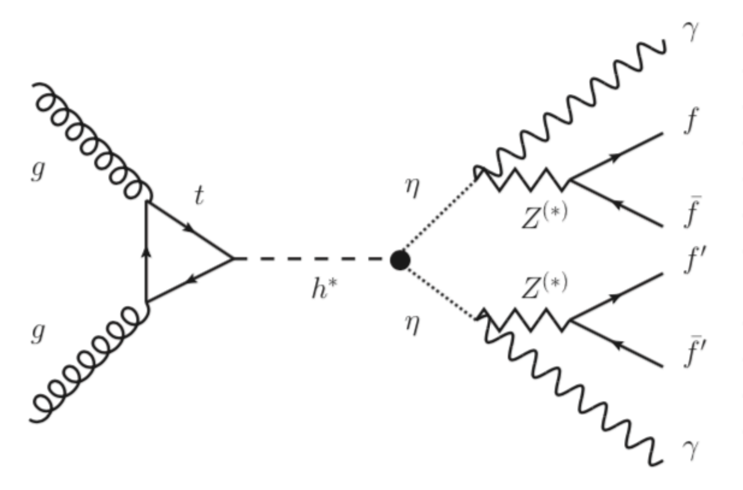


	BP1 (2.5,270)		BP2 (3,100)	
	$Y_\chi = 1/3$	$Y_\chi = 2/3$	$Y_\chi = 1/3$	$Y_\chi = 2/3$
$Z_{ggg\gamma}$	11.7	30.8	4.98	13.6
$Z_{gg\gamma\gamma}$	5.47	58.2	2.87	31.1

FCC-hh can reach in the multi-TeV range!

Light pseudo-scalars via the Higgs



D.Buarque Franzosi, G.Ferretti, L.Huang, J.Shu,
2005.13578

$\lambda \sim h\eta\eta$ coupling

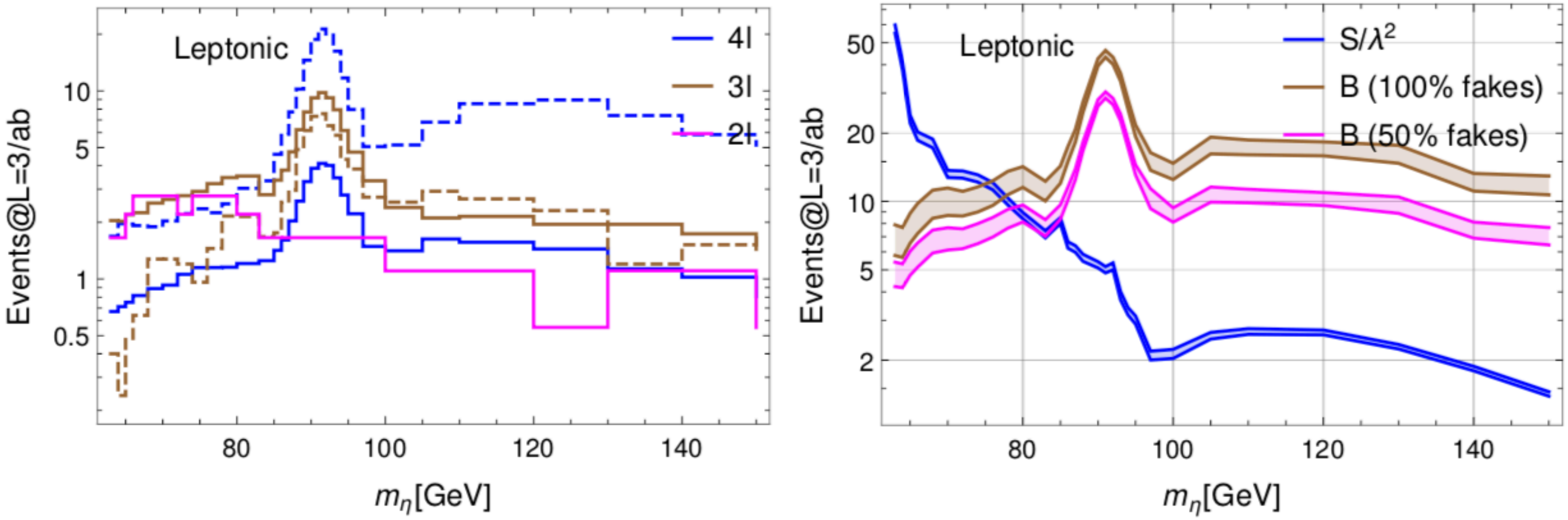


Figure 4. *Left:* Number of events for HL-LHC for the dominant background processes (2.5) after selections (3.1) and (3.2). The solid lines refer to samples with two ME photons ($n_\gamma = 2$) and the dashed lines to 1 ME photon ($n_\gamma = 1$). The dominant background for low m_η are $3\ell 2\gamma$ and $2\ell 2\gamma$ and for high values of m_η is $4\ell 1\gamma$ with a fake photon typically originating from an electron. *Right:* Total background (B) and signal (S) rates after selection cuts. The magenta curve is obtained with the reduction of 50% in fake photon rates. The bands indicates MC statistical error.

Sigma-assisted misalignment

D.Buarque Franzosi, G.C., A.Deandrea
1809.09146v2

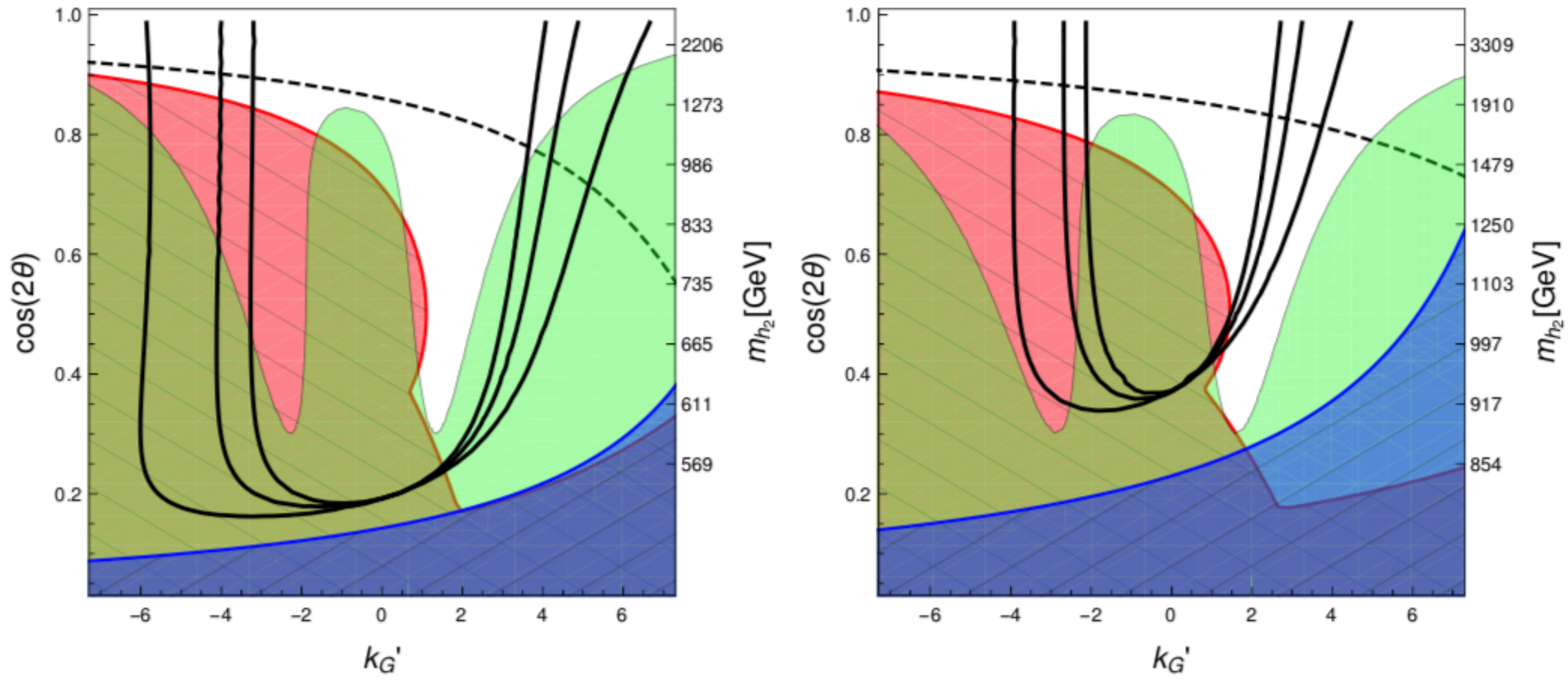
- Growing lattice evidence for light 0++ state in models with walking window

- The sigma mixes with the Higgs: universal effects for all cosets!

Sigma-assisted misalignment

D.Buarque Franzosi, G.C., A.Deandrea
1809.09146v2

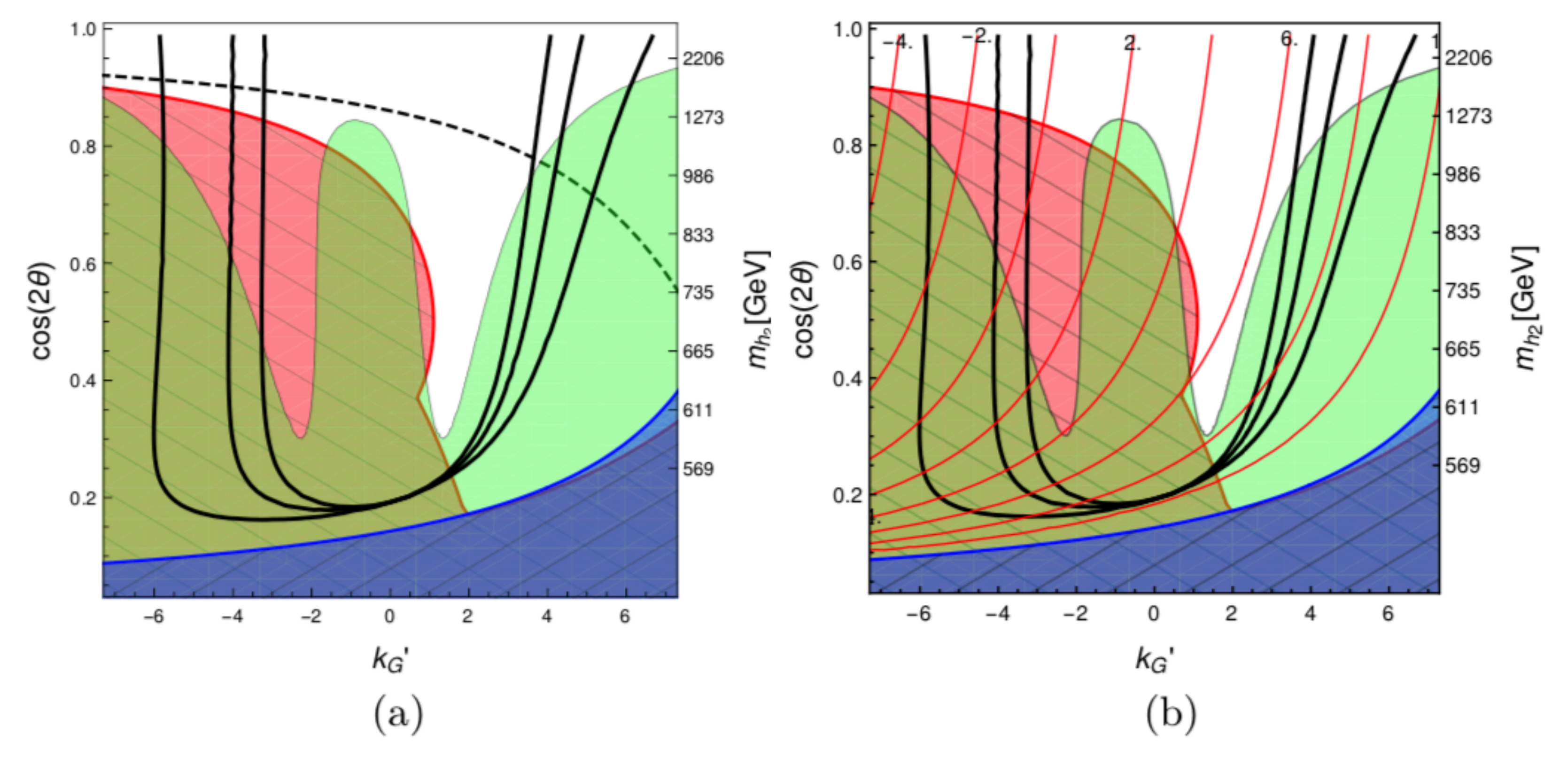
- Growing lattice evidence for light 0++ state in models with walking window (see later)



(a) (b)

Sigma-assisted misalignment

D.Buarque Franzosi, G.C., A.Deandrea
1809.09146v2



Low tuning predicts:

$m_{h_2} < 1\ TeV$

$k'_G \approx 1.5 \div 2$

Large width:

$h_2 \to ZZ$

$k'_t \approx 5 \div 7$