Composite Resonances

Natascia Vignaroli

1st FCC Physics Workshop

CERN, 19 Jan 2017

Composite Resonances

- Predicted in BSM models with a **new strong dynamics**

  LHC and especially FCC have the possibility to explore a new strong sector through the direct search for composite resonances

- Most notably are the prediction of **Composite Higgs Models** (connection with the explanation of the EWSB and Higgs naturalness problem)

SPIN-1	W', Z', G', ...
FERMIONS	VLQ top-partners
SCALARS	extra pNGBs, η'-like states ...

Spin-1 Resonances (two-site description)

ELE

V^{ele}

g^{ele}

$$\tan\theta = \frac{g^{ele}}{g^{com}}$$

mixing

COMP

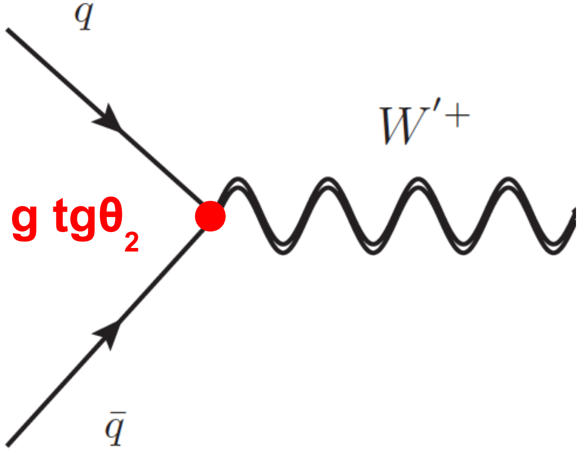
V^{com}

g^{com}

$$g_{SM} = g^{ele}\cos\theta = g^{com}\sin\theta$$

$$V' = \cos\theta\, V^{com} - \sin\theta\, V^{ele}$$

$$g^{ele} \approx g_{SM} \qquad 1 < g^{com} < 4\pi$$



g tgθ_2

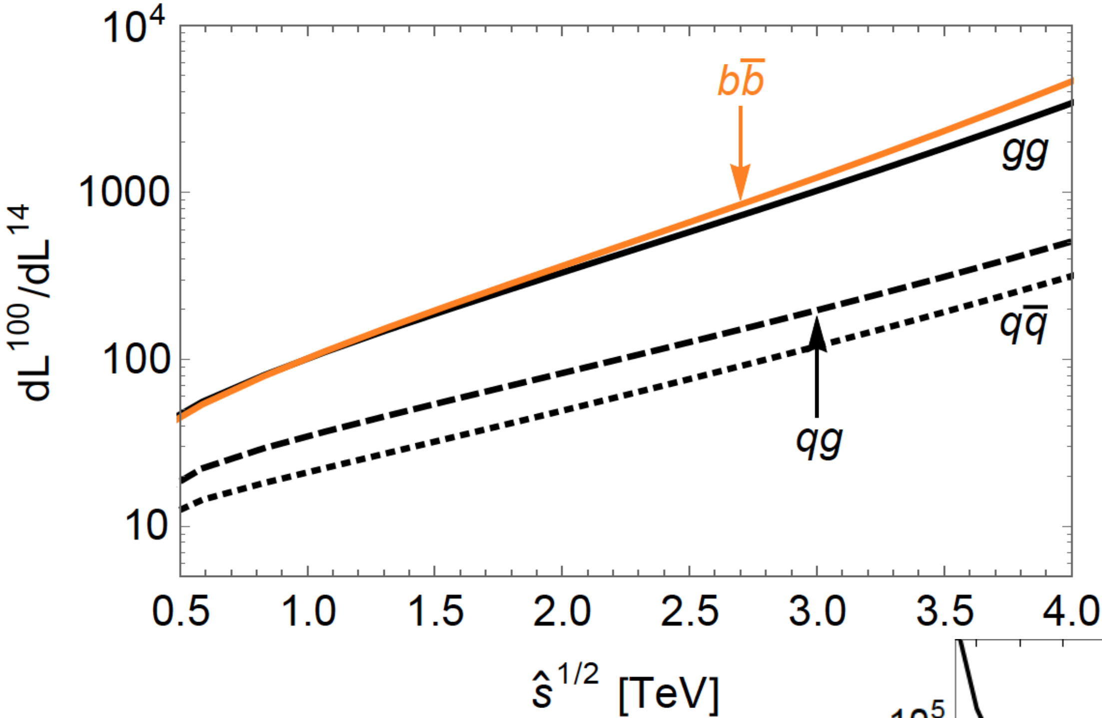
~ g^2/g_V

decay

$jj \quad l\nu \quad tb \quad WZ/Wh \quad$ VLQs

$g\tan\theta \qquad \sim g\, s_L^2 \cot\theta \qquad g\cot\theta$

= g_V



Physics opportunities of a 100 TeV proton–proton collider
Phys.Rept. 652 (2016) 1-49

Drell-Yan production

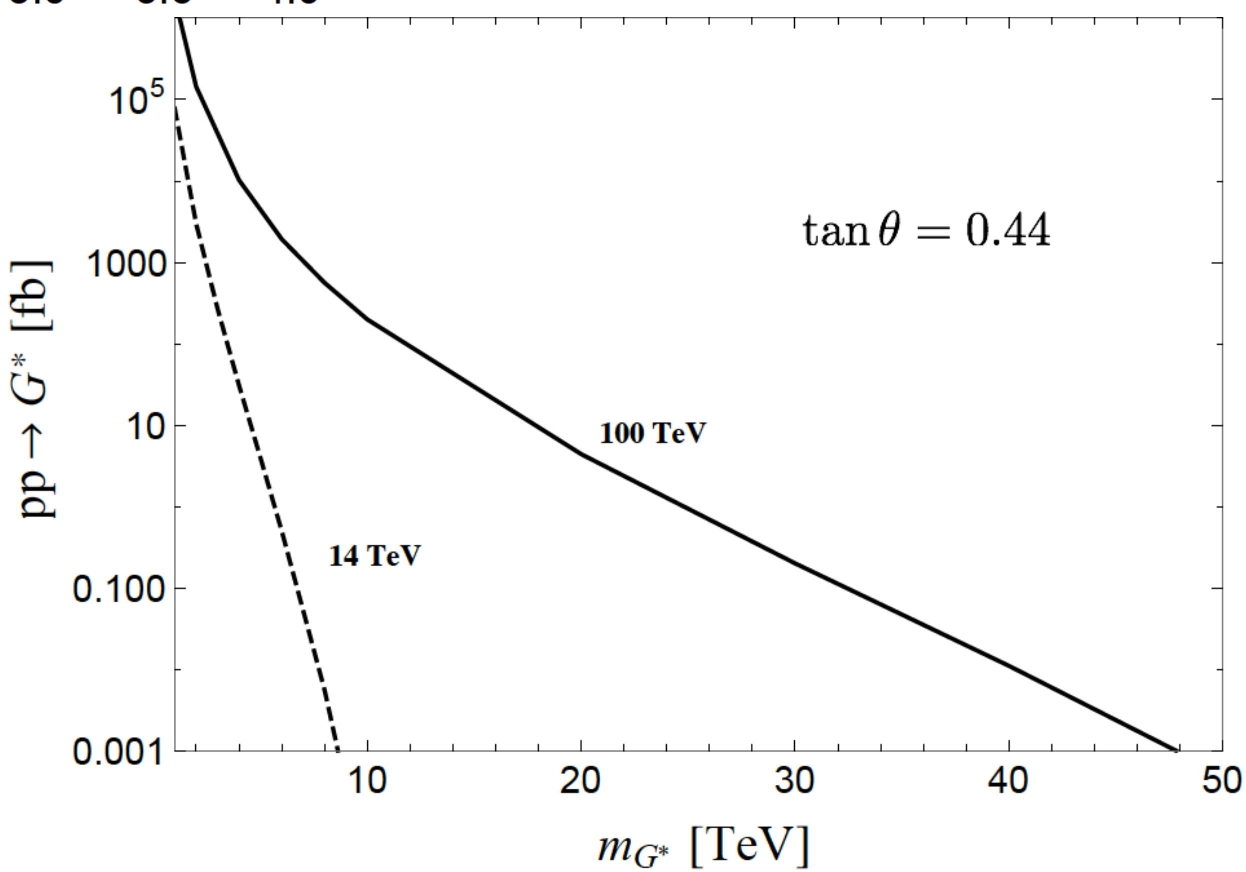
$$s_L \simeq s_R = 0.6$$

Intermediate top degree of compositeness

↓

$$b\bar{b} \to G^*$$

contribution ranges from
~7 % at 1 TeV to ~ 1 % at 10 TeV



Drell-Yan production (dijet final state)

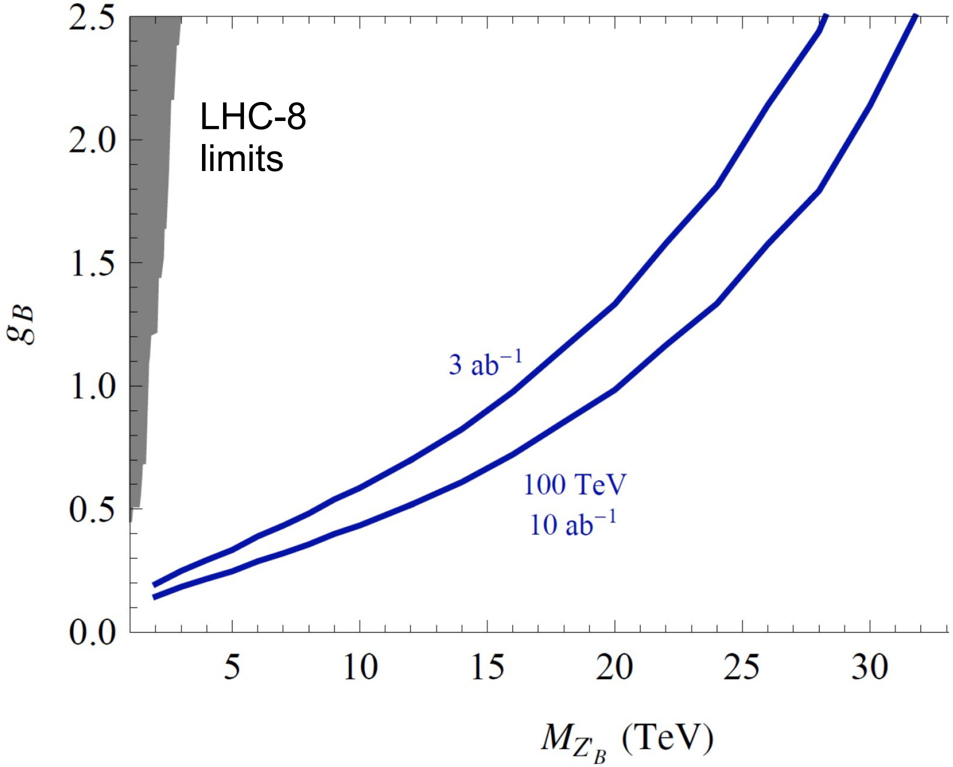
Felix Yu, arXiv:1308.1077
B. Dobrescu, F.Yu,
Phys.Rev. D88 (2013) no.3, 035021

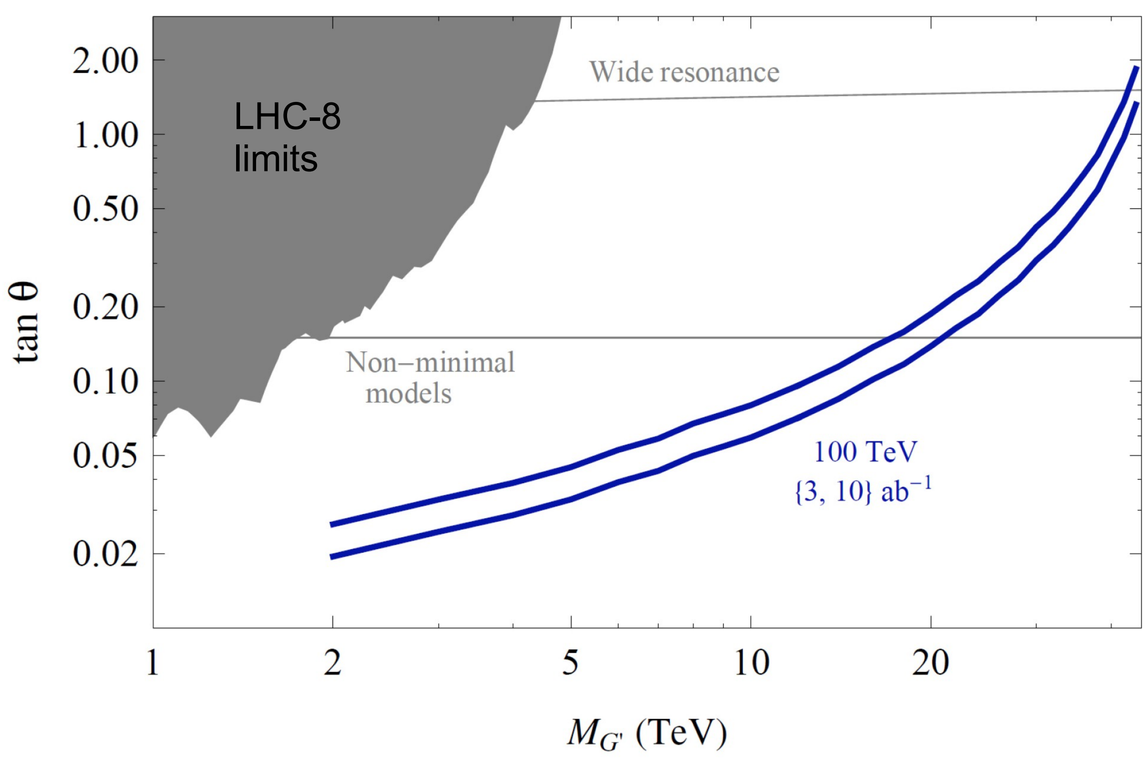
CMS-PAS-EXO-12-059 analysis + Crystall Ball fit

$$|\eta_j| < 2.5 \quad |\Delta\eta_{jj}| < 1.3$$

$$\mathcal{L} \supset \frac{g_B}{6} Z'_B \bar{q}\gamma^\mu q$$

$$\mathcal{L} \supset g_S \tan\theta \bar{q}\gamma^\mu T^a G'^a_\mu q$$



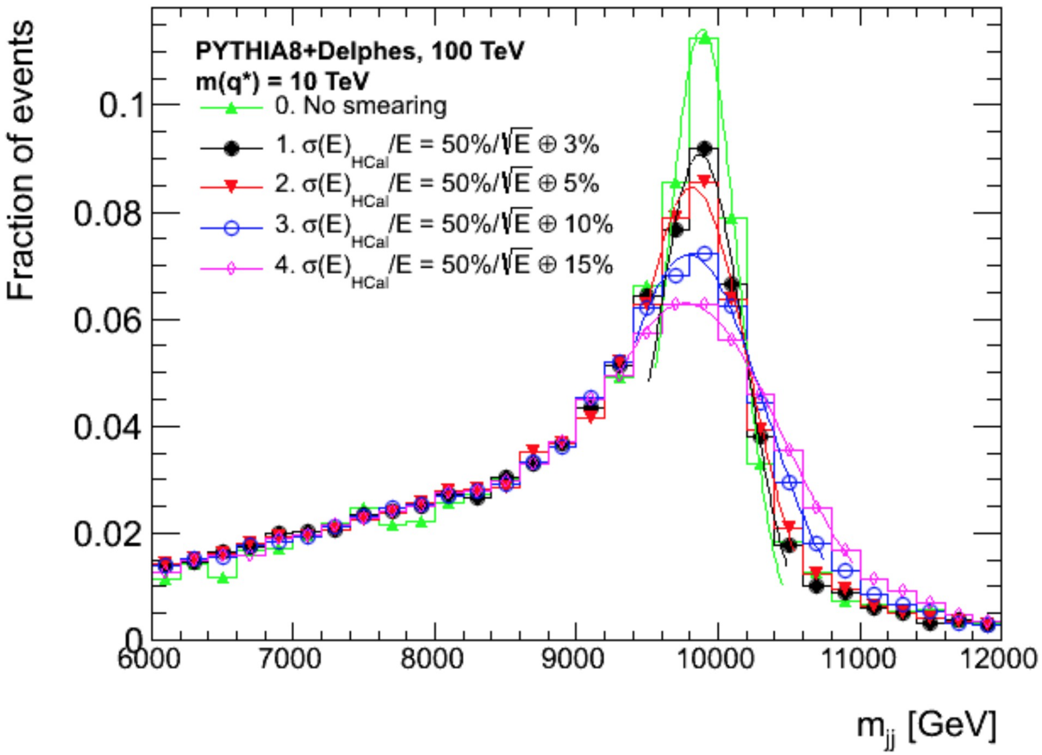


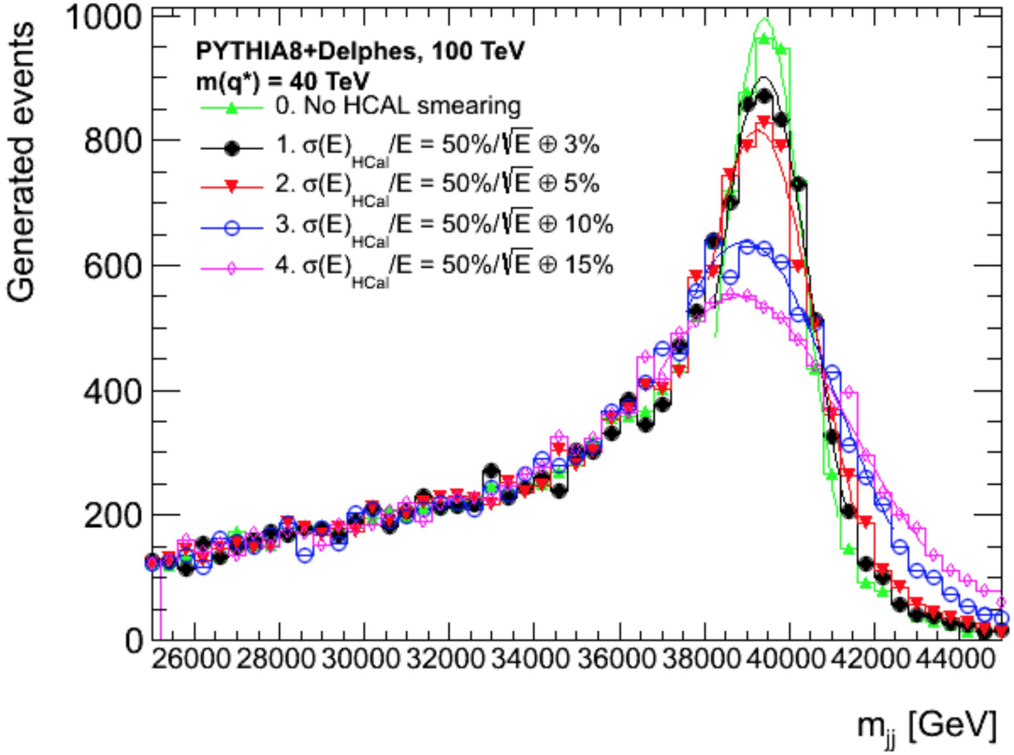
dijet final state: calorimeter requirements

Energy resolution:

$$\frac{[\sigma]}{E} = \frac{50}{E} \oplus c\%$$

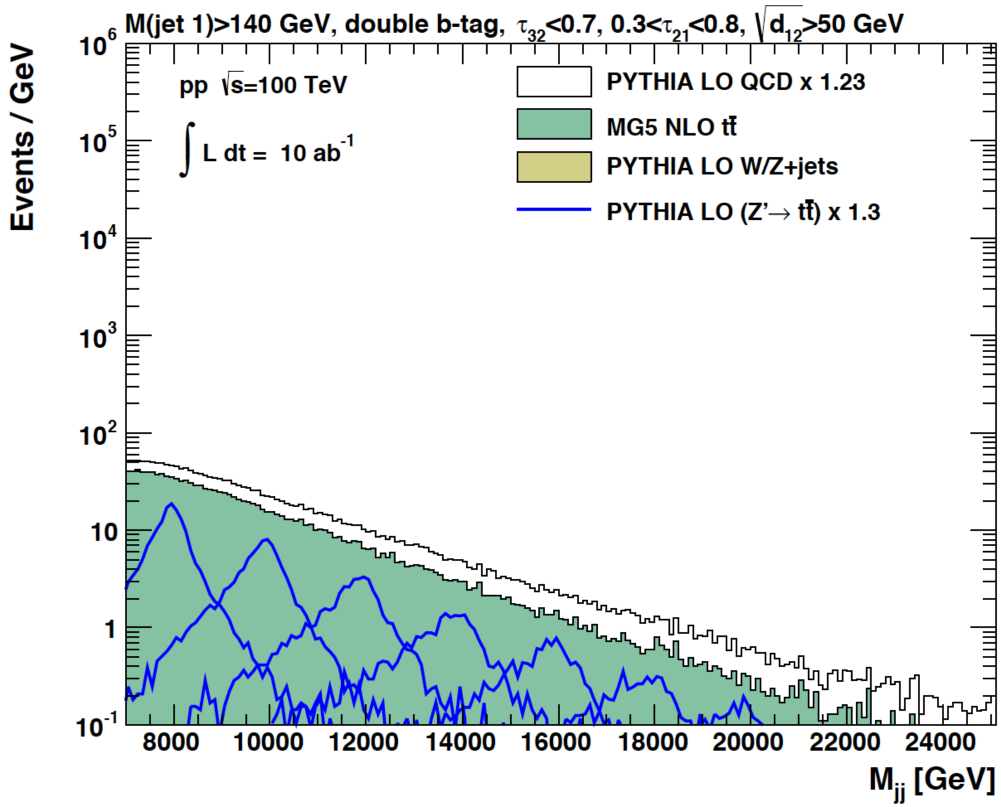
Physics at a 100 TeV pp collider: beyond the Standard Model phenomena,
arXiv: 1606.09447

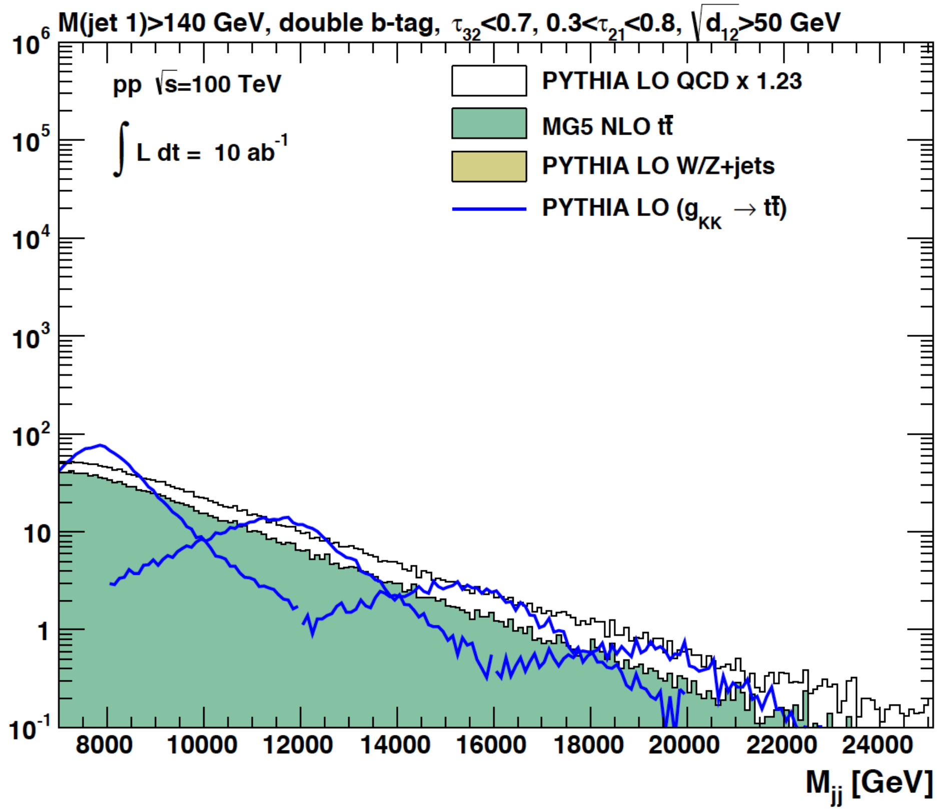




Drell-Yan production (ttbar final state)

Auerbach, Chekanov, Love, Proudfoot, Kotwal, PRD 91 034014





Boosted tops: substructure techniques applied
(N-subjettiness, splitting scale distribution in kT algorithm, ..)

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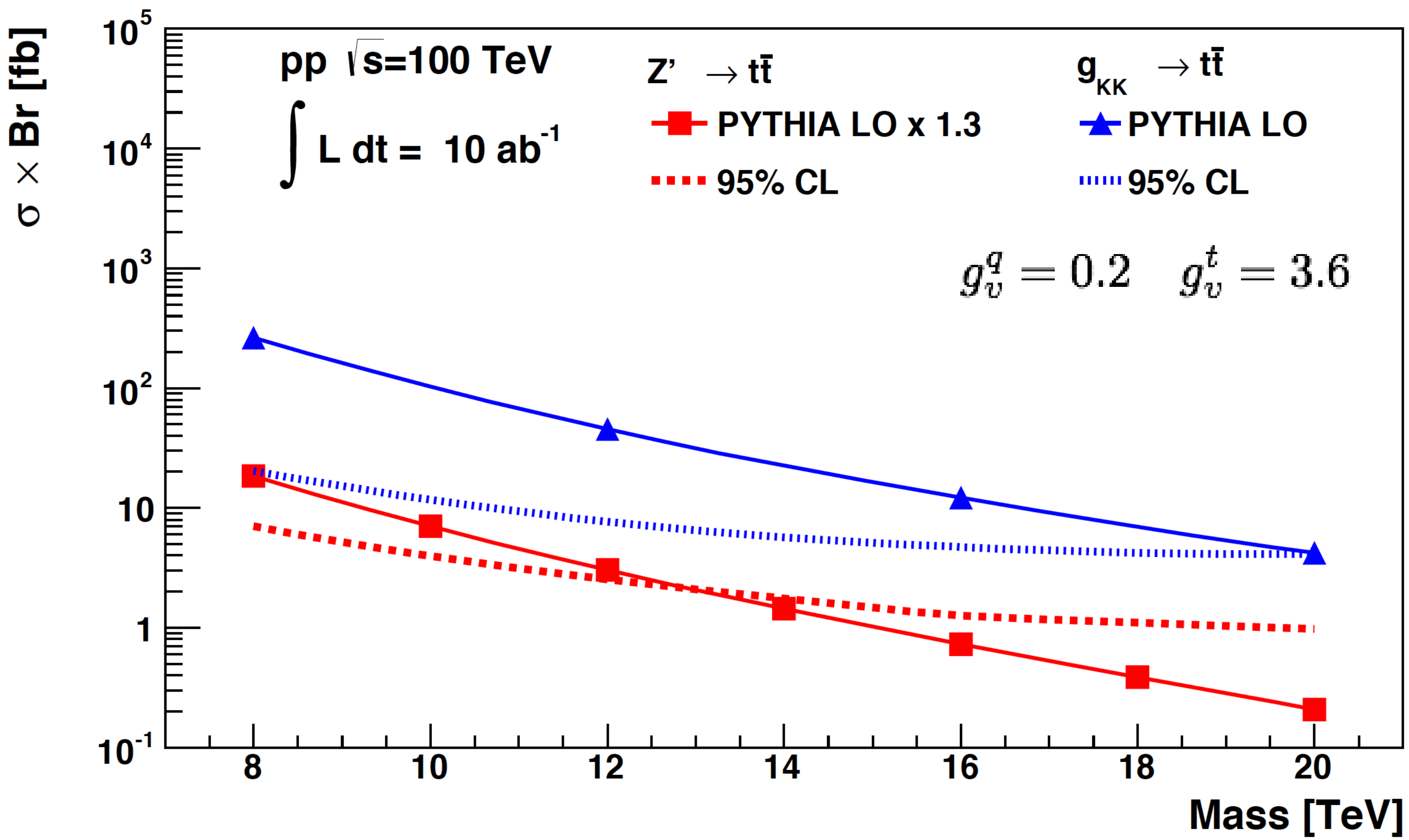
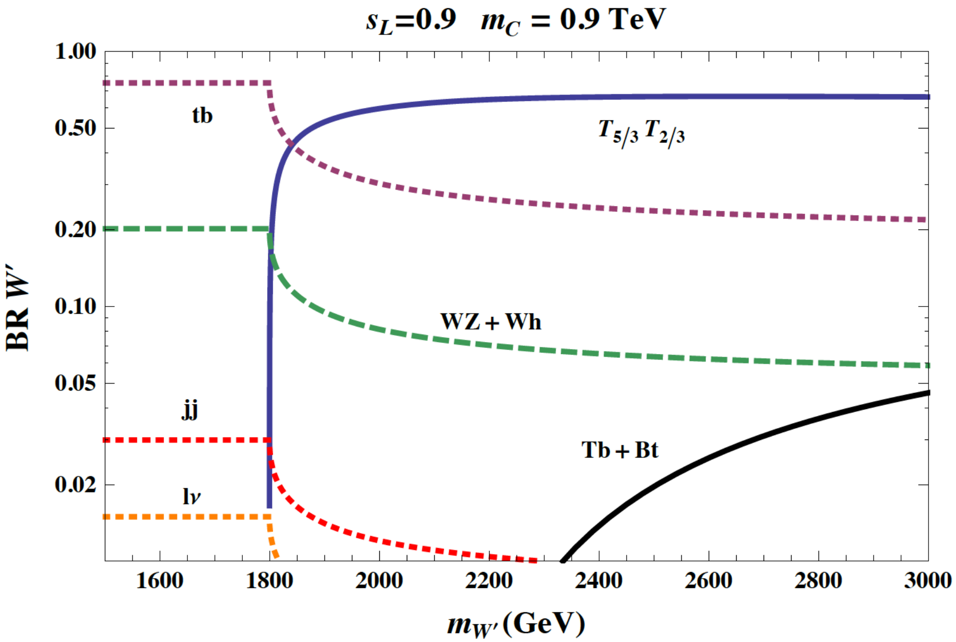
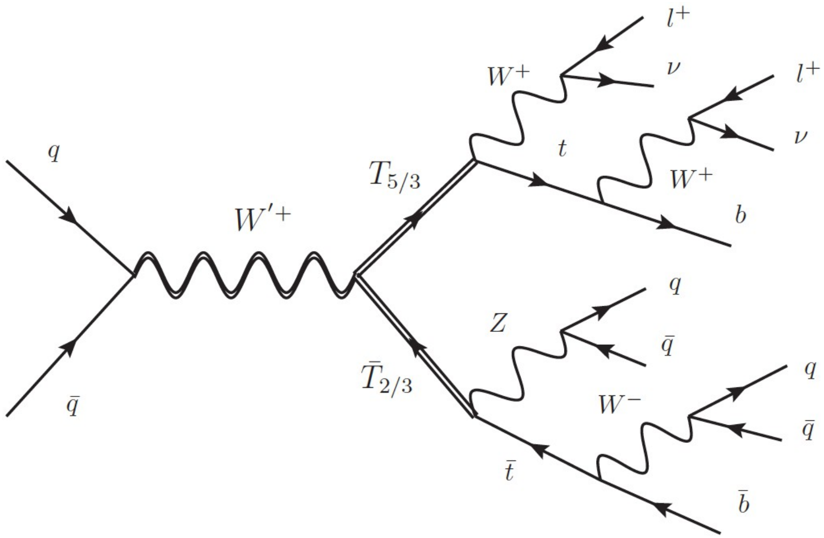
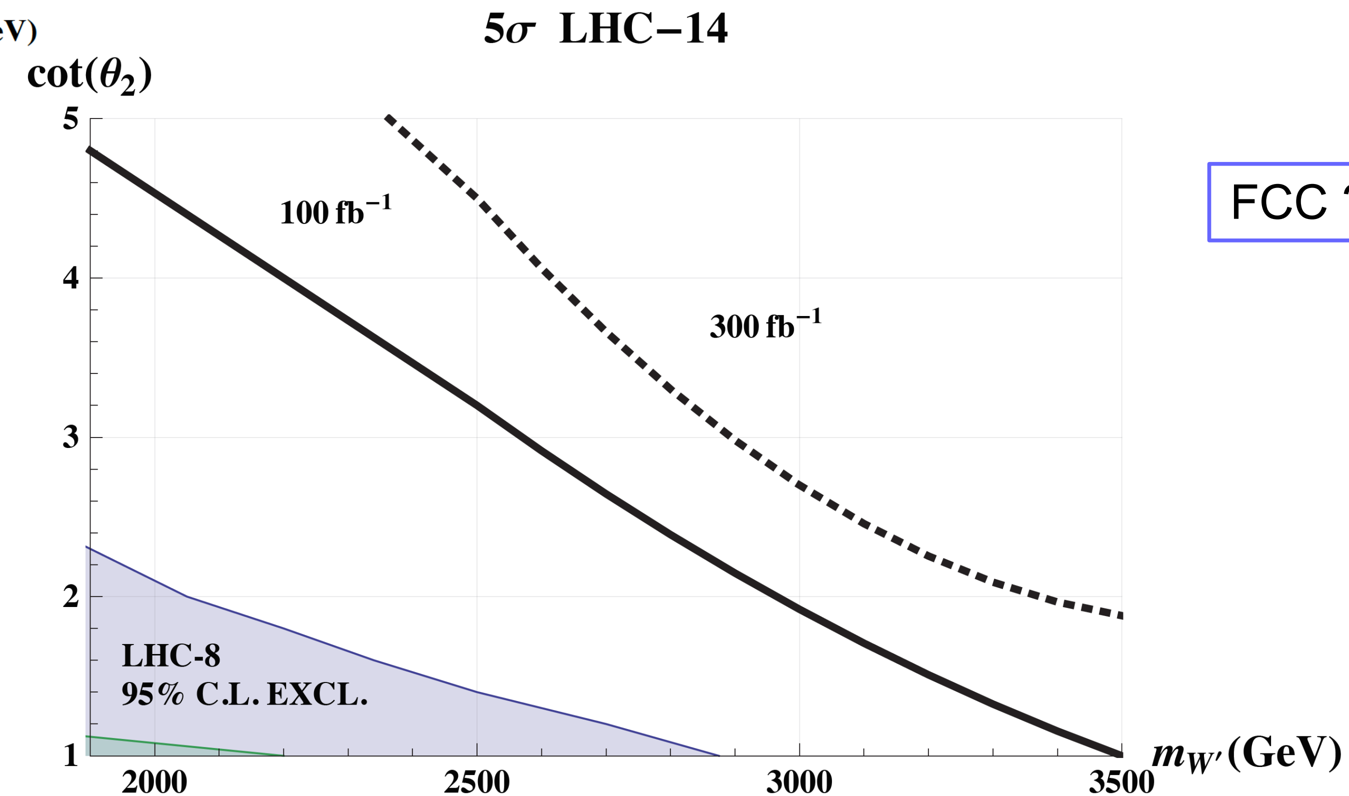


Boosted tops: substructure techniques applied
(N-subjettiness, splitting scale distribution in kT algorithm, ..)

Drell-Yan production (VLQ channels)







NV,
Phys.Rev. D89
(2014) no.9, 095027

FCC ?

Direct *vs* Indirect Probes

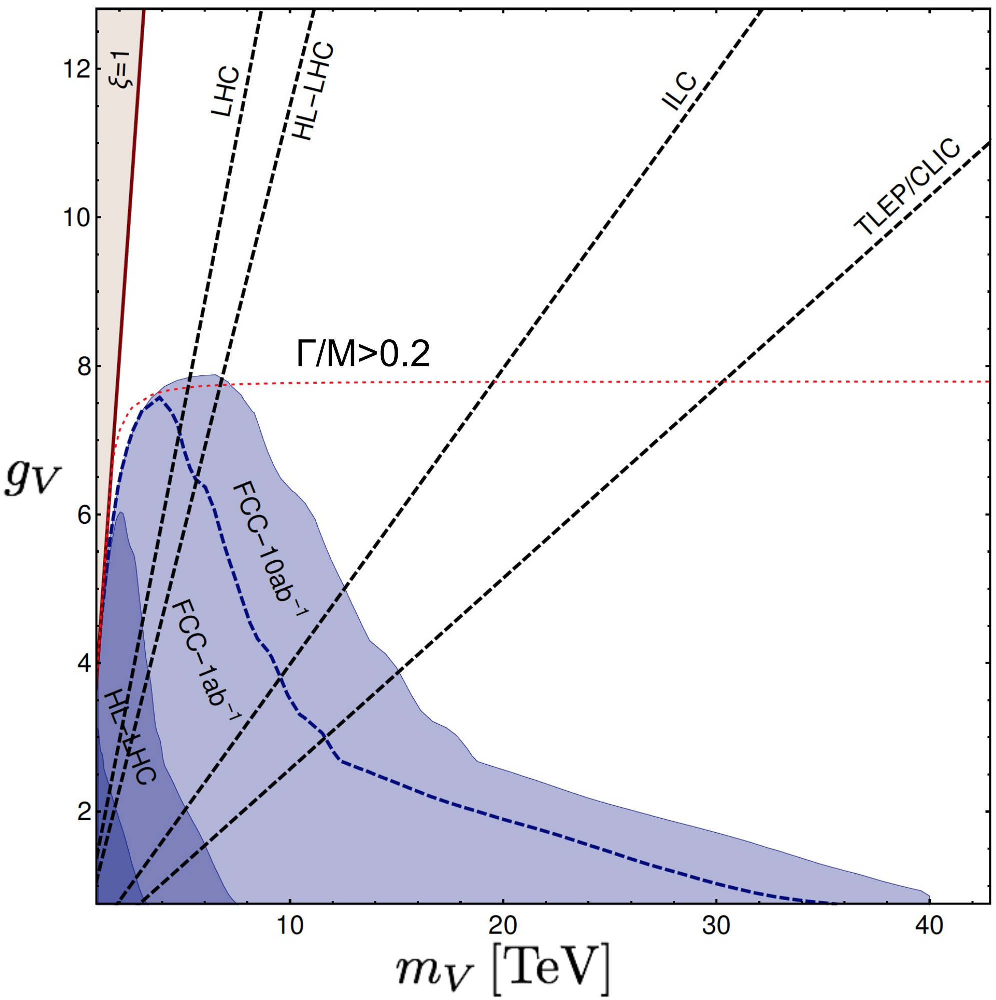
Thamm, Torre, Wulzer, JHEP 1507 (2015) 100

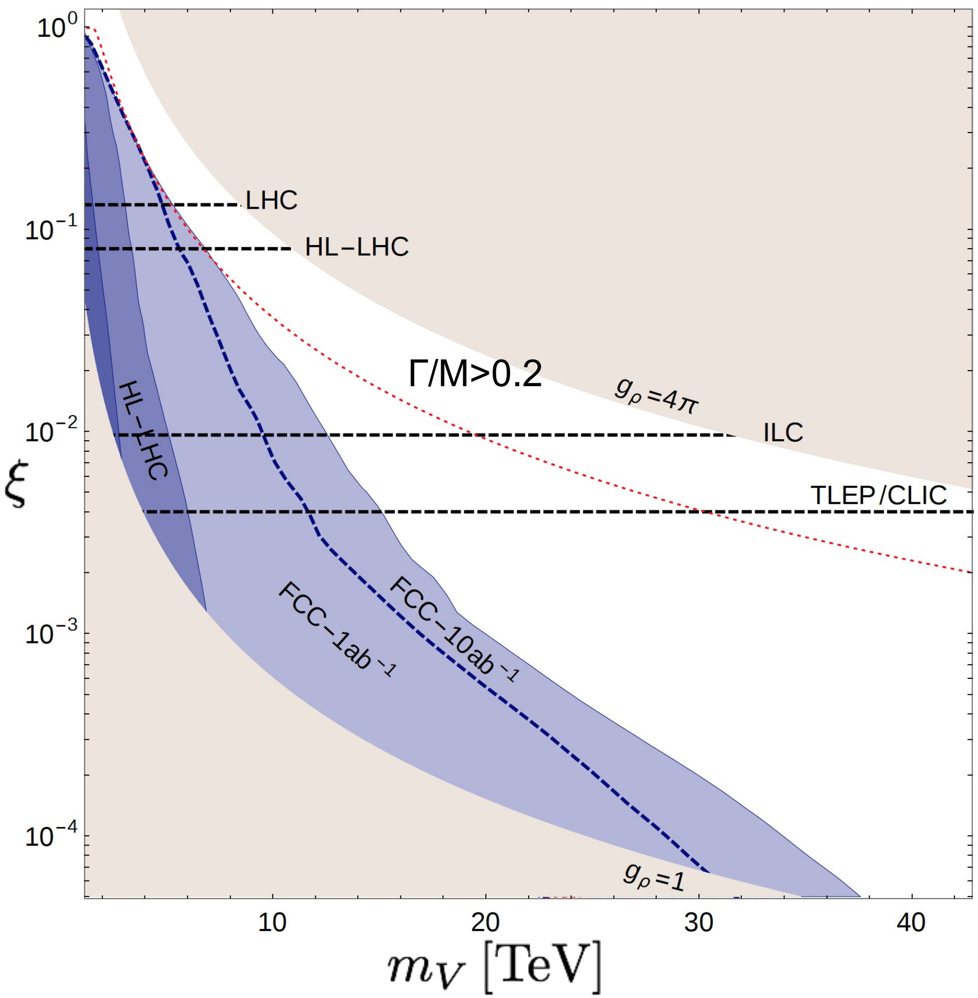
Vacuum misalignment parameter
(size of fine-tuning in pNGB CHM)

$$\xi = \left(\frac{v}{f}\right)^2 \sim v^2 \frac{g_V^2}{m_V^2}$$

Indirect probes →

- EWPD $\quad S \sim v^2/m_V^2$
- Modification of Higgs couplings $\quad k_V = \sqrt{1-\xi}$

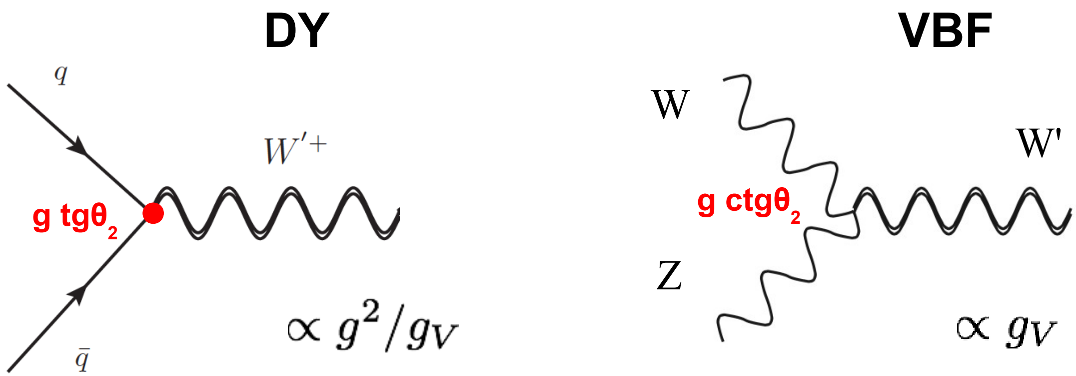


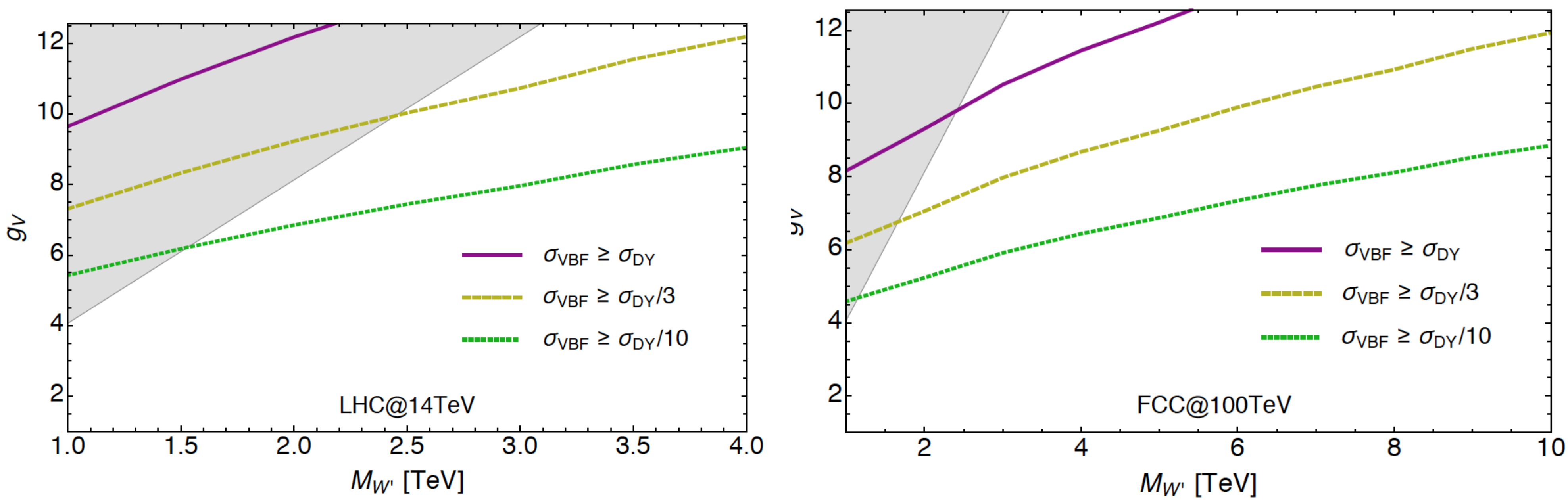


Direct search limits extrapolated from LHC-8 searches for narrow resonances in the dilepton and WZ final state

Probing the large g_V regime with VBF

K. Mohan, NV
JHEP 1510 (2015) 031





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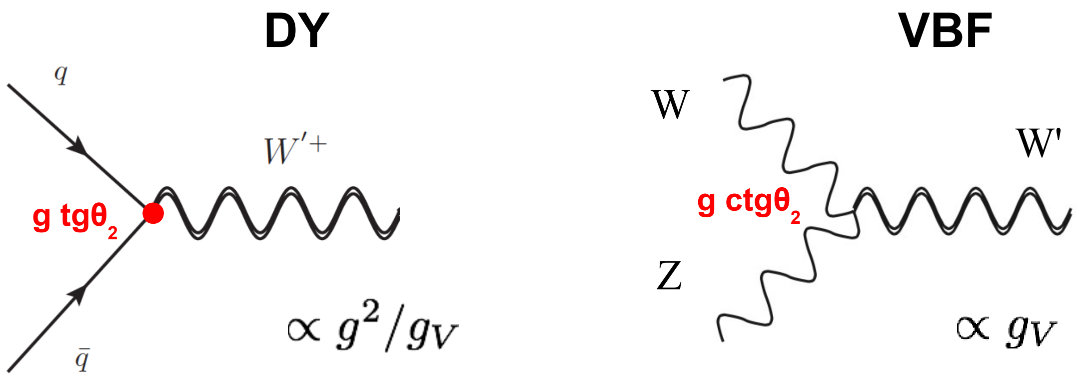
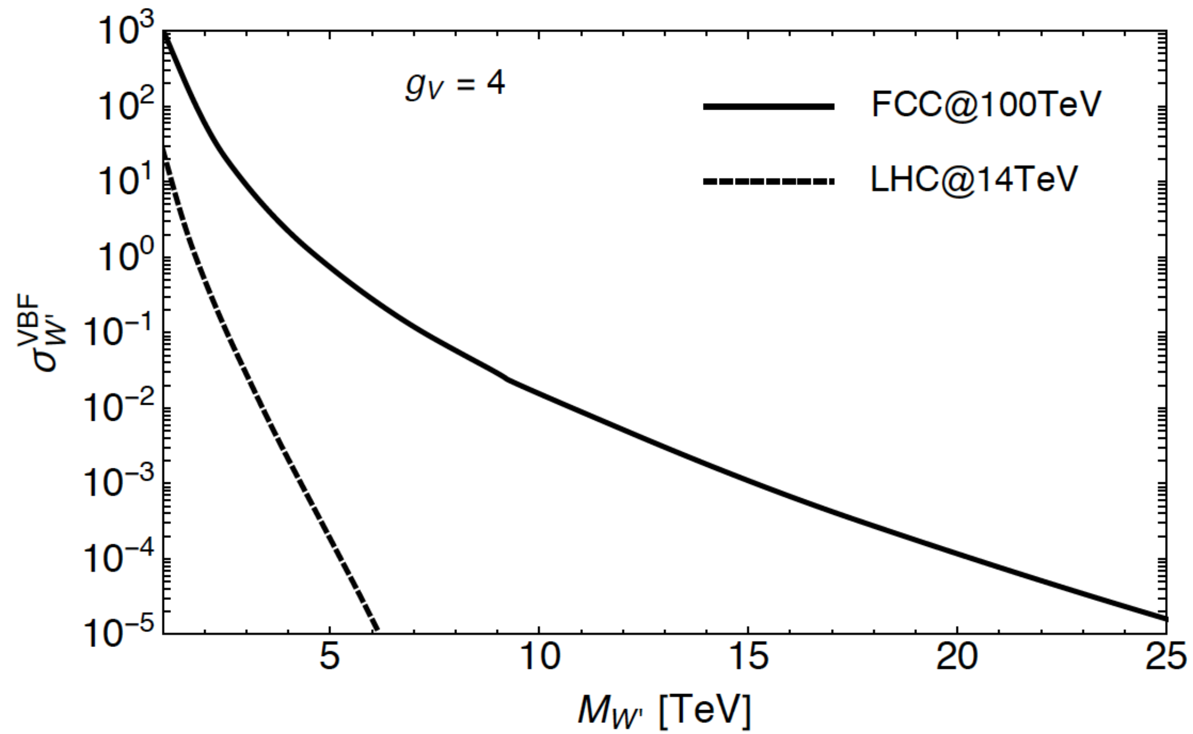
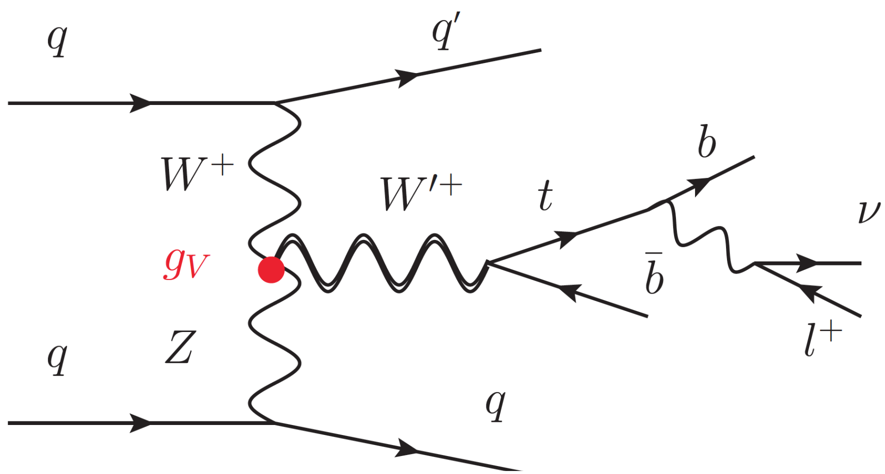




Probing the large g_V regime with VBF (tb channel)



BCKG

$WWbb \quad (\supset t\bar{t}, Wt)$

$Wbb + \text{jets}$

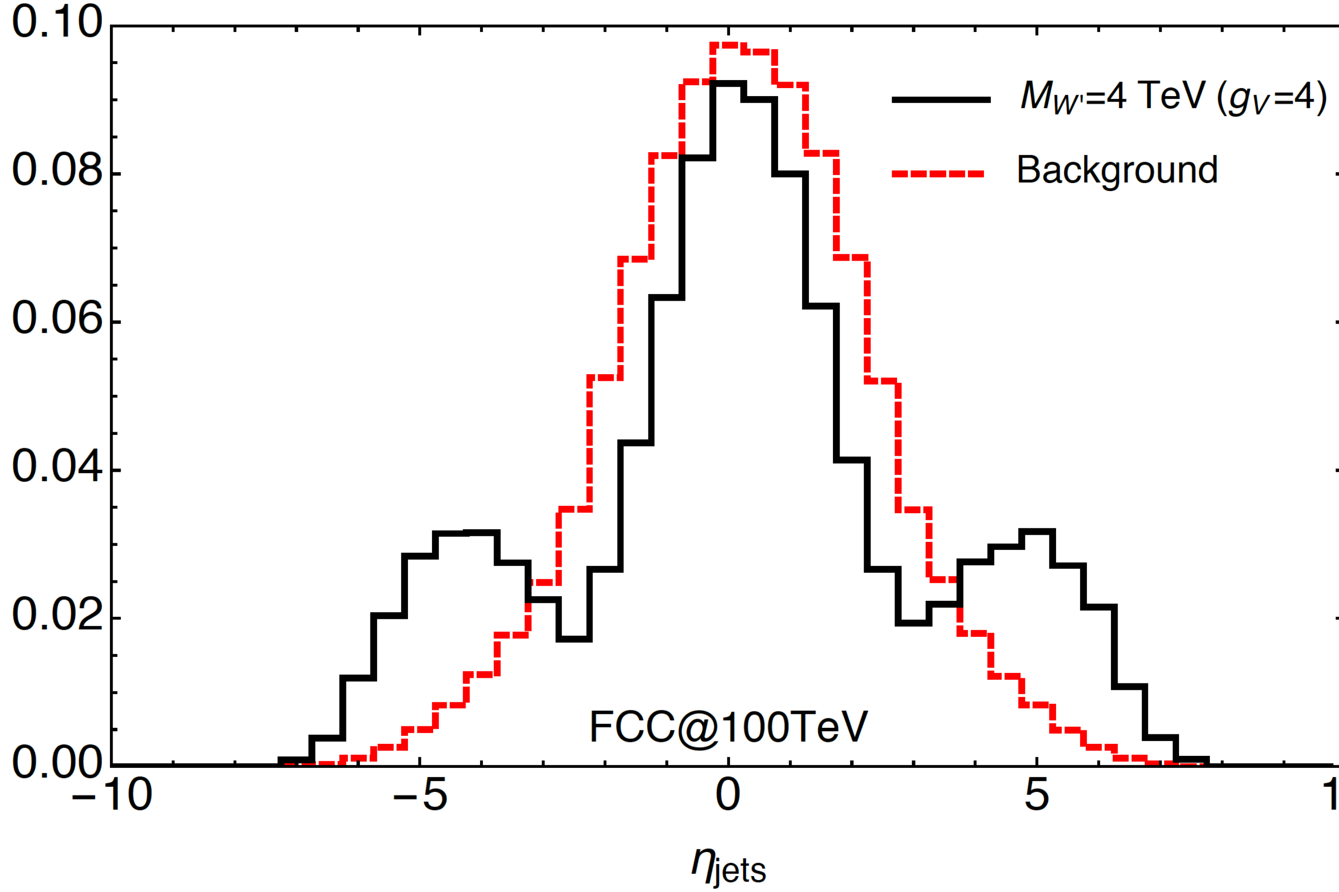
$tb + \text{jets}$

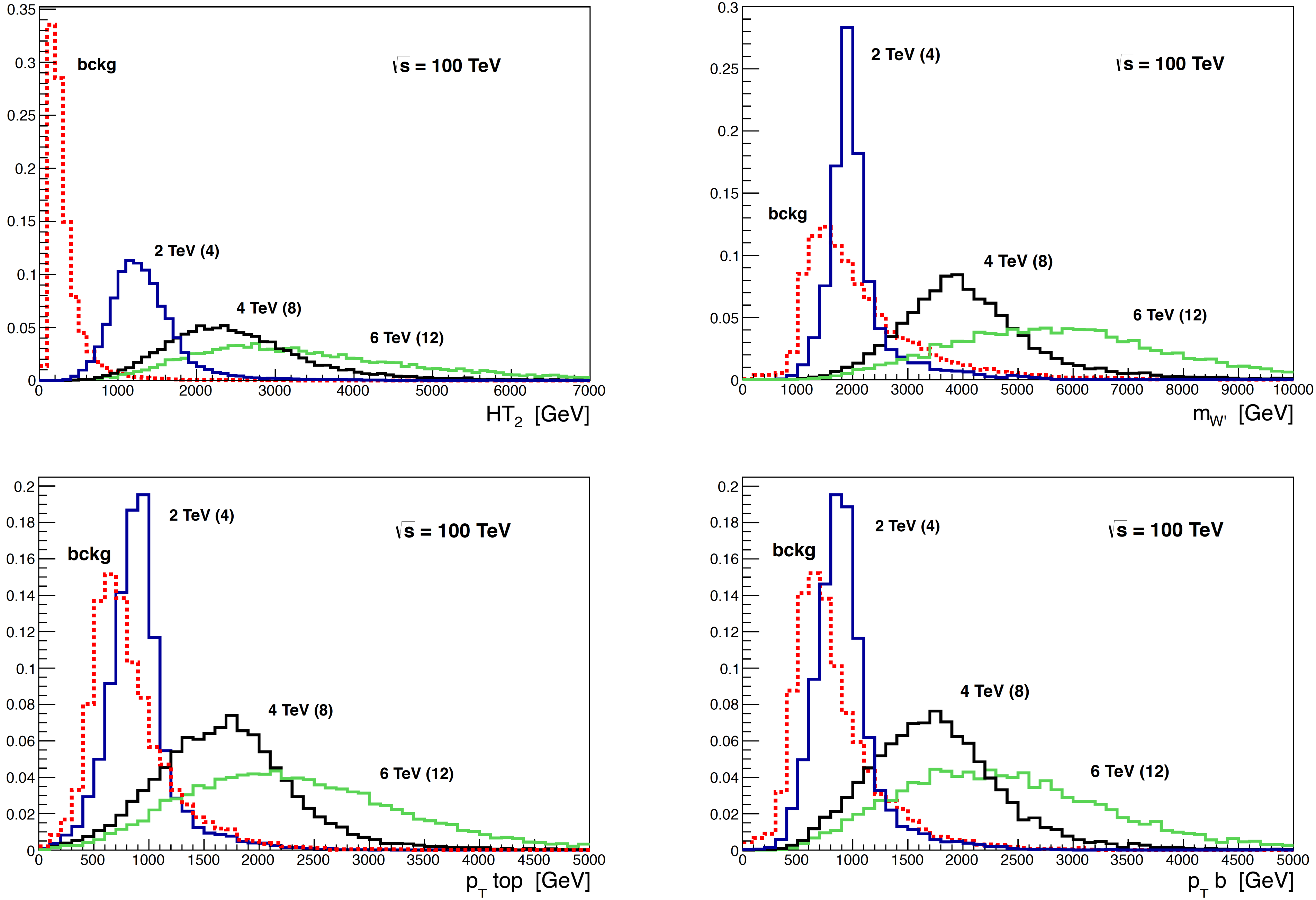
$s_L = 0.7$

$BR(W' \to tb) \simeq 0.6$

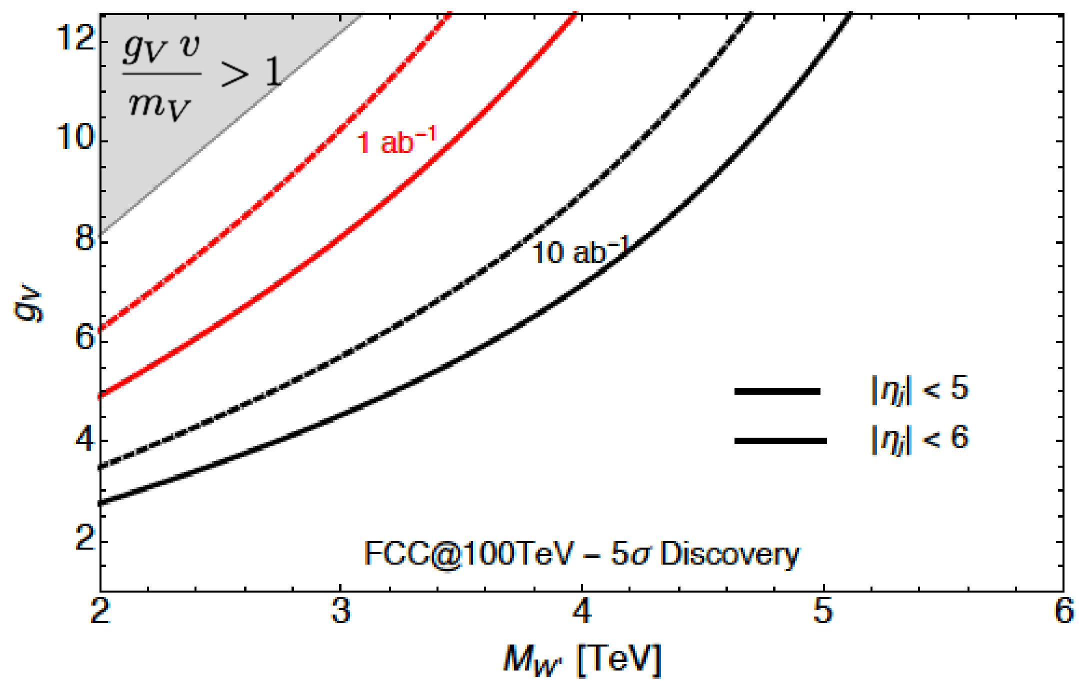
$|\eta_{Fj,Bj}| > 2.5$

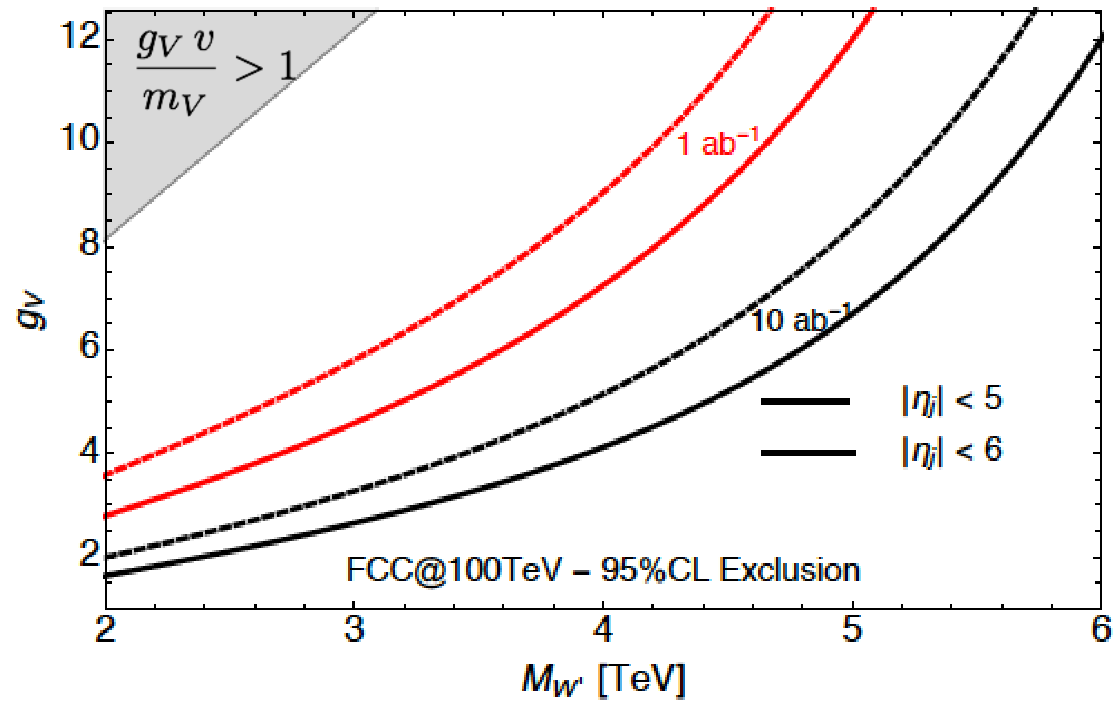
$|\eta_{Fj} - \eta_{Bj}| > 8$



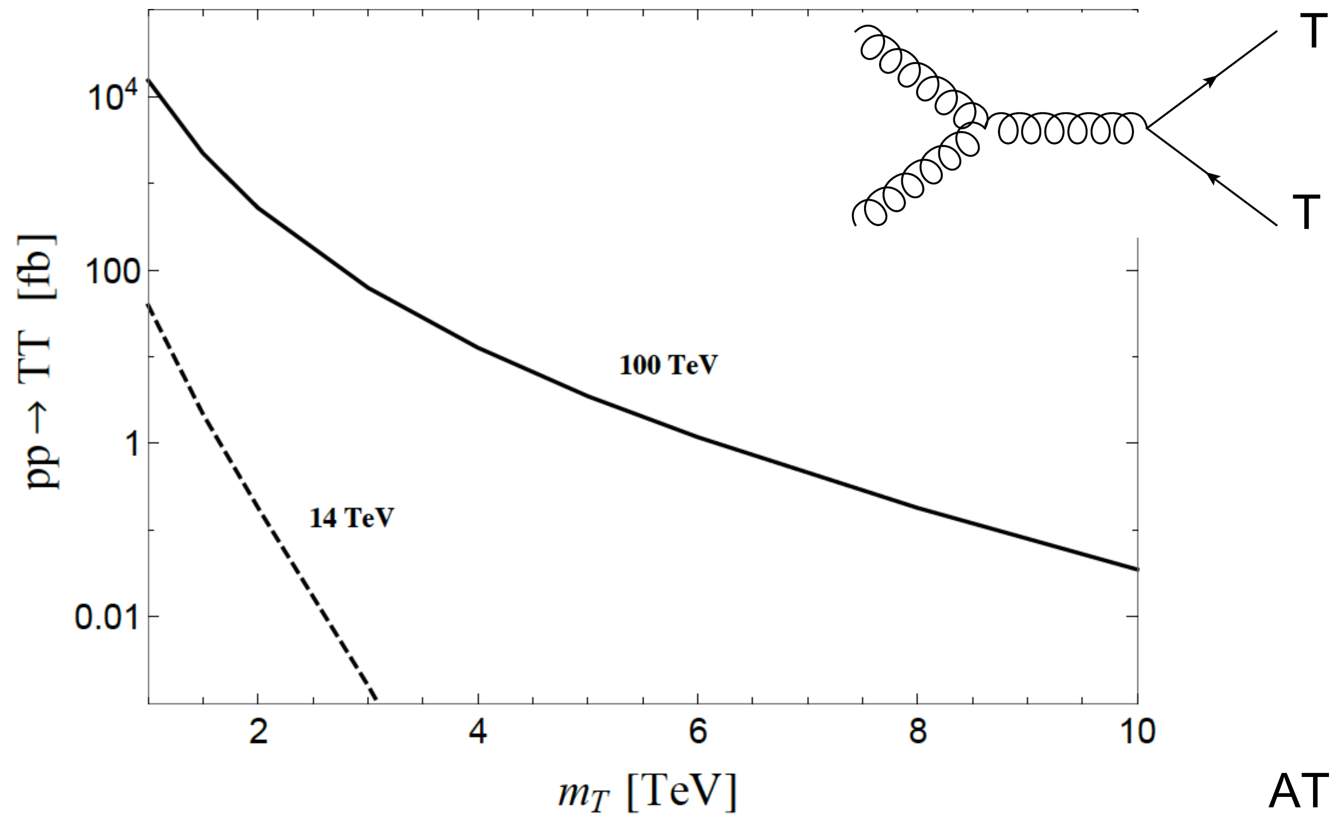


$M_{W'}$ (TeV)	2	3	4	5	6
$m_{W'}$ > (TeV)	1.5	2.5	3.5	4.0	5.0
p_T b, t > (TeV)	0.75	0.9	1.5	1.5	1.5

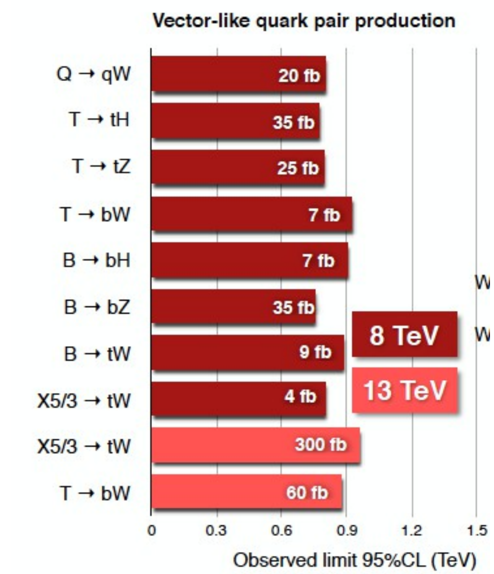

$\frac{g_V v}{m_V} > 1$
1 ab^{-1}
10 ab^{-1}
$|\eta_j| < 5$
$|\eta_j| < 6$
FCC@100TeV – 5σ Discovery
g_V
$M_{W'}$ [TeV]


$\frac{g_V v}{m_V} > 1$
1 ab^{-1}
10 ab^{-1}
$|\eta_j| < 5$
$|\eta_j| < 6$
FCC@100TeV – 95%CL Exclusion
g_V
$M_{W'}$ [TeV]

Composite fermions: Top-partners (pair production)



CMS



ATLAS

Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	$\geq$ 2 b, $\geq$ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	$\geq$ 1 b, $\geq$ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	$\geq$ 2 b, $\geq$ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	$\geq$ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \to WtWt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	3.2	$T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032

Lect.Notes Phys. 913 (2016)

Arkani-hamed, Han, Mangano, Wang, Phys.Rept. 652 (2016) 1-49

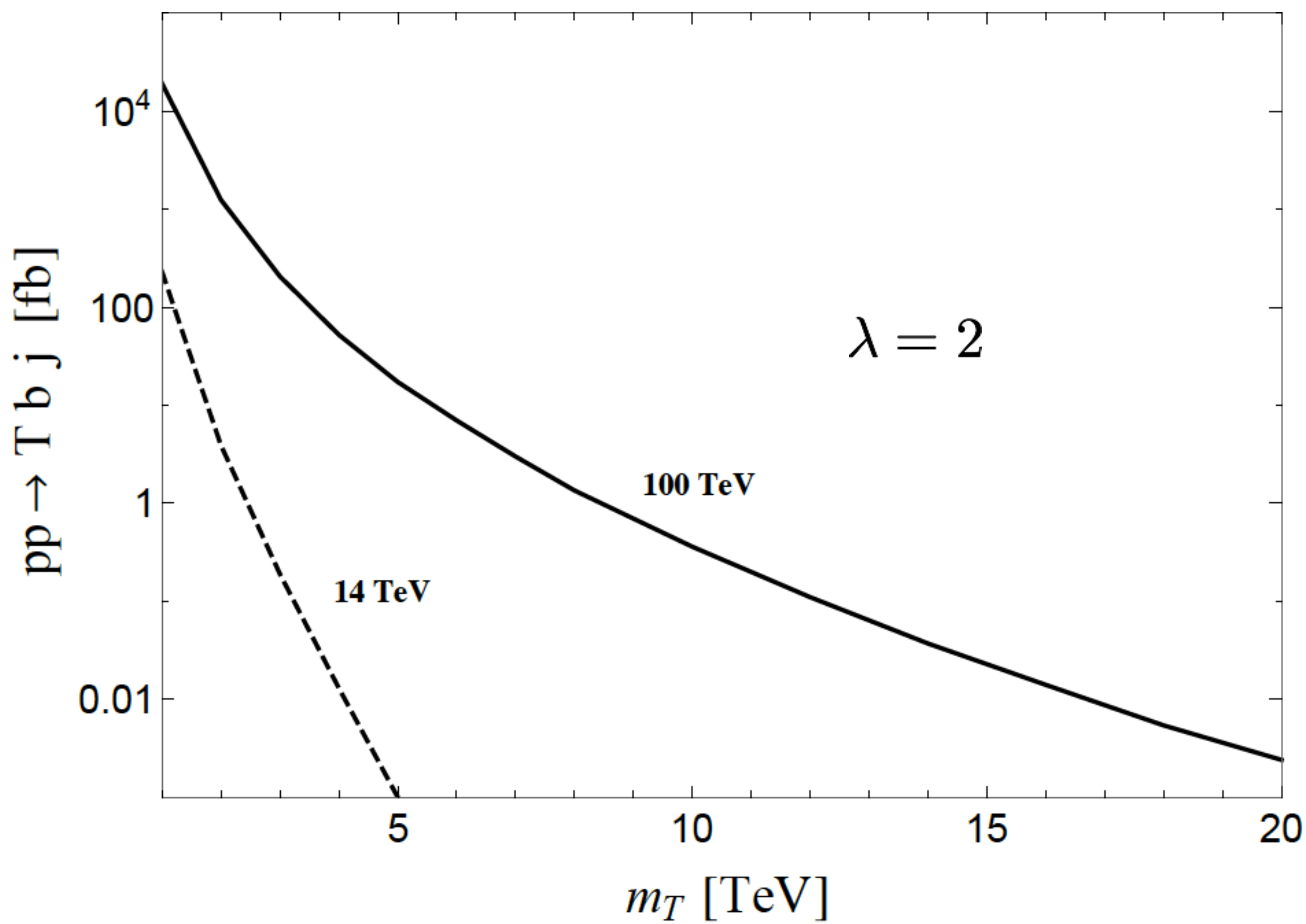
$$\Delta^{-1} \sim \left(\frac{500\,\mathrm{GeV}}{m_T}\right)^2$$

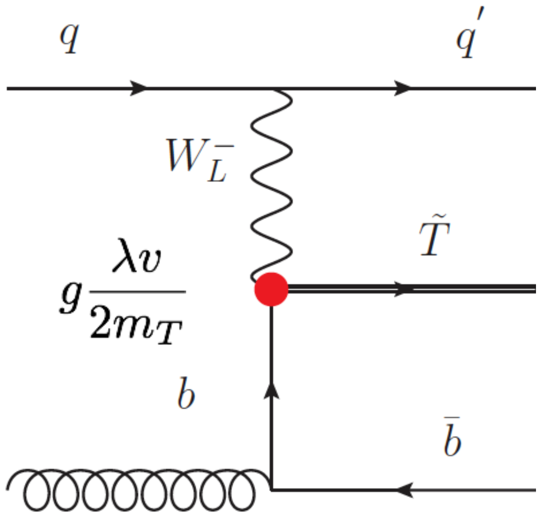
FCC:

Mass reach increase by roughly a factor of **5**

Fine-tuning can be pushed at the level of **10^{-3} - 10^{-4}**

Composite fermions: Top-partners (single EW production)





$$\lambda_{\tilde{T}} \simeq Y_* s_L c_R$$

$$\lambda_{T_{5/3}} \simeq Y_* s_R$$

Composite fermions: Top-partners

SNOWMASS 2013, arXiv:1311.2028

arXiv:1309.1888

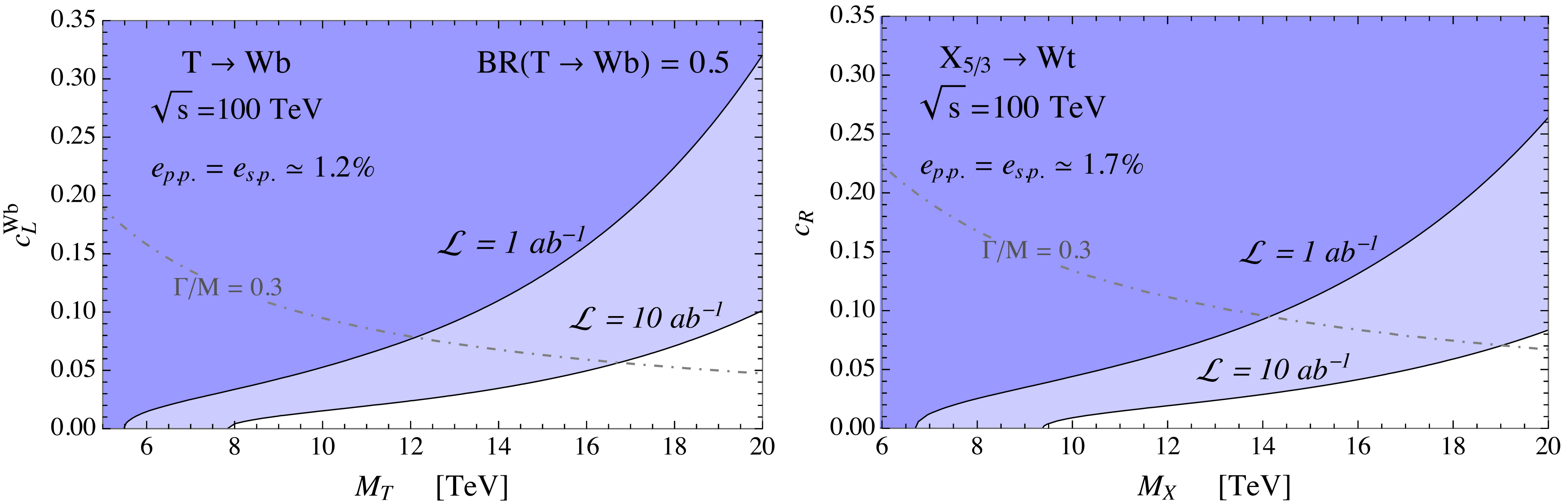
T → Ht (semi-leptonic) + T → Zt (Leptonic channel)

Collider	Luminosity	Pileup	3σ evidence	5σ discovery	95% CL
top-partner pair production					
LHC 14 TeV	300 fb^{-1}	50	1340 GeV	1200 GeV	1450 GeV
LHC 14 TeV	3 ab^{-1}	140	1580 GeV	1450 GeV	1740 GeV
LHC 33 TeV	3 ab^{-1}	140	2750 GeV	2400 GeV	3200 GeV
top-partner single production					
LHC 14 TeV	300 fb^{-1}	50	1275 GeV	1150 GeV	
LHC 14 TeV	3 ab^{-1}	140	1130 GeV	1000 GeV	
LHC 33 TeV	3 ab^{-1}	140	1350 GeV	1220 GeV	
LHC 100 TeV	3 ab^{-1}	50	1750 GeV	1600 GeV	
LHC 100 TeV	3 ab^{-1}	140	1750 GeV	1575 GeV	
bottom-partner pair production					
LHC 14 TeV	300 fb^{-1}	50	1210 GeV	1080 GeV	1330 GeV
LHC 14 TeV	3 ab^{-1}	140	1490 GeV	1330 GeV	>1500 GeV
LHC 33 TeV	300 fb^{-1}	50	> 1500 GeV	> 1500 GeV	> 1500 GeV
Charge 5/3 fermion pair production					
LHC 14 TeV	300 fb^{-1}	50	1.51 TeV	1.39 TeV	1.57 TeV
LHC 14 TeV	3 ab^{-1}	140	1.66 TeV	1.55 TeV	1.76 TeV
LHC 33 TeV	3 ab^{-1}	140	2.50 TeV	2.35 TeV	2.69 TeV

Composite fermions: Top-partners (pair + single prod.)

Matsedonskyi, Panico, Wulzer, JHEP 1412 (2014) 097

$$\mathcal{L} \supset \frac{g}{2} c_L^{wb} \bar{T}_L \gamma^\mu b_L W_\mu + \frac{g}{2} c_R \bar{T}_{5/3} \gamma^\mu t_R W_\mu$$



2/3 T → estimate based on reinterpretation of the LHC-8 analysis and, for s.p., on Ortiz et al. PRD90 (2014) no.7, 075009 [s.p. Wb in the fully hadronic channel]

5/3 X → estimate based on recasting of the LHC 14 TeV analysis: Avetisyan and Bose, arXiv:1309.2234 [p.p. same-sign dilepton channel]

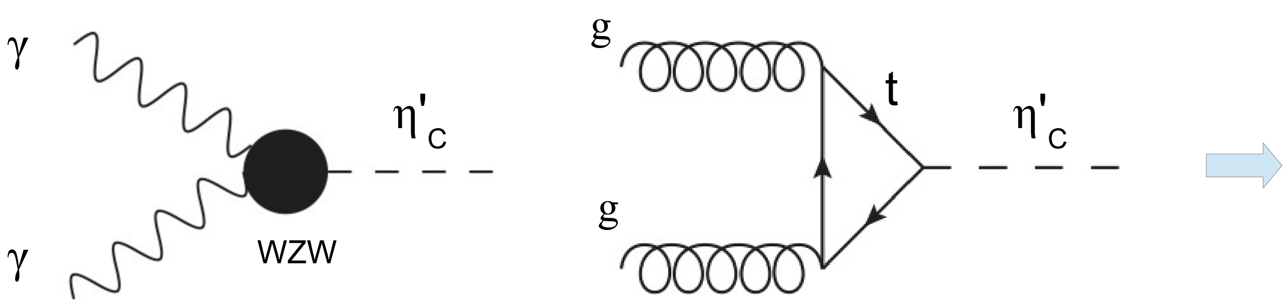
New composite scalars

- Extra pNGBs (from larger cosets. ex. SU(4)/Sp(4))

[ex. Bellazzini et al JHEP 1604 (2016) 072]

- η'-like composite states

[ex. Molinaro, Sannino, NV Nucl.Phys. B911 (2016) 106-126, Mod.Phys.Lett. A31 (2016) no.26, 1650155]



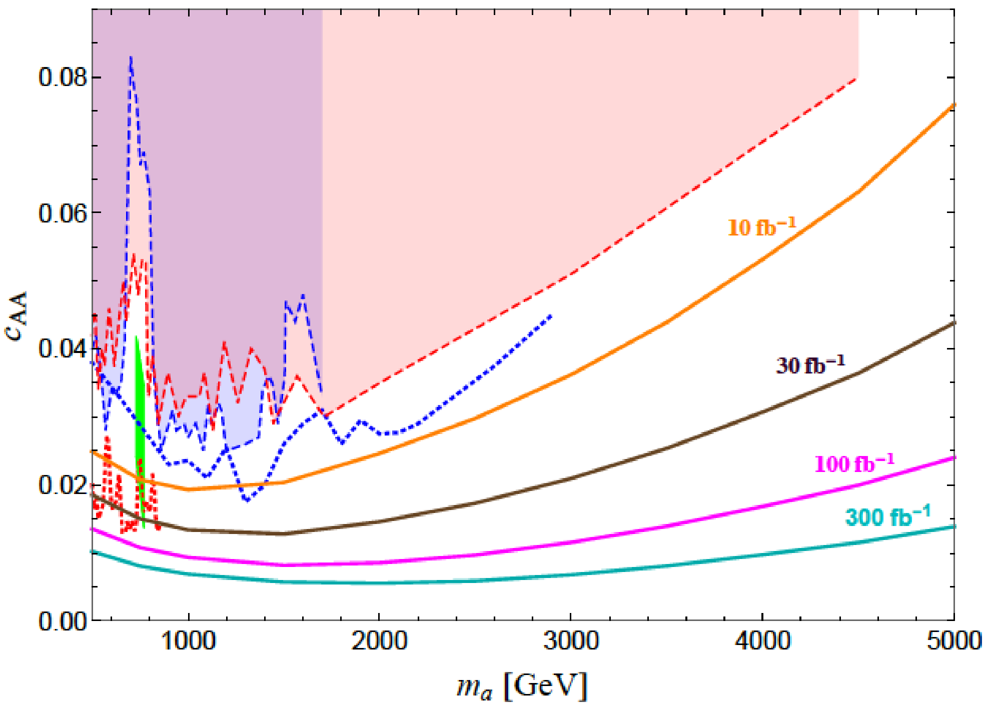
Dibosons (γγ) ,
tt, ..

Diphoton channel

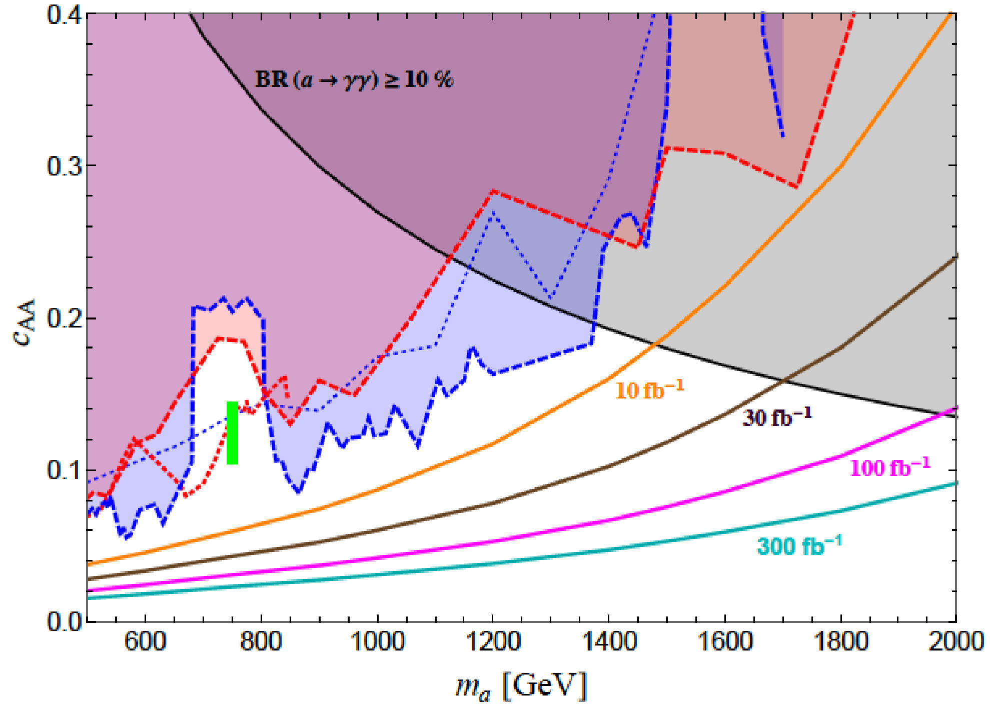
Molinaro, Sannino, NV,
Nucl.Phys. B911 (2016) 106-126

LHC-13

Photon fusion



Top-mediated Gluon fusion

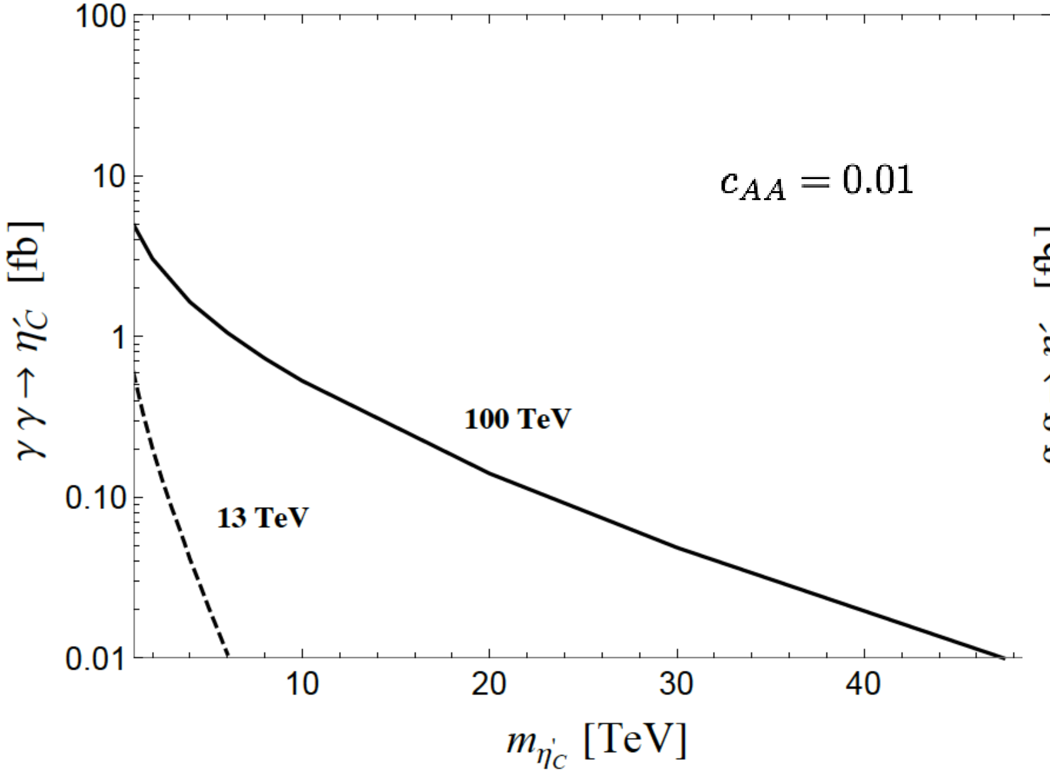


$$\mathcal{L}_{\rm eff} \supset -\frac{c_{AA}}{8v} a\, A^{\mu\nu} \tilde{A}_{\mu\nu}$$

$$\mathcal{L}_{\rm eff} \supset -i y_t \frac{m_t}{v} a\, \bar{t}\gamma_5 t - \frac{c_{AA}}{8v} a\, A^{\mu\nu} \tilde{A}_{\mu\nu}$$

New composite scalars

Photon fusion



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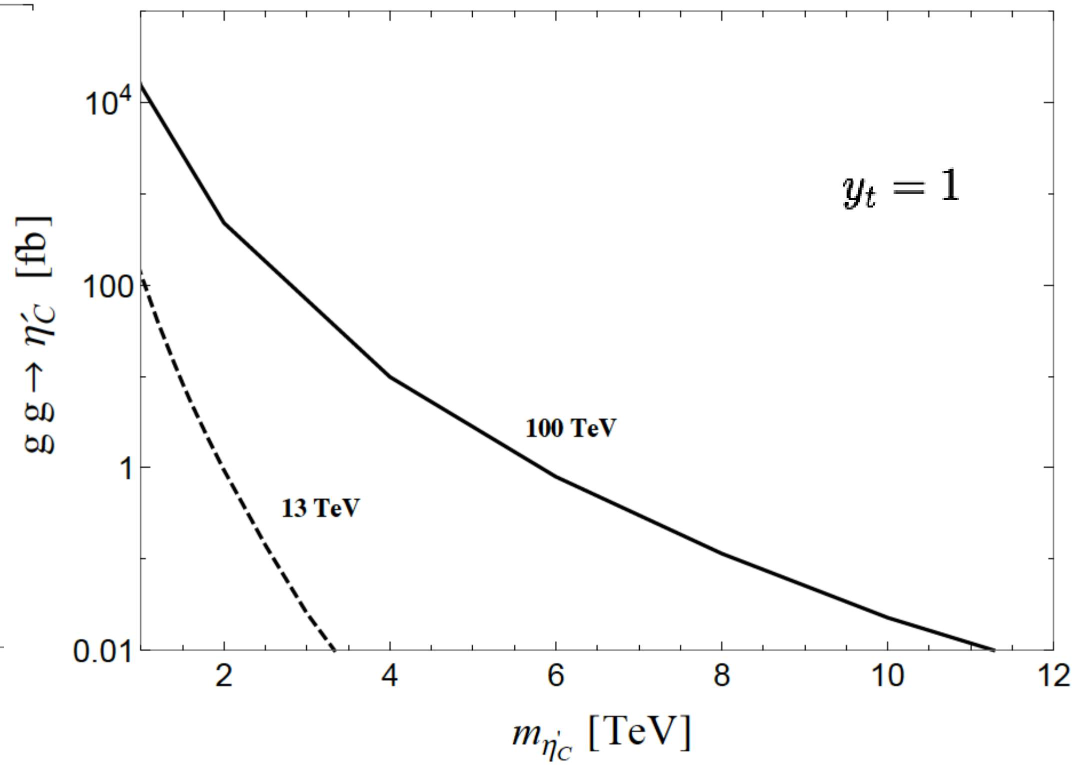
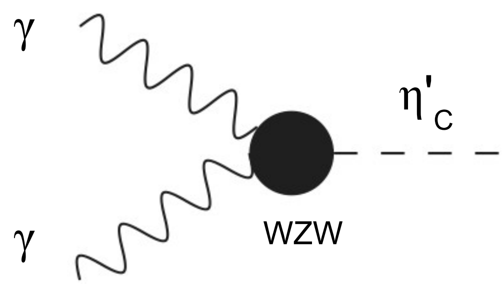


NNPDF2.3QED

(large uncertainty: >50% for masses above 1 TeV)

Testing BSM Strong Dynamics (topological sector) at FCC

Work in progress with E. Molinaro, F. Sannino and A. E. Thomsen



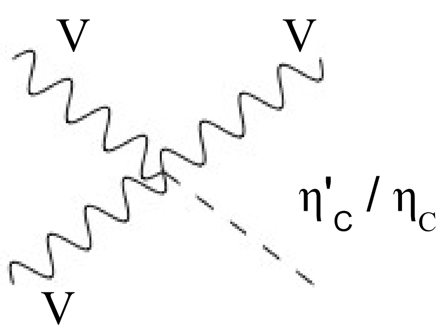
Interactions from
WESS-ZUMINO-WITTEN term

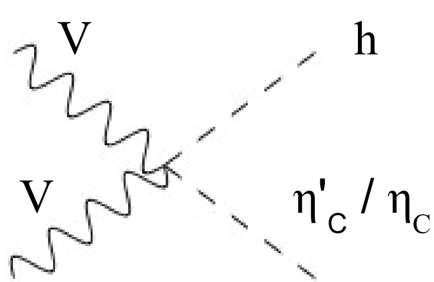
$$SU(4)/Sp(4) \qquad v = 2\sqrt{2} f \sin\theta$$

$$c_{AA} = \frac{\alpha}{2\pi} d(R) \sin\theta$$

Technifermions in pseudo-real representation R of the gauge group

New interactions





$$\mathcal{L}^{WZW} \supset d(R) \frac{\alpha}{\pi v^2} (\sin\theta)^3 \, h \, \partial_\mu \eta'_C \tilde{V}^{\mu\nu} V_\nu$$

FCC-hh:

$$m_{\eta_C} \sim m_{\eta'_C} \sim 1\,\mathrm{TeV}$$

$$d(R) = 10 \qquad \sin\theta = 0.25$$

$$\sigma_{VV \to h\eta_C} \sim \sigma_{VV \to h\eta'_C} \sim 0.1\,\mathrm{fb}$$

Conclusions

- 100 TeV collider can extend the reach for composite resonances in the multi-TeV region

  and can probe up to small couplings of the resonances

- New topologies may become relevant (ex VBF for W',Z')

- FCC can test the topological sector of the BSM strong dynamics

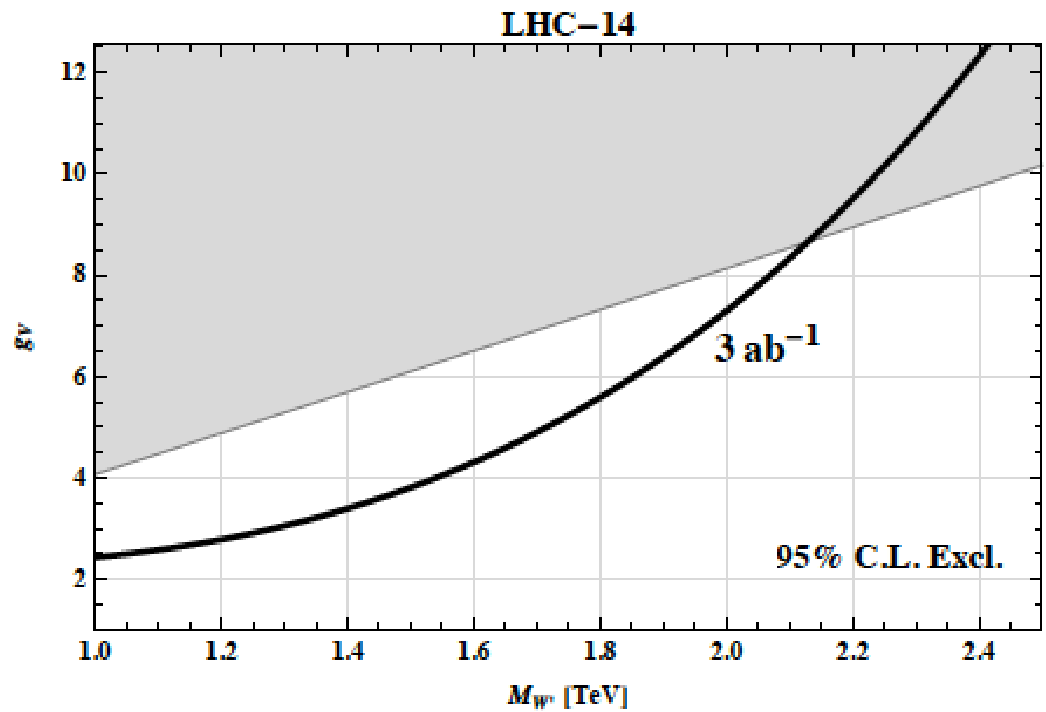
Extra slides

100 TeV	FJ, BJ tag		$\lvert\Delta\eta_{FJ,BJ}\rvert > 8$	
	$\lvert\eta_j\rvert < 5$	$\lvert\eta_j\rvert < 6$	$\lvert\eta_j\rvert < 5$	$\lvert\eta_j\rvert < 6$
($M_{W'}$ (TeV), g_V)				
(2, 4)	1.7	2.5	0.95	1.7
(3, 4)	0.33	0.48	0.21	0.35
(4, 4)	0.077	0.11	0.053	0.088
(4, 8)	0.24	0.36	0.17	0.29
(5, 8)	0.064	0.094	0.047	0.080
(6, 12)	0.030	0.044	0.023	0.036
WWbb	89	92	19	21
tb+jets	490	590	190	270
Wbb+jets	140	150	19	22
Tot. BCKG	720	830	230	310

Table 2: Signal and background cross sections, in fb, at a 100 TeV pp collider after the forward-backward jet tagging and the $\lvert\Delta\eta_{FJ,BJ}\rvert$ restriction (10). Results are shown for two different rapidity acceptances $\lvert\eta_j\rvert < 5, 6$.

100 TeV	signal		bckg	
	$\lvert\eta_j\rvert < 5$	$\lvert\eta_j\rvert < 6$	$\lvert\eta_j\rvert < 5$	$\lvert\eta_j\rvert < 6$
$(M_{W'}$ (TeV), $g_V)$				
(2, 4)	0.56	1.1	70	100
(3, 4)	0.13	0.25	31	45
(4, 4)	0.022	0.042	4.8	7.2
(4, 8)	0.082	0.15	4.8	7.2
(5, 8)	0.028	0.051	3.6	4.9
(6, 12)	0.013	0.022	1.4	1.8

Table 5: Signal and background cross sections, in fb, at a 100 TeV pp collider after the complete selection.


LHC−14
12
10
8
6
4
2
g_V
3 ab^{-1}
95% C.L. Excl.
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
$M_{W'}$ [TeV]