New Physics at the LHC, Bonn, 25 November 2015

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Composite heavy vector triplets in the ATLAS di-boson excess and at future colliders

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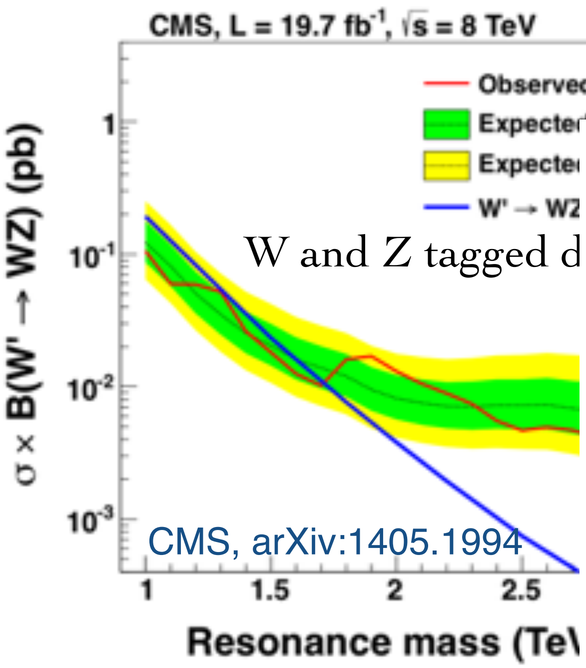
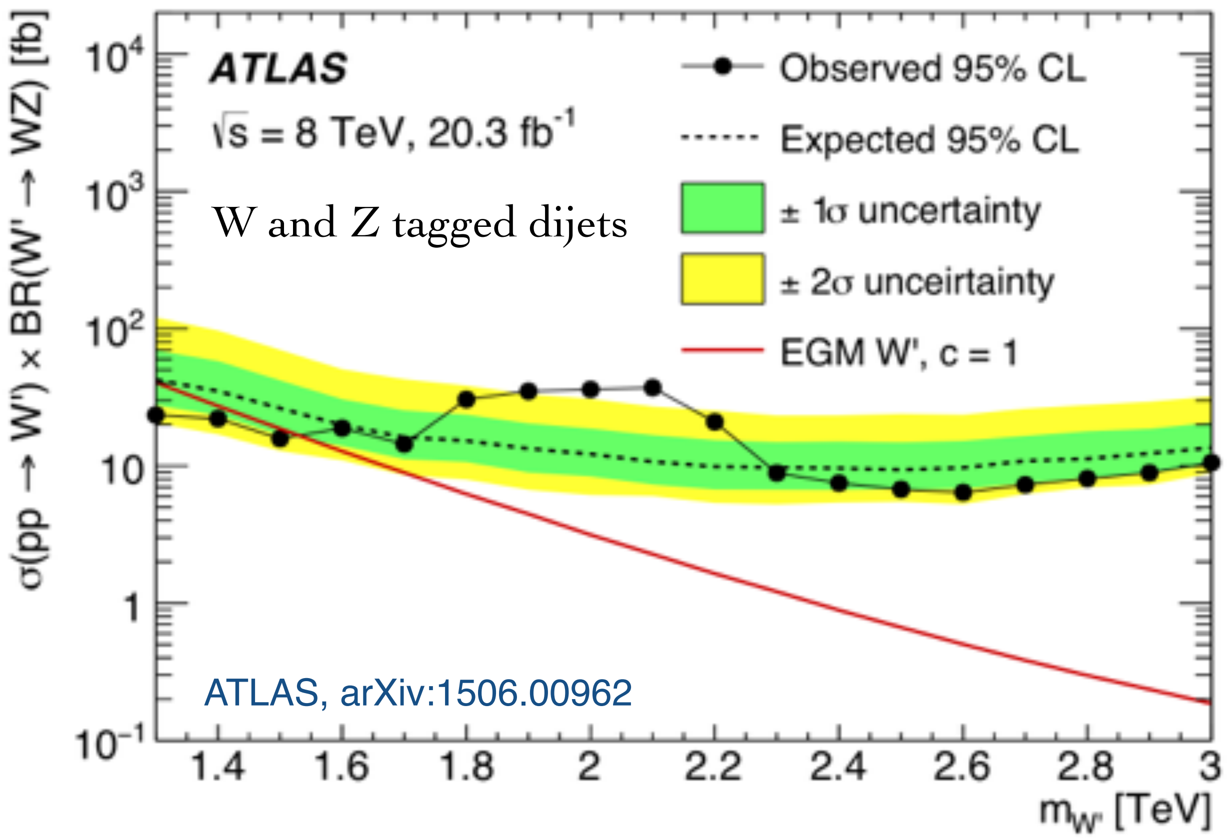
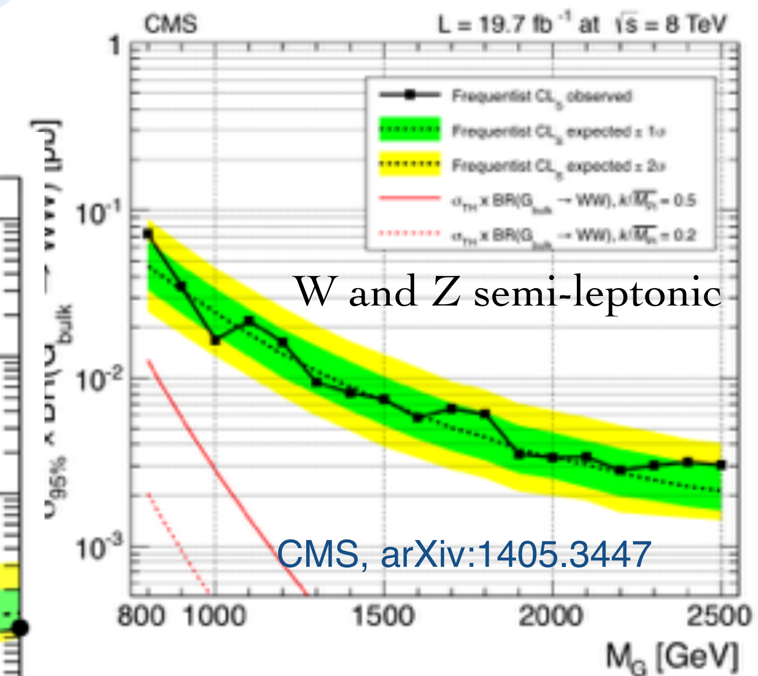
JGU Mainz

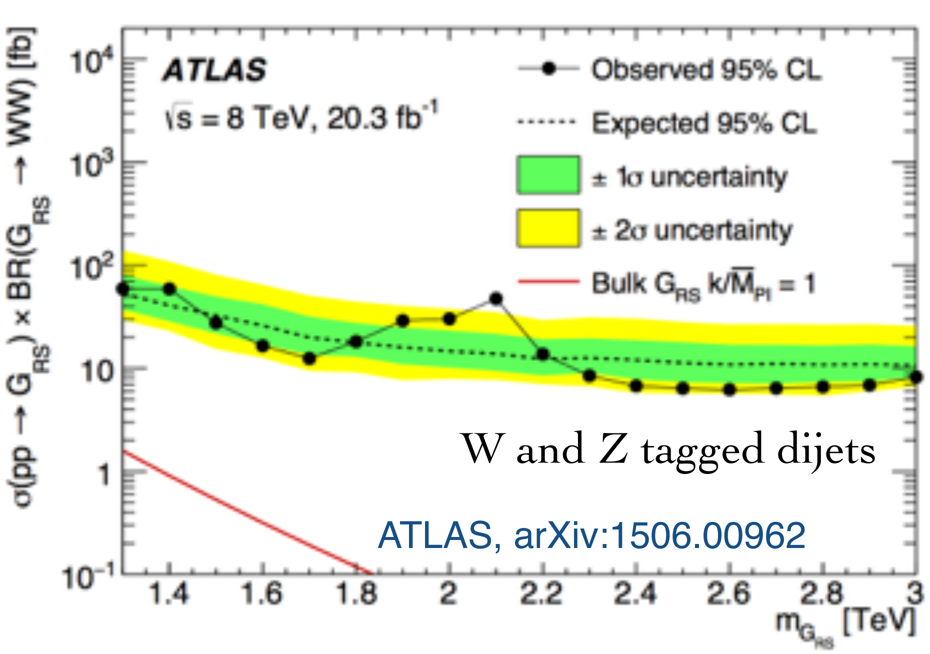
in collaboration with R. Torre and A. Wulzer
based on arXiv: 1506.08688 and 1502.01701

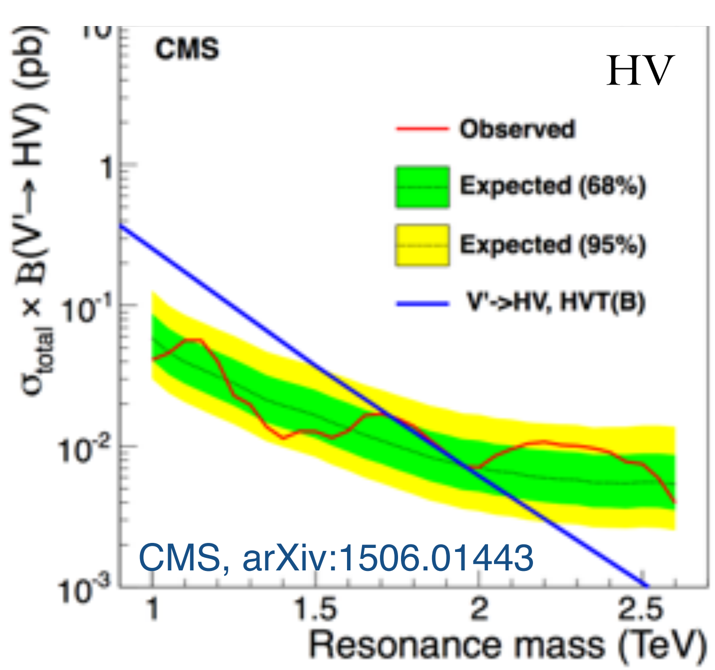
Di-boson excess?

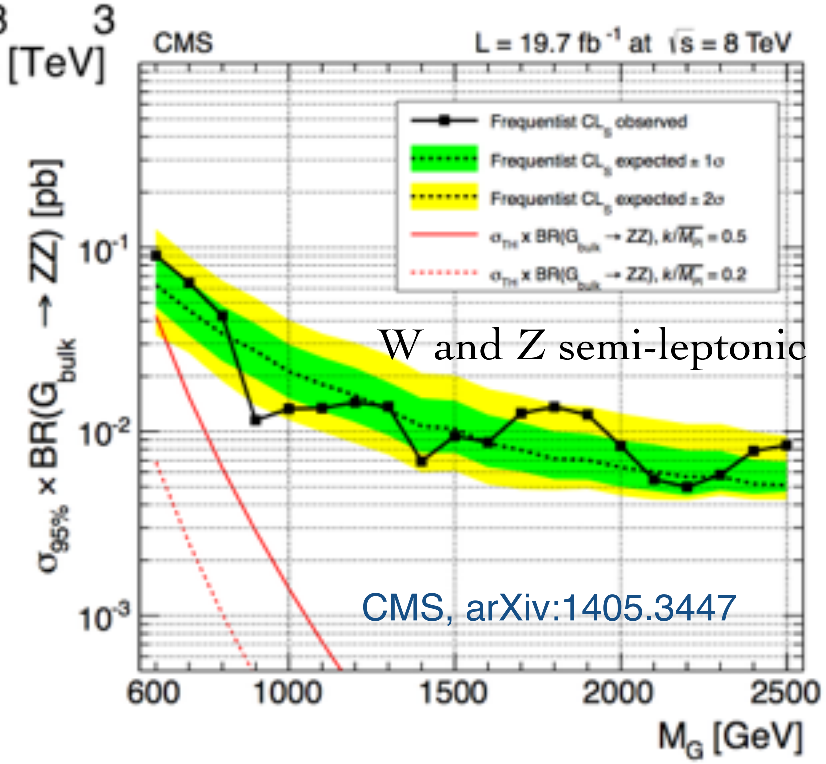




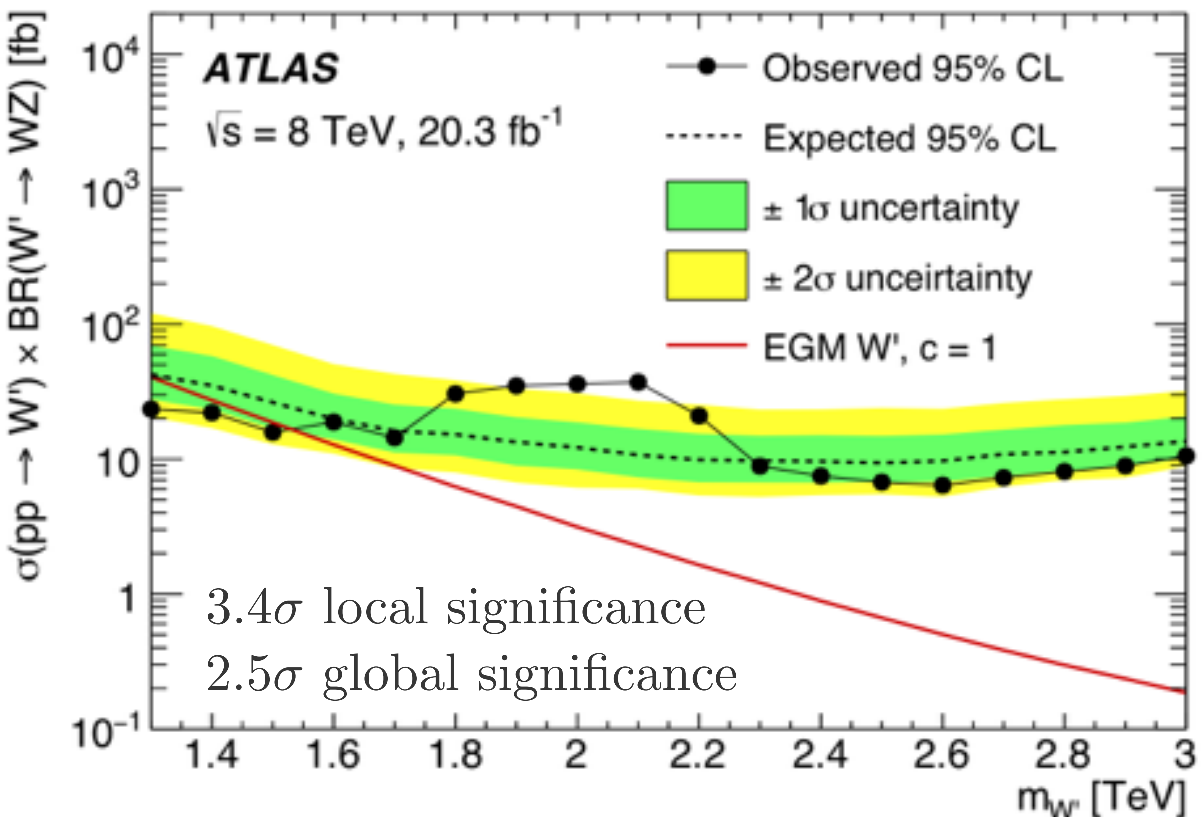


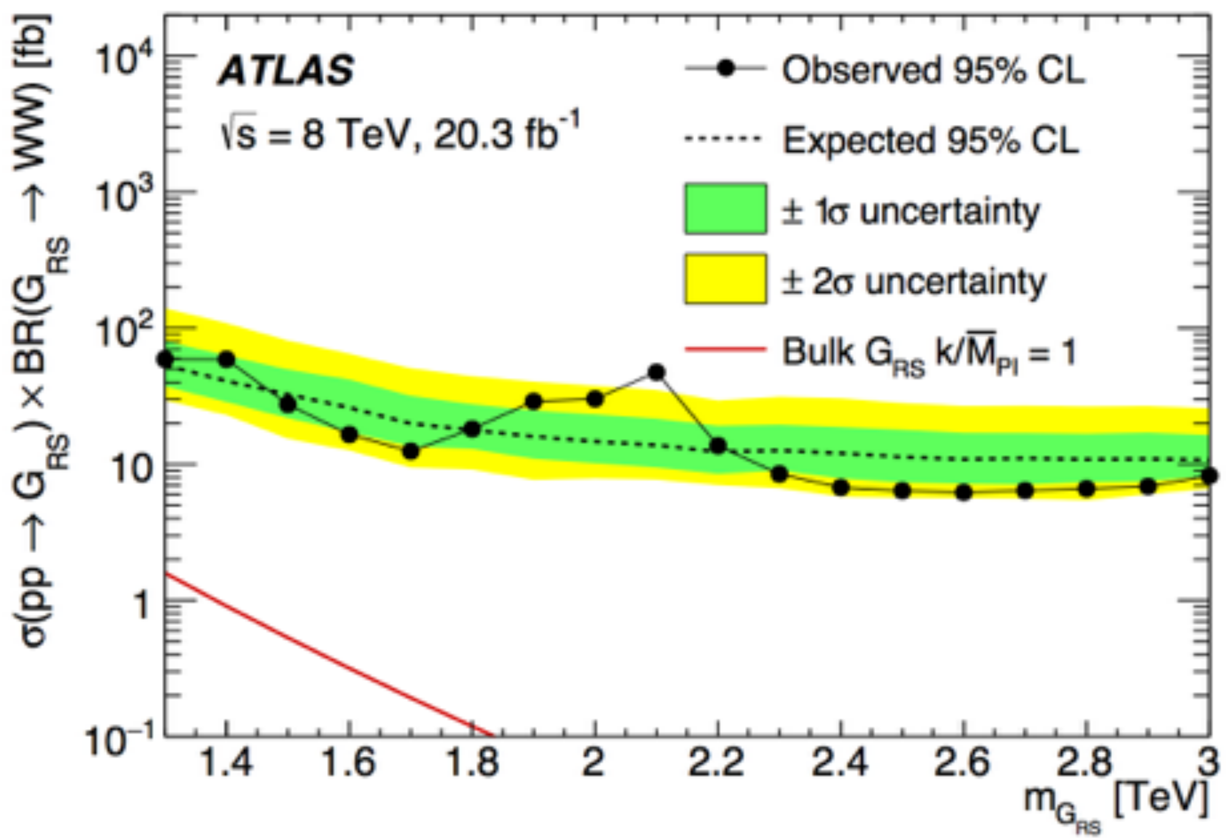


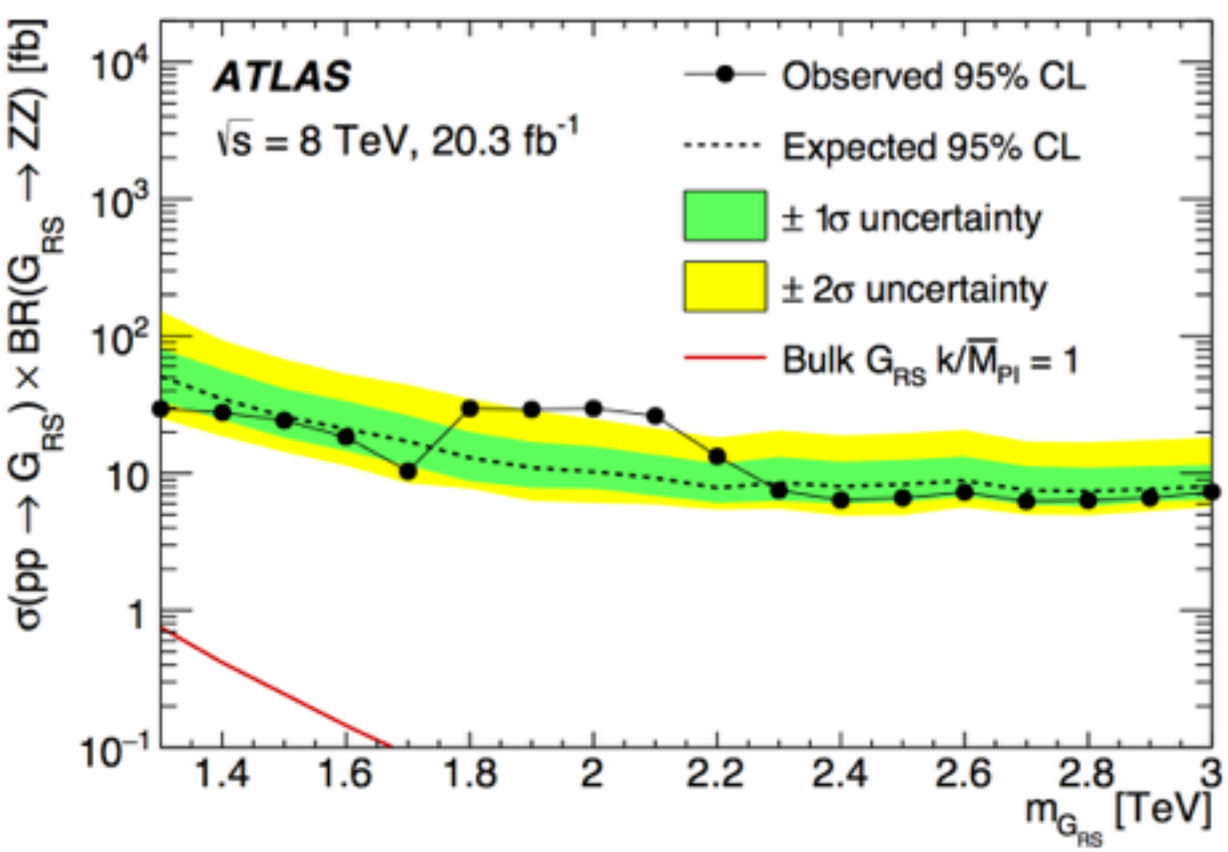




Di-boson excess?

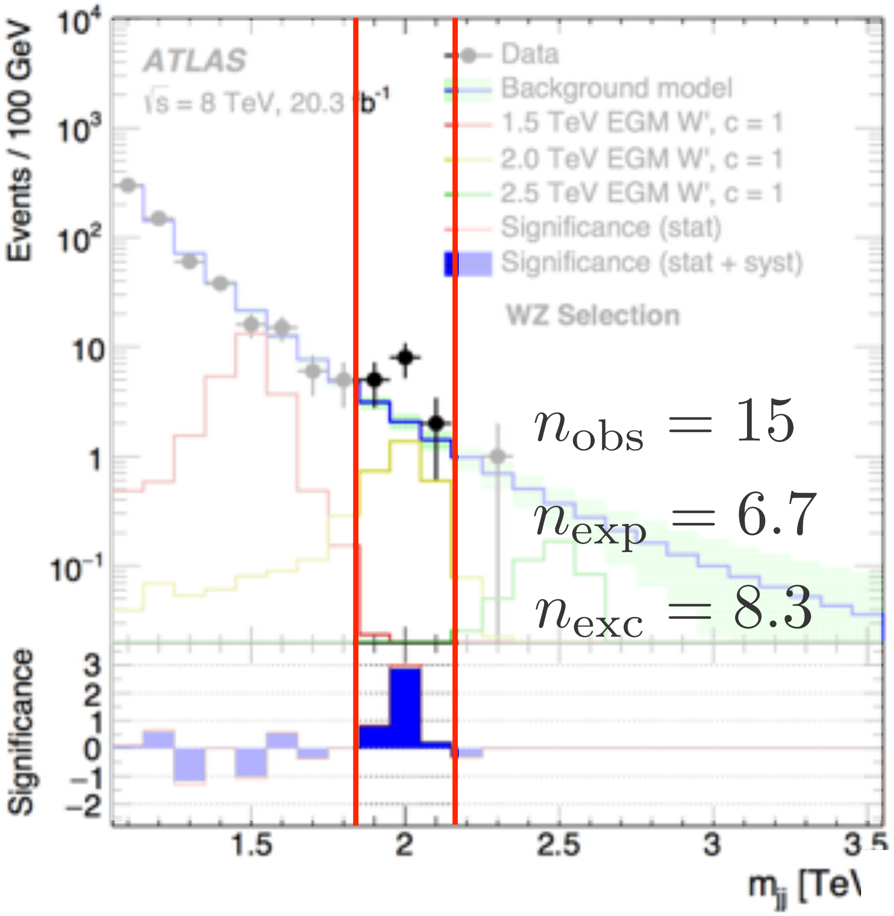


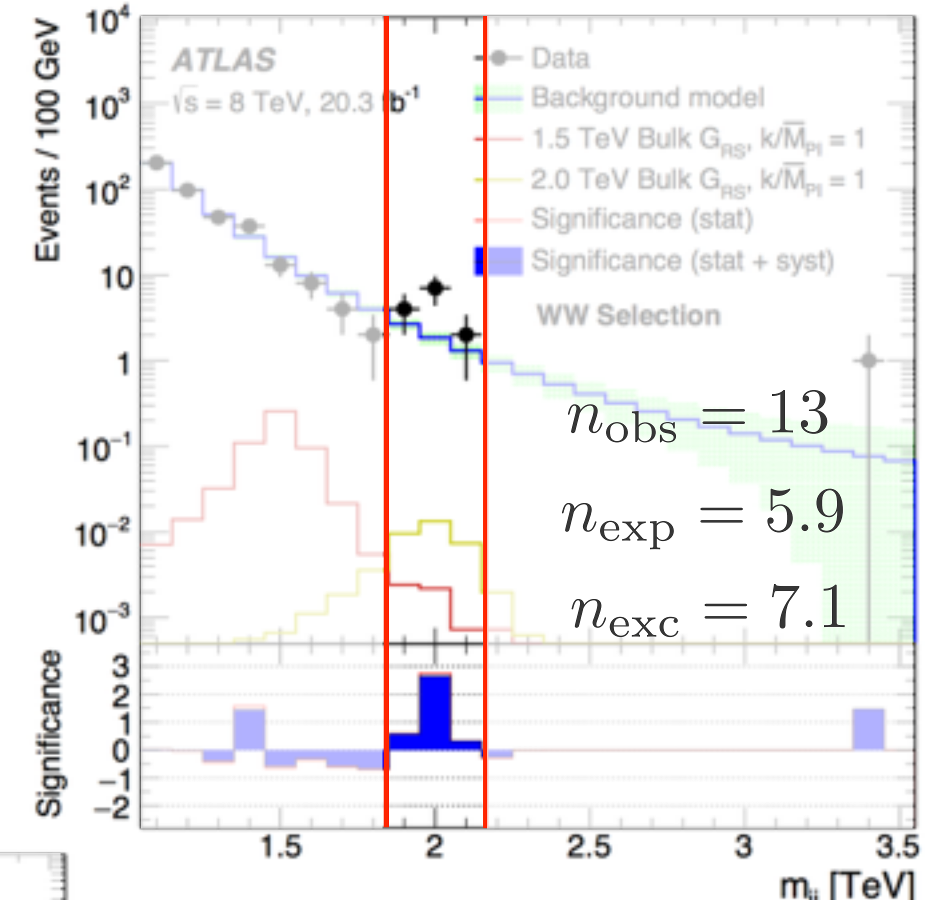


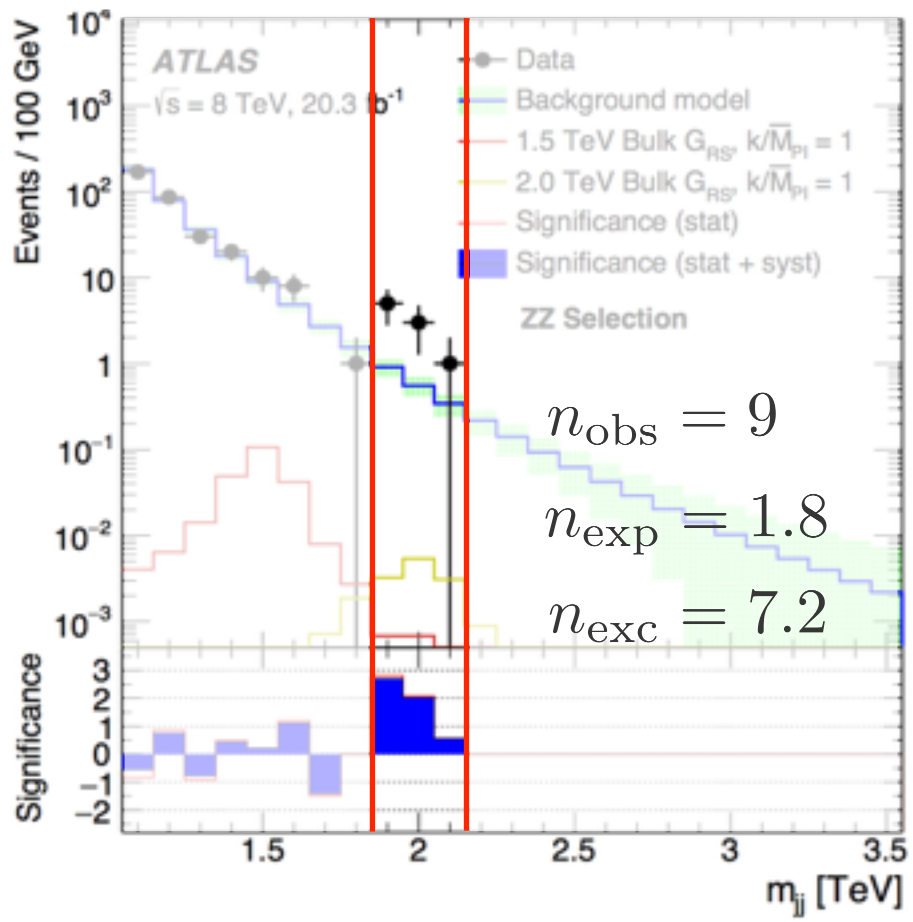


[ATLAS, arXiv:1506.00962]

Excess events



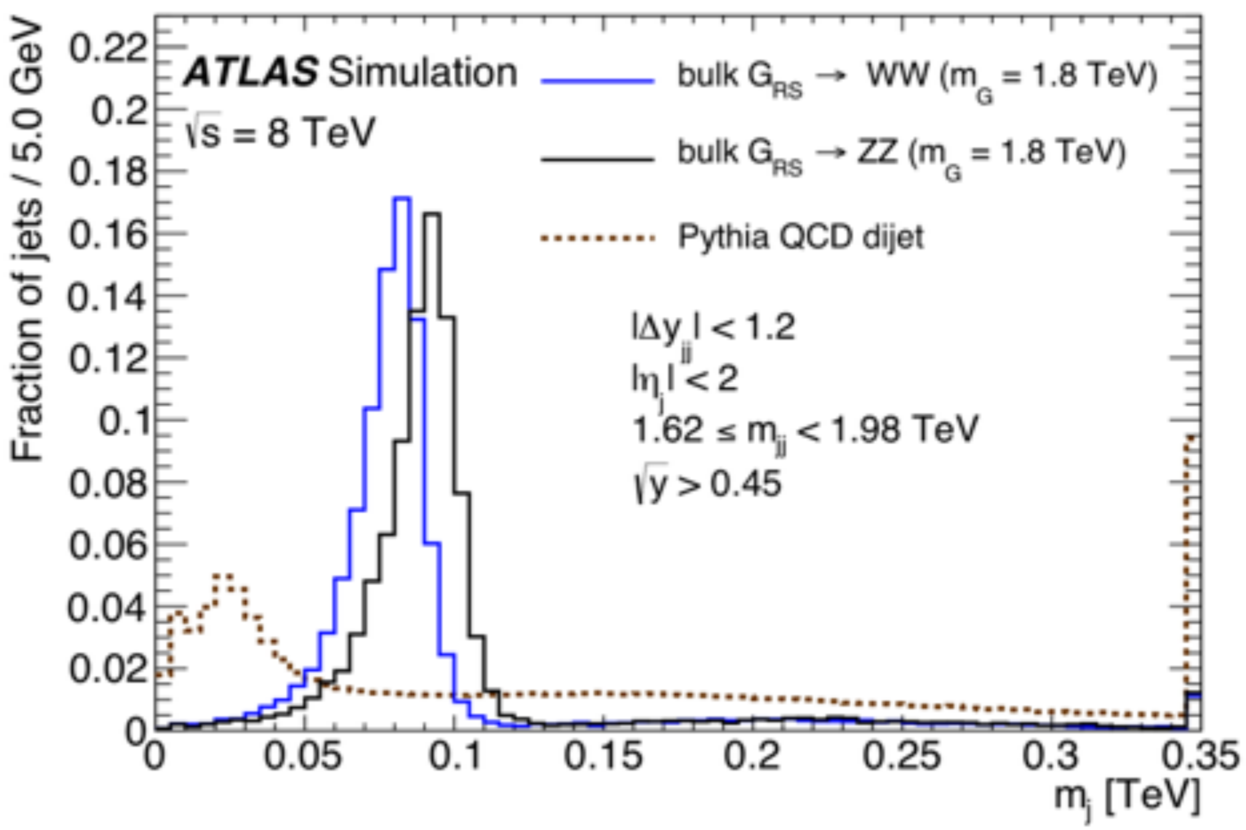




[ATLAS, arXiv:1506.00962]

Excess events

- W-fat jet: 69.4 GeV < m < 95.4 GeV
- Z-fat jet: 79.8 GeV < m < 105.8 GeV

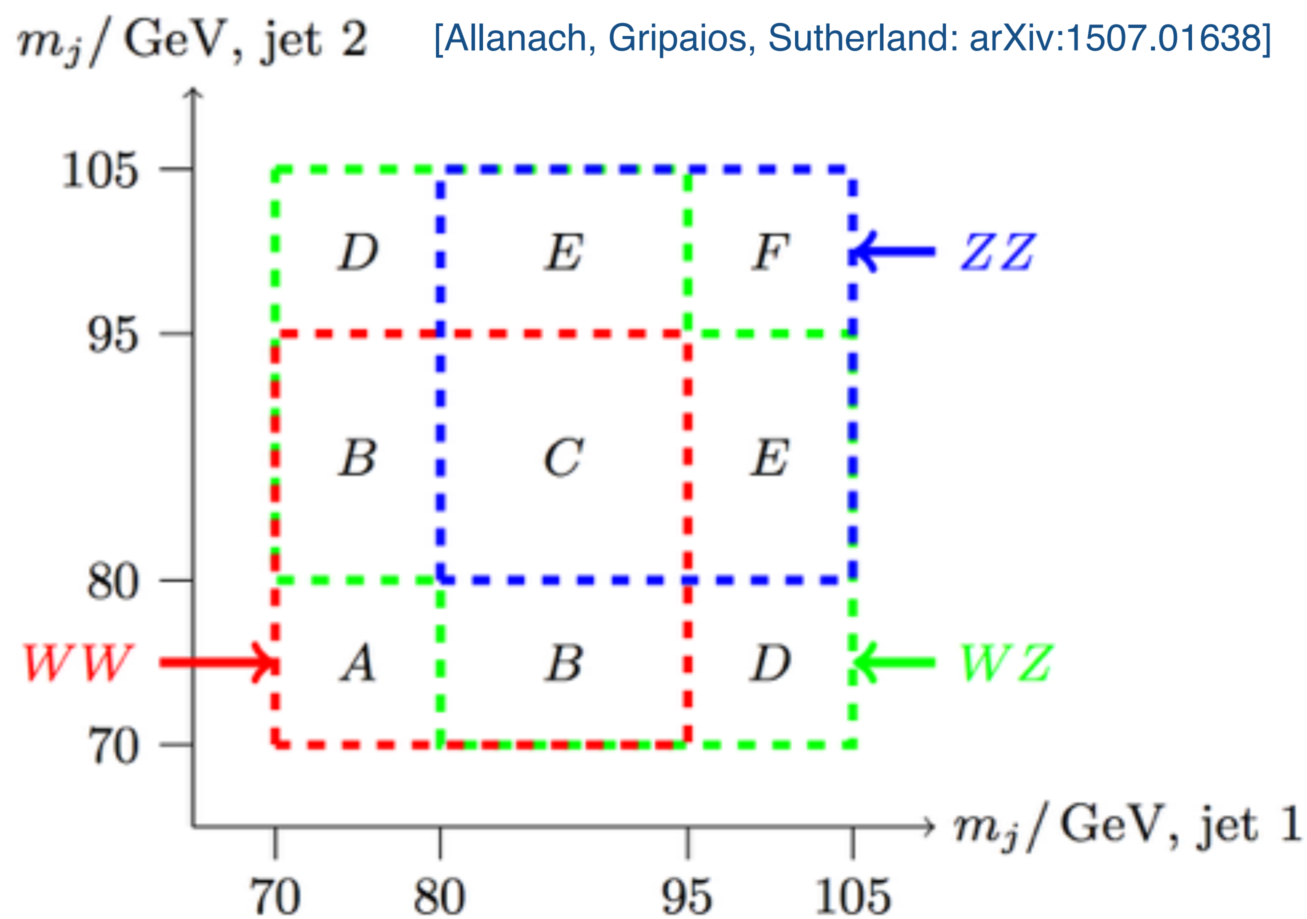


[ATLAS, arXiv:1506.00962]

- understand observed events and selection overlap
- need tagging efficiencies for a W and Z

Excess events

- overlap regions



- information from ATLAS

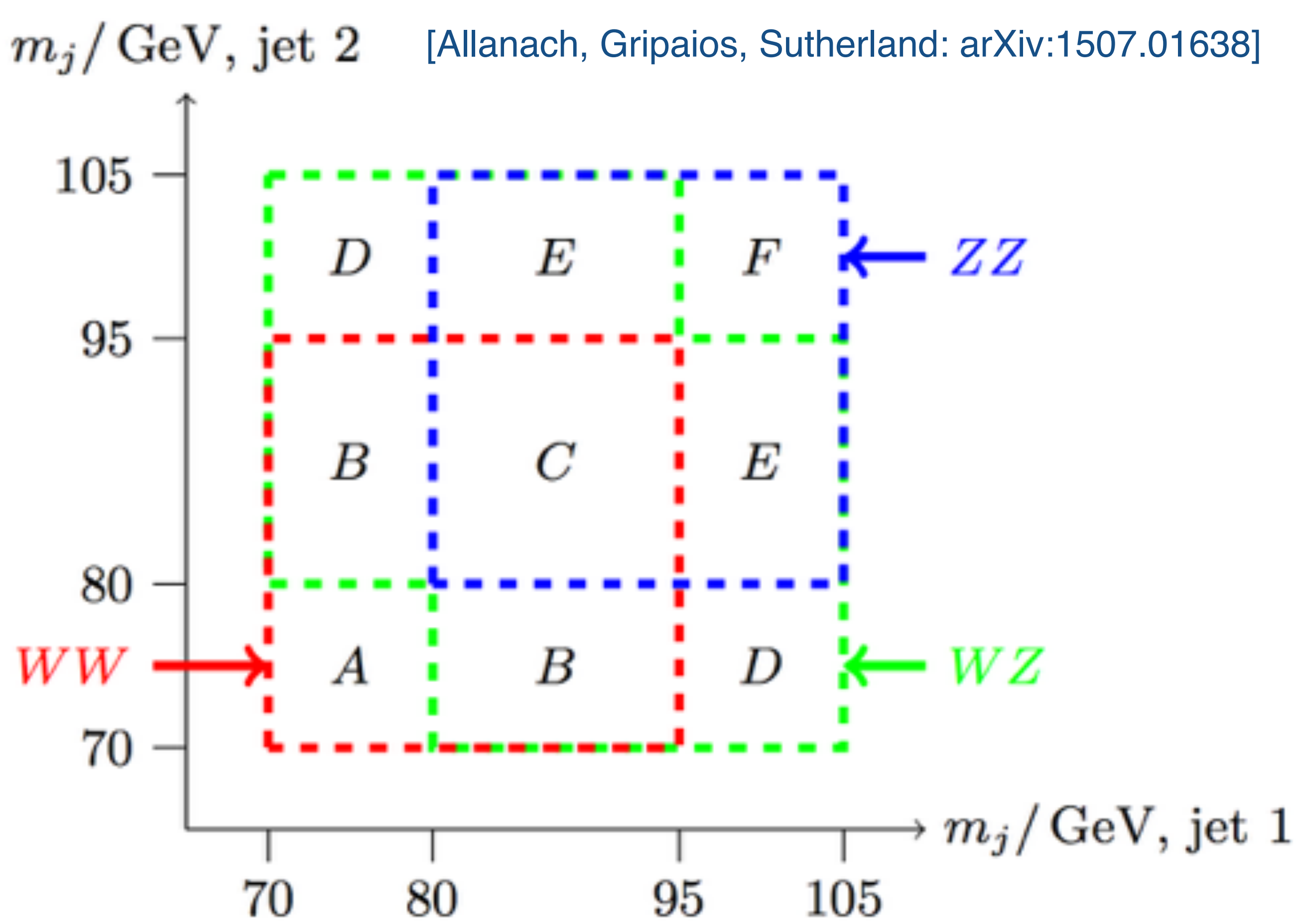
$$\begin{aligned} n_{WW} &= 13 \\ n_{ZZ} &= 9 \\ n_{WZ} &= 15 \\ n_{WW+ZZ} &= 17 \\ n_{WW+ZZ+WZ} &= 17 \end{aligned}$$

⇒

5 equations
6 unknowns

Excess events

- overlap regions



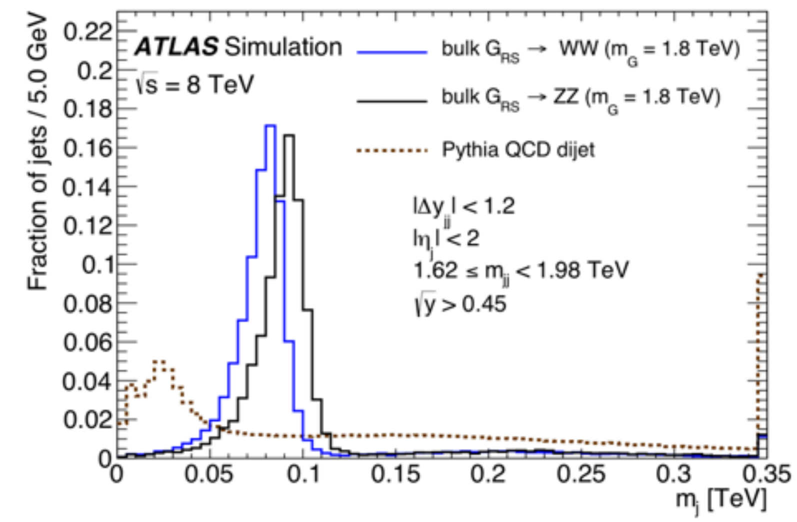
- 3 solutions:

A	B	C	D	E	F
2	6	5	0	4	0
1	7	5	0	3	1
0	8	5	0	2	2

Tagging efficiencies

- assign tagging efficiencies

	W jet tag only	W and Z jet tag	Z jet tag only
true W	0.25	0.36	0.04
true Z	0.11	0.39	0.21



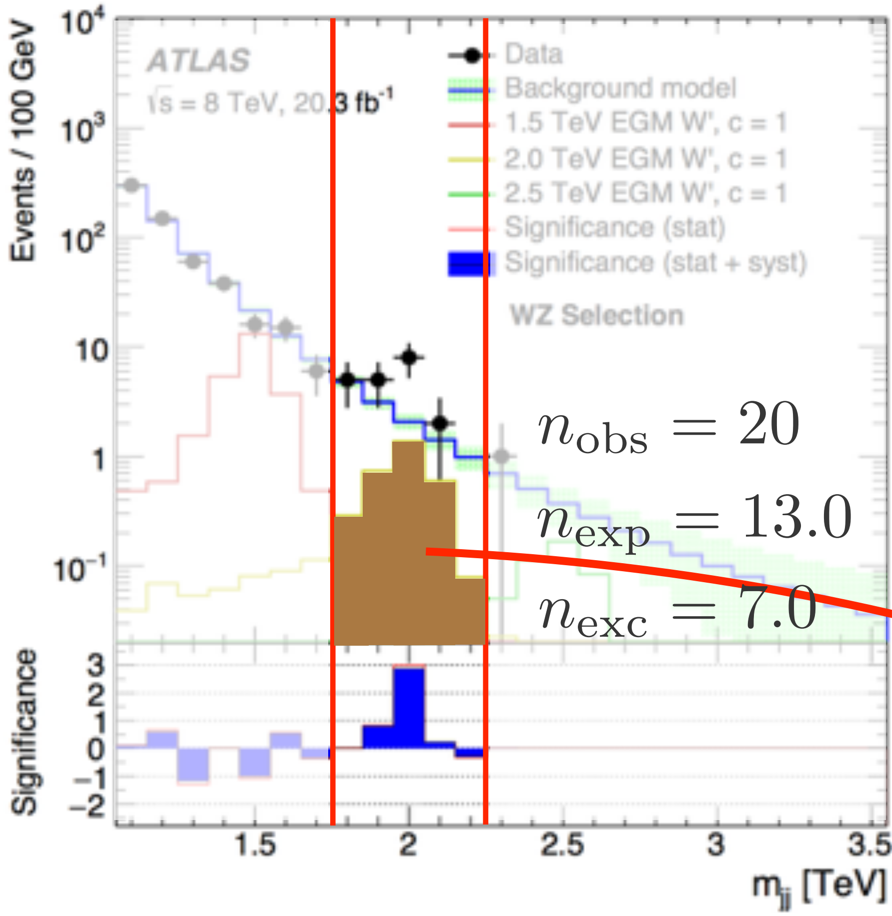
[ATLAS, arXiv:1506.00962]

- efficiency of jet invariant mass cuts

final state \ selection region	WW	WZ	ZZ
WW	0.39	0.37	0.16
WZ	0.33	0.44	0.25
ZZ	0.27	0.47	0.37

- extract signal CS from WZ channel and compare with the others

Signal cross section



$n_{\text{obs}} = 20$

$n_{\text{exp}} = 13.0$

$n_{\text{exc}} = 7.0$

$\text{BR}_{WZ\to\text{had}} \approx 0.47$

m [TeV]	$\Gamma_{W'}$ [GeV]	$\Gamma_{G_{\text{RS}}}$ [GeV]	$W' \to WZ$ $\sigma\times$BR [fb]	$f_{10\%}$	$G_{\text{RS}} \to WW$ $\sigma\times$BR [fb]	$f_{10\%}$	$G_{\text{RS}} \to ZZ$ $\sigma\times$BR [fb]	$f_{10\%}$
1.3	47	76	19.1	0.83	0.73	0.85	0.37	0.84
1.6	58	96	6.04	0.79	0.14	0.83	0.071	0.84
2.0	72	123	1.50	0.72	0.022	0.83	0.010	0.82
2.5	91	155	0.31	0.54	0.0025	0.78	0.0011	0.78
3.0	109	187	0.088	0.31	0.00034	0.72	0.00017	0.71

$$\frac{(\sigma\times\text{BR})_{\text{ATLAS}}}{\text{BR}_{WZ\to\text{had}}} = 3.17\ \text{fb}$$

3.1 events in 5 bins
2.7 events in 3 bins

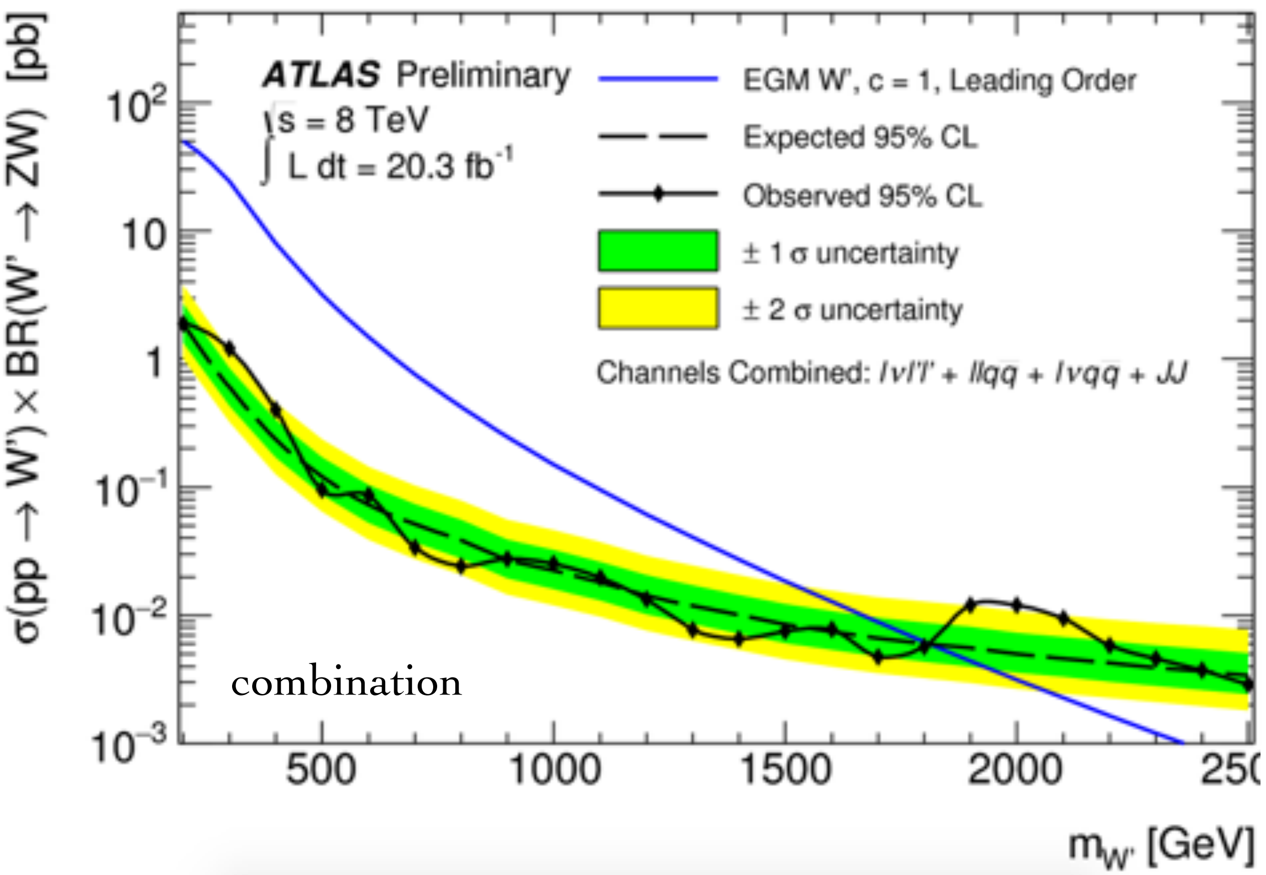
$$\sigma_{W'}\times\text{BR}_{W'\to WZ} = 7.1^{+3.9}_{-2.6}\ \text{fb}$$

$$S_{WZ} = 7.0^{+3.8}_{-2.6} \quad \text{(5 bins)}$$

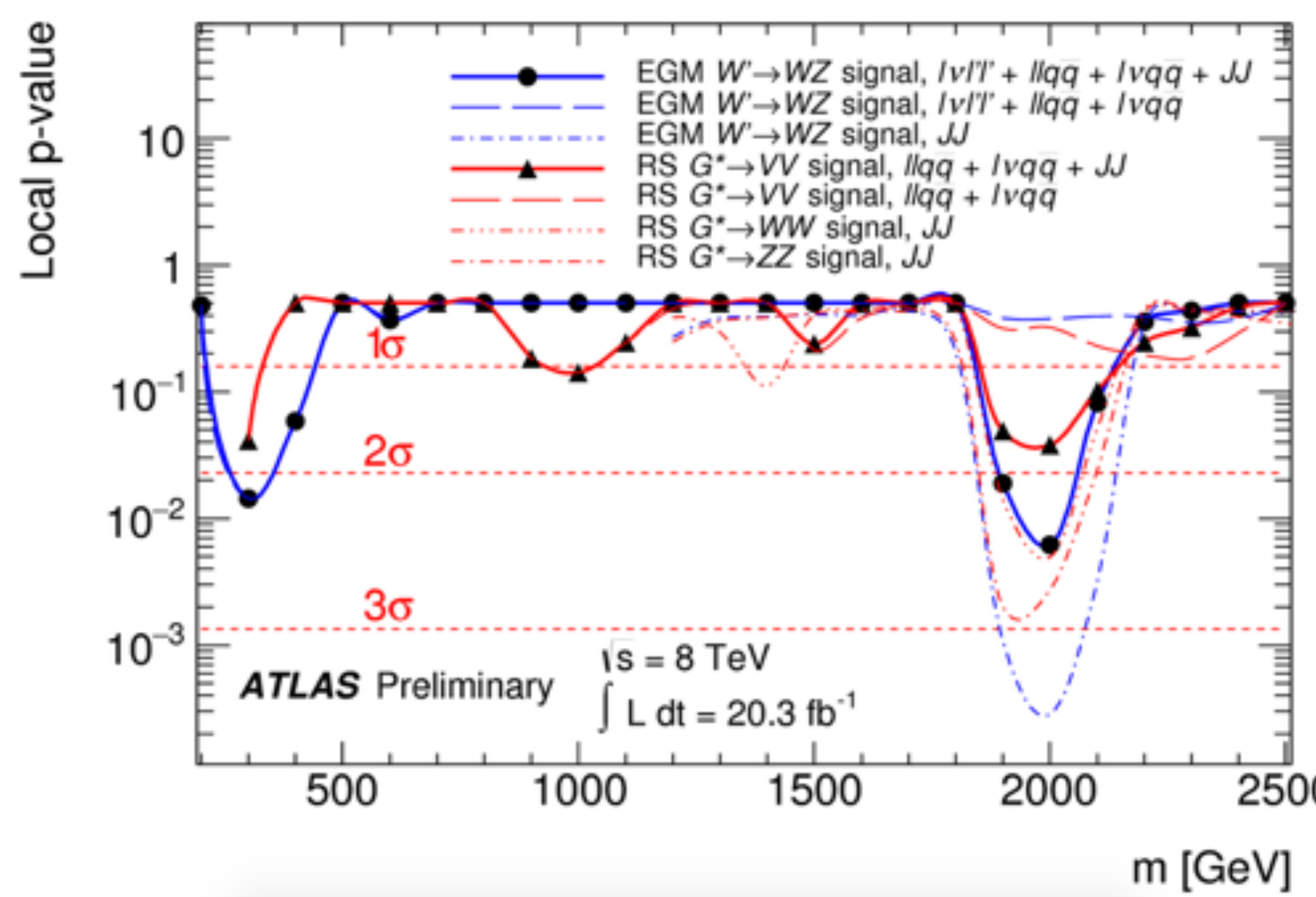
$$\sigma_{W'}\times\text{BR}_{W'\to WZ} = 9.7\ \text{fb}$$

$$S_{WZ} = 8.3 \quad \text{(3 bins)}$$

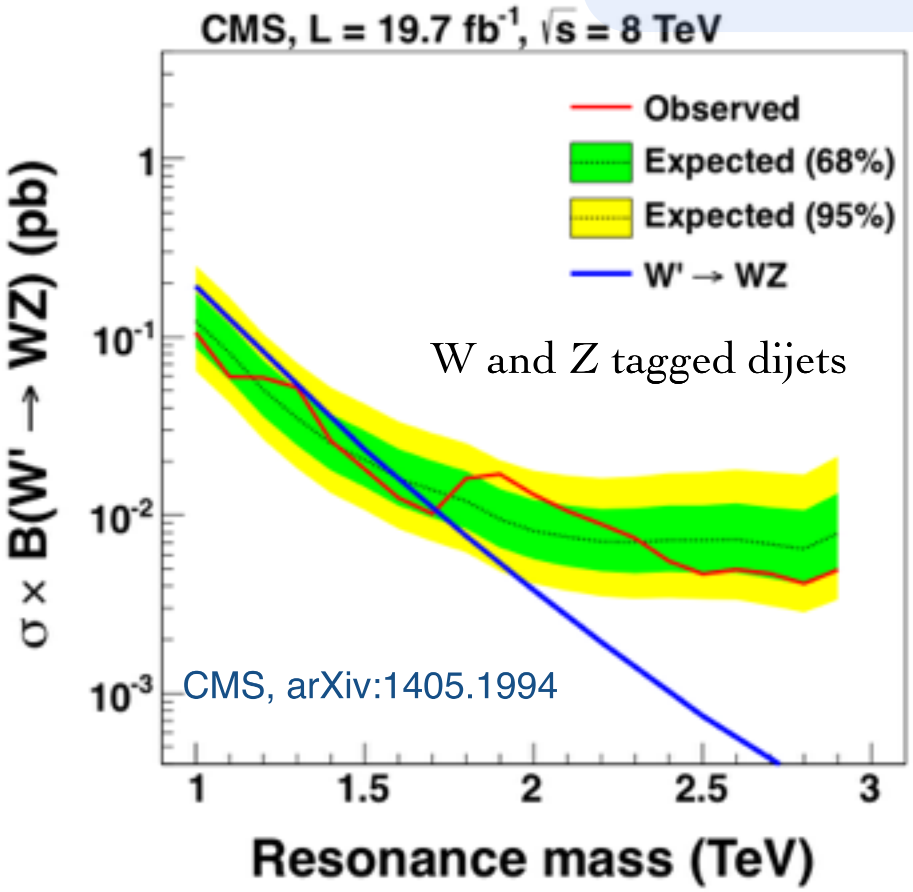
Other channels

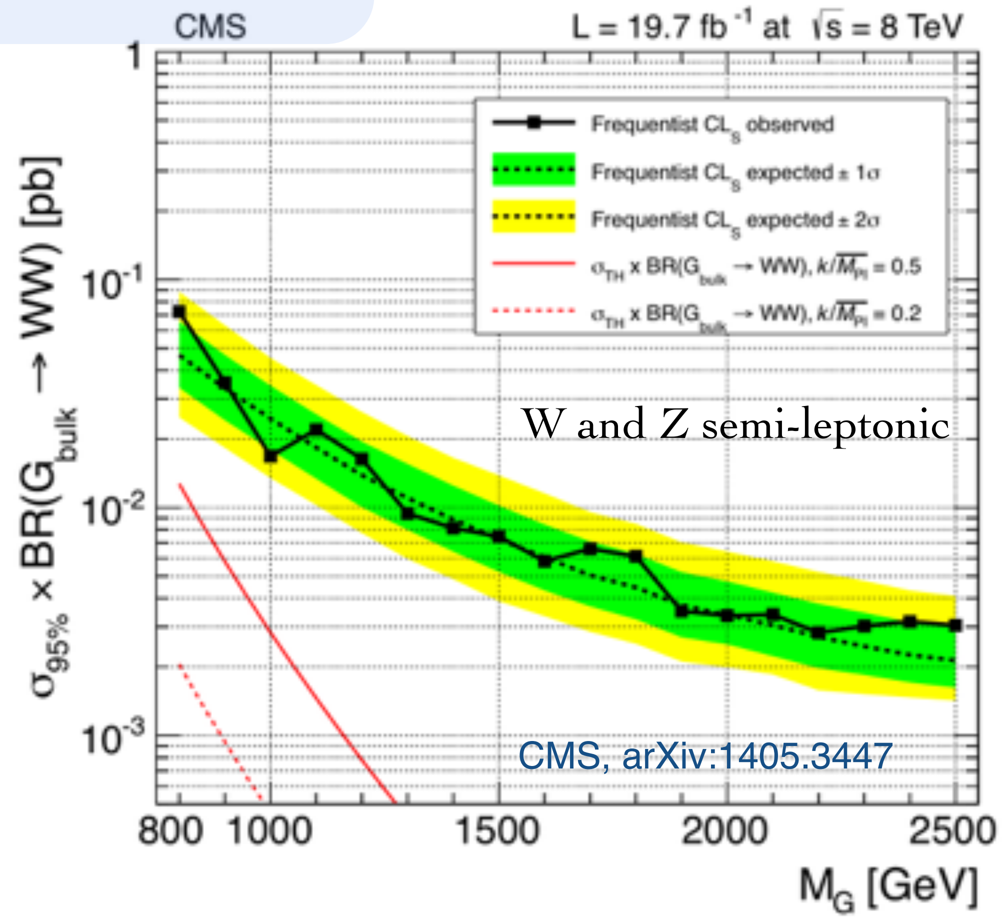


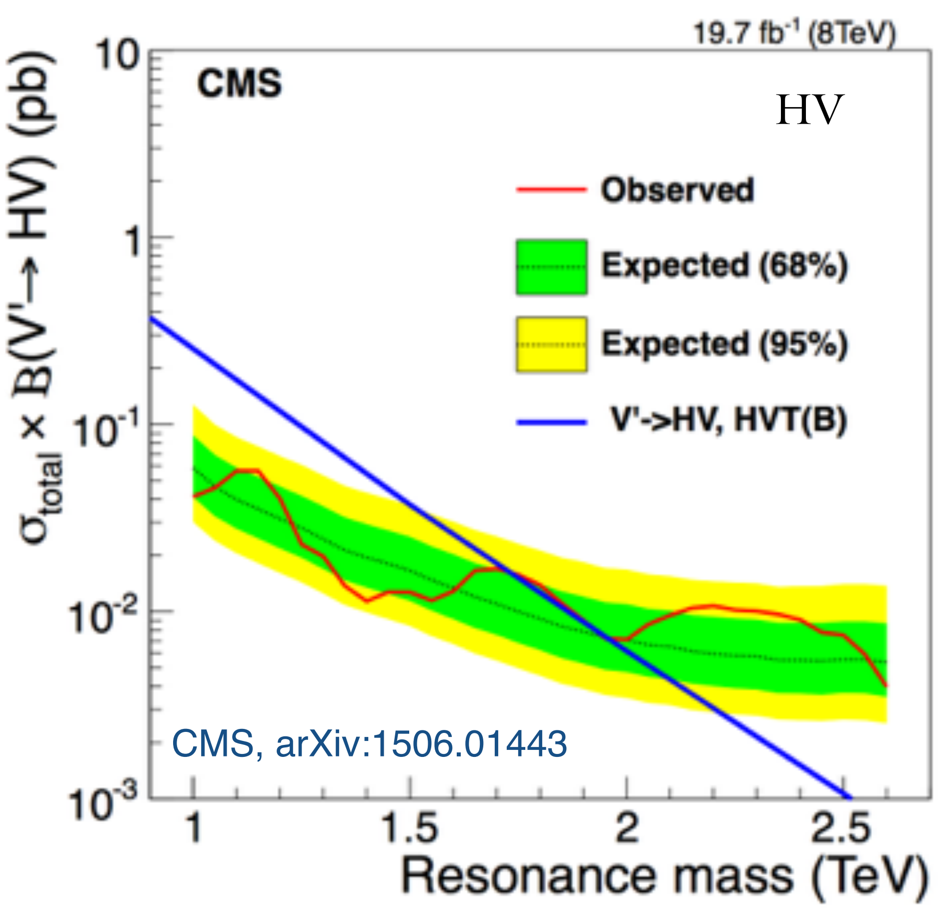
- combination of WZ channels
- hadronic channel driving the excess
- other channels very mild/no excess

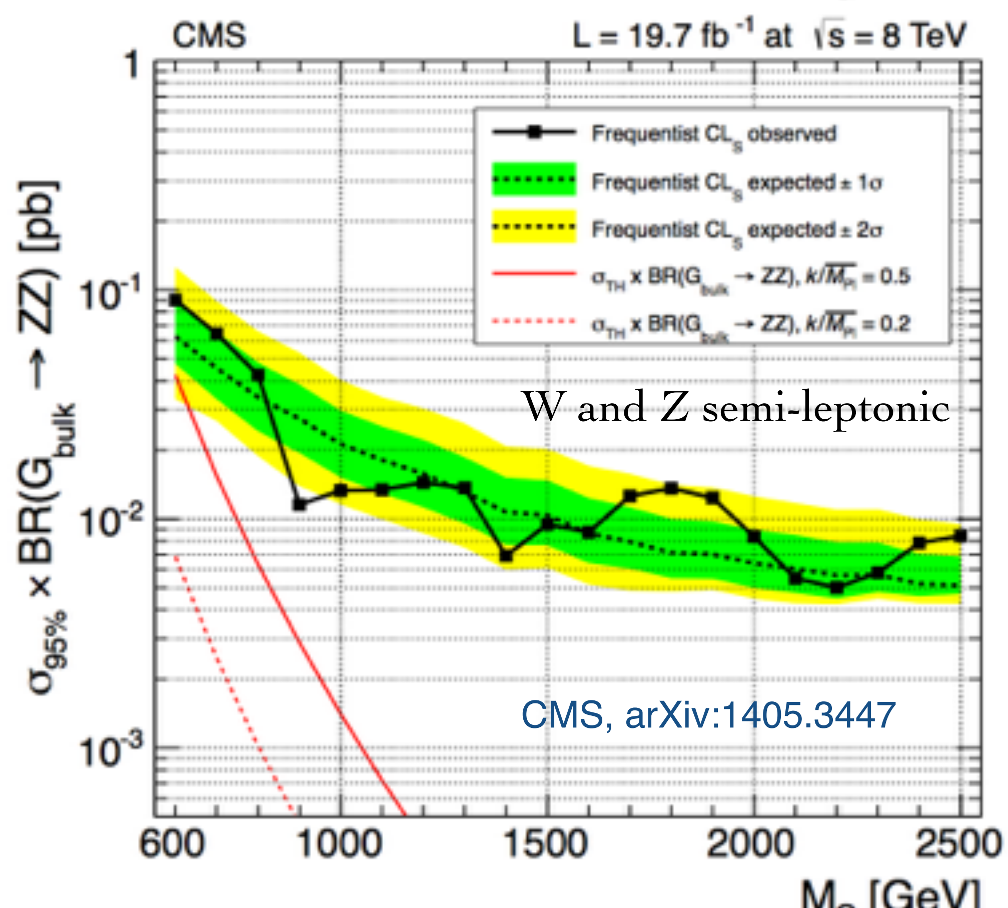


Bosonic channels at CMS

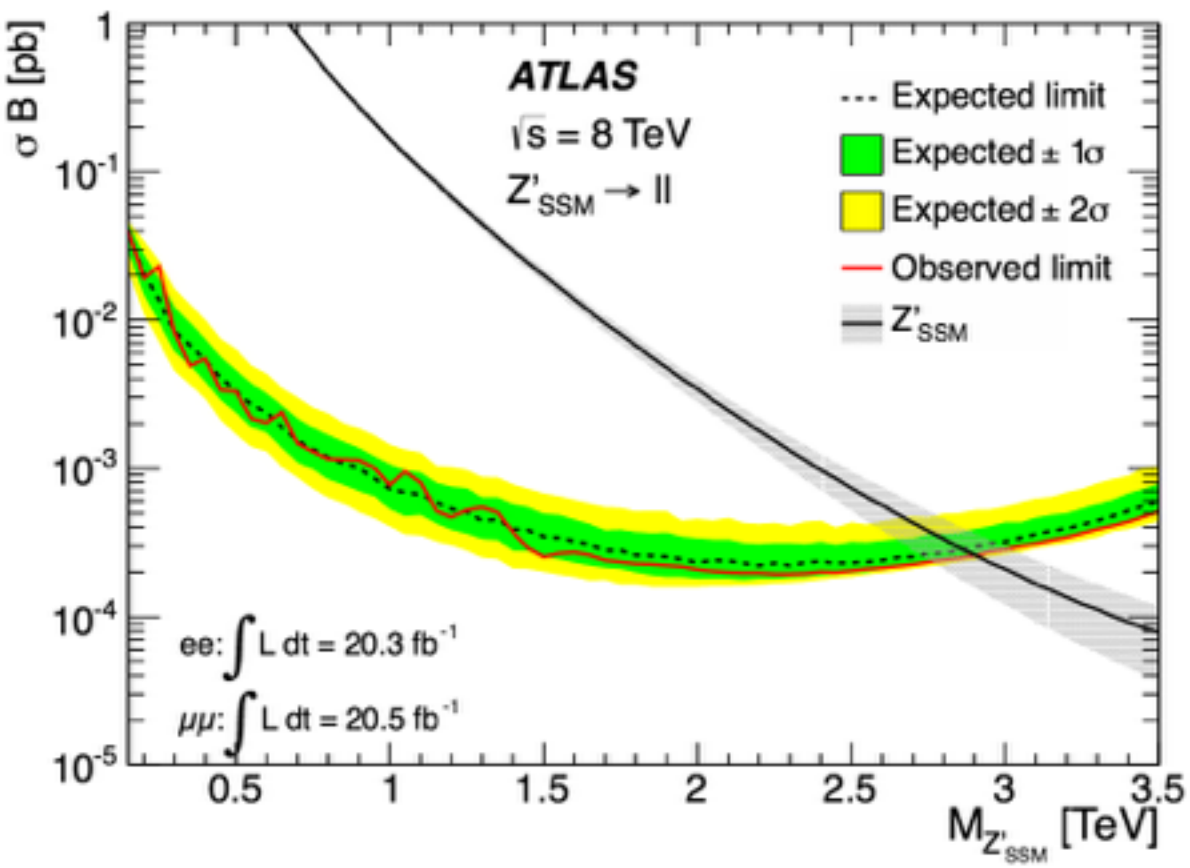


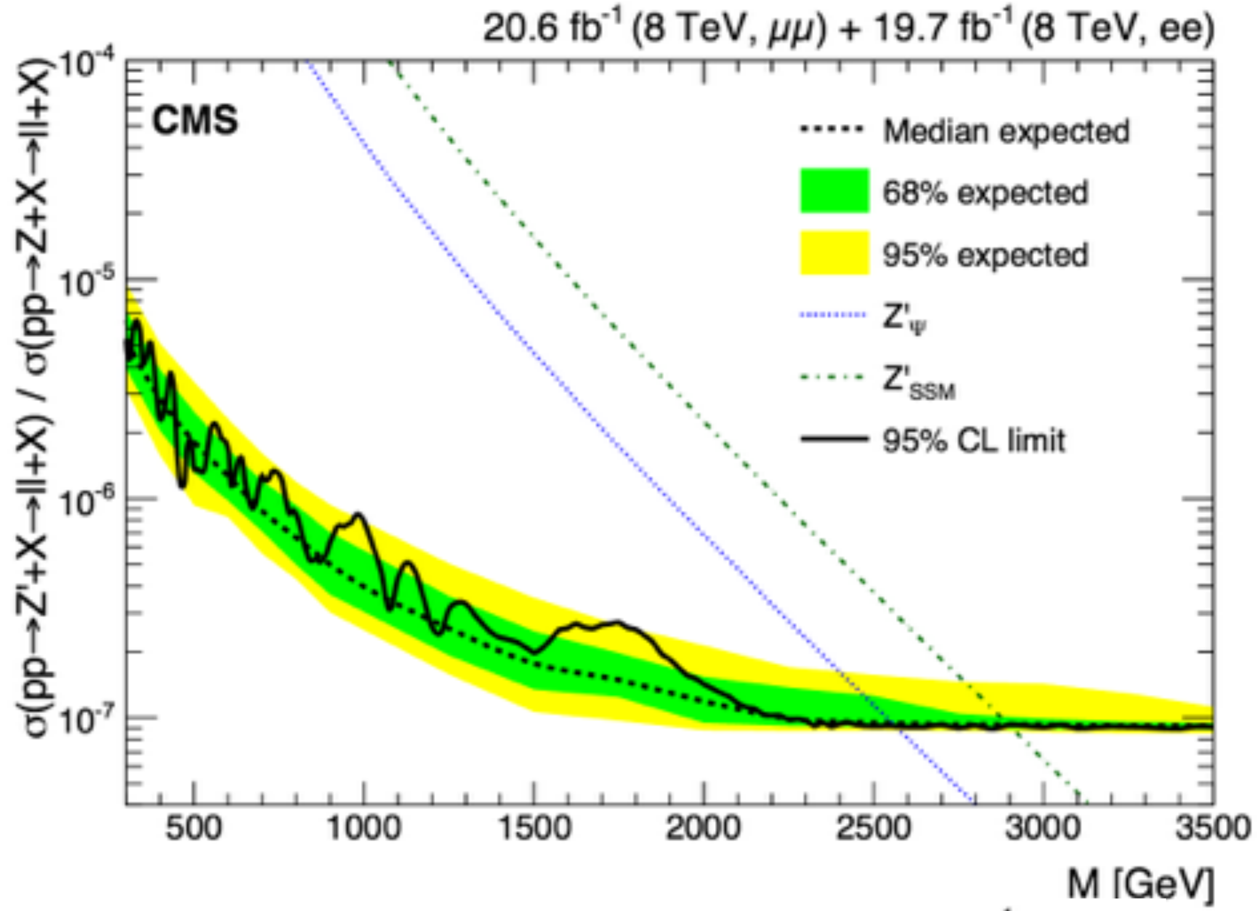


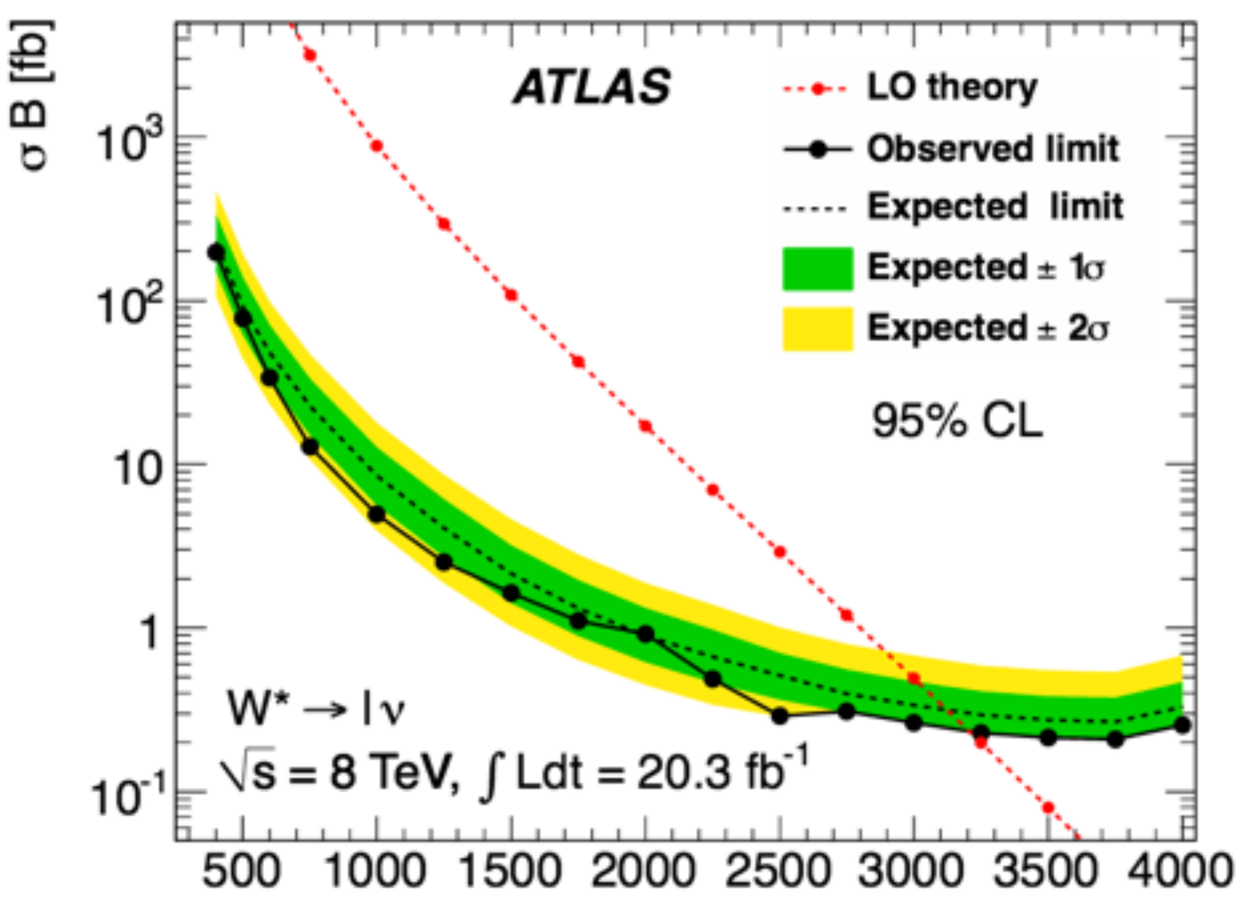


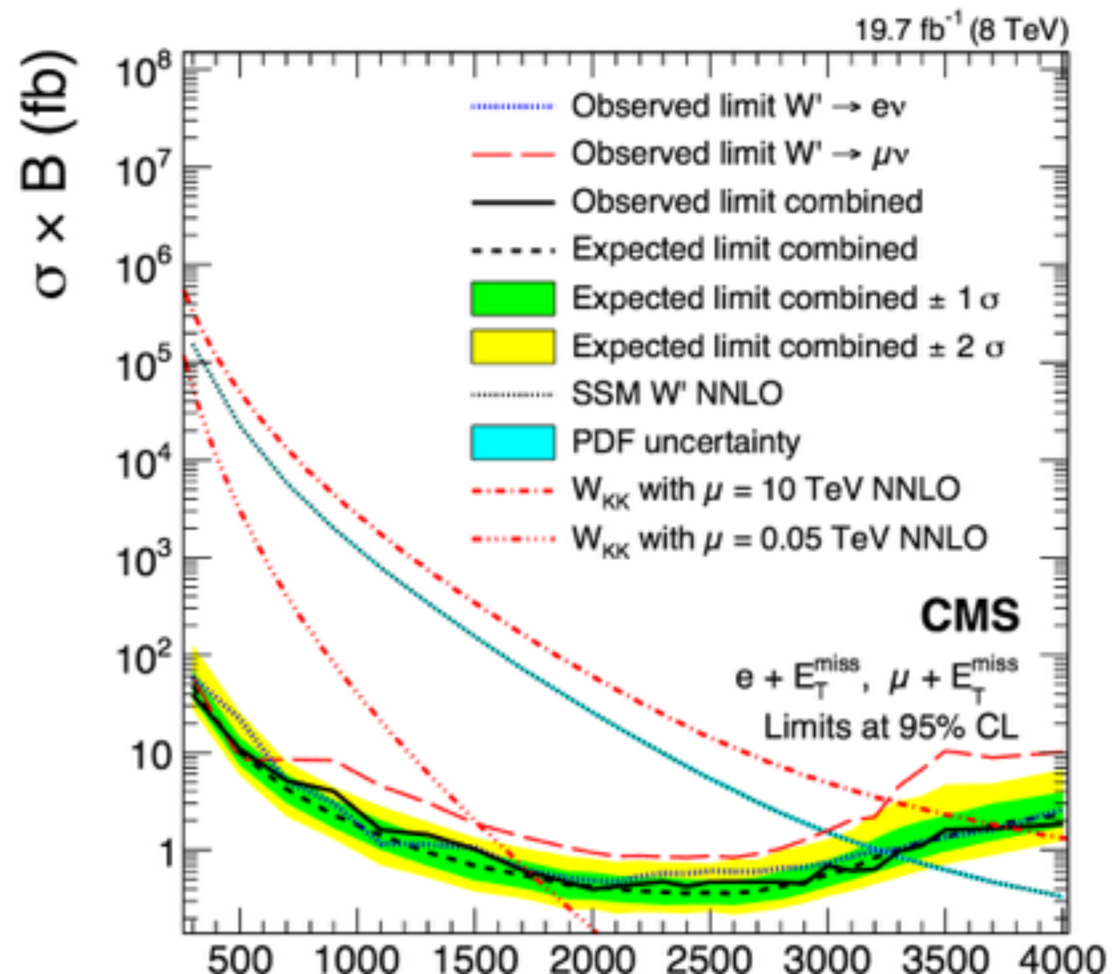


Leptonic channels





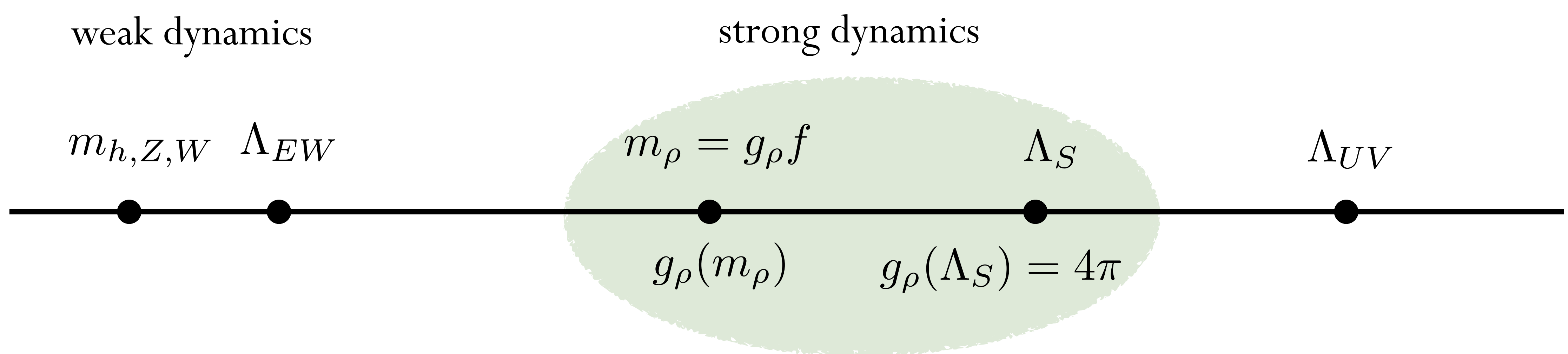




Composite Higgs Models

Composite Higgs Models

strongly coupled heavy sector at scale m_ρ



heavy resonances expected in the strong sector

above Λ_S H no longer elementary d.o.f. → solves hierarchy problem

still large separation between Λ_{EW} and Λ_S which requires some tuning

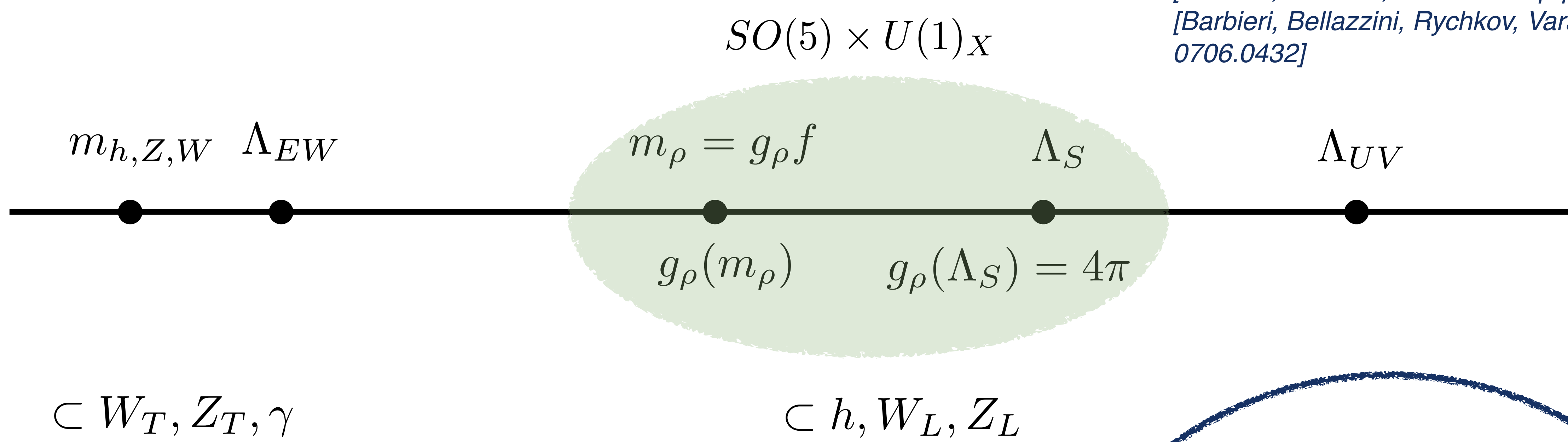
light Higgs present accidentally (e.g. light dilation)

or related to longitudinal polarisation of gauge bosons (pNGB)

Minimal Composite Higgs Models

[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]

strongly coupled heavy sector at scale m_ρ

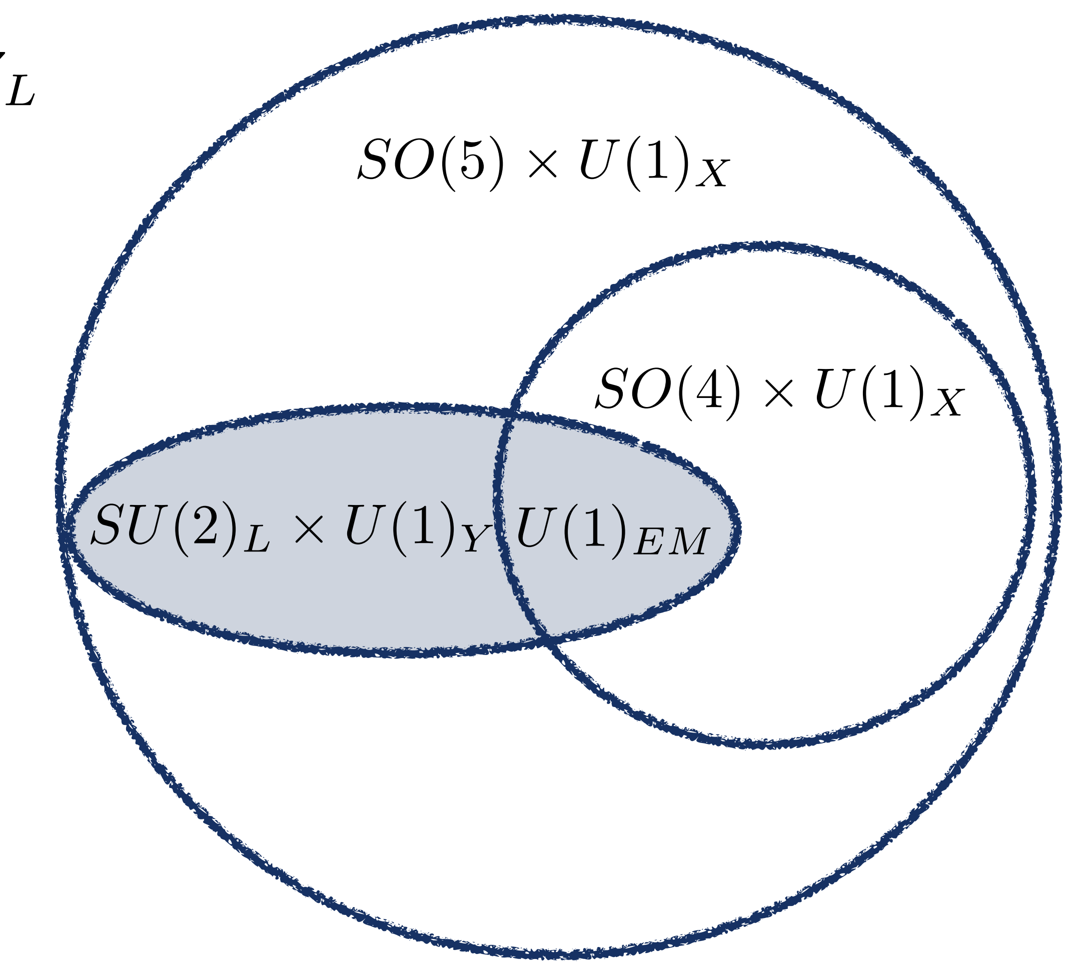


at scale $f > v$ spontaneously broken

to $SO(4) \times U(1)_X$

quadruplet of pNGB appears: H

→ to guarantee its lightness

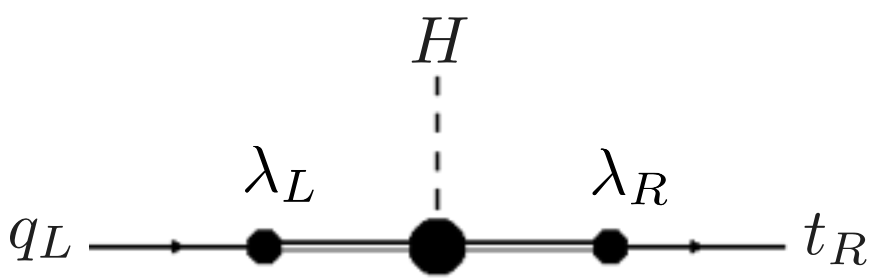


Minimal Composite Higgs

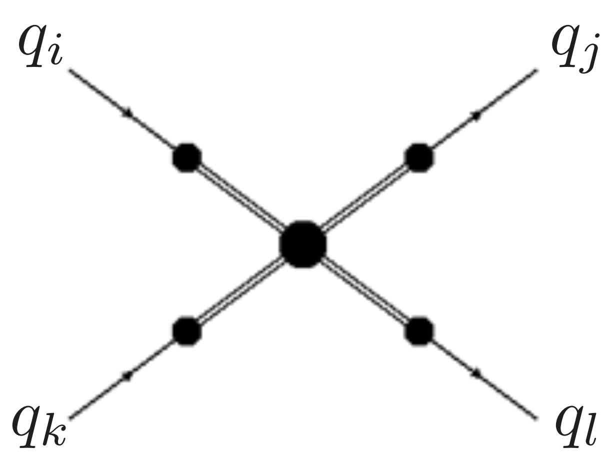
partial compositeness:
linear mixing between elementary and composite states

$$\mathcal{L}_{\text{mix}} = \lambda_L \, q_L \mathcal{O}_L^q + \lambda_R \, t_R \mathcal{O}_R^t + \text{h.c.} + g \, A_\mu \mathcal{J}^\mu$$

yields attractive flavour picture
[Csaki, Falkowski, Weiler: arXiv:0804.1954]



$$y_t \sim \frac{\lambda_L \lambda_R}{g_\psi} = \epsilon_L \epsilon_R g_\psi$$



$$\sim \epsilon^i \epsilon^j \epsilon^k \epsilon^l \, \frac{g_\psi^2}{m_\psi^2}$$

couplings to elementary states → break SO(5)
generate potential

Beyond the Minimal Model

can build larger cosets with additional physical scalars

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$	
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$	*[Agashe, Contino, Pomarol,…]*
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$	*[Gripaios, Pomarol, Riva, Serra 0902.1485]*
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}}+\bar{\mathbf{4}}_{-\mathbf{2}}=2\times(\mathbf{2},\mathbf{2})$	*[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.5403]*
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$	
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$	*[Chala 1210.6208]*
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_\mathbf{0}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$	
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$	
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$	*[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.5403]*
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{+\mathbf{5}}=2\times(\mathbf{2},\mathbf{2})$	
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$	

larger freedom for fermion representations

Composite Higgs Model

- predicts direct and indirect effects

- production of EW vector resonances (here consider 3 of $SU(2)_L$)

  [Pappadopulo, Thamm, Torre, Wulzer: 1402.4431]

- production of top partners light to reproduce m_h

  [Mrazek, Wulzer: arXiv:0909.3977]
  [De Simone, Matsedonskyi, Rattazzi, Wulzer: arXiv:1211.5663]

- modification of Higgs couplings

  $$a = g_{WWh} = \sqrt{1-\xi} \qquad \xi = \frac{v^2}{f^2}$$

- EWPT (sensitive to effects only computable in specific models)

- Flavour

Heavy vector triplets

Heavy vector triplets

- among the most well motivated particles
- appear in composite Higgs models but also in weakly coupled theories
- associated to the EW gauge symmetry
- consider a 3 of $SU(2)_L$

Phenomenological Lagrangian

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\, a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\, a}$$

$$+ i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\, a}_F$$

$$+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]\, c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\, a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\, a} V^b_\mu V^c_\nu$$

$$V = (V^+, V^-, V^0)$$

g_V typical strength of V interactions

c_i dimensionless coefficients

Weakly coupled model

$$g_V \sim g \sim 1$$

$$c_H \sim -g^2/g_V^2 \quad \text{and} \quad c_F \sim 1$$

Strongly coupled model

$$1 < g_V \leq 4\pi$$

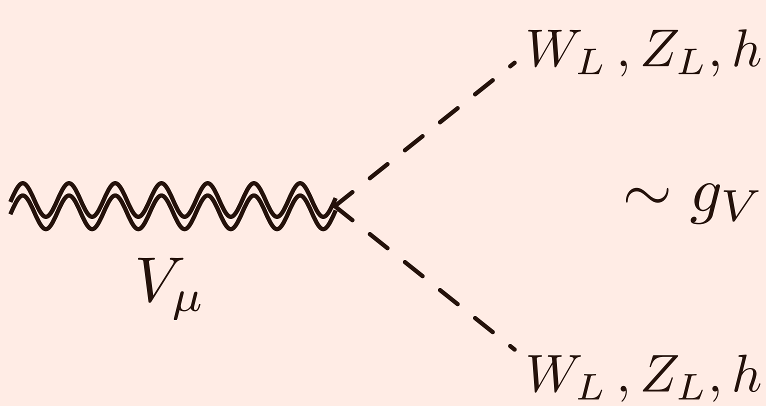
$$c_H \sim c_F \sim 1$$

Phenomenological Lagrangian

$$
\begin{aligned}
\mathcal{L}_V \;=\;& -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a} \\
& + i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a} \\
& + \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V_\mu^b V_\nu^c
\end{aligned}
$$

$$V = \left(V^+, V^-, V^0\right)$$

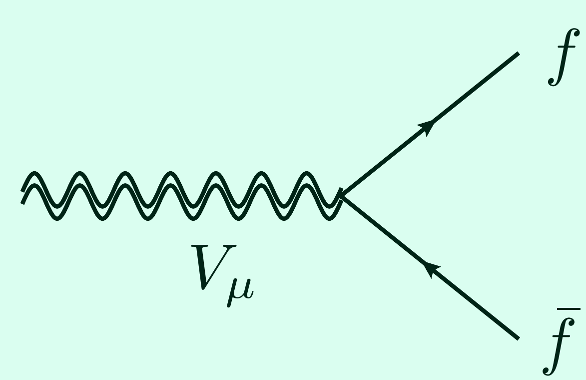
Coupling to SM Vectors



$\sim g_V c_H$

Coupling to SM fermions

$$J_F^{\mu\,a} = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$$



$$\sim \frac{g^2}{g_V} c_F$$

$$c_F V \cdot J_F \;\rightarrow\; c_l V \cdot J_l + c_q V \cdot J_q + c_3 V \cdot J_3$$

Phenomenological Lagrangian

$$\begin{aligned}\mathcal{L}_V &= -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a} \\ &+ i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\,a}_F \\ &+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V^b_\mu V^c_\nu\end{aligned}$$

$$V = (V^+, V^-, V^0)$$

- Couplings among vectors
- do not contribute to V decays
- do not contribute to single production
- only effects through (usually small) VW mixing

- ⇨ irrelevant for phenomenology ⇨ only need (c_H, c_F)

Production rates

- DY and VBF production

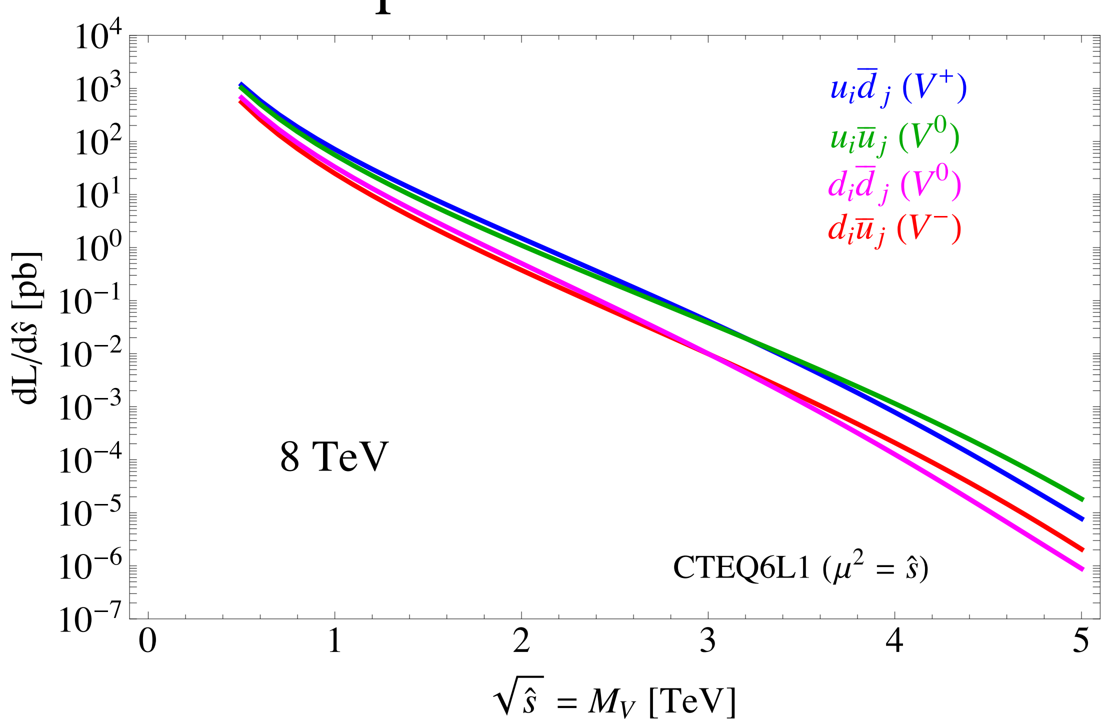
$$\sigma_{DY} = \sum_{i,j \in p} \frac{\Gamma_{V \to ij}}{M_V} \frac{4\pi^2}{3} \frac{dL_{ij}}{d\hat{s}} \bigg|_{\hat{s}=M_V^2} \qquad \sigma_{VBF} = \sum_{i,j \in p} \frac{\Gamma_{V \to W_{L\,i} W_{L\,j}}}{M_V} 48\pi^2 \frac{dL_{W_{L\,i} W_{L\,j}}}{d\hat{s}} \bigg|_{\hat{s}=M_V^2}$$

model dependent

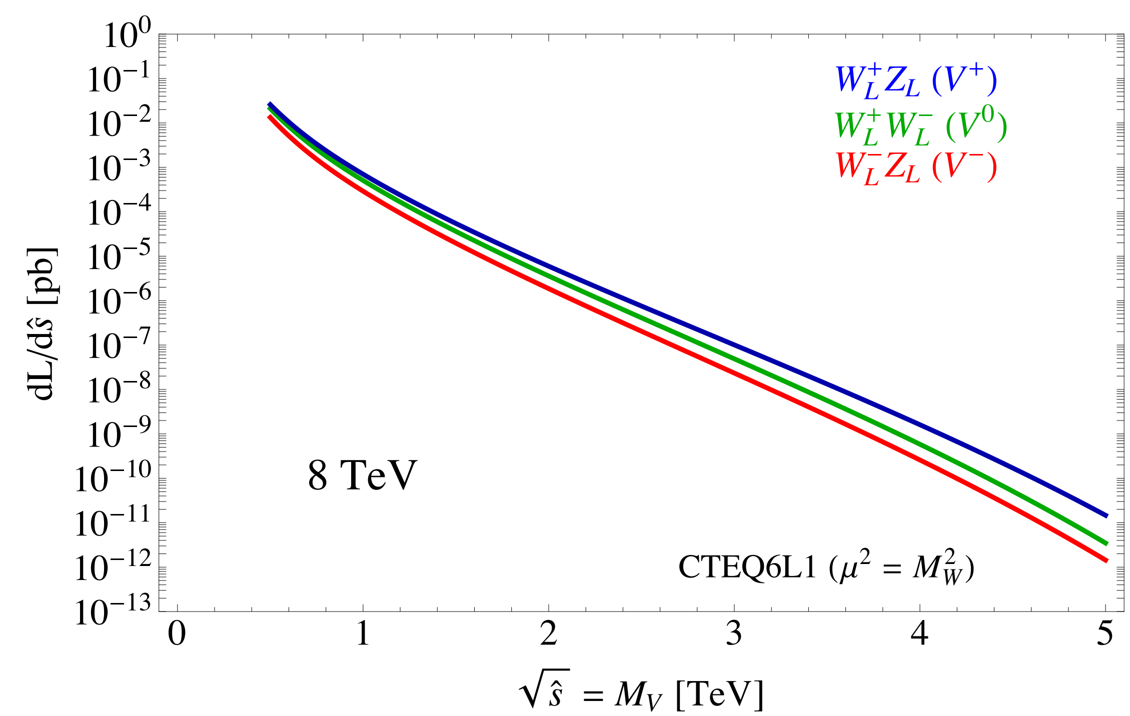
model independent

- can compute production rates analytically!
- easily rescale to different points in parameter space

quark initial state



vector boson initial state



Decay widths

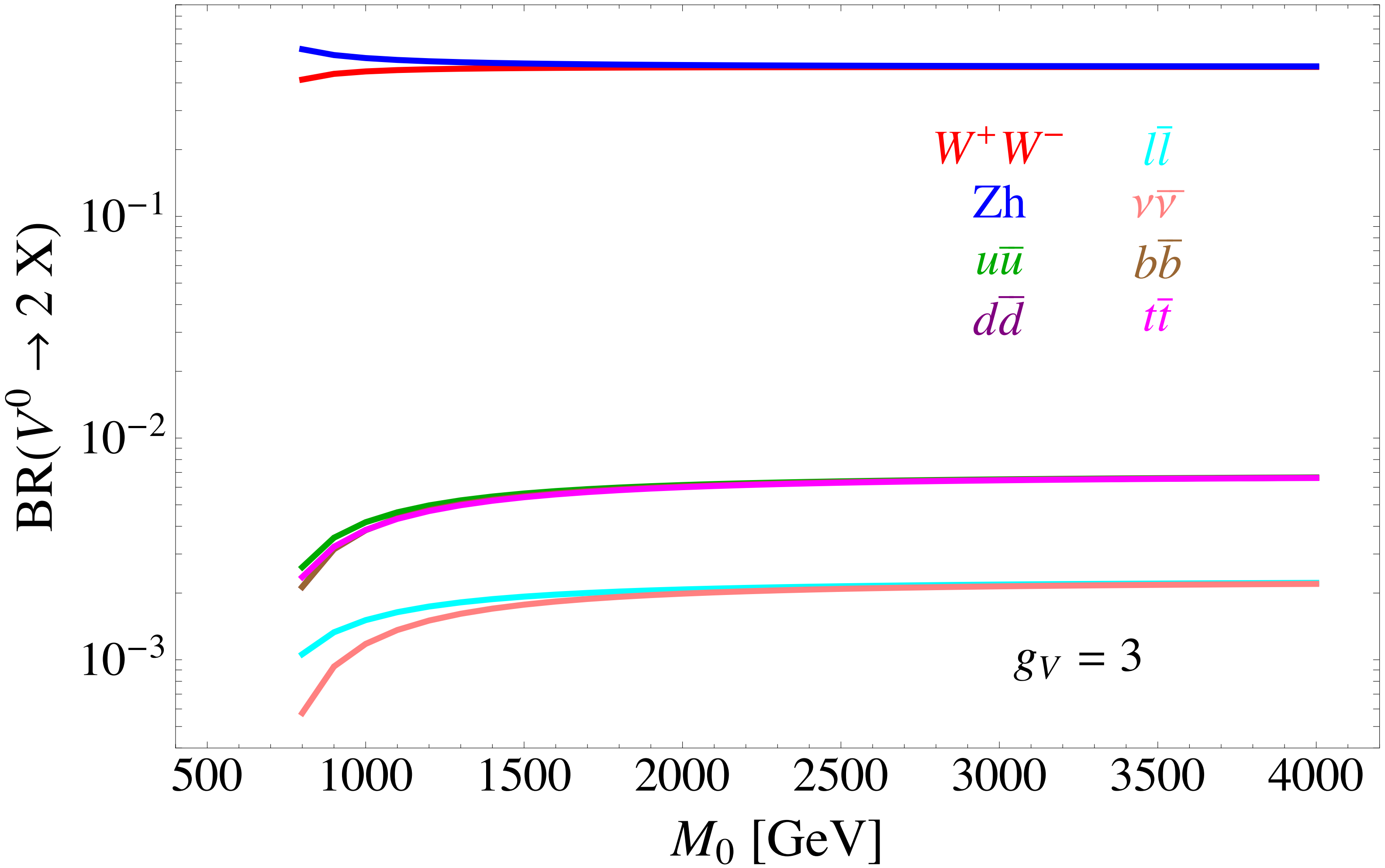
- relevant decay channels: di-lepton, di-quark, di-boson

$$\Gamma_{V_\pm \to f\bar{f}'} \simeq 2\,\Gamma_{V_0 \to f\bar{f}} \simeq N_c[f] \left(\frac{g^2 c_F}{g_V}\right)^2 \frac{M_V}{96\pi}\,,$$

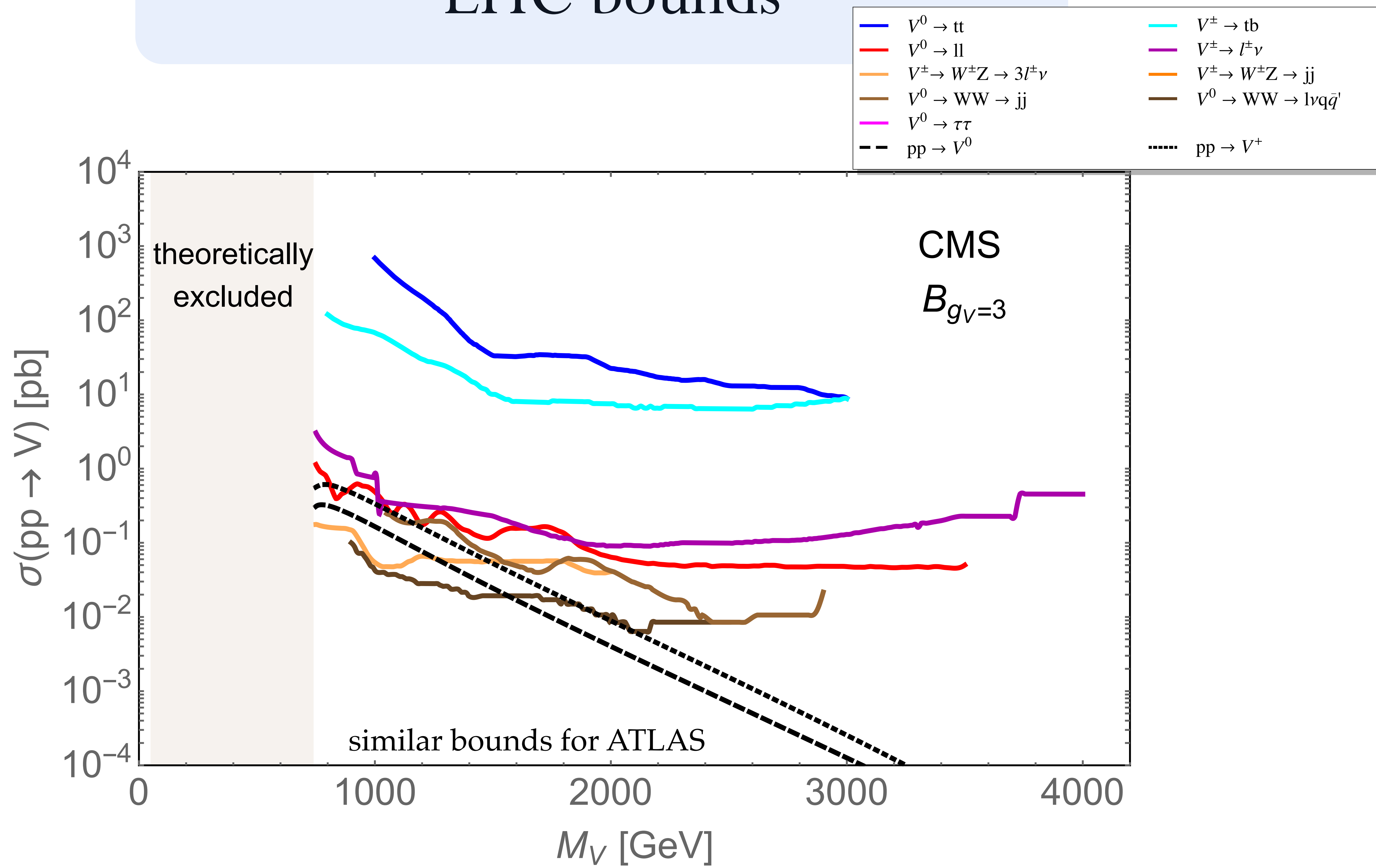
$$\Gamma_{V_0 \to W_L^+ W_L^-} \simeq \Gamma_{V_\pm \to W_L^\pm Z_L} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}\left[1 + \mathcal{O}(\zeta^2)\right]$$

$$\Gamma_{V_0 \to Z_L h} \simeq \Gamma_{V_\pm \to W_L^\pm h} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}\left[1 + \mathcal{O}(\zeta^2)\right]$$

$$g_V c_H \simeq -g_V\,, \qquad g^2 c_F/g_V \simeq g^2/g_V$$



LHC bounds



- excluded for masses < 1.5 TeV, unconstrained for larger g_V
- di-boson most stringent
- in excluded region $G_F,\ m_Z$ not reproduced

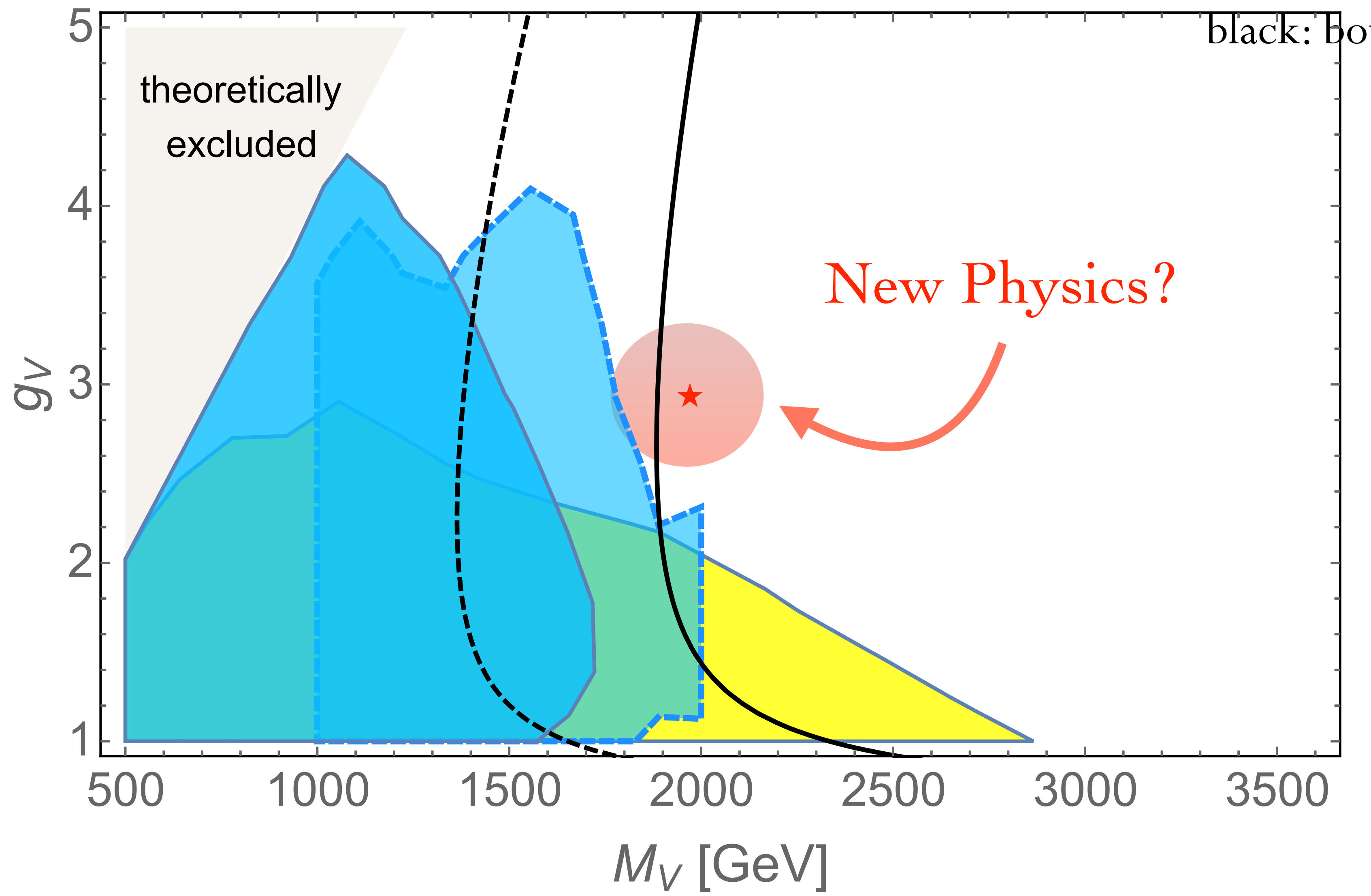
Heavy vector triplets in the di-boson excess

LHC bounds

- experimental limits converted into (M_V, g_V) plane

[Pappadopulo, Thamm, Torre, Wulzer, arXiv:1402.4431]

yellow: CMS $l^+\nu$ analysis
dark blue: CMS $WZ \to 3l\nu$
light blue: CMS $WZ \to jj$
black: bounds from EWPT



- similar exclusions at low g_V, leptonic final state dominates
- very different for larger coupling
- weaker limits if decay to top partners open

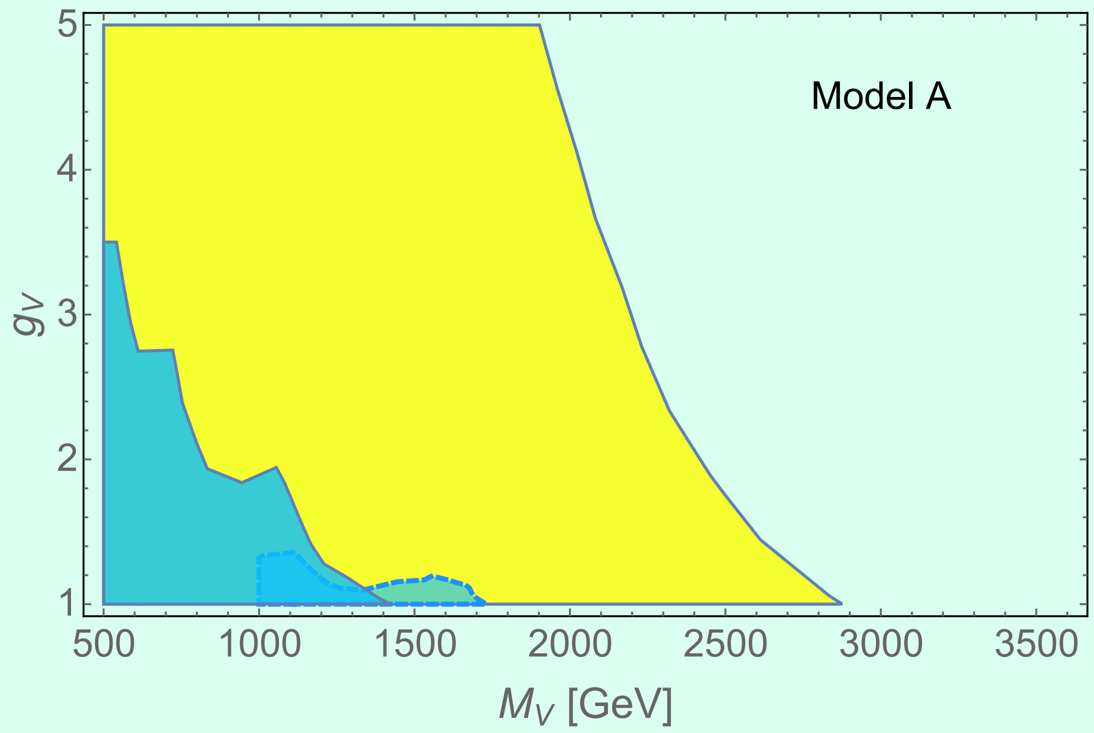
[Greco, Liu: arXiv:1410.2883]
[Chala, Juknevich, Perez, Santiago: arXiv:1411.1771]

LHC bounds

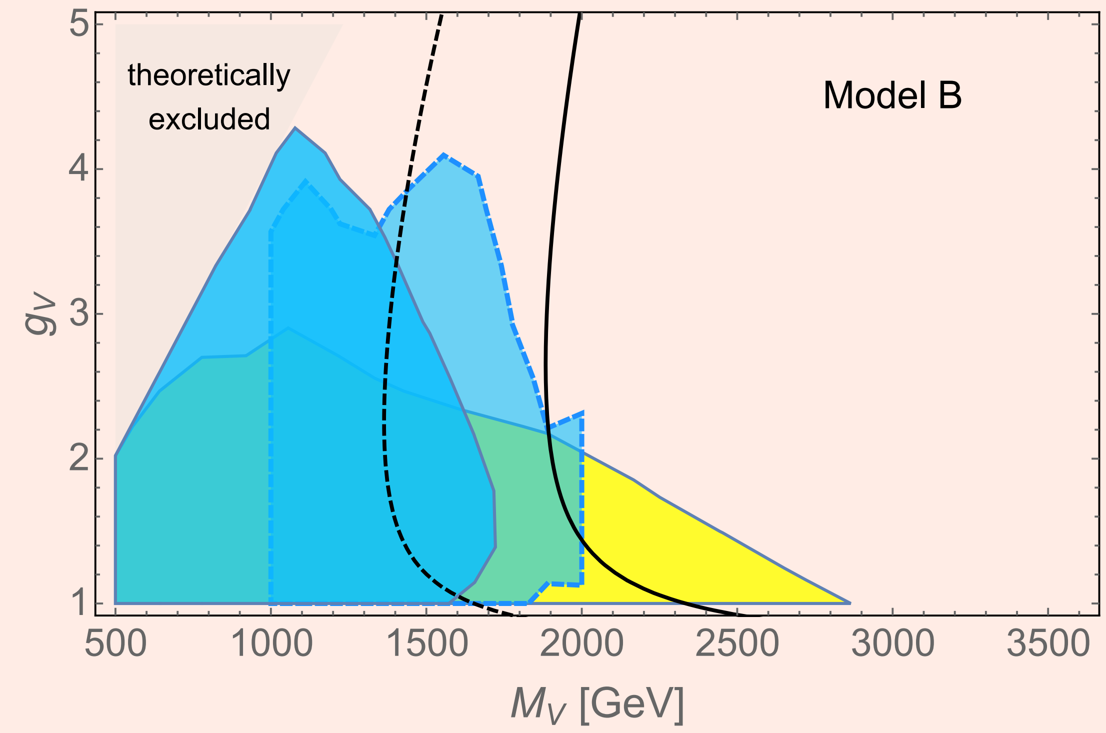
- compare with weakly coupled vectors

yellow: CMS $l^+\nu$ analysis
dark blue: CMS $WZ \to 3l\nu$
light blue: CMS $WZ \to jj$
black: bounds from EWPT

Weakly coupled model



Strongly coupled model



- strongly coupled vectors have weaker bounds

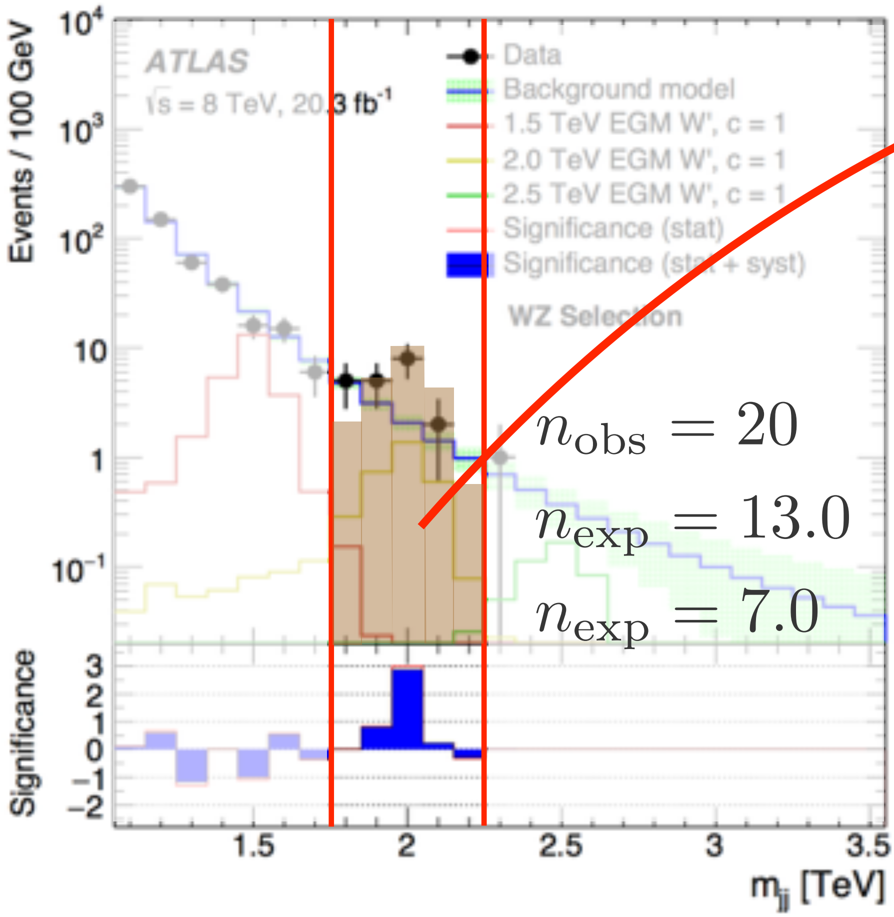
[Pappadopulo, Thamm, Torre, Wulzer, arXiv:1402.4431]

Composite HVT signal cross section

- neutral and charged components contribute to the various selection regions

$$S_{WZ} = \mathcal{L} \times \mathcal{A} \times \left[(\sigma \times \mathrm{BR})_{V^\pm} \, \mathrm{BR}_{WZ\to \mathrm{had}} \epsilon_{WZ\to WZ} + (\sigma \times \mathrm{BR})_{V^0} \, \mathrm{BR}_{WW\to \mathrm{had}} \epsilon_{WW\to WZ} \right]$$

- Once we fix the mass there is only one parameter g_V



$n_{\mathrm{obs}} = 20$

$n_{\mathrm{exp}} = 13.0$

$n_{\mathrm{exp}} = 7.0$

$$S_{WZ} = 7.0^{+3.8}_{-2.6}$$

m_V [TeV]	g_V	$(\sigma \times \mathrm{BR})_{V^\pm}$ [fb]	$(\sigma \times \mathrm{BR})_{V^0}$ [fb]
1.8	$3.95^{+1.65}_{-0.88}$	4.51	2.04
1.9	$3.37^{+1.63}_{-0.83}$	4.63	2.09
2.0	$2.81^{+1.54}_{-0.82}$	4.79	2.16

[Thamm, Torre, Wulzer, arXiv:1506.08688]

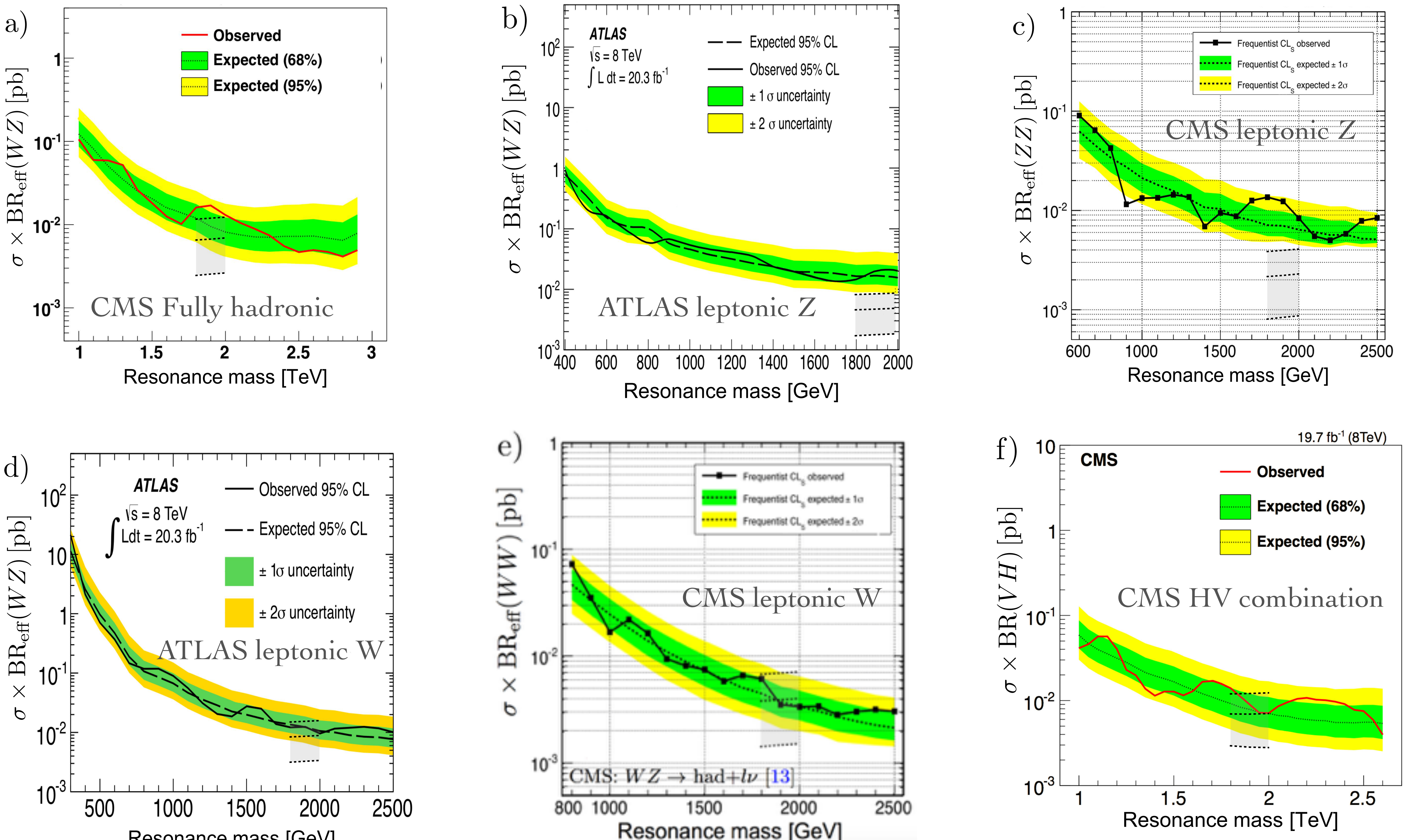
$$S_{WW} \in [2.2, 10.3]$$

$$S_{WW} = 4.2^{+3.2}_{-2.0}$$

$$S_{ZZ} \in [1.4, 6.6]$$

$$S_{ZZ} = 6.4^{+3.6}_{-2.4}$$

Compatibility with other searches



[Thamm, Torre, Wulzer, arXiv:1506.08688]

Implications for the MCHM

- fixing the parameters

$$m_V \sim 2\,\text{TeV} \qquad g_V \sim 3 \quad \Longrightarrow \quad f \sim 0.67\,\text{TeV} \qquad \xi \sim 0.14$$

- expect top partners below 2 TeV

  (current limits up to ~0.7 TeV)
- need to include decay into top partners
- need a new effective theory which includes new heavy states
- measure couplings of new states
- expect deviation in Higgs couplings

  $g_{WWh} \sim 0.93$ instead of 1

Implications for the MCHM

- fixing the parameters

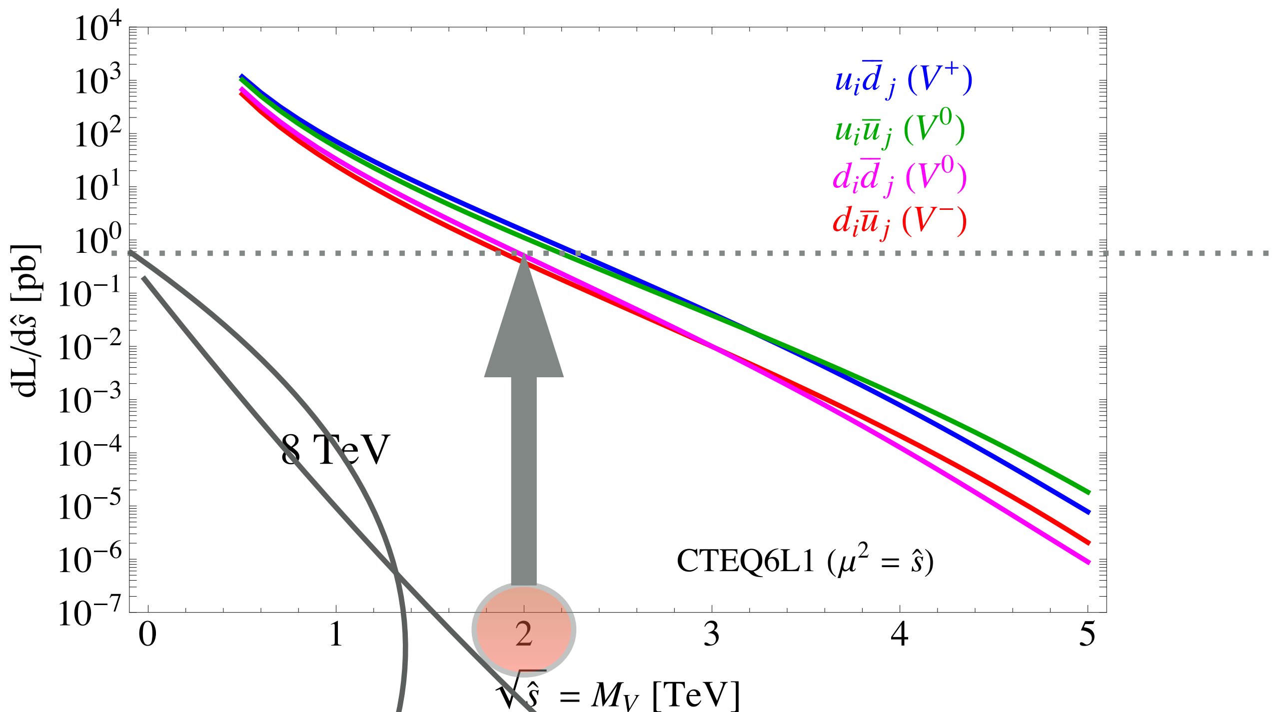
$$m_V \sim 2\,\mathrm{TeV} \qquad \qquad \qquad f \sim 0.67\,\mathrm{TeV}$$

$$g_V \sim 3 \qquad \Longrightarrow \qquad \xi \sim 0.14$$

- from CH perspective: very plausible
- very close to what we expect
- for now, only some fluctuations
- maybe exactly what a 2 TeV resonance should look like
- very soon, we will know more!

Heavy vector triplets at future colliders

Limit extrapolation

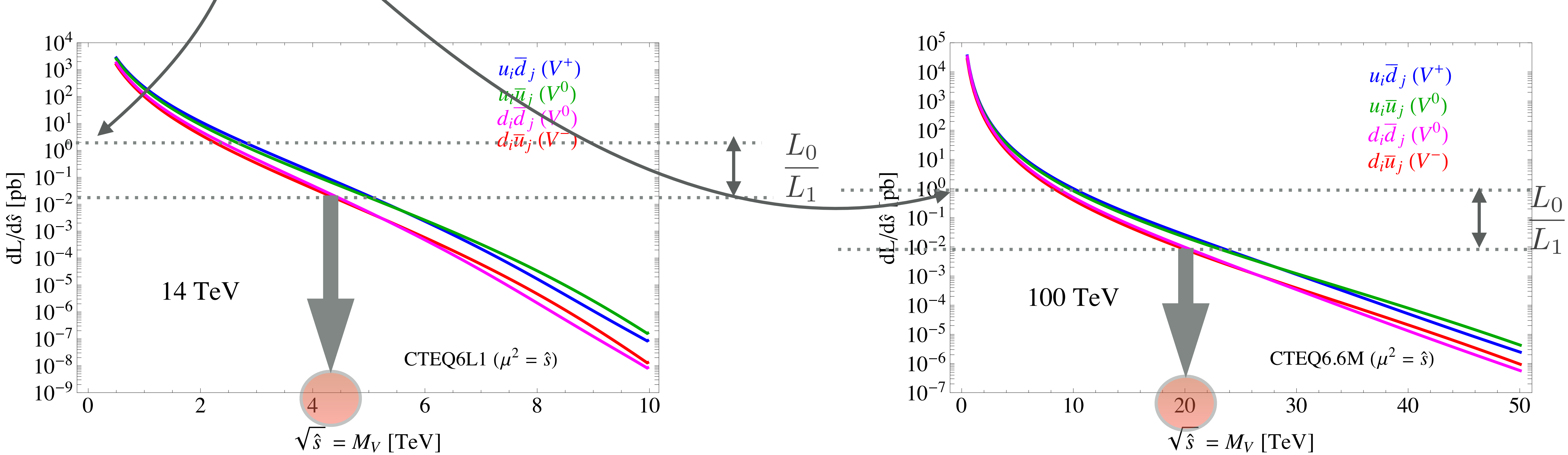


assume: excluded signal is only a function of number of background events

background rescales with parton luminosities

$$B(s, L, m_\rho) \propto L \cdot \sum_{\{i,j\}} \int d\hat{s} \frac{1}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\hat{s}} (\sqrt{\hat{s}}; \sqrt{s}) \left[\hat{s}\hat{\sigma}_{ij}(\hat{s})\right]$$

identify relevant background process



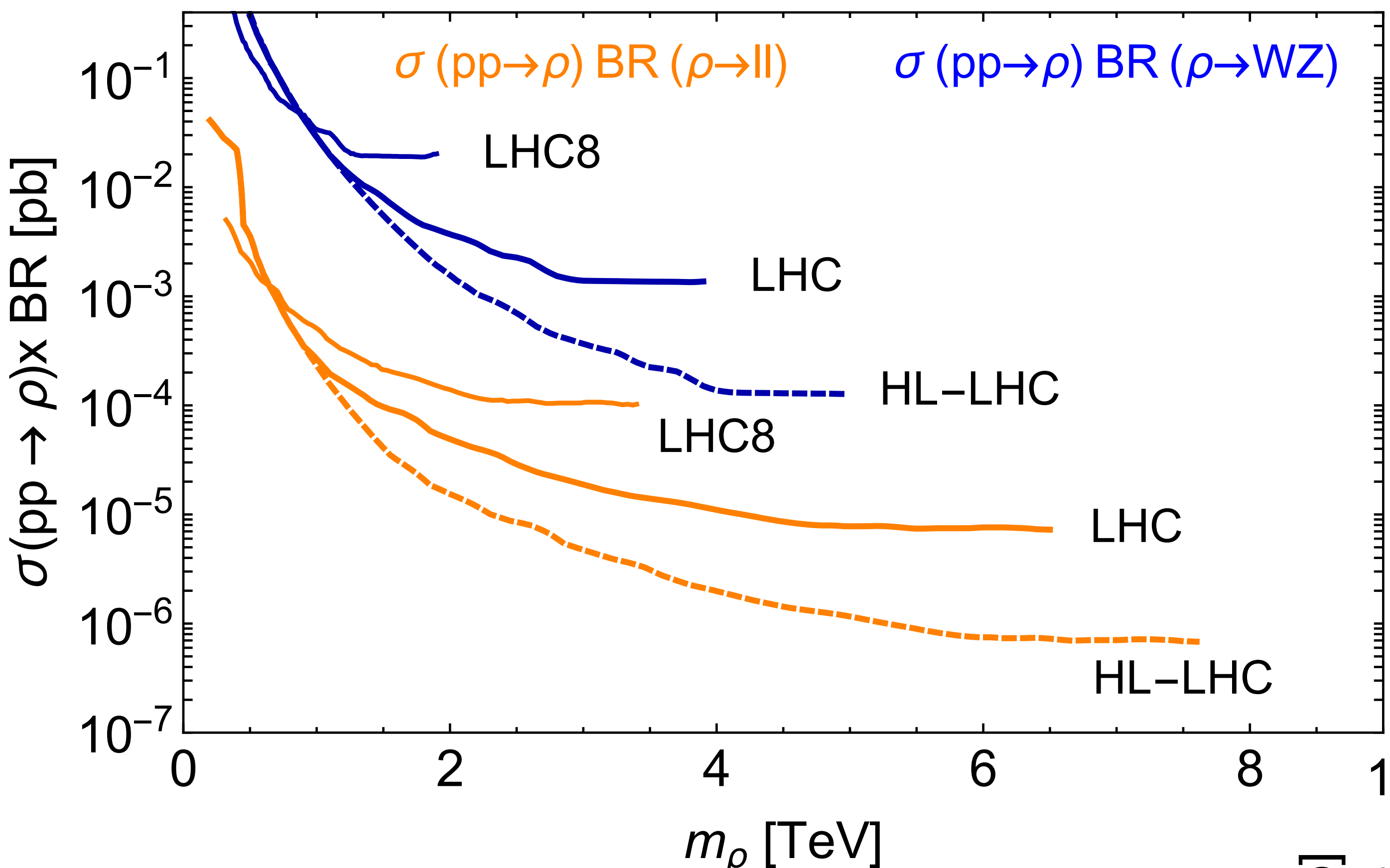
[Thamm, Torre, Wulzer: 1502.01701]

Limit extrapolation - assumptions

- limit only driven by background for a cut-and-count experiment of events within narrow window
- shape analyses depend on background and signal kinematical distributions
- however, no large deviations expected

Limit extrapolation

current 8 TeV LHC limits and extrapolated bounds

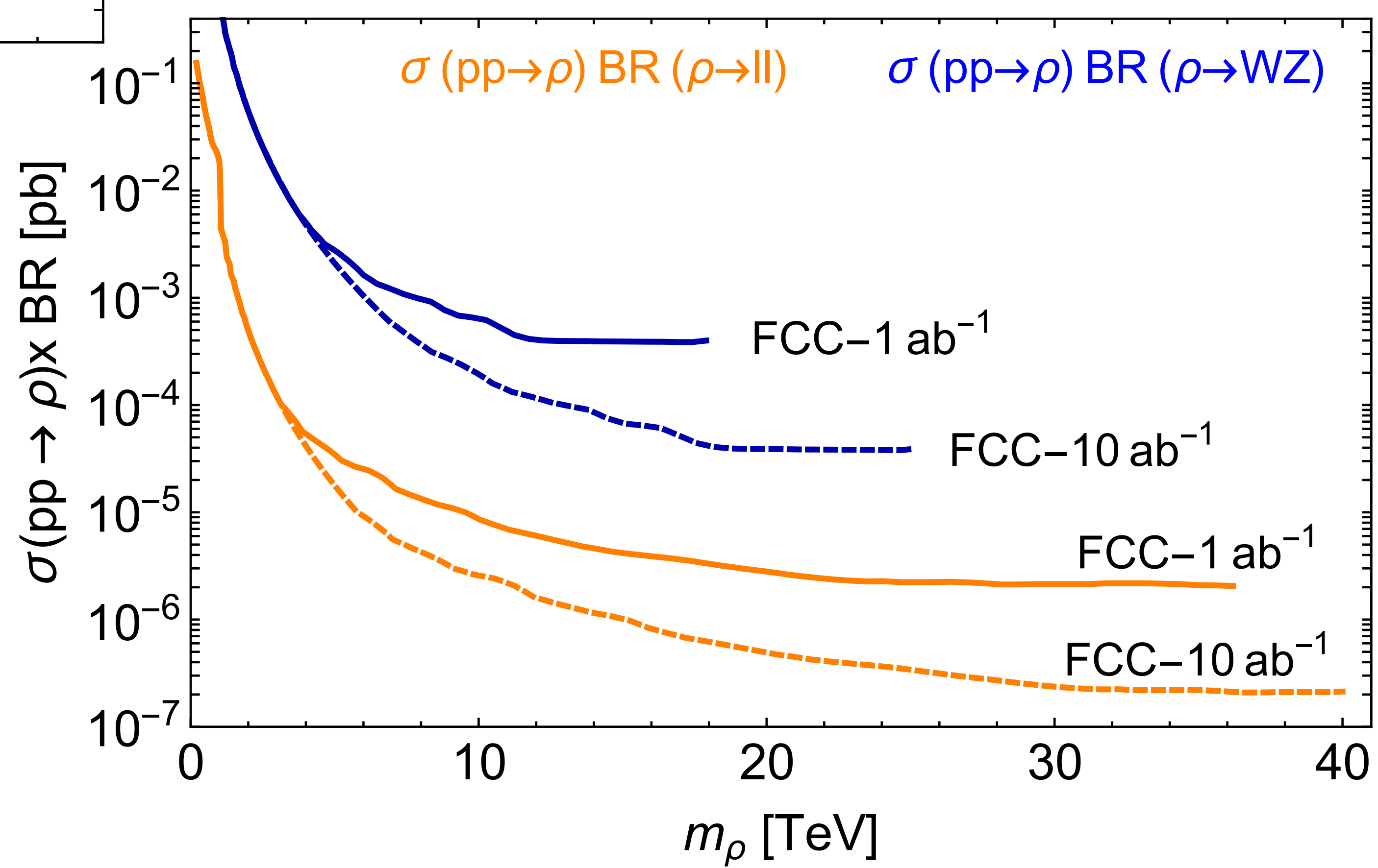


CMS search for

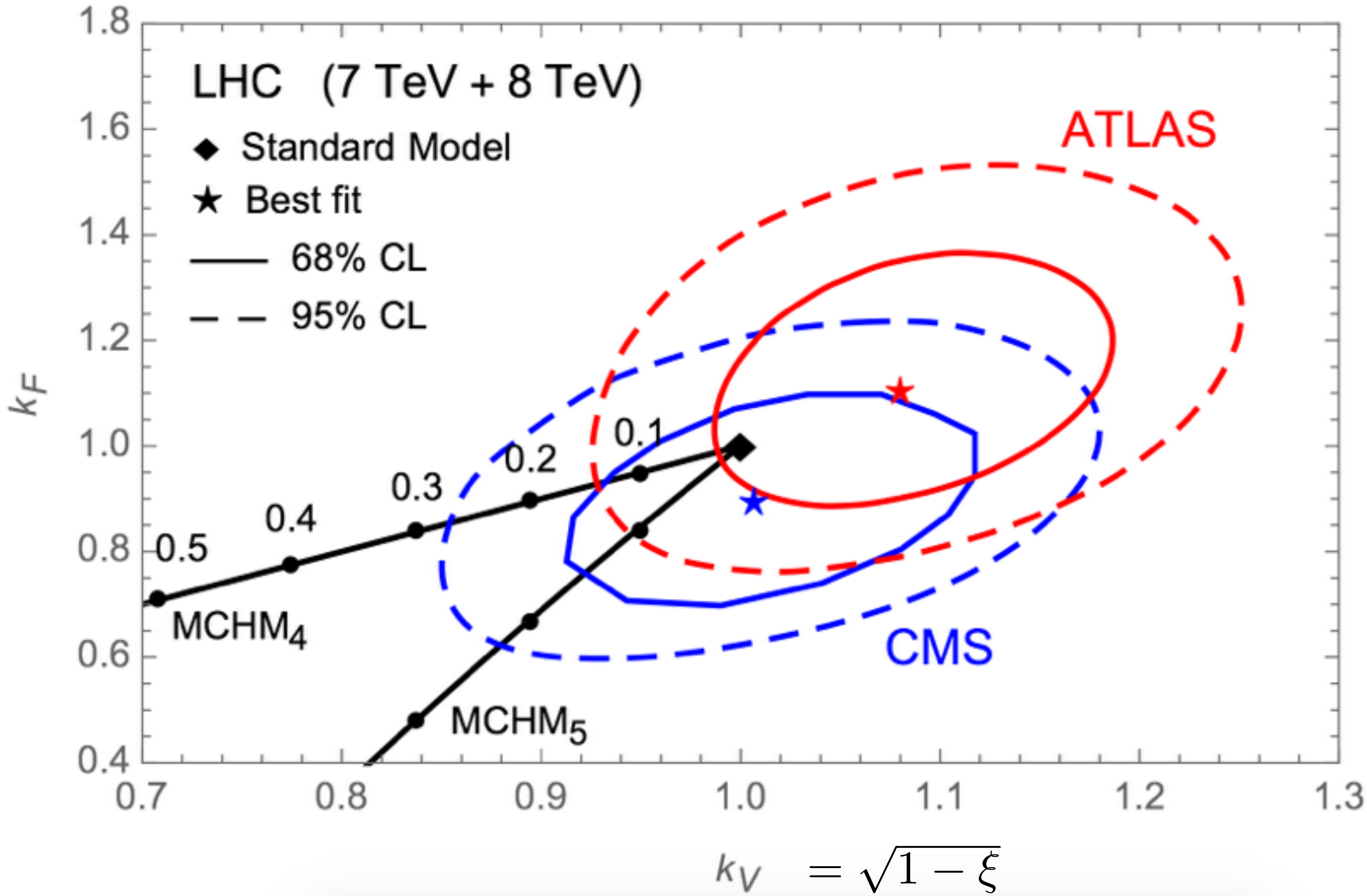
- opposite sign di-leptons
- fully leptonic WZ

[CMS-PAS-EXO-12-061]
[ATLAS 1405.4123]
[CMS 1407.3476]
[ATLAS 1406.4456]

- constant at large masses (zero background events)
- too conservative bounds at low masses



Indirect measurements



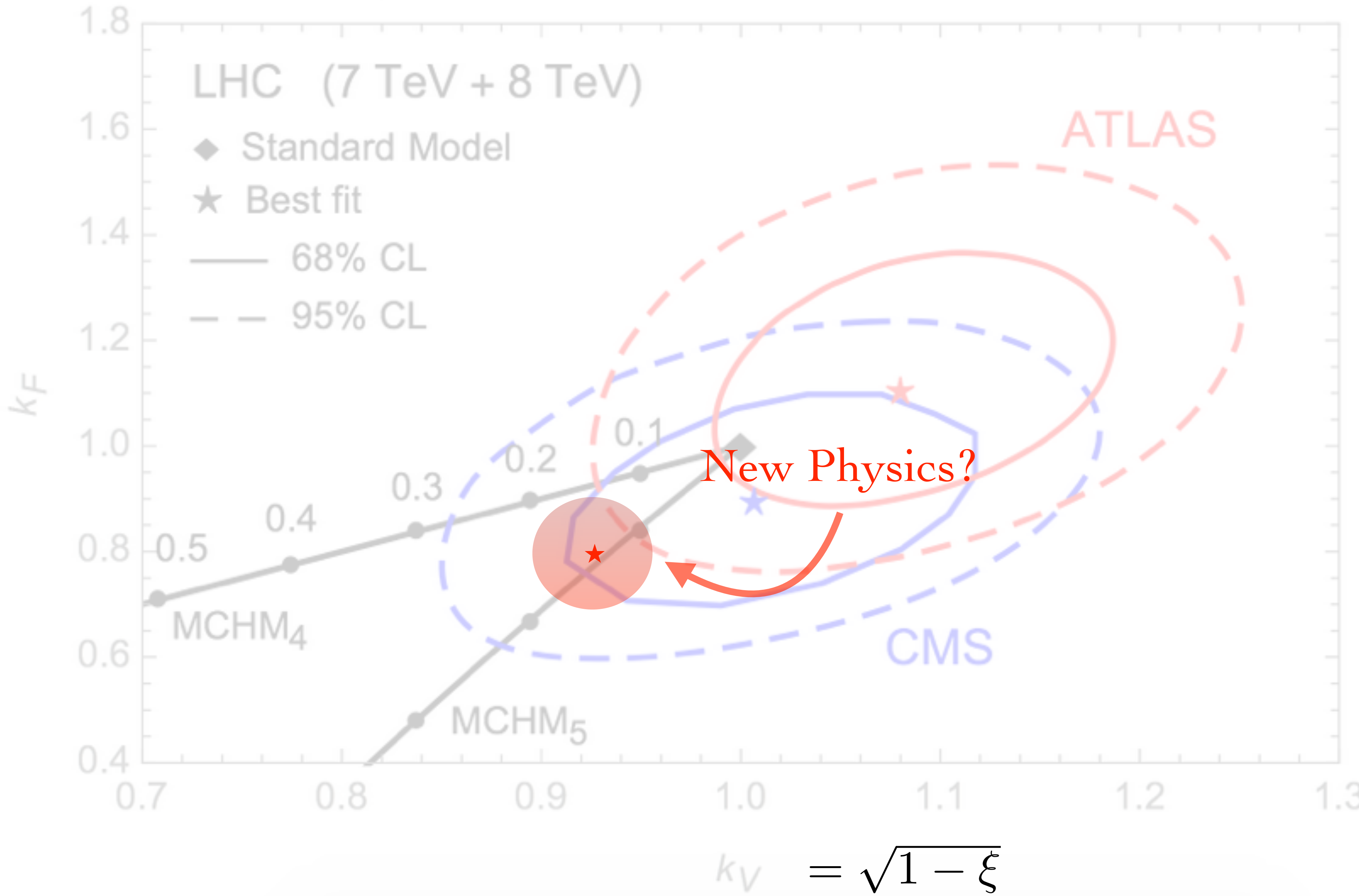
$= \sqrt{1-\xi}$

expected LHC reach: $\xi = 0.1$

MCHM4: $k_F = \sqrt{1-\xi}$

MCHM5: $k_F = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

Indirect measurements



$= \sqrt{1-\xi}$

expected LHC reach: $\xi = 0.1$

MCHM4: $k_F = \sqrt{1-\xi}$

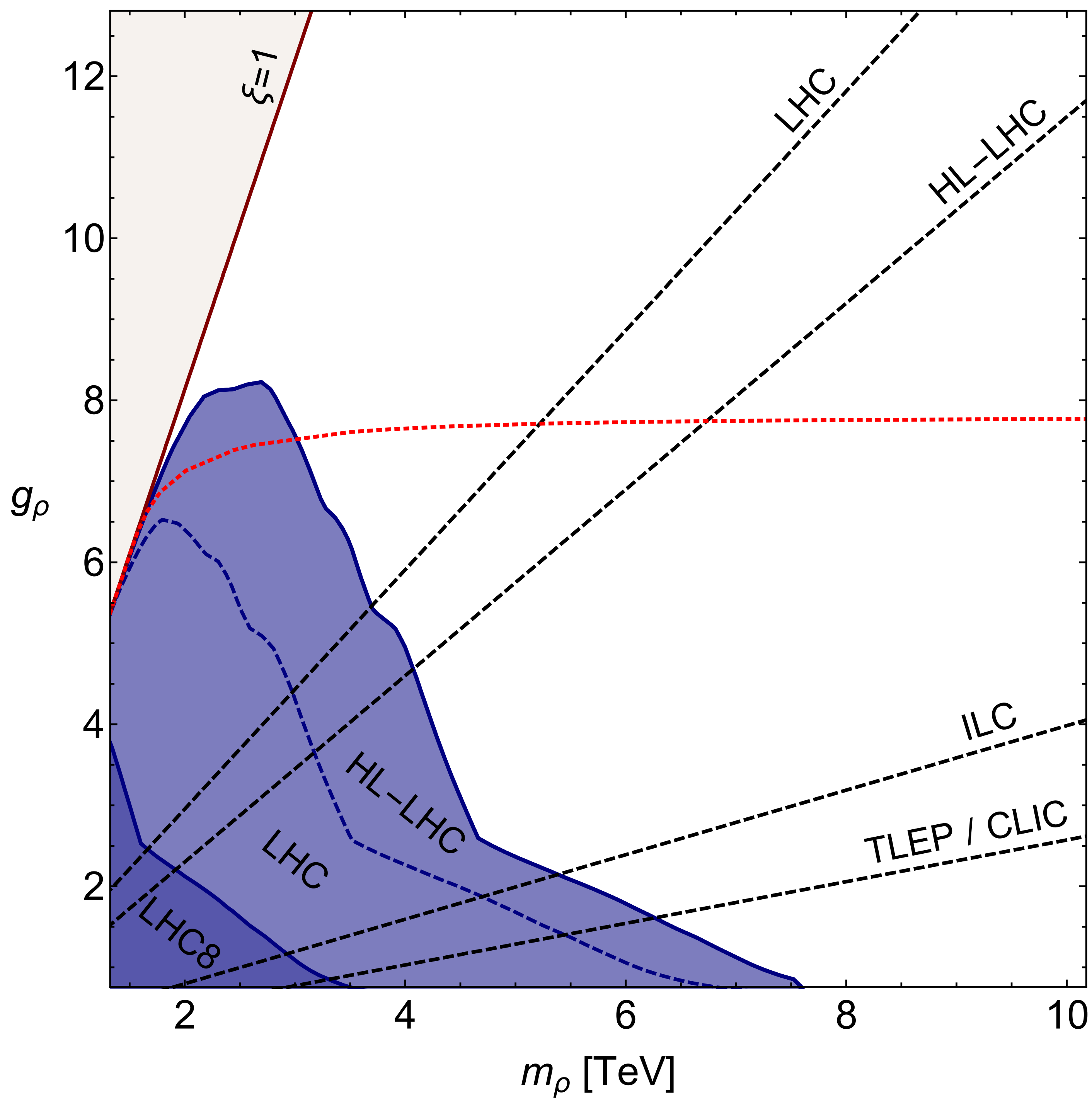
MCHM5: $k_F = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

Indirect measurements

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	$300\,\mathrm{fb}^{-1}$	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	$3\,\mathrm{ab}^{-1}$	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	$250\,\mathrm{fb}^{-1}$ $500\,\mathrm{fb}^{-1}$	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	$500\,\mathrm{fb}^{-1}$ $1.5\,\mathrm{ab}^{-1}$ $2\,\mathrm{ab}^{-1}$	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	$10\,\mathrm{ab}^{-1}$ $2.6\,\mathrm{ab}^{-1}$	2×10^{-3}

[CMS-NOTE-2012-006]
[ATL-PHYS-PUB-2013-014]
[Dawson et. al.1310.8361]
[CLIC 1307.5288]

Results in (m_ρ, g_ρ)



95% C.L.

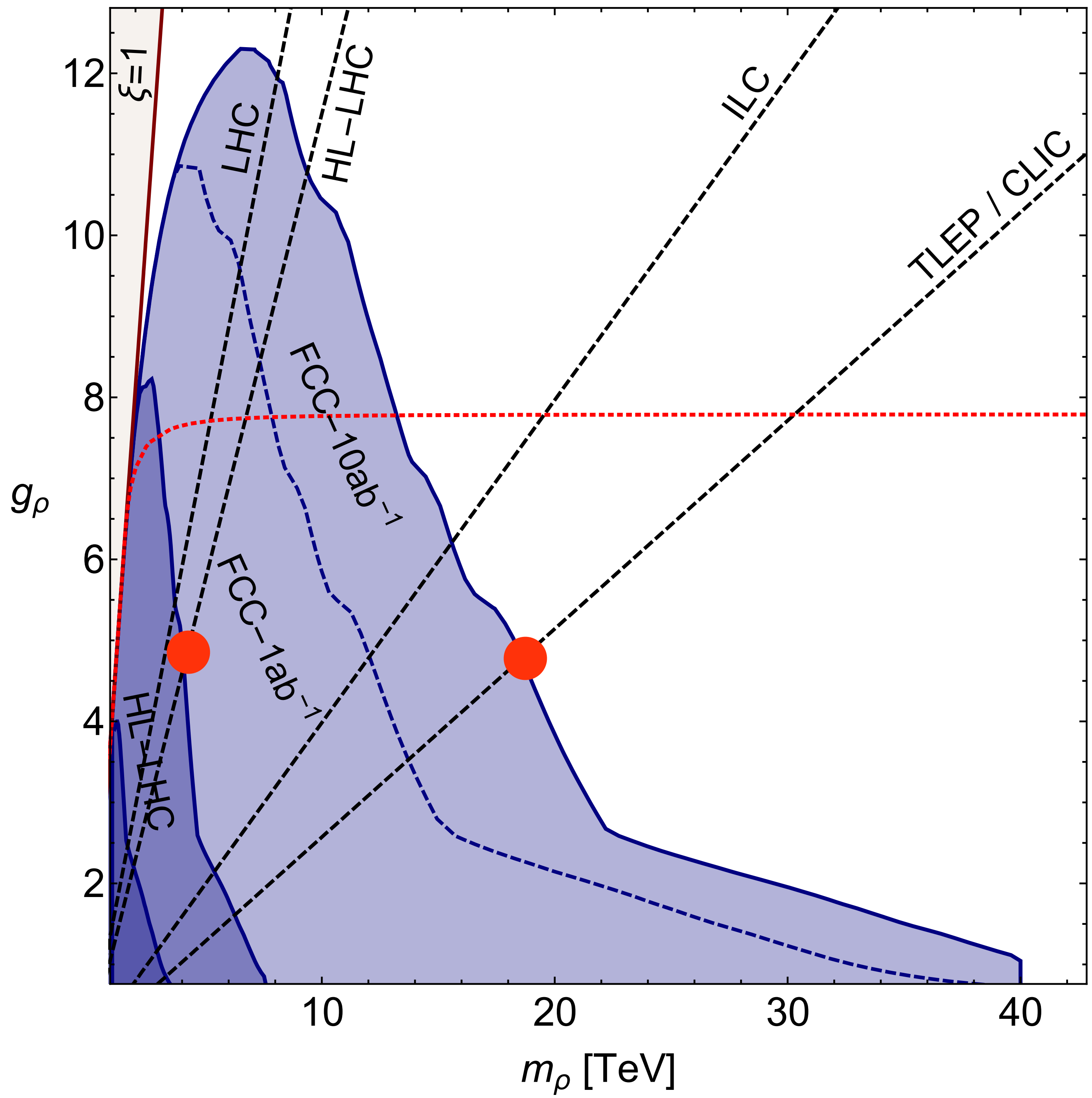
- theoretically excluded $\xi \leq 1$
- LHC8 at 8 TeV with 20 fb^{-1}

  LHC at 14 TeV with 300 fb^{-1}

  HL-LHC at 14 TeV with 3 ab^{-1}
- di-leptons more sensitive for small g_ρ
- di-boson more sensitive for large g_ρ
- increase in $\sqrt{s}$: improves mass reach
- increase in L: improves g_ρ reach
- resonances too broad for large g_ρ

[Thamm, Torre, Wulzer: 1502.01701]

Results in (m_ρ, g_ρ)

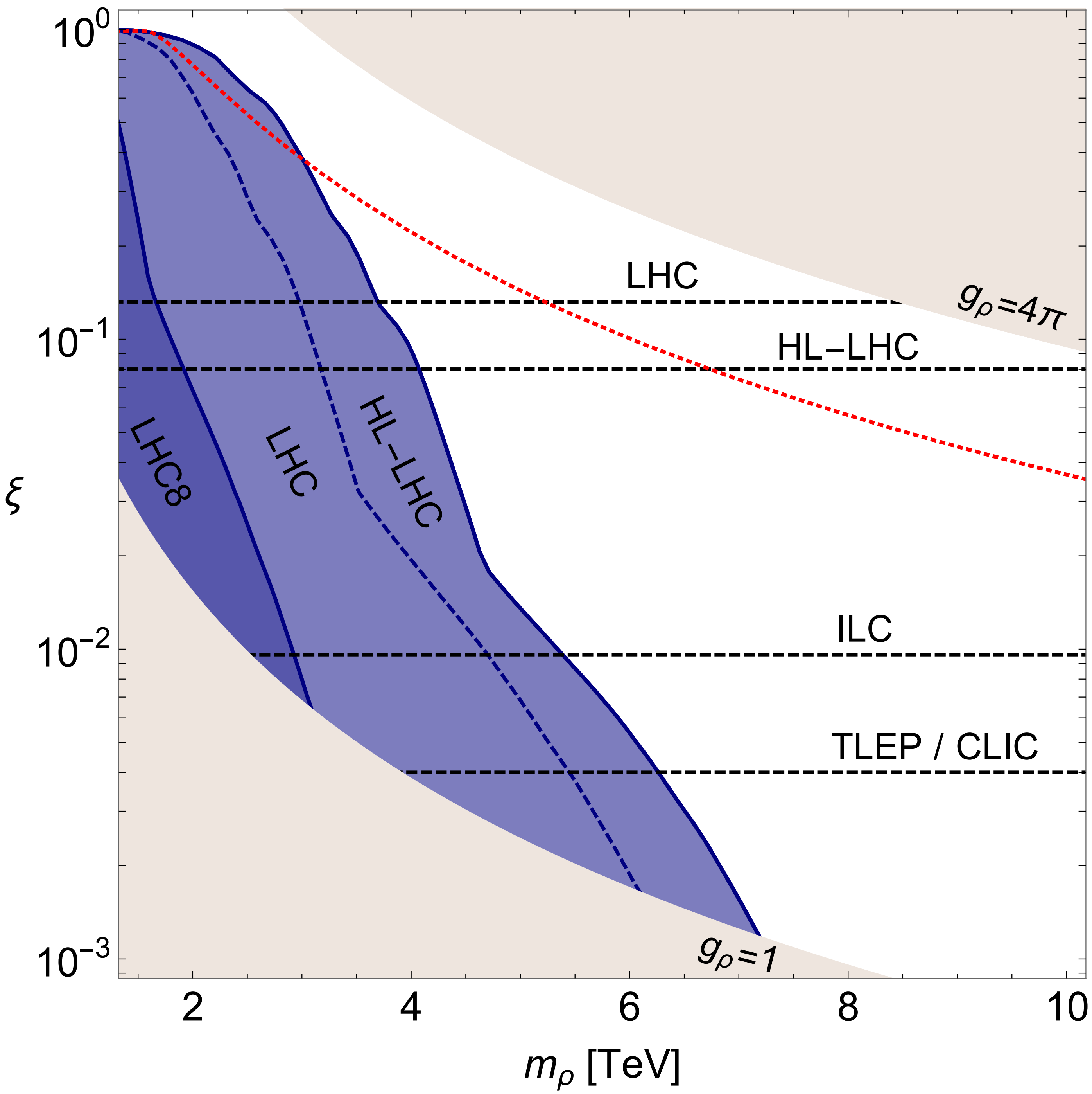


95% C.L.

- theoretically excluded $\xi \leq 1$
- LHC8 at 8 TeV with 20 fb^{-1}
  HL-LHC at 14 TeV with 3 ab^{-1}
- direct: more effective for small g_ρ
  ineffective for large g_ρ
- indirect: more effective for large g_ρ

[Thamm, Torre, Wulzer: 1502.01701]

Results in (m_ρ, ξ)



95% C.L.

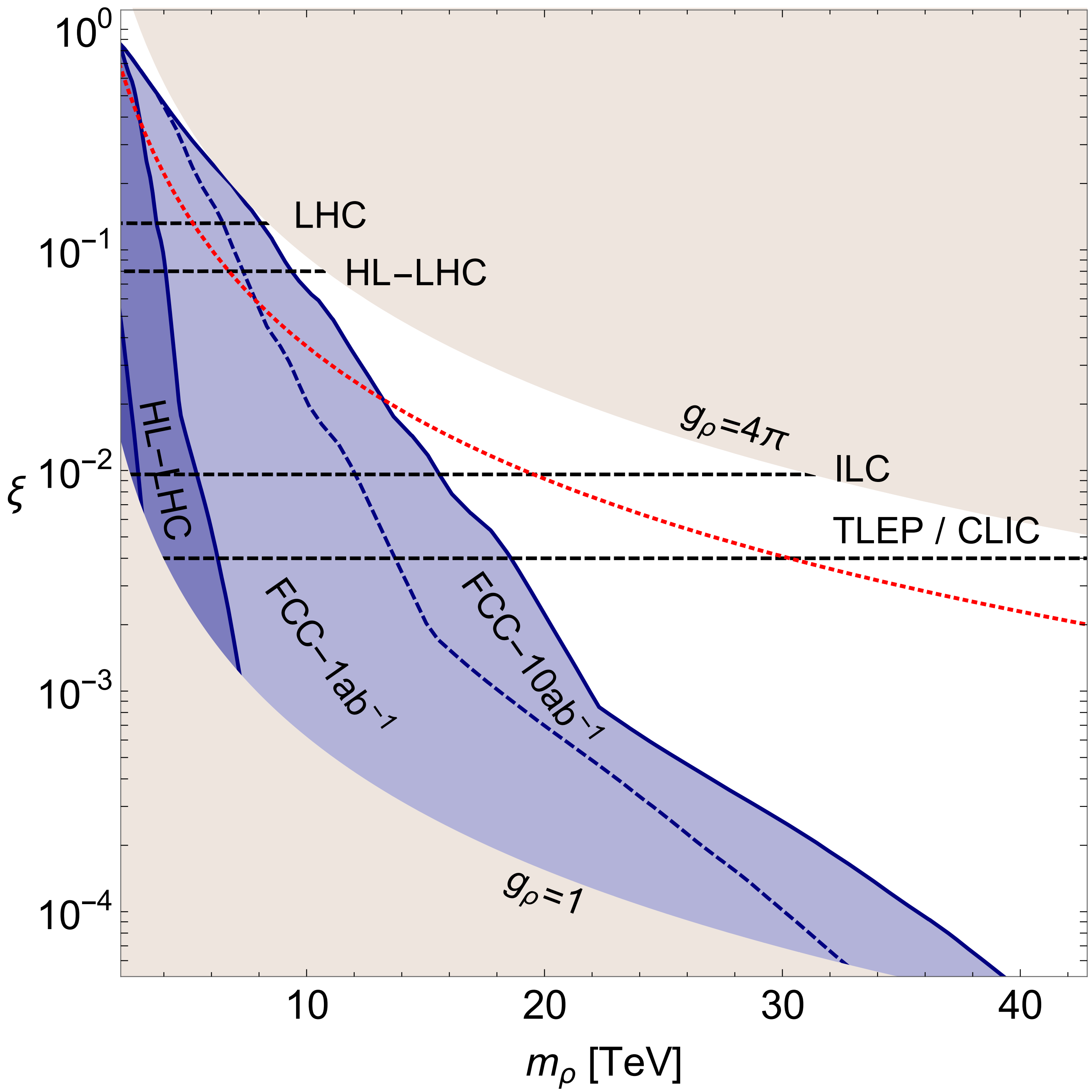
- theoretically excluded $1 \leq g_\rho \leq 4\pi$
- LHC8 at 8 TeV with 20 fb^{-1}

  LHC at 14 TeV with 300 fb^{-1}

  HL-LHC at 14 TeV with 3 ab^{-1}

[Thamm, Torre, Wulzer: 1502.01701]

Results in (m_ρ, ξ)



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  HL-LHC at 14 TeV with 3 ab^{-1}

[Thamm, Torre, Wulzer: 1502.01701]

Conclusions

- Composite Higgs models provide a very compelling framework
  - resonance at ~few TeV expected
- excess
  - maybe exactly what a resonance at the verge of discovery should look like?
  - learn much more from LHC Run II
- if not: many other ways to look for compositeness
  - direct: vector resonance and top partners
  - indirect: coupling modifications
- LHC probes only small region of parameter space
  - could learn a lot from future collider!