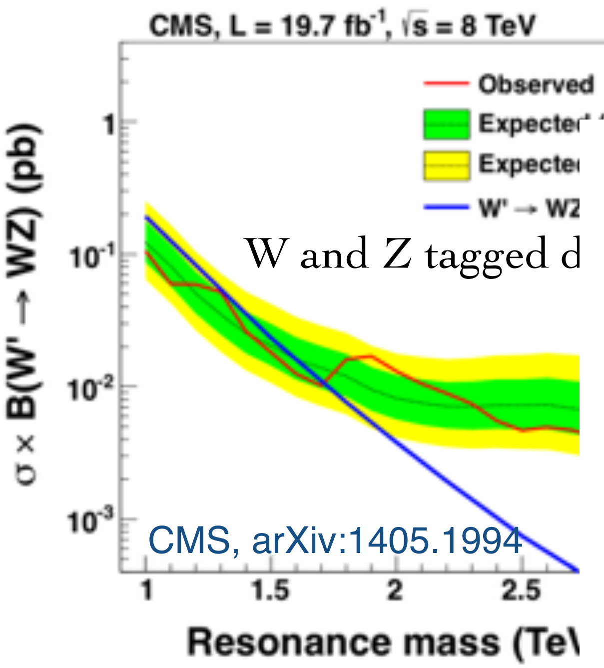
Gearing up for LHC 13, GGI, 18 September 2015

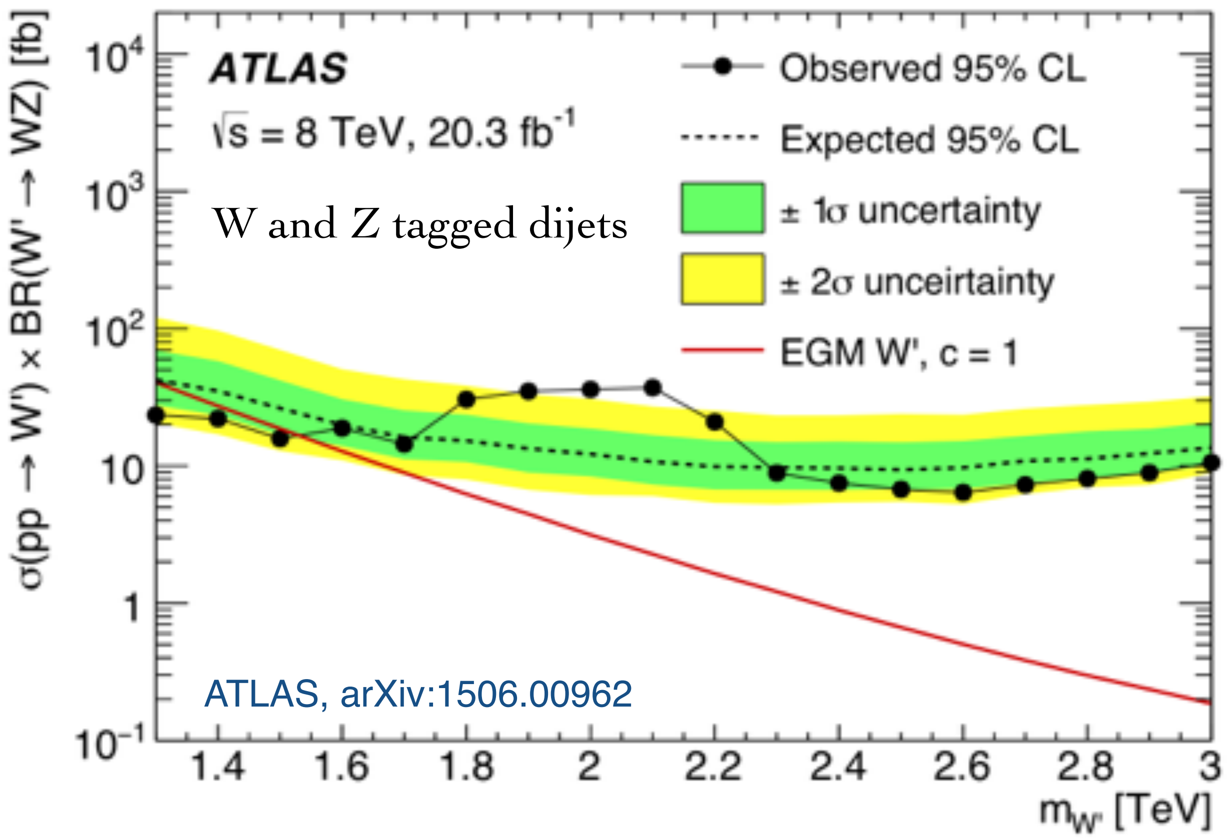
Composite heavy vector triples in the ATLAS di-boson excess and at future colliders

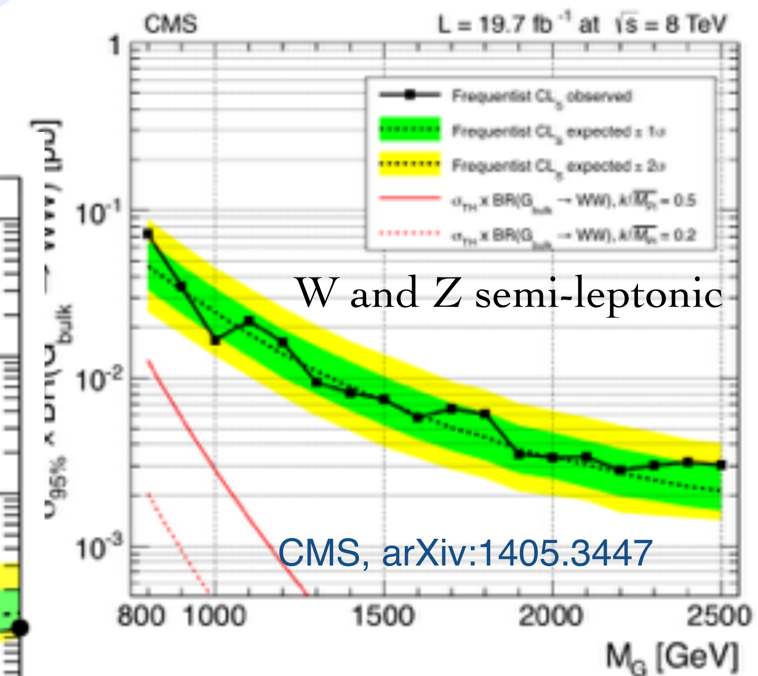
Andrea Thamm
JGU Mainz

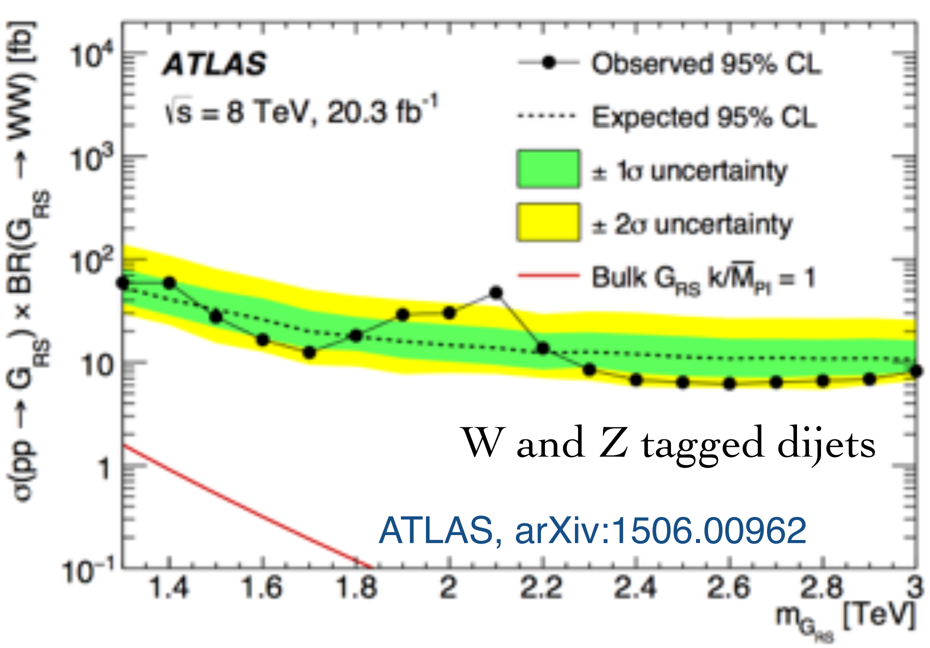
in collaboration with R. Torre and A. Wulzer
based on arXiv: 1506.08688 and 1502.01701

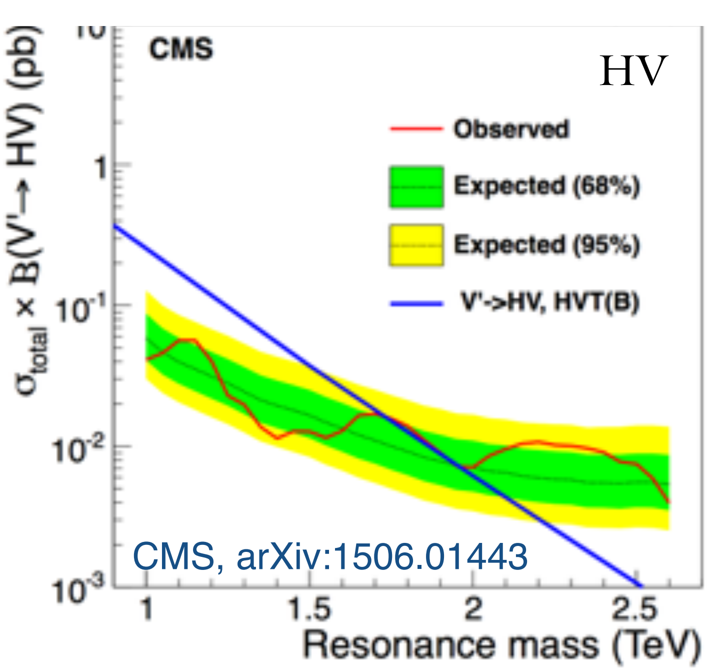
Di-boson excess?

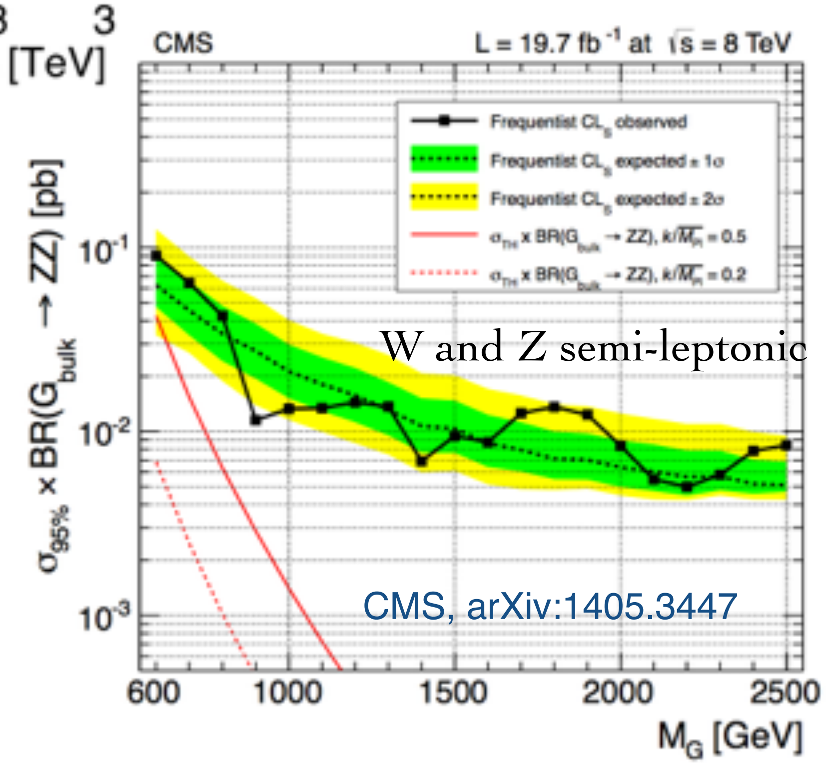




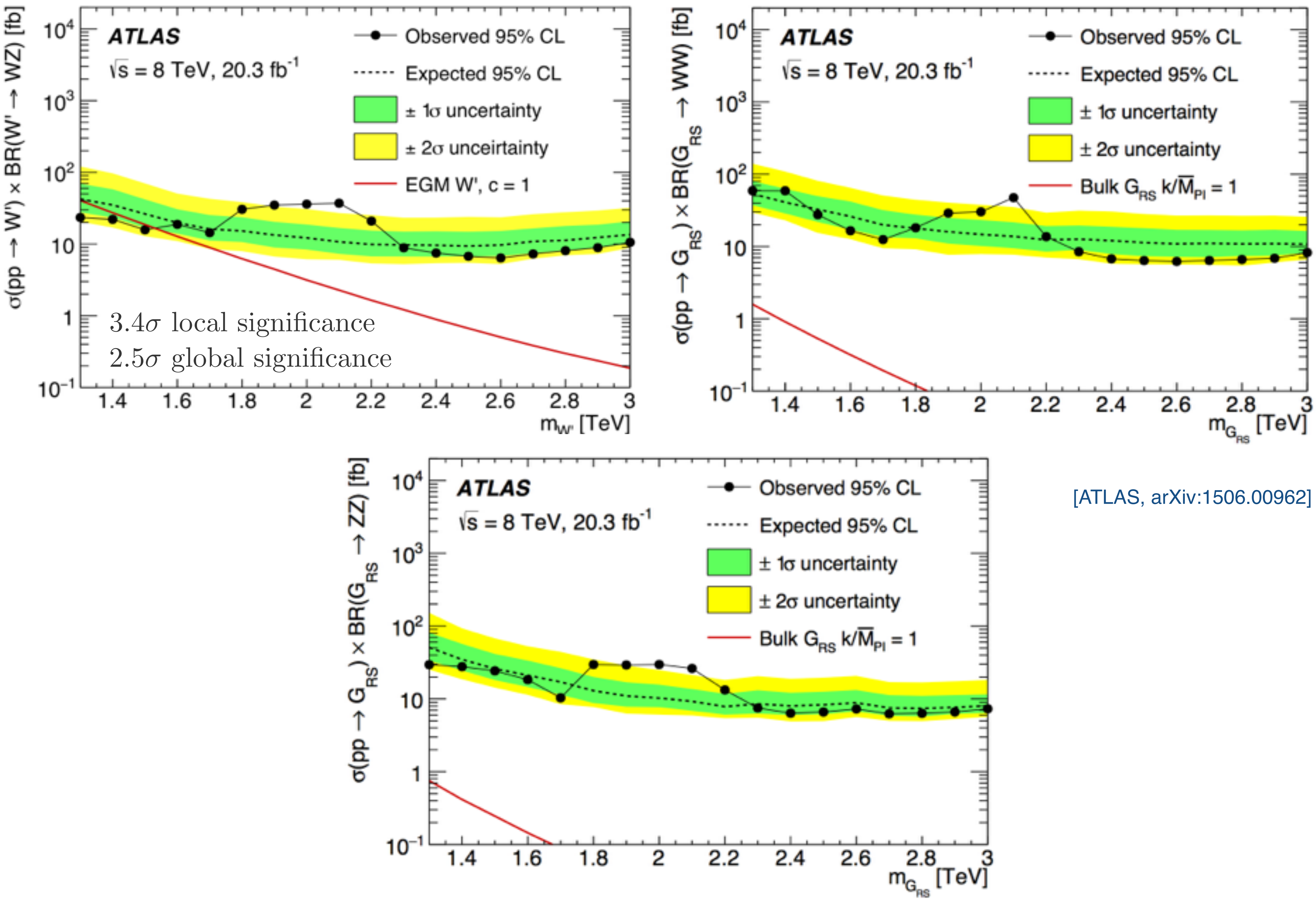








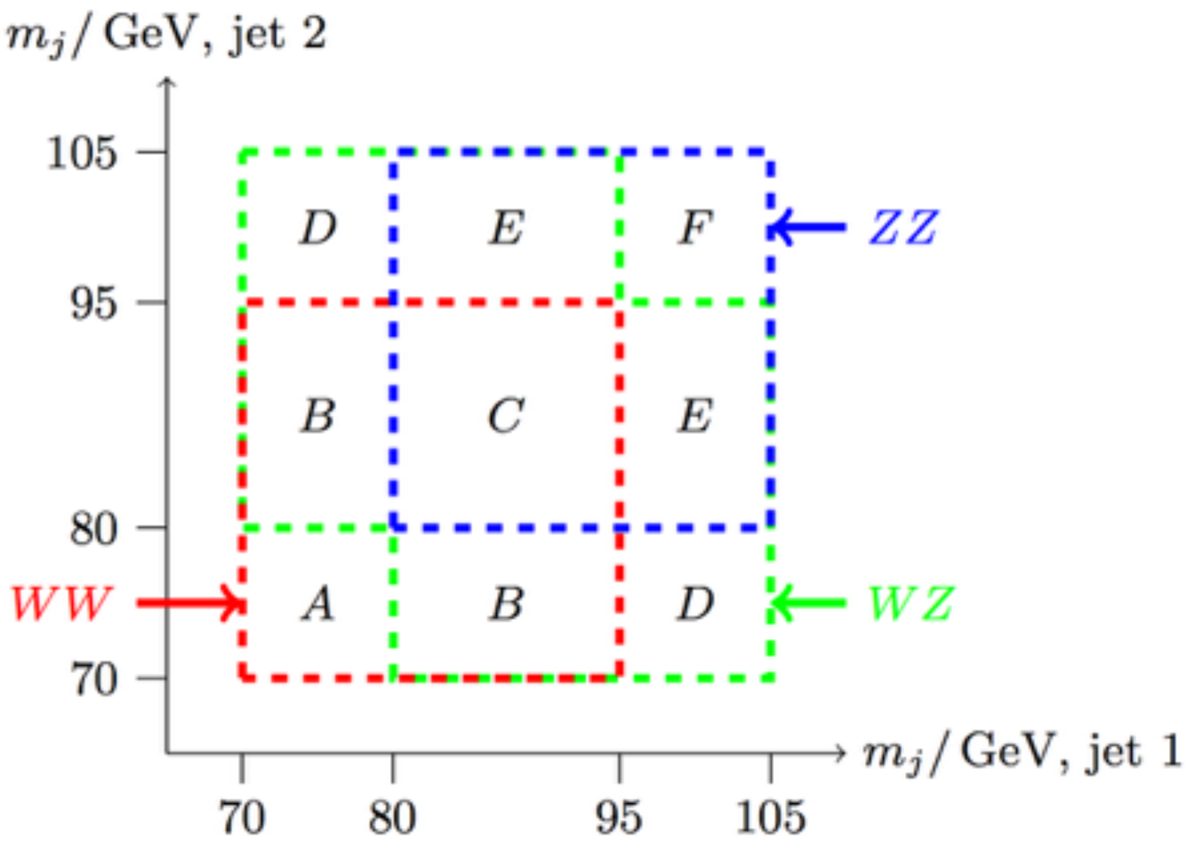
Di-boson excess?



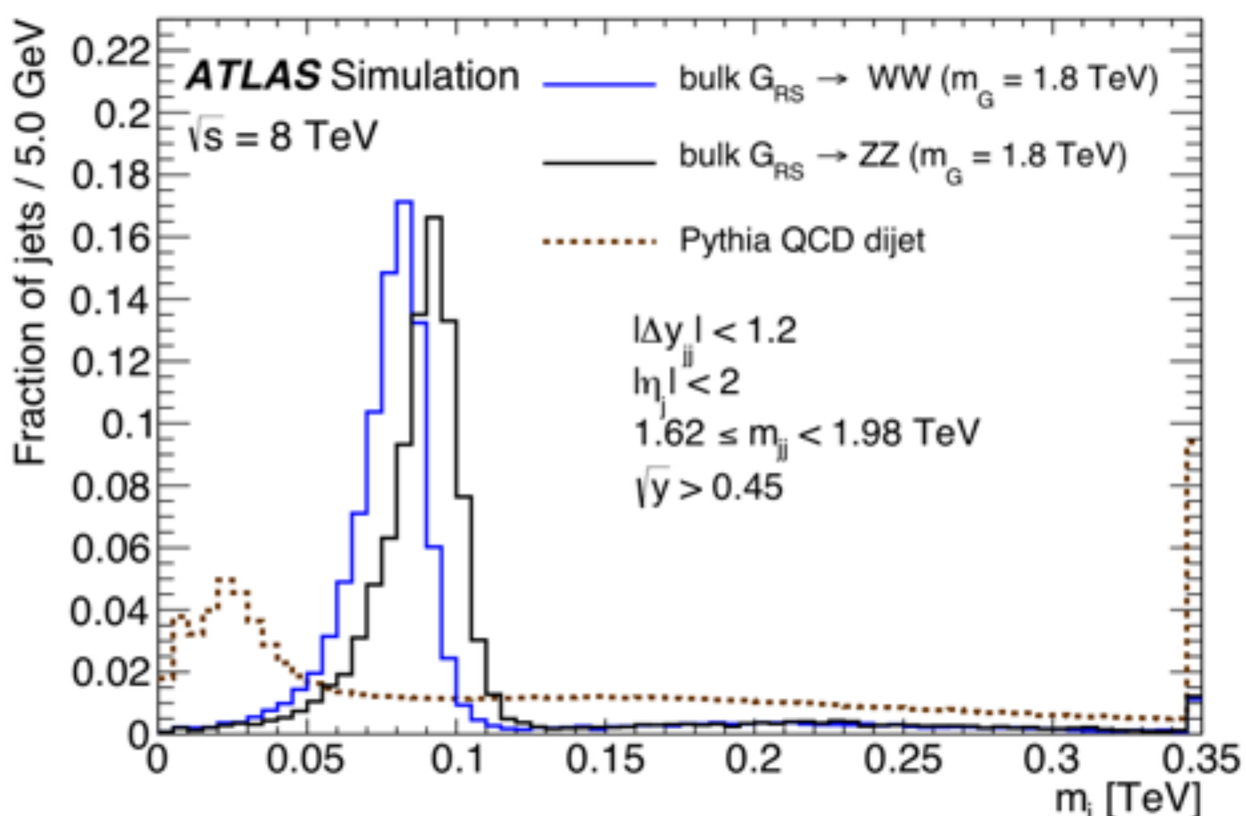
[ATLAS, arXiv:1506.00962]

Tagging efficiencies

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



[Allanach, Gripaios, Sutherland: arXiv:1507.01638]

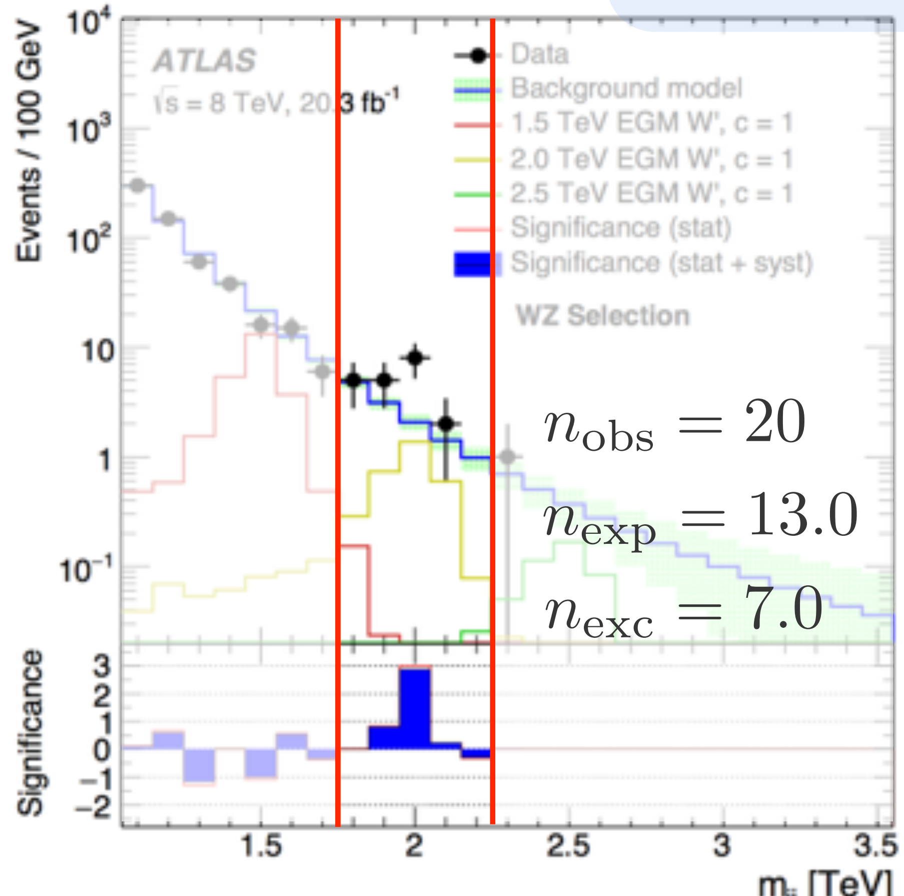


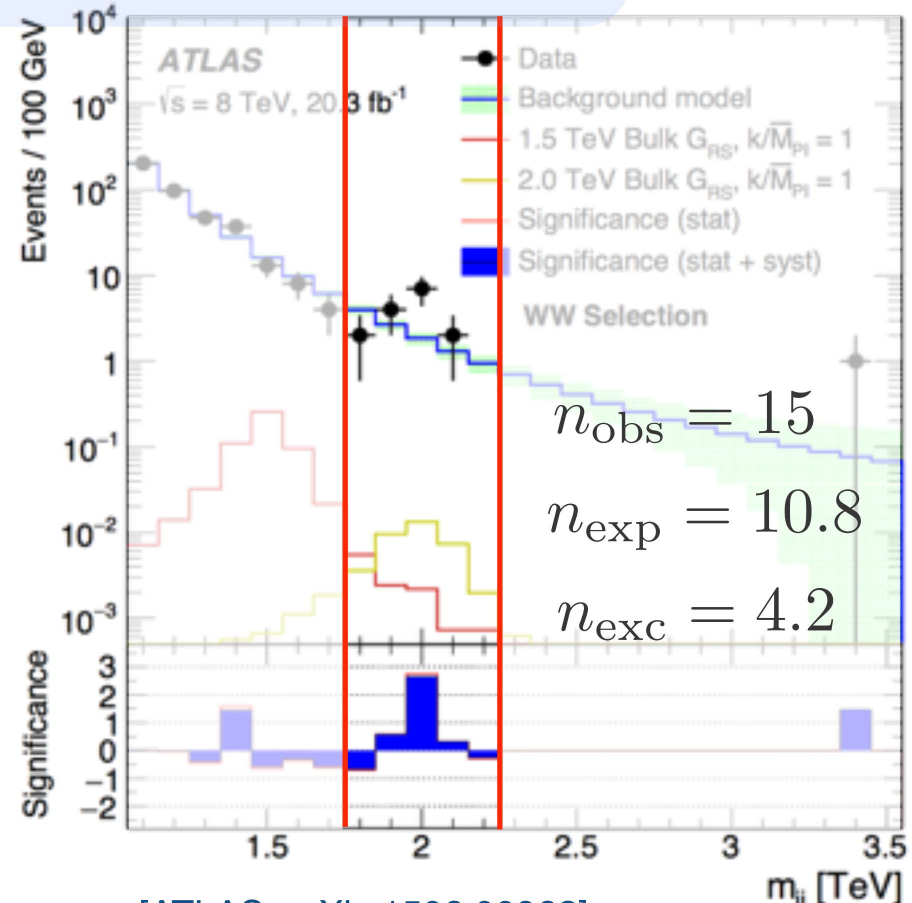
[ATLAS, arXiv:1506.00962]

- efficiency of jet invariant mass cuts

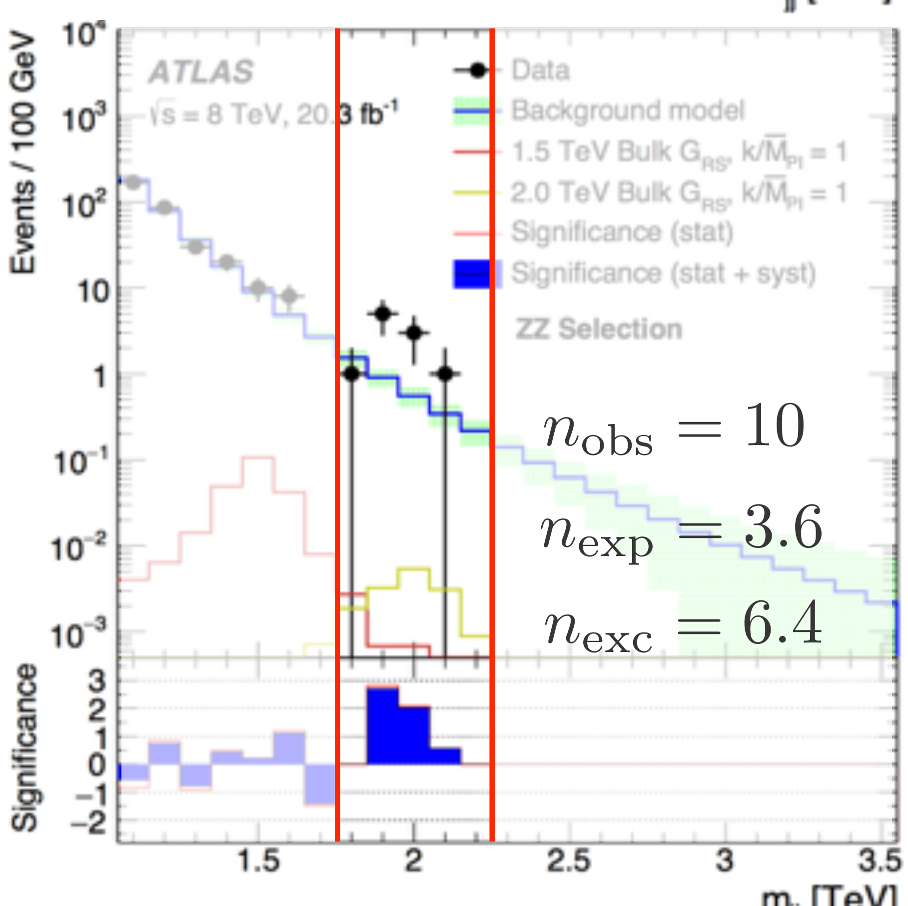
$$\begin{bmatrix} \epsilon_{WW\to WW} & \epsilon_{WZ\to WW} \\ \epsilon_{WW\to WZ} & \epsilon_{WZ\to WZ} \\ \epsilon_{WW\to ZZ} & \epsilon_{WZ\to ZZ} \end{bmatrix} = \begin{bmatrix} 0.51 & 0.42 \\ 0.48 & 0.57 \\ 0.21 & 0.32 \end{bmatrix}$$

Excess events





[ATLAS, arXiv:1506.00962]



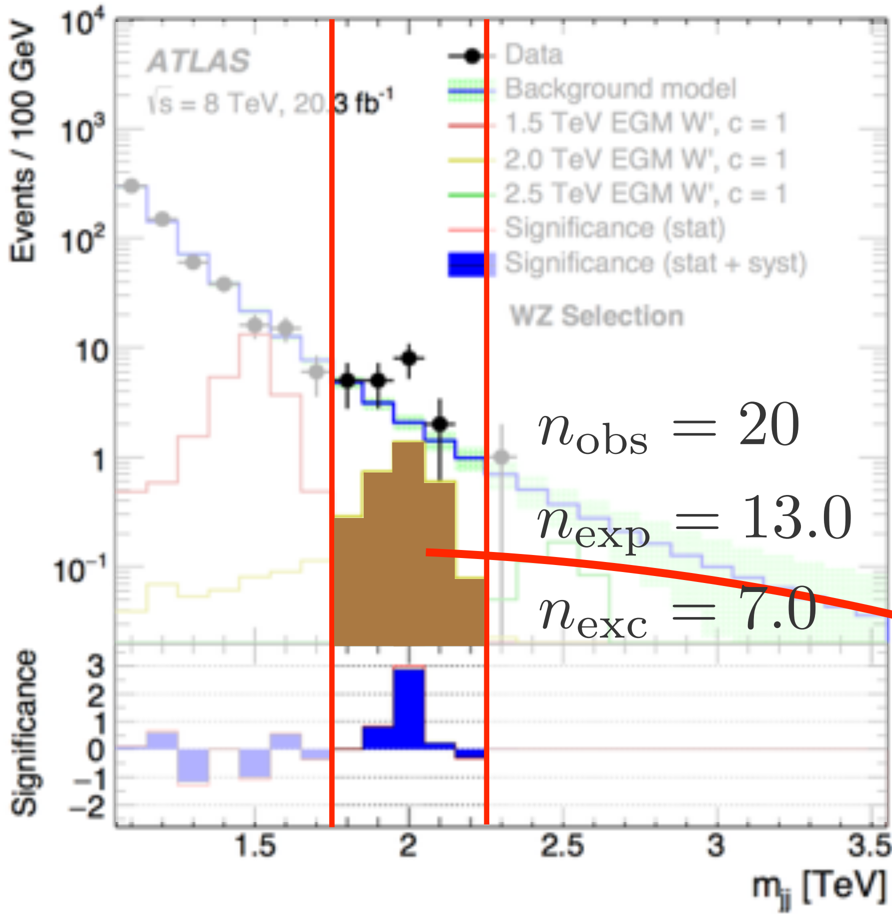
Big statistical uncertainties:

$$S_{WZ} = 7.0^{+3.8}_{-2.6}$$
$$S_{WW} = 4.2^{+3.2}_{-2.0}$$
$$S_{ZZ} = 6.4^{+3.6}_{-2.4}$$

combined fit only by ATLAS
lack information on the correlation of the big systematic uncertainties

We extract the signal CS from a single channel and compare with the others

Signal cross section



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

m [TeV]	$\Gamma_{W'}$ [GeV]	$\Gamma_{G_{\rm RS}}$ [GeV]	$W' \to WZ$ $\sigma \times$BR [fb]	$W' \to WZ$ $f_{10\%}$	$G_{\rm RS} \to WW$ $\sigma \times$BR [fb]	$G_{\rm RS} \to WW$ $f_{10\%}$	$G_{\rm RS} \to ZZ$ $\sigma \times$BR [fb]	$G_{\rm RS} \to ZZ$ $f_{10\%}$
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

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

3.4 events

$$\sigma_{W'} \times \mathrm{BR}_{W'\to WZ} = 6.5^{+5.1}_{-4.1} \text{ fb}$$

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

Heavy vector triples

Heavy vector triples

- 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 $SU(2)_L$

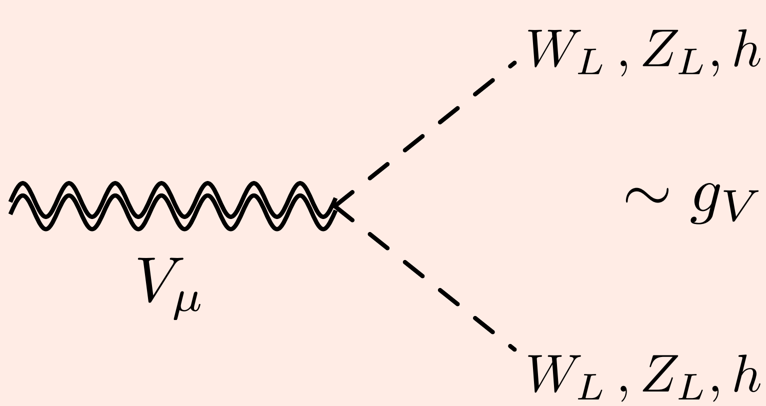
Phenomenological Lagrangian

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a} \qquad V = (V^+, V^-, V^0)$$

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

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

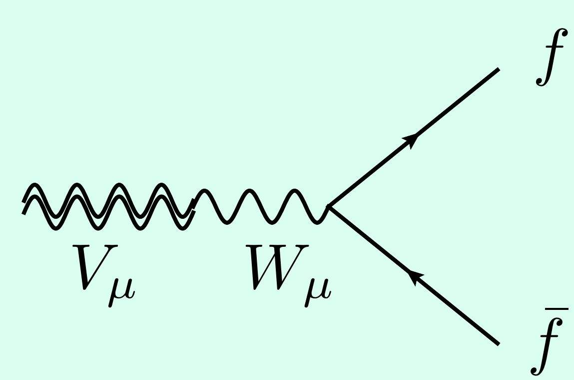
Coupling to SM Vectors



$\sim g_V c_H$

Coupling to SM fermions

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



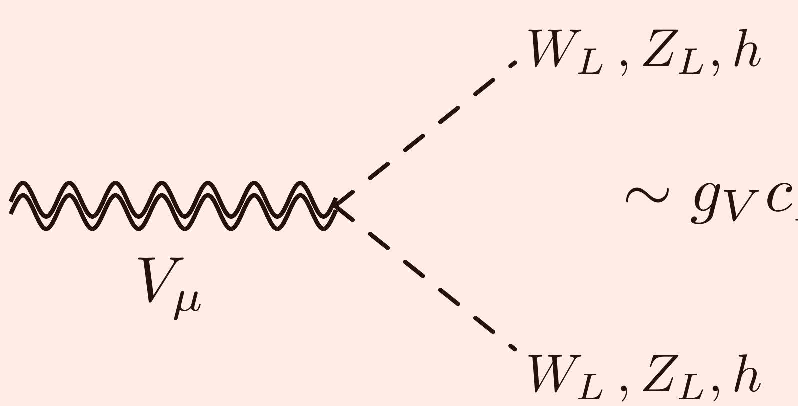
$$\sim \frac{g}{g_V} \times g\, c_F$$

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

Phenomenological Lagrangian

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a} \qquad V = \left(V^+, V^-, V^0\right)$$
$$+\, i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a}$$
$$+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V_\mu^b V_\nu^c$$

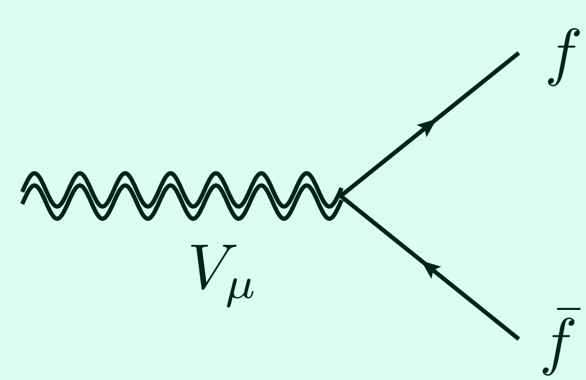
Coupling to SM Vectors



$\sim g_V c_H$

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

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

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

- 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)

Phenomenological Lagrangian

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

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

Weakly coupled model

Strongly coupled model

g_V typical strength of V interactions

$g_V \sim g \sim 1$

$1 < g_V \leq 4\pi$

c_i dimensionless coefficients

$c_H \sim -g^2/g_V^2$ and $c_F \sim 1$

$c_H \sim c_F \sim 1$

Production rates

- DY and VBF production

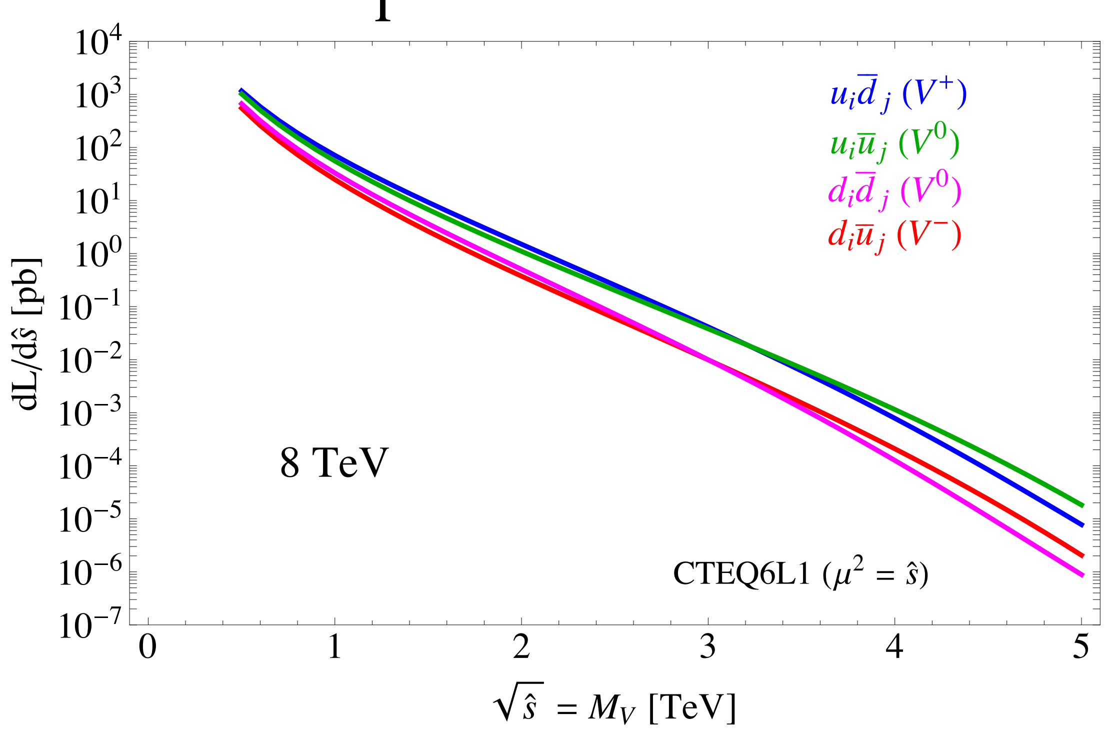
$$\sigma_{DY} = \sum_{i,j\in p} \frac{\Gamma_{V\to ij}}{M_V}\frac{4\pi^2}{3}\frac{dL_{ij}}{d\hat{s}}\Bigg|_{\hat{s}=M_V^2} \qquad \sigma_{VBF} = \sum_{i,j\in p} \frac{\Gamma_{V\to W_{L\,i}W_{L\,j}}}{M_V}48\pi^2\frac{dL_{W_{L\,i}W_{L\,j}}}{d\hat{s}}\Bigg|_{\hat{s}=M_V^2}$$

model dependent

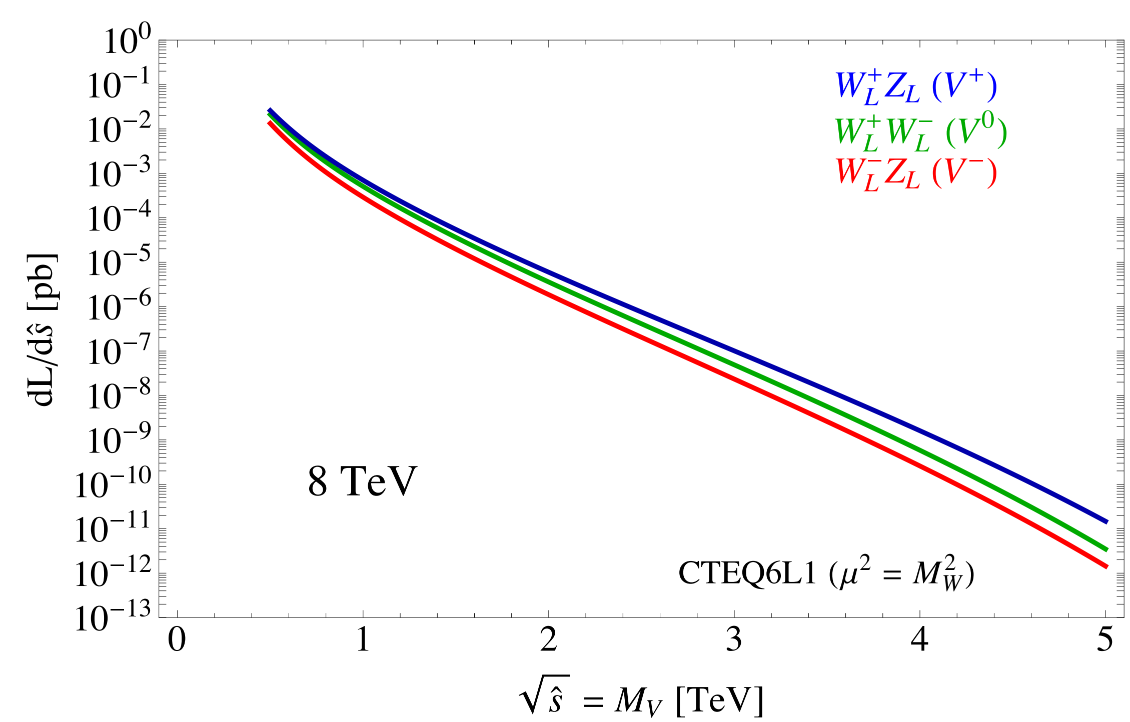
model independent

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

quark initial state



vector boson initial state



Decay widths

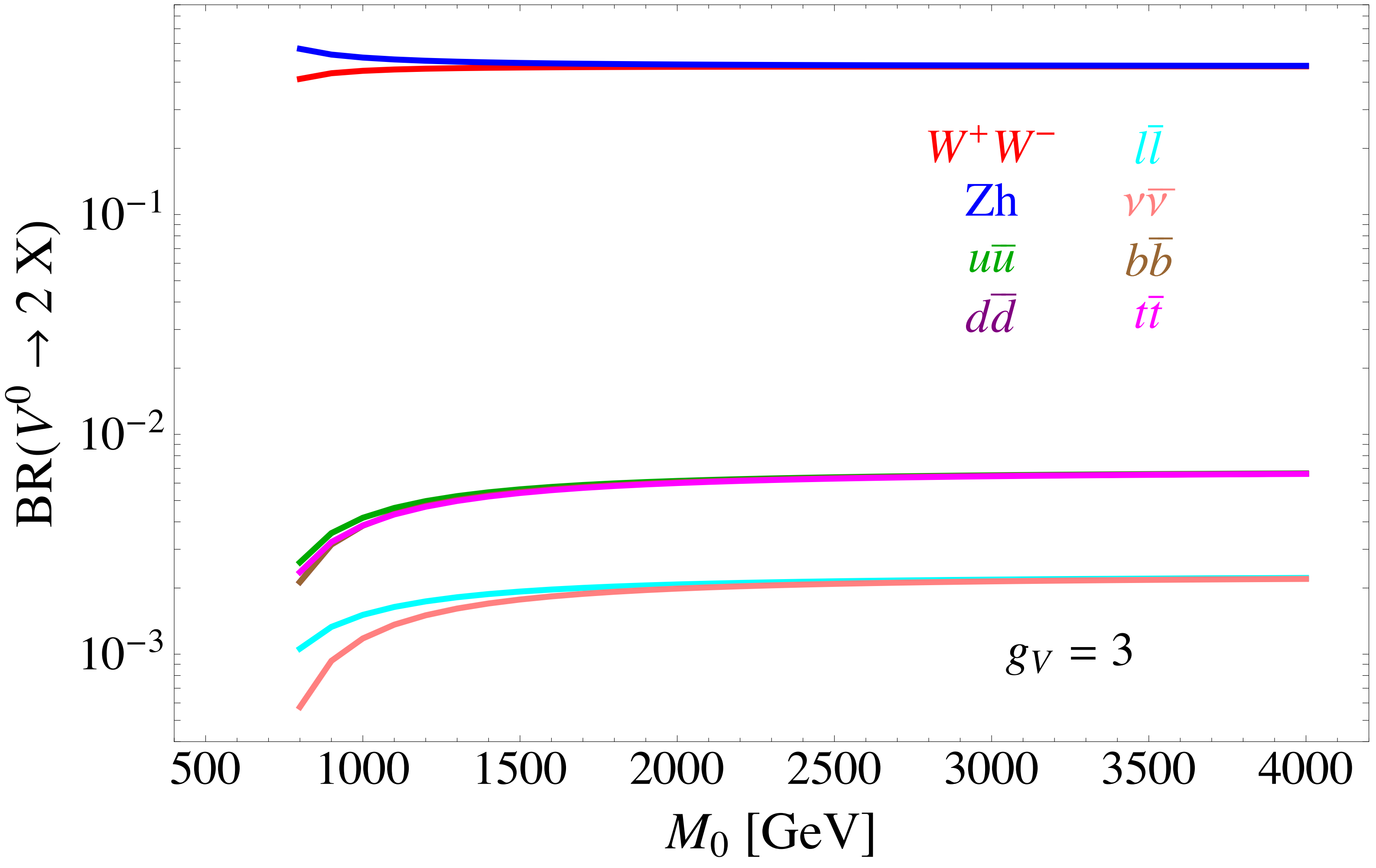
- relevant decay channels: di-lepton, di-quark, di-boson

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

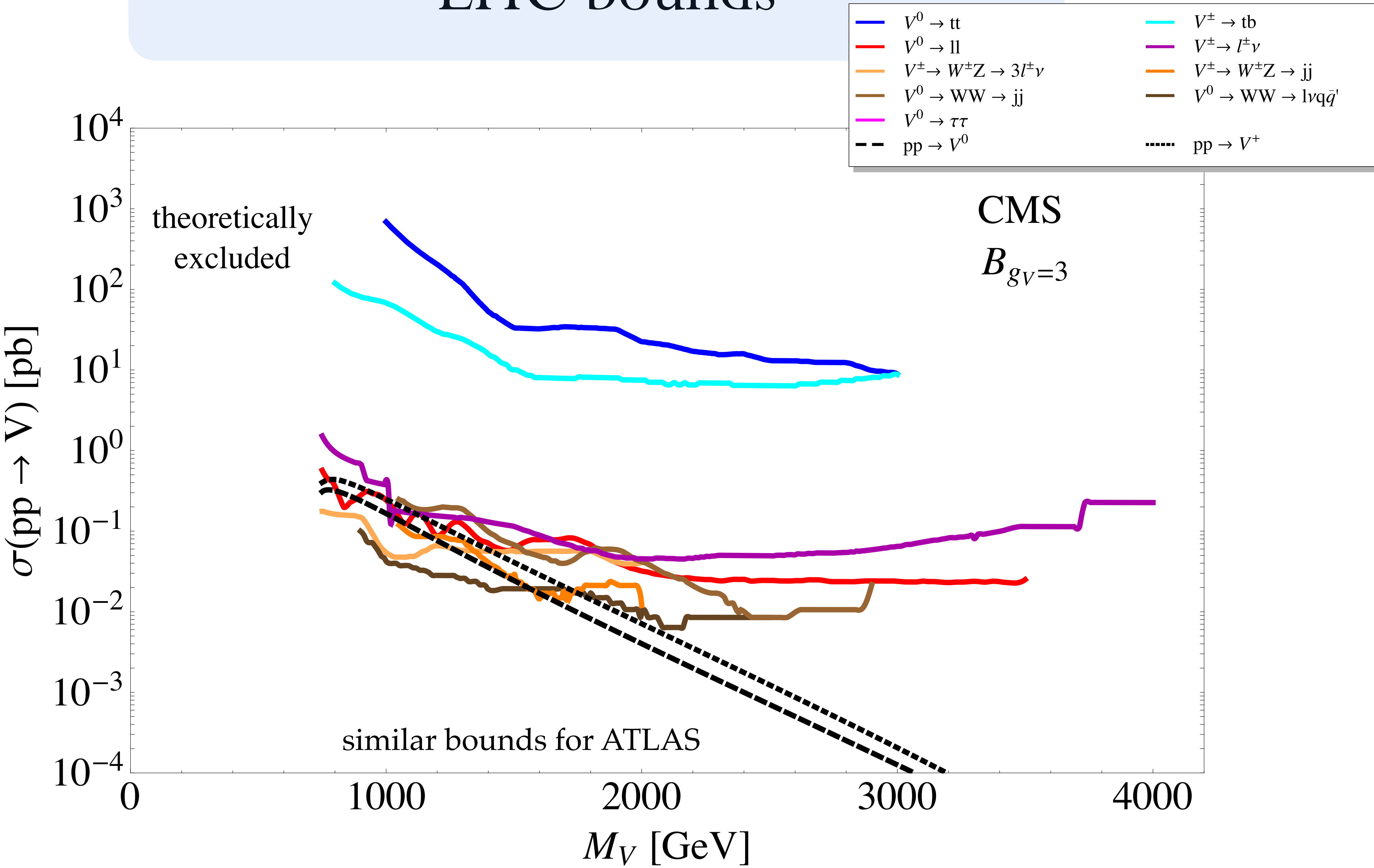
$$\Gamma_{V_0 \to W_L^+ W_L^-} \simeq \Gamma_{V_\pm \to W_L^\pm Z_L} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}\left[1+\mathcal{O}(\zeta^2)\right]$$

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

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



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

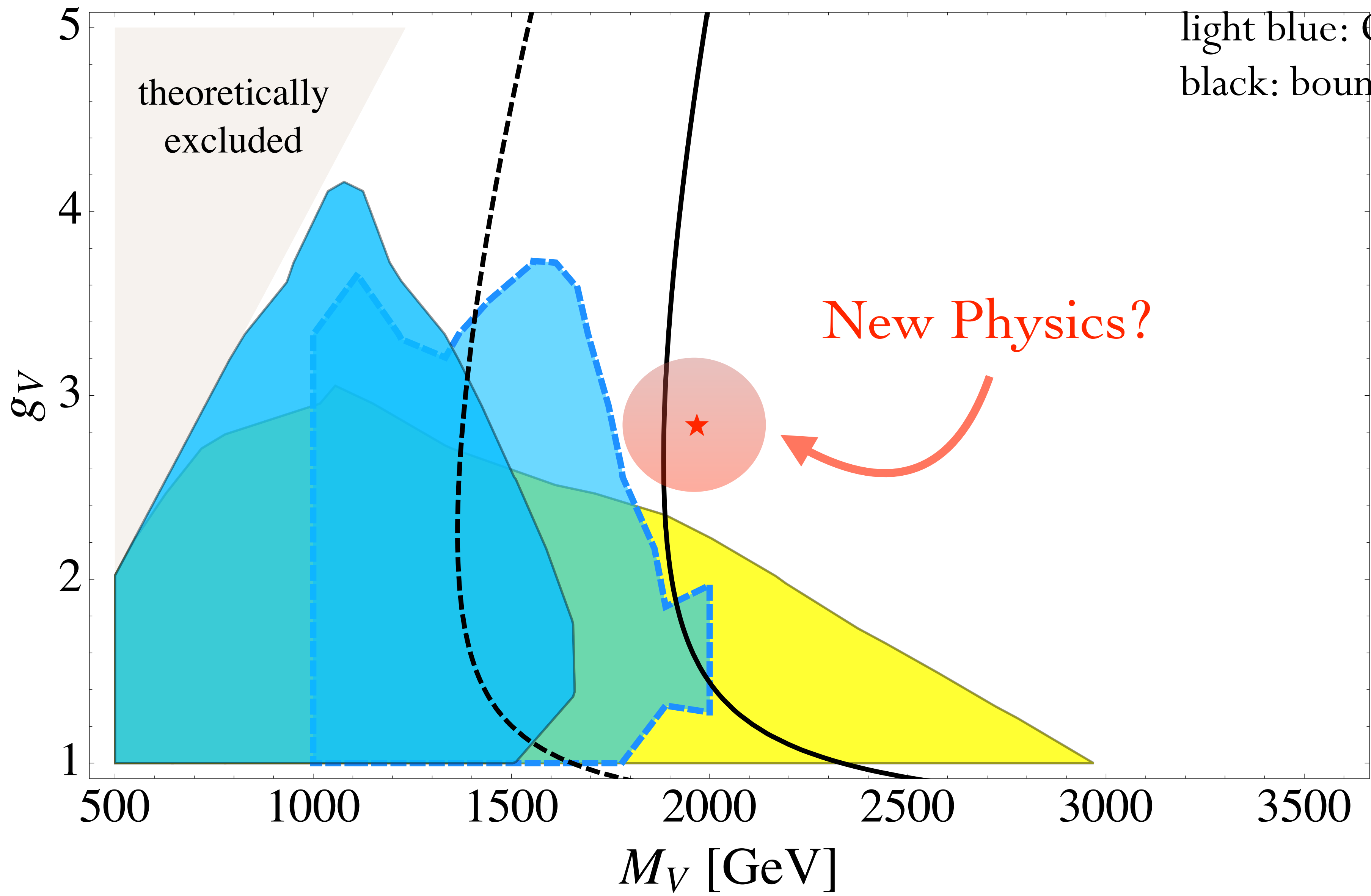
Heavy vector triples in the di-boson excess

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

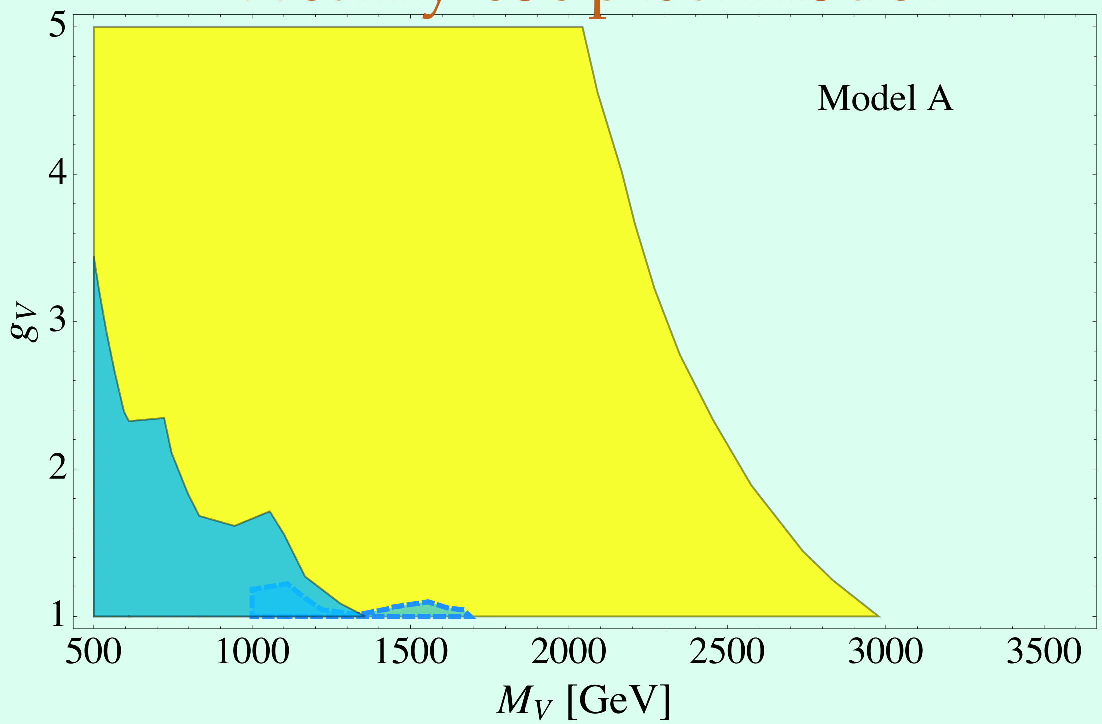
[Greco, Liu: arXiv:1410.2883]
[Chala, Juknevich, Perez, Santiago :arXiv:1411.1771]

LHC bounds

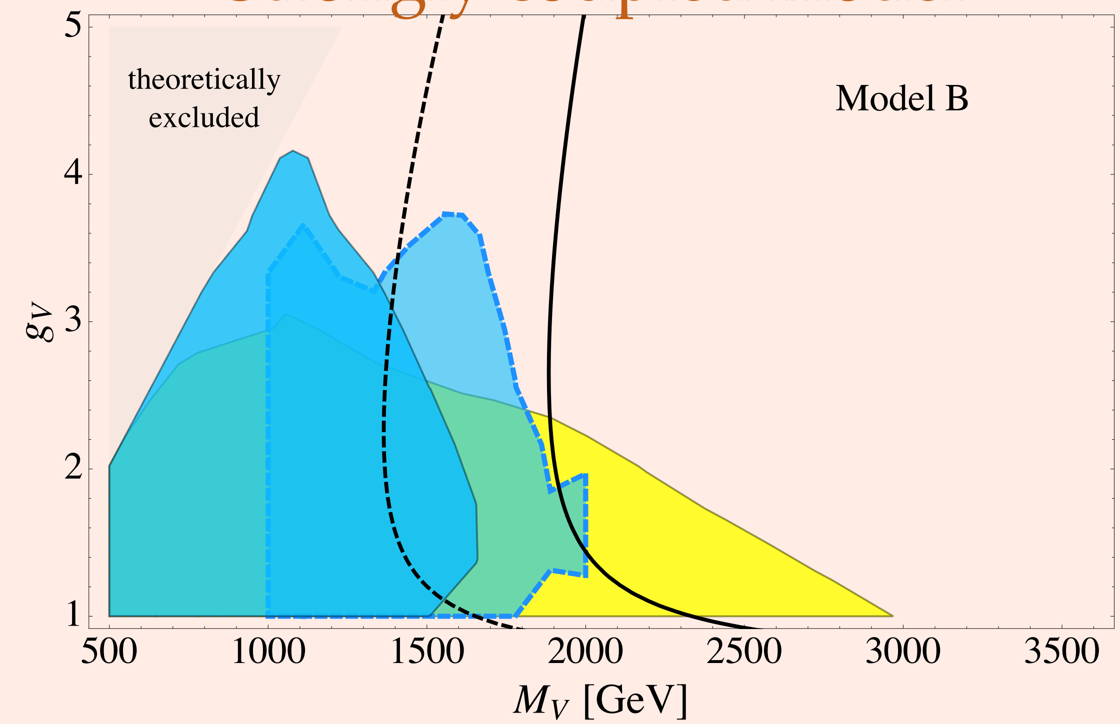
- compare with weakly coupled vectors

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

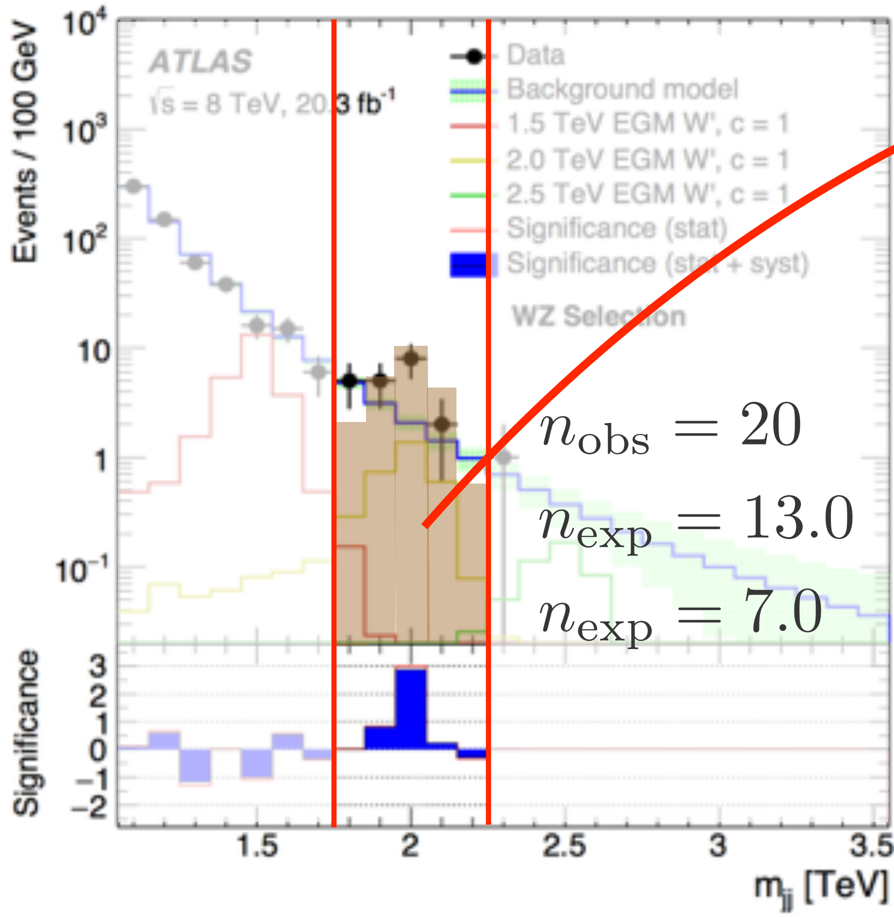
[Pappadopulo, Thamm, Torre, Wulzer, arXiv:1402.4431]

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



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

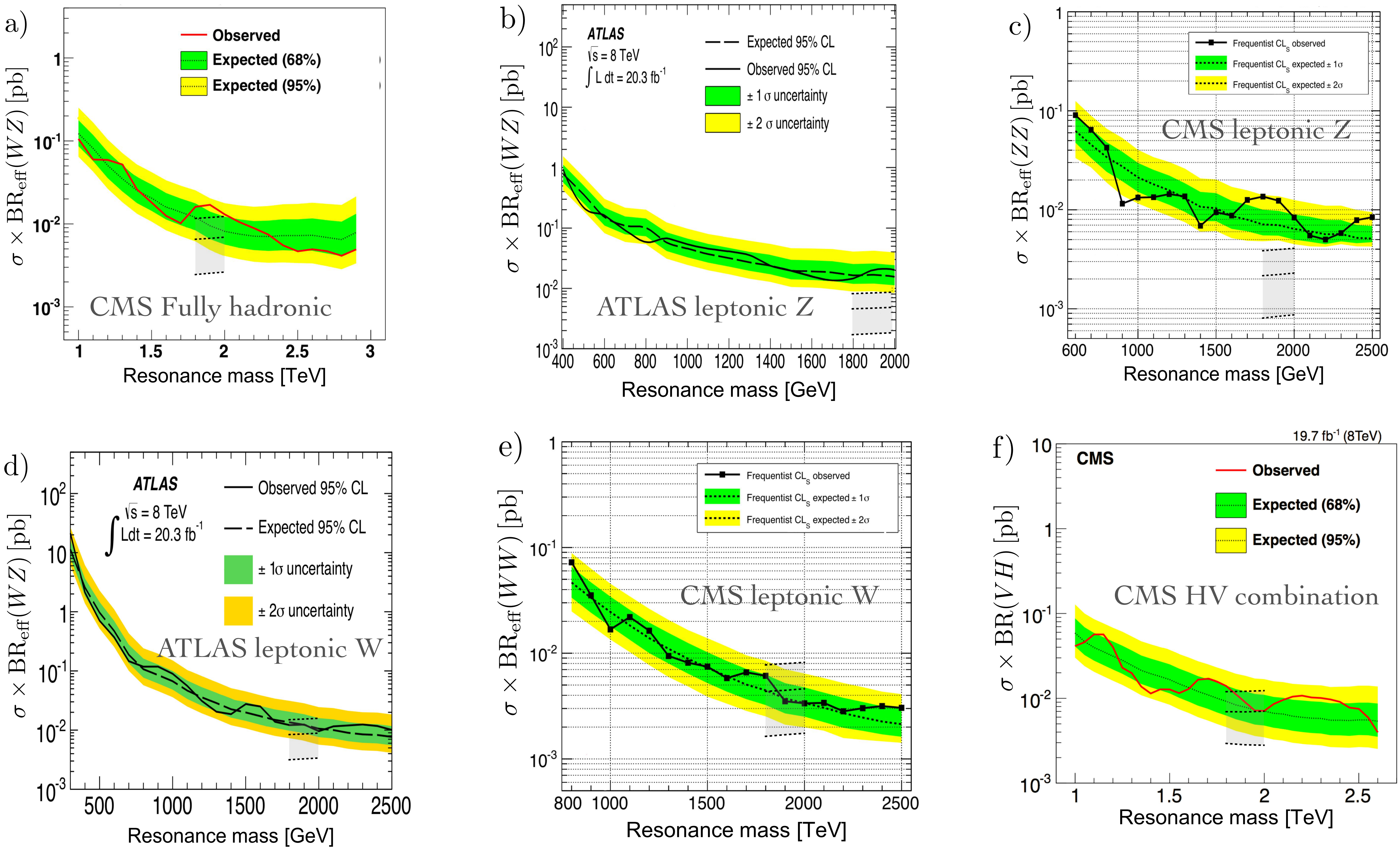
[Thamm, Torre, Wulzer, arXiv:1506.08688]

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

$$S_{WW} \in [2.2, 10.3] \qquad S_{ZZ} \in [1.4, 6.6]$$

$$S_{WW} = 4.2^{+3.2}_{-2.0} \qquad S_{ZZ} = 6.4^{+3.6}_{-2.4}$$

Compatibility with other searches



Thamm, Torre, Wulzer, arXiv:1506.08688

Conclusion I

- perfectly agrees with some channels
- could maybe even explain some small excesses
- maybe slight tension in other channels
- maybe this is exactly what we expect?

Heavy vector triples at future colliders

Composite Higgs models at future colliders

Limit extrapolation

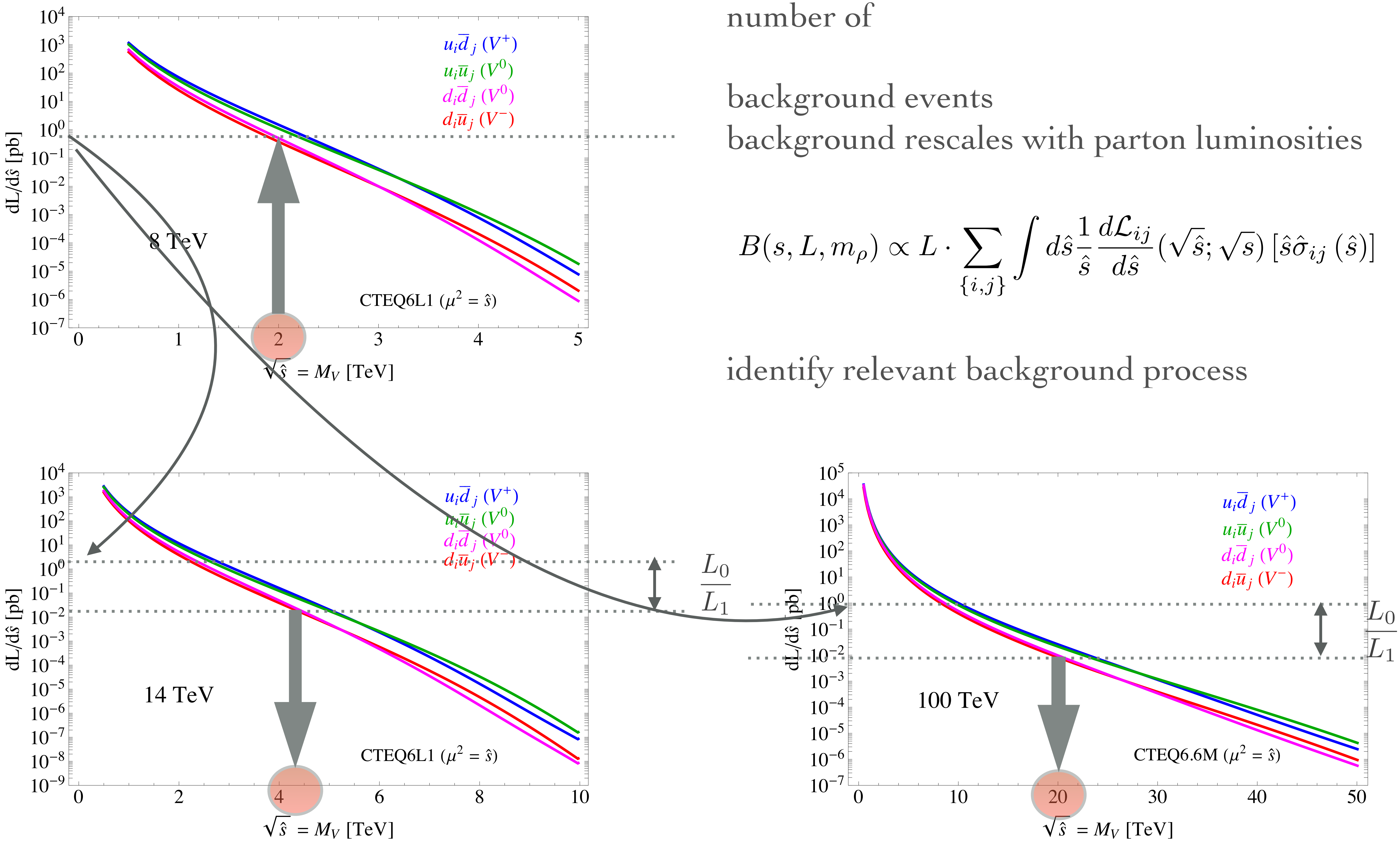
assume: excluded signal is only a function of number of

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



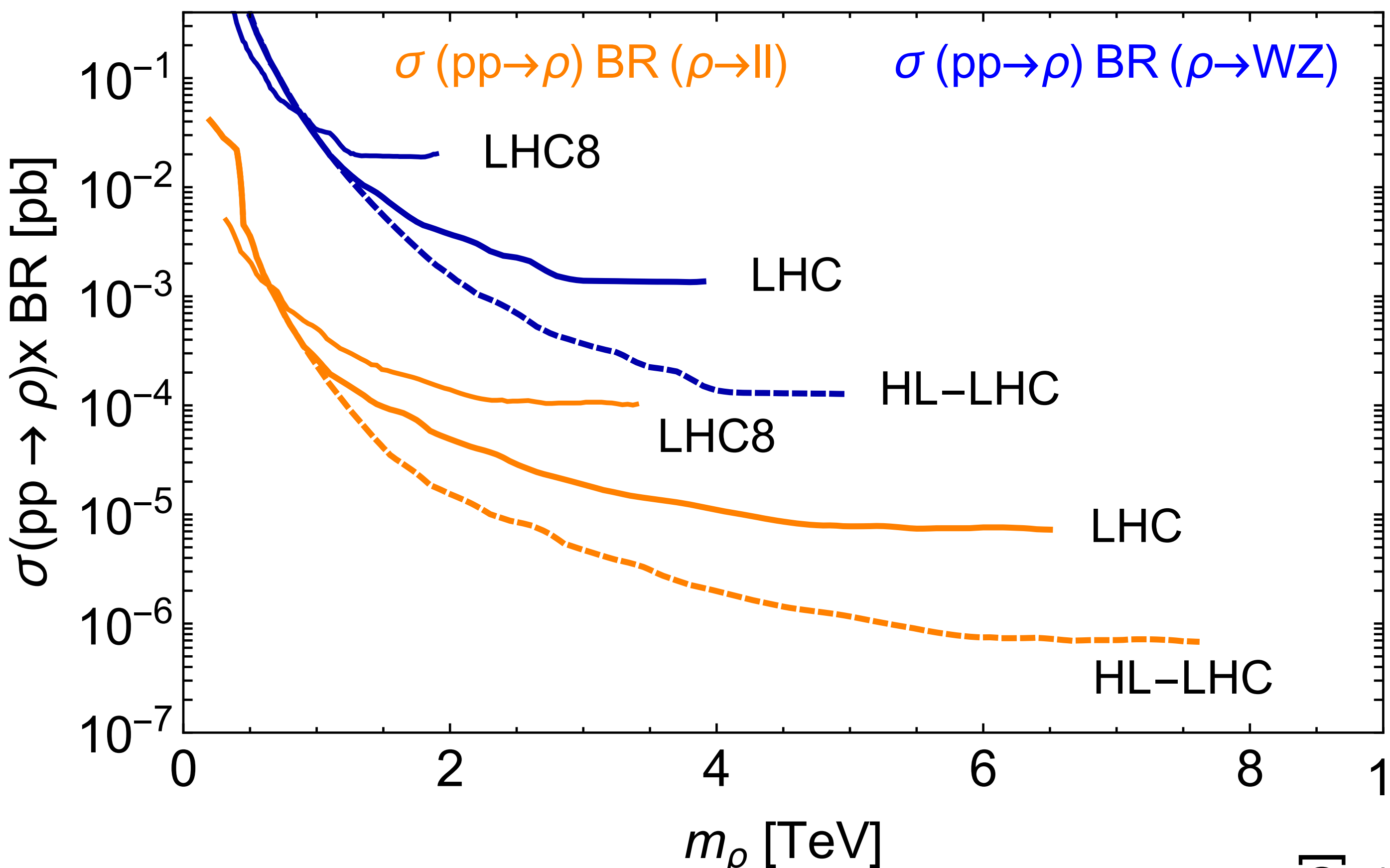
[Thamm, Torre, Wulzer: 1502.01701]

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

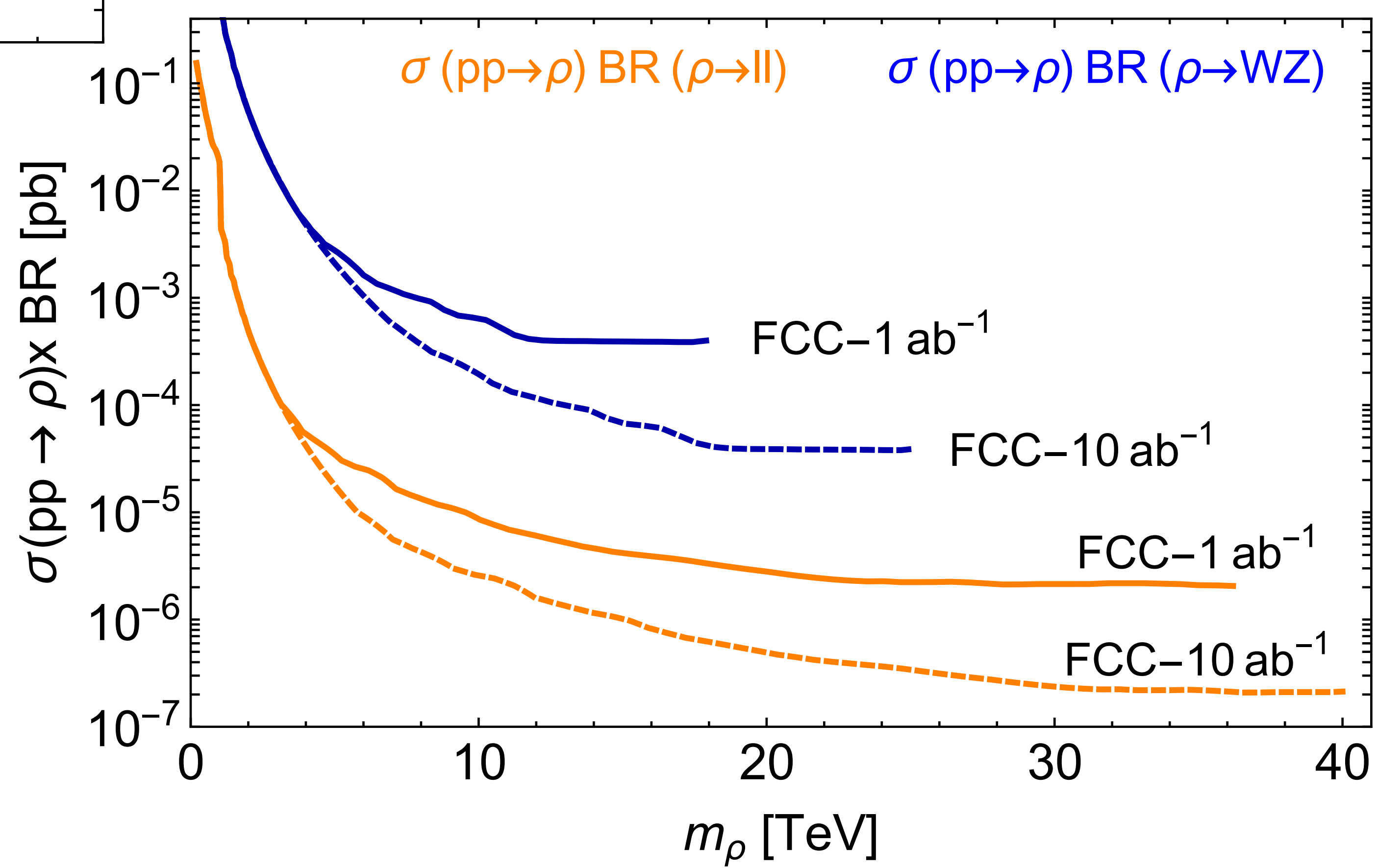


CMS search for

- 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



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 (mass controls generation of Higgs potential and fine-tuning, very model dependent)
  [Matsedonskyi, Panico, Wulzer: 1409.0100]

- modification of Higgs couplings (predictable in a fairly model-independent way)

$$a = g_{WWh} = \sqrt{1-\xi}$$

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

- Flavour

- for illustration focus on minimal composite Higgs model
- parameter space: m_ρ $\quad g_\rho \quad$ $\xi = \frac{g_\rho^2}{m_\rho^2} v^2$

Minimal Composite Higgs

[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]

assume global symmetry: SO(5)/SO(4)

breaking scale $f > v$

Higgs emerges as a pseudo-NG boson

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \dots\right)$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\left(\frac{m_h^2}{2v}\right)h^3 + d_4\left(\frac{m_h^2}{8v^2}\right)h^4 + \dots$$

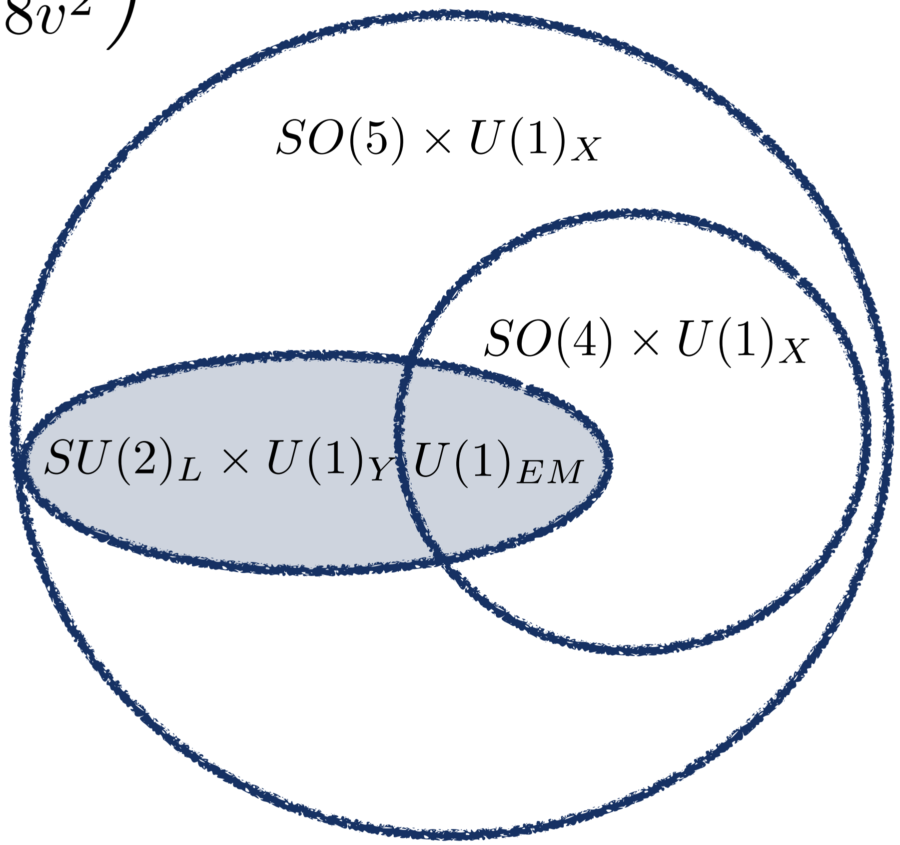
$$a = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

$$b_3 = -\frac{4}{3}\xi\sqrt{1-\xi}$$

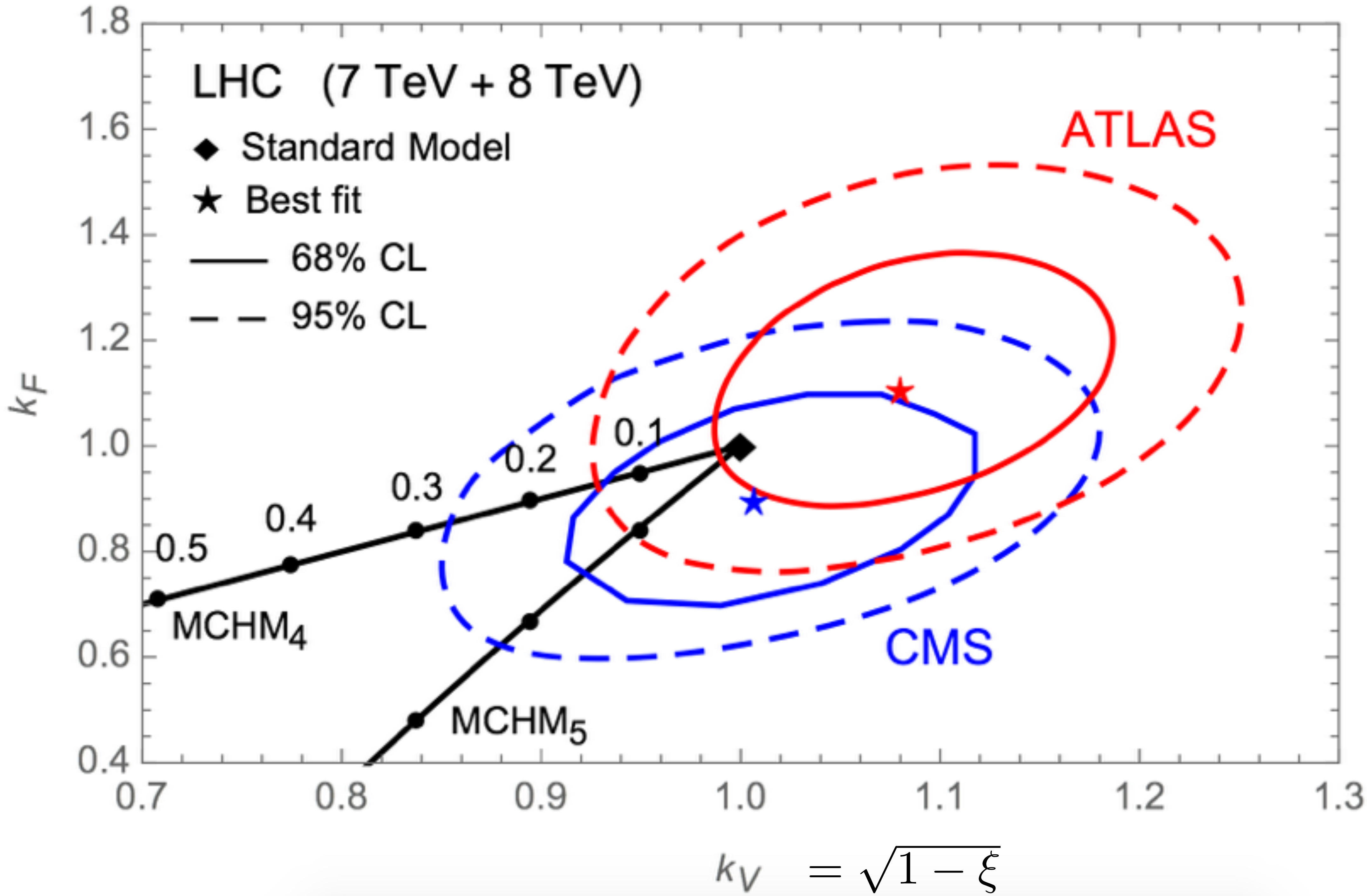
$$d_3^{(4)} = \sqrt{1-\xi}$$

where $\xi = \dfrac{v^2}{f^2}$



Higgs couplings receive corrections of order ξ

Indirect measurements



$= \sqrt{1-\xi}$

expected LHC reach: $\xi = 0.1$

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

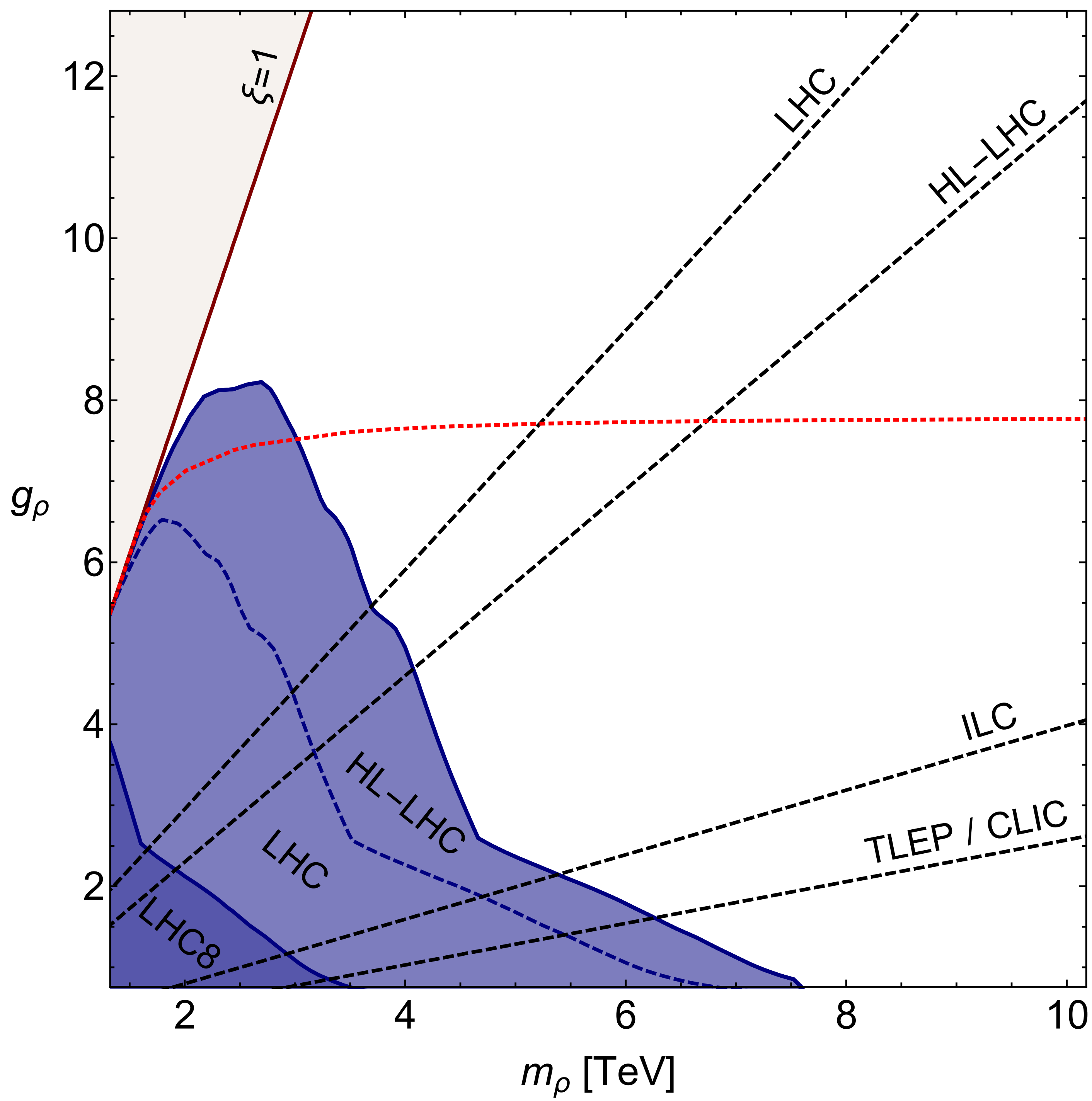
MCHM5: $k_F = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

Indirect measurements

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

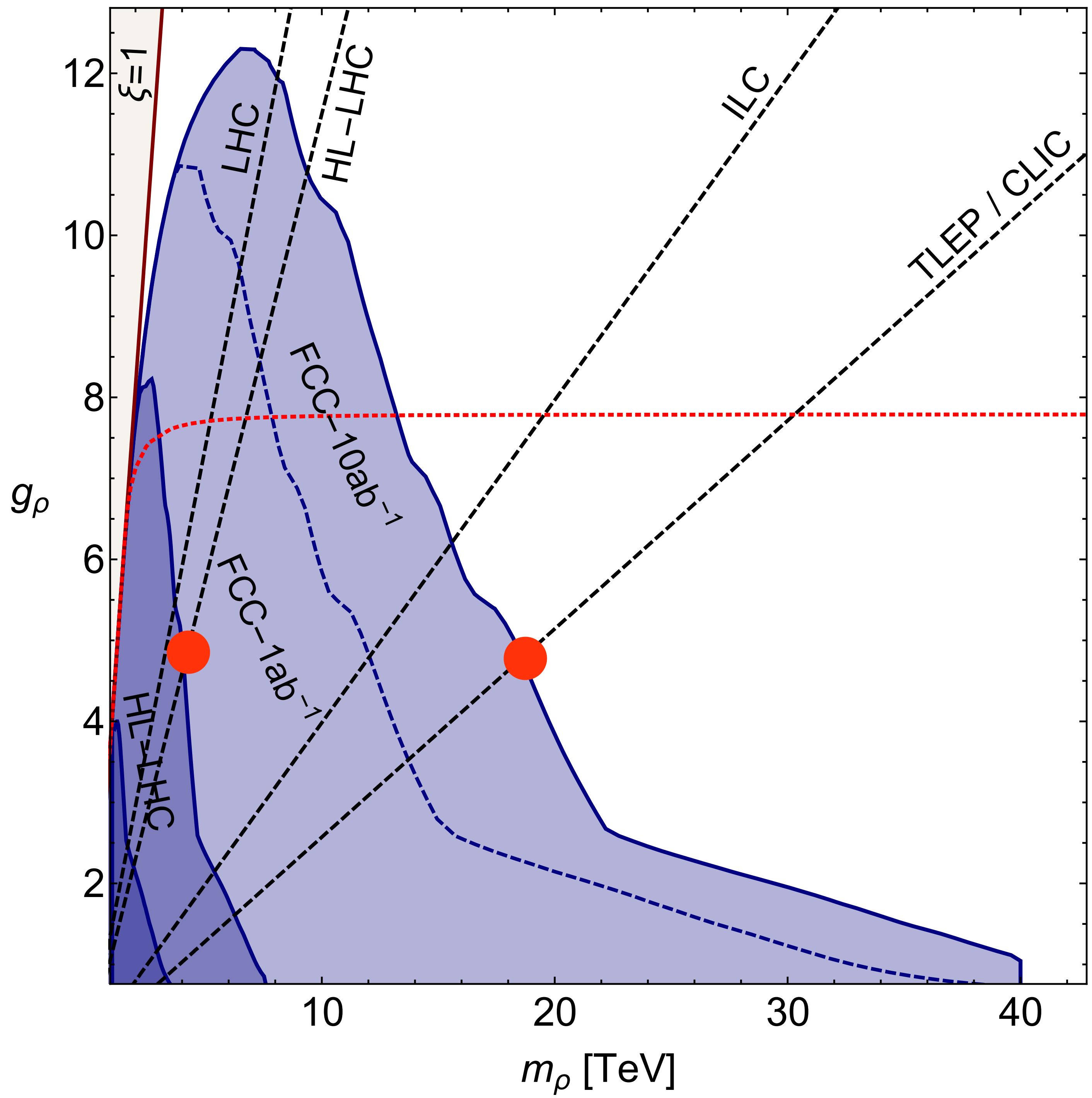
- theoretically excluded $\xi \leq 1$
- LHC8 at 8 TeV with 20 fb^{-1}

  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}

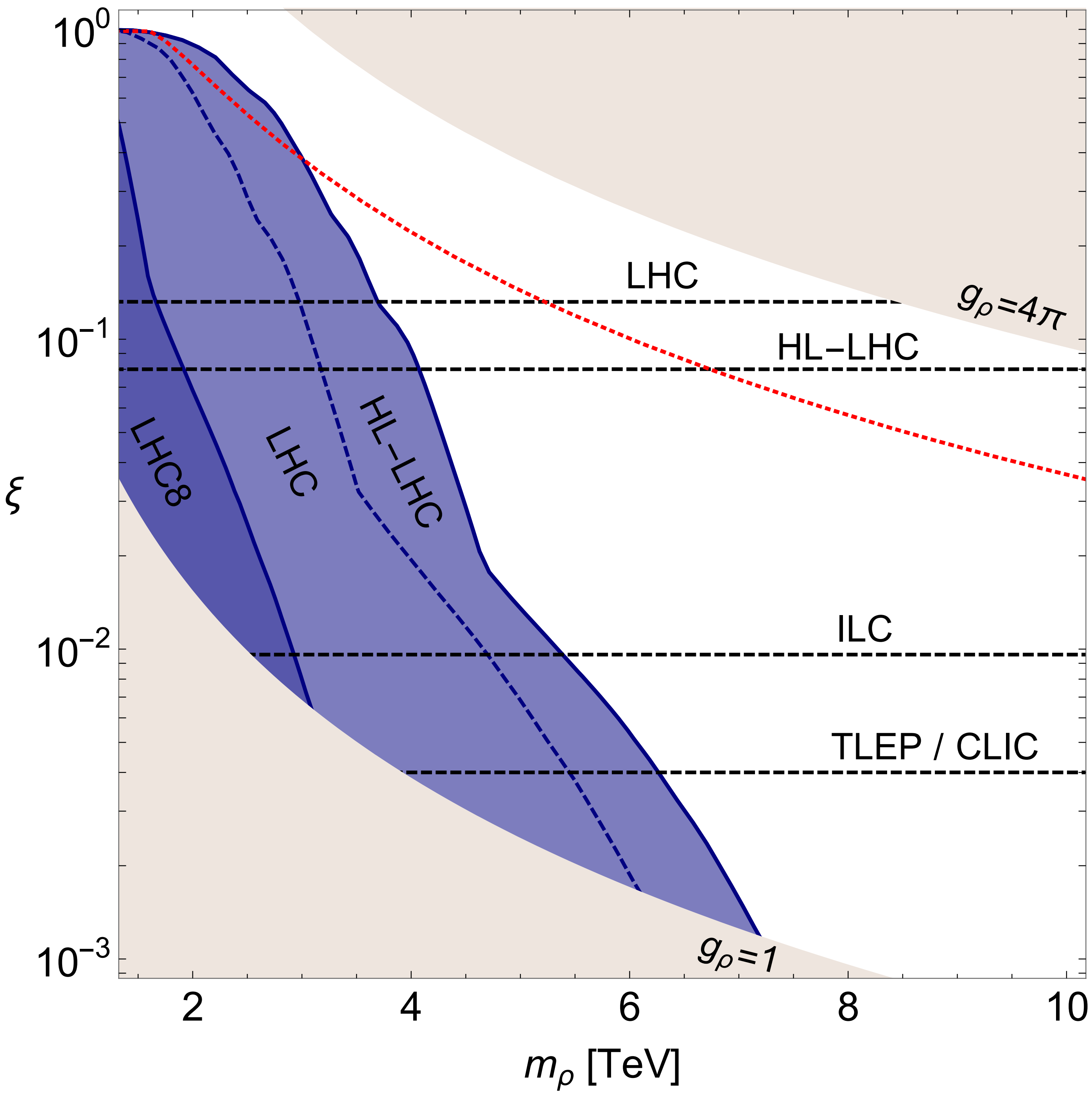
  HL-LHC at 14 TeV with 3 ab^{-1}

- 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.

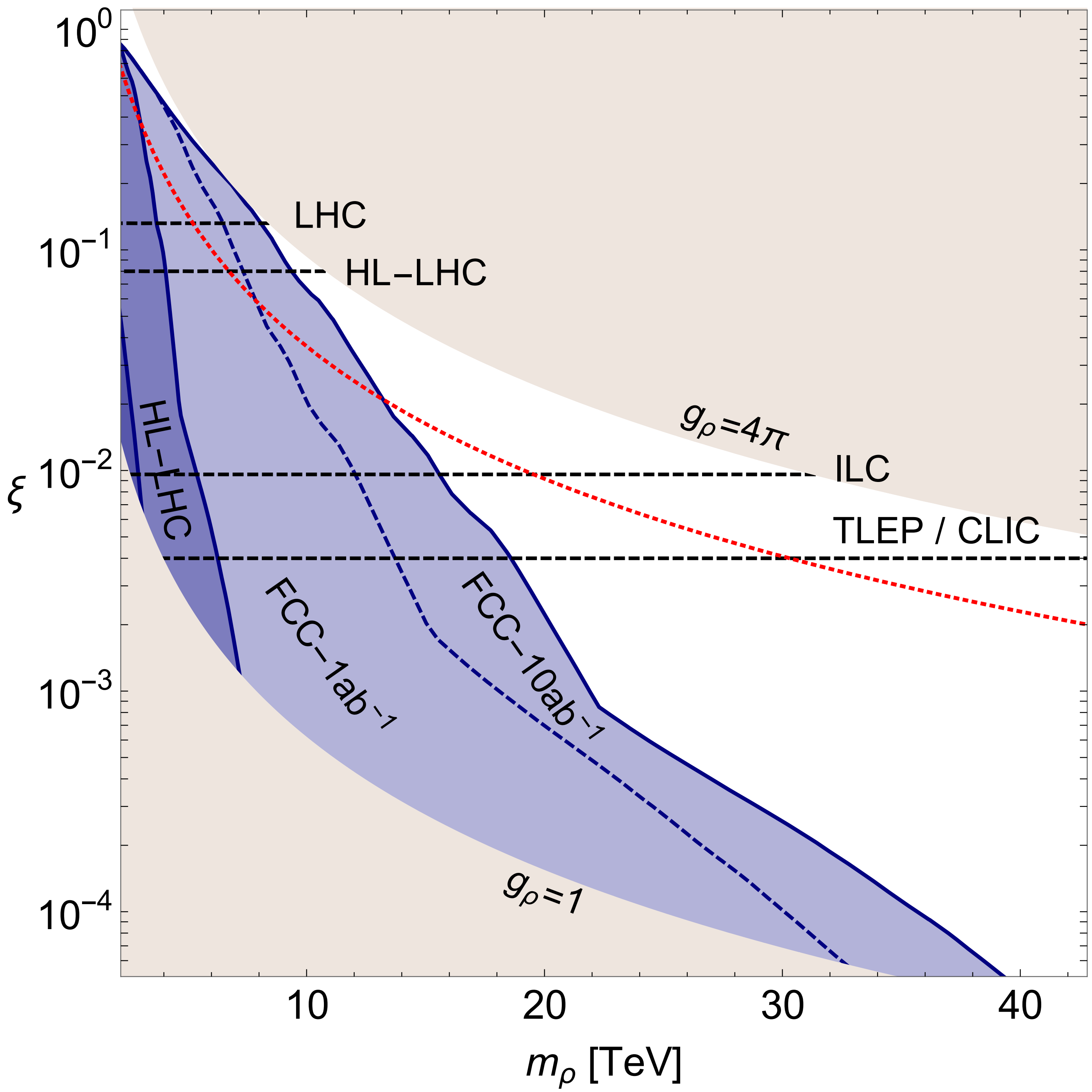
- theoretically excluded $1 \leq g_\rho \leq 4\pi$
- LHC8 at 8 TeV with 20 fb^{-1}

  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)



95% C.L.

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

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

[Thamm, Torre, Wulzer: 1502.01701]

Conclusions

- CH is a very compelling framework
- many ways to look for it:

  direct: vector resonance and top partners

  indirect: coupling modifications
- excess: maybe exactly what a resonance at the edge of discovery should look like?
- learn a lot from LHC RunII
- … and if not, then at a future collider!

Backup

Limit extrapolation

Input: experimental bounds on $\sigma{\times}\mathrm{BR}$ at $\sqrt{s_0} = 8\,\mathrm{TeV}$ with $L_0 \simeq 20\,\mathrm{fb}^{-1}$ for various search channels

- extrapolate limits to different proton-proton collider at $\sqrt{s}$ and L
- driven by number of background events in a small invariant mass window around the resonance peak

$$\frac{\Delta\hat{s}}{m_\rho^2} = 10\%$$

$$B(s, L, m_\rho) = B(s_0, L_0, m_\rho^0)$$

output

same limit on number of signal events

- excluded cross section at the equivalent mass

$$[\sigma{\times}\mathrm{BR}](s, L; m_\rho) = \frac{L_0}{L} \cdot [\sigma{\times}\mathrm{BR}](s_0, L_0; m_\rho^0)$$

Limit extrapolation - equivalent mass

- extraction of equivalent mass

[Thamm, Torre, Wulzer: 1502.01701]

$$B(s, L, m_\rho) = B(s_0, L_0, m_\rho^0)$$

- number of background events within window $\hat{s} \in [m_\rho^2 - \Delta\hat{s}/2, m_\rho^2 + \Delta\hat{s}/2]$

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

partonic cross-section
contributing to background

- partonic cross section: SM process much above SM masses

$$\left[\hat{s}\hat{\sigma}_{ij}(\hat{s})\right] \simeq c_{ij}$$

constant

- parton luminosities constant within small integration limit

$$B(s, L, m_\rho) \propto \frac{\Delta\hat{s}}{m_\rho^2} \cdot L \cdot \sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}} (m_\rho; \sqrt{s})$$

- equating backgrounds

$$\sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}} (m_\rho; \sqrt{s}) = \frac{L_0}{L} \sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}} (m_\rho^0; \sqrt{s_0})$$

Limit extrapolation - equivalent mass

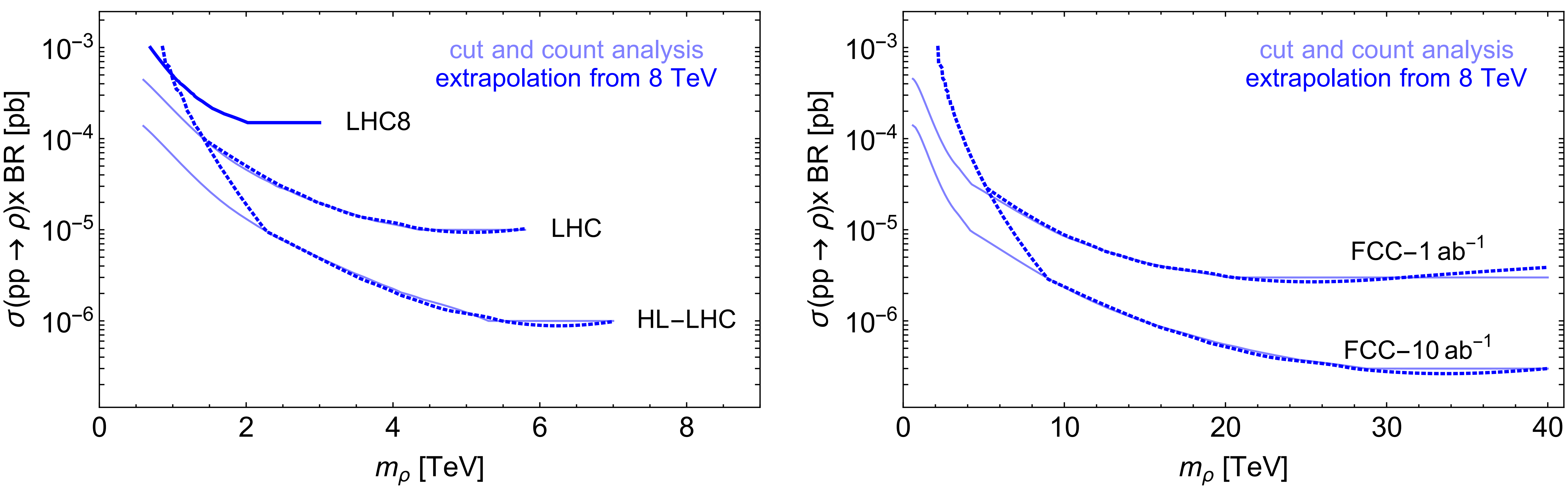
$$\sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_\rho; \sqrt{s}) = \frac{L_0}{L} \sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_\rho^0; \sqrt{s_0})$$

- need relevant background process and parton luminosities
- sum drops for single partonic initial state
- otherwise linear combination of parton luminosities weighted by c_{ij}

Limit extrapolation - equivalent mass

- Subtlety at low masses:

  lowest mass point of 8 TeV limit determined by sensitivity of specific analysis
- arbitrary lowest equivalent mass depending on luminosity
- smoothly raise luminosity of future collider
- extrapolated limit is the strongest at each mass
- low-mass limit conservative, not optimal



EWPT

- set some of strongest constraints on CH models
- incalculable UV contributions can relax constraints

$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{\Lambda}{m_h}\right) + \frac{m_W^2}{m_\rho^2} + \alpha\frac{g^2}{16\pi^2}\xi\,,$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{\Lambda}{m_h}\right) + \beta\frac{3y_t^2}{16\pi^2}\xi$$

tree level exchange of vector resonances

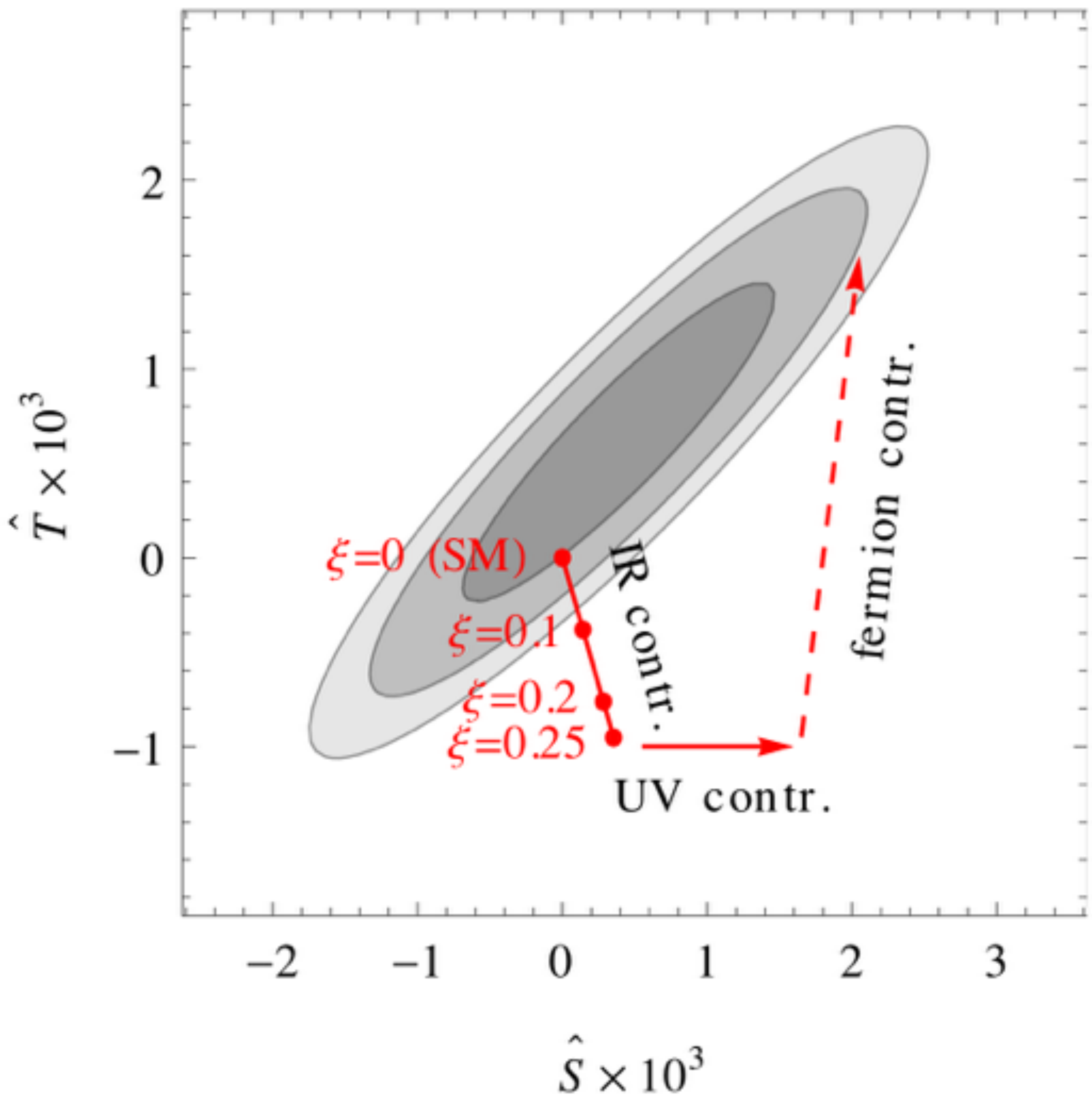
short distance effects

IR contribution due to Higgs coupling modifications

[Grojean, Matsedonskyi, Panico: 1306.4655]

- α and β constants of order 1
- define $\chi^2(\xi, m_\rho, \alpha, \beta)$ and marginalise

EWPT

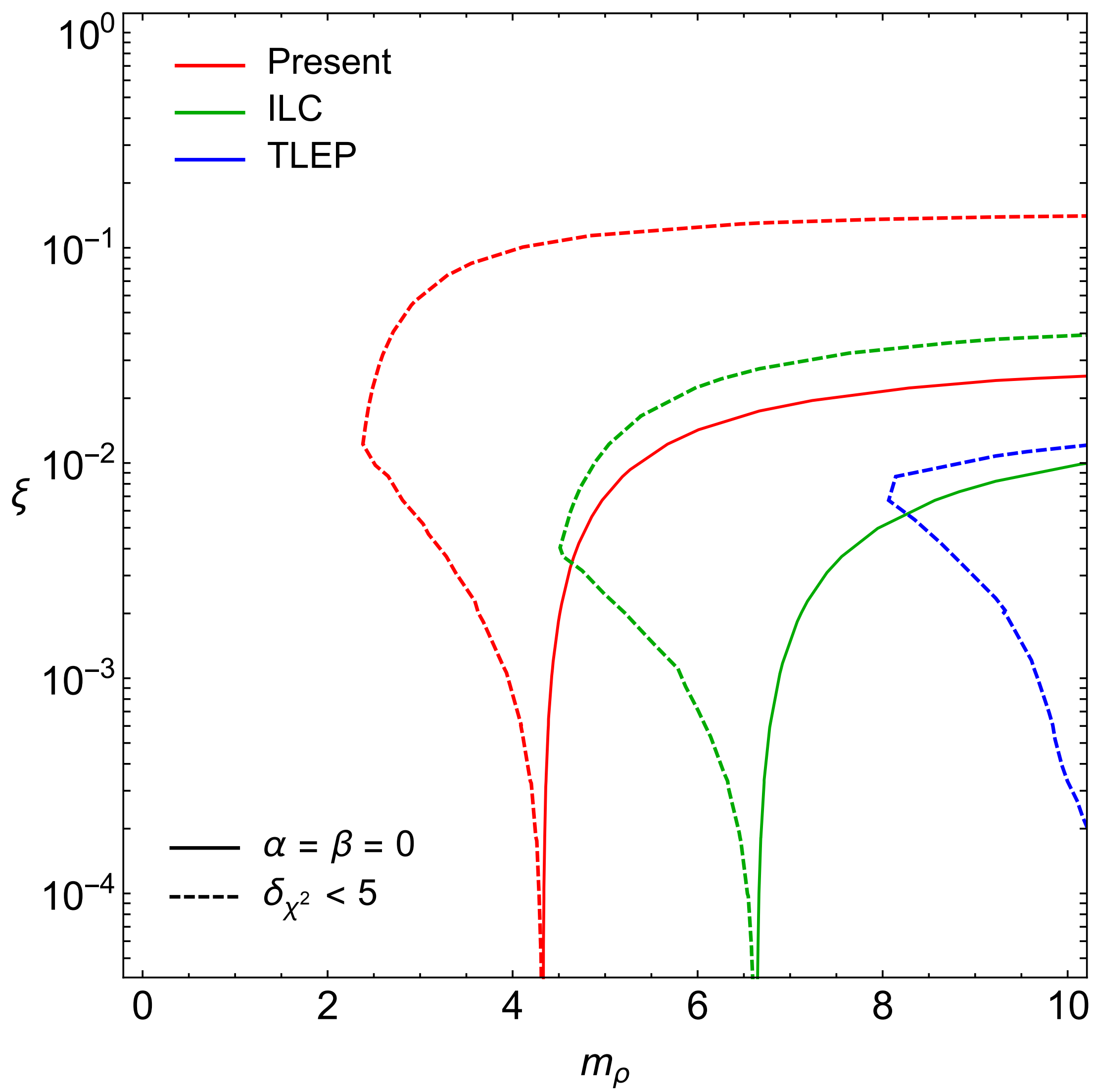


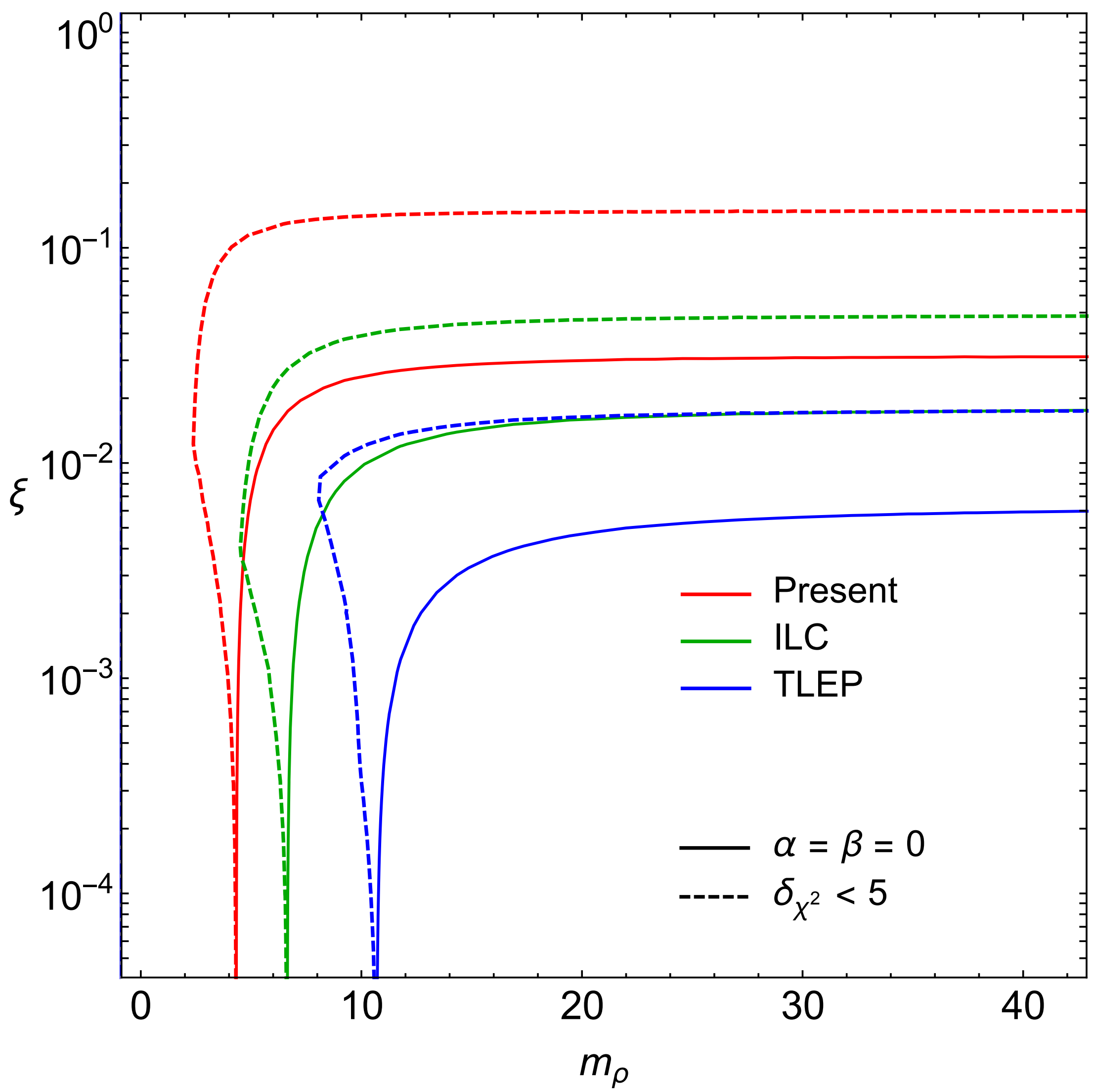
$\hat{T} \times 10^3$
$\hat{S} \times 10^3$
ξ=0 (SM)
ξ=0.1
ξ=0.2
ξ=0.25
IR contr.
UV contr.
fermion contr.

EWPT

- define $\chi^2(\xi, m_\rho, \alpha, \beta)$ and marginalise
- to avoid unnatural cancellations

$$\delta_{\chi^2} = \frac{\chi^2(\xi, m_\rho, \alpha = 0, \beta = 0)}{\chi^2(\xi, m_\rho, \alpha, \beta)}$$





[Baak et al: 1209.2716]
[Baak et al: 1407.3792]