ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Benasque, 17 April 2014

Heavy Vector Triplets: Bridging Theory and Data

Andrea Thamm

École Polytechnique Fédérale de Lausanne

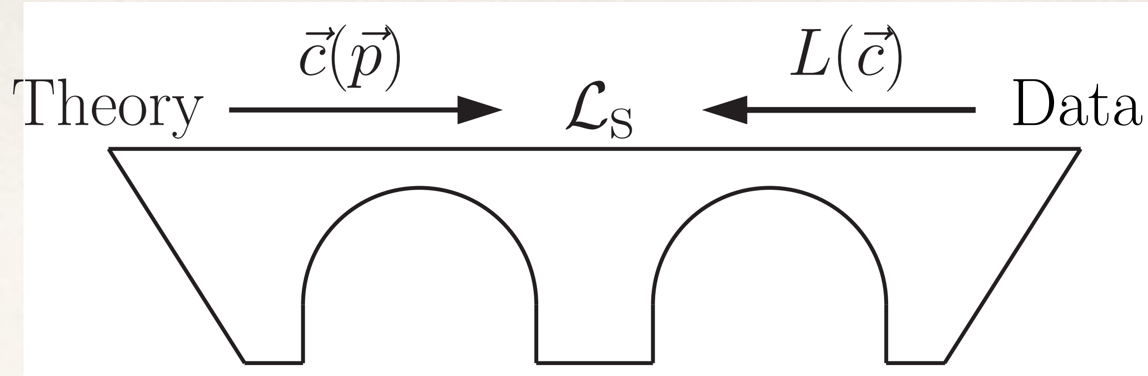
in collaboration with D. Pappadopulo, R. Torre, A. Wulzer
based on arXiv:1402.4431

Outline

1. Motivations
2. Simple Simplified Model
3. Limit setting procedure
4. Data and Bounds
5. Conclusions

Motivation

Motivation



- indirect probes of new physics very important
- at LHC also many direct probes, for example:

SPIN 1

Weakly coupled

Z' models,
sequential W' ,…

Strongly coupled

Composite Higgs models

very difficult to reinterpret

- aim: phenomenological Lagrangian for heavy spin-1 resonances
  to bridge between experimental data and theoretical models
- idea:
  - present bounds in terms of simplified model parameters
  - any model can be matched to simplified Lagrangian

A Simple Simplified Model

Phenomenological Lagrangian

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

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

Phenomenological Lagrangian

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

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

$$+ i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a}$$

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

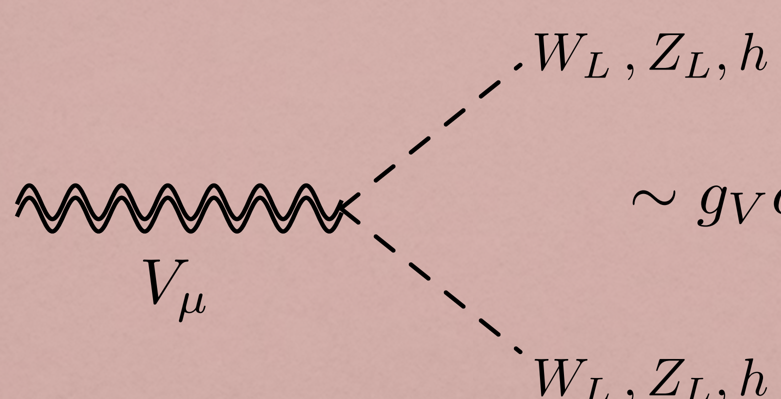
Phenomenological Lagrangian

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

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

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

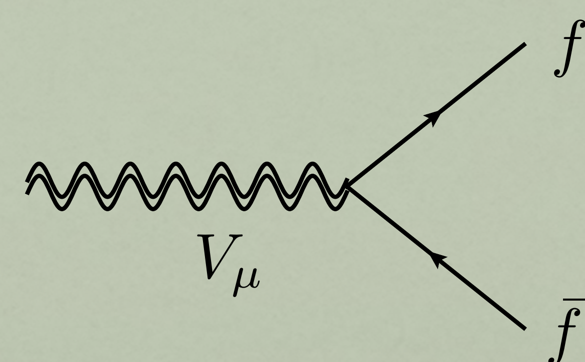
Coupling to SM Vectors



$\sim g_V c_H$

Coupling to SM fermions

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



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

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

Phenomenological Lagrangian

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

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

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

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

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

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

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

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

Weakly coupled model

Strongly coupled model

g_V typical strength of V interactions

Weakly coupled: $g_V \sim g \sim 1$

Strongly coupled: $g_V \leq 4\pi$

c_i dimensionless coefficients

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

Strongly coupled: $c_H \sim c_F \sim 1$

Production Rates

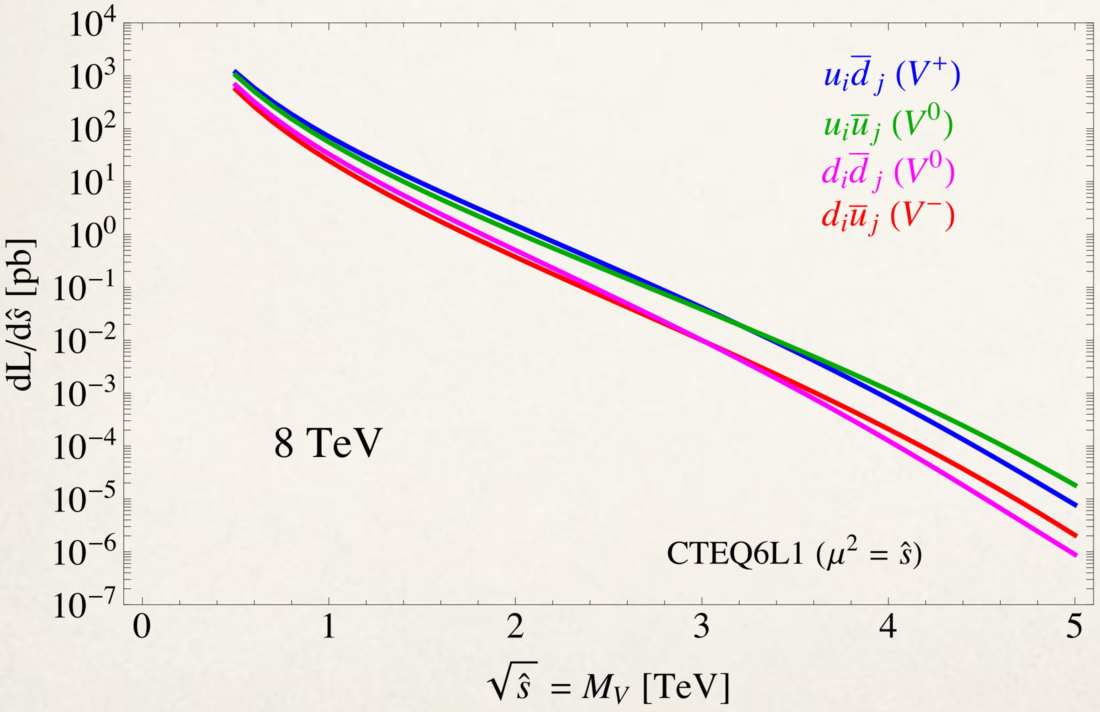
- DY and VBF production

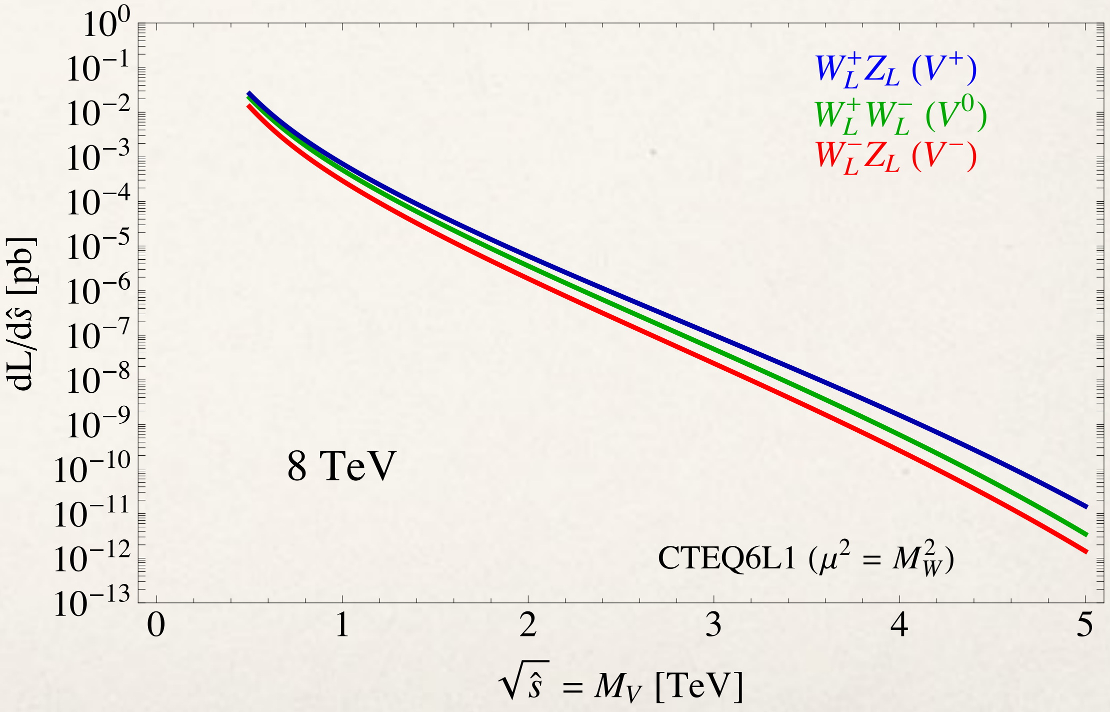
$$\sigma_{DY} = \sum_{i,j\in p} \frac{\Gamma_{V\to ij}}{M_V}\frac{4\pi^2}{3}\left.\frac{dL_{ij}}{d\hat{s}}\right|_{\hat{s}=M_V^2} \qquad \sigma_{VBF} = \sum_{i,j\in p} \frac{\Gamma_{V\to W_{L\,i}W_{L\,j}}}{M_V} 48\pi^2 \left.\frac{dL_{W_{L\,i}W_{L\,j}}}{d\hat{s}}\right|_{\hat{s}=M_V^2}$$

model dependent

model independent

- can compute production rates analytically!
- easily rescale to different points in parameter space
- VBF subleading in motivated part of parameter space





Decay widths

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

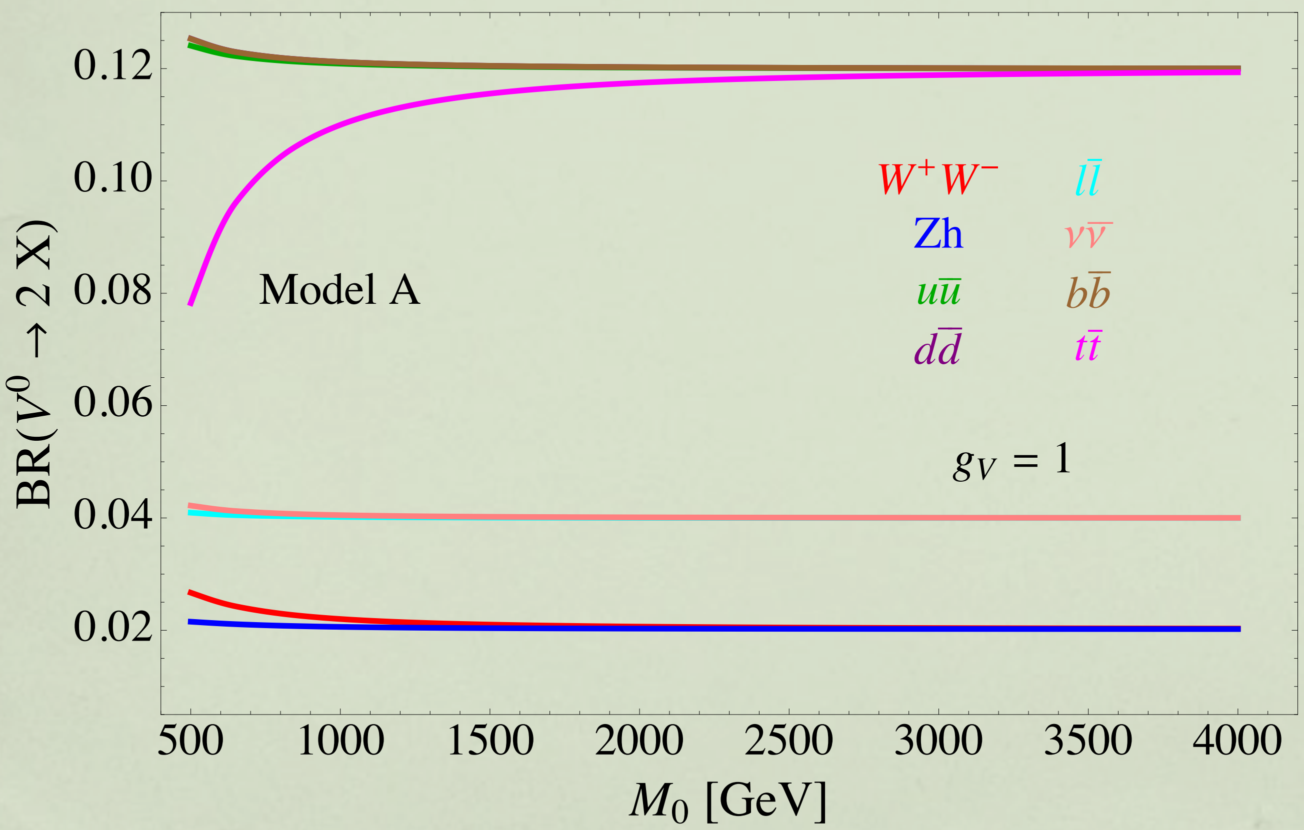
$$\Gamma_{V_\pm \to f\bar{f}'} \simeq 2\,\Gamma_{V_0 \to f\bar{f}} \simeq N_c[f] \left(\frac{g^2 c_F}{g_V}\right)^2 \frac{M_V}{96\pi}\,,$$

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

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

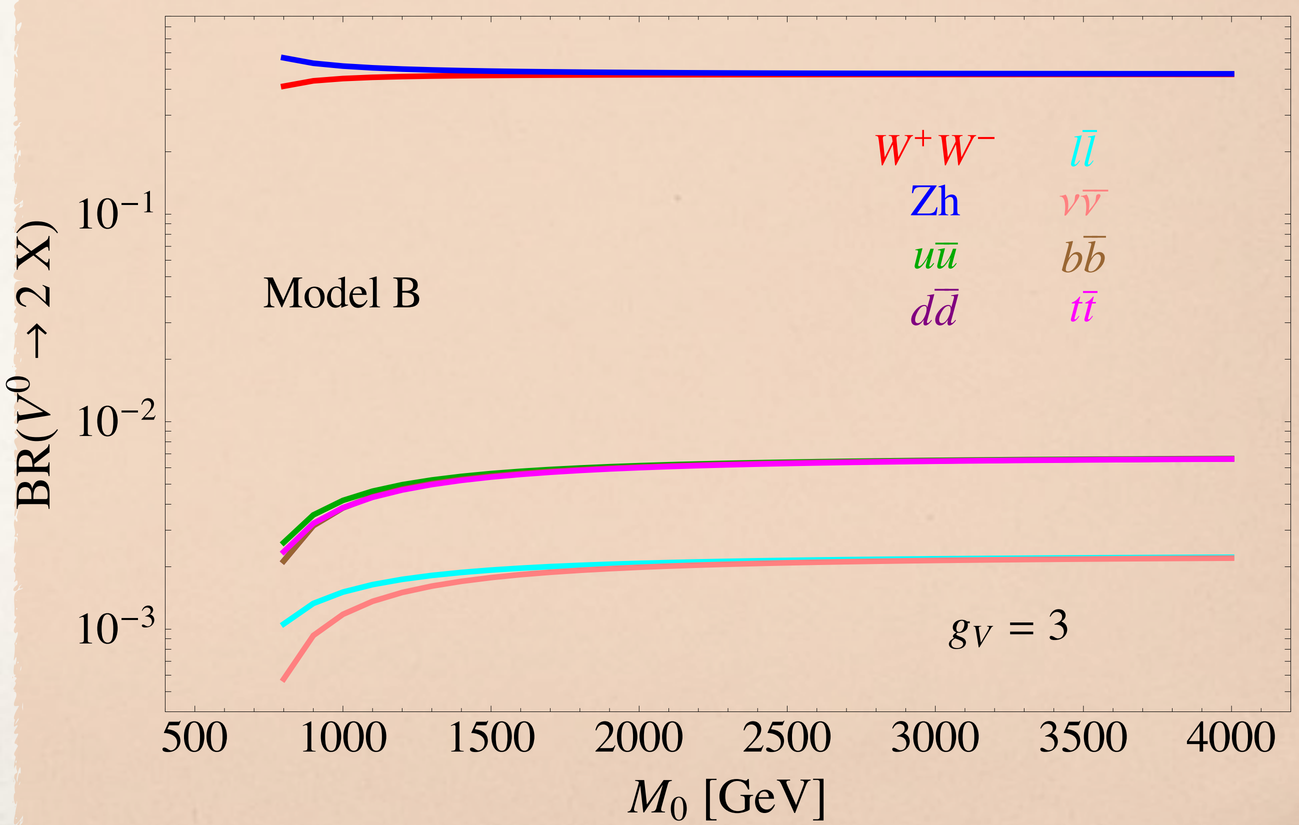
Weakly coupled model

$$g_V c_H \simeq g^2 c_F/g_V \simeq g^2/g_V$$



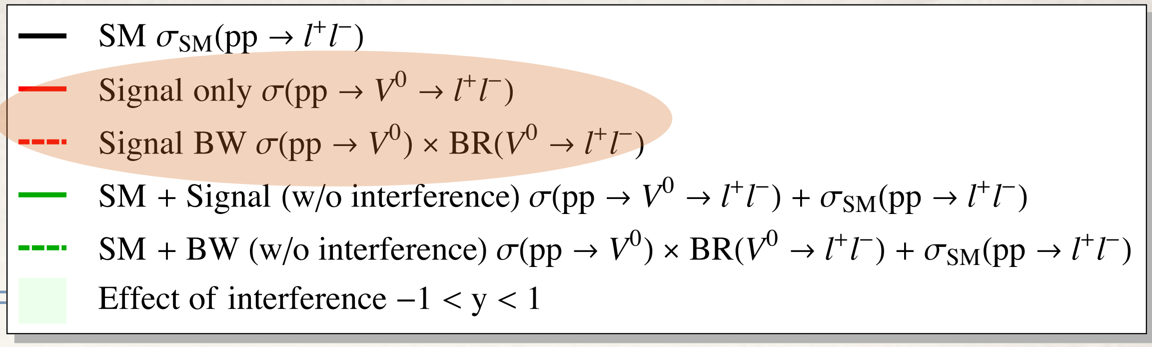
Strongly coupled model

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



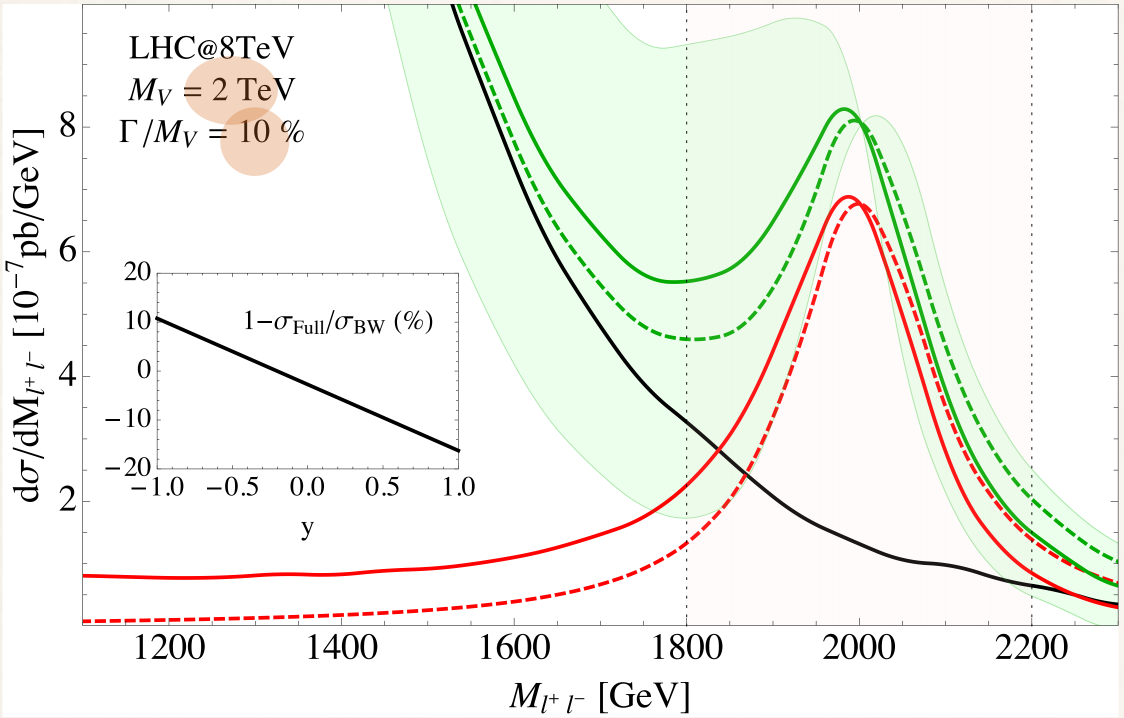
Data and Bounds

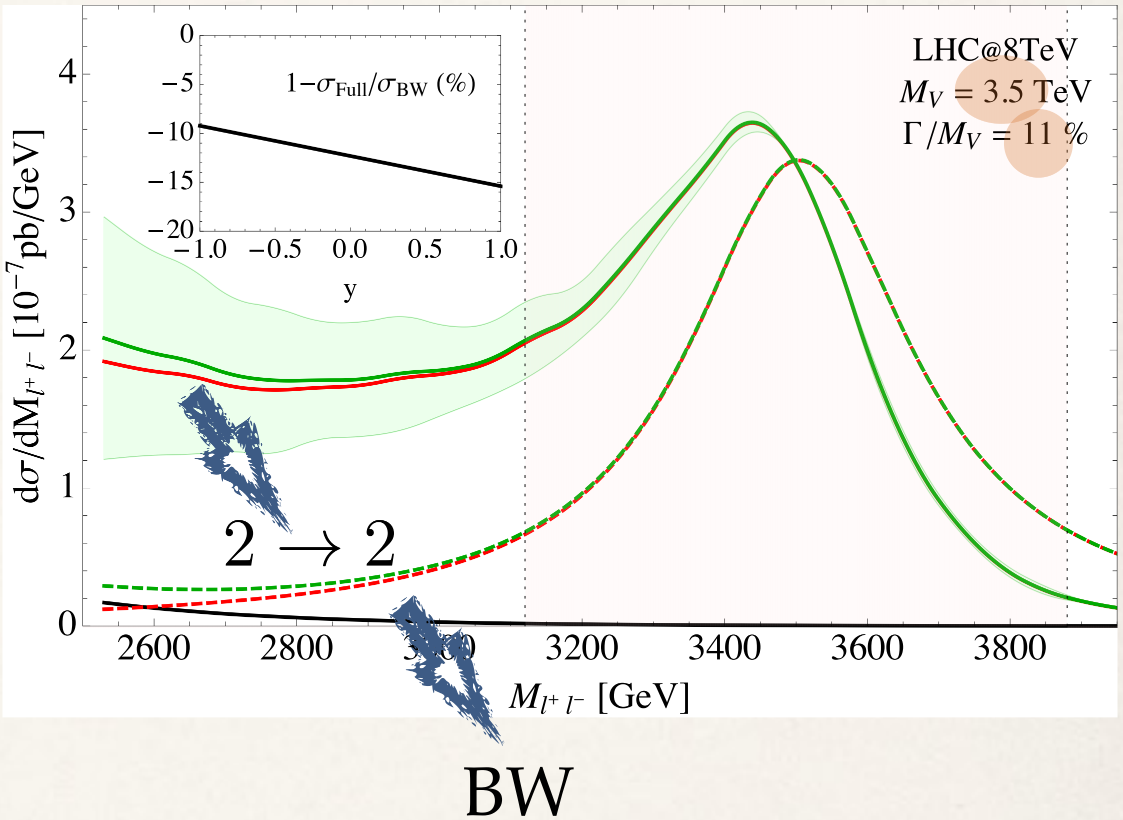
Limit setting



- want limits on $\sigma \times BR$ since model-independent
- must stay in a window around the peak, otherwise finite widths effects must be considered

Di-lepton searches for V_0

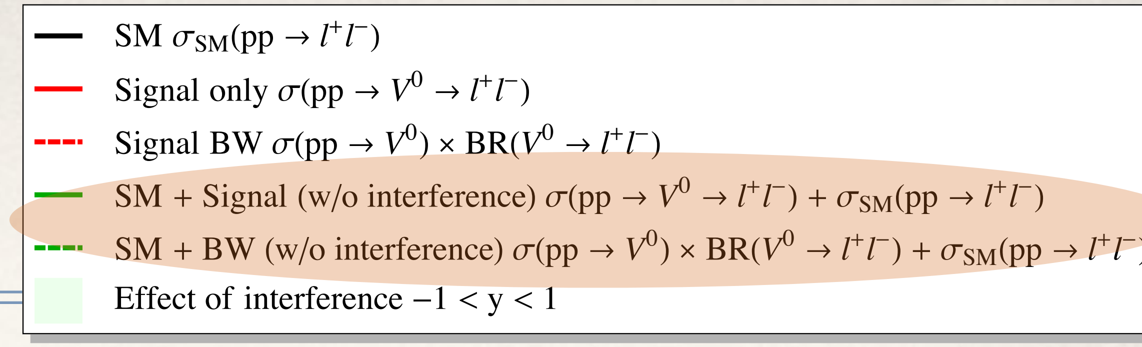




1. distortion from Breit-Wigner
   due to steep fall of parton luminosities at large energies
   - large distortion for non-negligible widths
   - still under control in window $[M - \Gamma, M + \Gamma]$ around the peak
   - but large tail

[Accomando, Becciolini, Balyaev, Moretti, Shepherd, arXiv:1304.6700]
[Accomando, Becciolini, de Curtis, Dominici, Fedeli, Shepherd, arXiv:1110.0713]

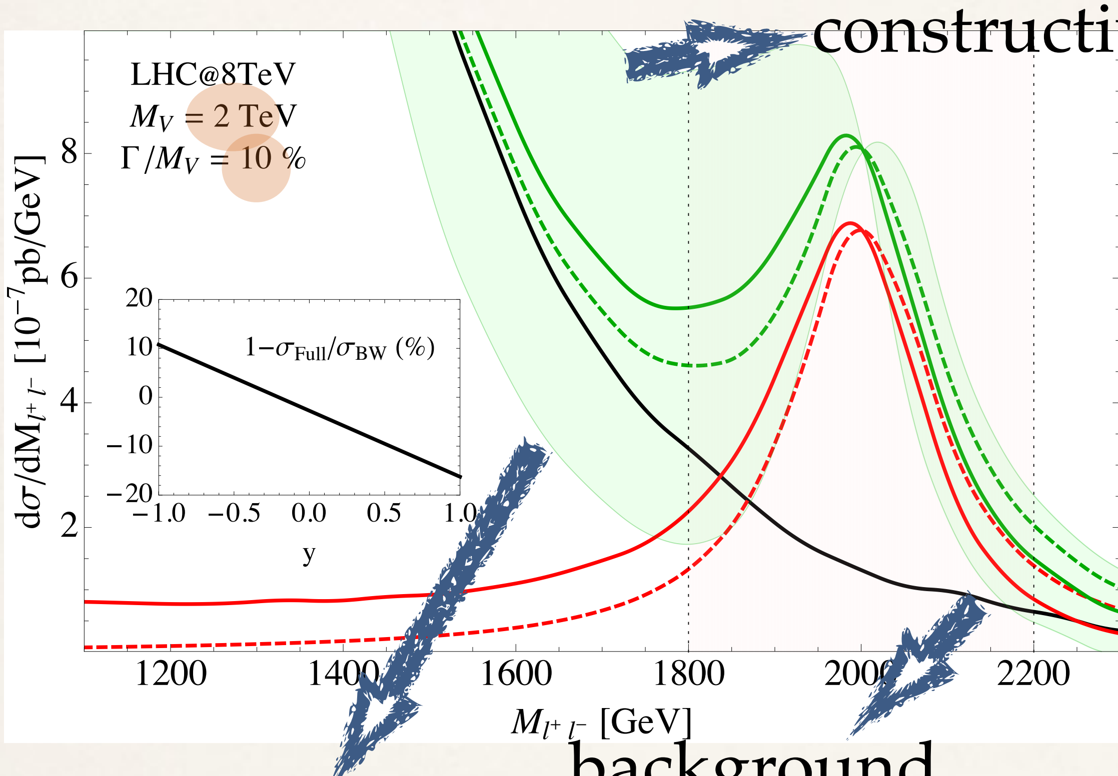
Limit setting

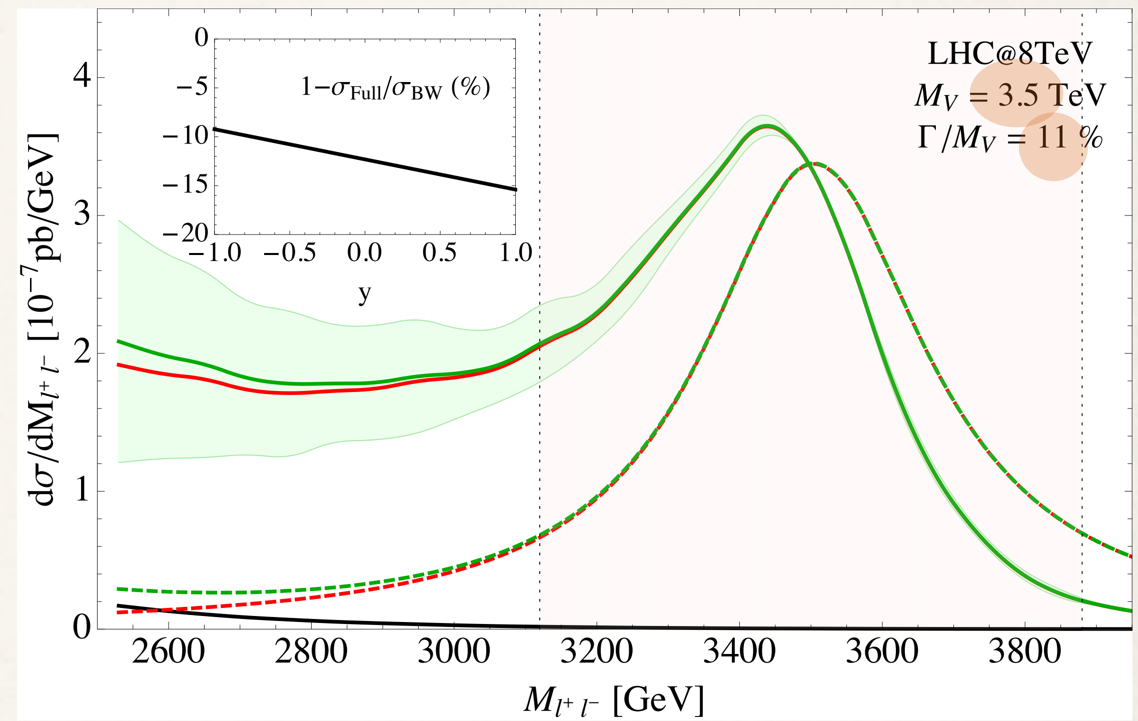


- want limits on $\sigma \times BR$ since model-independent
- must stay in a window around the peak, otherwise finite widths effects must be considered

Di-lepton searches for V_0

constructive





background

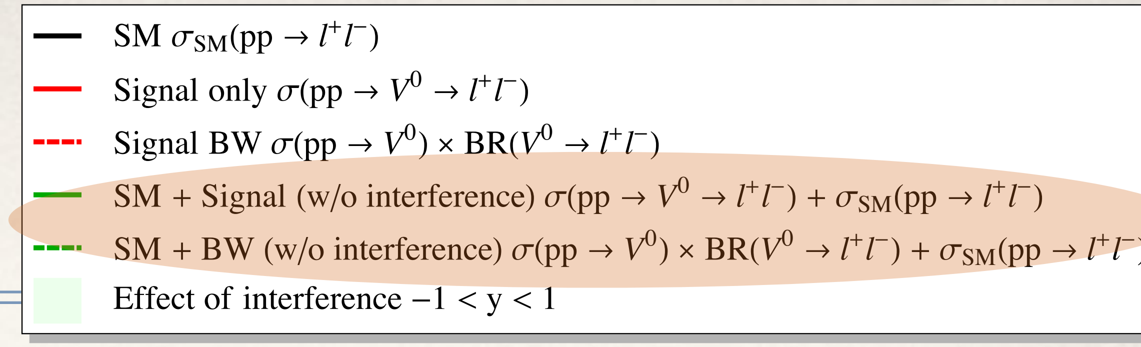
destructive

2. interference with SM background

- depends on S/B ratio
- can be a large effect
- tail strongly model dependent, not $\sigma \times BR$

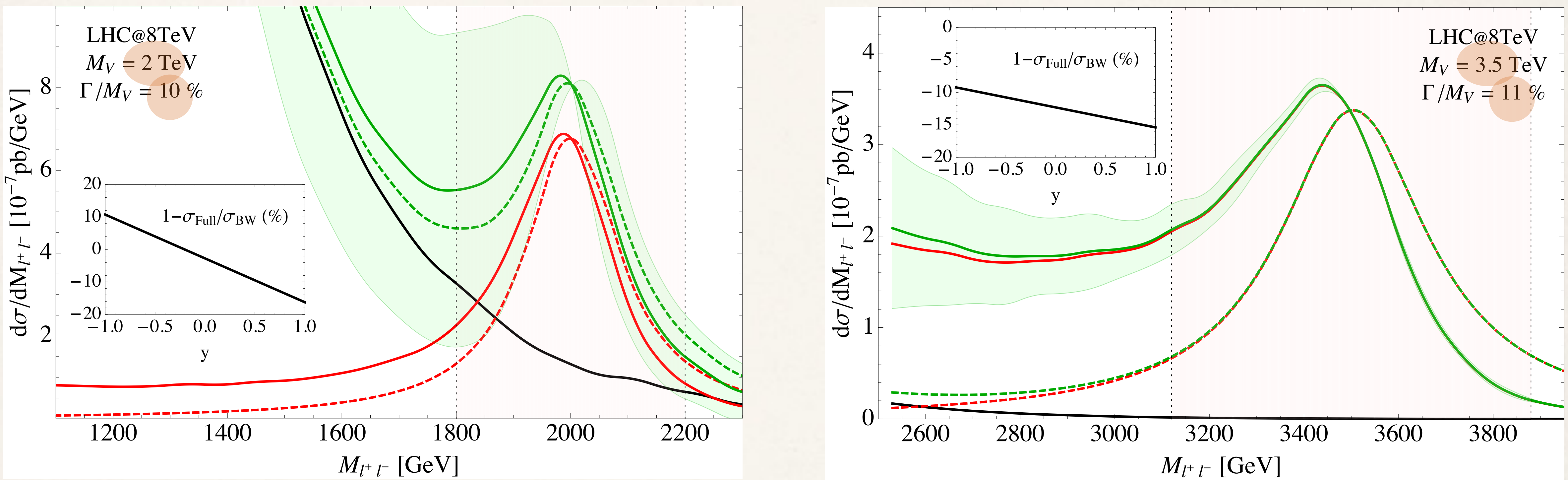
[Accomando, Becciolini, Balyaev, Moretti, Shepherd, arXiv:1304.6700]
[Accomando, Becciolini, de Curtis, Dominici, Fedeli, Shepherd, arXiv:1110.0713]

Limit setting



- want limits on $\sigma \times BR$ since model-independent
- must stay in a window around the peak, otherwise finite widths effects must be considered

Di-lepton searches for V_0



- searches only sensitive to the peak can be easily reused (give bounds on $\sigma \times BR$)
- searches sensitive to the tail only valid in the assumed model, not reusable

[Accomando, Becciolini, Balyaev, Moretti, Shepherd, arXiv:1304.6700]
[Accomando, Becciolini, de Curtis, Dominici, Fedeli, Shepherd, arXiv:1110.0713]

Limit setting: example

ATLAS

bounds set assuming a Z' tail

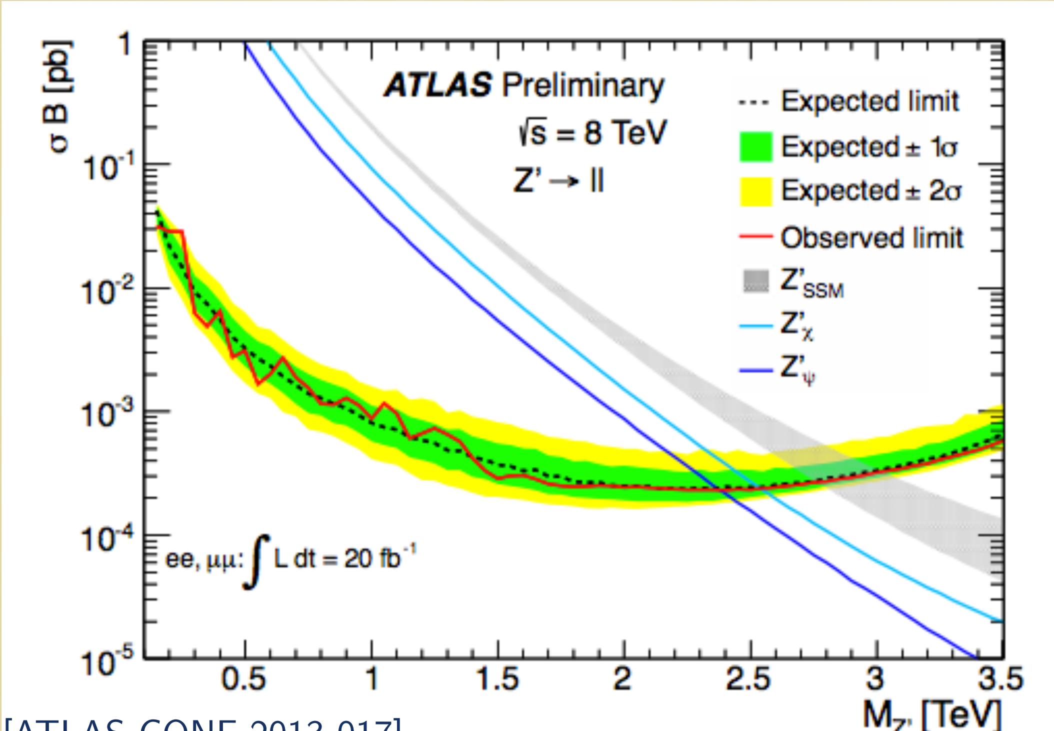
CMS

Gaussian shape around the peak
for very narrow resonance

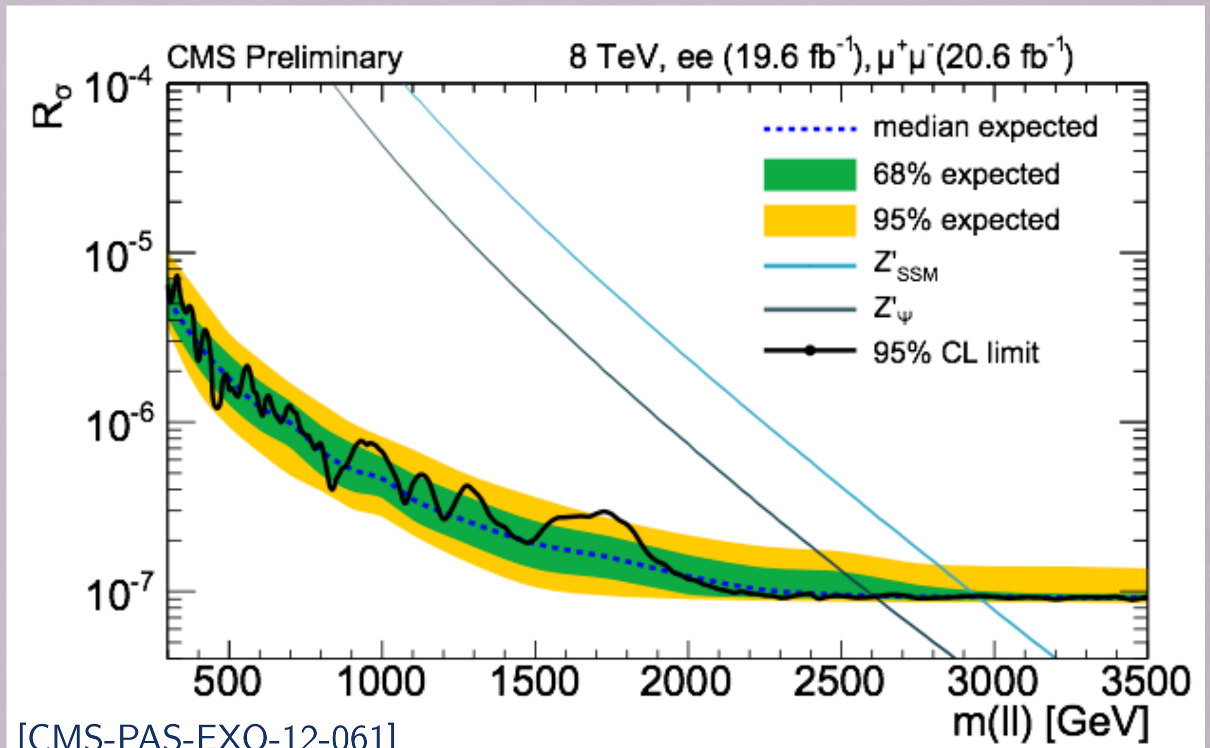
both neglect interference effects

not ok, since tail is considered

ok



[ATLAS-CONF-2013-017]



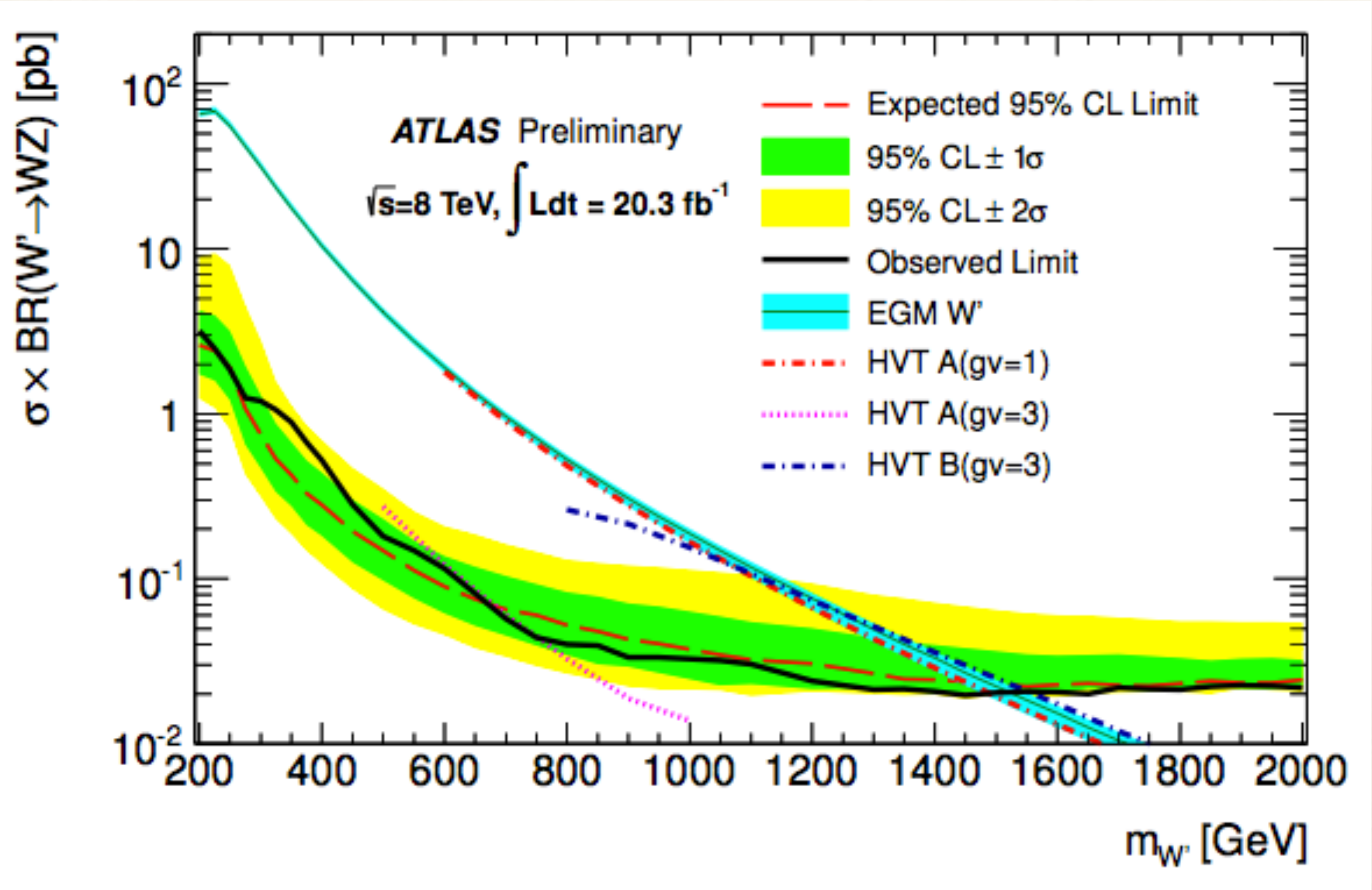
[CMS-PAS-EXO-12-061]

only valid in the assumed model
no bound on $\sigma \times BR$

reusable for very narrow resonance

Limit setting: example

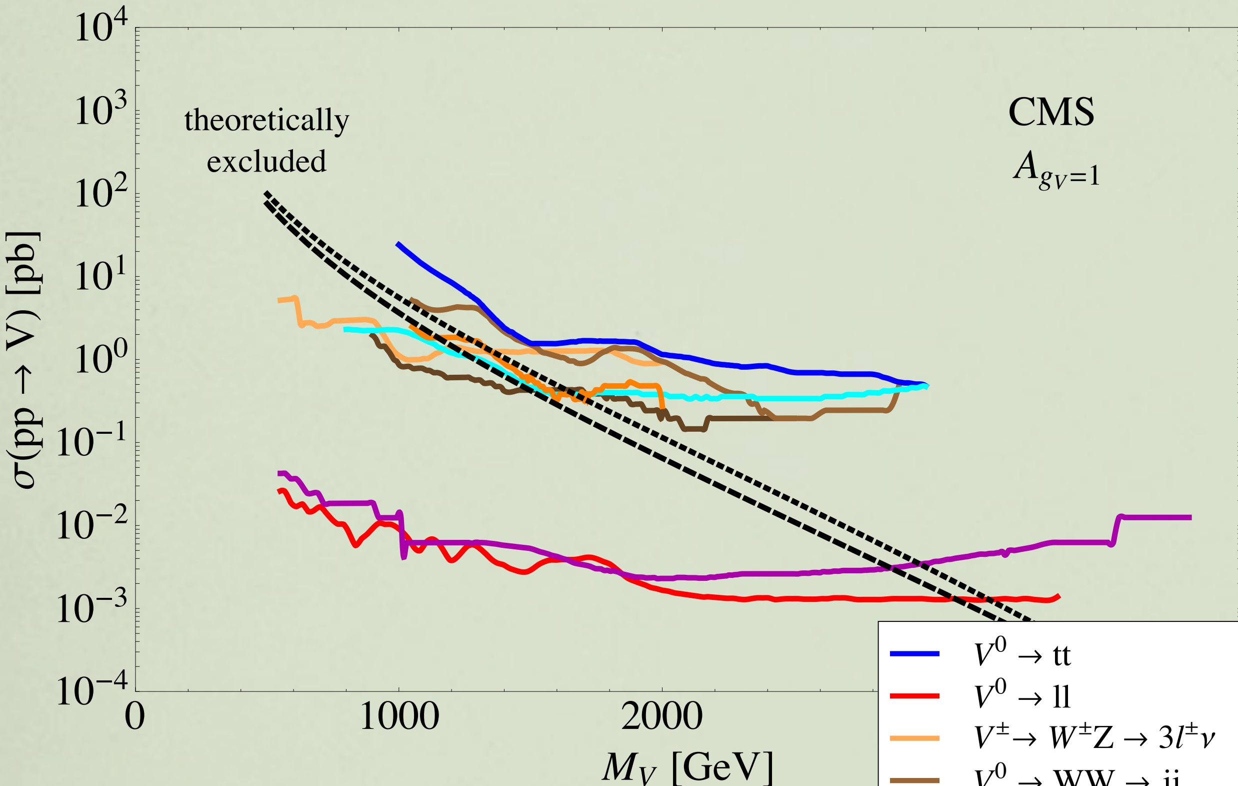
- ATLAS di-boson search using the simplified model
- ideally, also bounds on model parameters should be given



Taking the current bounds at face value…

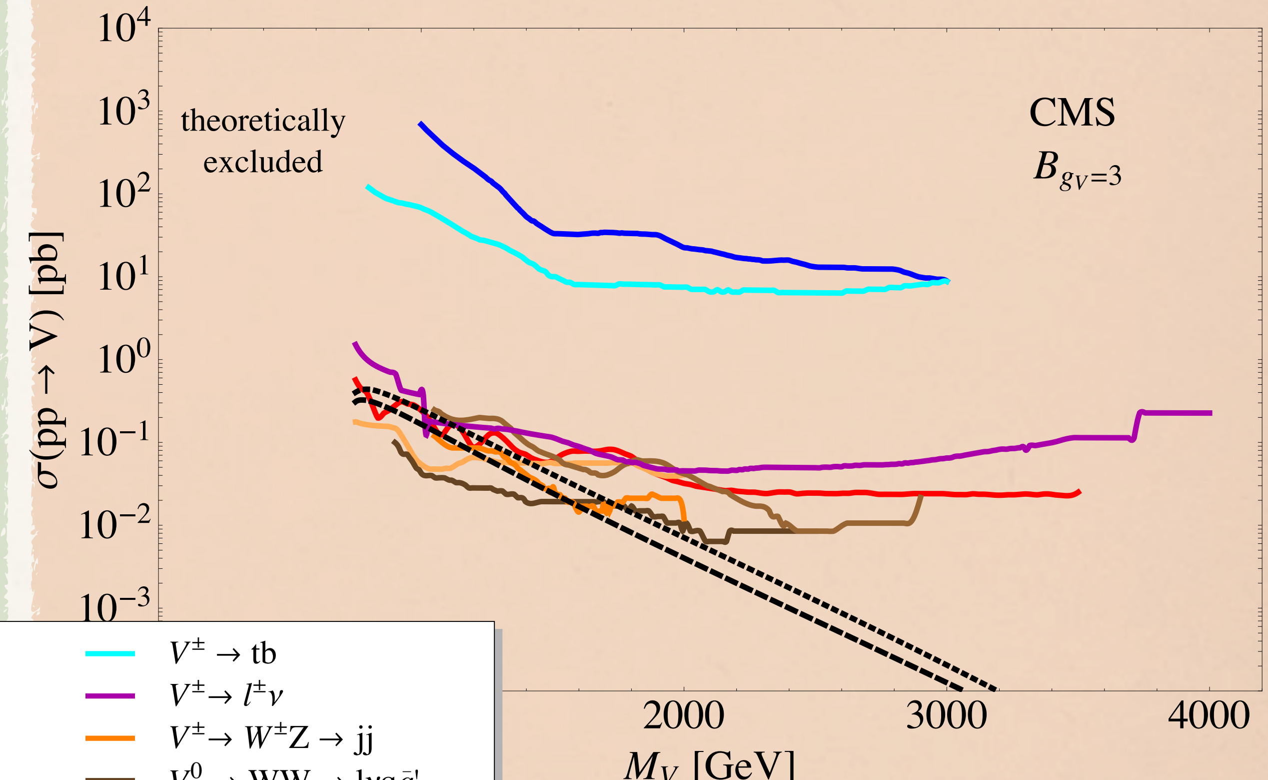
LHC Bounds

Weakly coupled model



- excluded for masses < 3 TeV
- di-lepton most stringent
- di-boson searches < 1-2 TeV
- reach of LHC at 14 TeV: 6 TeV
- reach of FCC at 100 TeV: 30 TeV

Strongly coupled model



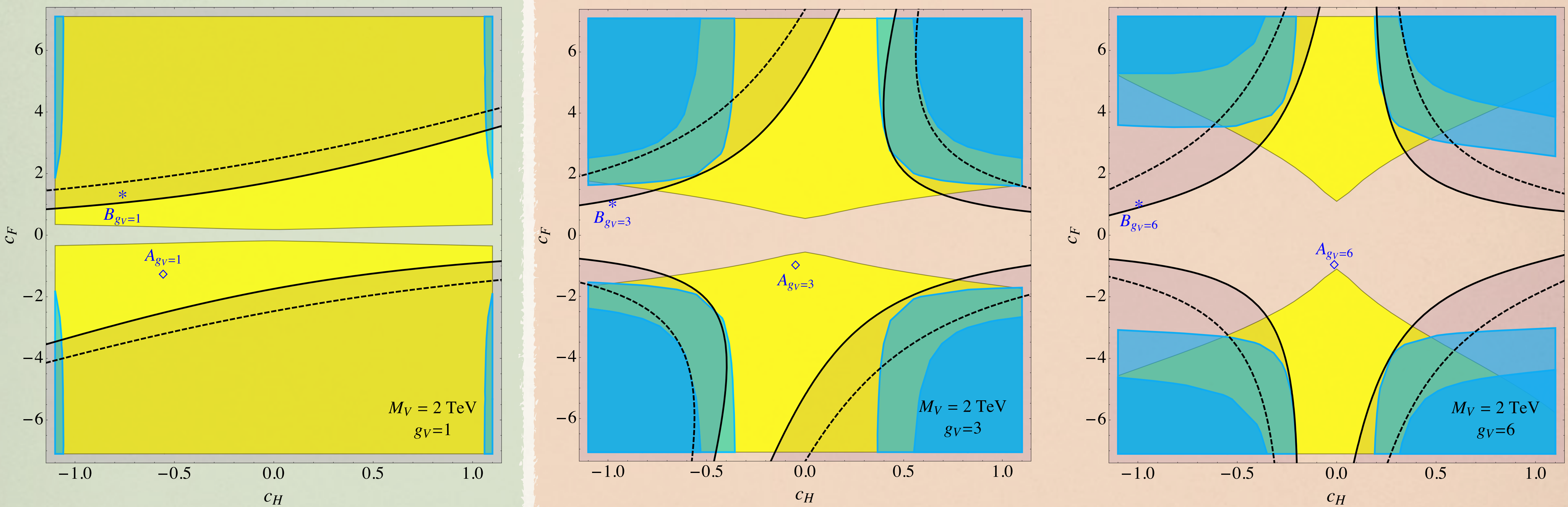
similar bounds for ATLAS

- excluded for masses < 1.5 TeV unconstrained for larger g_V
- di-boson most stringent
- in excluded region G_F, m_Z not reproduced
- reach of LHC at 14 TeV: 3-4 TeV
- reach of FCC at 100 TeV: 15-20 TeV

Limits on parameter space

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

- experimental limits converted into (c_H, c_F) plane



- $l\nu$ dominates
- EWPT not competitive
- only $-1 \lesssim c_F \lesssim 1$ allowed

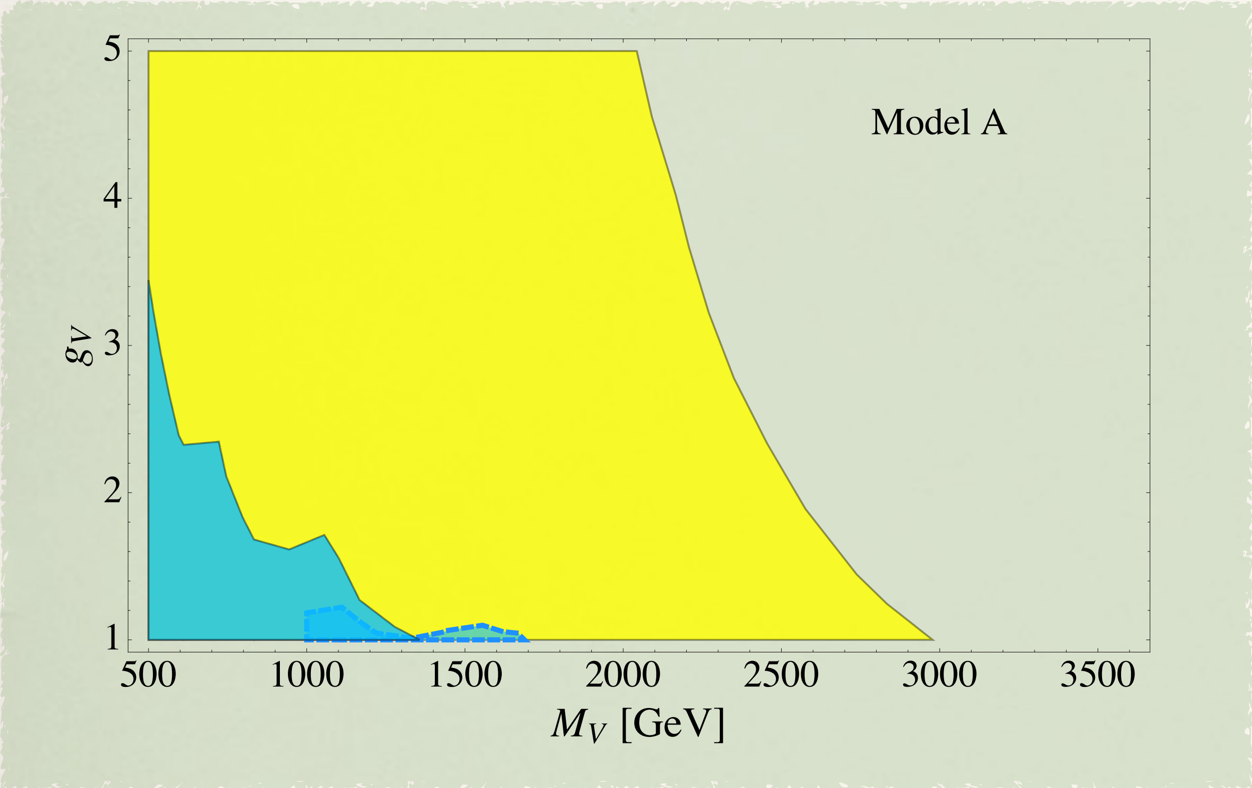
- EWPT become comparable
- di-bosons more and more relevant
- strongly coupled model evades bounds from direct searches

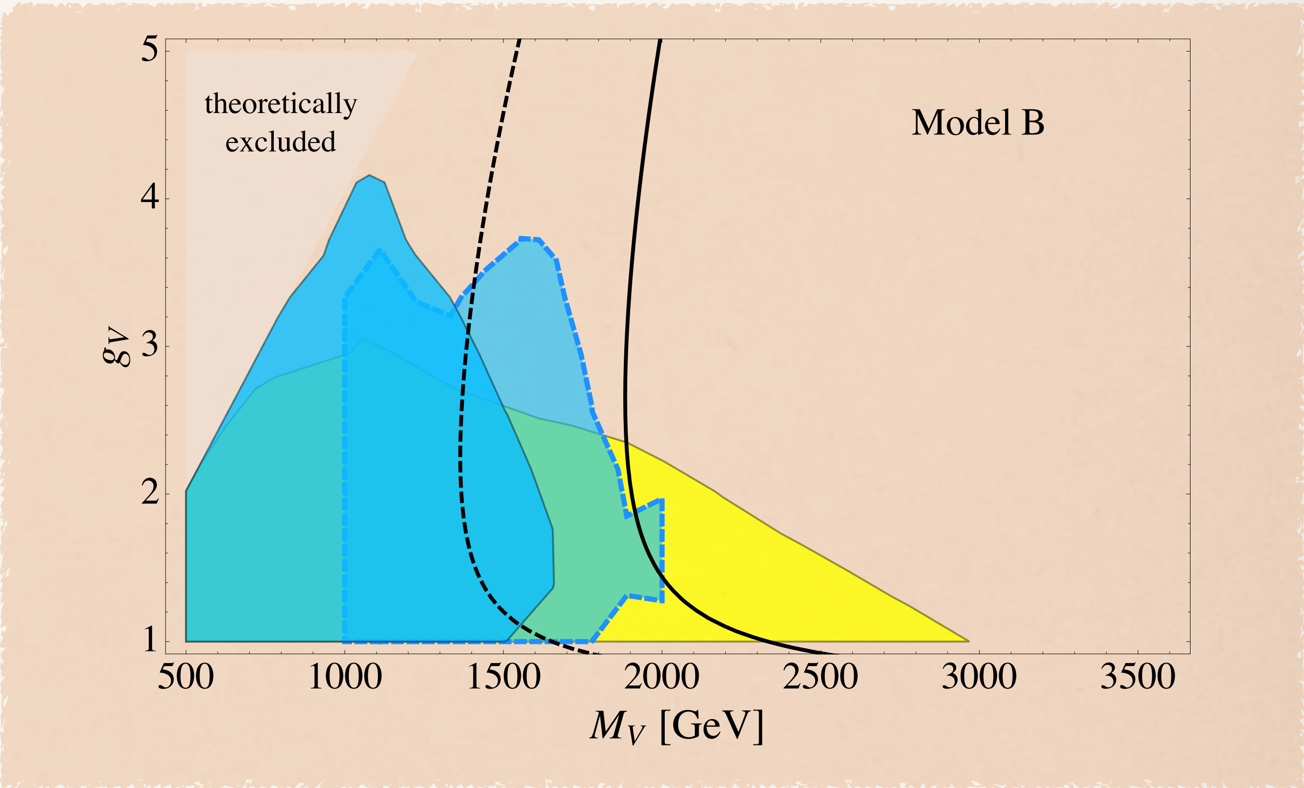
[Pappadopulo, Thamm, Torre, Wulzer, arXiv:1402.4431]

Limits on parameter space

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

- experimental limits converted into (M_V, g_V) plane





- similar exclusions at low g_V , leptonic final state dominates
- very different for larger coupling

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

Conclusions

1. If possible, experimental bounds should be presented in a model-independent, reusable way.

2. Limits should be set on $\sigma \times BR$ by focussing only on the on-shell signal region.

3. It would be useful to present results in terms of simplified model parameters which can be easily matched to any preferred model.

Back-up

Phenomenological Lagrangian

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

$$+ i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\, a}$$

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

- including only dim-4 operators is well justified in:
  weakly coupled models
  strongly coupled models that obey SILH power counting
- if higher dim. operators are unsuppressed:
  parametrisation insufficient

Relations and EWPT

- generalised custodial relation after rotation to mass basis

$$m_W^2 M_+^2 = \cos^2\theta_W m_Z^2 M_0^2 \,.$$

- require hierarchy $\quad \dfrac{m_{W,Z}}{M_{+,0}} \lesssim 10^{-1} \ll 1$

$$\Downarrow$$

- degeneracy $\quad M_+^2 = M_0^2\,(1+\mathcal{O}(\%))$
  - ⇒ expect comparable production rates
  - ⇒ phase space suppressed cascade decays
- naturally small mixing angles $\quad \theta_{N,C} \simeq c_H \dfrac{g_V \hat{v}}{2}\dfrac{m_{W,Z}}{m_V^2} \lesssim 10^{-1}$
- EWPT to ensure compatibility with experiment

$$g|_{\rm exp} = g + O(\hat{m}_W^2/\mu_V^2), \quad g'|_{\rm exp} = g' + O(\hat{m}_W^2/\mu_V^2) \qquad v^2|_{\rm exp}\hat{v}^2\left(1 - c_H^2\frac{g_V^2\hat{v}^2}{4\mu_V}\right)$$

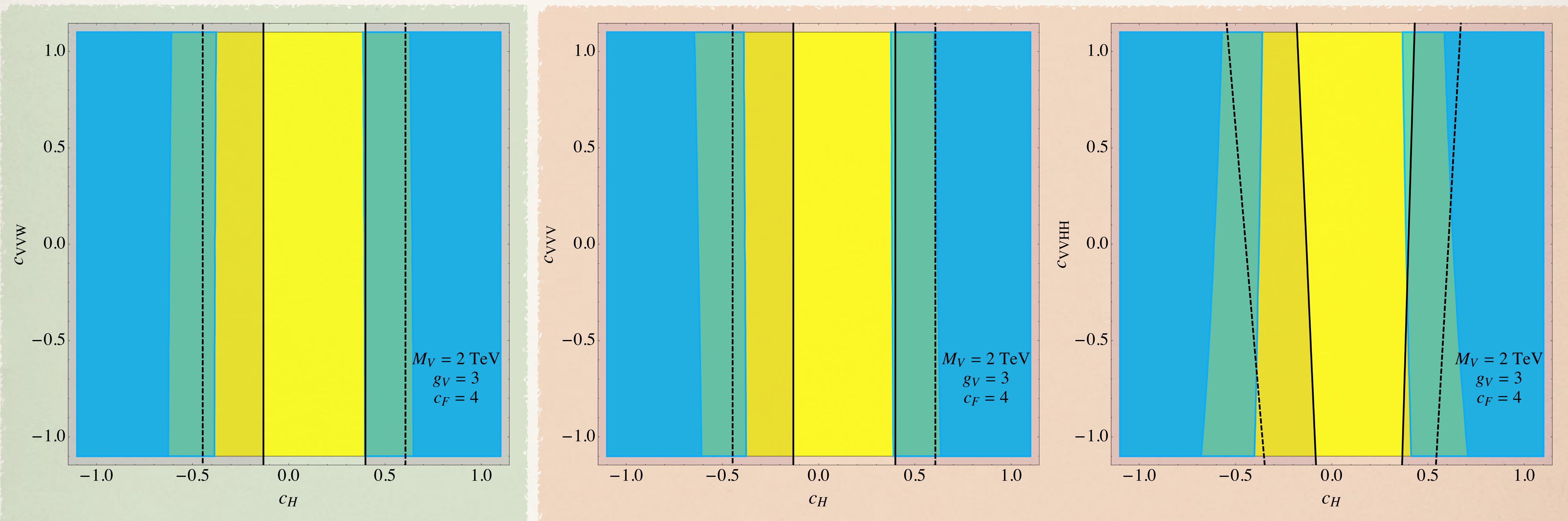
- to include corrections we fix $\quad (m_Z, M_0, G_F) \to (v, m_V, g)$

$$\hat{S} = \gamma_H^2 z^2 \frac{\hat{m}_W^2}{\mu_V^2} - \gamma_H\gamma_F\frac{\hat{m}_W^2}{\mu_V^2}, \qquad W = \gamma_F^2\frac{g^2}{g_V^2}\frac{m_W^2}{\mu_V^2}$$

Limits on parameter space

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

- experimental limits converted into (c_H, c_{VVV}) plane



- c_{VVW}, c_{VVV} and c_{VVHH} affect exclusion only marginally

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