JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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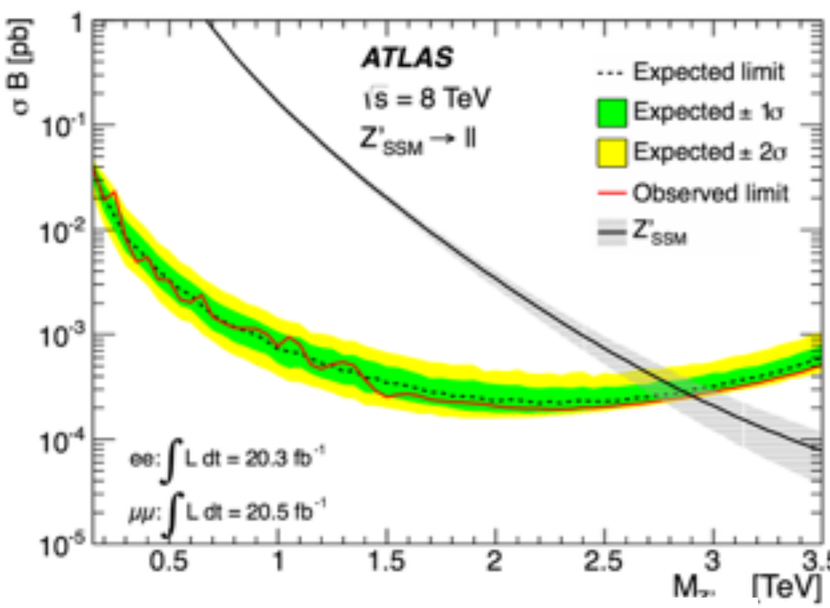
Heavy Vector Resonance at the LHC

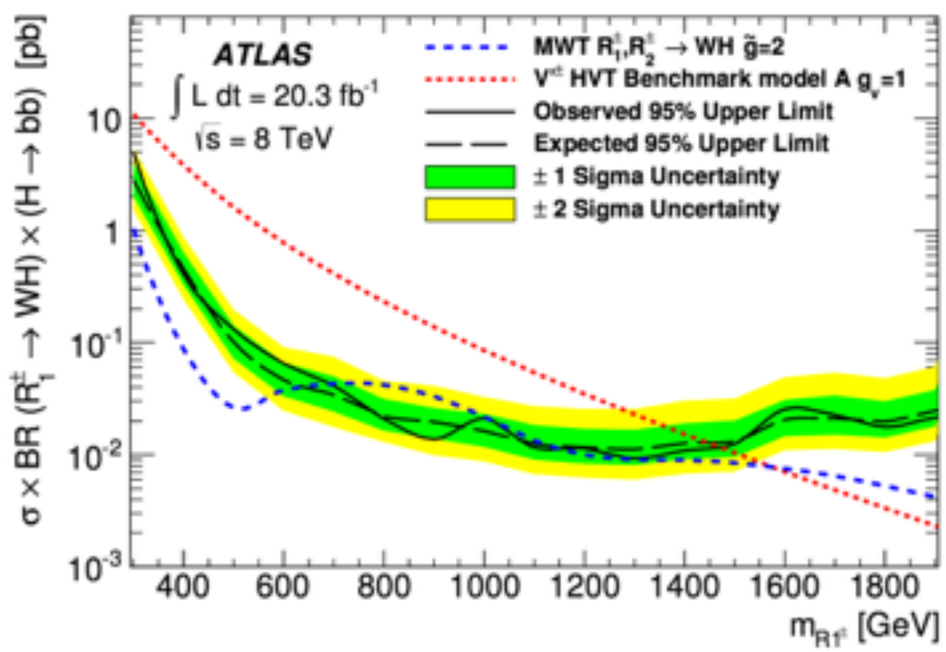
Andrea Thamm
JGU Mainz

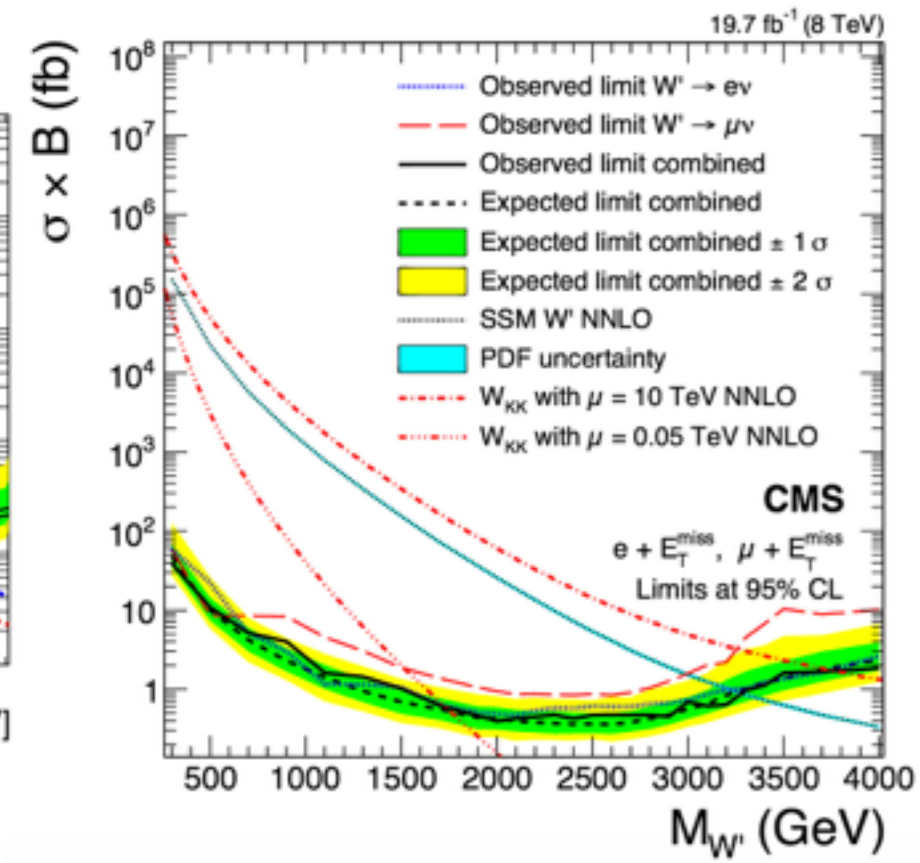
in collaboration with D. Pappadopulo, R. Torre and A. Wulzer
based on arXiv:1402.4431 and work in progress

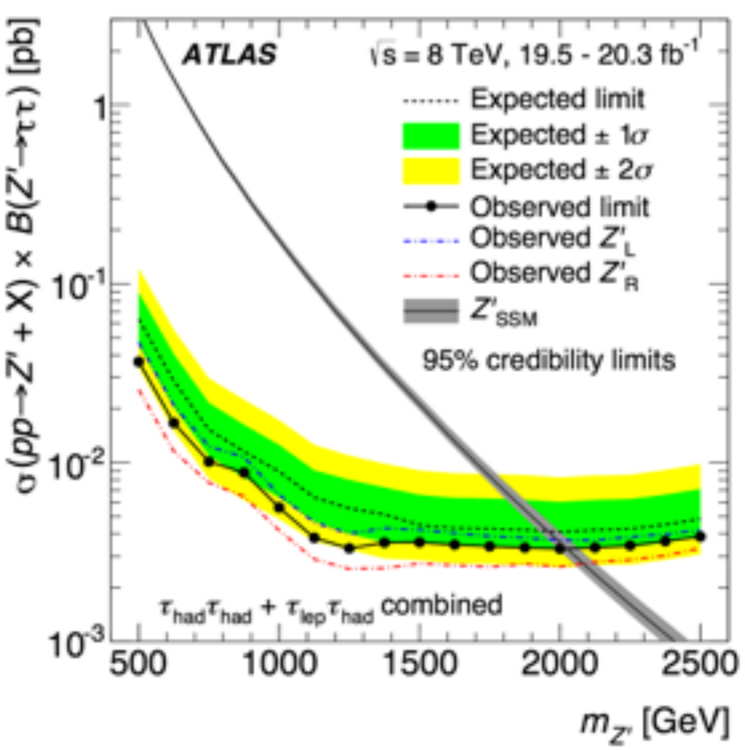
Heavy Vector Resonances

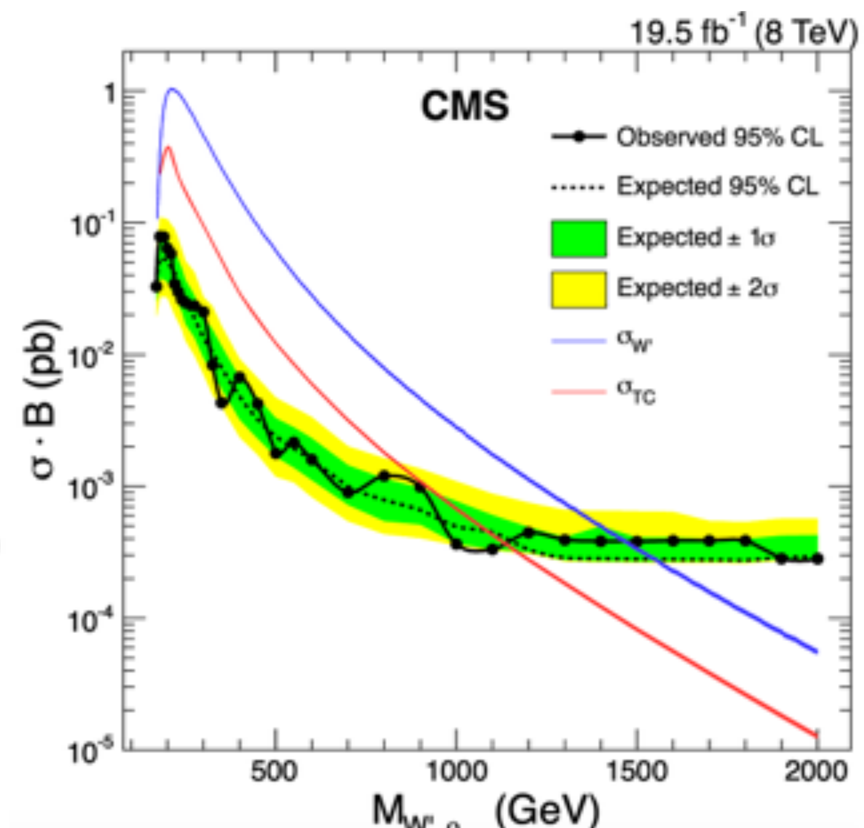
- many searches at 8 TeV and now ongoing at 13 TeV

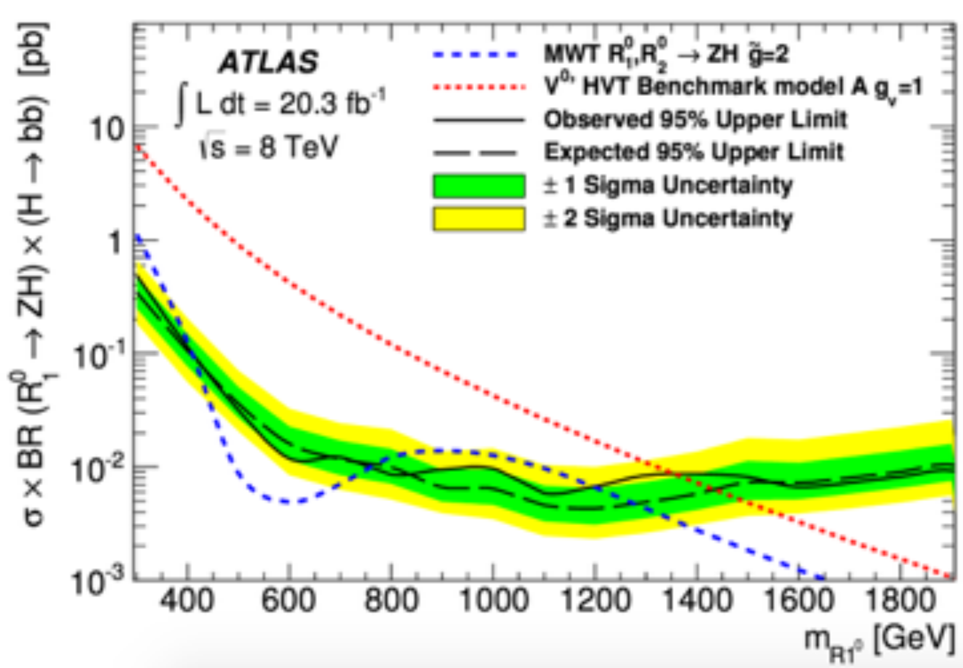












- and many more…

Heavy Vector Resonances

- heavy vectors among the most motivated direct searches
- since they appear in many NP models

Weakly coupled

Z' models,
sequential W' ,…

SPIN 1

Strongly coupled

Composite Higgs models

- various colourless vectors

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\mathcal{B}_\mu$	$\mathbf{1}$	$\mathbf{1}$	0
$\mathcal{B}_\mu^1$	$\mathbf{1}$	$\mathbf{1}$	1
$\mathcal{L}_\mu$	$\mathbf{1}$	$\mathbf{2}$	$-3/2$
$\mathcal{W}_\mu$	$\mathbf{1}$	$\mathbf{3}$	0
$\mathcal{W}_\mu^1$	$\mathbf{1}$	$\mathbf{3}$	1

⇨ singlets (work in progress)

⇨ no coupling to quarks

⇨ studied here!

⇨ no coupling to fermions

[del Aguila, de Blas, Perez-Victoria, arXiv:1005.3998]

- simplified model approach

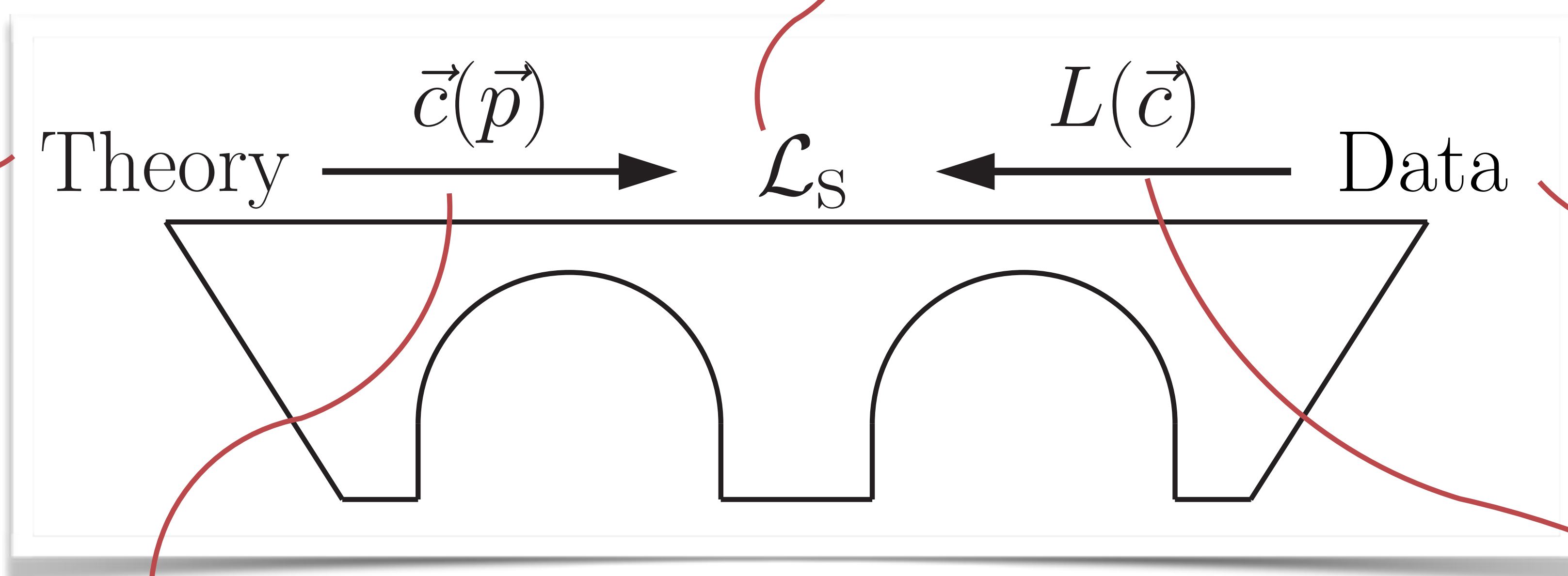
Bridge

- bounds are extremely general
- can be easily used in everyone's favorit model

Simplified Lagrangian
can be matched to explicit models

explicit models

limit on
$\sigma \times BR$



Simplified Lagrangian
parameters c fixed in terms of
explicit model parameters p

translate limits into bounds on
simplified model parameters

Phenomenological Lagrangian

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

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

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

g_V typical strength of V interactions

c_i dimensionless coefficients

Weakly coupled model	Strongly coupled model
$g_V \sim g \sim 1$	$1 < g_V \leq 4\pi$
$c_H \sim -g^2/g_V^2$ and $c_F \sim 1$	$c_H \sim c_F \sim 1$

Phenomenological Lagrangian

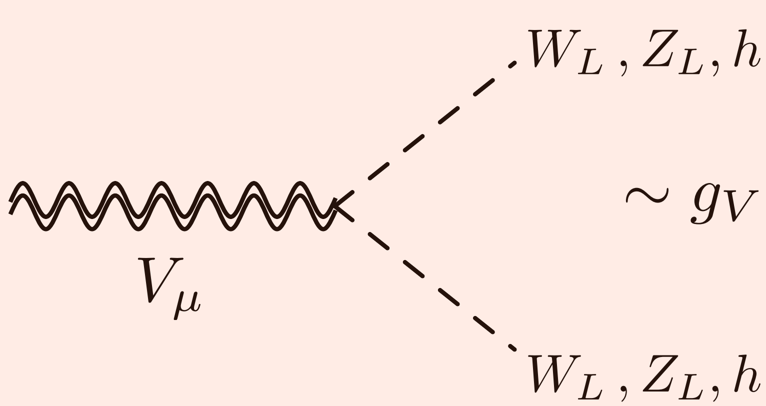
$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a}$$

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

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

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

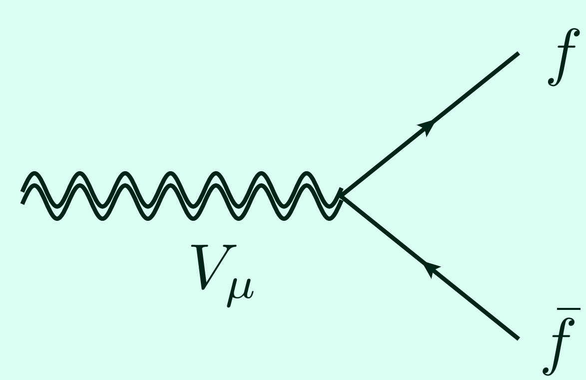
Coupling to SM Vectors



$\sim g_V c_H$

Coupling to SM fermions

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



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

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

Phenomenological Lagrangian

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

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

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

- 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

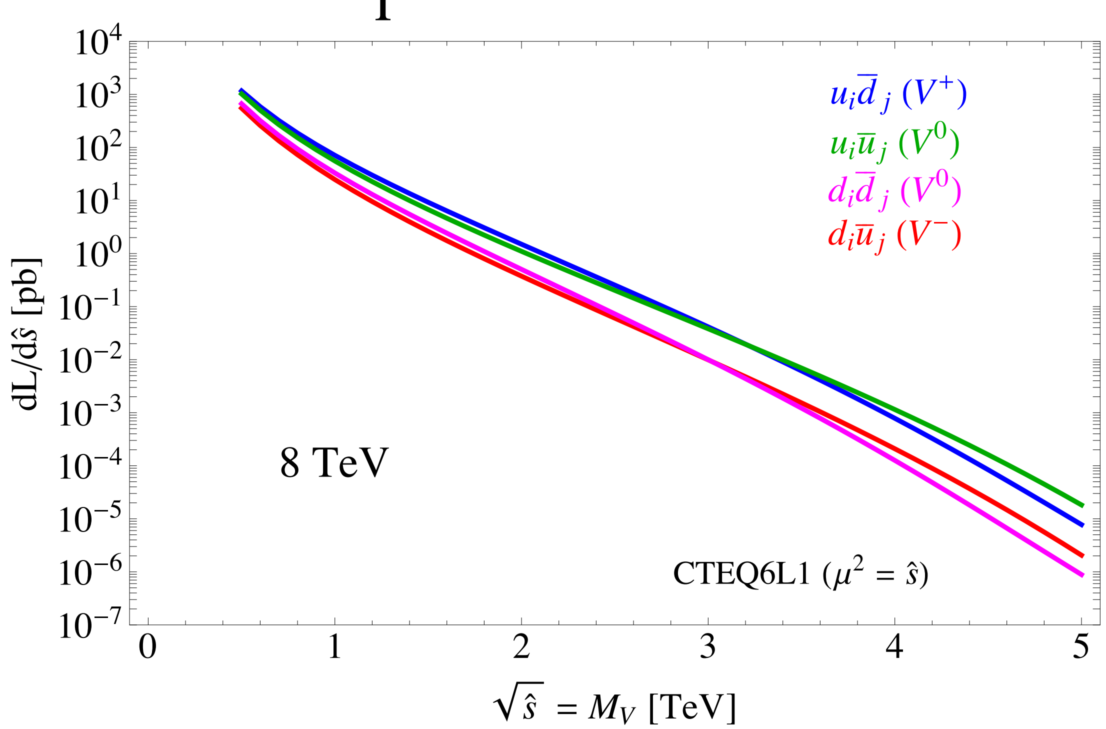
$$\sigma_{DY} = \sum_{i,j\in p} \frac{\Gamma_{V\to ij}}{M_V}\frac{4\pi^2}{3}\frac{dL_{ij}}{d\hat{s}}\Big|_{\hat{s}=M_V^2} \qquad \sigma_{VBF} = \sum_{i,j\in p} \frac{\Gamma_{V\to W_{L\,i}W_{L\,j}}}{M_V}48\pi^2\frac{dL_{W_{L\,i}W_{L\,j}}}{d\hat{s}}\Big|_{\hat{s}=M_V^2}$$

model dependent

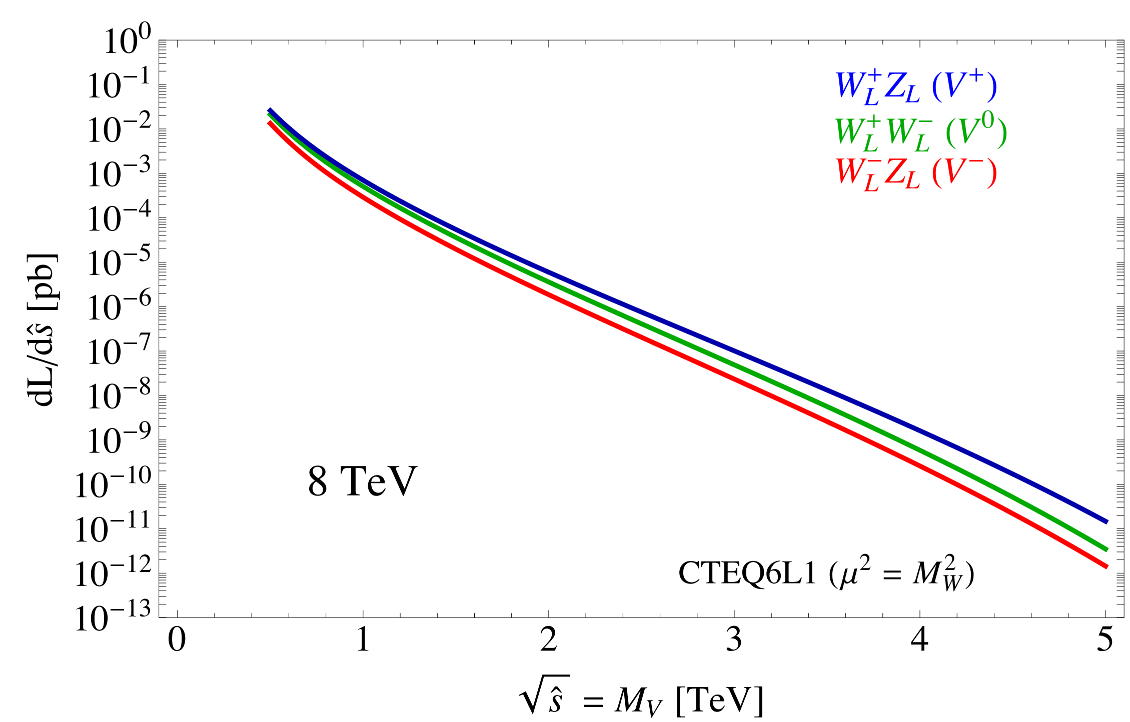
model independent

- 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

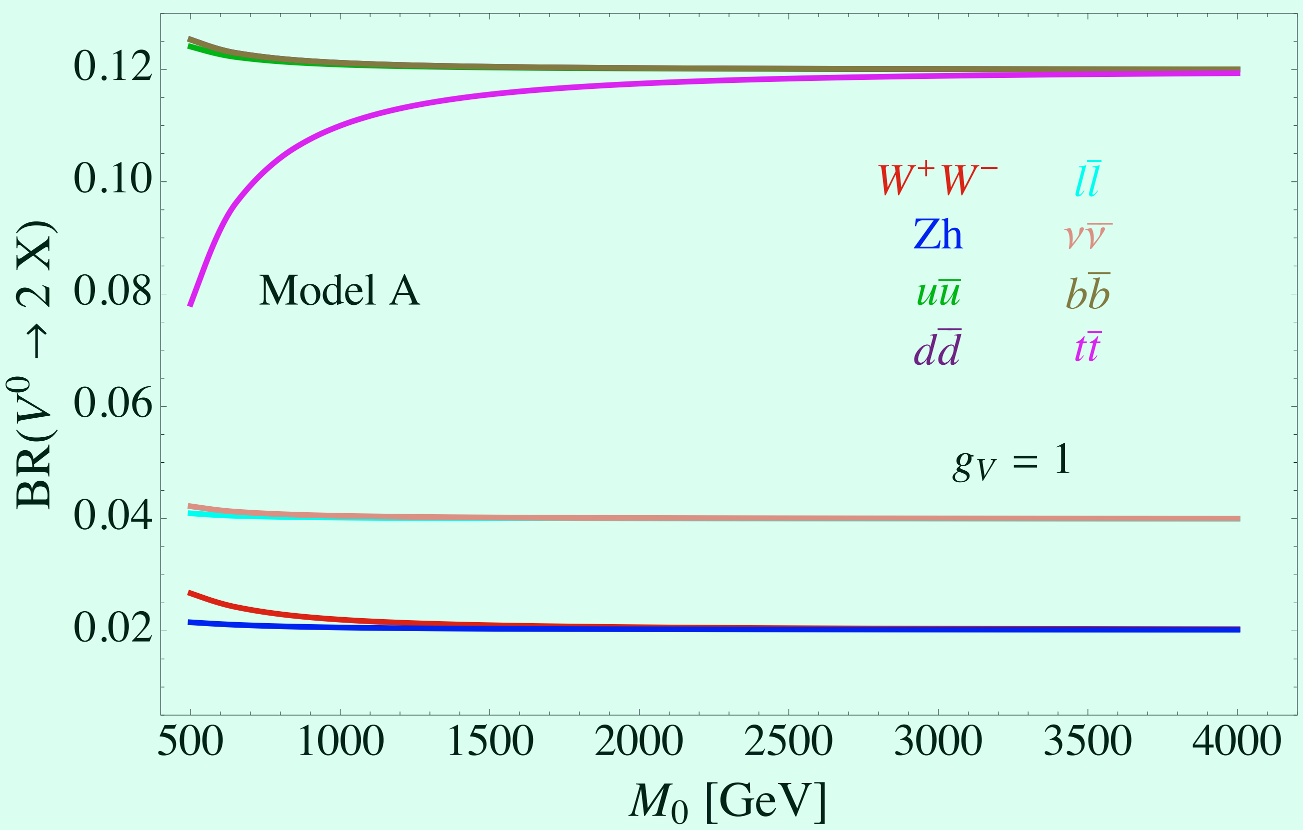
$$\Gamma_{V_\pm \to f\bar{f}'} \simeq 2\,\Gamma_{V_0 \to f\bar{f}} \simeq N_c[f] \left(\frac{g^2 c_F}{g_V}\right)^2 \frac{M_V}{96\pi}\,,$$

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

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

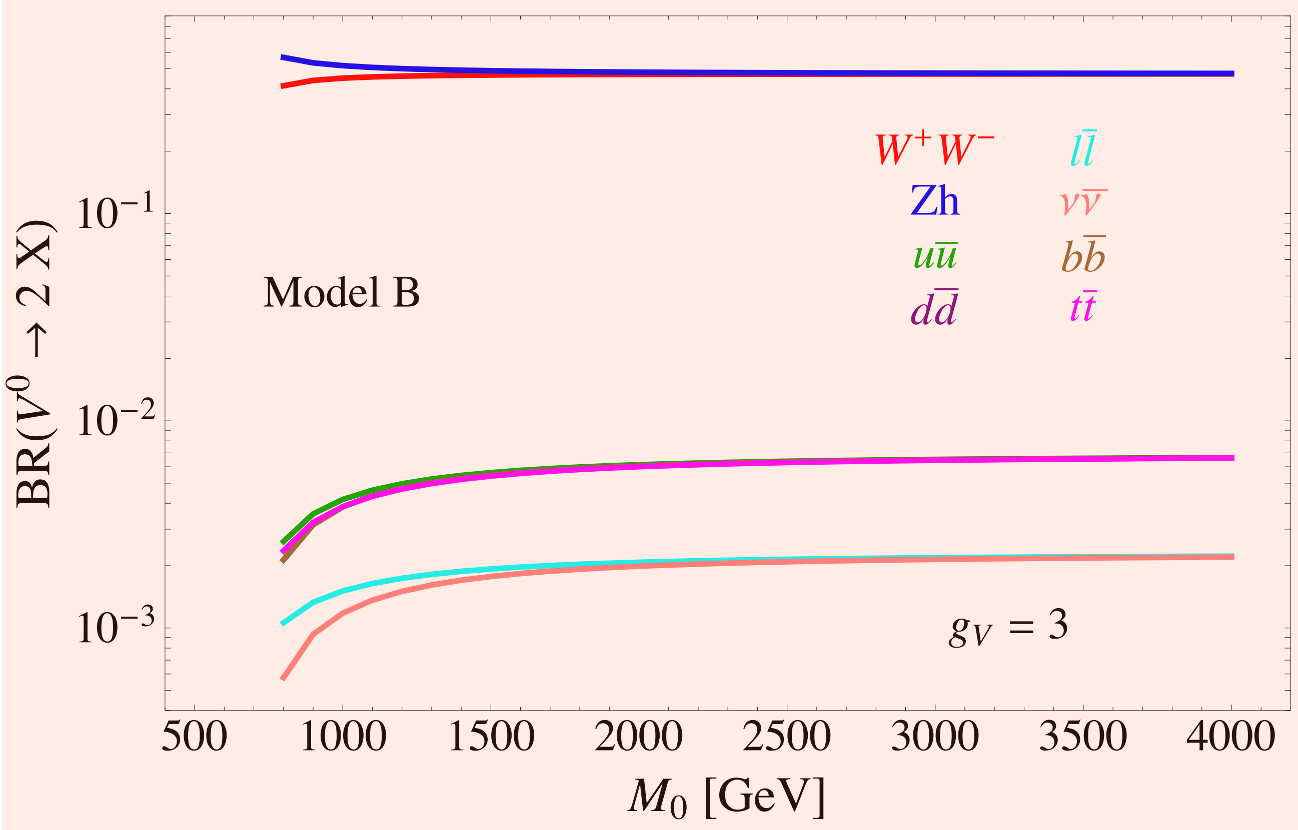
Weakly coupled model

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



Strongly coupled model

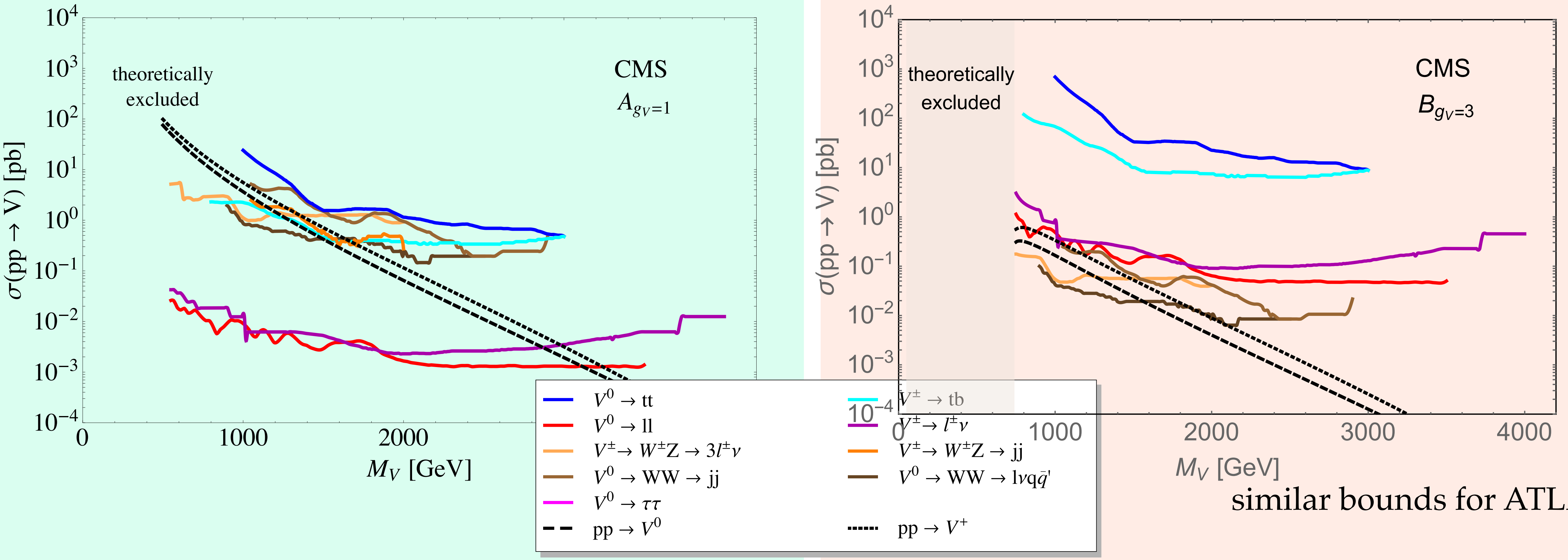
$g_V c_H \simeq -g_V\,, \qquad g^2 c_F / g_V \simeq g^2 / g_V$



LHC bounds

Weakly coupled model

Strongly coupled model



similar bounds for ATLAS

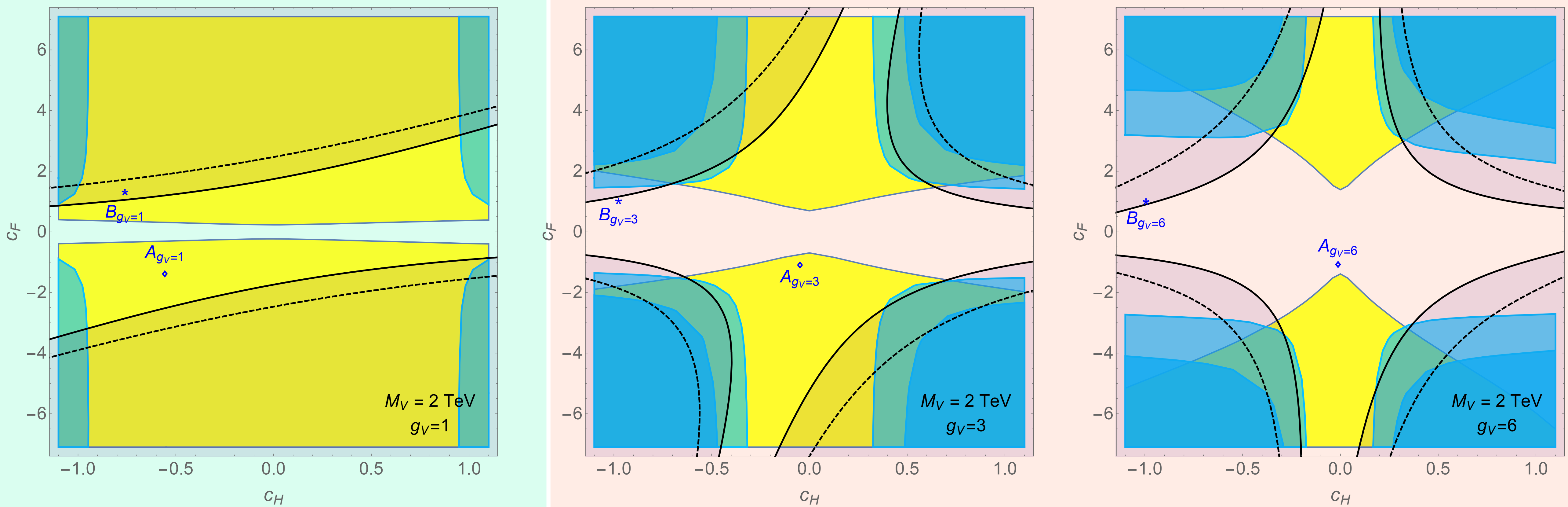
- excluded for masses < 3 TeV
- di-lepton most stringent
- di-boson searches < 1-2 TeV

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

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

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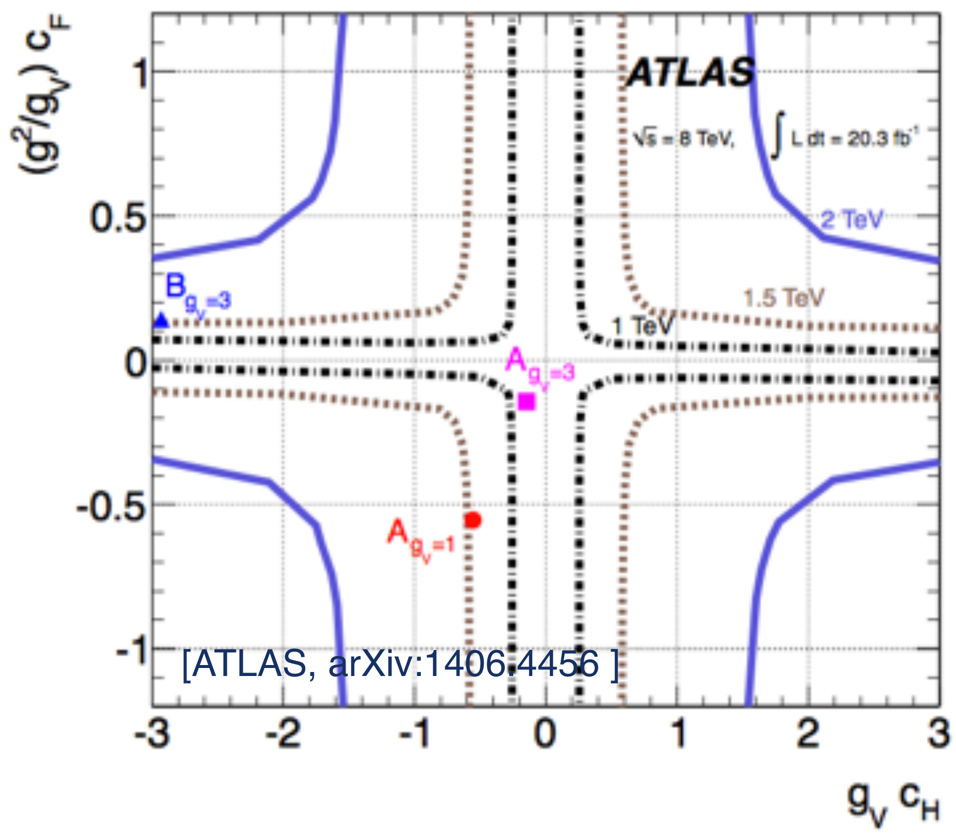
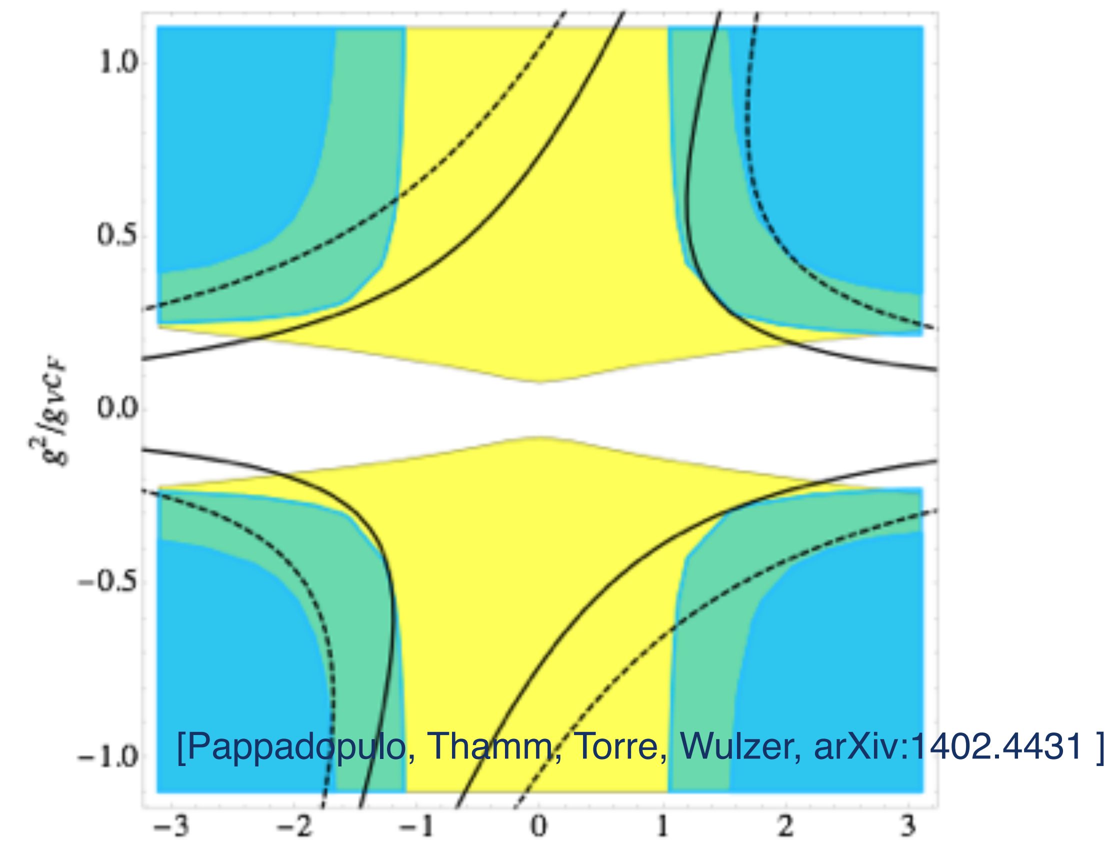
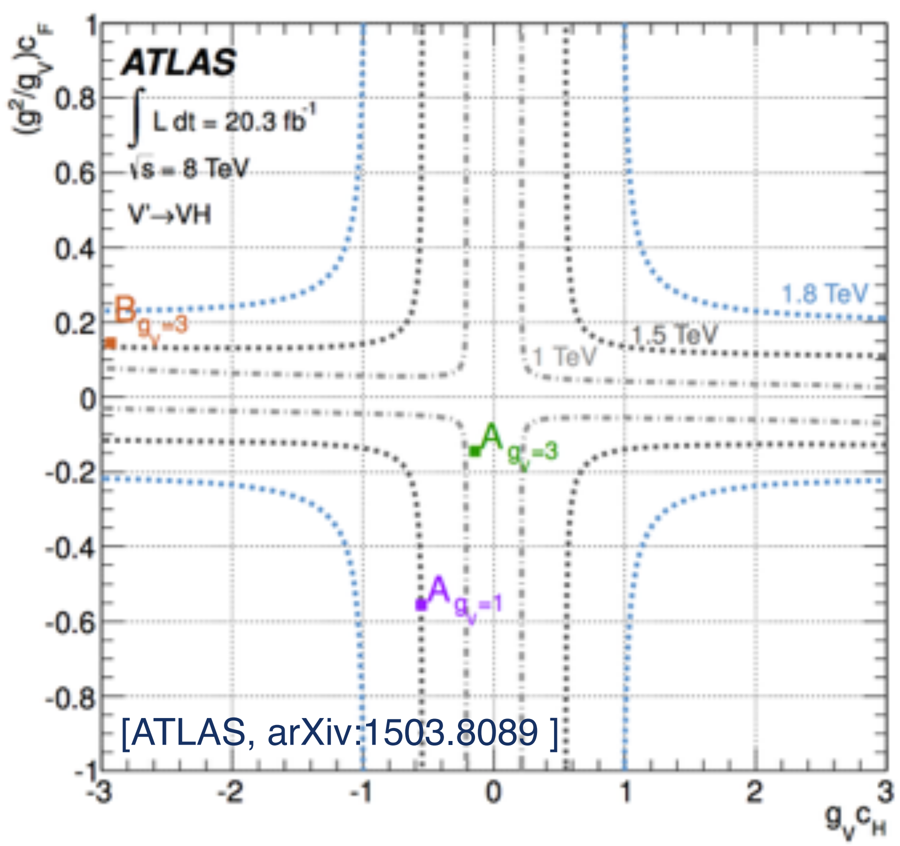
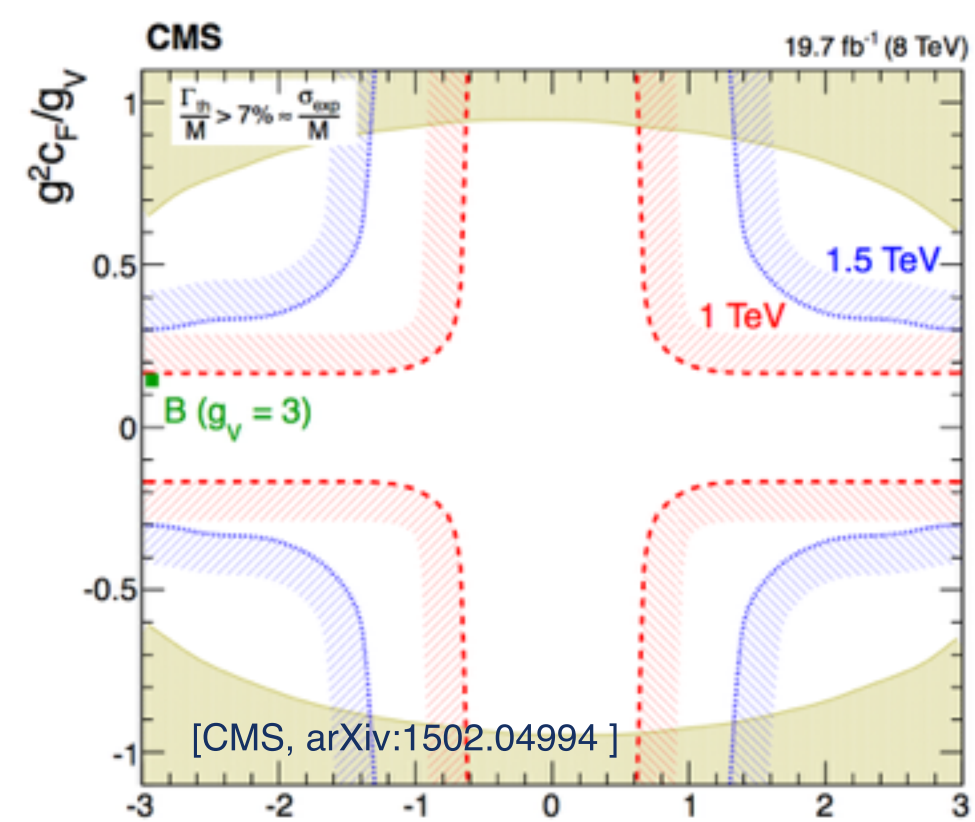


- ATLAS:
  W' to WZ





- ATLAS:
  V' to HV to (bb)(lep lep)
- CMS:
  Z' to HZ to (tau tau)(qq)



LHC bounds

- experimental limits converted into (M_V, g_V) plane

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

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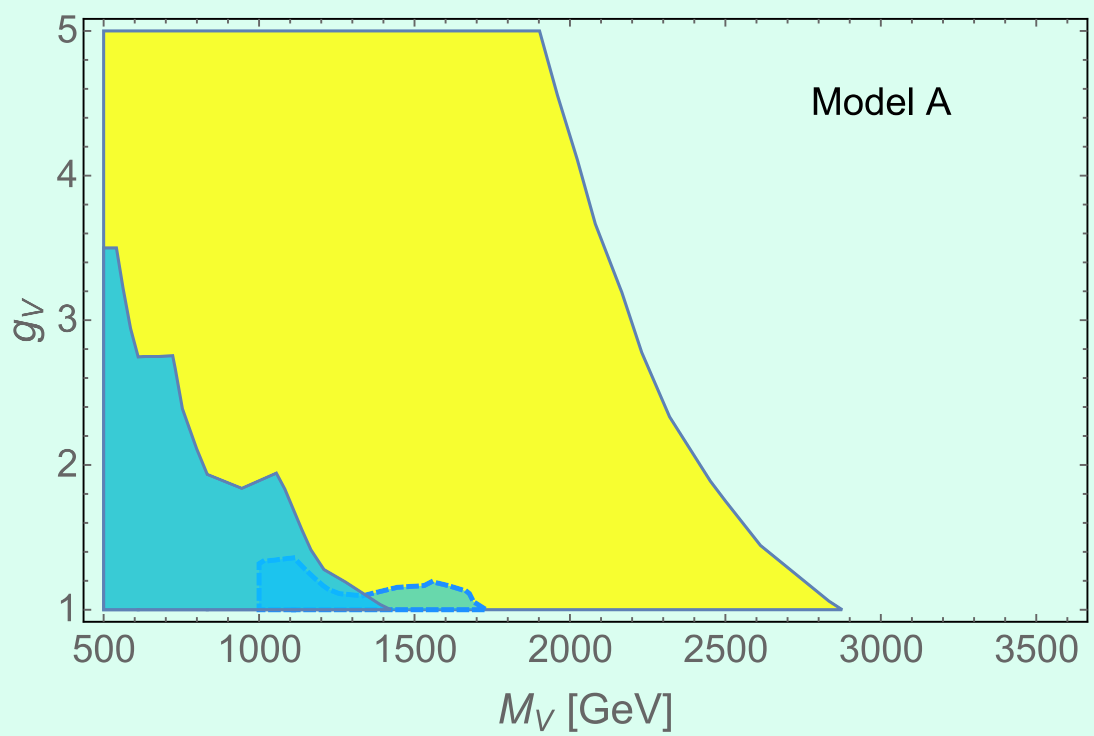
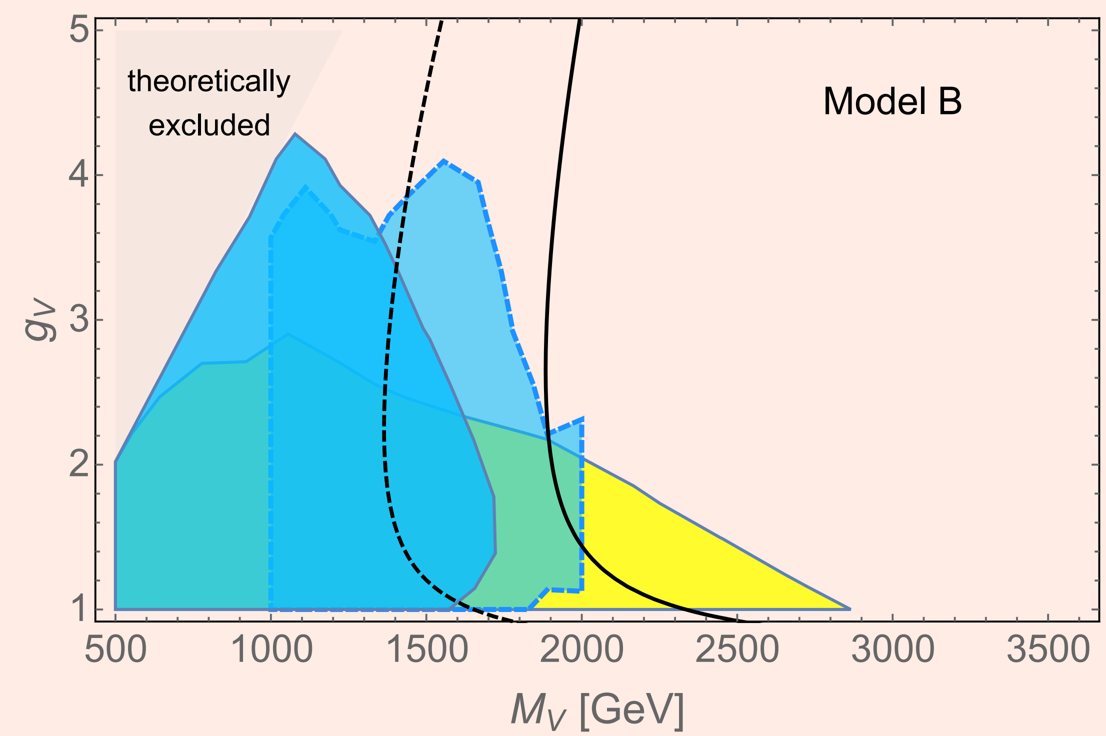
Weakly coupled model



Strongly coupled model



- leptonic final state dominates at low g_V
- 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]

Combination of searches

- simplified model makes combination of searches easy

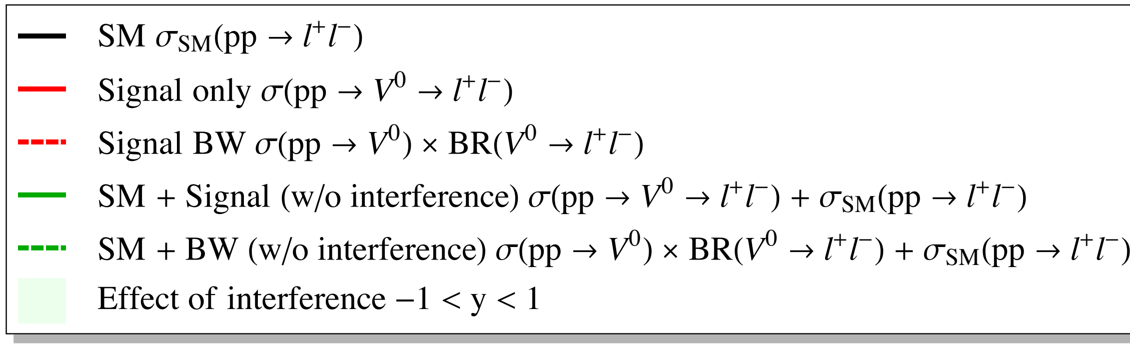
arXiv:1402.4431 to appear

Channel	$V^0 \in (\mathbf{1},\mathbf{3})_1$	$V^+ \in (\mathbf{1},\mathbf{3})_1$	$V^0 \in (\mathbf{1},\mathbf{1})_0$ $\in \mathbf{3}$ of $SU(2)_R$	$V^+ \in (\mathbf{1},\mathbf{1})_1$ $\in \mathbf{3}$ of $SU(2)_R$	Final states
ll	□	×	□□	×	-
$l\nu$	×	□	×	×	-
$l\nu_R$	×	×	×	□□	$llqq$
jj	□	□	□□	□□	-
tb	×	□	×	□□	-
tt	□	×	□□	×	-
WW	□	×	□□	×	$l\nu qq, qqqq$
ZZ	×	×	×	×	$llll, llqq, qqqq$
Zh	□	×	□□	×	$llbb, \nu\nu bb$
WZ	×	□	×	□□	$l\nu ll$,$llqq, l\nu qq, qqqq$
Wh	×	□	×	□□	$l\nu bb$,$qqbb$
$W\gamma$	×	□	×	□□	γqq ,$\gamma l\nu$
hh	×	×	×	×	$\{bb, \tau\tau, \gamma\gamma\} \otimes \{bb, \tau\tau, \gamma\gamma\}$,

Triplet of $SU(2)_L$ Singlet of $SU(2)_L$ Singlet of $SU(2)_L$

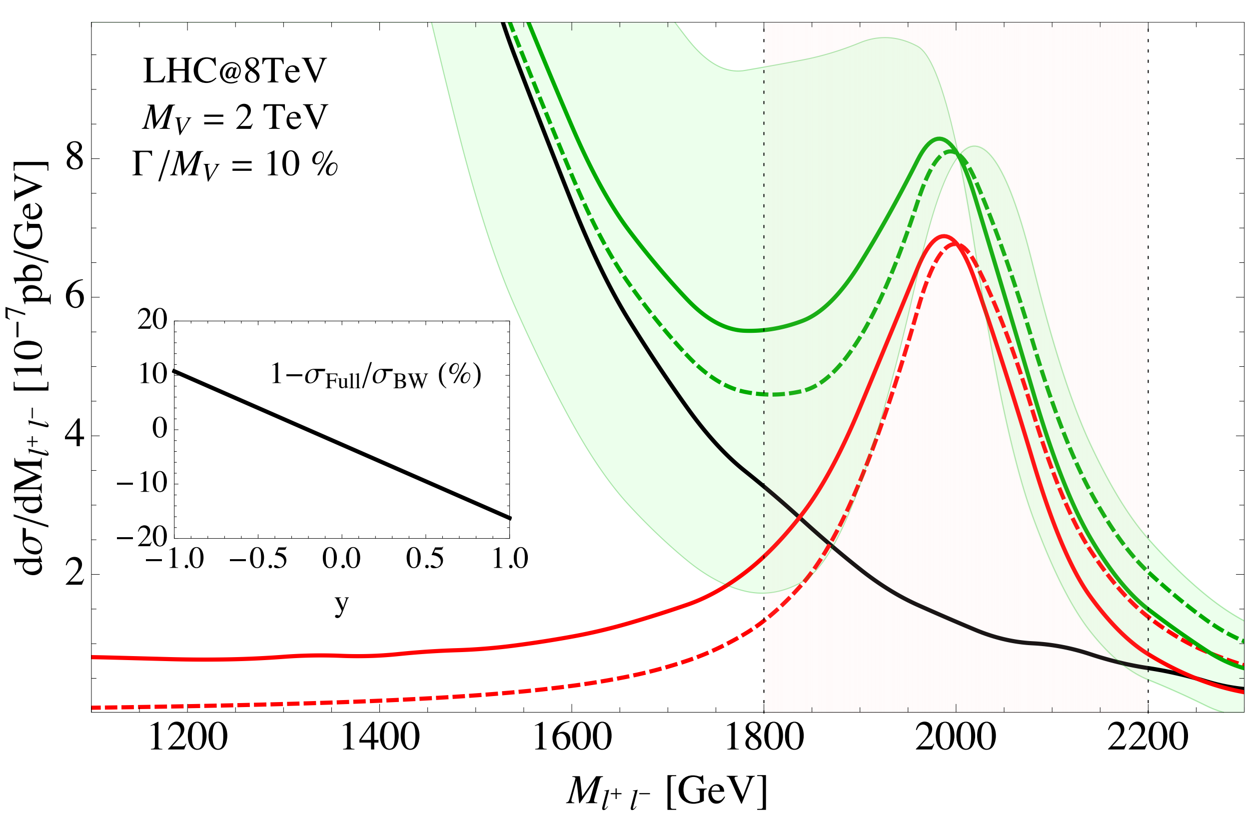
Limit setting

Limit setting

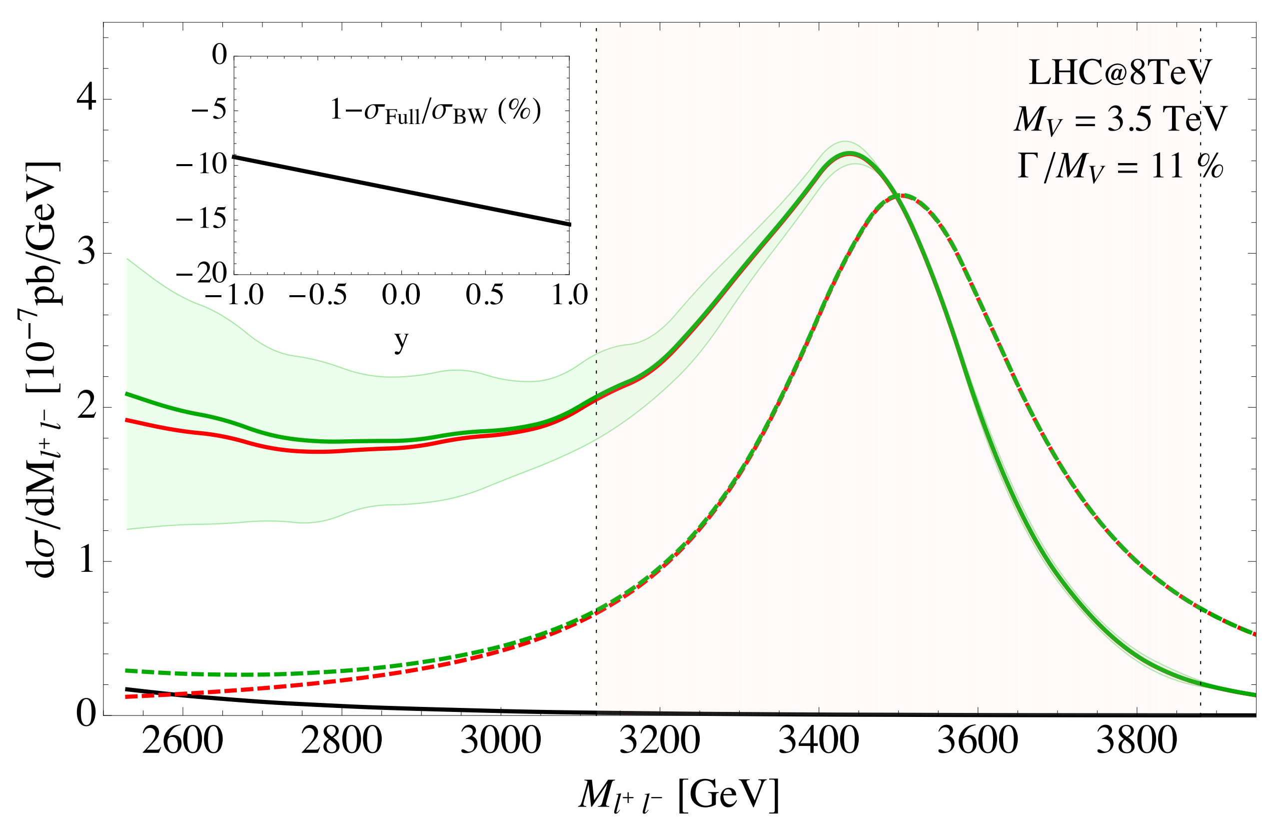


- want limits on $\sigma \times BR$ since model-independent
  can be easily reinterpreted
- but depends on details of analysis (assumed total width of resonance)
- discuss two (well known, but often forgotten) effects
- example: di-lepton invariant mass distribution

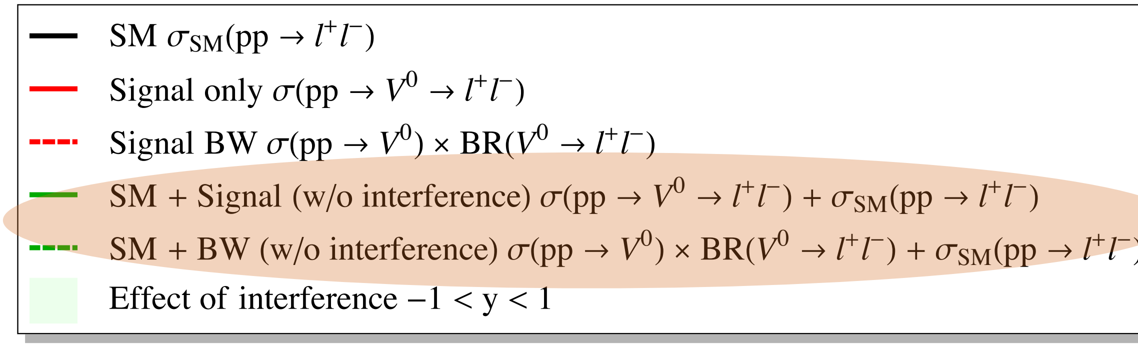
2 TeV resonance



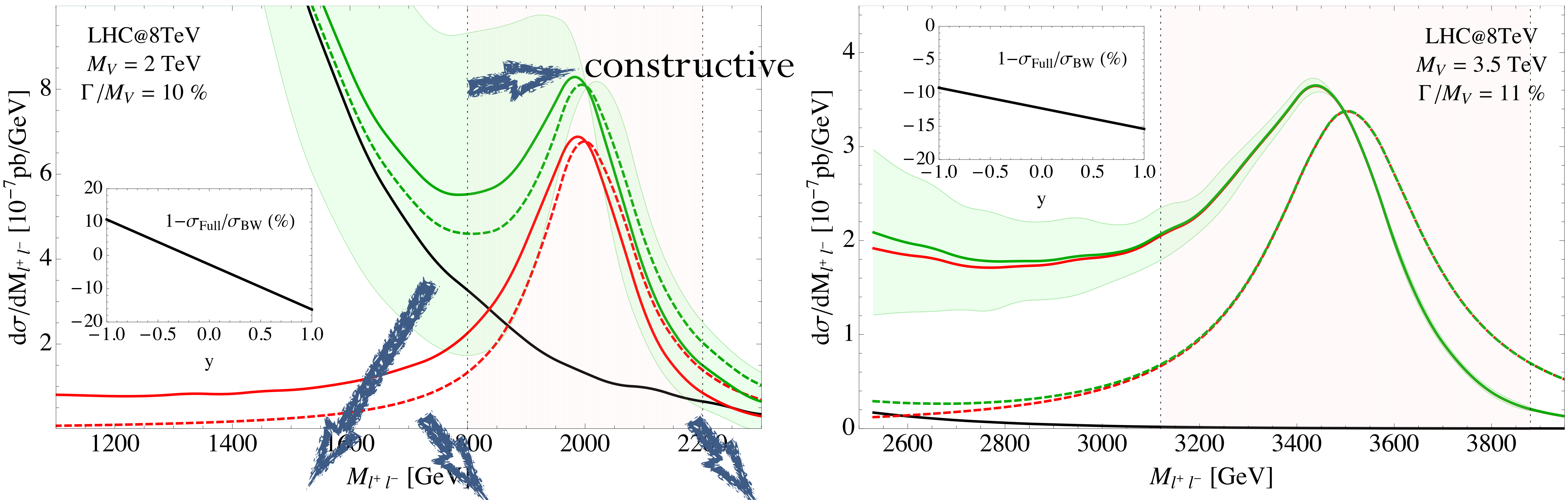
3.5 TeV resonance



Limit setting



1. Interference with SM background



destructive

background

$\sigma(pp \to V^0) \times \text{BR}(V^0 \to ll)$

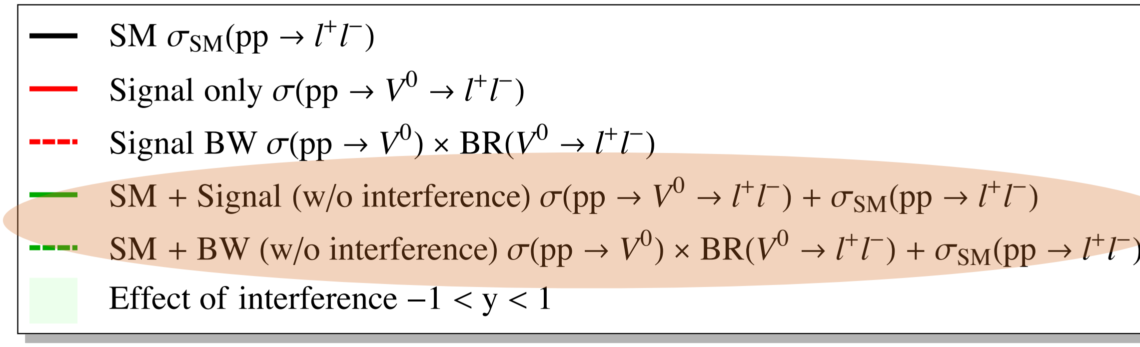
- depends on S/B ratio
- dashed green: signal + background with no interference
- green shaded region: constructive and destructive interference
  ⇨ can be large effect

$$\hat{\sigma}_I(\hat{s}) \propto \frac{(\hat{s} - M_V^2)}{(\hat{s} - M_V^2)^2 + M_V^2\Gamma^2}$$

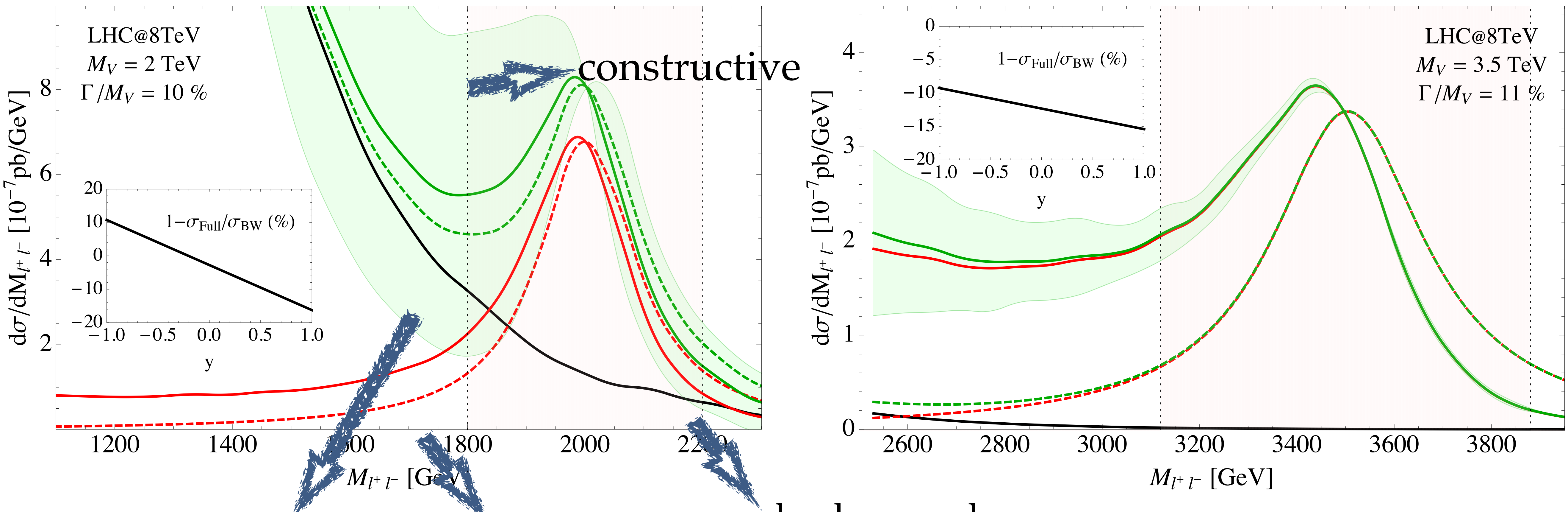
- interference vanishes exactly at $\hat{s} = M_V^2$, is odd around this point
- $[M_V - \Gamma, M_V + \Gamma]$ less sensitive

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

Limit setting



1. Interference with SM background



constructive

destructive

background

$$\sigma(pp \to V^0) \times \text{BR}\,(V^0 \to ll)$$

- parameterize interference as

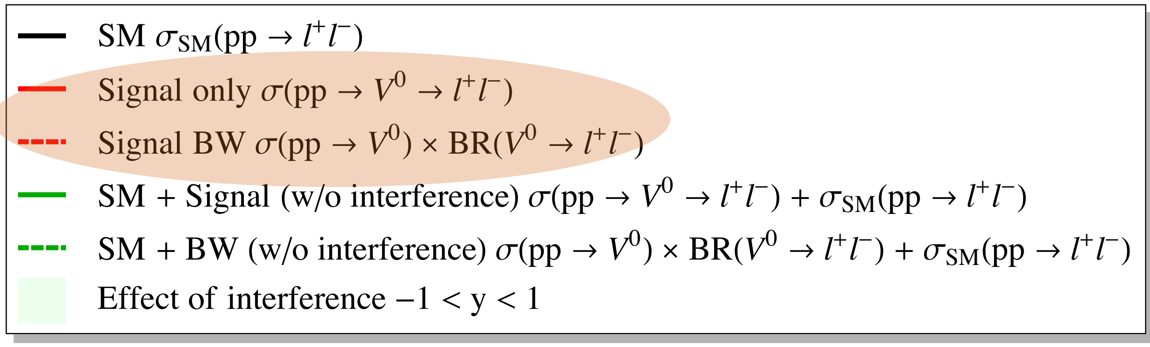
$$\frac{d\sigma_{\rm Full}}{dM_{l+l-}}(y) = \frac{d\sigma_{\rm B}}{dM_{l+l-}} + \frac{d\sigma_{\rm S}}{dM_{l+l-}} + y\,\frac{d\sigma_{\rm I}}{dM_{l+l-}}$$

- inset plot: $\left(y, 1 - \frac{\sigma_{Full}(y)}{\sigma^{BW}}\right)$

⇨ within mass window, deviation is $< 10\%$

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

Limit setting



2. Distortion from BW

[Accomando, Becciolini, Balyaev, Moretti, Shepherd, arXiv:1304.6700]
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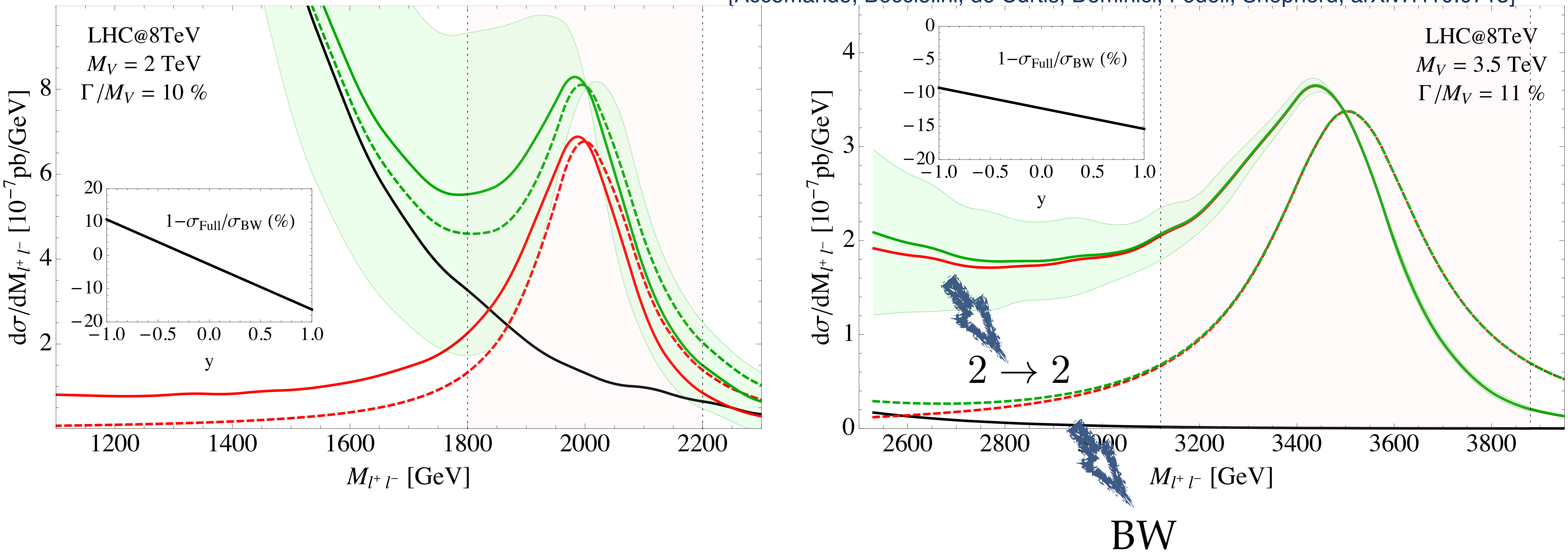


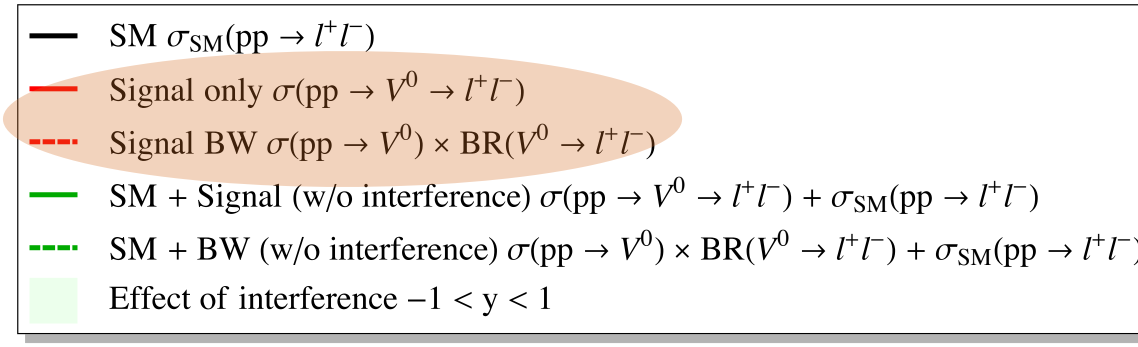
- due to steep fall of parton luminosities at large energies
- total BW cross section

$$\frac{d\sigma_S}{dM^2_{l^+l^-}} = \sum_{i,j} \frac{4\pi}{3} \frac{\Gamma_{V\to q_i q_j}\Gamma_{V\to l^+l^-}}{(M^2_{l^+l^-} - M^2_V)^2 + M^2_V\Gamma^2} \frac{M^2_{l^+l^-}}{M^2_V} \frac{dL_{ij}}{d\hat{s}}\bigg|_{\hat{s}=M^2_{l^+l^-}} \simeq \frac{dL_{ij}}{d\hat{s}}\bigg|_{\hat{s}=M^2_V}$$

- in peak region only $M_{l^+l^-} - M_V \sim \Gamma$

$$\frac{d\sigma_S}{dM^2_{l^+l^-}} = \sigma \times BR_{V\to l^+l^-} BW(M^2_{l^+l^-}; M_V, \Gamma)$$

Limit setting



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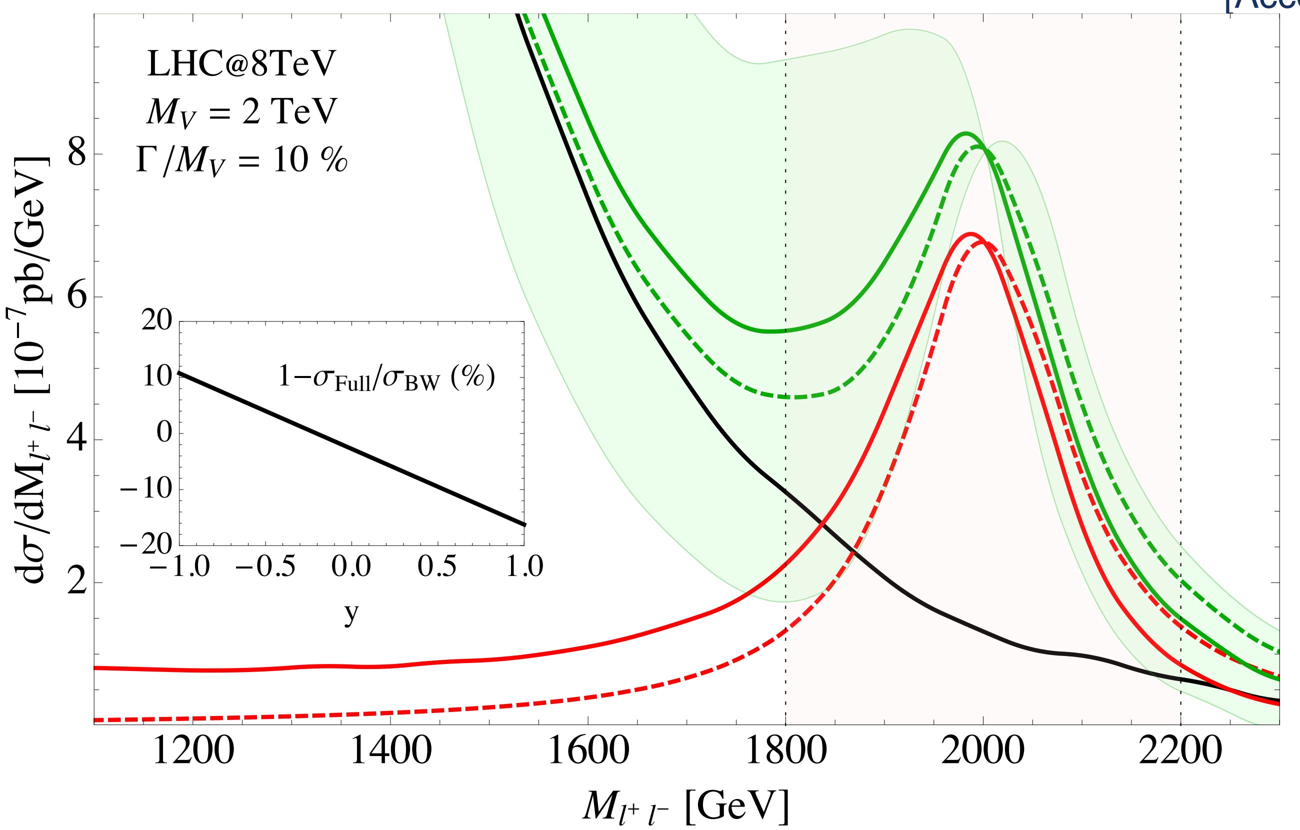
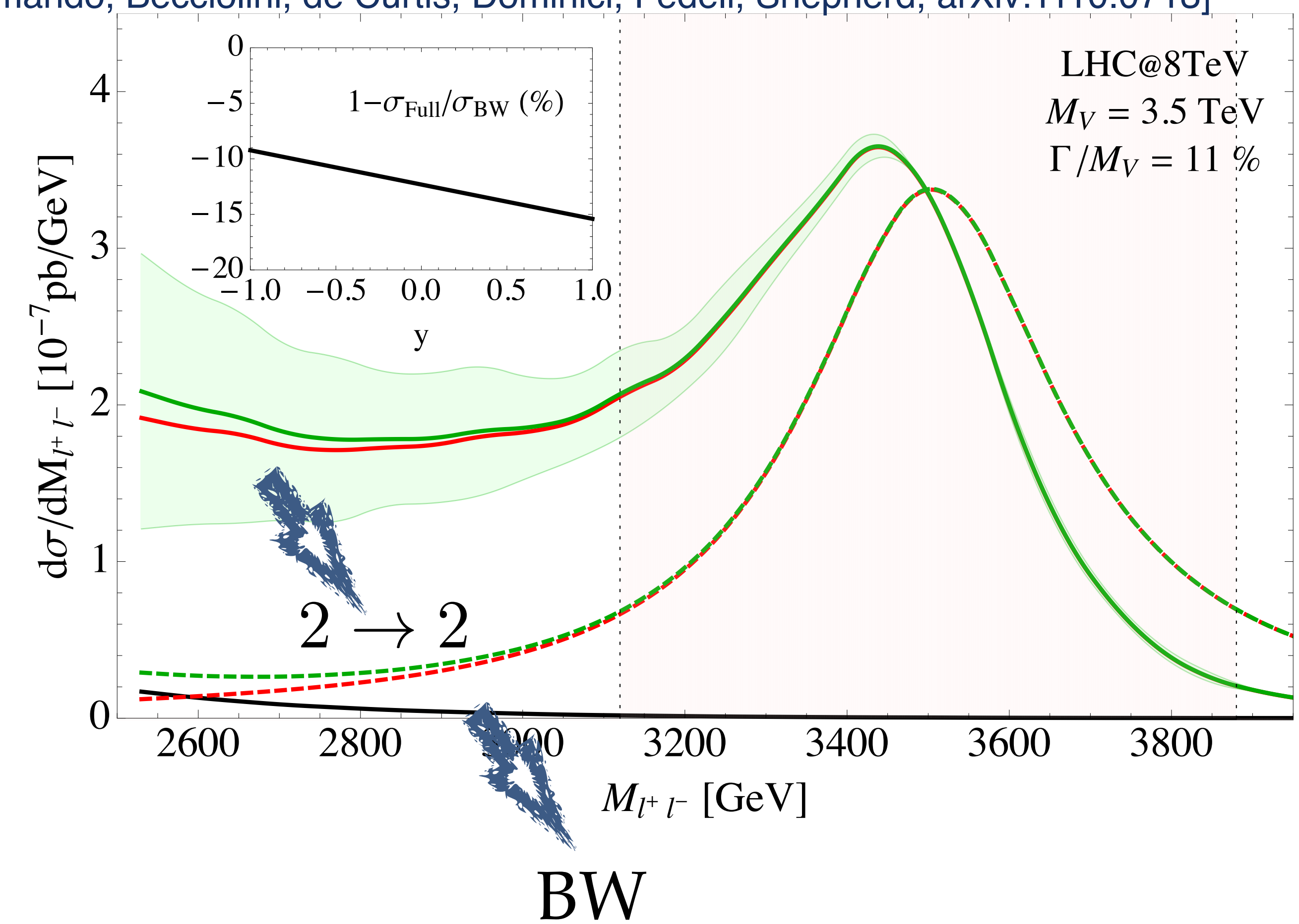


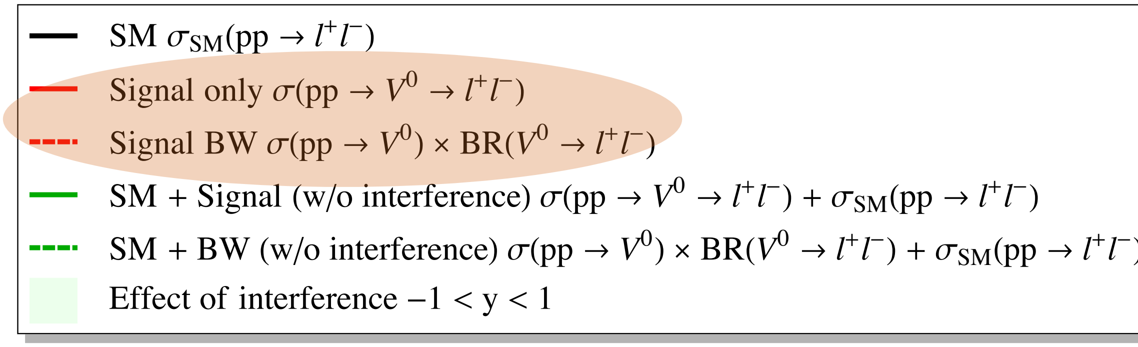


- assumption depends on variation of parton luminosities

$$\frac{M_{l^+l^-}^2}{M_V^2} \frac{dL_{ij}}{d\hat{s}}\bigg|_{\hat{s}=M_{l^+l^-}^2} \simeq \frac{dL_{ij}}{d\hat{s}}\bigg|_{\hat{s}=M_V^2}$$

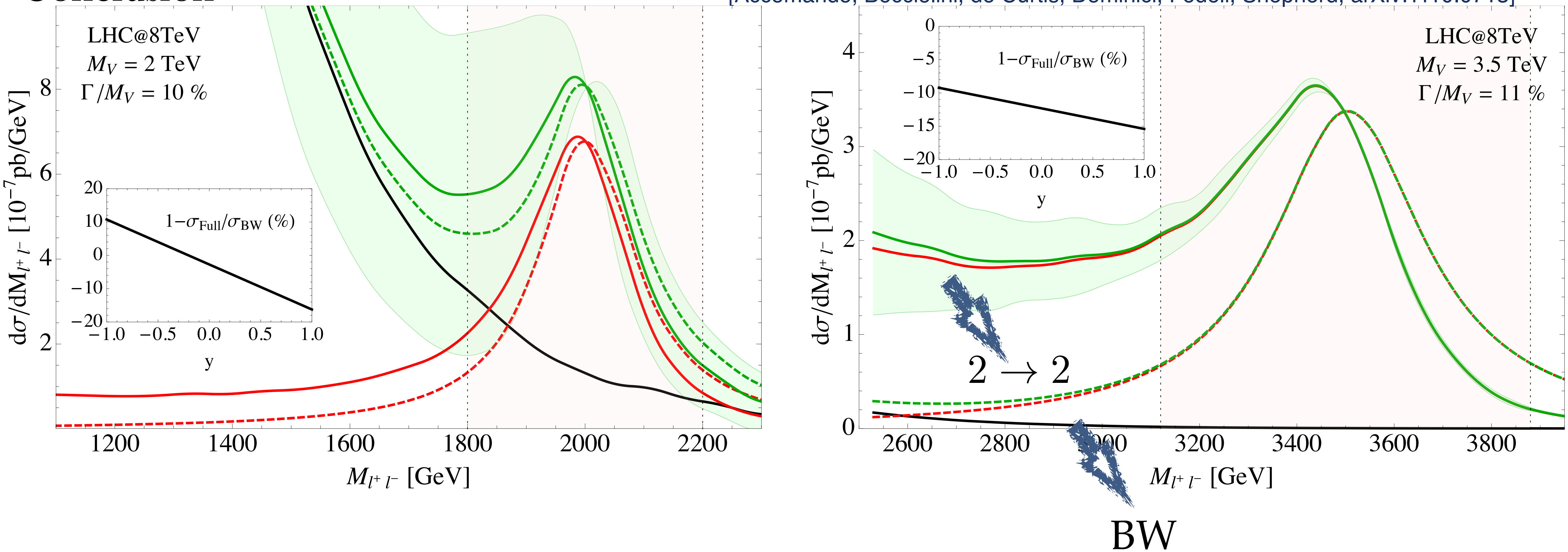
- agreement better for small width
- parton luminosities decrease faster at larger masses
- however, in peak region deviation $< 10\%$

Limit setting



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

Conclusion



- only limits set on peak region give model independent bounds (give bounds on $\sigma \times BR$ for each mass and width)
- searches sensitive to the tail only valid in the assumed model, not reusable

Conclusions

- model independent strategy to study heavy spin-1 triplets
- extremely useful to present results in terms of simplified model parameters

  allows easy reinterpretation
- limits should be set on $\sigma \times BR$ by focussing on the on-shell region