A case study of the LHC mass exclusion limits for the BSM vector resonances

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Introduction

- Higgs discovery
- EWSB = ? (BSM: strongly/weakly interacting)
- SM - not final theory
- BSMs predict new particles
- ATLAS and CMS resonance searches:

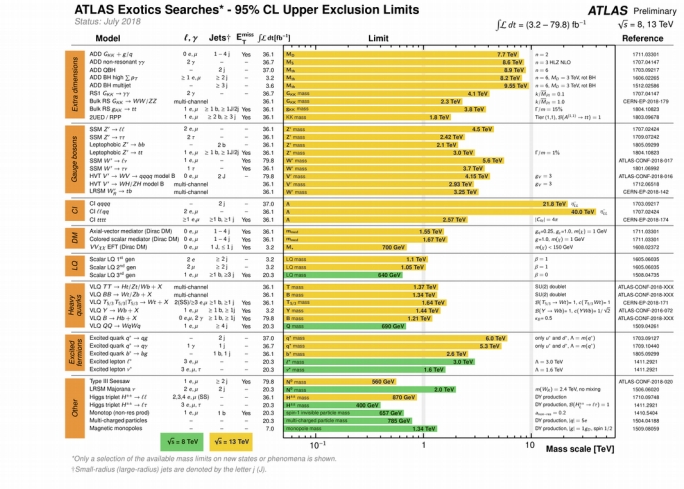
  no discovery yet → improving exclusion limits of BSM parameters

  - **Exclusion limits on Mass** (MEL)

Introduction

Experimantal direct searches:

- ATLAS+CMS
- ≤ 13 TeV, ≤ 80 fb^{-1}
- no “pp → R” signal ⇒ upper limits on “$\sigma_{prod} \times BR(R \to ab)$”
  - tailored for **narrow resonances**
  - some attempts beyond this restriction



ATLAS Exotics searches (July 2018) – vector resonances

Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	36.1	Z' mass	4.5 TeV
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV
	Leptophobic $Z' \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	3.0 TeV $\Gamma/m = 1\%$
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	79.8	W' mass	5.6 TeV
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass	3.7 TeV
	HVT $V' \to WV \to qqqq$ model B	0 e,μ	2 J	–	79.8	V' mass	4.15 TeV $g_V = 3$
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV $g_V = 3$
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass	3.25 TeV

Introduction

Plethora of BSMs

- huge task to check all – model dependency

- effective Lagrangian: a convenient tool for pheno
  - ➢ analytic tool as model independent as possible
  - ➢ data/observables/theory parameters connections
  - ➢ proper approximations

Our Goals

- vector resonances: strongly-interacting extensions of the SM

  well motivated – CHM, TC2, ...

- observability at the LHC

Particular questions

- **MEL**s

  - the impact of the resonance-to-fermions free params

- the role of the **b-quark proton contents**

- restriction by the **NWA** ($\Gamma/M<10\%$)

tBESS model

the effective Lagrangian

- the modified BESS model
  - BESS[R. Casalbuoni et al, PLB 155, 95 (1985); NPB282, 235 (1987)]
  - effective description via the Hidden Local Symmetry approach
  - a specific resonance-to-fermion interaction pattern
  - emphasizes **the role of the 3rd quark generation**
  - **avoids the EWPD low-energy limits**
- particle spectrum
  - **SM fields + vector resonance triplet**
- symmetry
  - global **SU(2)$_L$⊗ SU(2)$_R$ → SU(2)$_{L+R}$** (Higgs sector)
  - auxiliary SU(2)$_{HLS}$: the vector triplet as gauge bosons
  - non-linear sigma model (NGB)
  - the 125 GeV SU(2)$_{L+R}$ **scalar singlet** (Higgs)

tBESS model

Main features

- **$SU(2)_{L+R}$ triplet** of vector resonances
- its **mass** depends on the model's couplings
- neutral & charged vector resonances are **degenerate** in mass
- its **total width** grows with the resonance mass
- **direct couplings to fermions:** 3rd quark generation only
- mixing with SM GBs

tBESS model

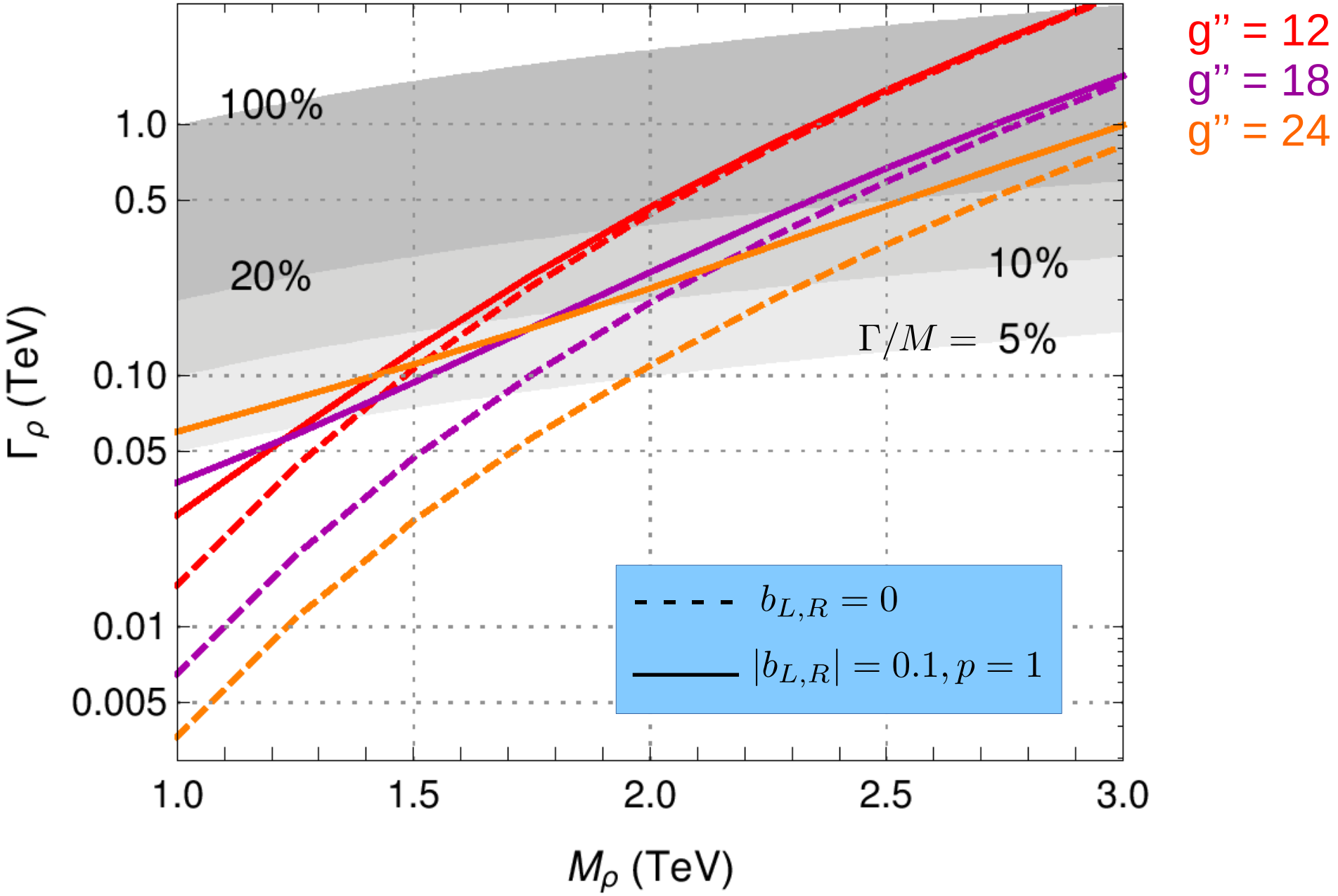
the Lagrangian's free parameters

- the gauge couplings:
  - g … $SU(2)_L$
  - g' … $U(1)_Y$
  - g''/2 … $SU(2)_{HLS}$
- the resonance masses: $M_\rho \approx \sqrt{\alpha} g'' v/2$
- the direct vector-to-fermion couplings:

vertex	$V^3 t_L t_L$, $V^3 b_L b_L$	$V^\pm t_L b_L$	$V^3 t_R t_R$	$V^3 b_R b_R$	$V^\pm t_R b_R$
cplng	b_L g''/2	b_L g''/2	b_R g''/2	p^2 b_R g''/2	p b_R g''/2

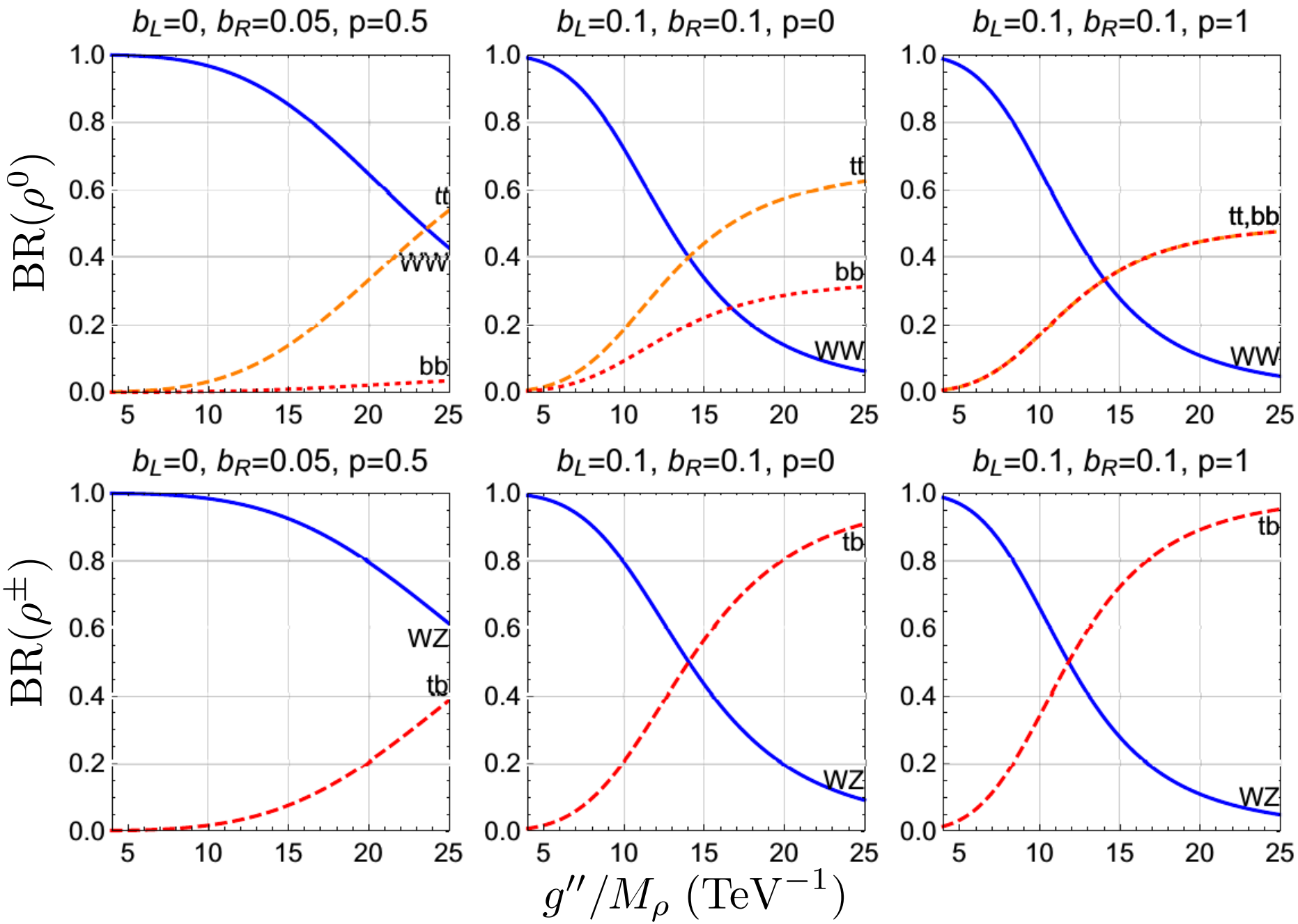
- mixing induced interactions of ρ to all fermions: ~ 1/g''
- perturbativity limit: $g''/2 \leq 4\pi$
- EWPD, Higgs sector measurements, unitarity limits: $g'' > 12$
- EWPD: $|b_{L,R}| < 0.1$

Total Decay Width of ρ_{tBESS}



g'' = 12
g'' = 18
g'' = 24

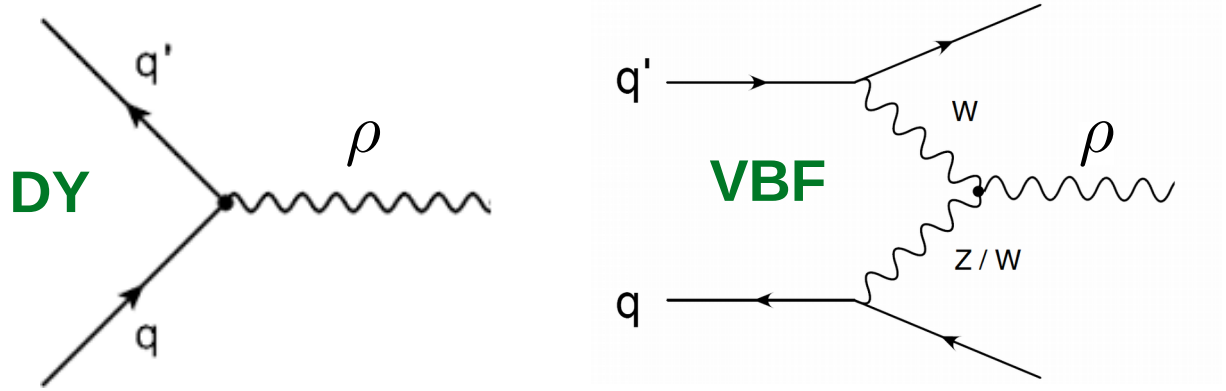
Dominant decay channels $\rho_{tBESS} \rightarrow AB$



Calculations

studied processes

- LHC **s-channel production** + **two-body decay**
- 2 production mechanisms: **DY** + **VBF**

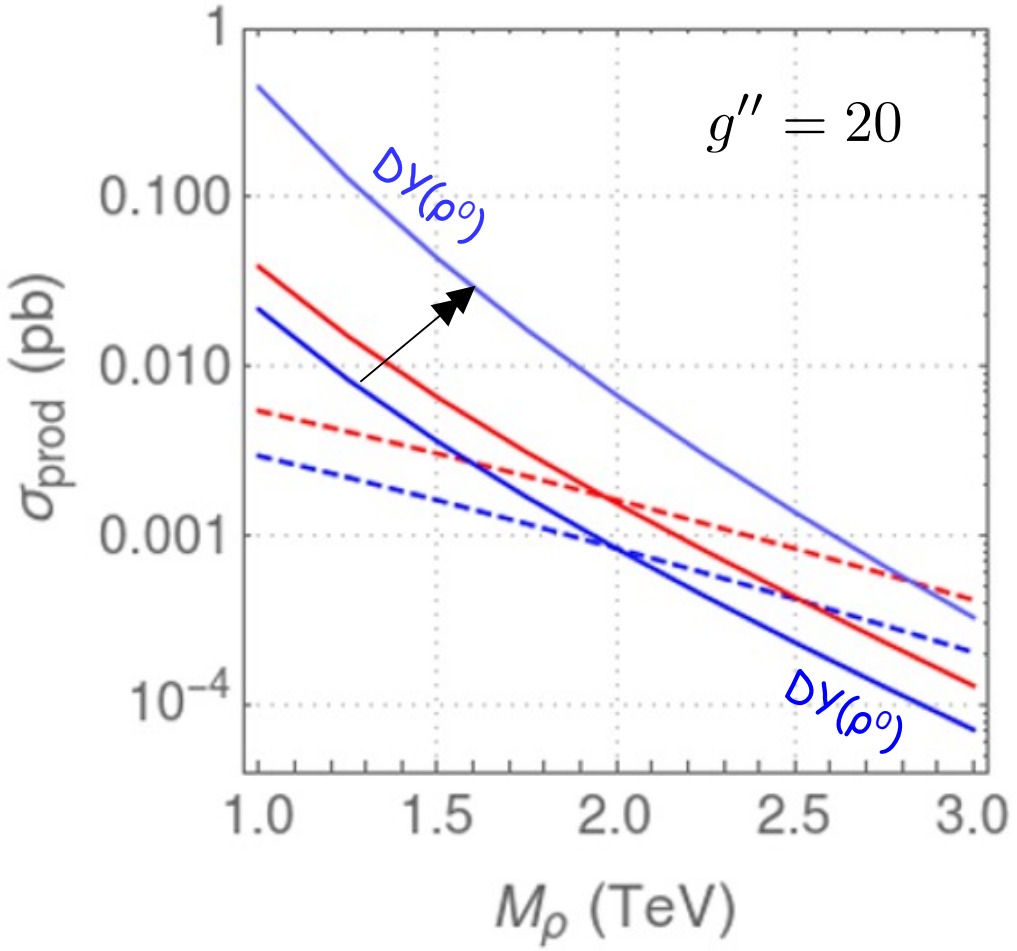


- used approximations: **NWA**(both) & **EWA**(VBF)

$$\sigma(pp \to abX) = \sigma_{\mathrm{prod}}(pp \to \rho X) \times \mathrm{BR}(\rho \to ab)$$

$$\sigma_{\mathrm{prod}}(pp \to \rho + X) = \sum_{i \leq j \in p} 16\pi^2 K_{ij} \frac{\Gamma_{\rho \to ij}}{M_\rho} \frac{dL_{ij}}{d\hat{s}}|_{\hat{s}=M_\rho^2}$$

Production XS



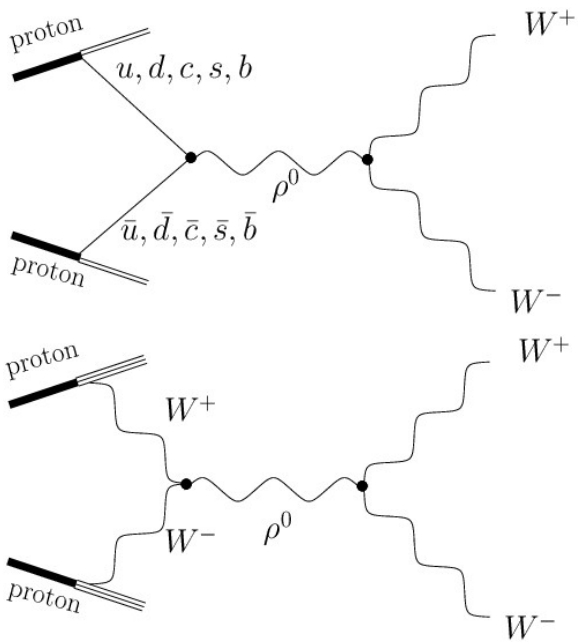
- the effect of the b-quark in proton: ⟶

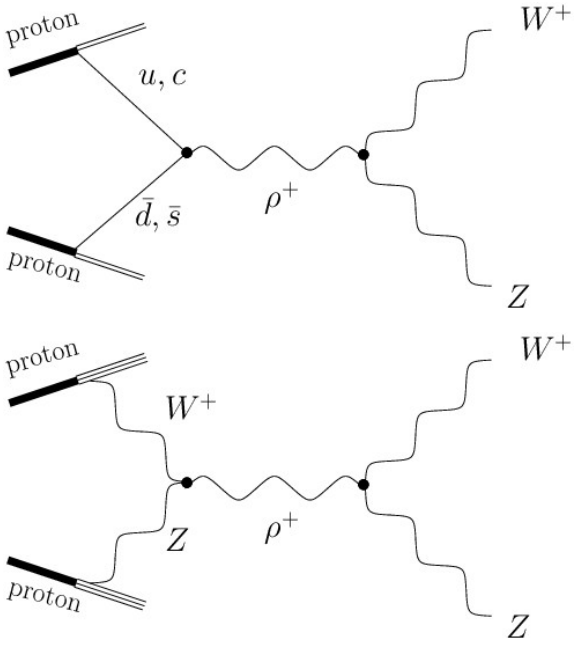
VBF($\rho^\pm$)
VBF(ρ^0)
DY($\rho^\pm$)
DY(ρ^0)
NDI
$(b_{L,R} = 0)$
DY(ρ^0)
$b_{L,R} = 0.1, p = 1$

Results

experimental input

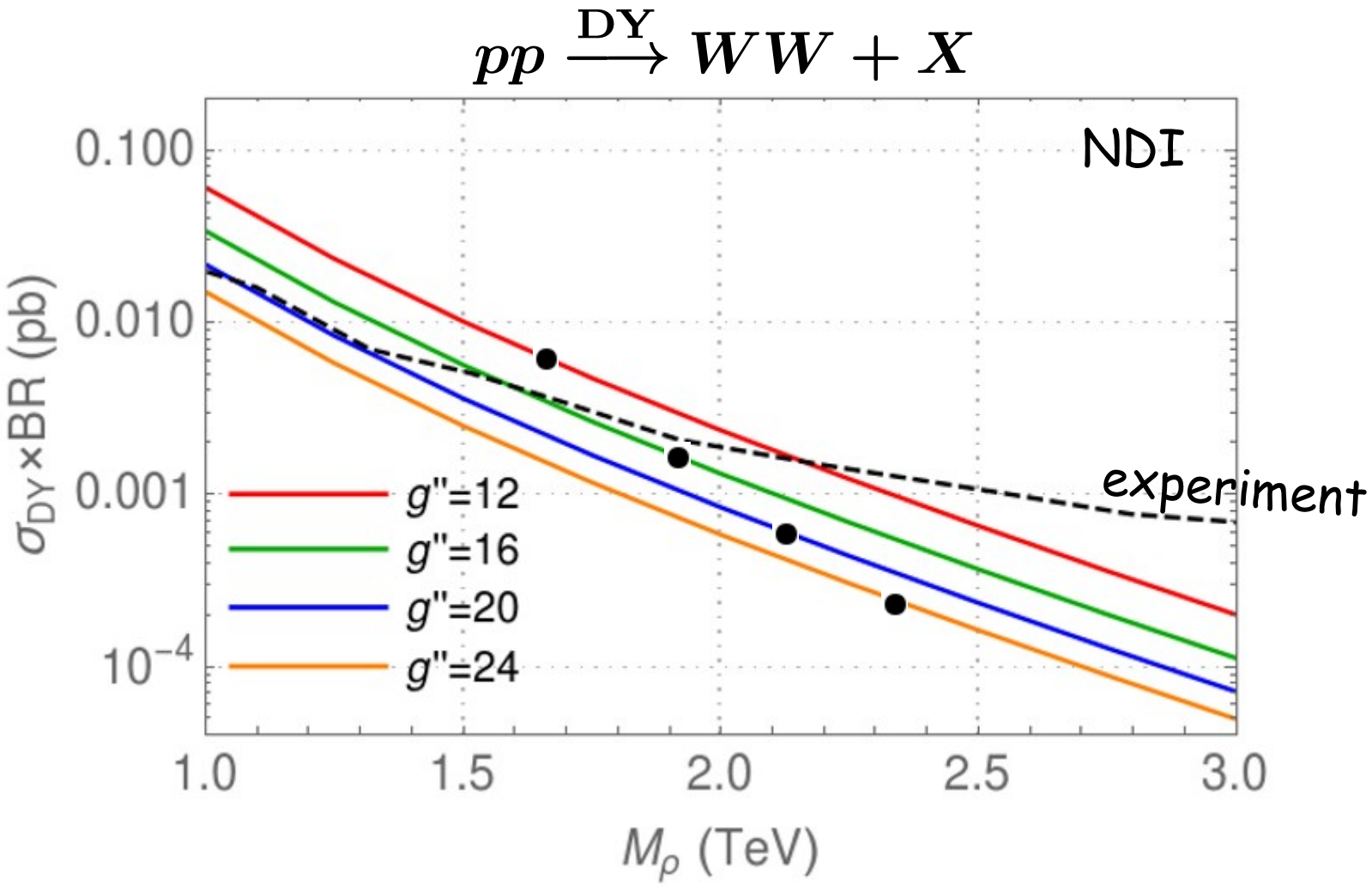
- ATLAS+CMS, ≤ 13 TeV, ≤ 36 fb^{-1}
- upper limits on "$\sigma_{prod} \times BR(R \rightarrow ab)$":
  - available: $WW, WZ, WH, ZH, jj, \ell\ell, \ell\nu, \tau\tau, \tau\nu, bb, tt, tb$
  - **restrictions from:** $\boldsymbol{WZ_{DY}, WW_{DY}, WZ_{DY+VBF}, WW_{DY+VBF}}$





Results

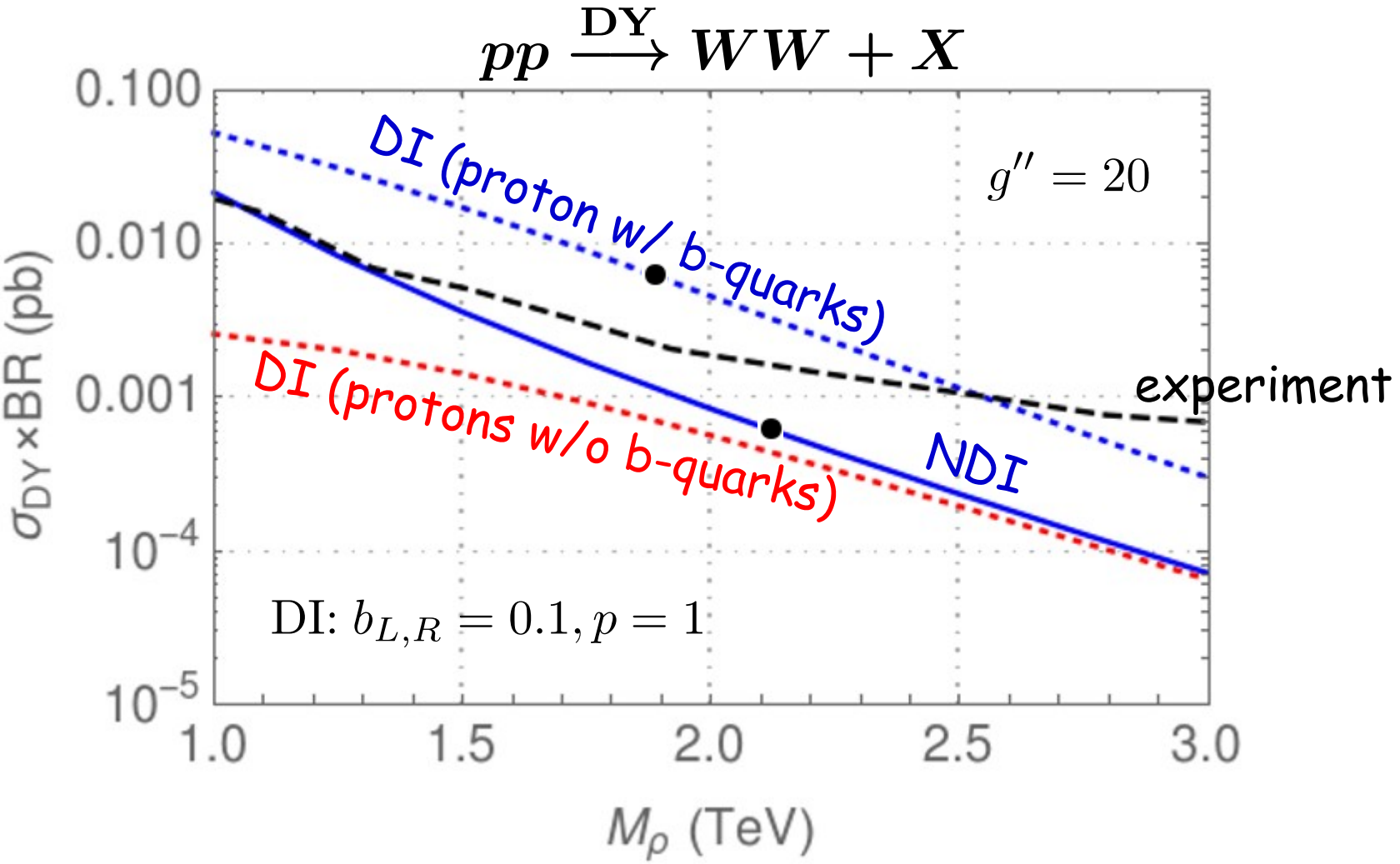
no direct interactions ($b_{L,R} = 0$)



- $\Gamma/M = 10\%$

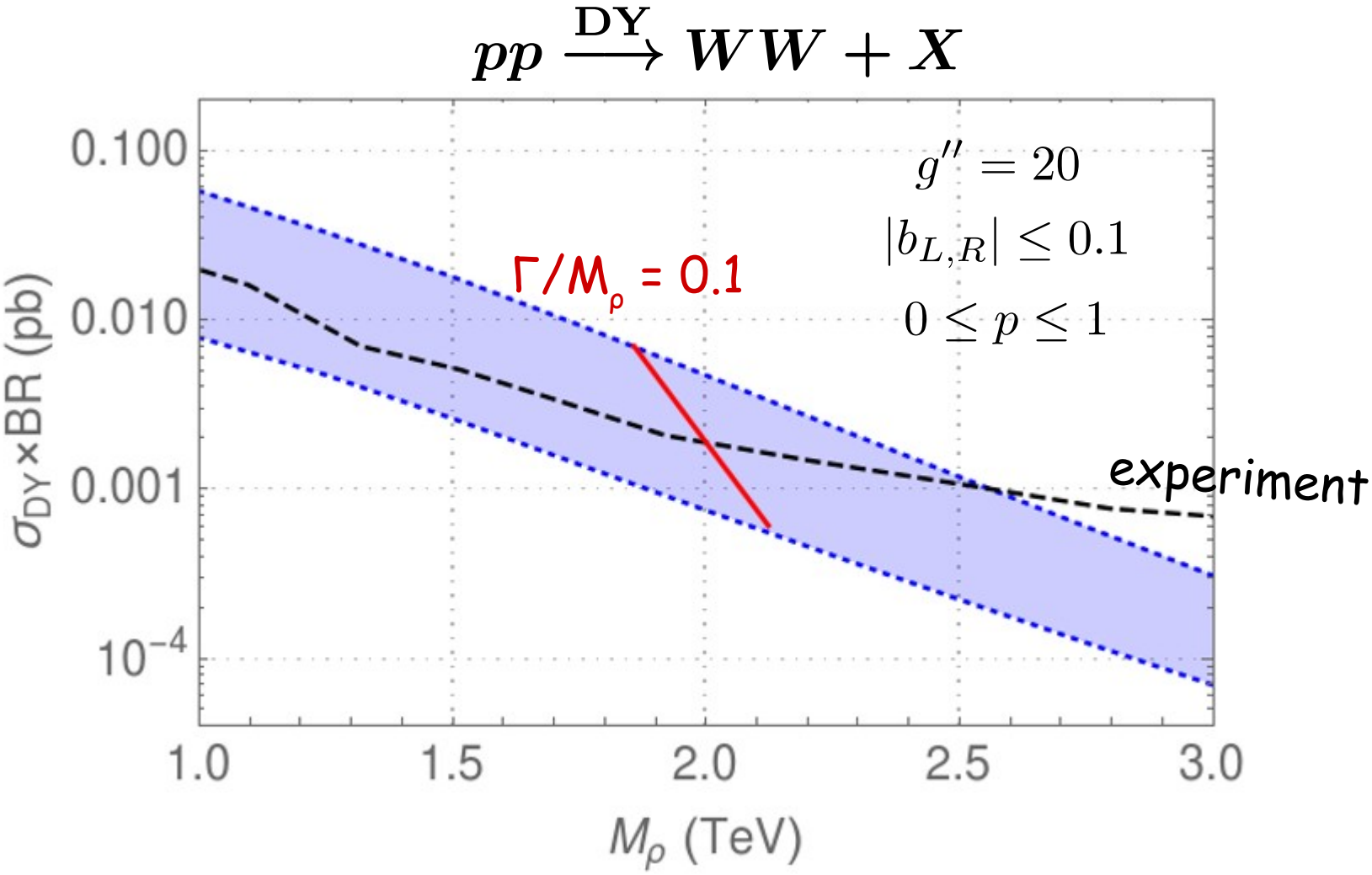
Results

the effect of the b-quark proton contents



Results

the direct interactions turned on



Results

MEL's for different scenarios

- the strongest of the $WZ_{\mathrm{DY}}, WW_{\mathrm{DY}}, WZ_{\mathrm{DY+VBF}}, WW_{\mathrm{DY+VBF}}$ limits

g''	MEL/TeV (Γ/M_ρ)		
	NDI $b_L = b_R = 0$ p irrelevant	DI free $b_L = b_R = b$ $p = 1$ for most relaxing b	DI $b_L = 0, b_R = 0.1$ free p for most relaxing p
16	2.07 (0.14)	2.04 (0.14), $b = 0.044$	2.02 (0.14), $p = 0.772$
17	1.95 (0.10)	1.92 (0.10), $b = 0.036$	1.87 (0.09), $p = 0.707$
18	1.83 (0.07)	1.77 (0.06), $b = 0.032$	1.68 (0.06), $p = 0.672$
19	1.70 (0.05)	1.64 (0.04), $b = 0.028$	1.49 (0.04), $p = 0.630$
20	1.60 (0.03)	1.53 (0.03), $b = 0.025$	1.33 (0.03), $p = 0.589$
21	1.51 (0.02)	1.44 (0.02), $b = 0.020$	no MEL for some p
22	1.43 (0.02)	1.38 (0.02), $b = 0.017$	no MEL for some p
23	1.37 (0.01)	1.30 (0.01), $b = 0.017$	no MEL for some p
24	1.31 (0.01)	1.11 (0.01), $b = 0.017$	no MEL for some p
25	1.24 (0.01)	1.03 (0.01), $b = 0.016$	no MEL for some p

Results: direct couplings constraints

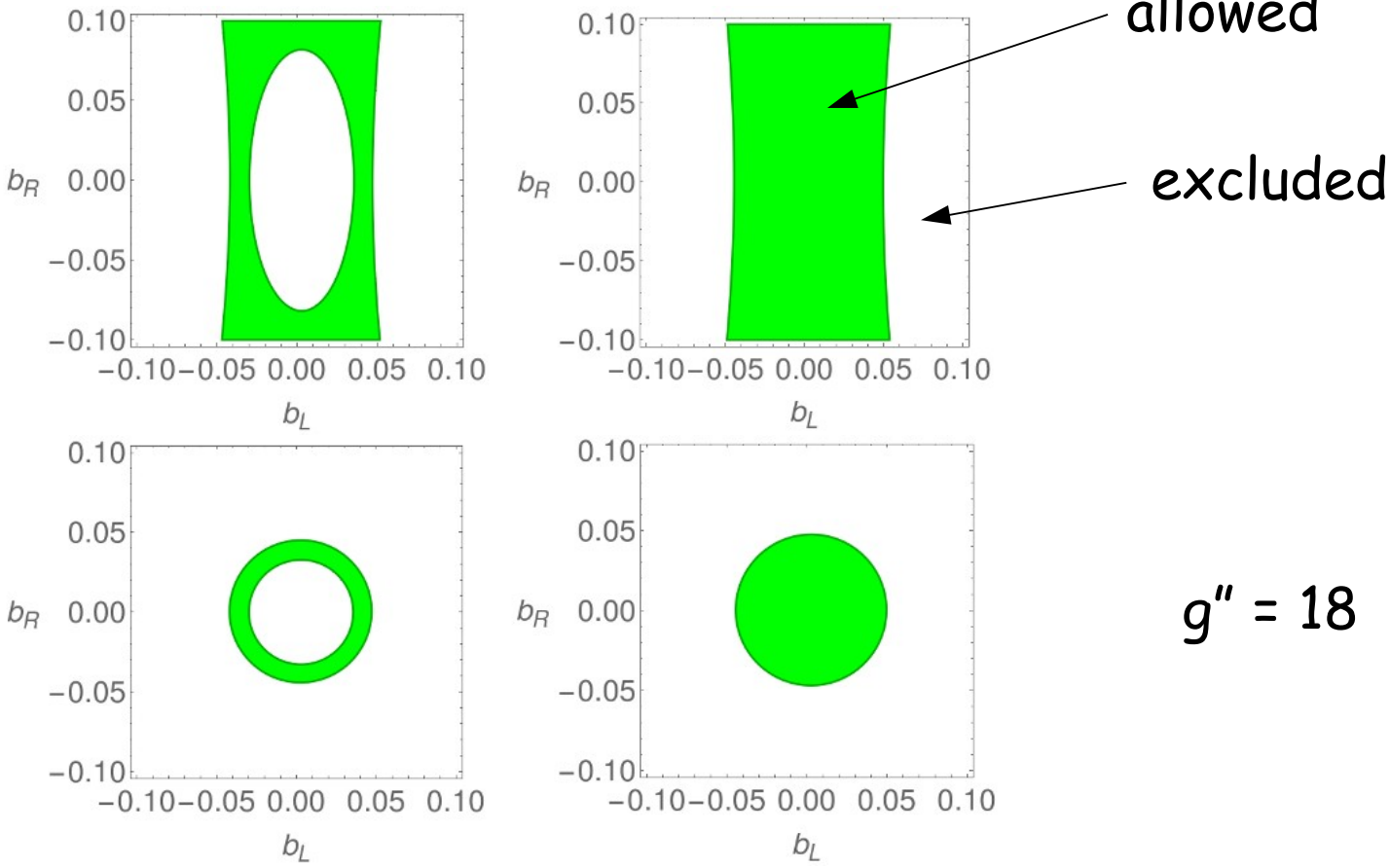
allowed values of $b_{L,R}$

- unification of the $WZ_{\mathrm{DY}}, WW_{\mathrm{DY}}, WZ_{\mathrm{DY+VBF}}, WW_{\mathrm{DY+VBF}}$ limits

$M_\rho = 1.80$ TeV $M_\rho = 1.85$ TeV

$p = 0.4$

$p = 1.0$



allowed

excluded

$g'' = 18$

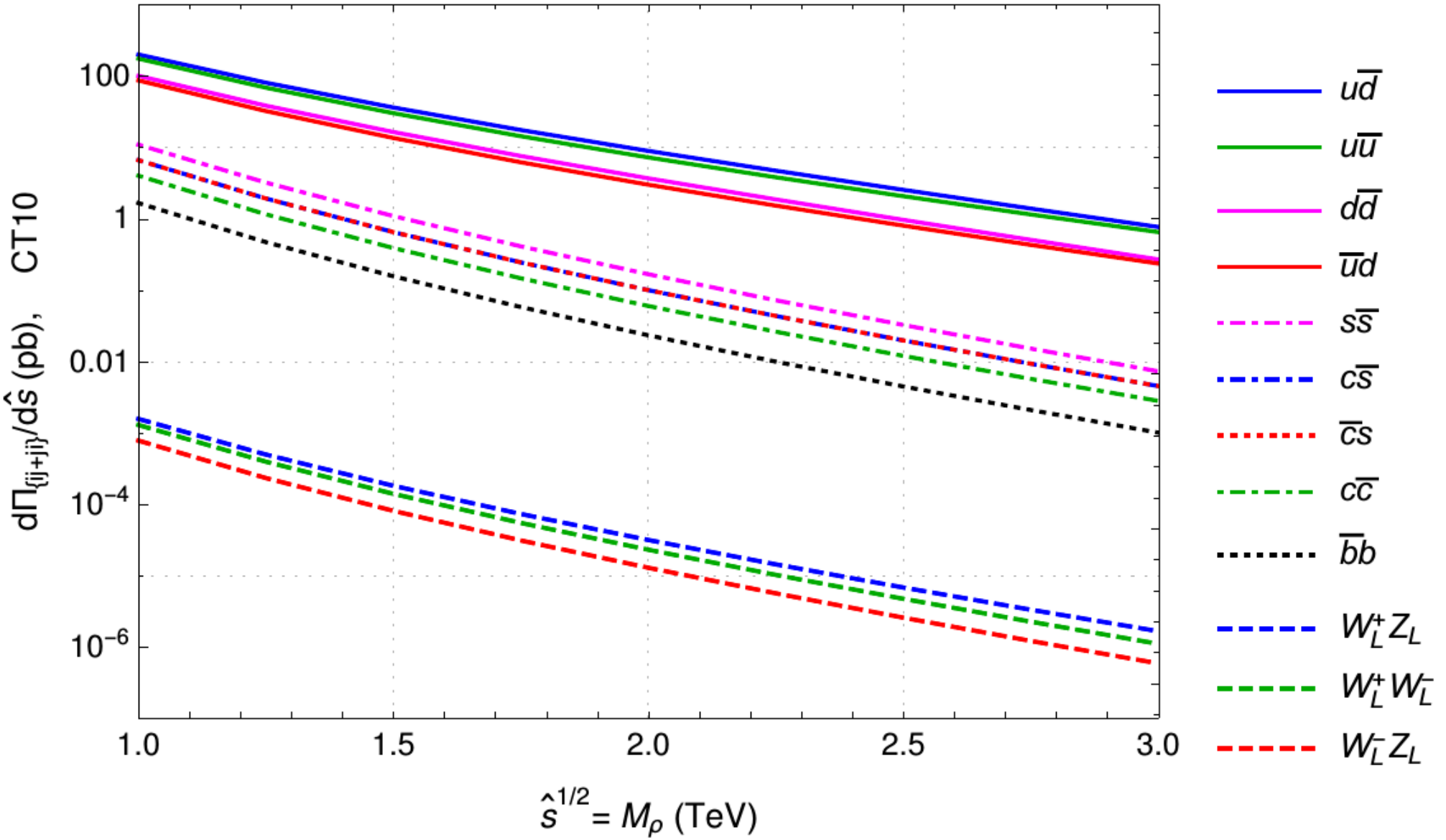
Summary

- MEL's of the tBESS vector resonance triplet were investigated
- the **b-quark contents** of the proton **cannot be ignored**
- NWA limitation: $\Gamma/M_\rho \leq 0.1\ (0.2) \Rightarrow M_\rho \leq 2.3\ (2.8)$TeV
- **there are param. space regions for which MEL ≤ 2TeV**
- **analysis beyond NWA required** for MEL ≥ 3TeV
- avoid the false generalization that the current vector resonance MEL's dwell at 5TeV or higher

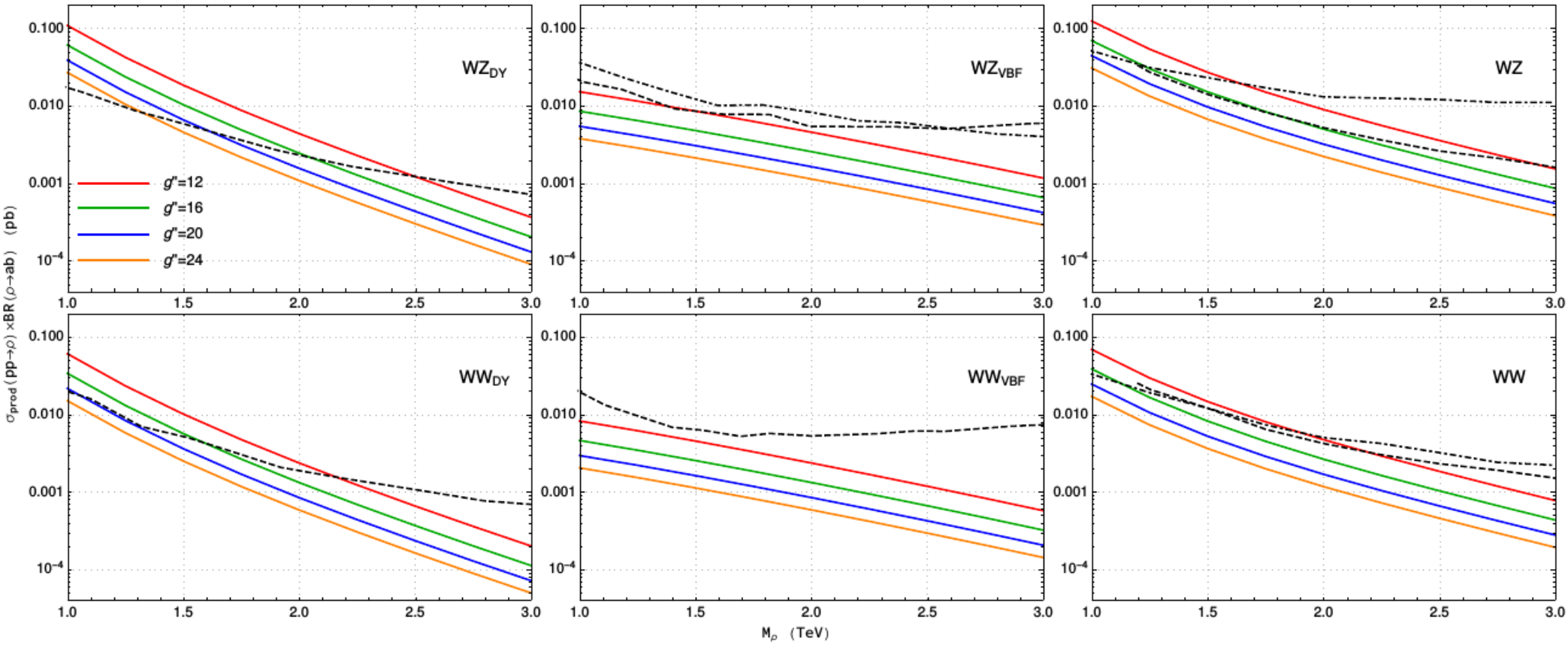
Backup

The LHC pp-dLuminosities

$s^{1/2} = 13$ TeV

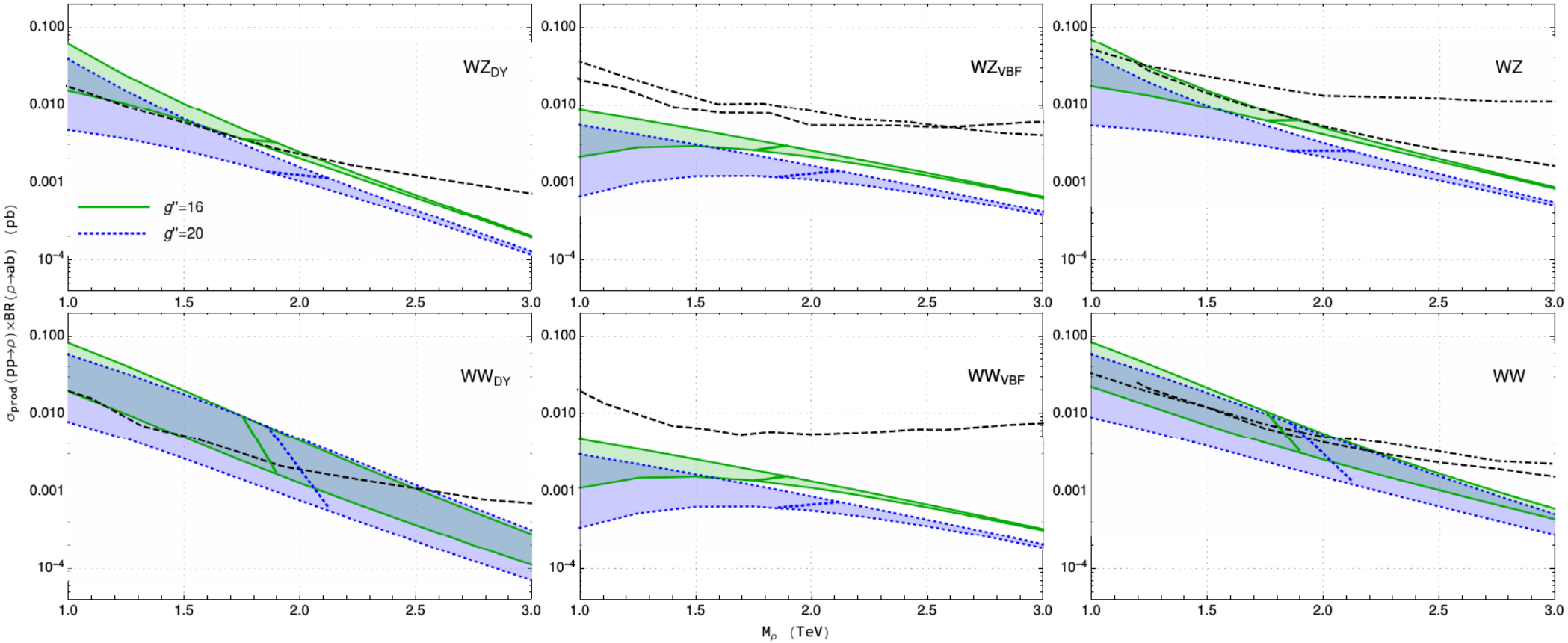


MELs: No direct interaction



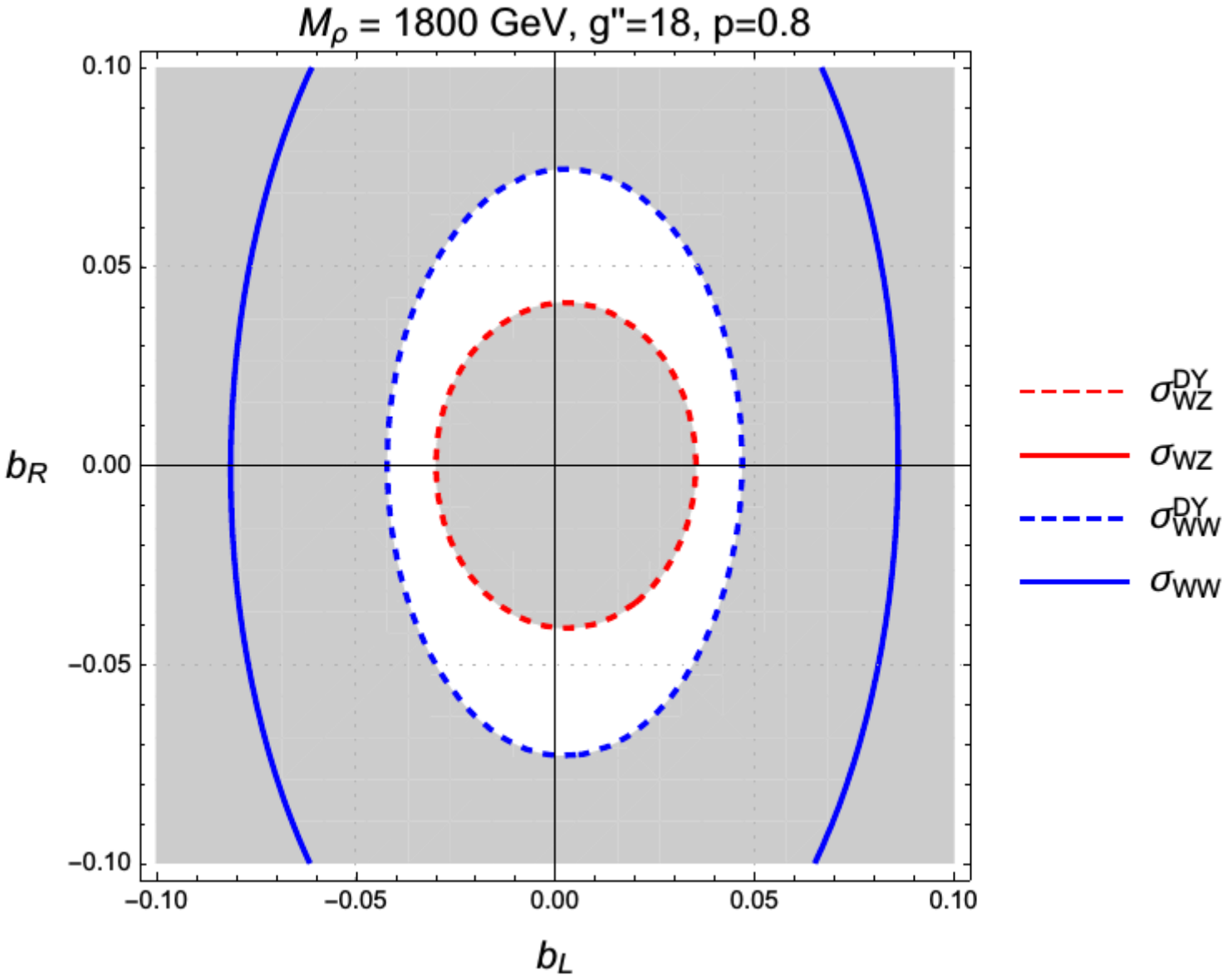
$$g'' = 20 \quad \rightarrow \quad M_\rho > 1.6 \text{ TeV}$$

MELs: General interaction

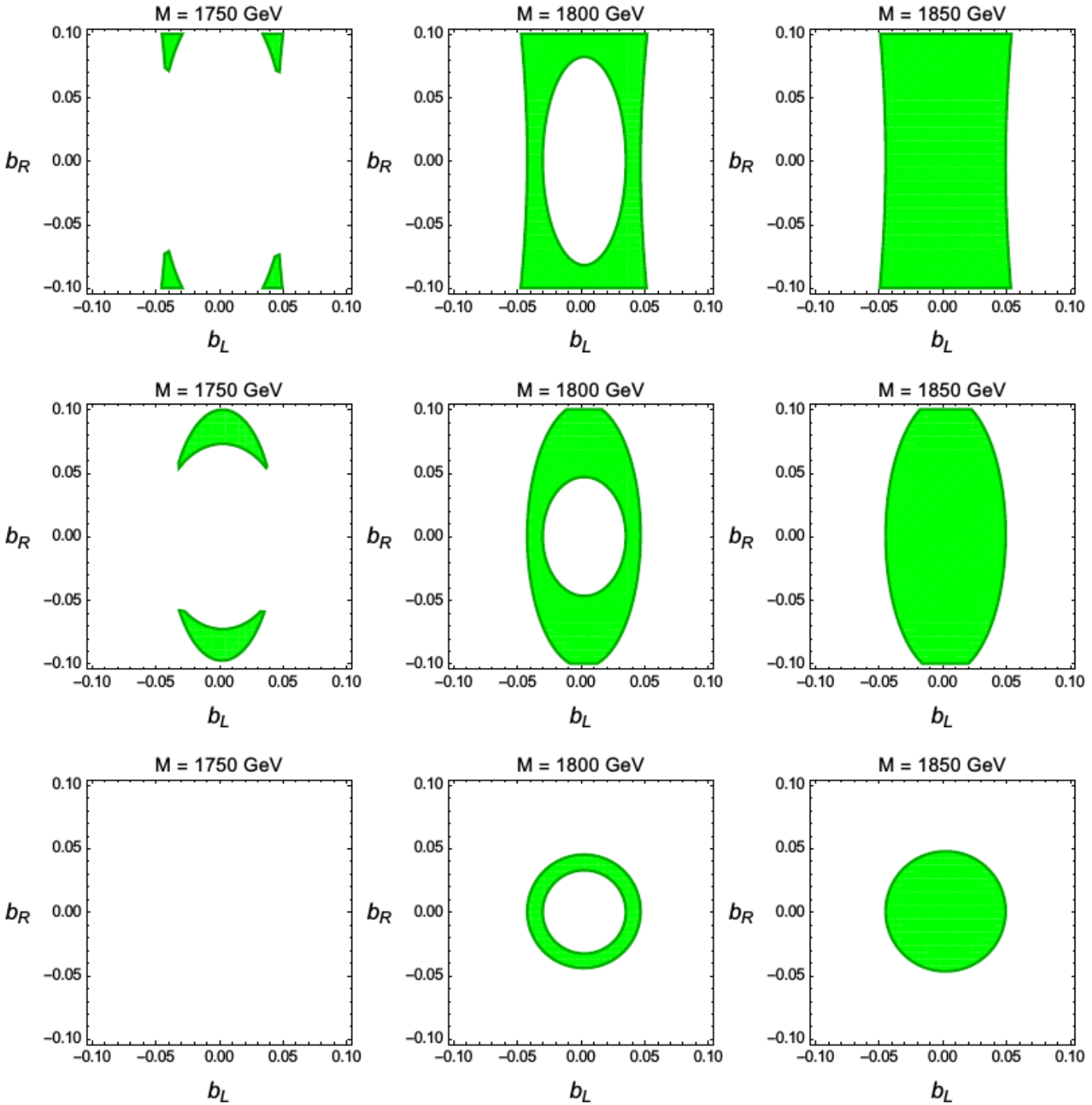


given g'' and DI scenario → MEL

Limits on DI parameters

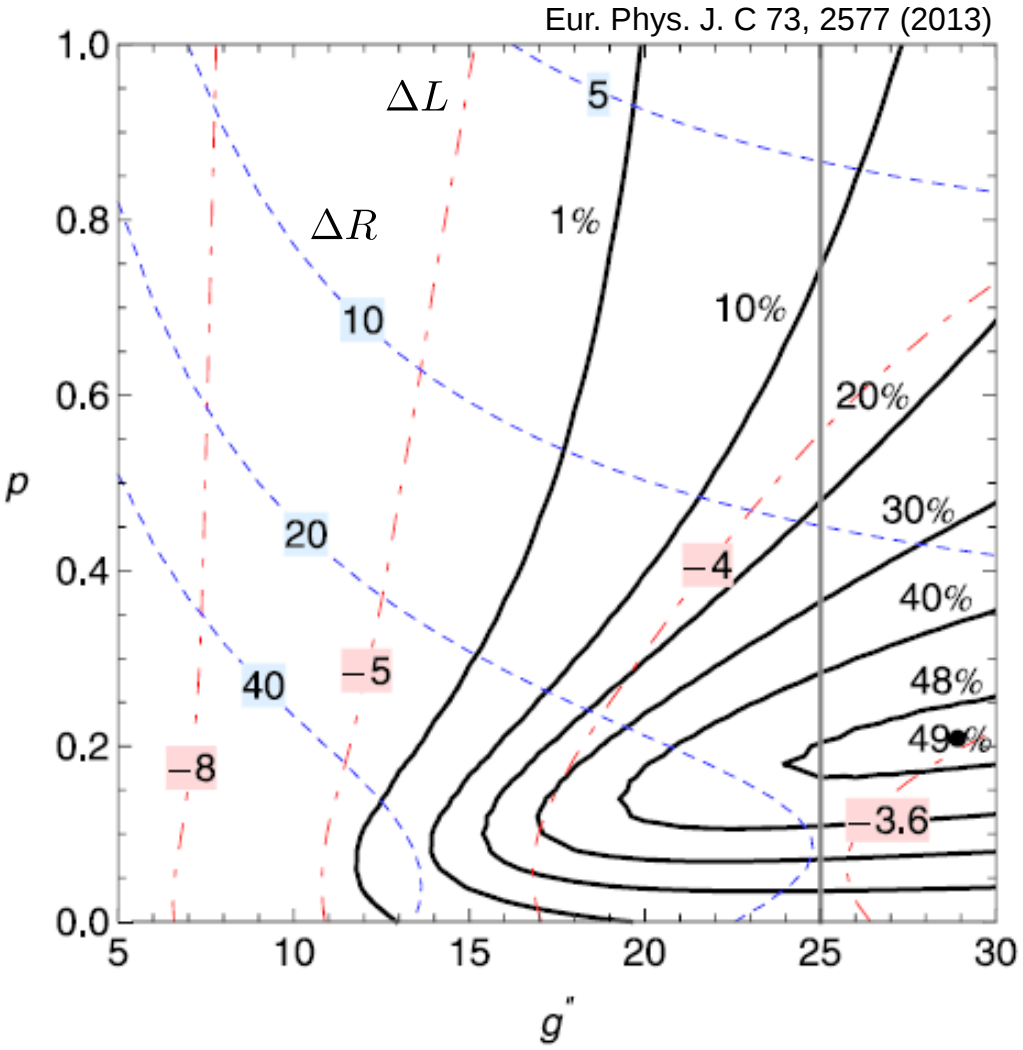


```
gpp = 18;
p = 0.4, 0.7, 1
```



Low-Energy limits

LE limits on $g'', p, \Delta L \equiv b_L - 2\lambda_L, \Delta R \equiv b_R + 2\lambda_R$
using (pseudo-)observables: $\Gamma_b(Z \to b\bar{b} + X)$, $\mathrm{BR}(B \to X_s\gamma)$,
ϵ_1, ϵ_2, ϵ_3 (BO: M_W/M_Z, $\Gamma_l(Z \to l\bar{l} + photons)$, $\mathrm{A}_l^{FB}(M_Z)$)

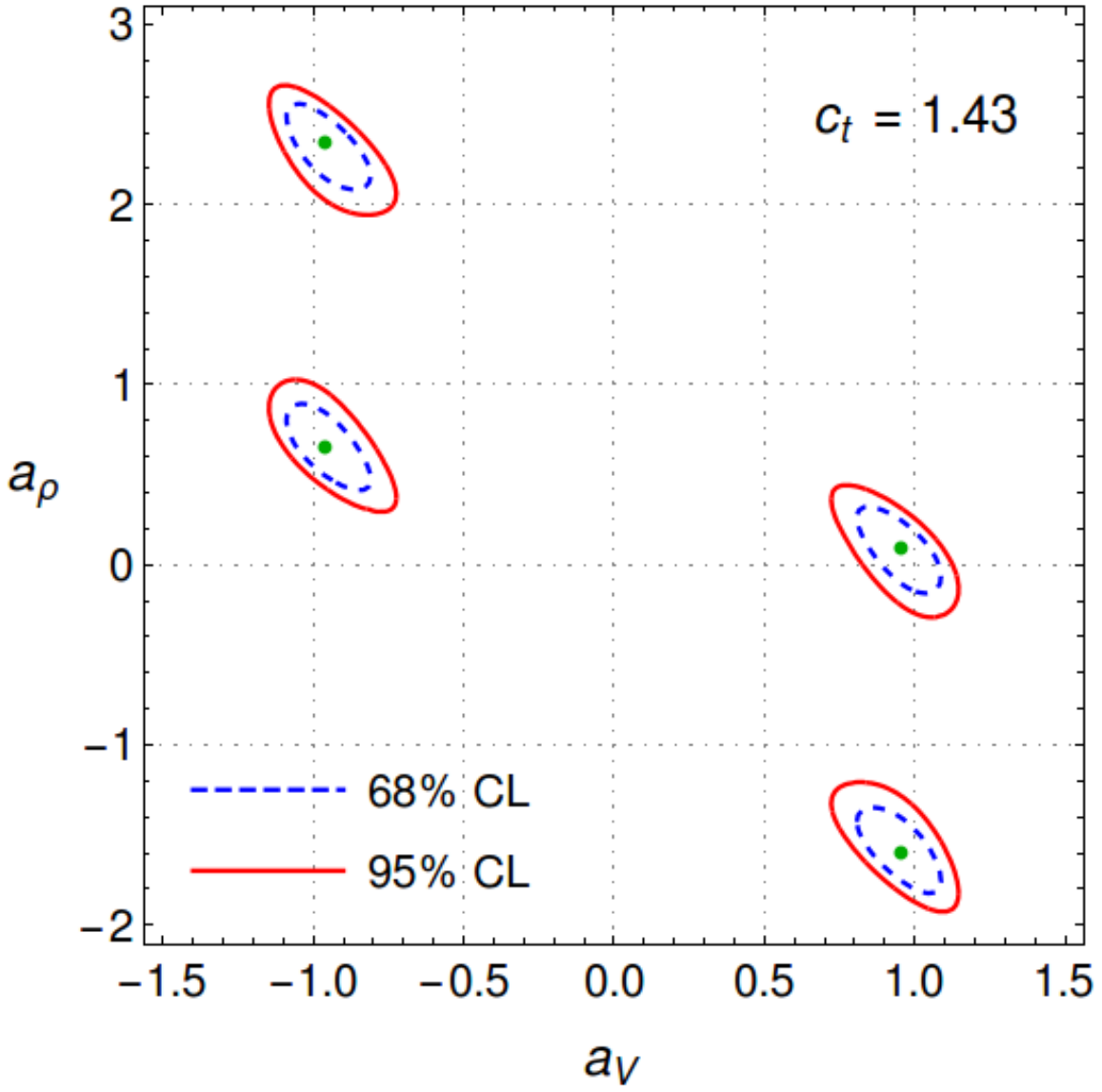


Fitting two parameters ΔL and ΔR: backing of the fit with given (g'', p) and the best-fit values of ΔL and ΔR (in thousandths)

95% CL limits of 4D fit (projections of 4D to 1D) ($\Lambda = 1$ TeV)

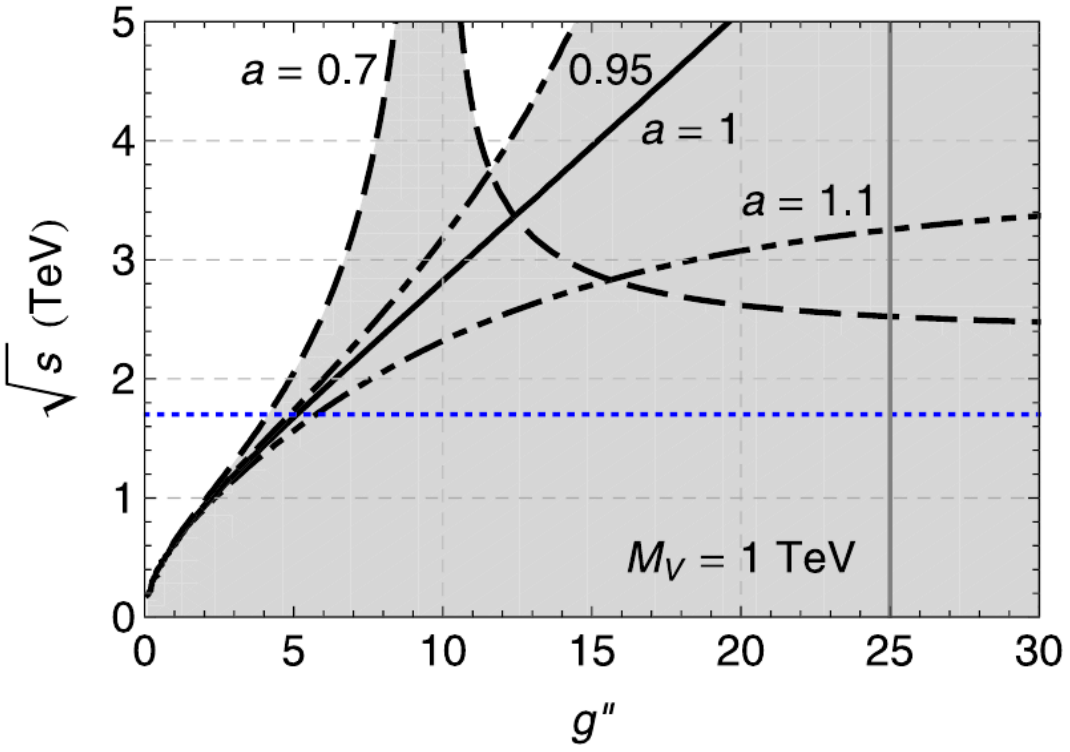
$12 < g''$
$-0.013 < \Delta L < 0.006$
$-0.006 < \Delta R < 0.056$
all interval $0 \leq p \leq 1$

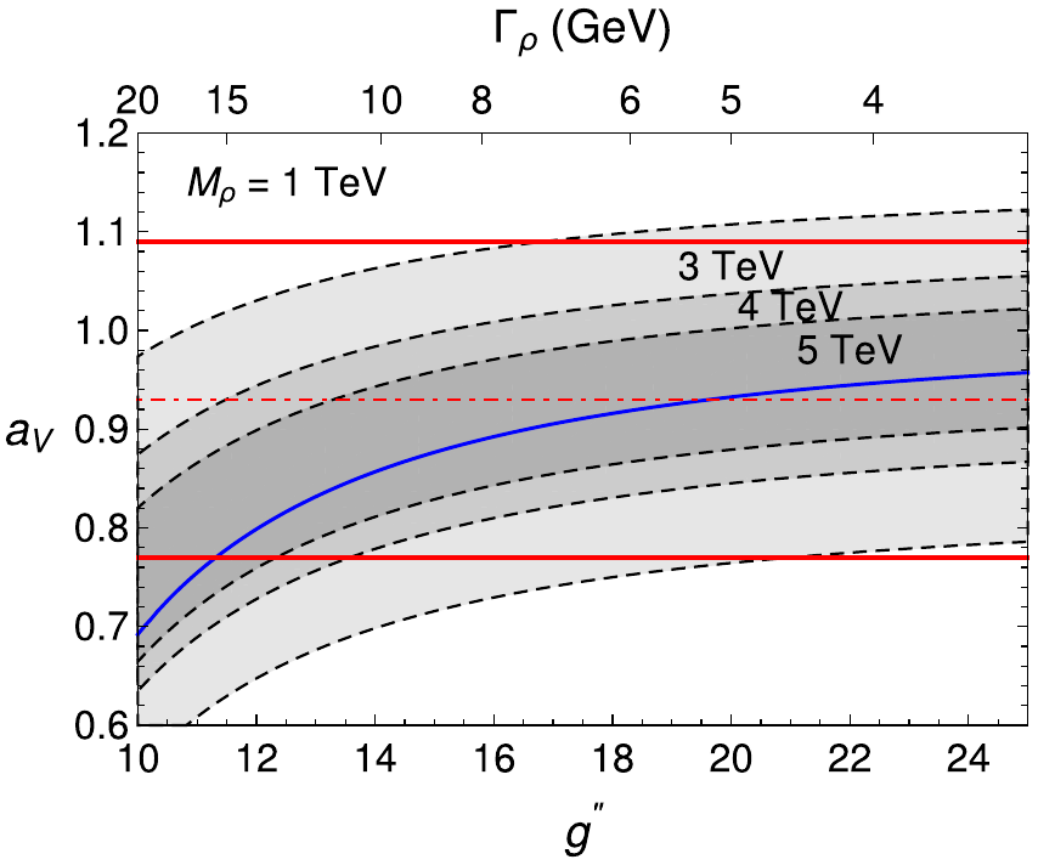
Kappa framework: contours of χ^2-cut, fixed c_t



parameter	sol1
c_t	$1.43^{+0.21}_{-0.24}$
a_V	$0.96^{+0.07}_{-0.08}$
a_ρ	$0.09^{+0.13}_{-0.14}$

Unitarity limits





Structure of tBESS Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm GB} + \mathcal{L}_{\rm ESB} + \mathcal{L}_{\rm ferm}$$

$$\mathcal{L}_{\rm GB} = \frac{1}{2g^2}{\rm Tr}(\boldsymbol{W}_{\mu\nu}\boldsymbol{W}^{\mu\nu}) + \frac{1}{2g'^2}{\rm Tr}(\boldsymbol{B}_{\mu\nu}\boldsymbol{B}^{\mu\nu}) + \frac{2}{g''^2}{\rm Tr}(\boldsymbol{V}_{\mu\nu}\boldsymbol{V}^{\mu\nu})$$

$$\mathcal{L}_{\rm ESB} = \mathcal{L}_h + \mathcal{L}_2$$

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}M_h^2 h^2 - c_h\,\frac{M_h^2}{2v}h^3 - c'_h\,\frac{M_h^2}{8v^2}h^4$$

$$\mathcal{L}_2 = -v^2[{\rm Tr}(\bar{\omega}^\perp)^2(1 + 2a_V\frac{h}{v} + a'_V\frac{h^2}{v^2} + \ldots) + \alpha{\rm Tr}(\bar{\omega}^\parallel)^2(1 + 2a_\rho\frac{h}{v} + a'_\rho\frac{h^2}{v^2} + \ldots)]$$

$$\mathcal{L}_{\rm ferm}^{\rm scalar} = -\sum_{k=1}^{6}\bar{\psi}_L^k U M_f^k(1 + c_f^k\frac{h}{v} + c_f'^k\frac{h^2}{v^2} + \ldots)\psi_R^k + {\rm h.c.}$$

$$\mathcal{L}_2 = \mathcal{M}(\alpha) + \frac{2a_V}{v}\mathcal{M}(\alpha r)h$$

$$\frac{2a_V}{v}\mathcal{M}(\alpha r)h = \frac{2h}{v}\left[\frac{1}{2}c_Z M_Z^2 Z_\mu Z^\mu + c_W M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}c_{\rho^0} M_{\rho^0}^2 \rho_\mu^0 \rho^{0\mu} + c_{\rho^\pm} M_{\rho^\pm}^2 \rho_\mu^+ \rho^{-\mu}\right.$$
$$\left. + c_{Z\rho^0} M_Z M_{\rho^0} Z_\mu \rho^{0\mu} + c_{W\rho^\pm} M_W M_{\rho^\pm}(W_\mu^+ \rho^{-\mu} + {\rm h.c.})\right] \qquad (1$$

Partial Decay widths

the phenomenological vertices

- $(V^3, V^{\pm}) \rightarrow (\rho^0, \rho^{\pm})$
- the gauge boson mixings: $\rho^0(V^3,W^3,B)$, $\rho^{\pm}(V^{\pm},W^{\pm})$
- **induced interactions** of ρ to all fermions: ~ 1/g''

the ρ decays (@LO)

$$\Gamma_{\rho\to WW,WZ} = \frac{M_\rho}{48\pi g''^2}\left(\frac{M_\rho}{v}\right)^4$$

$$\Gamma_{\rho\to tt} = \frac{M_\rho g''^2}{128\pi}\left(b_L^2 + b_R^2\right)$$

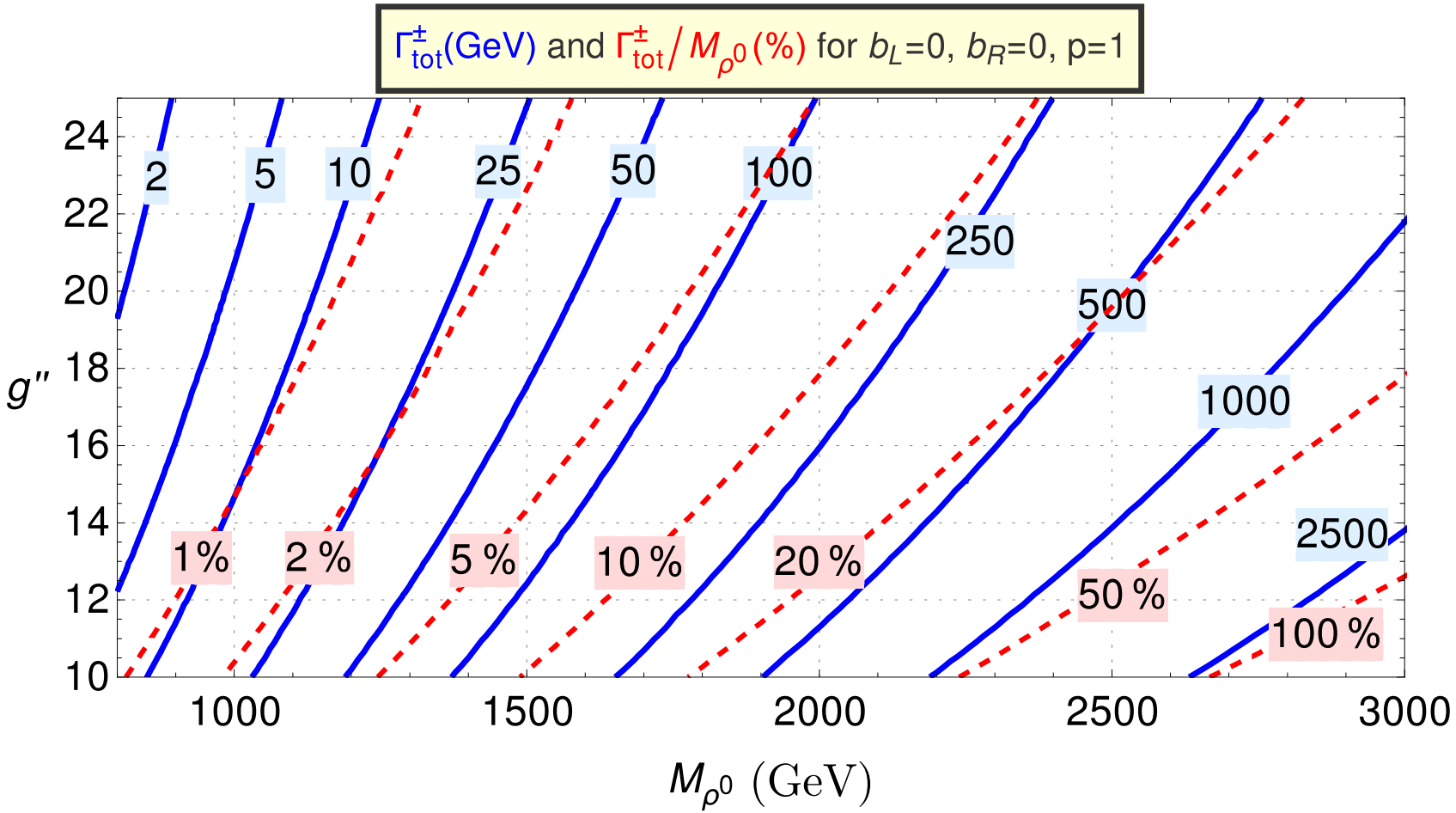
$$\Gamma_{\rho\to bb} = \frac{M_\rho g''^2}{128\pi}\left(b_L^2 + p^4 b_R^2\right)$$

$$\Gamma_{\rho\to tb} = \frac{M_\rho g''^2}{64\pi}\left(b_L^2 + p^2 b_R^2\right)$$

- $\rho \rightarrow$ light ferms, HZ, HW: **negligible** $\Gamma \sim 1/(g'')^2$

Total Decay Width and Fatness Contours of $\rho^{\pm}$

(NDI case; blue labels in GeV)



$$BR(\rho \to WZ) \simeq 1$$

Total Decay Width Contours of $\rho^{\pm}$

(labels in GeV)