Anomalous Top Couplings in WHIZARD

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in collaboration with Thorsten Ohl

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funded by:

Outline

Phenomenological studies on anomalous top couplings

- **idea:**
  - ➔ use the **large statistics** at *LHC* to **constrain** trilinear **top couplings** to vector bosons with previously unknown precision
  - ➔ **model-independent** effective approach to parameterize any new physics

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example: *tbW* coupling

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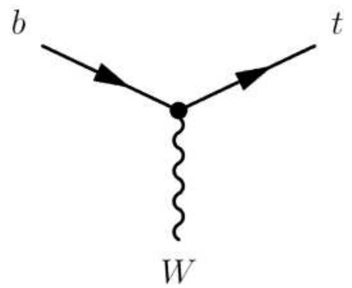

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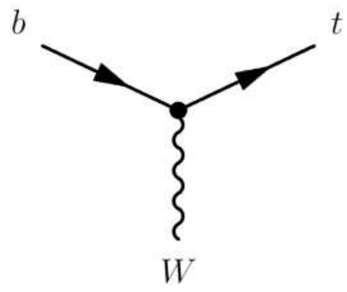
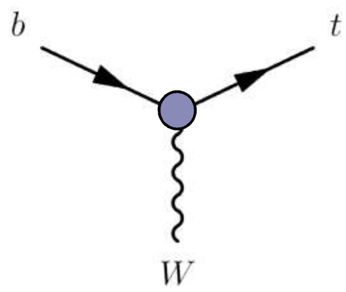


off-resonant
new physics



$\sim \gamma^{\mu}(1-\gamma_5)$ + e.g. $\sim \sigma^{\mu\nu} q_{\nu}(1+\gamma_5)$

Phenomenological studies on anomalous top couplings

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- **what has been done:**
  - ➔ theoretical understanding of the relations and **redundancies** among different operators in a full gauge invariant operator set generating the various anomalous trilinear top couplings
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  - ➔ plethora of **pheno & exp. studies**, e.g. anomalous QCD and *tbW* couplings
- **what we want to contribute:**
  - ➔ provide **all** possible anomalous top couplings in **one exhaustive MC tool**, i. e. WHIZARD 2 with anomalous tops
  - ➔ **automatically ensure gauge invariance** for all hard amplitudes relevant for detector level, including off-shell top production and subsequent decays
  - ➔ link to hadron shower/fragmentation to produce detector-relevant final states
  - ➔ do some phenomenological studies at *LHC & ILC*

Studies on anomalous *tbW* couplings

- parameterization of the vertex:

SM: $V_L = V_{tb} \approx 1$,
$V_R = g_L = g_R = V_L^{off} = 0$

$$\begin{aligned}\mathcal{L}_{tbW} = &-\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\left(V_L P_L + V_R P_R\right) t\, W_\mu^- + \mathrm{h.c.}\\ &-\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_W}\left(g_L P_L + g_R P_R\right) t\, W_\mu^- + \mathrm{h.c.}\\ &-\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\frac{q^2 - m_W^2}{m_W^2}\left(V_L^{\mathrm{off}} P_L\right) t\, W_\mu^- + \mathrm{h.c.}\ ,\end{aligned}$$

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cf. e.g. **[Aguilar-Saavedra et al. 07-09]**

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Luckily we have implemented

the **full package** in

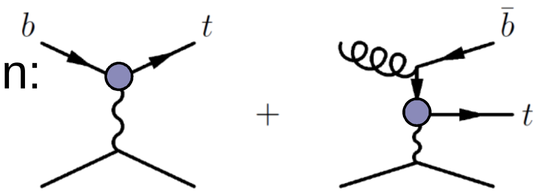
WHIZARD 2

Including **all** *tbW*, *ttZ*, *ttA* and *ttg* couplings!

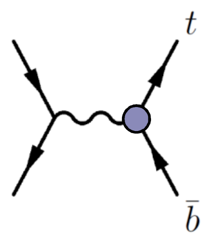
Single top cross sections: partonic production matrix elements

• different types of single top production considered

1) t-channel *tj* + *tbj* production:



2) s-channel *tb* production:



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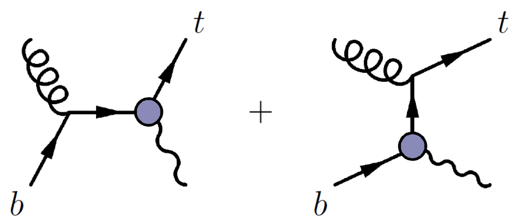

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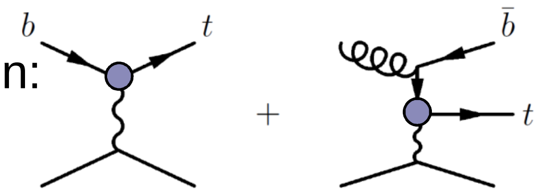

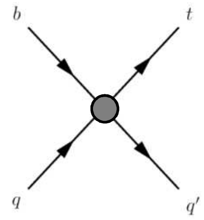

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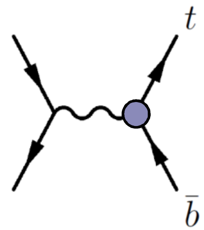

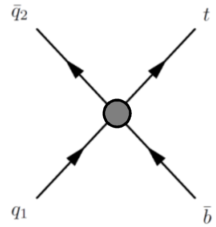

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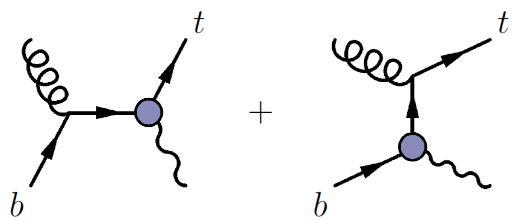

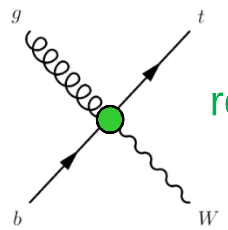

redundant
[AS et al. 09]

Single top cross sections

- **basic idea** to efficiently derive bounds from cross section measurements:

$$\boxed{\sigma_i^{\rm det}(\vec{g}) = \sum_j \varepsilon_{ij} \cdot \sigma_j^{\rm part}(\vec{g})}$$

➔ cross section $\sigma^{\rm det}$ of a given final state selection *i* (detector level)

with	j	partonic input processes
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- **nomenclature**:

full matrix element (ME) approach
[FB, T Ohl '12]

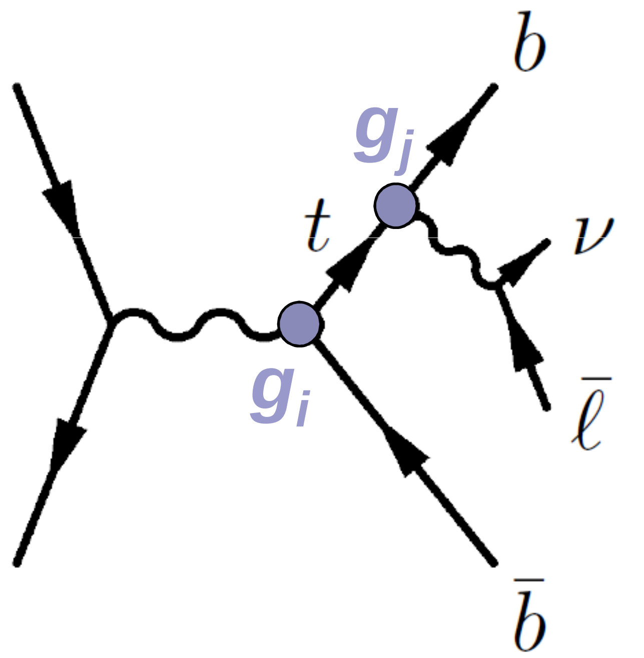
on-shell approach
e.g. [Aguilar-Saavedra '08]

(explanation follows…)

Single top cross sections

- typical **matrix element** (e.g. *s*-channel):

$$\sigma^{\text{part}}(\vec{g}) \sim \int \mathrm{d}\Phi \left| \quad \right|^2 \quad \sim \mathbf{f(g_i, g_j)\ ?}$$



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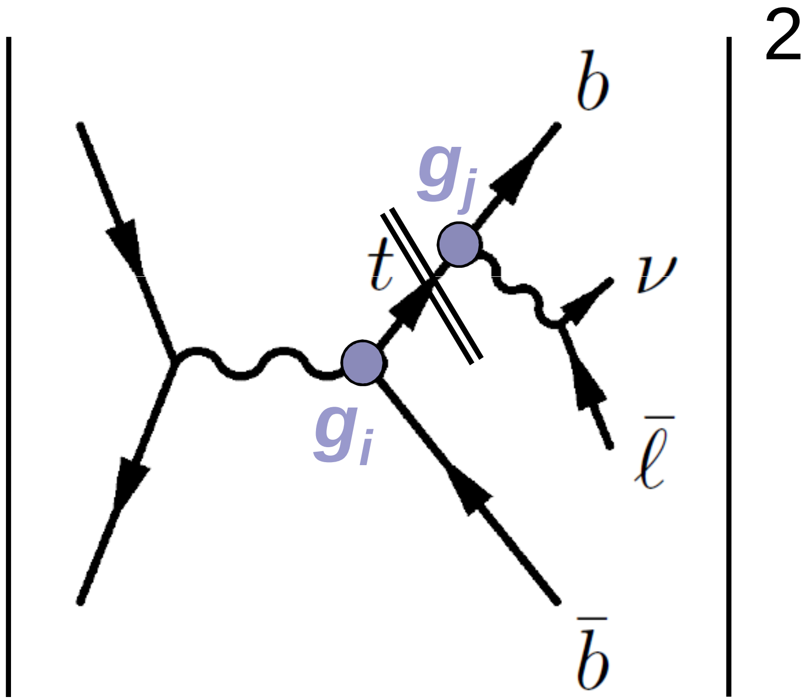

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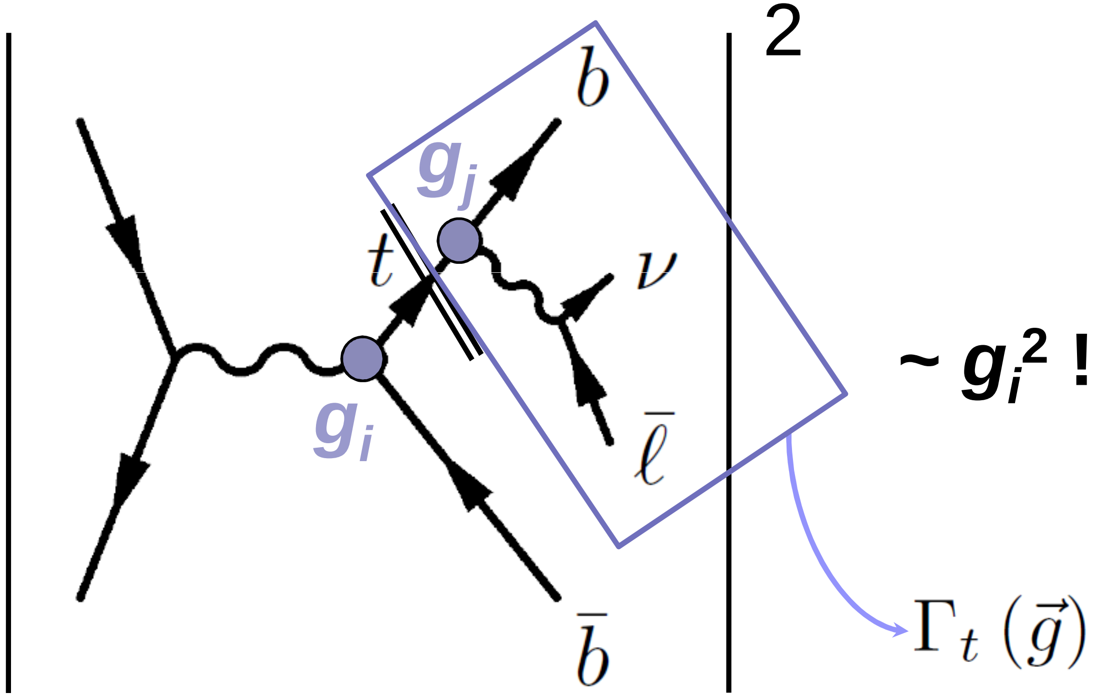

$\sim g_i^2$!!!

Narrow Width Approximation at work: ME ~ order 2 polynomial in ***g***

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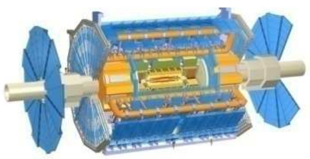

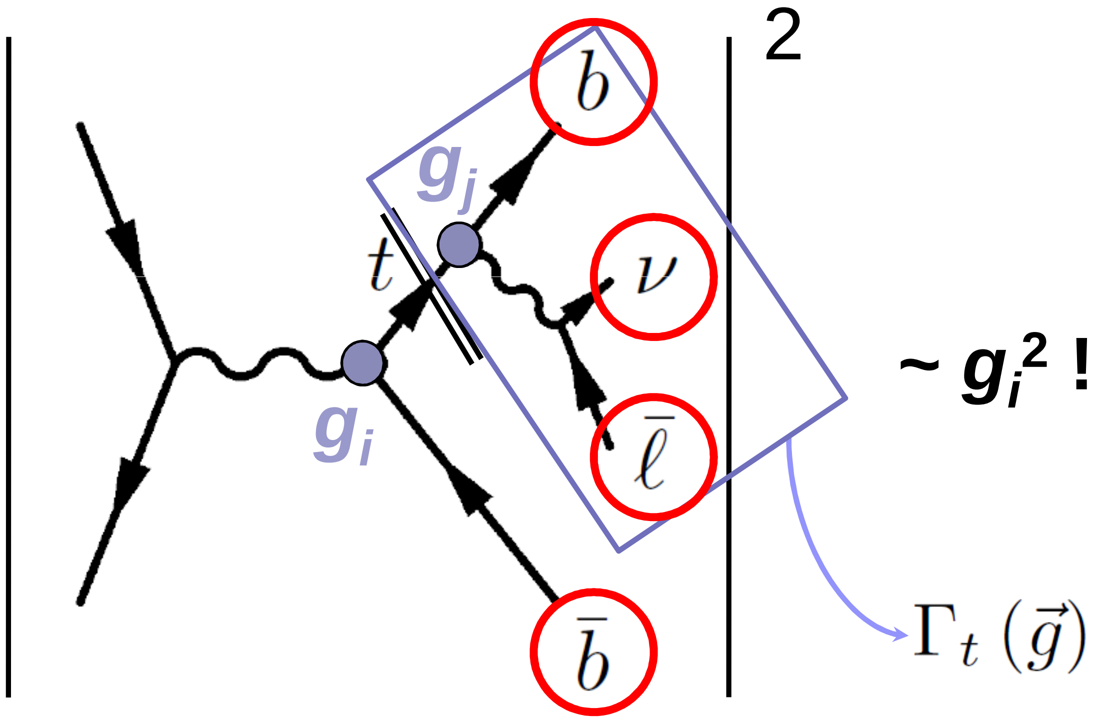

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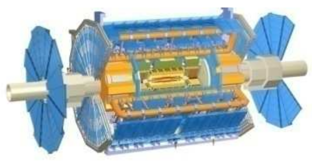

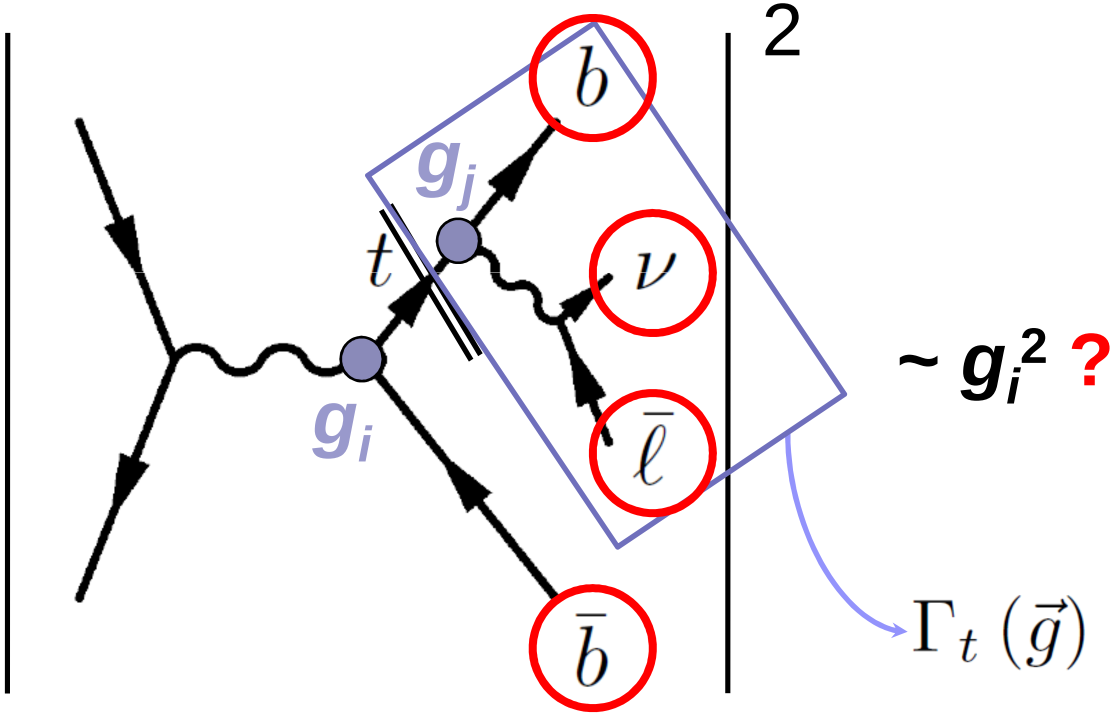

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e.g. [Aguilar-Saavedra '08]

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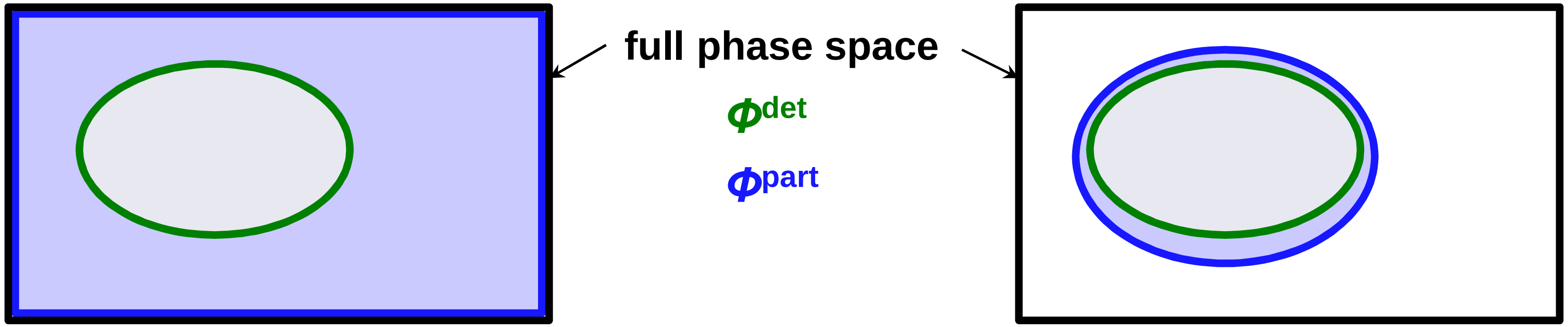

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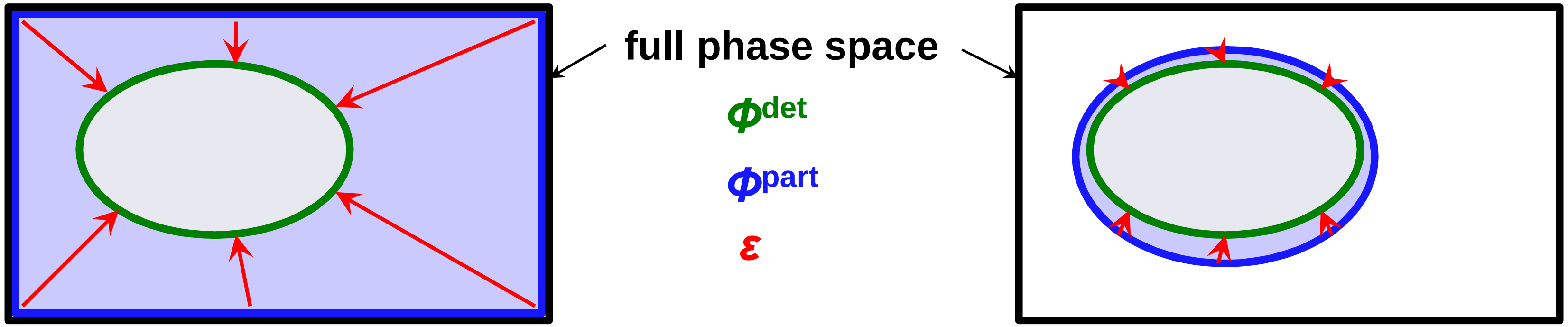

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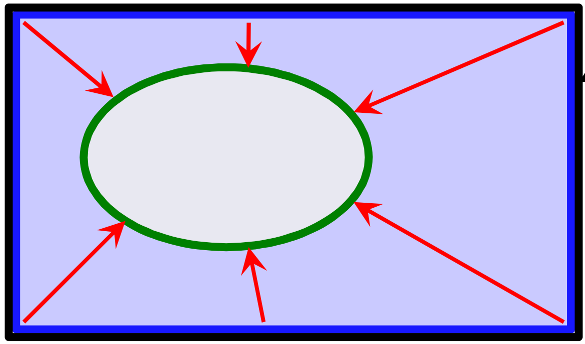
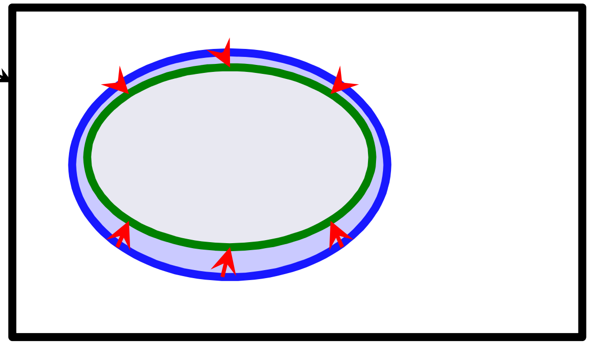


full phase space

Φ^{det}

Φ^{part}

ε



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con: neglects non-SM **distributions**

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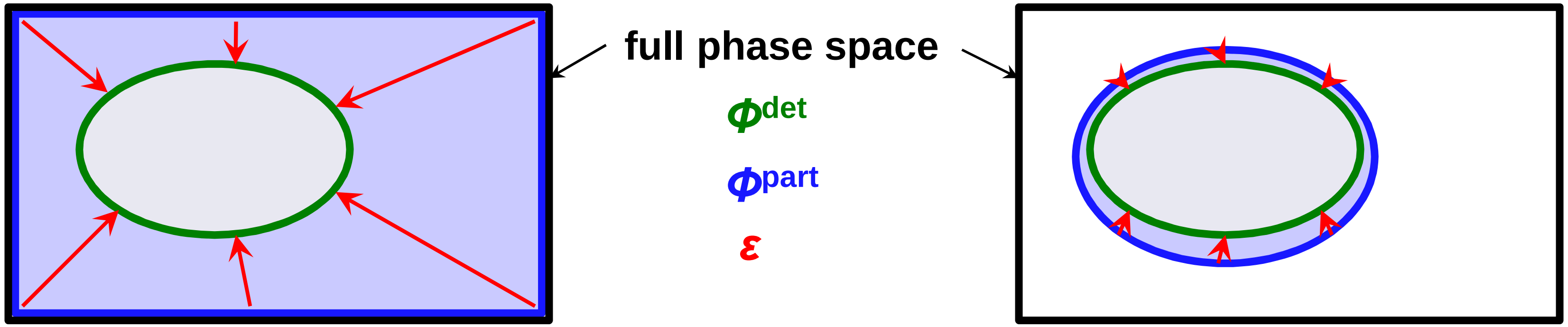

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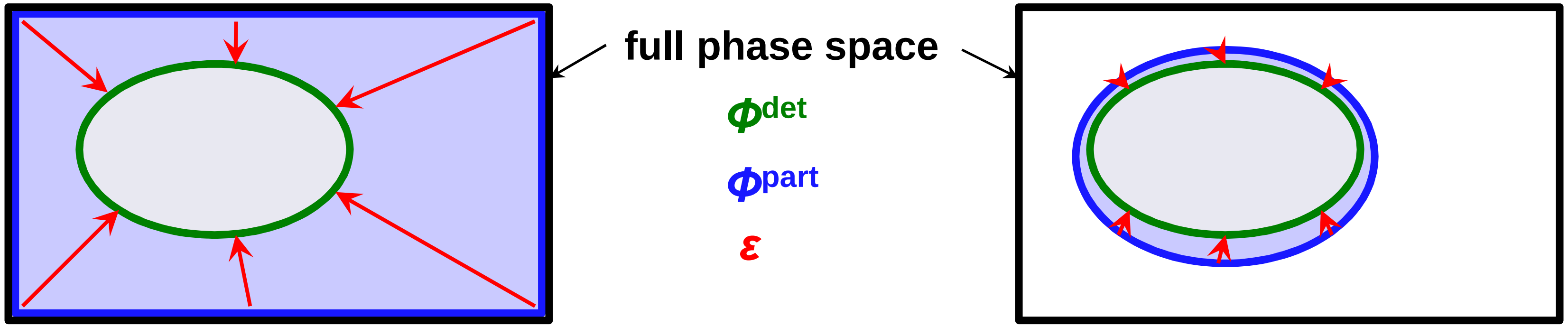

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compare!

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Partonic matrix elements [FB, T Ohl '12]

• different types of single top production considered

contact terms

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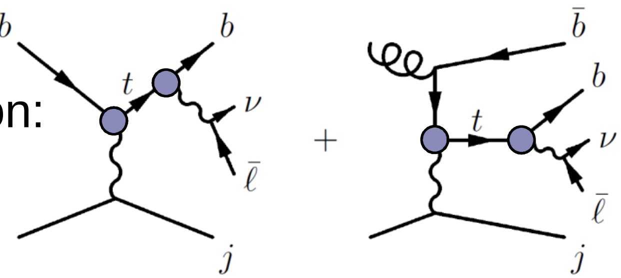
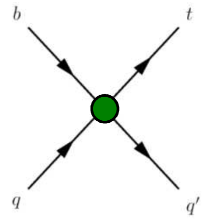
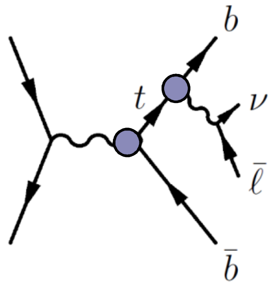
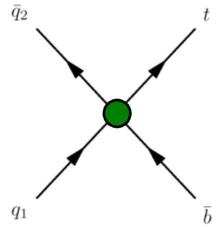




included

2) s-channel *tb* production:





included

3) *tW* production:

not included, because it's conceptually hard to

➔ model Φ^{part} *and* stay inclusive w.r.t. *s* & *t* channels

➔ remove huge *ttbar* in the *tWb* matrix element

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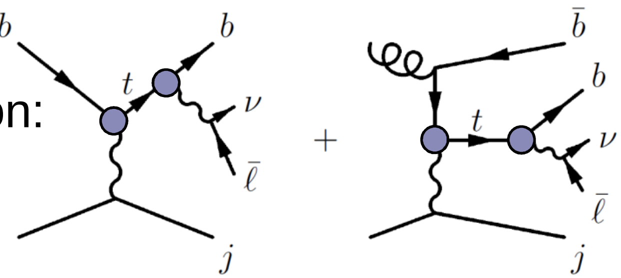

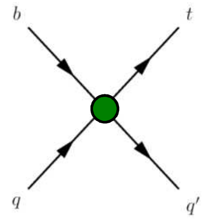

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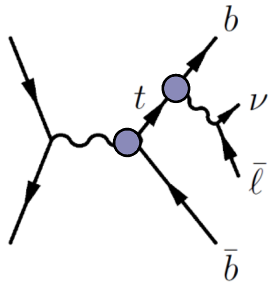

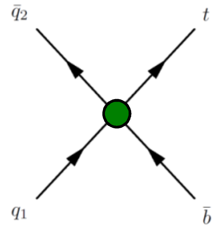

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➔ define partonic acceptance cuts ***Φ*****part** :

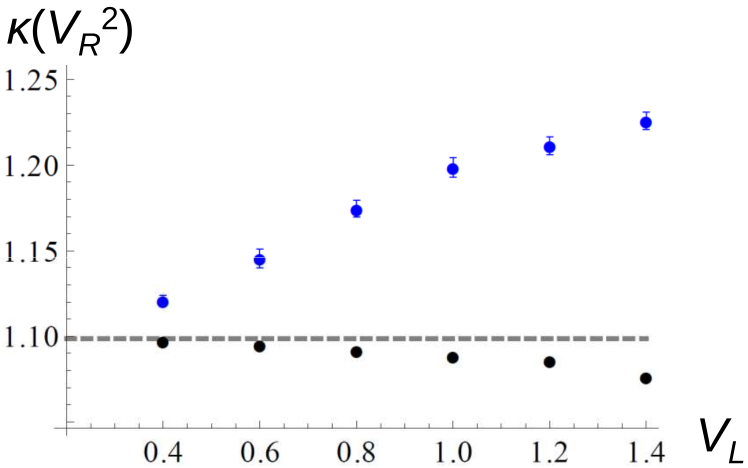
$$p_T(\ell, \nu) > 25\,\mathrm{GeV} \quad \text{and} \quad |\eta(\ell)| < 3\,,$$

$$p_T(j, b) > 30\,\mathrm{GeV} \quad \text{and} \quad |\eta(j, b)| < 5\,,$$

$$150\,\mathrm{GeV} < m_{b\ell\nu} < 225\,\mathrm{GeV}\,,$$

Comparison of detector acceptance and full phase space

- assume that the *on-shell* approximation holds
  ➔ **quadratic fits** to $\kappa_{\mathrm{full}}(\boldsymbol{g})$, e.g. for *t*-channel production:



Φ^{part} ~ detector acceptance

Φ^{part} = full phase space

on-shell result

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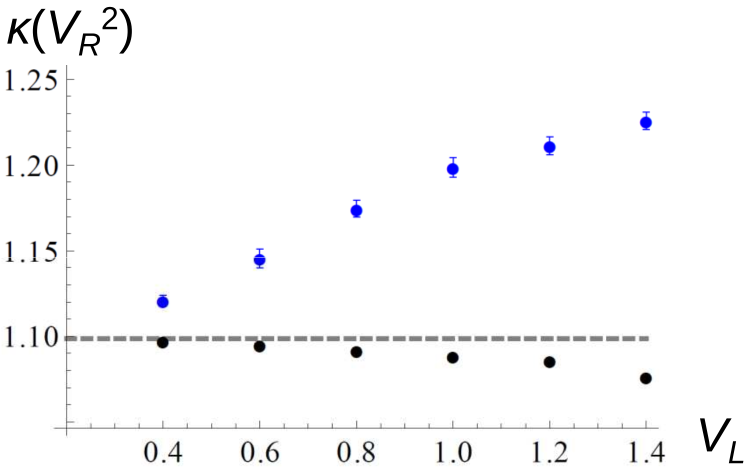

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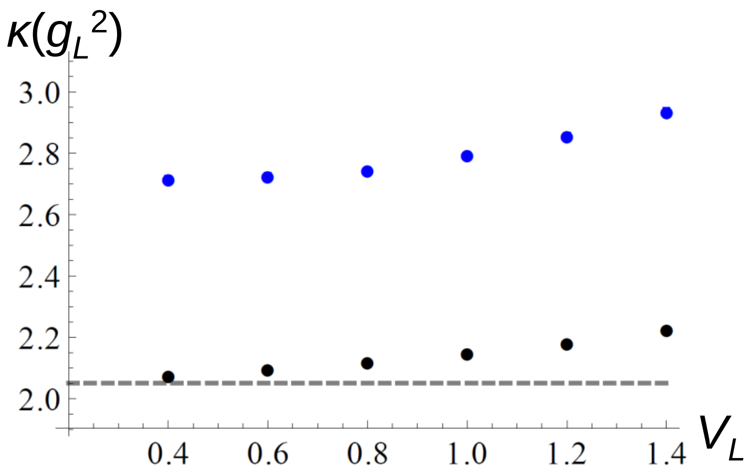
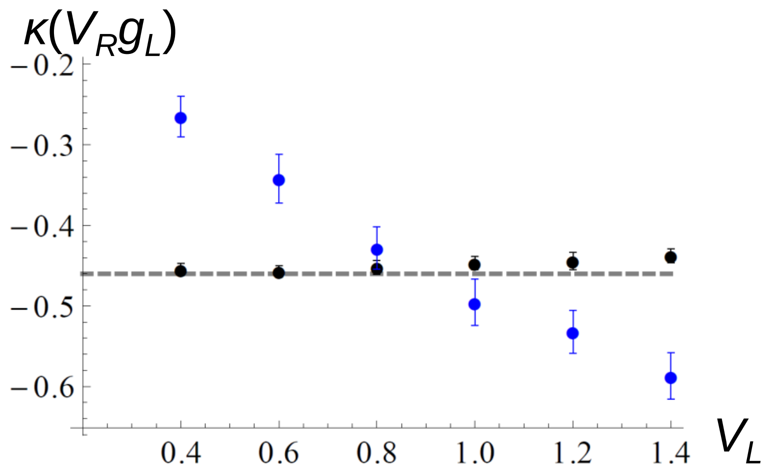
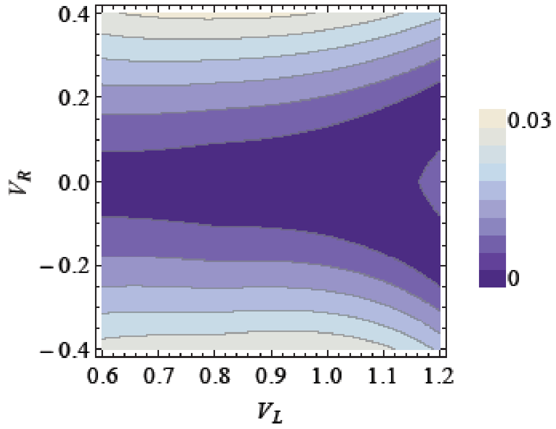




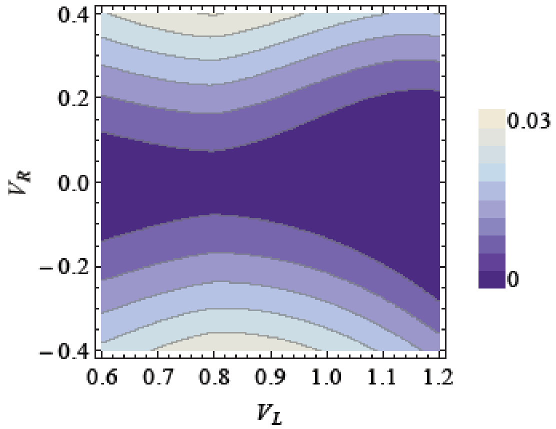
Comparison of partonic ME response κ_{on} and κ_{full}

• set **ε = 1** and **plot $|\kappa_{full}$ - $\kappa_{on}|$** in various anomalous coupling planes
➔ to be compared with exp. sensitivities of **~14 % (*tj* sel.)** resp. ~20 % (*tb* sel.)

tj



tbj



V_L – V_R plane

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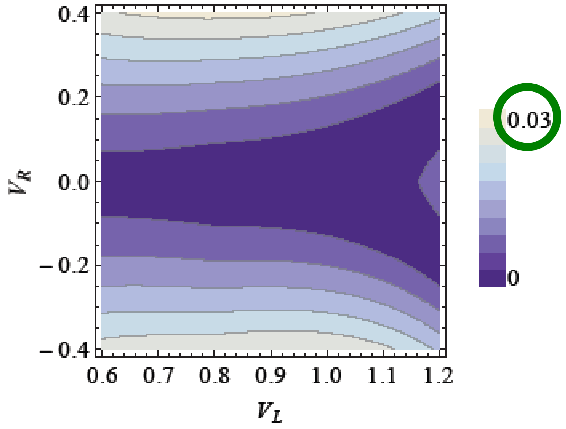

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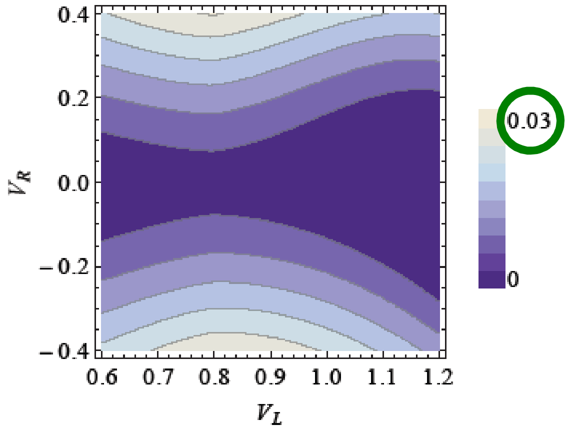

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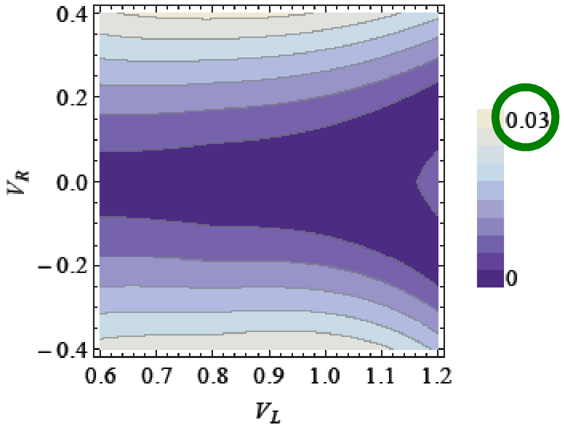
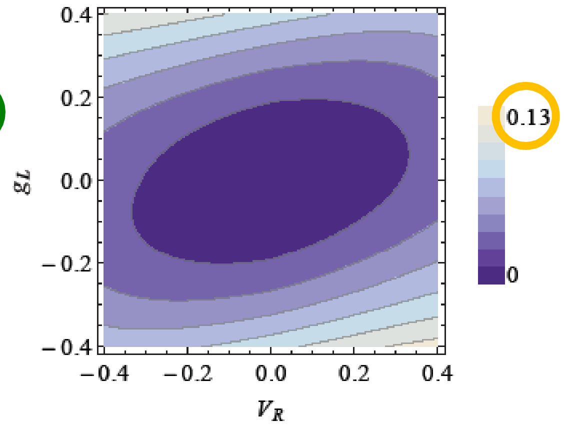
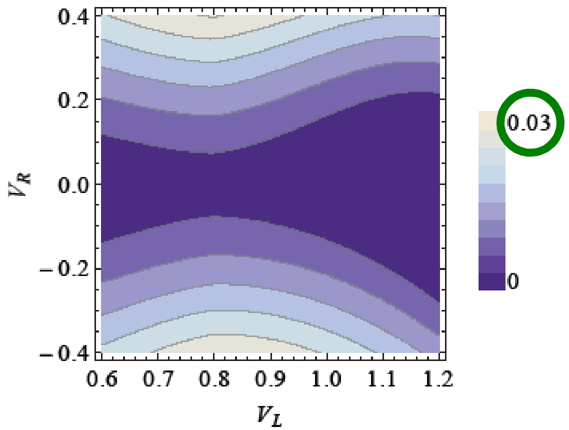
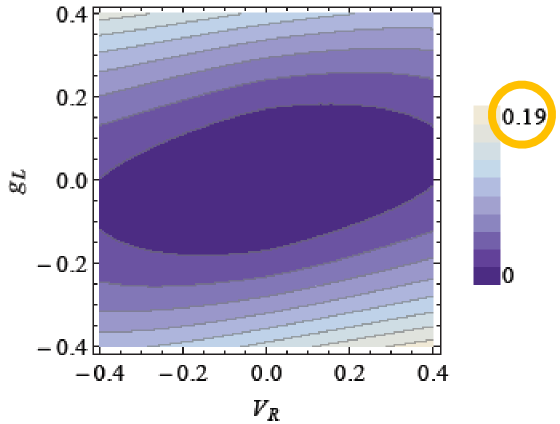




tbj





V_L – V_R plane ***V_R – g_L*** plane

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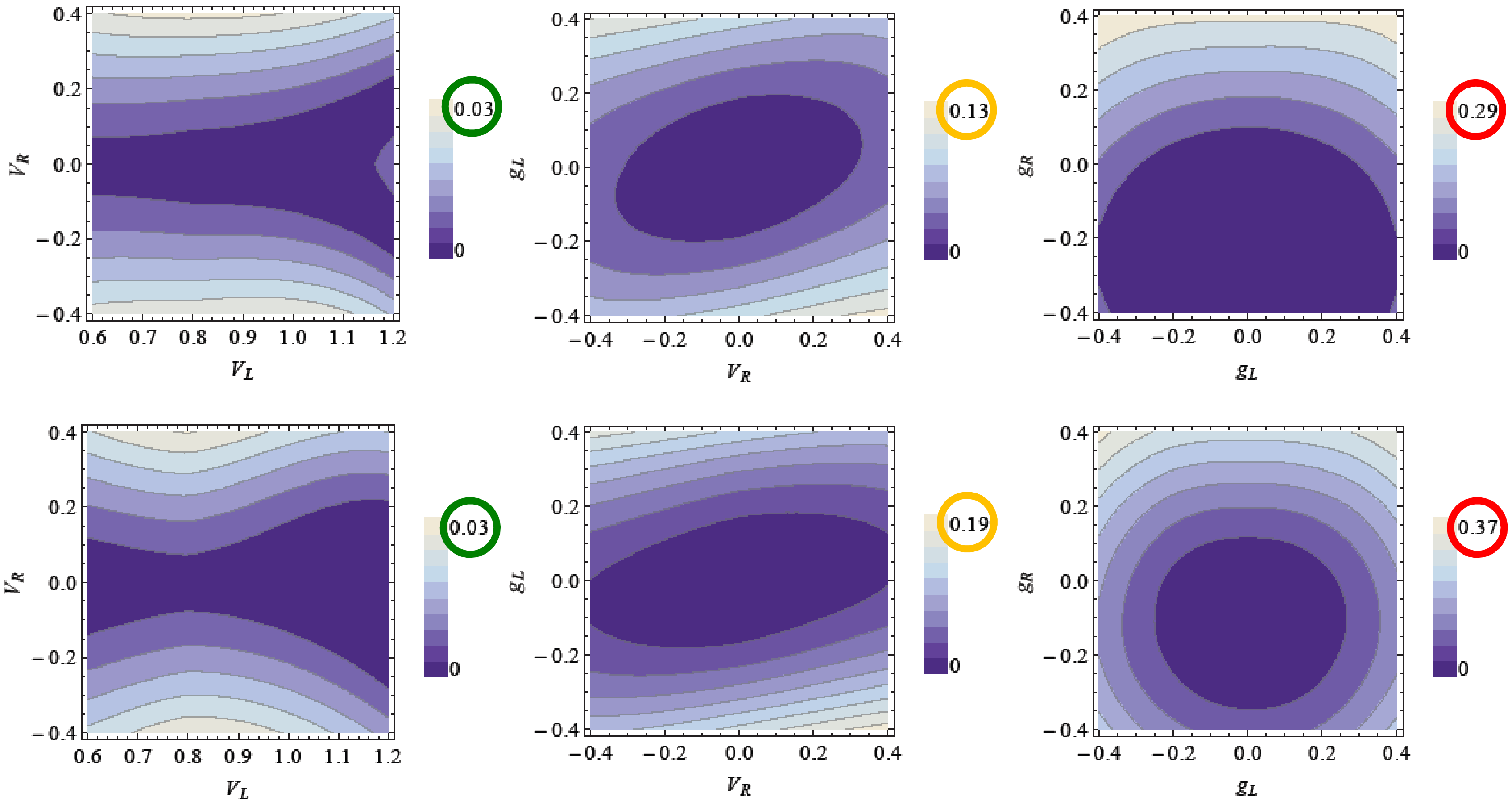
tbj



$V_L - V_R$ plane $V_R - g_L$ plane $g_L - g_R$ plane

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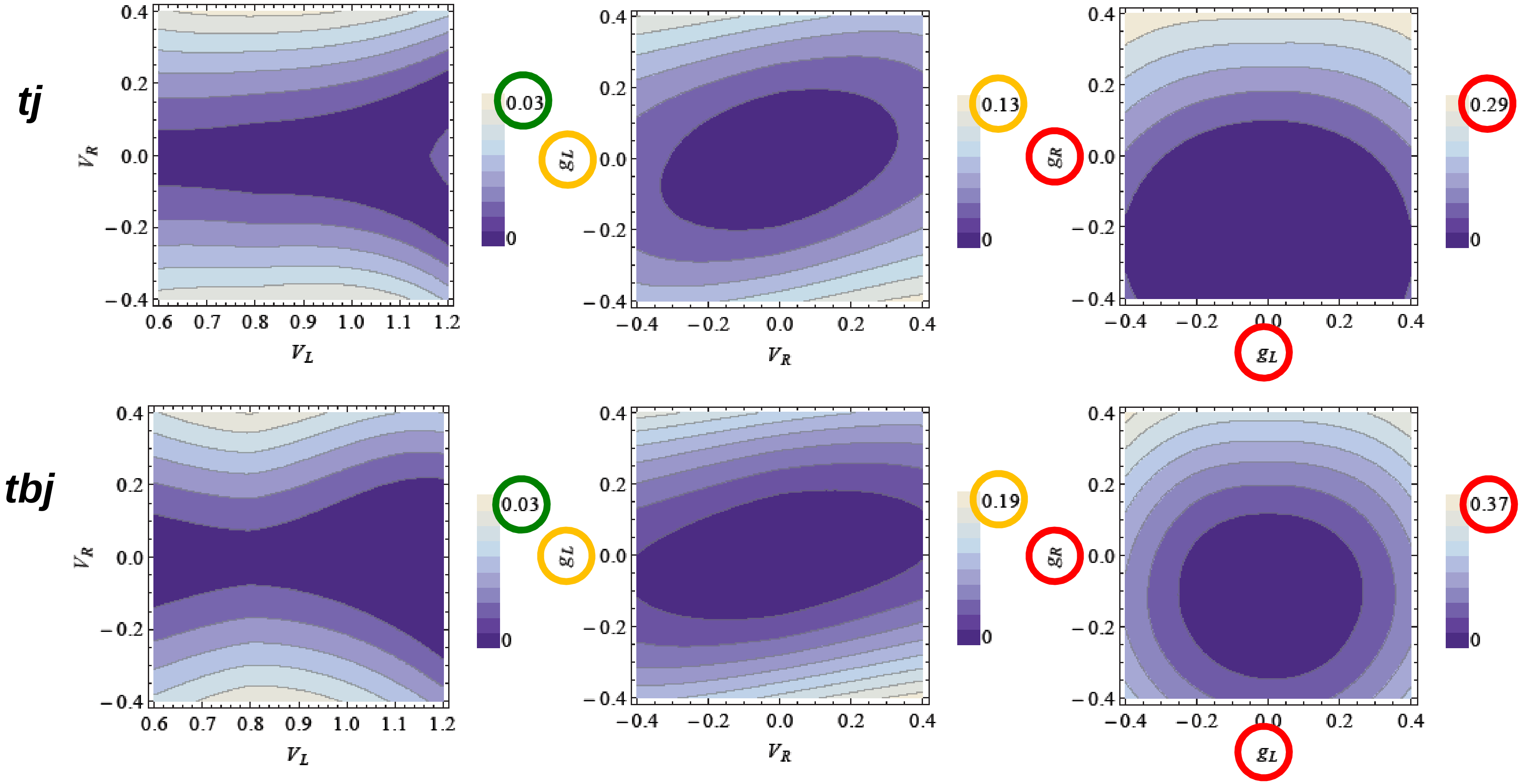
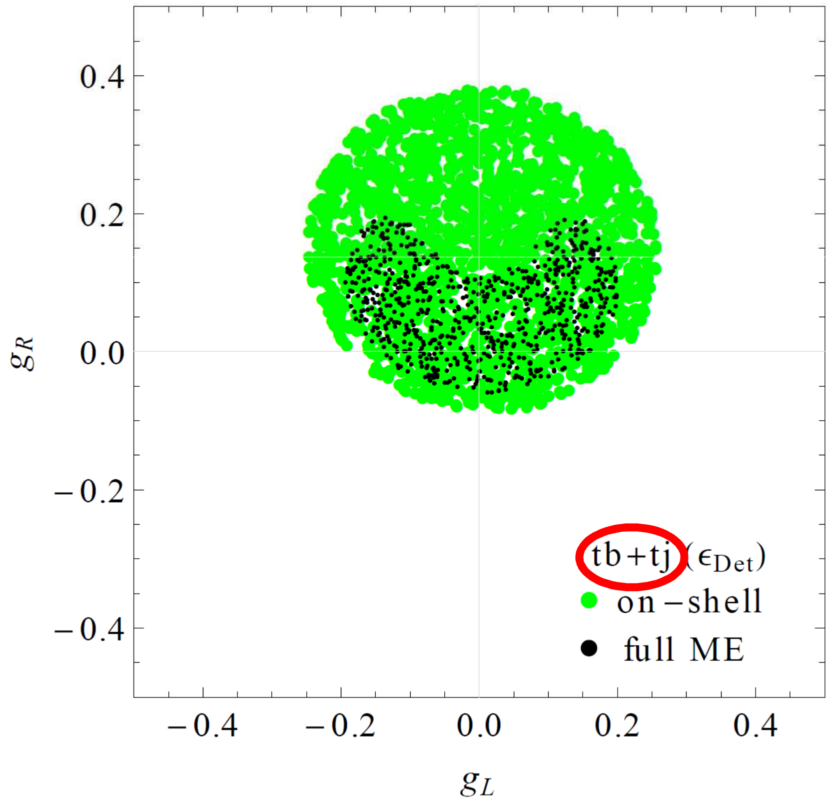


➔ largest discrepancy along **momentum-dependent couplings $g_{L,R}$**

Comparison of detector level limits

• set $\boldsymbol{\varepsilon = \varepsilon_{Det}}$ and plot 1σ combined limits in the $\boldsymbol{g_L - g_R}$ plane (V_L = 1, V_R = 0)



➔ **qualitatively different** limits in the *s* and *t* channel combination

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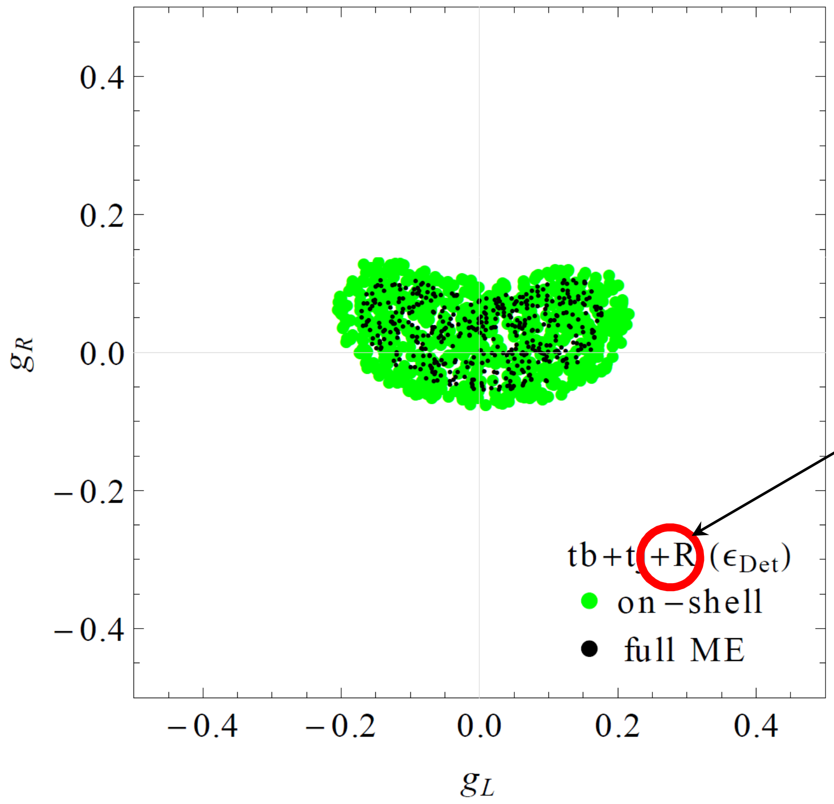

$$R := \frac{\sigma(\bar{t})}{\sigma(t)}$$

$$\frac{\Delta R}{R} \simeq 5\,\%$$

➔ ***R* observable** appears to relax the discrepancy …

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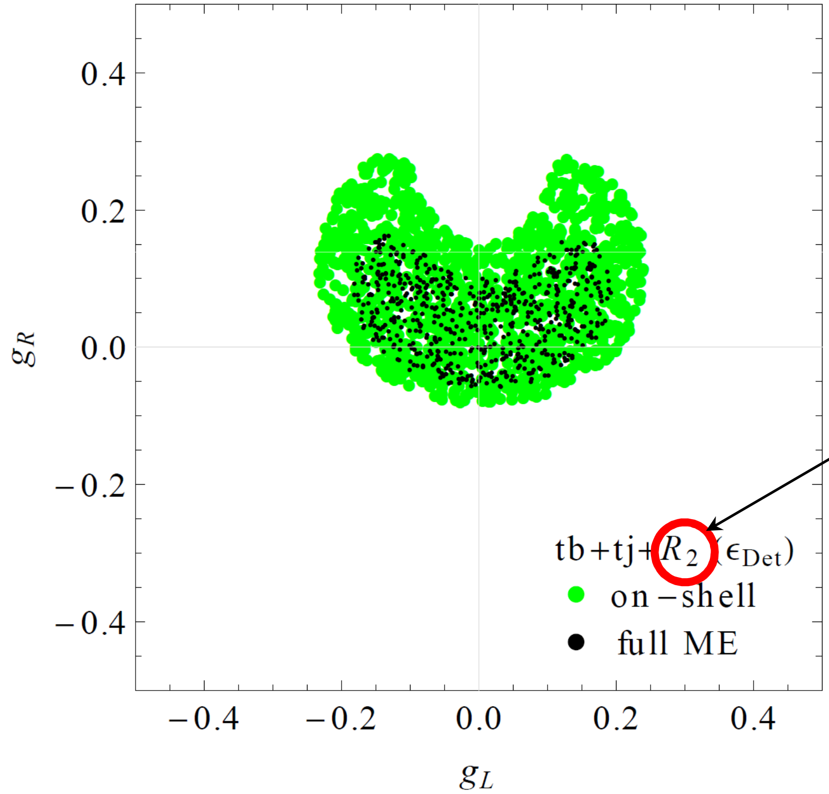

$$R := \frac{\sigma(\bar{t})}{\sigma(t)}$$

$$\frac{\Delta R}{R} \simeq 10\,\%$$

… but this **depends heavily** on the exp. uncertainty of *R*

Conclusions

- abundant **top production** at the ***LHC***
  - ➔ high statistics allows for precise measurements of top couplings etc.
  - ➔ look for deviations from SM in the min. set of trilinear top couplings *tfV*, *ttH*
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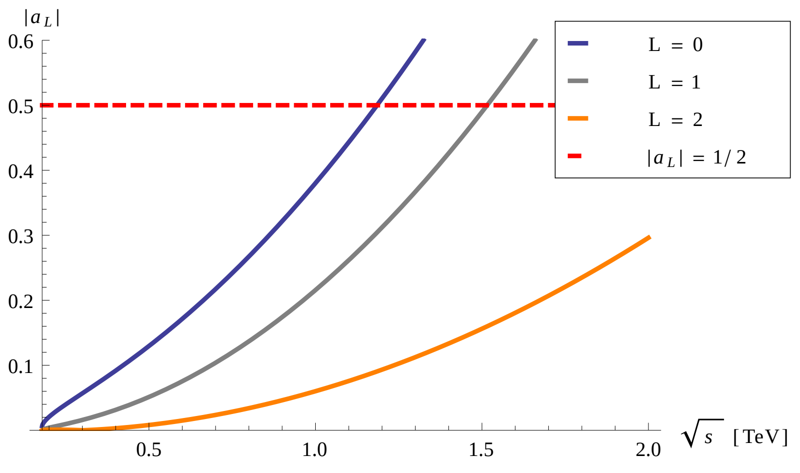
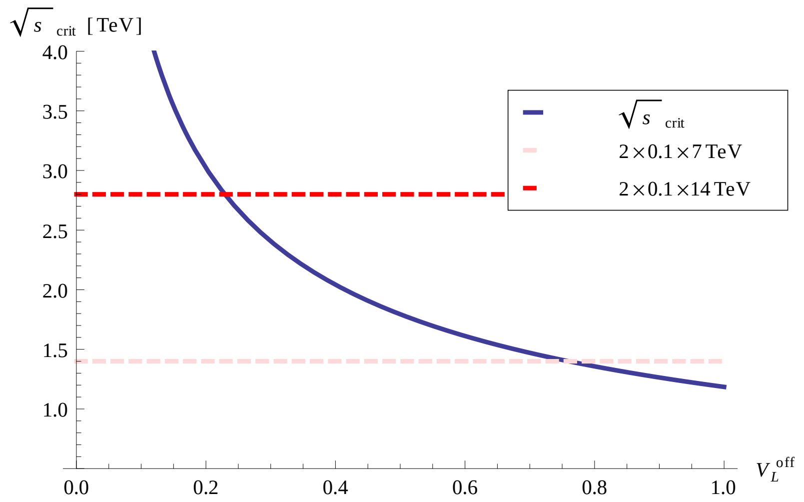
Thank you!

Unitarity bound on the contact coupling size

- perform a partial-wave analysis on the *ffff* contact diagram
- depending on input pdf's, infer unitarity limit on the coupling strength $\sim C/\Lambda^2$, in terms of V_L^{off}





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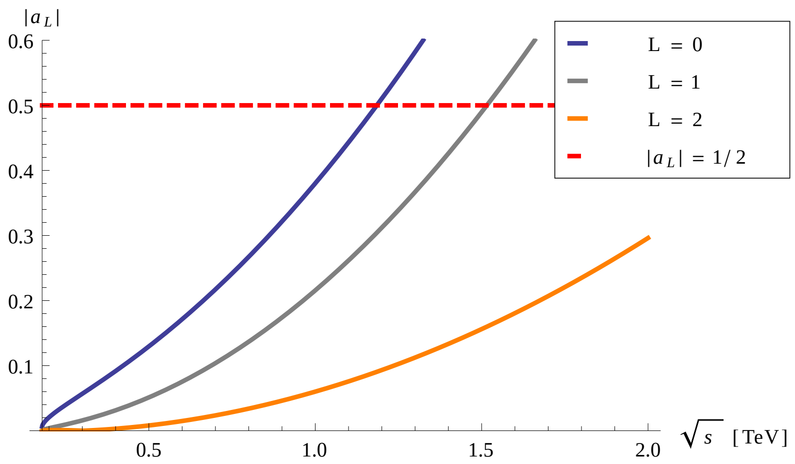

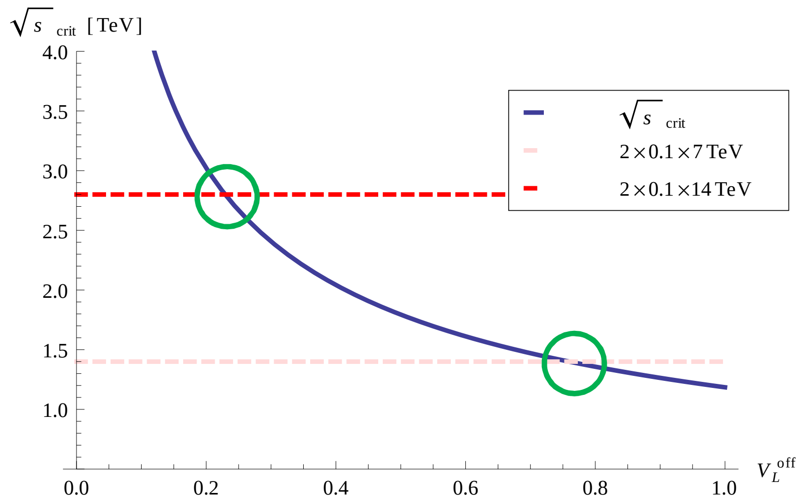

LHC @ 7 TeV: $V_L^{\text{off}} < 0.75$

LHC @ 14 TeV: $V_L^{\text{off}} < 0.25$ (exp. sensitivity ~ 0.05 @ 10 fb^{-1})

WHIZARD **validation**

- independent validation of WHIZARD 2:
  ➔ compute partonic *s* channel production *u dbar* → *t bbar* analytically (no cuts)
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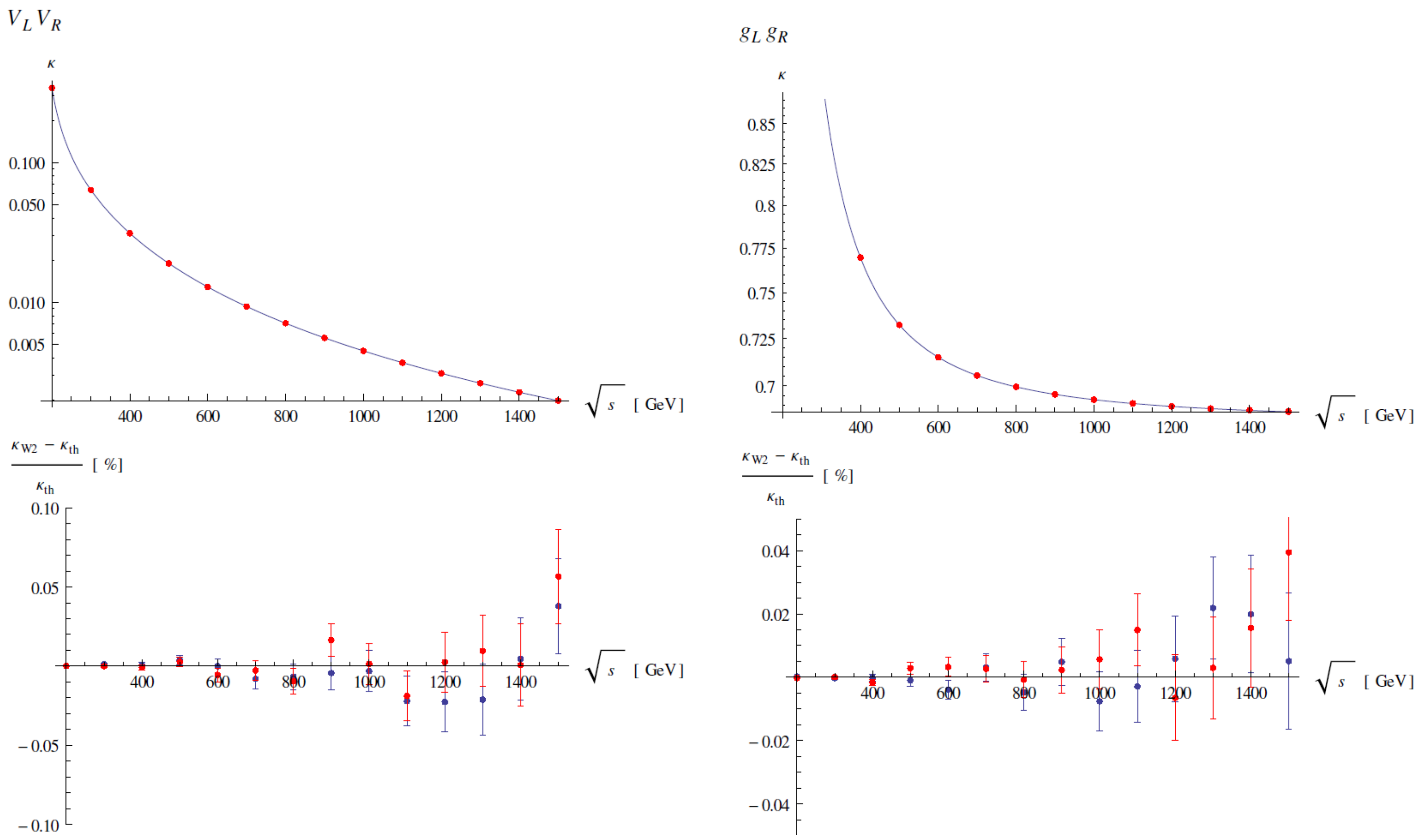

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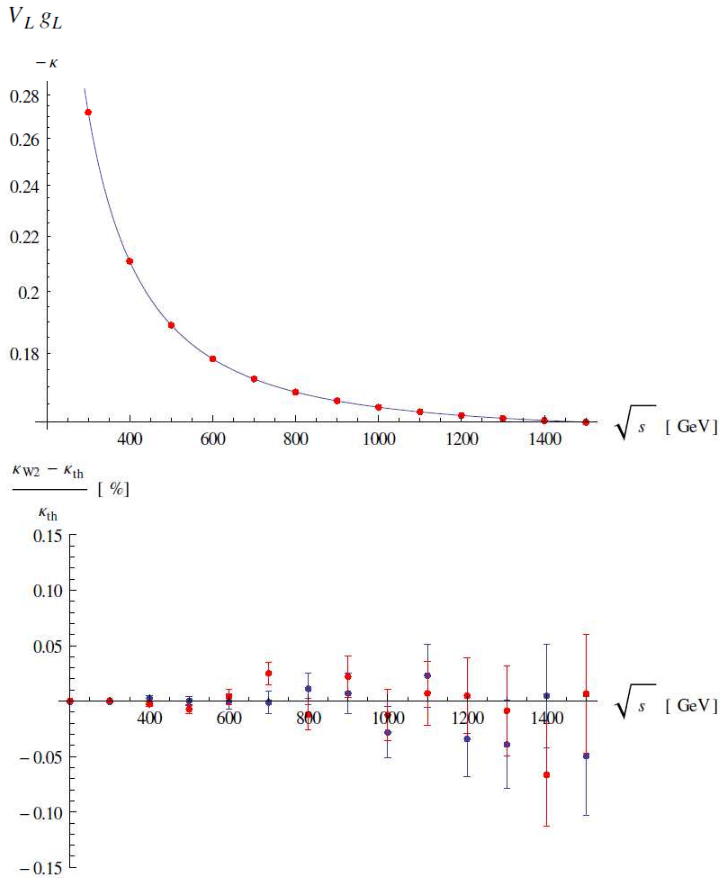

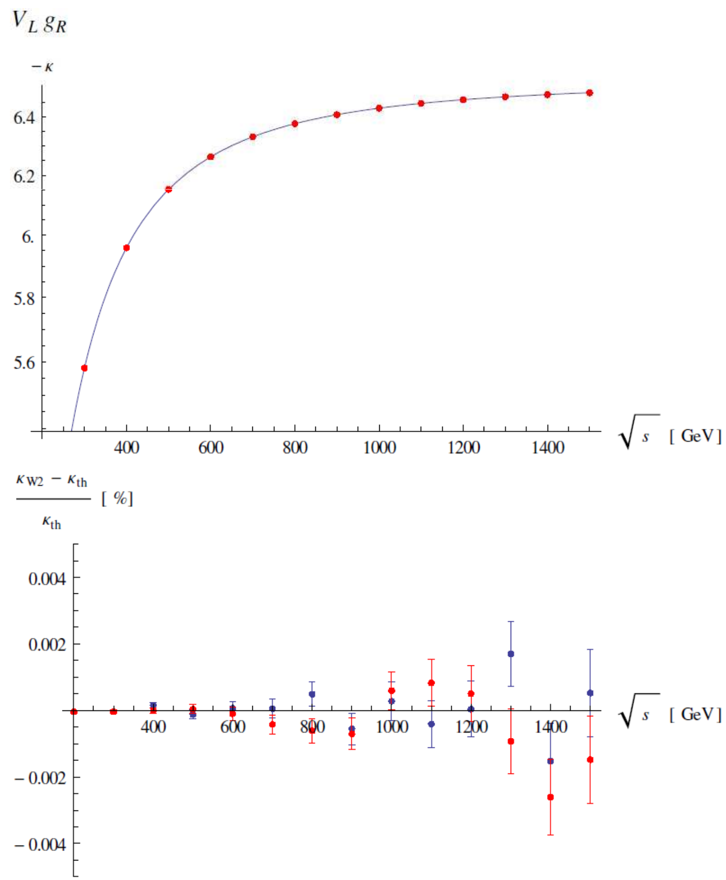

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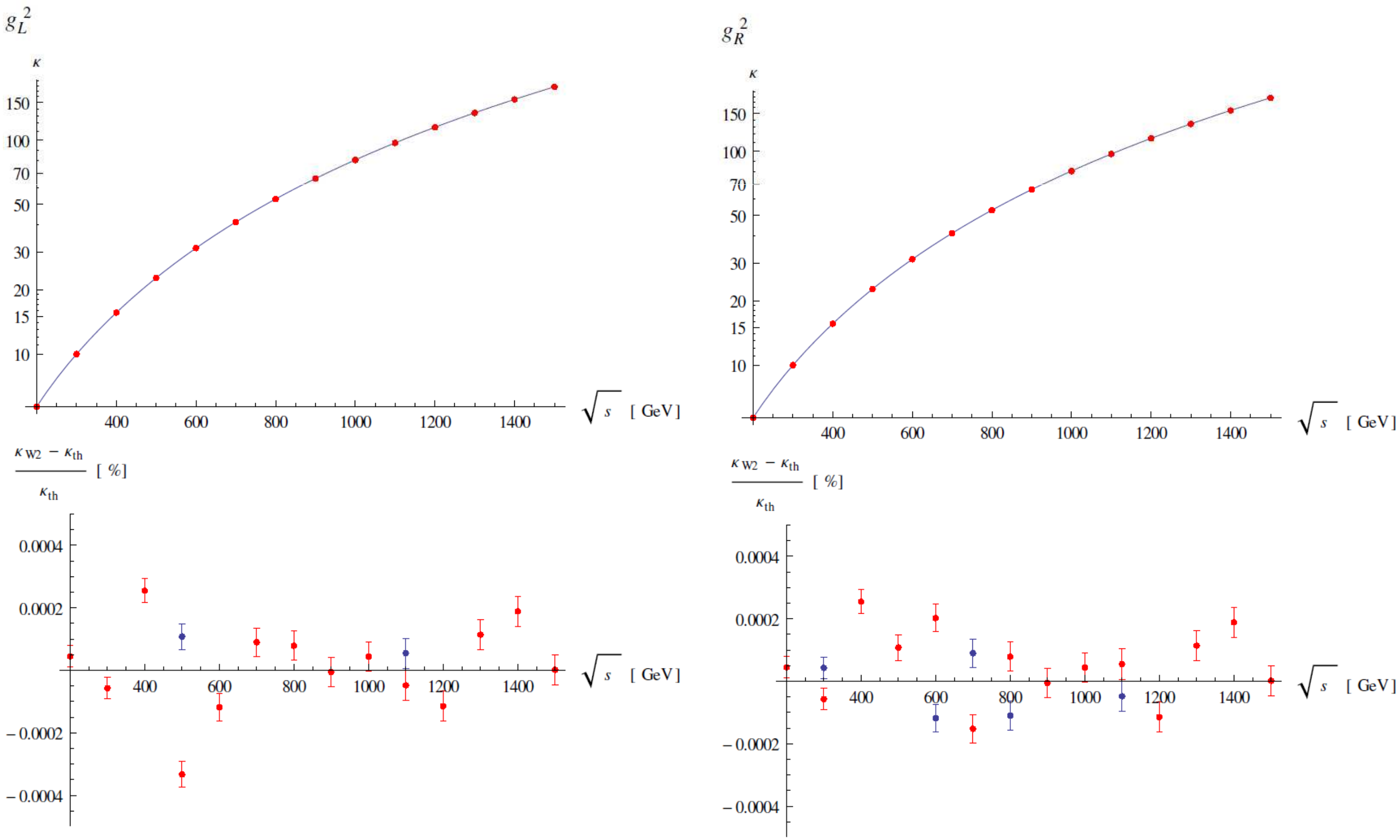

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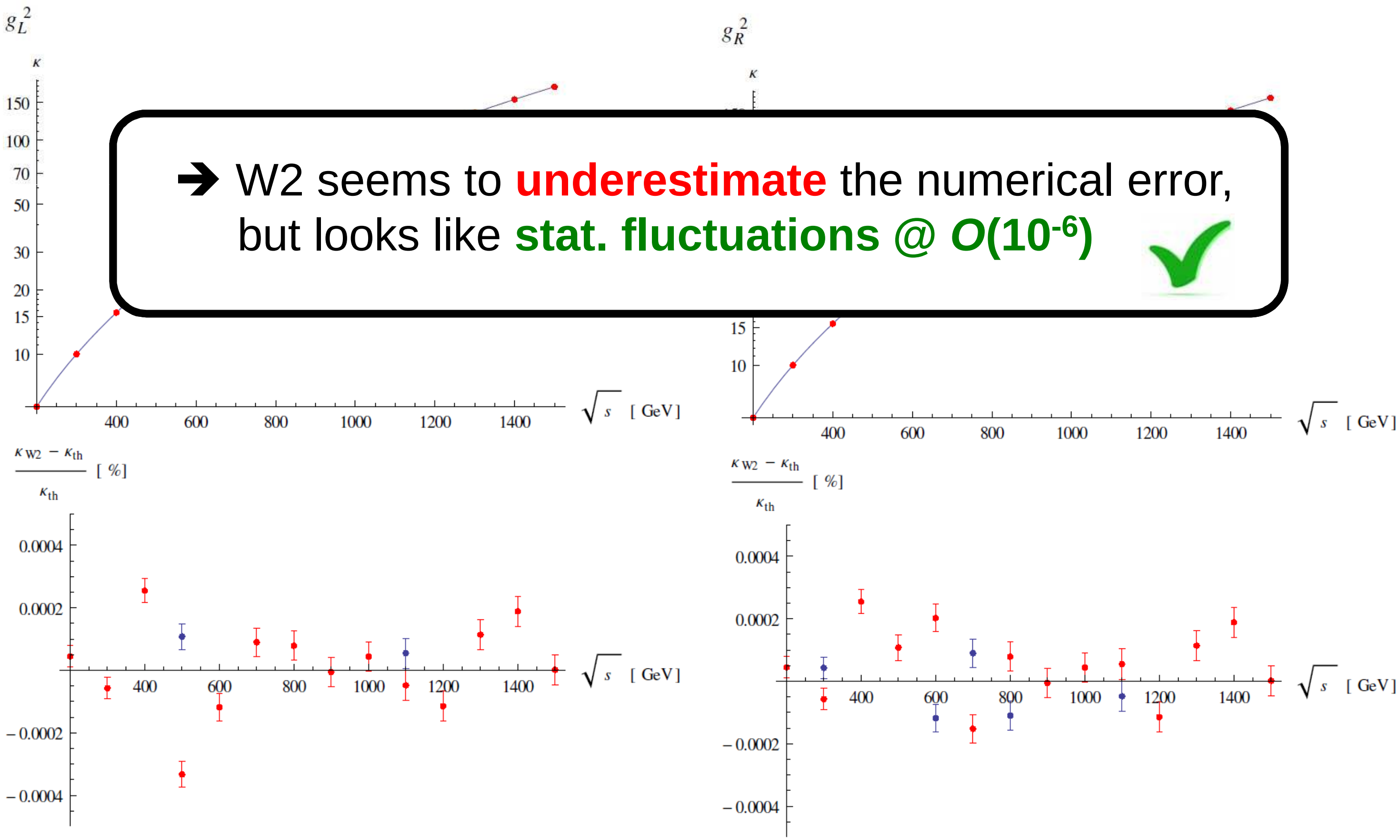
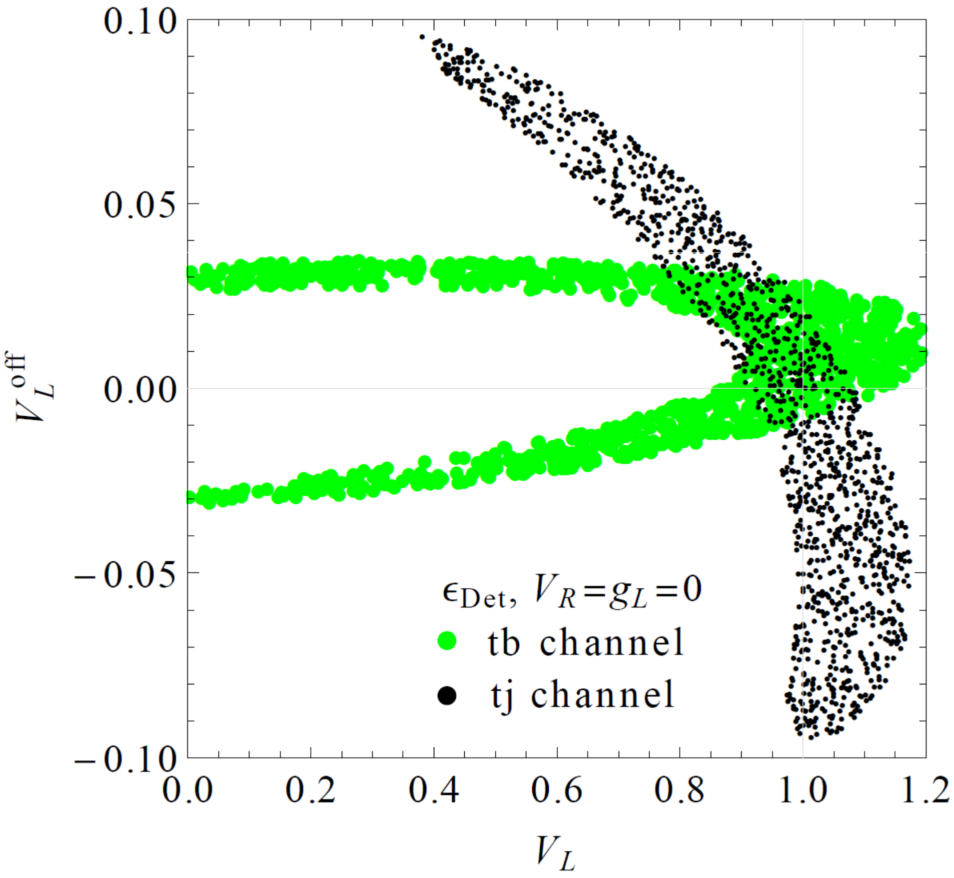


➔ W2 seems to **underestimate** the numerical error,
but looks like **stat. fluctuations @ *O*(10^{-6})** ✔

Include the contact interaction V_L^{off}

- set $\varepsilon = \varepsilon_{Det}$ and plot 1σ combined limits in the $V_L - V_L^{off}$ plane



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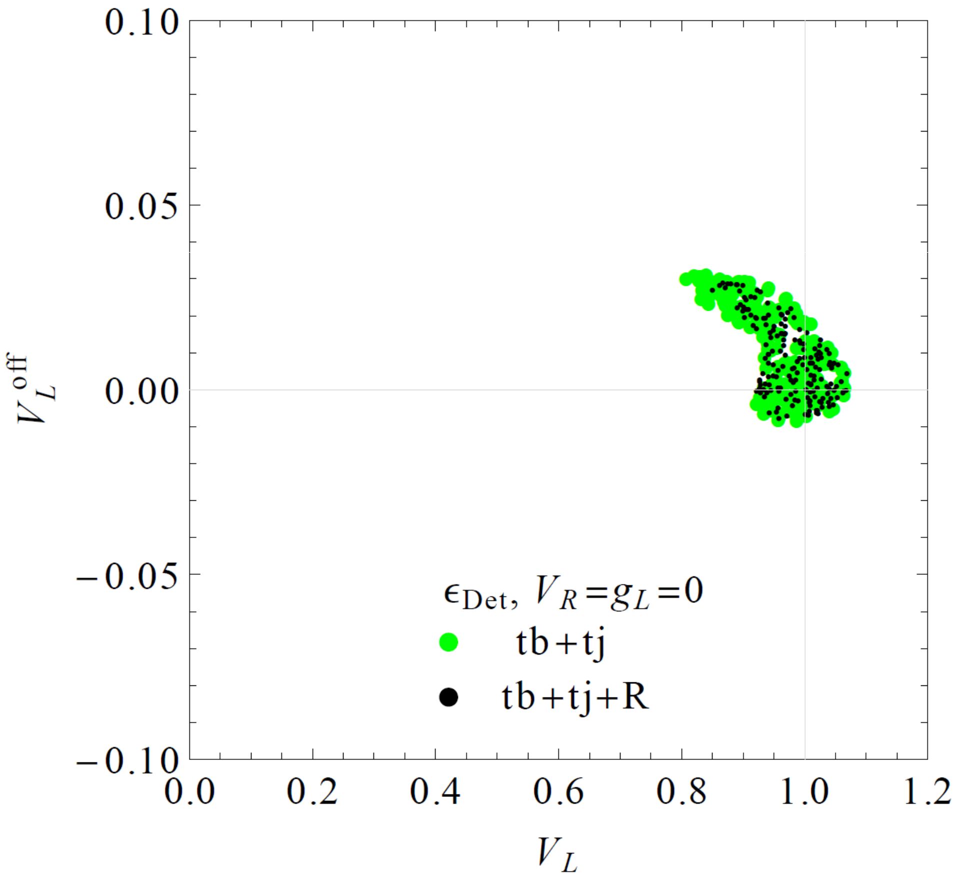

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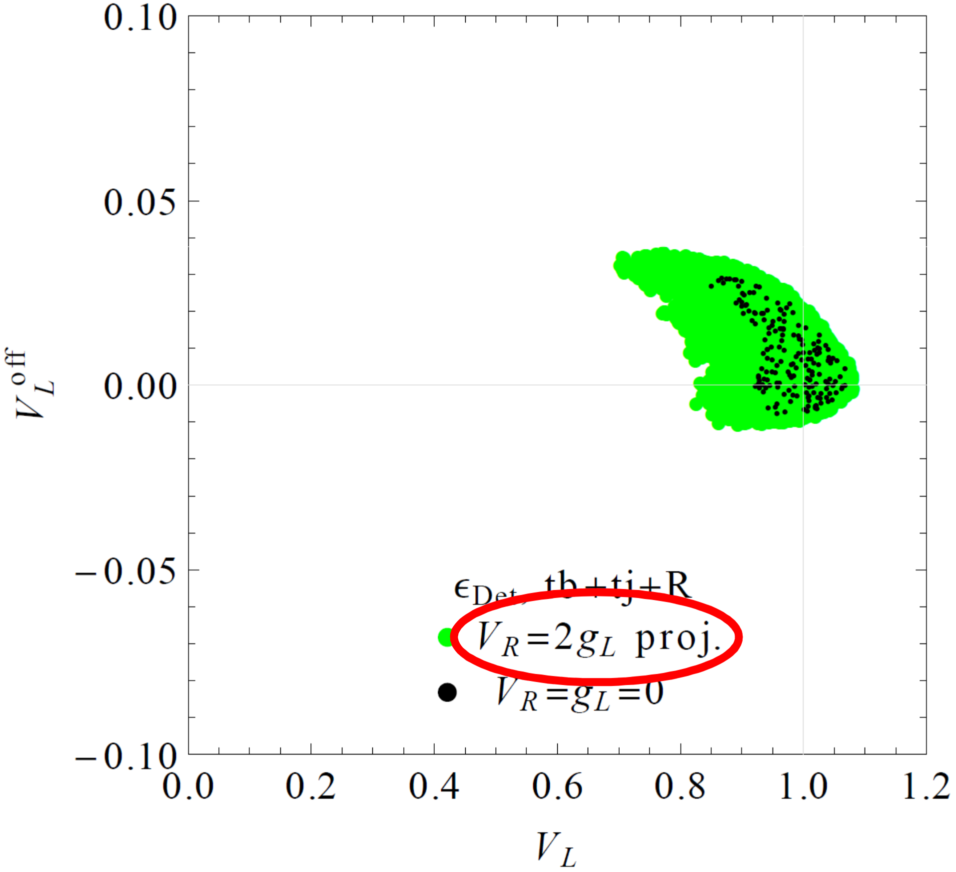

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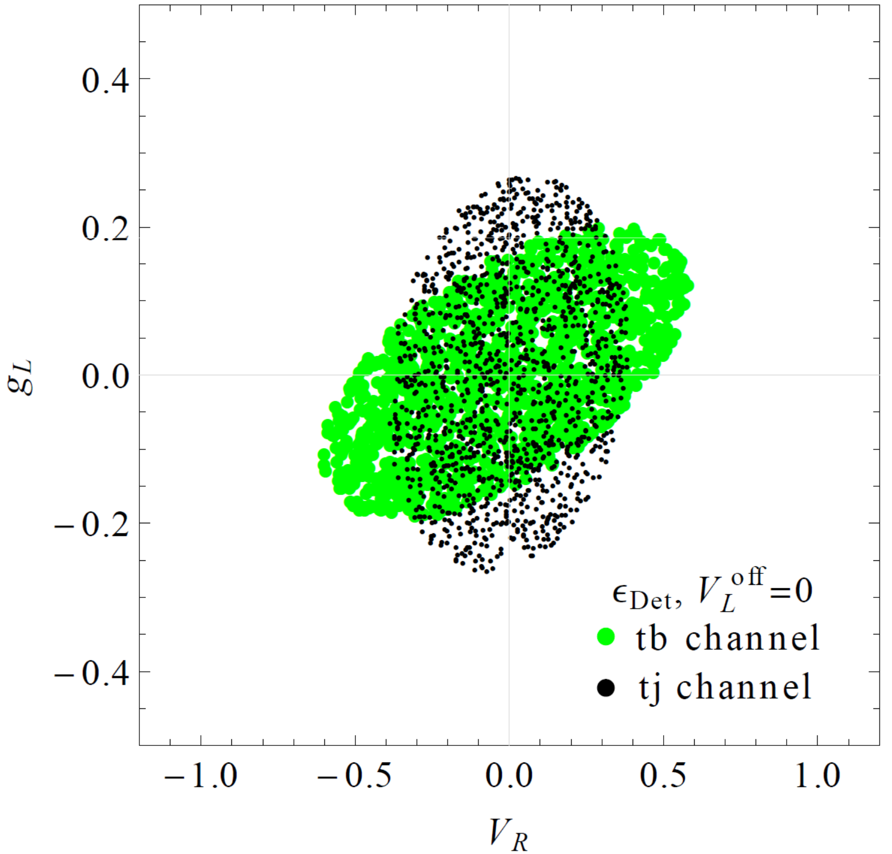

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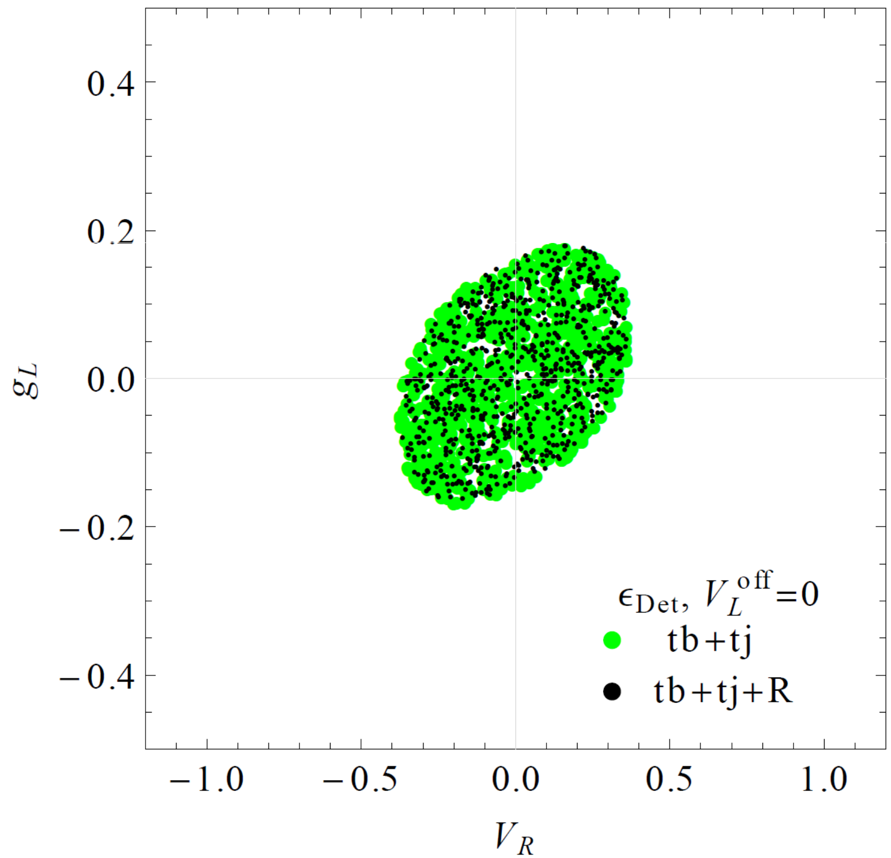

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