Anomalous Top Charged-current Contact Interactions in Single Top Production at the LHC

Fabian Bach
in collaboration with Thorsten Ohl

DESY Hamburg
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Outline

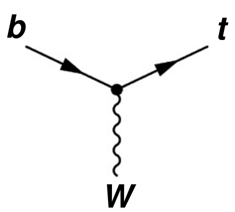
1. Motivation
2. Effective Field Theory & Anomalous Couplings
3. Single Top Differential Cross Sections
4. Conclusions

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

example: *tbW* vertex

SM



$\sim \gamma^{\mu}(1-\gamma_5)$

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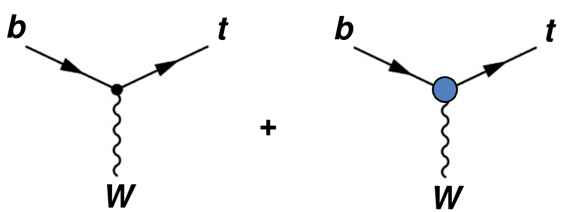

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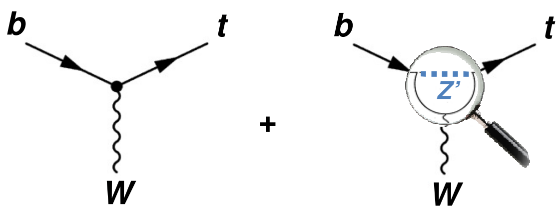

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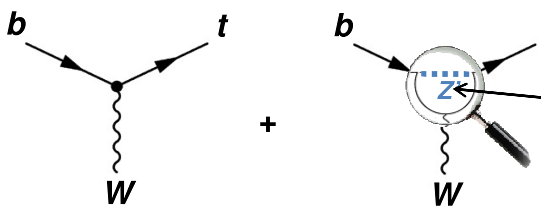

model builders, SuSy people: put your favorite particle **here**!

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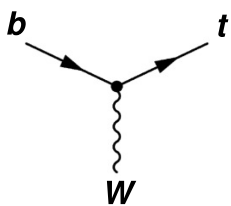

+

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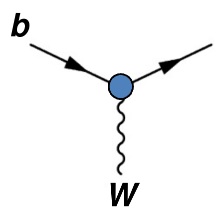

$\sim \gamma^{\mu}(1-\gamma_5)$

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

Effective Operator Approach

- integrate out model-dependent heavy excitations of new physics contributions
  ➔ **effective operators** with higher mass dim and suppression scale **Λ**:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

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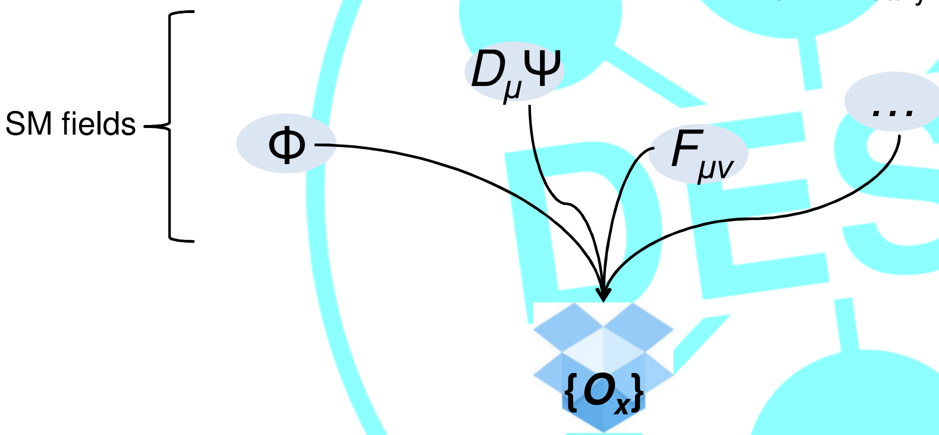
anom. top couplings: **all operators** with ≥ 1 heavy fermion fields



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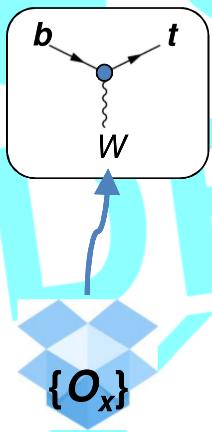

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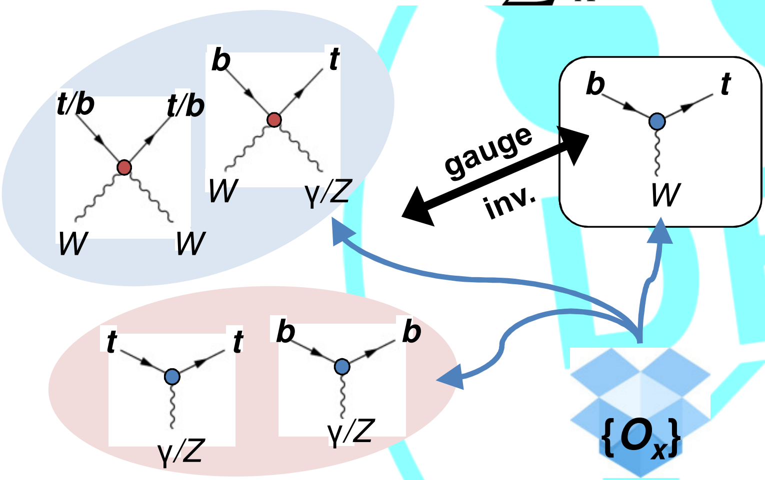

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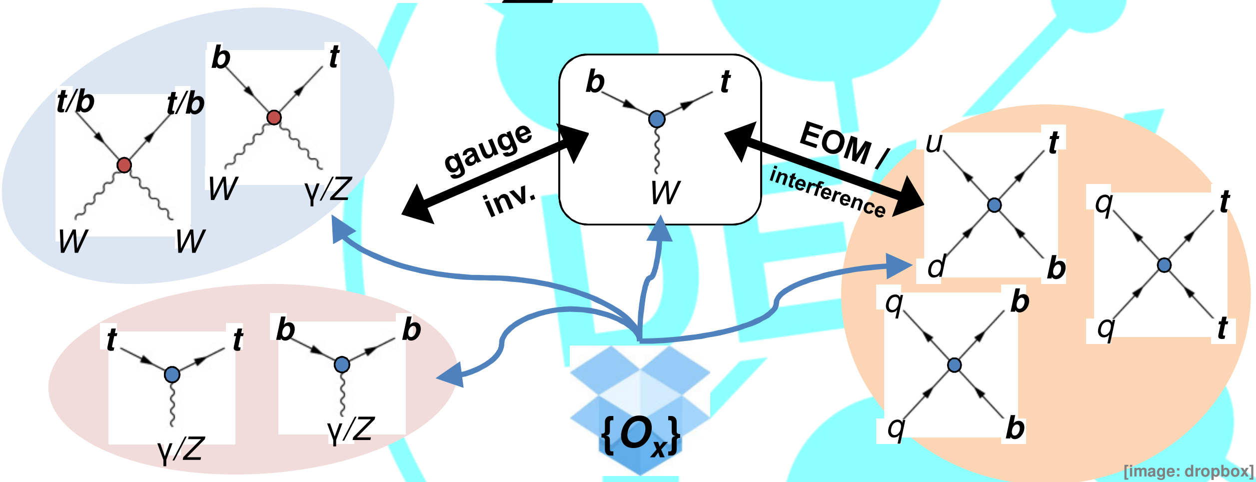
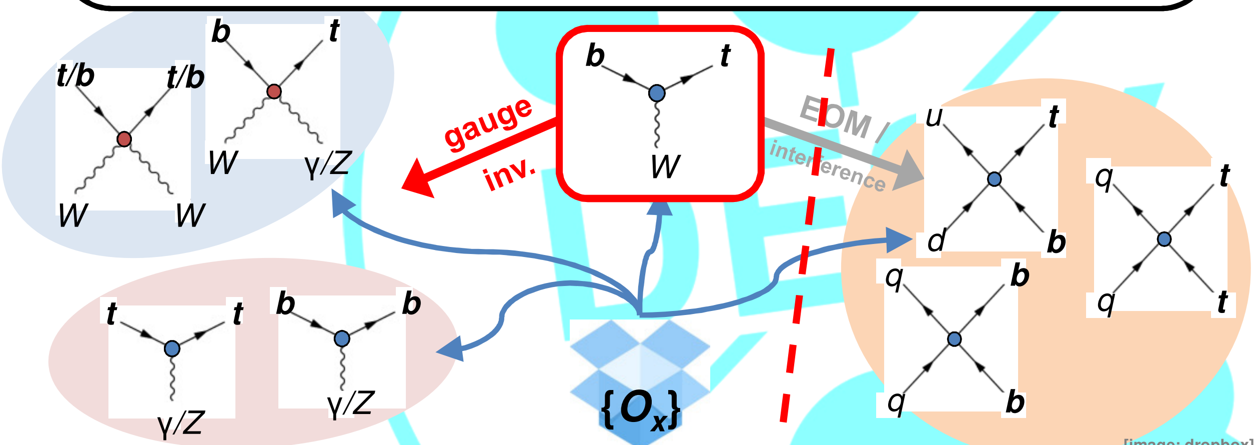


Effective Operator Approach

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

usual parameterisation
e.g. [Aguilar-Saavedra et al.]



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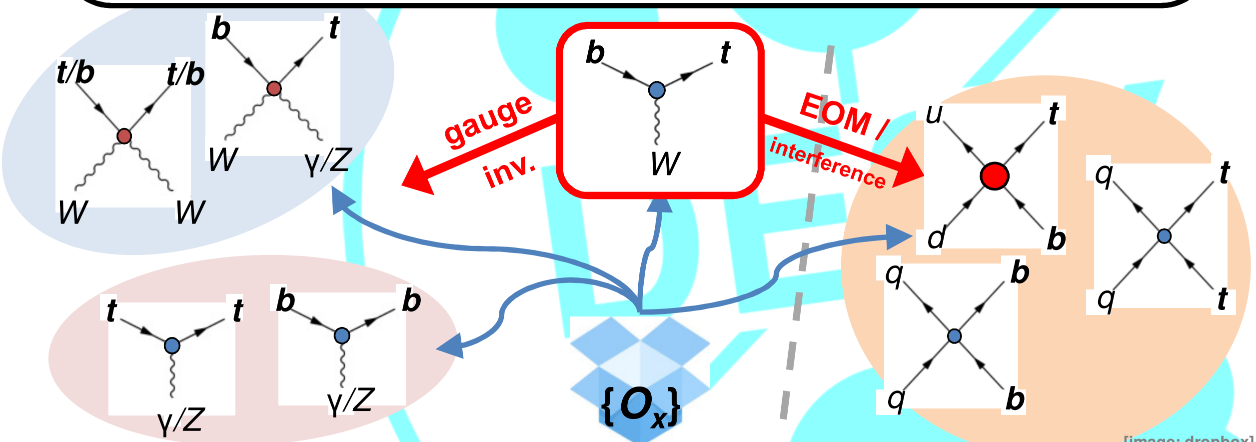
just another way of writing a *ffff* **contact interaction**



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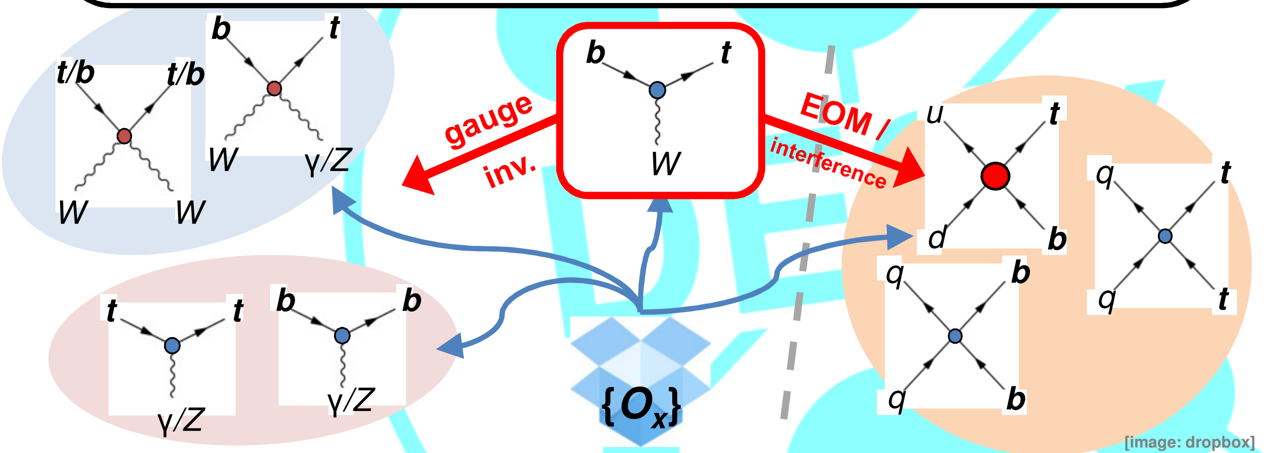

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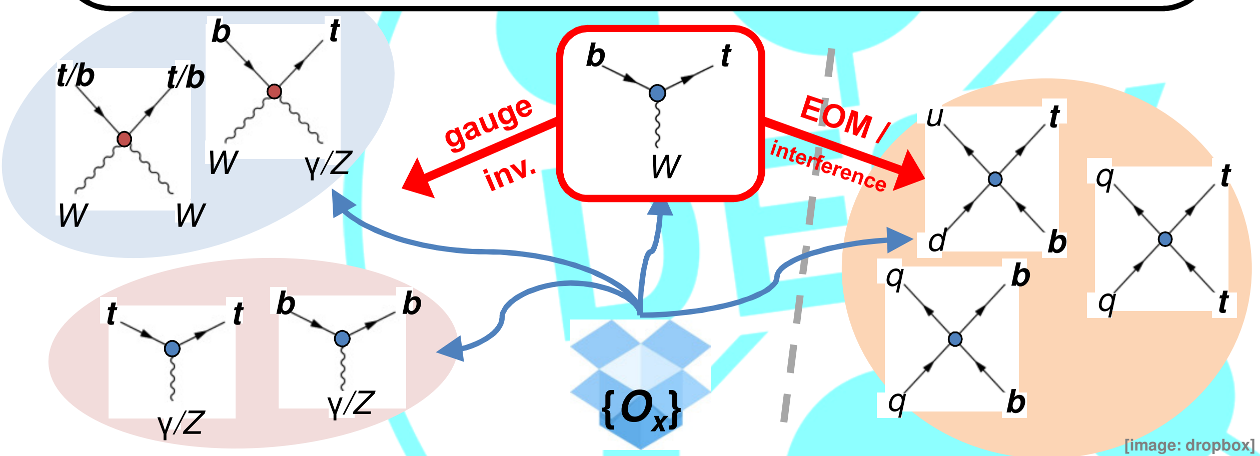
possible basis for **trilinear *tbW* couplings** including all interference effects
[FB, T Ohl '12]



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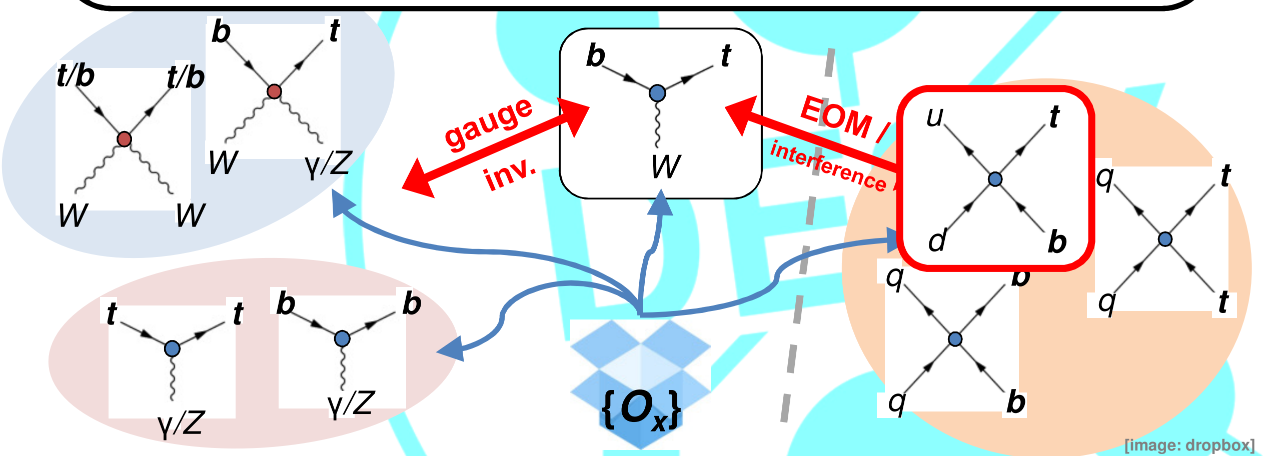
Effective Operator Approach

$$\Delta\mathcal{L}_{\mathrm{CC}} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\left(V_L + \frac{q^2-m_W^2}{m_W^2}V_L^{\mathrm{off}}\right)P_L\,t\,W^-_\mu + \mathrm{h.c.}$$
$$+\frac{1}{\Lambda^2}\left[S_L(\bar{b}P_L t)(\bar{u}_k P_L d_k) + S_R(\bar{b}P_R t)(\bar{u}_k P_R d_k) + \mathrm{h.c.}\right]$$

possible basis for ***tbqq'*** **contact couplings** including all interference effects (MFV scheme)

today!

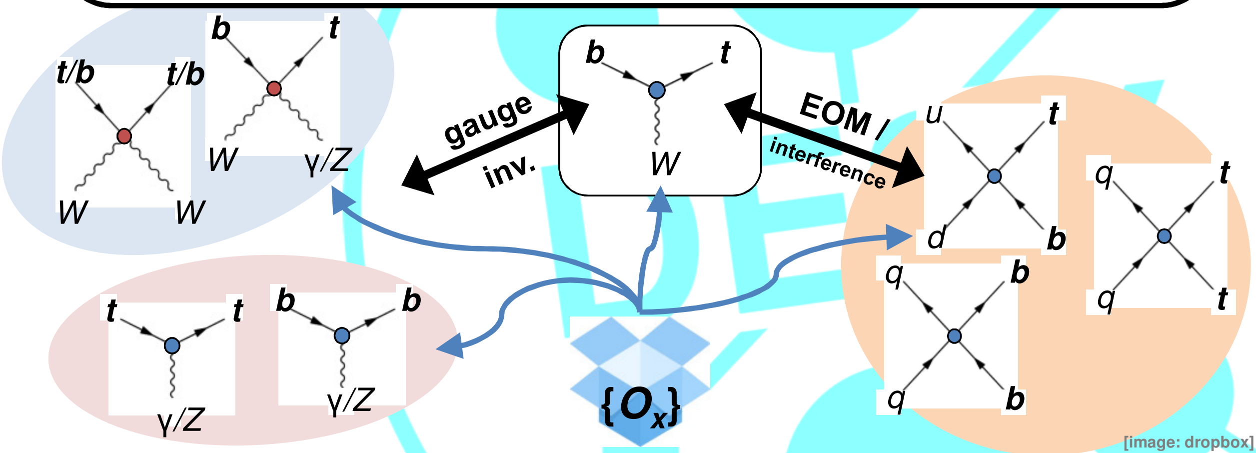


Effective Operator Approach

Find the **full package** in

WHIZARD 2

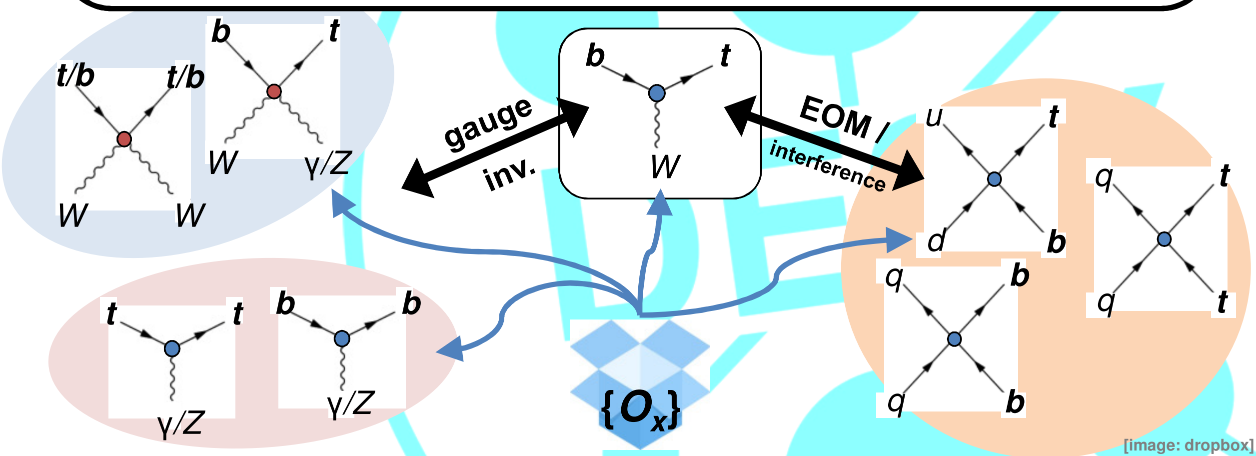
Including **all** *tbW*, *ttZ*, *ttA* and *ttg* + contact couplings!



Effective Operator Approach

***LHC observables for top charged currents*:**

1) **top pair production** ➔ largely QCD, **not sensitive**
2) **singe top production** ➔ electroweak, **sensitive** to *tbW*, *tbqq'*
3) **top decay products** ➔ electroweak, **sensitive** to *tbW*



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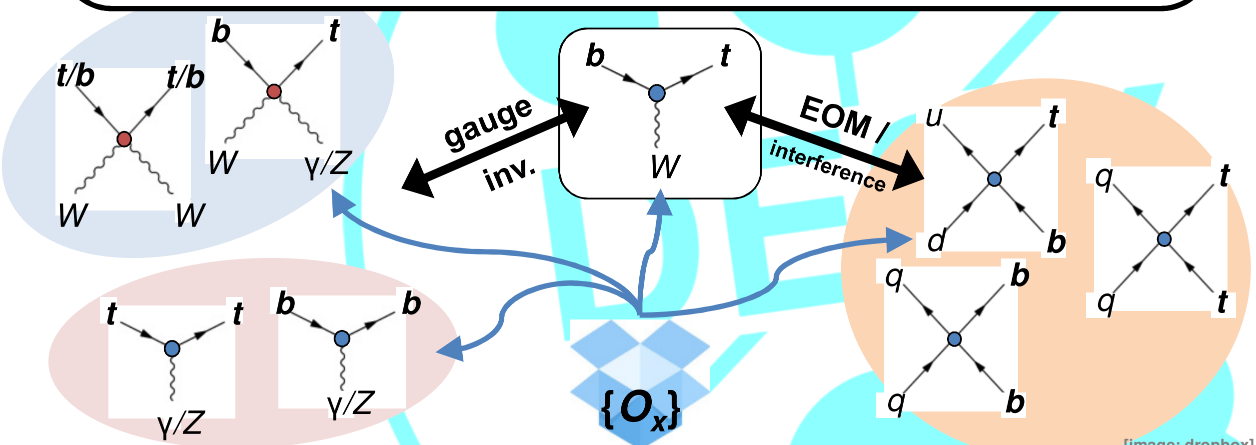

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Single top differential cross sections

$$\mathrm{d}\sigma_i^{\mathrm{det}}(\vec{g},\Phi) = \sum_{j=s,t} \epsilon_{ij}(\Phi) \cdot \mathrm{d}\sigma_j^{\mathrm{part}}(\vec{g},\Phi)$$

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phase space point Φ

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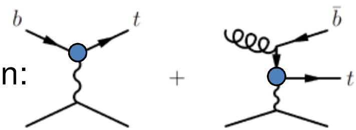
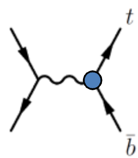


2) s-channel *tb* production:



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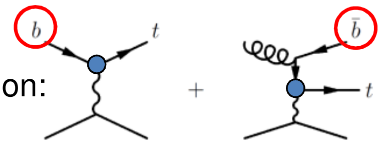

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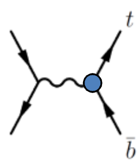
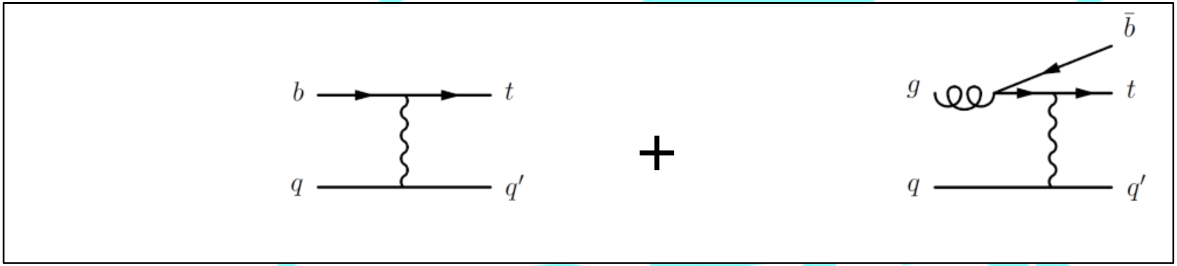


- *g*→*bb* splitting dominates pdf
- *b* tagging

➔ 2nd *b* part of the signature
➔ kinematics needs **matching**

Interlude: **matrix element matching**

- e. g. t-channel *tj + tbj* production:



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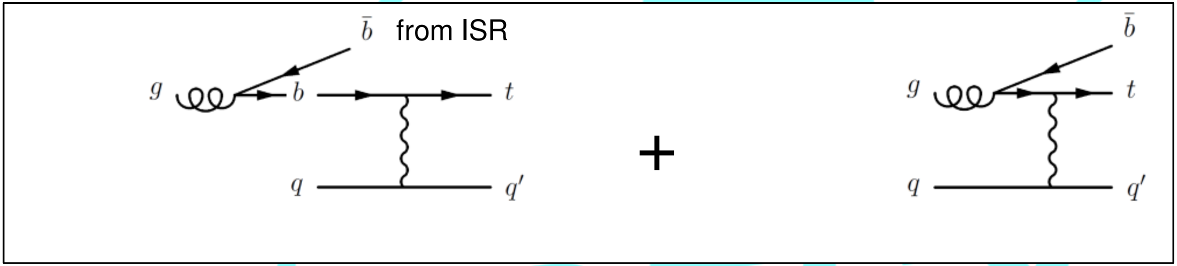

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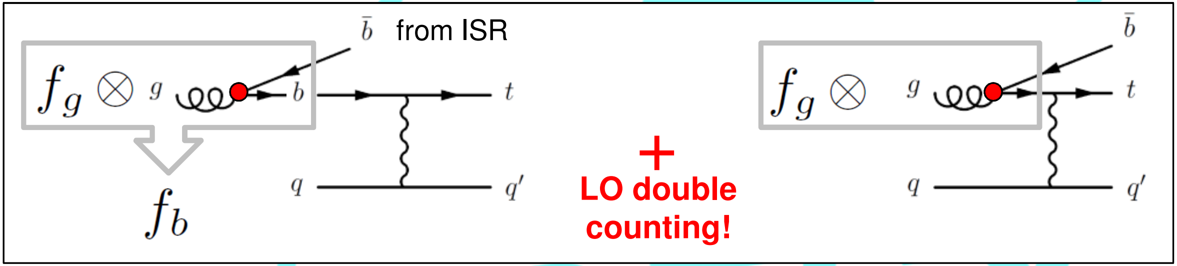

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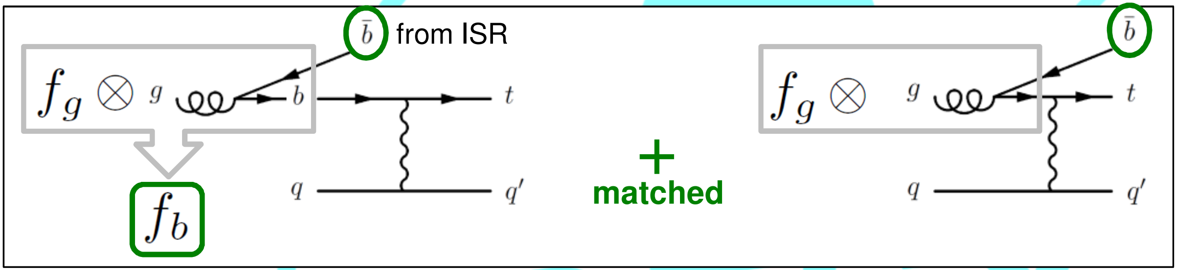

- automatically **subtract LO splitting from f_b**
  - ➔ link **HOPPET**[G Salam, J Rojo ´09] to **WHIZARD**
  - ➔ set beam switch (works with any Lhapdf input)

```
?lhapdf_hoppet_b_matching = true
```

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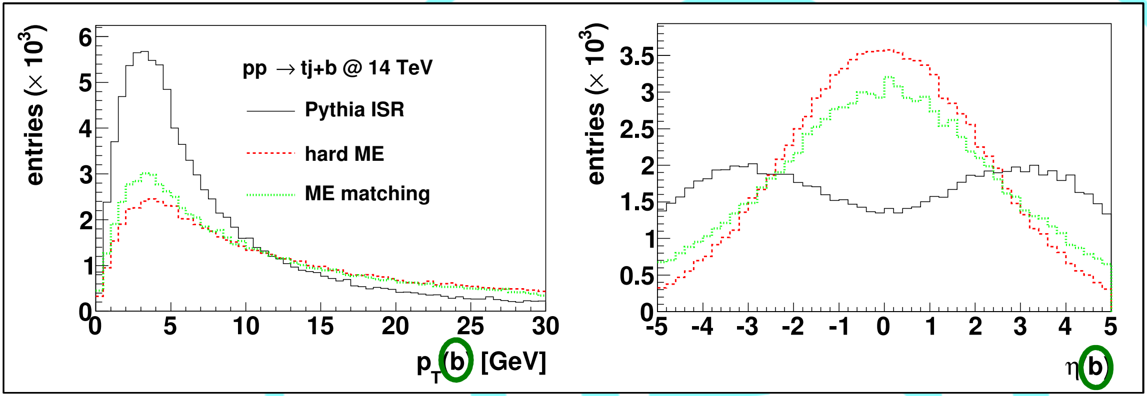

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SM N(N)LO
normalization

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BSM LO Monte Carlo

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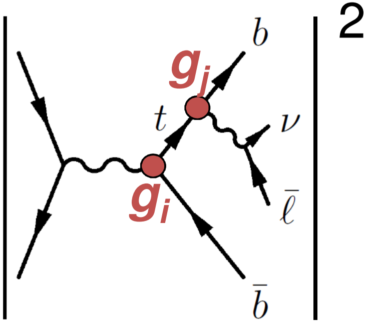
e.g. ***s* channel**

$$\mathrm{d}\sigma^{\mathrm{part}}(\vec{g},\Phi) \sim$$



$$\sim f(g_i, g_j)\ ?$$

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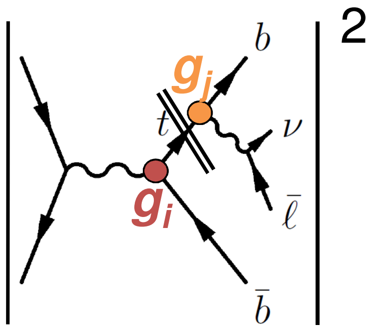

$$\sim f(g_i, g_j)\ ?$$

$$\boxed{\Gamma_t \sim \Gamma_t(V_L, V_R, g_L, g_R, V_L^{\mathrm{off}}, S_L, S_R)}$$

Single top differential cross sections

$$\mathrm{d}\sigma_i^{\mathrm{det}}(\vec{g},\Phi) = \sum_{j=s,t} \epsilon_{ij}(\Phi) \cdot \underbrace{\boxed{K_j}}_{\text{SM N(N)LO normalization}} \cdot \underbrace{\boxed{\mathrm{d}\sigma_j^{\mathrm{part}}(\vec{g},\Phi)}}_{\text{BSM LO Monte Carlo}}$$

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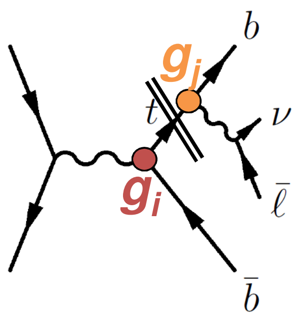

$$\Gamma_t \sim \Gamma_t(V_L, V_R, g_L, g_R, \boxed{\cancel{V_L^{\mathrm{off}}, S_L, S_R}})$$

kinematically **suppressed**!

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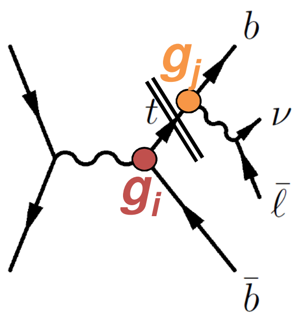


$$\Gamma_t \sim \Gamma_t(V_L, \boxed{V_R, g_L, g_R})$$ from ***W* helicities**!

Single top differential cross sections

$$\mathrm{d}\sigma_i^{\mathrm{det}}(\vec{g},\Phi) = \sum_{j=s,t} \epsilon_{ij}(\Phi) \cdot \boxed{K_j} \cdot \boxed{\mathrm{d}\sigma_j^{\mathrm{part}}(\vec{g},\Phi)}$$

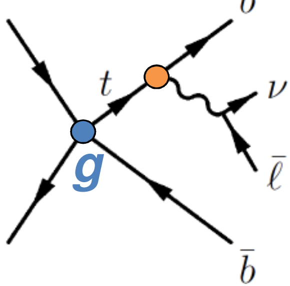
@ parameter point $\vec{g}$
phase space point Φ

SM N(N)LO normalization

BSM LO Monte Carlo

e.g. ***s* channel**

$$\mathrm{d}\sigma^{\mathrm{part}}(\vec{g},\Phi) \sim \left| \quad \right|^2 \sim \mathrm{d}\sigma_{ij}(\Phi)|_{W\text{-hel.}} \boxed{g_i g_j}$$



$\{V_L, V_L^{\mathrm{off}}, S_L, S_R\}$

$\Gamma_t \sim \Gamma_t(V_L, \boxed{V_R, g_L, g_R})$ from ***W* helicities**!

Single top differential cross sections

$$\mathrm{d}\sigma_i^{\mathrm{det}}(\vec{g},\Phi) = \sum_{j=s,t} \epsilon_{ij}(\Phi) \cdot \boxed{K_j} \cdot \boxed{\mathrm{d}\sigma_j^{\mathrm{part}}(\vec{g},\Phi)}$$

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SM N(N)LO normalization

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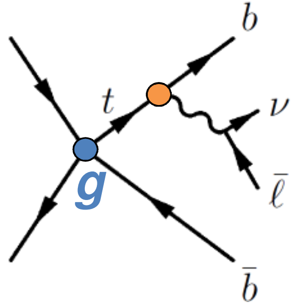
e.g. ***s*** **channel**

$$\mathrm{d}\sigma^{\mathrm{part}}(\vec{g},\Phi) \sim \left| \quad \right|^2$$



i **=** ***j*** or ***V**$_L$***–***V**$_L$$^{\mathrm{off}}$***

$$\sim \boxed{\mathrm{d}\sigma_{ij}}(\Phi)|_{W\text{-hel.}} \boxed{g_i g_j}$$

{*V*$_L$, *V*$_L$$^{\mathrm{off}}$, *S*$_L$, *S*$_R$}

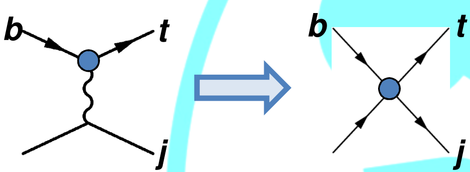
$\Gamma_t \sim \Gamma_t(V_L, \boxed{V_R, g_L, g_R})$ from ***W* helicities**!

Contact interactions & differential cross sections

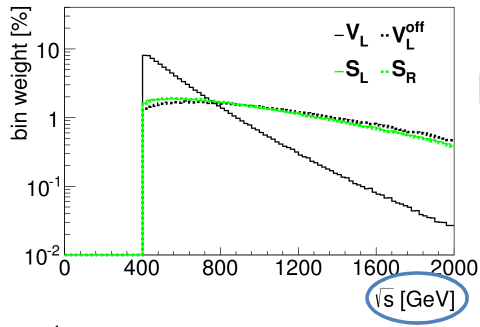
- approach: fix V_R, $g_{L,R}$ from W helicities
  ➔ single top prod. as a window to **charged current contact interactions**

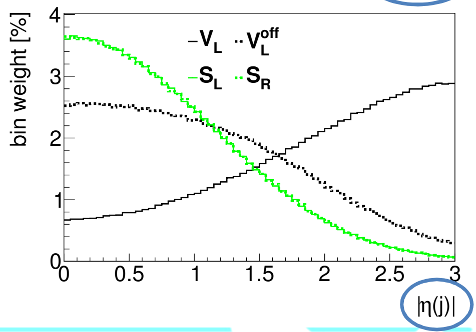
- coupling basis: $\{V_L,\ V_L^{\mathrm{off}},\ S_L,\ S_R\}$

- contact amplitudes lack W propagator:



➔ more central, high energetic distributions





Contact interactions & differential cross sections

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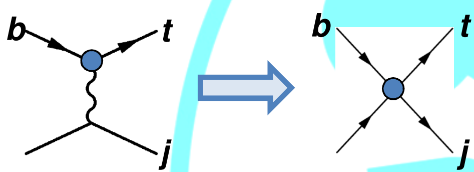
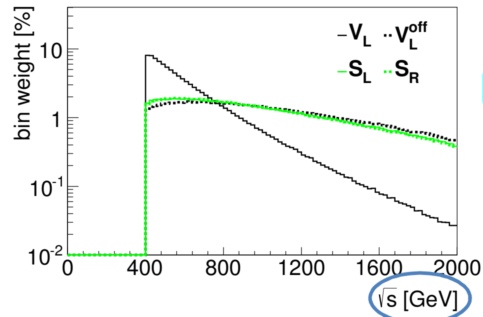
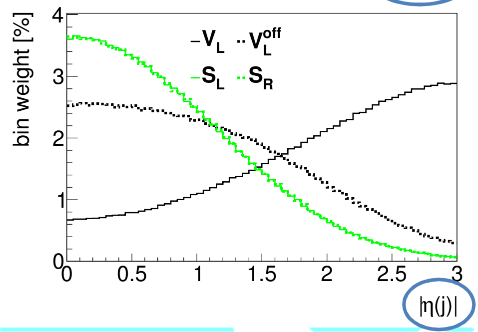


➔ more central, high energetic distributions
➔ $\sqrt{s}_{\mathbf{LHC}}$ **= 14 TeV**, partonic acceptance:

$$m_{tj} \equiv \sqrt{s} > 400\,\mathrm{GeV}$$
$$|\eta(j,b)| < 3$$





Parton level analysis

$\{V_L,\ V_L^{\mathrm{off}},\ S_L,\ S_R\}$

event samples with **one** coupling at **production** vertex

(+ 1 interference direction ~ $V_L V_L^{\mathrm{off}}$)

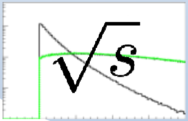
Parton level analysis

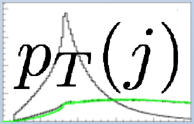
$\{V_L, V_L^{\mathrm{off}}, S_L, S_R\}$

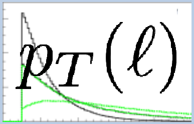
event samples with **one** coupling at **production** vertex

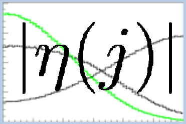
(+ 1 interference direction ~ $V_L V_L^{\mathrm{off}}$)

differential distributions of final state objects:









$$\left\{ \sqrt{s},\ p_T(j),\ p_T(\ell),\ |\eta(j)|,\ \dots \right\}$$

Parton level analysis

binned likelihood test:

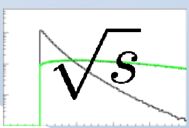
$$\chi^2(\vec{g}) = \sum_i \left(\frac{w_i^{\text{exp}} - w_i^{\text{th}}(\vec{g})}{\delta_i} \right)^2$$

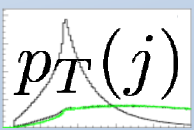
with *i* over all bins in the analysis

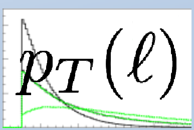
➔ **9 observables**: $\sqrt{s}$, E_T^{miss}, $p_T(b)$, $\eta(b)$, $p_T(\ell)$, $\eta(\ell)$, $p_T(j)$, $\eta(j)$, $\cos\theta_\ell$
in both channels

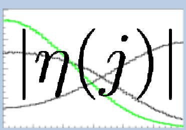
off)

differential distributions of final state objects:

{ 

, 

, 

, 

, ... }

Parton level analysis

binned likelihood test:

$$\chi^2(\vec{g}) = \sum_i \left(\frac{w_i^{\mathrm{exp}} - w_i^{\mathrm{th}}(\vec{g})}{\delta_i} \right)^2$$

@ L = 100 fb^{-1}

with *i* over all bins in the analysis

➔ **9 observables**: $\sqrt{s}$, E_T^{miss}, $p_T(b)$, $\eta(b)$, $p_T(\ell)$, $\eta(\ell)$, $p_T(j)$, $\eta(j)$, $\cos\theta_\ell$
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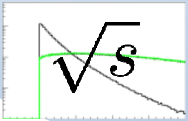
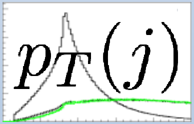
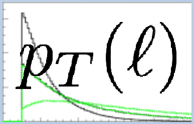
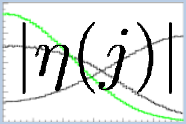
{ 

, 

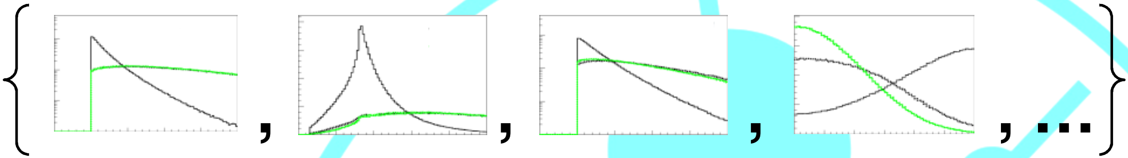
, 

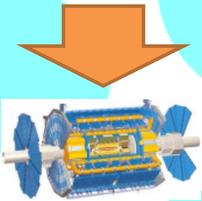
, 

, ... }

Detector level analysis

- infer binned detector efficiency matrix at the **SM point**





Pythia / Delphes

Detector level analysis

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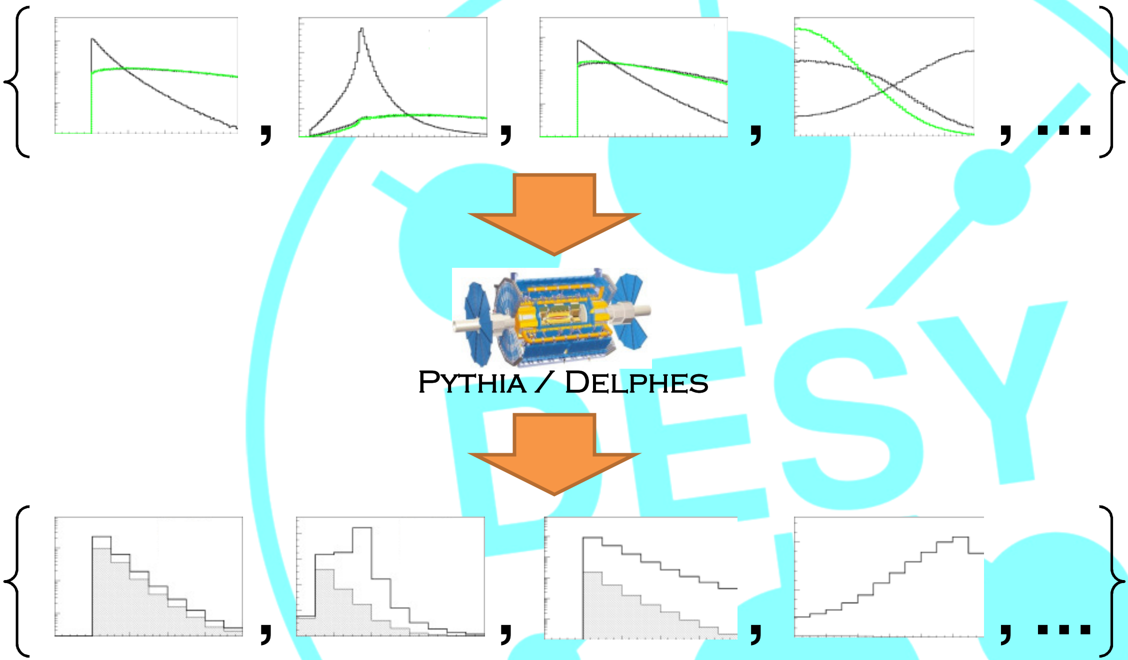

Detector level analysis

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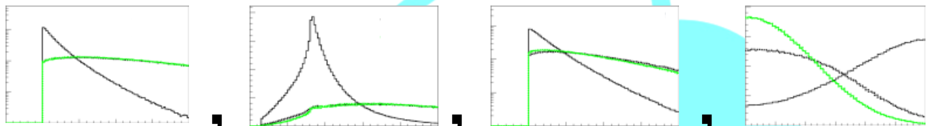
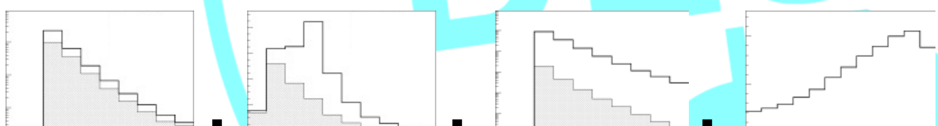


, , , , ...

$$\begin{pmatrix} \mathrm{eff}_{tb\rightarrow tb} & \mathrm{eff}_{tj\rightarrow tb} \\ \mathrm{eff}_{tb\rightarrow tj} & \mathrm{eff}_{tj\rightarrow tj} \end{pmatrix}$$

bin by bin…



, , , , ...

Detector level analysis

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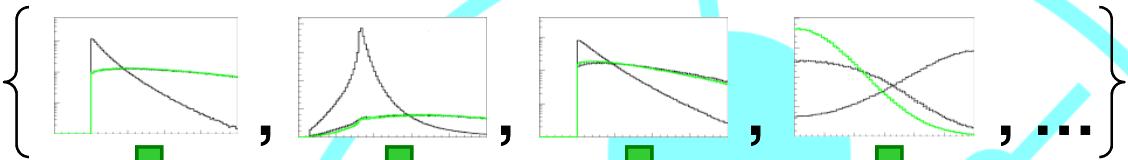
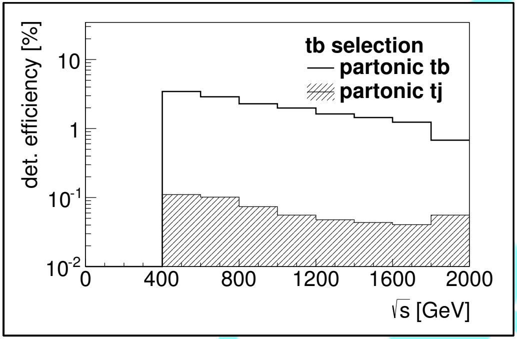


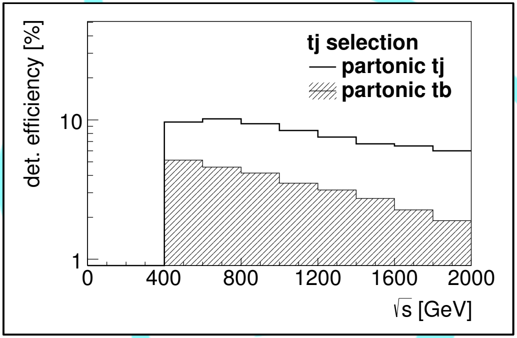
$$\begin{pmatrix} \mathrm{eff}_{tb\to tb} & \mathrm{eff}_{tj\to tb} \\ \mathrm{eff}_{tb\to tj} & \mathrm{eff}_{tj\to tj} \end{pmatrix}$$

bin by bin… **…for all channels, observables**

Detector level analysis

- infer binned detector efficiency matrix at the **SM point**





Detector level analysis

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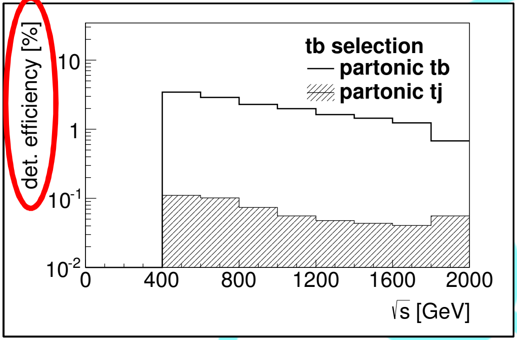

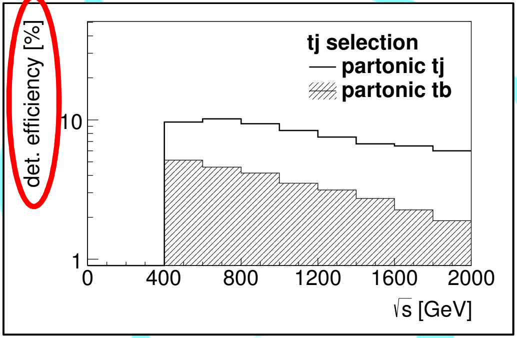

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Detector level analysis

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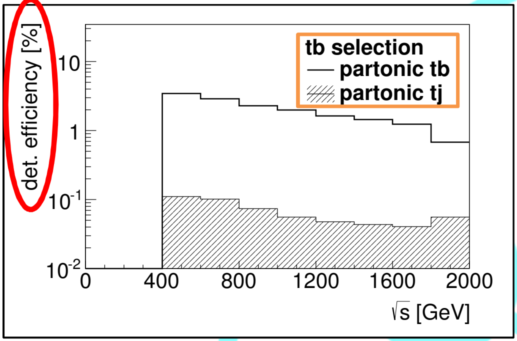

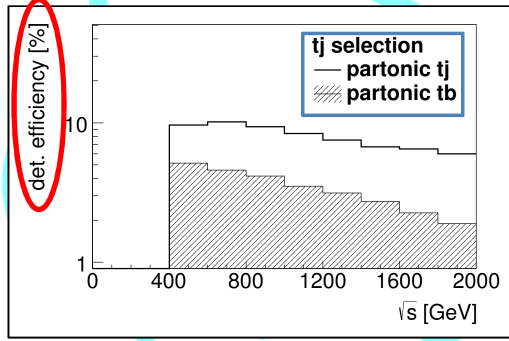

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Detector level analysis

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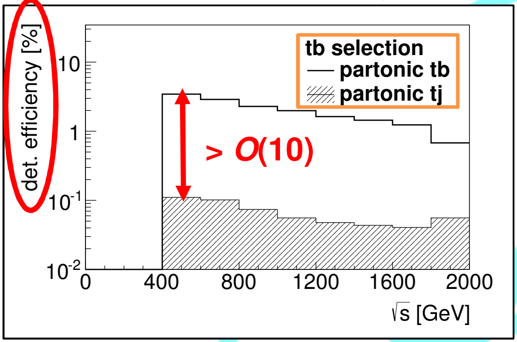

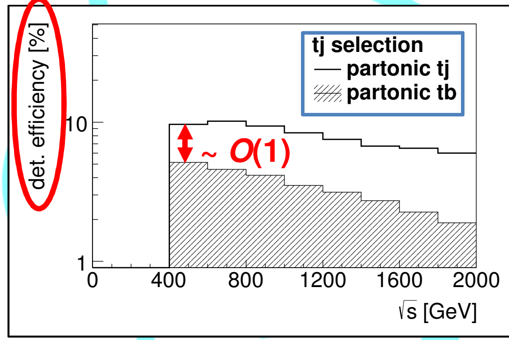

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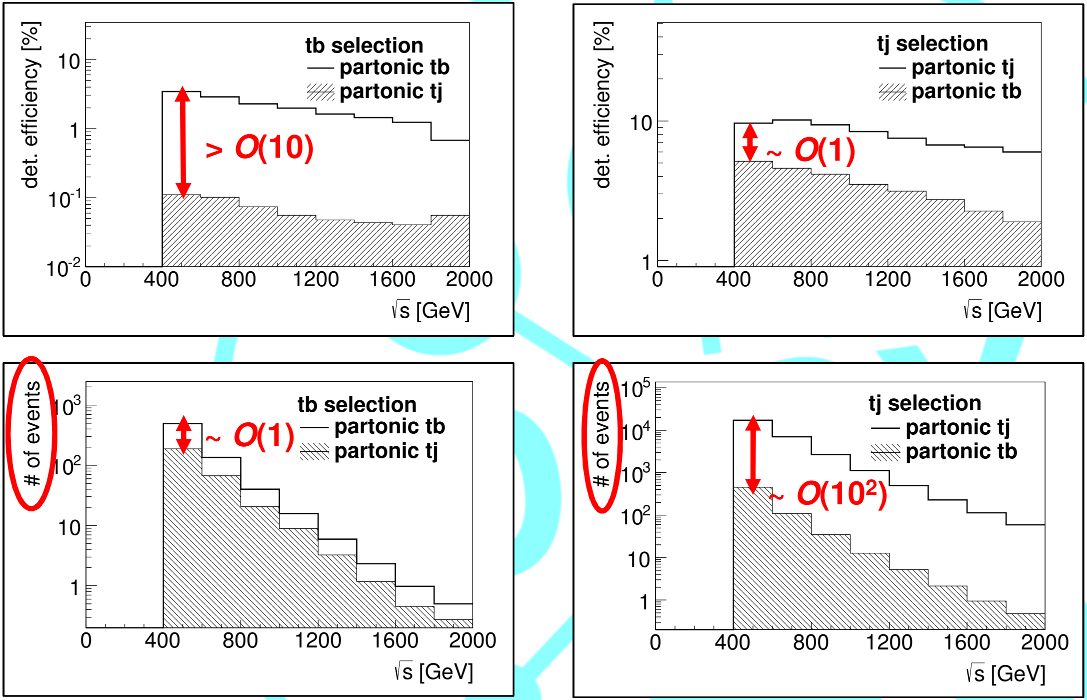
Detector level analysis

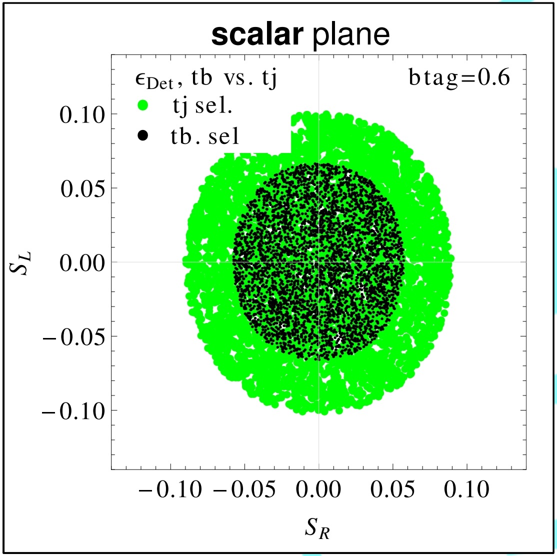
$\sigma_t \gg \sigma_s$

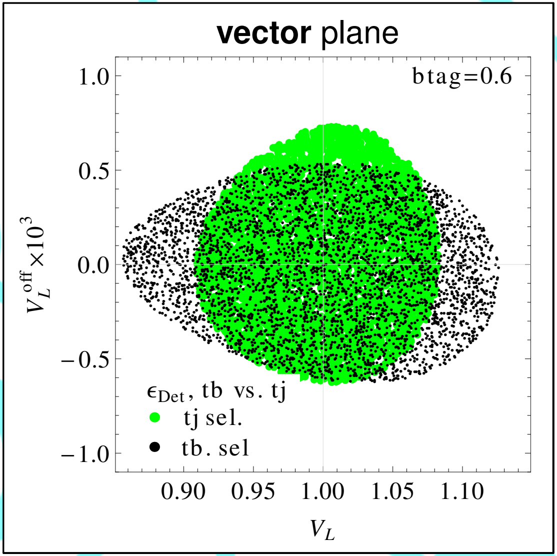
- infer binned detector efficiency matrix at the **SM point**



Detector level analysis

- detector level 1σ bounds: **scalar vs. vector couplings**





Detector level analysis

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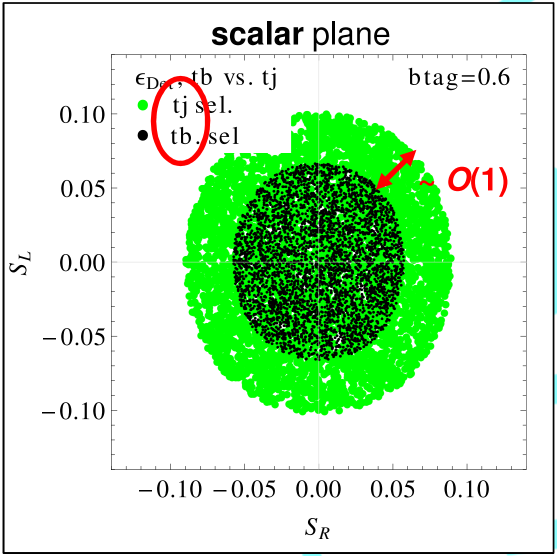
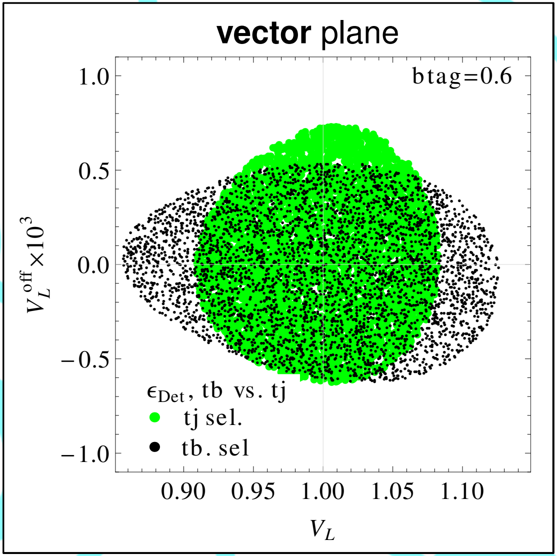
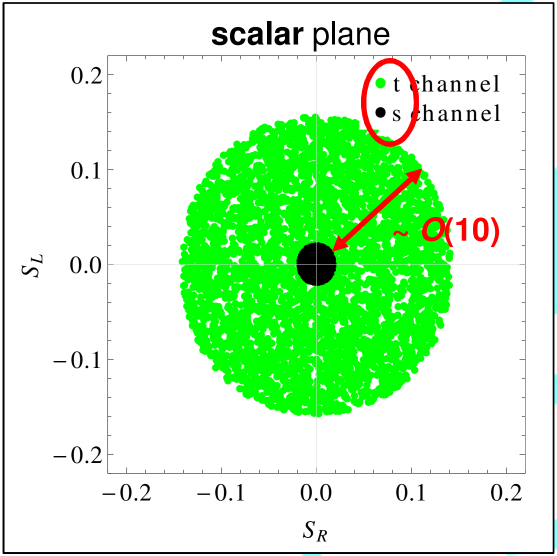
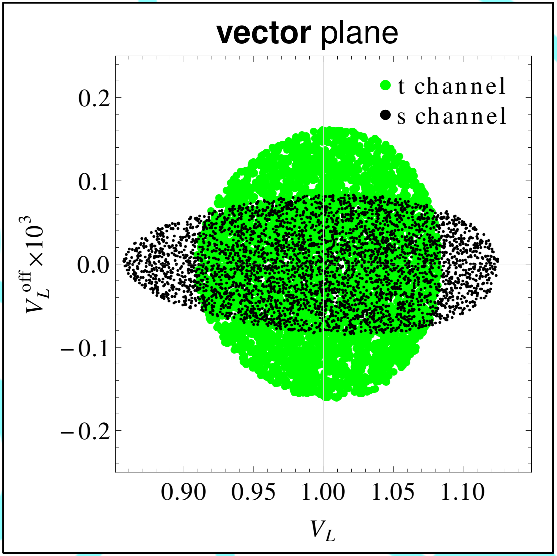




Detector level analysis

- compare **parton level** 1σ bounds:

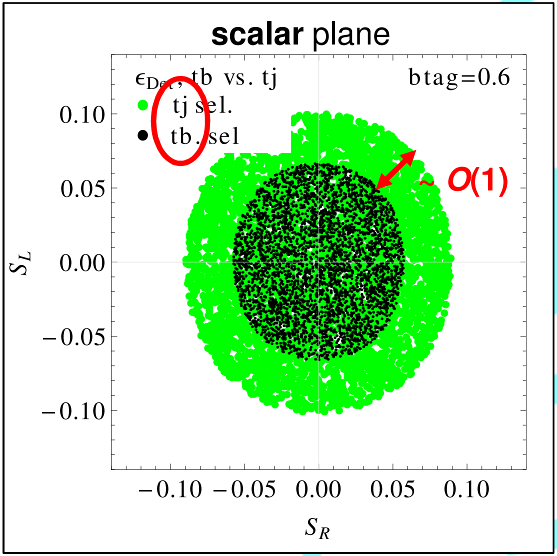


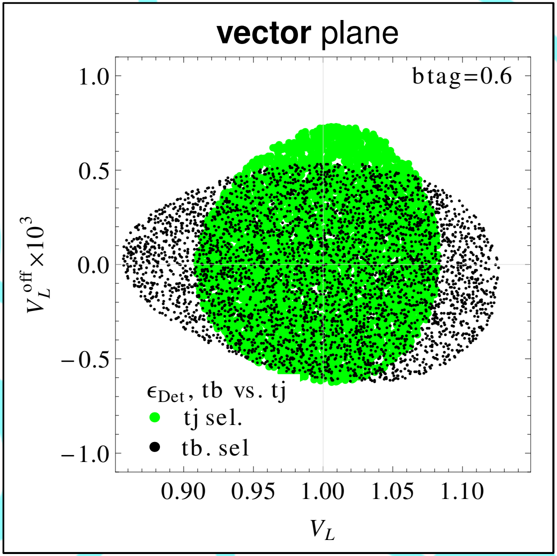


➔ **separate** analysis of ***s*** and ***t*** channel might hint at **vector** ←→ **scalar** nature

Detector level analysis

- back at **detector level** 1σ bounds:



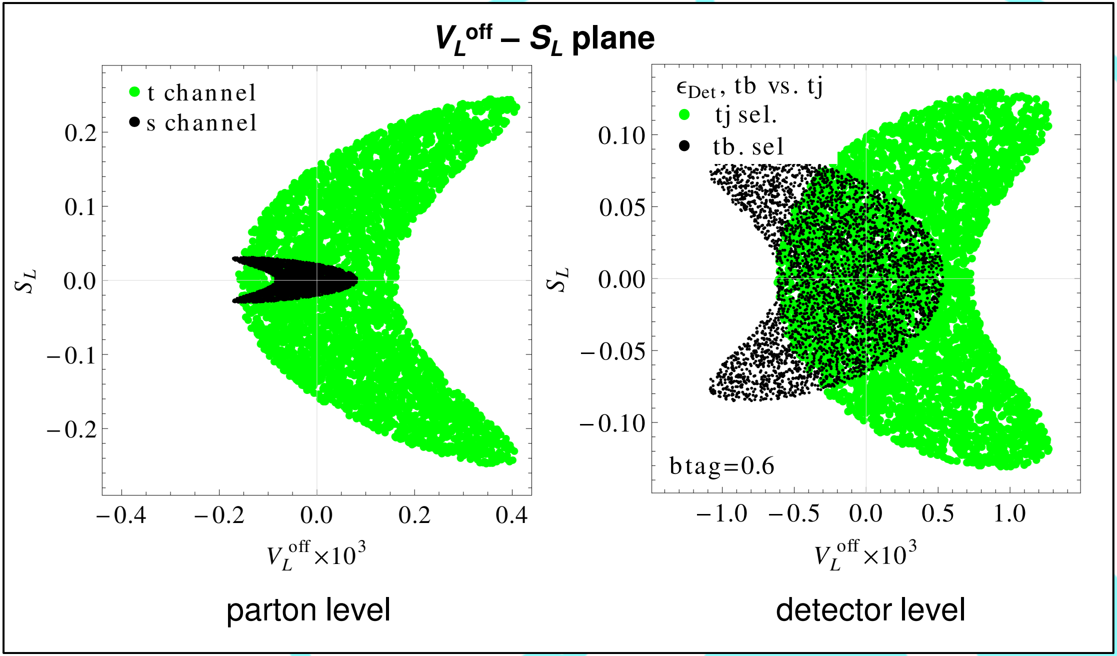


➔ ***s*** channel **diluted** at detector level

$\sigma_t \gg \sigma_s$

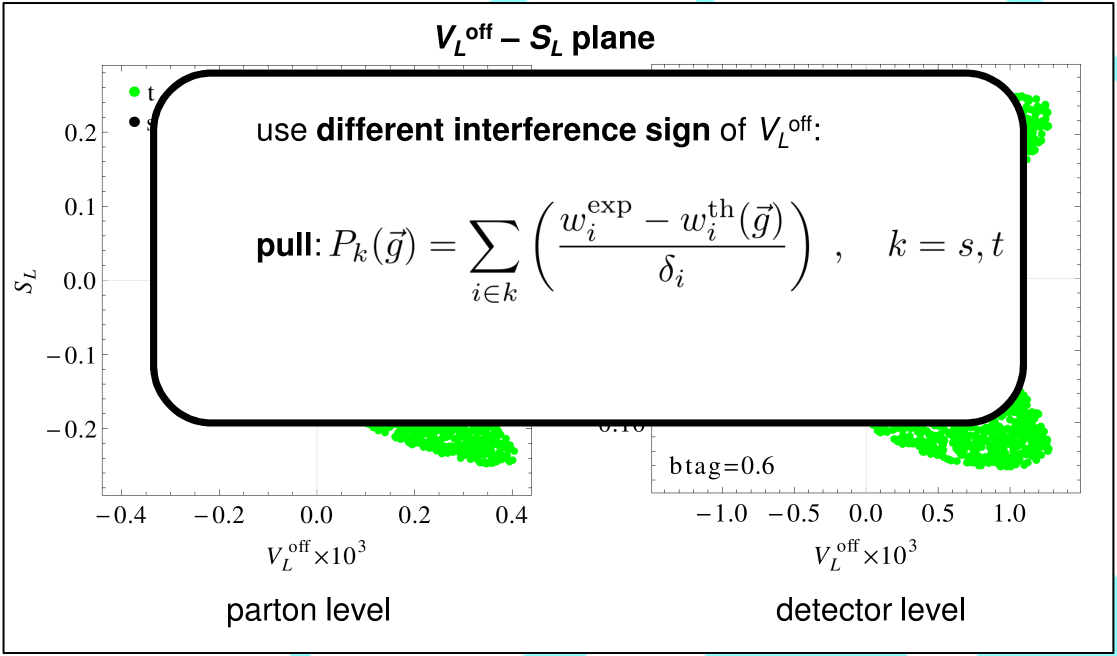
Detector level analysis

- distinguishing the couplings: **vector ⟵⟶ scalar**



Detector level analysis

- distinguishing the couplings: **vector ⇔ scalar**

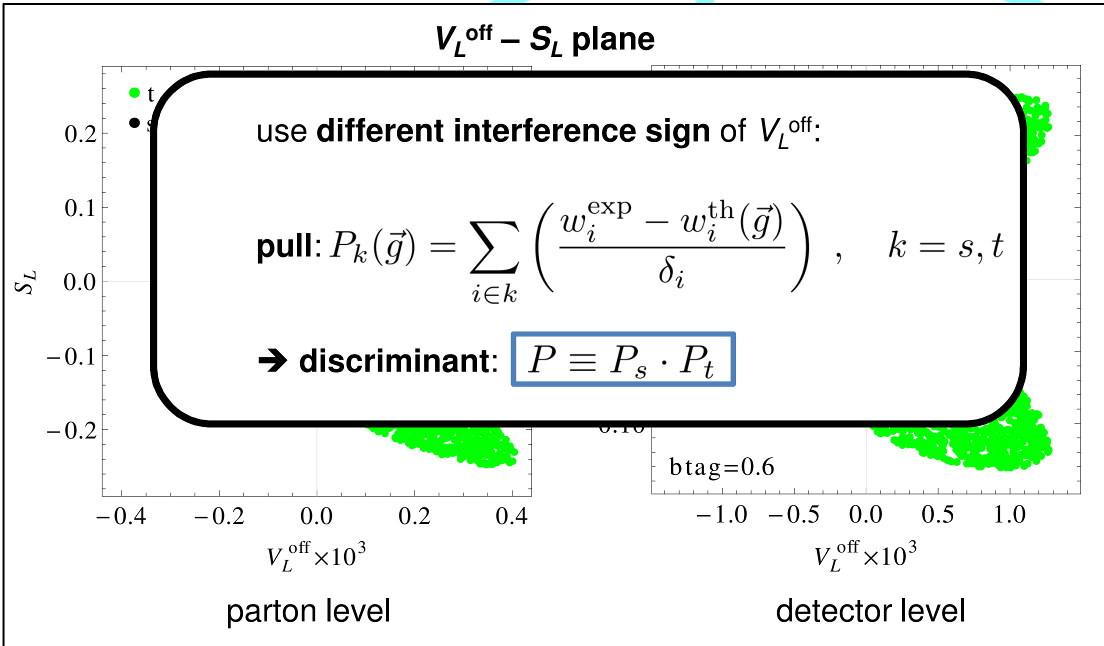


use **different interference sign** of V_L^{off}:

pull: $$P_k(\vec{g}) = \sum_{i \in k} \left(\frac{w_i^{\mathrm{exp}} - w_i^{\mathrm{th}}(\vec{g})}{\delta_i} \right) , \quad k = s, t$$

Detector level analysis

- distinguishing the couplings: **vector ⇐⇒ scalar**



use **different interference sign** of $V_L^{\rm off}$:

pull: $P_k(\vec{g}) = \sum_{i \in k} \left(\frac{w_i^{\rm exp} - w_i^{\rm th}(\vec{g})}{\delta_i} \right) \;, \qquad k = s, t$

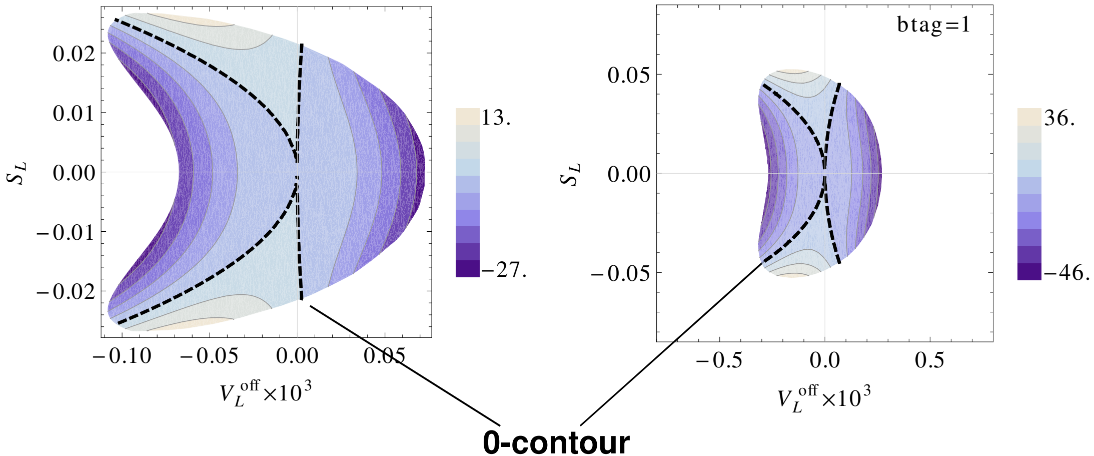
➔ **discriminant**: $\boxed{P \equiv P_s \cdot P_t}$

Detector level analysis

- distinguishing the couplings: **vector ←→ scalar**

V_L^{off} – S_L plane

s+t combined 1σ bounds **+ *P***



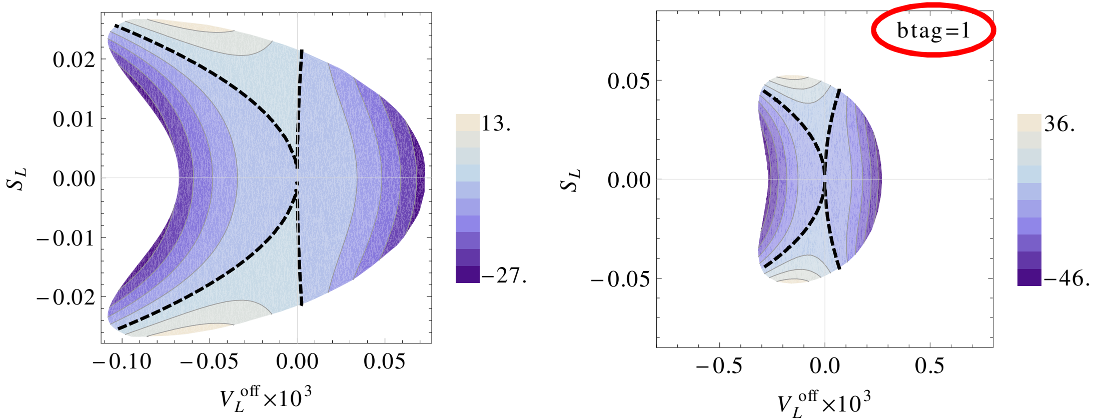
parton level $\quad P \equiv P_s \cdot P_t \quad$ detector level

Detector level analysis

- distinguishing the couplings: **vector ⬅➡ scalar**

V_L^{off} – S_L plane

s+t combined 1σ bounds **+ *P***



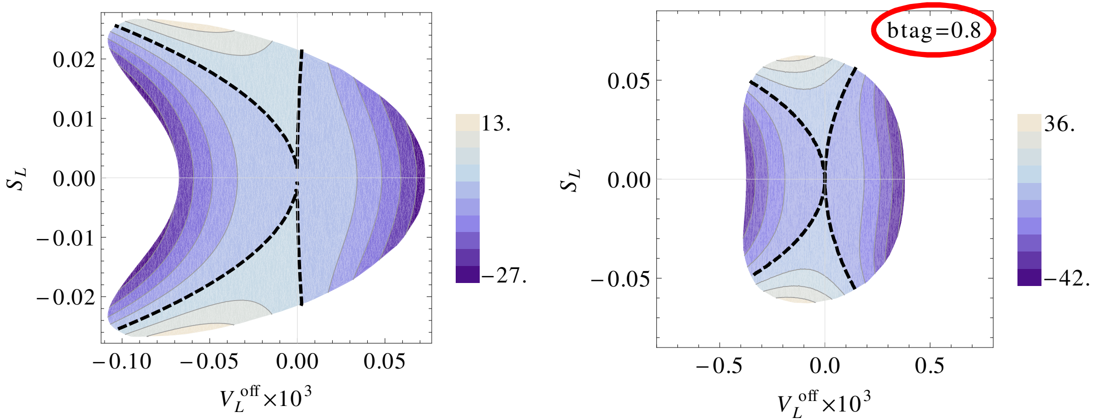
parton level $P \equiv P_s \cdot P_t$ detector level

Detector level analysis

- distinguishing the couplings: **vector ↔ scalar**

$V_L^{\rm off}$ – S_L plane

s+t combined 1σ bounds **+ *P***



parton level $\quad P \equiv P_s \cdot P_t \quad$ detector level

Detector level analysis

- distinguishing the couplings: **vector ←→ scalar**

V_L^{off} – S_L plane

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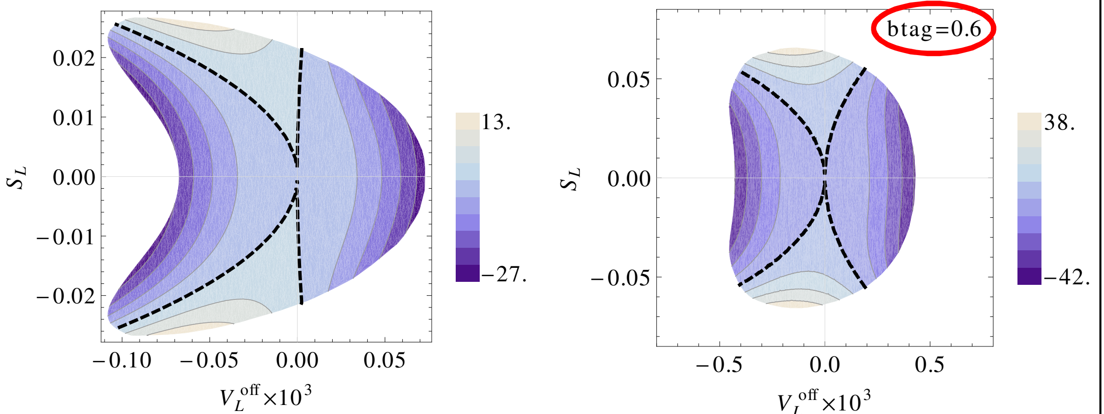


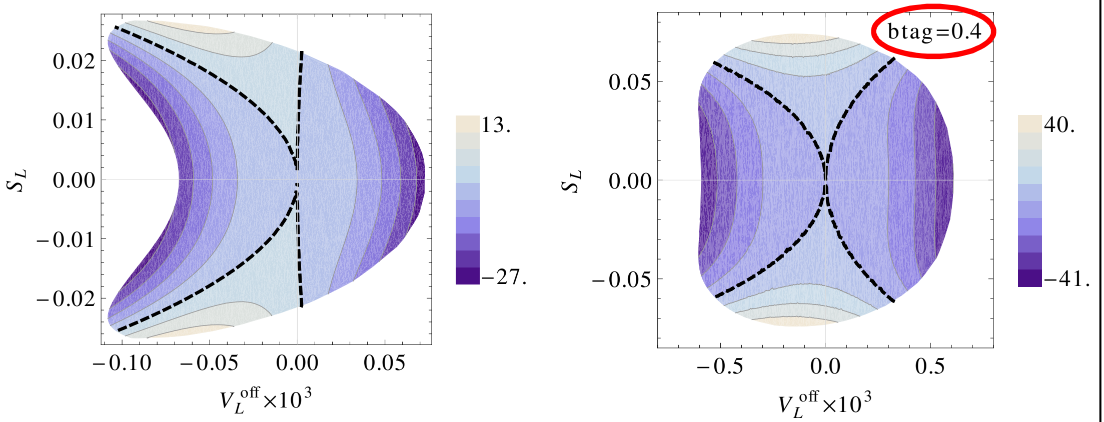
parton level $\quad P \equiv P_s \cdot P_t \quad$ detector level

Detector level analysis

- distinguishing the couplings: **vector ←→ scalar**

V_L^{off} – S_L plane

s+t combined 1σ bounds **+ *P***



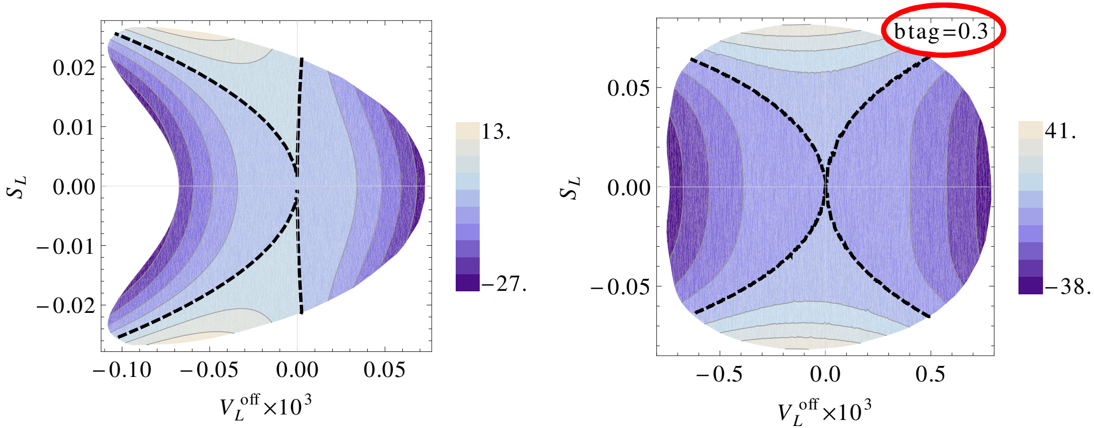
parton level $P \equiv P_s \cdot P_t$ detector level

Detector level analysis

- distinguishing the couplings: **vector ⇐⇒ scalar**

V_L^{off} – S_L plane

s+t combined 1σ bounds **+ *P***

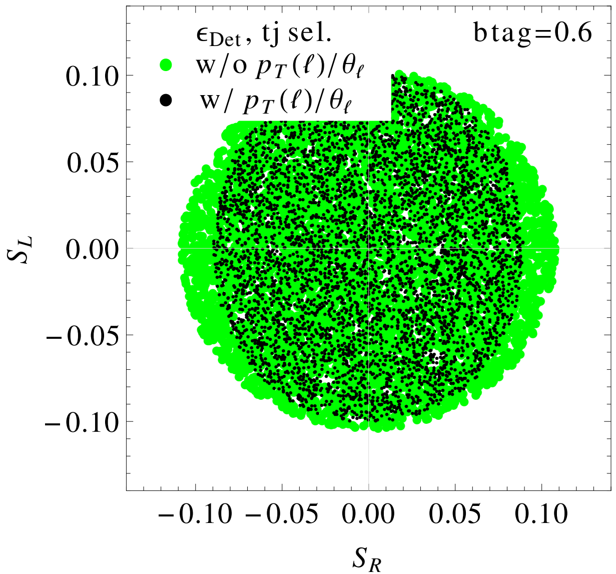


parton level $P \equiv P_s \cdot P_t$ detector level

Detector level analysis

- distinguishing the couplings: **left-handed ⟷ right-handed**

t channel @ **scalar** plane



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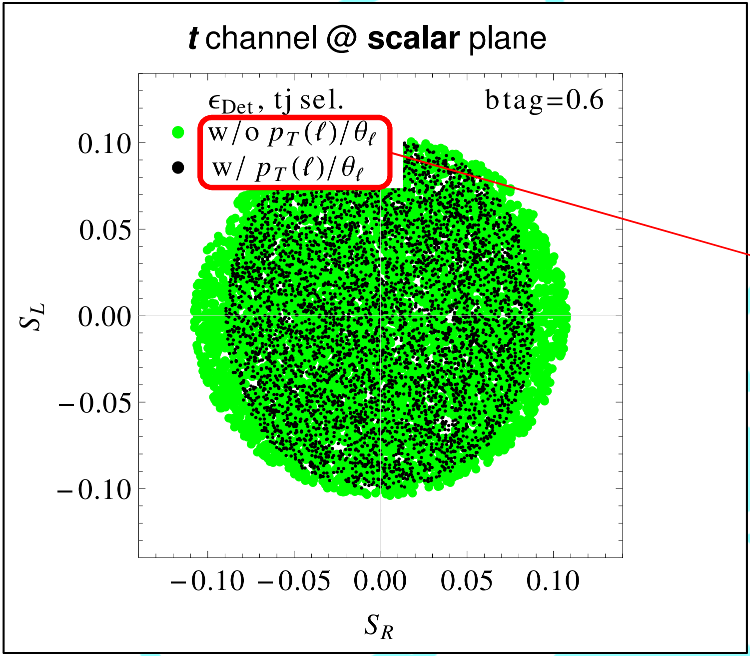

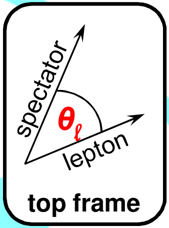

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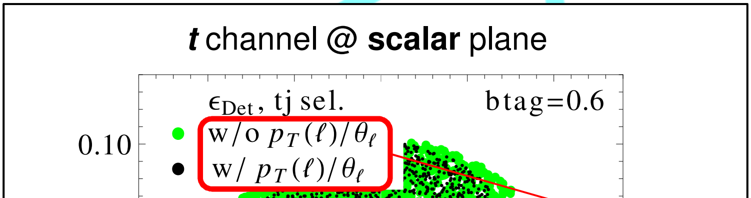

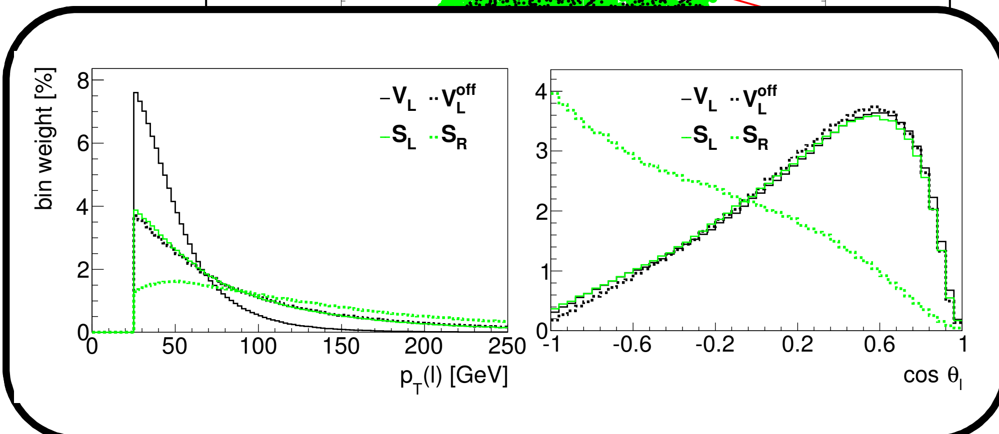

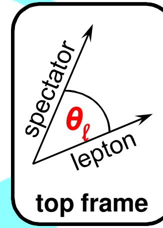

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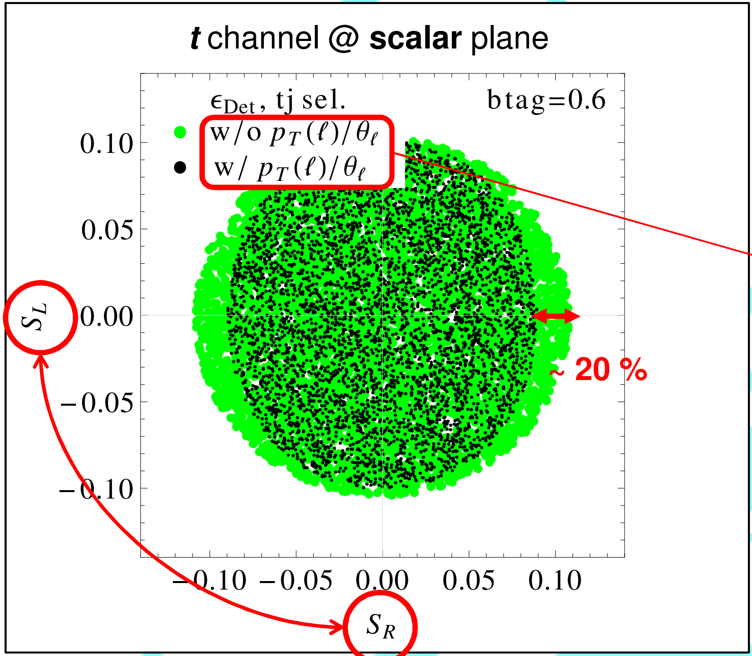

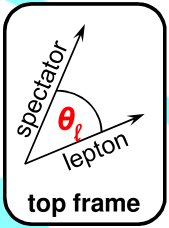

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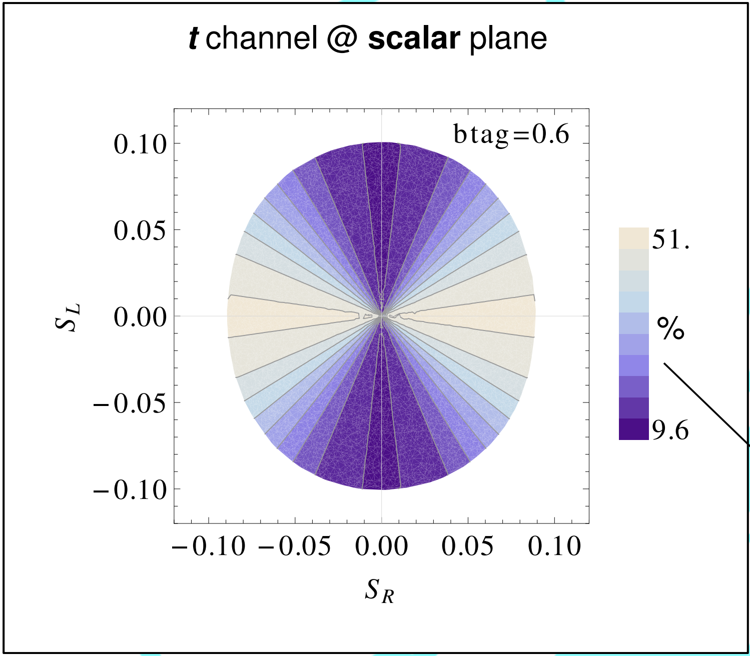

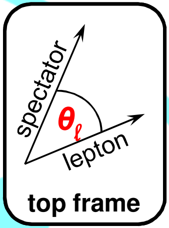

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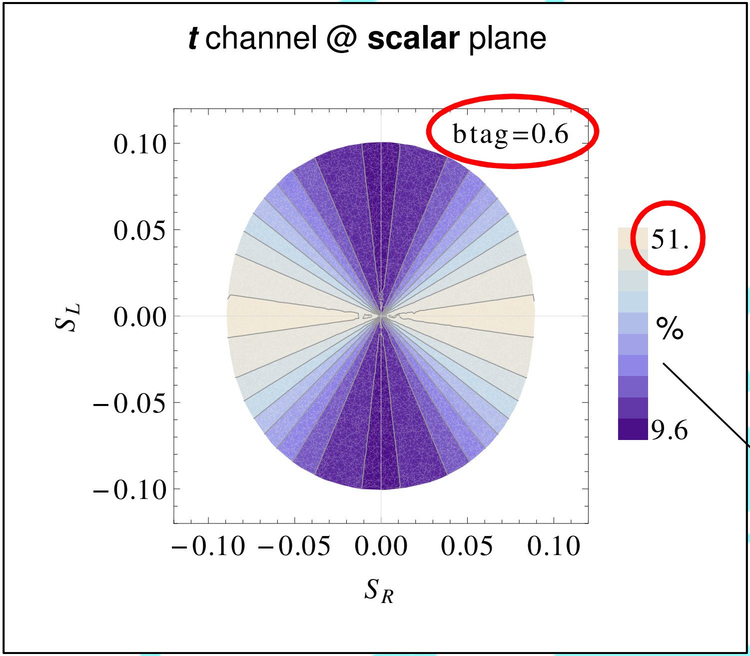

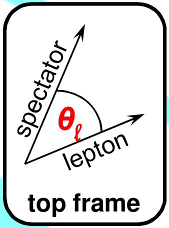

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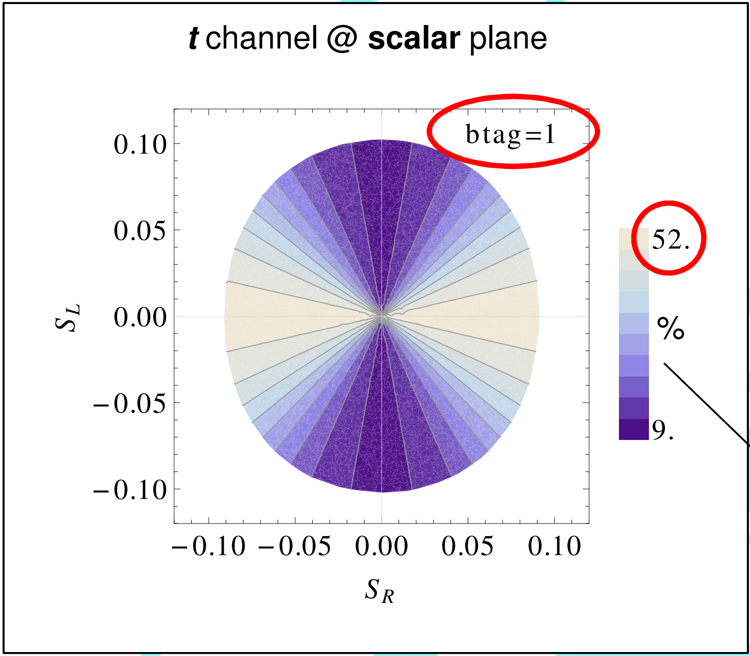

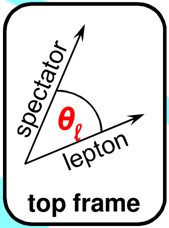

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Detector level analysis

- disambiguation of anomalous coupling structures from single top production

ΔV_L or contact cpl.?

Detector level analysis

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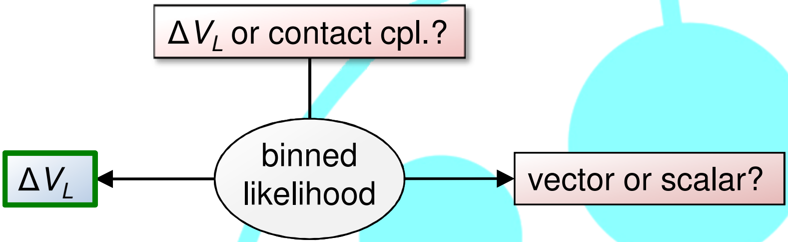

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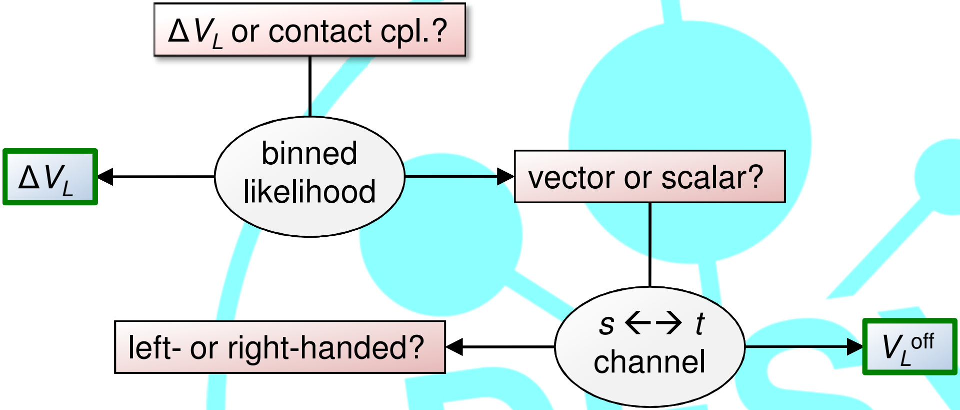

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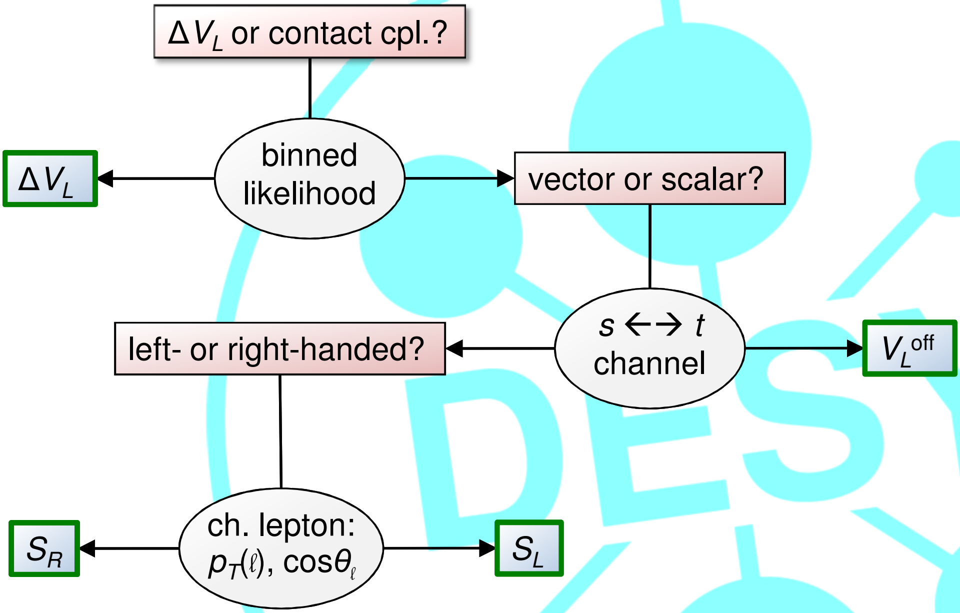

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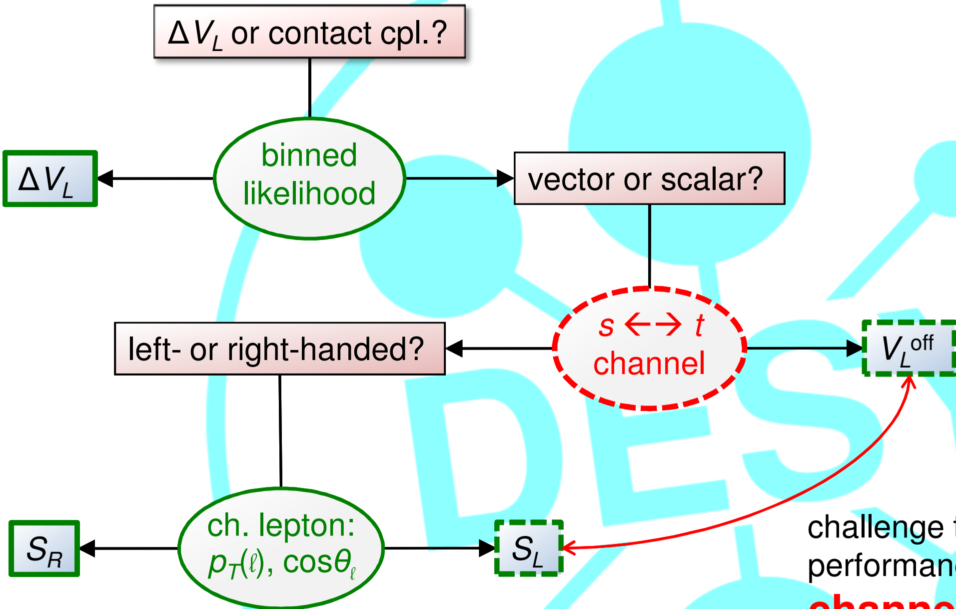

challenge to detector performance:

channel purity!

Conclusions

- abundant **top production** at the ***LHC***
  - ➔ precise measurements of top properties
  - ➔ look for non-SM couplings, minimal parametrisation from EFT
  - ➔ quartic terms required (e.g. *ttgg,* 4-fermion)

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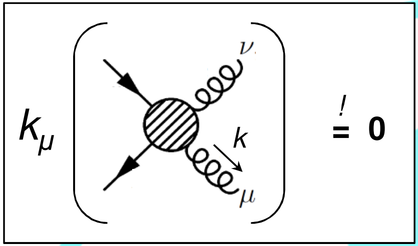
- **single top** results
  - ➔ window to charged-current contact couplings
  - ➔ experimental *s* vs. *t* channel disambiguation crucial

Backup

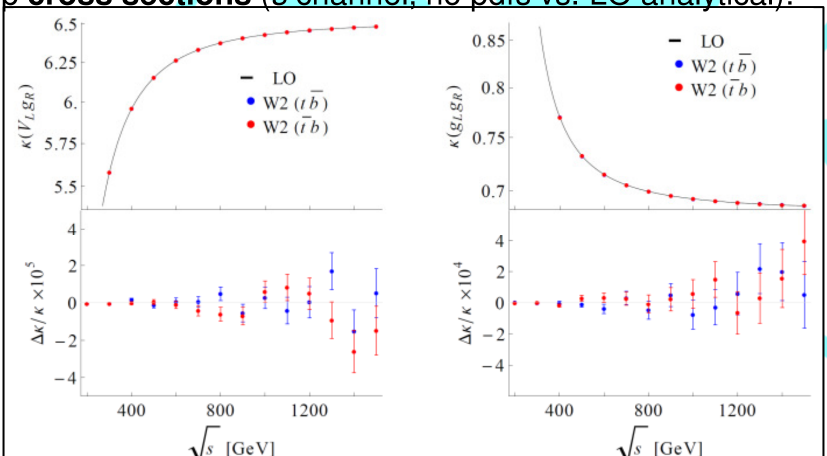
WHIZARD Validation

- **Ward identities**:



for *ttgg*, *ttWW*, *tbWA*, *tbWZ* amplitudes

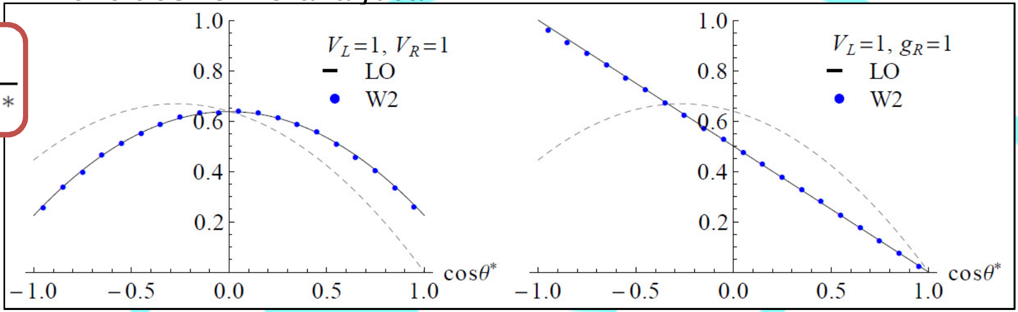
- single top **cross sections** (*s* channel, no pdfs vs. LO analytical):



WHIZARD Validation

- top decay *W* **helicities** vs. LO analytical:

$$\boxed{\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*}}$$



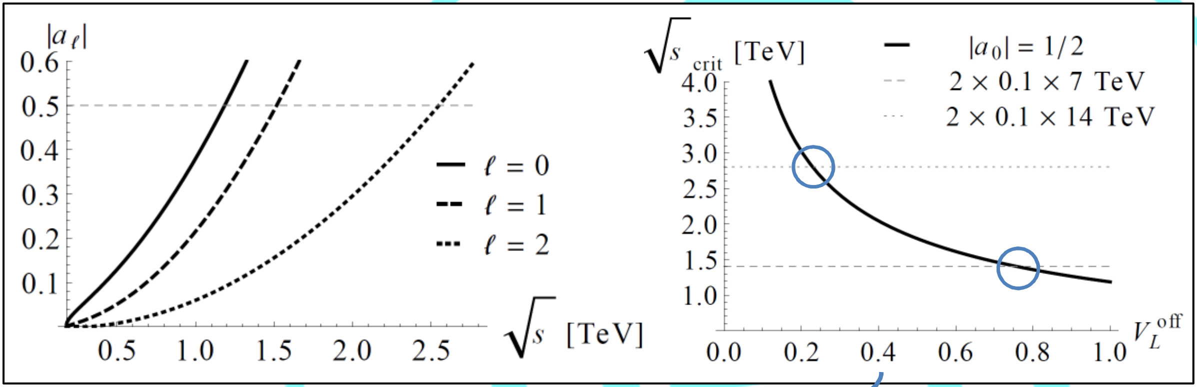
- top **spin analyzers**[Aguilar-Saavedra et al. '06] (vs. LO analytical):

$$\boxed{A_X = \frac{1}{2}\rho_z\alpha_X(\vec{g})}$$

sample V_L	V_R	g_L	g_R	A_ℓ LO	A_ℓ W2	A_b LO	A_b W2	A_ν LO	A_ν W2
1	0	0	0	0.500	0.500	-0.198	-0.199	-0.167	-0.164
1	1	0	0	0.329	0.326	0.000	0.000	-0.329	-0.327
1	0	1	0	0.502	0.500	-0.324	-0.322	-0.195	-0.194
1	0	0	1	-0.242	-0.232	0.166	0.161	0.055	0.056
0	1	1	0	-0.055	-0.057	-0.166	-0.159	0.242	0.230
0	1	0	1	0.195	0.195	0.324	0.322	-0.502	-0.501
0	0	1	1	0.353	0.355	0.000	0.000	-0.353	-0.354

Unitarity bound on the contact coupling size

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



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})

Contact interactions & differential cross sections

- different approach: fix V_R, $g_{L,R}$ from W helicities
  - ➔ single top production as a window to charged current contact interactions

$$\Delta\mathcal{L}_{\mathrm{CC}} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\big(V_L + \frac{q^2 - m_W^2}{m_W^2}V_L^{\mathrm{off}}\big)P_L\,t\,W_{\mu}^{-} + \mathrm{h.c.}$$
$$+\frac{1}{\Lambda^2}\Big[S_L^{(1)}\big(\bar{b}P_Lt\big)\big(\bar{u}_kP_Ld_k\big) + S_R^{(1)}\big(\bar{b}P_Rt\big)\big(\bar{u}_kP_Rd_k\big) + \mathrm{h.c.}$$
$$+ S_L^{(8)}\big(\bar{b}\lambda^aP_Lt\big)\big(\bar{u}_k\lambda^aP_Ld_k\big) + S_R^{(8)}\big(\bar{b}\lambda^aP_Rt\big)\big(\bar{u}_k\lambda^aP_Rd_k\big) + \mathrm{h.c.}\Big]$$

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\begin{aligned}
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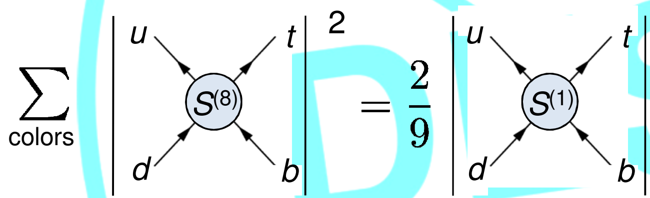
\end{aligned}
$$

➔ color structure of (pseudo-)scalar contact couplings:



kinematically degenerate!

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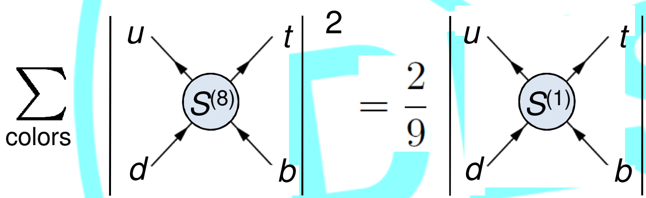

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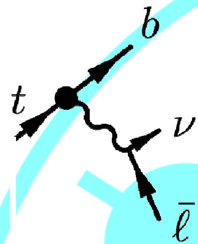
- basis for contact interactions: $\{V_L, V_L^{\mathrm{off}}, S_L, S_R\}$

Interlude: assessing the top spin

- use top decay products ℓ, ν, b „spin analyzers" [Aguilar-Saavedra et al. '06]



$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_X} = \frac{1}{2}(1 + \rho_z \alpha_X \cos\theta_X)$$

with $X = \ell, \nu, b$

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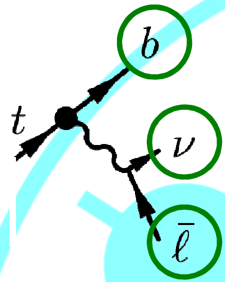

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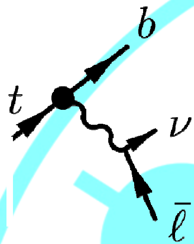

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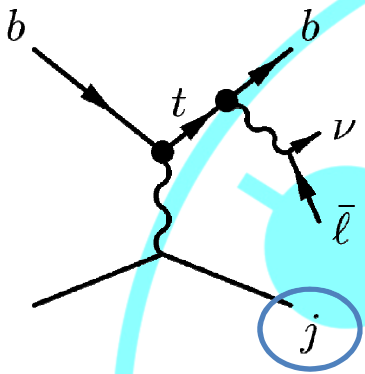

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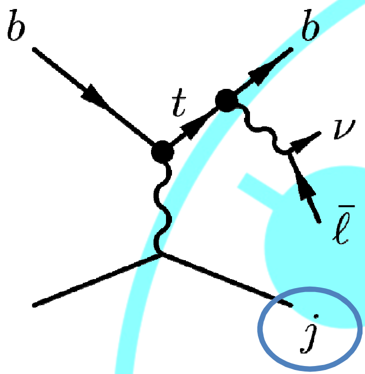

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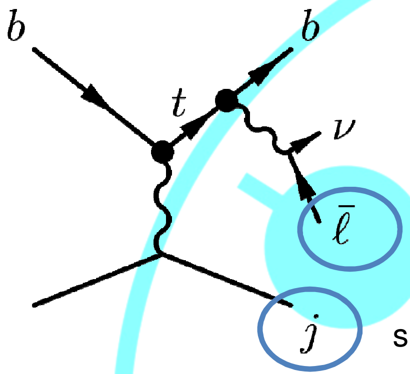

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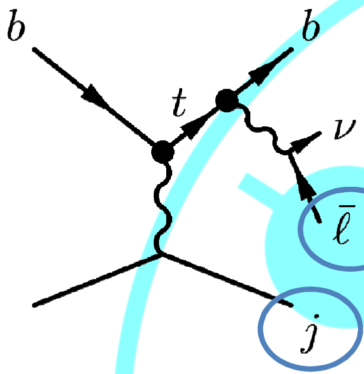

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➔ anomalous **top polarization** from **cosθ_ℓ**