Heavy new physics in top production and decay

C. Degrande
IPPP, University of Durham

DIS2014

Plan

- Introduction to EFT
- Top decay
- Top pair production
- Same sign top pair production
- Concluding remarks

EFT:Indirect access to heavy NP

E

Exp. range

NP scale

C. Degrande

EFT:Indirect access to heavy NP

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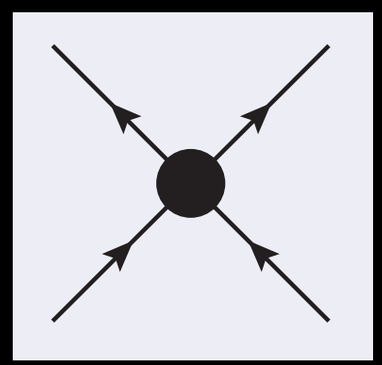
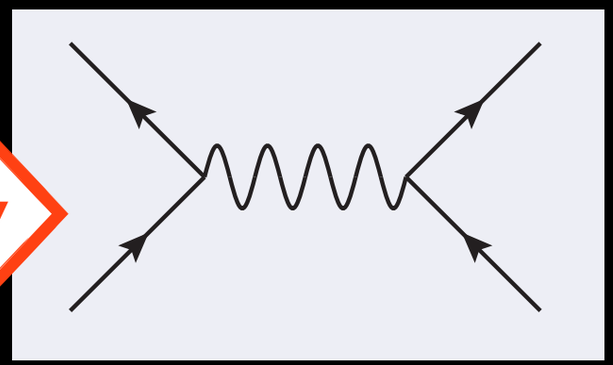
Effective Field Theory

EFT

Resonance



Complementary



$$\frac{-g^2}{\Lambda^2} + \mathcal{O}\left(\frac{p^2}{\Lambda^4}\right)$$

$$\frac{g^2}{p^2 - \Lambda^2}$$

Λ

"Global" shape effects

Peak in the invariant mass

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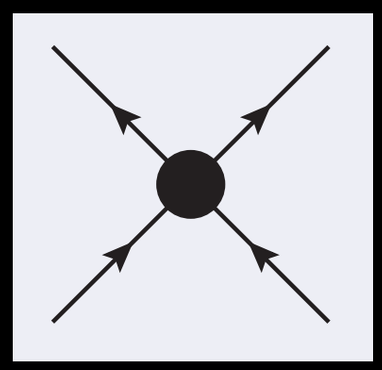
Effective Field Theory

EFT

Resonance



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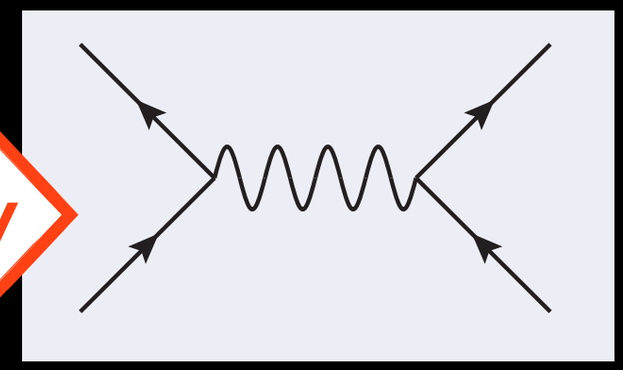

dim6

dim8...

$$\frac{-g^2}{\Lambda^2} + \mathcal{O}\left(\frac{p^2}{\Lambda^4}\right)$$

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EFT

Parametrize any NP but an ∞ number of coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

SM fields with SM symmetries

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EFT

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

SM fields with SM symmetries

- Assumption : $E_{exp} << \Lambda$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i} \frac{C_i}{\Lambda^2} \mathcal{O}_i^6$$

a finite number of coefficients =>Predictive!

- Model independent (i.e. parametrize a large class of models) : any HEAVY NP

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EFT contribution

- Interference only :

$$|M|^2 = |M_{SM}|^2 + 2\Re\left(M_{SM} M^*_{dim6}\right) + \mathcal{O}\left(\Lambda^{-4}\right)$$

$$|M_{dim6}|^2 + 2\Re\left(M_{SM} M^*_{dim8}\right)$$

- with the dominant (QCD) process

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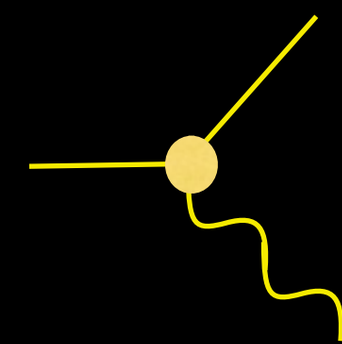
(SM-like) Top decay

$t \to bW$

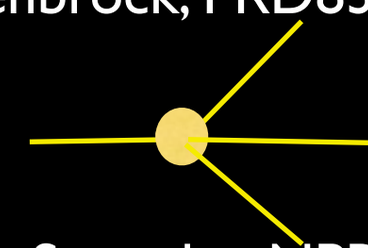
$$\mathcal{O}_{\phi q}^{(3)} = i\left(\phi^\dagger \tau^i D_\mu \phi\right)\left(\bar{Q}\gamma^\mu \tau^i Q\right) + h.c.$$
$$\mathcal{O}_{tW} = \bar{Q}\sigma_{\mu\nu}\tau^i t \tilde{\phi} W_i^{\mu\nu}.$$



C. Zhang, S Willenbrock, PRD83, 034008

$t \to bl\nu_l$

$$\mathcal{O}_{ql}^{(3)} = \left(\bar{Q}\gamma^\mu \tau^i Q\right)\left(\bar{l}\gamma_\mu \tau^i l\right)$$



J.A. Aguilar-Saavedra, NPB843, 683

+ one four-fermion operator for the hadronic decay

$$\frac{1}{2}\Sigma|M|^2 = \frac{V_{tb}^2 g^4 u(m_t^2 - u)}{2(s - m_W^2)^2}\left(1 + 2\frac{C_{\phi q}^{(3)} v^2}{V_{tb}\Lambda^2}\right) + \frac{4\sqrt{2}\mathrm{Re}C_{tW} V_{tb} m_t m_W}{\Lambda^2}\frac{g^2 su}{(s - m_W^2)^2}$$
$$+ \frac{4C_{ql}^{(3)}}{\Lambda^2}\frac{g^2 u(m_t^2 - u)}{s - m_W^2} + \mathcal{O}\left(\Lambda^{-4}\right)$$

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Width and W helicities

$$\frac{\Gamma\left(t \to be^+\nu_e\right)}{GeV} = 0.1541 + \left[0.019\frac{C^{(3)}_{\phi q}}{\Lambda^2} + 0.026\frac{C_{tW}}{\Lambda^2} + 0\frac{C^{(3)}_{ql}}{\Lambda^2}\right]\text{TeV}^2$$

$$\left.\begin{aligned} \frac{\Gamma_t}{GeV} &= \Gamma_{SM} + \left[0.17\frac{C^{(3)}_{\phi q}}{\Lambda^2} + 0.23\frac{C_{tW}}{\Lambda^2}\right]\text{TeV}^2 \\ \Gamma^*_{cms} &= 1.36^{+0.14}_{-0.11}\ \text{GeV} \\ \Gamma^{**}_{SM} &= 1.33\,\text{GeV} \end{aligned}\right\} \frac{C^{(3)}_{\phi q}}{\Lambda^2} + 1.35\frac{C_{tW}}{\Lambda^2} = 0.18^{+0.83}_{-0.66}\text{TeV}^{-2}$$

* arXiv:1404.2292
** M.Jezabek and J.H. Kuhn, NPB314,1

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{8}(1+\cos\theta)^2 F_R + \frac{3}{8}(1-\cos\theta)^2 F_L + \frac{3}{4}\sin^2\theta F_0$$

$$\begin{aligned} F_0 &= \frac{m_t^2}{m_t^2+2m_W^2} - \frac{4\sqrt{2}\text{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2} \\ F_L &= \frac{2m_W^2}{m_t^2+2m_W^2} + \frac{4\sqrt{2}\text{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2} \\ F_R &= 0 \end{aligned}$$

$$\left.\begin{aligned} F_0^{SM^*} &= 0.687 \pm 5 \\ F_0^{cms**} &= 0.685 \pm 0.027 \end{aligned}\right\} \frac{C_{tW}}{\Lambda^2} = 0.088^{+0.44}_{-0.45}\text{TeV}^{-2}$$

* A.Czarnecki, J. G. Korner, J. H. Piclum PRD81, 111503
**JHEP 10 (2013) 167

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Leptons invariant mass

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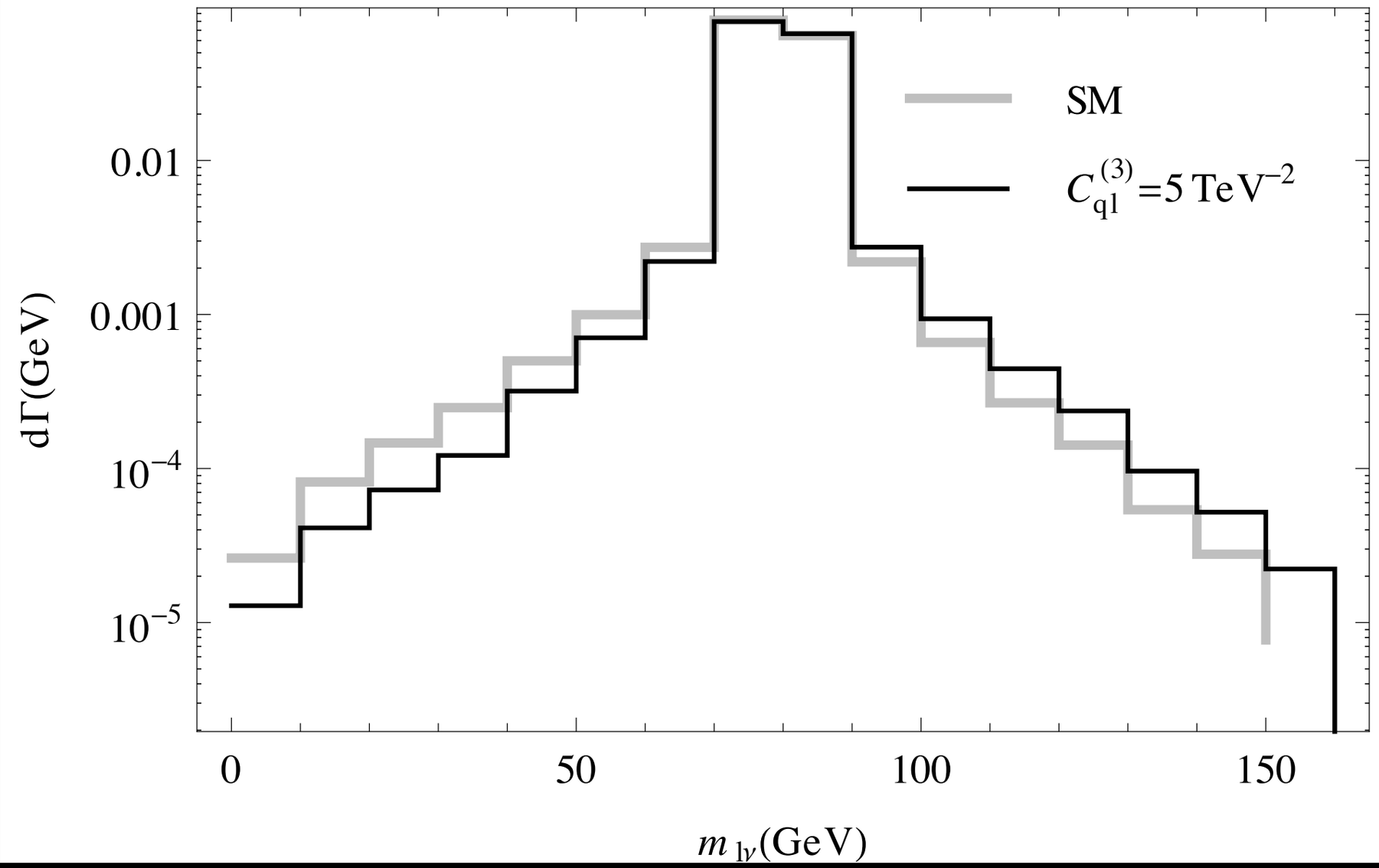

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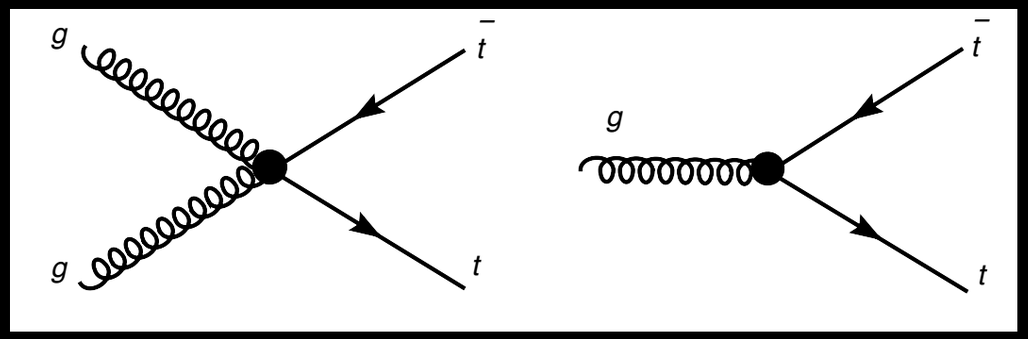
Top pair production

$$\mathcal{O}_{hG} = \bar{Q}\sigma_{\mu\nu}T^a t\tilde{\phi}G_a^{\mu\nu}$$



$$\mathcal{O}_{Rv} = \bar{t}\gamma_\mu T^a t \sum_{u,d,s,c} \bar{q}\gamma^\mu T^a q$$

$$\mathcal{O}_{Ra} = \bar{t}\gamma_\mu T^a t \sum_{u,d,s,c} \bar{q}\gamma^\mu\gamma_5 T^a q$$

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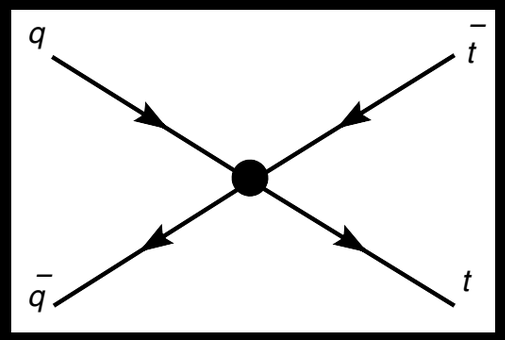

C.D., J.-M. Gerard, C. Grojean, F. Maltoni, G. Servant, JHEP 1103 (2011) 125

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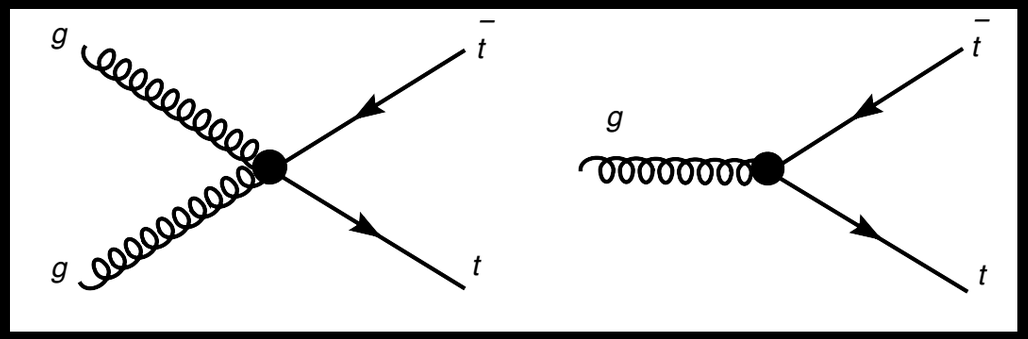

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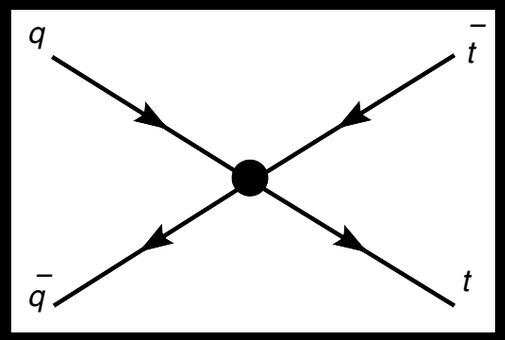

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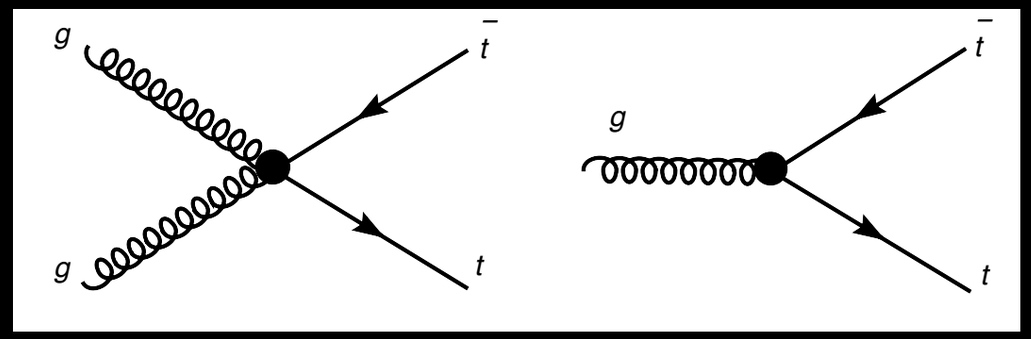

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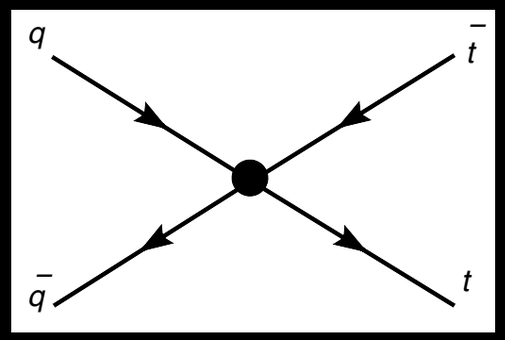

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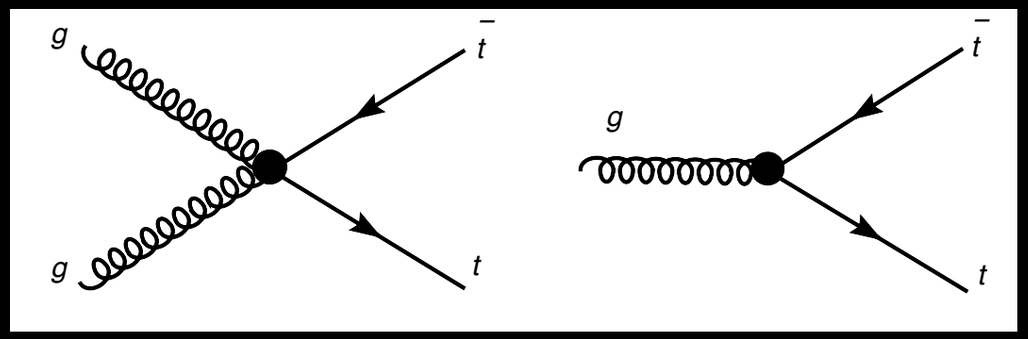

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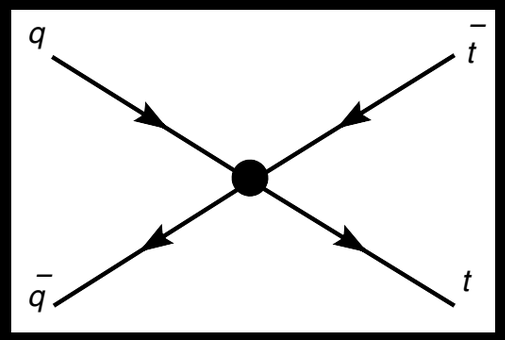

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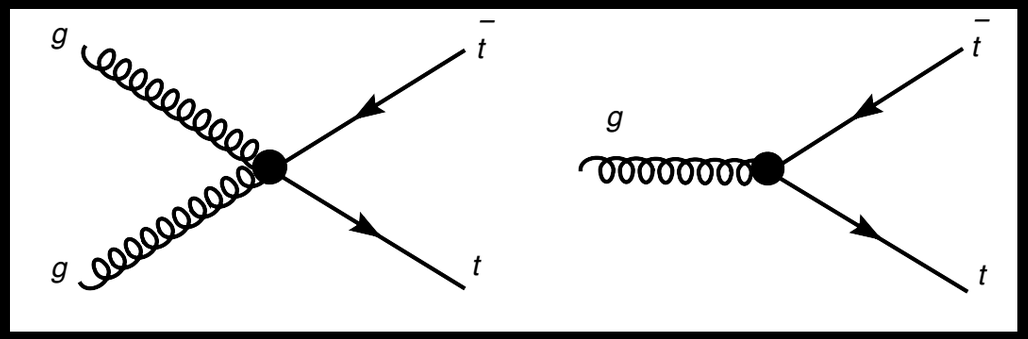

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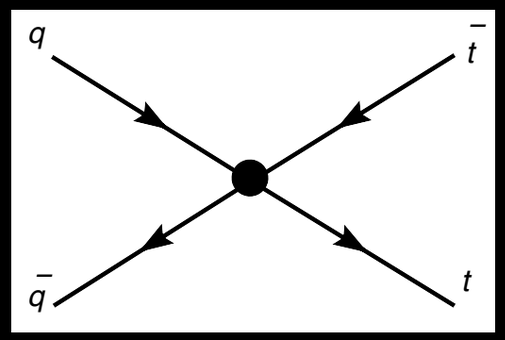
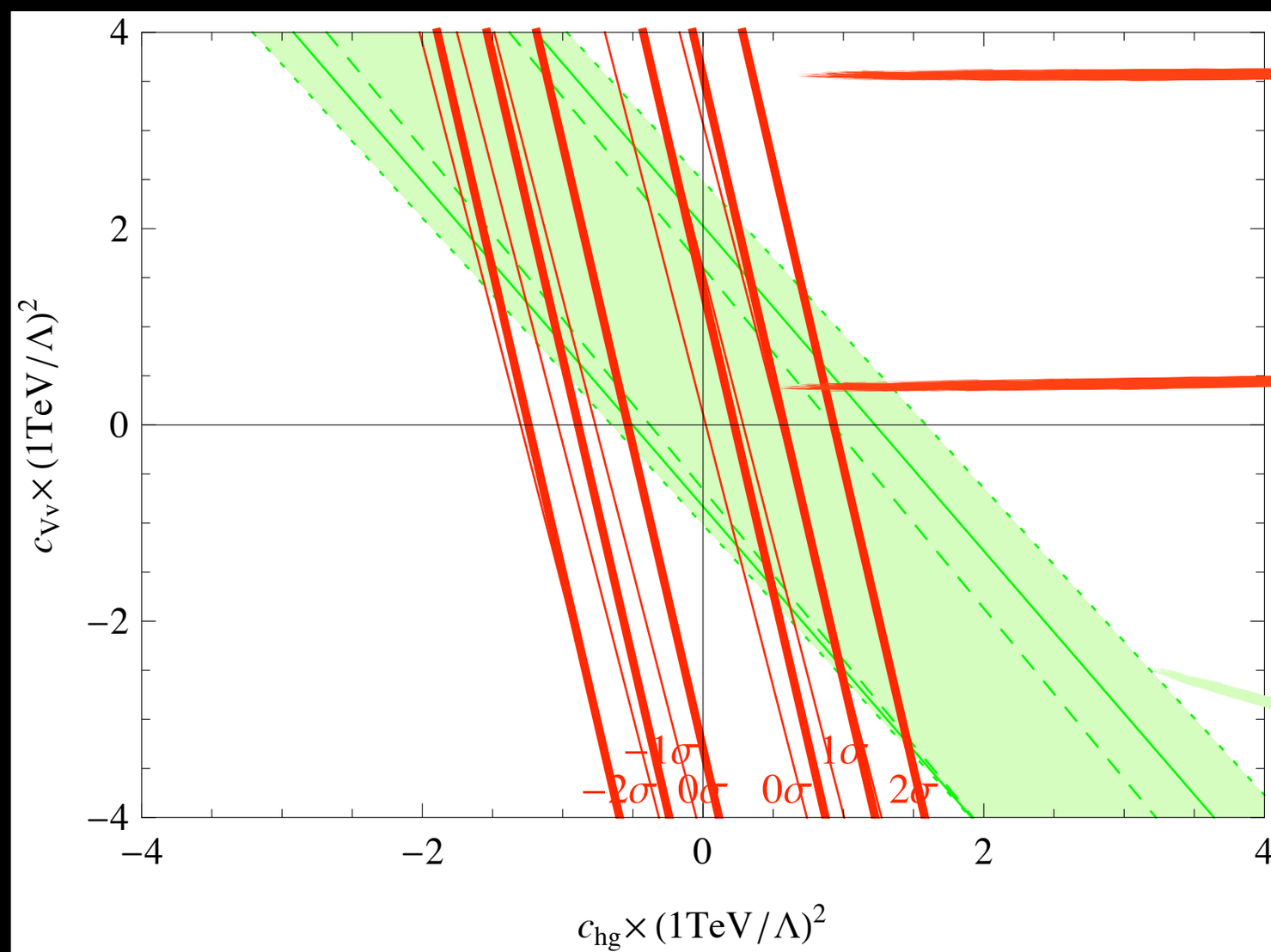


C.D., J.-M. Gerard, C. Grojean, F. Maltoni, G. Servant, JHEP 1103 (2011) 125

Total cross-section

NNLO+NNLL, Czakon, Fiedler & Mitov, PRL110 25, 252004

$c_{Vv} = c_{Rv} + c_{Lv}$



LHC, 8TeV
JHEP02(2014)0.24
239±2±11±6pb^{-1}

CMS, 7TeV
arXiv : 1208.2671 ,
161.9±2.5±5.1±3.6pb^{-1}

Tevatron 09/2012
Combination
7.65±0.20±0.36pb^{-1}

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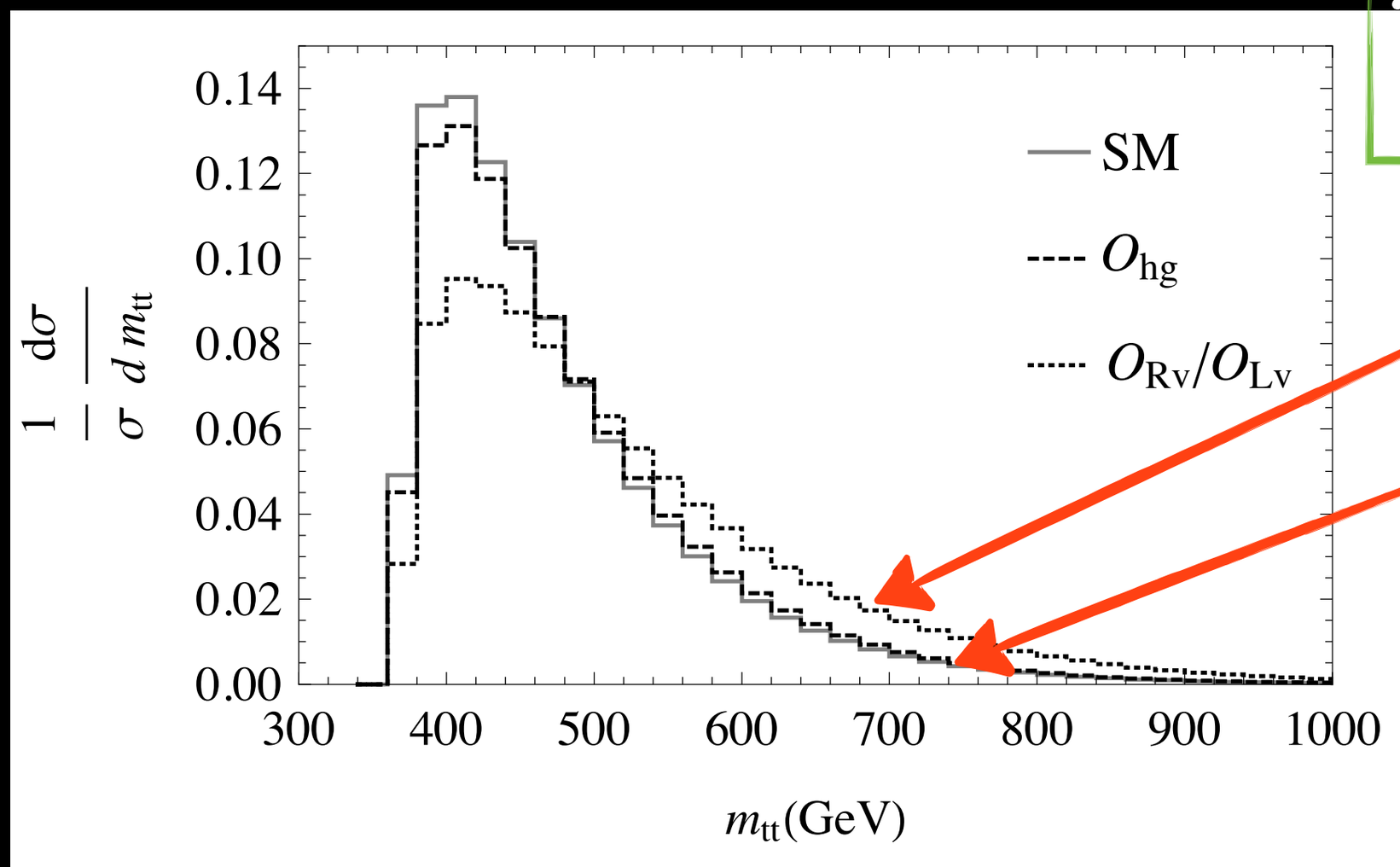
Invariant mass

! Unitarity for $s \gtrsim \Lambda^2$
but ~~assumption~~



$$\propto SM \times \frac{s}{\Lambda^2}$$

$$\propto SM \times \frac{m_t v}{\Lambda^2}$$

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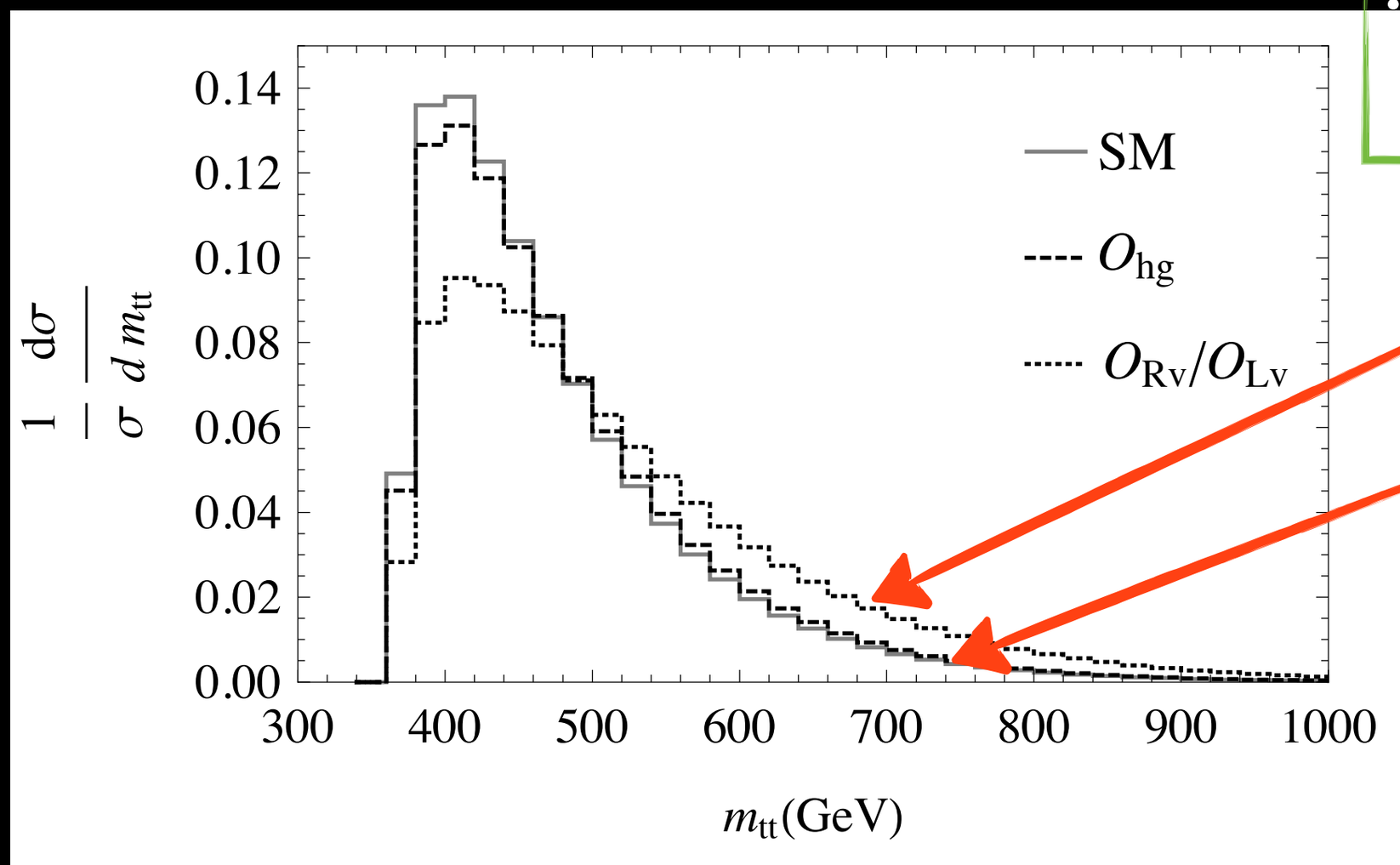

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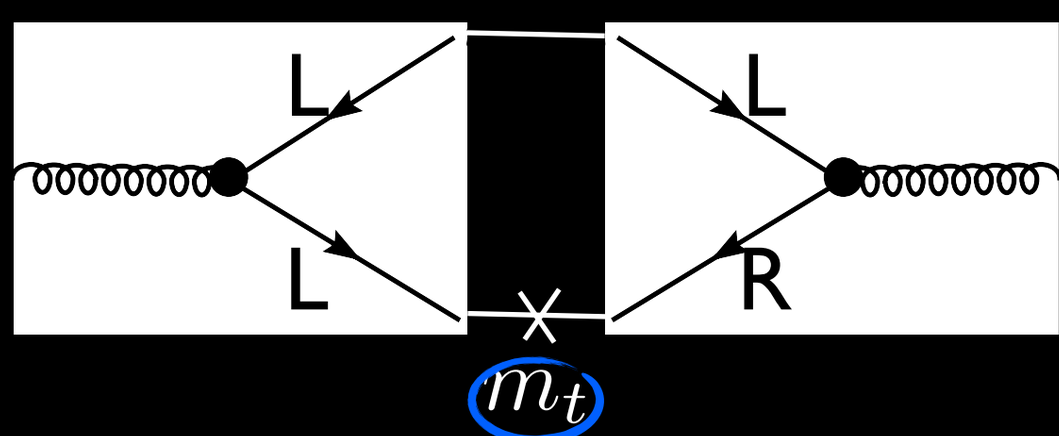

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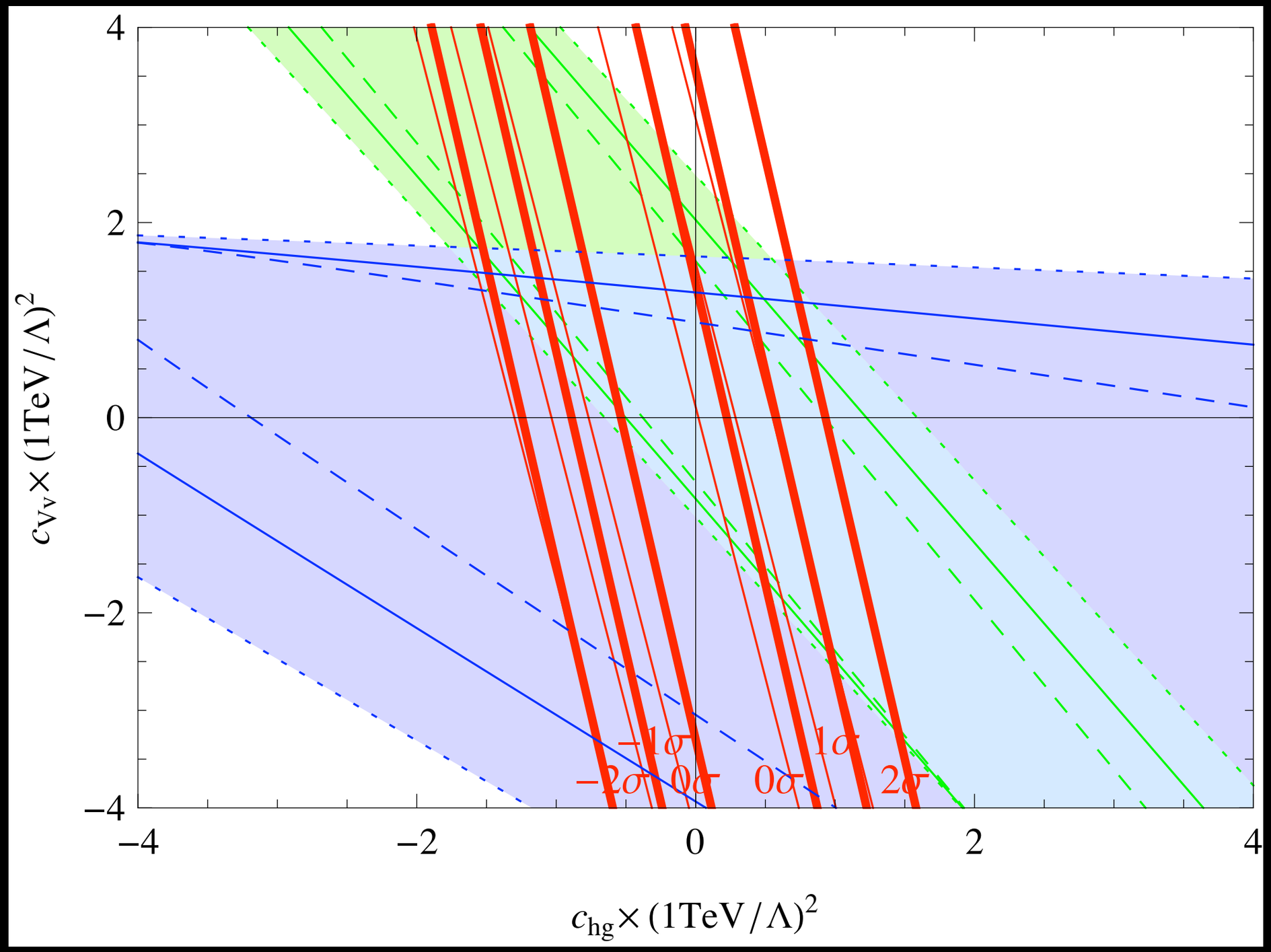
Constraints



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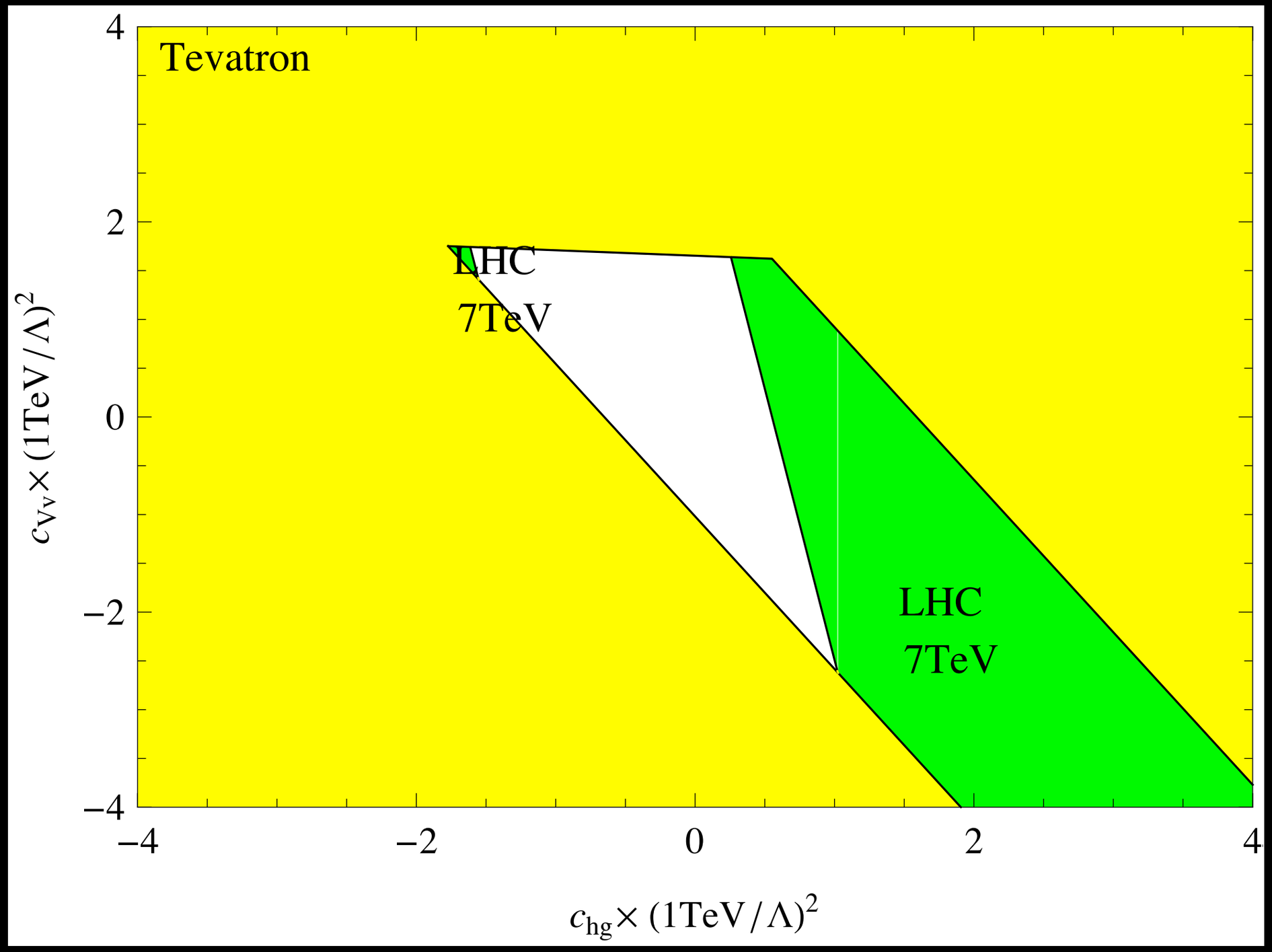

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FB asymmetry

$$A_{FB}^{obs} = 0.162 \pm 0.047$$ (CDF:1211.1003) $$c_{Aa} = c_{Ra} - c_{La}$$

$$A_{FB}^{SM} = 0.066 \pm 0.007$$

$$\delta A_{FB} = 0.047^{+0.016}_{-0.011} c_{Aa} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \Rightarrow c_{Aa} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 = 2.04^{+2.12}_{-1.38} \mathrm{TeV}^{-2}$$

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Only parameter!

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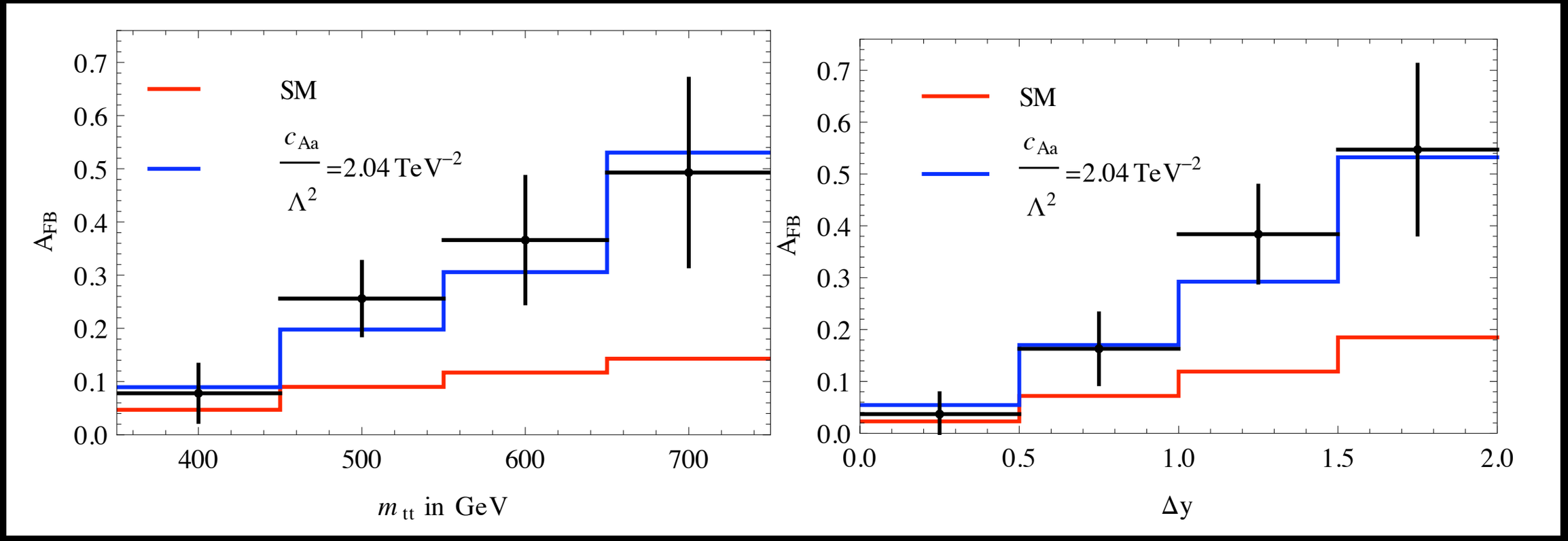
$$A_{FB}^{SM} = 0.066 \pm 0.007$$

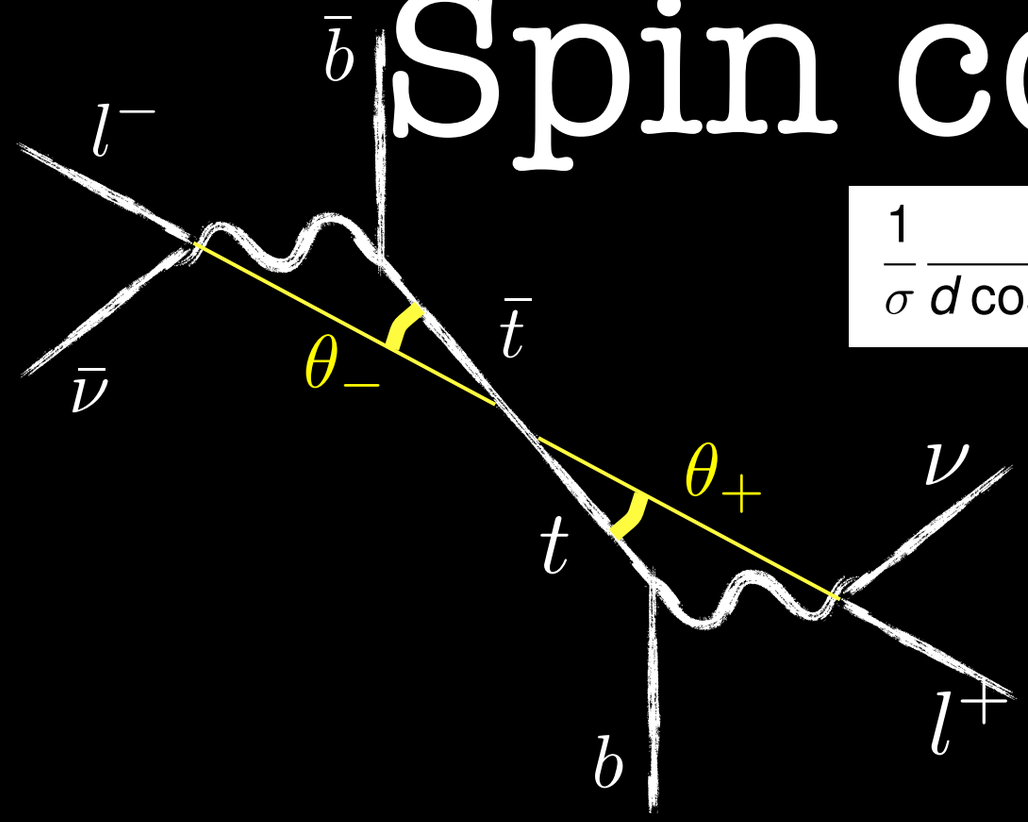
$$\delta A_{FB} = 0.047^{+0.016}_{-0.011} c_{Aa} \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 \Rightarrow c_{Aa} \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 = 2.04^{+2.12}_{-1.38} \text{TeV}^{-2}$$



LHC A_C (Atlas,1311.6724): $$c_{Aa} \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 = -0.72^{+1.77}_{-0.82} \text{TeV}^{-2}$$

C. Degrande

Spin correlations

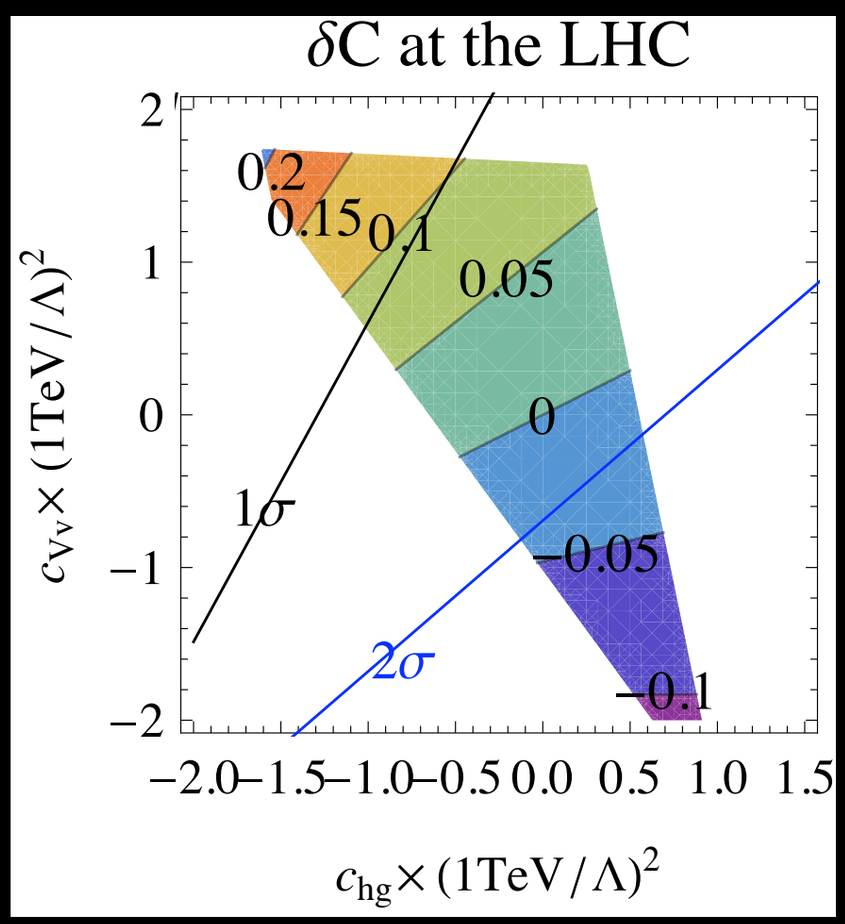


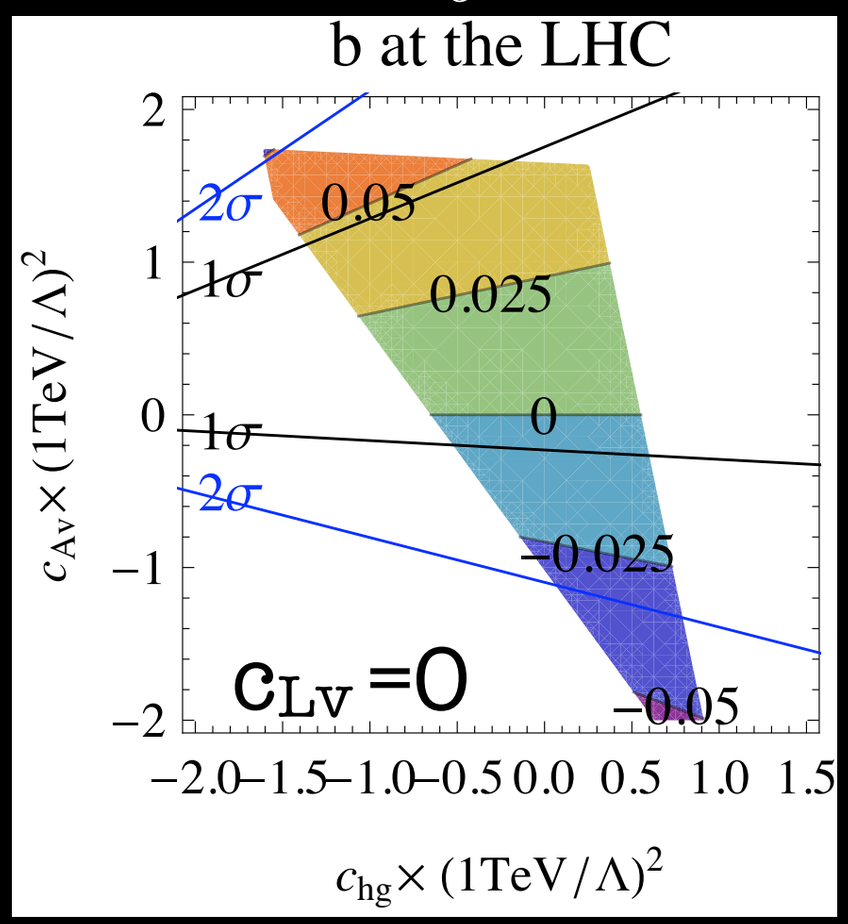
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + C\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\right)$$

$$C = \frac{1}{\sigma}\left(\sigma_{LR} + \sigma_{RL} - \sigma_{RR} - \sigma_{LL}\right)$$

$$b_+ = \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} + \sigma_{RR} - \sigma_{LL}\right)$$

$$b_- = \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} - \sigma_{RR} + \sigma_{LL}\right)$$





$c_{Av} = c_{Rv} - c_{Lv}$

Atlas 1307.6511
C=-0.08±0.13

CMS 1311.3924
b=0.02±0.027

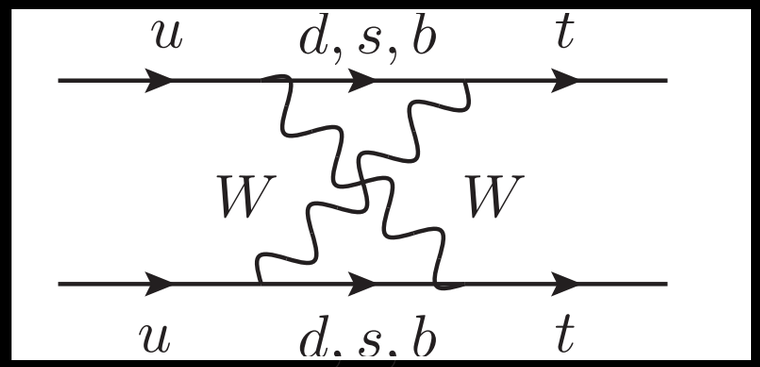
C. Degrande

Plan

- Introduction to EFT
- Top decay
- Top pair production
- Same sign top pair production
- Concluding remarks

Same sign top pair production

- Almost no SM contribution



$$\propto m_b^2 {V_{ub}}^2$$

$$|M|^2 \approx 0^2 + 2\Re\left(0 M^*_{dim6}\right) + |M_{dim6}|^2 + \mathcal{O}\left(\Lambda^{-6}\right)$$

$$\begin{aligned}
\mathcal{O}_{RR} &= [\bar{t}_R \gamma^\mu u_R]\,[\bar{t}_R \gamma_\mu u_R] \\
\mathcal{O}^{(1)}_{LL} &= [\bar{Q}_L \gamma^\mu q_L]\,[\bar{Q}_L \gamma_\mu q_L] \\
\mathcal{O}^{(3)}_{LL} &= [\bar{Q}_L \gamma^\mu \sigma^a q_L]\,[\bar{Q}_L \gamma_\mu \sigma^a q_L] \\
\mathcal{O}^{(1)}_{LR} &= [\bar{Q}_L \gamma^\mu q_L]\,[\bar{t}_R \gamma_\mu\, u_R] \\
\mathcal{O}^{(8)}_{LR} &= [\bar{Q}_L \gamma^\mu T^A q_L]\,[\bar{t}_R \gamma_\mu\, T^A u_R]
\end{aligned}$$

$$\Delta F = 2 \neq \Delta F = 0$$

$$\left|c^{(1)}_{LL} + c^{(3)}_{LL}\right| \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 < 2.1\,10^{-4}$$

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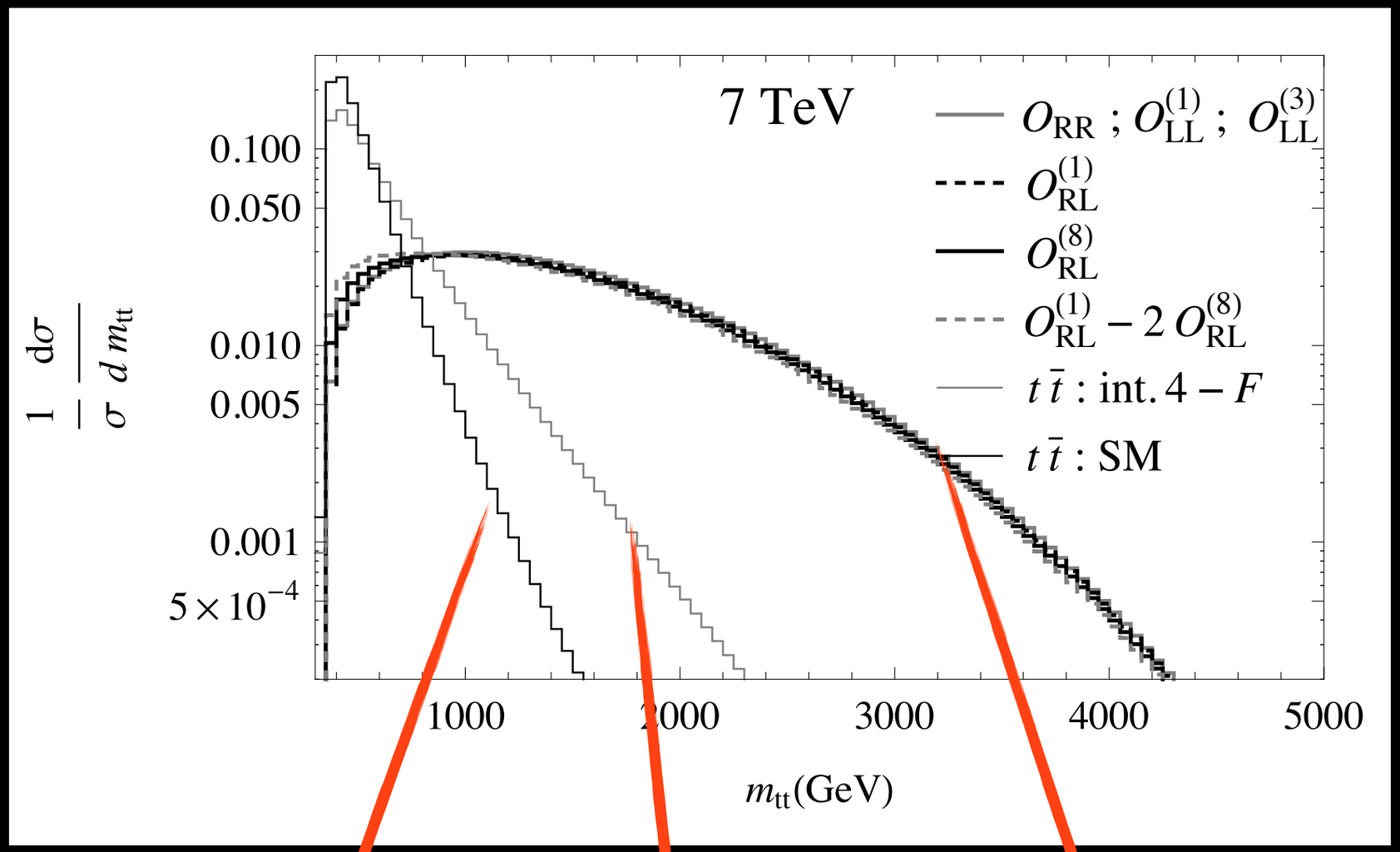
Invariant mass



EFT is only valid at low energies but a large contribution comes from the high energy region

$\sigma \propto 1/s$ $\sigma \propto 1/\Lambda^2$ $\sigma \propto s/\Lambda^4$

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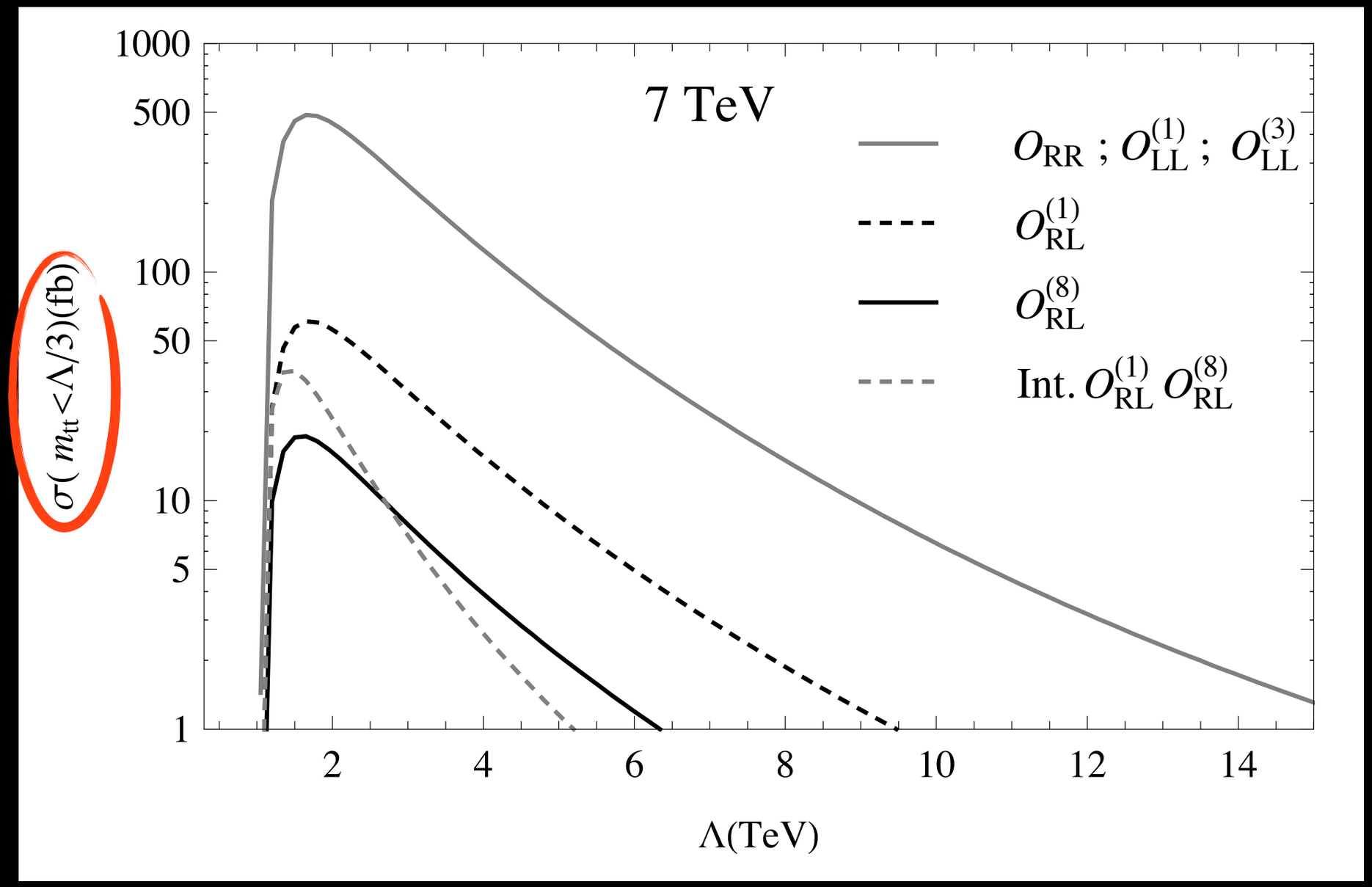
Cross-section



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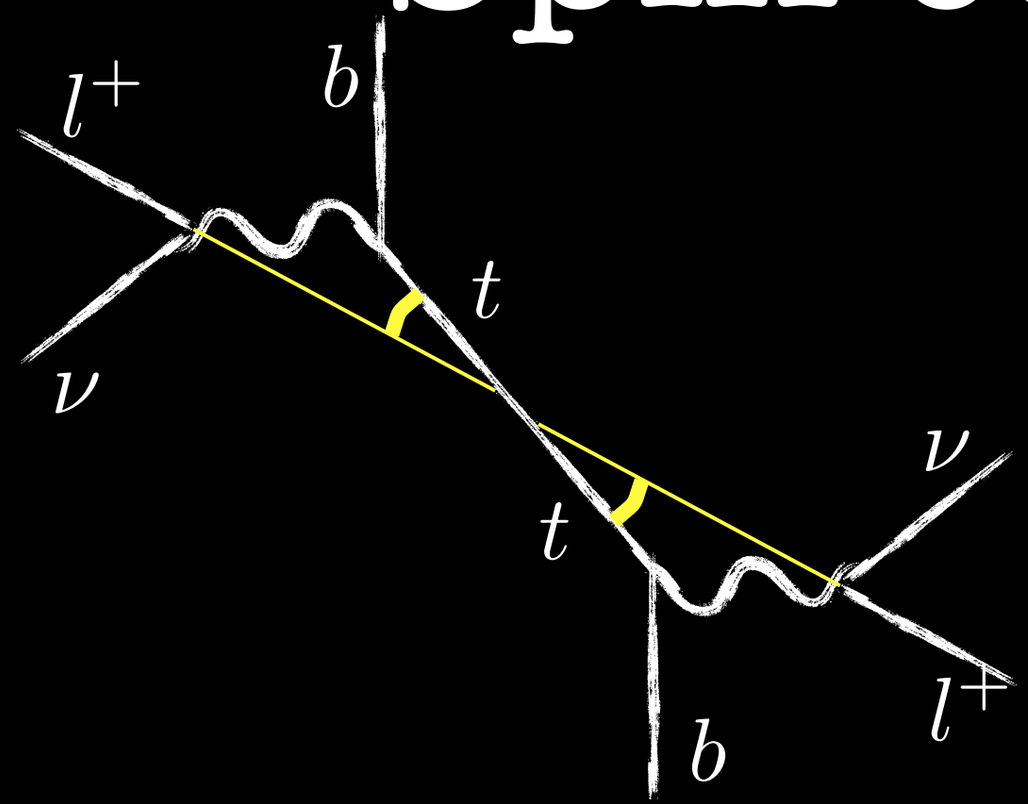
Spin correlations



$$C = \frac{1}{\sigma}\left(\sigma_{RR} + \sigma_{LL} - \sigma_{LR} - \sigma_{RL}\right)$$

$$b = \frac{1}{\sigma}\left(\sigma_{RR} - \sigma_{LL}\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + C\cos\theta_1\cos\theta_2 + b\left(\cos\theta_1 + \cos\theta_2\right)\right)$$

$$\mathcal{O}_{RR} \rightarrow \quad C = 1,\, b = 0.997$$

$$\mathcal{O}_{LL} \rightarrow \quad C = 1,\, b = -0.997$$

$$\mathcal{O}_{LR} \rightarrow \quad C \sim 1,\, b \sim 0$$

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Concluding remarks

- EFT is complementary to searches of new particles
- EFT is predictive = guide NP searches
  - Few operators have been neglected (small effects)
  - No new operators for single top
  - Common operators for other processes like tth
- Many other interesting processes with the top

C. Degrande

Concluding remarks

- EFT is complementary to searches of new particles
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