# Searches for new interactions within the SMEFT framework

**Luca Mantani**

UNIVERSITY OF CAMBRIDGE

MCnet

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**ν masses**

**Gravity**

**Dark Matter**

**Baryon asymmetry**

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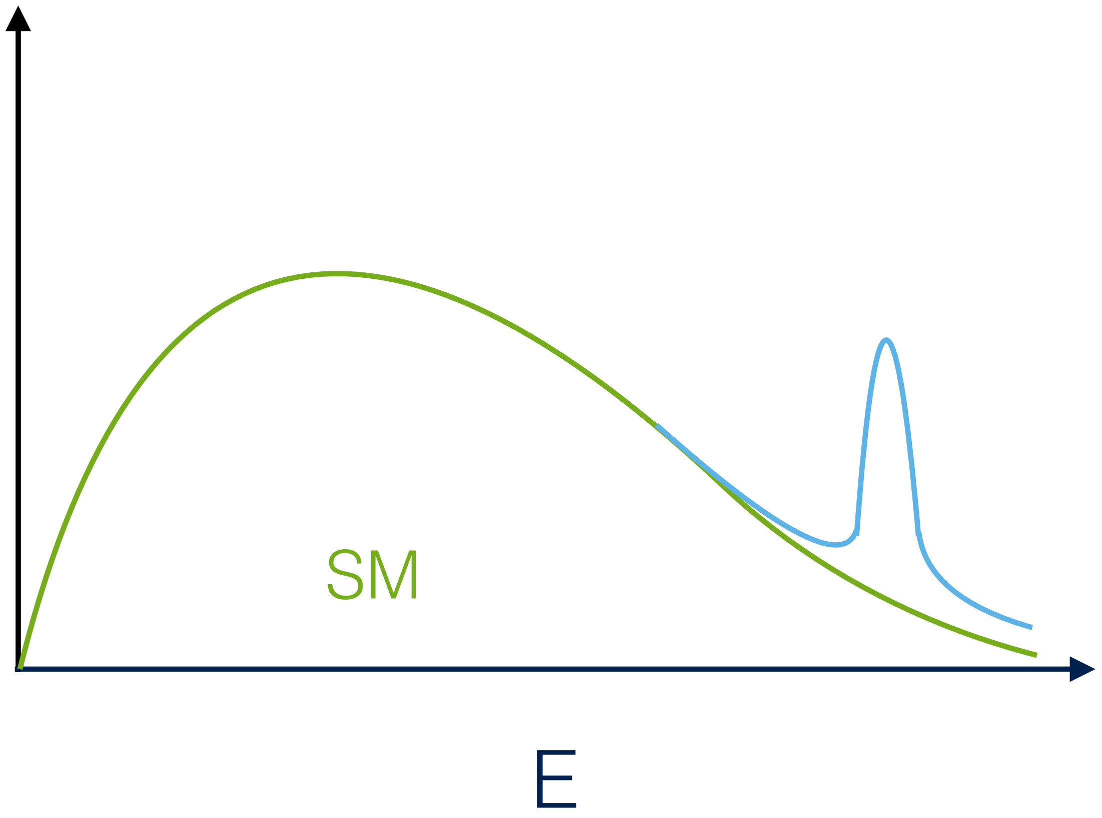
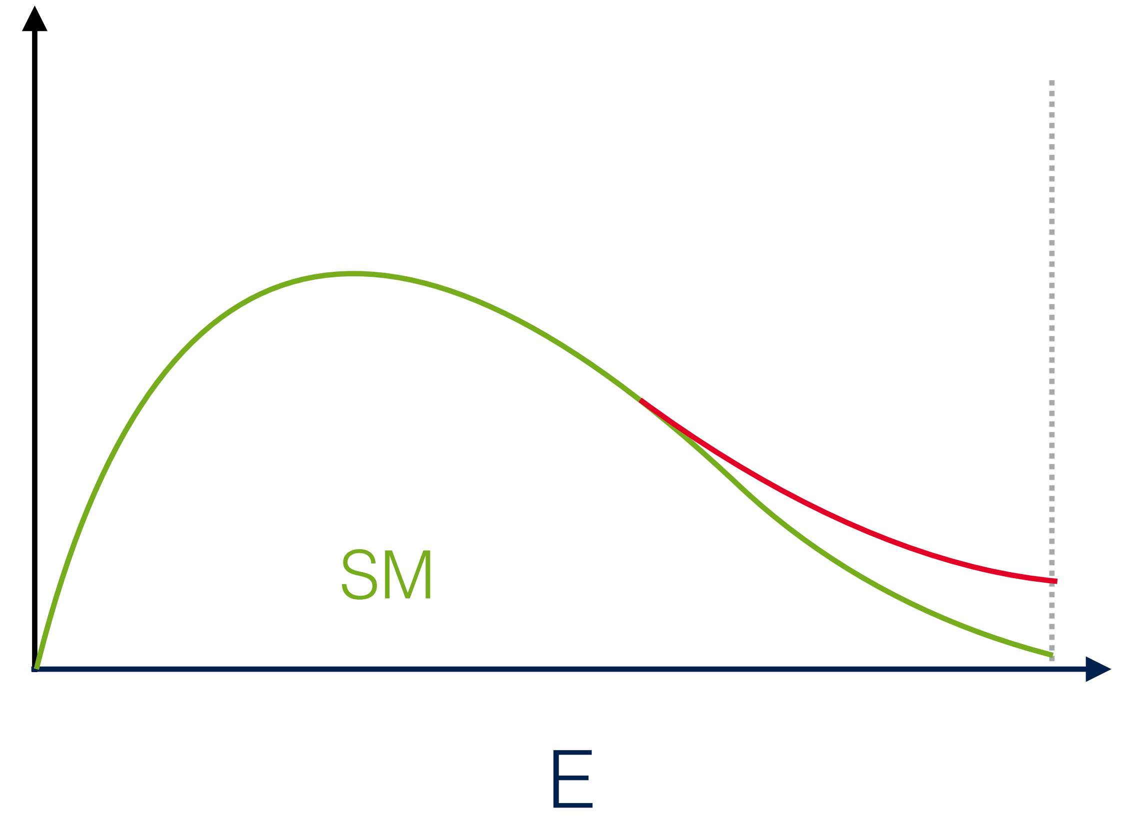
**Where do we go from here?**

## Direct search (Bumps)



**Direct search (Bumps)**

**Indirect (scouting tails)**



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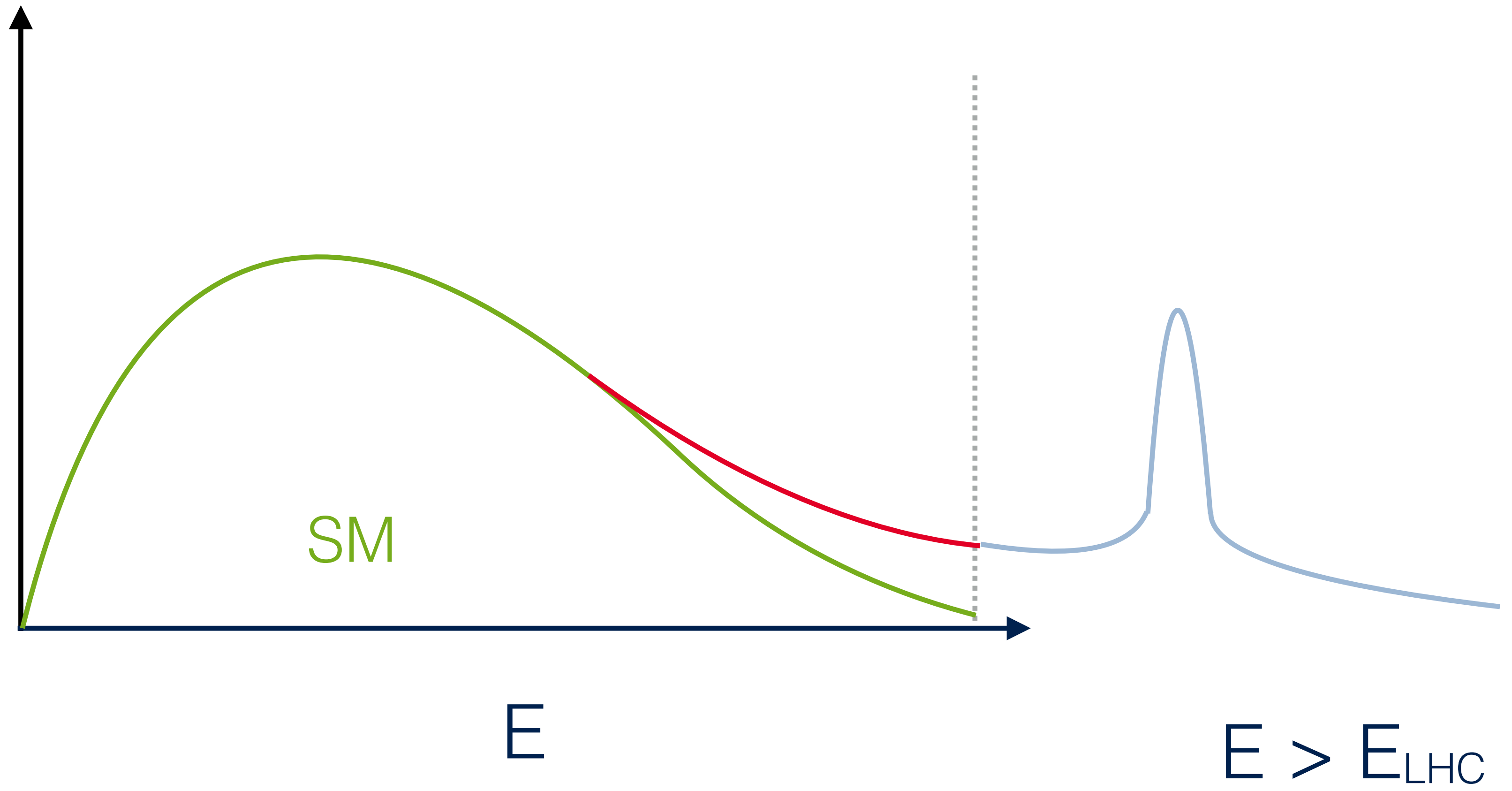
⇒ New physics is heavy



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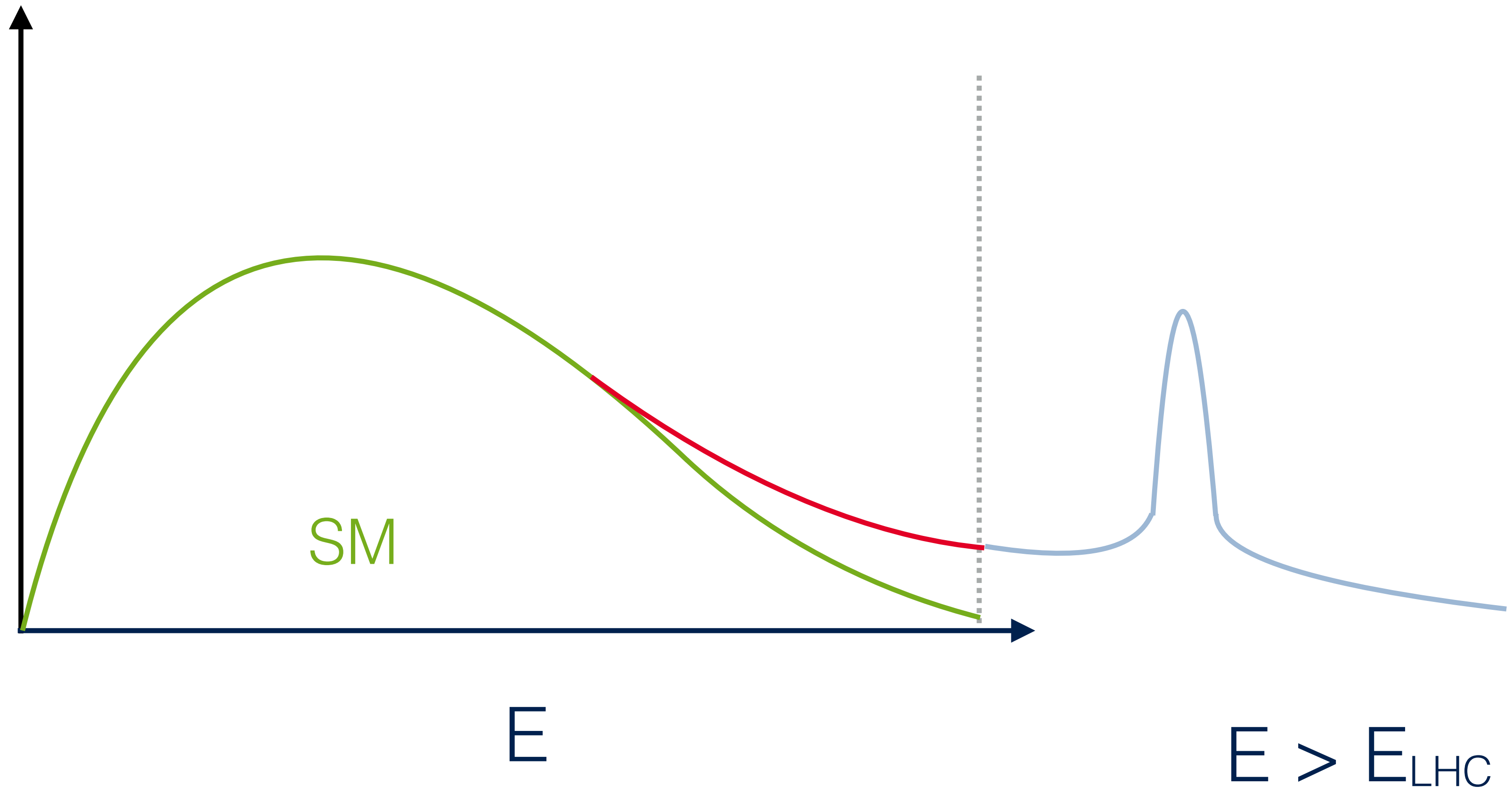
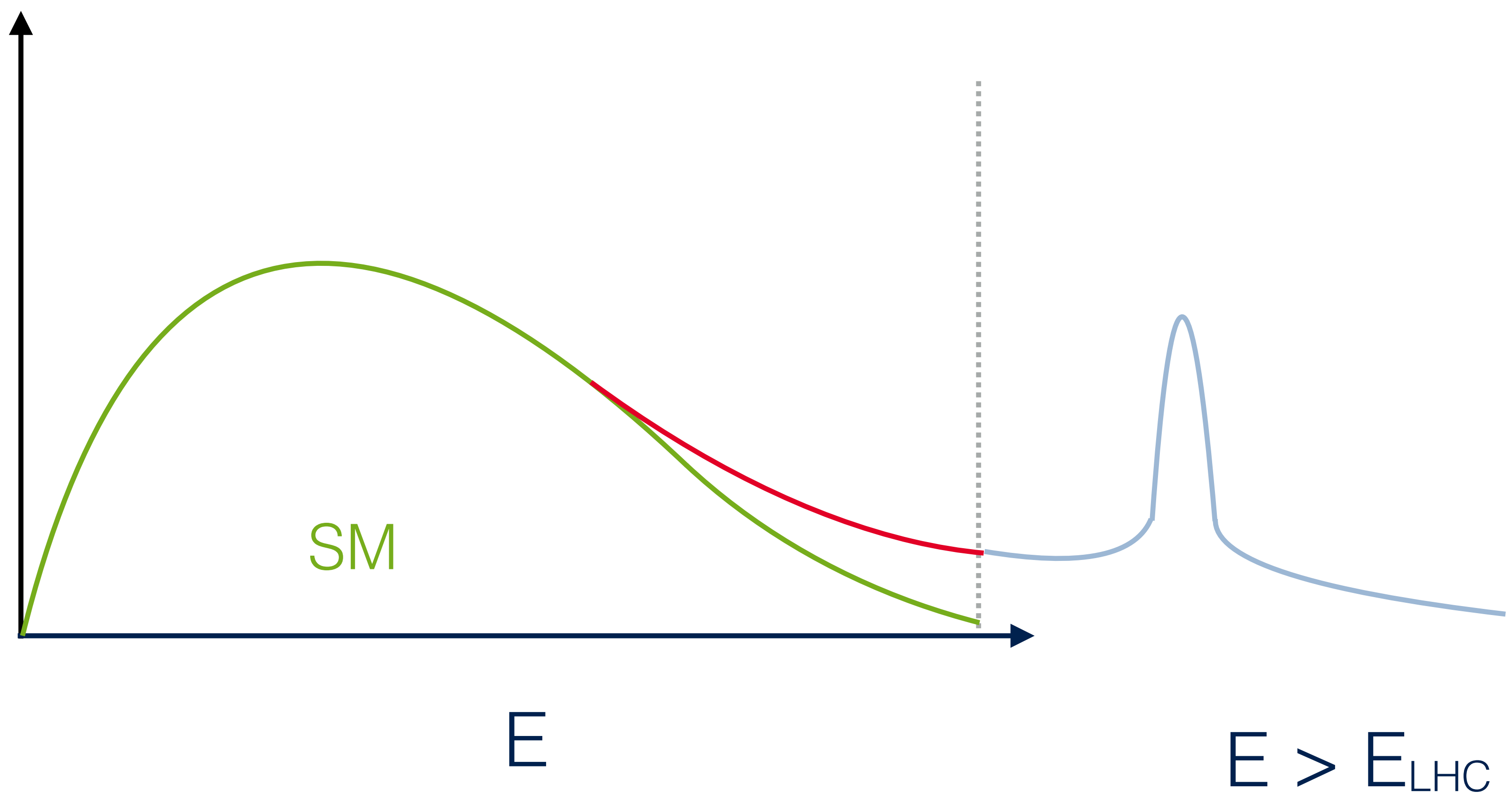



**Framework to describe both precision physics and Heavy New Physics.**

**Direct search (Bumps)**

**Indirect (scouting tails)**

$\Rightarrow$ New physics is heavy




**Framework to describe both precision physics and Heavy New Physics.**

**Standard Model Effective Field Theory (SMEFT)**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda}\mathcal{O}_i^5 + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i^6 + \ldots$$

- **Modified interactions among SM particles**
- **Higher dimensional operators preserve SM symmetries.**
- **Mappable to a large class of BSM models.**
- **Truncate at dim 6: leading corrections**

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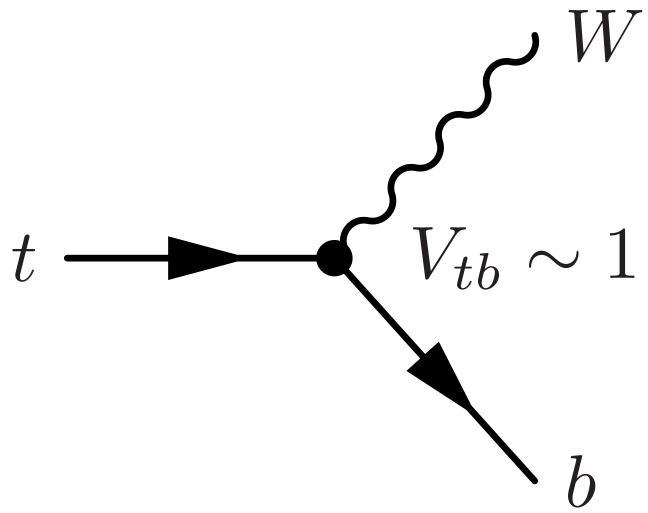
**EFT to-do list**

- **Define target operators: e.g. top-philic EFT** [arXiv:1802.07237]
- **Find optimal observables to probe them**
- **Compute with precision theoretical predictions (both SM and EFT)**
- **Make accurate measurements**

**The top quark is special.**

- The top couples to the Higgs strongly.
- It is the heaviest particle in the SM (unitarity bounds lower).
- Couples to W boson through its decay, before hadronisation (neutral gauge couplings less known).



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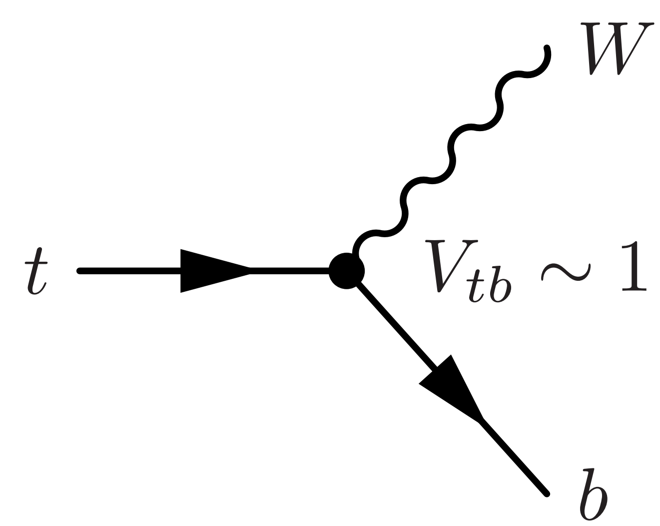


$10^9$ top pairs

$10^8$ single top

The LHC is a **top factory**

$10^7$ tt+W/Z/$\gamma$

$10^6$ ttH $10^4$ tttt

**We consider generic 2 to 2 processes** $f\,B \to f'\,B'$

| | Single-top | Two-top $(t\bar{t})$ |
|---|---|---|
| w/o Higgs | $b\,W \to t\,(Z/\gamma)$ | $t\,W \to t\,W$<br>$t\,(Z/\gamma) \to t\,(Z/\gamma)$ |
| w/ Higgs | $b\,W \to t\,h$ | $t\,(Z/\gamma) \to t\,h$<br>$t\,h \to t\,h$ |

**We study the processes in the high energy limit (s ~ -t >> v$^2$) for each helicity configuration, including the effects of the dim 6 operators.**
**As expected the maximum degree of growth of each amplitude is E$^2$, while for the SM they are at most constant in energy.**

Many operators lead to maximal growth

| | $\mathcal{O}_{\varphi D}$ | $\mathcal{O}_{\varphi \Box}$ | $\mathcal{O}_{\varphi B}$ | $\mathcal{O}_{\varphi W}$ | $\mathcal{O}_{\varphi WB}$ | $\mathcal{O}_{W}$ | $\mathcal{O}_{t\varphi}$ | $\mathcal{O}_{tB}$ | $\mathcal{O}_{tW}$ | $\mathcal{O}_{\varphi Q}^{(1)}$ | $\mathcal{O}_{\varphi Q}^{(3)}$ | $\mathcal{O}_{\varphi t}$ | $\mathcal{O}_{\varphi tb}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $bW \to tZ$ | $E$ | – | – | – | $E$ | $E^2$ | – | $E^2$ | $E^2$ | $E$ | $E^2$ | $E$ | $E^2$ |
| $bW \to t\gamma$ | – | – | – | – | $E$ | $E^2$ | – | $E^2$ | $E^2$ | – | – | – | – |
| $bW \to th$ | – | – | – | $E$ | – | – | $E$ | – | $E^2$ | – | $E^2$ | – | $E^2$ |

single-top

| | $\mathcal{O}_{\varphi D}$ | $\mathcal{O}_{\varphi \Box}$ | $\mathcal{O}_{\varphi B}$ | $\mathcal{O}_{\varphi W}$ | $\mathcal{O}_{\varphi WB}$ | $\mathcal{O}_{W}$ | $\mathcal{O}_{t\varphi}$ | $\mathcal{O}_{tB}$ | $\mathcal{O}_{tW}$ | $\mathcal{O}_{\varphi Q}^{(1)}$ | $\mathcal{O}_{\varphi Q}^{(3)}$ | $\mathcal{O}_{\varphi t}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $tW \to tW$ | $E$ | $E$ | – | $E$ | $E$ | $E^2$ | $E$ | $E$ | $E^2$ | $E^2$ | $E^2$ | $E^2$ |
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| $t\gamma \to t\gamma$ | – | – | $E$ | $E$ | $E$ | – | – | $E$ | $E$ | – | – | – |

two-top w/o Higgs

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $tZ \to th$ | $E$ | – | $E$ | $E$ | $E$ | – | $E$ | $E^2$ | $E^2$ | $E^2$ | $E^2$ | $E^2$ | – |
| $t\gamma \to th$ | – | – | $E$ | $E$ | $E$ | – | – | $E^2$ | $E^2$ | – | – | – | – |
| $th \to th$ | $E$ | $E$ | – | – | – | – | $E$ | – | – | – | – | – | – |

two-top w/ Higgs

Energy growing interference is rare: only longitudinal configurations

## How to access the high energy behaviour of the 2 to 2 scatterings?

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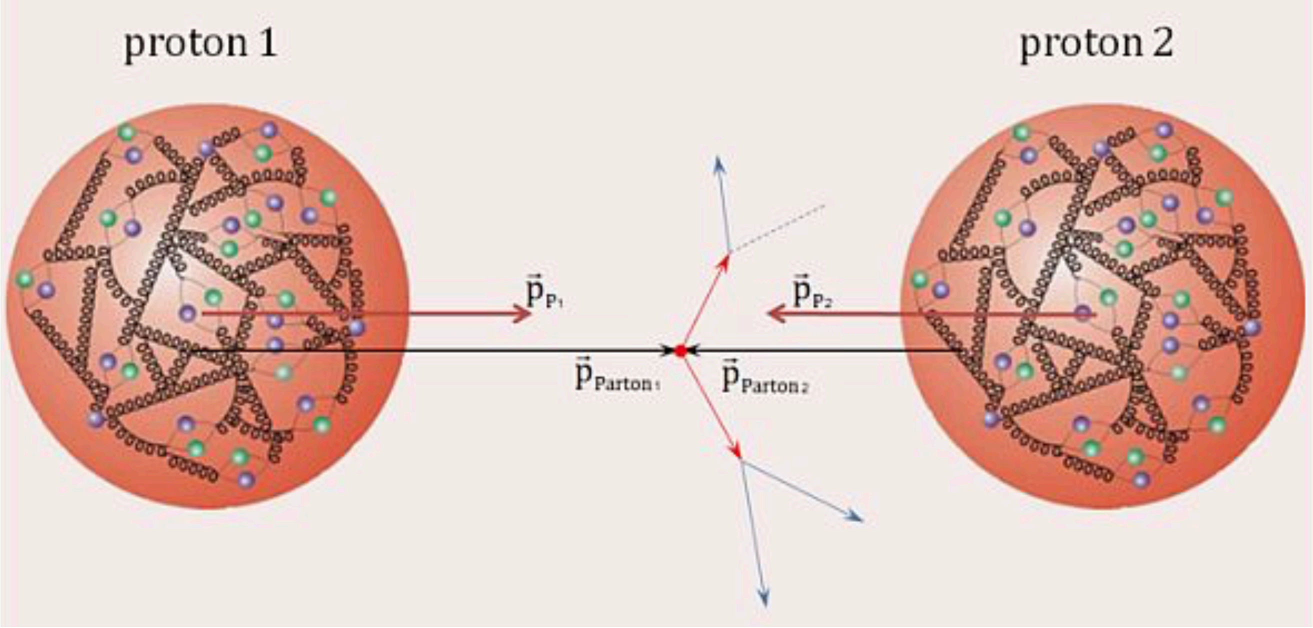
**LHC collides protons**



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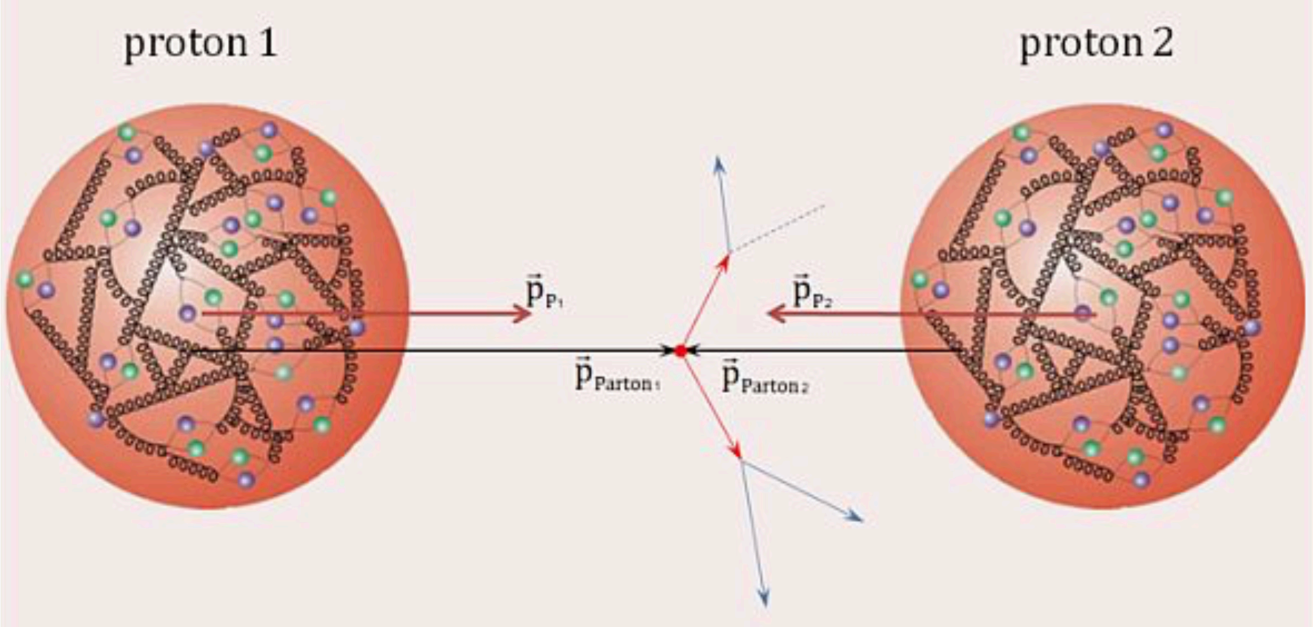
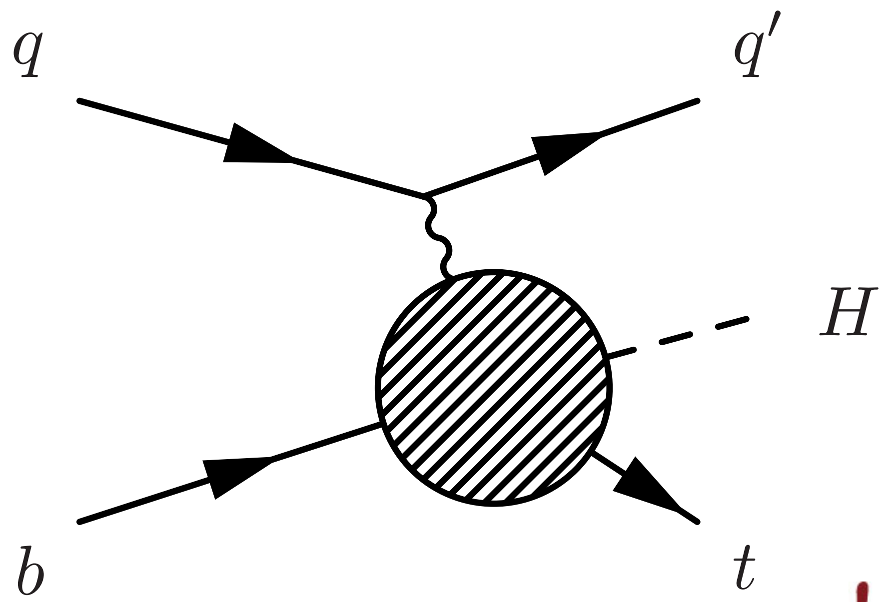



**Embed the 2 to 2 scattering**



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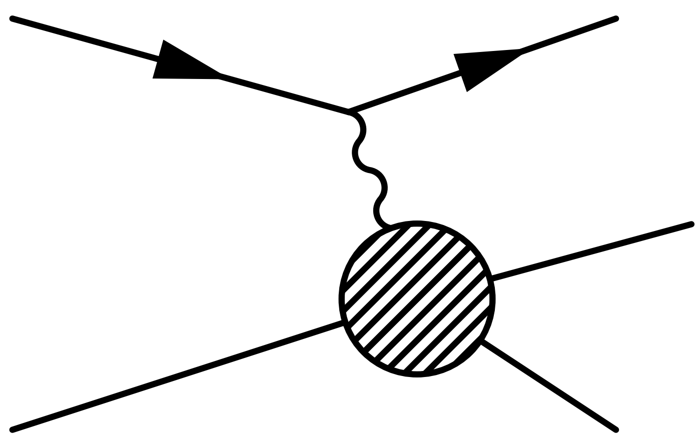
**How does the 2 to 2 behaviour translates to 2 to n?**
**We can have an analytical insight with EWA (P. Borel et al. arxiv:1202.1904)**




$$E \sim xE \sim (1-x)E, \qquad \frac{m}{E} \ll 1, \qquad \frac{p_\perp}{E} \ll 1$$

$$f_+ = \frac{(1-x)^2}{x} \frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2},$$

$$f_- = \frac{1}{x} \frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2},$$

$$f_0 = \frac{(1-x)^2}{x} \frac{2m^2 p_\perp}{(m^2(1-x)+p_\perp^2)^2}.$$

$$\frac{d\sigma_{EWA}}{dx\,dp_\perp}(qX \to q\prime Y) = \frac{C^2}{2\pi^2} \sum_{i=+,-,0} f_i \times d\sigma(W_i X \to Y)$$

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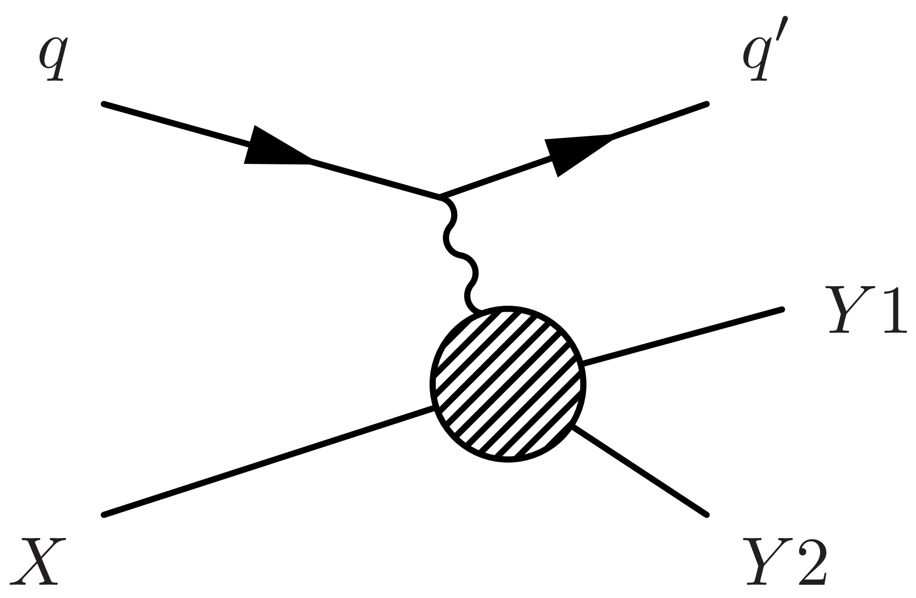


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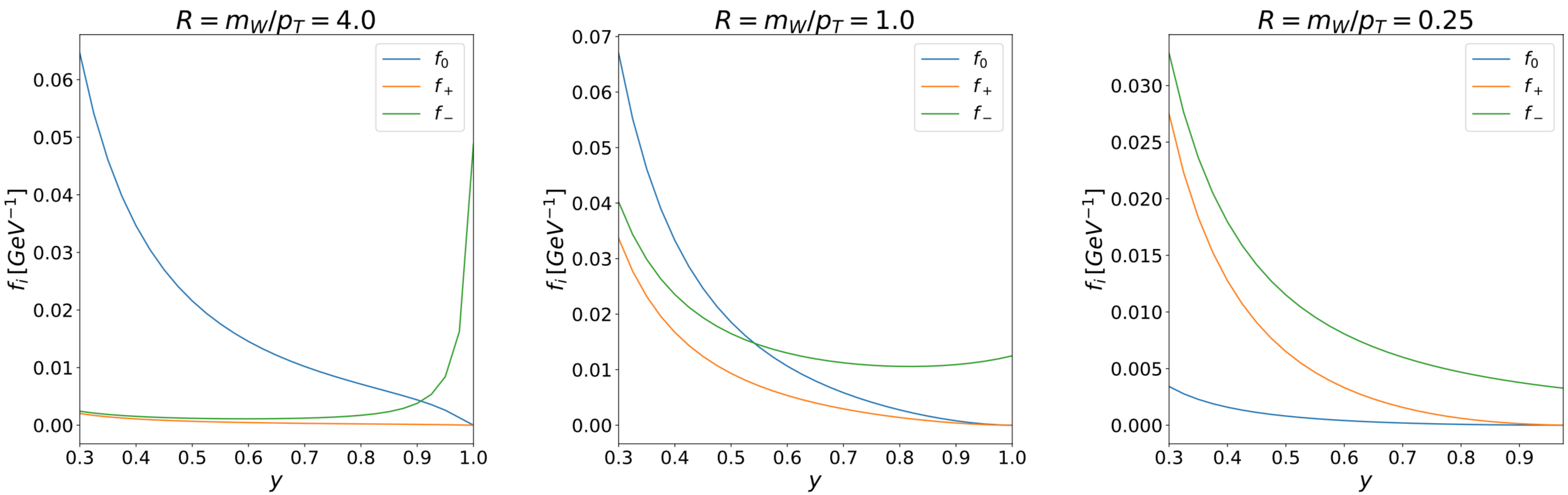
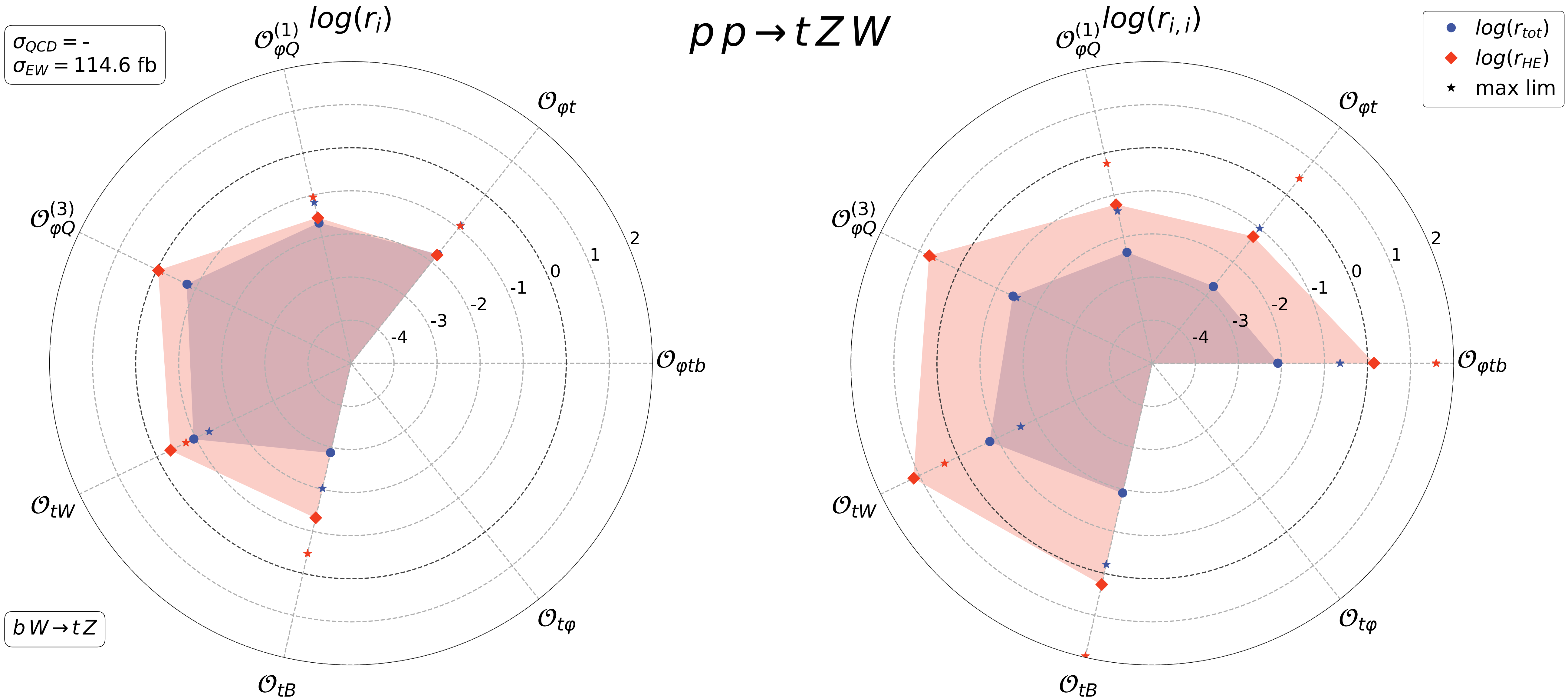
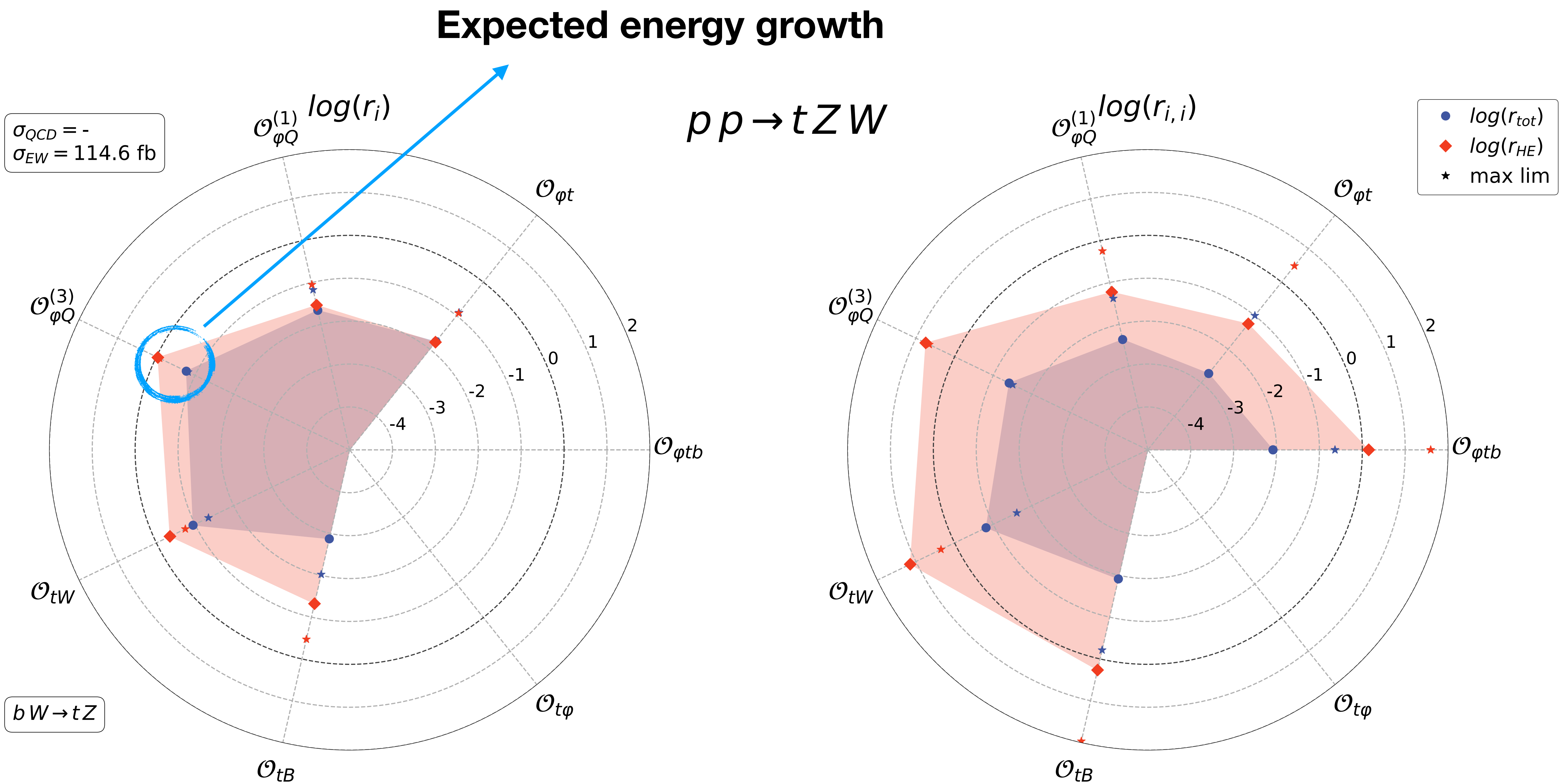





$$R(c_i) \equiv \frac{\sigma}{\sigma_{SM}} = 1 + c_i \frac{\sigma^i_{Int}}{\sigma_{SM}} + c_i^2 \frac{\sigma^{i,i}_{Sq}}{\sigma_{SM}} = 1 + c_i\, r_i + c_i^2\, r_{i,i}.$$

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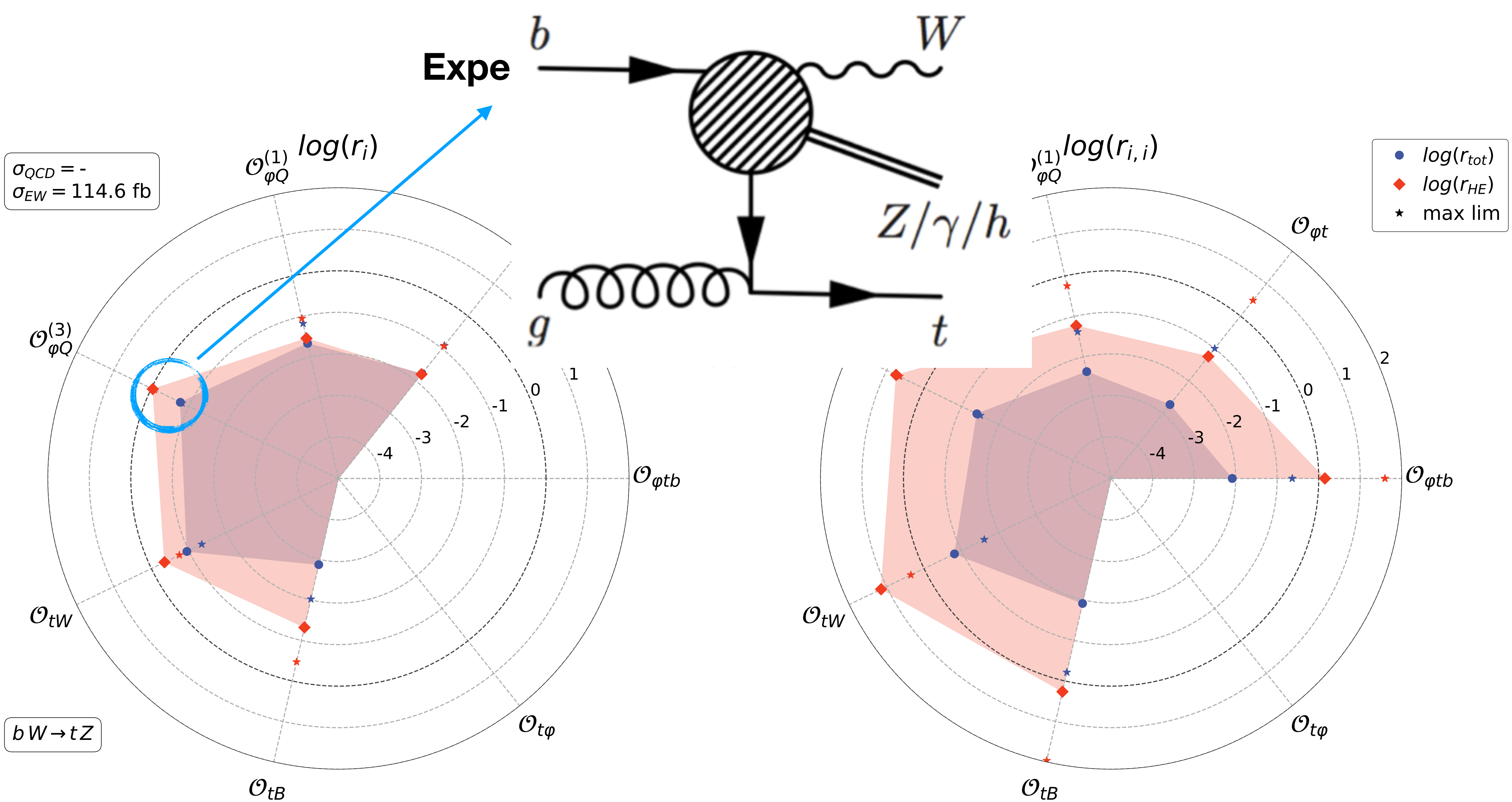
# An interesting process: tZW

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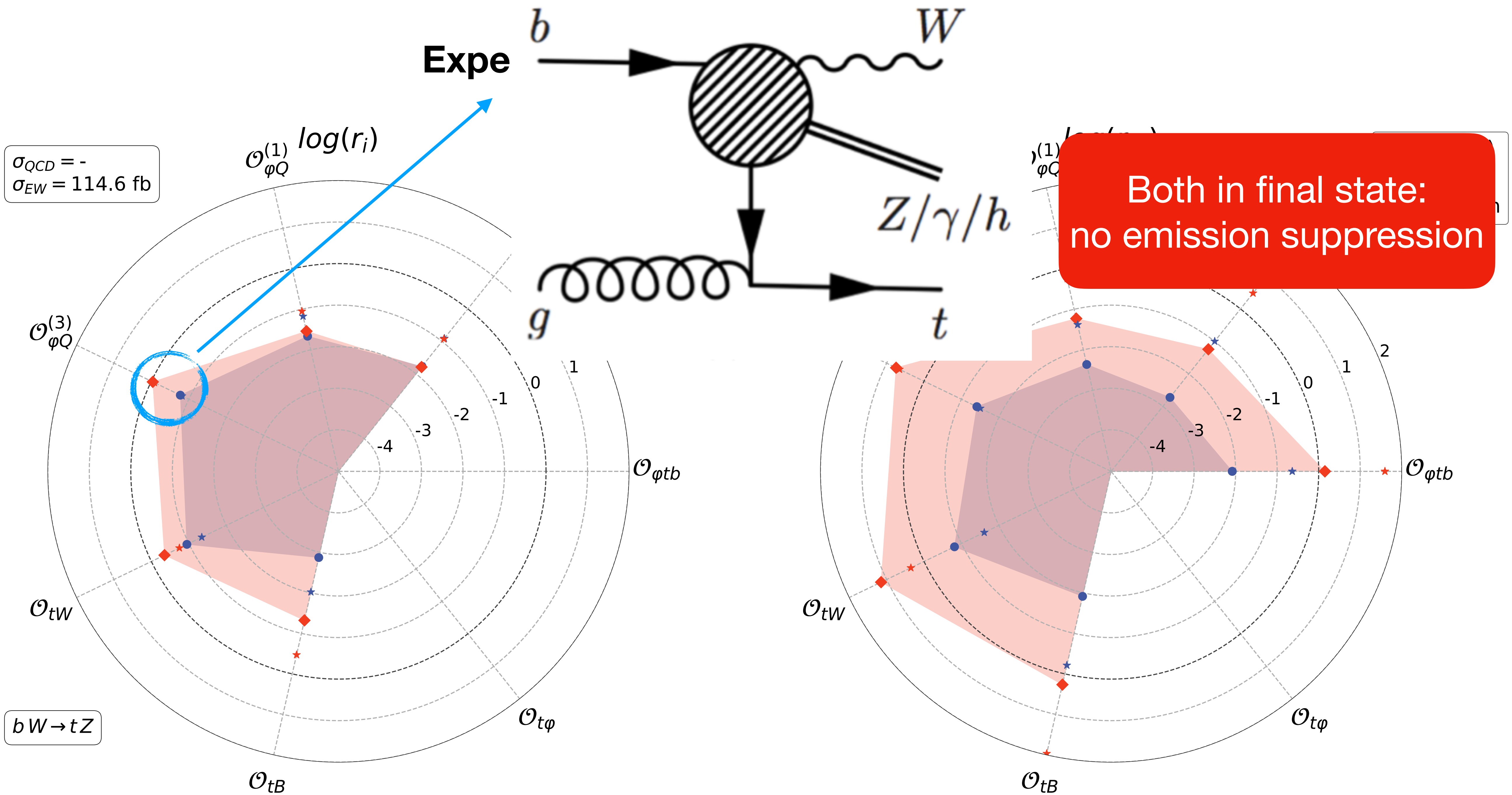


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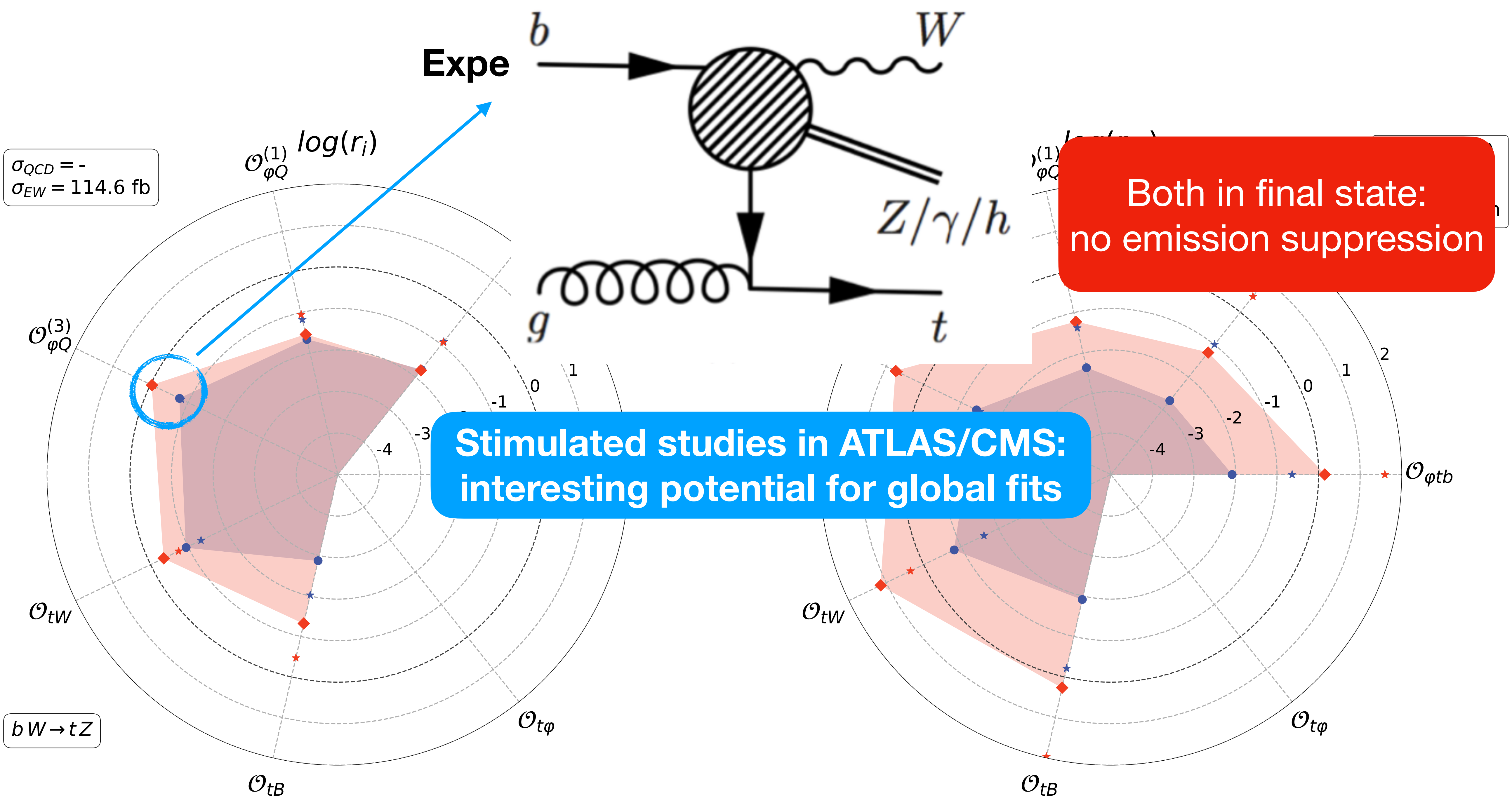


**Both in final state: no emission suppression**

**Stimulated studies in ATLAS/CMS: interesting potential for global fits**

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## Theory

**(N)NLO QCD + NLO EW** SM XS

**NLO-QCD, linear and quadratic,** EFT (**SMEFT@NLO**)

**PDFs,** avoid redundancy (no top)

## Data

**Higgs data** (inclusive, diff, STXS)

**Top quark data**

**Diboson production** (LEP + LHC)

SMEFiT

## Output

Validation statistical toolbox: **Fisher information, PCA, closure tests**

**Posterior probabilities** in EFT parameter space**, CL intervals**

## Methodology

Two independent fitting methods: **MCfit** and **Nested Sampling**

**Modular structure**: easy to add new theory predictions and data

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# Global fit result

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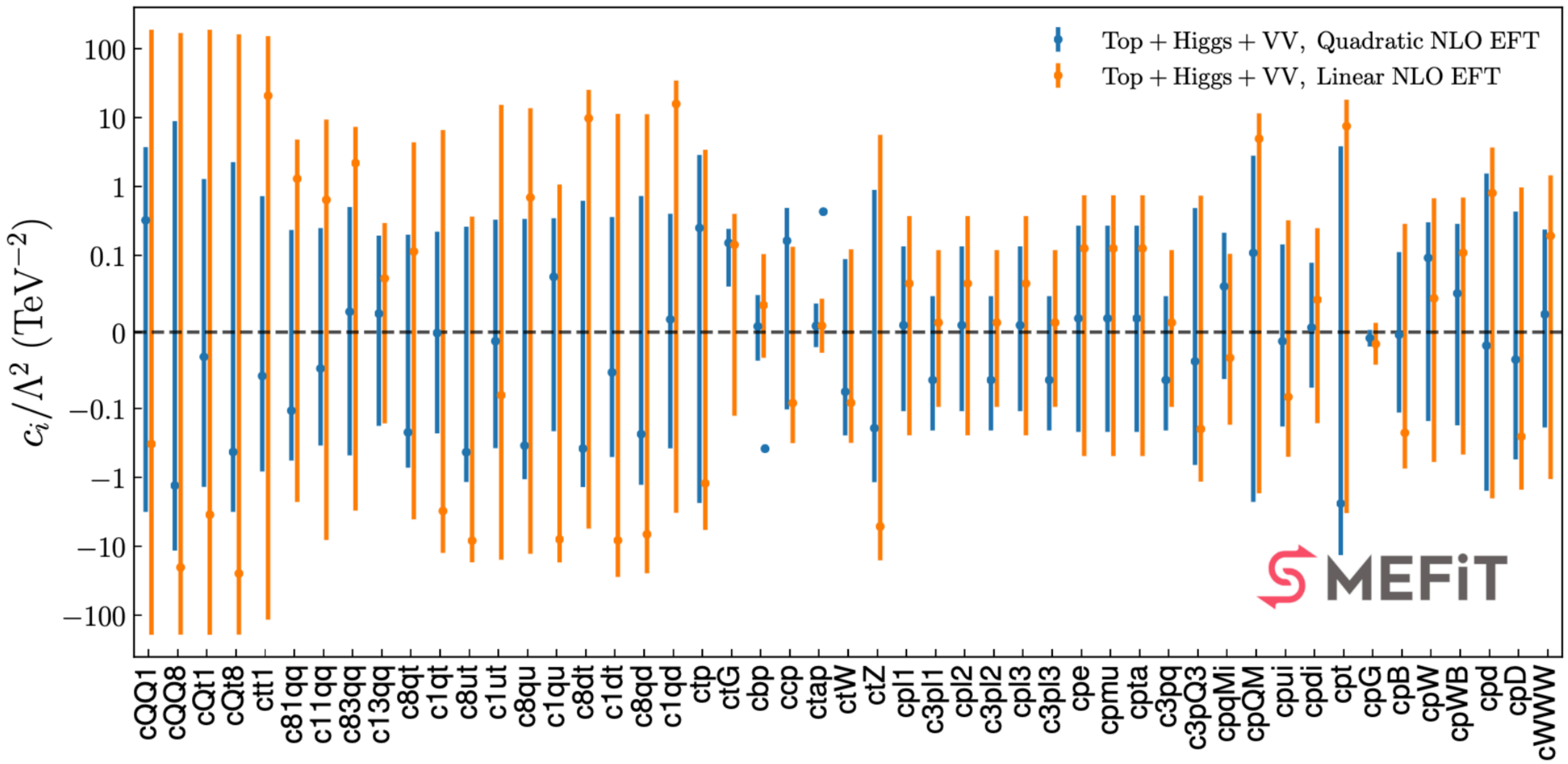


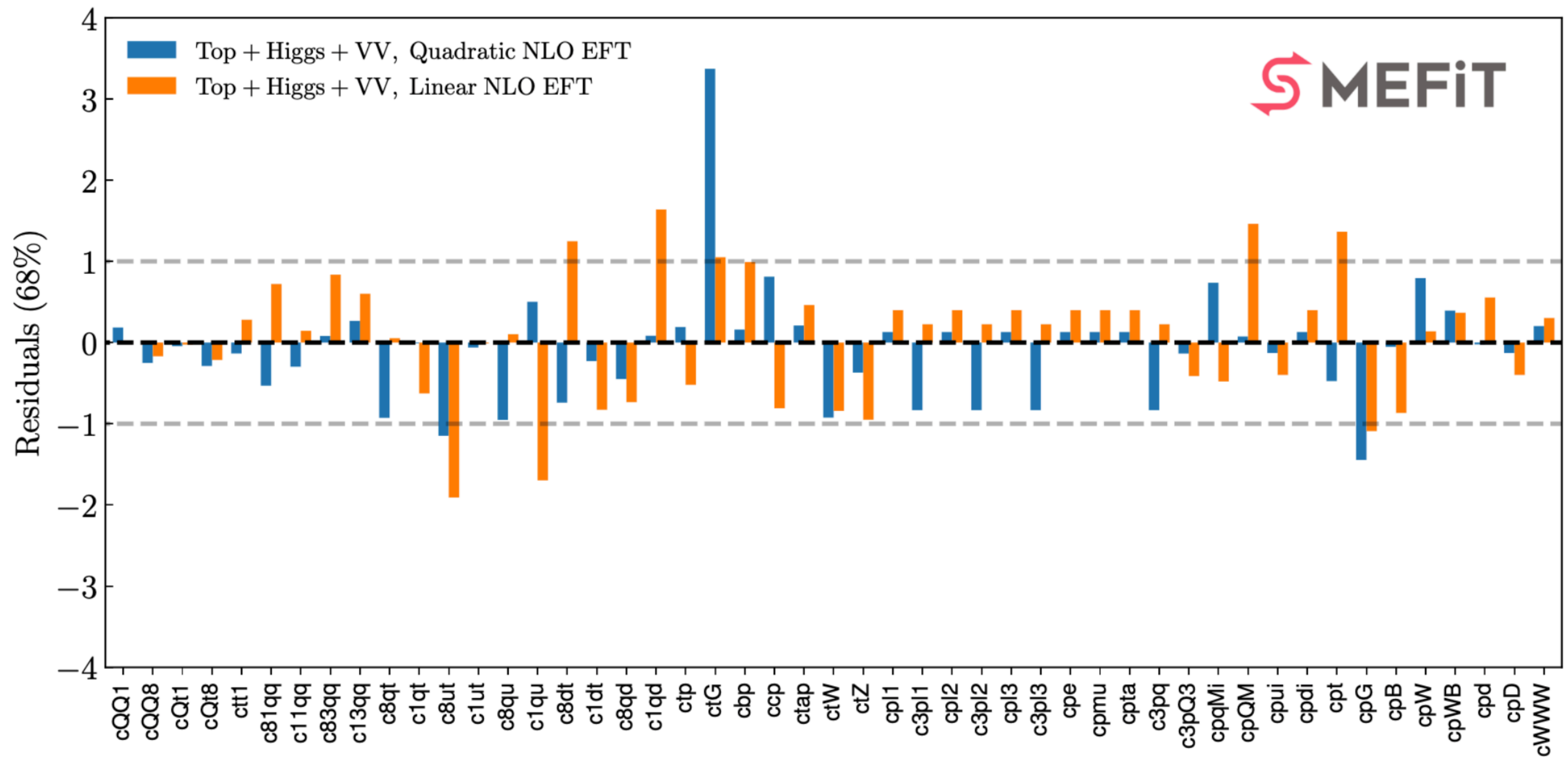

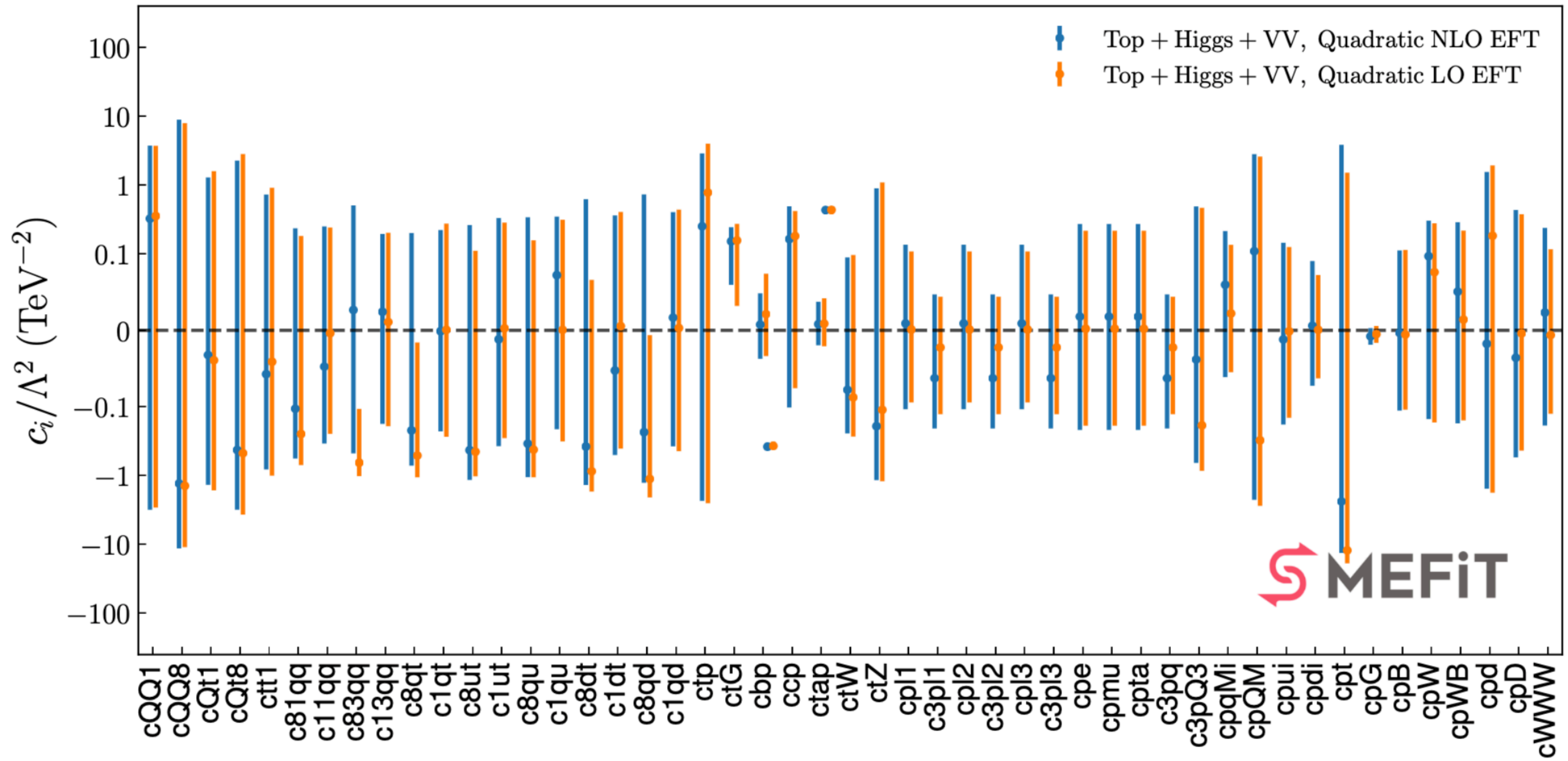
Top + Higgs + VV, Quadratic NLO EFT
Top + Higgs + VV, Quadratic LO EFT
$c_i/\Lambda^2$ (TeV$^{-2}$)
100
10
1
0.1
0
−0.1
−1
−10
−100
SMEFiT
cQQ1
cQQ8
cQt1
cQt8
ctt1
c81qq
c11qq
c83qq
c13qq
c8qt
c1qt
c8ut
c1ut
c8qu
c1qu
c8dt
c1dt
c8qd
c1qd
ctp
ctG
cbp
ccp
ctap
ctW
ctZ
cpl1
c3pl1
cpl2
c3pl2
cpl3
c3pl3
cpe
cpmu
cpta
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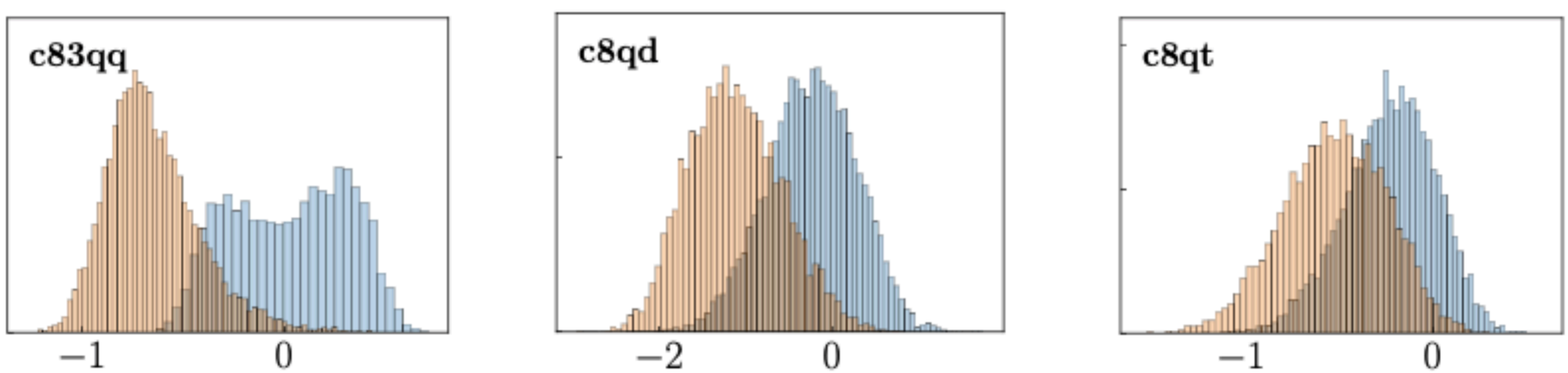
cpWB
cpd
cpD
cWWW


c83qq
−1
0
c8qd
−2
0
c8qt
−1
0



MCnet

Loop induced processes: not only precision!

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**Especially relevant for top loops: most strongly coupled particle**

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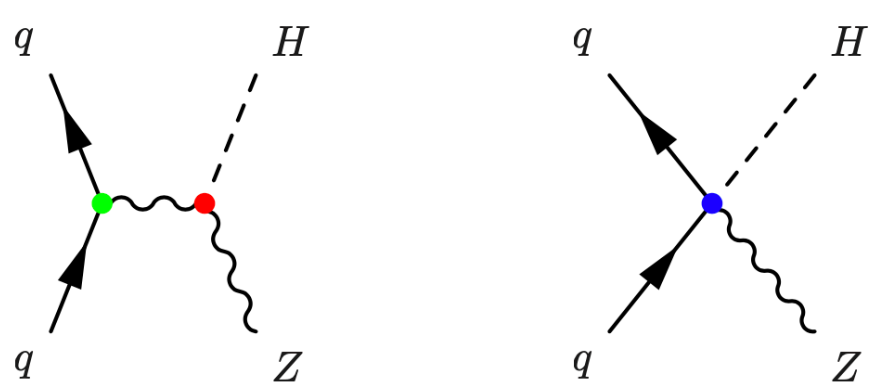


$$\mathcal{O}_{\varphi W}, \quad \mathcal{O}_{\varphi B}, \quad \mathcal{O}_{\varphi D}, \quad \mathcal{O}^{(3)}_{\varphi q_i}, \quad \mathcal{O}^{(1)}_{\varphi q_i}, \quad \mathcal{O}^{(1)}_{\varphi Q}, \quad \mathcal{O}^{(3)}_{\varphi Q},$$
$$\mathcal{O}^{(3)}_{\varphi l_1}, \quad \mathcal{O}^{(3)}_{\varphi l_2}, \quad \mathcal{O}_{\varphi u_i}, \quad \mathcal{O}_{\varphi d_i}$$

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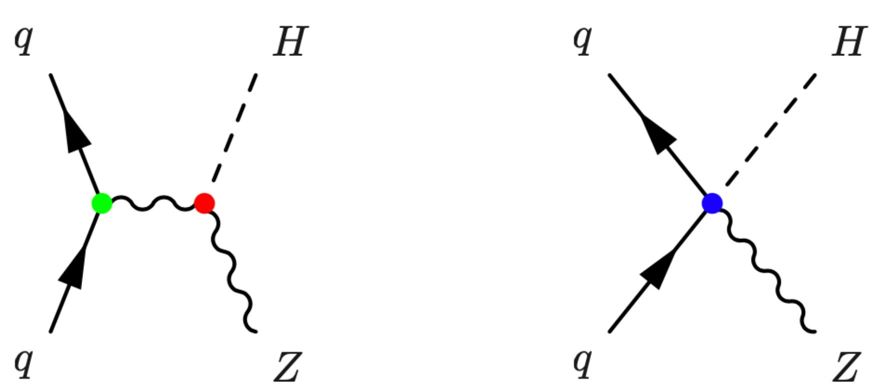


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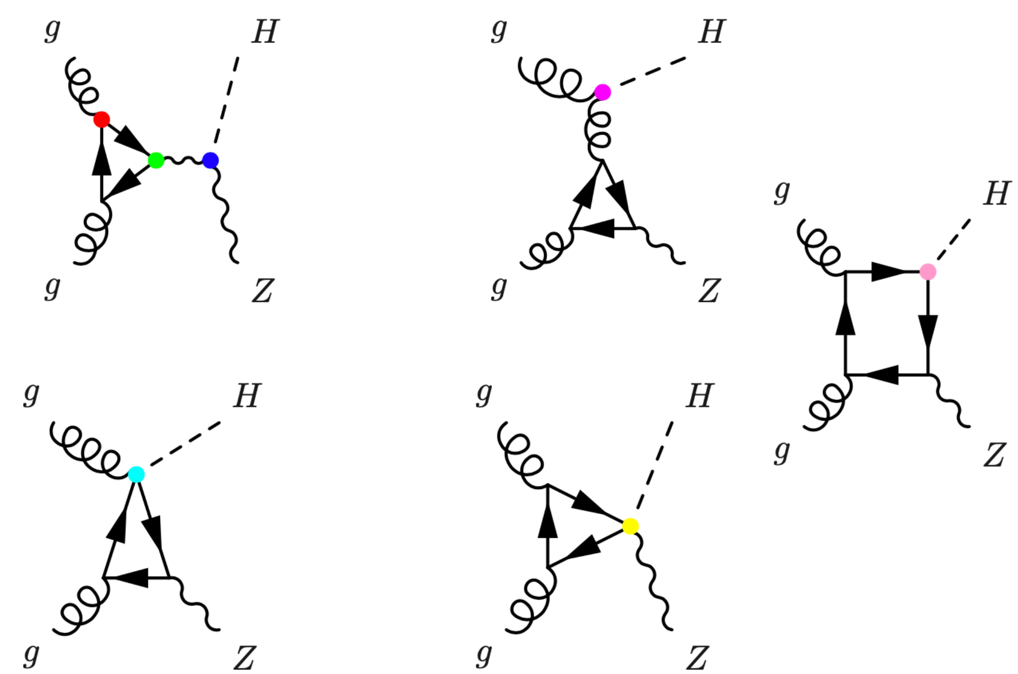


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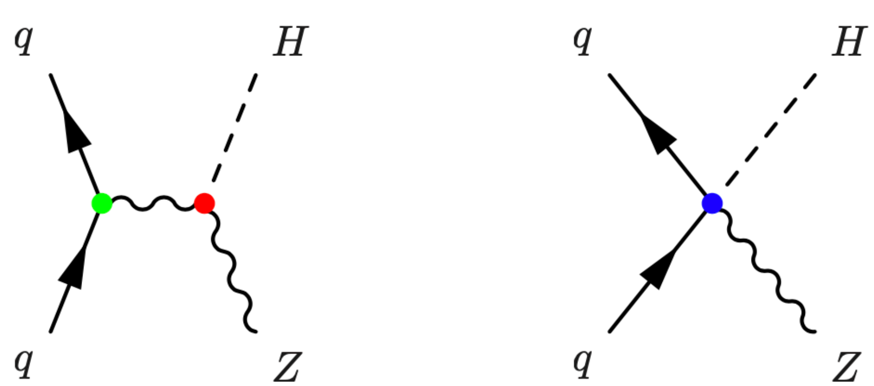


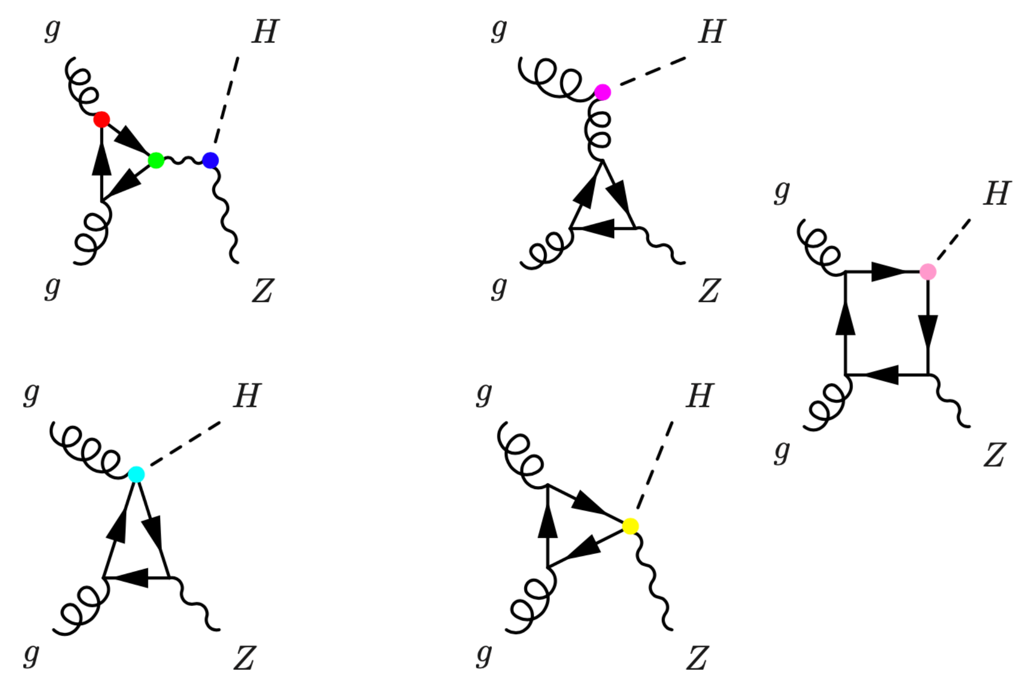


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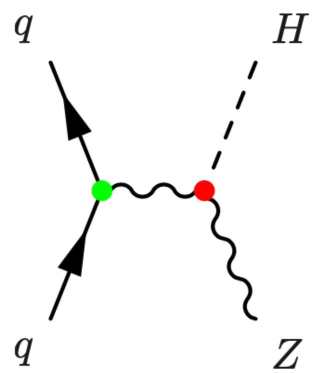
Sensitivity to top operators!

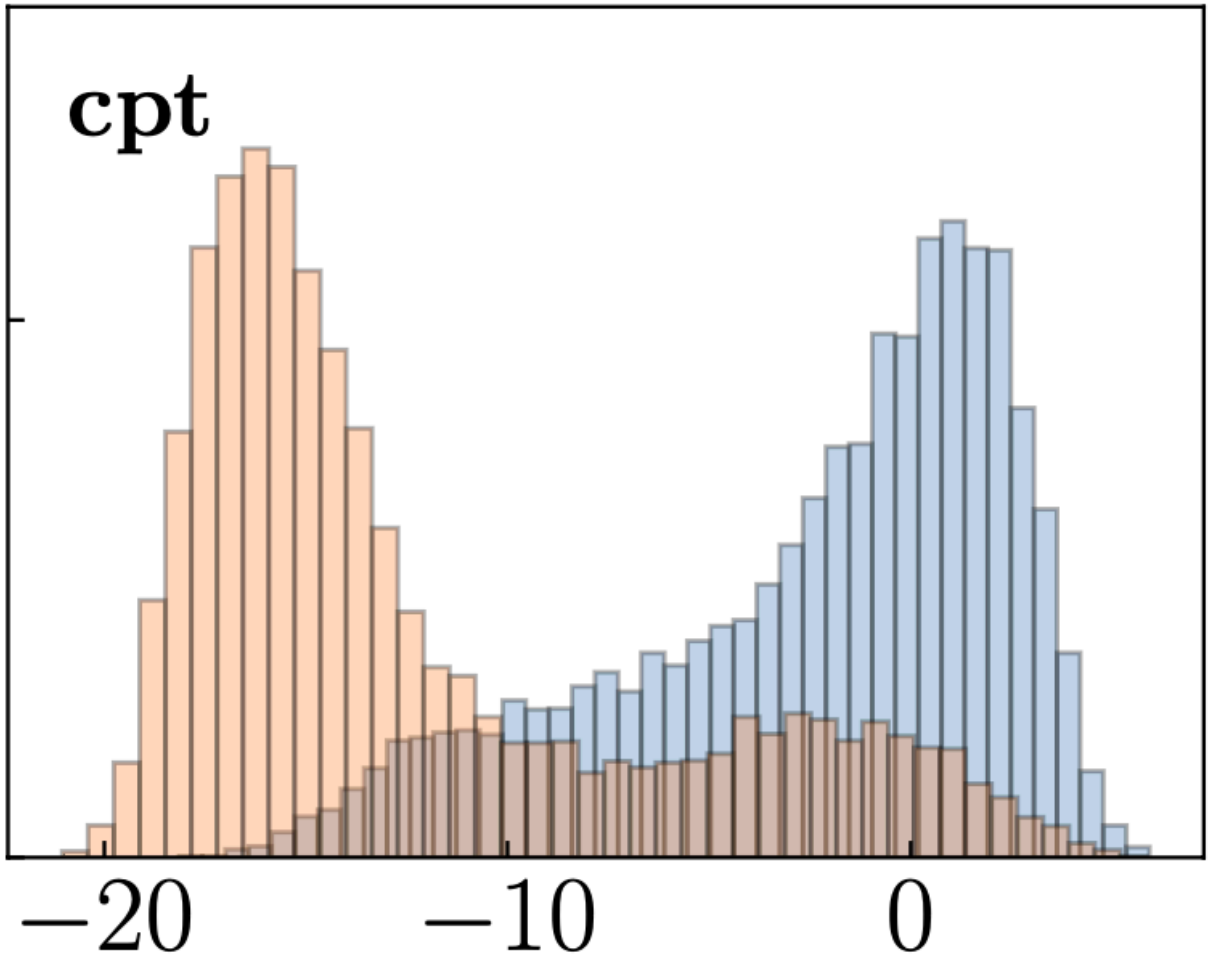
Loop induced processes: not only precision! → **New sensitivities**

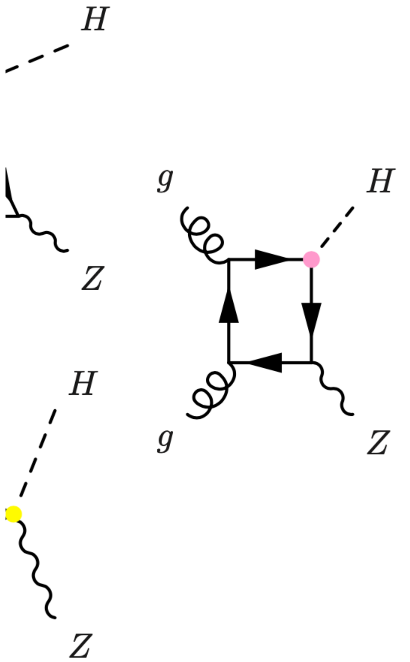
**Especially relevant for top loops: most strongly coupled particle**

LO EFT NLO EFT + gg -> ZH

**E.g.: pp**

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$\mathcal{O}_{tG}$, $\mathcal{O}_{\varphi G}$, $\mathcal{O}_{ll}$

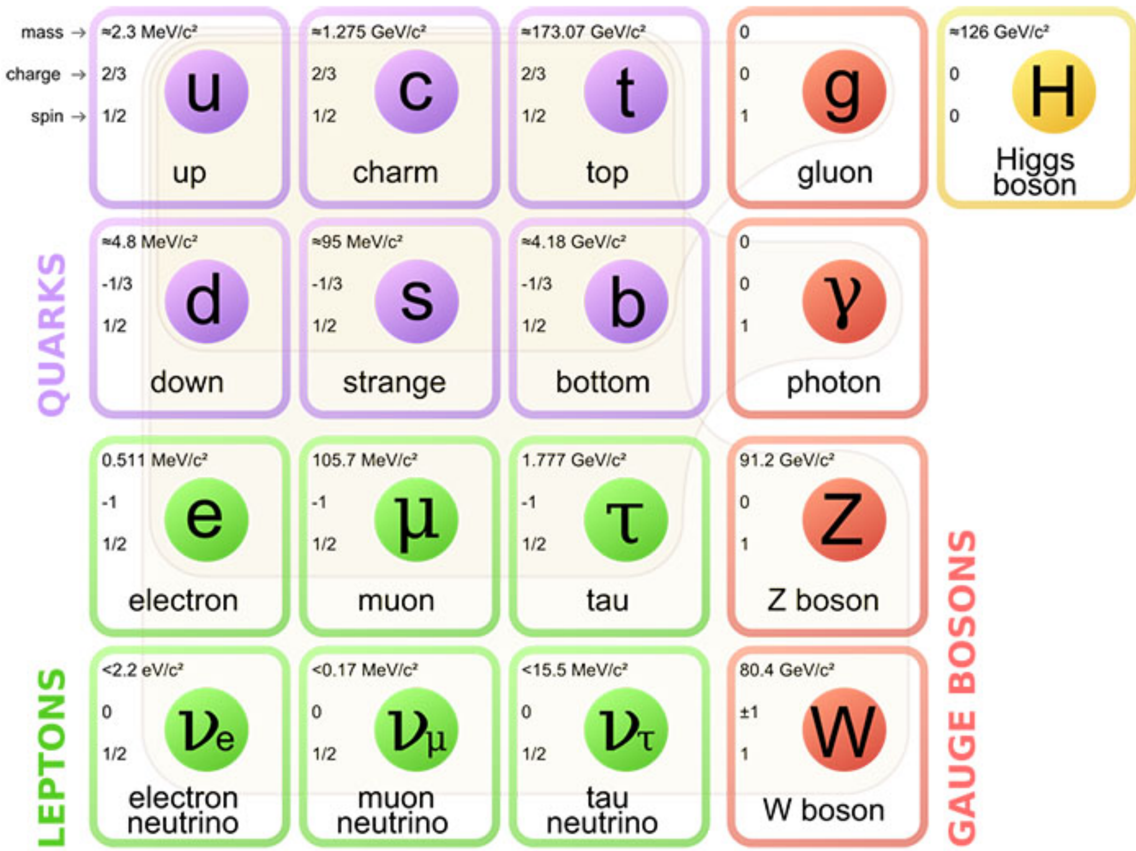
Sensitivity to top operators!

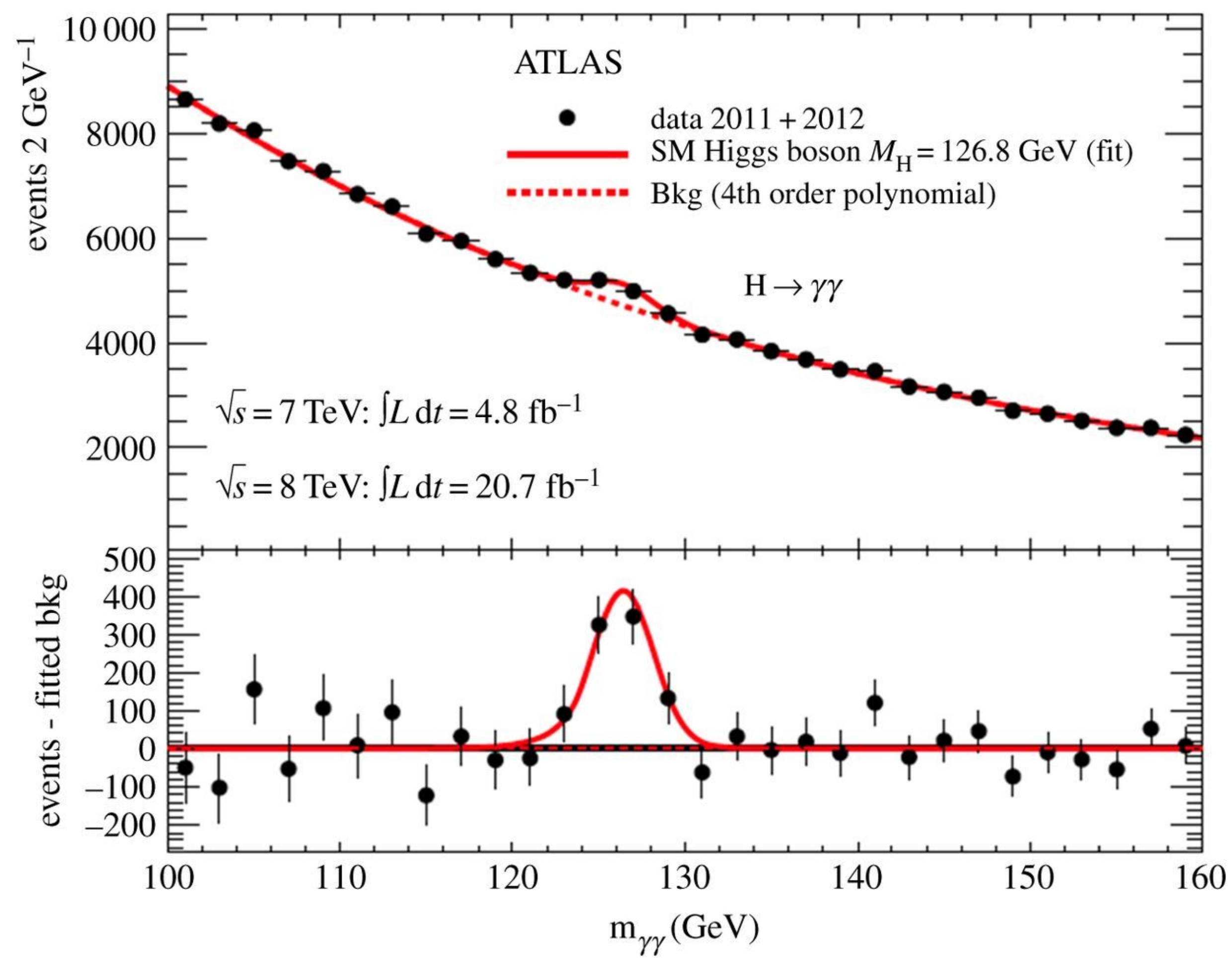
- Presented analysis on the possibility to uncover indirectly heavy NP at present and future colliders.
- Unitarity violating behaviours in the top EW sector in 2 -> 2 scatterings can be exploited to gain sensitivity on SMEFT operators.
- The interplay of Higgs, Top and diboson datasets has been discussed and a combined interpretation in the SMEFT presented.
- Entering a precision era, studying modified interactions in the SMEFT context is of crucial importance if we want to maximise the possibility to find SM deviations.

# THANKS!

# Back-up

**Theories and discoveries in particle physics in the last century lead us to have a deep insight into the structure and behaviour of matter.**



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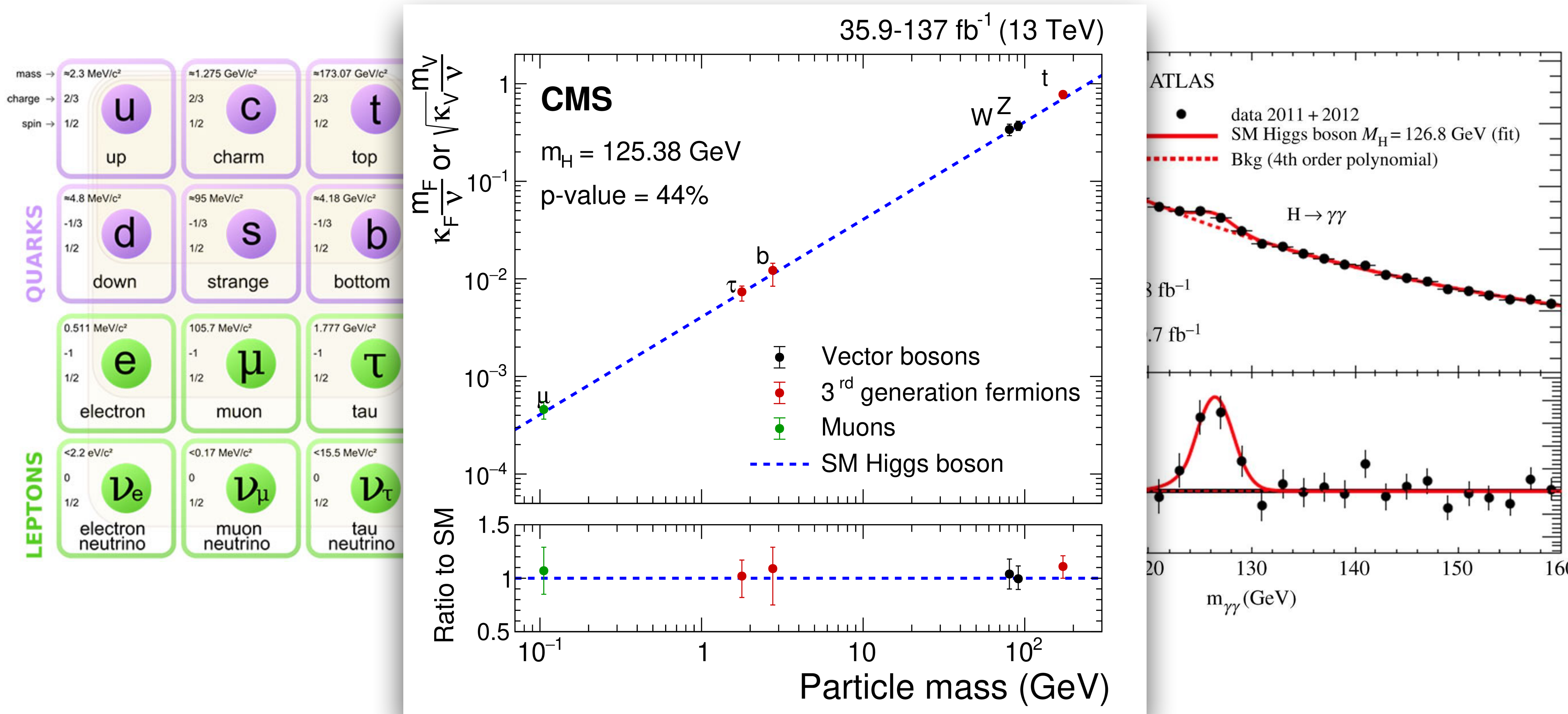


**The LHC has found a scalar particle that behaves like the SM Higgs.**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + Y_{ij}\bar{\psi}_i\psi_j\phi + D_{\mu}\phi D^{\mu}\phi - V(\phi)$$

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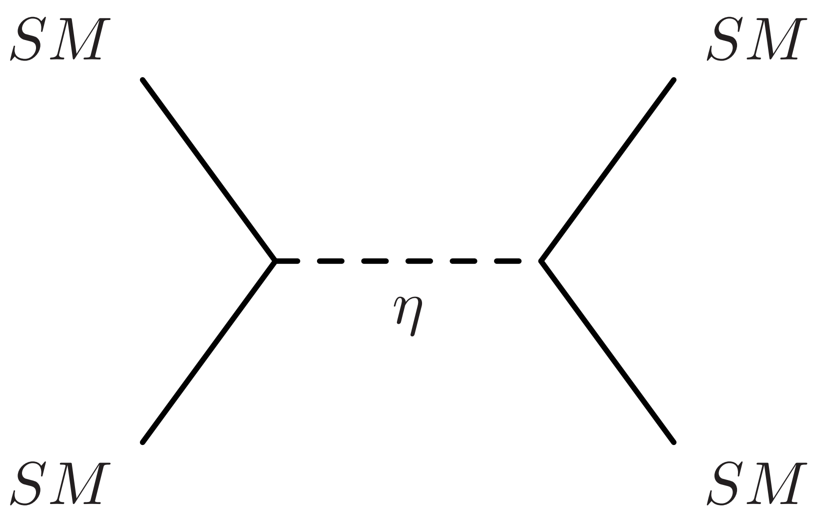

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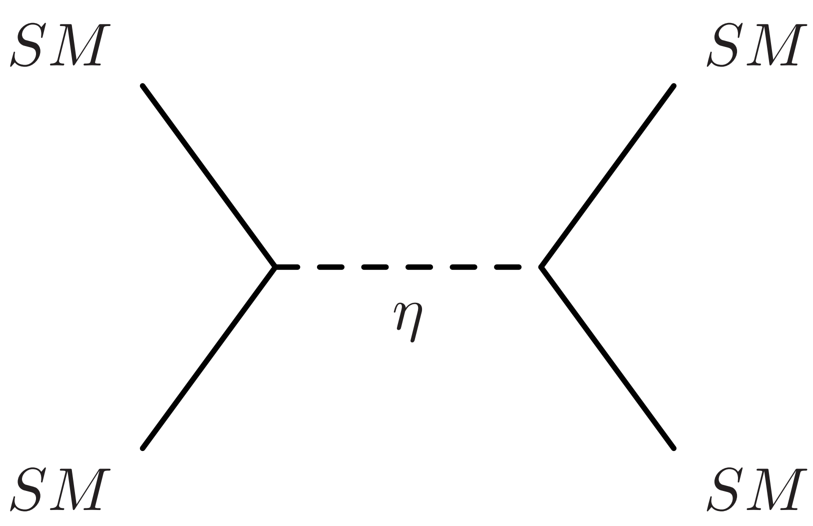


$M \equiv \Lambda$
$p^2 \ll \Lambda^2$

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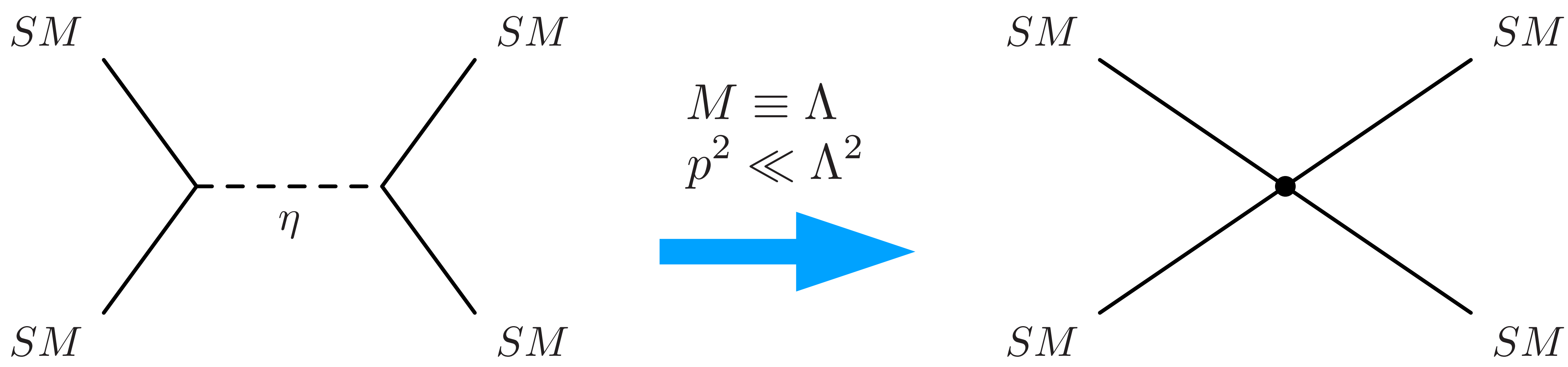

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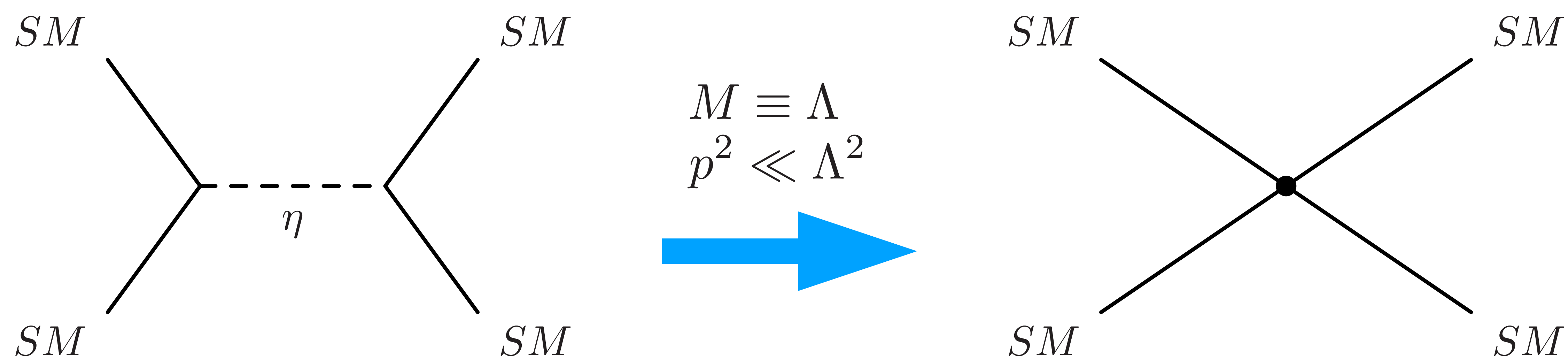


**Heavy states are integrated out** → $$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

**The maximum energy growth of an amplitude can be guessed from the contact term generated by higher dimension operators.**

**Let's consider a 2 to N scattering amplitude (mass dim 2-N):**

$$\mathcal{L} \supset \frac{1}{\Lambda^{K-4}} \mathcal{O}_K \quad \Rightarrow \quad \mathcal{M} \propto \frac{1}{\Lambda^{K-4}} E^{K-N-2}$$

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**Dim 6, 2 to 2**

$$\mathcal{M} \propto \frac{v^m}{\Lambda^2} \frac{E^{2-m+n}}{M_V^n}$$

**While SMEFT respects SSB, the Anomalous Coupling framework does not automatically.**

**AC parametrisation can lead to stronger energy growth.**
**The weak dipole operator in addition to modifications to tbW and ttZ interactions generate corresponding contact terms:**

$$\mathcal{O}_{tW} = i\big(\bar{Q}\sigma^{\mu\nu}\,\tau_I\,t\big)\,\tilde{\phi}\,W^I_{\mu\nu}+\text{h.c.} \quad \rightarrow \quad gv\,\bar{t}_L\sigma^{\mu\nu}t_R\,W^+_\mu W^-_\nu\,,\; gv\,\bar{b}_L\sigma^{\mu\nu}t_R\,Z_\mu W^-_\nu$$

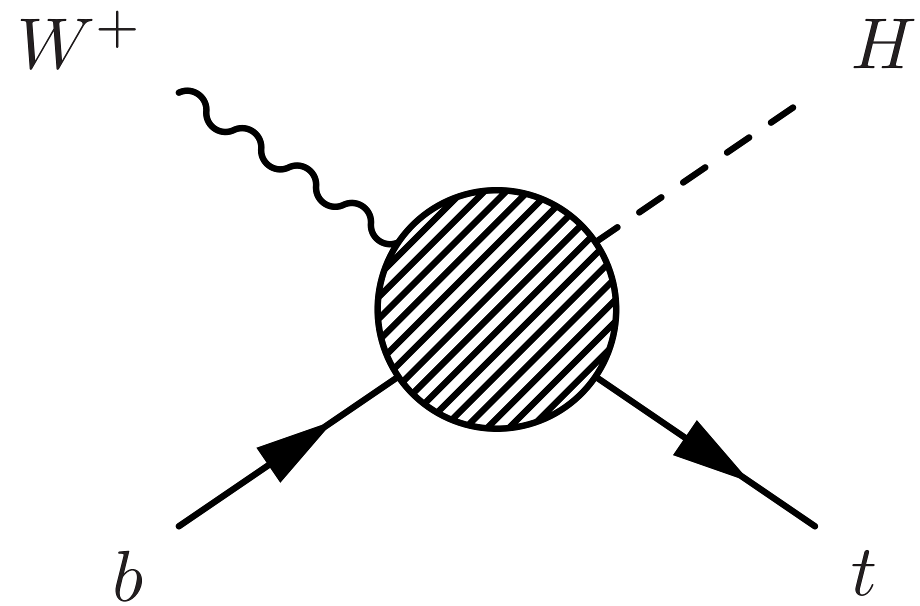
**These terms generate a $E^3$ energy growth which is exactly canceled by other contributions due to SU(2) gauge invariance.**
**On the other hand in the AC framework, including dipole-like interaction**

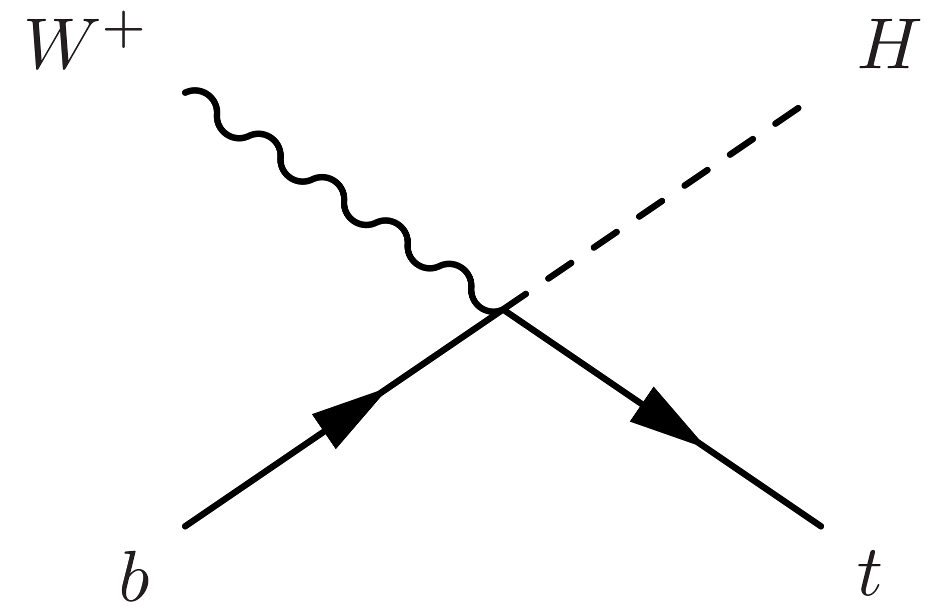
$$\mathcal{L}_{\text{dip.}} \supset -\frac{g}{\sqrt{2}}\bar{b}\,\sigma^{\mu\nu}\,(g_L P_L + g_R P_R)\,t\,\partial_\mu\,W_\nu$$

**Top decay is fine, tZj would be described differently.**

$$b\,W^+ \to t\,H$$

$$\mathcal{O}_{\varphi Q}^{(3)} \to v\,H\,W^+\,\bar{t}_L\,\gamma^\mu\,b_L + \text{h.c.}$$




$$\mathcal{M} \propto \frac{v^m}{\Lambda^2}\,\frac{E^{2-m+n}}{M_V^n}$$

| $\lambda_b,\ \lambda_W,\ \lambda_t$ | SM | $\mathcal{O}_{\varphi W}$ | $\mathcal{O}_{t\varphi}$ | $\mathcal{O}_{tW}$ | $\mathcal{O}_{\varphi Q}^{(3)}$ | $\mathcal{O}_{\varphi tb}$ |
|---|---|---|---|---|---|---|
| $-,0,-$ | $s^0$ | $s^0$ | $s^0$ | $s^0$ | $\sqrt{s(s+t)}$ | $-$ |
| $-,0,+$ | $\frac{1}{\sqrt{s}}$ | $-$ | $\sqrt{-t}v$ | $\frac{s m_W}{\sqrt{-t}}$ | $\sqrt{-t}m_t$ | $-$ |
| $+,0,-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_t$ |
| $+,0,+$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{s(s+t)}$ |
| $-,-,-$ | $\frac{1}{\sqrt{s}}$ | $\frac{s m_W}{\sqrt{-t}}$ | $-$ | $\sqrt{-t}m_t$ | $\sqrt{-t}m_W$ | $-$ |
| $-,-,+$ | $\frac{1}{s}$ | $-$ | $s^0$ | $\sqrt{s(s+t)}$ | $s^0$ | $-$ |
| $-,+,-$ | $\frac{1}{\sqrt{s}}$ | $\frac{m_W(s+t)}{\sqrt{-t}}$ | $-$ | $-$ | $-$ | $-$ |
| $-,+,+$ | $s^0$ | $s^0$ | $-$ | $s^0$ | $s^0$ | $-$ |
| $+,\pm,-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $s^0$ |
| $+,-,+$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $+,+,+$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_W$ |

**We indeed observe a $E^2$ growth in the (-,0,-) amplitude.**

**We turn to study how the energy growing behaviour can be probed by physical processes at colliders.**

- **2 to 3 and 2 to 4 scattering processes.**
- **Assess the sensitivity to the Wilson coefficients.**
- **We considered pp collider at 13 and 27 TeV as well as ee collider operating at 380, 1500 and 3000 GeV.**

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|---|---|---|---|---|---|
| | Individual | Marginalised | | Individual | Marginalised |
| $\mathcal{O}_{\varphi D}$ | [-0.021,0.0055] [16] | [-0.45,0.50] [16] | $\mathcal{O}_{t\varphi}$ | [-5.3,1.6] [17] | [-60,10] [17] |
| $\mathcal{O}_{\varphi\Box}$ | [-0.78,1.44] [16] | [-1.24,16.2] [16] | $\mathcal{O}_{tB}$ | [-7.09,4.68] [18] | – |
| $\mathcal{O}_{\varphi B}$ | [-0.0033,0.0031] [16] | [-0.13,0.21] [16] | $\mathcal{O}_{tW}$ | [-0.4,0.2] [17] | [-1.8,0.9] [17] |
| $\mathcal{O}_{\varphi W}$ | [-0.0093,0.011] [16] | [-0.50,0.40] [16] | $\mathcal{O}_{\varphi Q}^{(1)}$ | [-3.10,3.10] [18] | – |
| $\mathcal{O}_{\varphi WB}$ | [-0.0051,0.0020] [16] | [-0.17,0.33] [16] | $\mathcal{O}_{\varphi Q}^{(3)}$ | [-0.9,0.6] [17] | [-5.5,5.8] [17] |
| $\mathcal{O}_{W}$ | [-0.18,0.18] [19] | – | $\mathcal{O}_{\varphi t}$ | [-6.4,7.3] [17] | [-13,18] [17] |
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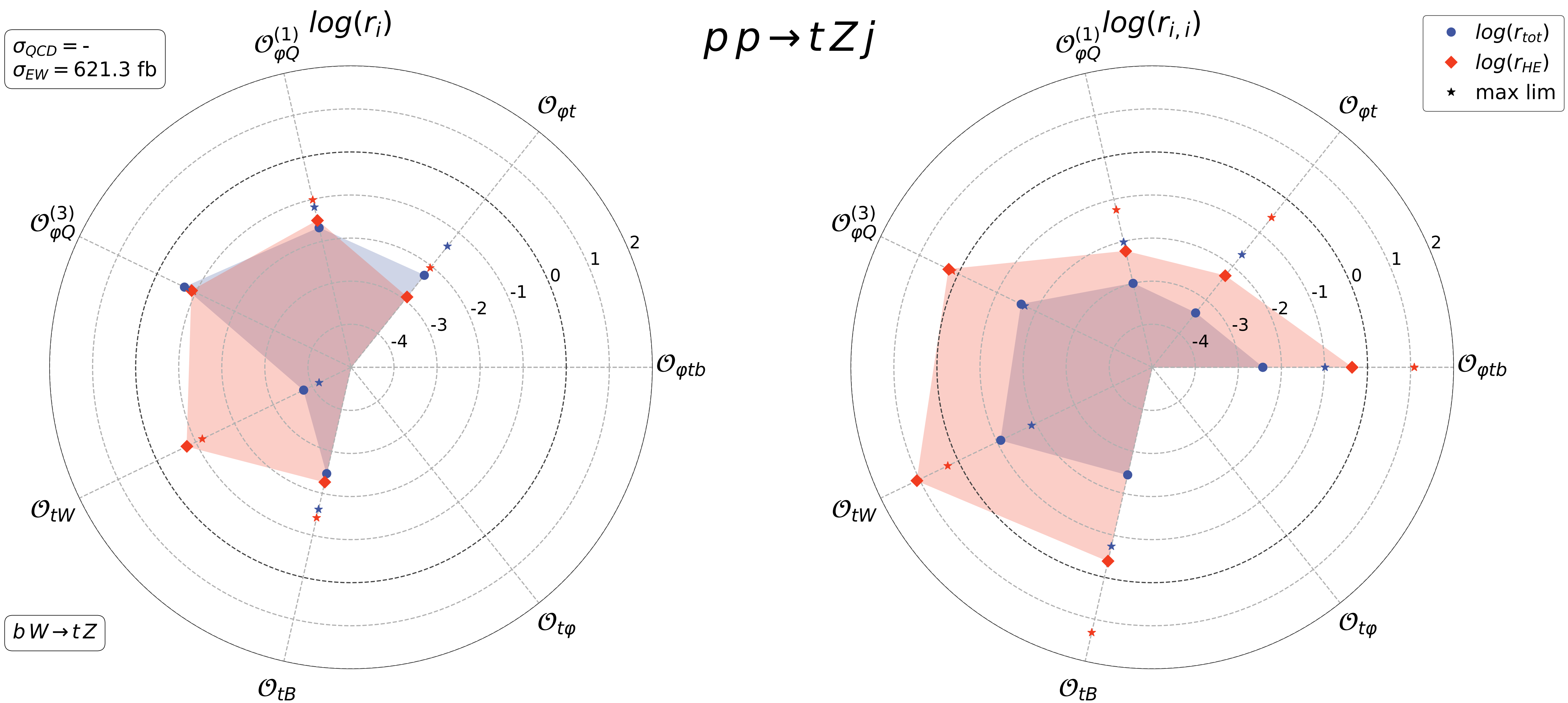
MCnet

$$R(c_i) \equiv \frac{\sigma}{\sigma_{SM}} = 1 + c_i \frac{\sigma^i_{Int}}{\sigma_{SM}} + c^2_{i,i} \frac{\sigma^{i,i}_{Sq}}{\sigma_{SM}} = 1 + r_i + r_{i,i}.$$

- **Computation performed with MG5 and SMEFT@NLO, in 5 flavour scheme.**
- **We compute the interference and square contribution for each operator relative to the EW SM cross section for p p collisions.**
- **The relative impact is computed for each operator with Wilson coefficient set to 1 TeV$^{-2}$.**
- **Compute both inclusive and high-energy restricted cross section.**
- **QCD background.**



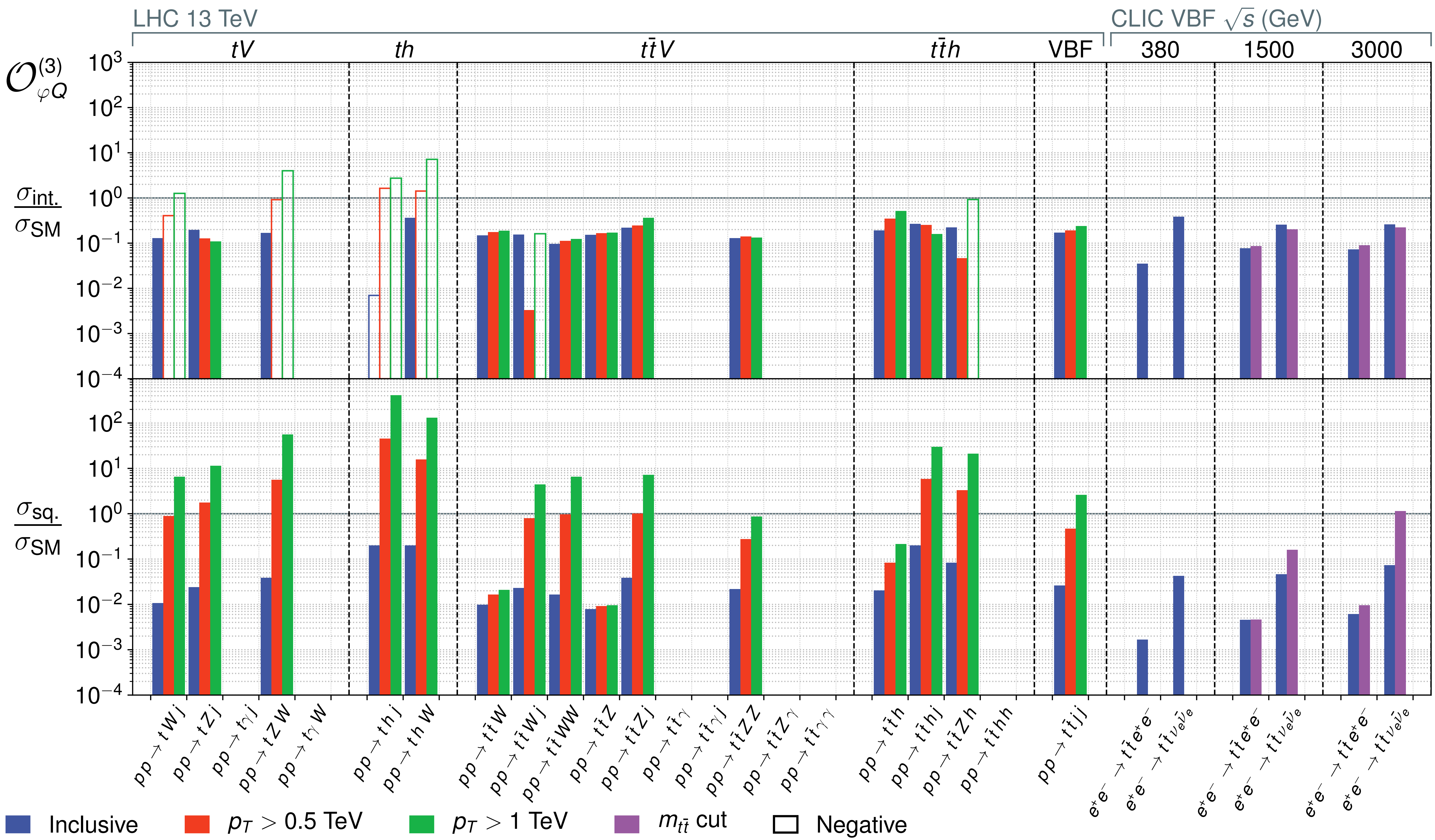
MCnet



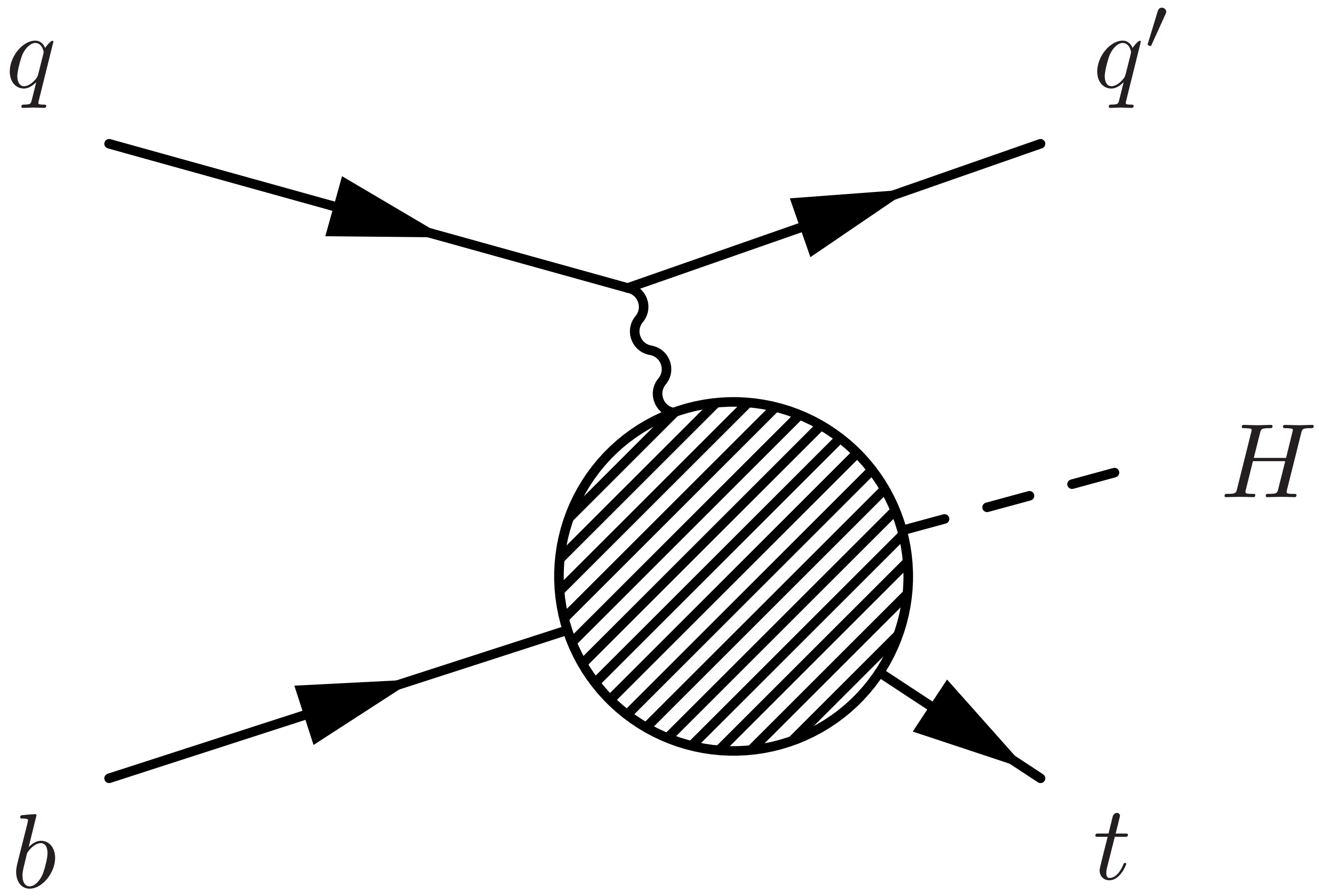

**CMS collaboration arXiv:1812.05900**



MCnet


LHC 13 TeV
CLIC VBF $\sqrt{s}$ (GeV)
$tV$
$th$
$t\bar{t}V$
$t\bar{t}h$
VBF
380
1500
3000
$\mathcal{O}^{(3)}_{\varphi Q}$
$\frac{\sigma_{\text{int.}}}{\sigma_{\text{SM}}}$
$\frac{\sigma_{\text{sq.}}}{\sigma_{\text{SM}}}$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$pp \to tWj$
$pp \to tZj$
$pp \to t\gamma j$
$pp \to tZW$
$pp \to t\gamma W$
$pp \to thj$
$pp \to thW$
$pp \to t\bar{t}W$
$pp \to t\bar{t}Wj$
$pp \to t\bar{t}WW$
$pp \to t\bar{t}Z$
$pp \to t\bar{t}Zj$
$pp \to t\bar{t}\gamma$
$pp \to t\bar{t}\gamma j$
$pp \to t\bar{t}ZZ$
$pp \to t\bar{t}Z\gamma$
$pp \to t\bar{t}\gamma\gamma$
$pp \to t\bar{t}h$
$pp \to t\bar{t}hj$
$pp \to t\bar{t}Zh$
$pp \to t\bar{t}hh$
$pp \to t\bar{t}jj$
$e^+e^- \to t\bar{t}e^+e^-$
$e^+e^- \to t\bar{t}\nu_e\bar{\nu}_e$
Inclusive
$p_T > 0.5$ TeV
$p_T > 1$ TeV
$m_{t\bar{t}}$ cut
Negative

**E = 2 TeV**



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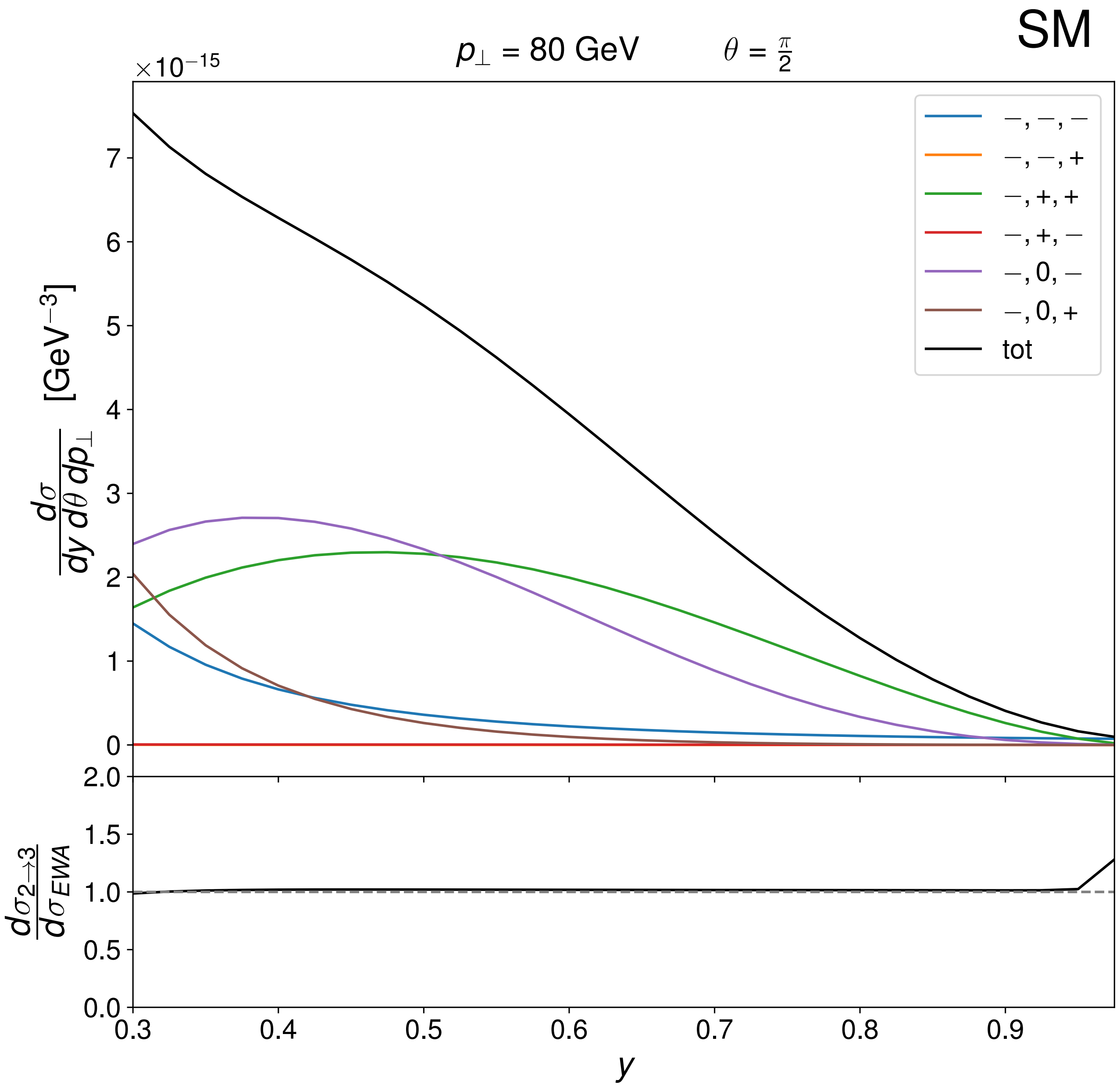
SM
$p_\perp$ = 80 GeV
$\theta = \frac{\pi}{2}$
$\times 10^{-15}$
$\frac{d\sigma}{dy\, d\theta\, dp_\perp}$ [GeV$^{-3}$]
−, −, −
−, −, +
−, +, +
−, +, −
−, 0, −
−, 0, +
tot
$\frac{d\sigma_{2\to3}}{d\sigma_{EWA}}$
$y$
0
1
2
3
4
5
6
7
0.0
0.5
1.0
1.5
2.0
0.3
0.4
0.5
0.6
0.7
0.8
0.9

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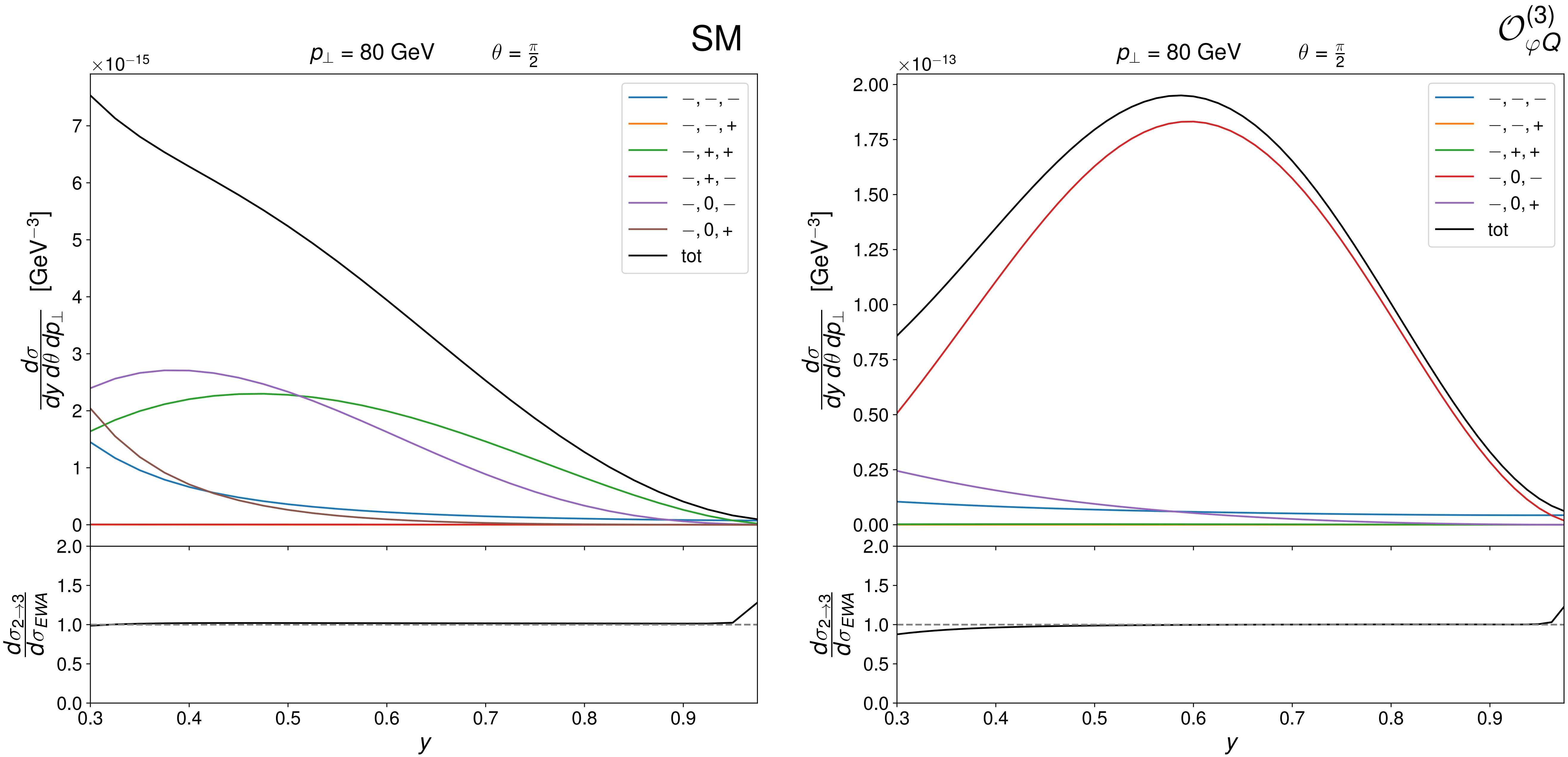
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−, −, −
−, −, +
−, +, +
−, +, −
−, 0, −
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tot
$\frac{d\sigma_{2\to 3}}{d\sigma_{EWA}}$
$y$
$\mathcal{O}_{\varphi Q}^{(3)}$
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$\times 10^{-13}$
$\frac{d\sigma}{dy\, d\theta\, dp_\perp}$ [GeV$^{-3}$]
−, −, −
−, −, +
−, +, +
−, 0, −
−, 0, +
tot
$\frac{d\sigma_{2\to 3}}{d\sigma_{EWA}}$
$y$

In summary, we found that:

- tZW and tZj optimal to access b W to t Z.
- tHW and tHj optimal for b W to t H.
- ttX processes are challenging because suppressed by s-channel propagator.
- Adding a jet increases the sensitivity (J. A. Dror et al. arXiv:1511.03674).
- ttXY and VBF-tt are promising but rate-limited (e+ e- collider for VBF).
- t Z to t H and t H to t H are the most difficult (future colliders).

$$\chi^2(\boldsymbol{c}) \equiv \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_i^{(\rm th)}(\boldsymbol{c}) - \sigma_i^{(\rm exp)}\right) \left(\text{cov}^{-1}\right)_{ij} \left(\sigma_j^{(\rm th)}(\boldsymbol{c}) - \sigma_j^{(\rm exp)}\right)$$

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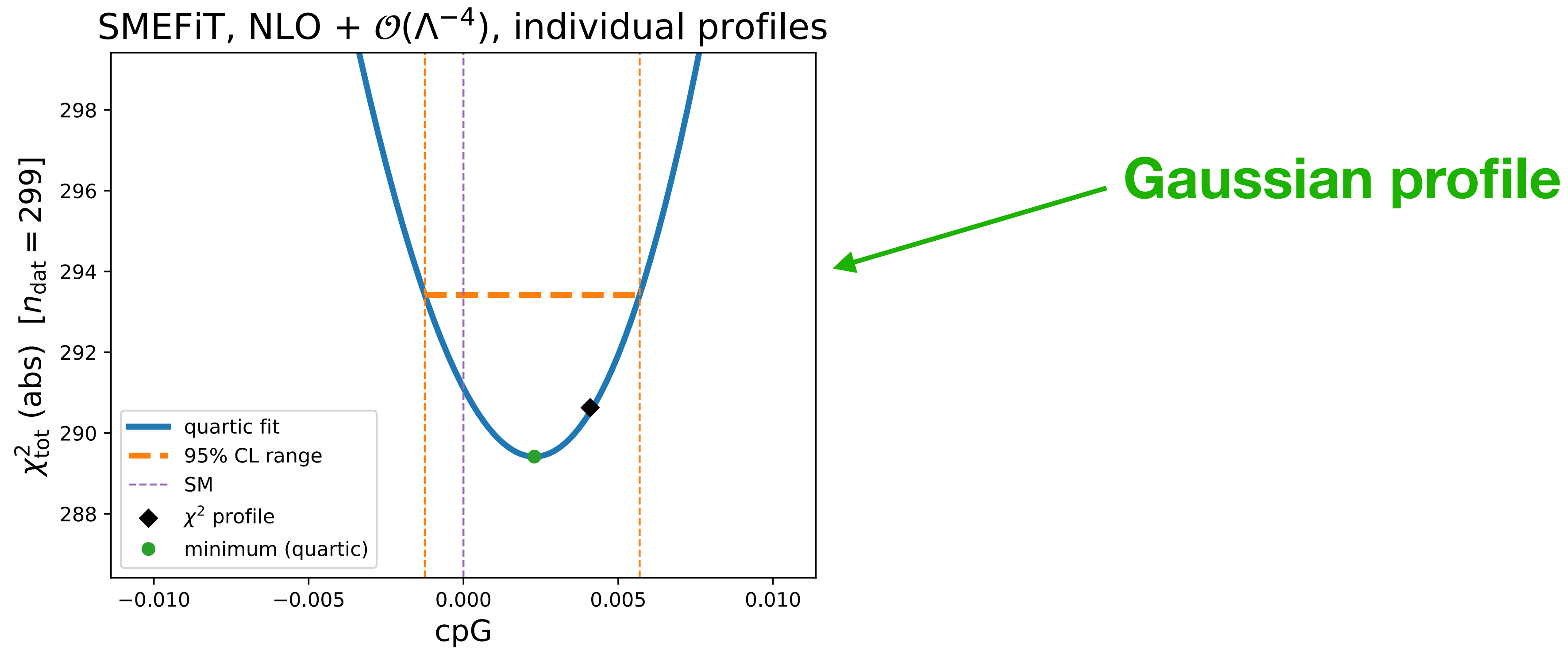

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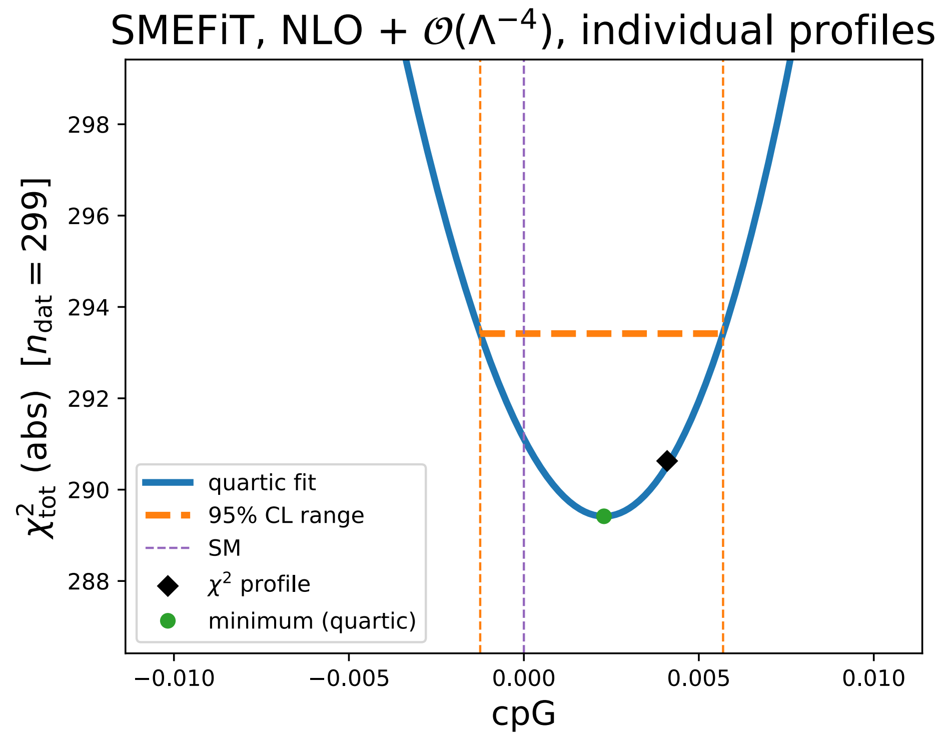
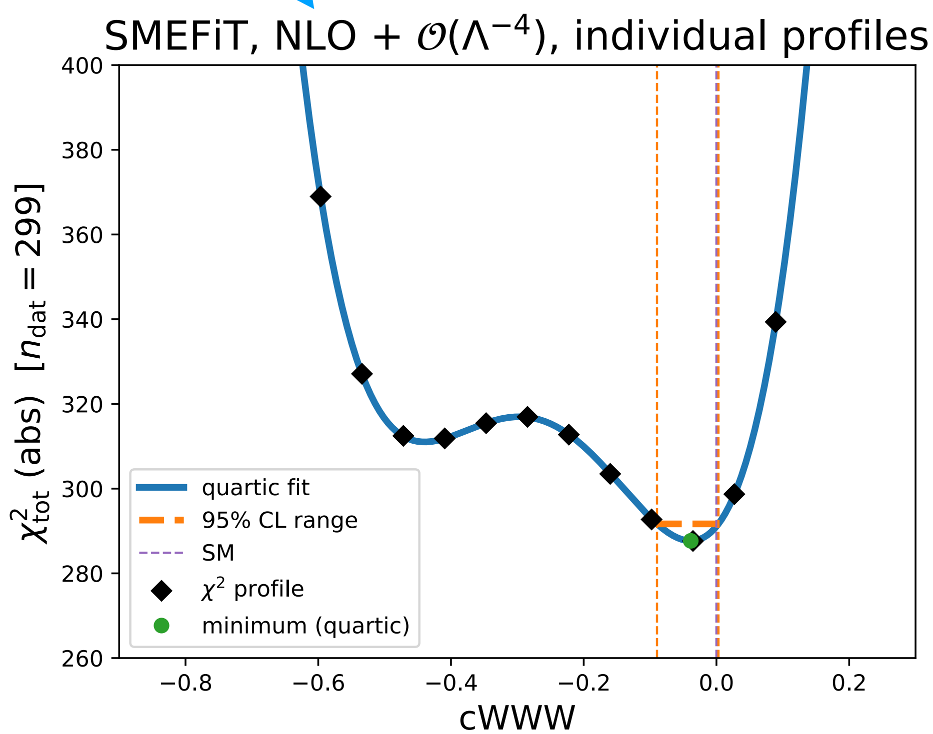



Gaussian profile

Non gaussian global minimum






MCnet

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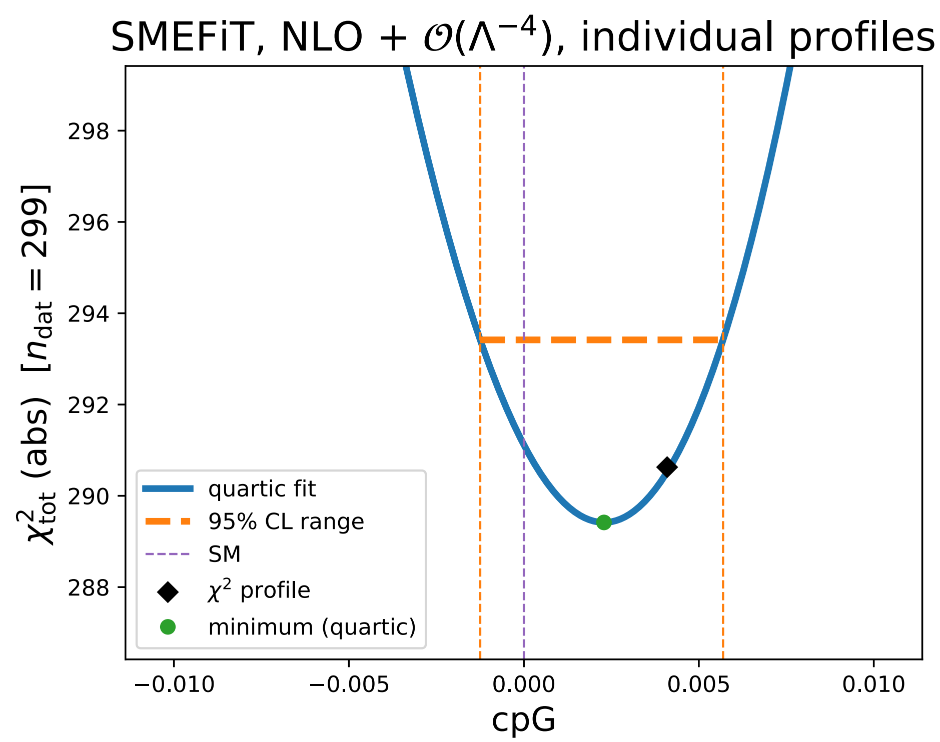
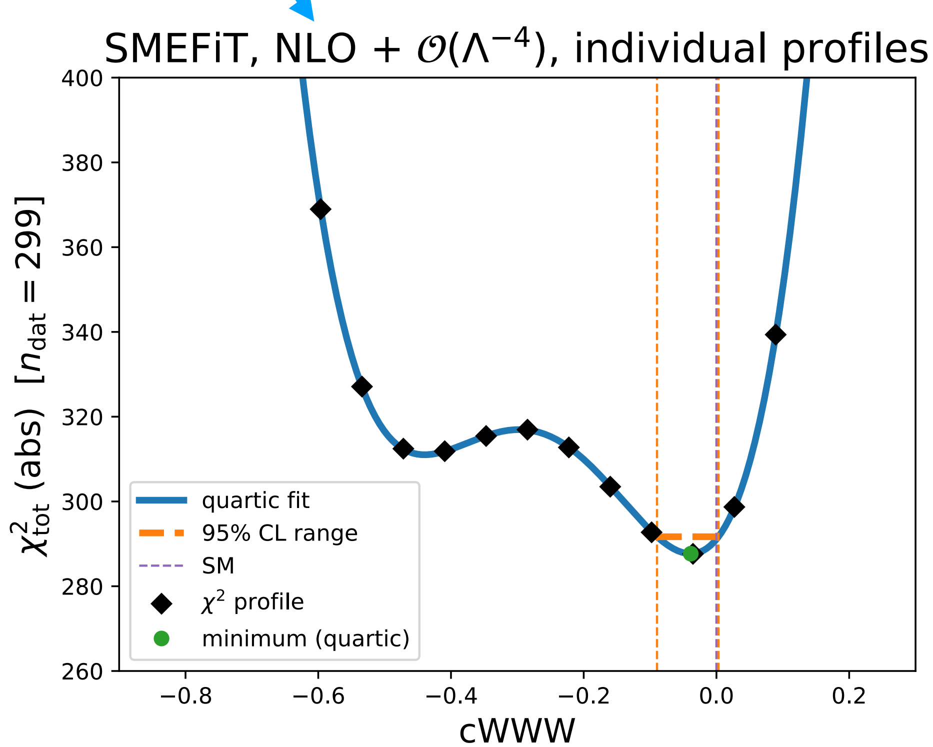
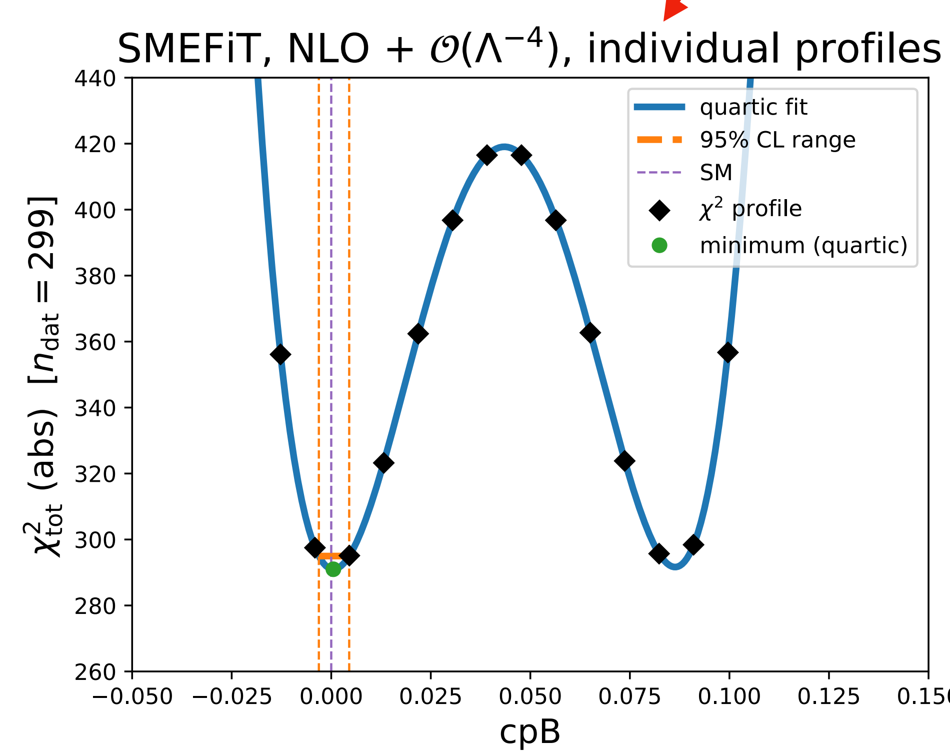



**Gaussian profile**

**Non gaussian global minimum**

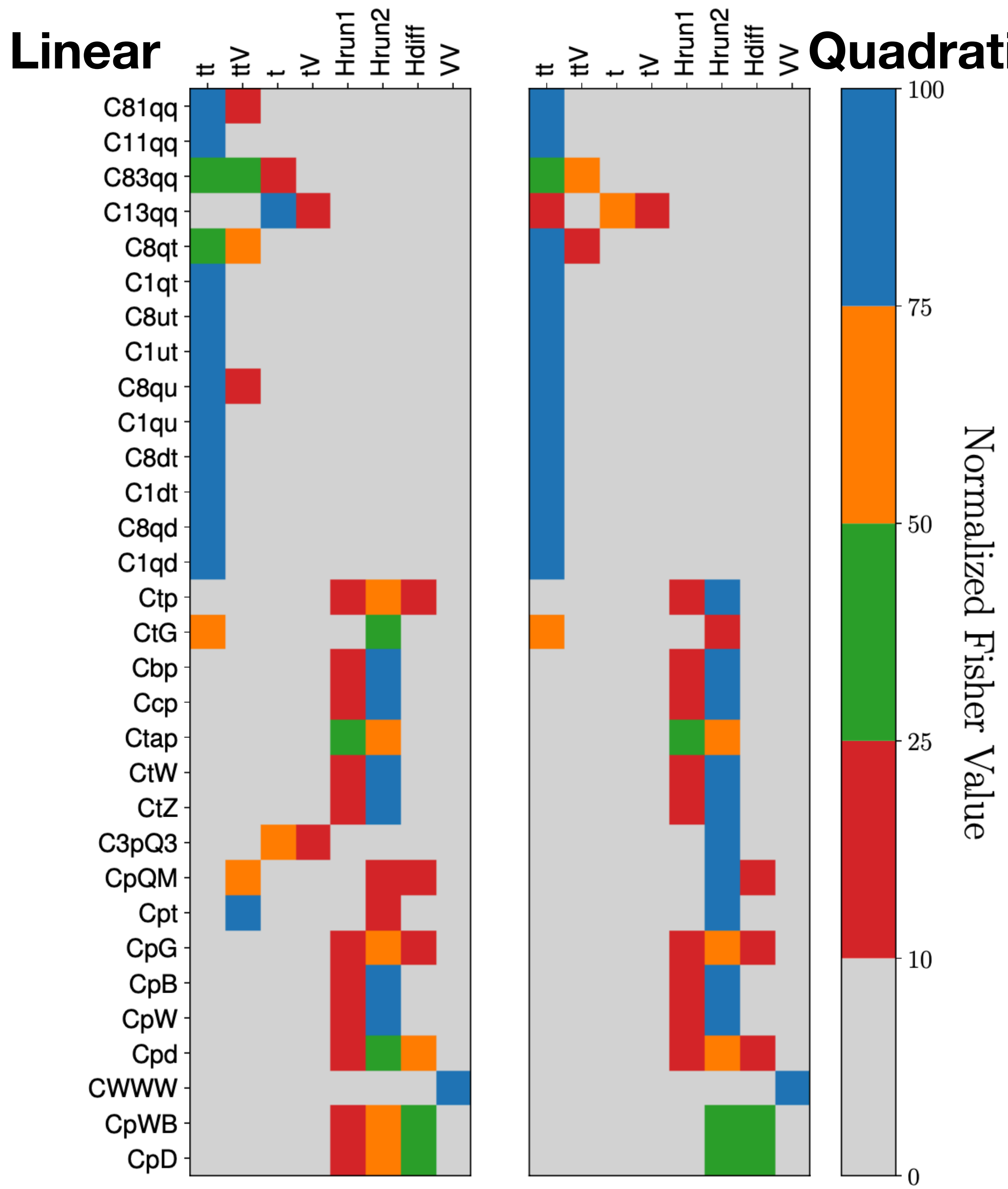
**Degenerate minima**



**Useful to gain insight from Information Geometry**

$$I_{ij}(\boldsymbol{c}) = -\mathrm{E}\left[\frac{\partial^2 \ln f\left(\boldsymbol{\sigma}_{\exp} \mid \boldsymbol{c}\right)}{\partial c_i \partial c_j}\right]$$






MCnet

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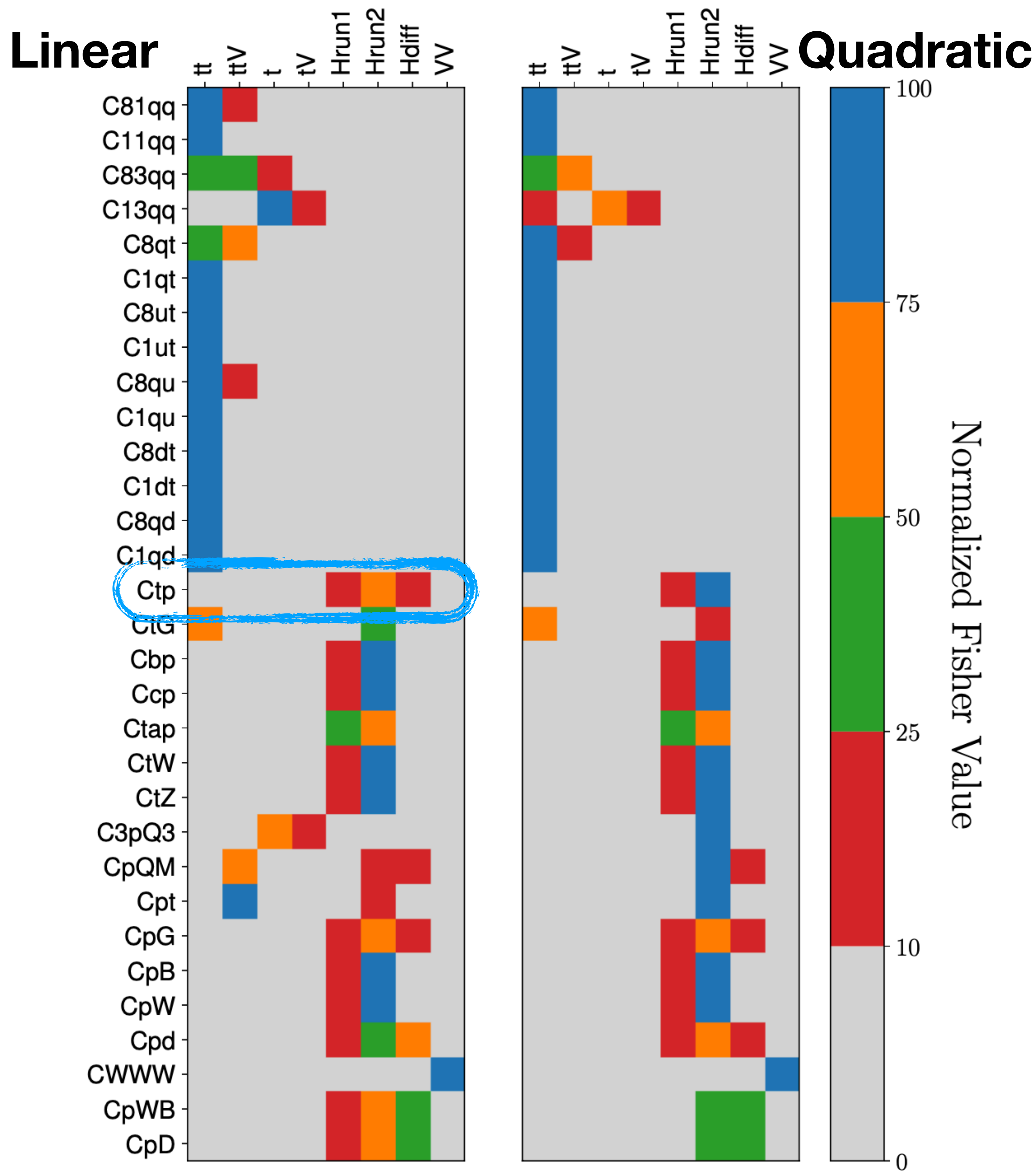


**Top Yukawa**

**Useful to gain insight from Information Geometry**

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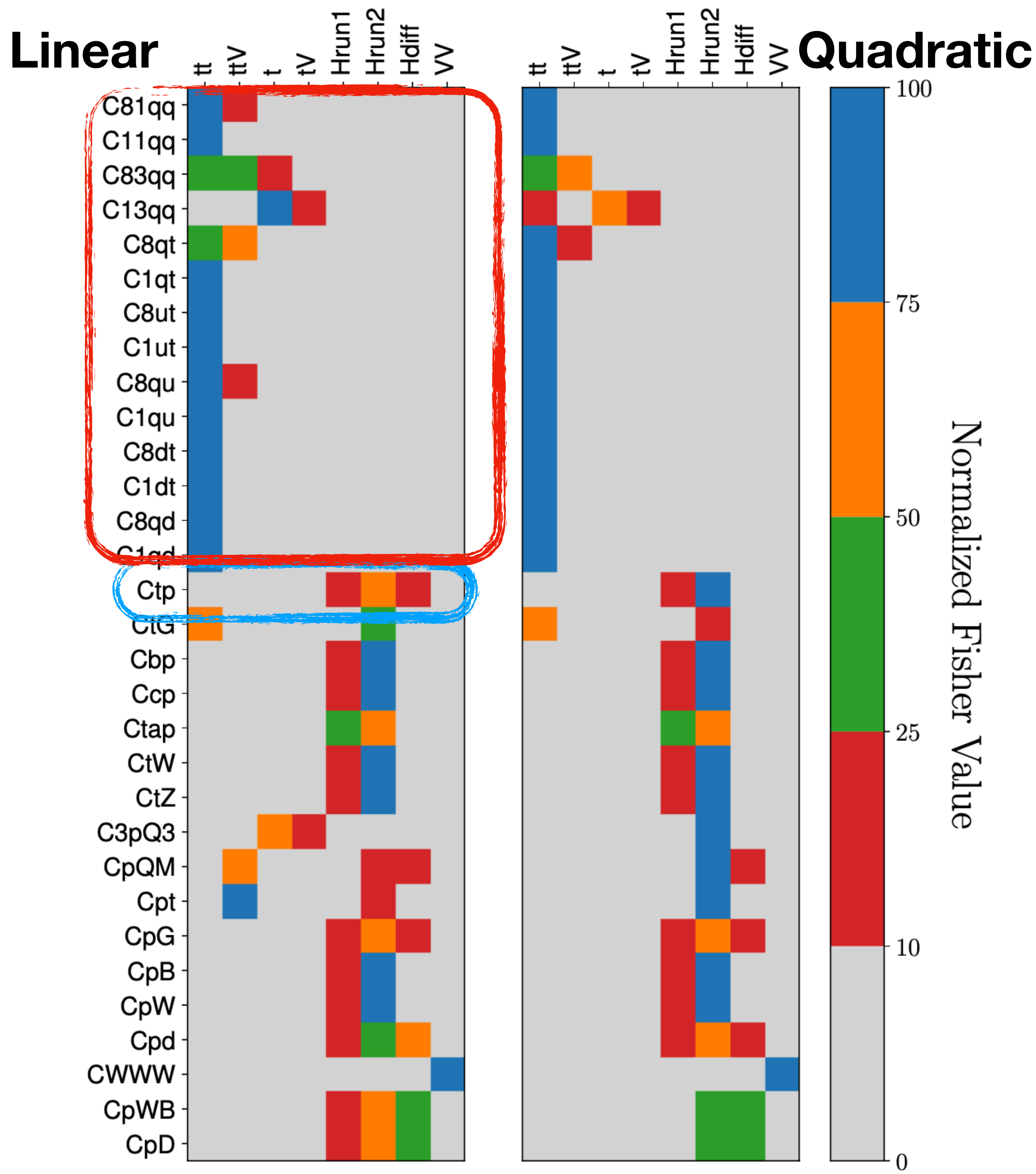


**Top Yukawa**

**Four fermion operators**



MCnet

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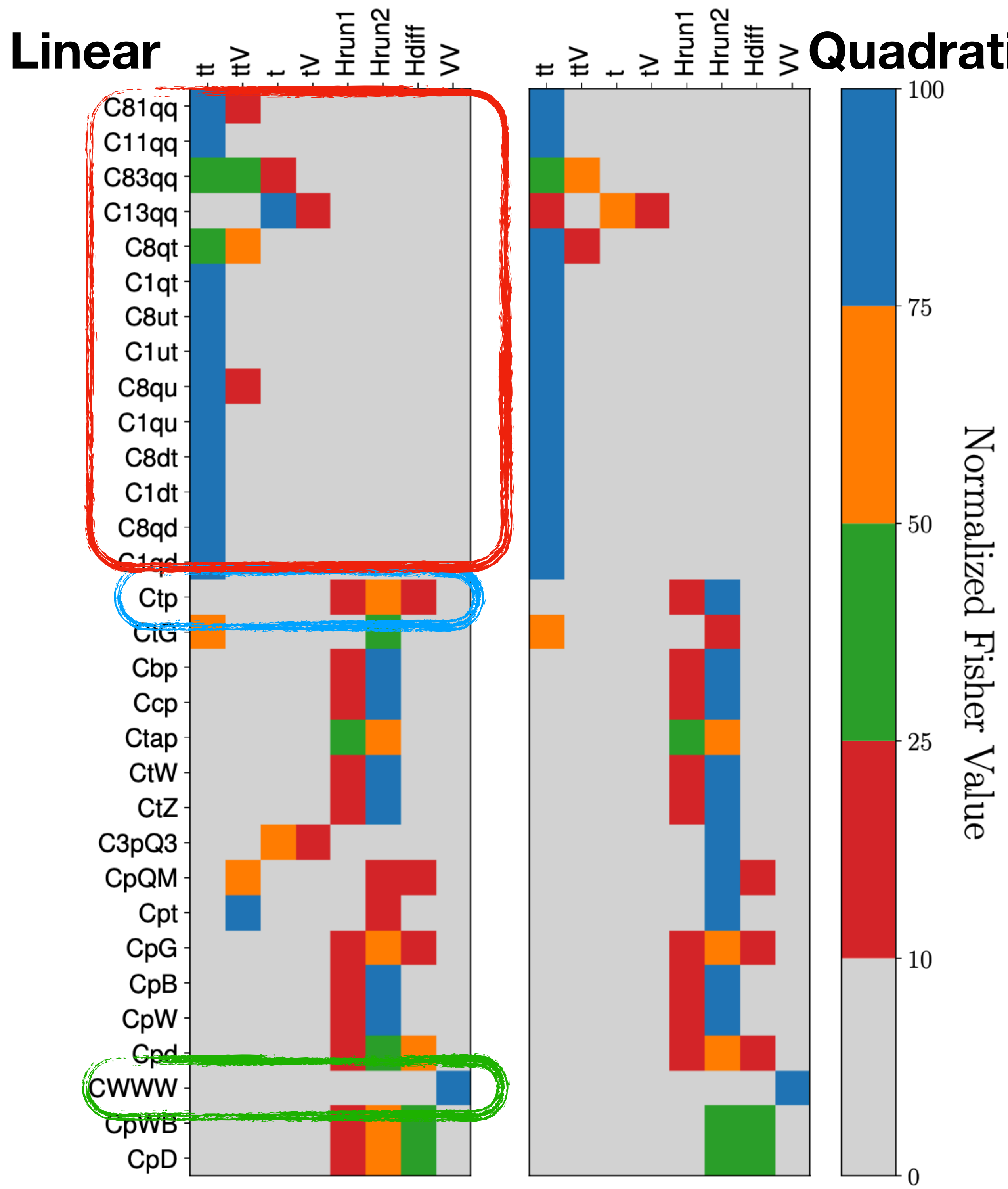


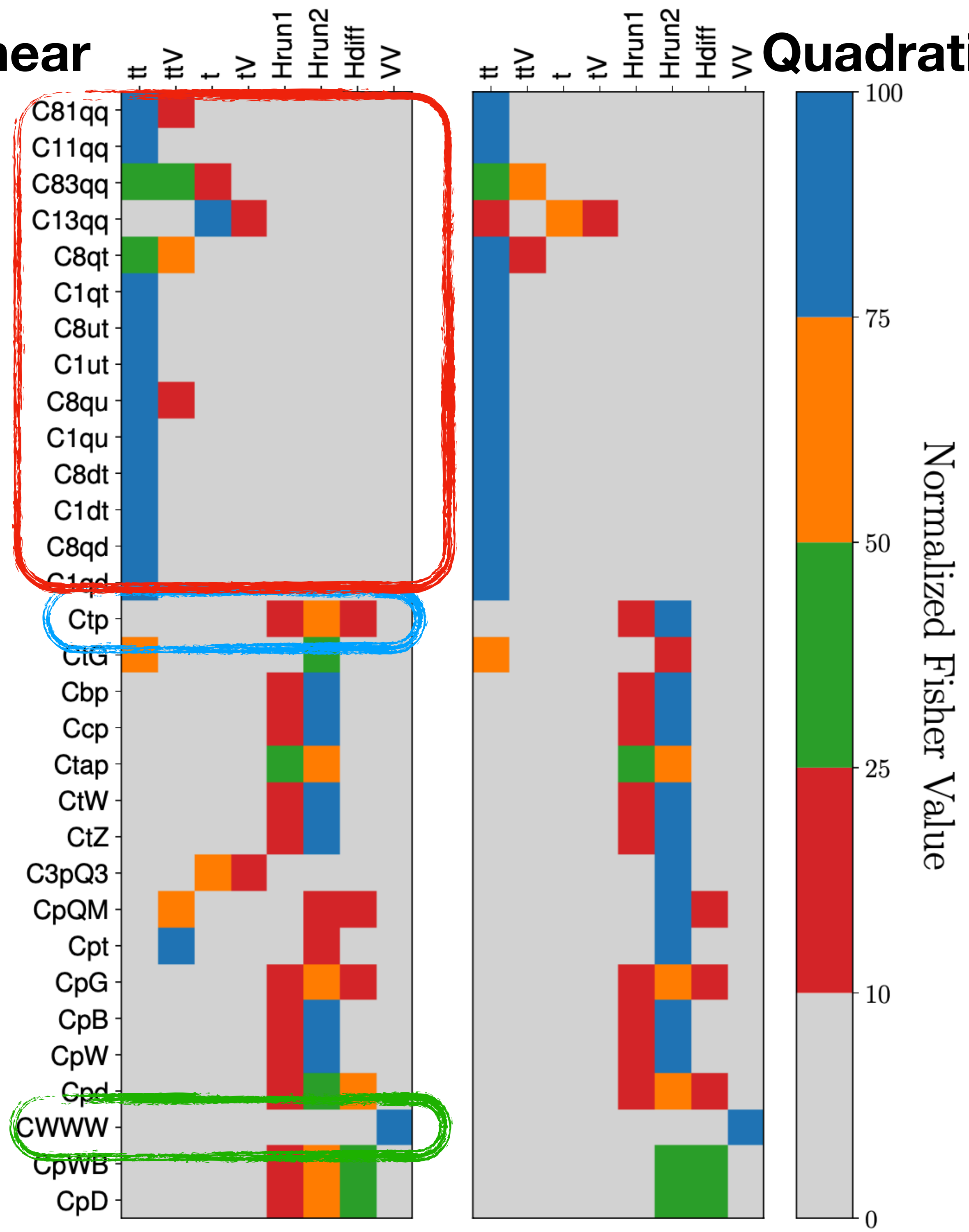

**Top Yukawa**

**Four fermion operators**

**TGC operator**

**Useful to gain insight from Information Geometry**

$$I_{ij}(\boldsymbol{c}) = -\mathrm{E}\left[\frac{\partial^2 \ln f\left(\boldsymbol{\sigma}_{\exp} \mid \boldsymbol{c}\right)}{\partial c_i \partial c_j}\right]$$




**Top Yukawa**

**Four fermion operators**

**TGC operator**

**In the quadratic case the picture does not change much**

**MCfit:** generate MC replicas to construct **probability distribution** in experimental data space.
Determine EFT coefficients **replica by replica.**

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(\mathcal{O}_i^{(\rm th)}\left(\{c_n^{(k)}\}\right) - \mathcal{O}_i^{(\rm art)(k)}\right)({\rm cov}^{-1})_{ij}\left(\mathcal{O}_j^{(\rm th)}\left(\{c_n^{(k)}\}\right) - \mathcal{O}_j^{(\rm art)(k)}\right)$$

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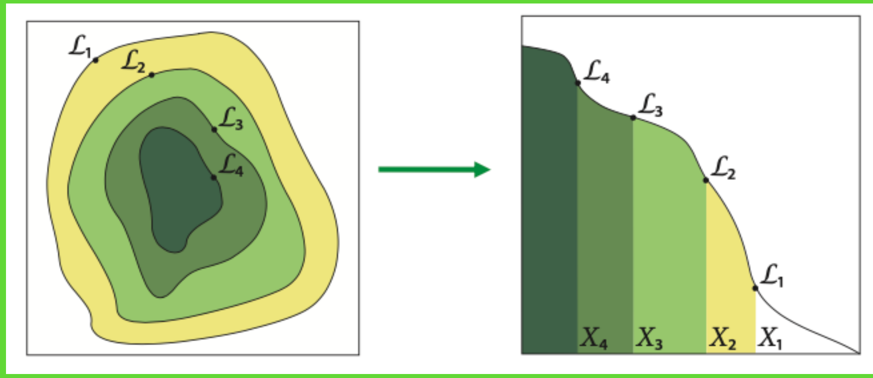
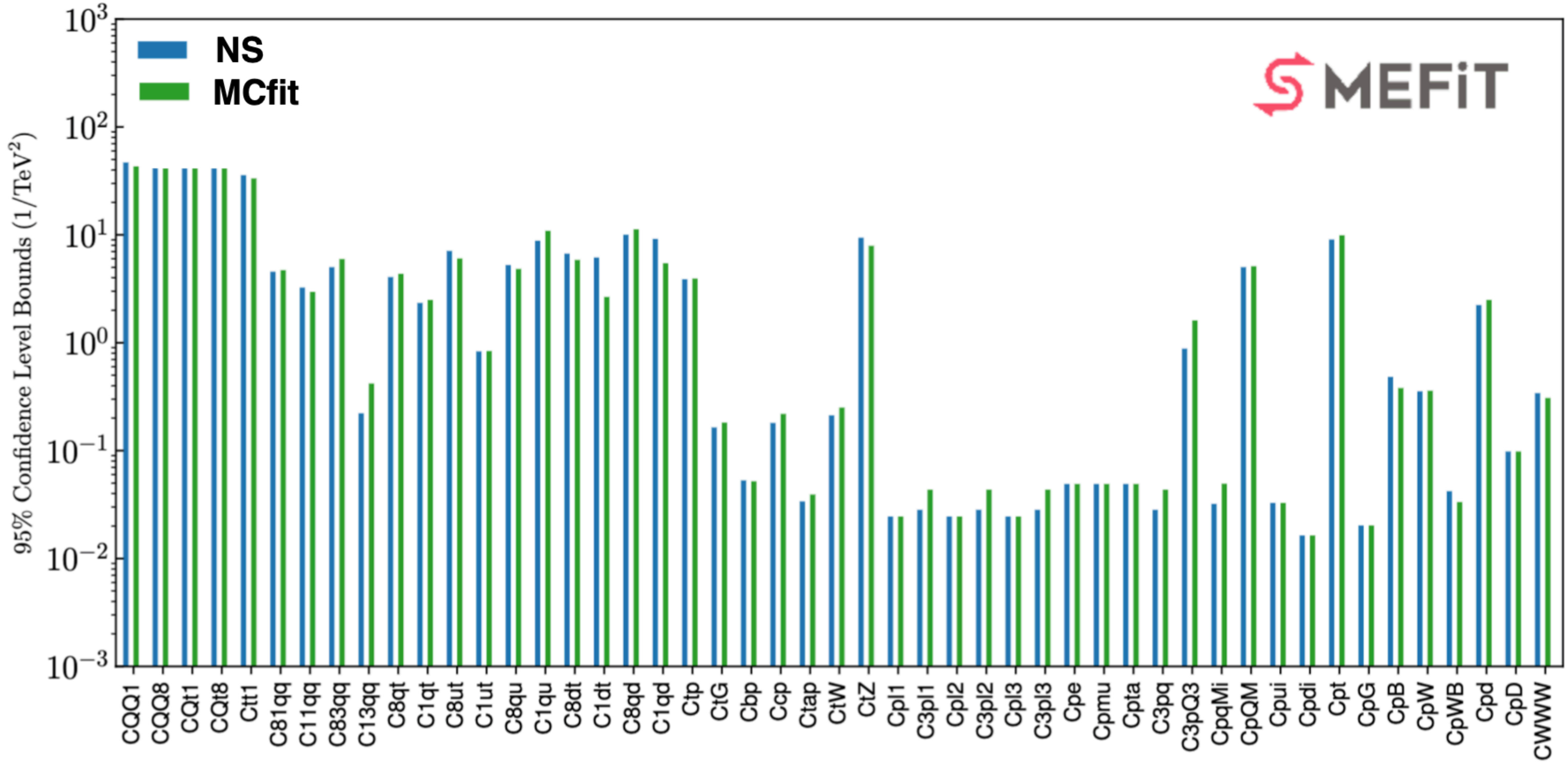
**Nested Sampling:** statistical mapping of the likelihood**.**

$$Z = \int d^N c \mathscr{L}\left(\text{data} \,|\, \vec{c}\right) \pi(\vec{c}) = \int_0^1 dX \mathscr{L}(X)$$



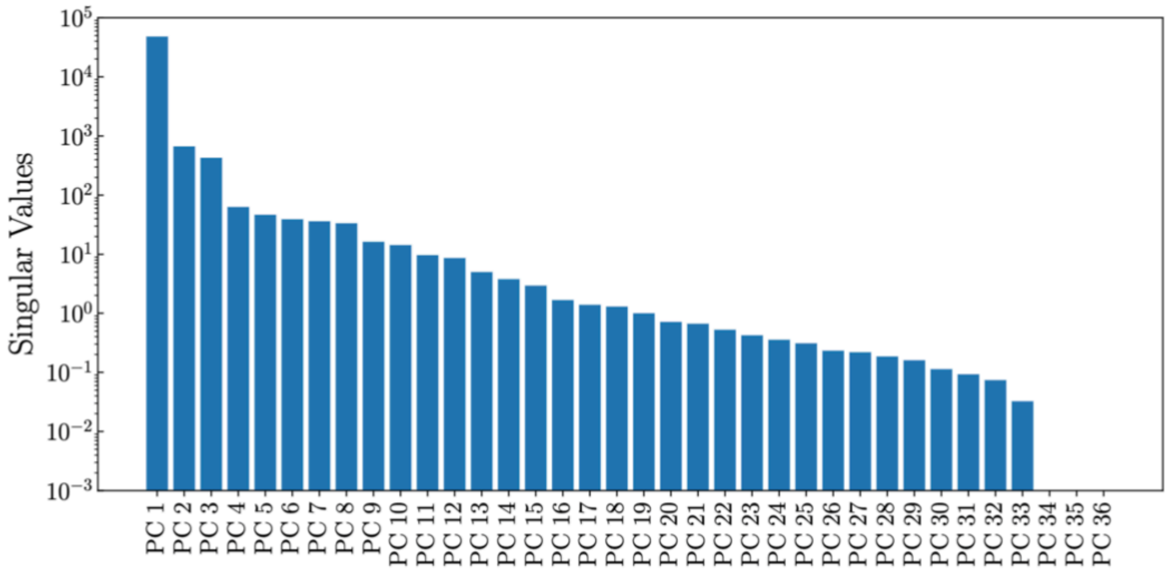

Samples from prior space to locate maximum.
No need for optimisers.
Construct posterior distribution.

**MCfit:** generate MC replicas to construct **probability distribution** in

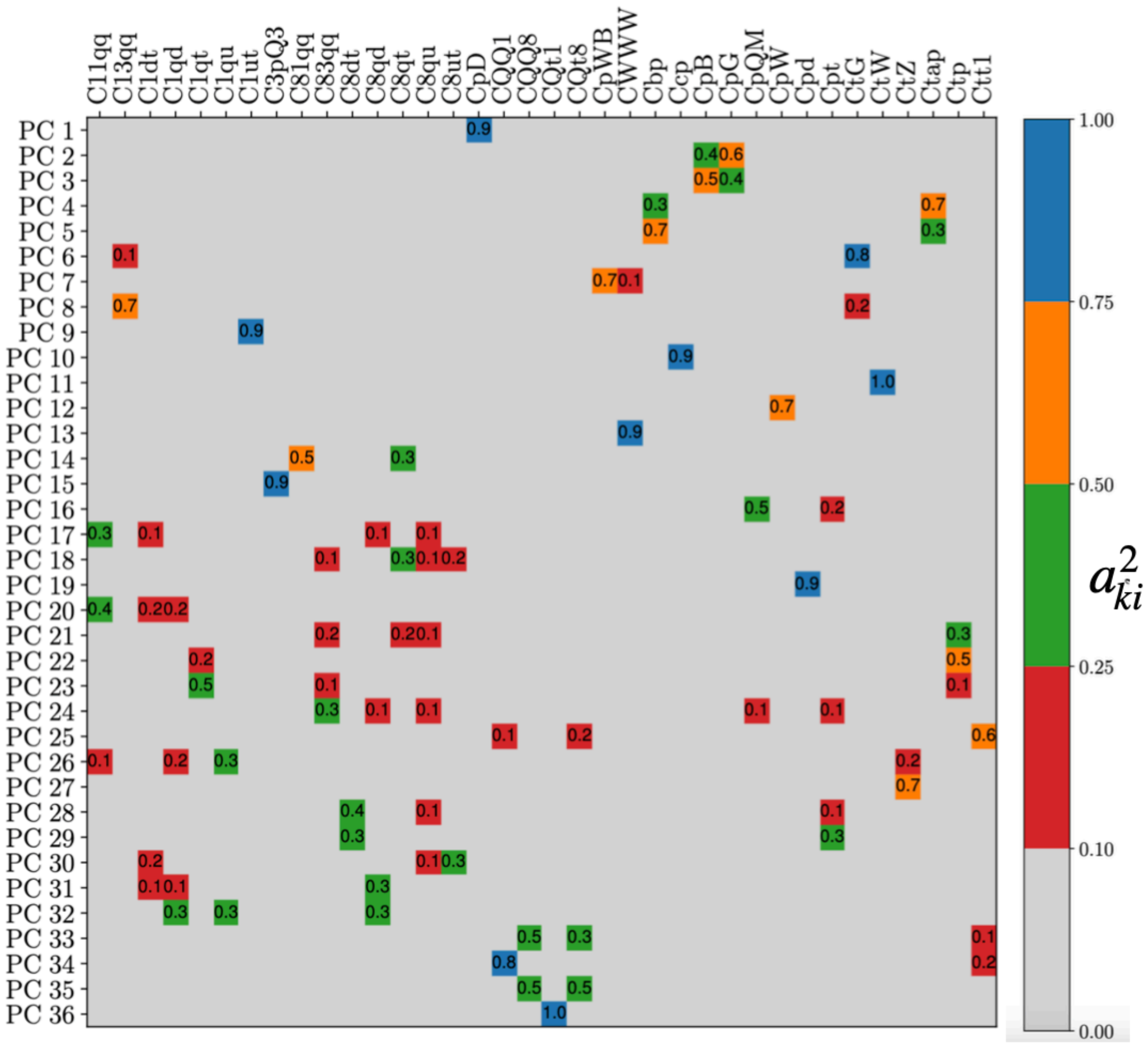




Construct posterior distribution.




$$\mathrm{PC}_k = \sum_{i=1}^{n_{\mathrm{op}}} a_{ki} c_i, \quad k = 1, \ldots, n_{\mathrm{op}} \qquad \left( \sum_{i=1}^{n_{\mathrm{op}}} a_{ki}^2 = 1 \forall k \right)$$



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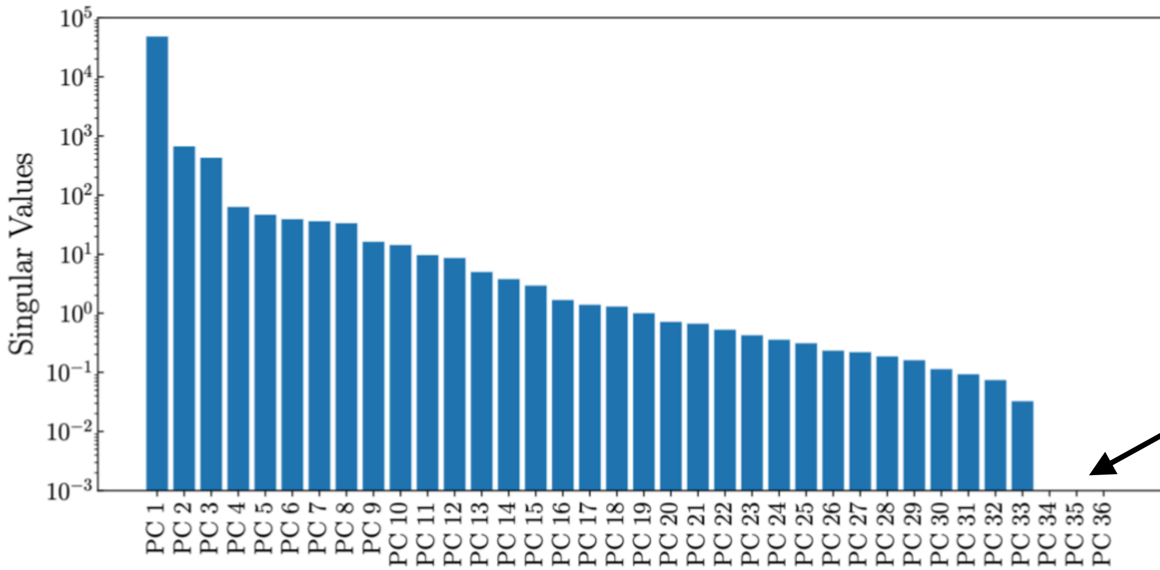
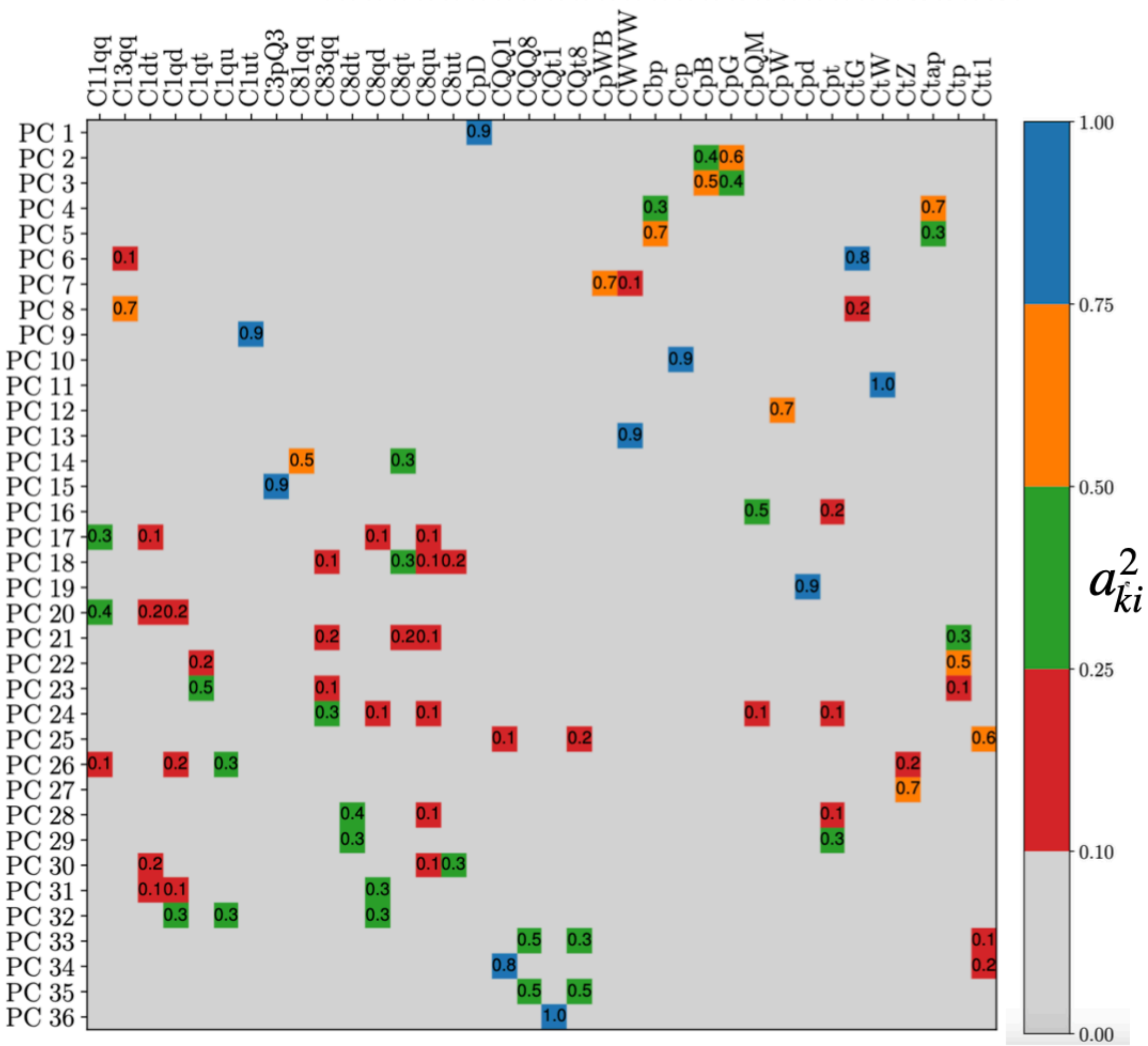
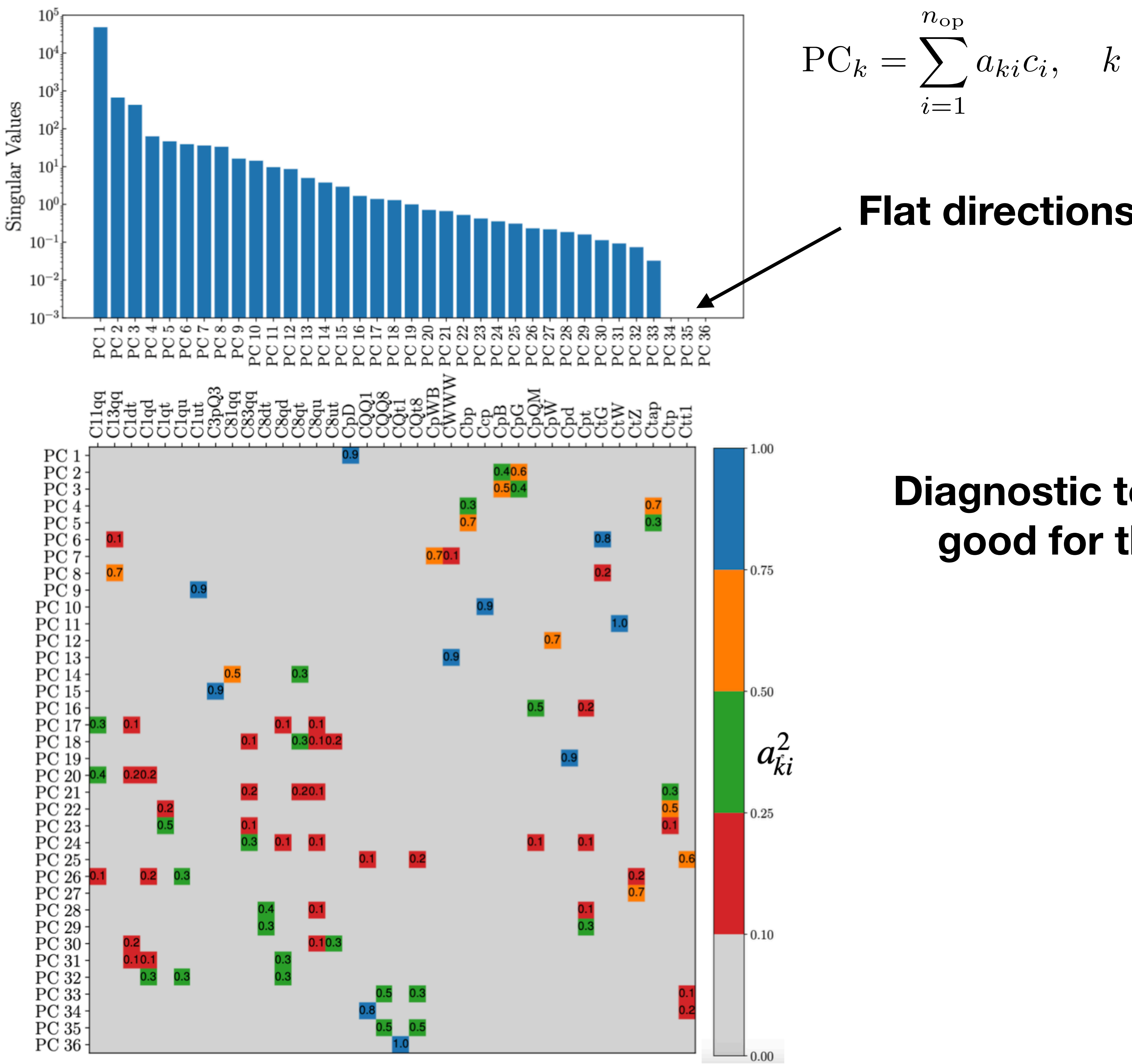



**Flat directions**



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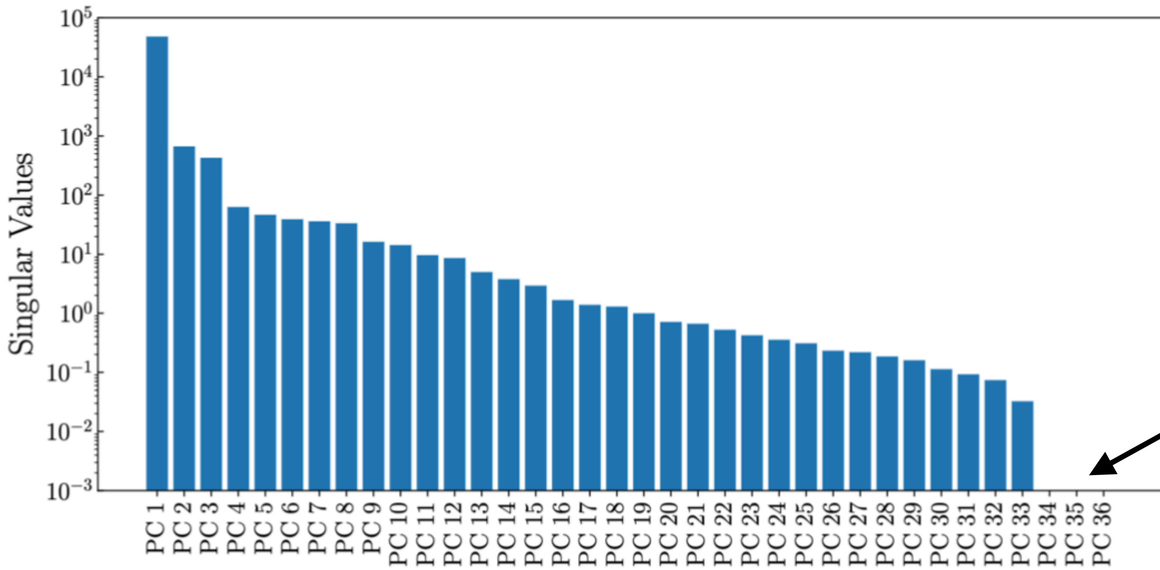
**Diagnostic tool: is the basis used good for the dimensionality?**

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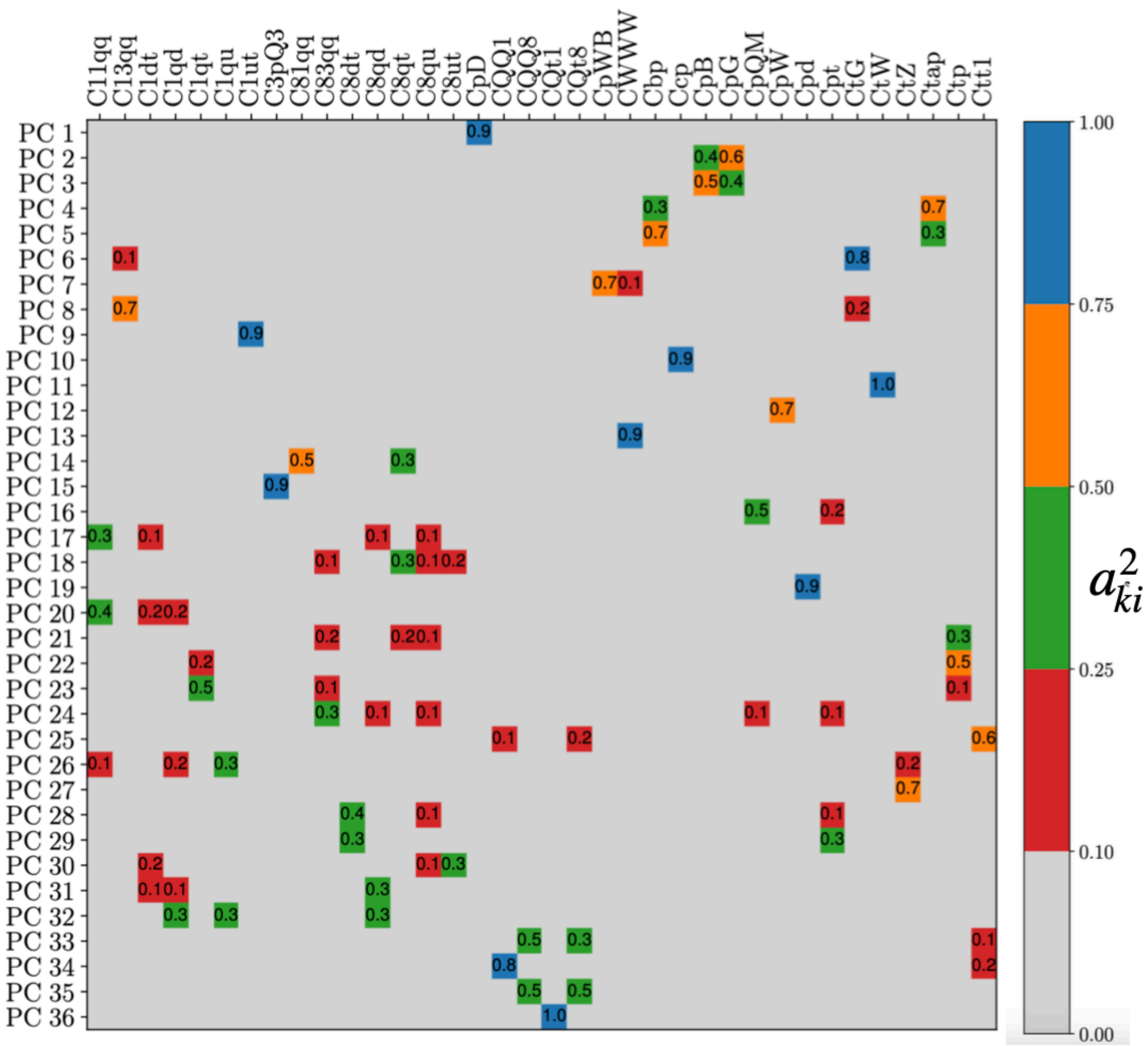
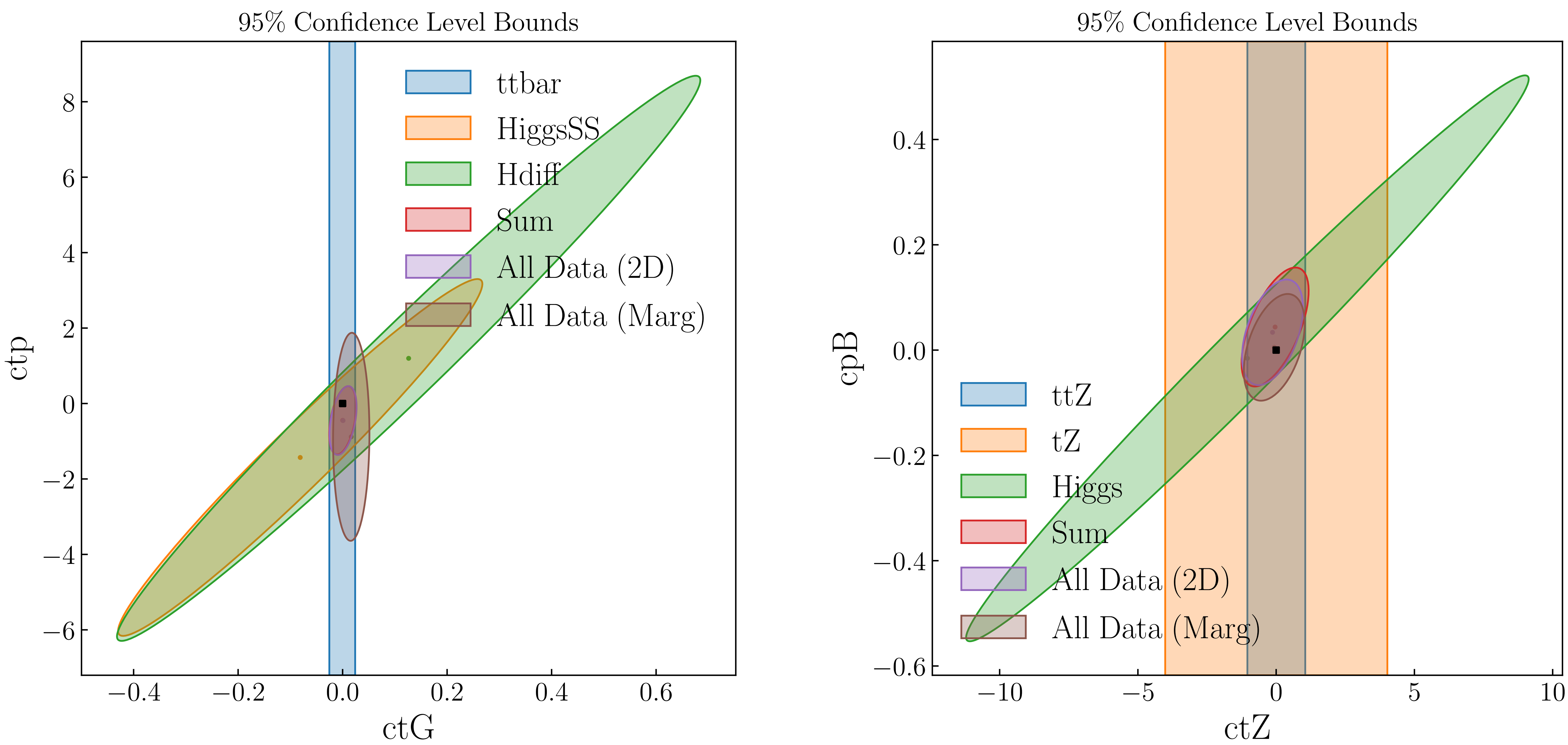
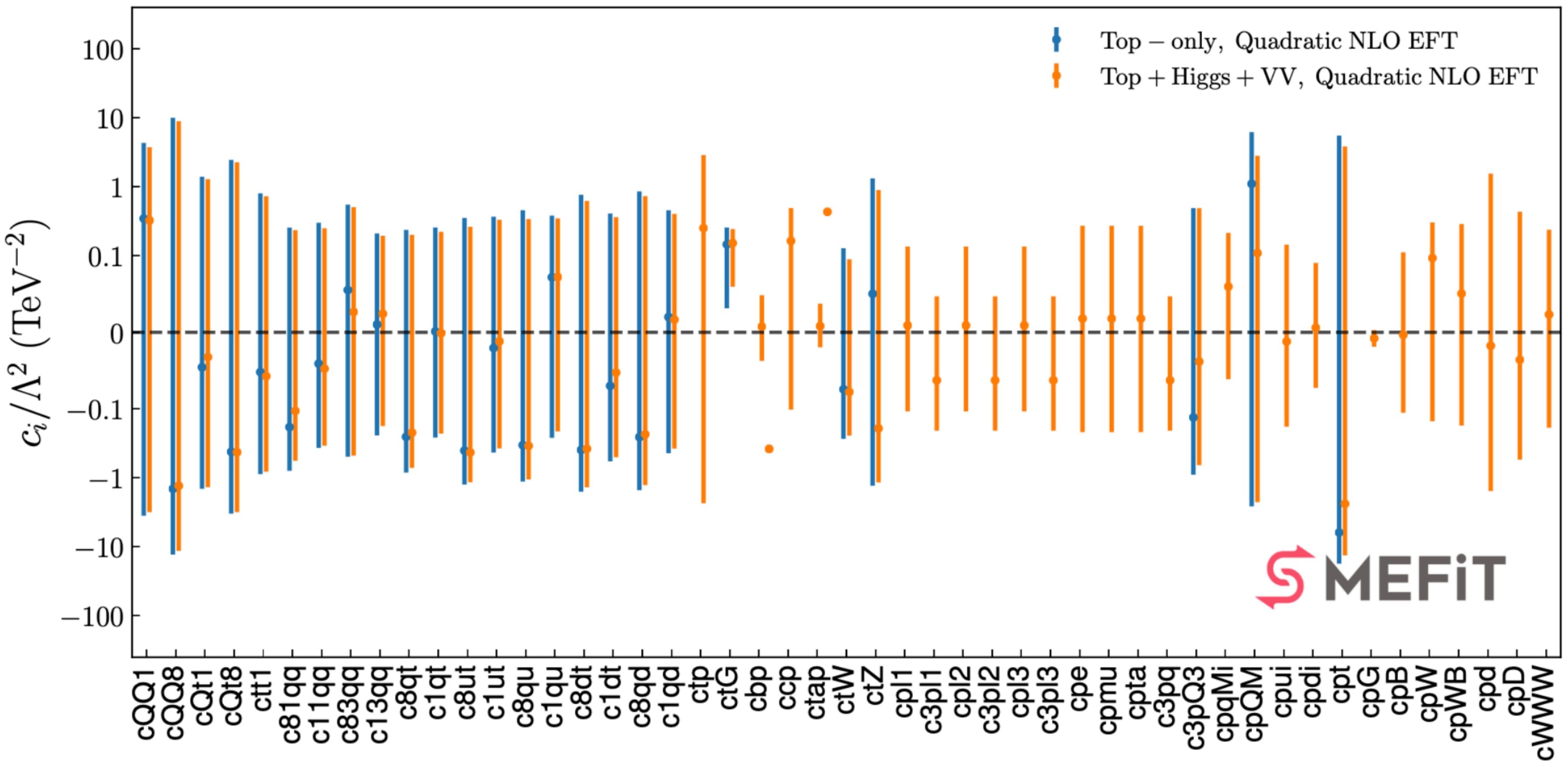
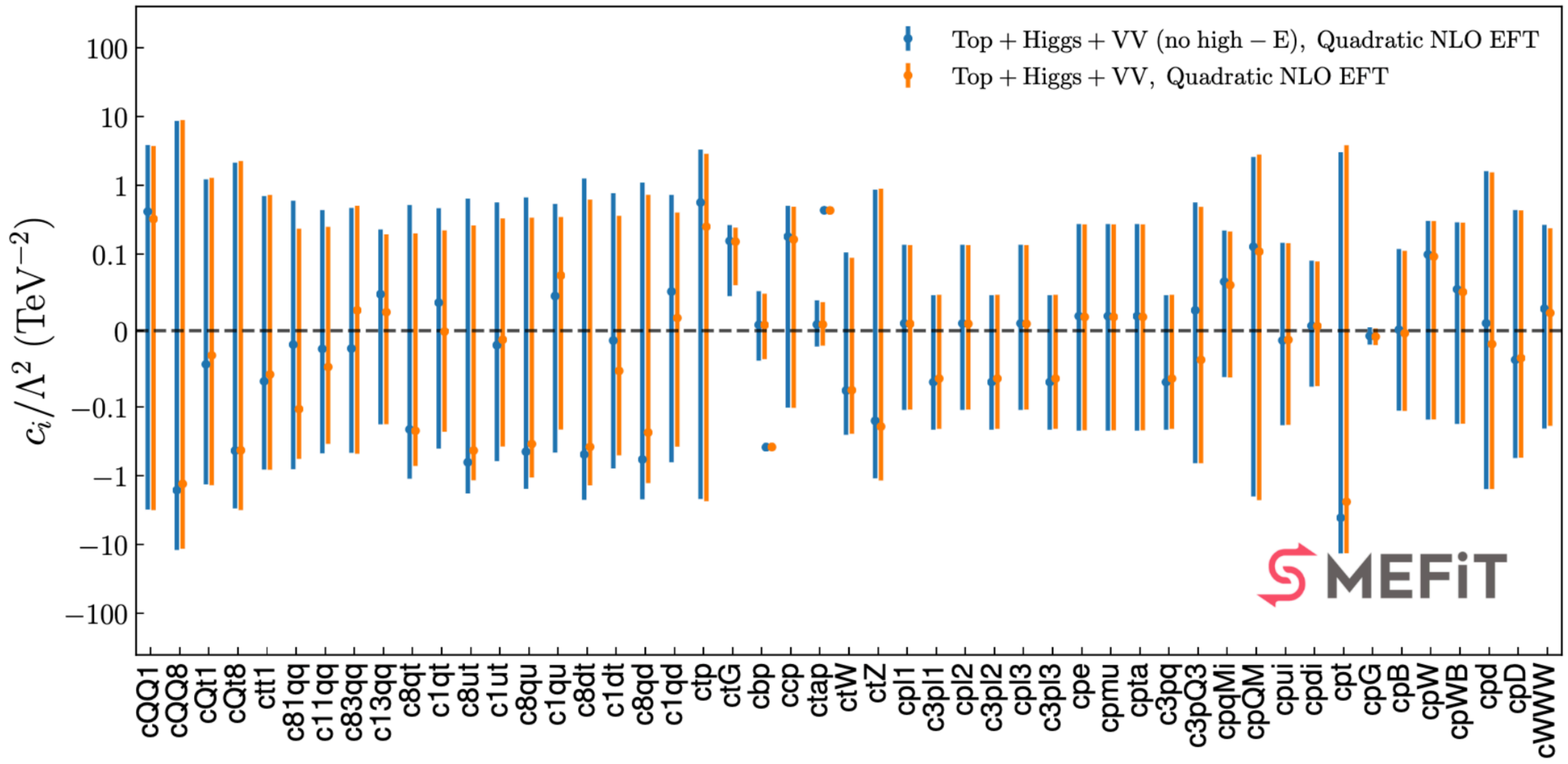



**Diagnostic tool: is the basis used good for the dimensionality?**

**Eventually one can fit in the PC basis (not done in the present fit)**


95% Confidence Level Bounds
ttbar
HiggsSS
Hdiff
Sum
All Data (2D)
All Data (Marg)
ctp
ctG
8
6
4
2
0
−2
−4
−6
−0.4
−0.2
0.0
0.2
0.4
0.6
95% Confidence Level Bounds
ttZ
tZ
Higgs
Sum
All Data (2D)
All Data (Marg)
cpB
ctZ
0.4
0.2
0.0
−0.2
−0.4
−0.6
−10
−5
0
5
10


Top − only, Quadratic NLO EFT
Top + Higgs + VV, Quadratic NLO EFT
$c_i/\Lambda^2\ (\mathrm{TeV}^{-2})$
SMEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW


Top + Higgs + VV (no high − E), Quadratic NLO EFT
Top + Higgs + VV, Quadratic NLO EFT
$c_i/\Lambda^2\ (\mathrm{TeV}^{-2})$
SMEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW

- **SMEFiT** is a **novel and flexible framework** for global EFT interpretations.
- **Already successfully employed for Top, Higgs and diboson data.**
- Several functionalities to **cross-check** and **validate** results**.**

New steps:

- **Add new data** (EWPO, low-E, VBS, Tevatron, recent LHC results, …)
- **Improve theory** (RGEs, NLO-QCD and EW in EFT, etc)
- **Improve fit methodology** (higher number of operators require better efficiency)

**Luminosities are assumed from MAP studies**

**Typical EW process at muon collider**

$$\sigma = \left(\frac{10\,\mathrm{TeV}}{\sqrt{s_\mu}}\right)^2 \cdot 10^3\,\mathrm{ab}$$

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**For** $N \sim 10^4$ → $\mathcal{L} \cdot \text{years} = \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 \cdot 10\,\text{ab}^{-1}$

| | $\sigma$ [fb] | $\sqrt{s}$ [TeV] | | $\sigma$ [fb] | $\sqrt{s}$ [TeV] |
|---|---|---|---|---|---|
| $t\bar{t}$ | $8.4 \cdot 10^{0}$ | 4.5 | $t\bar{t}ZZ$ | $2.2 \cdot 10^{-2}$ | 8.4 |
| $t\bar{t}Z$ | $5.3 \cdot 10^{-1}$ | 6.9 | $t\bar{t}HZ$ | $7.0 \cdot 10^{-3}$ | 11 |
| $t\bar{t}H$ | $7.6 \cdot 10^{-2}$ | 8.2 | $t\bar{t}HH$ | $5.9 \cdot 10^{-4}$ | 13 |
| $t\bar{t}WW$ | $1.2 \cdot 10^{-1}$ | 15 | $t\bar{t}t\bar{t}$ | $1.6 \cdot 10^{-3}$ | 22 |
| $HZ$ | $4.3 \cdot 10^{0}$ | 1.7 | $HHWW$ | $4.3 \cdot 10^{-3}$ | 9.2 |
| $HHZ$ | $2.1 \cdot 10^{-2}$ | 4.2 | $HZZ$ | $9.4 \cdot 10^{-2}$ | 2.7 |
| $HHHZ$ | $4.7 \cdot 10^{-5}$ | 6.9 | $HHZZ$ | $5.9 \cdot 10^{-4}$ | 5.7 |
| $HWW$ | $6.6 \cdot 10^{-1}$ | 4.5 | | | |
| $WW$ | $2.1 \cdot 10^{2}$ | 4.8 | $WWZ$ | $1.6 \cdot 10^{1}$ | 6.2 |
| $ZZ$ | $3.9 \cdot 10^{1}$ | 2.4 | $ZZZ$ | $4.8 \cdot 10^{-1}$ | 2.3 |



MCnet

| | $\sigma$ [fb] | $\sqrt{s}$ [TeV] | | $\sigma$ [fb] | $\sqrt{s}$ [TeV] |
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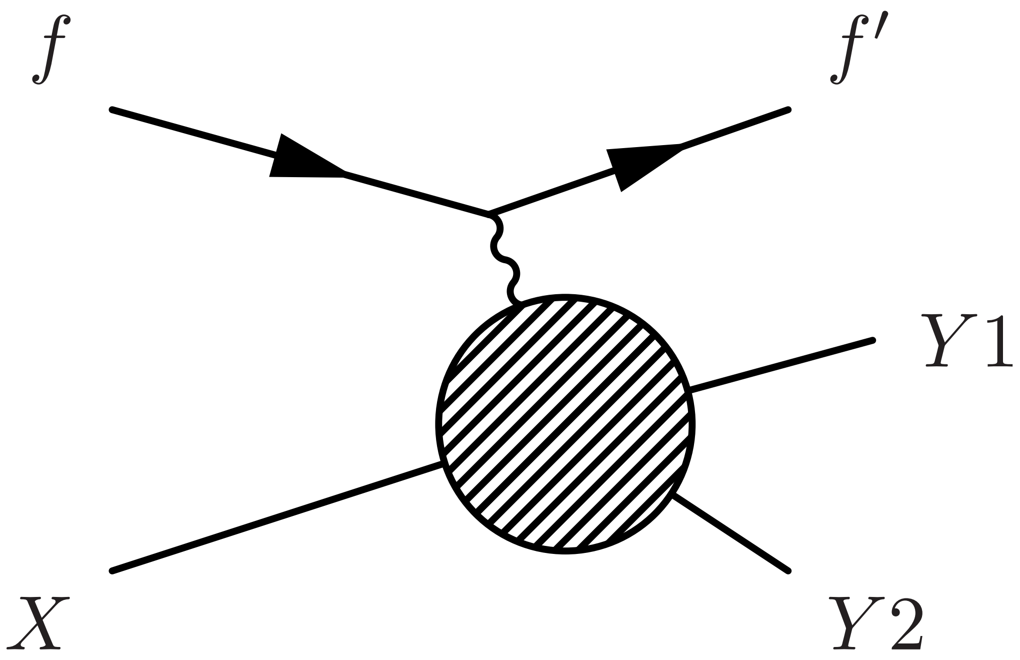
**Effectively a EW boson collider!**

**We can have an analytical insight with EWA**




$$E \sim xE \sim (1-x)E, \qquad \frac{m}{E} \ll 1, \qquad \frac{p_\perp}{E} \ll 1$$

$$f_+ = \frac{(1-x)^2}{x}\frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2},$$

$$f_- = \frac{1}{x}\frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2},$$

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[P. Borel et al. arXiv:1202.1904]

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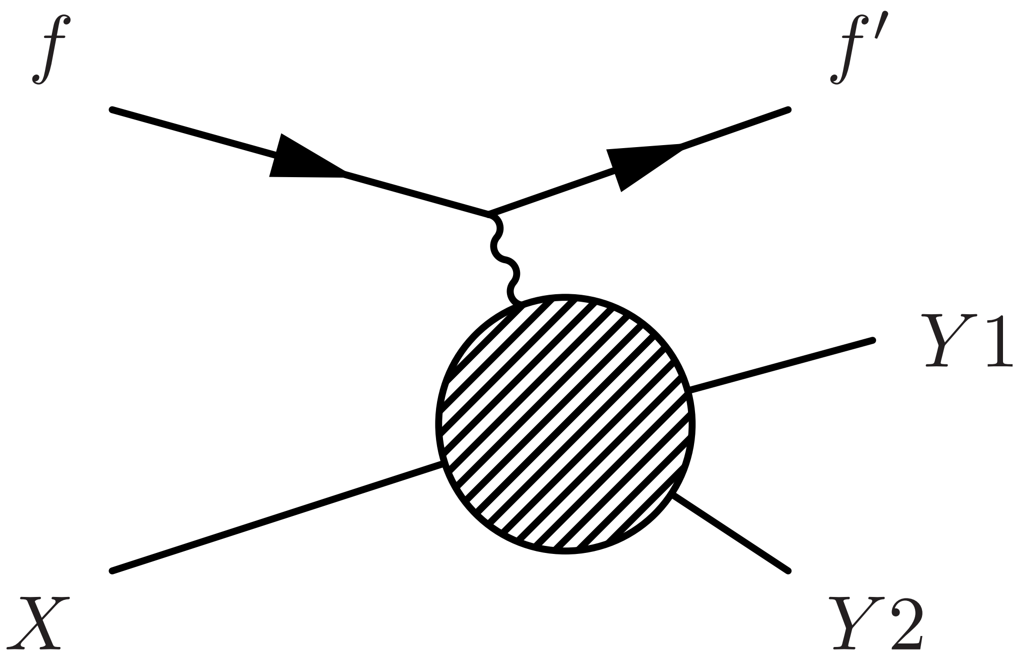


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[P. Borel et al. arXiv:1202.1904]

$$\frac{d\sigma_{EWA}}{dx dp_\perp}(fX \to f'Y) = \frac{C^2}{2\pi^2} \sum_{i=+,-,0} f_i \times d\sigma(W_i X \to Y)$$

**Weak bosons can be described as partons!**

**Muons decay!** → **R&D needed in accelerator and detector physics**

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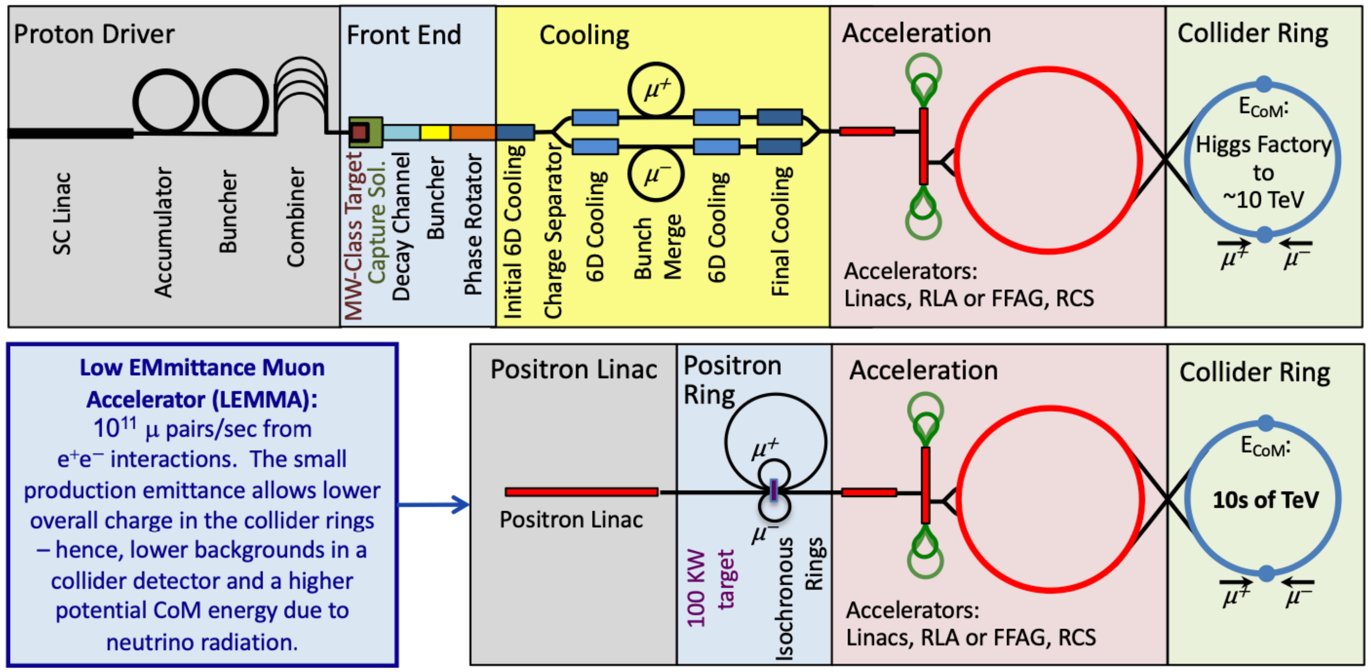
**Beam production**

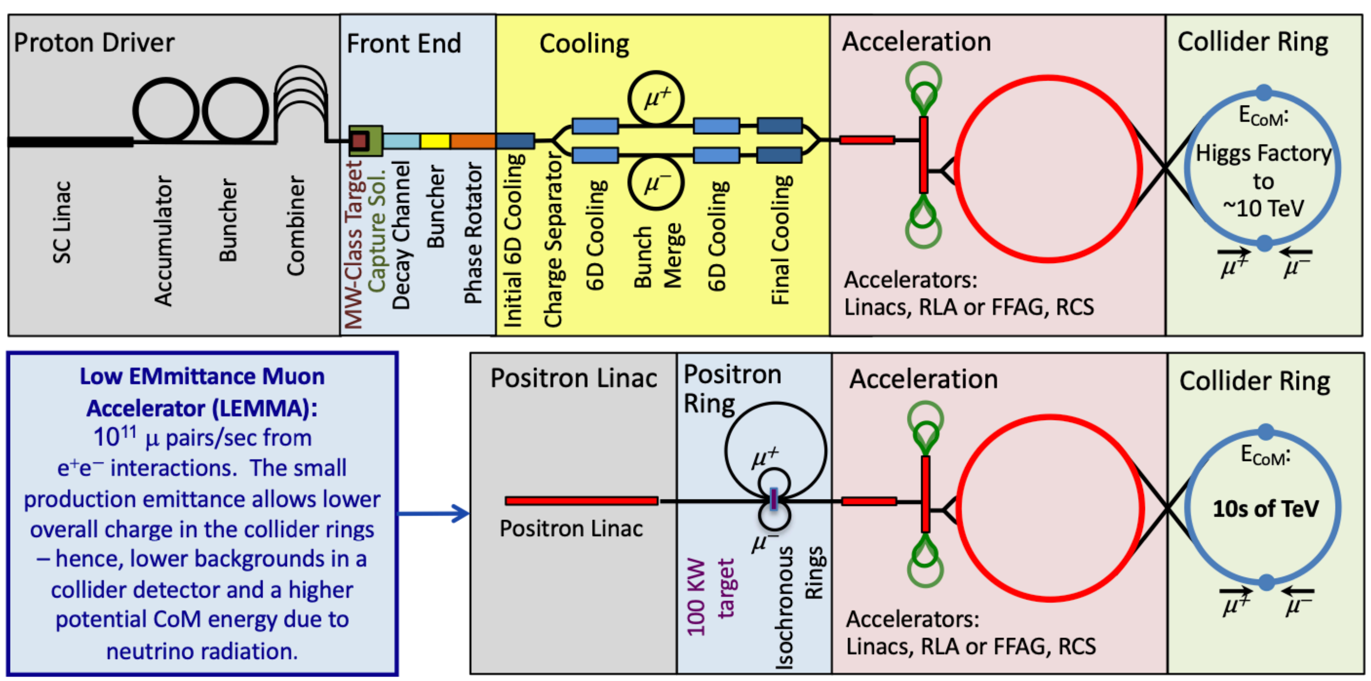



[Delahaye et al. arXiv:1901.06150]

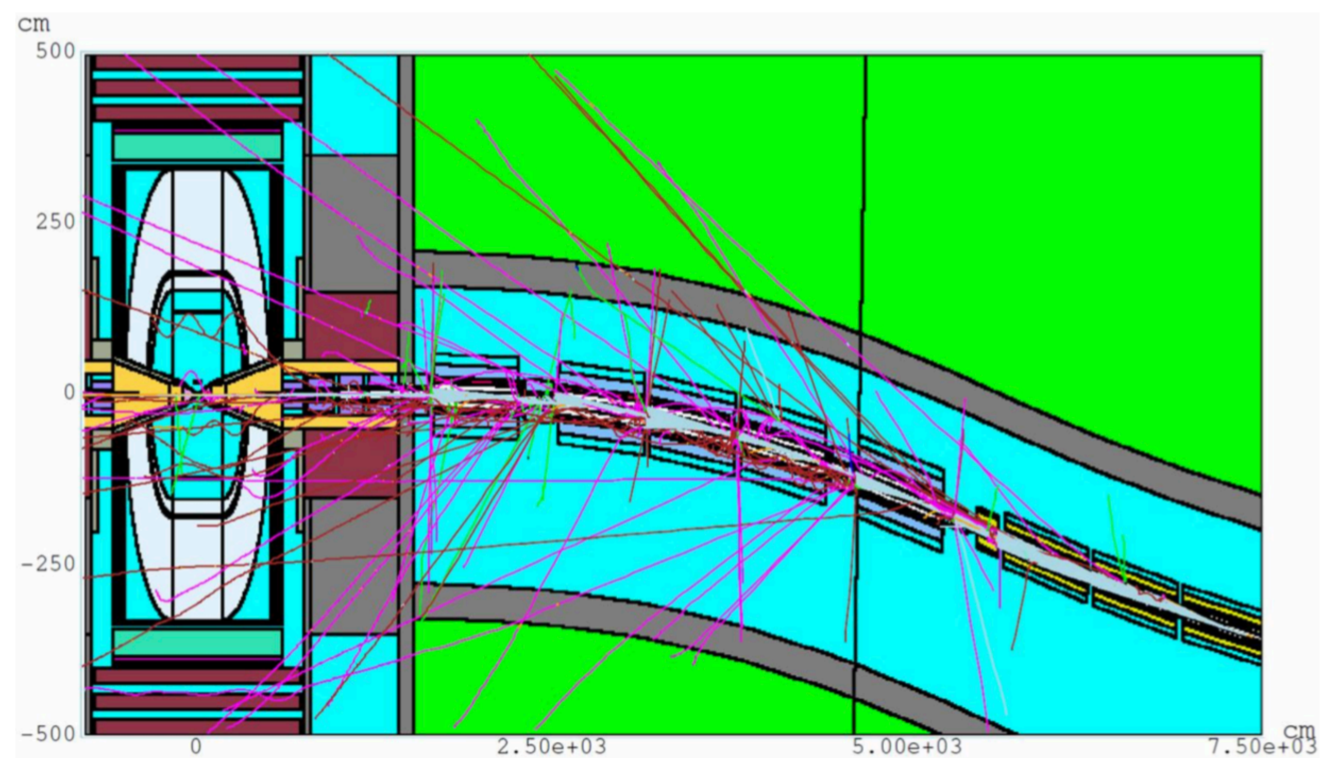
**Muons decay!** → **R&D needed in accelerator and detector physics**

**Beam production**

**Detector**




[Delahaye et al. arXiv:1901.06150]




[Bartosik et al. arXiv:2001.04431]



MCnet

**Different mode of production at different energies**

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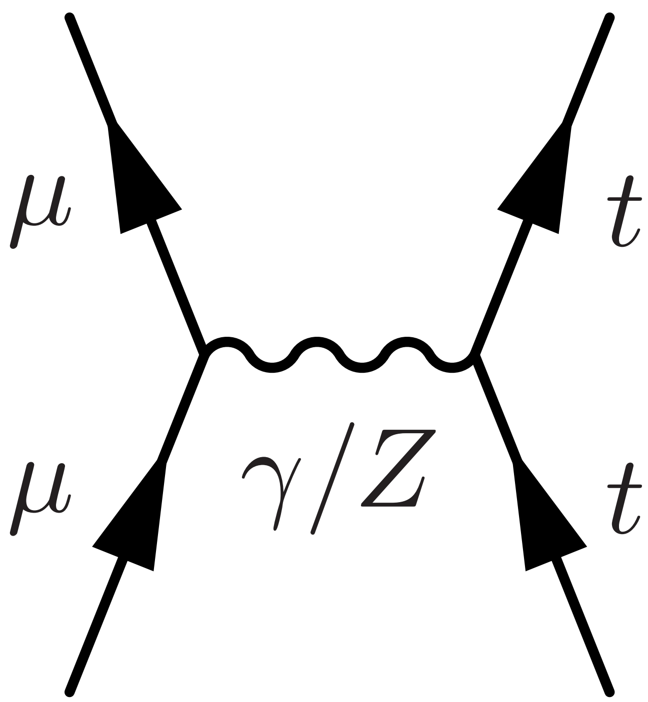
$$\sqrt{s} \lesssim 1\text{-}5\ \text{TeV}$$




**s-channel**

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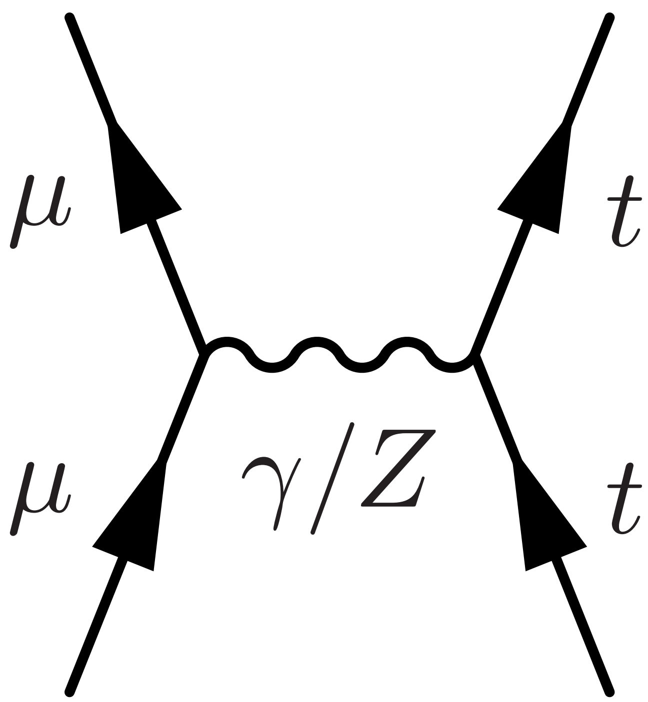
$\sqrt{s} \lesssim$ 1-5 TeV

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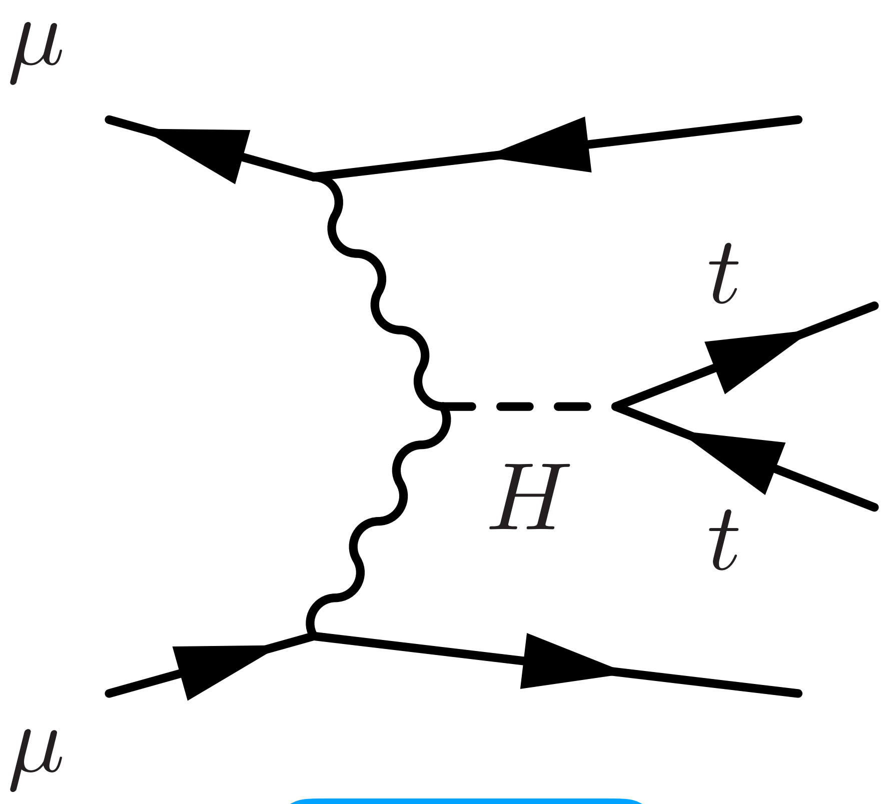


**VBF**

**Resonance production**

$$M_X = \sqrt{s_\mu}$$

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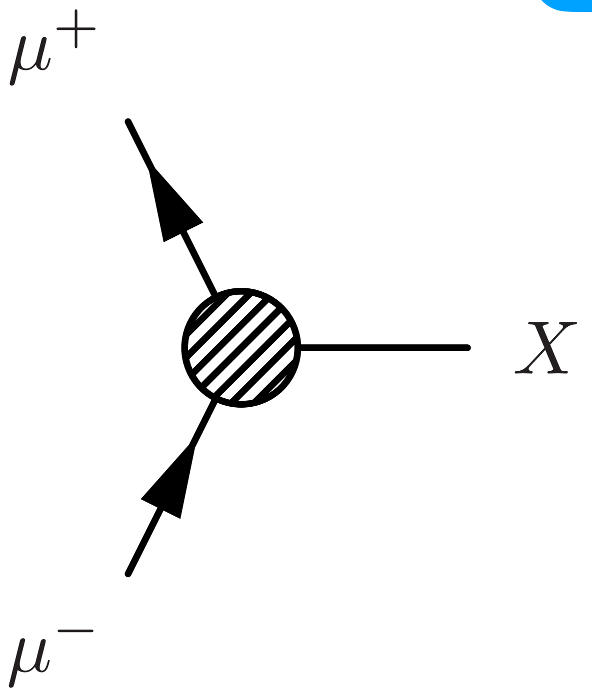


$$\sigma_\mu(s_\mu) = [\hat{\sigma}]_\mu$$

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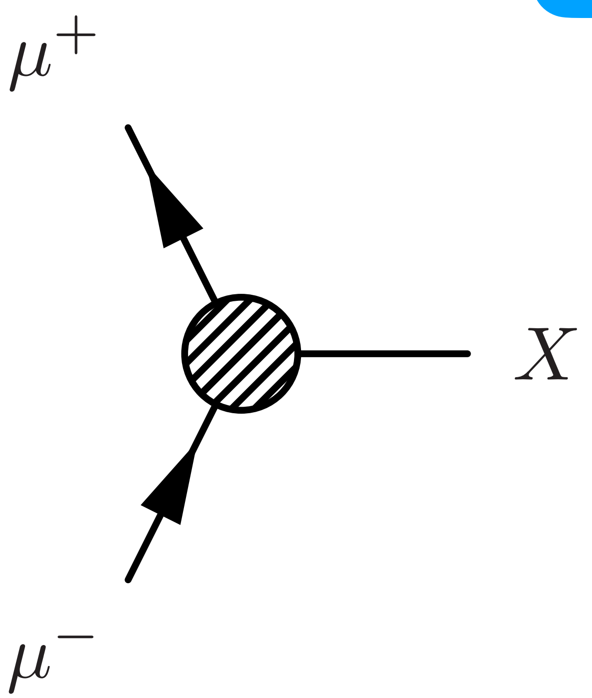
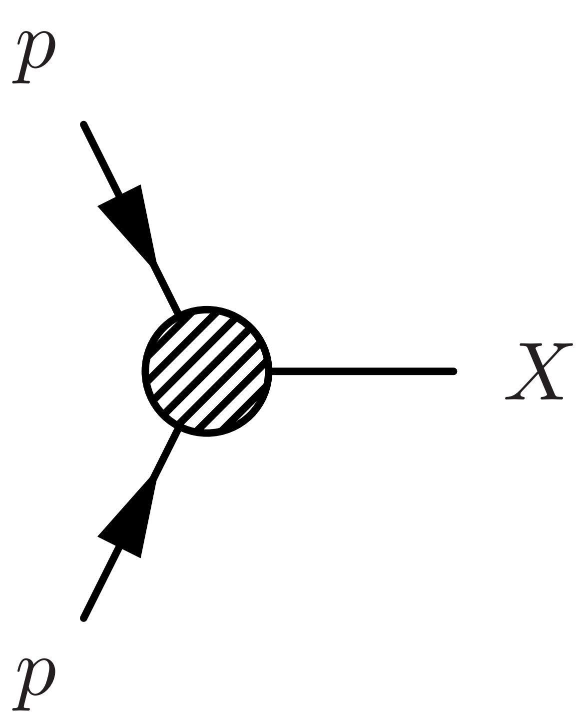
$\sqrt{s_\mu}$




$$\sigma_\mu(s_\mu) = [\hat{\sigma}]_\mu$$

$\sqrt{s_p}$




$$\sigma_p(s_p) = \int_{\tau_0}^{1} d\tau \sum_{ij} \Phi_{ij}(\tau, \mu_f) \; [\hat{\sigma}_{ij}]_p \, \delta\left(\tau - \frac{M_X^2}{s_p}\right)$$

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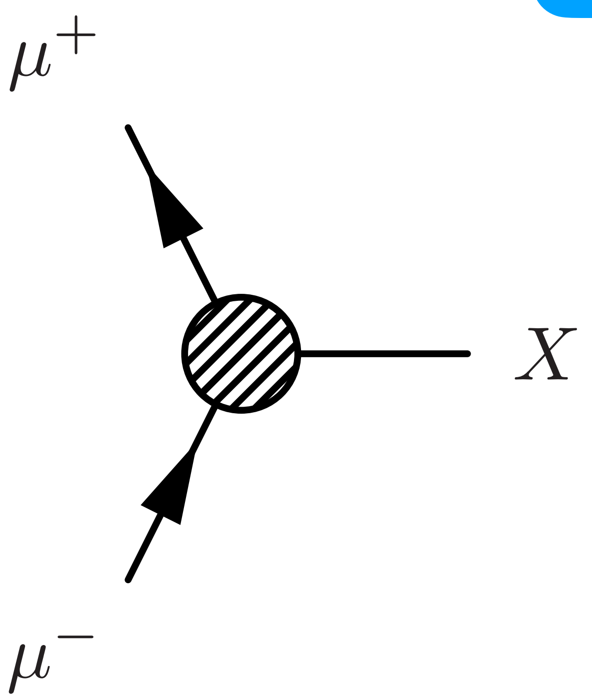


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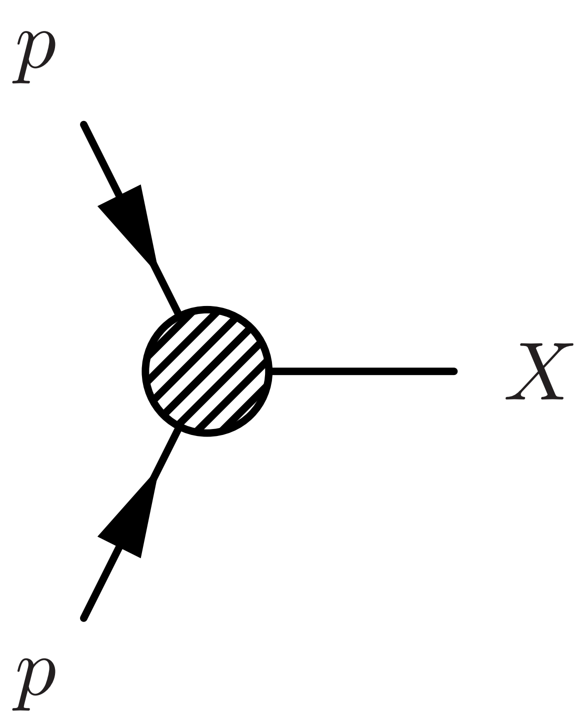


**Parton lumi**

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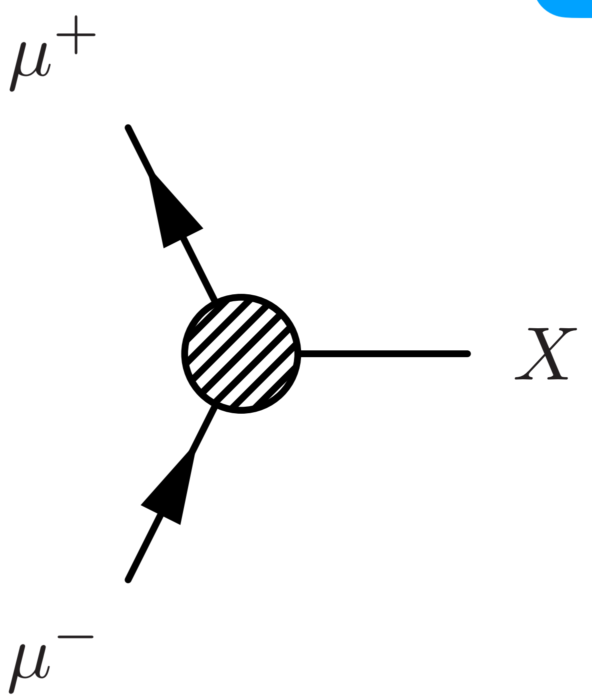


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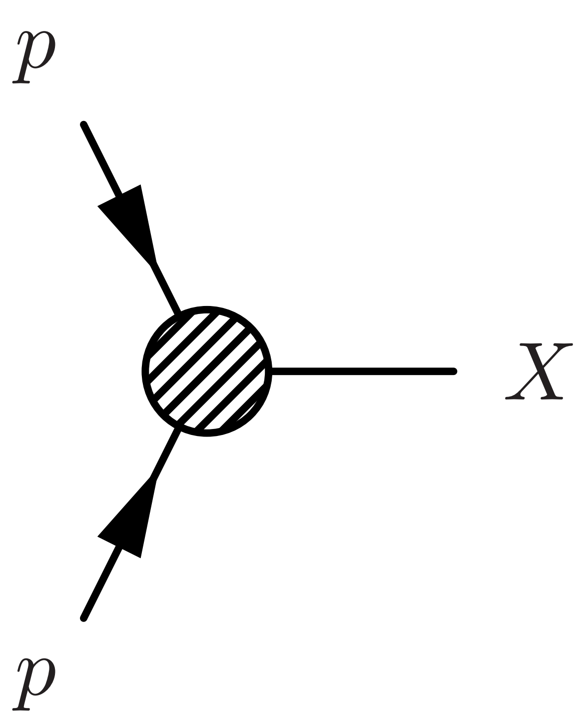


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**Hard XS**

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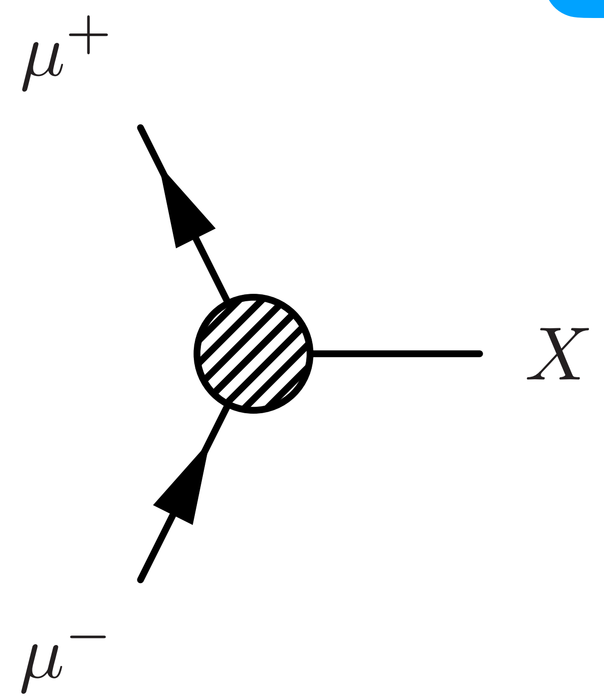


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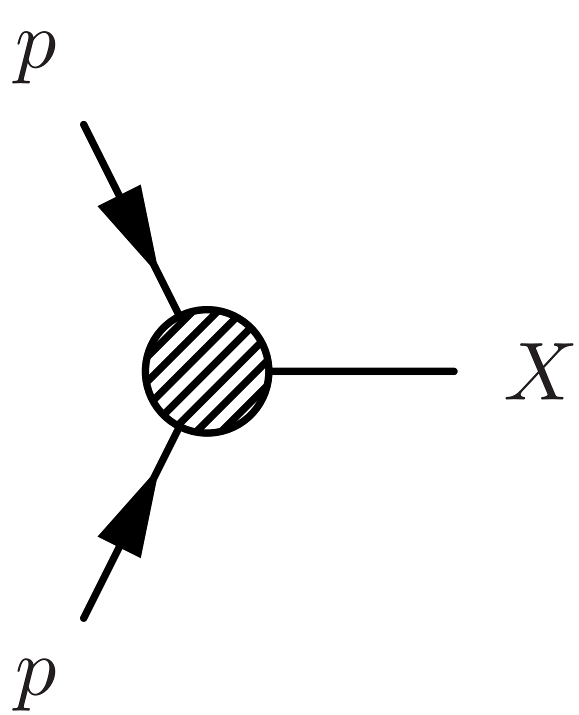


**Parton lumi**

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**Hard XS**

$$\sigma_\mu(s_\mu) = \sigma_p(s_p)$$

$$\sum_{ij} \Phi_{ij}\left(\frac{s_\mu}{s_p}, \frac{\sqrt{s_\mu}}{2}\right) = \frac{[\hat{\sigma}]_\mu}{[\hat{\sigma}]_p} \equiv \frac{1}{\beta}$$

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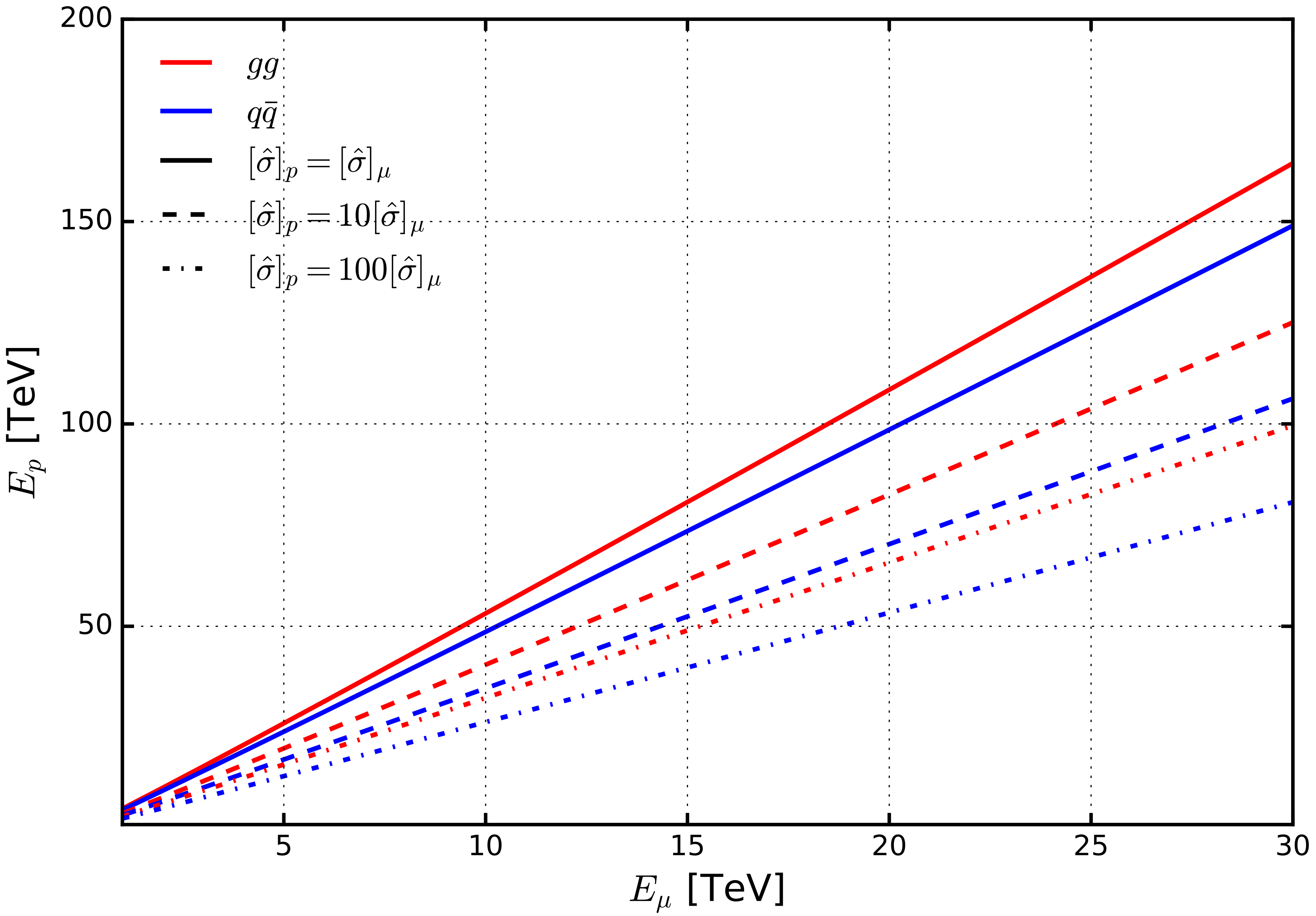

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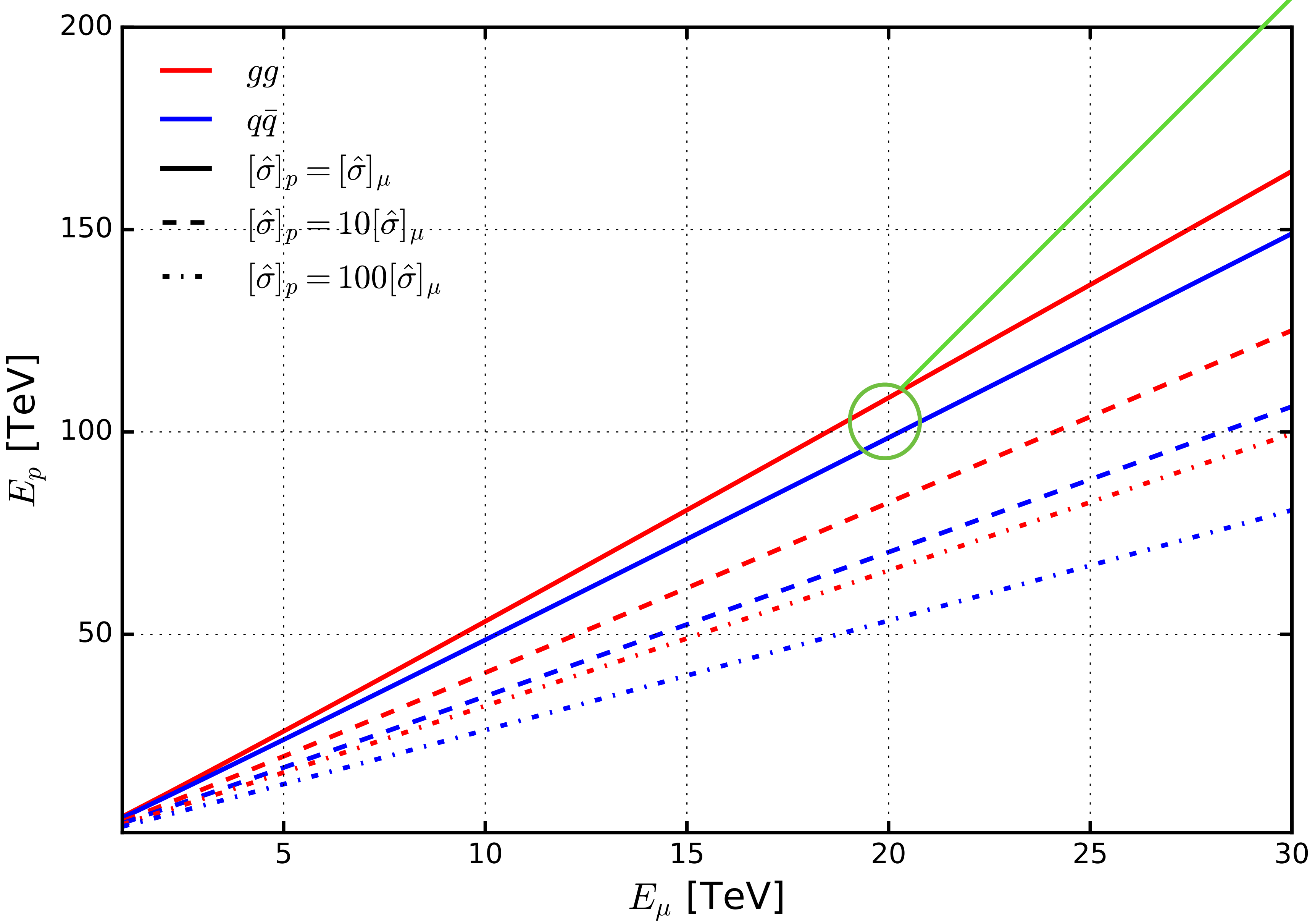
**FCC comparable!**



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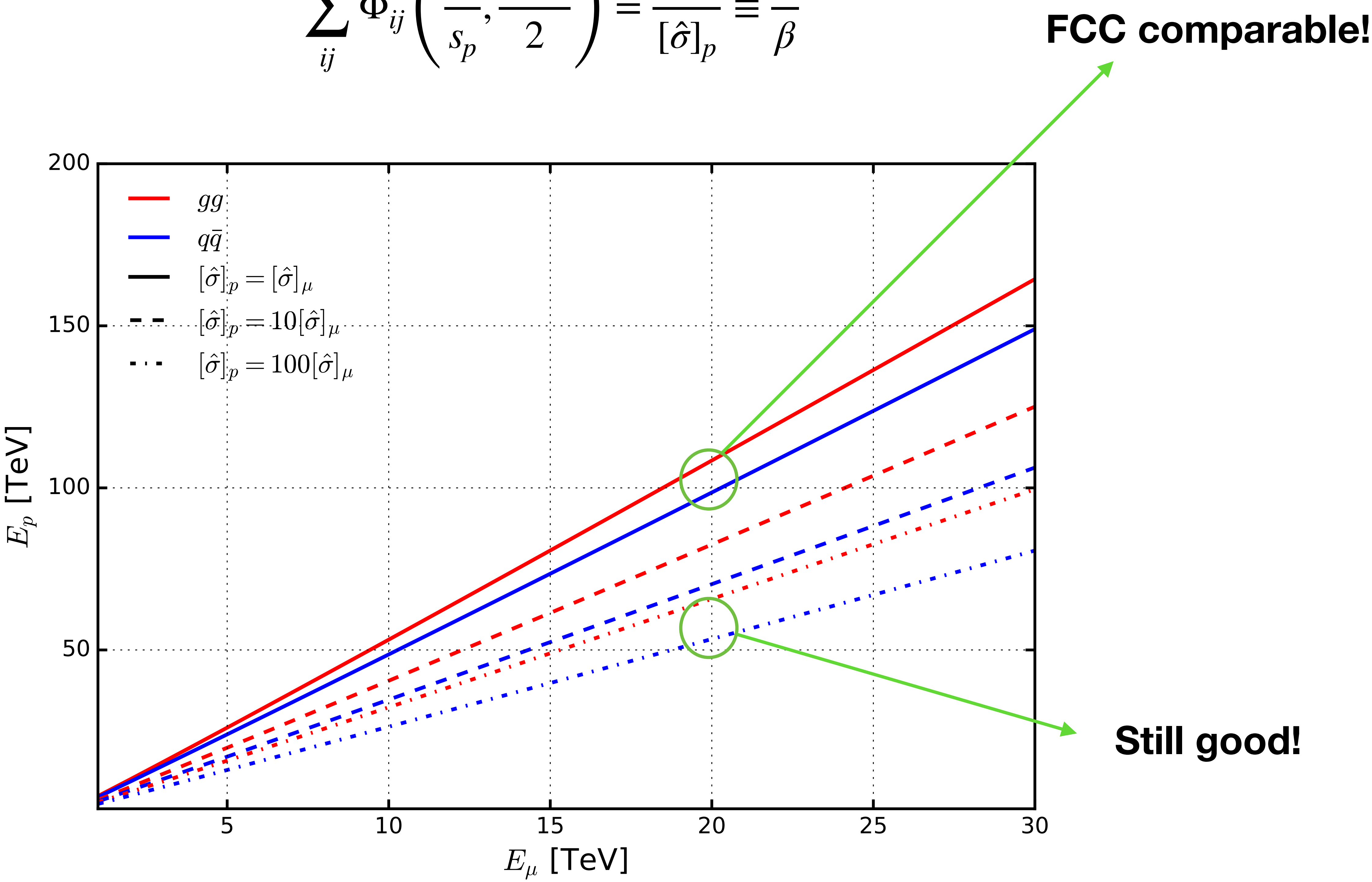

**Pair production**

$$M_X = 0.9 \times \sqrt{s_\mu}/2$$

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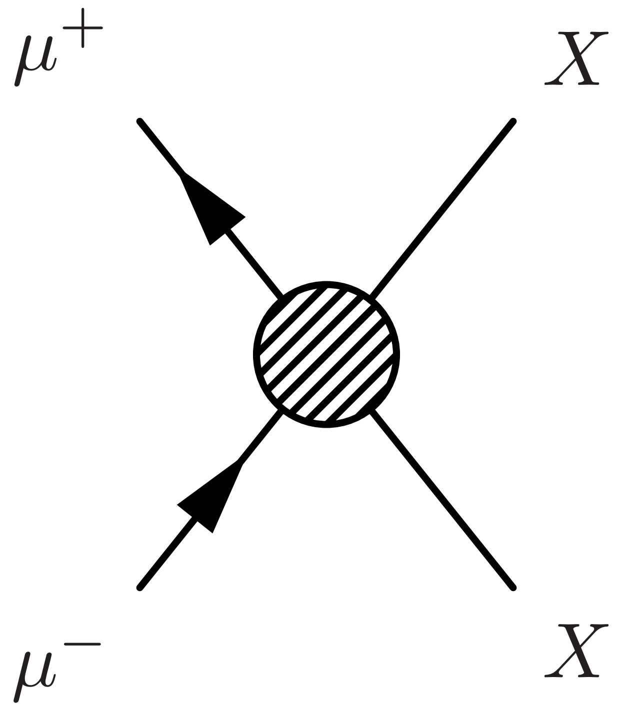
$$M_X = 0.9 \times \sqrt{s_\mu}/2$$

$$\sqrt{s_\mu}$$

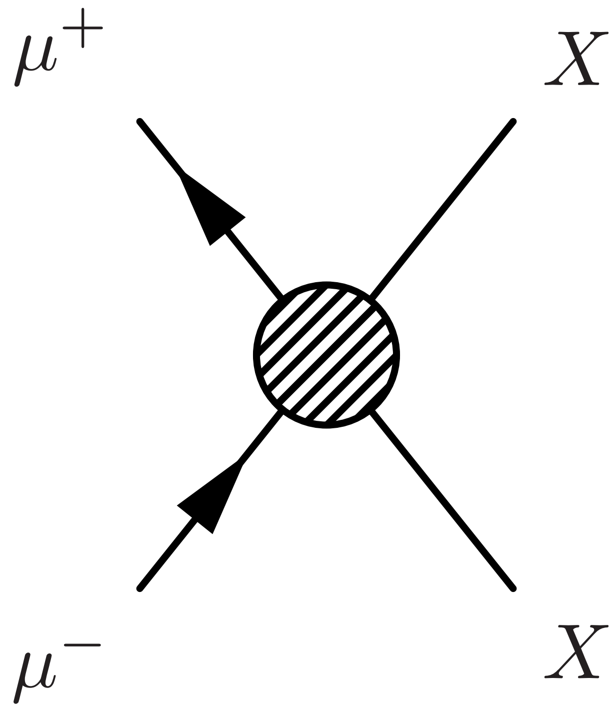



$$\sigma_\mu(s_\mu) = \frac{1}{s_\mu}[\hat{\sigma}\hat{s}]_\mu$$

**Pair production**

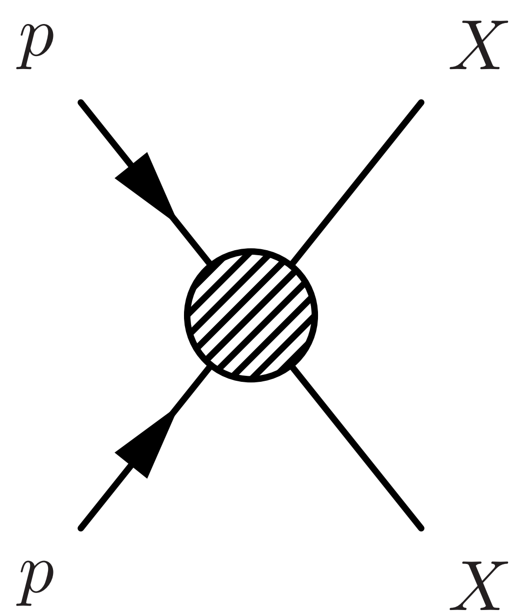
$$M_X = 0.9 \times \sqrt{s_\mu}/2$$

$$\sqrt{s_\mu}$$




$$\sigma_\mu(s_\mu) = \frac{1}{s_\mu}[\hat{\sigma}\hat{s}]_\mu$$

$$\sqrt{s_p}$$

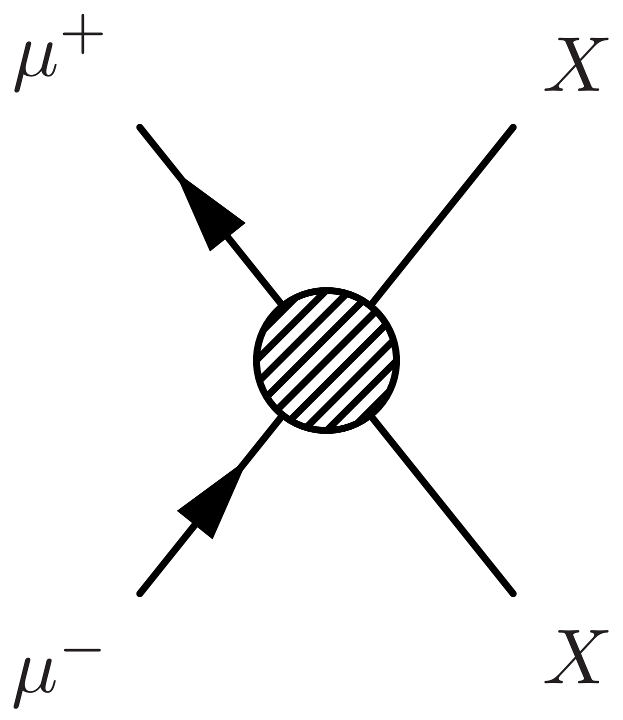



$$\sigma_p(s_p) = \frac{1}{s_p}\int_{\tau_0}^{1} d\tau \frac{1}{\tau} \sum_{ij} \Phi_{ij}(\tau, \mu_f) \ [\hat{\sigma}_{ij}\hat{s}]_p$$

**Pair production**

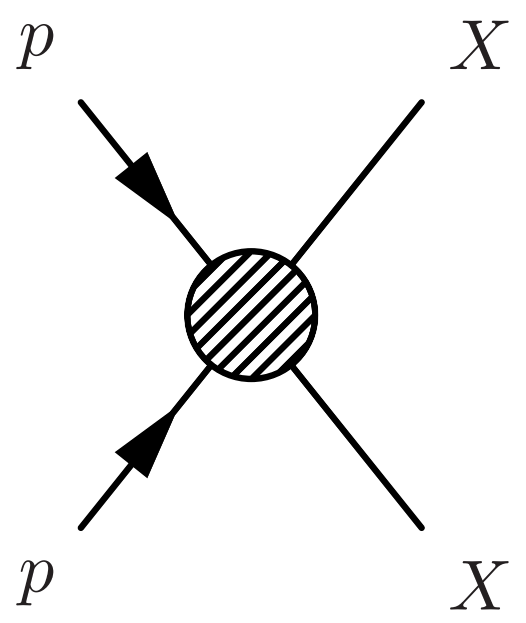
$$M_X = 0.9 \times \sqrt{s_\mu}/2$$

$\sqrt{s_\mu}$




$$\sigma_\mu(s_\mu) = \frac{1}{s_\mu}[\hat{\sigma}\hat{s}]_\mu$$

$\sqrt{s_p}$




$$\sigma_p(s_p) = \frac{1}{s_p}\int_{\tau_0}^{1} d\tau \frac{1}{\tau} \sum_{ij} \Phi_{ij}(\tau, \mu_f) \; [\hat{\sigma}_{ij}\hat{s}]_p$$

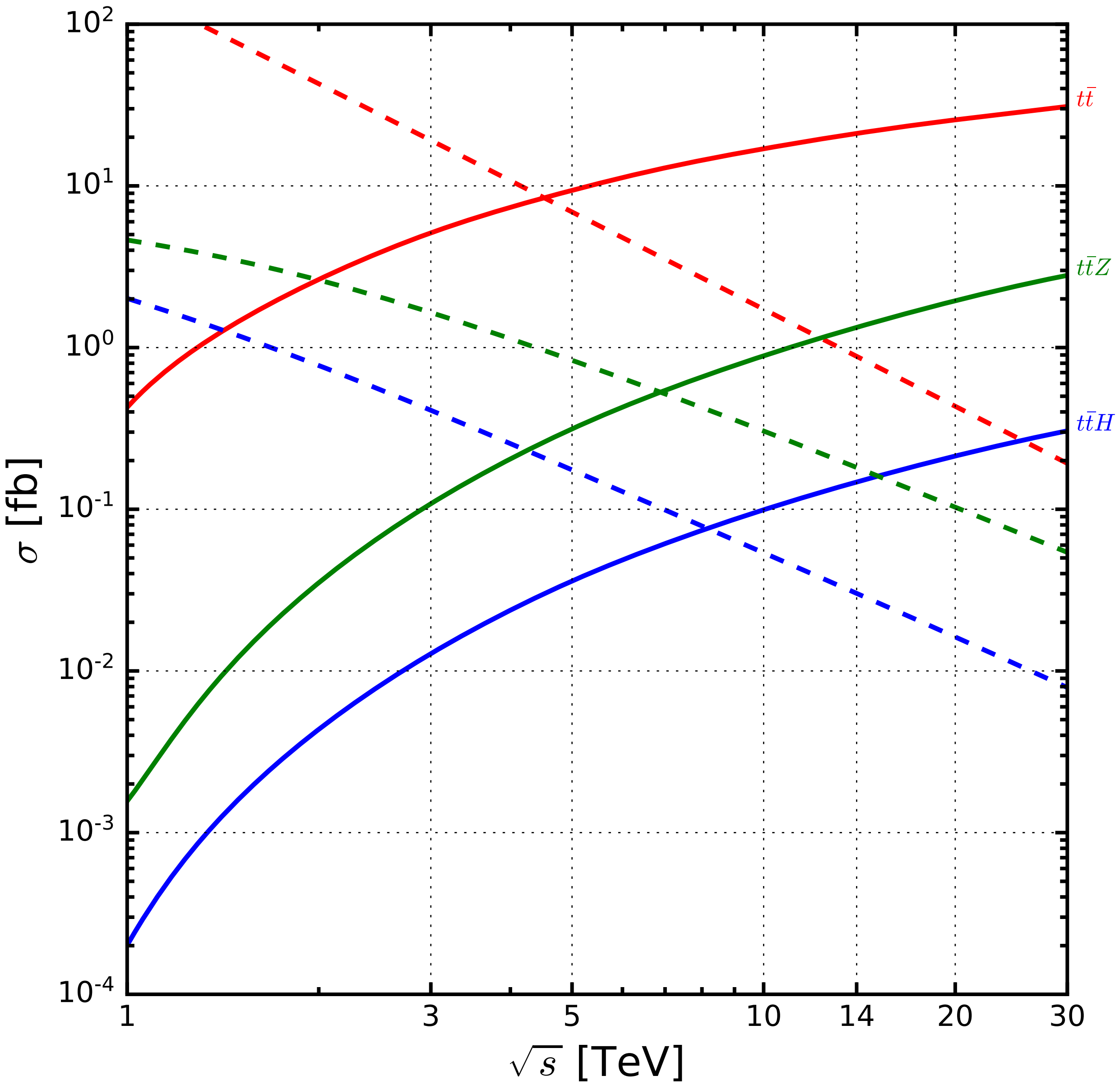
$$\sigma_\mu(s_\mu) = \sigma_p(s_p)$$



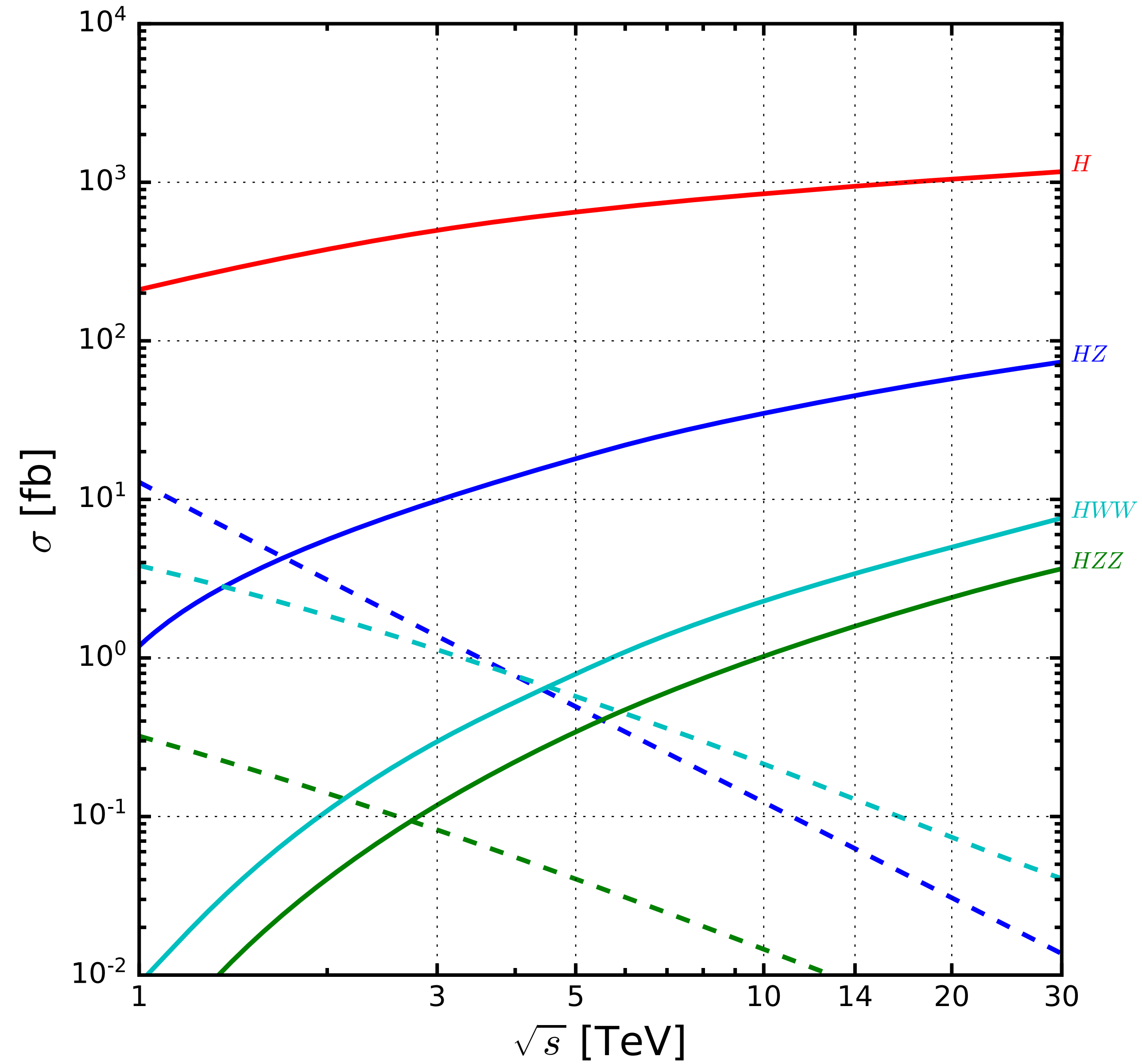
MCnet

s-channel (dashed) — VBF (solid)

**ttX**

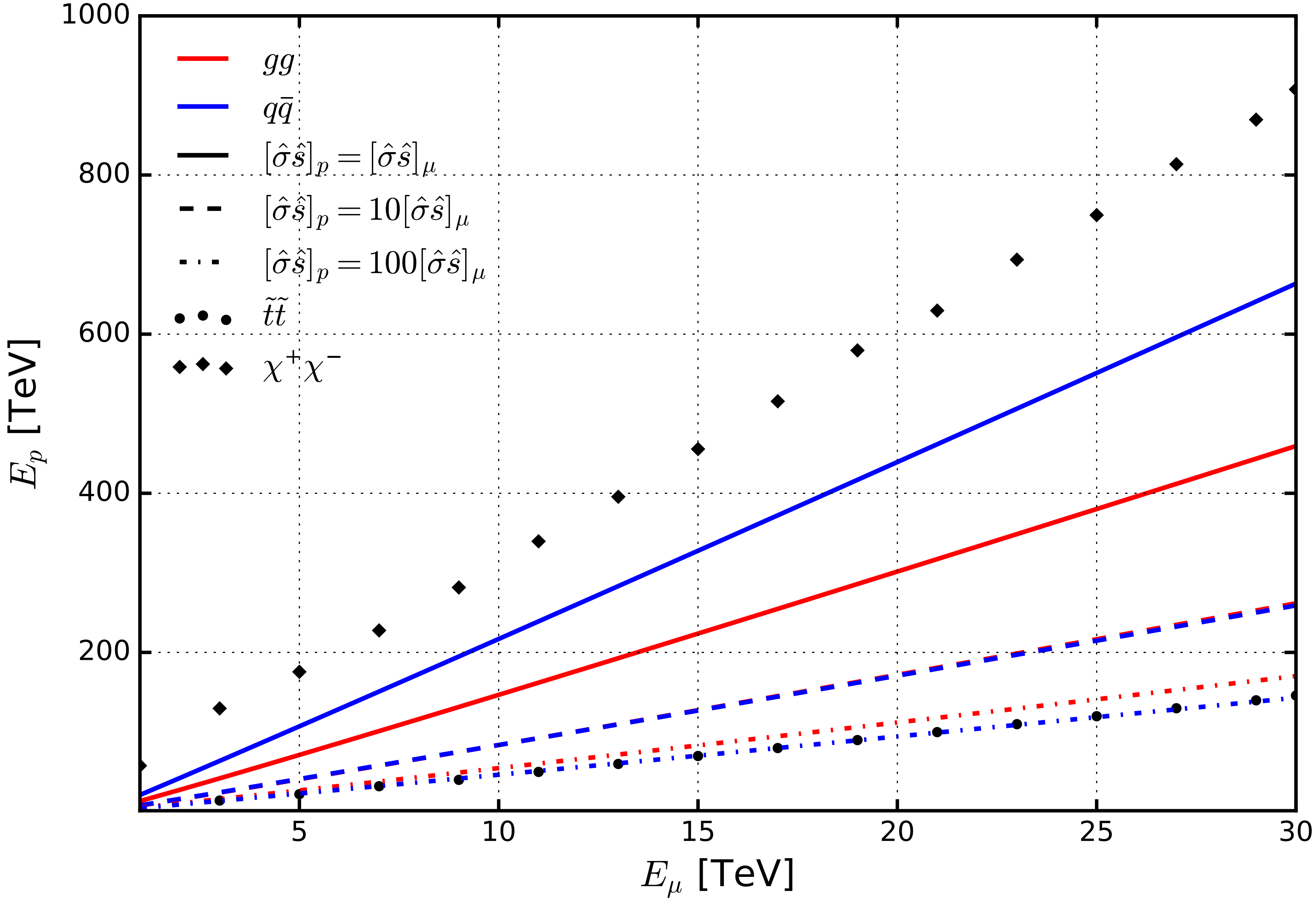



**HX**

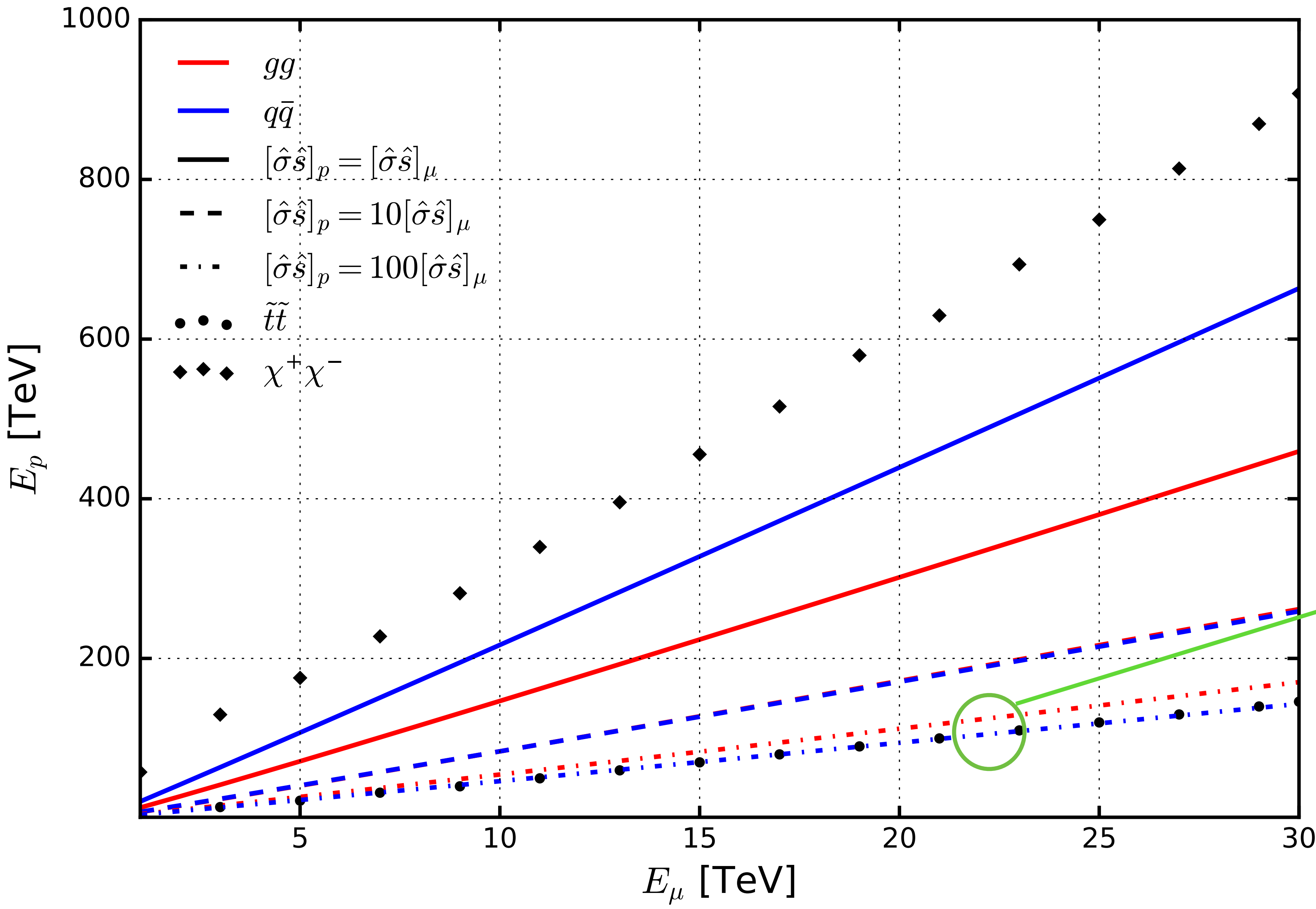


$$\frac{s_\mu}{s_p} \int_{\frac{s_\mu}{s_p}}^{1} d\tau \, \frac{1}{\tau} \sum_{ij} \Phi_{ij}\left(\tau, \frac{\sqrt{s_\mu}}{2}\right) = \frac{[\hat{\sigma}\hat{s}]_\mu}{[\hat{\sigma}\hat{s}]_p} \equiv \frac{1}{\beta}$$

$$\frac{s_\mu}{s_p}\int_{\frac{s_\mu}{s_p}}^{1} d\tau \, \frac{1}{\tau} \sum_{ij} \Phi_{ij}\left(\tau, \frac{\sqrt{s_\mu}}{2}\right) = \frac{[\hat{\sigma}\hat{s}]_\mu}{[\hat{\sigma}\hat{s}]_p} \equiv \frac{1}{\beta}$$

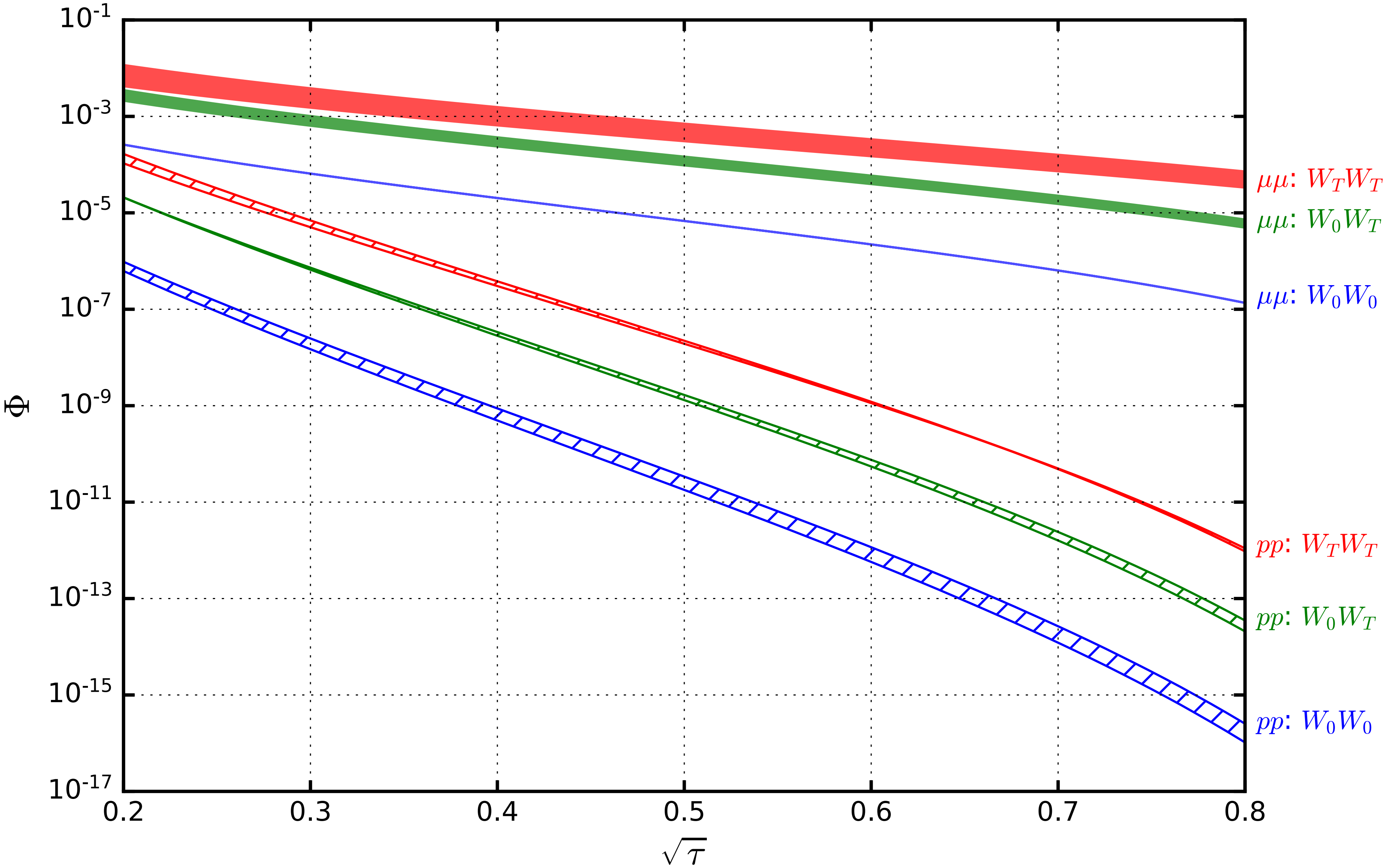


$$\frac{s_\mu}{s_p}\int_{\frac{s_\mu}{s_p}}^{1} d\tau\ \frac{1}{\tau}\sum_{ij}\Phi_{ij}\left(\tau,\frac{\sqrt{s_\mu}}{2}\right) = \frac{[\hat{\sigma}\hat{s}]_\mu}{[\hat{\sigma}\hat{s}]_p} \equiv \frac{1}{\beta}$$

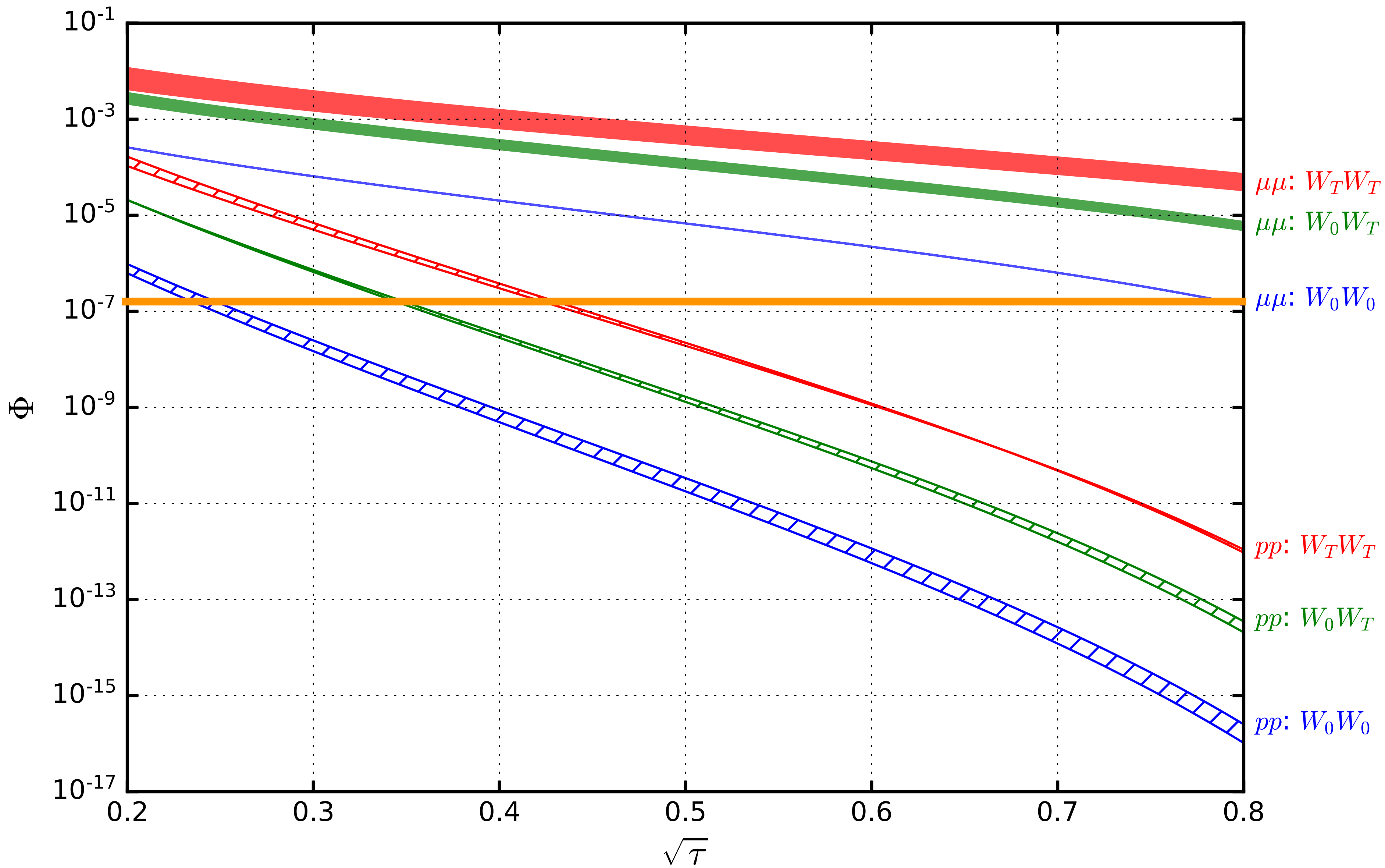



**Stop prod well described**

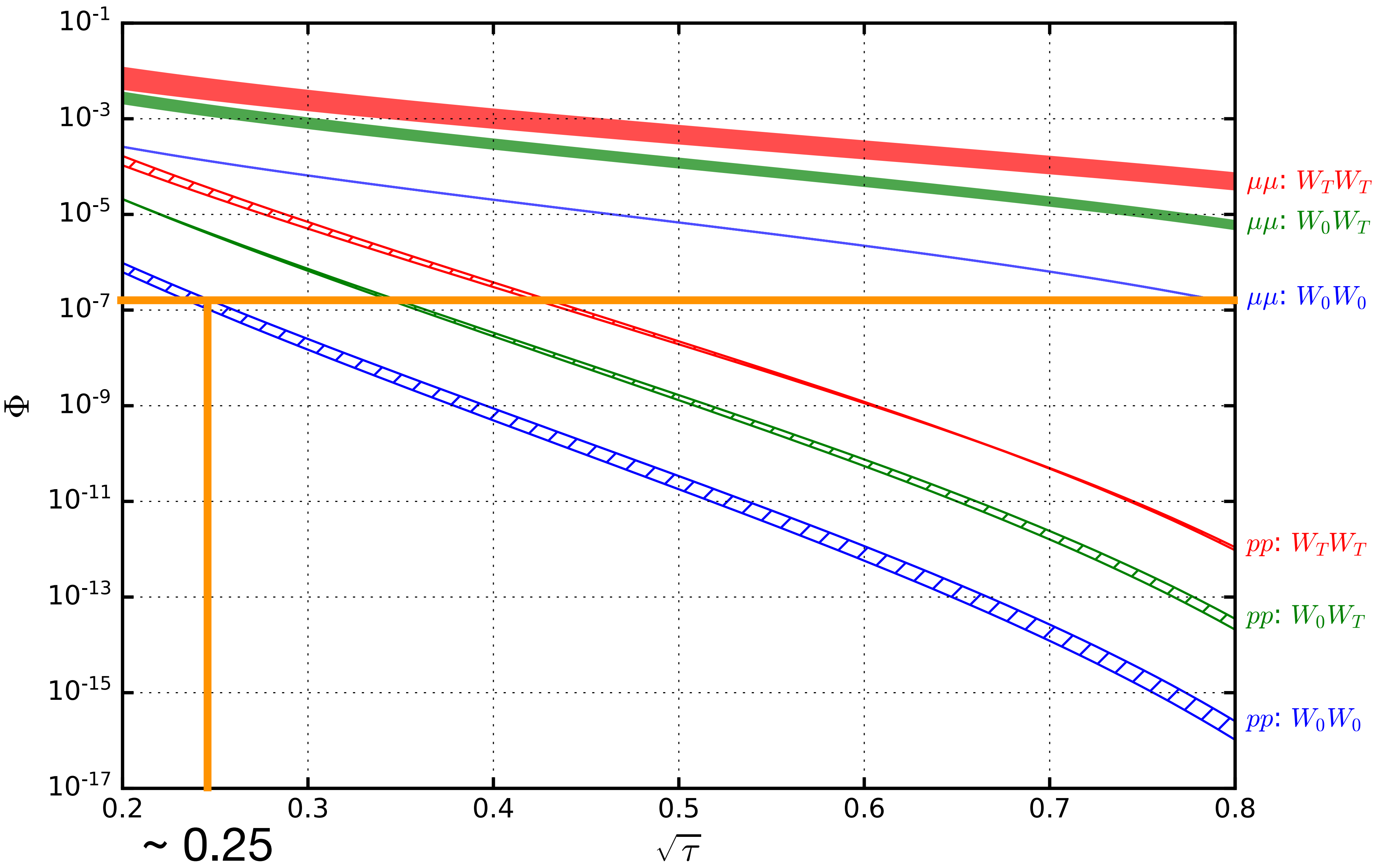
$$\Phi_{W^+_{\lambda_1} W^-_{\lambda_2}}(\tau, \mu_f) = \int_\tau^1 \frac{d\xi}{\xi}\; f_{W_{\lambda_1}/\mu}\left(\xi, \mu_f\right) f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi}, \mu_f\right)$$



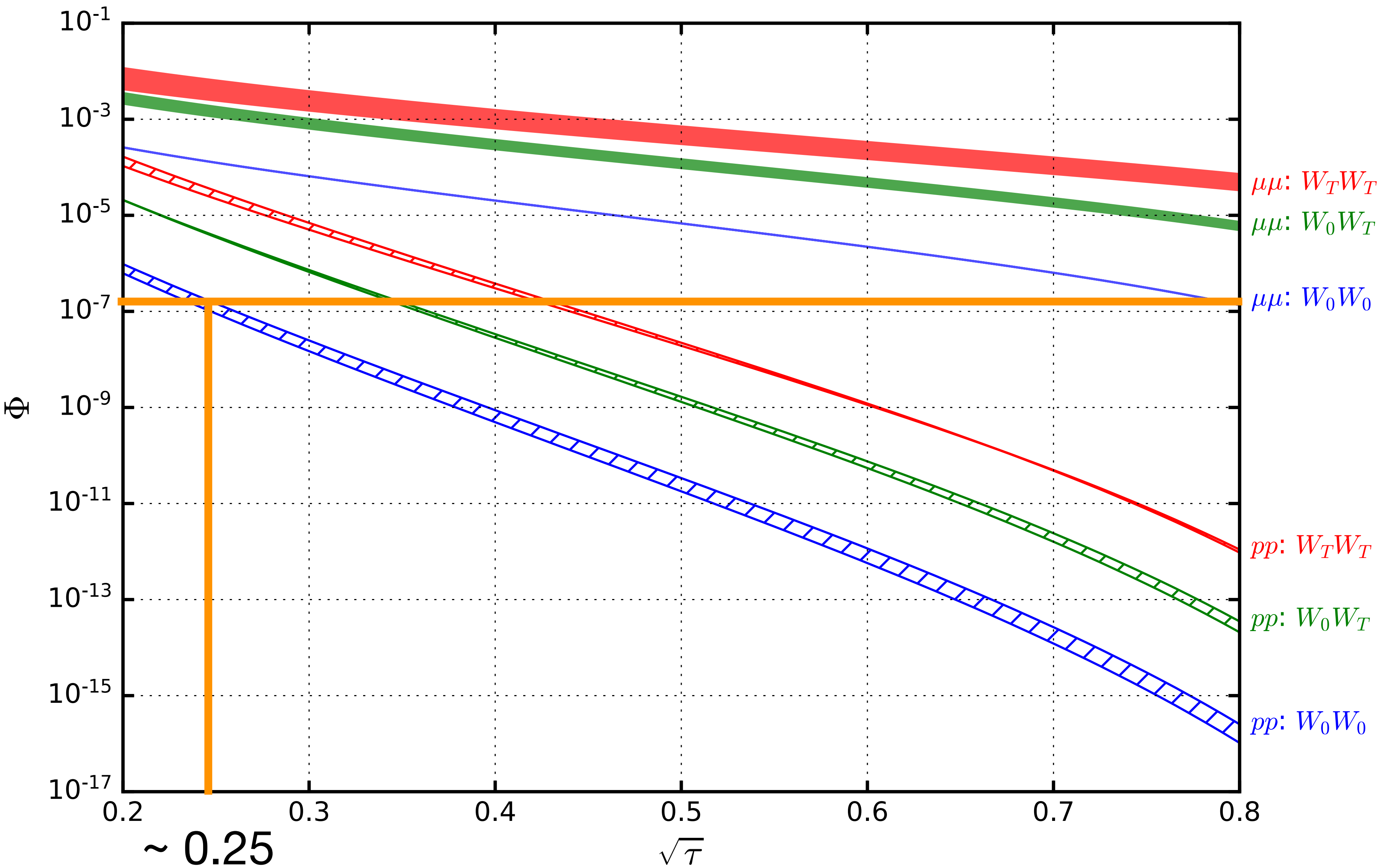
$$\Phi_{W^+_{\lambda_1} W^-_{\lambda_2}}(\tau, \mu_f) = \int_\tau^1 \frac{d\xi}{\xi} \, f_{W_{\lambda_1}/\mu}\left(\xi, \mu_f\right) \, f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi}, \mu_f\right)$$



$$\Phi_{W^+_{\lambda_1} W^-_{\bar{\lambda}_2}}(\tau, \mu_f) = \int_\tau^1 \frac{d\xi}{\xi}\, f_{W_{\lambda_1}/\mu}\left(\xi, \mu_f\right) f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi}, \mu_f\right)$$



$$\Phi_{W^+_{\lambda_1} W^-_{\lambda_2}}(\tau, \mu_f) = \int_\tau^1 \frac{d\xi}{\xi} \; f_{W_{\lambda_1}/\mu}\left(\xi, \mu_f\right) f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi}, \mu_f\right)$$

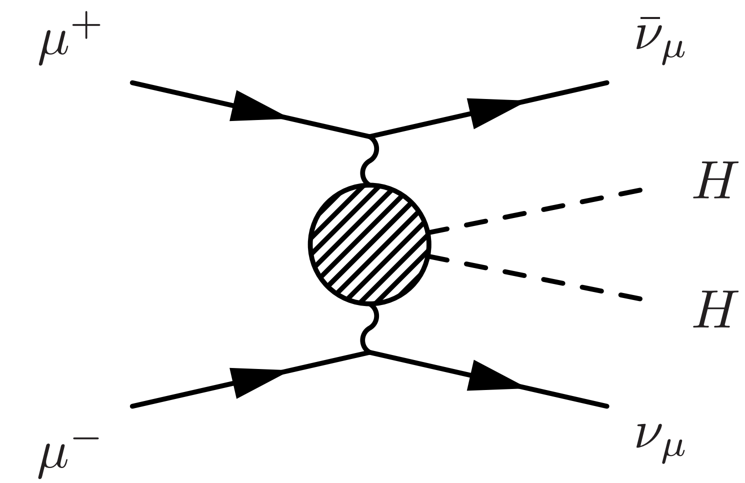


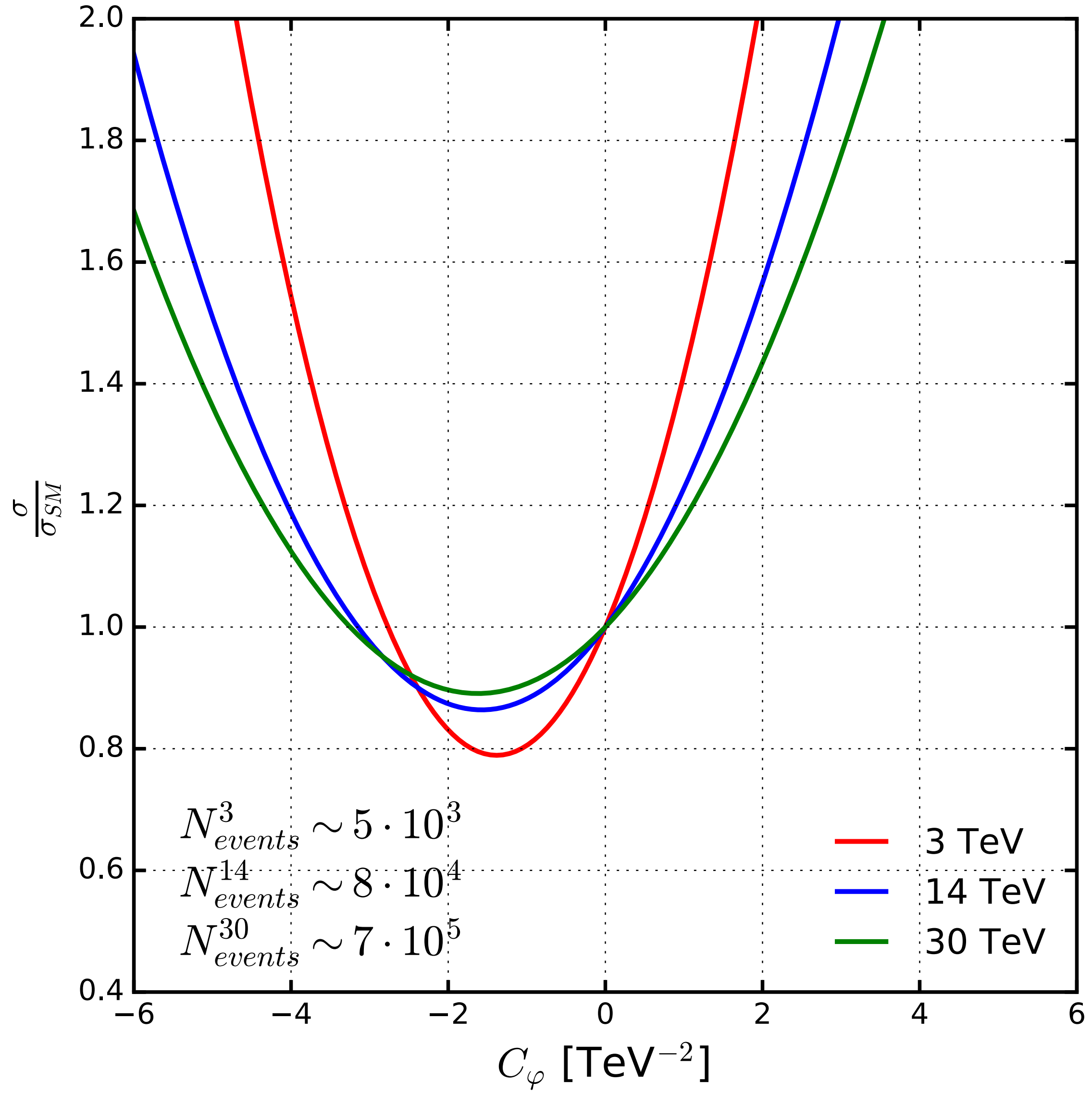

**0.8/0.25 ~ 3.5**

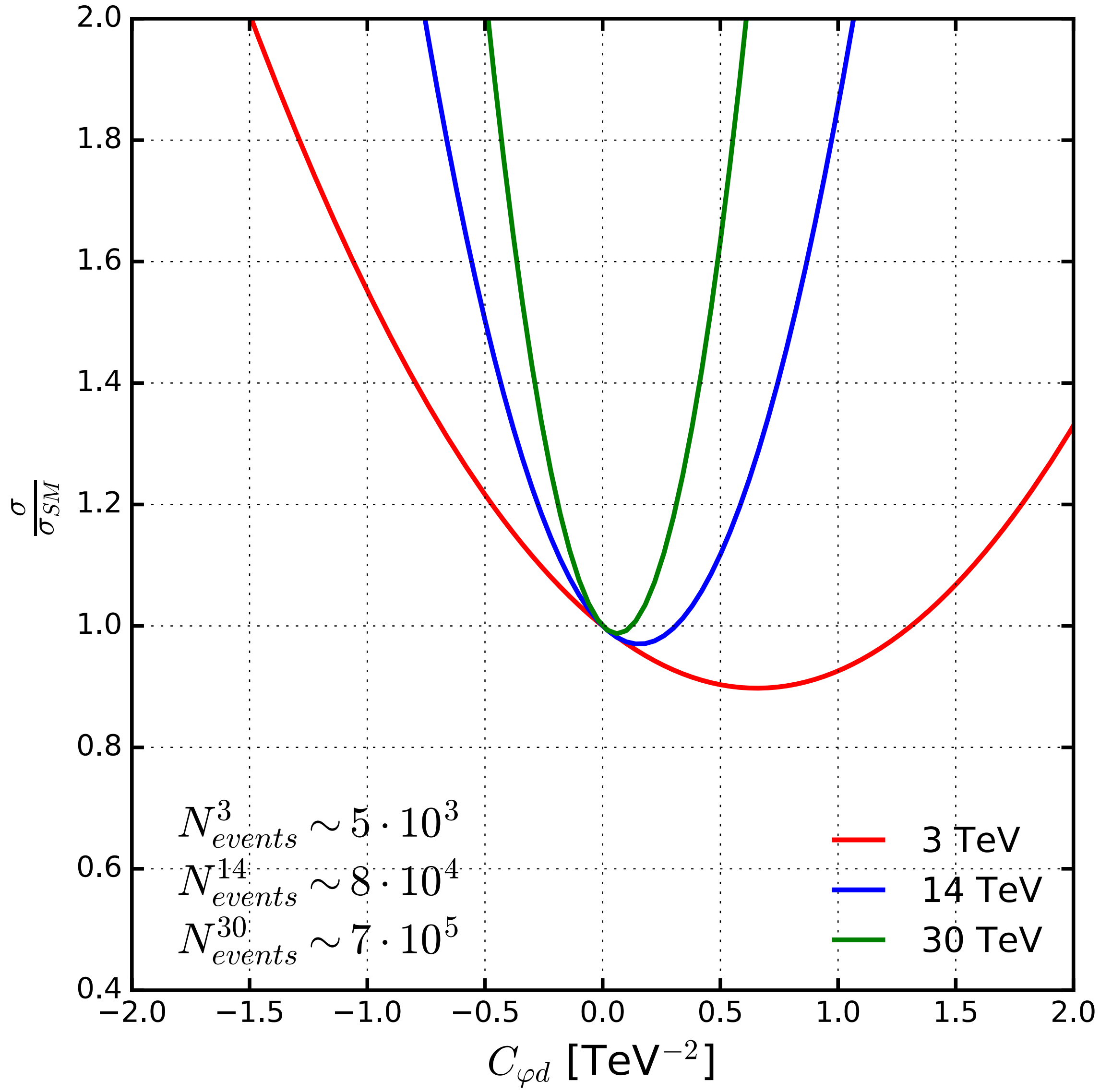
**Muon 14 TeV ~ Proton 50 TeV**

$\mathcal{L}_3 = 6\,\mathrm{ab}^{-1}$
$\mathcal{L}_{14} = 20\,\mathrm{ab}^{-1}$
$\mathcal{L}_{30} = 100\,\mathrm{ab}^{-1}$

**HH production**



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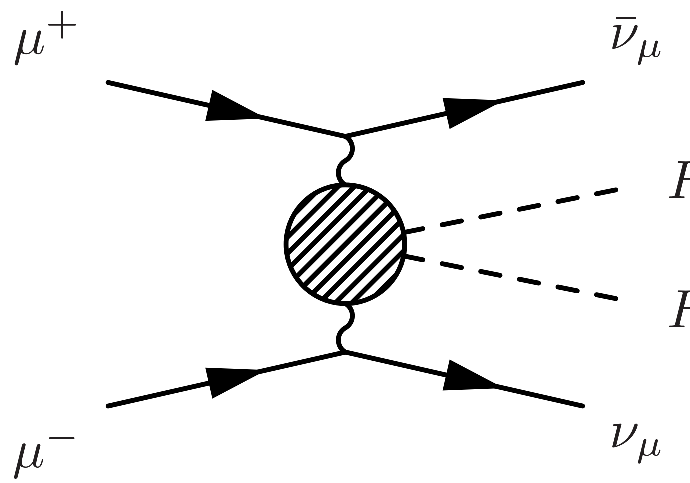
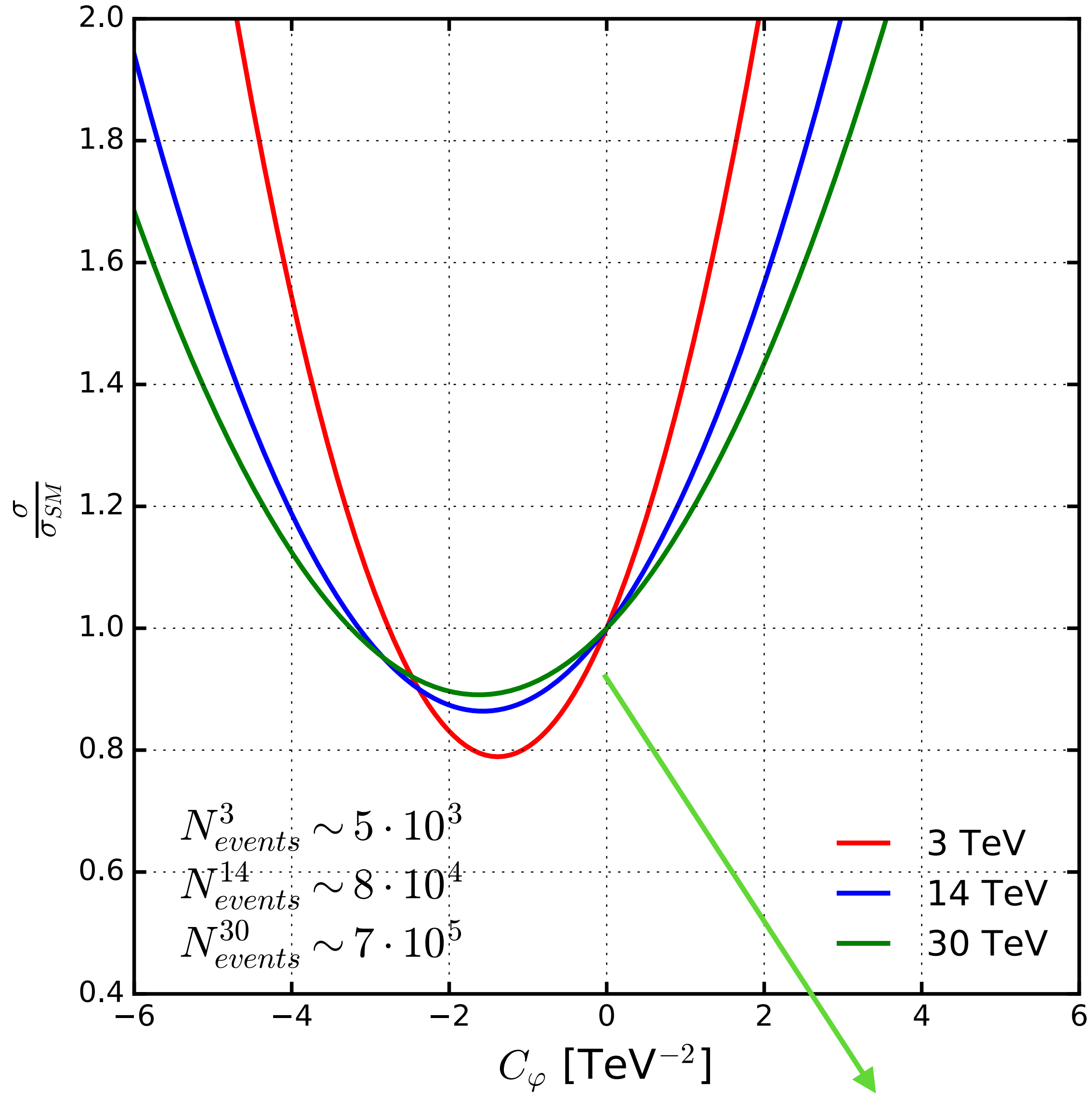
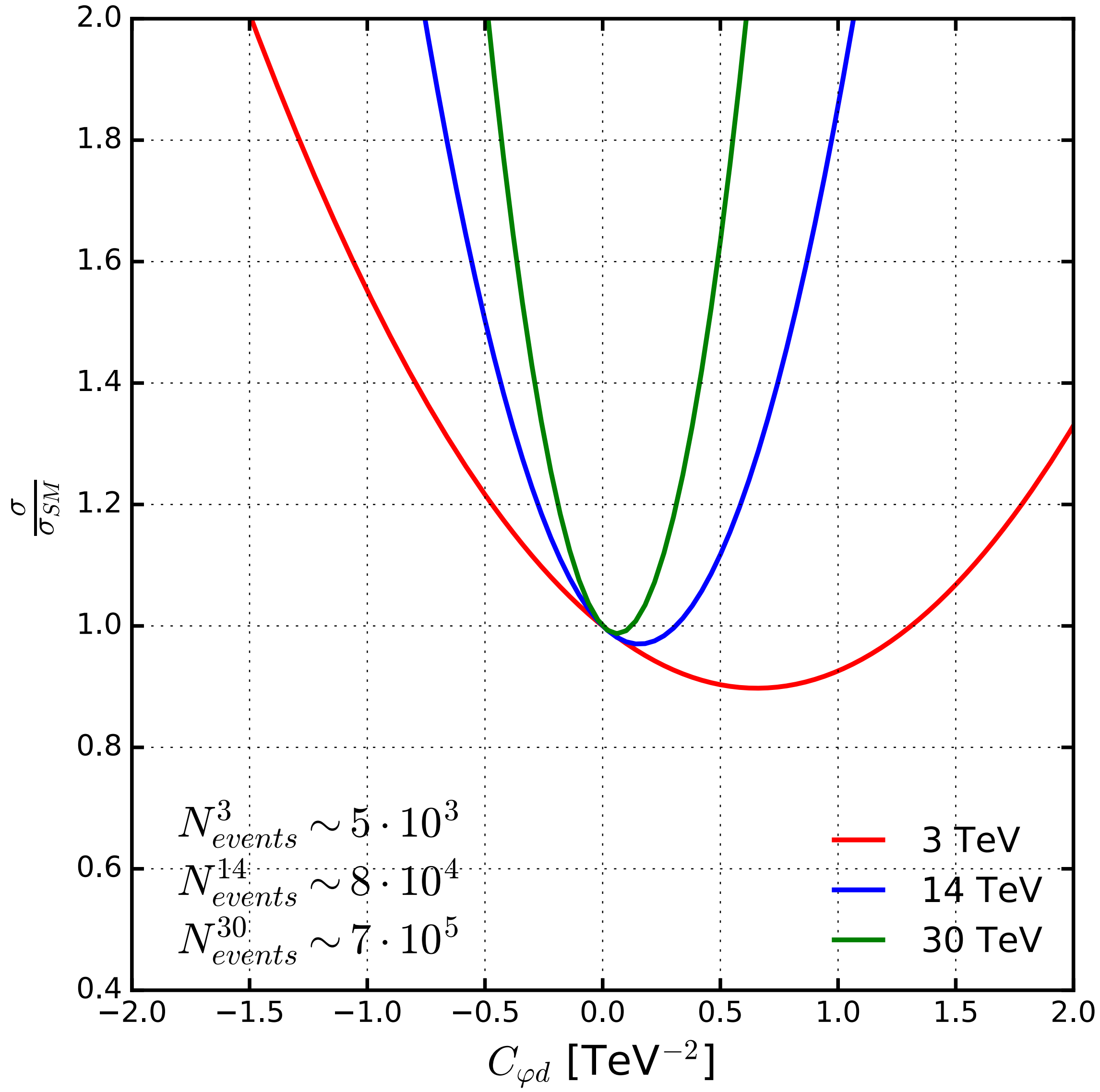
$$\mathcal{L}_{30} = 100\,\mathrm{ab}^{-1}$$

**HH production**



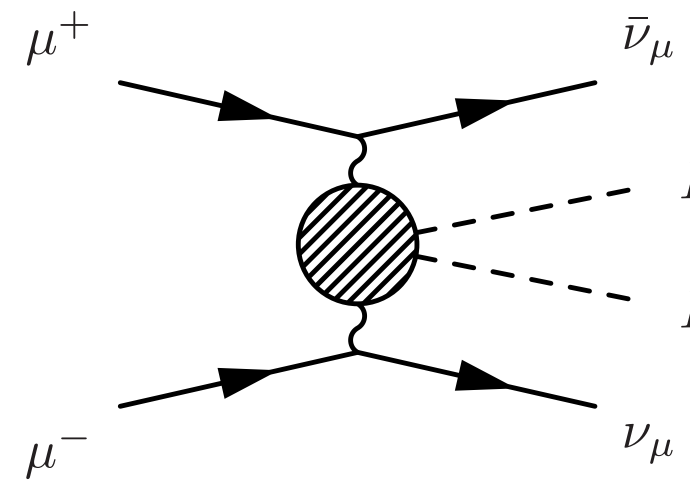



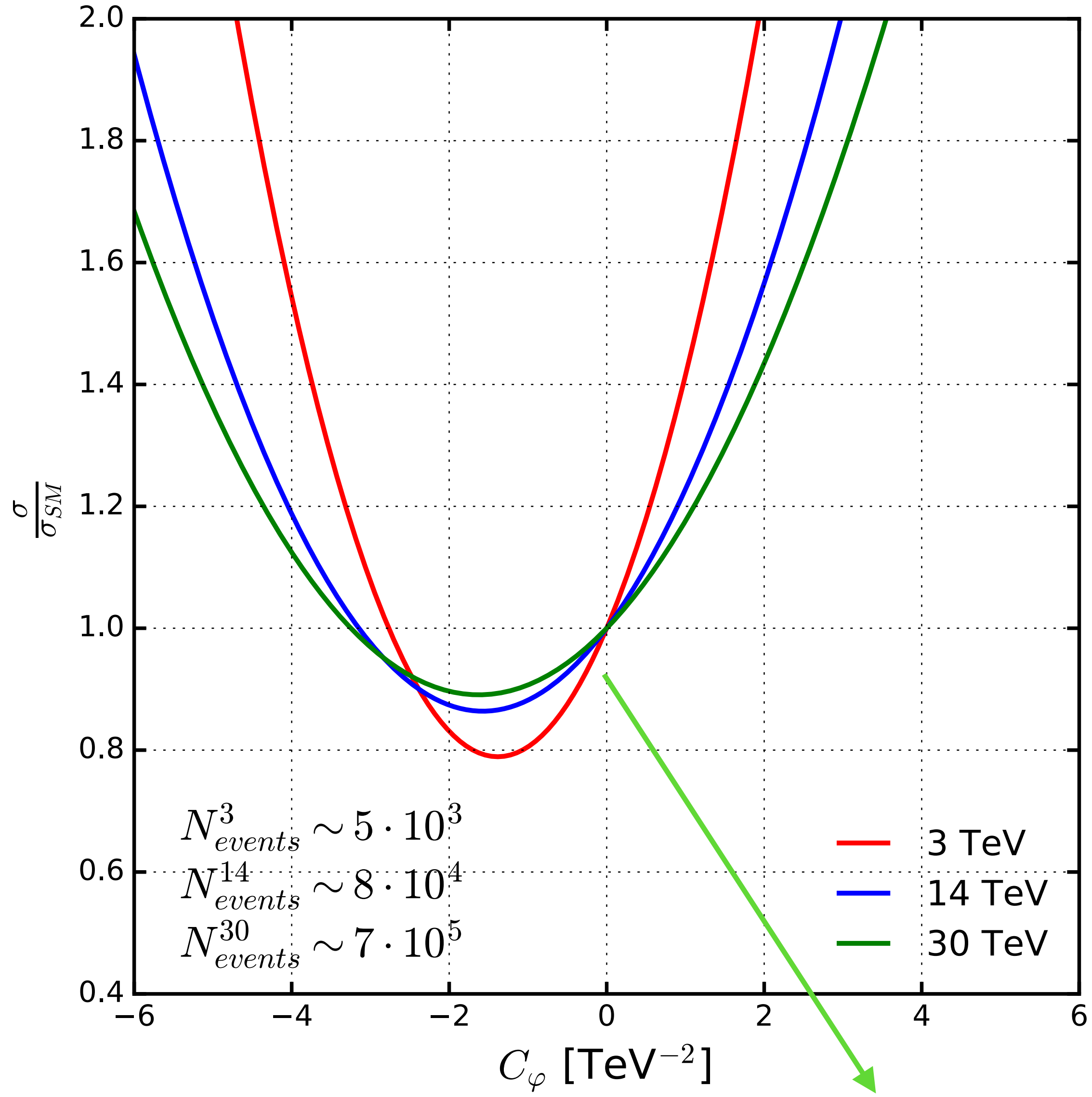



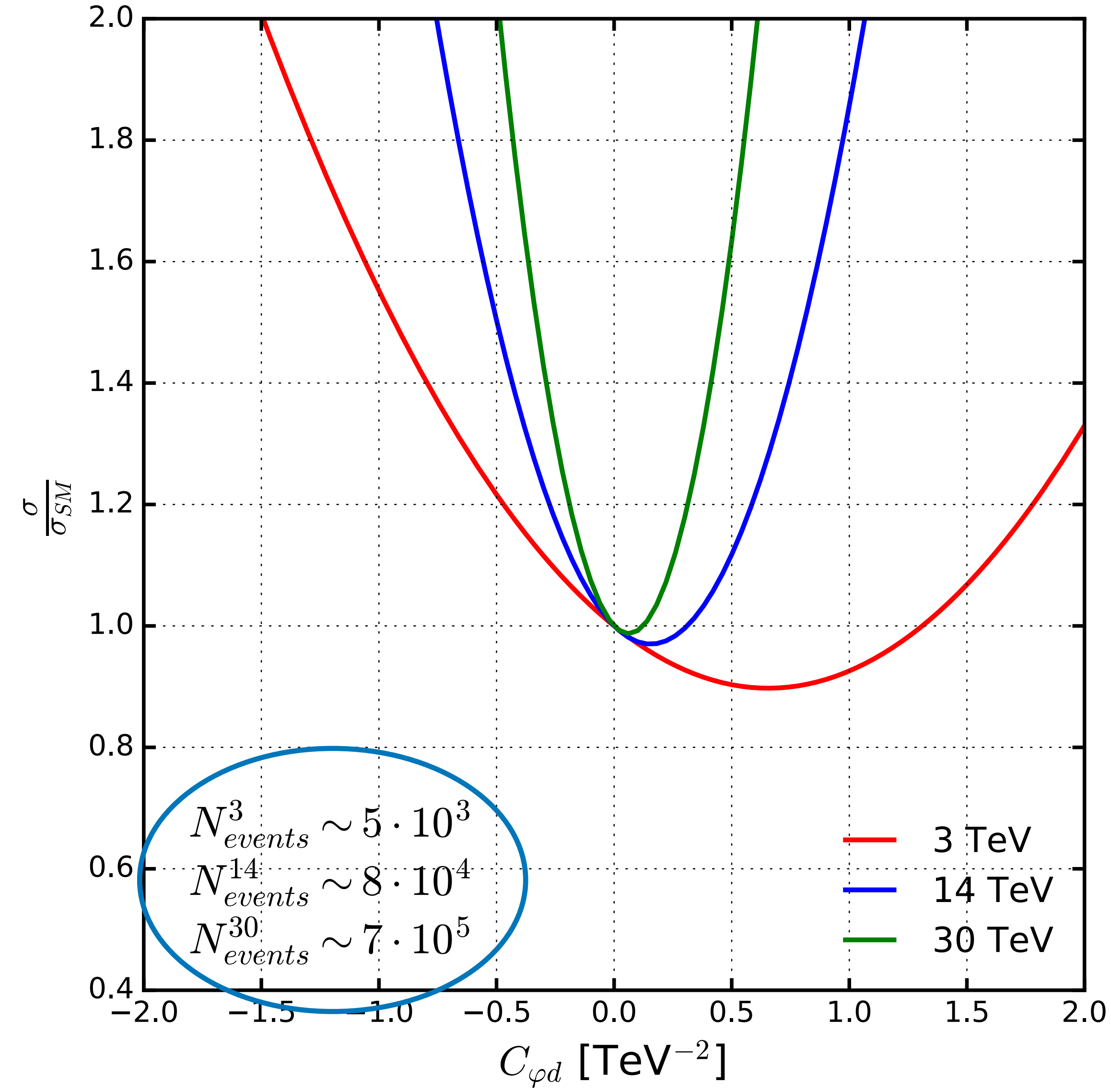

**High energy not helping!**

$$\mathcal{L}_3 = 6\,\text{ab}^{-1}$$
$$\mathcal{L}_{14} = 20\,\text{ab}^{-1}$$
$$\mathcal{L}_{30} = 100\,\text{ab}^{-1}$$

**HH production**



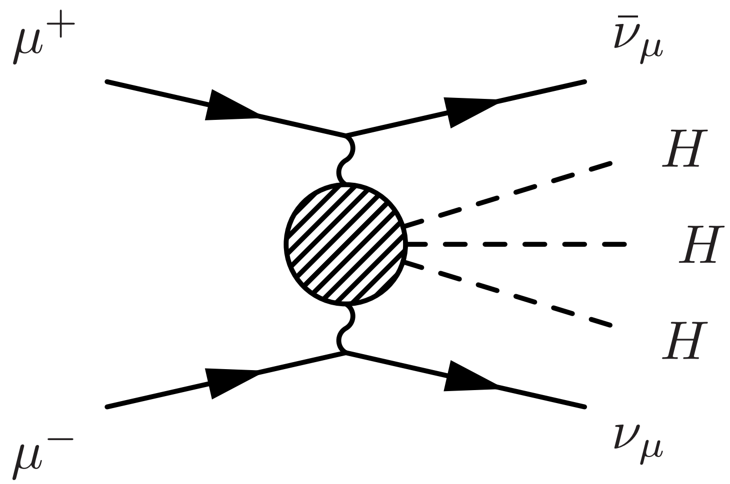



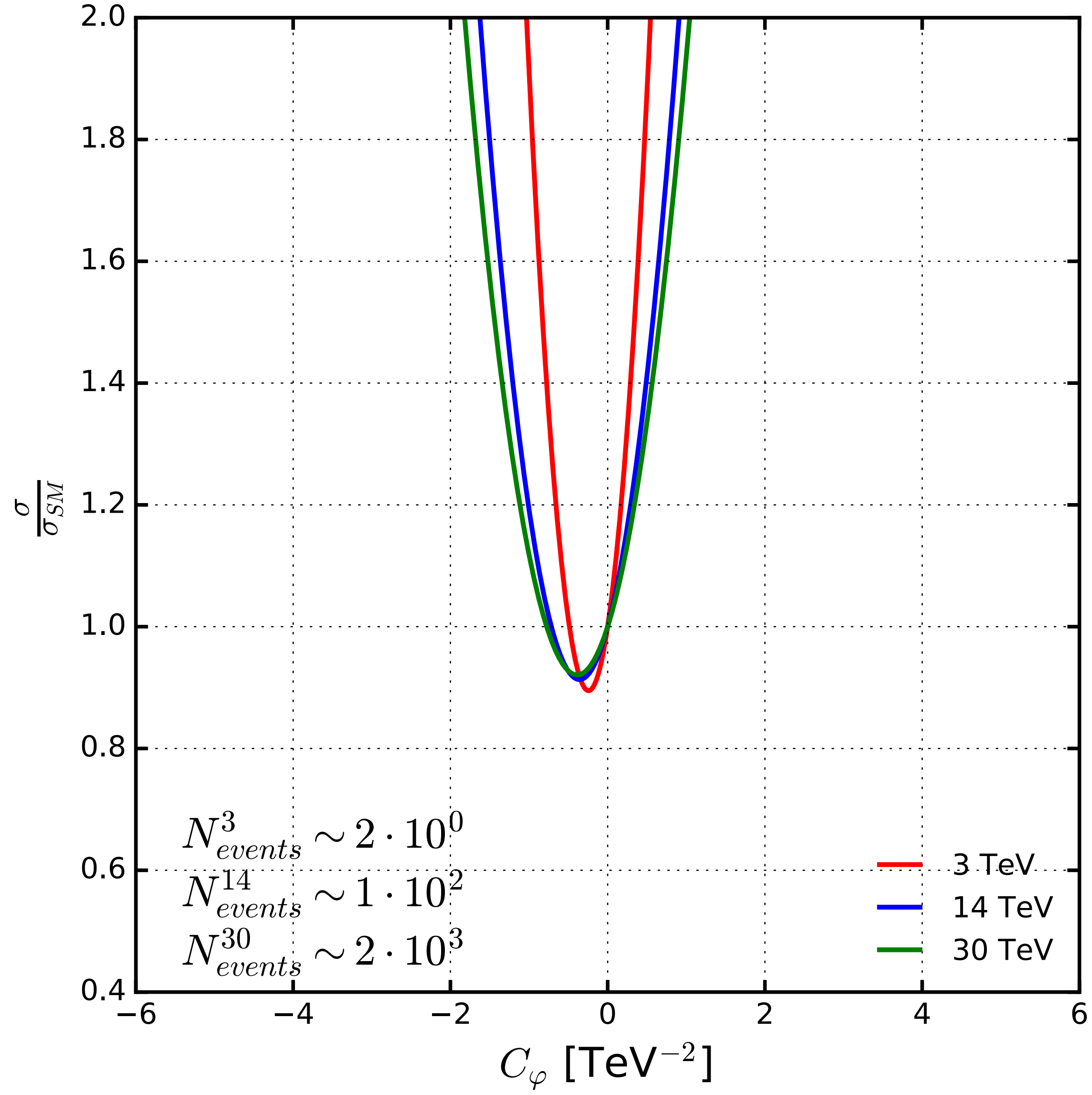

**High energy not helping!**

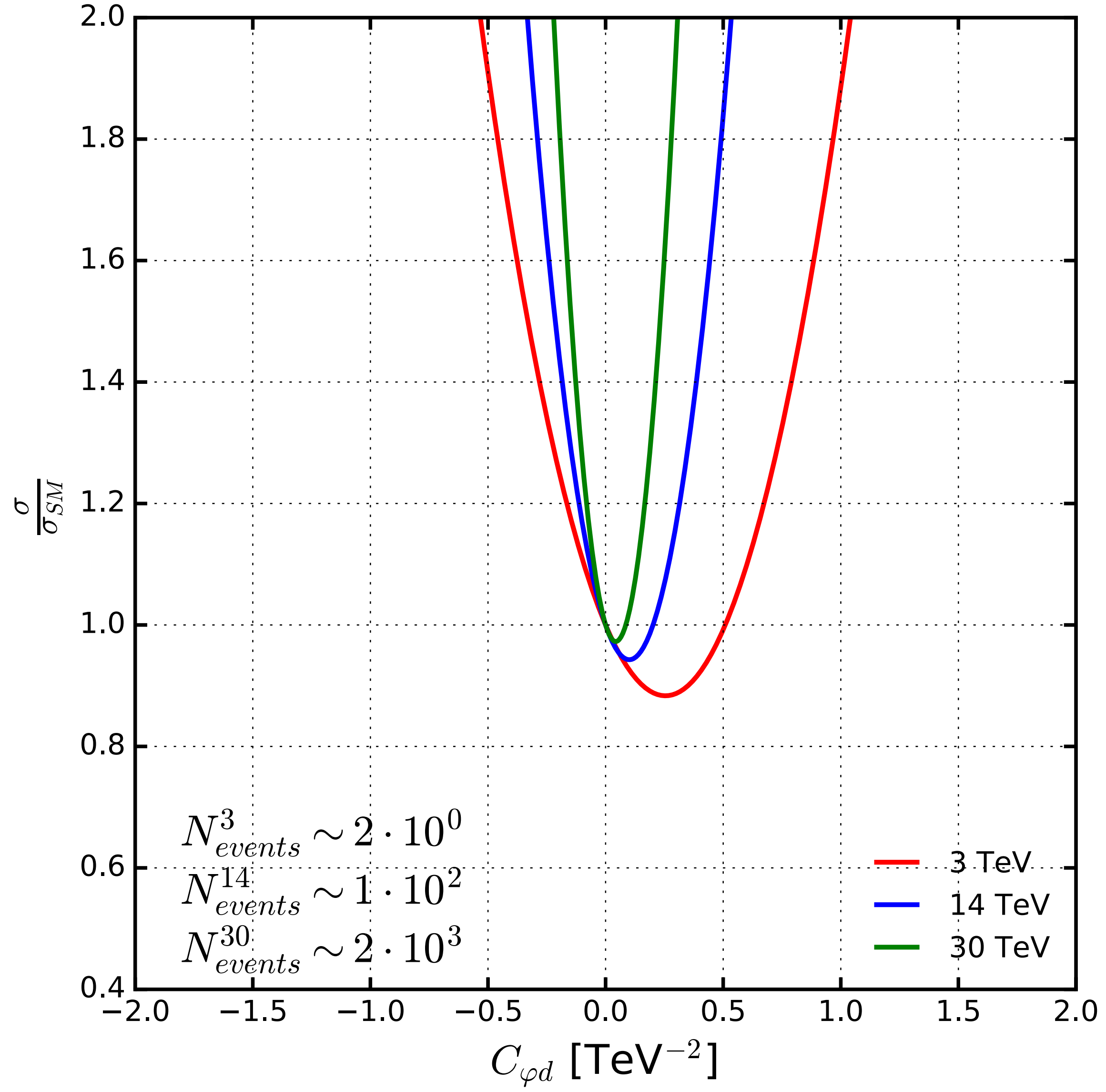
**Many events!**

$$\mathcal{L}_3 = 6\,\mathrm{ab}^{-1}$$
$$\mathcal{L}_{14} = 20\,\mathrm{ab}^{-1}$$
$$\mathcal{L}_{30} = 100\,\mathrm{ab}^{-1}$$

**HHH production**



$$\mathcal{L}_3 = 6\,\mathrm{ab}^{-1}$$
$$\mathcal{L}_{14} = 20\,\mathrm{ab}^{-1}$$
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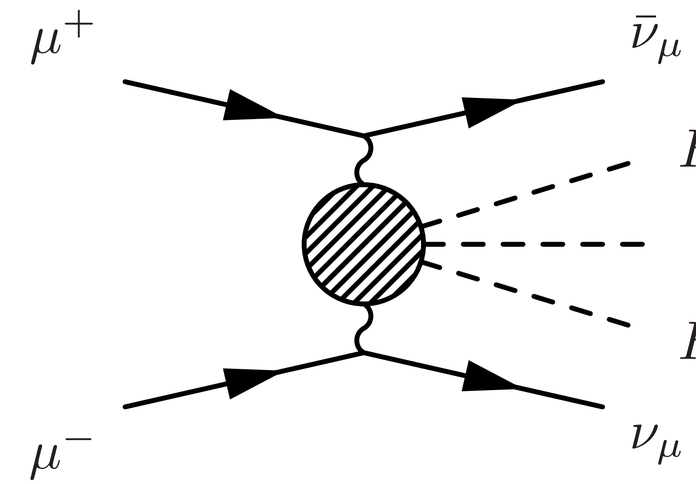
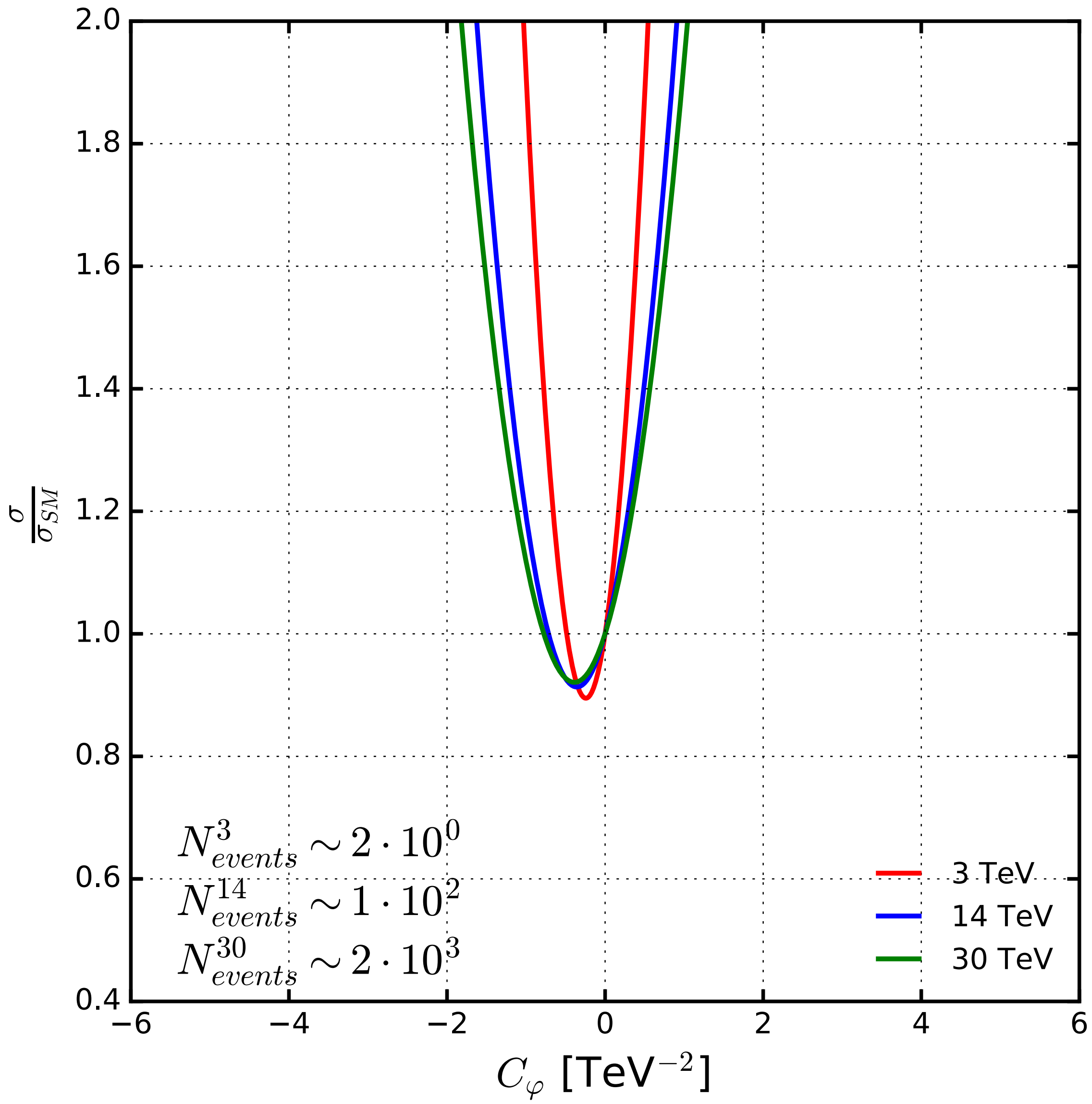
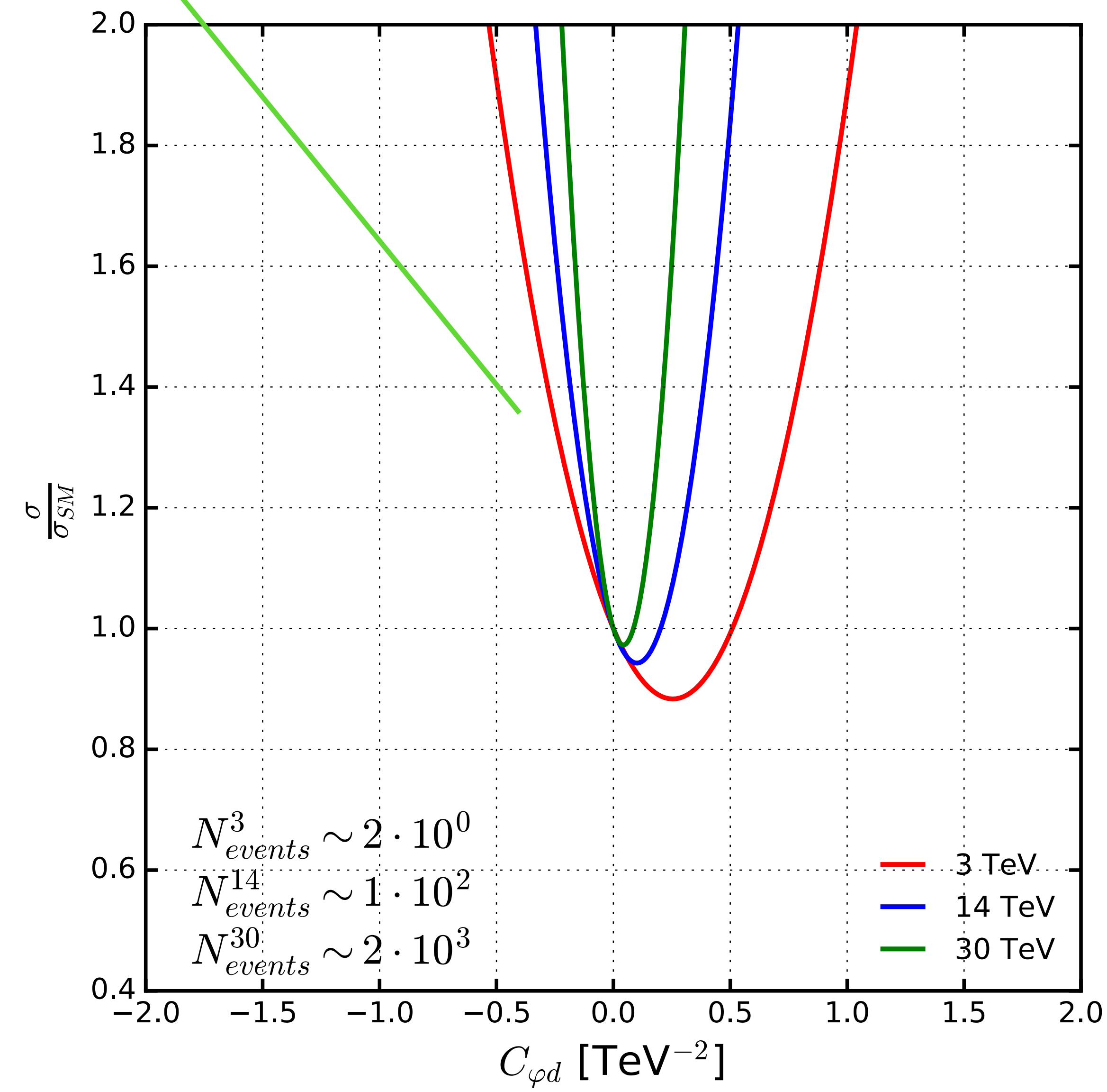
**HHH production**



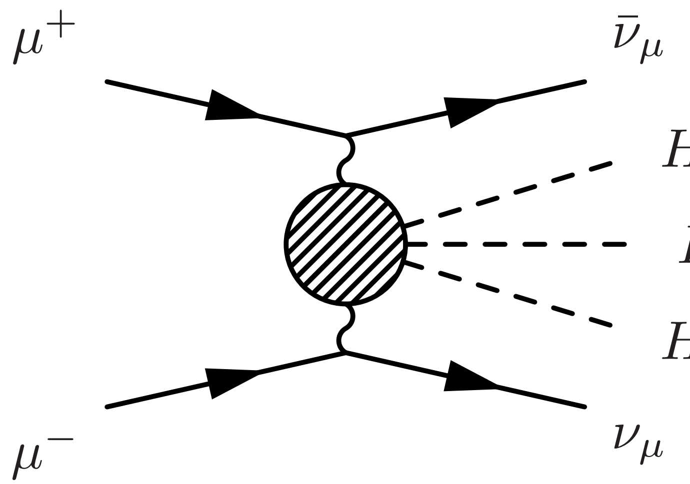

**Higher sensitivity**



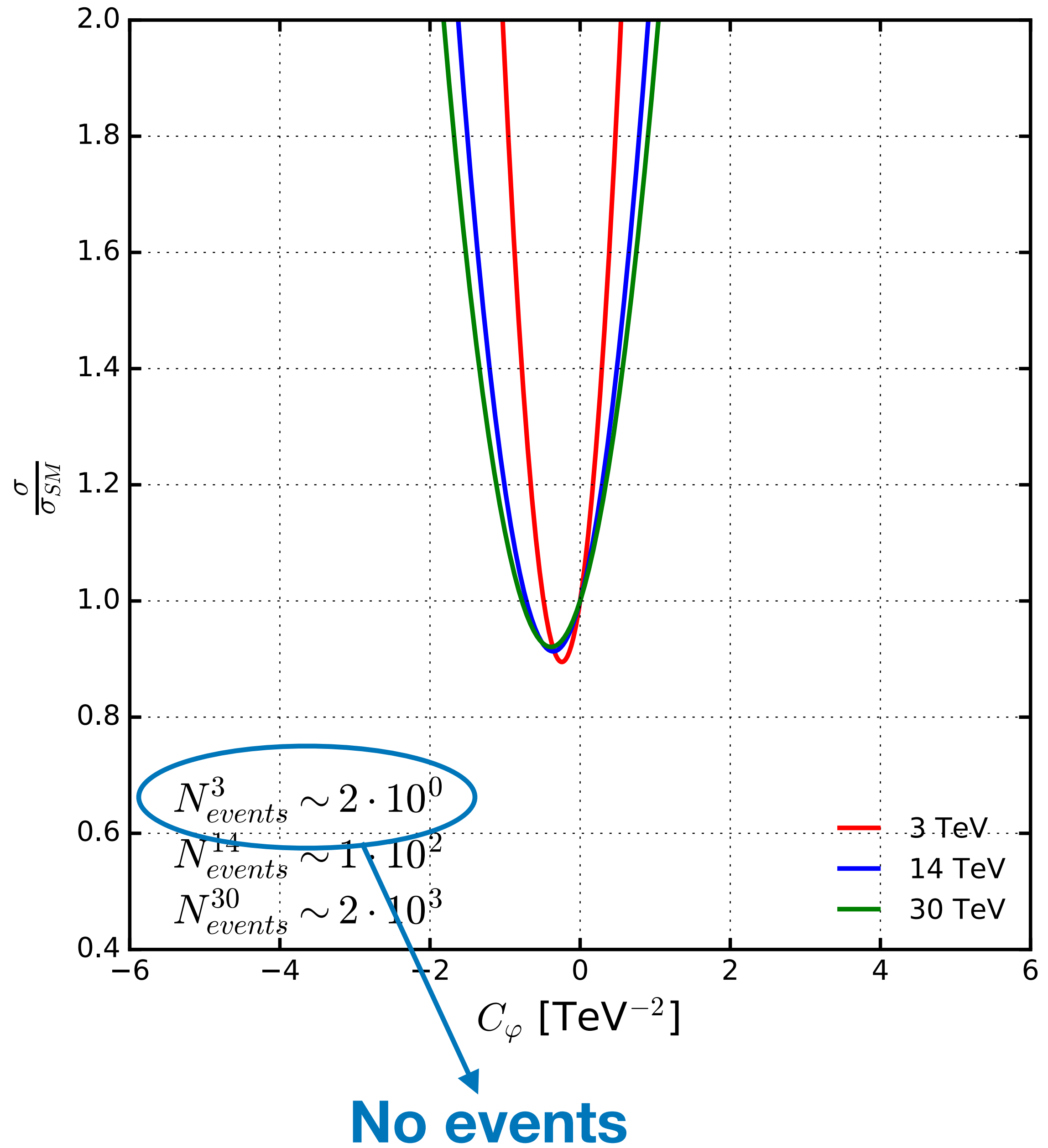



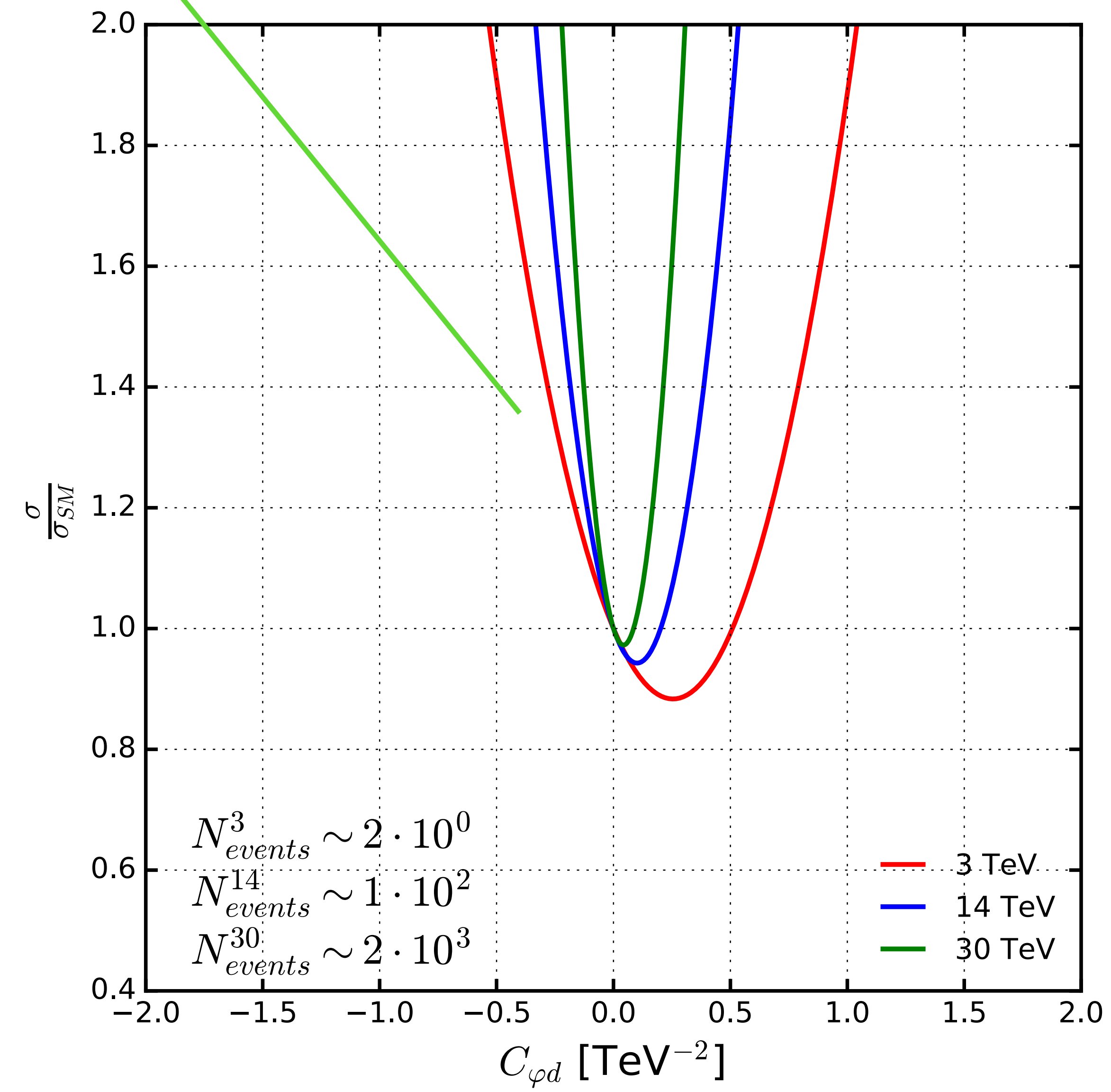
$\mathcal{L}_3 = 6\,\mathrm{ab}^{-1}$
$\mathcal{L}_{14} = 20\,\mathrm{ab}^{-1}$
$\mathcal{L}_{30} = 100\,\mathrm{ab}^{-1}$

**HHH production**



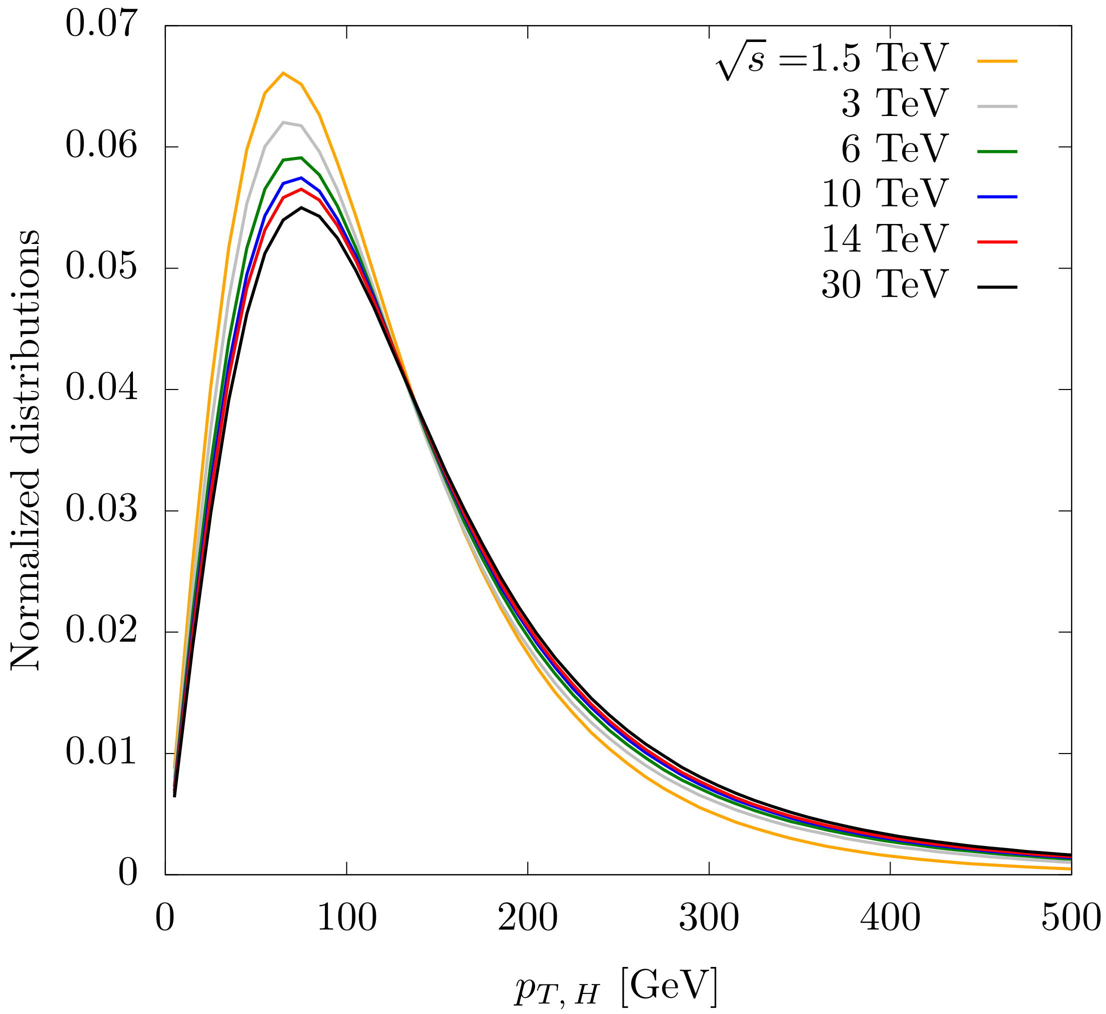

**Higher sensitivity**

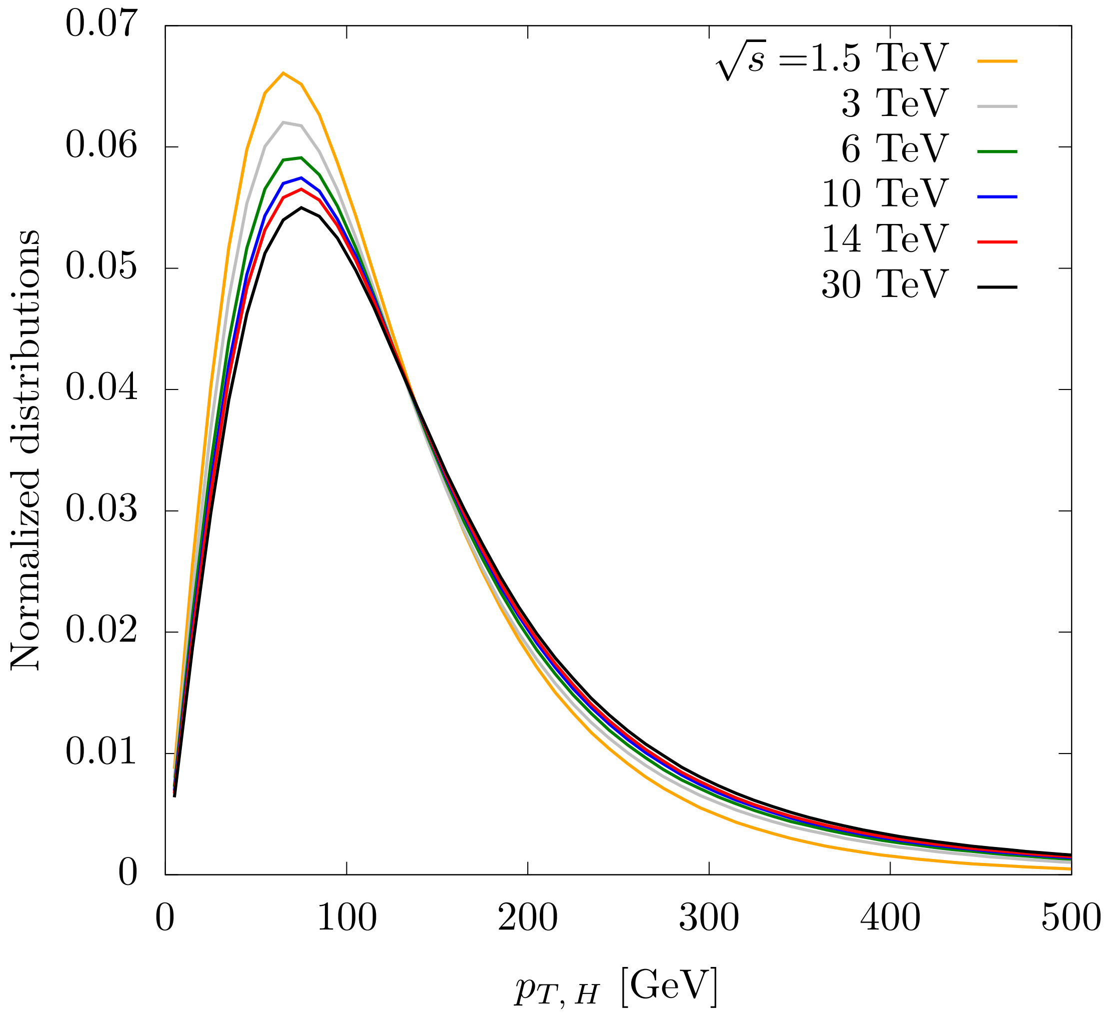


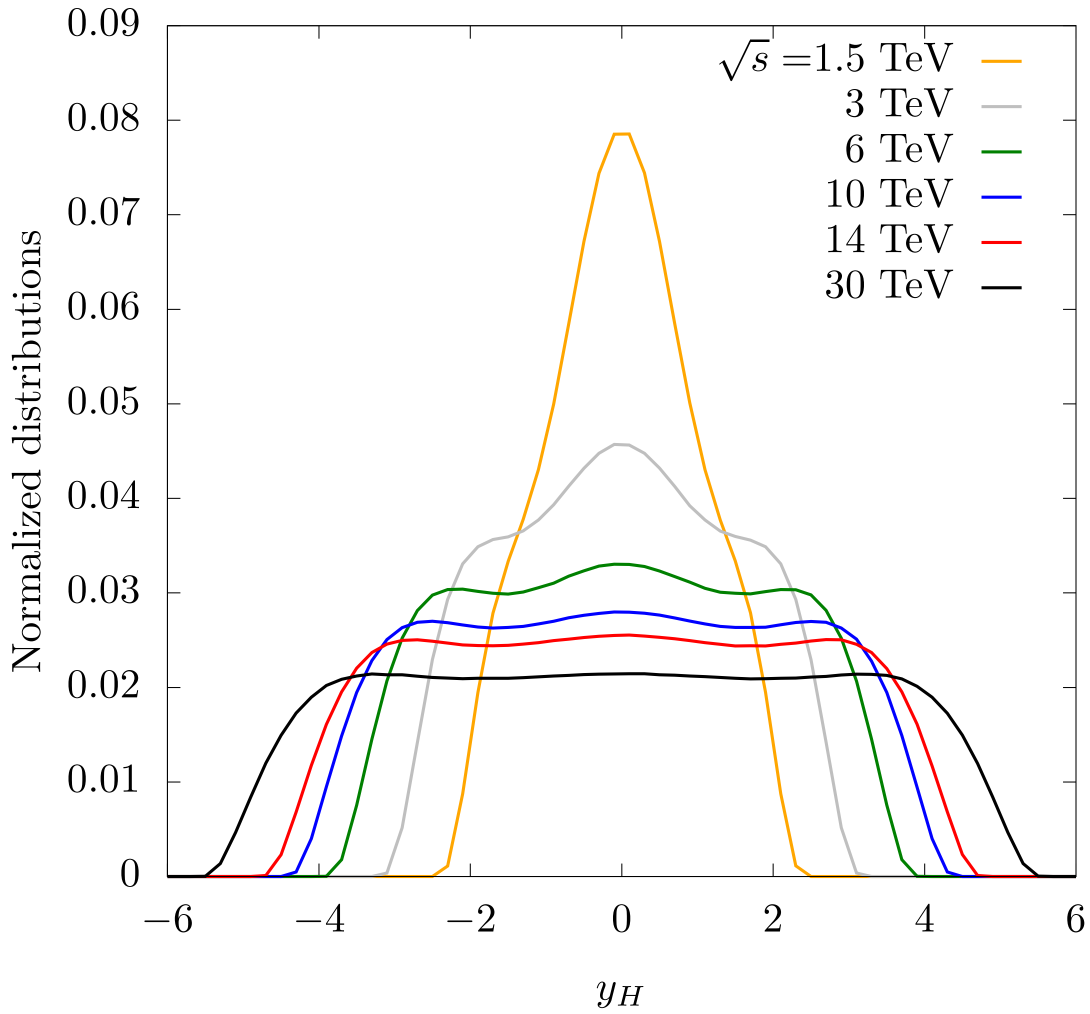



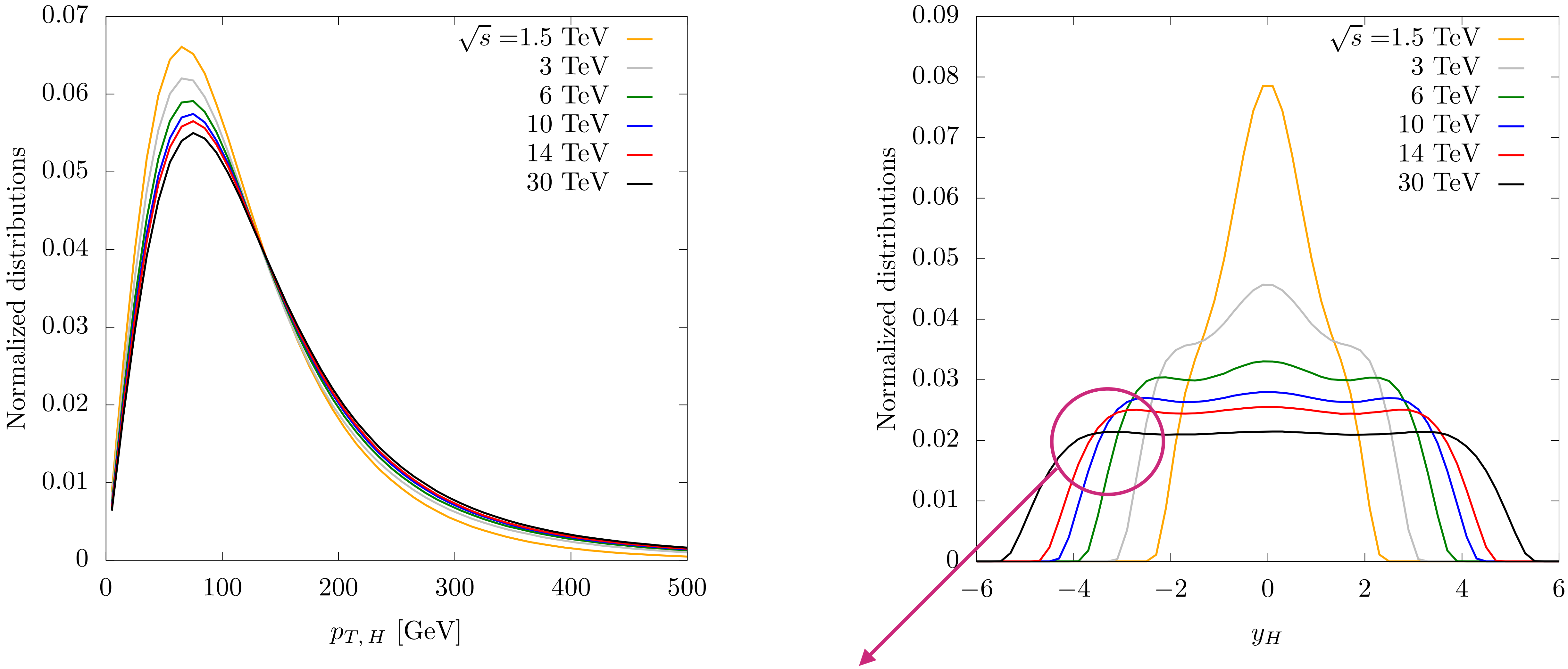



MCnet

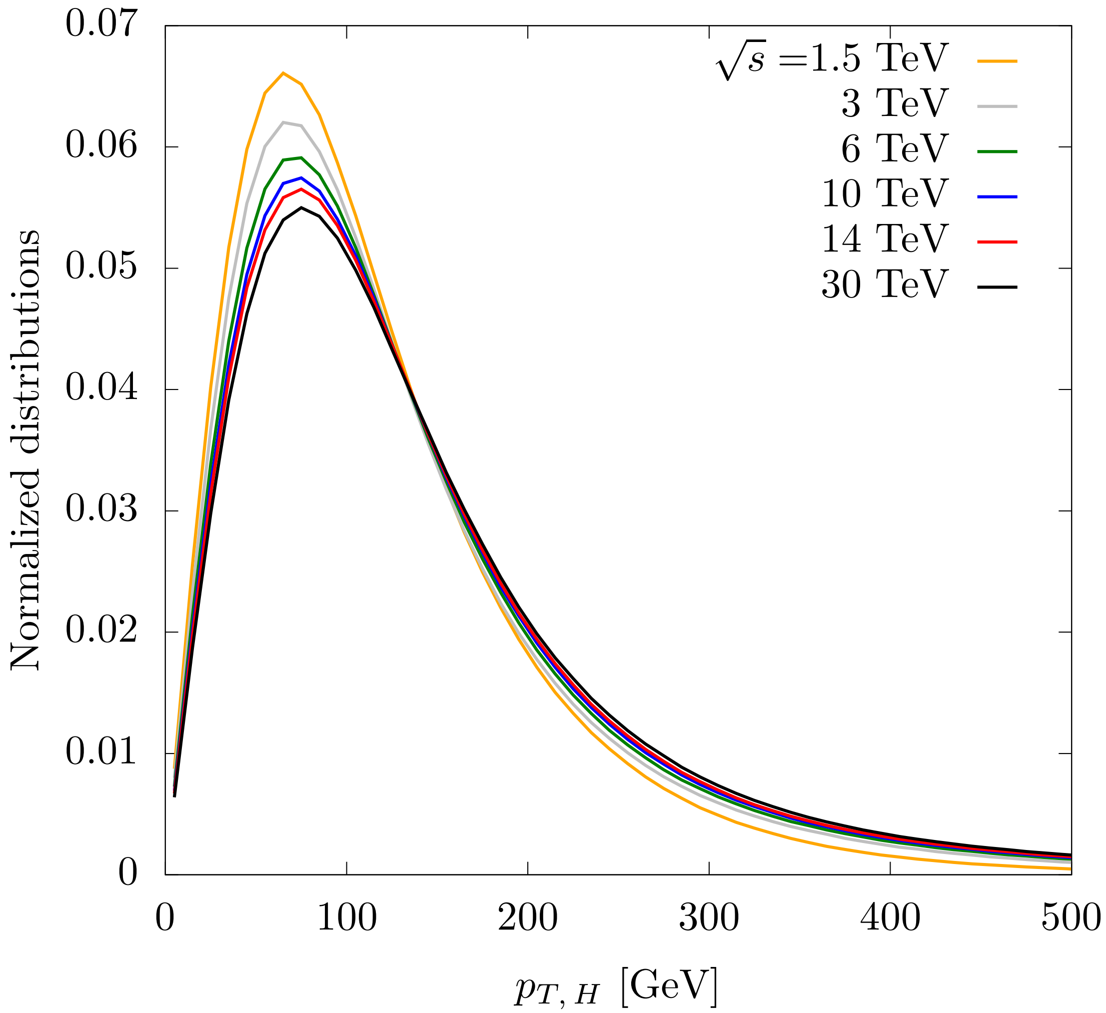

Normalized distributions
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
100
200
300
400
500
$p_{T,\,H}$ [GeV]
$\sqrt{s}$ =1.5 TeV
3 TeV
6 TeV
10 TeV
14 TeV
30 TeV

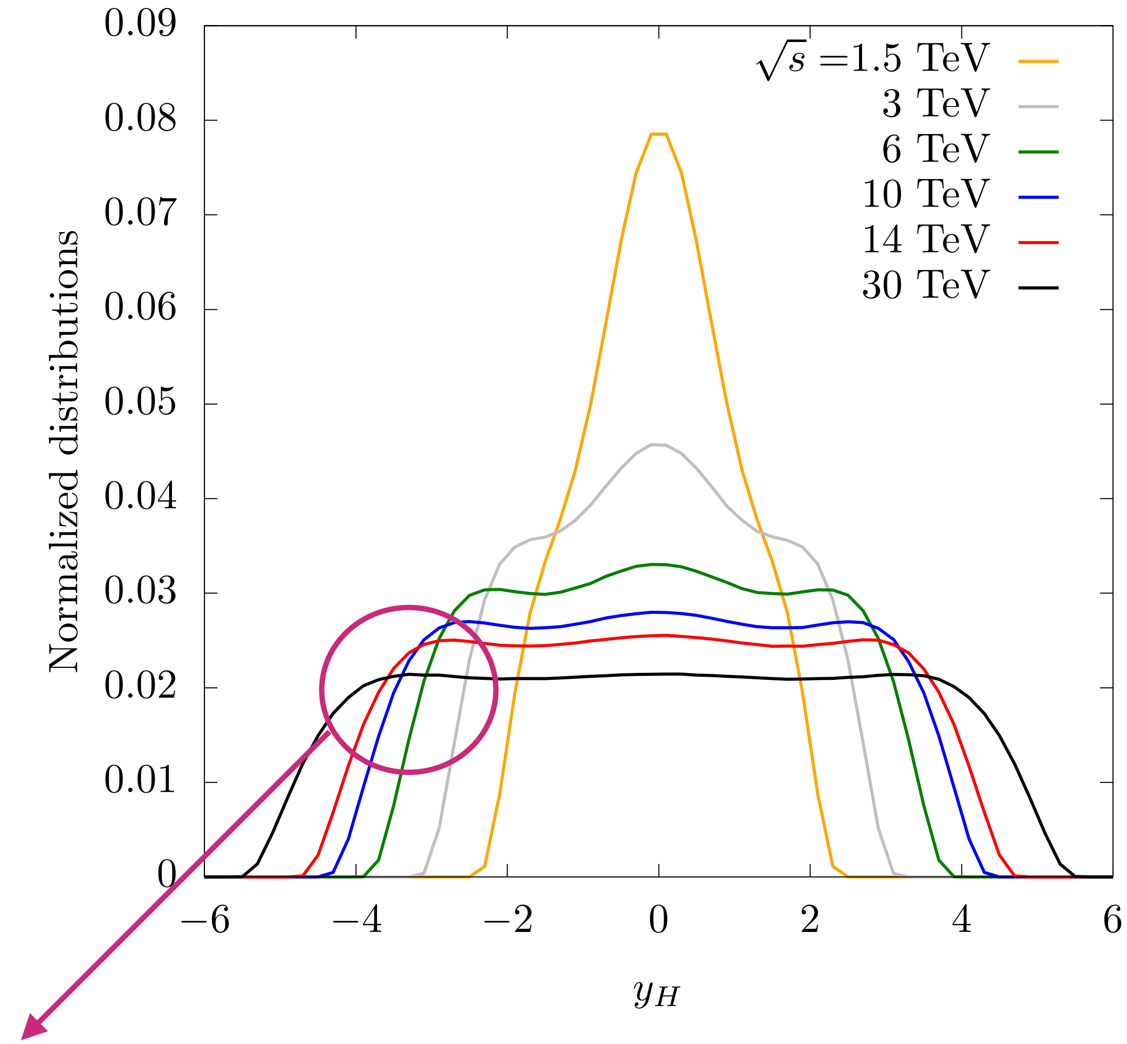

$\sqrt{s}$ =1.5 TeV
3 TeV
6 TeV
10 TeV
14 TeV
30 TeV
Normalized distributions
$p_{T,H}$ [GeV]
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
100
200
300
400
500


$\sqrt{s}$ =1.5 TeV
3 TeV
6 TeV
10 TeV
14 TeV
30 TeV
Normalized distributions
$y_H$
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−6
−4
−2
0
2
4
6



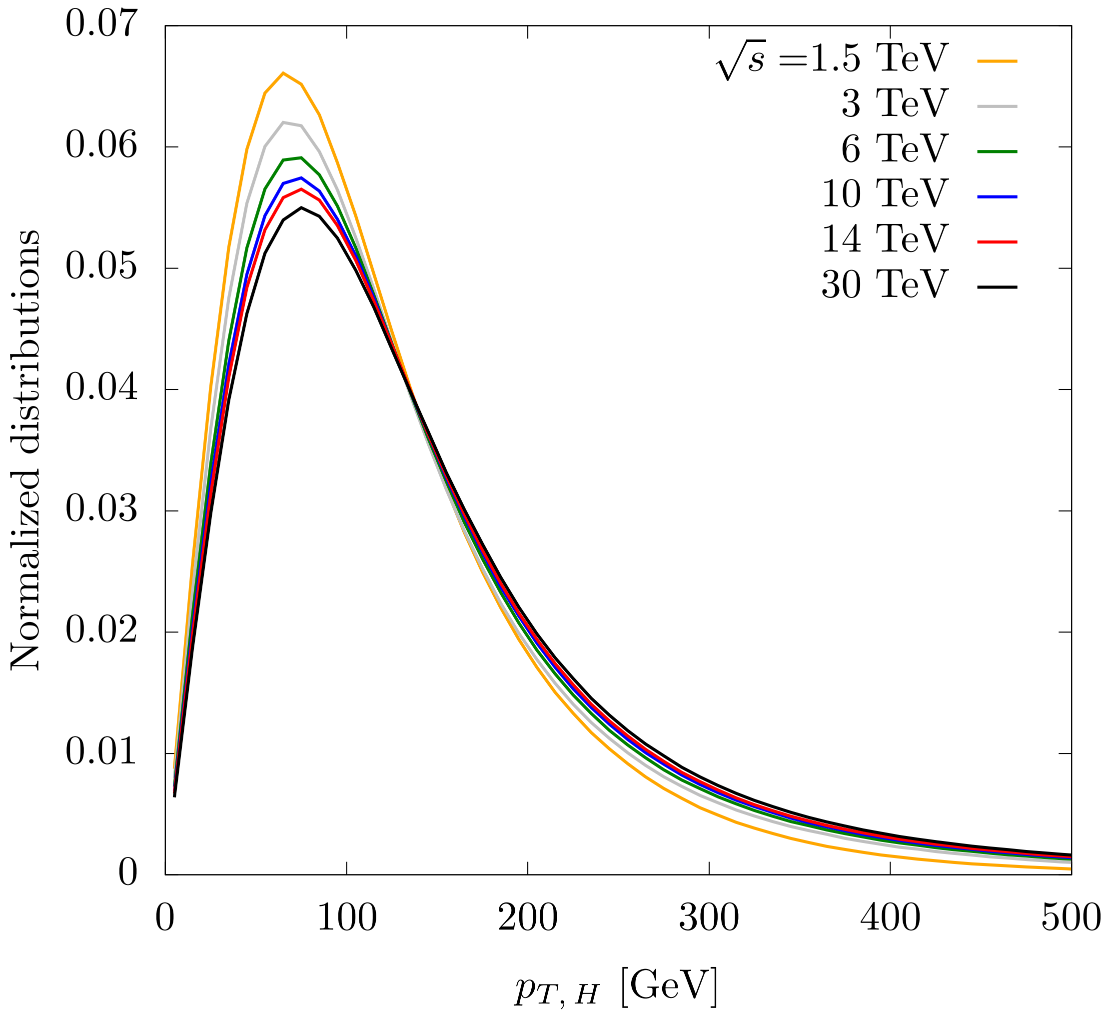

**Production in forward region at high energy!**

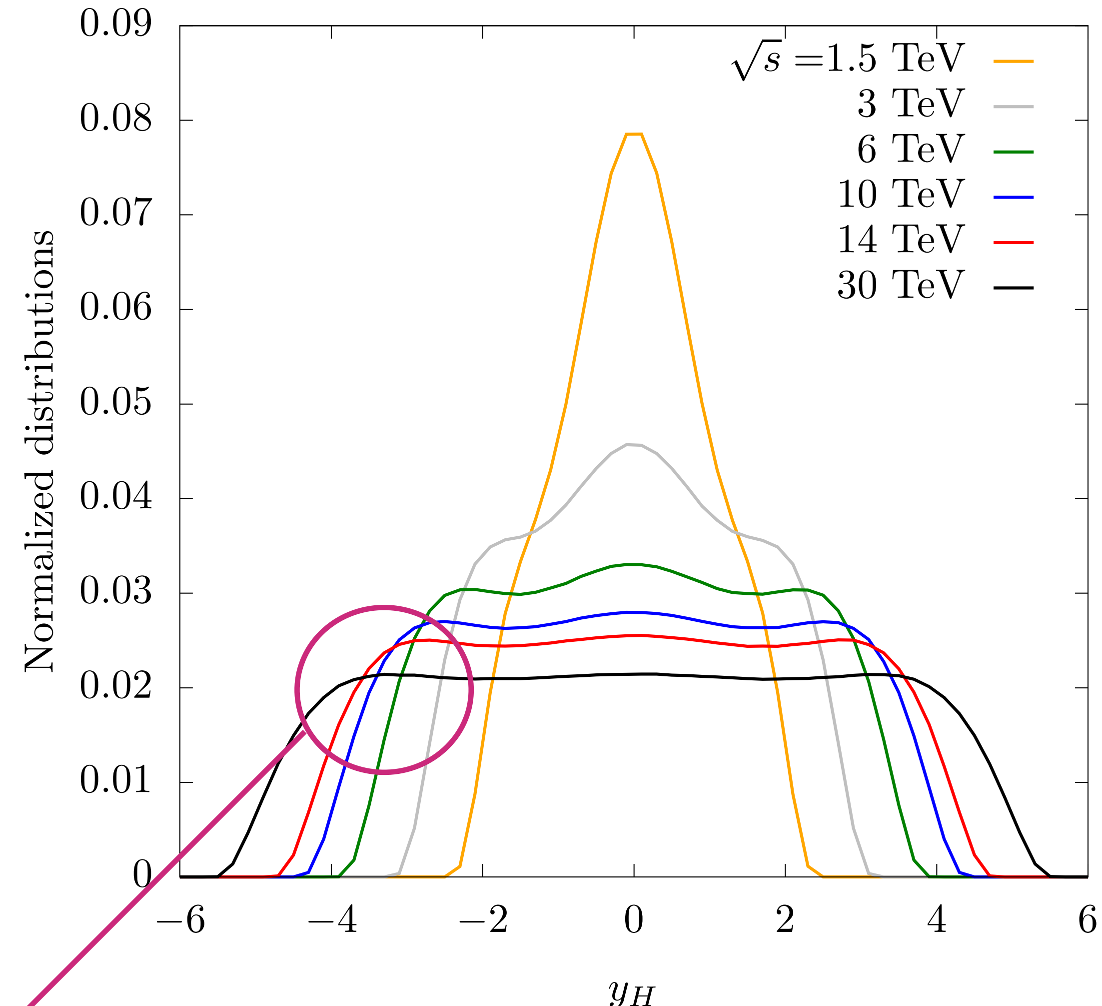



**Production in forward region at high energy!**

**Detector studies have shields in the forward region due to beam-induced background**




**Production in forward region at high energy!**

**Detector studies have shields in the forward region due to beam-induced background**

**Important to have high rapidity coverage**

$$|\eta| < 5$$

$$p_T^b > 20\text{GeV}$$

$$A \sim 60 - 70\%$$

$$\lambda_3 = \lambda_{SM}(1+\delta_3) = \kappa_3\lambda_{SM}$$

$$\lambda_4 = \lambda_{SM}(1+\delta_4) = \kappa_4\lambda_{SM}$$

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$$\sigma = \sigma_{SM} + c_2\delta_3 + c_3\delta_4 + c_4\delta_3\delta_4 + c_5\delta_3^2 + c_6\delta_4^2 + c_7\delta_3^3 + c_8\delta_3^2\delta_4 + c_9\delta_3^4$$

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**SMEFT scenario** $\delta_4 = 6\,\delta_3$

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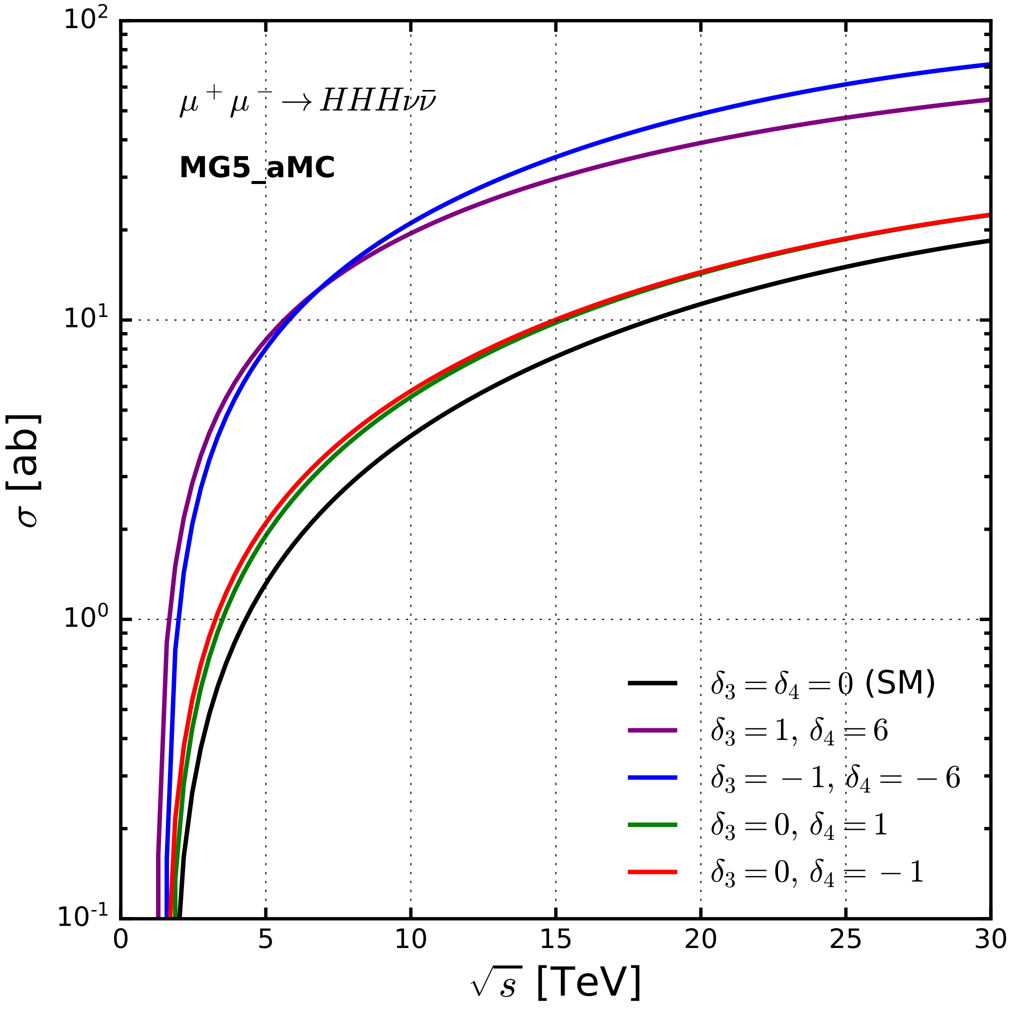
**SMEFT scenario** $\delta_4 = 6\,\delta_3$



$$\lambda_3 = \lambda_{SM}(1+\delta_3) = \kappa_3 \lambda_{SM}$$

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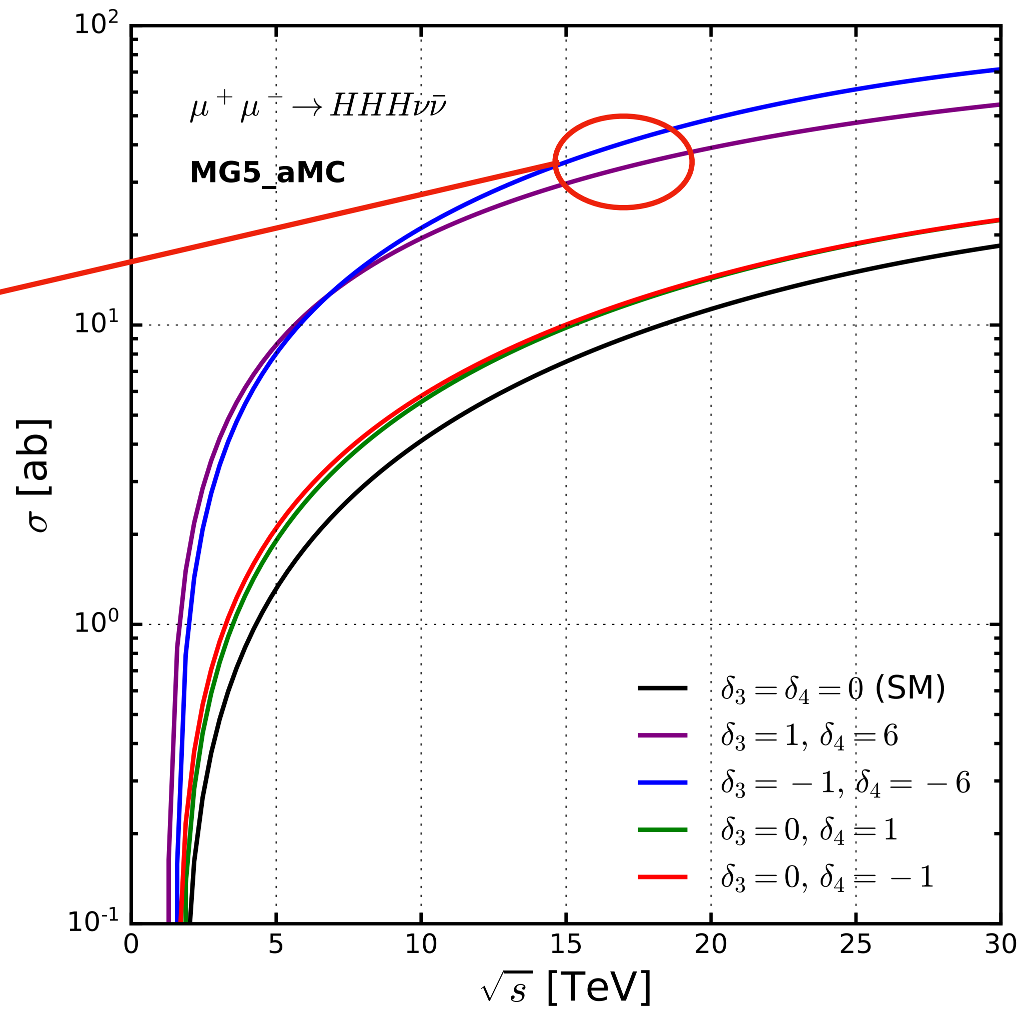
**SMEFT scenario** $\delta_4 = 6\,\delta_3$

**Huge effects in SMEFT caused by trilinear shift**



$$\lambda_3 = \lambda_{SM}(1+\delta_3) = \kappa_3 \lambda_{SM}$$

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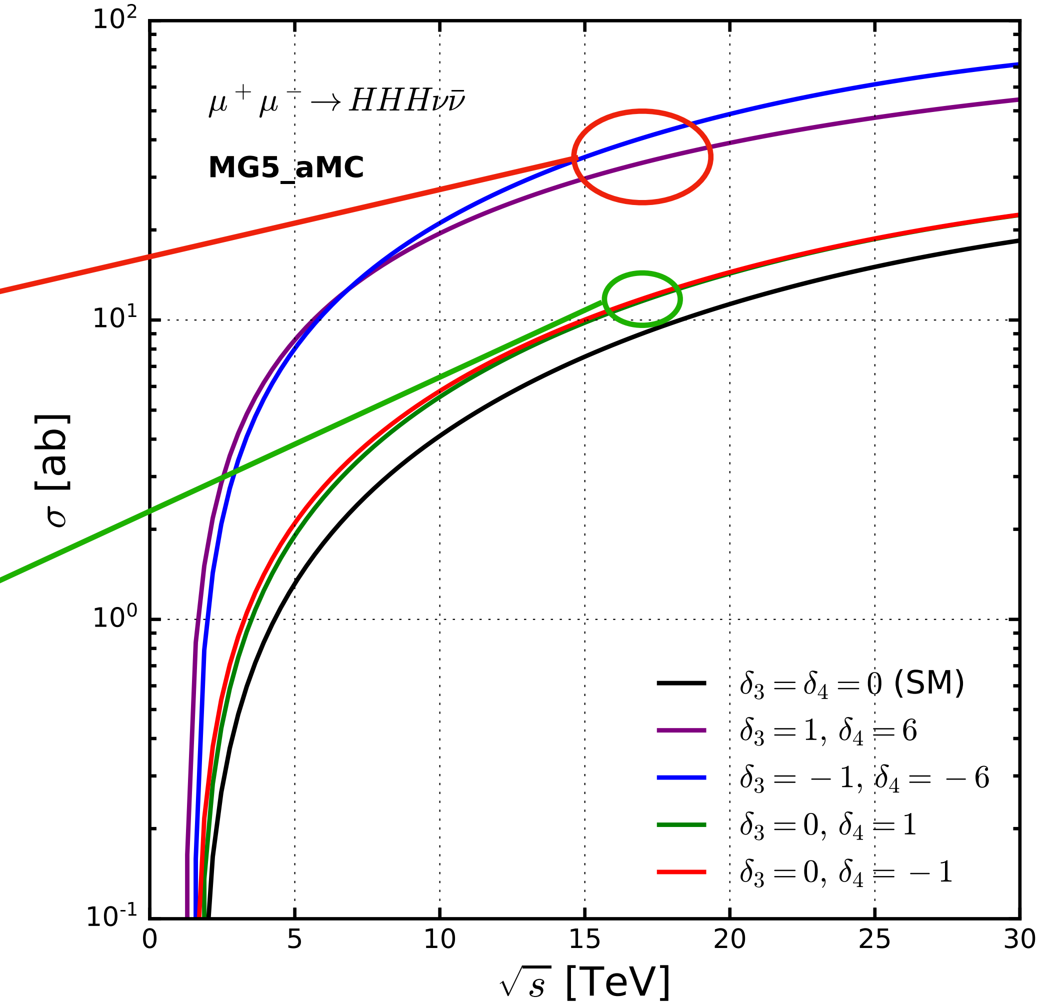
$$\sigma = \sigma_{SM} + c_2\delta_3 + c_3\delta_4 + c_4\delta_3\delta_4 + c_5\delta_3^2 + c_6\delta_4^2 + c_7\delta_3^3 + c_8\delta_3^2\delta_4 + c_9\delta_3^4$$

**SMEFT scenario** $\delta_4 = 6\,\delta_3$

**Huge effects in SMEFT caused by trilinear shift**

**Quartic deviations less sensitivity sign hardly distinguishable**



**Three operators directly affect Higgs self interaction**

$$\mathcal{O}_\varphi = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \supset v^3 H^3 + \frac{3}{2} v^2 H^4,$$
$$\mathcal{O}_{\varphi d} = \left(\varphi^\dagger\varphi\right)\Box\left(\varphi^\dagger\varphi\right) \supset 2v\left(H\Box H^2 + H^2\Box H\right) + H^2\Box H^2,$$
$$\mathcal{O}_{\varphi D} = \left(\varphi^\dagger D_\mu\varphi\right)^\dagger\left(\varphi^\dagger D^\mu\varphi\right) \supset \frac{v}{2} H\partial_\mu H\partial^\mu H + \frac{H^2}{4}\partial_\mu H\partial^\mu H.$$

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Constrained by EWPO

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Constrained by EWPO

**We look at HH and HHH production**

$$\sigma = \sigma_{SM} + \sum_i c_i \sigma^i_{Int} + \sum_{i,j} c_{i,j}\sigma^{i,j}_{Sq}$$

**Three operators directly affect Higgs self interaction**

$$\mathcal{O}_\varphi = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \supset v^3 H^3 + \frac{3}{2} v^2 H^4,$$

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**Constrained by EWPO**

**We look at HH and HHH production**

$$\sigma = \sigma_{SM} + \sum_i c_i \sigma^i_{Int} + \sum_{i,j} c_{i,j}\sigma^{i,j}_{Sq}$$

$$R(c_i) \equiv \frac{\sigma}{\sigma_{SM}} = 1 + c_i\frac{\sigma^i_{Int}}{\sigma_{SM}} + c^2_{i,i}\frac{\sigma^{i,i}_{Sq}}{\sigma_{SM}} = 1 + r_i + r_{i,i}.$$



MCnet

### Three operators directly affect Higgs self interaction

$$\mathcal{O}_{\varphi} = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \supset v^3 H^3 + \frac{3}{2} v^2 H^4,$$

$$\mathcal{O}_{\varphi d} = \left(\varphi^\dagger\varphi\right)\Box\left(\varphi^\dagger\varphi\right) \supset 2v\left(H\Box H^2 + H^2\Box H\right) + H^2\Box H^2,$$

$$\mathcal{O}_{\varphi D} = \left(\varphi^\dagger D_\mu\varphi\right)^\dagger\left(\varphi^\dagger D^\mu\varphi\right) \supset \frac{v}{2} H\partial_\mu H\partial^\mu H + \frac{H^2}{4}\partial_\mu H\partial^\mu H.$$

**Constrained by EWPO**

### We look at HH and HHH production

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**Sensitivity linear**

**Three operators directly affect Higgs self interaction**

$$\mathcal{O}_\varphi = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \supset v^3 H^3 + \frac{3}{2} v^2 H^4,$$

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~~$$\mathcal{O}_{\varphi D} = \left(\varphi^\dagger D_\mu \varphi\right)^\dagger \left(\varphi^\dagger D^\mu \varphi\right) \supset \frac{v}{2} H \partial_\mu H \partial^\mu H + \frac{H^2}{4} \partial_\mu H \partial^\mu H.$$~~

**Constrained by EWPO**

**We look at HH and HHH production**

$$\sigma = \sigma_{SM} + \sum_i c_i \sigma^i_{Int} + \sum_{i,j} c_{i,j} \sigma^{i,j}_{Sq}$$

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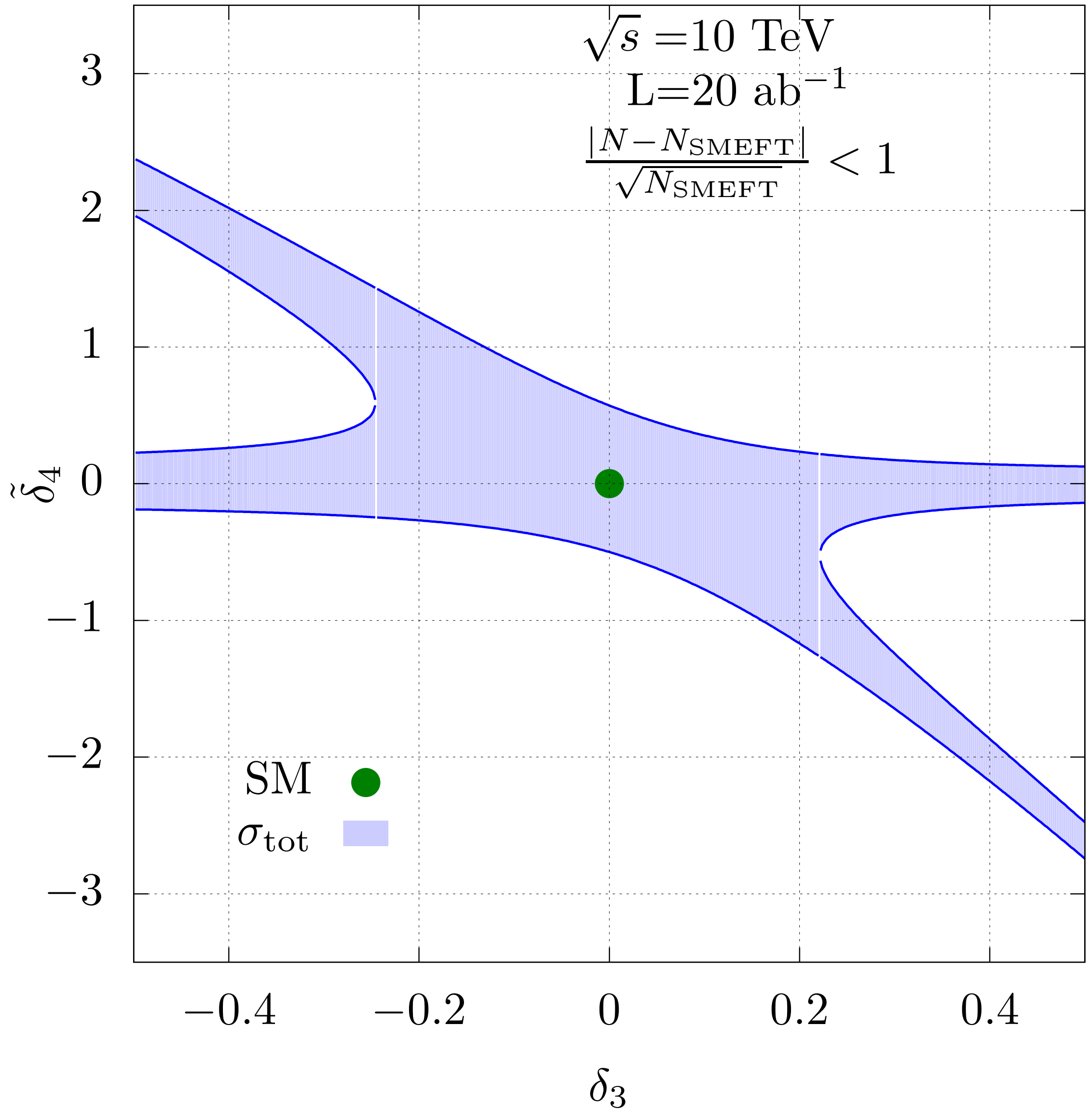
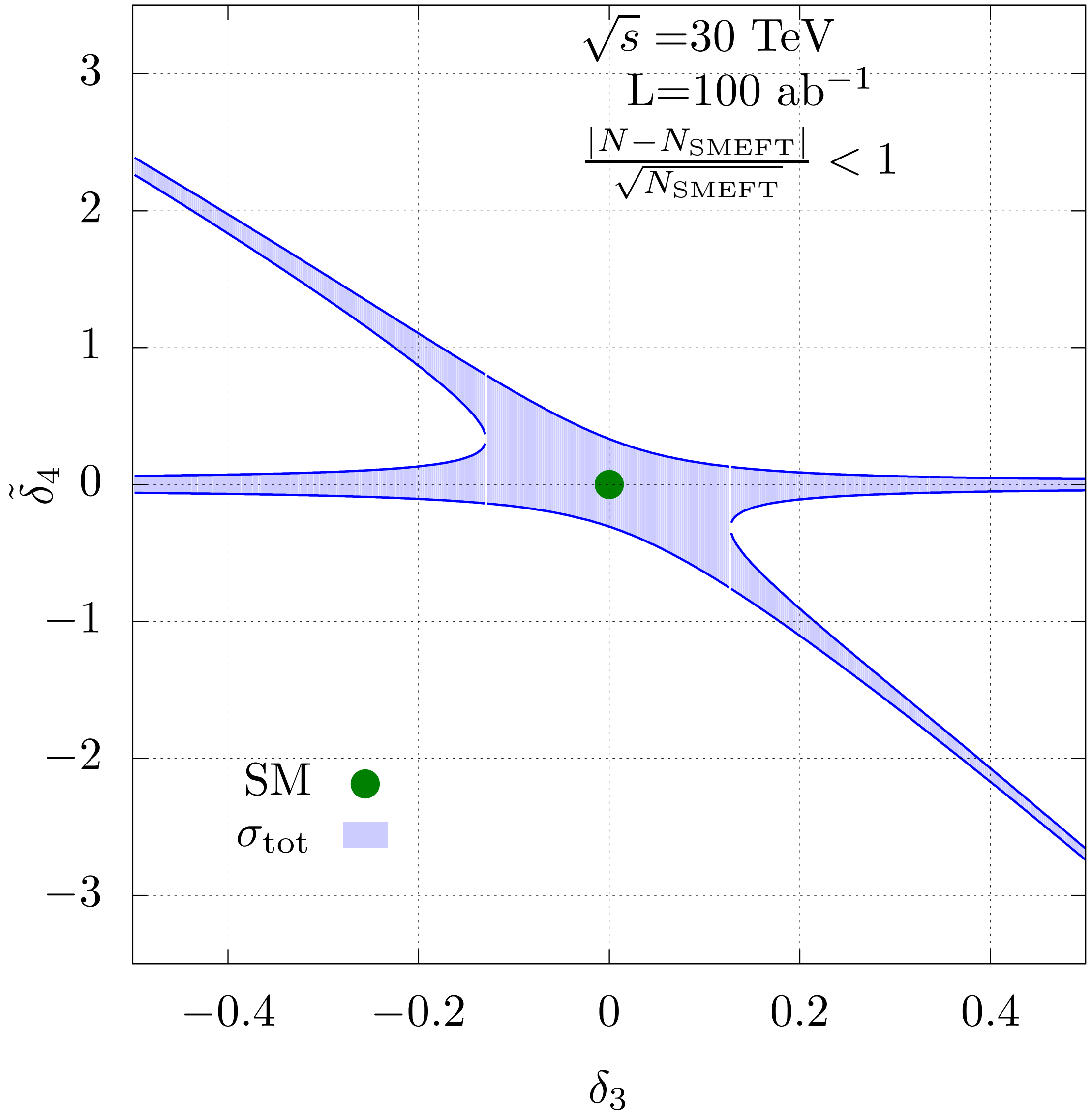
**Sensitivity linear** ($r_i$)

**Sensitivity quadratic** ($r_{i,i}$)

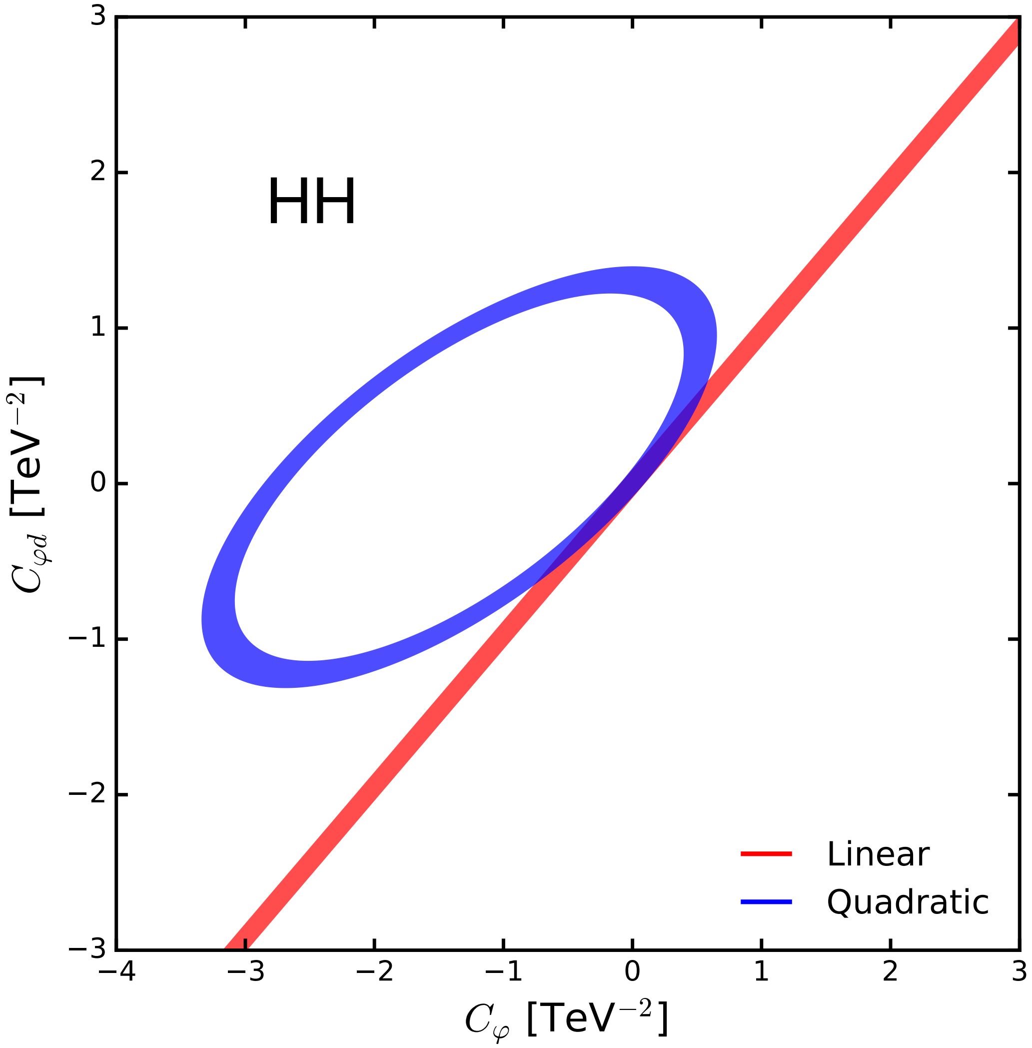
$$\tilde{\delta}_4 = \delta_4 - 6\,\delta_3$$



**3 TeV collider**

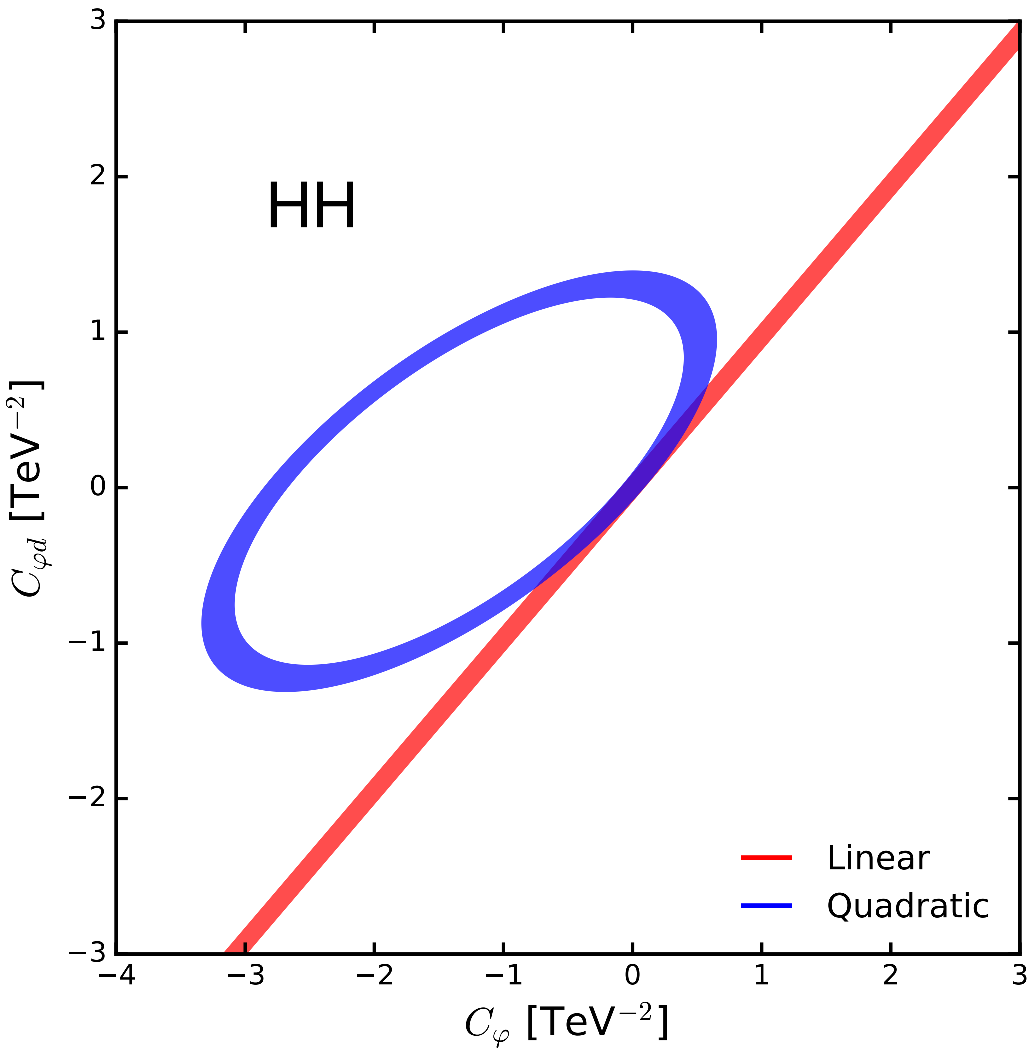
$$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L} \cdot (\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L} \cdot \sigma_{SM}}} \leq 2$$



**3 TeV collider**

$$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L}\cdot(\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L}\cdot\sigma_{SM}}} \leq 2$$

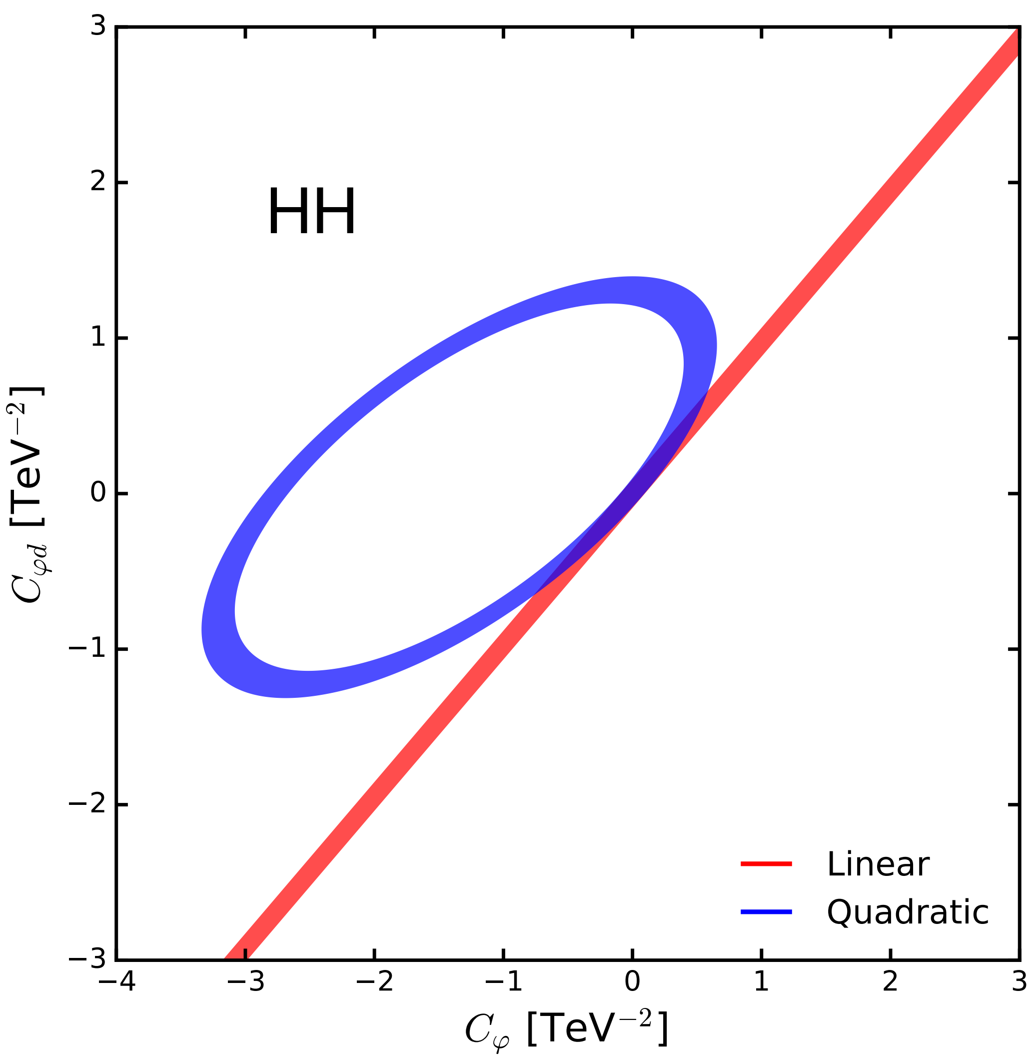
**14 TeV collider**

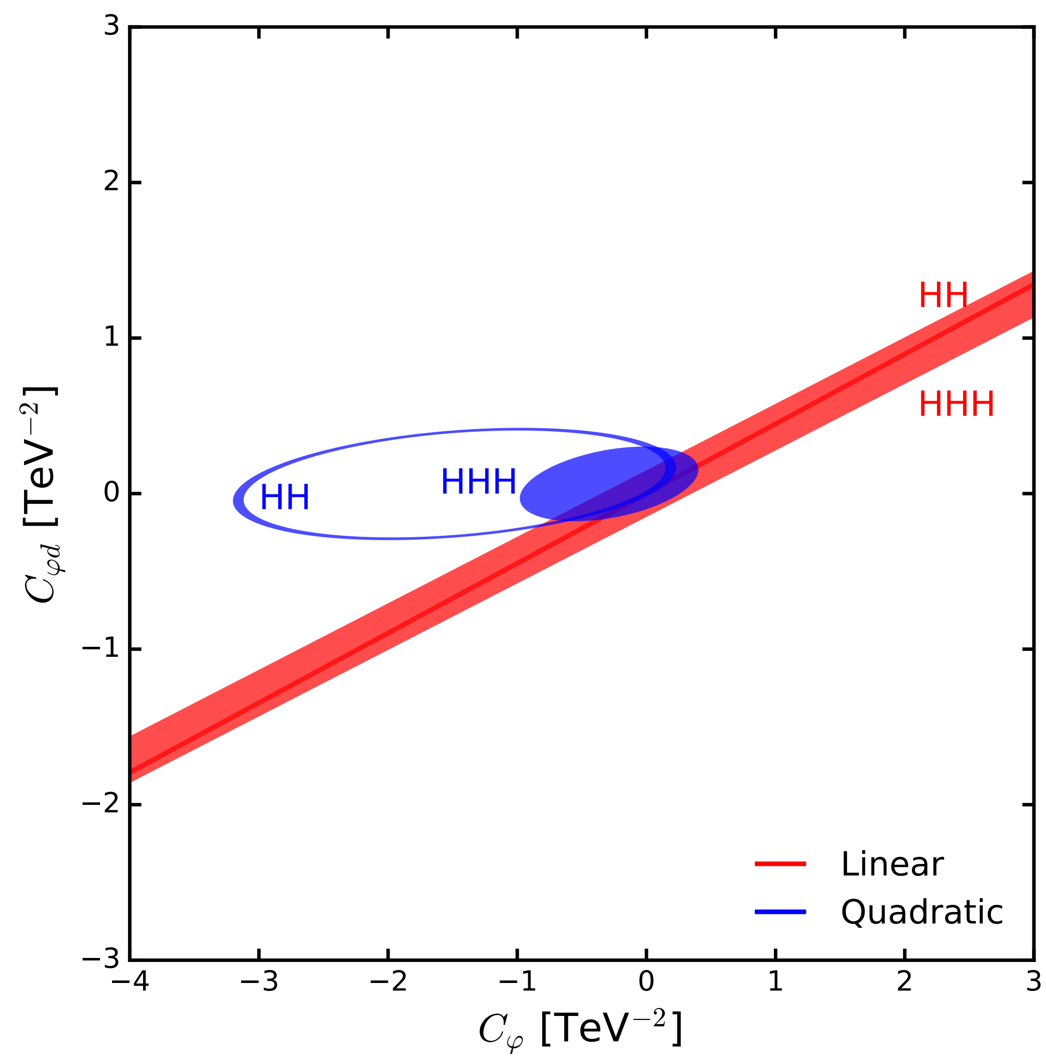


**3 TeV collider**

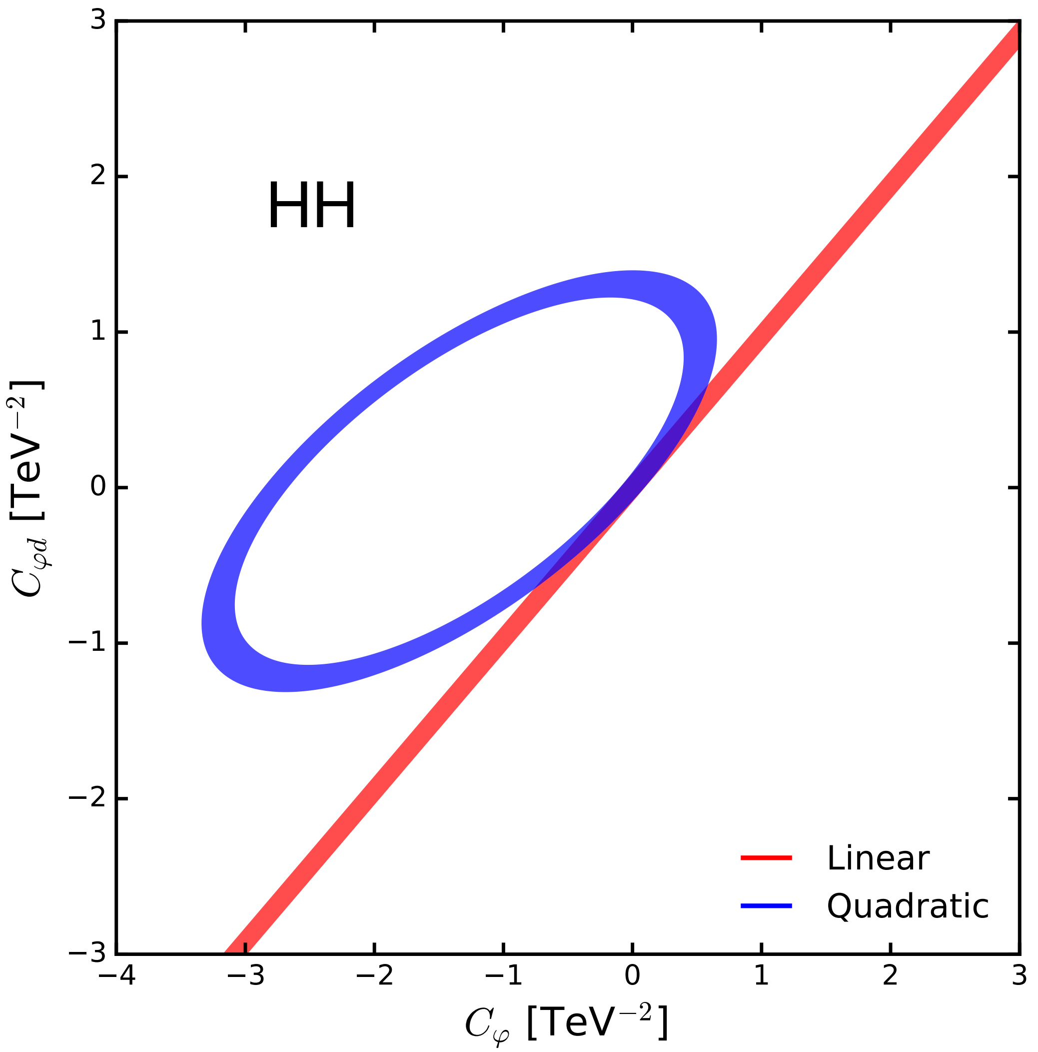
$$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L}\cdot(\sigma-\sigma_{SM})|}{\sqrt{\mathcal{L}\cdot\sigma_{SM}}} \leq 2$$

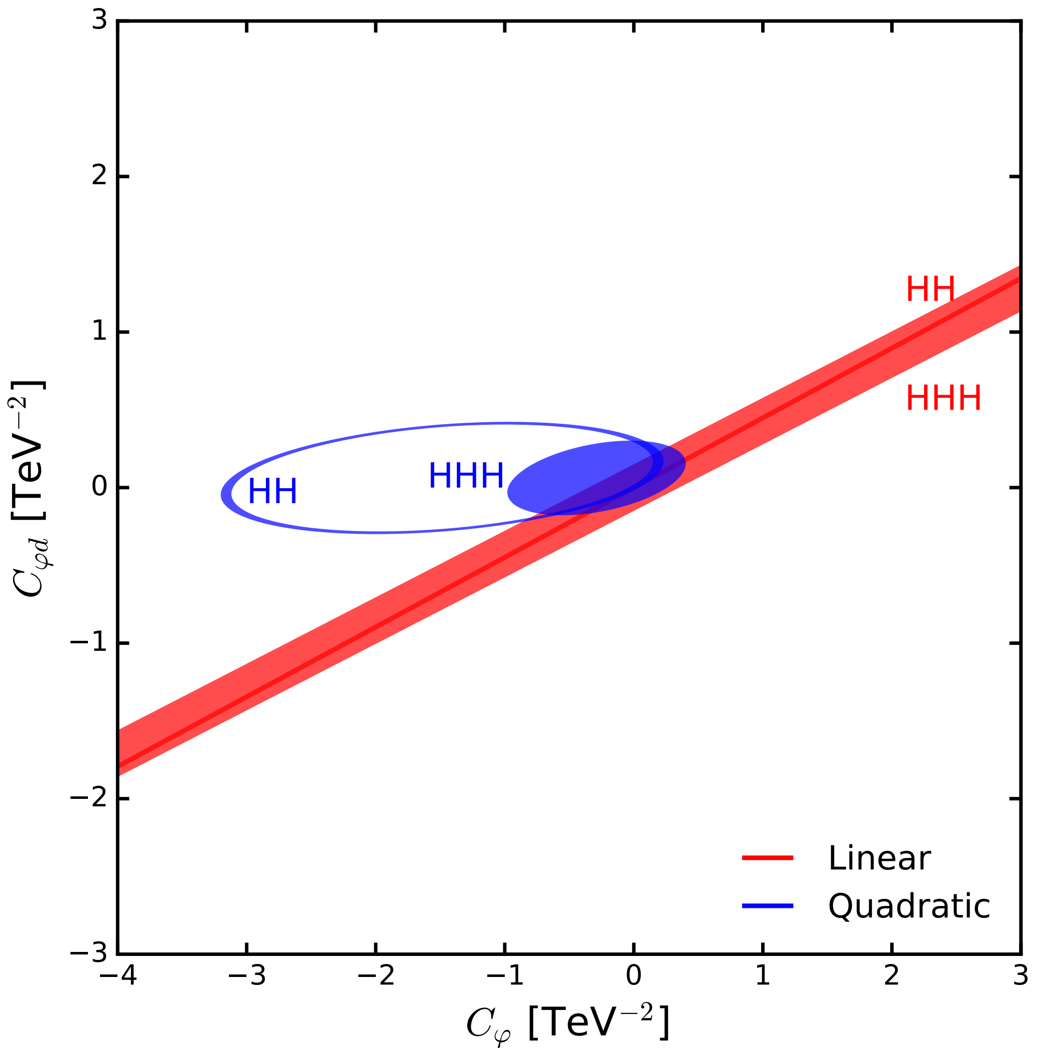
**14 TeV collider**



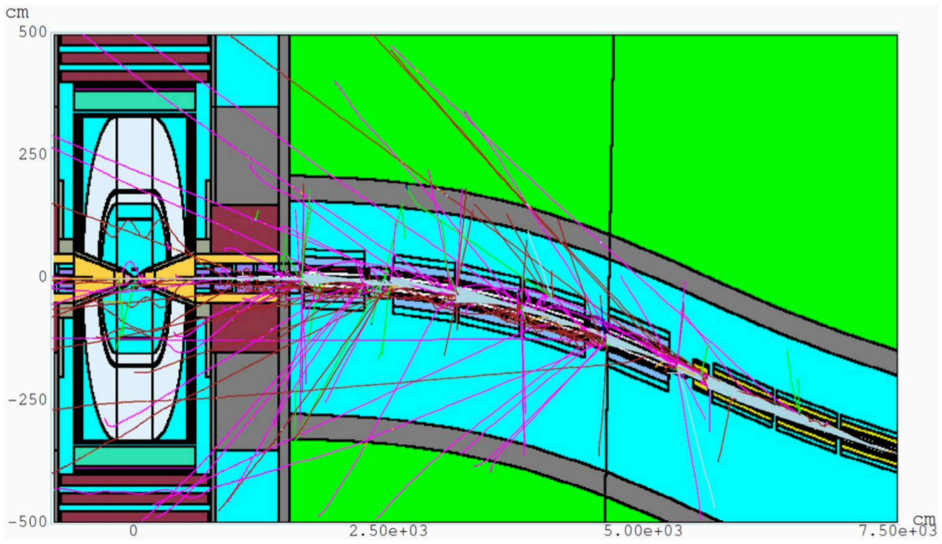
**3 TeV collider** $$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L} \cdot (\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L} \cdot \sigma_{SM}}} \leq 2$$ **14 TeV collider**



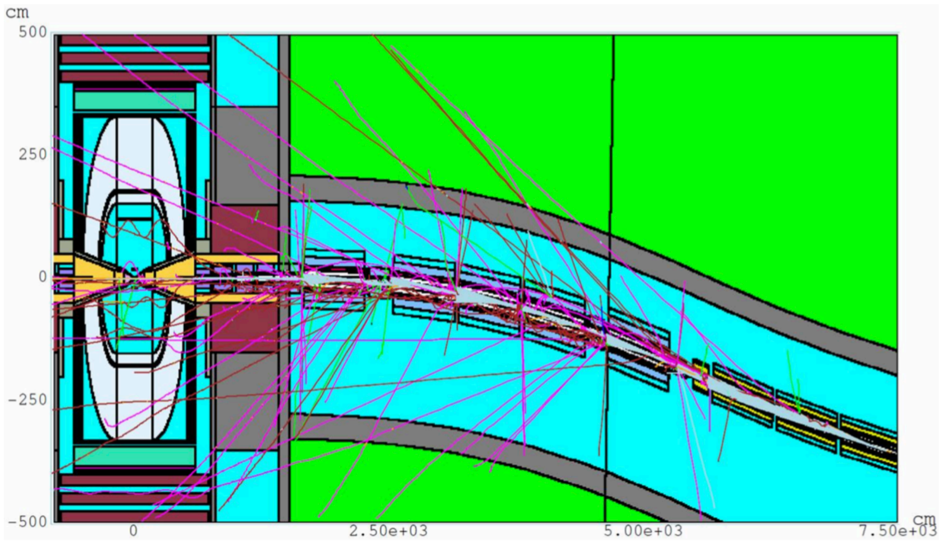

| | 3 TeV | 14 TeV |
|---|---|---|
| $\mathcal{C}_{\varphi}$ | [-3.33, 0.65] | [-0.66, 0.23] |
| $\mathcal{C}_{\varphi d}$ | [-1.31, 1.39] | [-0.17, 0.30] |

**95% confidence level**




**Nozzles:**
**Detector must be shielded from beam radiation**

**5-10 degrees blind spot at 3 TeV**



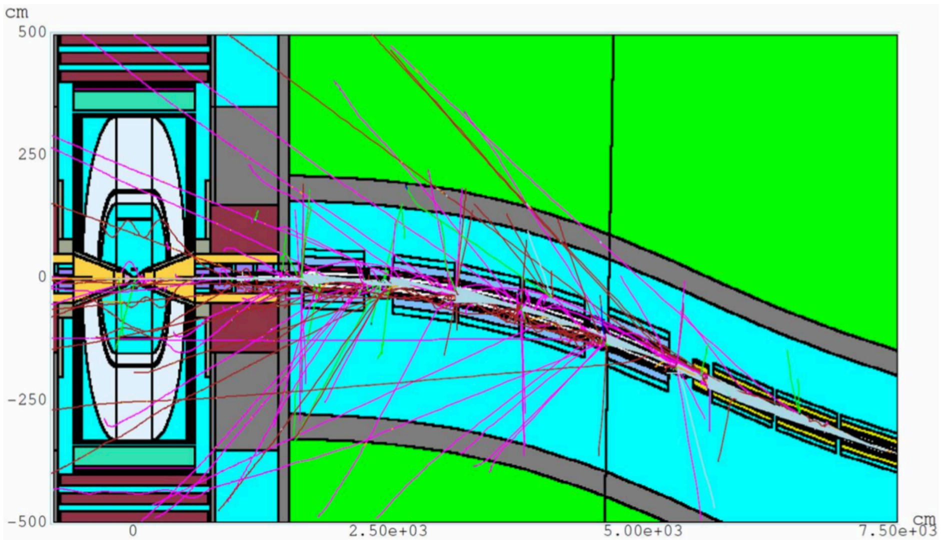

**Nozzles:**
**Detector must be shielded from beam radiation**

**5-10 degrees blind spot at 3 TeV**

**At higher energies the angle can be reduced!**

# Rapidity coverage

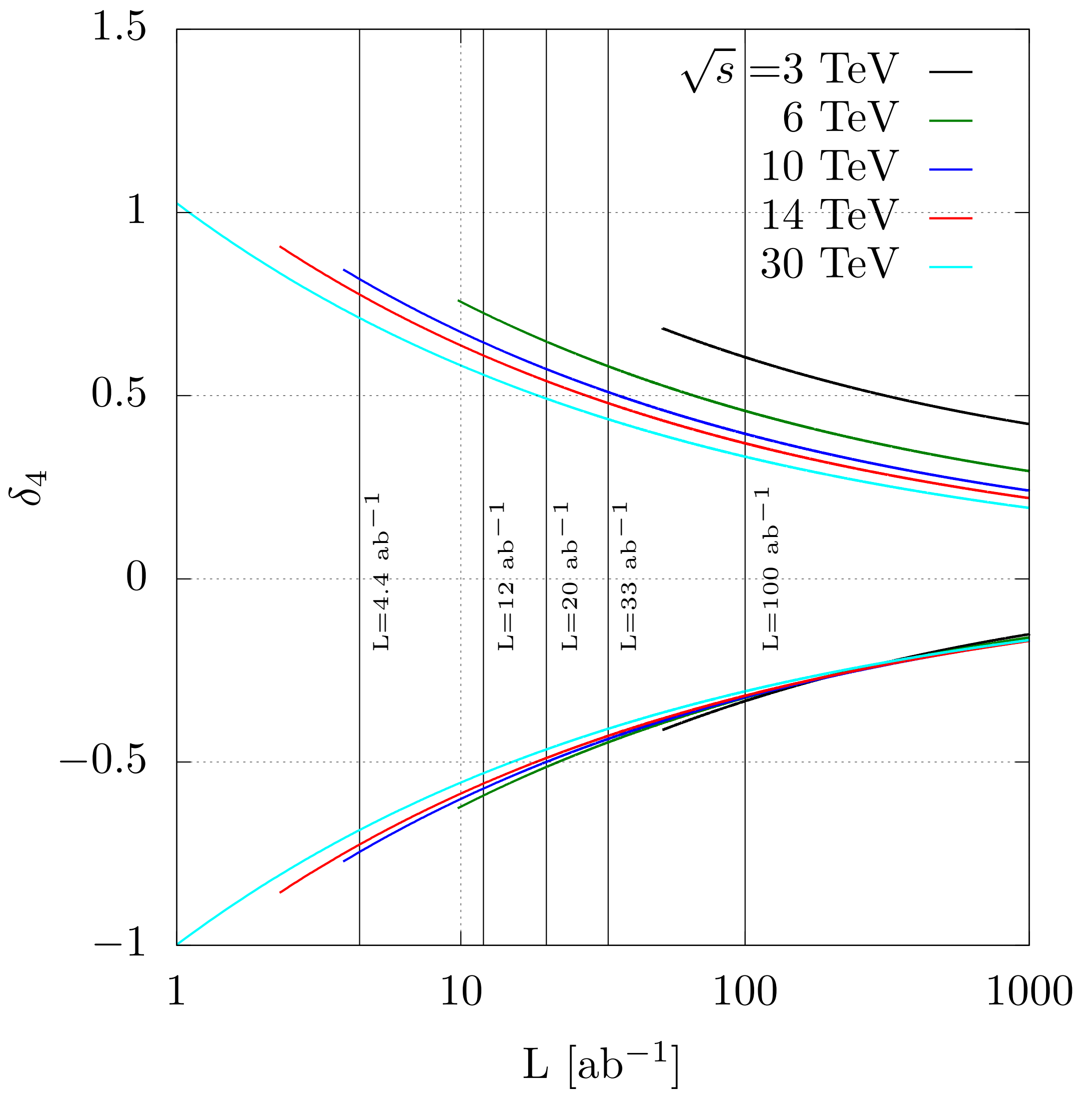


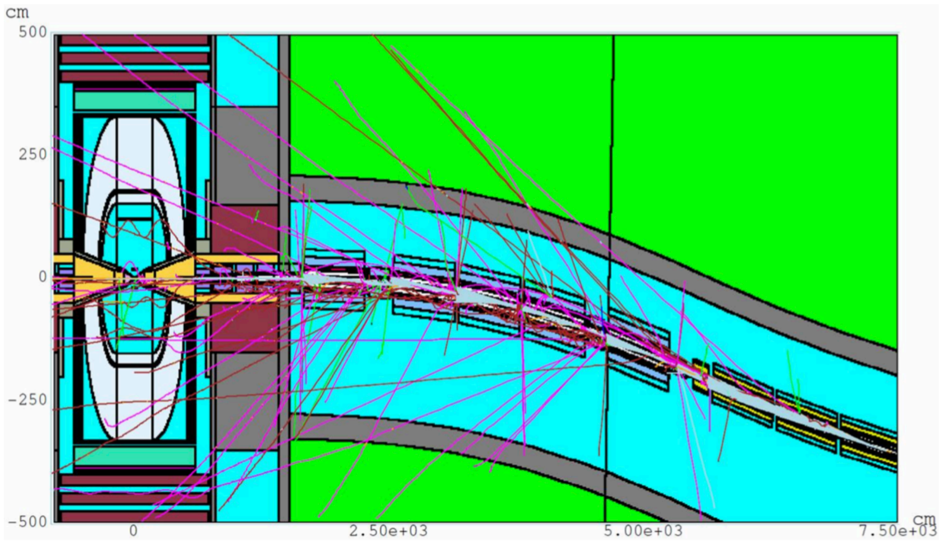



**Nozzles:**
**Detector must be shielded from beam radiation**

**5-10 degrees blind spot at 3 TeV**

**At higher energies the angle can be reduced!**





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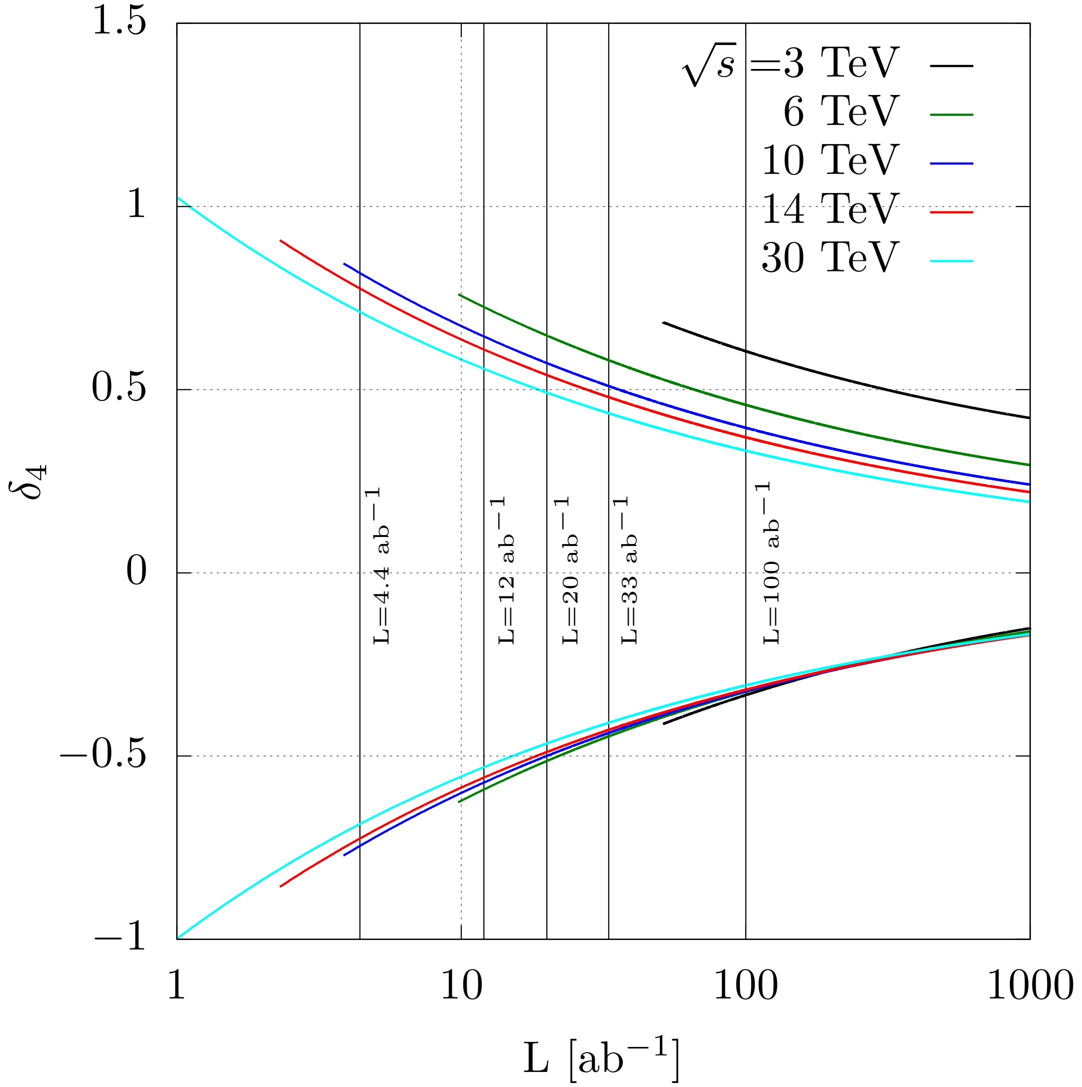
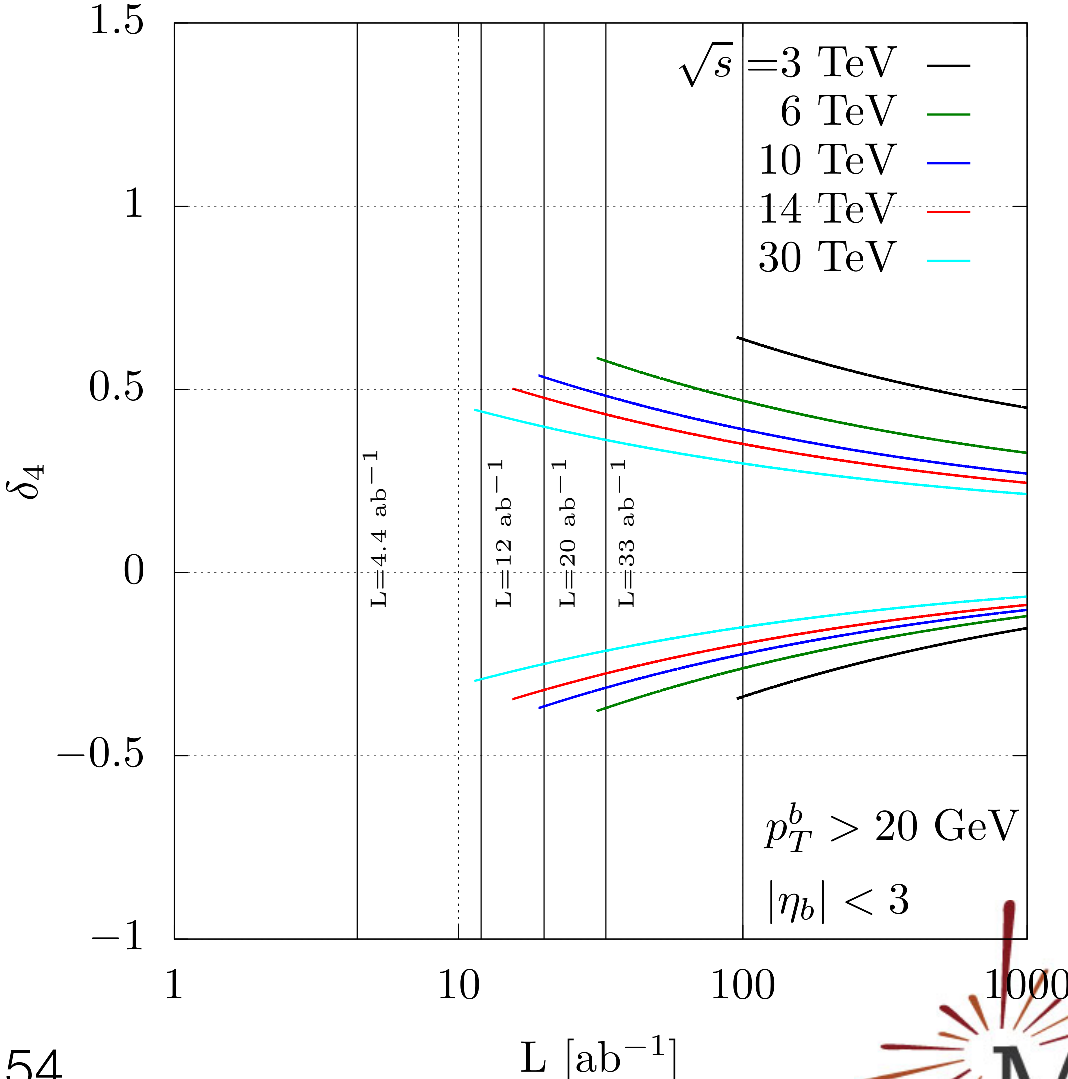
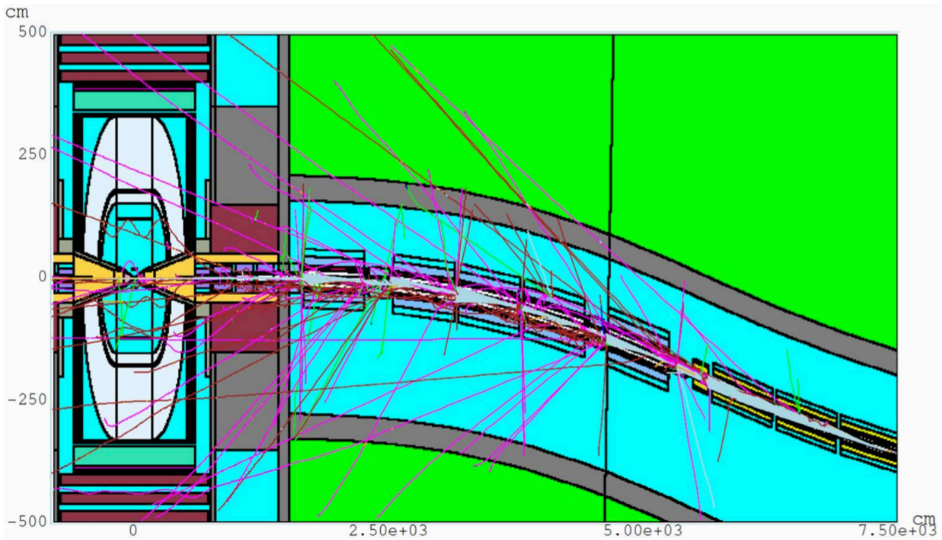





MCnet



**Nozzles:**
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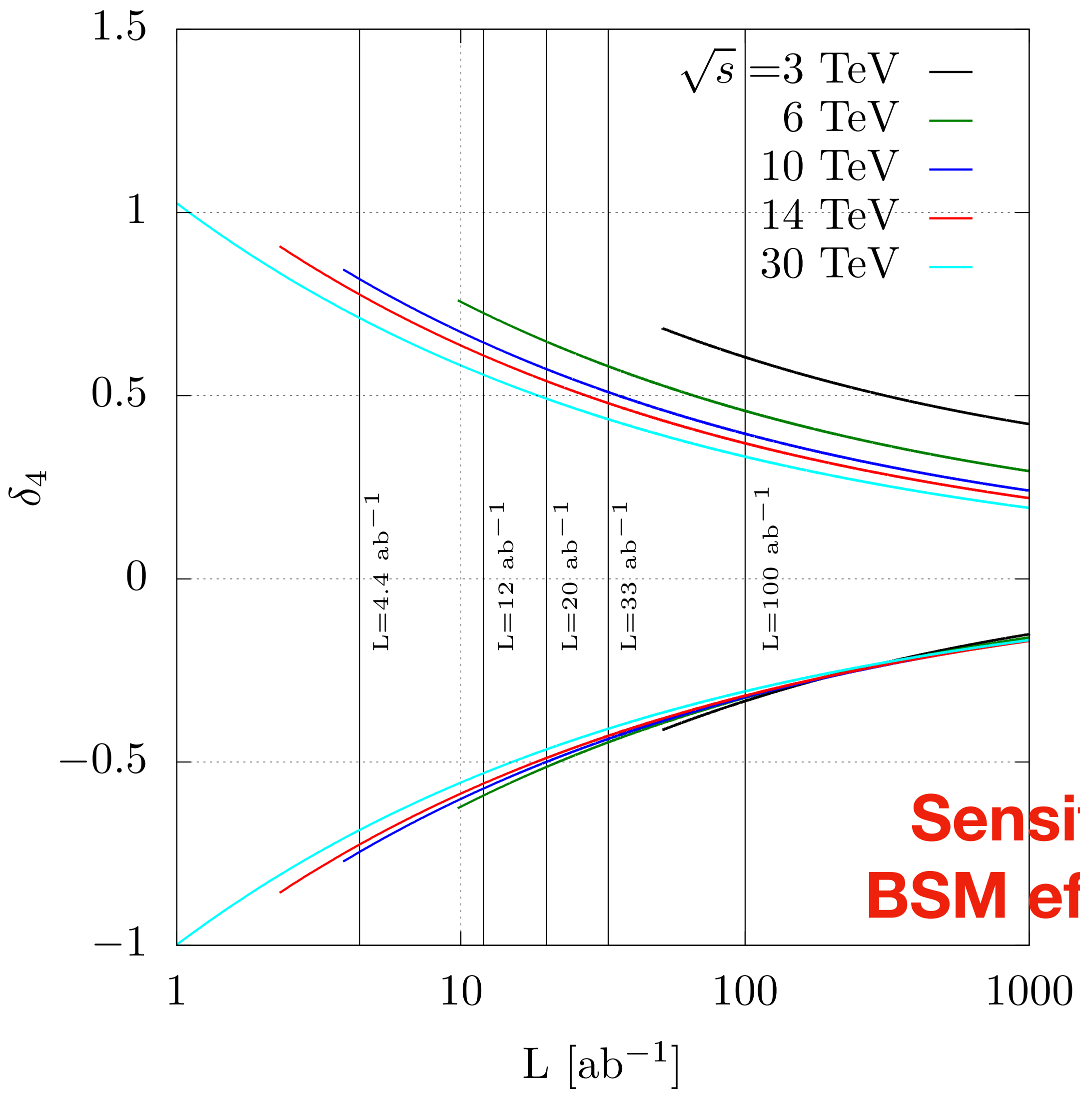
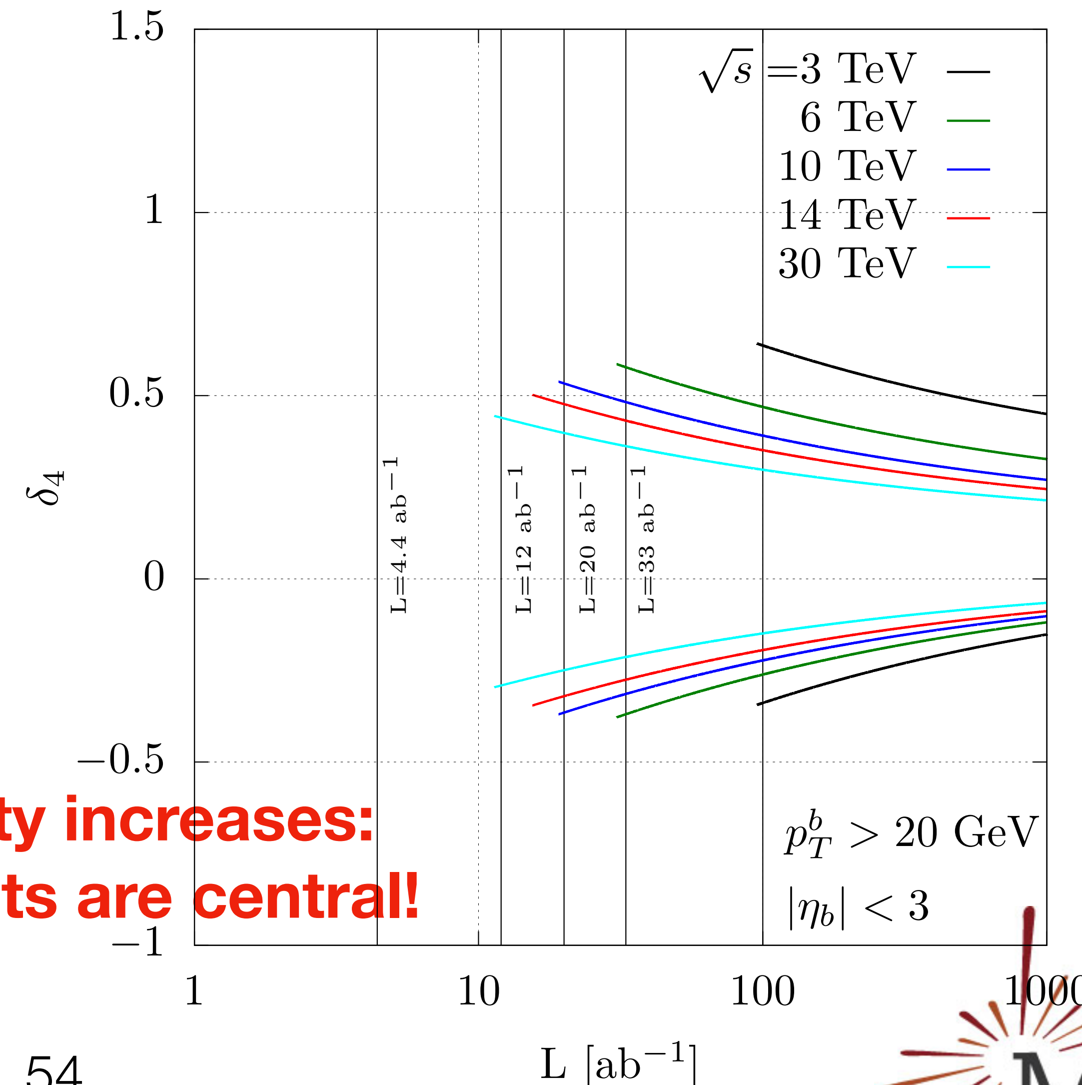



**Sensitivity increases:**
**BSM effects are central!**

- Muon collider is a dream machine.
- Both precision and discovery potential are top notch.
- A multi-TeV machine would be effectively a EW boson collider.
- Projected to be better than every proposed collider to measure the Higgs self interaction.
- For the quartic coupling, factor ~10 improvement over FCC.
- No background or optimisation on kinematics was performed.

$$bW^+ \to tZ$$

| $\lambda_b, \lambda_W, \lambda_t, \lambda_Z$ | SM | $\mathcal{O}_{\varphi D}$ | $\mathcal{O}_{\varphi WB}$ | $\mathcal{O}_W$ | $\mathcal{O}_{tB}$ | $\mathcal{O}_{tW}$ | $\mathcal{O}_{\varphi Q}^{(1)}$ | $\mathcal{O}_{\varphi Q}^{(3)}$ | $\mathcal{O}_{\varphi t}$ | $\mathcal{O}_{\varphi tb}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $-, 0, -, 0$ | $s^0$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $s^0$ | $-$ | $\sqrt{s(s+t)}$ | $-$ | $-$ |
| $-, 0, +, 0$ | $\frac{1}{\sqrt{s}}$ | $\sqrt{-t}m_t$ | $-$ | $-$ | $\sqrt{-t}m_W$ | $\frac{m_W(s+t)}{\sqrt{-t}}$ | $\sqrt{-t}m_t$ | $\sqrt{-t}m_t$ | $\sqrt{-t}m_t$ | $-$ |
| $+, 0, -, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $+, 0, +, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{s(s+t)}$ |
| $-, 0, -, -$ | $\frac{1}{\sqrt{s}}$ | $-$ | $\frac{s m_W}{\sqrt{-t}}$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $\sqrt{-t}m_t$ | $\sqrt{-t}m_t$ | $-$ | $\sqrt{-t}m_W$ | $-$ | $-$ |
| $-, -, -, 0$ | $\frac{1}{\sqrt{s}}$ | $-$ | $-$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_W$ | $-$ | $-$ |
| $-, 0, +, -$ | $s^0$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $-$ |
| $-, -, +, 0$ | $\frac{1}{s}$ | $s^0$ | $s^0$ | $s^0$ | $s^0$ | $\sqrt{s(s+t)}$ | $s^0$ | $s^0$ | $s^0$ | $-$ |
| $-, 0, -, +$ | $\frac{1}{\sqrt{s}}$ | $-$ | $\frac{m_W(s+t)}{\sqrt{-t}}$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $-, +, -, 0$ | $\frac{1}{\sqrt{s}}$ | $-$ | $-$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $-, 0, +, +$ | $\frac{1}{s}$ | $s^0$ | $-$ | $-$ | $\sqrt{s(s+t)}$ | $\sqrt{s(s+t)}$ | $s^0$ | $s^0$ | $s^0$ | $-$ |
| $-, +, +, 0$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $-$ | $s^0$ | $-$ | $s^0$ | $-$ | $-$ |
| $+, 0, -, \pm$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $s^0$ |
| $+, -, -, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $s^0$ |
| $+, 0, +, -$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $+, \pm, \mp, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $+, 0, +, +$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_W$ |
| $+, +, +, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_W$ |

$$bW^+ \to tZ$$

| $\lambda_b, \lambda_W, \lambda_t, \lambda_Z$ | SM | $\mathcal{O}_{\varphi D}$ | $\mathcal{O}_{\varphi WB}$ | $\mathcal{O}_W$ | $\mathcal{O}_{tB}$ | $\mathcal{O}_{tW}$ | $\mathcal{O}_{\varphi Q}^{(1)}$ | $\mathcal{O}_{\varphi Q}^{(3)}$ | $\mathcal{O}_{\varphi t}$ | $\mathcal{O}_{\varphi tb}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $-, 0, -, 0$ | $s^0$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $s^0$ | $-$ | $\sqrt{s(s+t)}$ | $-$ | $-$ |
| $-, 0, +, 0$ | $\frac{1}{\sqrt{s}}$ | $\sqrt{-t}m_t$ | $-$ | $-$ | $\sqrt{-t}m_W$ | $\frac{m_W(s+t)}{\sqrt{-t}}$ | $\sqrt{-t}m_t$ | $\sqrt{-t}m_t$ | $\sqrt{-t}m_t$ | $-$ |
| $+, 0, -, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $+, 0, +, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{s(s+t)}$ |
| $-, 0, -, -$ | $\frac{1}{\sqrt{s}}$ | $-$ | $\frac{s m_W}{\sqrt{-t}}$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $\sqrt{-t}m_t$ | $\sqrt{-t}m_t$ | $-$ | $\sqrt{-t}m_W$ | $-$ | $-$ |
| $-, -, -, 0$ | $\frac{1}{\sqrt{s}}$ | $-$ | $-$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_W$ | $-$ | $-$ |
| $-, 0, +, -$ | $s^0$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $-$ |
| $-, -, +, 0$ | $\frac{1}{s}$ | $s^0$ | $s^0$ | $s^0$ | $s^0$ | $\sqrt{s(s+t)}$ | $s^0$ | $s^0$ | $s^0$ | $-$ |
| $-, 0, -, +$ | $\frac{1}{\sqrt{s}}$ | $-$ | $\frac{m_W(s+t)}{\sqrt{-t}}$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $-, +, -, 0$ | $\frac{1}{\sqrt{s}}$ | $-$ | $-$ | $\frac{m_W^2(s+t)}{\sqrt{-t}v}$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $-, 0, +, +$ | $\frac{1}{s}$ | $s^0$ | $-$ | $-$ | $\sqrt{s(s+t)}$ | $\sqrt{s(s+t)}$ | $s^0$ | $s^0$ | $s^0$ | $-$ |
| $-, +, +, 0$ | $s^0$ | $s^0$ | $s^0$ | $-$ | $-$ | $s^0$ | $-$ | $s^0$ | $-$ | $-$ |
| $+, 0, -, \pm$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $s^0$ |
| $+, -, -, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $s^0$ |
| $+, 0, +, -$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $+, \pm, \mp, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $+, 0, +, +$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_W$ |
| $+, +, +, 0$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ | $\sqrt{-t}m_W$ |

| | $tWj$ | $tZj$ | $t\gamma j$ | $tWZ$ | $tW\gamma$ | $thj$ | $thW$ |
|---|---|---|---|---|---|---|---|
| $bW \to tZ$ | ✓ | ✓ | | ✓ | | | |
| $bW \to t\gamma$ | ✓ | | ✓ | | ✓ | | |
| $bW \to th$ | | | | | | ✓ | ✓ |

| | $t\bar{t}W(j)$ | $t\bar{t}WW$ | $t\bar{t}Z(j)$ | $t\bar{t}\gamma(j)$ | $t\bar{t}\gamma\gamma$ | $t\bar{t}\gamma Z$ | $t\bar{t}ZZ$ | $VBF$ |
|---|---|---|---|---|---|---|---|---|
| $tW \to tW$ | ✓ | ✓ | | | | | | ✓ |
| $tZ \to tZ$ | | | ✓ | | | | ✓ | ✓ |
| $tZ \to t\gamma$ | | | ✓ | ✓ | | ✓ | | ✓ |
| $t\gamma \to t\gamma$ | | | | ✓ | ✓ | | | ✓ |

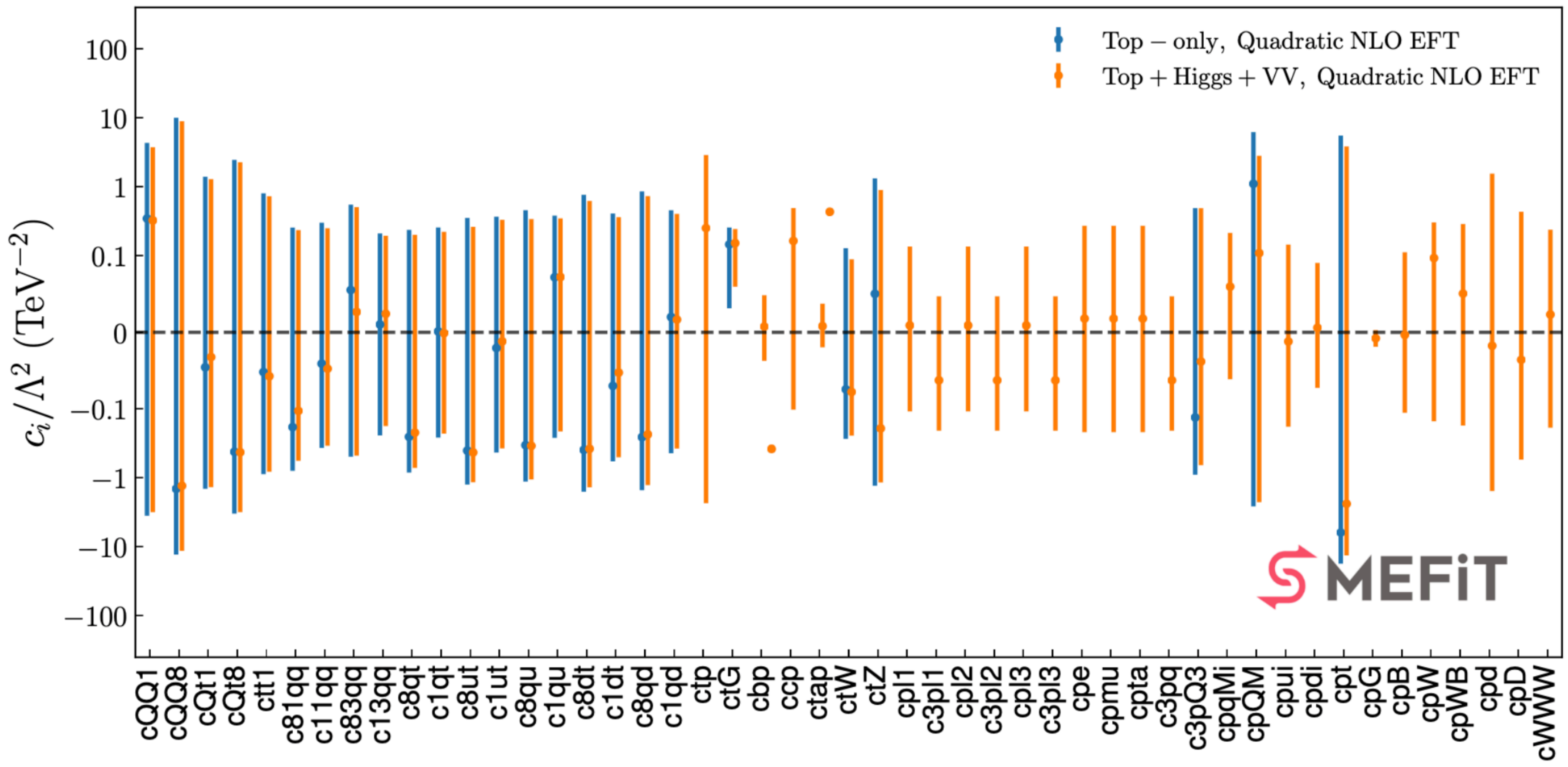
| | $t\bar{t}h(j)$ | $t\bar{t}Zh$ | $t\bar{t}\gamma h$ | $t\bar{t}hh$ |
|---|---|---|---|---|
| $tZ \to th$ | ✓ | ✓ | | |
| $t\gamma \to th$ | ✓ | | ✓ | |
| $th \to th$ | | | | ✓ |

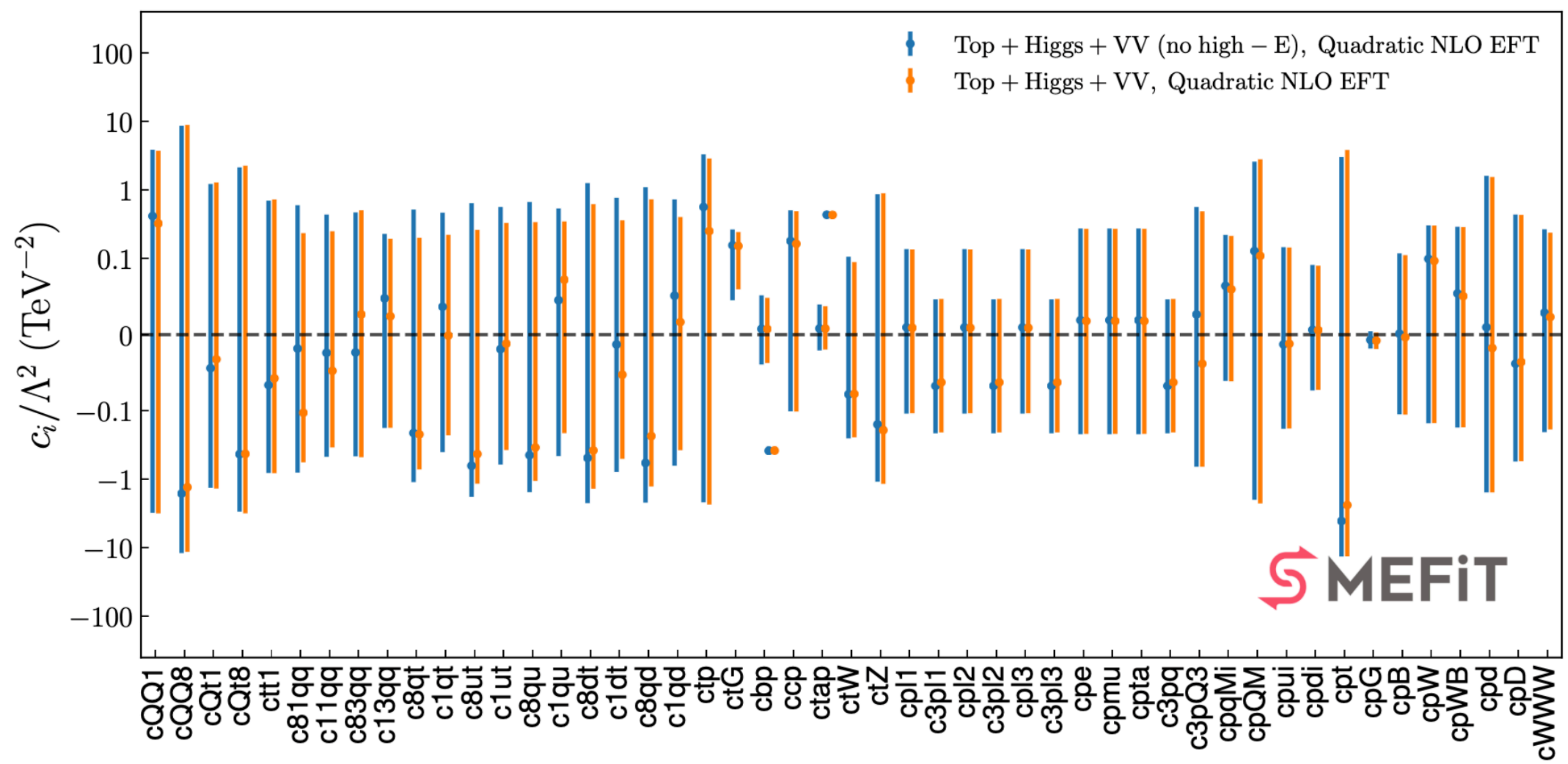
| Category | Processes | $n_{\rm dat}$ |
|---|---|---|
| Top quark production | $t\bar{t}$ (inclusive) | 94 |
| | $t\bar{t}Z$, $t\bar{t}W$ | 14 |
| | single top (inclusive) | 27 |
| | $tZ$, $tW$ | 9 |
| | $t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$ | 6 |
| | **Total** | **150** |
| Higgs production and decay | Run I signal strengths | 22 |
| | Run II signal strengths | 40 |
| | Run II, differential distributions & STXS | 35 |
| | **Total** | **97** |
| Diboson production | LEP-2 | 40 |
| | LHC | 30 |
| | **Total** | **70** |
| Baseline dataset | **Total** | **317** |

| Class | $N_{\rm dof}$ | Independent DOFs | DoF in EWPOs |
|---|---|---|---|
| four-quark (two-light-two-heavy) | 14 | $c_{Qq}^{1,8}$, $c_{Qq}^{1,1}$, $c_{Qq}^{3,8}$ $c_{Qq}^{3,1}$, $c_{tq}^{8}$, $c_{tq}^{1}$, $c_{tu}^{8}$, $c_{tu}^{1}$, $c_{Qu}^{8}$, $c_{Qu}^{1}$, $c_{td}^{8}$, $c_{td}^{1}$, $c_{Qd}^{8}$, $c_{Qd}^{1}$ | |
| four-quark (four-heavy) | 5 | $c_{QQ}^{1}$, $c_{QQ}^{8}$, $c_{Qt}^{1}$ $c_{Qt}^{8}$, $c_{tt}^{1}$ | |
| four-lepton | 1 | | $c_{ll}$ |
| two-fermion (+ bosonic fields) | 23 | $c_{t\varphi}$, $c_{tG}$, $c_{b\varphi}$, $c_{c\varphi}$, $c_{\tau\varphi}$, $c_{tW}$, $c_{tZ}$, $c_{\varphi Q}^{(3)}$, $c_{\varphi Q}^{(-)}$, $c_{\varphi t}$ | $c_{\varphi l_1}^{(1)}$, $c_{\varphi l_1}^{(3)}$, $c_{\varphi l_2}^{(1)}$ $c_{\varphi l_2}^{(3)}$, $c_{\varphi l_3}^{(1)}$, $c_{\varphi l_3}^{(3)}$, $c_{\varphi e}$, $c_{\varphi \mu}$, $c_{\varphi \tau}$, $c_{\varphi q}^{(3)}$, $c_{\varphi q}^{(-)}$, $c_{\varphi u}$, $c_{\varphi d}$ |
| Purely bosonic | 7 | $c_{\varphi G}$, $c_{\varphi B}$, $c_{\varphi W}$, $c_{\varphi d}$, $c_{WWW}$ | $c_{\varphi WB}$, $c_{\varphi D}$ |
| Total | 50 (36 independent) | 34 | 16 (2 independent) |



MCnet


Top – only, Quadratic NLO EFT
Top + Higgs + VV, Quadratic NLO EFT
$c_i/\Lambda^2$ (TeV$^{-2}$)
100
10
1
0.1
0
−0.1
−1
−10
−100
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW
SMEFiT

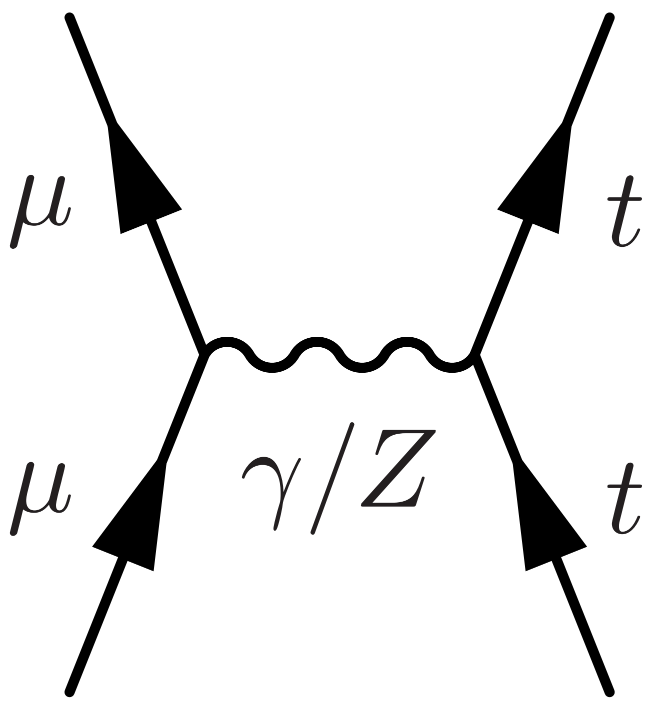

Top + Higgs + VV (no high – E), Quadratic NLO EFT
Top + Higgs + VV, Quadratic NLO EFT
$c_i/\Lambda^2$ (TeV$^{-2}$)
100
10
1
0.1
0
−0.1
−1
−10
−100
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW
SMEFiT

MCnet

**Different mode of production at different energies**

**Different mode of production at different energies**

$$\sqrt{s} \lesssim 1\text{-}5\ \mathrm{TeV}$$

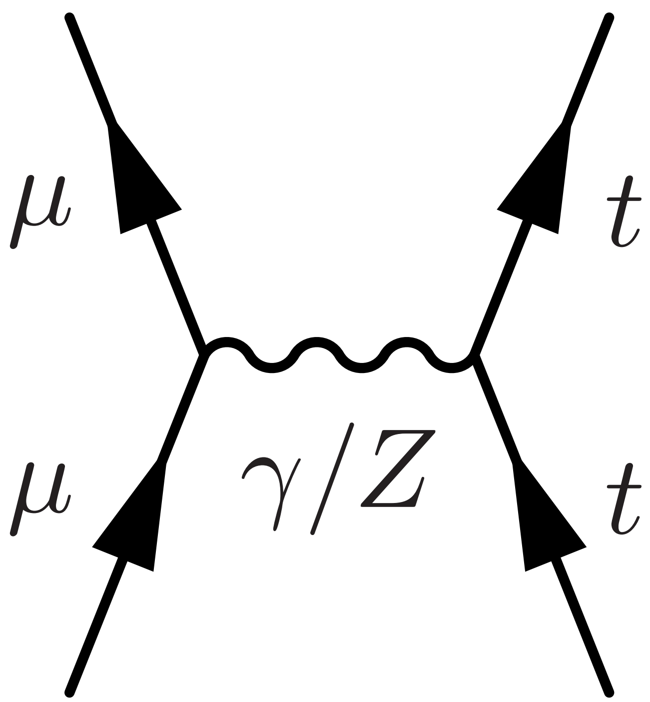



**s-channel**

*Luca Mantani*

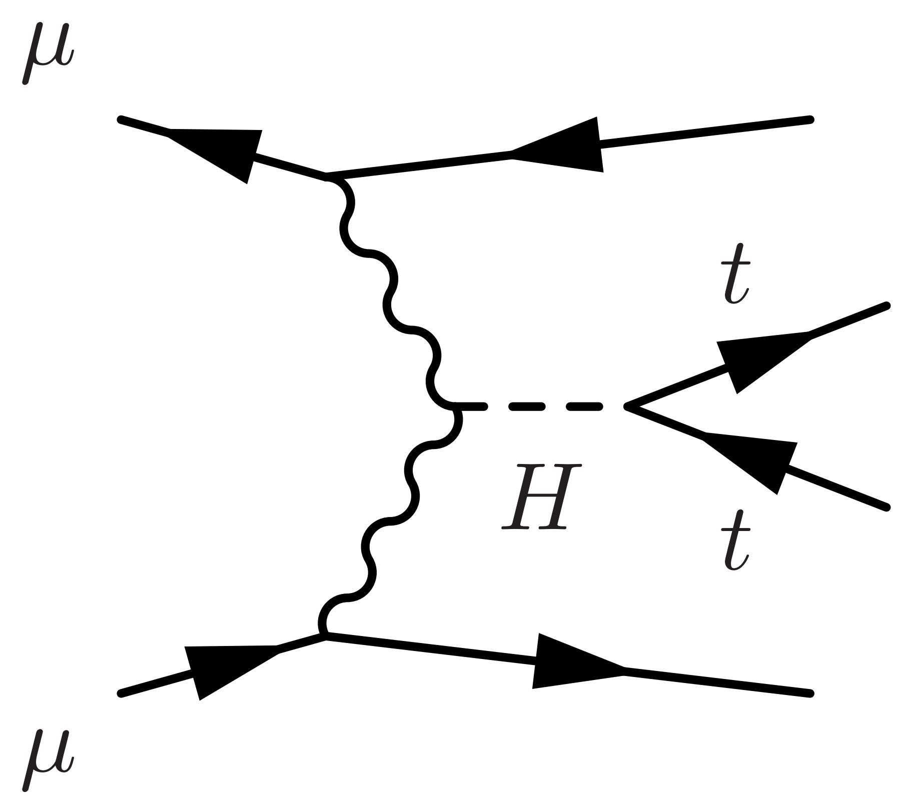
**Different mode of production at different energies**

$$\sqrt{s} \lesssim 1\text{-}5\,\text{TeV}$$




**s-channel**

$$\sqrt{s} \gtrsim 1\text{-}5\,\text{TeV}$$




**VBF**



MCnet

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

[A. Abada et al.
Eur. Phys. J. C 79 (2019) no.6, 474 ]

$$\lambda_3 = \lambda_4 = m_H^2/2v^2 \equiv \lambda_{SM}$$

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

$$\lambda_3 = \lambda_4 = m_H^2 / 2v^2 \equiv \lambda_{SM}$$

[A. Abada et al.
Eur. Phys. J. C 79 (2019) no.6, 474 ]

**HH and radiative corrections to single Higgs**
**FCC ~ 5%**



MCnet

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

[A. Abada et al.
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$$\lambda_3 = \lambda_4 = m_H^2/2v^2 \equiv \lambda_{SM}$$

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**Challenging even at FCC!**

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$$\text{CLIC} \sim [-5, 5]$$
$$\text{FCC} \sim [-2, 4]$$

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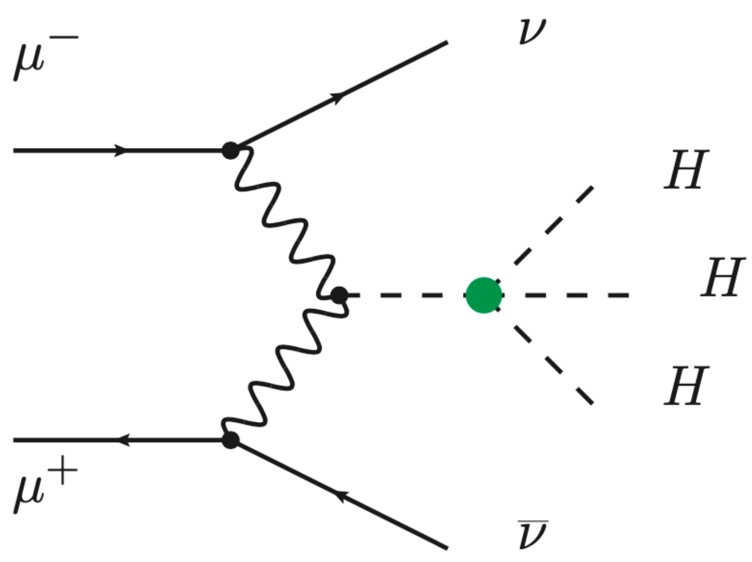


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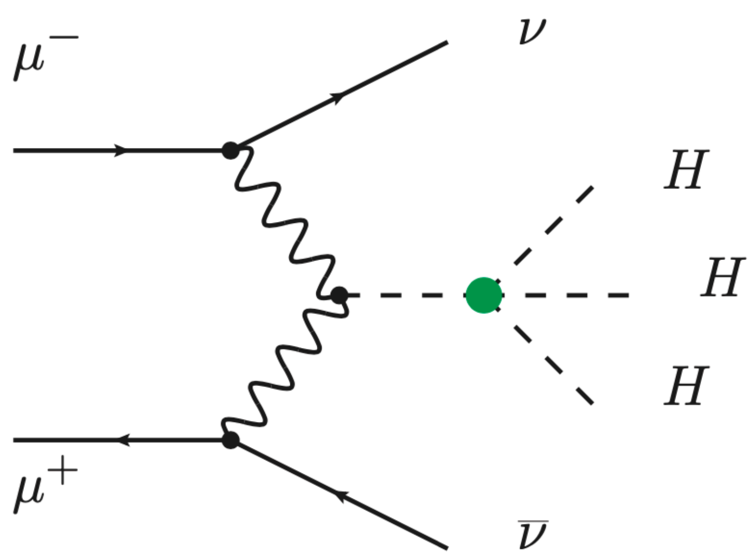


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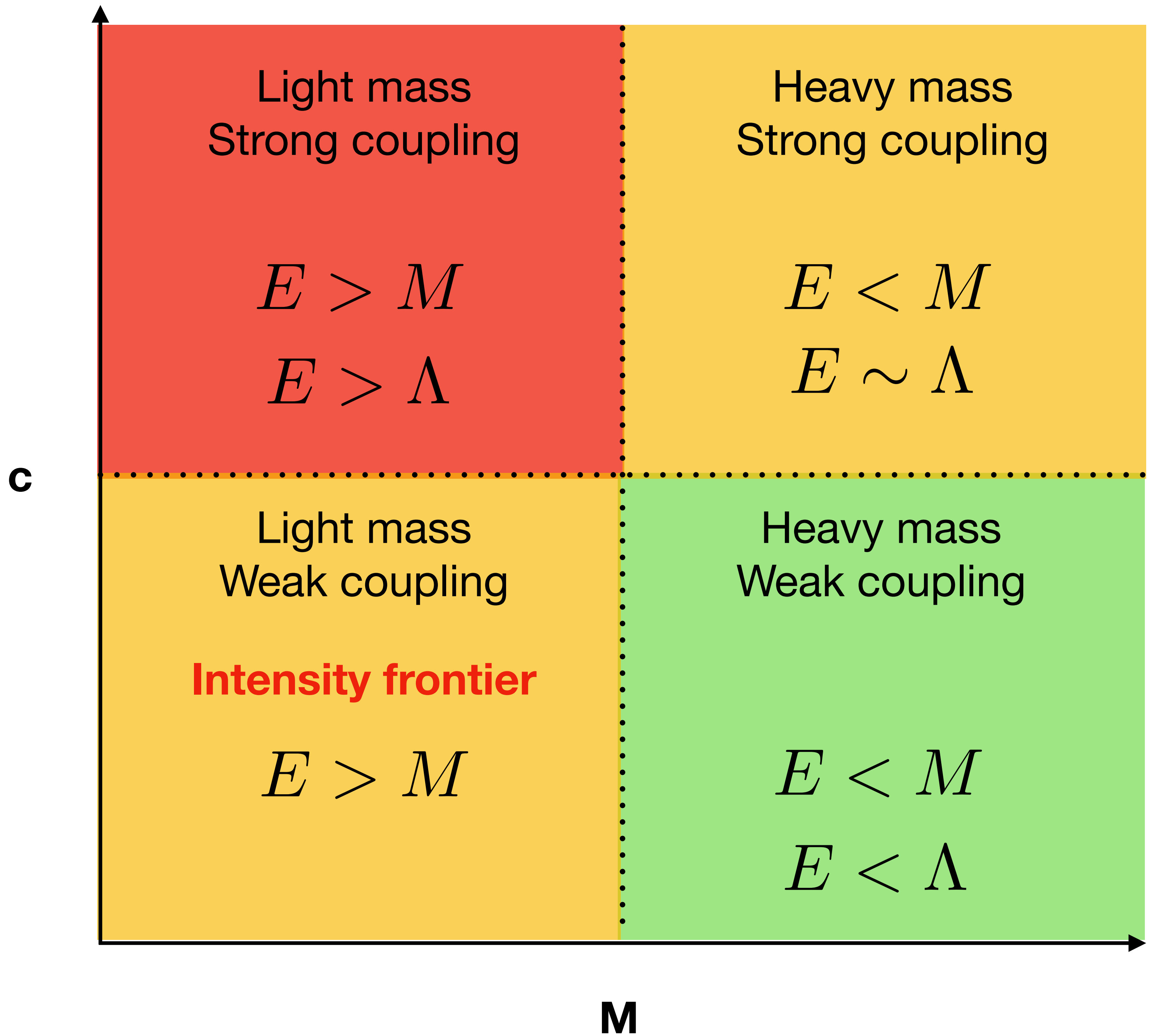
| $\sqrt{s}$ (TeV) / L (ab$^{-1}$) | 1.5 / 1.2 | 3 / 4.4 | 6 / 12 | 10 / 20 | 14 / 33 | 30 / 100 |
|---|---|---|---|---|---|---|
| $\sigma_{SM}$ (ab) [$N_{\text{ev}}$] | | | | | | |
| $\sigma^{\text{tot}}$ | 0.03 [0] | 0.31 [1] | 1.65 [20] | 4.18 [84] | 7.02 [232] | 18.51 [1851] |
| $\sigma(M_{HHH} < 3$ TeV) | 0.03 [0] | 0.31 [1] | 1.47 [18] | 2.89 [58] | 3.98 [131] | 6.69 [669] |
| $\sigma(M_{HHH} < 1$ TeV) | 0.02 [0] | 0.12 [1] | 0.26 [3] | 0.37 [7] | 0.45 [15] | 0.64 [64] |

$$\Lambda \sim \frac{M}{c}$$



| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$ |
| $Q_{\widetilde{G}}$ | $f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde{G}}$ | $\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde{W}}$ | $\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde{B}}$ | $\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde{W}B}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p \gamma^\mu d_r)$ |