Higgs couplings and VBF at Muon Colliders

[A. Costantini et al. arXiv:2005.10289] [M. Chiesa al. arXiv:2003.13628]

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In collaboration with:
F. Maltoni, R. Ruiz, A. Costantini, F. De Lillo, X. Zhao, M. Chiesa, B. Mele, F. Piccinini

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PBSP

Snowmass contributions

- Muon collider physics summary [arXiv:2203.07256]
- The physics case of a 3 TeV muon collider stage [arXiv:2203.07261]

Higgs Physics and EFT interpretation

- Vector boson fusion at multi-TeV muon colliders [arXiv:2005.10289]
- Two Paths Towards Precision at a Very High Energy Lepton Collider [arXiv:2012.11555]
- Higgs Boson Studies at Future Particle Colliders [arXiv:1905.03764]
- Electroweak couplings of the Higgs boson at a multi-TeV muon collider [arXiv:2008.12204]
- …

Dark Matter

- Wimps at high energy muon collider [arXiv:2009.11287]
- Hunting wino and higgsino dark matter at the muon collider [arXiv:2102.11292]
- …

g-2 and B-anomalies

- Muon g-2 at multi-TeV muon collider [arXiv:2012.03928]
- Probing the RK anomaly at a muon collider [arXiv:2103.01617]
- …

Hadron collider

QCD background

High energy

Initial state unknown

Hadron collider

QCD background

High energy

Initial state unknown

e+ e- collider

Synchroton radiation

Precision

Known initial state

High energy **Precision**

Muon collider

Different mode of production at different energies

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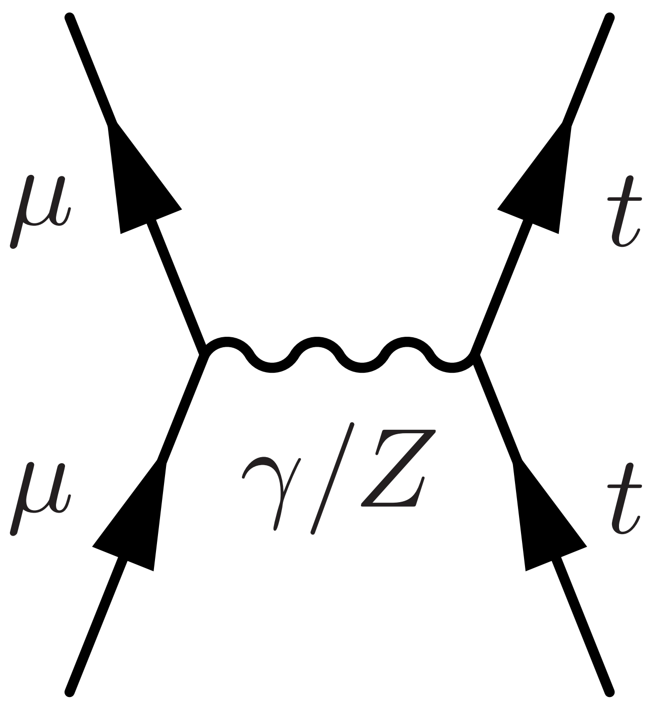
$$\sqrt{s} \lesssim 1\text{-}5\ \mathrm{TeV}$$



s-channel

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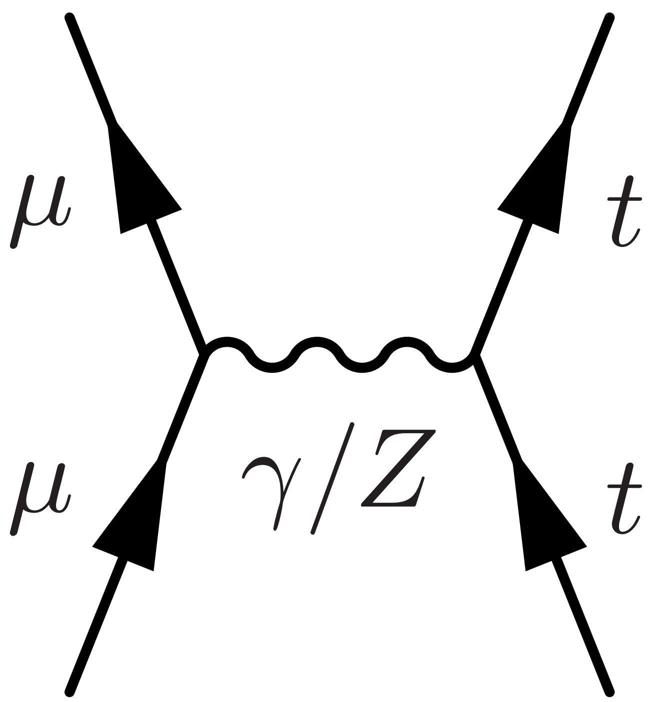
$\sqrt{s} \lesssim$ 1-5 TeV



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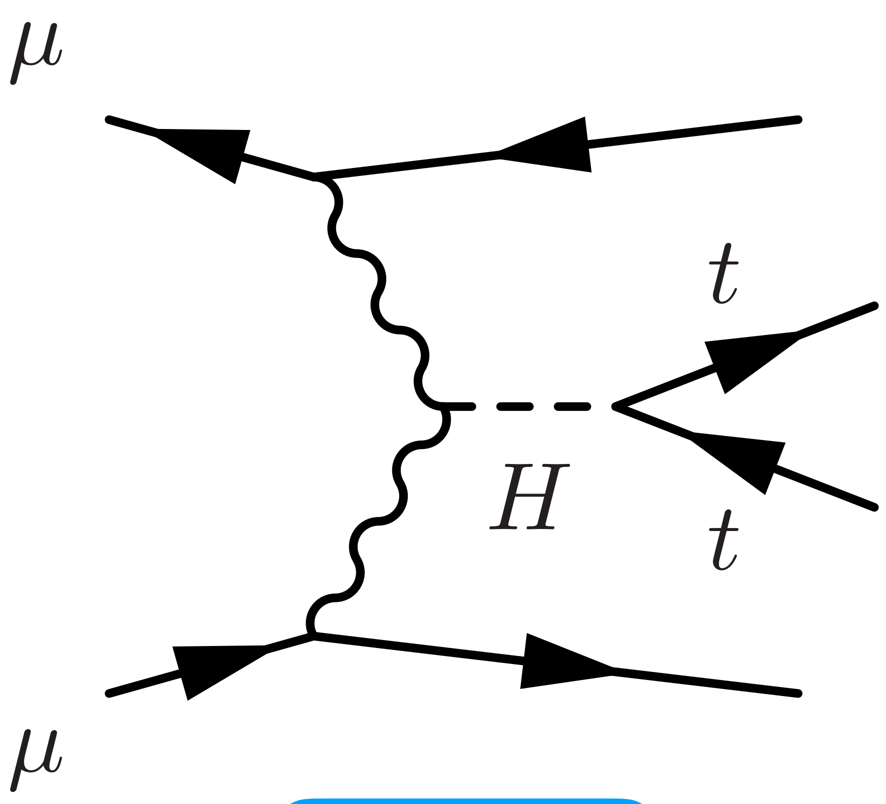
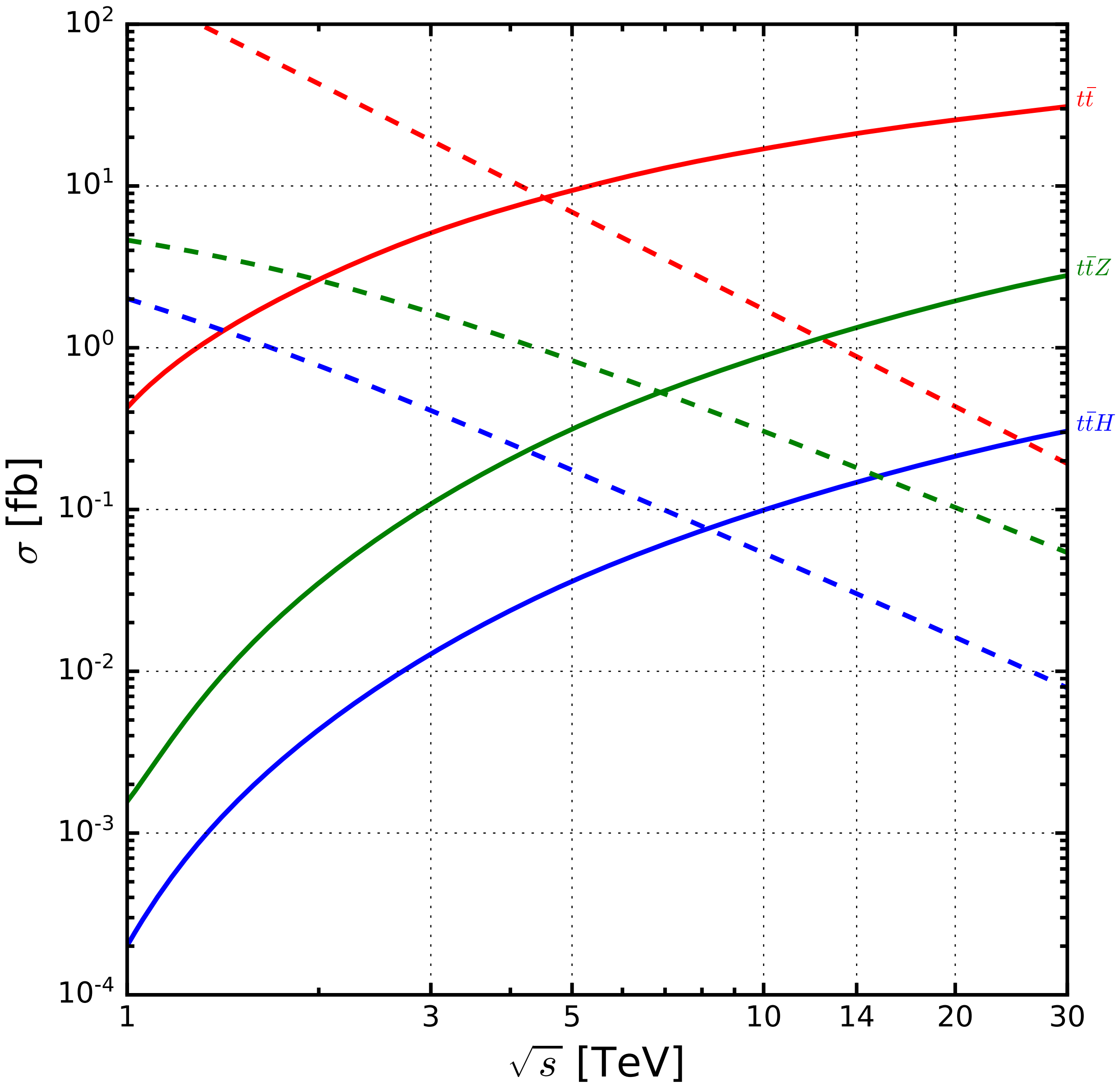


VBF

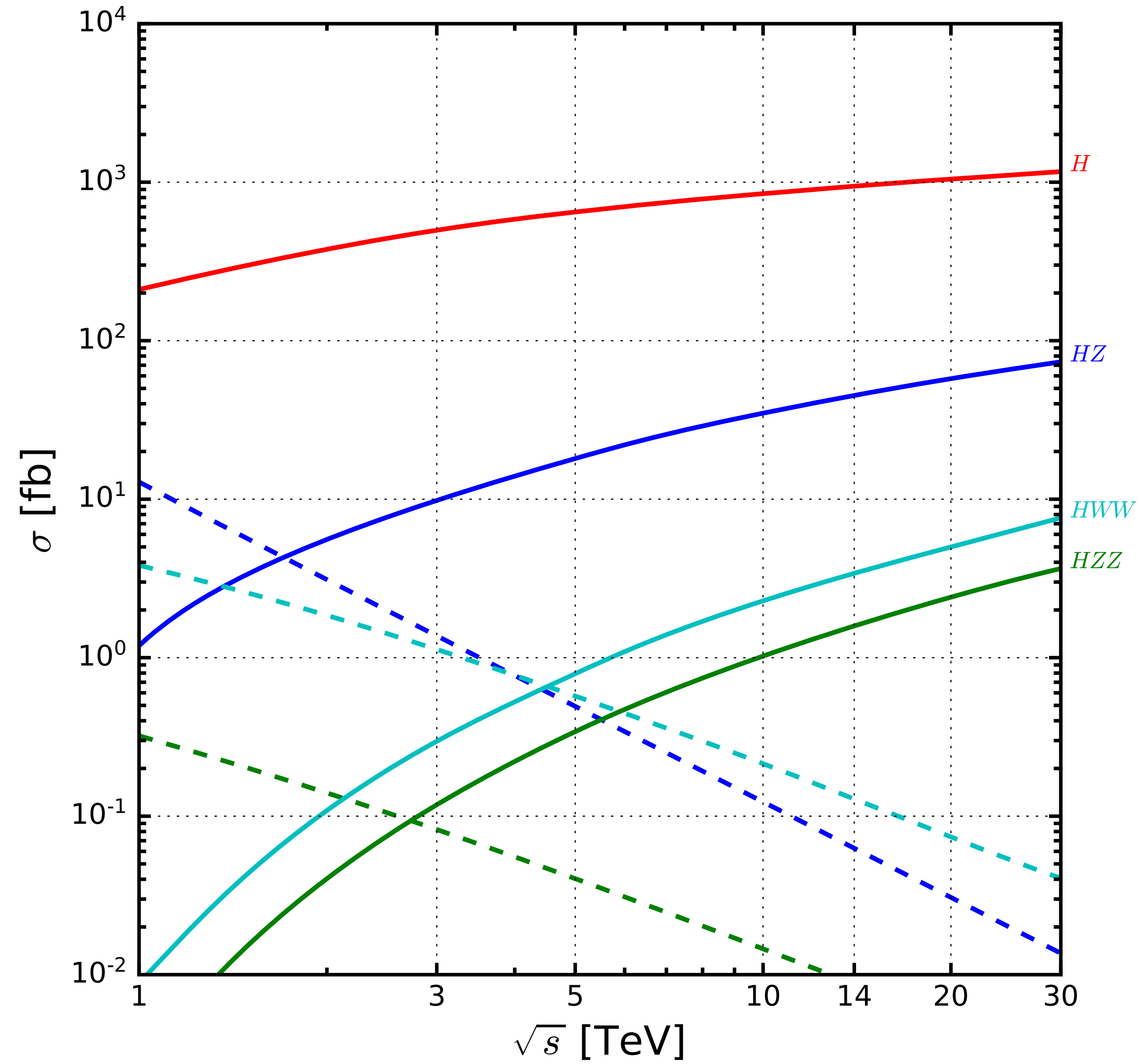
s-channel (dashed line)

VBF (solid line)

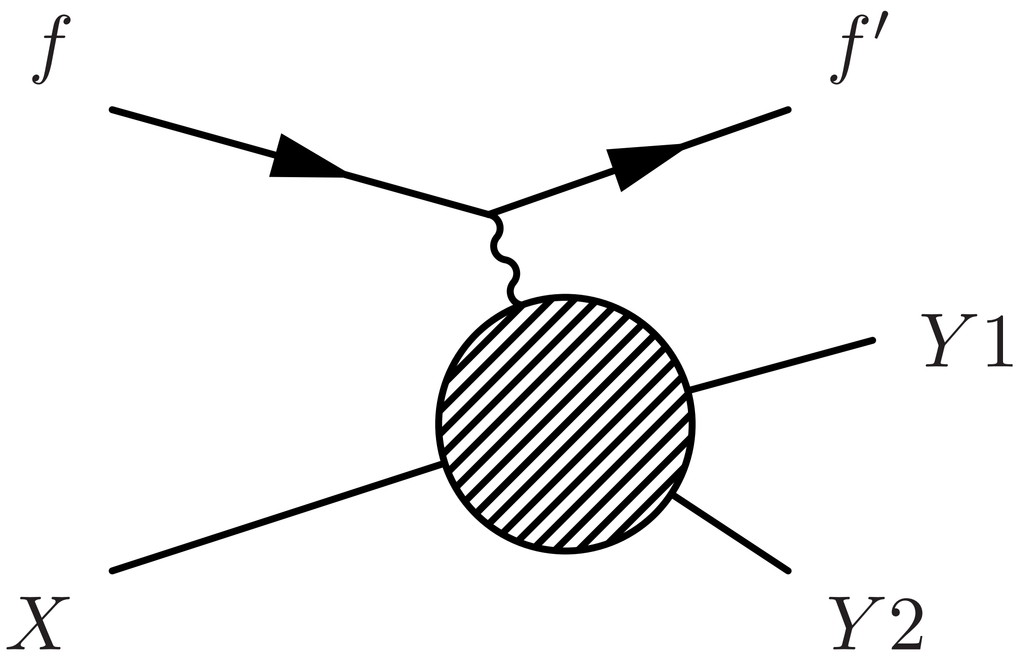
ttX



HX



We can have an analytical insight with EWA



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

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

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

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

[R. Ruiz et al. arXiv:2111.02442] [P. Borel et al. arXiv:1202.1904]

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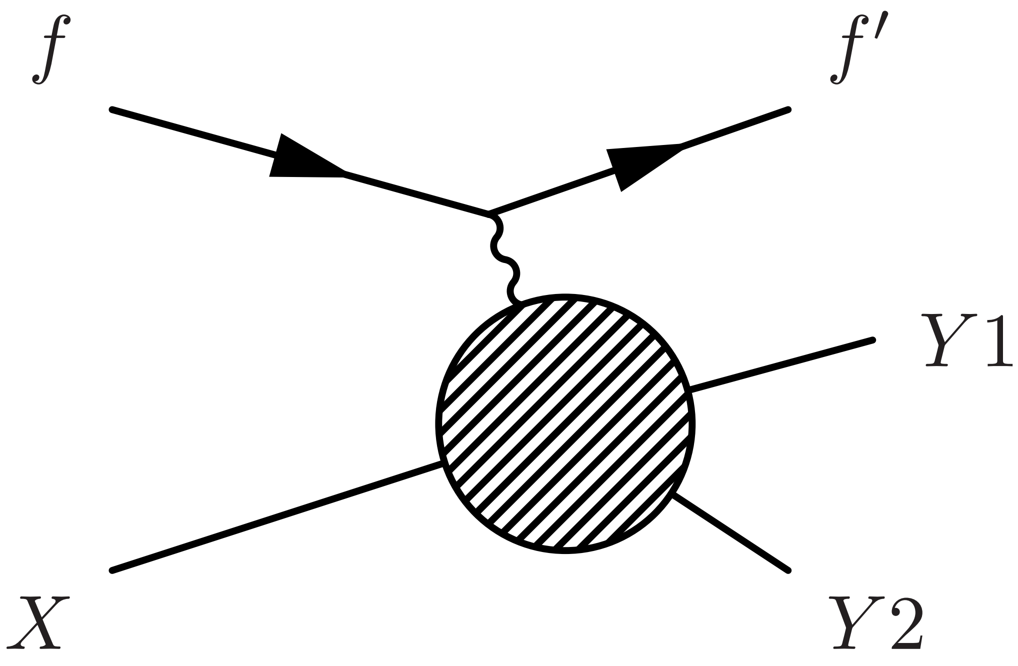

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$$\frac{d\sigma_{EWA}}{dx dp_\perp}(fX \to f'Y) = \frac{C^2}{2\pi^2} \sum_{i=+,-,0} f_i \times d\sigma(W_i X \to Y)$$

Weak bosons can be described as partons!

Discovery potential

Pair production

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

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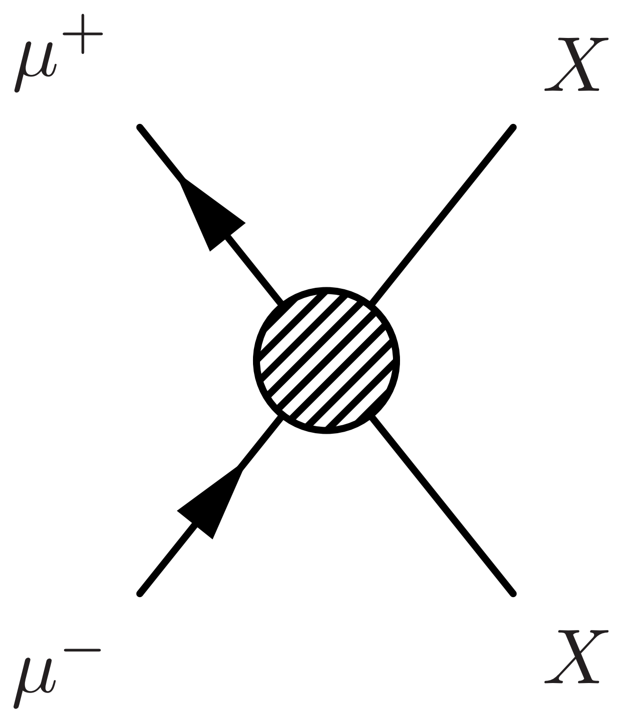
$\sqrt{s_\mu}$



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

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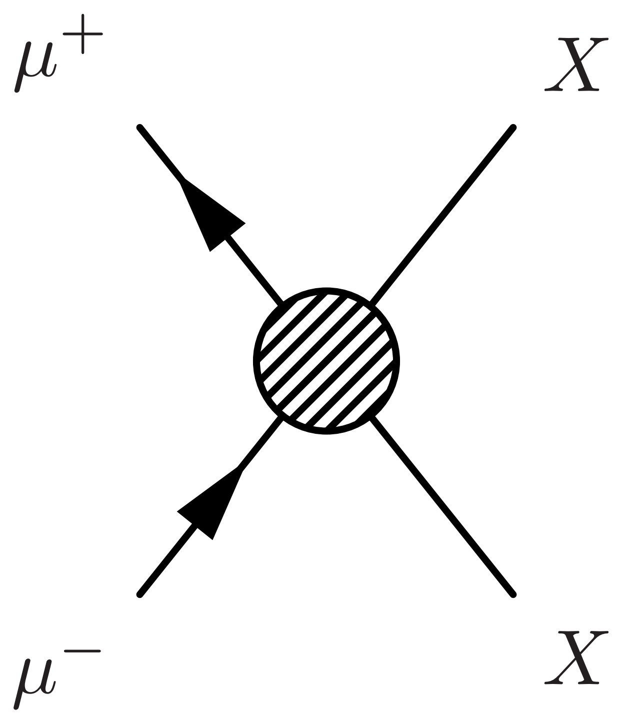

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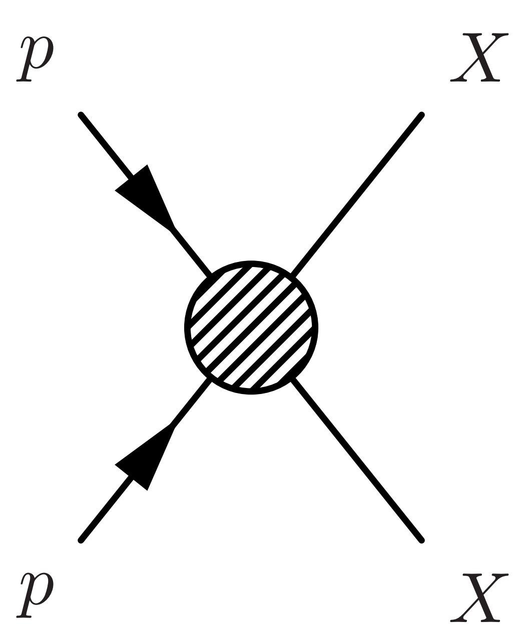

$$\sigma_p(s_p) = \frac{1}{s_p}\int_{\tau_0}^{1} d\tau \frac{1}{\tau} \sum_{ij} \Phi_{ij}(\tau, \mu_f) \; [\hat{\sigma}_{ij}\hat{s}]_p$$

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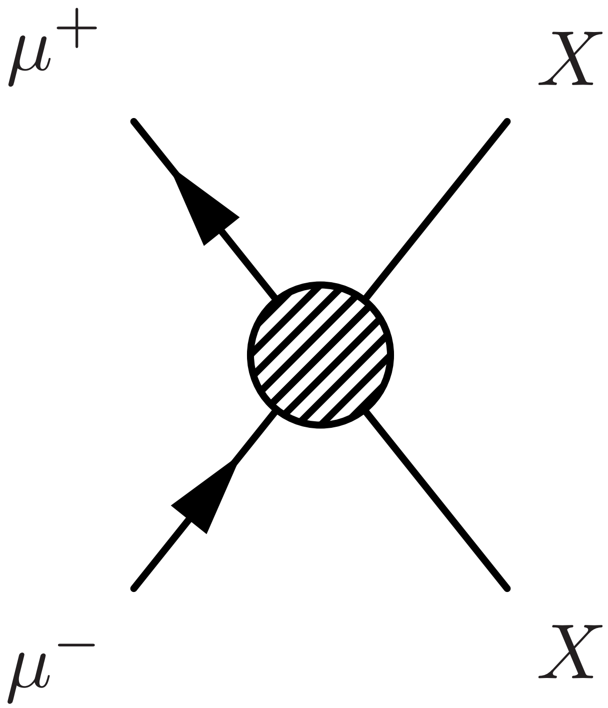

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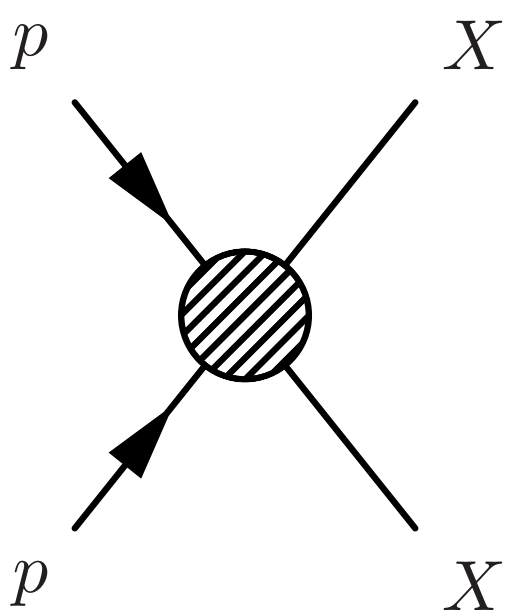

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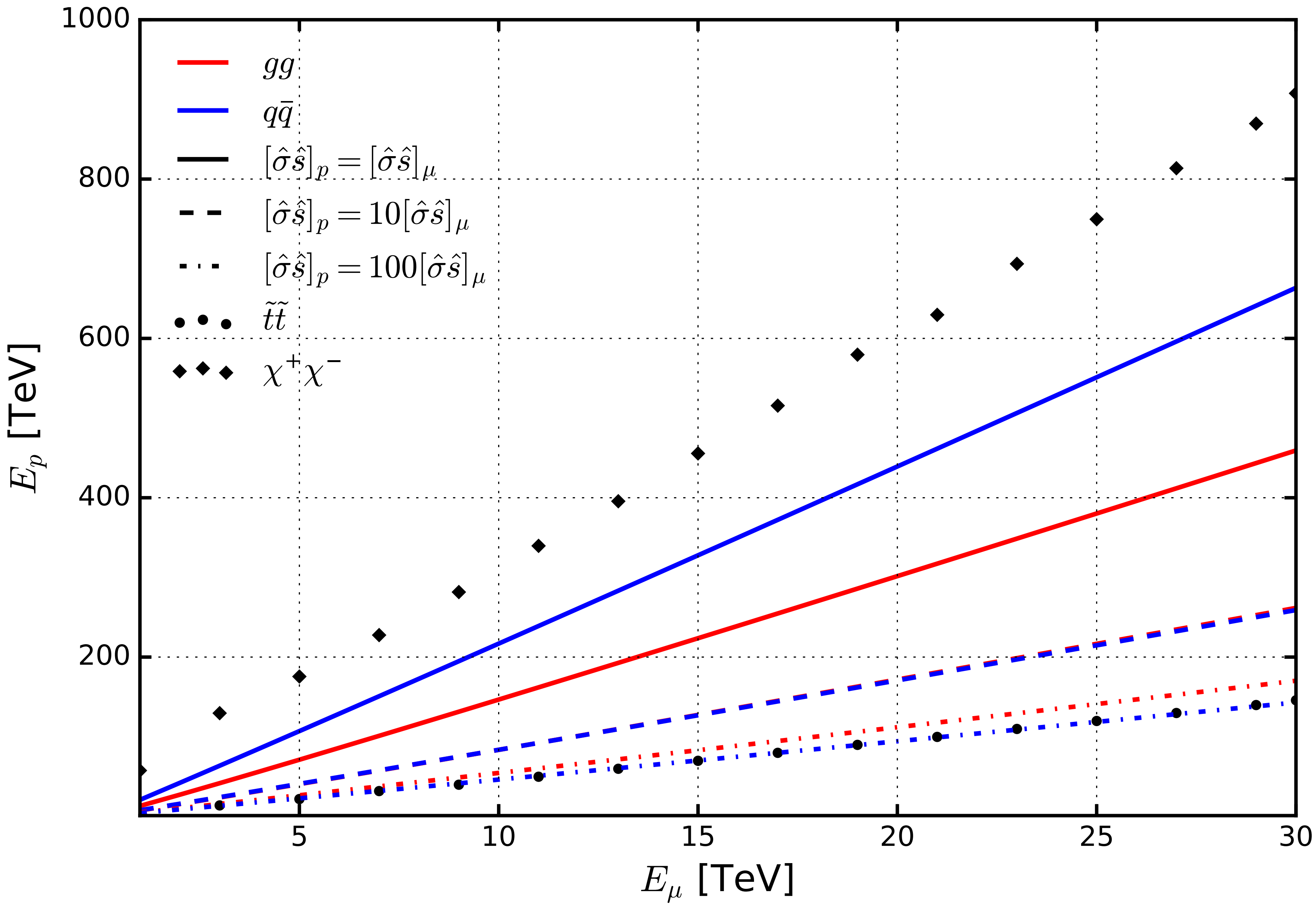

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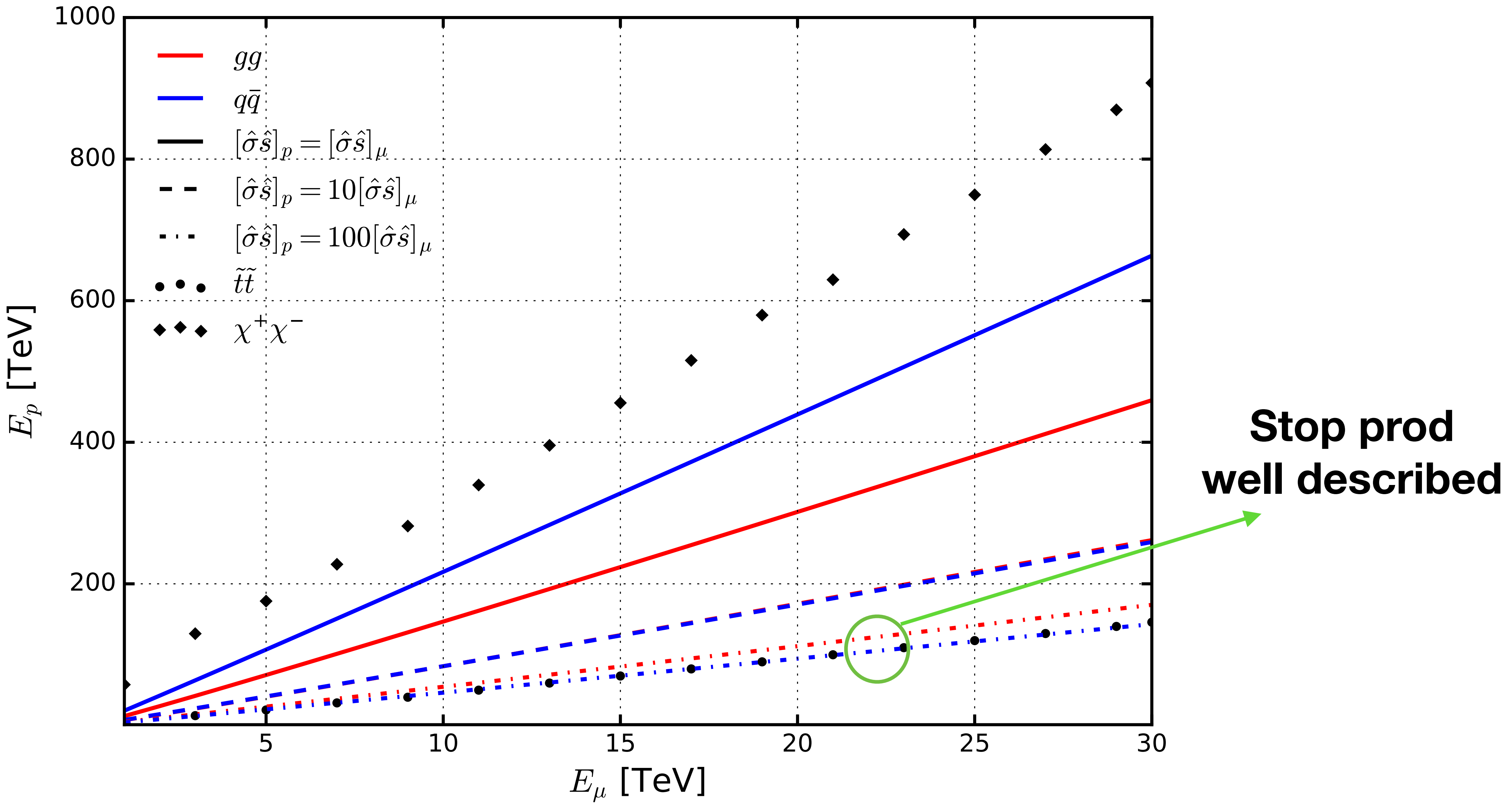
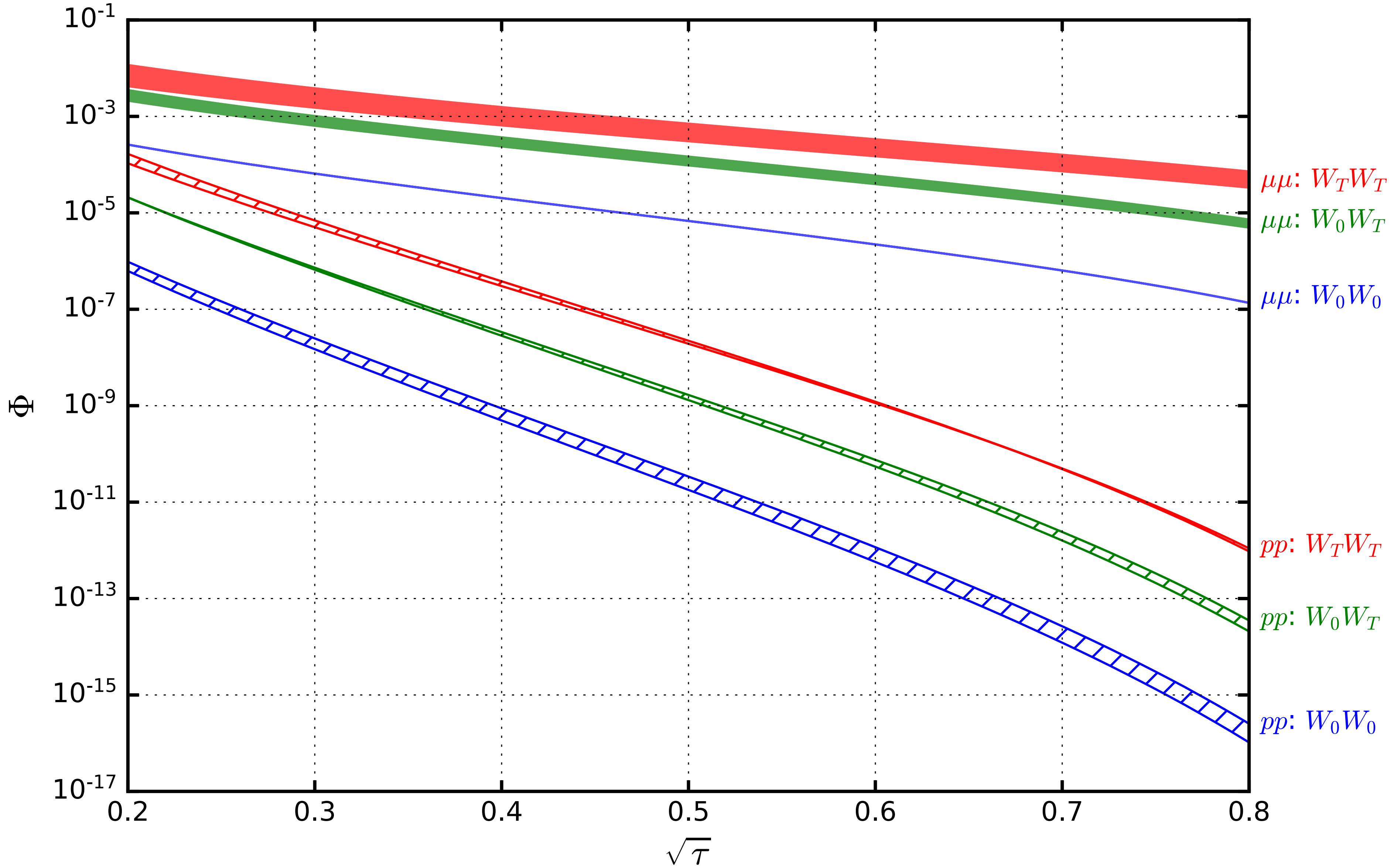


$$\Phi_{W^+_{\lambda_1} W^-_{\lambda_2}}(\tau, \mu_f) = \int_\tau^1 \frac{d\xi}{\xi}\, f_{W_{\lambda_1}/\mu}\left(\xi, \mu_f\right)\, f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi}, \mu_f\right)$$



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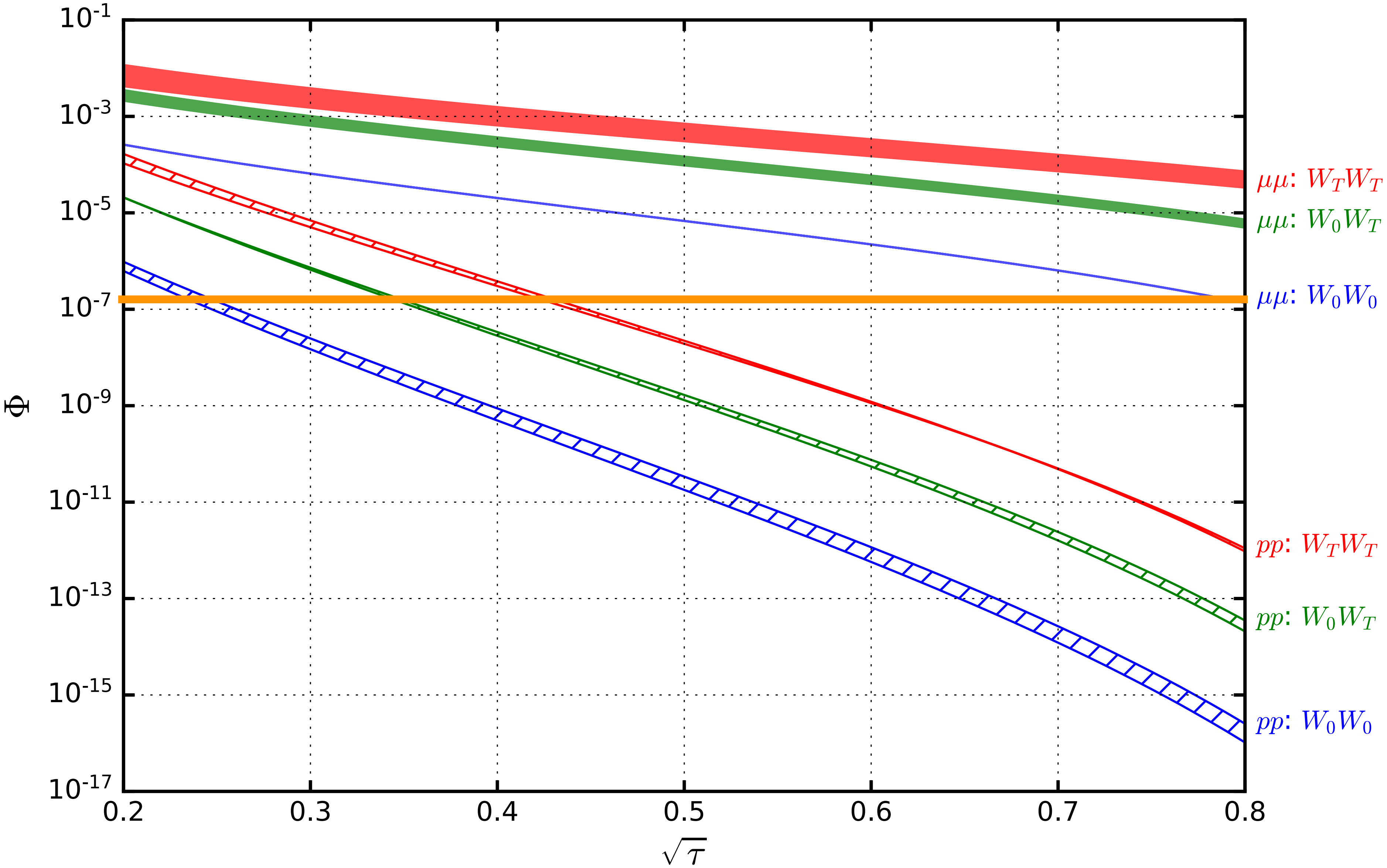

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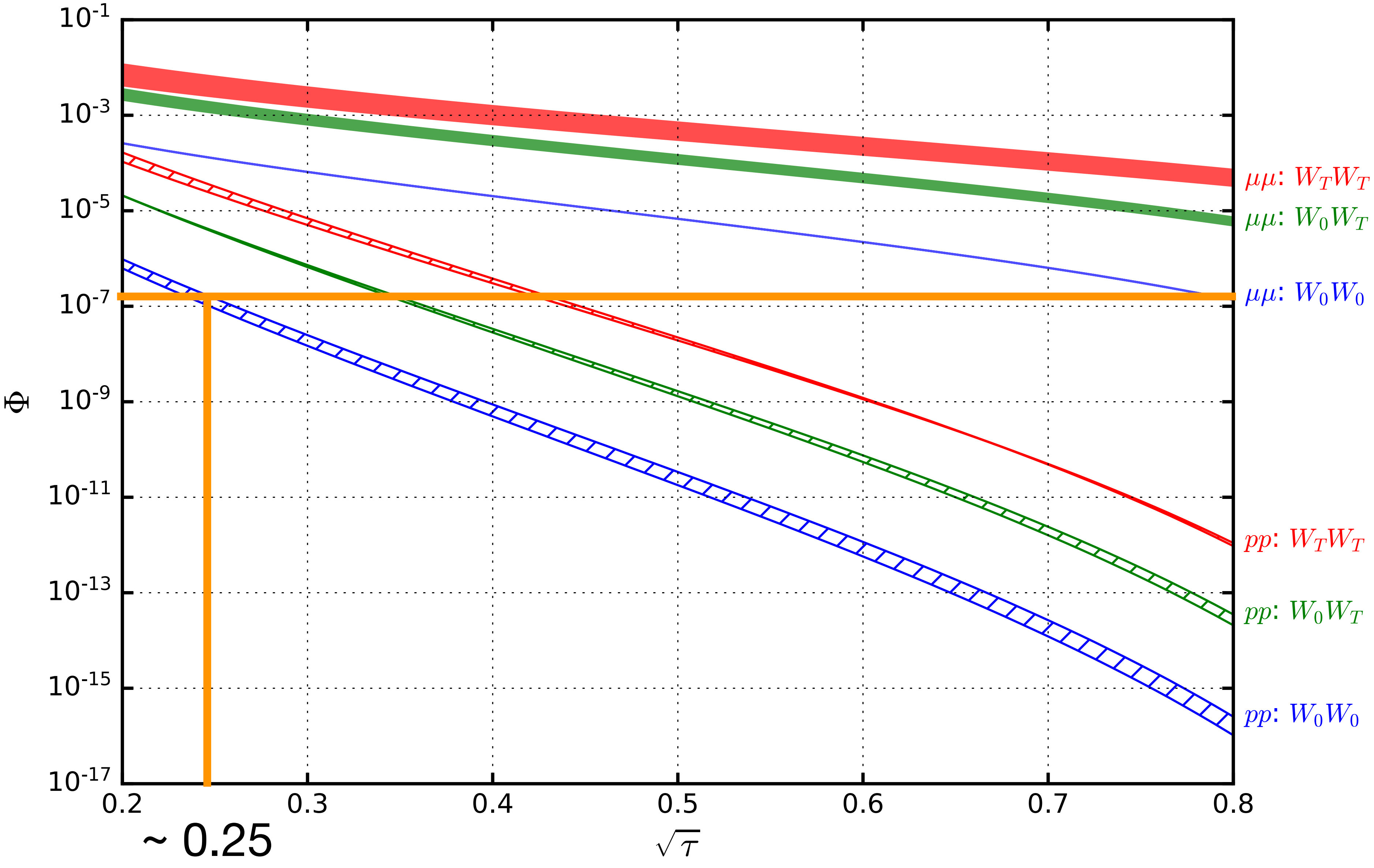

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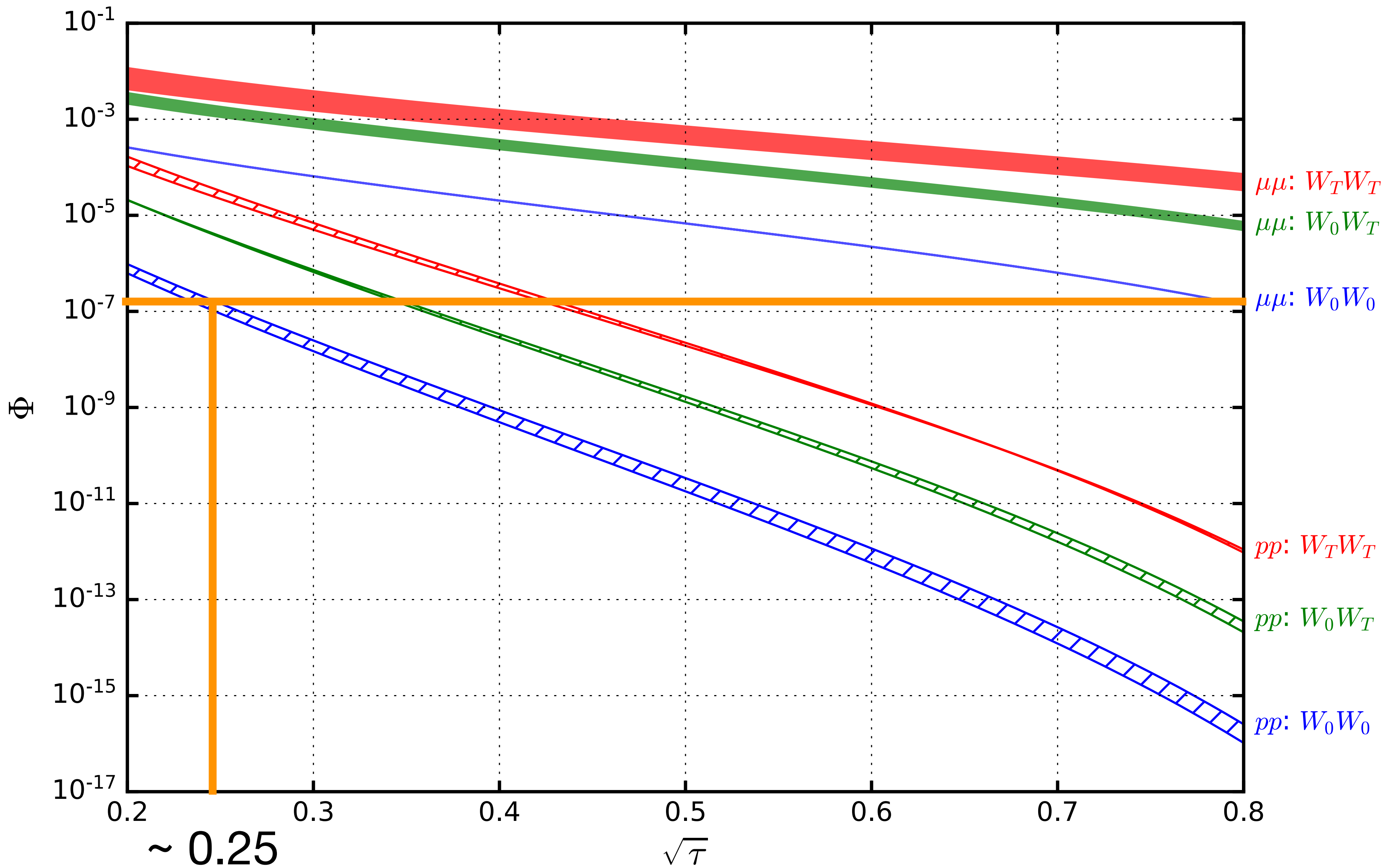
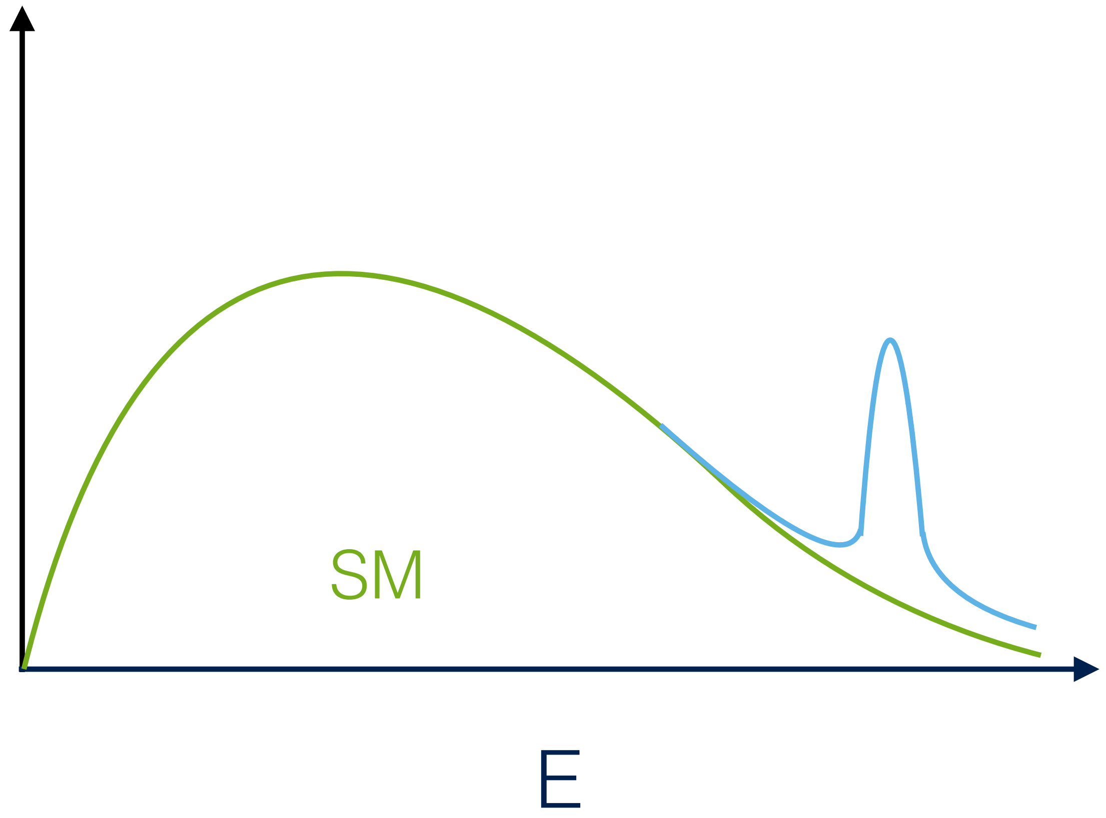


0.8/0.25 ~ 3.5

Muon 14 TeV ~ Proton 50 TeV

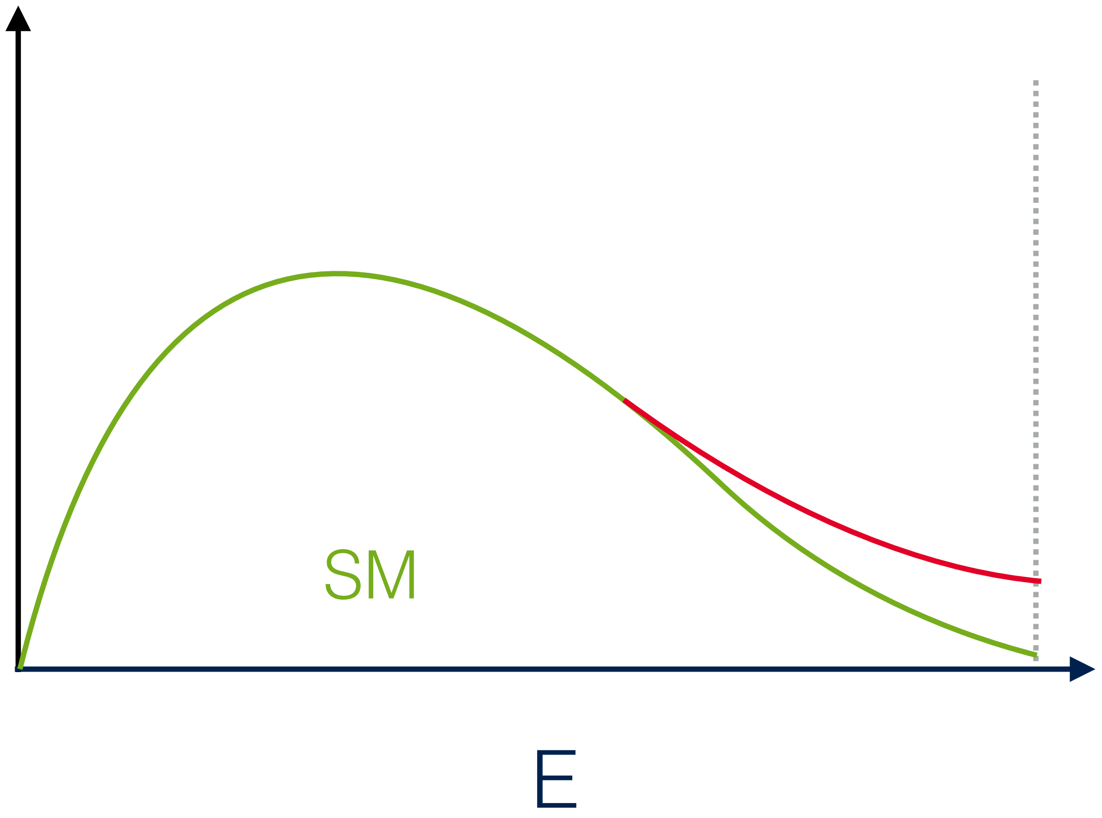
Precision potential

Direct search (Bumps)



Direct search (Bumps)

Indirect (scouting tails)



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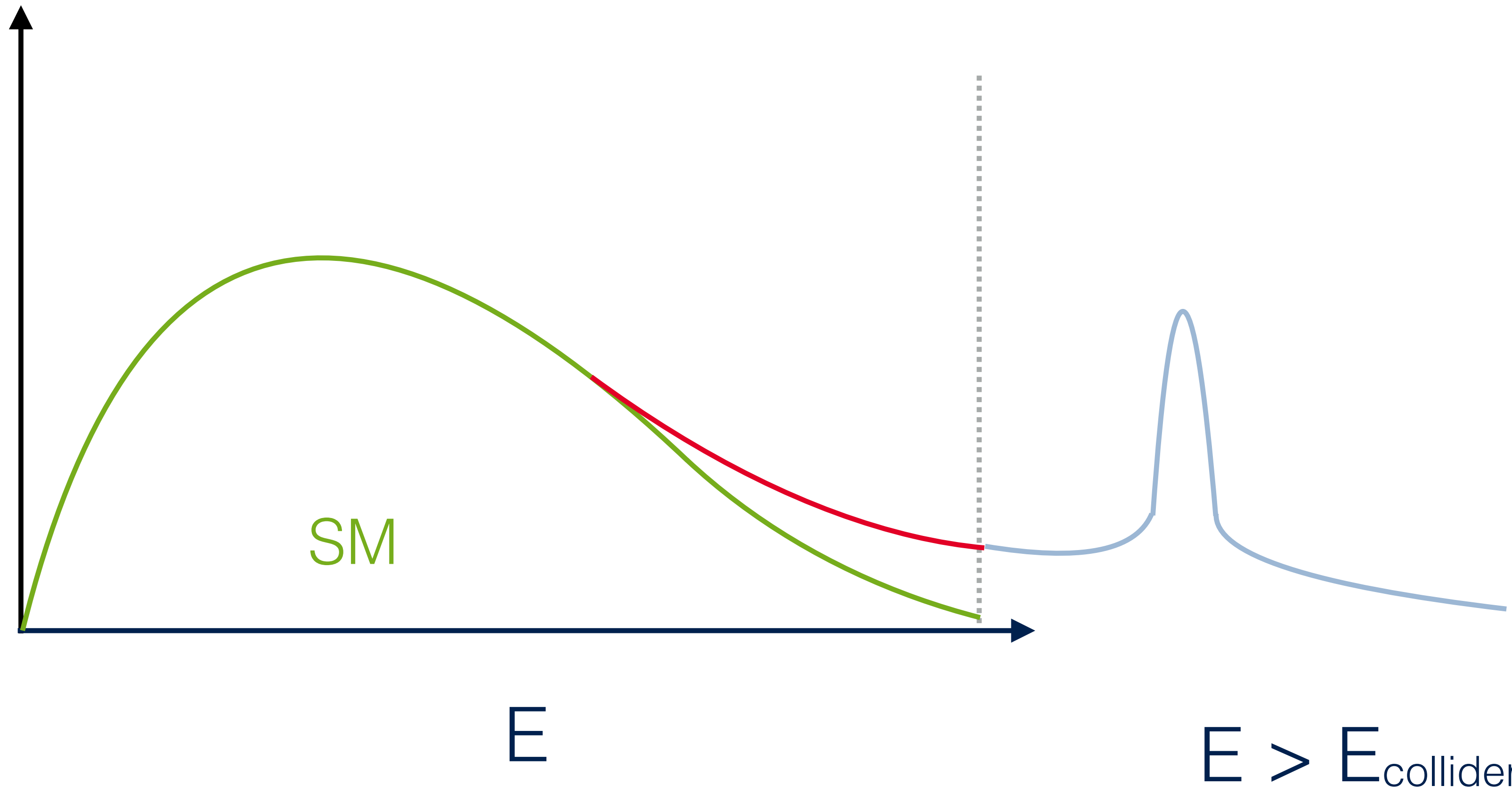
⇒ New physics is heavy



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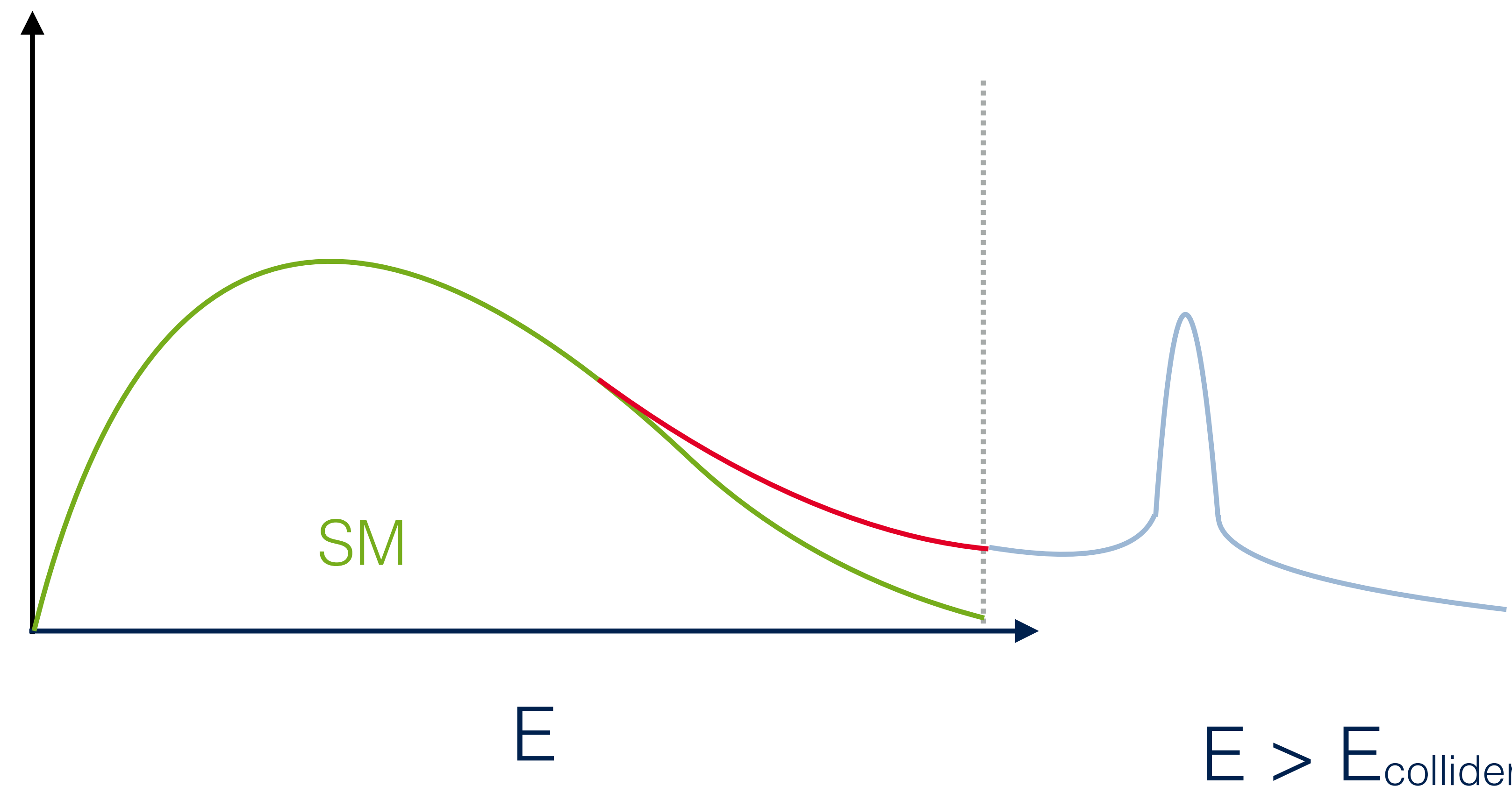

Important to assess the potential of a muon collider in indirect searches

Direct search (Bumps)

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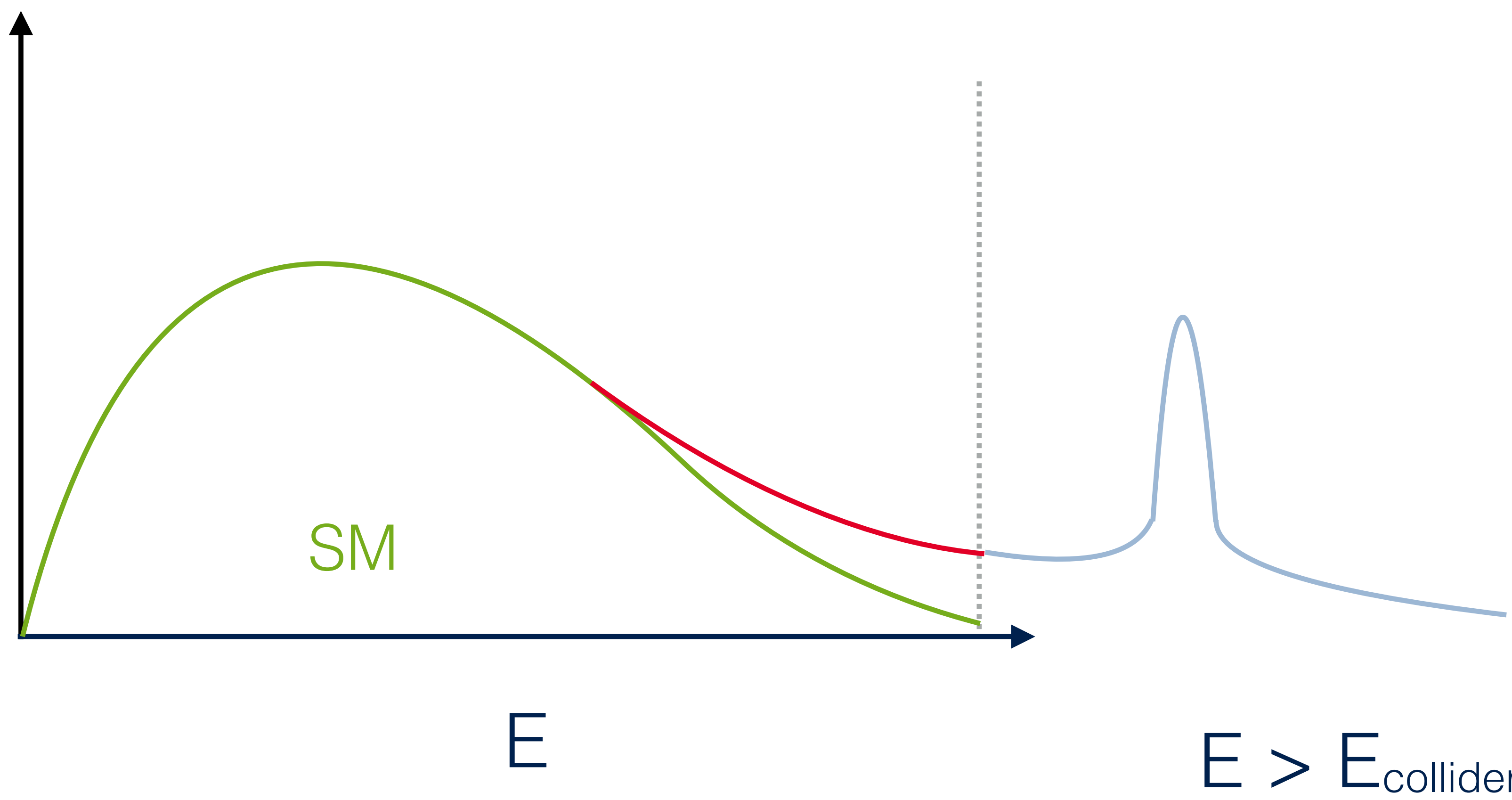

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New physics effects can lead to unitarity violating behaviours at high energy

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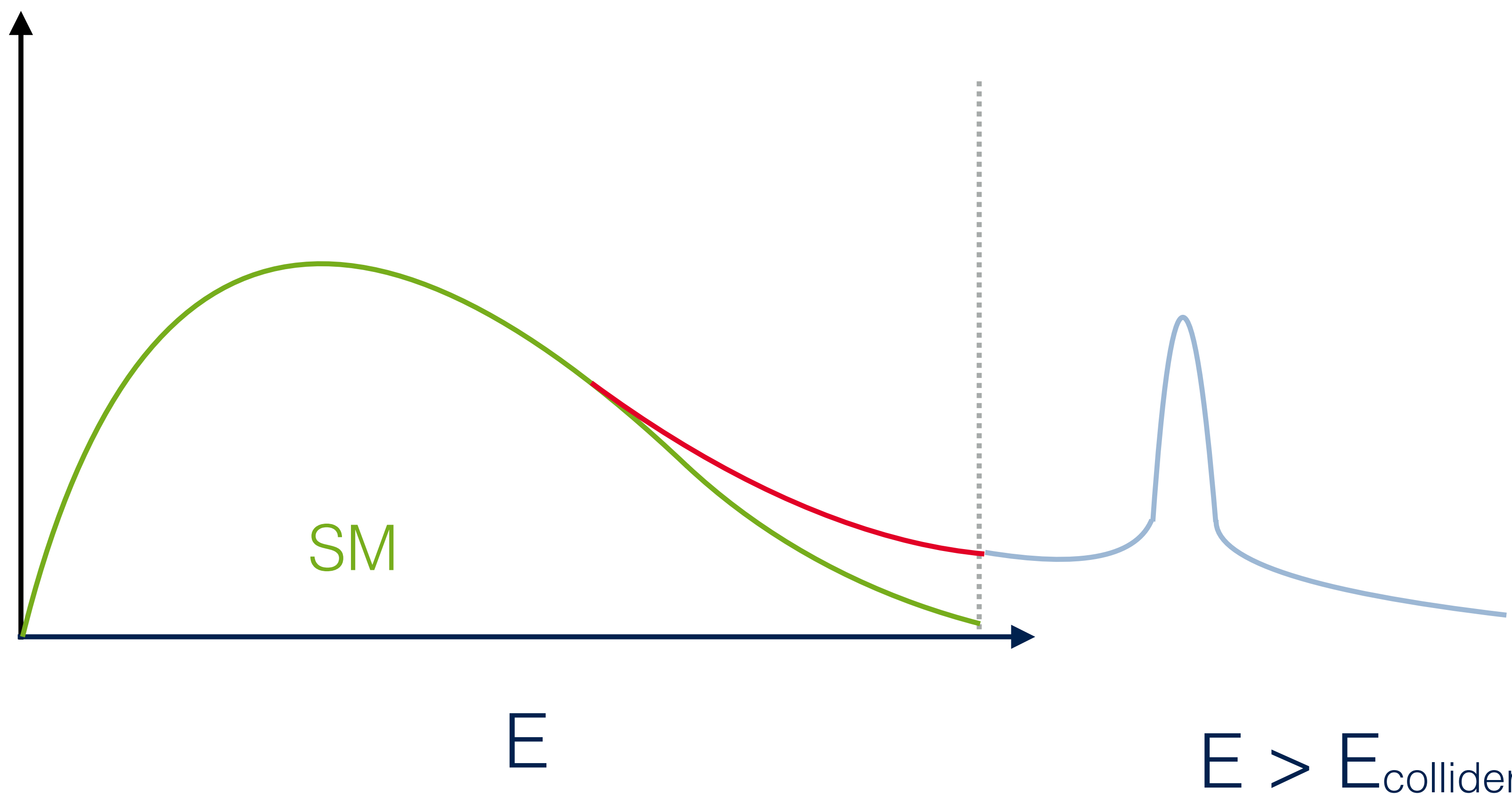

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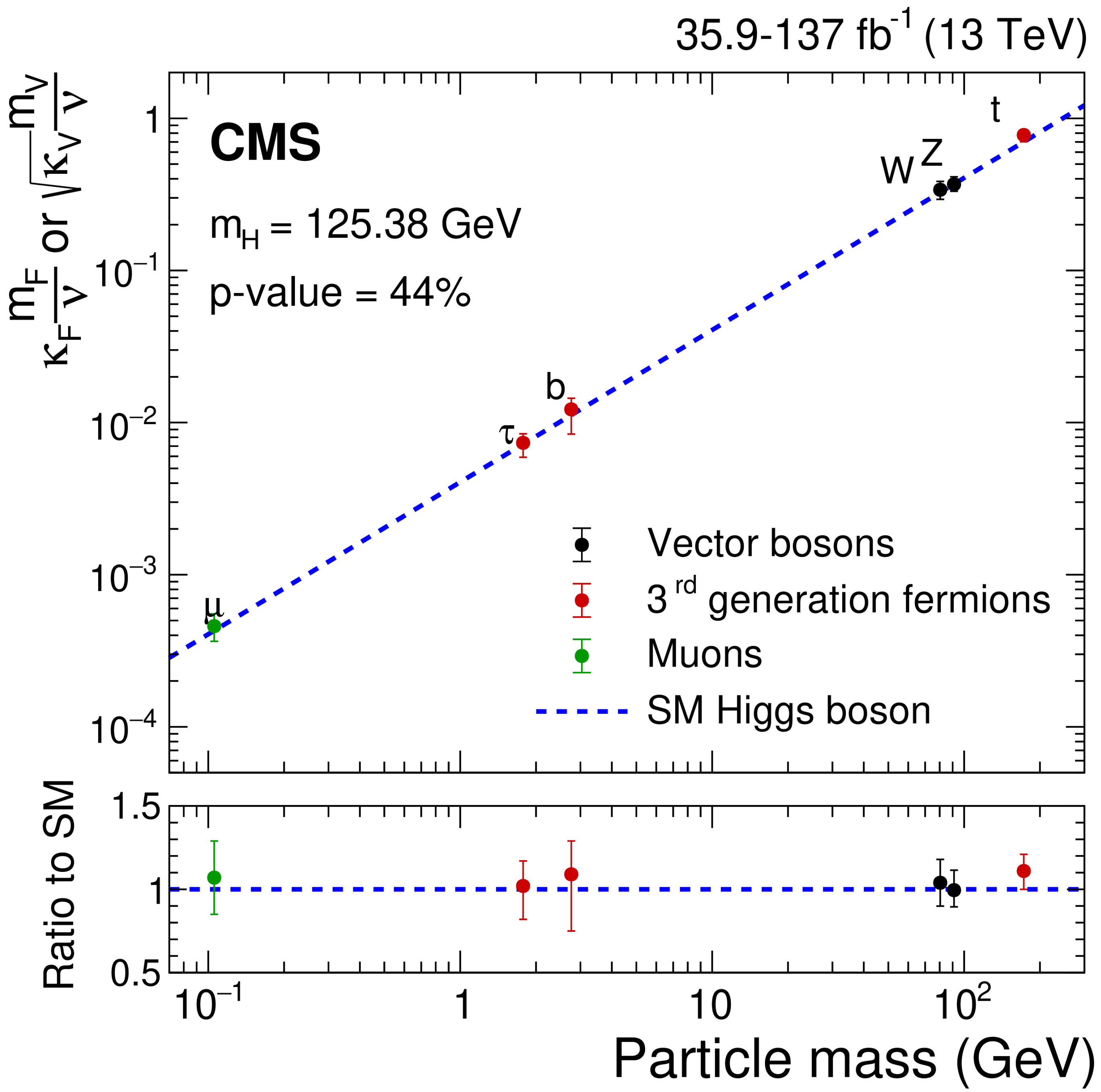
New physics effects can lead to unitarity violating behaviours at high energy

High energy tails → **Less statistics, more sensitivity**

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

It couples to masses.



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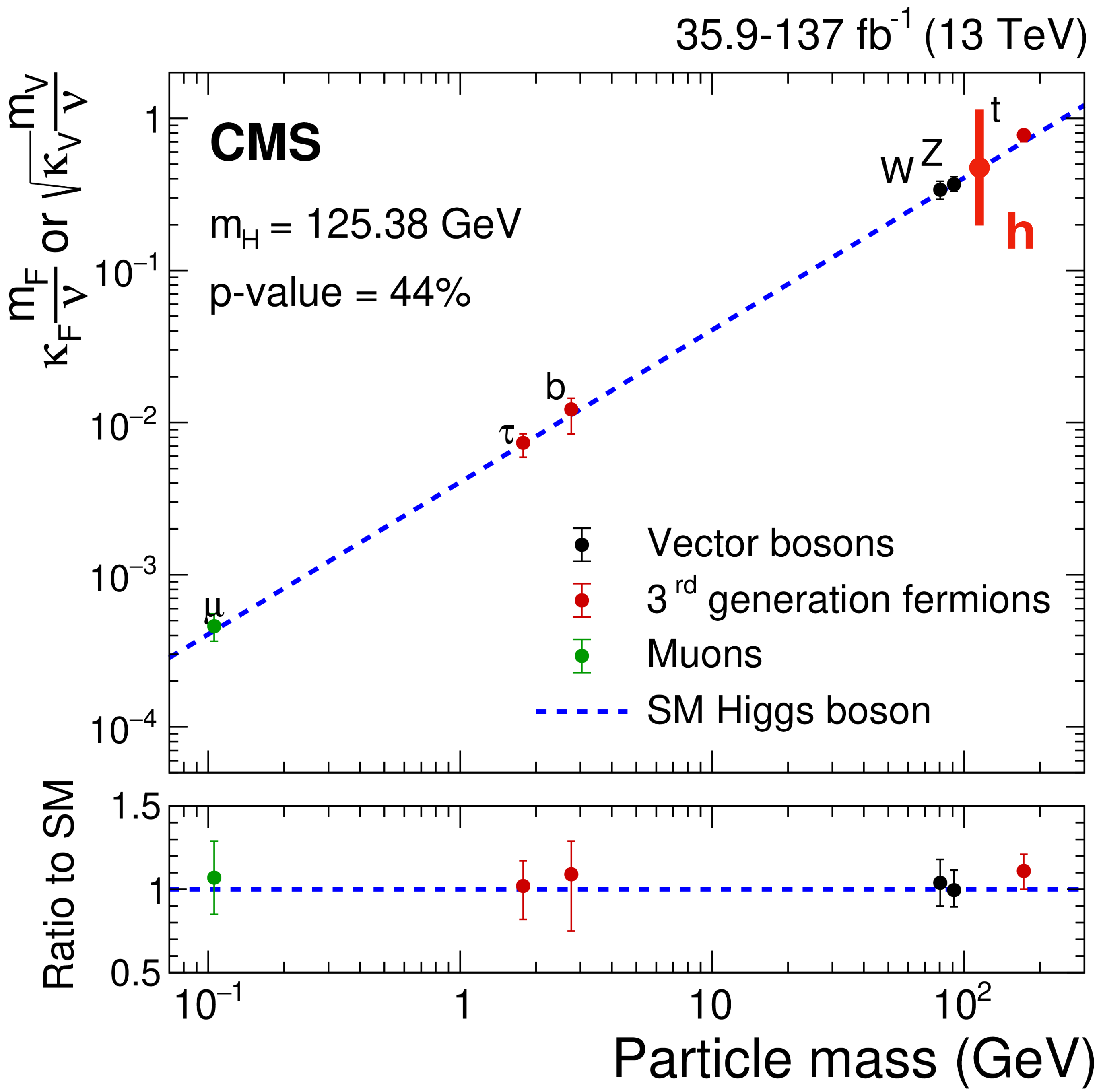

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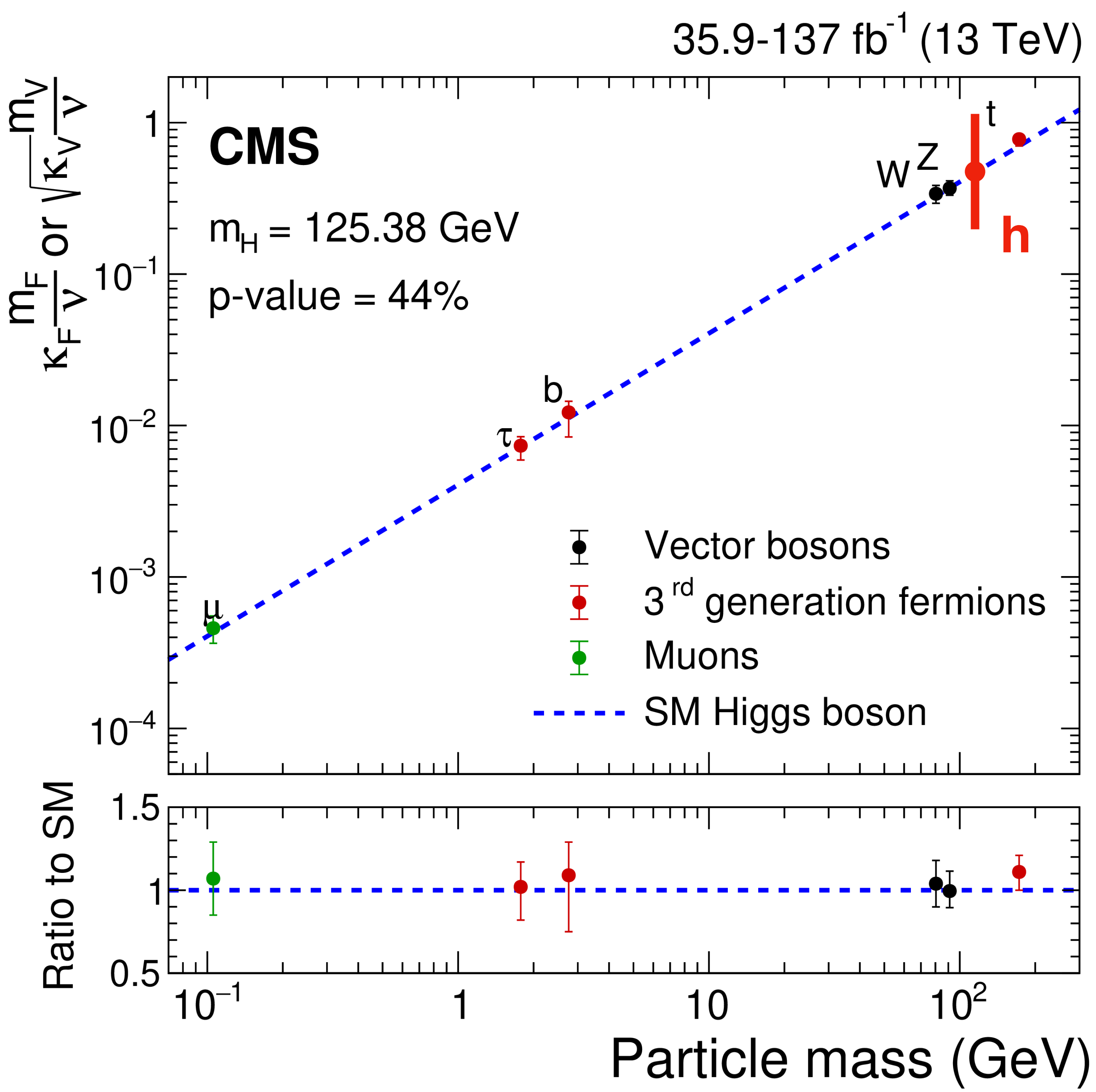

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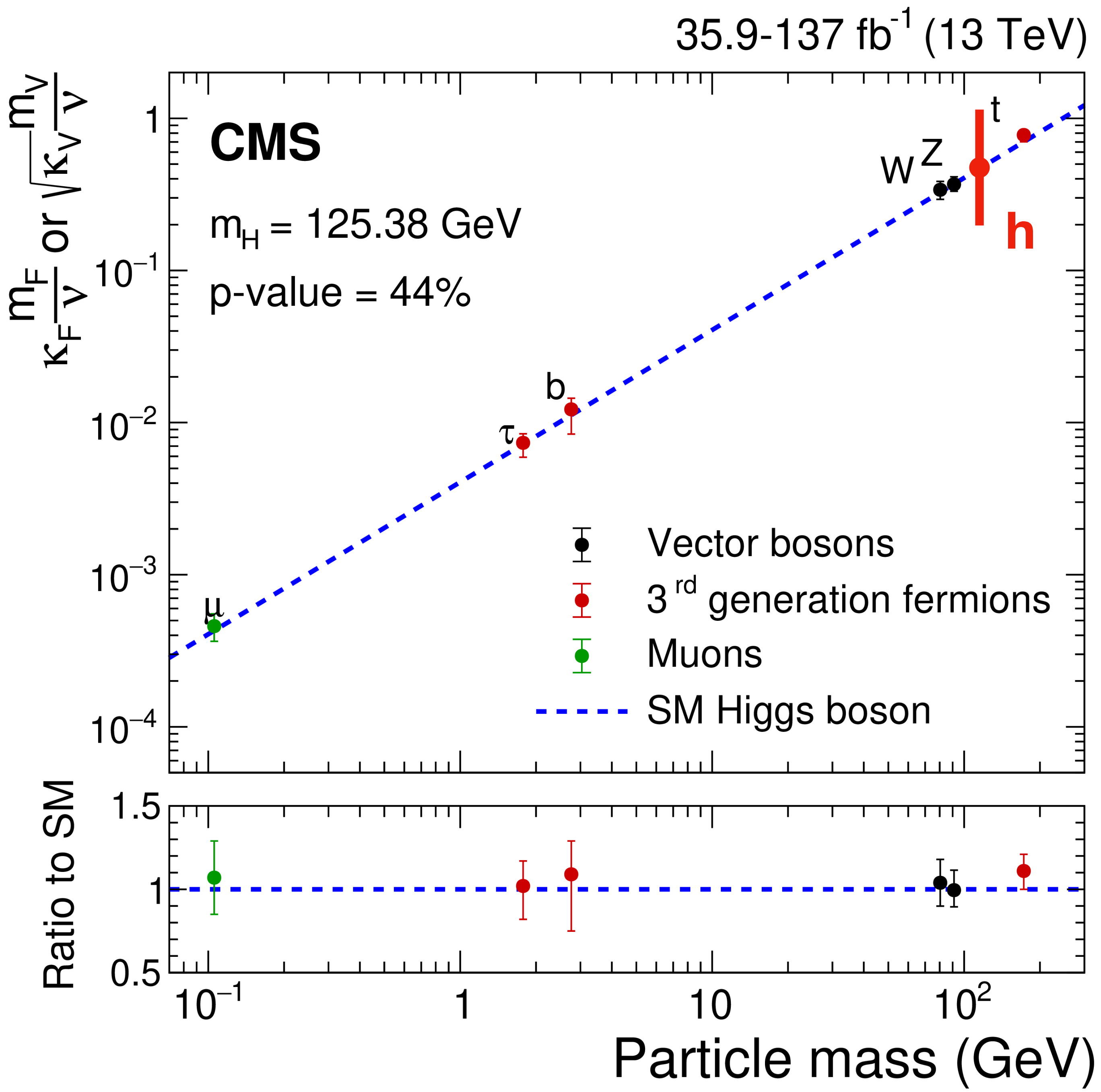

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Is a low energy lepton collider enough?

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

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

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

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HH and radiative corrections to single Higgs
FCC ~ 5%

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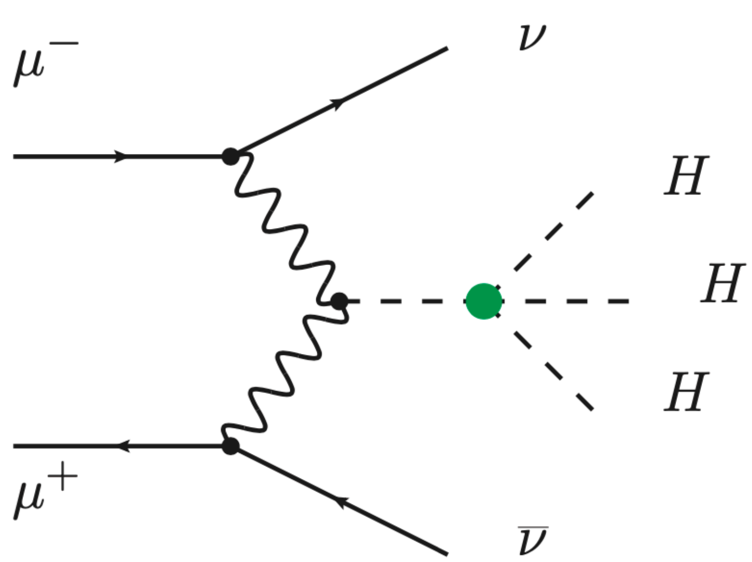

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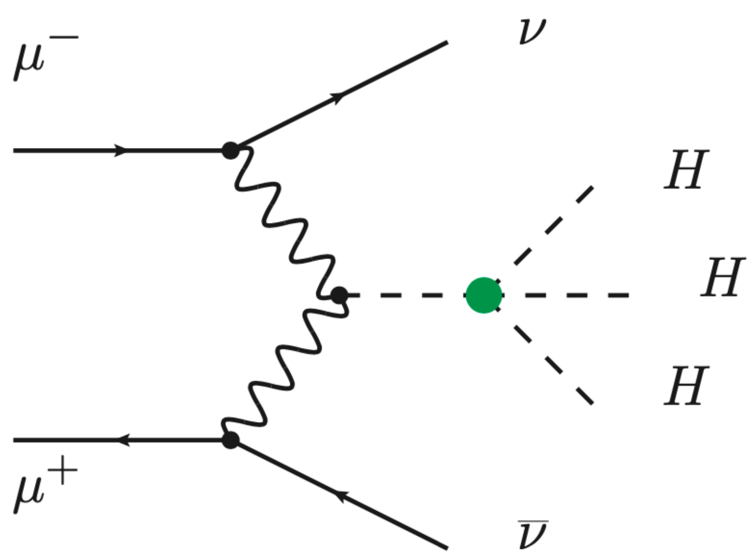

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σ_{SM} (ab) [N_{ev}]						
σ^{tot}	0.03 [0]	0.31 [1]	1.65 [20]	4.18 [84]	7.02 [232]	18.51 [1851]
$\sigma(M_{HHH} < 3$ TeV)	0.03 [0]	0.31 [1]	1.47 [18]	2.89 [58]	3.98 [131]	6.69 [669]
$\sigma(M_{HHH} < 1$ TeV)	0.02 [0]	0.12 [1]	0.26 [3]	0.37 [7]	0.45 [15]	0.64 [64]

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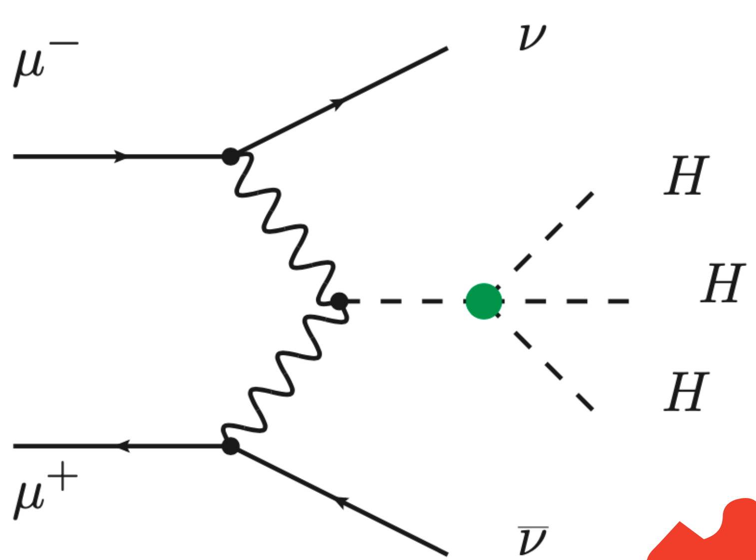

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SMEFT scenario $\delta_4 = 6\,\delta_3$

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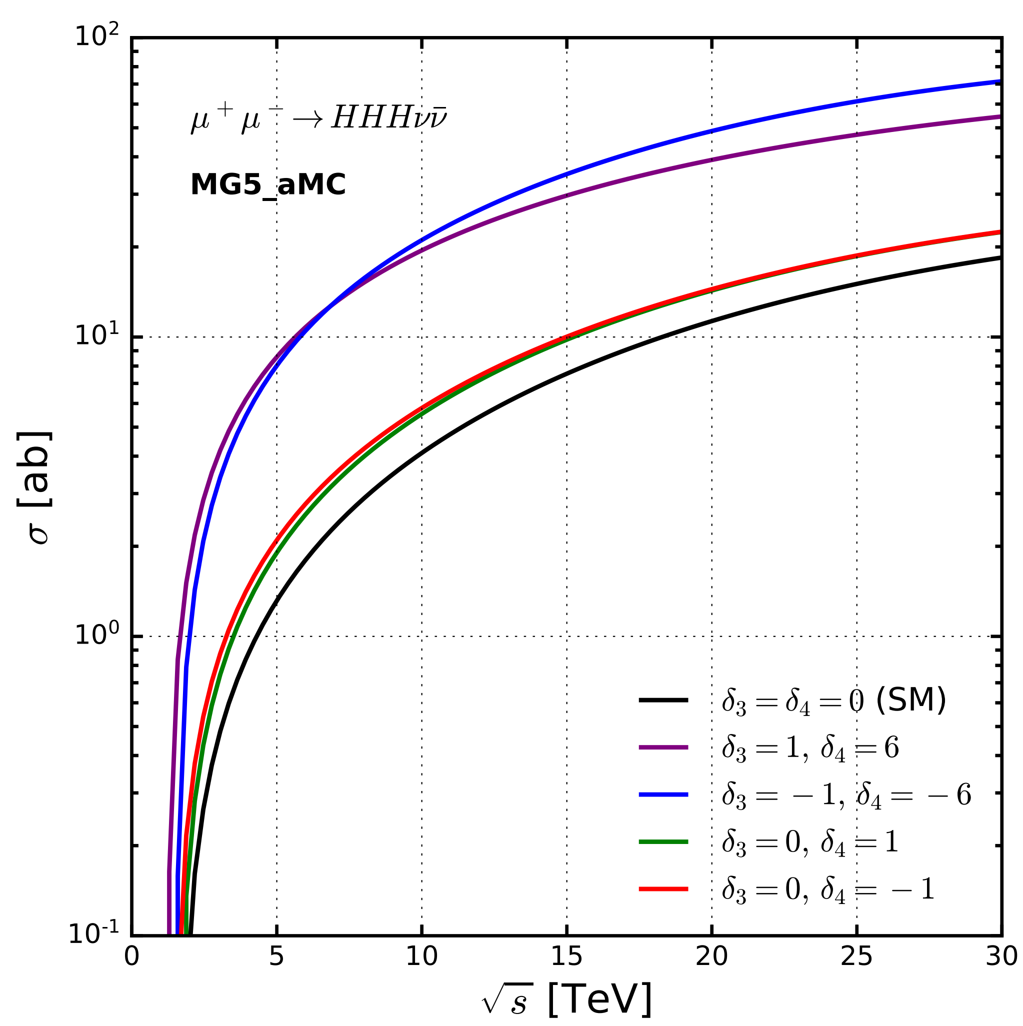

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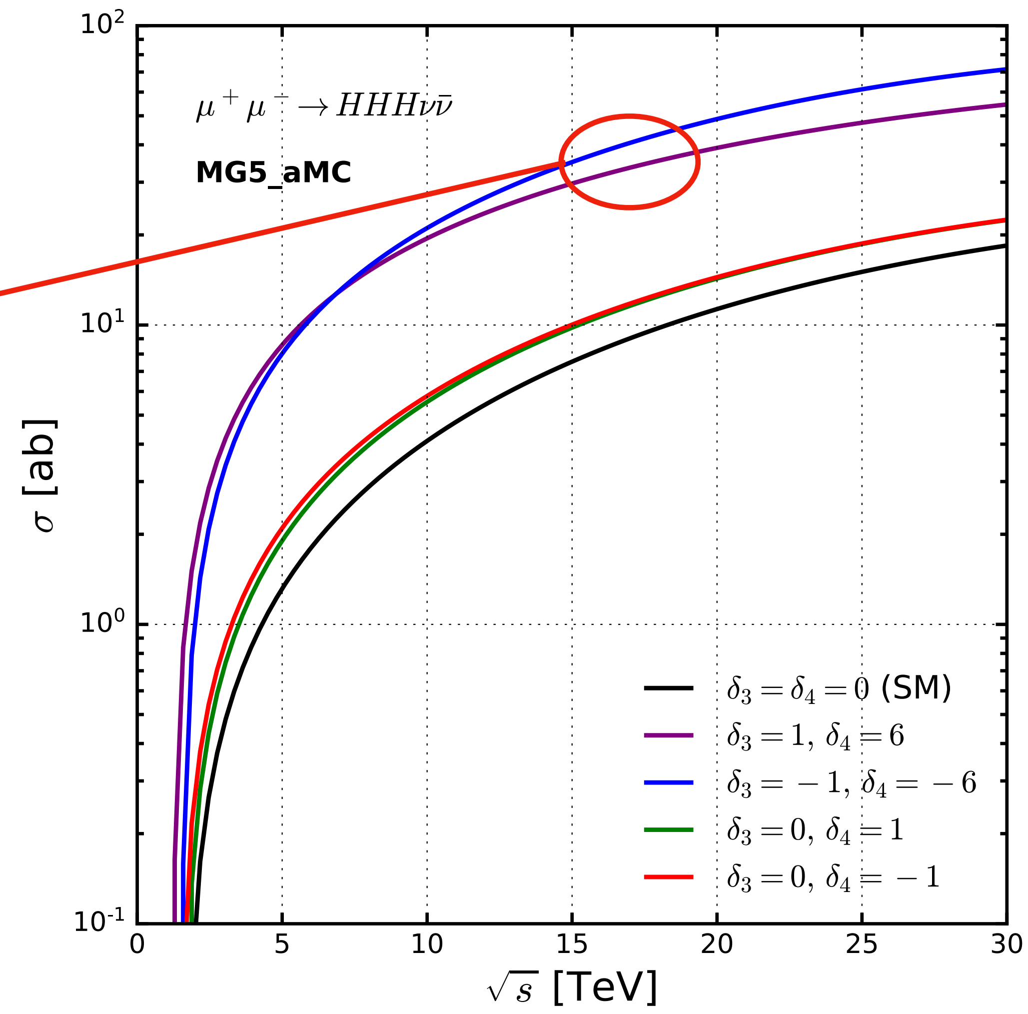
Huge effects in SMEFT caused by trilinear shift



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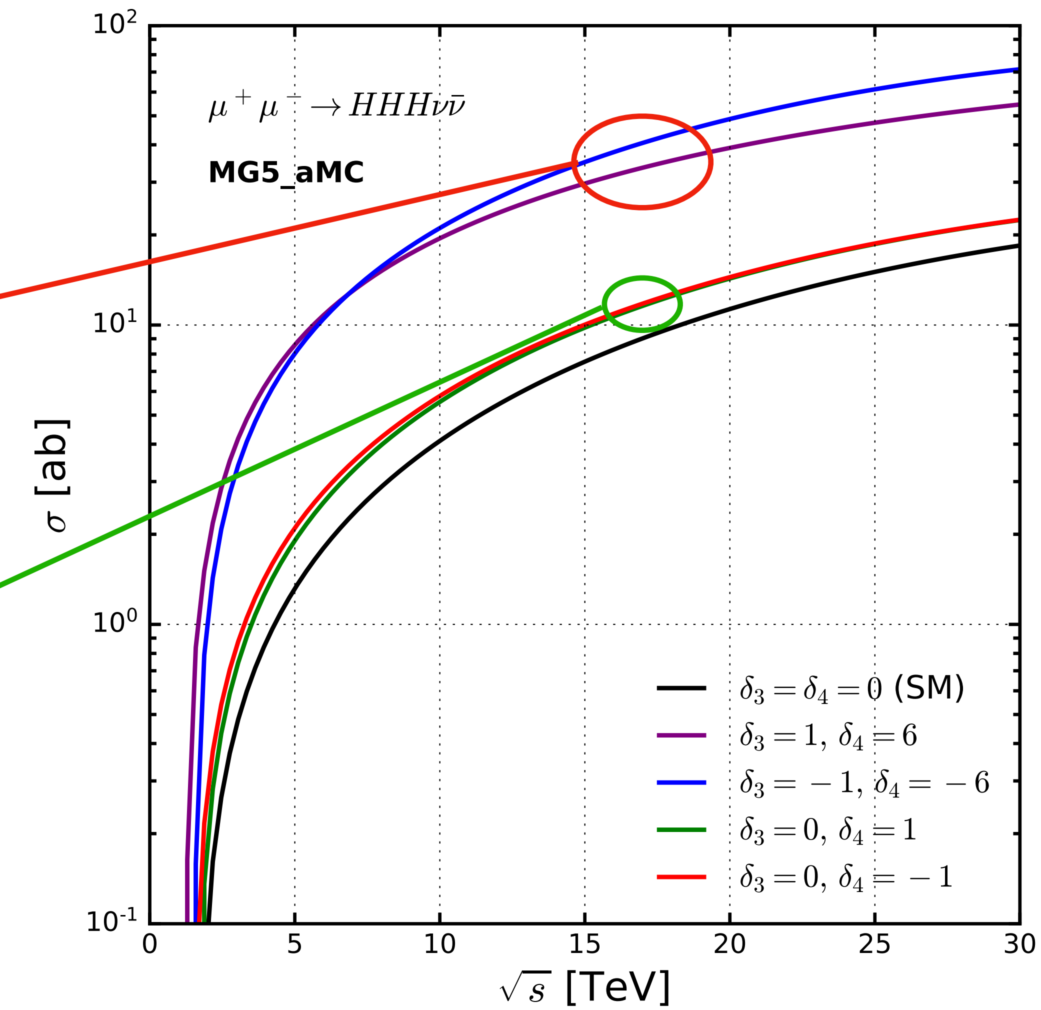
$$\sigma = \sigma_{SM} + c_2\delta_3 + c_3\delta_4 + c_4\delta_3\delta_4 + c_5\delta_3^2 + c_6\delta_4^2 + c_7\delta_3^3 + c_8\delta_3^2\delta_4 + c_9\delta_3^4$$

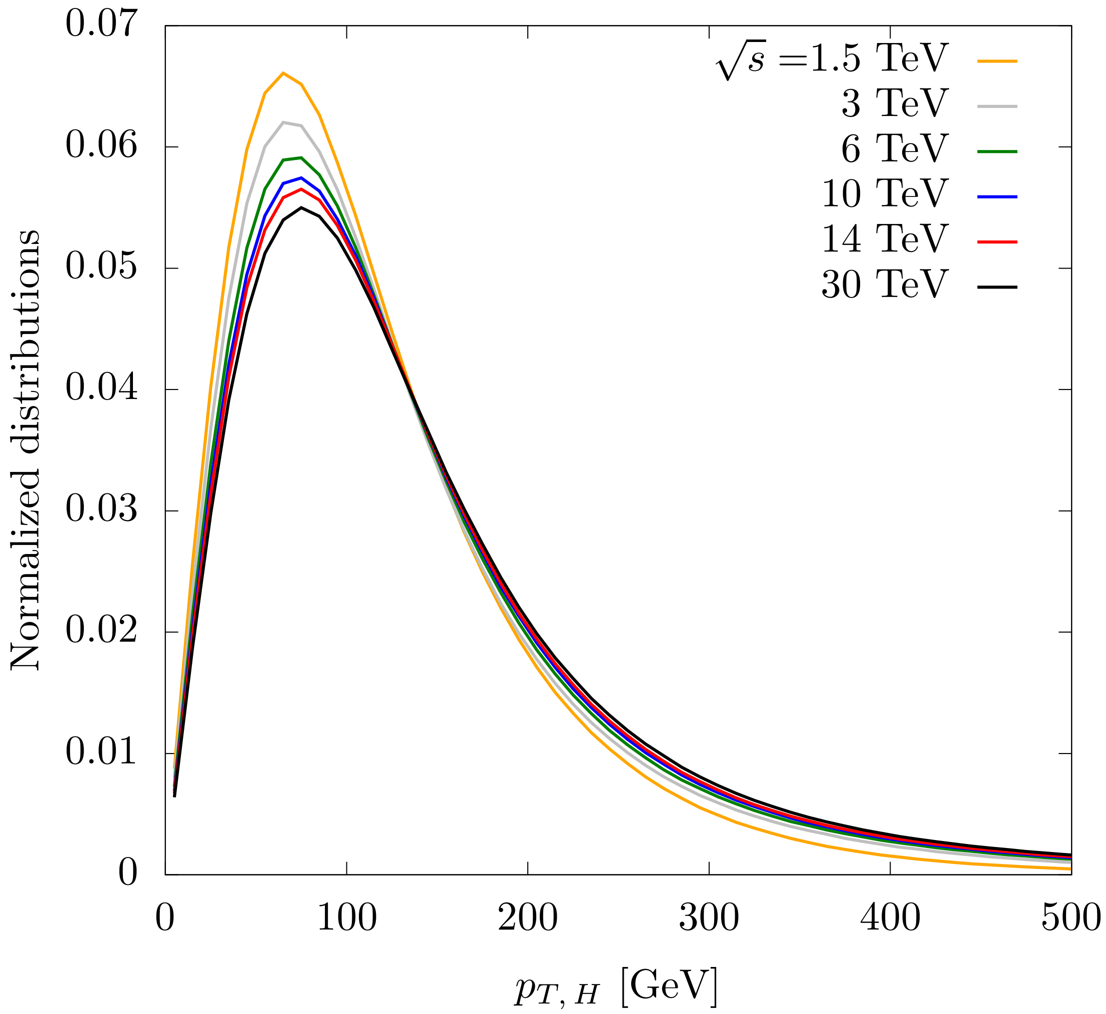
$$\mathcal{O}_\varphi = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$$

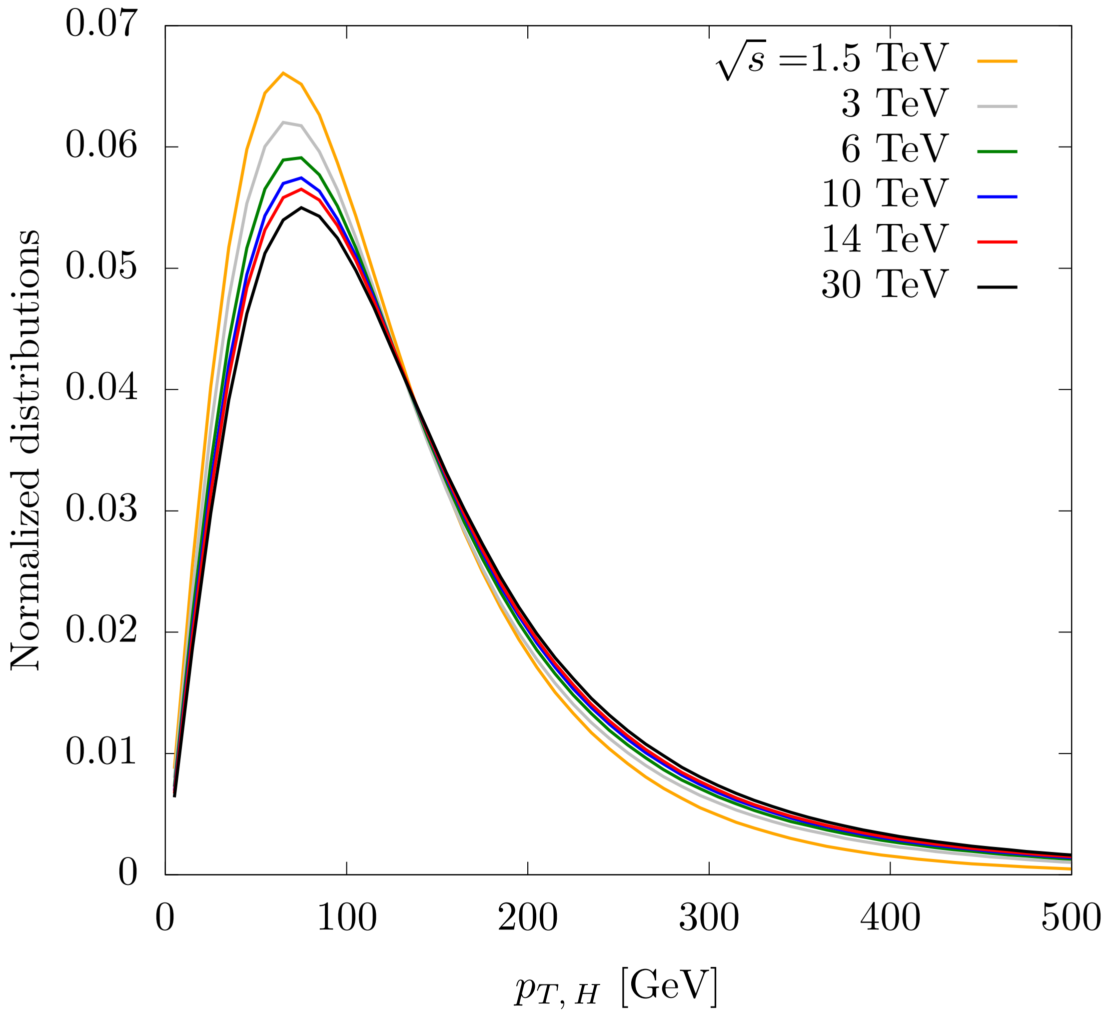
SMEFT scenario $\delta_4 = 6\,\delta_3$

Huge effects in SMEFT caused by trilinear shift

Quartic deviations less sensitivity sign hardly distinguishable




$\sqrt{s}$ =1.5 TeV
3 TeV
6 TeV
10 TeV
14 TeV
30 TeV
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]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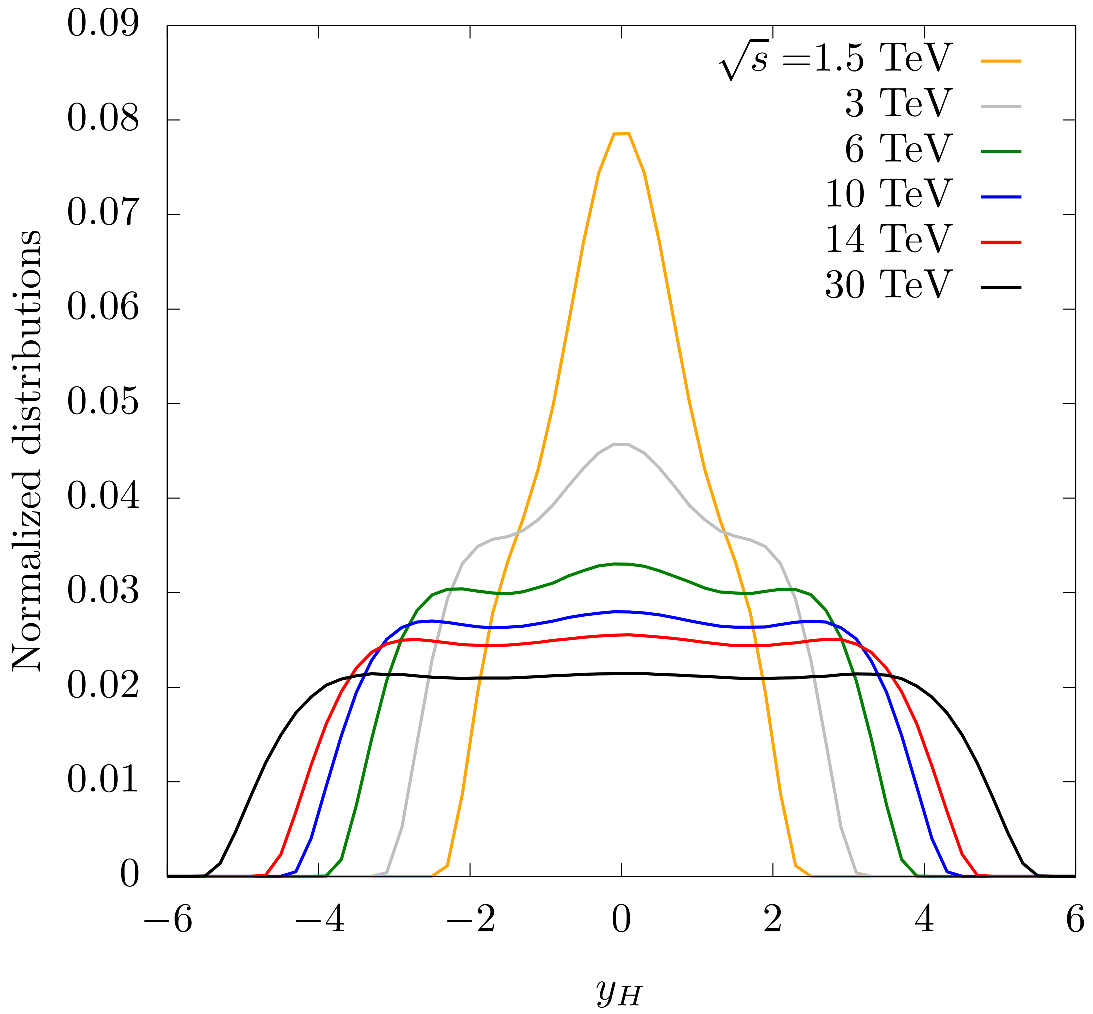
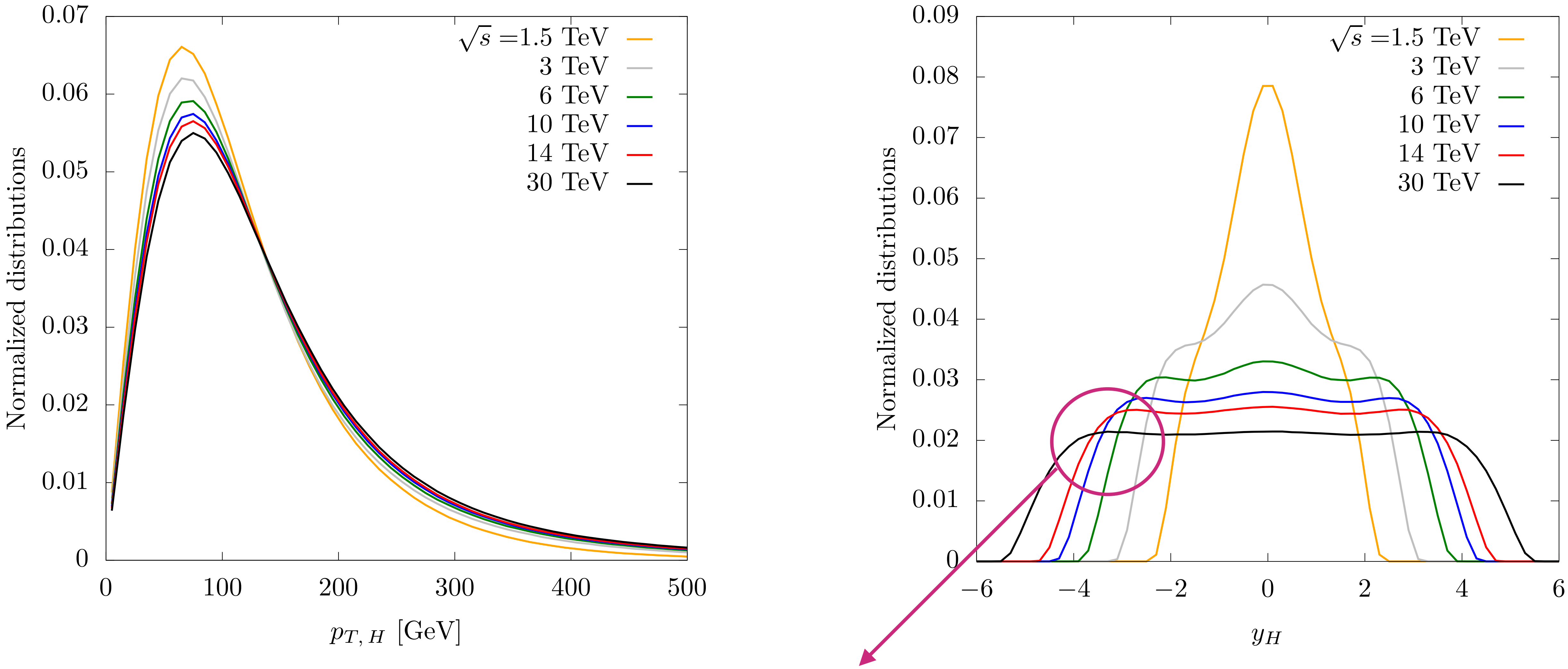
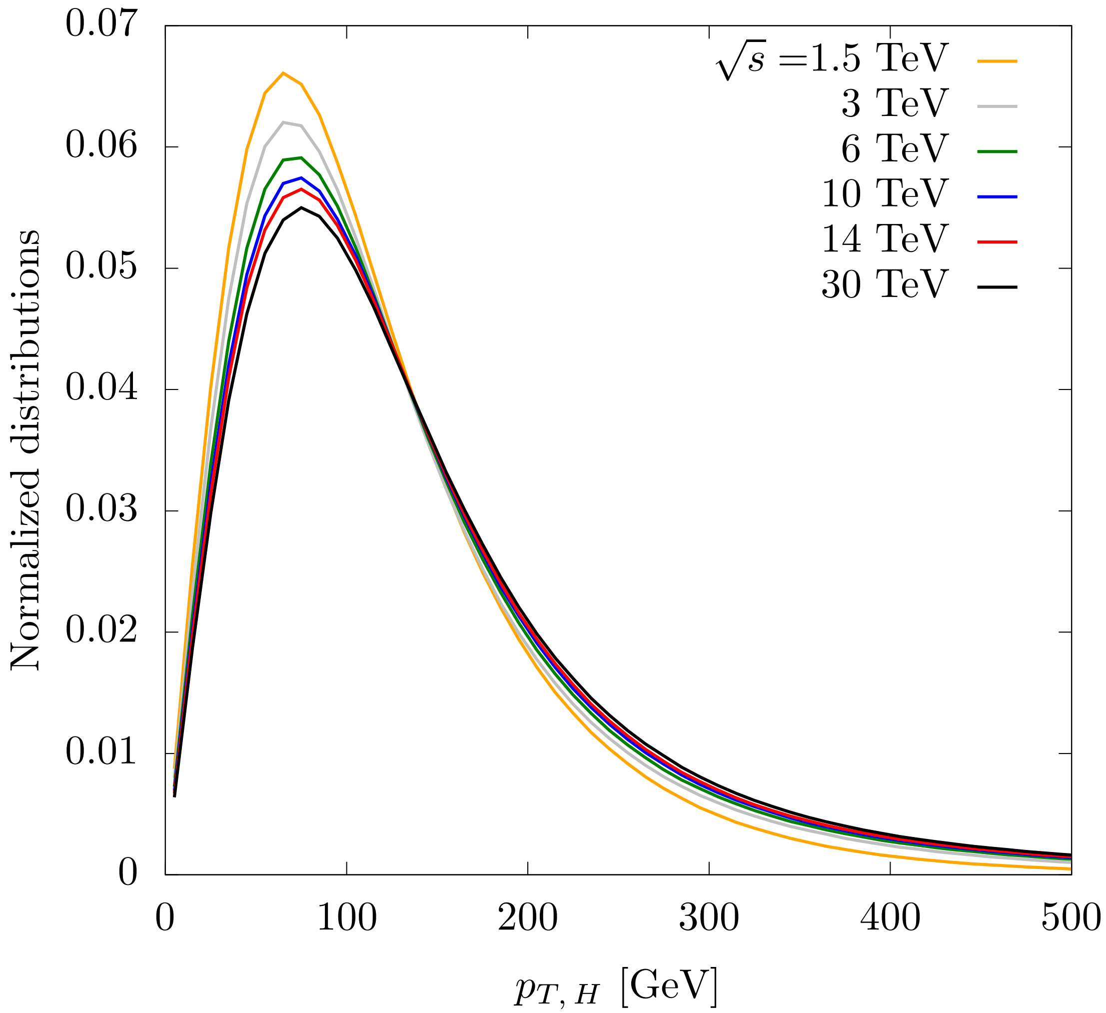
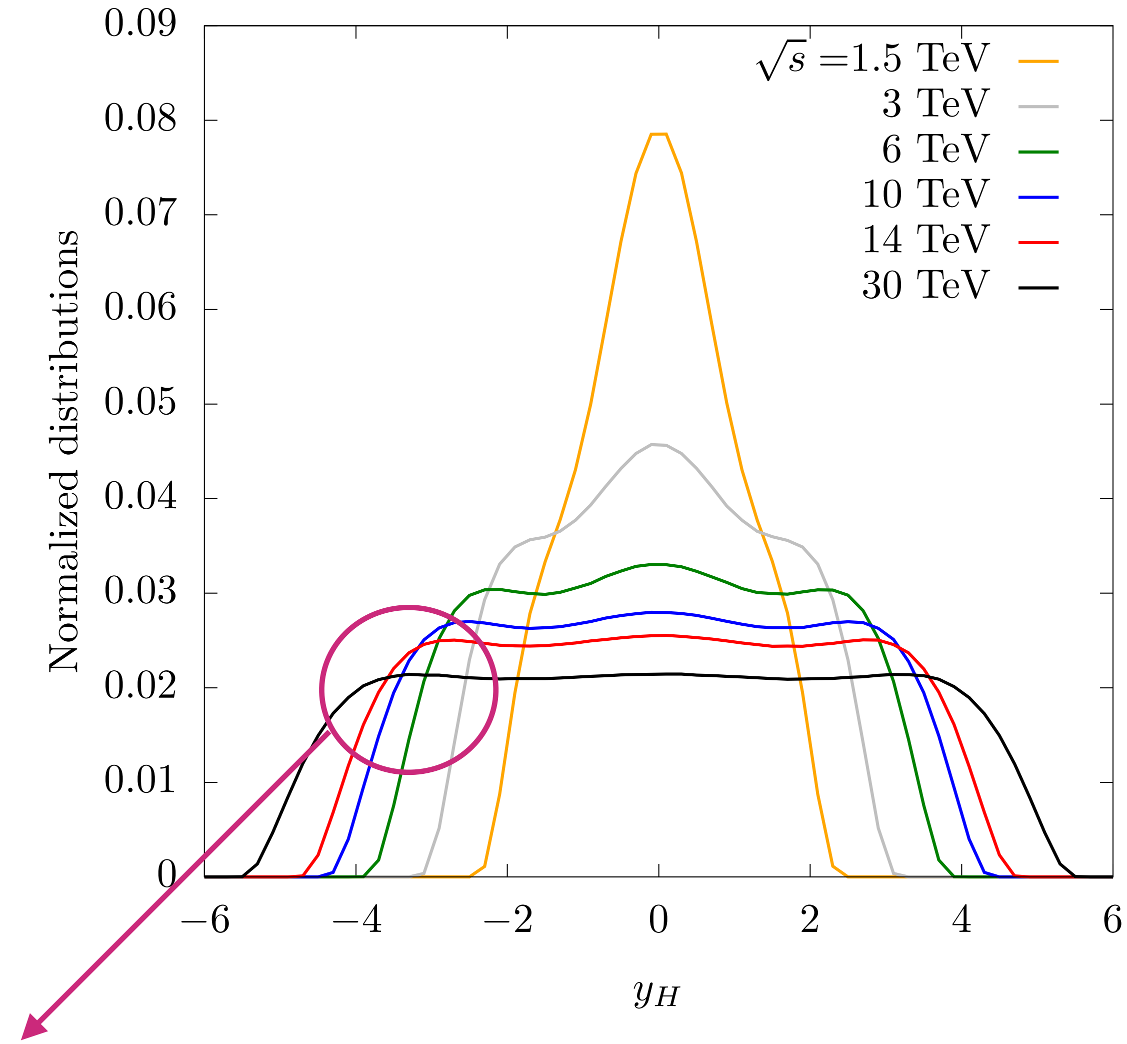

Normalized distributions
y_H
$\sqrt{s}$ =1.5 TeV
3 TeV
6 TeV
10 TeV
14 TeV
30 TeV
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−6
−4
−2
0
2
4
6



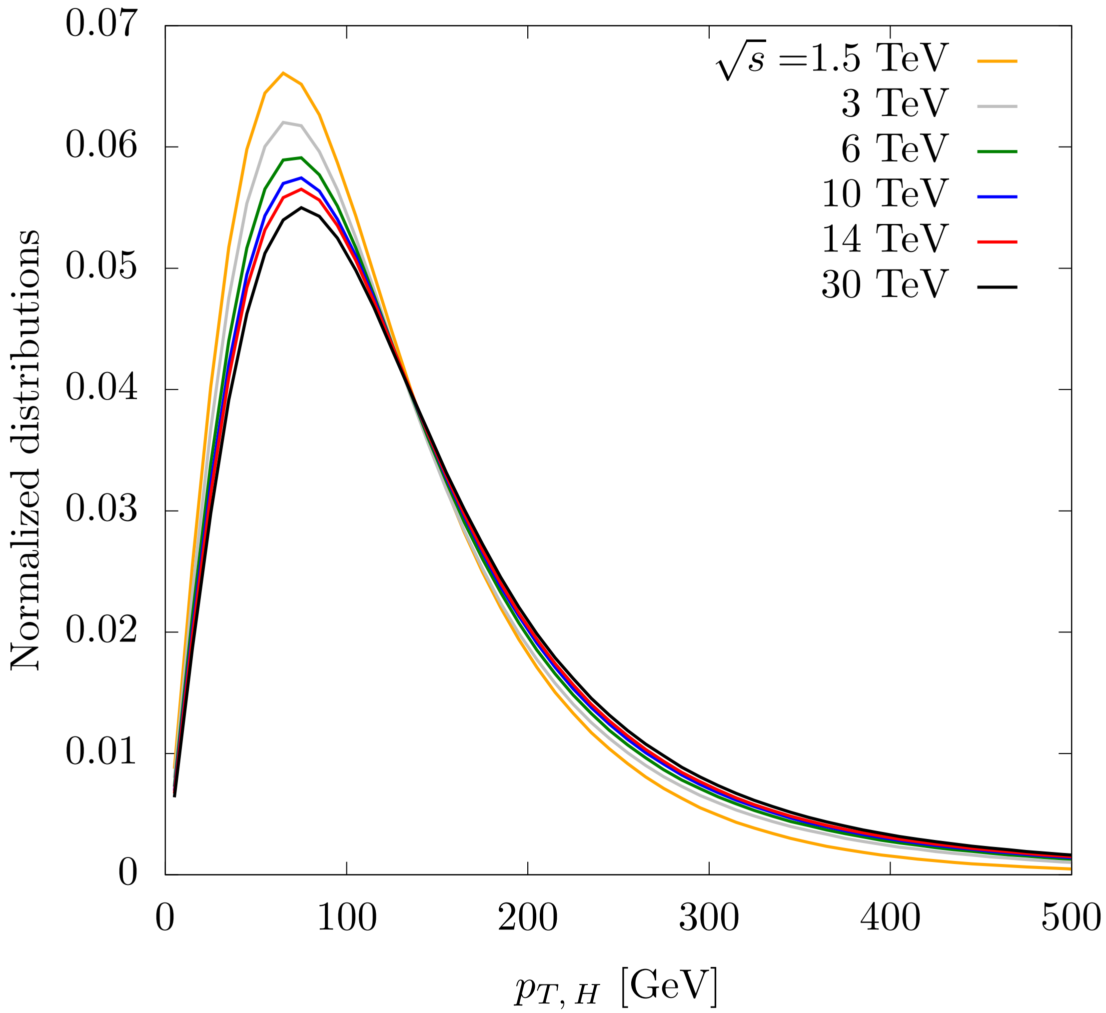
Production in forward region at high energy!

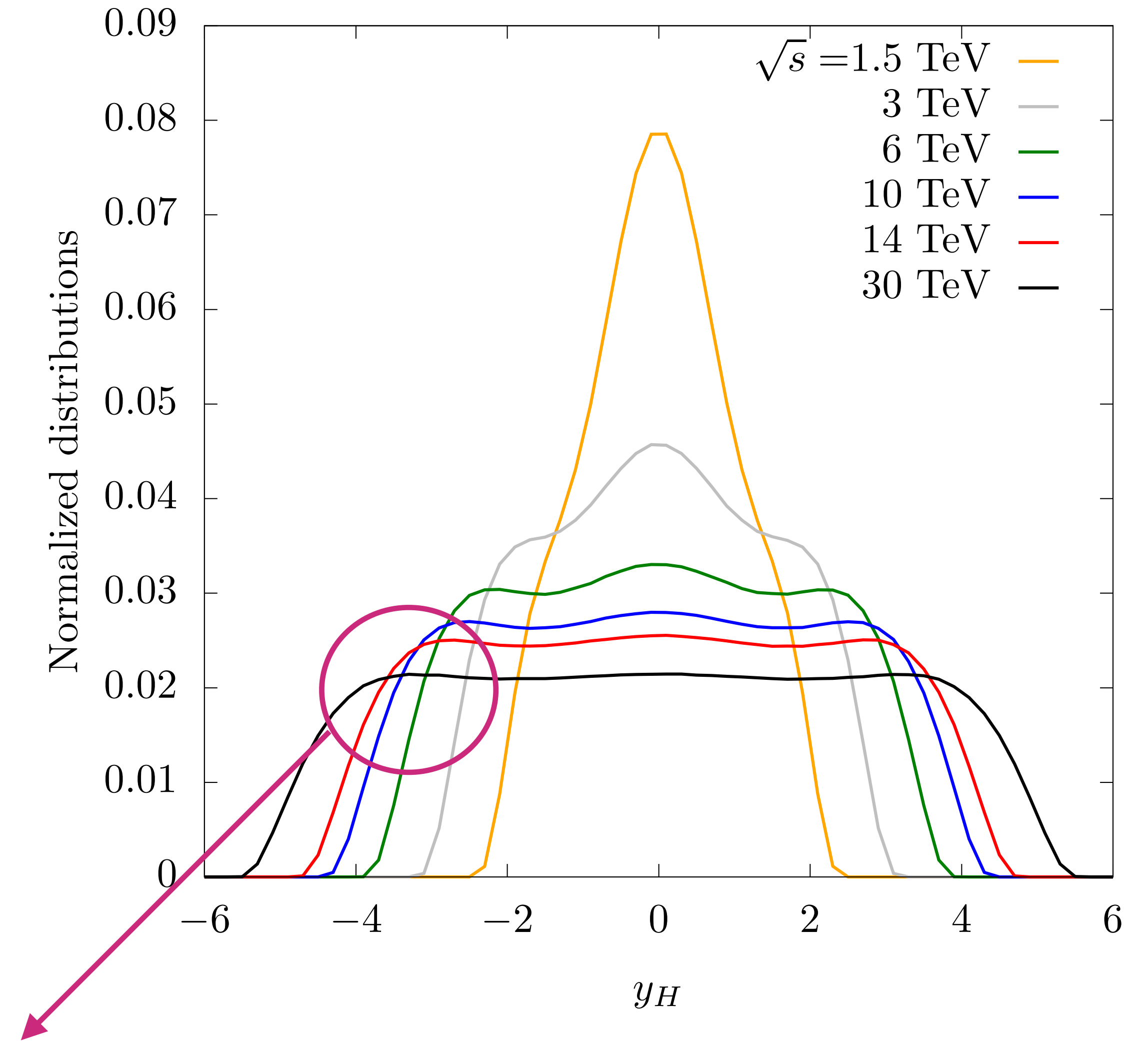




Production in forward region at high energy!

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





Production in forward region at high energy!

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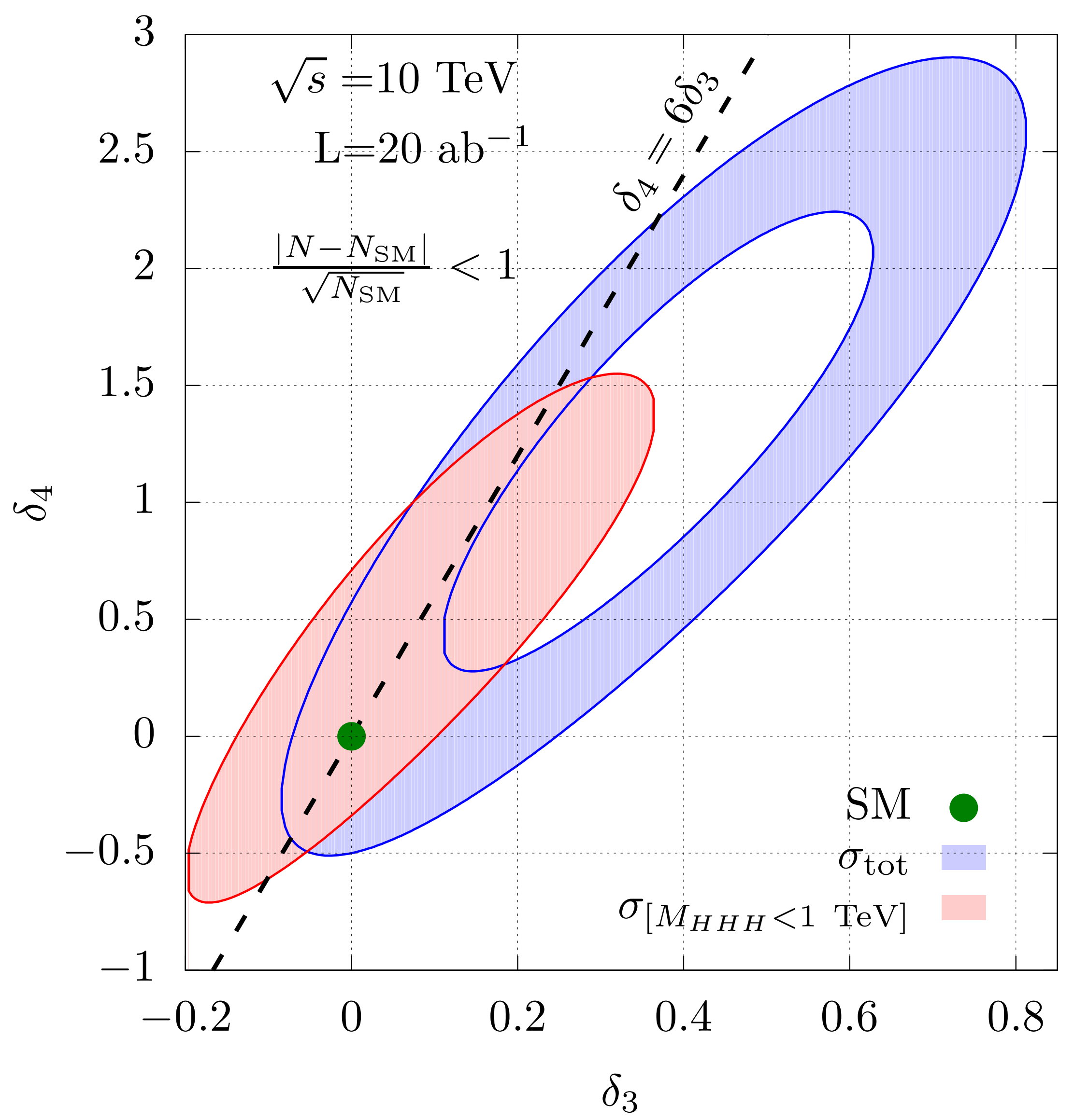
$$|\eta| < 5$$

Important to have high rapidity coverage

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

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

$$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L} \cdot (\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L} \cdot \sigma_{SM}}} \leq 1$$



$$10\,\text{TeV} \quad \delta_4 \sim [-0.4, 0.7]$$

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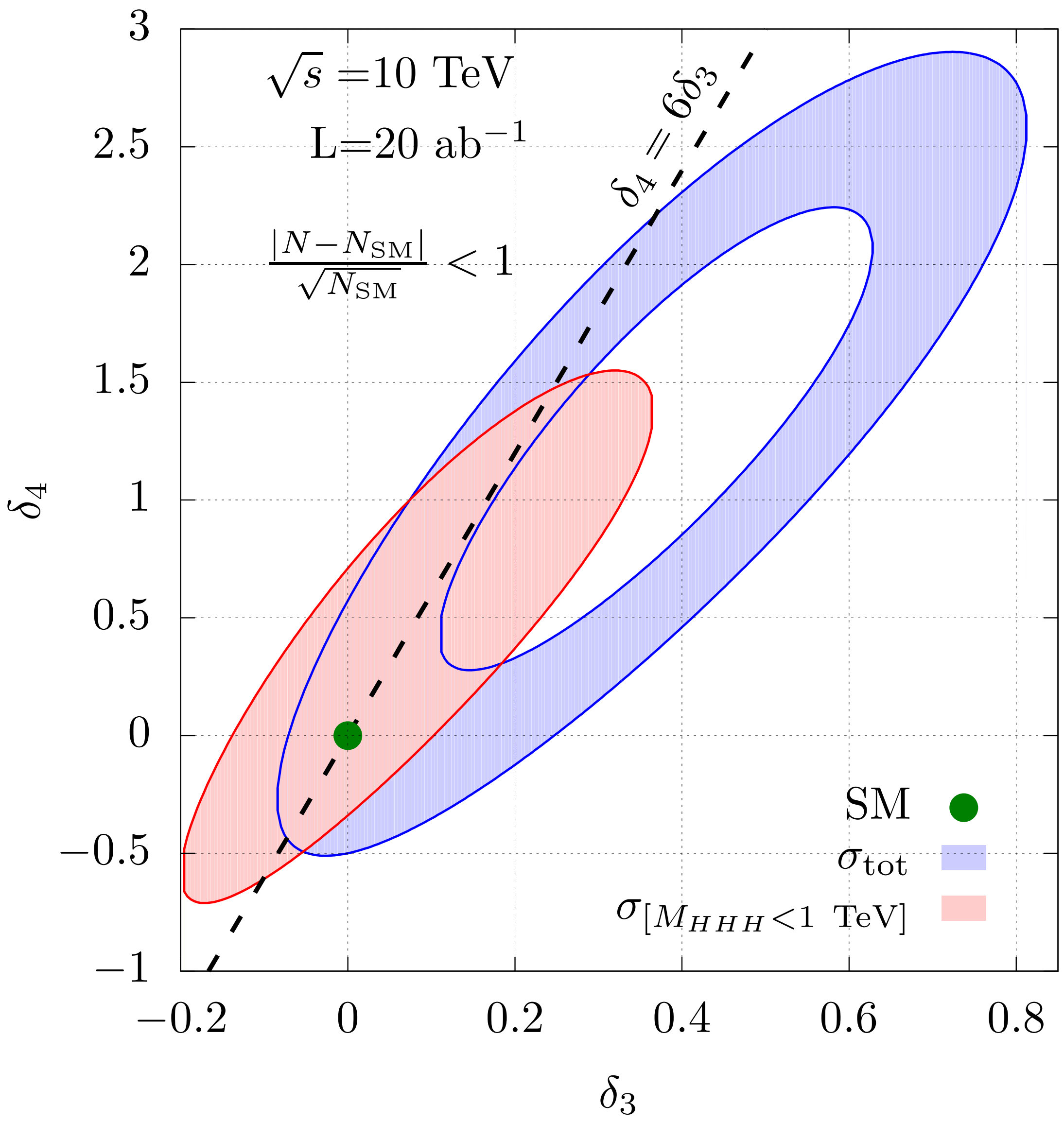
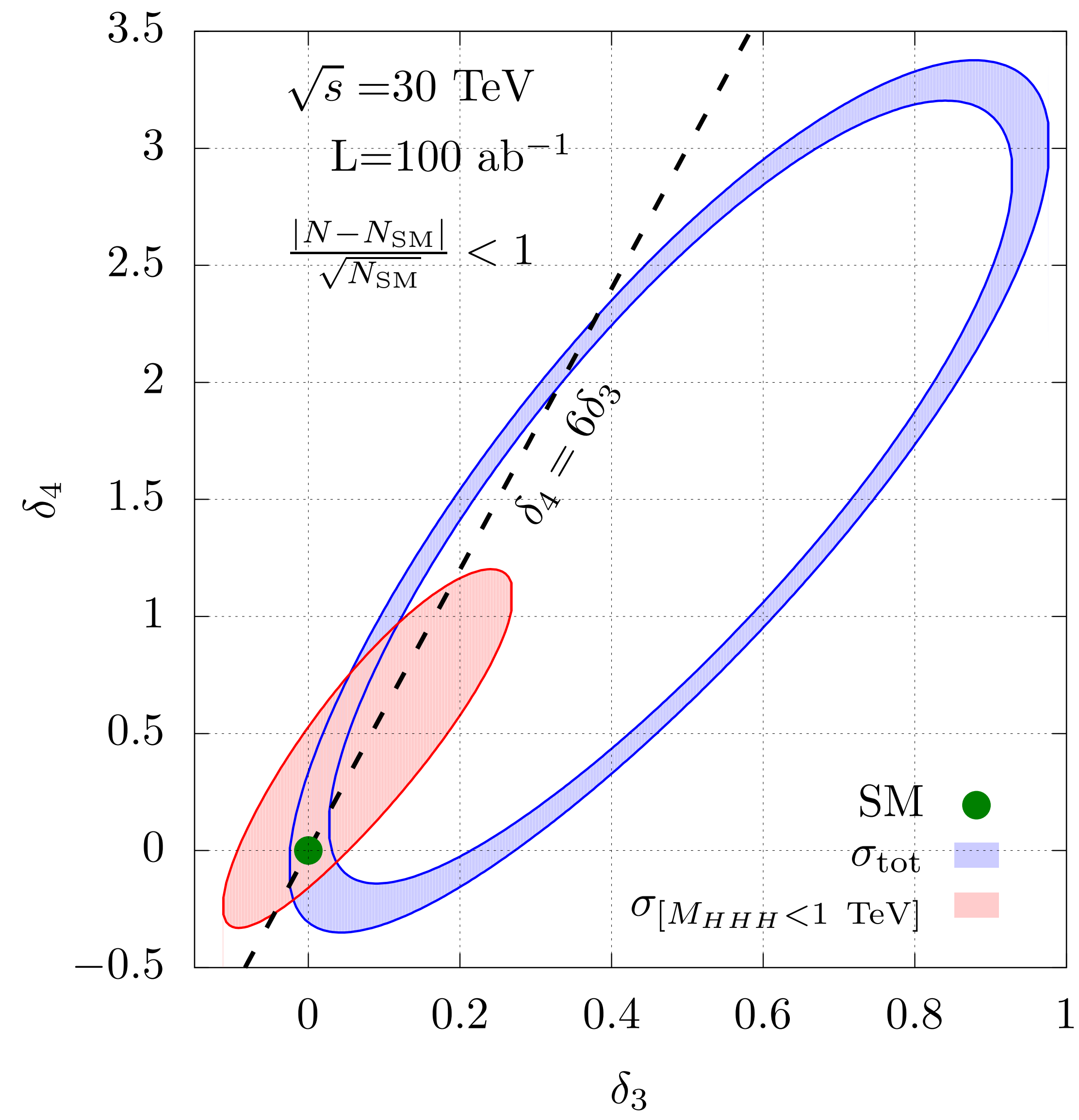
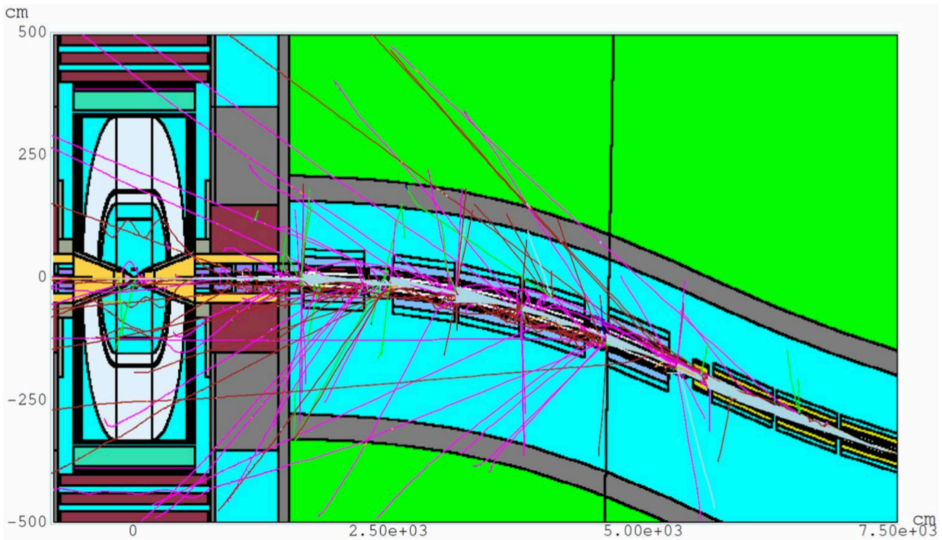




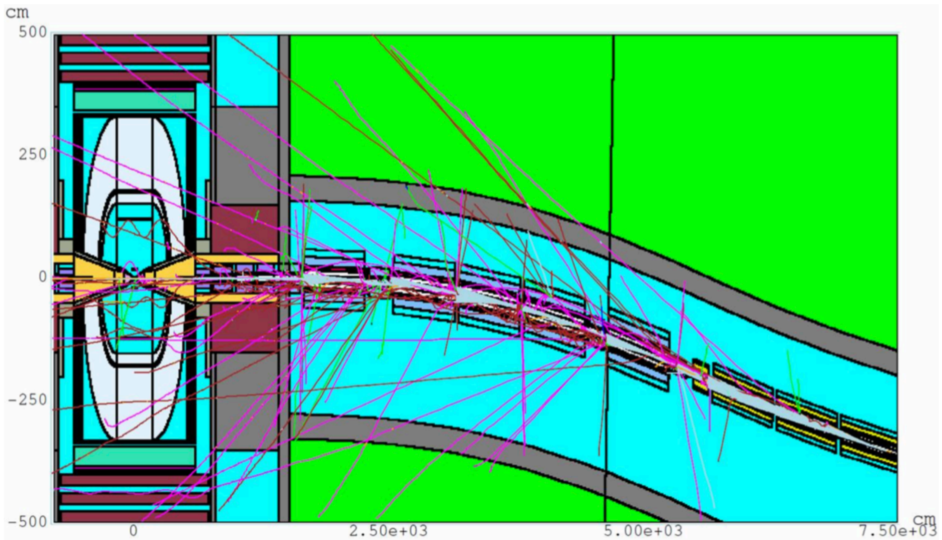
10 TeV $\quad \delta_4 \sim [-0.4, 0.7]$

30 TeV $\quad \delta_4 \sim [-0.2, 0.5]$



Nozzles:
Detector must be shielded from beam radiation

5-10 degrees blind spot at 3 TeV



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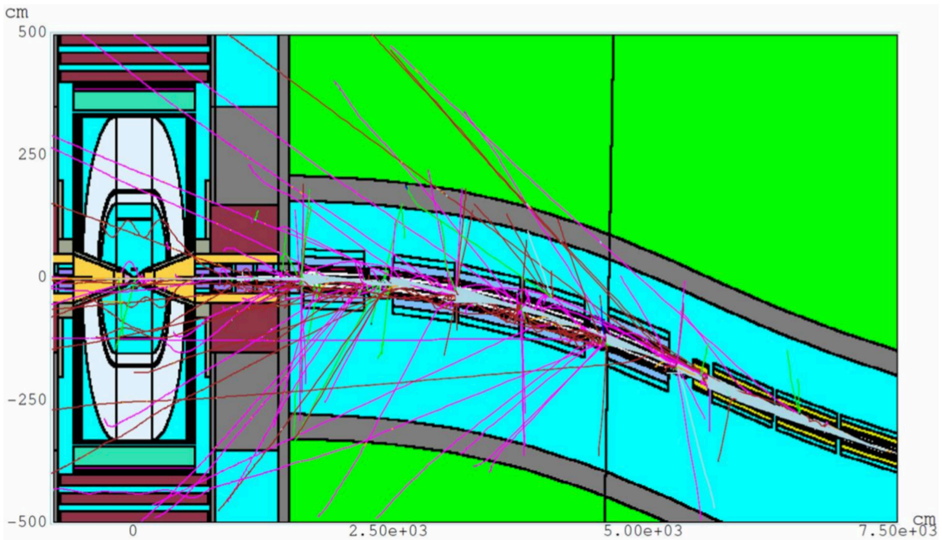
At higher energies the angle can be reduced!



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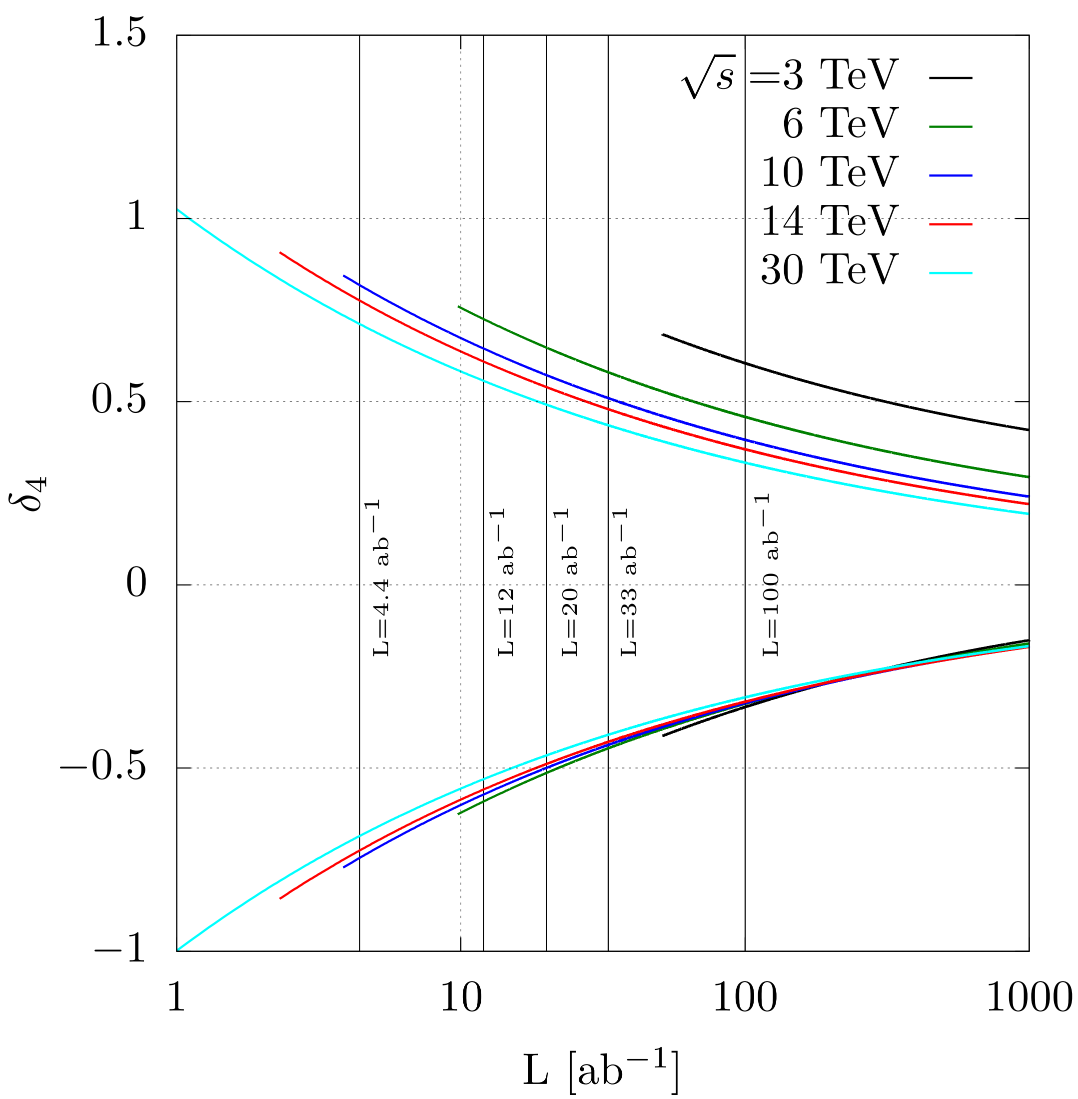

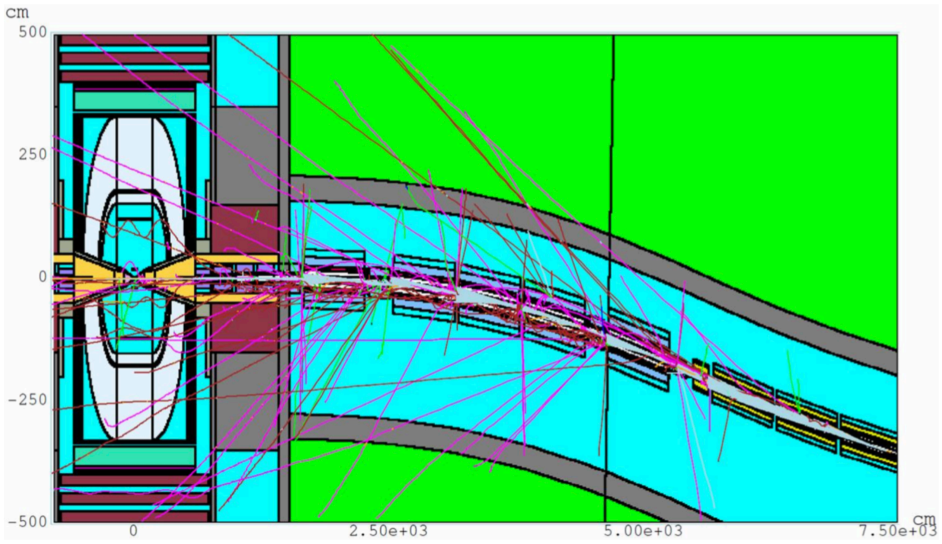

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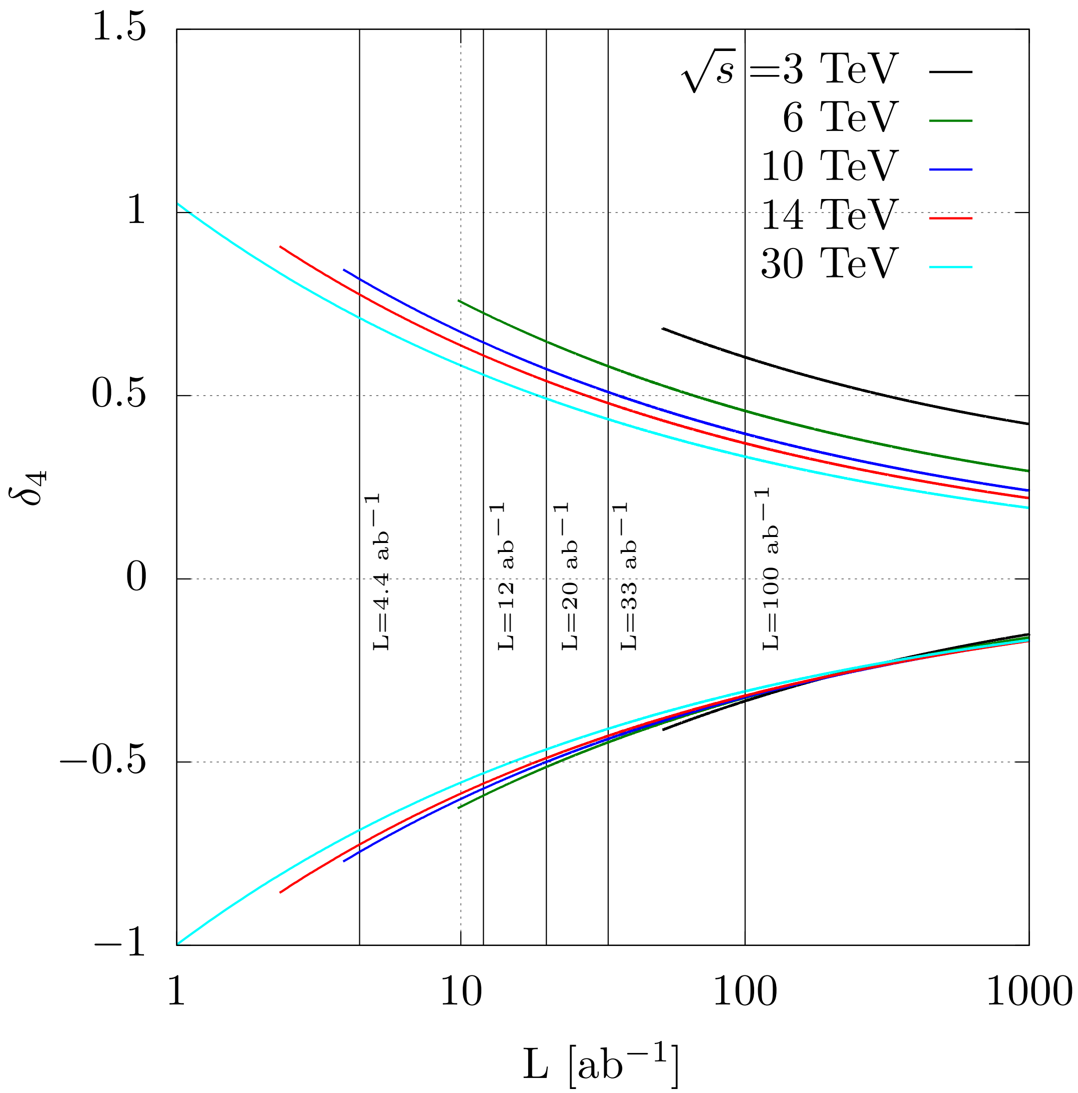

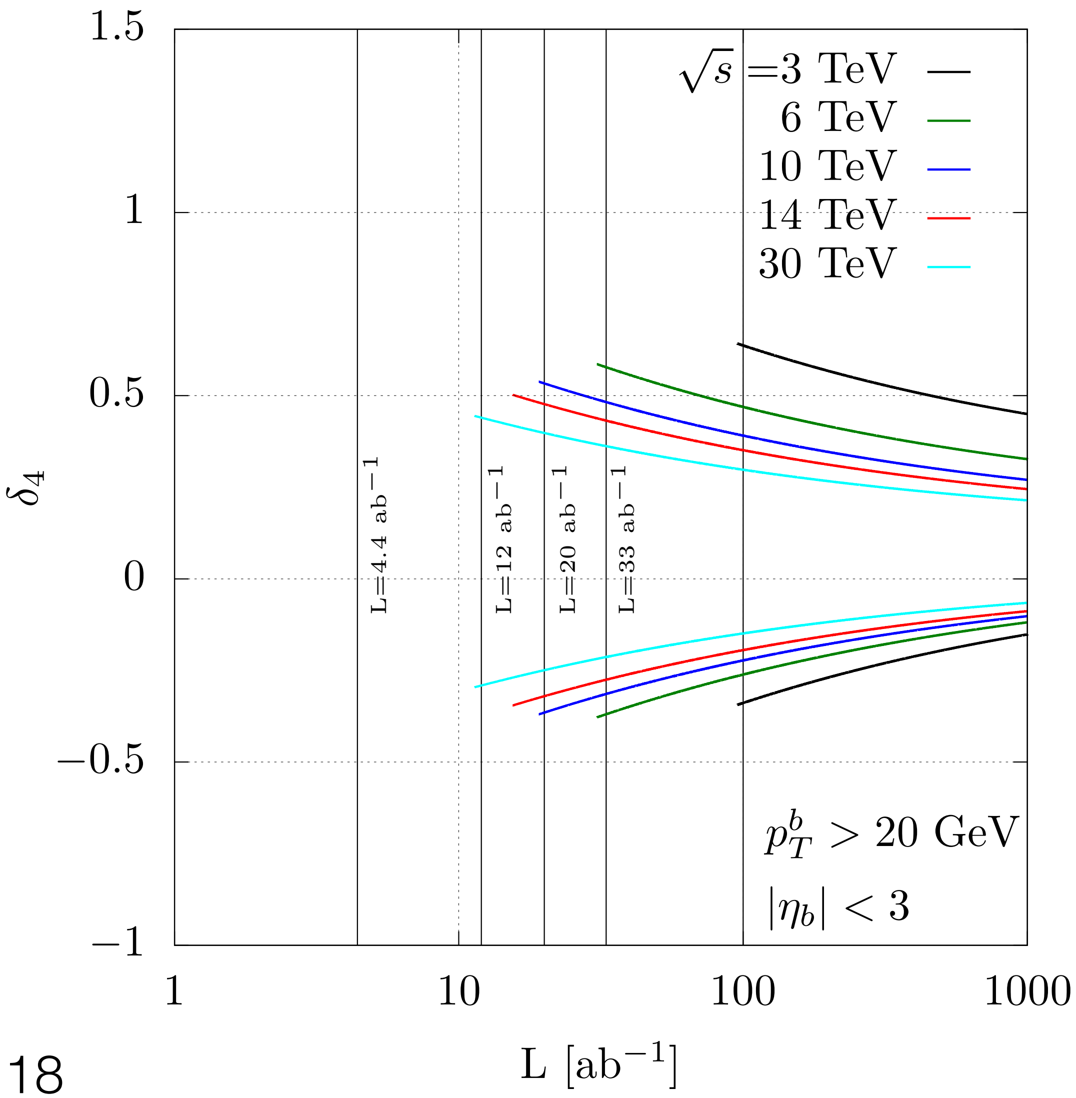

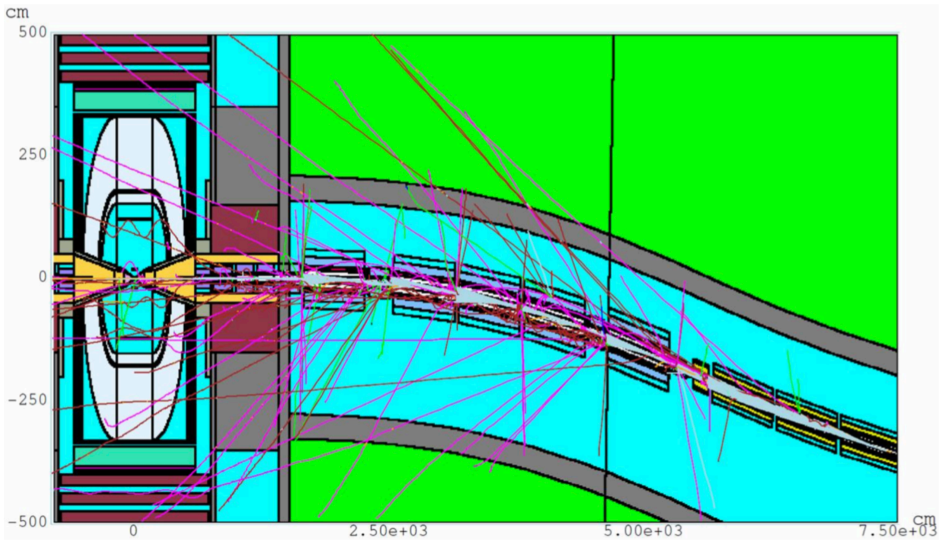

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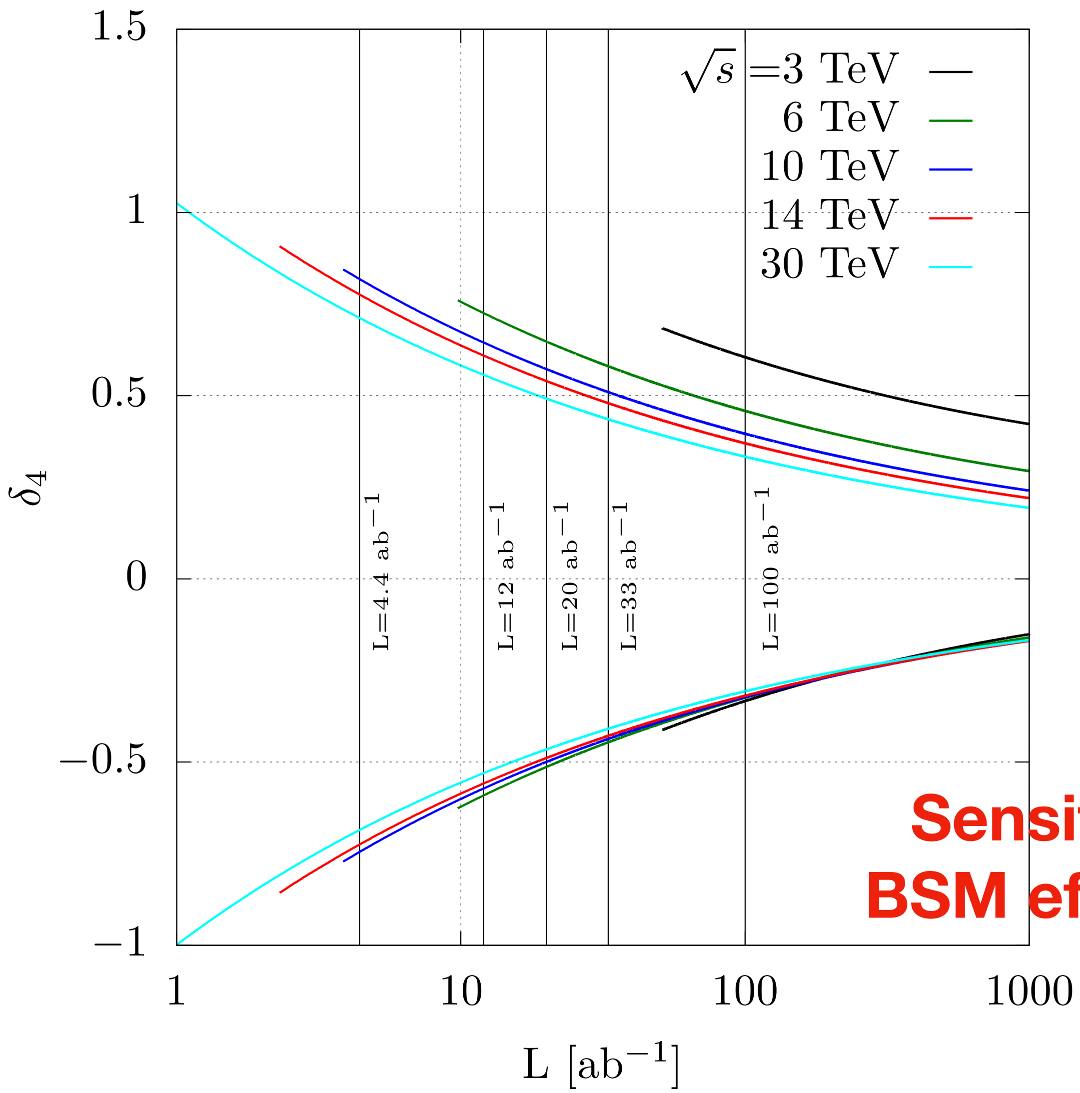

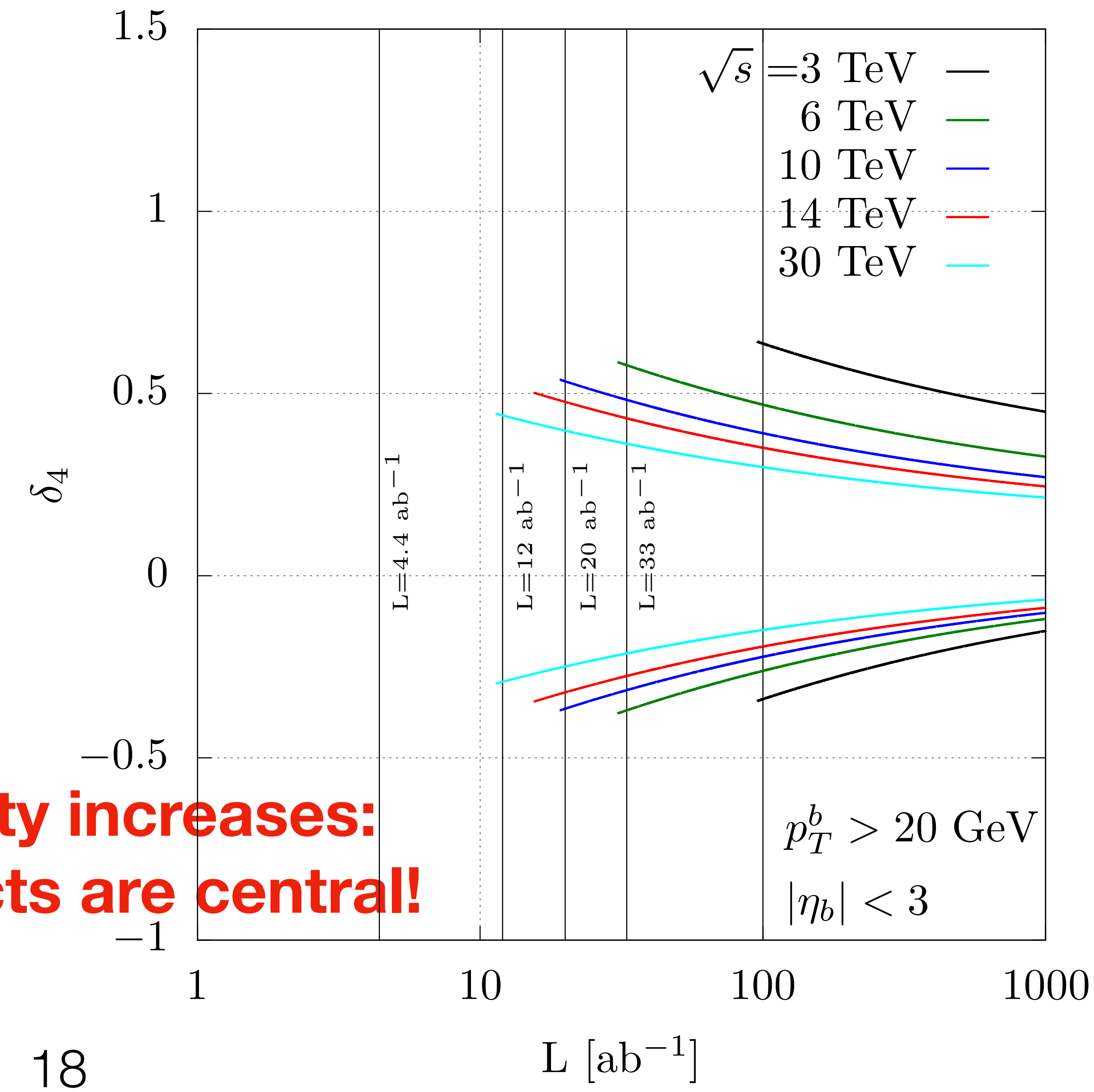

Sensitivity increases:
BSM effects are central!

- 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
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Thanks!

Backup

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

	σ [fb]	$\sqrt{s}$ [TeV]		σ [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

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Effectively a EW boson collider!

Resonance production

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

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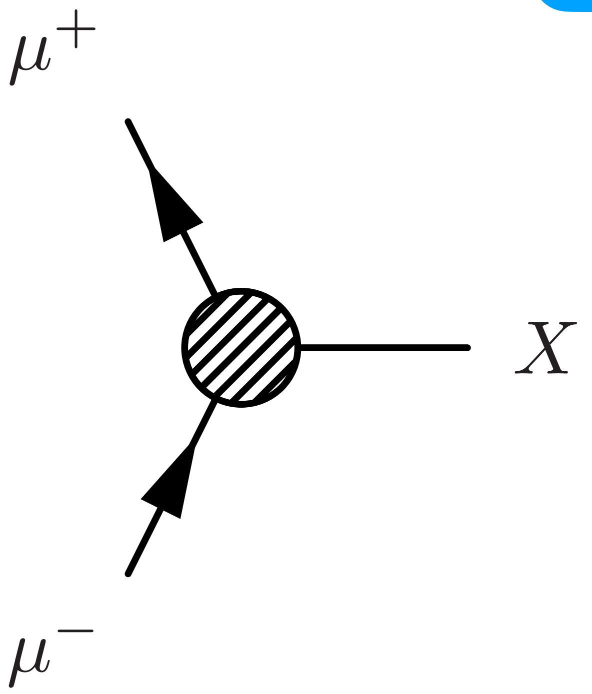

$$\sigma_\mu(s_\mu) = [\hat{\sigma}]_\mu$$

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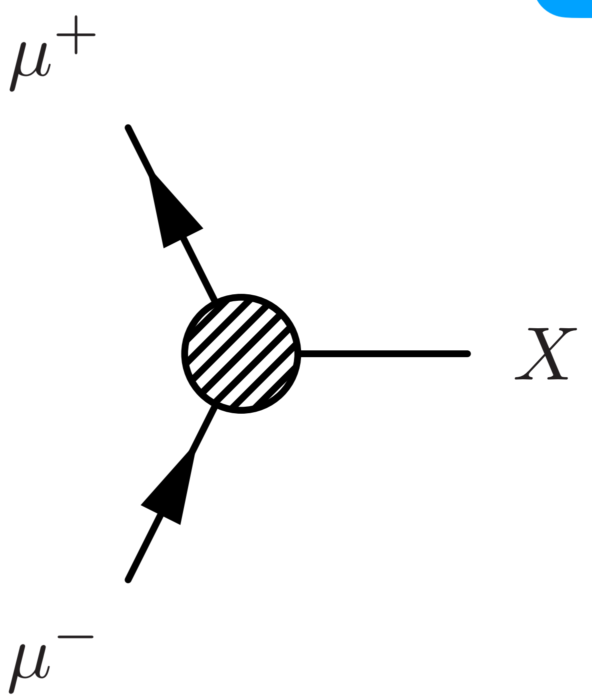
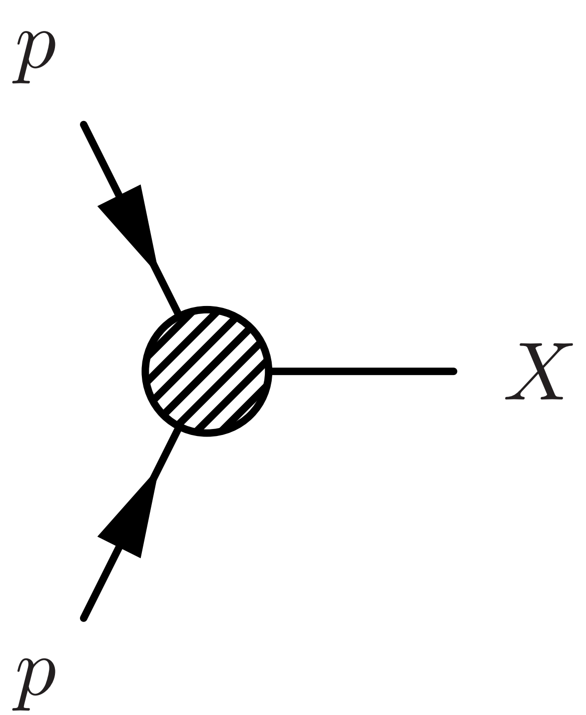


$$\sigma_\mu(s_\mu) = [\hat{\sigma}]_\mu$$

$$\sqrt{s_p}$$



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

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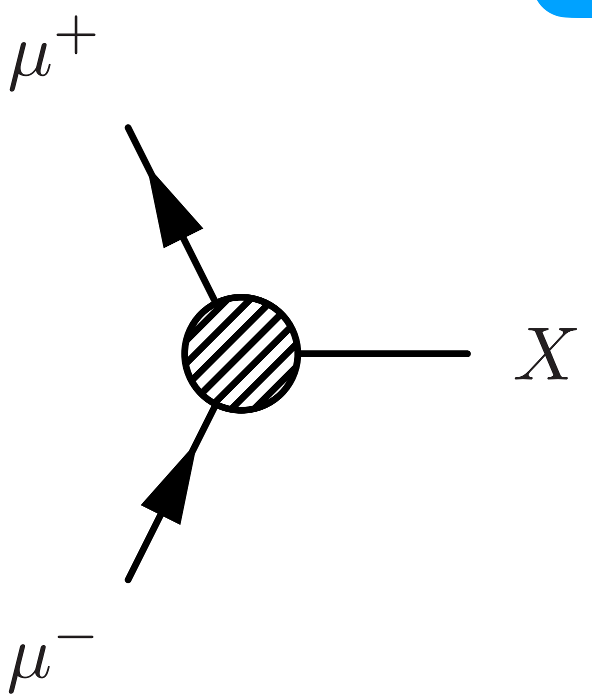

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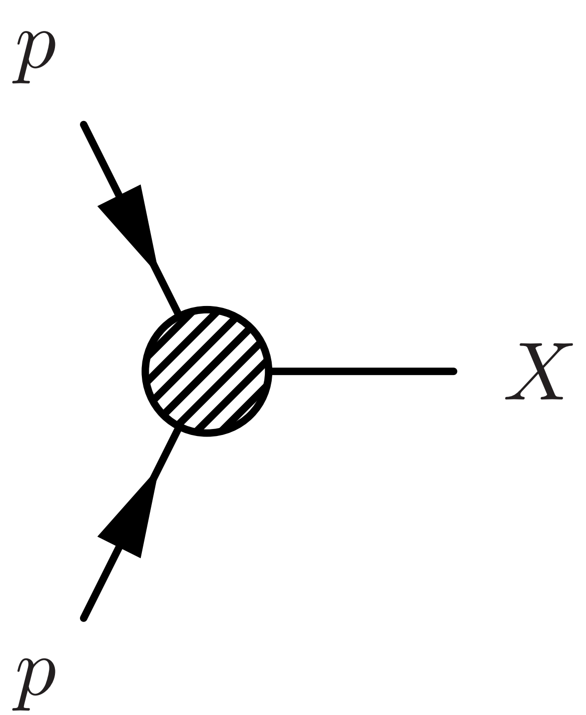

Parton lumi

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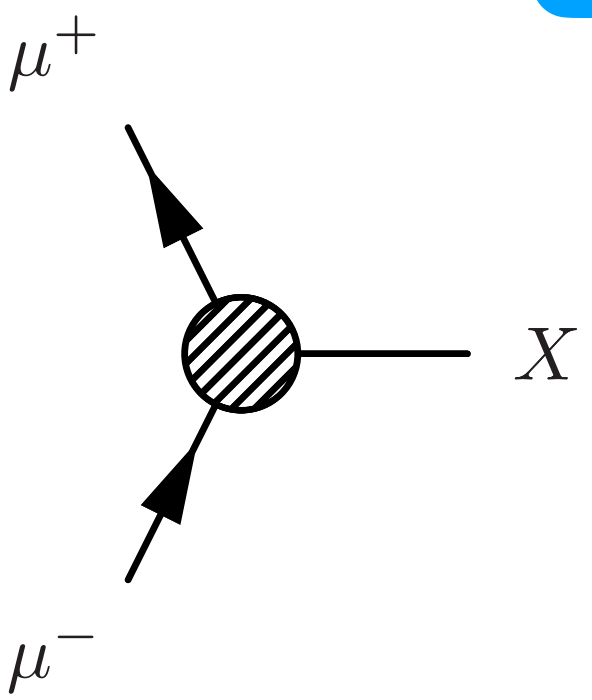

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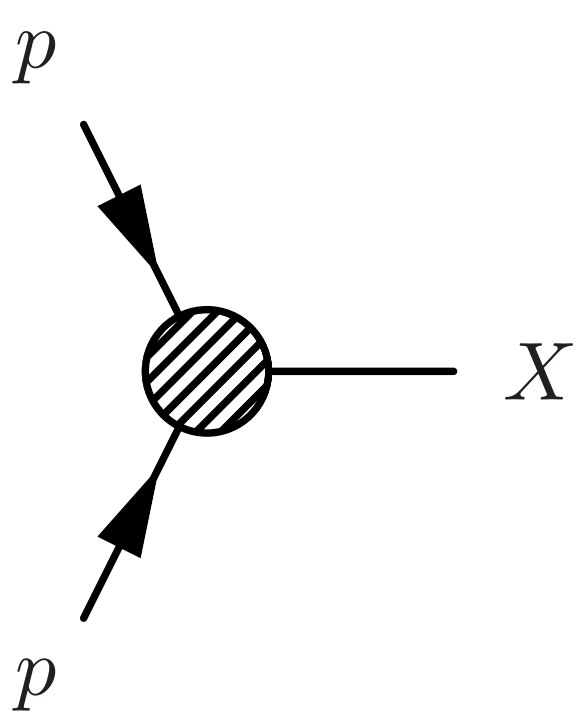

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Hard XS

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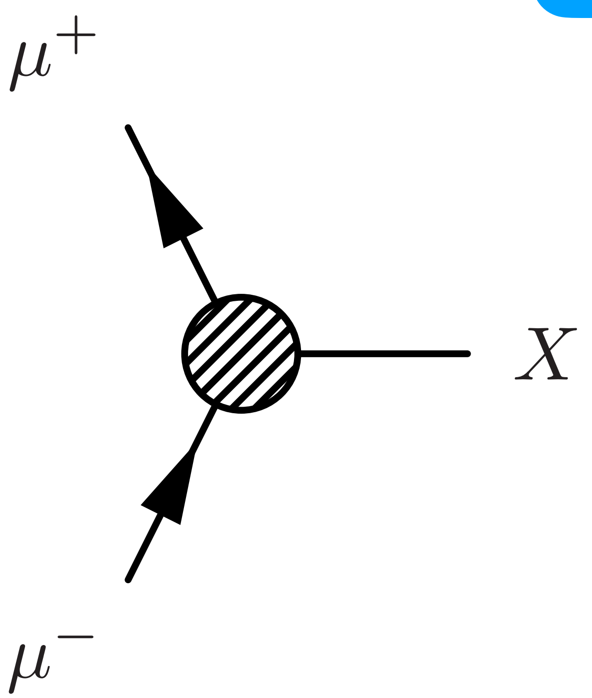

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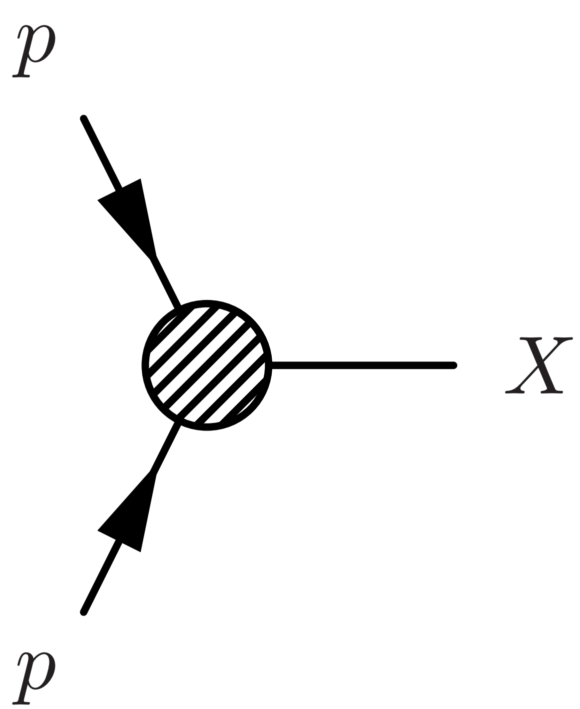

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Hard XS

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

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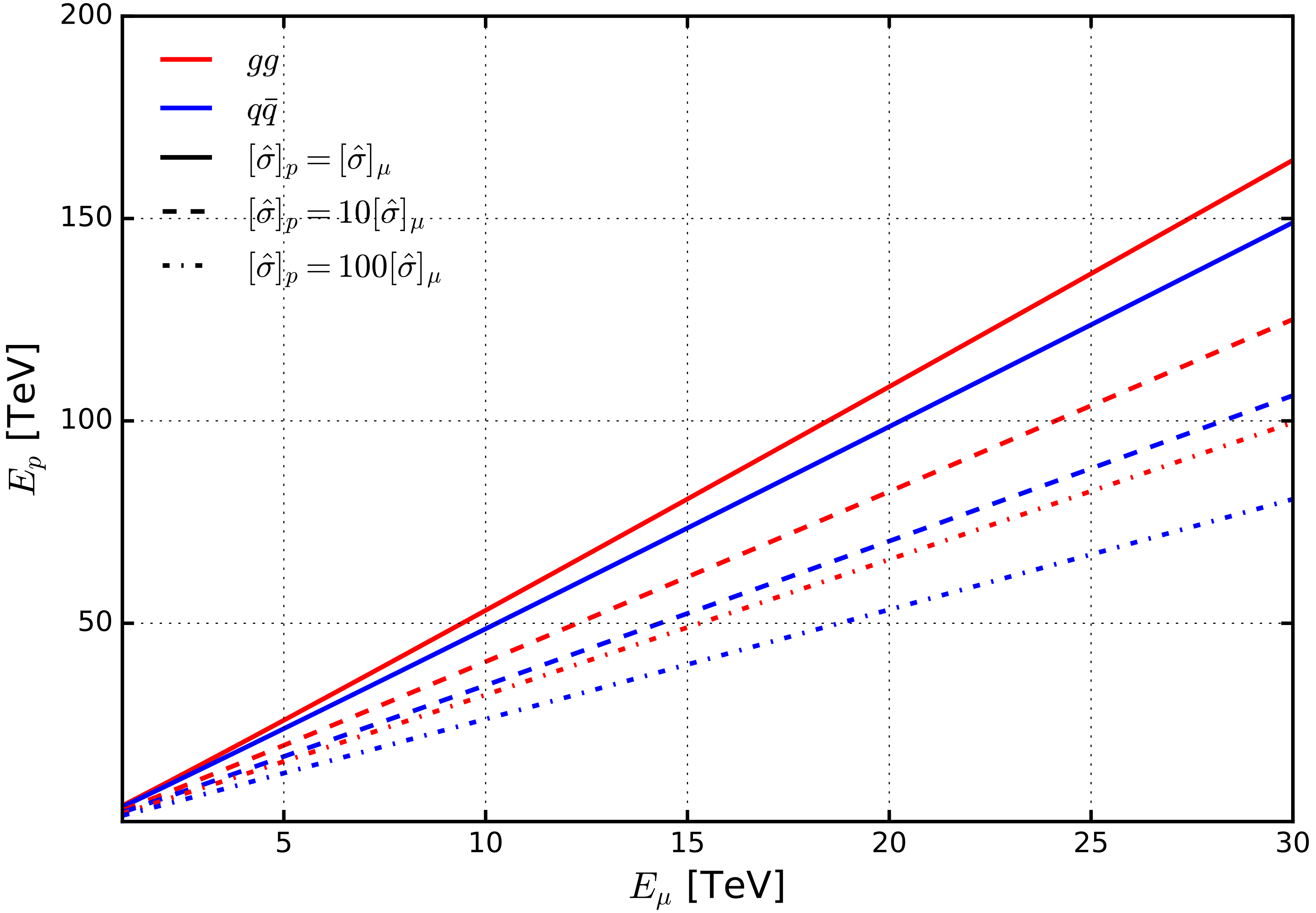

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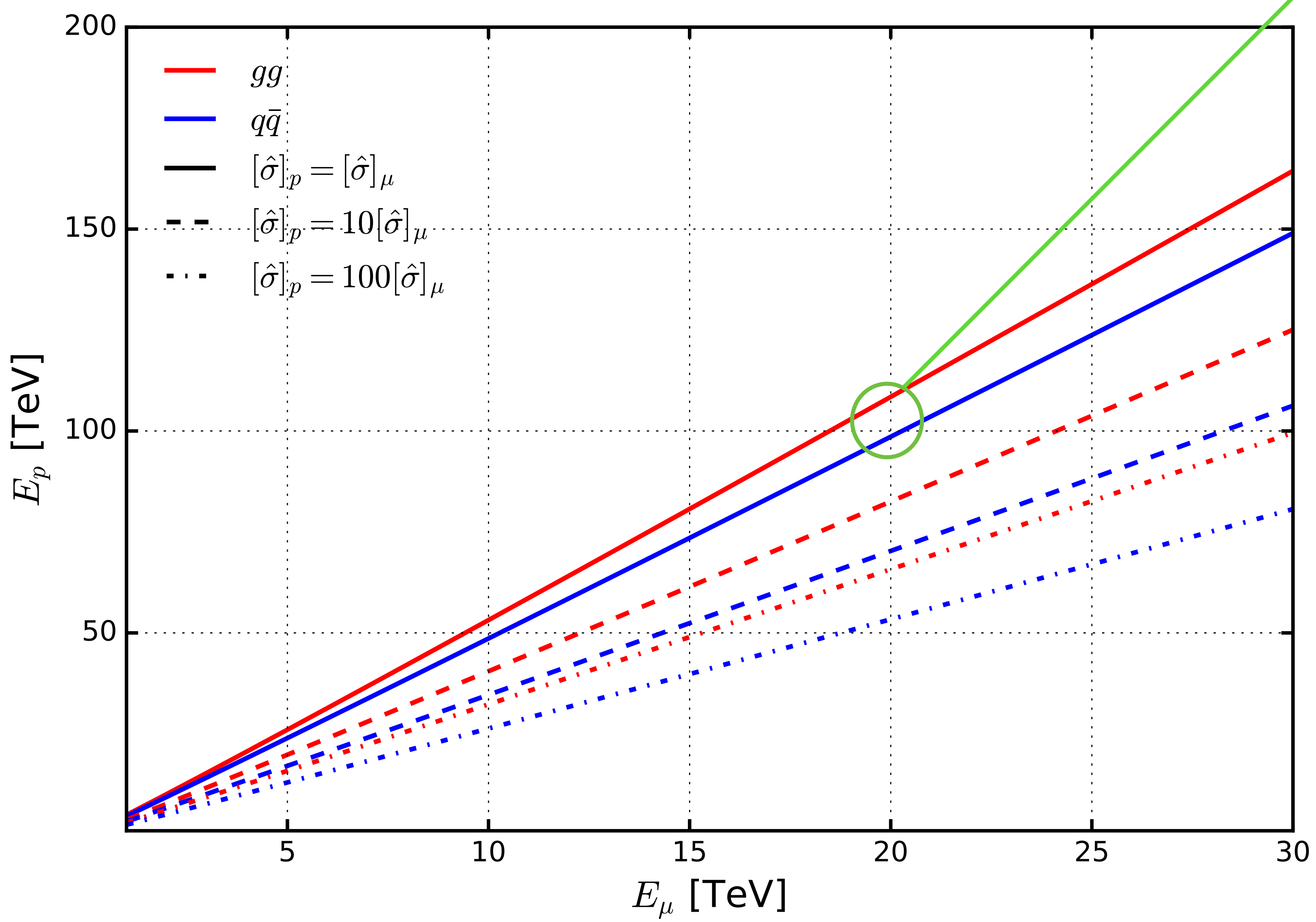
FCC comparable!



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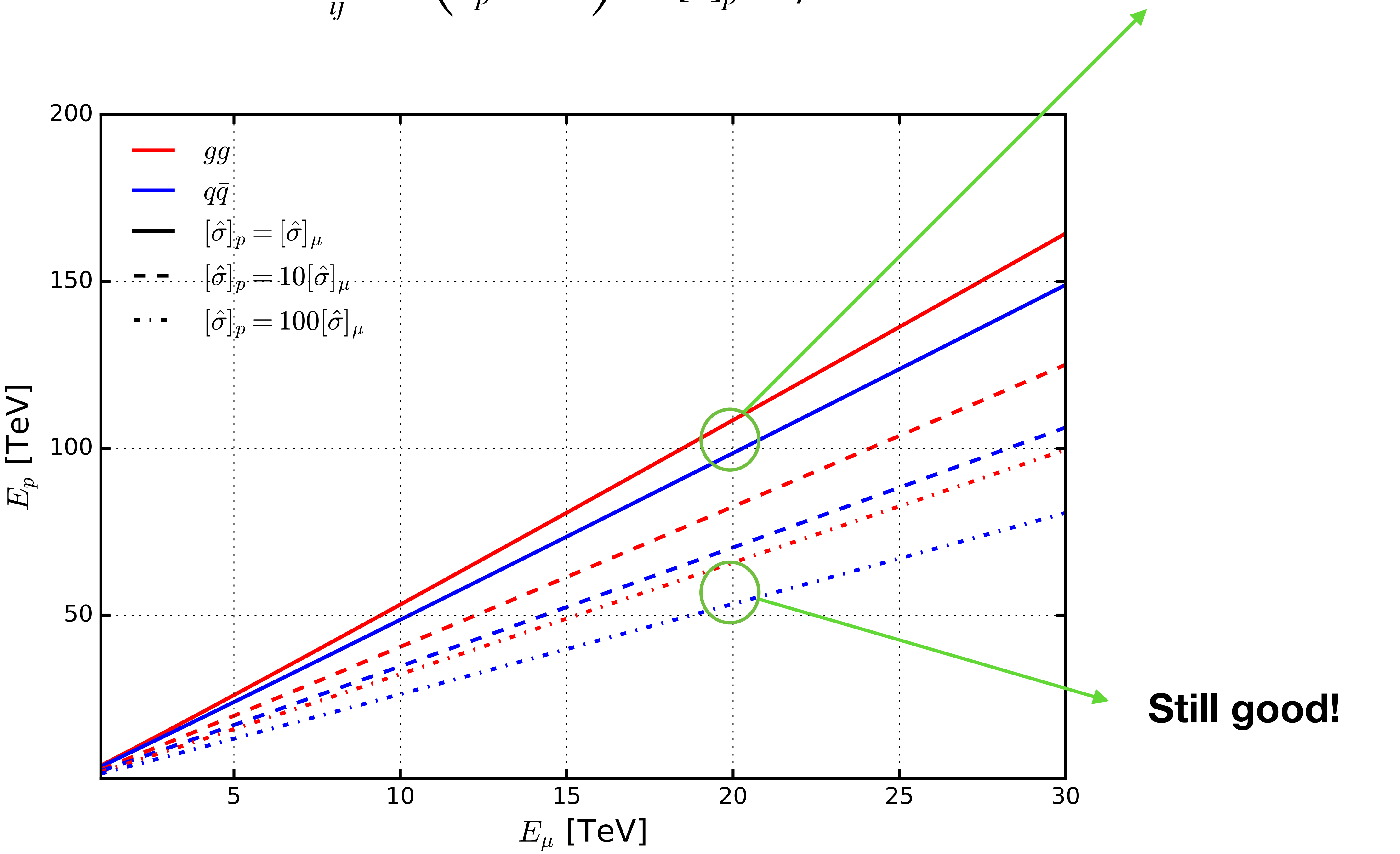
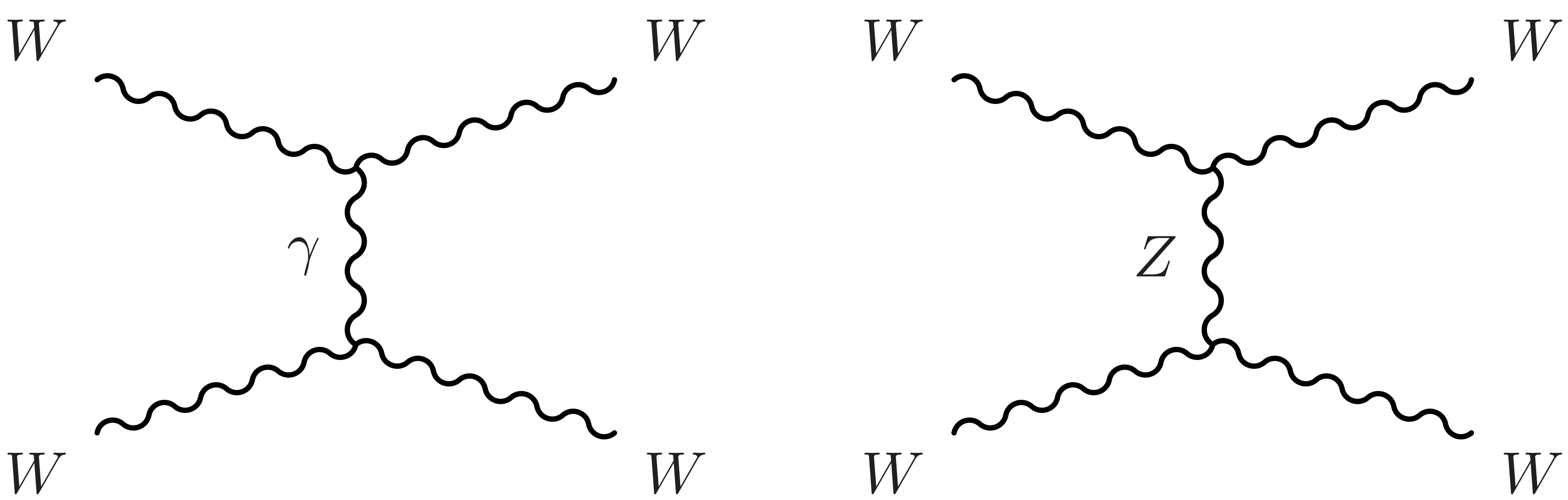


The most well-known example is longitudinal W-boson scattering

$$W_L W_L \to W_L W_L$$



$$\propto E^4$$

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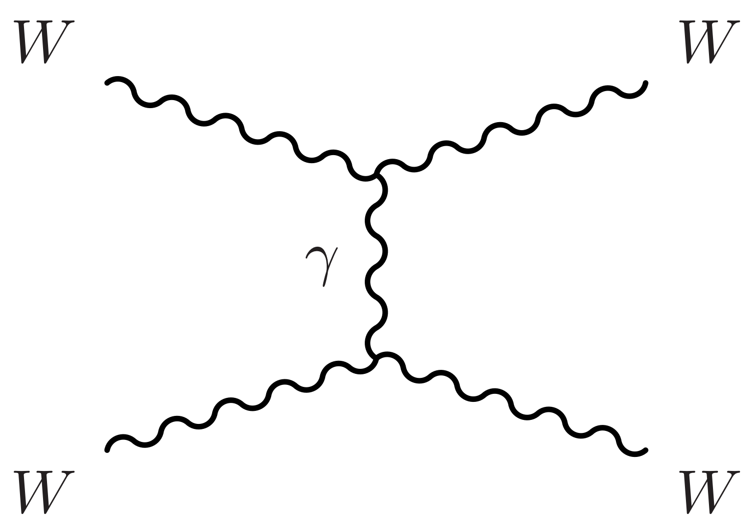
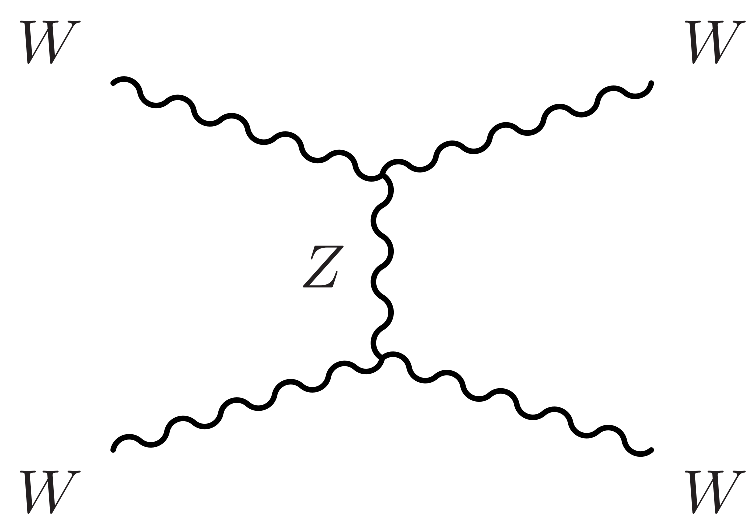
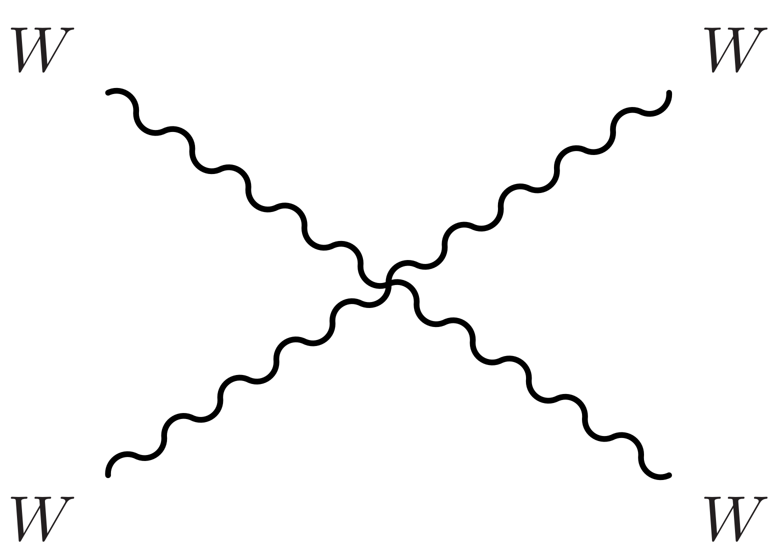




$$\propto E^2$$



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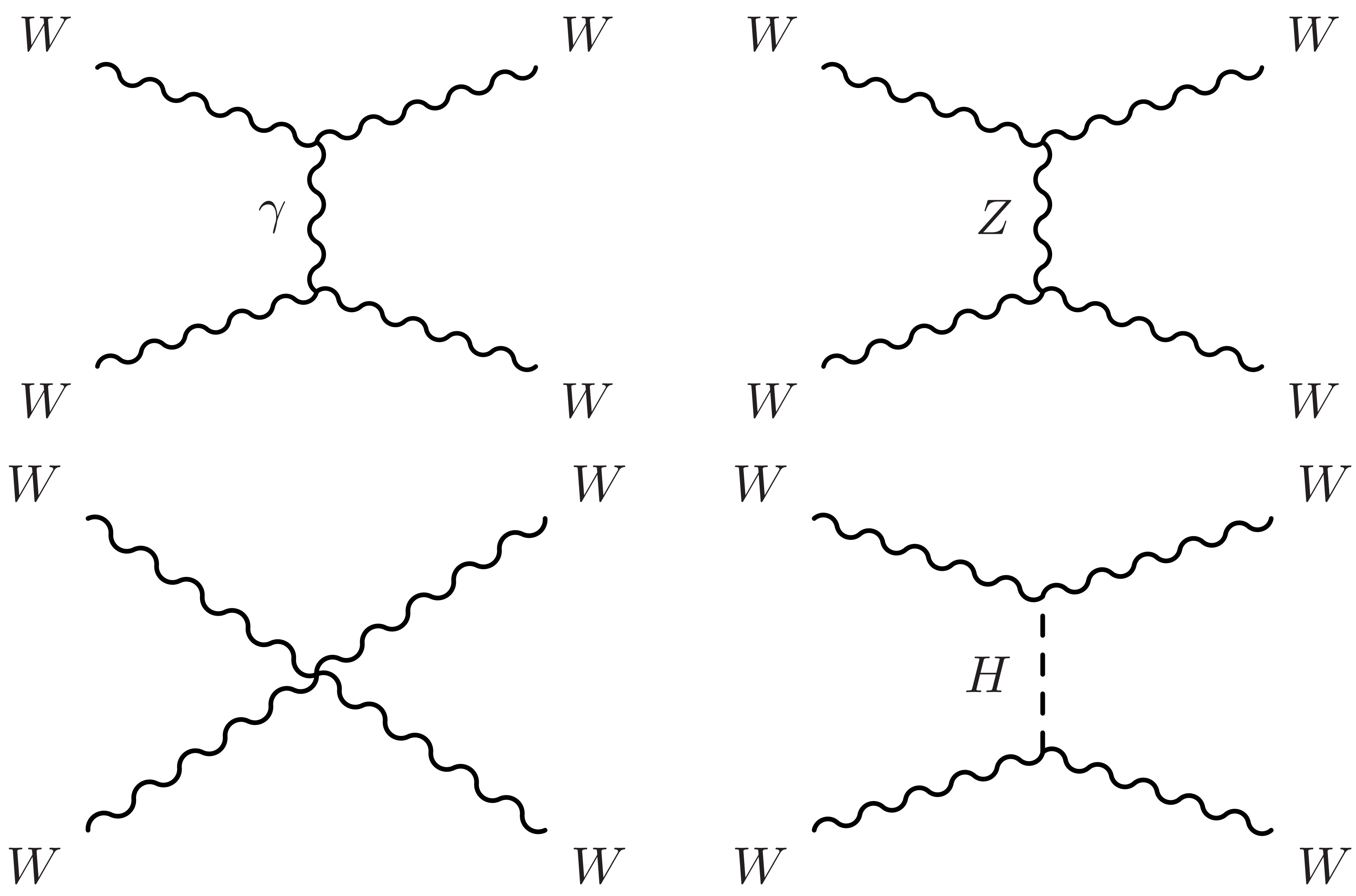

$$\propto E^0$$

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

- **Higher dimensional operators preserve SM symmetries.**
- **Mappable to a large class of BSM models.**
- **Warsaw basis truncated at dim 6.**

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Dim 6 operators introduce energy growing effects

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Not every operator generates energy growing effects!

Luca Mantani

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):

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[F. Maltoni et al. JHEP 10 (2019) 004

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Dim 6, 2 to 2

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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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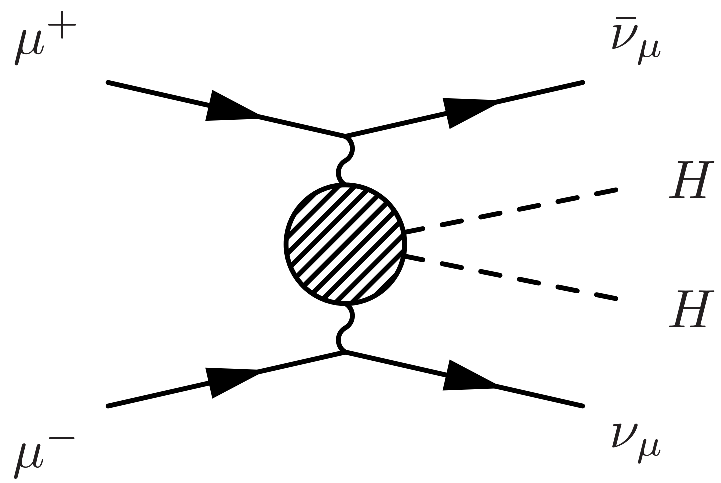
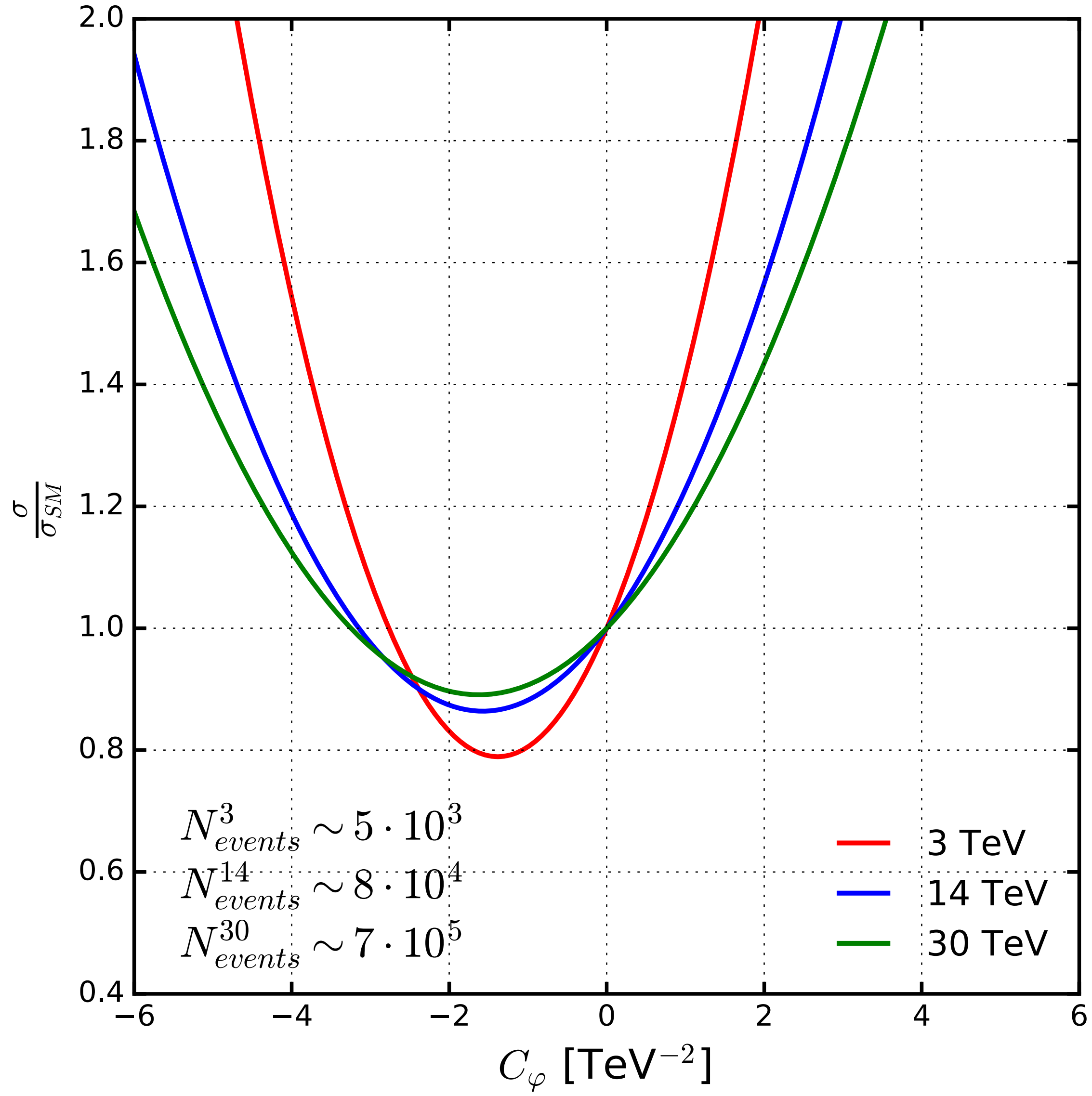
Sensitivity linear

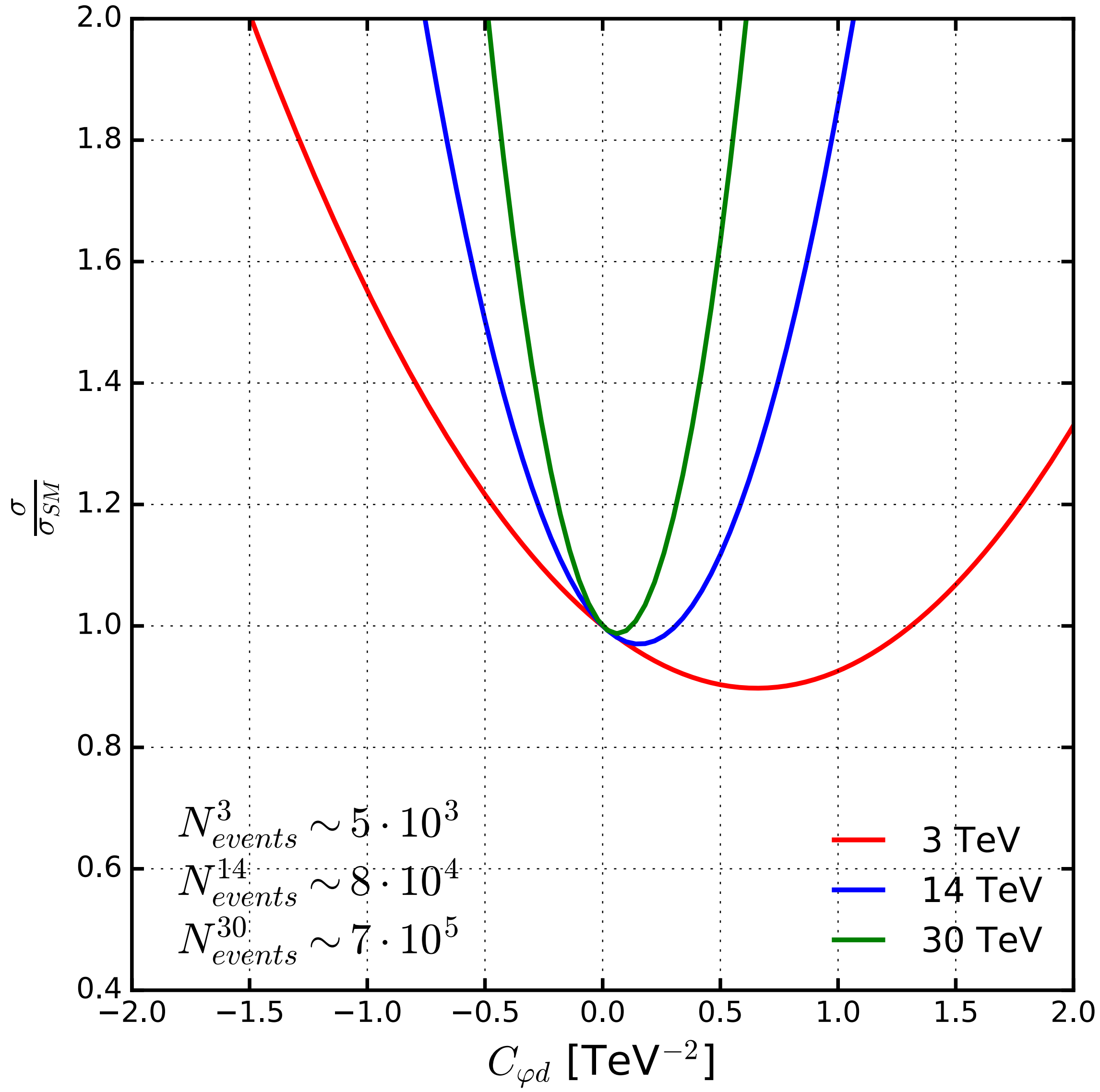
Sensitivity quadratic

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

HH production







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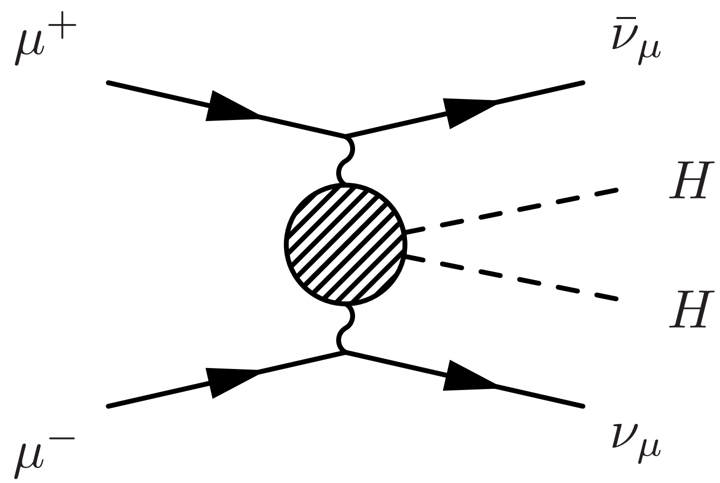

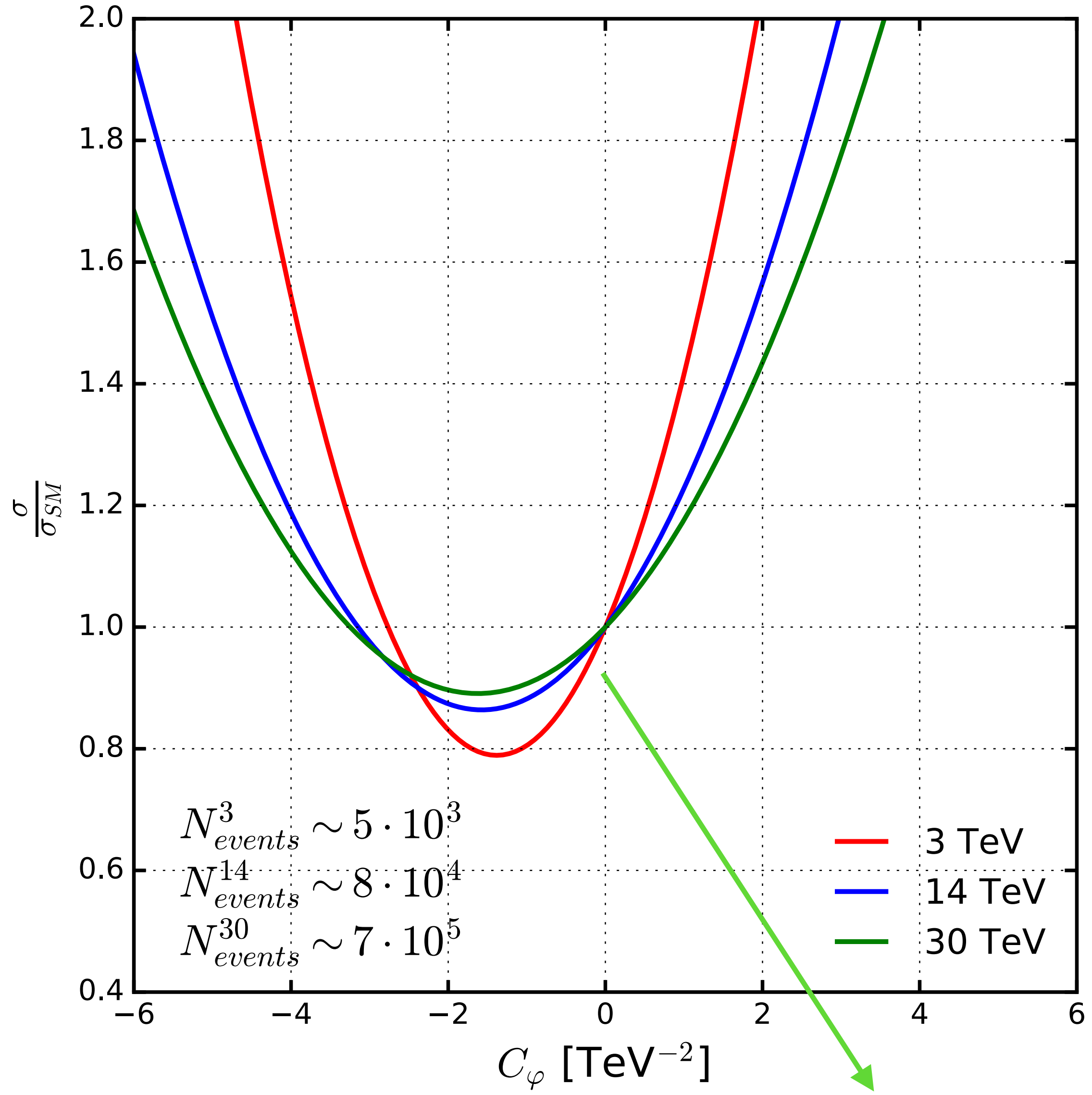

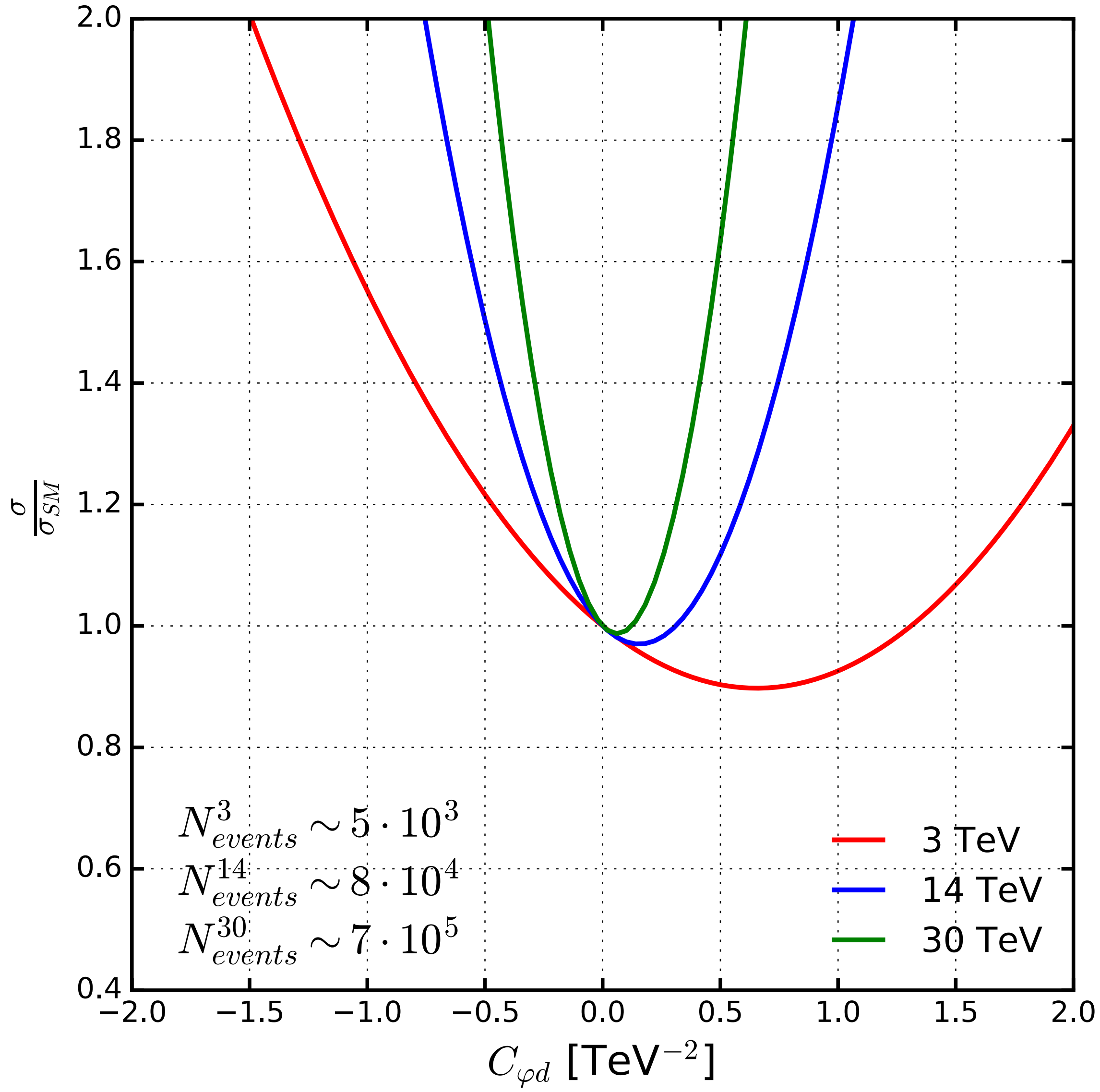

High energy not helping!

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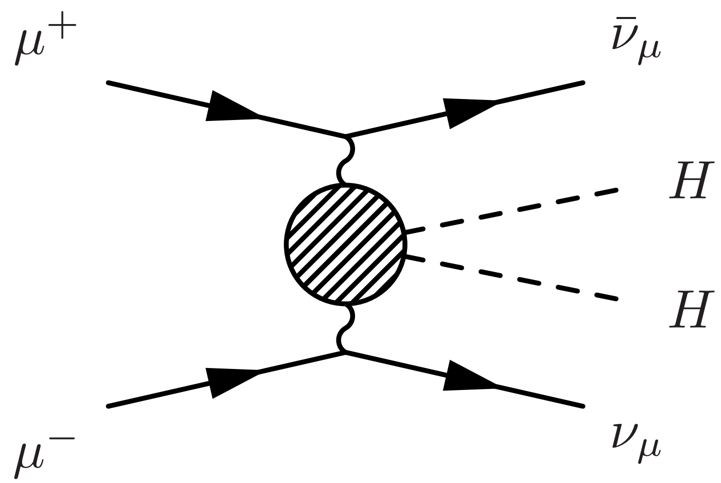

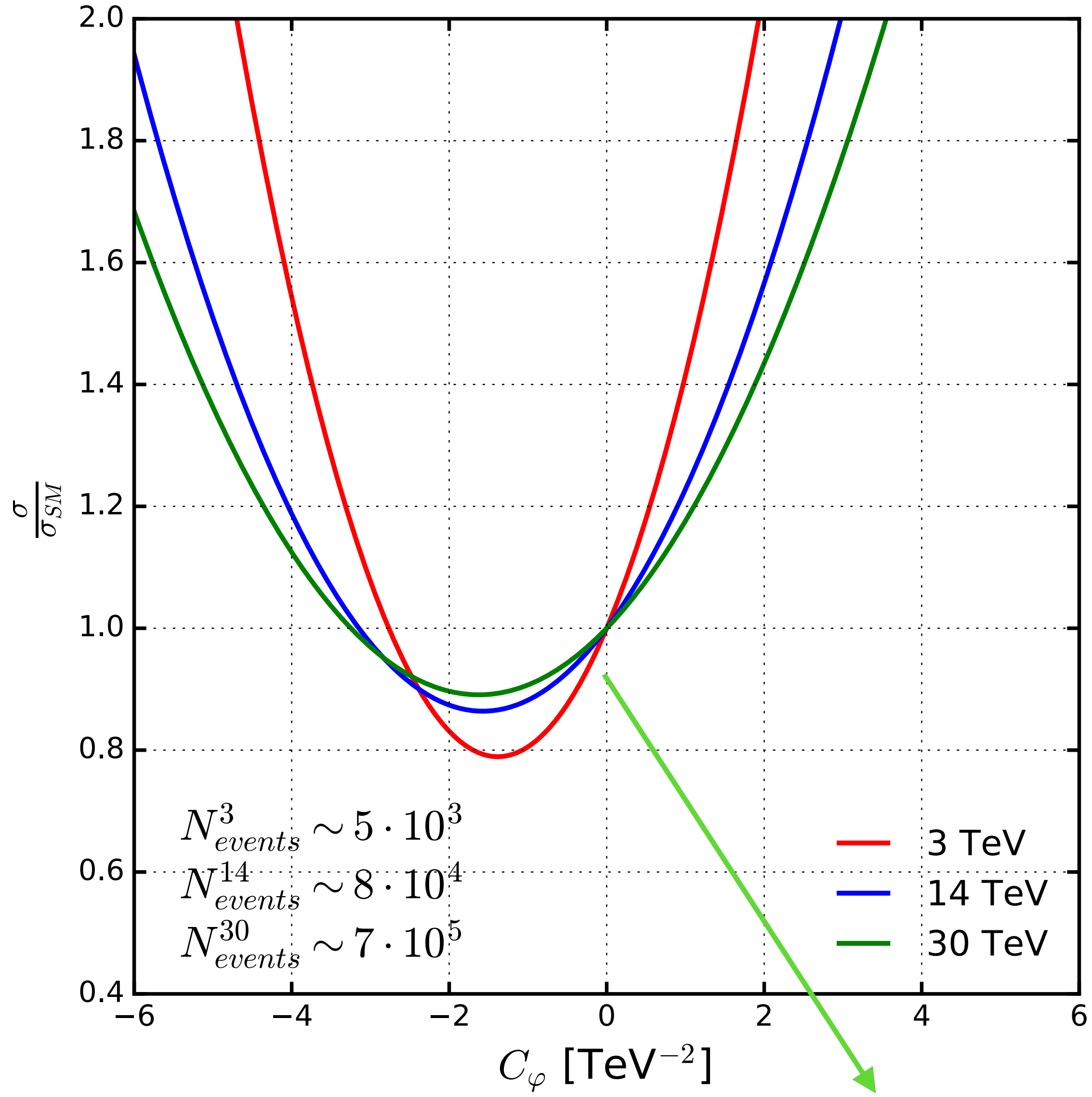

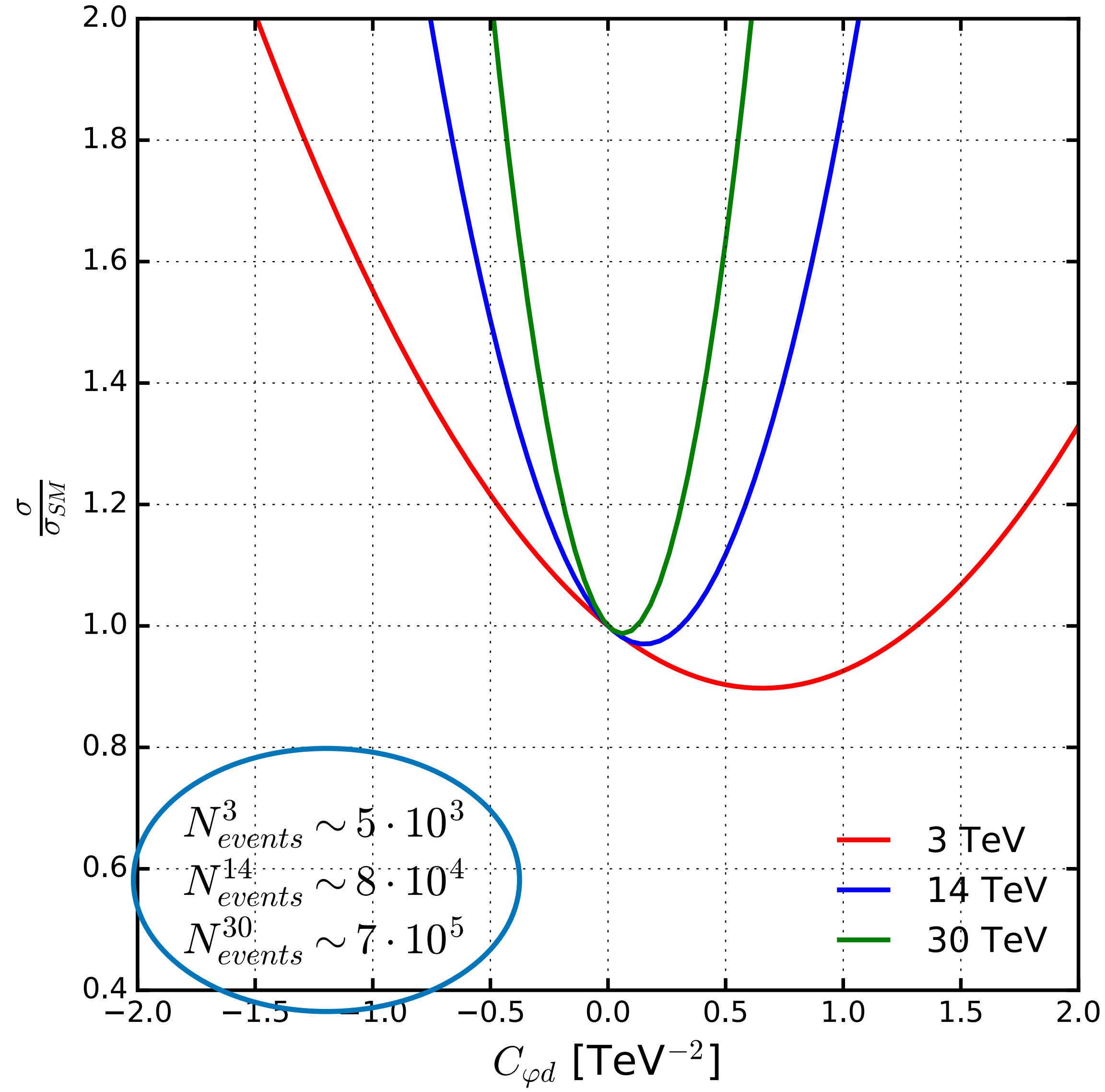

High energy not helping!

Many events!

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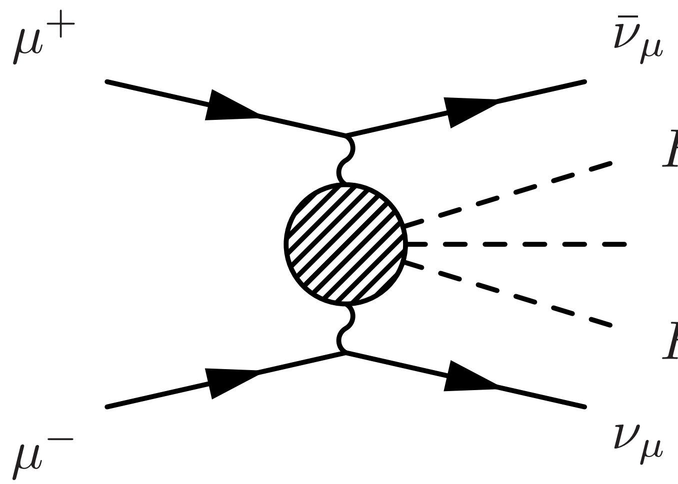
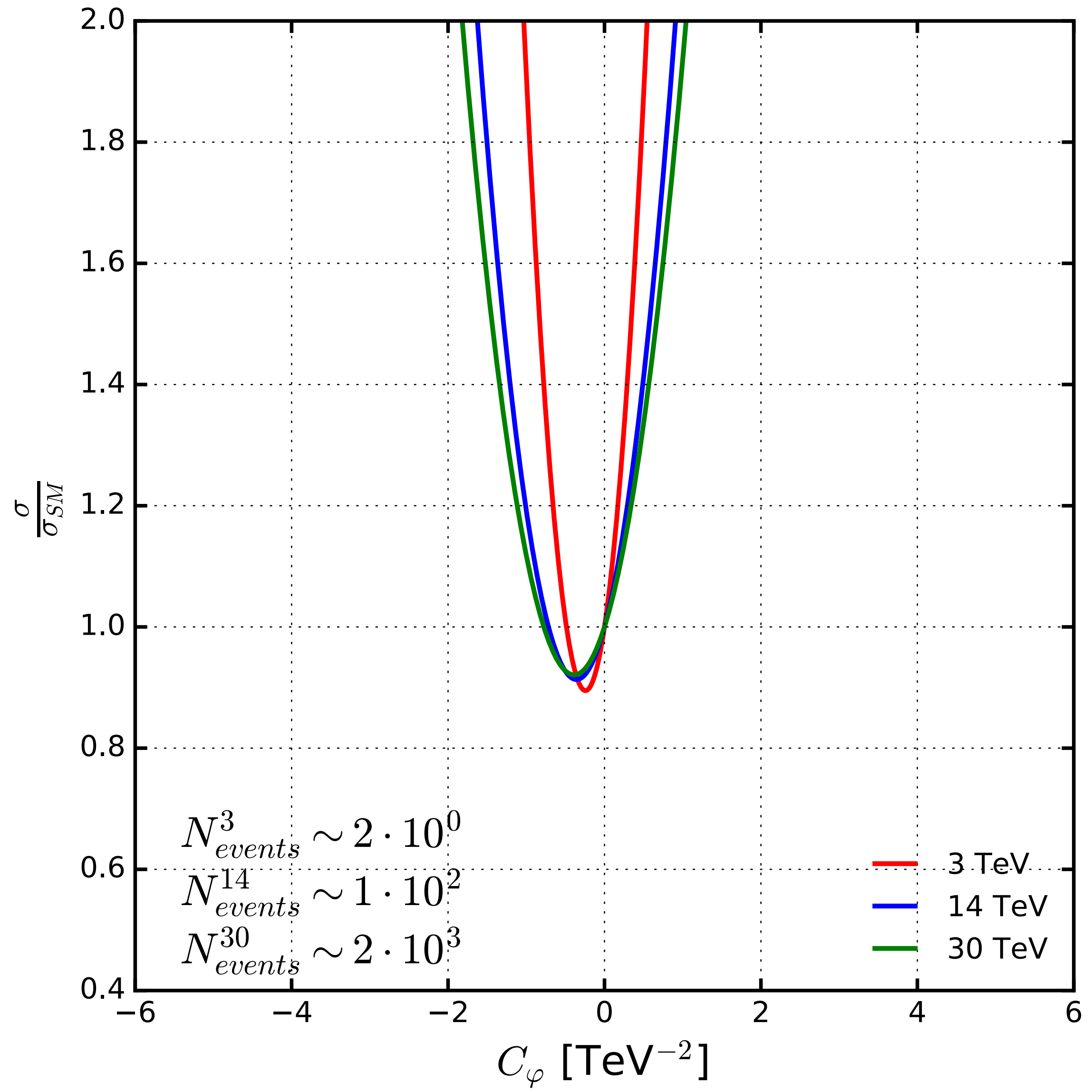
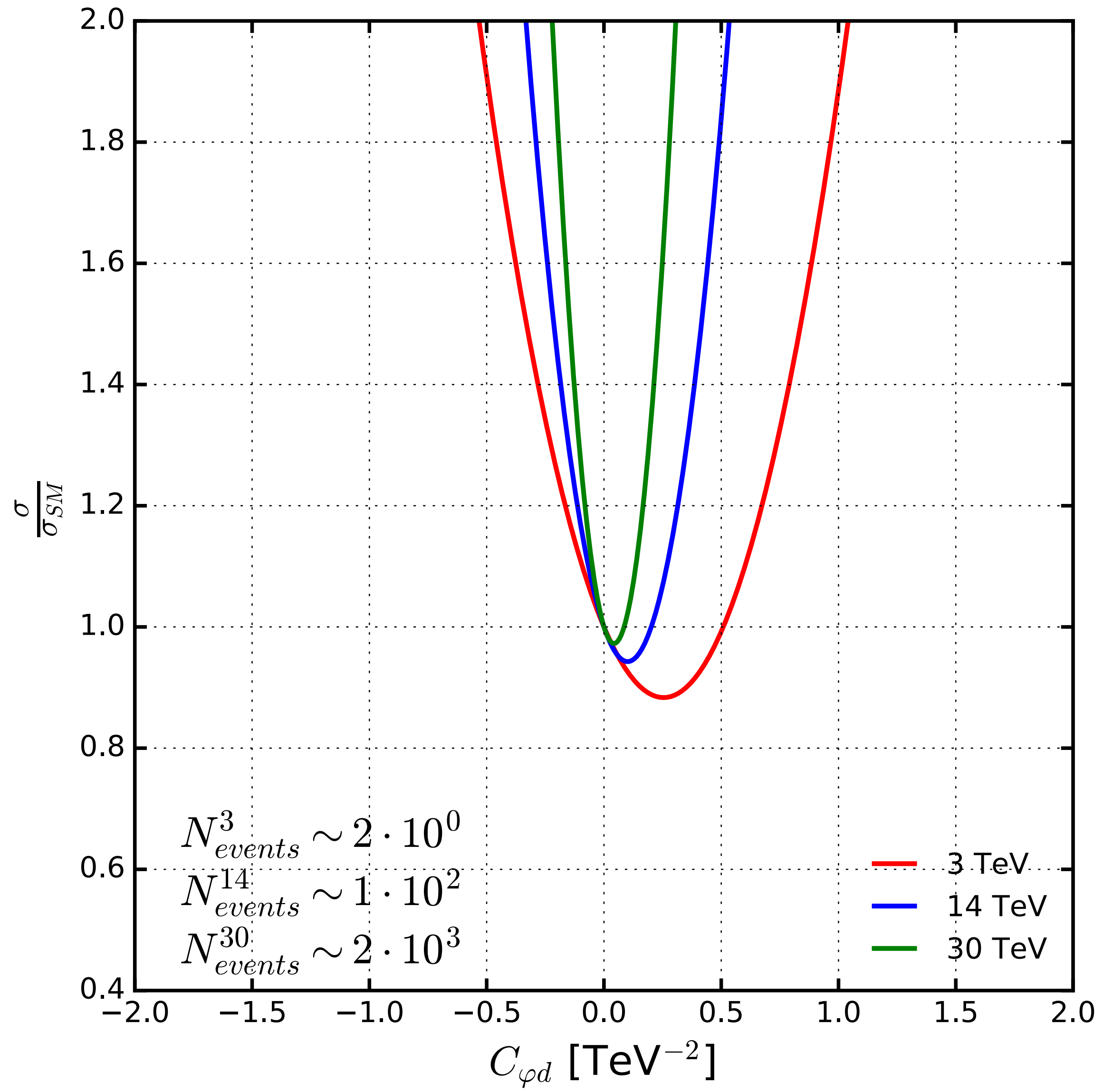
HHH production







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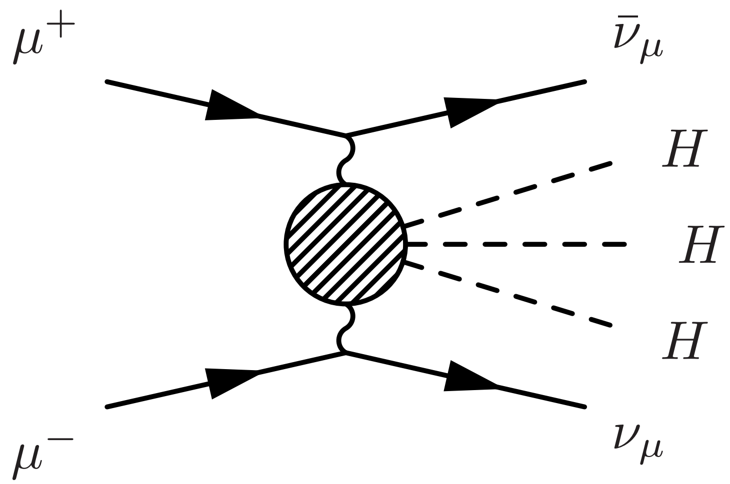
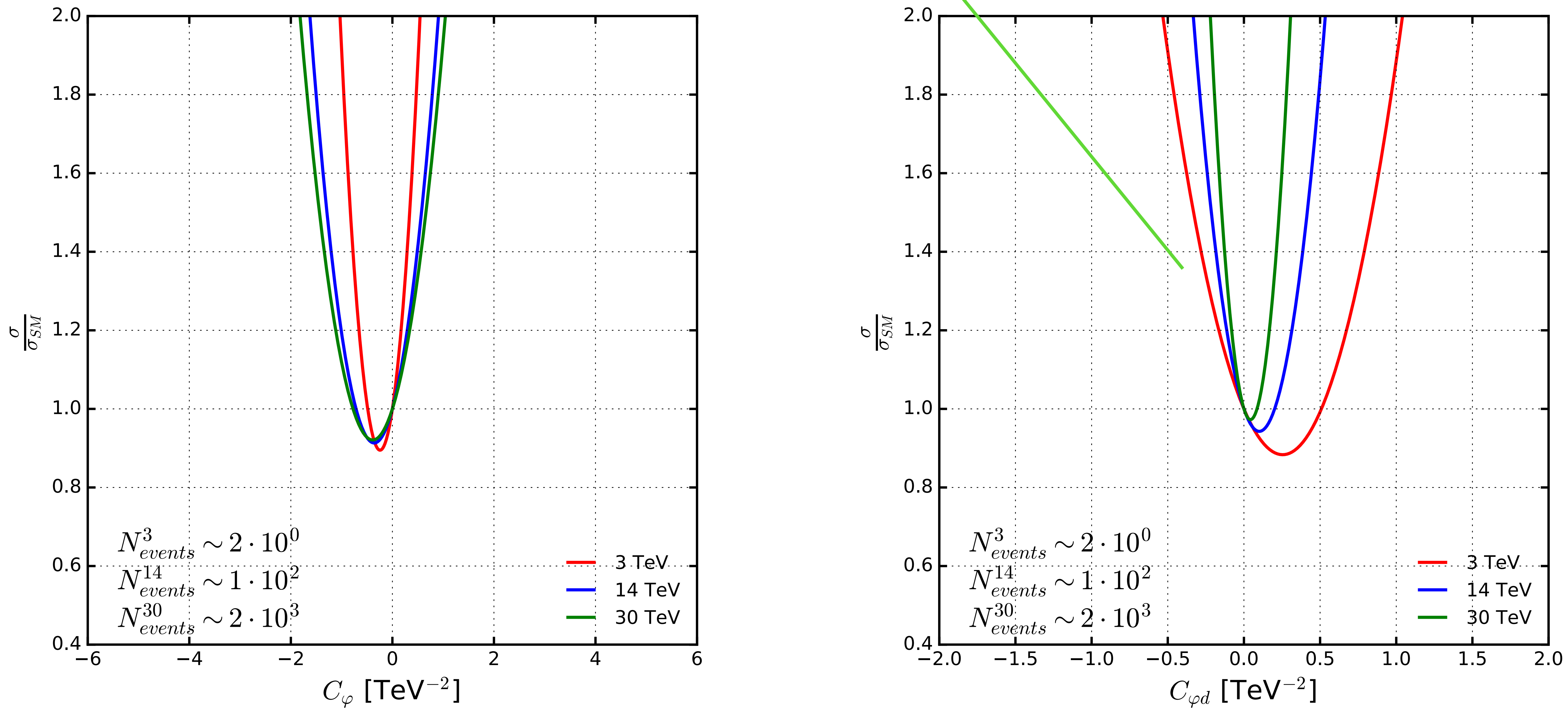


Higher sensitivity



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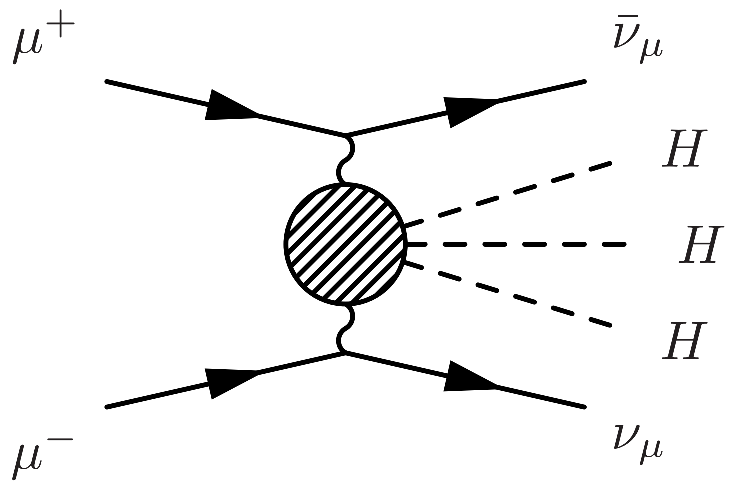

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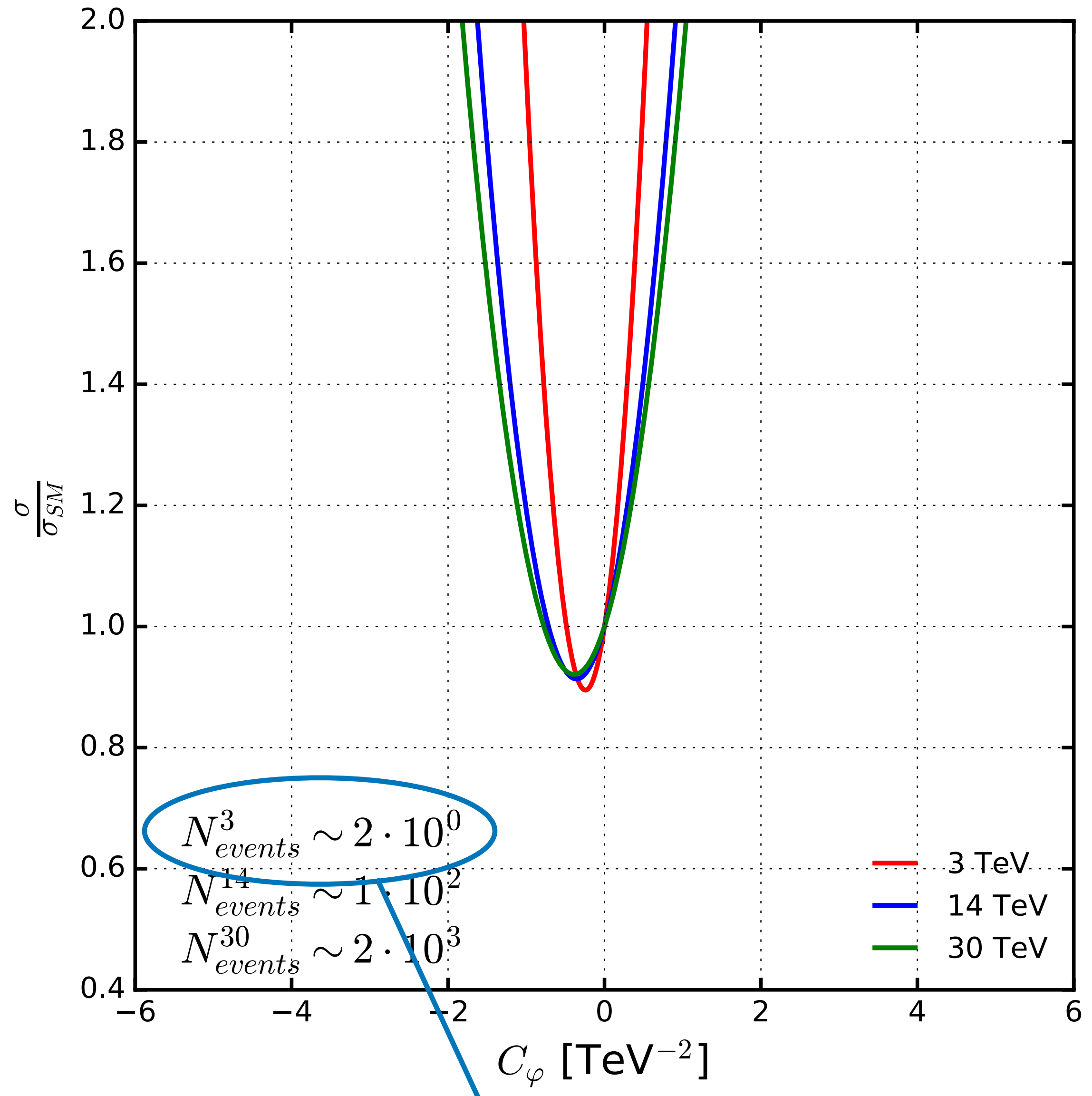
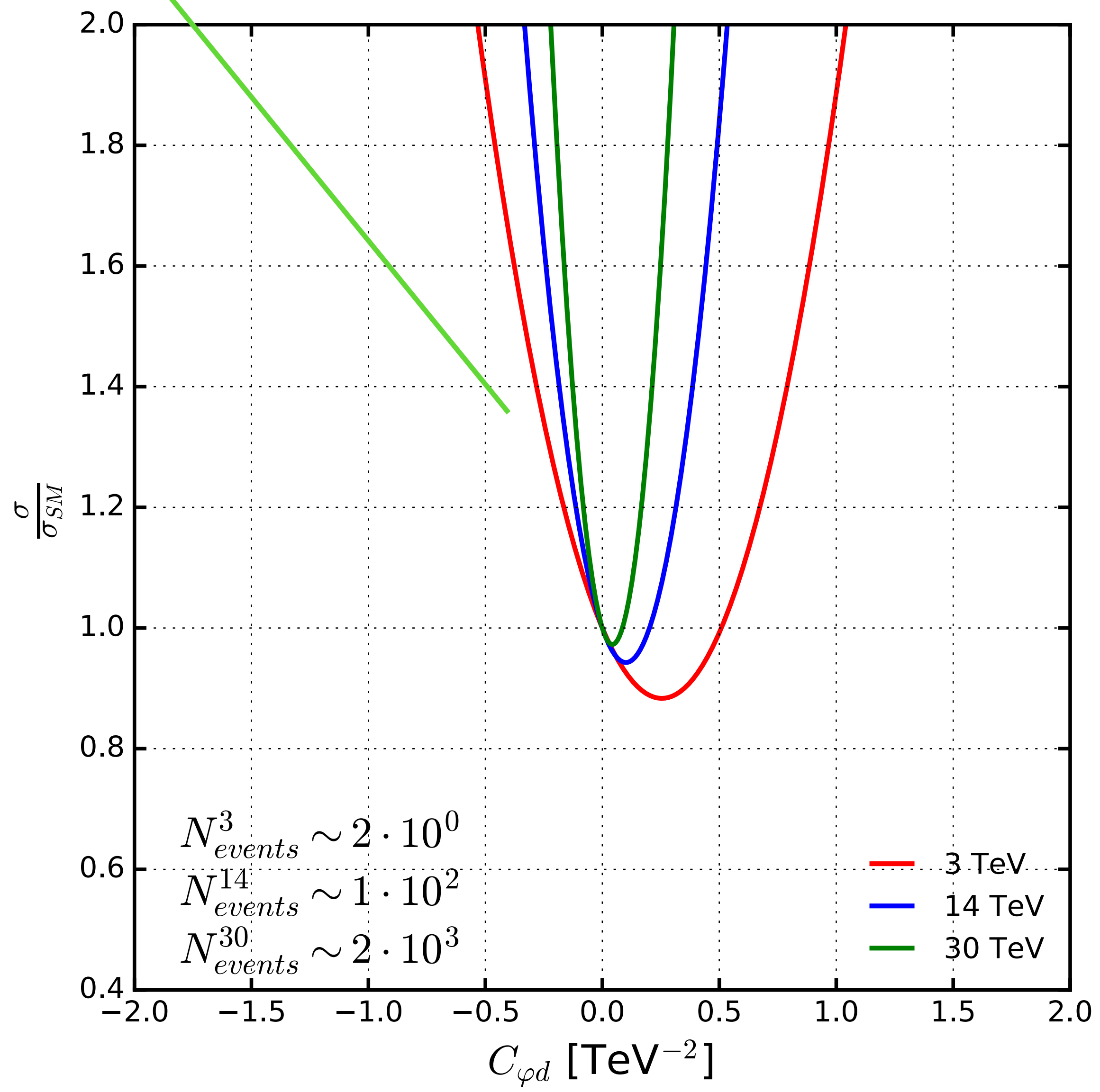
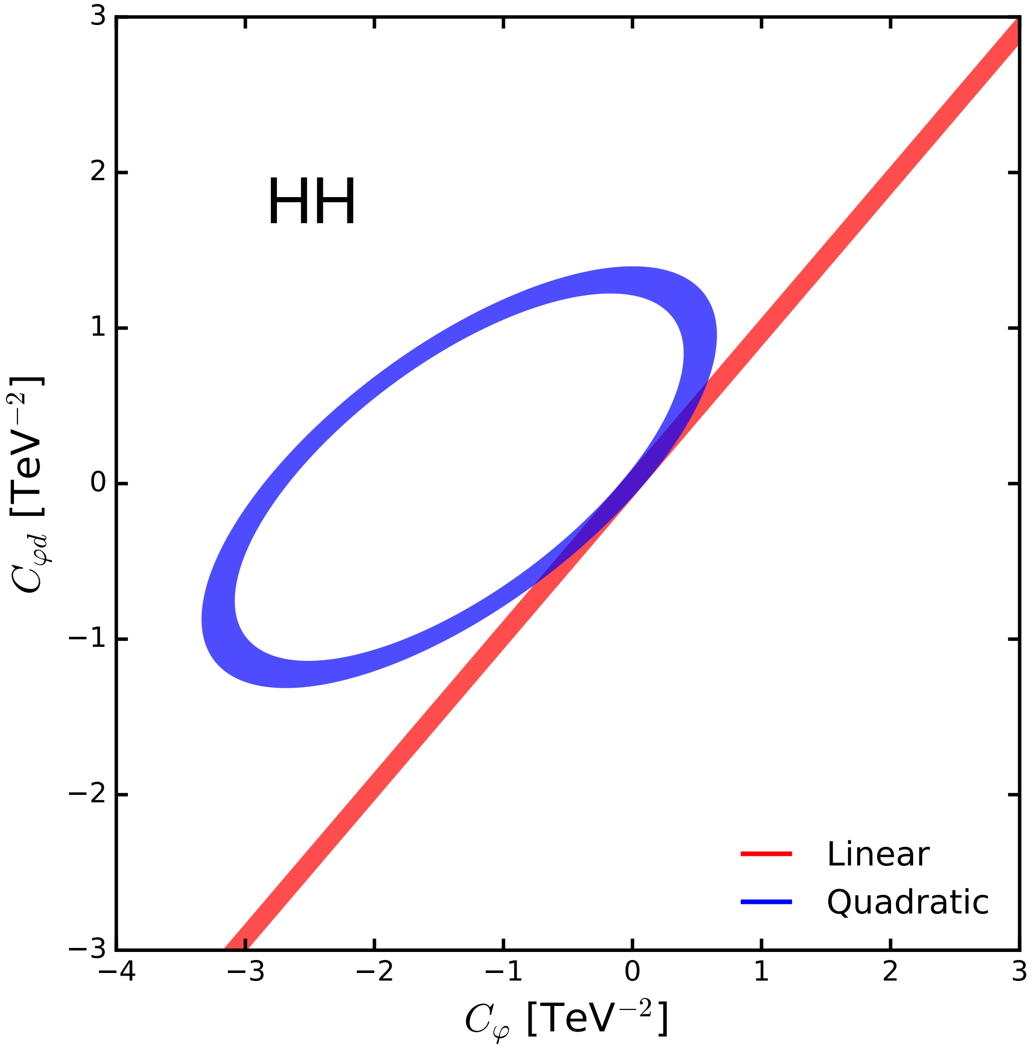




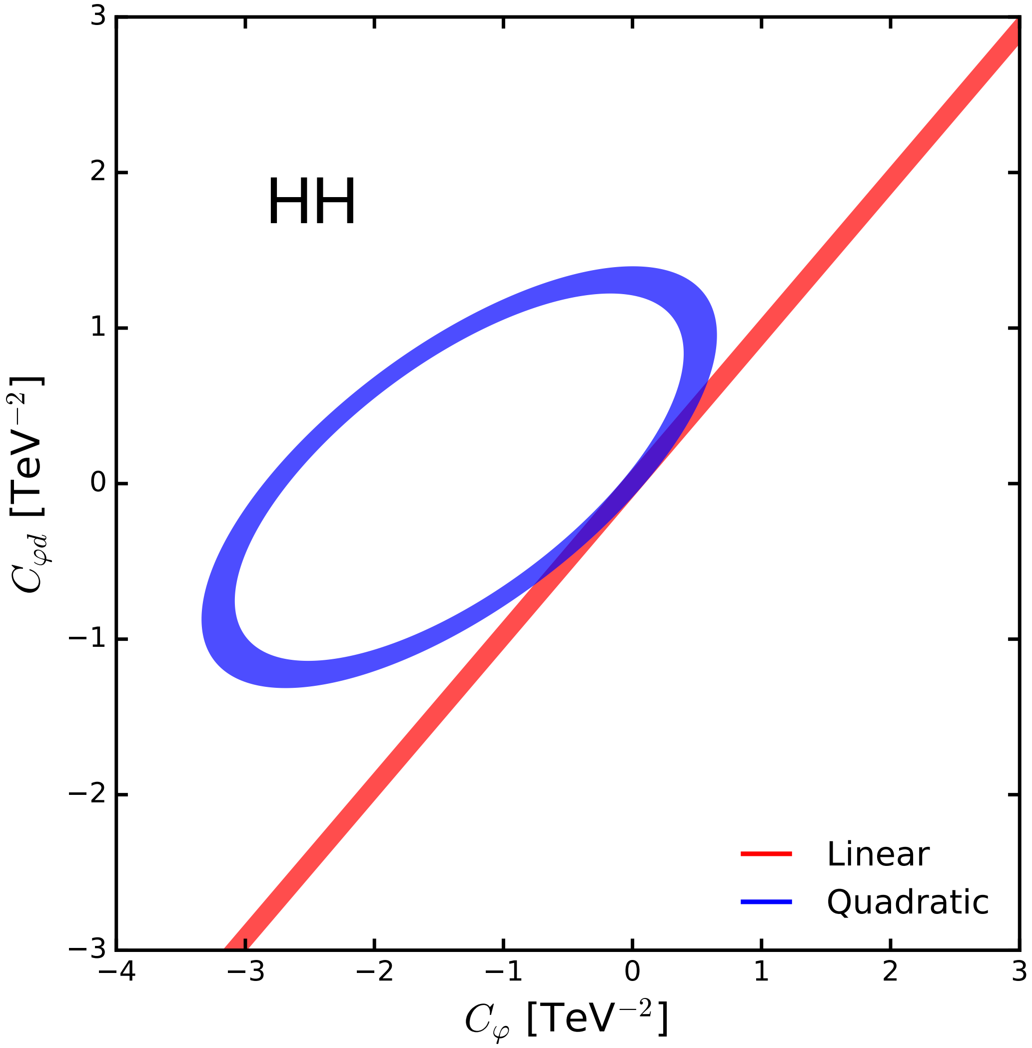
No events

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**



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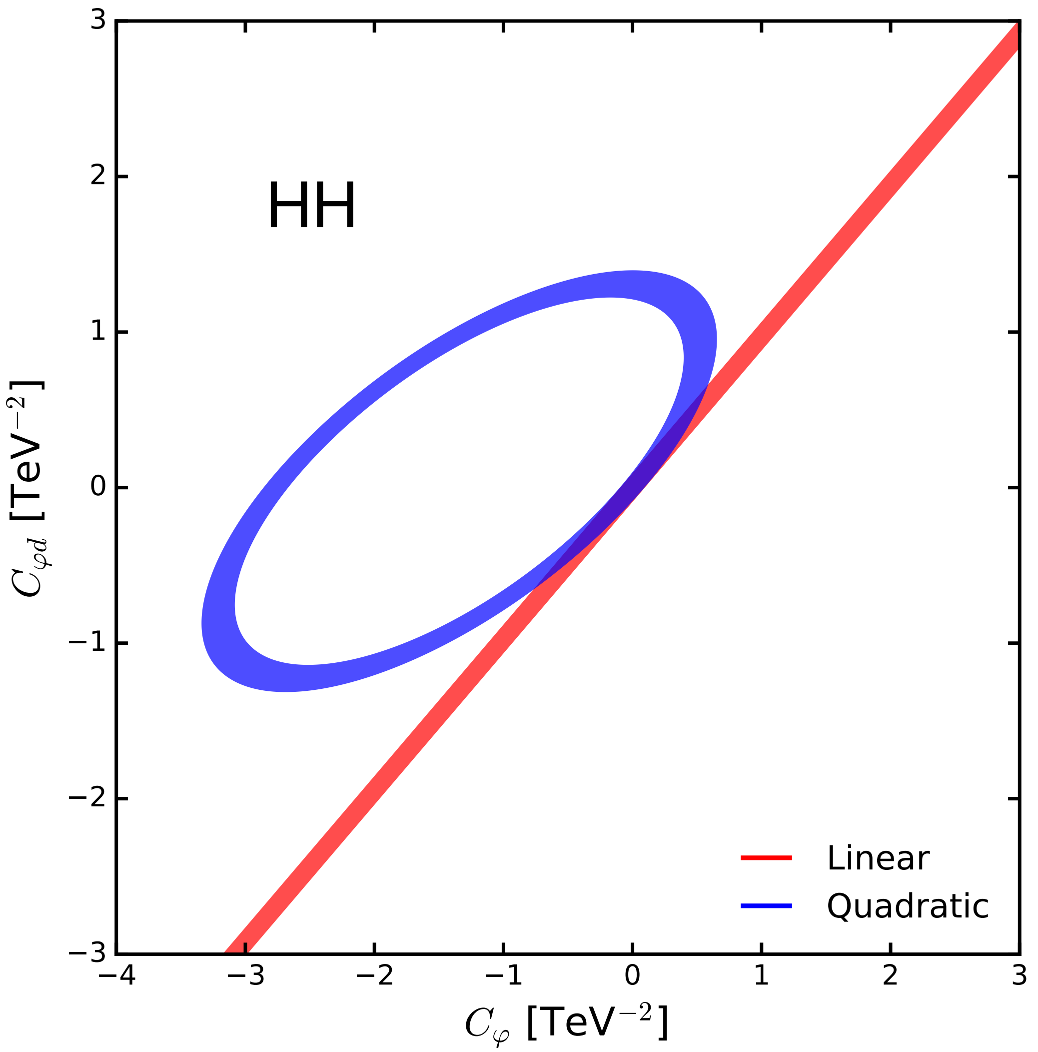

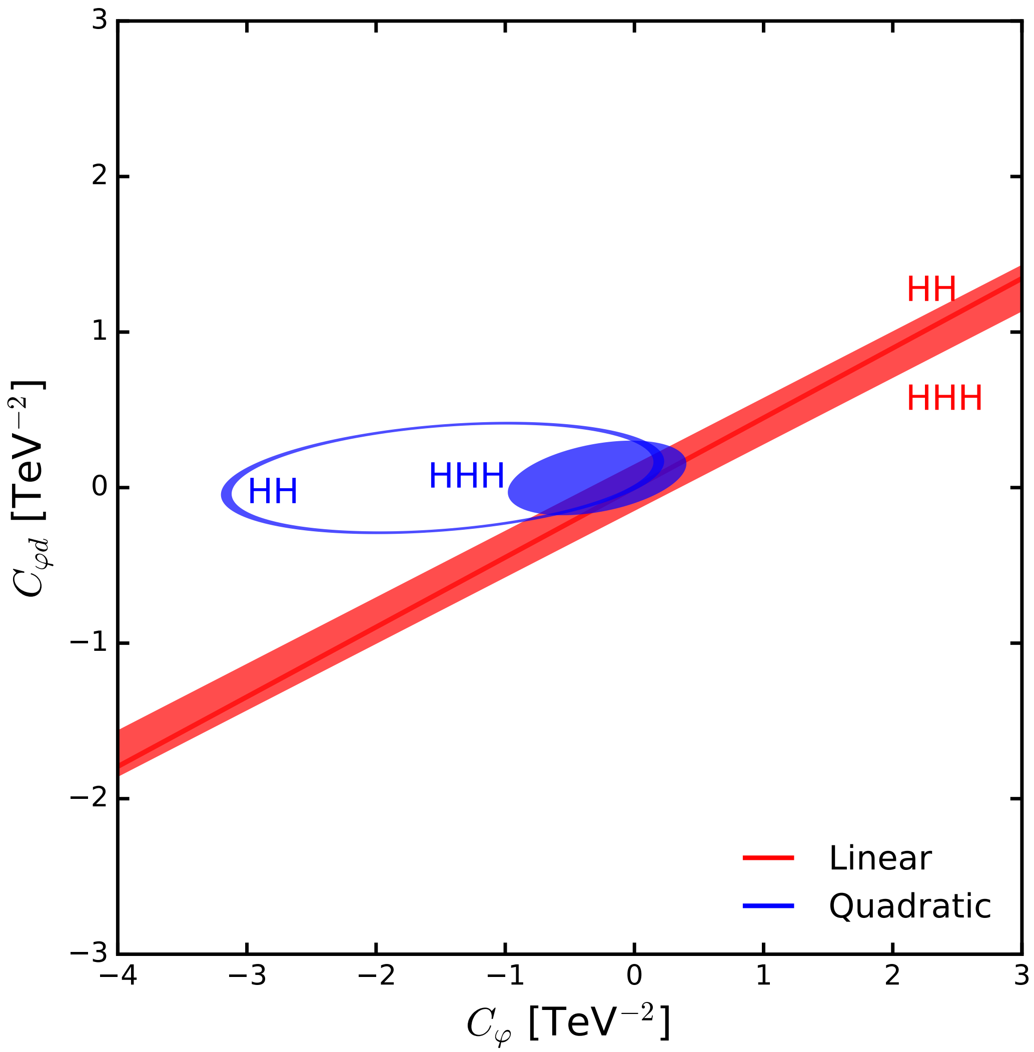

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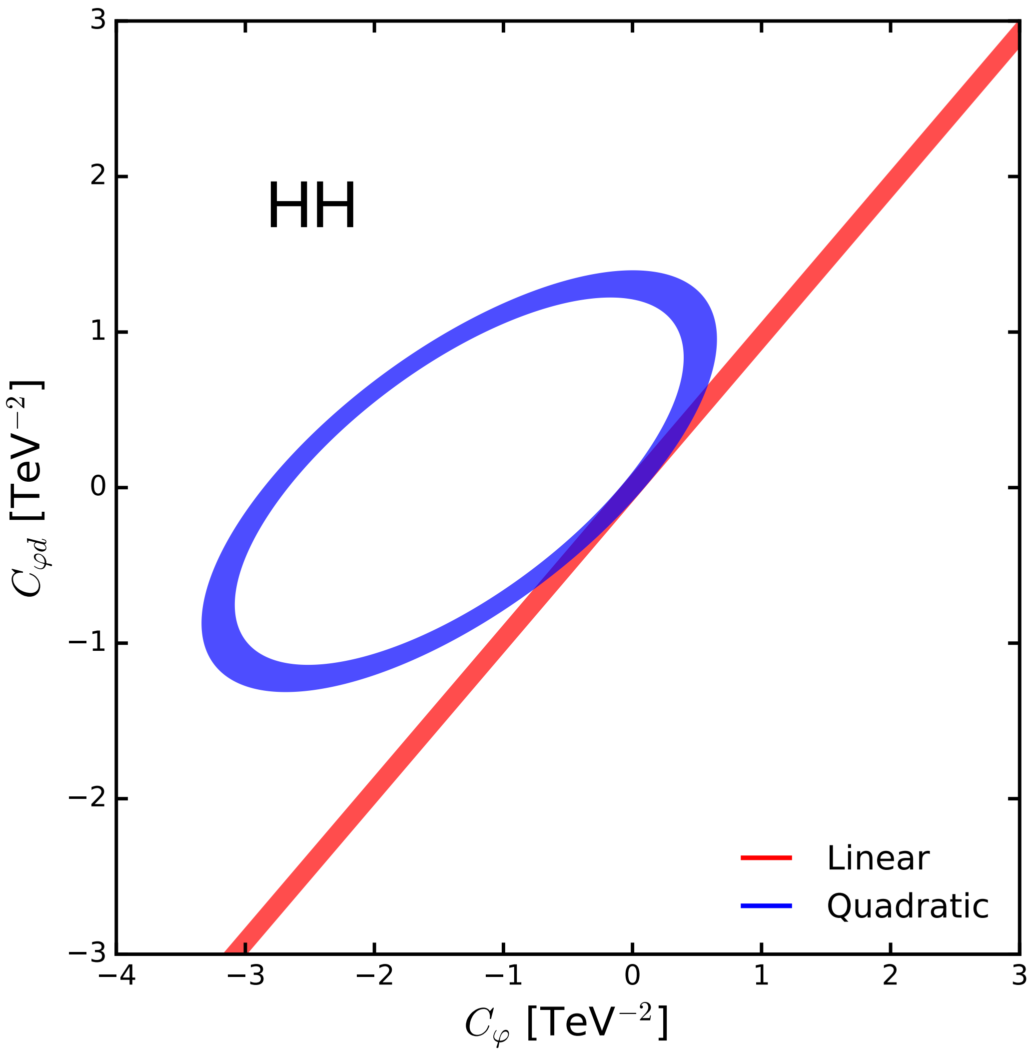
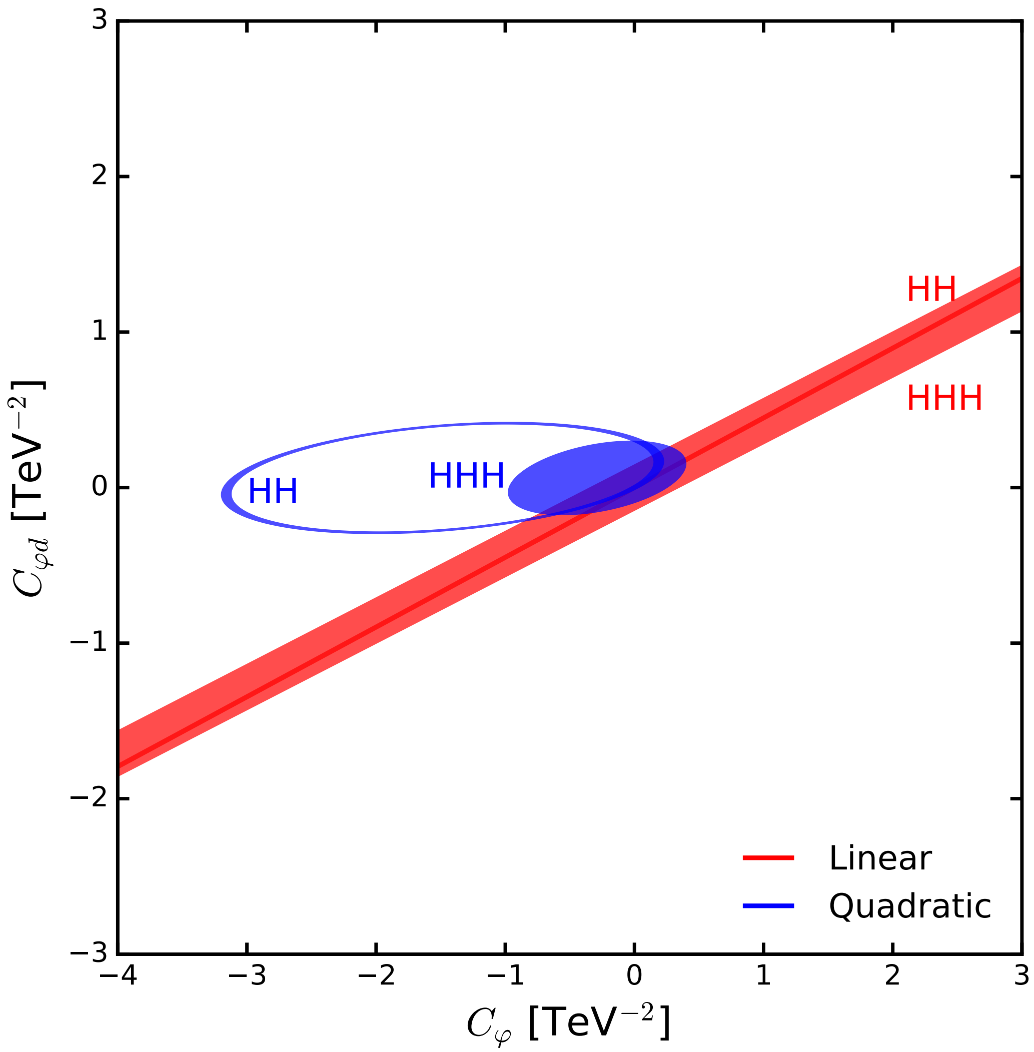
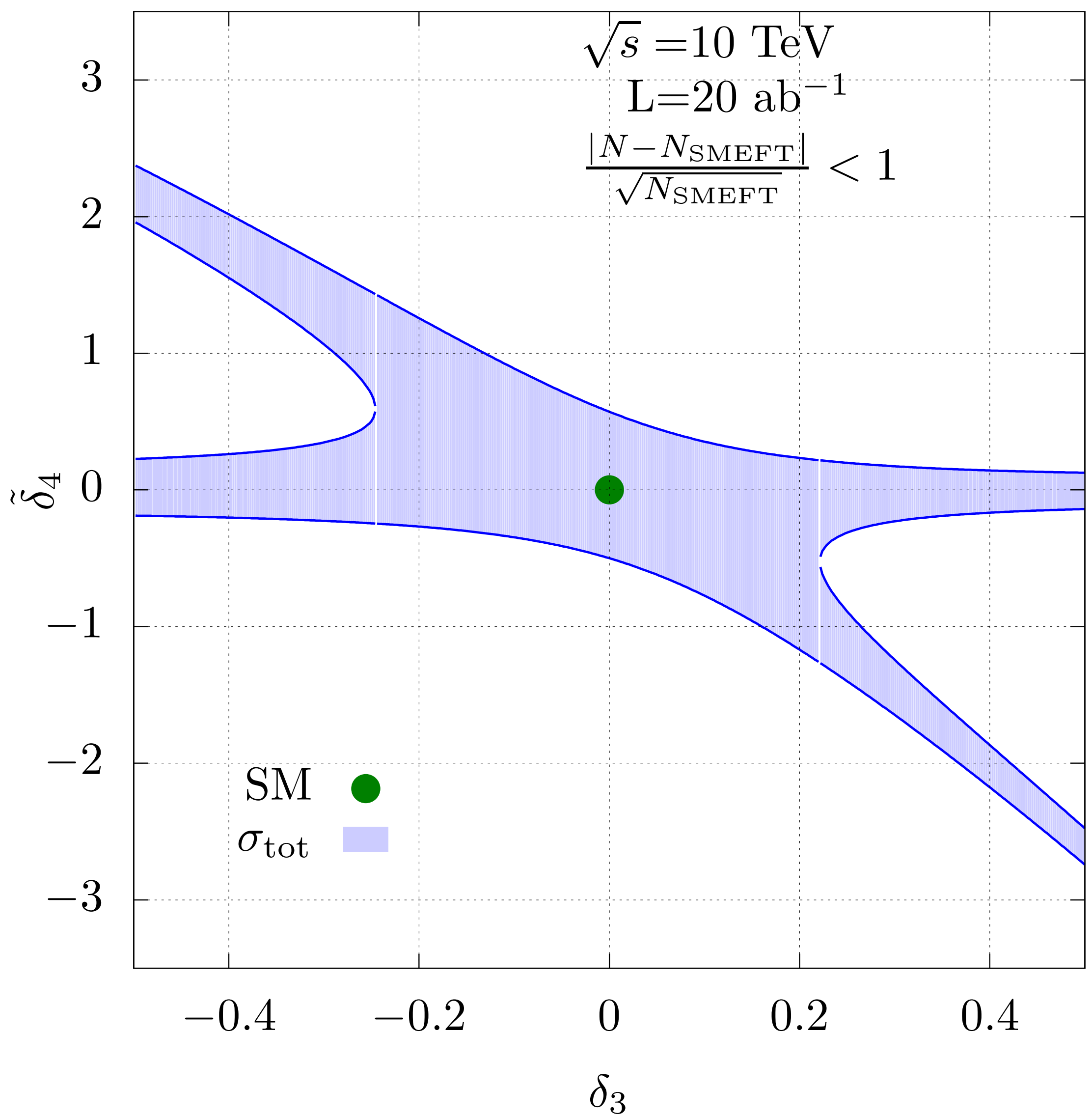


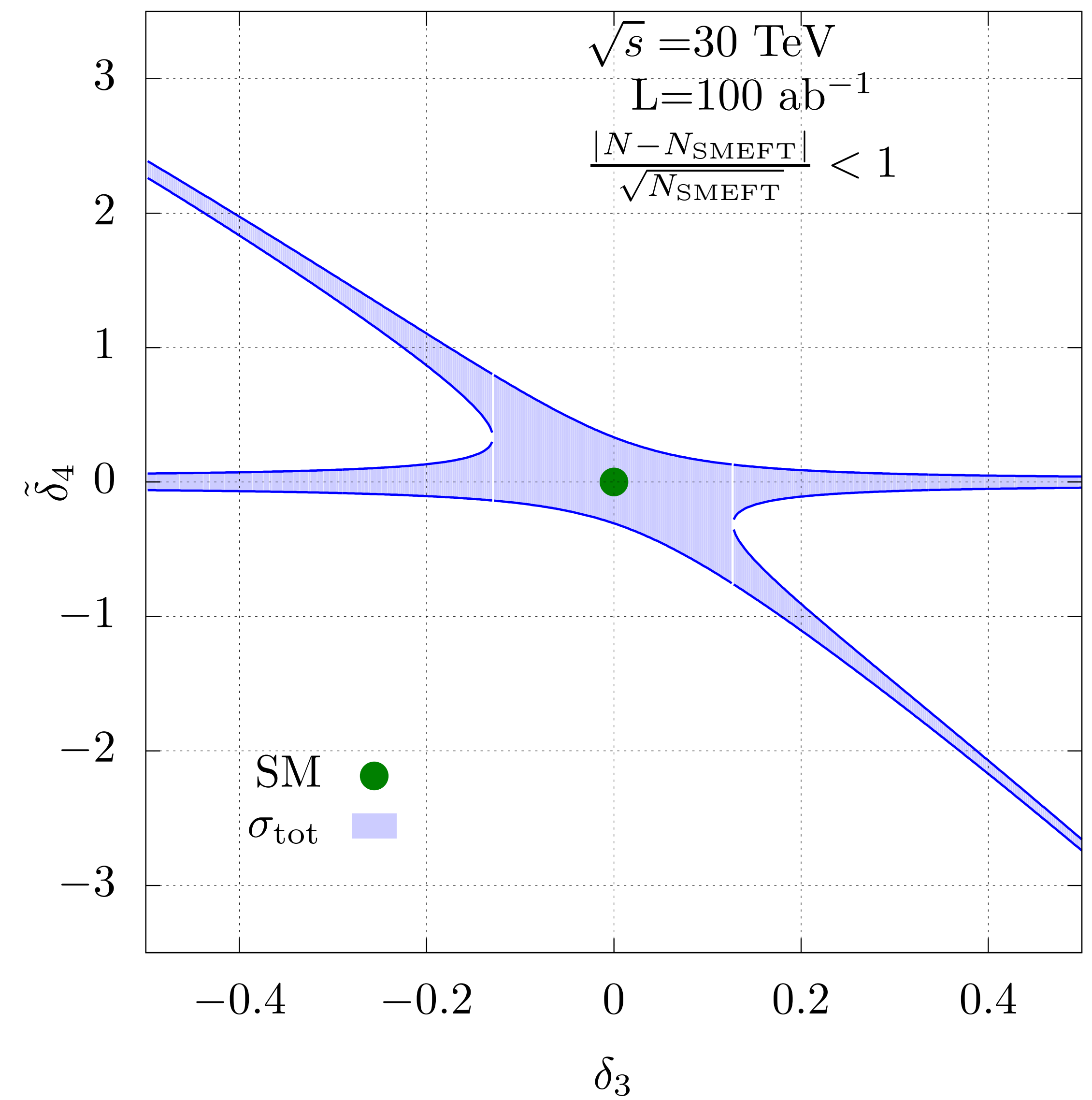


	3 TeV	14 TeV
$\mathcal{C}_{\varphi}$	[-3.33, 0.65]	[-0.66, 0.23]
$\mathcal{C}_{\varphi d}$	[-1.31, 1.39]	[-0.17, 0.30]

95% confidence level

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

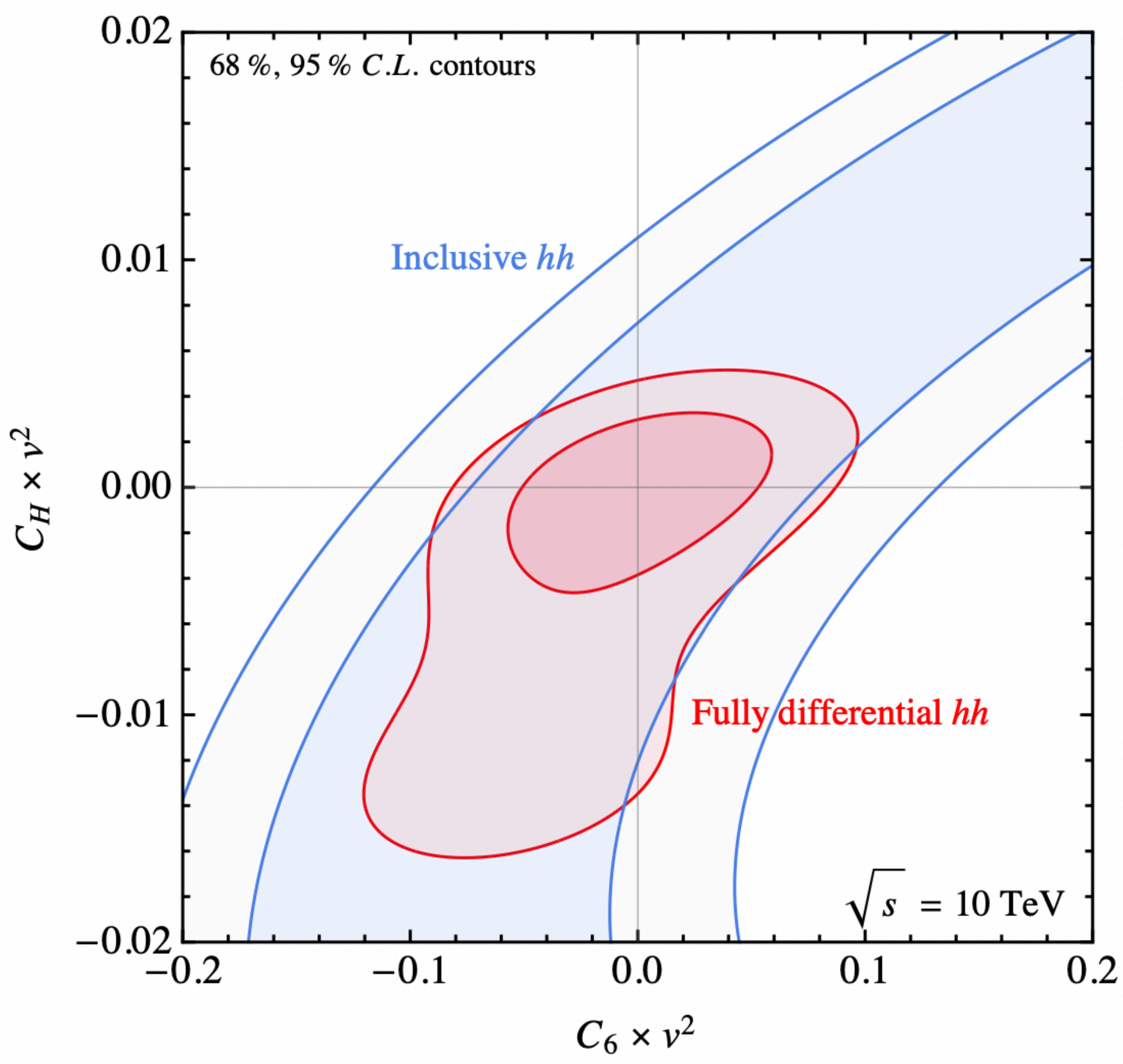


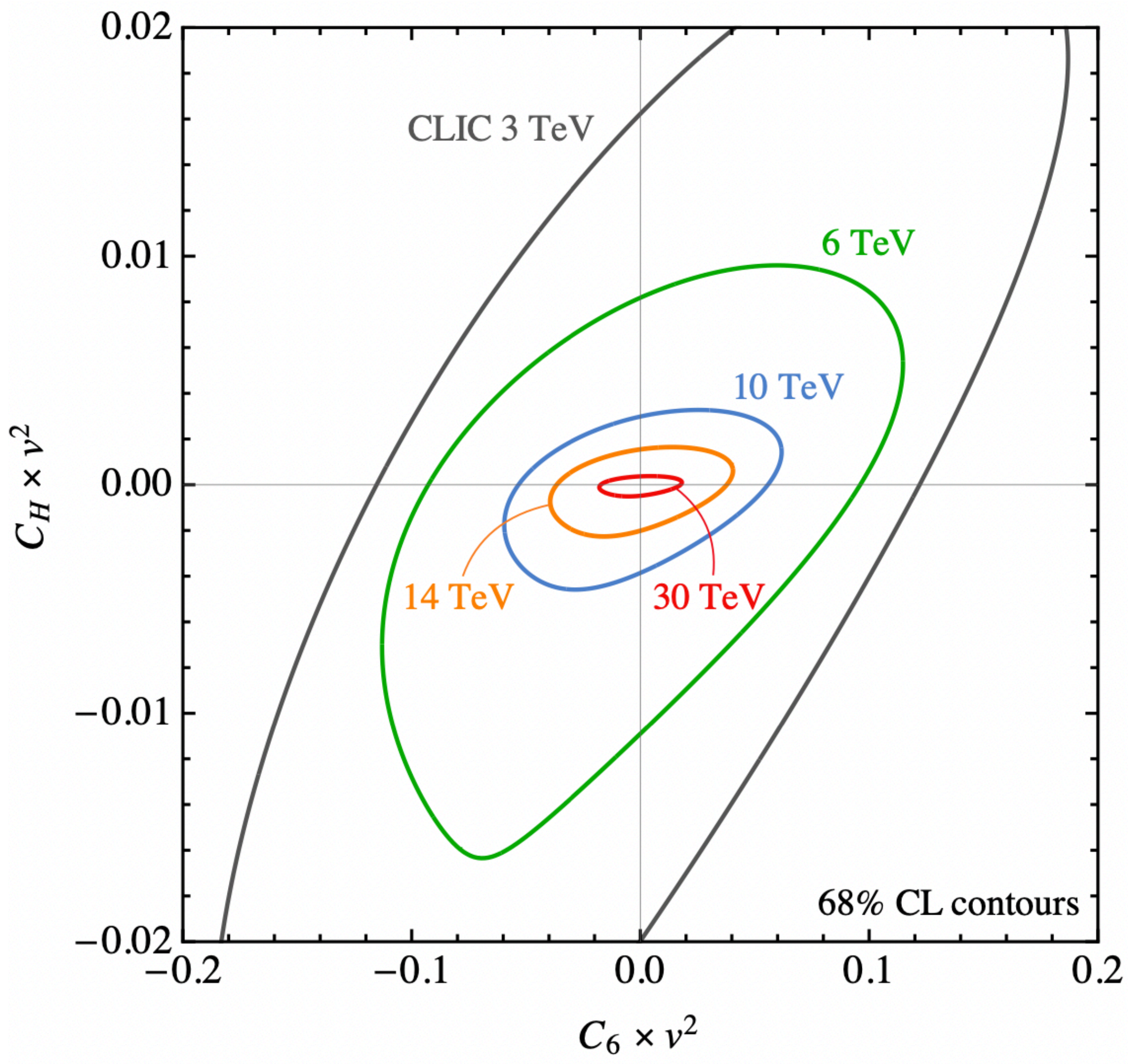


[Buttazzo, Franceschini, Wulzer arXiv:2012.11555]

$$\mathcal{O}_6 = -\frac{m_h^2}{2v^2}\left(H^\dagger H - \frac{v^2}{2}\right)^3, \qquad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu (H^\dagger H)\right)^2$$

$$\delta\kappa_3 = v^2\left(C_6 - \frac{3}{2}C_H\right) \qquad \kappa = \kappa_V = \kappa_f = 1 - \frac{C_H v^2}{2}$$





10 TeV