



Probing strong EWSB with future colliders

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JGU Mainz

in collaboration with D. Pappadopulo, R. Torre and A. Wulzer
based on arXiv: 1402.4431 and 1502.01701

Future colliders

Lepton colliders

Hadron colliders

ILC, CLIC, TLEP

LHC, FCC-hh

high precision measurements

high energy reach

suited for indirect searches

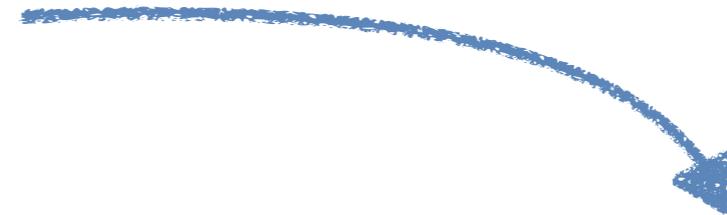
suited for direct searches

complementary

need theory bias to compare reach in same parameter space

Composite Higgs Model

- predicts direct and indirect effects



- production of EW vector resonances (here consider 3 of $SU(2)_L$)

[Pappadopulo, Thamm, Torre, Wulzer: 1402.4431]

- production of top partners (mass controls generation of Higgs potential and fine-tuning, very model dependent)

[Matsedonskyi, Panico, Wulzer: 1409.0100]

- modification of Higgs couplings (predictable in a fairly model-independent way)

$$a = g_{WW_h} = \sqrt{1 - \xi}$$

- EWPT (sensitive to effects only computable in specific models)
- Flavour

- for illustration focus on minimal composite Higgs model

- parameter space:

m_ρ

g_ρ

$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2$$

Minimal Composite Higgs

assume global symmetry: $SO(5)/SO(4)$

breaking scale $f > v$

Higgs emerges as a pseudo-NG boson

$$\mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - V(h) + \frac{v^2}{4} \text{Tr} (D_\mu \Sigma^\dagger D^\mu \Sigma) \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + b_3 \frac{h^3}{v^3} + \dots \right)$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \left(\frac{m_h^2}{2v} \right) h^3 + d_4 \left(\frac{m_h^2}{8v^2} \right) h^4 + \dots$$

$$a = \sqrt{1 - \xi}$$

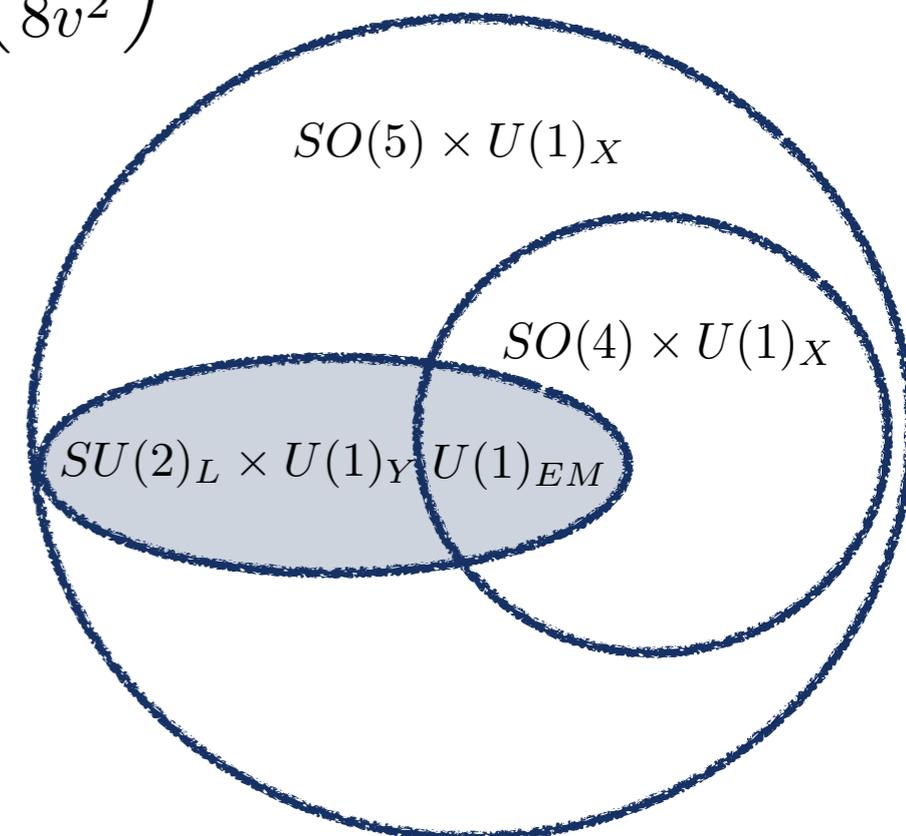
$$b = 1 - 2\xi$$

$$b_3 = -\frac{4}{3} \xi \sqrt{1 - \xi}$$

$$d_3^{(4)} = \sqrt{1 - \xi}$$

$$\xi = \frac{v^2}{f^2}$$

[Contino, Nomura, Pomarol: hep-ph/0306259]
 [Agashe, Contino, Pomarol: hep-ph/0412089]
 [Agashe, Contino: hep-ph/0510164]
 [Contino, Da Rold, Pomarol: hep-ph/0612048]
 [Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]



Higgs couplings receive corrections of order ξ

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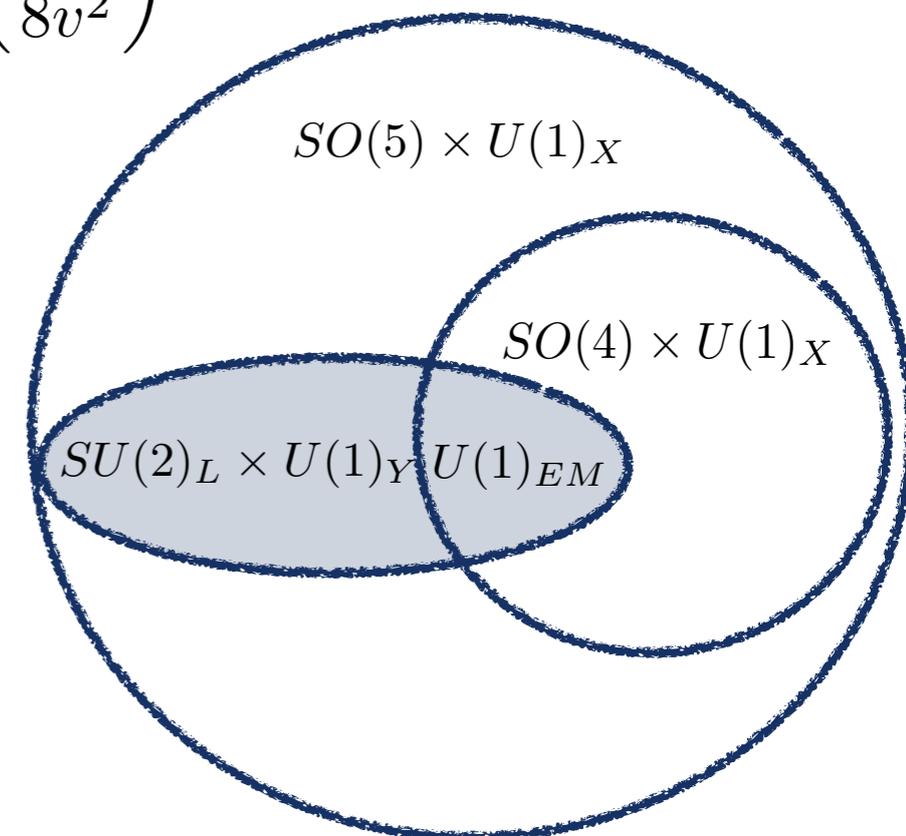
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Direct vs indirect

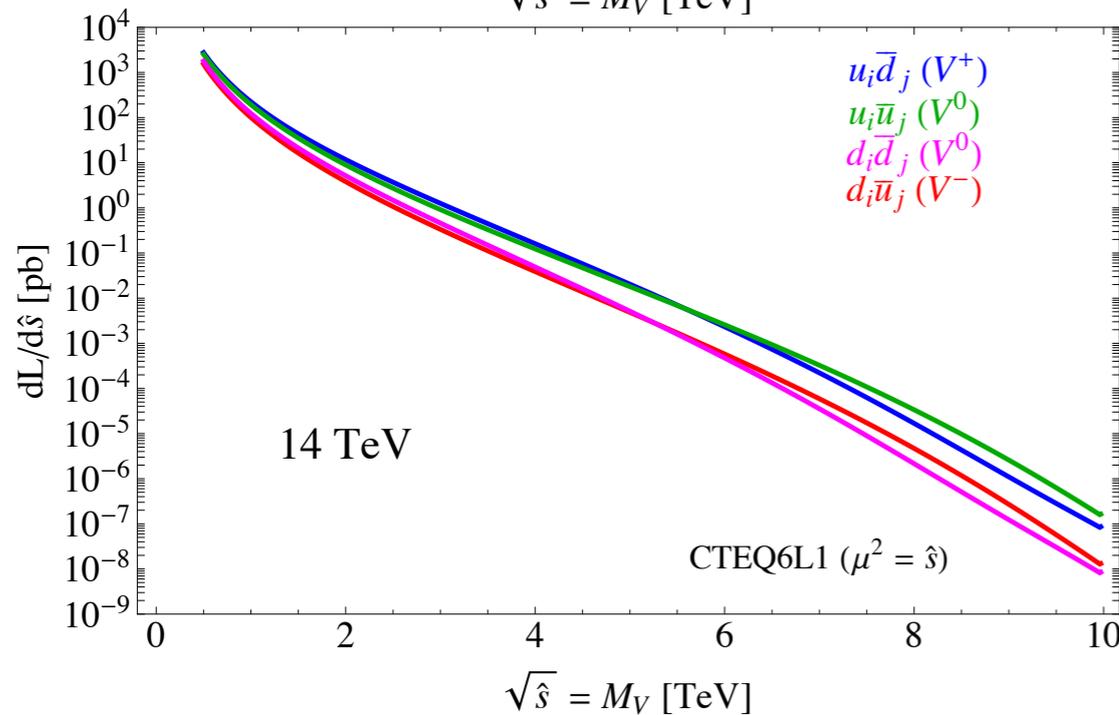
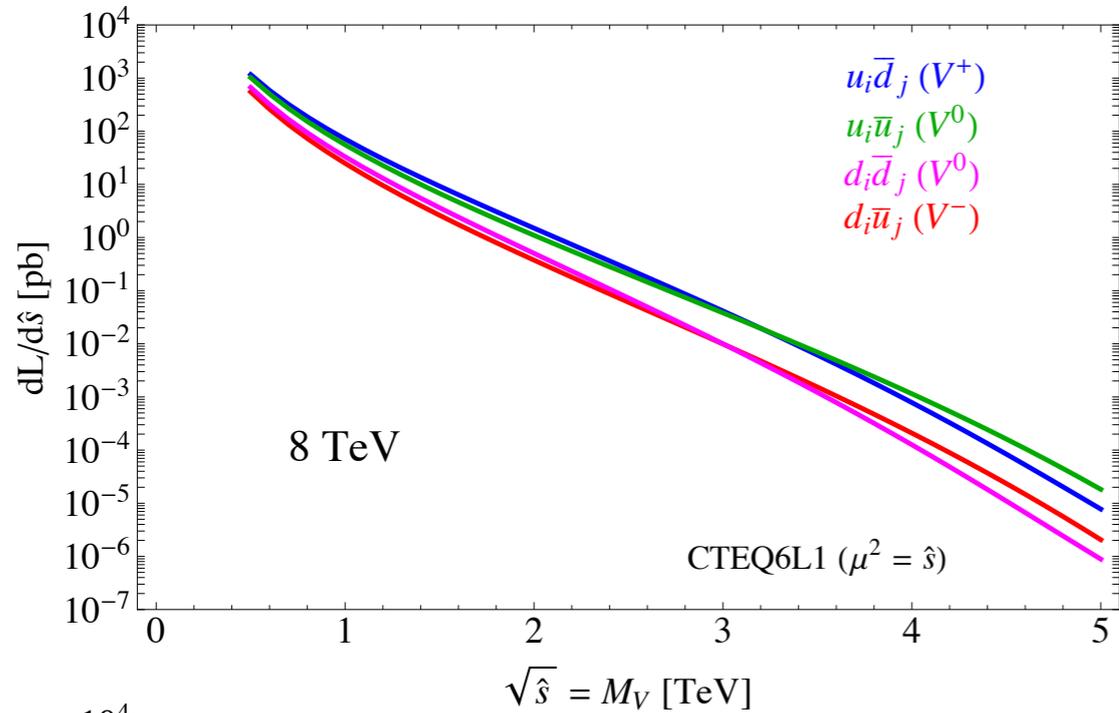
- compare the reach of direct and indirect searches on MCHM parameter space
- many studies on sensitivity of indirect measurements at future lepton colliders
 - [CMS-NOTE-2012-006]*
 - [ATL-PHYS-PUB-2013-014]*
 - [Dawson et. al.1310.8361]*
 - [CLIC 1307.5288]*
- current vector resonance searches at 8 TeV LHC
- show extrapolation procedure to estimate bounds at 14 and 100 TeV

Indirect measurements

Collider	Energy	Luminosity	$\xi [1\sigma]$
LHC	14 TeV	300 fb ⁻¹	6.6 – 11.4 × 10 ⁻²
LHC	14 TeV	3 ab ⁻¹	4 – 10 × 10 ⁻²
ILC	250 GeV + 500 GeV	250 fb ⁻¹ 500 fb ⁻¹	4.8-7.8 × 10 ⁻³
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb ⁻¹ 1.5 ab ⁻¹ 2 ab ⁻¹	2.2 × 10 ⁻³
TLEP	240 GeV + 350 GeV	10 ab ⁻¹ 2.6 ab ⁻¹	2 × 10 ⁻³

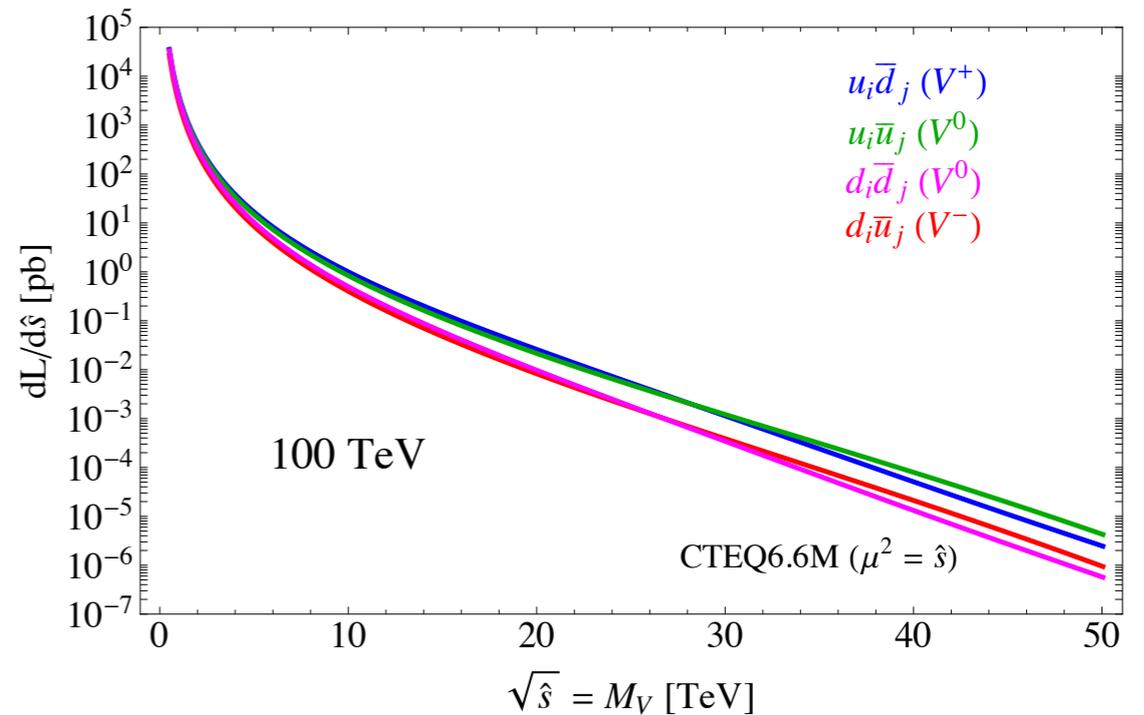
Limit extrapolation

background rescales with parton luminosities



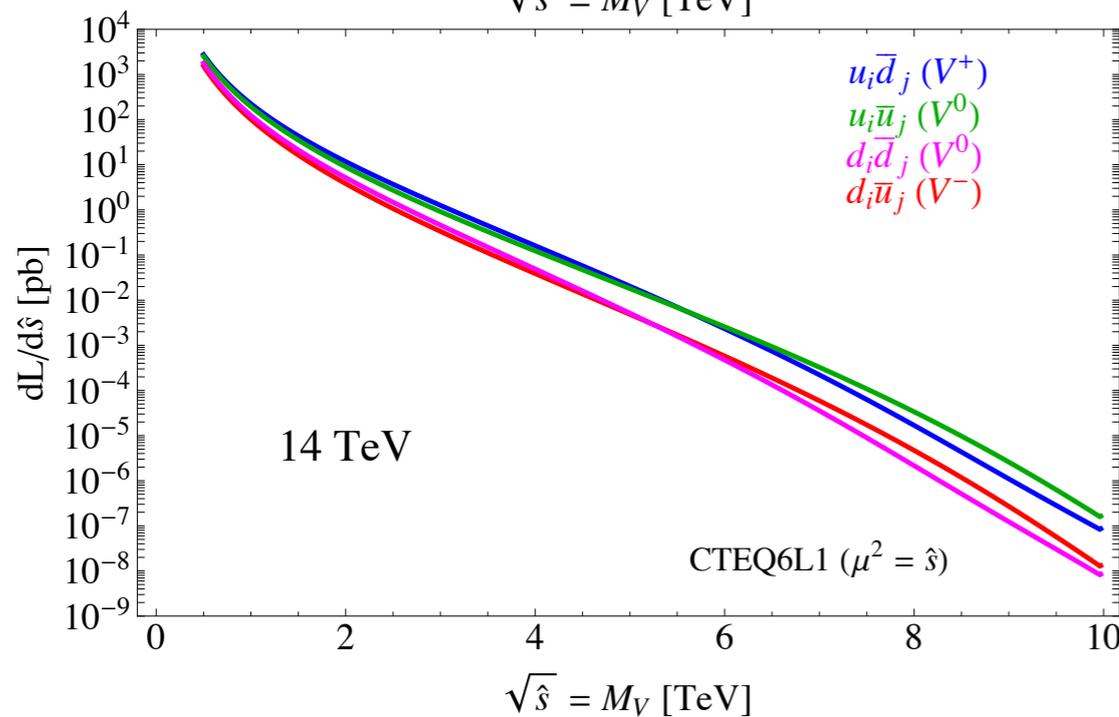
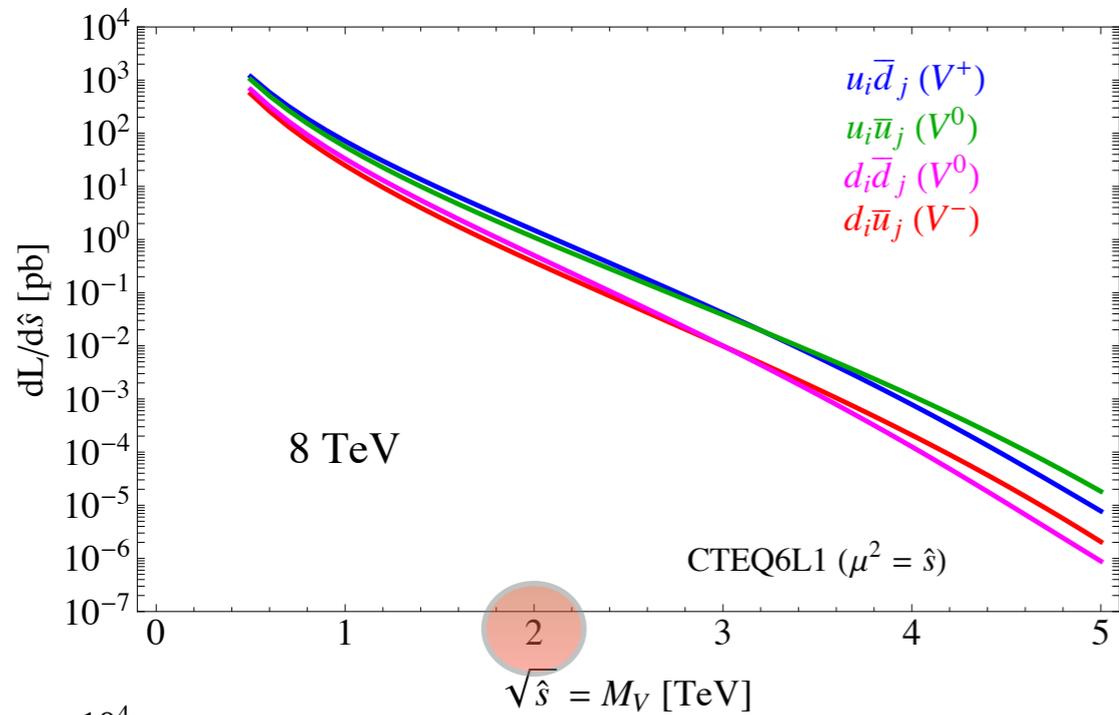
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$$\sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_\rho; \sqrt{s}) = \frac{L_0}{L} \sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_\rho^0; \sqrt{s_0})$$



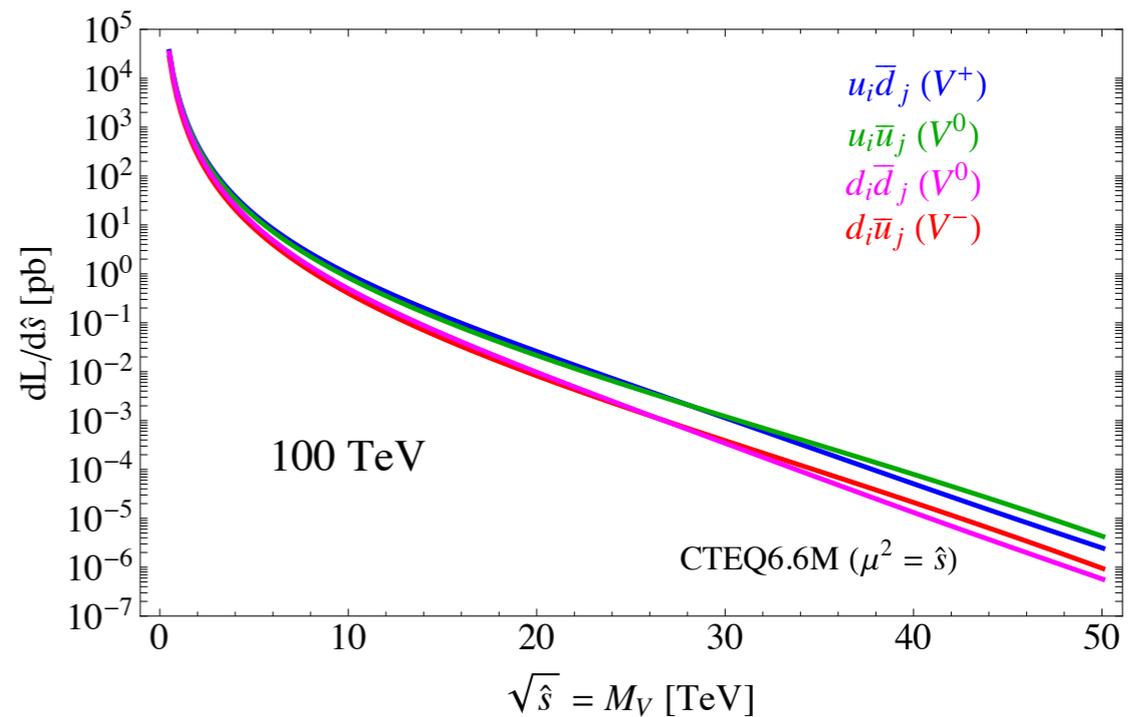
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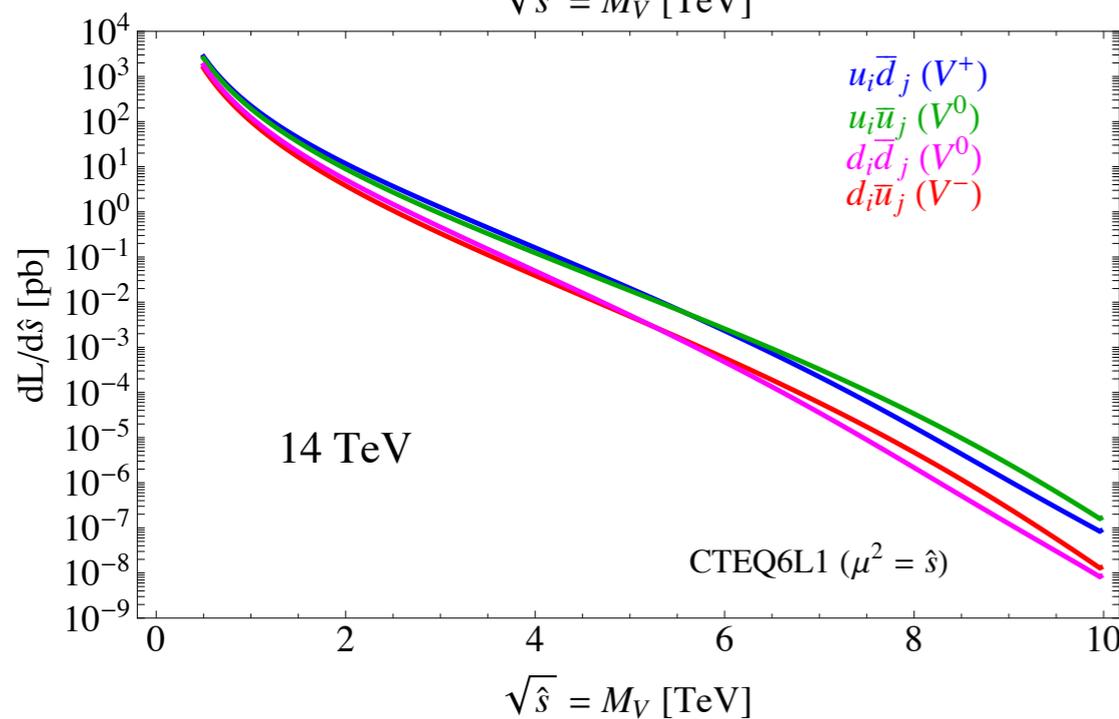
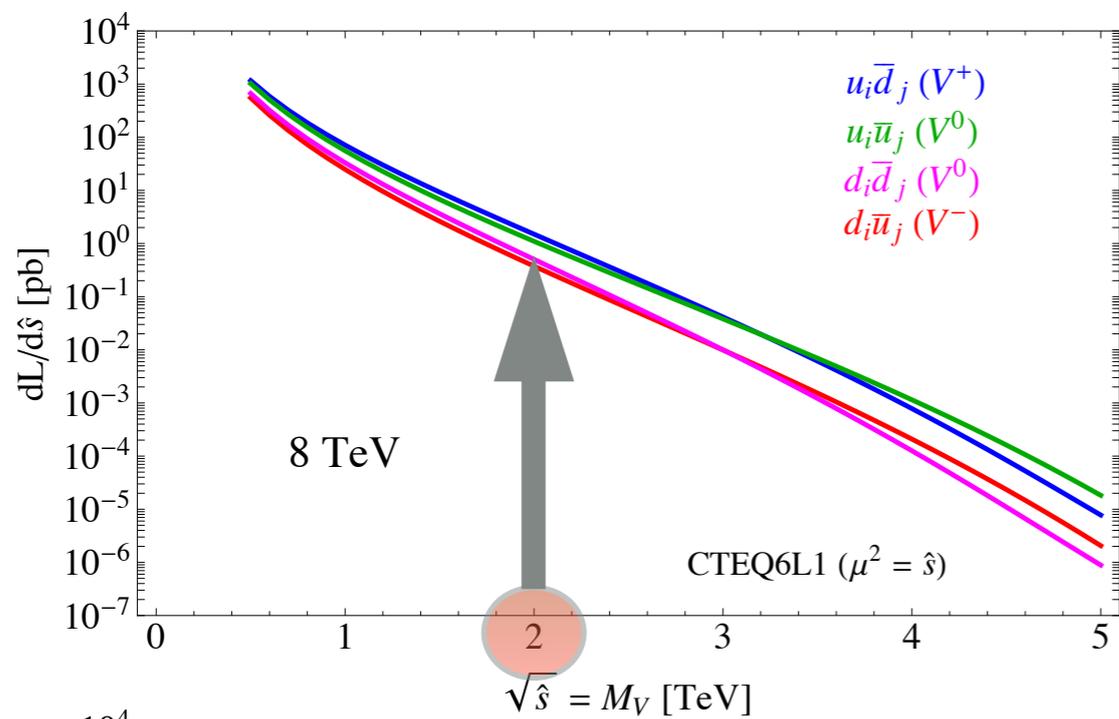
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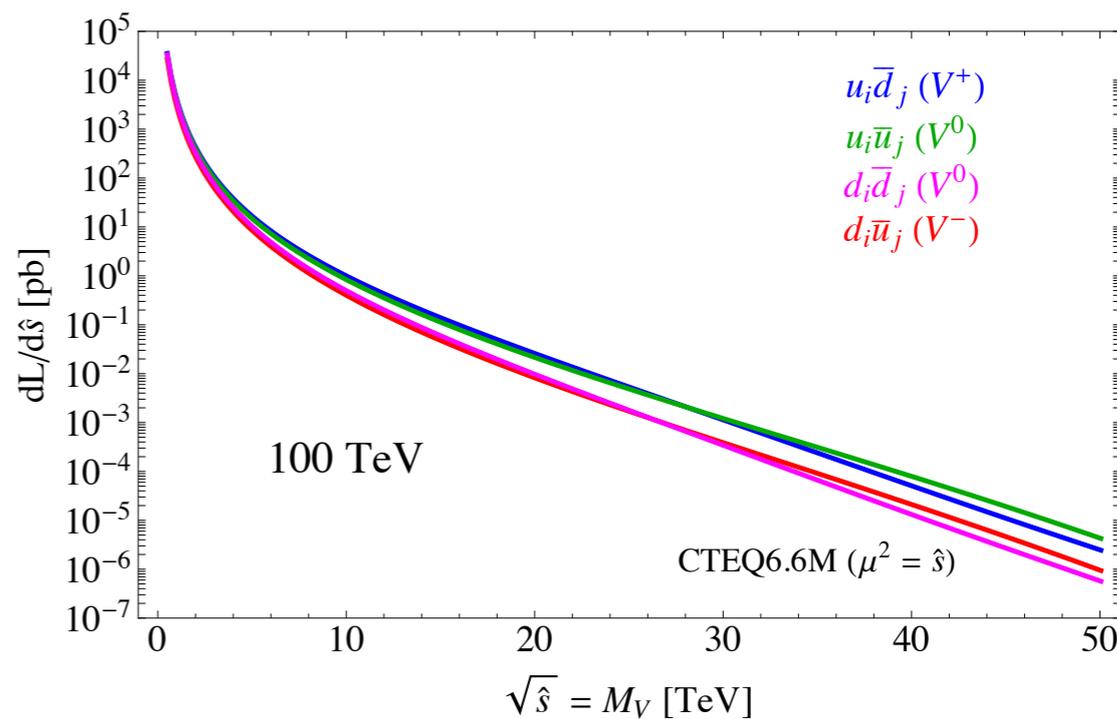
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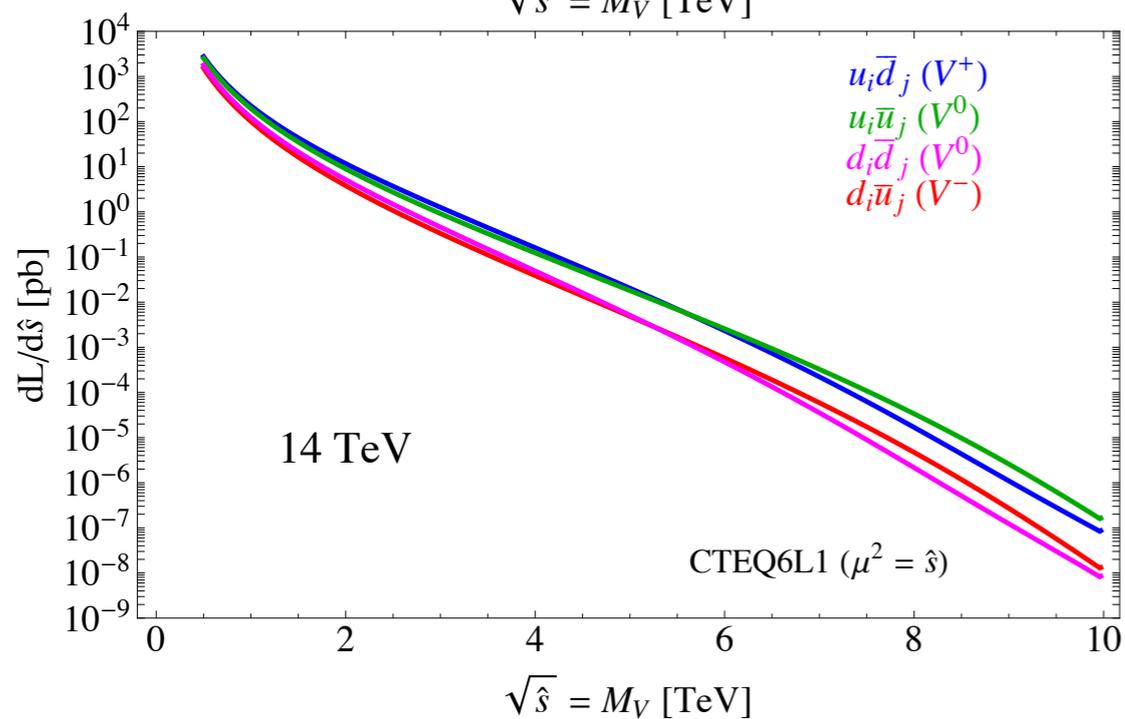
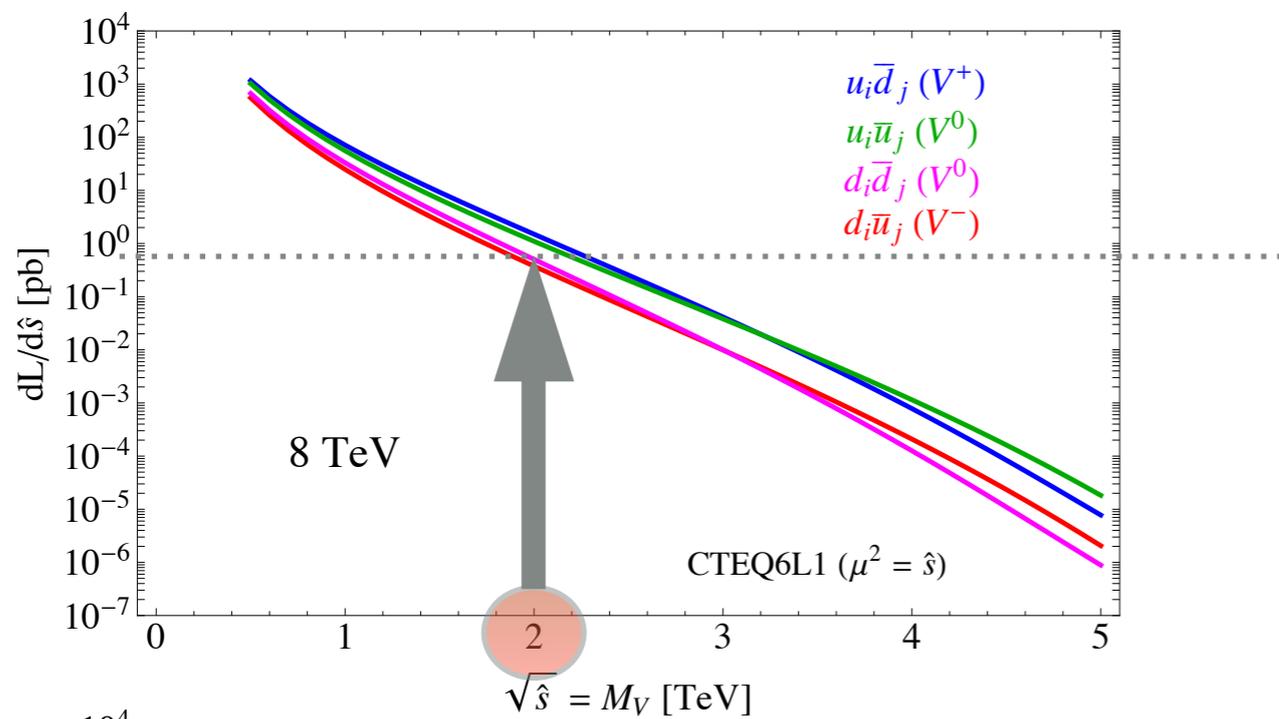
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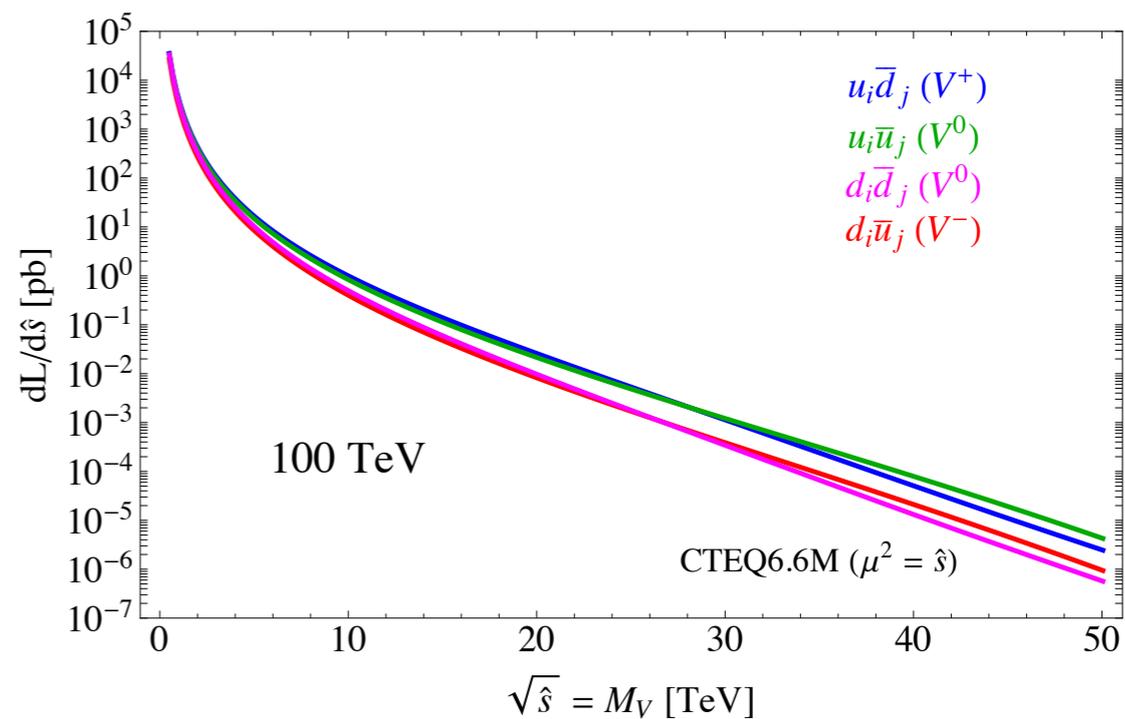
Limit extrapolation

background rescales with parton luminosities



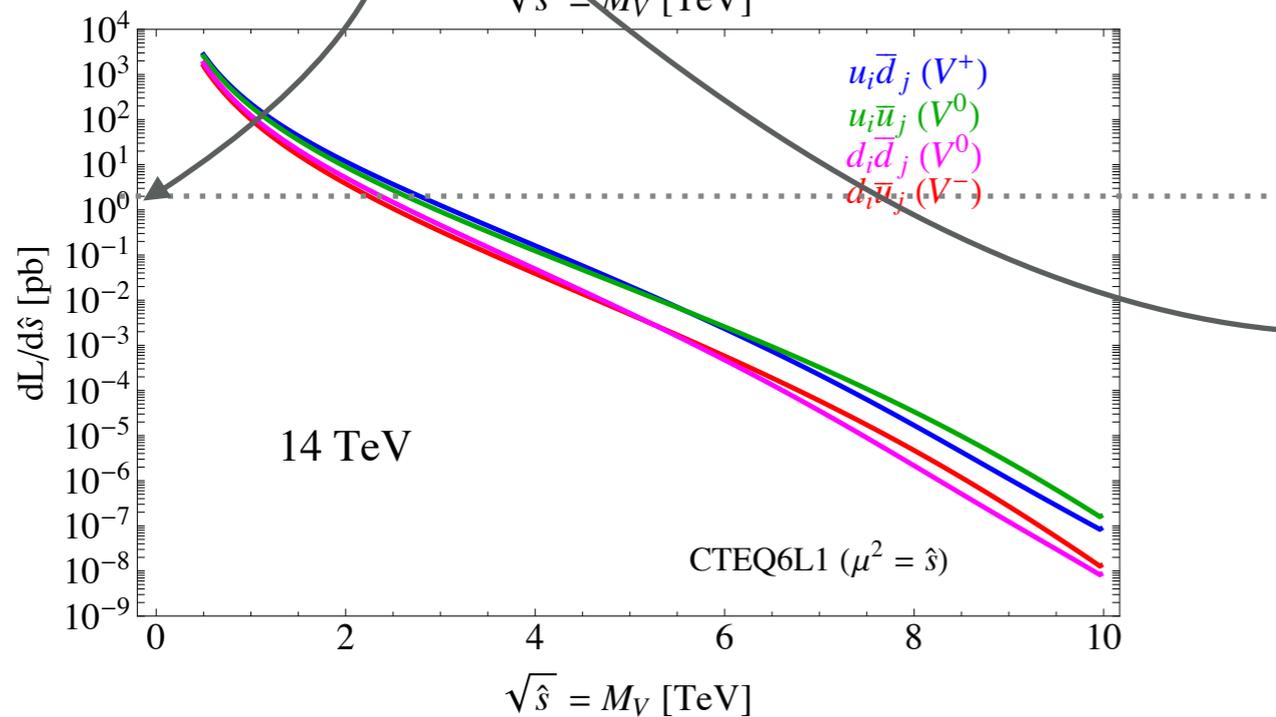
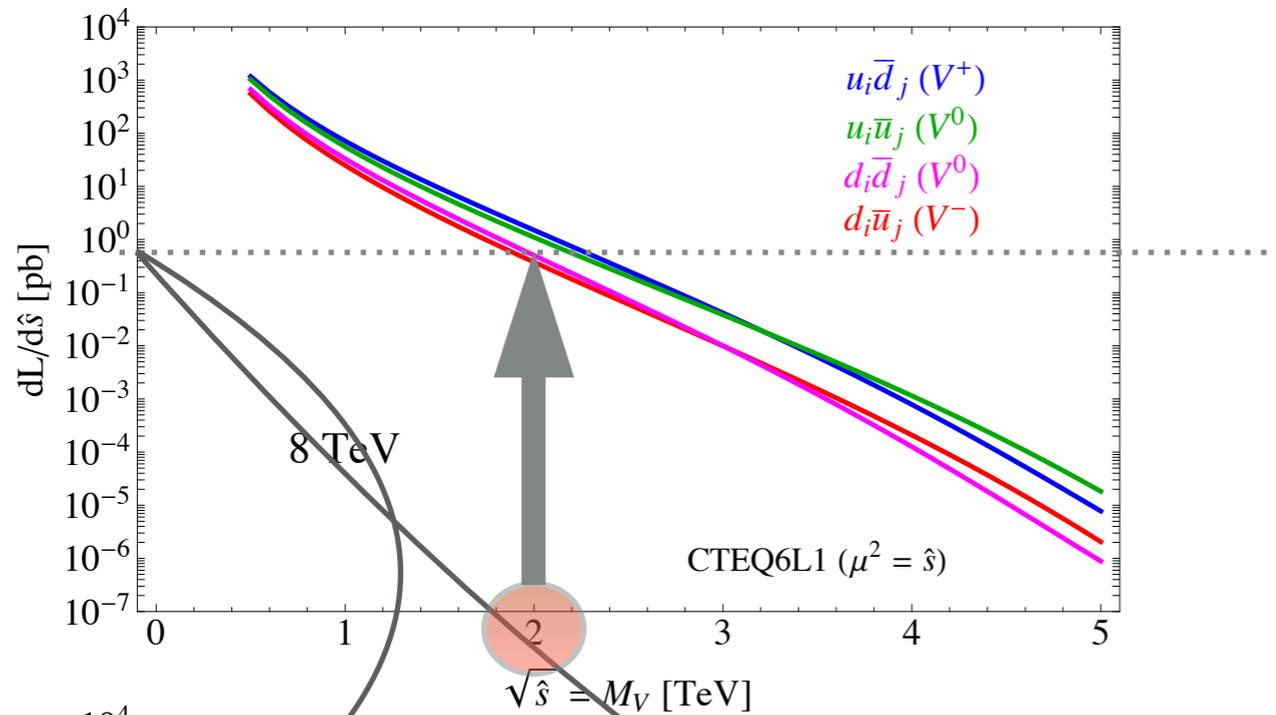
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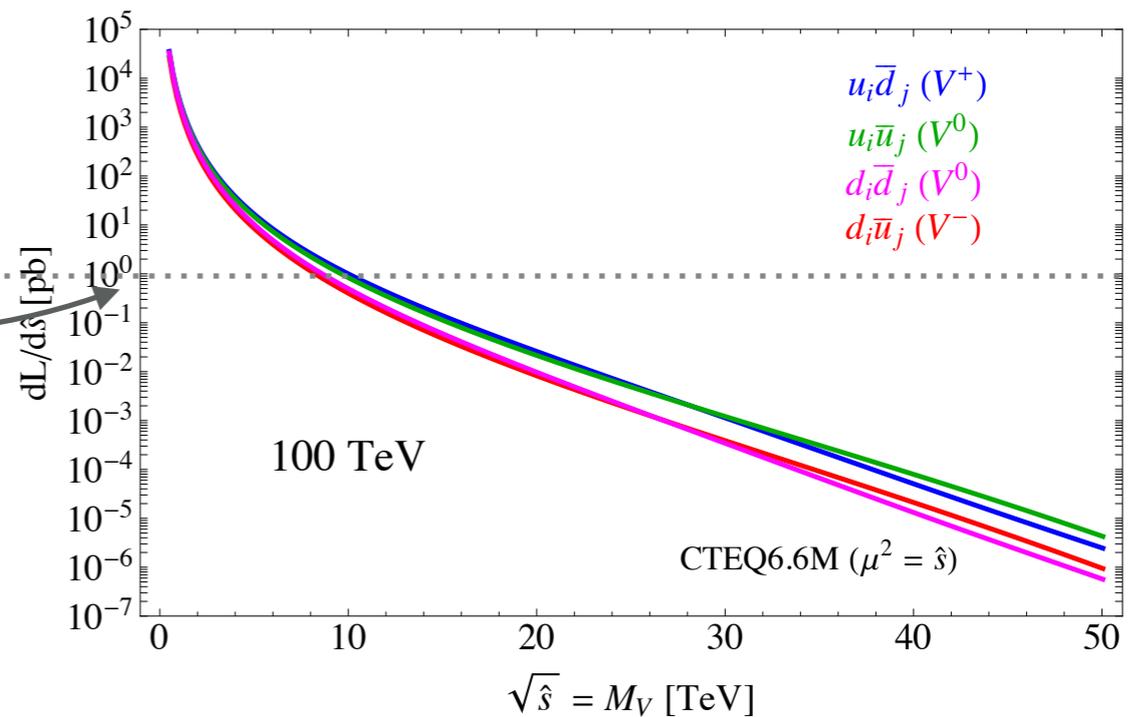
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background rescales with parton luminosities



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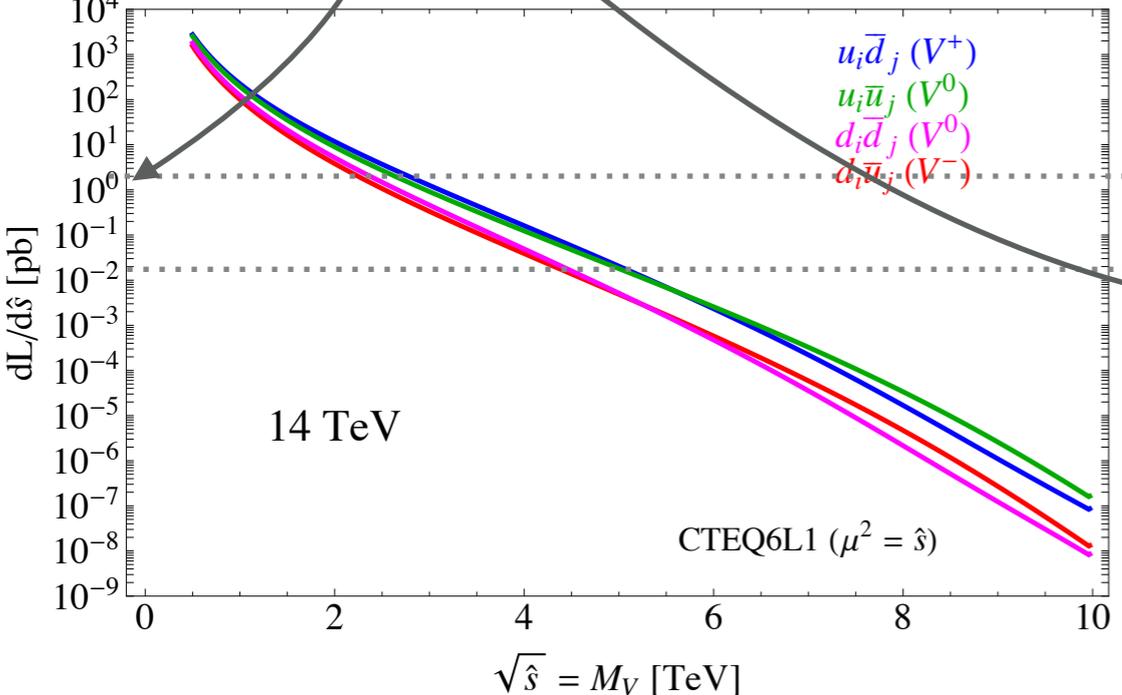
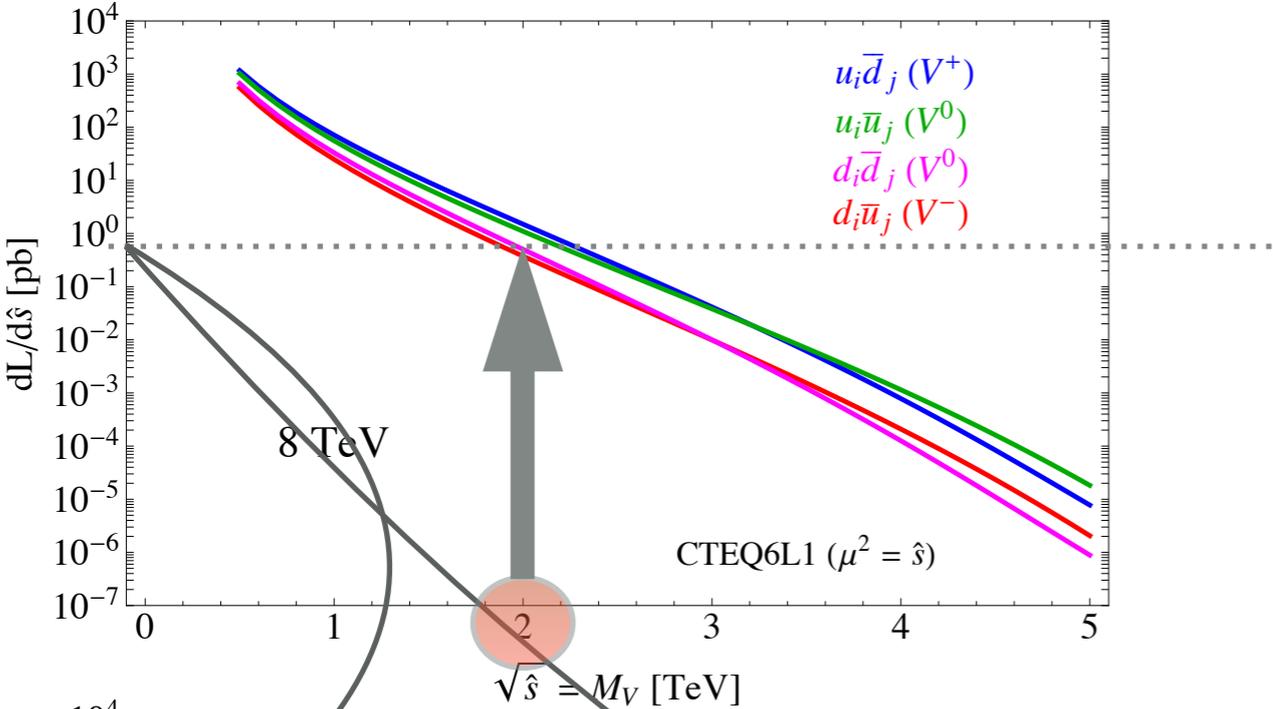
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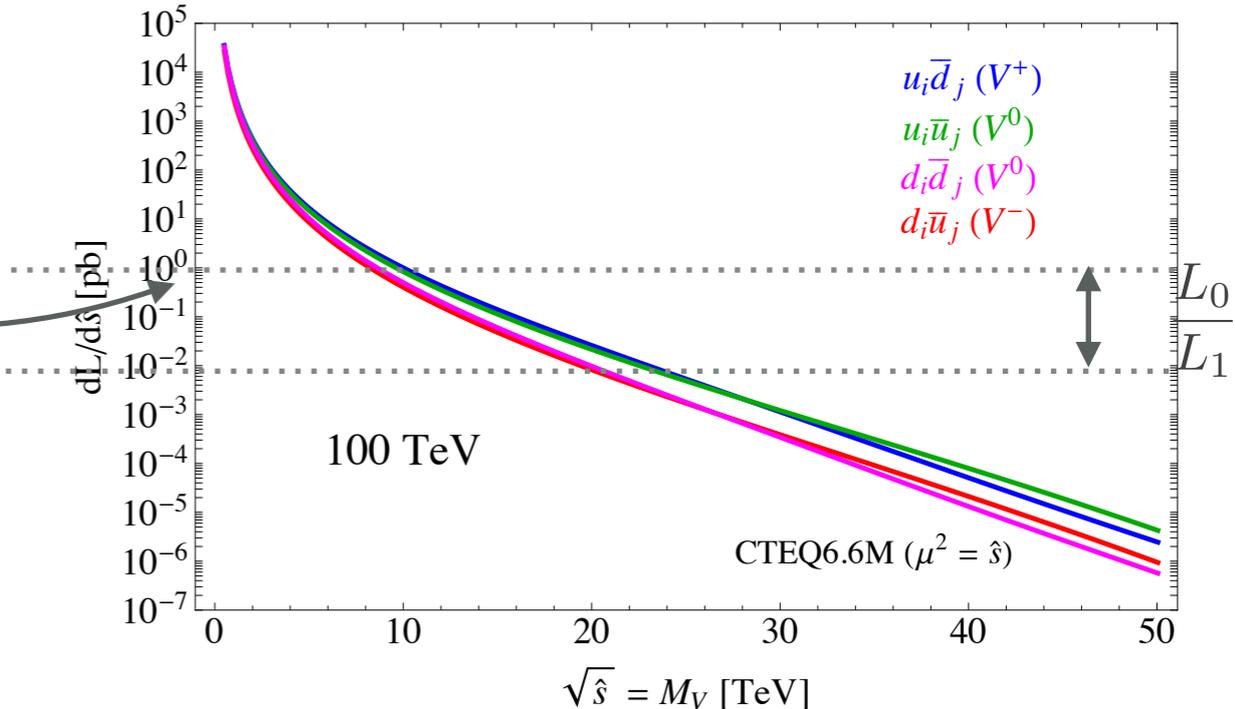
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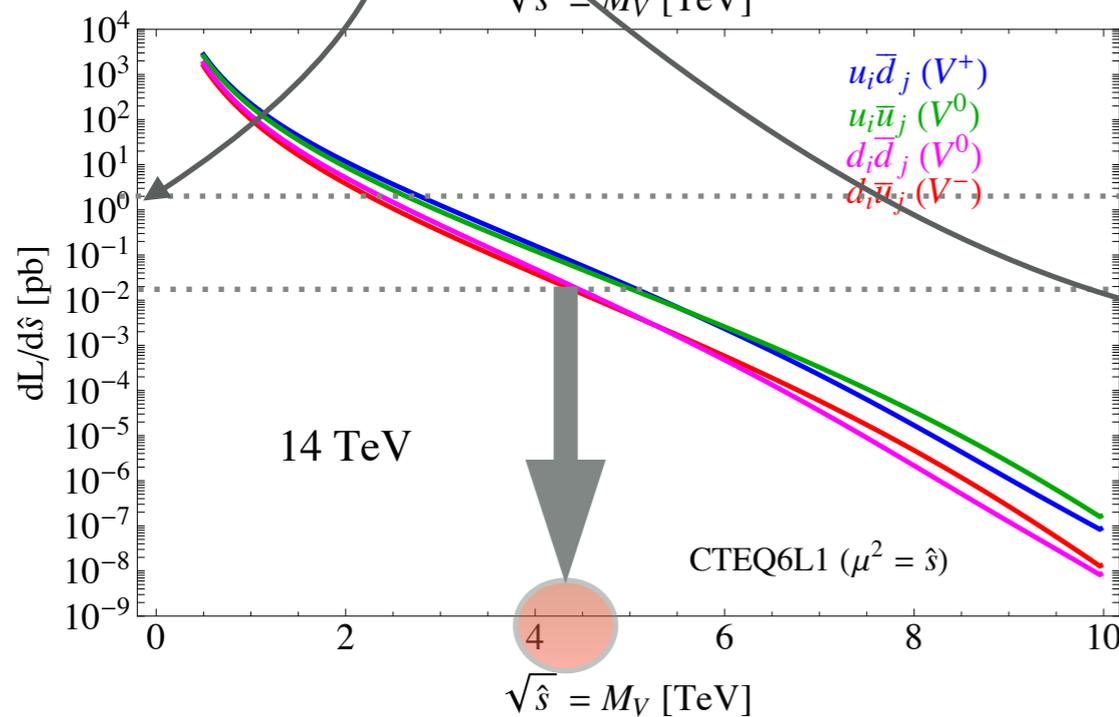
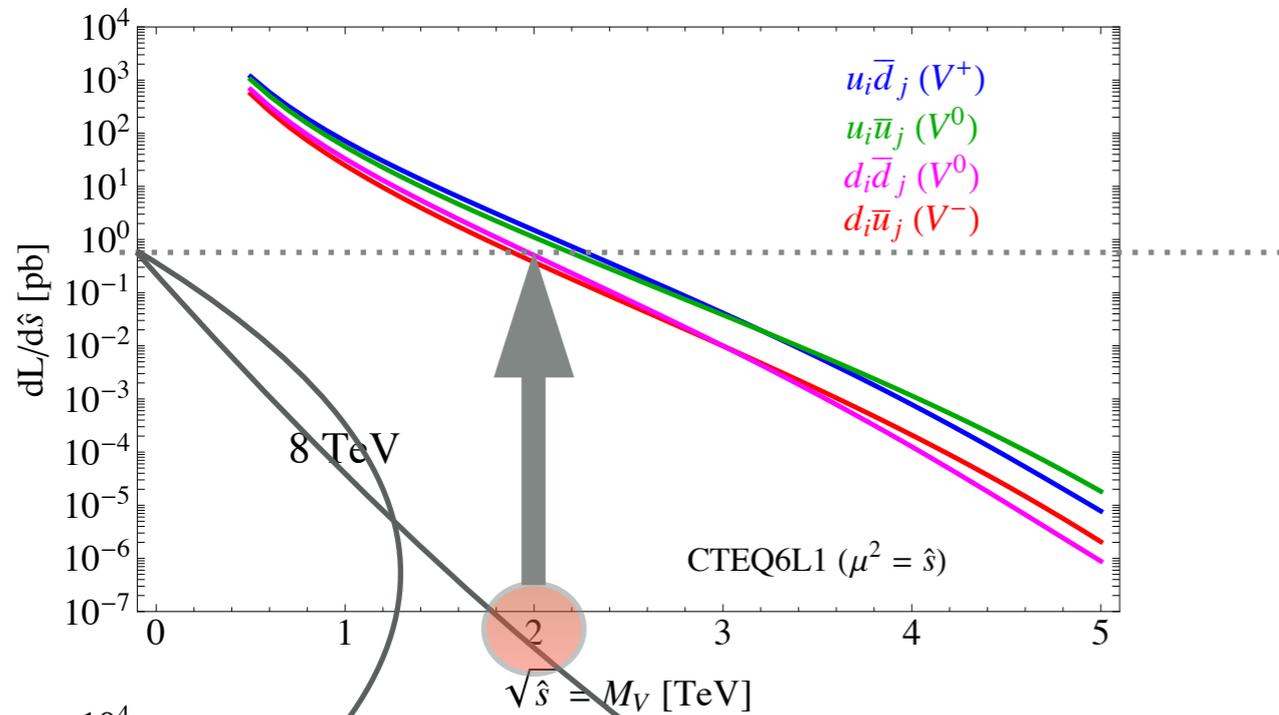


[Thamm, Torre, Wulzer: 1502.01701]

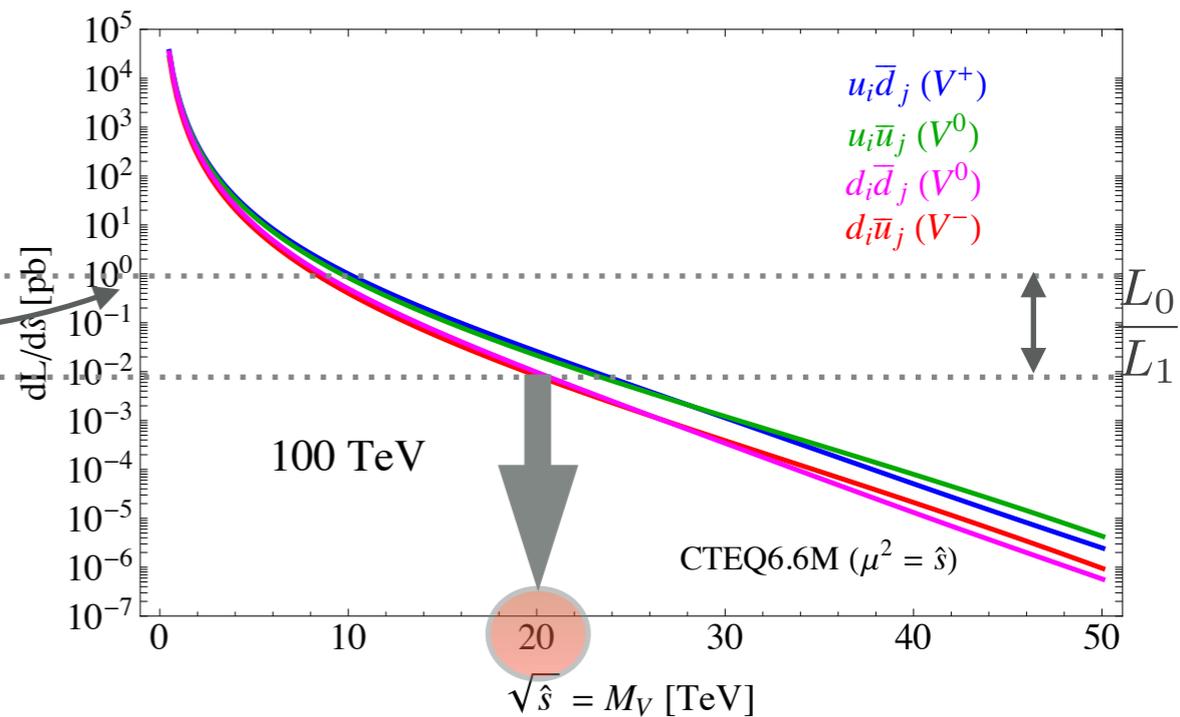
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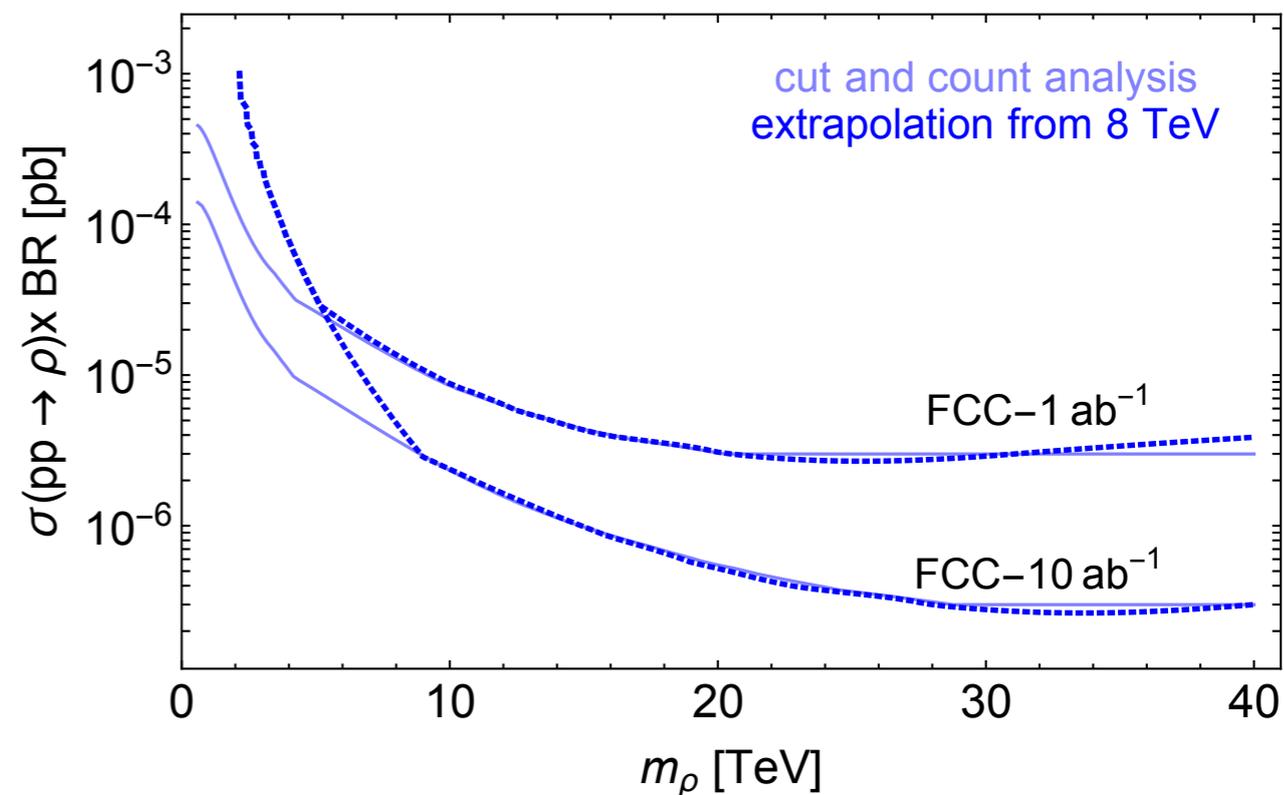
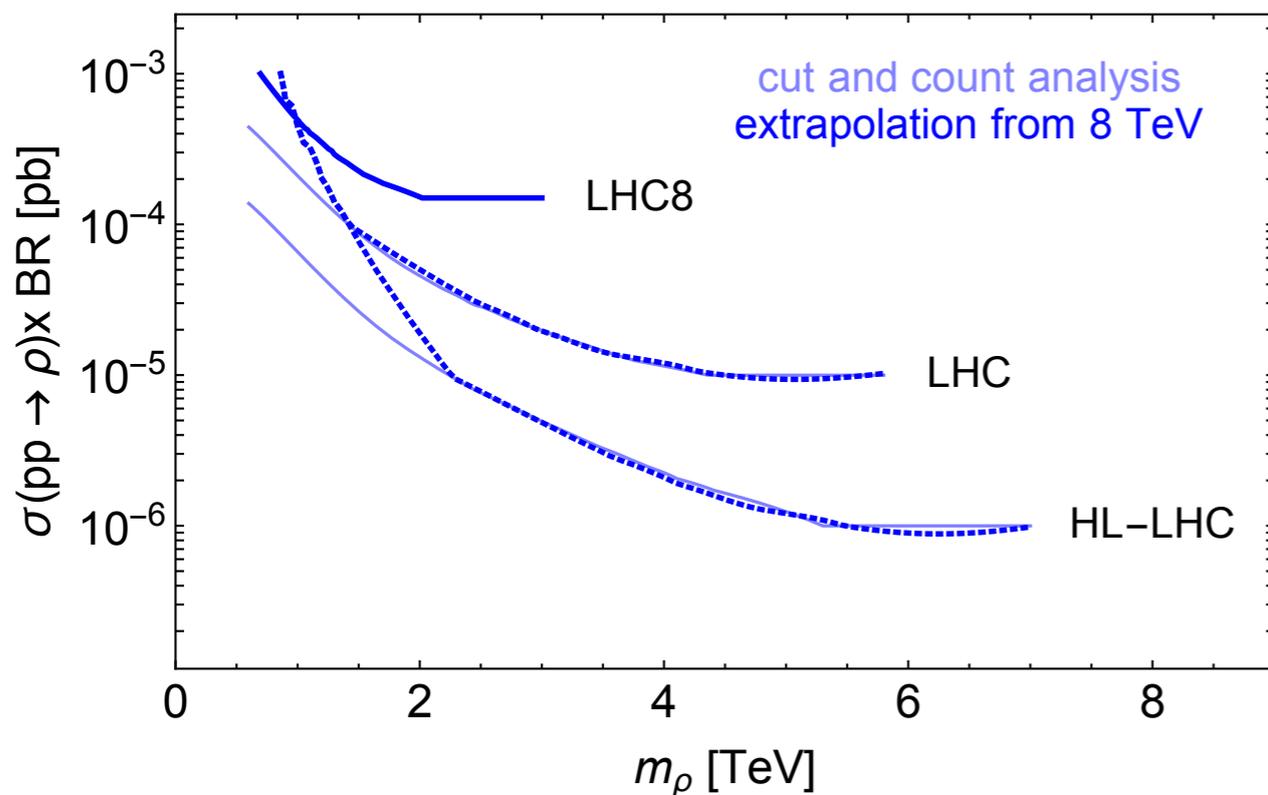


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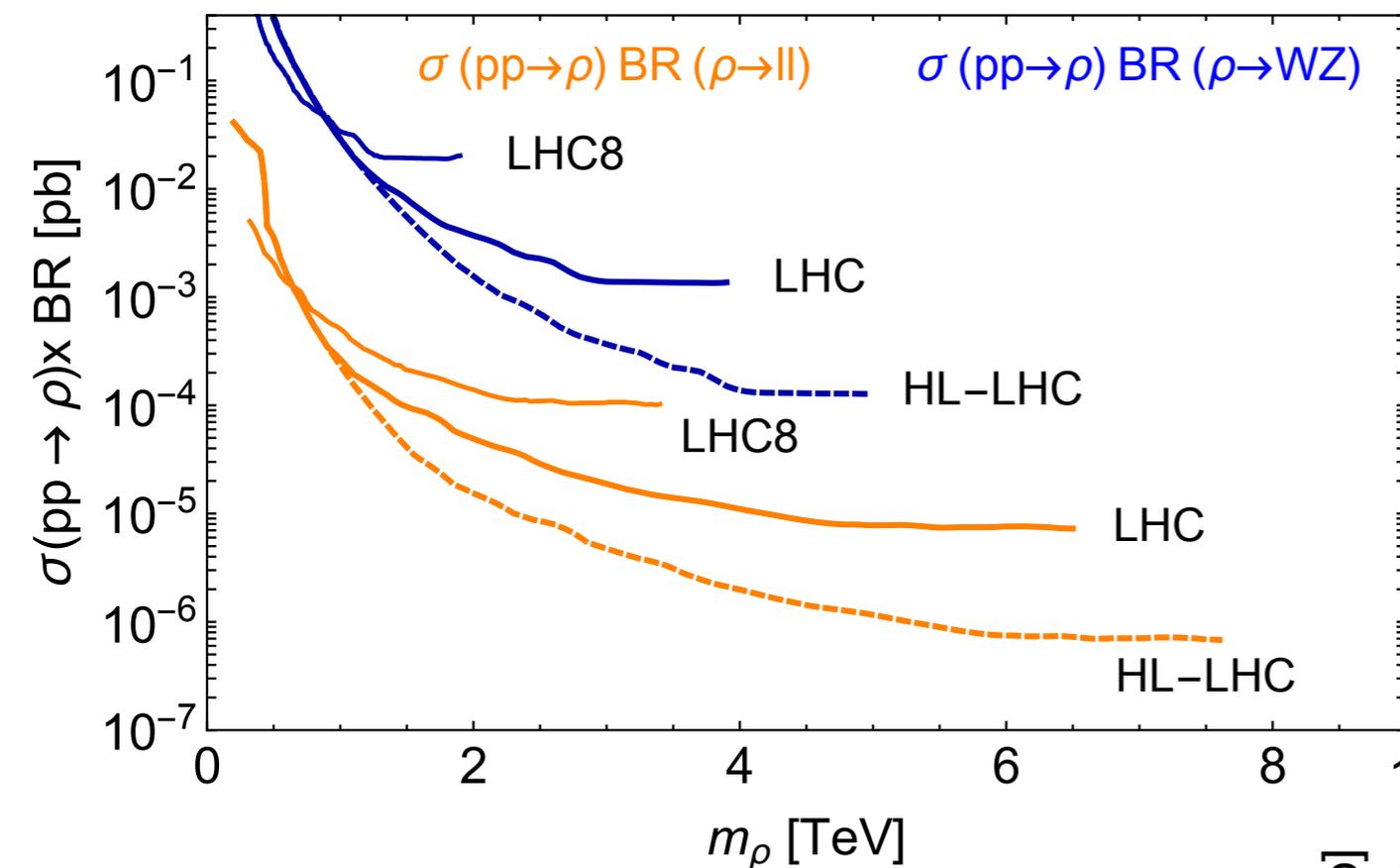
Limit extrapolation - assumptions

- limit only driven by background for a cut-and-count experiment of events within narrow window
- shape analyses depend on background and signal kinematical distributions
- however, no large deviations expected



Limit extrapolation

current 8 TeV LHC limits and extrapolated bounds



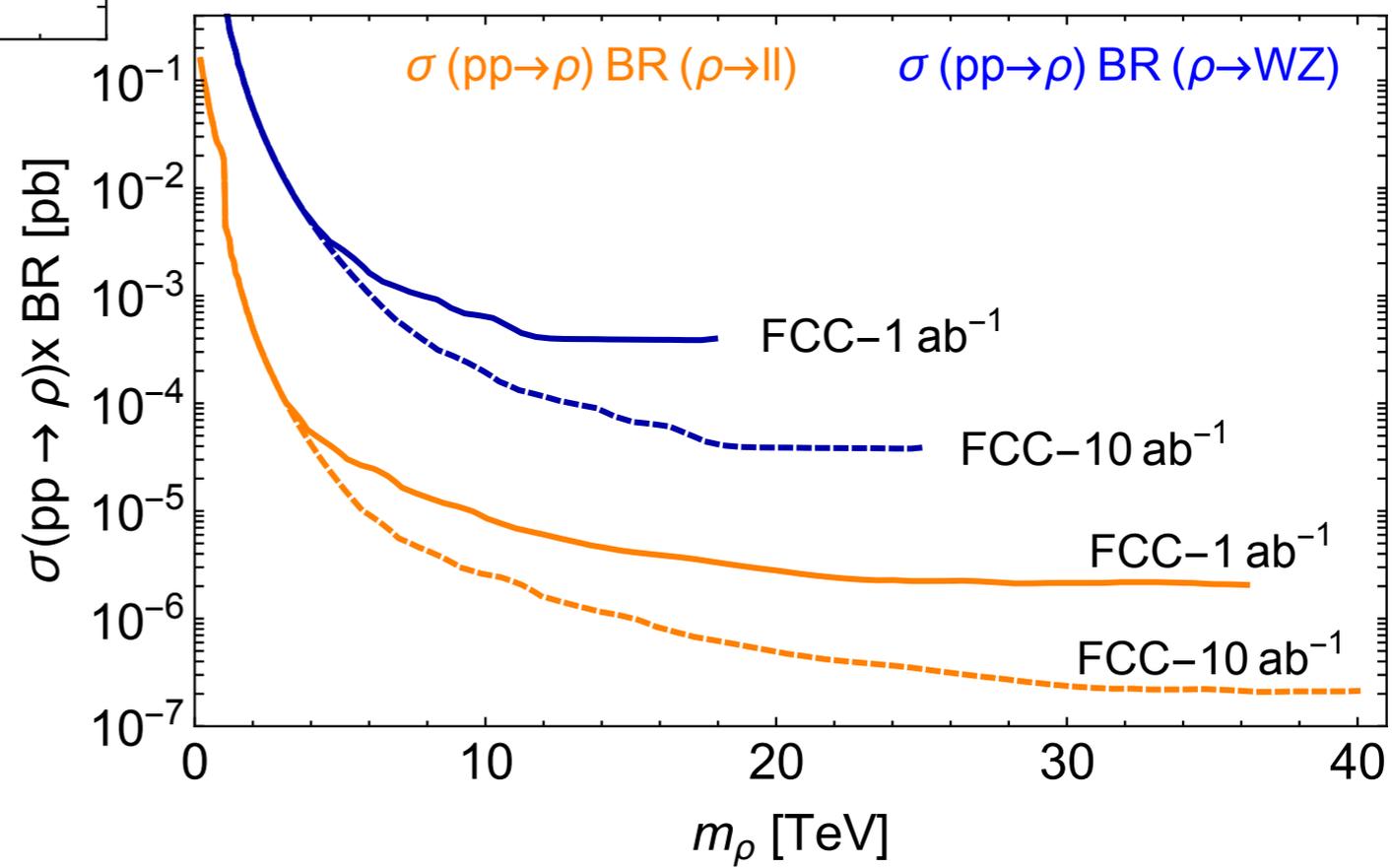
CMS search for

- opposite sign di-leptons
- fully leptonic WZ

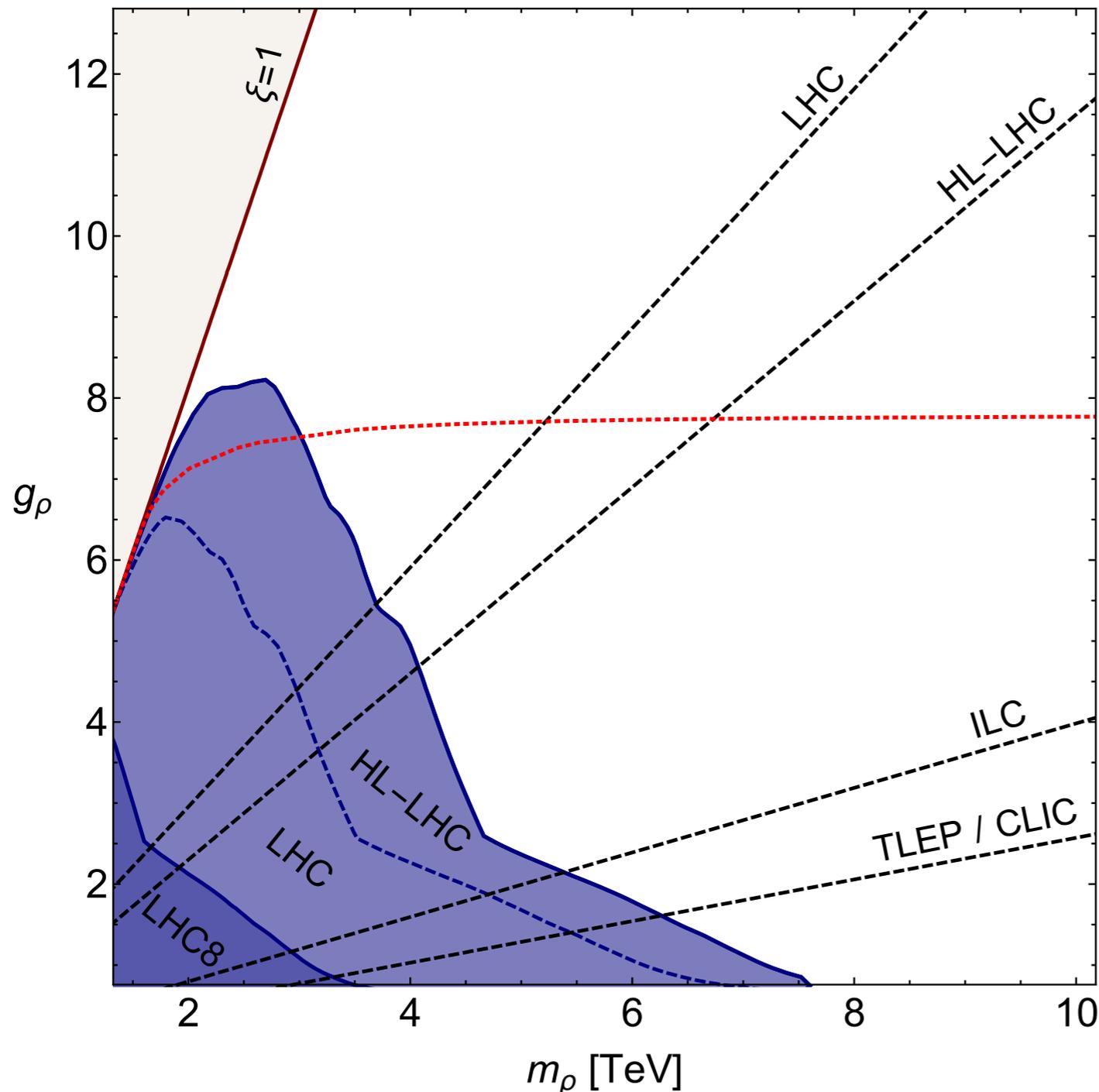
[CMS-PAS-EXO-12-061]
[ATLAS 1405.4123]

[CMS 1407.3476]
[ATLAS 1406.4456]

- constant at large masses
(zero background events)
- too conservative bounds at low masses



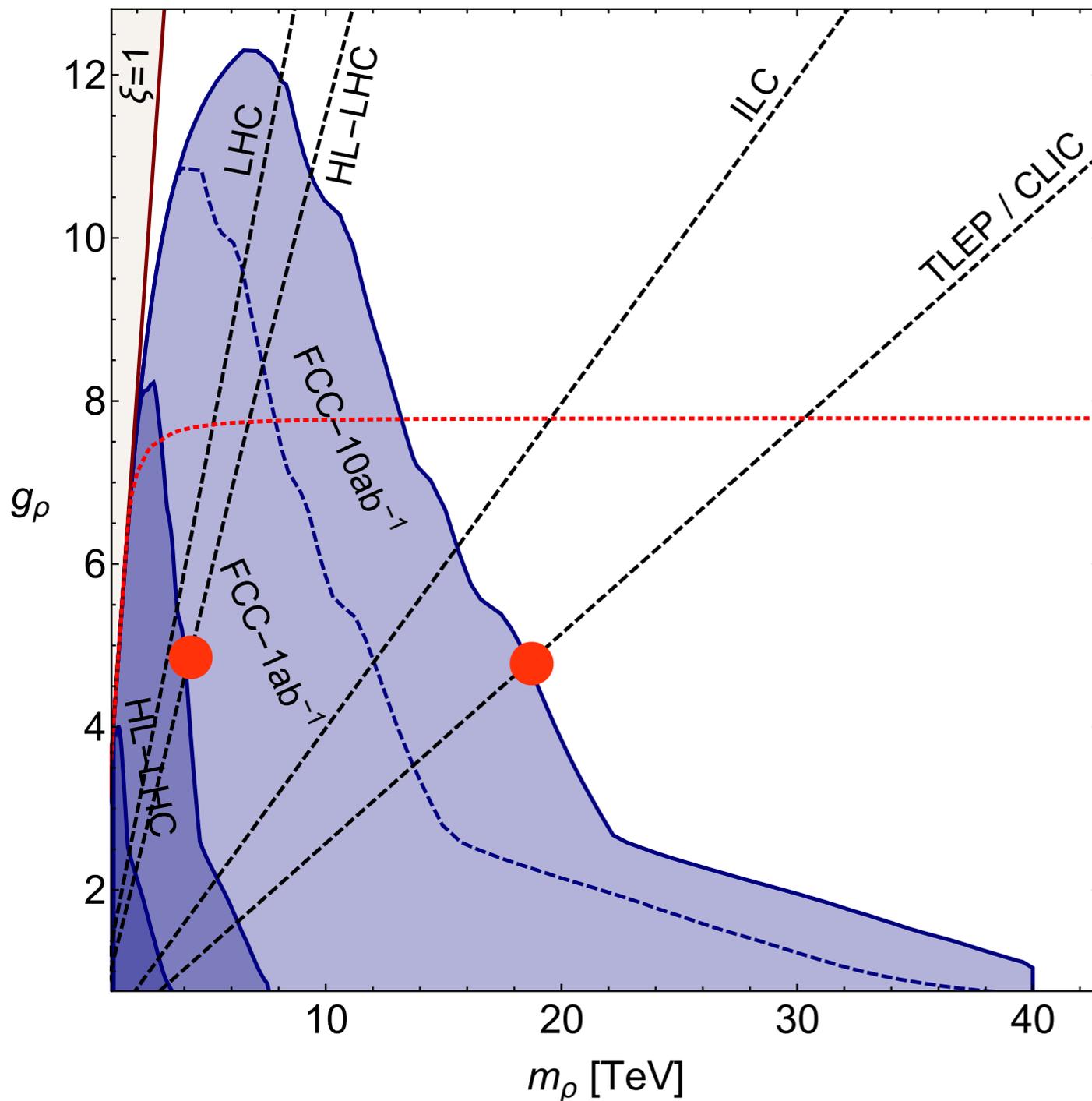
Results in (m_ρ, g_ρ)



95% C.L.

- theoretically excluded $\xi \leq 1$
- LHC8 at 8 TeV with 20 fb^{-1}
- LHC at 14 TeV with 300 fb^{-1}
- HL-LHC at 14 TeV with 3 ab^{-1}
- di-leptons more sensitive for small g_ρ
- di-boson more sensitive for large g_ρ
- increase in \sqrt{s} : improves mass reach
- increase in L: improves g_ρ reach
- resonances too broad for large g_ρ

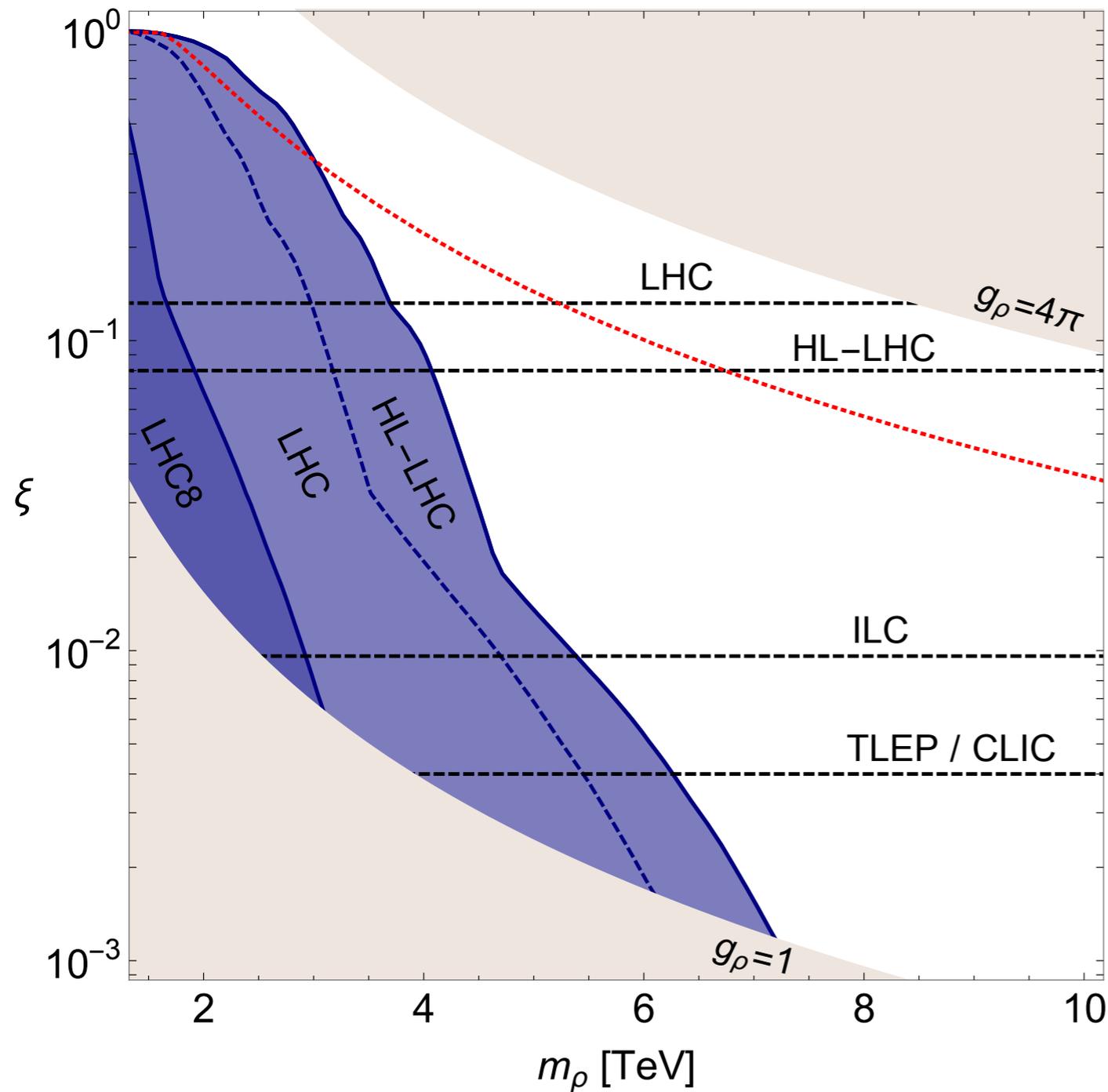
Results in (m_ρ, g_ρ)



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HL-LHC at 14 TeV with 3 ab⁻¹
- direct: more effective for small g_ρ
ineffective for large g_ρ
- indirect: more effective for large g_ρ

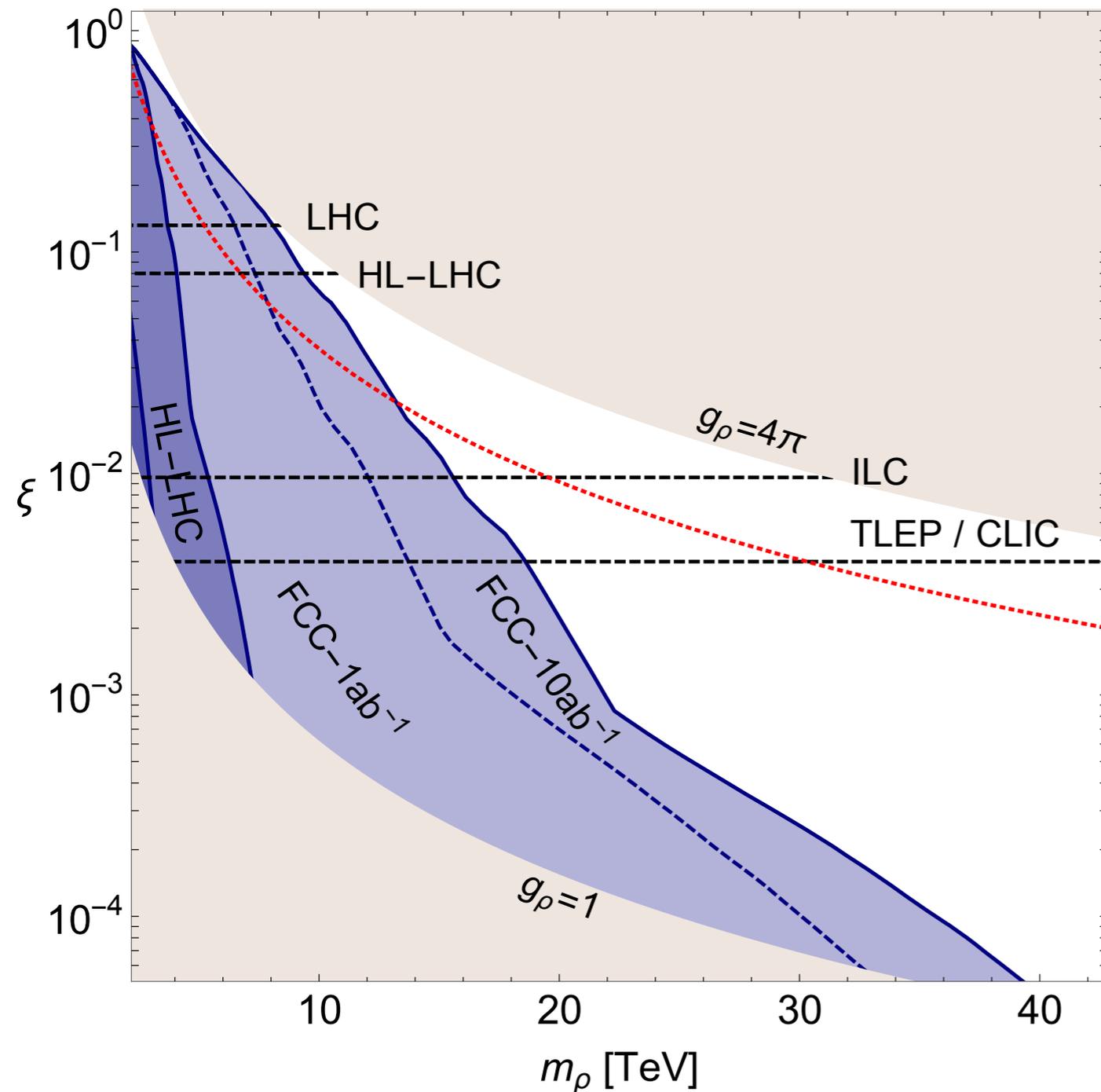
Results in (m_ρ, ξ)



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- theoretically excluded $1 \leq g_\rho \leq 4\pi$
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Conclusions

- direct and indirect searches complementary
- reach of direct and indirect searches depend on coupling g_ρ
 - weak coupling favours direct
 - strong coupling favours indirect
- at this stage no clear favourite
- need more information: potential in precision measurements of FCC

Backup

Limit extrapolation

Input: experimental bounds on $\sigma \times \text{BR}$ at $\sqrt{s_0} = 8 \text{ TeV}$ with $L_0 \simeq 20 \text{ fb}^{-1}$ for various search channels



- extrapolate limits to different proton-proton collider at \sqrt{s} and L
- driven by number of background events in a small invariant mass window around the resonance peak

$$\frac{\Delta \hat{s}}{m_\rho^2} = 10\%$$

$$B(s, L, m_\rho) = B(s_0, L_0, m_\rho^0)$$

output

same limit on number of signal events

- excluded cross section at the equivalent mass

$$[\sigma \times \text{BR}](s, L; m_\rho) = \frac{L_0}{L} \cdot [\sigma \times \text{BR}](s_0, L_0; m_\rho^0)$$

Limit extrapolation - equivalent mass

- extraction of equivalent mass

[Thamm, Torre, Wulzer: 1502.01701]

$$B(s, L, m_\rho) = B(s_0, L_0, m_\rho^0)$$

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partonic cross-section
contributing to background

- partonic cross section: SM process much above SM masses

$$[\hat{s}\hat{\sigma}_{ij}(\hat{s})] \simeq c_{ij} \rightarrow \text{constant}$$

- parton luminosities constant within small integration limit

$$B(s, L, m_\rho) \propto \frac{\Delta\hat{s}}{m_\rho^2} \cdot L \cdot \sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_\rho; \sqrt{s})$$

- equating backgrounds

$$\sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_\rho; \sqrt{s}) = \frac{L_0}{L} \sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_\rho^0; \sqrt{s_0})$$

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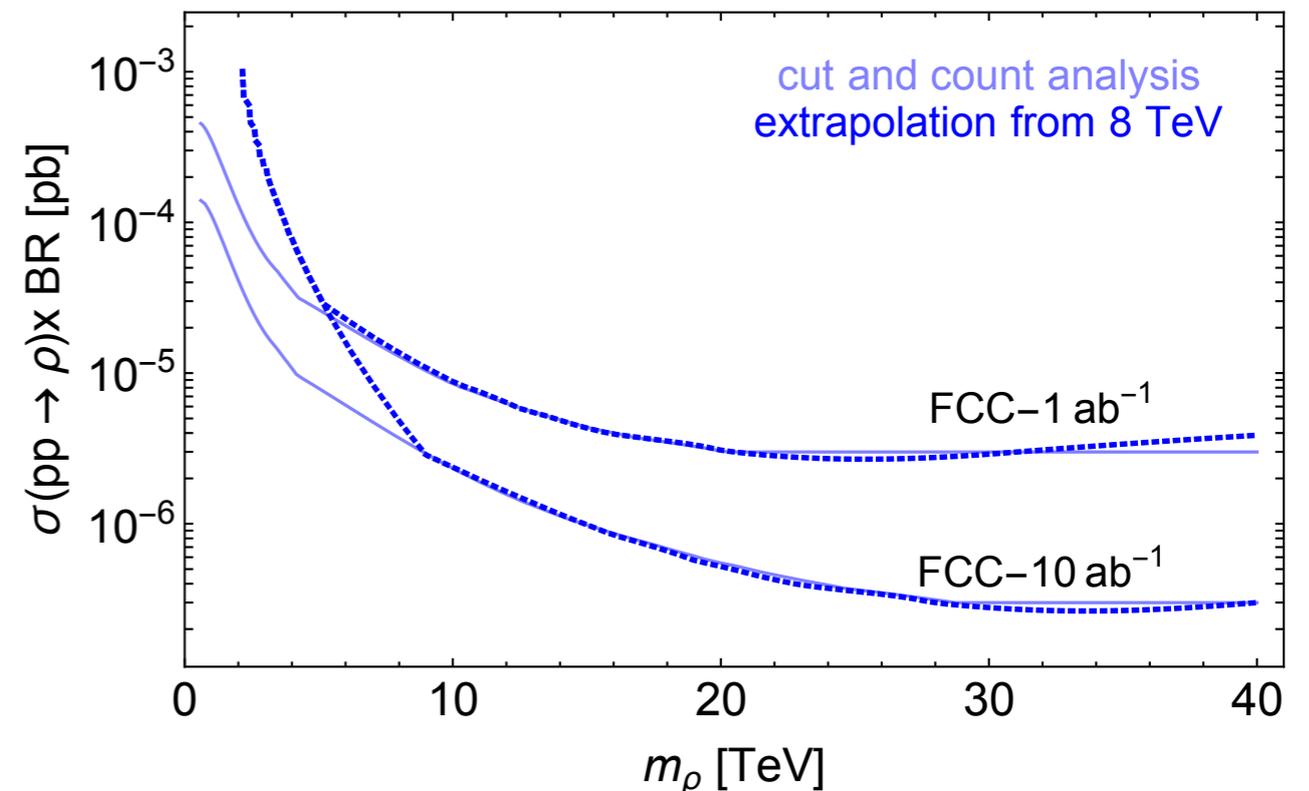
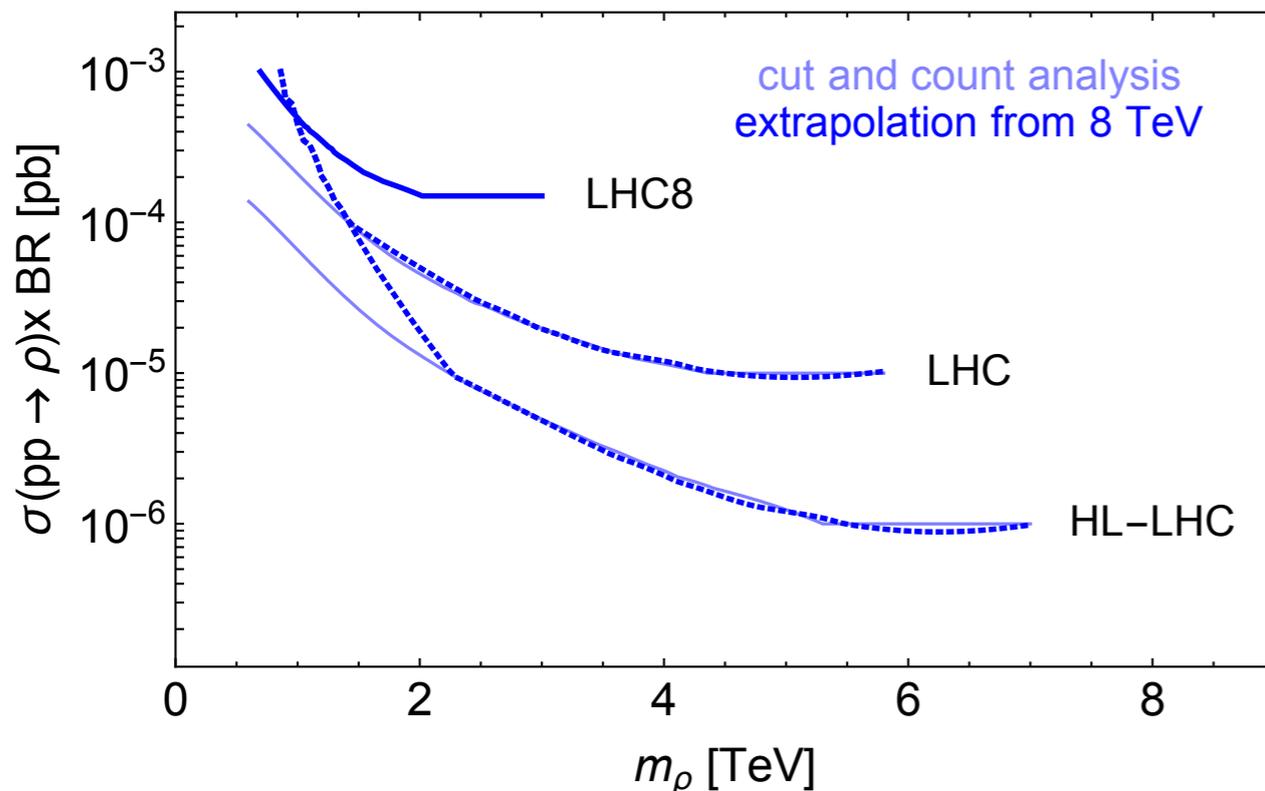
Limit extrapolation - equivalent mass

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- need relevant background process and parton luminosities
- sum drops for single partonic initial state
- otherwise linear combination of parton luminosities weighted by c_{ij}

Limit extrapolation - equivalent mass

- Subtlety at low masses:
 - lowest mass point of 8 TeV limit determined by sensitivity of specific analysis
- arbitrary lowest equivalent mass depending on luminosity
- smoothly raise luminosity of future collider
- extrapolated limit is the strongest at each mass
- low-mass limit conservative, not optimal



EWPT

- set some of strongest constraints on CH models
- incalculable UV contributions can relax constraints

$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{\Lambda}{m_h}\right) + \frac{m_W^2}{m_\rho^2} + \alpha \frac{g^2}{16\pi^2}\xi,$$
$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{\Lambda}{m_h}\right) + \beta \frac{3y_t^2}{16\pi^2}\xi$$

tree level exchange of vector resonances

IR contribution due to Higgs coupling modifications

short distance effects

[Grojean, Matsedonskyi, Panico: 1306.4655]

- α and β constants of order 1
- define $\chi^2(\xi, m_\rho, \alpha, \beta)$ and marginalise

EWPT

- define $\chi^2(\xi, m_\rho, \alpha, \beta)$ and marginalise
- to avoid unnatural cancellations

$$\delta_{\chi^2} = \frac{\chi^2(\xi, m_\rho, \alpha = 0, \beta = 0)}{\chi^2(\xi, m_\rho, \alpha, \beta)}$$

