Workshop on the physics of HL-LHC,
and perspectives at HE-LHC,
01 November 2017

Direct vs indirect future probes of a strong electroweak symmetry breaking sector

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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

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[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer: arXiv:1609.08157]
[Alioli, Farina, Pappadopulo, Ruderman: arXiv:1706.03068]

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 (light to reproduce m_h)

  [Mrazek, Wulzer: arXiv:0909.3977]
  [De Simone, Matsedonskyi, Rattazzi, Wulzer: arXiv:1211.5663]

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

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

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

- Flavour

- for illustration focus on minimal composite Higgs model
- parameter space: m_ρ $\quad g_\rho$ $\quad \xi = \frac{g_\rho^2}{m_\rho^2} v^2$

Minimal Composite Higgs

[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]

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

breaking scale $f > v$

Higgs emerges as a pseudo-NG boson

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

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

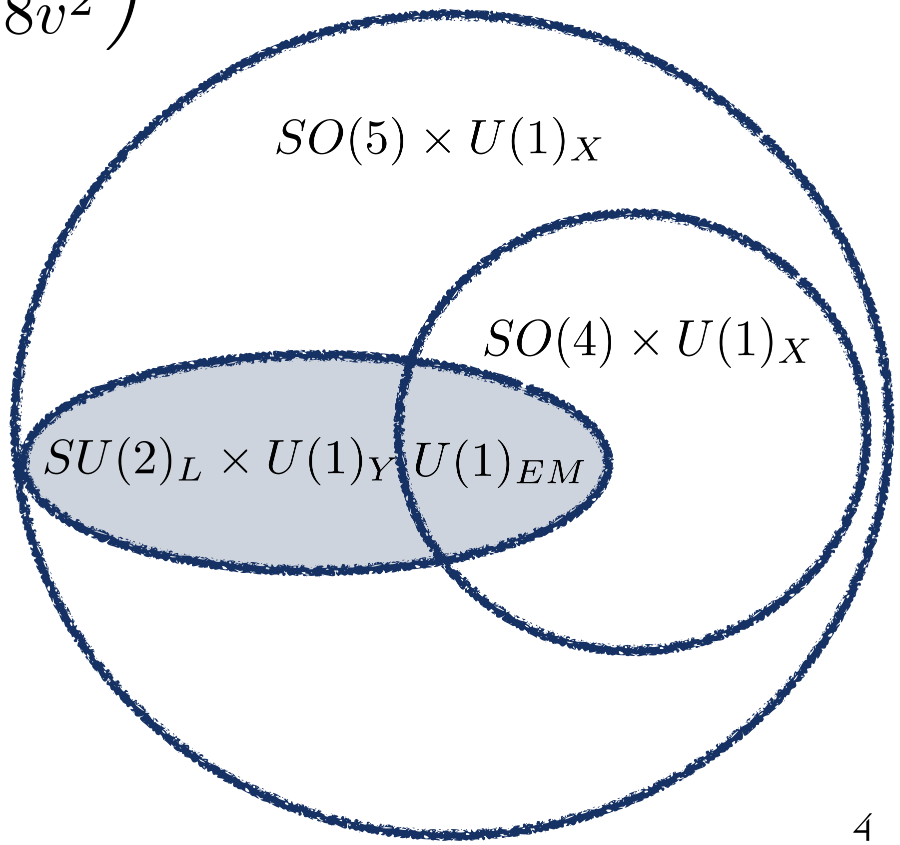
$$a = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

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

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

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



Higgs couplings receive corrections of order ξ

Direct vs indirect

- compare the reach of direct and indirect searches on MCHM parameter space
- many studies on sensitivity of indirect measurements at various 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 and 13 TeV LHC
- show extrapolation procedure to estimate bounds at 14 and 27 TeV

Indirect measurements

Collider	Energy	Luminosity	ξ [1σ]
LHC	$14\,\text{TeV}$	$300\,\text{fb}^{-1}$	$6.6 - 11.4 \times 10^{-2}$
LHC	$14\,\text{TeV}$	$3\,\text{ab}^{-1}$	$4 - 10 \times 10^{-2}$
ILC	$250\,\text{GeV}$ $+\ 500\,\text{GeV}$	$250\,\text{fb}^{-1}$ $500\,\text{fb}^{-1}$	4.8-7.8 $\times 10^{-3}$
CLIC	$350\,\text{GeV}$ $+\ 1.4\,\text{TeV}$ $+\ 3.0\,\text{TeV}$	$500\,\text{fb}^{-1}$ $1.5\,\text{ab}^{-1}$ $2\,\text{ab}^{-1}$	2.2 $\times 10^{-3}$
TLEP	$240\,\text{GeV}$ $+\ 350\,\text{GeV}$	$10\,\text{ab}^{-1}$ $2.6\,\text{ab}^{-1}$	2×10^{-3}

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Indirect measurements

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2×10^{-3}
LHC	27 TeV	3 ab^{-1}	???
LHC	27 TeV	10 ab^{-1}	???

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Direct measurements - Limit extrapolation

Input: experimental bounds on $\sigma\times\mathrm{BR}$ at $\sqrt{s_0} = 8\,\mathrm{TeV}$ with $L_0 \simeq 20\,\mathrm{fb}^{-1}$ 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

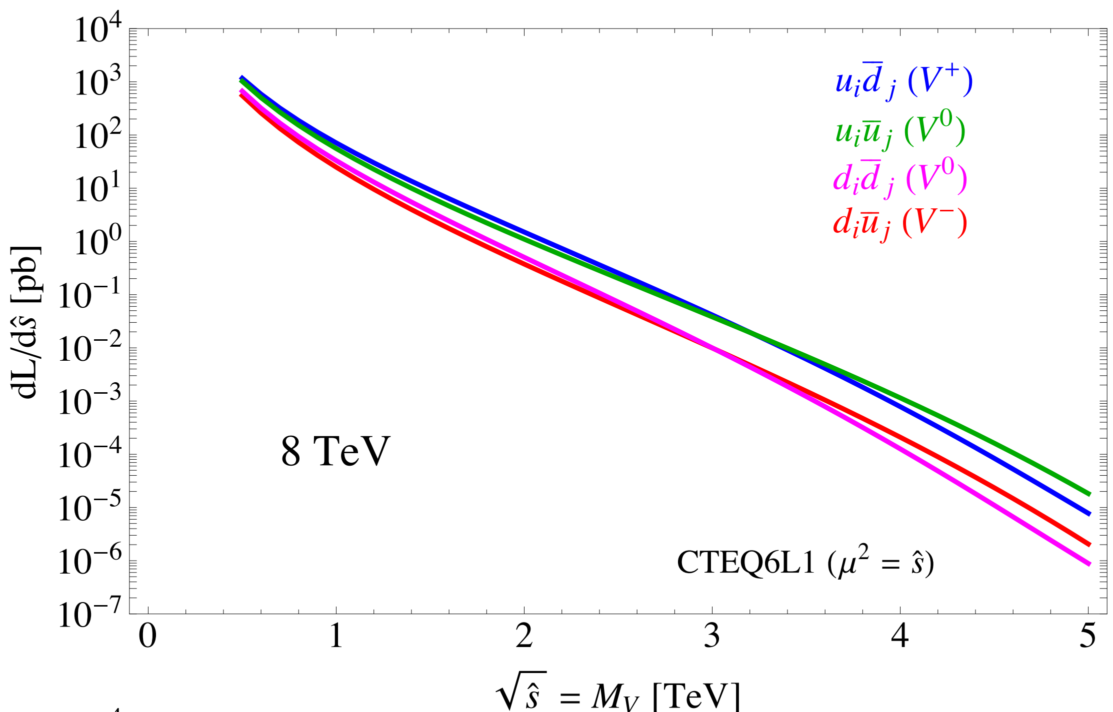
$$[\sigma\times\mathrm{BR}](s, L; m_\rho) = \frac{L_0}{L}\cdot[\sigma\times\mathrm{BR}](s_0, L_0; m_\rho^0)$$

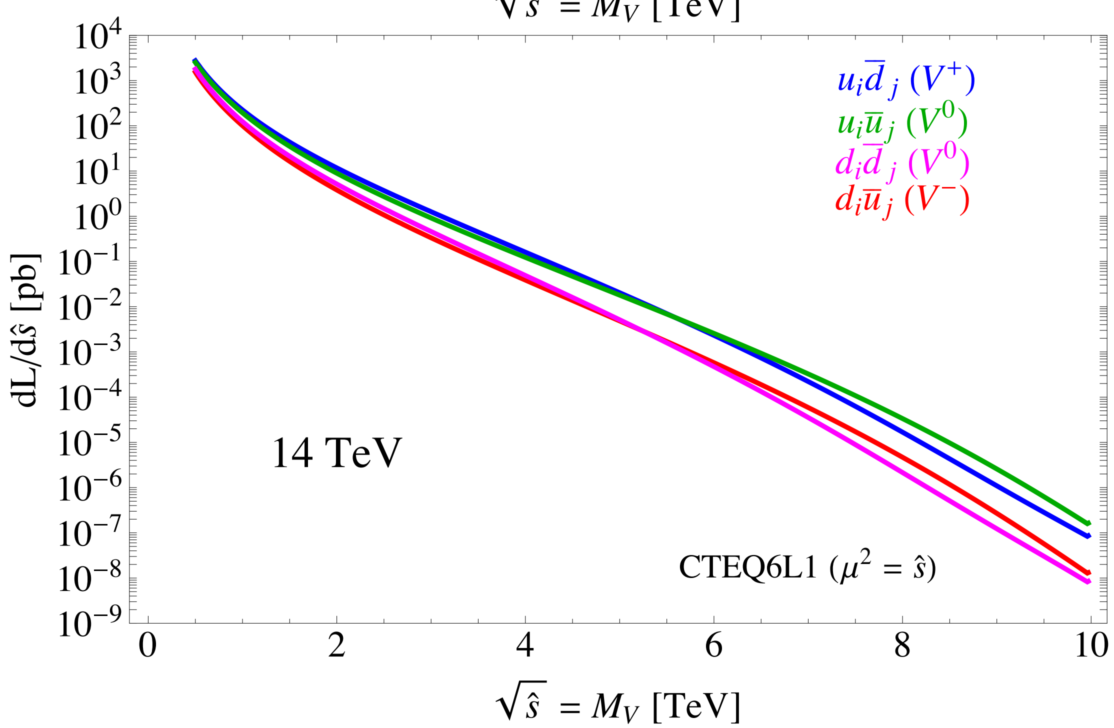
Direct measurements - Limit extrapolation

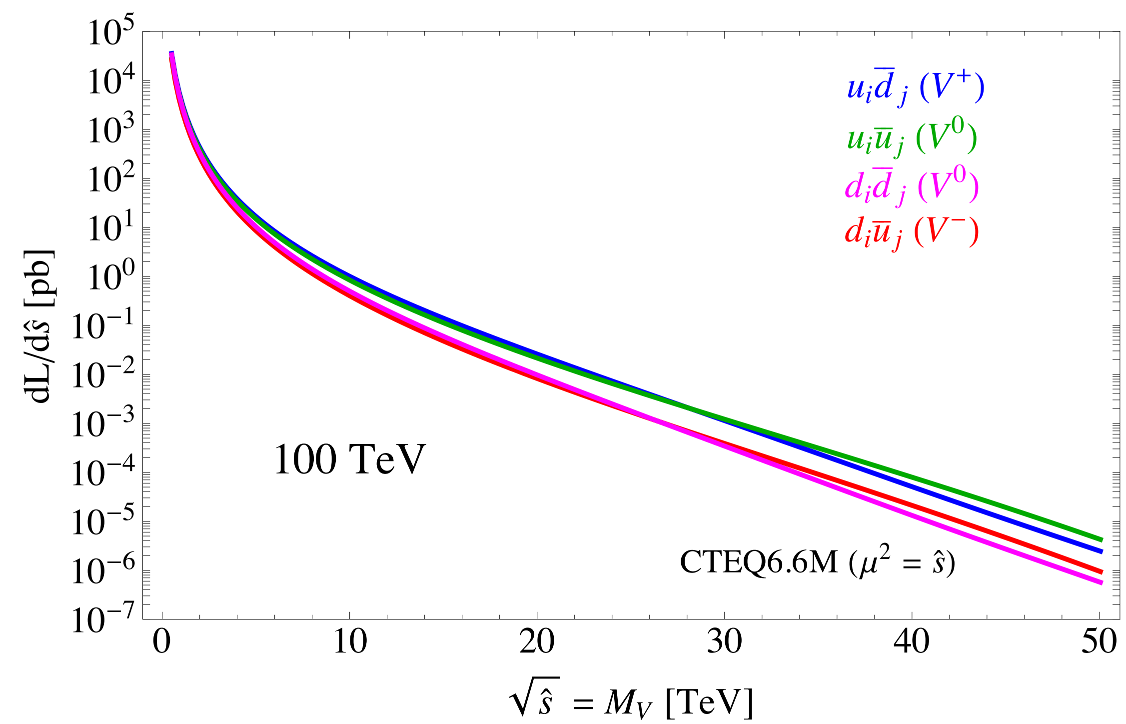
background rescales with parton luminosities

$$B(s, L, m_\rho) \propto L \cdot \sum_{\{i,j\}} \int d\hat{s} \frac{1}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(\sqrt{\hat{s}}; \sqrt{s}) \left[\hat{s}\hat{\sigma}_{ij}(\hat{s})\right]$$

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







[Thamm, Torre, Wulzer: 1502.01701]

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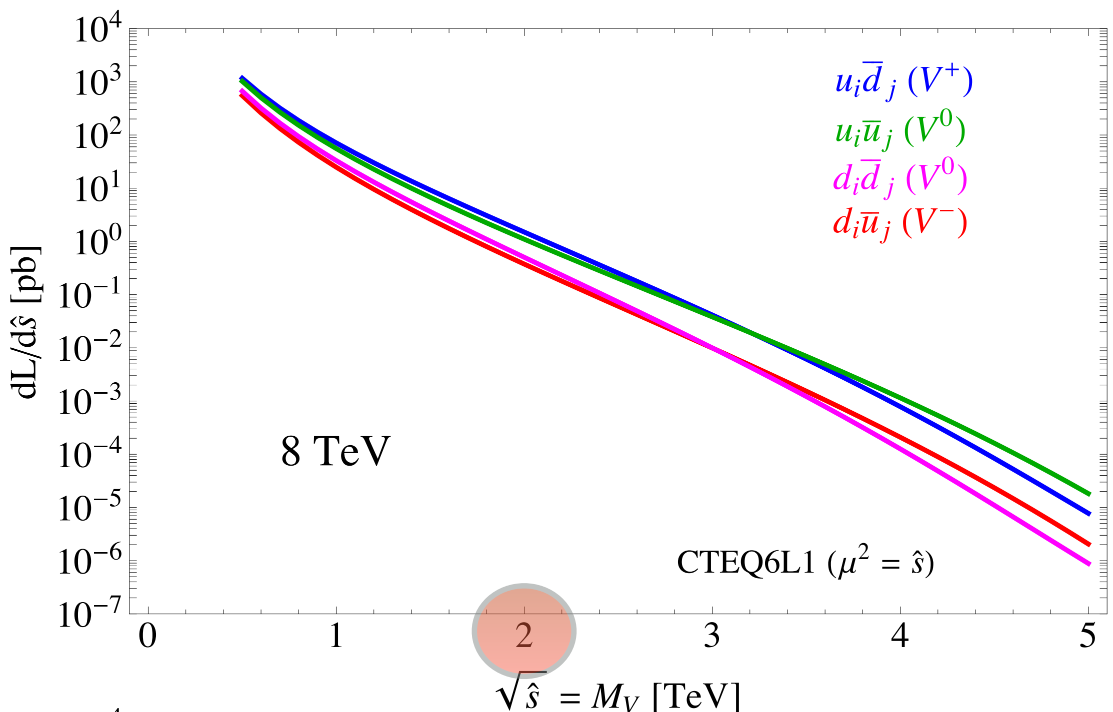

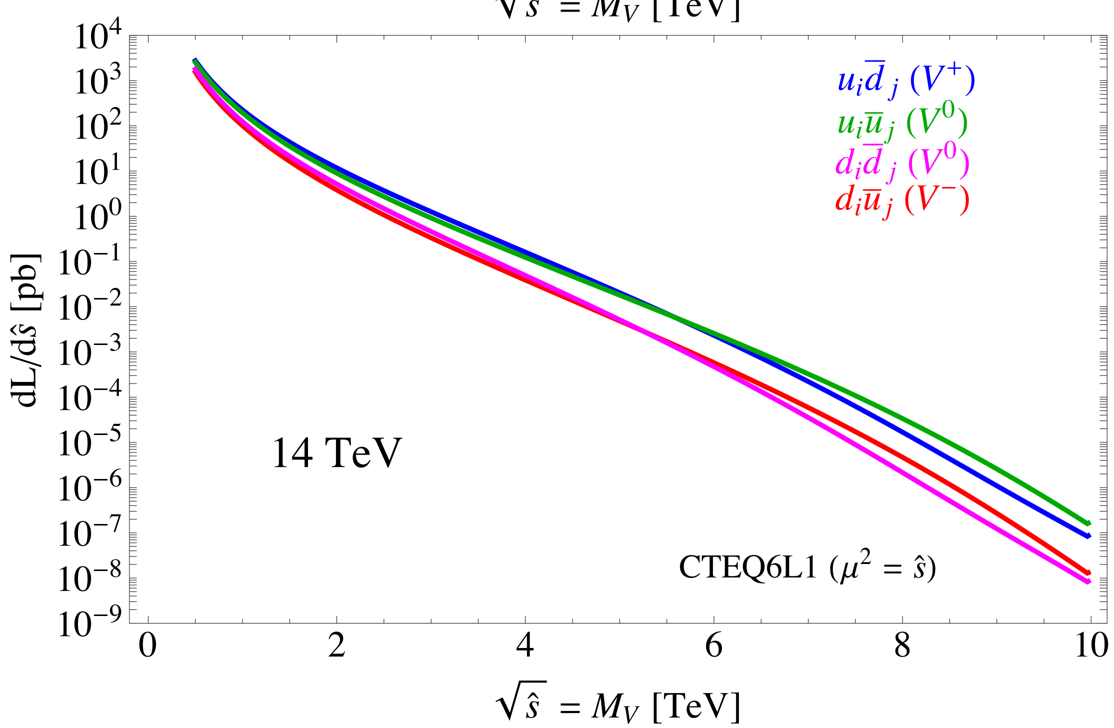

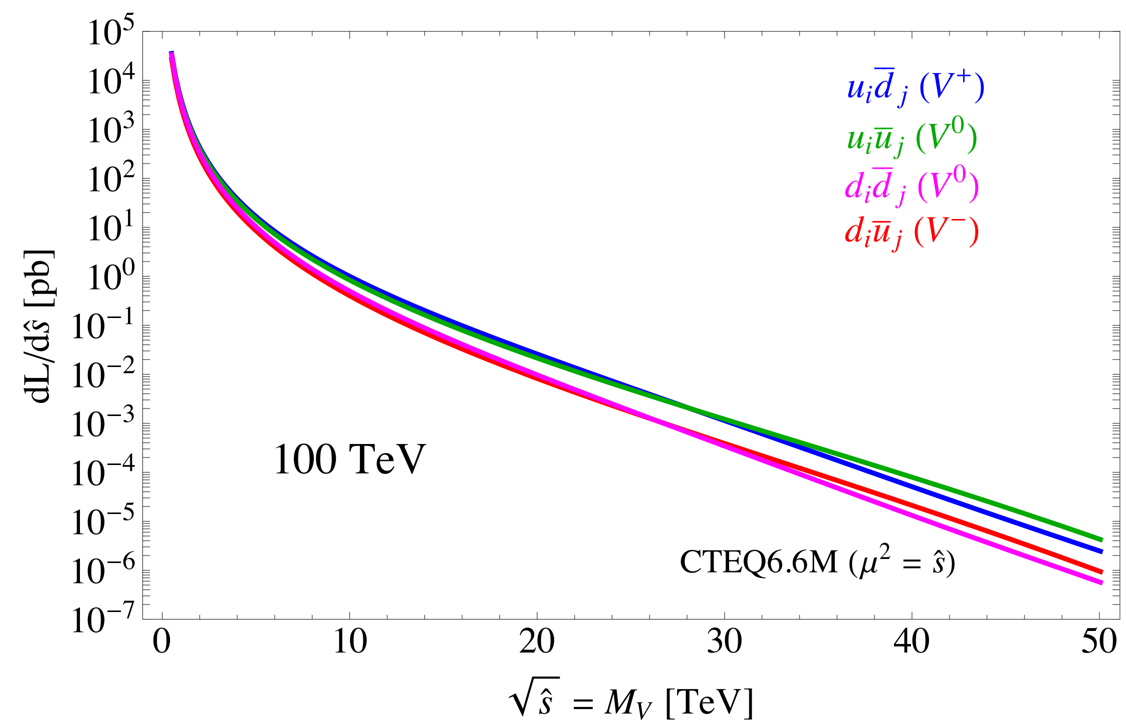

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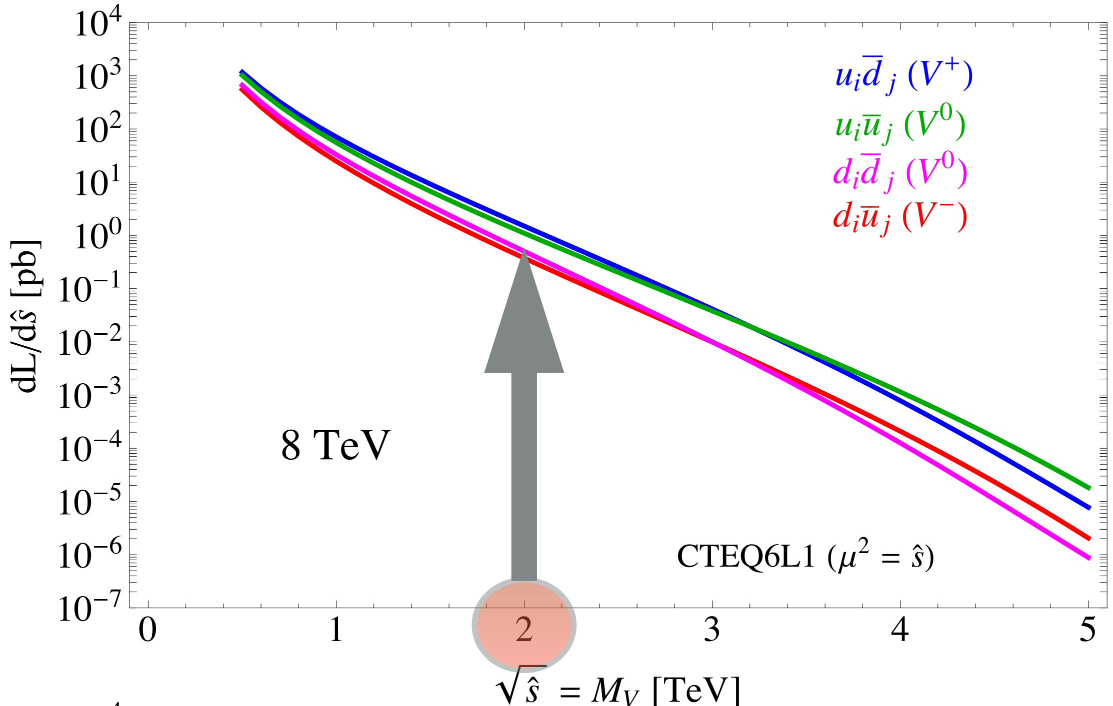

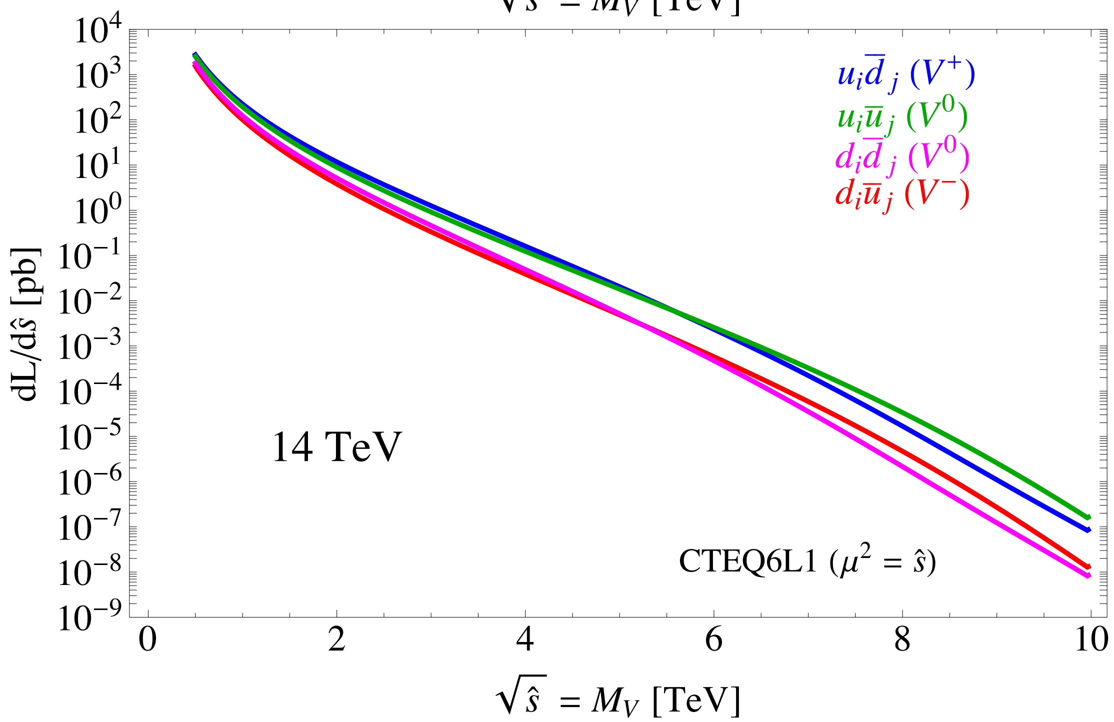

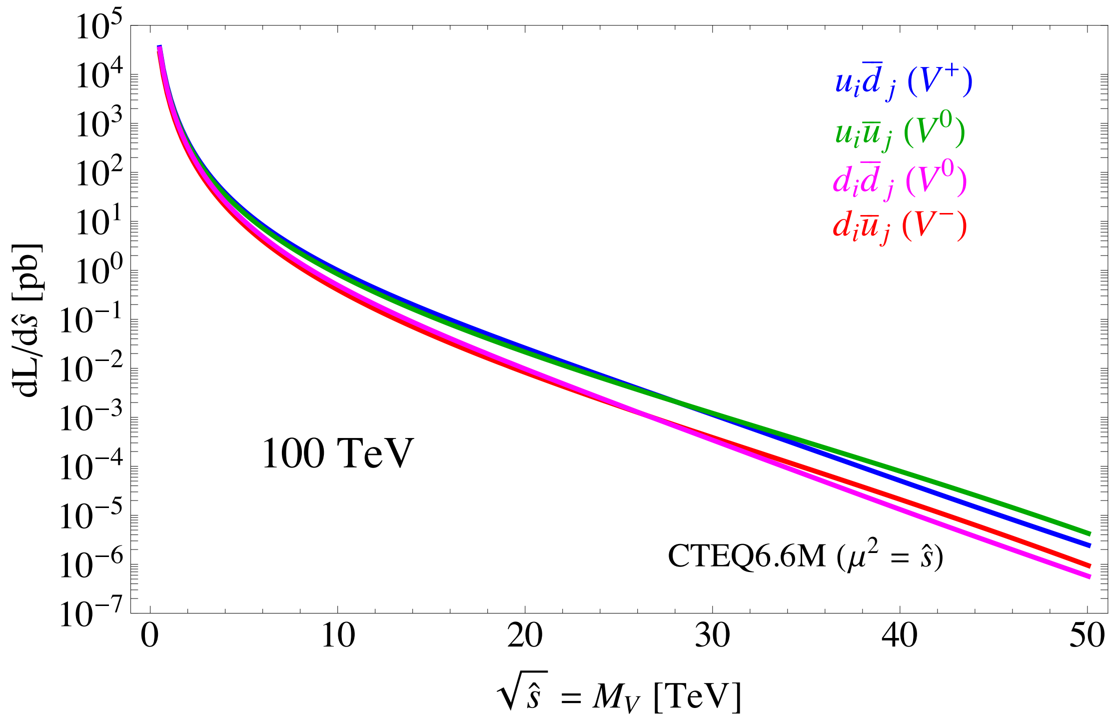

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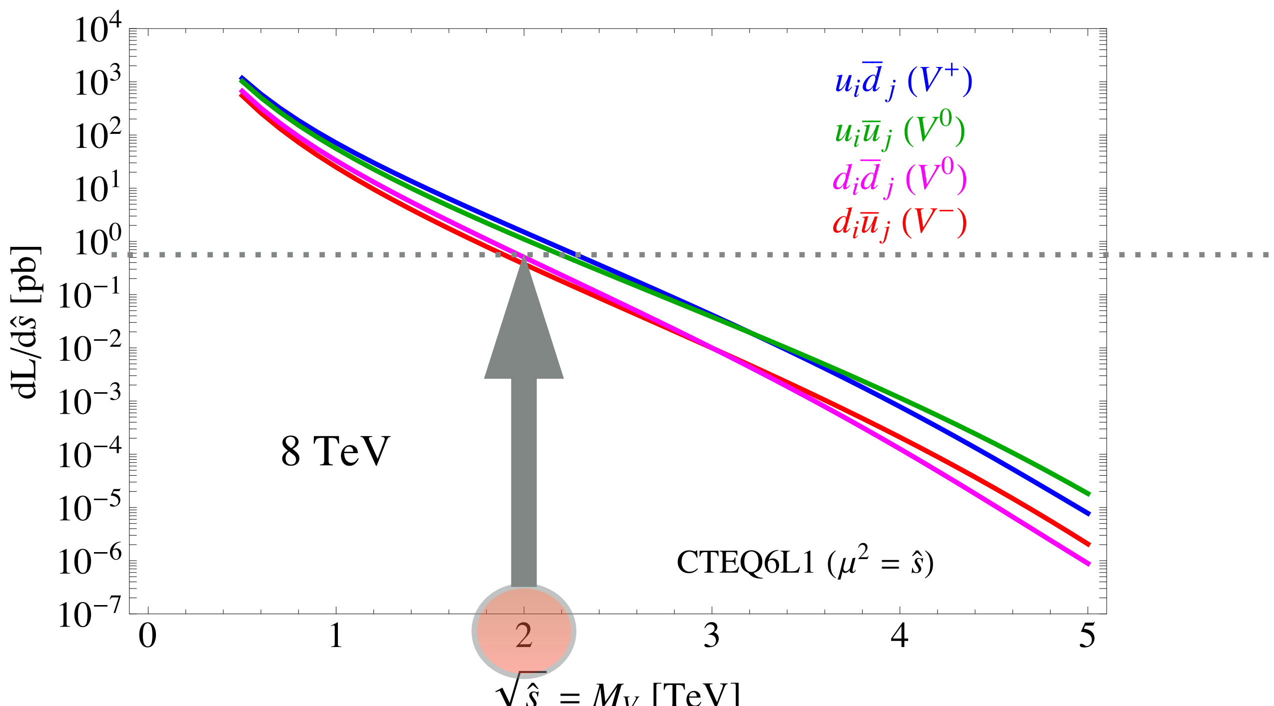

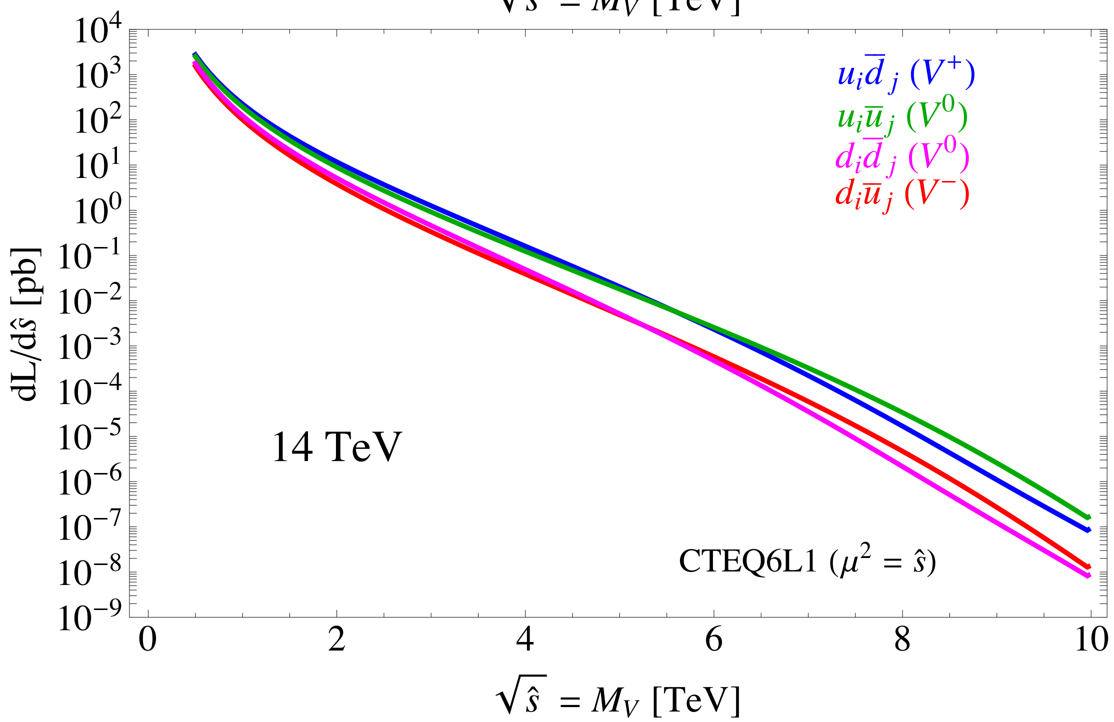

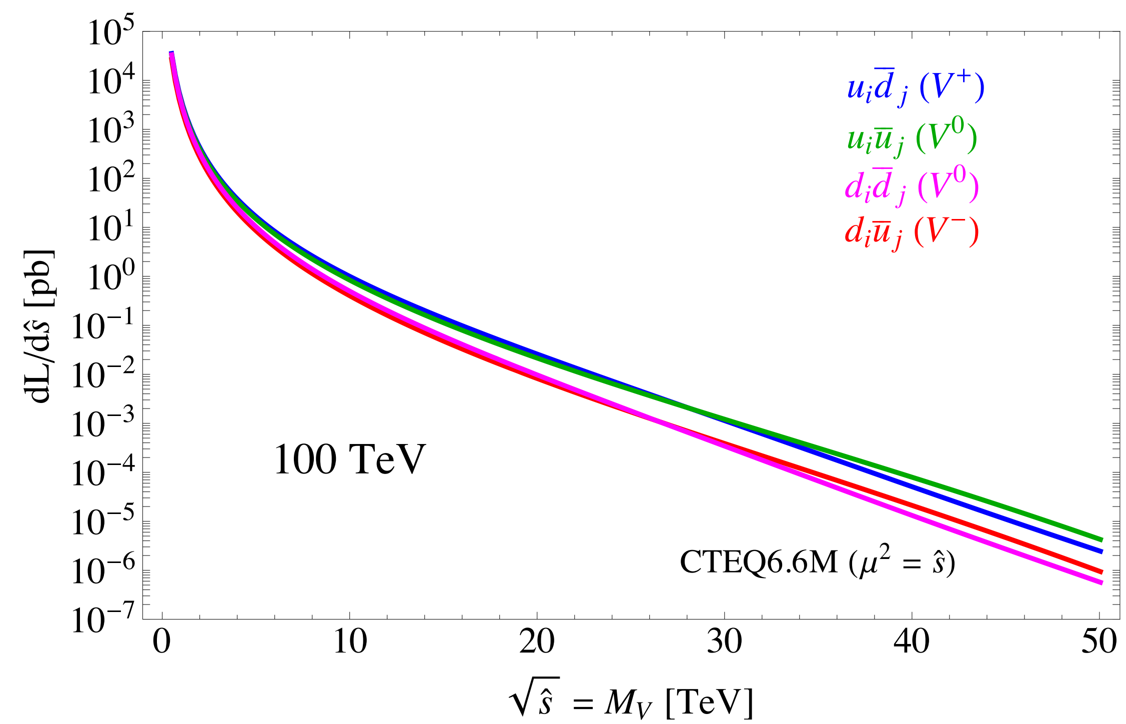

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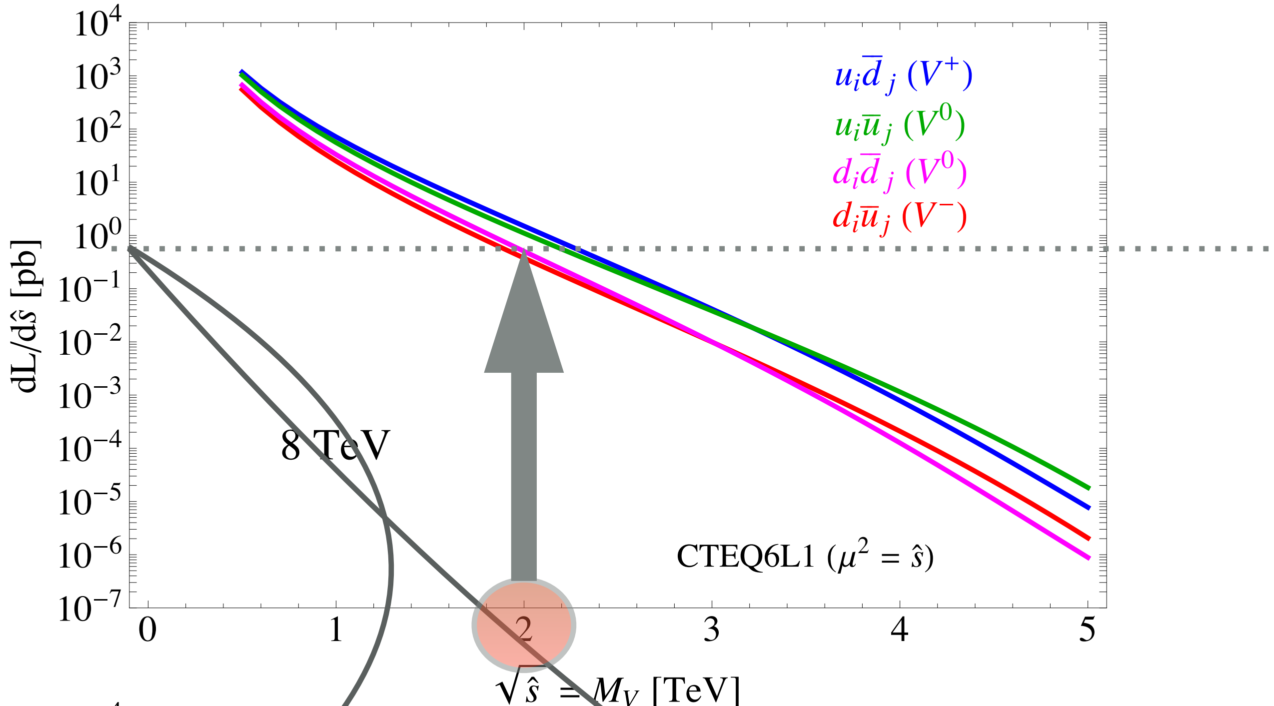

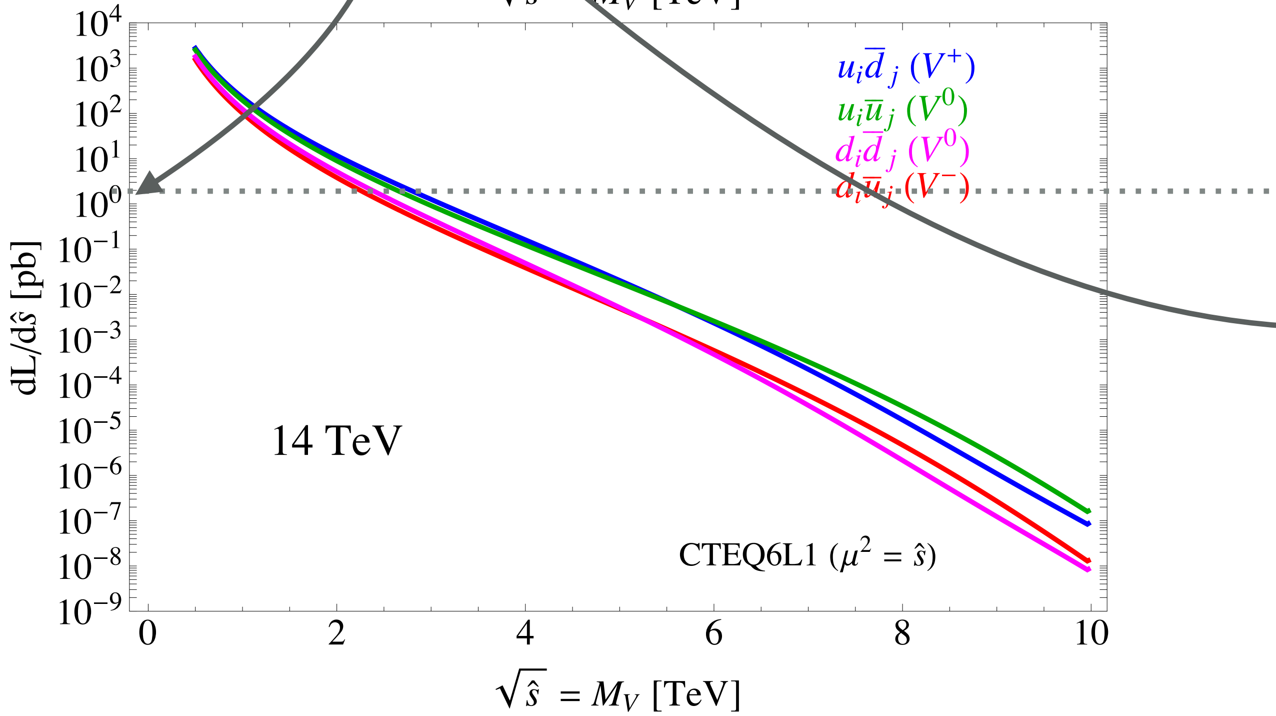

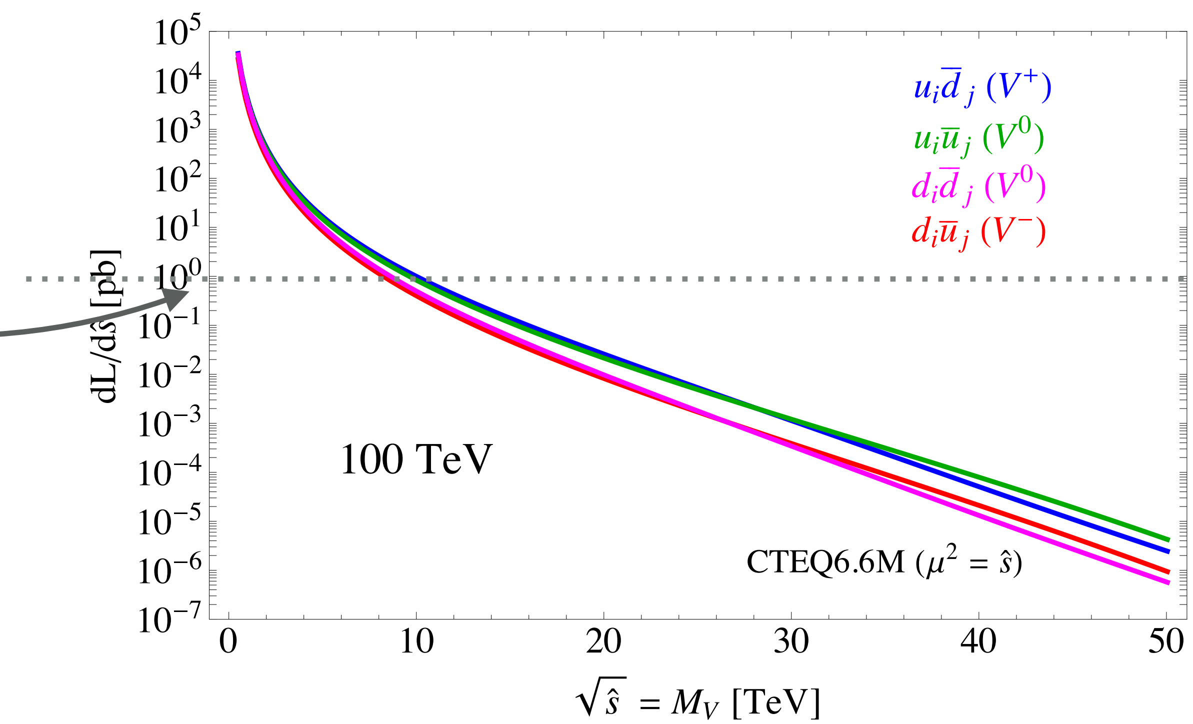

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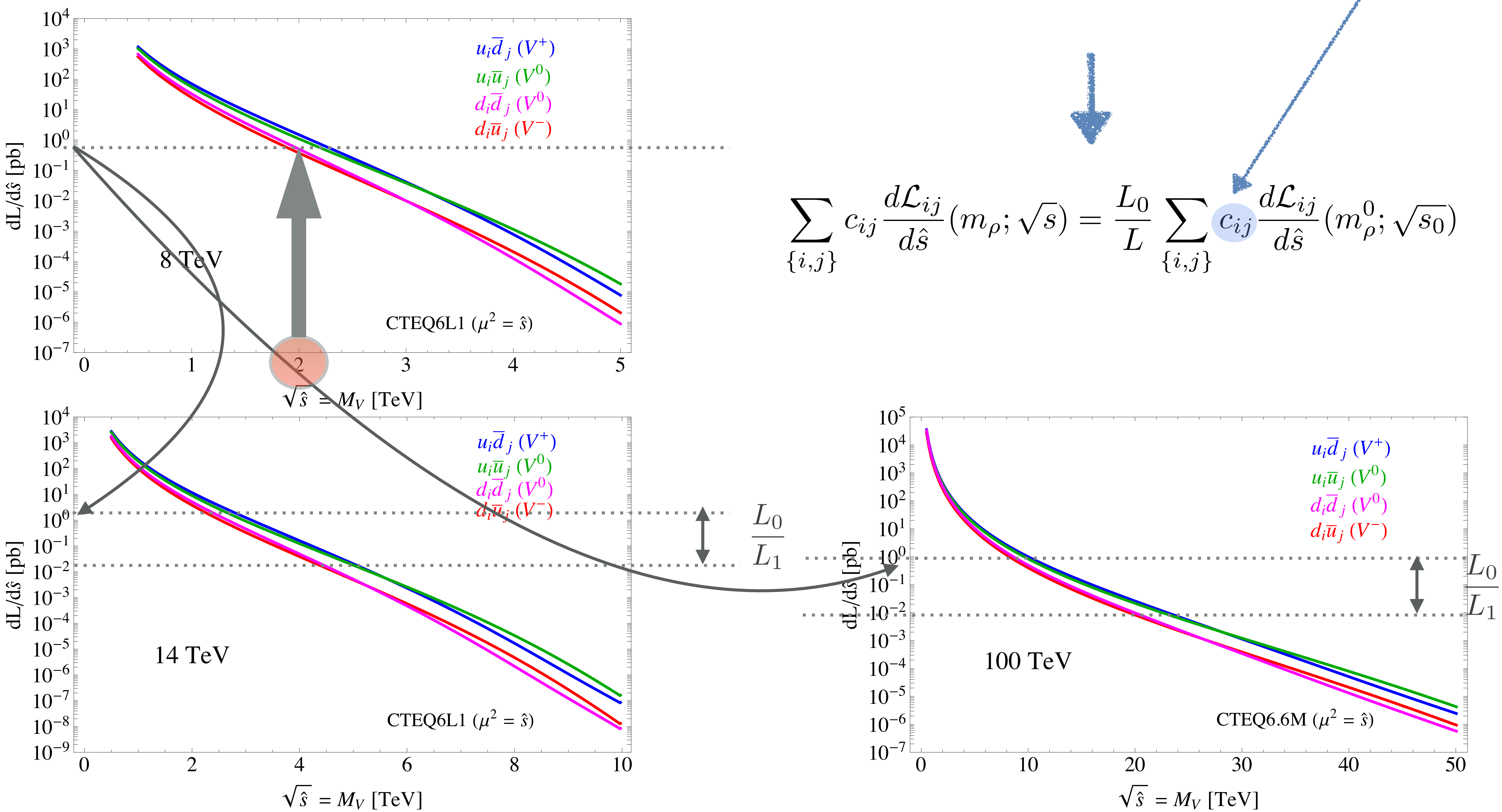

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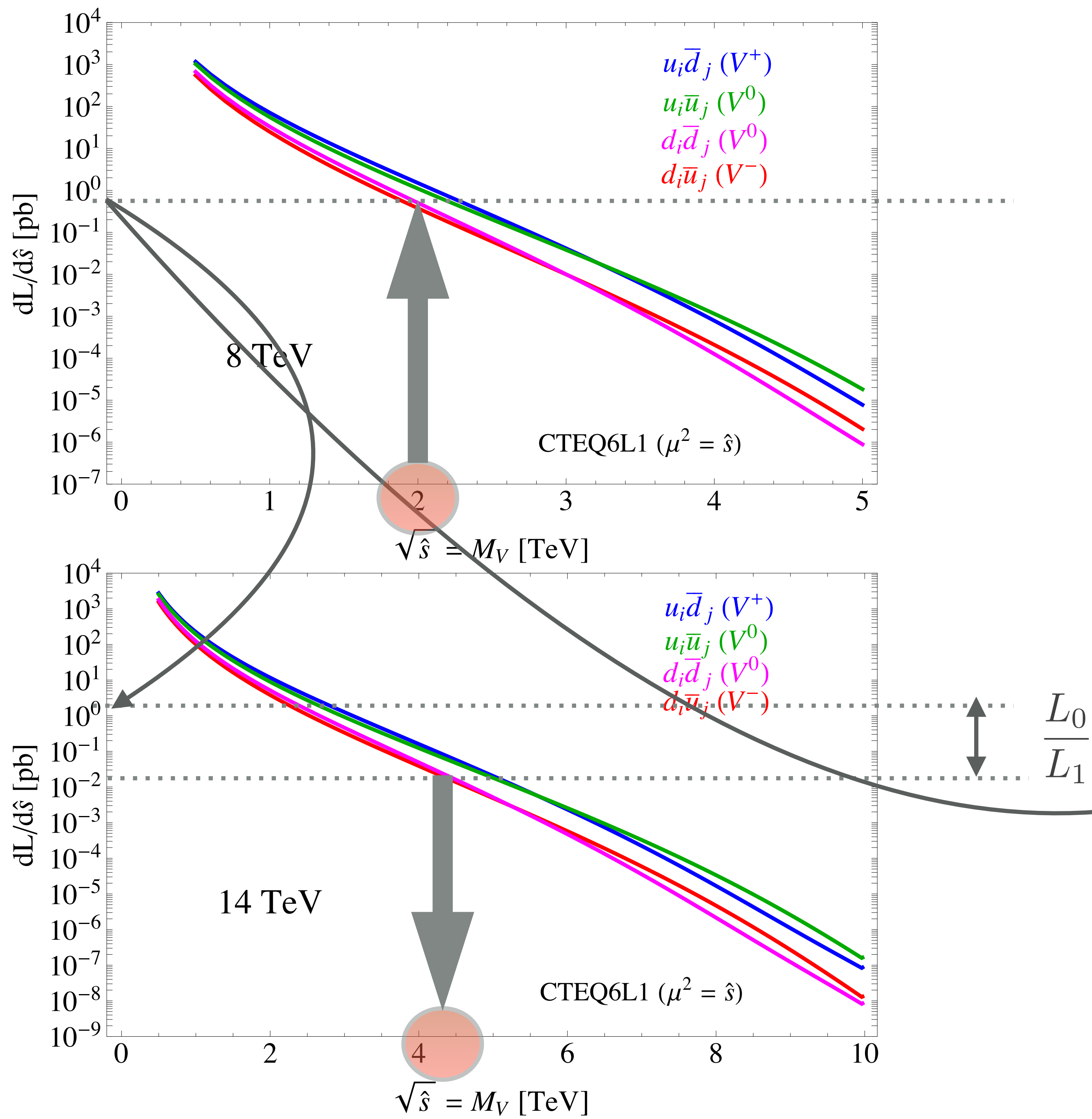
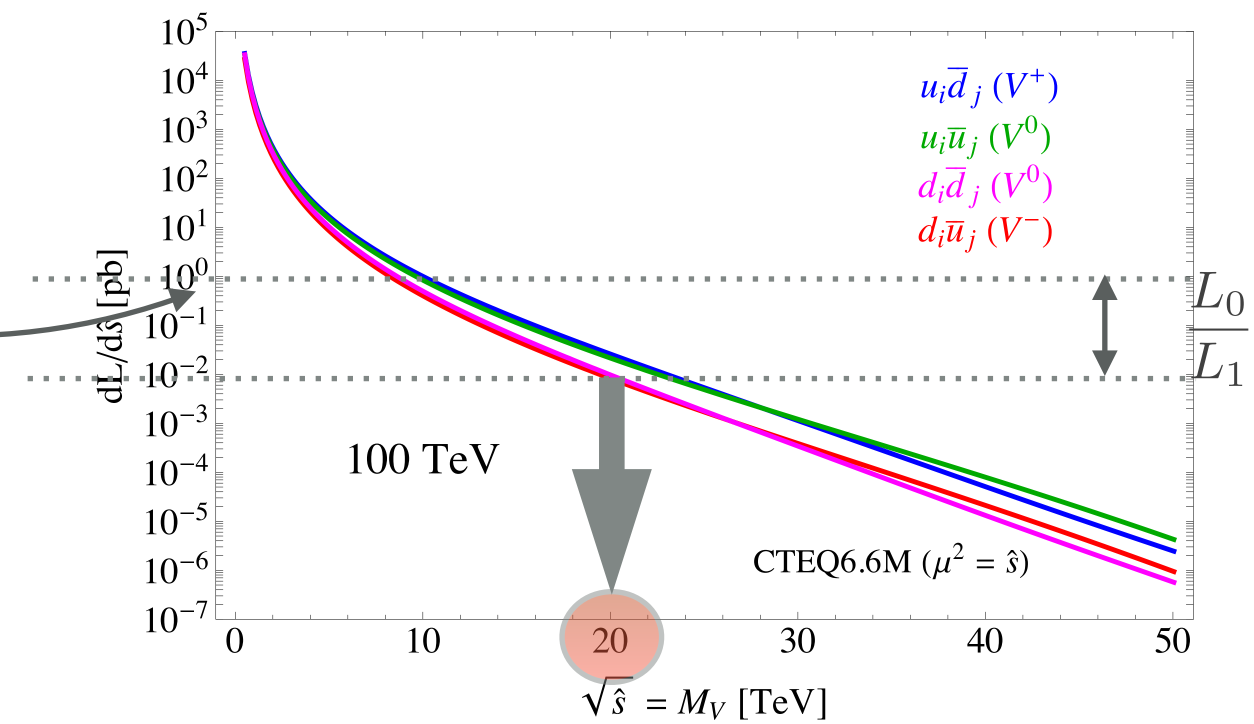
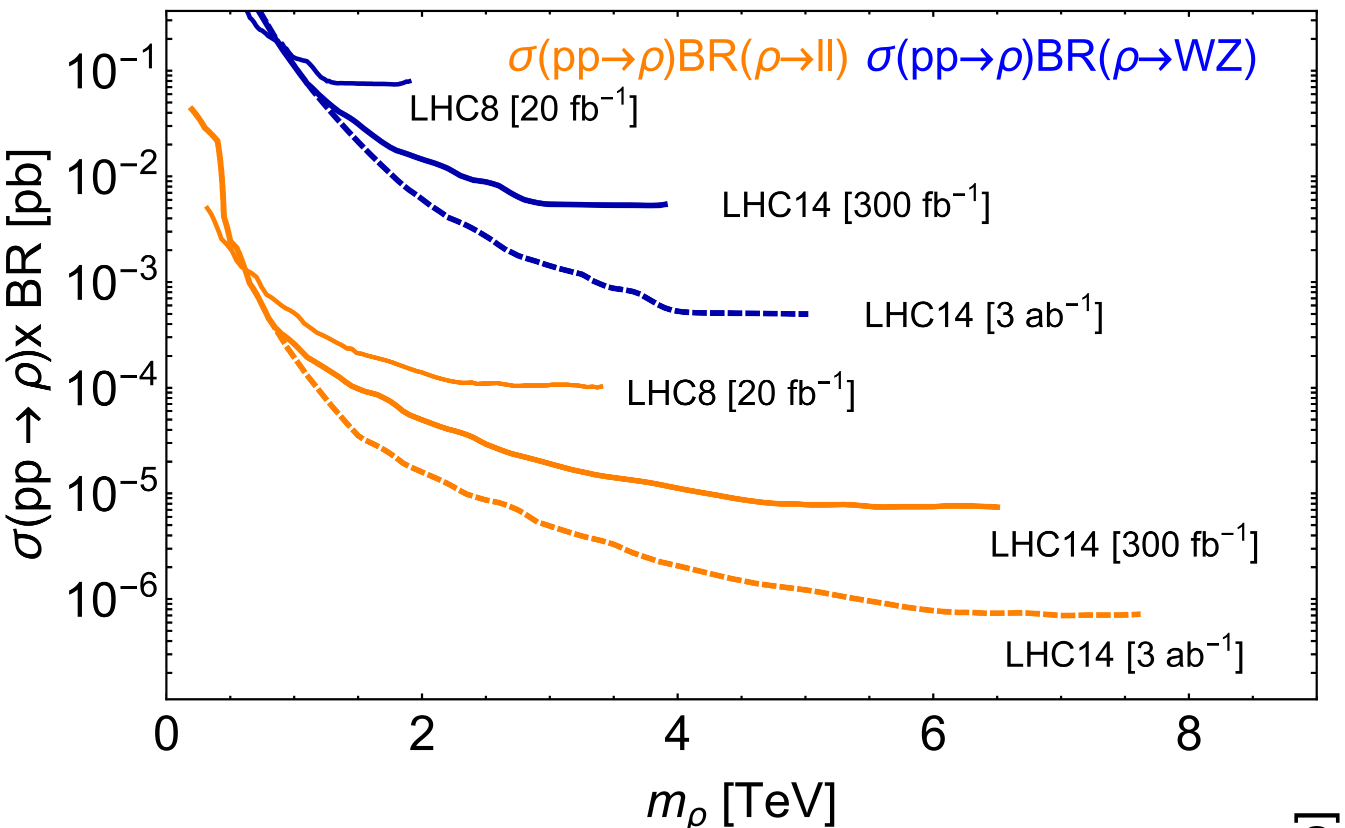




[Thamm, Torre, Wulzer: 1502.01701]

Direct measurements - Limit extrapolation

current 8 TeV LHC limits and extrapolated bounds



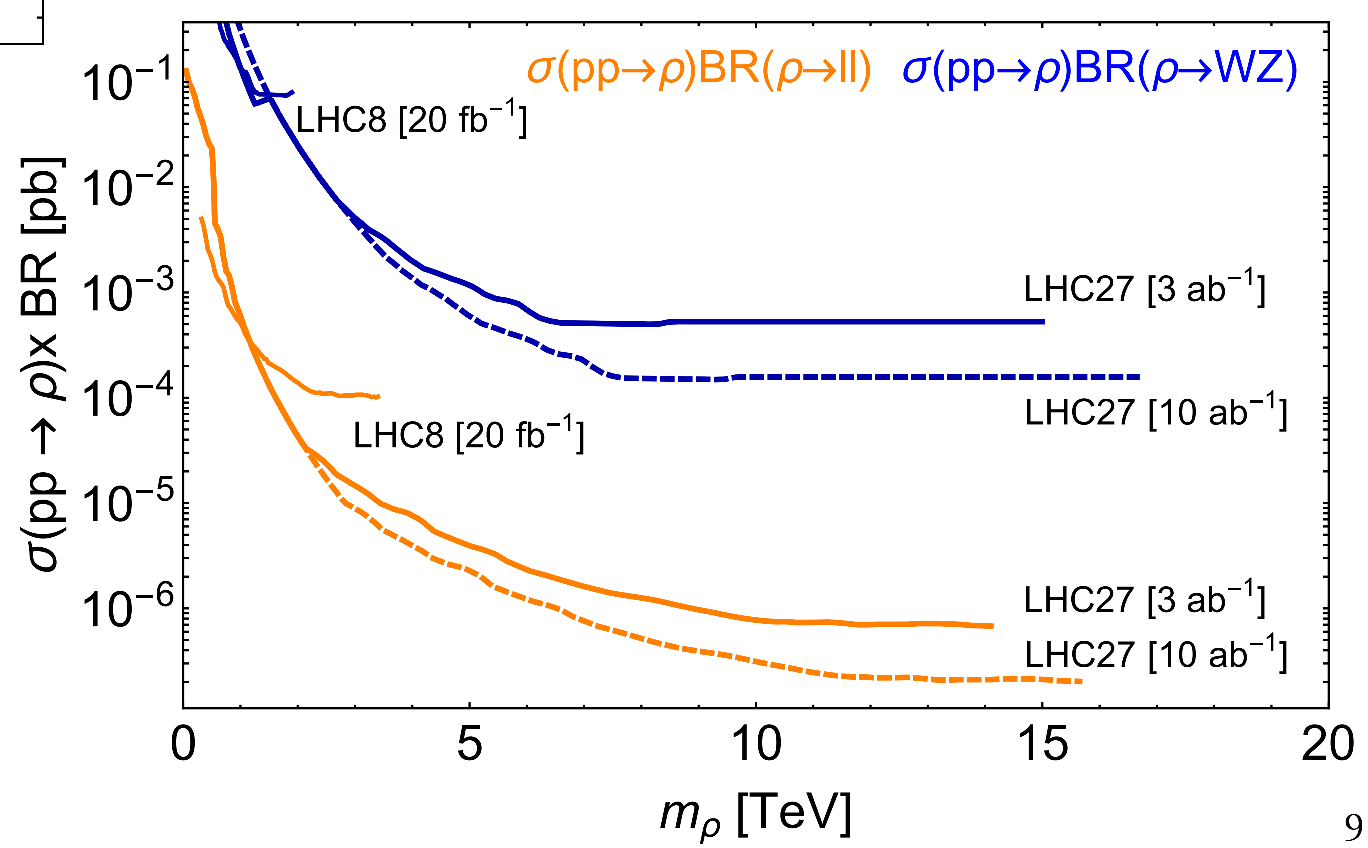
CMS search for

- opposite sign di-leptons
- fully leptonic WZ

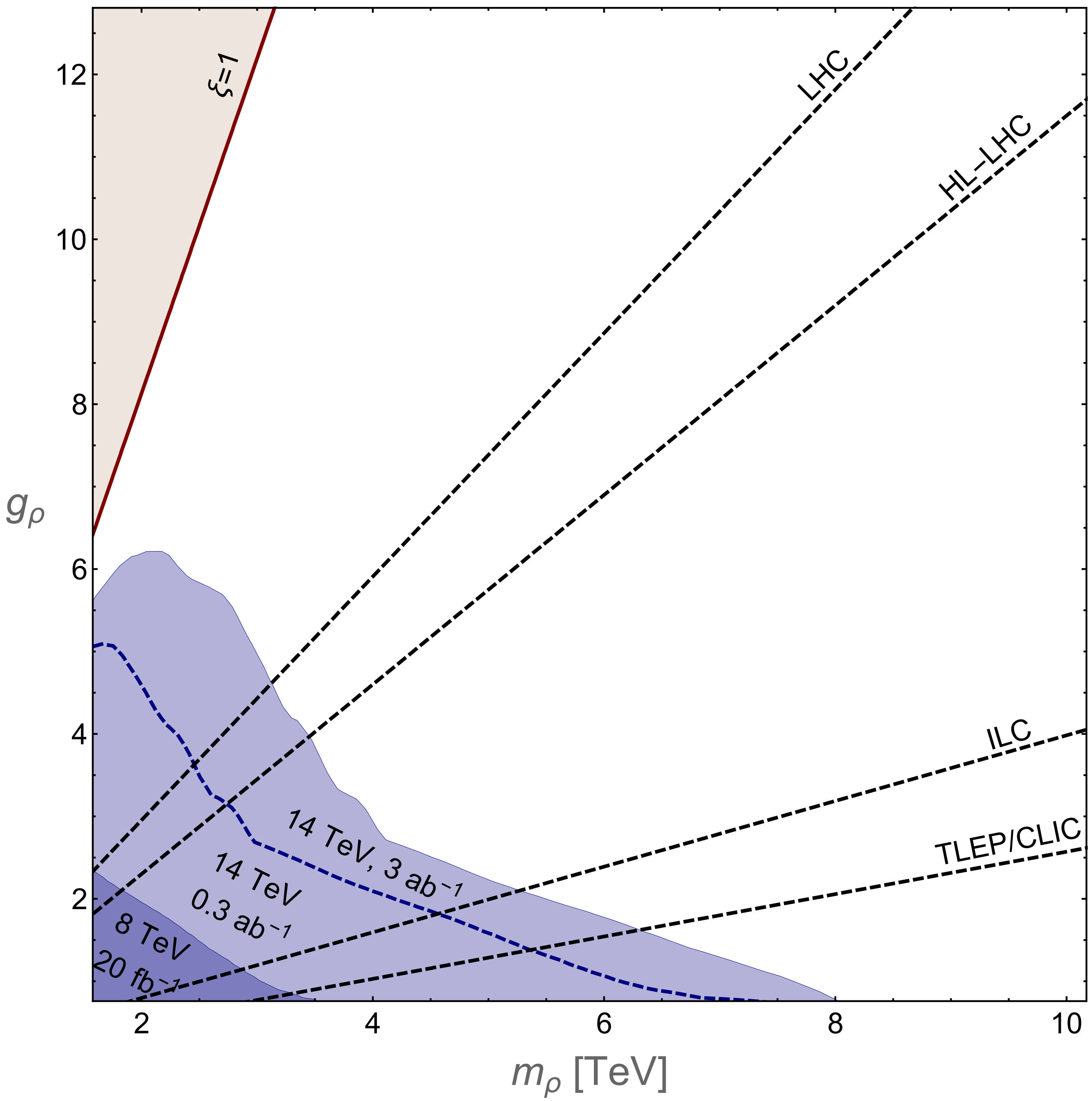
[CMS-PAS-EXO-12-061]
[ATLAS 1405.4123]

[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 $\xi \leq 1$
- LHC 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

[Thamm, Torre, Wulzer: 1502.01701]

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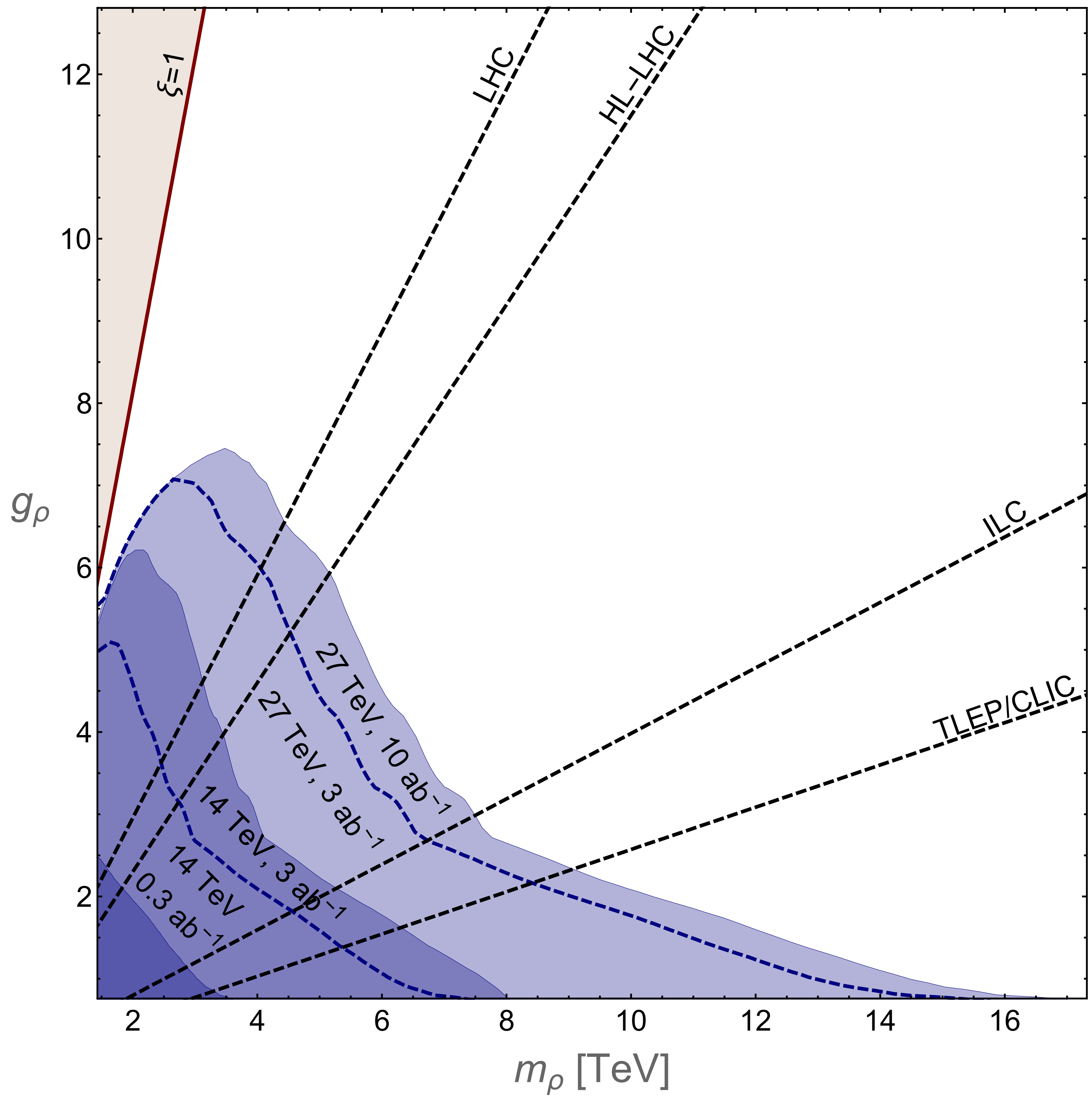

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- direct: more effective for small g_ρ

  ineffective for large g_ρ

- indirect: more effective for large g_ρ

[Thamm, Torre, Wulzer: 1502.01701]

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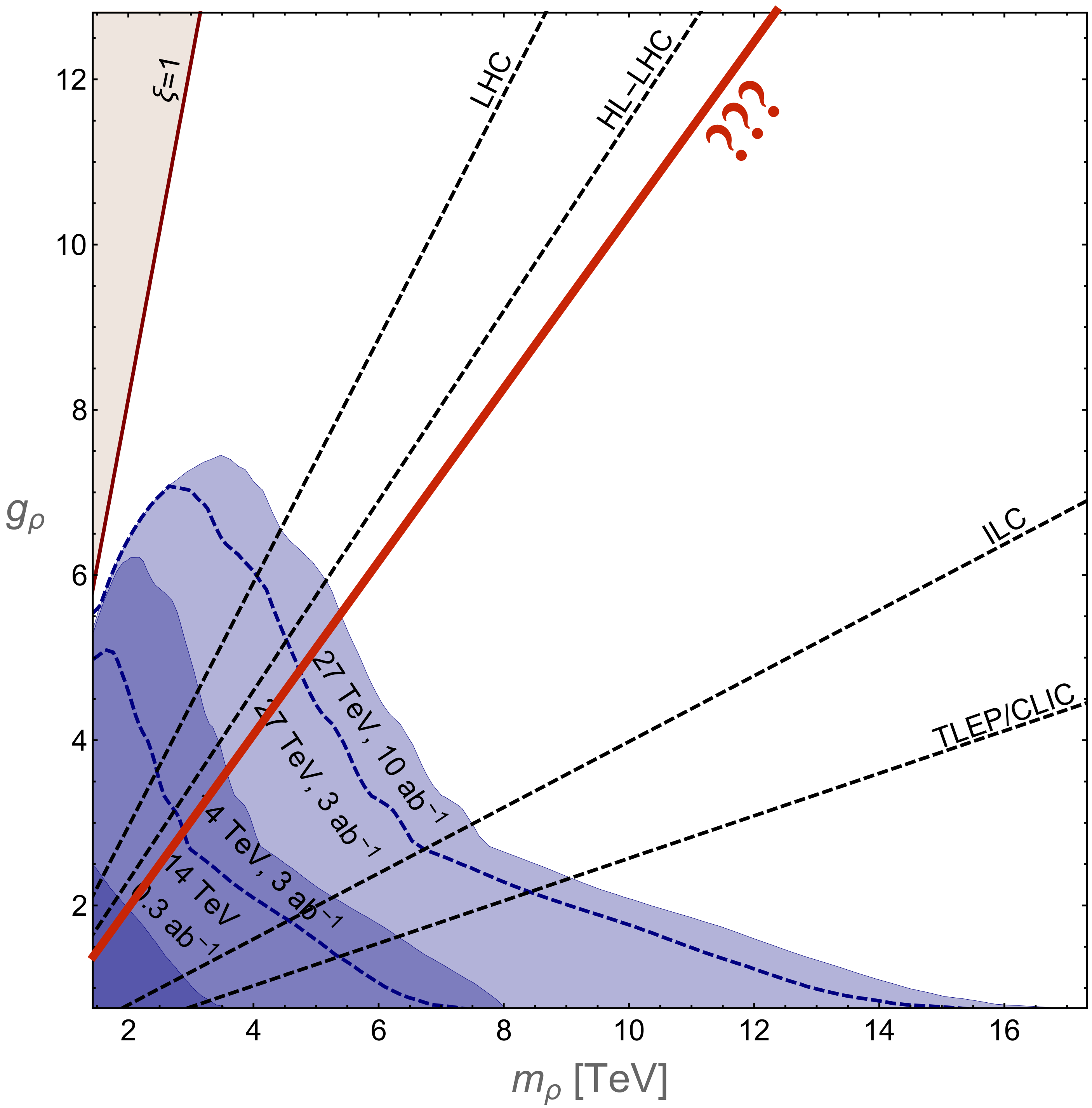

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- direct: more effective for small g_ρ
  ineffective for large g_ρ
- indirect: more effective for large g_ρ

[Thamm, Torre, Wulzer: 1502.01701]

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 27 TeV LHC

Backup

Limit extrapolation - equivalent mass

[Thamm, Torre, Wulzer: 1502.01701]

- extraction of equivalent mass

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

- number of background events within window $\hat{s} \in [m_\rho^2 - \Delta\hat{s}/2, m_\rho^2 + \Delta\hat{s}/2]$

$$B(s, L, m_\rho) \propto L \cdot \sum_{\{i,j\}} \int d\hat{s} \frac{1}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\hat{s}} (\sqrt{\hat{s}}; \sqrt{s}) \left[\hat{s}\hat{\sigma}_{ij}(\hat{s})\right]$$

partonic cross-section contributing to background

- partonic cross section: SM process much above SM masses

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

- 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

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

Limit extrapolation - equivalent mass

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Limit extrapolation - equivalent mass

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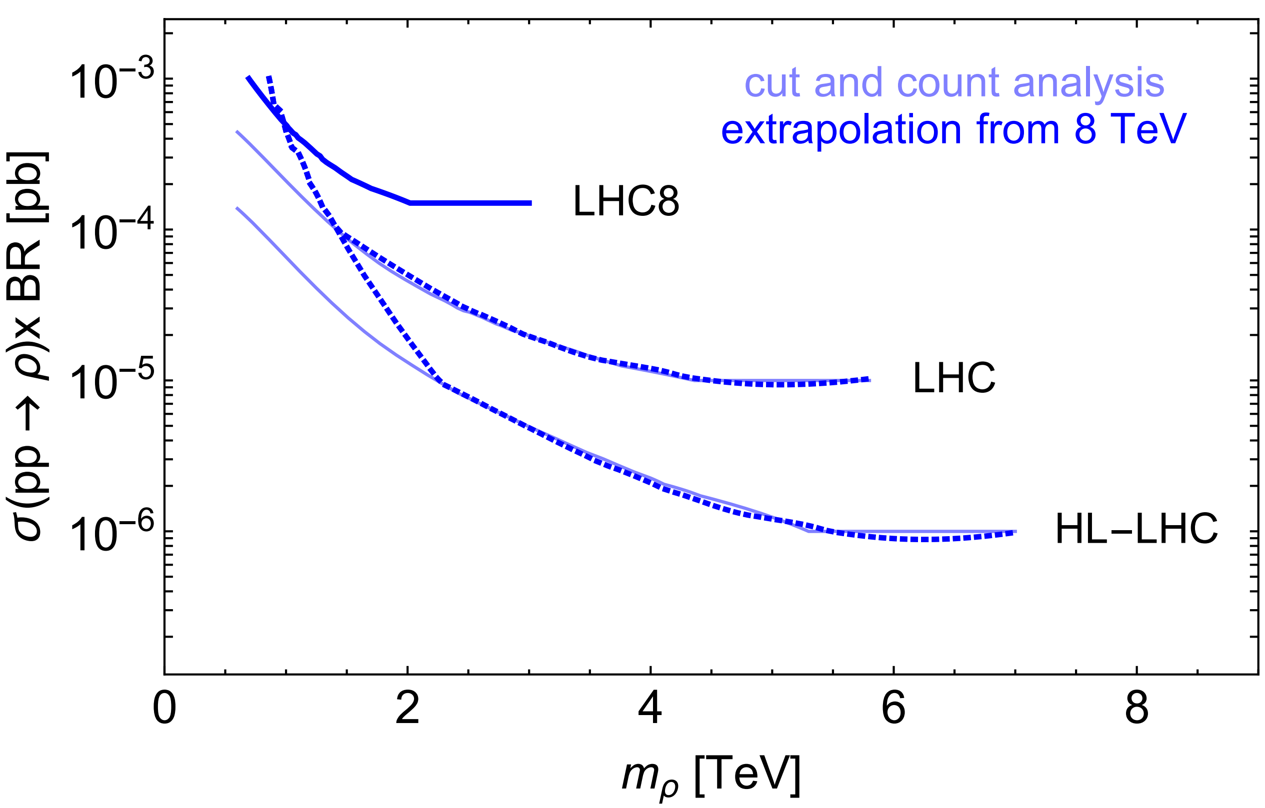
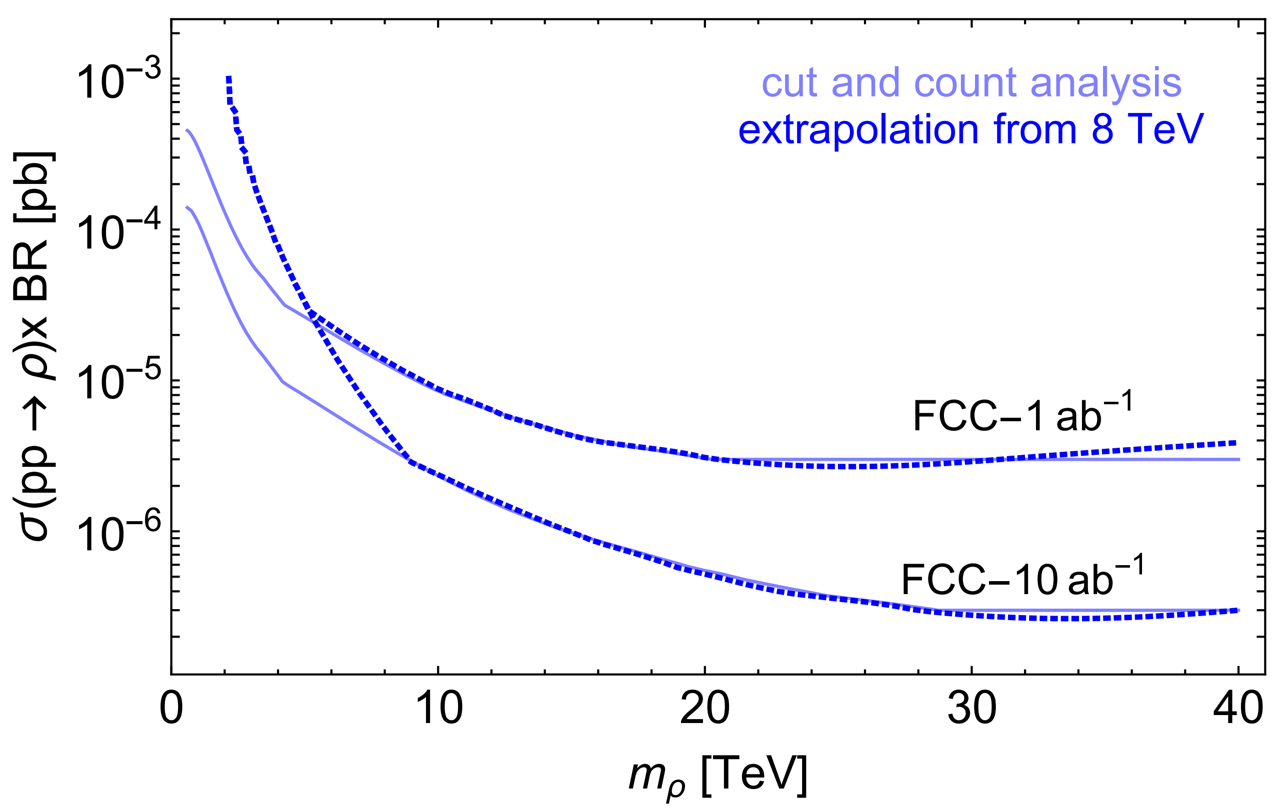
- need relevant background process and parton luminosities
- sum drops out for single partonic initial state
- otherwise linear combination of parton luminosities weighted by c_{ij}

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 - 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