Higgs theory at NNLO

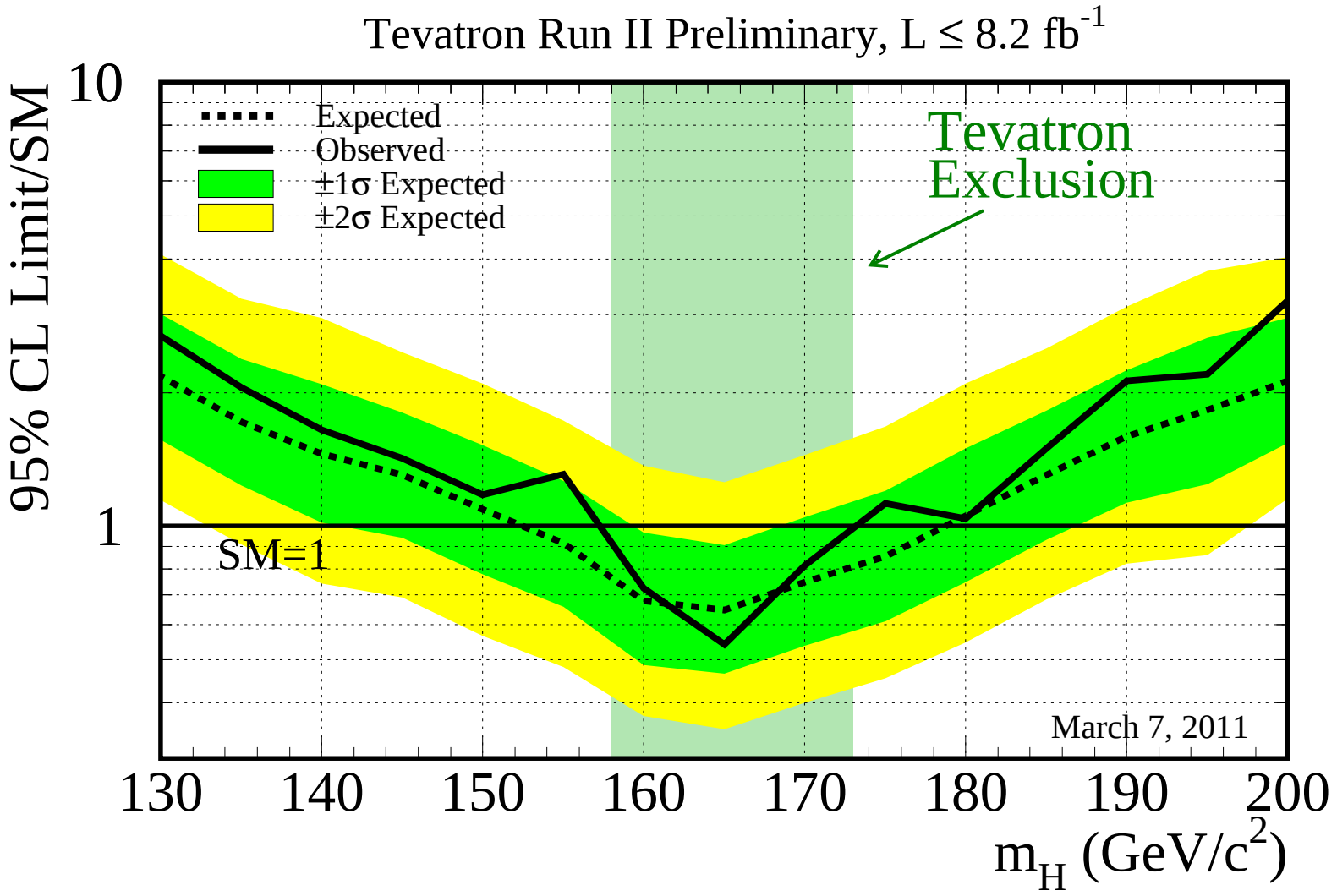
Robert Harlander

BU Wuppertal

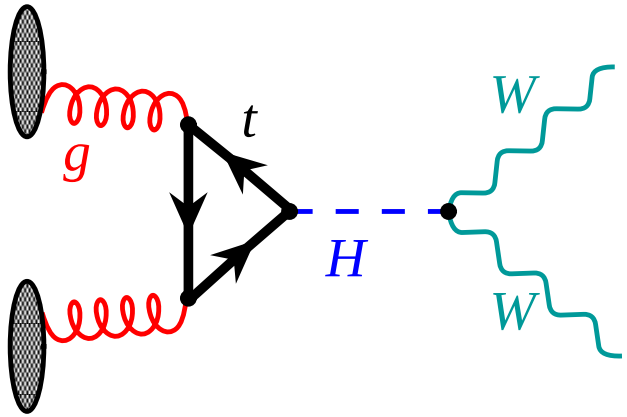
Standard Model Benchmarks at High-Energy Hadron Colliders
DESY Zeuthen, 17 June 2011

Supported by: BMBF, DFG, Helmholtz Alliance "Physics at the Terascale", LHCPhenoNet

Higgs search at the Tevatron



Gluon Fusion



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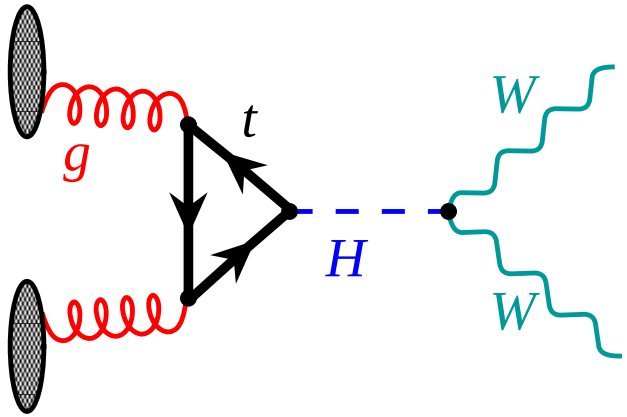

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- sensitive to heavy particle spectrum

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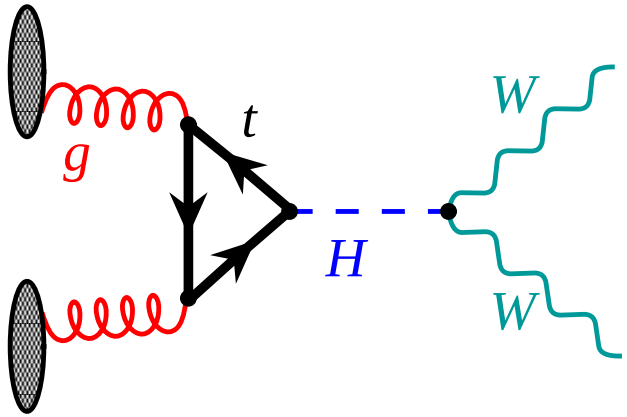

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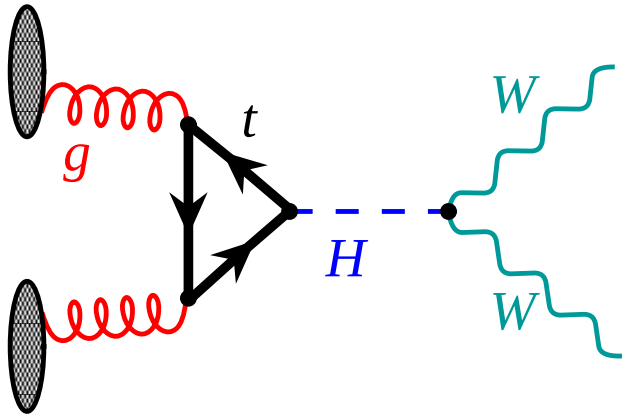

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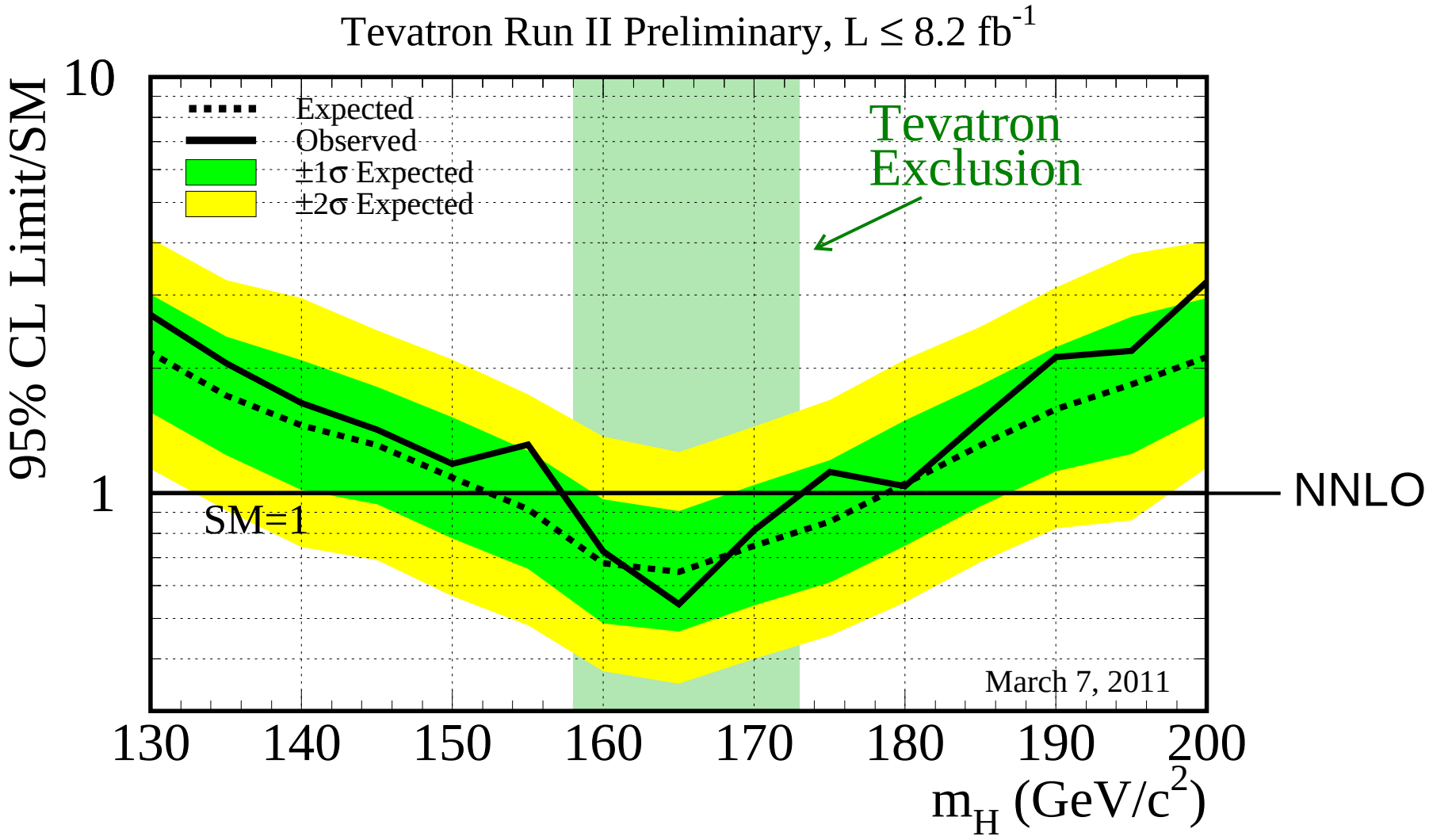

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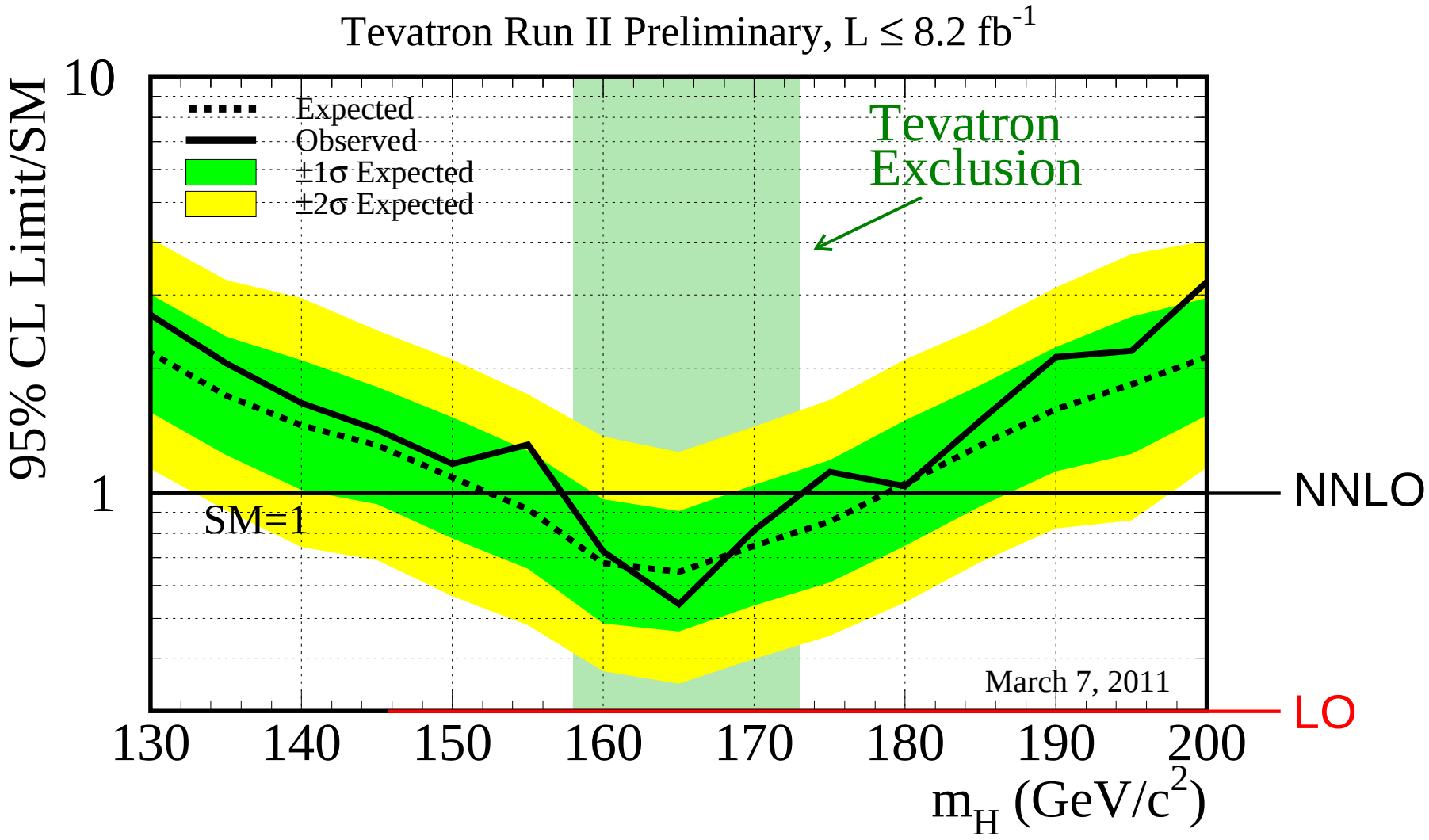

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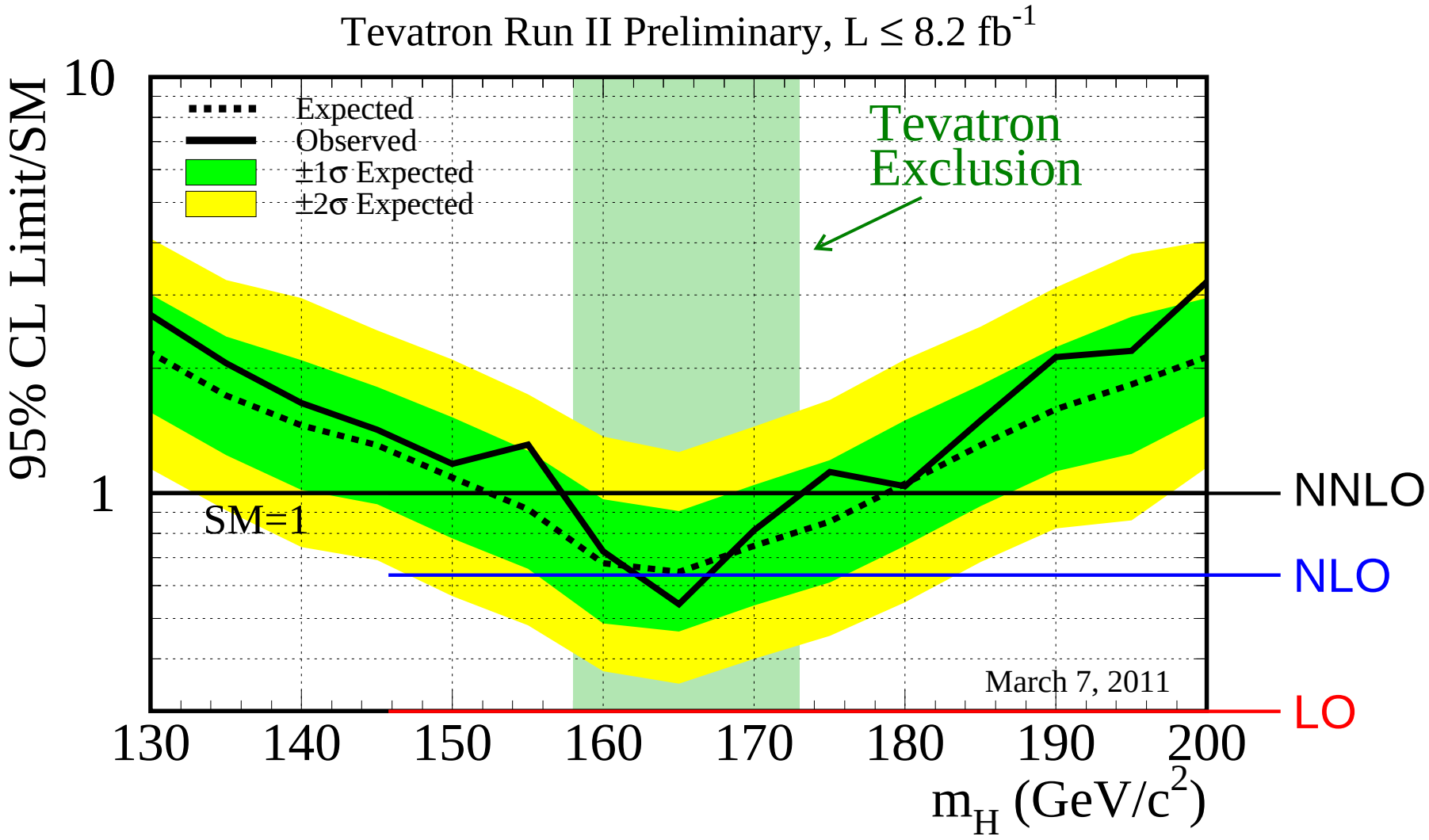

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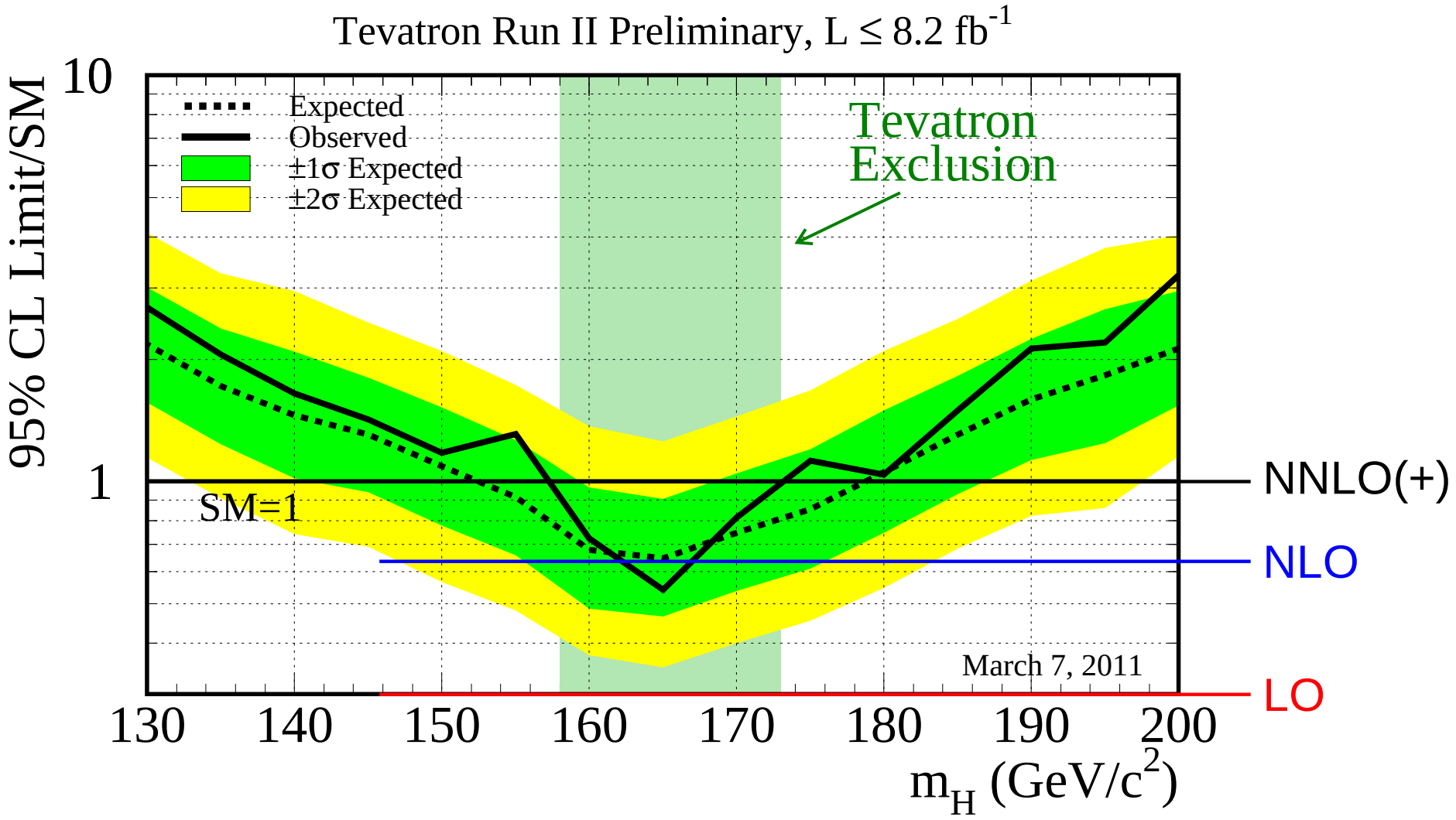

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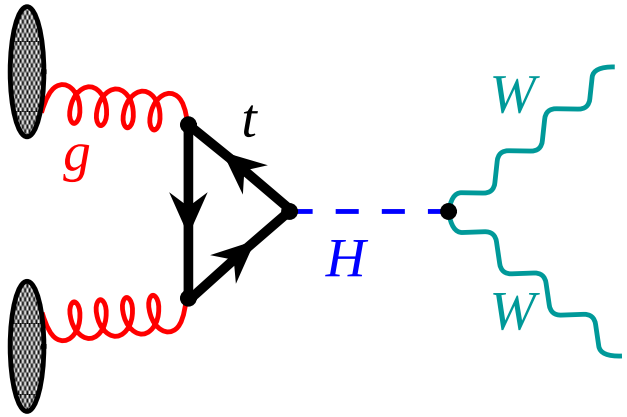

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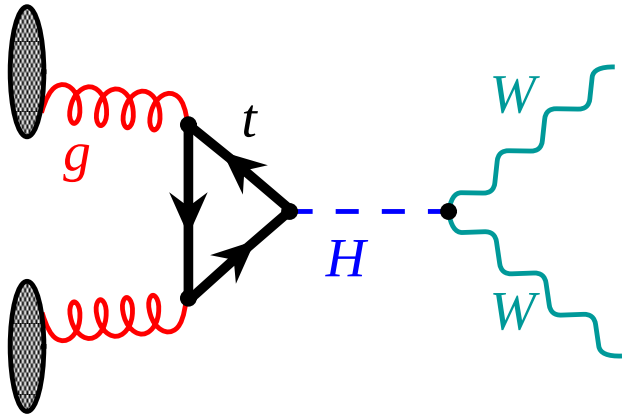

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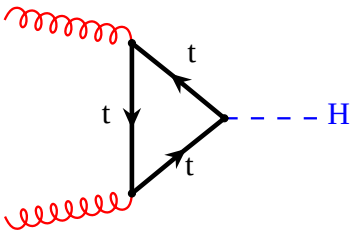
Gluon fusion

- effective theory for $m_t \gg M_H$:



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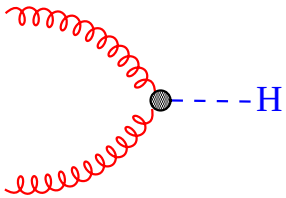

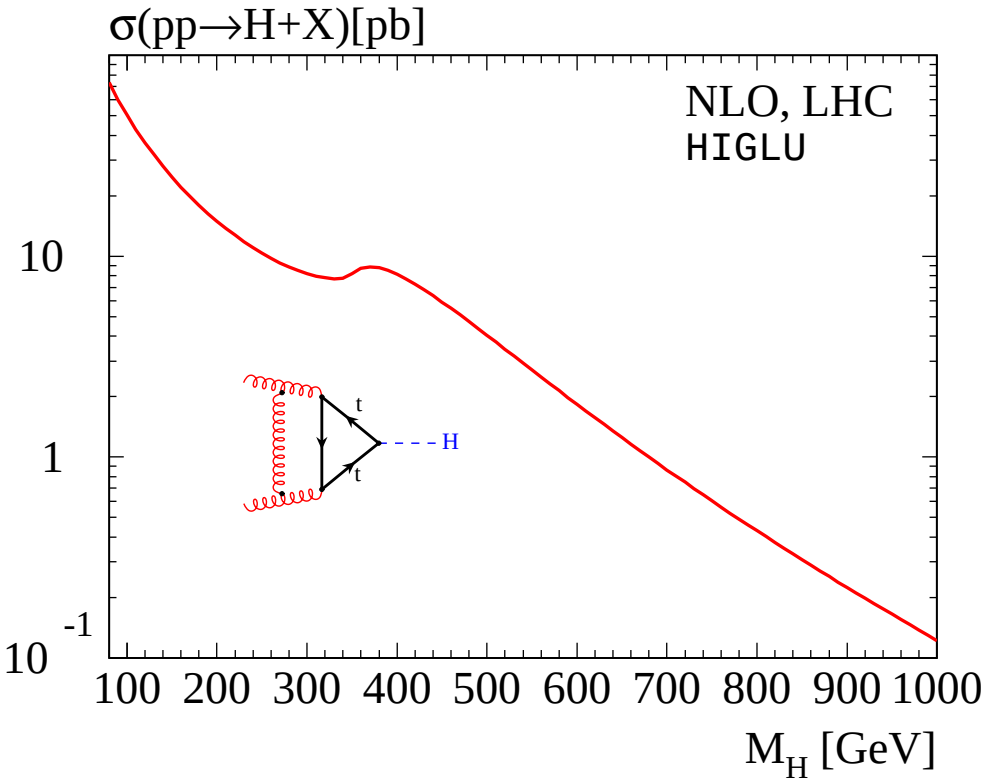

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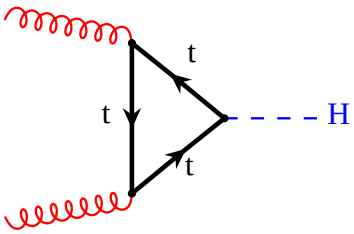

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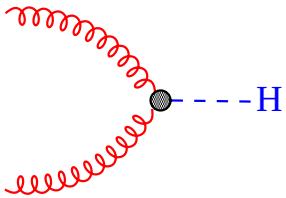

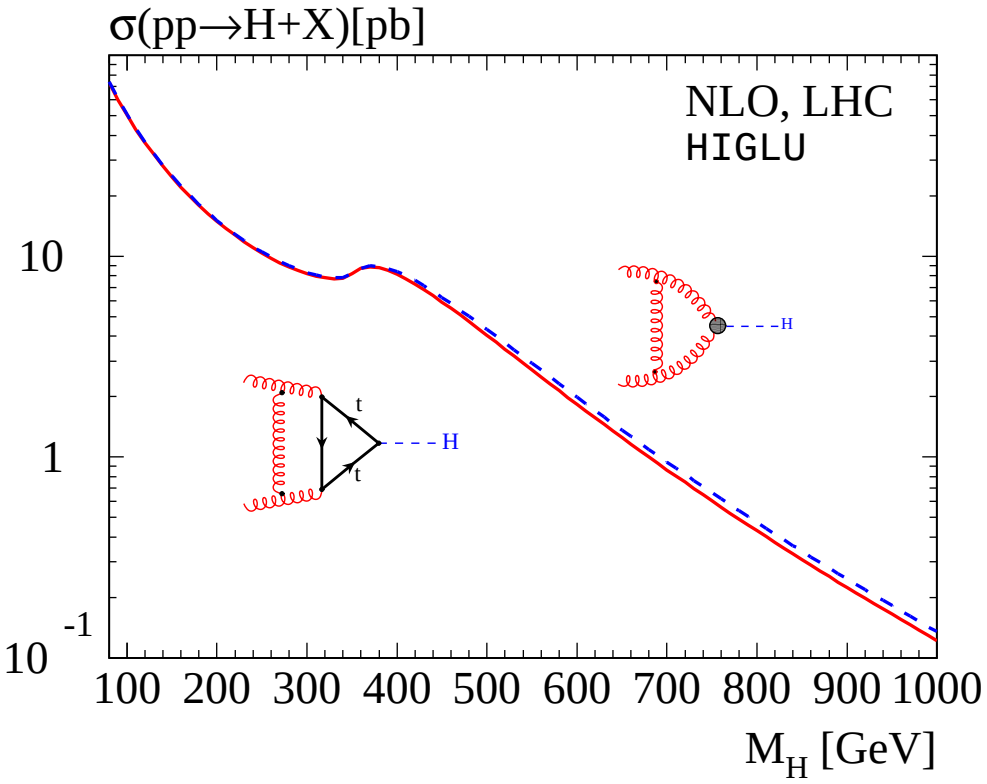

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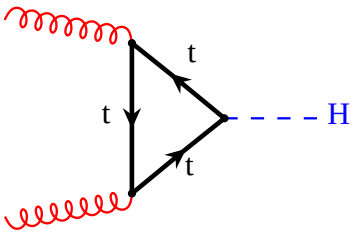

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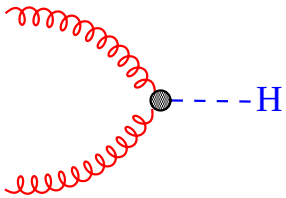

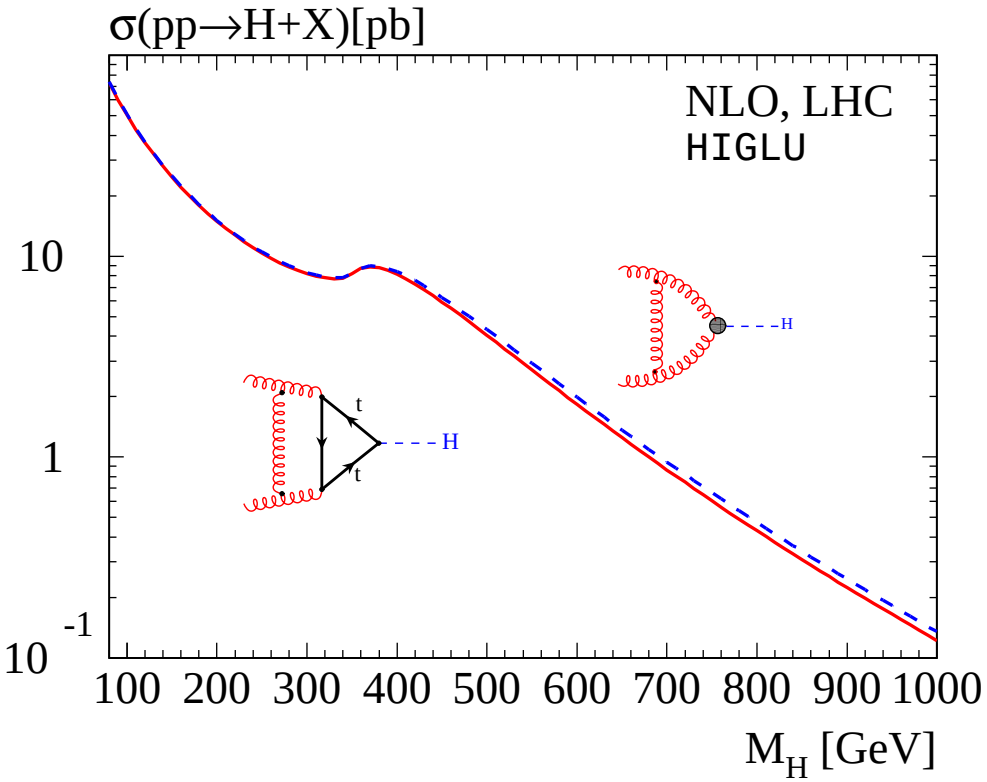

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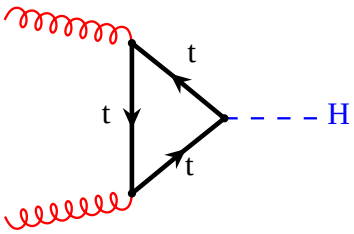

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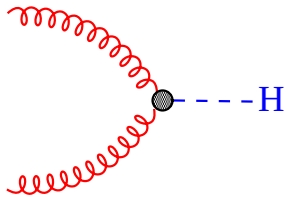

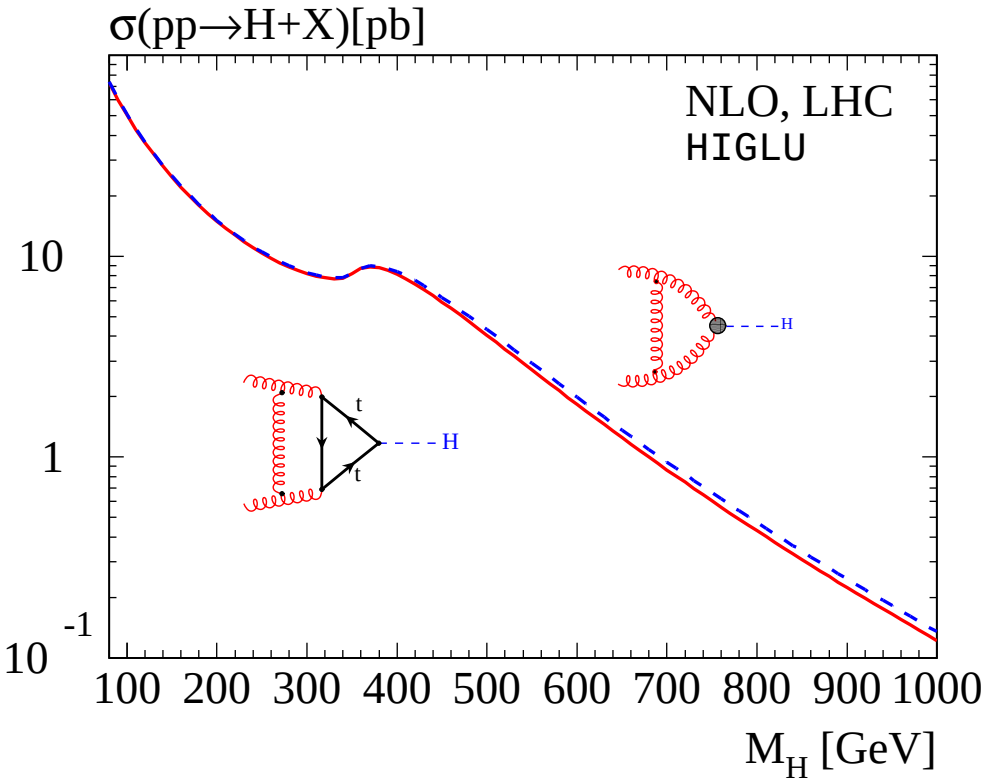

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NNLO?

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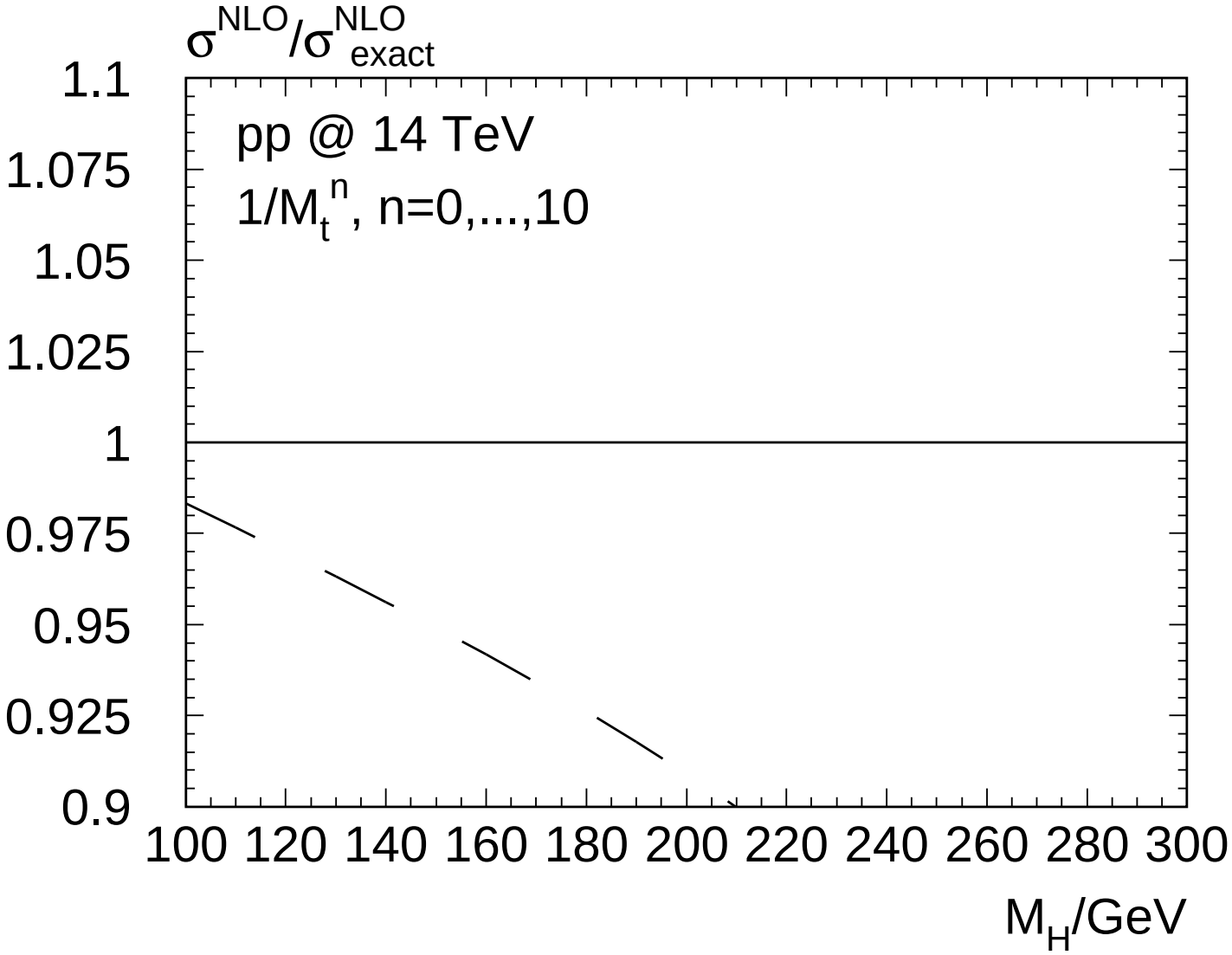

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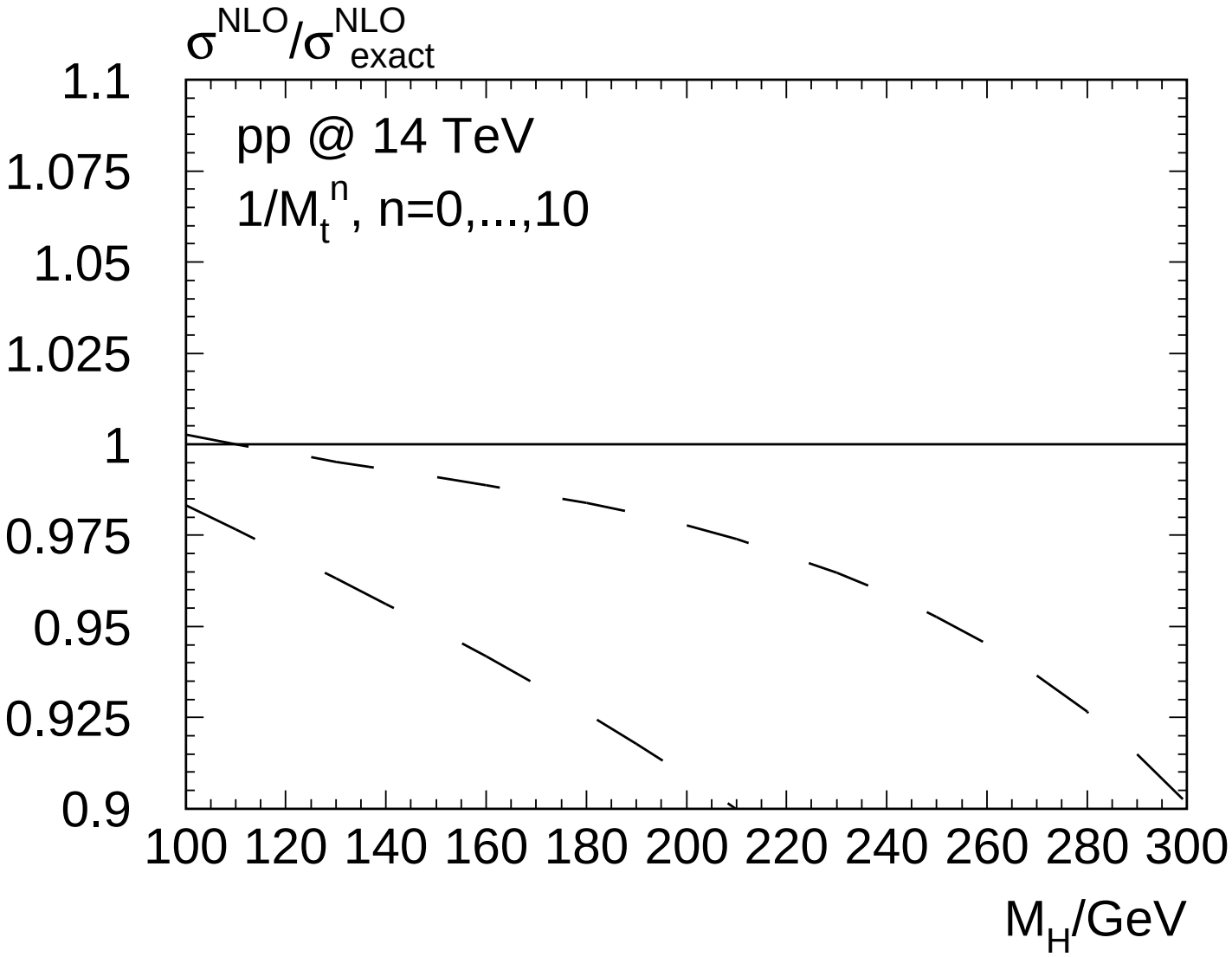

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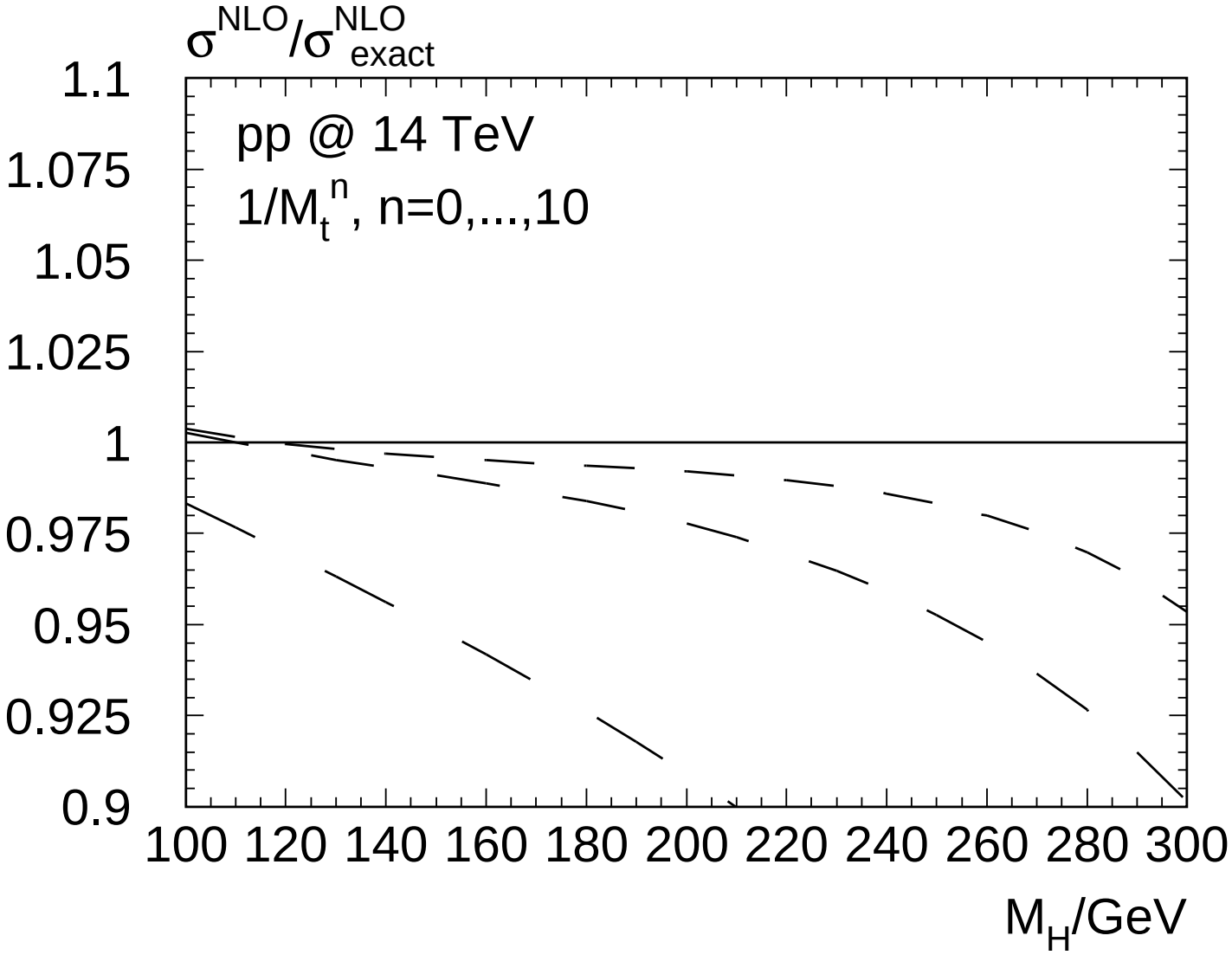

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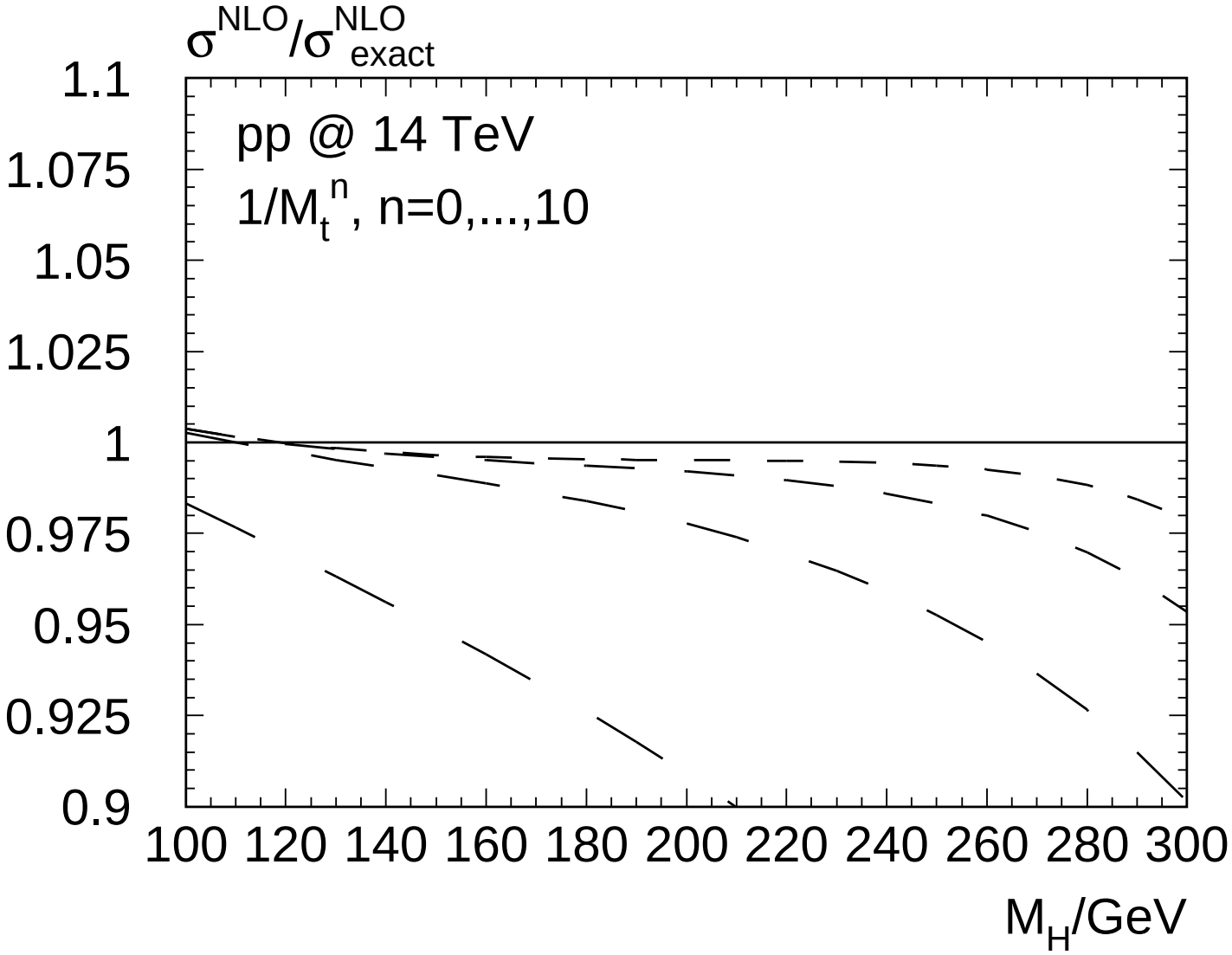

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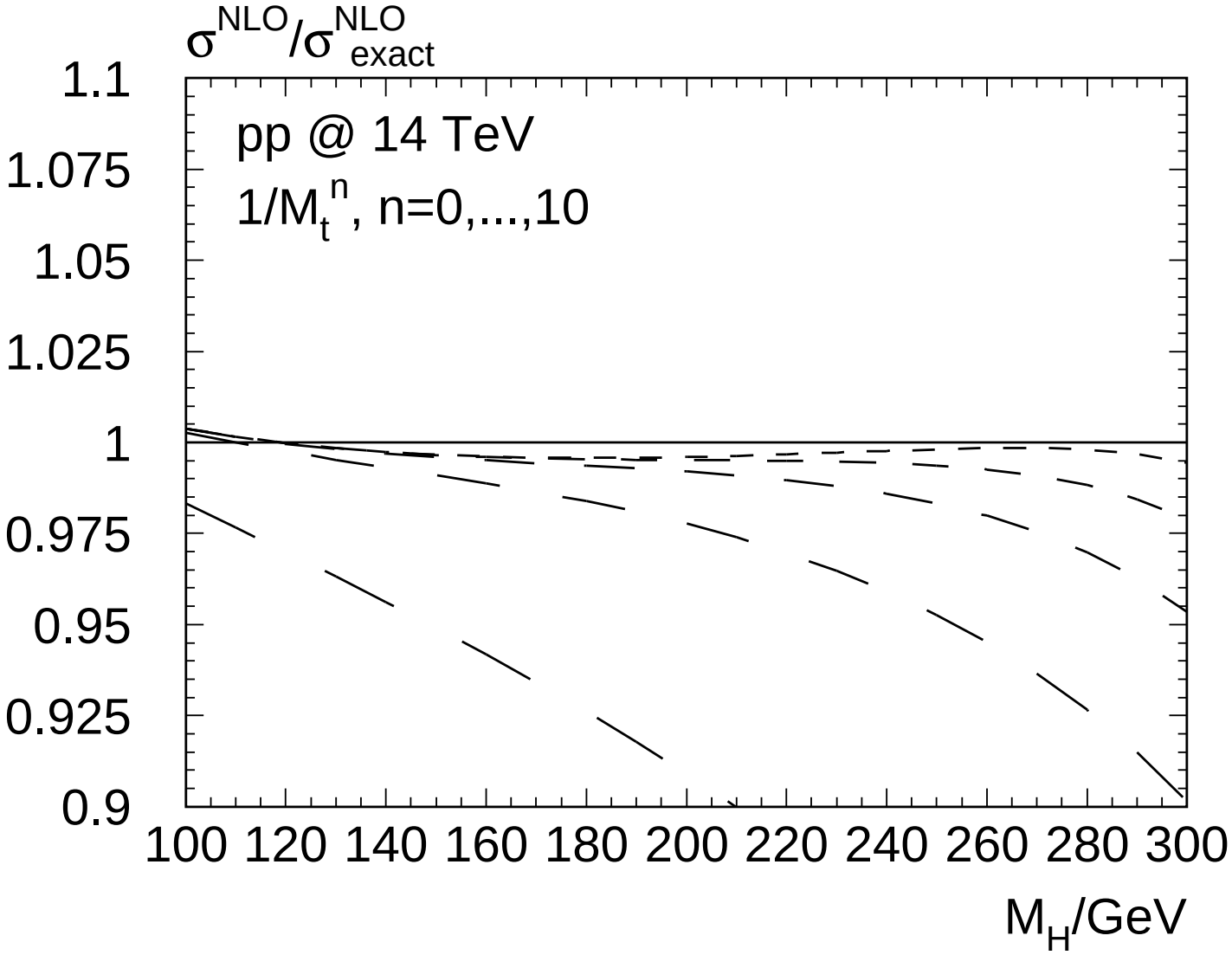

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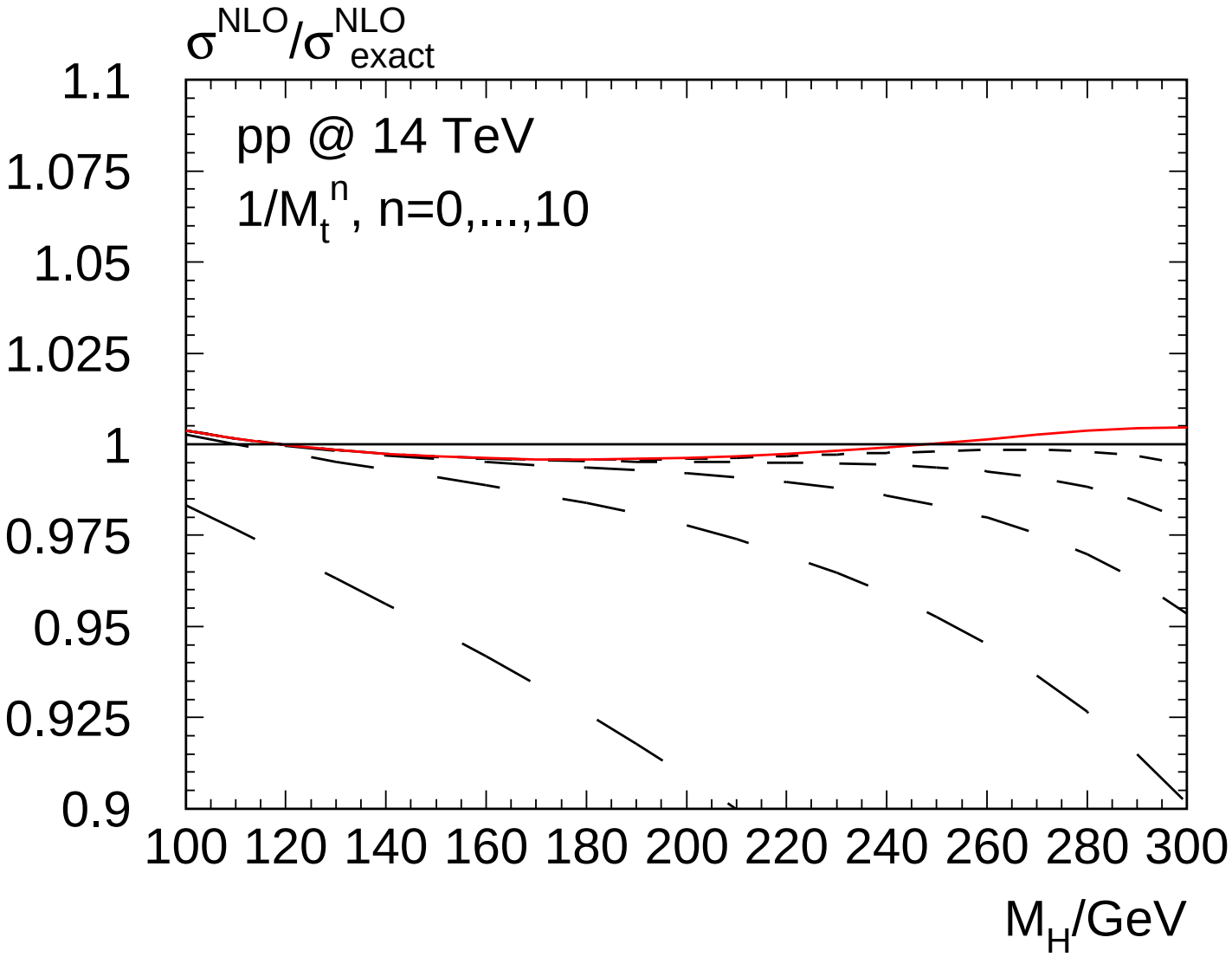

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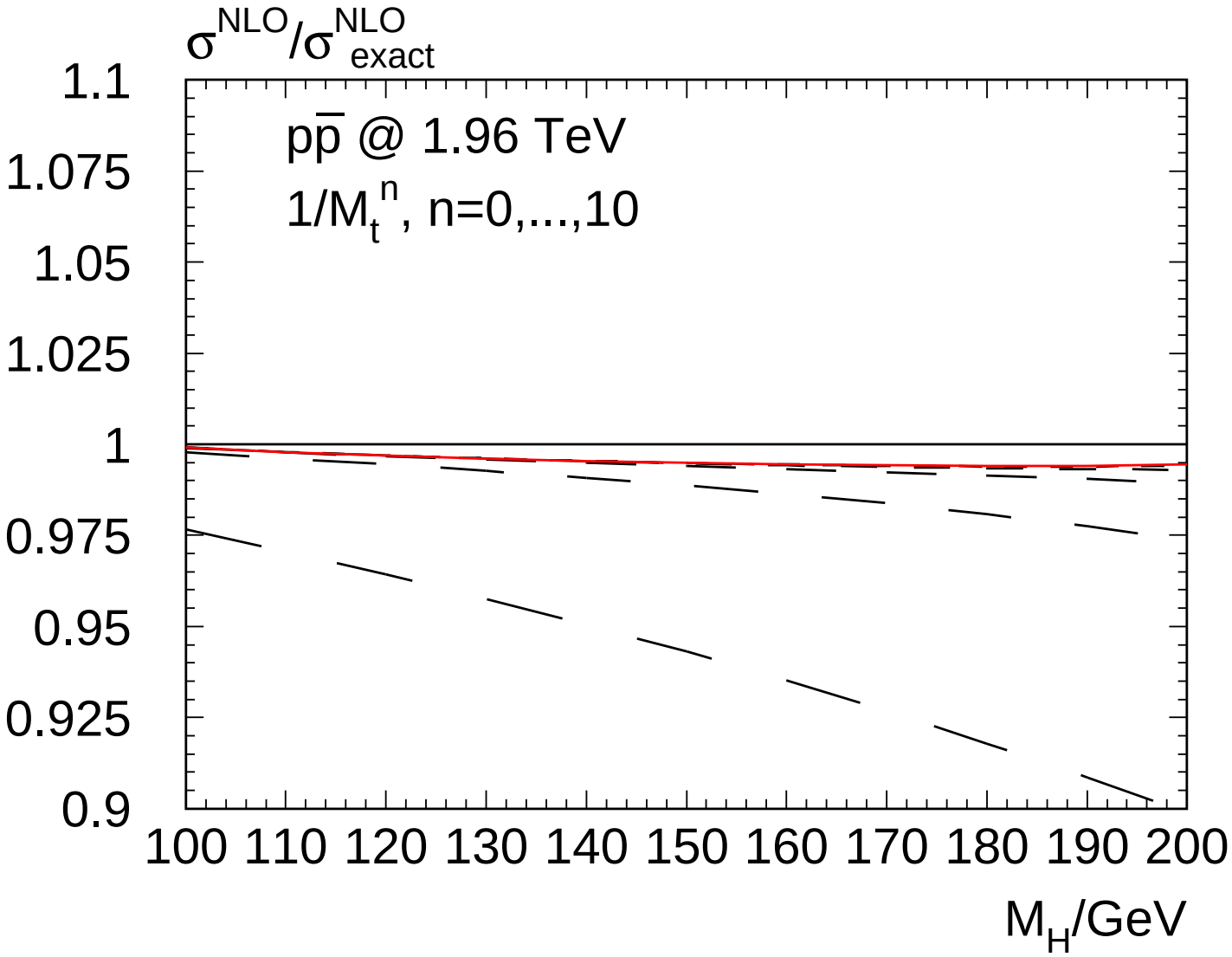

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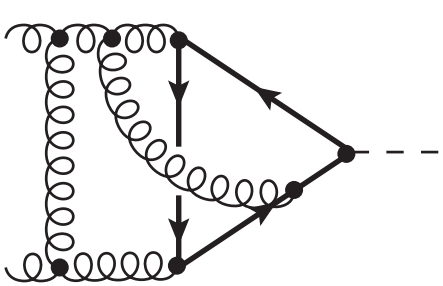

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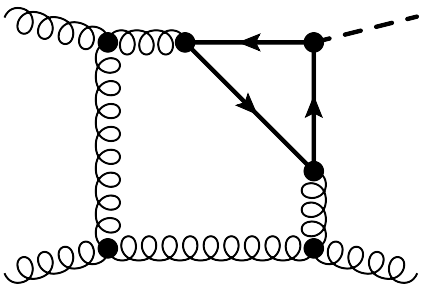

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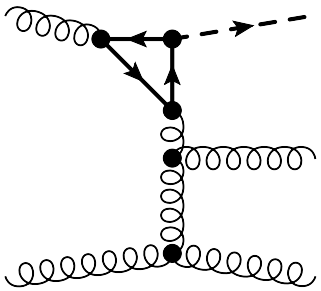

114

[RH, Ozeren '09]
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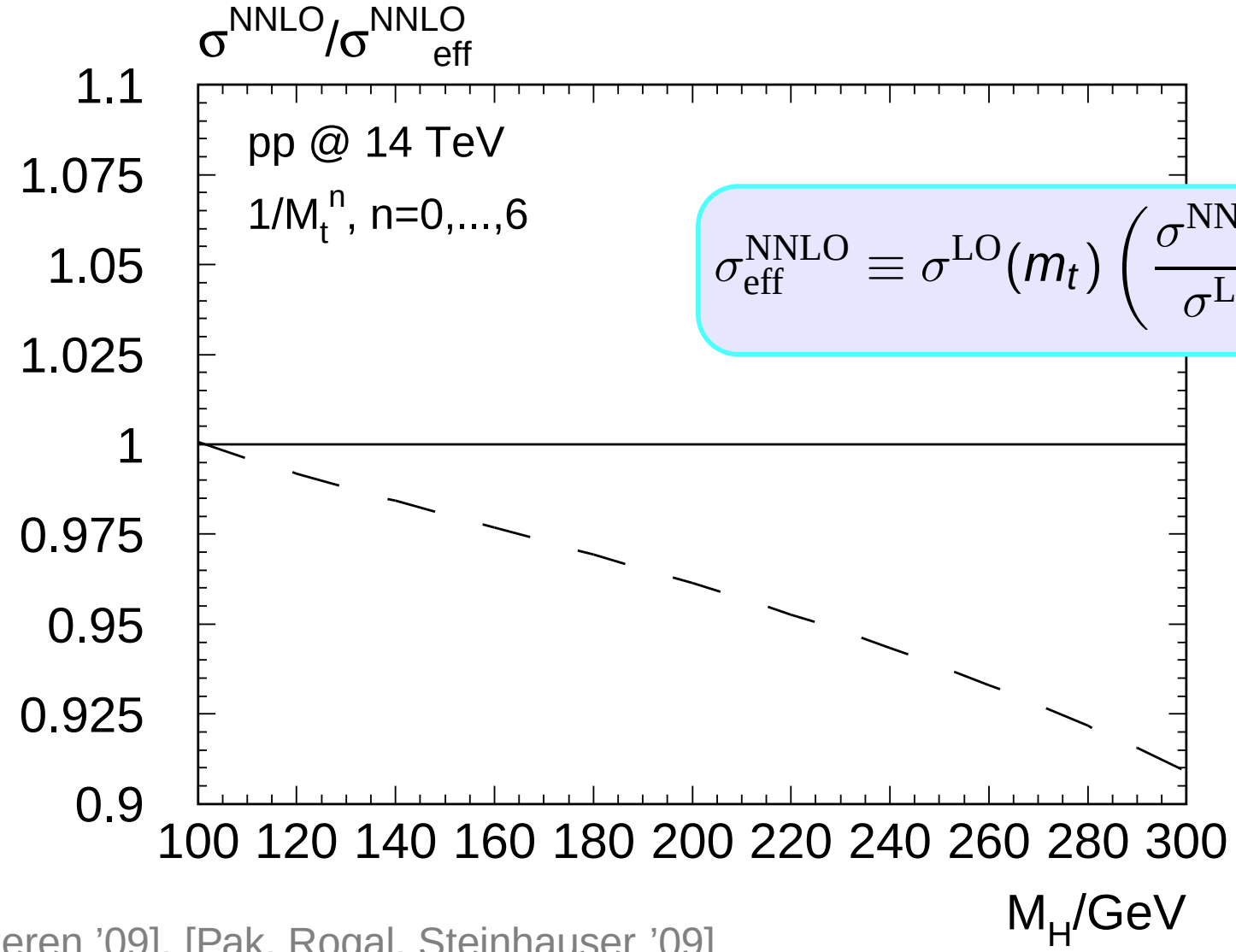

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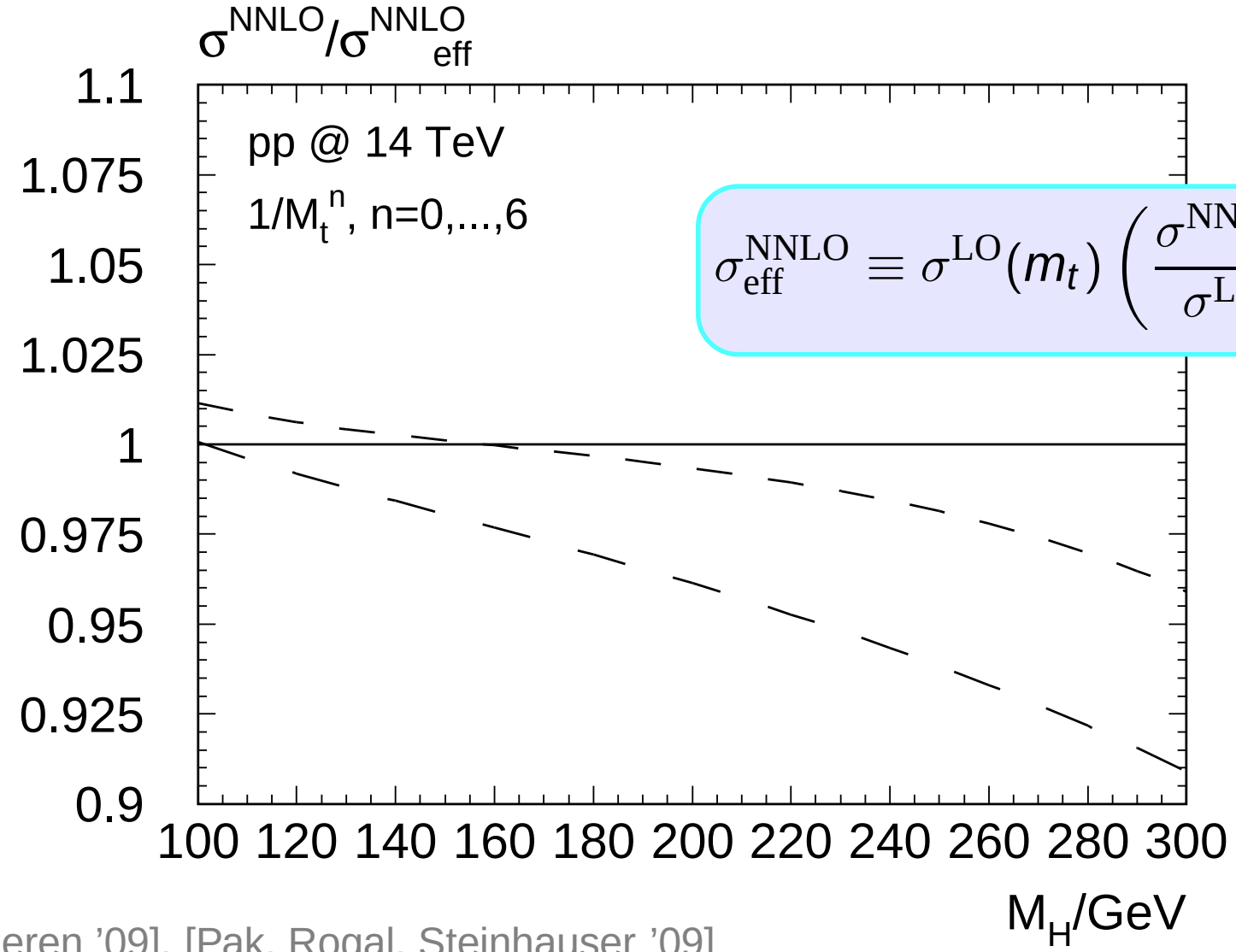

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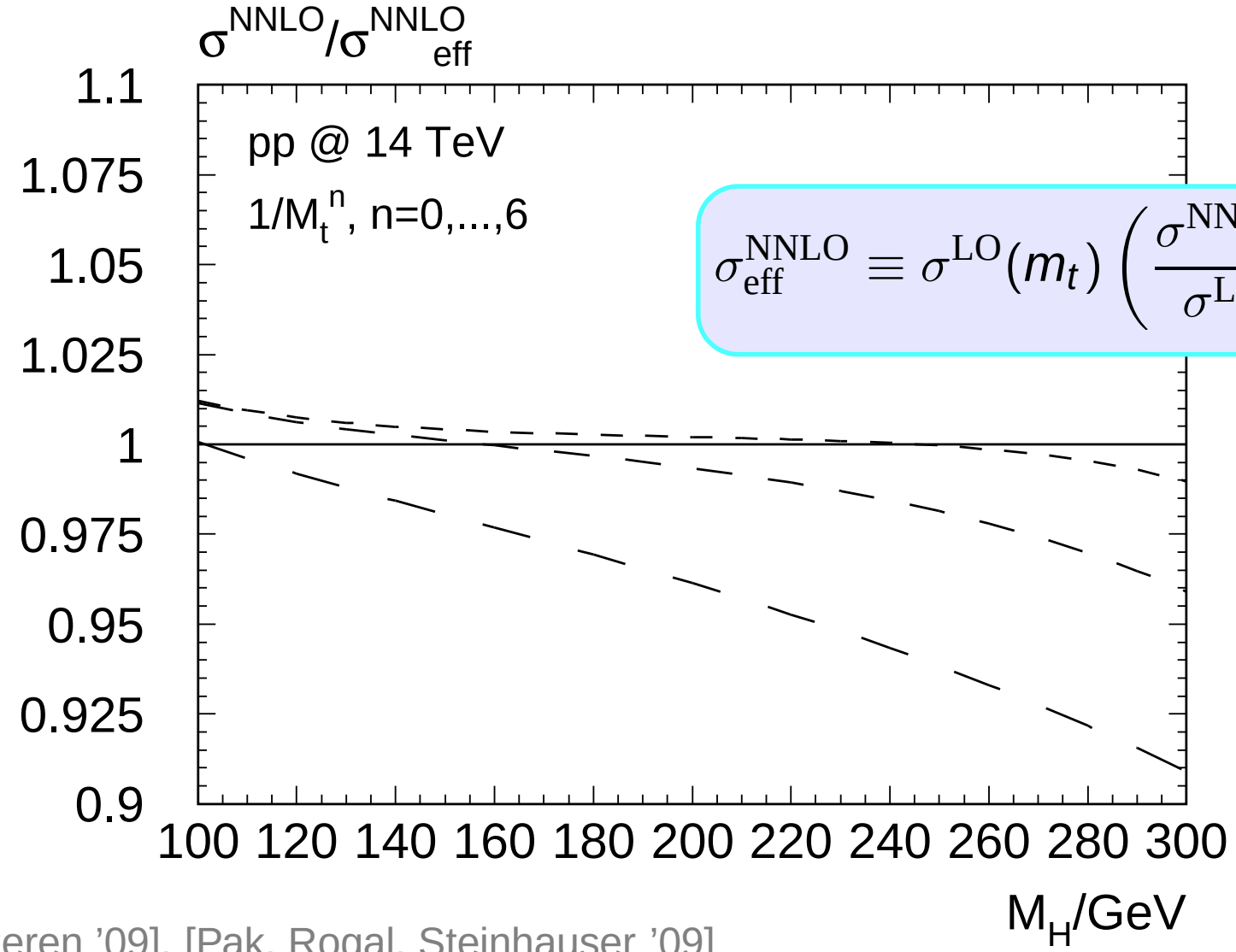

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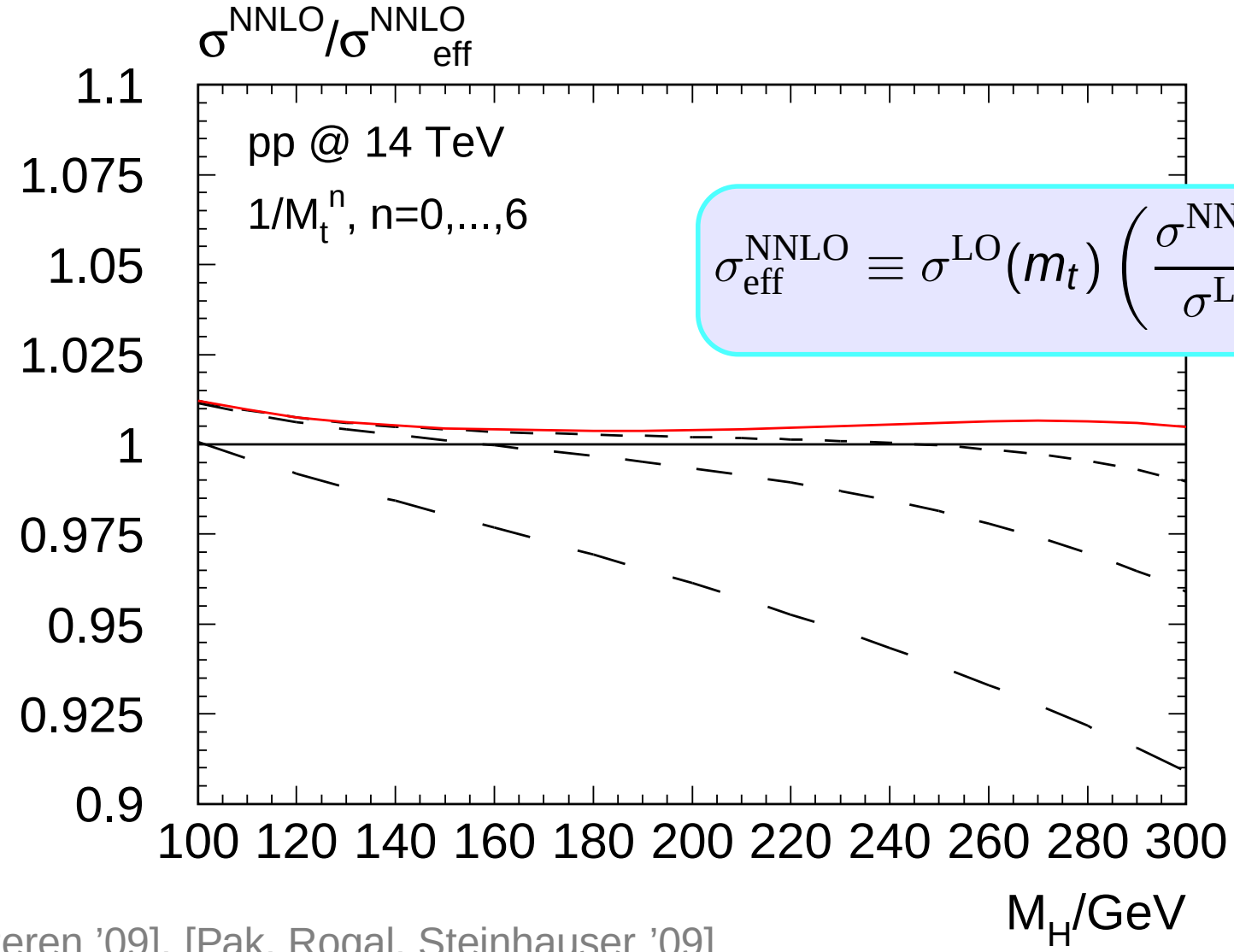

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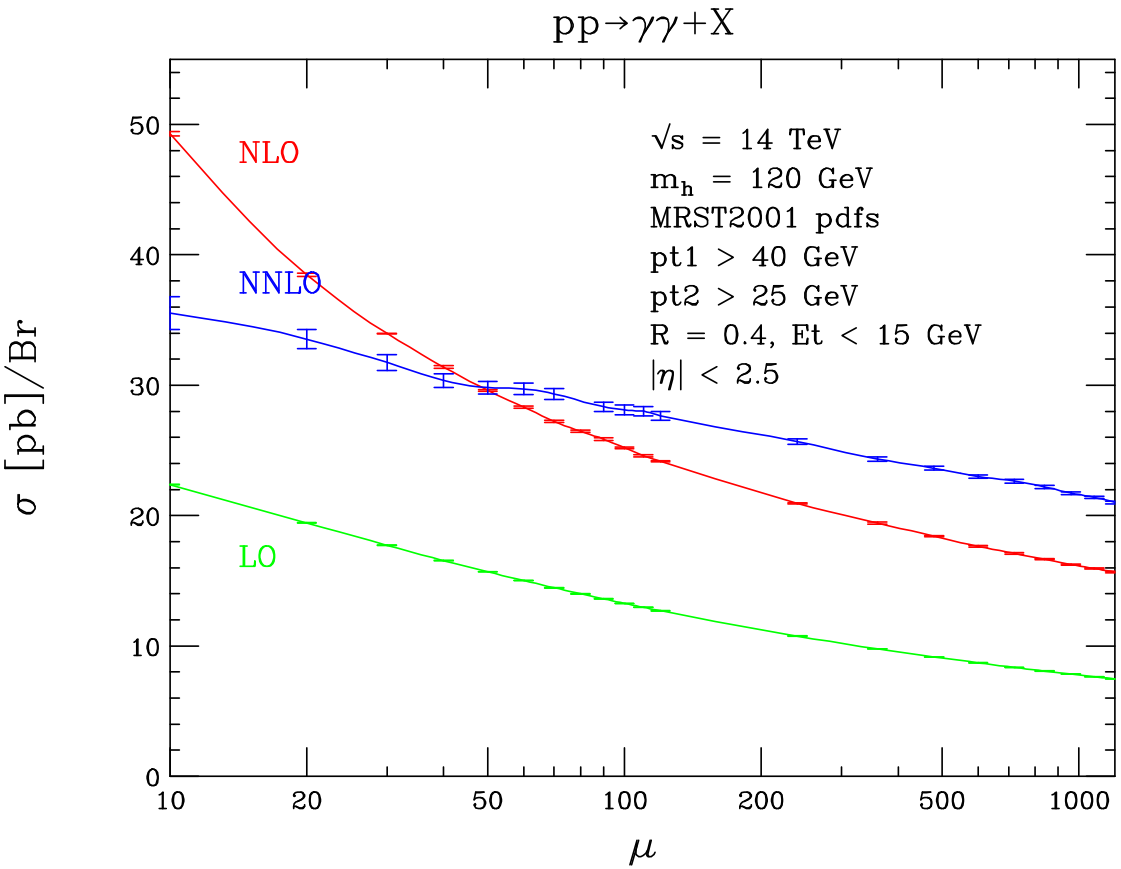

- **FEHiP**
  [Anastasiou, Melnikov, Petriello '04]
- **HNNLO**
  [Catani, Grazzini '08]

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- soft gluon resummation (or $\mu_F = \mu_R = m_H/2$) $\rightarrow$ +13%

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  [Anastasiou, Boughezal, Petriello '09]

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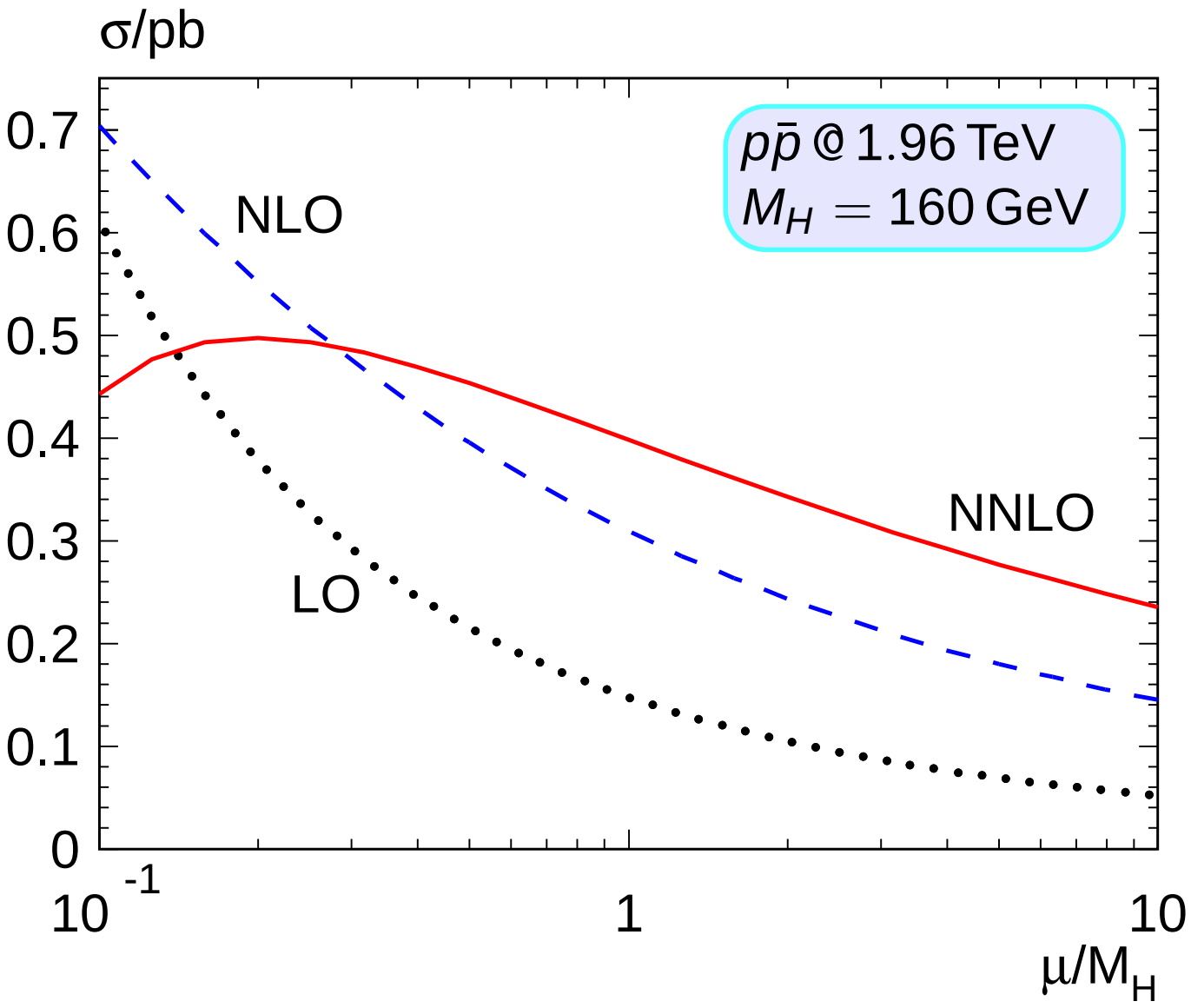
  - estimate higher orders from scale variation
  - range of μ variation is (at best) a convention — often: $M/2 < \mu < 2M$

μ dependence



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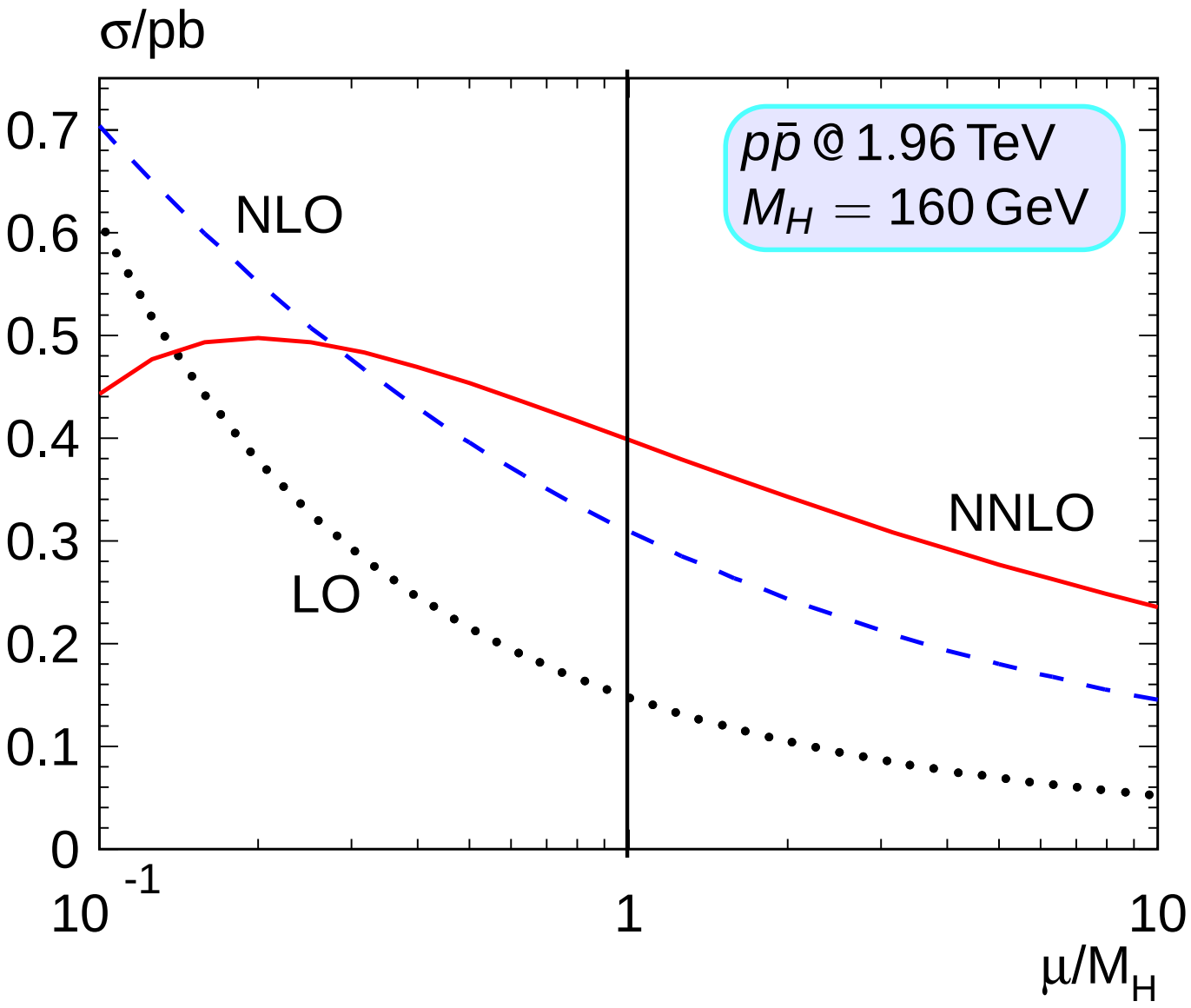

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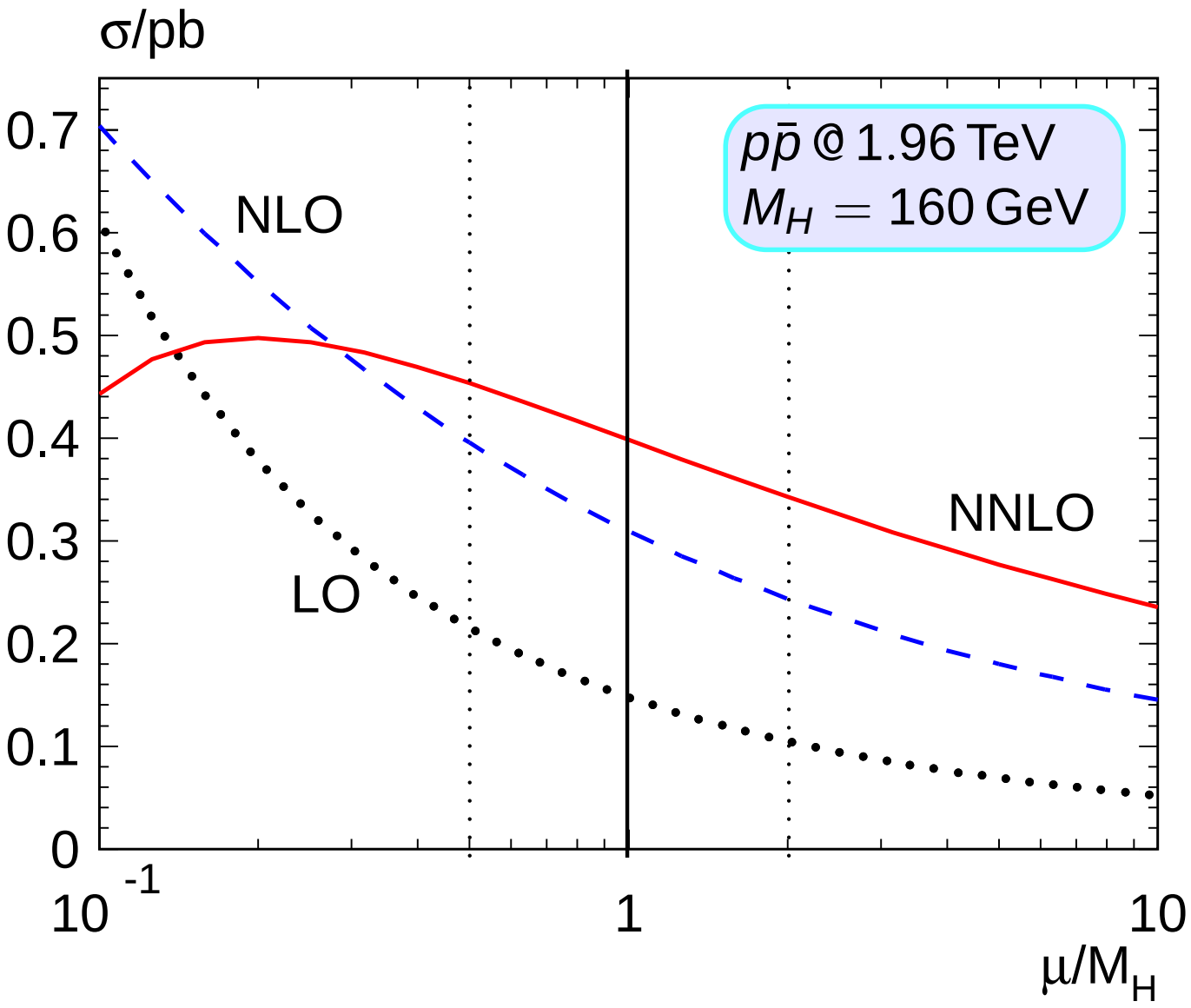

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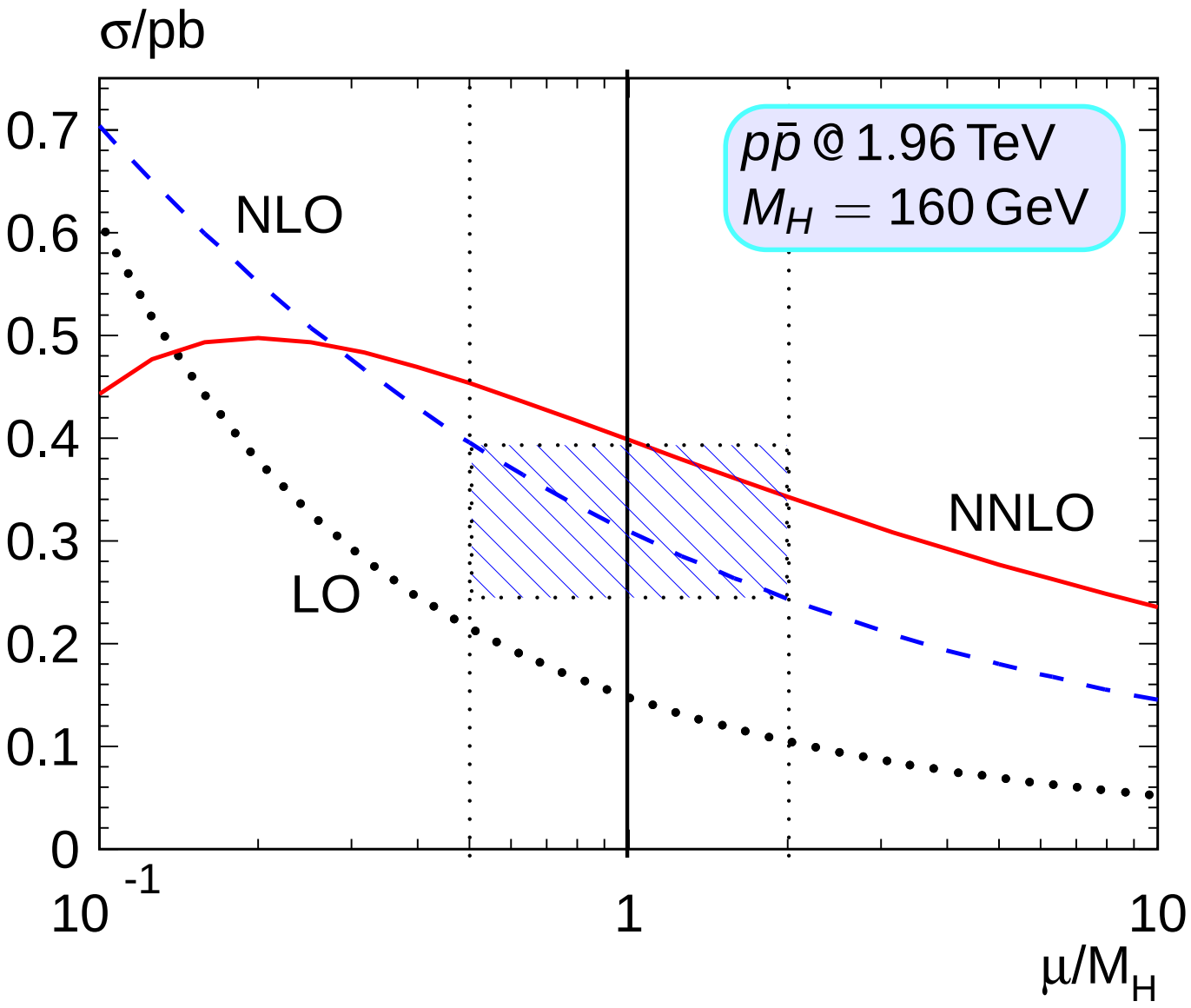

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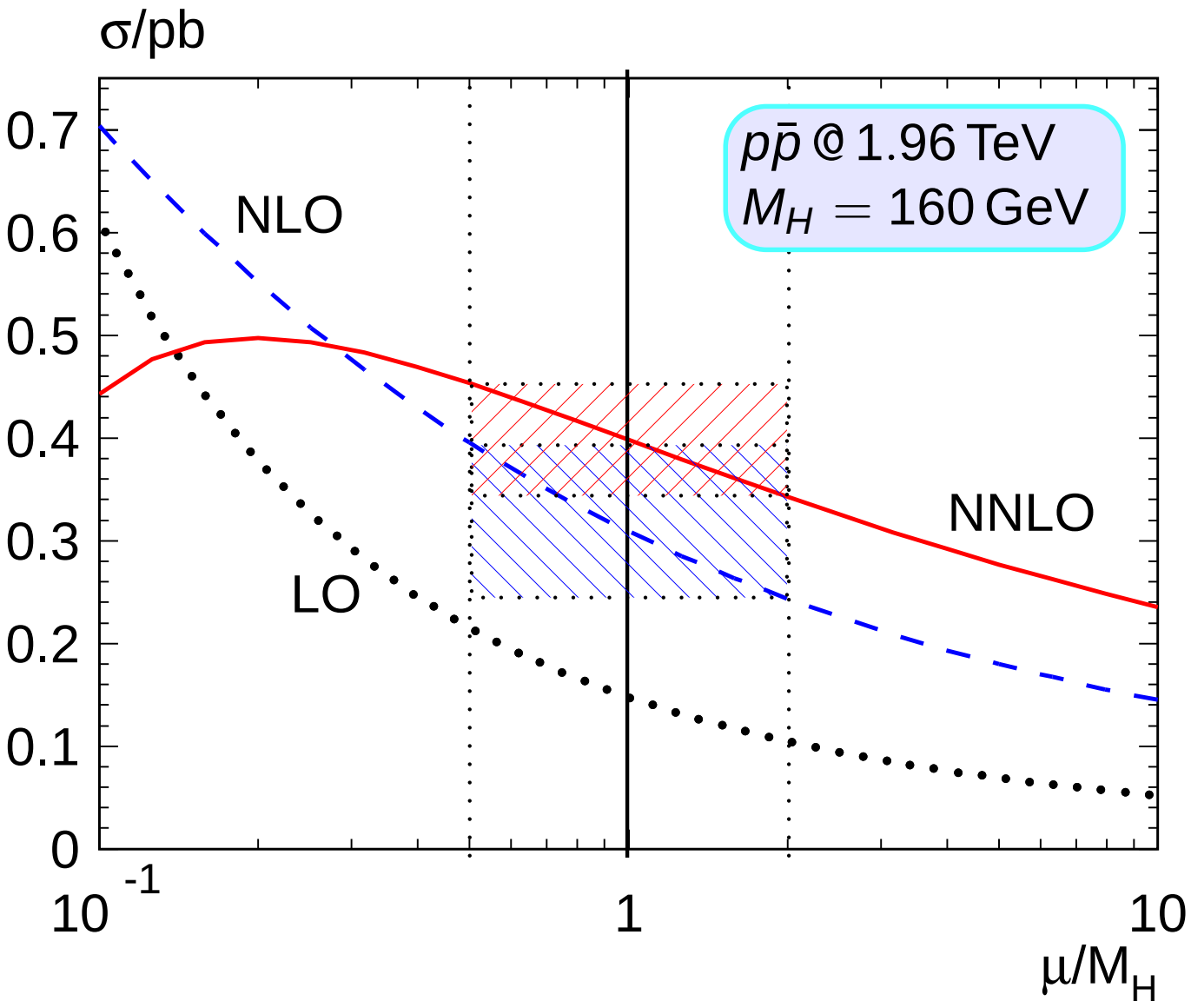

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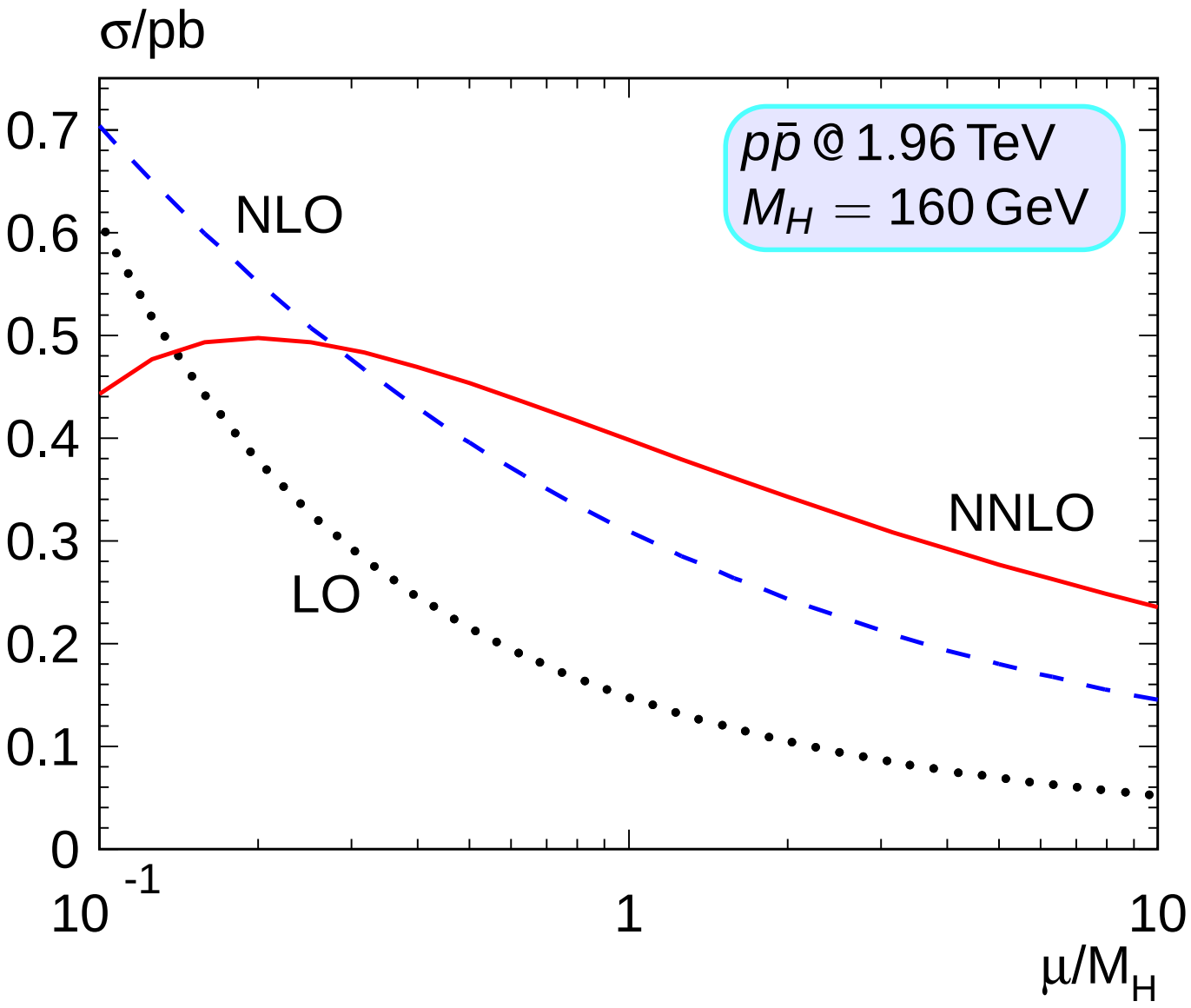

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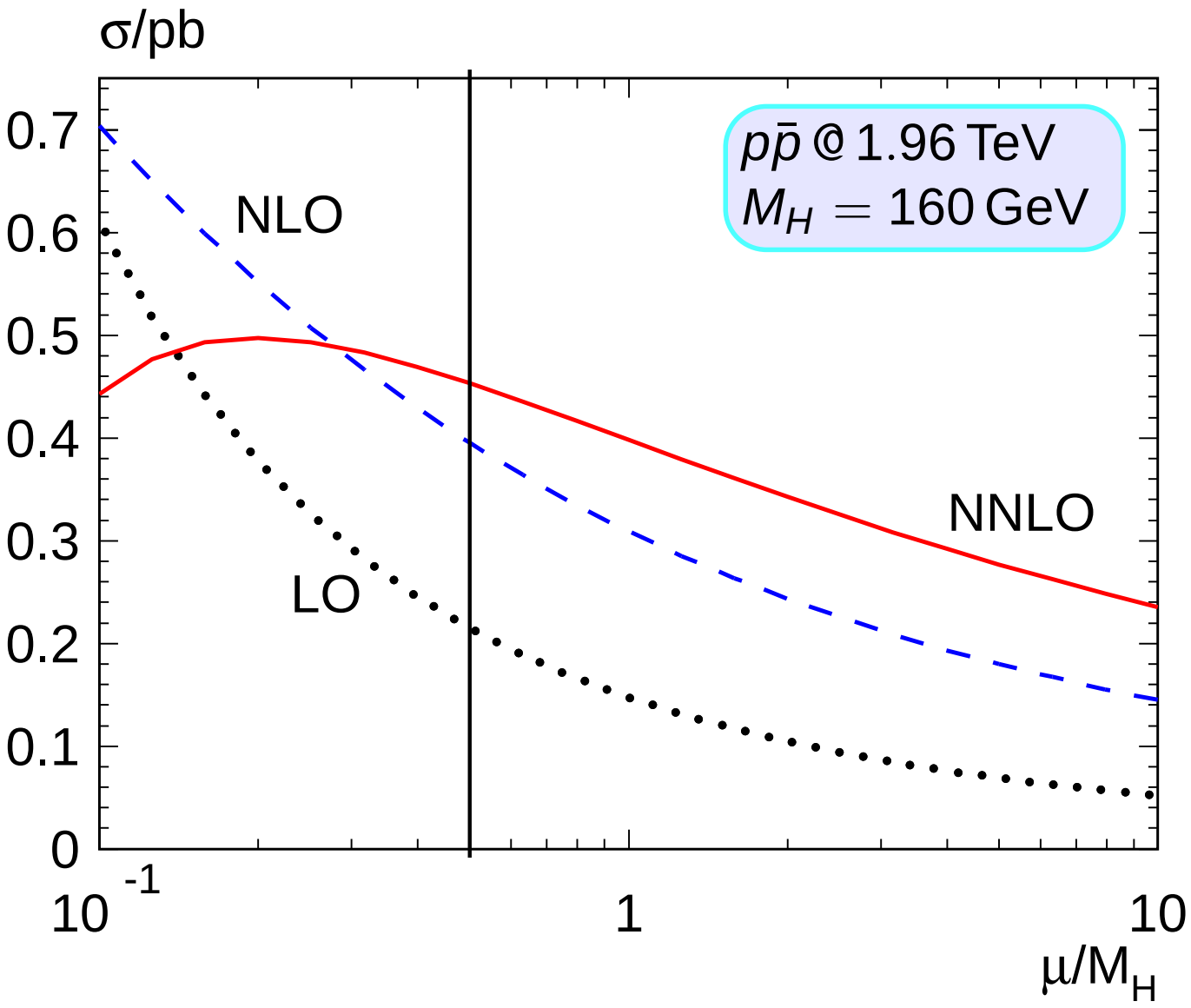

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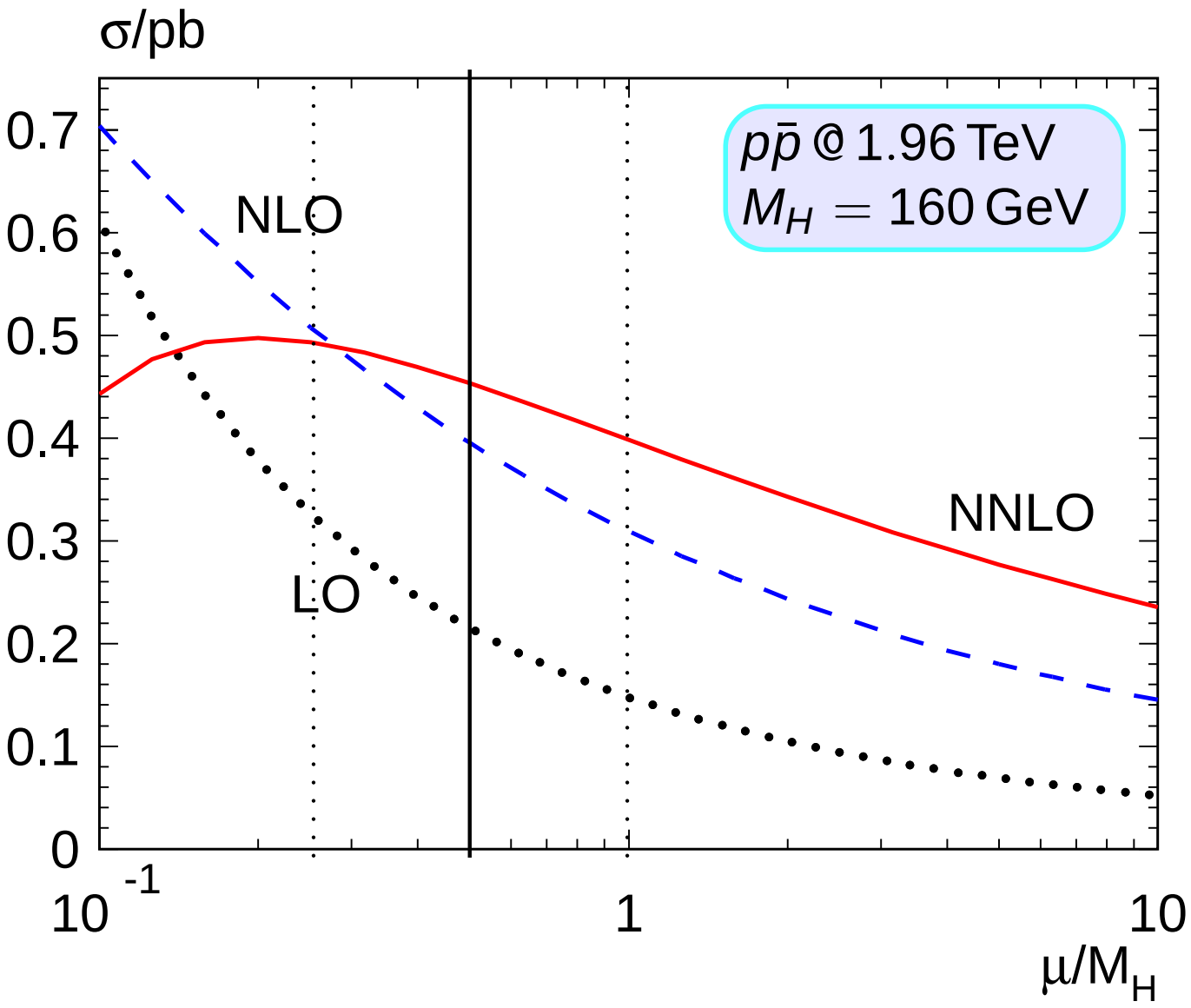

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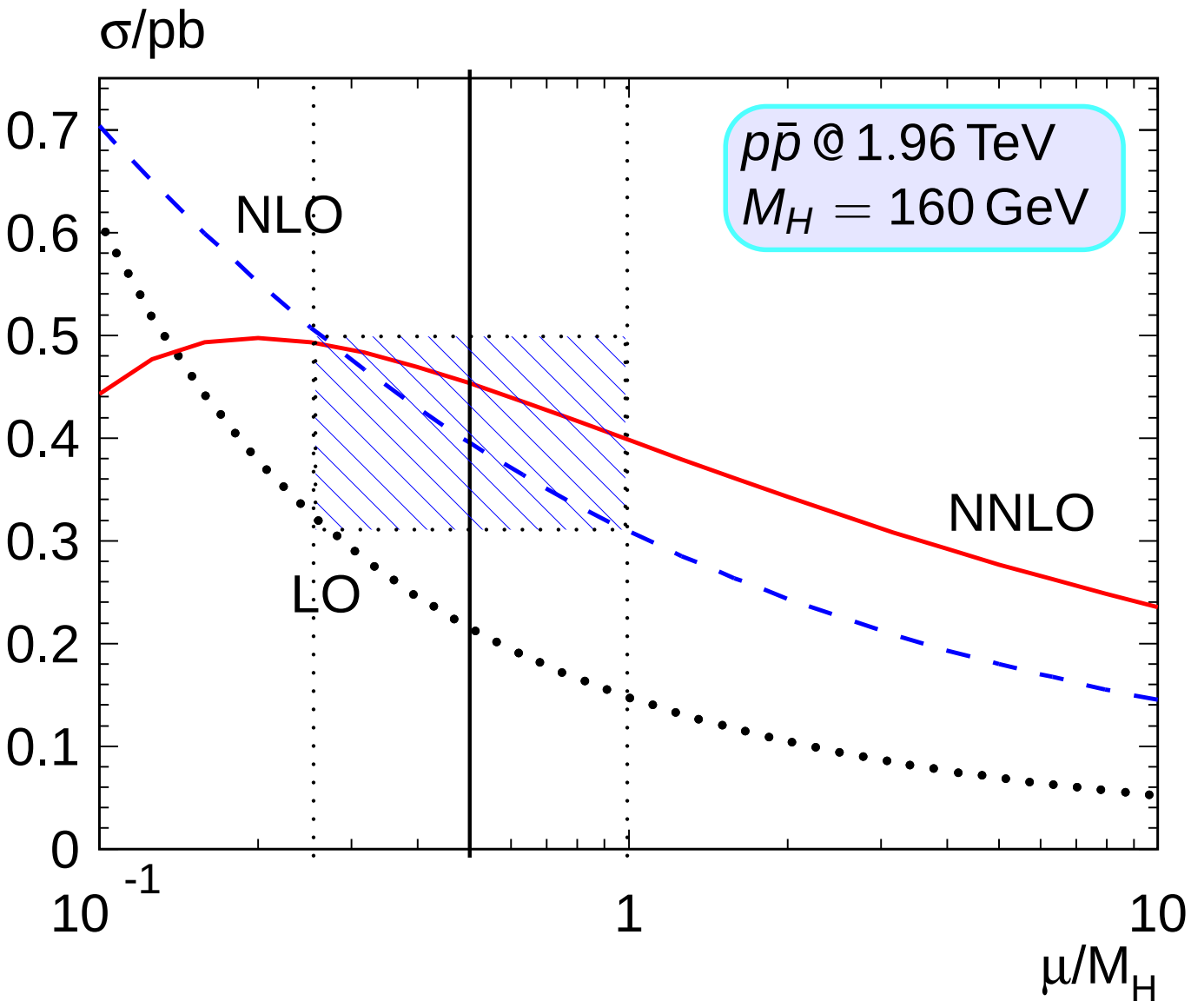

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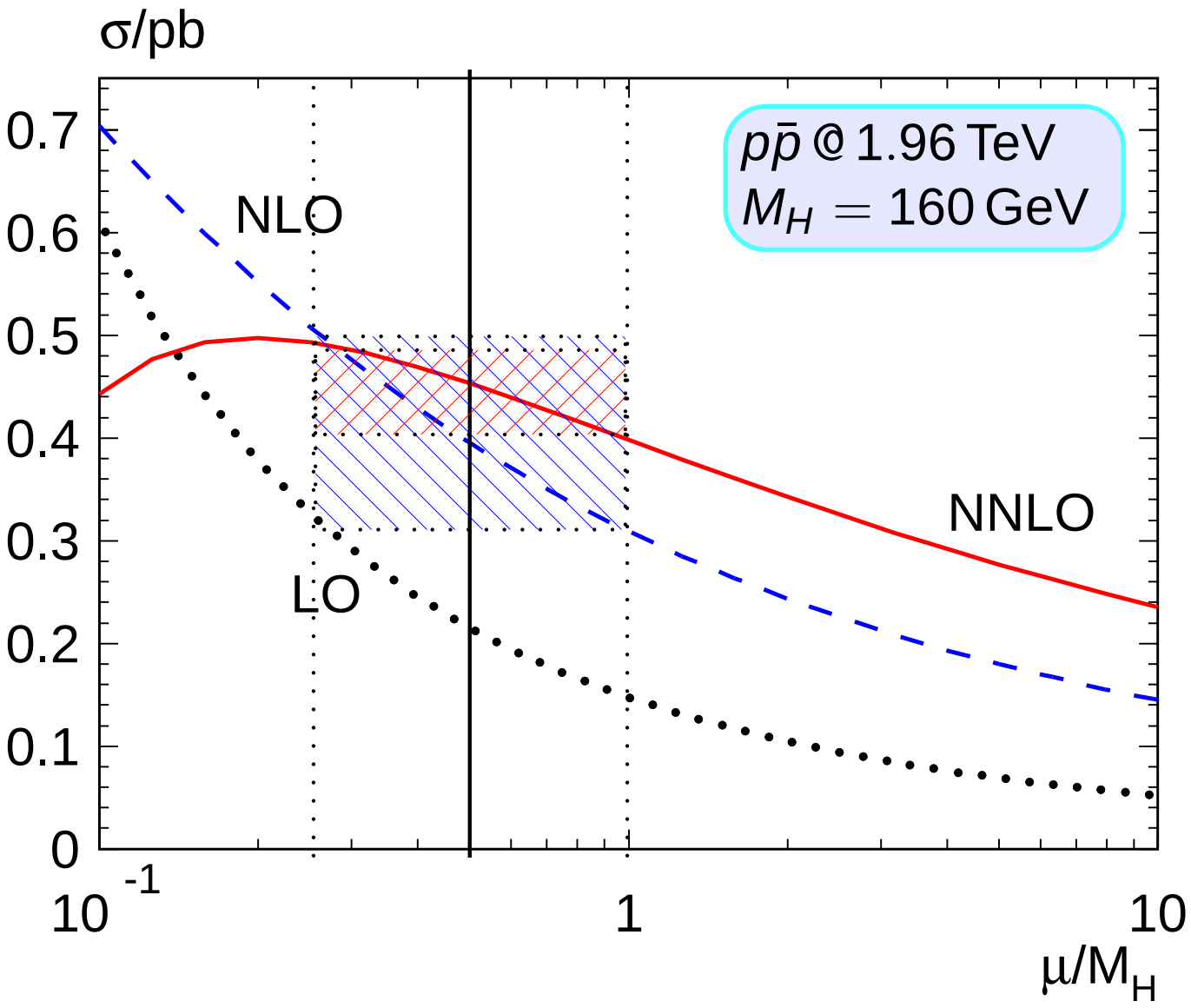

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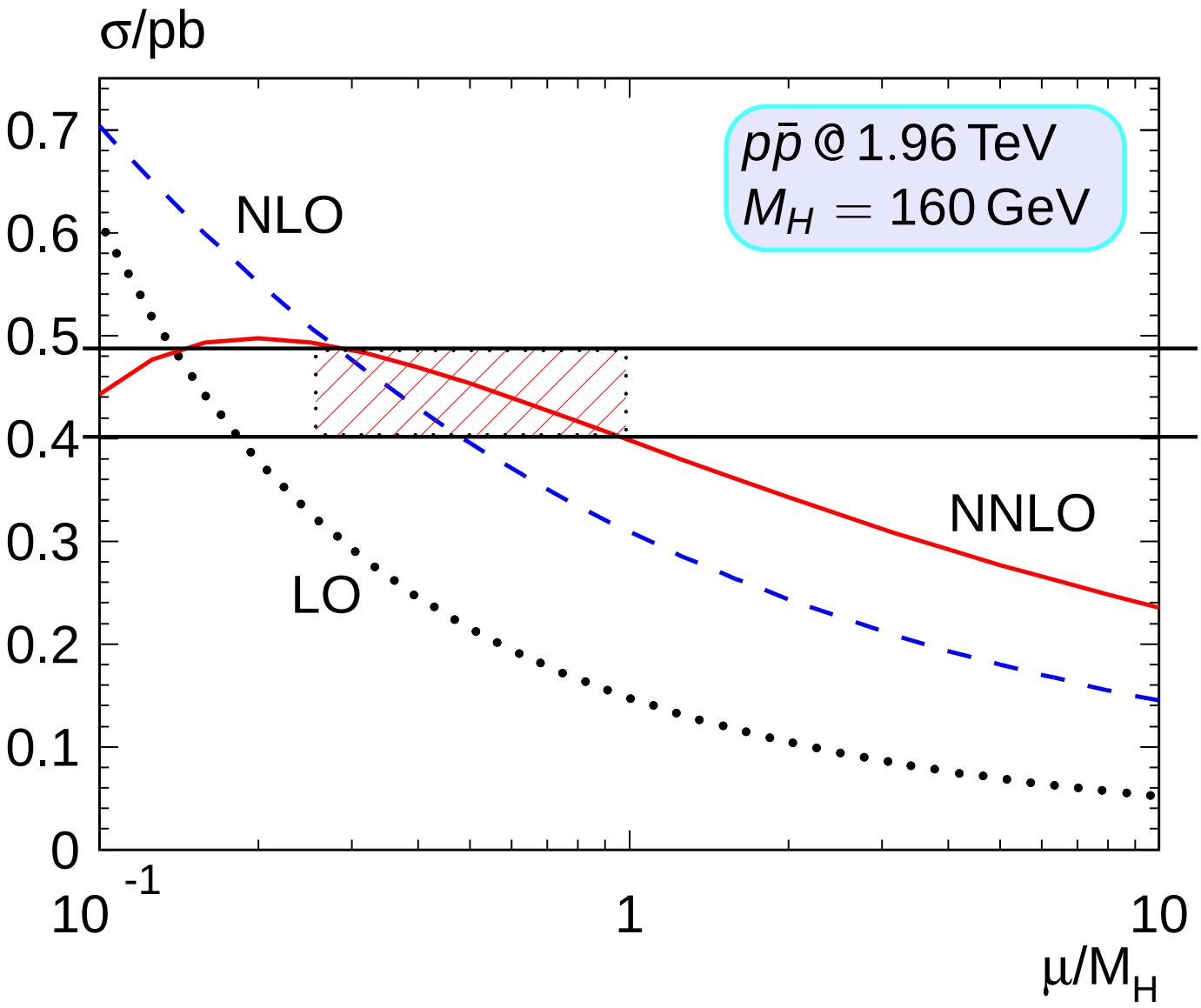

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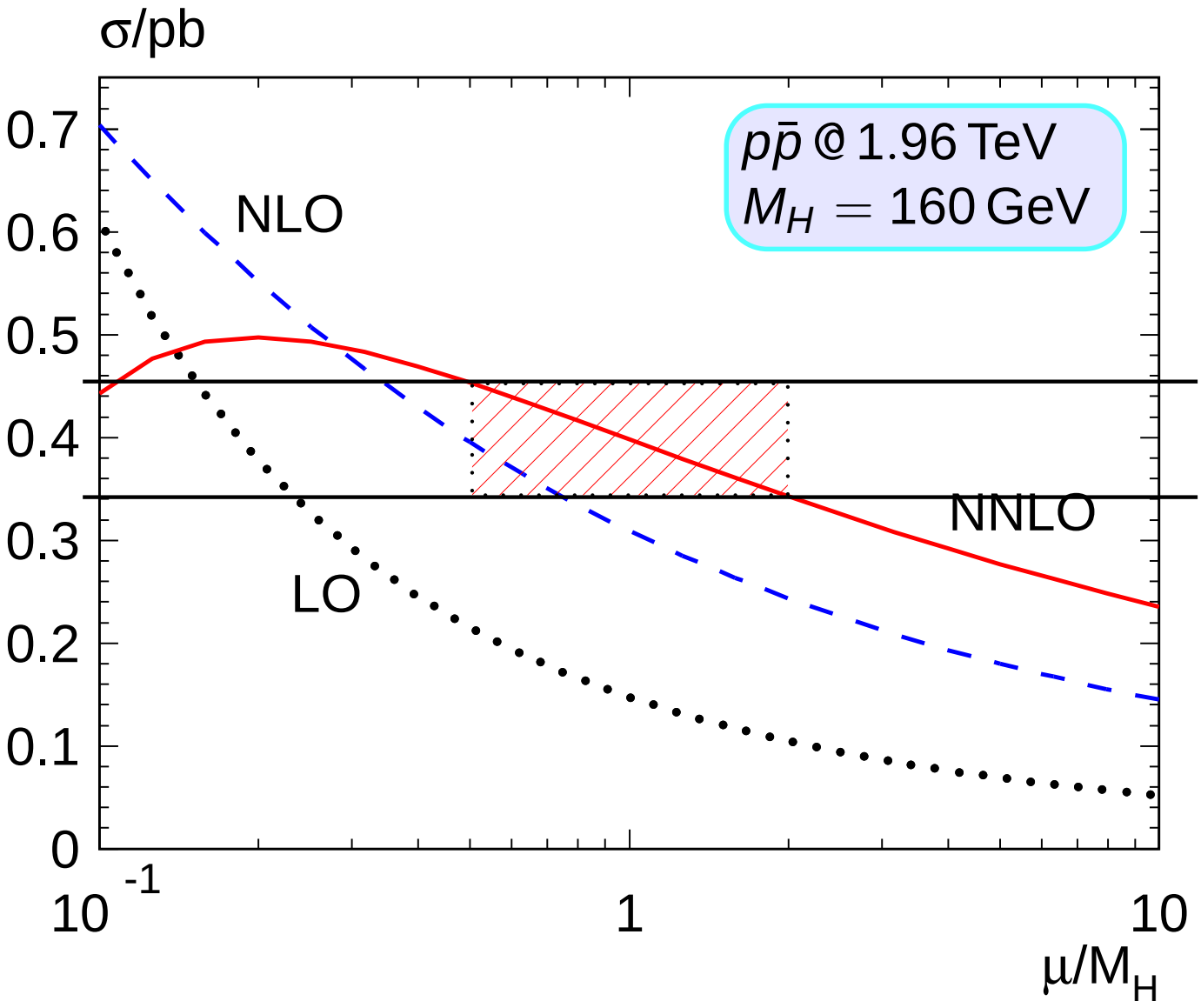

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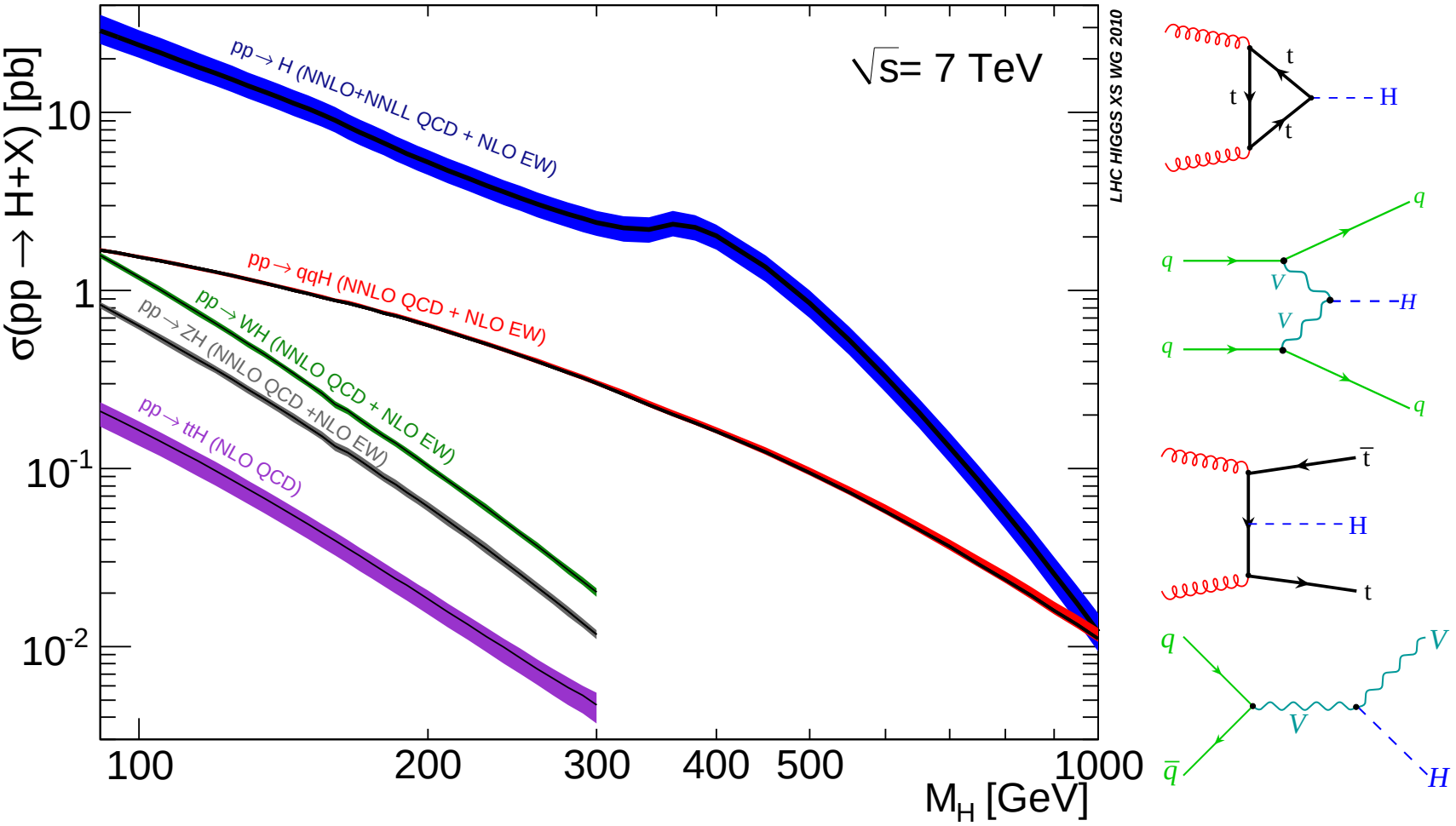
- my opinion:
  - provide exclusion for a "central" theory prediction
  - decouple "theory error" from experimental error
  - equivalently: don't normalize to SM

Higgs cross sections



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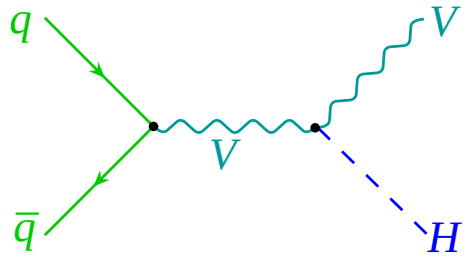

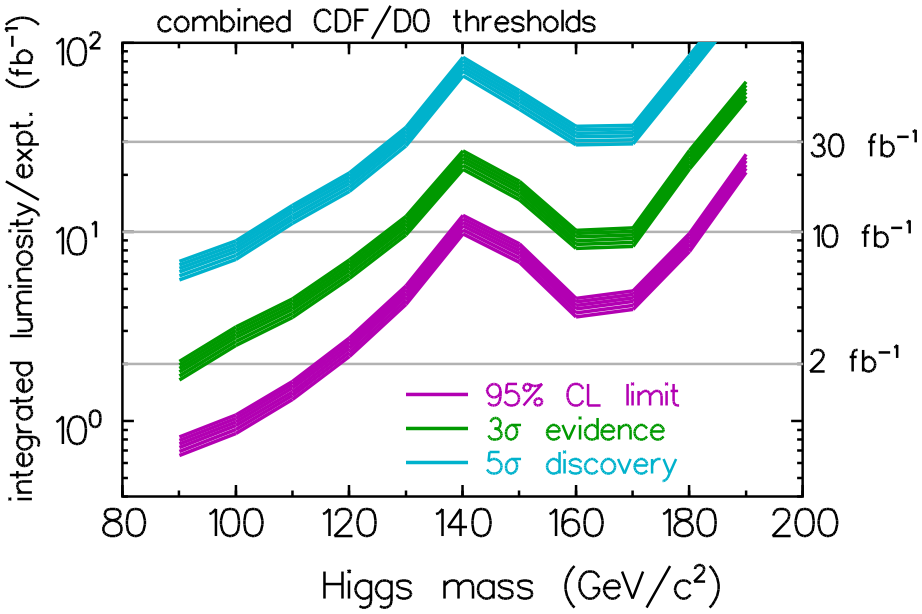

[Tev Higgs WG '00]

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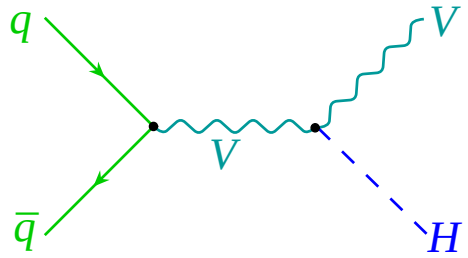

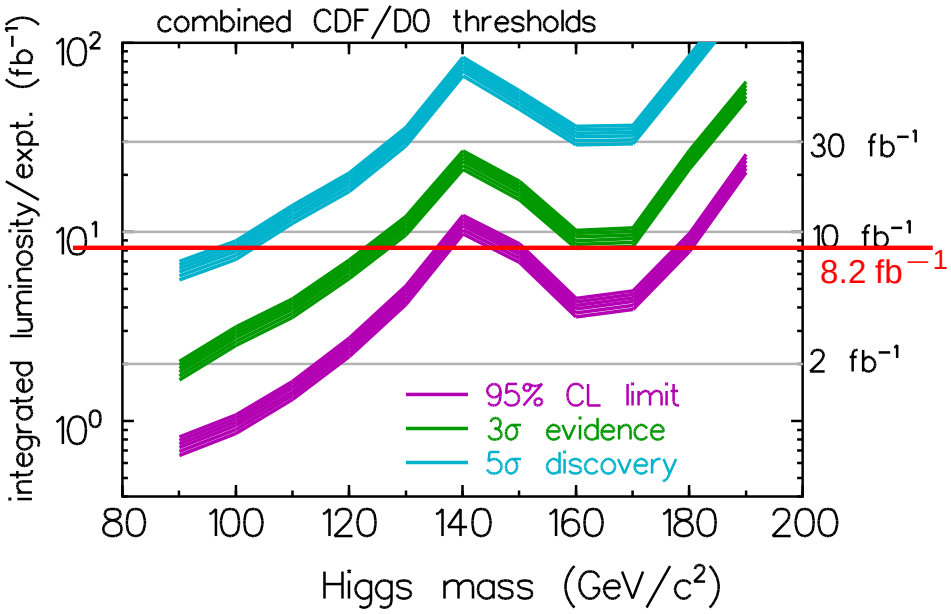

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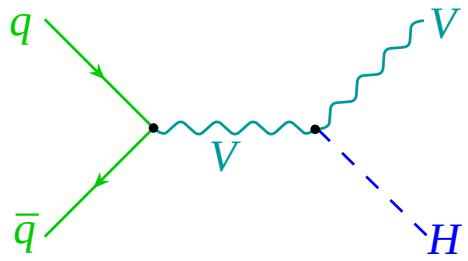

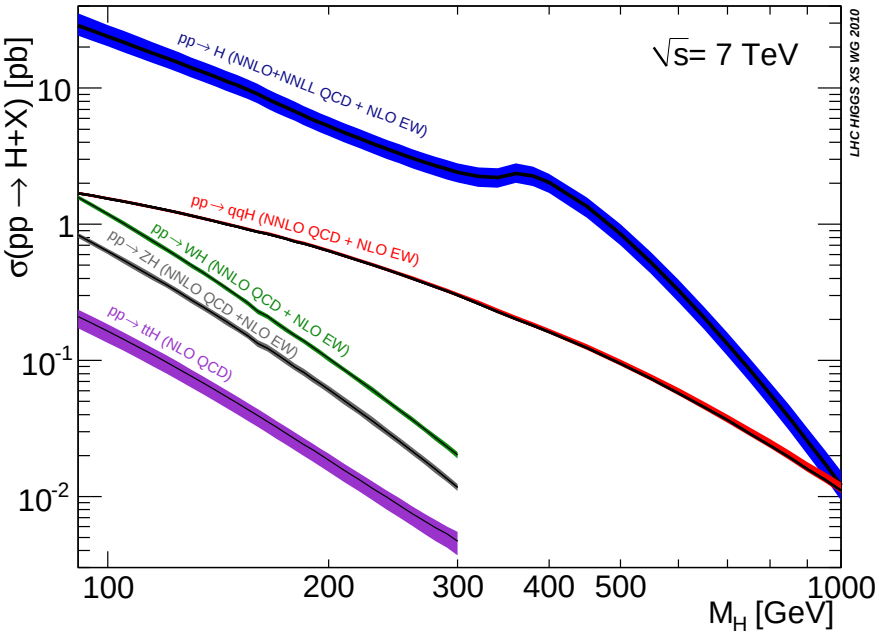

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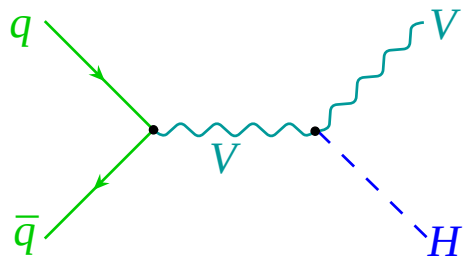

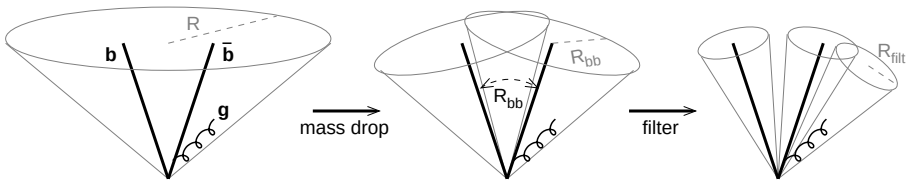

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- use jet sub-structure:

  [Butterworth *et al.* 08]

  promising for $M_H \approx 120$ GeV

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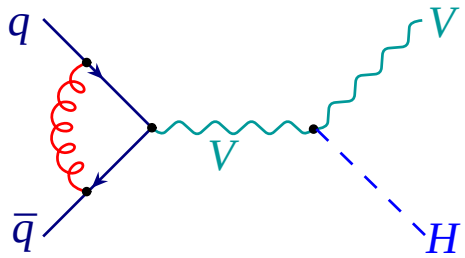

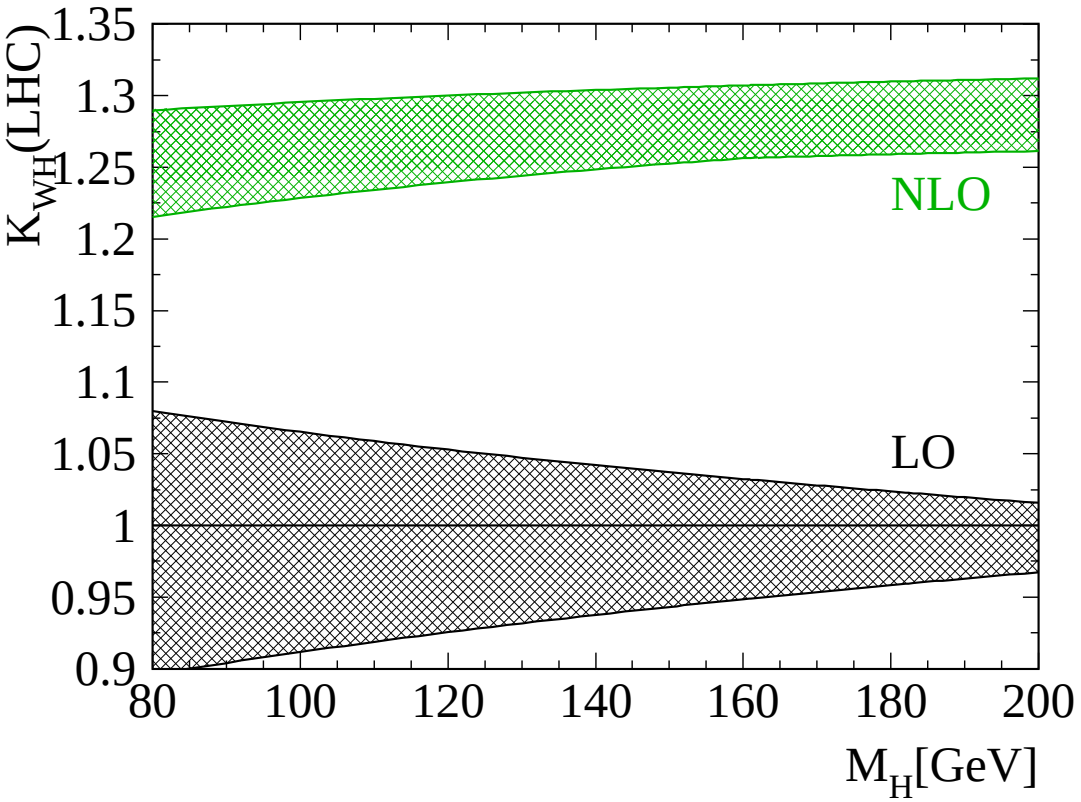

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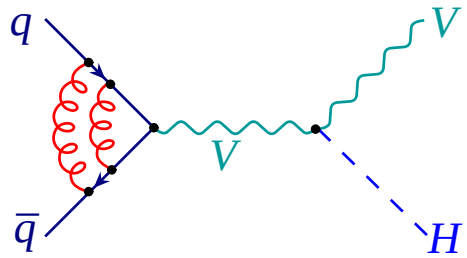

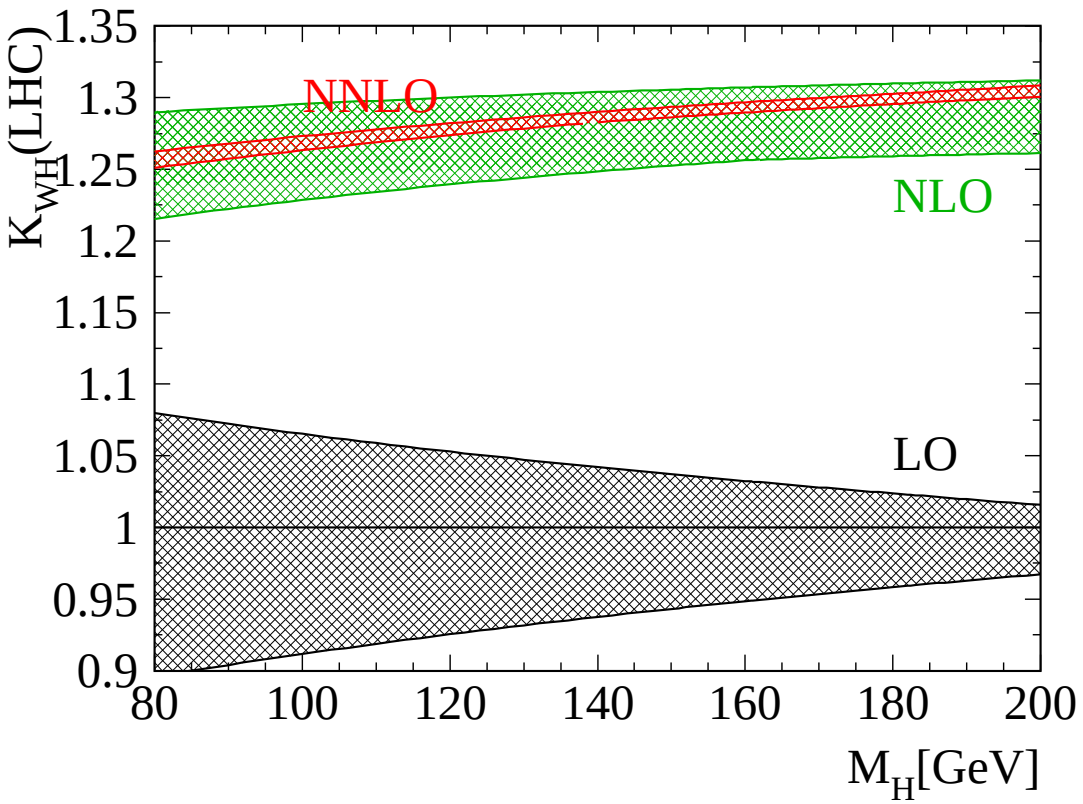

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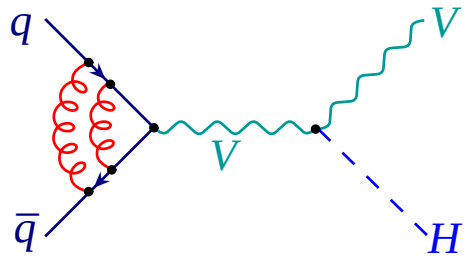

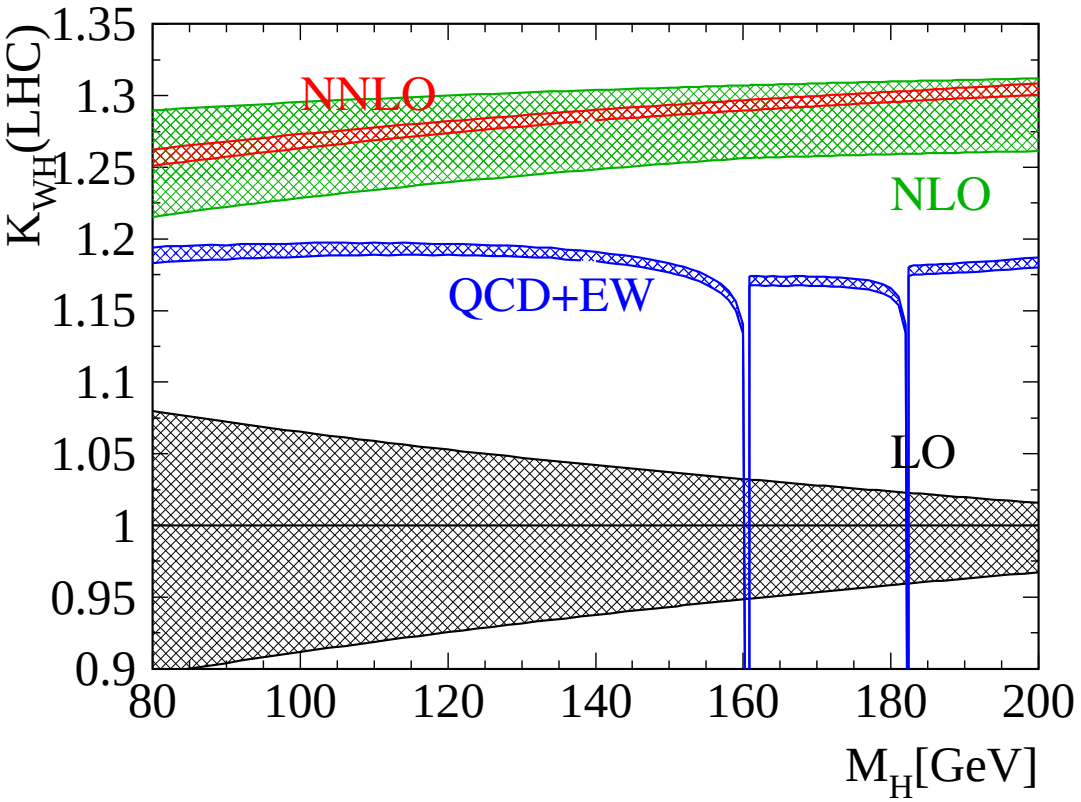

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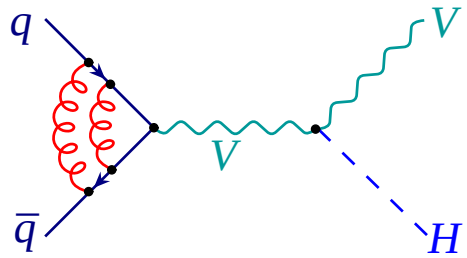

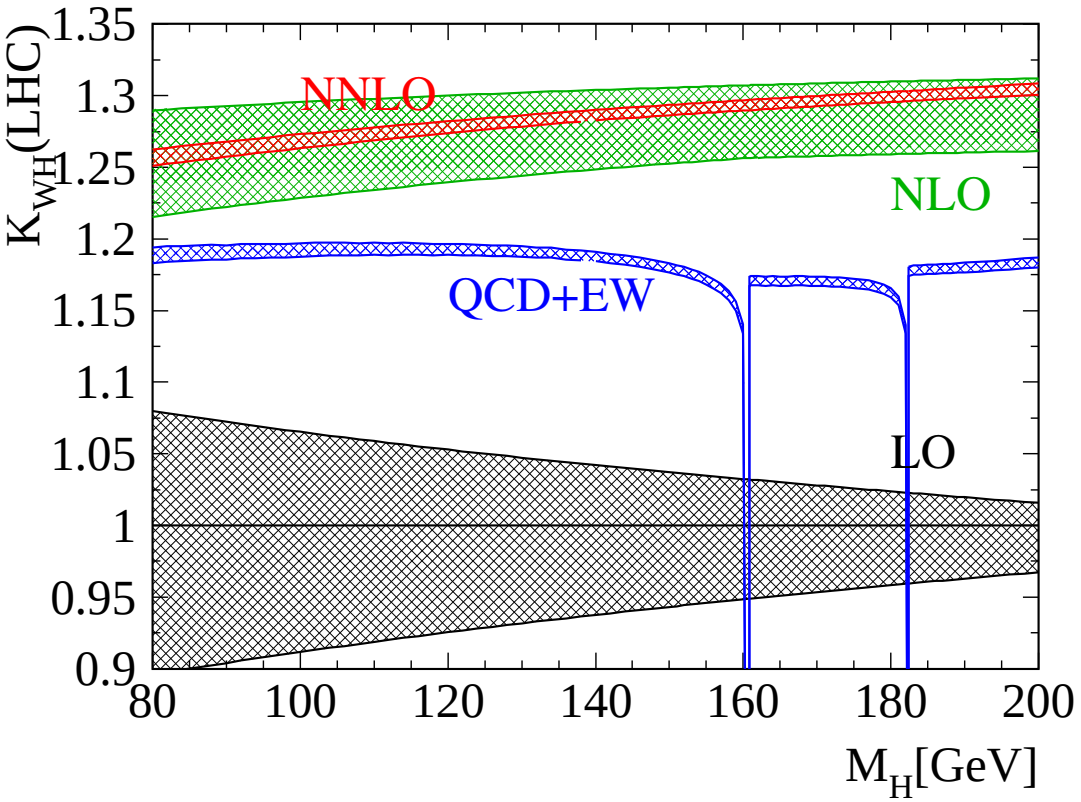

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update:

[Brein, R.H., Wiesemann, Zirke '11]

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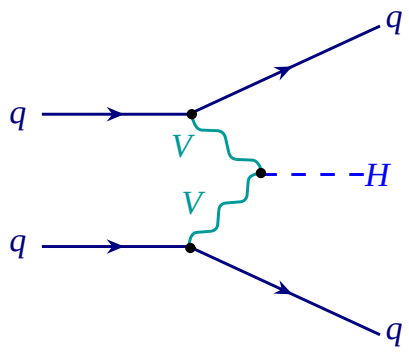

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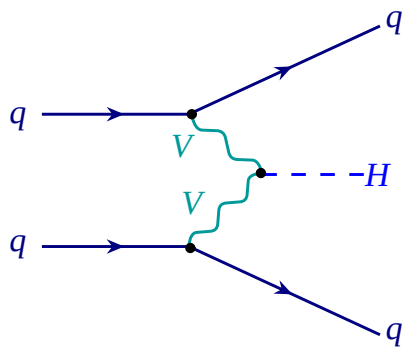

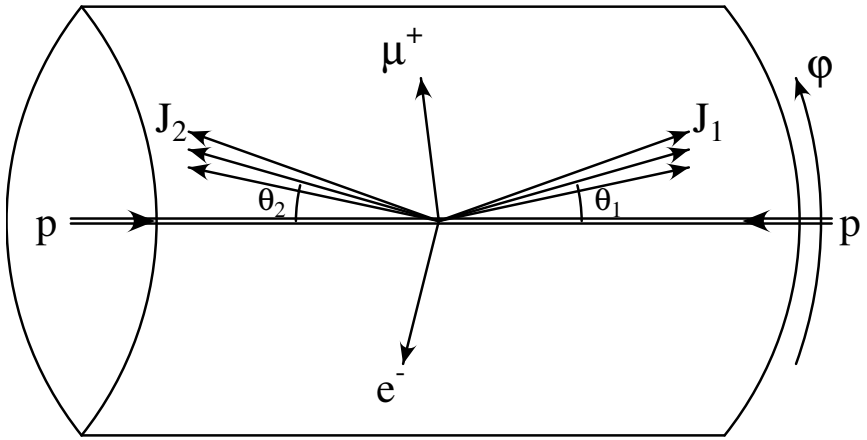

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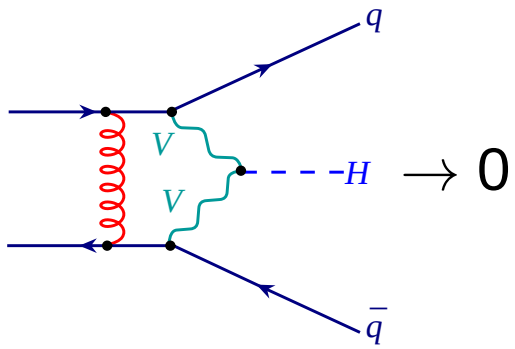
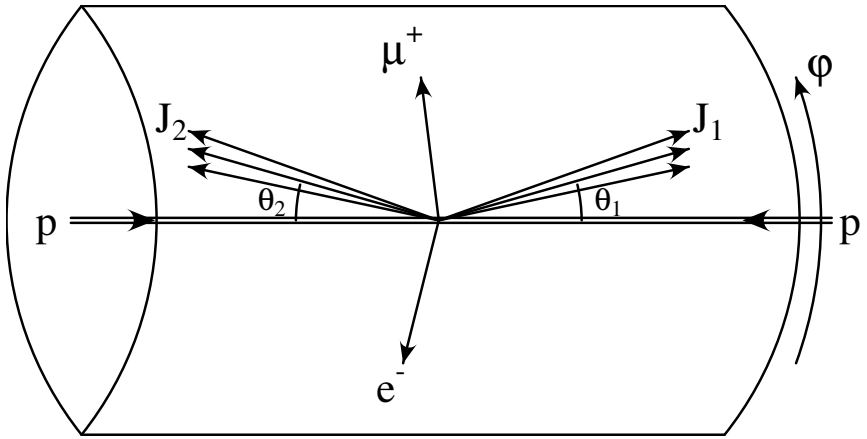


$\to 0$



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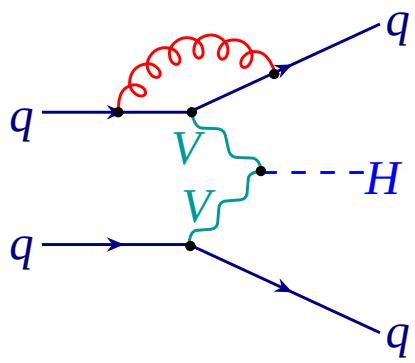
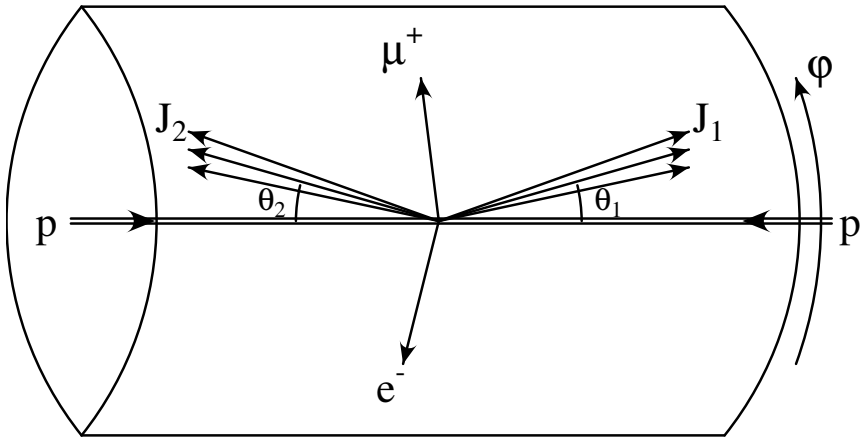
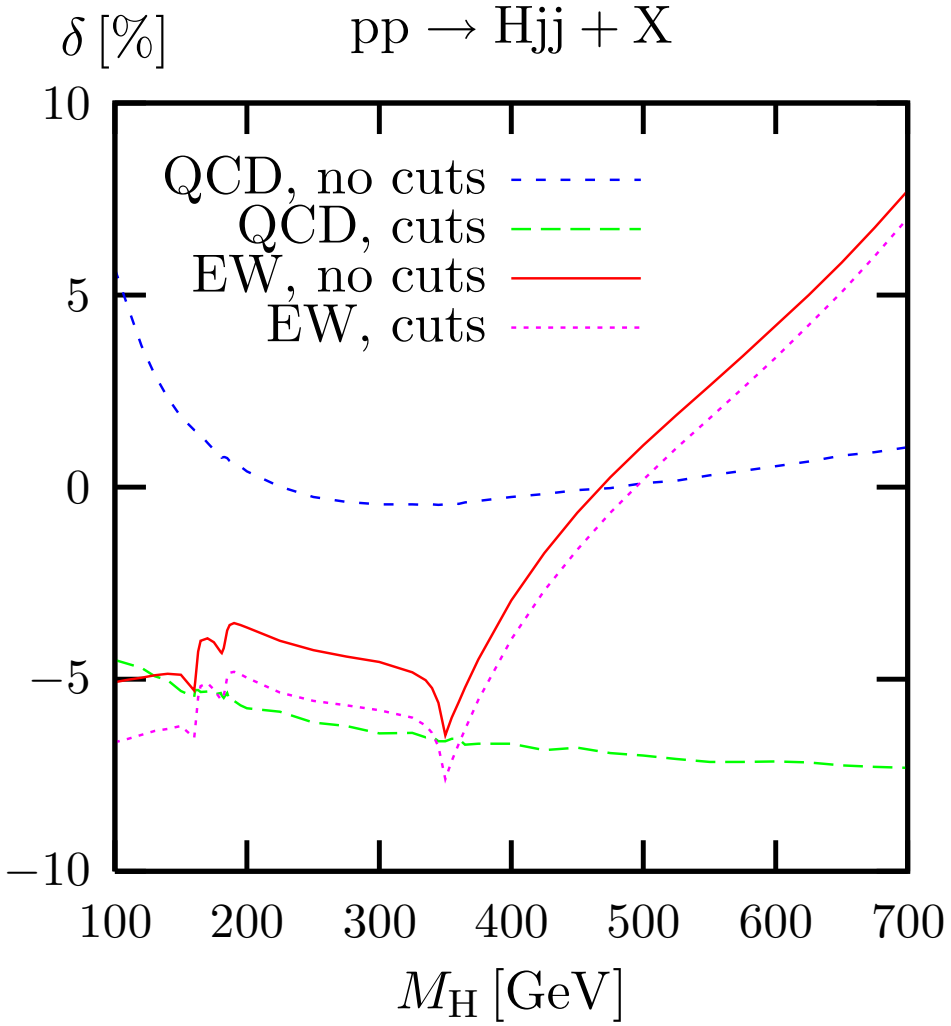




NLO QCD: [Figy, Oleari, Zeppenfeld '03]

+ EW: [Ciccolini, Denner, Dittmaier '08]

WBF: QCD+EW corrections



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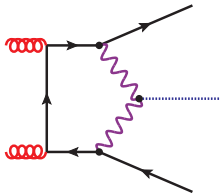

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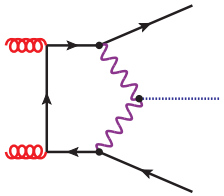

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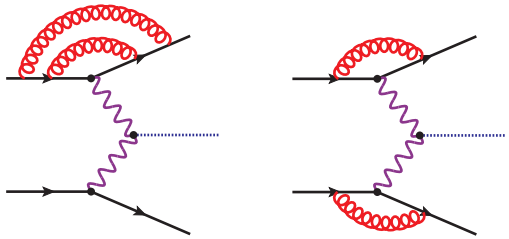

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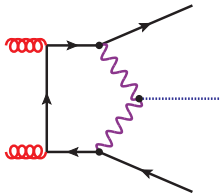

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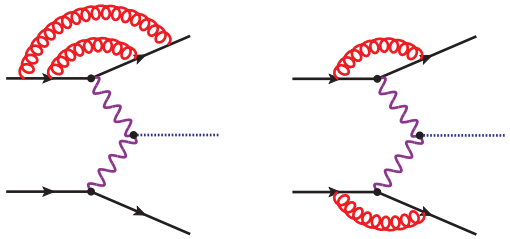

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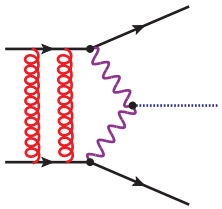
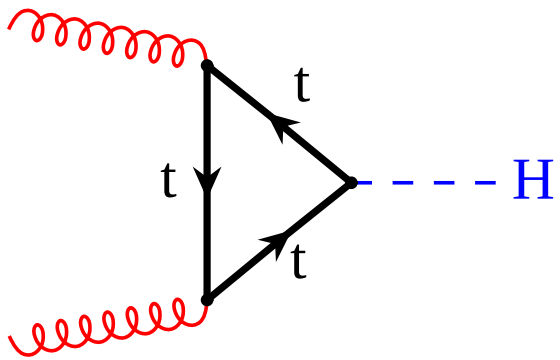


BSM Higgs

Gluon Fusion: 4^{th} generation



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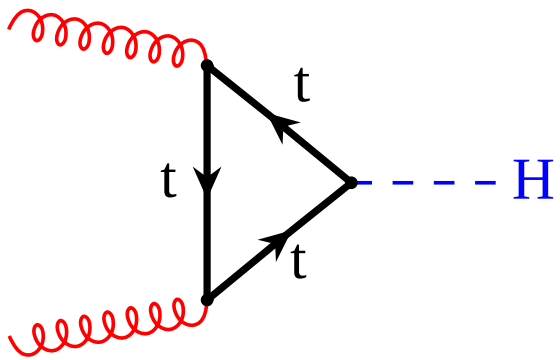
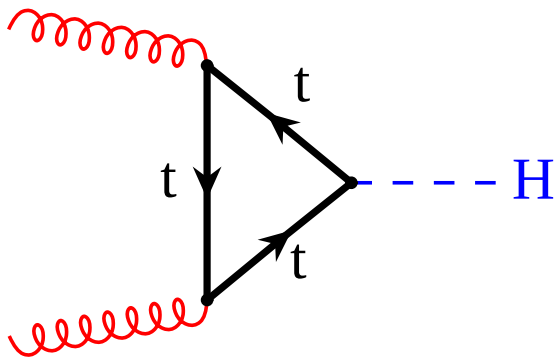


- sensitive to heavy particle spectrum

$$\sigma \overset{m_t \gg M_H}{\longrightarrow} \frac{\pi}{256\sqrt{2}} \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{y_t}{m_t}\right)^2$$

Gluon Fusion: 4^{th} generation



- sensitive to heavy particle spectrum

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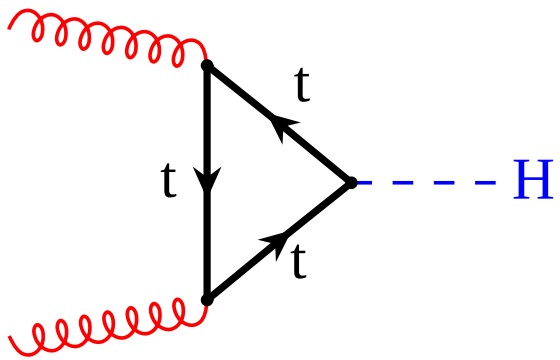

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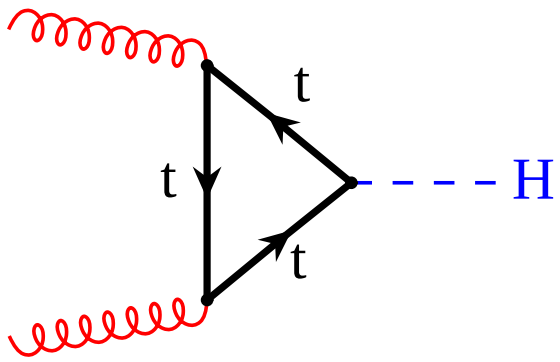

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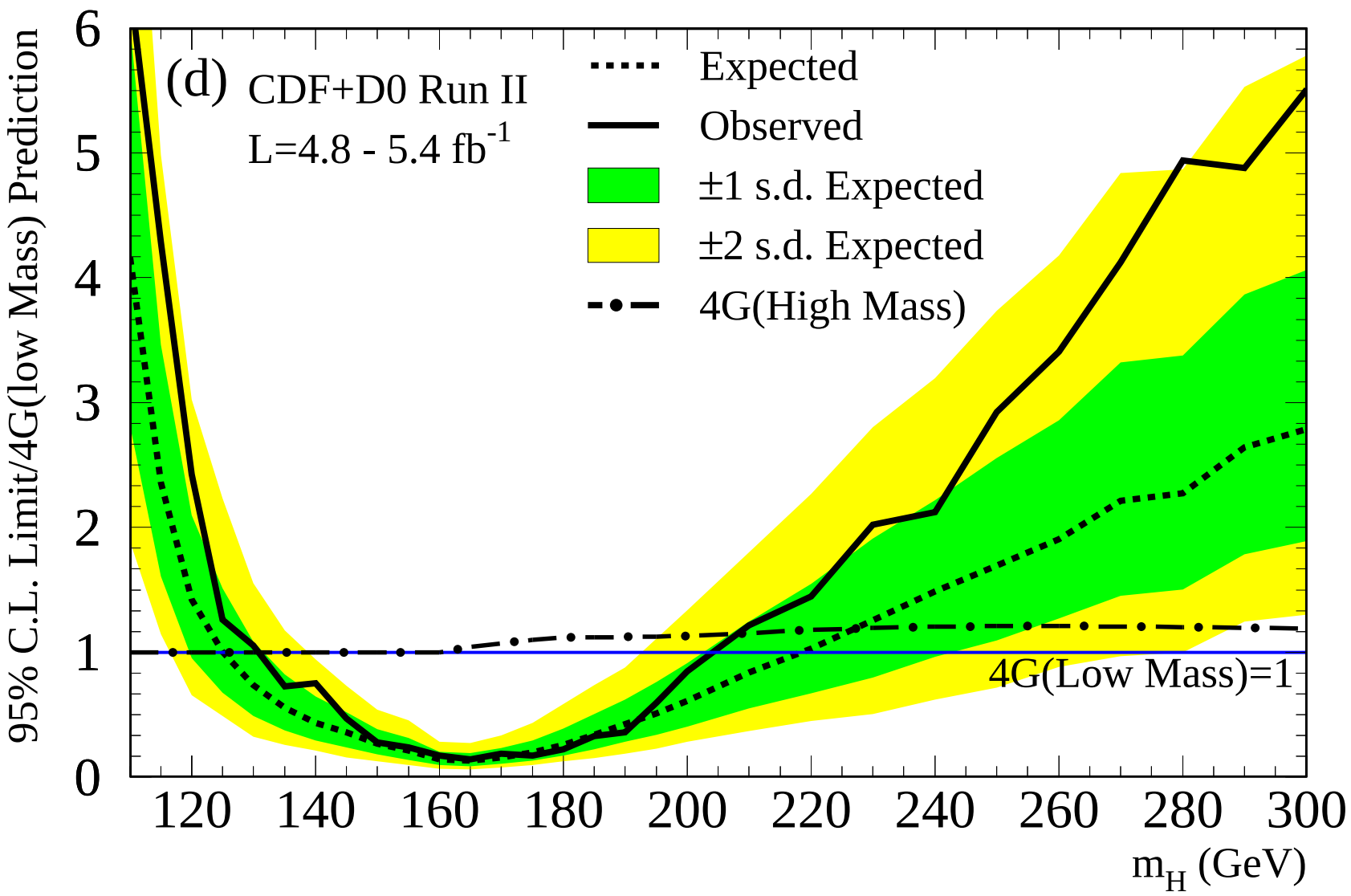
NNLO: [Anastasiou, Buehler, Furlan, Herzog, Lazopoulos '11]

Higgs with 4th generation



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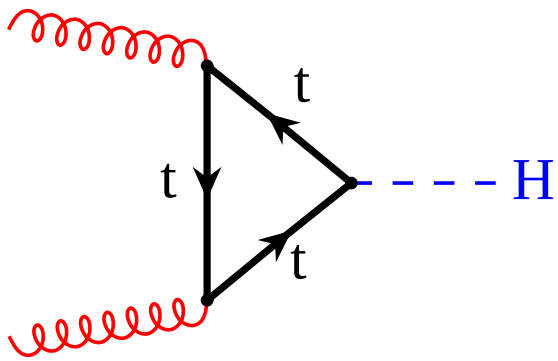

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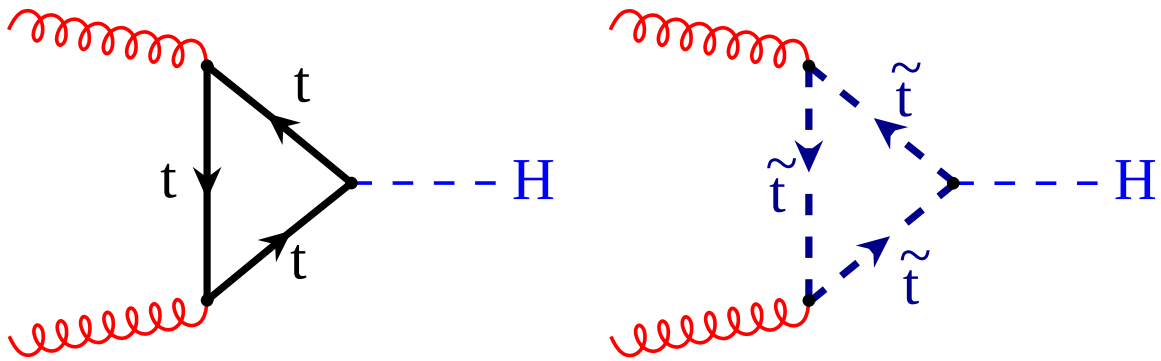

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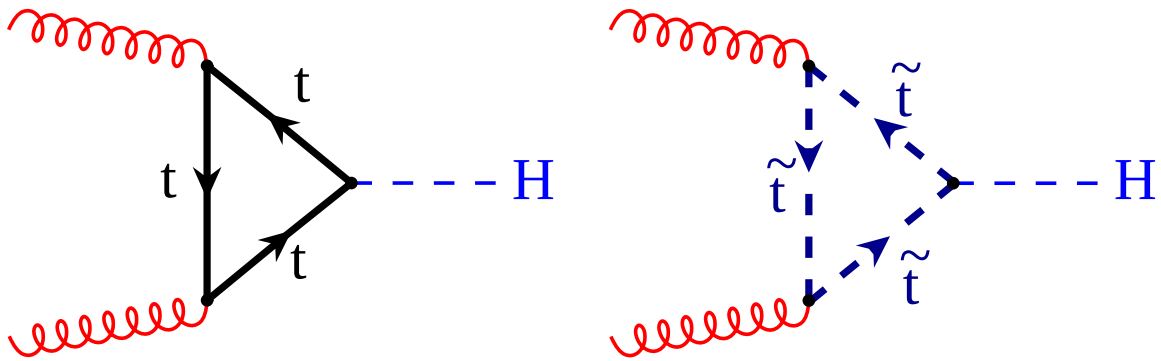

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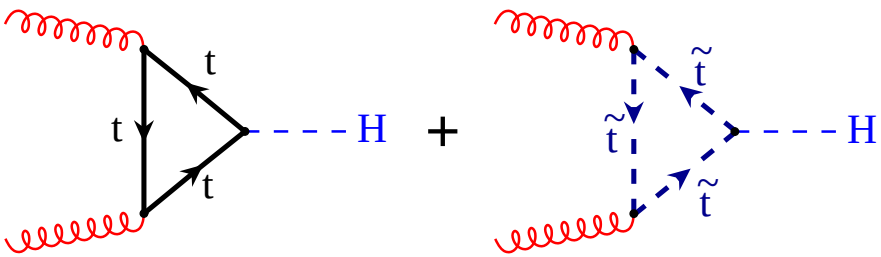

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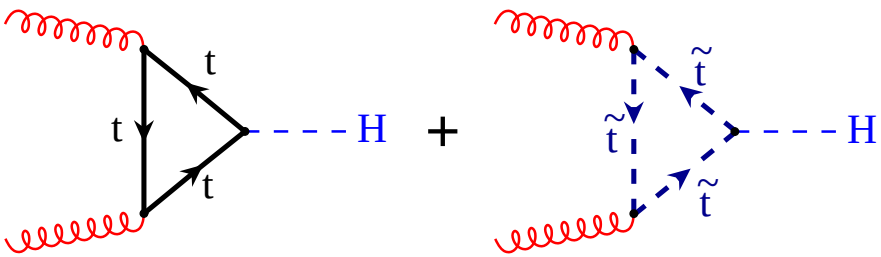

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$\tan\beta = 10\,,$
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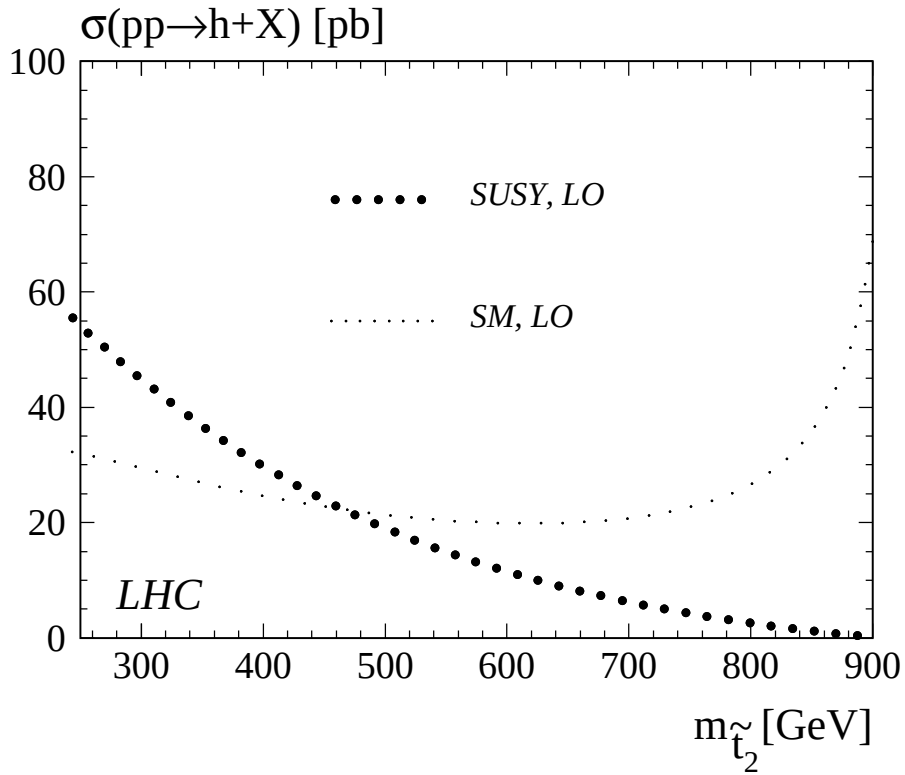
$\theta_t = \frac{\pi}{4}$



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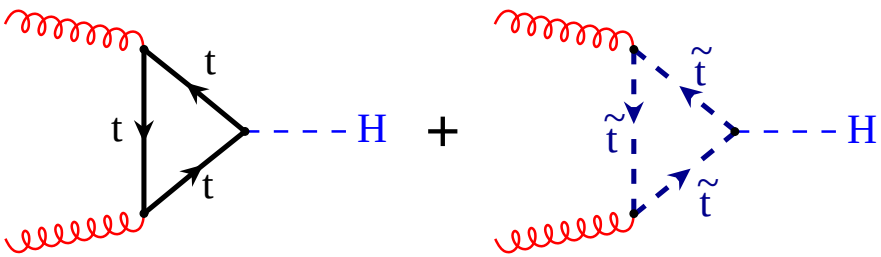

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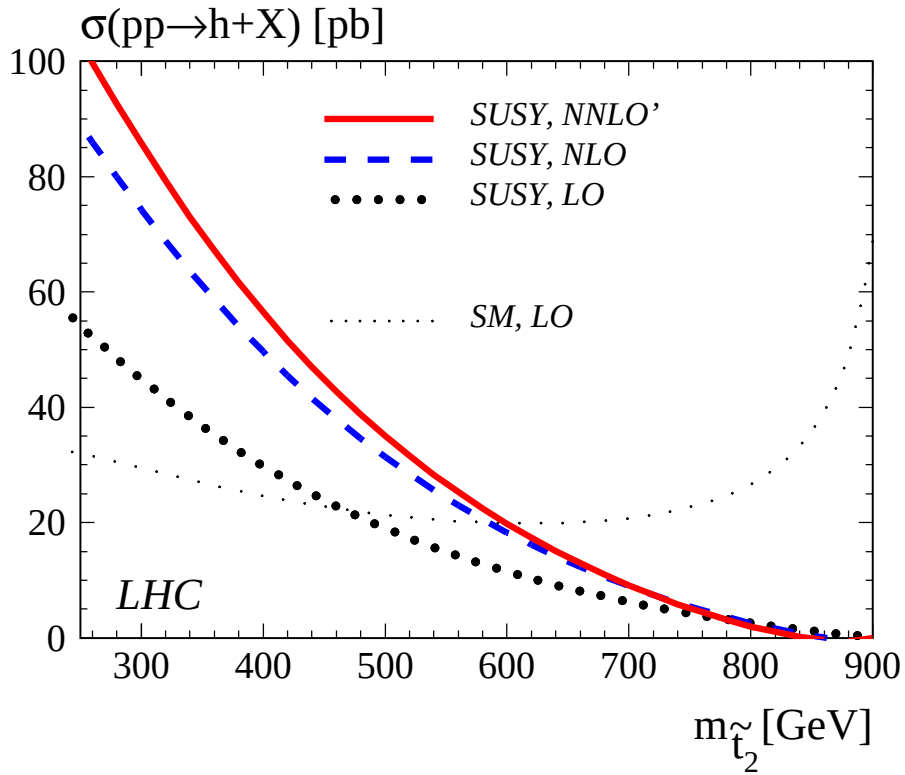

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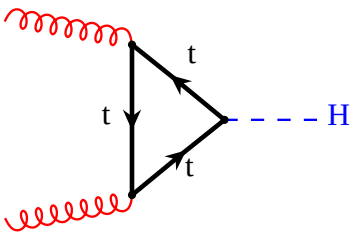

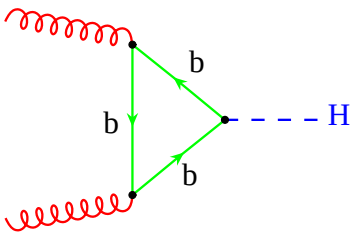

NLO

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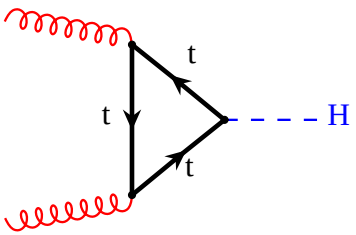

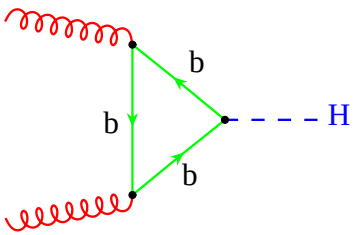

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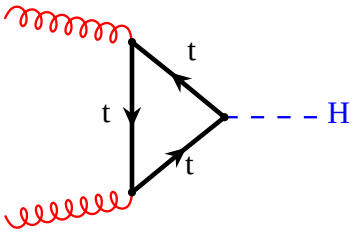
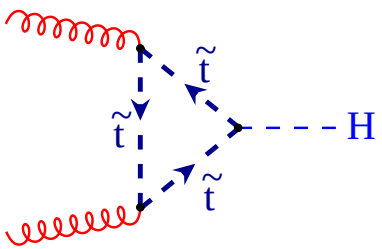
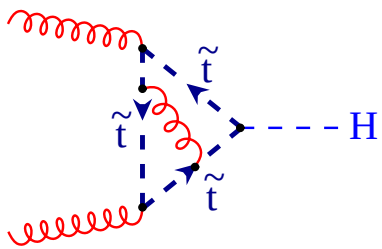


NNLO

[RH, Kilgore '02]
[Anastasiou, Melnikov '02]
[Ravindran, Smith, van Neerven '03]
[Marzani, Ball, del Duca, Forte, Vicini '08]
[RH, Marzani, Mantler, Ozeren '10]
[Pak, Rogal, Steinhauser '10]

Known components





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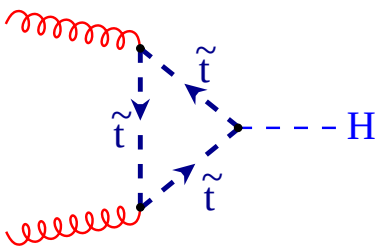

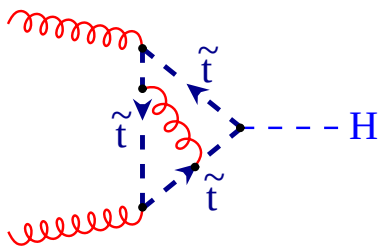

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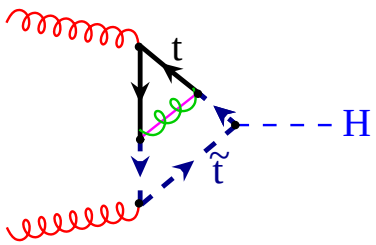

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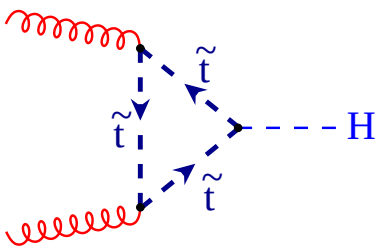

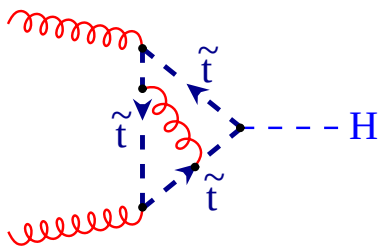

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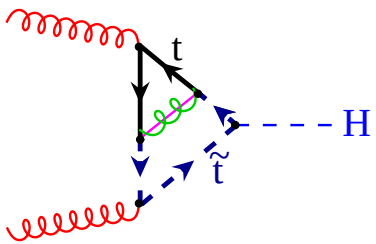

NLO

[RH, Steinhauser '03]
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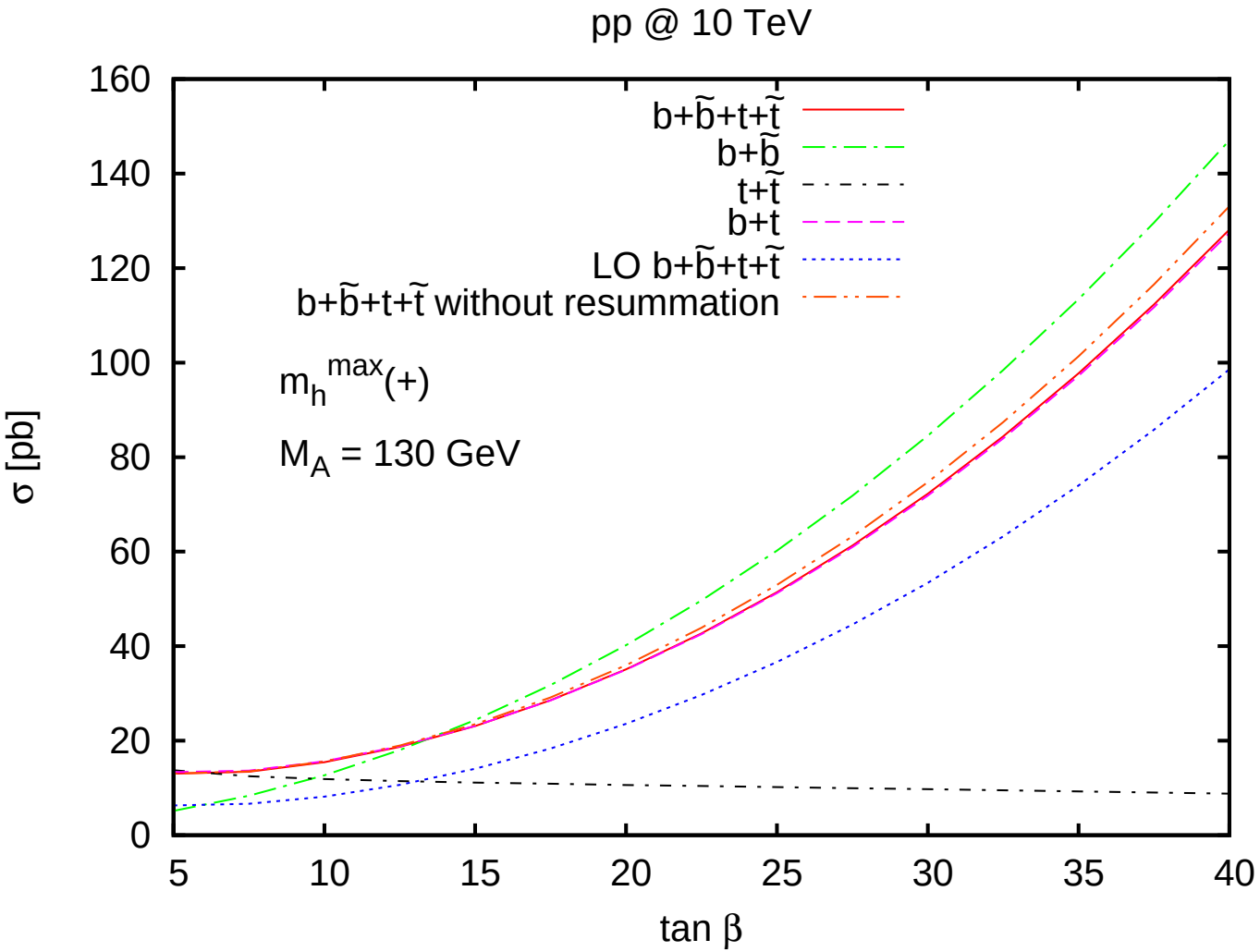
[Degrassi, Slavich '08]

bottom/sbottom

NLO

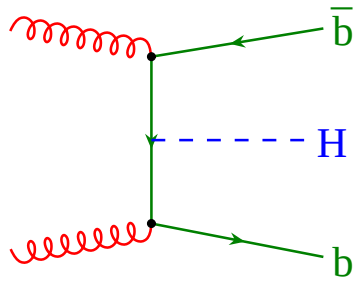
[Degrassi, Slavich '10]
[RH, Hofmann, Mantler '10]

Effects of SUSY



[RH, Hofmann, Mantler '10]

$H/A + b\bar{b}$



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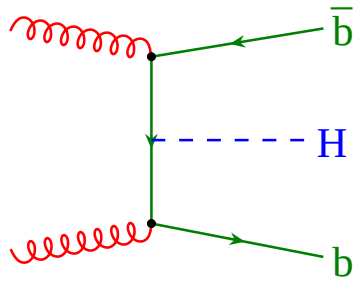

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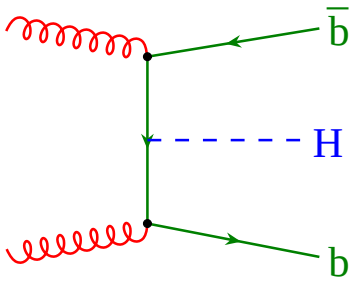

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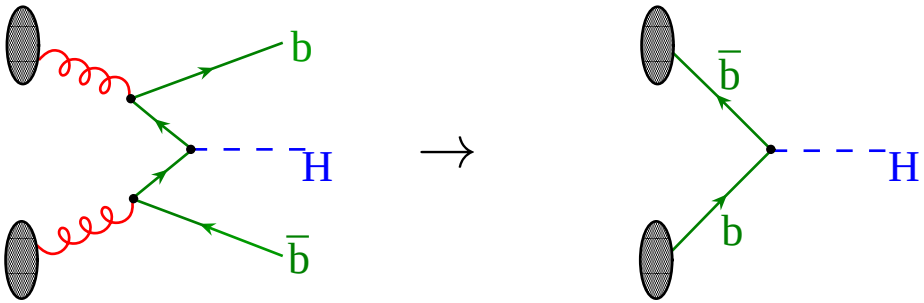
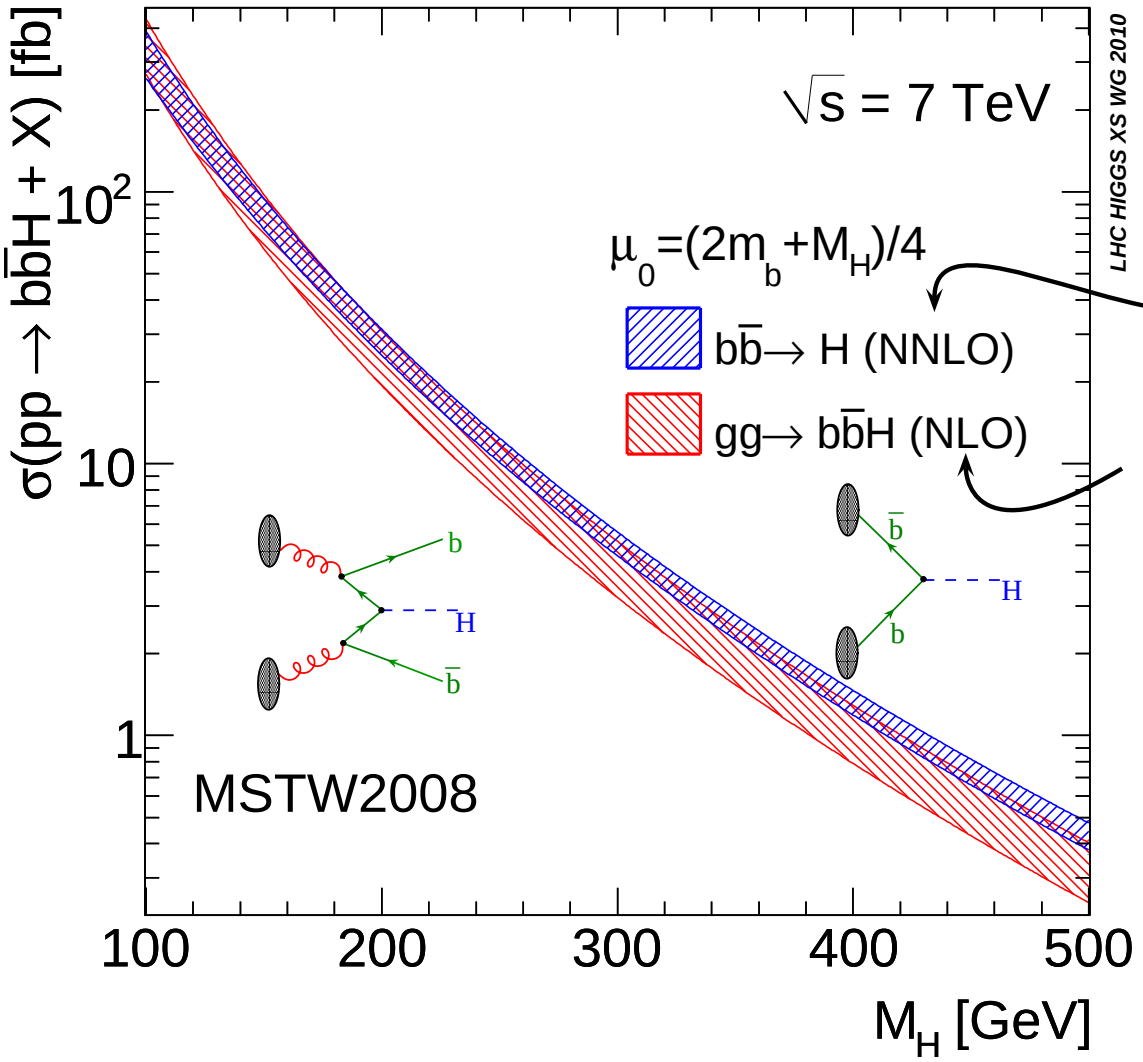


$pp \to H + b\bar{b}$



[RH, Kilgore '03]

[Dittmaier, Krämer, Spira '04]

[Dawson, Jackson, Reina, Wackeroth '04]

electro-weak:

[Dittmaier, Krämer, Mück, Schlüter '06]

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- $b\bar{b} \to H$: only total inclusive cross section

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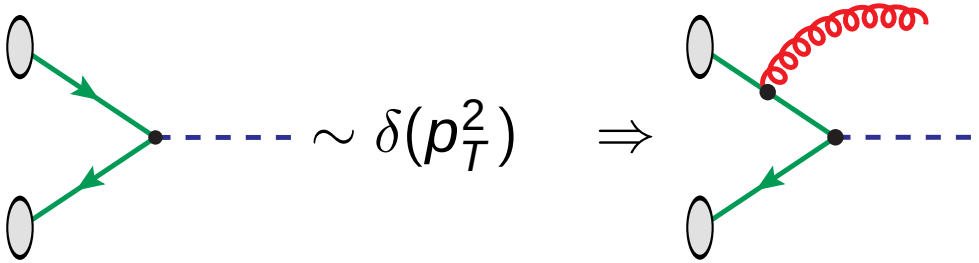

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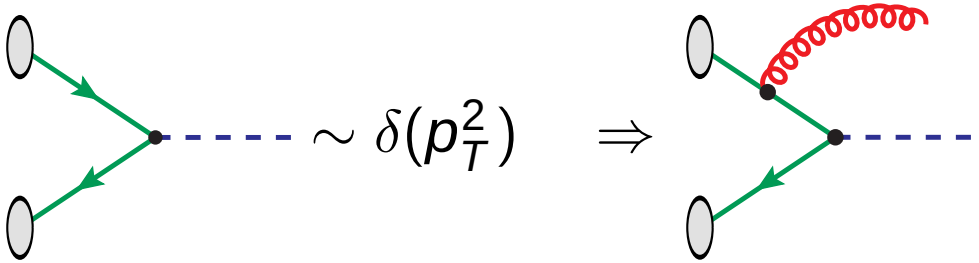
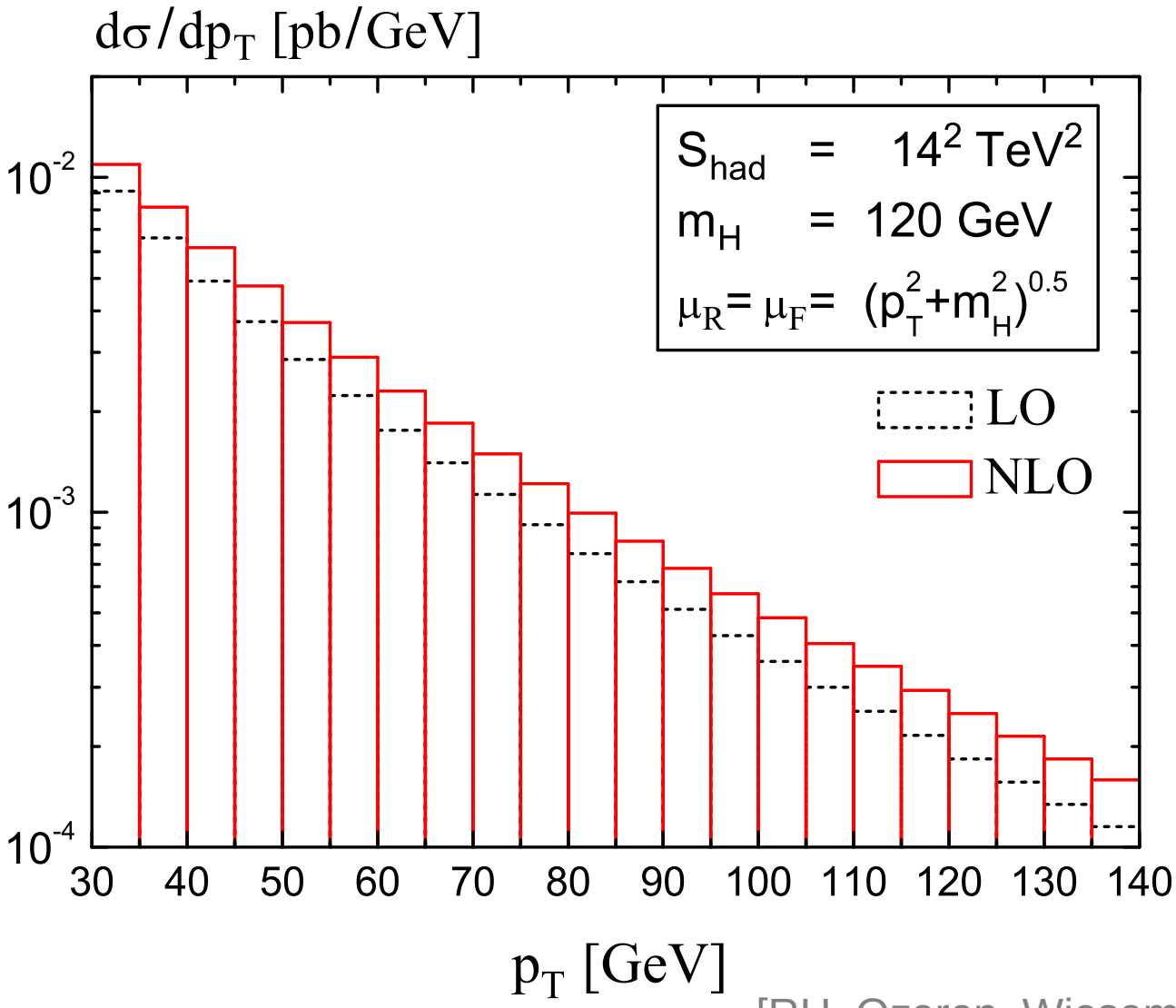


consistent treatment requires NLO

Distributions



[RH, Ozeren, Wiesemann '10]

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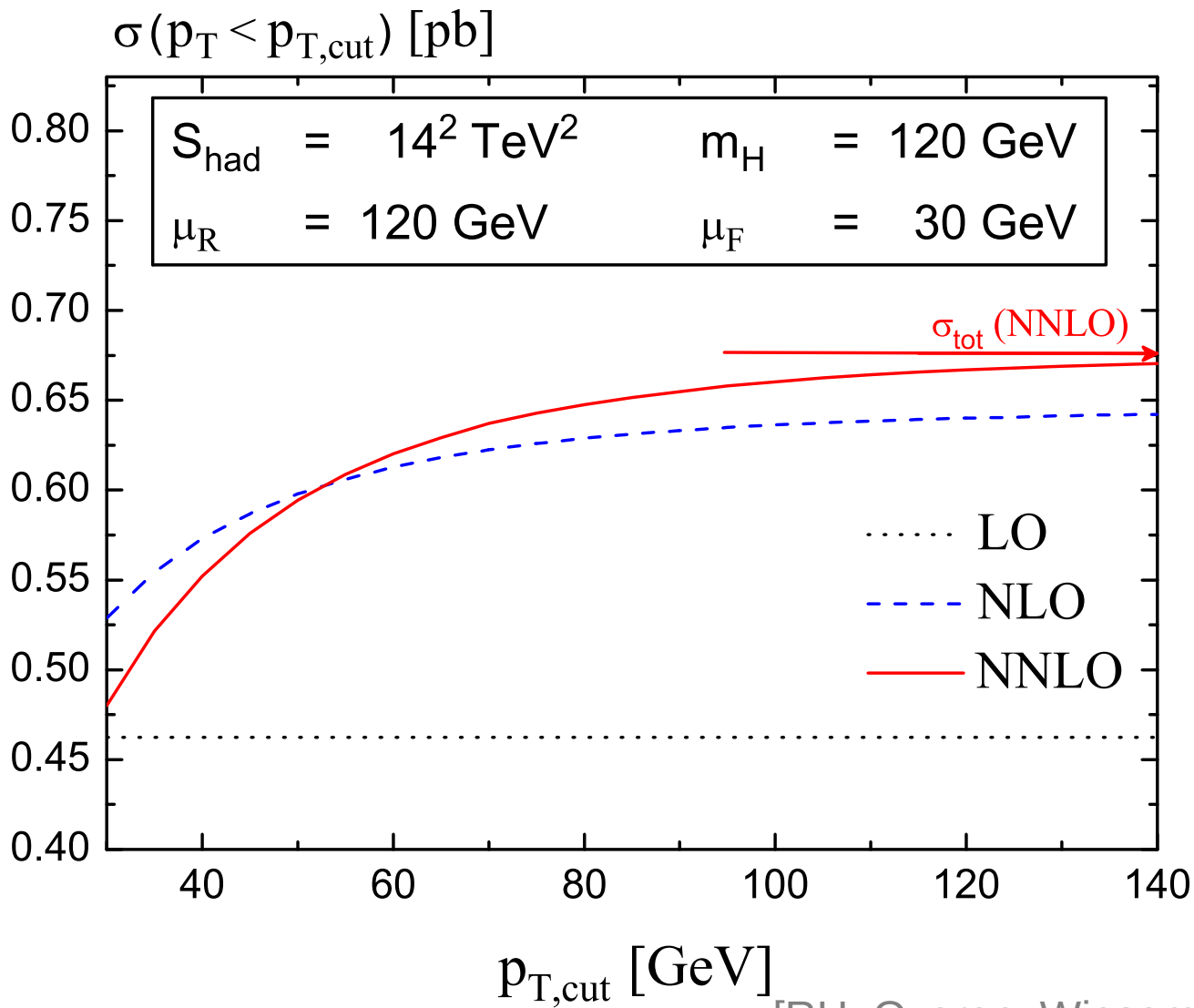
p_T veto



[RH, Ozeren, Wiesemann '10]

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  `http://www.robert-harlander.de/software`

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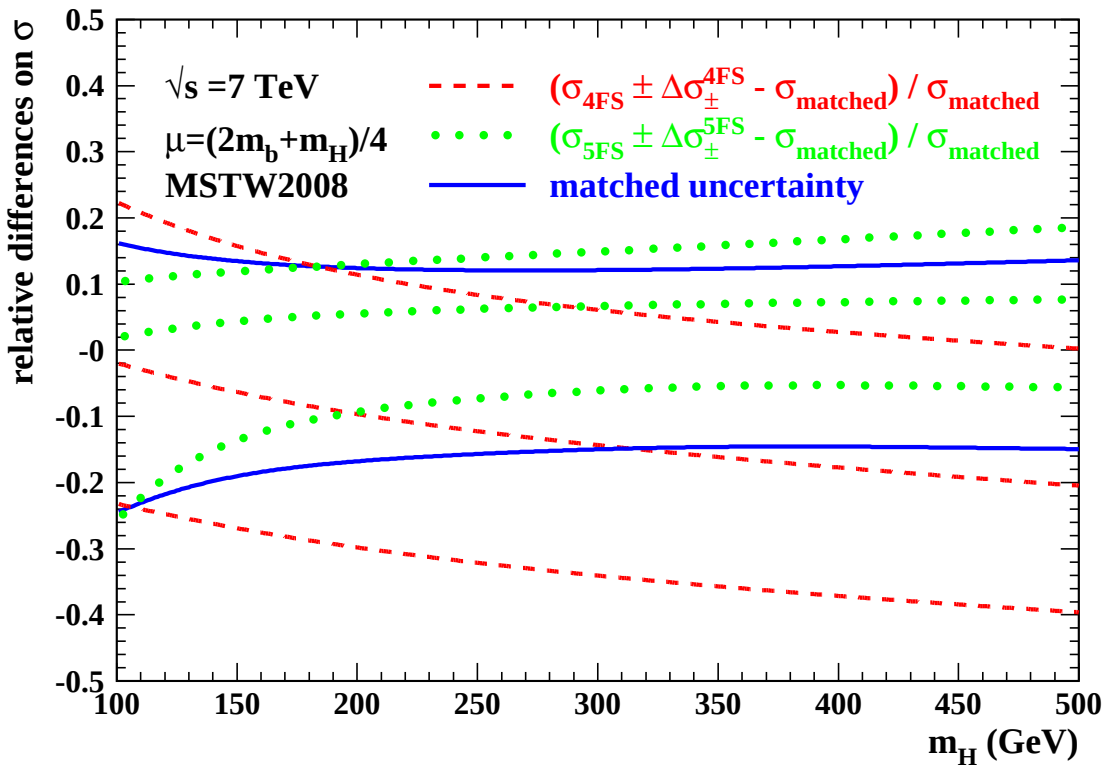
- control non-perturbative uncertainties!
  PDFs, underlying event, ...
- **ggh@nnlo**, **bbh@nnlo**, **vh@nnlo**
  `http://www.robert-harlander.de/software`
- **vbf@nnlo**, **HNNLO**, **FEHiP**, ...

Reactions

- [Anastasiou, Boughezal, Petriello ’09]
- [de Florian, Grazzini ’09]
- [Ahrens, Becher, Neubert, Yang ’10]
- [Baglio, Djouadi ’10]
- [Demartin, Forte, Mariani, Rojo, Vicini ’10]
- [C.F. Berger, Marcantonini, Stewart, Tackmann, Waalewijn ’10]
- [Alekhin, Blümlein, Jimenez-Delgado, Moch, Reya ’10]
- [Baglio, Djouadi, Ferrag, Godbole ’11]
- [. . .]

Backup Slides

Santander matching



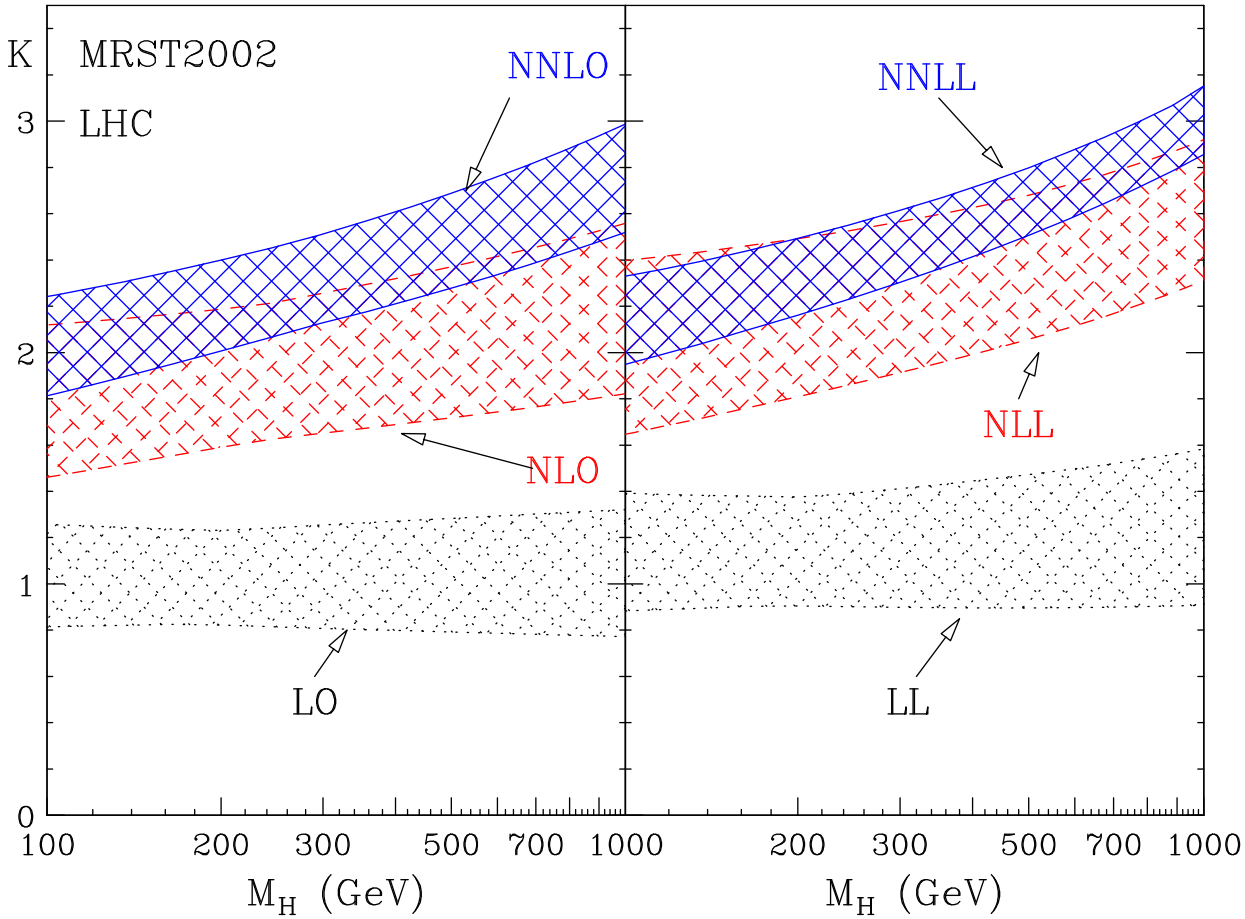
[R.H., Krämer, Schumacher '11]

$$\sigma = \frac{\sigma_{4\mathrm{FS}} + w\sigma_{5\mathrm{FS}}}{1+w}$$

$$\Delta\sigma = \frac{\Delta\sigma_{4\mathrm{FS}} + w\Delta\sigma_{5\mathrm{FS}}}{1+w}$$

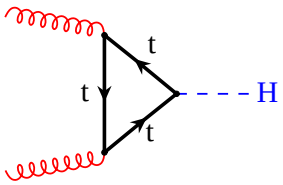
$$w = \ln\frac{m_H}{m_b} - 2$$

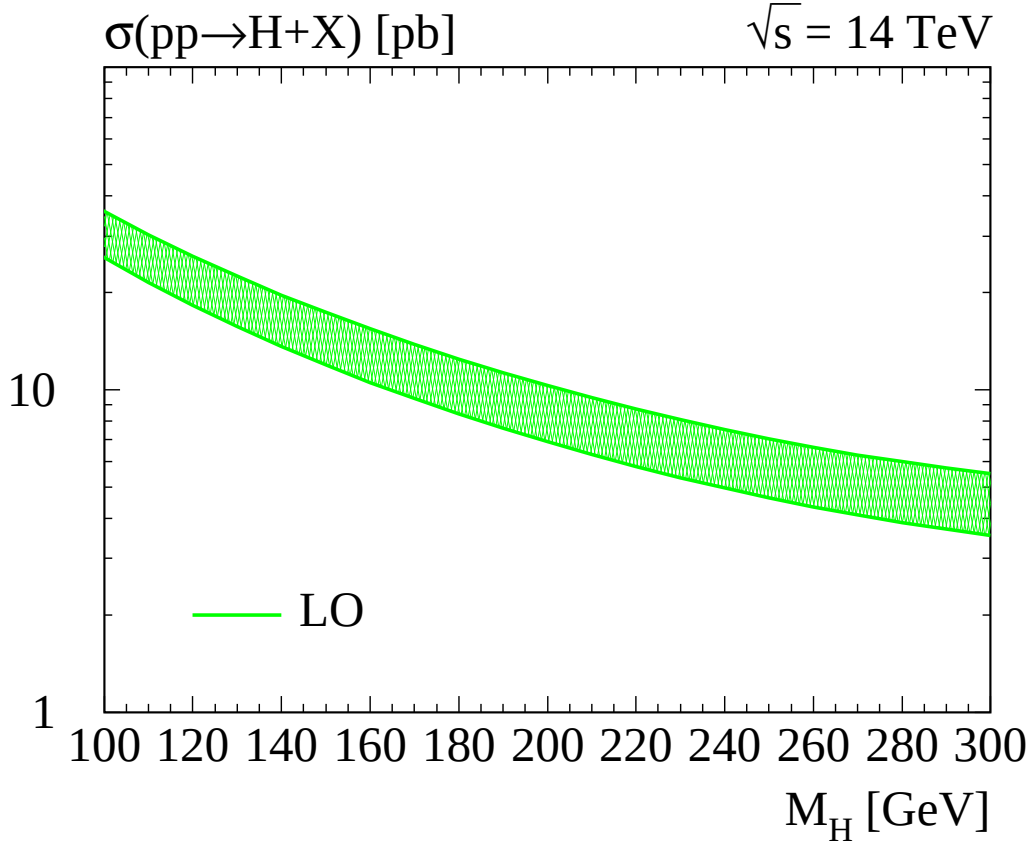
Soft gluon resummation



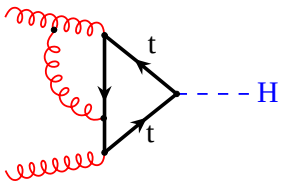
[Catani, de Florian, Grazzini, Nason ('03)]

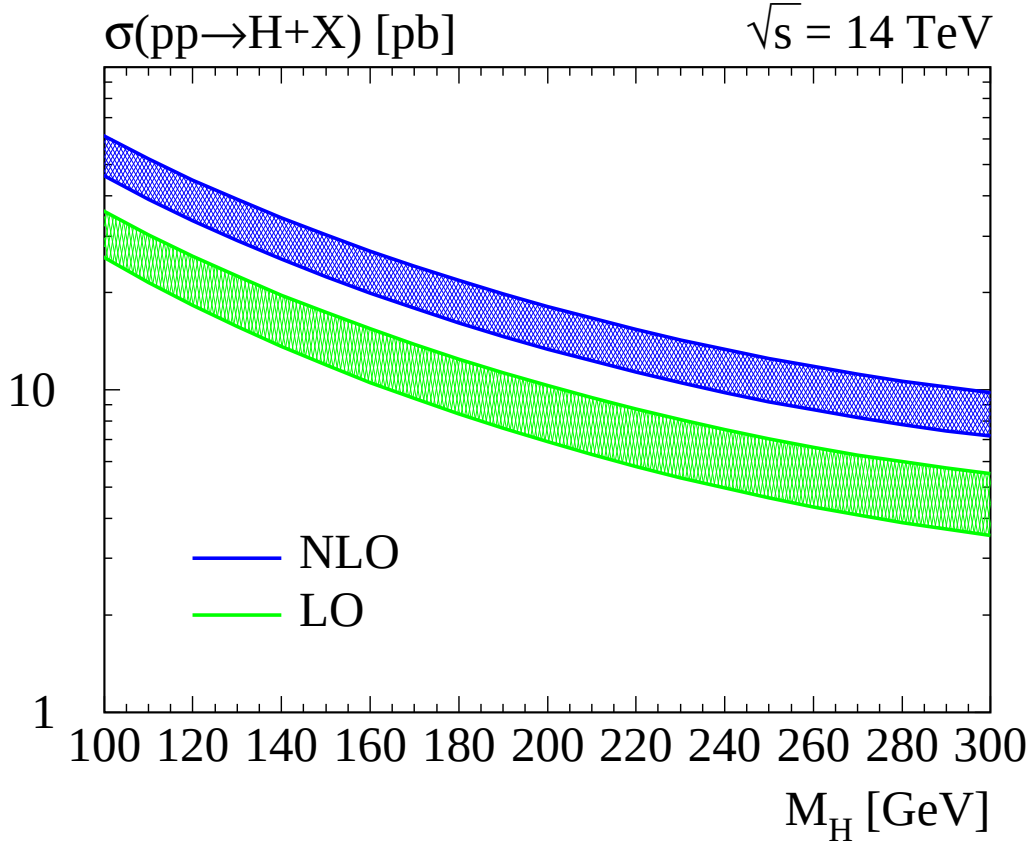
Gluon fusion: theory prediction





Gluon fusion: theory prediction

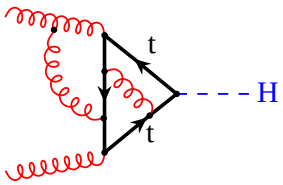


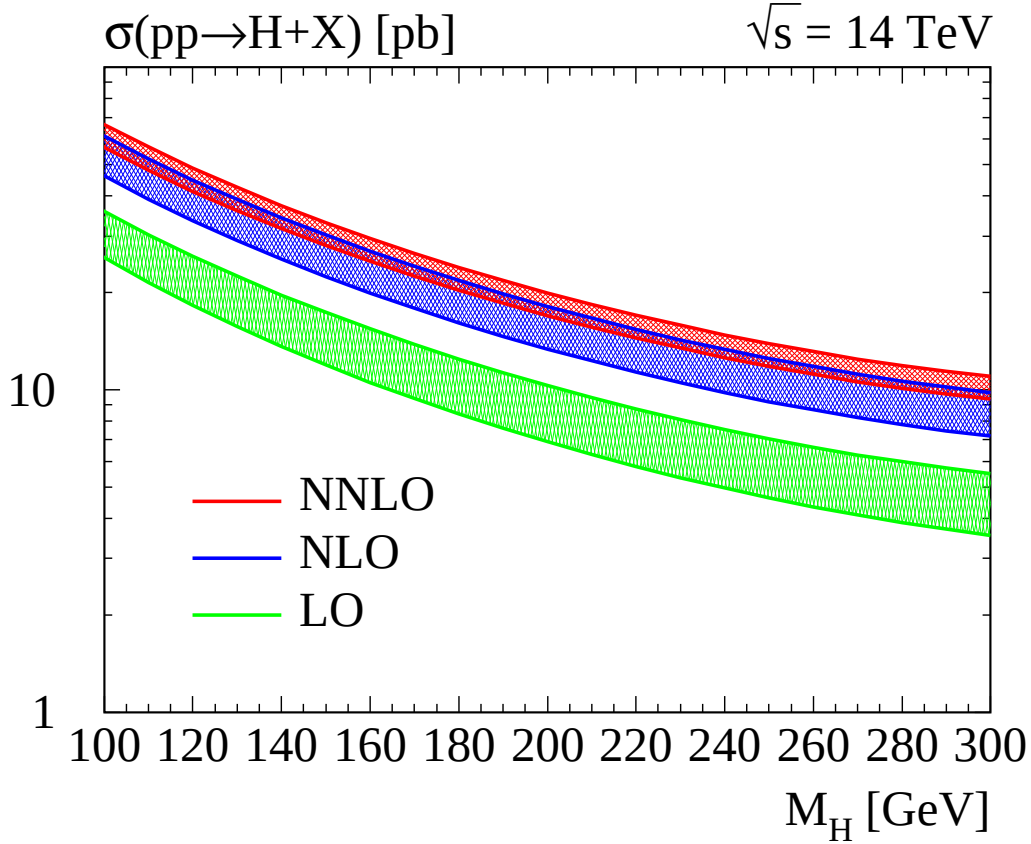


[Spira, Djouadi, Graudenz, Zerwas '91/'93]

[Dawson '91]

Gluon fusion: theory prediction





[R.H., Kilgore '02]
[Anastasiou, Melnikov '02]
[Ravindran, Smith, v. Neerven '03]
[Spira, Djouadi, Graudenz, Zerwas '91/'93]
[Dawson '91]

Higgs Cross Section

M_H (GeV)	ABM10 [8]	ABKM09 [9]	JR [10]	MSTW08 [11]	HERAPDF [12]
100	1.438 ± 0.066	1.380 ± 0.076	1.593 ± 0.091	1.682 ± 0.046	1.417
110	1.051 ± 0.052	1.022 ± 0.061	1.209 ± 0.078	1.265 ± 0.038	1.055
115	0.904 ± 0.047	0.885 ± 0.055	1.060 ± 0.072	1.104 ± 0.034	0.917
120	0.781 ± 0.042	0.770 ± 0.050	0.933 ± 0.067	0.968 ± 0.031	0.800
125	0.677 ± 0.038	0.672 ± 0.045	0.823 ± 0.062	0.851 ± 0.029	0.700
130	0.588 ± 0.034	0.589 ± 0.041	0.729 ± 0.058	0.752 ± 0.026	0.615
135	0.513 ± 0.031	0.518 ± 0.037	0.647 ± 0.054	0.666 ± 0.024	0.541
140	0.449 ± 0.028	0.456 ± 0.034	0.576 ± 0.050	0.591 ± 0.022	0.479
145	0.394 ± 0.025	0.403 ± 0.031	0.514 ± 0.047	0.527 ± 0.020	0.424
150	0.347 ± 0.023	0.358 ± 0.028	0.461 ± 0.044	0.471 ± 0.018	0.377
155	0.306 ± 0.020	0.318 ± 0.026	0.413 ± 0.041	0.421 ± 0.017	0.336
160	0.271 ± 0.019	0.283 ± 0.024	0.371 ± 0.039	0.378 ± 0.016	0.300
165	0.240 ± 0.017	0.253 ± 0.022	0.335 ± 0.036	0.341 ± 0.014	0.269
170	0.213 ± 0.015	0.226 ± 0.020	0.302 ± 0.034	0.307 ± 0.013	0.241
175	0.190 ± 0.014	0.203 ± 0.019	0.274 ± 0.032	0.278 ± 0.012	0.217
180	0.169 ± 0.013	0.182 ± 0.017	0.248 ± 0.030	0.251 ± 0.012	0.195
185	0.151 ± 0.012	0.164 ± 0.016	0.225 ± 0.028	0.228 ± 0.011	0.176
190	0.136 ± 0.011	0.148 ± 0.015	0.205 ± 0.027	0.207 ± 0.010	0.159
200	0.109 ± 0.009	0.121 ± 0.013	0.170 ± 0.024	0.172 ± 0.009	0.131

Higgs Cross Section