

# Progress on SM Higgs precision calculations

Robert Harlander

RWTH Aachen University

31st Rencontres de Blois  
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Deutsche  
Forschungsgemeinschaft  
**DFG**



Bundesministerium  
für Bildung  
und Forschung

# The Standard Model

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“Of course, [this] model has too many arbitrary features to be taken seriously.”

S. Weinberg '67

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- parity violation
- gauge structure
- hypercharges
- number of generations
- Higgs representation
- $y_t=1$  vs.  $y_b = 0.02$  vs.  $y_\mu = 0.0006$
- CKM hierarchy
- is naturalness a thing?



# The Standard Model

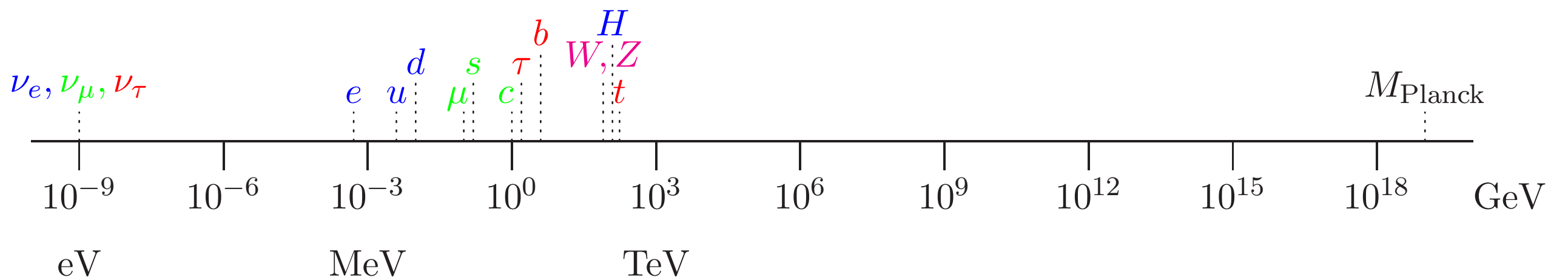
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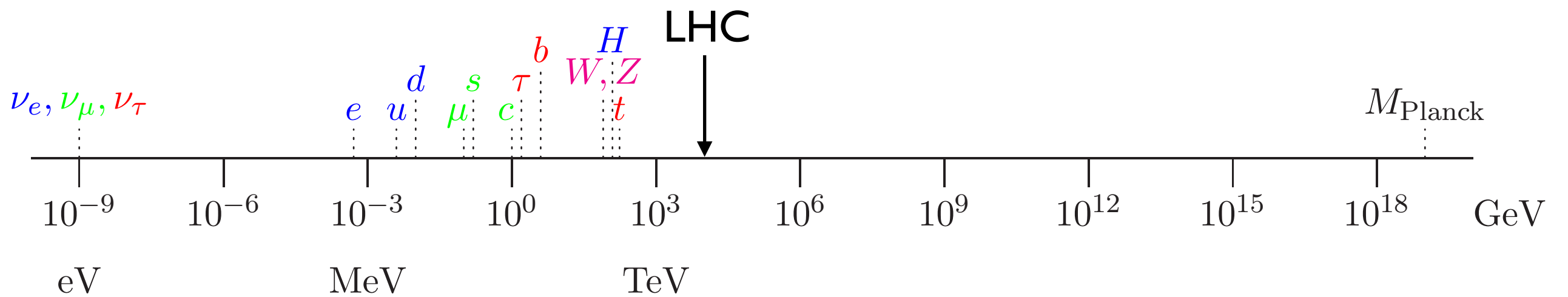
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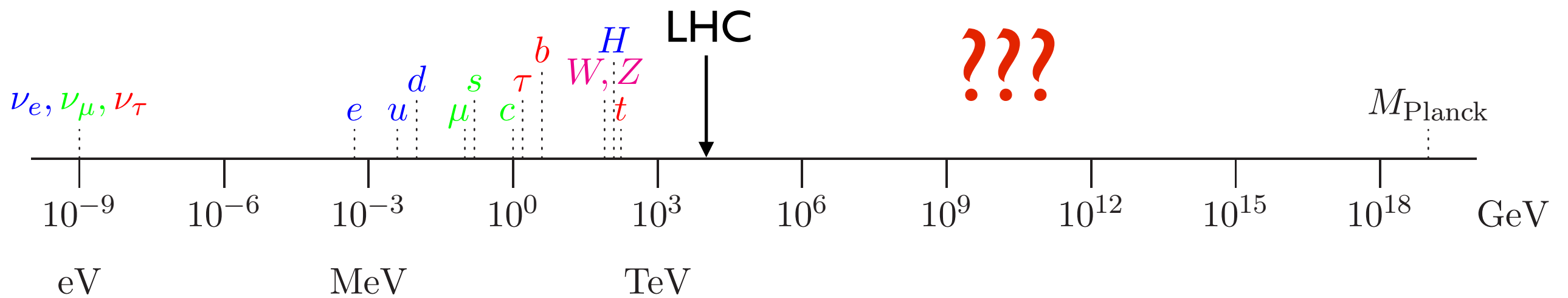


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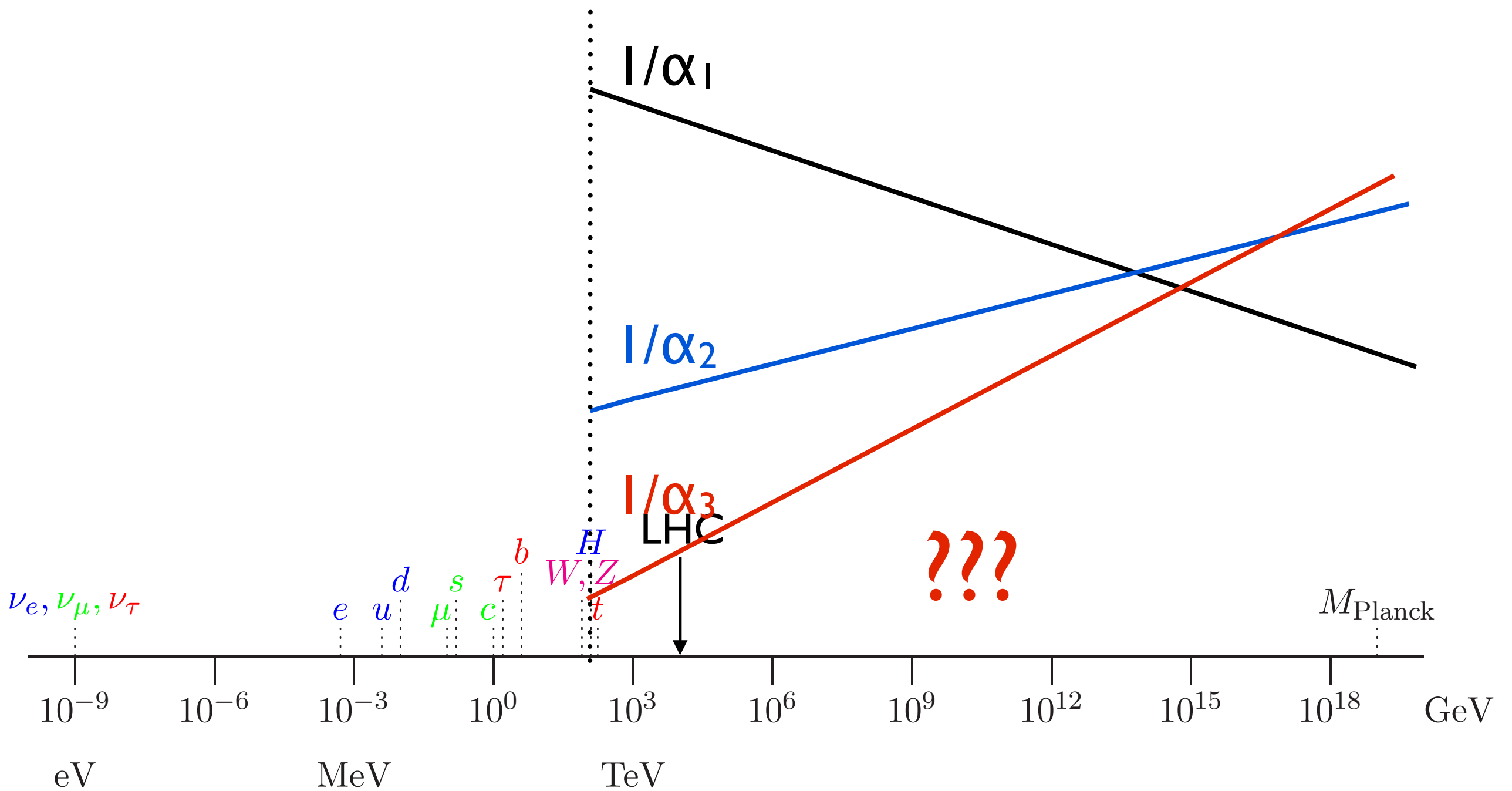
... and it's incomplete,  
of course...

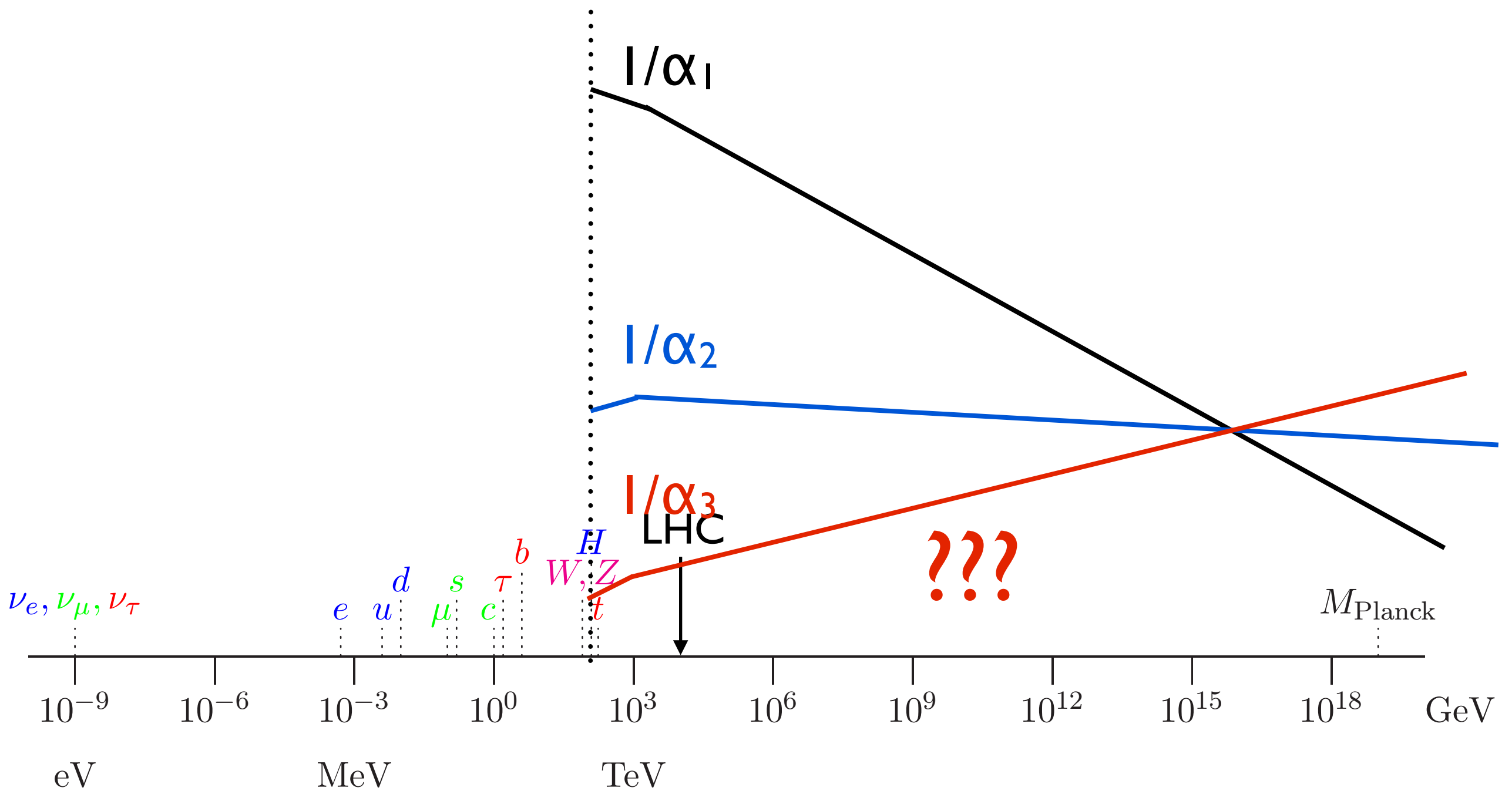


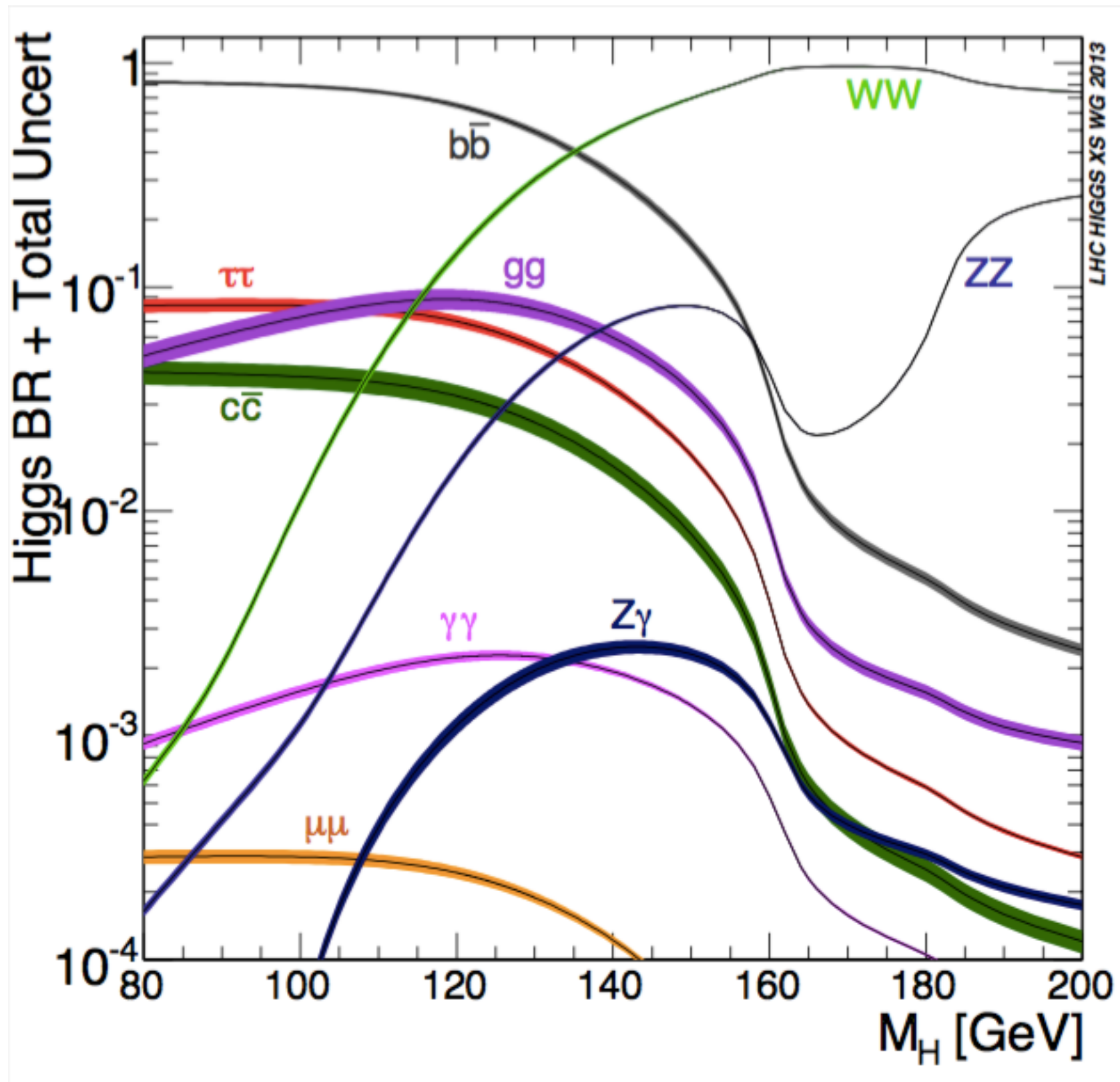


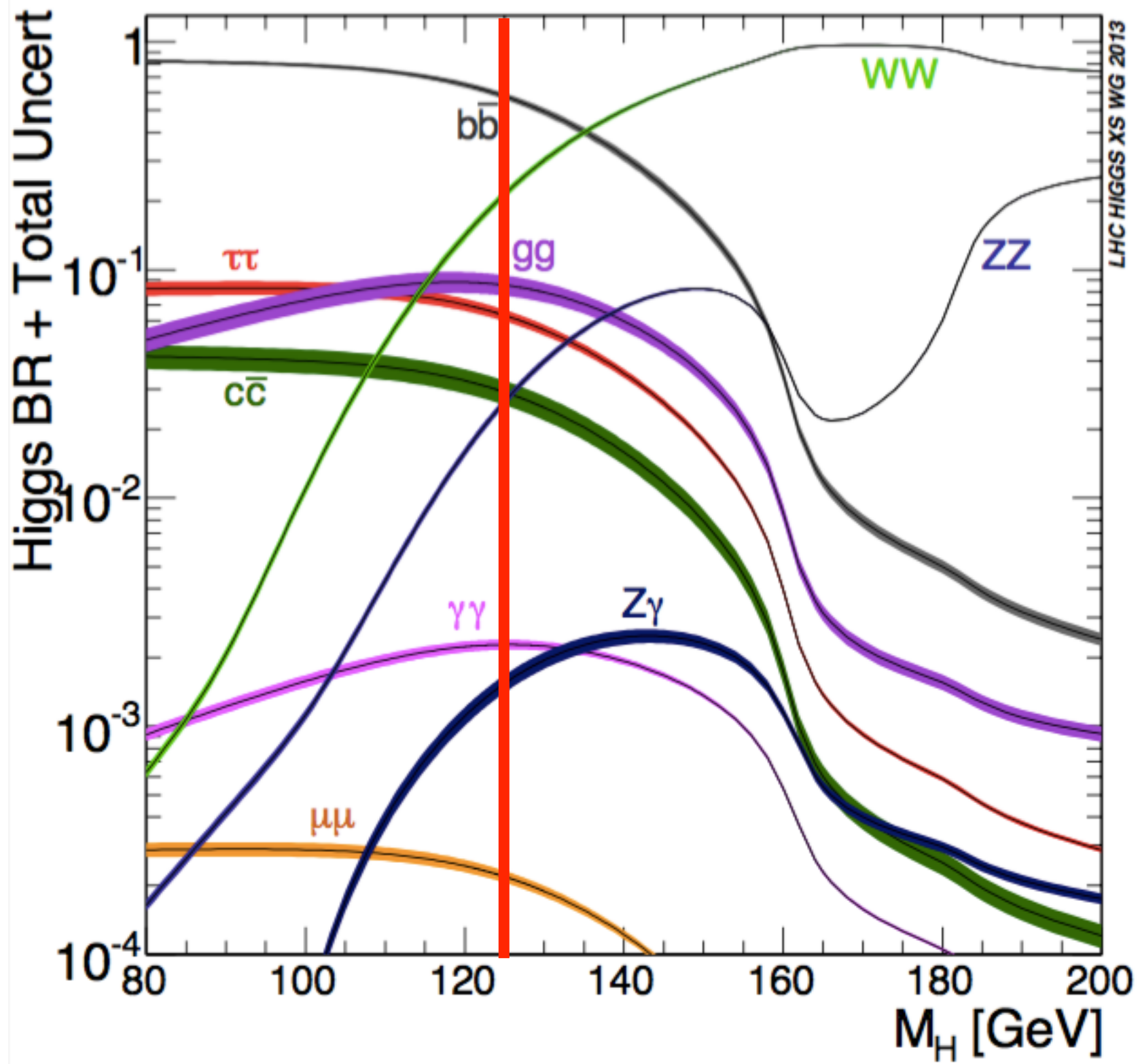








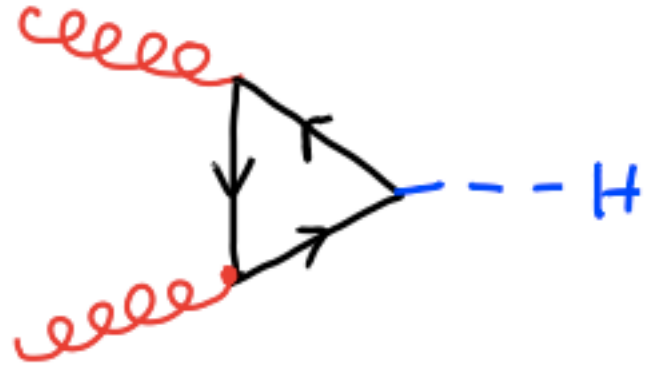




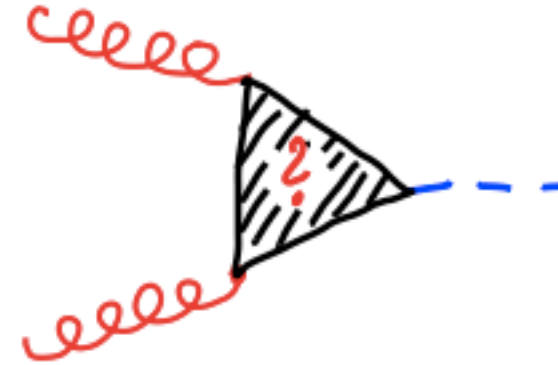
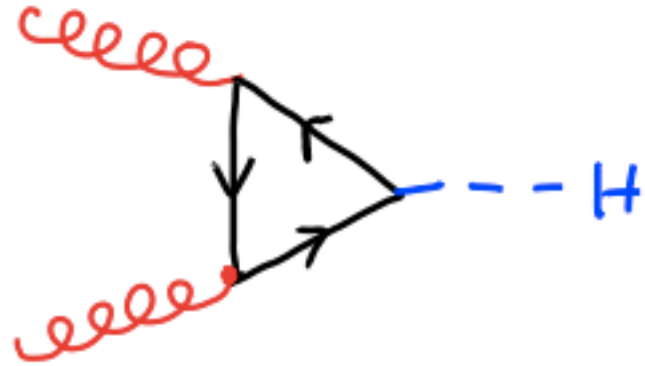


# Higgs as a probe

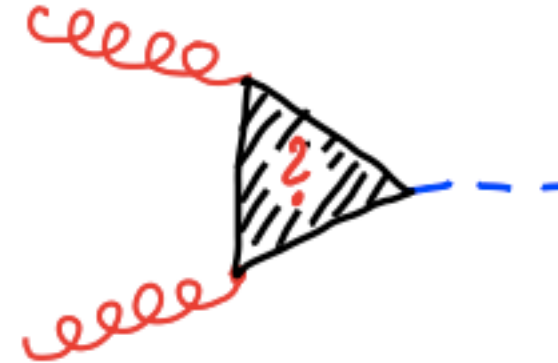
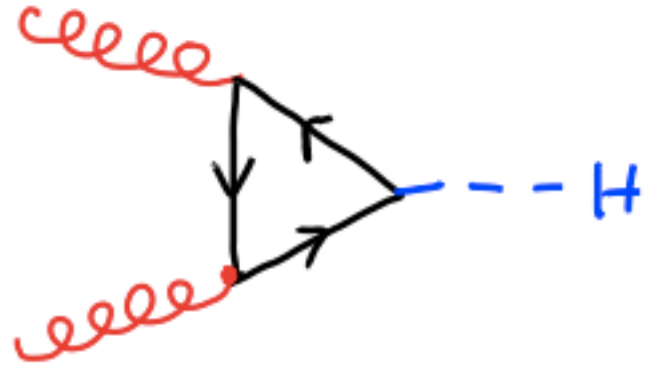
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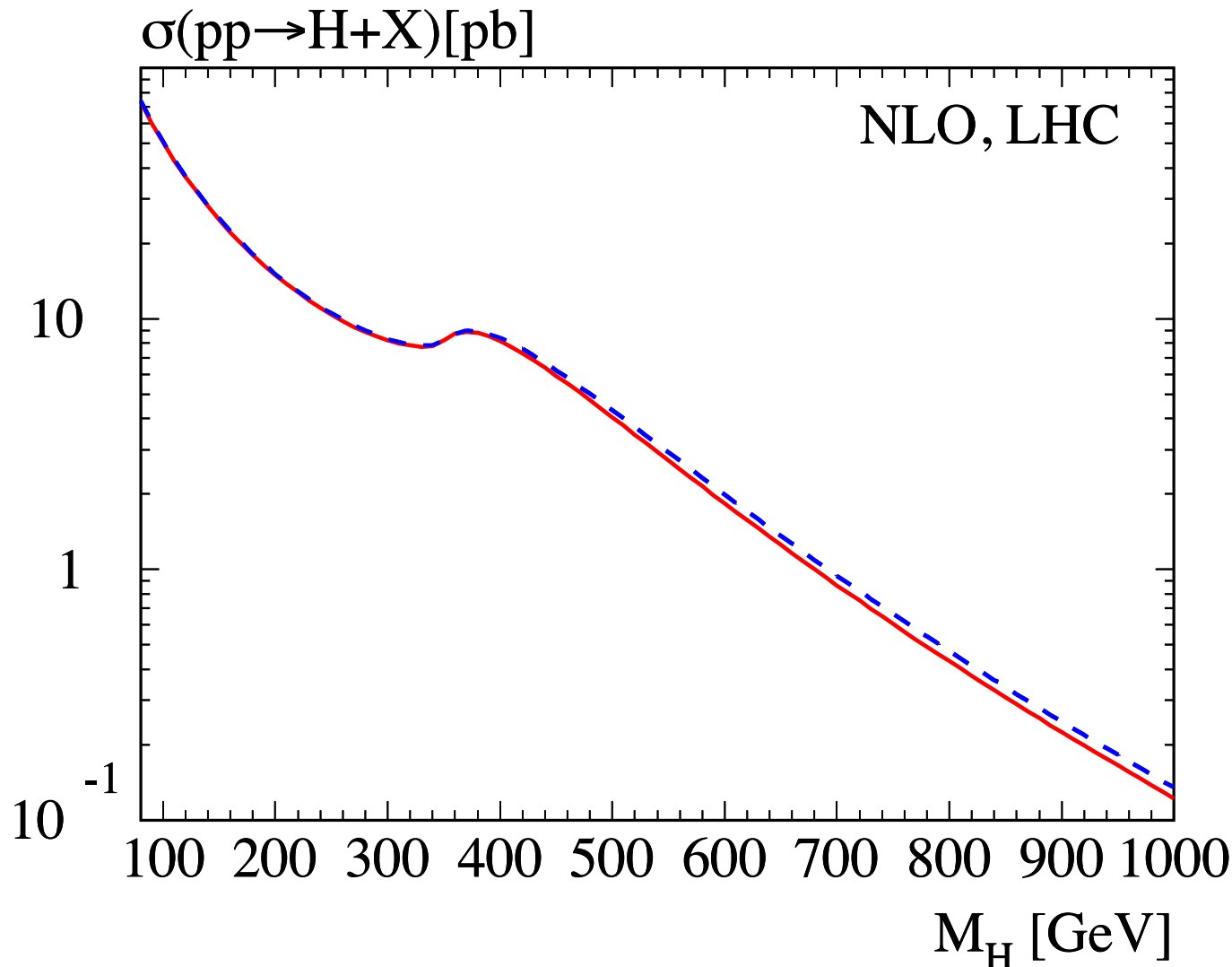
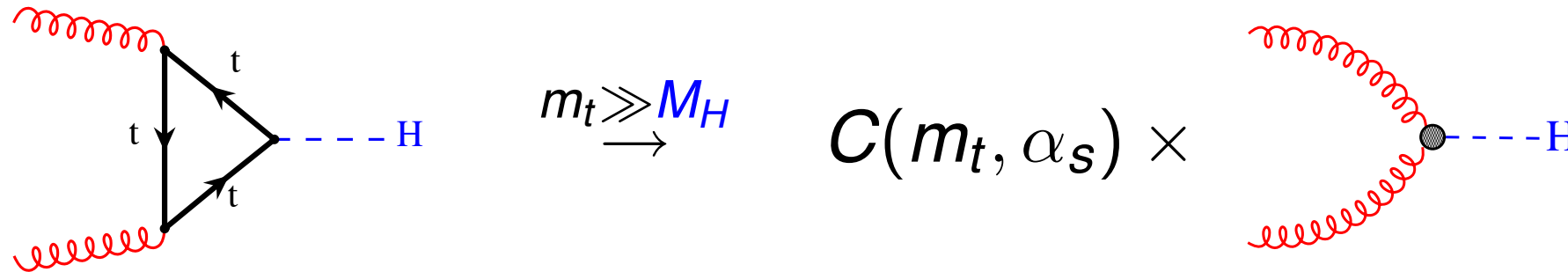


# Higgs as a probe



$$\sqrt{\hat{s}} = M_H$$

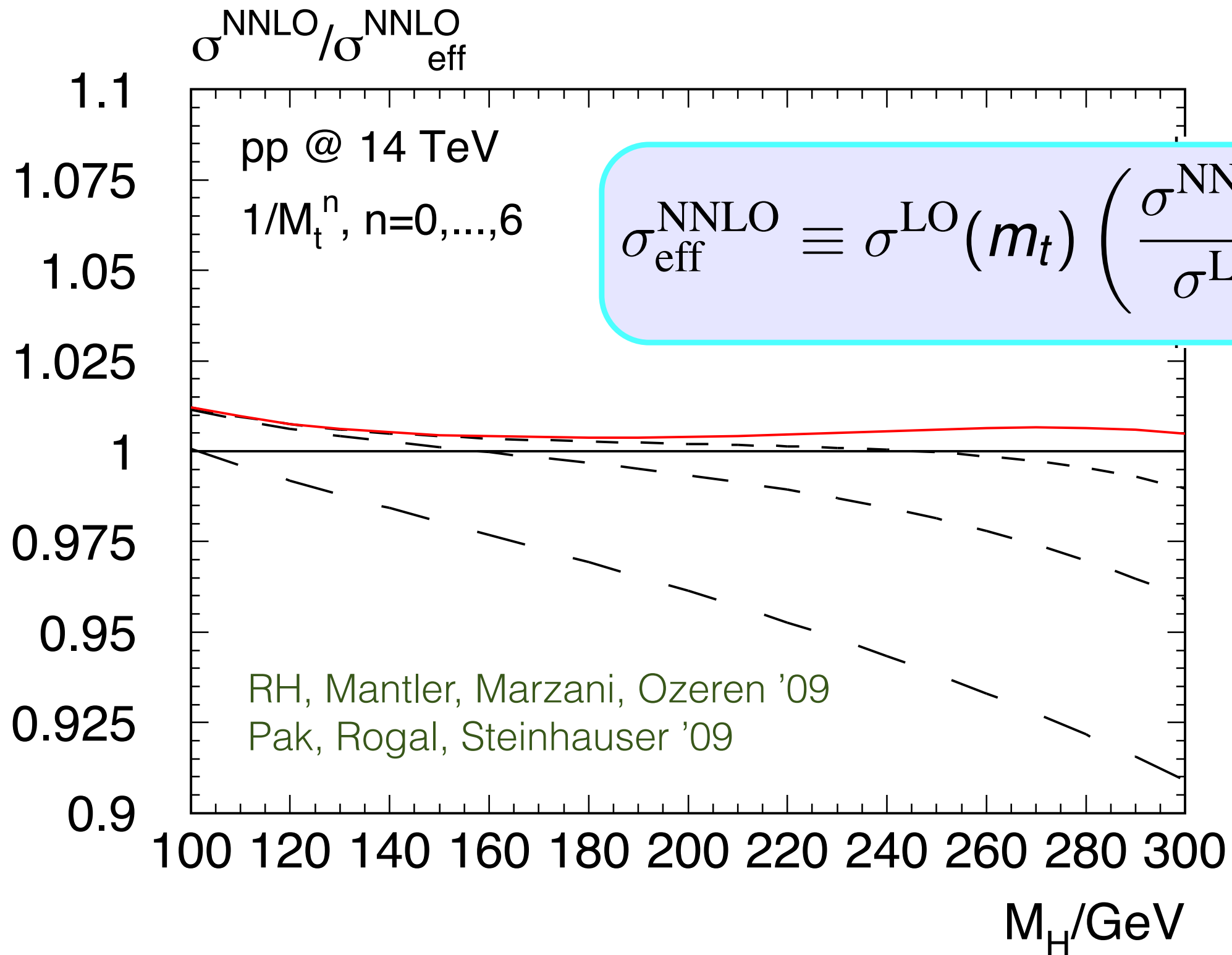
# Heavy-top limit

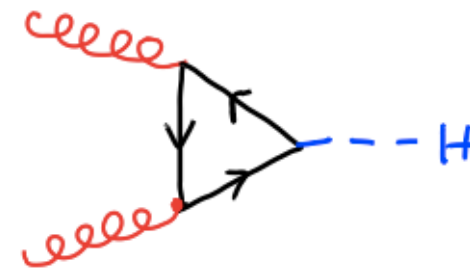
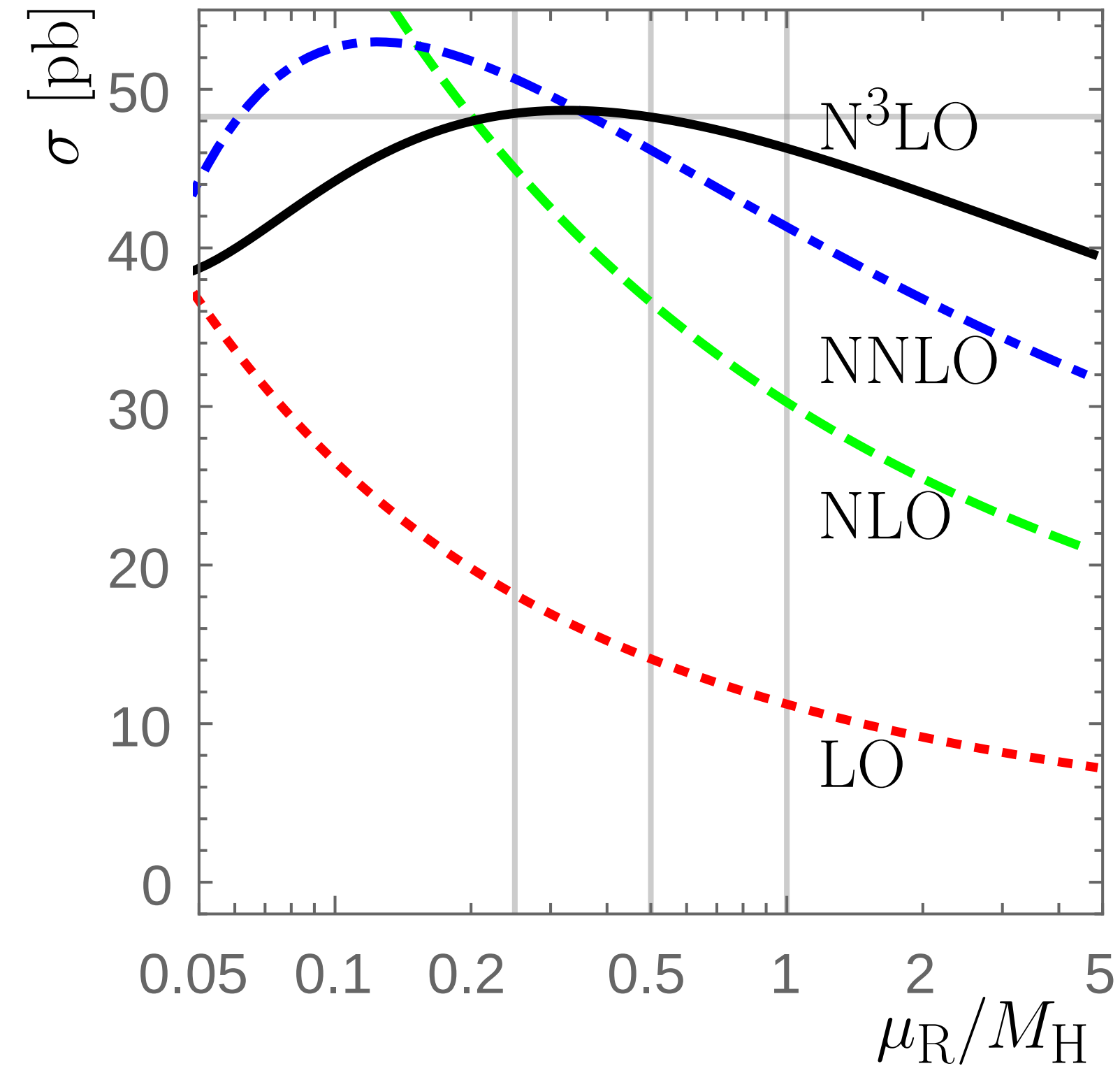


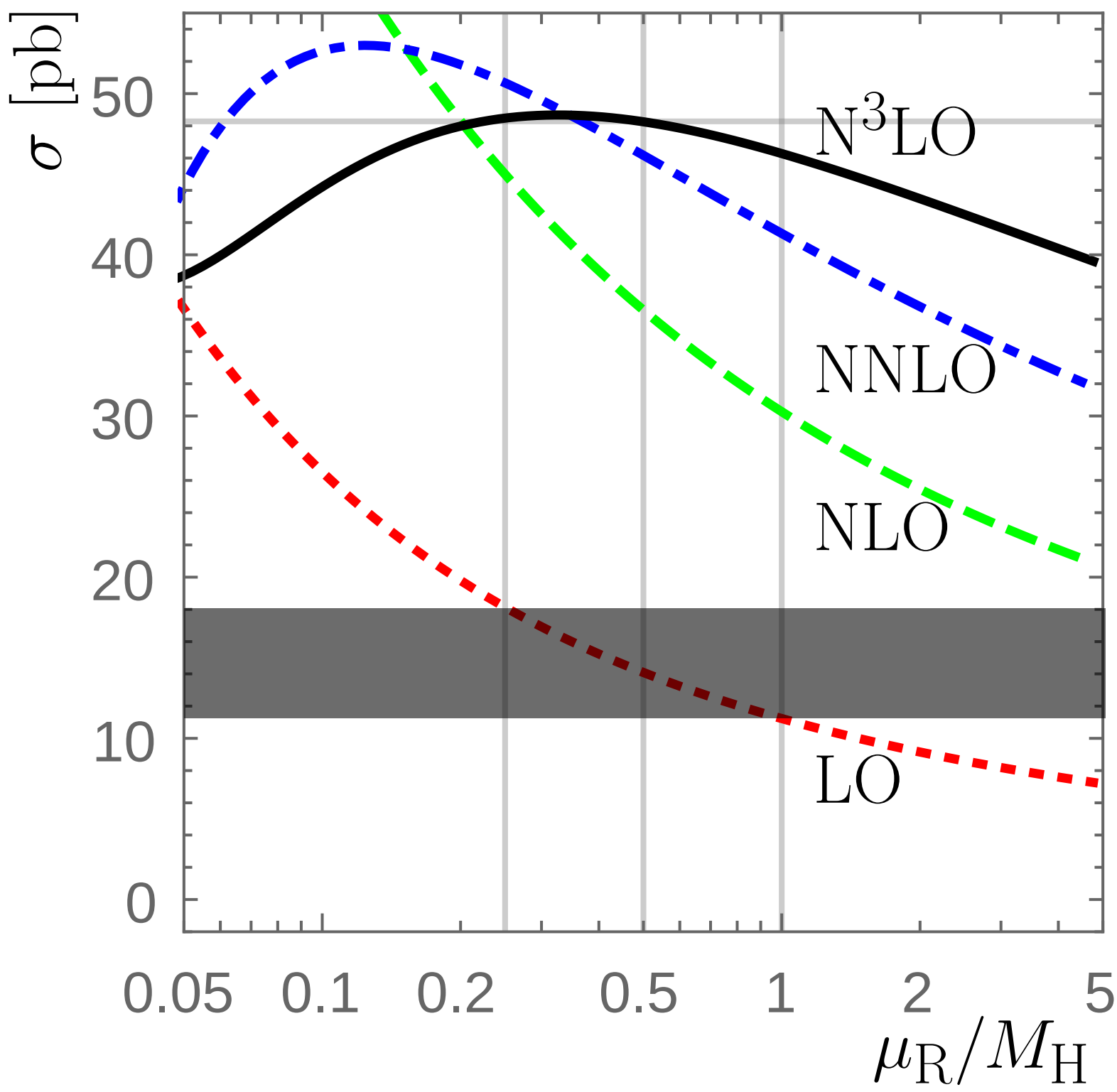
$$\sigma_{\infty}^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t) \left( \frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}} \right)_{m_t \rightarrow \infty}$$

Graudenz, Djouadi, Spira, Zerwas '93

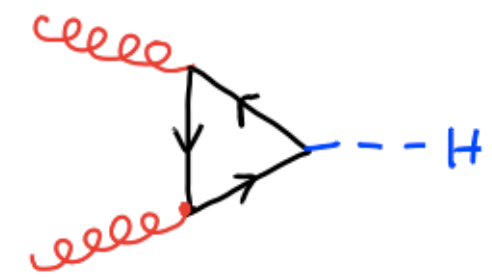


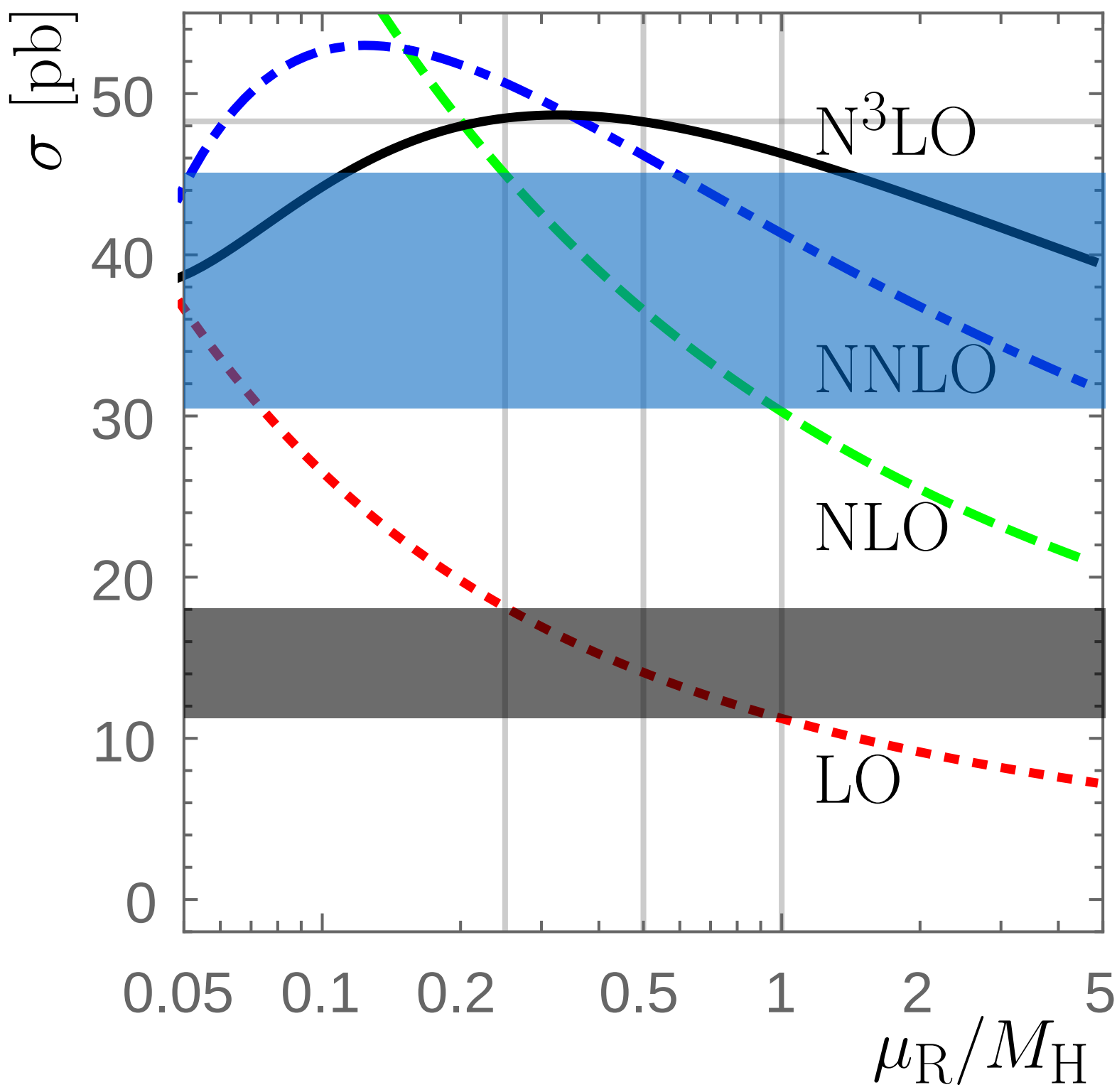






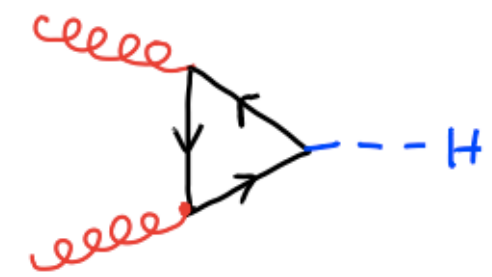
1976



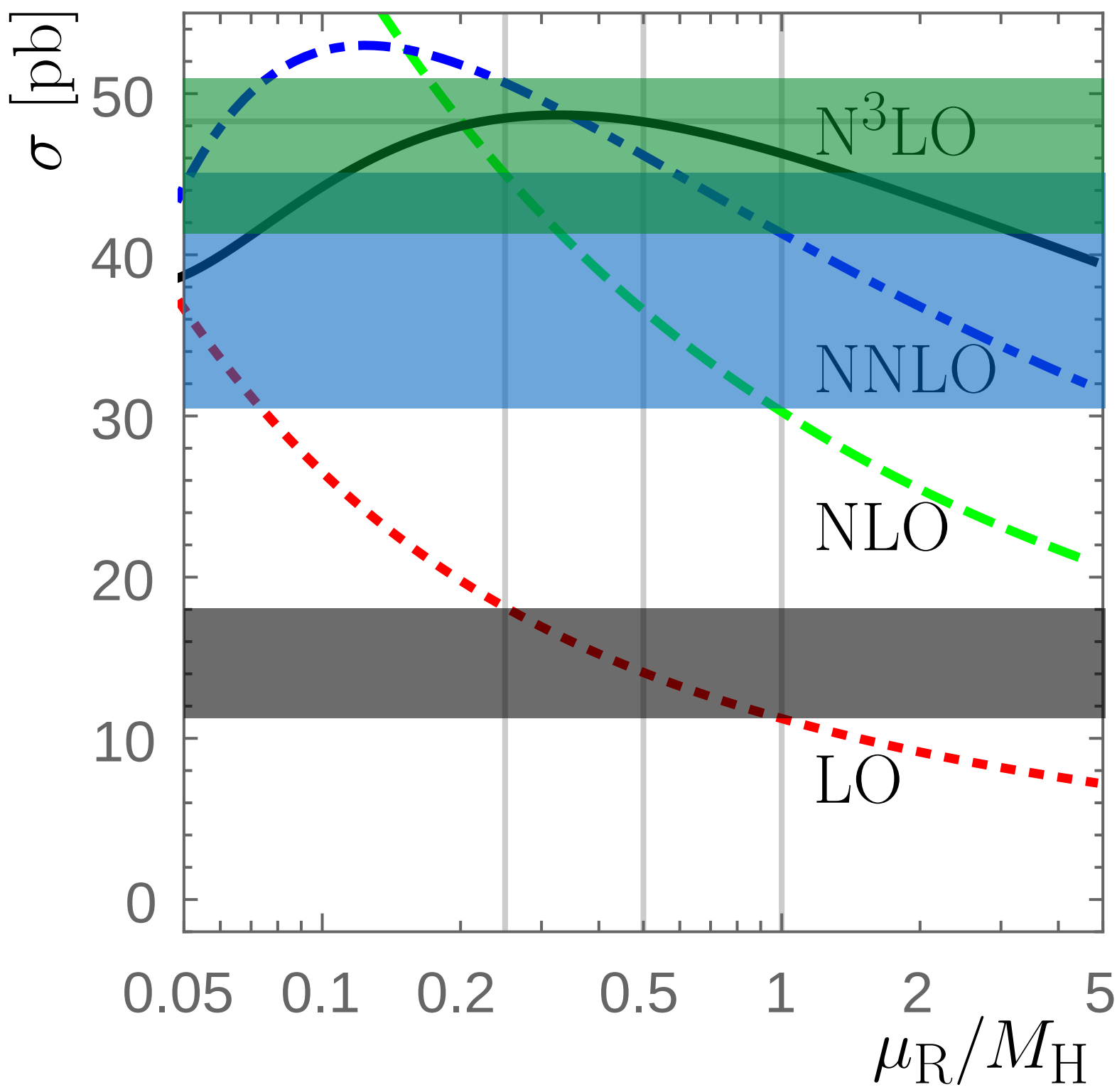


1991

1976



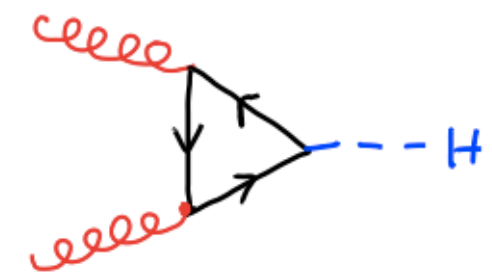


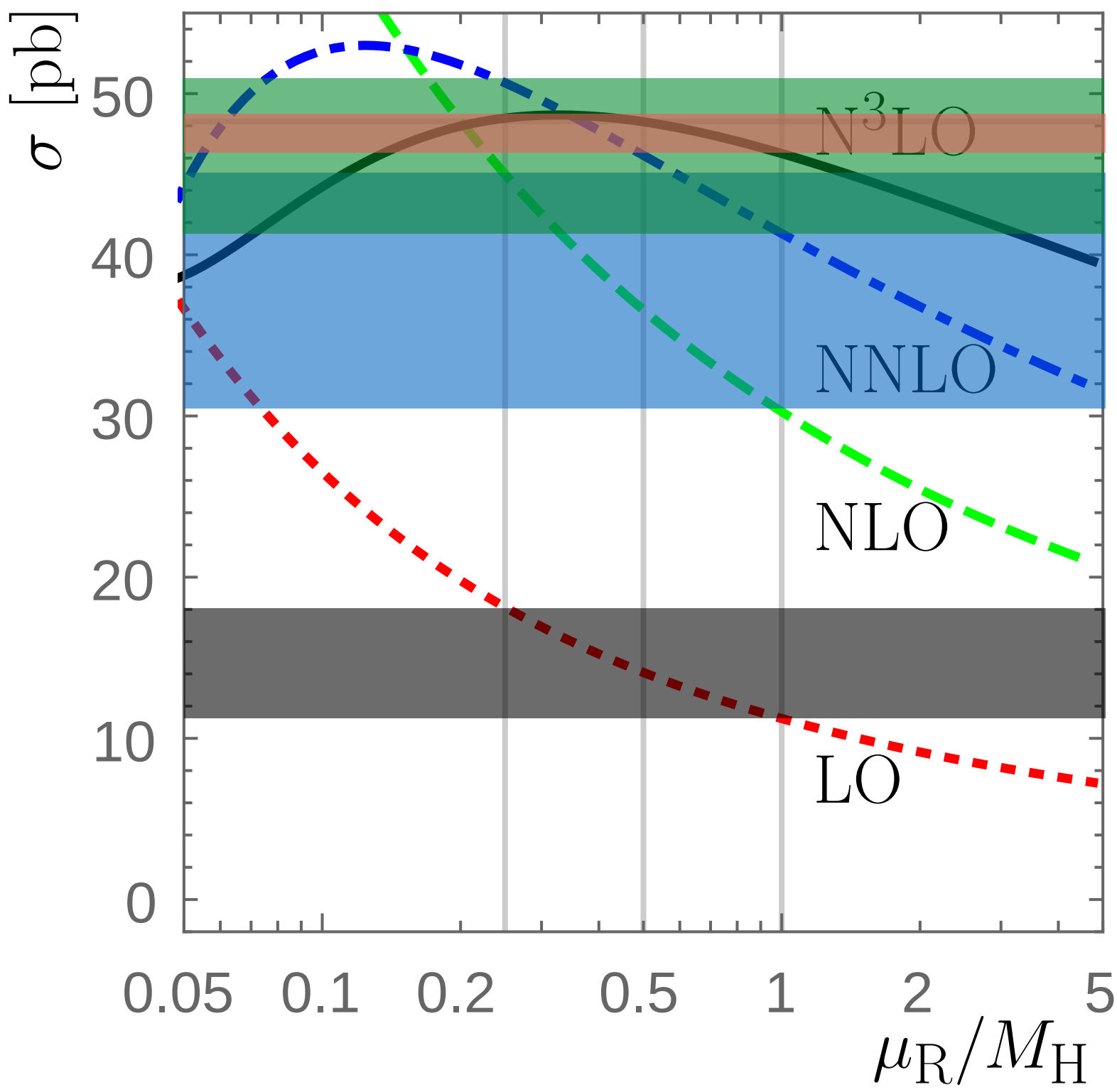


2002

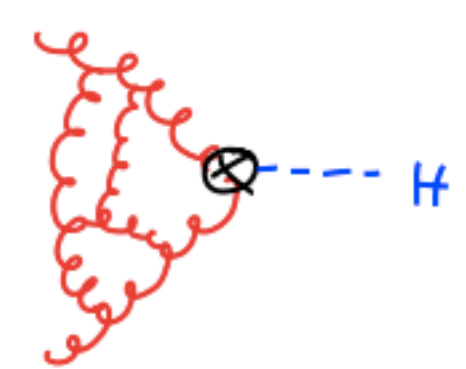
1991

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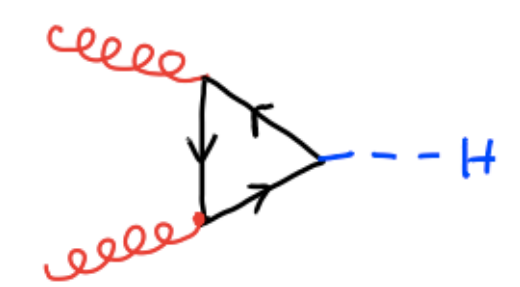


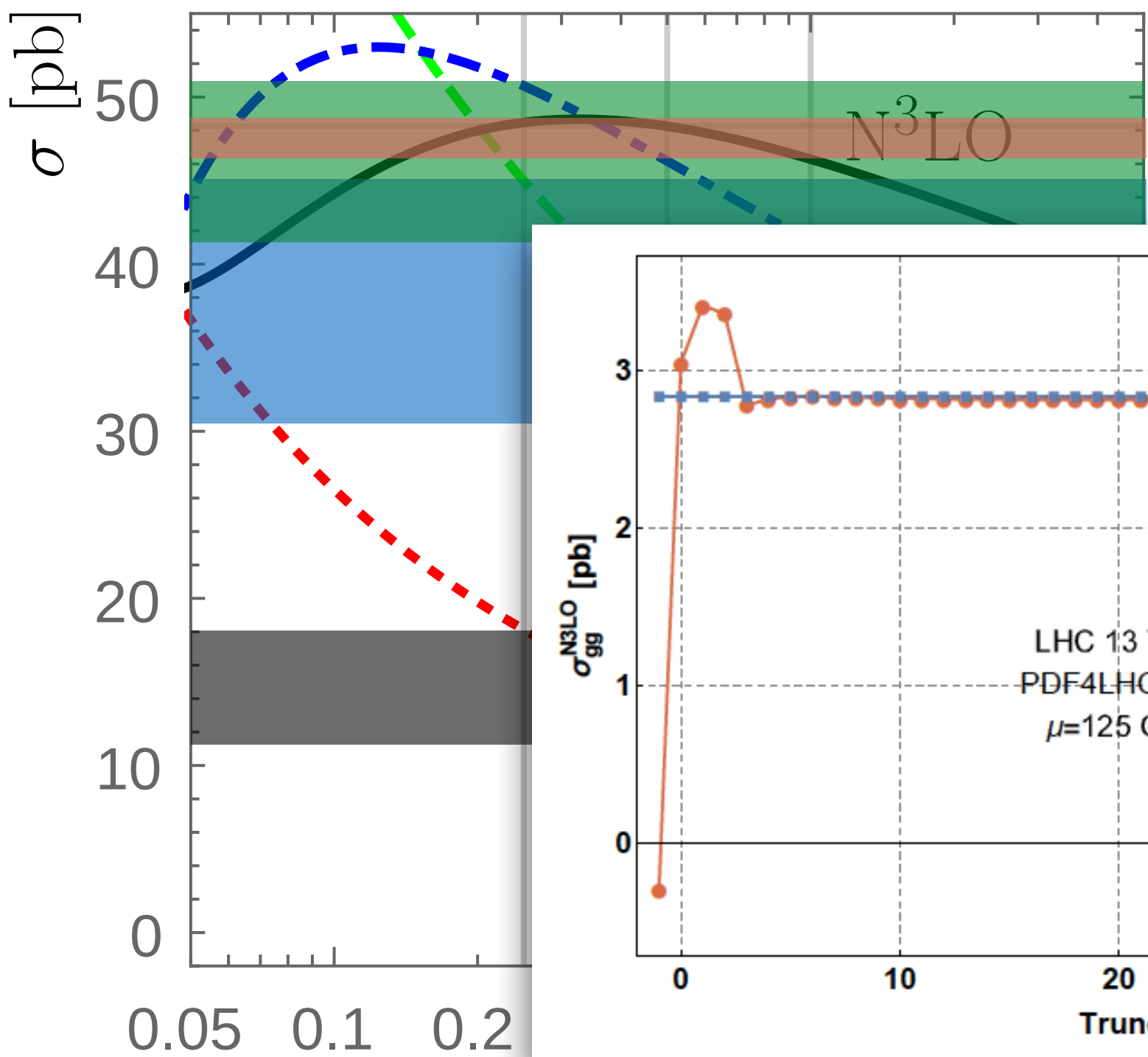
Anastasiou *et al.*  
 2015  
 2002



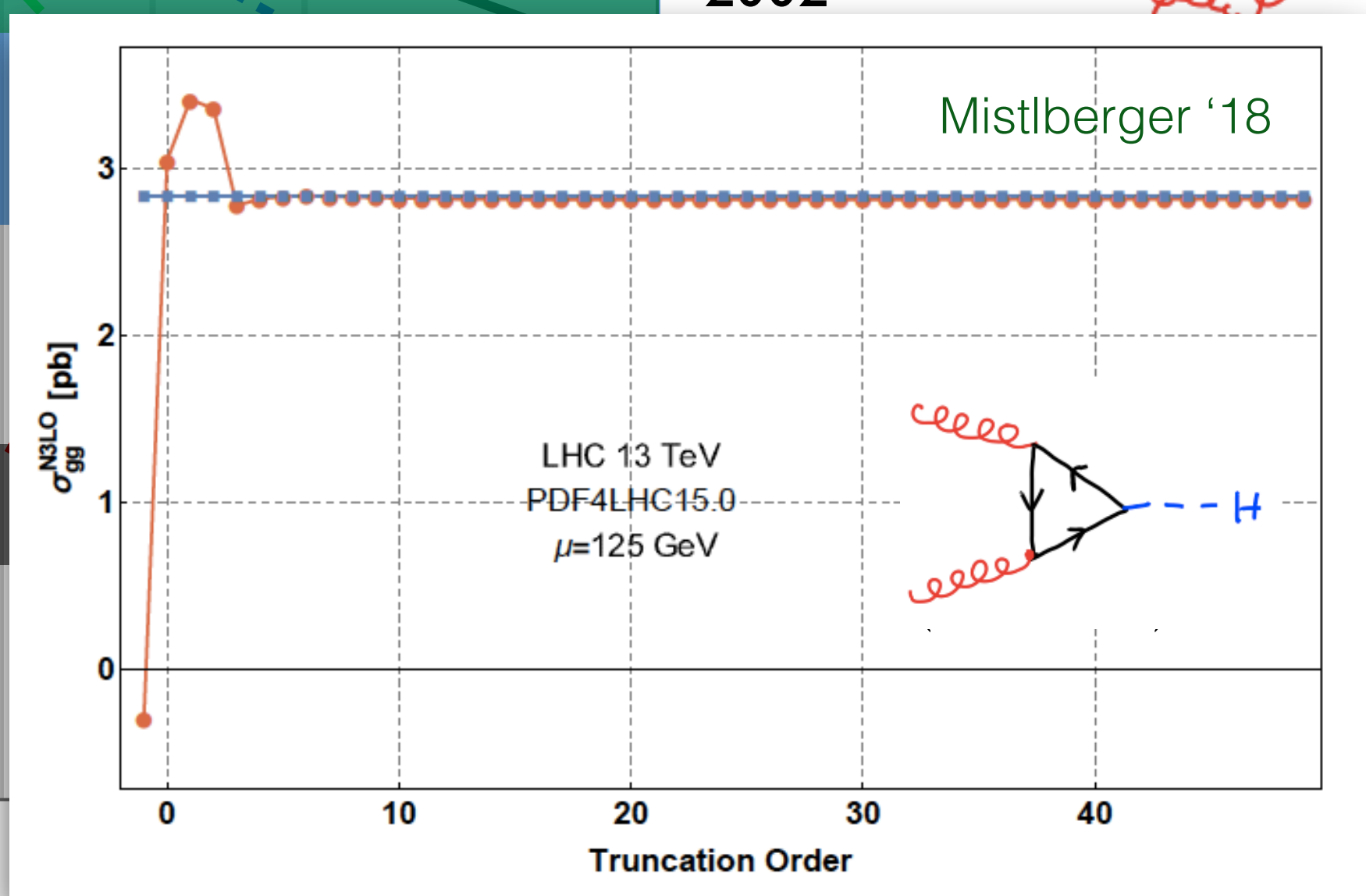
1991

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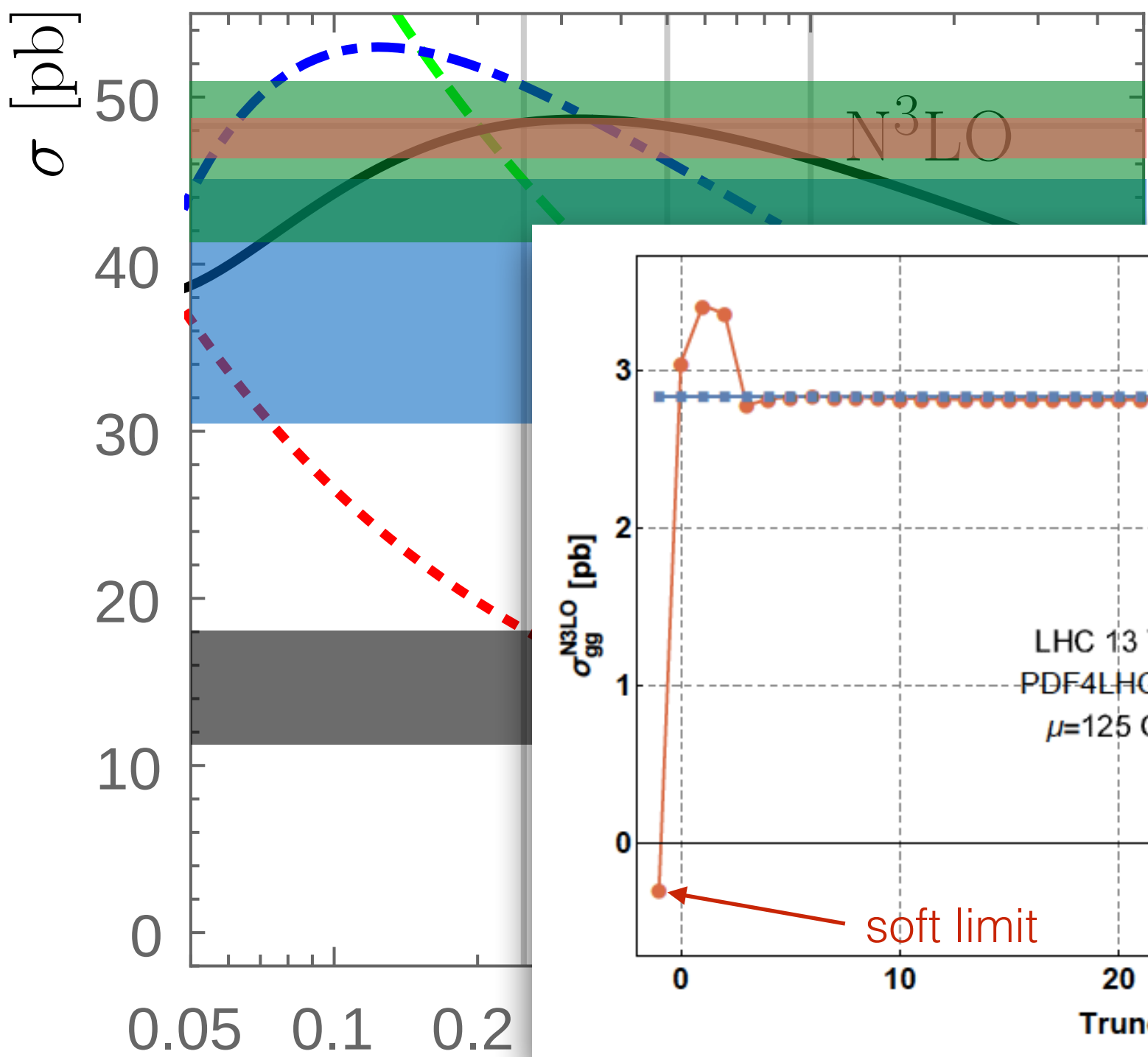




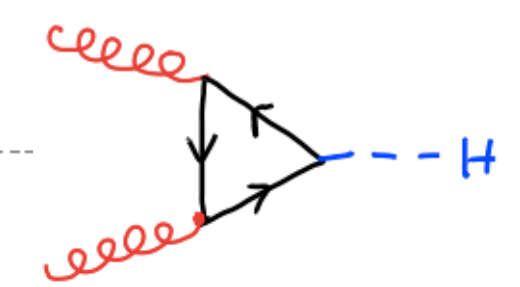
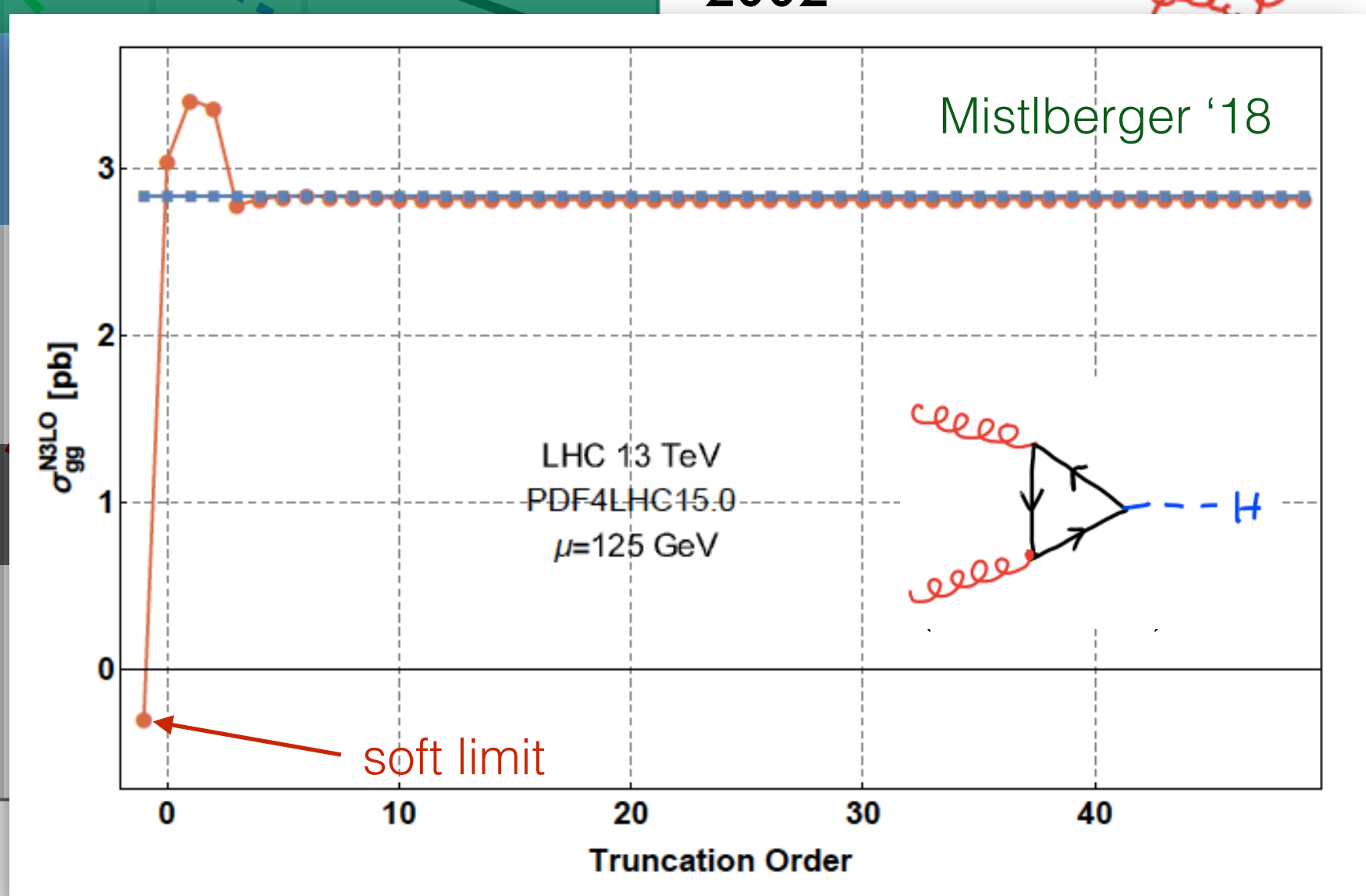
Anastasiou *et al.*  
 2015  
 2002



$$\mu_R/M_H$$

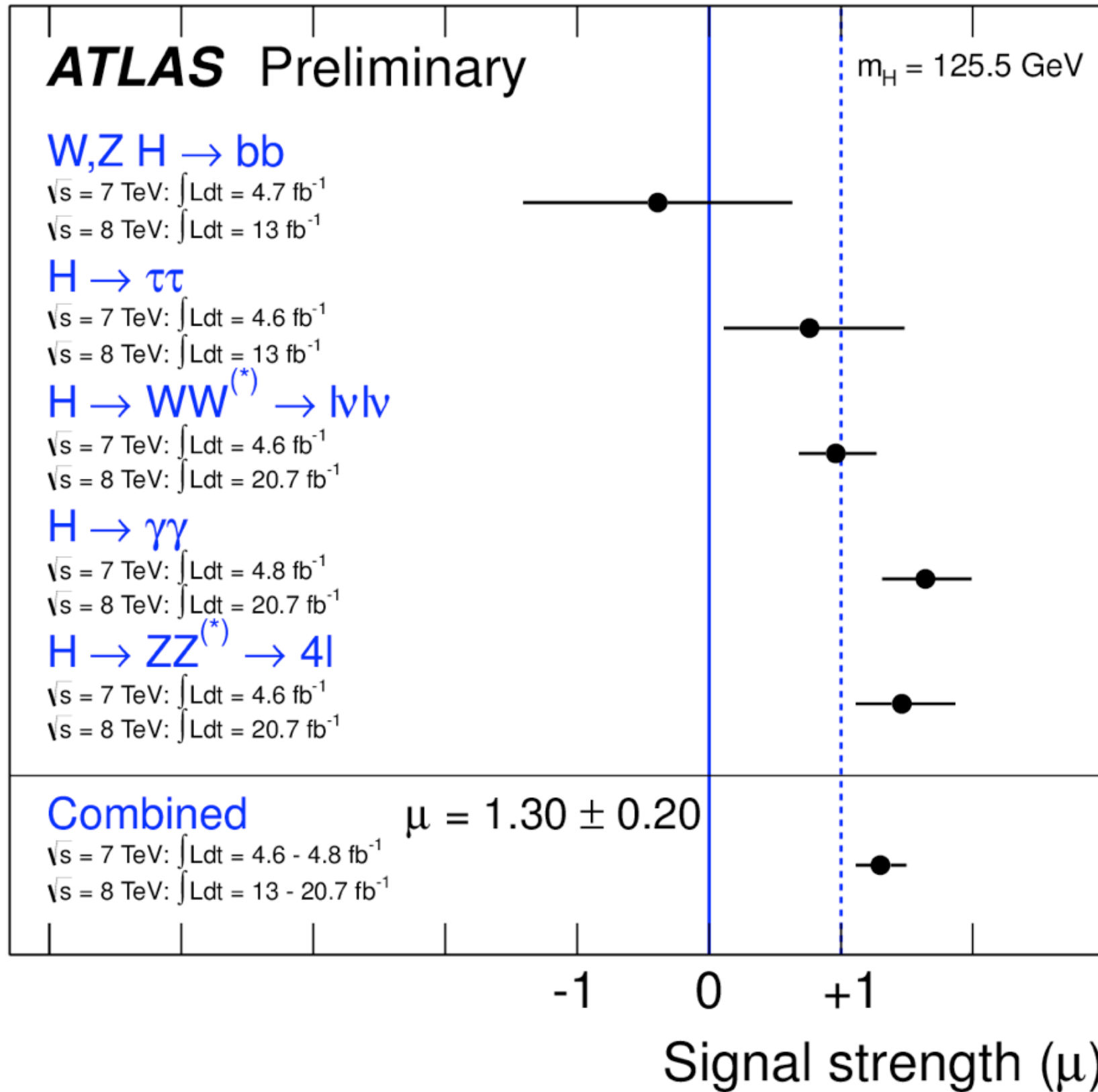


Anastasiou *et al.*  
 2015  
 2002

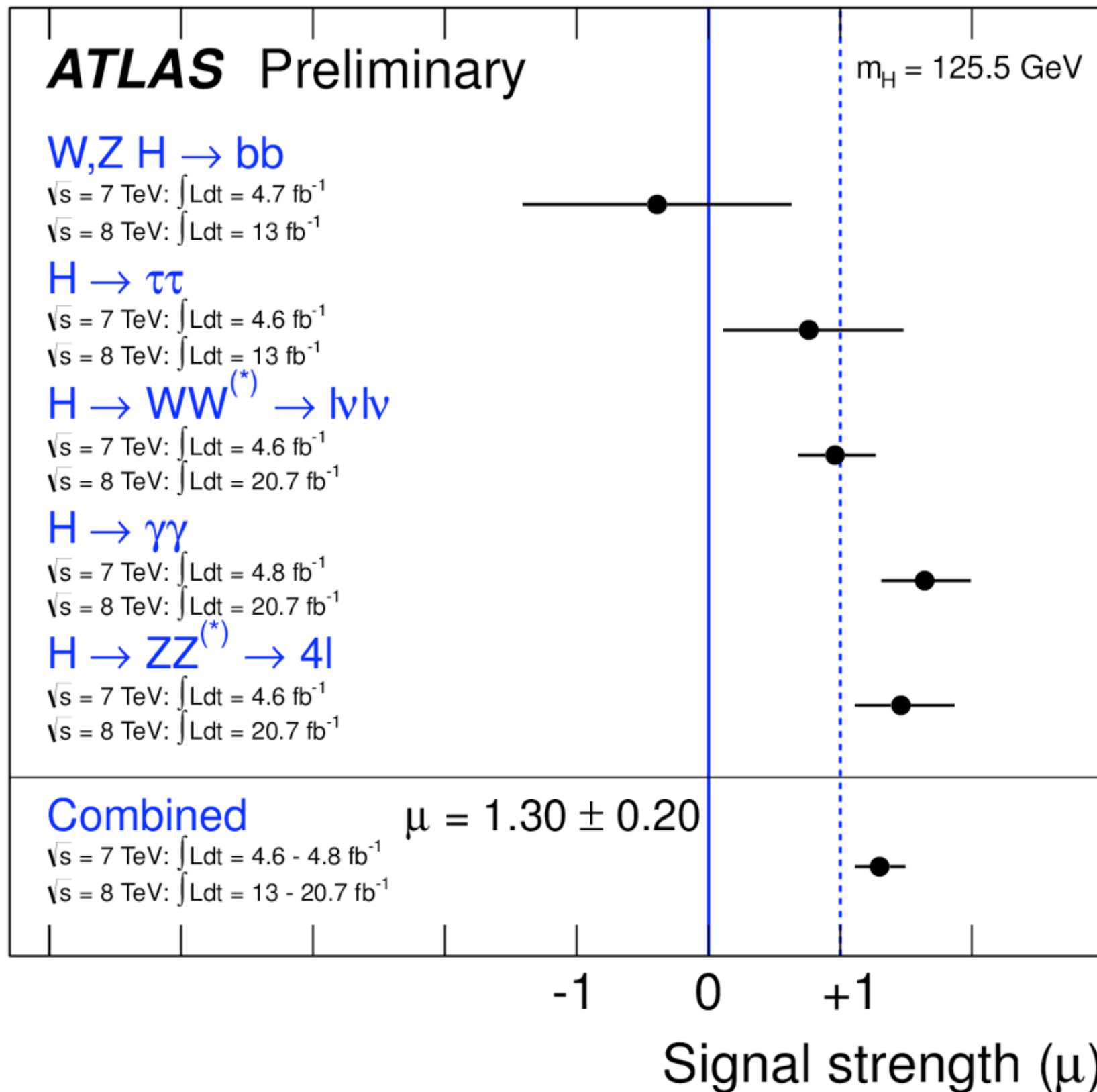


$$\mu_R/M_H$$



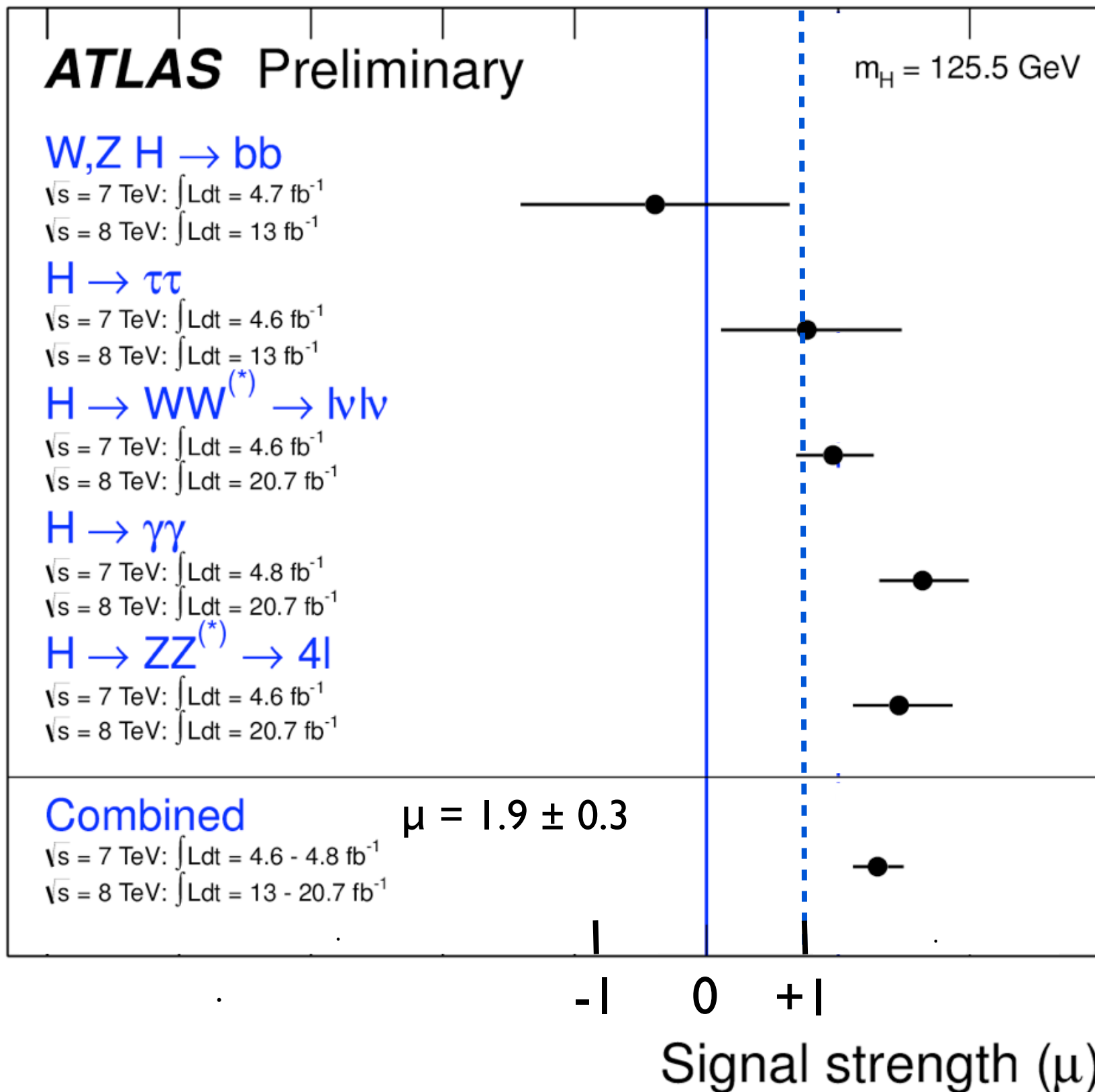


March 2013



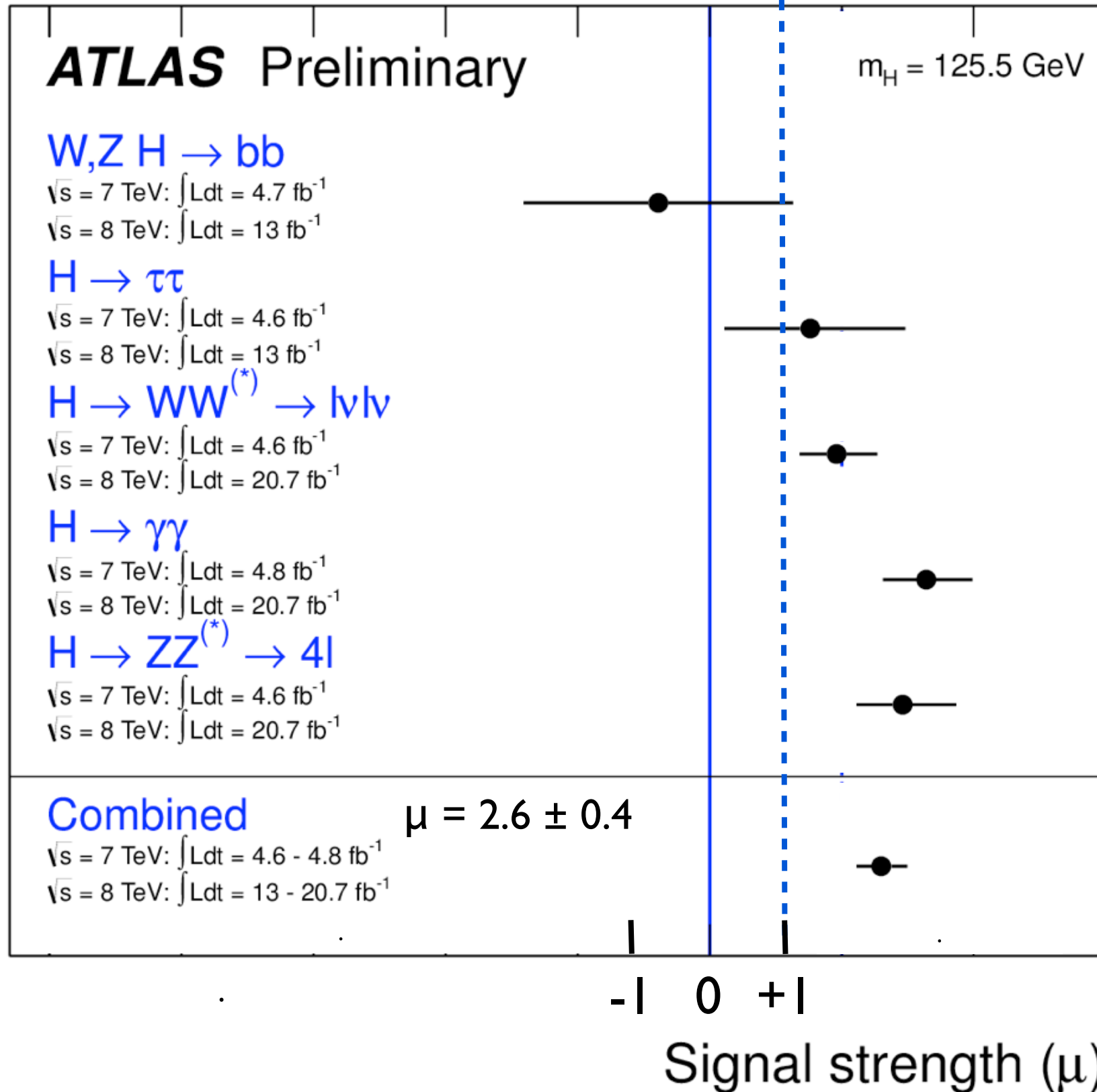
March 2013

# NLO



highly  
unofficial  
and  
scetchy!

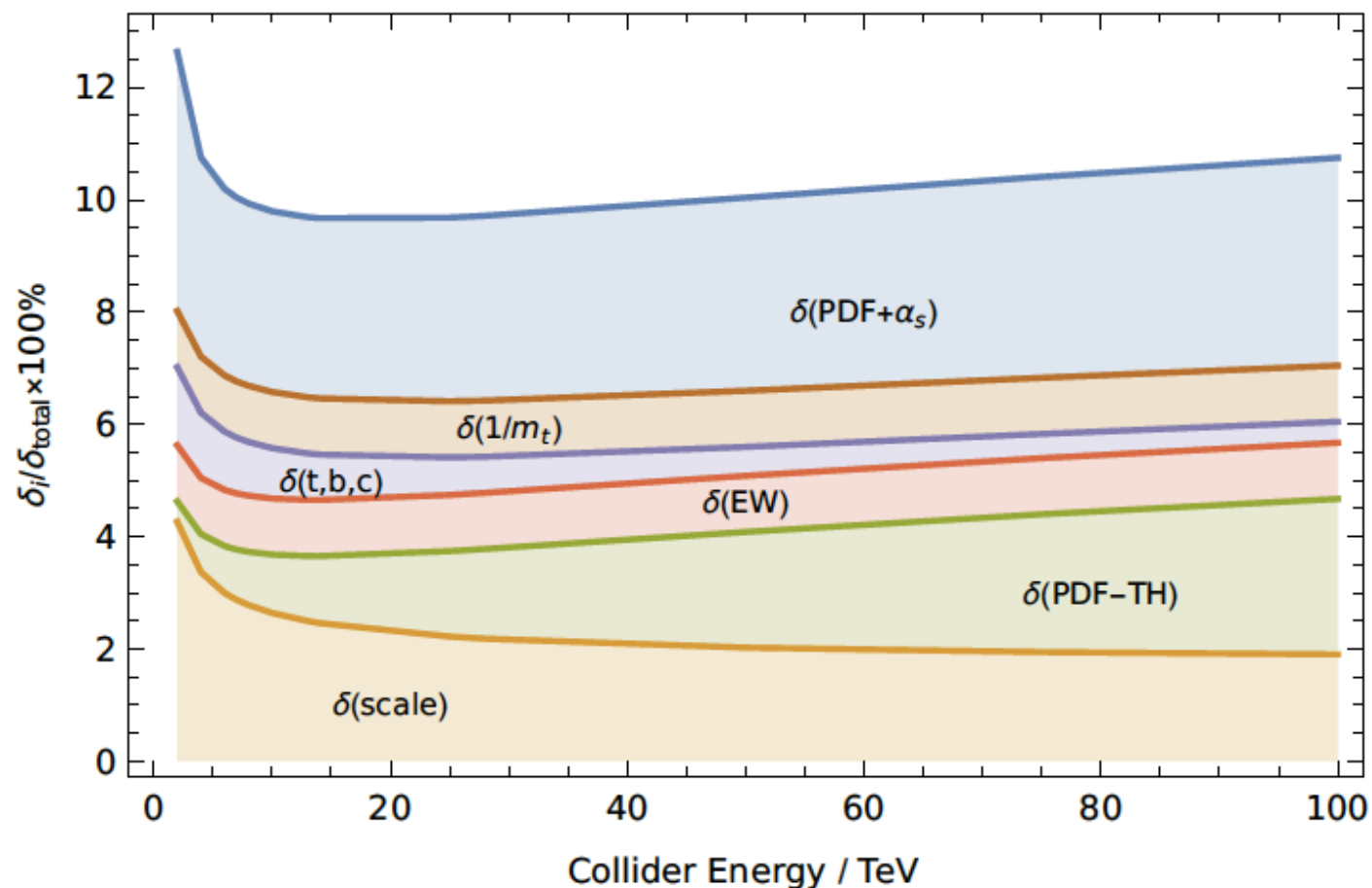
LO



highly  
unofficial  
and  
scetchy!

# Total cross section

$\sqrt{s}$	$\sigma$	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
13 TeV	48.61 pb	$+2.08\text{pb}$ $\left( \begin{array}{l} +4.27\% \\ -6.49\% \end{array} \right)$ $-3.15\text{pb}$	$\pm 0.89\text{ pb}$ ( $\pm 1.85\%$ )	$+1.24\text{pb}$ $\left( \begin{array}{l} +2.59\% \\ -2.62\% \end{array} \right)$ $-1.26\text{pb}$
14 TeV	54.72 pb	$+2.35\text{pb}$ $\left( \begin{array}{l} +4.28\% \\ -6.46\% \end{array} \right)$ $-3.54\text{pb}$	$\pm 1.00\text{ pb}$ ( $\pm 1.85\%$ )	$+1.40\text{pb}$ $\left( \begin{array}{l} +2.60\% \\ -2.62\% \end{array} \right)$ $-1.41\text{pb}$
27 TeV	146.65 pb	$+6.65\text{pb}$ $\left( \begin{array}{l} +4.53\% \\ -6.43\% \end{array} \right)$ $-9.44\text{pb}$	$\pm 2.81\text{ pb}$ ( $\pm 1.95\%$ )	$+3.88\text{pb}$ $\left( \begin{array}{l} +2.69\% \\ -2.64\% \end{array} \right)$ $-3.82\text{pb}$

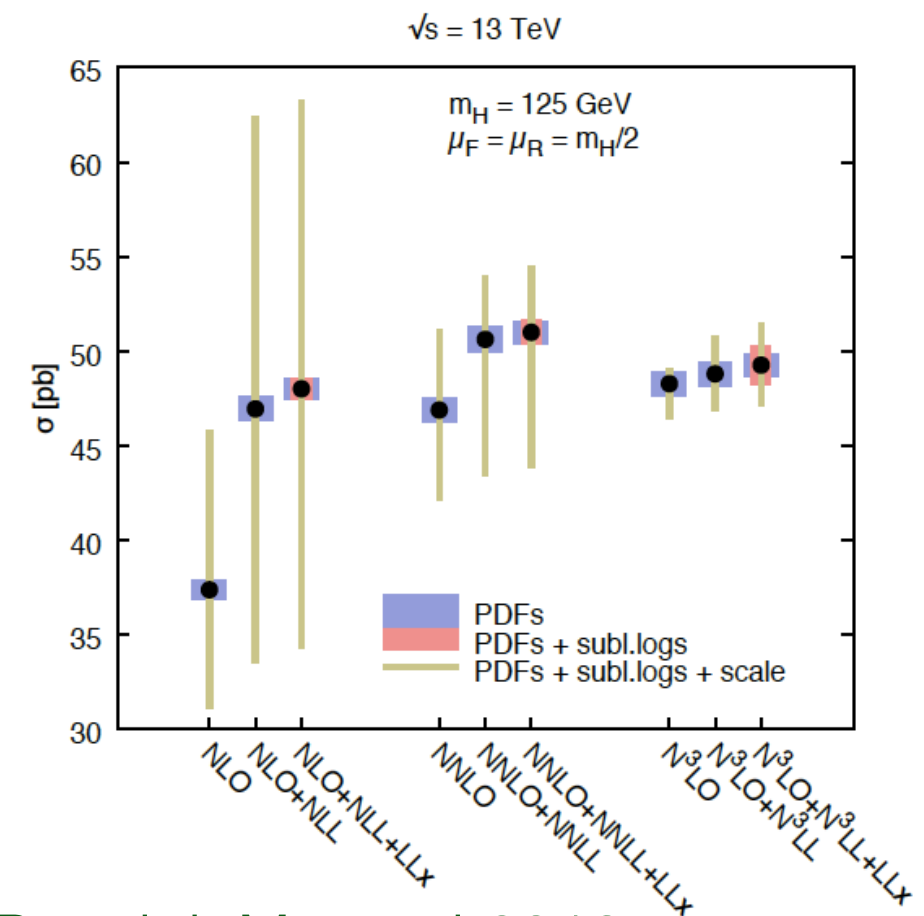
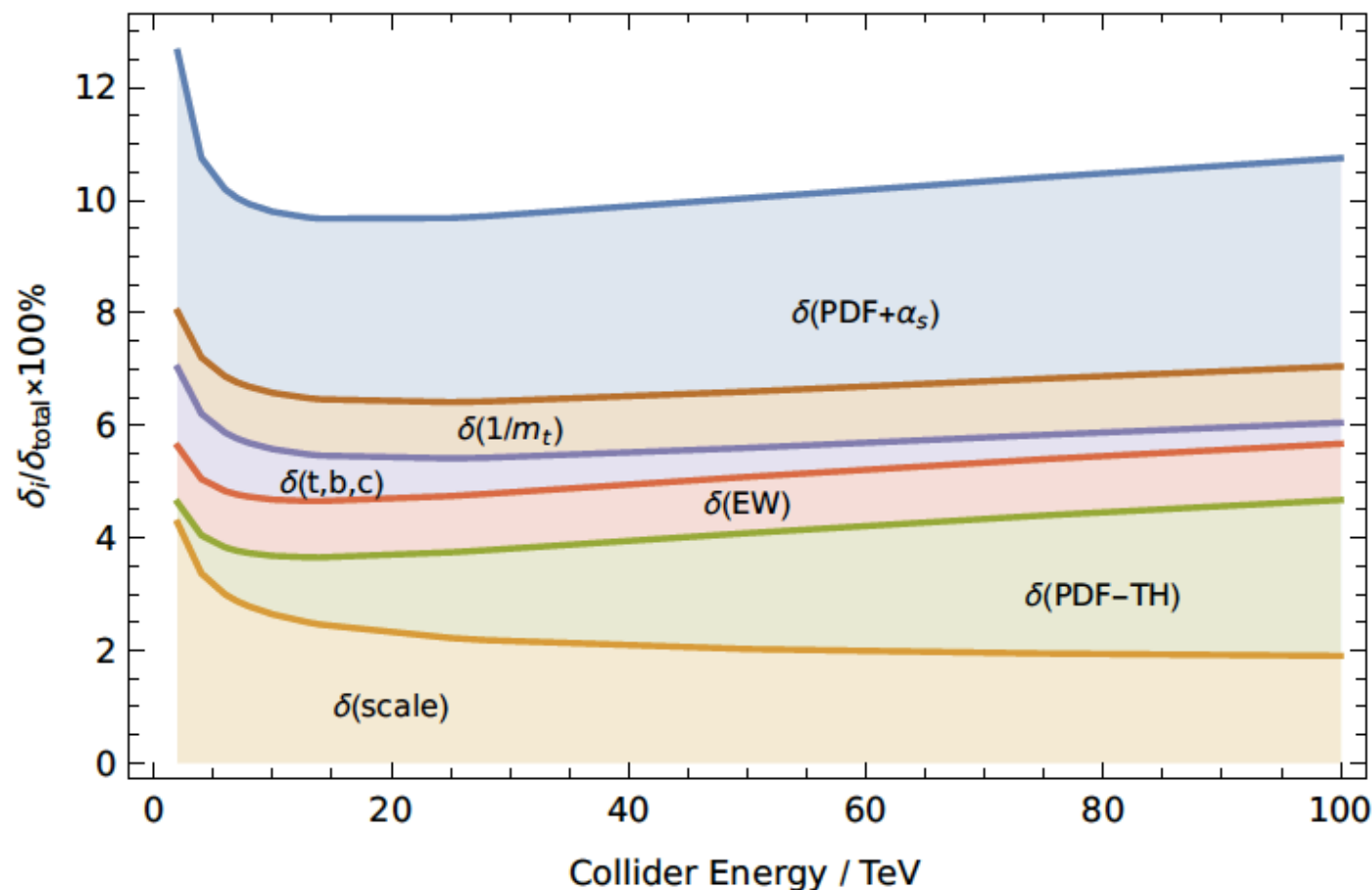


QCD/EW:  
complete factorization  
Anastasiou, Boughezal, Petriello '09

Checked by  
explicit calculations:  
Bonetti, Melnikov, Tancredi '17  
Anastasiou *et al.* '18

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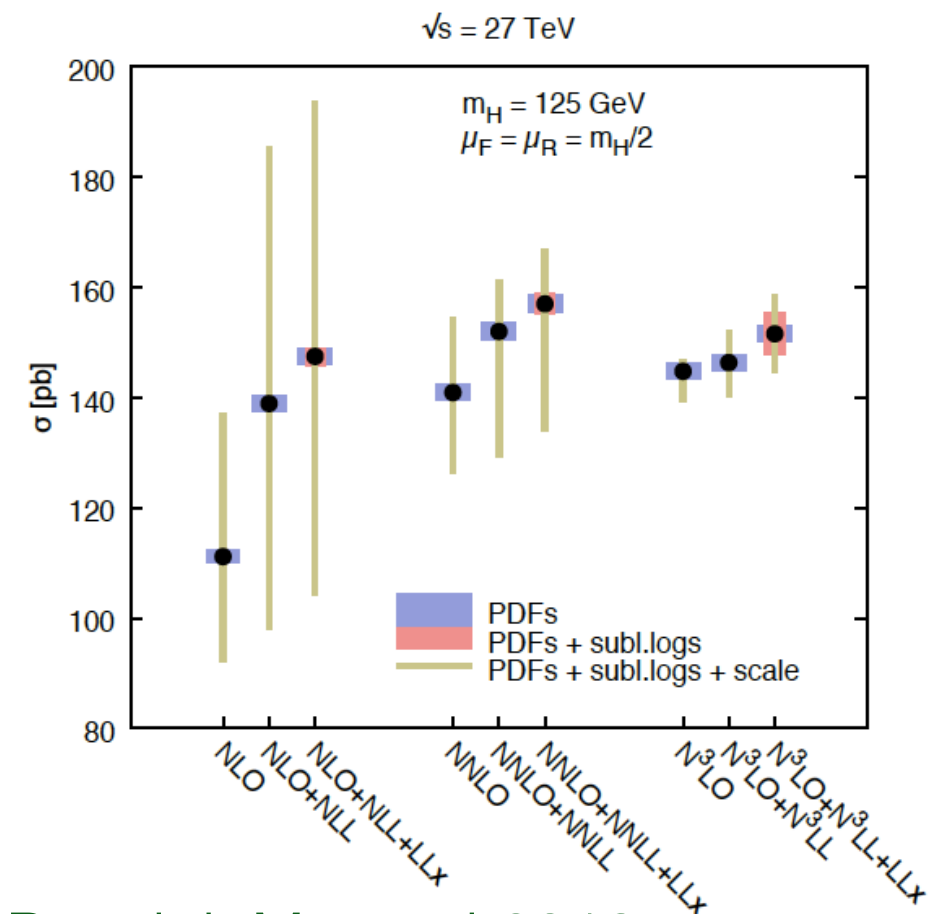
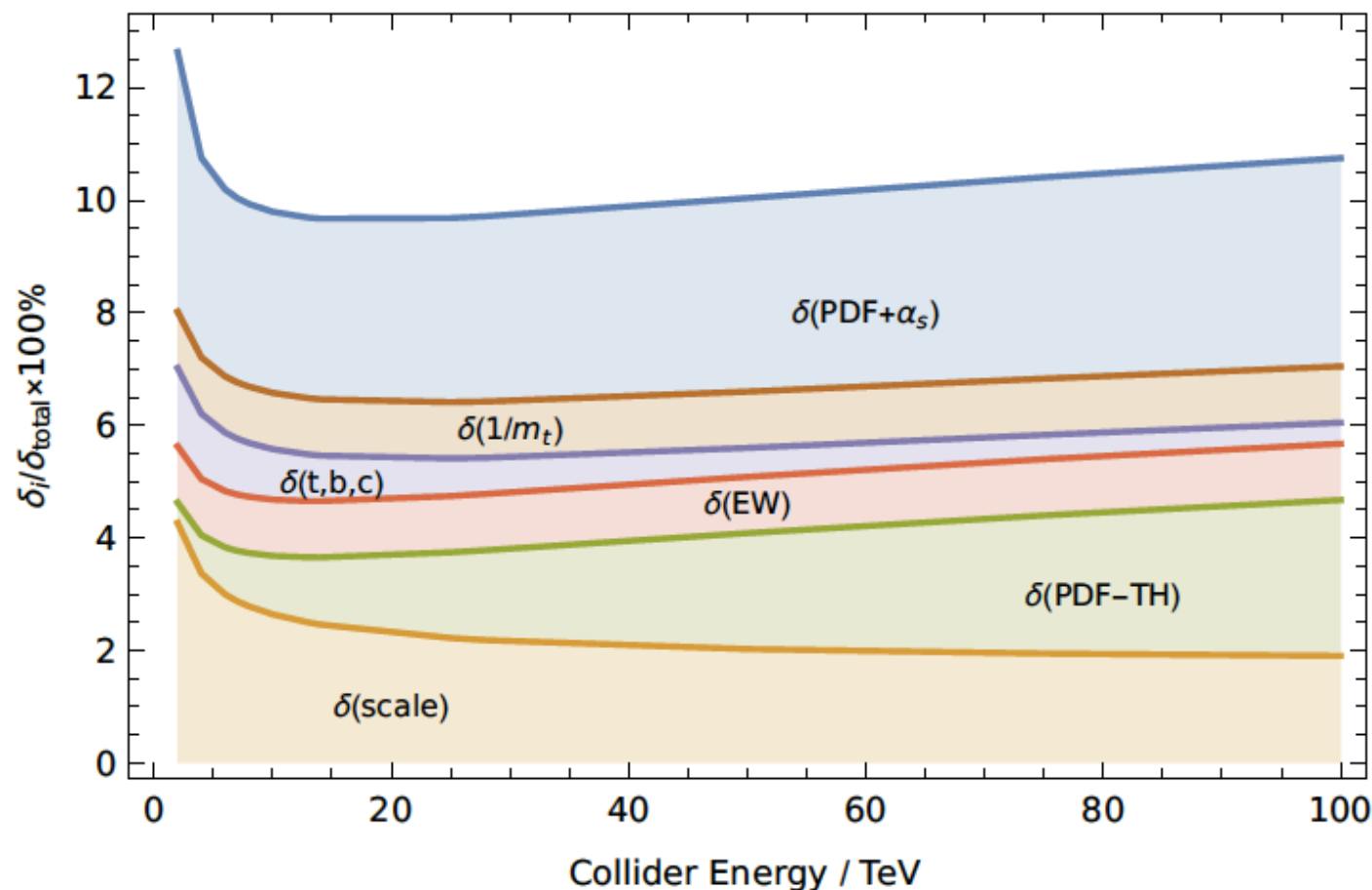


Bonvini, Marzani 2018



# Total cross section

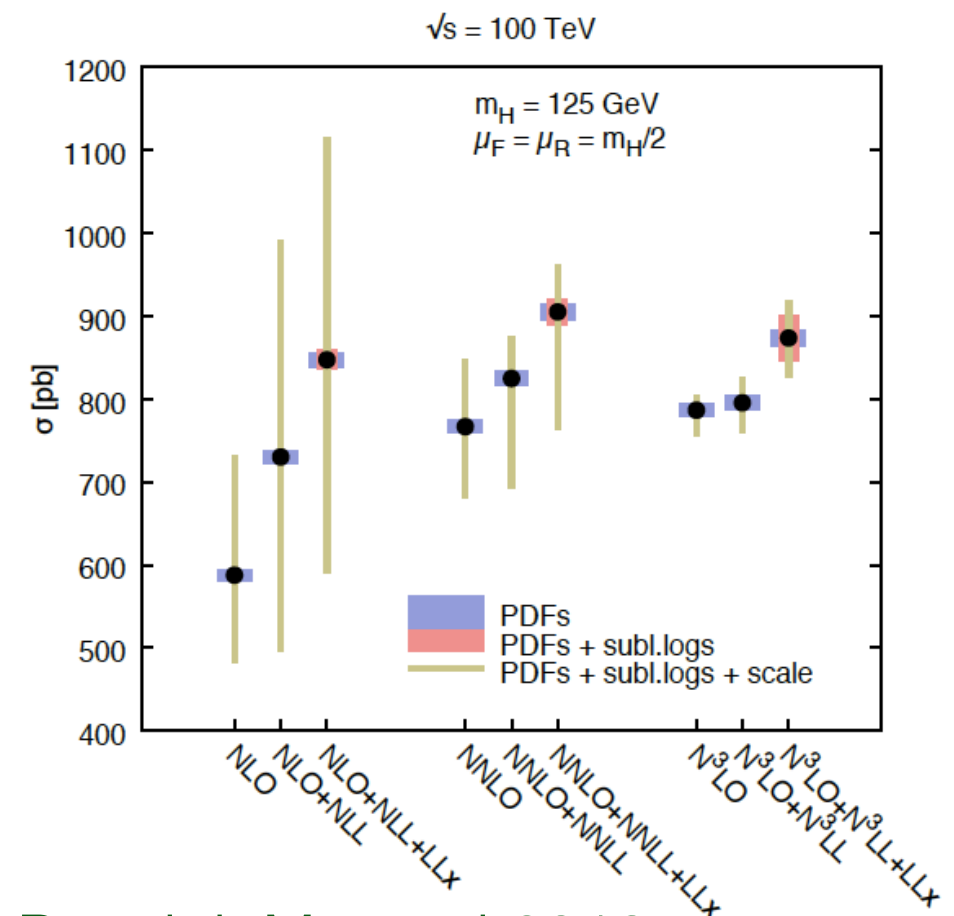
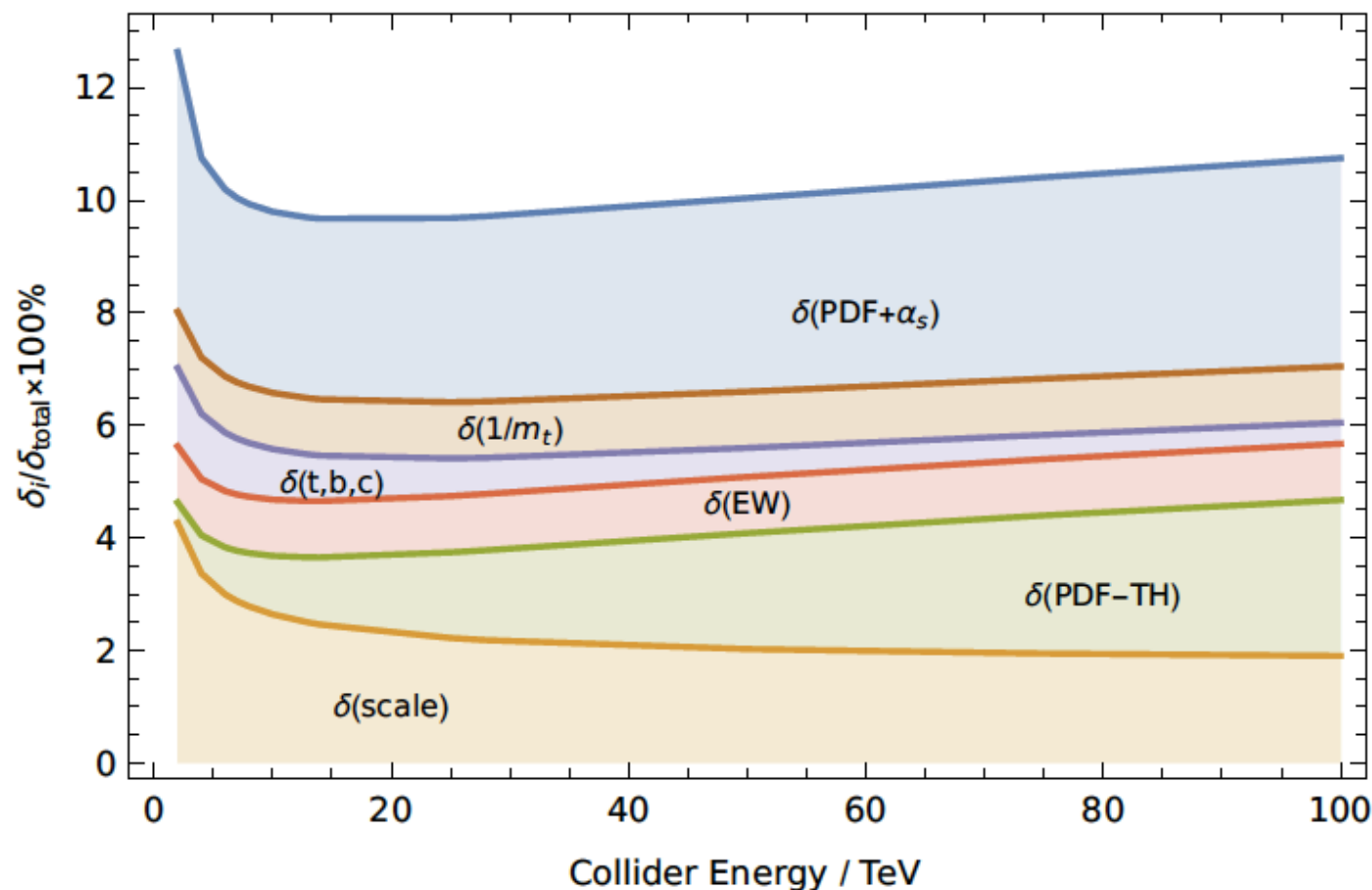
$\sqrt{s}$	$\sigma$	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
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Bonvini, Marzani 2018

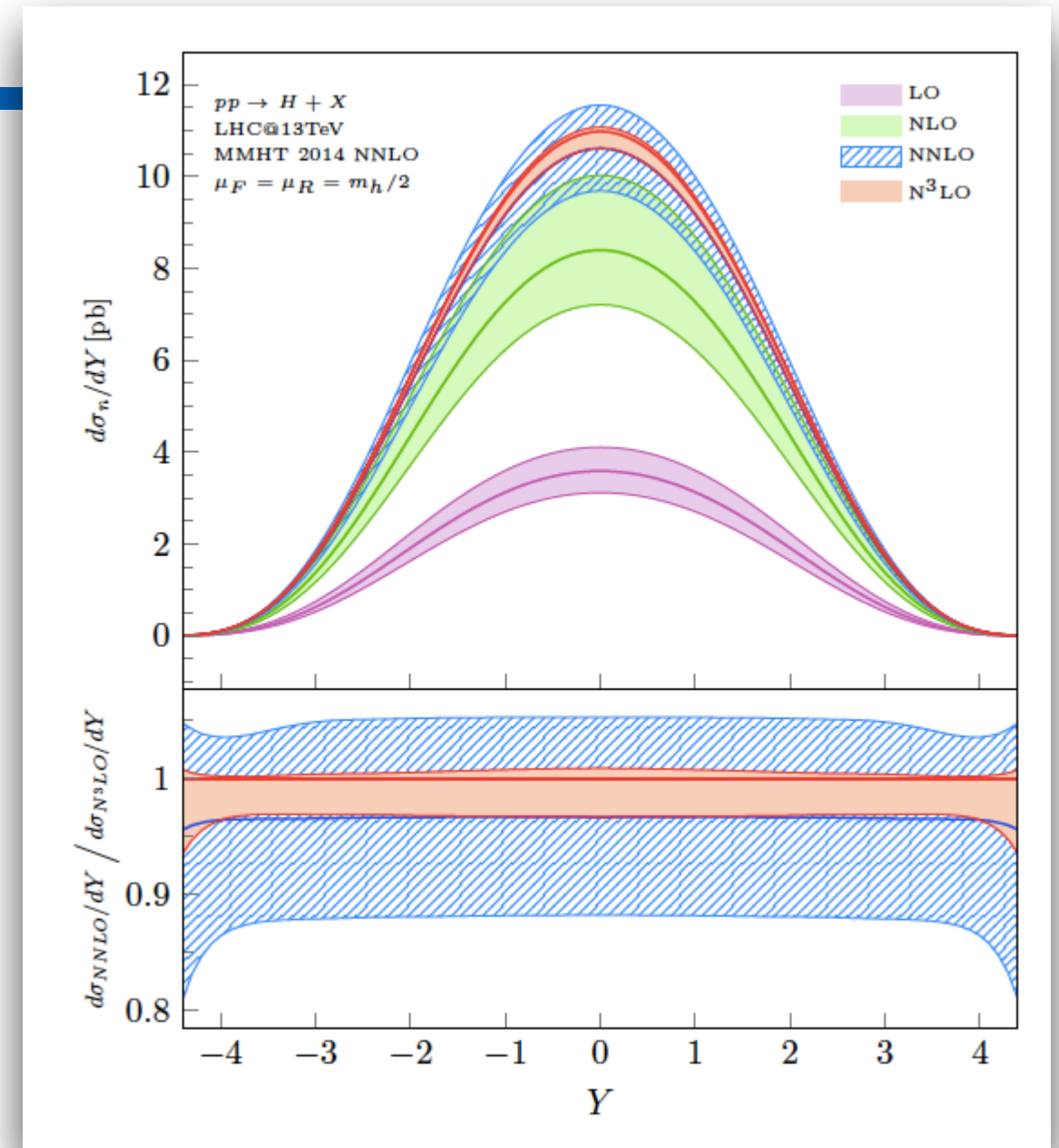
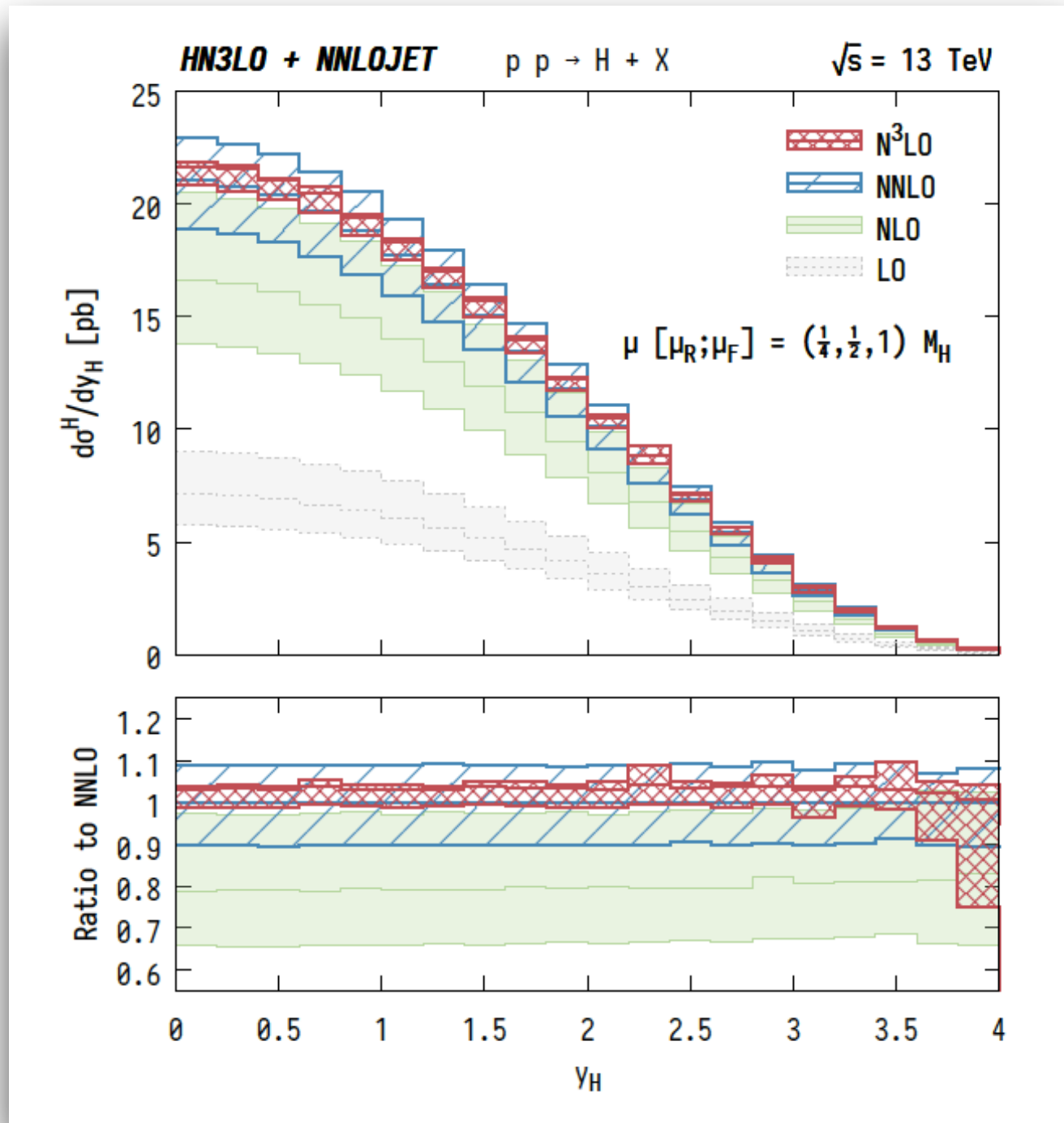
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Bonvini, Marzani 2018

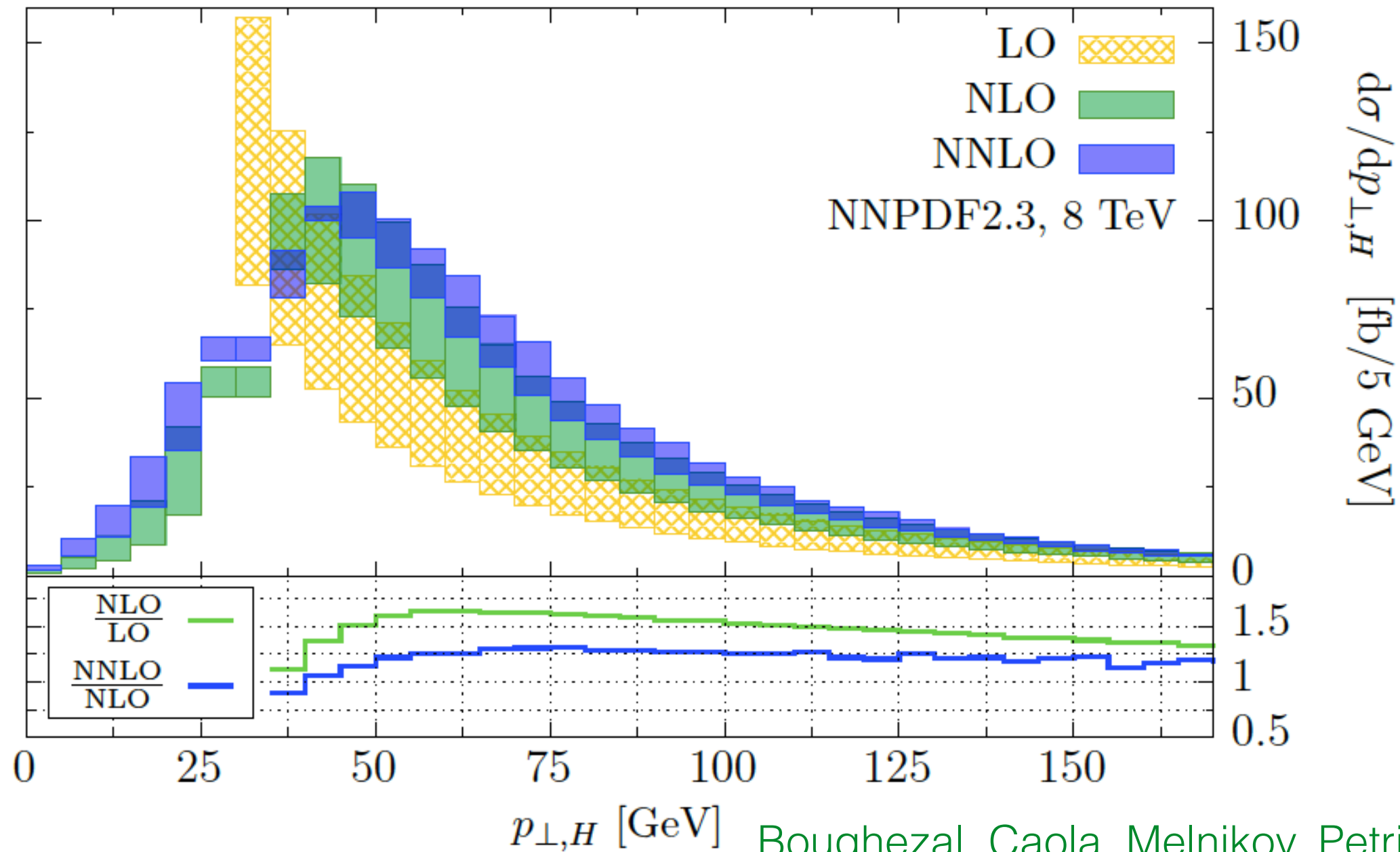
# Distributions



Dulat, Mistlberger, Pelloni 2018

Cieri, Chen, T. Gehrman, Glover, Huss 2018

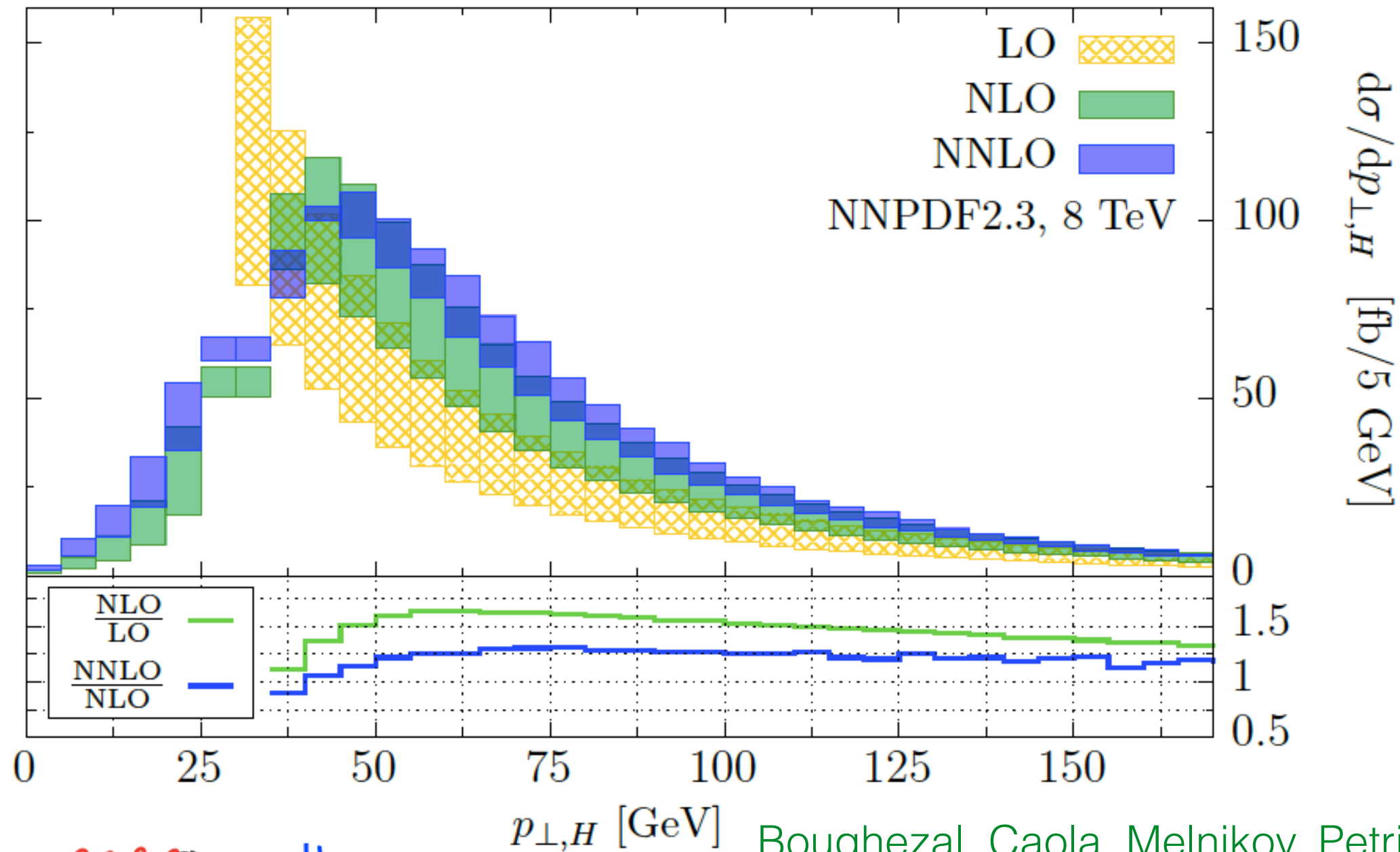
# NNLO $p_T$



Boughezal, Caola, Melnikov, Petriello, Schulze '13  
Chen, T. Gehrmann, Glover, Jaquier '14  
Boughezal, Focke, Giele, Liu, Petriello '15

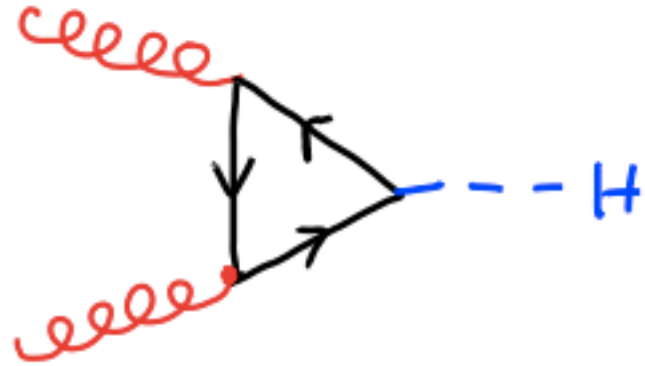


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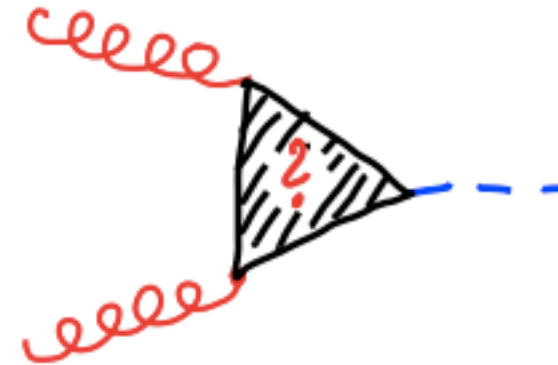
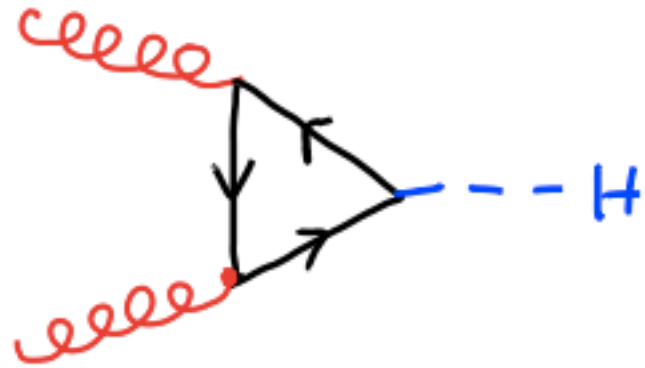
# Higgs as a probe



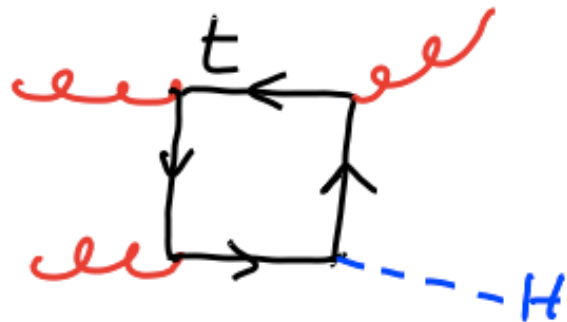
$$\sqrt{\hat{s}} = M_H$$



# Higgs as a probe

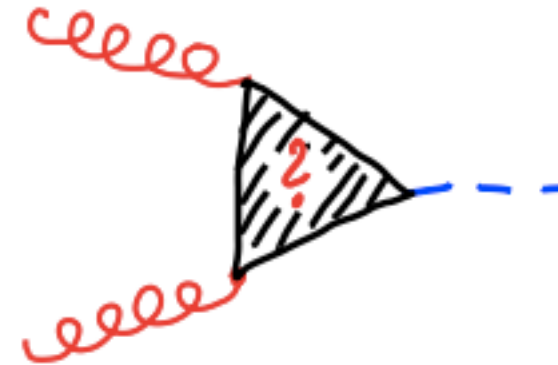
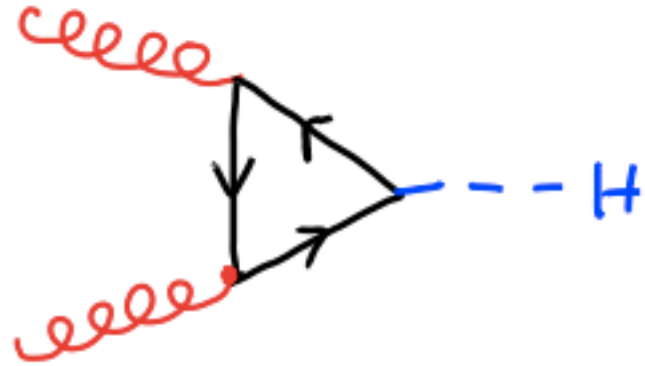


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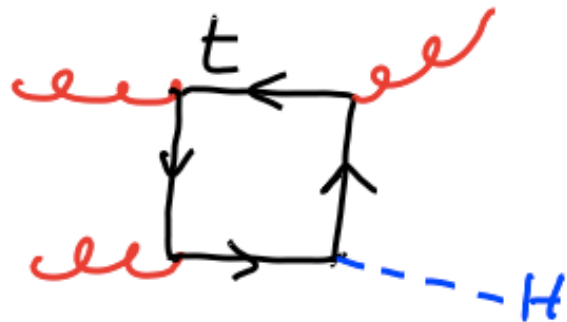


$$\sqrt{\hat{s}} \sim p_T + M_H$$
$$m_t \rightarrow \infty?$$

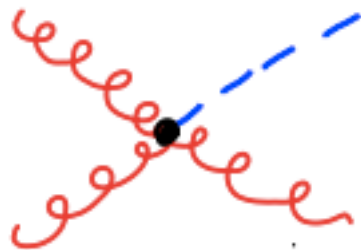
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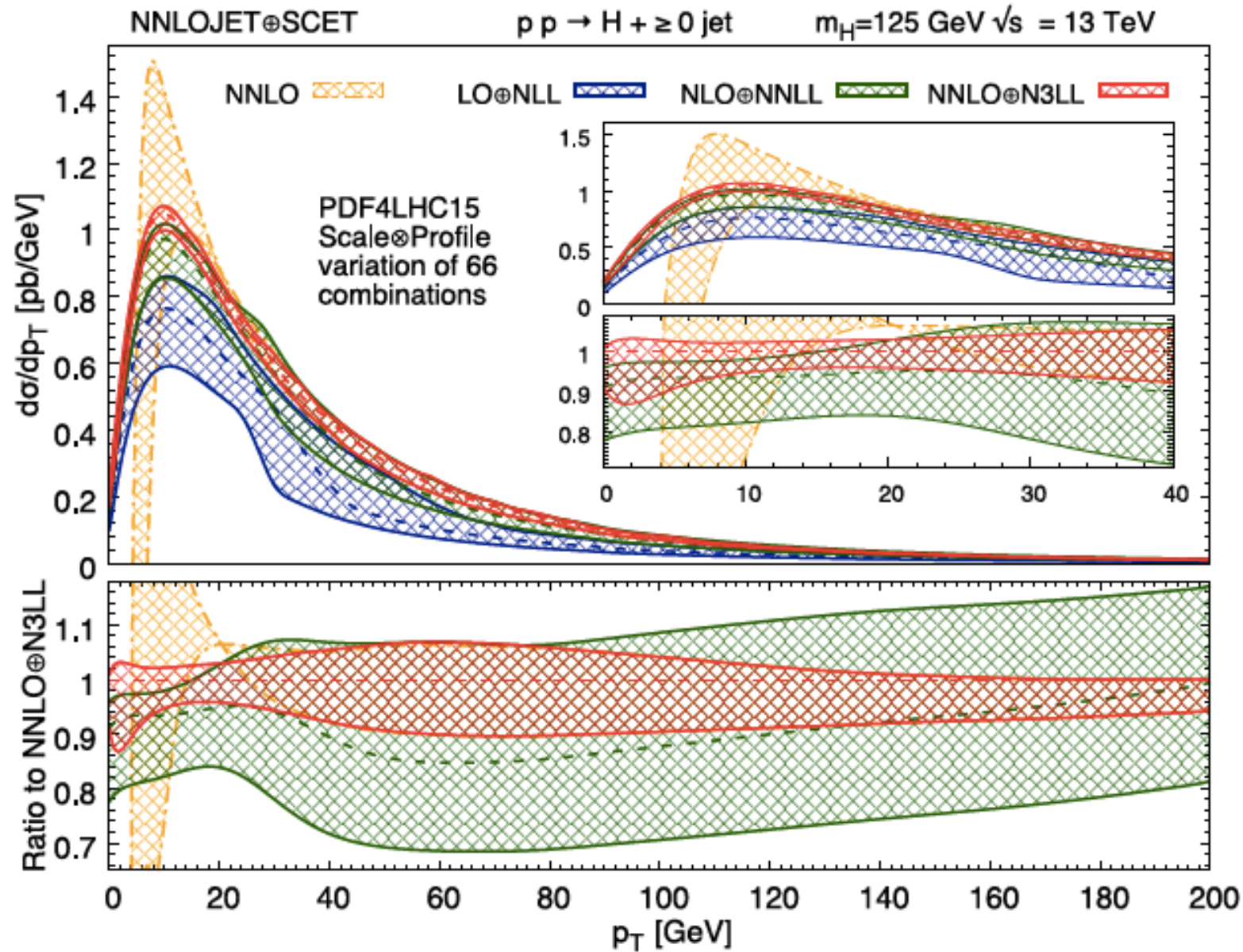
$$\sqrt{\hat{s}} = M_H$$



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$$m_t \rightarrow \infty?$$



# Small- $p_T$ resummation

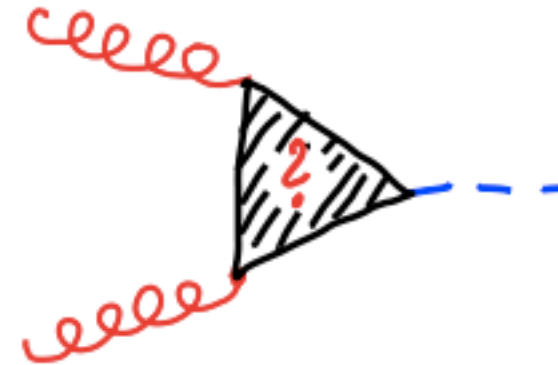
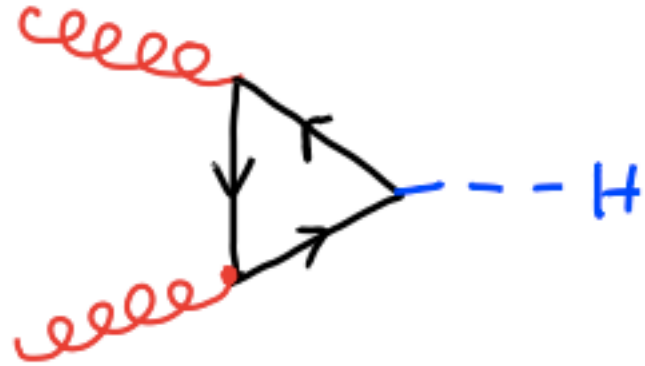


$NNLO \oplus N^3LL$

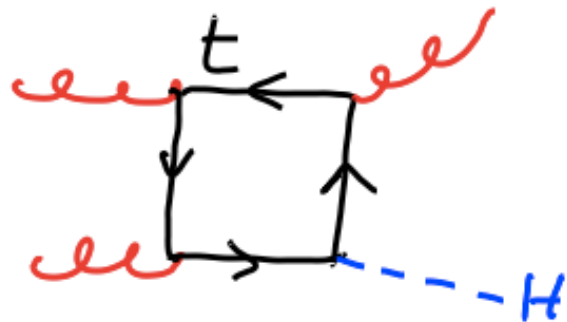
Chen *et al.* 2018

Bizoń, Monni, Re, Rottoli, Torielli 2017

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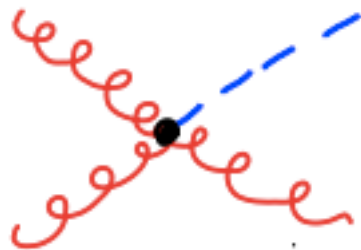


$$\sqrt{\hat{s}} = M_H$$

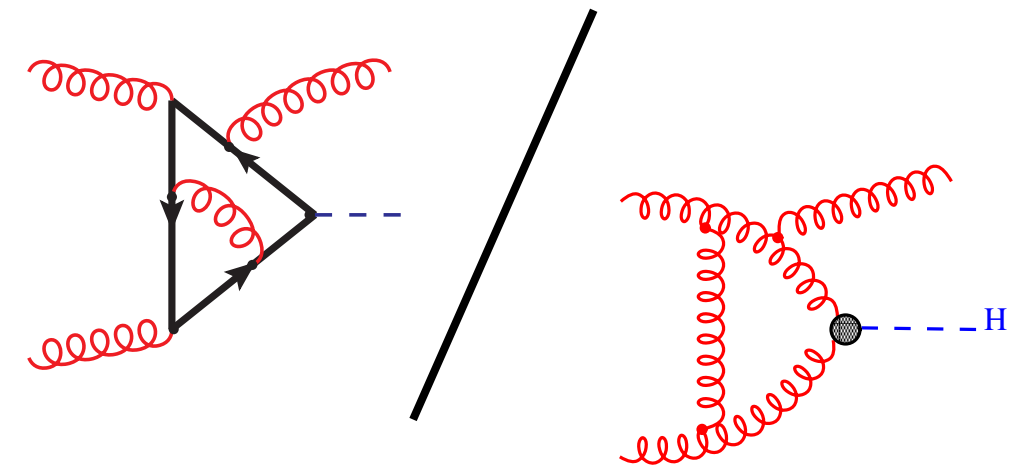
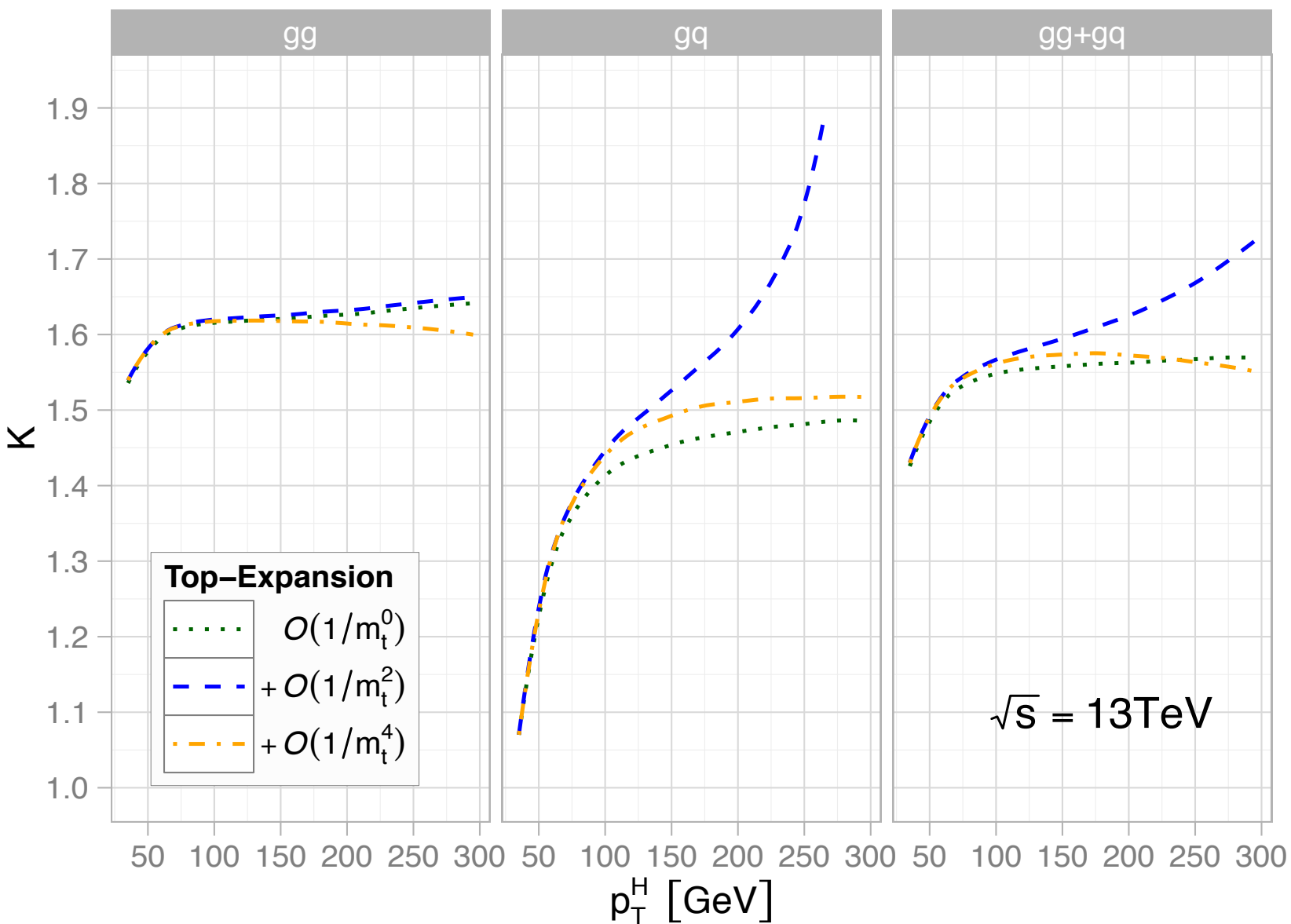


$$\sqrt{\hat{s}} \sim p_T + M_H$$

$$m_t \rightarrow \infty?$$



# 1/m<sub>t</sub> expansion

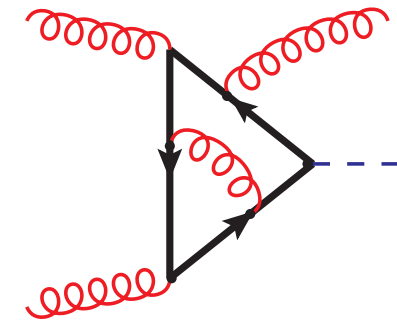
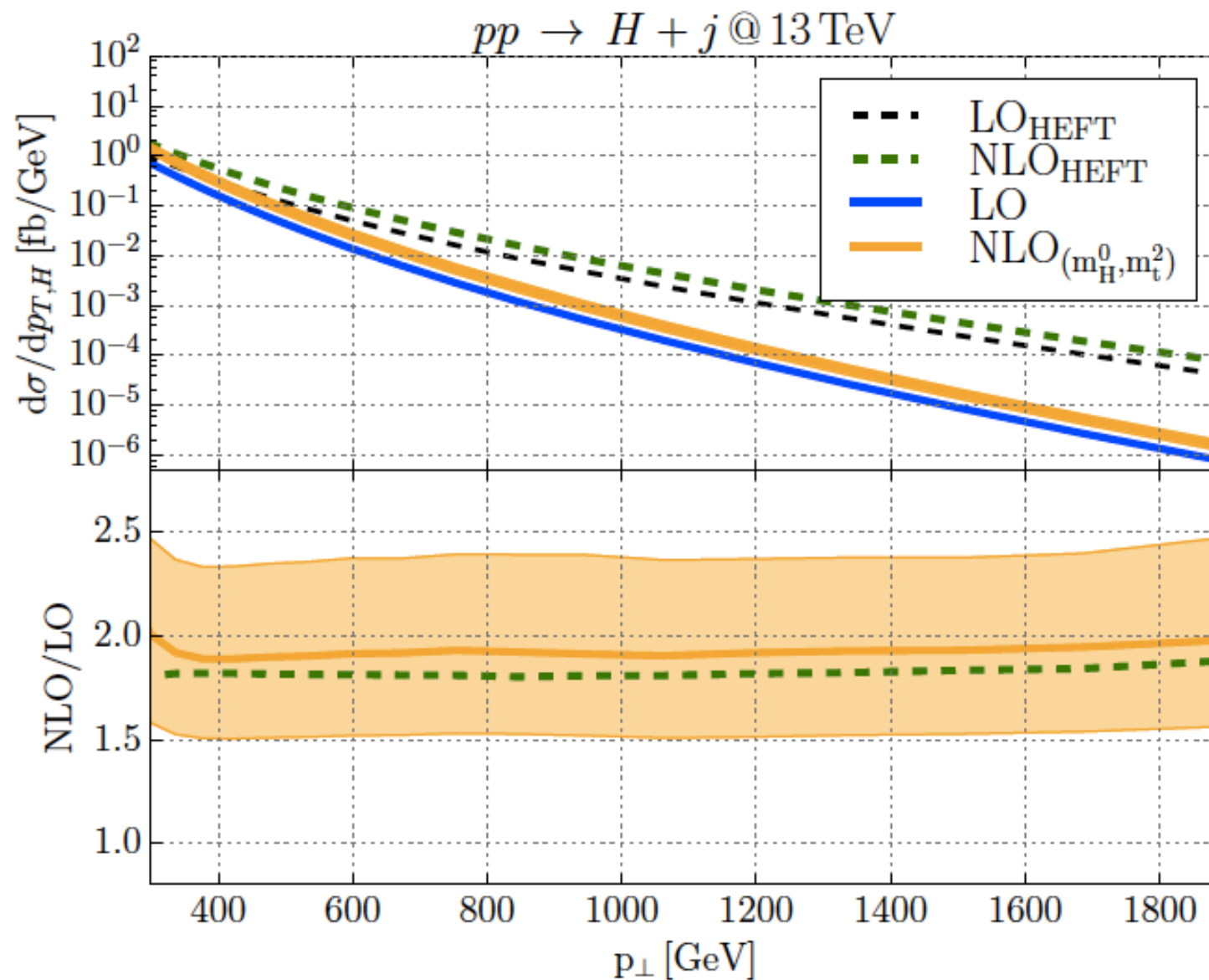


RH, Neumann, Ozeren,  
Wiesemann '12

Neumann, Wiesemann '14

Neumann, Williams '17

# Large $p_T$

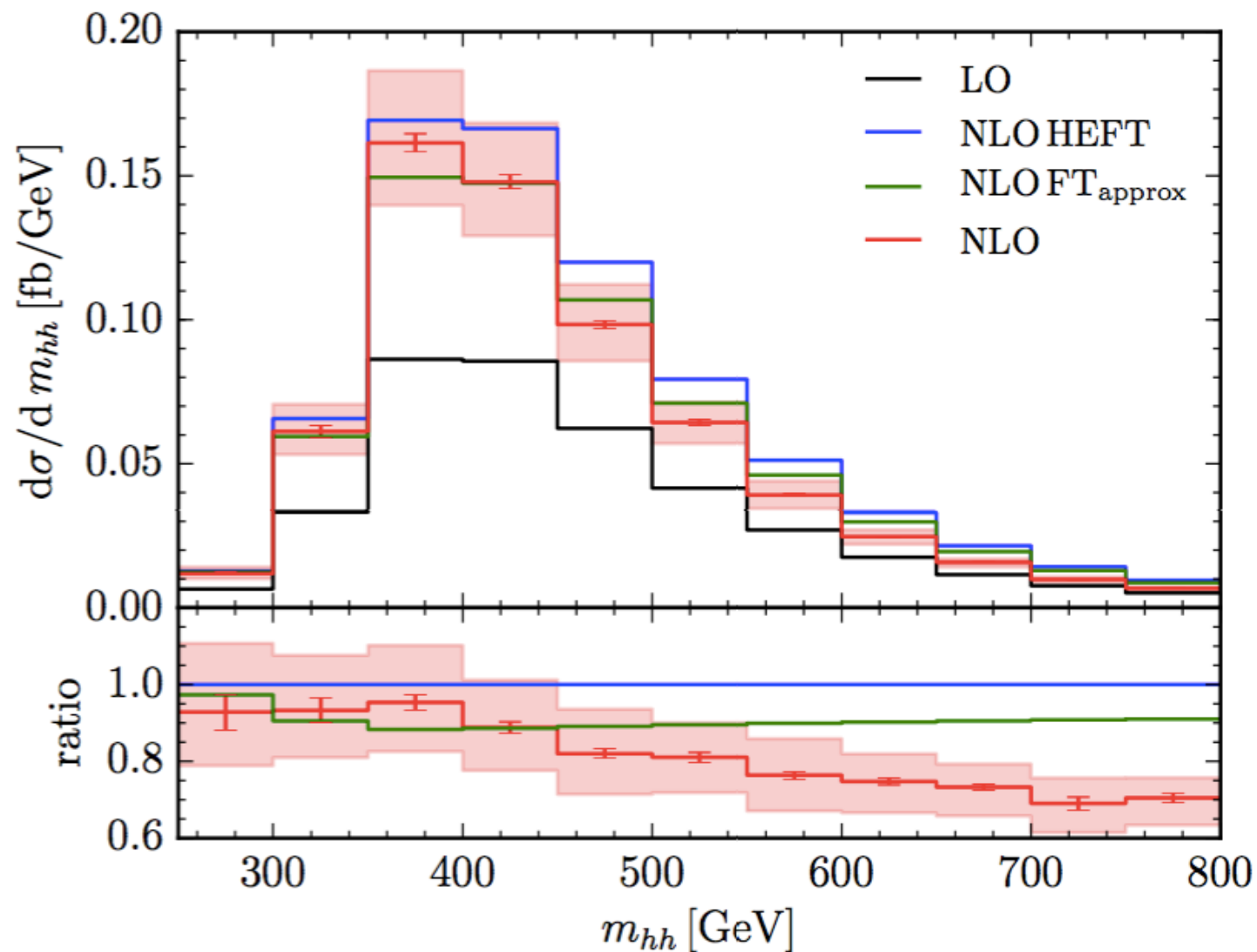


$$p_{\perp} \gg m_t, M_h$$

Lindert, Kudashkin, Melnikov, Wever 2018  
 exact  $m_t$  dependence: S.P. Jones, Kerner, Luisoni 2018

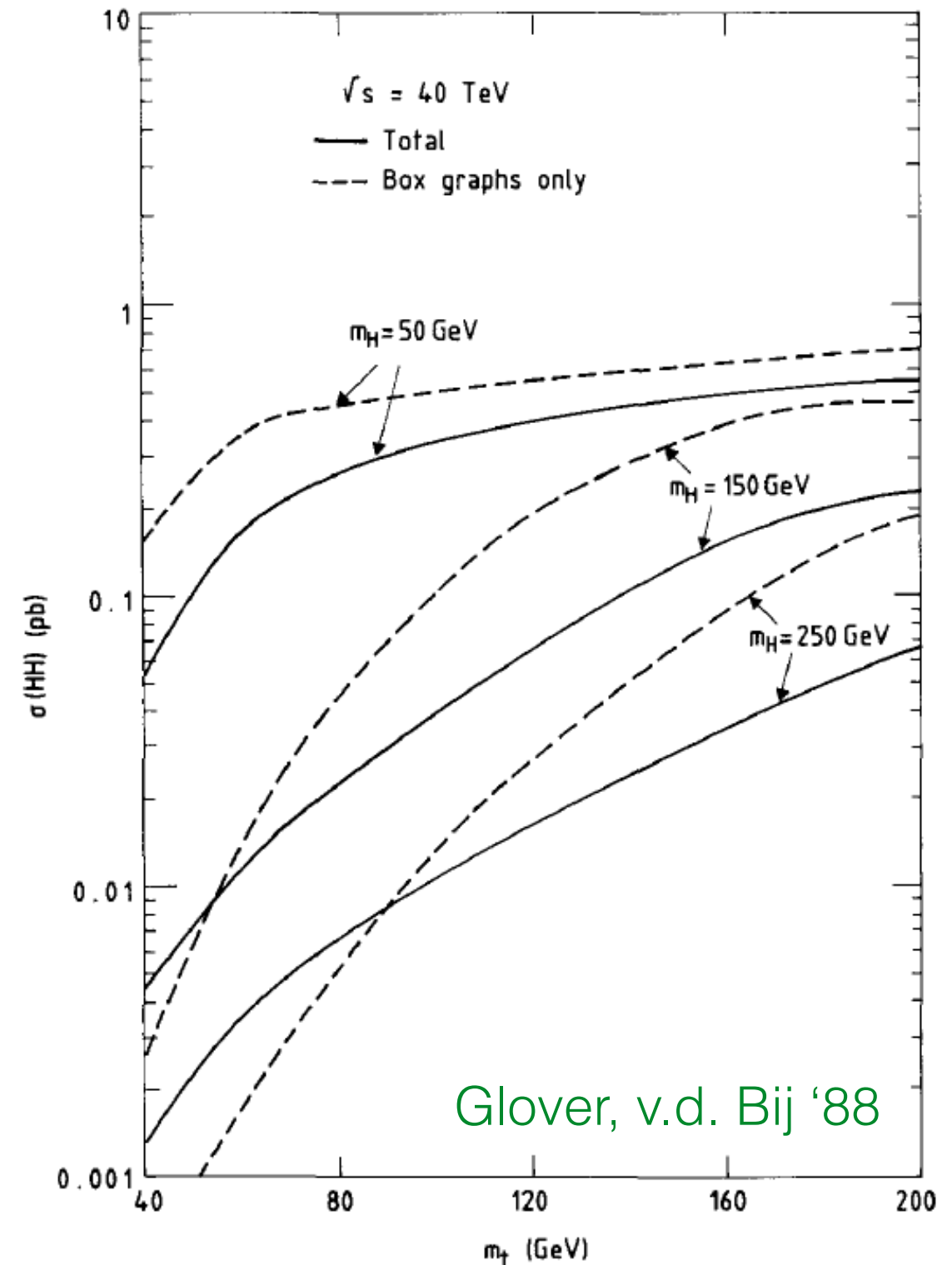
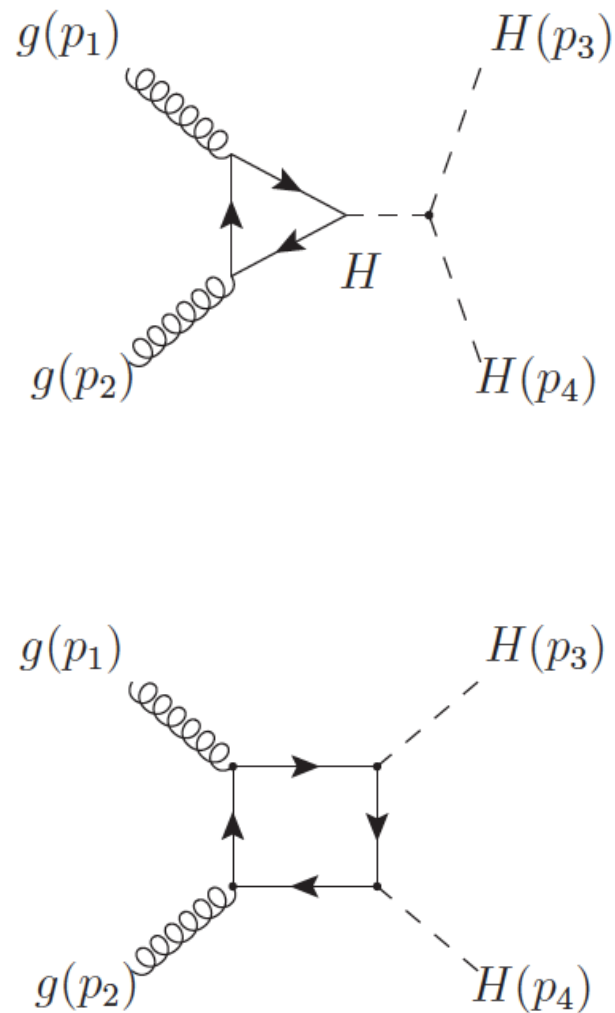


# NLO HH with top mass

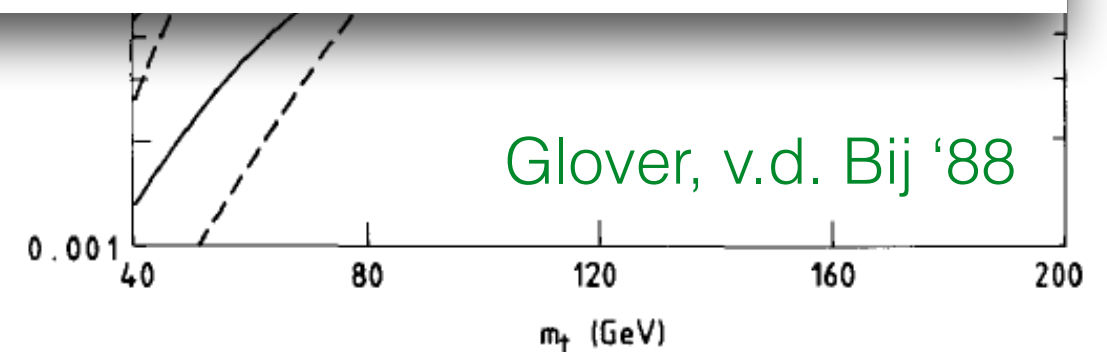
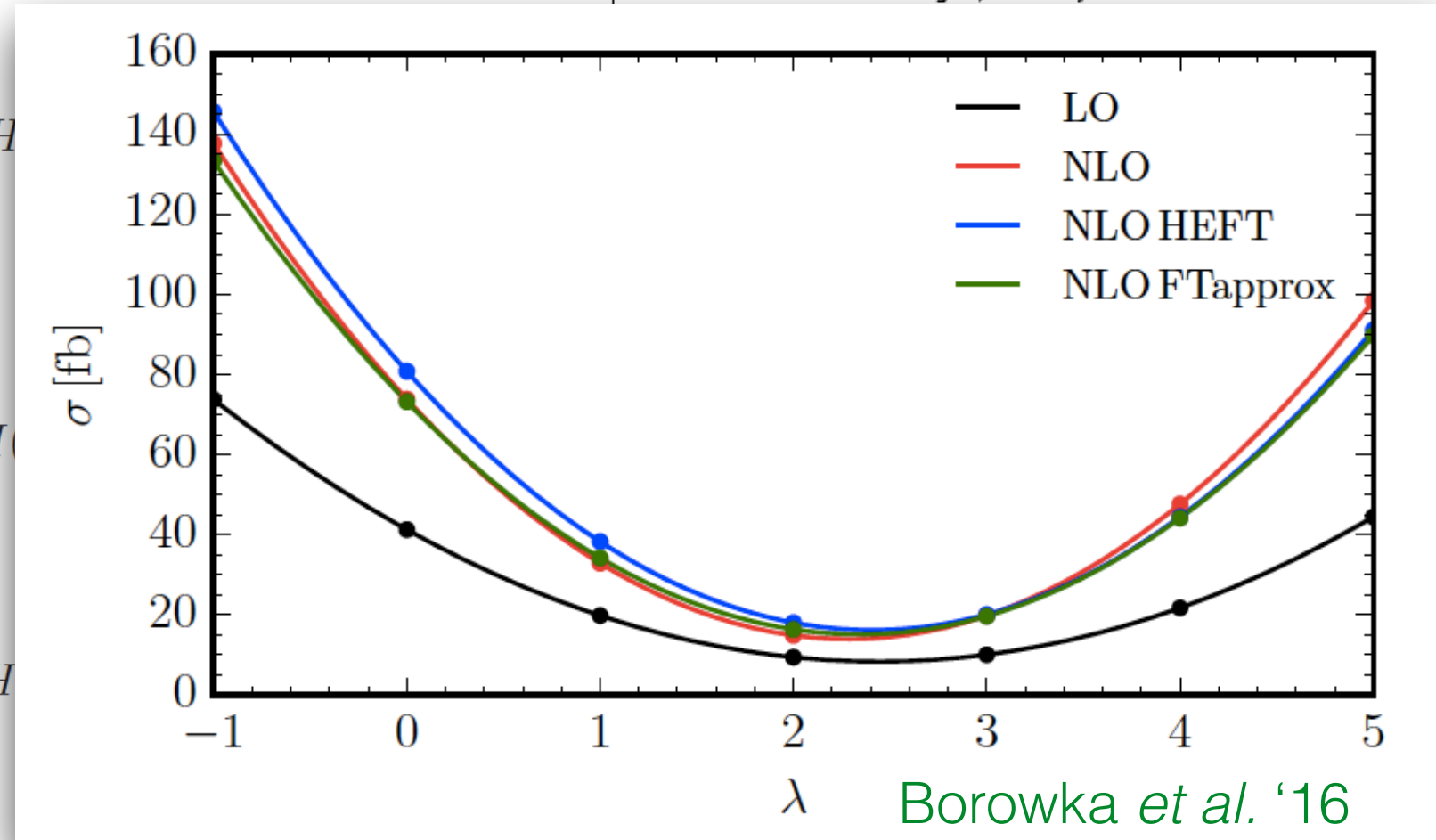
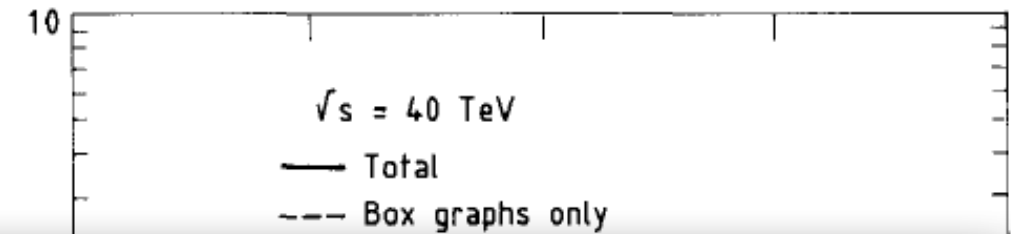
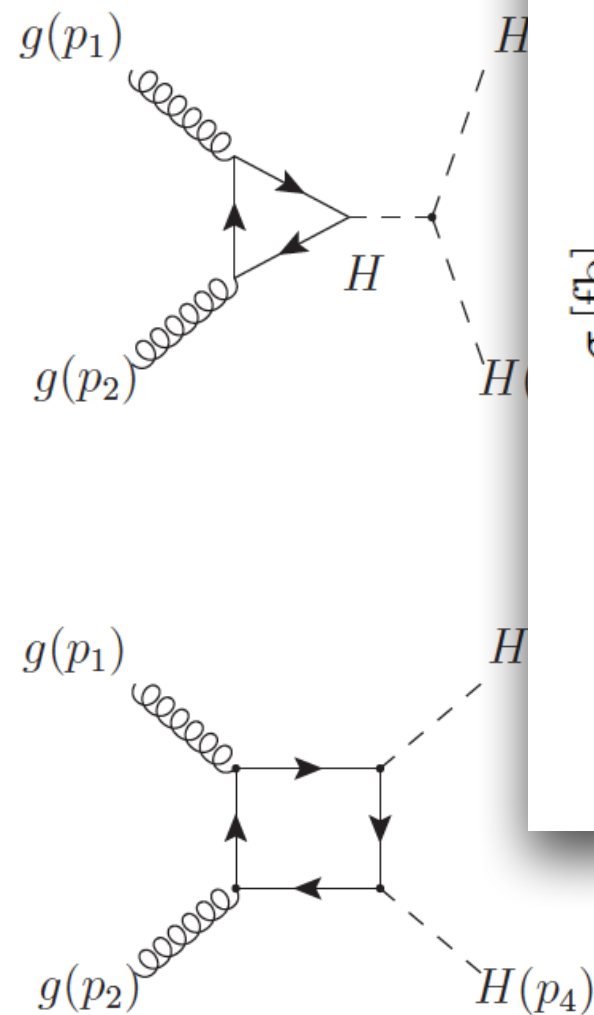


Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke '16  
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18

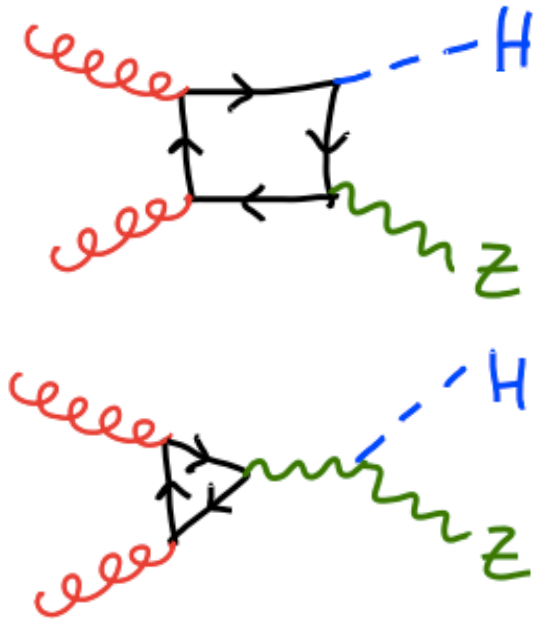
# Box-triangle interference



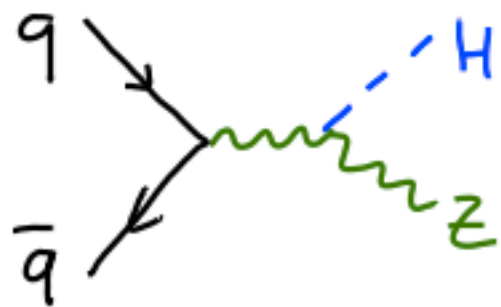
# Box-triangle interference



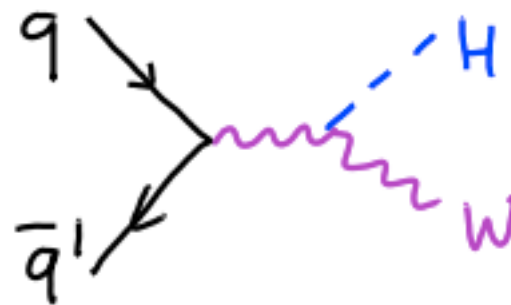
# WH/ZH production



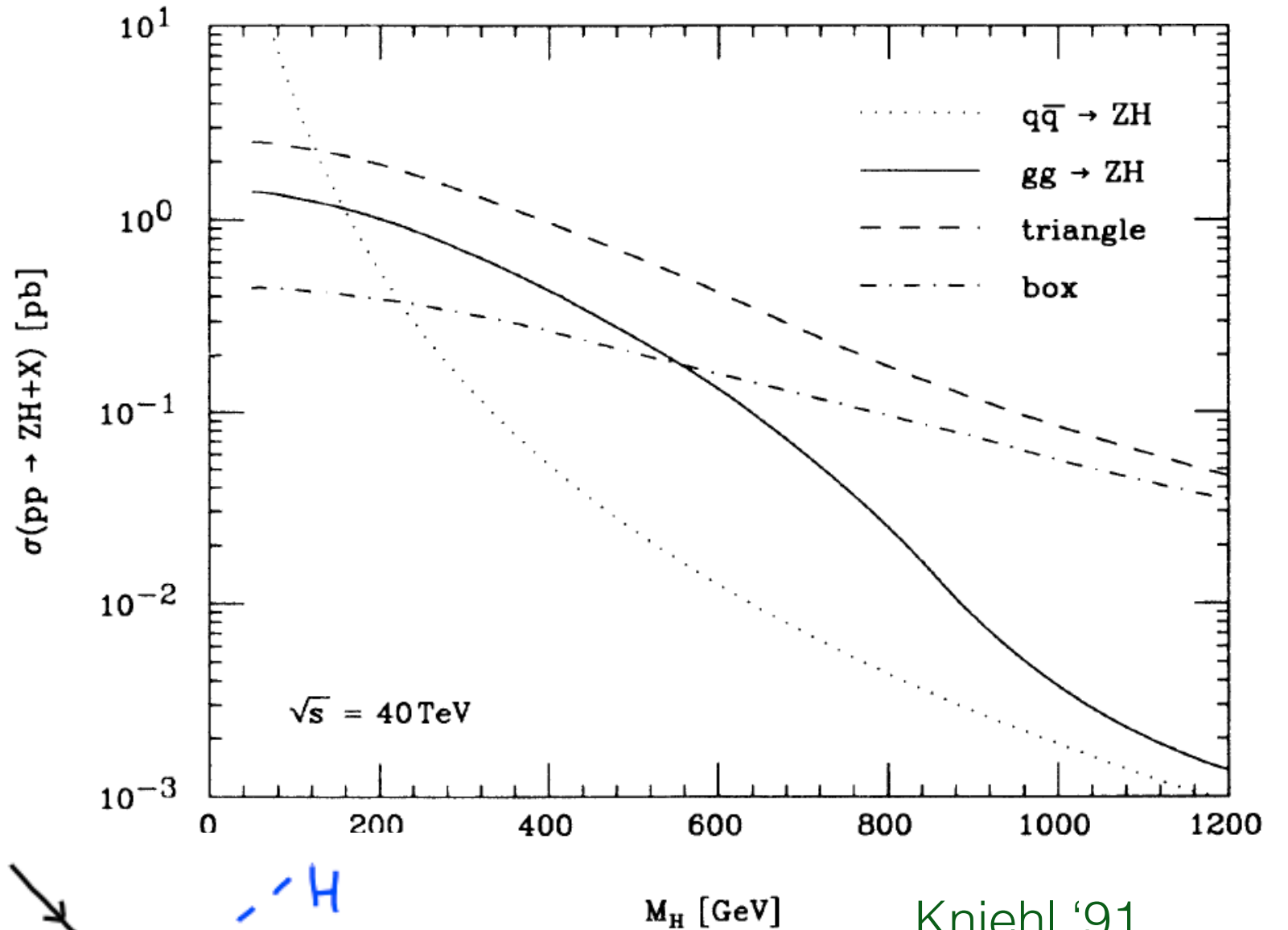
dominant:



“=”



“Drell-Yan-like”



$M_H$  [GeV]

Kniehl '91

# WH/ZH production

Consider ratio:

$$\frac{\sigma_{ZH}}{\sigma_{WH}}$$

“Drell-Yan-like”: NNLO

Caola, Luisoni, Melnikov, Röntsch 2017

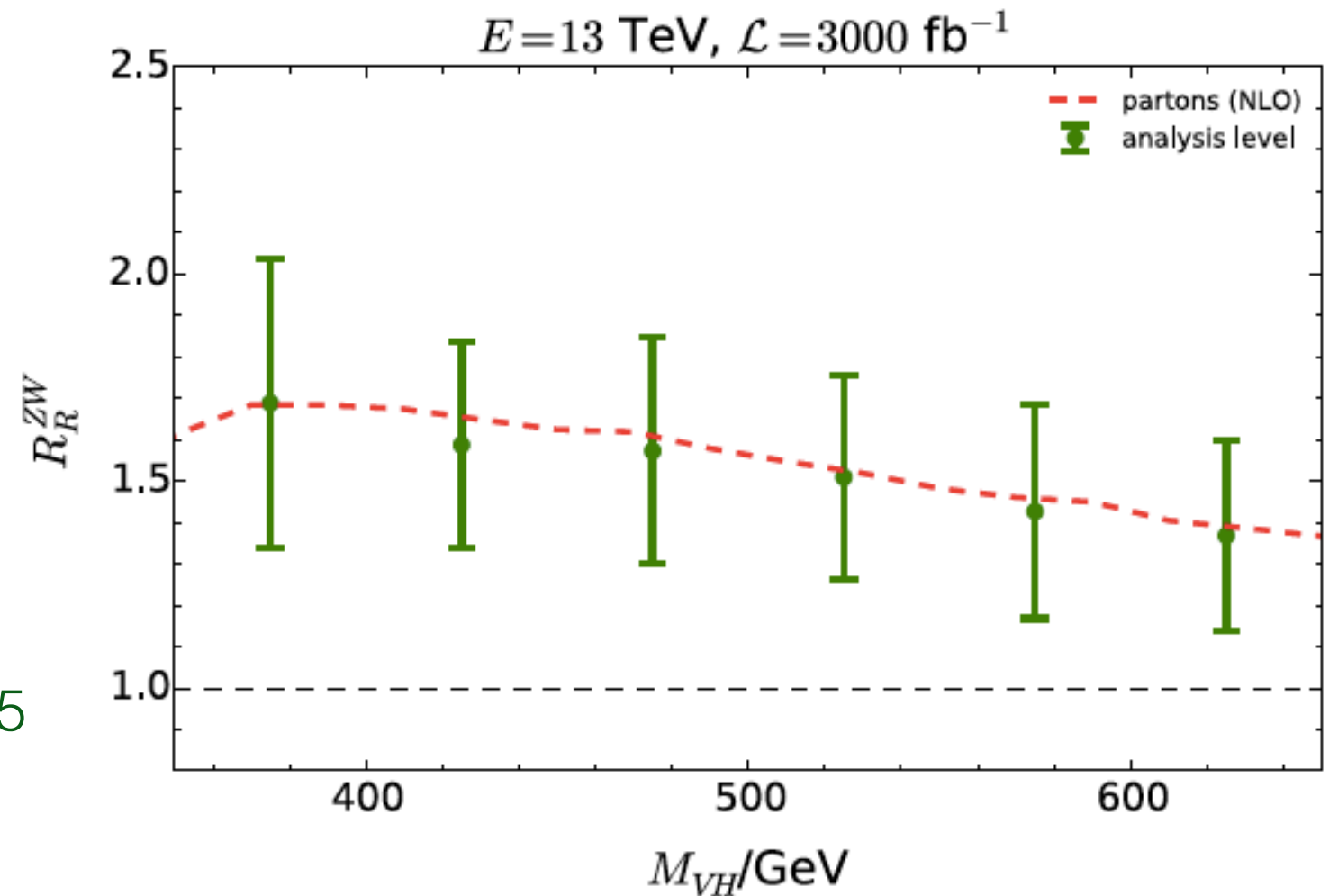
Ferrera, Grazzini, Tramontano 2011, 2015

$gg \rightarrow ZH$  NLO

heavy top

Altenkamp, Dittmaier, RH, Rzehak, Zirke 2013

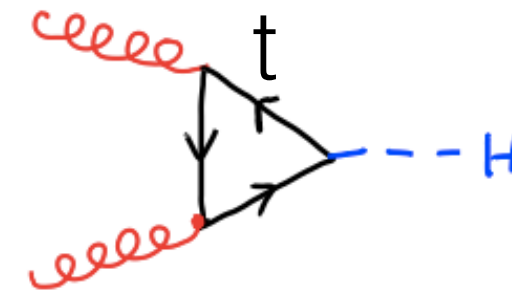
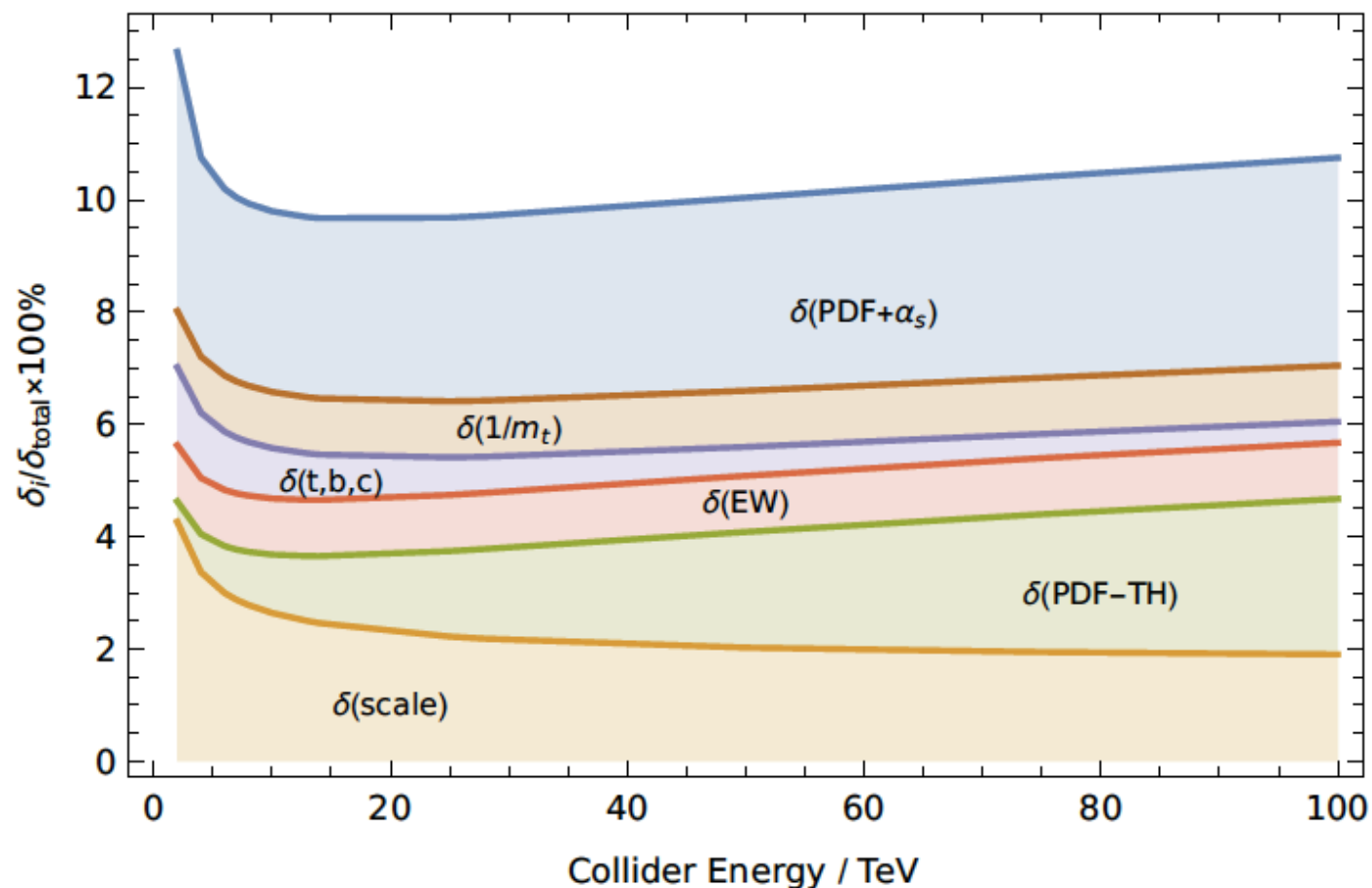
Hasselhuhn, Luthe, Steinhauser 2016



RH, Klappert, Pandini, Papaefstathiou 2018

# Total cross section

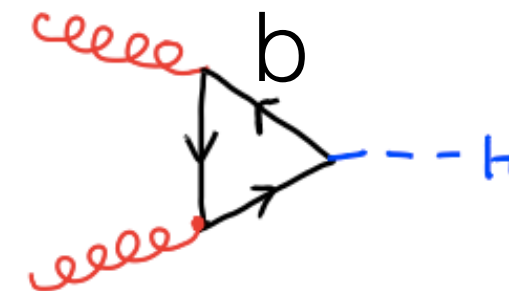
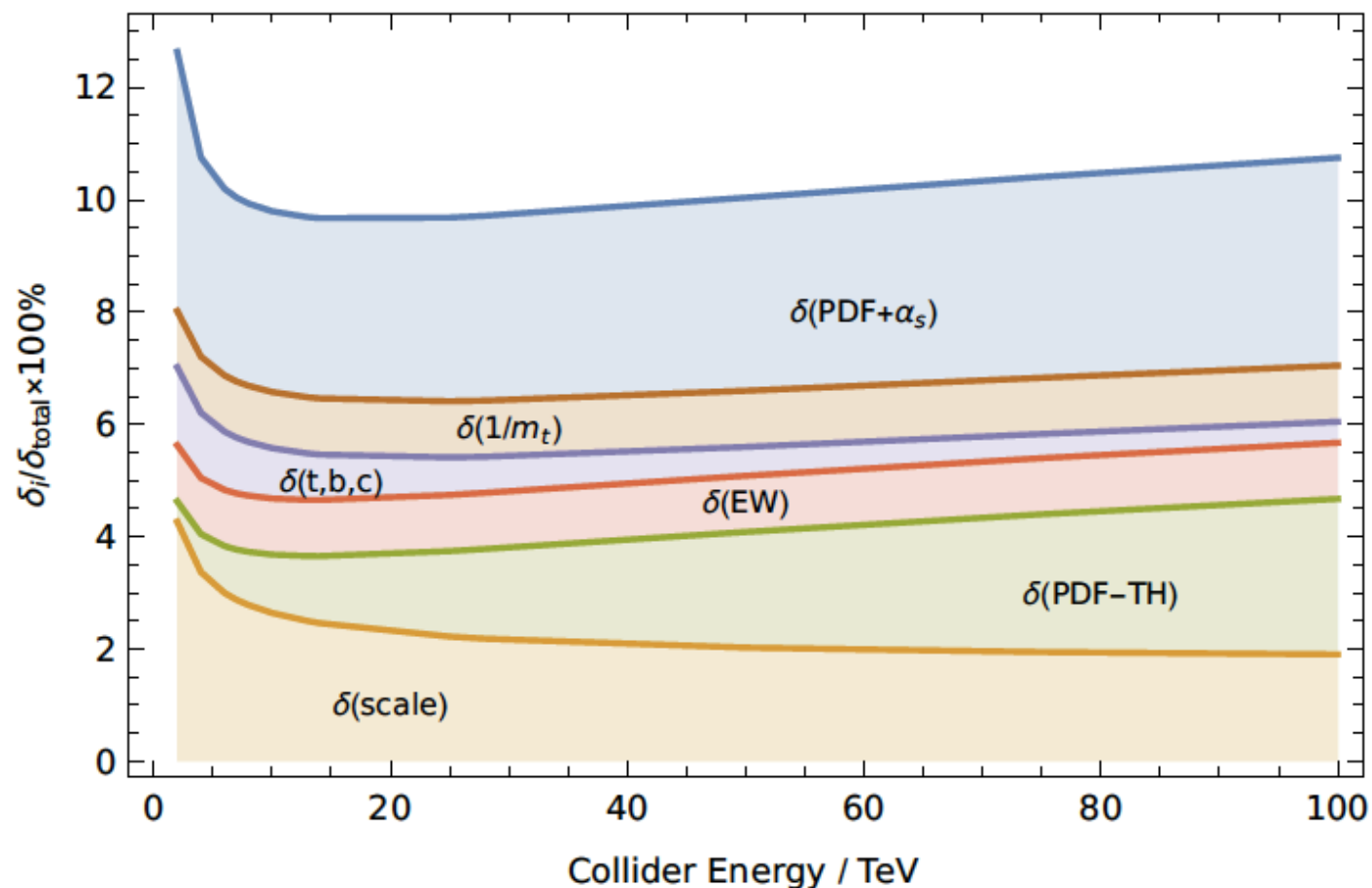
$\sqrt{s}$	$\sigma$	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
13 TeV	48.61 pb	$+2.08\text{pb}$ $-3.15\text{pb}$ $\left( \begin{array}{l} +4.27\% \\ -6.49\% \end{array} \right)$	$\pm 0.89\text{ pb}$ ( $\pm 1.85\%$ )	$+1.24\text{pb}$ ( $+2.59\%$ ) $-1.26\text{pb}$ ( $-2.62\%$ )
14 TeV	54.72 pb	$+2.35\text{pb}$ $-3.54\text{pb}$ $\left( \begin{array}{l} +4.28\% \\ -6.46\% \end{array} \right)$	$\pm 1.00\text{ pb}$ ( $\pm 1.85\%$ )	$+1.40\text{pb}$ ( $+2.60\%$ ) $-1.41\text{pb}$ ( $-2.62\%$ )
27 TeV	146.65 pb	$+6.65\text{pb}$ $-9.44\text{pb}$ $\left( \begin{array}{l} +4.53\% \\ -6.43\% \end{array} \right)$	$\pm 2.81\text{ pb}$ ( $\pm 1.95\%$ )	$+3.88\text{pb}$ ( $+2.69\%$ ) $-3.82\text{pb}$ ( $-2.64\%$ )





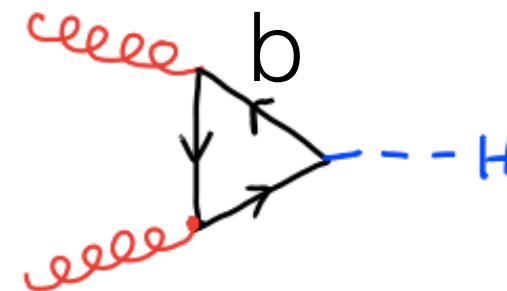
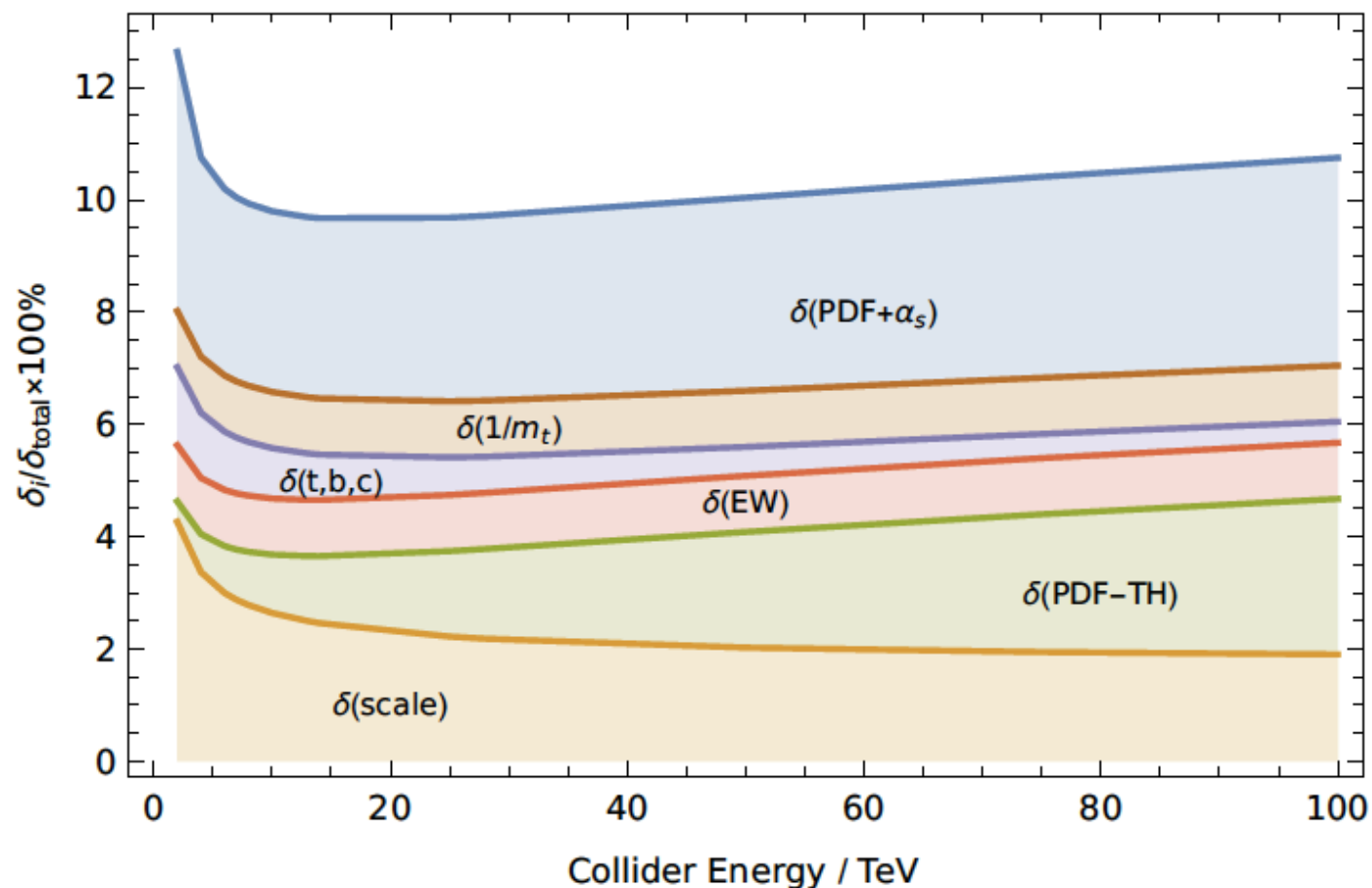
# Total cross section

$\sqrt{s}$	$\sigma$	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
13 TeV	48.61 pb	$+2.08\text{pb}$ $-3.15\text{pb}$ $\left( \begin{array}{l} +4.27\% \\ -6.49\% \end{array} \right)$	$\pm 0.89\text{ pb}$ ( $\pm 1.85\%$ )	$+1.24\text{pb}$ $-1.26\text{pb}$ $\left( \begin{array}{l} +2.59\% \\ -2.62\% \end{array} \right)$
14 TeV	54.72 pb	$+2.35\text{pb}$ $-3.54\text{pb}$ $\left( \begin{array}{l} +4.28\% \\ -6.46\% \end{array} \right)$	$\pm 1.00\text{ pb}$ ( $\pm 1.85\%$ )	$+1.40\text{pb}$ $-1.41\text{pb}$ $\left( \begin{array}{l} +2.60\% \\ -2.62\% \end{array} \right)$
27 TeV	146.65 pb	$+6.65\text{pb}$ $-9.44\text{pb}$ $\left( \begin{array}{l} +4.53\% \\ -6.43\% \end{array} \right)$	$\pm 2.81\text{ pb}$ ( $\pm 1.95\%$ )	$+3.88\text{pb}$ $-3.82\text{pb}$ $\left( \begin{array}{l} +2.69\% \\ -2.64\% \end{array} \right)$



# Total cross section

$\sqrt{s}$	$\sigma$	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
13 TeV	48.61 pb	$+2.08\text{pb}$ $\left( \begin{array}{l} +4.27\% \\ -6.49\% \end{array} \right)$ $-3.15\text{pb}$	$\pm 0.89\text{ pb}$ ( $\pm 1.85\%$ )	$+1.24\text{pb}$ $\left( \begin{array}{l} +2.59\% \\ -2.62\% \end{array} \right)$ $-1.26\text{pb}$
14 TeV	54.72 pb	$+2.35\text{pb}$ $\left( \begin{array}{l} +4.28\% \\ -6.46\% \end{array} \right)$ $-3.54\text{pb}$	$\pm 1.00\text{ pb}$ ( $\pm 1.85\%$ )	$+1.40\text{pb}$ $\left( \begin{array}{l} +2.60\% \\ -2.62\% \end{array} \right)$ $-1.41\text{pb}$
27 TeV	146.65 pb	$+6.65\text{pb}$ $\left( \begin{array}{l} +4.53\% \\ -6.43\% \end{array} \right)$ $-9.44\text{pb}$	$\pm 2.81\text{ pb}$ ( $\pm 1.95\%$ )	$+3.88\text{pb}$ $\left( \begin{array}{l} +2.69\% \\ -2.64\% \end{array} \right)$ $-3.82\text{pb}$

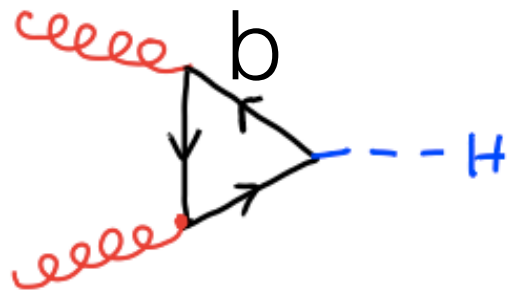


No “heavy-bottom limit”  
Only NLO result!

LO: -10%

NLO: -1%

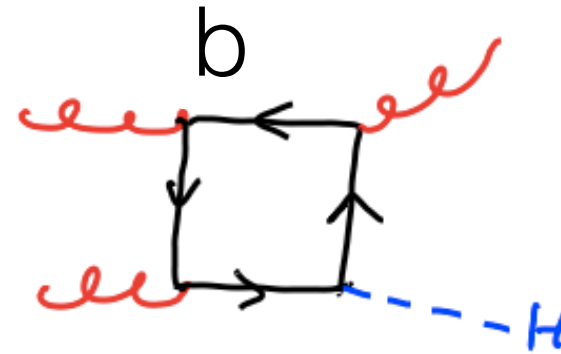
# Bottom quark effects



No “heavy-bottom limit”  
Only NLO result!

LO: -10%

NLO: -1%



Interference with top:

$$m_b, m_t, M_H, p_T$$

renormalization scale?  
resummation scale?

resummation of large logs [Melnikov, Penin 2016](#)

NLO  $p_t$  top-bottom interference [Lindert, Melnikov, Tancredi, Wever 2017](#)

→Napoletano

# What made all of this possible...

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Integration-by-Parts

Chetyrkin, Tkachov 1981

Laporta algorithm

Laporta 2000

Canonical basis

Henn 2013

Sector decomposition

Binoth, Heinrich 2000

NNLO subtraction

Catani, Grazzini 2007

Gehrmann-De Ridder, Gehrmann, Glover ++ 2005ff

Czakon 2010

Boughezal, Melnikov, Petriello 2012

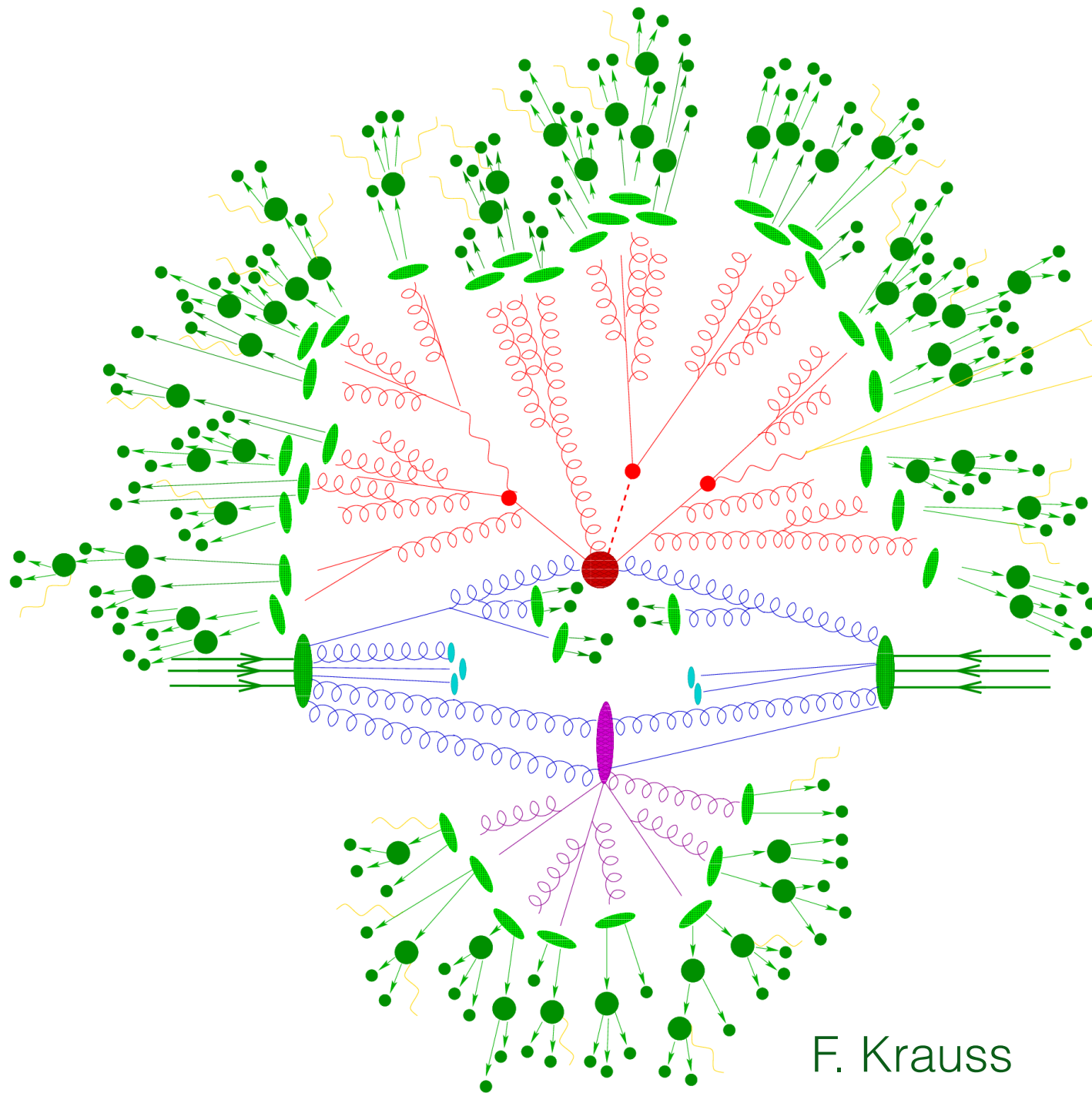
Paola, Melnikov, **Röntsch** 2017

Stuart, Tackmann, Waalewijn 2010

Boughezal, Liu, Petriello 2015

Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015

# Things I skipped...



NNLO  $\otimes$  PS

Hamilton, Nason, Re, Zanderighi 2013

Alioli, C.W. Bauer, Berggren,  
Tackmann, Walsh, Zuberi 2014

Höche, Li, Prestel 2014

$gg \rightarrow H$  with  $m_t$  effects

Hamilton, Nason, Zanderighi 2015

WH, ZH

Astill, Bizoń, Re, Zanderighi 2016, 2018

F. Krauss



# Things I skipped...

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VBF: N<sup>3</sup>LO    Dreyer, Karlberg 2018

HH: NLO  $\hat{s} \rightarrow \infty$     Davies, Mishima, Steinhauser, Wellmann 2018

towards NNLO    Davies, Herren, Mishima, Steinhauser 2018  
Grigo, Hoff, Steinhauser 2015  
De Florian, Mazzitelli 2015, 2018  
De Florian, Grazzini, Hanga, Kallweit, Lindert,  
Meierhöfer, Mazzitelli, Rathlev 2016

Approximation methods    Xu, Yang 2019  
Borowka, Gehrmann, Hulme 2018

Analytic calculations    Frellesvig, Bonciani, Del Duca, Moriello,  
Henn, Smirnov 2018  
Badger, Chicherin, Gehrmann, Heinrich, Henn,  
Peraro, Wasser, Zhang, Zola 2019  
Chaubey, Weinzierl 2019

...

... and much more!



# Things I skipped...

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Decays...

# Conclusions

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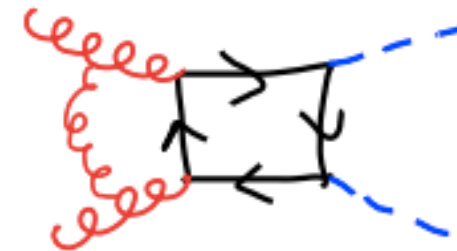
Enormous progress within the last 10-20 years

NLO: fully automated

NNLO: state of the art

First  $N^3$ LO results

Current challenge: 2-loop multileg



# Conclusions

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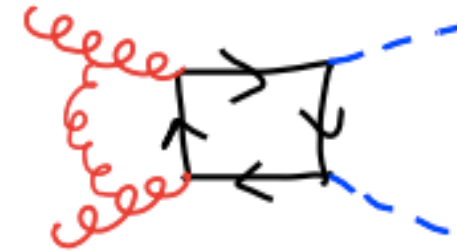
Enormous progress within the last 10-20 years

NLO: fully automated

NNLO: state of the art

First N<sup>3</sup>LO results

Current challenge: 2-loop multileg



Theory will be ready for the next step.