

Discovery of a Higgs boson

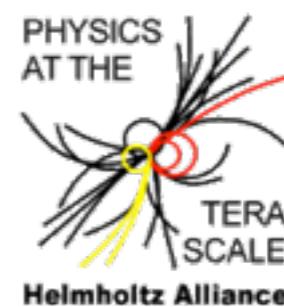
– The role of theory –

Robert Harlander
Bergische Universität Wuppertal

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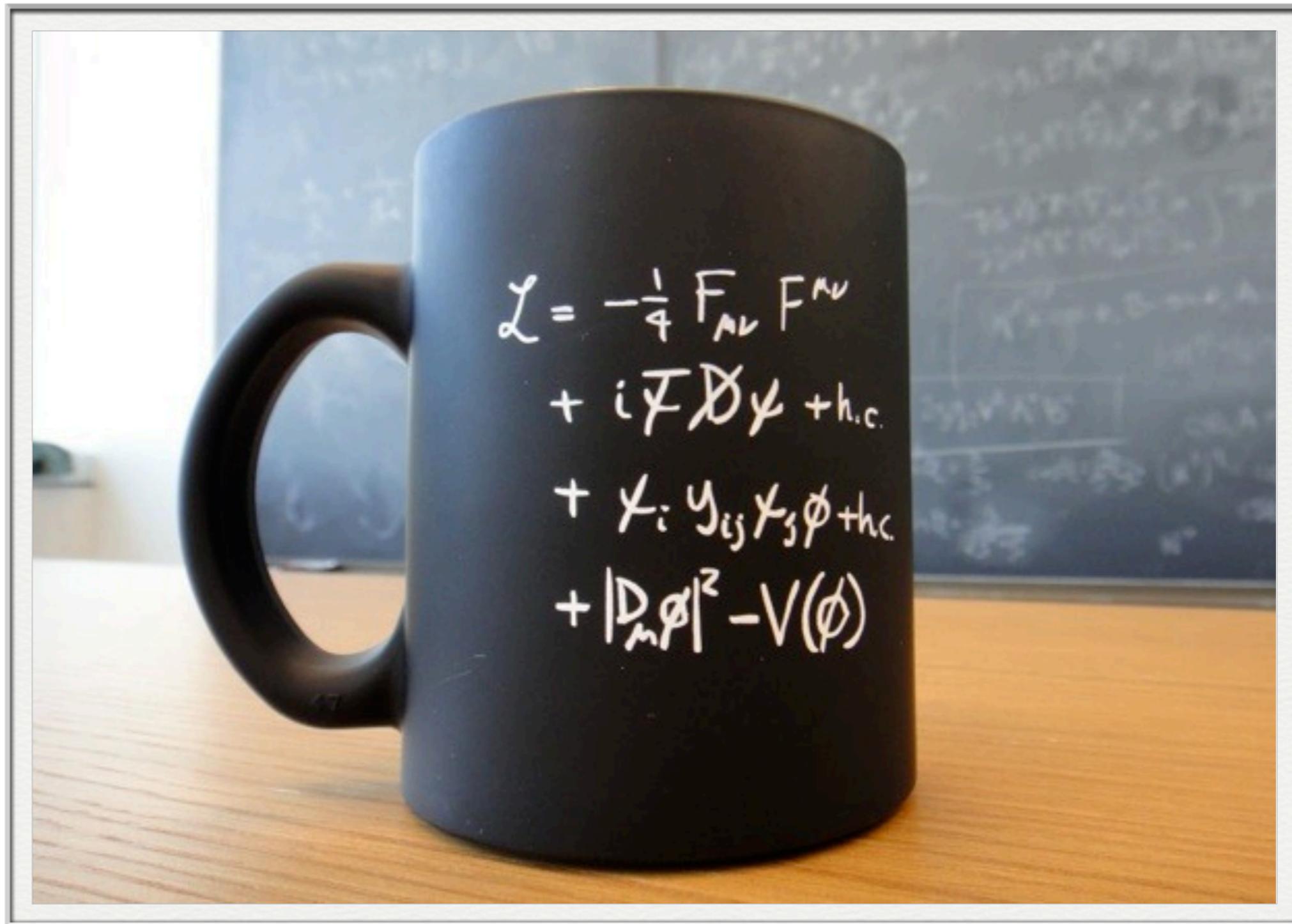


The role of theory:

- Foundations
- Calculations
- Implications

Foundations

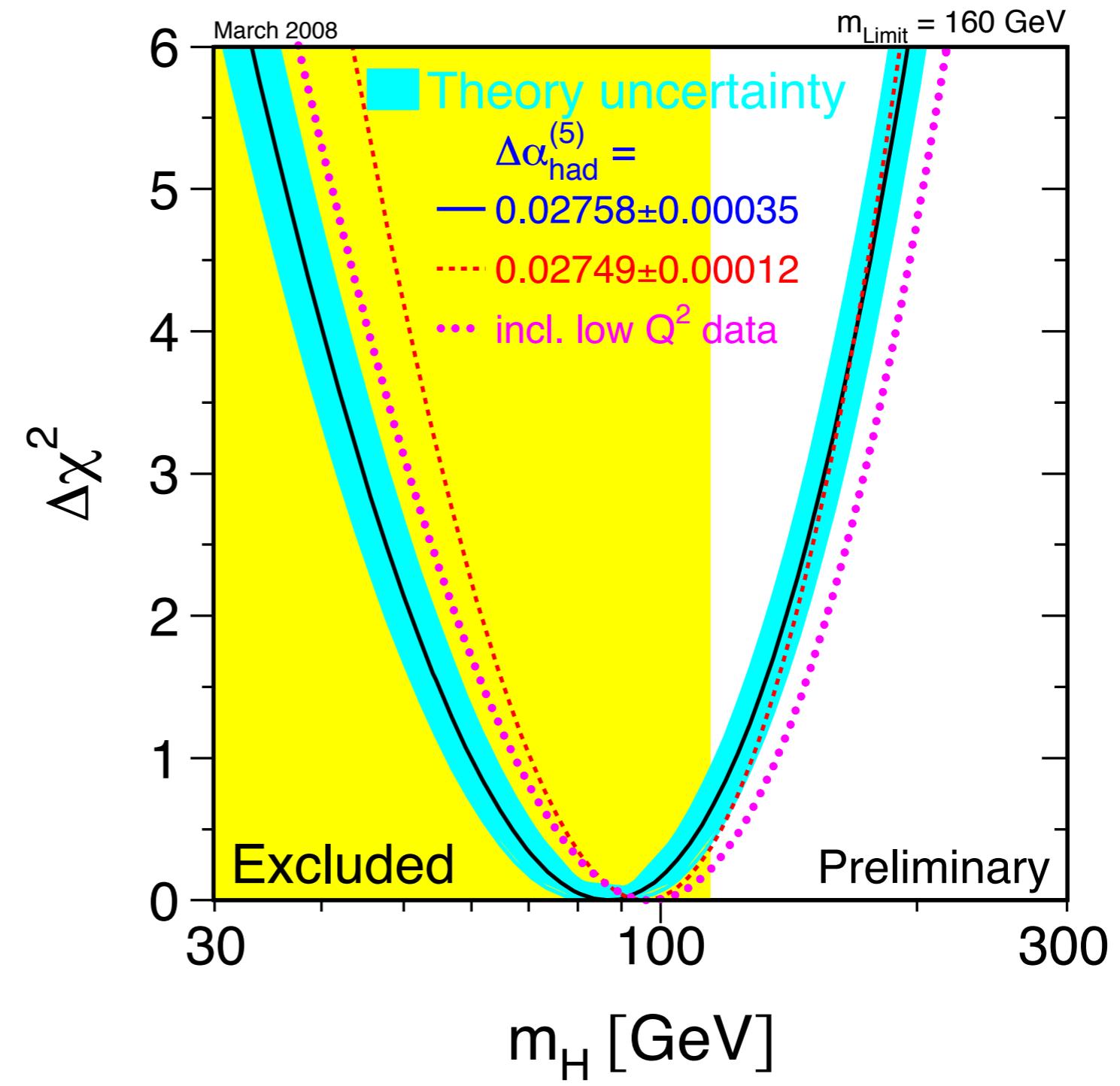
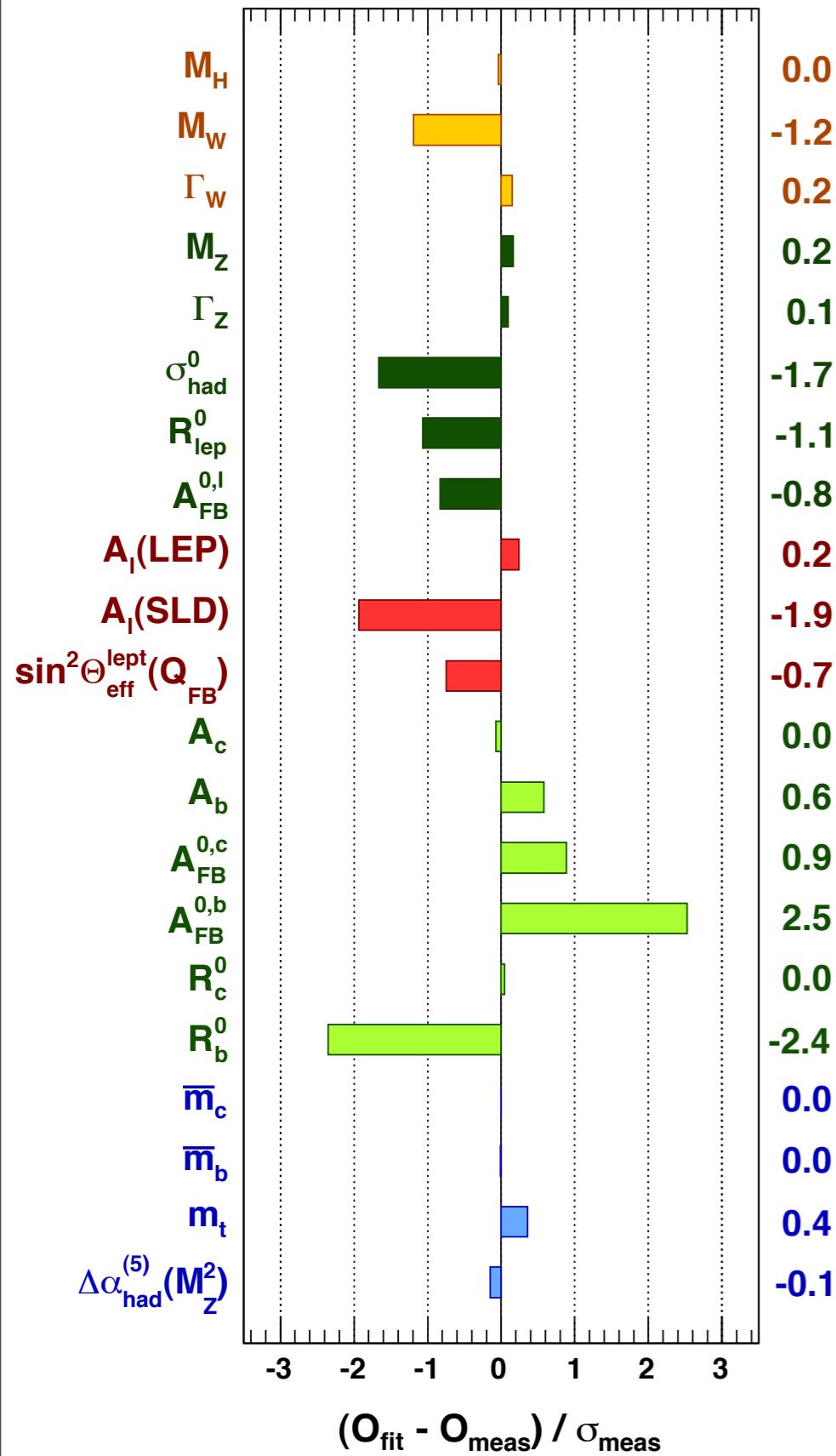
Foundations

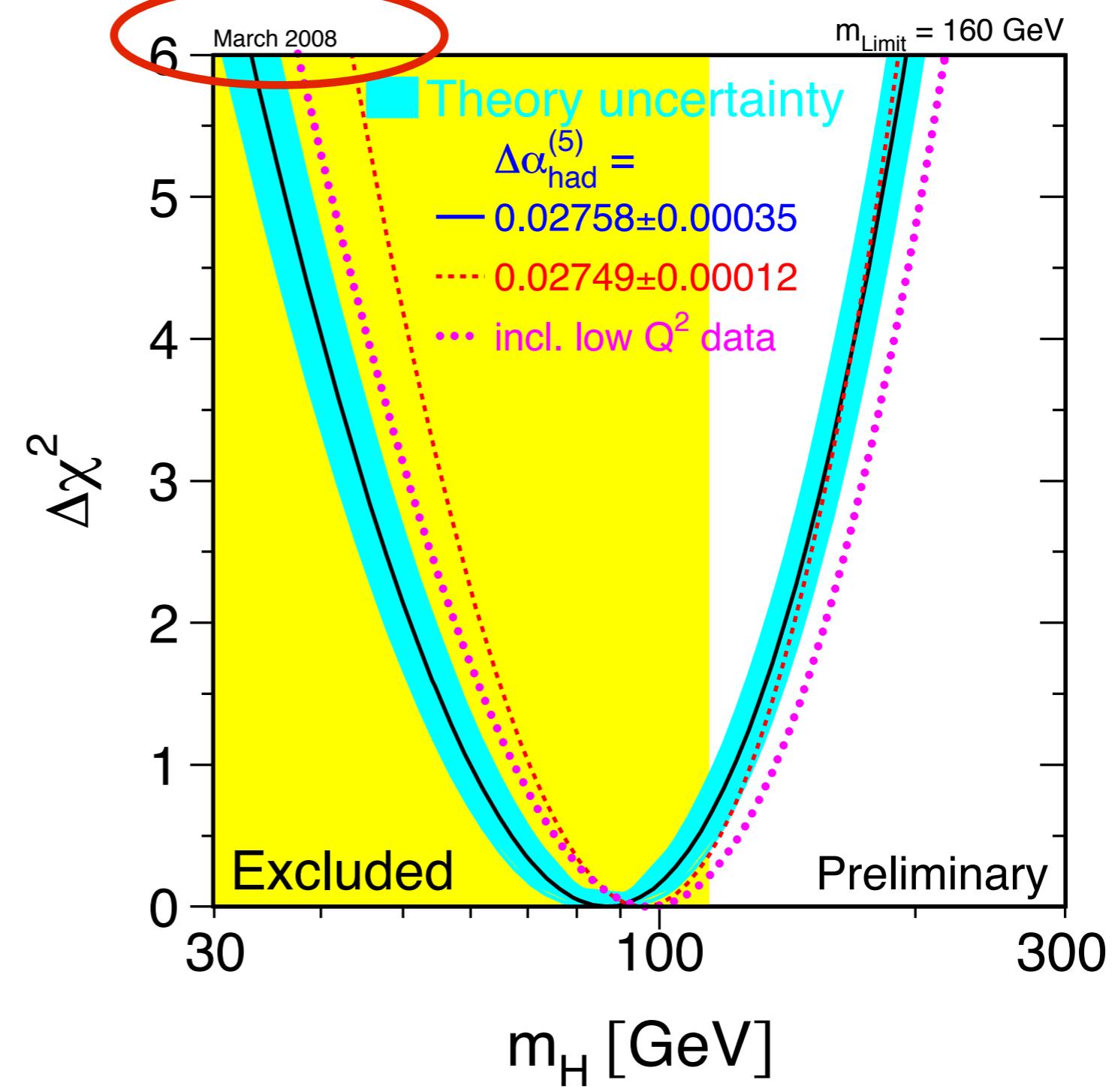
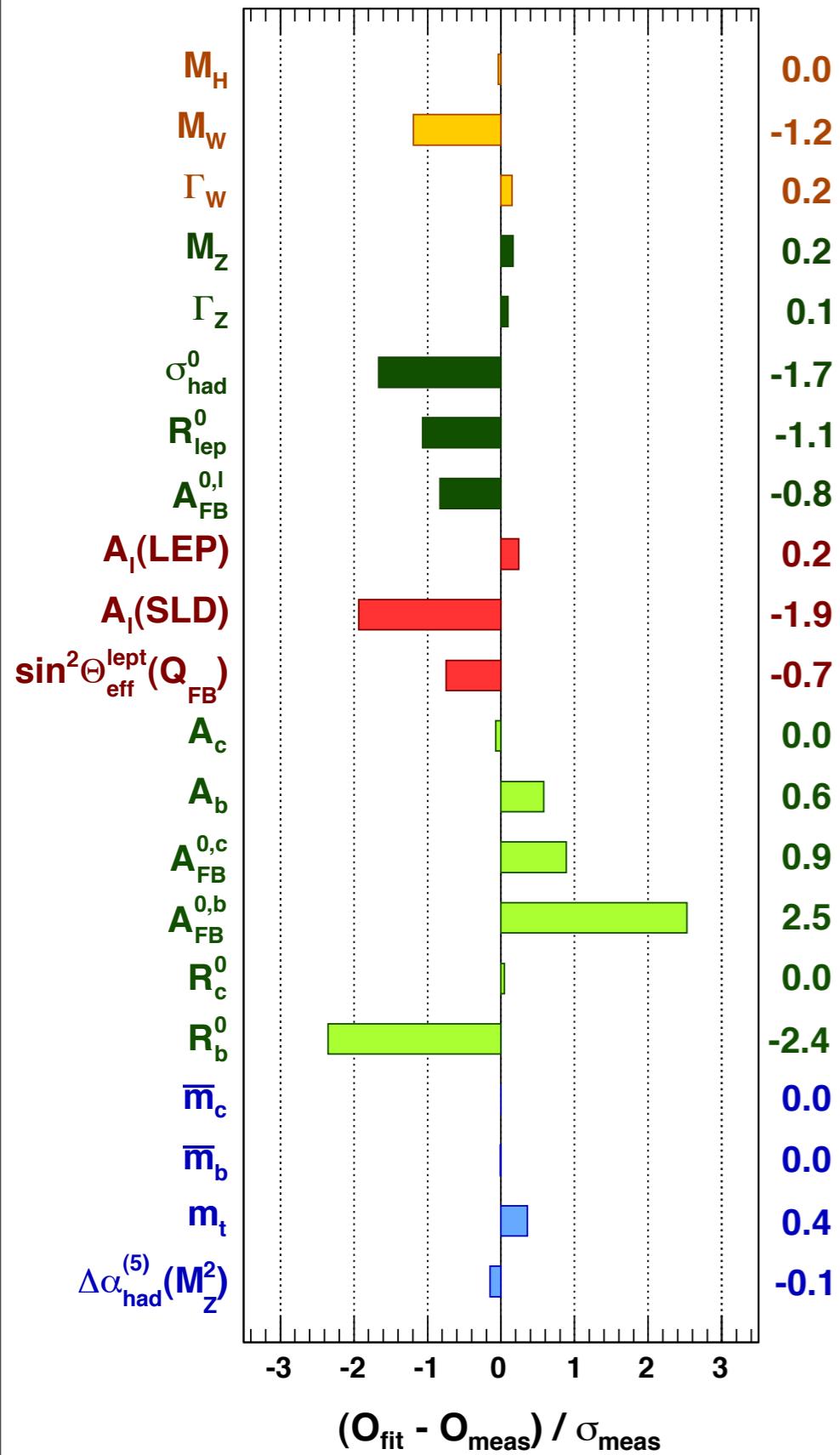


Calculations

Calculations

- The LEP era: **getting convinced**





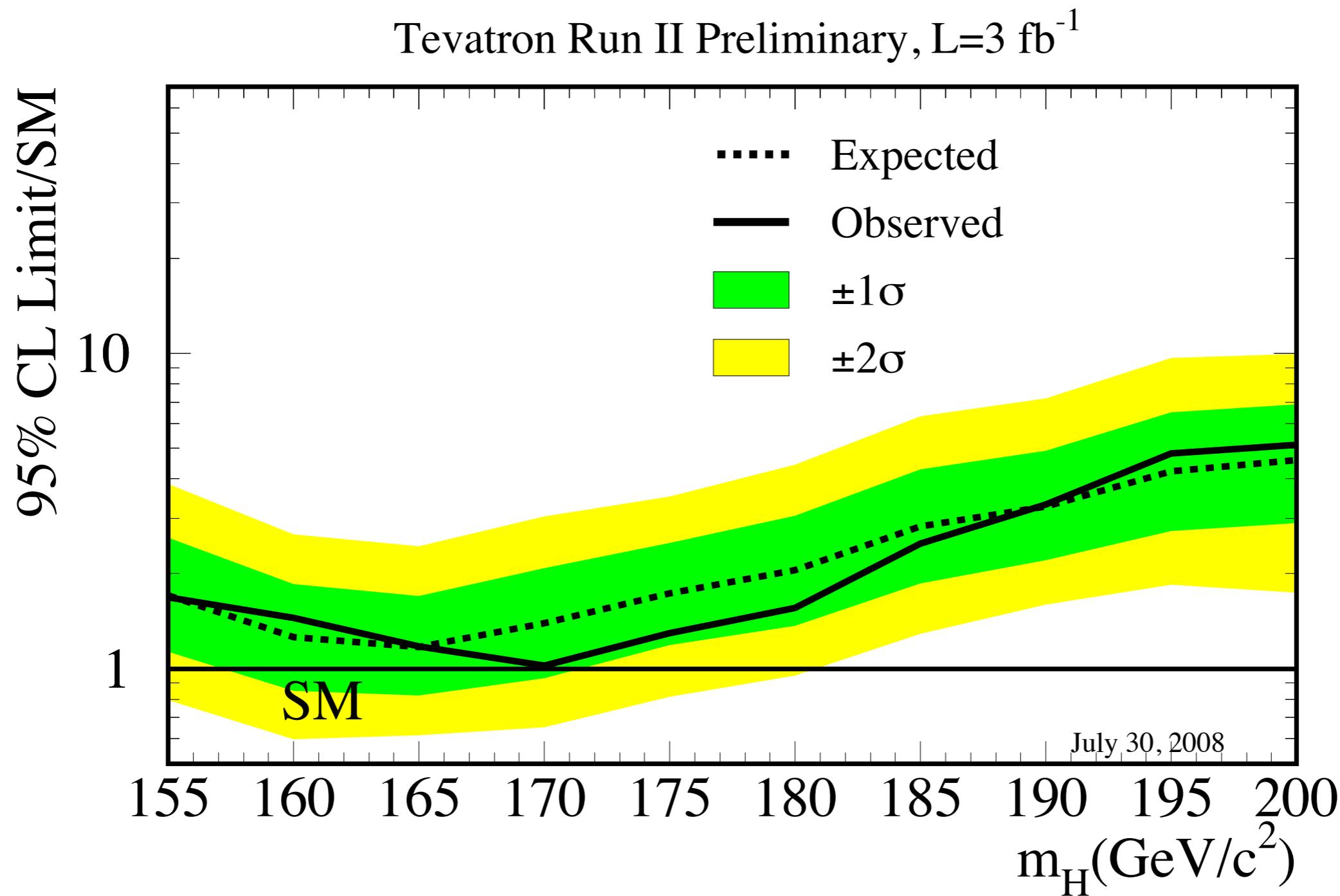
Calculations

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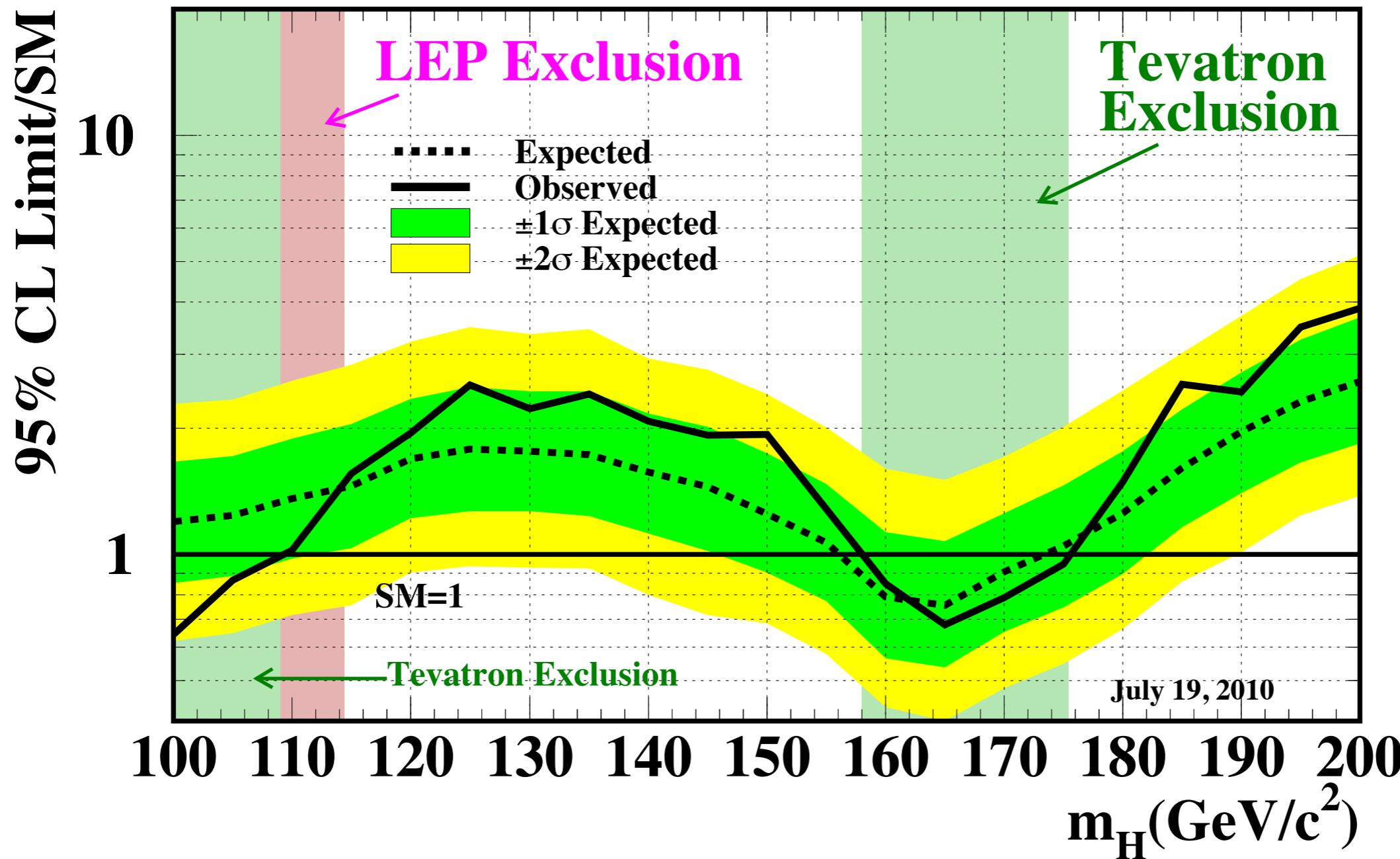
Calculations

- The LEP era: **getting convinced**
- The Tevatron era: **cornering it**

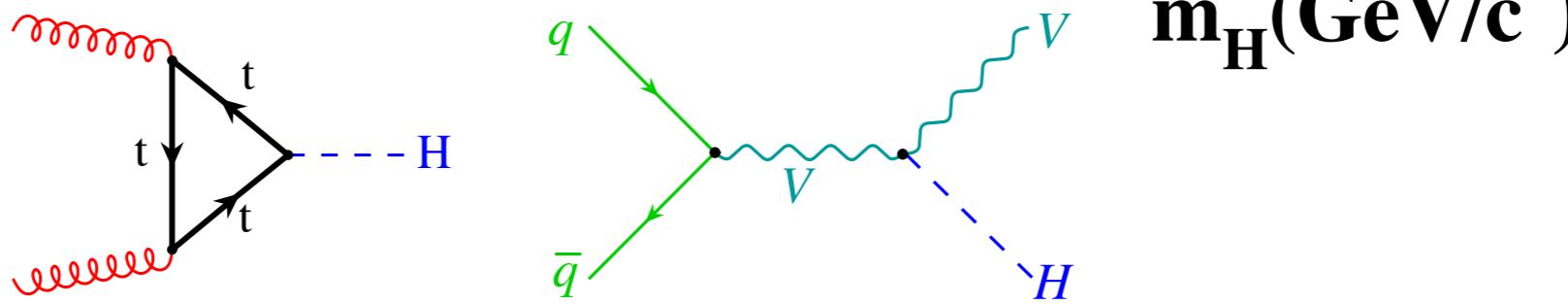
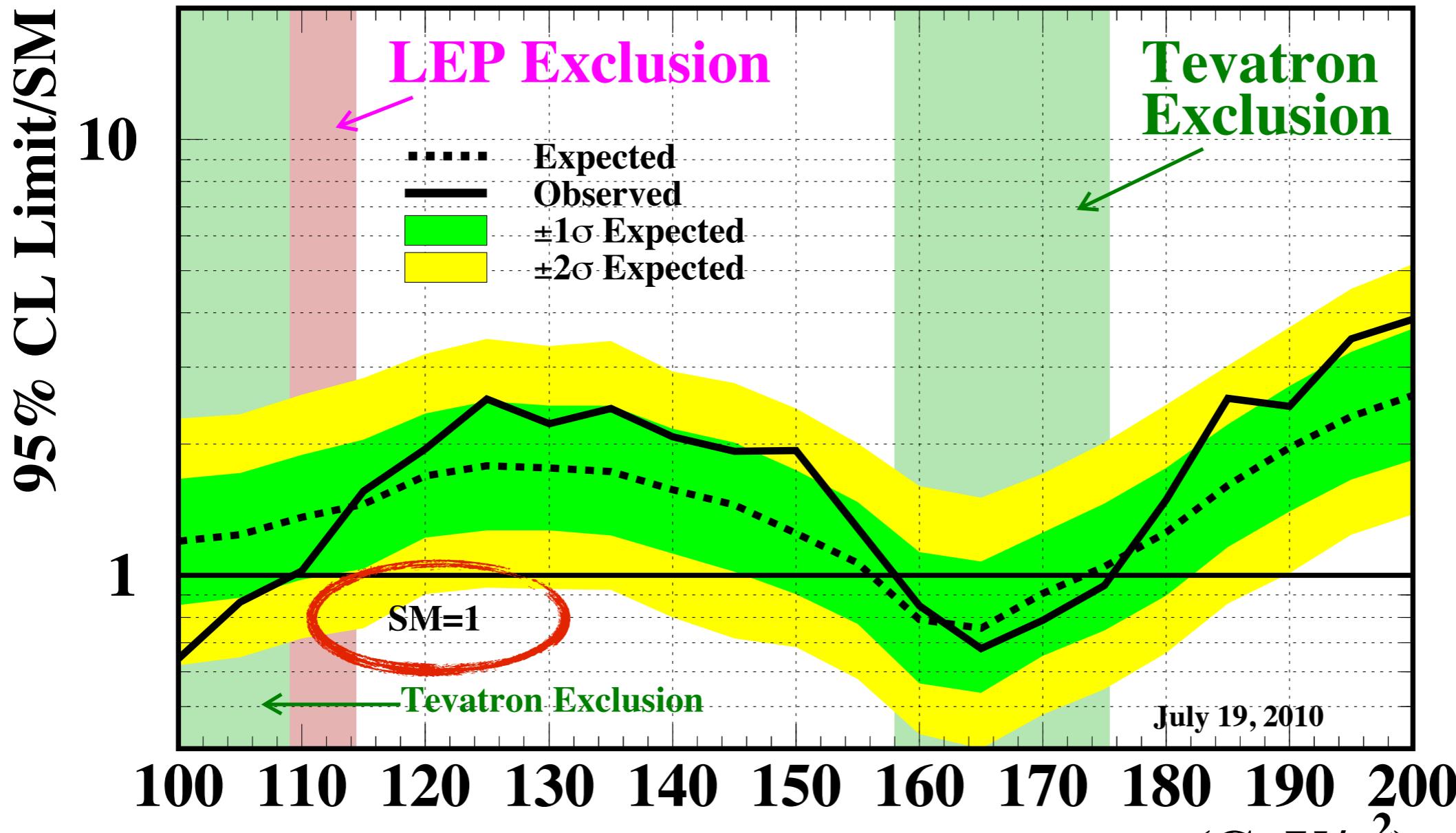
Tevatron exclusion



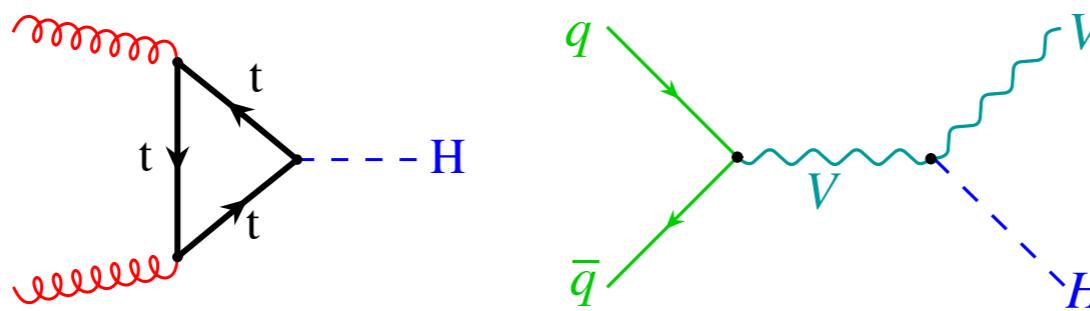
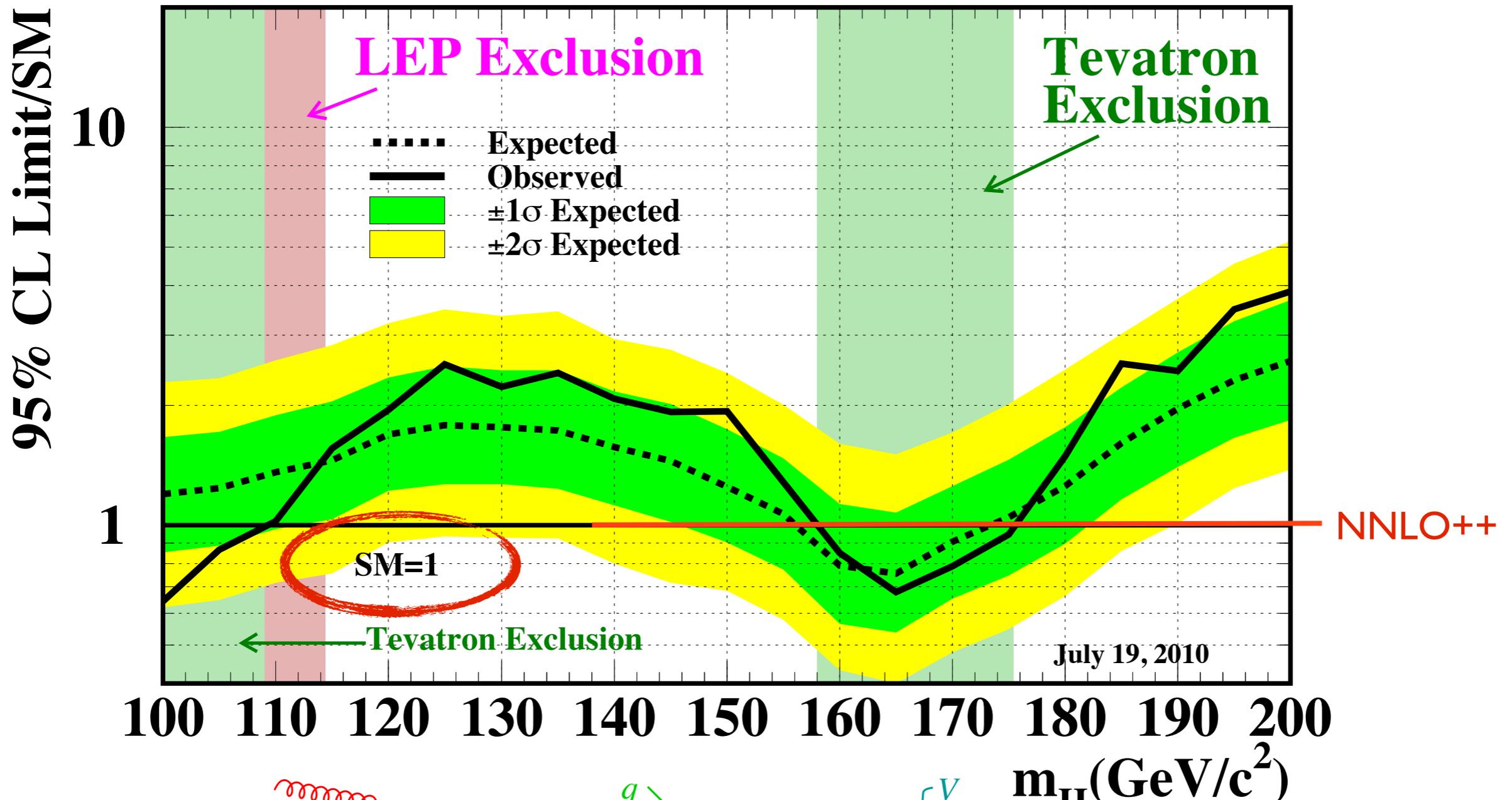
Tevatron Run II Preliminary, $\langle L \rangle = 5.9 \text{ fb}^{-1}$



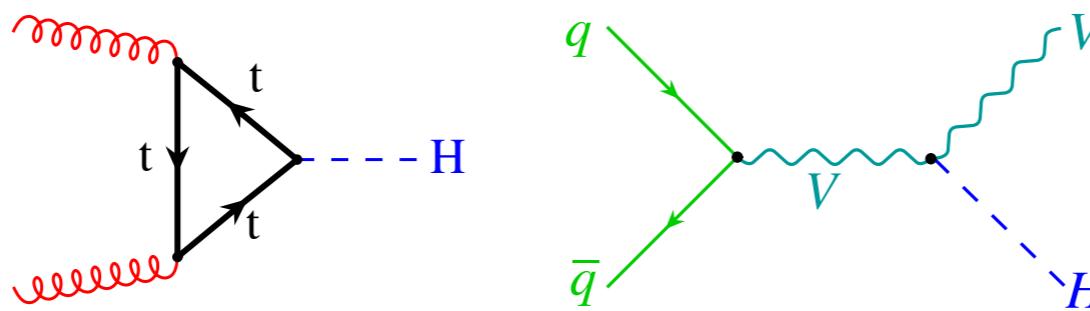
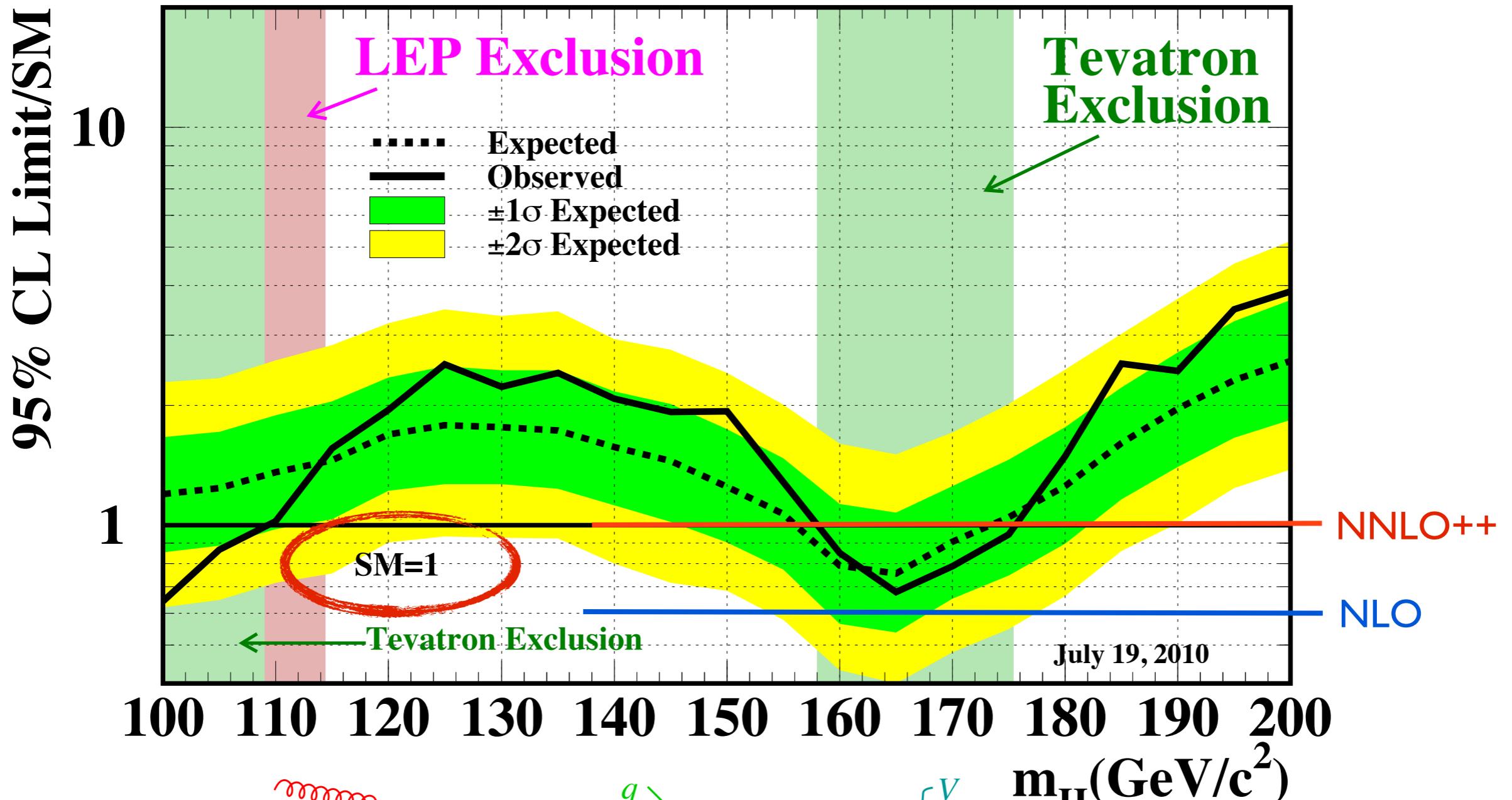
Tevatron Run II Preliminary, $\langle L \rangle = 5.9 \text{ fb}^{-1}$



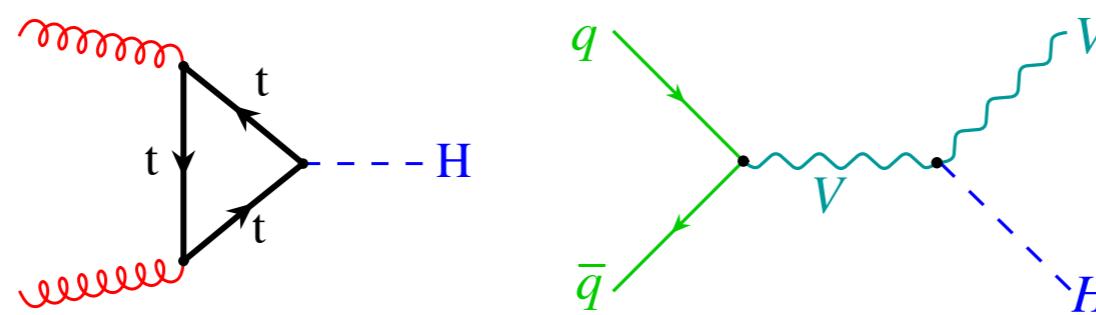
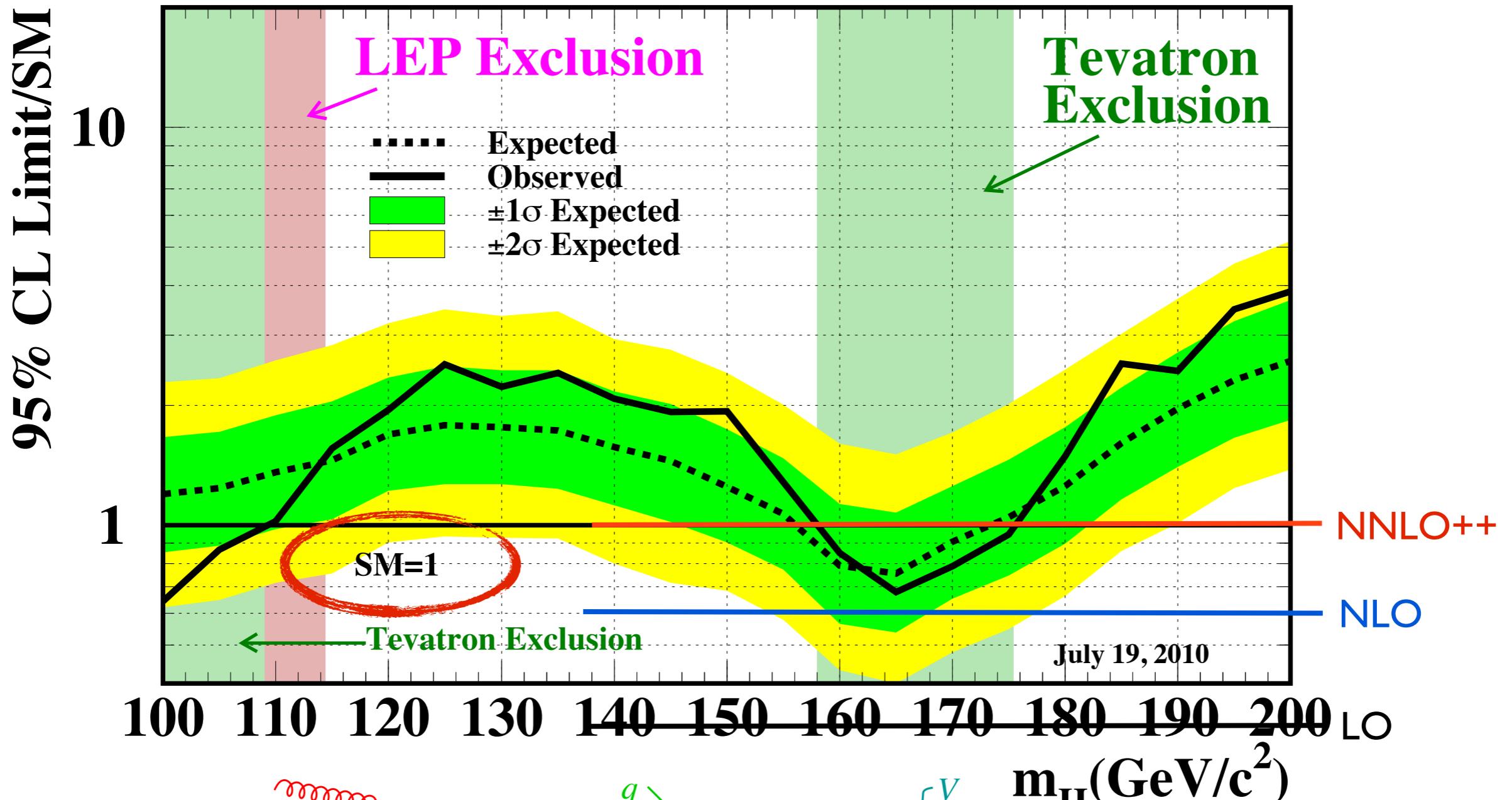
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Tevatron Run II Preliminary, $\langle L \rangle = 5.9 \text{ fb}^{-1}$



Calculations

- The LEP era: **getting convinced**
- The Tevatron era: **cornering it**

Calculations

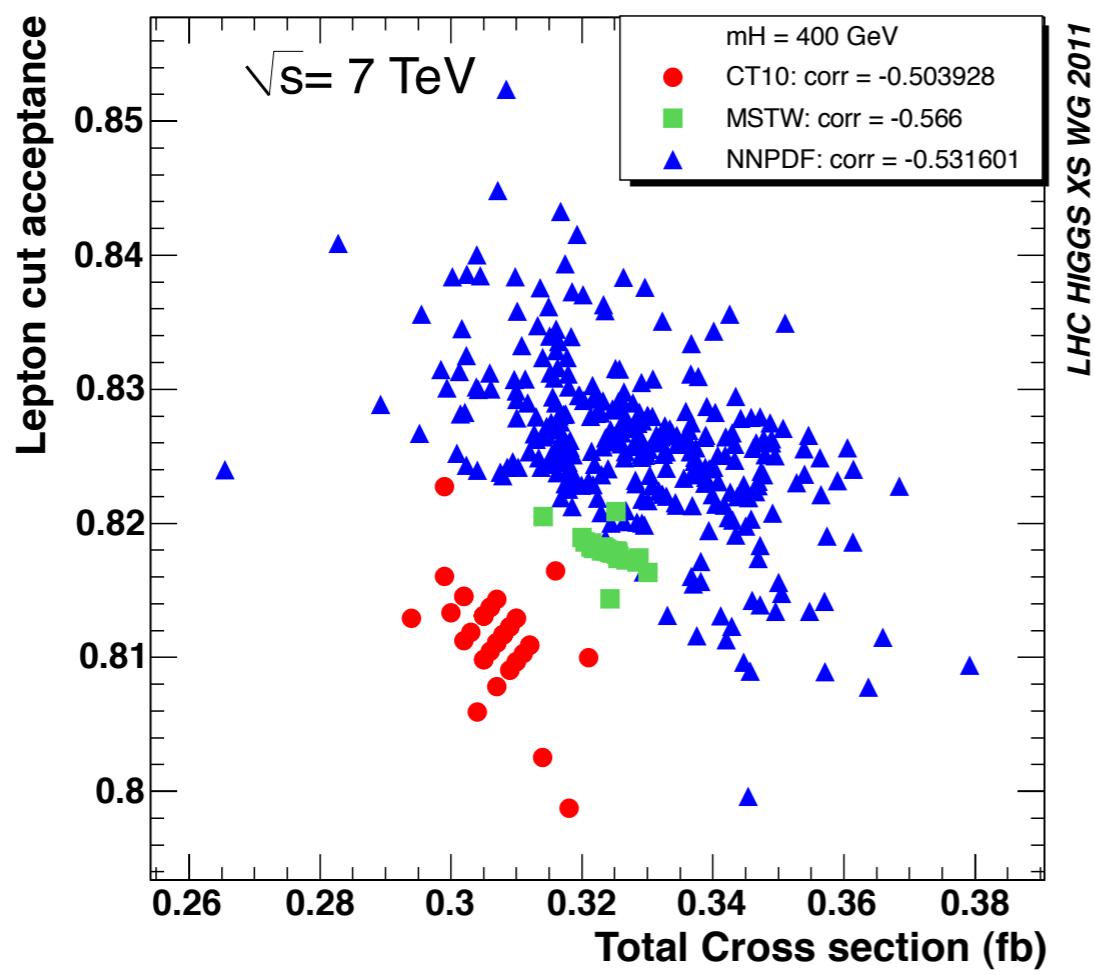
- The LEP era: **getting convinced**
- The Tevatron era: **cornering it**
- The LHC era: **nailing it**

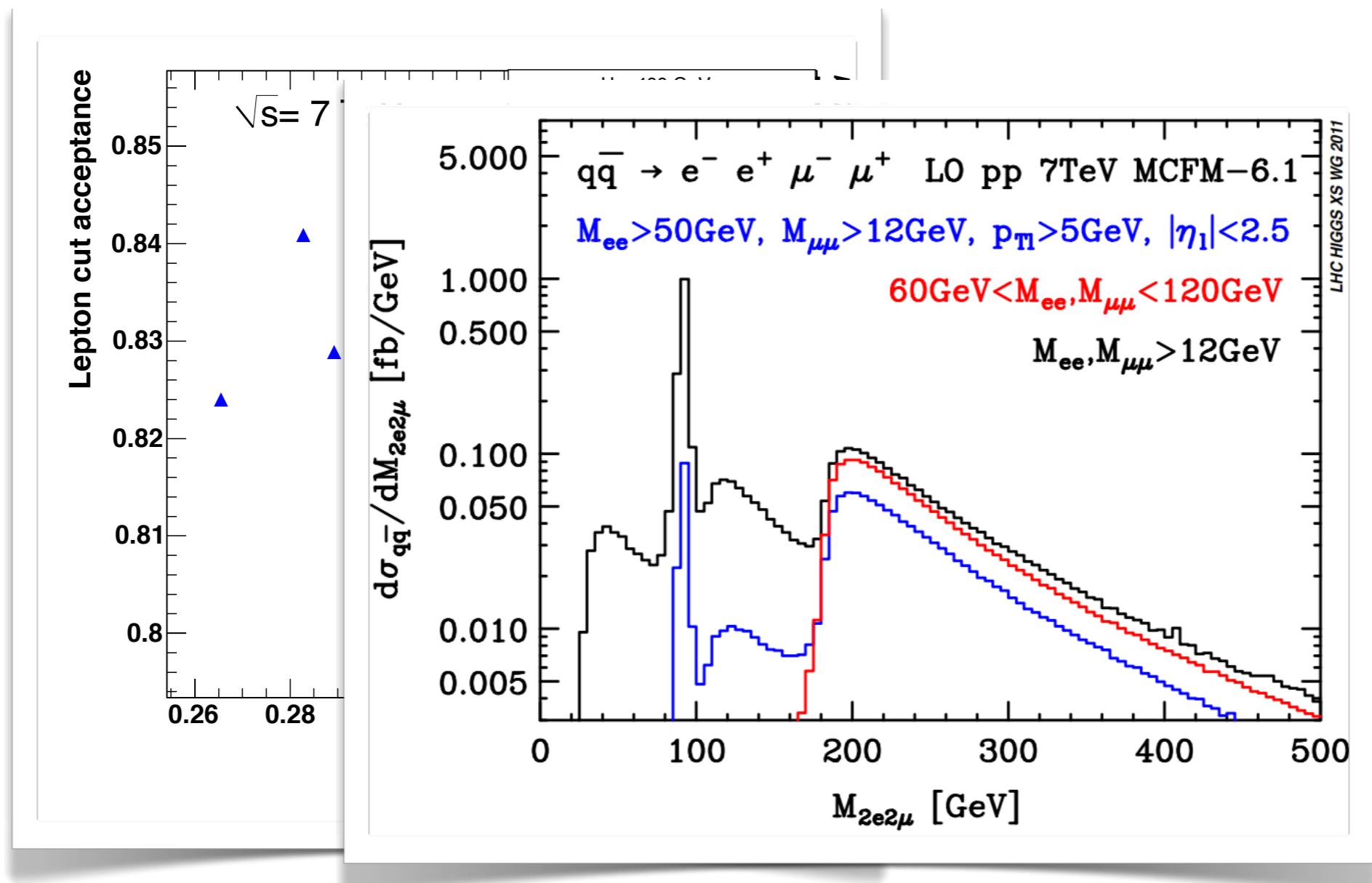


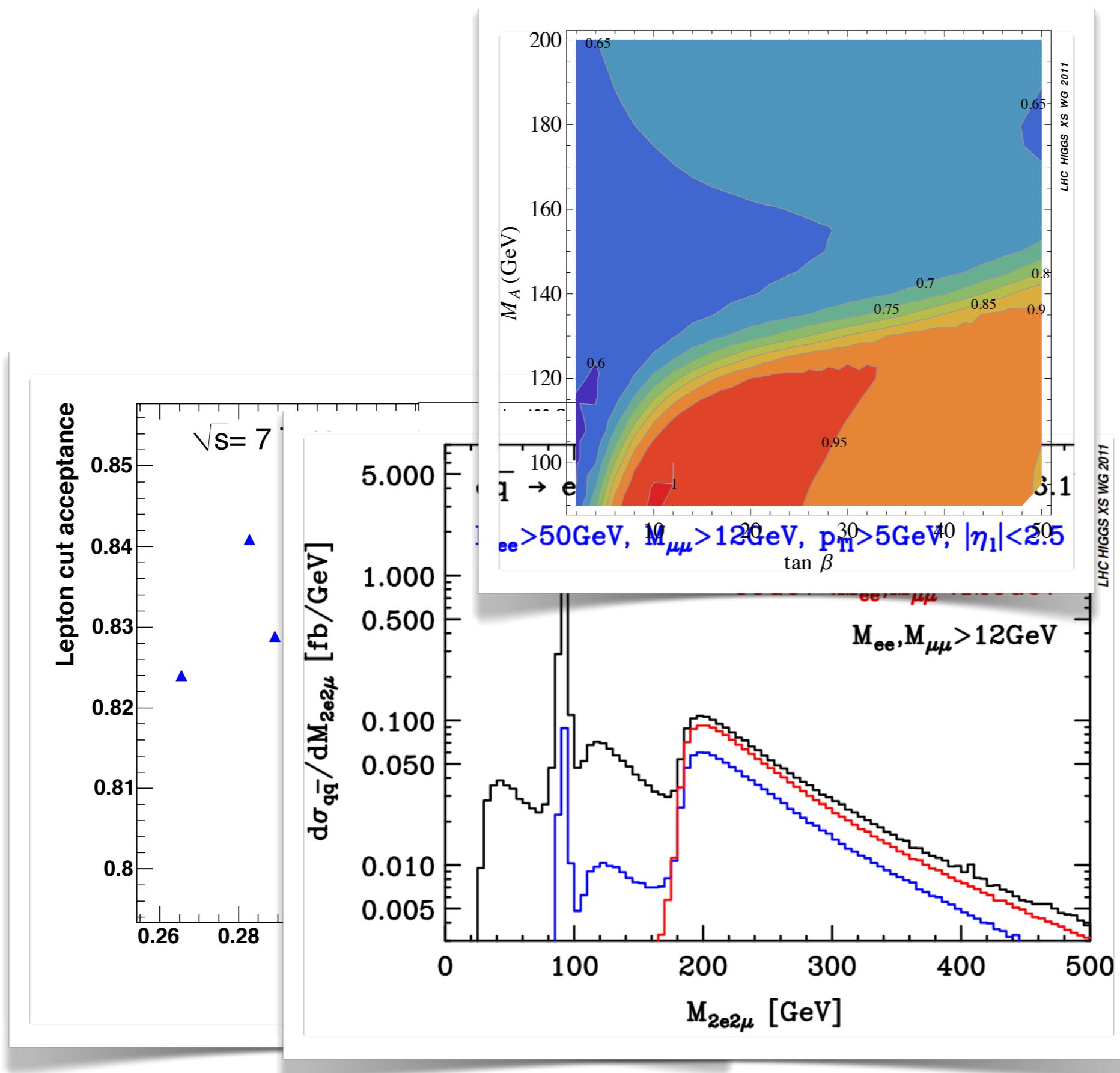
LHC Higgs Cross Section Working Group

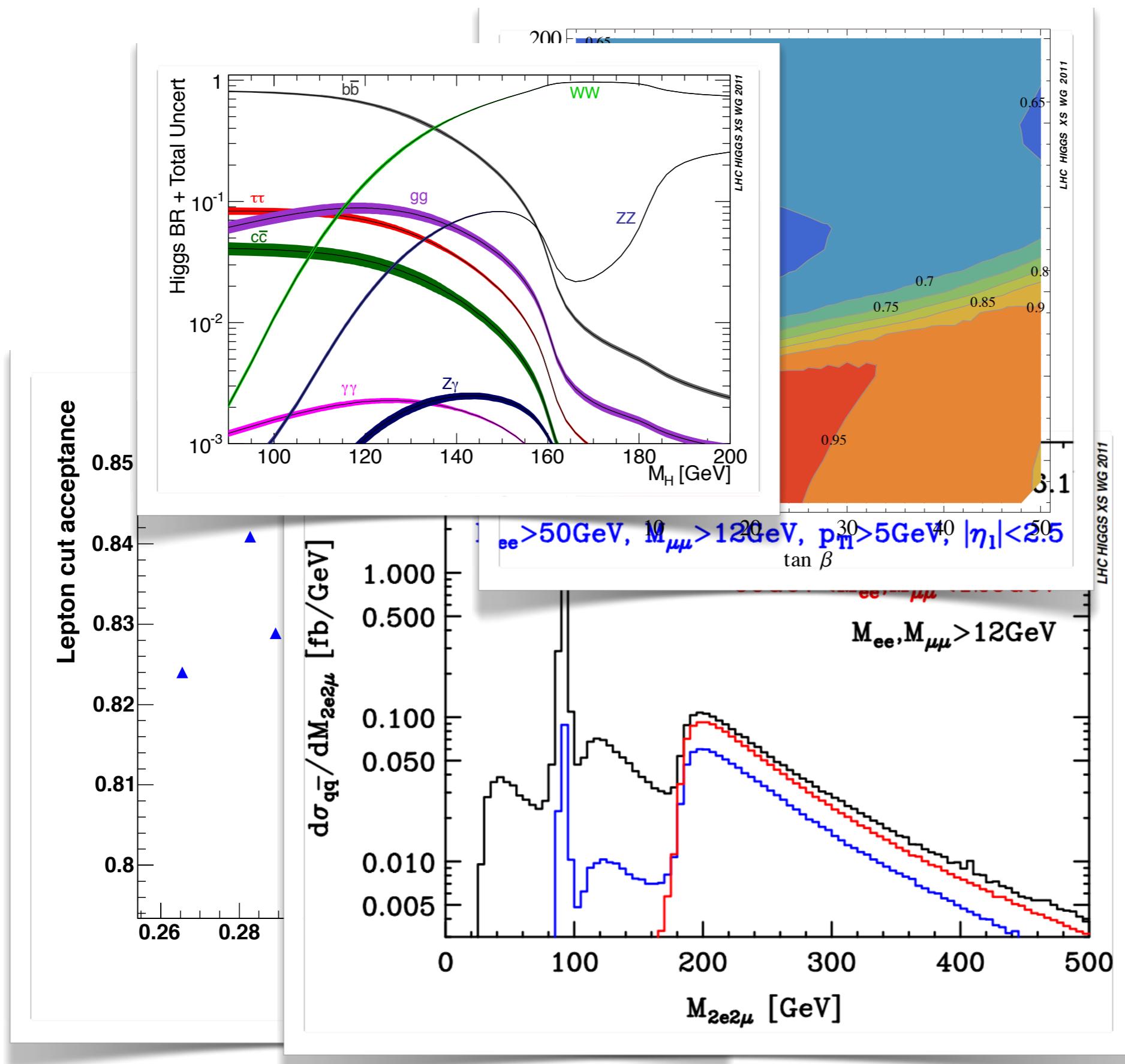
[↓ LHC Higgs Cross Section Working Group](#)

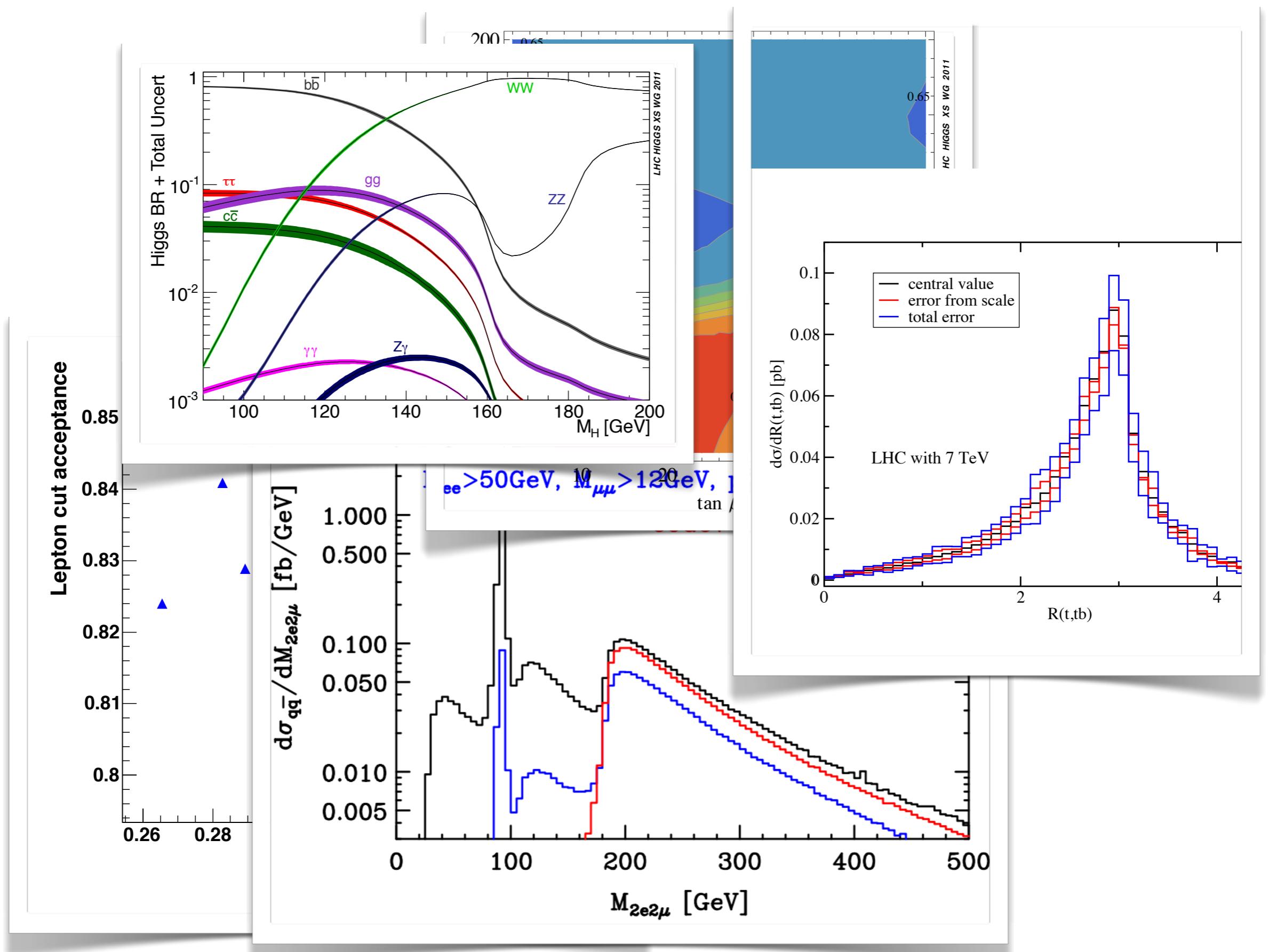
- [↓ News](#)
- [↓ Overview](#)
- [↓ CERN Reports: Handbook of LHC Higgs Cross Sections](#)
- [↓ Preprints](#)
- [↓ Higgs cross sections at 7, 8 and 14 TeV](#)
- [↓ Latest plots](#)
- [↓ Information](#)
- [↓ Workshops](#)
- [↓ Communication Tools](#)
- [↓ Organization](#)

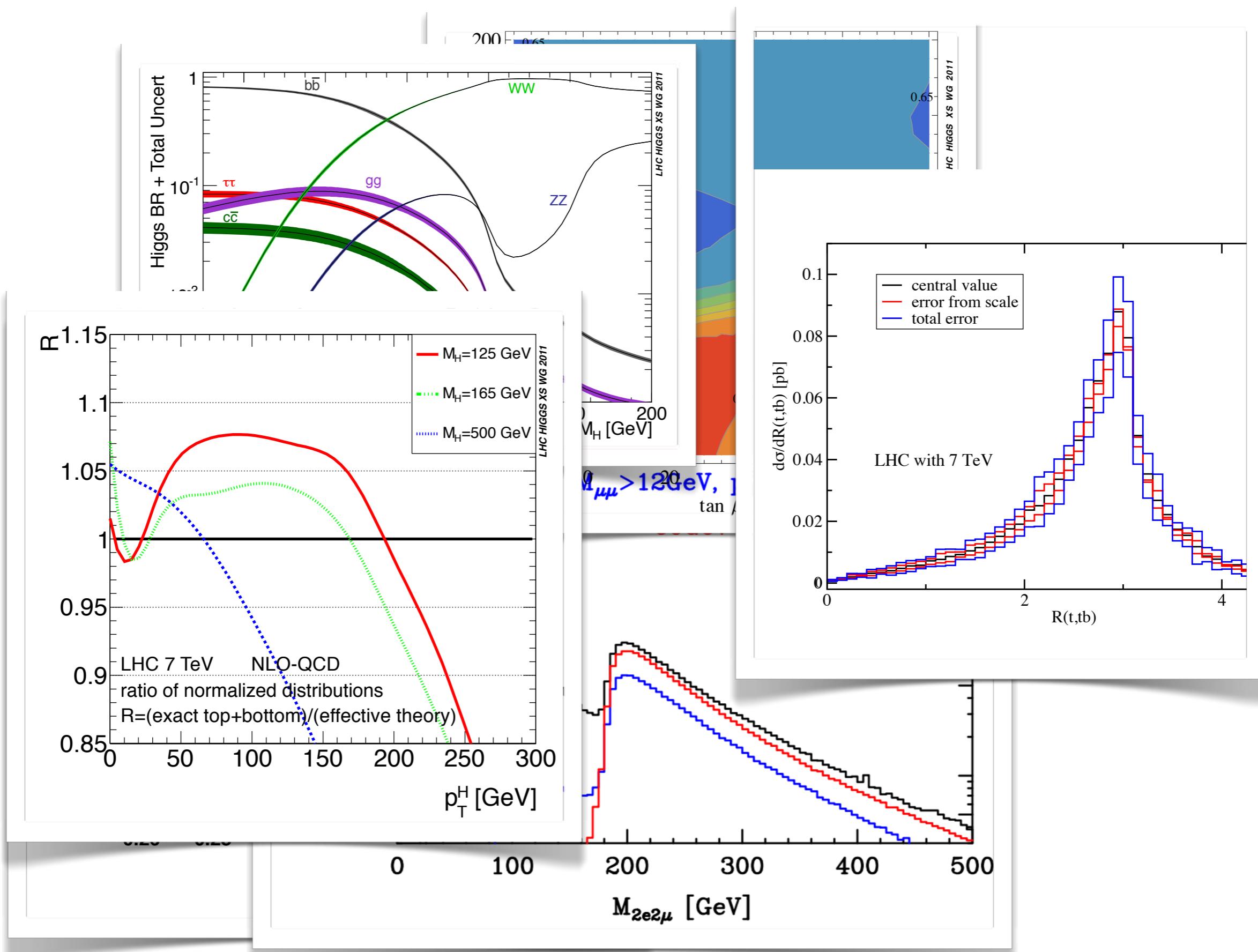


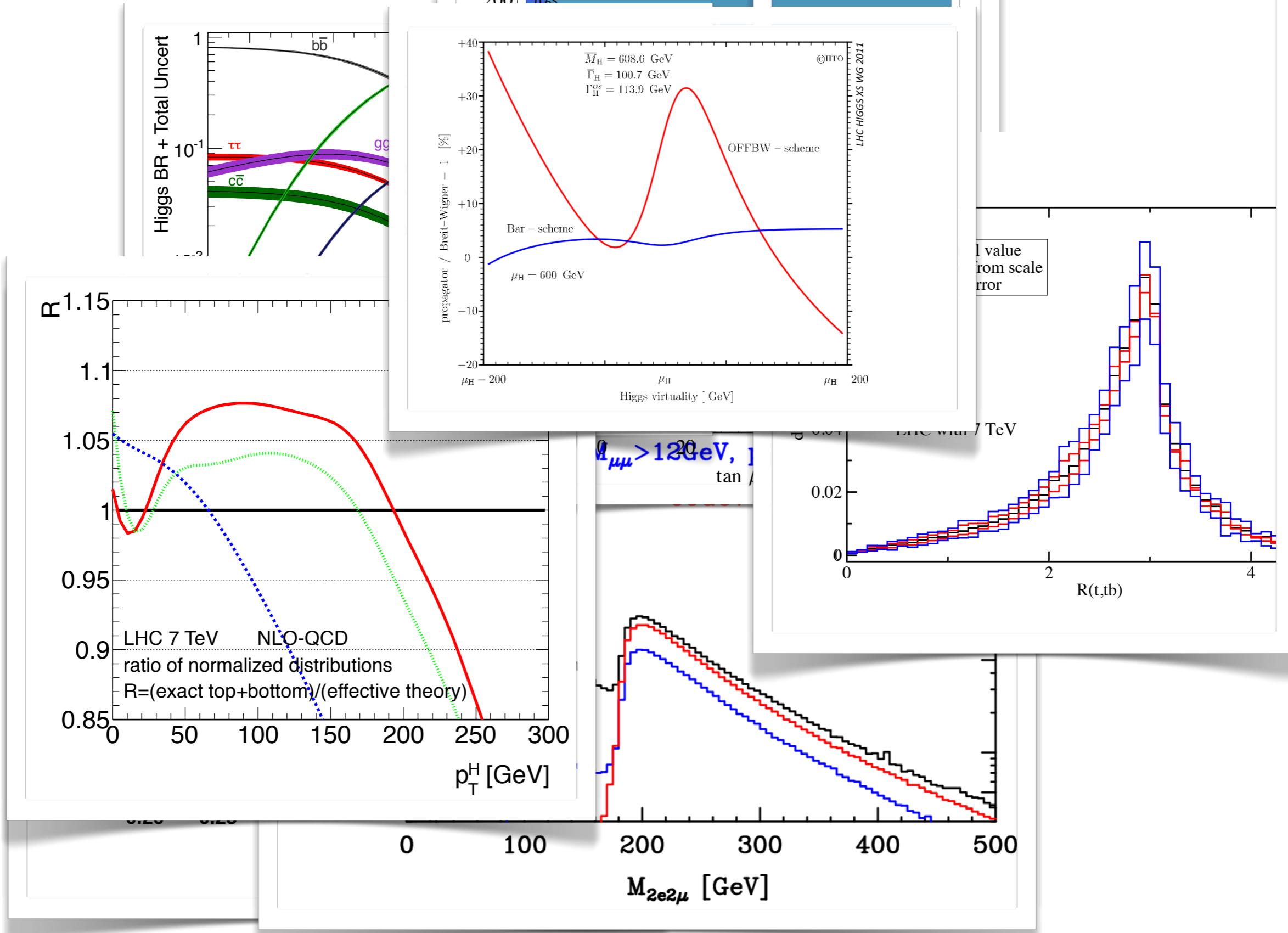


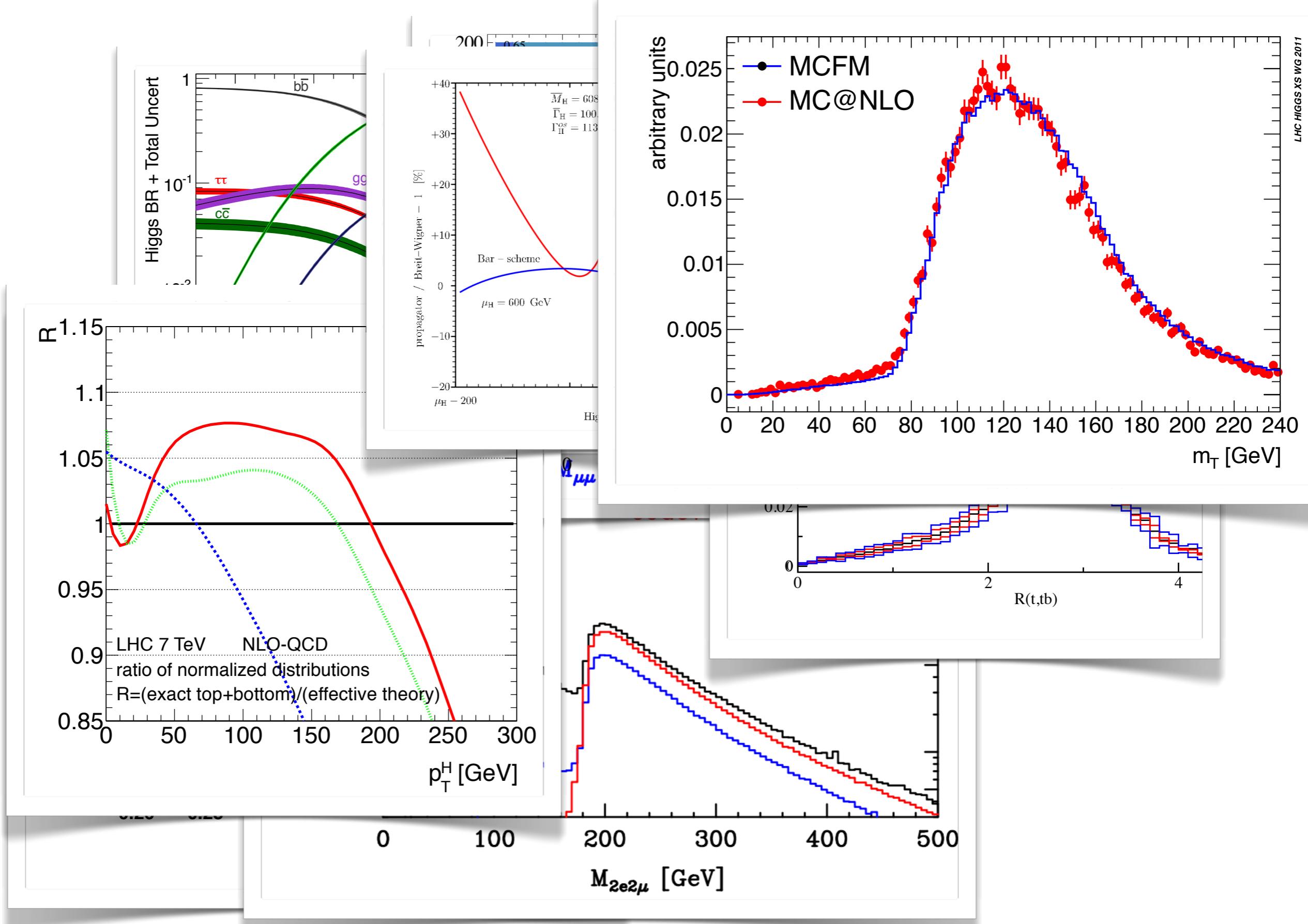


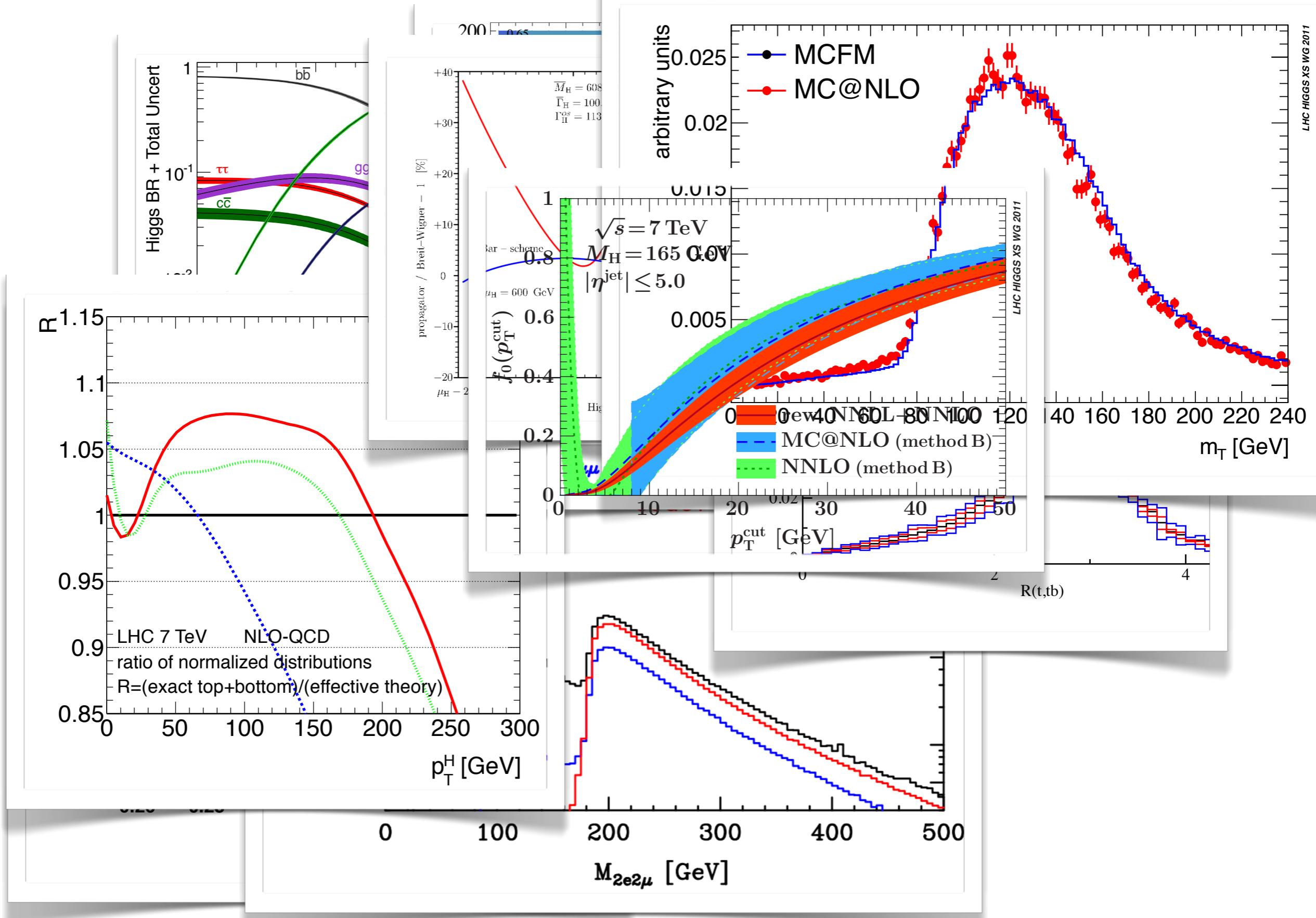


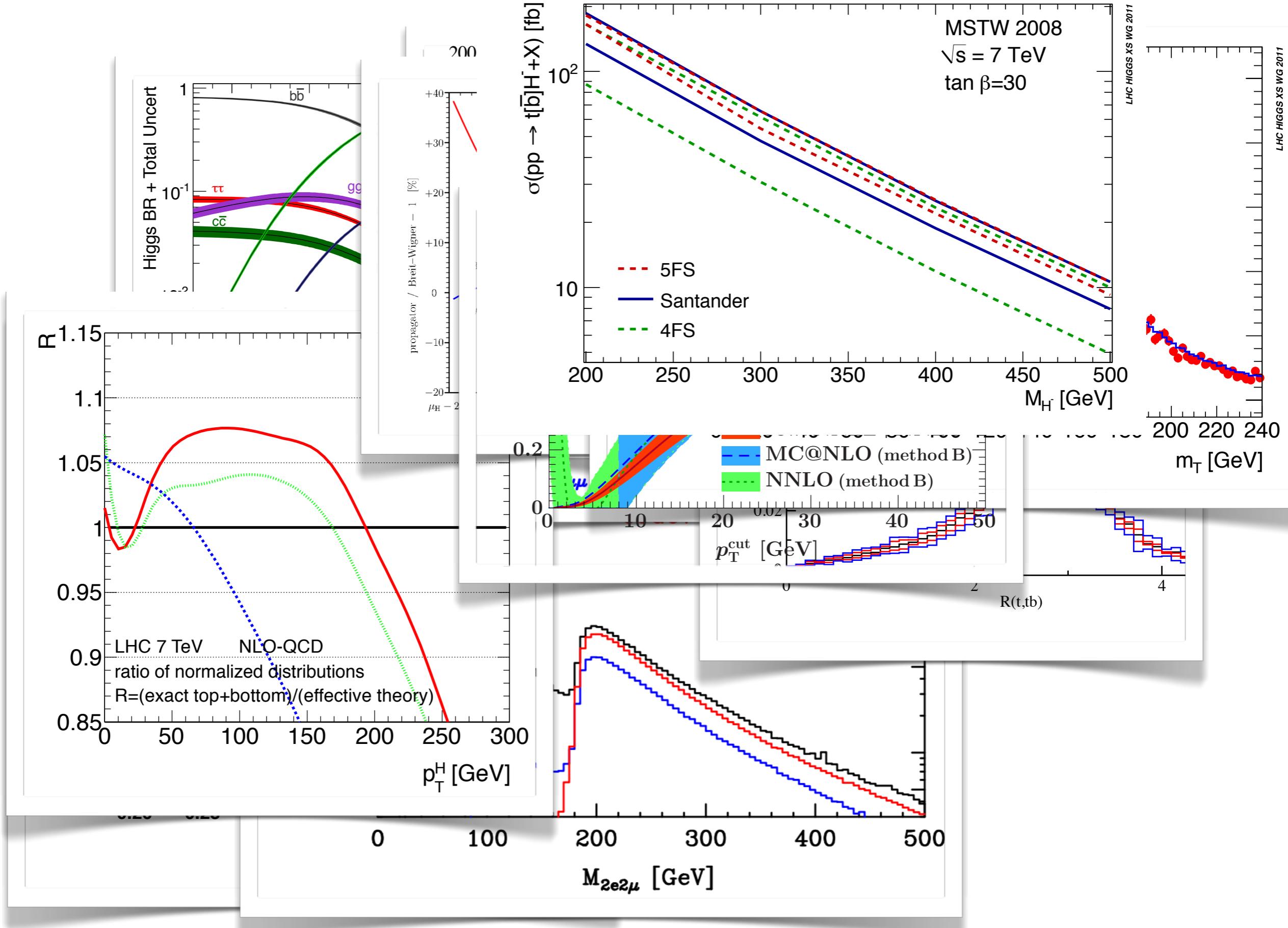


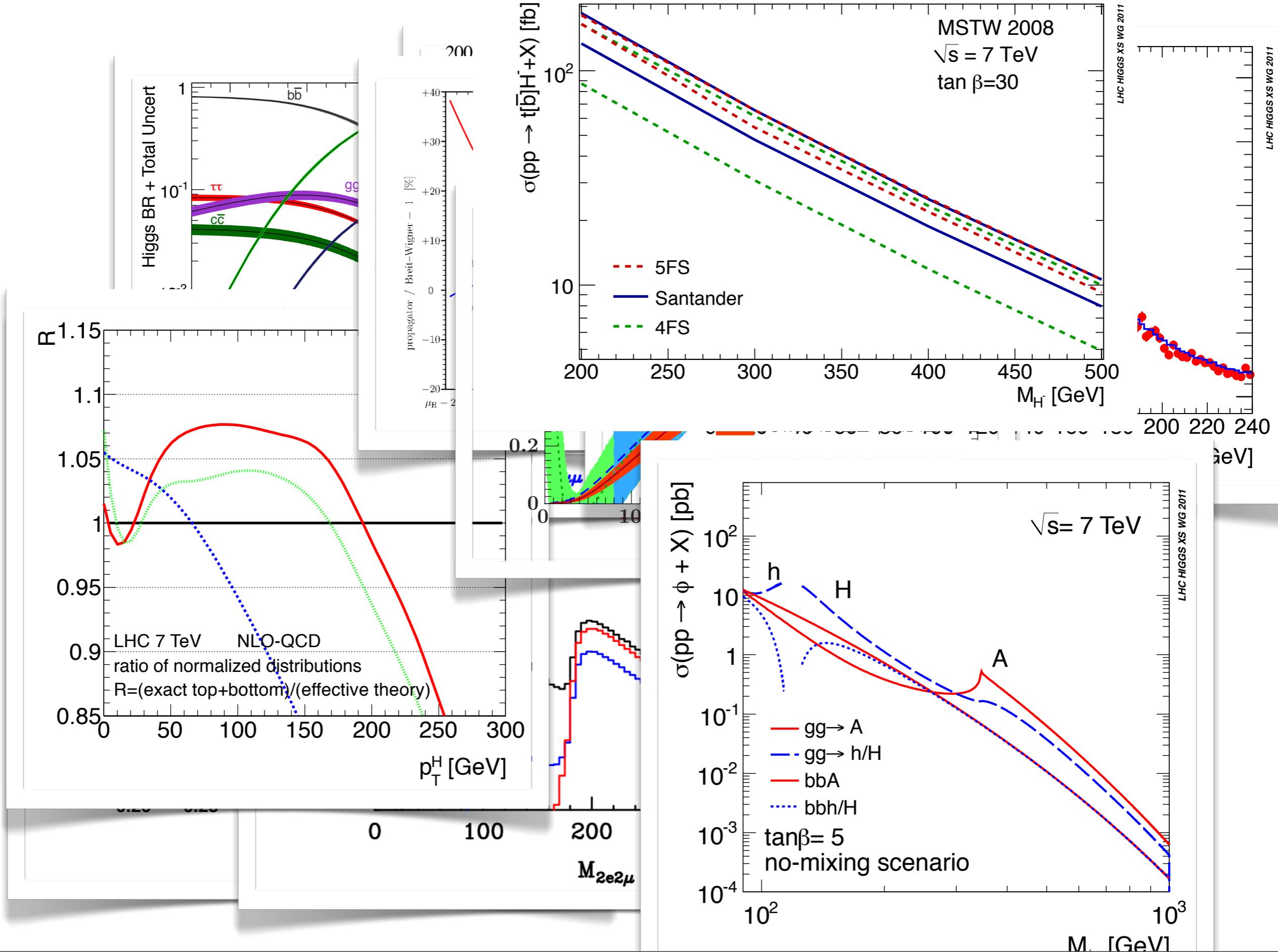


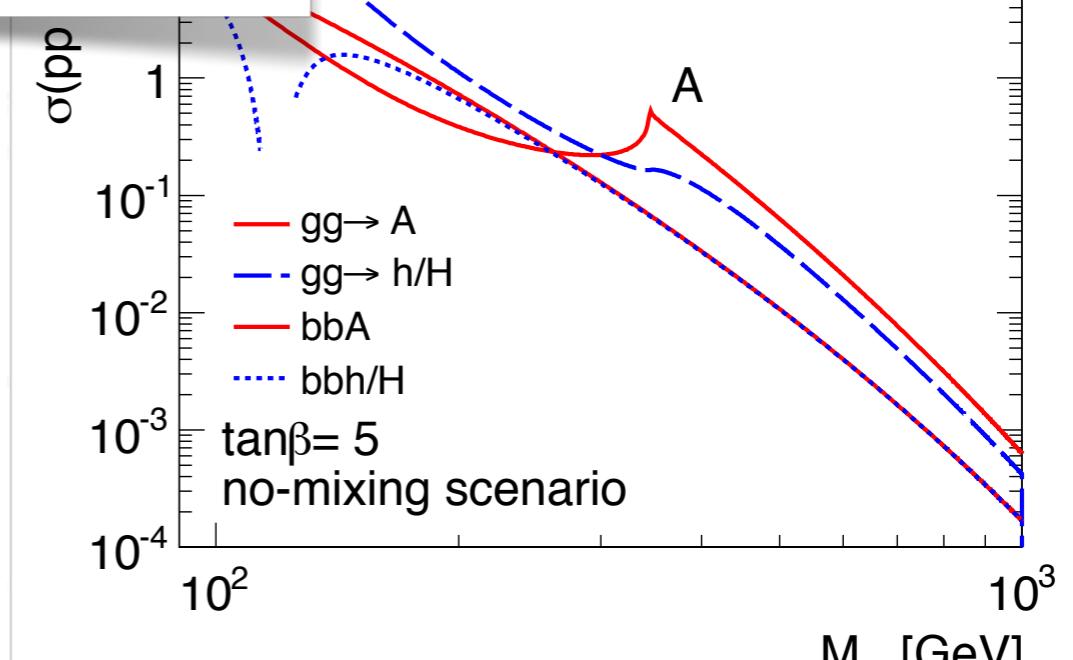
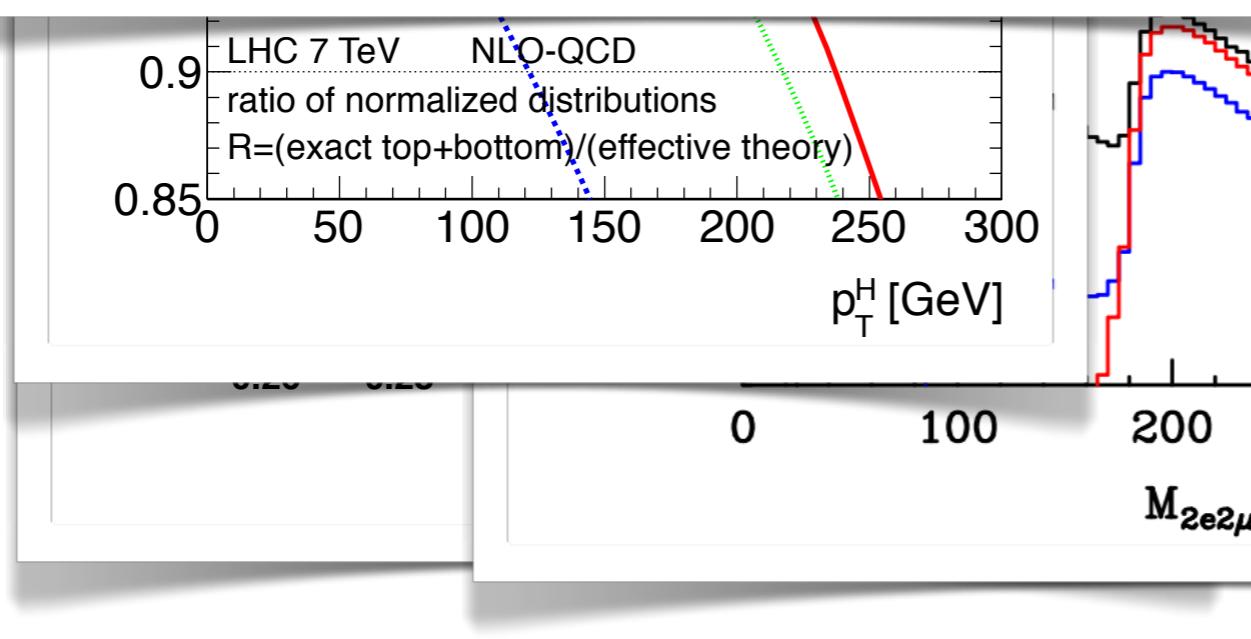
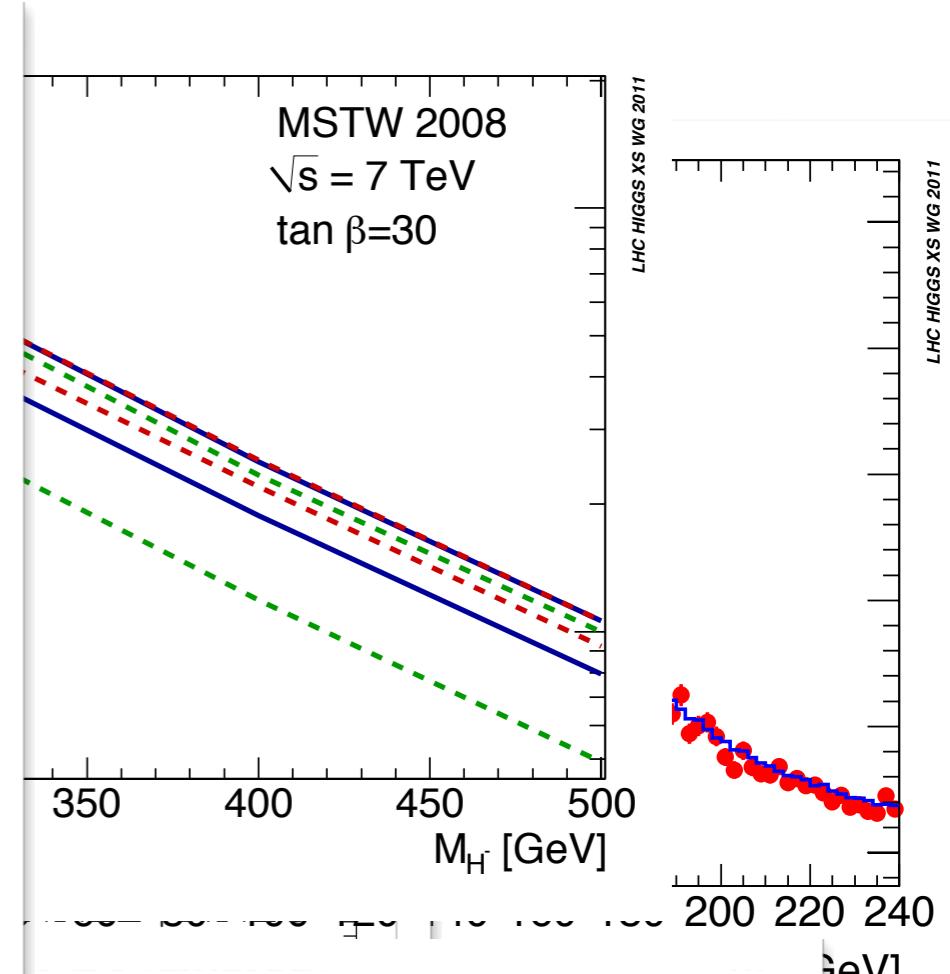
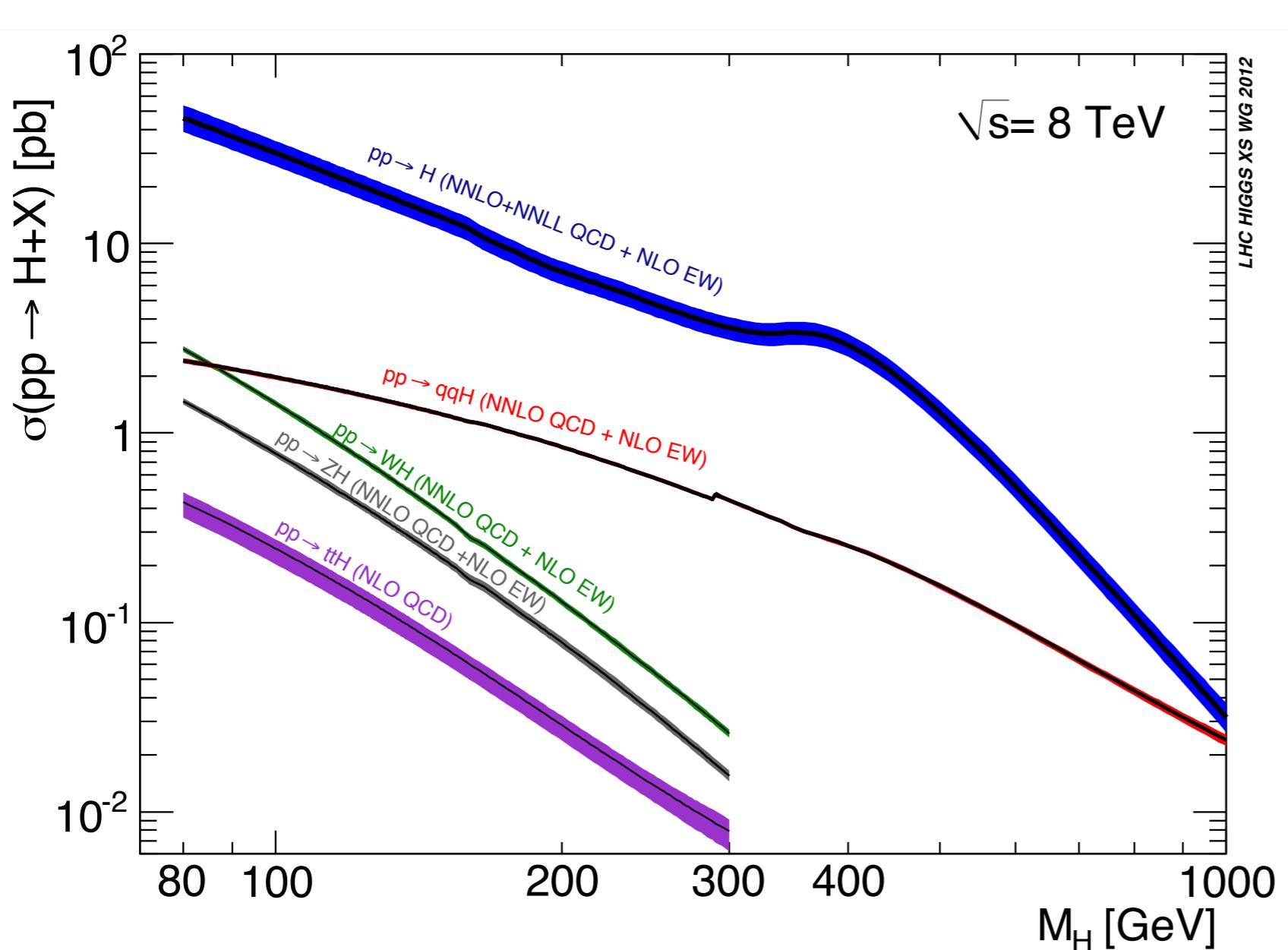


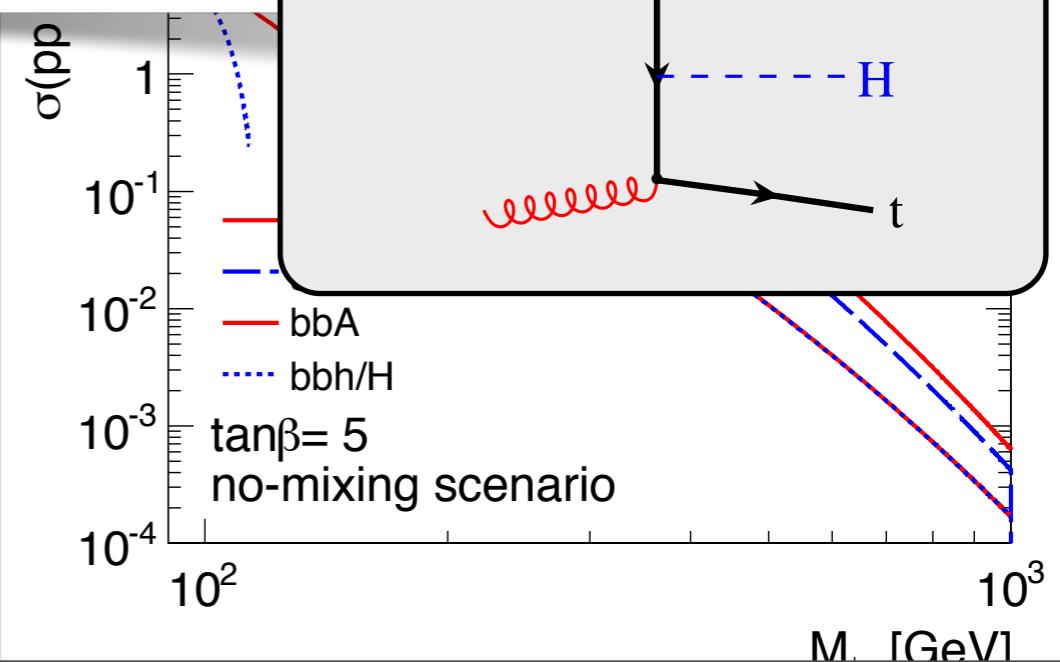
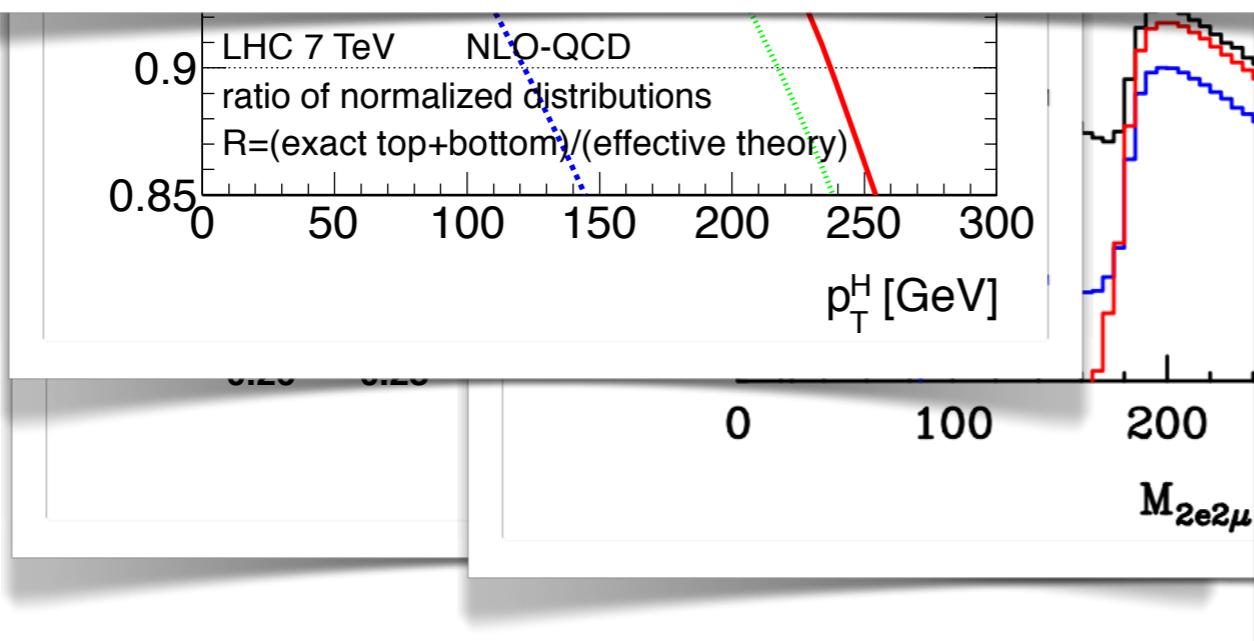
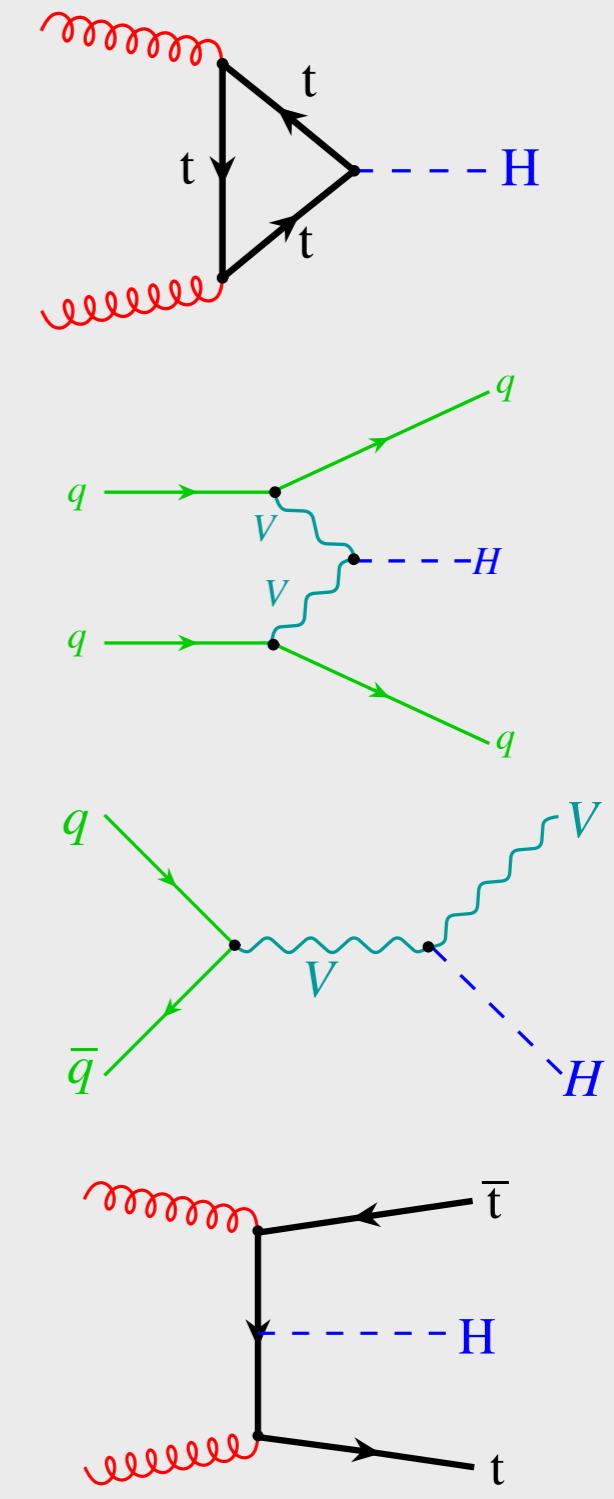
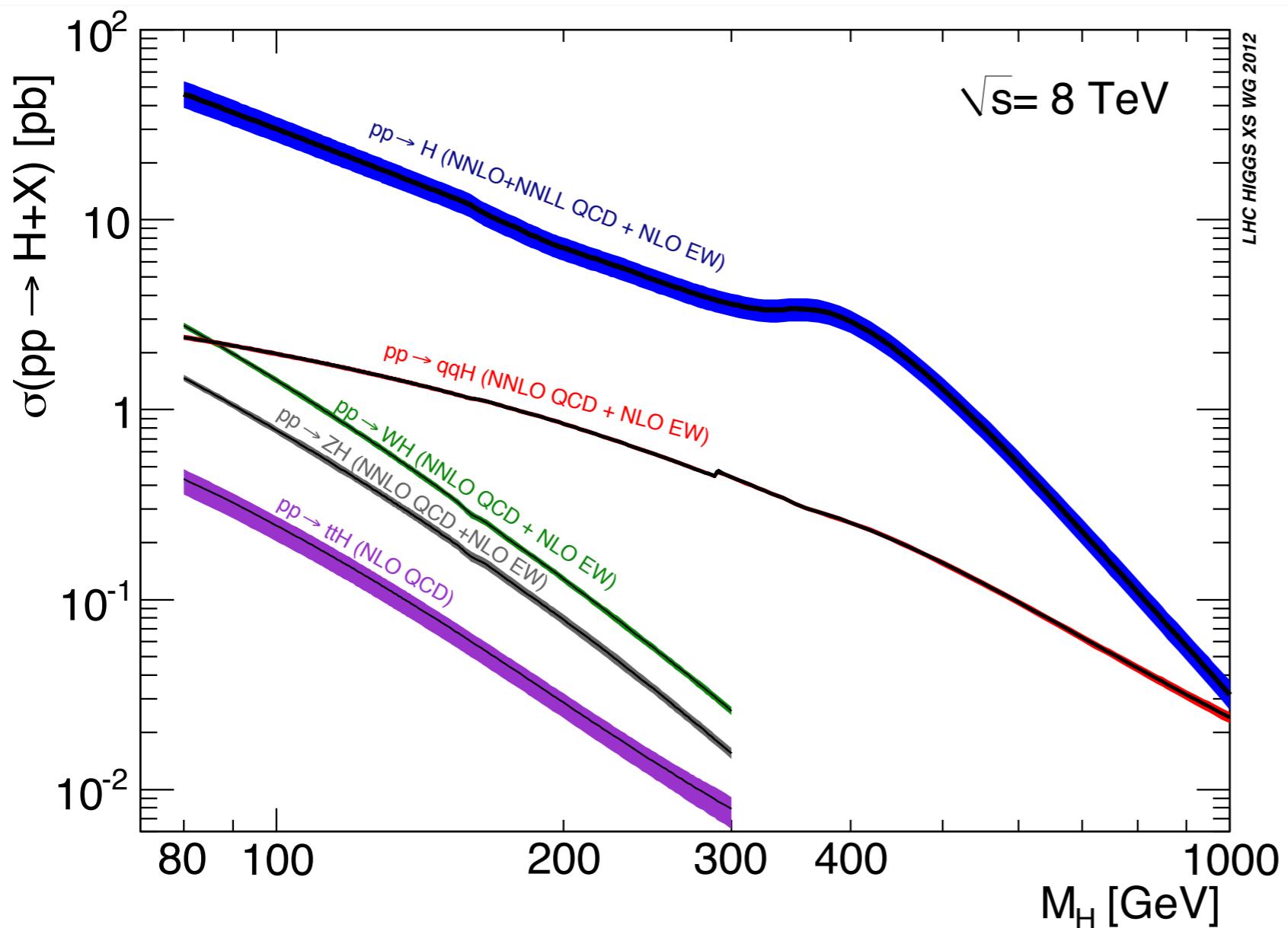




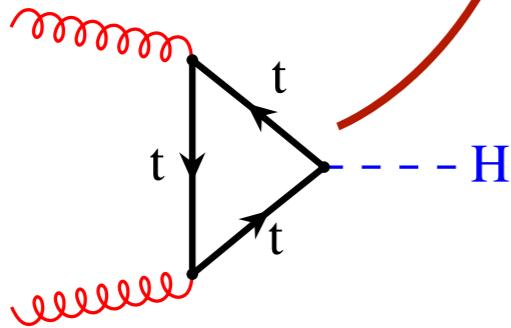
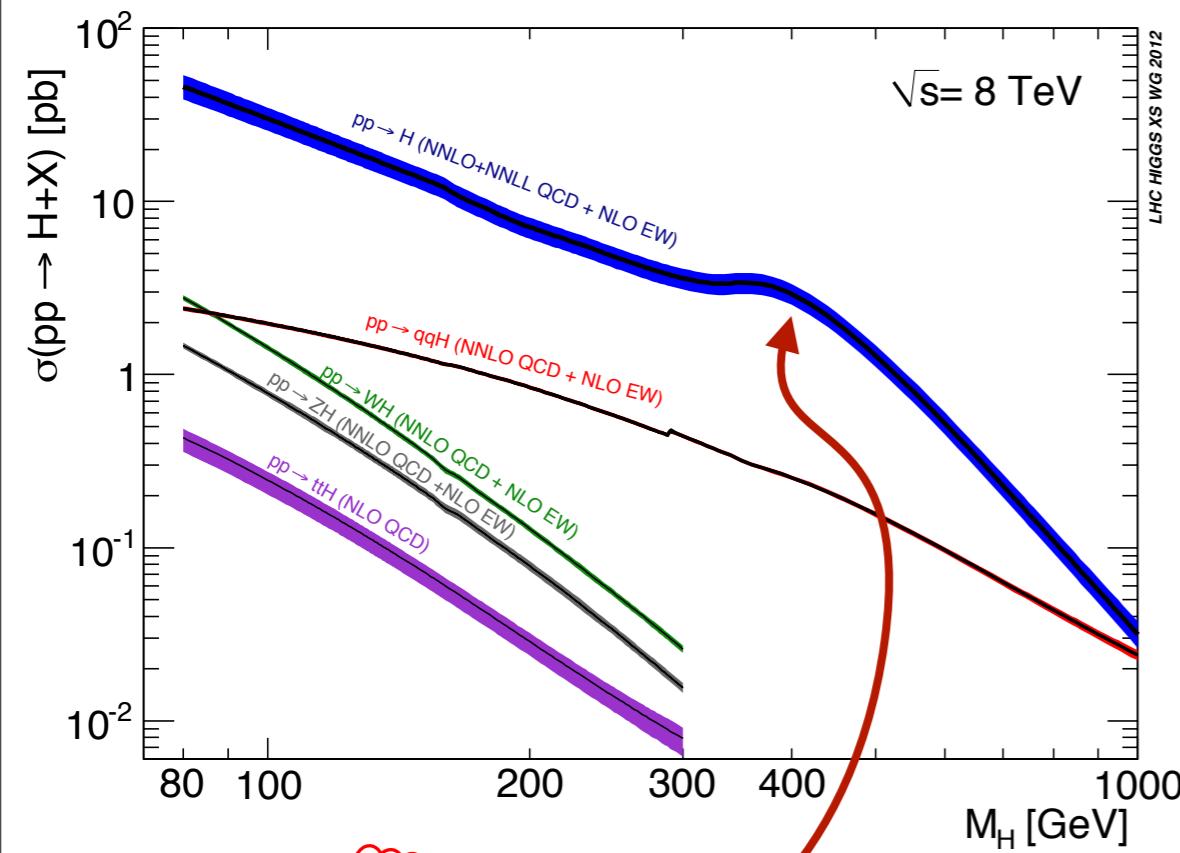








Gluon fusion



NLO: Spira, Djouadi, Graudenz, Zerwas '91, '93
Dawson '91

NNLO: RH, Kilgore '02
Anastasiou, Melnikov '02
Ravindran, Smith, v. Neerven '03

Resummation:

Catani, de Florian, Grazzini, Nason '02
Ahrens, Becher, Neubert, Zhang '08

Electroweak:

Actis, Passarino, Sturm, Uccirati '08
Aglietti, Bonciani, Degrassi, Vicini '04
Degrassi, Maltoni '04
Djouadi, Gambino '94

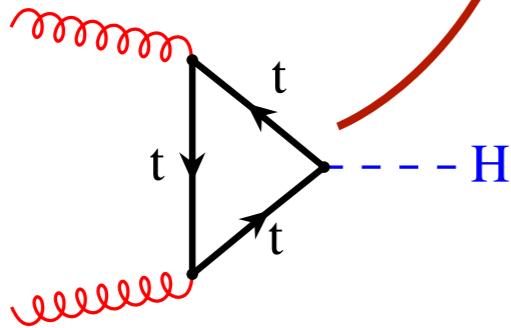
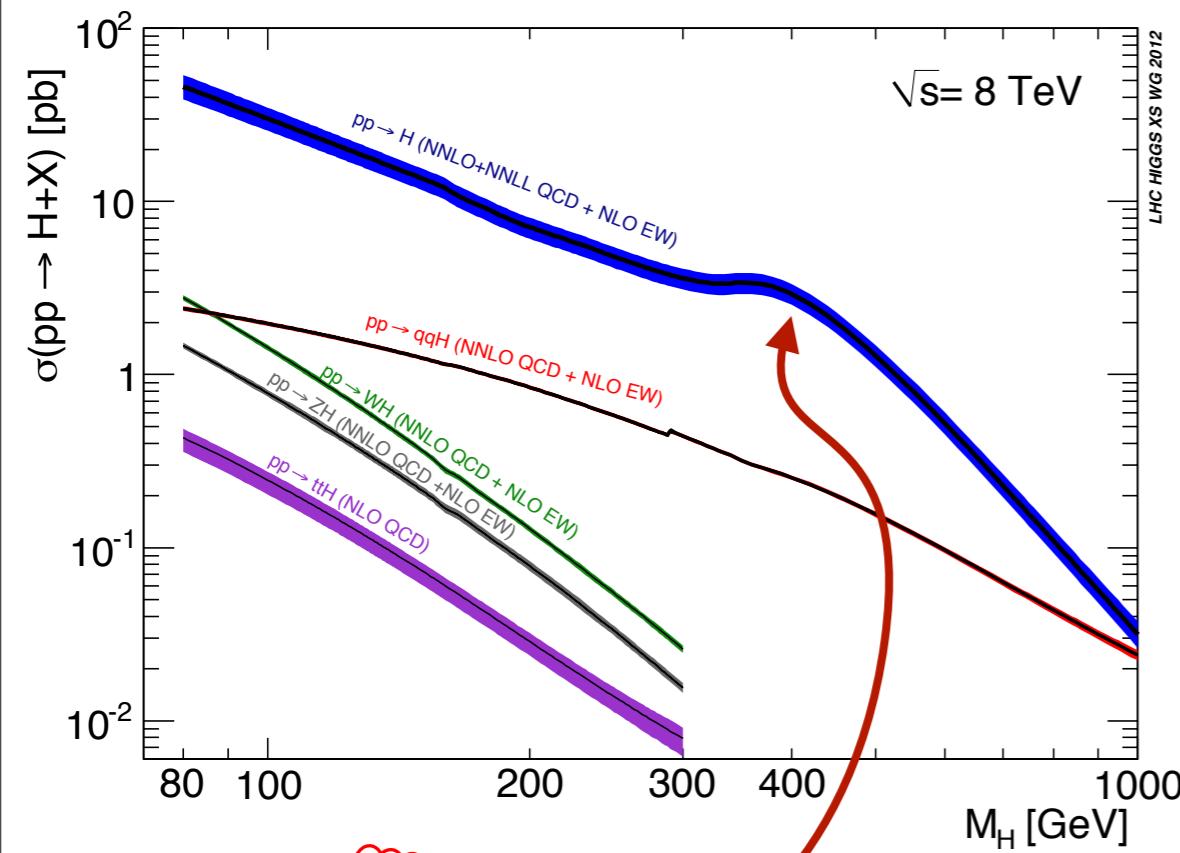
Mixed EW/QCD:

Anastasiou, Boughezal, Petriello '09

Fully differential NNLO:

Anastasiou, Melnikov, Petriello '04
Catani, Grazzini '07

Gluon fusion



NLO: Spira, Djouadi, Graudenz, Zerwas '91, '93
Dawson '91 ~80%

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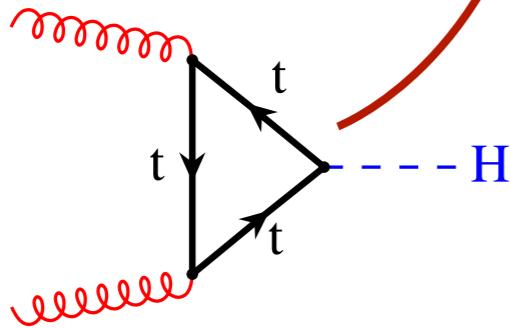
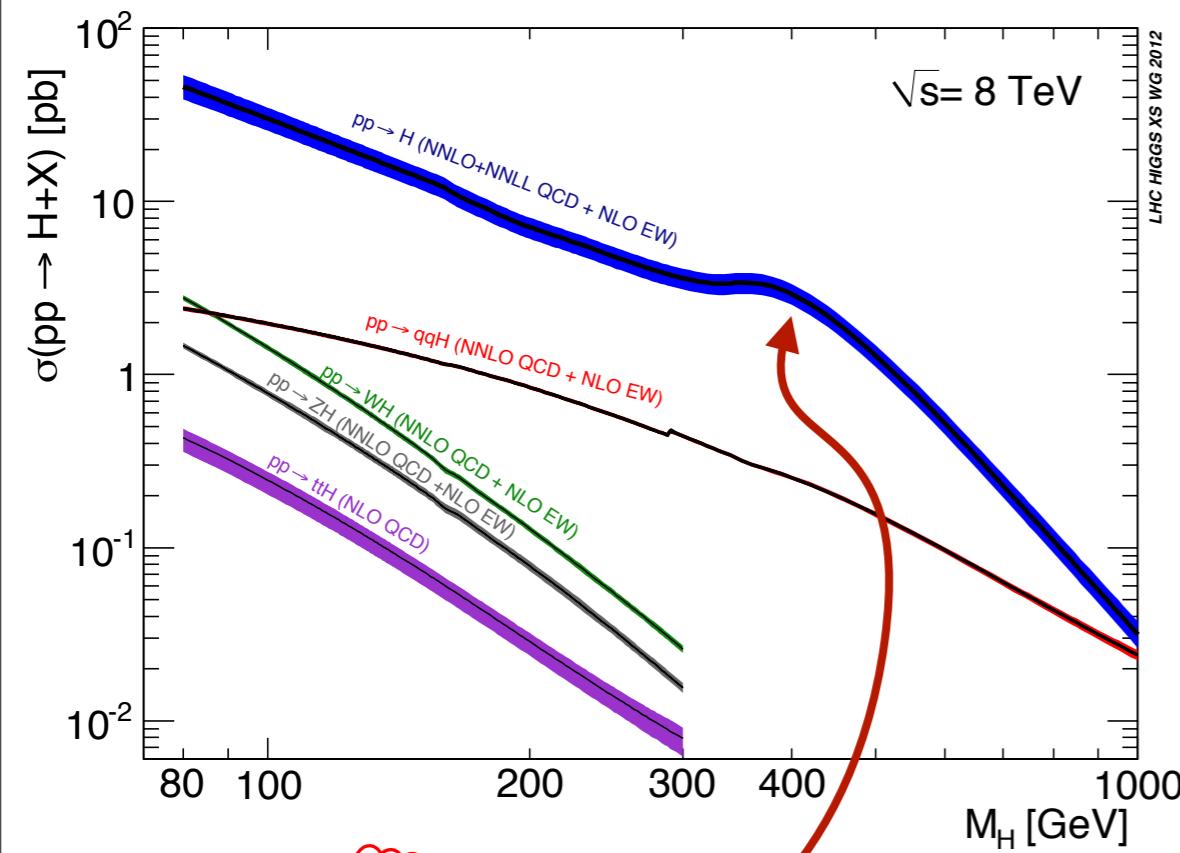
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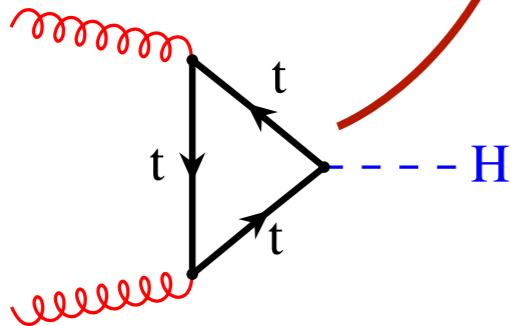
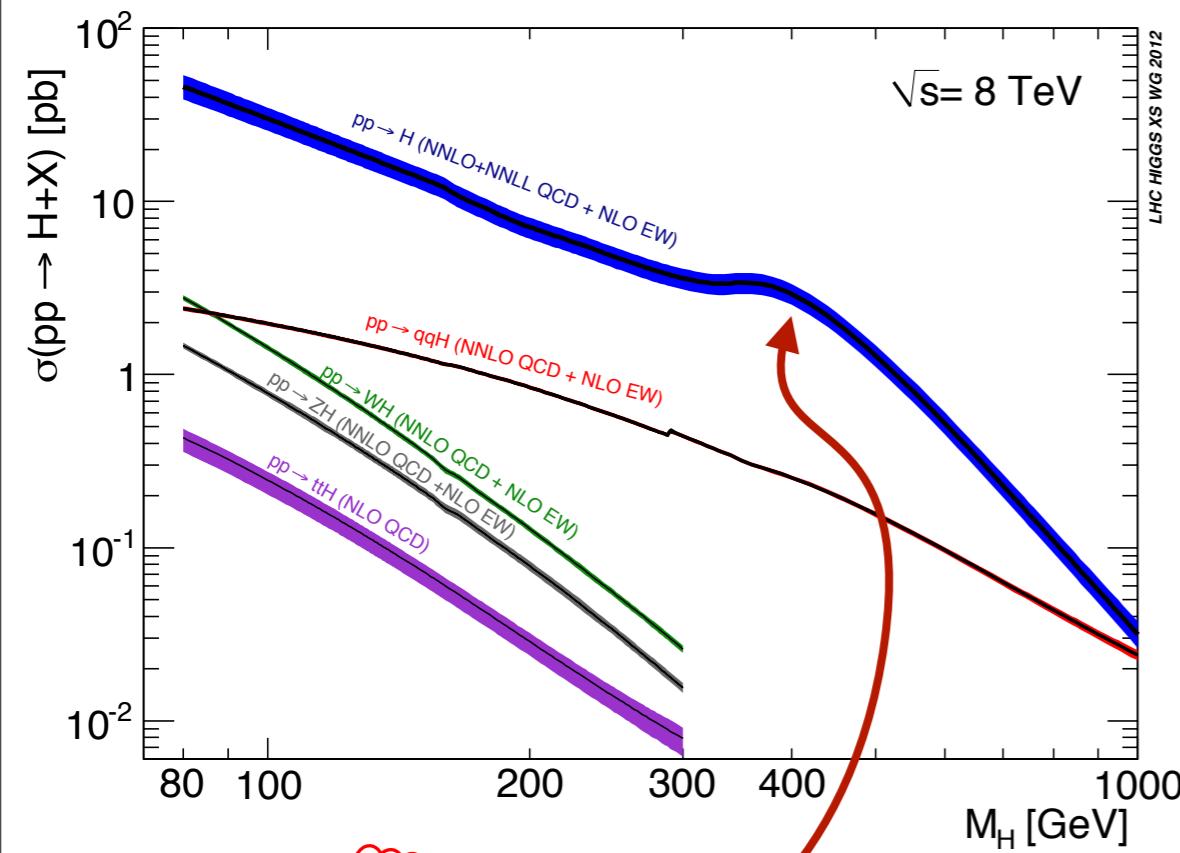
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Resummation:

Catani, de Florian, Grazzini, Nason '02
Ahrens, Becher, Neubert, Zhang '08 ~10%

Electroweak:

Actis, Passarino, Sturm, Uccirati '08
Aglietti, Bonciani, Degrassi, Vicini '04
Degrassi, Maltoni '04
Djouadi, Gambino '94

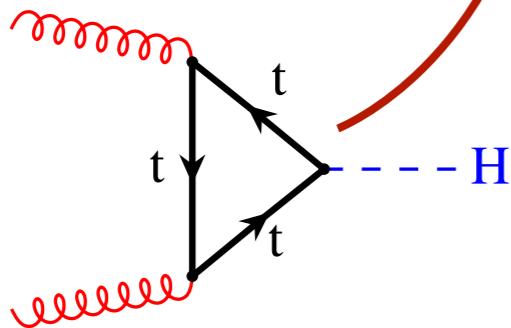
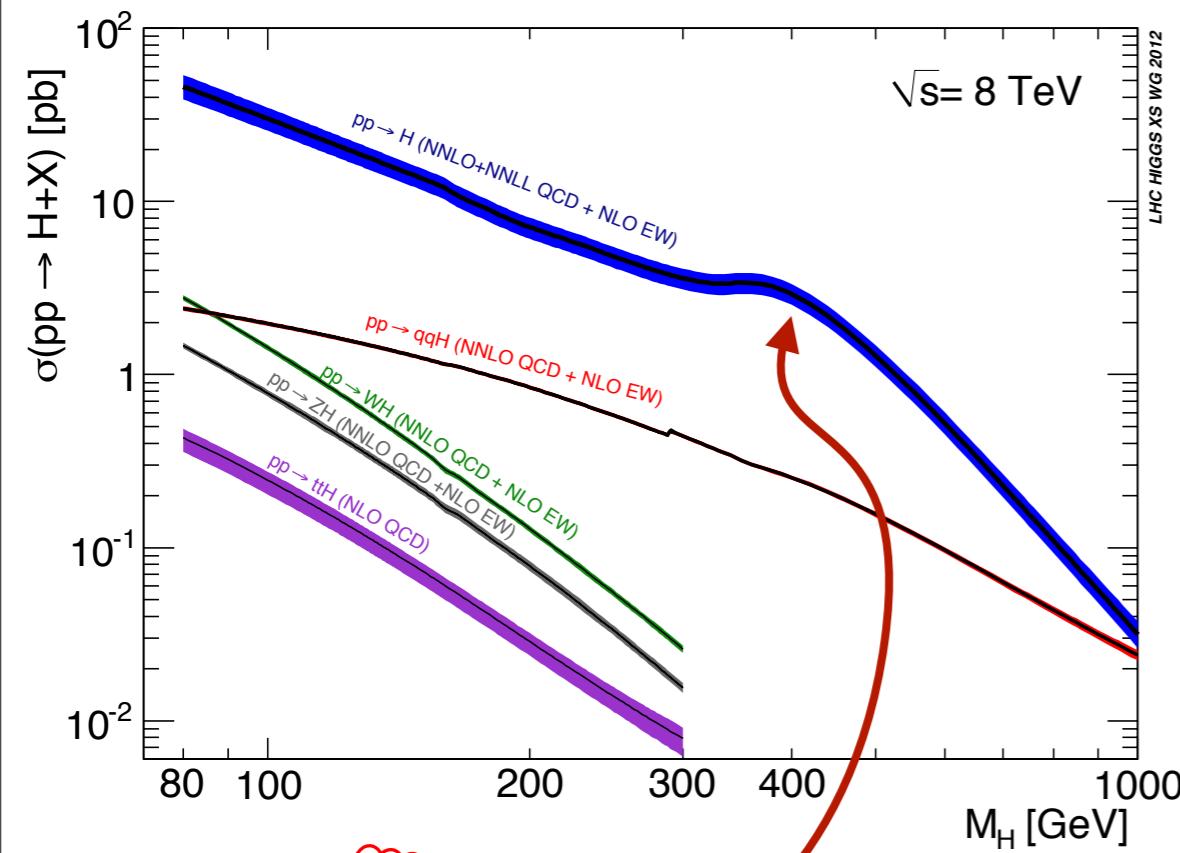
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Anastasiou, Melnikov '02
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Catani, de Florian, Grazzini, Nason '02
Ahrens, Becher, Neubert, Zhang '08 ~10%

Electroweak:

Actis, Passarino, Sturm, Uccirati '08
Aglietti, Bonciani, Degrassi, Vicini '04
Degrassi, Maltoni '04
Djouadi, Gambino '94 ~5%

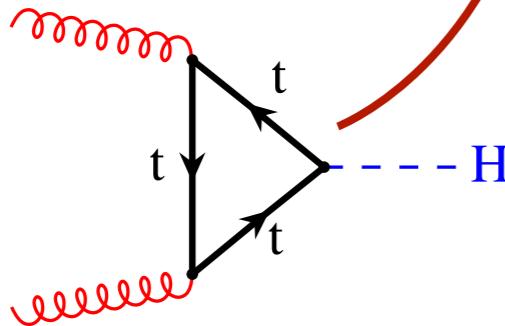
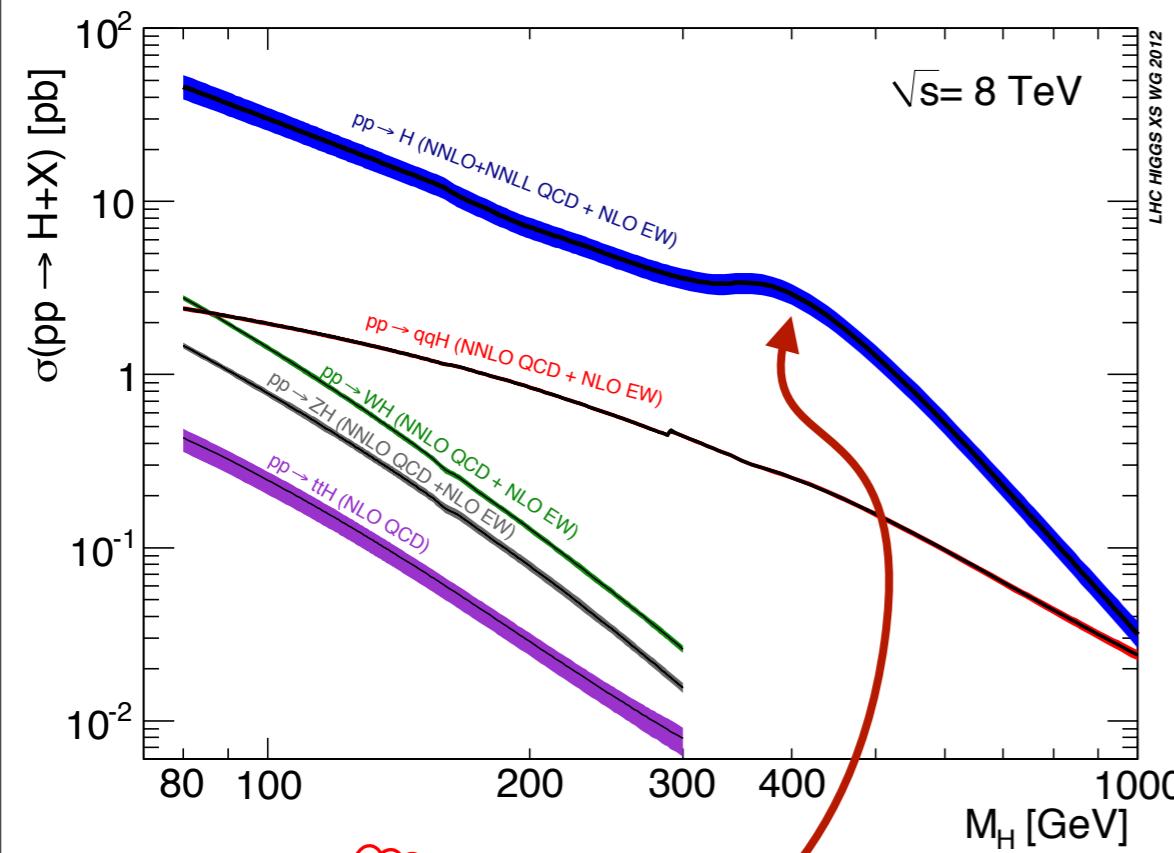
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Fully differential NNLO:

Anastasiou, Melnikov, Petriello '04
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Gluon fusion



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

NLO: Spira, Djouadi, Graudenz, Zerwas '91, '93
Dawson '91 ~80%

NNLO: RH, Kilgore '02
Anastasiou, Melnikov '02
Ravindran, Smith, v. Neerven '03 ~30%

Resummation:

Catani, de Florian, Grazzini, Nason '02
Ahrens, Becher, Neubert, Zhang '08 ~10%

Electroweak:

Actis, Passarino, Sturm, Uccirati '08
Aglietti, Bonciani, Degrassi, Vicini '04
Degrassi, Maltoni '04
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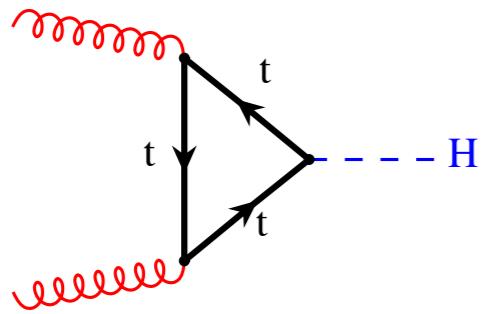
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Fully differential NNLO:

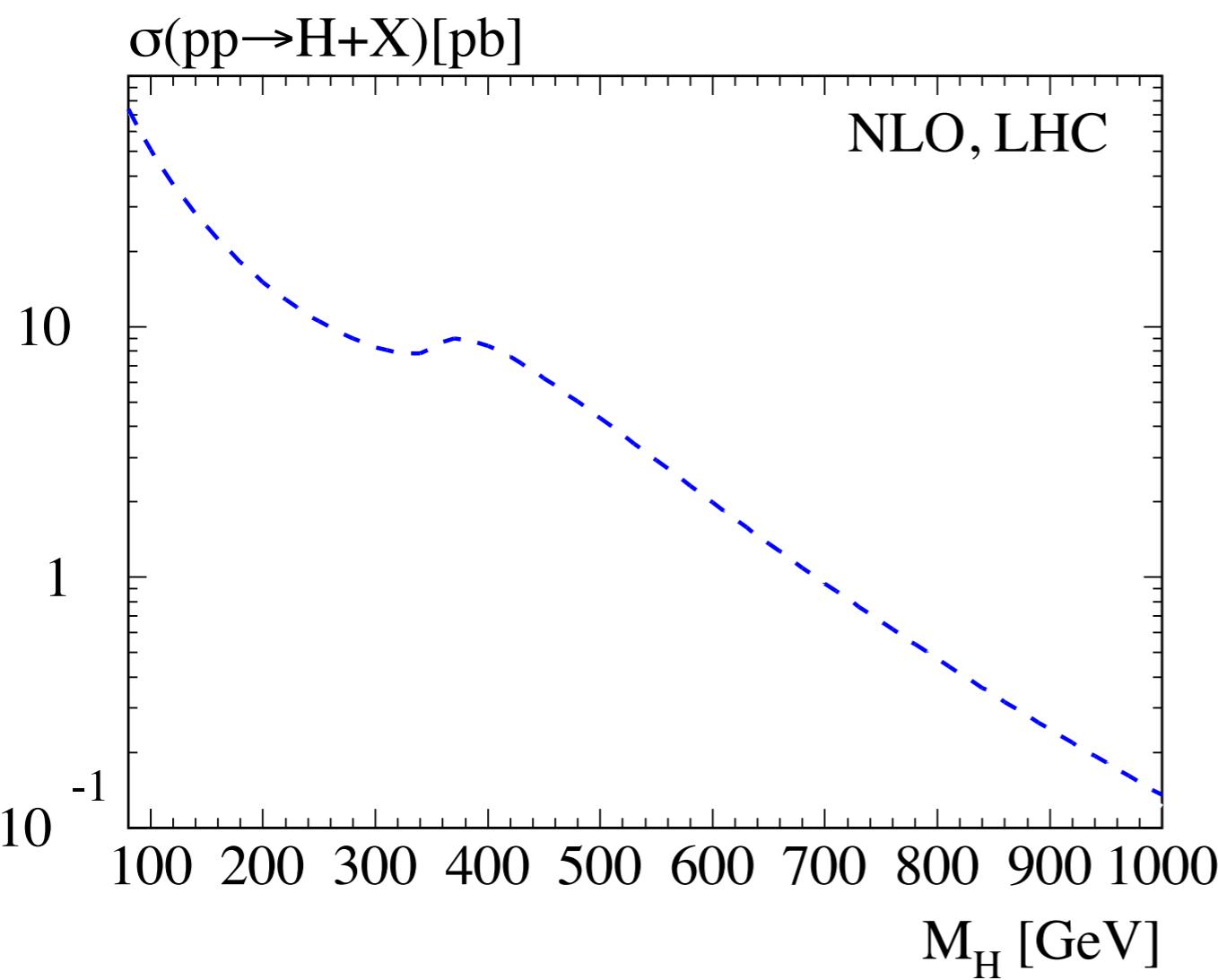
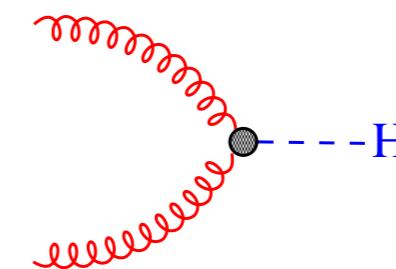
Anastasiou, Melnikov, Petriello '04
Catani, Grazzini '07

Effective Theory:



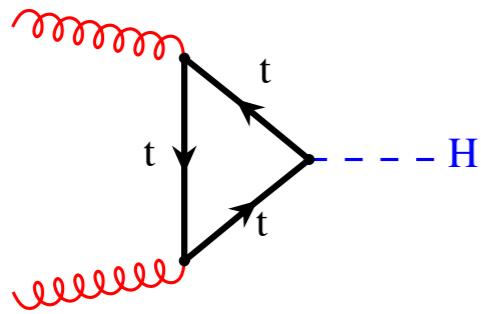
$$m_t \gg M_H$$

$$C(m_t, \alpha_s) \times$$



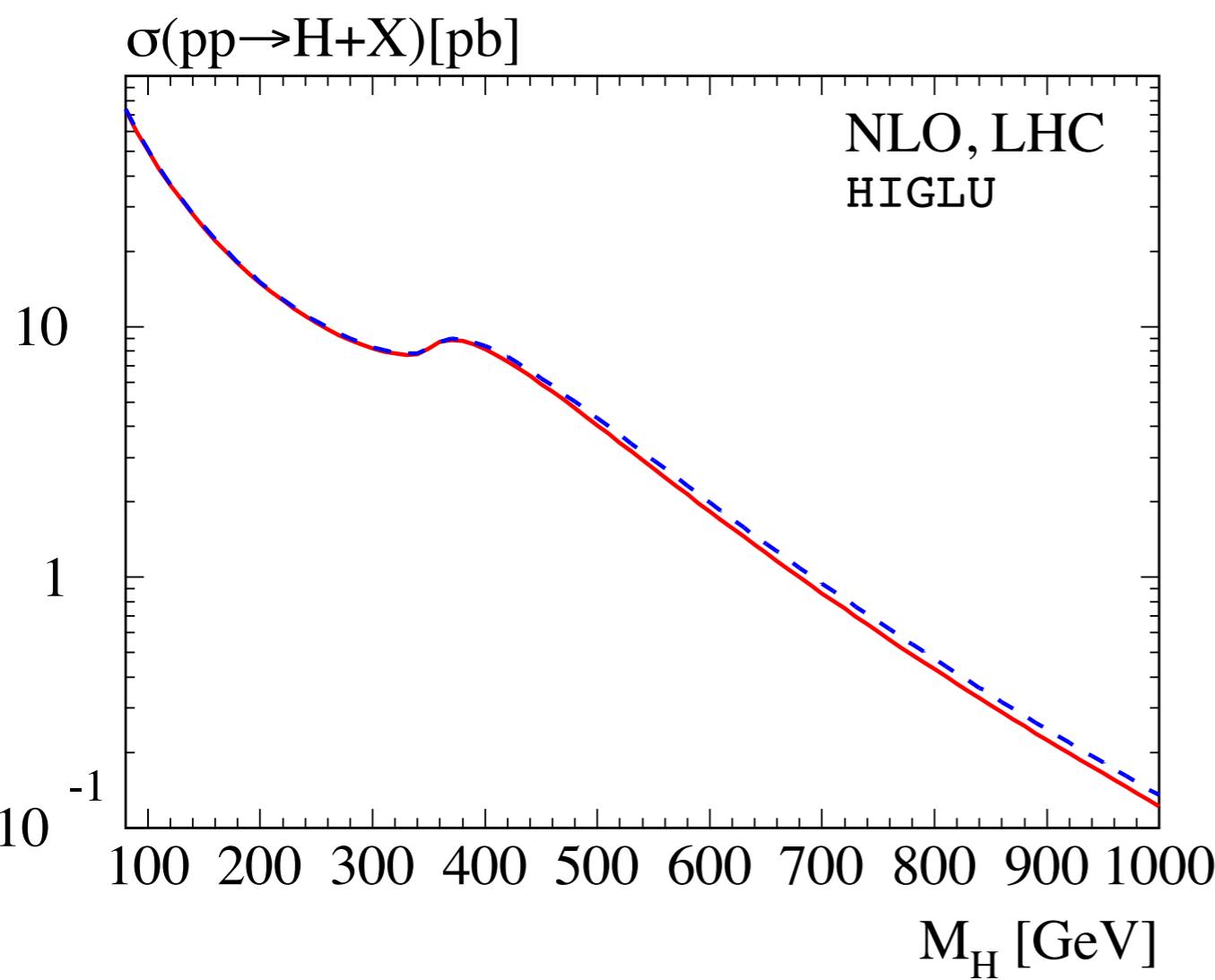
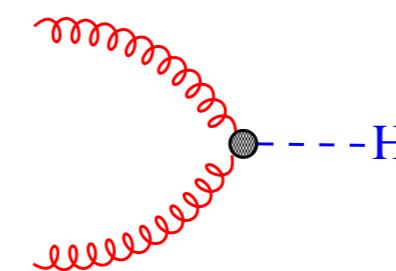
$$\sigma_{\infty}^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t) \left(\frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}} \right)_{m_t \rightarrow \infty}$$

Effective Theory:



$$m_t \gg M_H$$

$$C(m_t, \alpha_s) \times$$



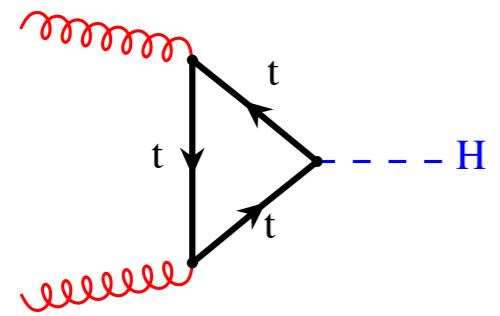
$$\sigma_\infty^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t) \left(\frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}} \right)_{m_t \rightarrow \infty}$$

NLO:

Djouadi, Spira, Zerwas '93

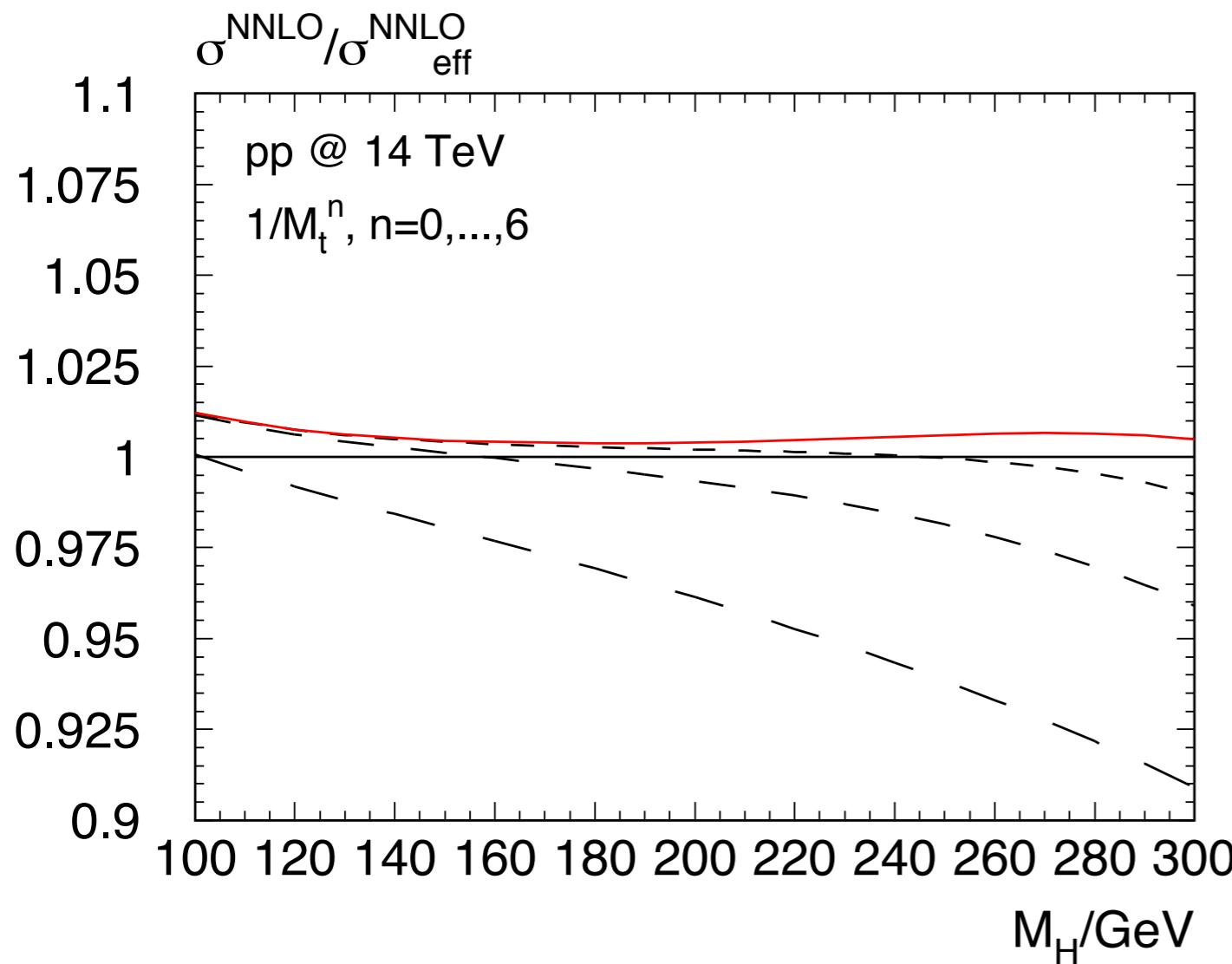
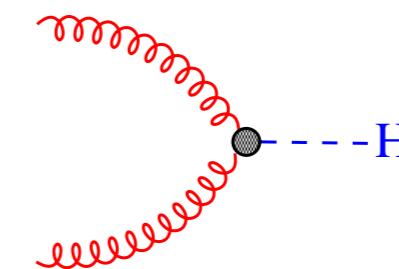
Krämer, Laenen, Spira '96

Effective Theory:



$m_t \gg M_H$

$C(m_t, \alpha_s) \times$



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

NLO:

Djouadi, Spira, Zerwas '93

Krämer, Laenen, Spira '96

NNLO:

Marzani et al. '08

RH, Mantler, Marzani, Ozeren '09

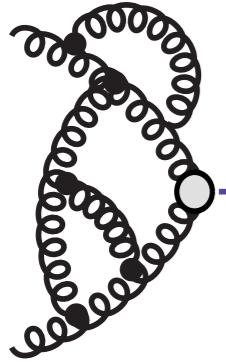
Pak, Rogal, Steinhauser '09

Gluon fusion: recent progress

- **Higgs line shape**
Goria, Passarino, Rosco '12; Anastasiou, Buehler, Herzog, Lazopoulos '11
- **Signal/Background interference**
Glover, v.d. Bij '89; Binoth, Ciccolini, Kauer, Krämer '06;
Campbell, Ellis, Williams '11; Kauer '12; Passarino '12
S.P. Martin '13
- **validity of effective $1/m_t$ theory**
RH, Mantler, Marzani, Ozeren '09; Pak, Rogal, Steinhauser '09
Alwall, Li, Maltoni '11; Bagnaschi, Degrassi, Slavich, Vicini '11
RH, Neumann, Wiesemann '12
- **jet veto uncertainties**
Anastasiou, Dissertori, Grazzini, Stöckli, Webber '09
Stewart, Tackmann '11
Banfi, Monni, Salam, Zanderighi '12; Becher, Neubert '12
Tackmann, Walsh, Zuberi '12

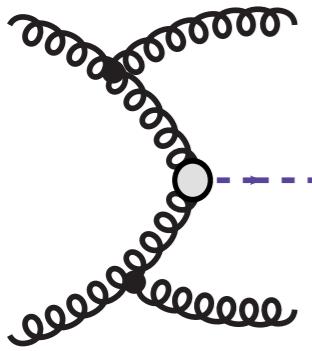
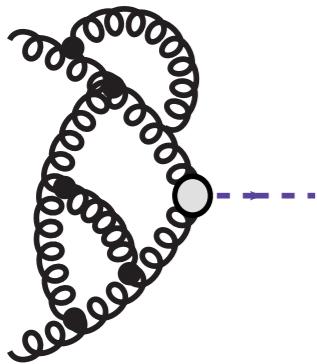
Towards NNNLO:

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Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09
Lee, Smirnov, Smirnov '10
Gehrmann, Glover, Huber, Ikizlerli, Studerus '09

Towards NNNLO:

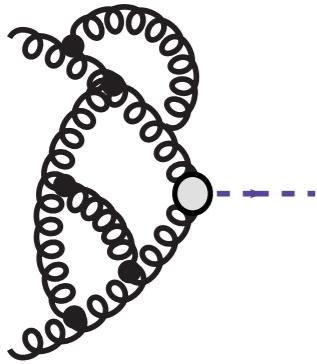


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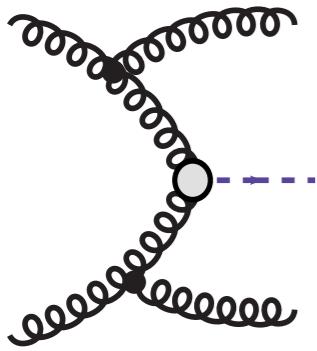
$O(\epsilon)$

Anastasiou, Bühler, Duhr, Herzog '12
Hoschele, Hoff, Pak, Steinhauser, Ueda '12

Towards NNNLO:

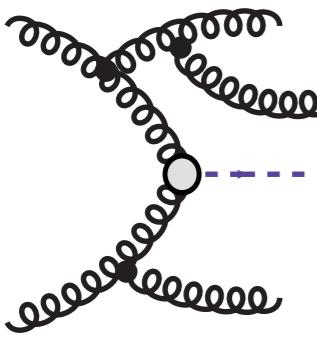


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Lee, Smirnov, Smirnov '10
Gehrmann, Glover, Huber, Ikizlerli, Studerus '09



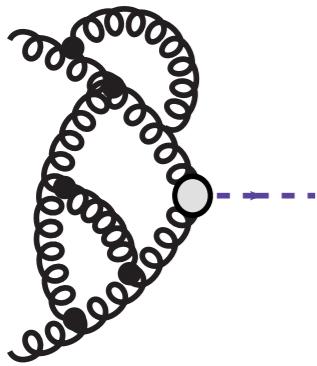
$O(\epsilon)$

Anastasiou, Bühler, Duhr, Herzog '12
Hoschele, Hoff, Pak, Steinhauser, Ueda '12



Anastasiou, Duhr, Dulat, Mistlberger '13

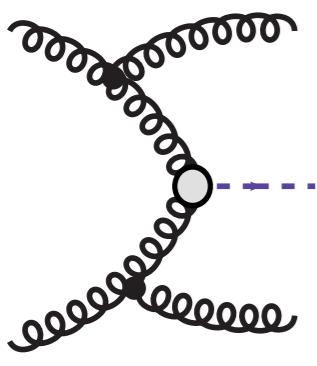
Towards NNNLO:



Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09

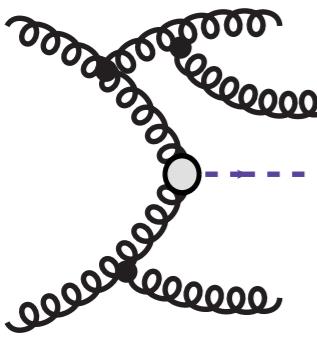
Lee, Smirnov, Smirnov '10

Gehrmann, Glover, Huber, Ikizlerli, Studerus '09

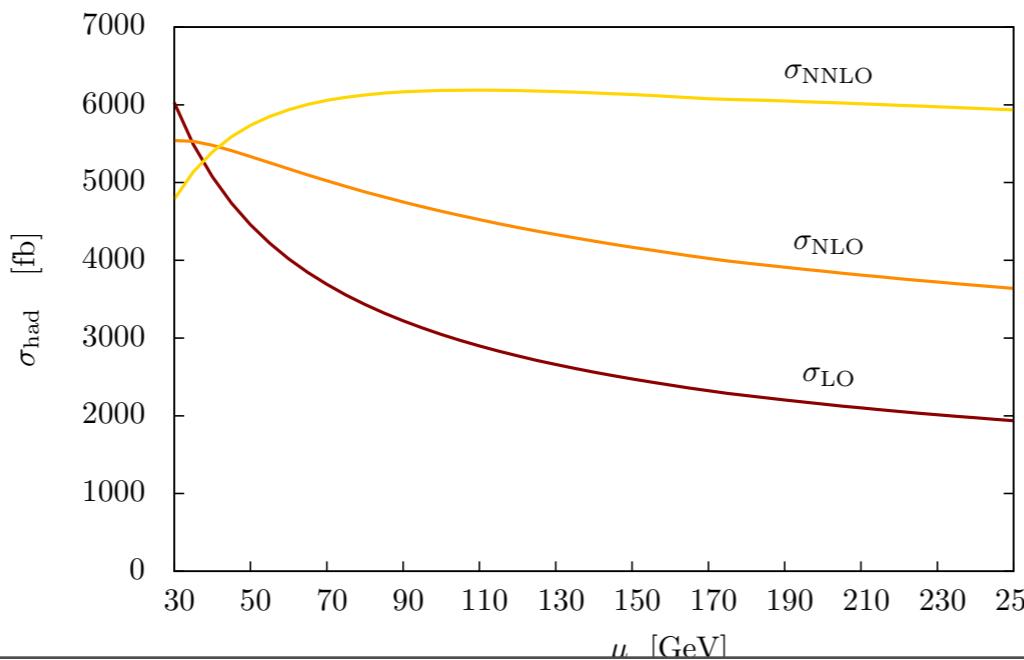
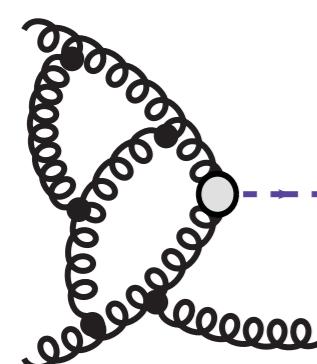


$\mathcal{O}(\epsilon)$

Anastasiou, Bühler, Duhr, Herzog '12
Hoschele, Hoff, Pak, Steinhauser, Ueda '12

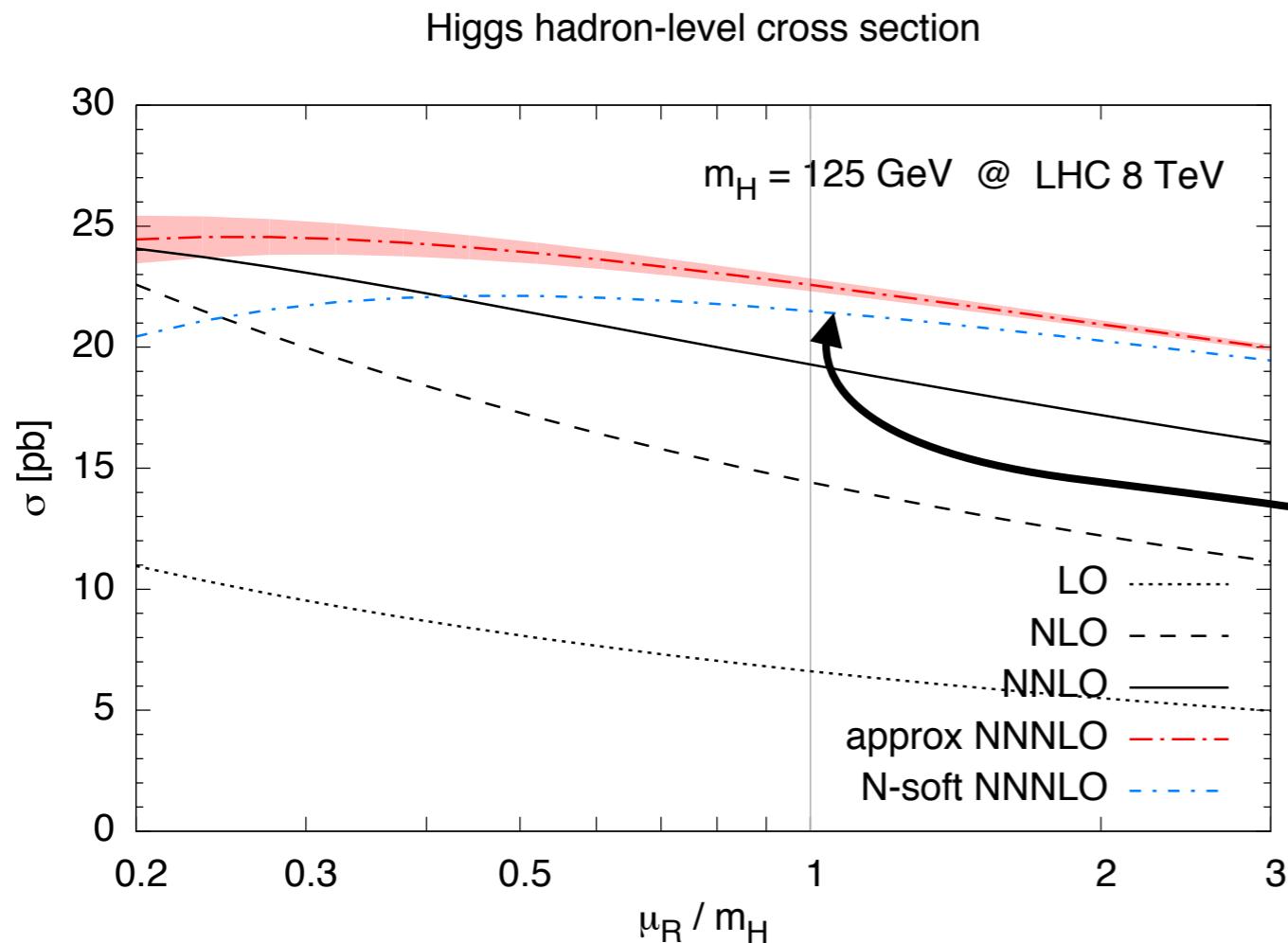


Anastasiou, Duhr, Dulat, Mistlberger '13



Boughezal, Caola, Melnikov,
Petriello, Schulze '13

Approximate NNNLO:



Ball, Bonvini, Forte, Marzani,
Ridolfi '13

Combination of low- and high-
energy limit, including finite m_t !

Moch, Vogt '05
low-energy limit, infinite m_t

ATLAS Preliminary

$W, Z H \rightarrow bb$

$\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.7 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

$H \rightarrow \tau\tau$

$\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

$\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int L dt = 20.7 \text{ fb}^{-1}$

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int L dt = 20.7 \text{ fb}^{-1}$

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

$\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int L dt = 20.7 \text{ fb}^{-1}$

Combined

$\mu = 1.30 \pm 0.20$

$\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 - 4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 - 20.7 \text{ fb}^{-1}$

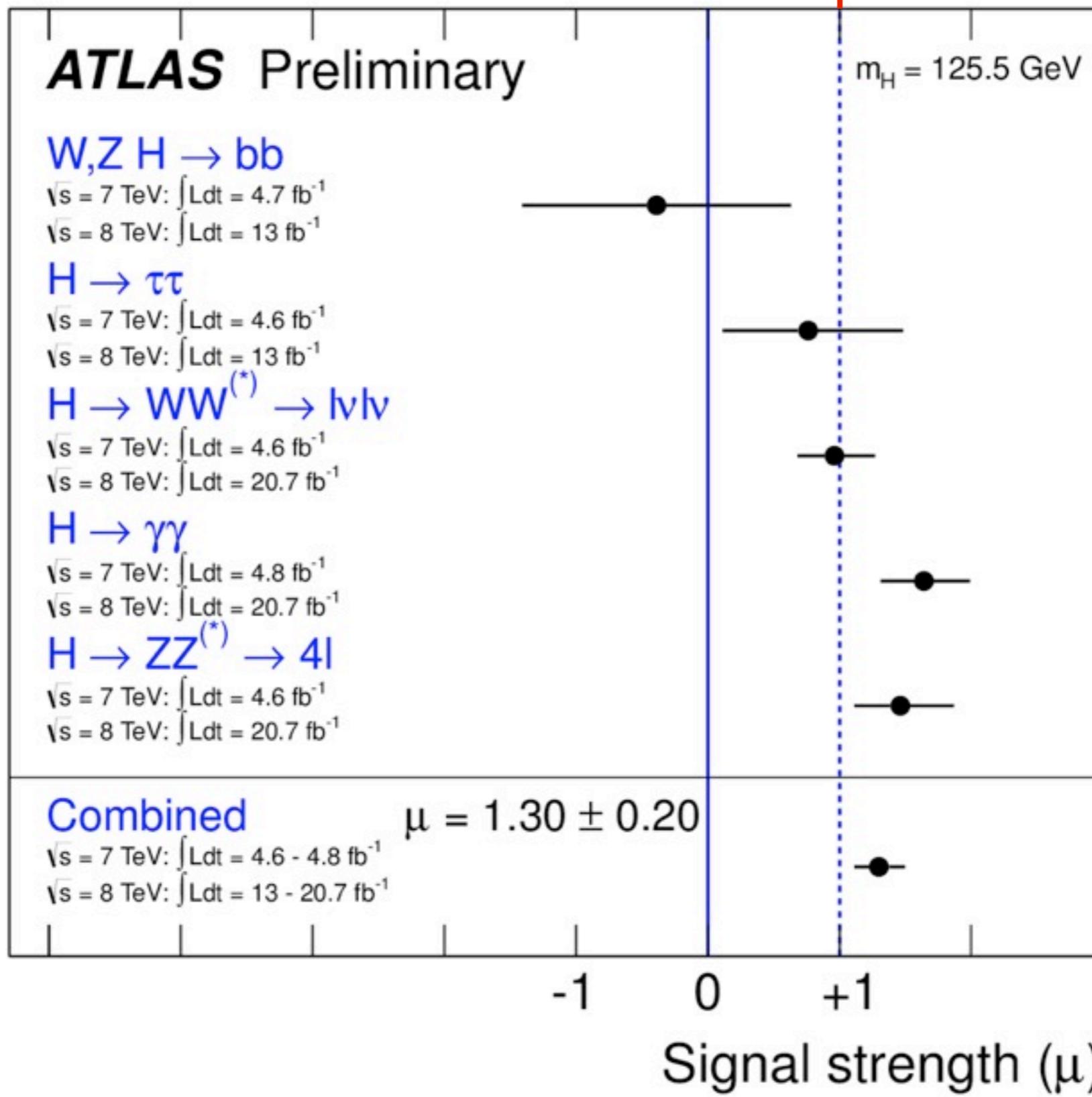
$m_H = 125.5 \text{ GeV}$

March 2013

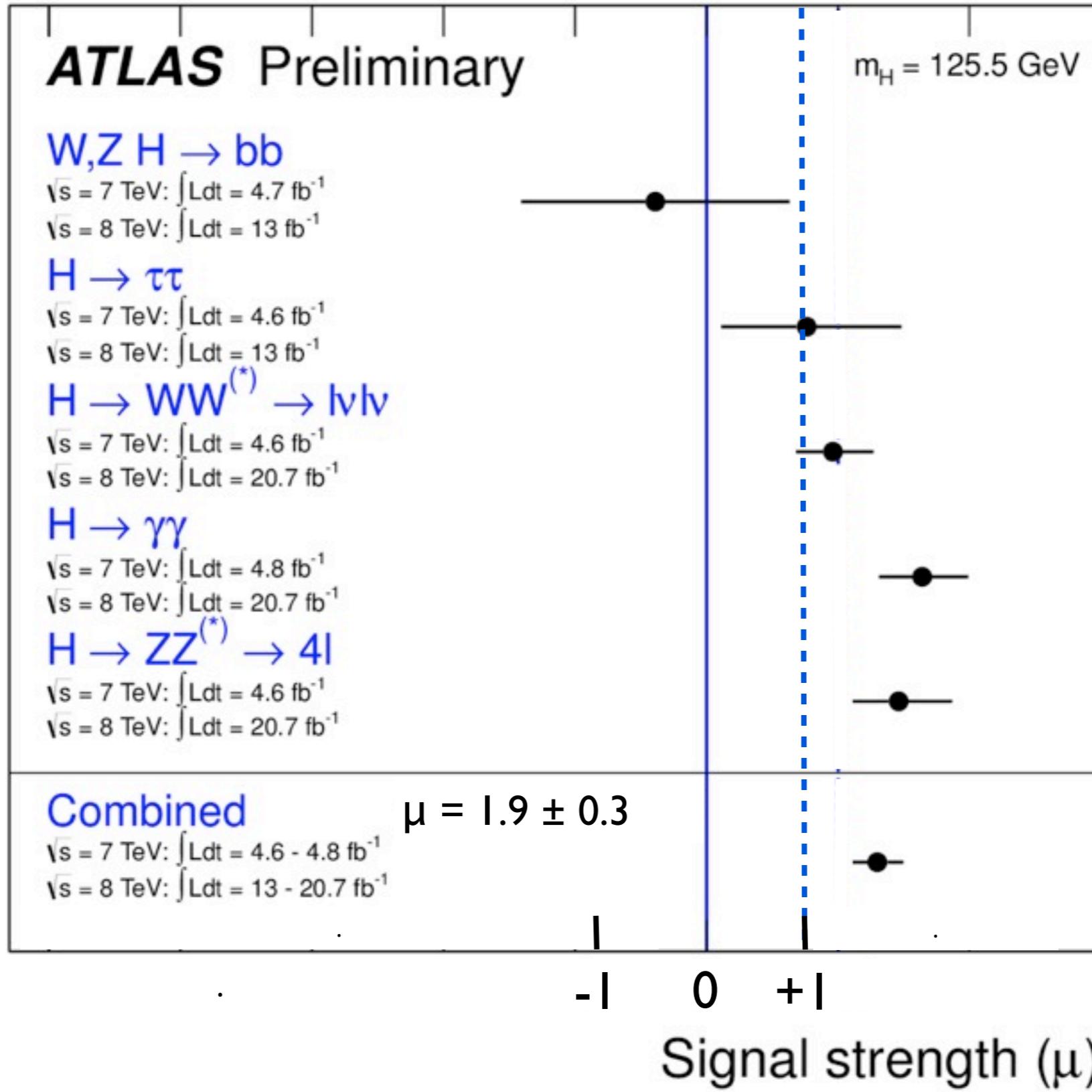
-1 0 +1

Signal strength (μ)

NNLO+

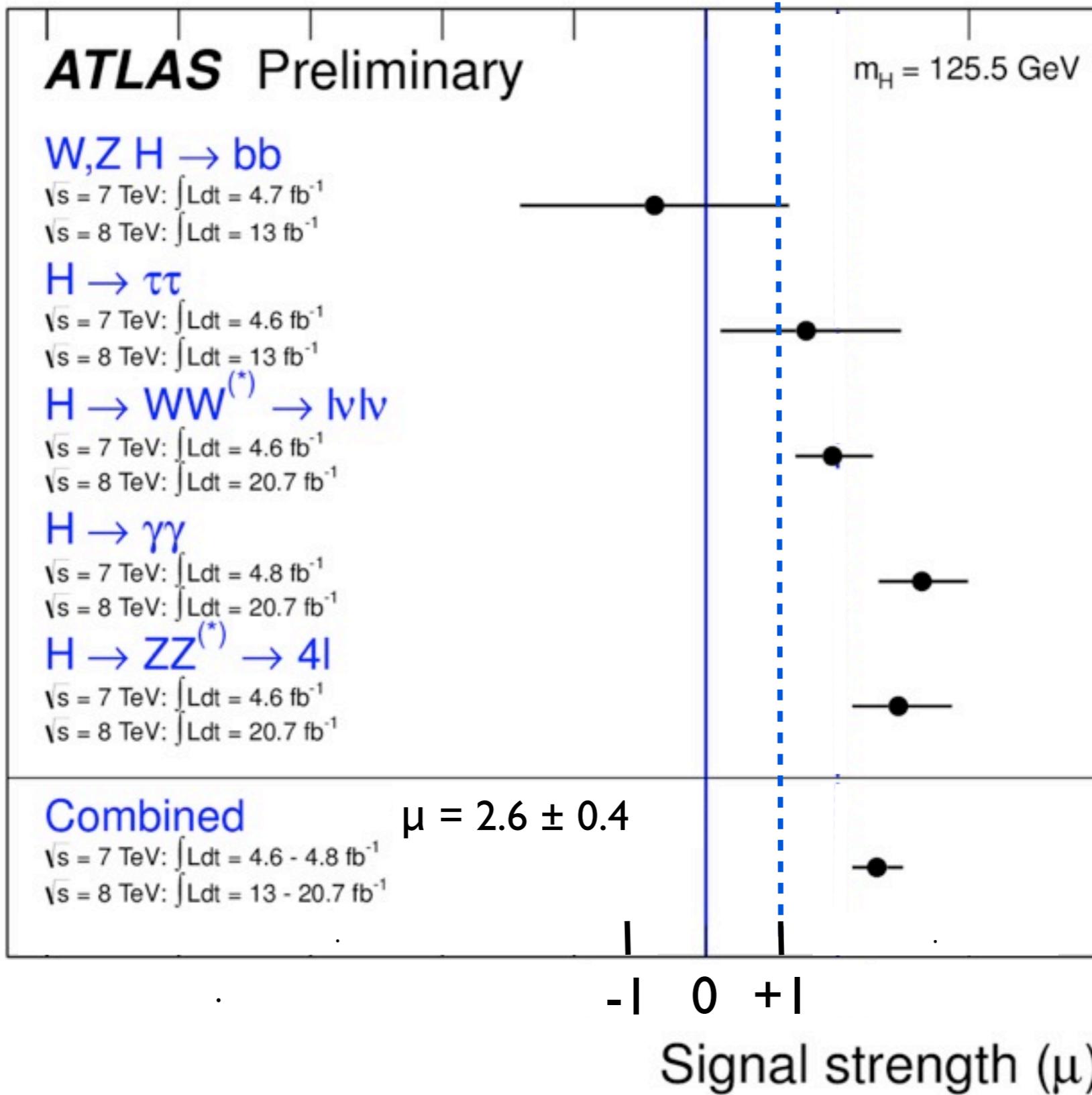


March 2013



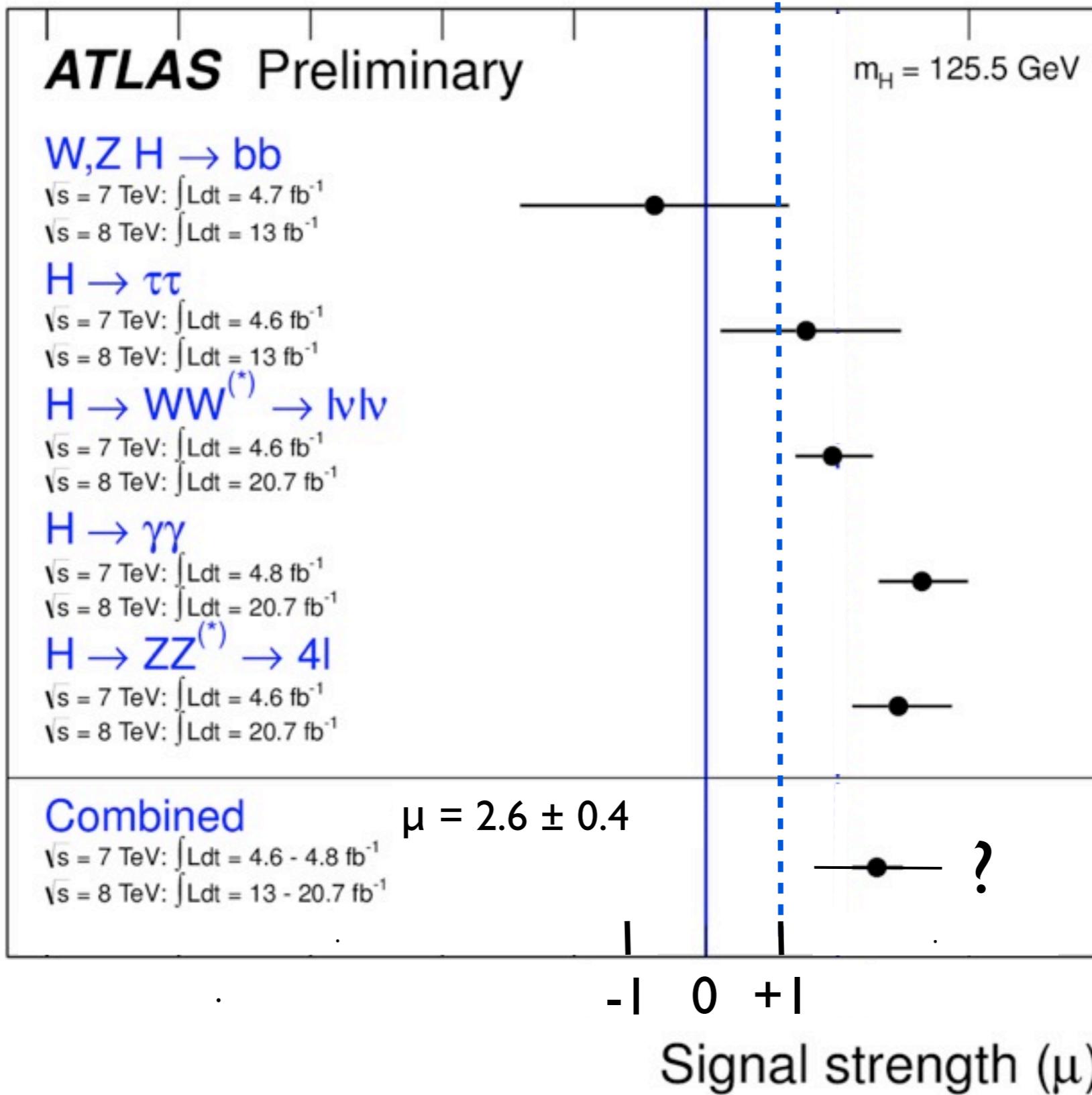
highly
unofficial
and
sketchy!

LO

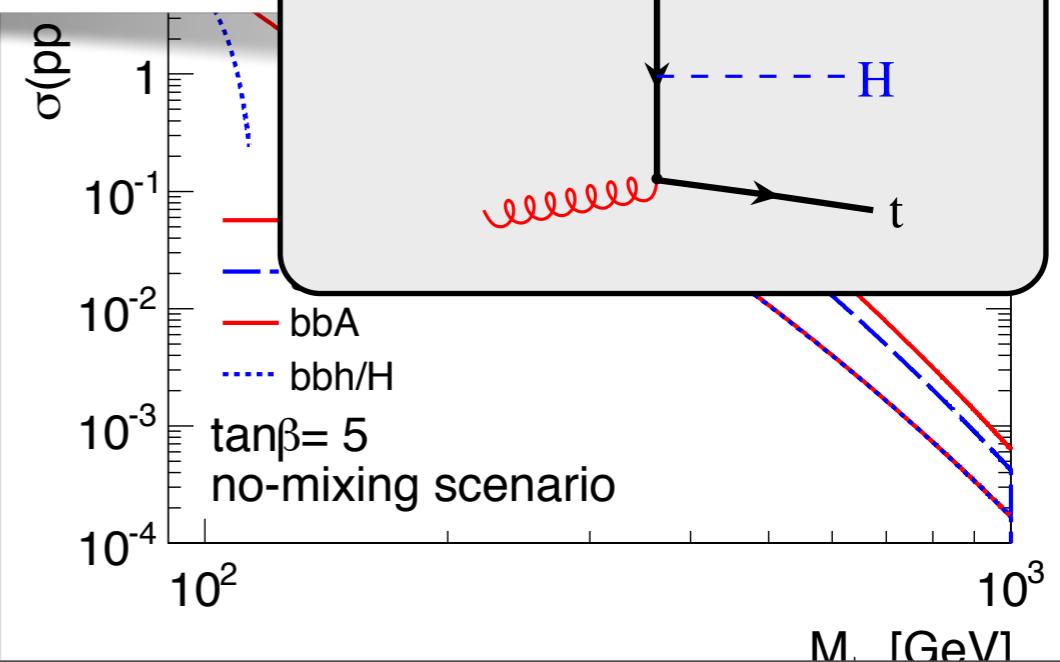
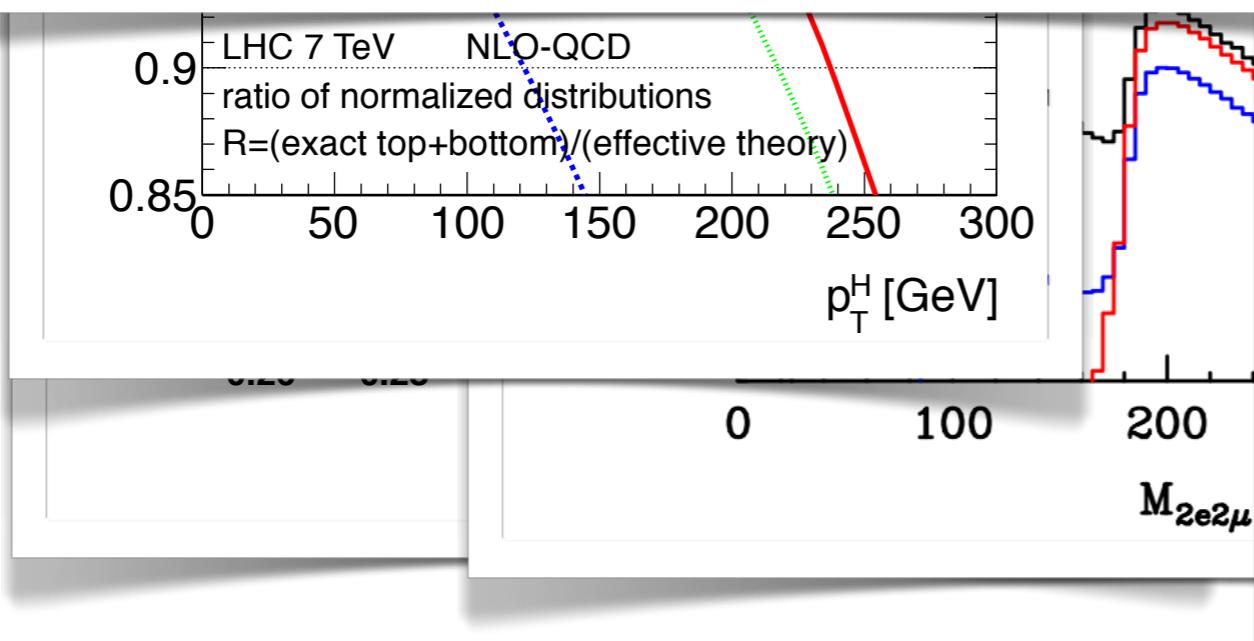
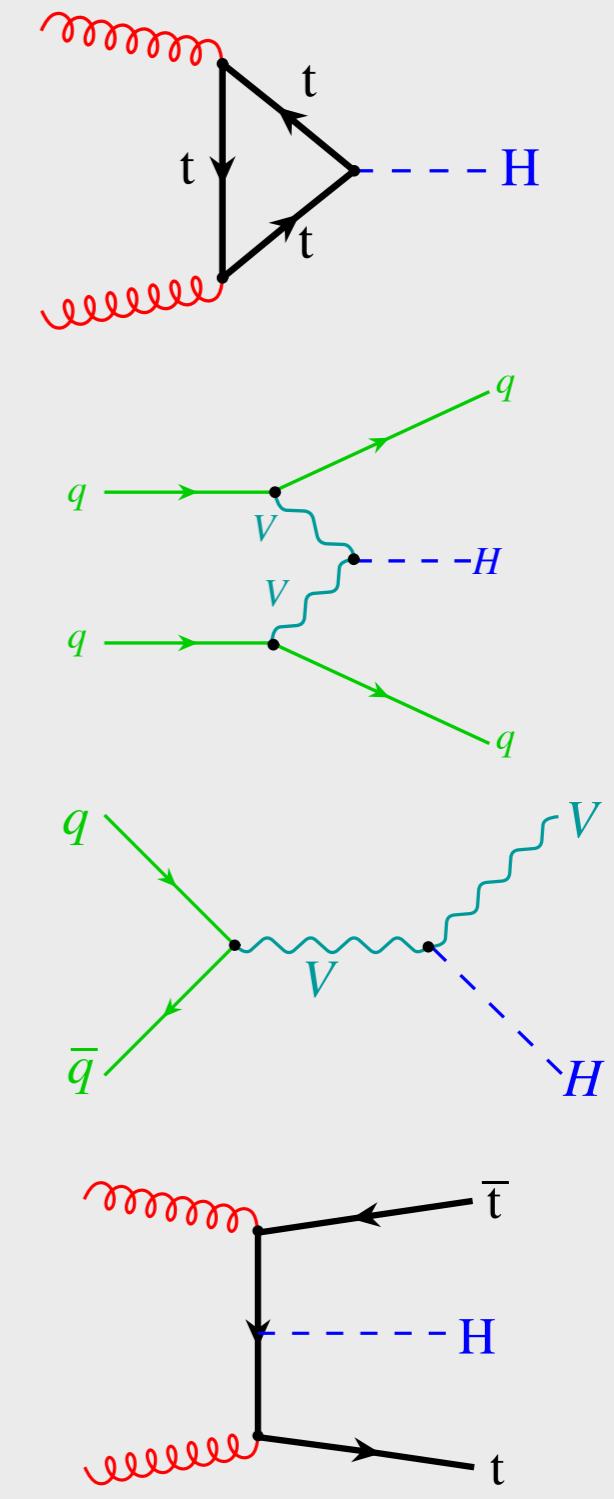
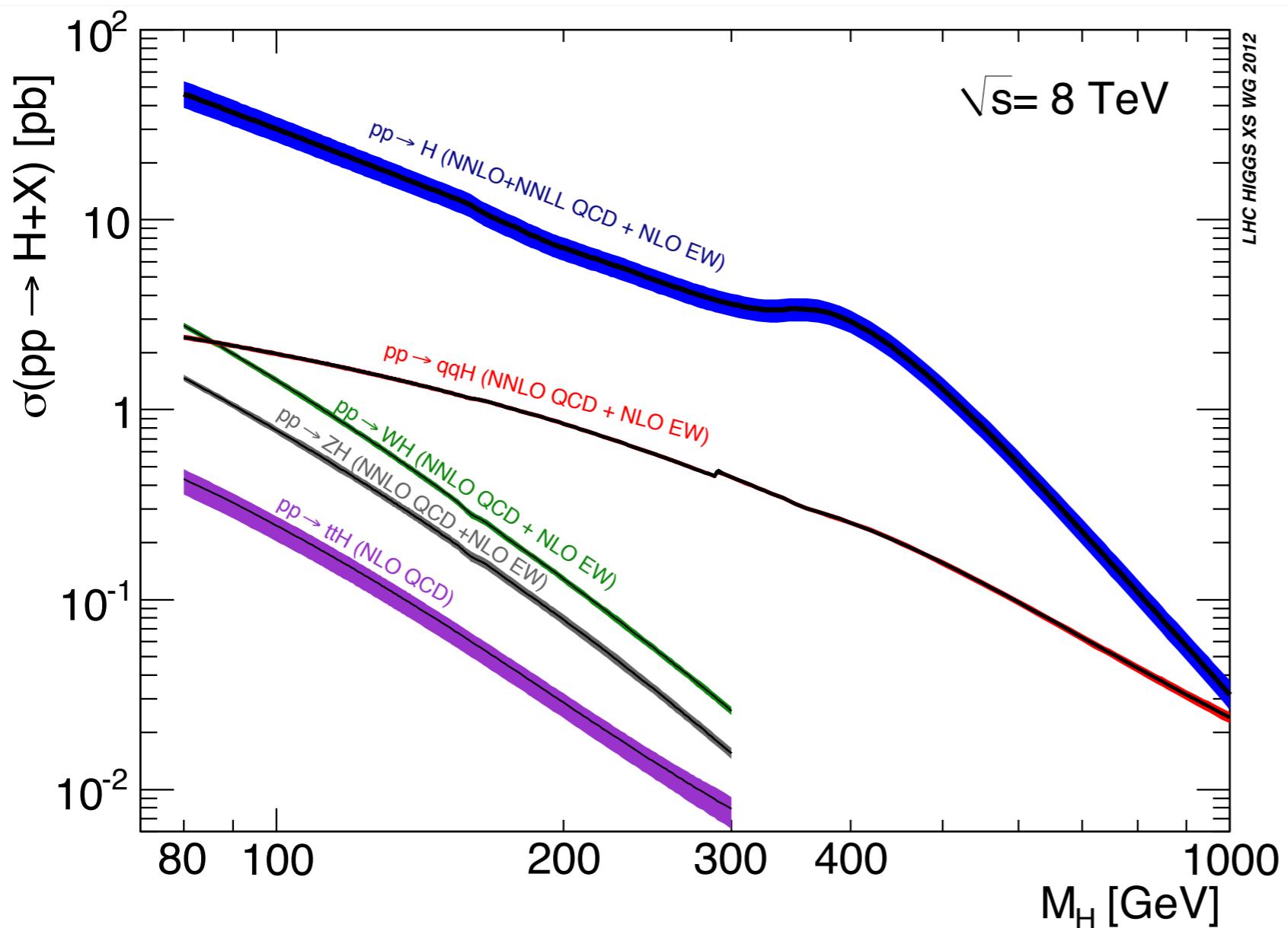


highly
unofficial
and
sketchy!

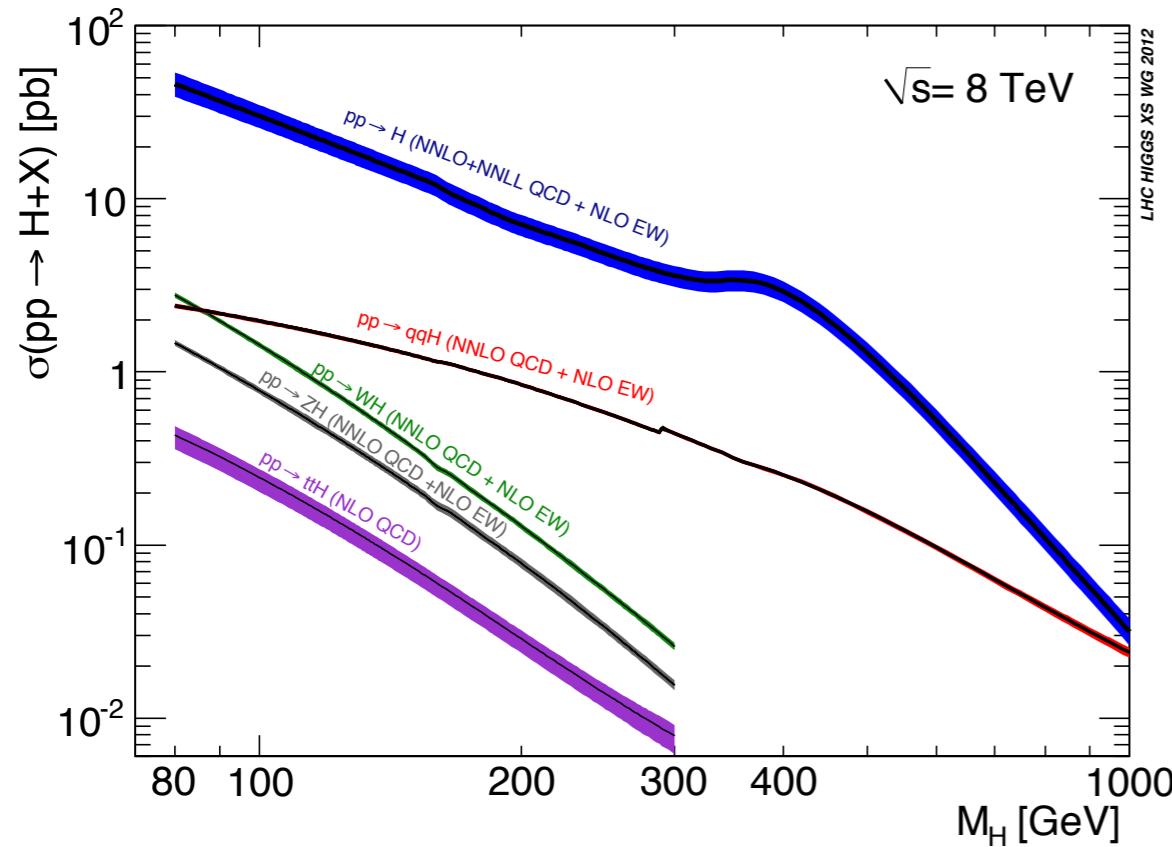
LO



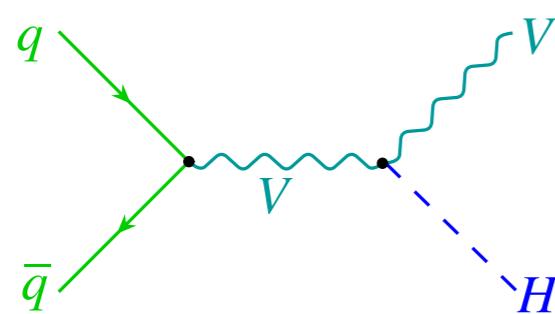
highly
unofficial
and
sketchy!



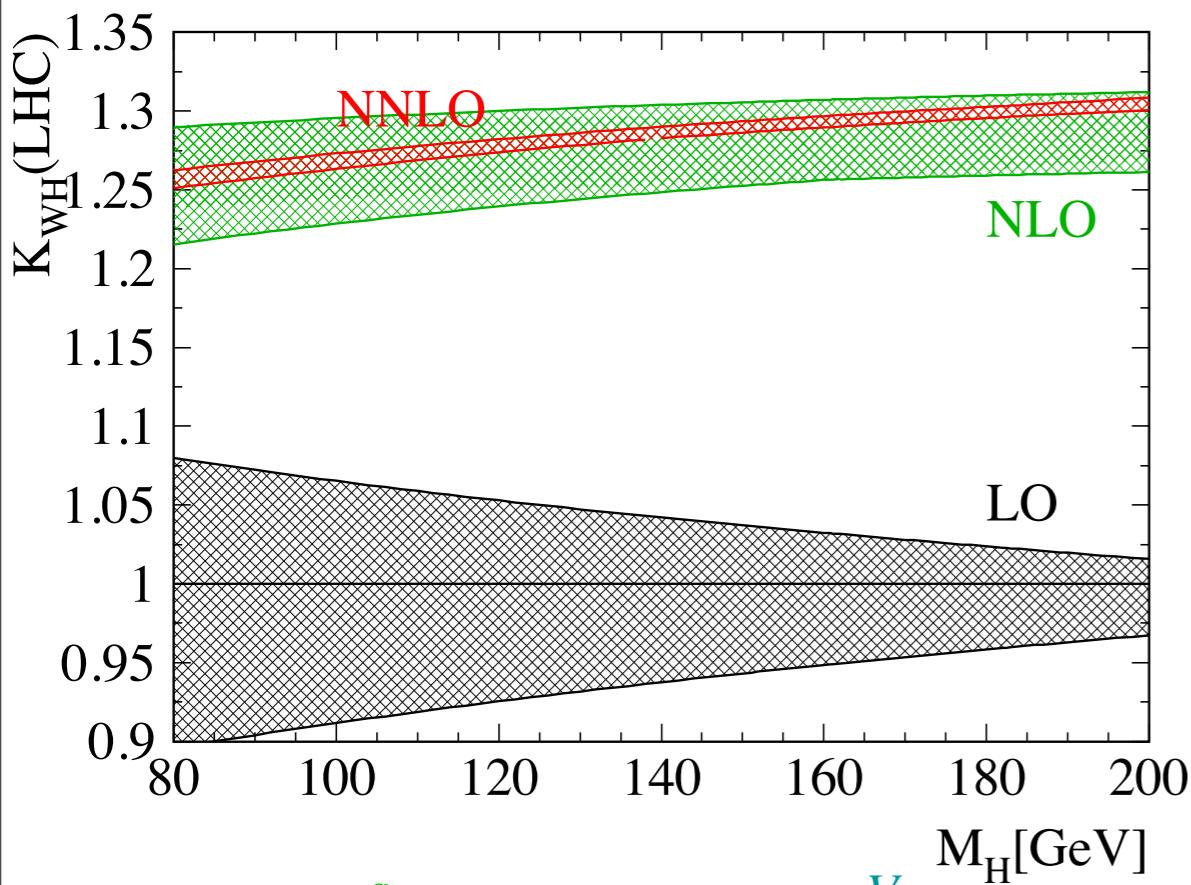
Higgs Strahlung



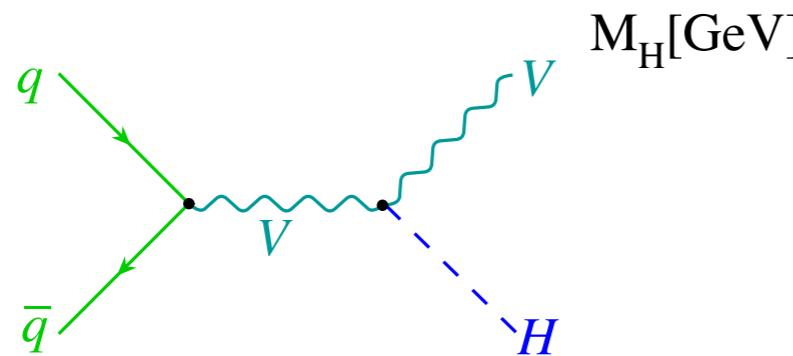
NLO: Han, Willenbrock '90
 NNLO: Brein, Djouadi, RH '03
 EW: Ciccolini, Dittmaier, Krämer '03



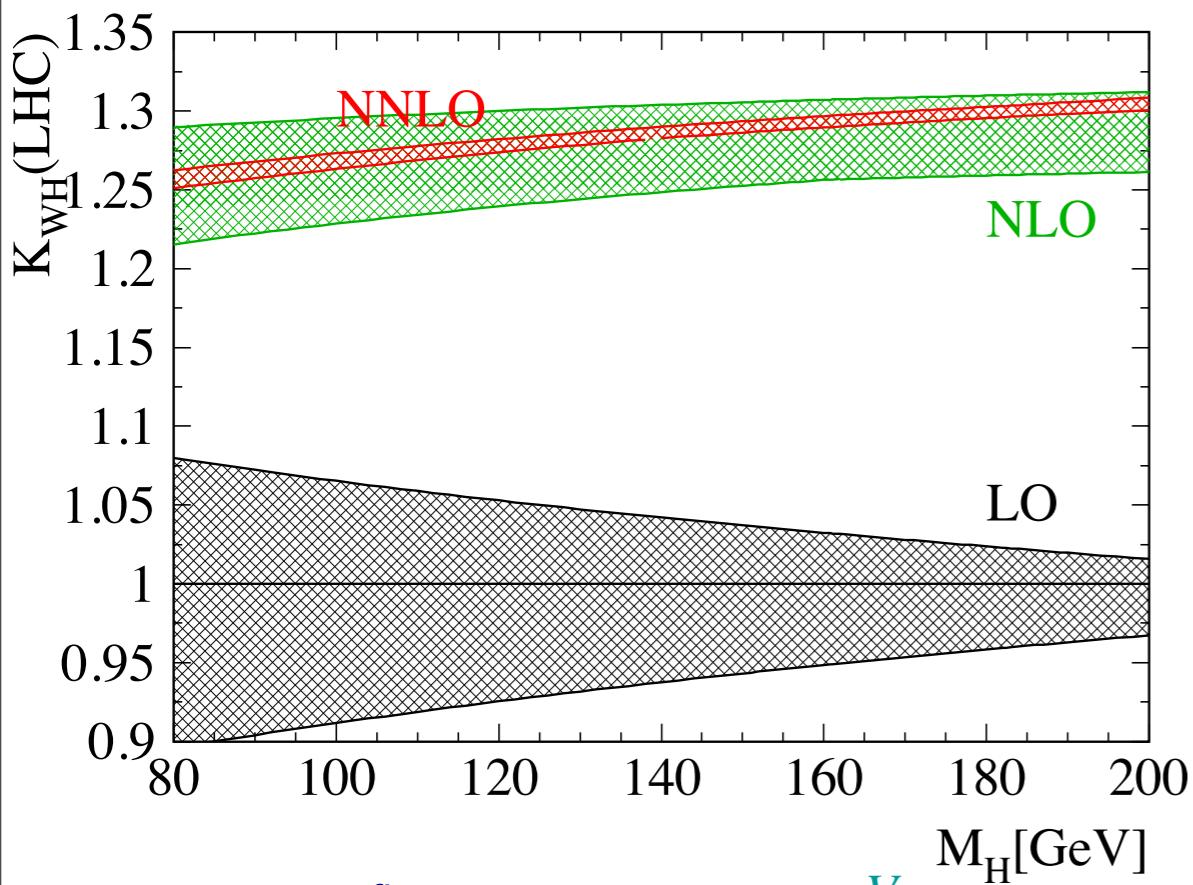
Higgs Strahlung



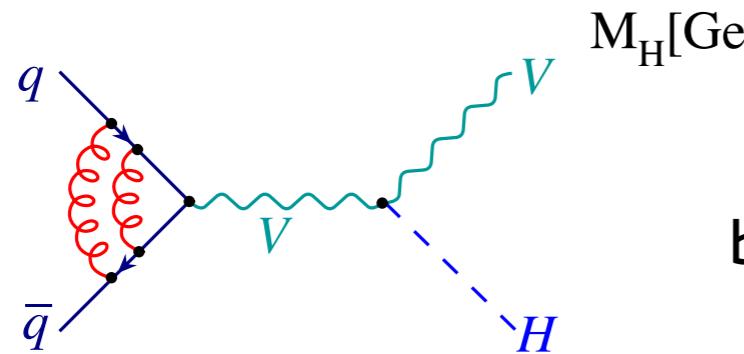
NLO: Han, Willenbrock '90
NNLO: Brein, Djouadi, RH '03
EW: Ciccolini, Dittmaier, Krämer '03



Higgs Strahlung

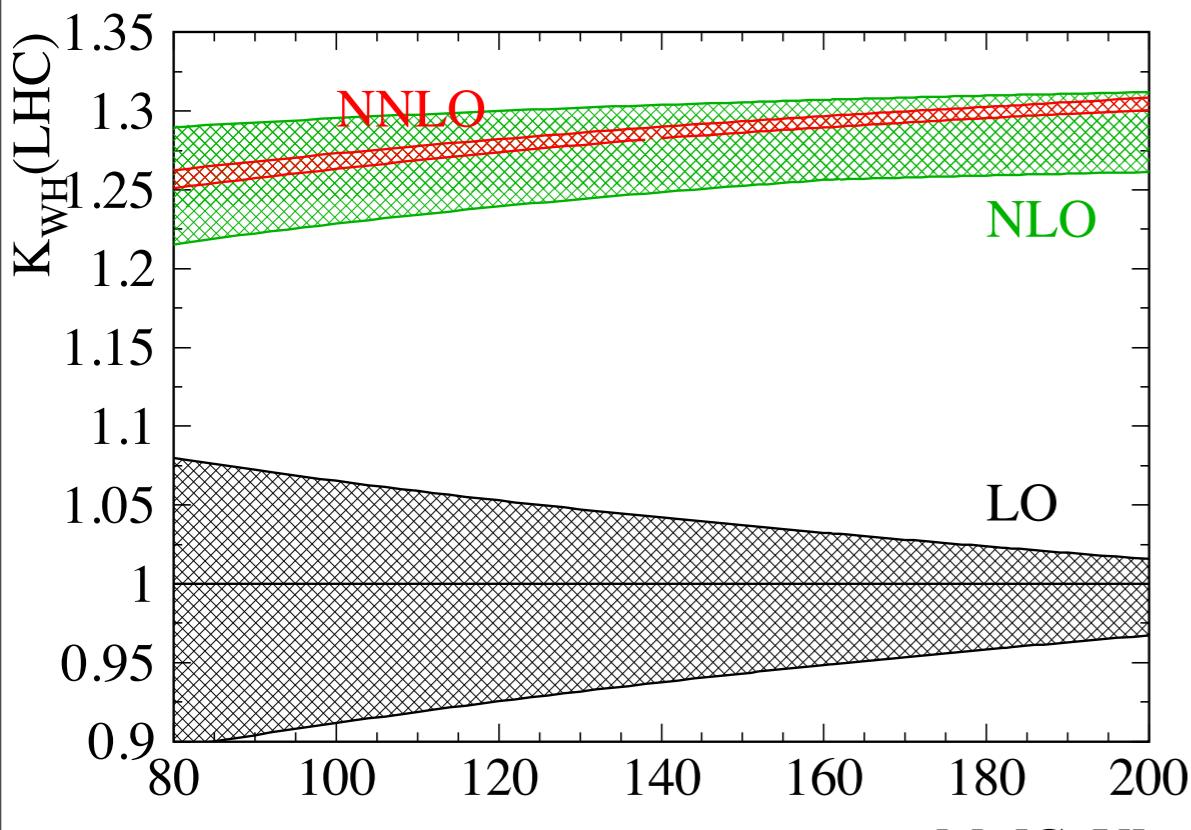


NLO: Han, Willenbrock '90
NNLO: Brein, Djouadi, RH '03
EW: Ciccolini, Dittmaier, Krämer '03

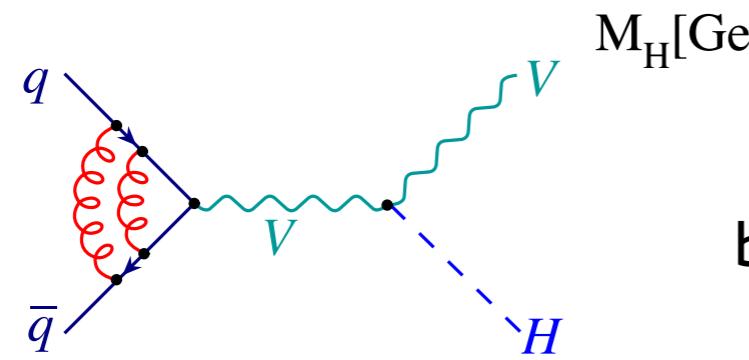


based on Hamberg, v. Neerven, Matsuura '91

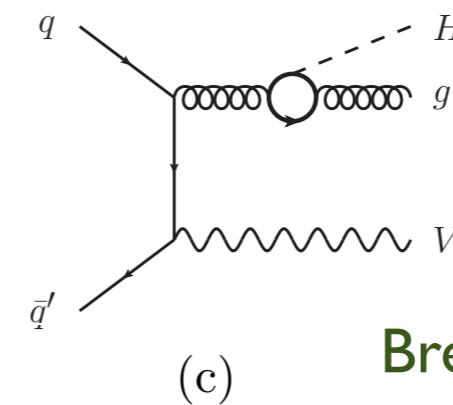
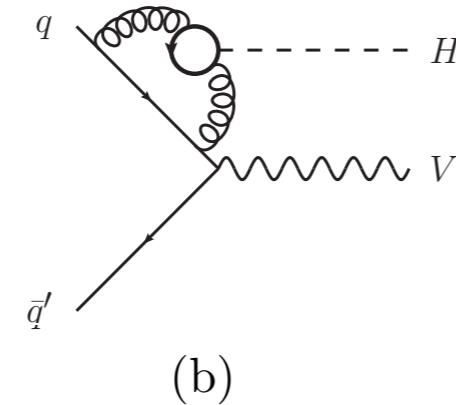
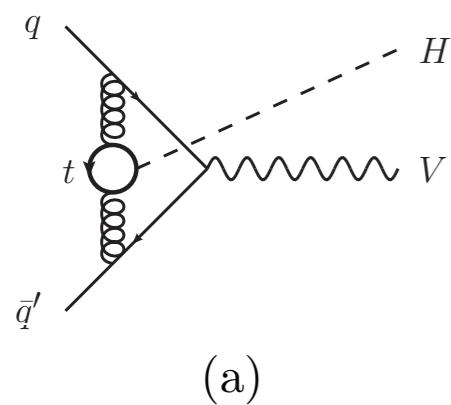
Higgs Strahlung



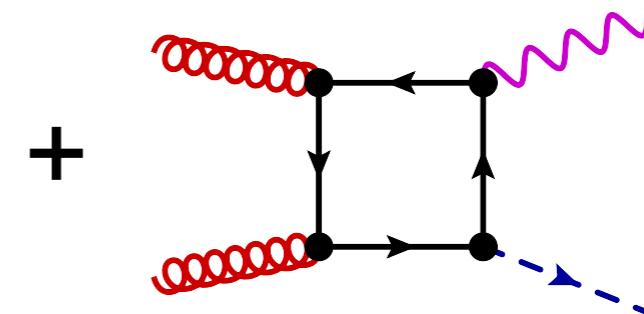
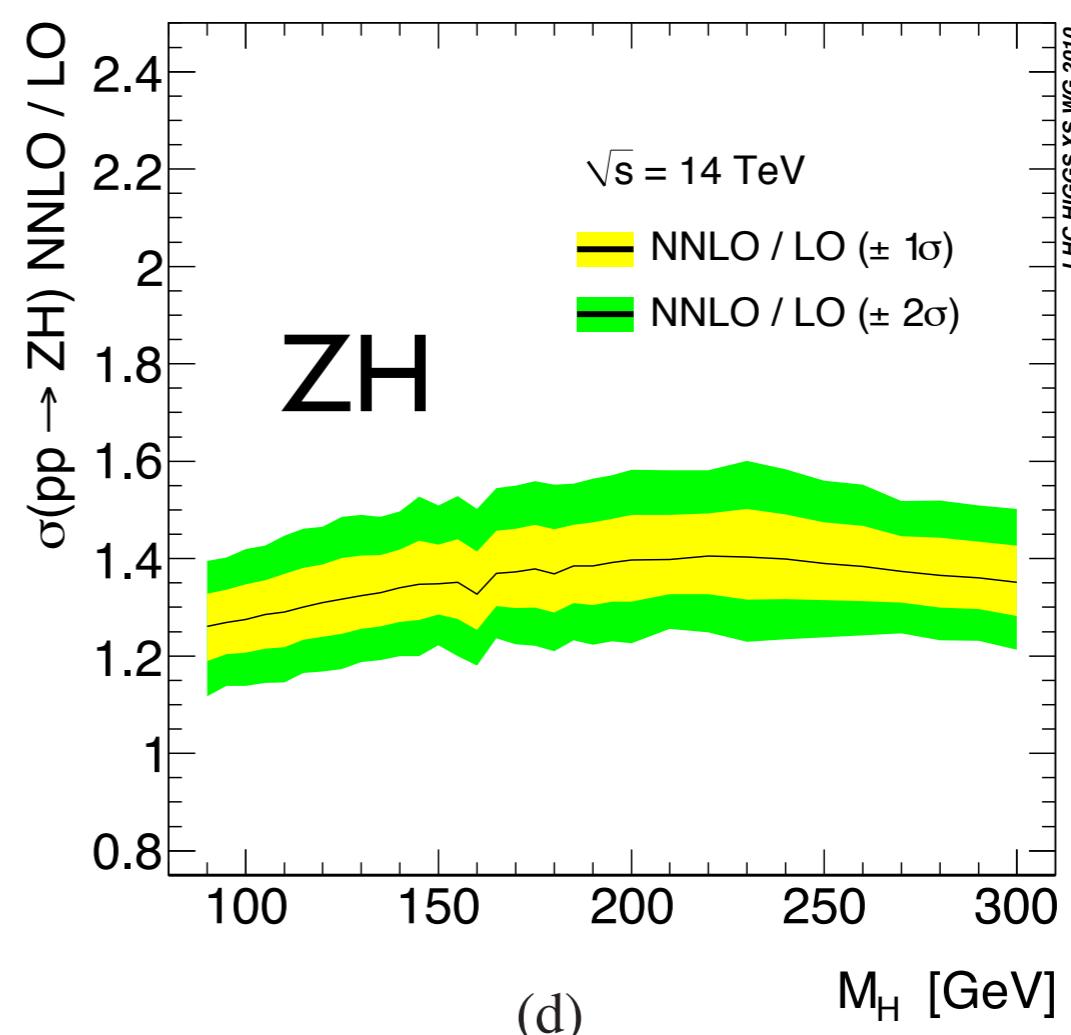
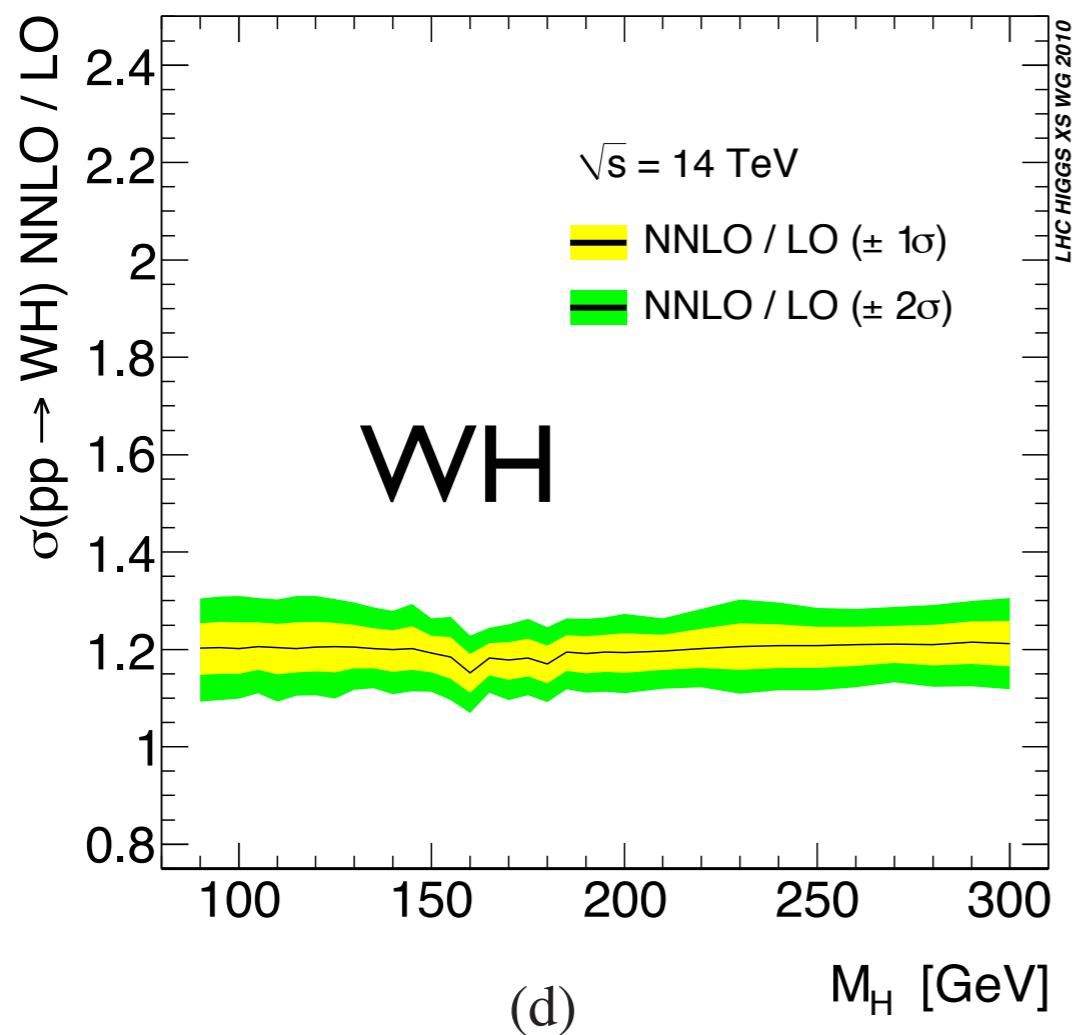
NLO: Han, Willenbrock '90
NNLO: Brein, Djouadi, RH '03
EW: Ciccolini, Dittmaier, Krämer '03

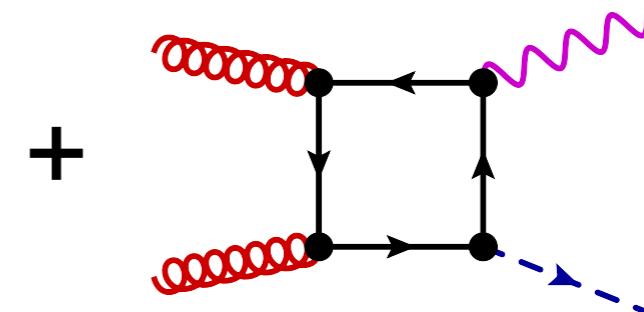
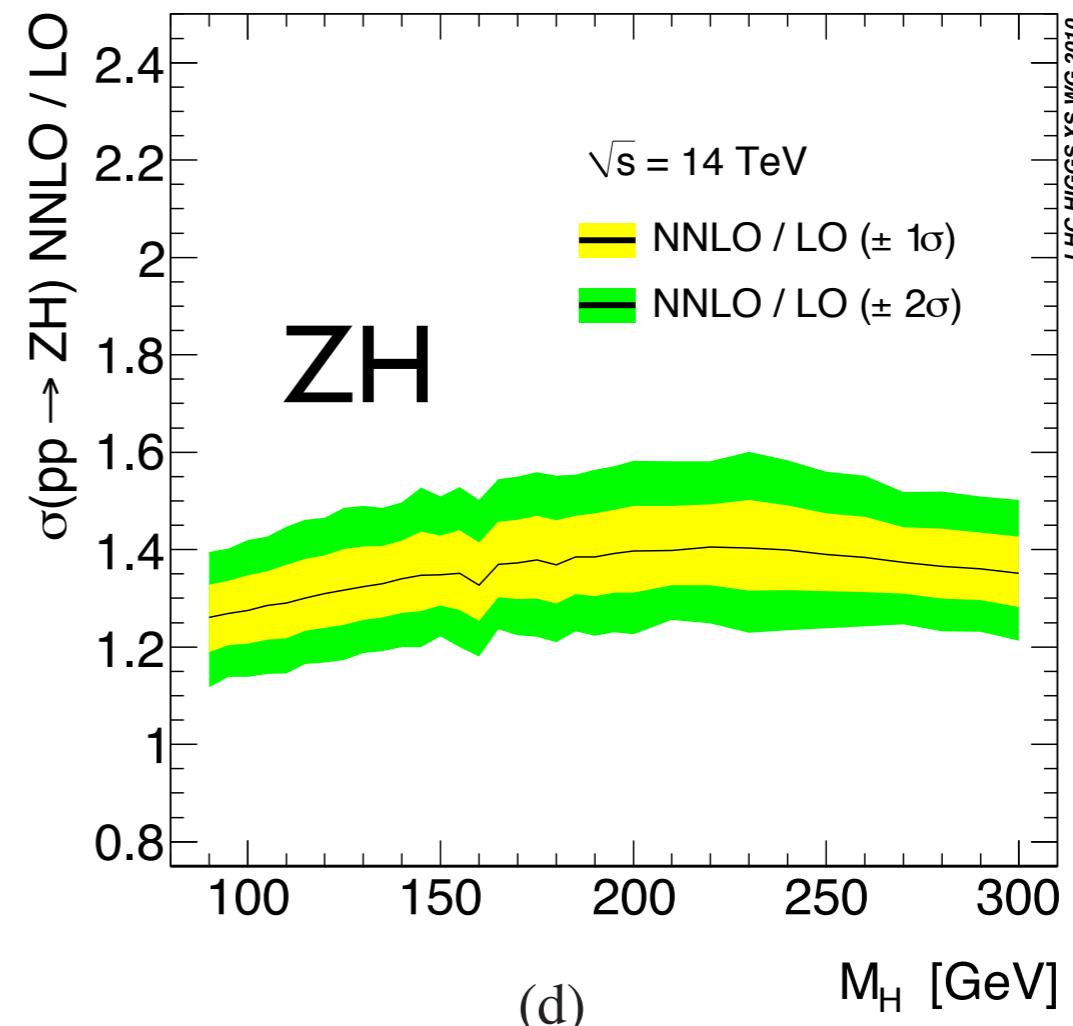
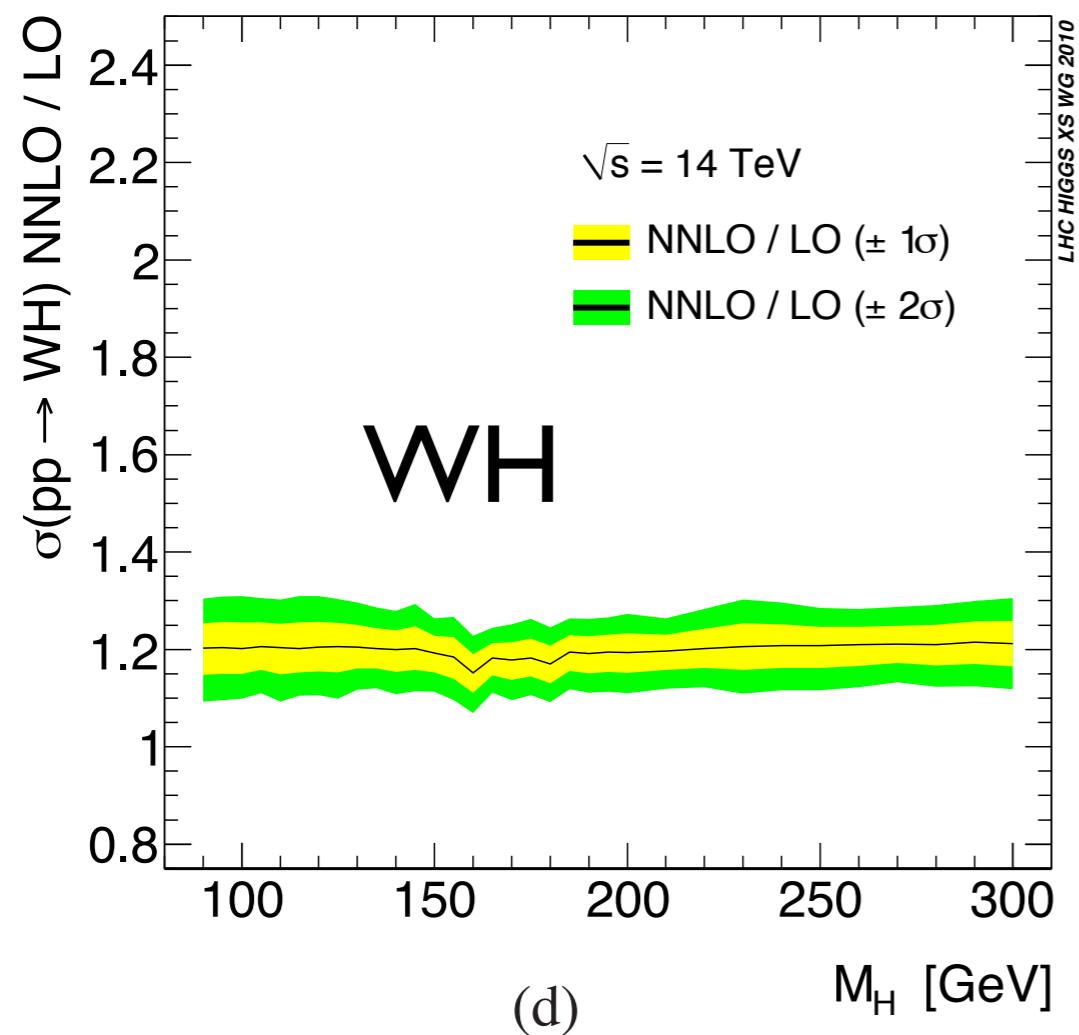


based on Hamberg, v. Neerven, Matsuura '91



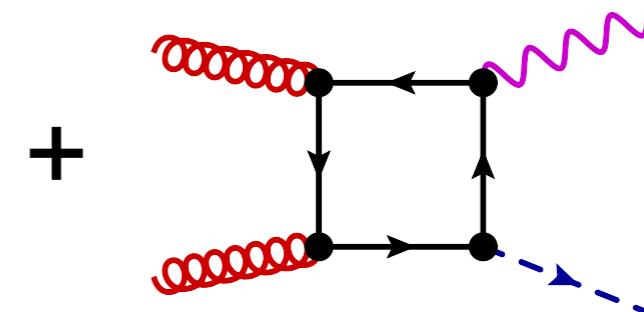
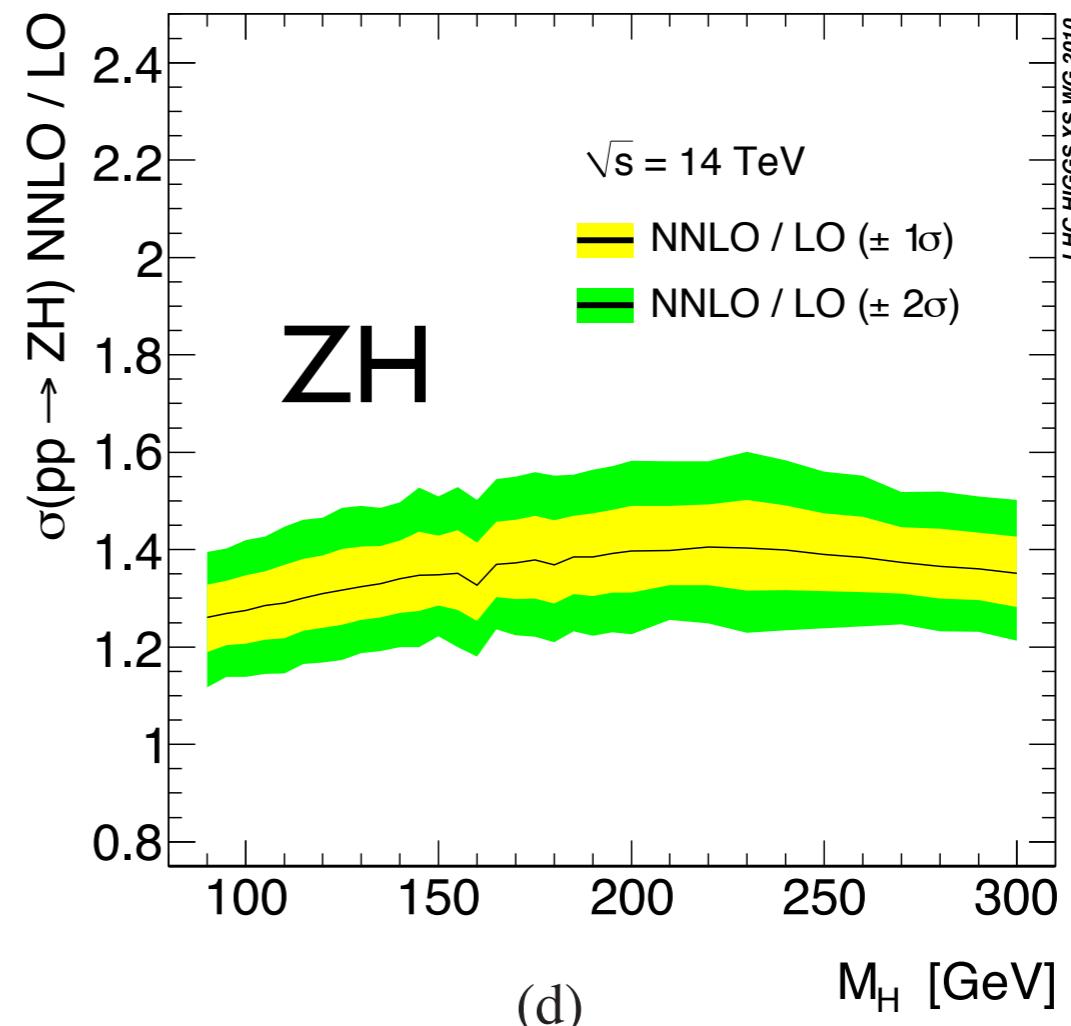
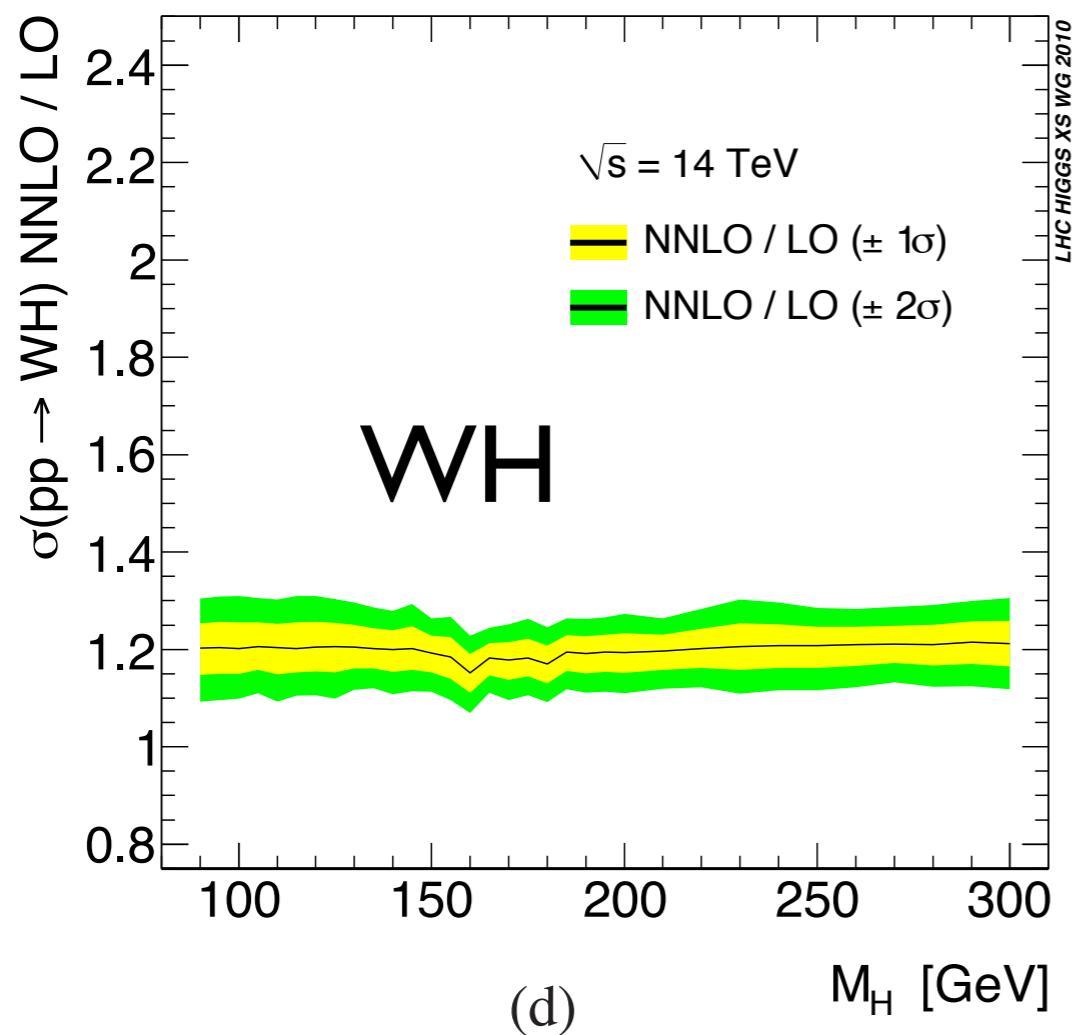
Brein, RH, Wiesemann, Zirke '11





Kniehl '90

NLO: Altenkamp, Dittmaier, RH, Rzehak, Zirke '12

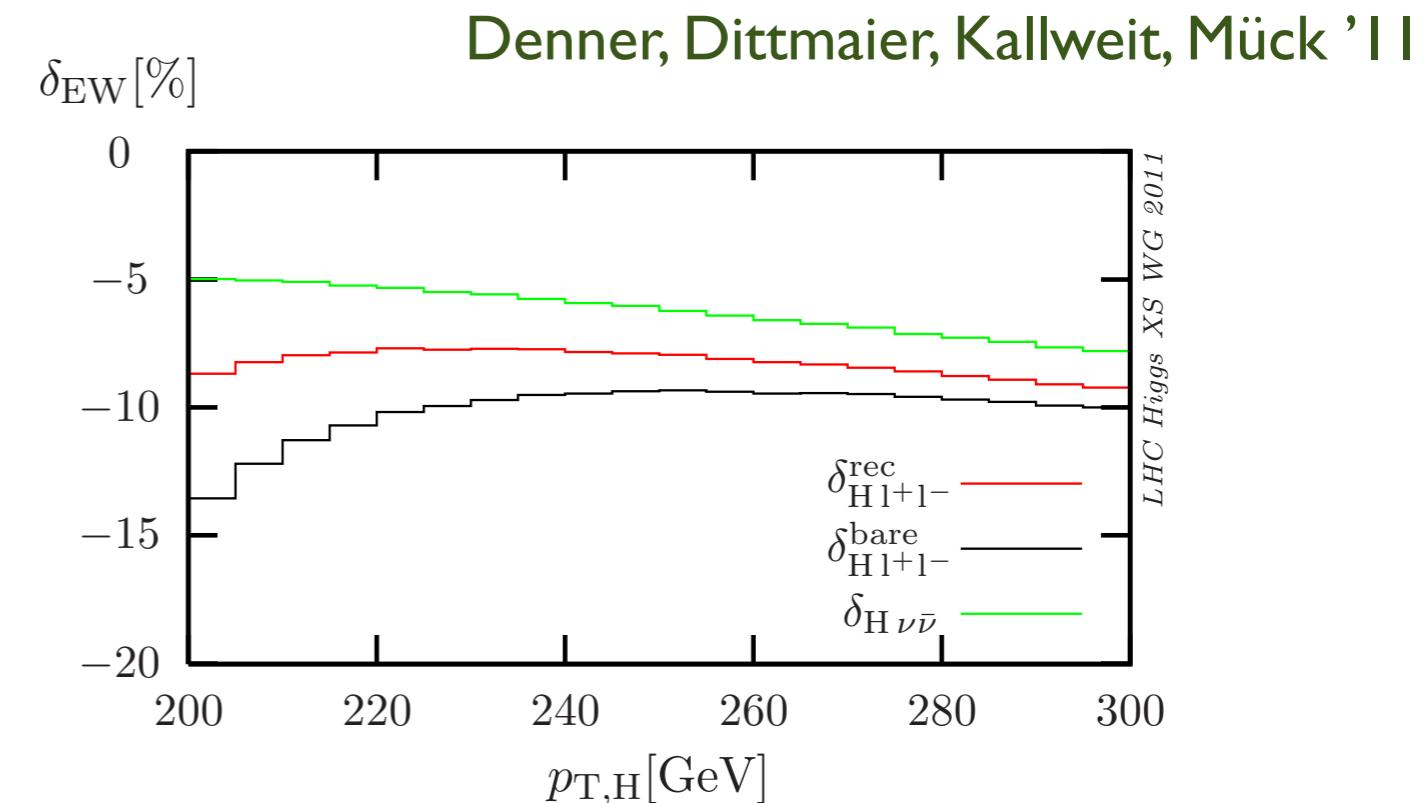
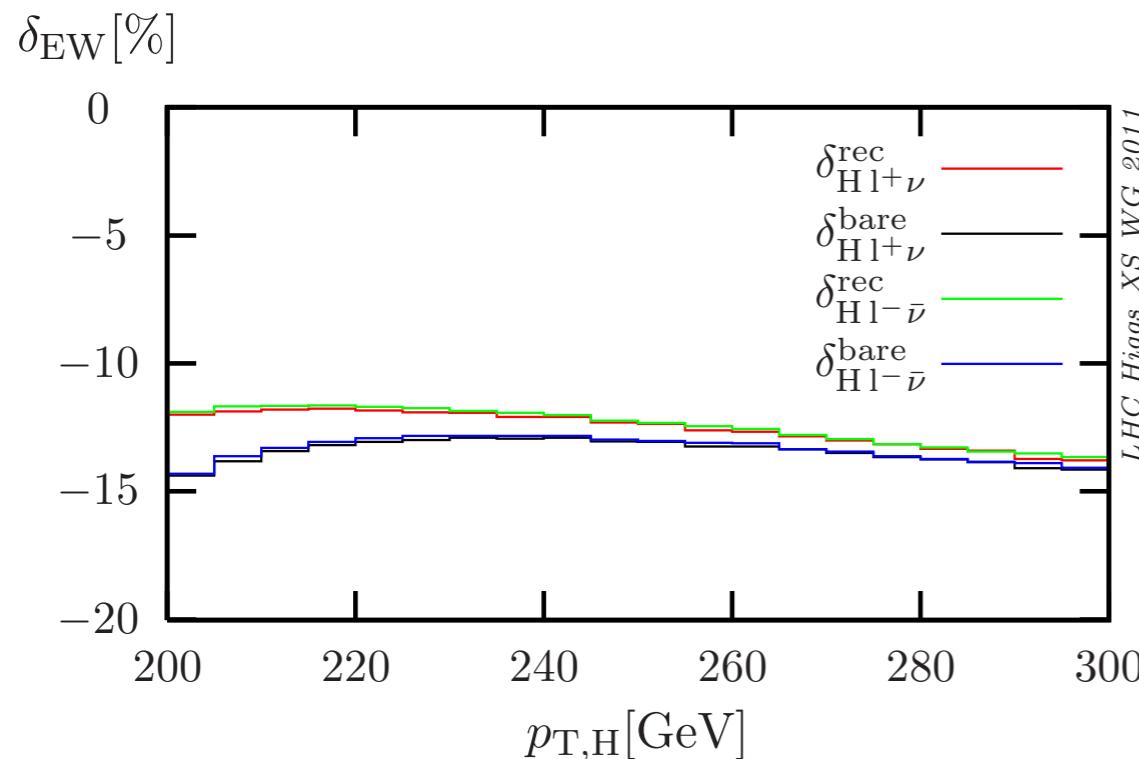
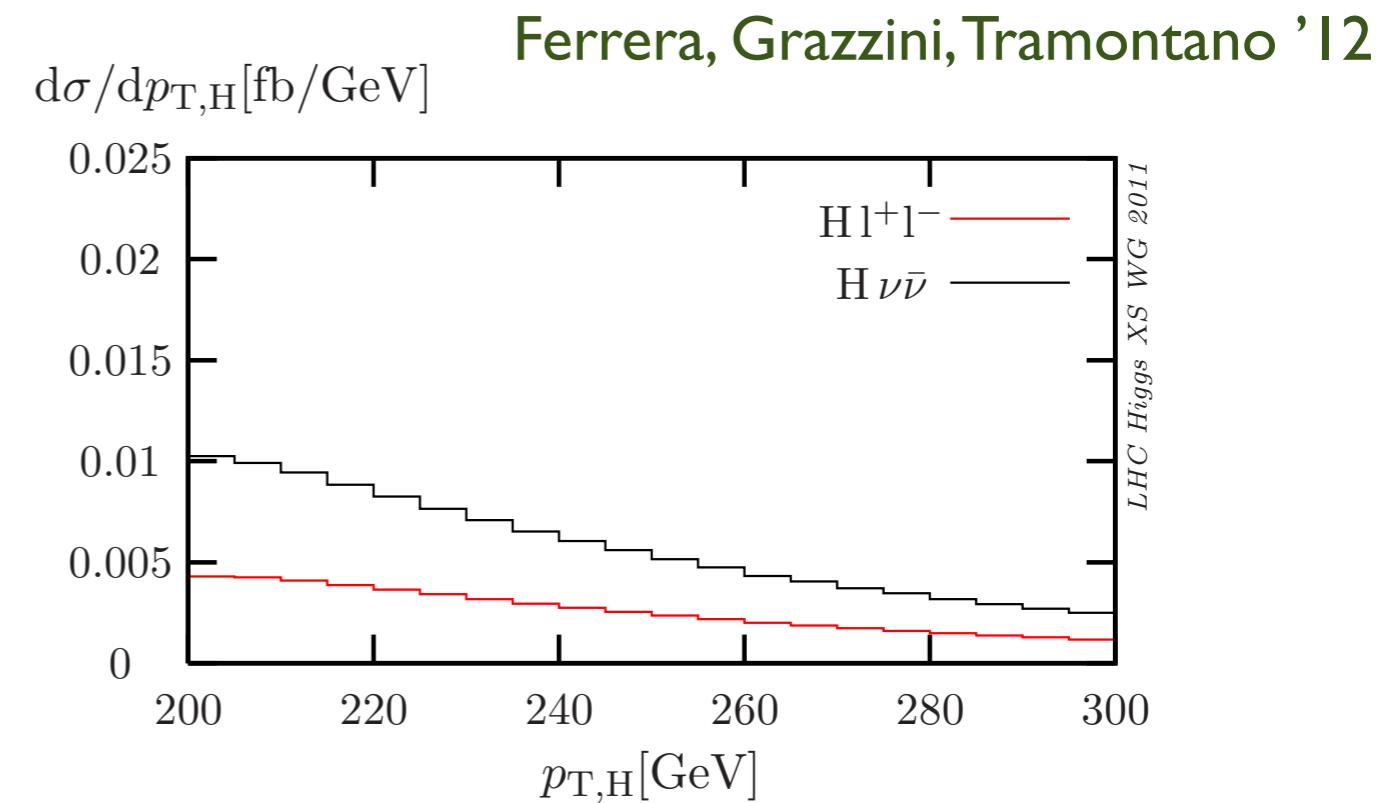
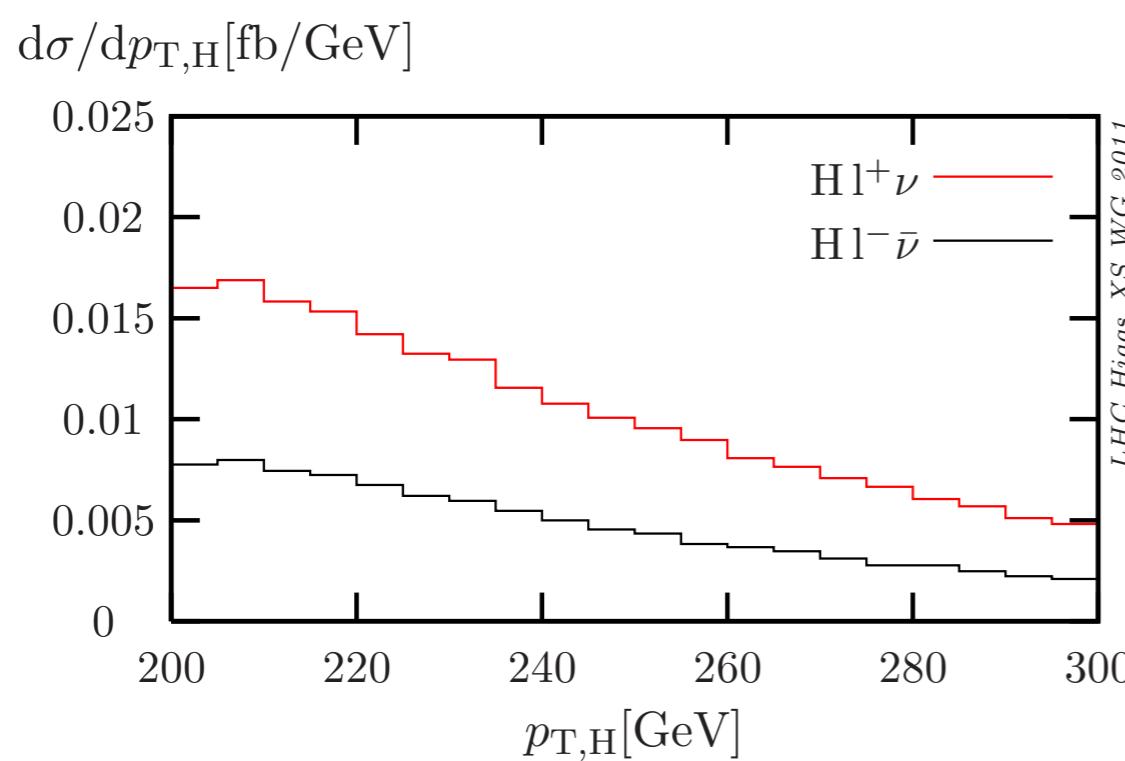


Kniehl '90

NLO: Altenkamp, Dittmaier, RH, Rzehak, Zirke '12

vh@nnlo: Brein, RH, Zirke '12

Higgs Strahlung: fully differential NNLO

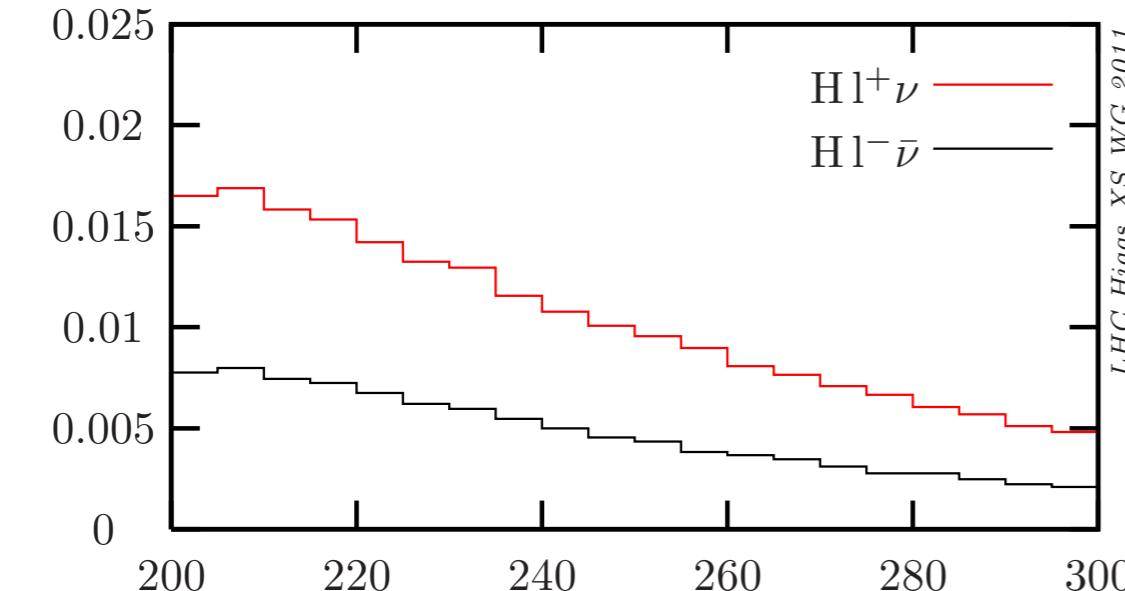


Ferrera, Grazzini, Tramontano '12

Denner, Dittmaier, Kallweit, Mück '11

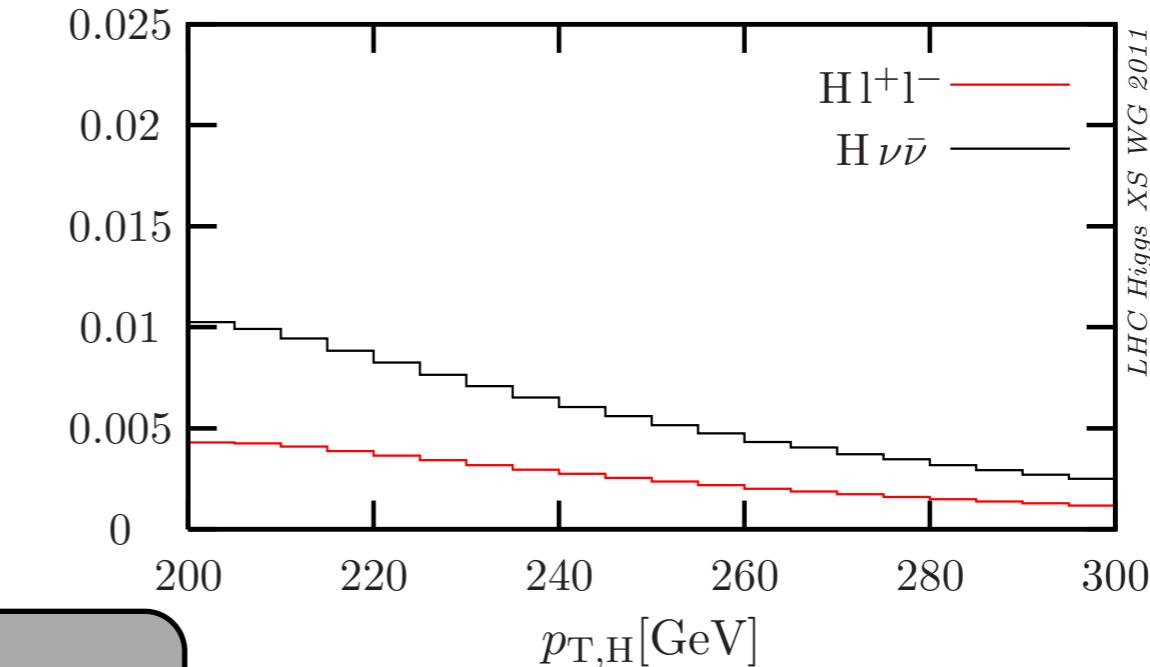
Higgs Strahlung: fully differential NNLO

$d\sigma/dp_{T,H} [\text{fb}/\text{GeV}]$



Ferrera, Grazzini, Tramontano '12

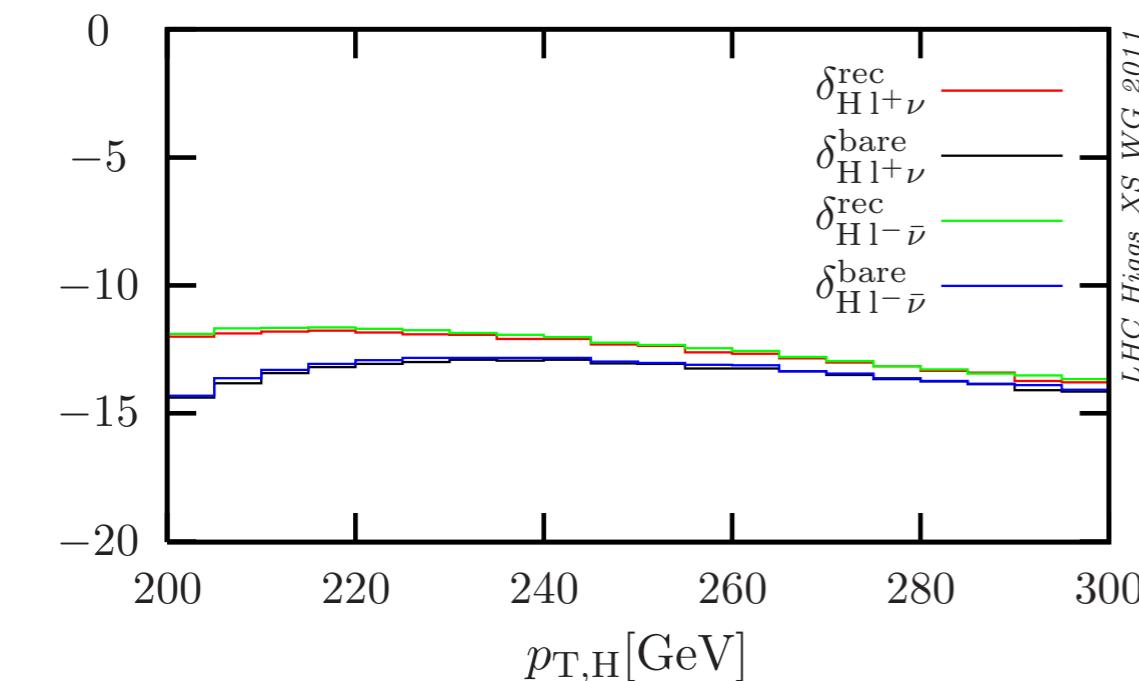
$d\sigma/dp_{T,H} [\text{fb}/\text{GeV}]$



Recall boosted Higgs!

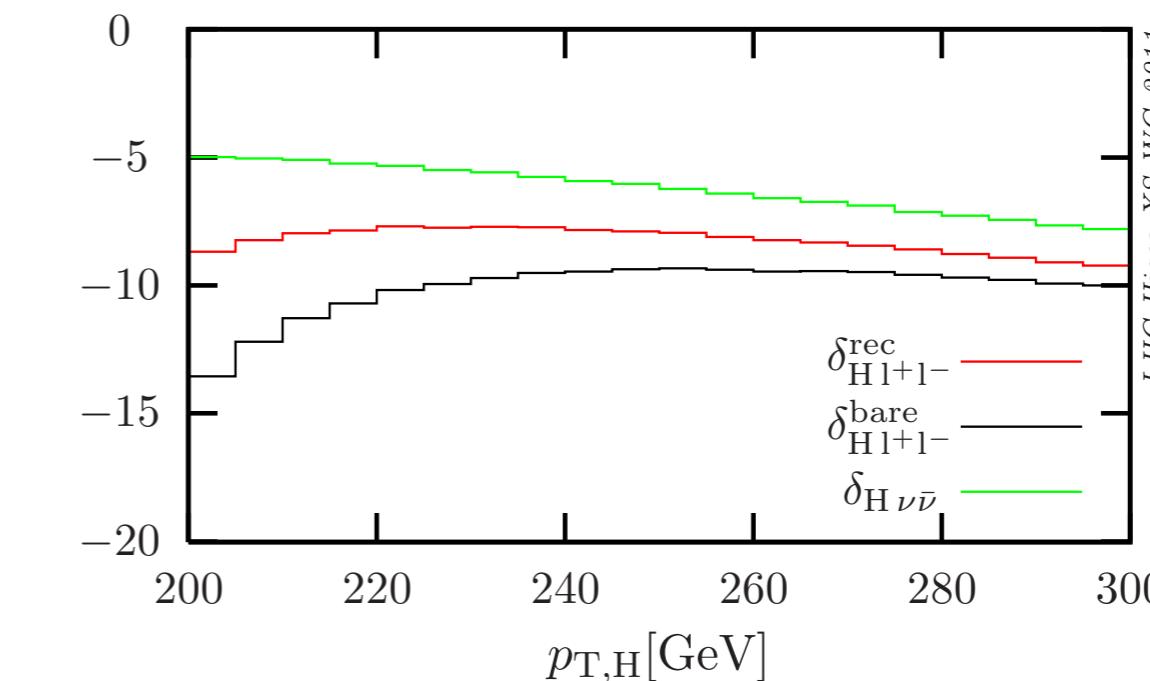
Butterworth et al. '08

$\delta_{\text{EW}} [\%]$

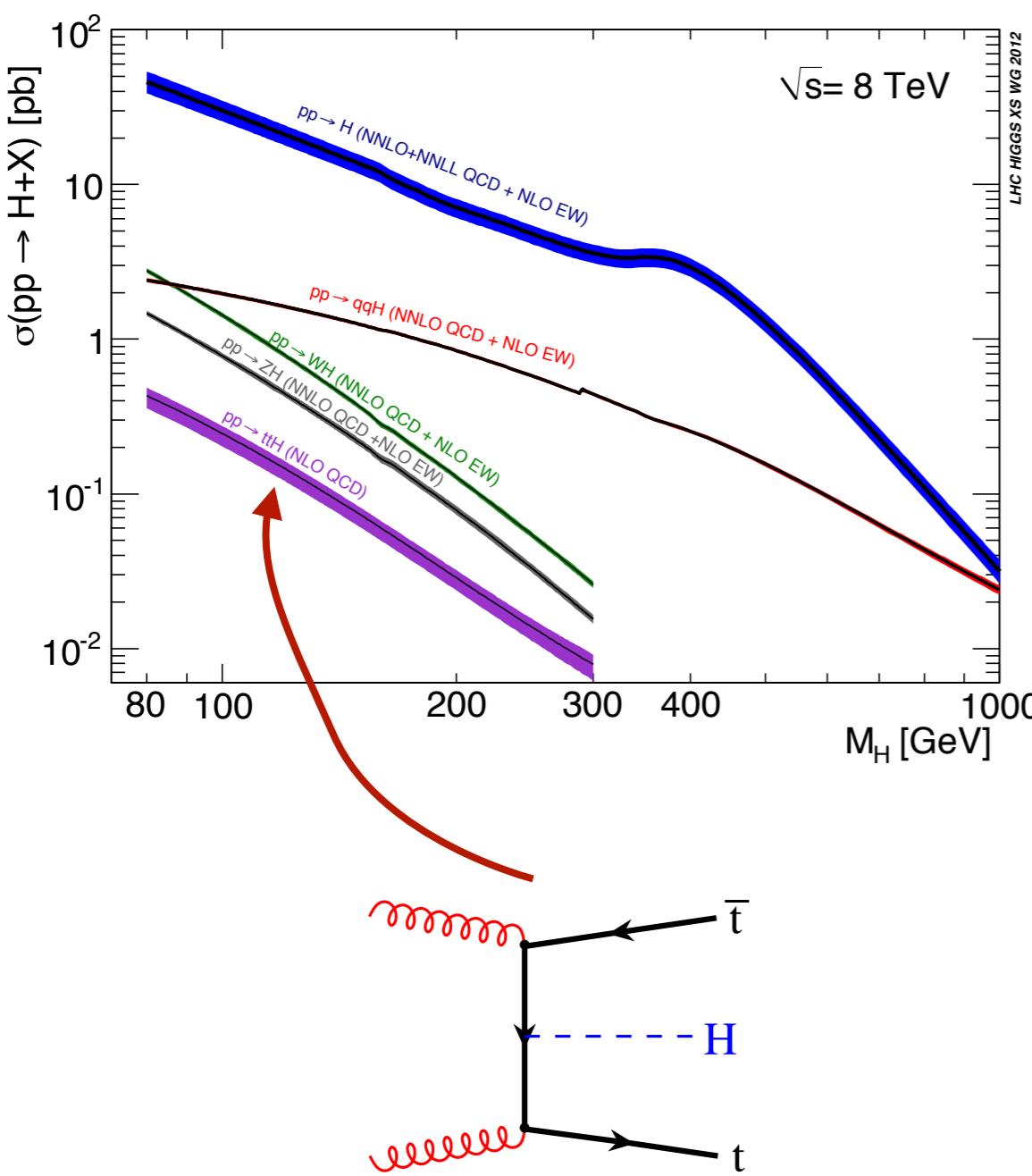


Denner, Dittmaier, Kallweit, Mück '11

$\delta_{\text{EW}} [\%]$

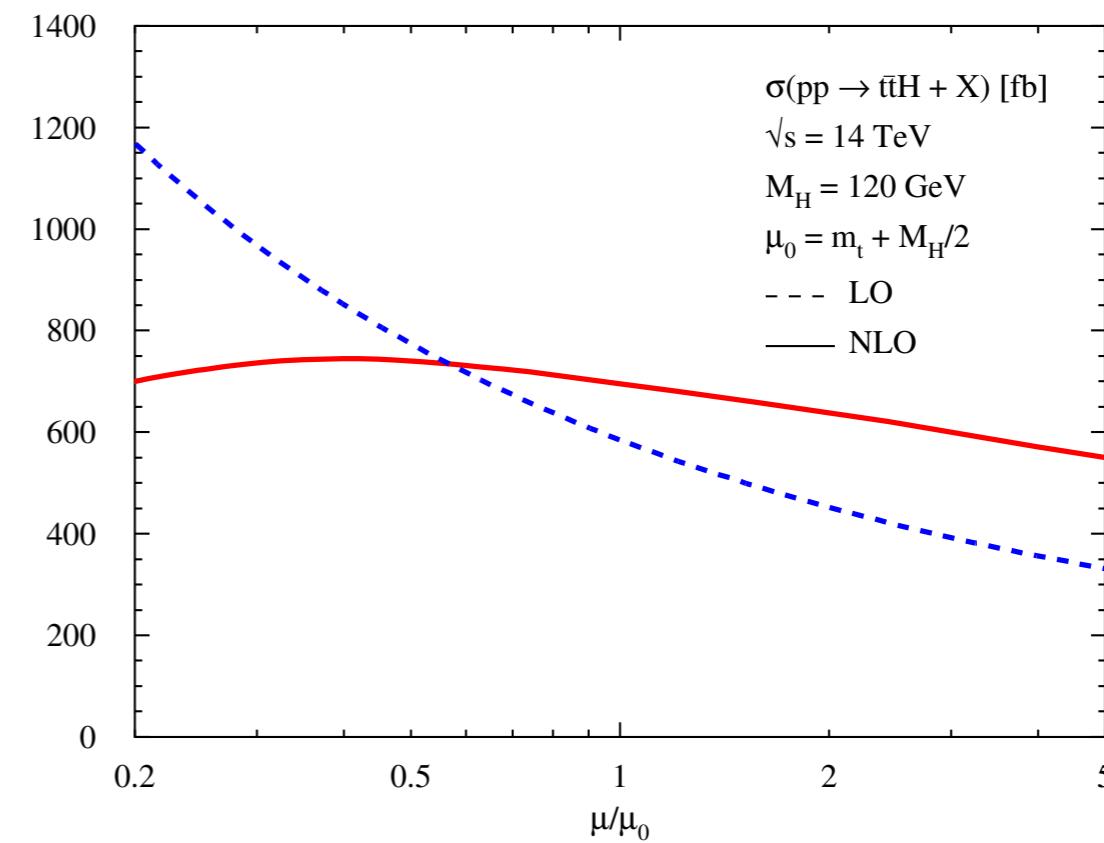


$t\bar{t}H$

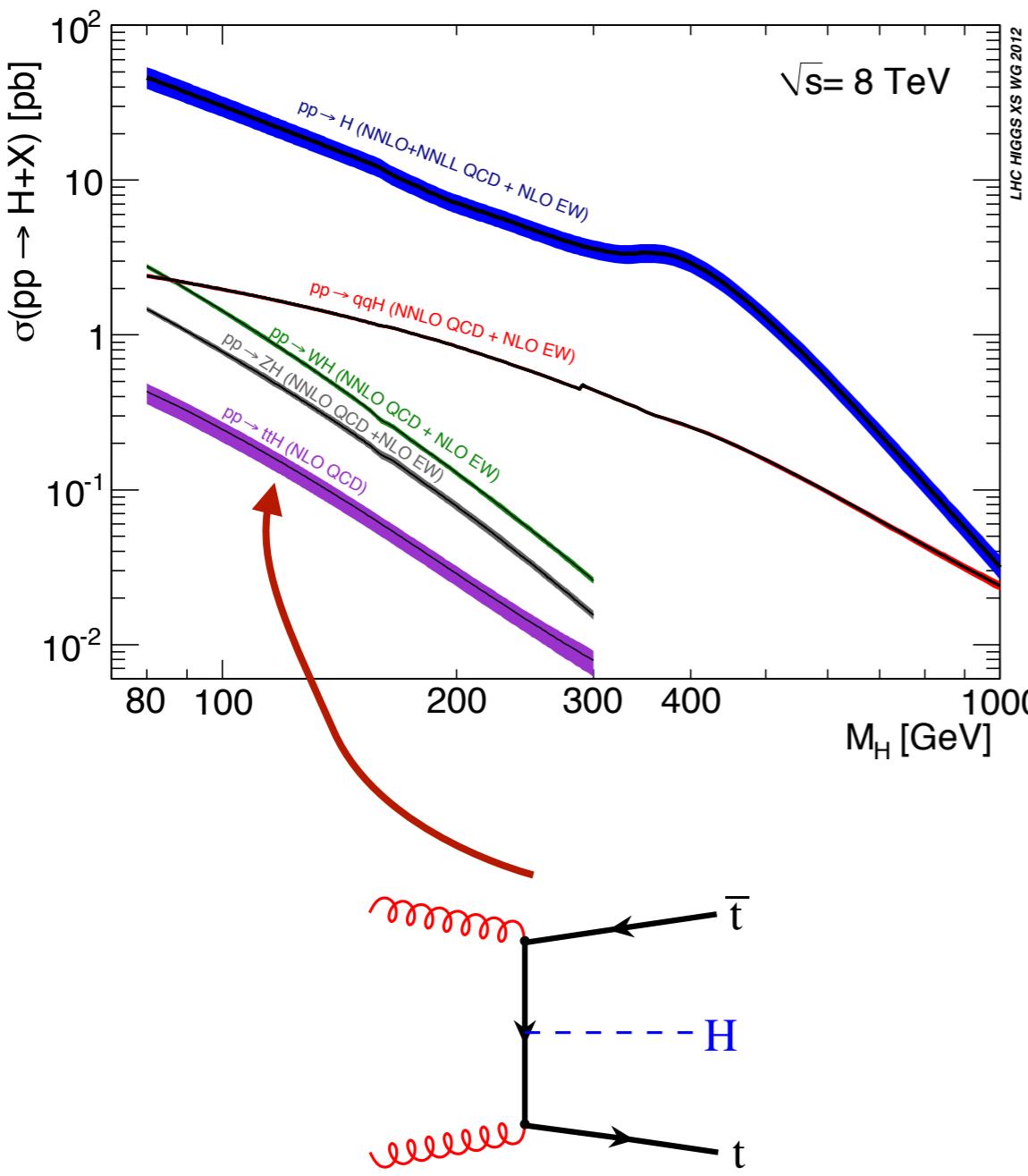


NLO:

Beenakker, Dittmaier, Krämer,
Plümper, Spira, Zerwas '01;
Dawson, Reina, Wackerlo, Orr,
Jackson '01-'03;



$t\bar{t}H$

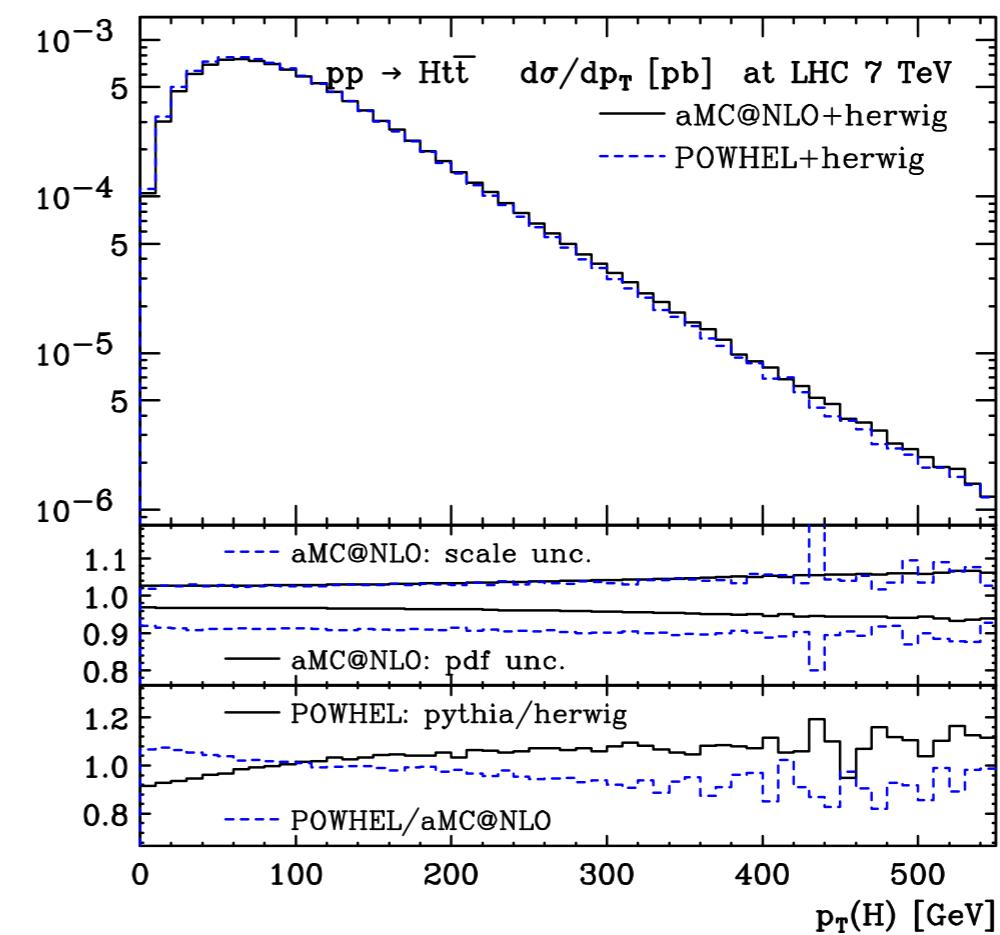


NLO:

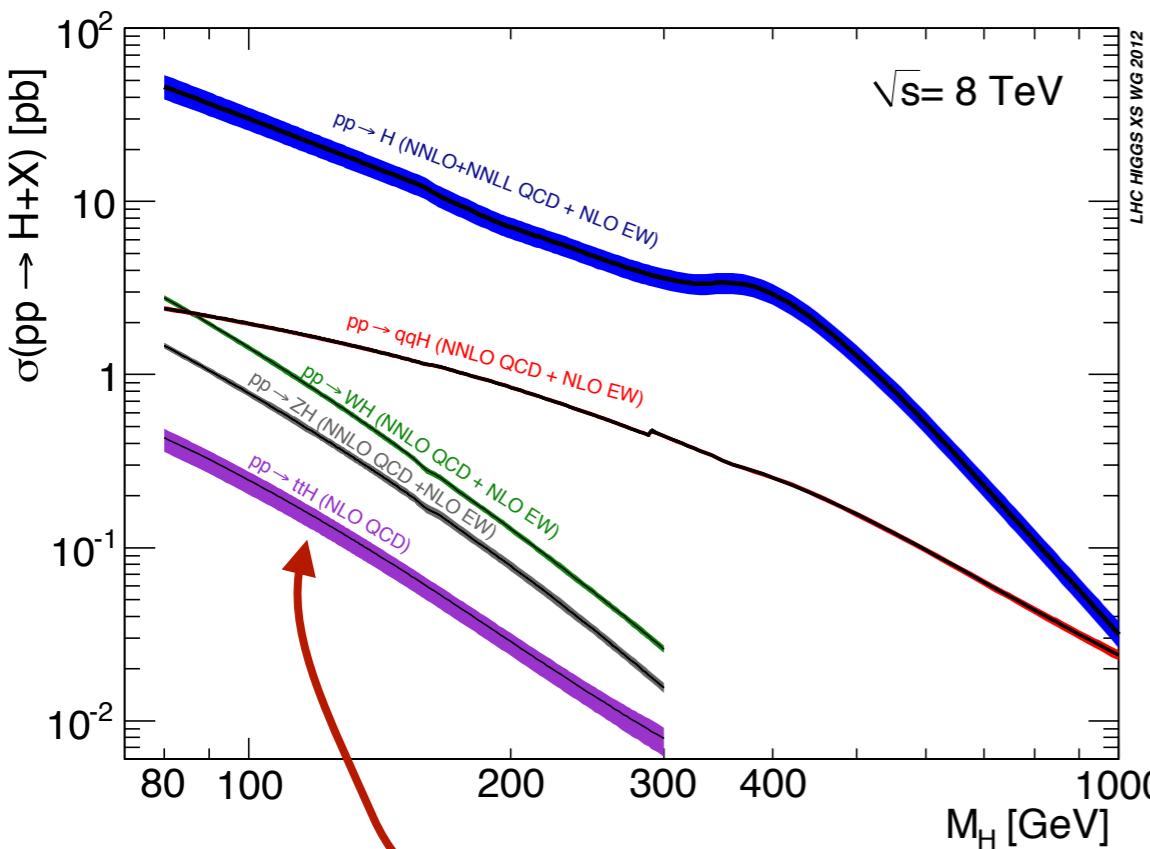
Beenakker, Dittmaier, Krämer,
Plümper, Spira, Zerwas '01;
Dawson, Reina, Wackerlo, Orr,
Jackson '01-'03;

NLO+PS:

Frederix, Frixione, Hirschi, Maltoni,
Pittau, Torielli '12 → **aMC@NLO**
Garzelli, Kardos, Papadopoulos,
Trócsányi '11 → **PowHel**



$t\bar{t}H$



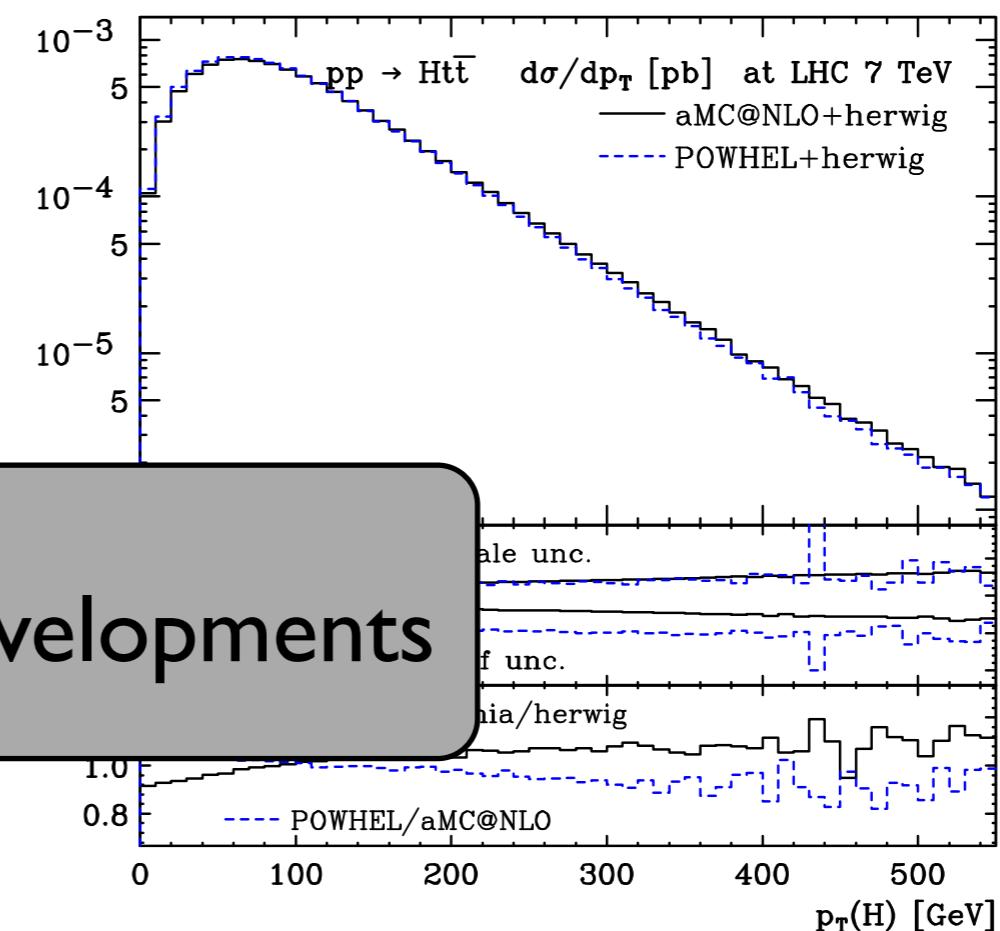
Required BG calculations
 \Rightarrow big impact on theory developments
 (see talk by S. Pozzorini)

NLO:

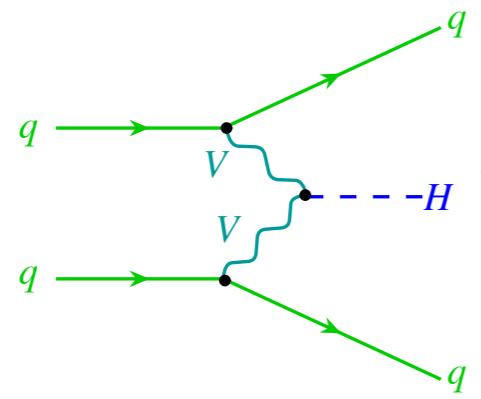
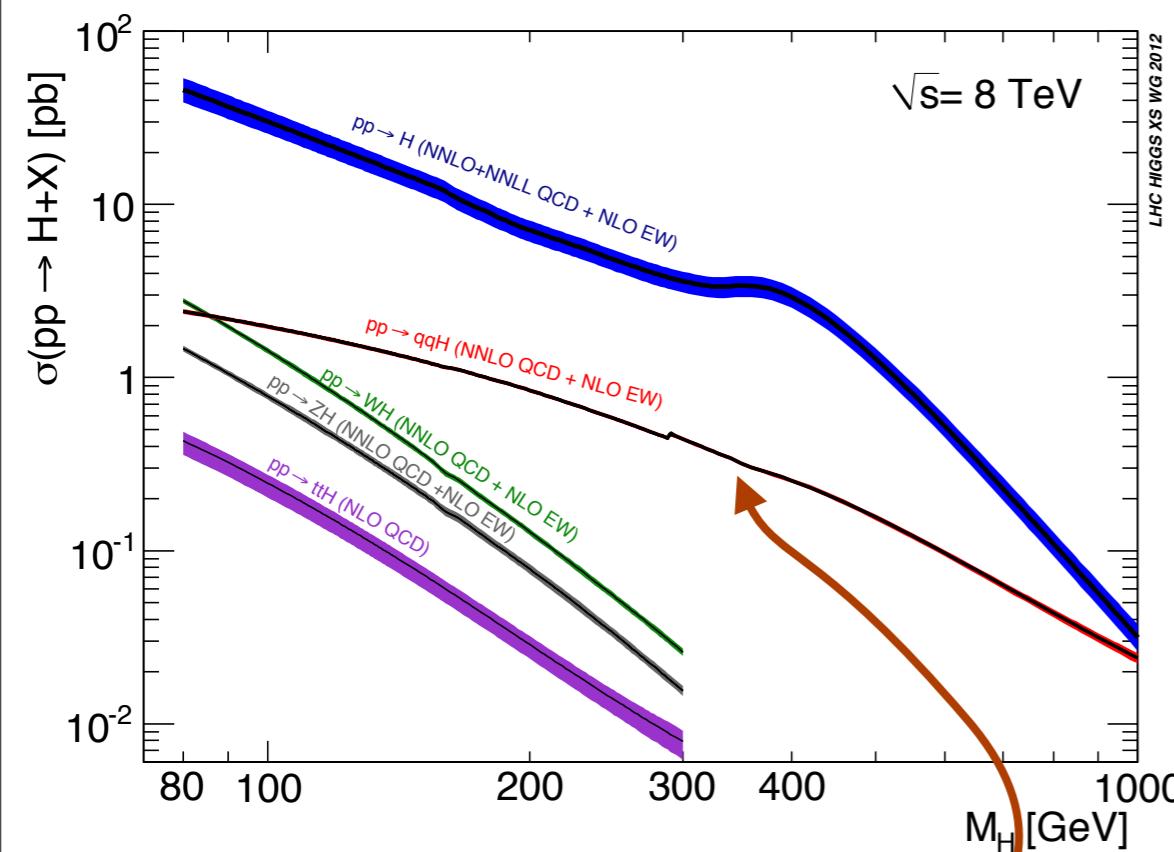
Beenakker, Dittmaier, Krämer,
 Plümper, Spira, Zerwas '01;
 Dawson, Reina, Wackerlo, Orr,
 Jackson '01-'03;

NLO+PS:

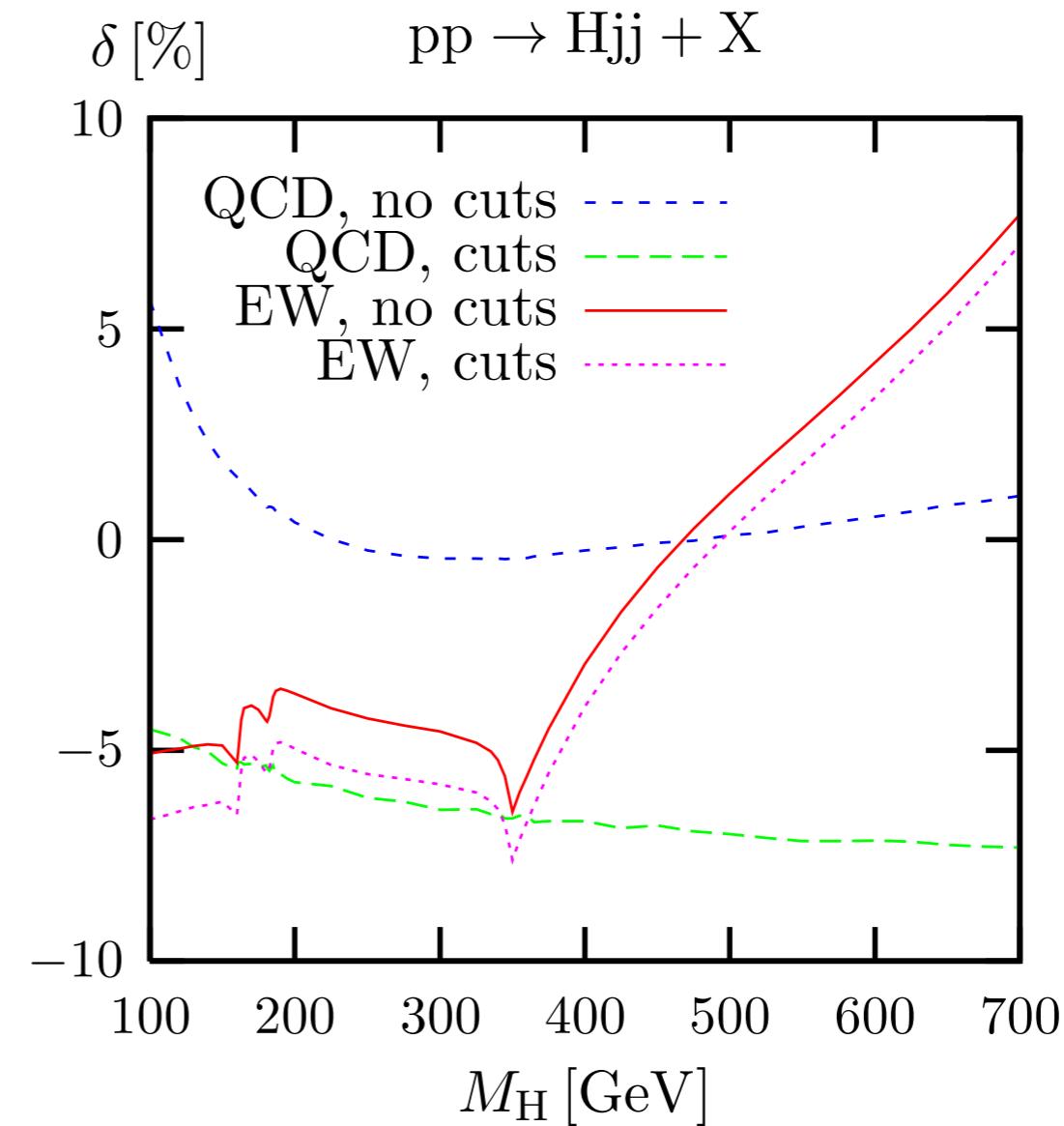
Frederix, Frixione, Hirschi, Maltoni,
 Pittau, Torielli '12 \rightarrow aMC@NLO
 Garzelli, Kardos, Papadopoulos,
 Trócsányi '11 \rightarrow PowHel



Weak Boson Fusion



NLO QCD: Figy, Oleari, Zeppenfeld '03 → **vbfnlo**
 NLO QCD+EW: Ciccolini, Denner,
 Dittmaier '08 → **HAWK**
 NLO SUSY: Hollik, Plehn, Rauch, Rzehak '09
 Figy, Palmer, Weiglein '10



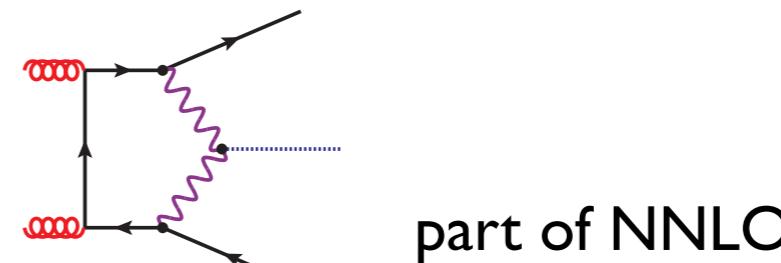
Weak Boson Fusion: Beyond NLO

- gluon fusion/WBF interference

Andersen, Binoth, Heinrich, Smillie '07; Bredenstein, Hagiwara, Jäger '08

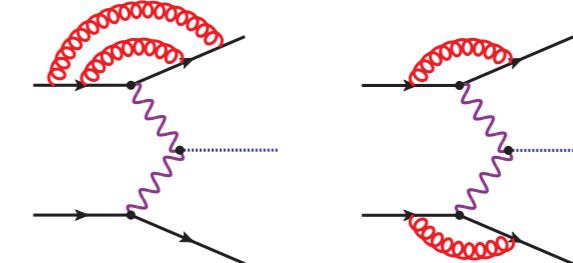
- gluon induced WBF

RH, Vollinga, Weber '08

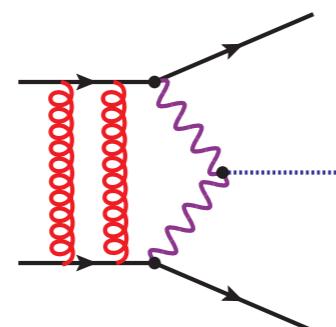


- DIS-like NNLO (inclusive)

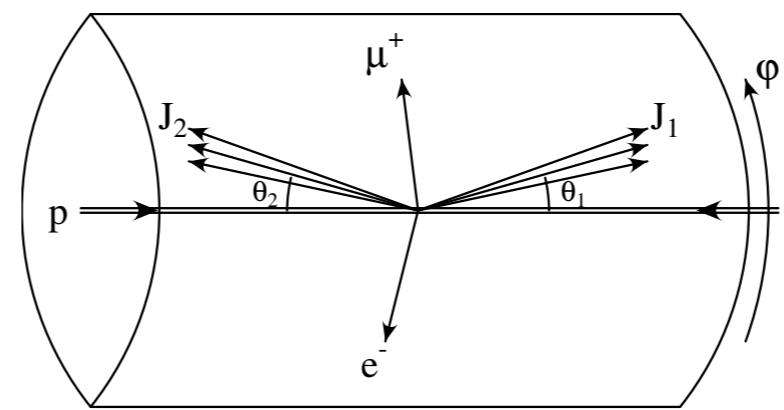
Bolzoni, Maltoni, Moch, Zaro '11

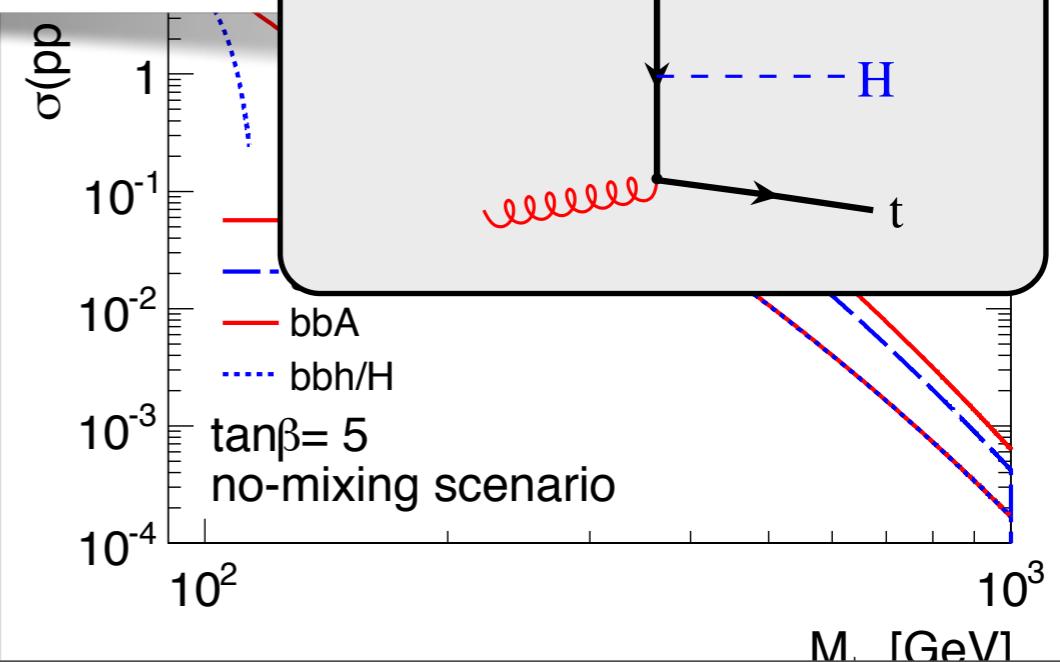
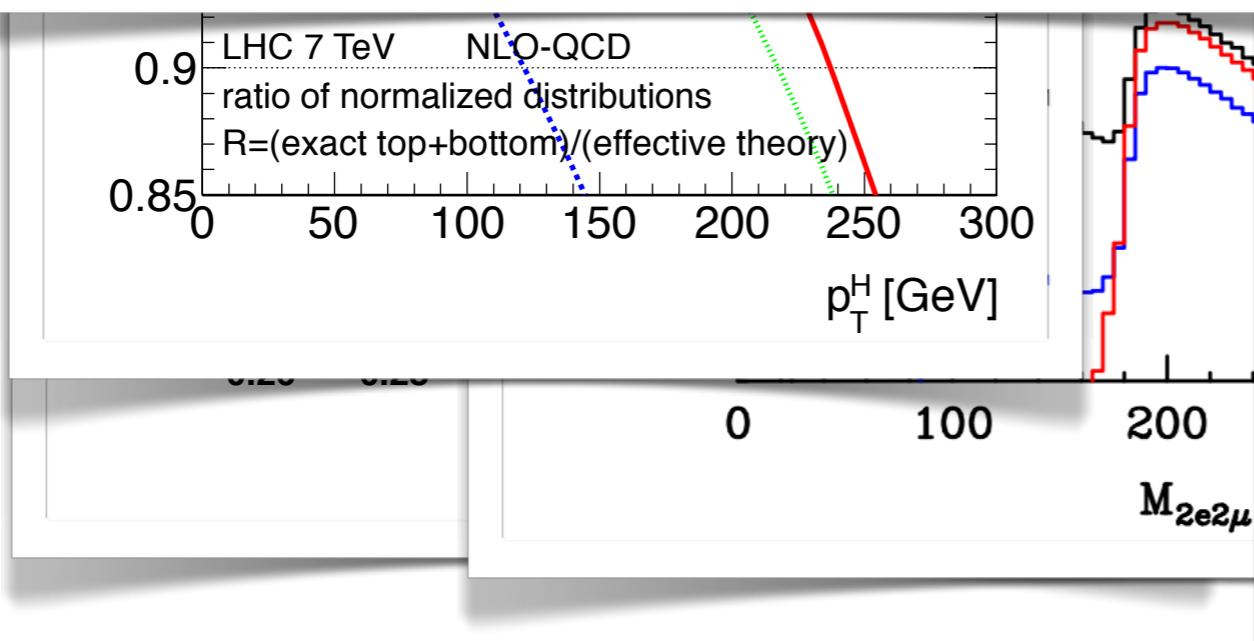
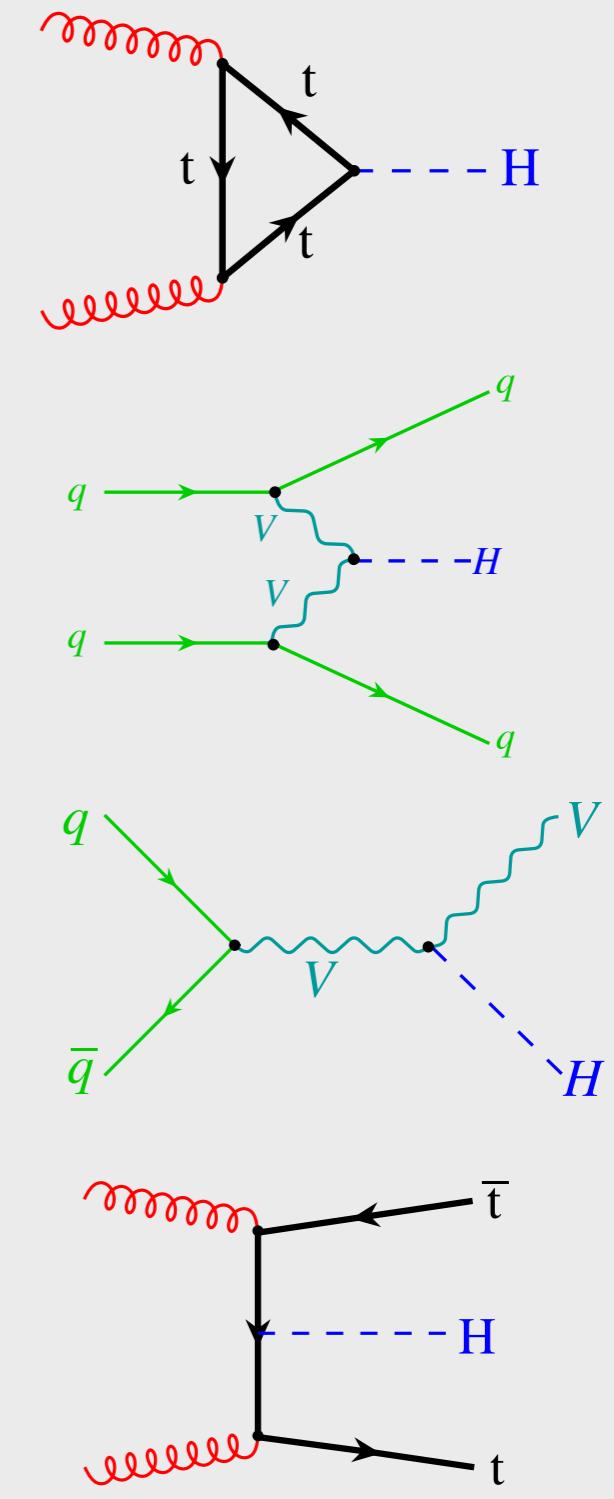
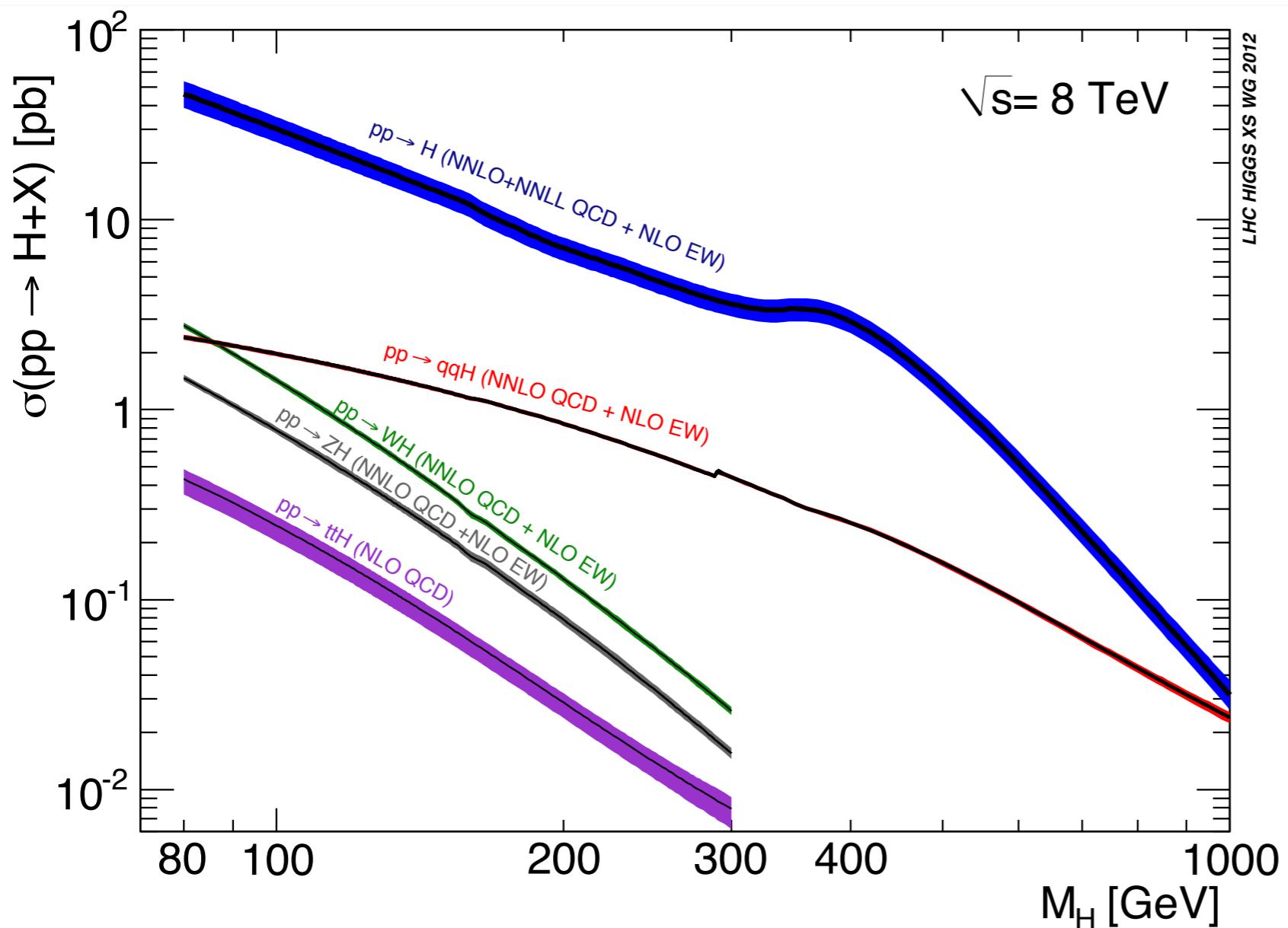


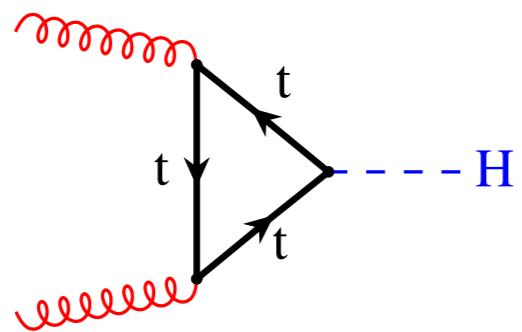
- missing:



- distributions:

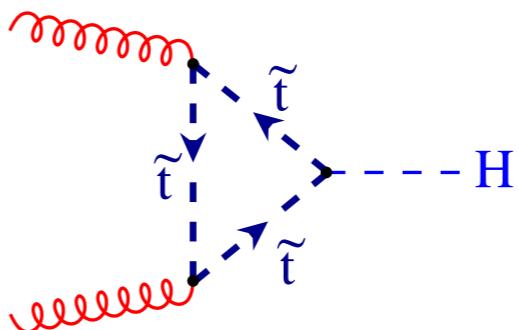
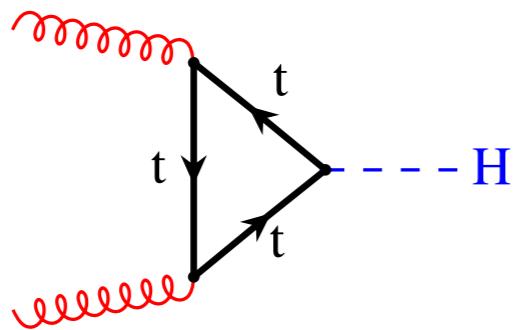






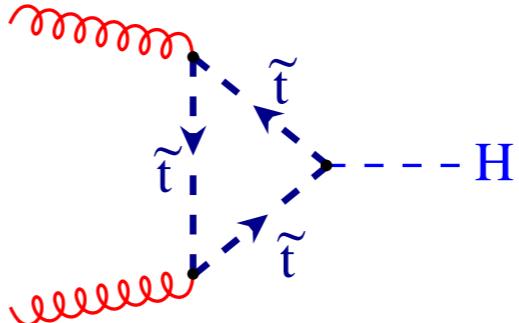
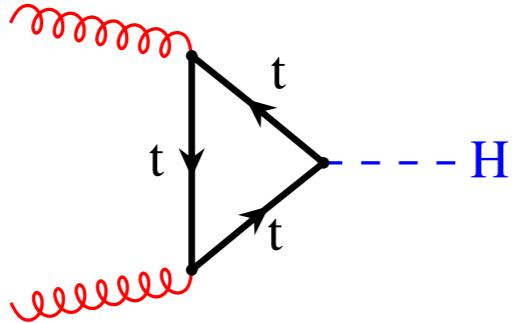
sensitive to heavy particle spectrum

Supersymmetry



sensitive to heavy particle spectrum

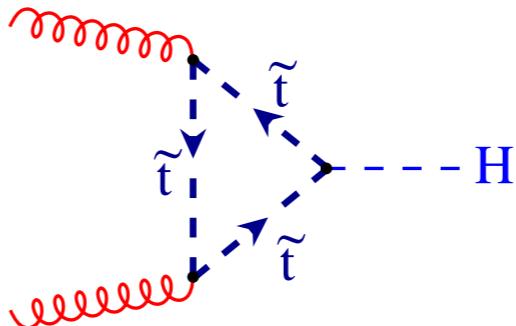
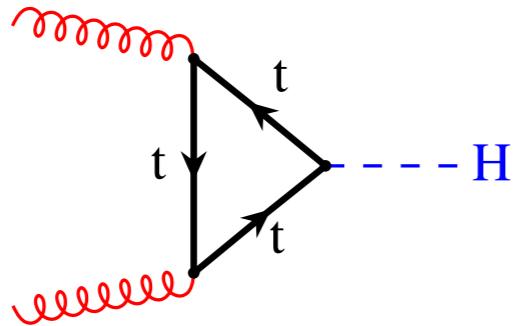
Supersymmetry



sensitive to heavy particle spectrum

LHC Higgs XS WG, YR2: no SUSY particles in loops

Supersymmetry



sensitive to heavy particle spectrum

LHC Higgs XS WG, YR2: no SUSY particles in loops

All contributions for NLO MSSM Higgs known:

Supersymmetry



sensitive to heavy particle spectrum

LHC Higgs XS WG, YR2: no SUSY particles in loops

All contributions for NLO MSSM Higgs known:

NLO: RH, Steinhauser '04; Anastasiou, Beerli, Daleo '08; + Bucherer, Kunszt '06;
Mühlleitner, Rzehak, Spira '07/'08; Aglietti, Bonciani, Degrassi, Vicini '06;
RH, Hofmann, Mantler '11; Degrassi, Slavich '08/'10; + Bagnaschi, Vicini '11/'12

Supersymmetry



sensitive to heavy particle spectrum

LHC Higgs XS WG, YR2: no SUSY particles in loops

All contributions for NLO MSSM Higgs known:

NLO: RH, Steinhauser '04; Anastasiou, Beerli, Daleo '08; + Bucherer, Kunszt '06;
Mühlleitner, Rzehak, Spira '07/'08; Aglietti, Bonciani, Degrassi, Vicini '06;
RH, Hofmann, Mantler '11; Degrassi, Slavich '08/'10; + Bagnaschi, Vicini '11/'12

Even NNLO: RH, Steinhauser '03; Pak, Steinhauser, Zerf '10/'12

- SusHi
- Changelog
- Examples
- Contact
- Download

SusHi

Download

Version 1.0.5 (13.03.2013) is available here: [Download](#)

Details

SusHi ([Supersymmetric Higgs](#)) is a Fortran code, which calculates Higgs cross sections in gluon fusion and bottom-quark annihilation at hadron colliders in the SM and the MSSM. Apart from inclusive cross sections up to NNLO QCD, differential cross sections with respect to the Higgs' transverse momentum and (pseudo)rapidity can be calculated. In case of gluon fusion, SusHi contains NLO QCD contributions from the third family of quarks and squarks, NNLO corrections due to top-quarks, approximate NNLO corrections due to top squarks and electro-weak effects. It supports various renormalization schemes for the sbottom sector and the bottom Yukawa coupling, as well as resummation effects of higher order tan(beta)-enhanced sbottom contributions. SusHi provides a link to FeynHiggs for the calculation of Higgs masses in the MSSM.

Starting with V 1.0.2 gluon fusion and bottom-quark annihilation cross sections for the [2-Higgs-Doublet-Model \(2HDM\)](#) can be calculated. Our notation is shortly explained [here](#).

For example input and output files regarding [recent MSSM benchmark scenarios](#) we refer to the "[Examples](#)" page as well.

Reference

If you use SusHi for your publication, please [refer to the following paper](#):

[SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM](#)

[Robert V. Harlander, Stefan Liebler, Hendrik Mantler](#)

[arXiv:1212.3249 \(CPC in print. DOI\)](#)

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- Examples
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SusHi

Download

[Version 1.0.5 \(13.03.2013\)](#) is available.

Details

SusHi ([Supersymmetric Higgs](#)) is a program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM. Apart from inclusive cross sections, it also provides differential distributions with respect to the Higgs' transverse momentum and its decay channel. In case of gluon fusion, SusHi contains a full NNLO calculation of the production of quarks and squarks, NNLO corrections to the annihilation of top squarks and electro-weak sbottoms, and higher order tan(beta)-enhanced sbottom contributions. It also provides a framework for the calculation of Higgs masses and couplings.

Starting with V 1.0.2 gluon fusion and annihilation in the 2-Higgs-Doublet-Model (2HDM) is supported. A short introduction to the 2HDM is shortly explained [here](#).

For example input and output files refer to the [Examples](#) page as well as to the [Documentation](#) page. For more information we refer to the "Examples" page as well as to the "Documentation" page.

- full MSSM @ NLO
- SM @ NNLO
- 2HDM
- bbh
- various ren. schemes
- link to FeynHiggs
- link to LHAPDF
- ...

RH, Liebler, Mantler '12

Reference

If you use SusHi for your publication, please refer to the following paper:

[SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM](#)

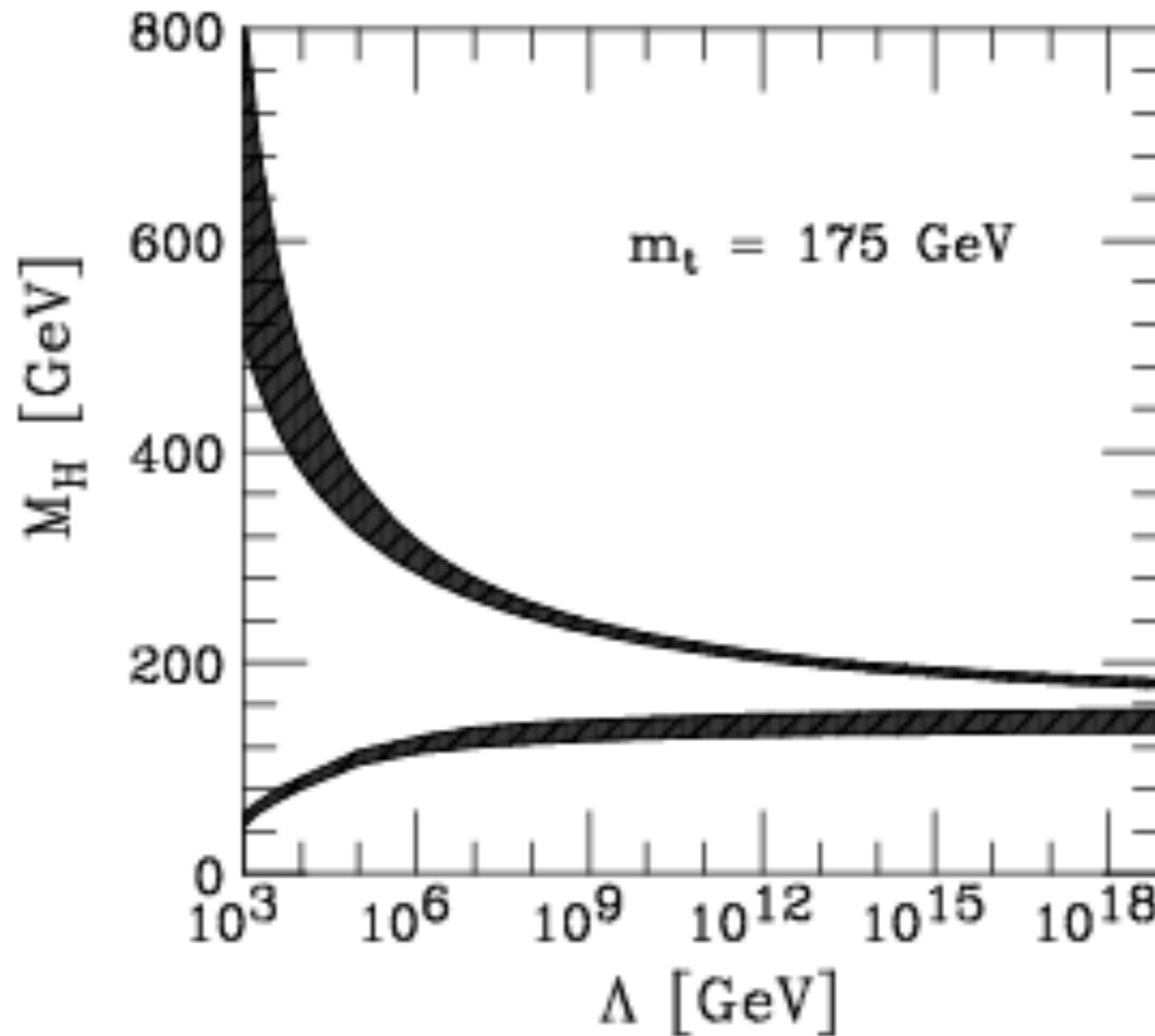
Robert V. Harlander, Stefan Liebler, Hendrik Mantler

[arXiv:1212.3249 \(CPC in print. DOI\)](#)

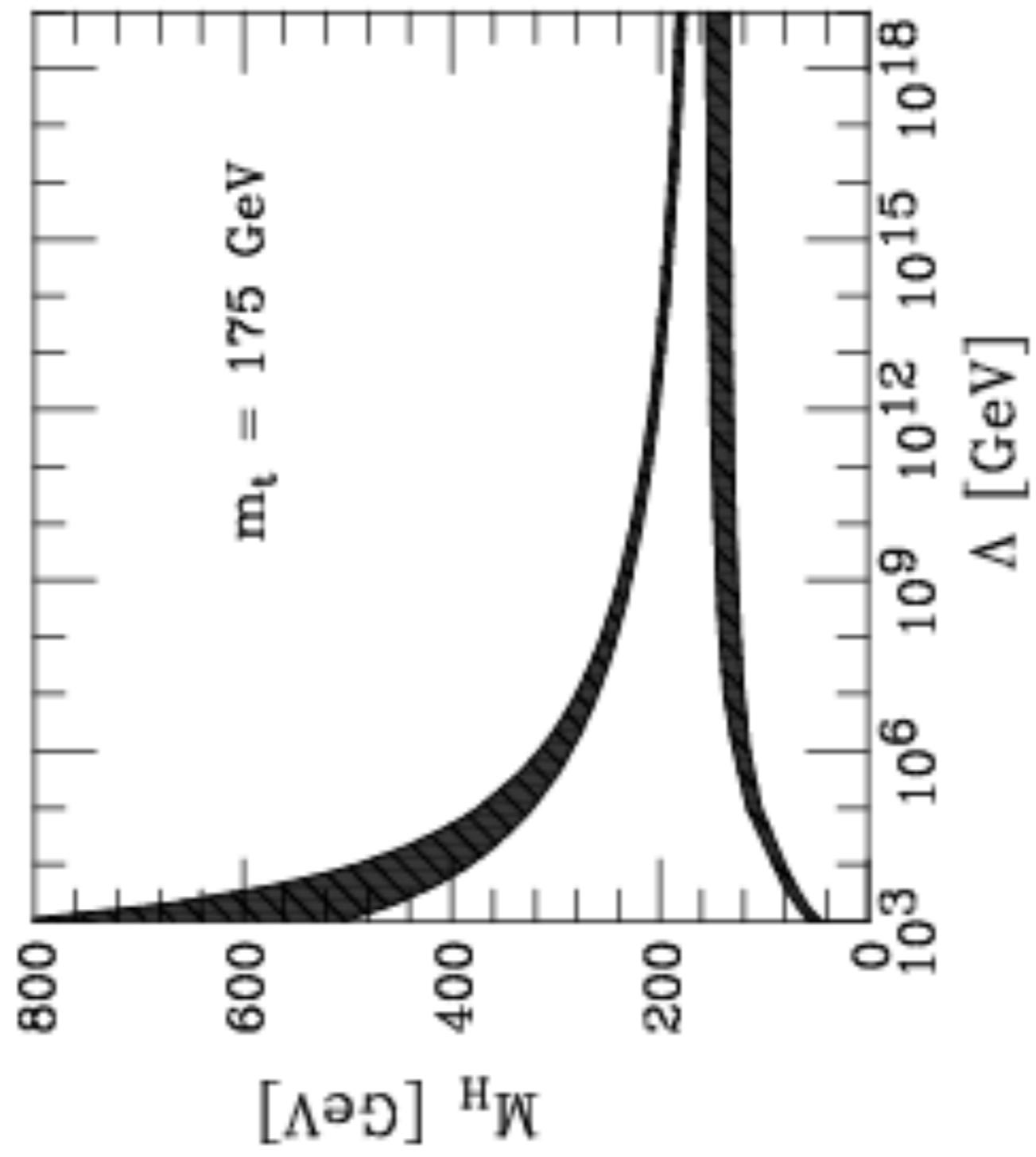
Implications

Implications

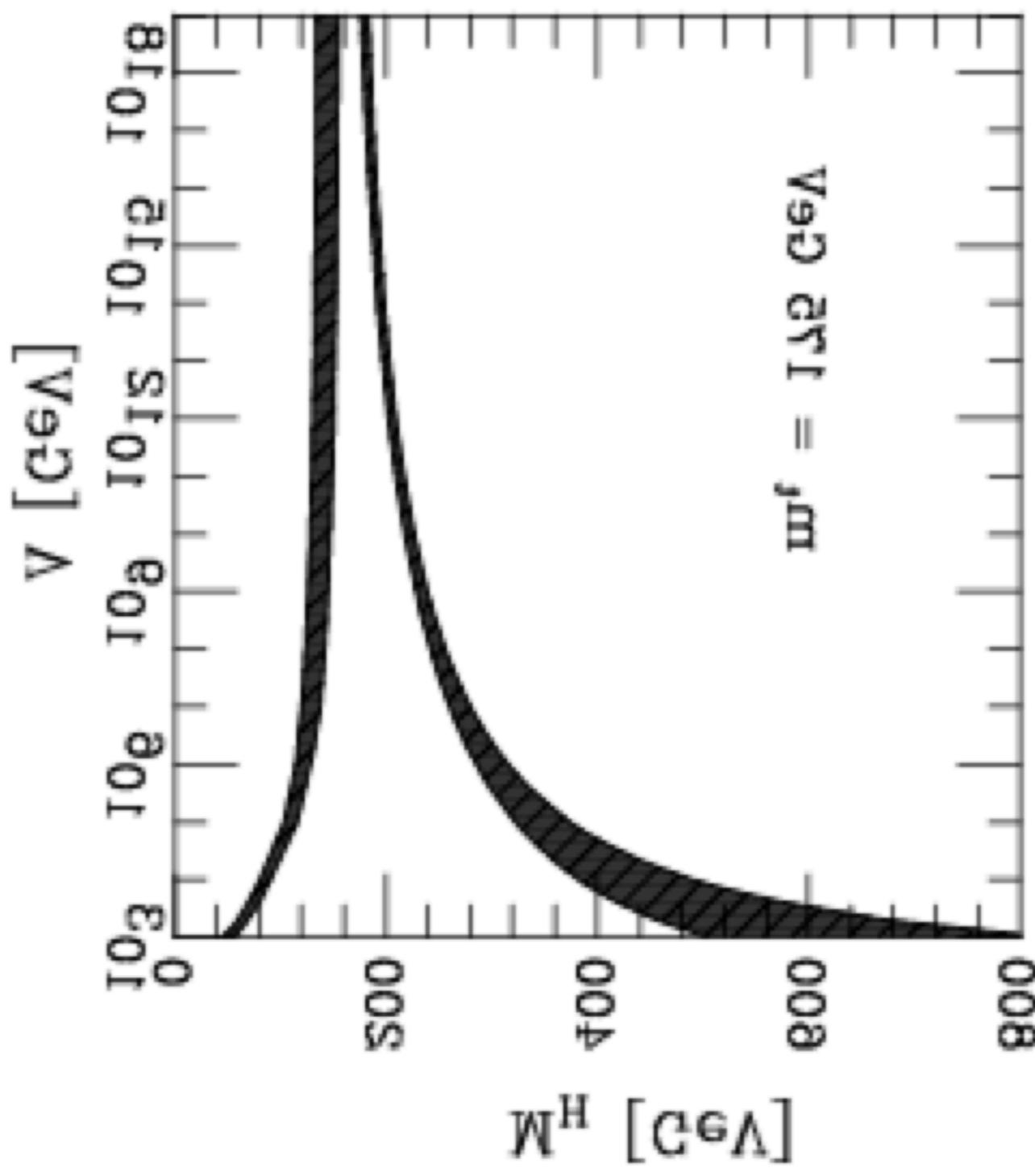
... or: be careful what you wish for ...



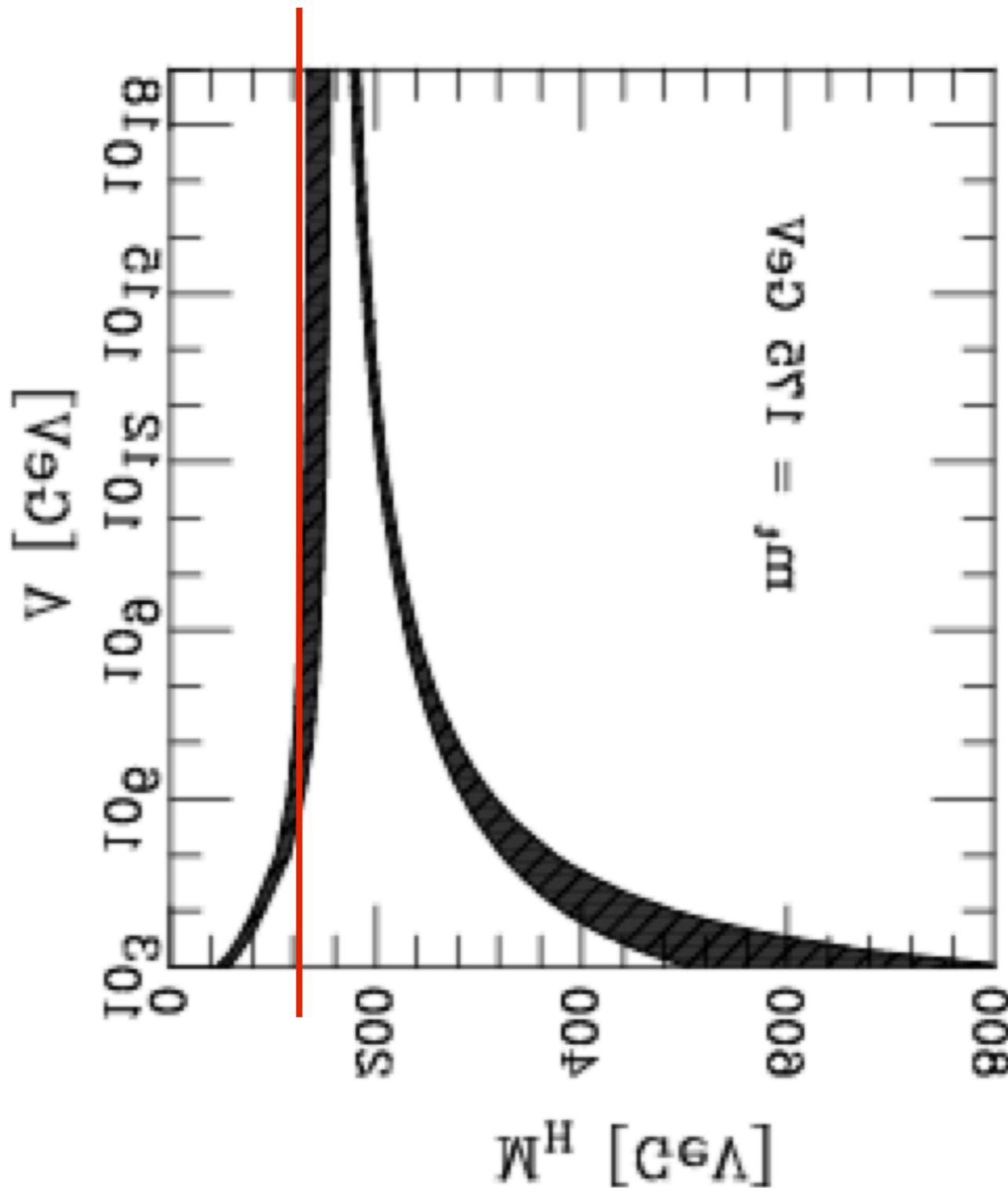
Hambye, Riesselmann '97



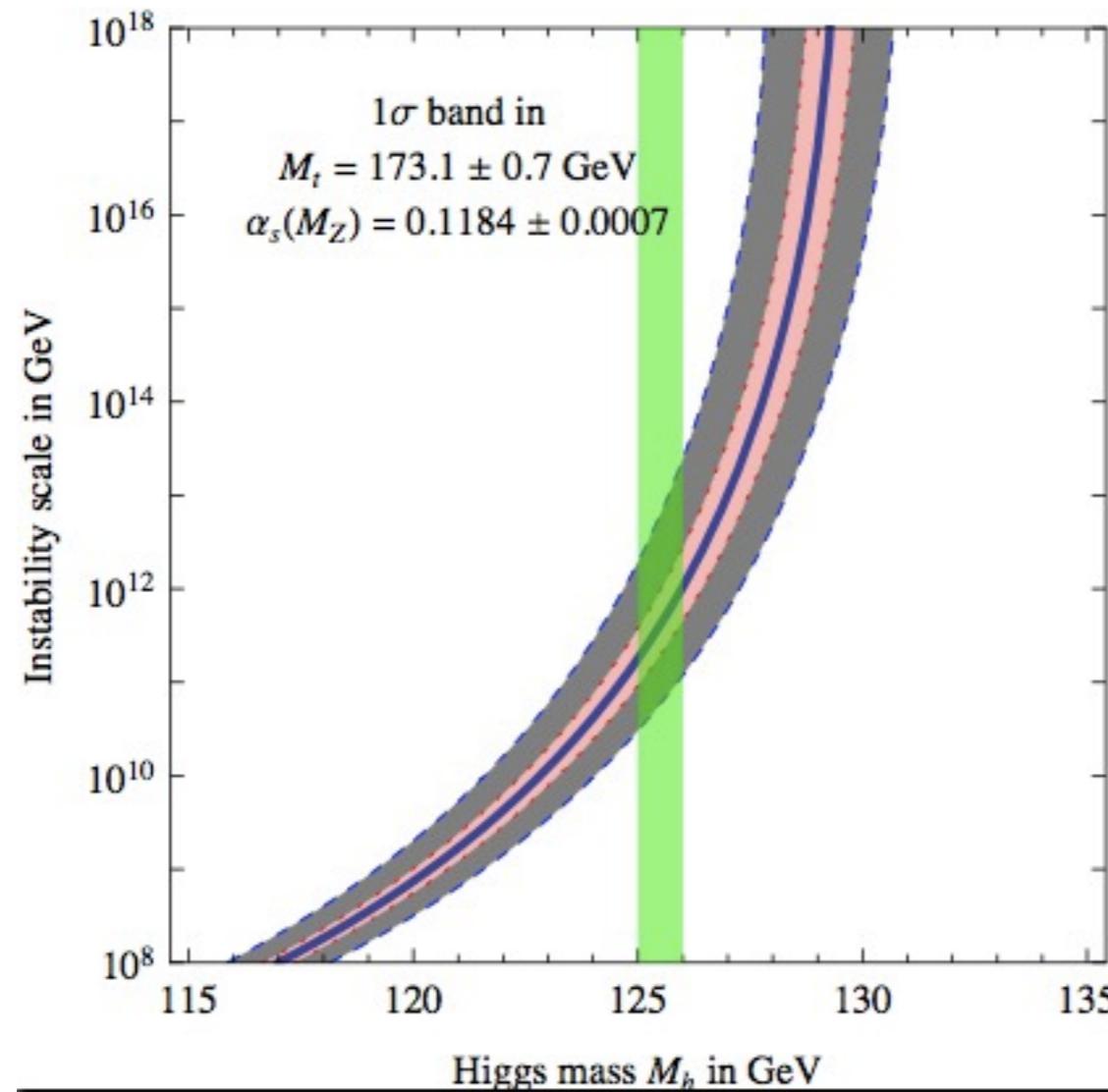
Hambye, Riesselmann '97



Hambye, Riesselmann '97

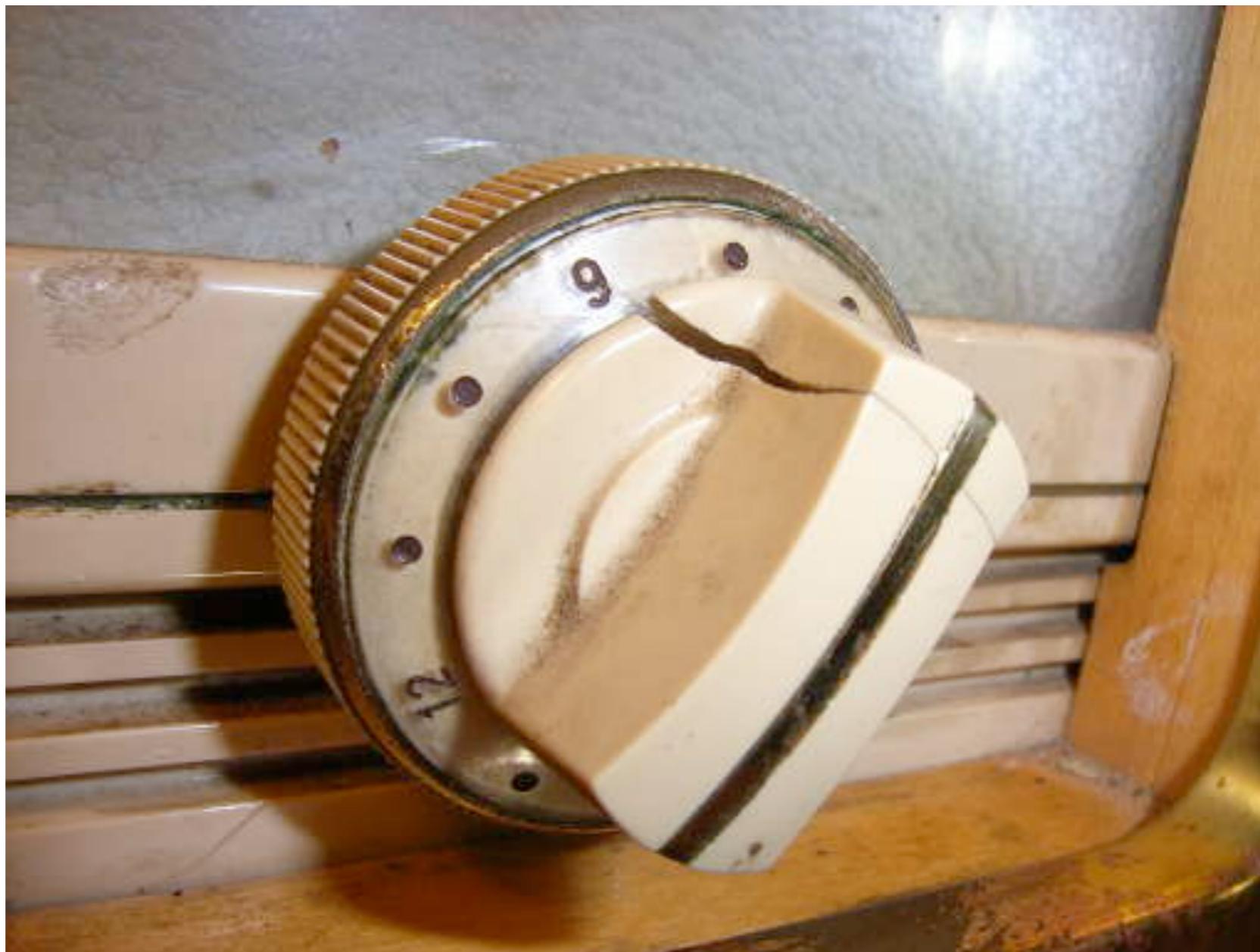


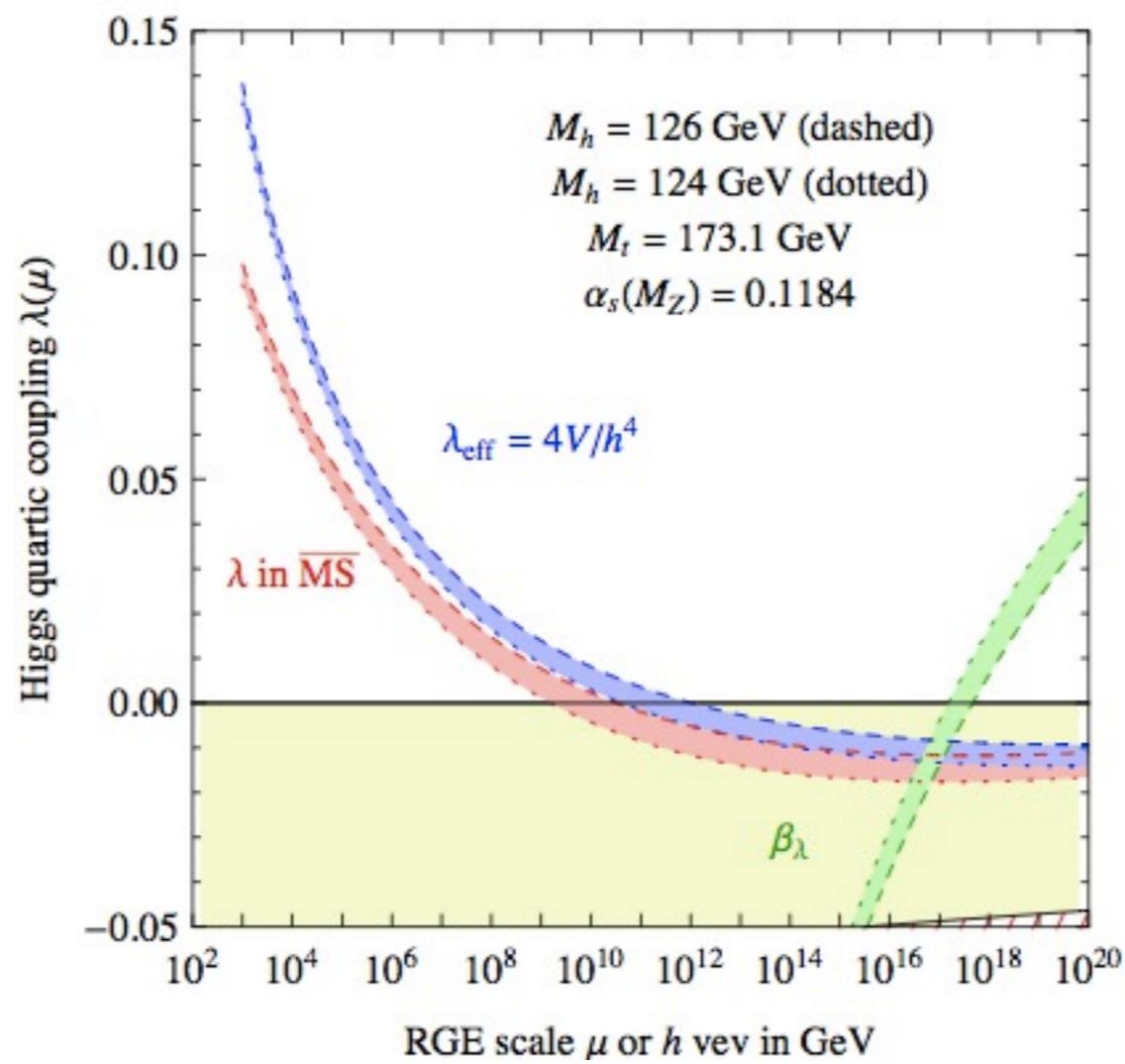
Hambye, Riesselmann '97



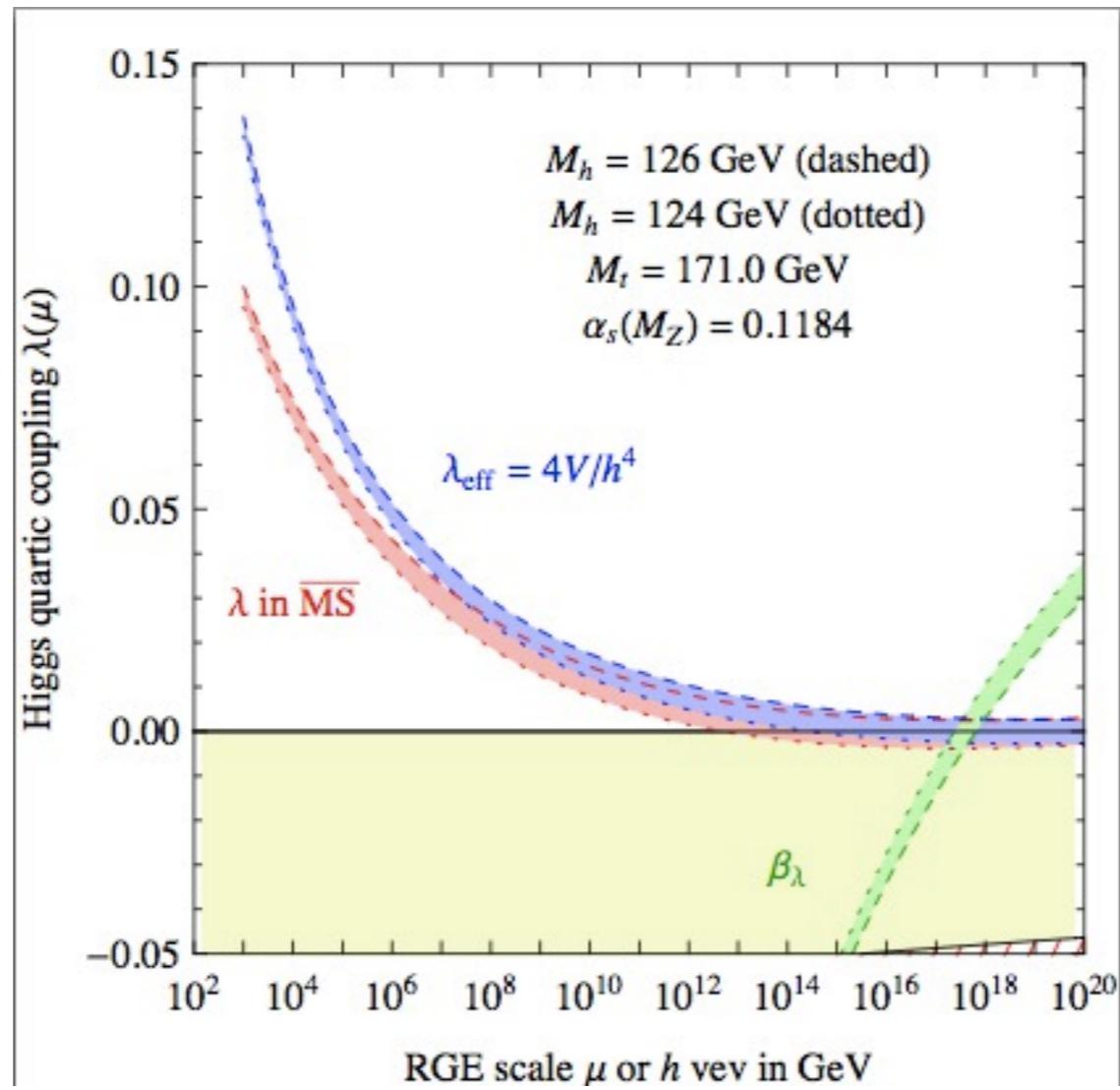
Degassi, Di Vita, Elias-Miro, Espinosa,
Giudice, Isidori, Strumia '12

What about fine tuning?

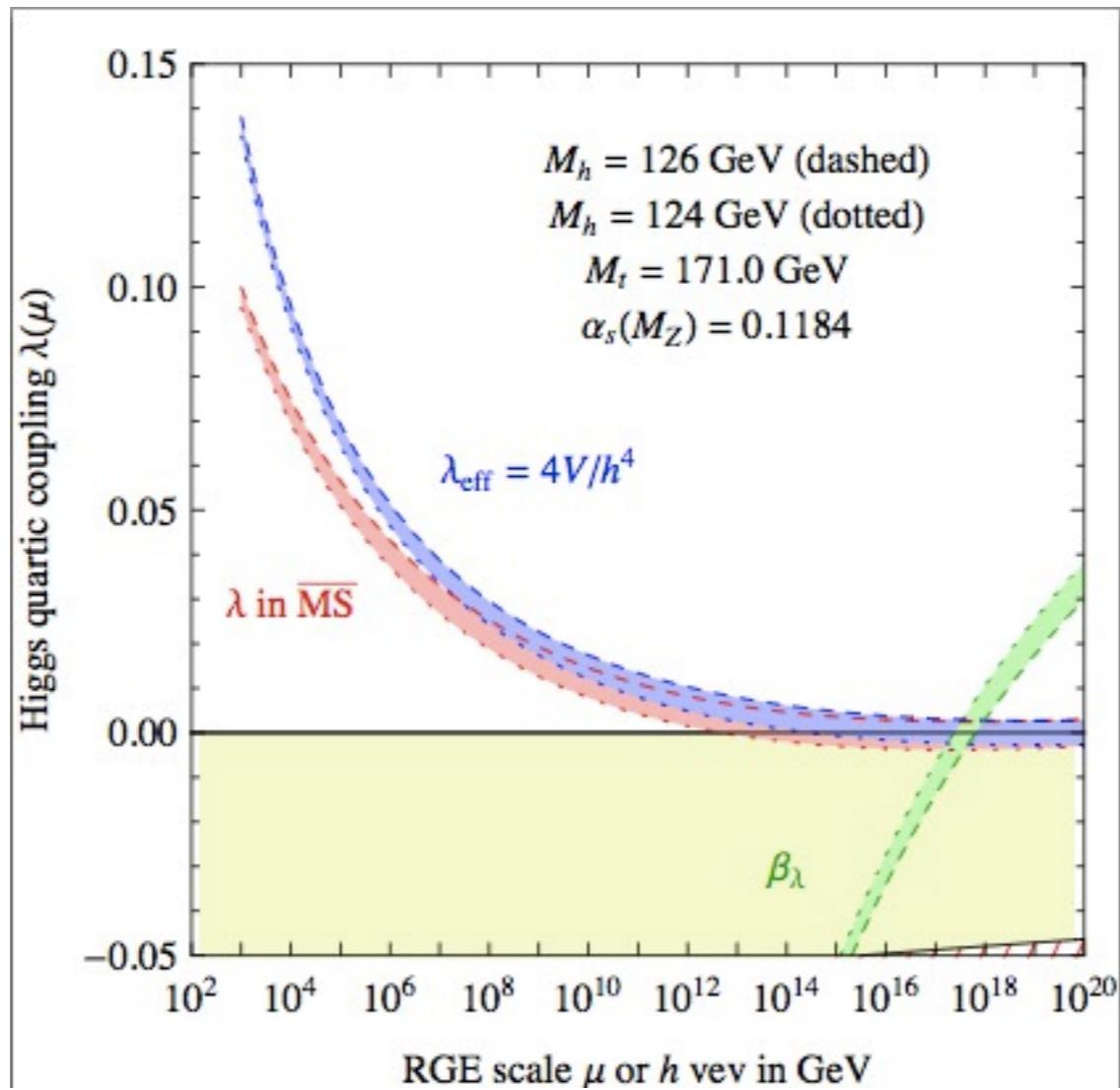




Degrandi, Di Vita, Elias-Miro, Espinosa,
Giudice, Isidori, Strumia '12



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Degrandi, Di Vita, Elias-Miro, Espinosa,
Giudice, Isidori, Strumia '12

Shaposhnikov, Wetterich '10

the running of the quartic scalar self interaction at scales beyond the Planck at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This is of the short distance running and holds for a wide class of extensions of the SM as well.

114 comments

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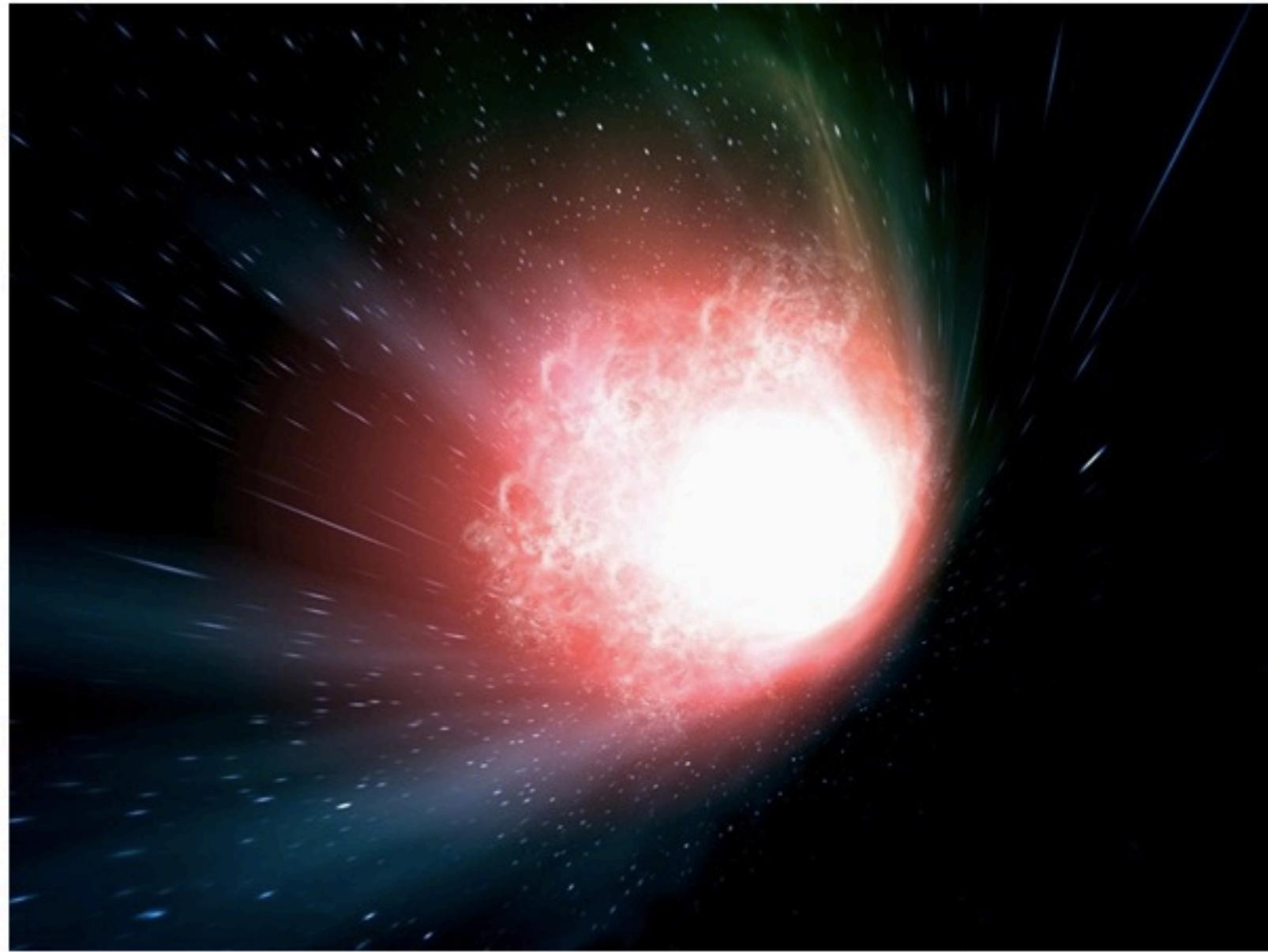
71

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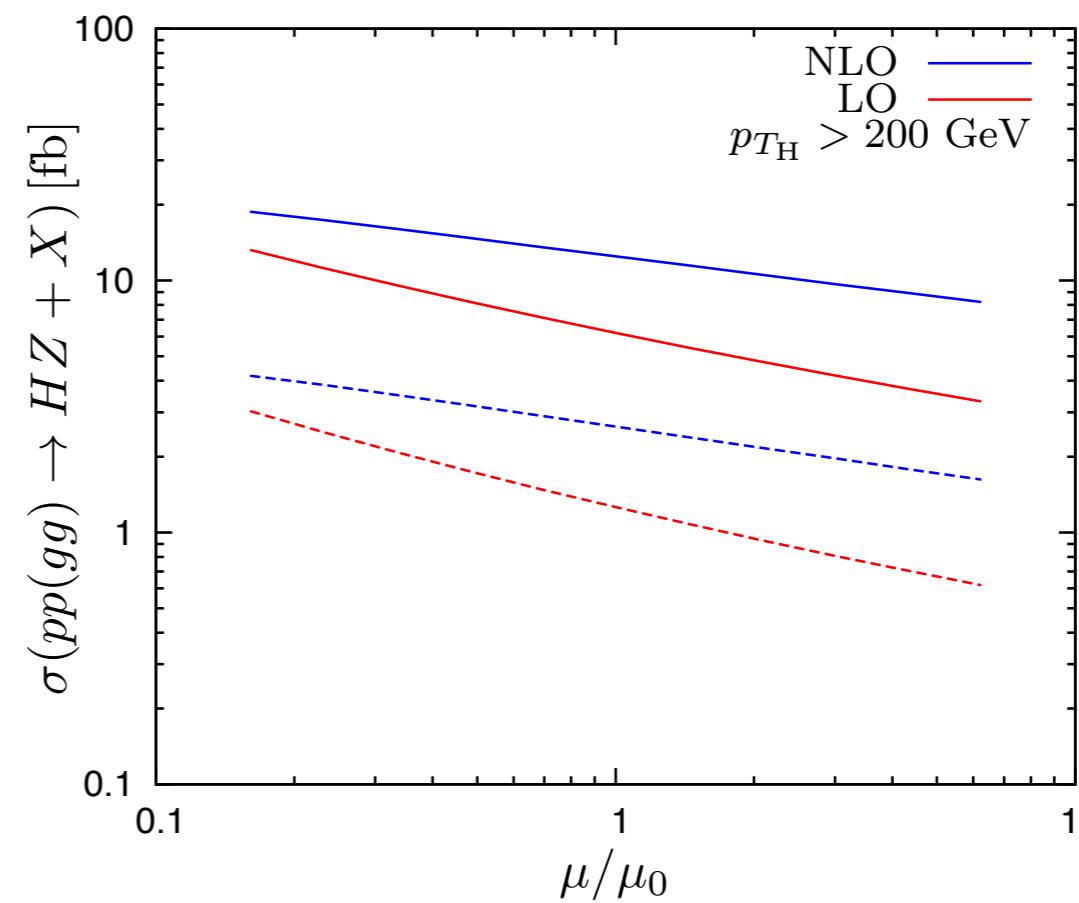
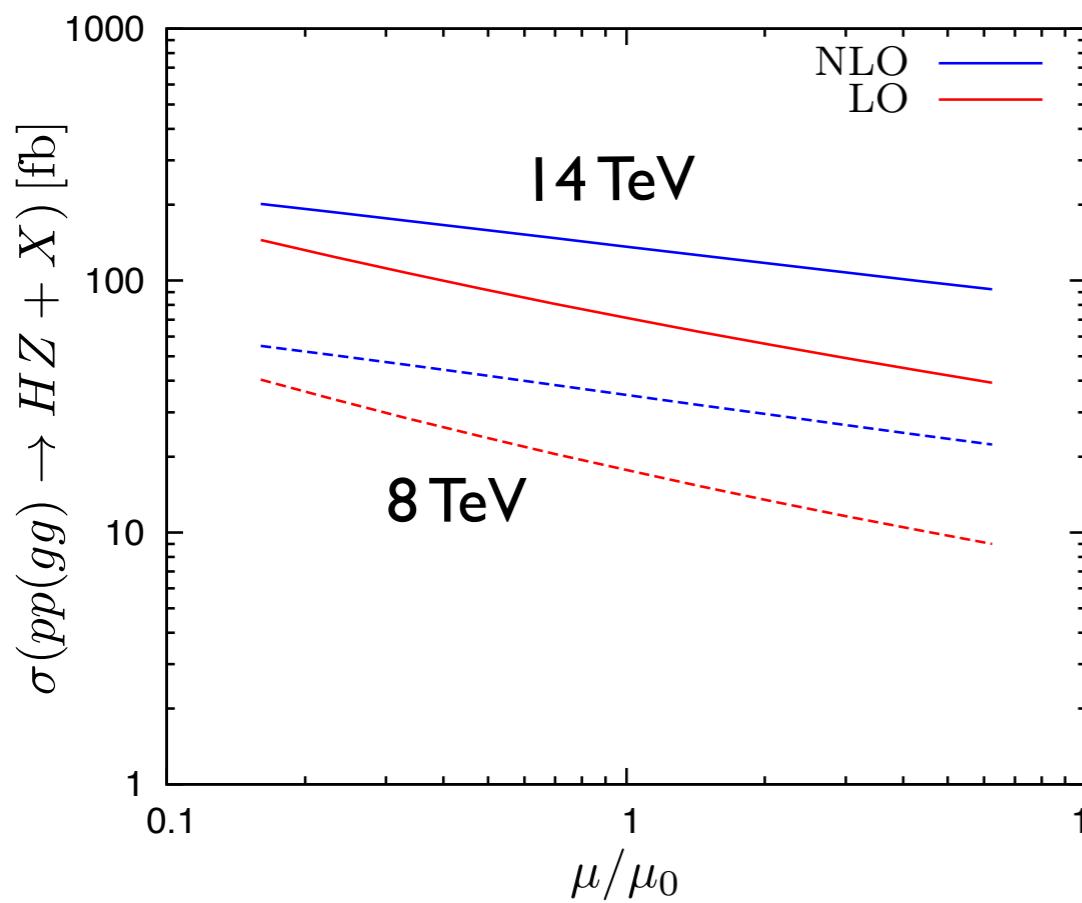
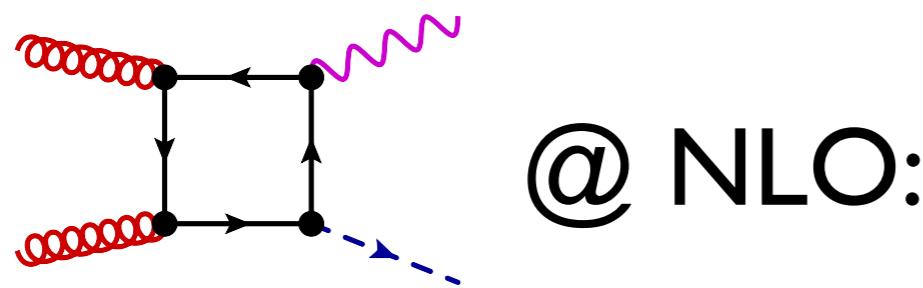
Print

Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



Conclusions

- Heuer: I think we have it!
RH: Me too.
- importance of theory undeniable
- error estimates will become crucial
- revival of precision physics?



Altenkamp, Dittmaier, RH, Rzehak, Zirke '12