Theoretical Aspects of Higgs Productions at the LHC

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- Higgs phenomenon
- Unitarity, vacuum stability ...
- Why N^iLO for Higgs
- Higgs with Jets, tops
- Higgs Characterisation
- Conclusion

Symposium on Astro-particle and Nuclear physics, Jamia Milia, Jan 21-22, 2014.

Discovery of Higgs-like boson

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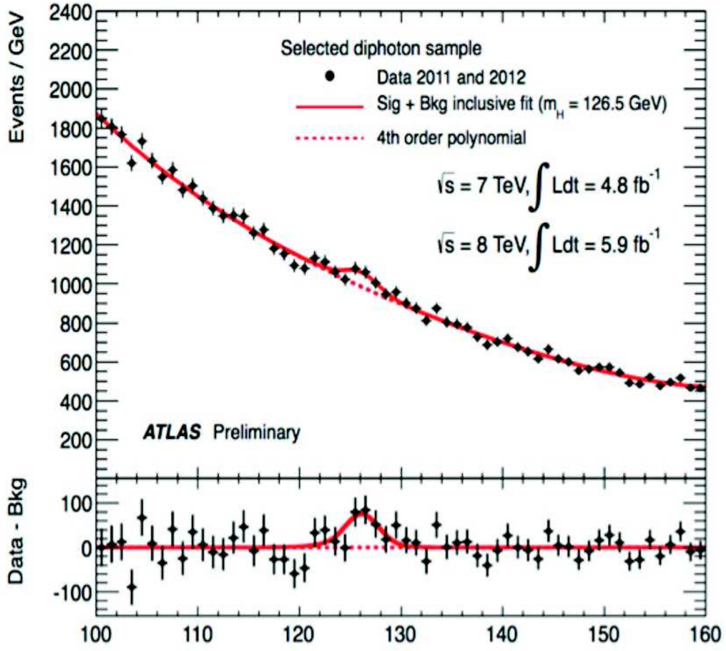
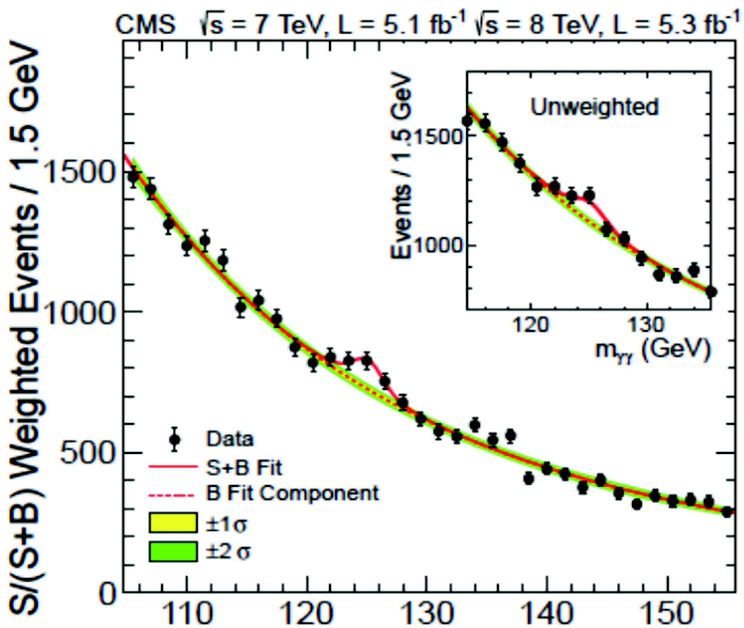


$M_{\gamma\gamma}$ (GeV)



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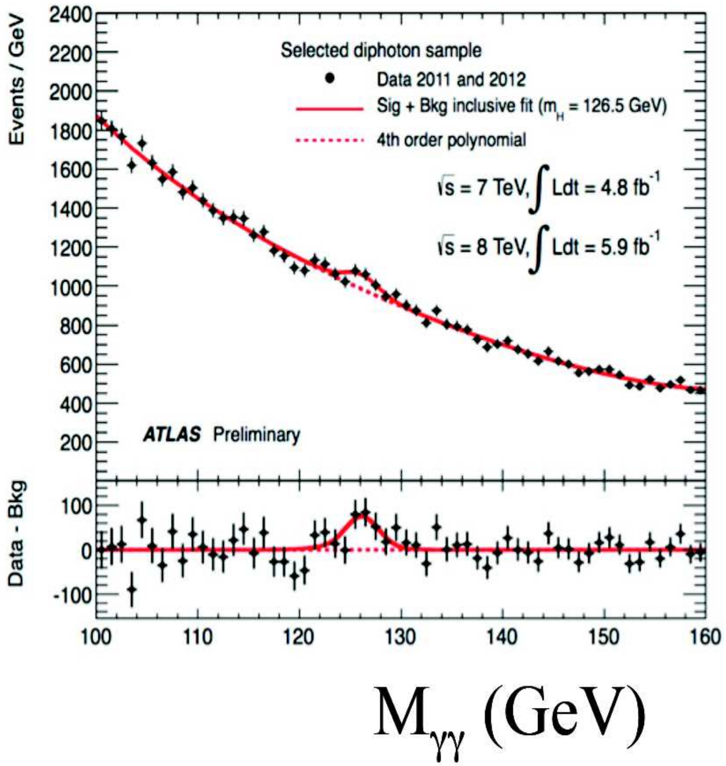

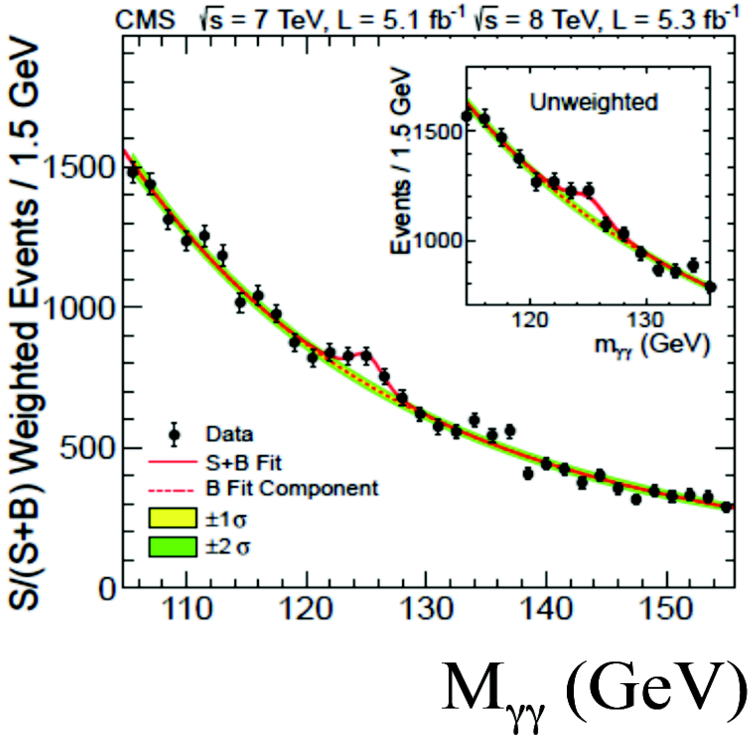

- Two high energetic photons ($E_T > 25, 35$ GeV)
- Inviriant mass distribution
- Background: Sideband method (data based)

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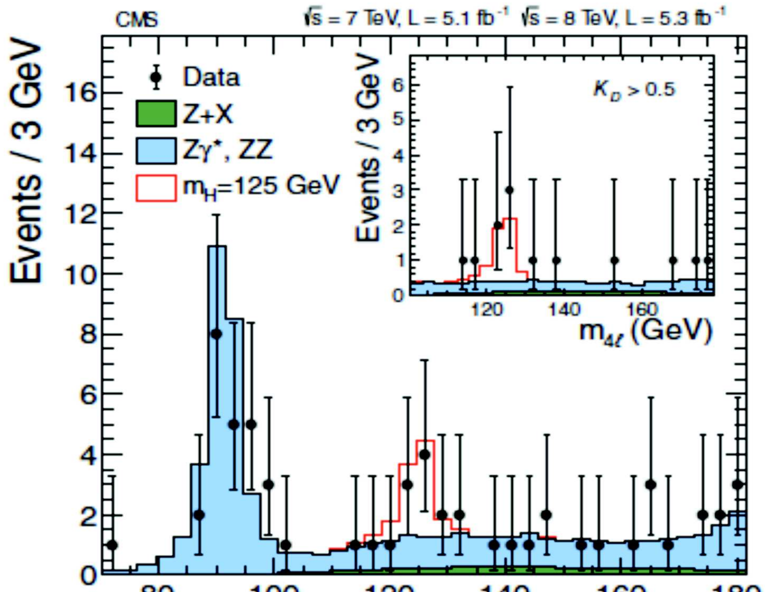

M_{4l} (GeV)

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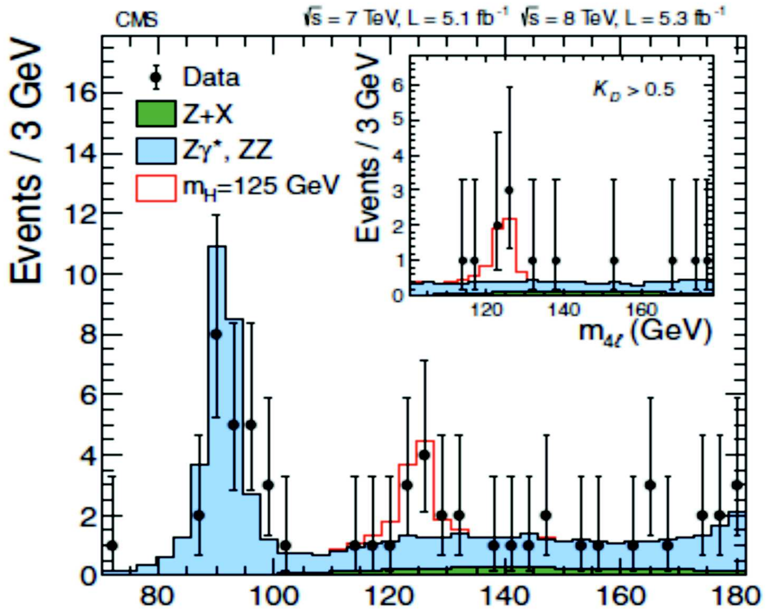

M_{4l} (GeV)

- Four leptons in the final state
- Z mass constraint

Standard Model fit (Experiment)

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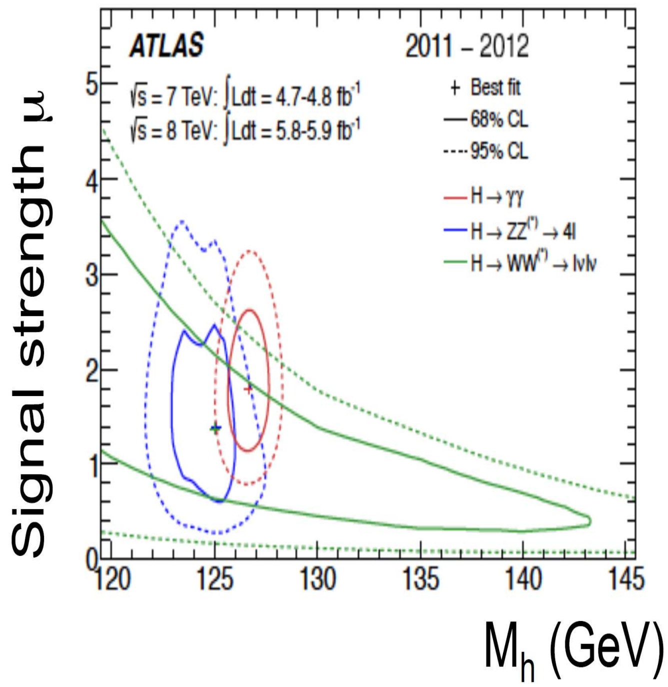

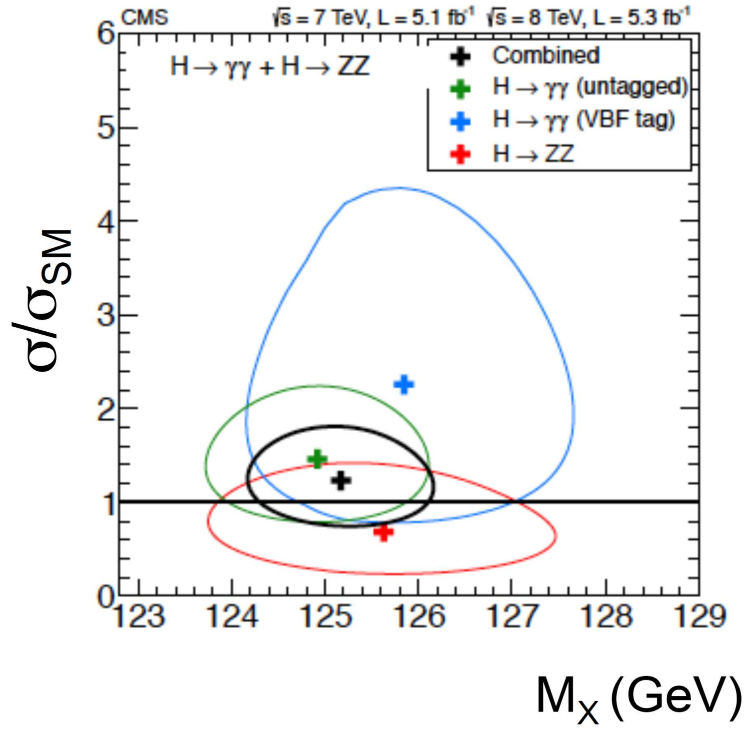

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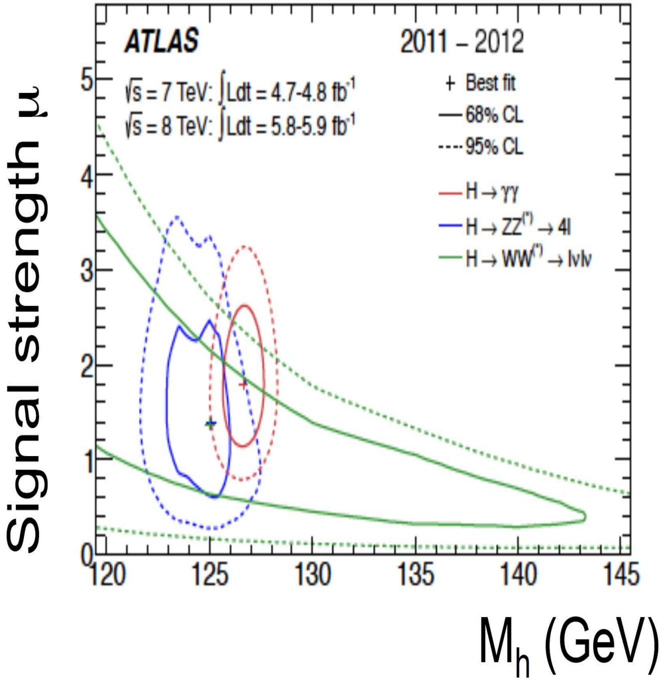

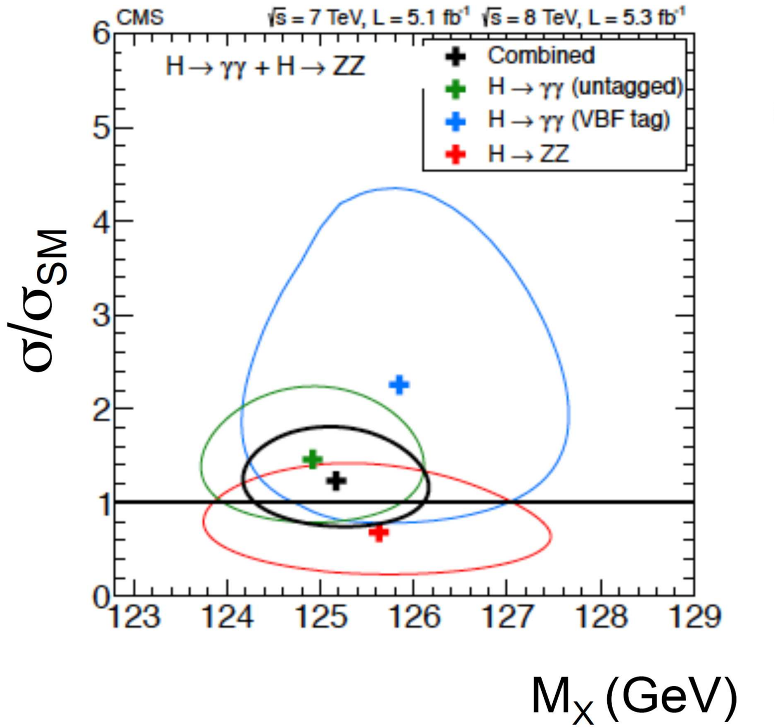

- ATLAS: $m_h = \mathbf{125 \pm 0.4}(stat) \pm \mathbf{0.5}(sys)$ GeV
- CMS: $m_h = \mathbf{126 \pm 0.4}(stat) \pm \mathbf{0.5}(sys)$ GeV

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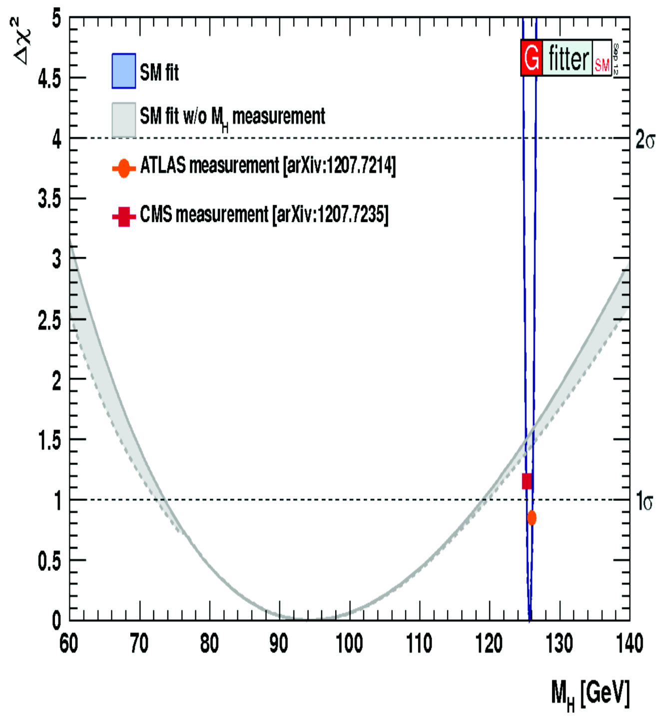

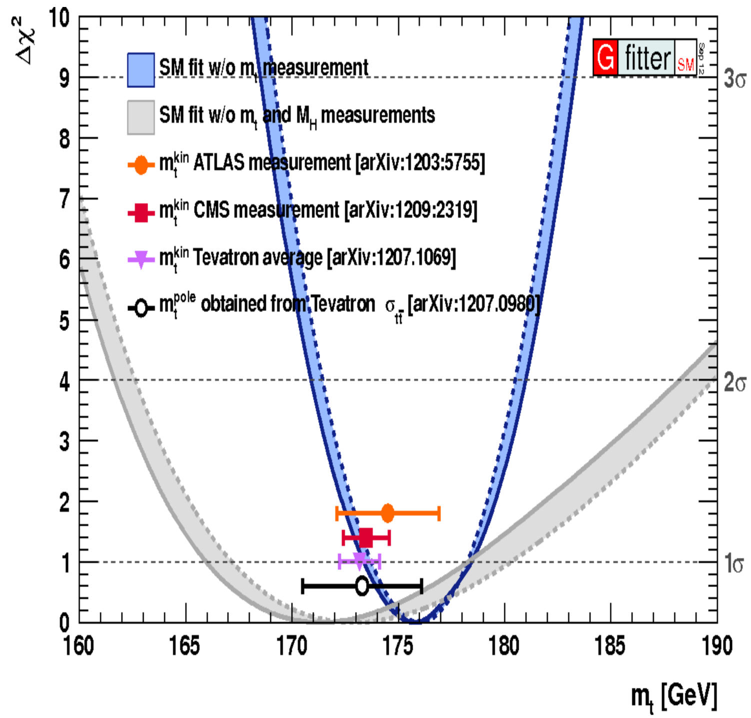

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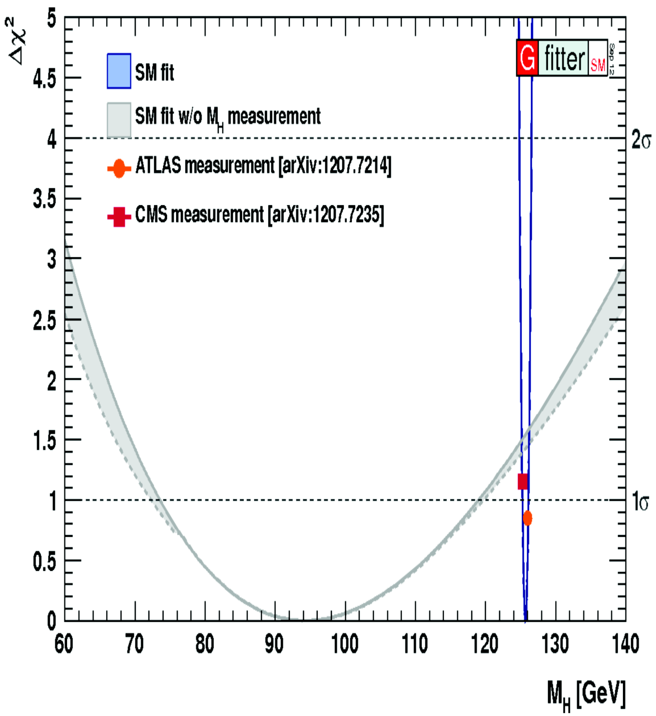

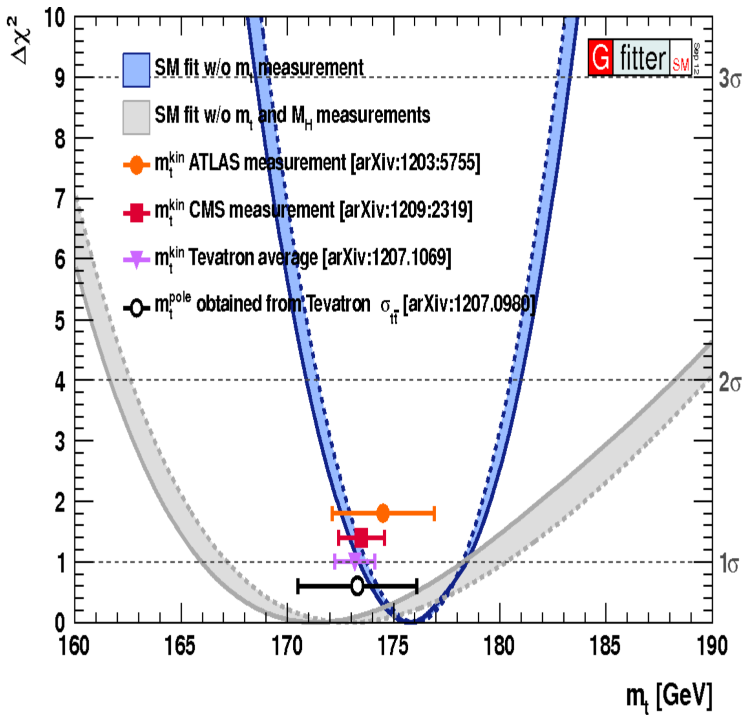

- Fit by theory colleagues
- Uses state of the art calculations in standard model and most of the available data on precision measurements from experiments such as LEP, Tevatron etc

Scalar field and Yukawa sectors in the SM

- Gauge principle in Quantum field theory provides framework to study interaction of elementary particles

- Gauge symmetry severely constraints the mass terms of gauge fields and matter fields.

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• The $SU(2)_L \times U(1)_Y$ invariant Yukawa interaction Lagrangian is given by

$$\mathcal{L}_Y = Y_e \overline{L} \Phi e_R + Y_u \overline{Q}_L \tilde{\Phi} u_R + Y_d \overline{Q}_L \Phi d_R + h.c$$

where $\tilde{\Phi} = i\tau_2 \Phi^*$ with $Y(\tilde{\Phi}) = -1$

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- $\zeta_i(x)$ are called Goldstone bosons (massless,spinless)
- $h(x)$ is called the Higgs boson.

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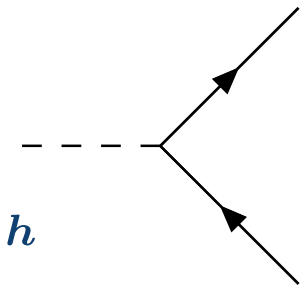

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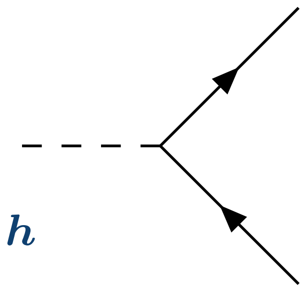

Masses and Vertices of $W^{\pm}, Z, \gamma$ bosons

$$|\mathcal{D}_\mu \Phi|^2 \quad \Longrightarrow \quad \frac{v^2}{8}\left(1+\frac{h(x)}{v}\right)^2 \left(g^2\left[(\mathcal{A}_\mu^{U1})^2+(\mathcal{A}_\mu^{U2})^2\right]+\left[g\mathcal{A}_\mu^{U3}-g' B_\mu^{U})^2\right]\right)$$

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where the masses of $W^{\pm}, Z, \gamma$ bosons:

$$\boxed{M_W^2 = \frac{g^2 v^2}{4}, \qquad M_Z^2 = \frac{v^2}{4}(g^2 + g'^2), \qquad M_\gamma = 0}$$

The vertices are

$$h(x) V_{i\mu} V_i^{*\mu} \quad \Longrightarrow \quad 2i\frac{M_i^2}{v} g_{\mu\nu}, \qquad h(x)h(x) V_{i\mu} V_i^{*\mu} \quad \Longrightarrow \quad 2i\frac{M_{V_i}^2}{v^2} g_{\mu\nu}$$

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- Finiteness of λ coupling upto a cut off scale of the theory: Droping gauge and Yukawa contributions,

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- If $\Lambda_P = 10^{19}$ GeV, the higgs has to be light $m_h \leq 145$ GeV.
- If $\Lambda_P = 10^{3}$ GeV, the higgs has to be heavy $m_h \leq 750$ GeV.

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$$m_h \geq 129.2 + 1.8 \times \left(\frac{m_t^{\rm pole} - 173.2 \text{ GeV}}{0.9 \text{ GeV}} \right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0 \text{ GeV} .$$

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which can give stringiant condition on vacuum stability with small error on the higgs mass.

Vacuum stability

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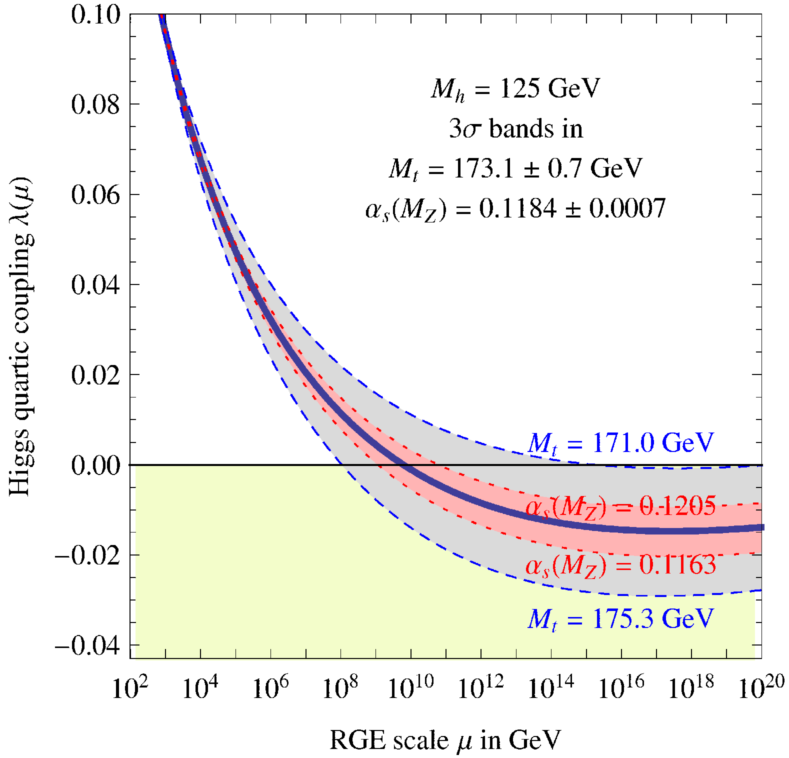

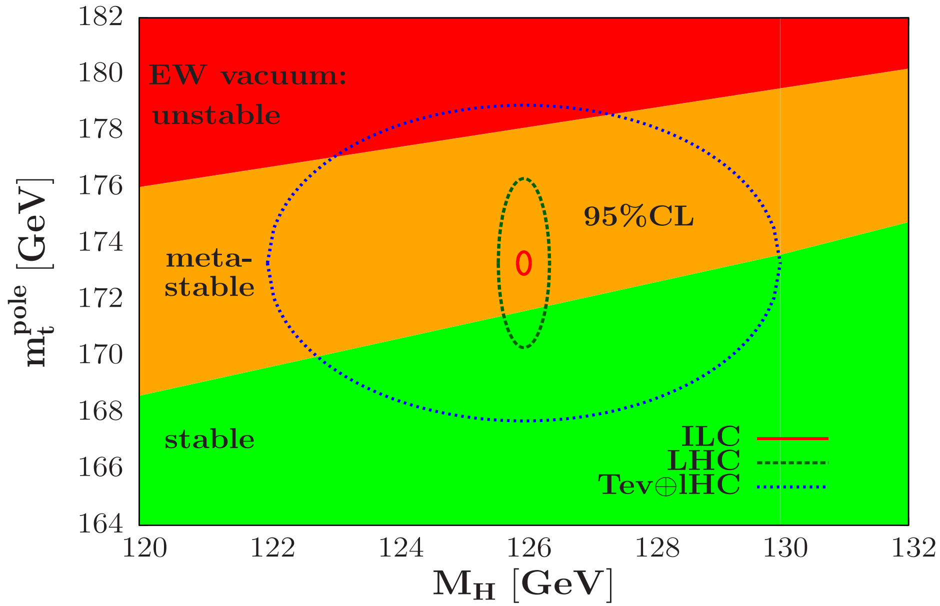

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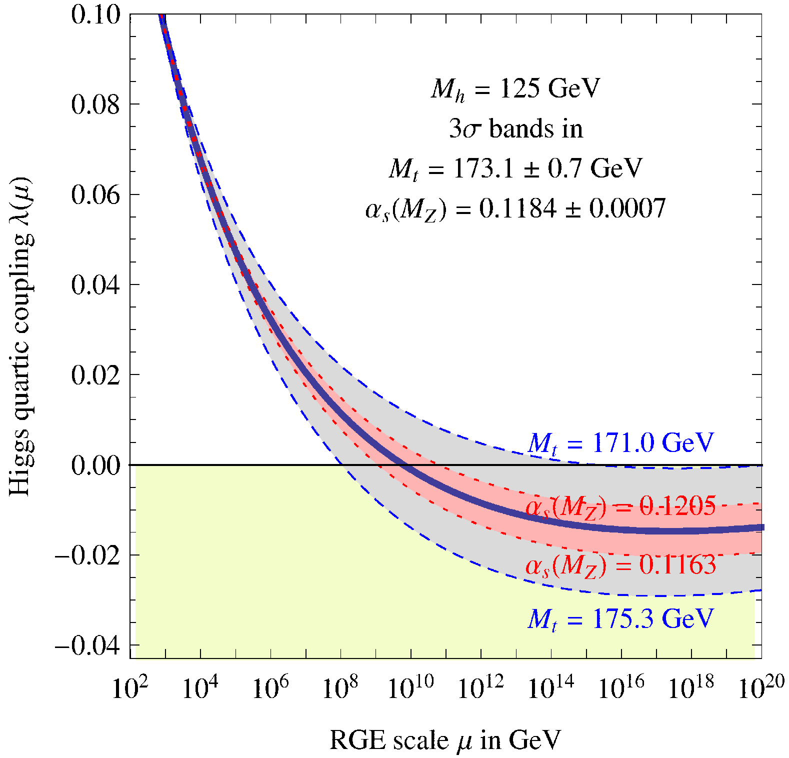

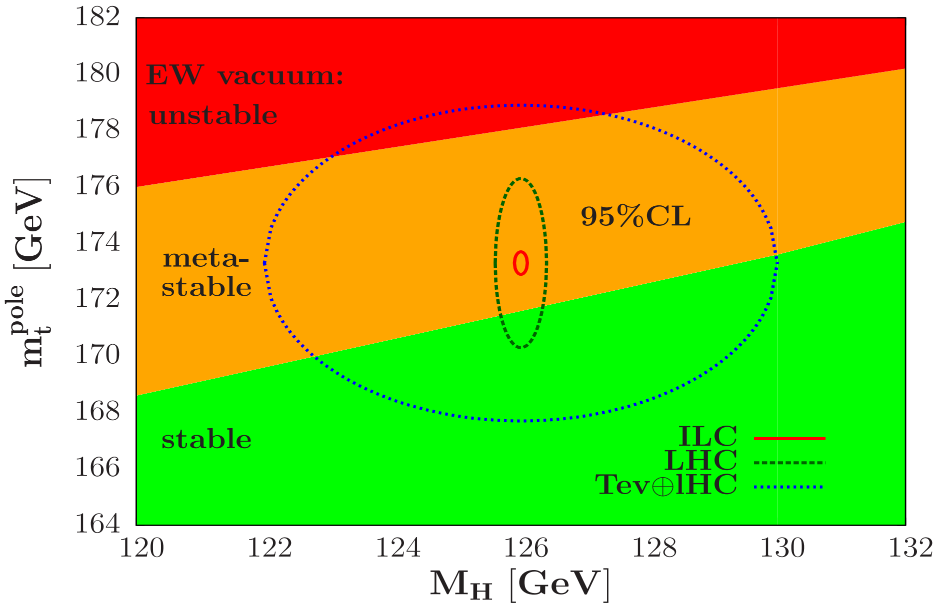

- λ is sensitive to top mass
- Stability of vacuum can be answered only if the error on the top mass goes down significantly.
- e^+e^- machine can give better measurement of top mass

Higgs Mass

[Summer 2004, LEPEWWG]

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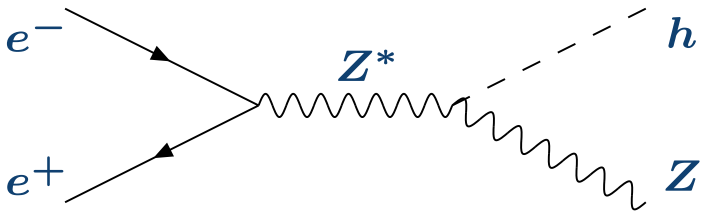
Direct:



$$m_h > 114.4\ GeV$$

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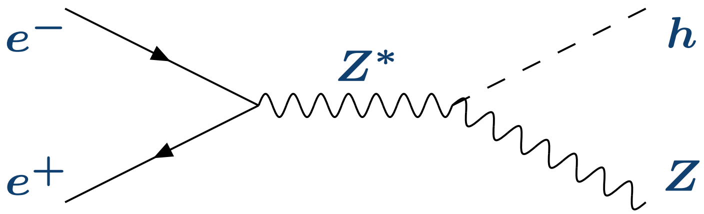

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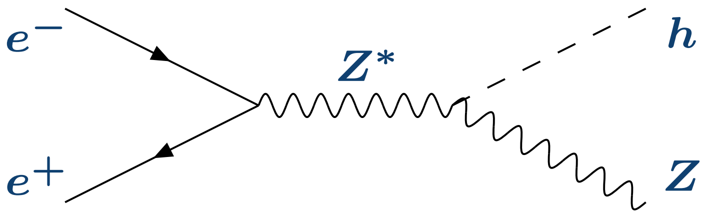

$m_h > 114.4\ GeV$

- LEP is a e^+e^- collider with $\sqrt{s} = 209$ GeV
- Primary search mode $e^+e^- \to hZ$
- On-shell higgs can be produced if the mass of the higgs is less than $\sqrt{s} - M_Z = 118$ GeV
- Low statistics and insufficient energy available give the lower bound $m_h > 114.4\ GeV$.

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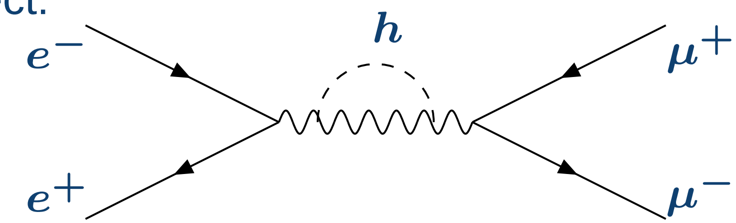
Indirect:



$$m_h < 260\ GeV\ (\ 95\%\ CL)$$

$$\Delta\chi^2(m_h, x) = \chi^2(m_h, x) - \chi^2_{min}$$

- $\Delta\chi^2 < (1.96)^2$ gives 95% CL allowed mass range for higgs mass m_h.
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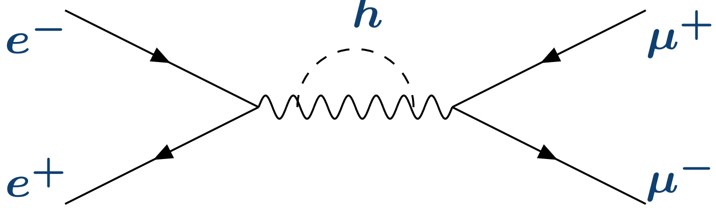

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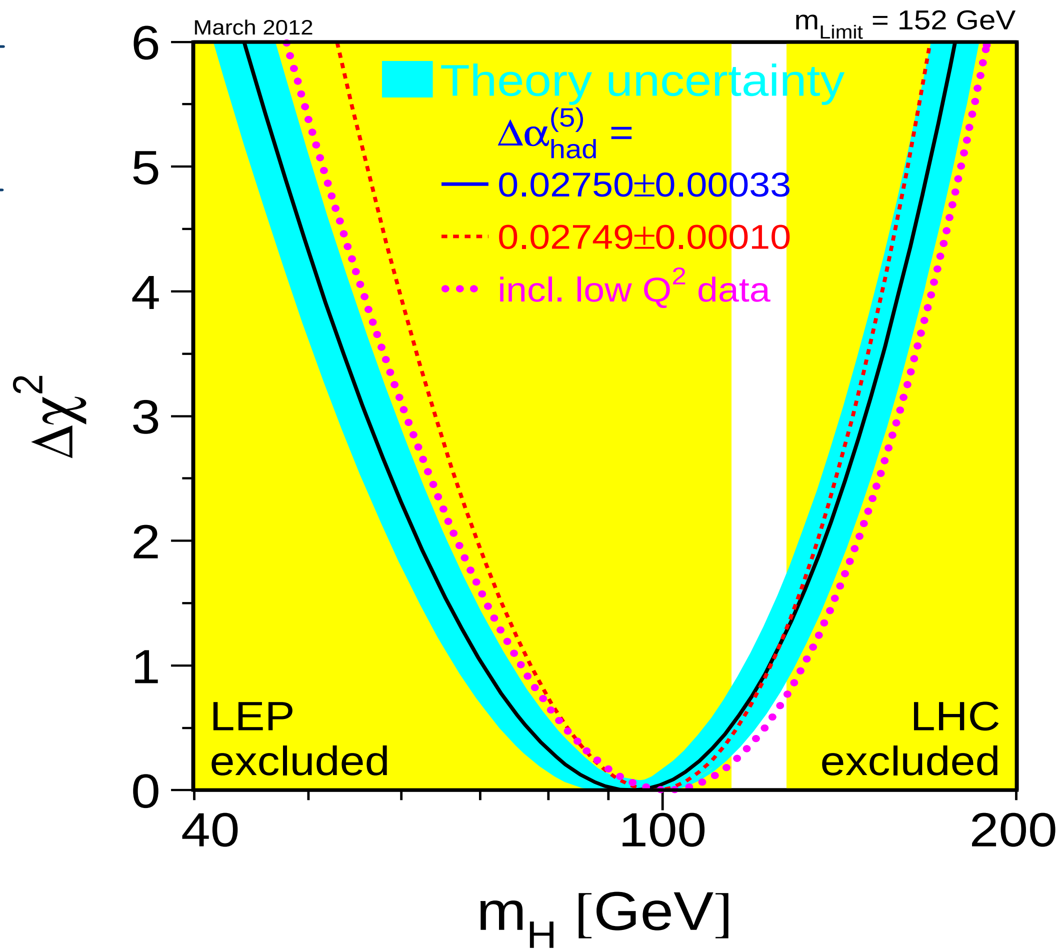

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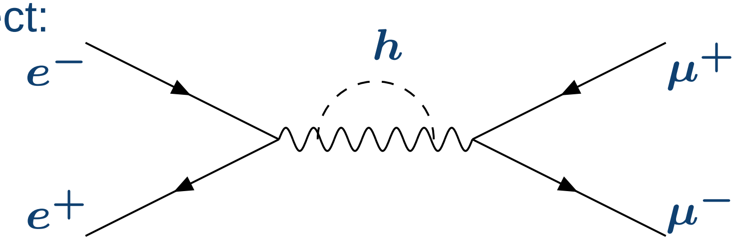

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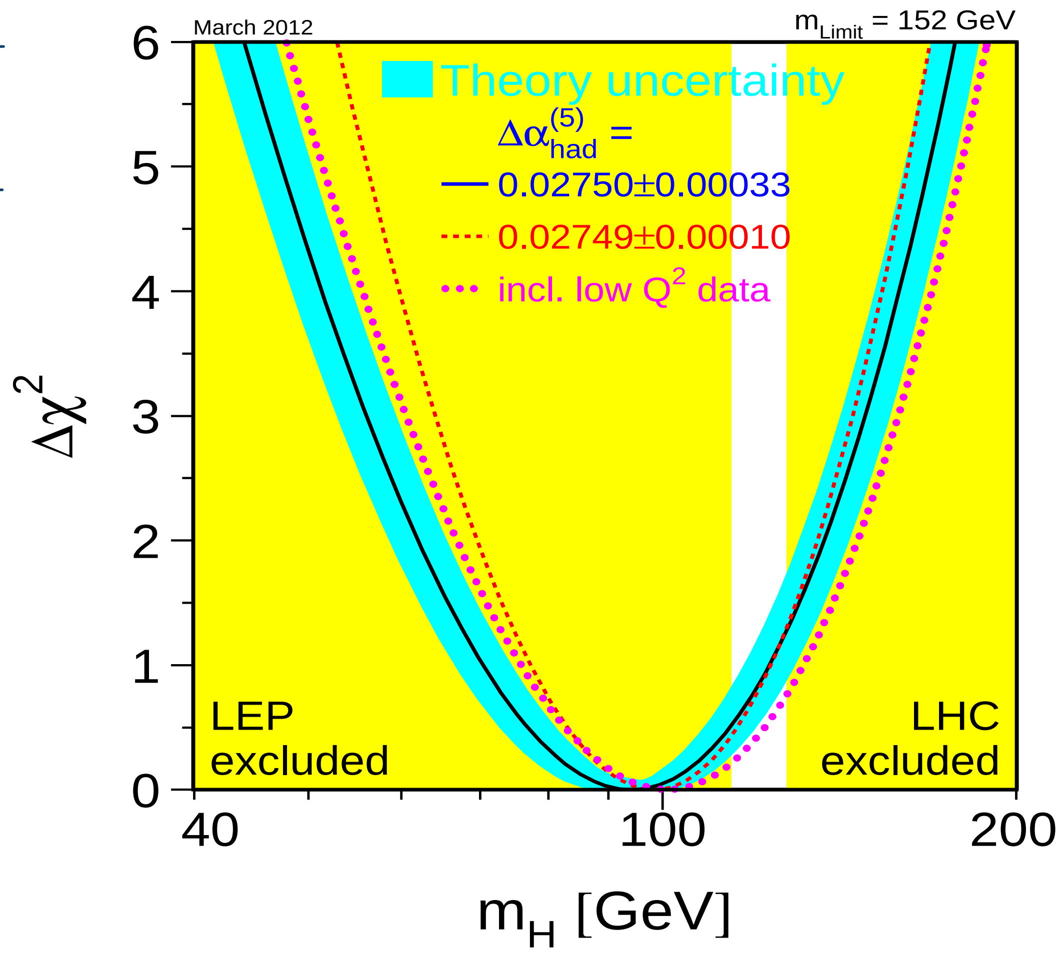

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Winter 2011: Combined Tevatron updates

Data of $\mathbf{8.3 fb^{-1}}$ exclude Higgs of mass in $\mathbf{158 < m_H < 173\ GeV/c^2}$ at $\mathbf{95\%}$ CL.

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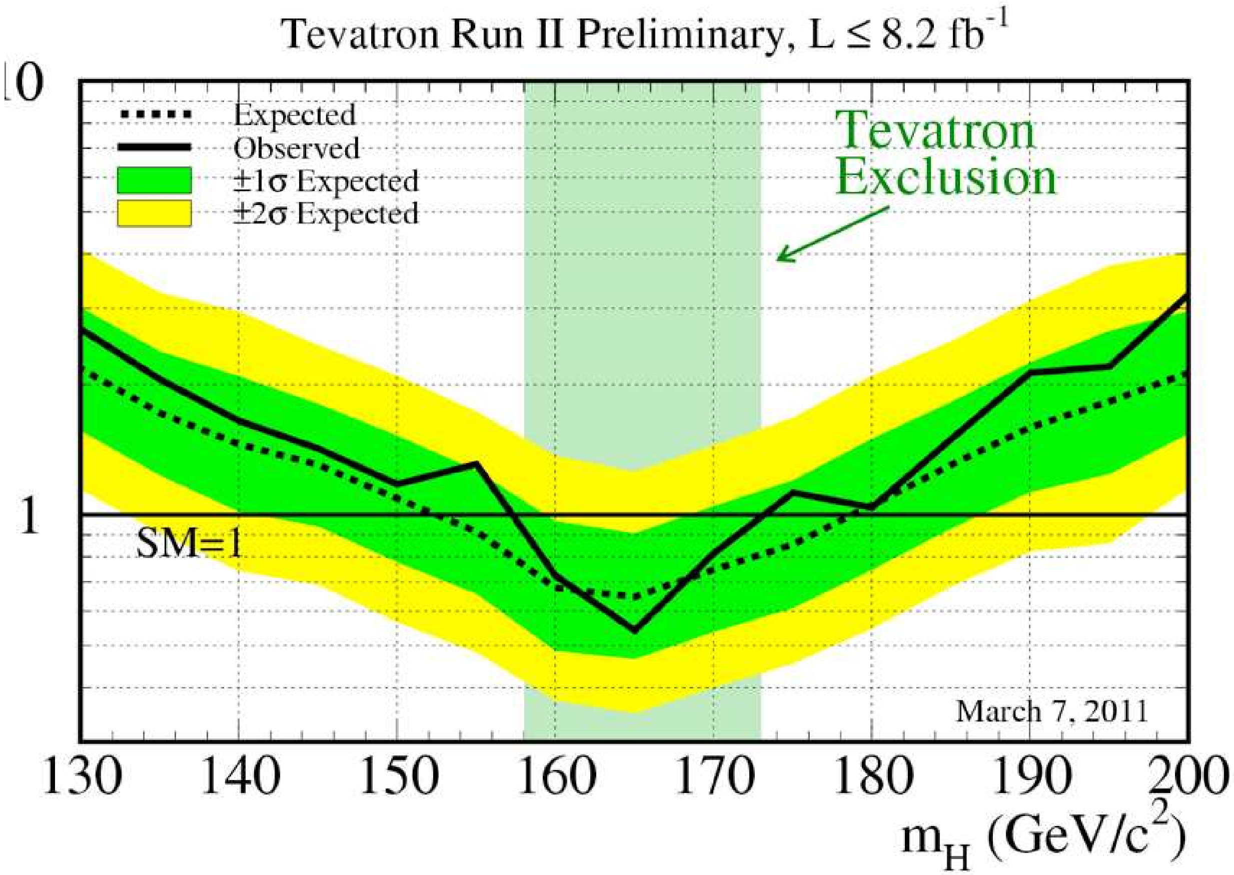

Higgs Production at the LHC ($8\ TeV$)

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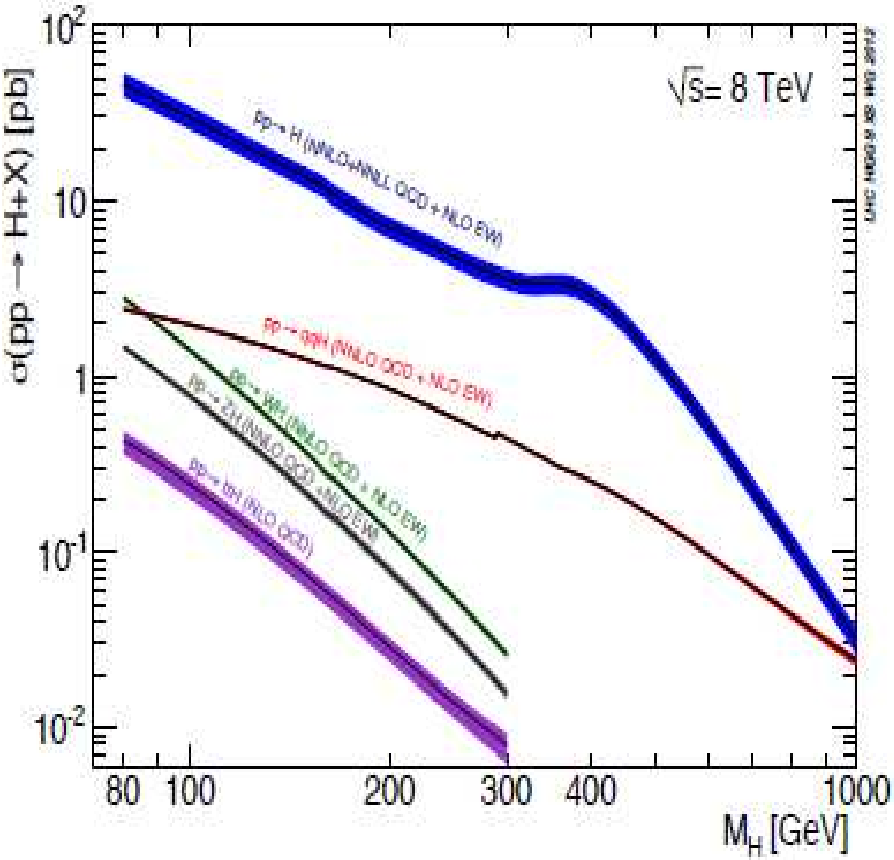

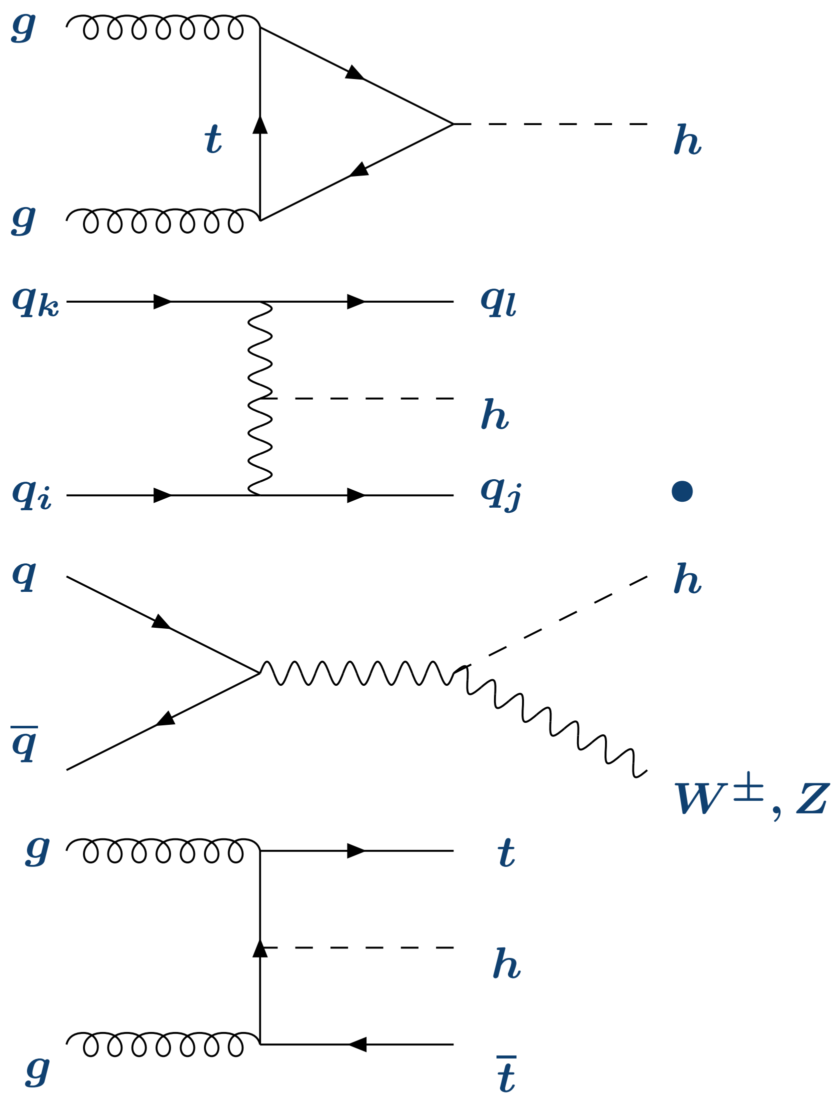

First three productions are known to NNLO level in QCD •
• the last one is known only upto NLO level.

Width of the Higgs boson

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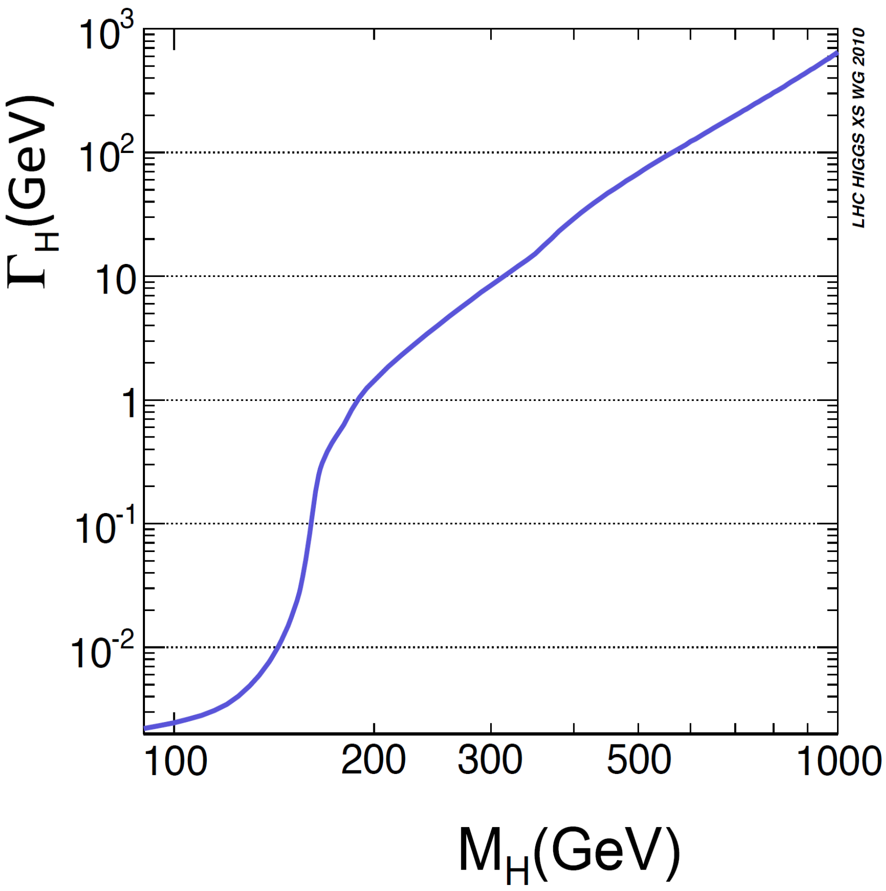

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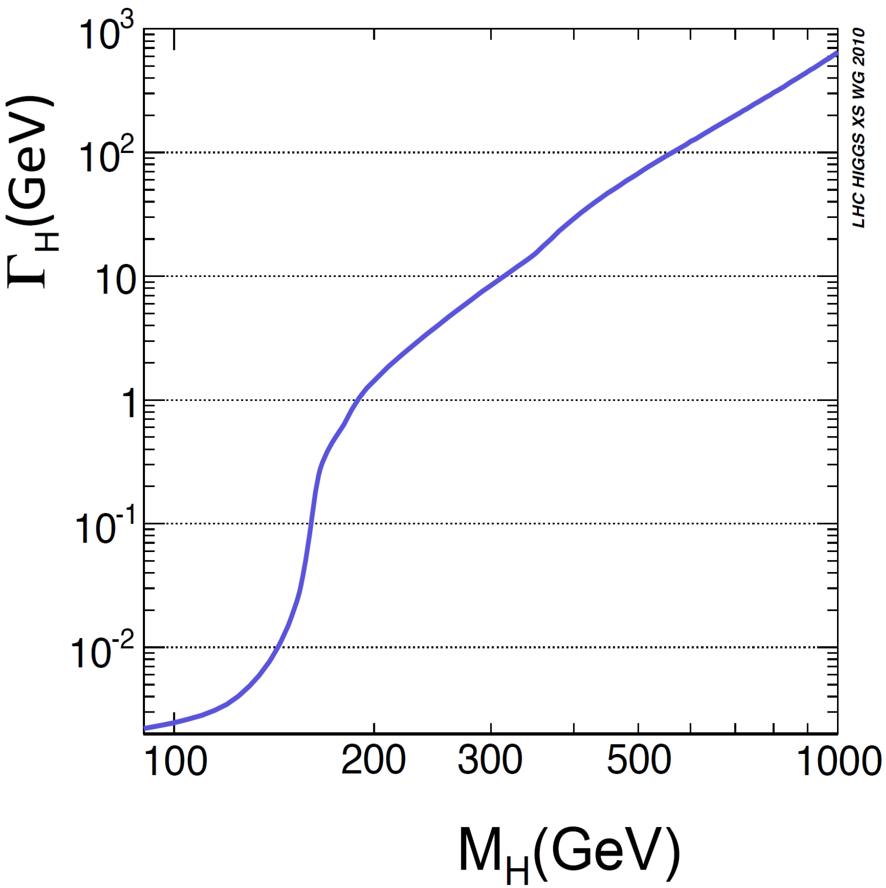

Width of the light Higgs boson is very small and hence the interference effects are negligible

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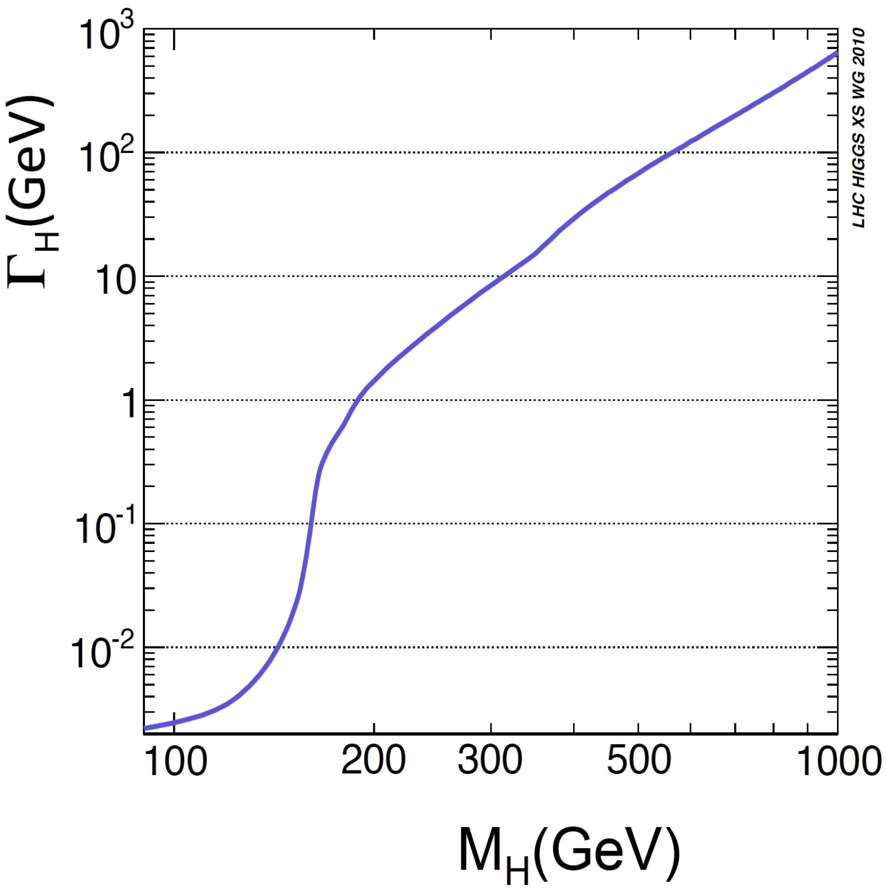

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Mass resolution in $\gamma\gamma$ and ZZ channels is very good.

Theory influence on the rates

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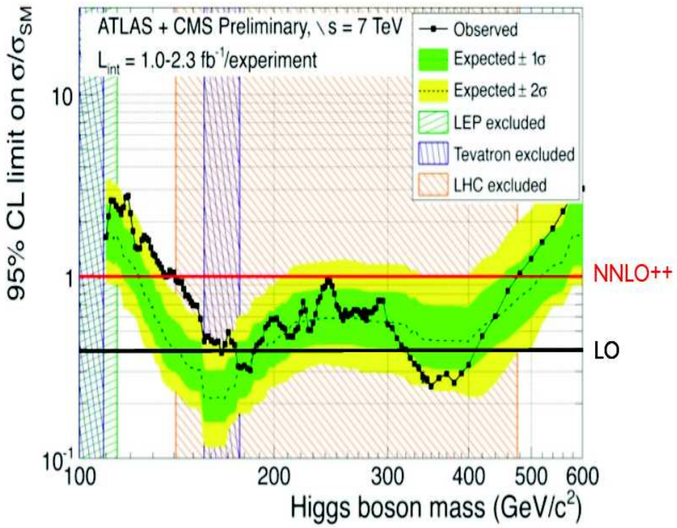

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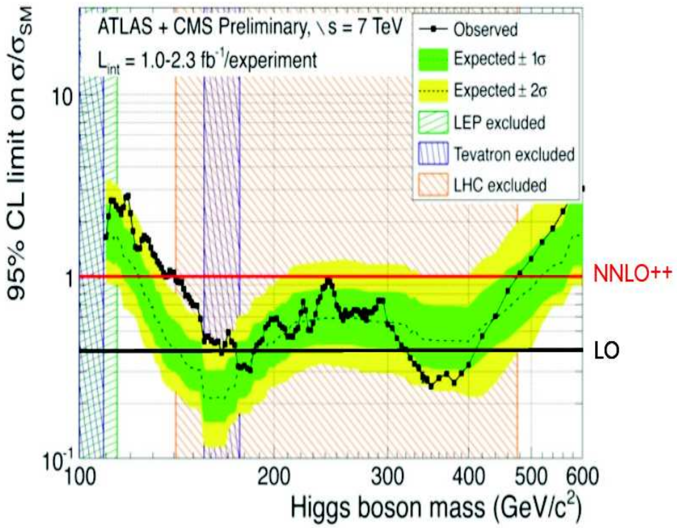

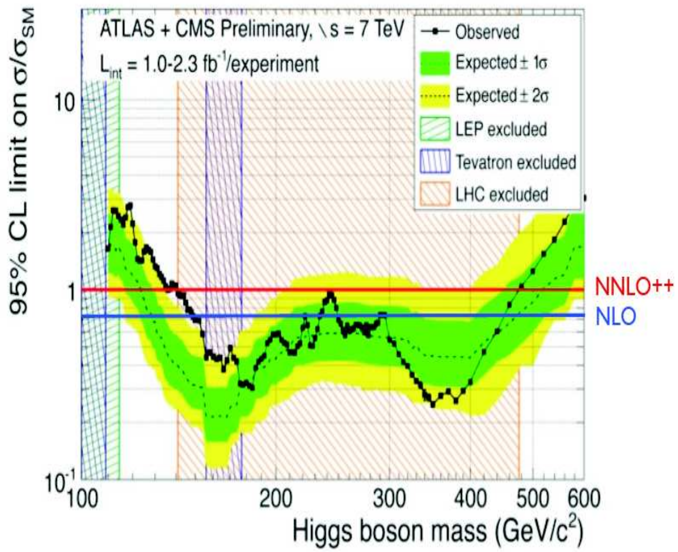

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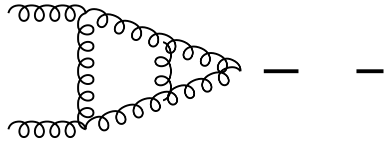

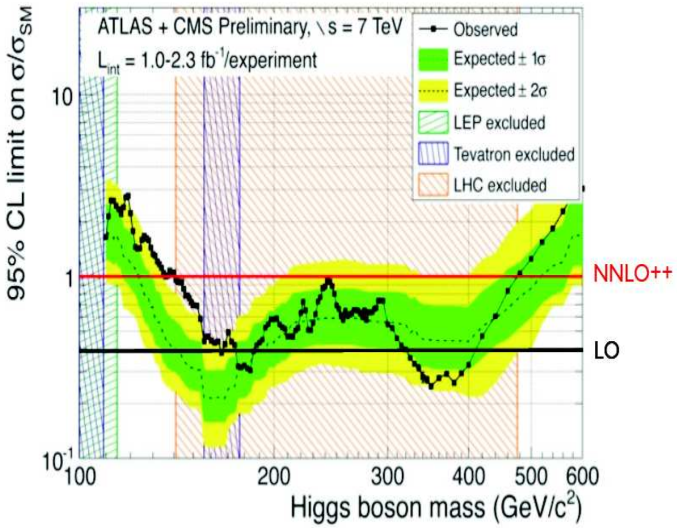

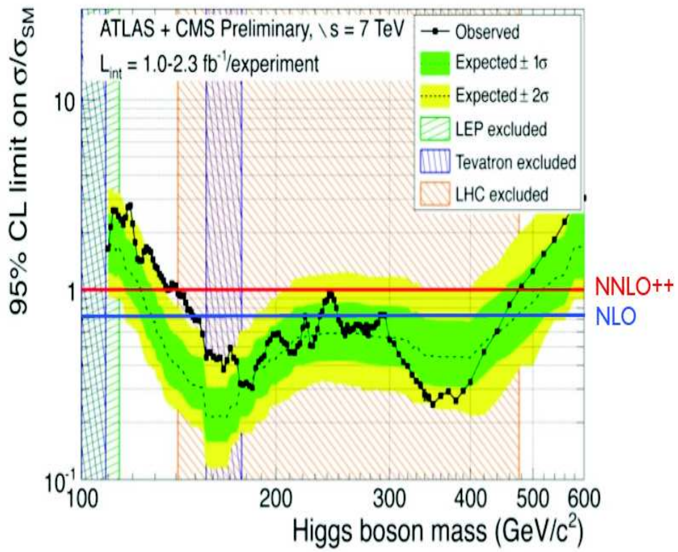

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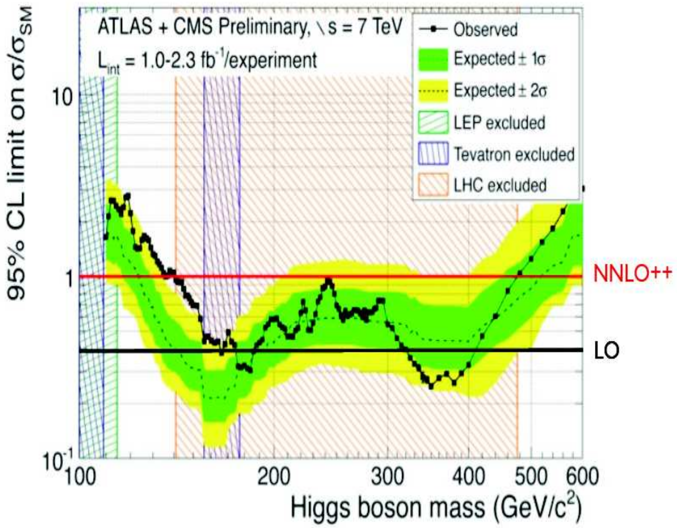

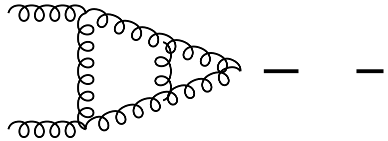

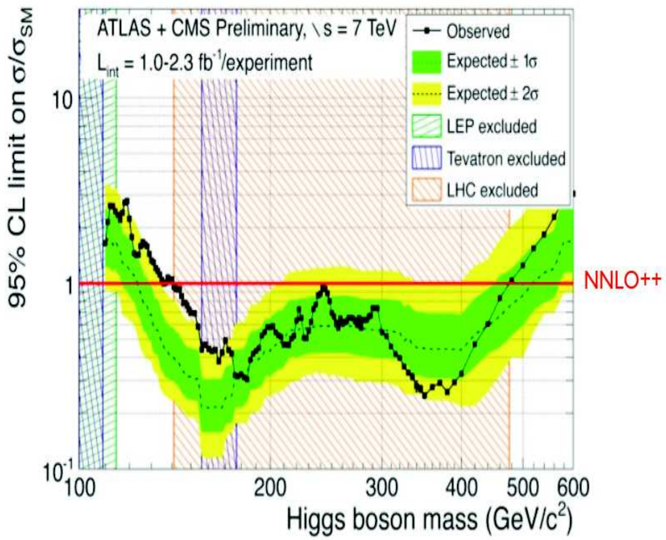

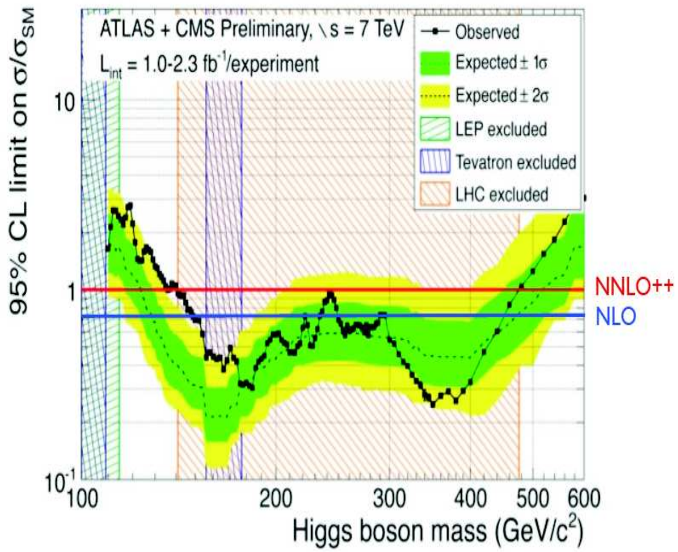

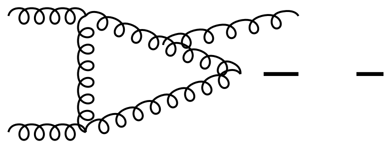

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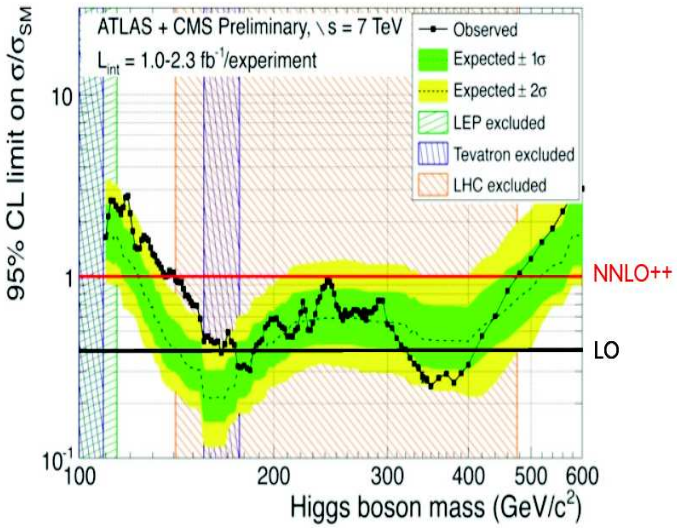

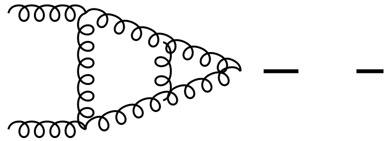

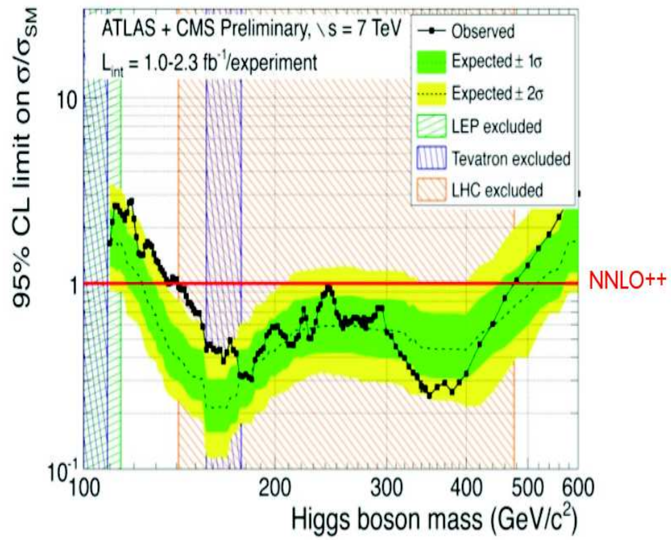

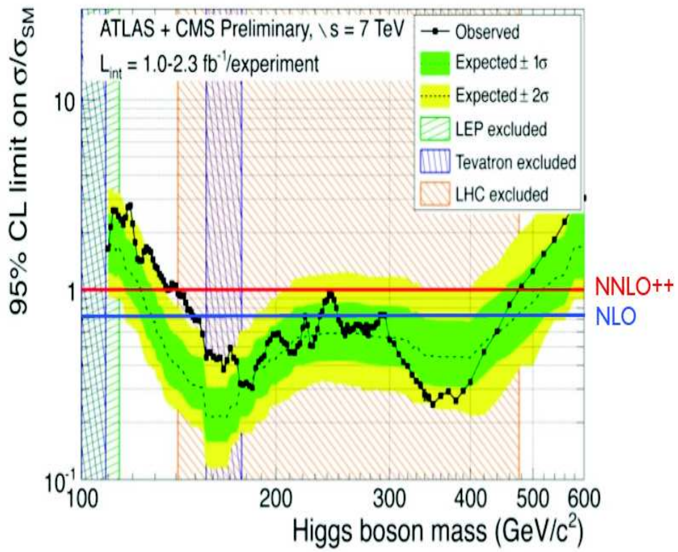

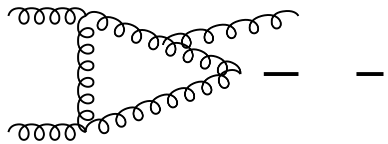

- To exclude something we need to understand the signal well
- To discover something we need to understand the background well

R.Harlander

Why LO, NLO and NNLO for Higgs production

$$P_1 + P_2 \rightarrow higgs + X$$

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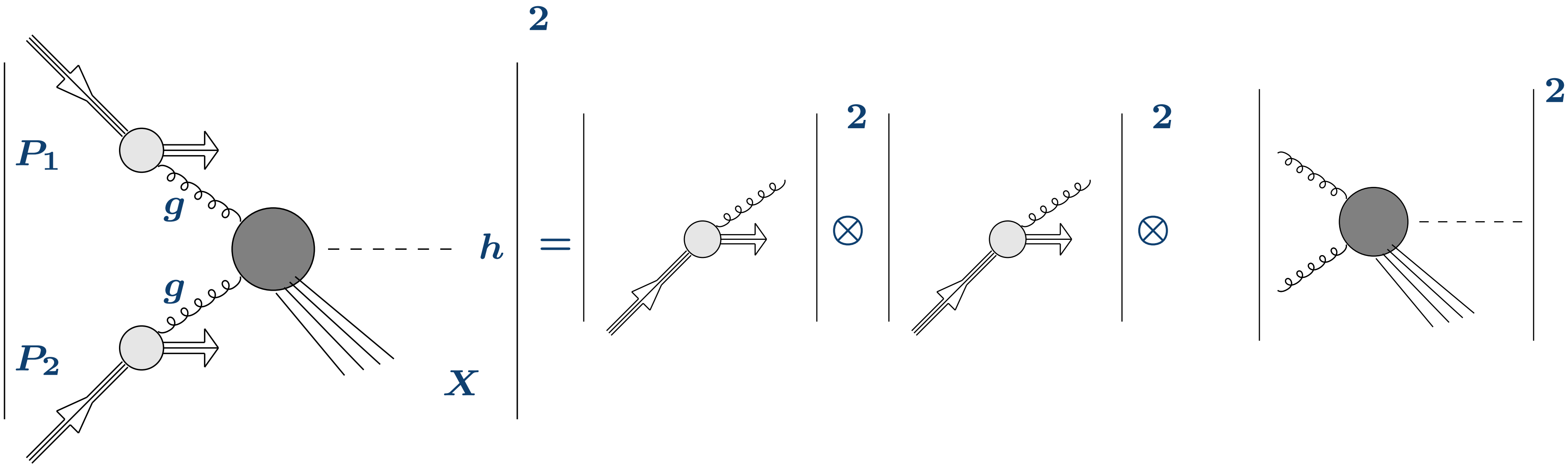

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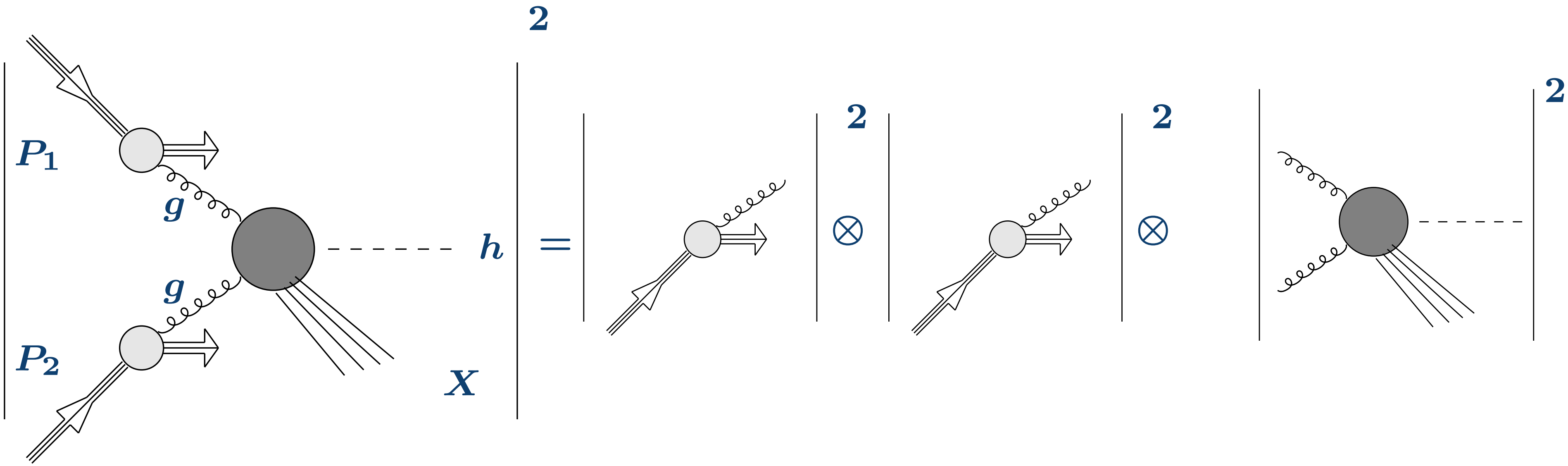

Extraction of non-perturbative functions:

- $f_a(x)$ are parton distribution functions inside the hadron P.
- Non-perturbative in nature and process independent.

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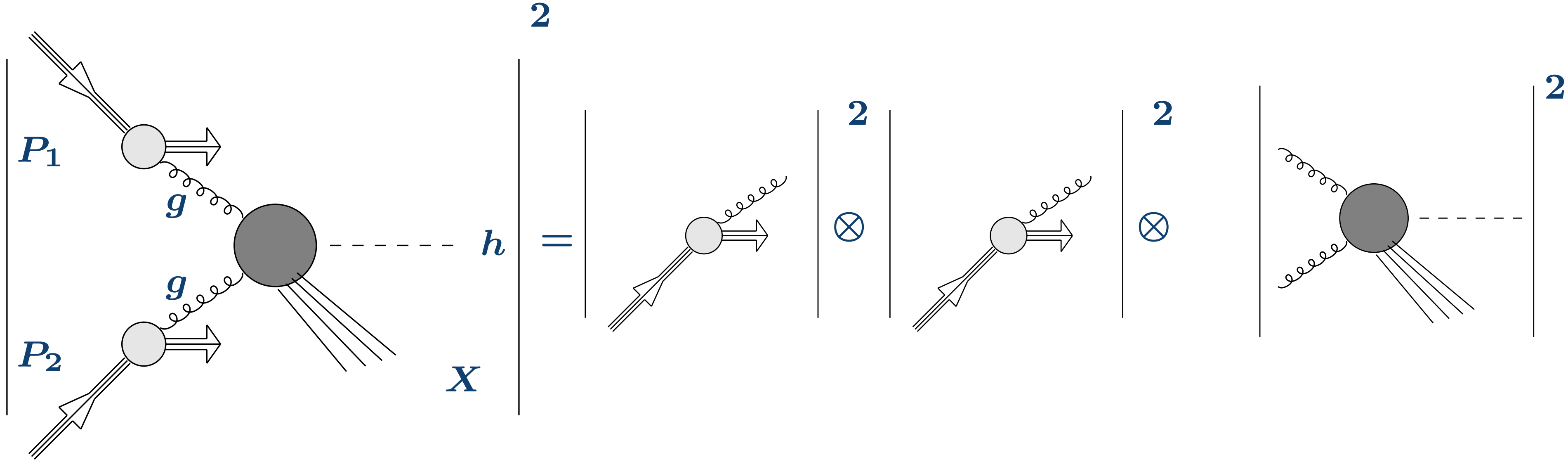

Extraction of non-perturbative functions:

- $f_a(x)$ are parton distribution functions inside the hadron P.
- Non-perturbative in nature and process independent.

Large Perturbative corrections:

- $\hat{\sigma}_{ab}$ are the partonic cross sections.
- Perturbatively calculable.

Why LO, NLO and NNLO for Higgs production

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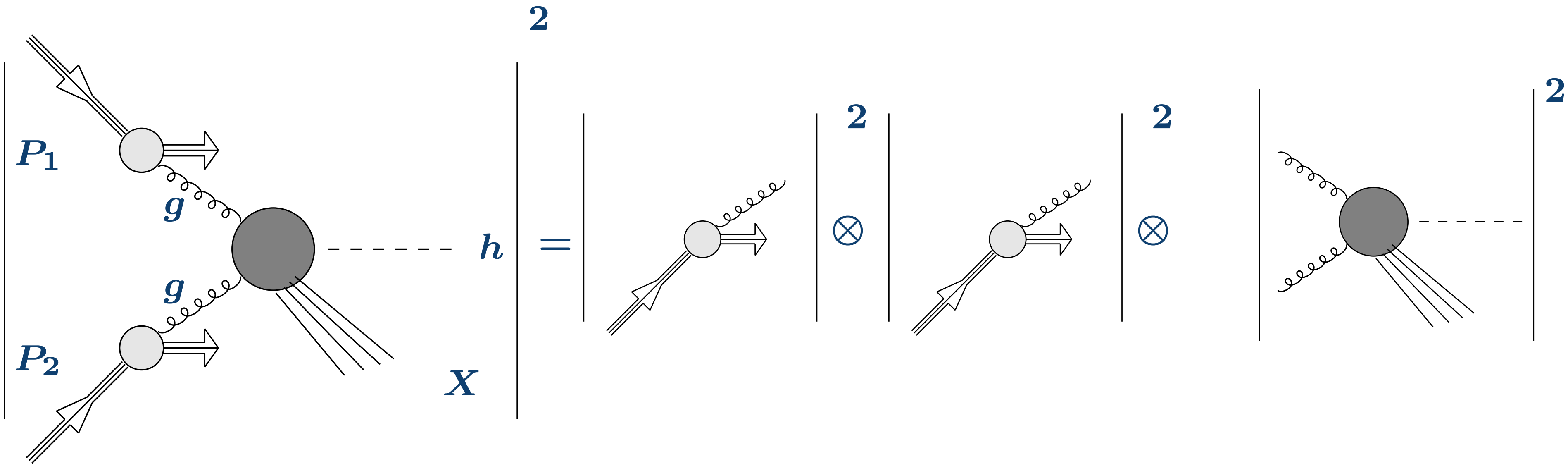

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PDF from LHC

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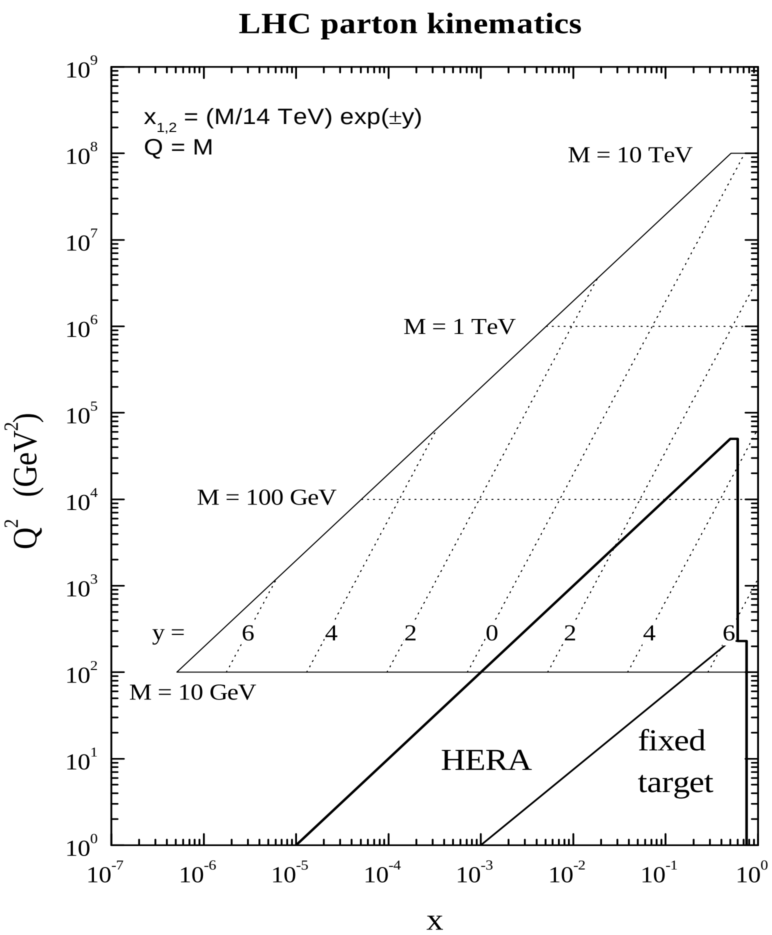

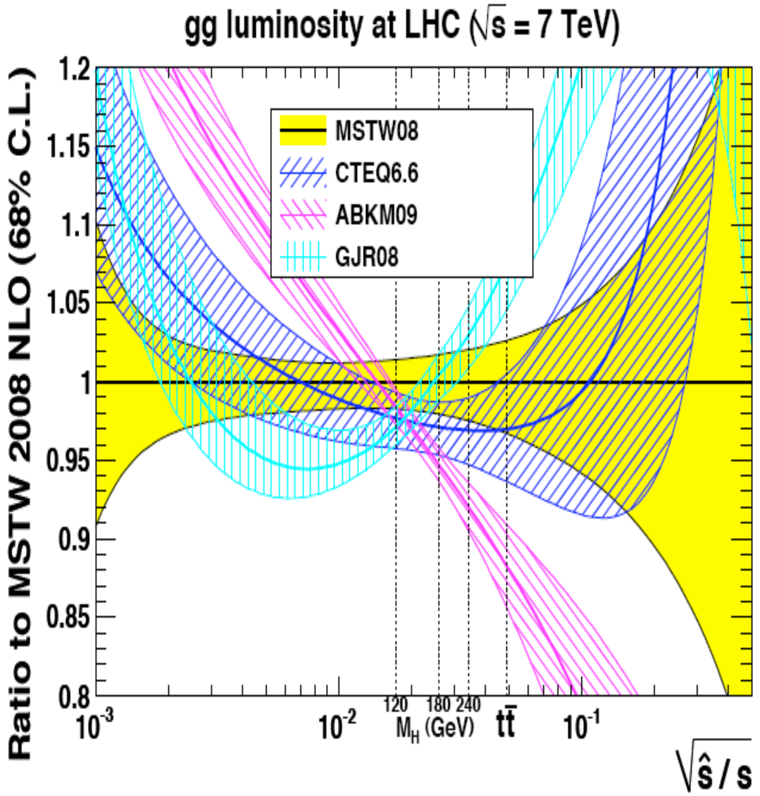

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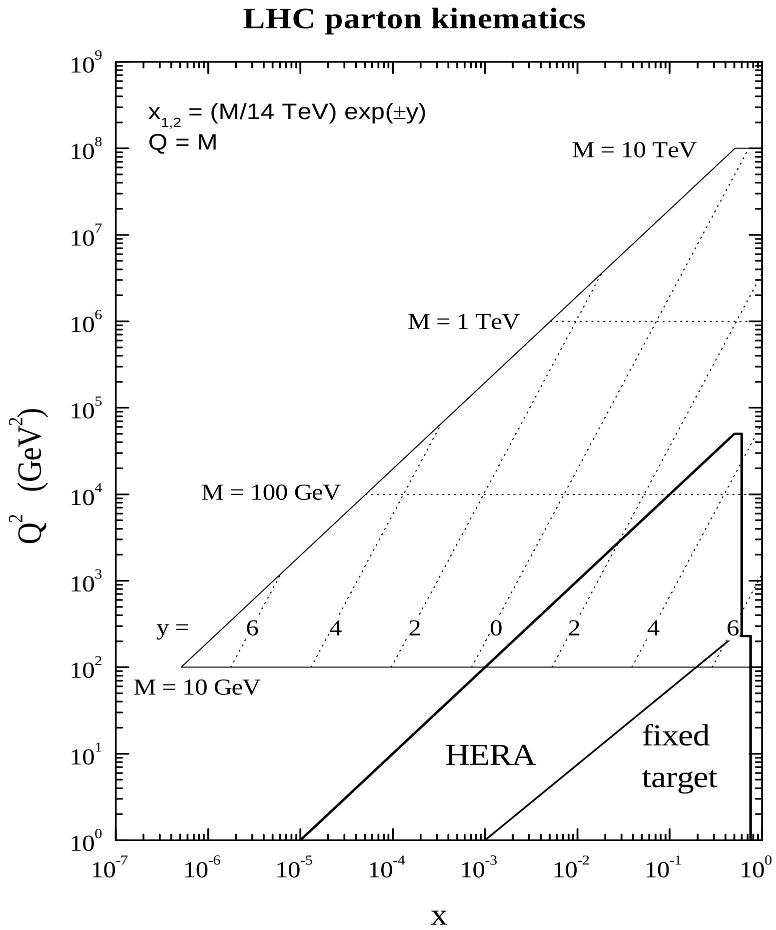

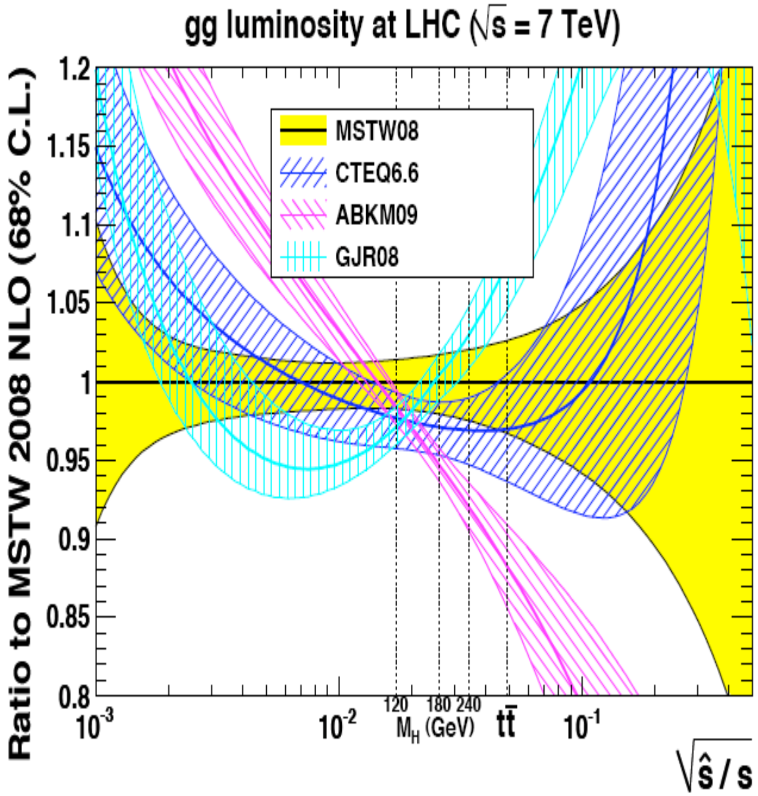

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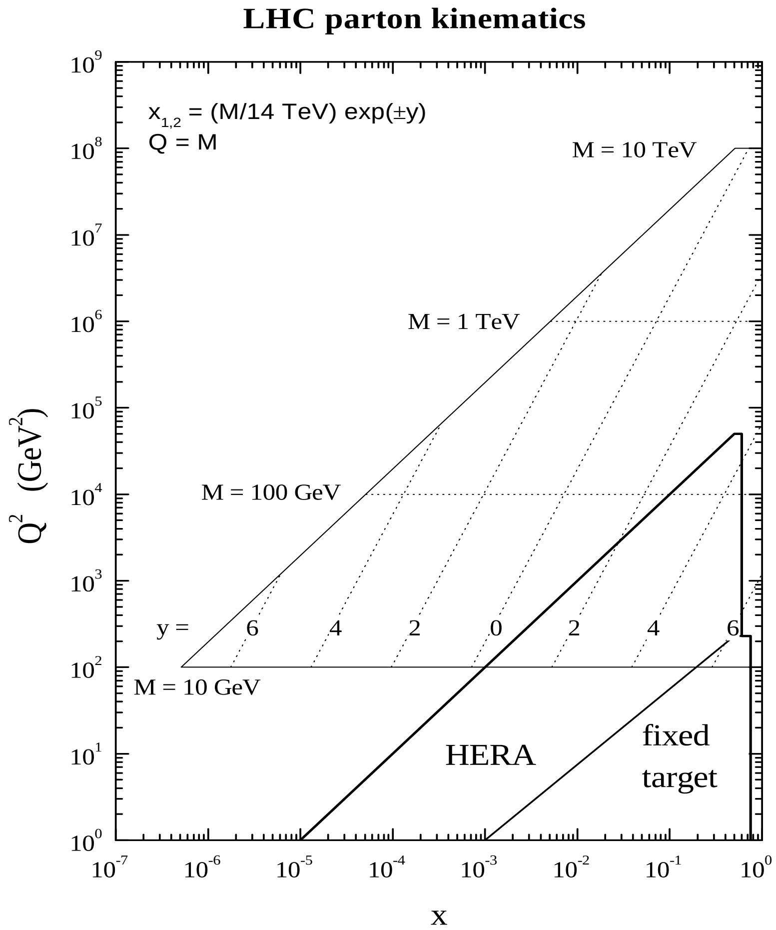

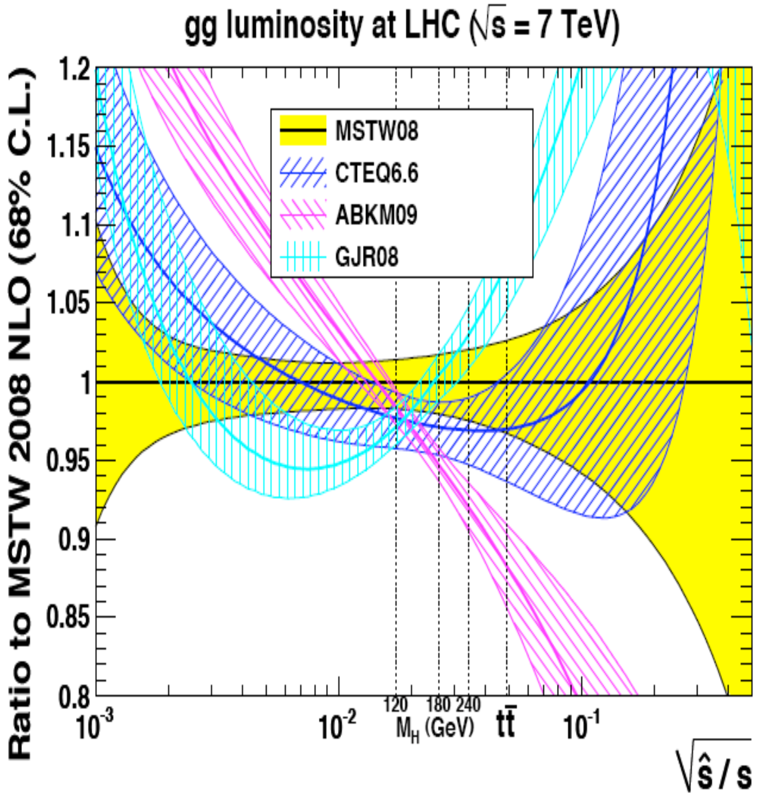

- MSTW, ABM and NNPDF come with different PDF sets with different choices of α_s, m_c, m_b
- Choice of PDF set can bring in significant uncertainty of the order 10 to 20%

Partonic Cross section

Partonic Cross section

$$2S\, d\sigma^{P_1 P_2}\left(\tau, m_h^2\right) = \sum_{ab} \int_\tau^1 \frac{dx}{x} \Phi_{ab}\left(x, \mu_F\right) 2\hat{s}\, d\hat{\sigma}^{ab}\left(\frac{\tau}{x}, m_h^2, \mu_F\right)$$

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- $d\hat{\sigma}^{ab}$ is perturbatively computable as a power series in $\alpha_s(\mu_R)$, where μ_R is the

renormalisation scale.

$$d\hat{\sigma}^{ab}\left(\mu_F\right) = \alpha_s^d(\mu_R) \sum_{i=0} \alpha_s^i(\mu_R) d\hat{\sigma}^{ab,(i)}\left(\mu_F, \mu_R\right)$$

- Renormalisation group equation:

$$\boxed{\mu_R^2 \frac{d}{d\mu_R^2} \alpha_s(\mu_R) = \beta\left(\alpha_s(\mu_R)\right)}$$

- Fixed order results are often sensitive to μ_R. • Many new production channels open up

beyond LO.

Gluon fusion to Higgs at Leading Order(LO)

Hinchcliff, many others

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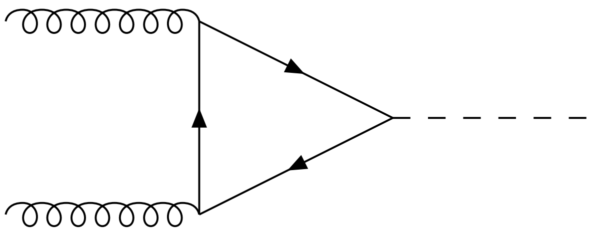

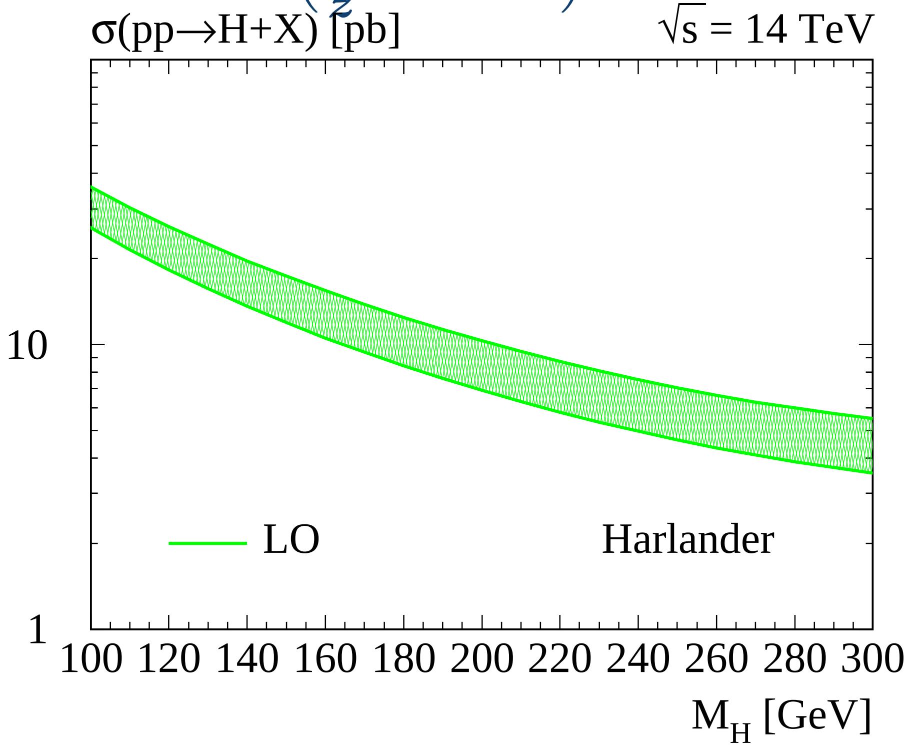

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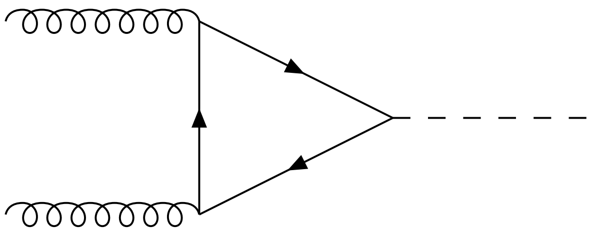

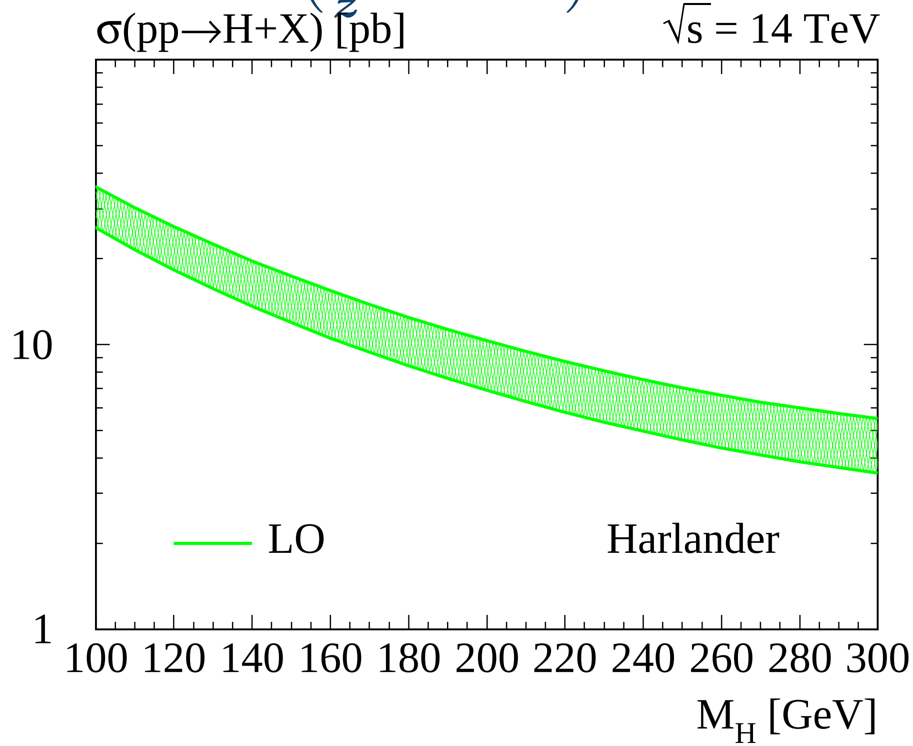

$$\hat{\sigma}_{gg}^{(0)}(\hat{s}, \mu_R) \sim \alpha_s^2(\mu_R) \left[F(G_F, m_t, m_h) \right],$$

- Leading order is uncontrolable due to μ_R scale and can not be used for any study in the present form.
- Only higher order corrections can provide sensible result thanks to RG equation

$$\mu^2 \frac{d}{d\mu^2} \sigma = 0$$

NNLO QCD corrected Higgs Cross section at $\sqrt{S} = 14$ TeV

$m_H/2 < \mu_F = \mu_R < 2m_H$

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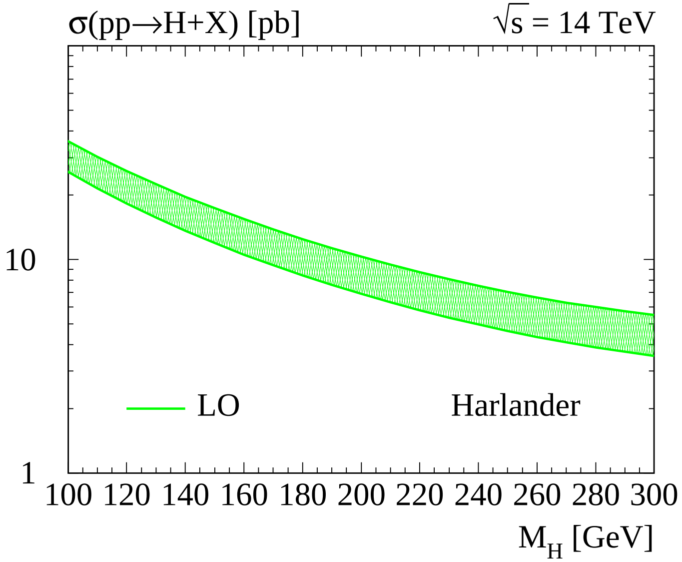

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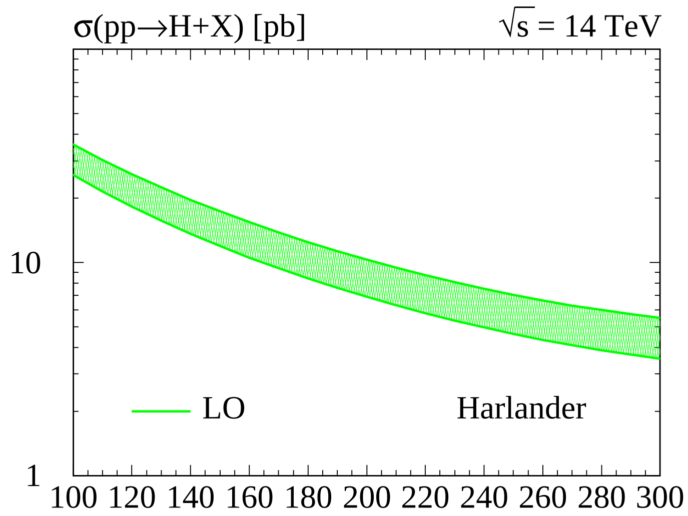

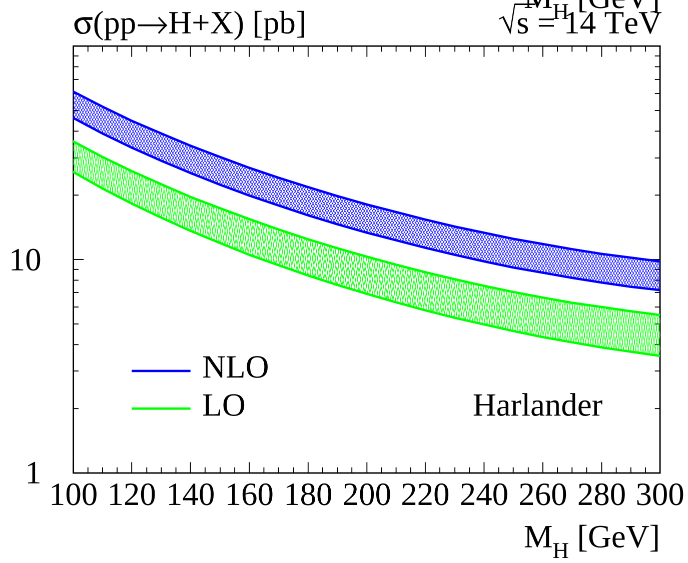

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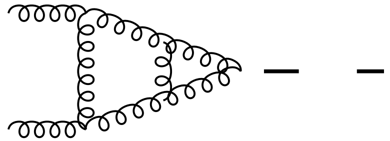

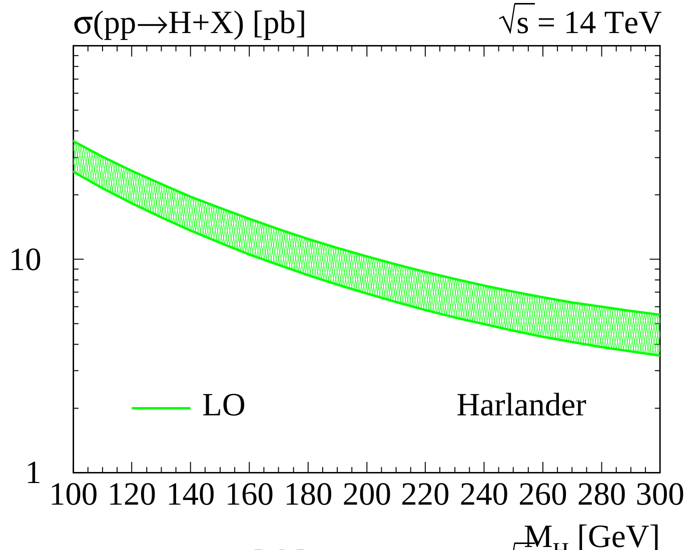

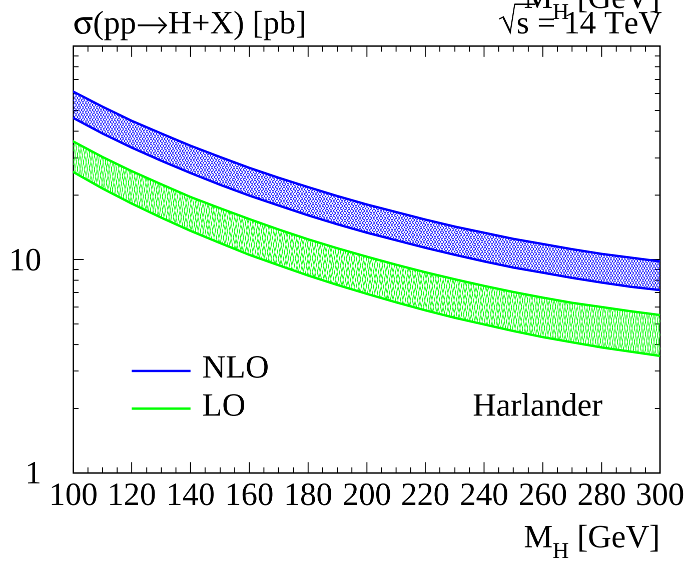

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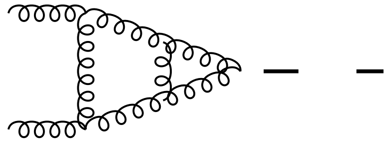
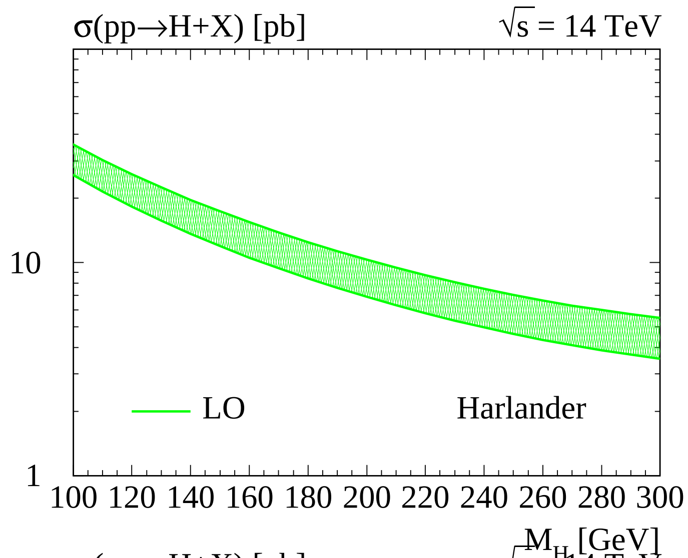
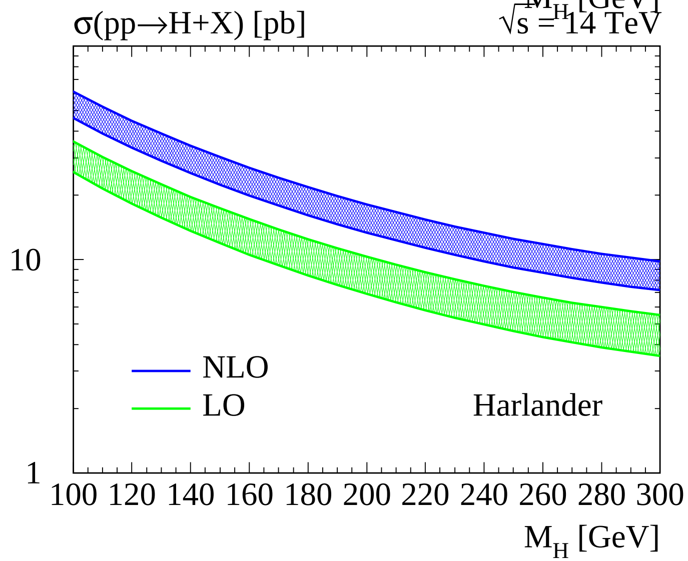
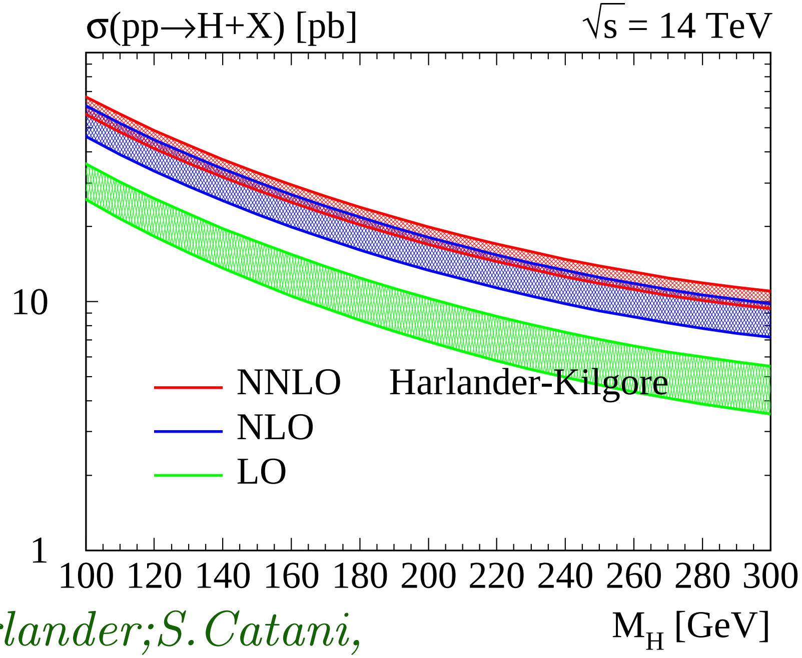


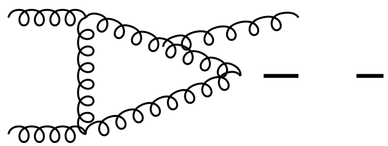




A.Djouadi,D.Grandenz,M.Spira,P.Zerwas



R.Harlander;S.Catani,
D.DeFlorian,M.Grazzini;
R.Harlander,B.Kilgore;C.Anastasiou,Melnikov;
VR,J.Smith,W.L.van Neerven



Soft gluons dominate!

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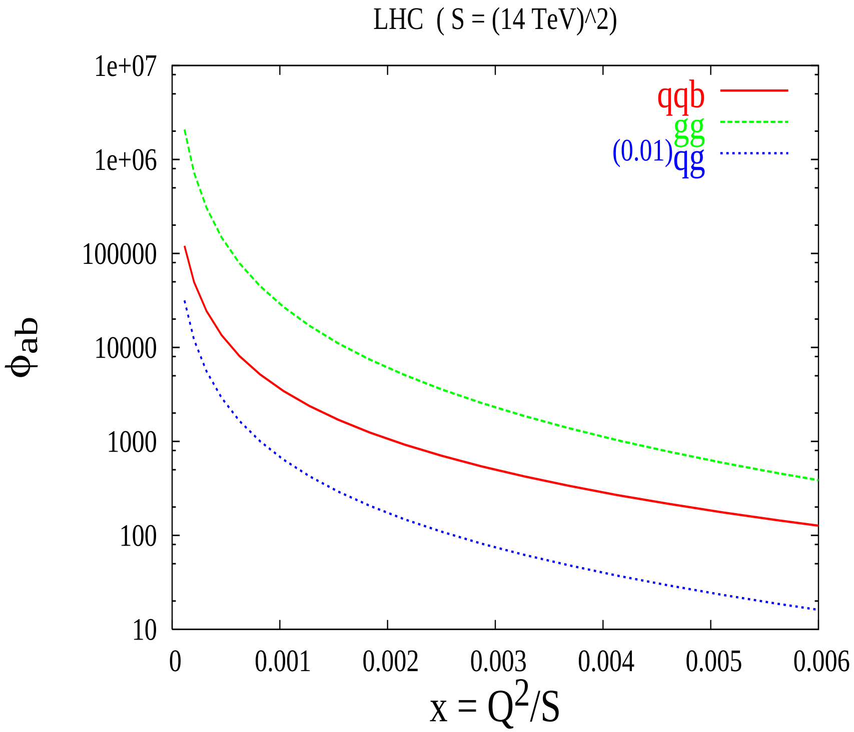

Gluon flux is largest at LHC •
Soft gluon NNLL resummation gives less than 9% correction at the LHC

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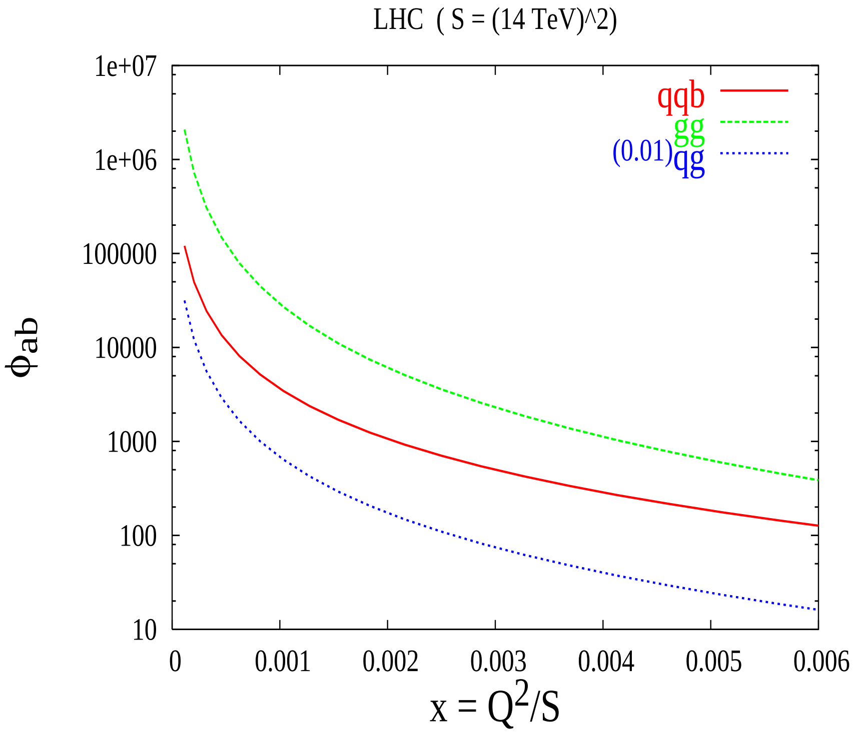

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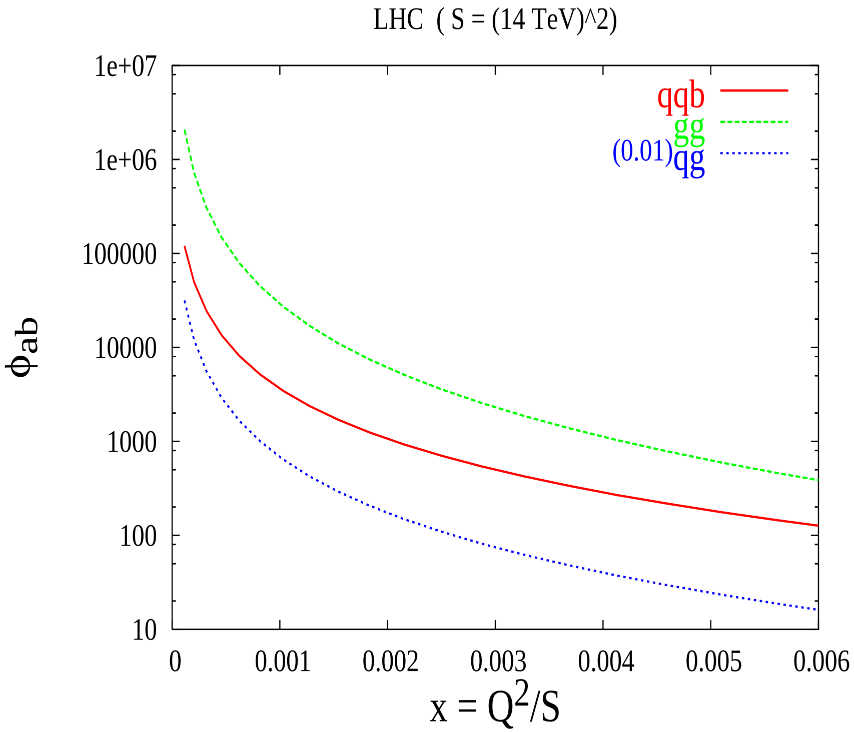

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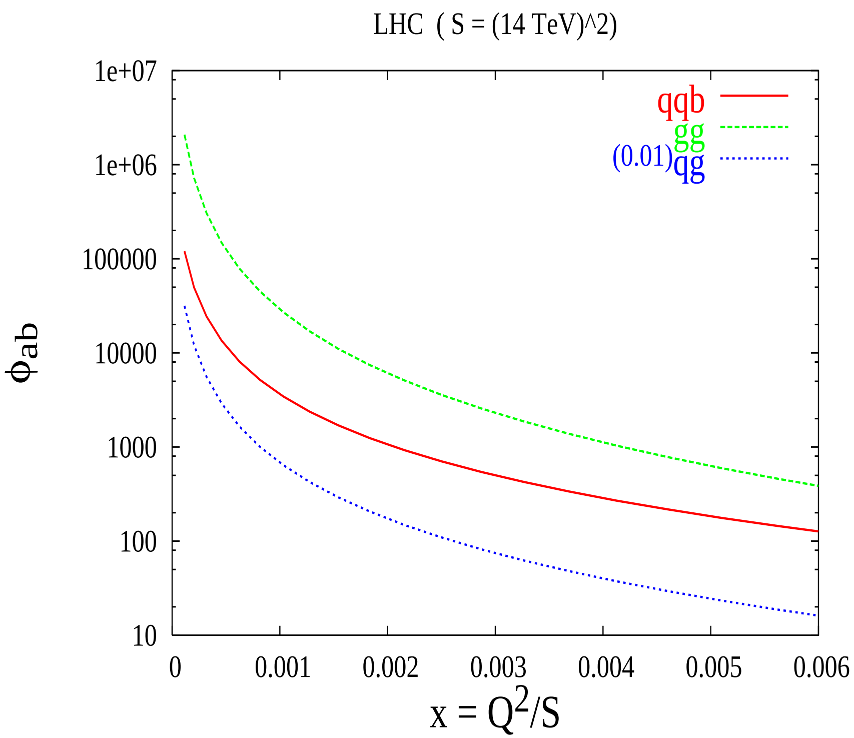

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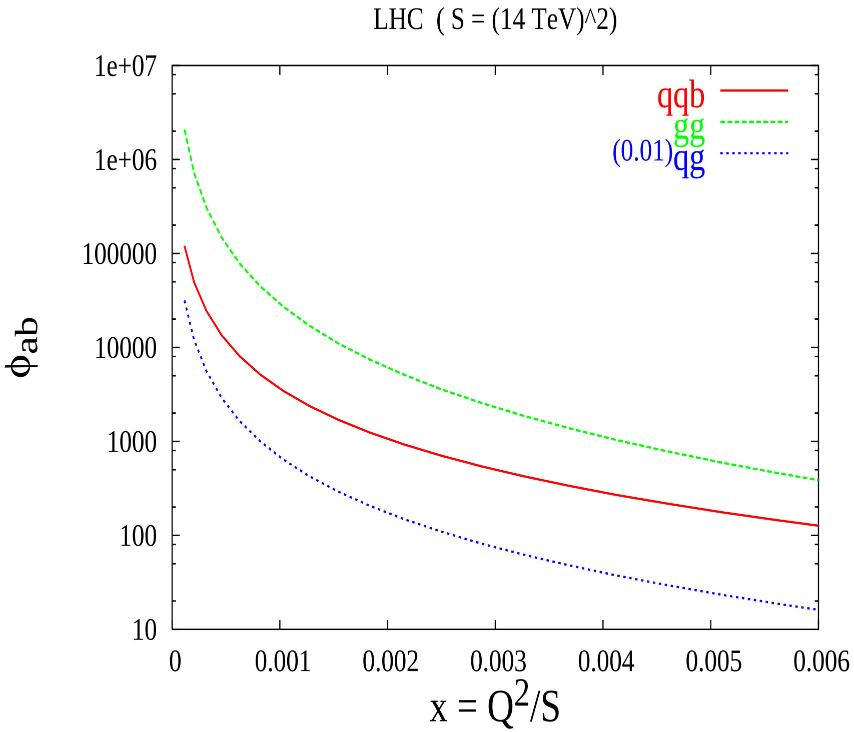

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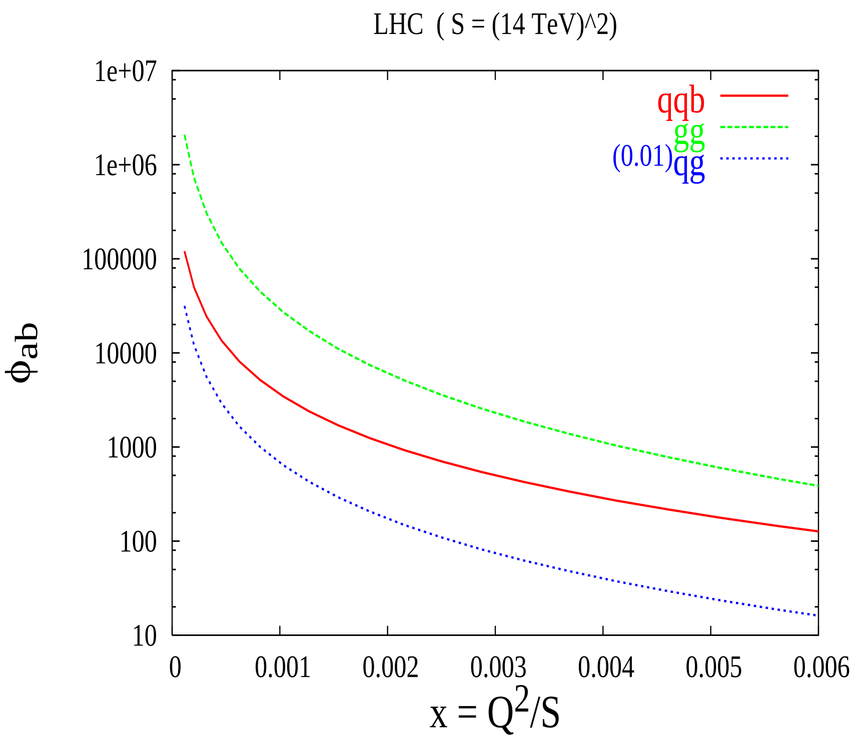

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2-loop Electroweak, Mixed QCD and Electroweak, b quark contributions:

U.Aglietti et al;G.Degrassi,F.Maltoni;G.Passarino et al;Anastasiou et al;W.Keung,F.Petriello,O.Brein

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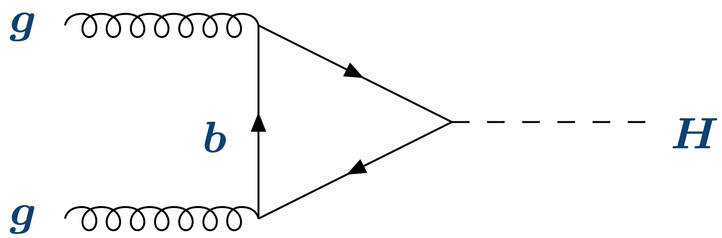

"interferece" with "t" loop + NLO QCD

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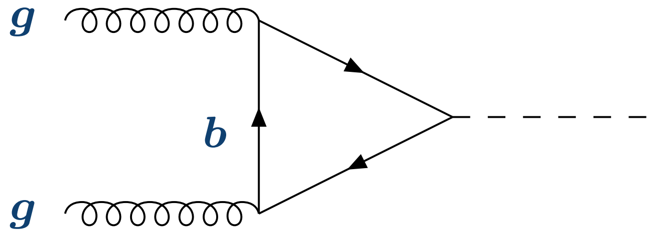
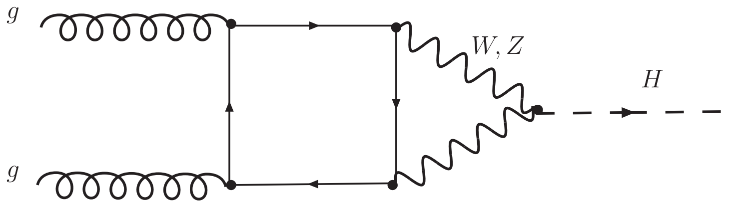
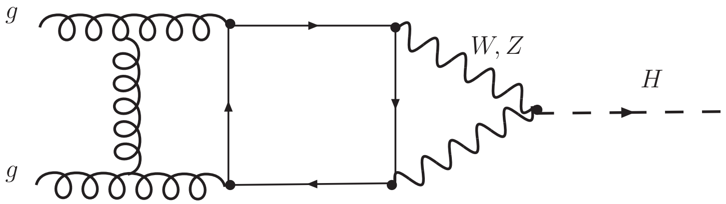
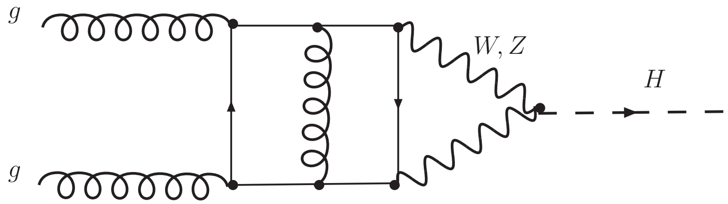


H "interferece" with "t" loop + NLO QCD

Pure QCD processes interference with Electroweak Processes:







Electroweak: $5\%(m_H = 120$ Gev) and -2% ($m_H = 300$GeV); b quark loops contribute $5-6\%$ at $m_H = 120$ GeV at LHC

Renormalisation group improved result

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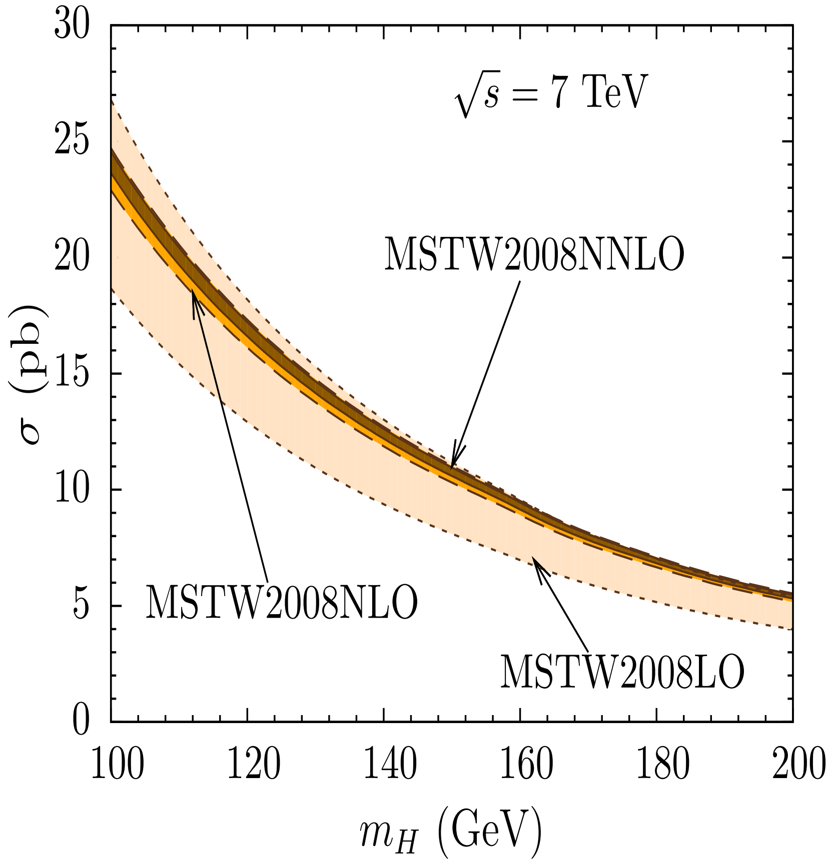

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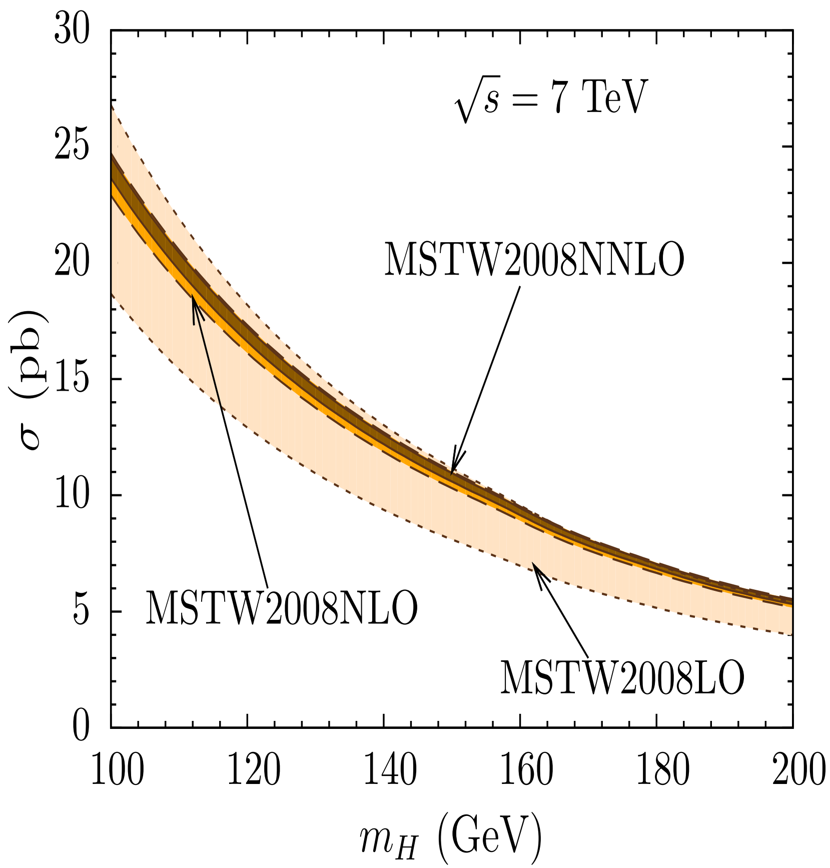

Ahrens, Becher, Neubert, Yang:

- NLO with exact top quark mass contributions,
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- EW corrections given by Passarino et al
- **use exact solutions to the RG equations of soft, collinear and hard pieces** of the cross section.

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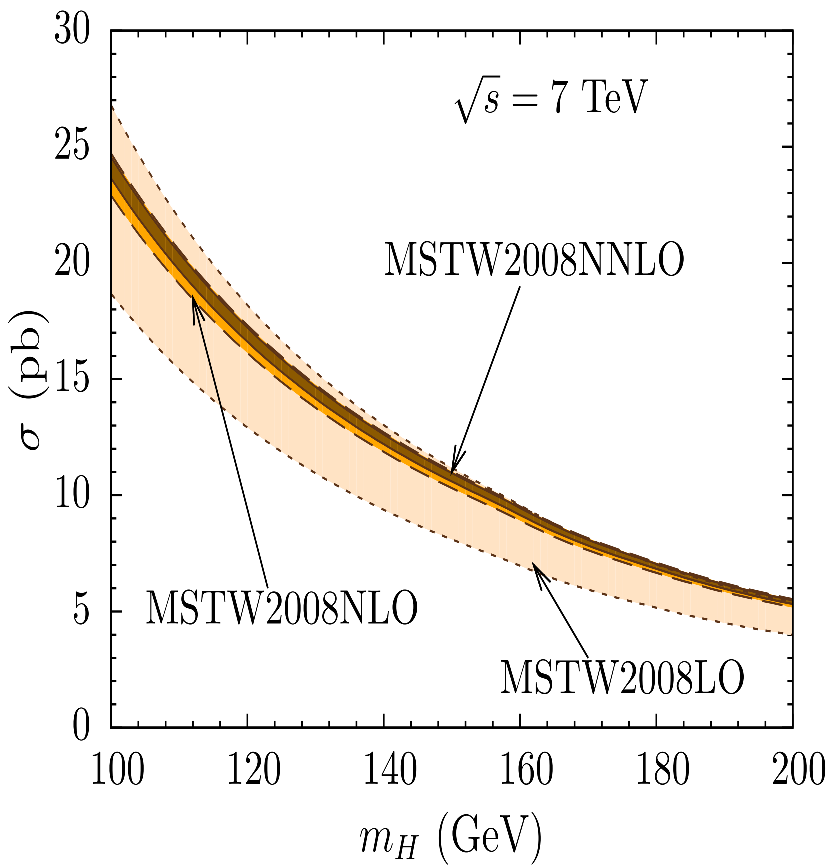

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Good perturbative stability from LO onwards.

μ_R, μ_F and PDF dependence in Higgs production ($8\ TeV$)

MSTW PDF set ($\boldsymbol{\sigma}$ in pb and errors($\pm$) in $\%$): $VR,\ J.\ Smith$

μ_R, μ_F and PDF dependence in Higgs production ($8\ TeV$)

MSTW PDF set ($\boldsymbol{\sigma}$ in pb and errors($\pm$) in %): *VR, J. Smith*

m_H	NNLO	μ_R	$\mu_{R,3}$	μ_F	μ	$\text{NNLO}_{\overline{\mu}}$	PDF	N^3LO_{sv}	μ_R
123	18.99	$^{+10.82}_{-10.41}$	$^{+16.70}_{-16.04}$	$^{-0.43}_{+0.53}$	$^{+10.44}_{-9.93}$	**20.97**	$^{+2.50}_{-3.12}$	19.79	$^{+0.10}_{-2.32}$
124	18.68	$^{+10.80}_{-10.39}$	$^{+16.66}_{-16.01}$	$^{-0.41}_{+0.51}$	$^{+10.43}_{-9.94}$	**20.62**	$^{+2.51}_{-3.12}$	19.46	$^{+0.09}_{-2.28}$
125	18.37	$^{+10.77}_{-10.37}$	$^{+16.63}_{-15.99}$	$^{-0.39}_{+0.50}$	$^{+10.43}_{-9.94}$	**20.28**	$^{+2.51}_{-3.13}$	19.13	$^{+0.08}_{-2.24}$
126	18.07	$^{+10.75}_{-10.35}$	$^{+16.59}_{-15.96}$	$^{-0.37}_{+0.47}$	$^{+10.42}_{-9.94}$	**19.95**	$^{+2.52}_{-3.13}$	18.82	$^{+0.07}_{-2.19}$
127	17.78	$^{+10.73}_{-10.33}$	$^{+16.56}_{-15.93}$	$^{-0.35}_{+0.45}$	$^{+10.41}_{-9.95}$	**19.63**	$^{+2.52}_{-3.13}$	18.51	$^{+0.06}_{-2.15}$

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Uncertainty in NNLO result:

- μ_R variation ($m_h/2 < \mu_R < 2m_h$) gives 11%
- μ_R variation ($m_h/3 < \mu_R < 3m_h$) gives 17%
- μ_F variation ($m_h/2 < \mu_R < 2m_h$) gives 0.5%
- $\mu_R = \mu_F = 1/2m_h$ resummes soft gluons
- MSTW PDF gives 3%
- N^3LO_{sv} gives around 3%

PDF dependence in Higgs production ($8\ TeV$)

$VR,\ J.\ Smith$

PDF dependence in Higgs production ($8\ TeV$)

Differnet PDF sets (m_h in GeV and cross sections in pb): *VR, J. Smith*

m_h	NNLO				$\mathbf{N^3LO}_{sv}$			
	MSTW	ABM	CT	NNPDF	MSTW	ABM	CT	NNPDF
120	19.98	18.51	19.86	21.00	20.83	21.04	20.26	20.91
121	19.64	18.18	19.52	20.65	20.47	20.62	19.91	20.56
122	19.31	17.89	19.20	20.30	20.13	20.32	19.57	20.21
123	18.99	17.58	18.88	19.96	19.79	19.97	19.24	19.87
124	18.68	17.29	18.57	19.63	19.46	19.63	18.92	19.54
125	18.37	16.99	18.27	19.31	19.13	19.28	18.61	19.21
126	18.07	16.71	17.97	18.99	18.82	18.96	18.31	18.89
127	17.78	16.43	17.68	18.66	18.51	18.64	18.01	18.53
128	17.49	16.16	17.39	18.52	18.21	18.32	17.72	18.61
129	17.21	15.91	17.12	18.09	17.91	18.04	17.43	17.99

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- ABM is $\mathbf{7.4\%}$ smaller than MSTW
- CT is just $\mathbf{0.5\%}$ smaller than MSTW
- NNPDF is $\mathbf{5\%}$ larger than MSTW
- All PDFs give almost same results for $\boldsymbol{N^3LO_{sv}}$ corrected cross section.

Soft gluons at N^3LO_{pSV} for Higgs production ($8\ TeV$)

VR, J. Smith

$$R = \frac{\sigma_{N^iLO}(\mu)}{\sigma_{N^iLO}(\mu_0)}$$

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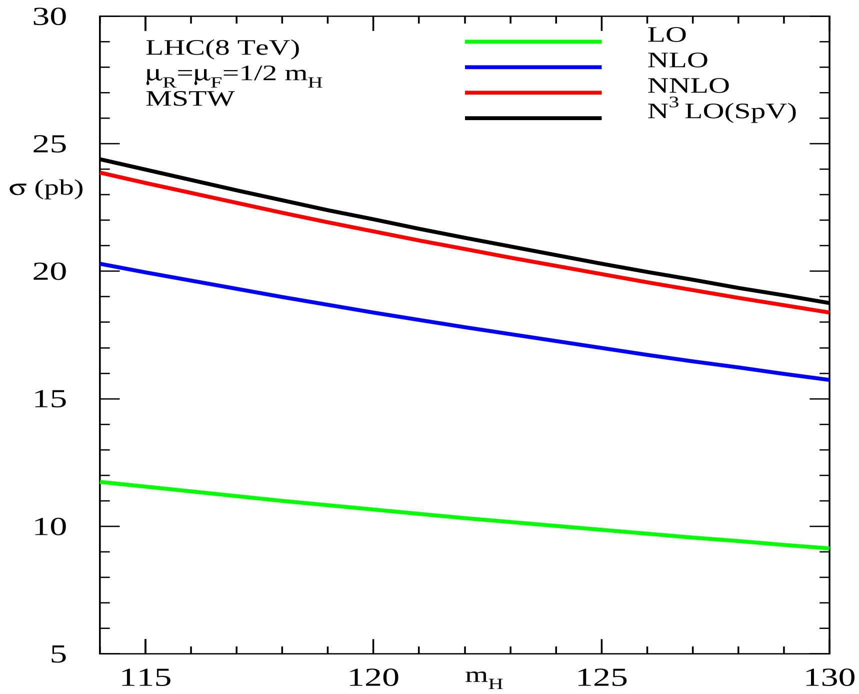

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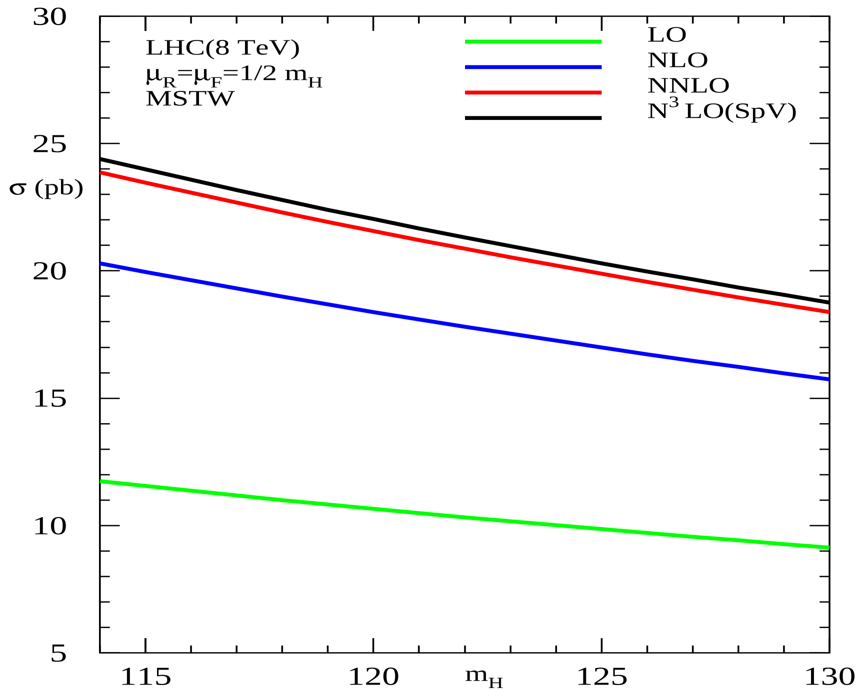

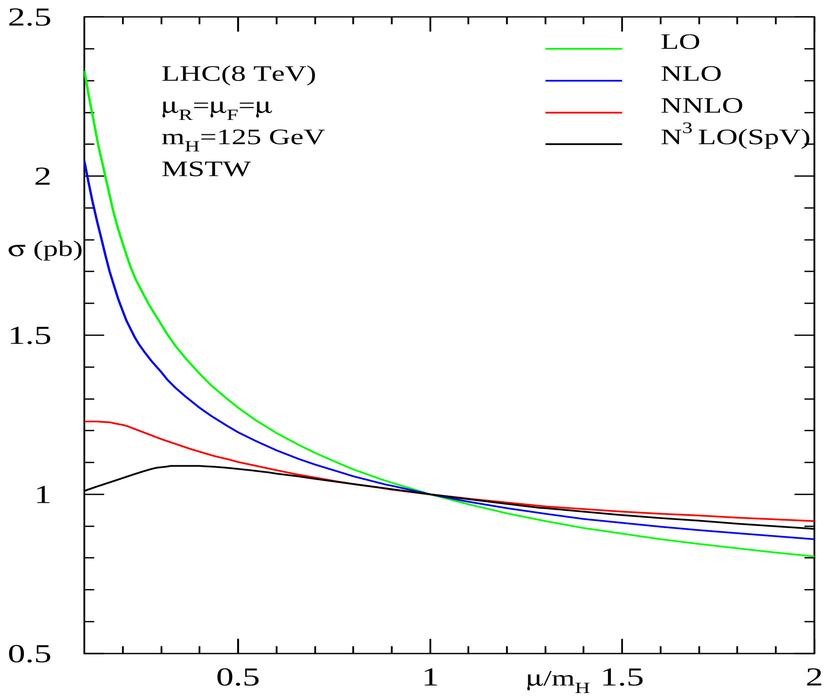

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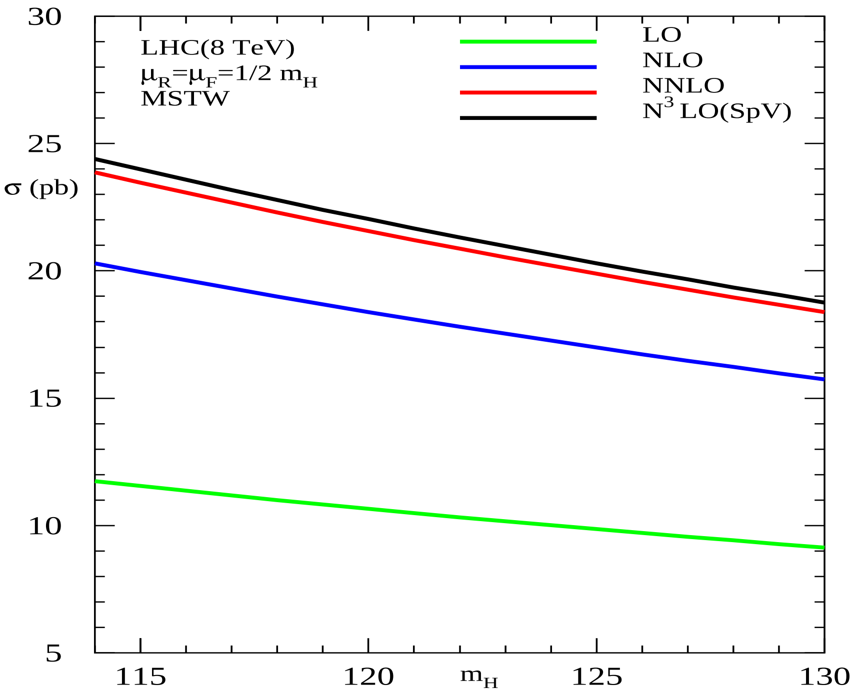

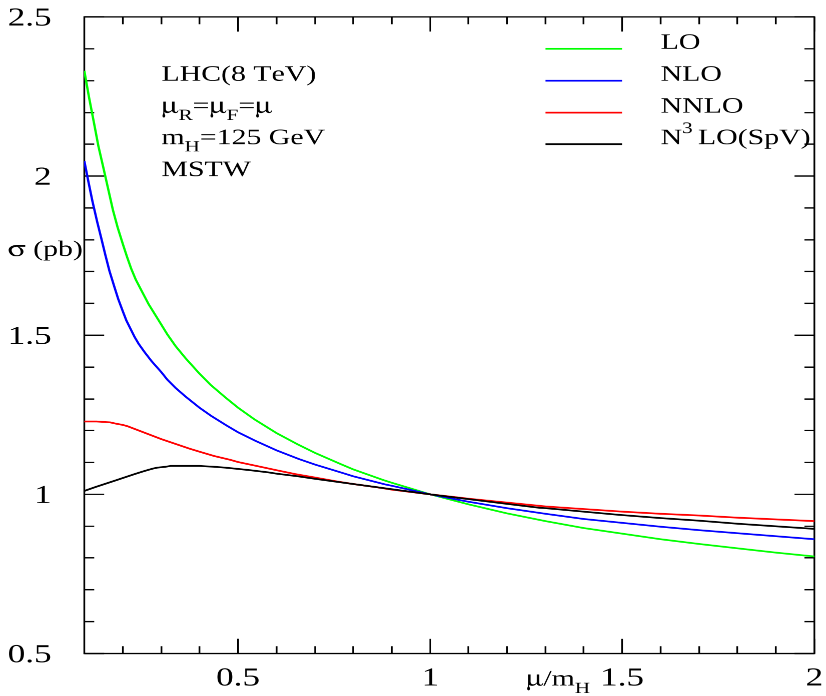

- NLO increases the cross section by 80%,
- NNLO to 30%,
- resummation to 10% and electoweak effects by 5%

Update-1: Anastasiou-Boughezal-Petriello-Stoeckli:

Update-1: Anastasiou-Boughezal-Petriello-Stoeckli:

- Exact NLO cross section with full dependence on the top- and bottom-quark masses
- NNLO cross section-Effective Field Theory, i.e., in the large-m_t limit
- EW contributions evaluated in the complete factorization scheme

$$\sigma = \sum_{i=0}^{\infty} \alpha_s^i \sigma_{QCD}^{(i)} \otimes (1 + \delta_{EW})$$

- Mixed QCD-EWcontributions are also accounted for, together with some effects from EW corrections at finite transverse momentum.
- The effect of soft-gluon resummation is mimicked by choosing the central value of the renormalization and factorization scales as $\mu_R = \mu_F = M_H/2$.

Update-2: de Florian-Grazzini:

Update-2: de Florian-Grazzini:

- Exact NLO cross section with full dependence on the top- and bottom-quark masses, computed with the program HIGLU,
- the NLL resummation of soft-gluons,
- the NNLL+NNLO corrections are consistently added in the large-mt limit
- corrected for EW contributions in the complete factorization scheme.
- The central value of factorization and renormalization scales is chosen to be $\mu_F = \mu_R = M_H$

Comparison

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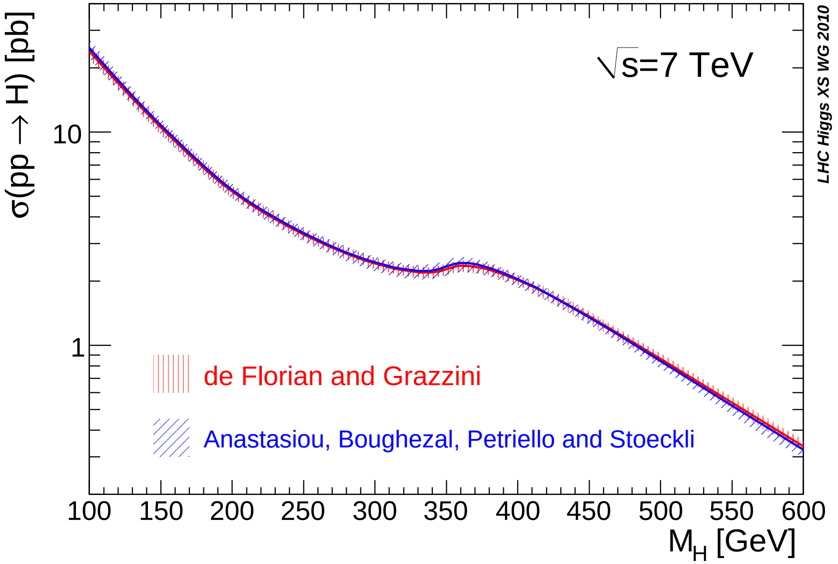
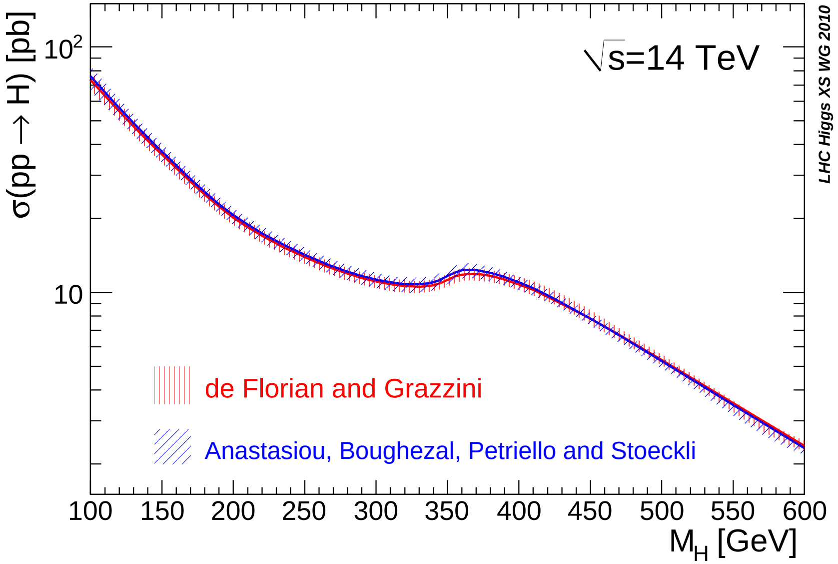


σ(pp → H) [pb]
√s=7 TeV
LHC Higgs XS WG 2010
10
1
de Florian and Grazzini
Anastasiou, Boughezal, Petriello and Stoeckli
100 150 200 250 300 350 400 450 500 550 600
M_H [GeV]



σ(pp → H) [pb]
√s=14 TeV
LHC Higgs XS WG 2010
10^2
10
de Florian and Grazzini
Anastasiou, Boughezal, Petriello and Stoeckli
100 150 200 250 300 350 400 450 500 550 600
M_H [GeV]

Final numbers for gluon fusion for $m_h = 125$ GeV

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Production cross section at $\sqrt{s} = 7$ TeV with scale($\mu_R = \mu_F$) and PDF($+\alpha_s$) unctertainties:

$$\sigma = 15.31^{11.7\%}_{-7.8\%}(scale)^{+7.8\%}_{-7.3\%}(PDF + \alpha_s)pb$$

Production cross section at $\sqrt{s} = 8$ TeV:

- de Florian et al:

$$\sigma = 19.52^{7.2\%}_{-7.8\%}(\mathrm{scale})^{+7.5\%}_{-6.9\%}(\mathrm{PDF} + \alpha_\mathrm{s})pb$$

- Anastasiou et al:

$$\sigma = 20.69^{8.4\%}_{-9.3\%}(\mathrm{scale})^{+7.8\%}_{-7.5\%}(\mathrm{PDF} + \alpha_\mathrm{s})pb$$

Towards N^3LO corrected Higgs cross section

Anastasiou et.al

Towards N^3LO corrected Higgs cross section

Anastasiou et.al

- Square of one-loop virtuals to N^3LO

$$
\begin{aligned}
g(p_1) + g(p_2) &\quad \rightarrow g(p_3) + H(p_4) \\
q(p_1) + g(p_2) &\quad \rightarrow q(p_3) + H(p_4) \\
q(p_1) + \bar{q}(p_2) &\quad \rightarrow g(p_3) + H(p_4)
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Anastasiou et.al

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- Performing a loop-expansion of the amplitudes

$$\mathcal{A}_X = \sum_{j=0}^{\infty} \mathcal{A}_X^{(j)}$$

in the effective theory with j being the number of loops, we have:

$$|\mathcal{A}_X|^2 = \left|\mathcal{A}_X^{(0)}\right|^2 + 2\Re\left(\mathcal{A}_X^{(0)}\mathcal{A}_X^{(1)^*}\right) + \left[\left|\mathcal{A}_X^{(1)}\right|^2 + 2\Re\left(\mathcal{A}_X^{(0)}\mathcal{A}_X^{(2)^*}\right)\right] + \ldots$$

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Anastasiou et.al

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$$\sigma_X^{1\otimes 1} = s^{-1-\varepsilon}\,\frac{\mathcal{N}_X\,(4\pi)^{\varepsilon}}{16\pi\,\Gamma(1-\varepsilon)}\,\delta^{1-2\varepsilon}\int_0^1 d\lambda\,[\lambda\,(1-\lambda)]^{-\varepsilon}\sum\left|\mathcal{A}_X^{(1)}\right|^2 .$$

Towards N^3LO corrected Higgs cross section

Anastasiou et.al

- Square of one-loop virtuals to N^3LO

$$\begin{aligned} g(p_1) + g(p_2) &\to g(p_3) + H(p_4) \\ q(p_1) + g(p_2) &\to q(p_3) + H(p_4) \\ q(p_1) + \bar{q}(p_2) &\to g(p_3) + H(p_4) \end{aligned}$$

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- Reverse Unitarity and Integration parts lead to 19 master integrals
- Differential equation method is used to solve the master integrals

Alternate approach towards N^3LO

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Kilgore

- Threshold expansion
- Square of the one-loop contribution to the cross section as an extended threshold expansion.
- Obtain enough terms to invert the series and determine the closed functional form through order ε.
- The method has been applied to get earlier results at NLO and NNLO level for inclusive cross sections in closed form, in terms of G-functions and the hypergeometric functions $_2F_1$ and $_3F_2$.
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- These functions can be readily expanded to all orders in ε

$$2F_1(1, -\varepsilon; 1-\varepsilon; -xy/\overline{y}) = \sum_{n=0}^{\infty} \frac{\overline{x}}{n!} \frac{(-\varepsilon)_n}{n!} \left(2F_1(1, -\varepsilon, 1-\varepsilon, -y/\overline{y}) - \overline{y} \sum_{m=0}^{n-1} y^m \frac{m!}{(1-\varepsilon)_m} \right)$$

Higgs + 2 jets at NLO

H. van Deurzen et al.

Higgs + 2 jets at NLO

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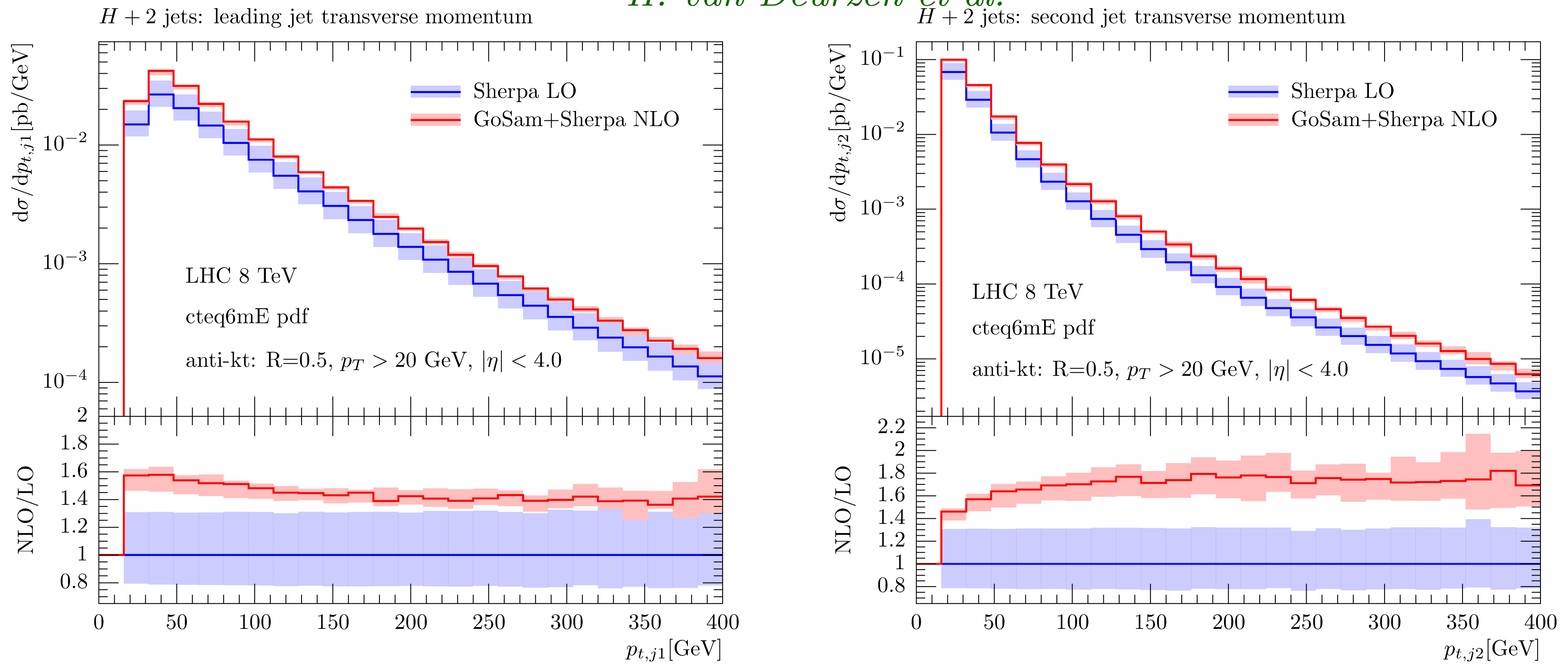

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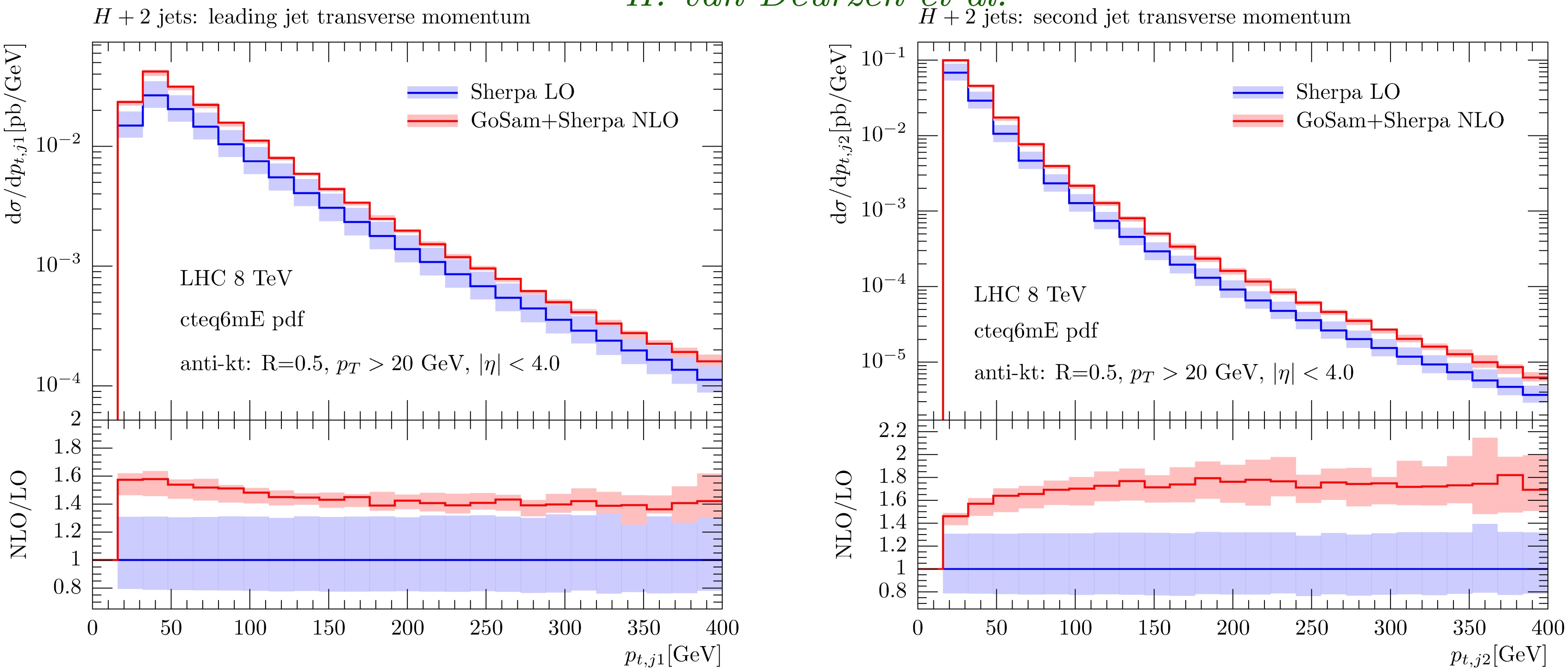


- Transverse momentum p_T of the first and the second jet.

$$\sigma_{\rm LO}[\text{pb}] = 1.90^{+0.58}_{-0.41}\,, \qquad \sigma_{\rm NLO}[\text{pb}] = 2.90^{+0.05}_{-0.20}\,,$$

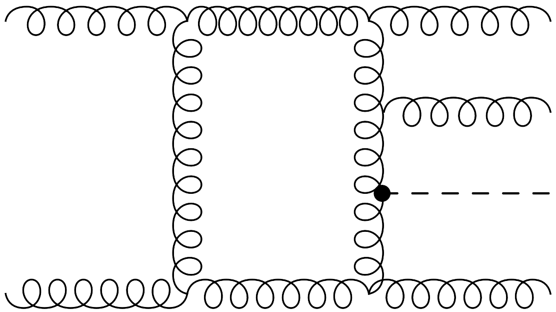
- Scale variation:

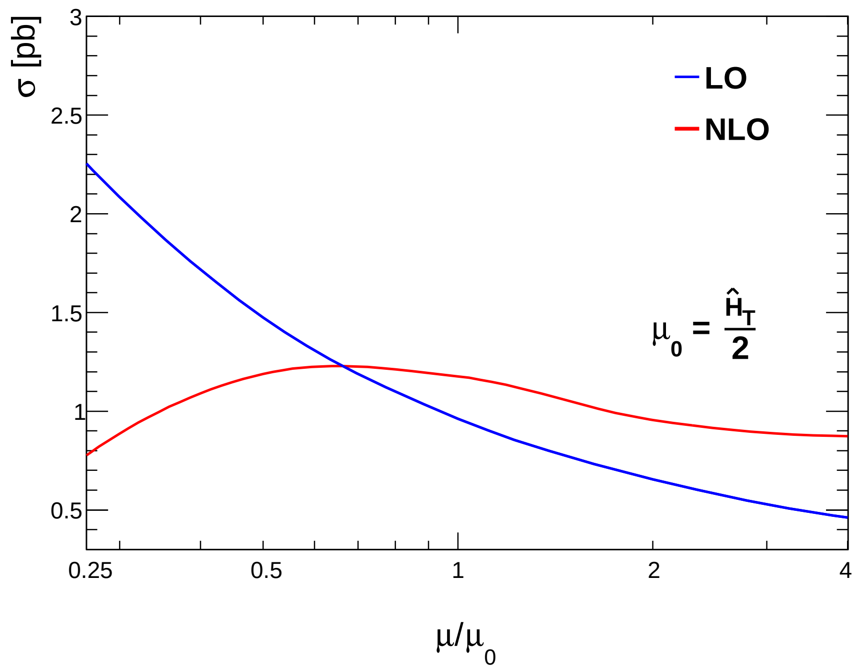
$$\frac{1}{2}\hat{H}_t < \mu < 2\hat{H}_t\,.$$

Higgs + 3-jets in gluon-gluon fusion

Higgs + 3-jets in gluon-gluon fusion

G. Cullen et al.





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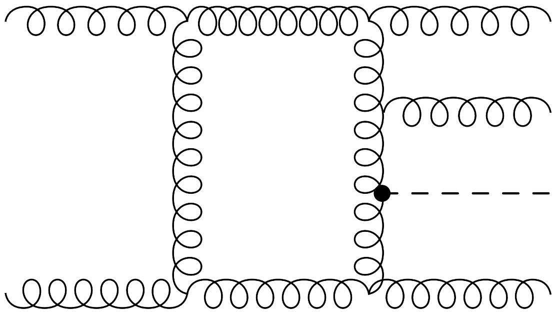

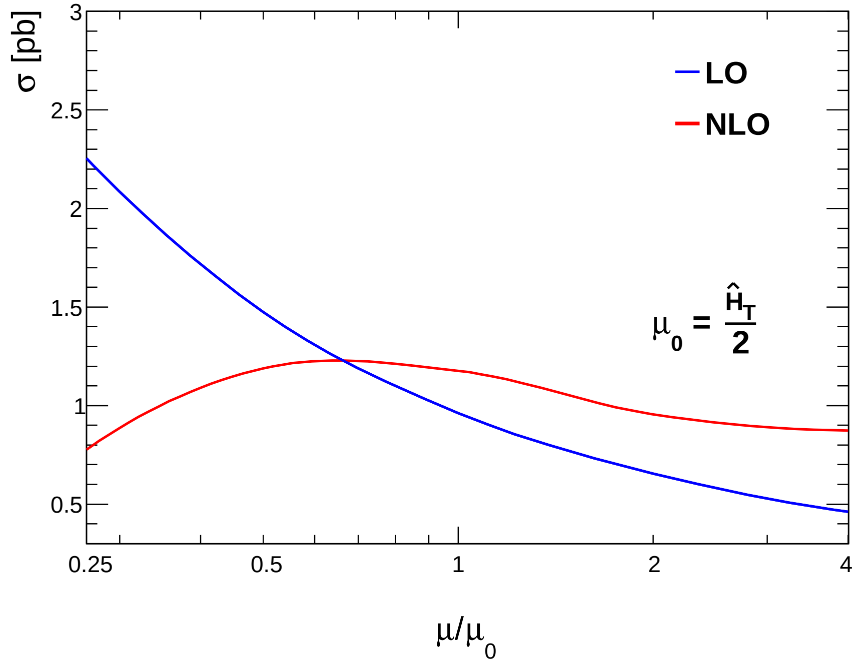

- Jets are clustered using the anti-k_t-algorithm implemented in FastJet with radius $R = 0.5$ and a minimum transverse momentum of $p_{T,jet} > 20$ GeV and pseudorapidity $|\eta| < 4.0$.
- The renormalization and factorization scales are set to

$$\mu_F = \mu_R = \frac{\hat{H}_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right) ,$$

- The strong coupling is therefore evaluated at different scales according to $\alpha_s^5 \to \alpha_s^2(m_H)\alpha_s^3(\hat{H}_T/2)$.

Higgs + 3-jets via vector boson fusion (VBF)

F. Campanario et al.

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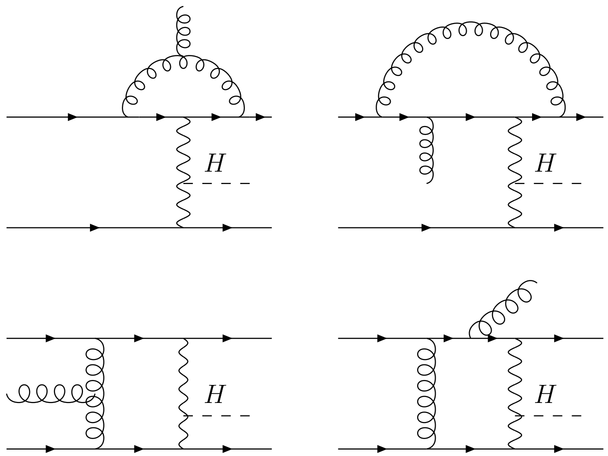

- Higgs production via Vector Boson Fusion (VFB) can disentangle the Higgs boson's coupling to fermionns and gauge bosons.
- Taging two jets with Higgs and vetoing soft jets in the central region can significantly reduce the QCD background as well as Higgs plus two jets from gluon-gluon fusion.
- Ratio of Higgs+3 jets to Higgs+2 jets need to known accurately.

Method:

- Spin helicity package MATCHBOX provides real emission amplitudes, spin summation, subtraction terms for IR singularities
- ColorFull and ColurMath packages to do color algebra
- Passarino-Veltman reduction and Denner-Dittmaier scheme to do one-loop reduction and evaluation.

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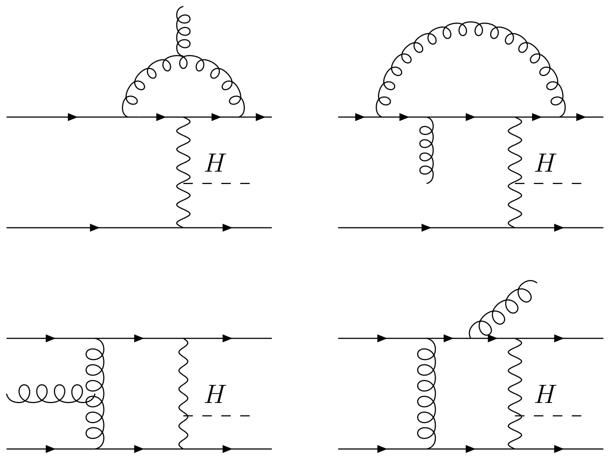

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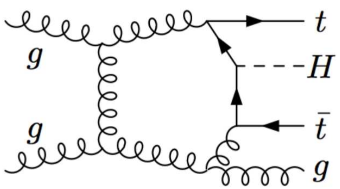

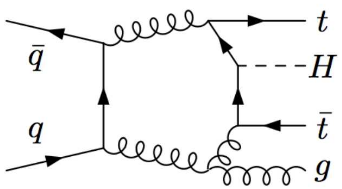

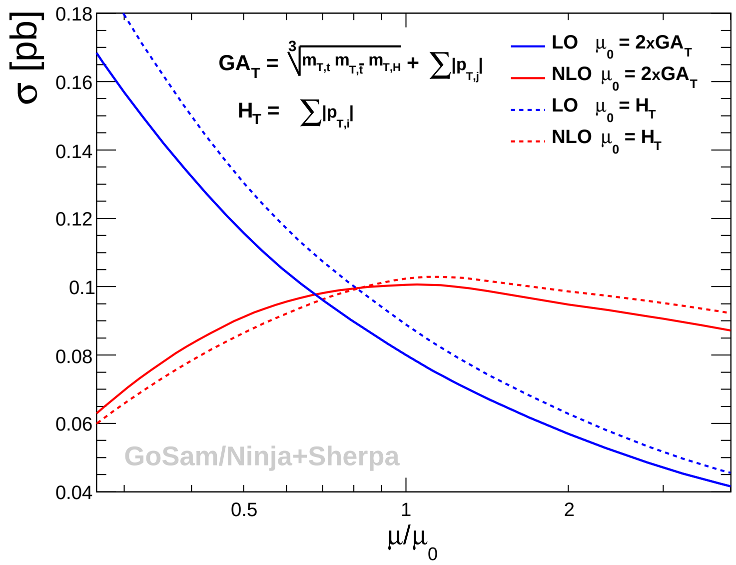

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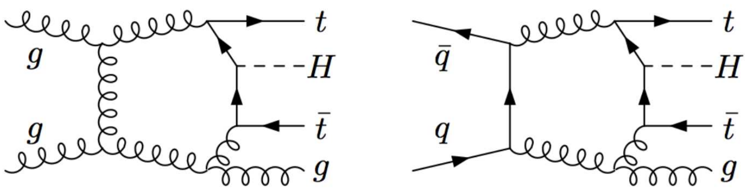

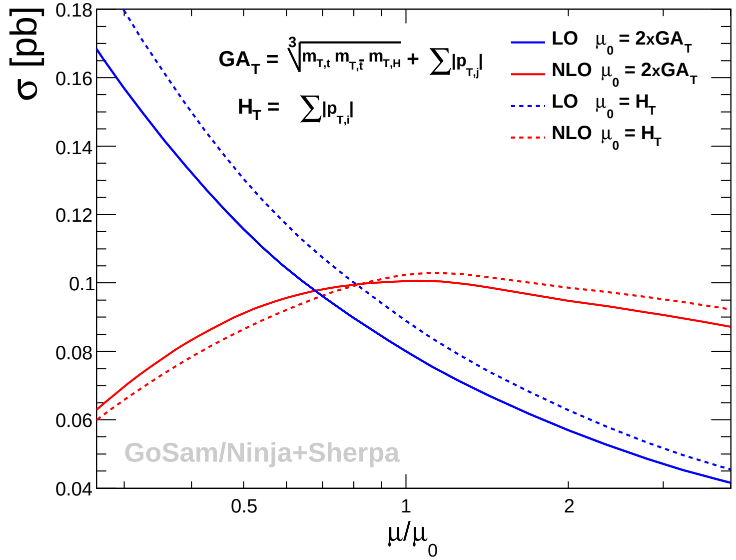

- The Born and the real emission matrix elements are computed using SHERPA and the library AMEGIC which implements the Catani-Seymour dipole formalism. SHERPA also performs the integration over the phase space and the analysis.
- The virtual corrections are generated with the GOSAM which combines automated diagram generation and algebraic manipulation with d-dimensional integrand-level reduction.
- The virtual amplitudes of $t\bar{t}Hj$ have been decomposed in terms of MIs using for the first time the *integrand reduction via Laurent expansion*, implemented in the $C++$ library NINJA.

Higgs Characterisation at NLO

F. Maltoni,Prakash Mathews, VR et al.

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- Effective Field Theory (EFT) approach to study the nature of interaction of Higgs with the other SM particles. *Biswarup's talk*
- Not only useful for SM electroweak precision physics, but also pin down BSM effects.

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- Effective Field Theory (EFT) approach to study the nature of interaction of Higgs with the other SM particles. *Biswarup's talk*
- Not only useful for SM electroweak precision physics, but also pin down BSM effects.
- EFT contains only SM particles and the symmetries at the EW scale.

$$\mathcal{L}_{HC,J} = \mathcal{L}_{SM-H} + \mathcal{L}_J \ ,$$

  - reduces significantly the possible interaction terms in the Lagrangian
  - Higgs boson with various spin-partiy assignment

Higgs Characterisation at NLO

F. Maltoni, Prakash Mathews, VR et al.

- Effective Field Theory (EFT) approach to study the nature of interaction of Higgs with the other SM particles. *Biswarup's talk*
- Not only useful for SM electroweak precision physics, but also pin down BSM effects.
- EFT contains only SM particles and the symmetries at the EW scale.

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  - reduces significantly the possible interaction terms in the Lagrangian
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- EFT has been implemented in FeynRules and passed to the Madgraph5 and aMC@NLO framework by means of UFO model file.
  - improvable with new operators,
  - higher order QCD effects can be incorporated systematically.
  - multi-parton tree-level computation with parton shower,
  - next to leading order calculations matched with parton sowers.

Higgs Characterisation for spin-0 Higgs

Buchmuller et al, Grzadkowski et al

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dimension-6 operators with pair of fermions

$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar{\psi}_f \left(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5 \right) \psi_f X_0 \, ,$$

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dimension-6 operators with pair of vector bosons

$$\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \left(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\right)\big] \Big\} X_0 \,,
\end{aligned}$$

$$c_\alpha \equiv \cos\alpha \,, \quad s_\alpha \equiv \sin\alpha \,,$$

Higgs Characterisation with spin-2 Higgs

J. Ellis et al

Minimal coupling to spin-2 Higgs with fermions:

$$\mathcal{L}_2^f = -\frac{1}{\Lambda} \sum_{f=q,\ell} \kappa_f \, T^f_{\mu\nu} X_2^{\mu\nu} \, ,$$

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$$\mathcal{L}_2^V = -\frac{1}{\Lambda} \sum_{V=Z,W,\gamma,g} \kappa_V \, T^V_{\mu\nu} X_2^{\mu\nu} \, .$$

where $T^{\mu\nu}$ is the energy momentum tensor of SM fields.

$$\begin{aligned} T^f_{\mu\nu} =& - g_{\mu\nu}\Big[\bar{\psi}_f(i\gamma^\rho D_\rho - m_f)\psi_f - \frac{1}{2}\partial^\rho(\bar{\psi}_f i\gamma_\rho\psi_f)\Big] \\ &+ \Big[\frac{1}{2}\bar{\psi}_f i\gamma_\mu D_\nu \psi_f - \frac{1}{4}\partial_\mu(\bar{\psi}_f i\gamma_\nu\psi_f) + (\mu \leftrightarrow \nu)\Big] , \\ T^\gamma_{\mu\nu} =& - g_{\mu\nu}\Big[-\frac{1}{4}A^{\rho\sigma}A_{\rho\sigma} + \partial^\rho\partial^\sigma A_\sigma A_\rho + \frac{1}{2}(\partial^\rho A_\rho)^2\Big] \\ &- A_\mu^\rho A_{\nu\rho} + \partial_\mu\partial^\rho A_\rho A_\nu + \partial_\nu\partial^\rho A_\rho A_\mu \, , \end{aligned}$$

Higgs Characterisation

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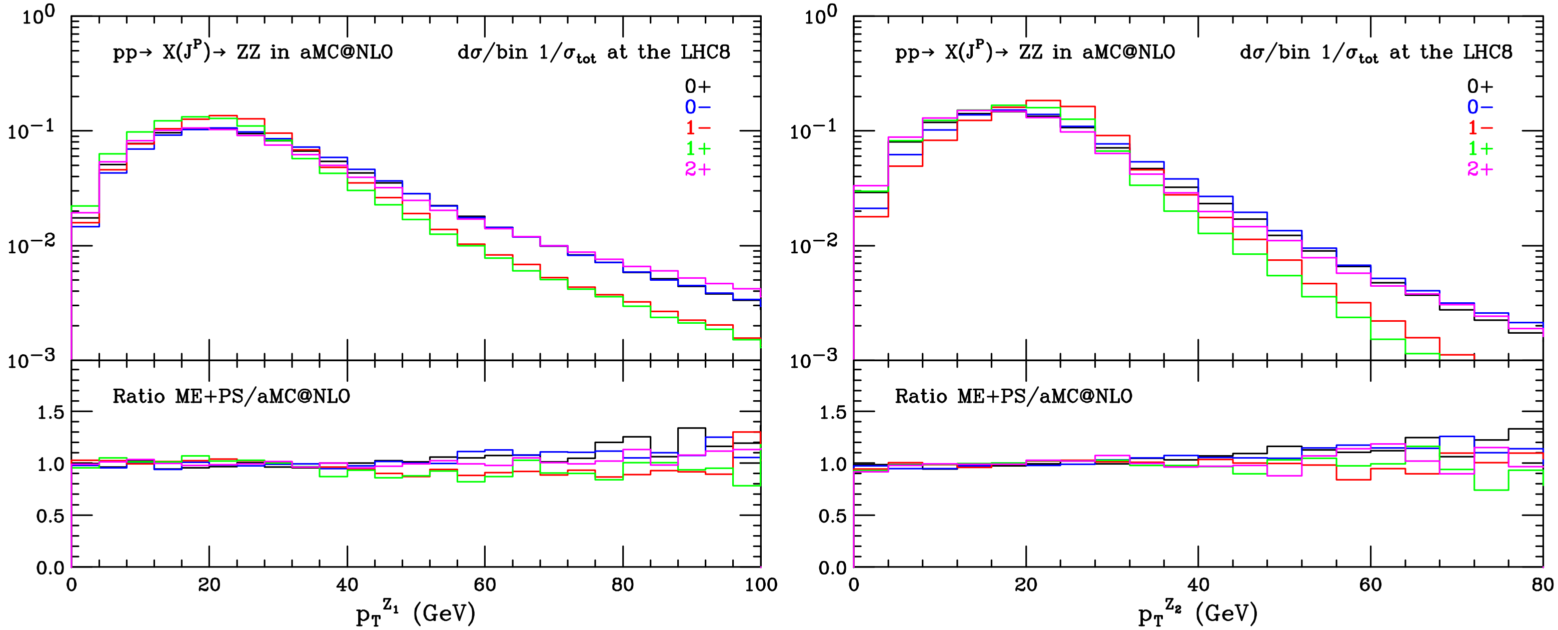

The transverse momentum of the Z boson with the highest and lowest reconstructed mass, $p_T^{Z_1}$ and $p_T^{Z_2}$, in $X(\to ZZ^*) \to \mu^+\mu^-e^+e^-$.

Higgs Characterisation: Non-universal couplings

F. Maltoni,Prakash Mathews, VR et al.

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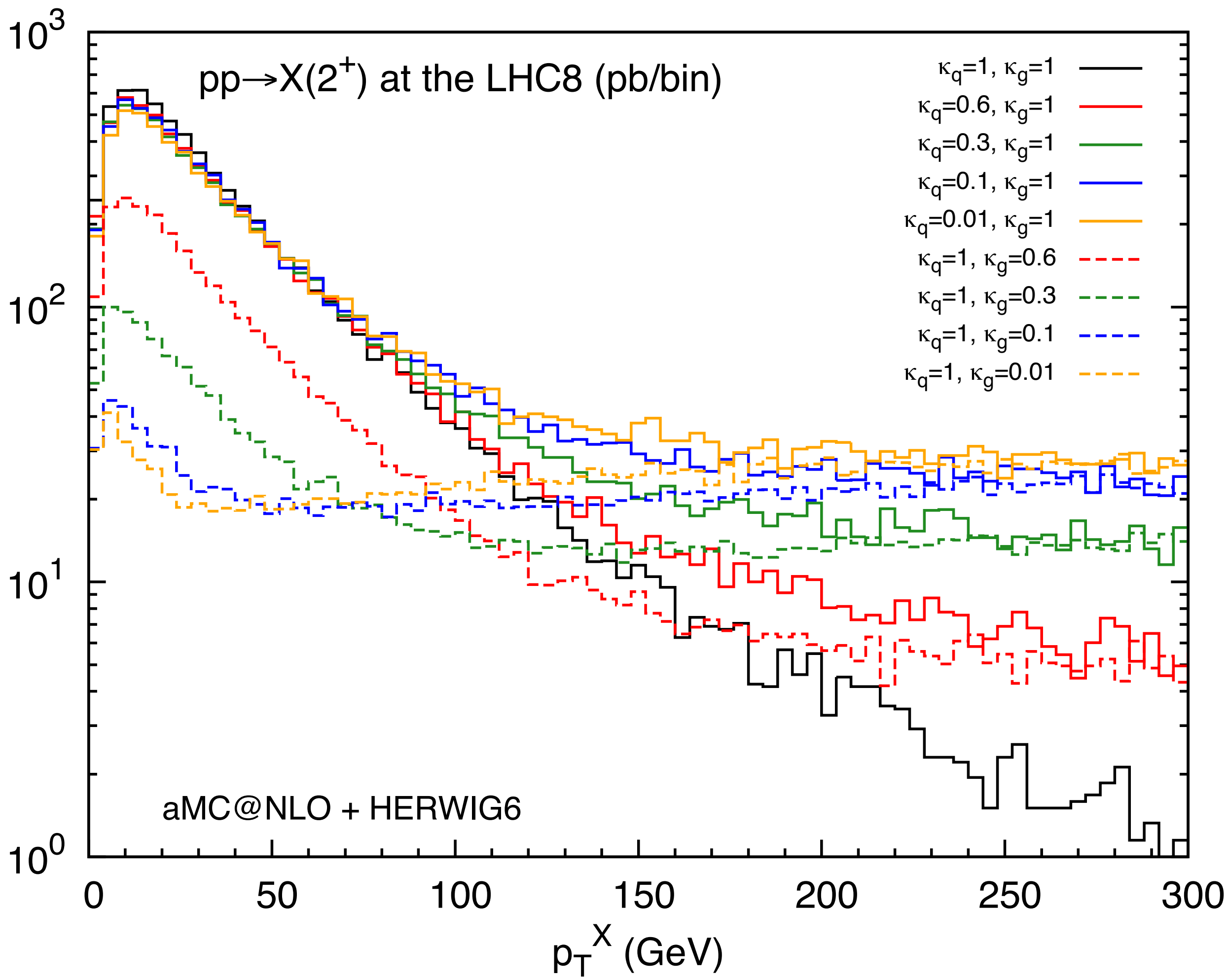

The transverse momentum p_T^X of a spin-2 state with non universal couplings to quarks and gluons $\kappa_q \neq \kappa_g$ as obtained from aMC@NLO. • It violates unitarity.

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Characterisation with MADGRAF frame work is a new tool in the market to analyse Higgs boson's spin-partity and its coupling to SM particles in a model independent way.