QCD and Higgs at the LHC

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Outline

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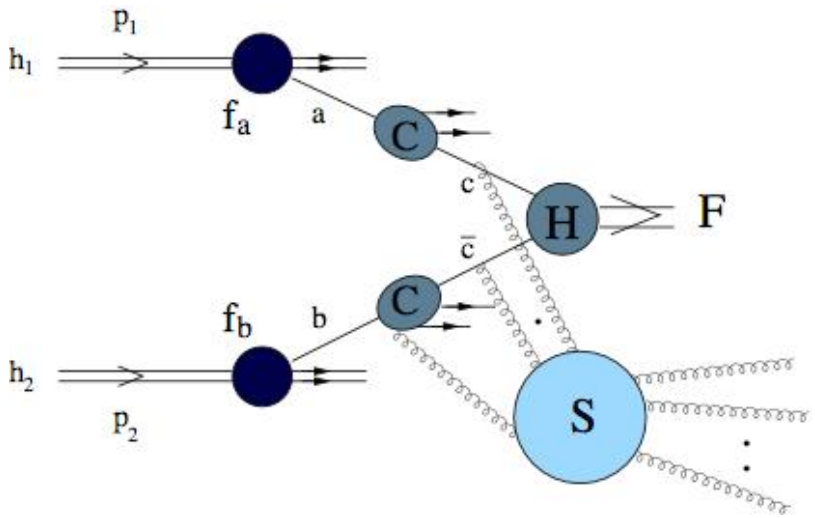
Hadronic cross sections in perturbative QCD



- h_1, h_2 = initial state hadrons (with momenta p_1, p_2)
- f_a, f_b = parton distribution functions
- C = coefficient functions (partonic splitting)
- H = perturbatively computed partonic event
- F = final state particle(s)
- S = resummation of soft radiation from incoming partons

$\rightarrow$ Precise predictions depend on good knowledge of f,C,H *and* S!

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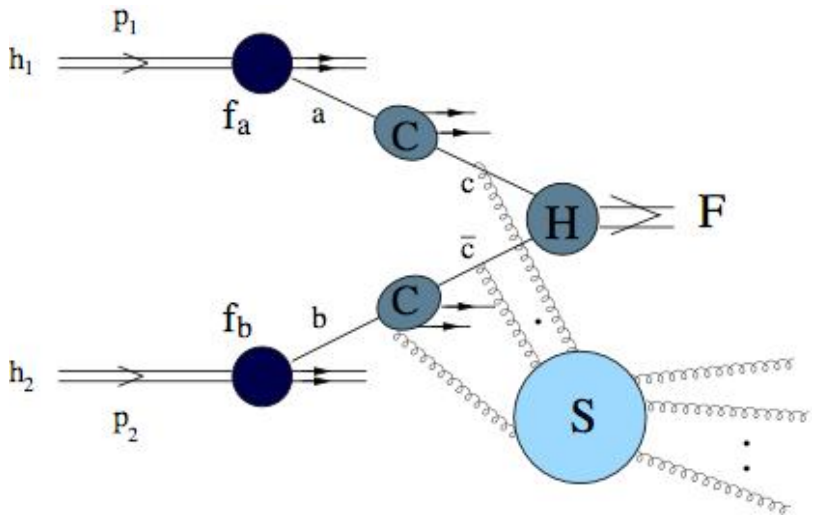

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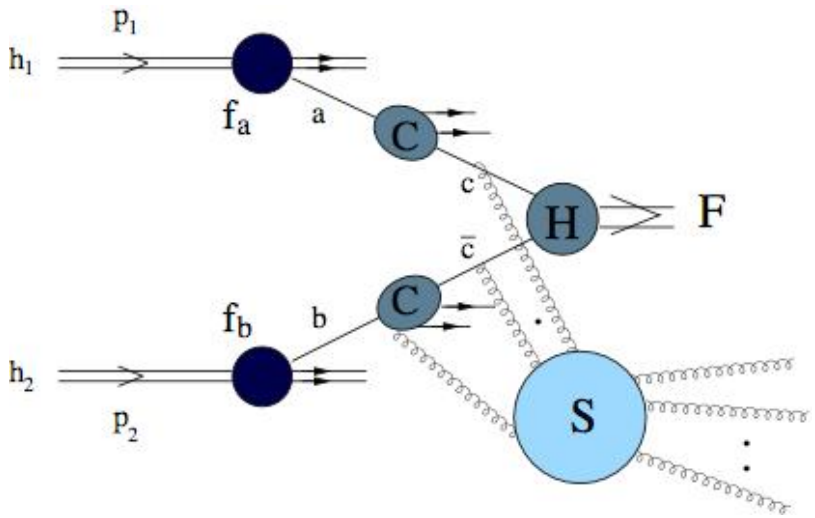

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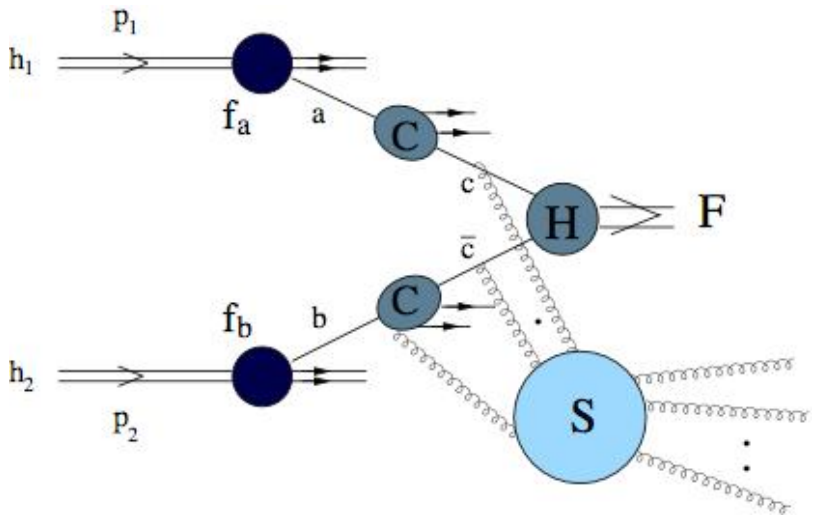

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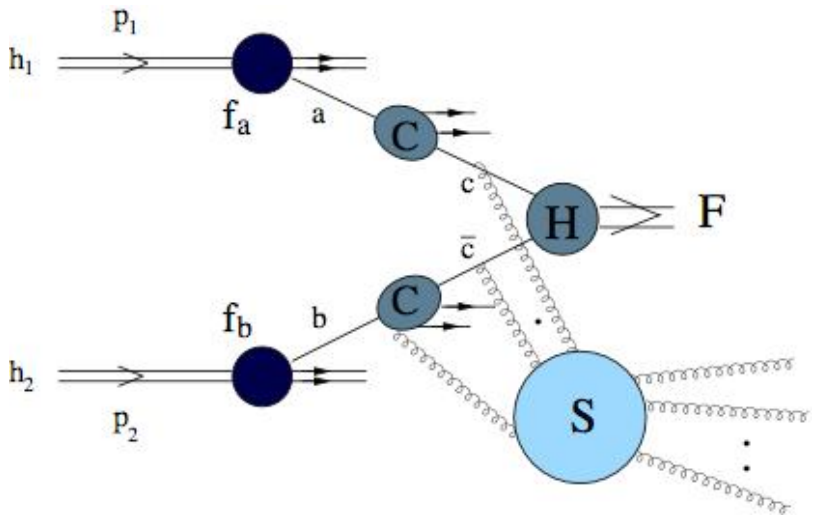

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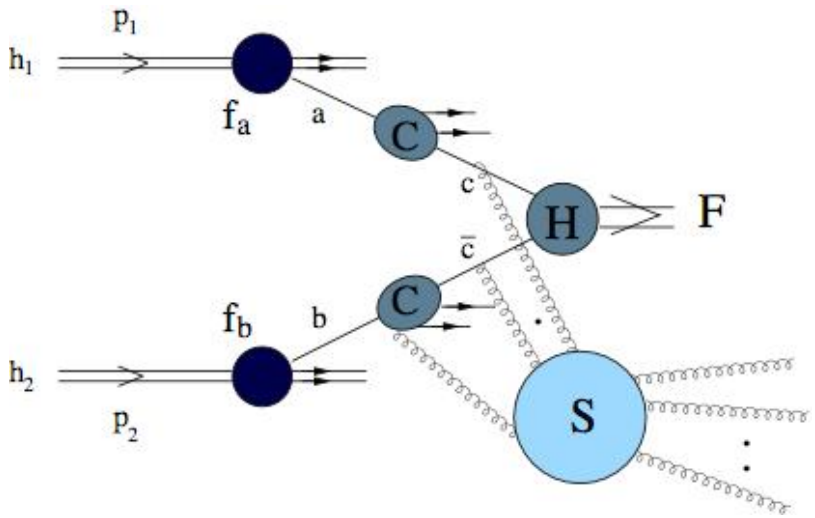

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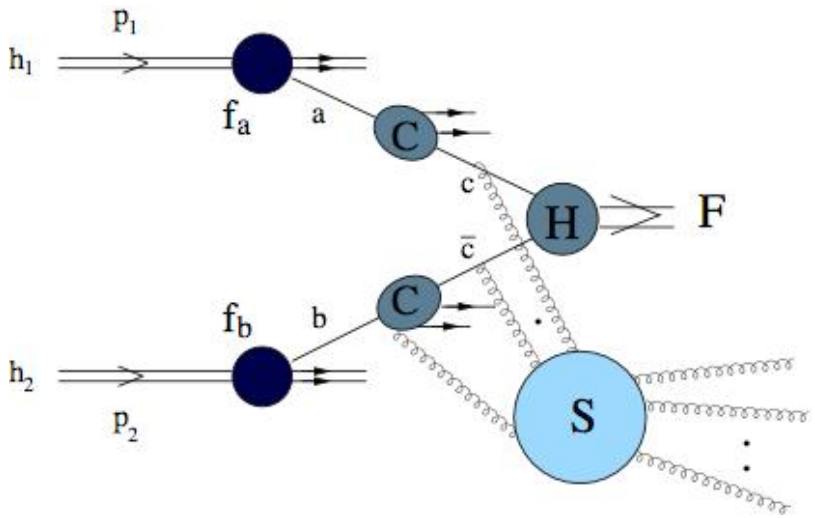

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Inclusive QCD hard scattering

$$h_1(p_1) + h_2(p_2) \rightarrow F(Q) + X$$

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K-factor

- LO cross sections suffer from large scale uncertainties: σ^{part} does not depend on $\mu_R, \mu_F \rightarrow$ *pdfs and* α_S *dependence are not balanced*
- Reliable results start at NLO

$$K = \frac{\sigma_{HO}(pp \rightarrow H + X)}{\sigma_{LO}(pp \rightarrow H + X)}$$

- α_S and pdfs have to be consistently evaluated at HO and LO as well (otherwise K could be larger,since α_S(NLO) < α_S(LO))
- Partonic cross sections known up to NNLO
  AP functions recently computed to 3-loops
  $\rightarrow$compute *full NNLO K-factors*

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Scale dependence

- Usually one fixes a "natural" scale μ_0 (typically the one that allows to absorb large logarithms...)
- Then μ_R, μ_F are independently or collectively varied within

$$\frac{\mu_0}{a} \leq \mu_F, \mu_R \leq \mu_0 a$$

- Dependence on $\mu_R, \mu_F \rightarrow$ evaluation of theoretical uncertainty ?
  - The narrower the uncertainty band is, the smaller the HO corrections are expected to be (not always true!)
  - In principle the scale uncertainty should be reduced when going to higher orders (not always true!)
  - BUT remember that all this is unphysical and there is no rigorous way to estimate the theoretical uncertainty other than performing the higher-order calculation!

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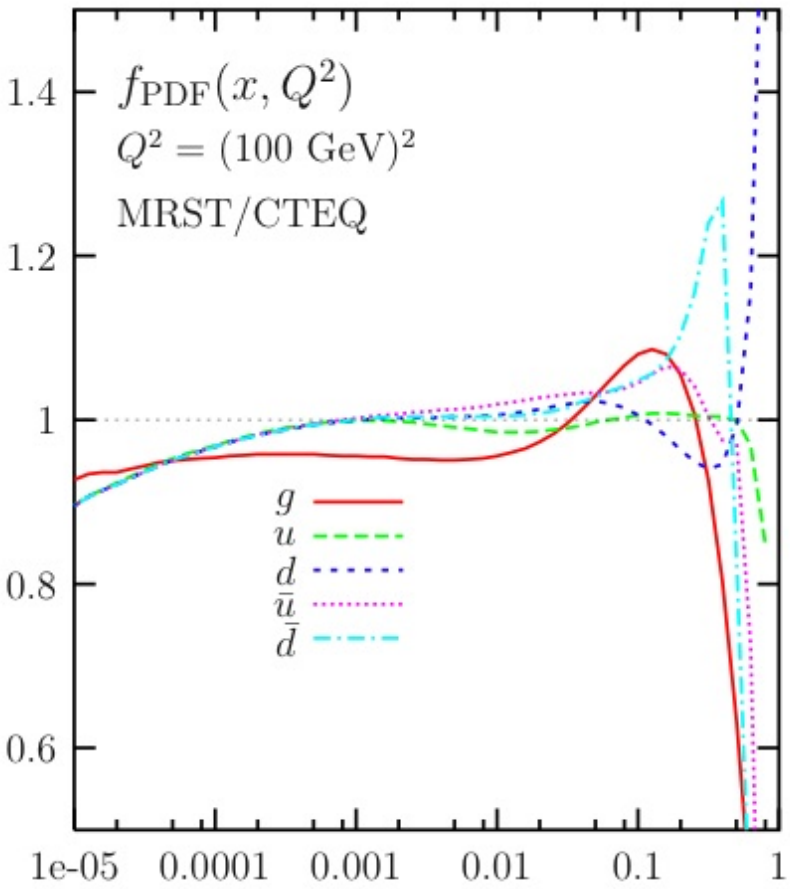

- Differences between pdfs arise from
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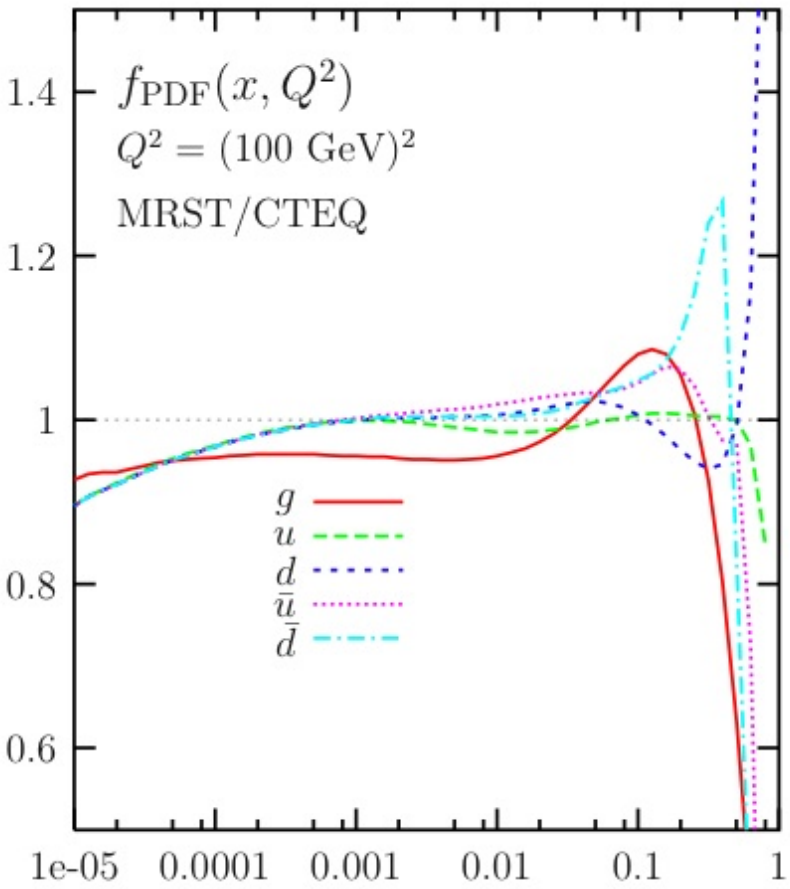

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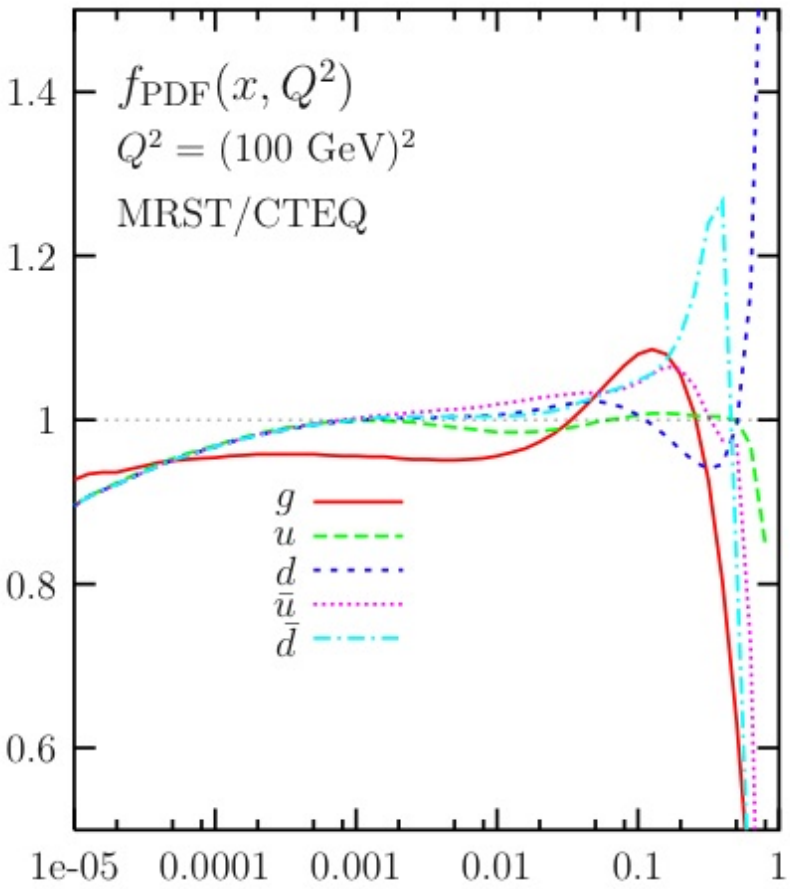

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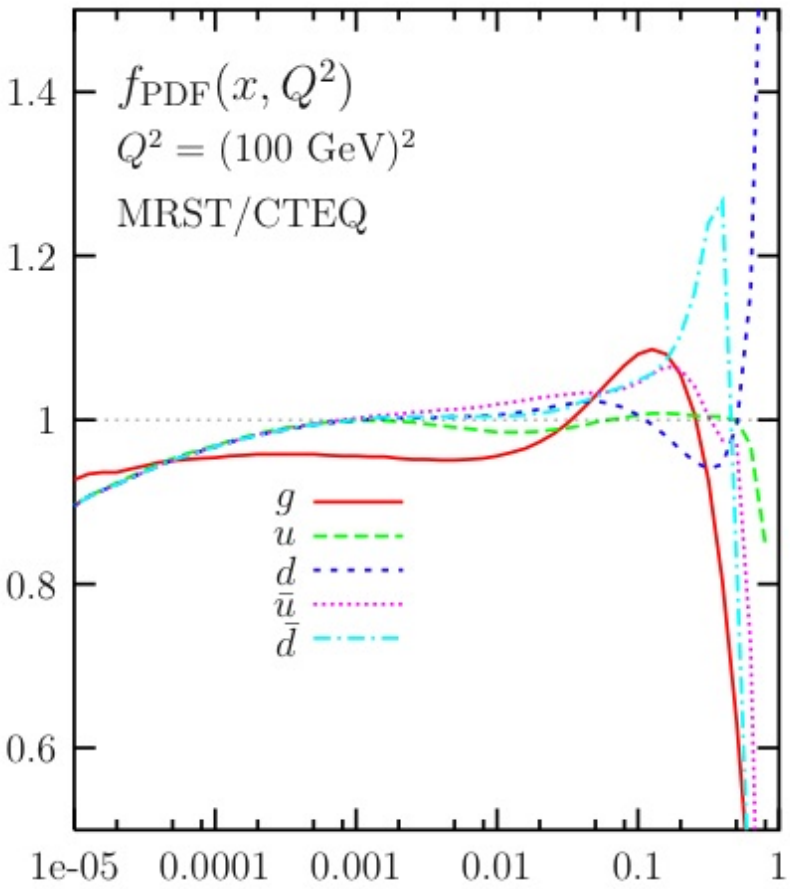

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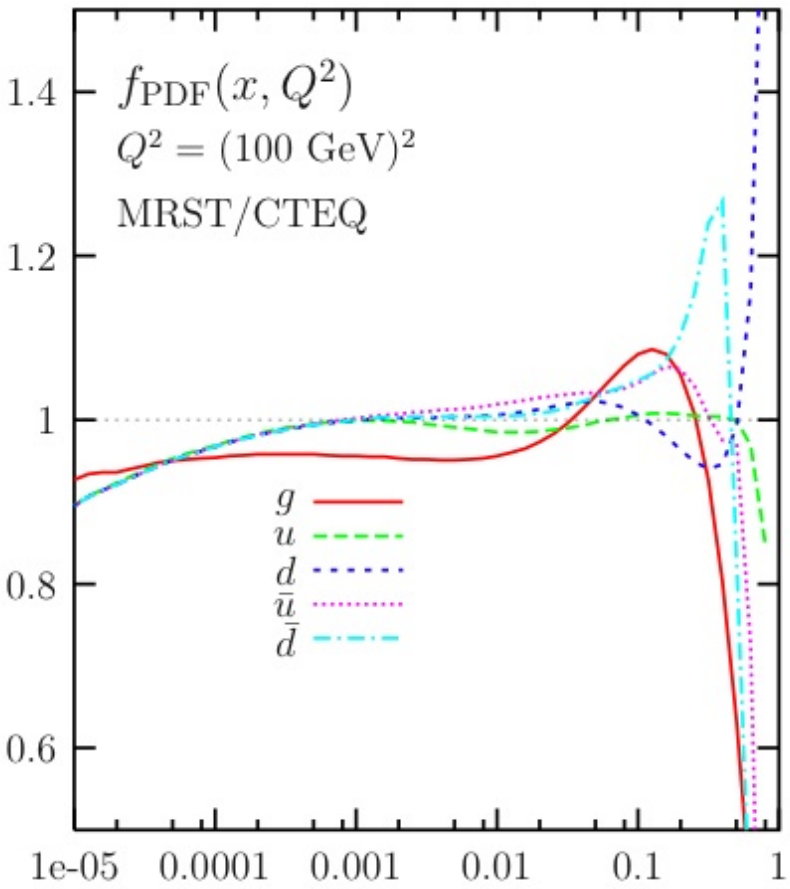

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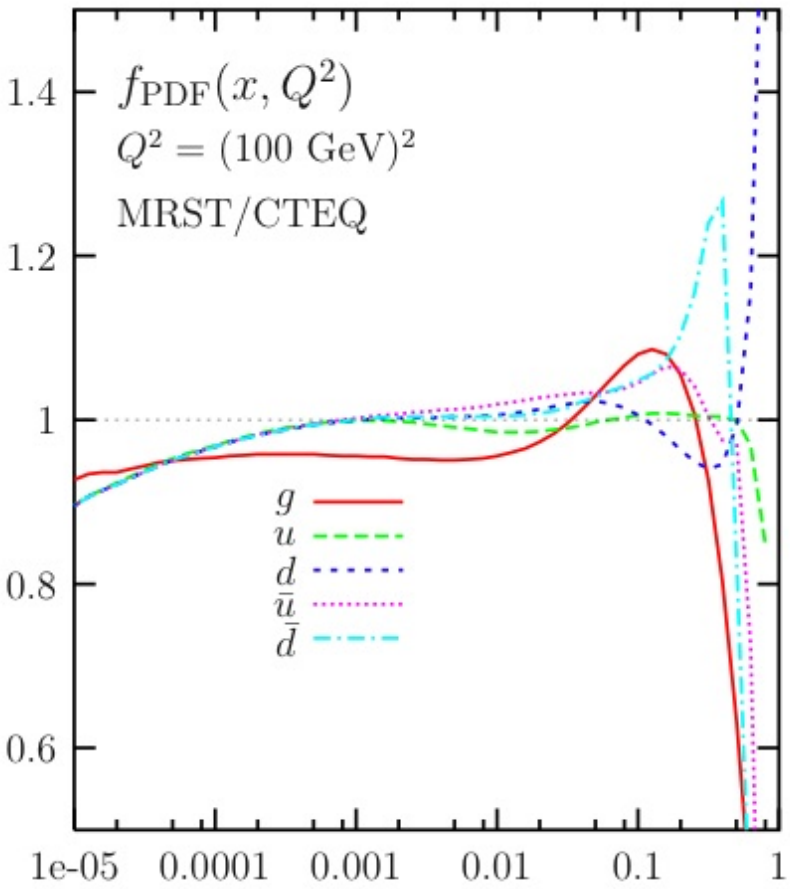

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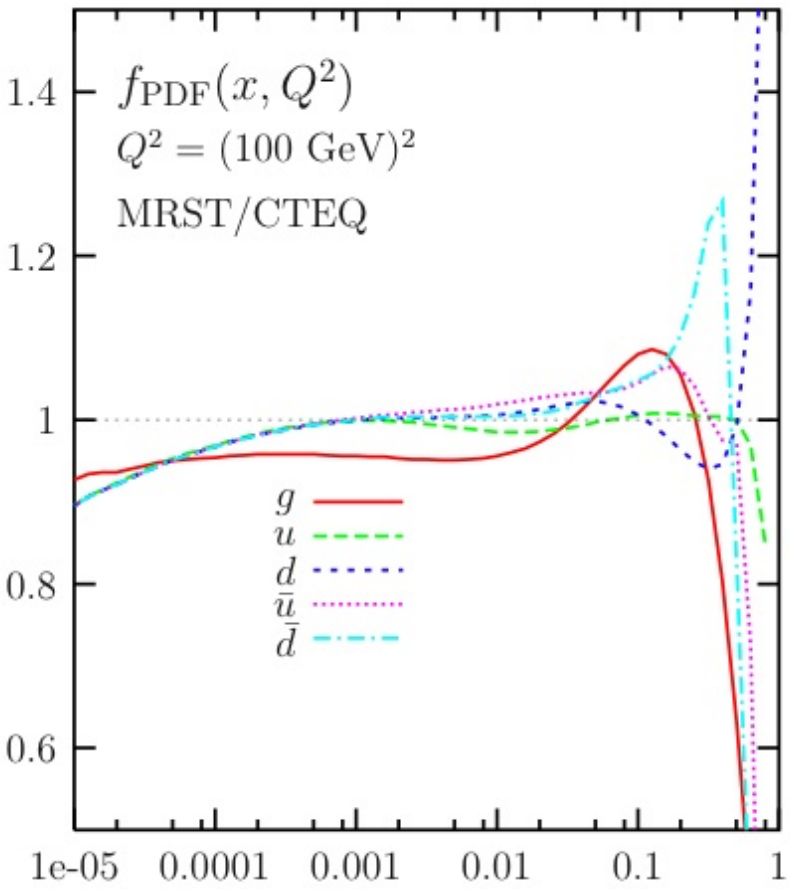

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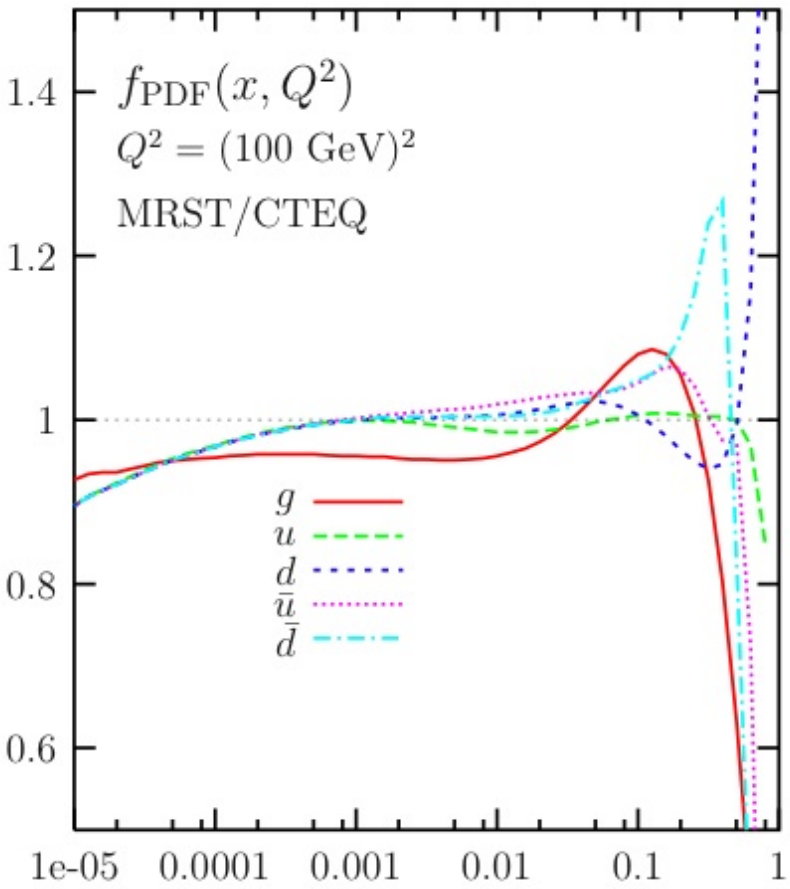

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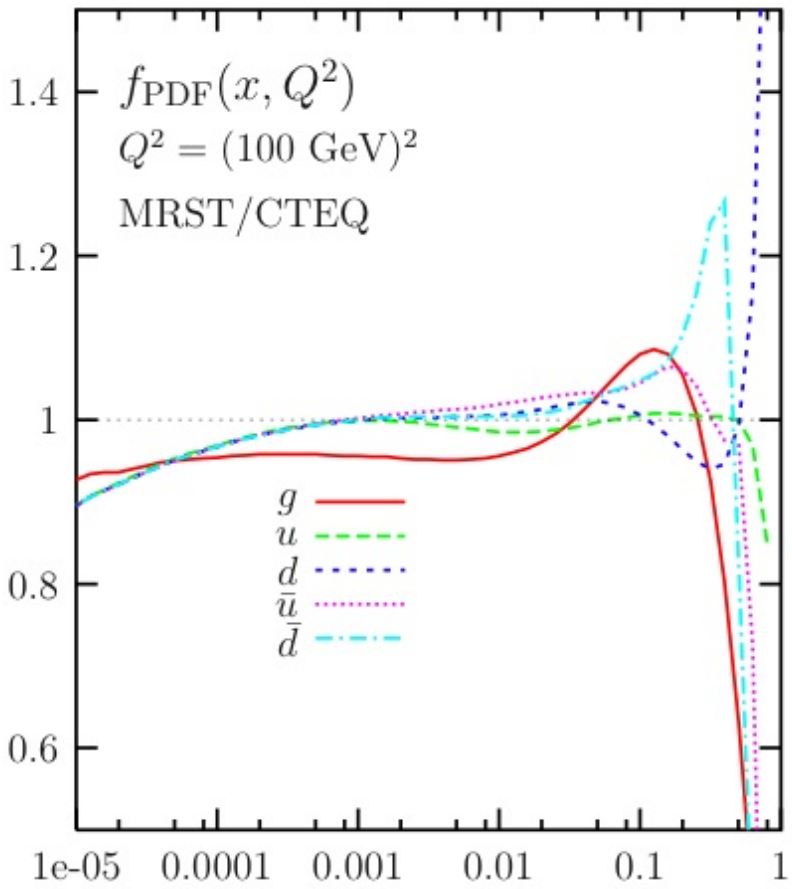

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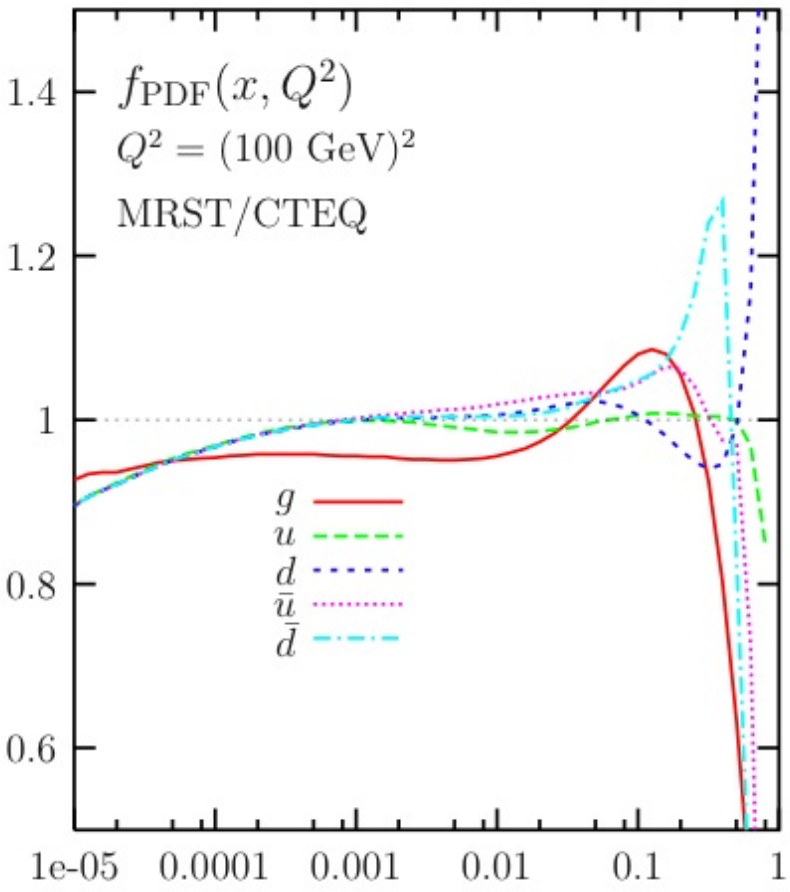

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The Higgs mechanism

- Standard Model: SU(2)×U(1) gauge theory
  → $m_l = m_B = 0$
- "Simple-minded" insertion of mass terms in the Lagrangian
  → both gauge invariance and renormalizability spoiled
- **SSB** leads to Goldstone bosons
  → global symmetry: m=0
  → local symmetry: m>0
- Local SSB (Higgs mechanism) provides masses to $W^{\pm}, Z^0$ and fermions through trilinear Yukawa couplings
- *"Remnant"*: **neutral, scalar, massive** boson **H**

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Mass bounds: theoretical arguments

- SM is an effective theory: New Physics must show up at some energy scale Λ
- Higgs self-coupling $2\lambda = (M_H/v)^2$
- Triviality. λ increases with the energy, eventually reaching the Landau pole: the larger M_H, the nearest the singularity
  $\longrightarrow$ upper bound on M_H (if we want $\Lambda <$ Landau pole)
- Vacuum stability. Top quark loop corrections may cause $\lambda < 0$ and, thus, unstable EW vacuum
  $\longrightarrow$ lower bound on MH (to balance loop contributions) and New Physics at Λ to preserve the EW vacuum
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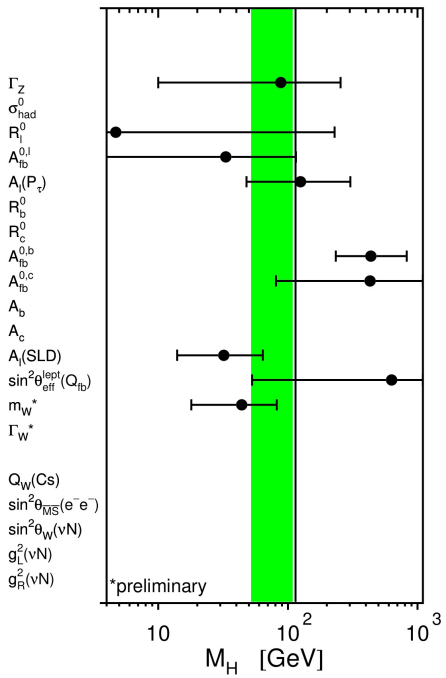

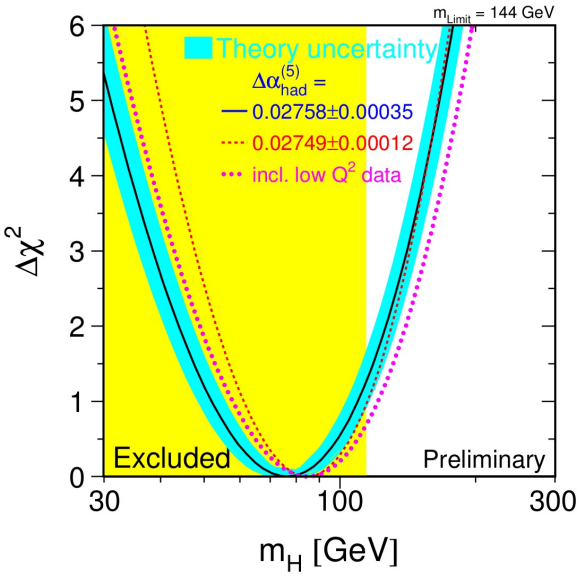

[LEPEWWG(Winter2007)]

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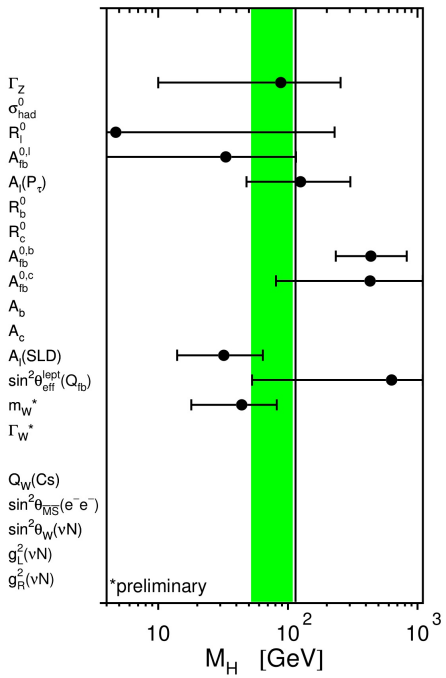

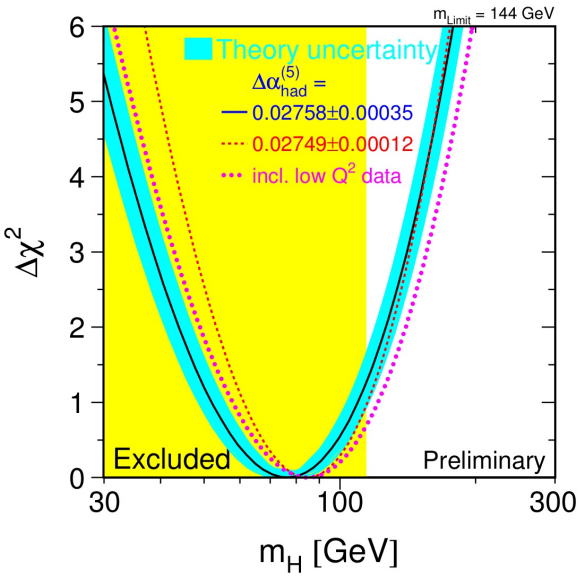

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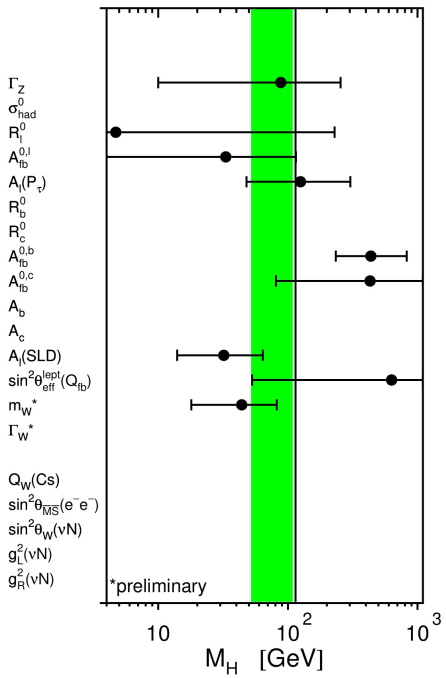

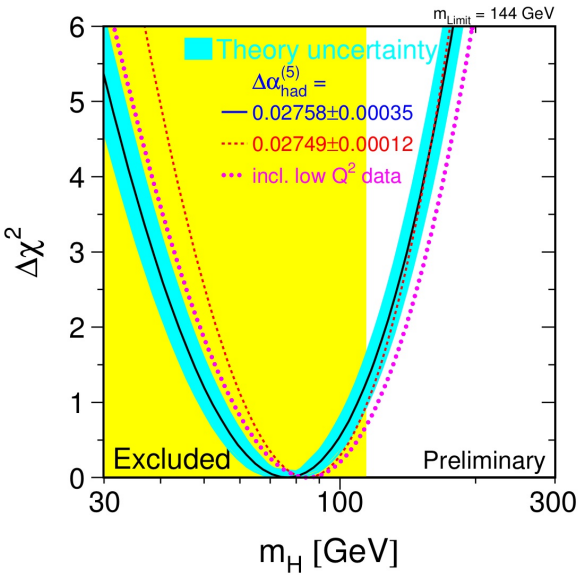

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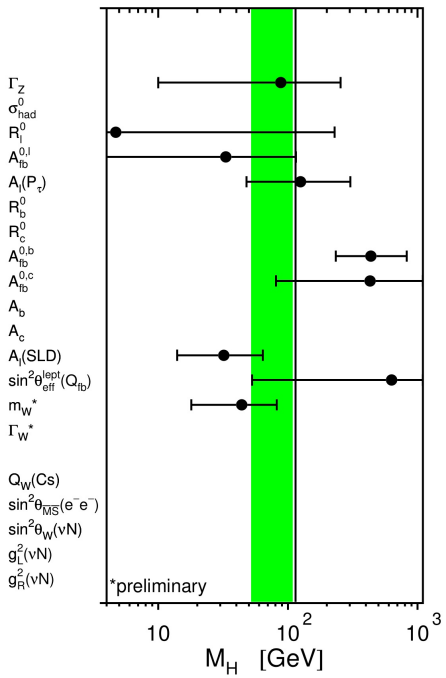

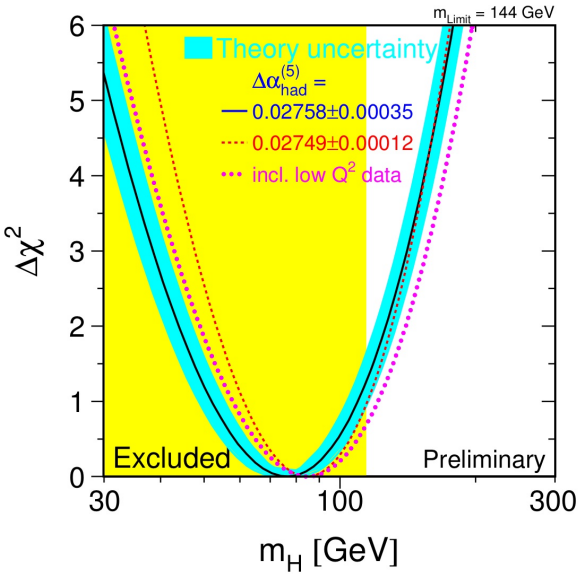

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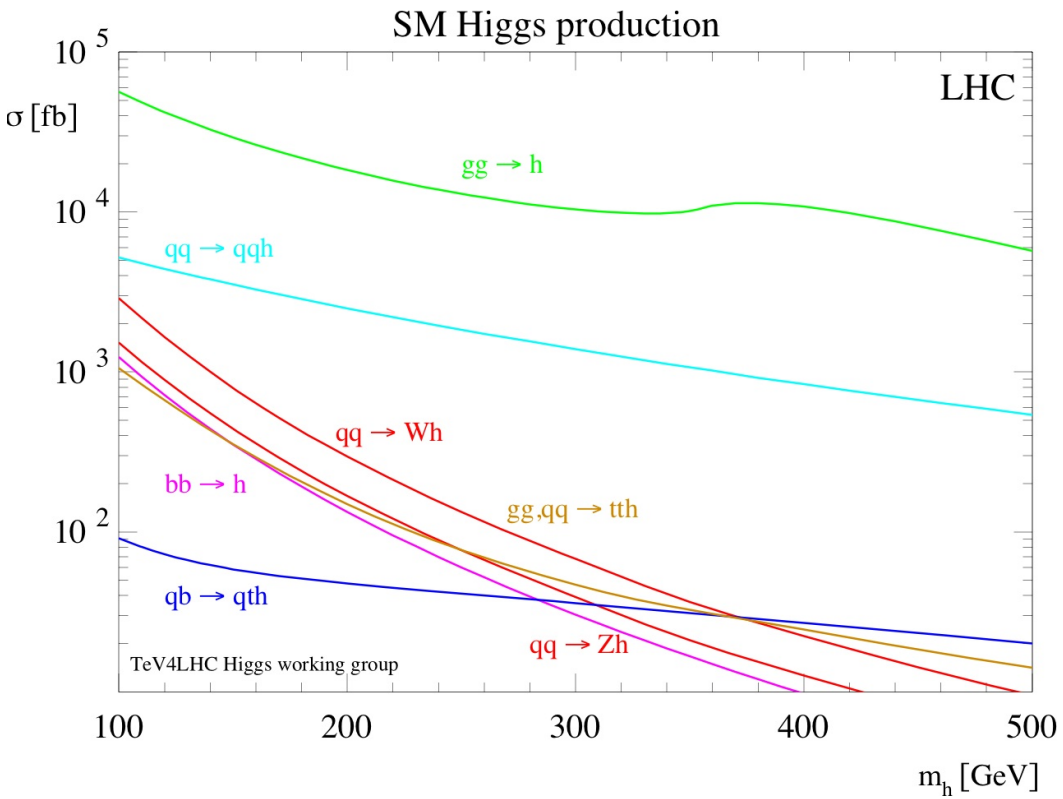

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- Gluon fusion: dominant production channel over entire mass range (large gluon luminosity)
- Vector boson fusion: very clean experimental signature
- Associated production: maybe important in the low mass region (provided a good b-tagging!)
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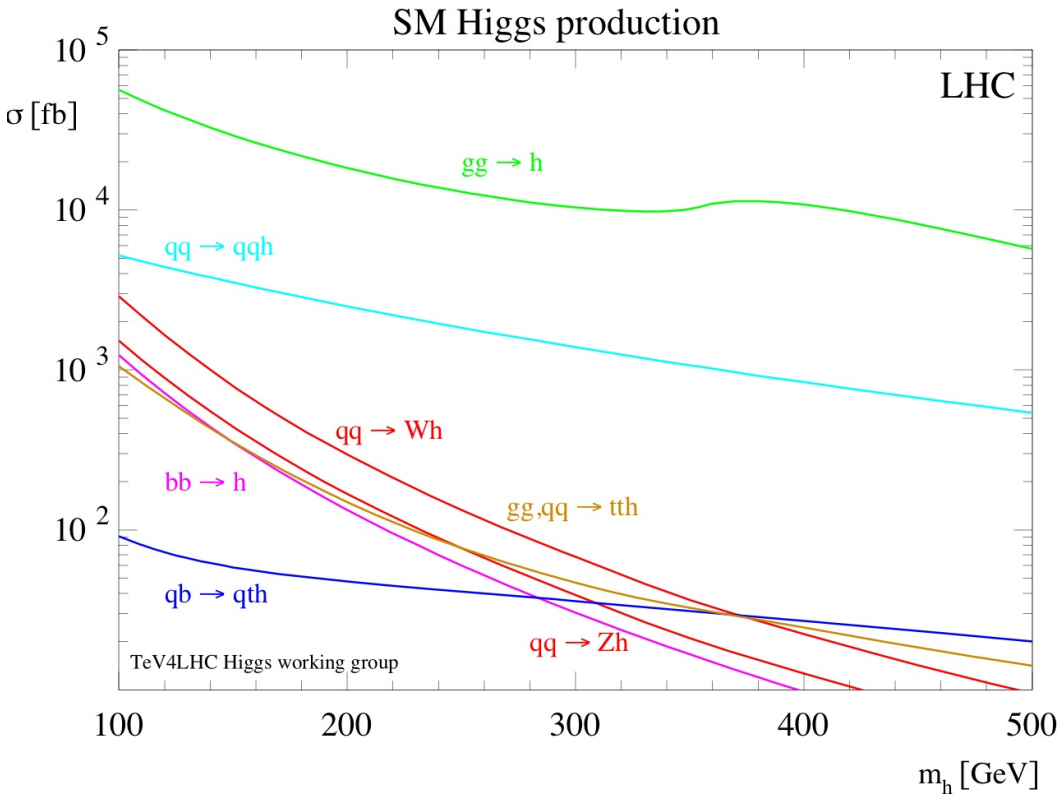

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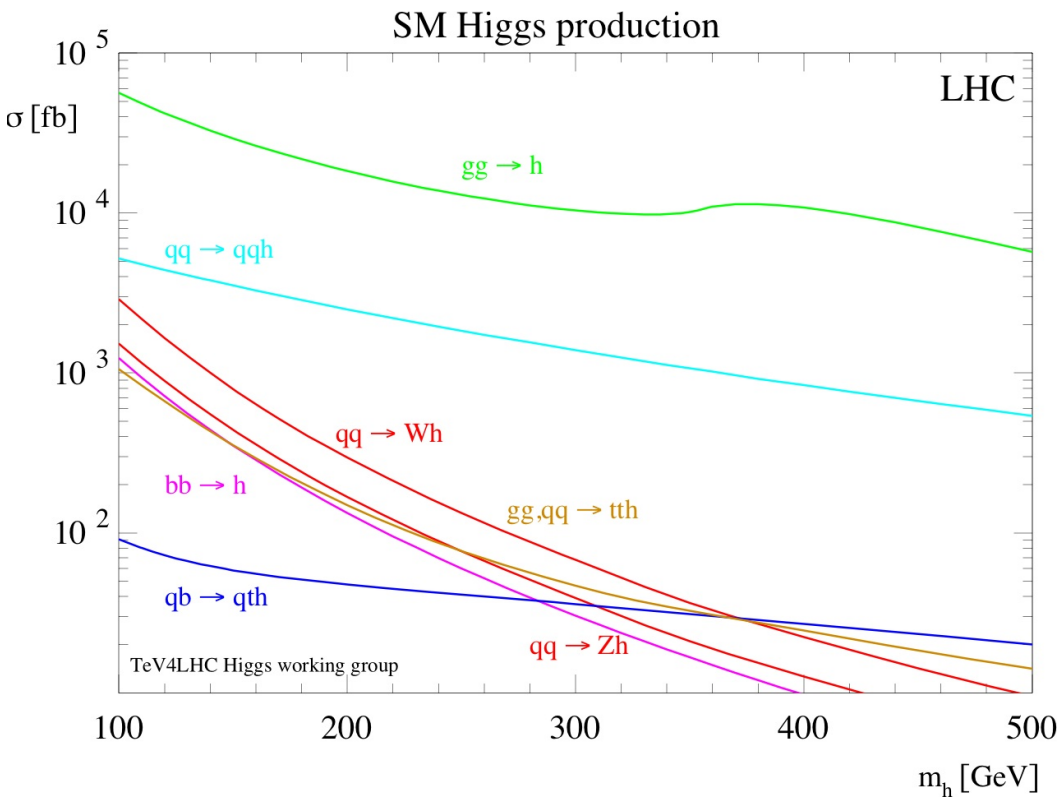

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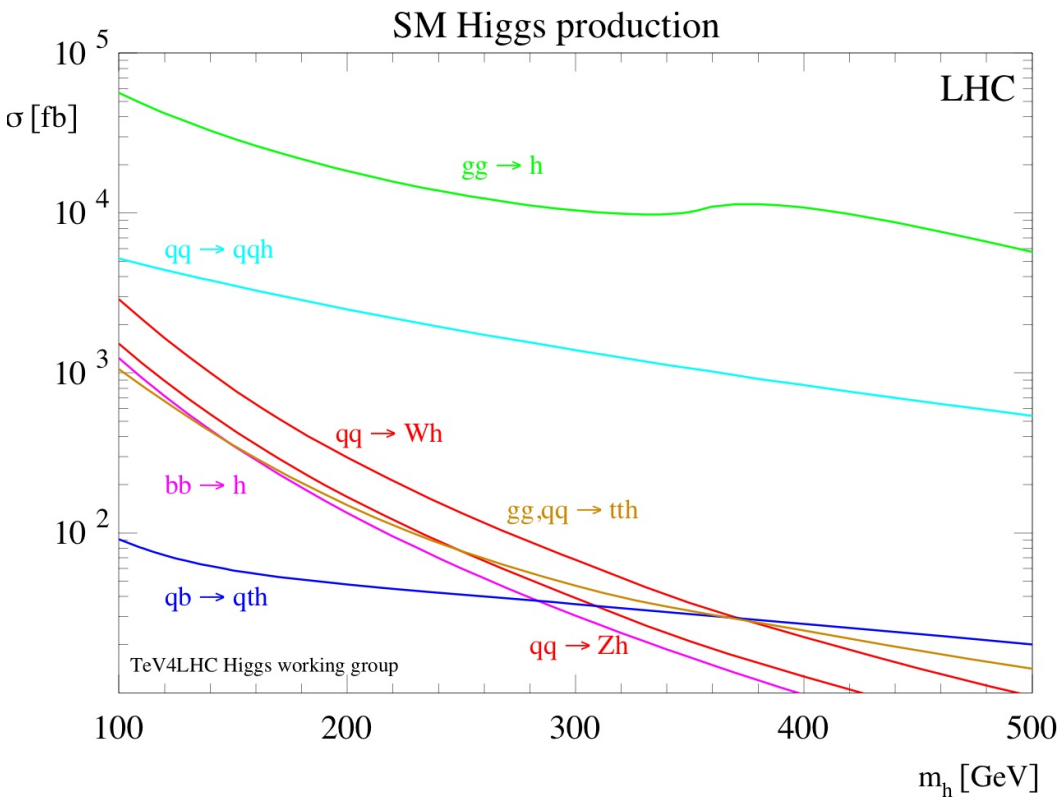

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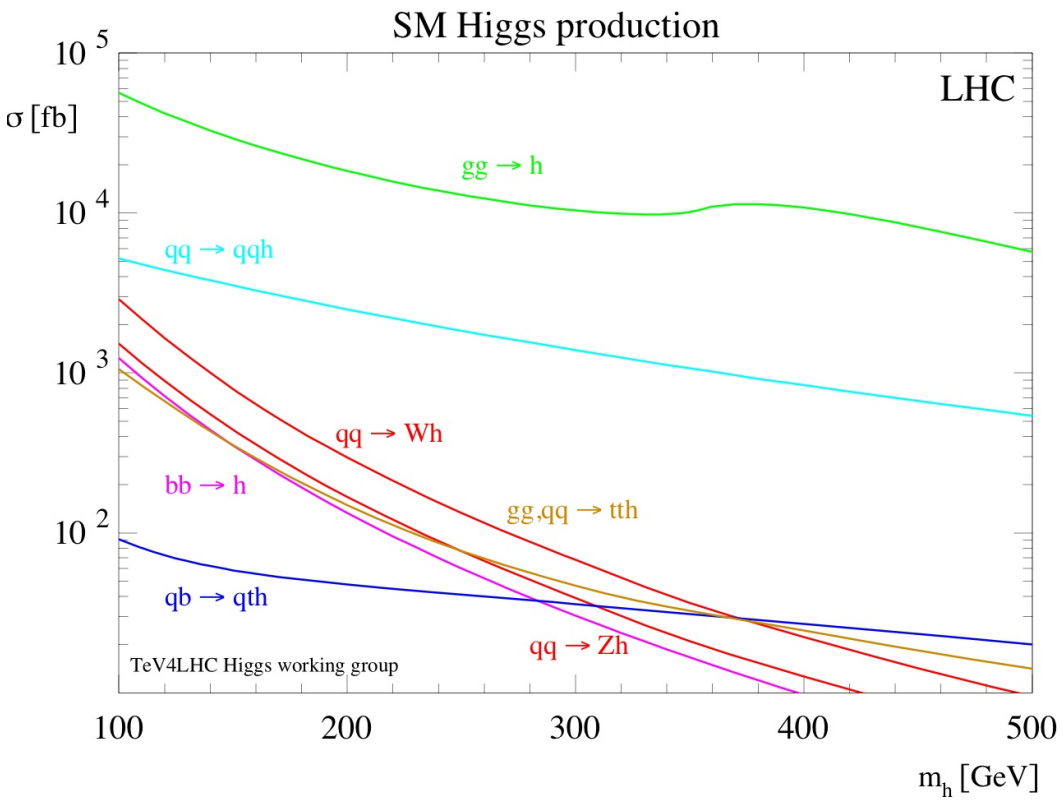

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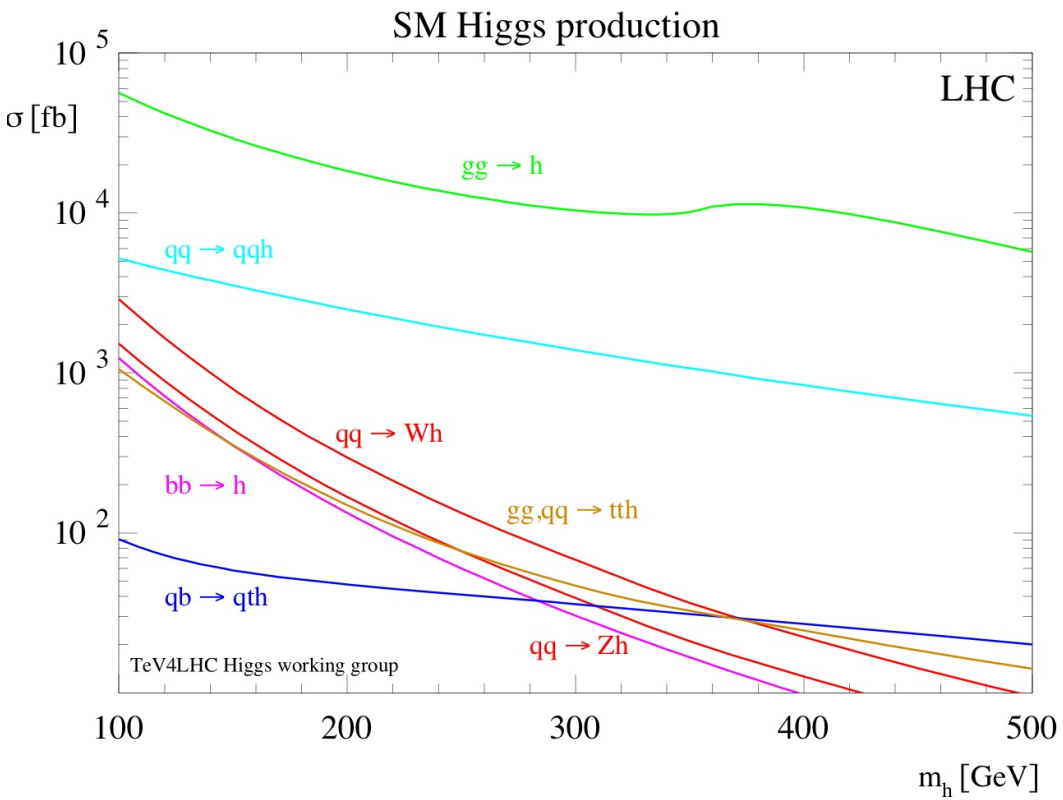

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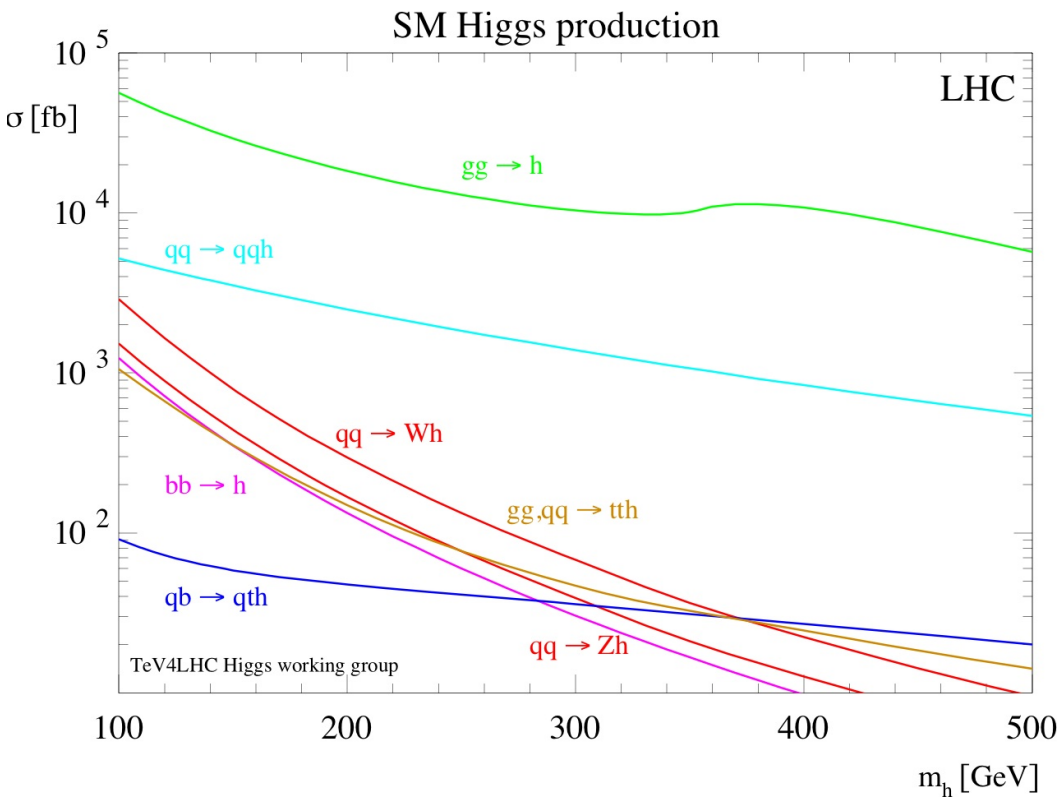

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The gg $\longrightarrow$ H channel

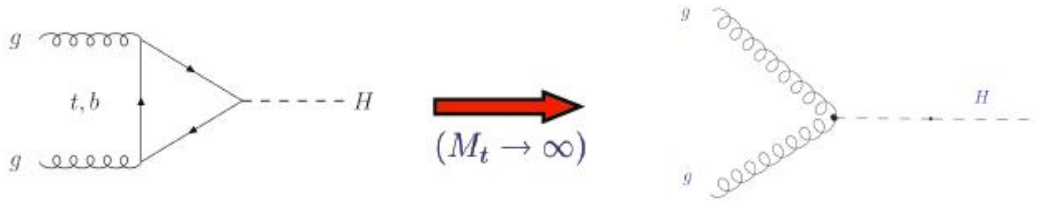
- Coupling mediated by triangular heavy quark loops
- Higgs coupling $\propto$ fermion mass $\longrightarrow$ top loops dominate
- LO = $\mathcal{O}(\alpha_S^2)$ computed a long time ago...

[Georgi,Glashow,Machacek,Nanopoulos(1978)]

- NLO QCD corrections very large (*K-factor* $\sim$ *80-100 % !*)

[Spira,Djouadi,Graudenz,Zerwas(1991,1995)]

- Higher-order calculations extremely difficult: considerable simplifications arise when $m_H \leq 2m_t$



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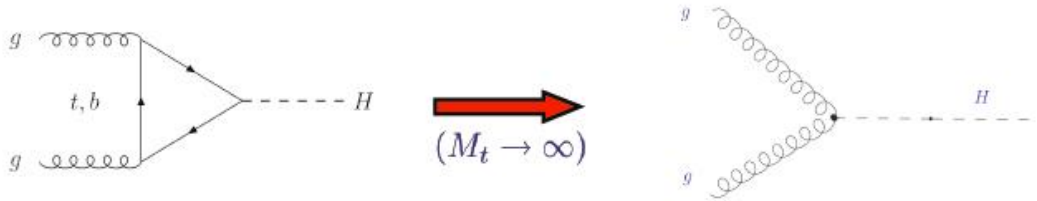

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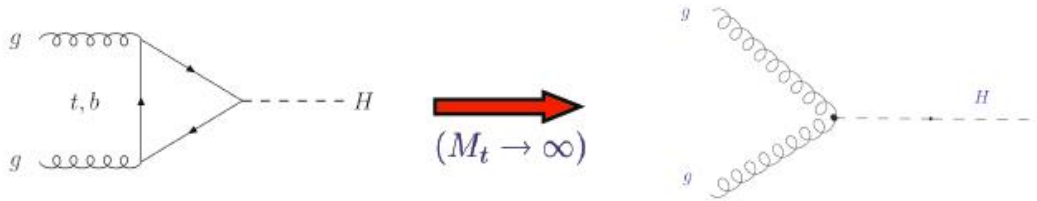

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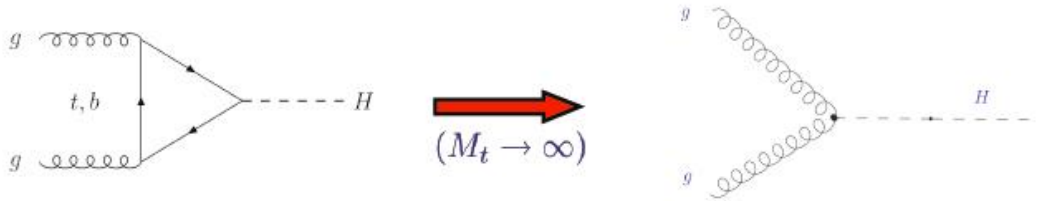

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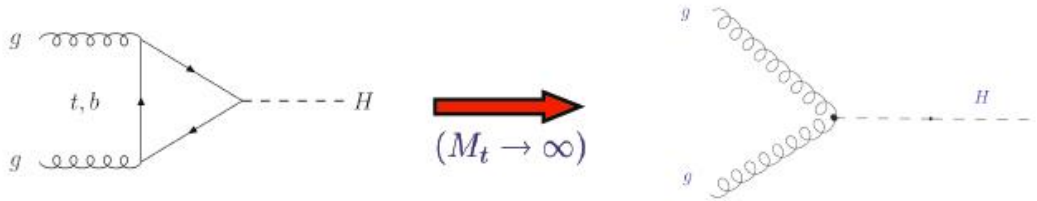

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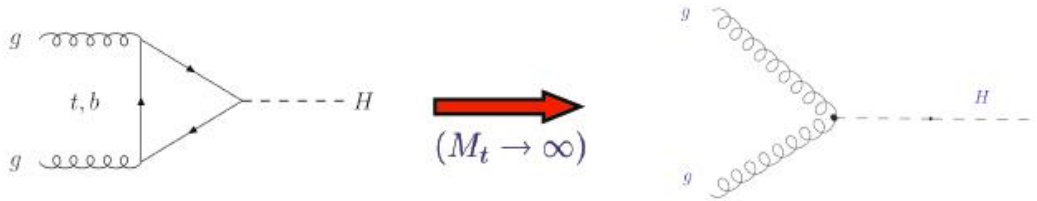

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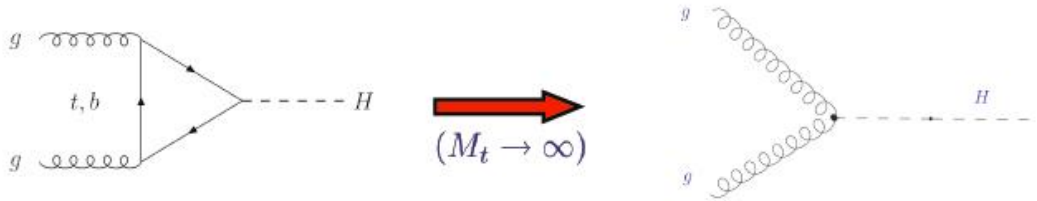

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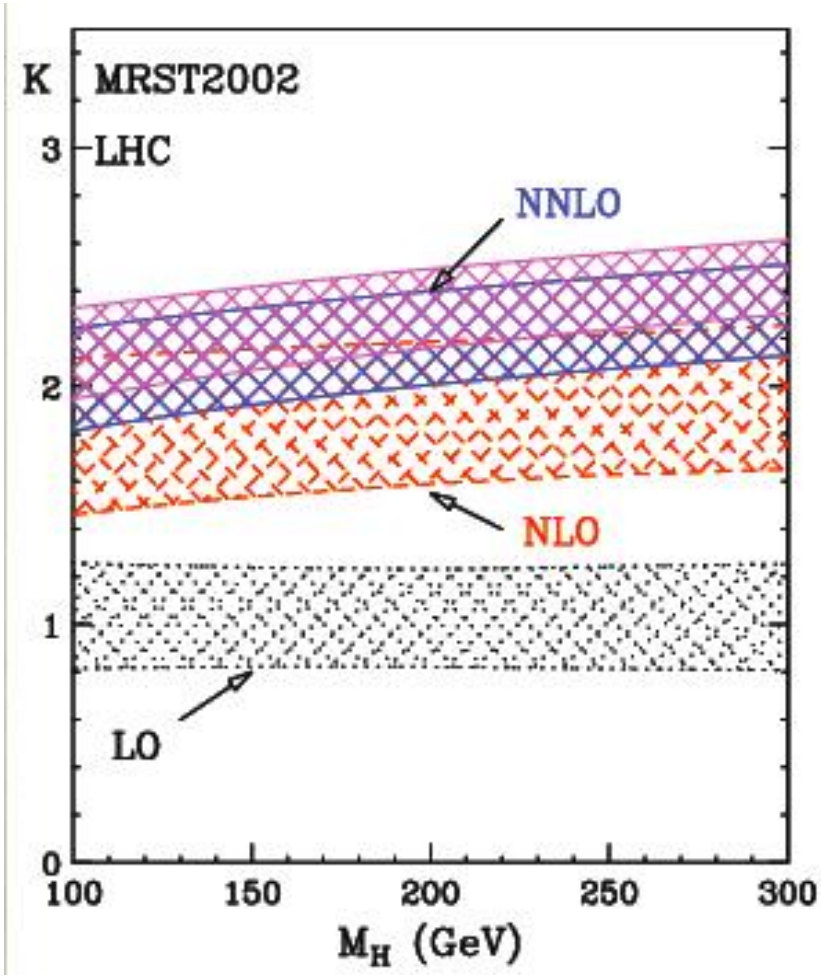

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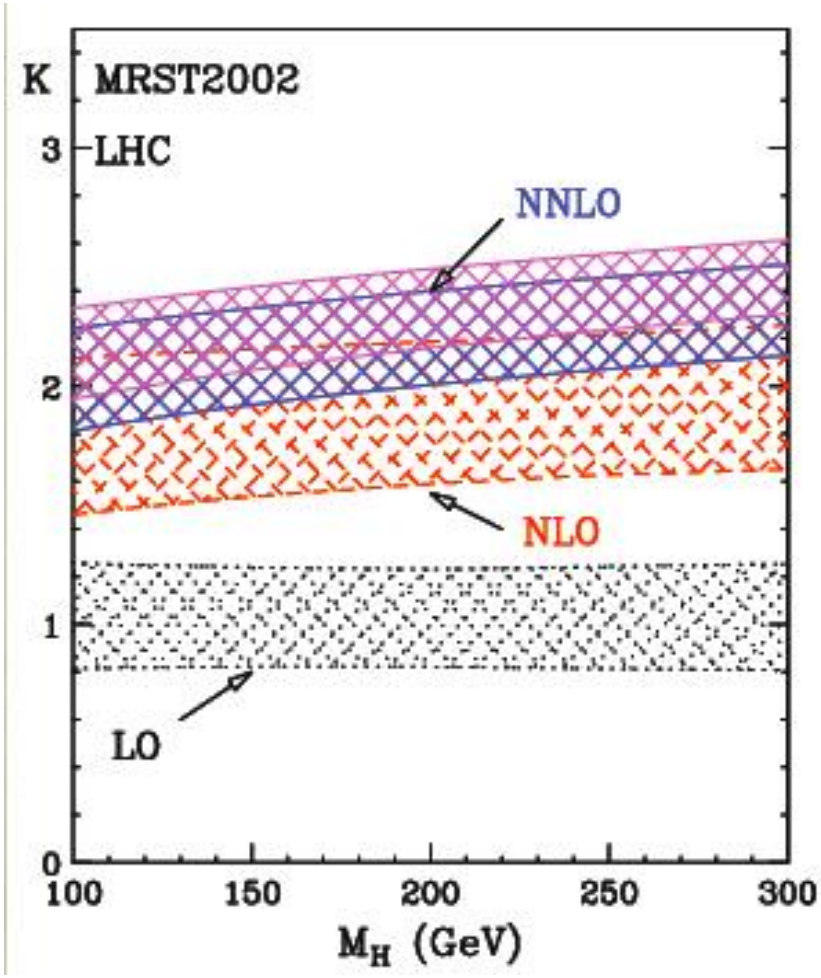

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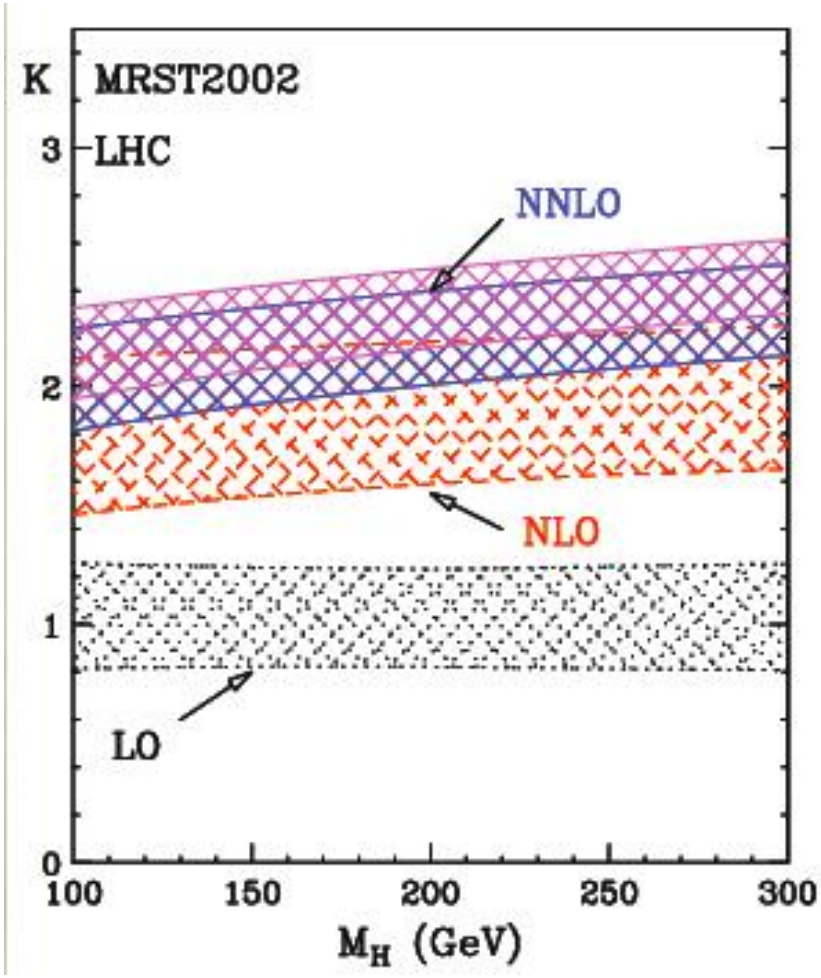

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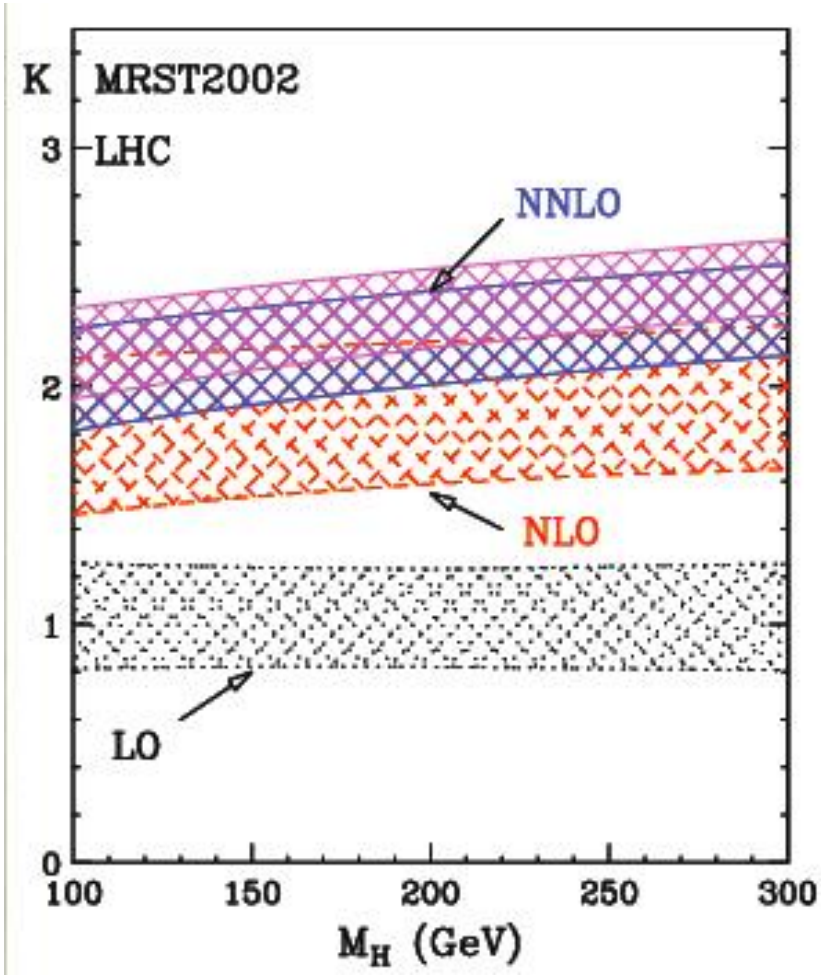

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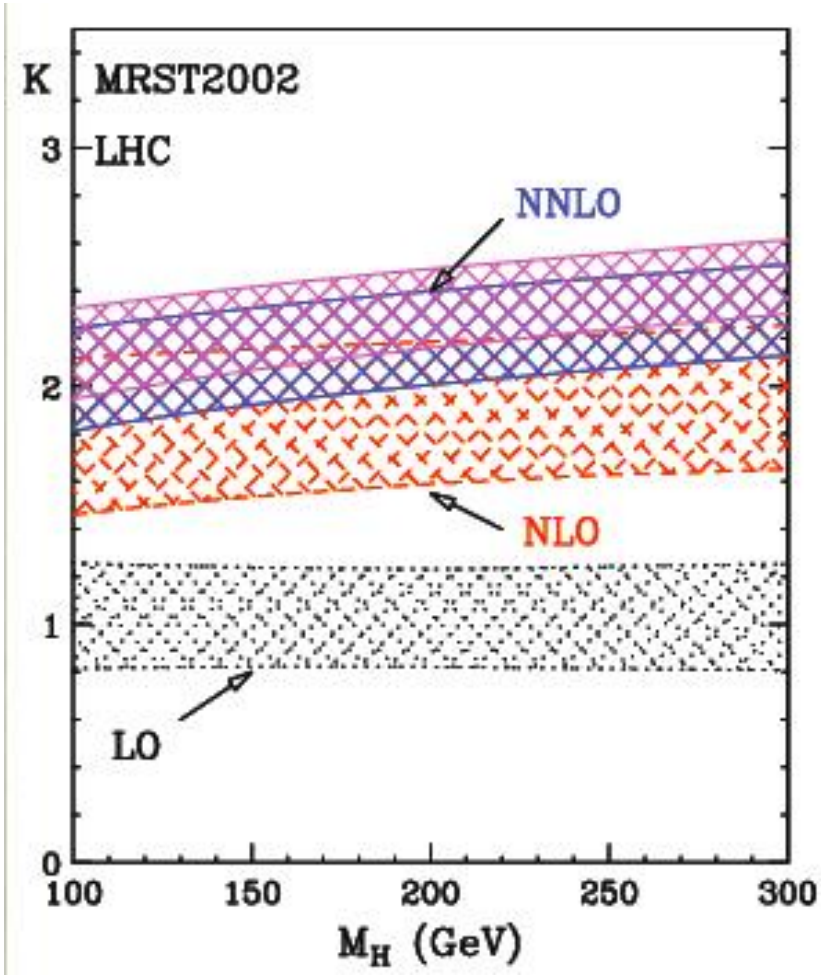

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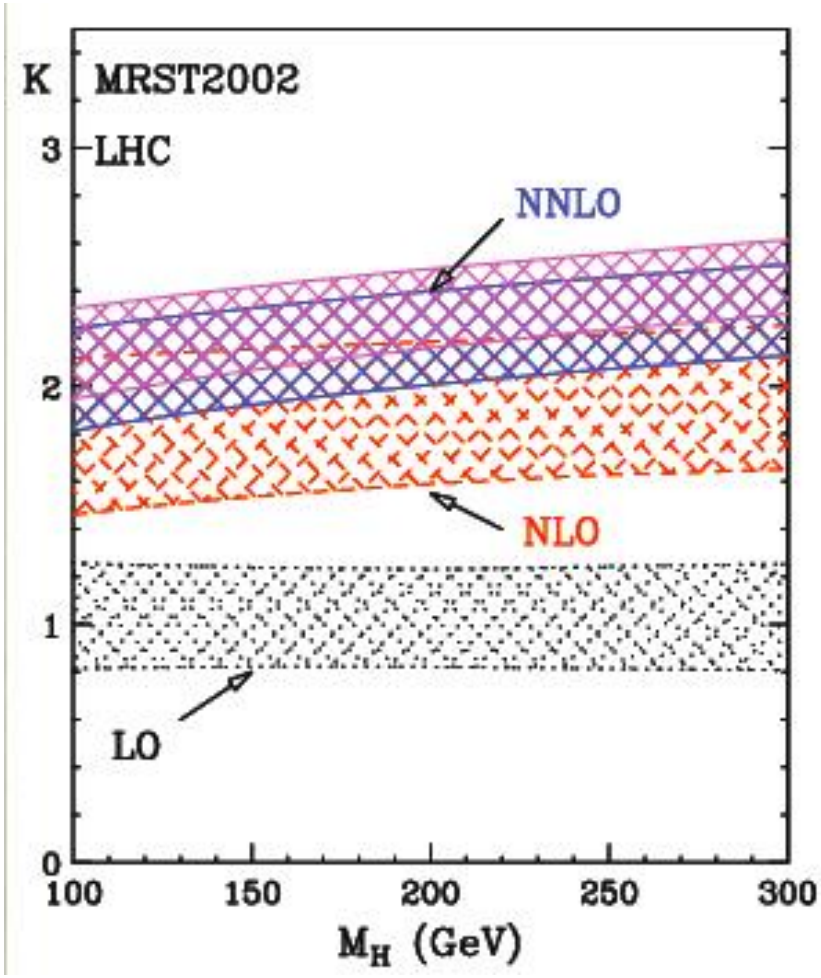

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- Transverse-momentum distribution

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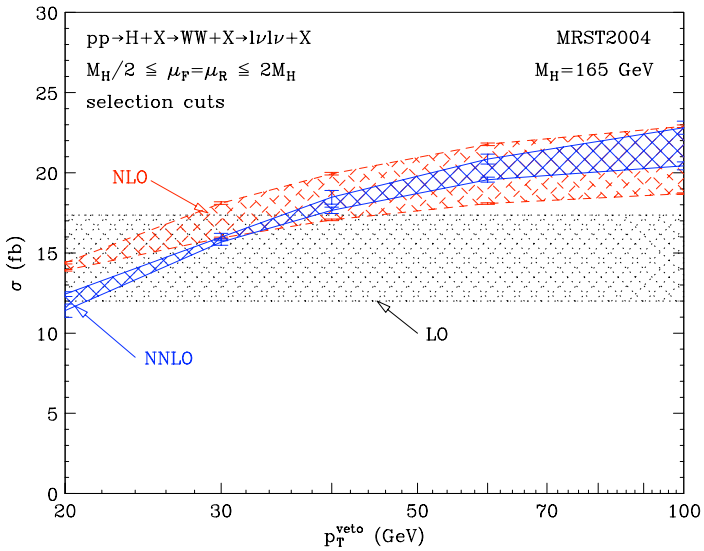

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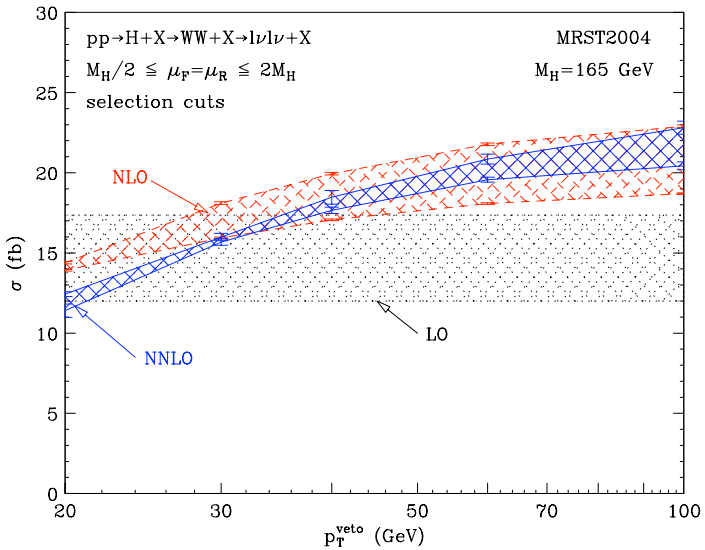

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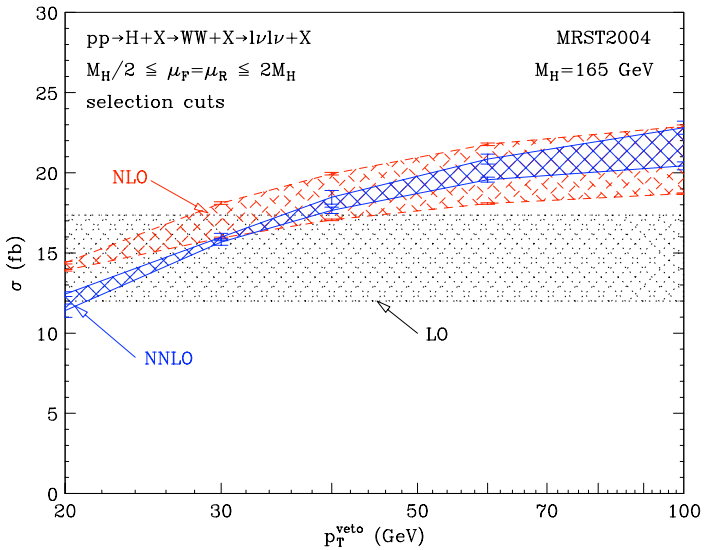

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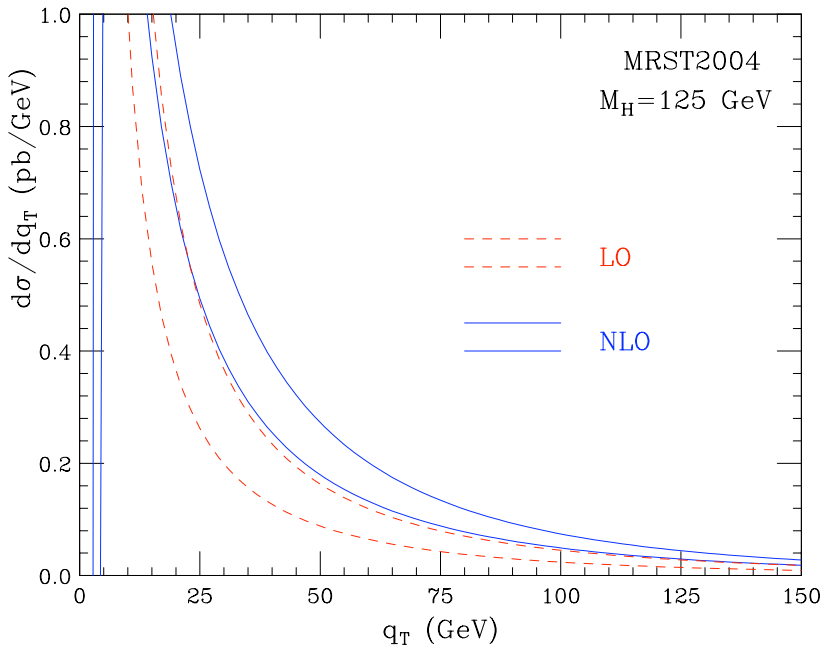
The small-q_T region ($q_T \ll M_H$)

- Bulk of the events in the region $q_T \ll M_H$
- Kinematical unbalance between real and virtual contributions

$\longrightarrow$ perturbative coefficients enhanced by $\alpha_S^n \log^m\left(\frac{M_H^2}{q_T^2}\right)$

$\longrightarrow$ convergence of perturbative result completely spoiled



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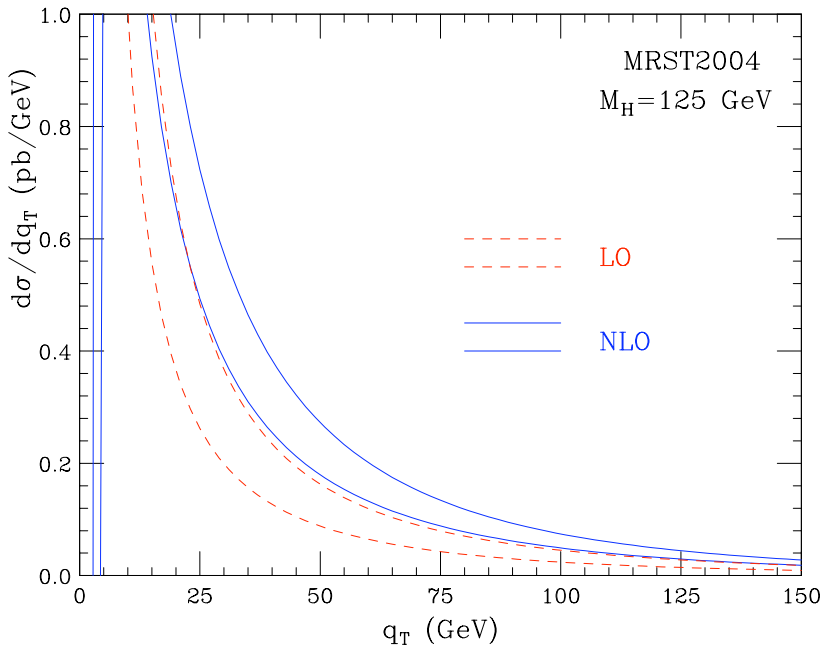

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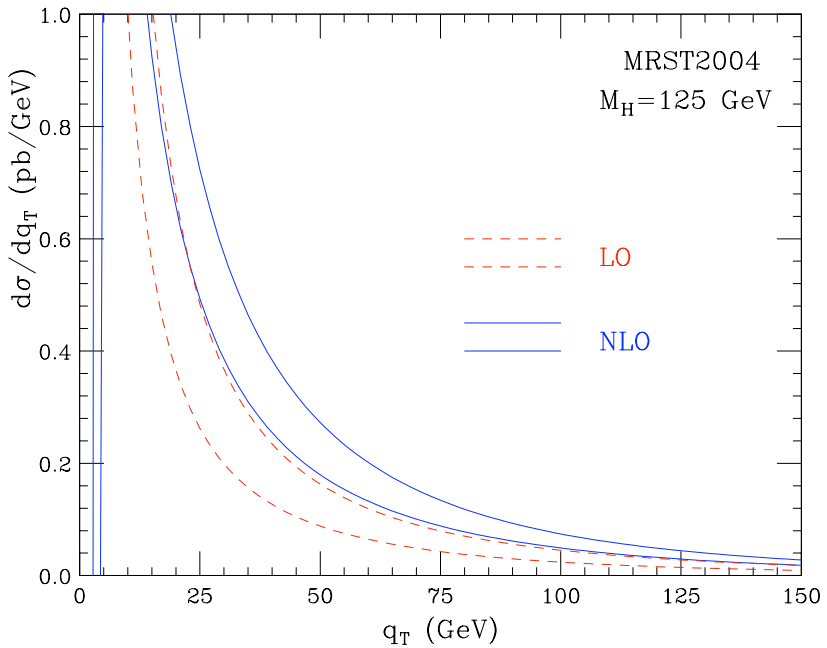

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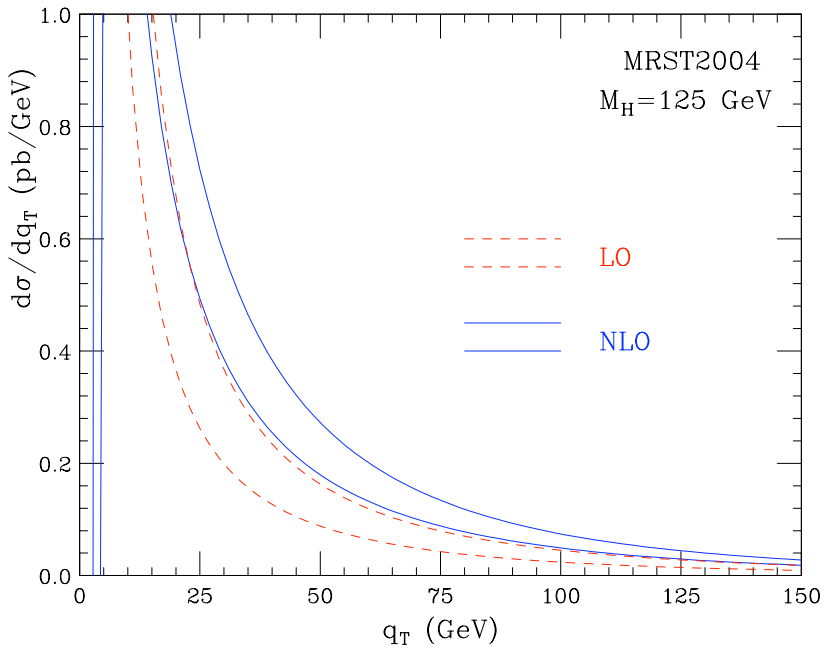

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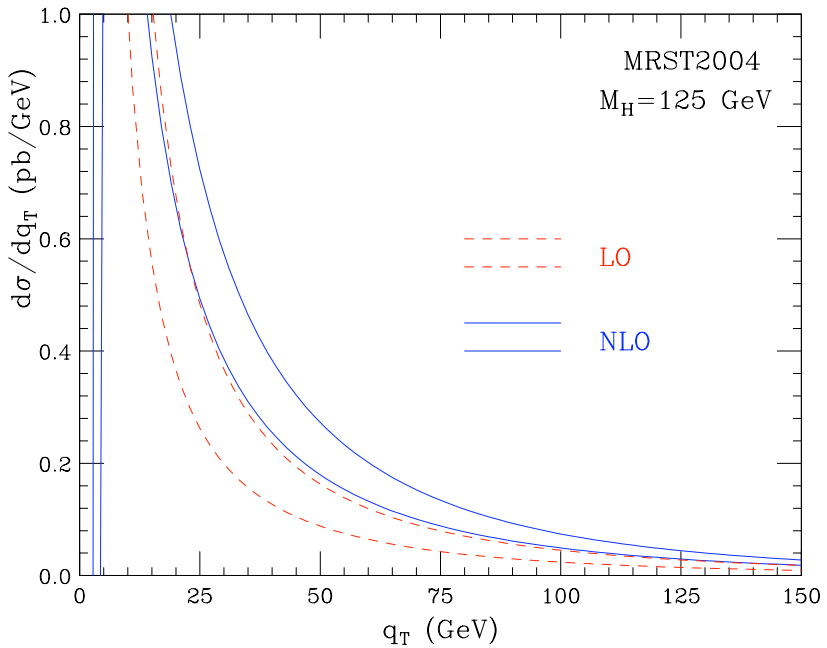

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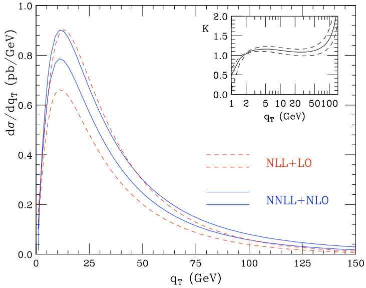

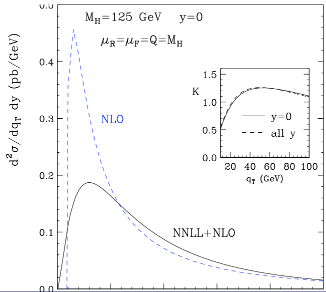

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  - → very good convergence of the resummed perturbative result
- q_T-dependent K-factor

$$K(q_T) = \frac{d\sigma_{NNLL+NLO}(\mu_F, \mu_R)}{d\sigma_{NLL+LO}(\mu_F = \mu_R = M_H)}$$

  - $\sim$ 1.1-1.2 in the central region
  - increase (decrease) drastically for $q_T > 50$ ($q_T < 2$)
  - no simple rescaling of NLL+LO

[HqT: http://theory.infn.it/grazzini/codes.html]

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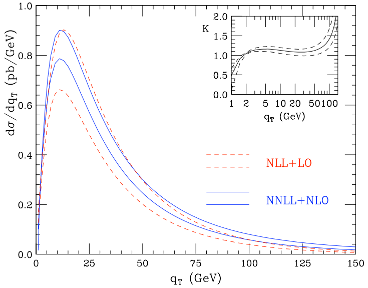

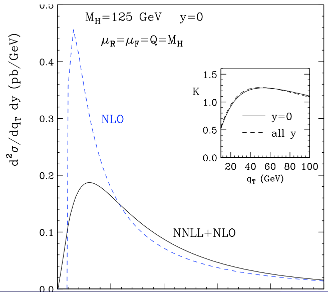

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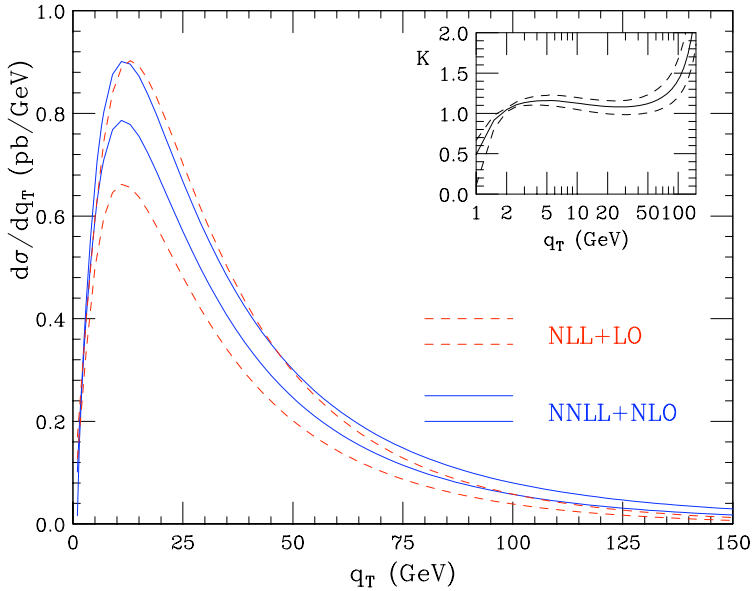

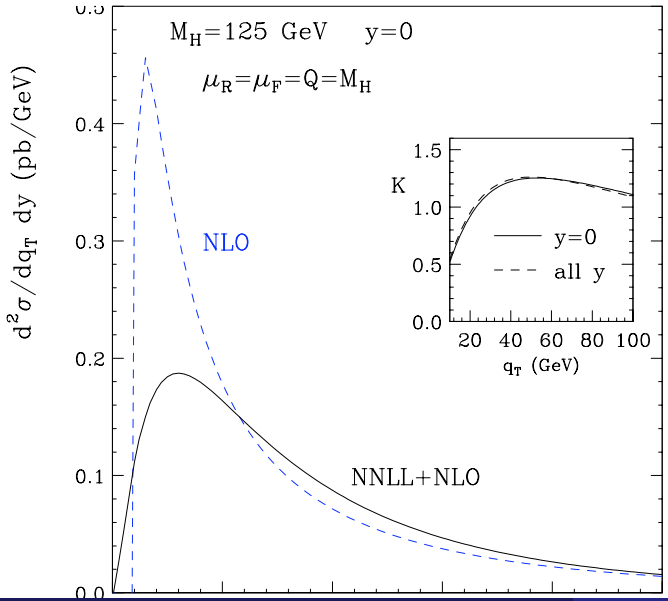

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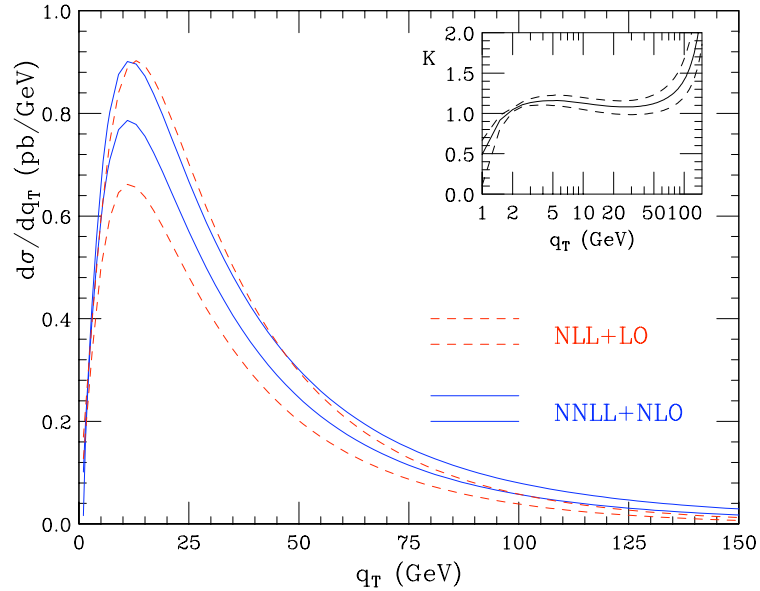

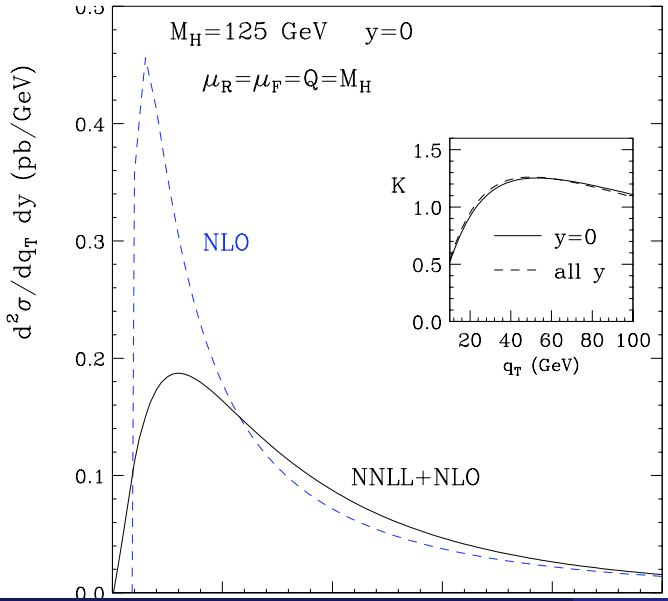

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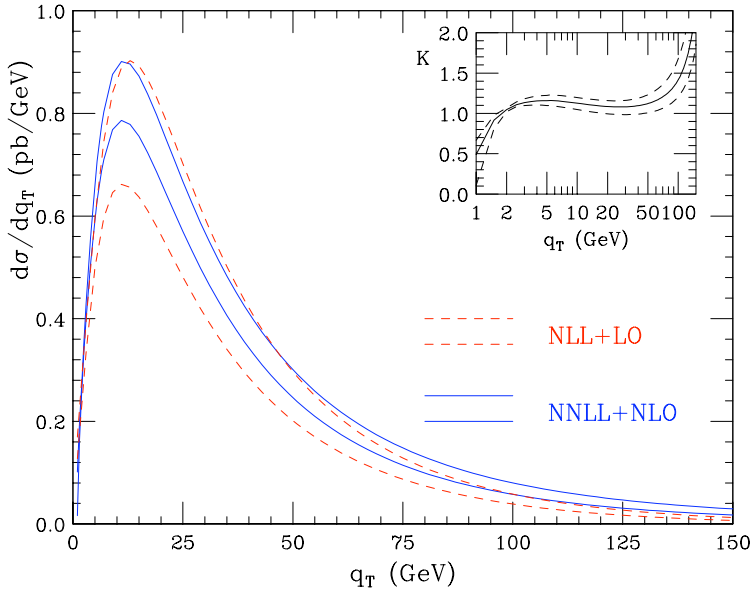

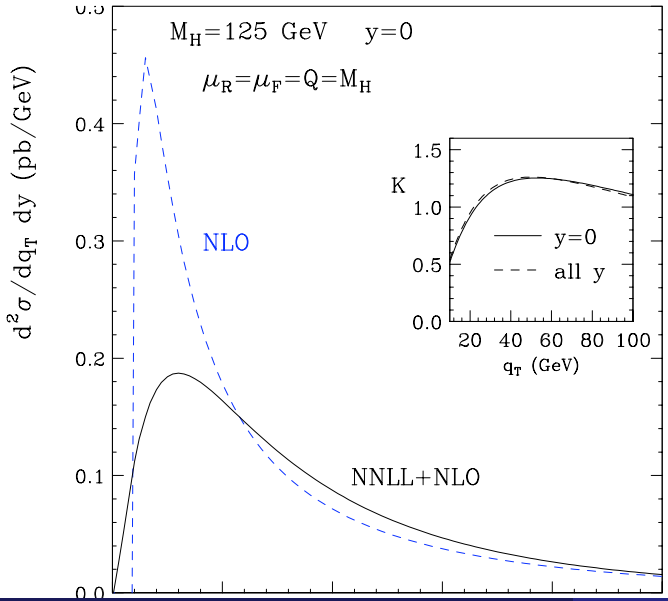

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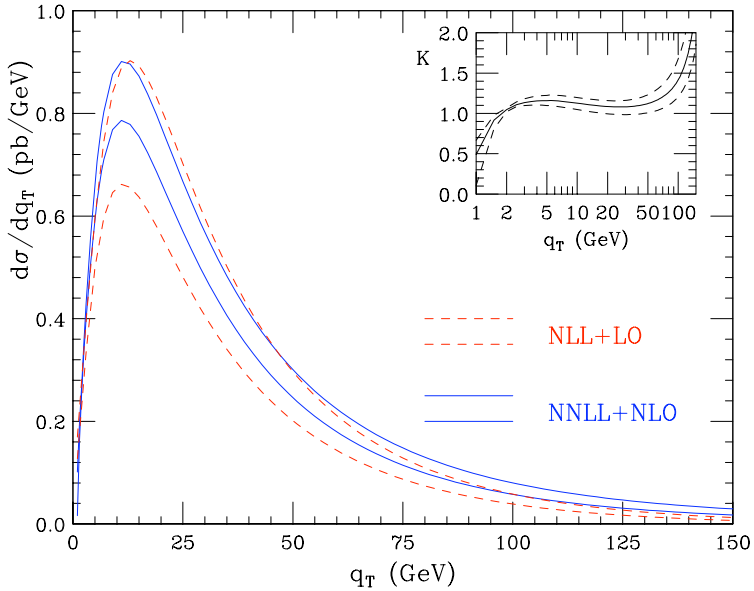

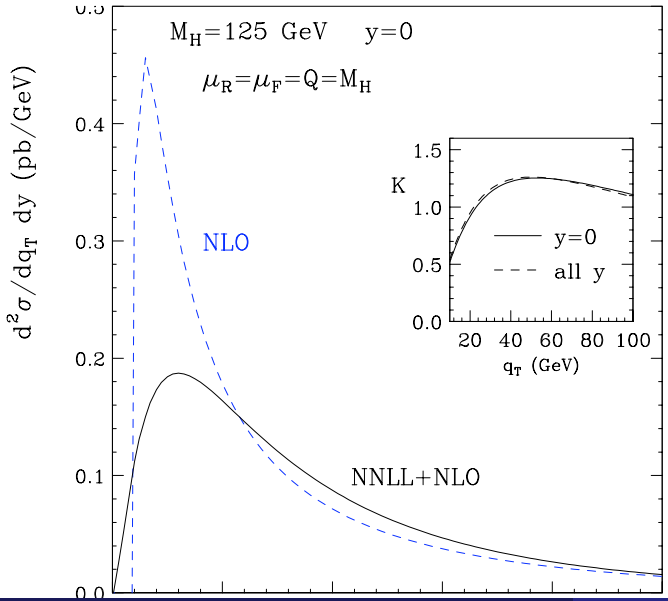

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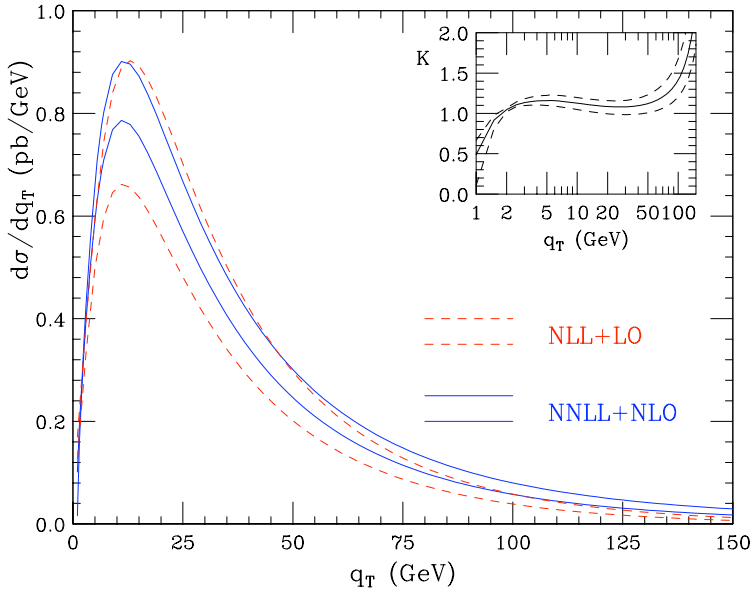

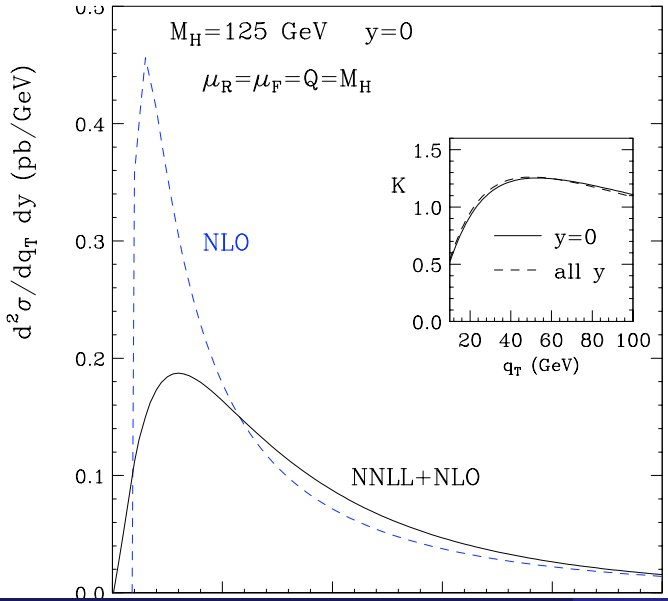

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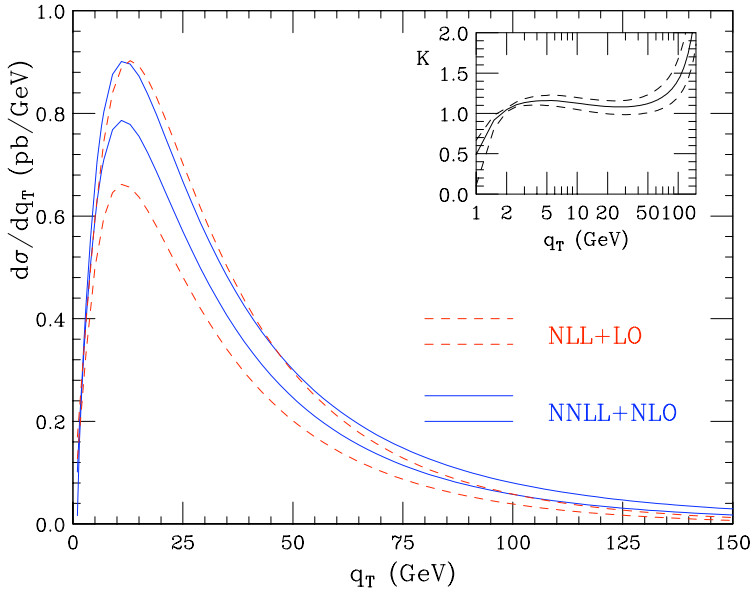

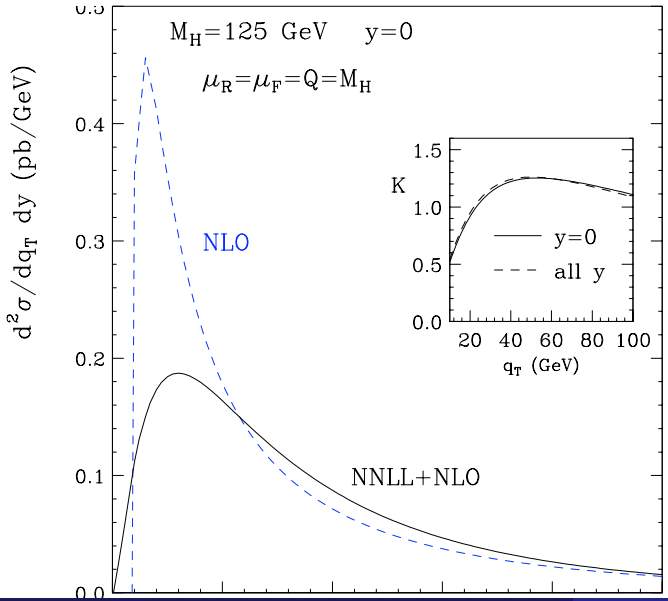

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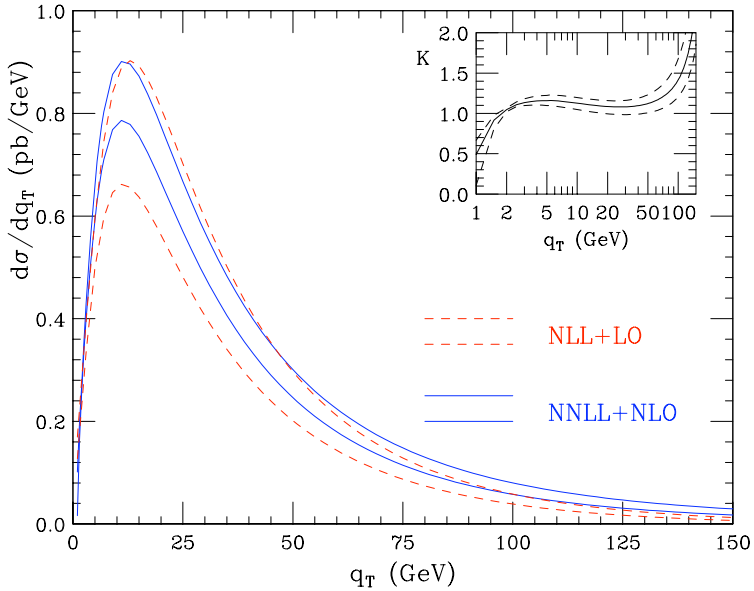

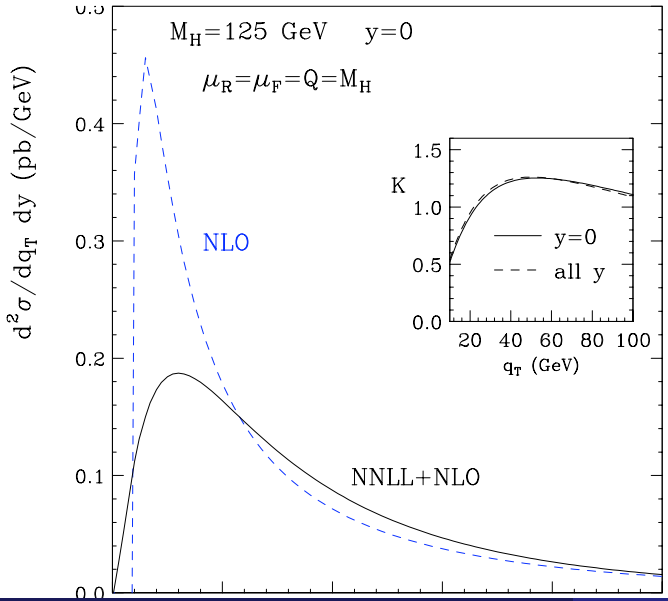

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Vector boson fusion 1

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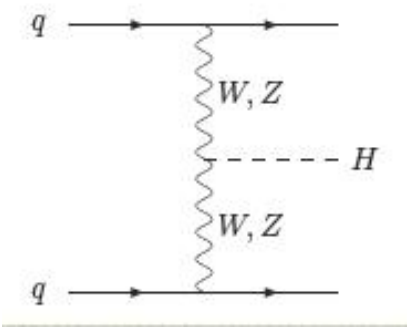
- Weak boson colourless

$\rightarrow$ two highly energetic outgoing jets (1 TeV)

$\rightarrow$ large rapidity interval between jets

$\rightarrow$ no hadronic activity in the rapidity interval between jets



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- Cross-section: 20% wrt to gluon fusion, comparable when $m_H \sim$600 GeV

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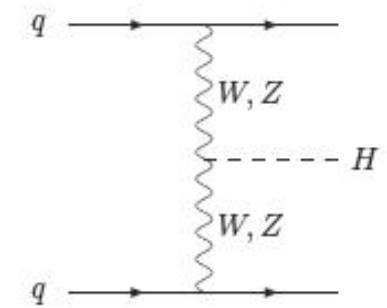

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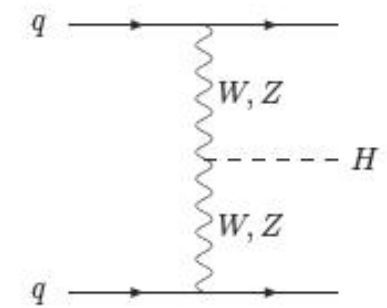

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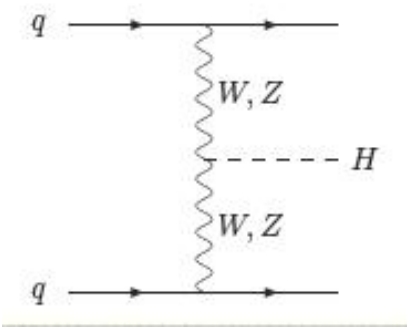

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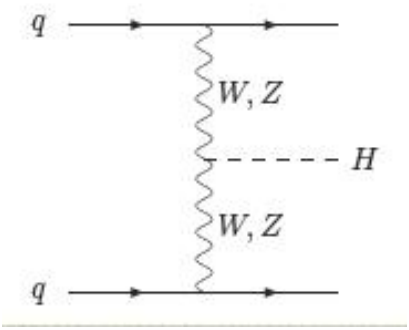

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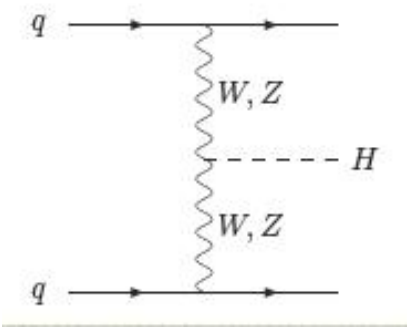

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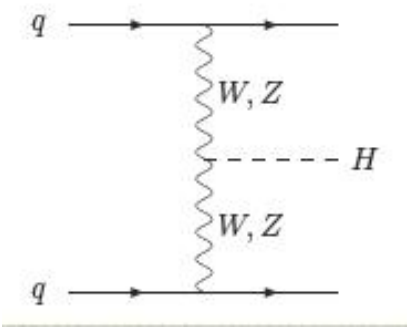

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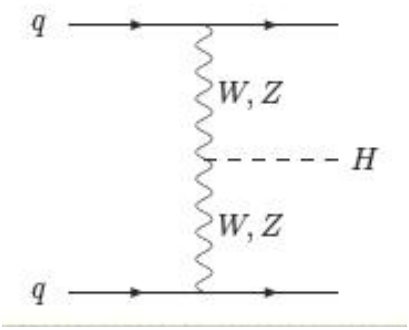

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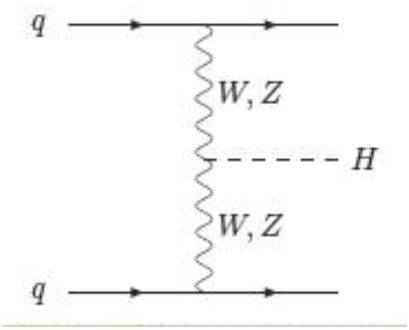

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  [Cahn,Dawson(1984)]
- NLO QCD:
  $\sim$ 5-10% increase
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  [Han,Willenbrock(1991)]
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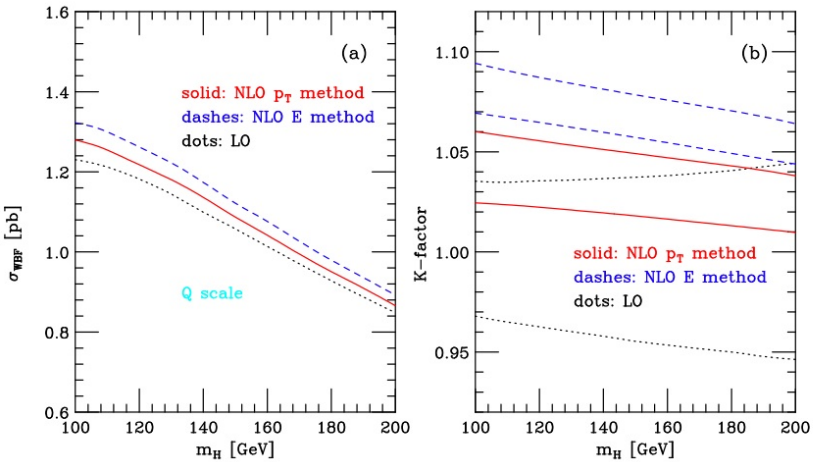

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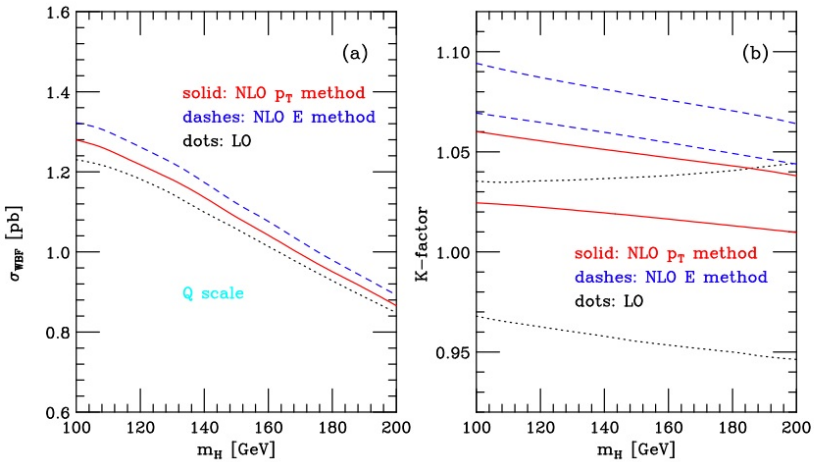

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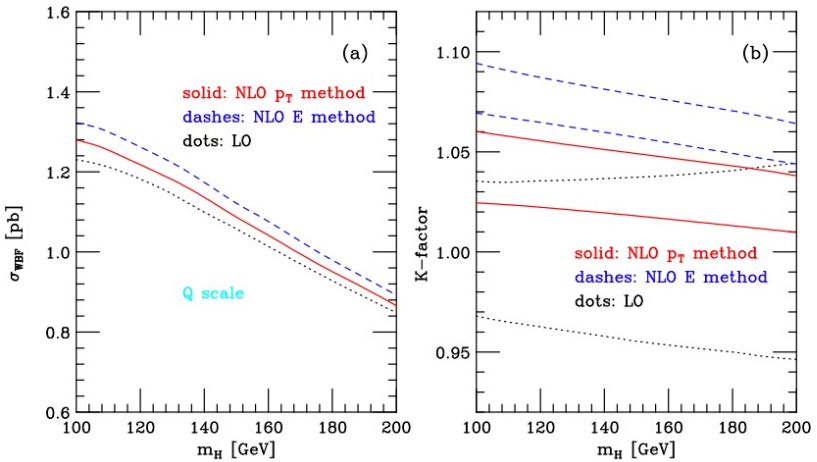

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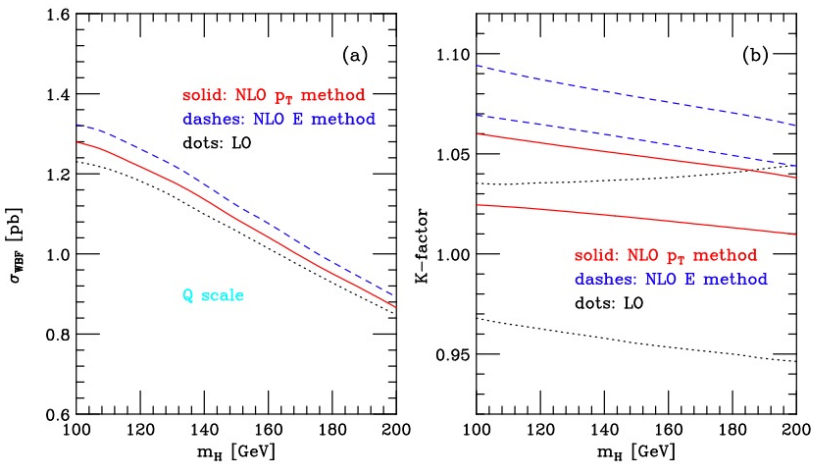

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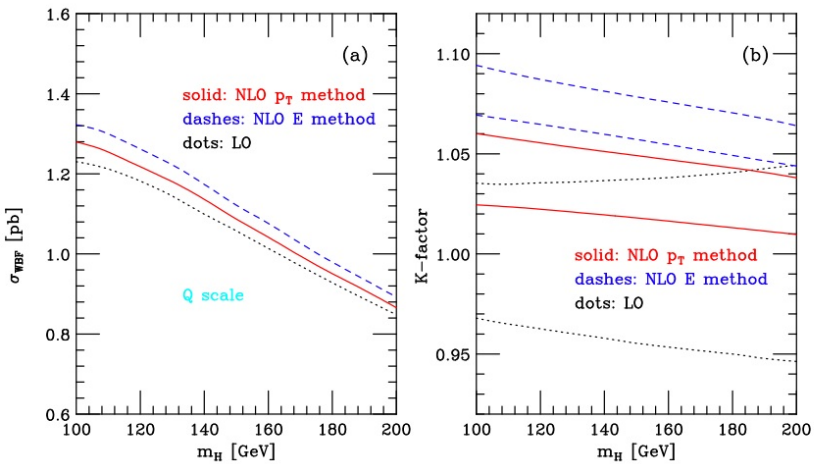

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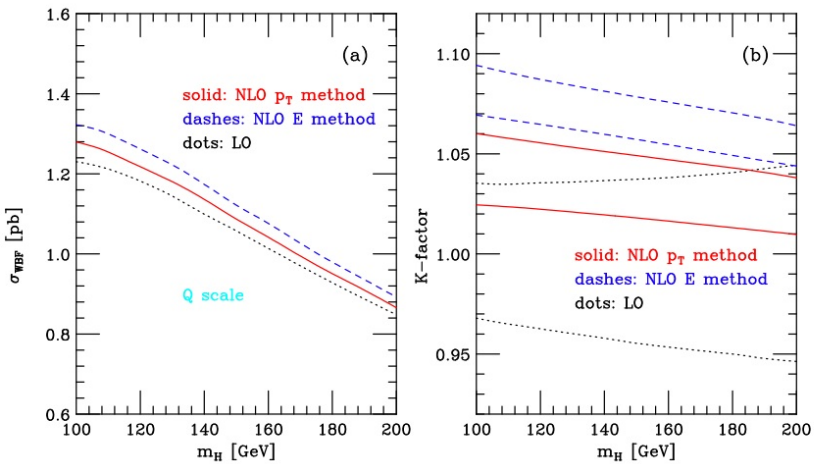

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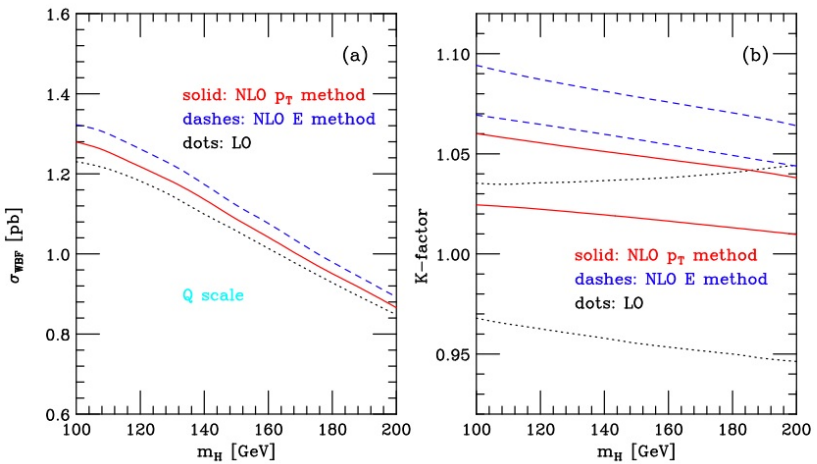
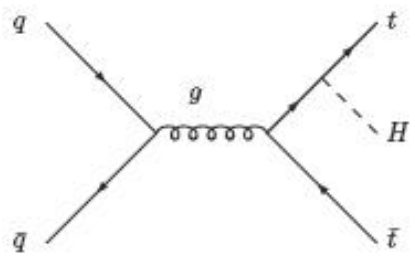
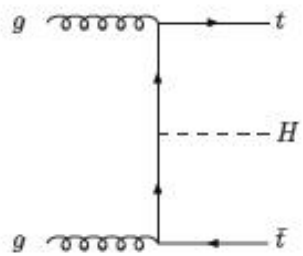
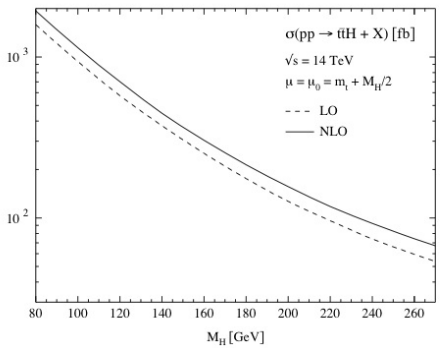


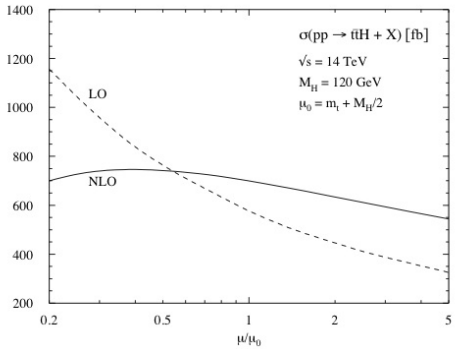
Associated production with top

- Important in the low-mass region: allow to search for $H \to bb$ decay
- Good b-tagging and high-luminosity required
- Useful channel to measure ttH Yukawa coupling
- LO: known since long time [Kunszt(1984)]
- NLO QCD (massive pentagons!): $\sim$20% increase $\sim$15% scale dependence [Beenakker,Dittmaier,Kraemer,Plumper,Spira,Zerwas(2001);Dawson,Orr,Reina,Wackeroth(2003)]









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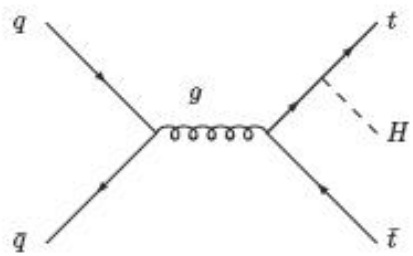

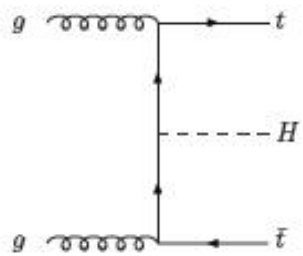

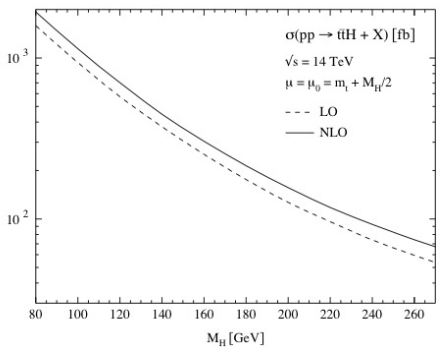

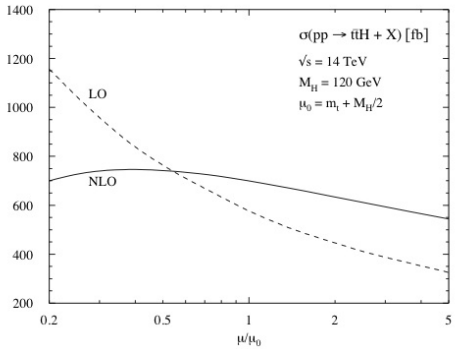

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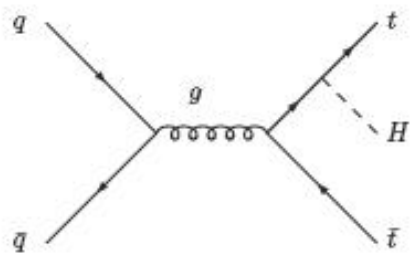

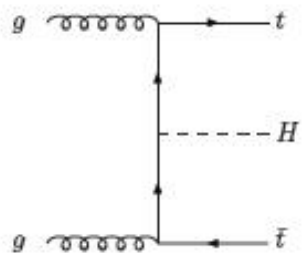

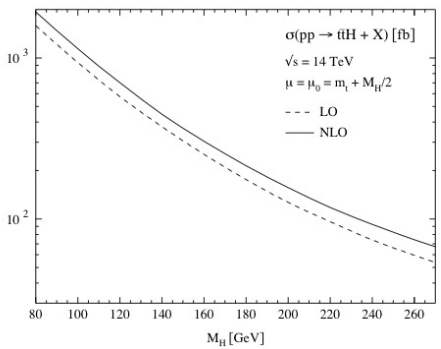

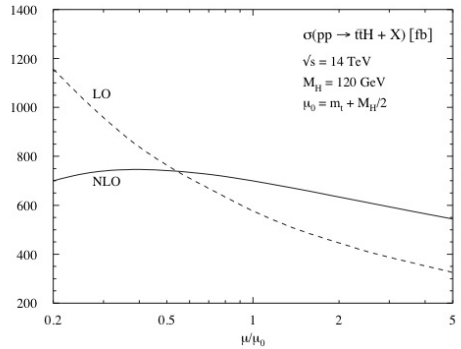

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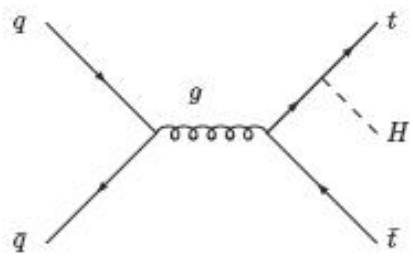

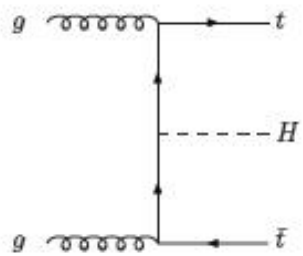

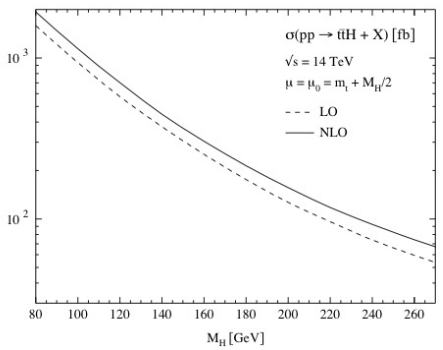

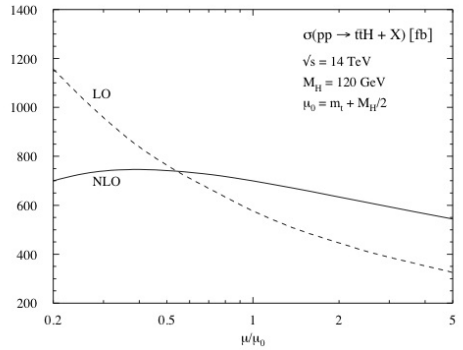

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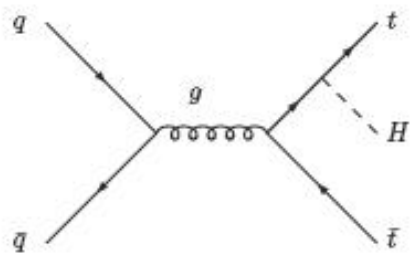

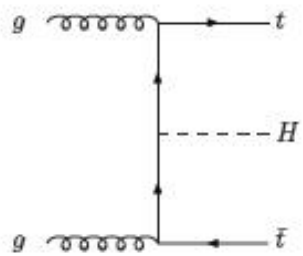

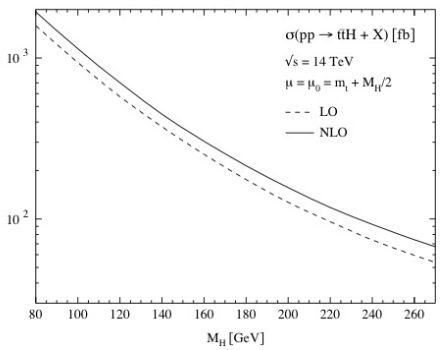

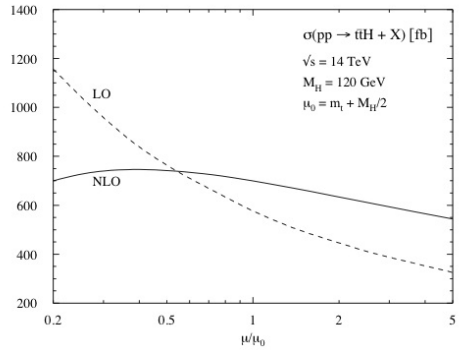

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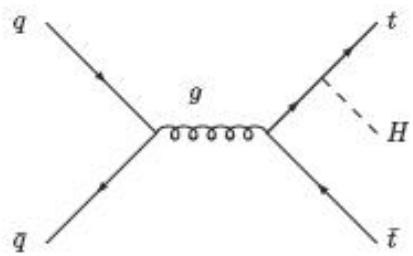

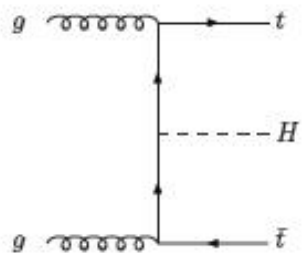

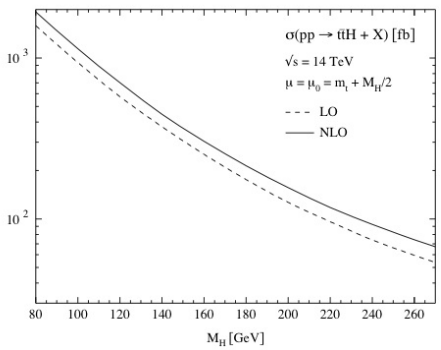

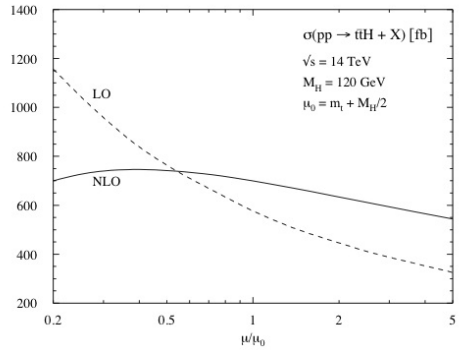

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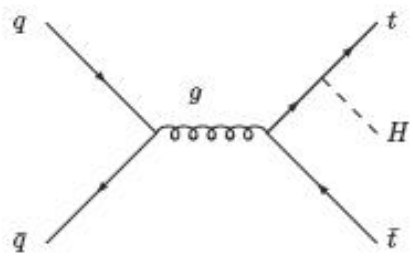

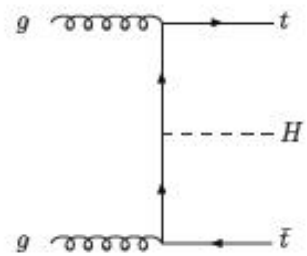

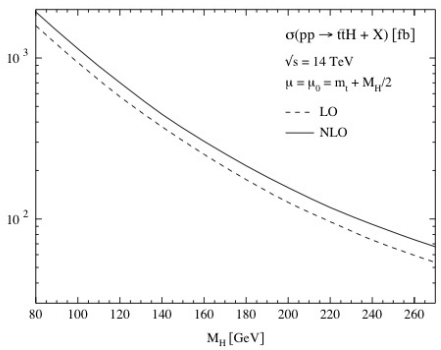

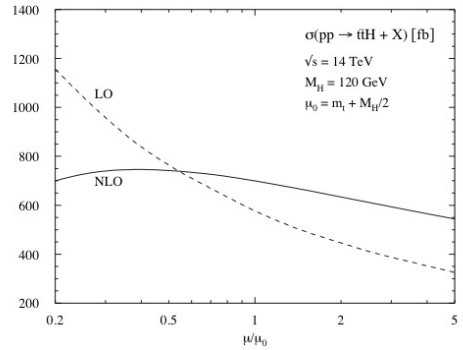

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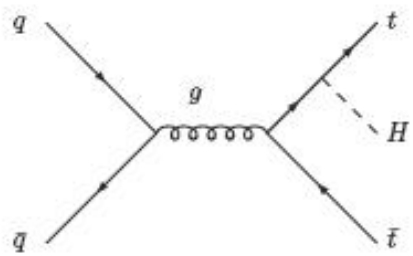

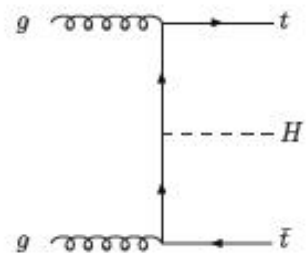

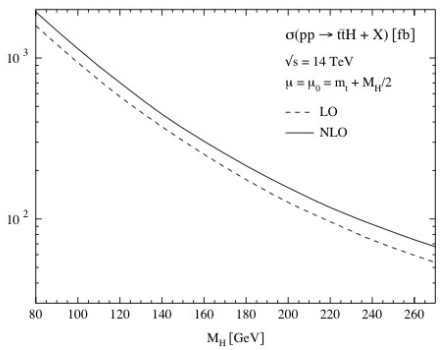

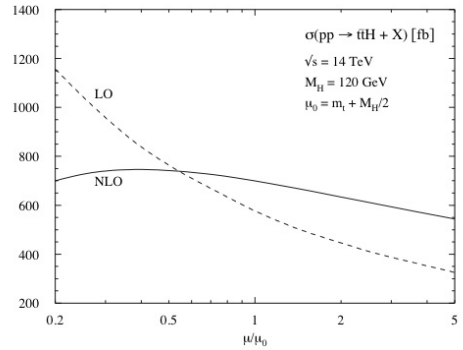

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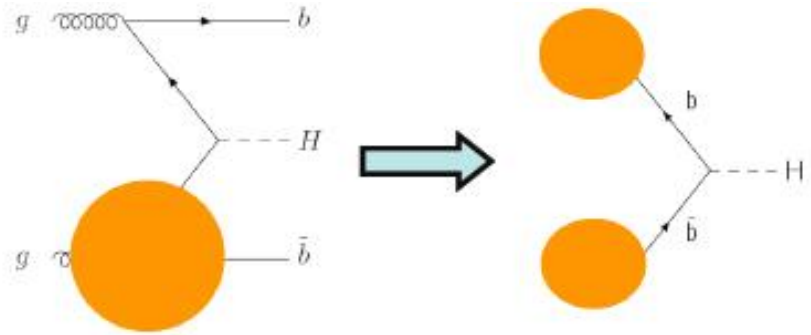

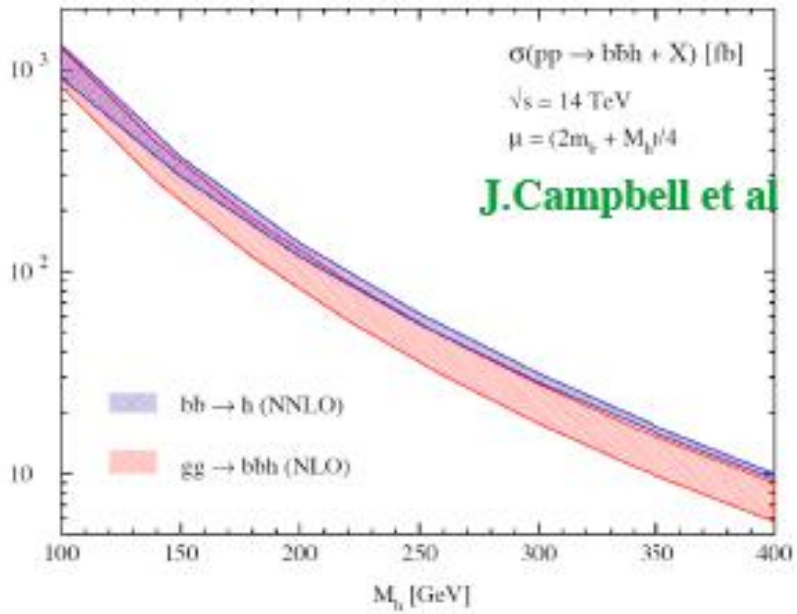

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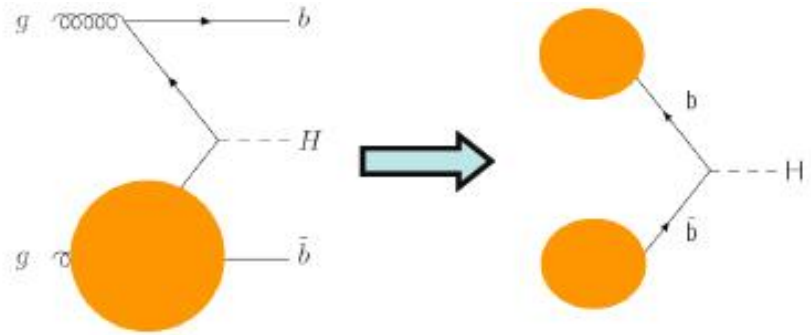

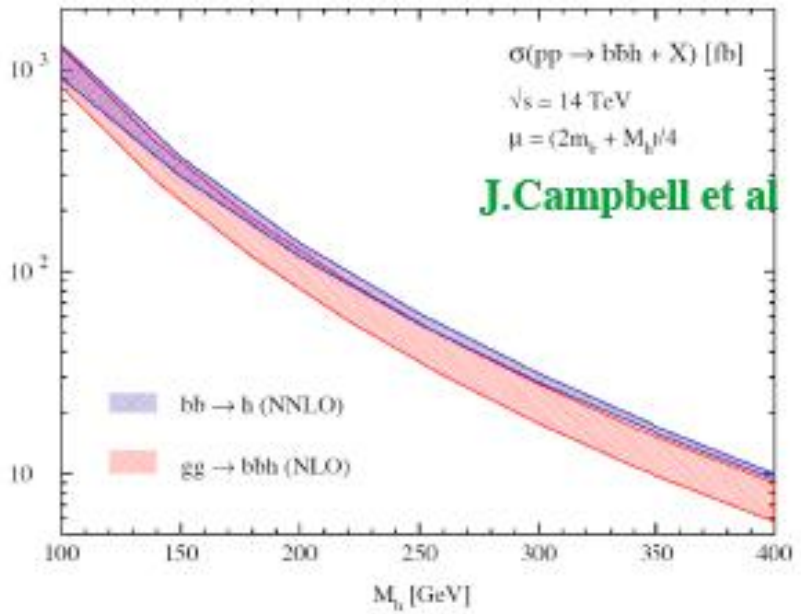

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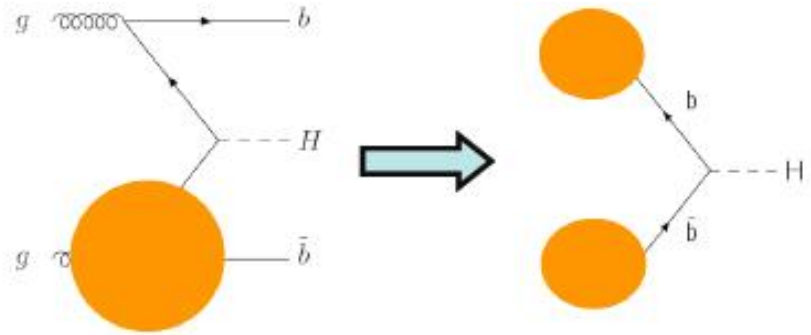

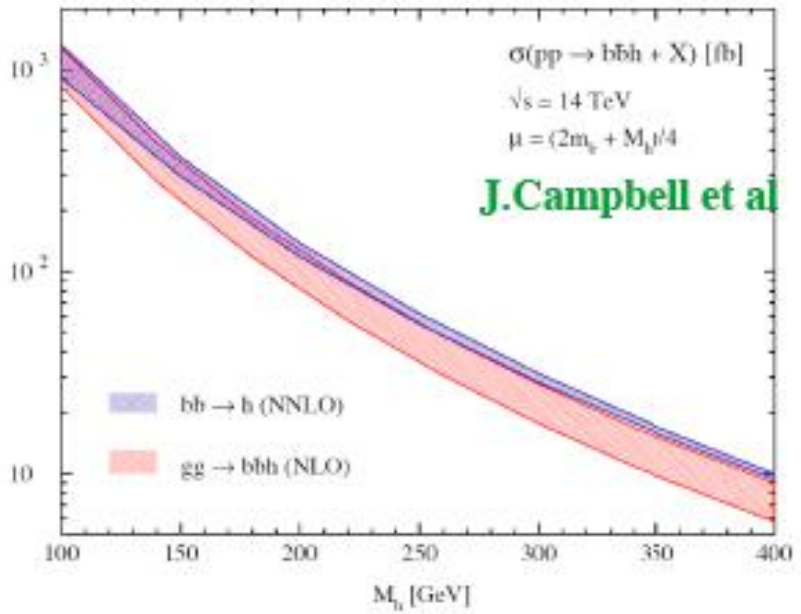

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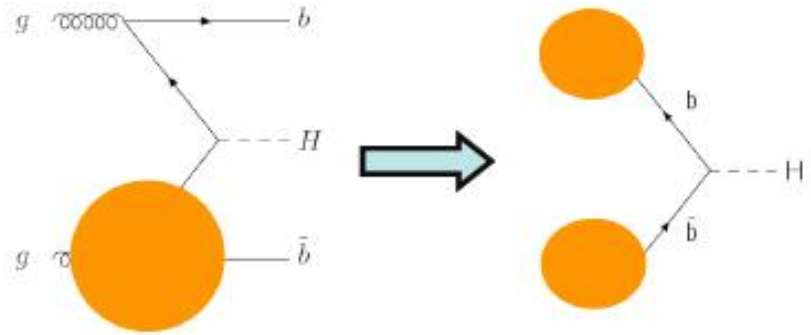

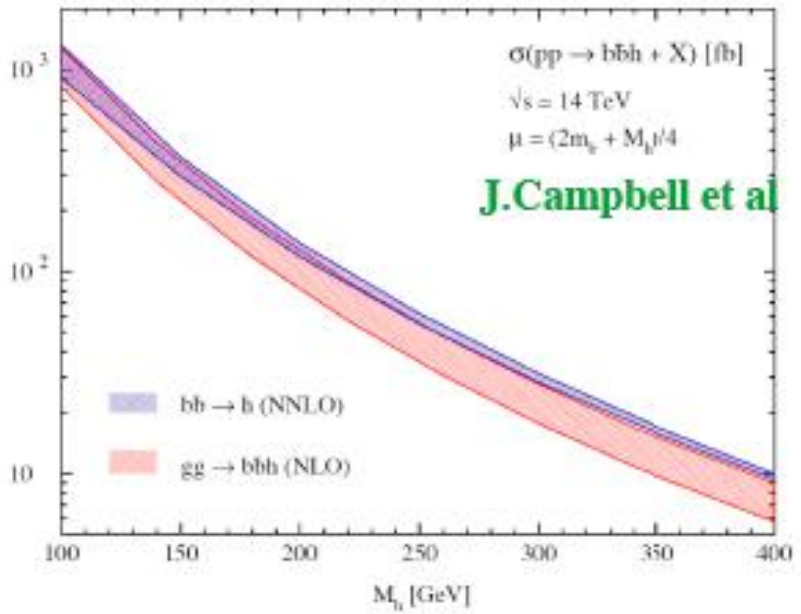

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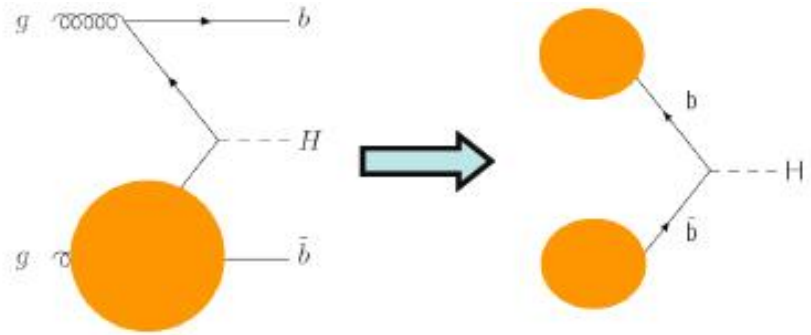

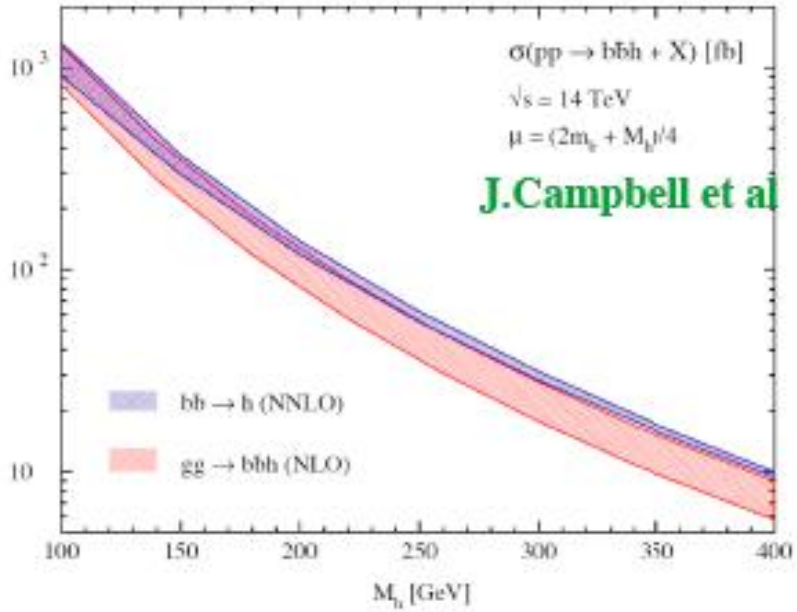

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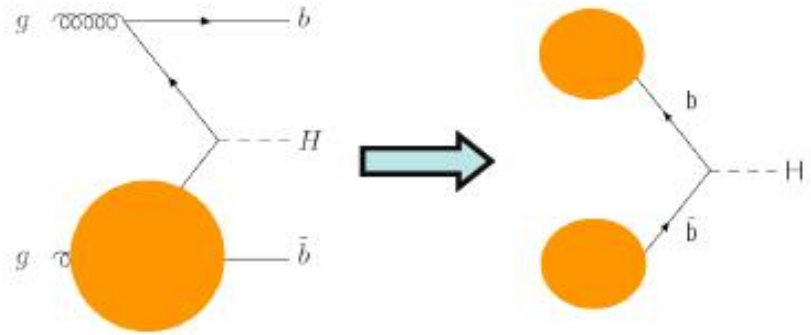

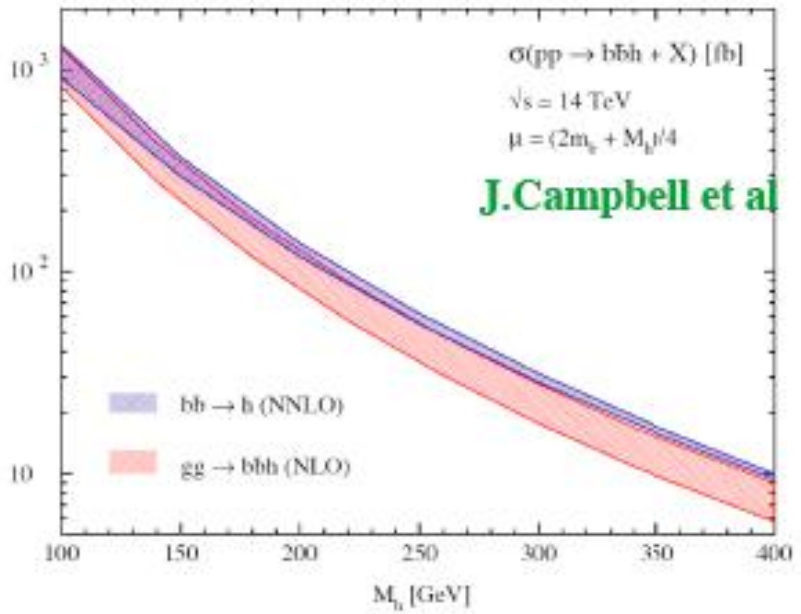

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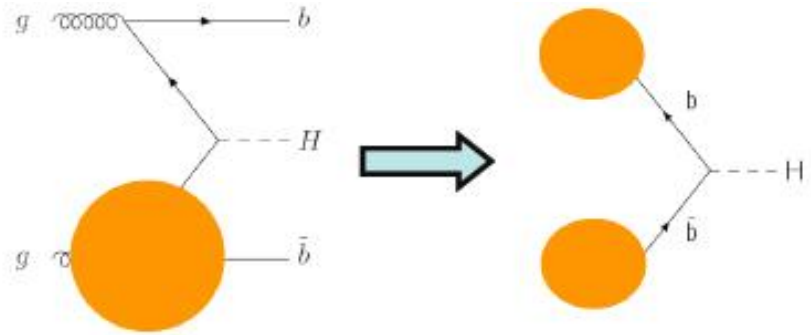

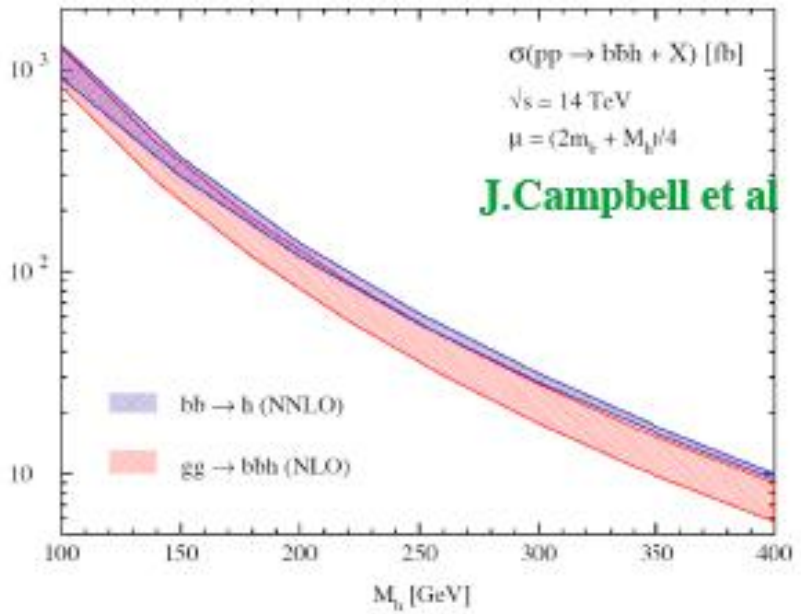

Associated production with bottom

- Small σ but enhanced at large $\tan\beta$ MSSM
- No b-tagging
- collinear $g \to bb$ splitting: $\alpha_S \log(M_H/m_b)$

$\to$ resum them through b pdfs

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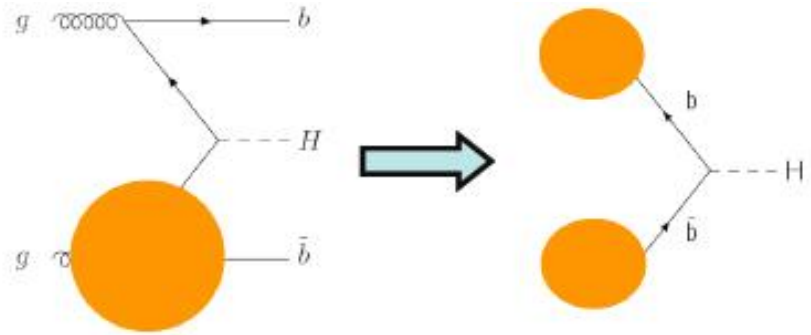

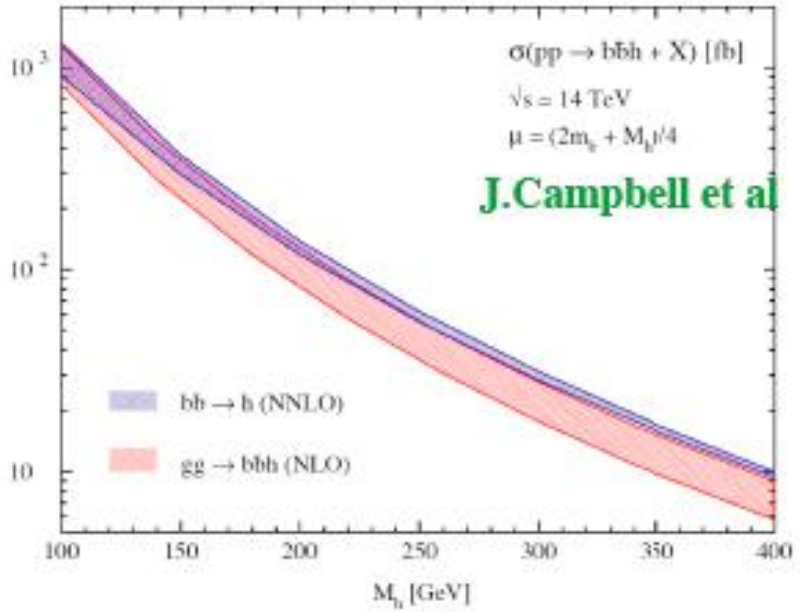

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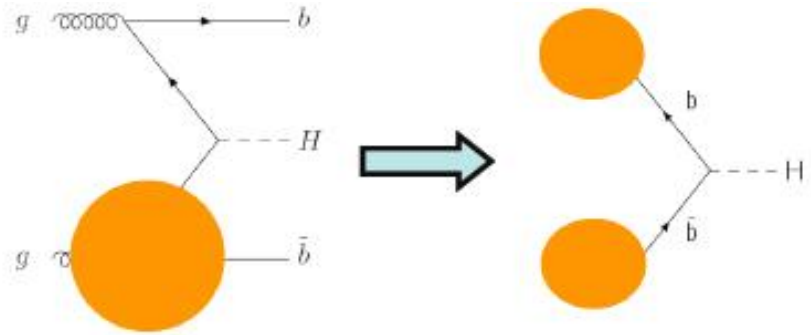

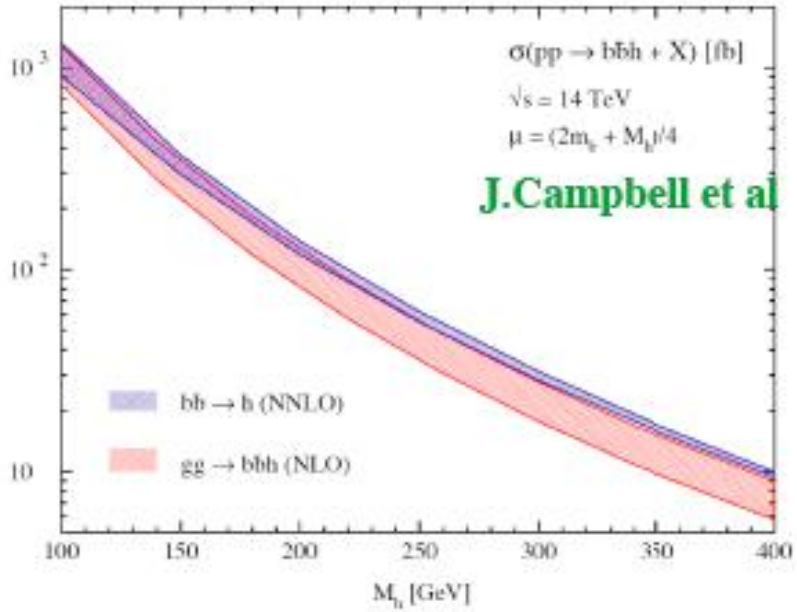

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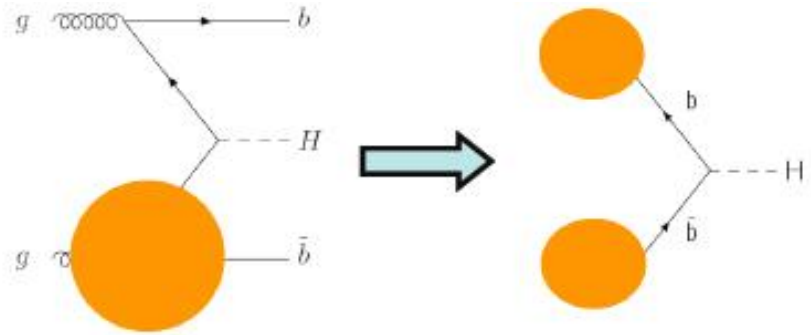

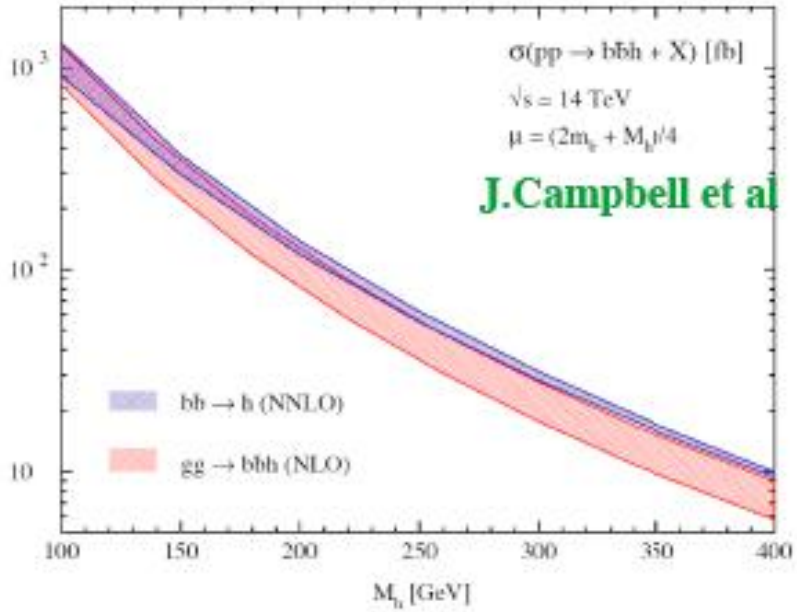

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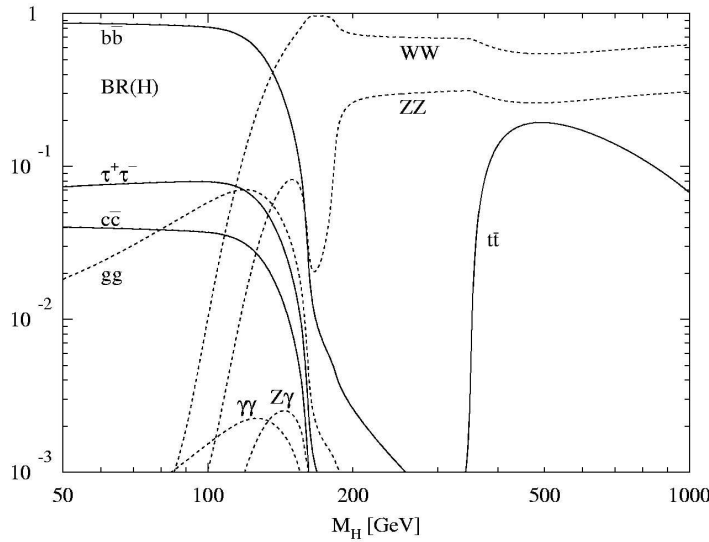

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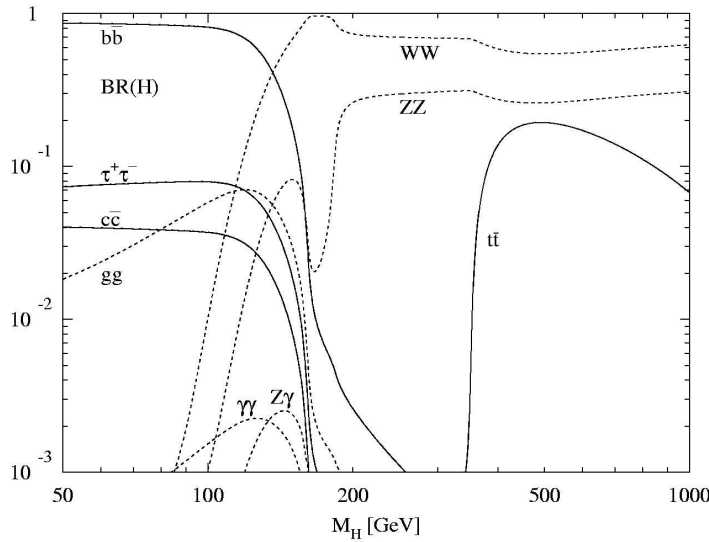

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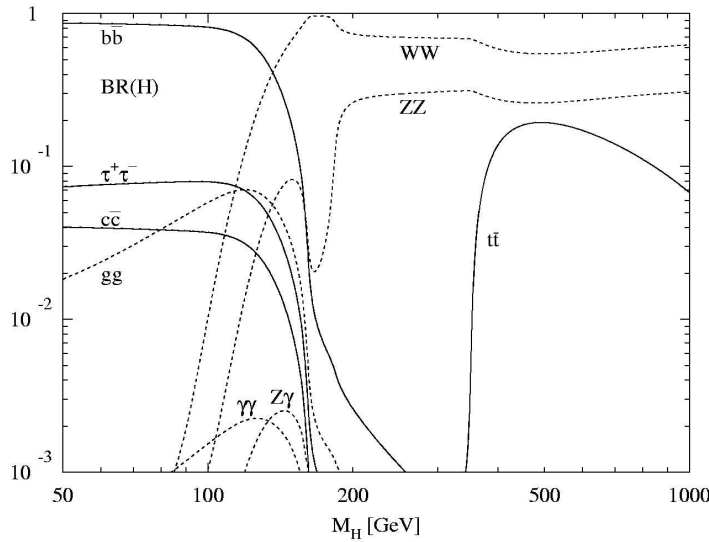

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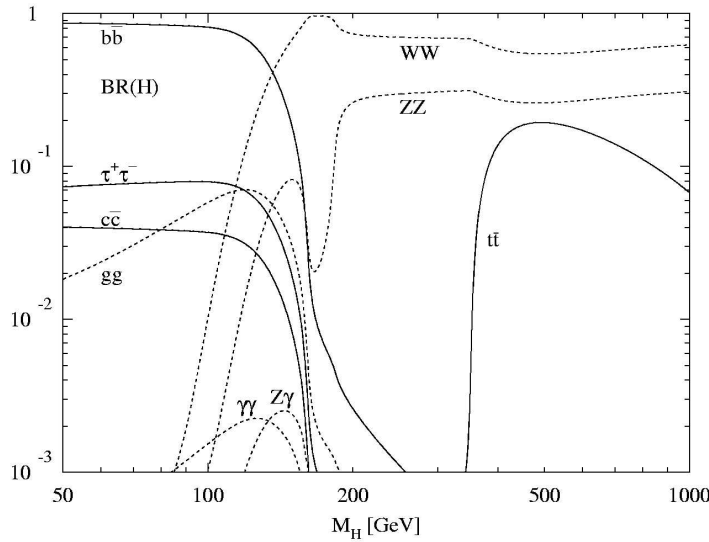

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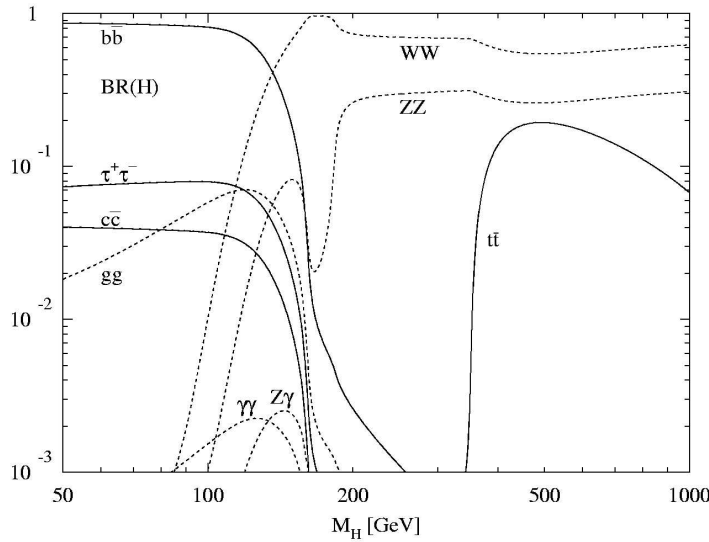

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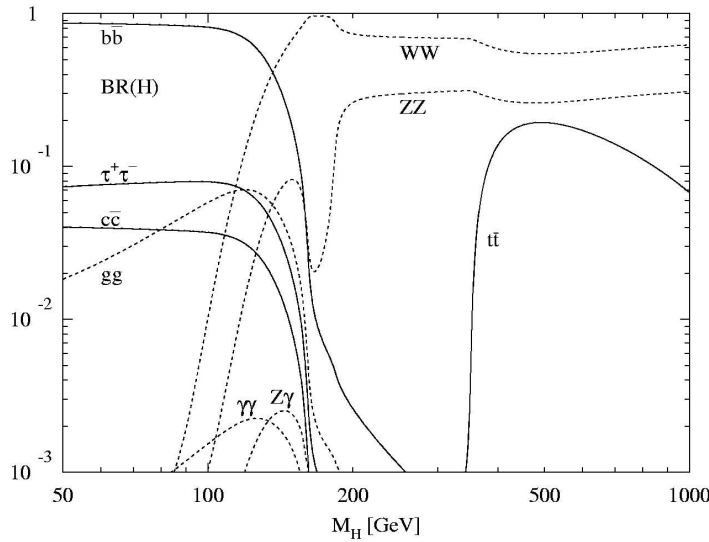

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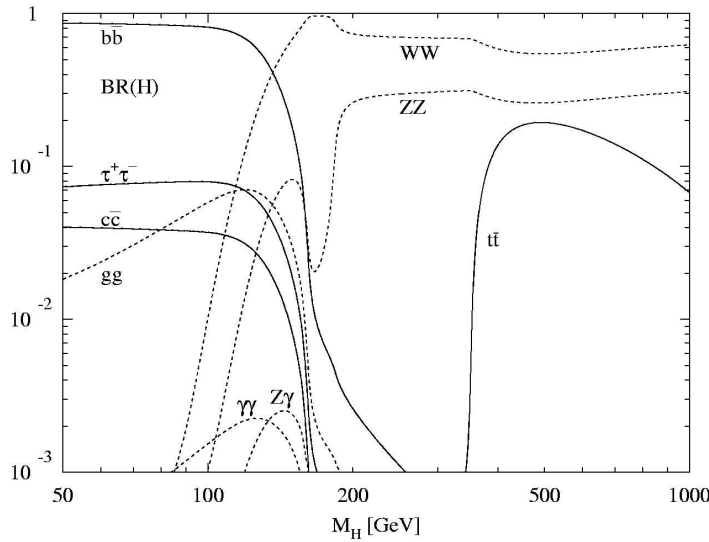

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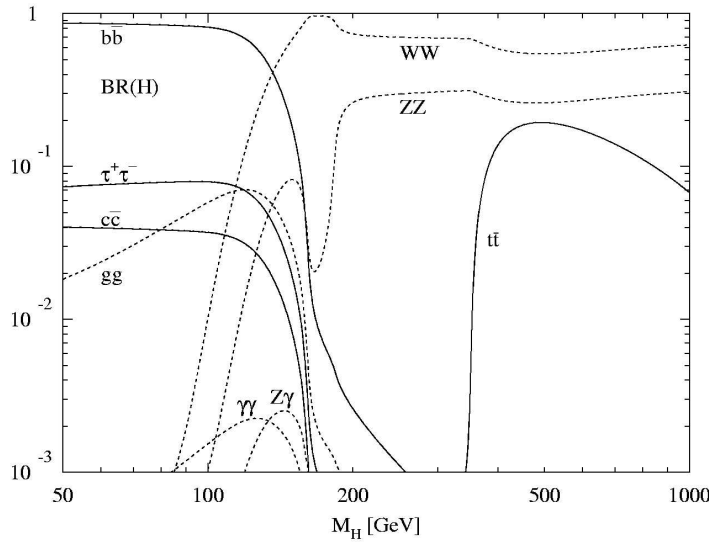

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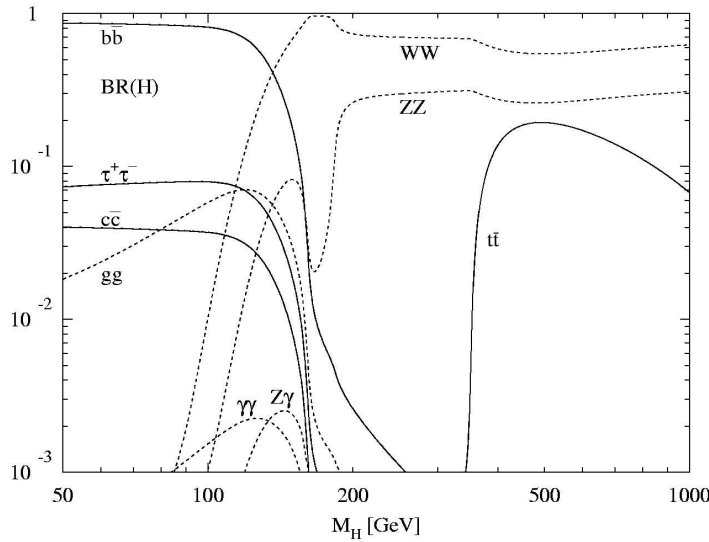

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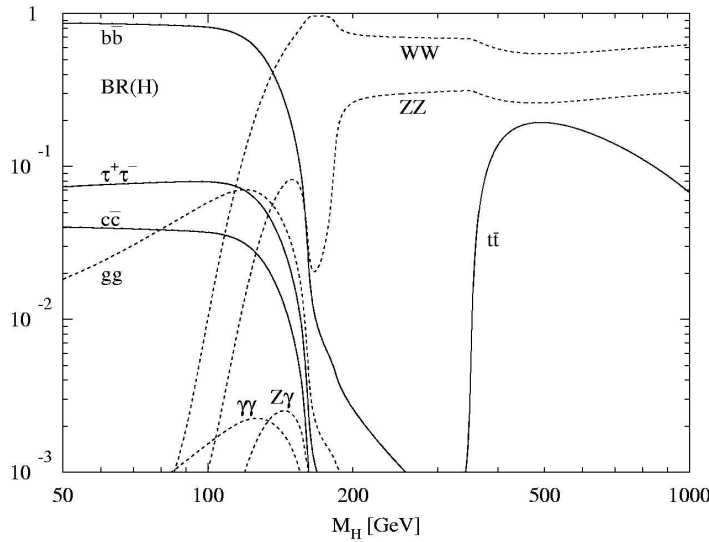

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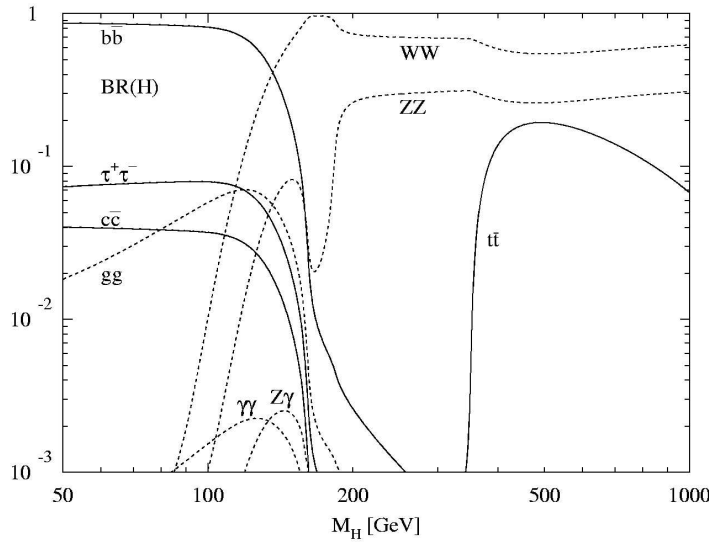

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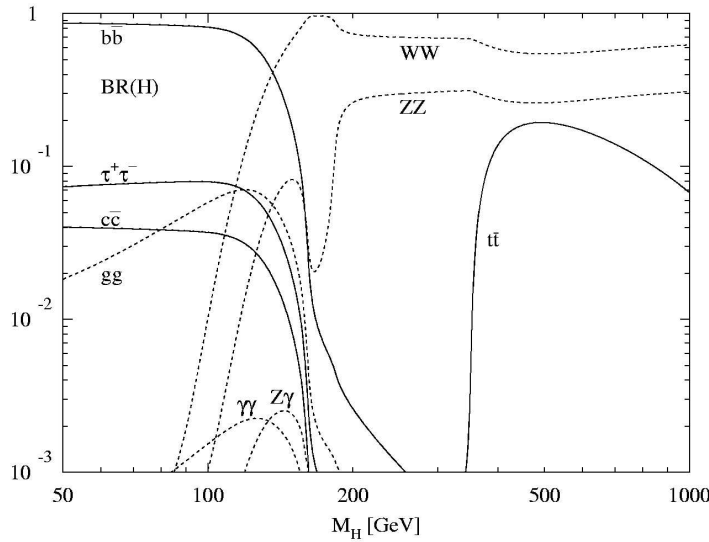

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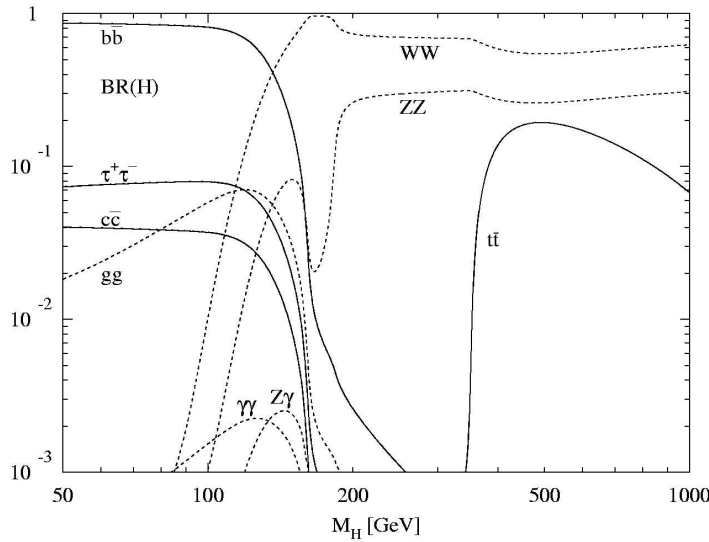

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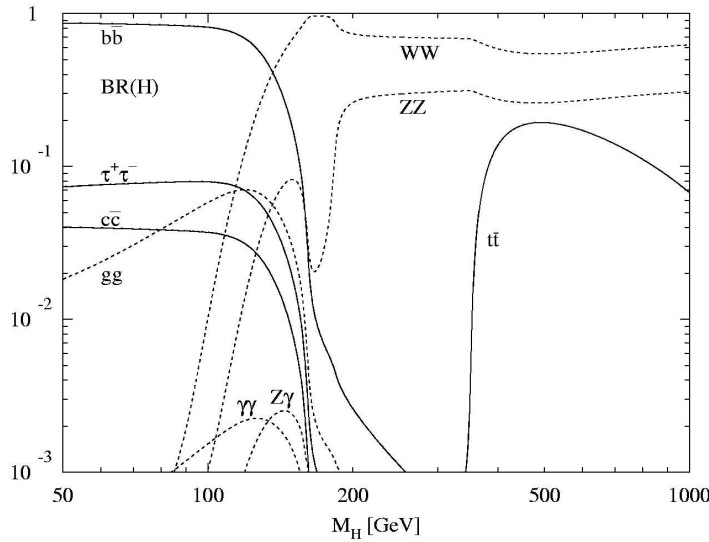

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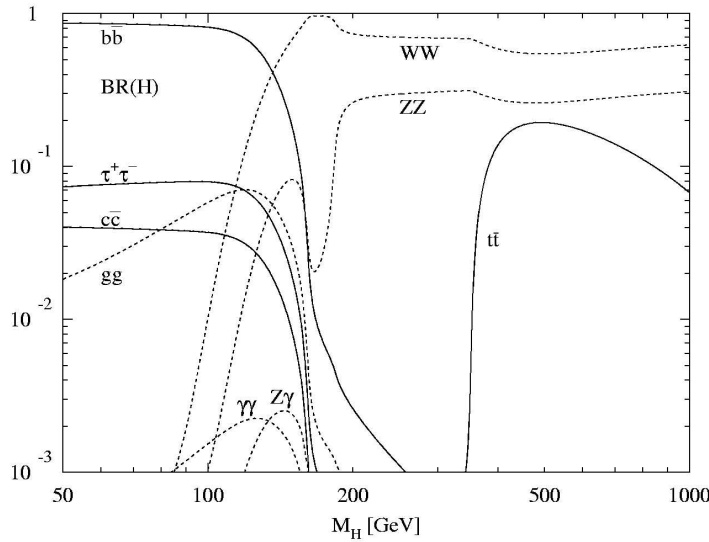

- $M_H < 140$ GeV
  - bb $\sim$ 82%
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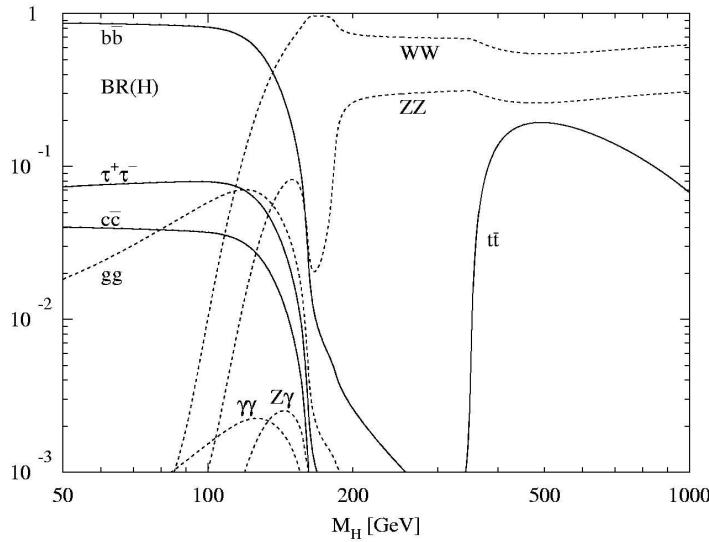

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