Higgs boson(s) at hadronic colliders : from the Standard Model to SUSY

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(based on: J.B. and A. Djouadi, JHEP 1010:064 (2010)
J.B. and A. Djouadi, arXiv:1012.0530 (submitted to JHEP)
J.B. and A. Djouadi, arXiv:1012.2748 (submitted to PRL)
J.B., A. Djouadi, S. Ferrag, R. Godbole, arXiv:1101.1832 (submitted to PRL))

Electroweak symmetry breaking: why do we need the Higgs?

- Weak bosons massive, but mass terms breaks explicitely gauge symmetry:

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  $\sigma_{\mathrm{WWscattering}} \propto s^2$ without a scalar field. Stabilized with a scalar field which looks like the Higgs field

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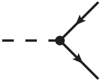
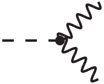
Simplest solution is a complex scalar field which sponteanously breaks the SM $SU(3) \times SU(2) \times U(1)$: the Brout-Englert-Higgs-Kibble field

Higgs couplings

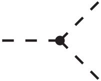
After EWSB: Higgs boson couples to fermions and gauge bosons:



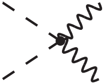
$$g_{Hff} = \frac{M_f}{v} \times (-\imath)$$



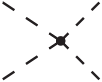
$$g_{HVV} = 2\frac{2M_V^2}{v} \times (\imath g_{\mu\nu})$$



$$g_{HHH} = \frac{3M_H^2}{v} \times (-\imath)$$



$$g_{HHVV} = \frac{2M_V^2}{v^2}$$



$$g_{HHHH} = \frac{3M_H^2}{v^2}$$

$Hff \propto m_f$: Higgs couples mostly to top and bottom quarks in fermion loops
ggH and $\gamma\gamma H$ couplings occur at one-loop level

Theoretical bounds on Higgs mass

- Unitarity and perturbativity constraint: if unitarity required above Fermi energy:

$$\frac{M_H^2}{8\pi v^2} \leq \frac{1}{2} \Rightarrow M_H \lesssim 870 \text{ GeV in } WW \text{ scattering}$$

  Other processes + loops: $M_H \lesssim 710$ GeV

  Similar bound required by perturbativity of λ coupling

- Triviality constraint: running λ coupling must remain finite $\Rightarrow$ define a range where SM is valid

  If new physics at the **TeV scale**, RGE impose $M_H \lesssim 700$ GeV

  If SM valid up to GUT scale, $M_H \lesssim 200$ GeV

- Stability constraint: Higgs potential bounded from below even with quantum corrections $\Rightarrow \lambda(Q) > 0$

  Impose $M_H \gtrsim 50$ GeV **if** new physics at **TeV scale**

  $M_H \gtrsim 130$ GeV if SM valid up to GUT scale

Theoretical bounds on Higgs mass

All theoretical constraints put SM Higgs mass in the range
50 GeV $\lesssim$ $\mathbf{M_H}$ $\lesssim$ 700 GeV
if new physics arises at $\sim$ **1 TeV**.

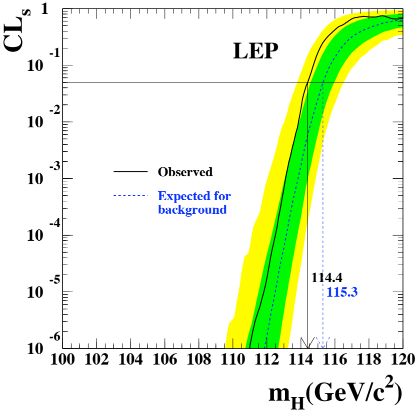
Range 130 GeV $\lesssim M_H \lesssim$ 180 GeV required
if SM valid up to the Planck scale.

Direct searches at LEP and Tevatron

Direct LEP2 searches ($\sqrt{s} = 209$ GeV) using $e^+e^- \to Z^* \to ZH$ production channel followed by $H \to b\bar{b}, \tau^+\tau^-$:

$M_H > 114.4$ GeV at 95% CL in SM

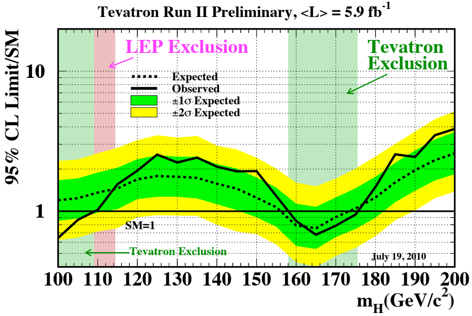
(LEPHWG, Phys. Lett. B 565, 61-75 (2003))



$CL_s = 0.05$ is the 95% CL lower bound of the signal+background over background hypothesis

Direct searches at LEP and Tevatron

Tevatron II: 2009 95% CL exclusion band updated in July 2010 to $158 - 175$ GeV Higgs mass range (arXiv:1007.4587v1 [hep-ex])



This bound is still debated in (J.B. and A. Djouadi, JHEP 1010:064 (2010))

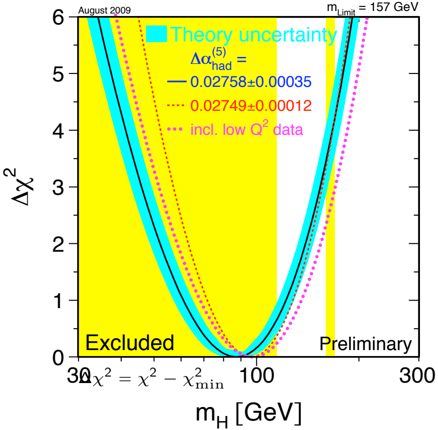
Precision measurements

Combining all precision data: M_Z, Γ_Z, M_W, Γ_W, $\sin\theta_W$, $\Delta\alpha_S(M_Z)$, $\sigma_{\nu-N(\mathrm{DIS})}$, etc...:

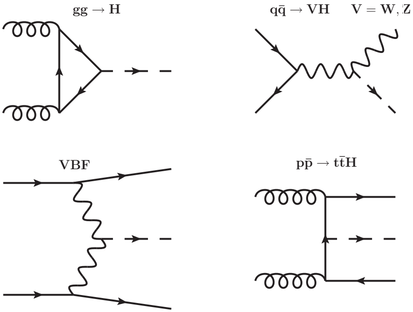
$$M_H = 87^{+35}_{-26}\ \text{GeV},\ M_H < 157\ \text{GeV}$$
(95 % CL best fit)

Including direct searches, $M_H^{\max} < 186$ GeV

(arXiv:0911.2604 [hep-ex] (2009))



Higgs cross sections at hadron colliders

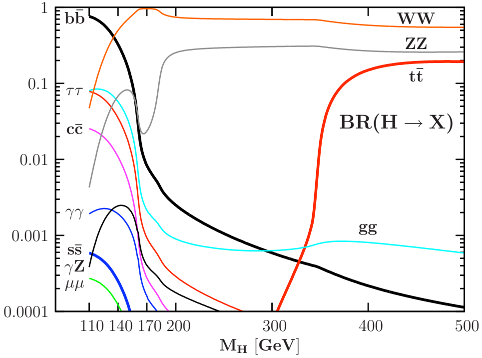


- gluon–gluon fusion and Higgs–strahlung known at NNLO in QCD
- $t\bar{t}H$ known at NLO only
- VBF pushed partly to NNLO in 2010
  (Bolzoni, Maltoni, Moch, Zaro; arXiv:1003.4451)

Higgs decay and its interesting channels

Main discovery channels at Tevatron:

1. $H \to b\bar{b}$: dominant decay in the low Higgs mass range, use with b–tagging
2. $H \to W^*W^*$: most interesting channel for high Higgs mass range with leptons decay from W^*s ; $b\bar{b}$ dominant but plagued with huge QCD backgrounds
3. $H \to \gamma\gamma$, $H \to \ell\ell$: BR too small & production cross sections too small to be useful at Tevatron (w.r.t. luminosity

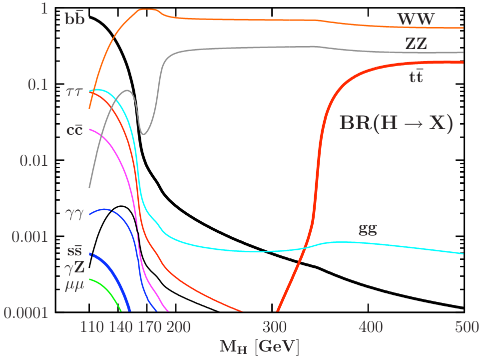


Higgs decay and its interesting channels

Main discovery channels at LHC:

Nearly all channels contribute on the entire Higgs mass range. Main channels:

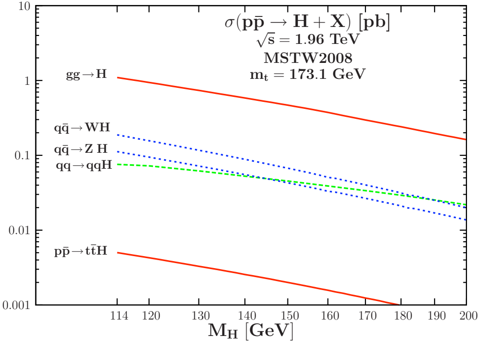
1. $H \to \gamma\gamma$: cleanest channel for low Higgs mass $\lesssim 135$ GeV with gluon–gluon fusion or VH production (and VBF with high luminosity)
2. $H \to ZZ$: second dominant channel for $M_H \gtrsim 180$ GeV; golden channel with its associated $H \to WW$ through gg fusion production; ZZ and WW backgrounds needed to be known quite precisely
3. $H \to \tau\tau$: promising for $M_H \sim 120 - 140$ GeV after VBF production



Higgs production at the Tevatron

$M_H \gtrsim 150$ GeV, $gg \to H$ channel
Exact at NLO QCD[a], $K_{\rm NLO} \sim 2$
Infinite top mass at NNLO QCD[b], $K_{\rm NNLO} \sim 3$
Exact NLO EW corrections[c],
Effective NNLO mixed QCD-EW[d]: $\simeq \pm$ a few %

$M_H \lesssim 150$ GeV, $p\bar{p} \to HV$ channel
Exact at NNLO QCD[e], $K_{\rm NNLO} \sim 1.5$
Exact NLO EW corrections[f] $\simeq -5\%$



[a] Dawson (EFT, 1991), Djouadi, Spira & Zerwas (EFT, 1991); Spira, Djouadi, Graudenz, Zerwas (1995)
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[c] Djouadi & Gambino (1994), Aglietti *et al.* (2004), Degrassi & Maltoni (2004), Actis *et al.* (2008)
[d] Anastasiou, Boughezal, Pietriello (2009)
[e] Hamberg, V. d. Neerven & Matsuura (1991), Brein, Djouadi & Harlander (2004)
[f] Ciccolini, Dittmaier, Krämer (2003)

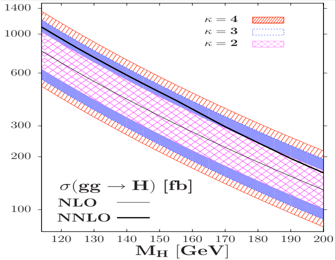
Scale uncertainty

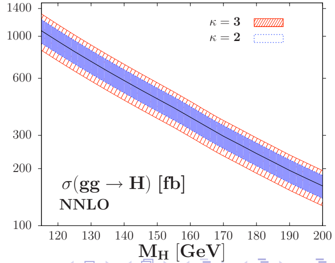
Higher orders (HO) guessed with μ_R, μ_F variation around central $\mu_0 = \frac{1}{2} m_H$

$$\frac{m_H}{\kappa} \leq \mu_R, \mu_F \leq \kappa m_H$$

Small HO $\Rightarrow \kappa = 2$ enough (ex. $q\bar{q} \to HV$)

Large HO in $gg \to H$ ($K_{HO} \simeq 3$)
guess scale domain from σ_{NLO}:
NLO band catches σ_{NNLO}
$\Rightarrow \kappa = 3$ needed (at least) according to our criterium





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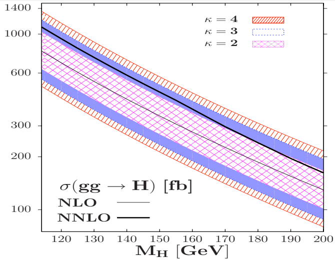
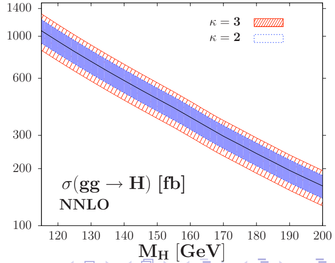
Small HO $\Rightarrow \kappa = 2$ enough (ex. $q\bar{q} \to HV$)

Large HO in $gg \to H$ ($K_{HO} \simeq 3$)
guess scale domain from $\sigma_{\rm NLO}$:
NLO band catches $\sigma_{\rm NNLO}$
$\Rightarrow \kappa = 3$ needed (at least) according to our criterium
NNLO $gg \to H$: $\simeq$ **+15%, −20% scale variation**

(good agreement with CDF/D0 jet analysis)





PDFs+α_s uncertainties and EFT

1. PDF+$\boldsymbol{\Delta}^{\rm exp+th}\boldsymbol{\alpha_s}$:

   PDFs only: $\simeq \pm 8\%$ with MSTW set, **25% discrepency with other sets (ABKM)**

   Use MSTW PDF+$\Delta^{\rm exp}\alpha_s$ correlations set$\Rightarrow$ 14% at 90%CL, still discrepency with ABKM

   Include $\Delta^{\rm th}\alpha_s^{\rm NNLO} = 0.002$ with MSTW fixed-α_s central sets, reconcile both sets

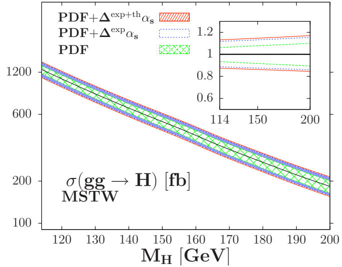
   $\alpha_s^{\rm ABKM} = 0.1147 \pm 0.0012({\rm exp}) \pm 0.002$ (**th**) consistent with N^{3}LO analysis (hep-ph/0607200)

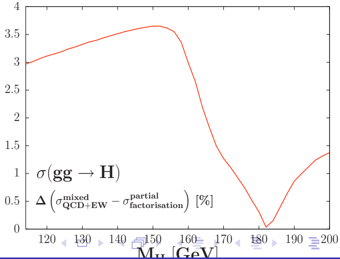
   $\sigma^{\rm NNLO}_{gg\to H}$: $\simeq$ **13 – 15% error from PDFs**

2. EFT error at NNLO: few **(non-negligible) %**

   Missing b–loop at NNLO and ($m_b^{\rm OS, \overline{MS}}$)

   Error on mixed QCD–EW corrections



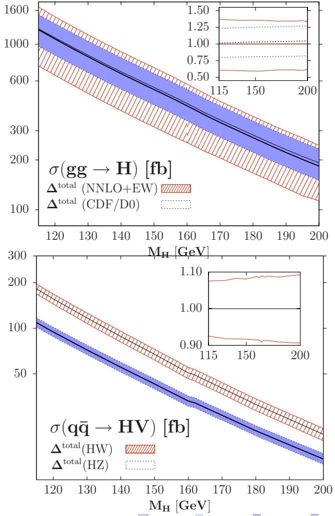


Putting together all the errors

Combining the errors: quadature or linear?

Quadratic sum assumes no corelation between the different sources of errors: too optimistic. Linear addition: too consertative

Reasonable way: add in quadature PDF+$\Delta^{\text{exp+th}}\alpha_s$ on $^{\min}_{\max}\sigma(\mu)$ and eventually linearly the small EFT errors



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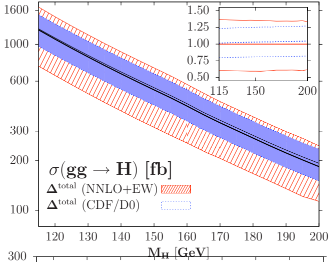
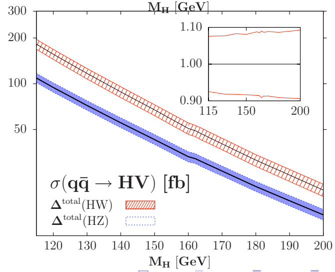
$gg \to H$: $\sim \pm 38\% \gg \sim 20\%$ CDF/D0

$p\bar{p} \to HV$: $\sim \pm 10\% > \sim 5\%$ CDF/D0

$p\bar{p} \to HV$ much more under control

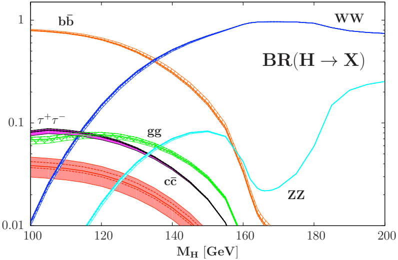




A small interlude on Higgs BR uncertainties

Higgs decay branching ratios: also affected by various uncertainties: α_s experimental uncertainty, $\overline{m}_b$ and $\overline{m}_c$ errors

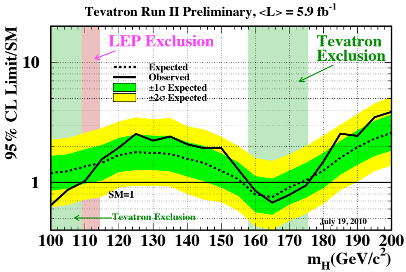
Experimental errors $\Rightarrow$ added in quadrature to obtain the overall uncertainty



Have to be taken into account when dealing with Higgs mass 95% CL exclusion limits

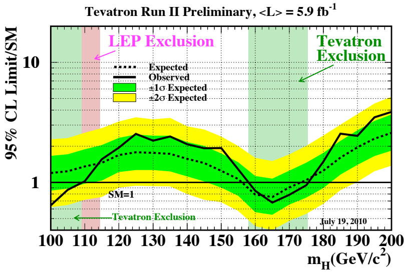
CDF+D0 exclusion bands?

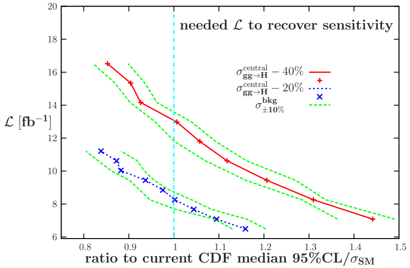
CDF& D0: excluded $M_H \in [158 - 175]$ GeV (arXiv:1007.4587 [hep-ex])



CDF+D0 exclusion bands?

CDF& D0: excluded $M_H \in [158 - 175]$ GeV (arXiv:1007.4587 [hep-ex])
But with our combinaison of uncertainties:



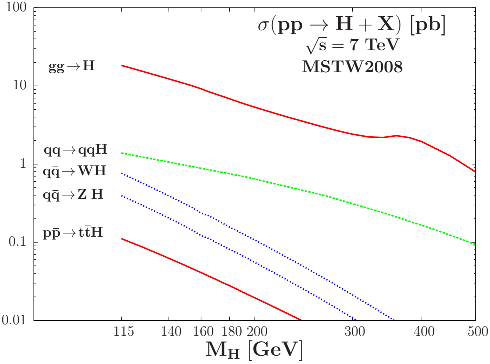


Luminosity required to recover the exclusion band is 2× the current used: **This 95% CL exclusion should therefore be reconsidered**

Gluon–gluon fusion Higgs production at the lHC

$gg \to H$ at the lHC (LHC with 7 TeV and 1 fb^{-1})

Start with HIGLU (M. Spira):
Exact at NLO QCD[a], $K_{\rm NLO} \sim 1.9$
And include relevant HO corrections:
EFT at NNLO QCD[b], $K_{\rm NNLO} \sim 2.5$
(NNLL: $\approx +10\%$ not included)[c]
Exact NLO EW corrections[d]
+EFT NNLO mixed QCD-EW[e]
$\simeq$ a few % for both corrections.
Tevatron : $K_{\rm NLO} \sim 2$, $K_{\rm NNLO} \sim 3$



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Scale variation and PDFs+α_s uncertainties

Following the outlines of section 2

Scale variation: $\kappa = 2$ enough at lHC

$M_H/\kappa \leq \mu_R, \mu_F \leq \kappa M_H$

$\sigma^{\rm NNLO}_{gg\to H}$: $\simeq \pm 10\%$ **scale variation**

PDF+$\boldsymbol{\Delta}^{\rm exp+th}\alpha_s$:

use MSTW PDF+$\Delta^{\rm exp}\alpha_s$ correlations set

$\Delta^{\rm th}\alpha_s = 0.002$ with MSTW fixed-α_s central sets

$\sigma^{\rm NNLO}_{gg\to H}$: $\simeq \pm 9\%$ **error from PDFs**

Error from use of EFT at NNLO: $\simeq 5\%$

Missing b–loop at NNLO and ($m_b^{\rm OS, \overline{MS}}$)

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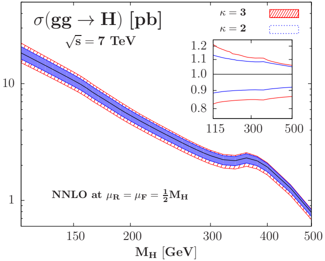

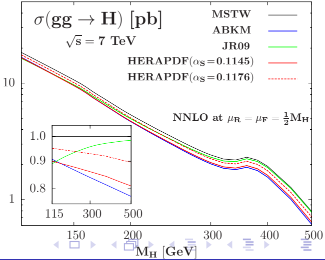

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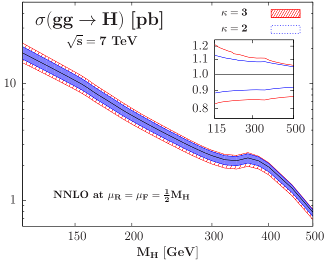
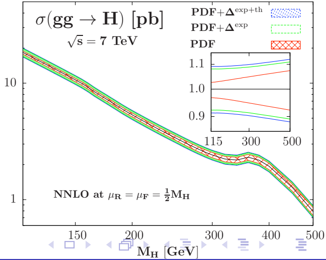


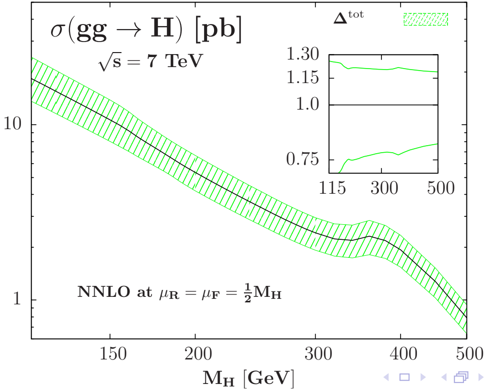


Final result with all errors combined

Combination: same exercice as at Tevatron

Final error in gg → H: $\sim \pm 25\%$

much more under control than at Tevatron ($\sim \pm 38\%$ error).



Why a new (super)symmetry?

- Higgs mass receives quadratically divergent quantum corrections in the SM $\delta M_H \sim \frac{m_t^2 \Lambda^2}{8\pi}$:
  how to stabilize the Higgs mass without (too much) fine tuning? Could be achieved with a new symmetry...

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- Need to provide a **dark matter** candidate: a new massive neutral stable particle?
- SUSY: a symmetry between bosons and fermions. Add new fermionic operators Q_a following the (super)–algebra

$$[P_\mu, Q_a] = 0, \quad [Q_a, Q_b] = 0, \quad \{Q_a, Q_b\} = 2\gamma^\mu_{ab} P_\mu$$

Bosons/fermions grouped in (super)multiplet, lagrangian SUSY-invariant

Anomalies, broken SUSY and R–parity

SUSY not exact $\Rightarrow$ SUSY is broken.

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Then introduce new particles (component of supermultiplets) with higher masses than the EW scale. Anomalies cancellation between the supermultiplets requires 2 Higgs doublets:

Welcome to the h, H CP-even scalar Higgs, the A CP-odd scalar Higgs and the $H^{\pm}$ charged Higgs!
2 vev v_1, v_2, new parameter $\tan\beta = \frac{v_1}{v_2}$

For the following $\phi = A, H, h$

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Welcome to the h, H CP-even scalar Higgs, the A CP-odd scalar Higgs and the $H^{\pm}$ charged Higgs!
2 vev v_1, v_2, new parameter $\tan\beta = \frac{v_1}{v_2}$

For the following $\phi = A,\ H,\ h$

R–parity: assign (-1) for new super–particles (sparticles), (+1) for standard particles; cross sections and decay multiplicatively invariant under R–parity

Anomalies, broken SUSY and R–parity

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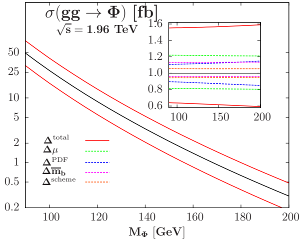
The lightest sparticle χ_0 stable through R–parity: (one of) the candidate(s) for dark matter!

MSSM $gg \to \phi$ production

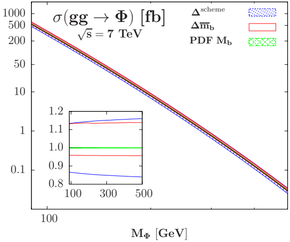
Repeat the same exercice as in section 2.

- Focuse on the *b*–loop (dominant at relevant $\tan\beta$)
- Calculation done at NLO only
- *b*–mass uncertainties become important

Tevatron: $\sim +58\%, -40\%$.



lHC: $\sim +53\%, -38\%$



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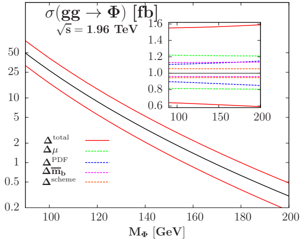

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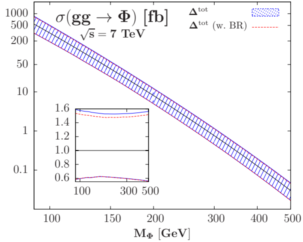

MSSM $b\bar{b} \to \phi$ production

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b–fusion comes into the game, process known at NNLO

Repeat the same guideline as in section 2, with $\kappa = 3$ and $\mu_0 = \frac{1}{4} M_H$

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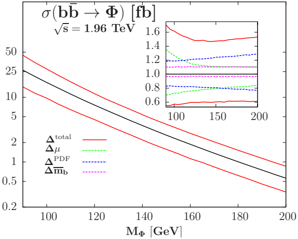

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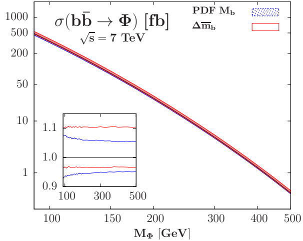

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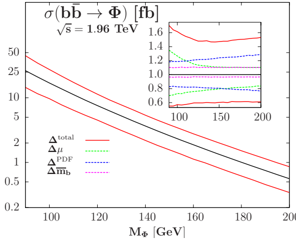

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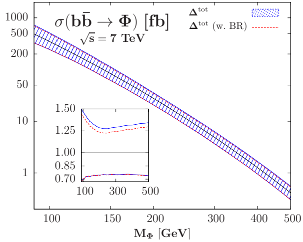


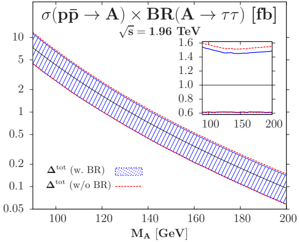
Combinaison of the two channels and with Higgs decay

A (not so easy) example of combinaison: adding the decay $\phi \to \tau^+\tau^-$ and combining the two production channels together.

Addition of the production channel weighted according to relative importance of each channel

m_b–uncertainties between production and decay anti-correlated: nearly vanish during the combinaison

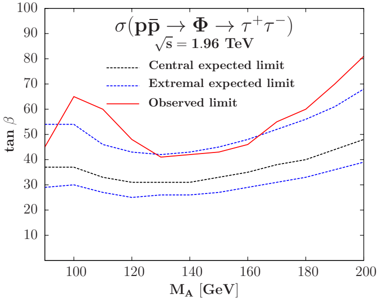
Tevatron: $\sim +50\%, -39\%$



Limits on the MSSM parameter space

$p\bar{p} \to \Phi \to \tau\tau$ gives limits on the $\tan\beta - M_A$ parameter space

Theoretical uncertainties extremely important:



With theoretical uncertainties, only $\tan\beta > 45$ **excluded**

Summary and conclusion

Higgs production in the (MS)SM:

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- The LHC is THE machine where the Higgs boson is to be observed, and the theoretical expectations are much more under control
- Higgs production enhanced in the MSSM: more odds to find the elusive particle

  Theoretical uncertainties helps to restore a large part of the $\tan\beta - M_A$ parameter space excluded by CDF/D0