Phänomenologie von Higgs-Bosonen

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

outline :

- Higgs Bosons: why and what to expect ?
  - The Origin of the Electroweak Interaction
  - Electroweak Symmetry Breaking, Higgs mechanism
  - Higgs Sectors
- How to find Higgs Bosons ?
  - Higgs Production and Decay
  - Higgs Search Programme
- Selected Higgs Physics Projects
  - SM Higgsstrahlung
  - Higgs + high-p_T Jet: MSSM vs. SM
  - HiggsBounds

- Higgs Bosons: why and what to expect ?

– The Origin of the Electroweak Interaction

beta decay

Hahn, Meitner (1911): observation :

$$n \longrightarrow p\, e^- + \text{missing energy}$$

continous energy spectrum of electrons

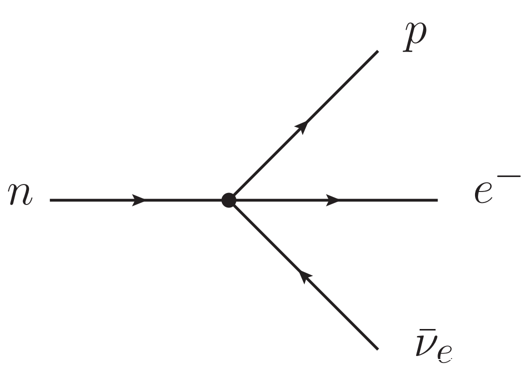
$\updownarrow$

discrete energy difference between n and p state

Bohr: energy is *really* missing

Pauli (1930): $n \to p\, e^- +$ neutrino (very weakly interacting)

Fermi (1934):



$$\mathcal{L} \propto G_F[\bar\psi_A \underbrace{(\gamma_\mu - \gamma_\mu\gamma_5)}_{V-A} \psi_B][\bar\psi_C \underbrace{(\gamma^\mu - \gamma^\mu\gamma_5)}_{V-A} \psi_D]$$

$$\propto G_F[\bar\psi_A \gamma_\mu P_L \psi_B][\bar\psi_C \gamma^\mu P_L \psi_D]$$

with $P_L = \frac{1}{2}(1-\gamma_5)$

short-range interaction of left-chiral components

good approximation for energies well below $G_F^{-1} \approx 300\,\text{GeV}$.

but: bad high energy behaviour

beta decay

Quark parton model [Bjorken, Paschos; Feynman 1969]

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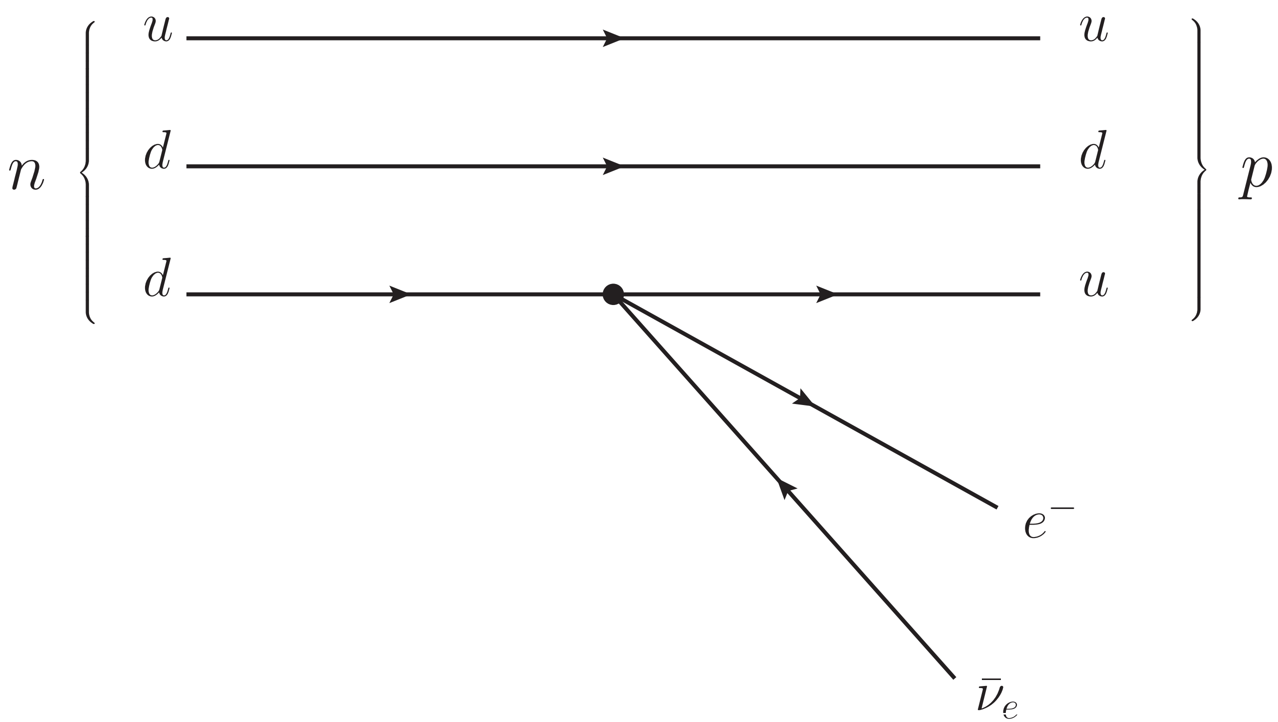
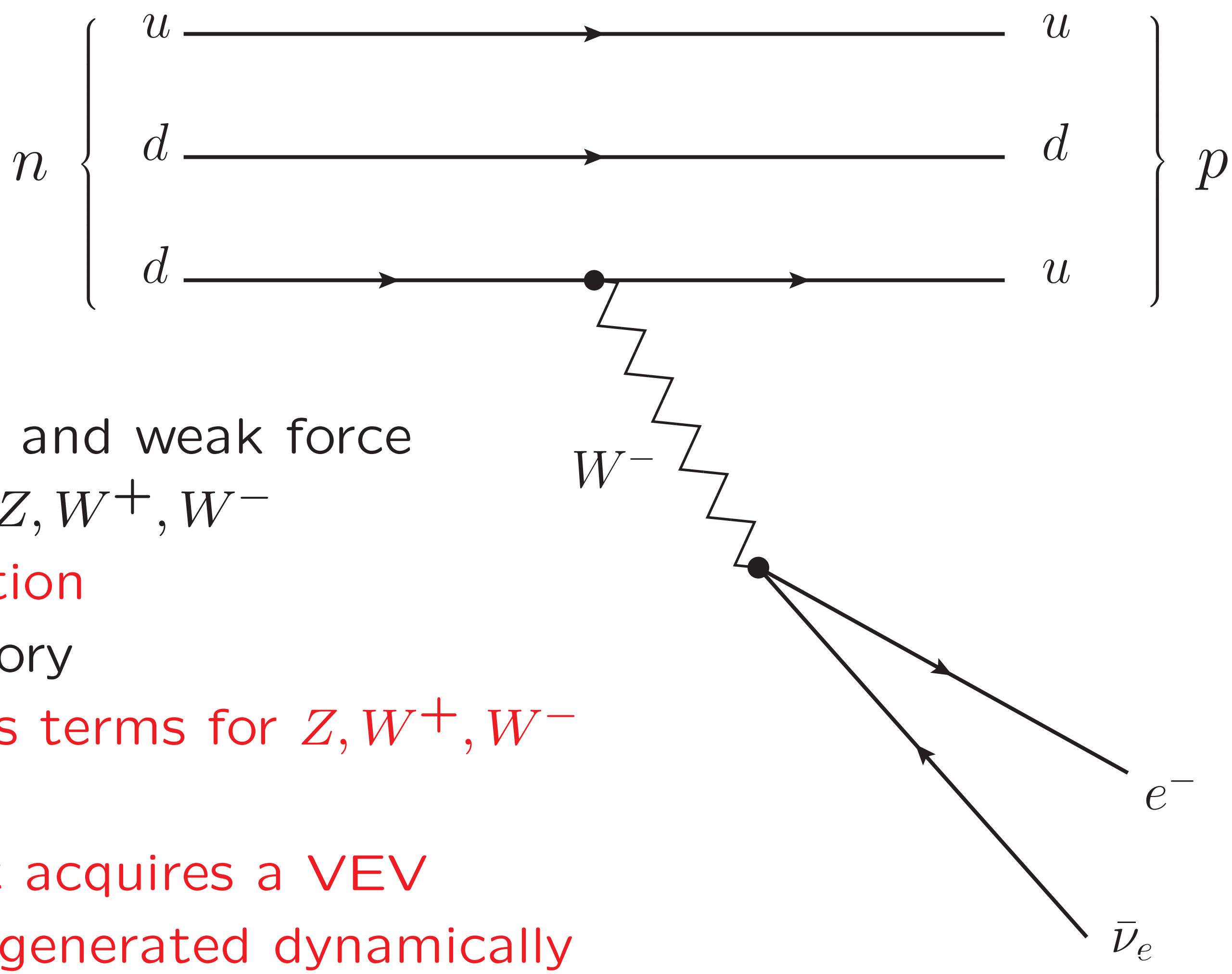


beta decay

Quark parton model [Bjorken, Paschos; Feynman 1969]:

with electroweak interaction [Glashow 1961, Salam 1968, Weinberg 1967]



- unification of electrom. and weak force
- massive vector bosons Z, W^+, W^-
  → short range interaction
- SU(2)×U(1) gauge theory
  → forbids explicit mass terms for Z, W^+, W^-
- Higgs mechanism
  → one scalar multiplet acquires a VEV
  → Z, W^+, W^- masses generated dynamically
  → good high energy behaviour

– Electroweak Symmetry Breaking, Higgs mechanism

Experiment:		Theory:
massive gauge bosons exist	$\longrightarrow$ problem $\longleftarrow$	electroweak gauge symmetry
($W^{\pm}$,Z)		forbids mass terms
		for gauge bosons

solution: **spontaneous symmetry breaking (SSB)**:

introduce gauge invariant dynamics, which breaks gauge symmetry in the ground state.

– Electroweak Symmetry Breaking, Higgs mechanism

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massive gauge bosons exist ($W^{\pm}$,Z)	→ problem ←	electroweak gauge symmetry forbids mass terms for gauge bosons

solution: **spontaneous symmetry breaking (SSB)**:

introduce gauge invariant dynamics, which breaks gauge symmetry in the ground state.

> One major task in high energy particle physics is:
> to unravel the nature of electroweak symmetry breaking.

– Electroweak Symmetry Breaking, Higgs mechanism

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massive gauge bosons exist	→ problem ←	electroweak gauge symmetry
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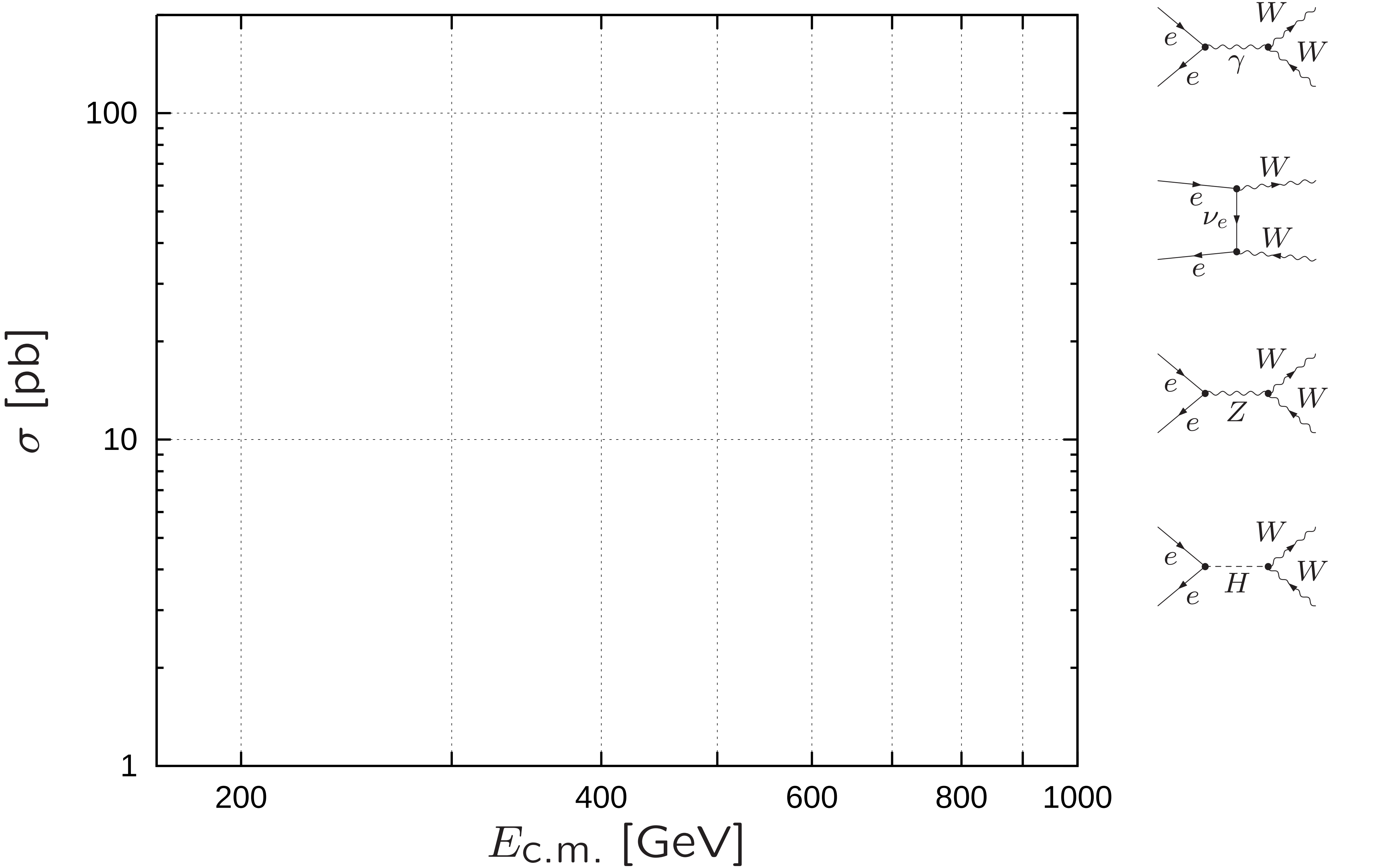
solution: **spontaneous symmetry breaking (SSB)**:

introduce gauge invariant dynamics, which breaks gauge symmetry in the ground state.

SSB can be realised by

- weakly interacting scalar gauge multiplets that acquire a VEV → Higgs mechanism
- strongly interacting dynamics, e.g. particles that form scalar condensates with a VEV

$\sigma(e^+e^- \to W^+W^-)$ at tree-level



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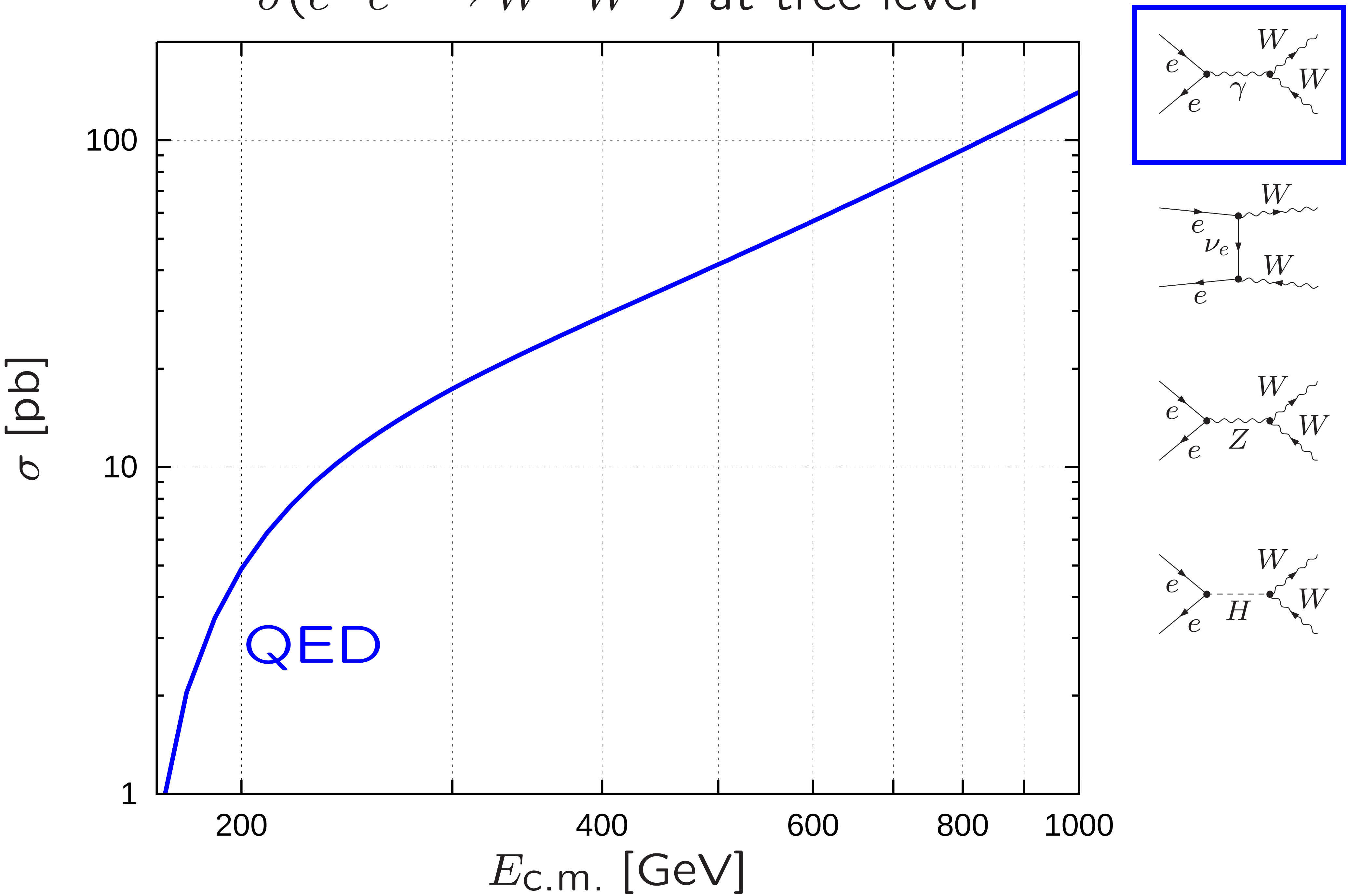

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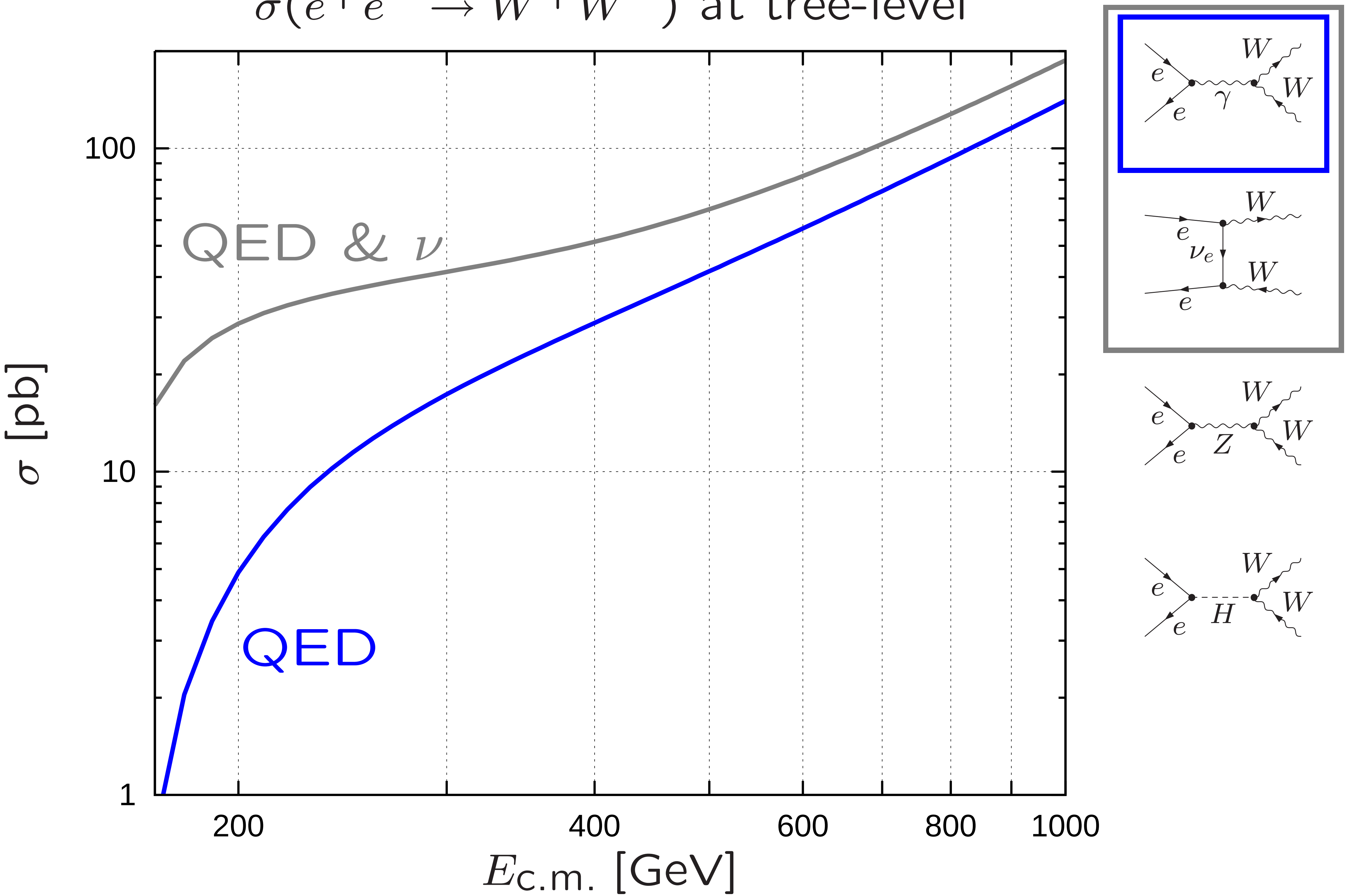

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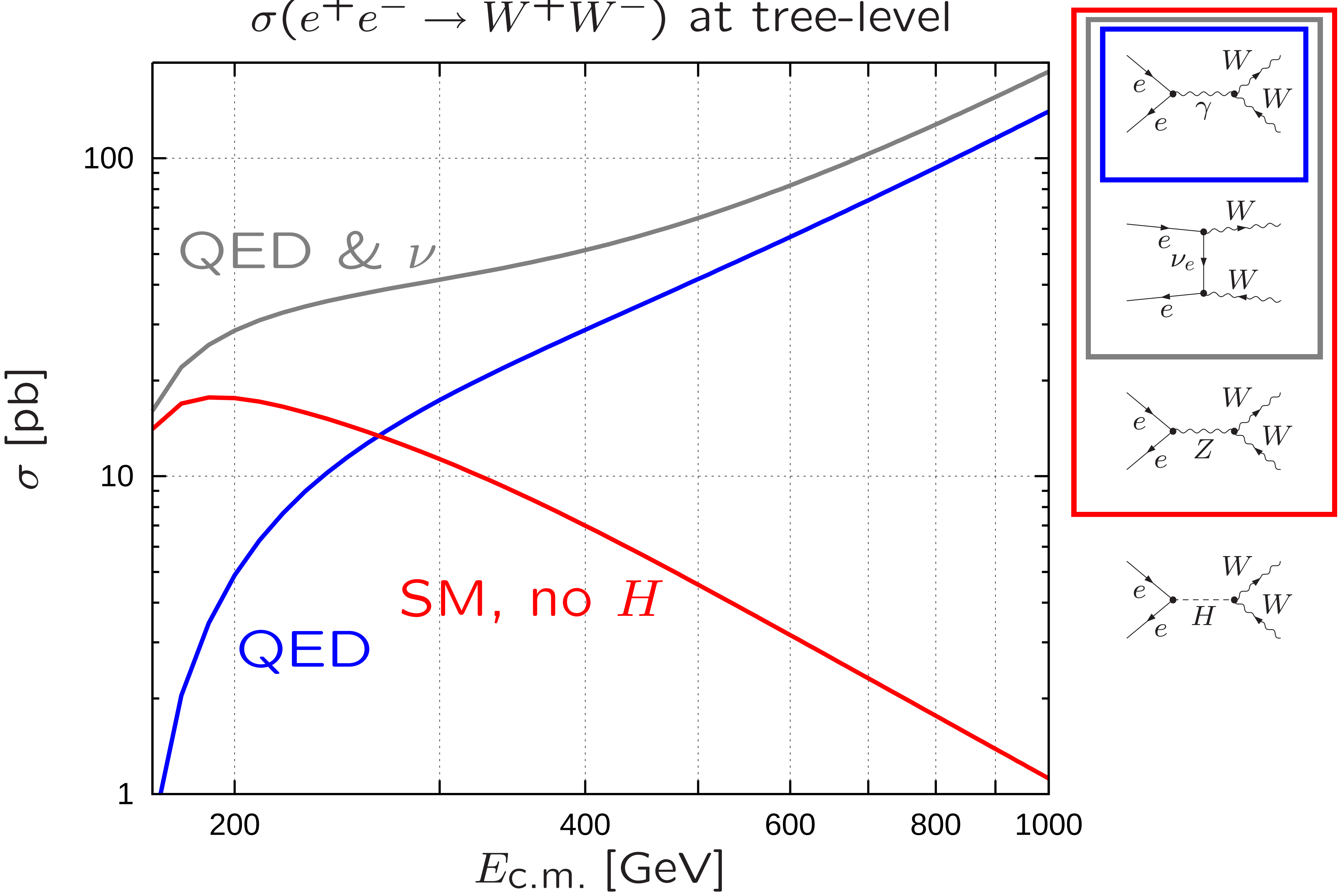

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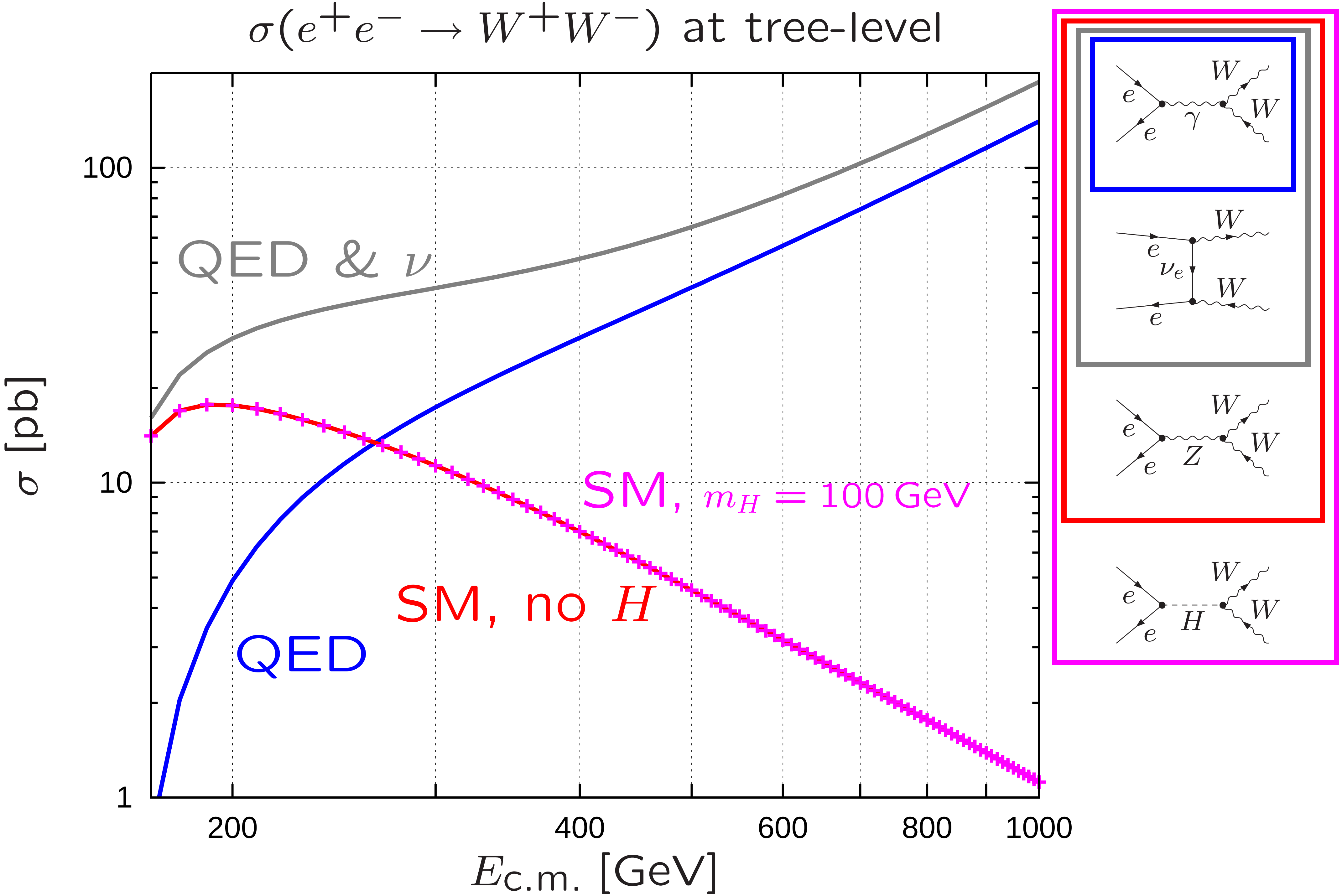
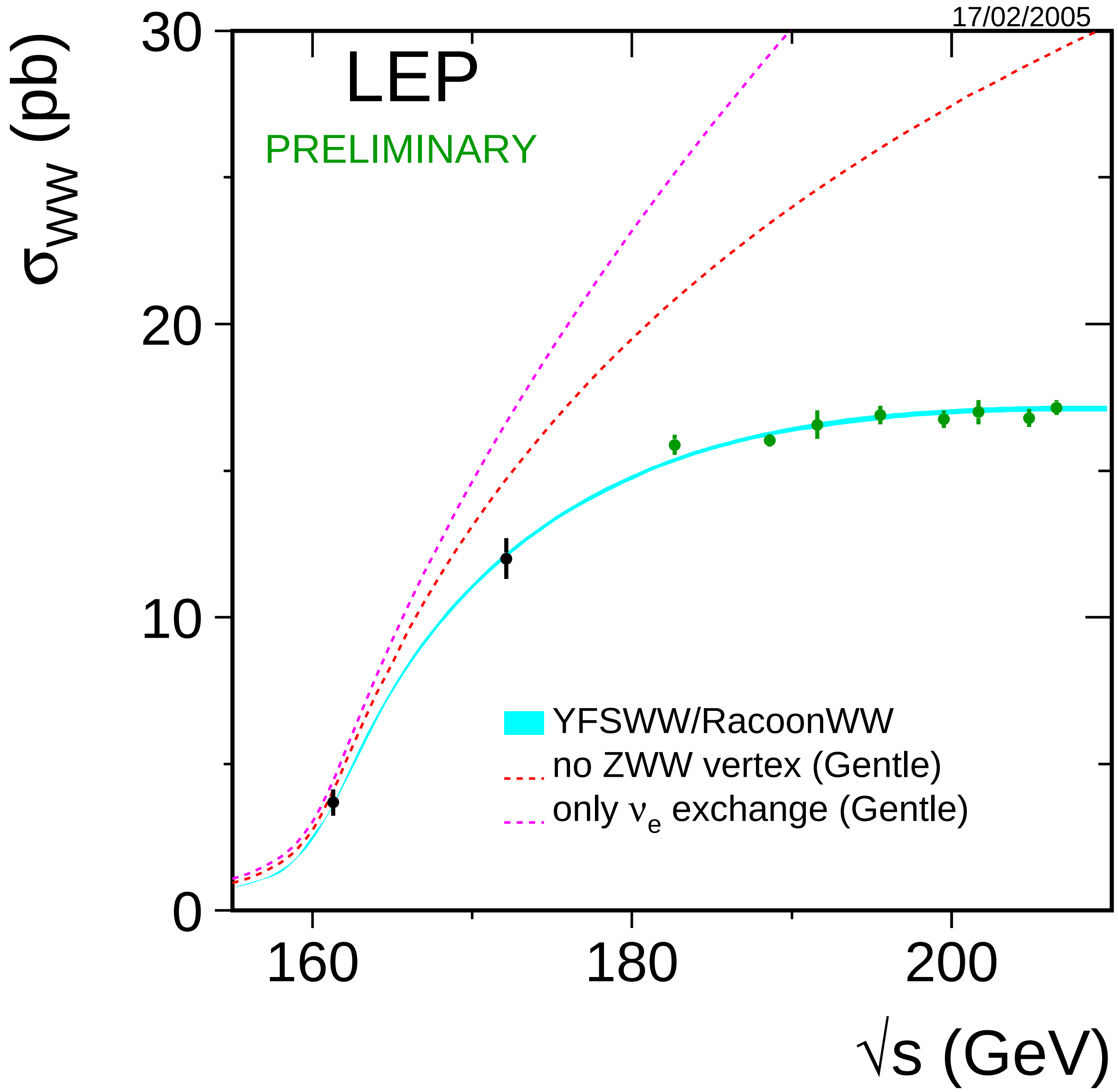
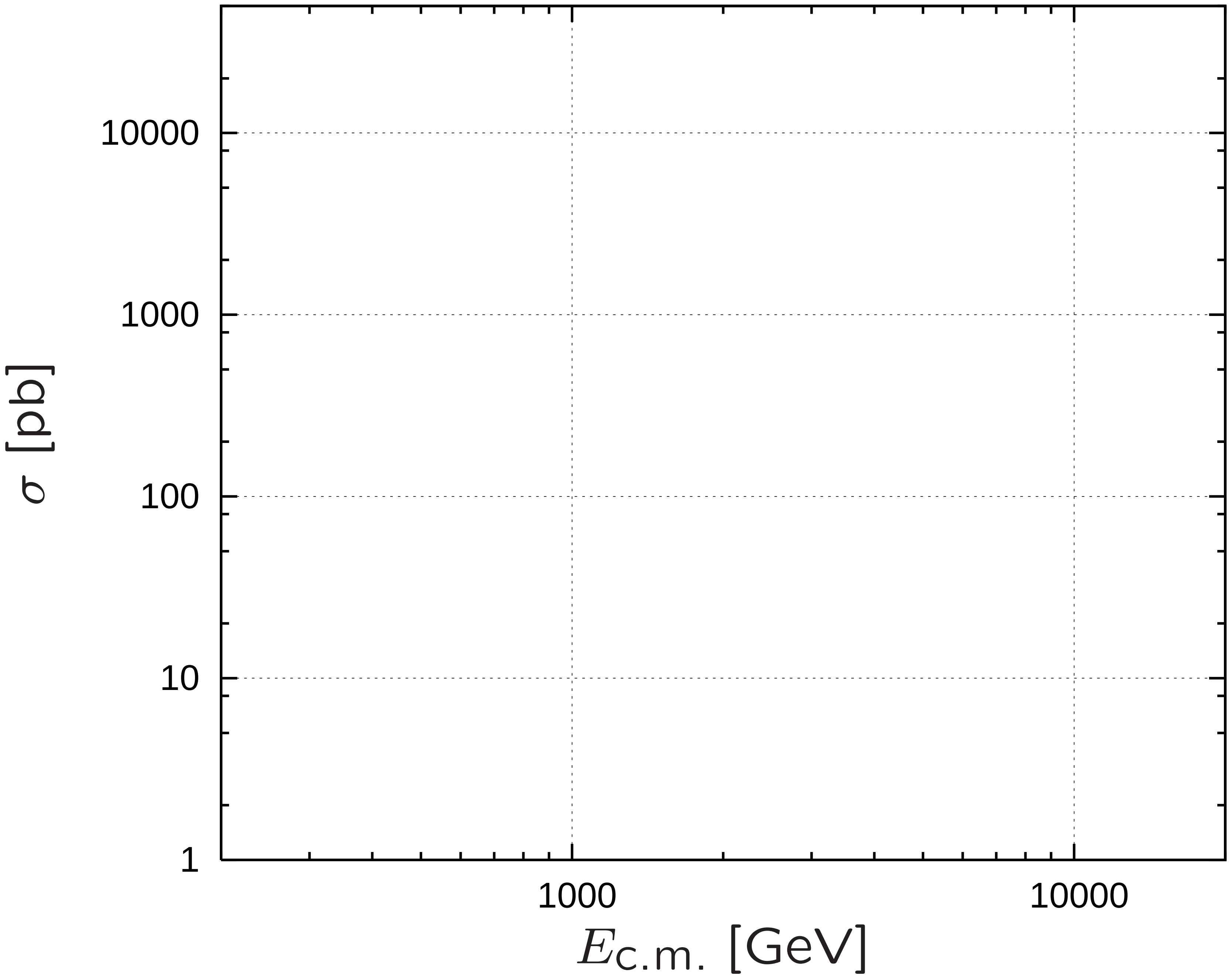
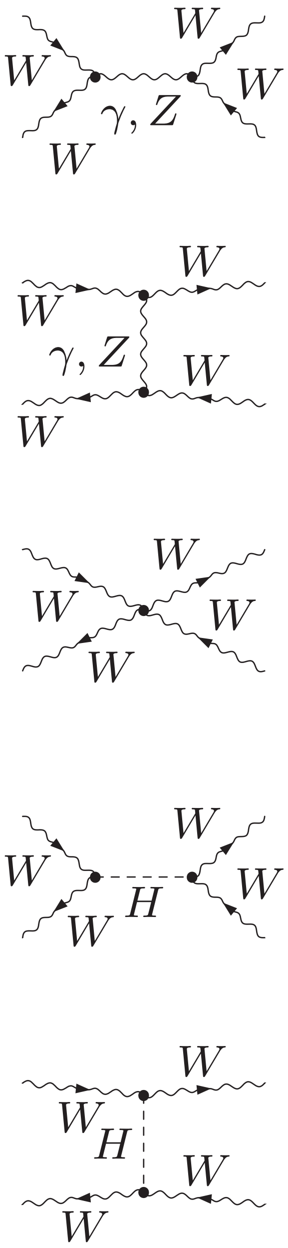


measurement of $\sigma(e^+e^- \to W^+W^-)$ at LEP 2:



$\sigma(W_L W_L \to W_L W_L)$ at tree-level





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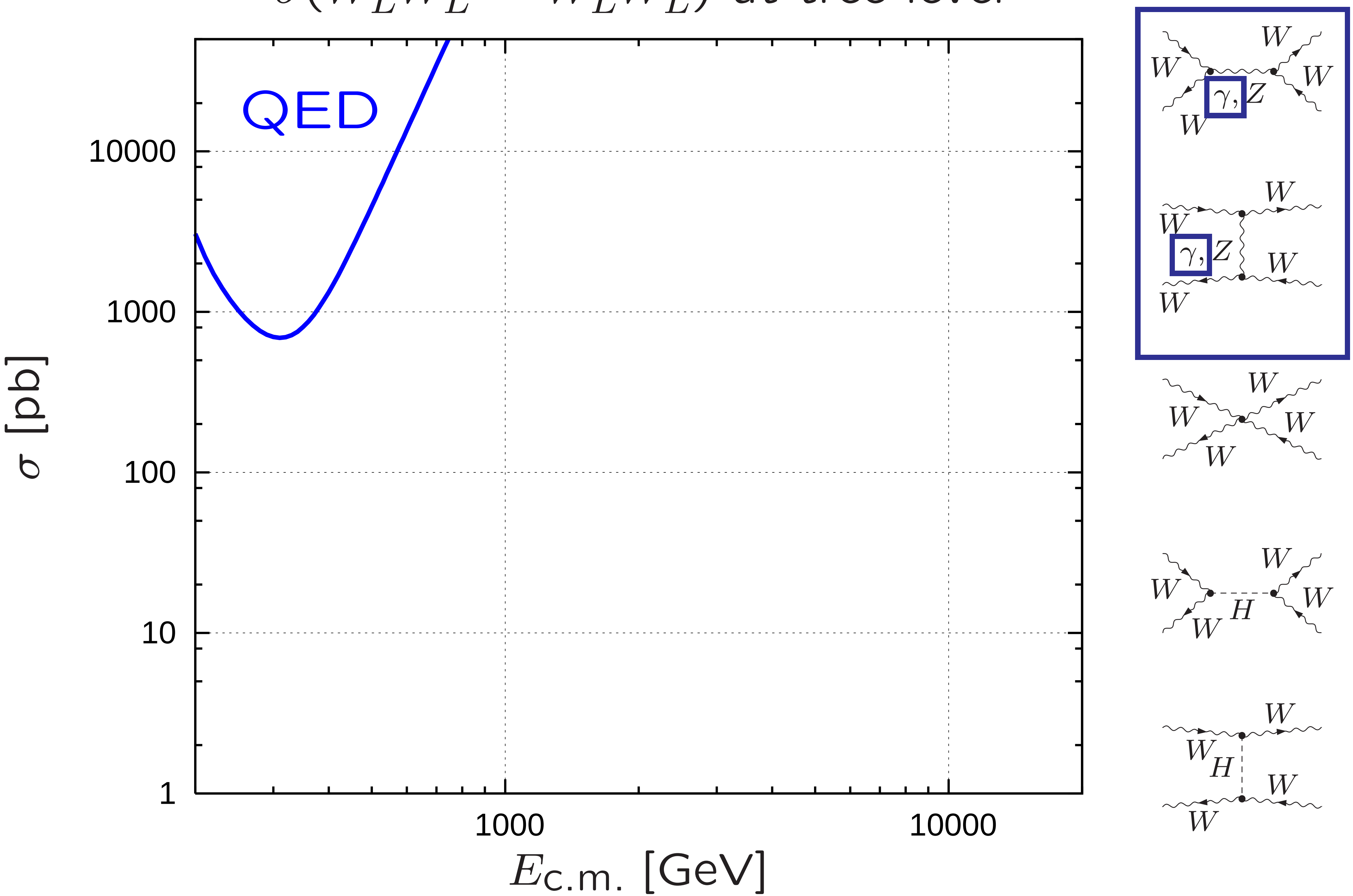

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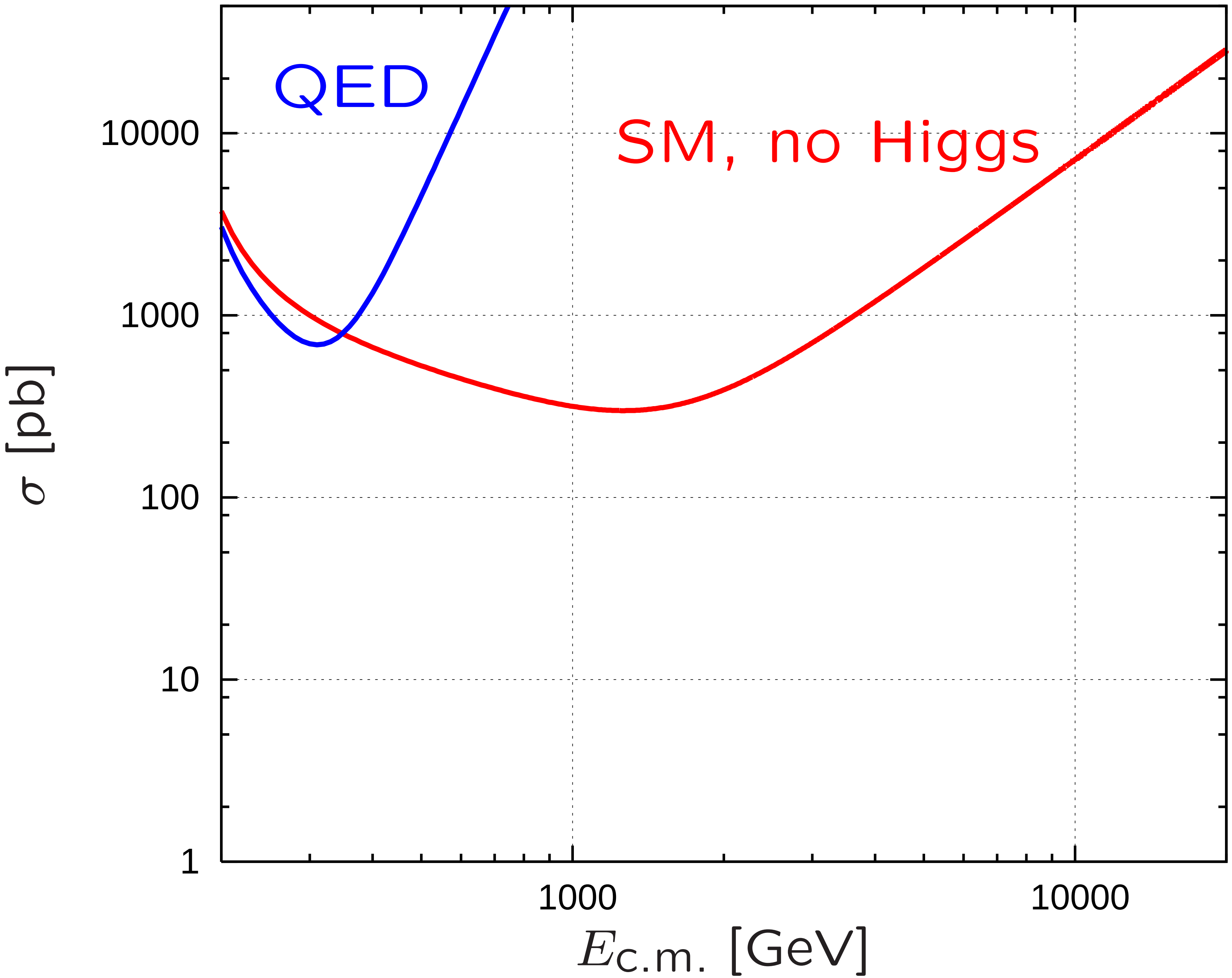

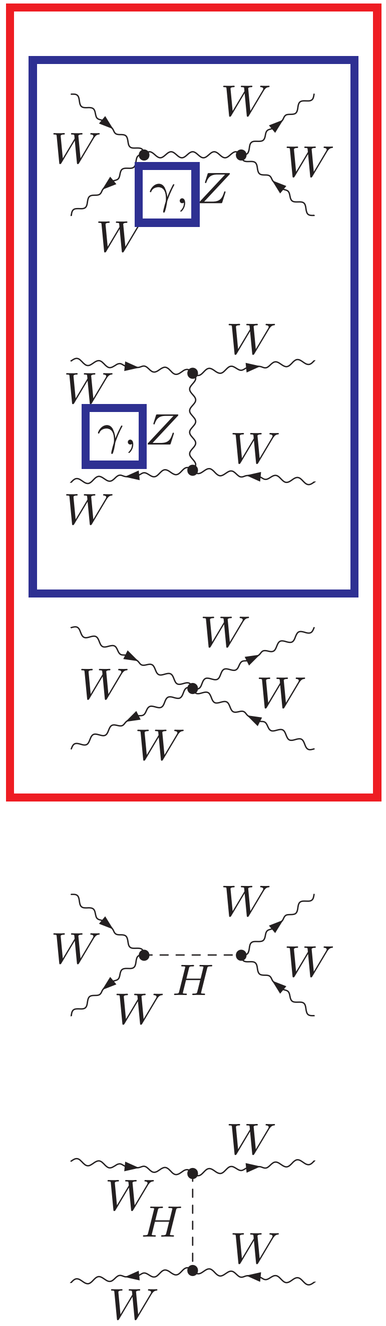

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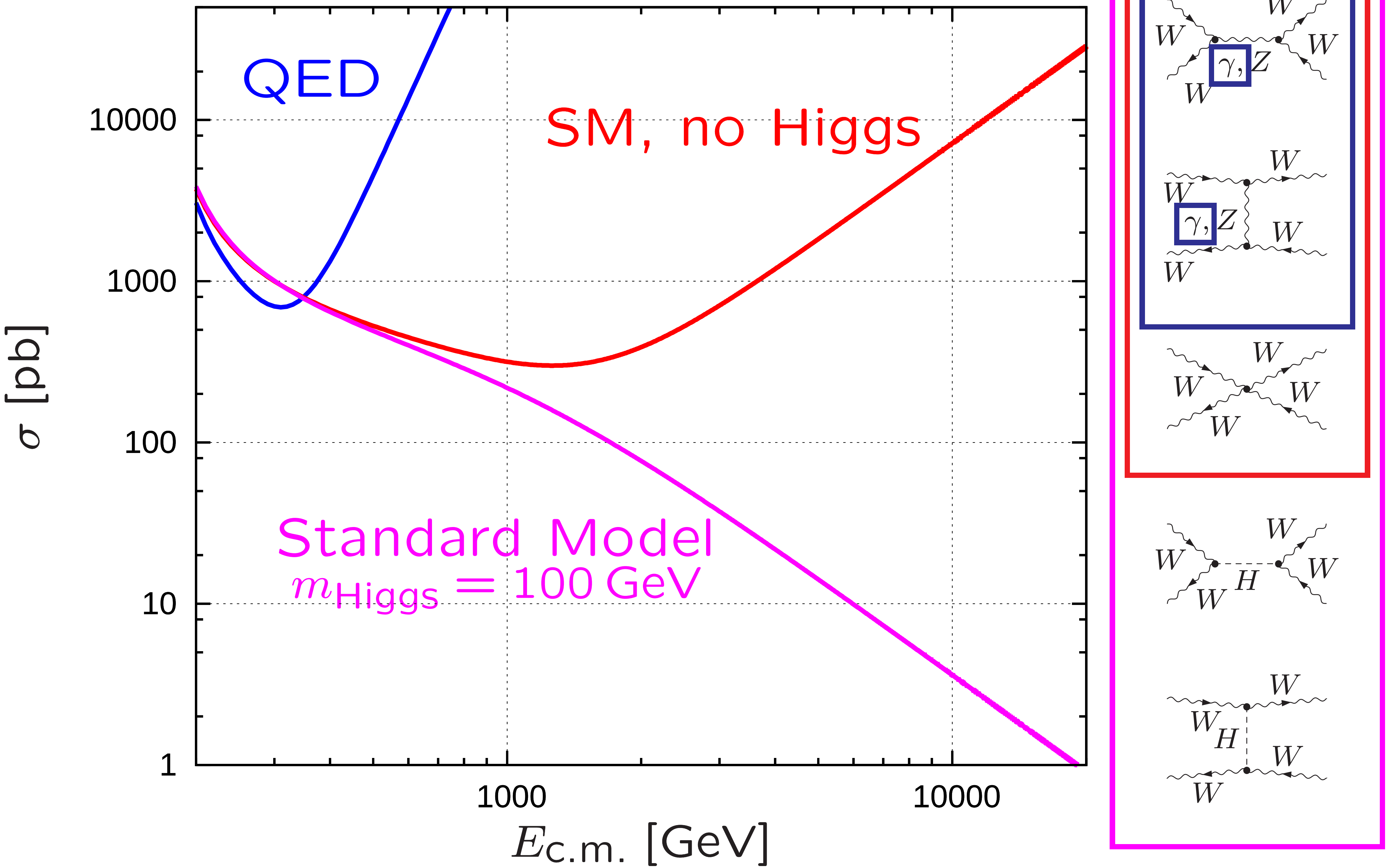


– Higgs Sectors

Experimental situation so far:

- no Higgs signal.
- no significant deviation from SM.

Theory:

- many distinct possibilities to realise the Higgs mechanism

  which meet major constraints, like

  - the electroweak rho-parameter
    $\rho_{\text{exp.}} = \frac{m_W}{\cos\theta_W m_Z} \approx 1$ up to a few per mille
  - absence of flavour changing neutral currents (FCNC).
  - upper bounds on production cross sections
    from negative direct search results (LEP, Tevatron)

$\longrightarrow$ take extensions of the SM (Higgs sector) seriously

SM and simple extensions

SM:

matter, gauge bosons + 1 Higgs doublet Φ

$\rightarrow$ 1 physical Higgs boson

$\swarrow$ $\searrow$

THDM: (two Higgs doublet model)

SM matter, SM gauge bosons
+ 2 Higgs doublets Φ_1, Φ_2

MSSM: (minimal supersymmetric standard model)

SM matter, SM gauge bosons
+ 2 Higgs doublets Φ_1, Φ_2
+ Superpartners

$\rightarrow$ 5 physical Higgs bosons: h^0, H^0, A^0, H^+, H^-

note! : charged Higgs bosons cannot appear with *one* Higgs doublet

$\rightarrow$ **discovery of $H^\pm$: unambiguous sign of an extended Higgs sector**

Consequences of Supersymmetry for the MSSM Higgs sector

- MSSM *only* consistent with two Higgs doublets

- all Φ^4-interactions determined by gauge couplings

  $\longrightarrow$ only two Higgs sector input parameters:

  m_{A^0} (mass of A^0), $\tan\beta$ ($= v_2/v_1$, ratio of VEVs)

  instead of seven in the THDM:

  $$m_{A^0}, \tan\beta \quad + \quad \underbrace{m_{h^0}, m_{H^0}, m_{H^\pm}, \alpha, M^2(= v^2\lambda_5)}_{\text{in the MSSM functions of } m_{A^0},\ \tan\beta}$$

  $\longrightarrow$ bound on lightest neutral Higgs mass ($m_{h^0} \lesssim 135\,\text{GeV}$)

- large quantum corrections to Higgs masses (esp. to m_{h^0})

  present status:

  real MSSM: three-loop (SUSY QCD) precision

  [Harlander, Kant, Mihaila, Steinhauser '08]

  complex MSSM: two-loop (SUSY QCD) precision

  [Heinemeyer, Hollik, Rzehak, Weiglein '07]

- How to find Higgs Bosons ?

– Higgs Production and Decay

Higgs mechanism ⟶ Higgs couplings $\propto$ mass

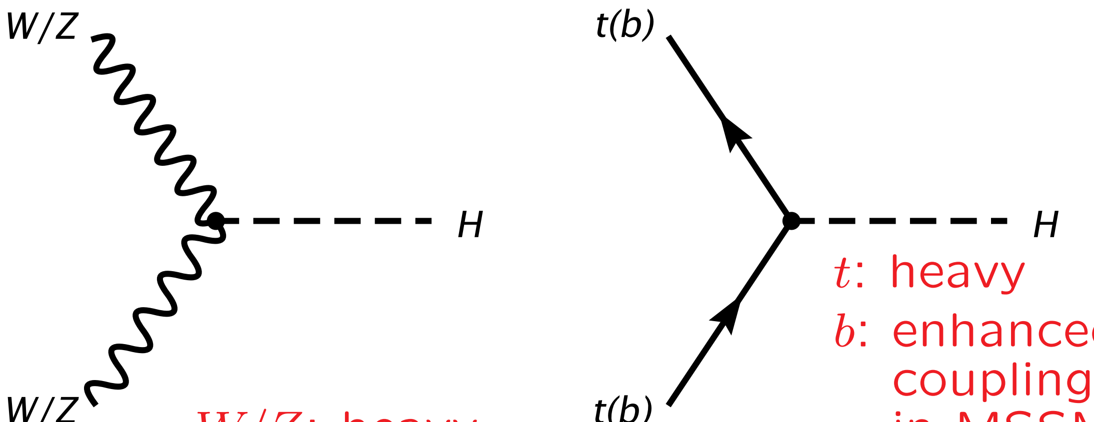
⟶ Problem: ordinary matter is made of very light particles:

e^-,u-, d-quarks, gluons ⟶ (essentially) no coupling to the Higgs

⟶ At colliders: Higgs couples to heavy intermediate particles

with non-suppressed couplings to ordinary matter.

⟶ most important couplings:

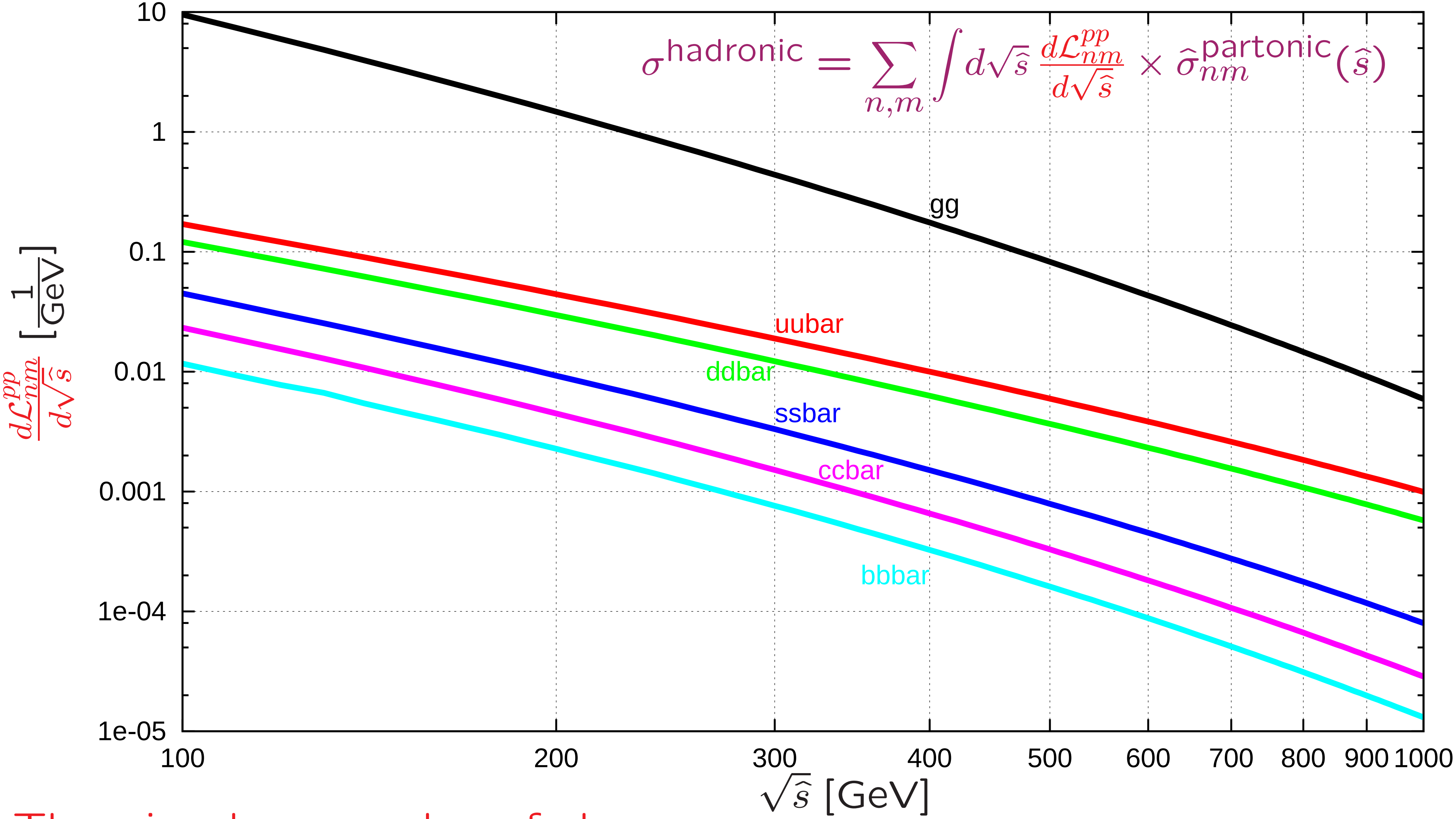


W/Z: heavy

t: heavy

b: enhanced coupling in MSSM

Parton luminosities $\frac{d\mathcal{L}^{pp}_{nm}}{d\sqrt{\hat{s}}}$ at the LHC:



There is a huge number of gluons
with small momentum fractions
still having enough energy to produce Higgs particles.

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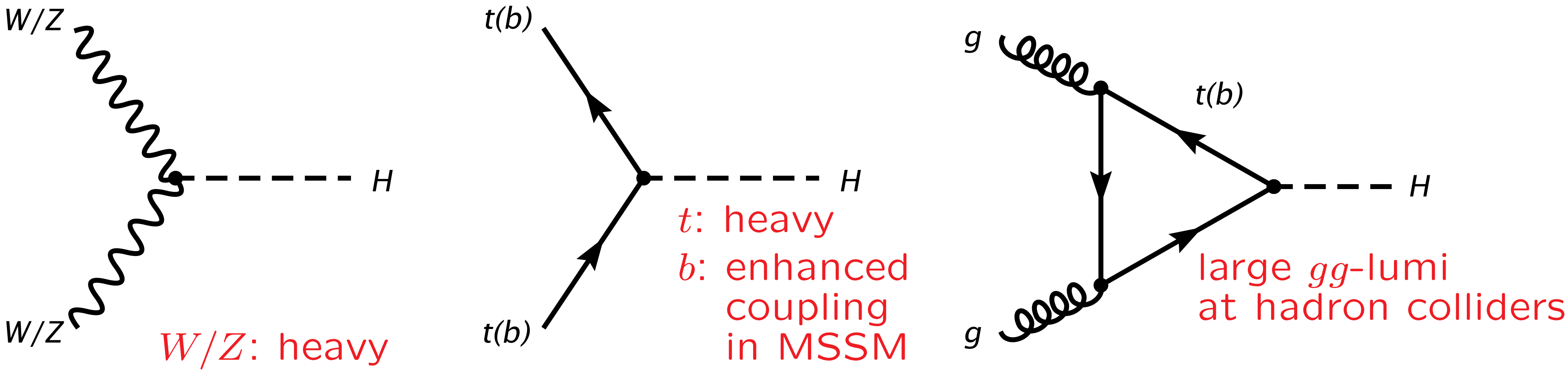

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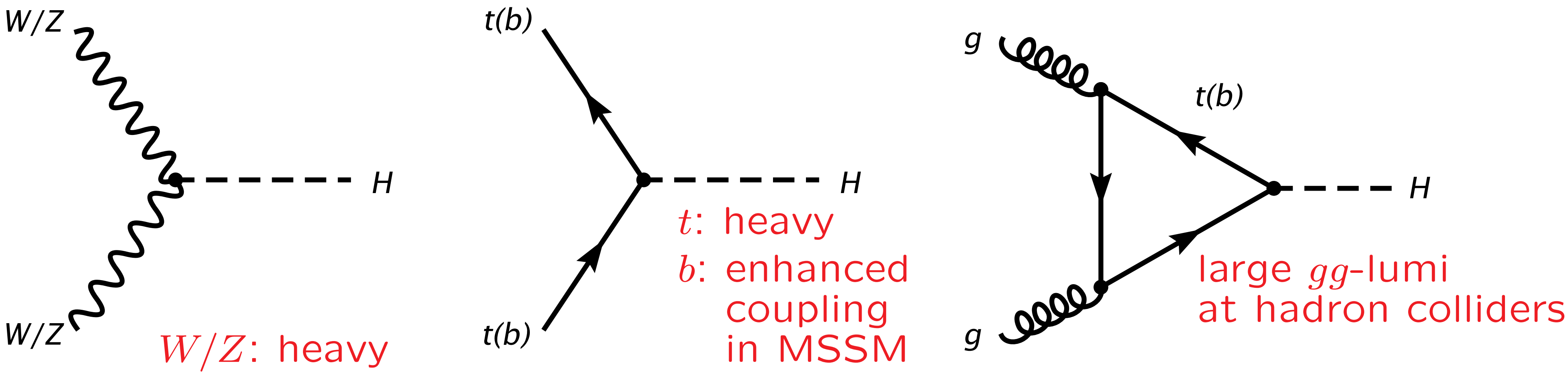

Therefore, most important couplings at high energy hadron colliders

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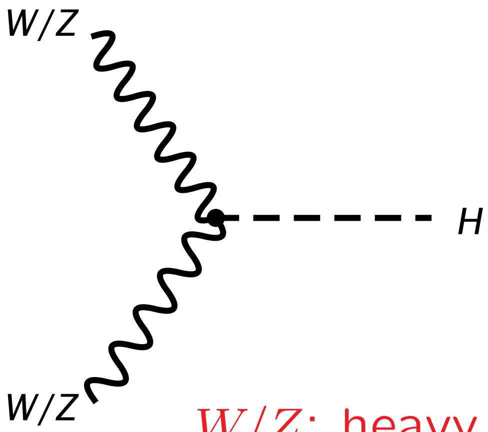

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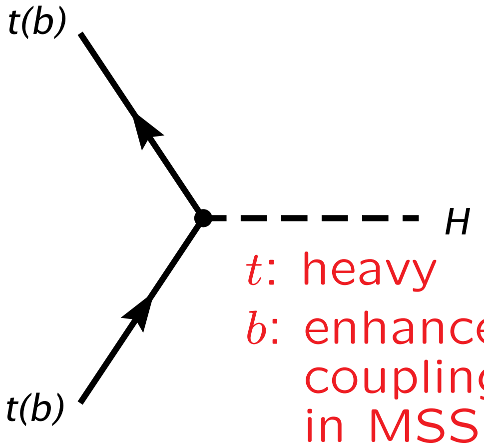

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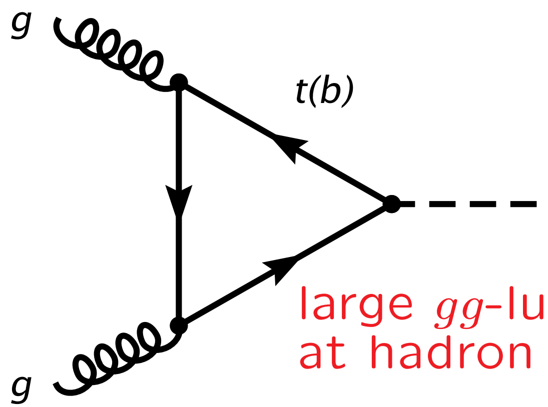
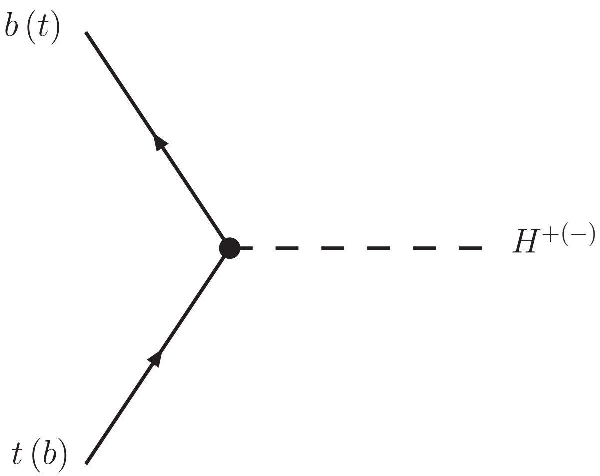
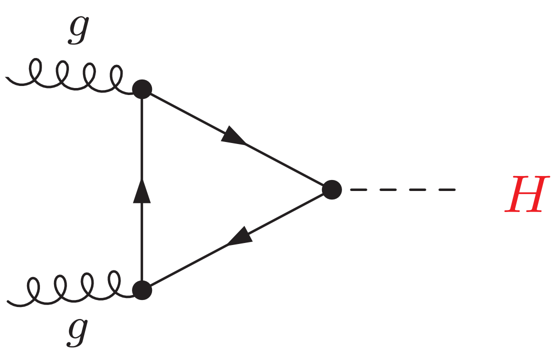


large gg-lumi at hadron colliders

… for charged Higgs production:



Important neutral Higgs production processes (at high energy hadron colliders):



gluon fusion, $gg \longrightarrow H$

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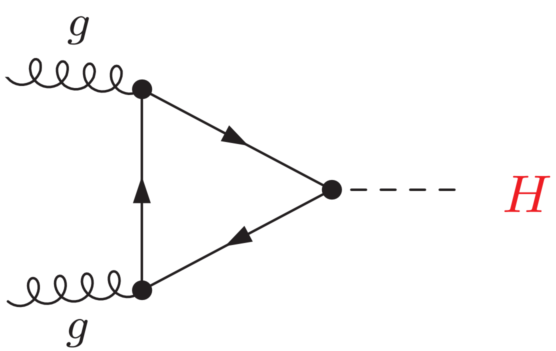

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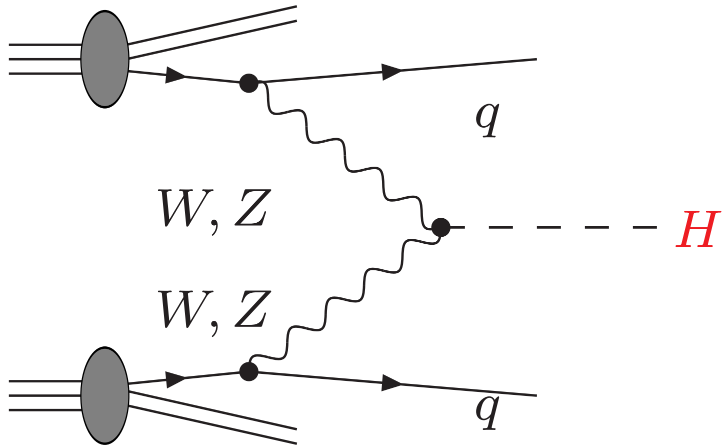

vector boson fusion, $qq \longrightarrow qqH$

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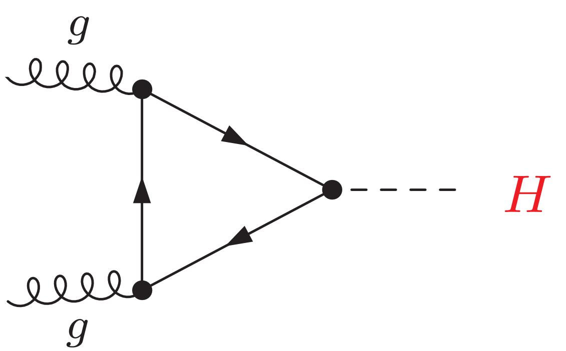

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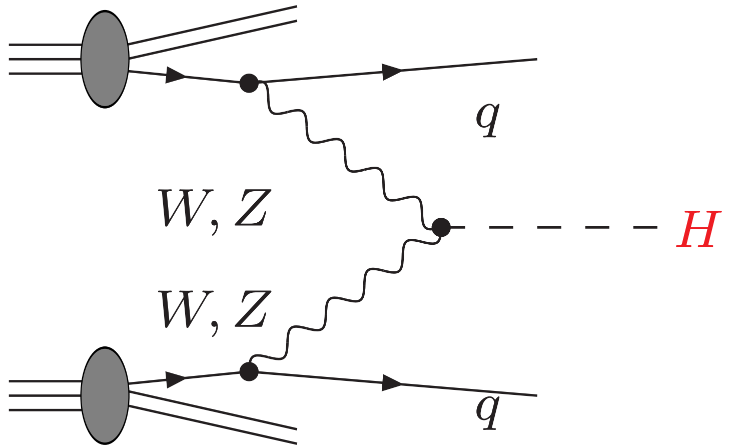

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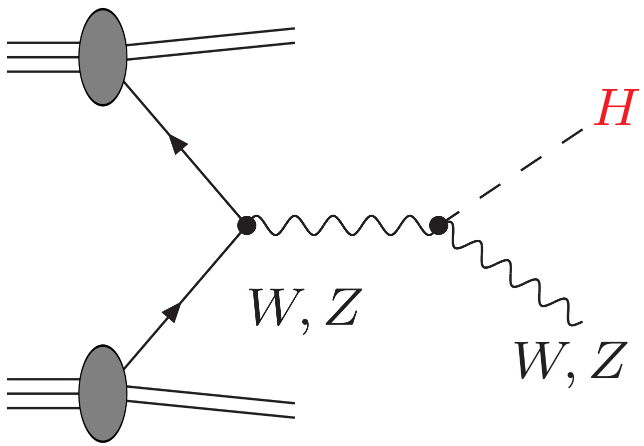
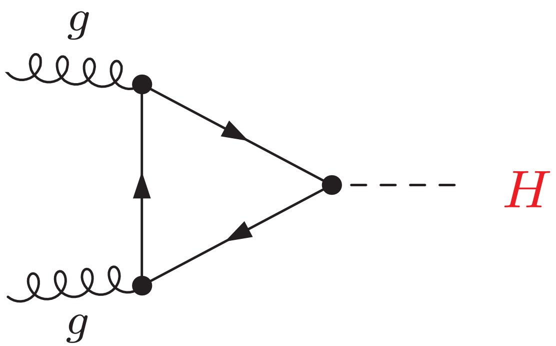
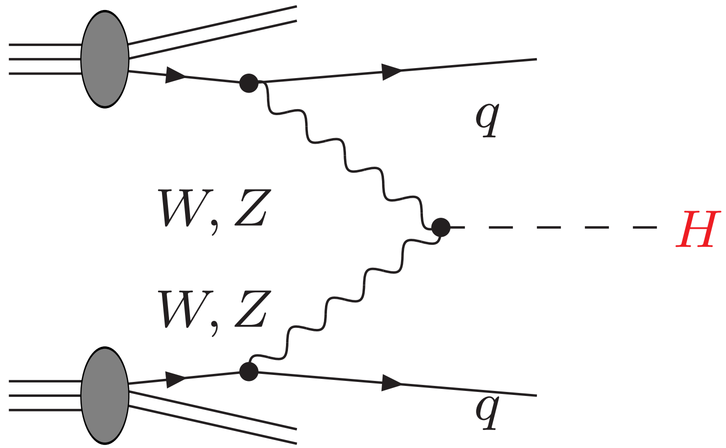


Higgs strahlung, $q\overline{q}' \longrightarrow VH$

Important neutral Higgs production processes (at high energy hadron colliders):



gluon fusion, $gg \to H$



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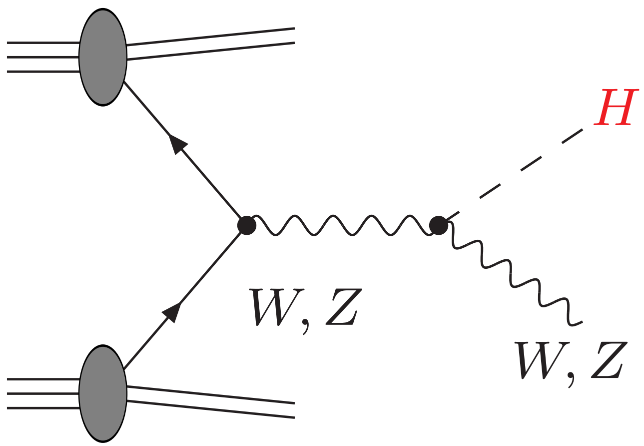

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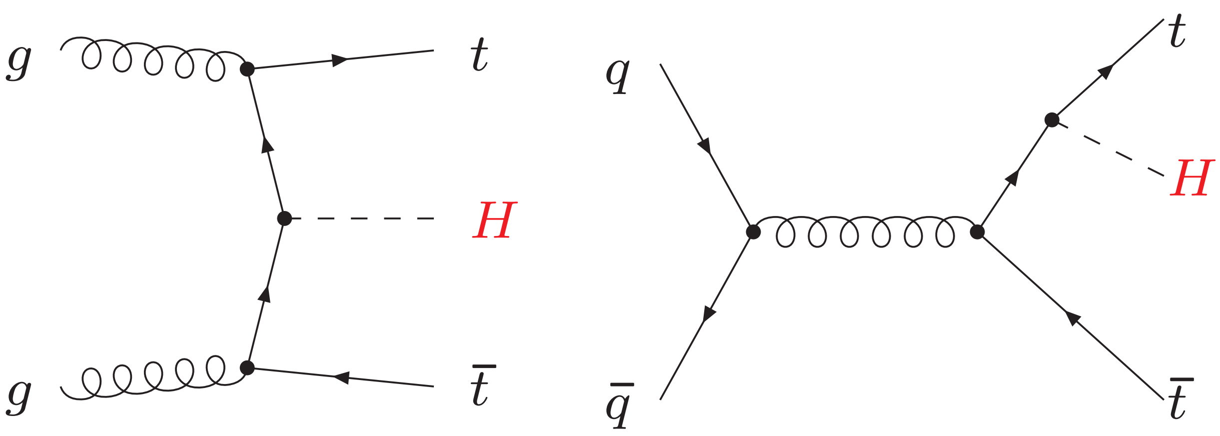

$t\bar{t}H$ **production**

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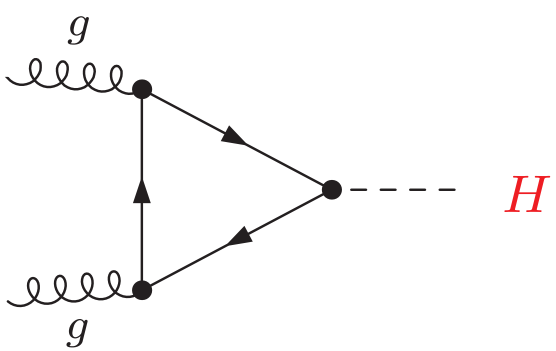

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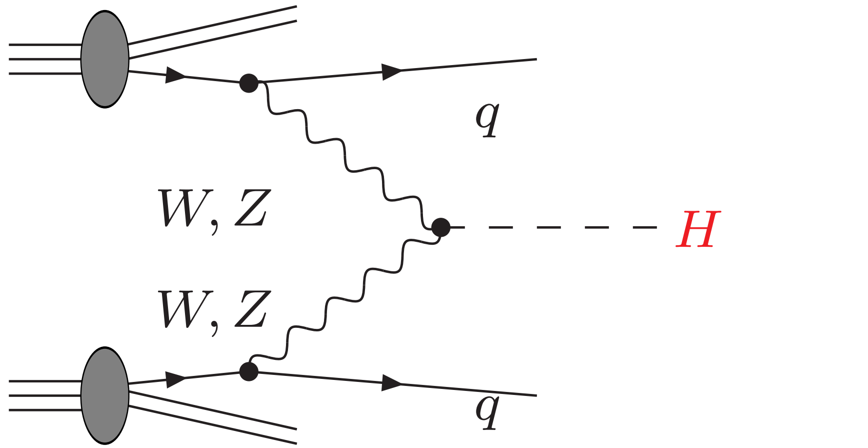

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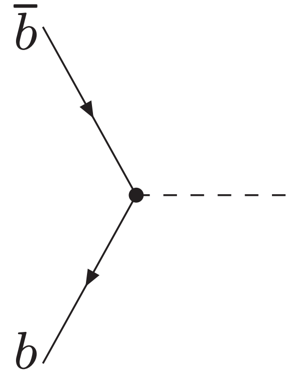
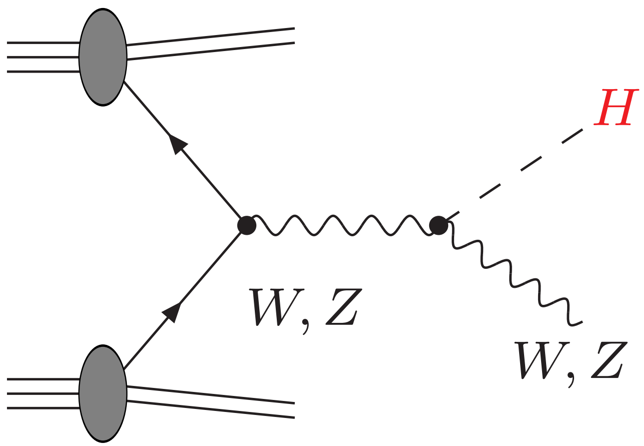
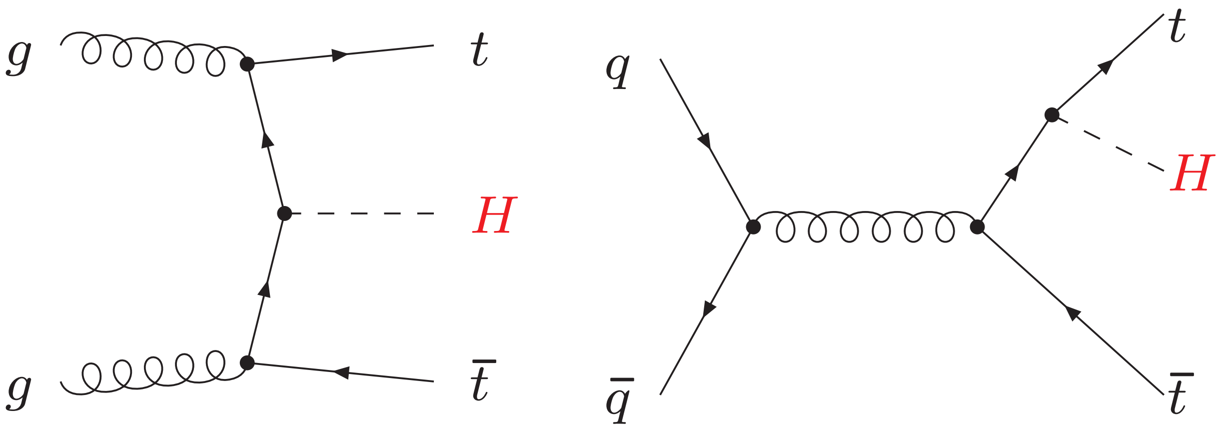


$b\bar{b} \longrightarrow H$

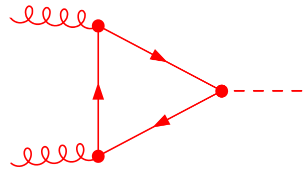


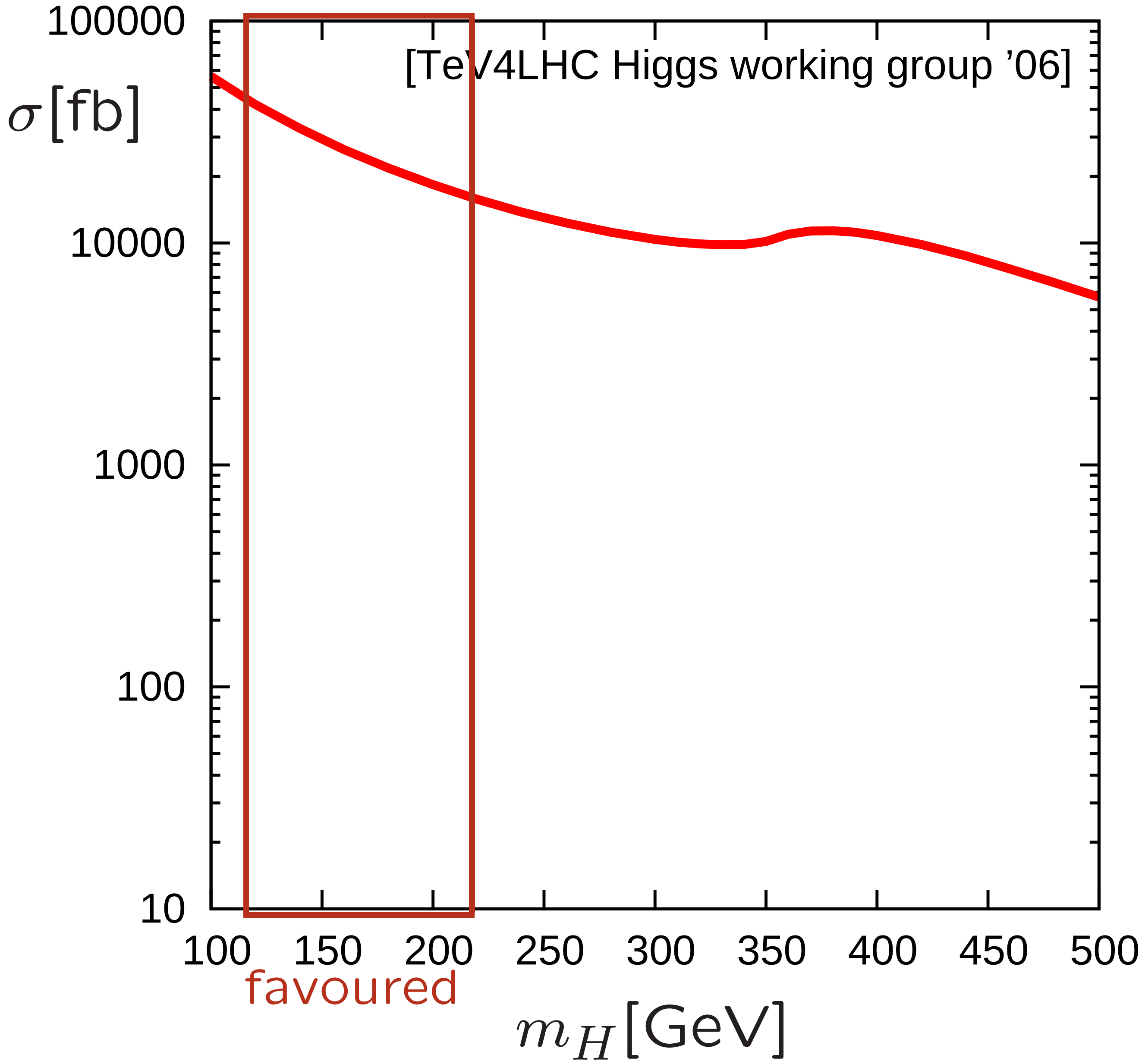
Higgs strahlung, $q\bar{q}' \longrightarrow VH$



$t\bar{t}H$ **production**

Predictions: SM Higgs production @ **LHC** :





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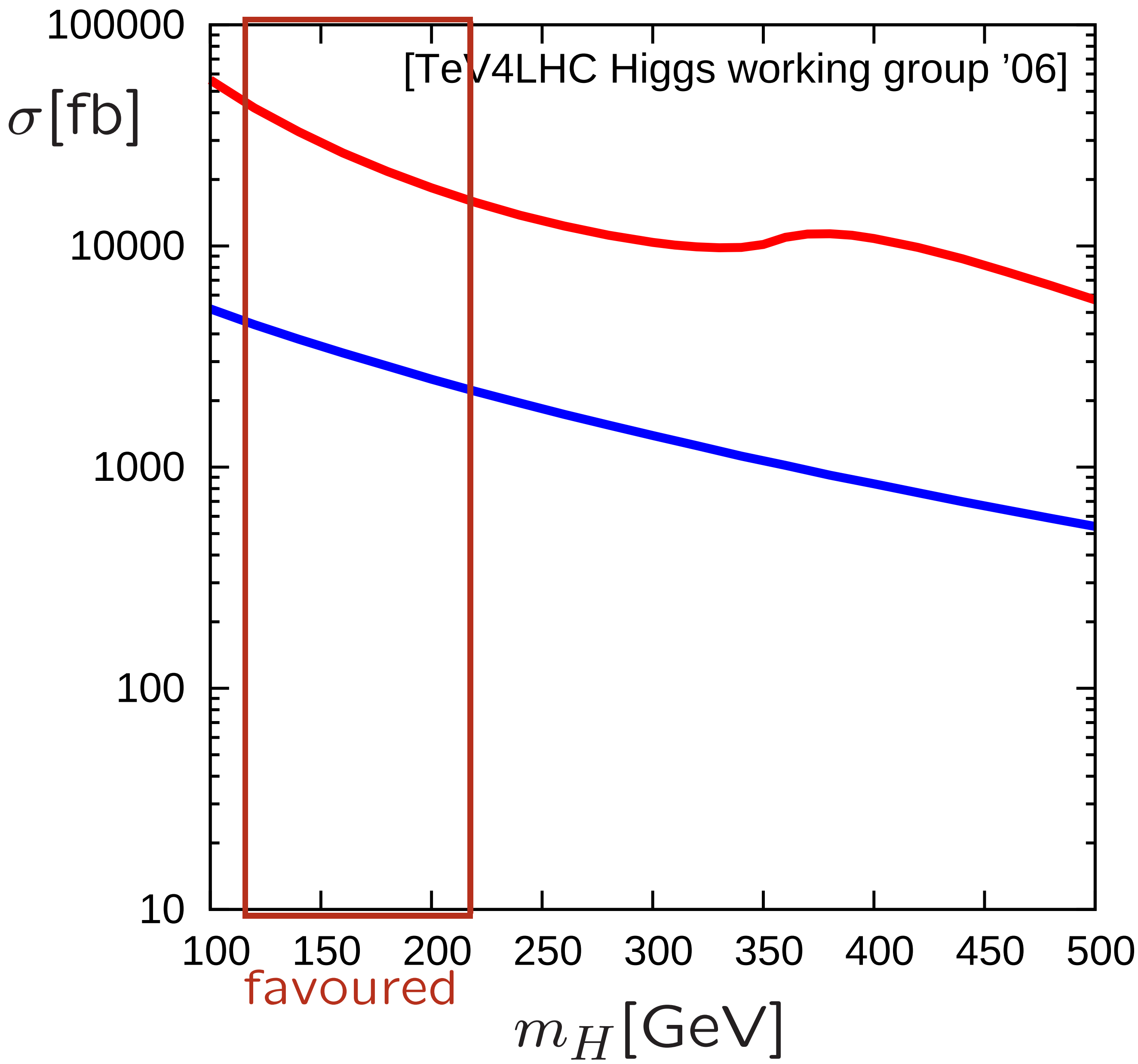

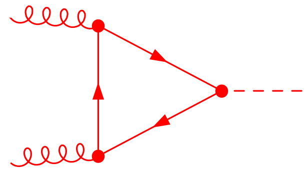

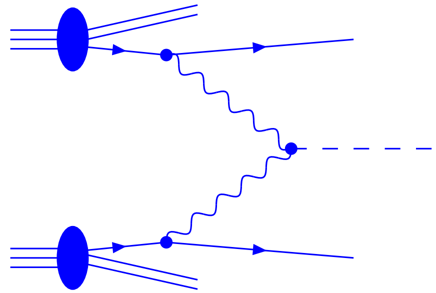

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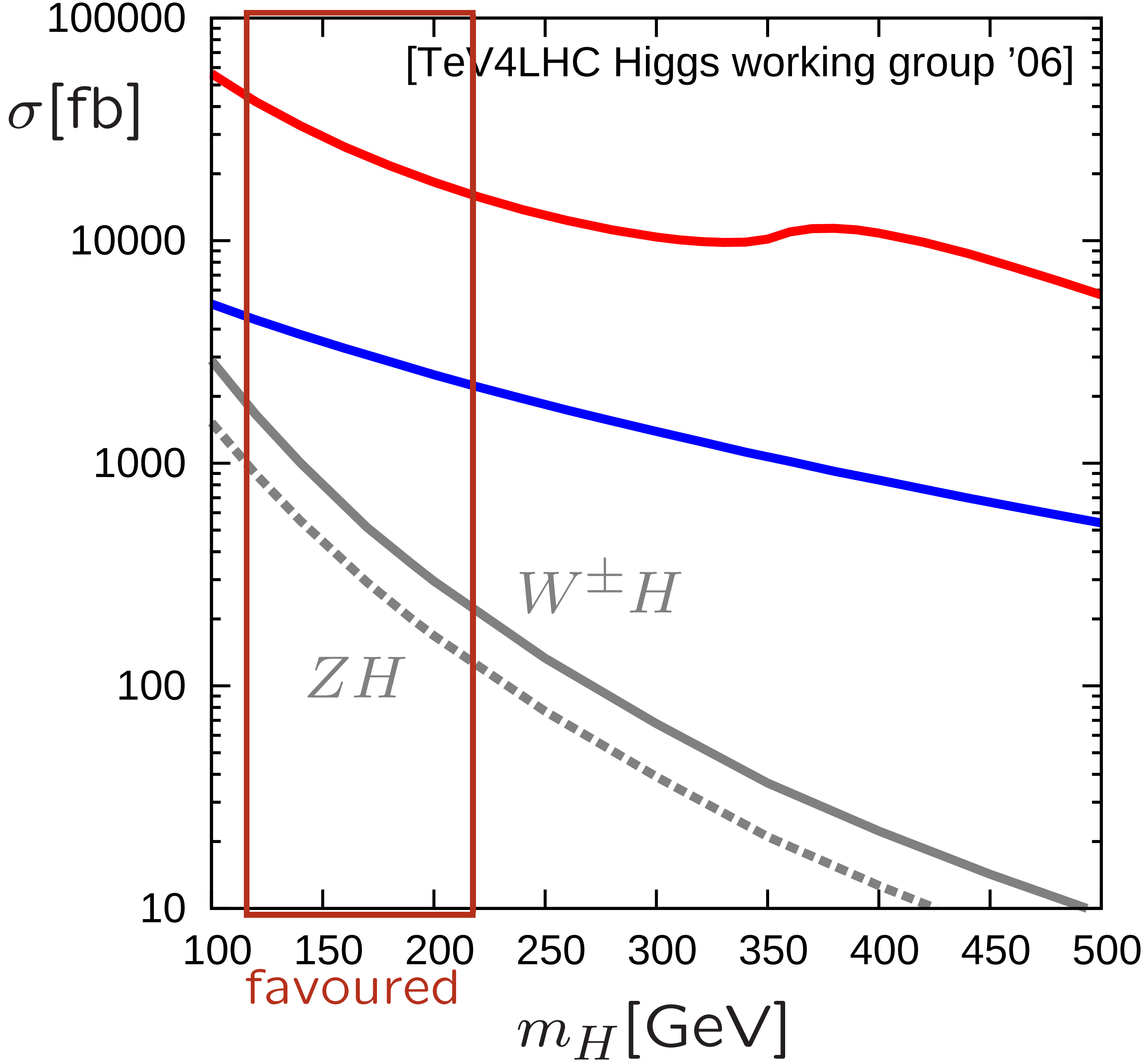

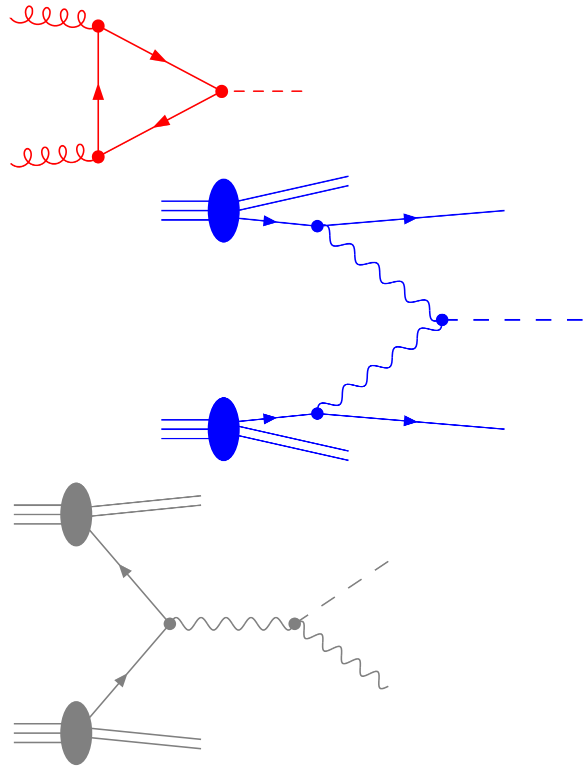

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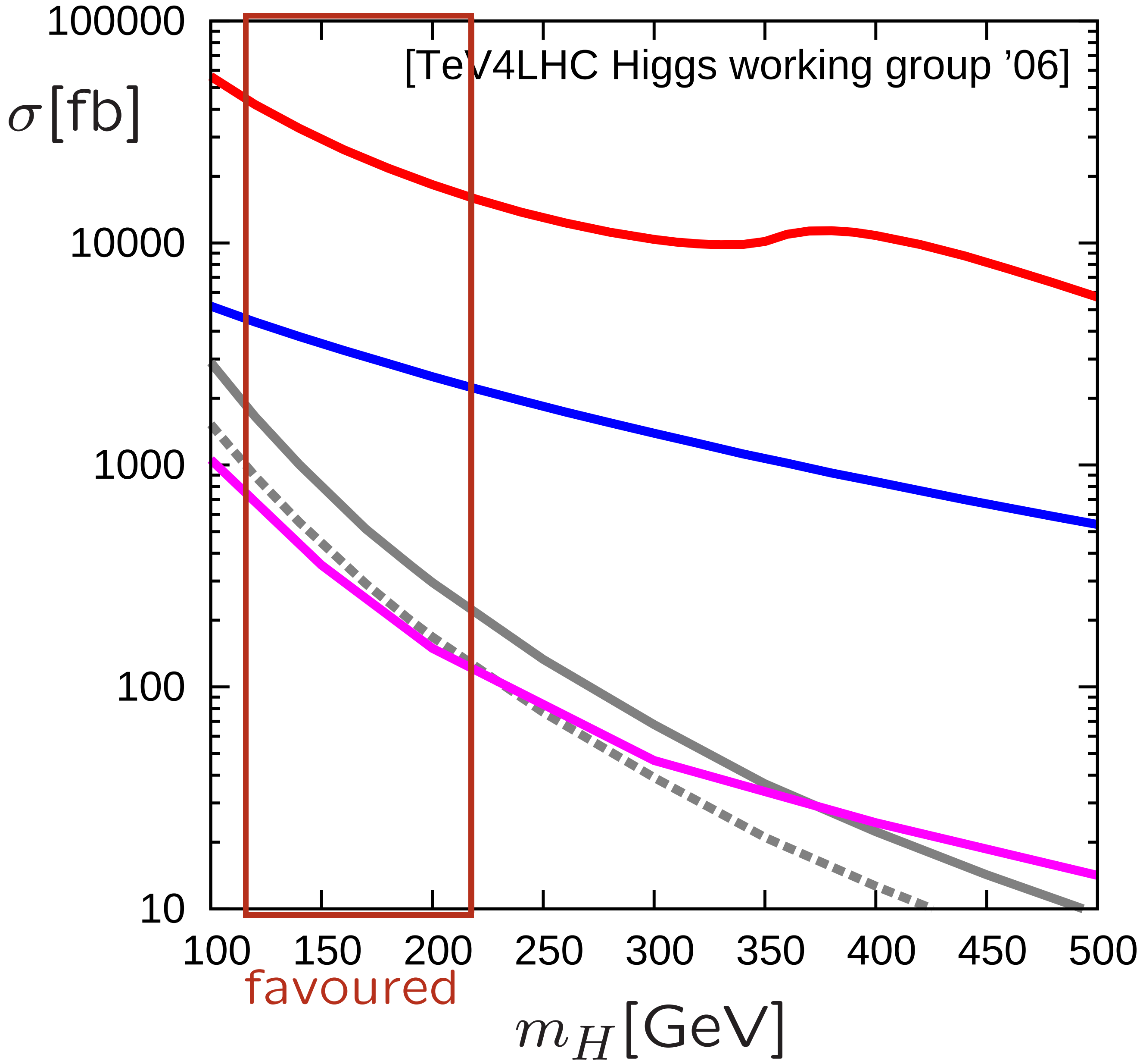
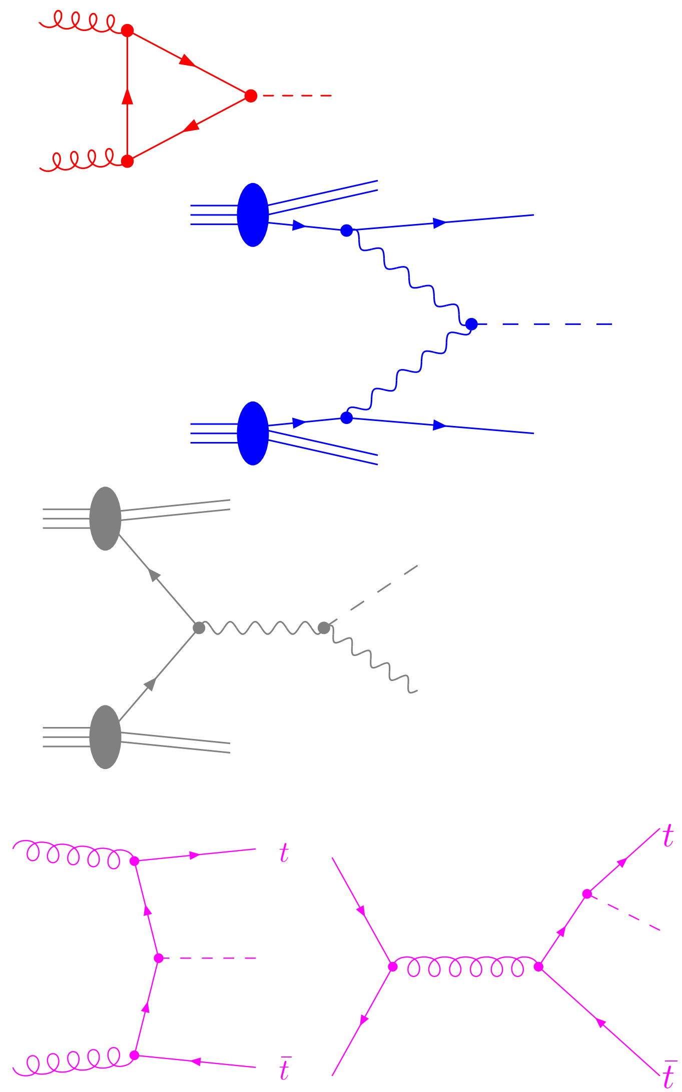
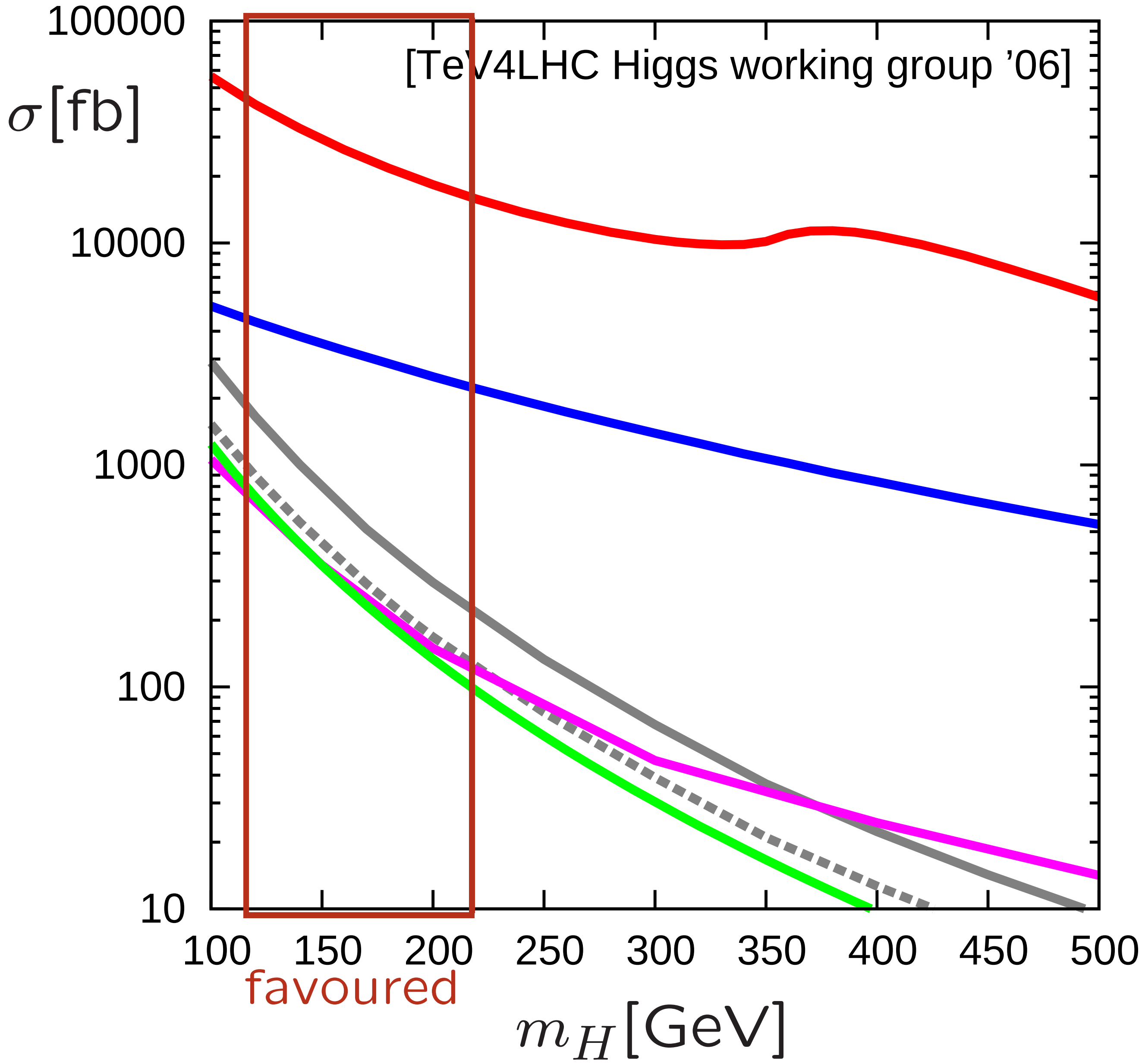
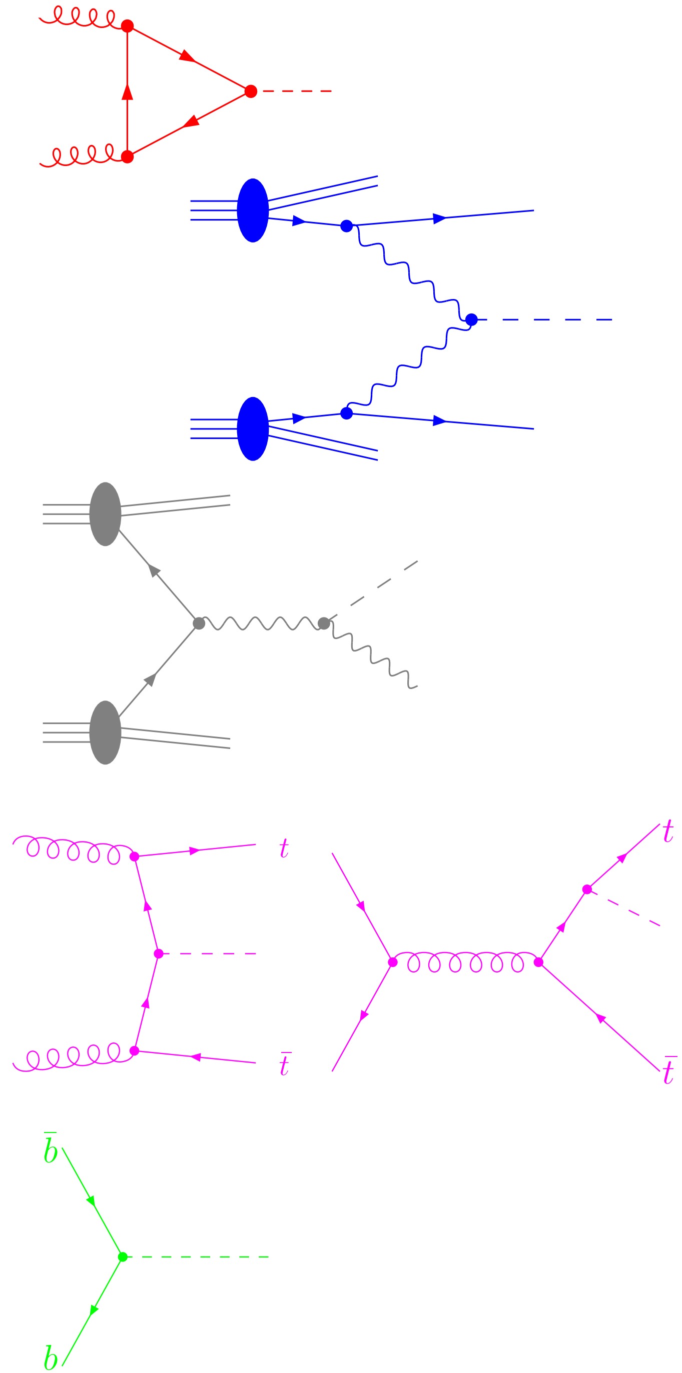


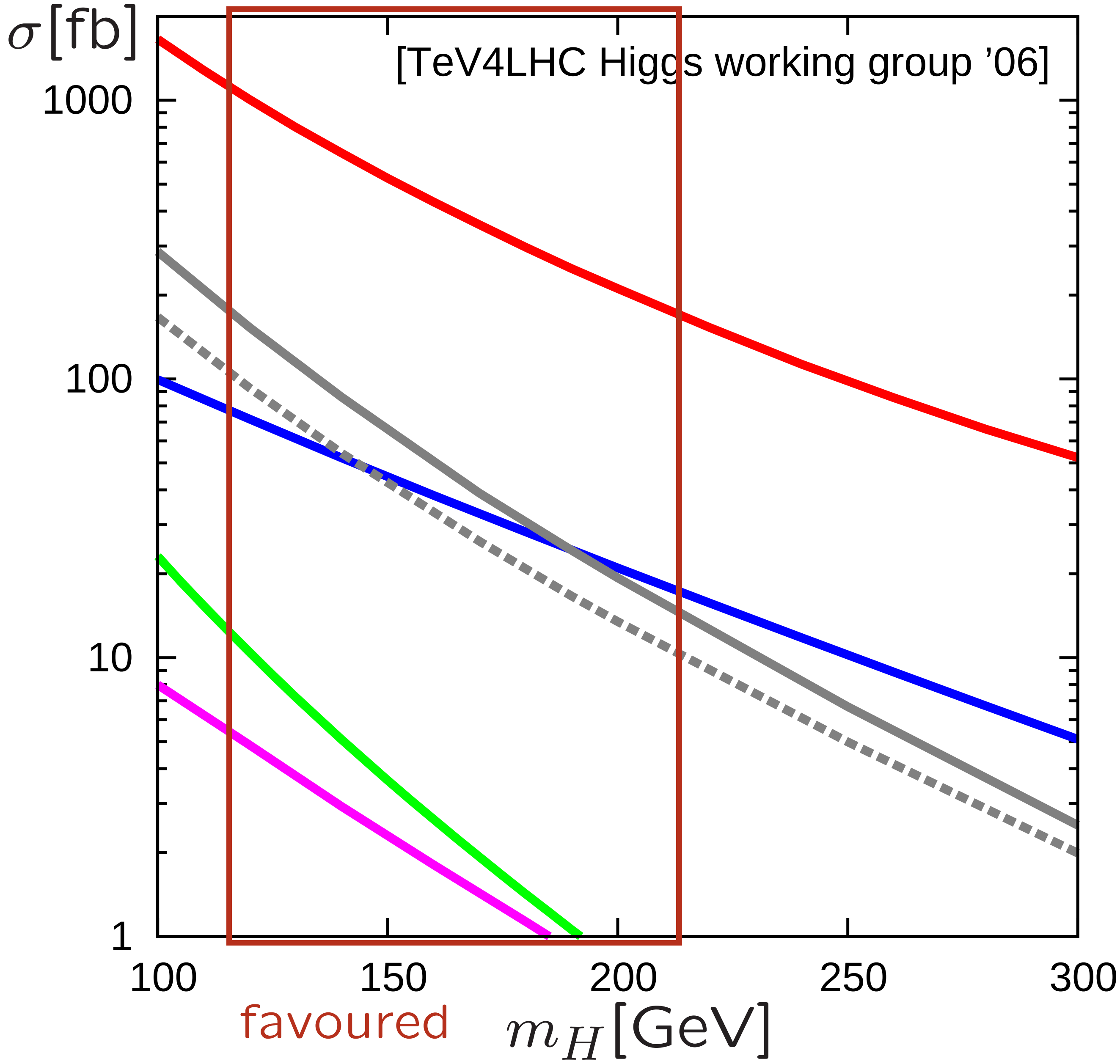


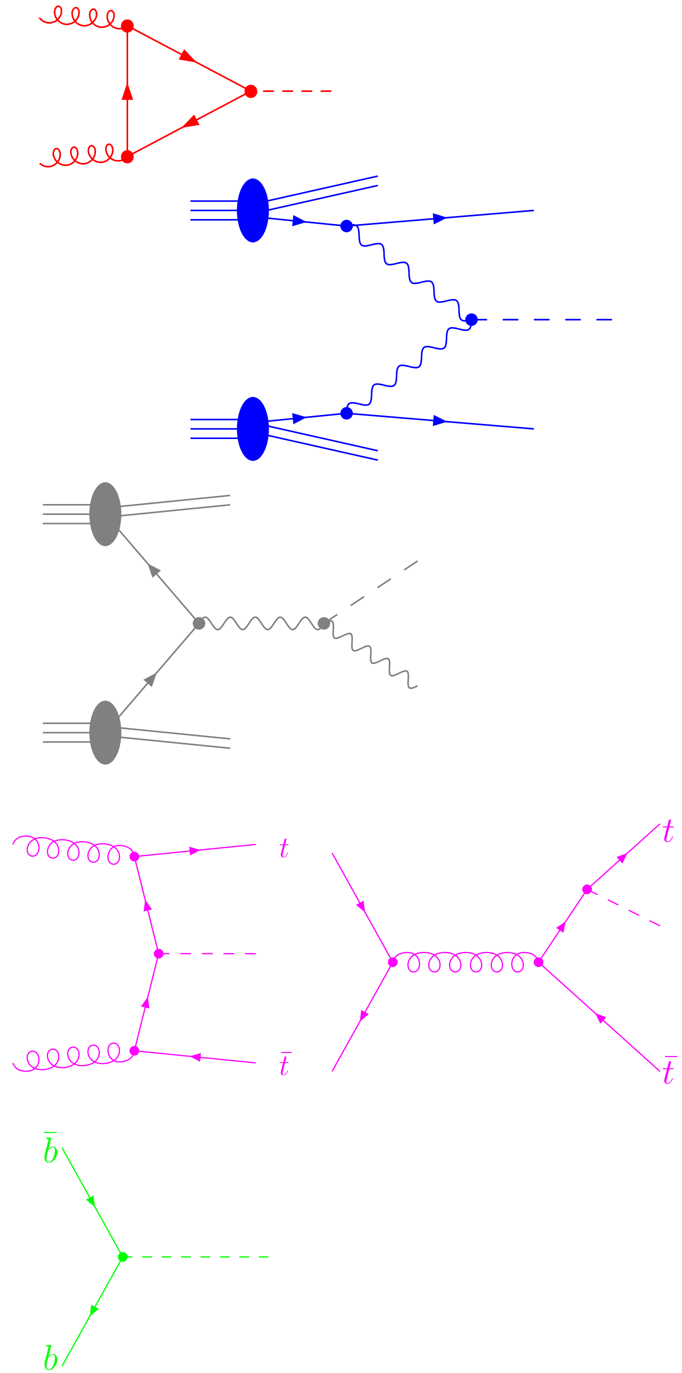
Predictions: SM Higgs production @ LHC :





Predictions: SM Higgs production @ **Tevatron** :





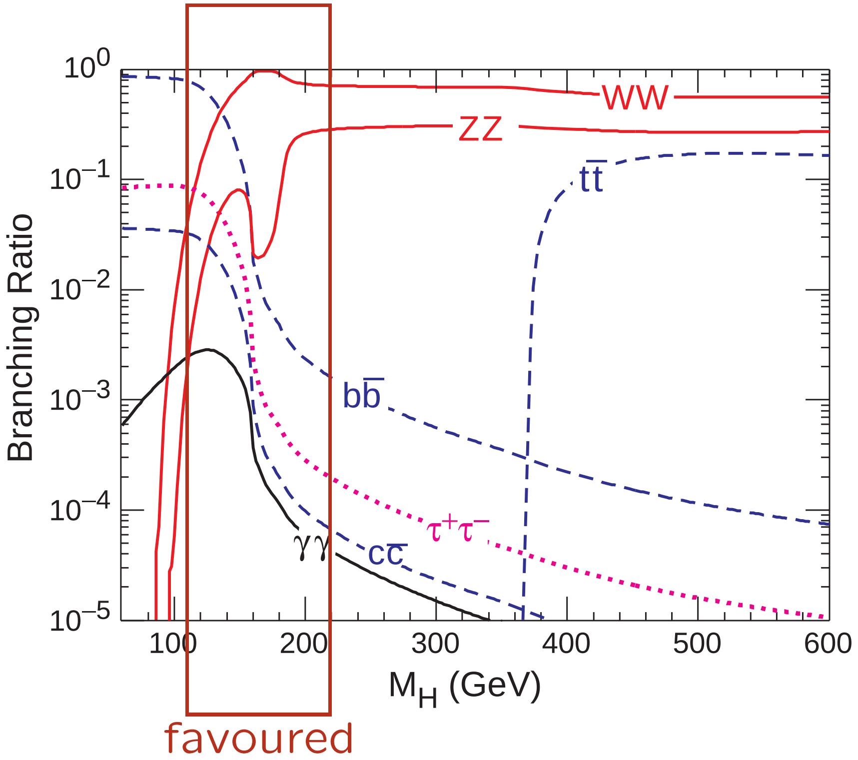
SM Higgs decay branching ratios
and
signal significance @ LHC

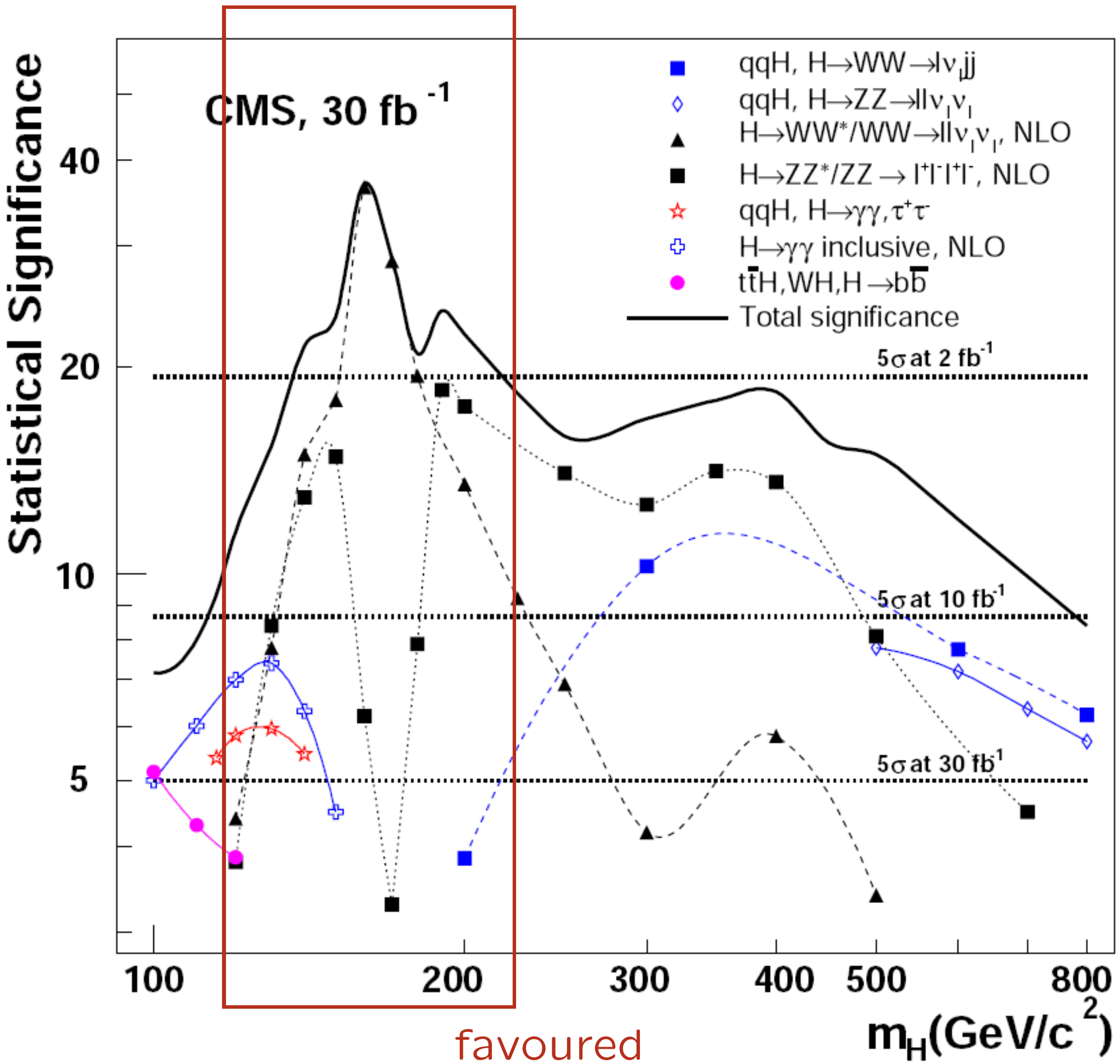
note!

rate alone is not enough!

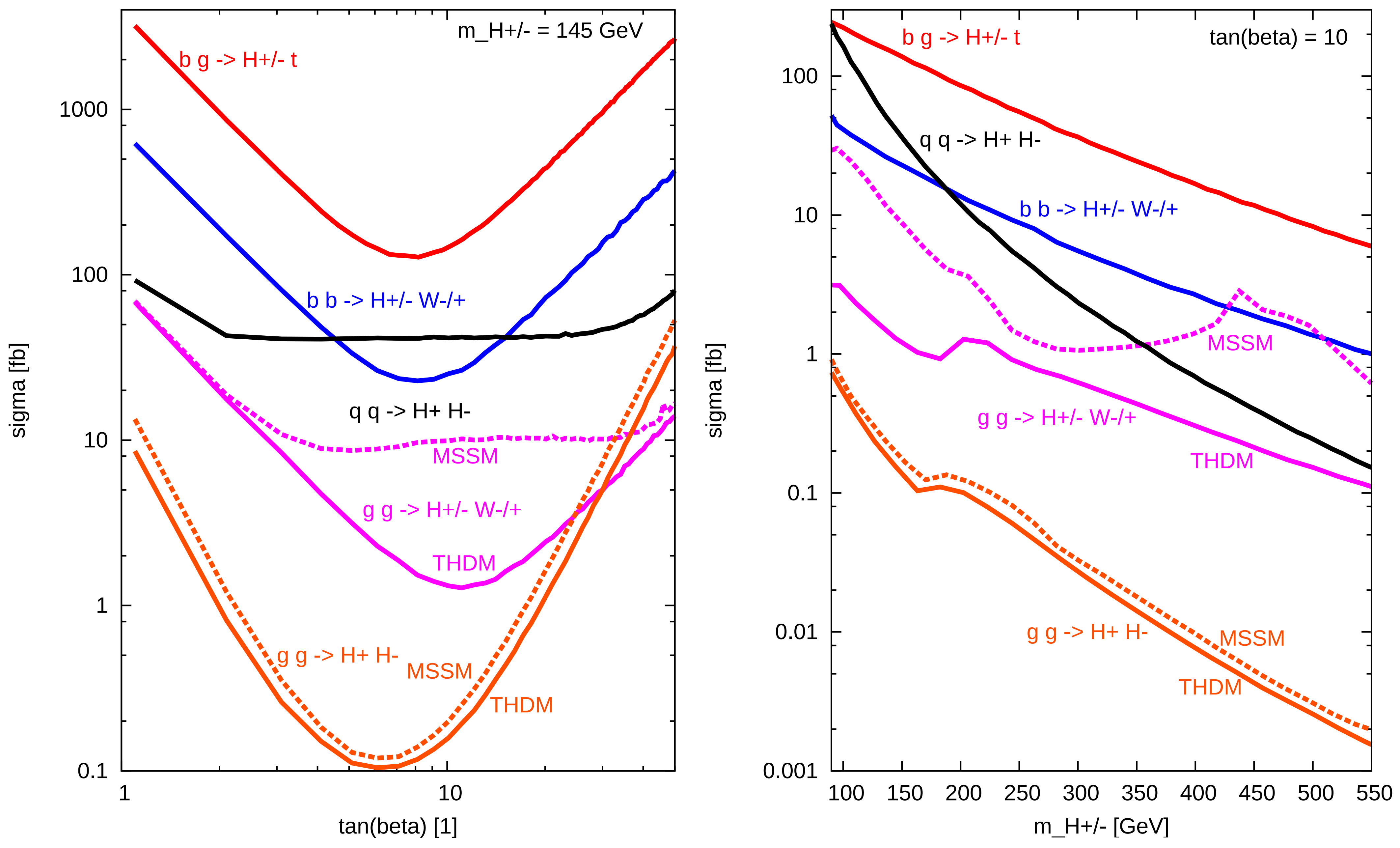
signals need to be silhouetted

against **huge** QCD background





Predictions: charged Higgs cross sections @ **LHC**:



– Higgs Search Programme

1. establish a Higgs signal
   production & decay $\longrightarrow$ rates & signatures, mass measurement

2. make sure it's a Higgs (measuring properties)
   angular distributions $\longrightarrow$ spin, parity, CP properties
   partial decay widths $\longrightarrow$ couplings to other particles
   ...

3. detailed probe of the Higgs sector (determining the underlying model)
   pair production $\longrightarrow$ self-couplings
   ("reconstruction" of the Higgs potential)
   quantum effects
   $\longrightarrow$ information on particles too heavy to be directly observed
   ...

Step 3: performance of the LHC limited, ideal task for the ILC.

- Selected Higgs Physics Projects

outline of the following:

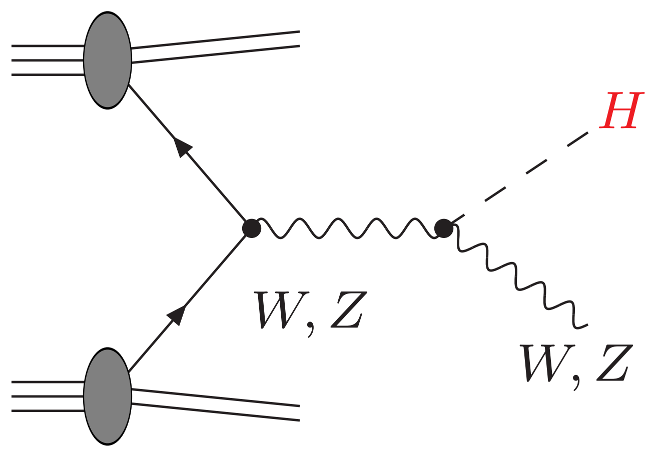
- SM Higgsstrahlung

- Higgs + high-p_T Jet: MSSM vs. SM

- HiggsBounds

– SM Higgsstrahlung

– SM Higgsstrahlung



Higgs strahlung, $q\bar{q}' \to VH$

Our calculation: [OBr, Djouadi, Harlander '03]

Observation 1:

In LO/NLO QCD the cross section factorizes ($V = W, Z$):

$$\frac{d\sigma}{dk^2}(q\bar{q} \to HV) = \sigma(q\bar{q} \to V^\star(k)) \cdot \frac{d\Gamma}{dk^2}(V^\star(k) \to HV)\,.$$

Observation 2:

Complete NNLO QCD corr. to $\sigma(q\bar{q} \to V^\star)$ are known

[Hamberg, van Neerven, Matsuura '91; Harlander, Kilgore '02].

$\longrightarrow$ Idea : Use $\sigma_{\mathrm{NNLO}}(q\bar{q} \to V^\star)$ to evaluate $\sigma(pp \to HV)$.

status of theory predictions:

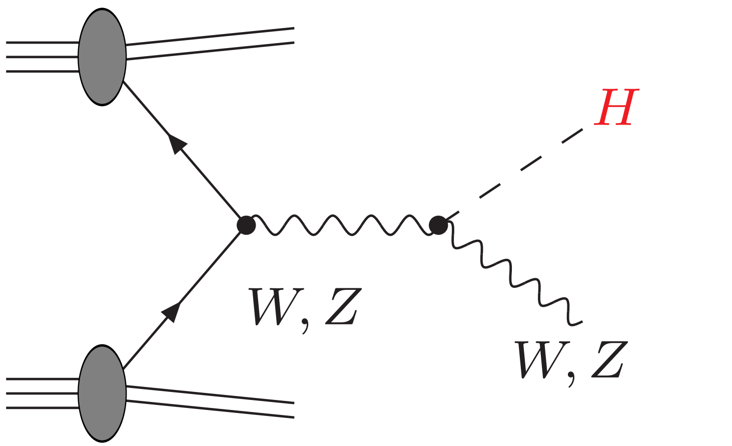
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

SM, NNLO QCD [OBr, Djouadi, Harlander '03]

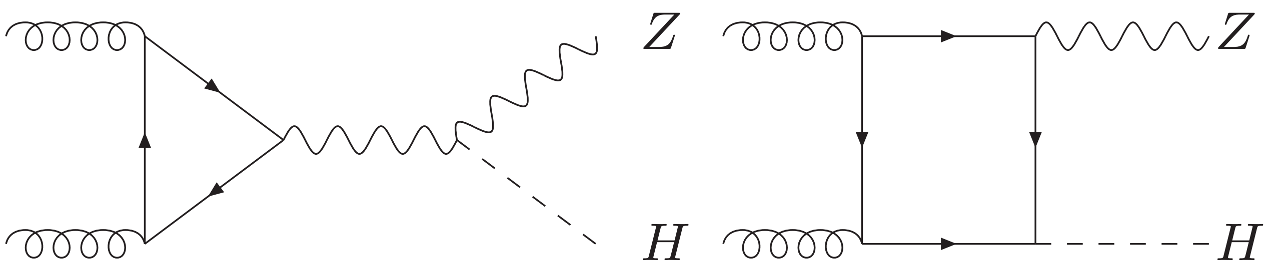
SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

MSSM, NLO SUSY-QCD [Djouadi, Spira '00]

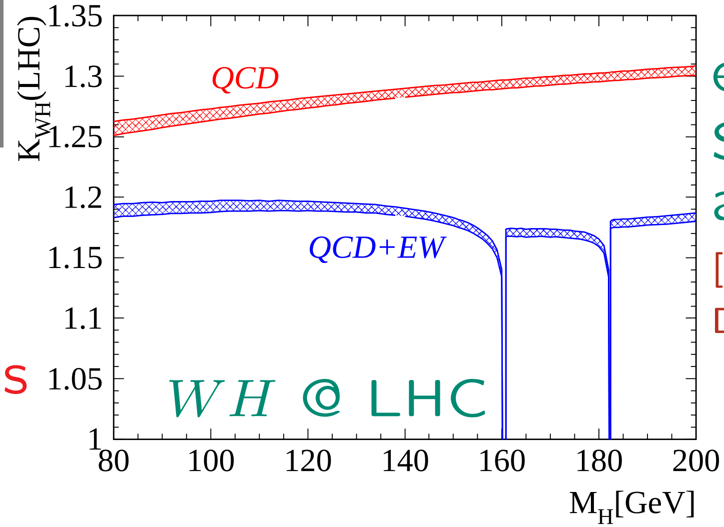


Higgs strahlung, $q\bar{q}' \to VH$

note! additional parton process for ZH @ NNLO



[Dicus, Kao '88; Kniehl '90]



example:
SM K-factors
and scale uncertainty
[OBr, Ciccolini, Dittmaier,
Djouadi, Harlander, Krämer '04;

→ our results regularly used
by Tevatron collaborations

status of theory predictions:

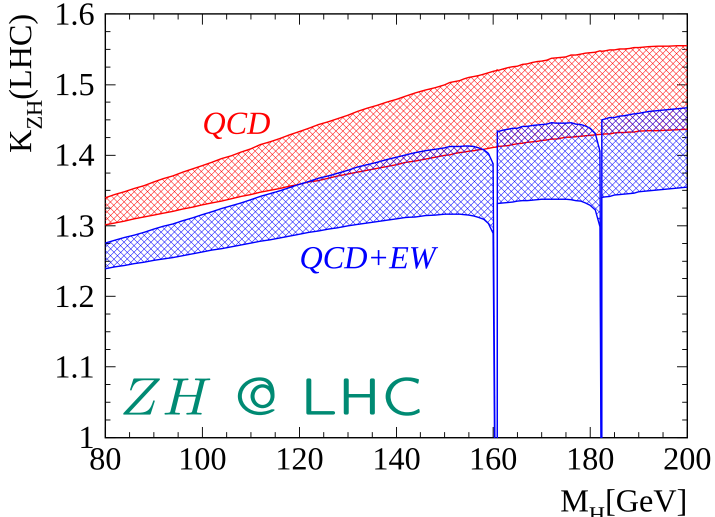
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

SM, NNLO QCD [OBr, Djouadi, Harlander '03]

SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

MSSM, NLO SUSY-QCD [Djouadi, Spira '00]



– Higgs + high-p_T Jet: MSSM vs. SM

– Higgs + high-p_T Jet: MSSM vs. SM

[OBr, Hollik '03; '07] (full MSSM), [Field, Dawson, Smith '04] (MSSM, no superpartners), [Langenegger et al. '06] (MSSM with soft-gluon resummation, no superpartners)

Motivation:

* richer kinematical structure compared to inclusive Higgs production
* promising simulation results in the SM case
[Abdullin et al. '98 & '02; Zmushko '02; Mellado et al. '05]
* process loop-induced → potentially large effects from virtual particles

partonic processes similar to the SM:

gluon fusion	$gg \to h^0 g$,
quark-gluon scattering	$q(\bar{q})g \to h^0 q(\bar{q})$,
$q\bar{q}$ annihilation	$q\bar{q} \to h^0 g$

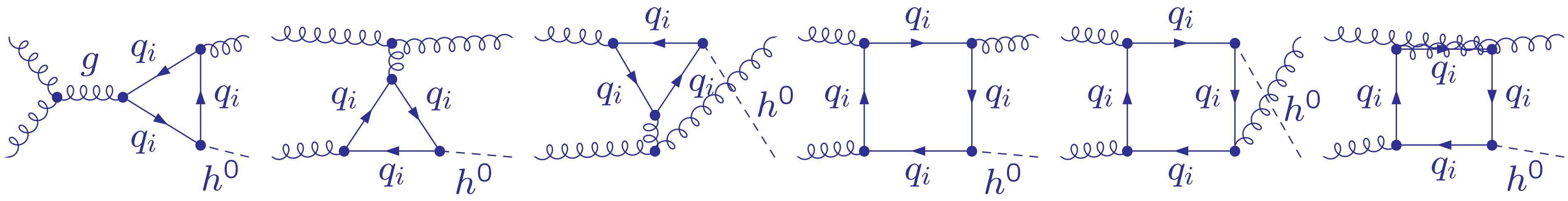
but: * different Higgs Yukawa-couplings : $g^{\text{MSSM}}_{q\bar{q}h^0} = g^{\text{SM}}_{q\bar{q}H} \times f_q(\alpha, \beta)$
→ mainly change of overall rate

* additional superpartner-loops (even additional topologies)
→ also angular distribution changed

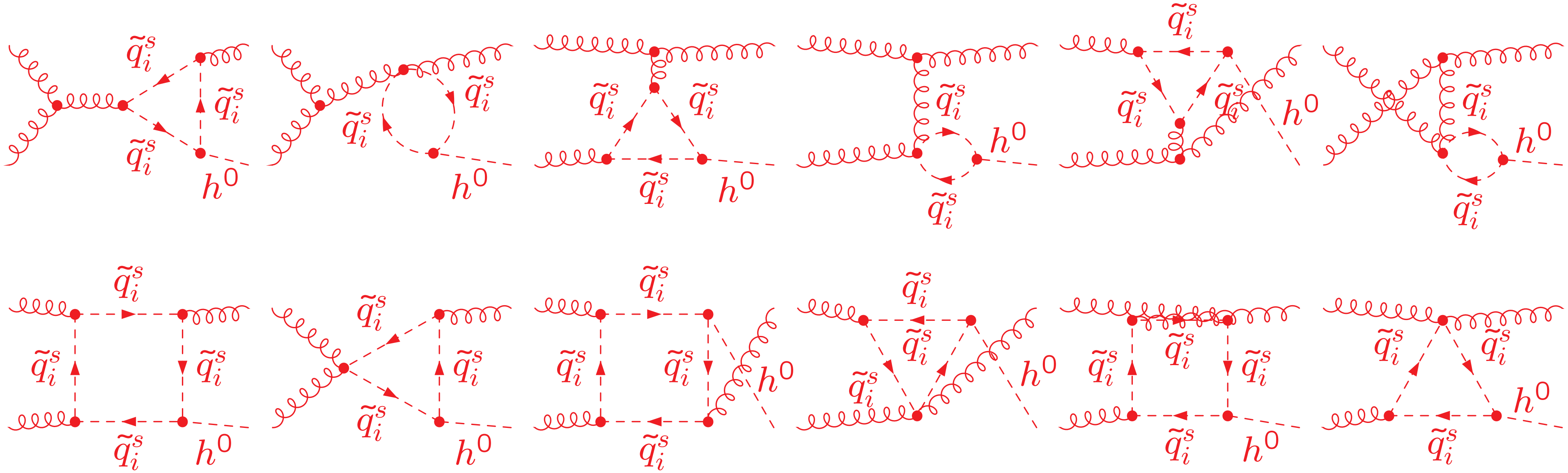
Feynman graphs :

gluon fusion, $gg \to h^0 g$

quark loops

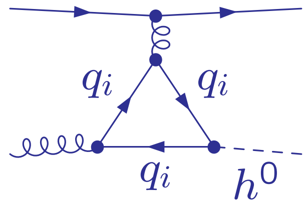


superpartner loops

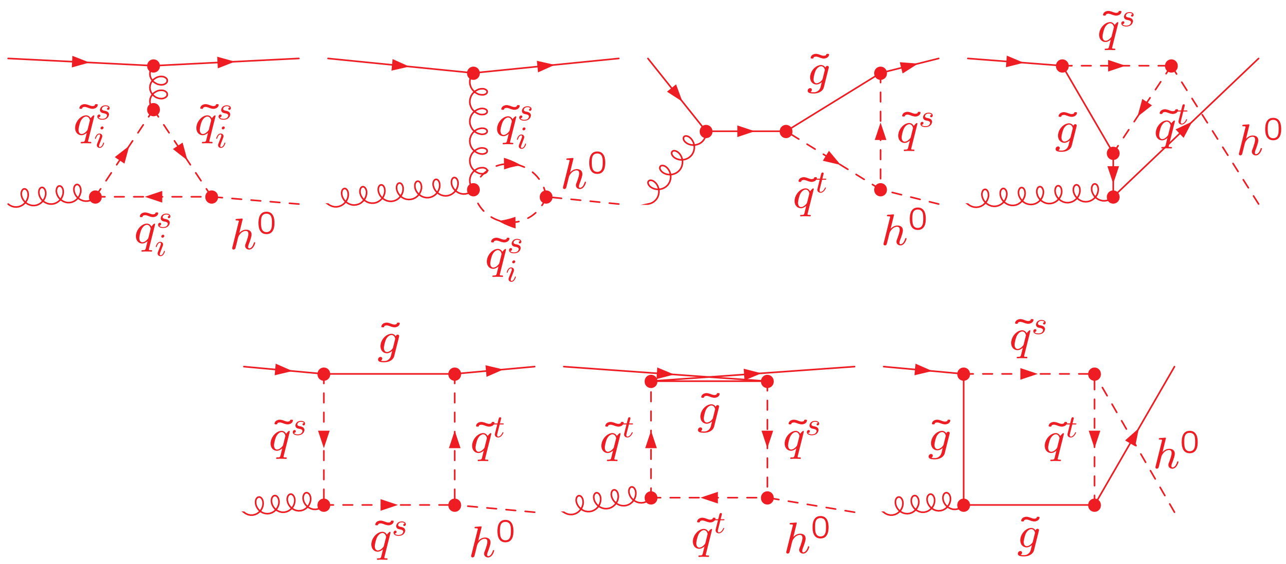


quark gluon scattering, $qg \to h^0 q$

quark loops

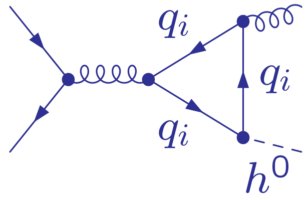


superpartner loops

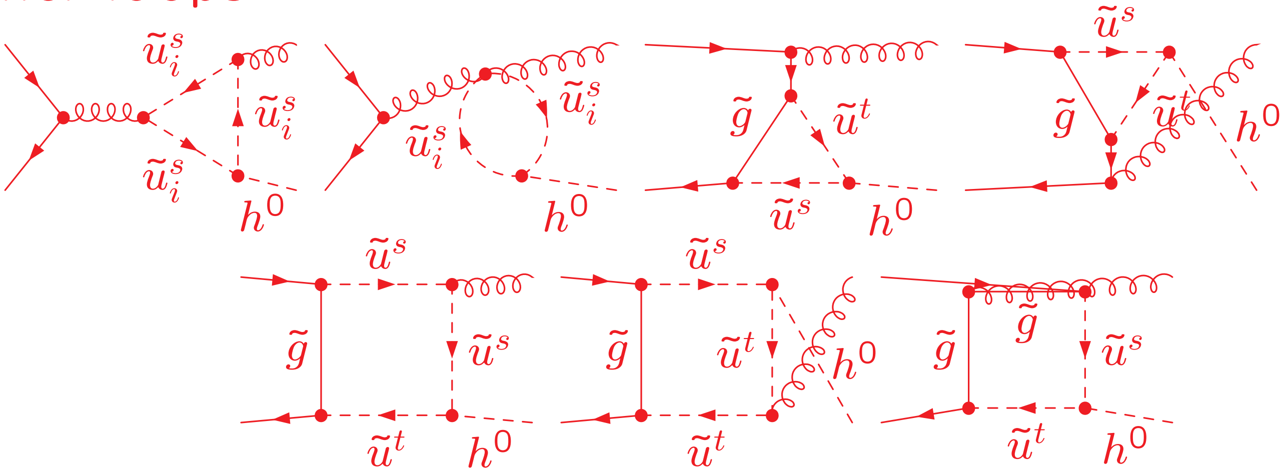


quark anti-quark annihilation, $q\bar{q} \longrightarrow h^0 g$

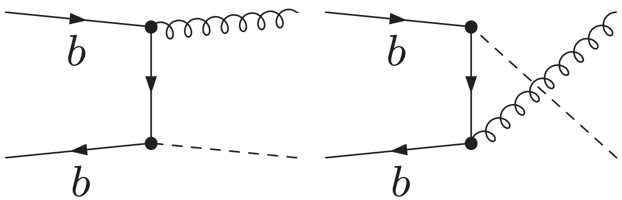
quark loops



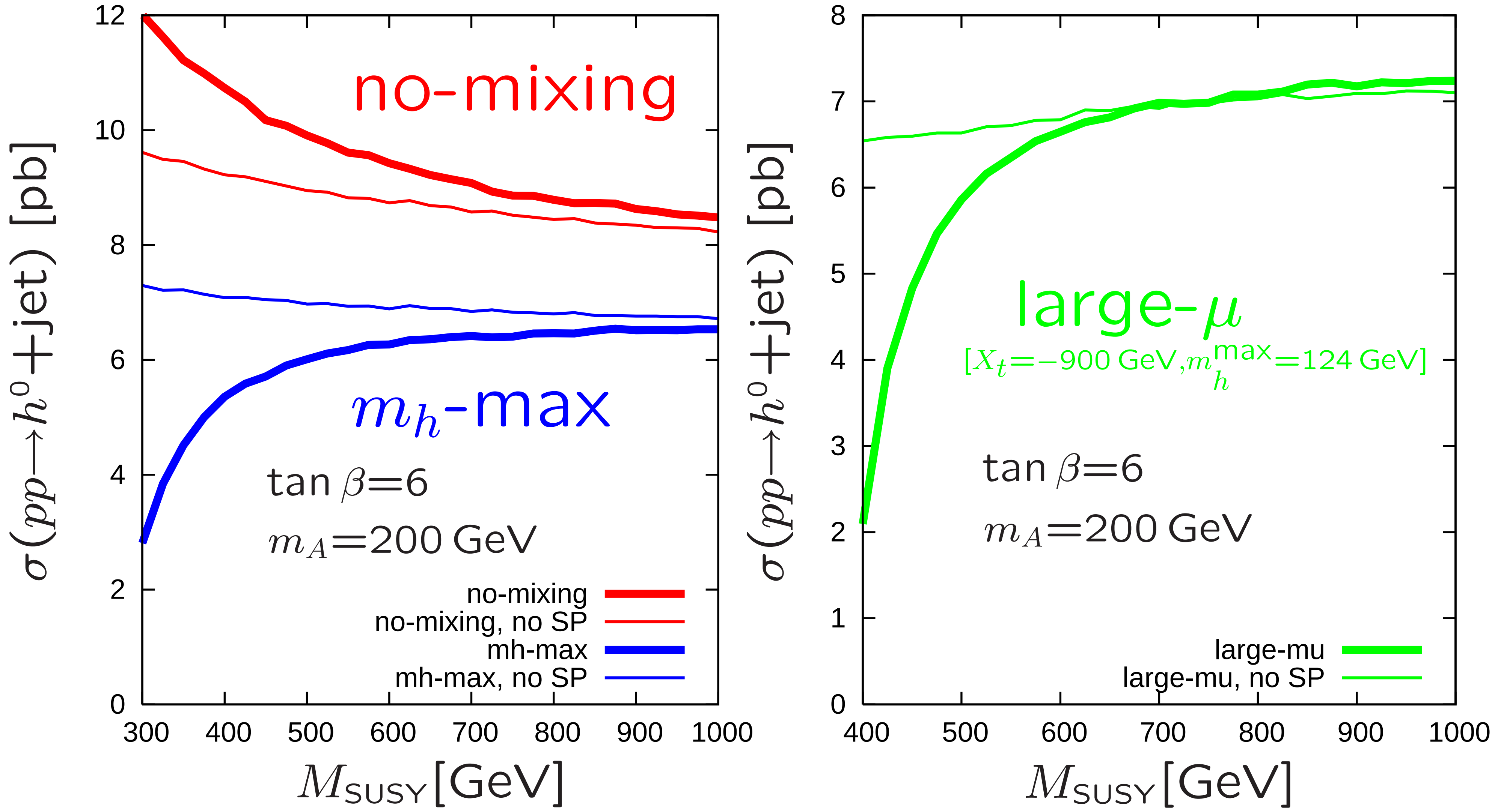
superpartner loops



b-quark processes: bg scattering, $bg \longrightarrow h^0 b$,
$b\bar{b}$ annihilation, $b\bar{b} \longrightarrow h^0 g$

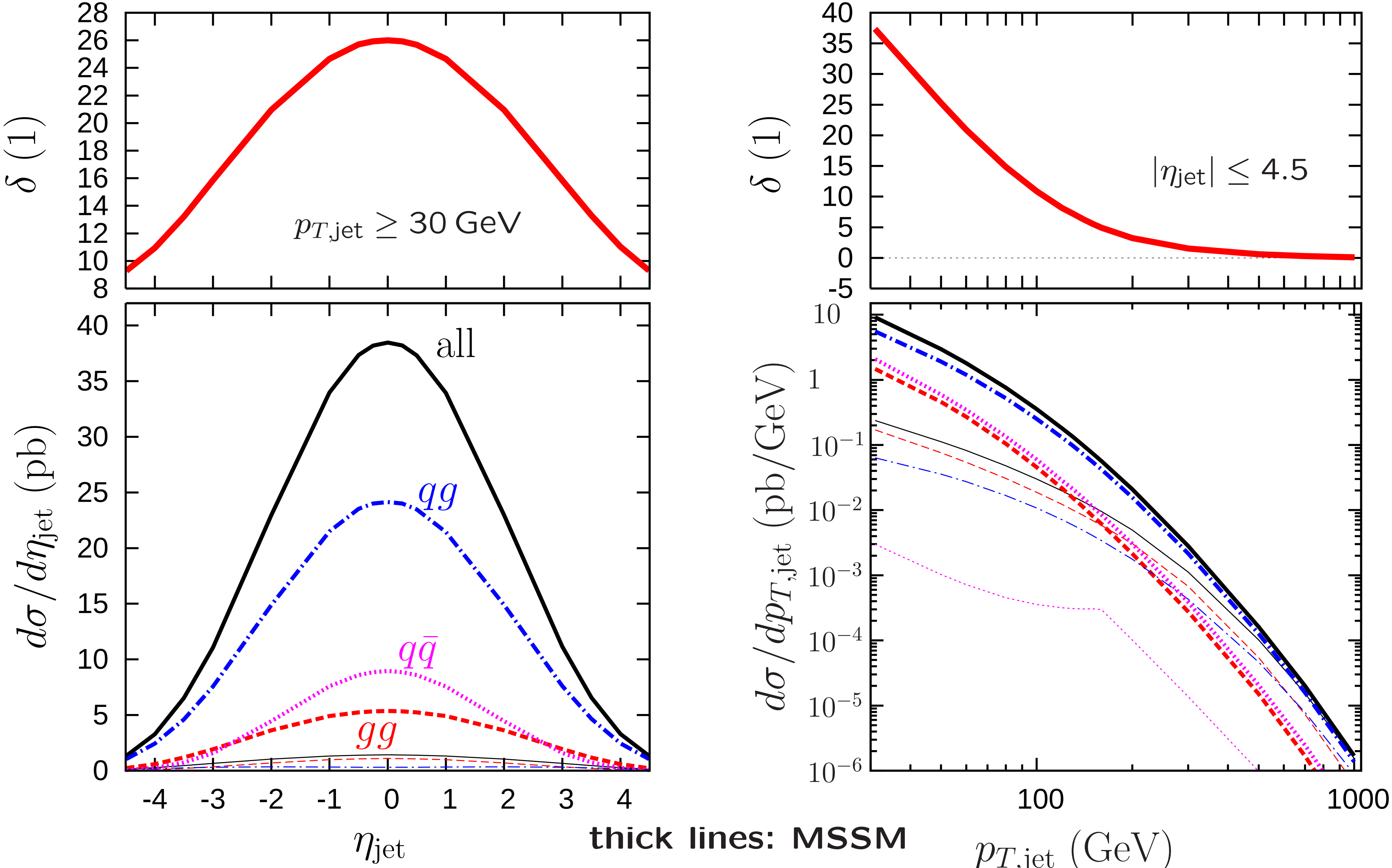


dependence on squark mass scale (M_{SUSY}):



$p_{T,\mathrm{jet}}$- and η_{jet}-dependence, low-m_A case

LHC, m_h-**max scenario**, $M_{\mathrm{SUSY}} = 400$ **GeV**, $m_A = 110$ **GeV**, $\tan\beta = 30$

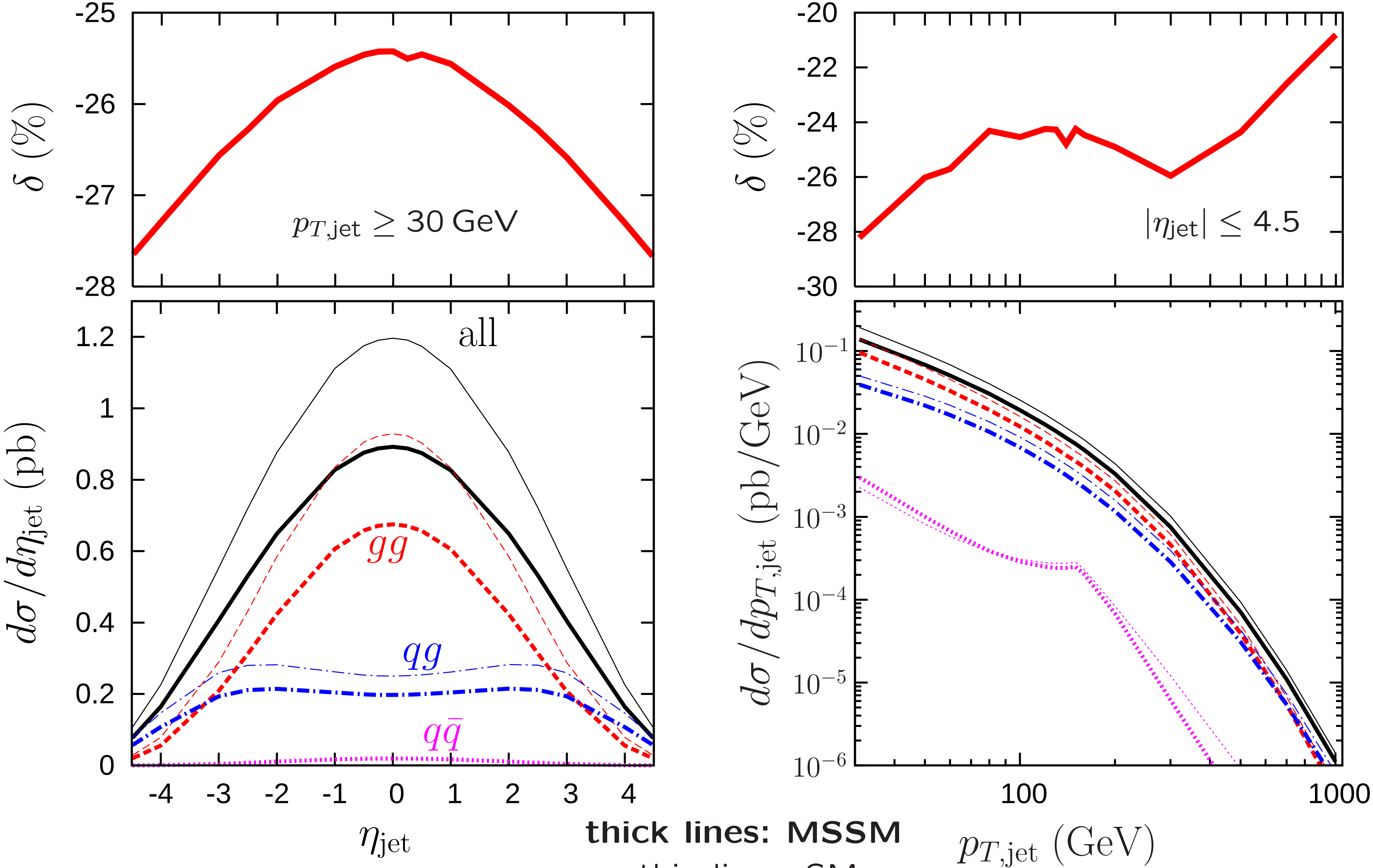


thick lines: MSSM

thin lines: SM

$p_{T,\text{jet}}$- and η_{jet}-dependence, high-m_A case

LHC, **m_h-max scenario**, $M_{\text{SUSY}} = 400$ **GeV**, $m_A = 400$ **GeV**, $\tan\beta = 30$



thick lines: MSSM

thin lines: SM

Recent development: theoretical study of SM Higgs + high-p_T jet:

[Keung, Petriello '09]

1. finite quark mass effects on p_T distribution
   $\longrightarrow$ already included in our calculation [OBr, Hollik '03; '07]

2. electroweak loop effects on p_T distribution
   $\longrightarrow$ calculation done, numerical study is work in progress

$\longrightarrow$ comparison with Keung and Petriello successfully completed

$\longrightarrow$ studied effects on η distribution as well

$\longrightarrow$ also found : $bg \to Hb$, $b\bar{b} \to Hg$ conribute relevantly

$\longrightarrow$ calculation of MSSM pendant is work in progress

– HiggsBounds

– Motivation

Higgs search results:

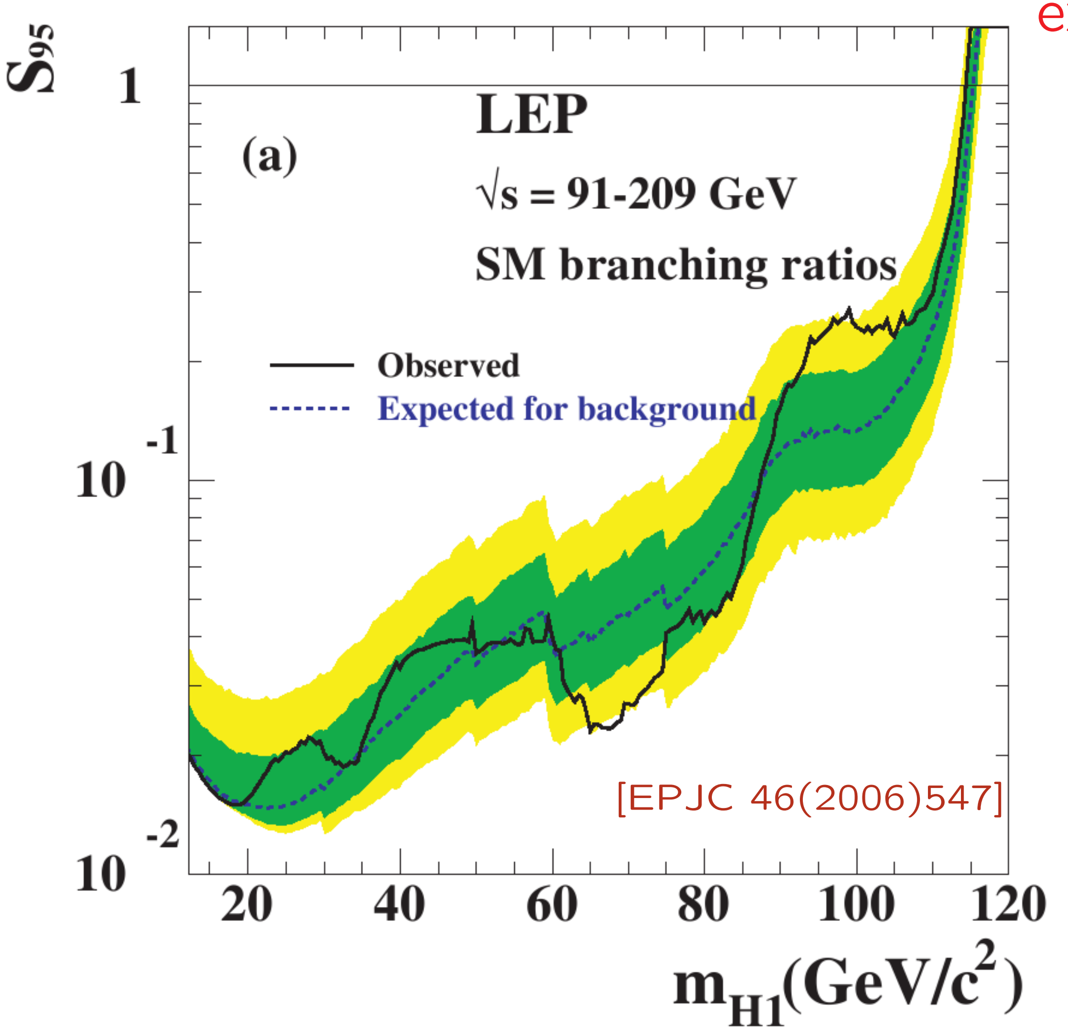
- So far: no Higgs signals.
  - LEP searched for them.
  - Tevatron is currently searching for them.

- Tevatron and LEP turn(ed) the non-observation of Higgs signals into 95% C.L. limits on rates/cross sections of ...

  a) ... individual signal topologies,
  e.g. $e^+e^- \to h_i Z \to b\bar{b}Z$, $p\bar{p} \to h_i \to W^+W^-$,

  b) ... combinations of signal topologies
  e.g. SM, MSSM combined limits.

Higgs search results: example 1: LEP SM combined limit



exclusion: rejection of the Higgs hypothesis

$$S_{95}(m_{H1}) := \frac{\sigma_{\rm min}}{\sigma_{\rm SM}}(m_{H1})$$

where $\sigma_{\rm min}(m_{H1})$ is the Higgs prod. cross section where data and Higgs hypothesis are compatible with 5% probability.

A SM-like model with

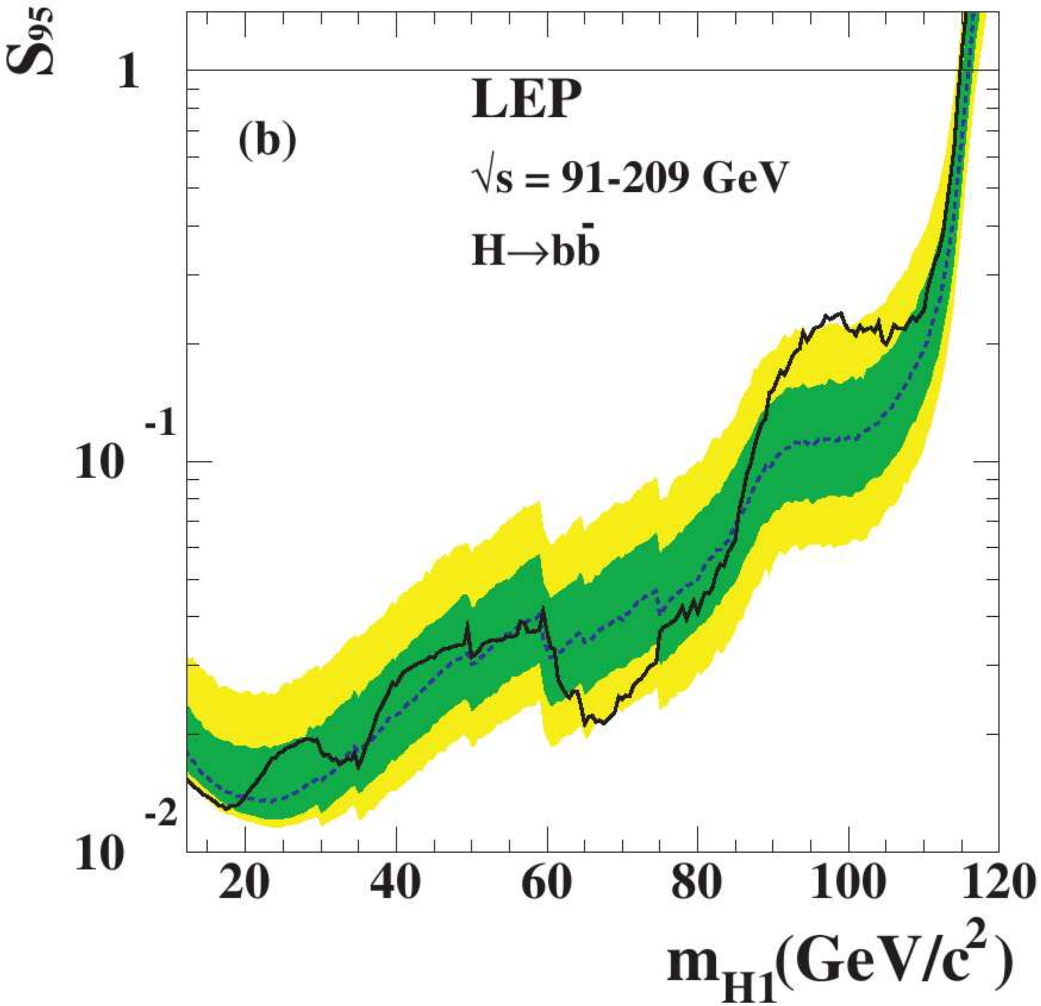
$$\sigma_{\rm model}(m_{H1}) > \sigma_{\rm min}(m_{H1})$$

or $\frac{\sigma_{\rm model}(m_{H1})}{\sigma_{\rm min}(m_{H1})} > 1$

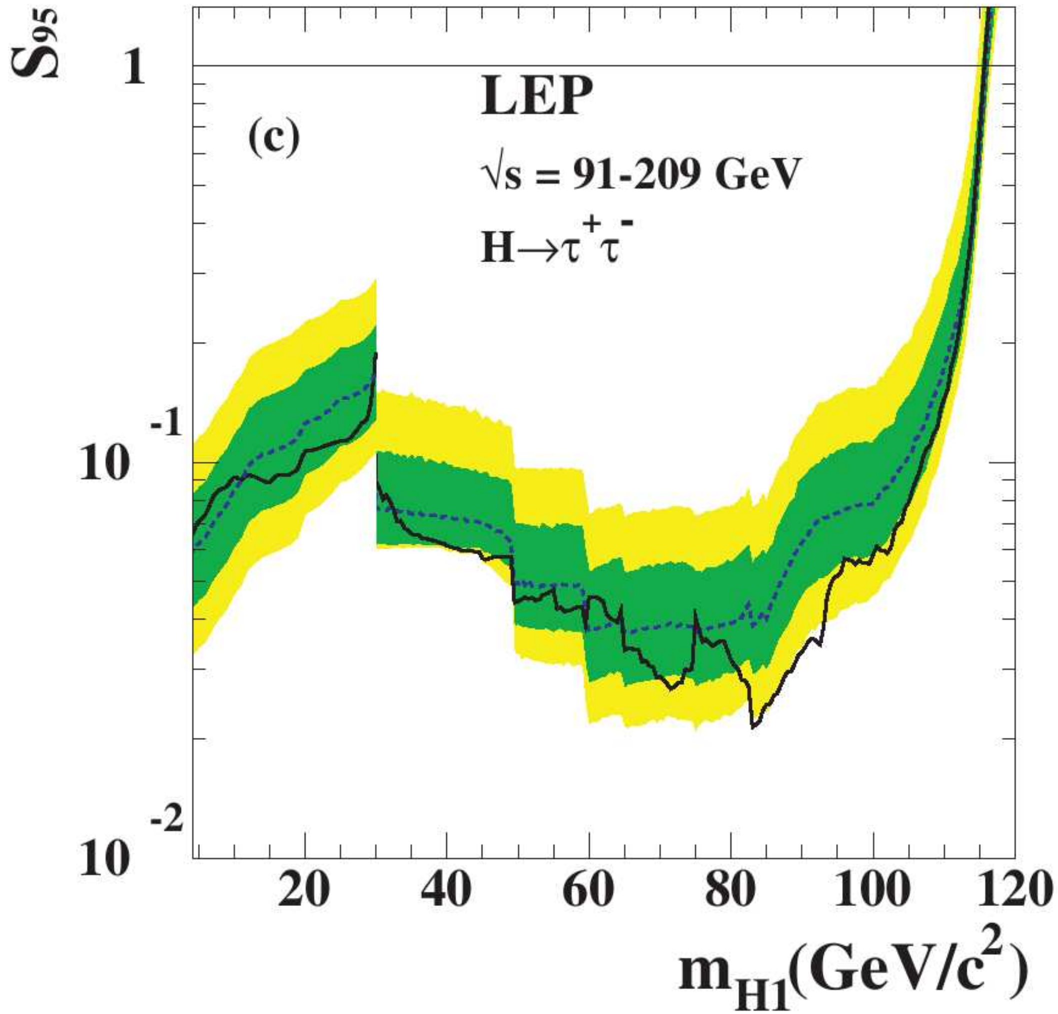
is said to be excluded at the 95% C.L.

example 2: LEP single topology limits, assuming HZ production and ...

a) ... BR($H \to b\bar{b}$)=1

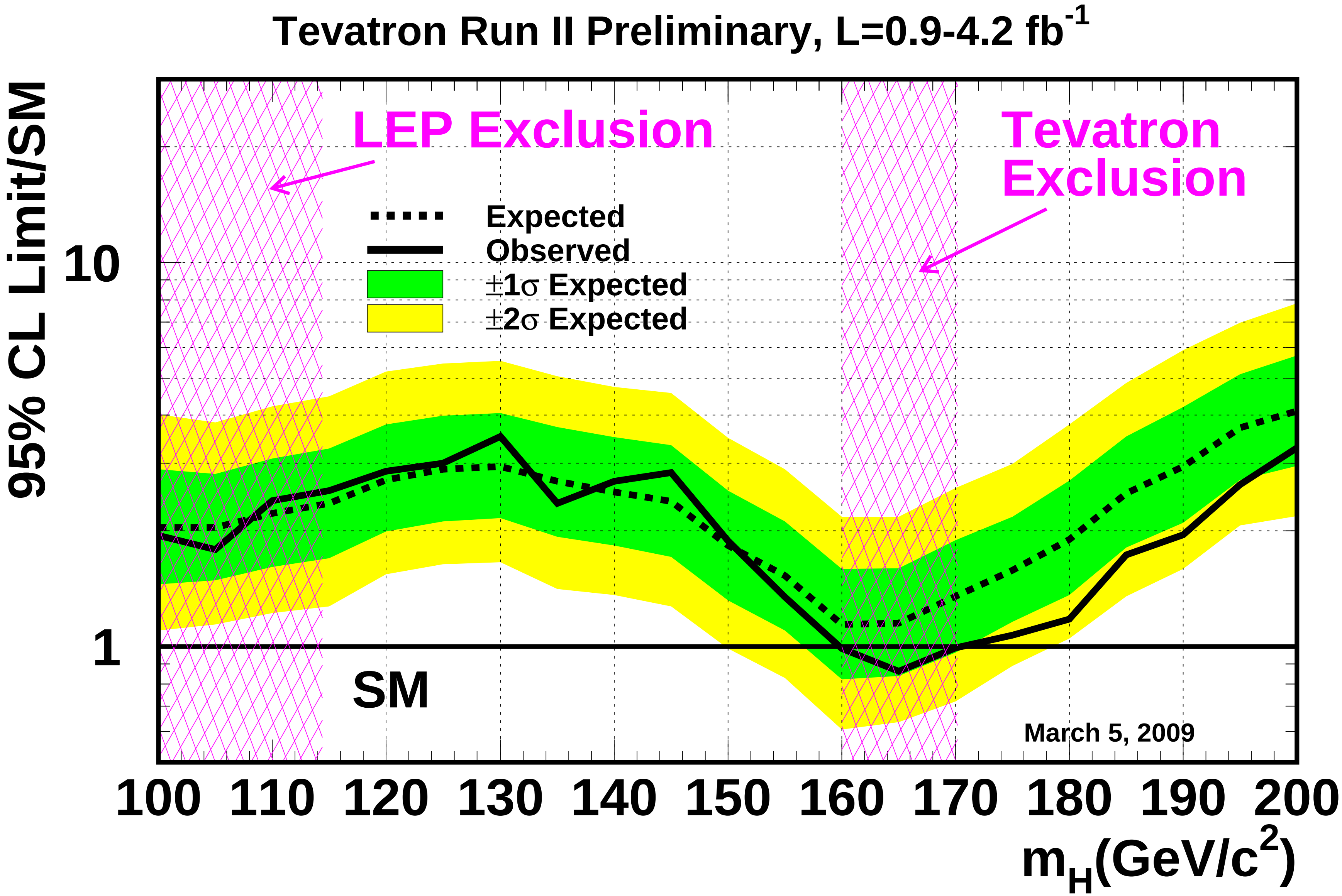


b) ... BR($H \to \tau^+\tau^-$)=1



[EPJC 46(2006)547]

example 3: Tevatron SM combined limit [CDF note 9713, DØ note 5889]



HiggsBounds:

[Bechtle, OBr, Heinemeyer, Weiglein, Williams '08]

Test theoretical predictions of models with arbitrary Higgs sectors against exclusion bounds obtained from Higgs searches at LEP and the Tevatron.

- Easy access to all relevant Higgs exclusion limits
  including information not available in the publications.
  (e.g. expected 95% CL cross section limits for some LEP combinations)

- Applicable to models with arbitrary Higgs sectors (narrow widths assumed)

  HiggsBounds Input: the predictions of the model for:
  # of Higgs bosons h_i , m_{h_i}, $\Gamma_{\text{tot}}(h_i)$, $\text{BR}(h_i \to \ldots)$,
  production cross section ratios (wrt reference values)

- Combination of results from LEP and Tevatron possible

- Three ways to use HiggsBounds:
  command line, library of subroutines (Fortran 77/90), web interface

  www.ippp.dur.ac.uk/HiggsBounds

– Implementation

Basic idea:

- Evaluate model prediction

$$Q_{\text{model}}(X) = \frac{[\sigma \times \text{BR}]_{\text{model}}}{[\sigma \times \text{BR}]_{\text{ref}}} \qquad \text{(reference: usually SM)}$$

  of a search topology of an analysis X,
  for given Higgs masses + deviations from the reference.

- From the experimental analysis X, read off the corresponding observed 95% C.L. limit: $Q_{\text{observed}}(X)$.

- If $\frac{Q_{\text{model}}(X)}{Q_{\text{observed}}(X)} > 1$ the model is excluded by this analysis at 95% C.L.

→ Problem : how to combine search results without losing the 95% C.L. ?

Answer: We can't do that.

Only a dedicated experimental analysis can do that.

However: we can always use the analysis of highest statistical sensitivity.

How to preserve the 95% C.L. limit:

- Obtain for each analysis X the experimental expected limit $Q_{\text{expected}}(X)$.
- Determine the analysis X_0 with the highest sensitivity for the signal, i.e. of all analyses X find the one X_0 where $\frac{Q_{\text{model}}(X)}{Q_{\text{expected}}(X)}$ is maximal.
- If for this analysis $\frac{Q_{\text{model}}(X_0)}{Q_{\text{observed}}(X_0)} > 1$ the model is excluded at 95% C.L.

implemented analyses : LEP [HiggsBounds 1.2.0]

We include expected and observed S_{95} values for the following analyses

1. $e^+e^- \to (h_k)Z \to (b\bar{b})Z$, [EPJC 46(2006)547]
2. $e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$, [EPJC 46(2006)547]
3. $e^+e^- \to (h_k)Z \to (\gamma\gamma)Z$, [LEP Higgs WG note 2002-02]
4. $e^+e^- \to (h_k)Z \to (\text{anything})Z$, [OPAL, EPJC 27(2003)311]
5. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b}b\bar{b})Z$, [EPJC 46(2006)547]
6. $e^+e^- \to (h_k \to h_i h_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$, [EPJC 46(2006)547]
7. $e^+e^- \to (h_k h_i) \to (b\bar{b}b\bar{b})$, [EPJC 46(2006)547]
8. $e^+e^- \to (h_k h_i) \to (\tau^+\tau^-\tau^+\tau^-)$, [EPJC 46(2006)547]
9. $e^+e^- \to (h_k \to h_i h_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$, [EPJC 46(2006)547]
10. $e^+e^- \to (h_k \to h_i h_i)h_i \to (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$, [EPJC 46(2006)547]
11. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$, [LEP Higgs WG]
12. $e^+e^- \to (h_k \to b\bar{b})(h_i \to \tau^+\tau^-)$, [LEP Higgs WG]
13. $e^+e^- \to (h_k \to \tau^+\tau^-)(h_i \to b\bar{b})$, [LEP Higgs WG]

Inclusion of additional topologies is work in progress
(e.g. $e^+e^- \to h_k Z, h_k \to$ invisible; $e^+e^- \to h_k Z, h_k \to$ 2 jets, ...)

implemented analyses : Tevatron [HiggsBounds 1.2.0]

single topology analyses

search topology X (analysis)	reference ($\star$=published)
$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (CDF with 4.1 [2.7]fb^{-1})	CDF note 9475 [CDF '09]*
$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (DØ with 4.2 fb^{-1})	DØ note 5876
$p\bar{p} \to WH \to l\nu b\bar{b}$ (CDF with 4.3 [2.7] fb^{-1})	CDF '09 [CDF '09]*
$p\bar{p} \to WH \to l\nu b\bar{b}$ (DØ with 5.0 [1.1] fb^{-1})	DØ note 5972 [DØ '08]*
$p\bar{p} \to WH \to W^+W^-W^\pm$ (DØ with 3.6 fb^{-1})	DØ note 5873
$p\bar{p} \to WH \to W^+W^-W^\pm$ (CDF with 2.7 fb^{-1})	CDF note 7307 v3
$p\bar{p} \to H \to W^+W^- \to l^+l'^-$ (DØ with 3.0 fb^{-1})	DØ note 5757
$p\bar{p} \to H \to W^+W^- \to l^+l'^-$ (CDF with 3.0 fb^{-1})	CDF '08*
$p\bar{p} \to H \to \gamma\gamma$ (DØ with 4.2 [2.7] fb^{-1})	DØ note 5858 [DØ '09]*
$p\bar{p} \to H \to \tau^+\tau^-$ (CDF with 1.8 fb^{-1})	CDF '09*
$p\bar{p} \to H \to \tau^+\tau^-$ (DØ with 2.2 [1.0] fb^{-1})	DØ 5740 [DØ '08]*
$p\bar{p} \to H \to \tau^+\tau^-$ (CDF & DØ with 1.8 & 2.2 fb^{-1})	CDF note 9888, DØ note 5980
$p\bar{p} \to bH, H \to \tau^+\tau^-$ (DØ with 2.7 [0.328] fb^{-1})	DØ note 5985 [DØ '09]*
$p\bar{p} \to bH, H \to b\bar{b}$ (CDF with 1.9 fb^{-1})	CDF note 9284
$p\bar{p} \to bH, H \to b\bar{b}$ (DØ with 2.6 [1.0] fb^{-1})	DØ note 5726 [DØ '08]*

implemented analyses : Tevatron [HiggsBounds 1.2.0]

analyses combining topologies

search topology X (analysis)	reference ($\star$=publ.)
$p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{\text{miss.}}$ (CDF with 3.6 [1.0] fb^{-1})	CDF note 9891 [CDF '08]*
$p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{\text{miss.}}$ (DØ with 2.1 [0.93] fb^{-1})	D0 note 5586 [DØ '08]*
$p\bar{p} \to H/HW/HZ/H$ via VBF, $H \to \tau^+\tau^-$ (CDF with 2.0 fb^{-1})	CDF note 9248
$p\bar{p} \to H/HW/HZ/H$ via VBF, $H \to WW$ (CDF with 4.8 fb^{-1})	CDF note 9887
$p\bar{p} \to H/HW/HZ/H$ via VBF, $H \to WW$ (CDF with 3.0-4.2 fb^{-1})	DØ note 5871
Combined SM analysis (CDF & DØ with 0.9 – 1.9 fb^{-1})	hep-ex/0712.2383
Combined SM analysis (CDF & DØ with 1.0 – 2.4 fb^{-1})	hep-ex/0804.3423
Combined SM analysis (CDF & DØ with 3.0 fb^{-1})	hep-ex/0808.0534
Combined SM analysis (CDF with 3.0 fb^{-1})	CDF note 9674
Combined SM analysis (CDF & DØ with 0.9 – 4.2 fb^{-1}) [At the moment, used only for $m_H \geq 155$ GeV.]	hep-ex/0903.4001
Combined SM analysis (CDF with 2.0 – 4.8 fb^{-1})	CDF note 9897

Development of HiggsBounds 2.0.0
is supported by the Helmholtz Alliance.

Input required by HiggsBounds: (example: input option `effC`)

number of Higgs bosons: n_{Higgs}

masses: m_{h_k} ,

total widths: $\Gamma_{\text{tot}}(h_k)$,

normalised squared effective couplings:

$$\left(\frac{g^{\text{model}}_{h_k ZZ}}{g^{\text{SM}}_{HZZ}}\right)^2, \quad \left(\frac{g^{\text{model}}_{h_k WW}}{g^{\text{SM}}_{HWW}}\right)^2, \quad \left(\frac{g^{\text{model}}_{h_k \gamma\gamma}}{g^{\text{SM}}_{H\gamma\gamma}}\right)^2, \quad \left(\frac{g^{\text{model}}_{h_k gg}}{g^{\text{SM}}_{Hgg}}\right)^2,$$

$$\left(\frac{g^{\text{model}}_{h_k bb,\text{eff}}}{g^{\text{SM}}_{Hbb}}\right)^2, \quad \left(\frac{g^{\text{model}}_{h_k \tau\tau,\text{eff}}}{g^{\text{SM}}_{H\tau\tau}}\right)^2, \quad \left(\frac{g^{\text{model}}_{h_k h_i Z}}{g^{\text{ref}}_{H'HZ}}\right)^2,$$

branching ratios: $\text{BR}_{\text{model}}(h_k \to h_i h_i)$,

for $k, i \in \{1, \ldots, n_{\text{Higgs}}\}$.

model predictions $Q_{\text{model}}(X)$ calculated with this input: LEP examples:

$$Q_{\text{model}}\left[e^+e^- \to (h_1)Z \to (b\bar{b})Z\right] = \frac{\sigma_{\text{model}}(h_1 Z)}{\sigma_{\text{ref}}(HZ)} \text{BR}_{\text{model}}(h_1 \to b\bar{b})\,,$$

$$Q_{\text{model}}\left[e^+e^- \to (h_2)Z \to (h_1 h_1)Z \to (b\bar{b}b\bar{b})Z\right] = \frac{\sigma_{\text{model}}(h_2 Z)}{\sigma_{\text{ref}}(HZ)} \text{BR}_{\text{model}}(h_2 \to h_1 h_1) \text{BR}_{\text{model}}(h_1 \to b\bar{b})^2$$

with

$$\frac{\sigma_{\text{model}}(e^+e^- \to h_k Z)}{\sigma_{\text{ref}}(e^+e^- \to HZ)} = \left(\frac{g^{\text{model}}_{h_k ZZ}}{g^{\text{SM}}_{HZZ}}\right)^2, \quad \frac{\sigma_{\text{model}}(e^+e^- \to h_k h_i)}{\sigma_{\text{ref}}(e^+e^- \to H'H)} = \left(\frac{g^{\text{model}}_{h_k h_i Z}}{g^{\text{ref}}_{H'HZ}}\right)^2,$$

$$\text{BR}_{\text{model}}(h_k \to b\bar{b}) = \text{BR}_{\text{SM}}(H \to b\bar{b})(m_H)\, \frac{\Gamma^{\text{SM}}_{\text{tot}}(m_H)}{\Gamma_{\text{tot}}(h_k)}\Bigg|_{m_H = m_{h_k}} \left(\frac{g^{\text{model}}_{h_k bb,\text{eff}}}{g^{\text{SM}}_{Hbb}}\right)^2.$$

green: provided functions using HDECAY 3.303 [Djouadi et al.'98]

– Applications

application 1: re-evaluation of SM exclusion with improved prediction

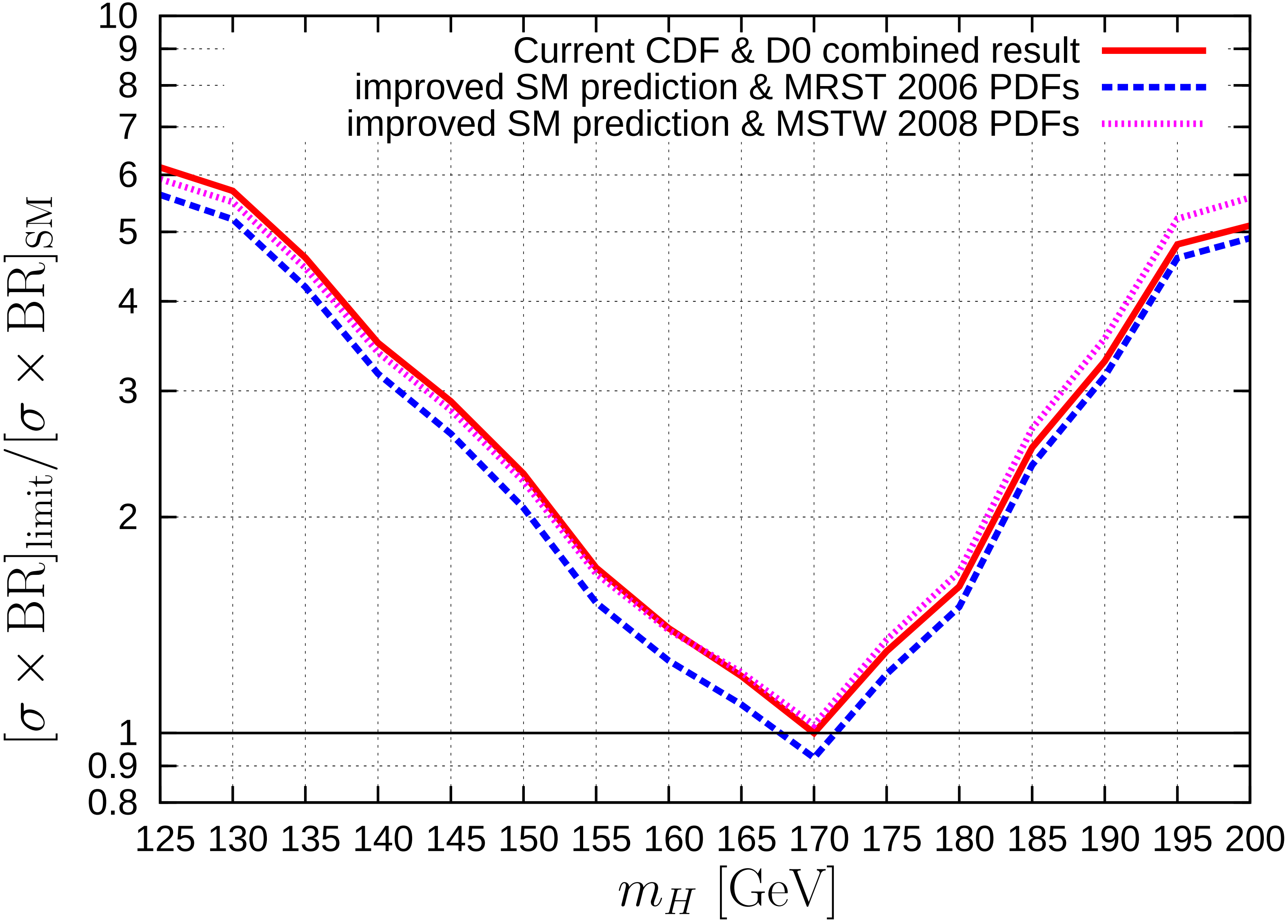
recent developments:

- Improved SM prediction for $\sigma(p\bar{p} \to gg \to H)$:
  mixed QCD-Electroweak corrections [Anastasiou, Boughezal, Petriello '08]
  $\rightarrow$ **"Our results motivate a reconsideration of the Tevatron exclusion limits."**

- Updated determination of PDFs: MSTW 2008 [Martin at al. '08]

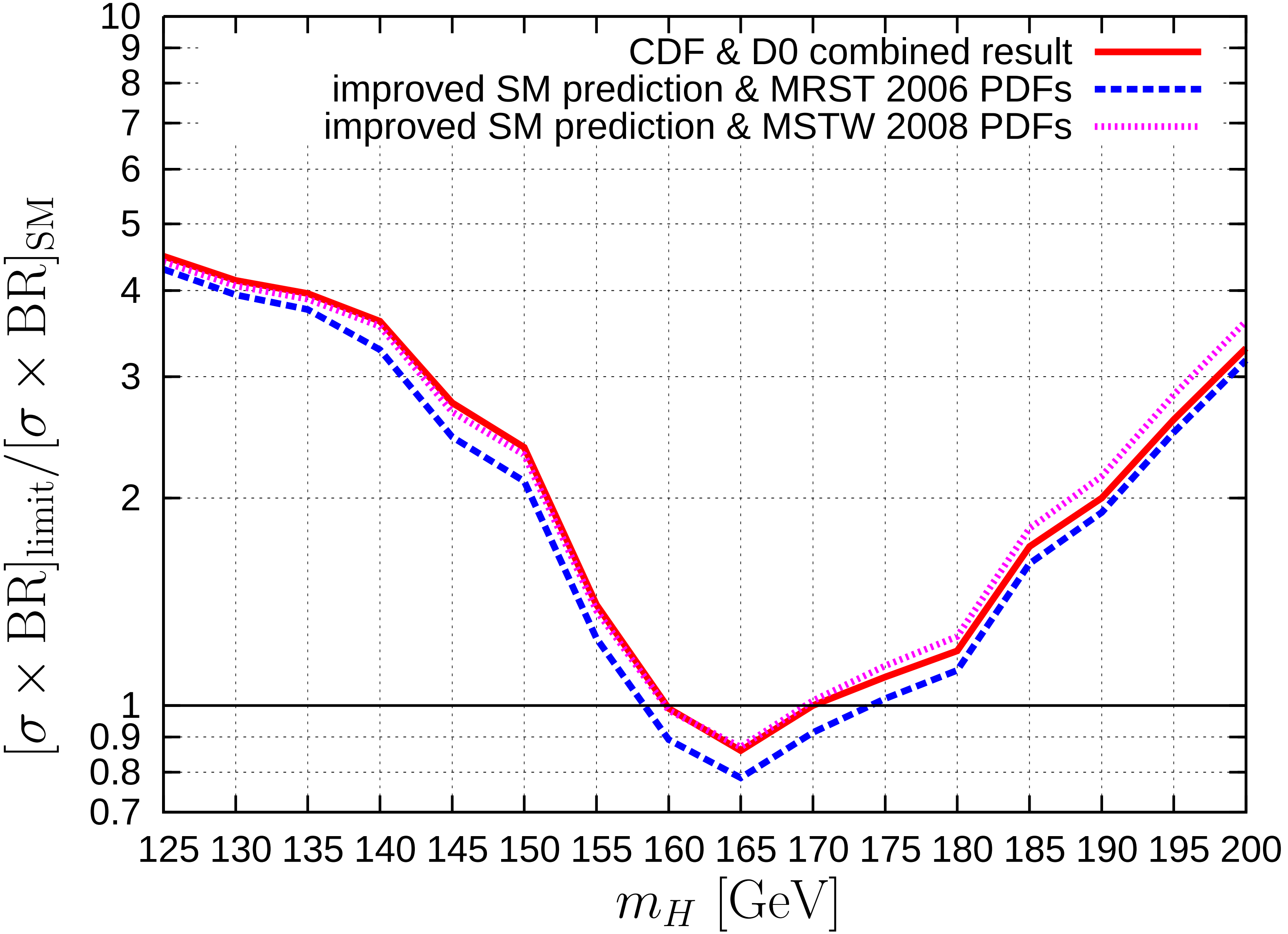
application 1: re-evaluation of SM exclusion with improved prediction

before March 2009



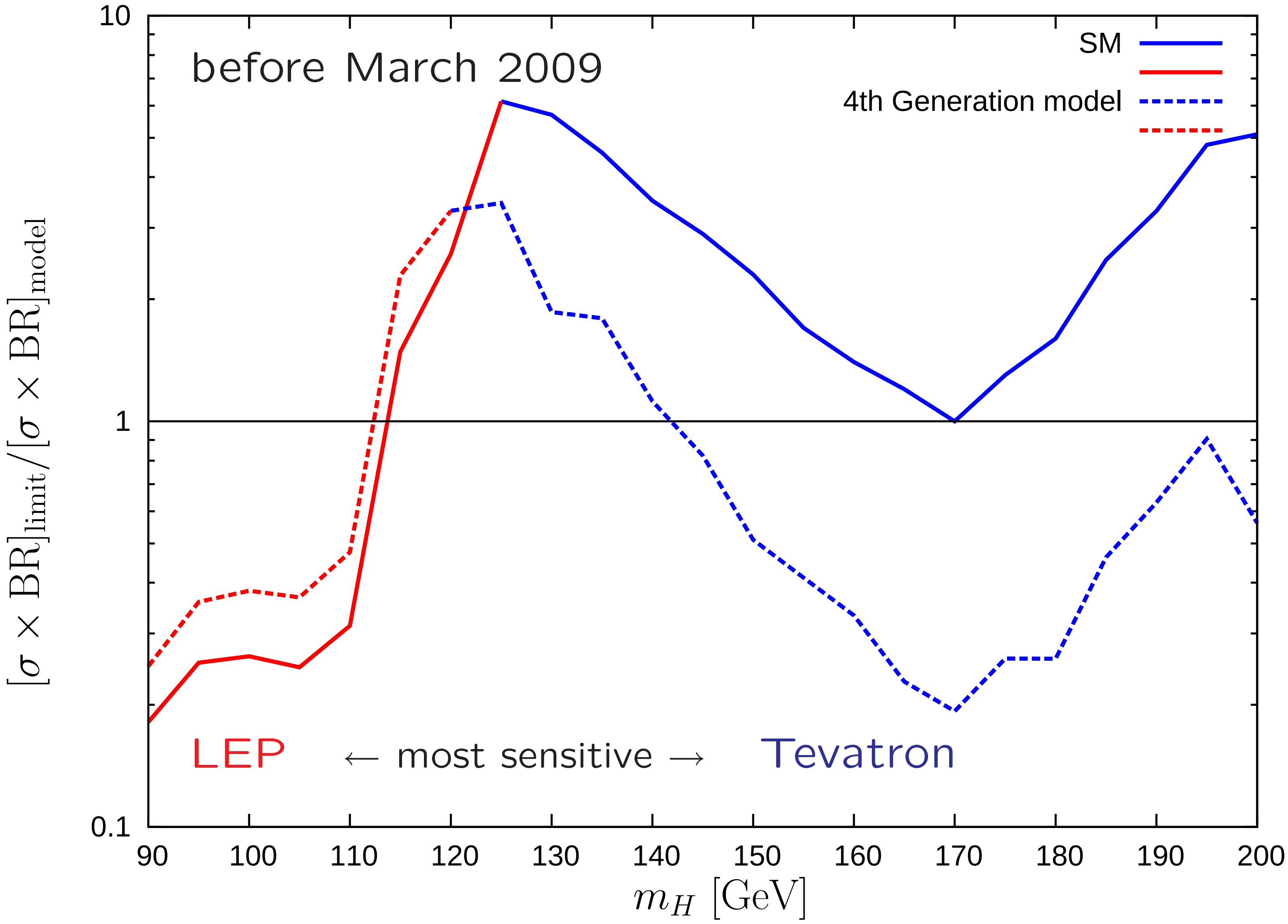
application 1: re-evaluation of SM exclusion with improved prediction

August 2009



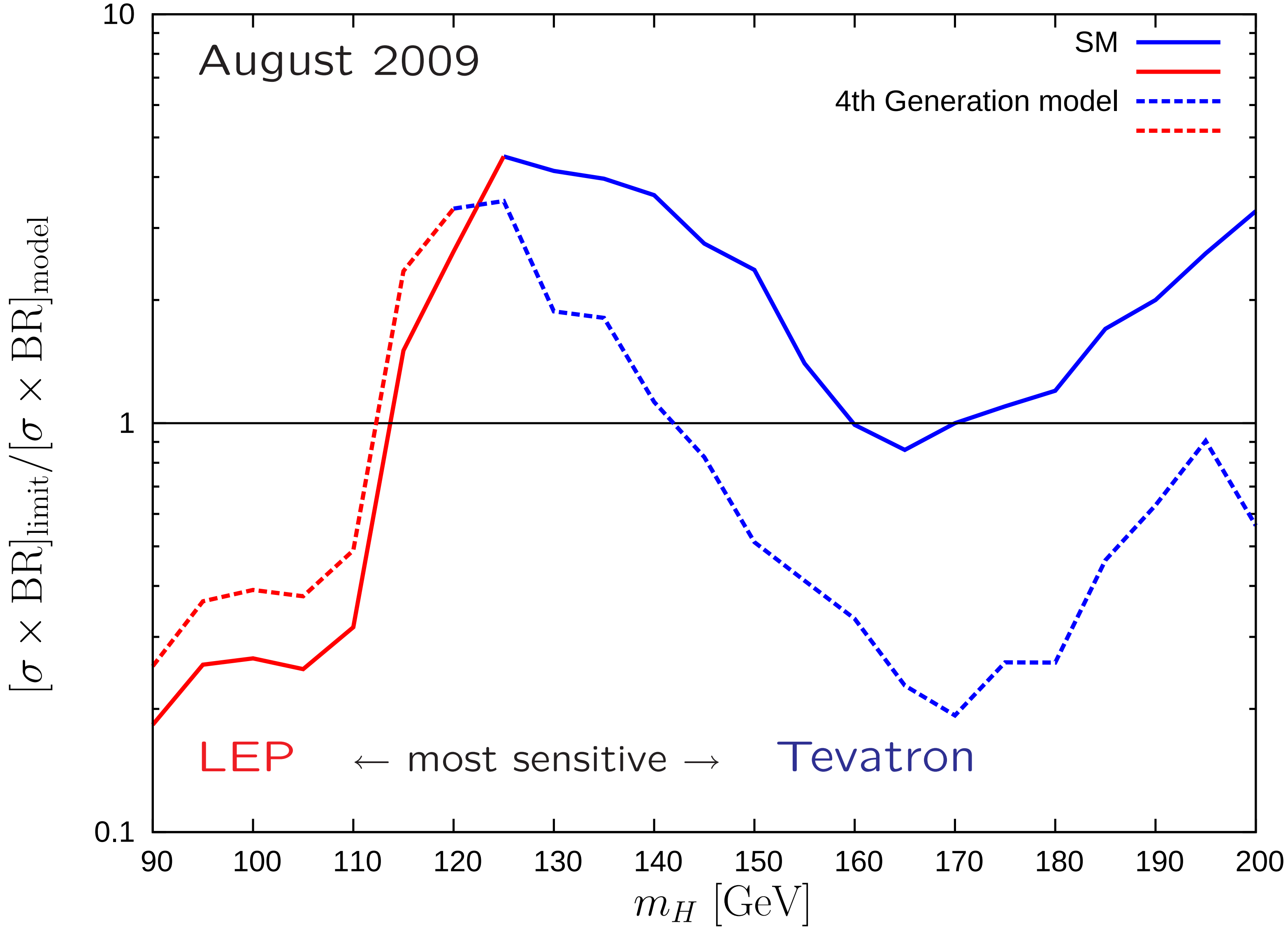
application 2: SM versus Fourth Generation Model exclusion

$$\Gamma(H \to gg)_{\text{model}} = 9 \times \Gamma(H \to gg)_{\text{SM}}$$



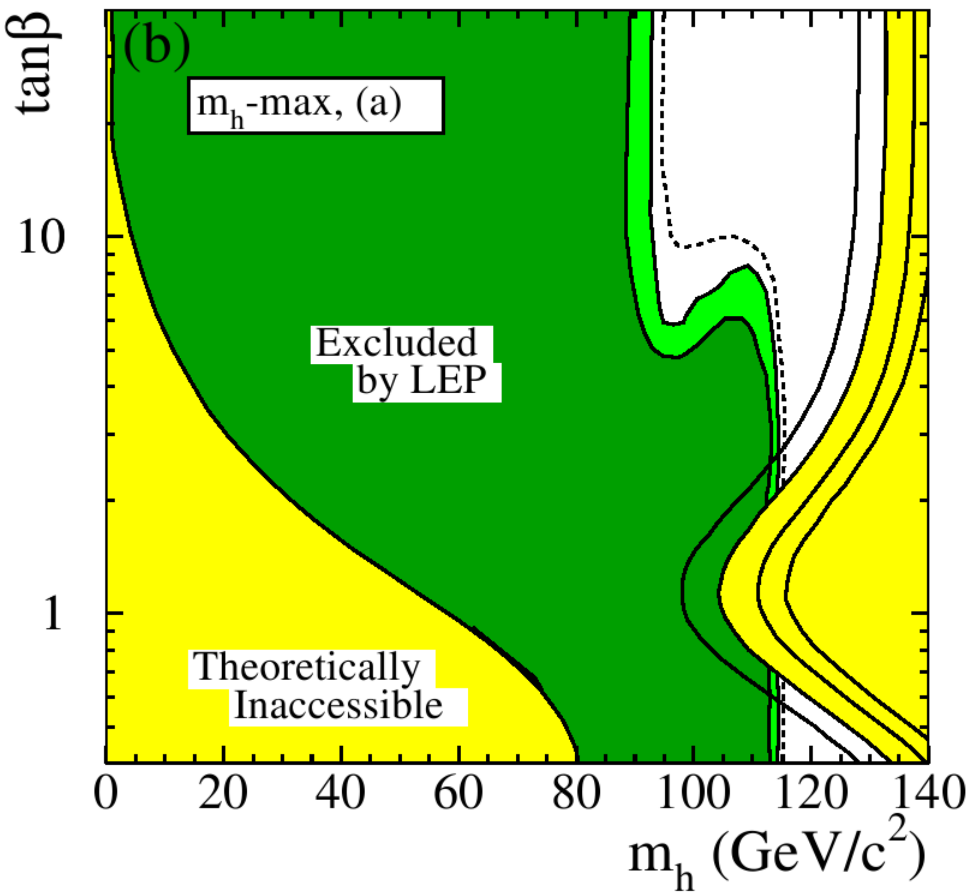
application 2: SM versus Fourth Generation Model exclusion

$$\Gamma(H \to gg)_{\text{model}} = 9 \times \Gamma(H \to gg)_{\text{SM}}$$

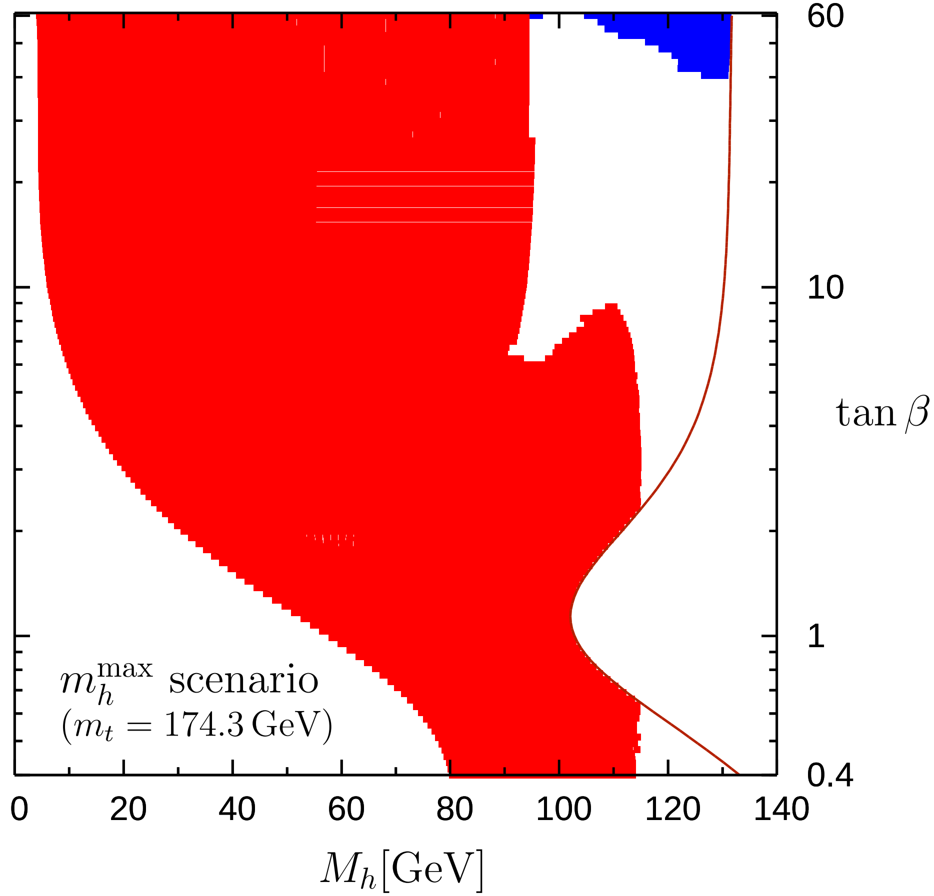


application 3: MSSM benchmark scenarios, exclusion update

a) [EPJC 46(2006)547]

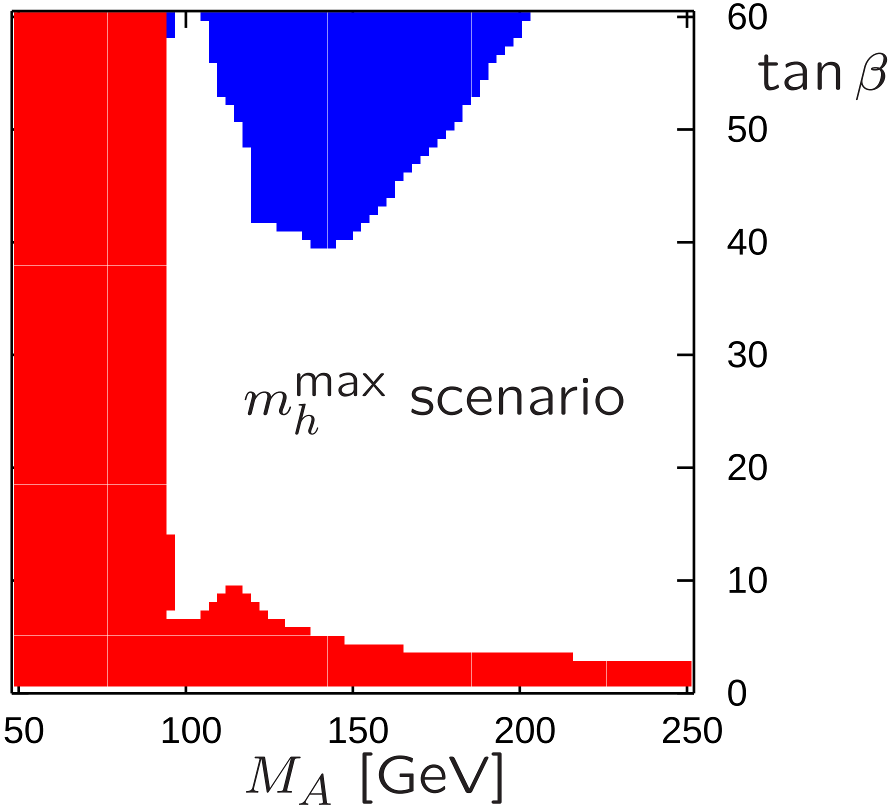


b) **HiggsBounds**
with: new m_t,
impoved m_h prediction,
Tevatron data included



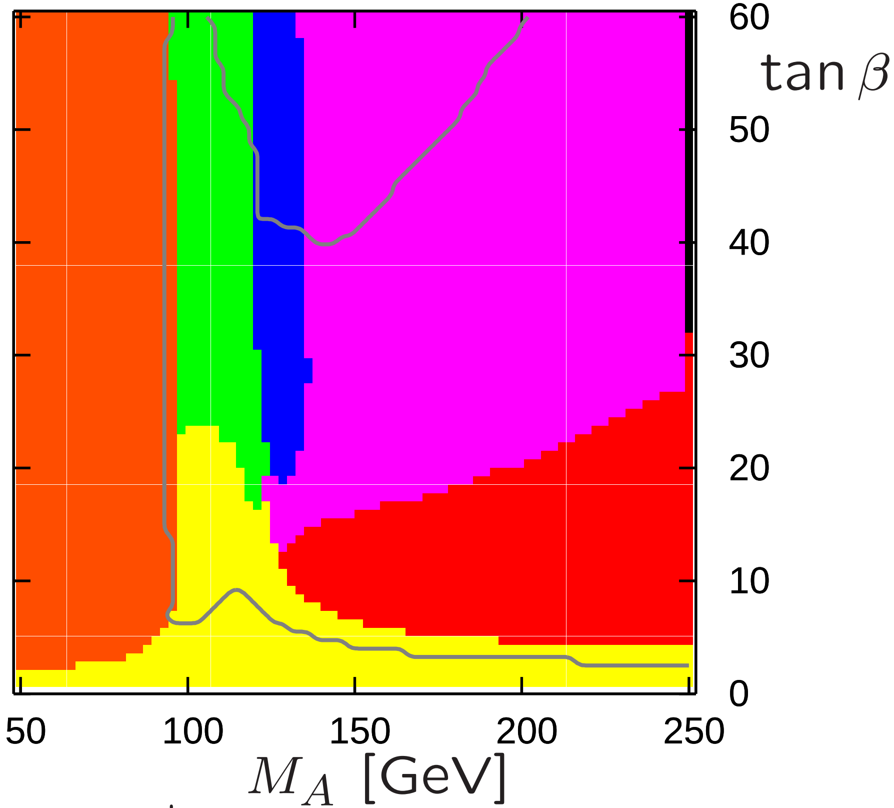
application 3: MSSM benchmark scenarios, exclusion update (before March 2009)

a) LEP and Tevatron exclusion



■ : LEP exclusion
■ : Tevatron exclusion

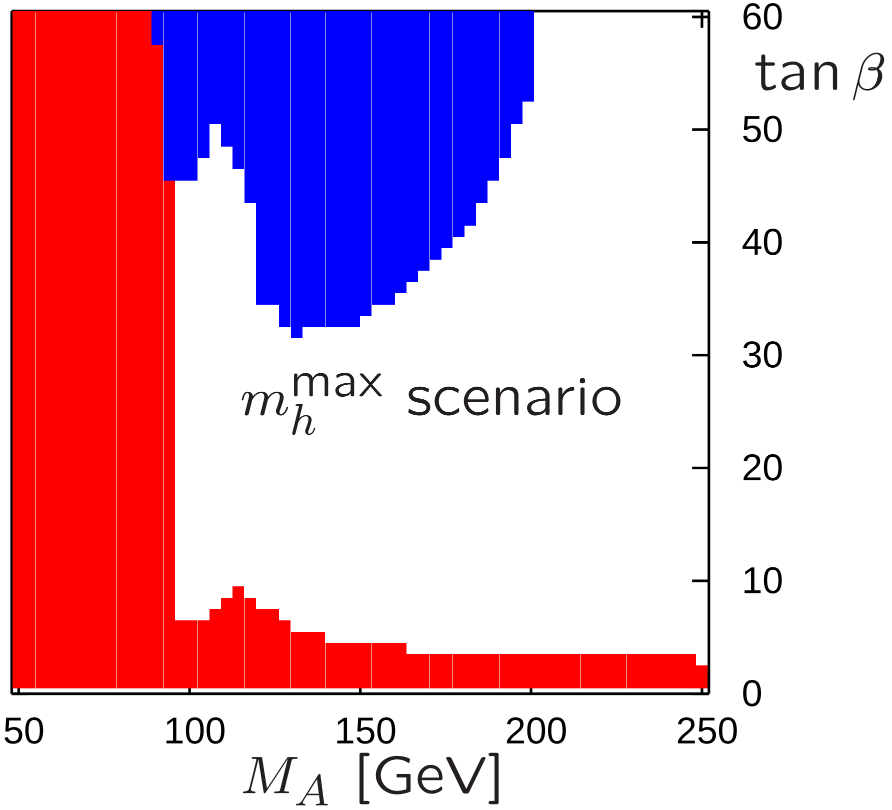
b) highest sensitivity



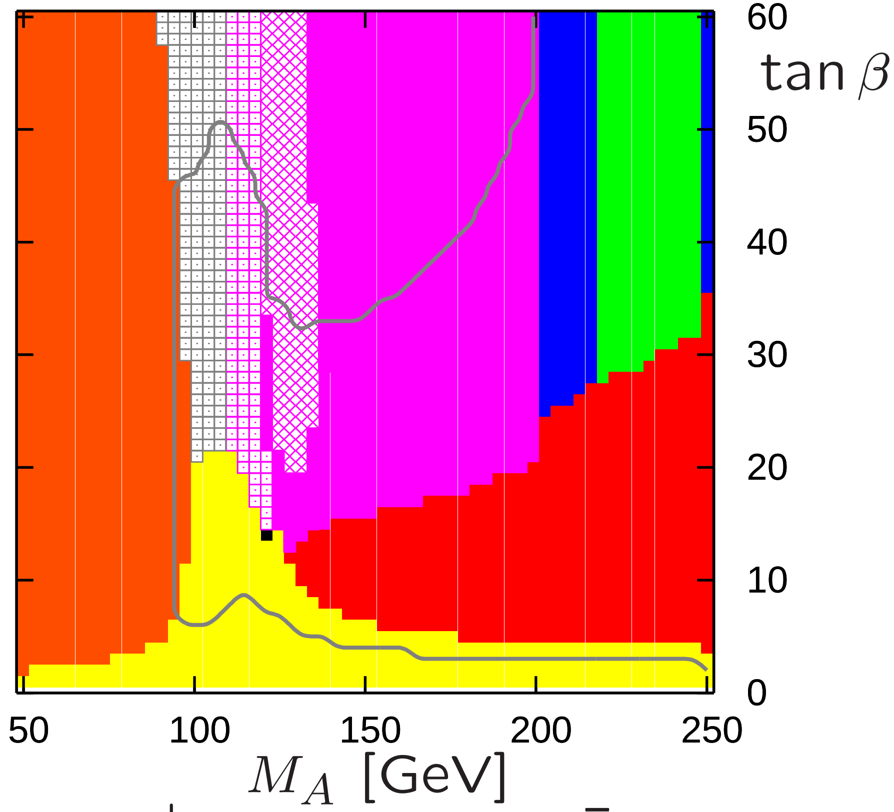
■ : $e^+e^- \to hZ, h \to b\bar{b}$
■ : $e^+e^- \to hA \to b\bar{b}b\bar{b}$
■ : $p\bar{p} \to hW \to b\bar{b}l\nu$ [CDF note 9463]
■ : $p\bar{p} \to h/A \to \tau^+\tau^-$ [CDF note 9071]
■ : $p\bar{p} \to h/H/A \to \tau^+\tau^-$ [CDF note 9071]
■ : $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF note 9071]
■ : $p\bar{p} \to H/A \to \tau^+\tau^-$ [DØ'08]

application 3: MSSM benchmark scenarios, exclusion update (August 2009)

a) LEP and Tevatron exclusion



b) highest sensitivity



■ : LEP exclusion

■ : Tevatron exclusion

⊡ : $p\bar{p} \to b\,h/A \to b\tau^+\tau^-$ [D0 note 5985]

⊡ : $p\bar{p} \to h/A \to \tau^+\tau^-$ [CDF & D0 '09]

■ : $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF & D0 '09]

× : $p\bar{p} \to h/H/A \to \tau^+\tau^-$ [CDF & D0 '09]

■ : $e^+e^- \to hZ, h \to b\bar{b}$ [LEP EPJC 46 ...]

■ : $e^+e^- \to hA \to b\bar{b}b\bar{b}$ [LEP EPJC 46 ...]

■ : $p\bar{p} \to hW \to b\bar{b}l\nu$ [CDF '09]

■ : $p\bar{p} \to HW \to b\bar{b}l\nu$ [CDF '09]

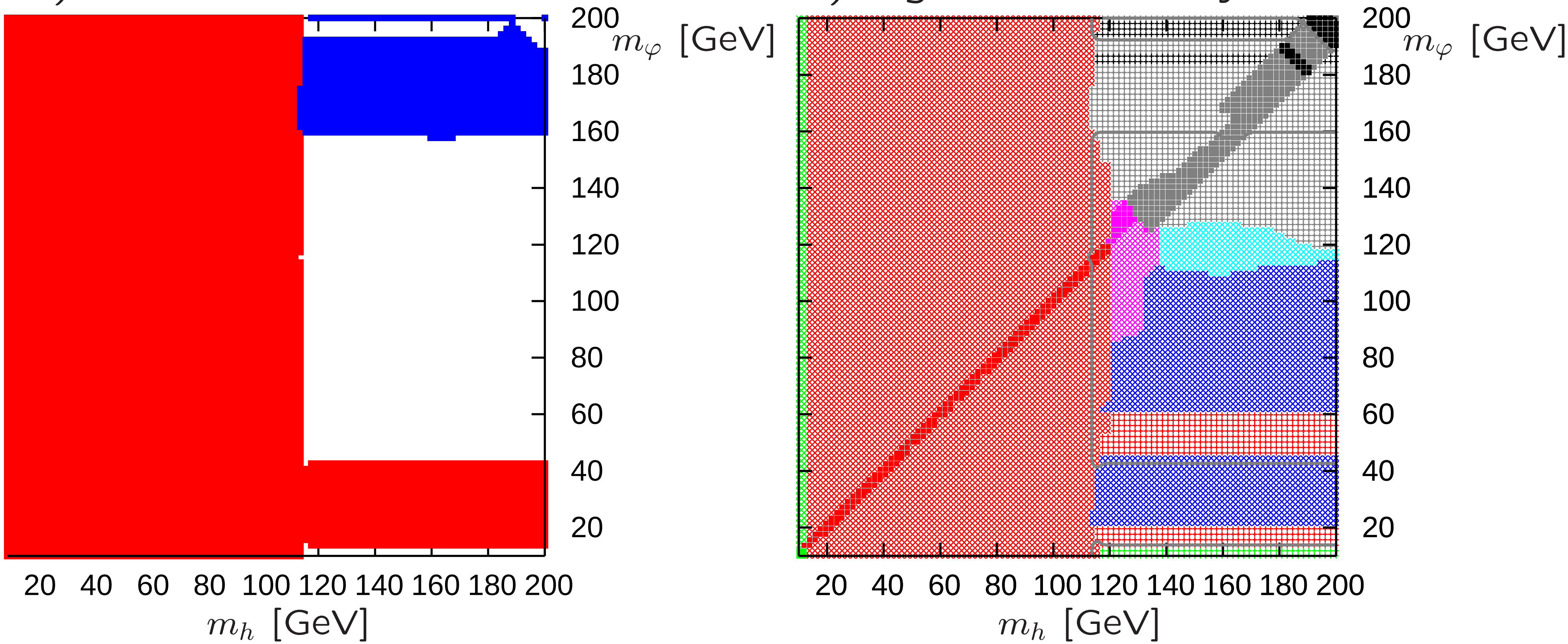
■ : $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF '09]

■ : $p\bar{p} \to H/A \to \tau^+\tau^-$ [D0 note 5740]

application 4: Randall-Sundrum model, excluded parameter space

parameter: $\Lambda_\varphi = 1$ TeV, $\xi = 0$, mass eigenvalues: m_h, m_φ

a) LEP and Tevatron exclusion   b) highest sensitivity



■ : LEP exclusion

■ : Tevatron exclusion

×/+/■ ($\phi = h/\varphi$/both): $e^+e^- \to \phi Z, \phi \to b\bar{b}$ [EPJC 46 ...]

×/+/■: $e^+e^- \to \phi Z, \phi \to$ anything [OPAL '03]

×: $e^+e^- \to \phi Z, \phi \to$ 2 jets [LEP Higgs WG]

×/■: $p\bar{p} \to \phi W \to b\bar{b}l\nu$ [CDF note 9596]

×: $p\bar{p} \to \phi W \to 3W$ [D0 note 5873]

+/■: $p\bar{p} \to \phi \to WW \to l\nu l\nu$ [D0 note 5757]

+/■: $p\bar{p} \to \phi \to WW \to l\nu l\nu$ [CDF '08]

– Status and Outlook

- The code is publicly available (current verison: 1.2.0).

  Please visit the web page www.ippp.dur.ac.uk/HiggsBounds/ for downloading the package or using the web interface.

- reception so far very encouraging: e.g. used in or by
  FeynHiggs, Fittino, MasterCode, 2HDMC, DarkSusy,
  S. Kraml et al., M. Carena et al.

- Current work:
  – inclusion of new Tevatron analyses (which need additional input)
  – inclusion of LEP analyses with $H \to$ invis., $H \to$ 2 jets, etc.
  – inclusion of charged Higgs analyses

- Plans:
  – providing CL_{s+b} for given m_H and $\sigma \times$ BR ($\to$ useful for model fitting)
  – inclusion of width-dependent limits

summary

- We are sure to observe electroweak symmetry breaking in nature.
  However, up to now, we have no clue how it is realised.
  The Higgs mechanism allows to describe EWSB consistently up to very high energy.

- Search for Higgs boson(s): 1. establish a signal /
  2. make sure it's a Higgs / 3. determine the underlying model.

- SM simulations show: Higgs + high-p_T jet is a promising alternative to the inclusive production. Differences between MSSM and SM also extend to shapes of differential distributions.

- HiggsBounds: powerful tool for constraining Higgs sectors of new physics models systematically.

- Backup

– MSSM

Supersymmetry . . .

. . . is *the* extension of the Poincaré-symmetry of space-time

. . . leads to a symmetry between Fermions & Bosons

gauge theory with minimal SUSY :

- same # of fermionic & bosonic d. o. f.
  → a superpartner of different spin exists for each particle

- couplings are correlated
  → e.g. scalar 4-point int. ↔ gauge couplings

- superpartners have the same mass
  → SUSY must be broken at the electroweak scale

gauge theory with broken SUSY :

- superpartner masses enter as additional free parameters (essentially)

Minimal supersymmetric Standard Model (MSSM):

gauge group : $SU(3)_{\text{colour}} \times SU(2)_{\text{isospin}} \times U(1)_{\text{hypercharge}}$

particle content :

regular particles		spin	superpartners		spin
fermions	quarks u, d, s, c, b, t leptons $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$	$\frac{1}{2}$	sfermions	squarks $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$ sleptons $\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau$	0
gauge bosons	$G, W^\pm, Z, \gamma$	1	gauginos	$\tilde{G}, \tilde{W}^\pm, \tilde{Z}, \tilde{\gamma}$	$\frac{1}{2}$
Higgs bosons	H_1, H_2	0	Higgsinos	$\tilde{H}_1, \tilde{H}_2$	$\frac{1}{2}$

$\tilde{W}^\pm, \tilde{Z}, \tilde{\gamma}$ and $\tilde{H}_1, \tilde{H}_2$ mix to charginos $\chi_1^\pm, \chi_2^\pm$ and neutralinos $\chi_1^0, \ldots, \chi_4^0$

R-parity : discrete, multiplicative quantum number

$$R(\text{regular particles}) = +1$$
$$R(\text{superpartners}) = -1$$

$\longrightarrow$ designed to avoid large Flavour Canging Neutral Currents (FCNC)

consequences of R-parity conservation:

- all interactions involve an *even* number of superpartners
  $\longrightarrow$ superpartners can only be pair-produced

- the lightest superpartner (LSP) is stable
  $\longrightarrow$ the LSP is a candidate for dark matter

– SM extensions

SM extensions: what is anticipated ?

extra gauge groups

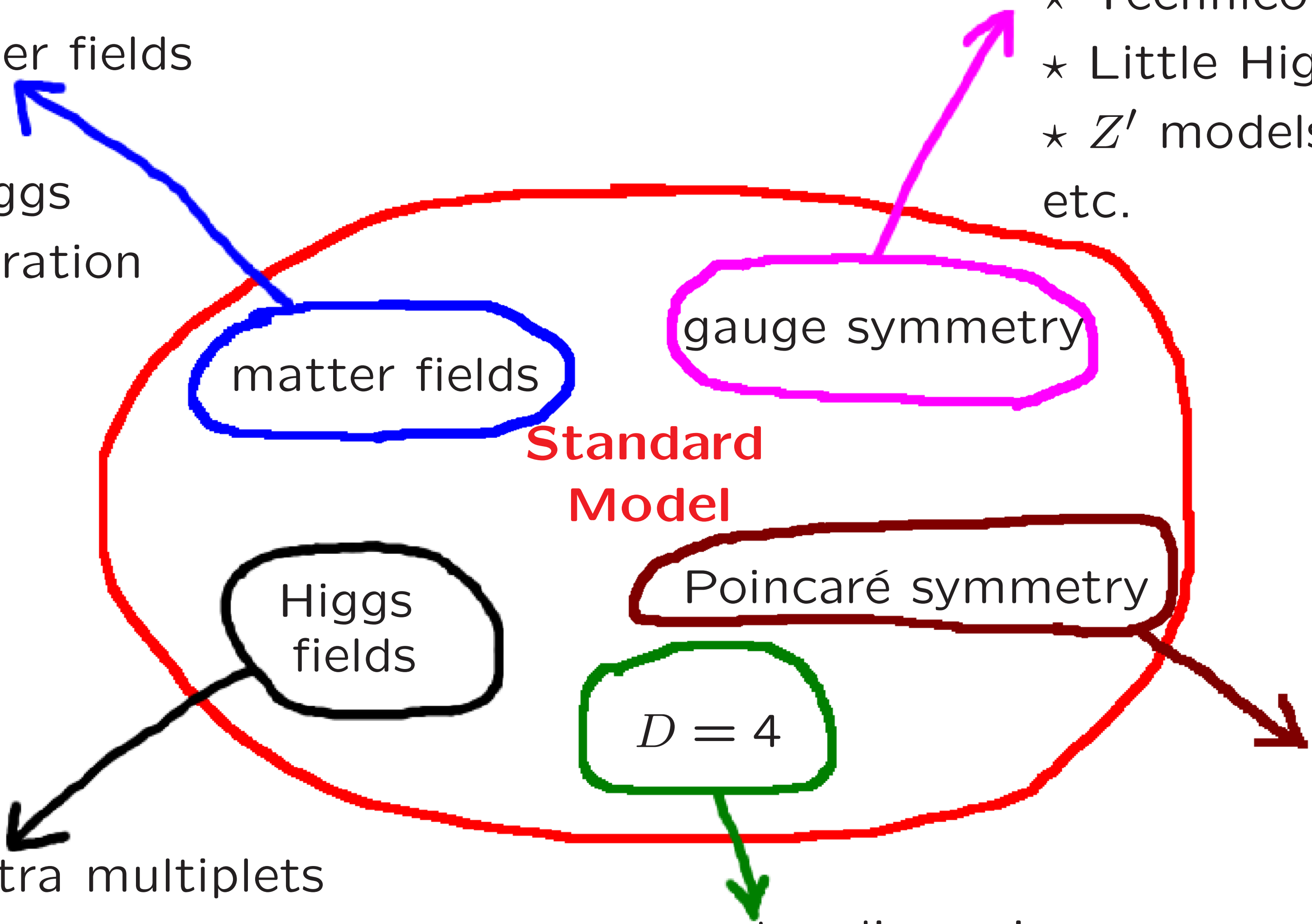
- ⋆ GUT
- ⋆ Technicolor
- ⋆ Little Higgs models
- ⋆ Z' models

etc.

extra matter fields

- ⋆ SUSY
- ⋆ Little Higgs
- ⋆ 4th generation

etc.



supersymmetry

- ⋆ MSSM
- ⋆ NMSSM,...

etc.

change/extra multiplets

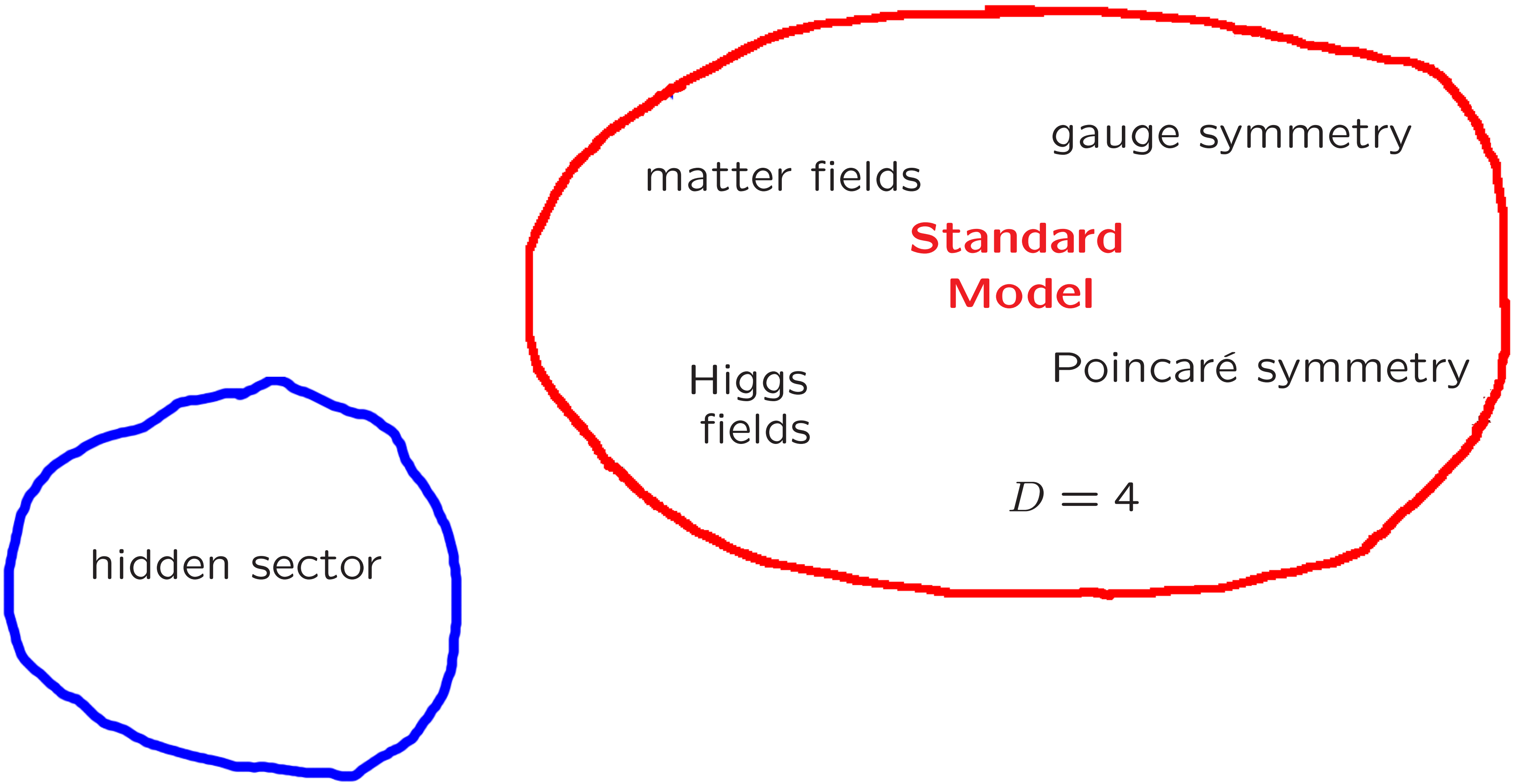
- ⋆ SUSY
- ⋆ Little Higgs
- ⋆ Higgs triplet models

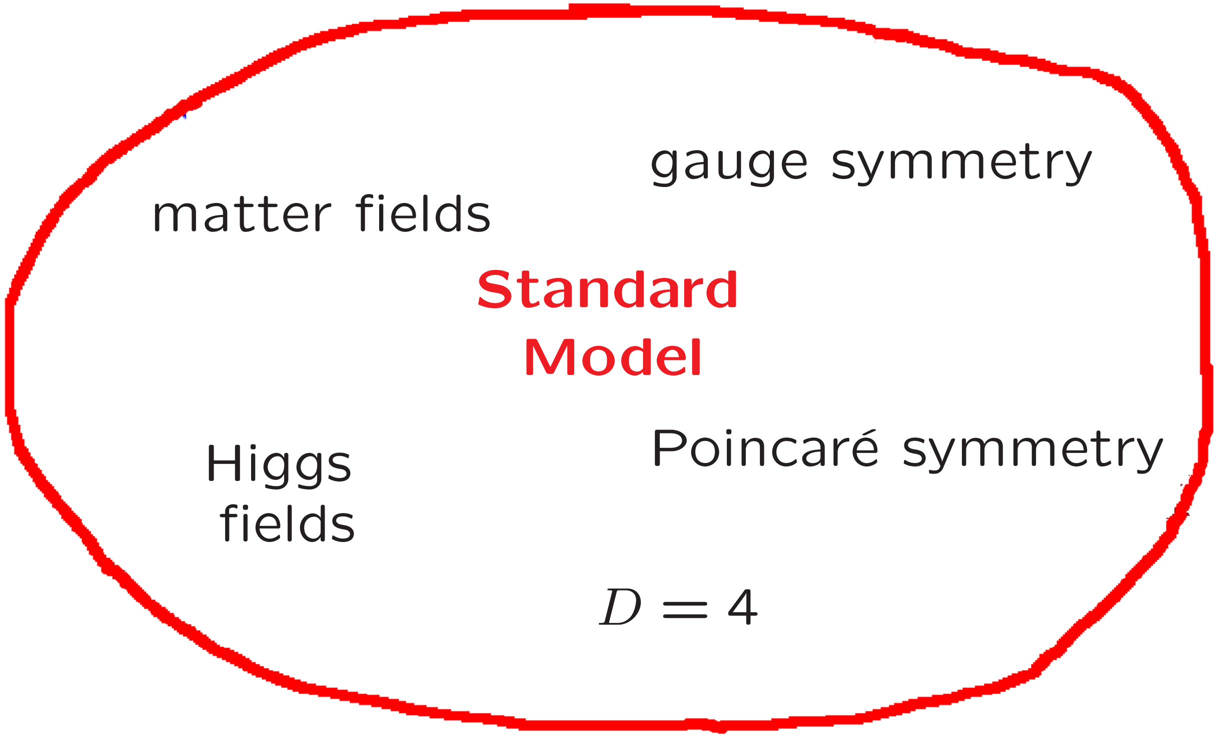
etc.

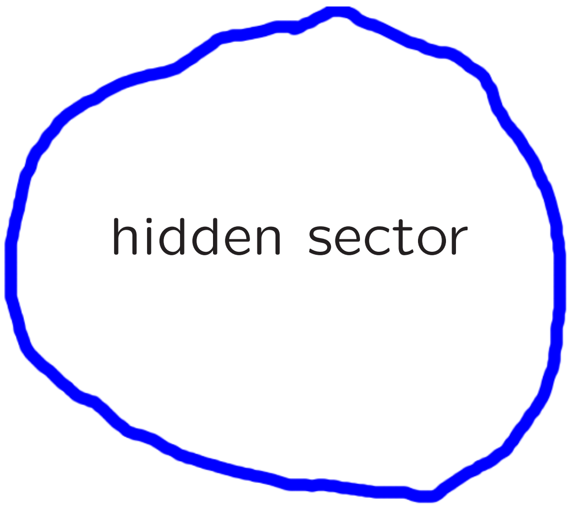
extra dimensions

- ⋆ universal ED
- ⋆ Randall-Sundrum

etc.


gauge symmetry
matter fields
Standard
Model
Poincaré symmetry
Higgs
fields
$D = 4$
hidden sector





Higgs (Φ): promising "portal" to the hidden sector

via interaction $\mathcal{L} \propto \Phi^\dagger \Phi \, \mathrm{O}_{\text{hidden sector}}$