Phenomenology of Higgs Bosons

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

outline :

- How to find Higgs Bosons ?

- HiggsBounds

- Higgs + high-p_T Jet in the SM (MSSM)

- How to find Higgs Bosons ?

– Why Higgs Bosons ?

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

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

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

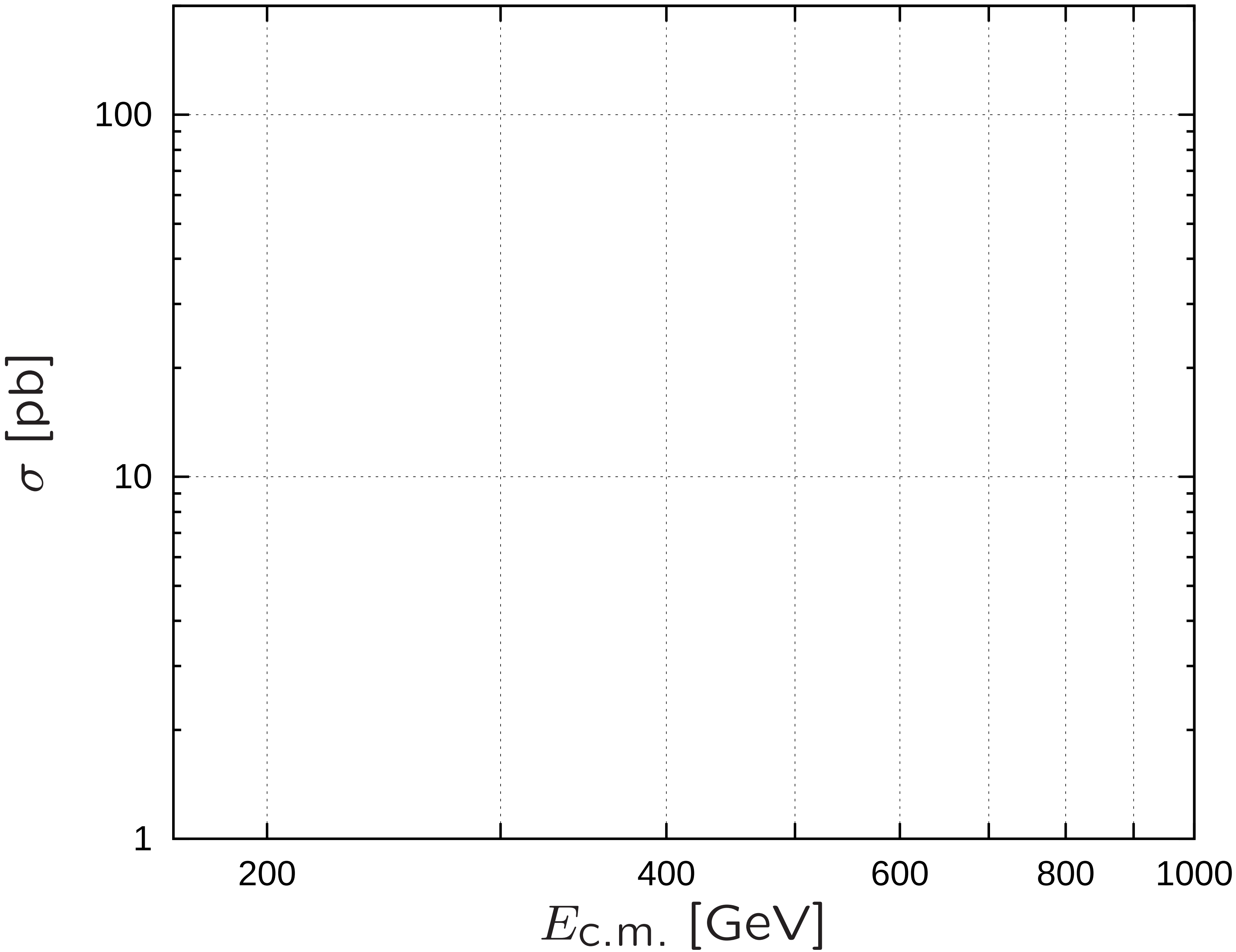
introduce gauge invariant dynamics, which breaks gauge symmetry in the ground state.

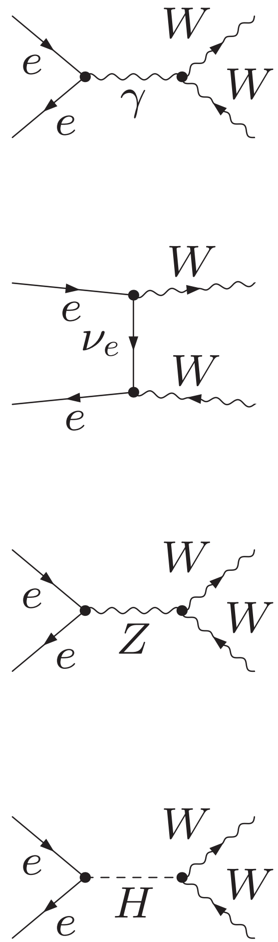
SSB can be realised by

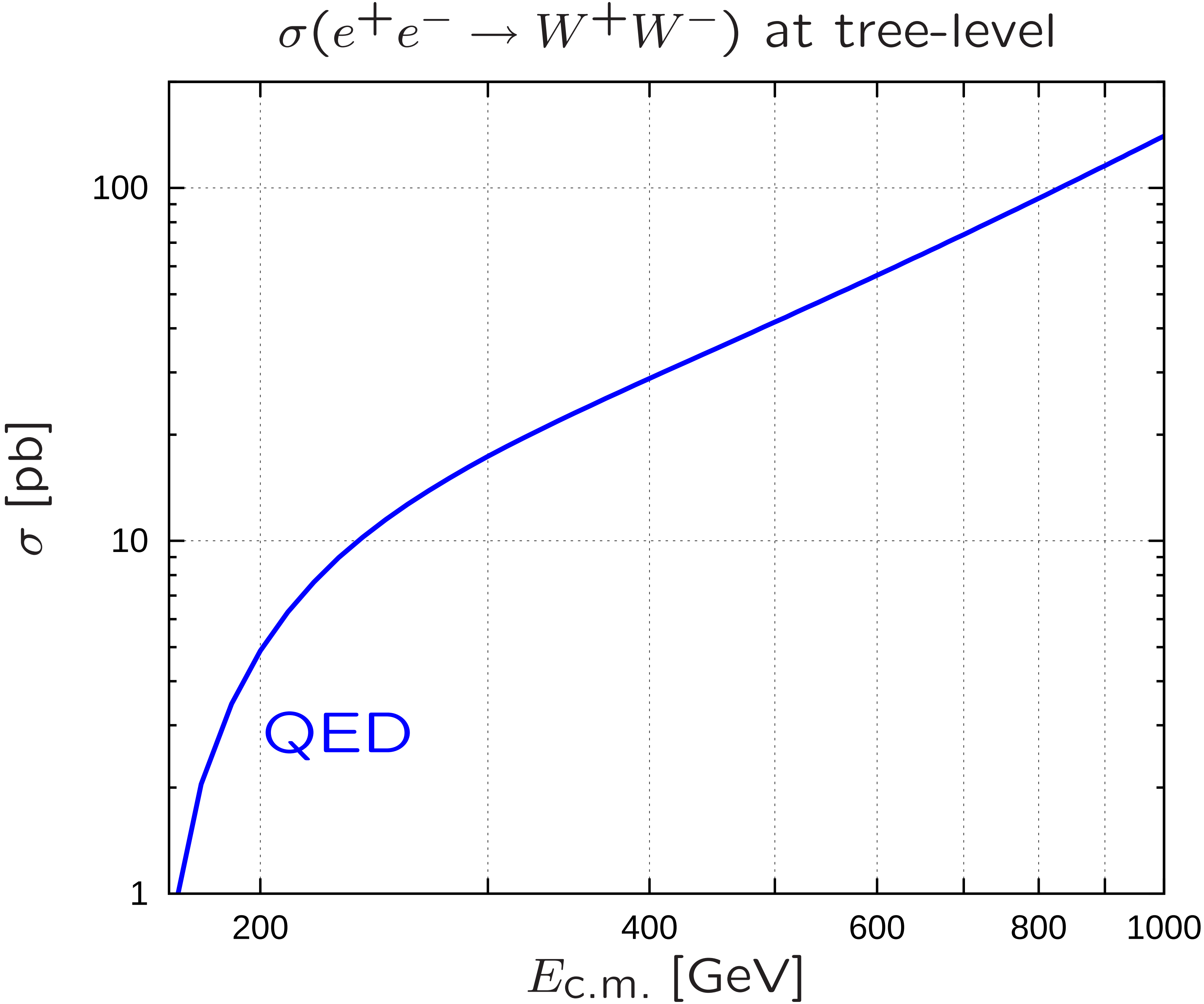
- weakly interacting scalar gauge multiplets that acquire a VEV
$\longrightarrow$ Higgs mechanism

- strongly interacting dynamics, e.g. particles that form scalar condensates with a VEV

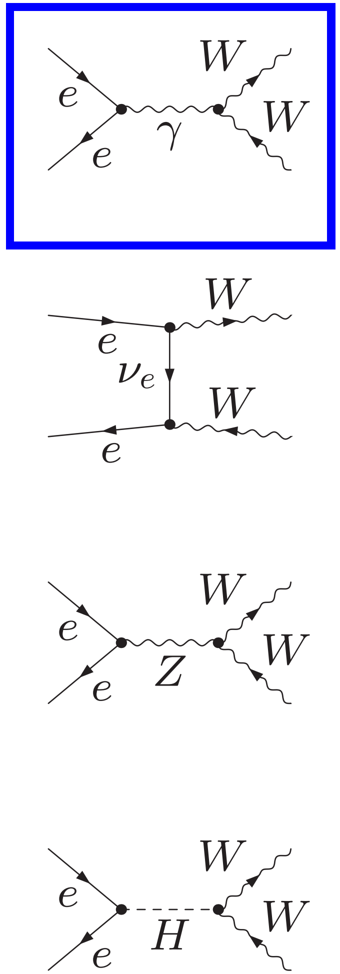
$\sigma(e^+e^- \to W^+W^-)$ at tree-level







$\sigma(e^+e^- \to W^+W^-)$ at tree-level
100
10
1
σ [pb]
200
400
600
800
1000
$E_{\text{c.m.}}$ [GeV]
QED



e
e
γ
W
W
e
ν_e
e
W
W
e
e
Z
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W
e
e
H
W
W

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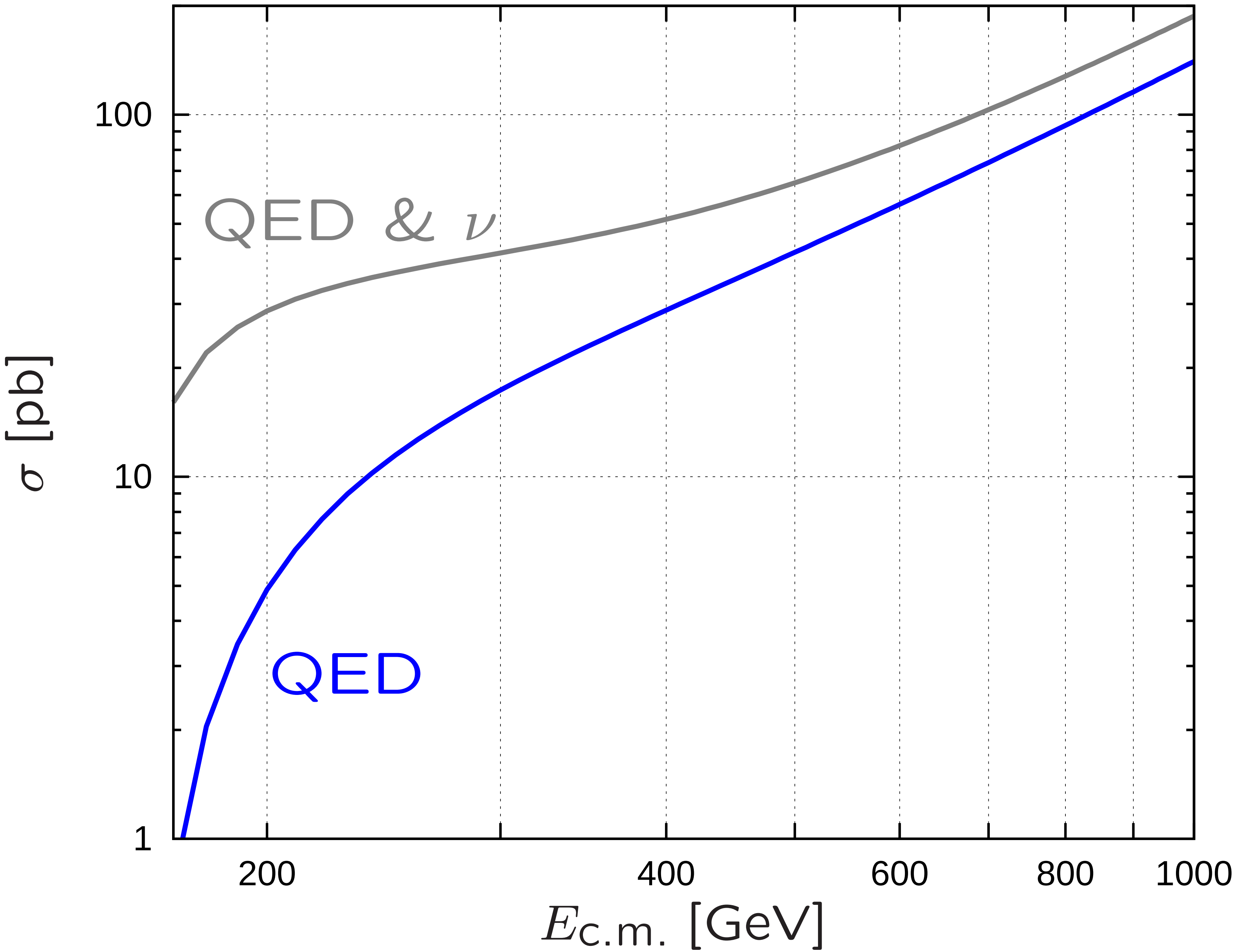

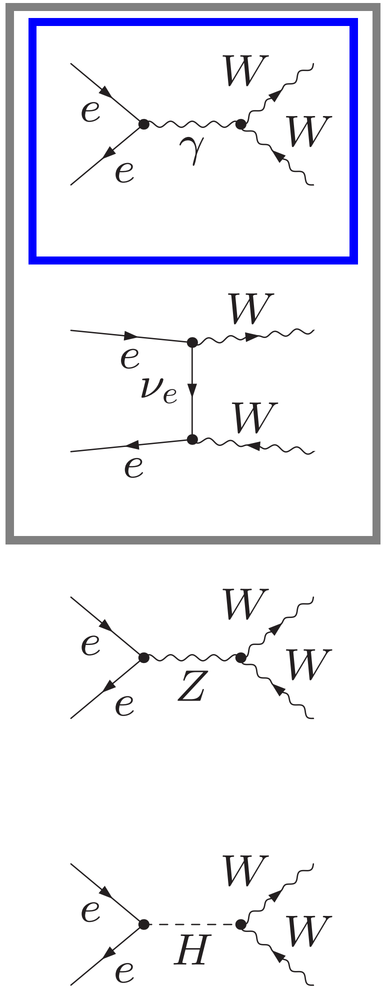

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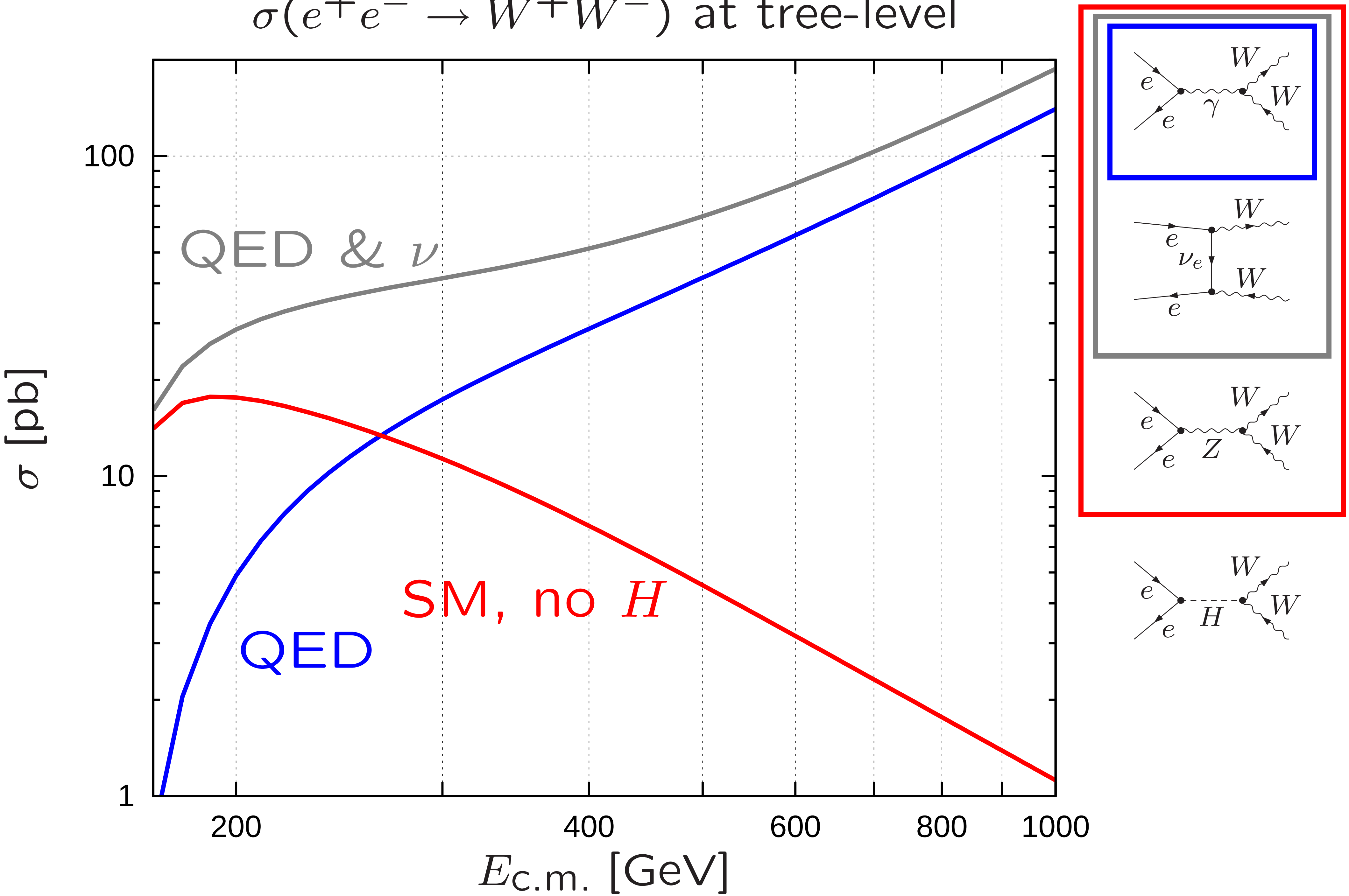

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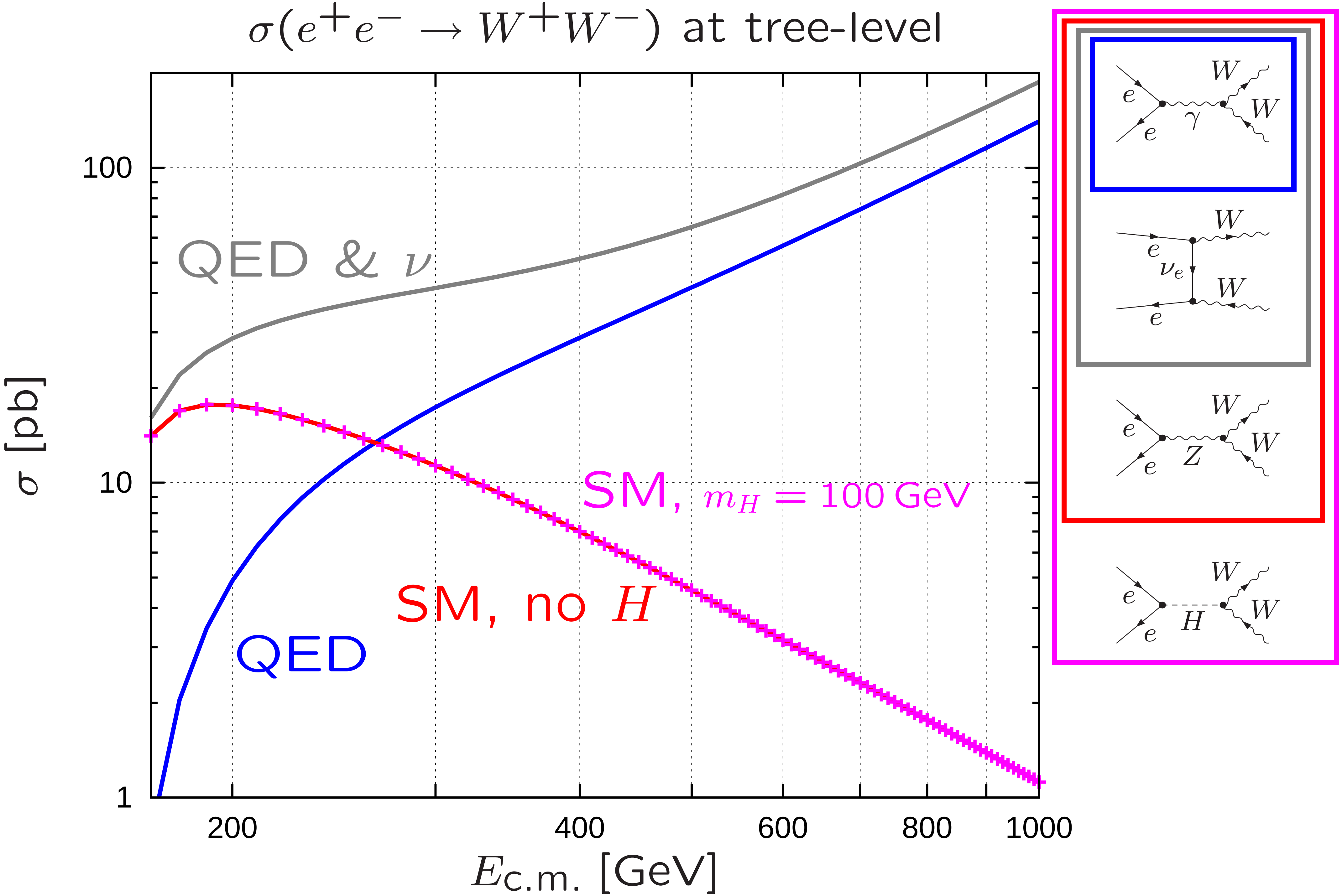
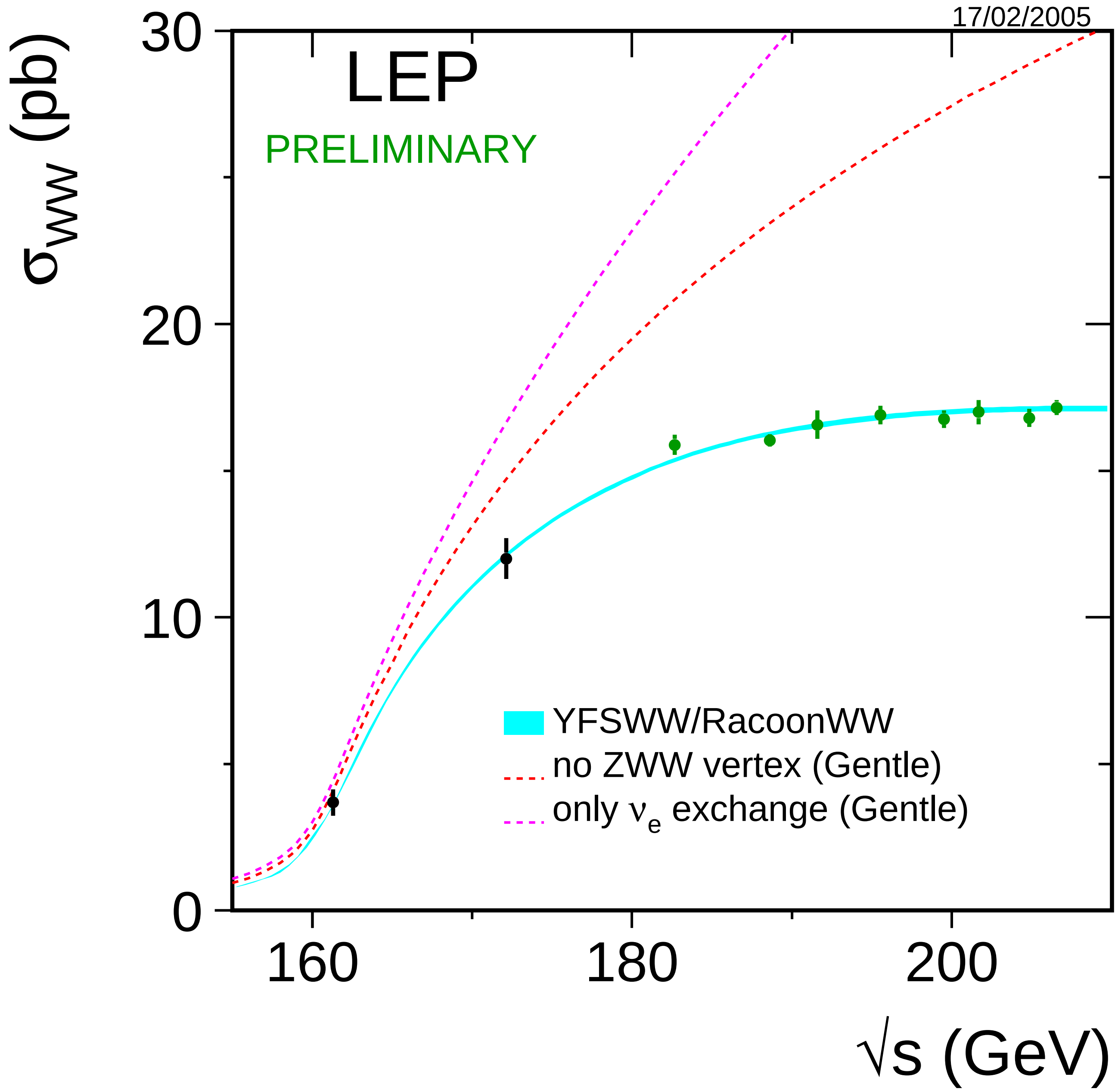
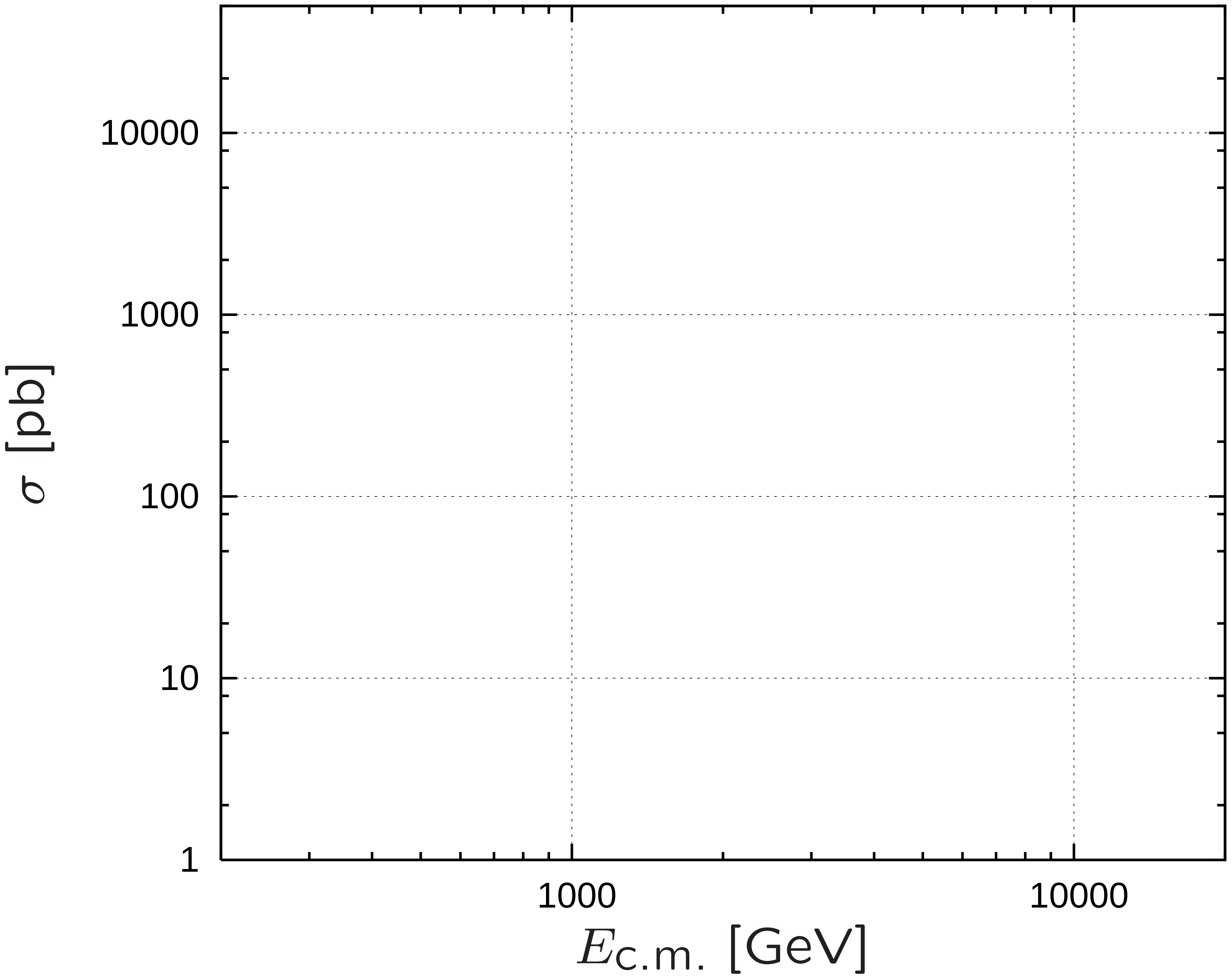
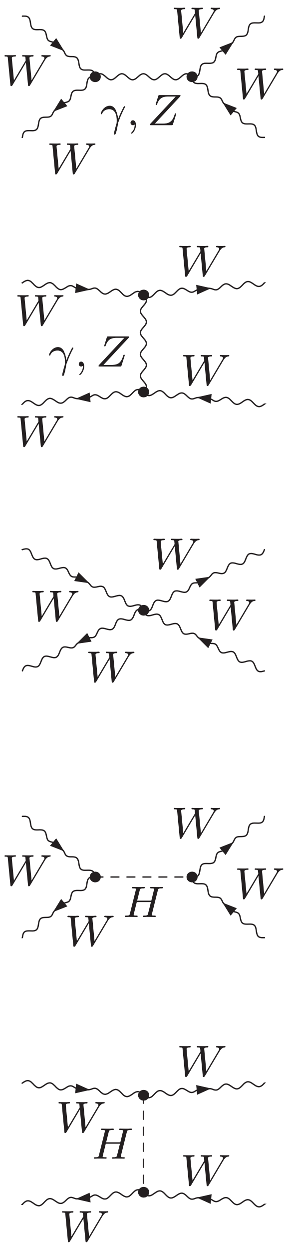


measurement of $\sigma(e^+e^- \rightarrow W^+W^-)$ at LEP 2:

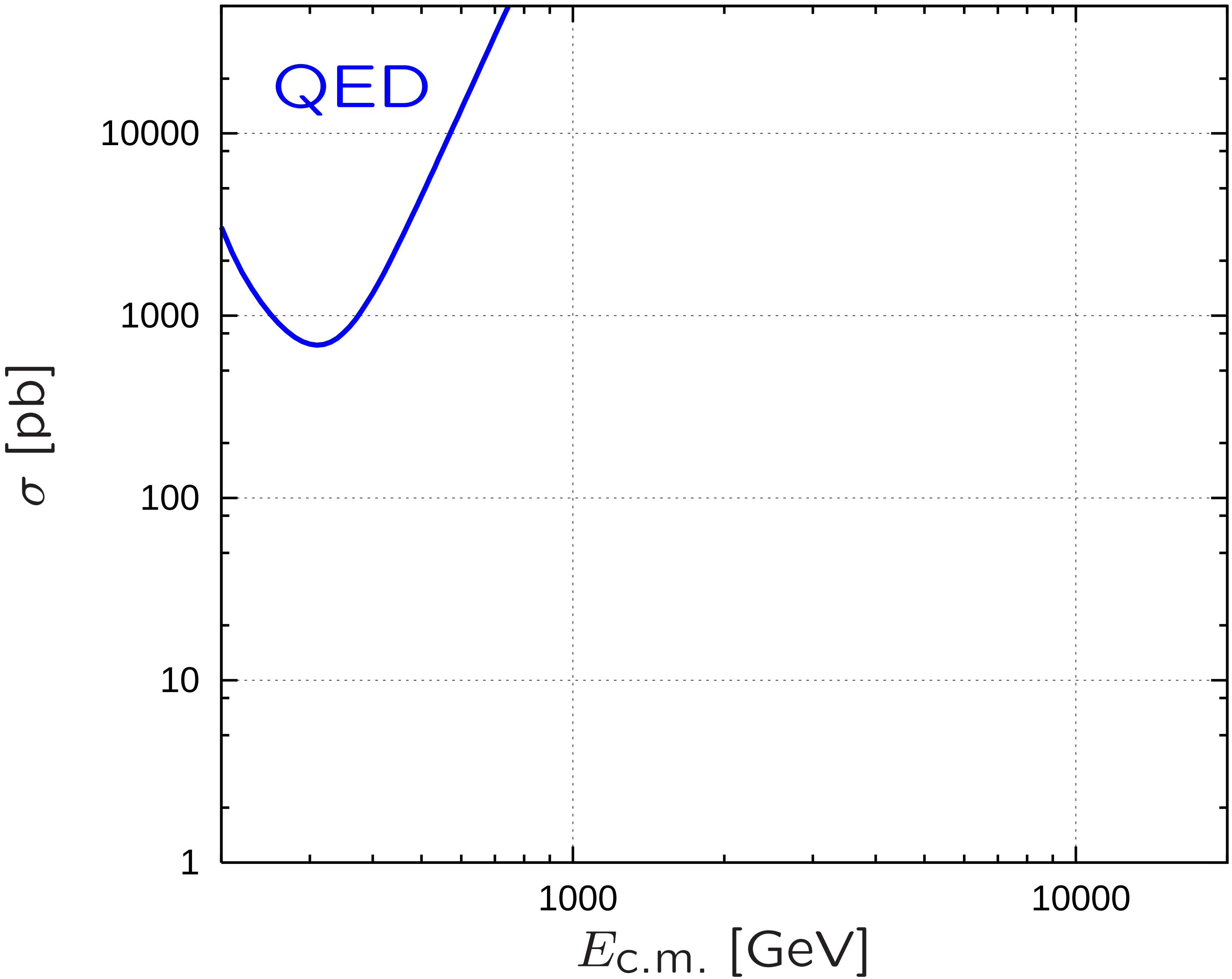


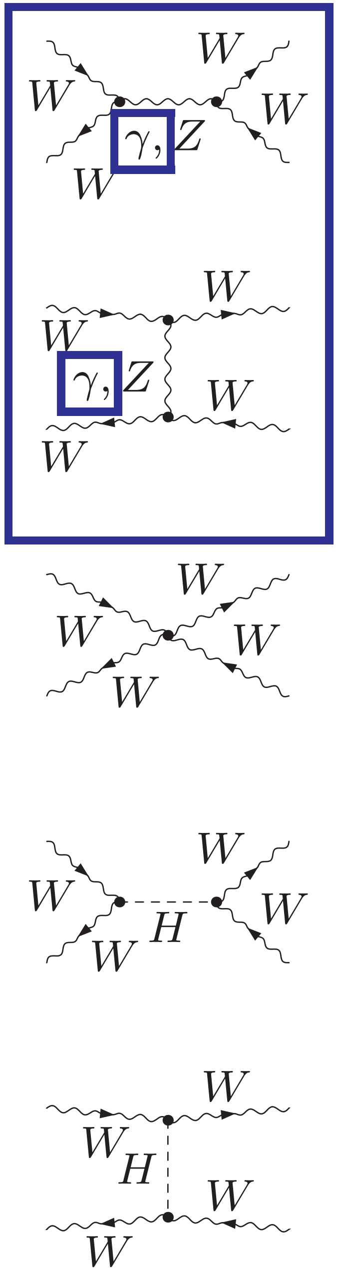
$\sigma(W_L W_L \to W_L W_L)$ at tree-level





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





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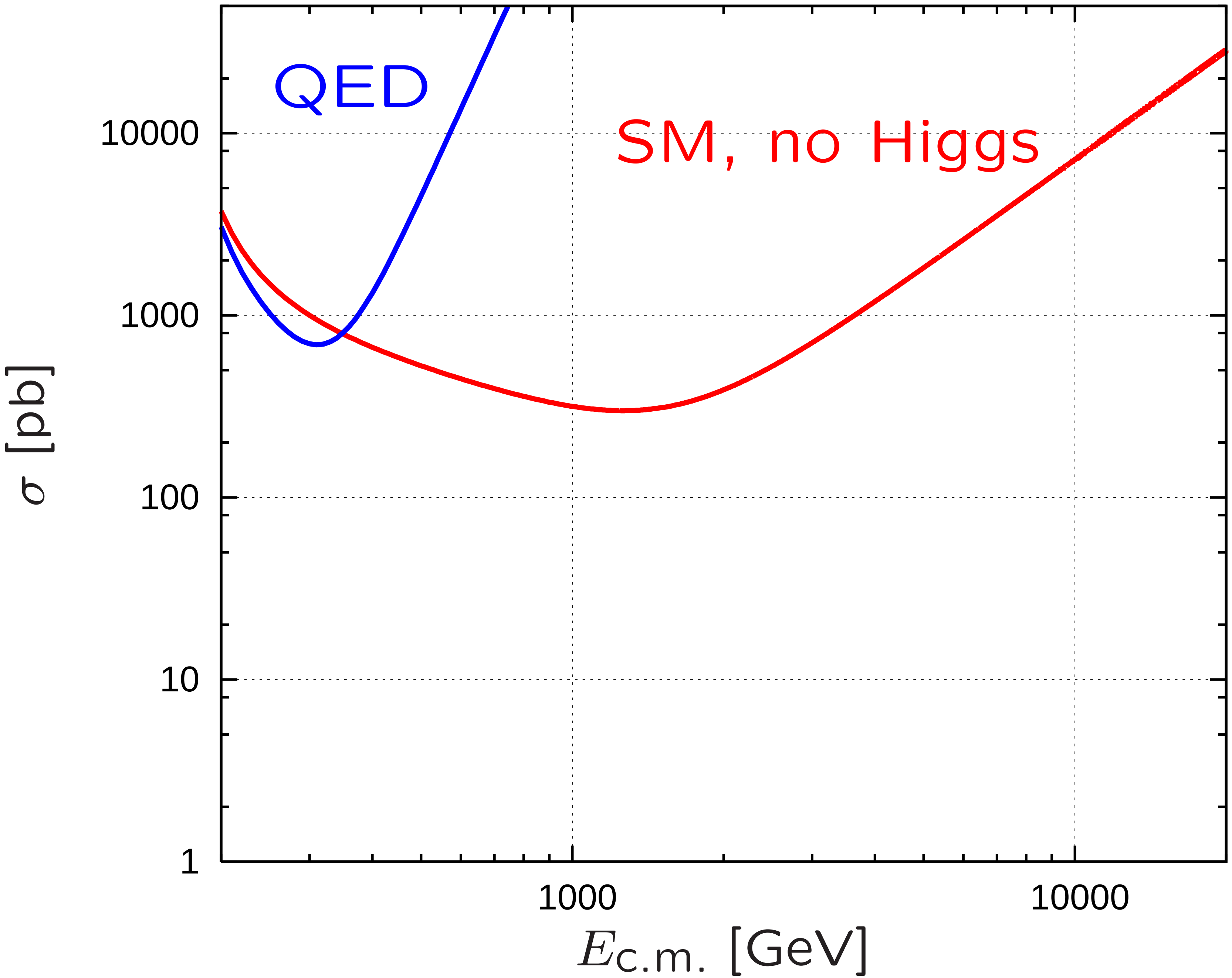
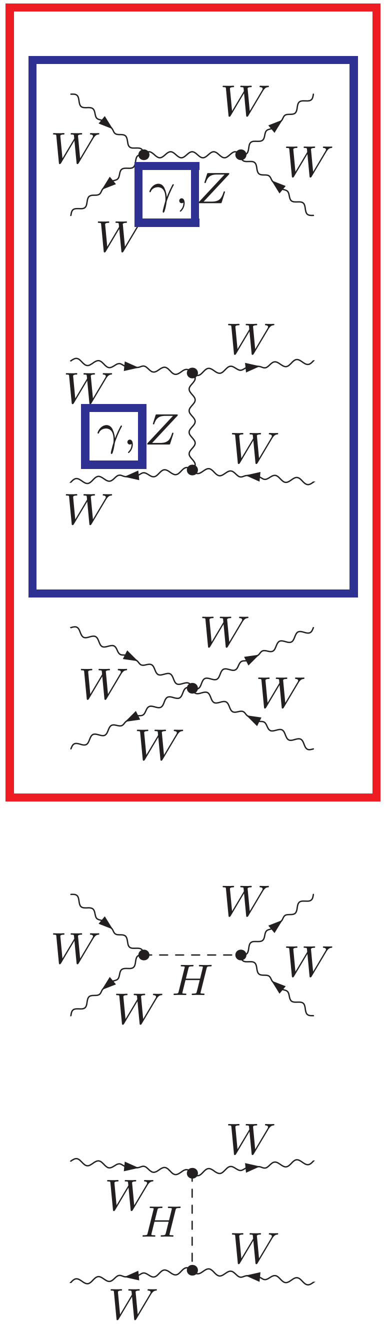
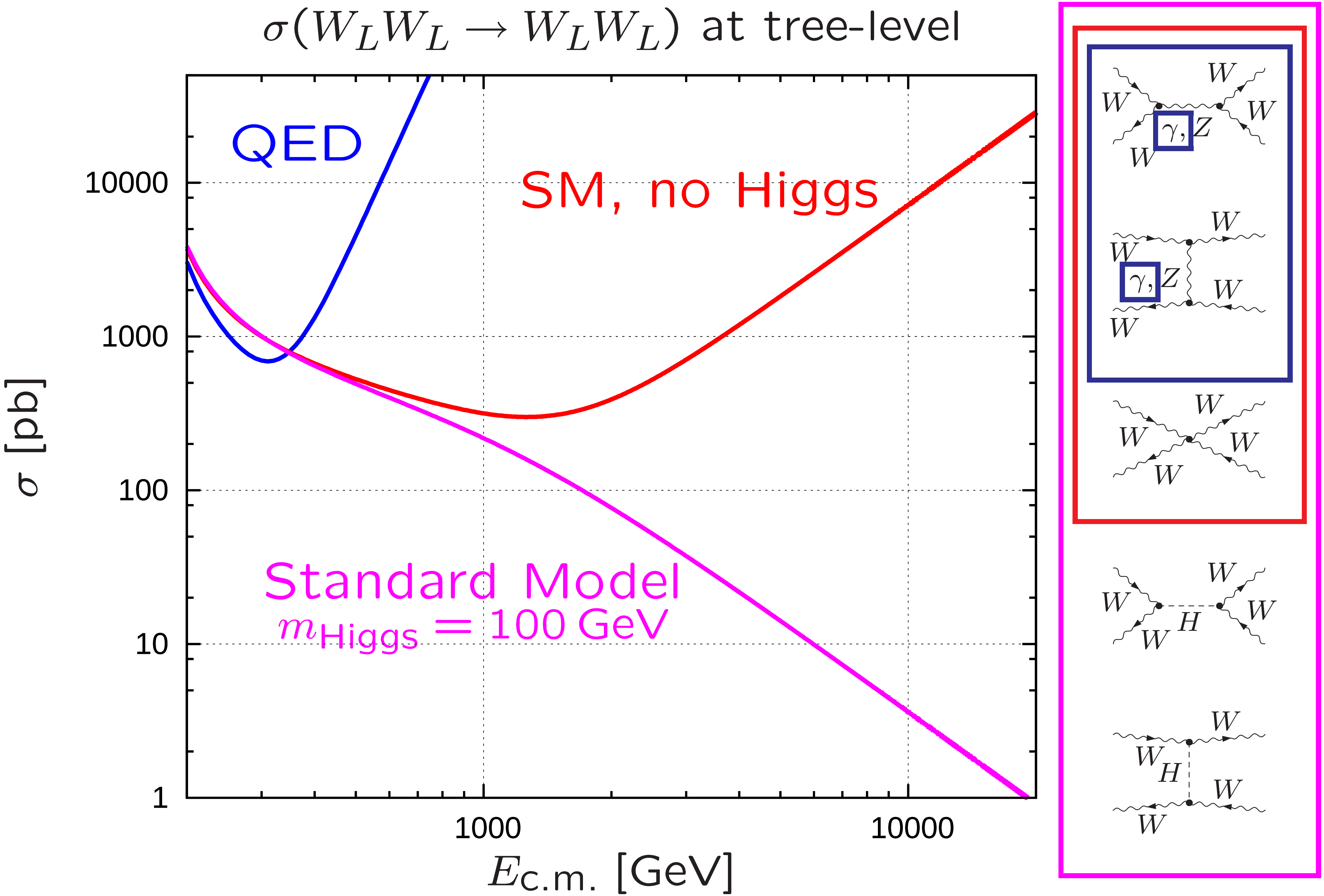






$\sigma(W_L W_L \to W_L W_L)$ at tree-level
QED
SM, no Higgs
Standard Model
$m_{\text{Higgs}} = 100\,\text{GeV}$
σ [pb]
$E_{\text{c.m.}}$ [GeV]
1
10
100
1000
10000
1000
10000
W
γ, Z
H

– Restrictions on 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 Higgs signal cross sections
    from negative direct search results (LEP, Tevatron)

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

– Higgs in the Standard Model and Extensions

SM:

matter, gauge bosons + 1 Higgs doublet Φ

$\rightarrow$ 1 physical Higgs boson

$\swarrow$ $\searrow$

THDM:	**MSSM:**
(two Higgs doublet model)	(minimal supersymmetric standard model)
SM matter, SM gauge bosons	SM matter, SM gauge bosons
+ 2 Higgs doublets Φ_1, Φ_2	+ 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]

– Higgs Production and Decay

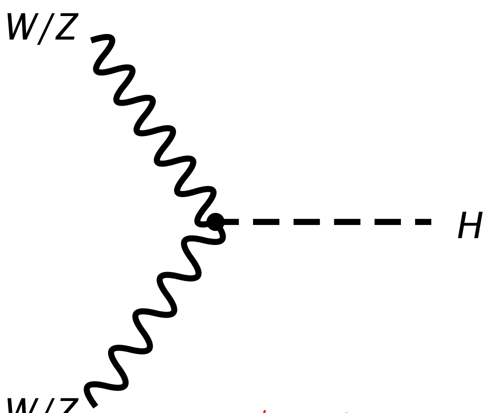
Higgs mechanism $\longrightarrow$ Higgs couplings $\propto$ mass

$\longrightarrow$ Problem: ordinary matter is made of very light particles:

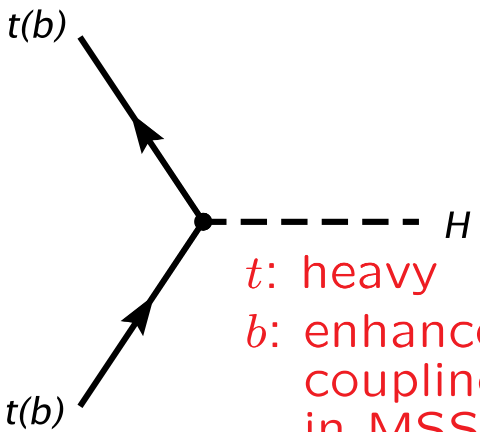
e^-,u-, d-quarks, gluons $\longrightarrow$ (essentially) no coupling to the Higgs

$\longrightarrow$ At colliders: Higgs couples to heavy intermediate particles with non-suppressed couplings to ordinary matter.

$\longrightarrow$ most important couplings:



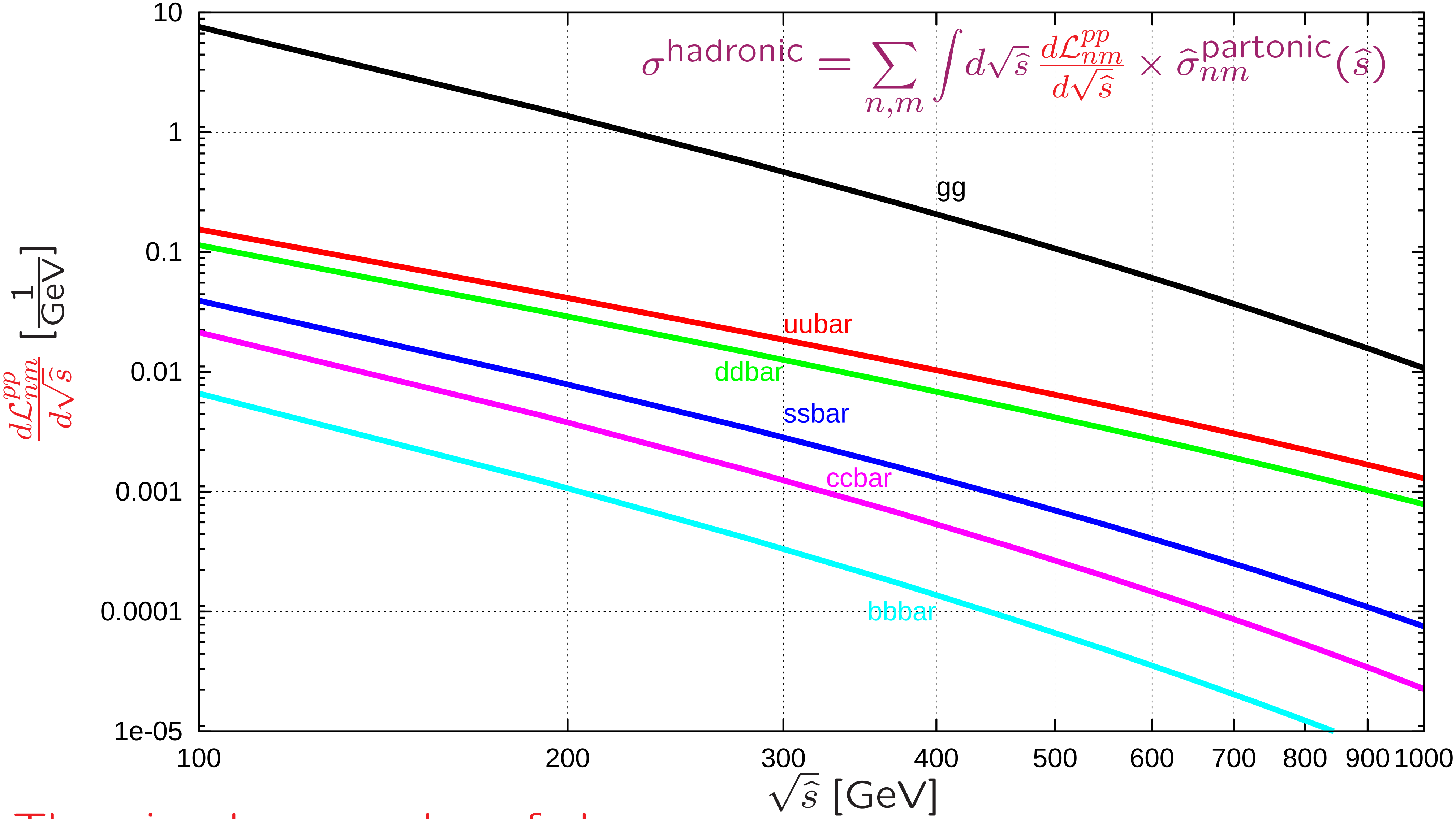
W/Z: heavy



t: heavy

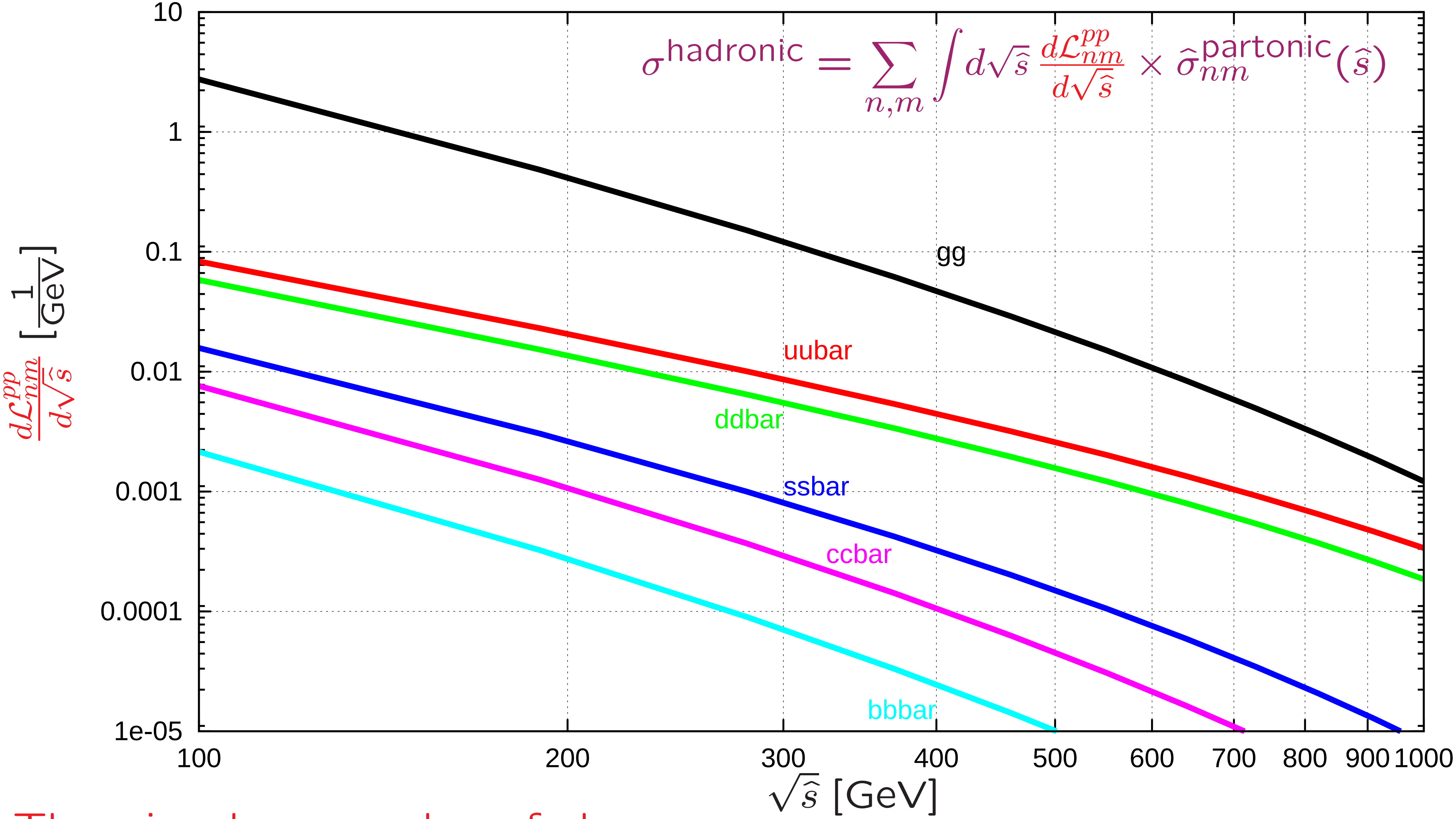
b: enhanced coupling in MSSM

Parton luminosities $\frac{d\mathcal{L}^{pp}_{nm}}{d\sqrt{\hat{s}}}$ at the LHC ($\sqrt{s} = 14\,\text{TeV}$):



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

Parton luminosities $\frac{d\mathcal{L}^{pp}_{nm}}{d\sqrt{\hat{s}}}$ at the LHC ($\sqrt{s} = 7\,\text{TeV}$):



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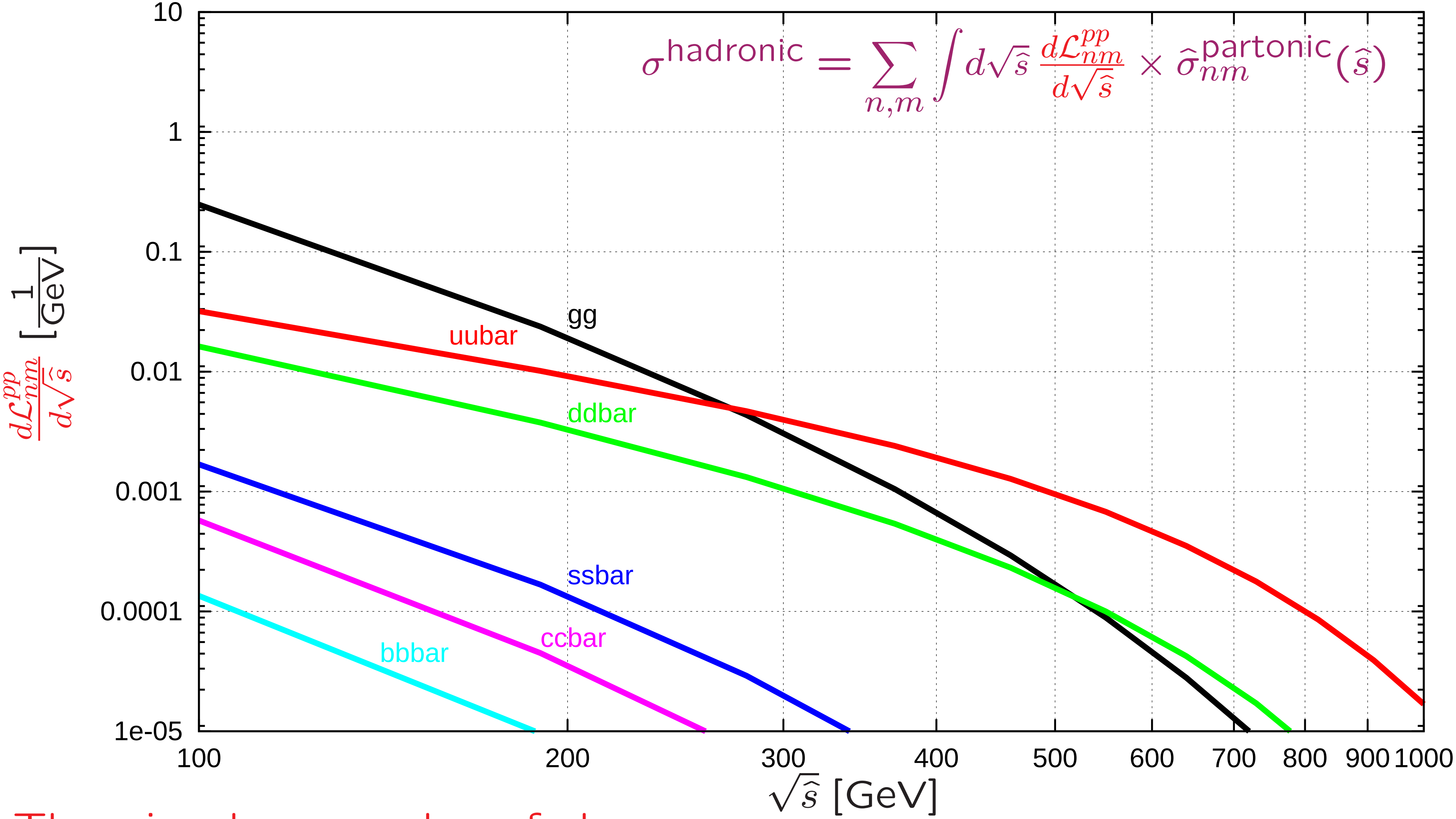
Parton luminosities $\frac{d\mathcal{L}^{pp}_{nm}}{d\sqrt{\hat{s}}}$ at the Tevatron:



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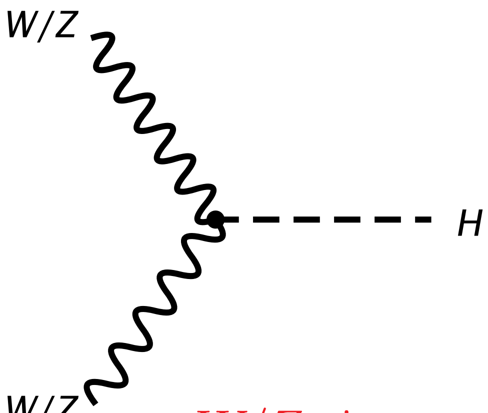

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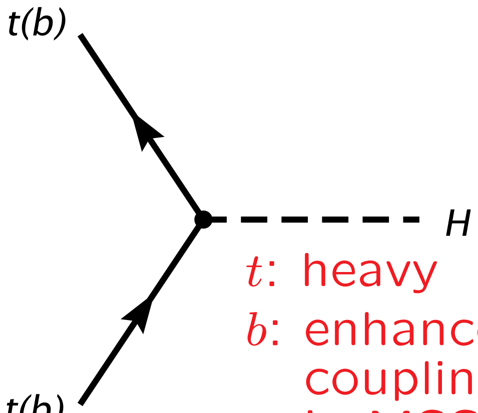

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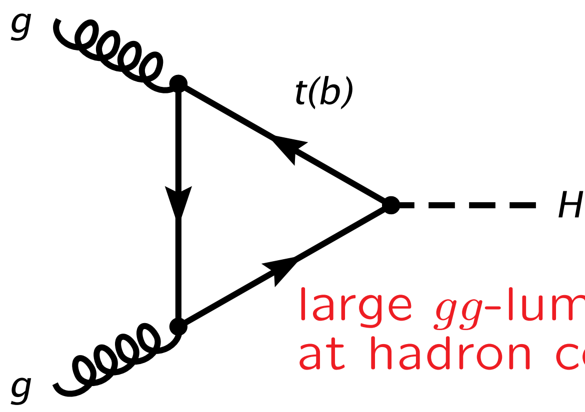

large gg-lumi at hadron colliders

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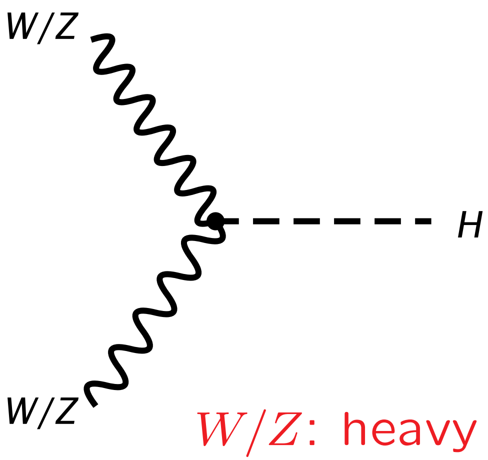

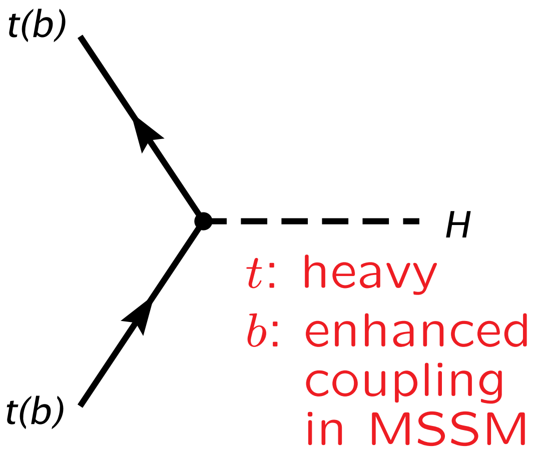

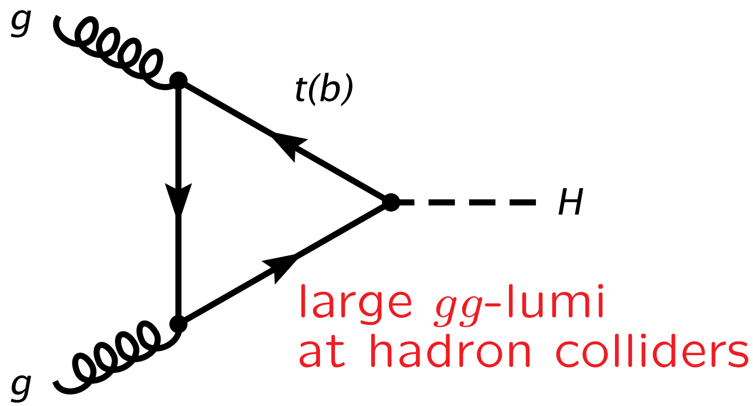

Therefore, most important couplings at high energy hadron colliders

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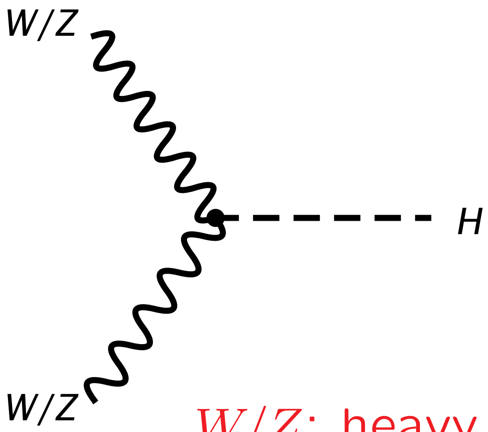
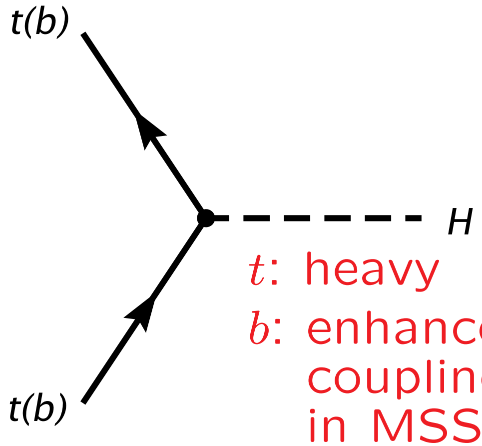


W/Z: heavy



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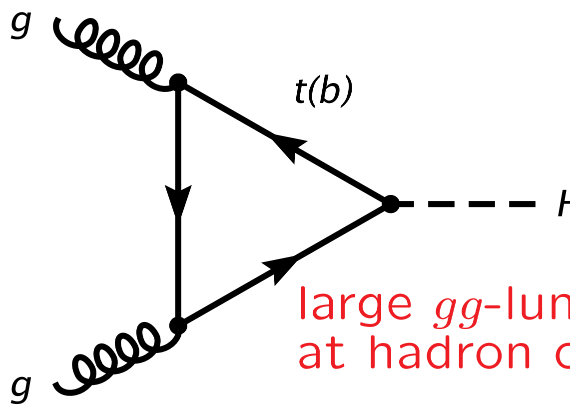
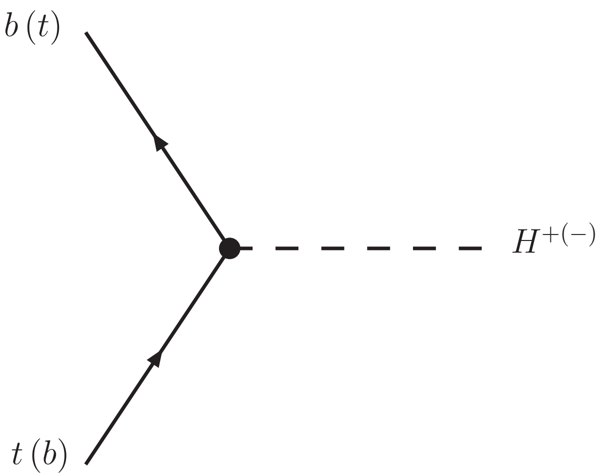
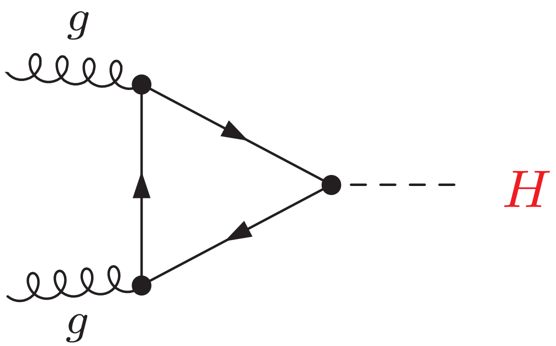


large gg-lumi at hadron colliders

... for charged Higgs production:



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



gluon fusion, $gg \longrightarrow H$

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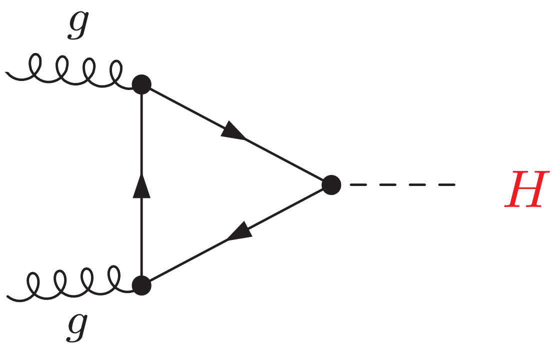

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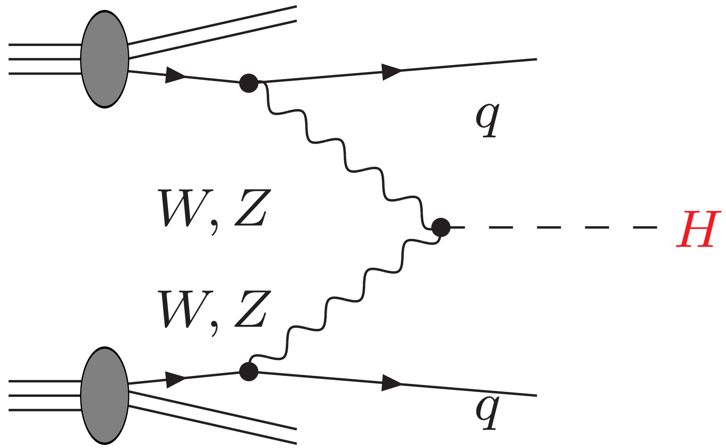

vector boson fusion, $qq \longrightarrow qqH$

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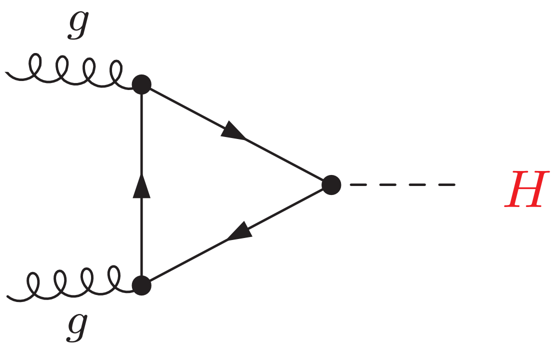

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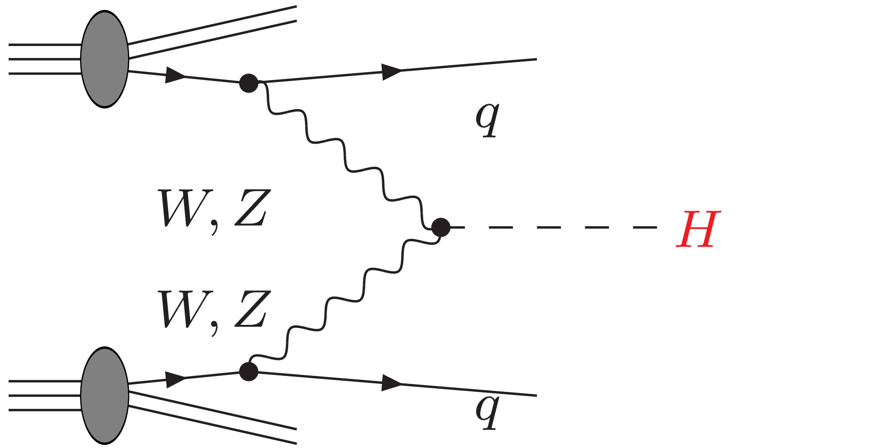

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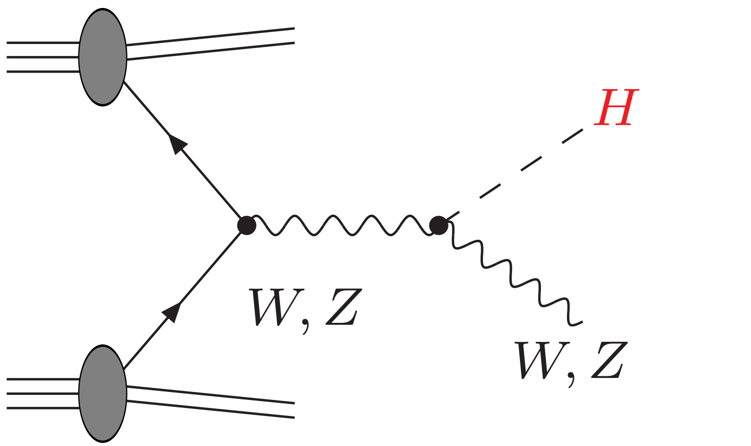

Higgs strahlung, $q\overline{q}' \longrightarrow VH$

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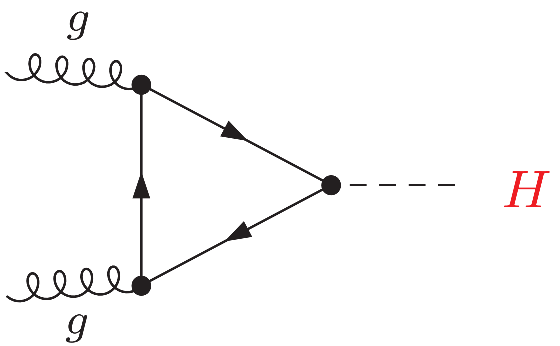

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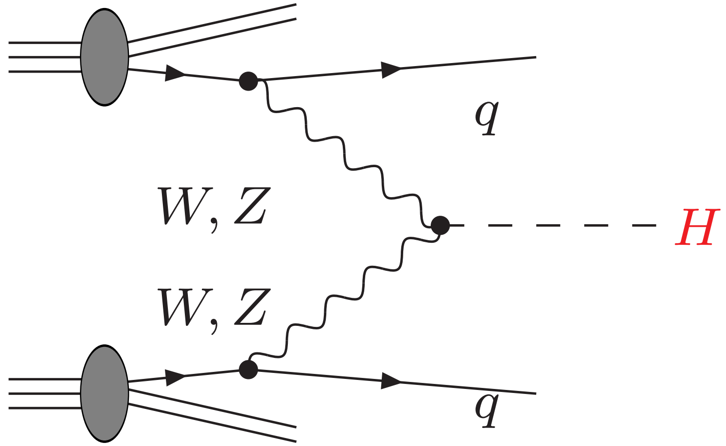

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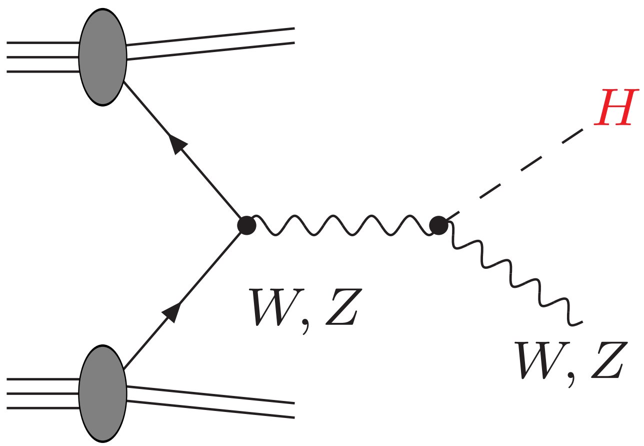

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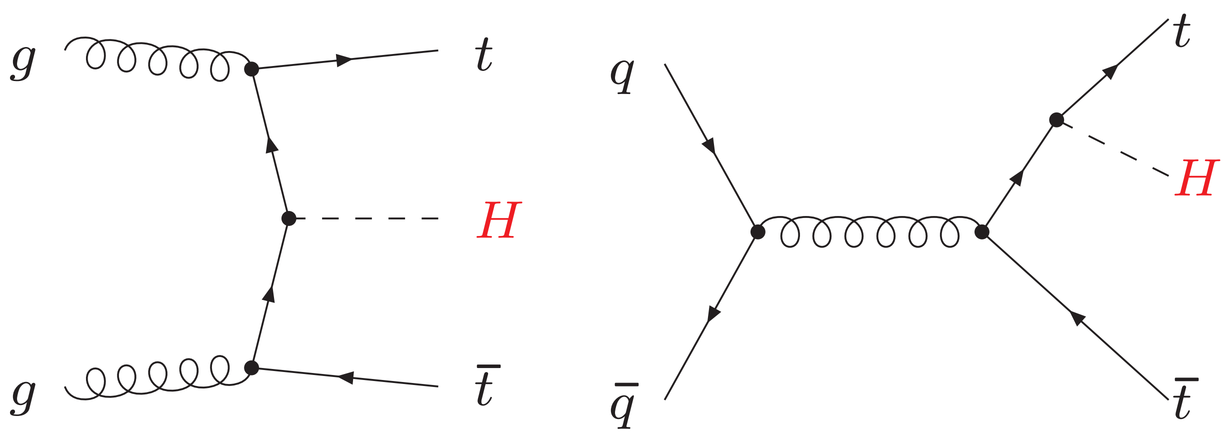

$t\bar{t}H$ **production**

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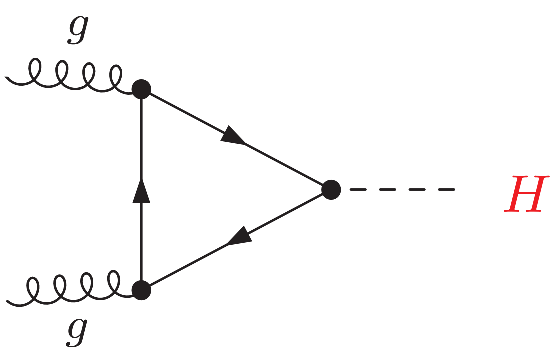

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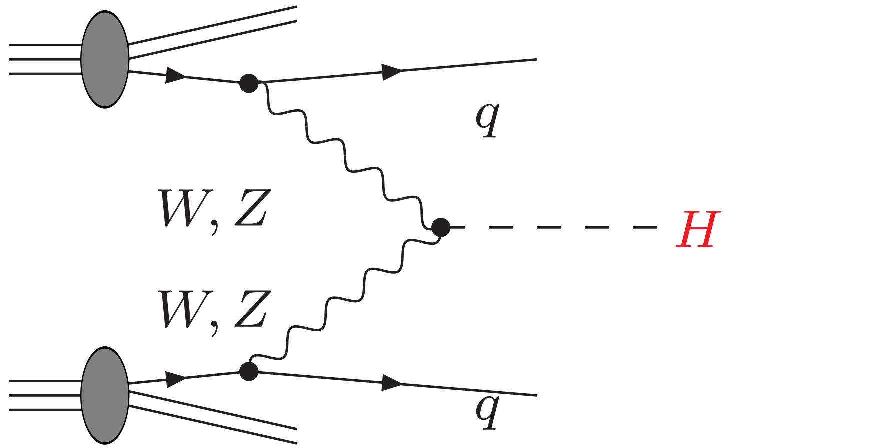

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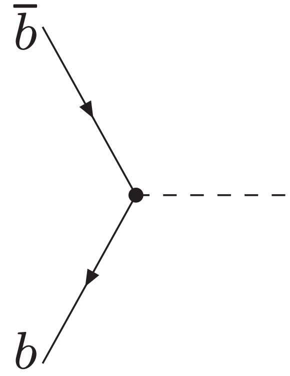
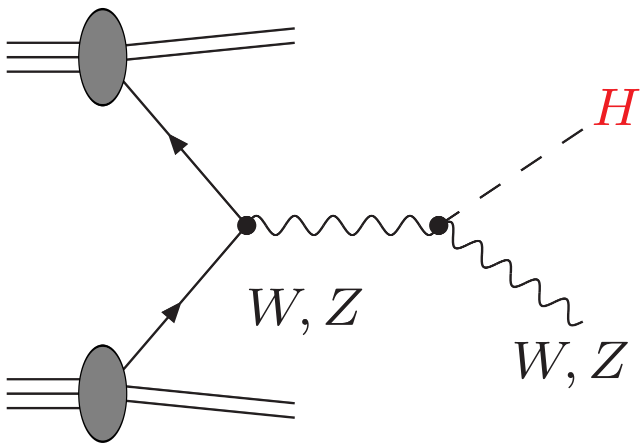
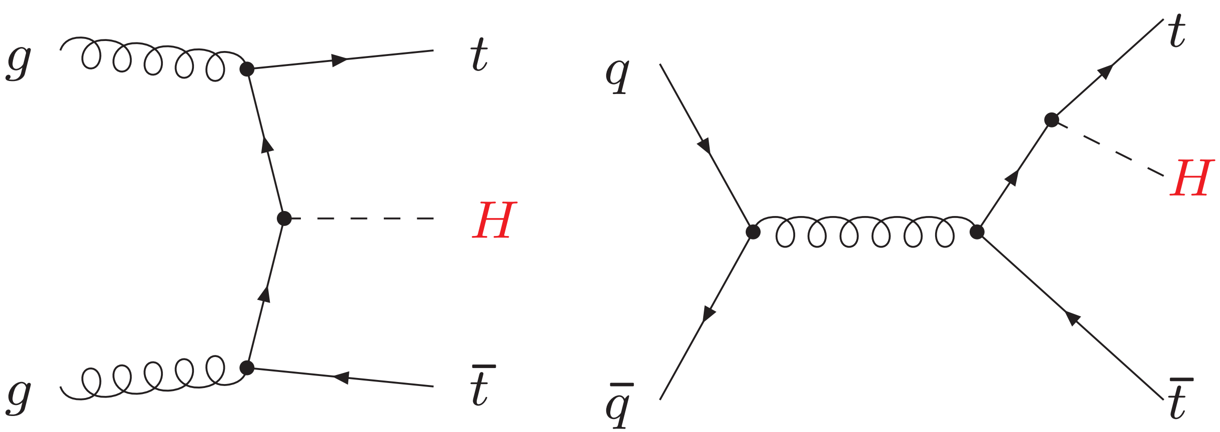


$b\bar{b} \to H$

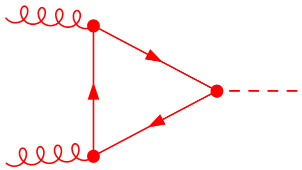


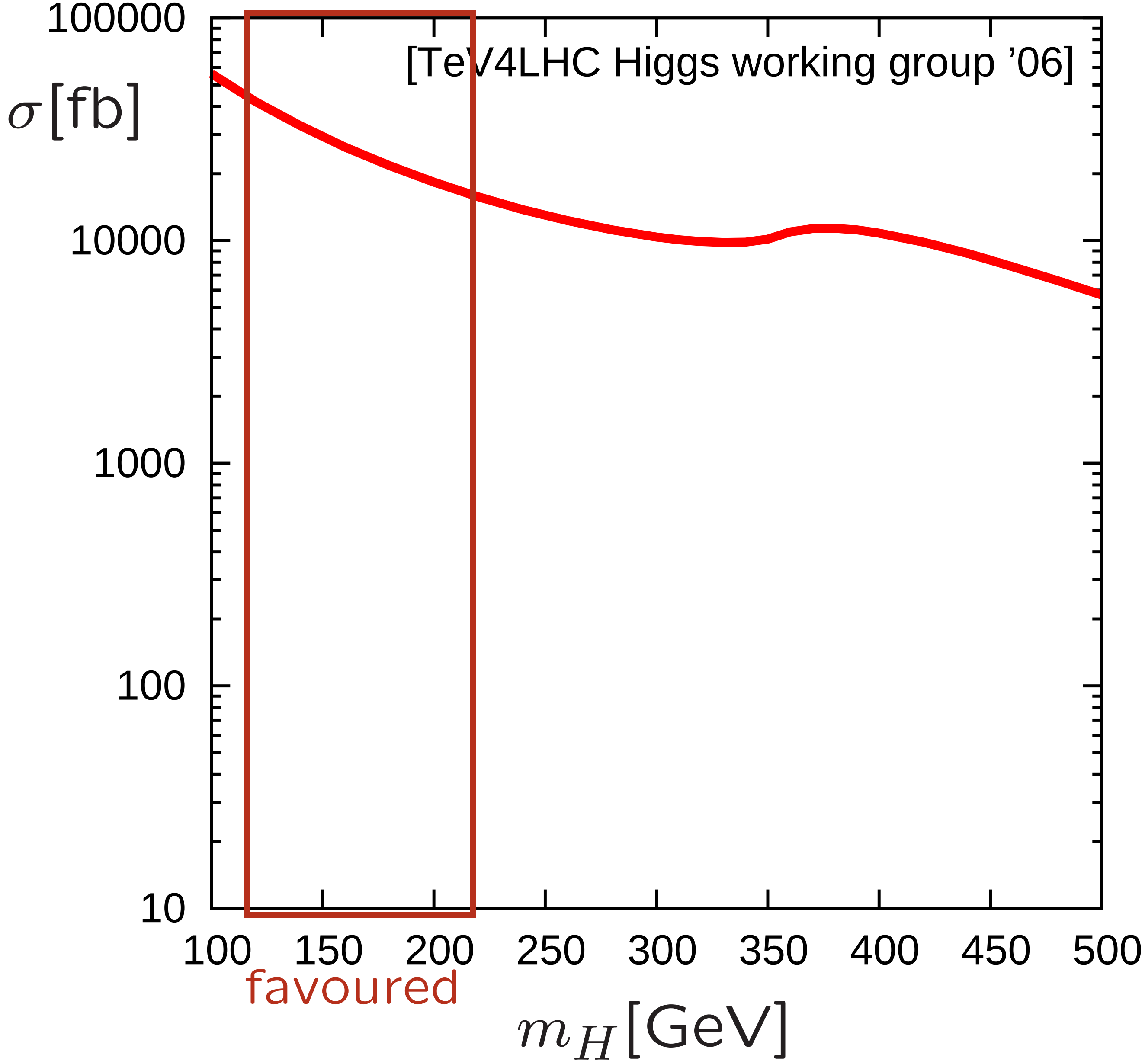
Higgs strahlung, $q\bar{q}' \to VH$



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

Predictions: SM Higgs production @ LHC :





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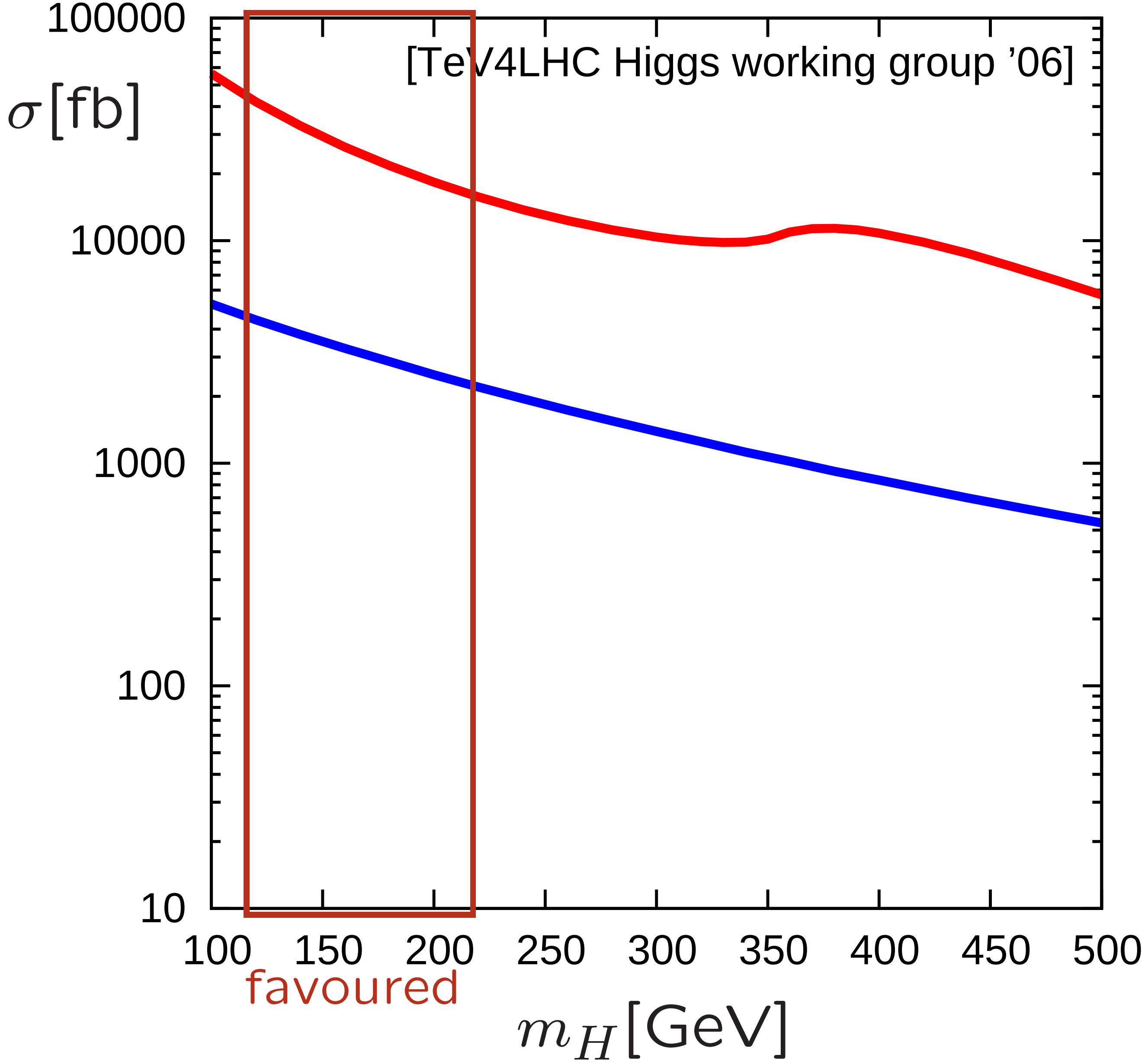

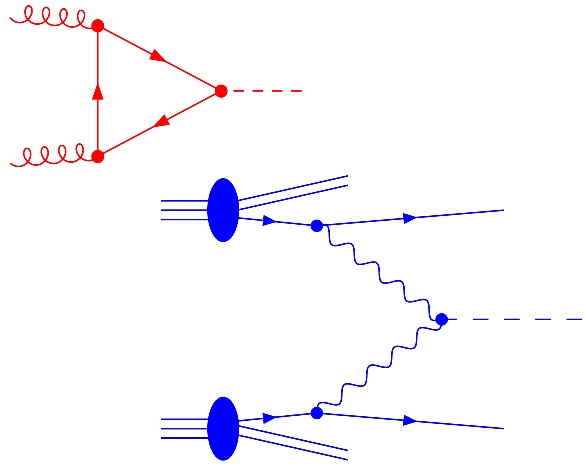

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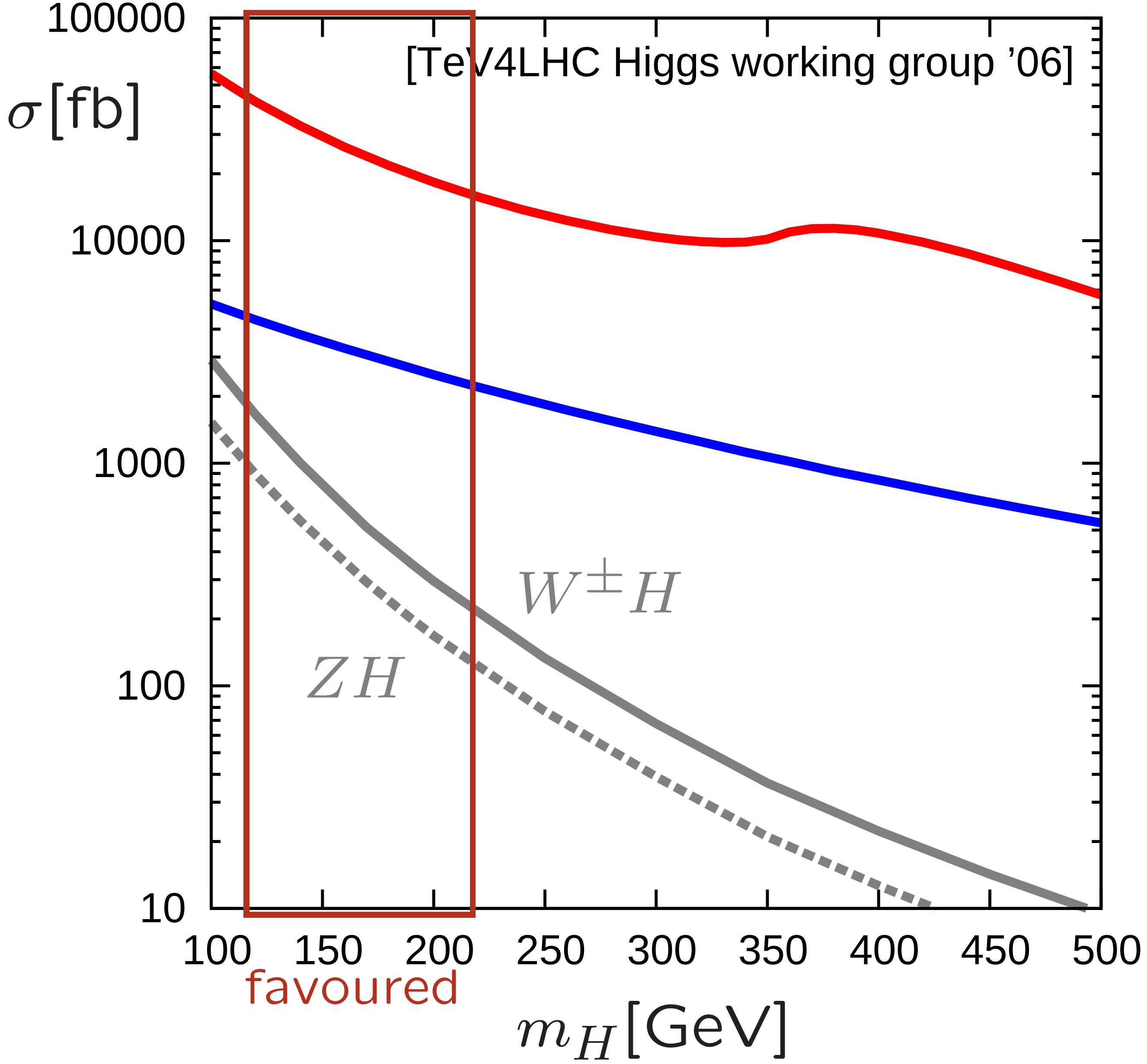

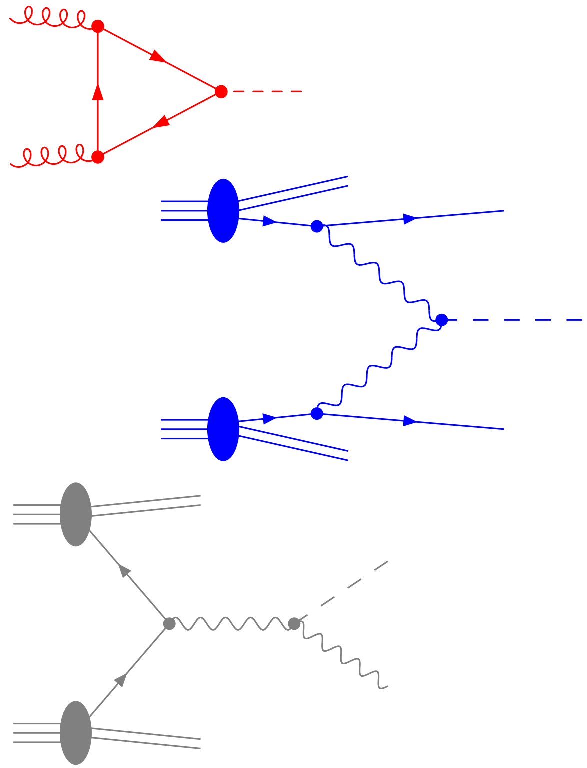

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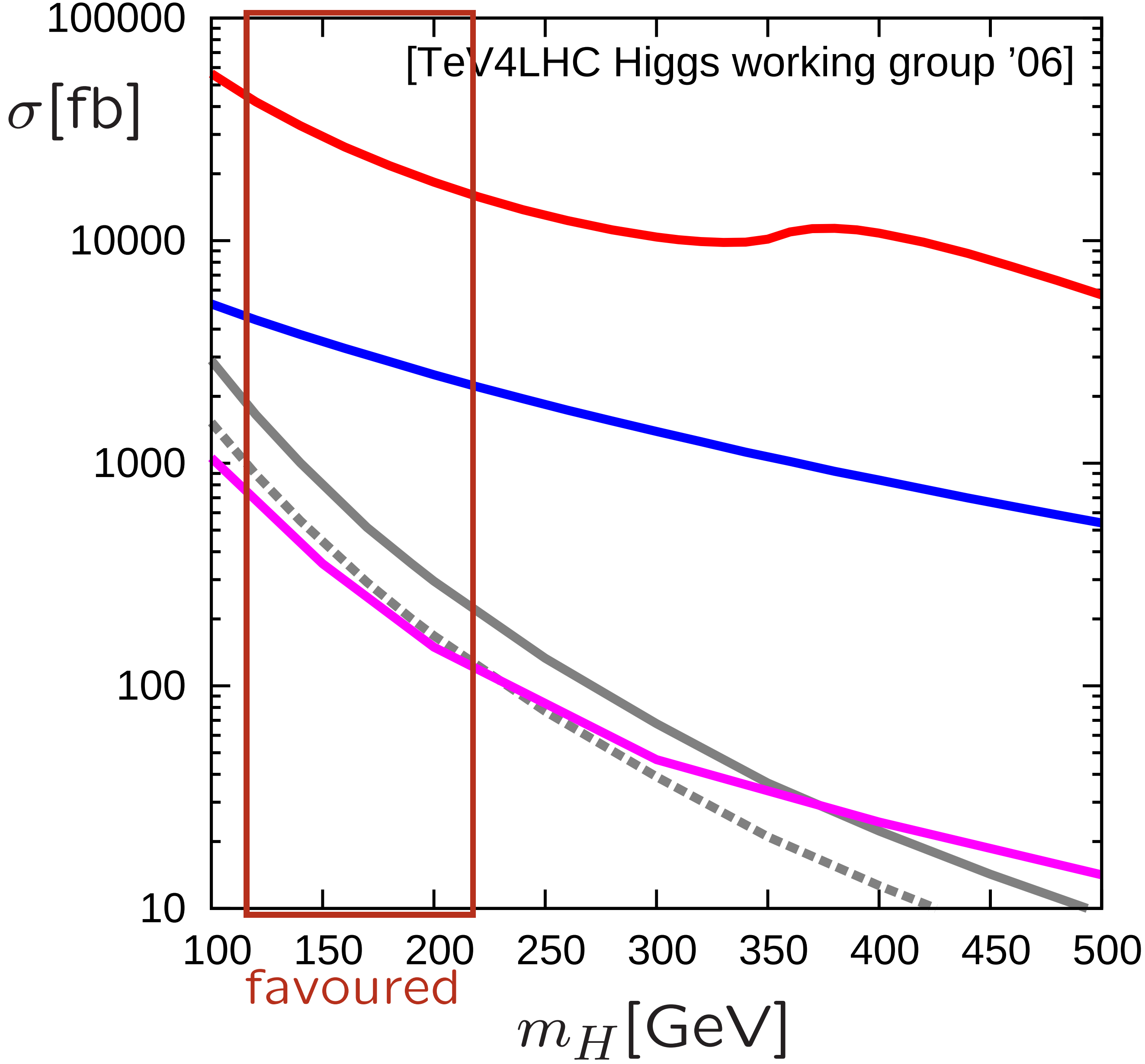
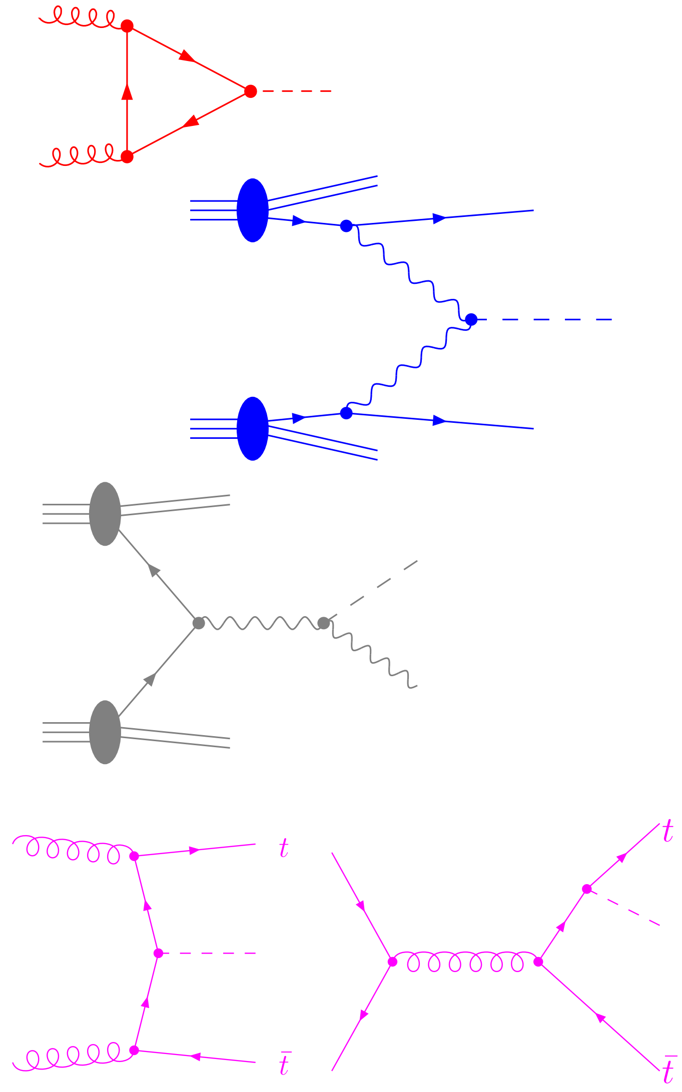
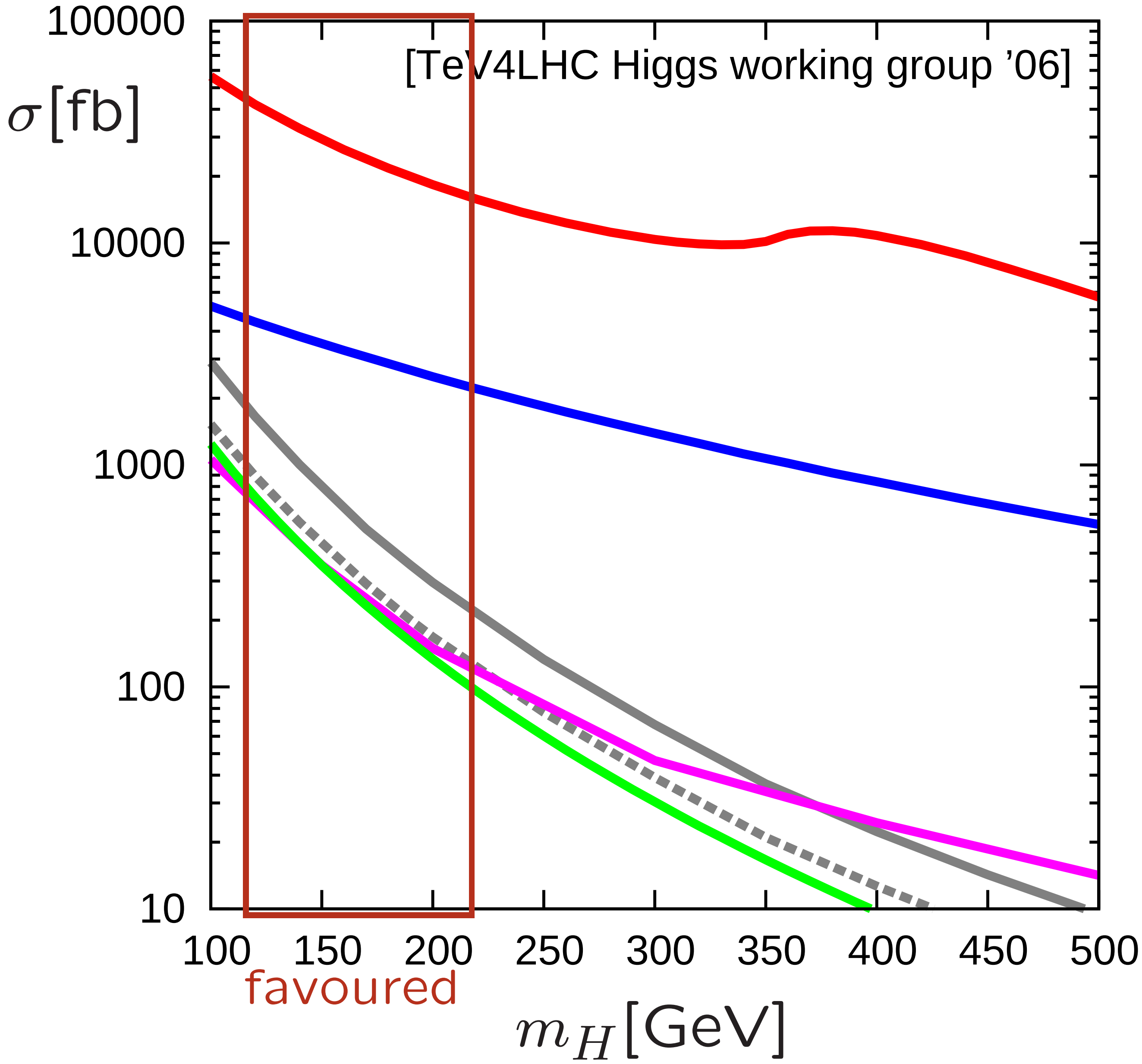
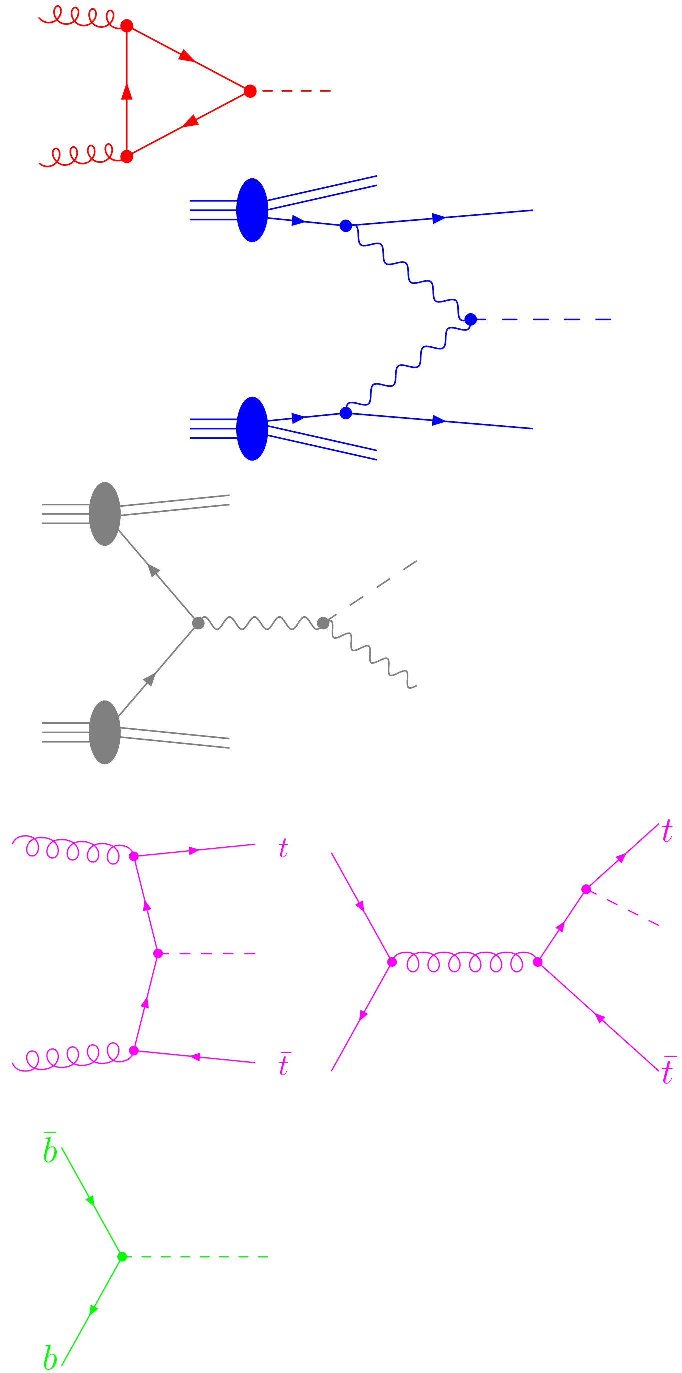


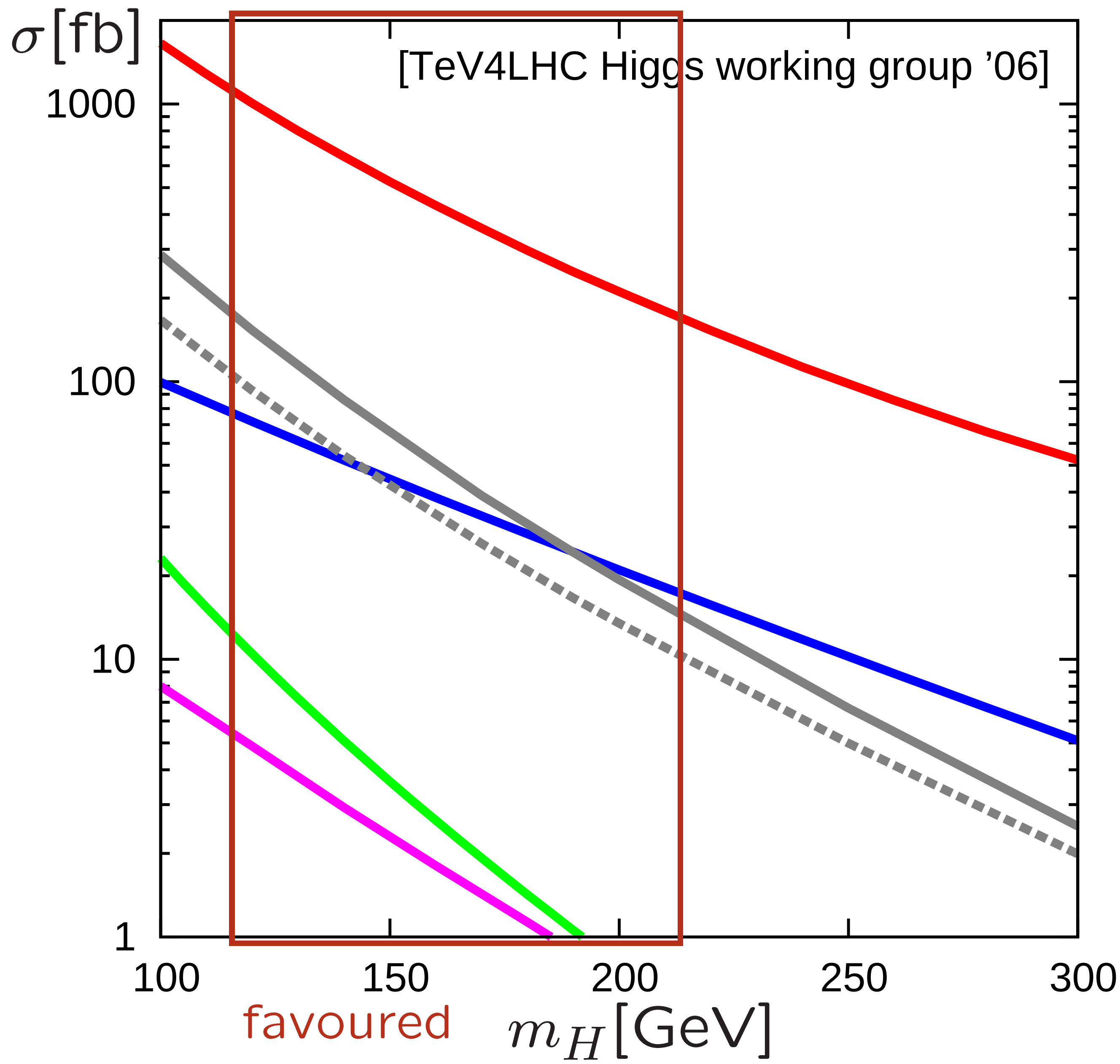


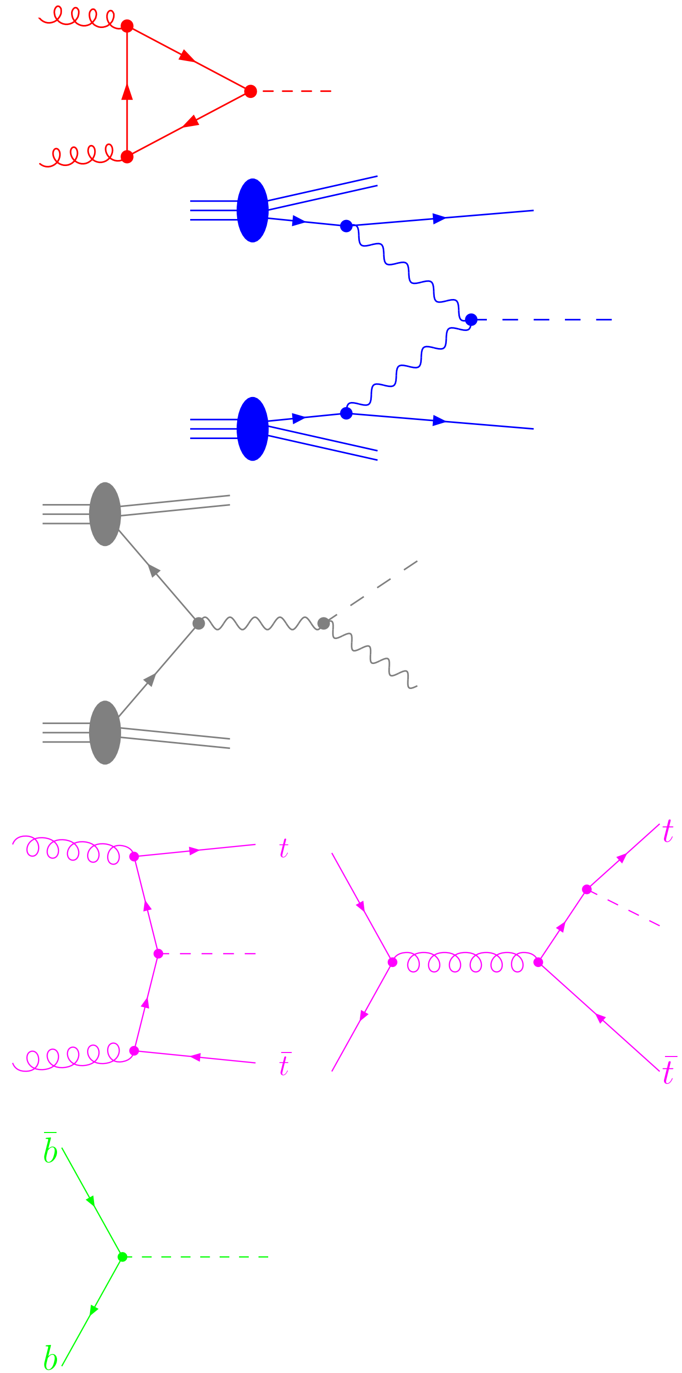
Predictions: SM Higgs production @ **LHC** :





Predictions: SM Higgs production @ Tevatron :





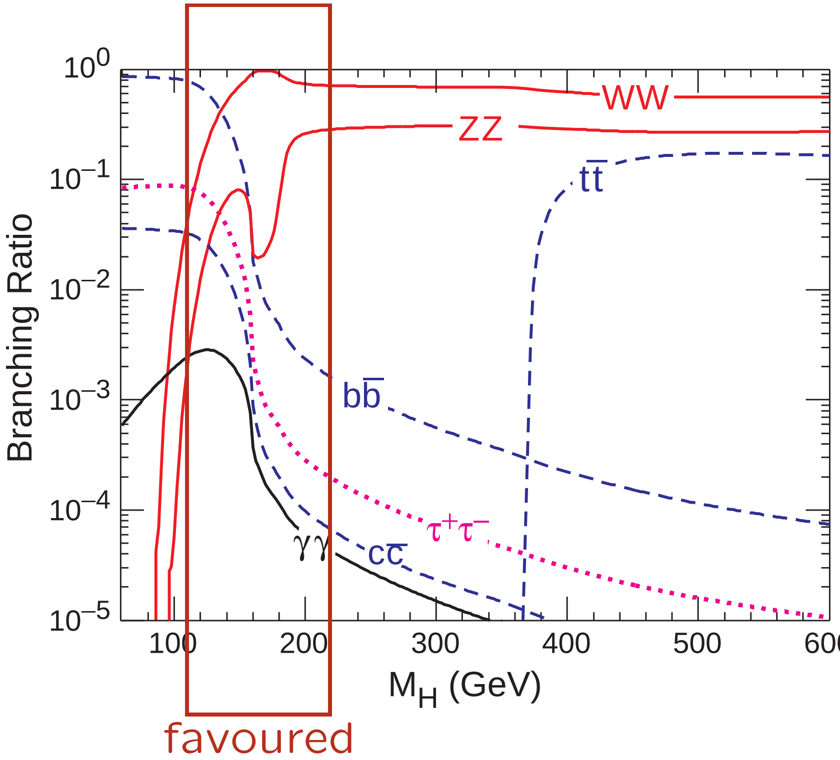
SM Higgs decay branching ratios
and
signal significance @ LHC

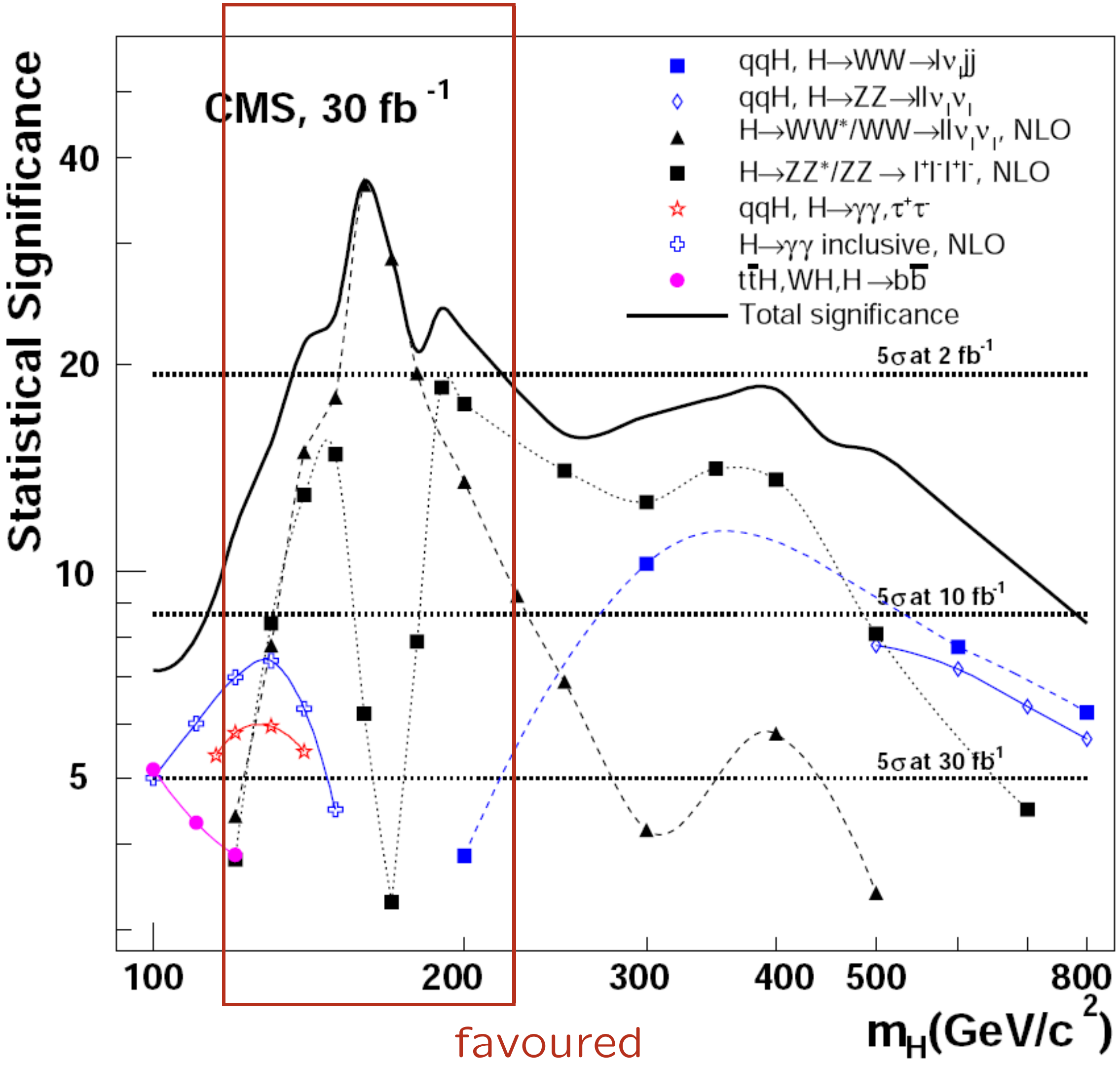
note!

rate alone is not enough!

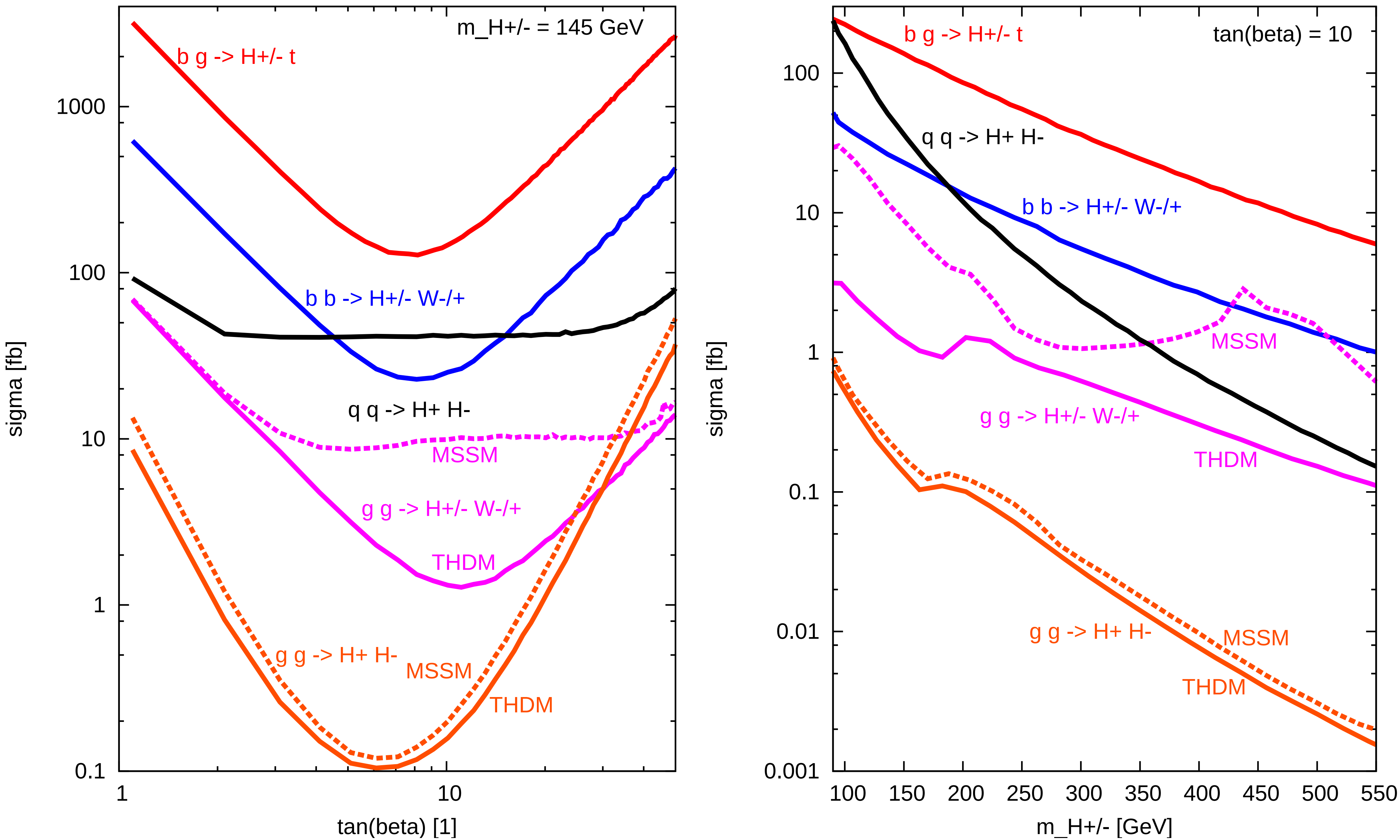
signals need to be silhouetted

against **huge** QCD background





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



- 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,

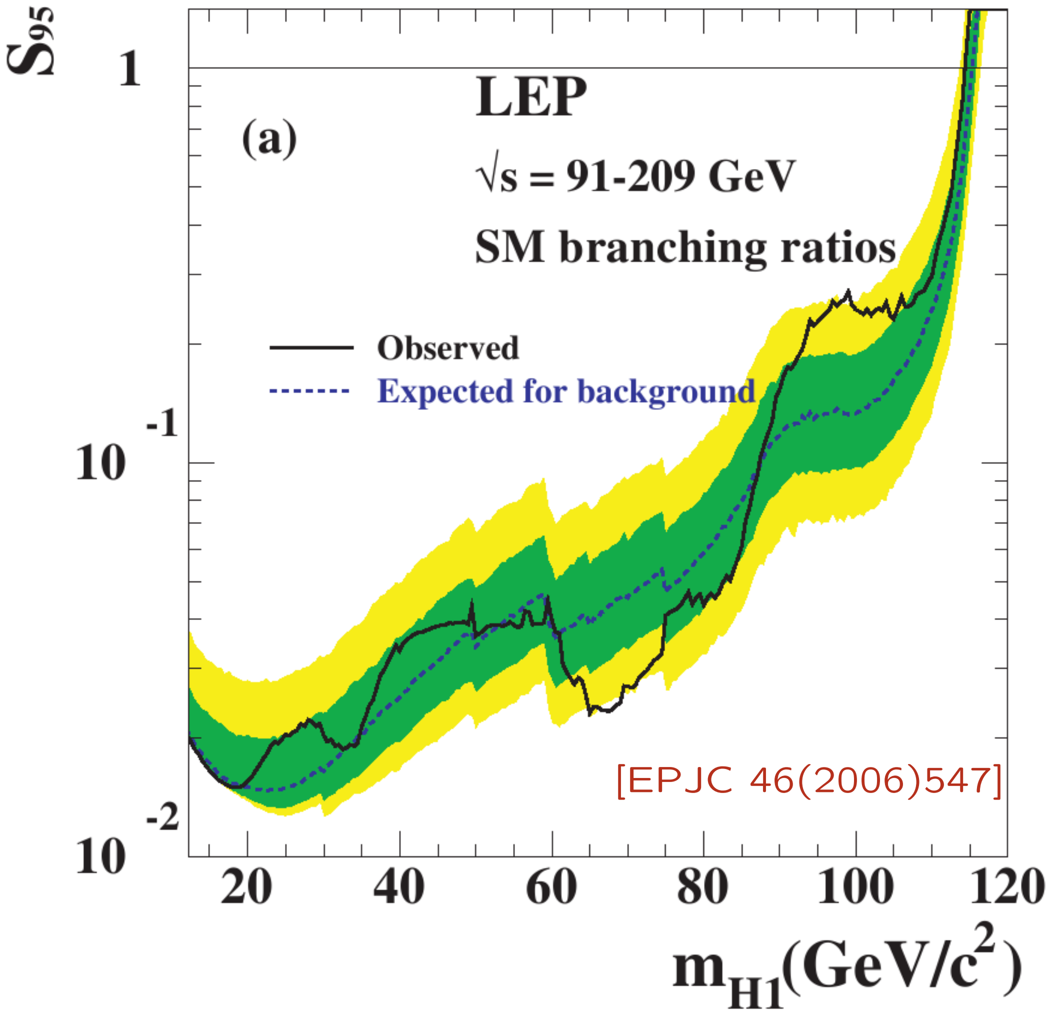
  e.g. $e^+e^- \to h_i Z \to b\bar{b}Z$, $p\bar{p} \to h_i \to W^+W^-$,

  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



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

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

A SM-like model with

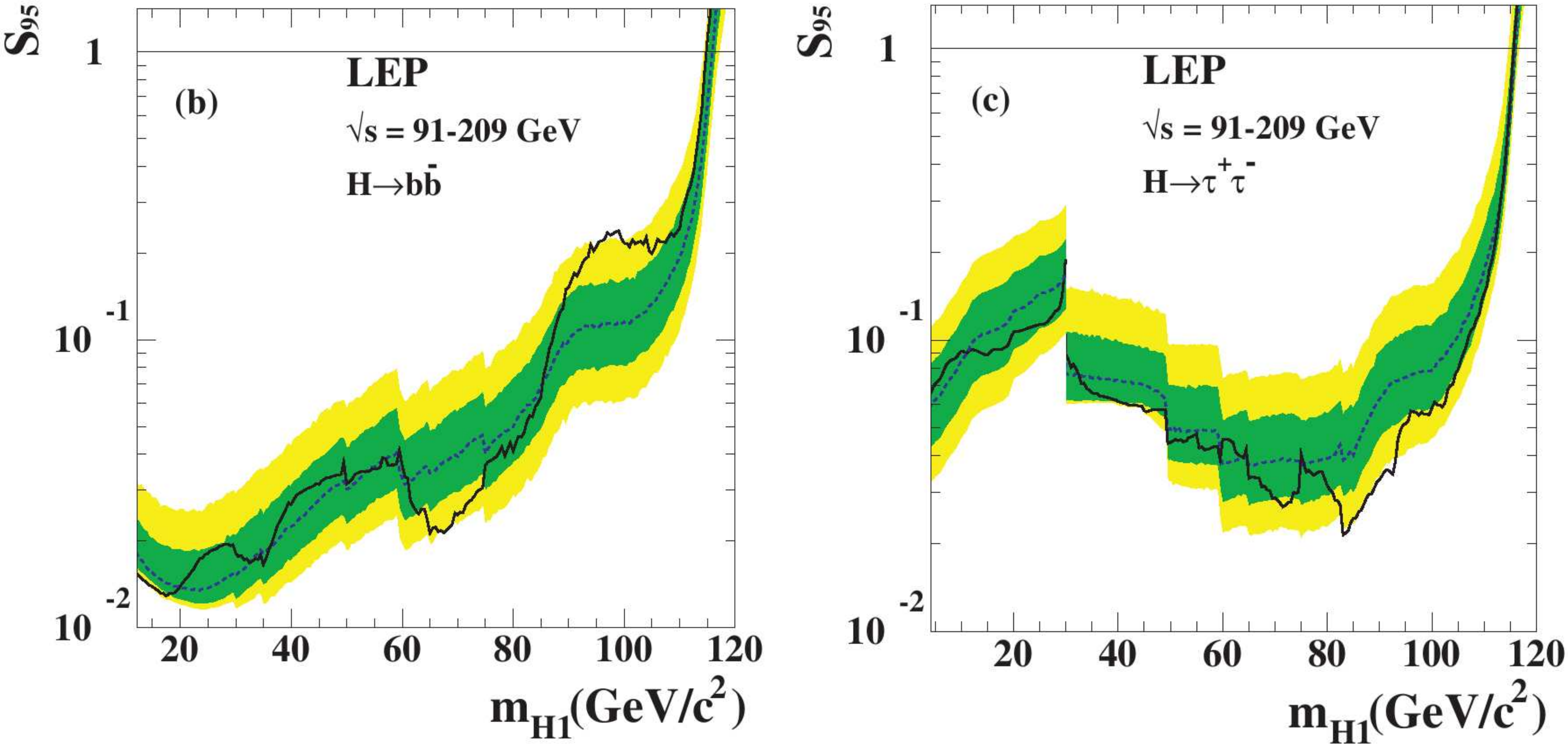
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\text{min}}(m_{H1})$$

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

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

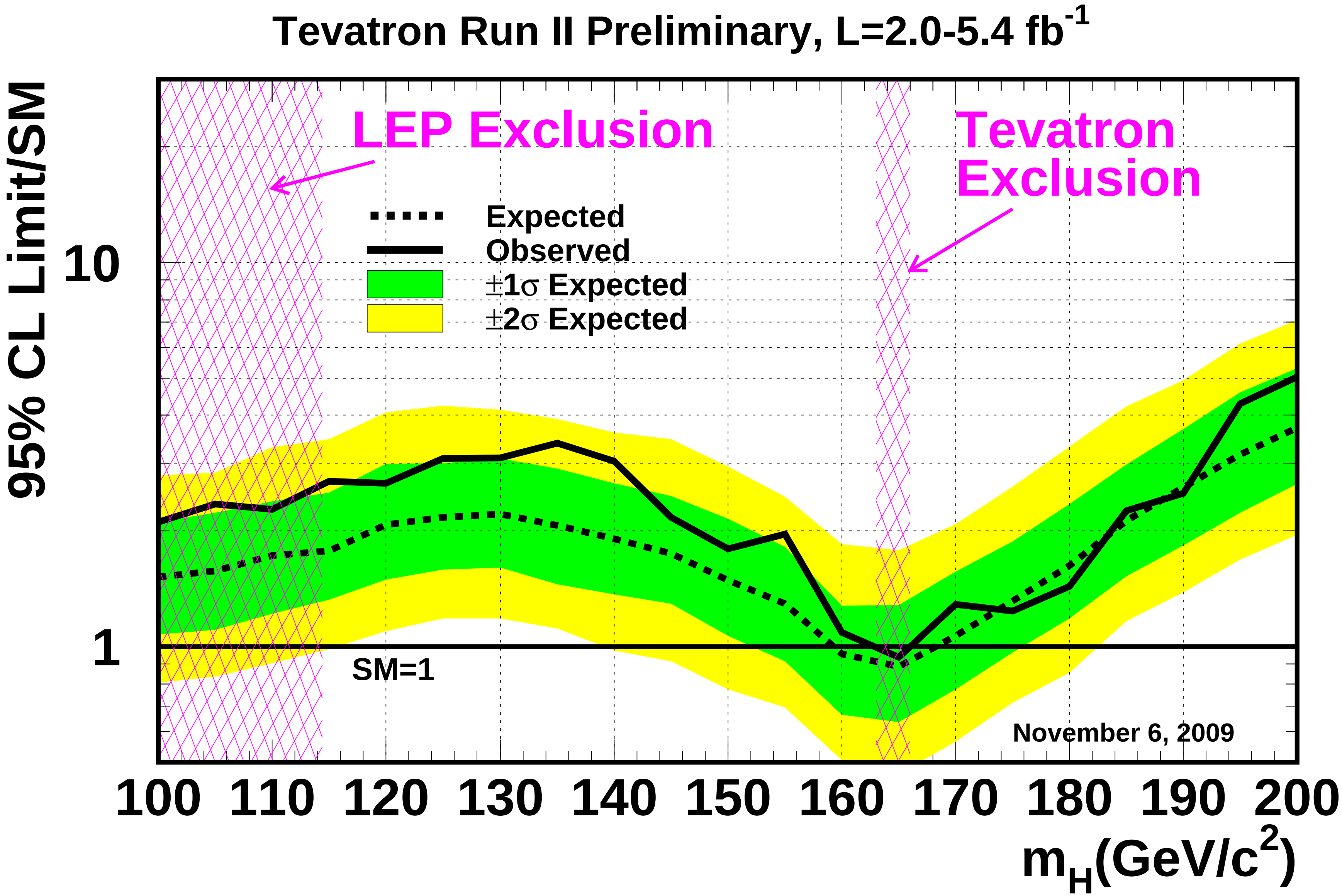
example 2: LEP single topology limits, assuming HZ production and ...

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 9998, DØ note 5983]



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

Test models with arbitrary Higgs sectors against exclusion bounds from LEP/Tevatron Higgs searches.

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

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

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

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

with

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

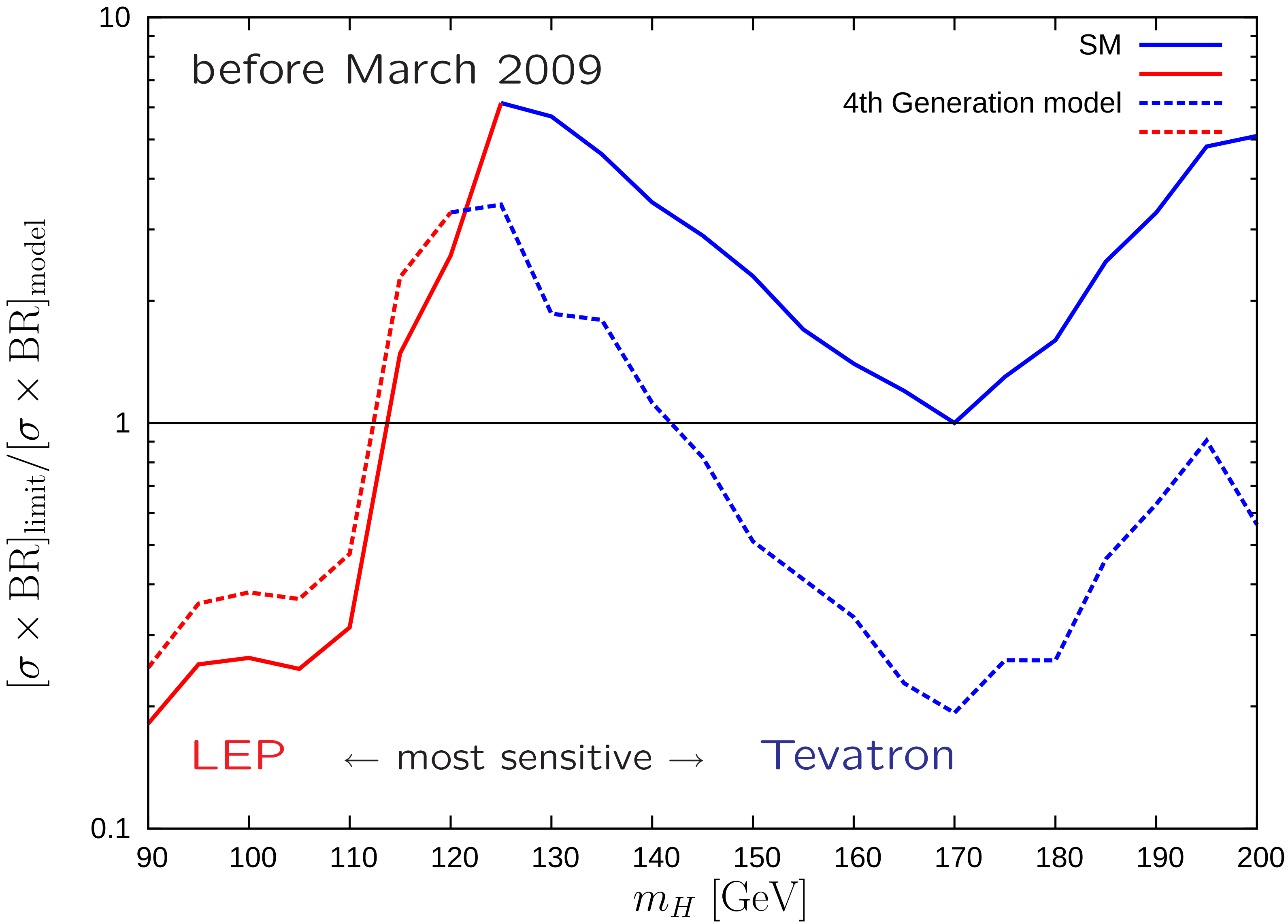
$$\text{BR}_{\text{model}}(h_k \to b\bar{b}) = \text{BR}_{\text{SM}}(H \to b\bar{b})(m_H) \left.\frac{\Gamma^{\text{SM}}_{\text{tot}}(m_H)}{\Gamma_{\text{tot}}(h_k)}\right|_{m_H = m_{h_k}} \left(\frac{g^{\text{model}}_{h_k bb,\text{eff}}}{g^{\text{SM}}_{Hbb}}\right)^2.$$

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

– Applications

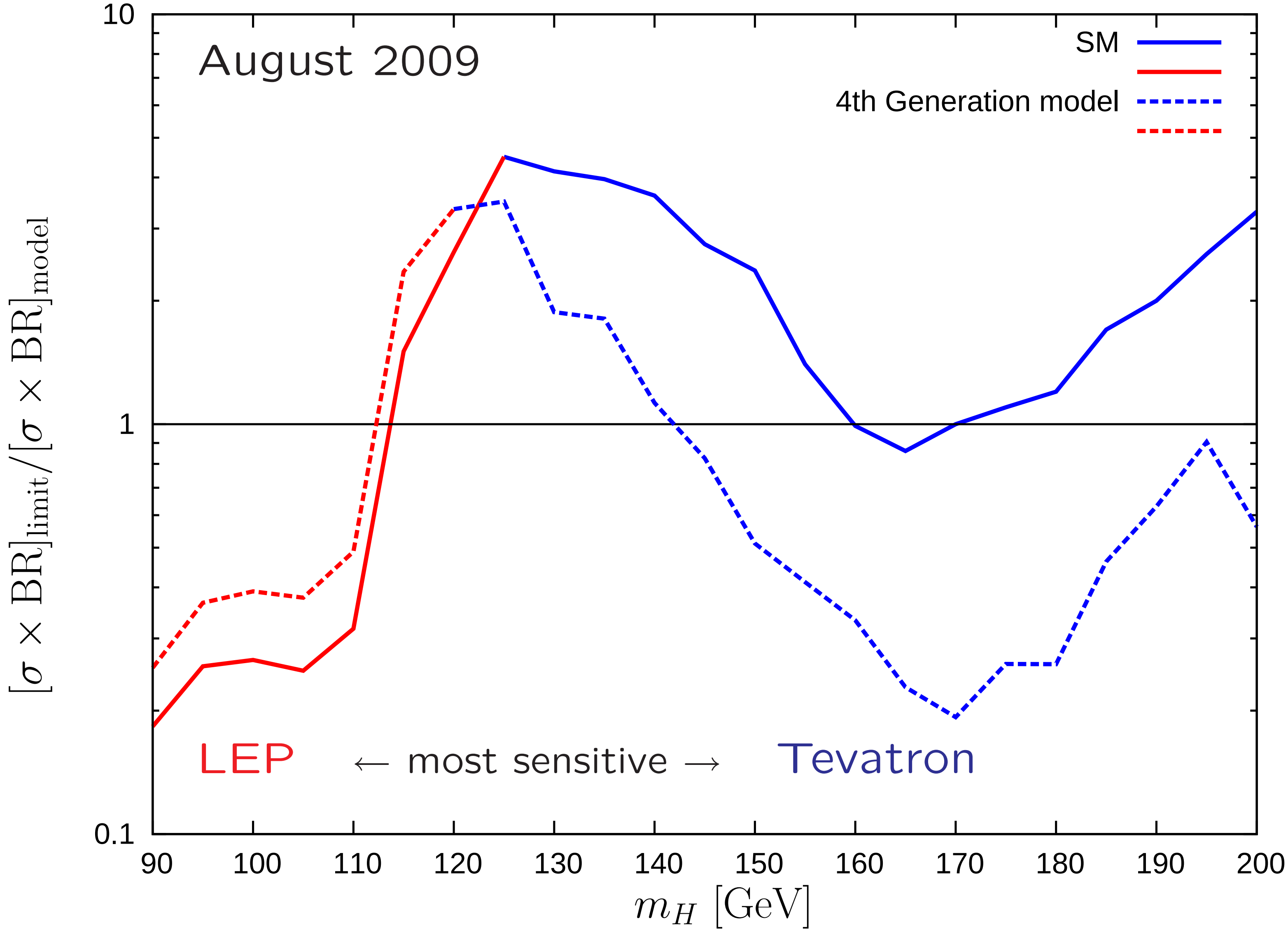
application 1: SM versus Fourth Generation Model exclusion

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



application 1: SM versus Fourth Generation Model exclusion

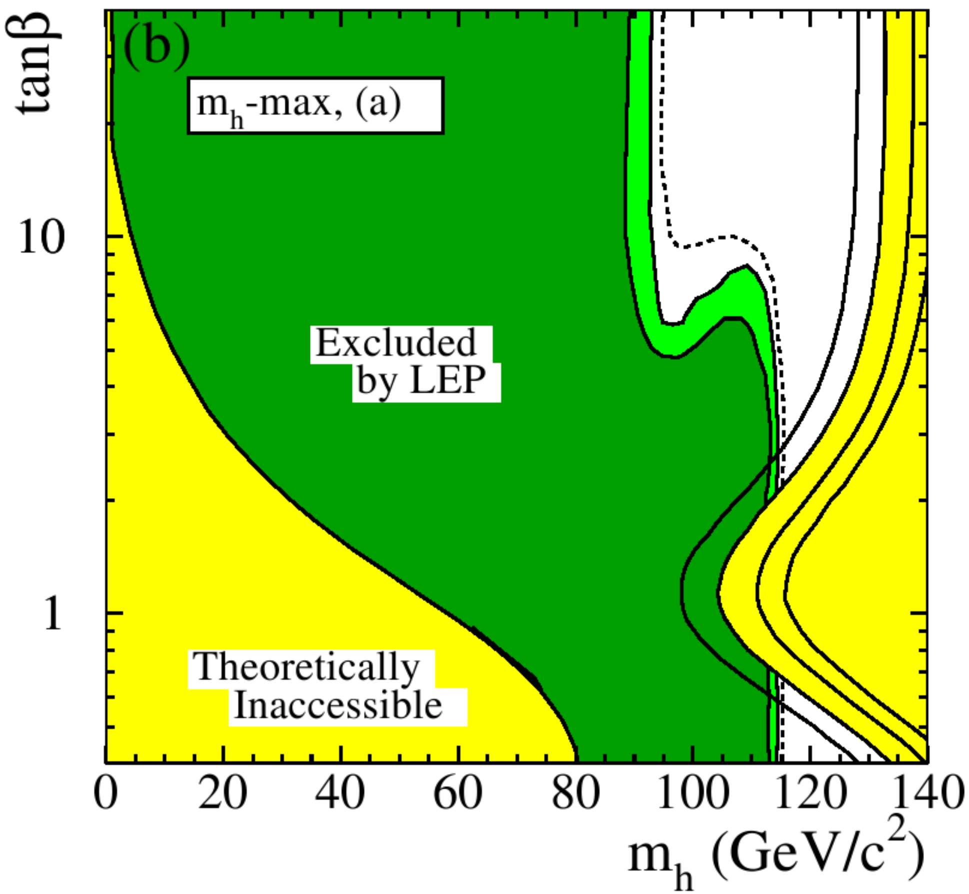
$$\Gamma(H \to gg)_{\text{model}} = 9 \times \Gamma(H \to gg)_{\text{SM}}$$

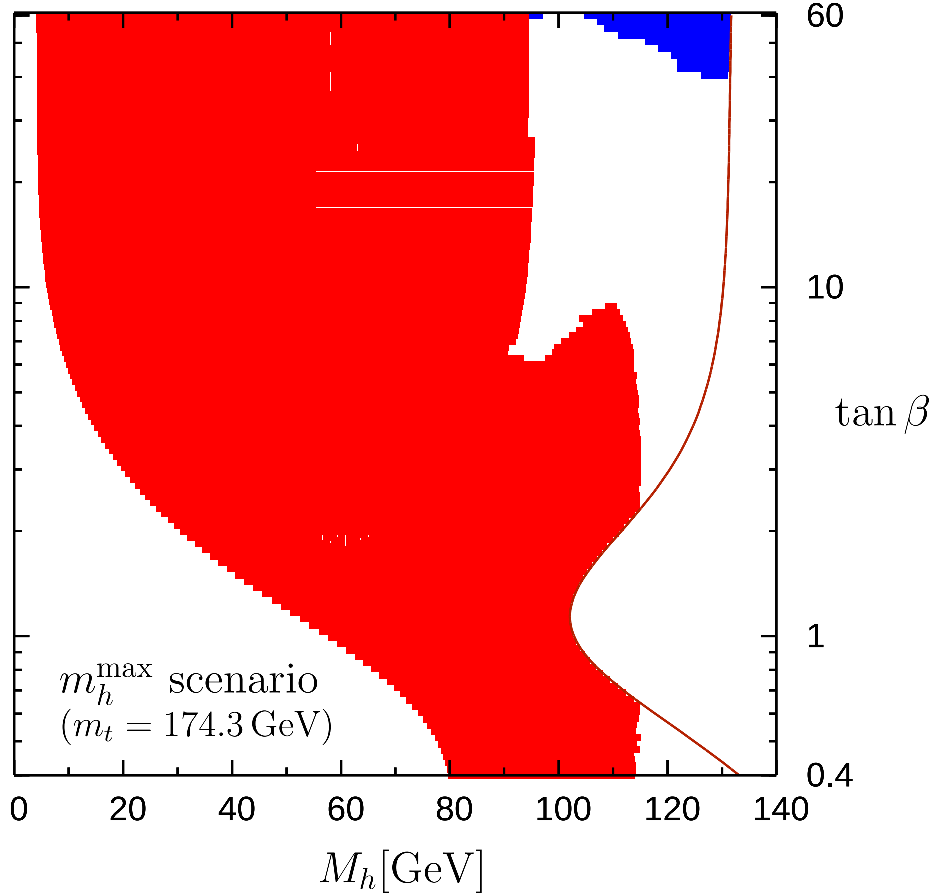


application 2: MSSM benchmark scenarios, exclusion update

a) [EPJC 46(2006)547]

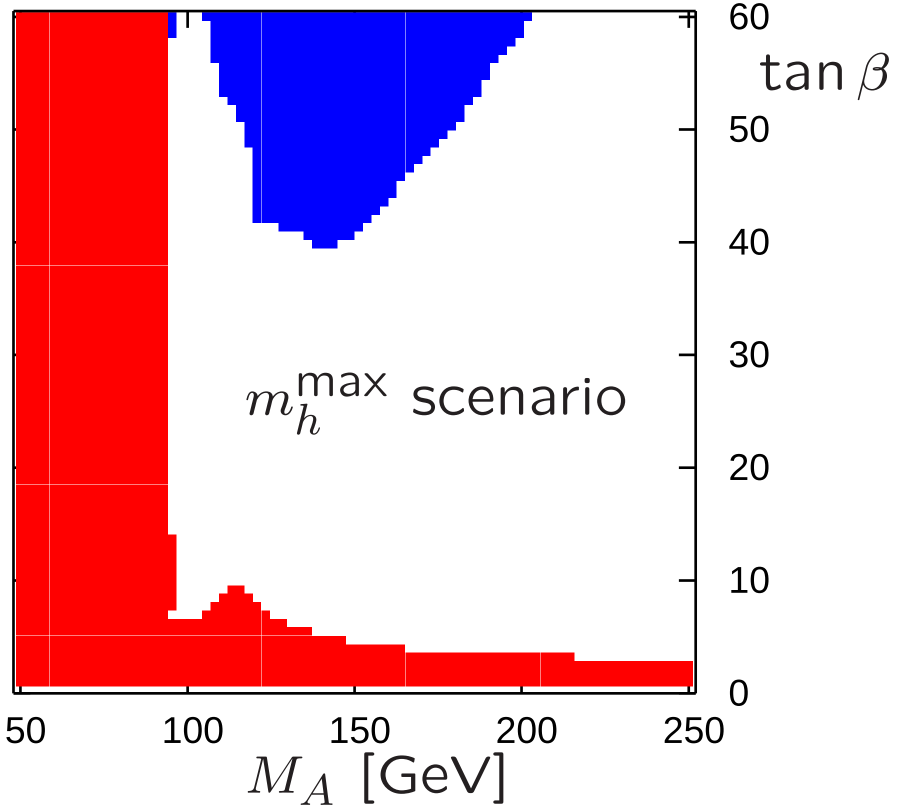
b) **HiggsBounds**
with: new m_t,
impoved m_h prediction,
Tevatron data included





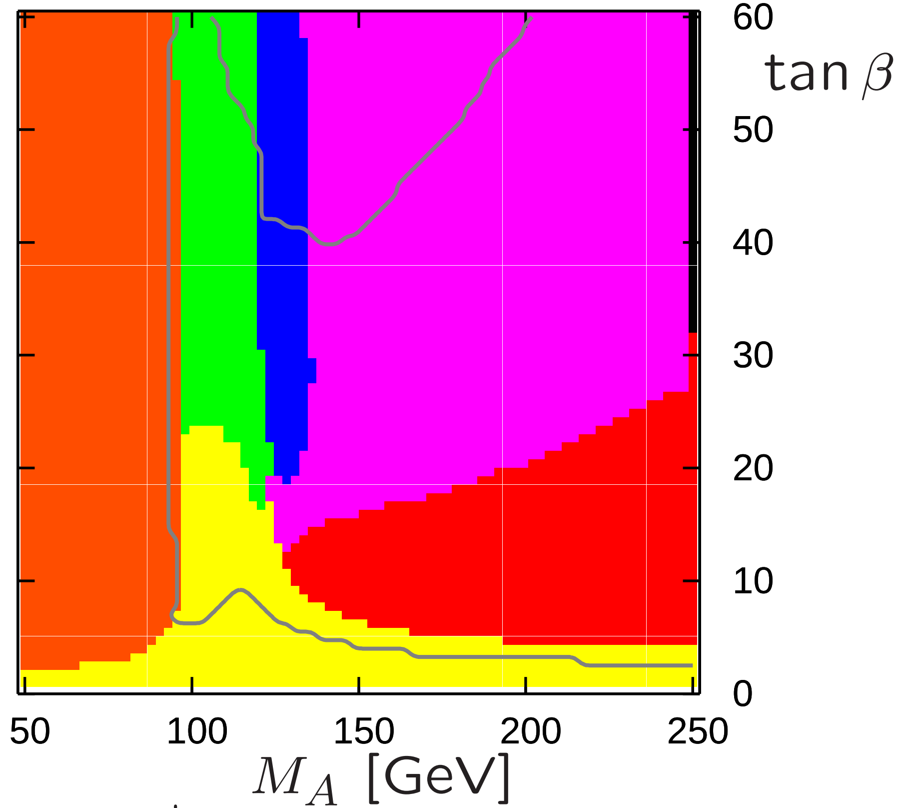
application 2: MSSM benchmark scenarios, exclusion update (before March 2009)

a) LEP and Tevatron exclusion



- : LEP exclusion
- : Tevatron exclusion

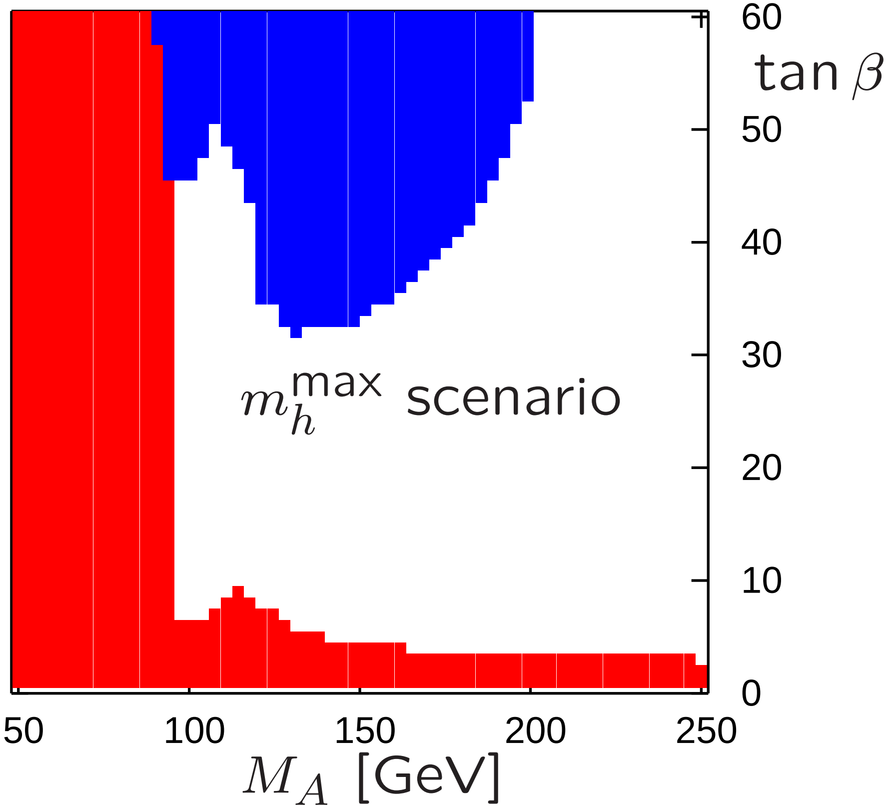
b) highest sensitivity



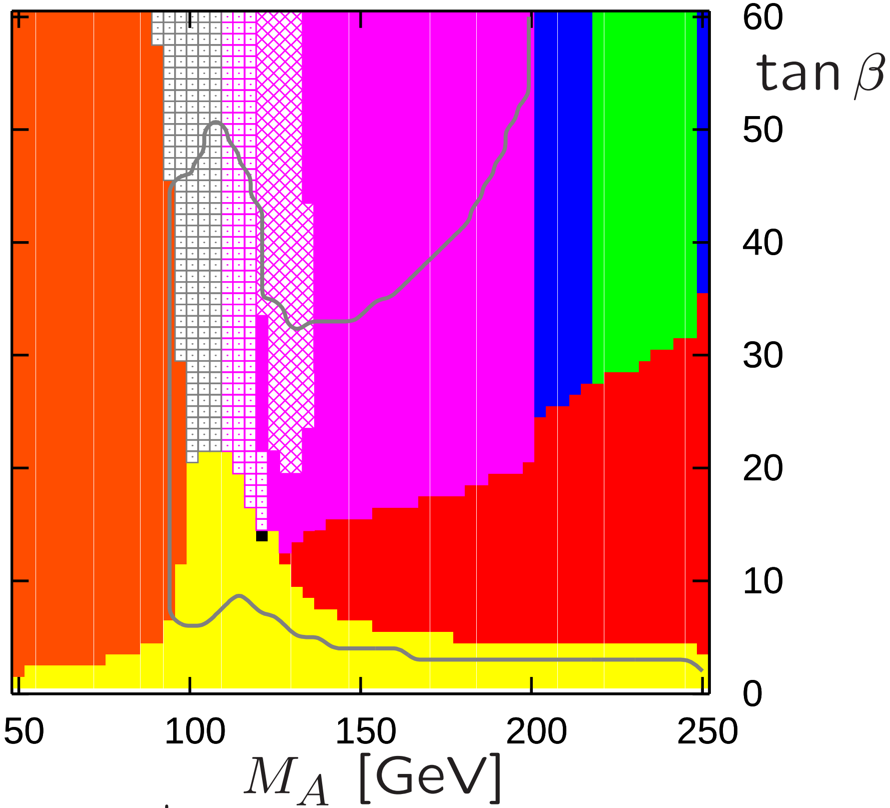
- : $e^+e^- \to hZ, h \to b\bar{b}$
- : $e^+e^- \to hA \to b\bar{b}b\bar{b}$
- : $p\bar{p} \to hW \to b\bar{b}l\nu$ [CDF note 9463]
- : $p\bar{p} \to h/A \to \tau^+\tau^-$ [CDF note 9071]
- : $p\bar{p} \to h/H/A \to \tau^+\tau^-$ [CDF note 9071]
- : $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF note 9071]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

application 2: 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]

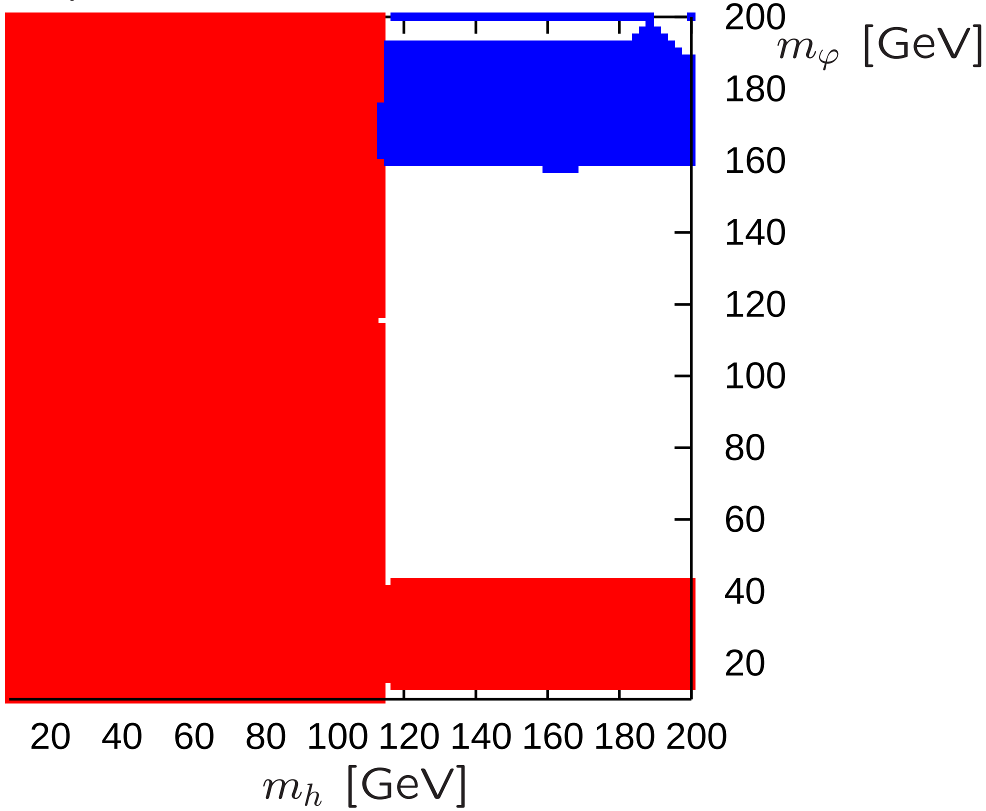
■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF '09]

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

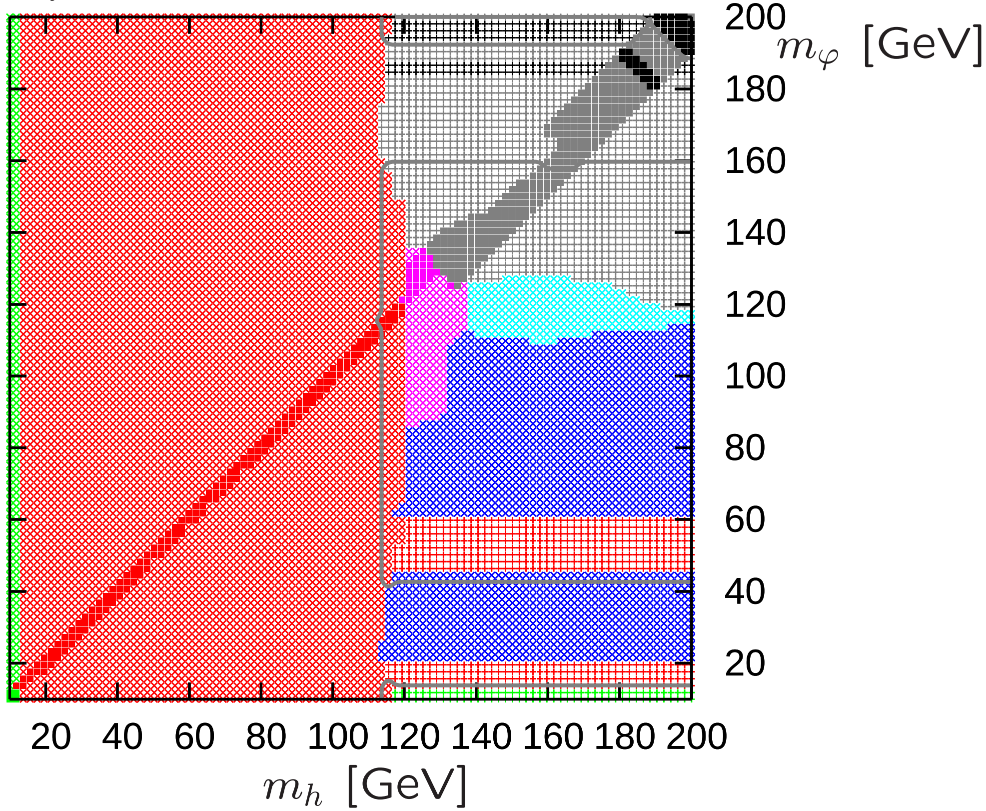
application 3: Randall-Sundrum model, excluded parameter space

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., W. Bernreuther et al., etc.

- Current work: (will soon appear as version 2.0.0)
  – inclusion of new Tevatron analyses (which need additional input)
  – inclusion of LEP analyses wBith $H \to$ invis., $H \to$ 2 jets, etc.
  – inclusion of charged Higgs analyses

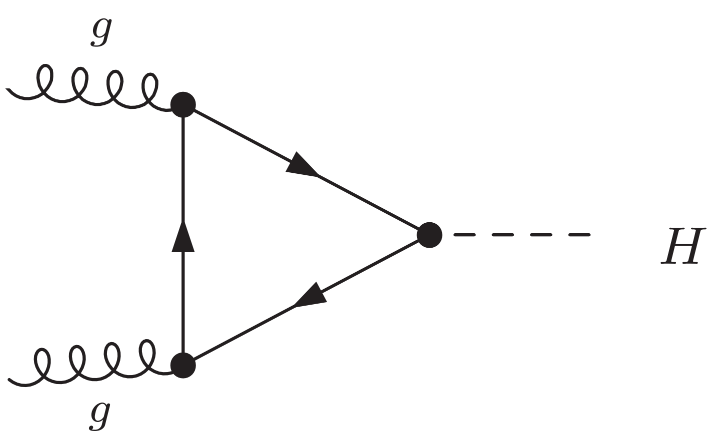
- Plans:
  – providing CL_{s+b} for given m_H and $\sigma \times$ BR ($\to$ useful for model fitting)
  – inclusion of width-dependent limits

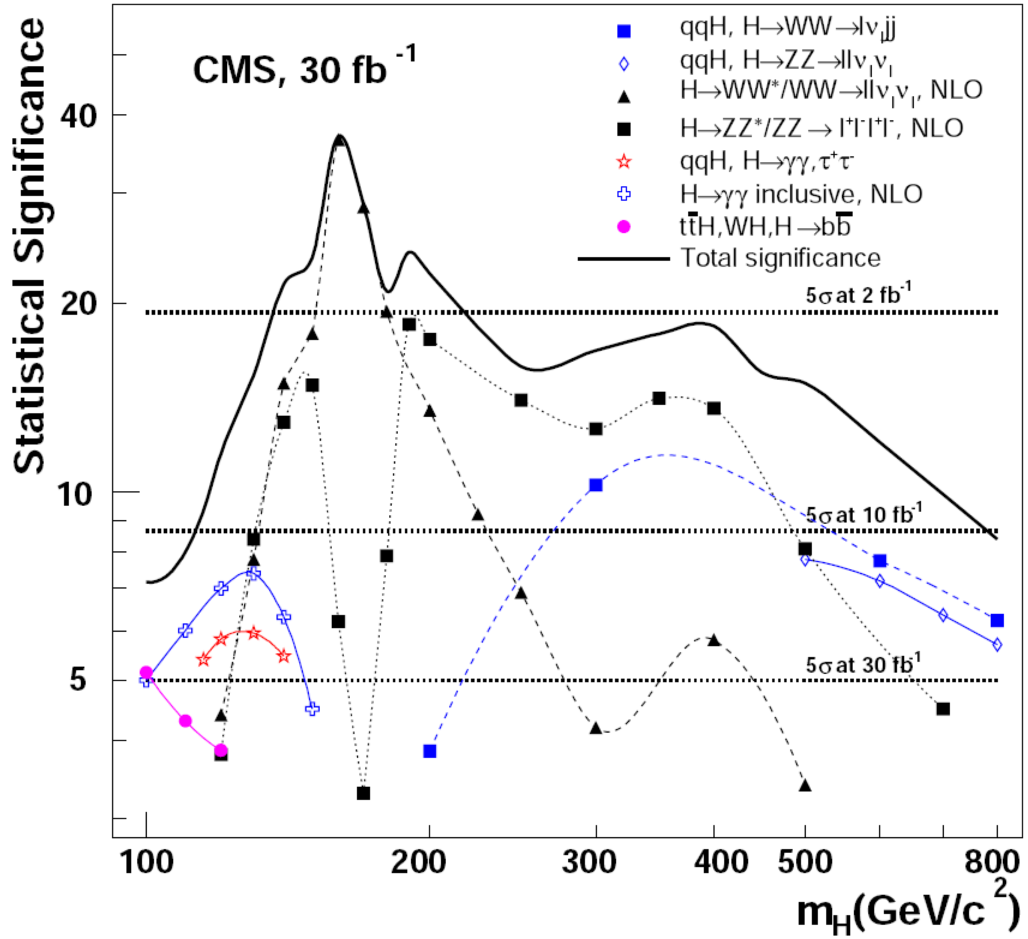
- Higgs + high-p_T Jet in the SM (MSSM)

• Higgs + high-p_T Jet in the SM (MSSM)

– Motivation

SM Higgs production @ LHC mainly via gluon fusion:





Detection ($m_H \approx 100 - 140$GeV): mainly via the rare decay $H \to \gamma\gamma$.

Higgs + Jet

suggestion: study Higgs events with a high-p_T hadronic jet

LO QCD $\mathcal{O}(\alpha_S^3\alpha)$: [van der Bij et al. '87; Baur, Glover '89]

NLO QCD $\mathcal{O}(\alpha_S^4\alpha)$: [de Florian, Grazzini, Kunszt '99]

+ NLL soft gluon threshold resummation: [de Florian, Kulesza, Vogelsang '05]

advantages:

* richer kinematical structure compared to inclusive Higgs production.
  - $\rightarrow$ allows for refined cuts
  - $\rightarrow$ better signal significance $(S/\sqrt{B})$

* background predictions e.g. for $H \rightarrow \gamma\gamma$ under better theoretical control

disadvantage:

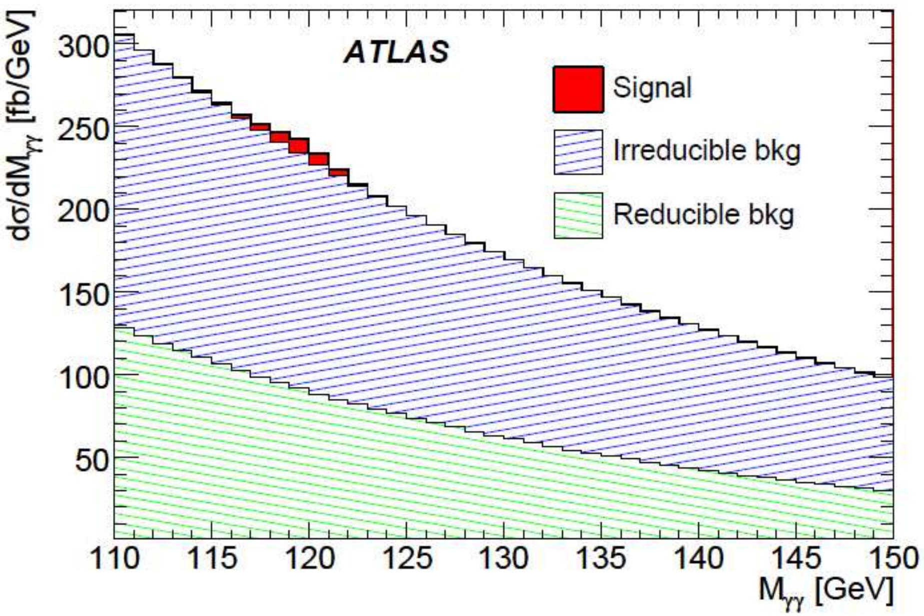
* lower rate than inclusive Higgs production

simulations show:

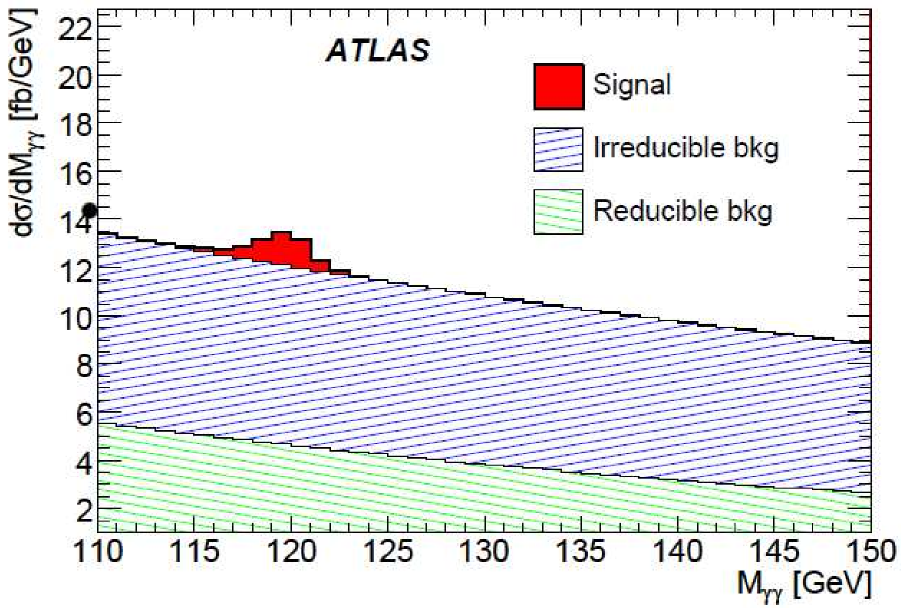
$H+$jet production is a promising alternative (supplement) to the inclusive SM Higgs production for $m_H \approx 100 - 140$GeV.

[ATLAS expected performance 2008]:

inclusive H, $H \to \gamma\gamma$



H+1 jet, $H \to \gamma\gamma$



available codes: SM:

- Higgsjet [de Florian, Grazzini, Kunszt '99]
  NLO QCD cross section for $pp \to H + \text{jet}$ (large m_t approx.)
  also: soft gluon resummation [de Florian, Kulesza, Vogelsang '05]
- HqT [Bozzi, Catani, de Florian, Grazzini '03 & '06]
  p_T-distribution for $pp \to H + X$ (large m_t approx.)
  including resummation at $NLL + LO$ and $NNLL + NLO$ QCD accuracy
- MC@NLO [Frixione, Webber '02; Frixione, Nason, Webber '05]
  contains $pp \to H + X$ event generation at NLO QCD accuracy
  (large m_t approx.)
- FEHiP [Anastasiou, Melnikov, Petriello '05],
  HNNLO [Catani, Grazzini '07;Grazzini '08]
  NNLO QCD differential cross section for $pp \to H + X$ (large m_t approx.)
- HPro [Anastasiou, Bucherer, Kunszt '09]
  corrects large m_t approx. NNLO QCD differential predictions
  by finite m_t & m_b terms from NLO QCD

NNLO QCD accuracy (large m_t approx.) $\propto$ 10% (scale variation)
$\to$ further improvements need to consider other 10%-ish effects

available codes: MSSM:

- HJET 1.3 [OBr, Hollik '03; '07]
  LO QCD full MSSM (no approximations)
  & LO QCD SM (no approximations):

$$\sigma^{\text{total}}_{\text{hadronic}}, \quad \frac{d\sigma_{\text{hadronic}}}{d\sqrt{\hat{s}}}, \quad \frac{d\sigma_{\text{hadronic}}}{dp_T}, \quad \frac{d\sigma_{\text{hadronic}}}{d\eta_{\text{jet}}}, \quad \frac{d^2\sigma_{\text{hadronic}}}{dp_T\, d\eta_{\text{jet}}}, \quad \ldots$$

- HIGLU 2.500 [Spira April 2010]
  NLO QCD full MSSM (no approximations)
  & NLO QCD SM (no approximations):

$$\frac{d\sigma_{\text{hadronic}}}{dp_T}, \quad \frac{d\sigma^2_{\text{hadronic}}}{dp_T dY_H}$$

– How to improve the Higgs + Jet prediction?

- go beyond the large m_t approximation
  in the NLO QCD prediction for the Higgs p_T distribution

- NNLO QCD corrections (in the large m_t approximation)

- consider other LO effects
  * non-QCD: electroweak LO contributions
  * QCD 5-flavour scheme: b quark parton process contributions

– New LO Contributions in the SM

– Previous Study   [Keung, Petriello '09]

SM Higgs p_T distribution with ...

1. ... finite quark mass effects (m_t, m_b) in one-loop QCD amplitude:

   → already included in [..., OBr, Hollik '03; '07]

   large-m_t approximation : $m_t \to \infty$, no b loops

   → effective ggH and $gggH$ vertices (effective field theory (EFT))

   $$\sigma^{\text{large-}m_t\text{ approx}} = \left(\frac{\sigma^{\text{exact}}_{gg\to H}}{\sigma^{\text{EFT}}_{gg\to H}}\right)\sigma^{\text{EFT}}$$

   comparison of approximations ($m_H = 120\,\text{GeV}$):   Tevatron

   * finite m_t (no b loops) vs. large-m_t approx : $\begin{cases} \approx \pm 4\%,\ p_T = 15..110\,\text{GeV} \\ \approx 37\%,\ p_T \approx 150\,\text{GeV} \end{cases}$
   * finite m_t *and* m_b vs. finite m_t (no b loops) : $\begin{cases} -8\%..0,\ p_T = 15..50\,\text{GeV} \\ < 3\%,\ p_T > 50\,\text{GeV} \end{cases}$

2. ... electroweak one-loop effects: $\{\ 0..-9\%,\ p_T = 15..140\,\text{GeV}$

→ 5-flavour PDFs used but b quark parton processes not considered.

– New LO Contributions in the SM

– Previous Study [Keung, Petriello '09]

SM Higgs p_T distribution with ...

1. ... finite quark mass effects (m_t, m_b) in one-loop QCD amplitude:

   → already included in [..., OBr, Hollik '03; '07]

   large-m_t approximation : $m_t \to \infty$, no b loops

   → effective ggH and $gggH$ vertices (effective field theory (EFT))

   $$\sigma^{\text{large-}m_t\text{ approx}} = \left(\frac{\sigma^{\text{exact}}_{gg\to H}}{\sigma^{\text{EFT}}_{gg\to H}}\right)\sigma^{\text{EFT}}$$

   comparison of approximations ($m_H = 120$ GeV): LHC ($\sqrt{s} = 10$ TeV)

   * finite m_t (no b loops) vs. large-m_t approx : $\begin{cases} 0..-4\%,\ p_T = 30..150\text{ GeV} \\ -30\%,\ p_T = 300\text{ GeV} \end{cases}$
   * finite m_t *and* m_b vs. finite m_t (no b loops) : $\begin{cases} -4\%..0,\ p_T = 30..60\text{ GeV} \\ < 4\%,\ p_T > 60\text{ GeV} \end{cases}$

2. ... electroweak one-loop effects: $\{\ 0..-3\%,\ p_T = 30..300$ GeV

→ 5-flavour PDFs used but b quark parton processes not considered.

– This Study [OBr '10]

SM Higgs p_T and η_{jet} distribution with ...

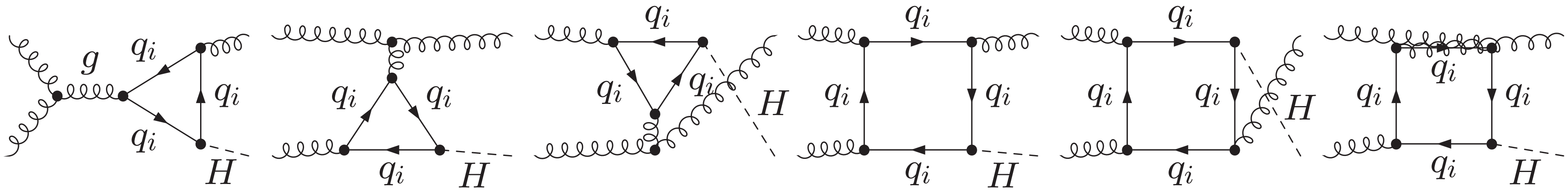
1. ... finite quark mass effects (m_t, m_b) in one-loop QCD amplitude:

2. ... electroweak one-loop effects

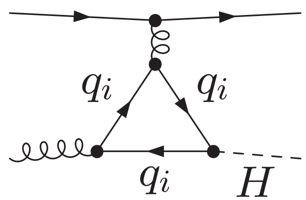
3. ... contributions from b-quark parton processes
   * leading QCD and electroweak effects

Gluon & Light Quark (u, d, s, c) QCD Contribution : $\mathcal{O}(\alpha_S^3 \alpha)$

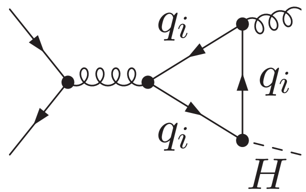
gluon fusion, $gg \longrightarrow Hg$



quark gluon scattering, $qg \longrightarrow Hq$

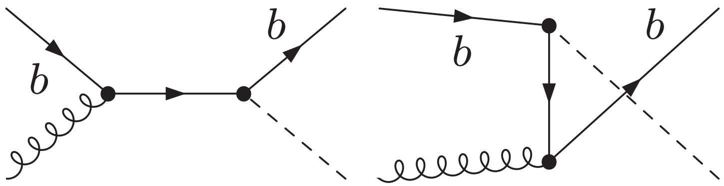


quark anti-quark annihilation, $q\bar{q} \longrightarrow Hg$

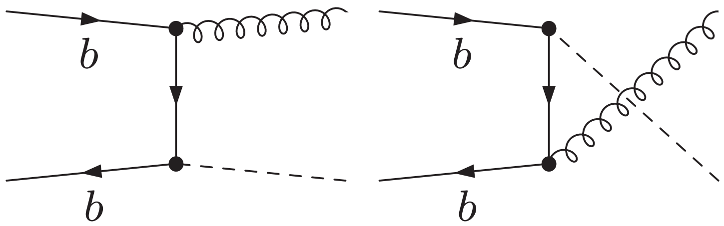


Bottom Quark QCD Contribution : $\mathcal{O}(\alpha_S \alpha)$

quark gluon scattering, $bg \rightarrow Hb$



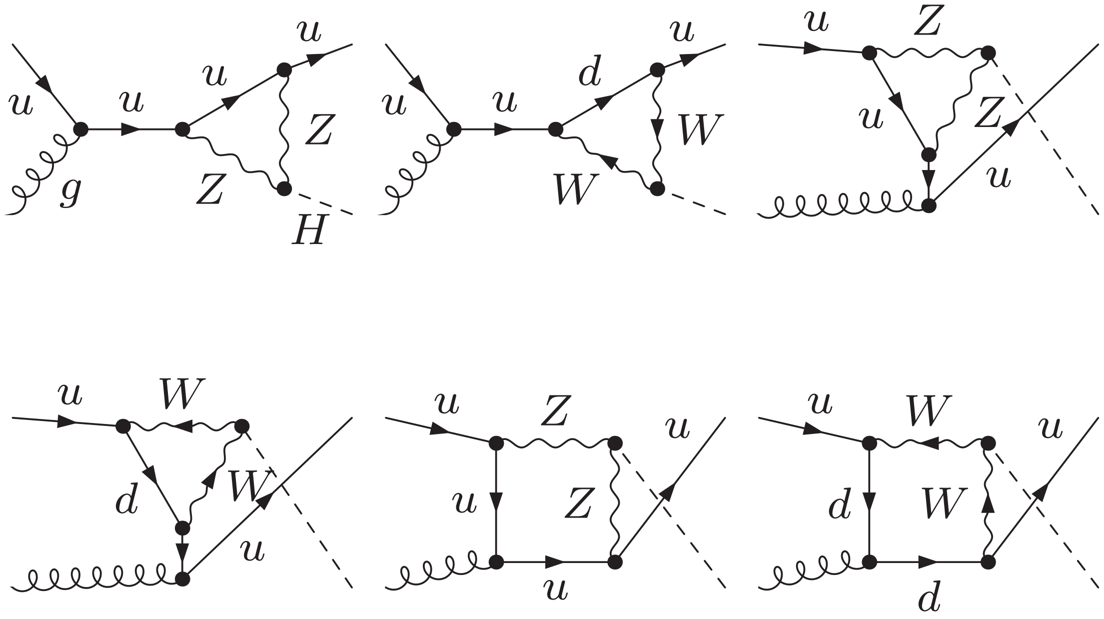
quark anti-quark annihilation, $b\bar{b} \rightarrow Hg$



Light Quark (u, d, s, c) EW Contribution : $\mathcal{O}(\alpha_S \alpha^3)$

[Mrenna, Yuan '96; Keung, Petriello '09]

quark gluon scattering, $qg \longrightarrow Hq$



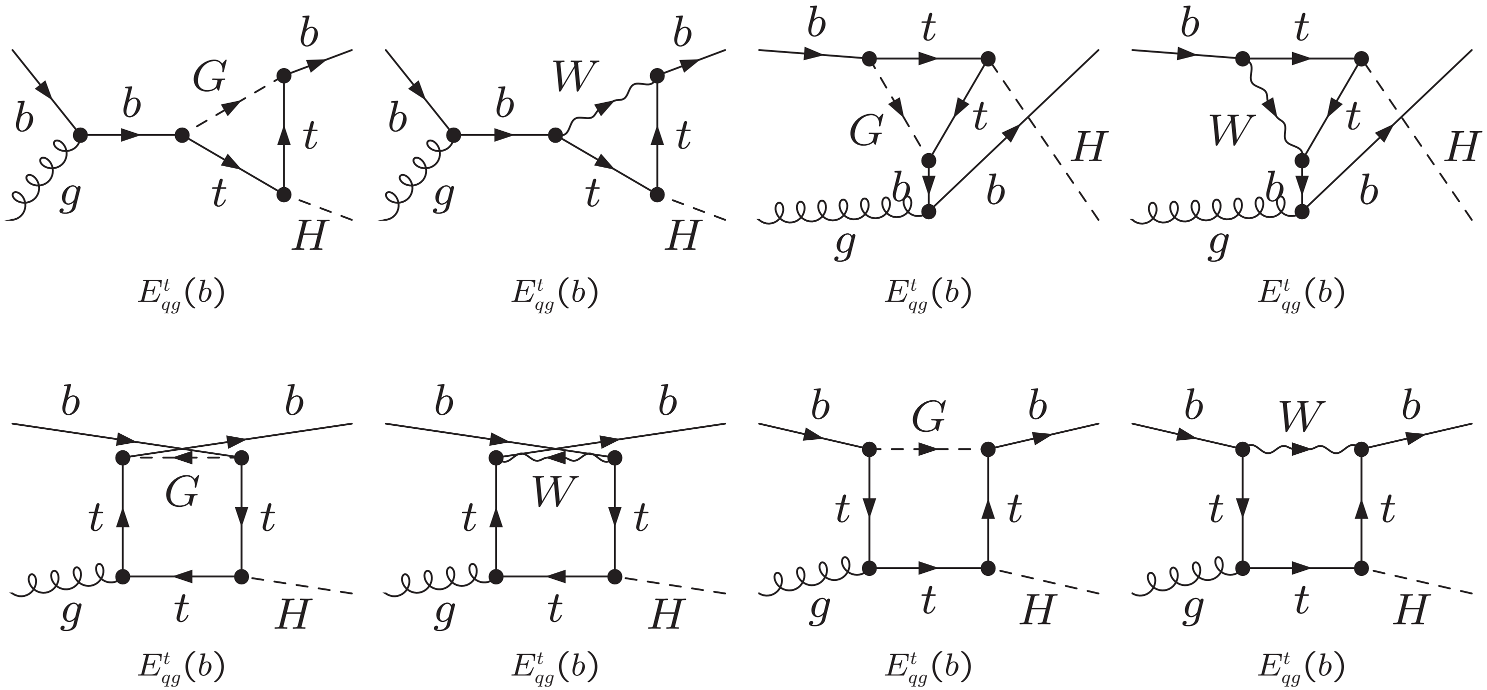
quark anti-quark annihilation, $q\bar{q} \longrightarrow Hg$

crossed diagrams

Bottom Quark EW Contribution : $\mathcal{O}(\alpha_S \alpha^3)$

[Mrenna, Yuan '96]

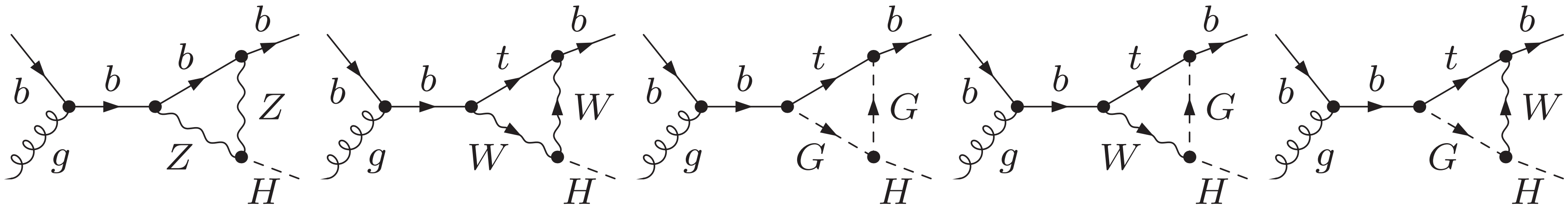
quark gluon scattering, $bg \to Hb$, $\mathcal{O}(\alpha_S \alpha^2 \alpha_t)$



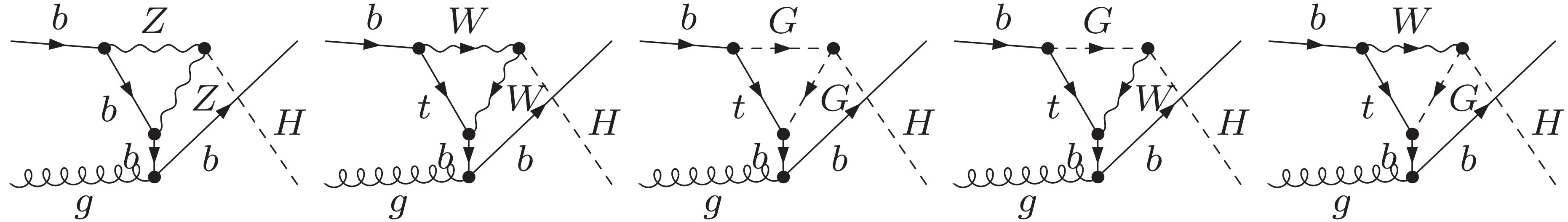
Bottom Quark EW Contribution : $\mathcal{O}(\alpha_S \alpha^3)$

[Mrenna, Yuan '96]

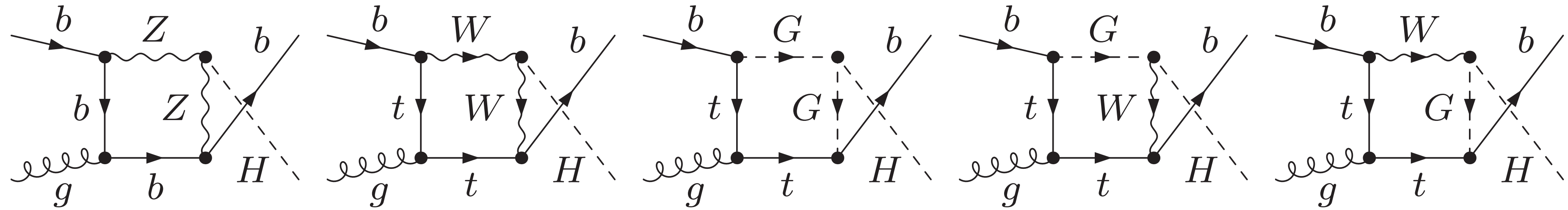
quark gluon scattering, $bg \to Hb$, $\mathcal{O}(\alpha_S \alpha^3)$ "non α_t"



$C_{qg}(b)$ $C_{qg}(b)$ $F_{qg}(b)$ $F_{qg}(b)$ $F_{qg}(b)$



$C_{qg}(b)$ $C_{qg}(b)$ $F_{qg}(b)$ $F_{qg}(b)$ $F_{qg}(b)$



$C_{qg}(b)$ $C_{qg}(b)$ $F_{qg}(b)$ $F_{qg}(b)$ $F_{qg}(b)$

Calculational Approach

- respect the hierarchy of Yukawa couplings:

  $\alpha_q = y_q^2/4\pi = \frac{1}{4\pi} m_q^2/v^2$ ($v = 246\,\text{GeV}$)

  $\rightarrow \alpha_t = 3.9 \cdot 10^{-2}$, $\alpha_b = 2.3 \cdot 10^{-6}$ and $\frac{\alpha_b}{\alpha_t} \approx \alpha^2(0) < \alpha_S^4(m_Z)$

  $\rightarrow$consider LO QCD and EW contributions to the full polynomial in $\sqrt{\alpha_t}$ and $\sqrt{\alpha_b}$ in the cross section predictions

- light quark (u, d, s, c) processes:

  * full mass dependence in m_t, m_b

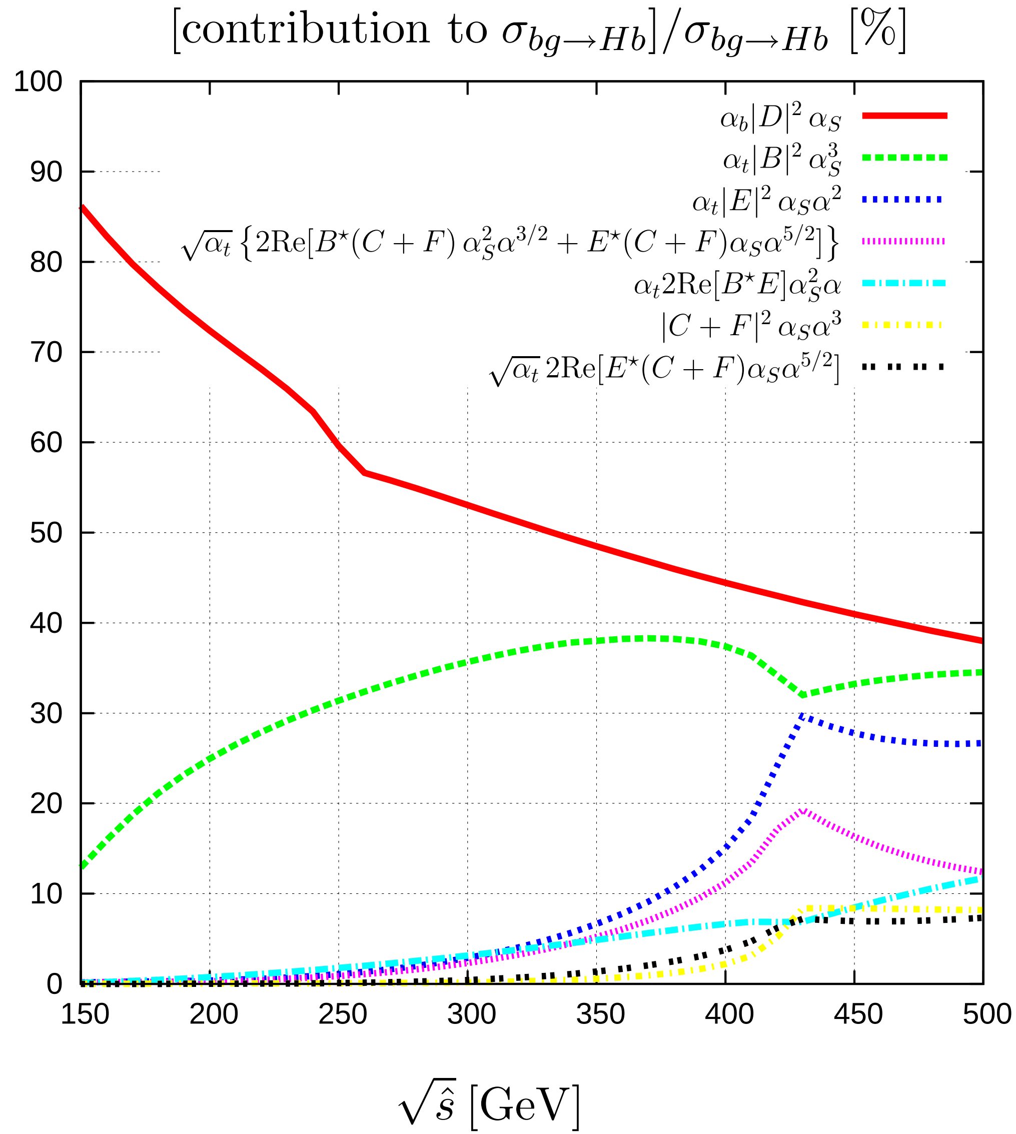
- bottom-quark processes:

  * 5-flavour scheme:
    - $m_b = 0$ to be consistent with parton model
    - only b Yukawa coupling y_b retained non-zero

    $\Longleftrightarrow$ retaining leading powers in a systematic expansion in m_b

  * for the tree-level amplitude:
    - factorisation scale choice $\mu_F = m_H/4$
    - NLO running m_b in b Yukawa coupling

example: contributions to bottom gluon scattering



$$\mathcal{M}_{qg}(b) = D_{qg}(b) g_S y_b + B^t_{qg}(b) g_S^3 y_t + E^t_{qg}(b) g_S e^2 y_t + \left(C_{qg}(b) + F_{qg}(b)\right) g_S e^3$$

$$|\mathcal{M}_{qg}(b)|^2/(4\pi)^4 = \alpha_b\left\{ |D_{qg}(b)|^2 \alpha_S \right\}(4\pi)^{-2}$$
$$+\,\alpha_t\left\{ |B_{qg}{}^t(b)|^2\alpha_S^3 + 2\mathrm{Re}\left[B^\star_{qg}{}^t(b)E_{qg}{}^t(b)\right]\alpha_S^2\alpha + |E_{qg}{}^t(b)|^2\alpha_S\alpha^2\right\}$$
$$+\sqrt{\alpha_t}\left\{ 2\mathrm{Re}\left[B^\star_{qg}{}^t(b)(C_{qg}(b)+F_{qg}(b))\right]\alpha_S^2\alpha\sqrt{\alpha} + 2\mathrm{Re}\left[E^\star_{qg}{}^t(b)(C_{qg}(b)+F_{qg}(b))\right]\alpha_S\alpha^2\sqrt{\alpha}\right\}$$
$$+\,|C_{qg}(b)+F_{qg}(b)|^2\alpha_S\alpha^3 \,.$$

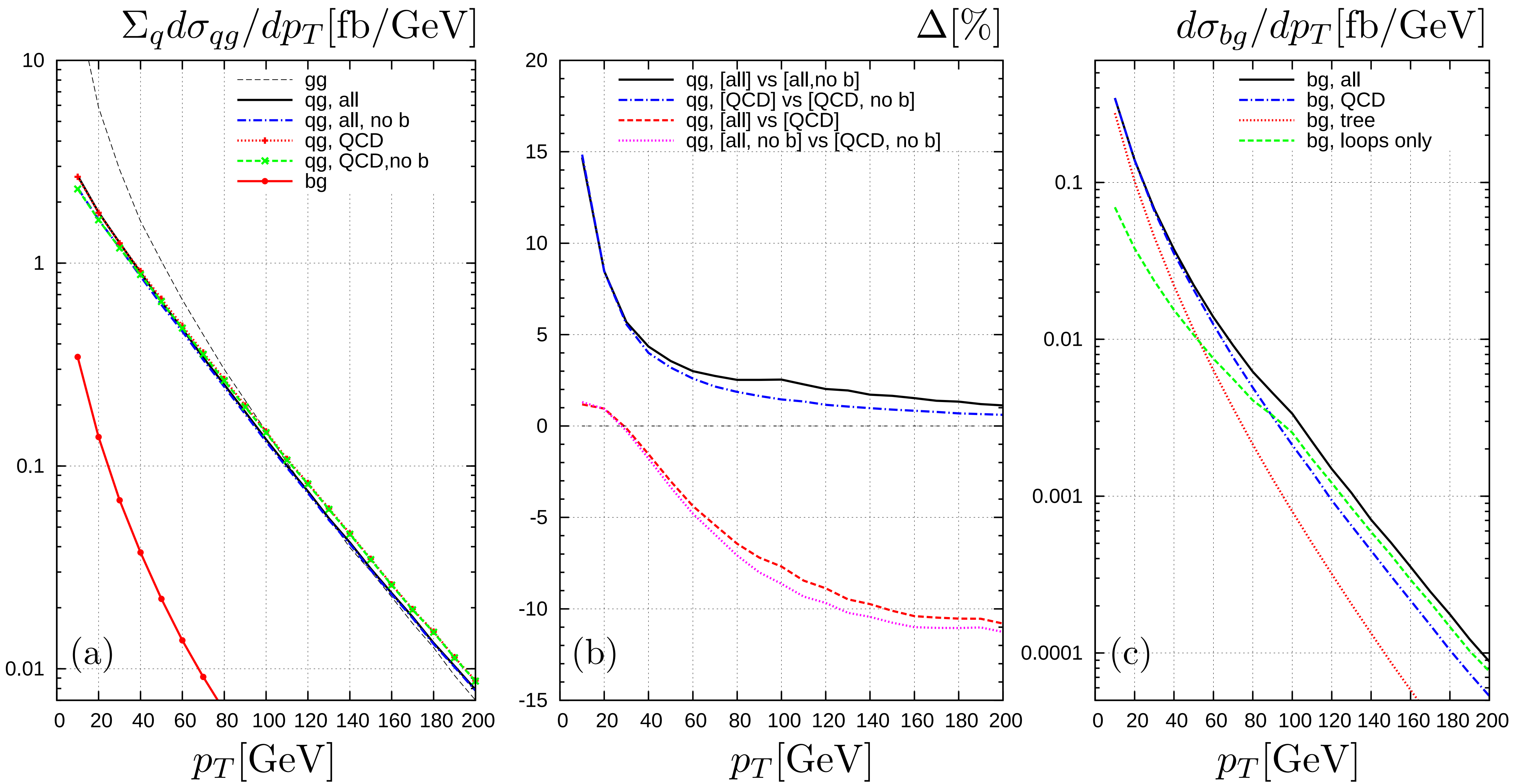
– Numerical Results

Tevatron ($\sqrt{S} = 1.96\,\text{TeV}$), differential hadronic cross sections

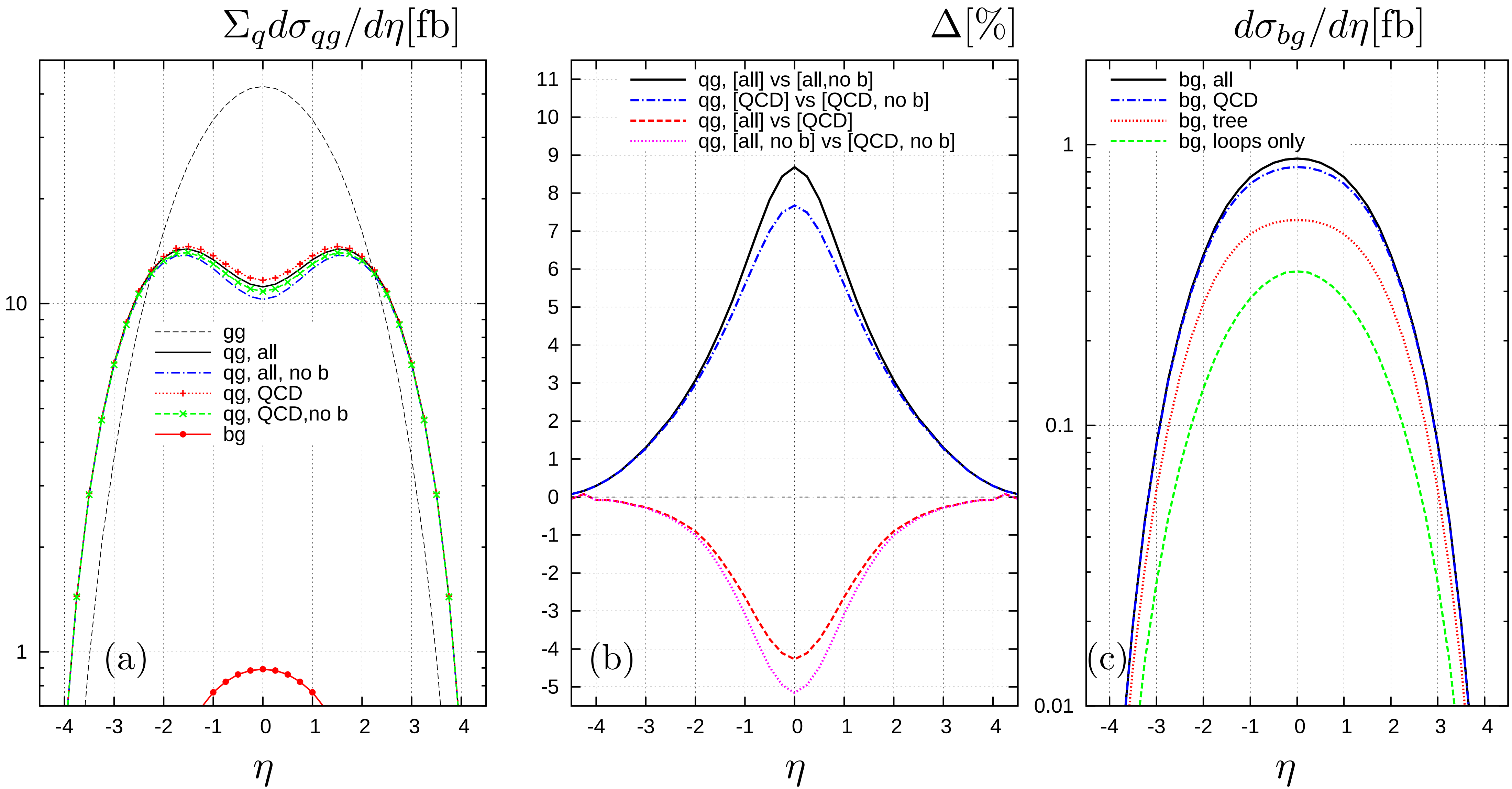
$$\frac{d\sigma(S,p_{T,\text{jet}})}{dp_{T,\text{jet}}}, \ |\eta_{\text{jet}}| < 2.5$$

$$\frac{d\sigma(S,\eta_{\text{jet}})}{d\eta_{\text{jet}}}, \ p_{T,\text{jet}} > 15\,\text{GeV}$$

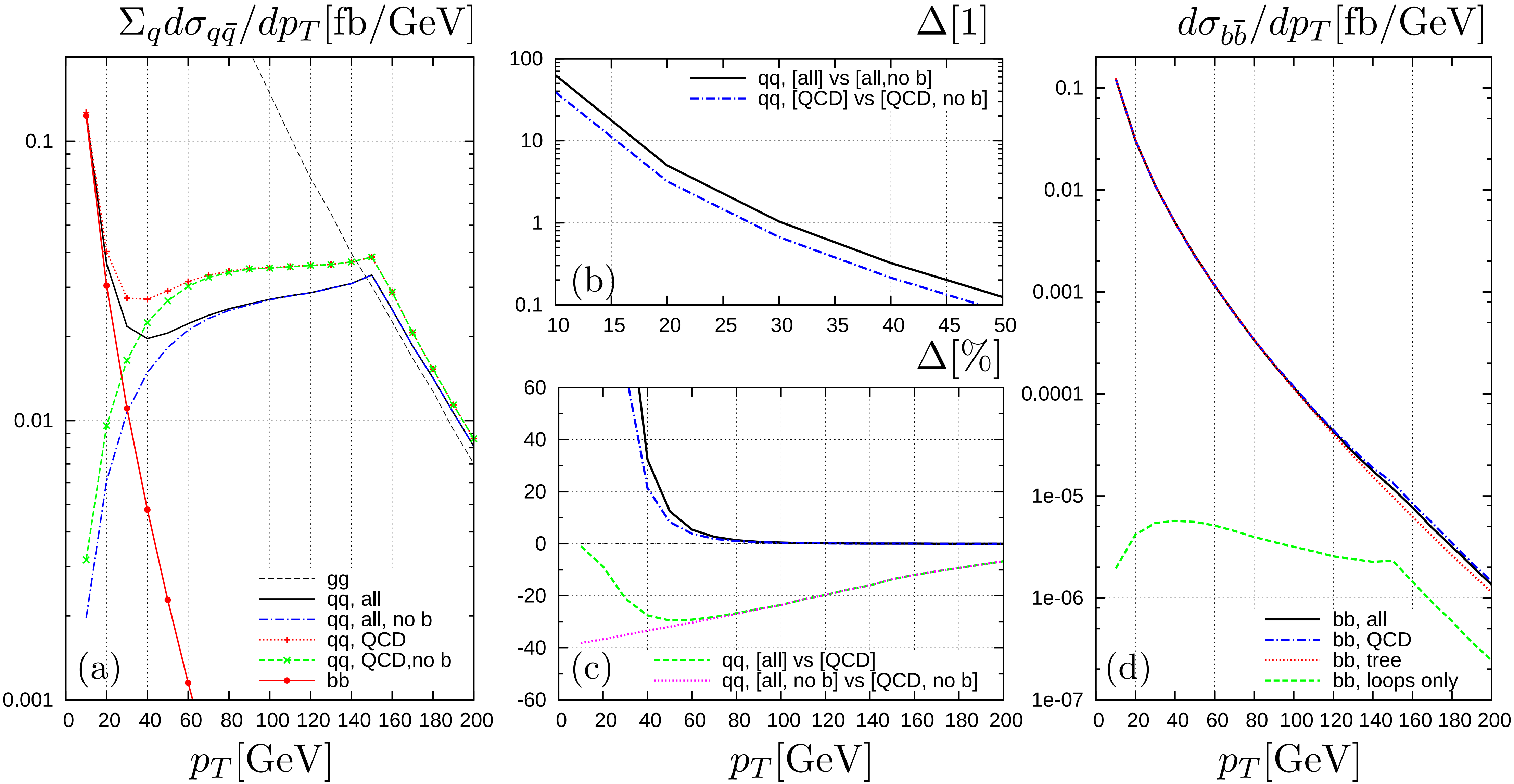
$p_{T,\text{jet}}$ distribution : quark–gluon scattering $(m_H = 120\,\text{GeV})$



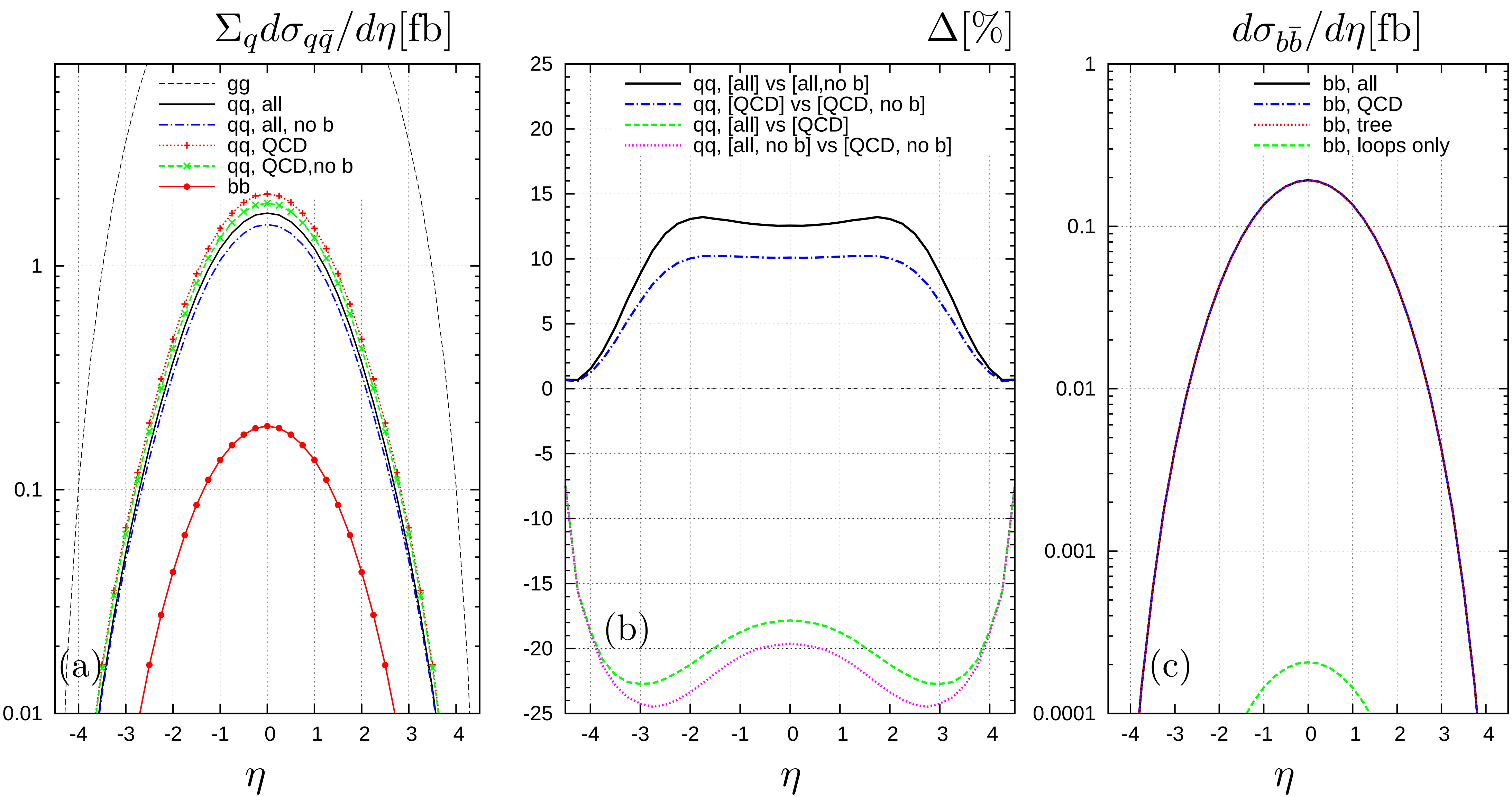
$\eta_{\rm jet}$ distribution : quark–gluon scattering ($m_H = 120$ GeV)



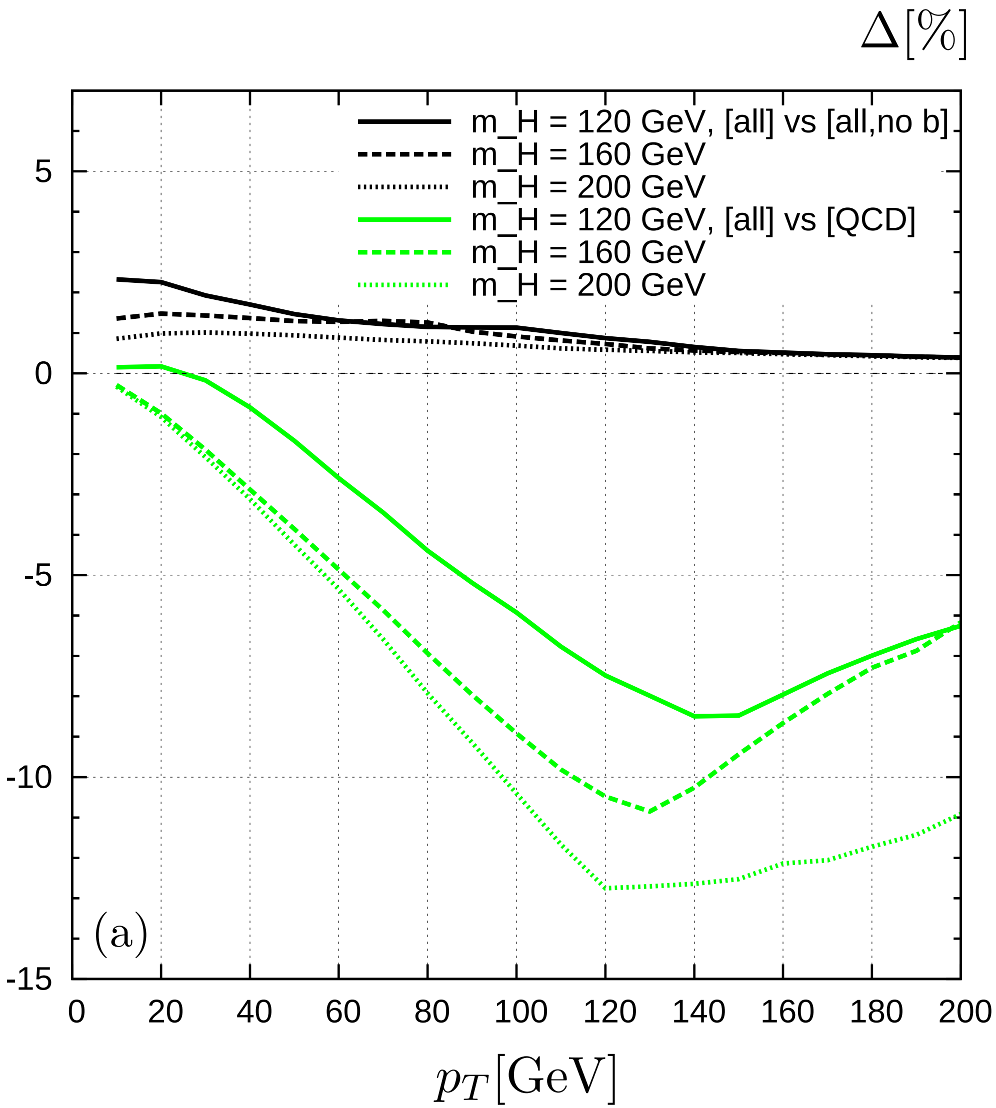
$p_{T,\mathrm{jet}}$ distribution : $q\bar{q}$ annihilation $(m_H = 120\,\mathrm{GeV})$

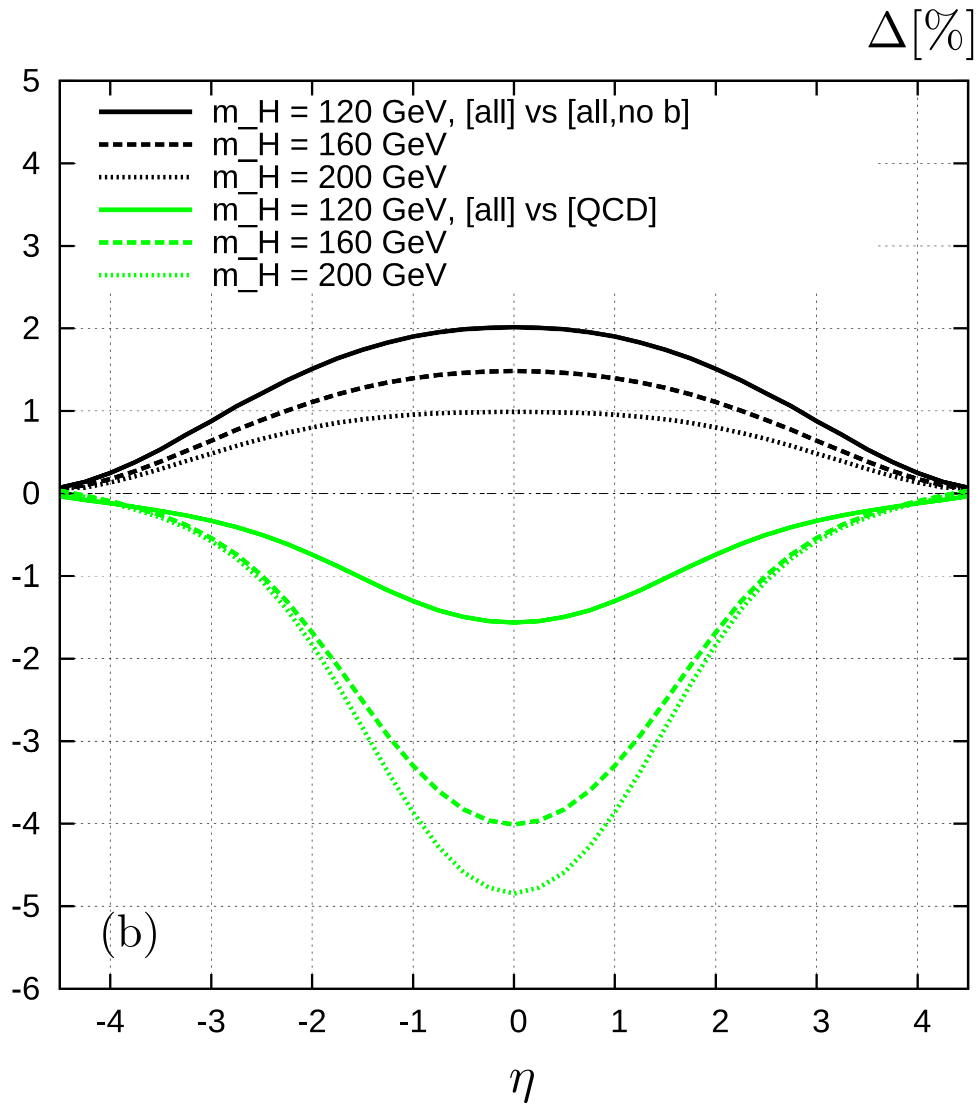


η_{jet} distribution : $q\bar{q}$ annihilation ($m_H = 120$ GeV)



effects on the of the total Higgs + Jet distributions: $(m_H = 120\,\text{GeV})$



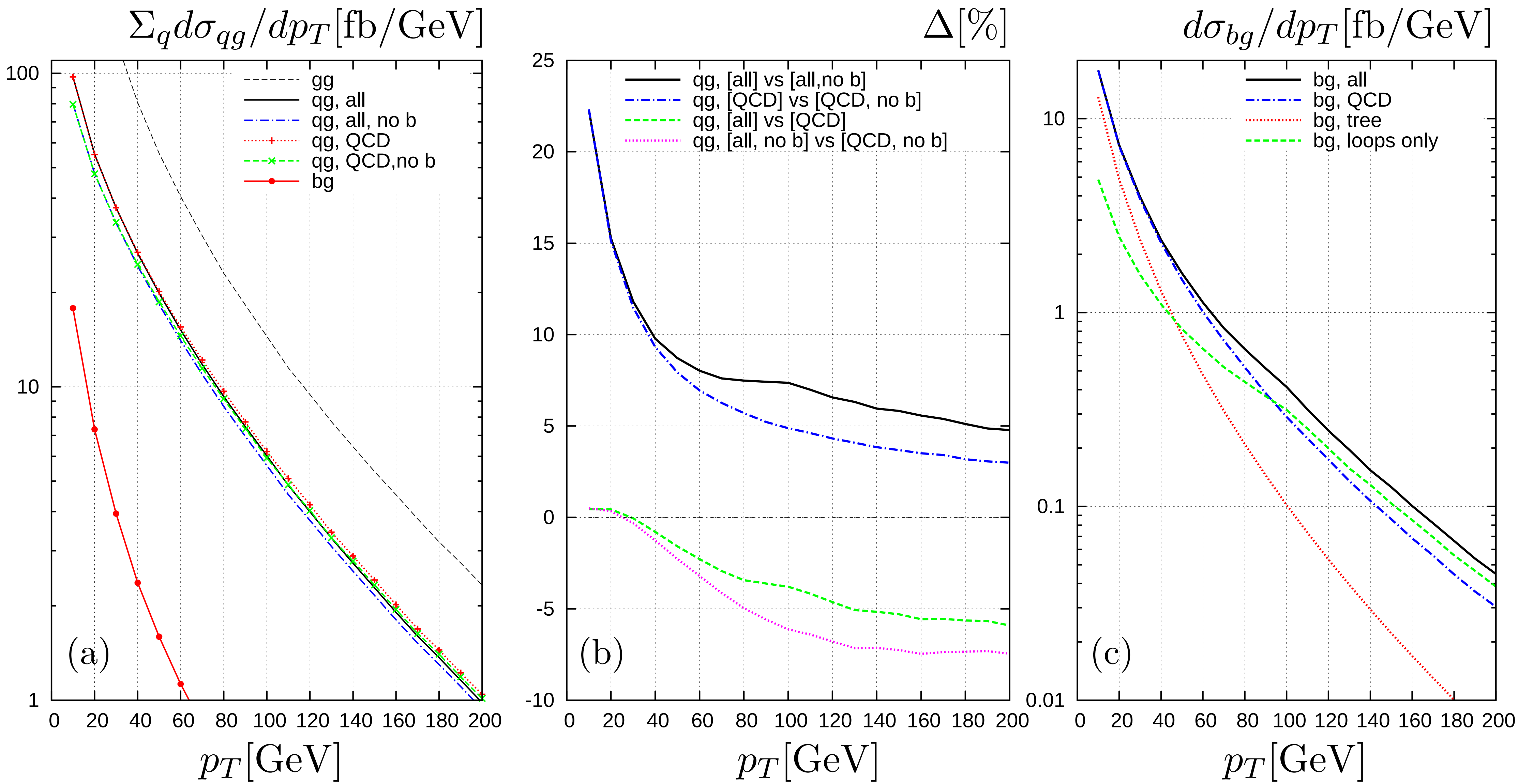


LHC ($\sqrt{S} = 10\,\text{TeV}$), differential hadronic cross sections

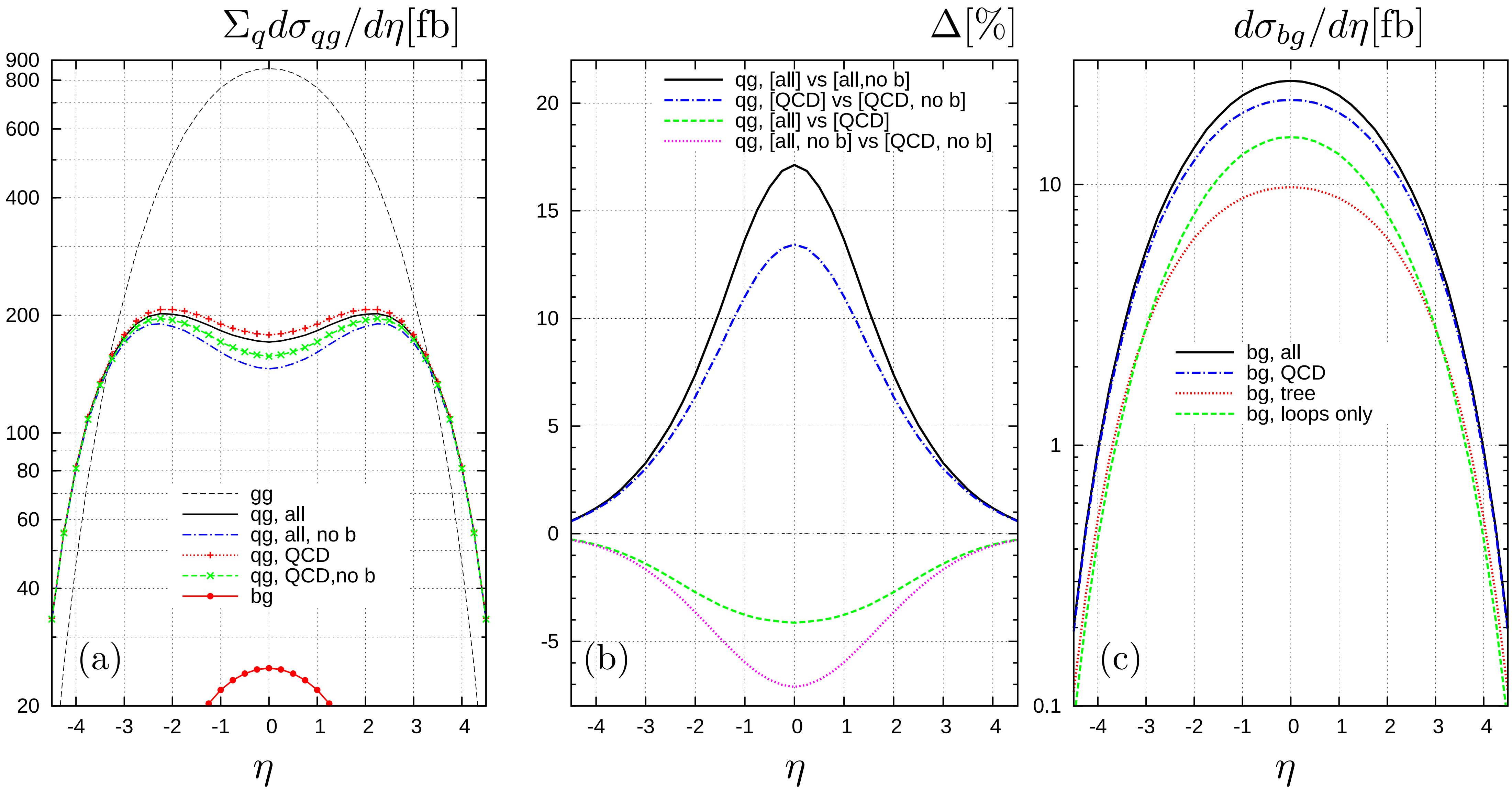
$$\frac{d\sigma(S, p_{T,\text{jet}})}{dp_{T,\text{jet}}}, \;\; |\eta_{\text{jet}}| < 4.5$$

$$\frac{d\sigma(S, \eta_{\text{jet}})}{d\eta_{\text{jet}}}, \;\; p_{T,\text{jet}} > 30\,\text{GeV}$$

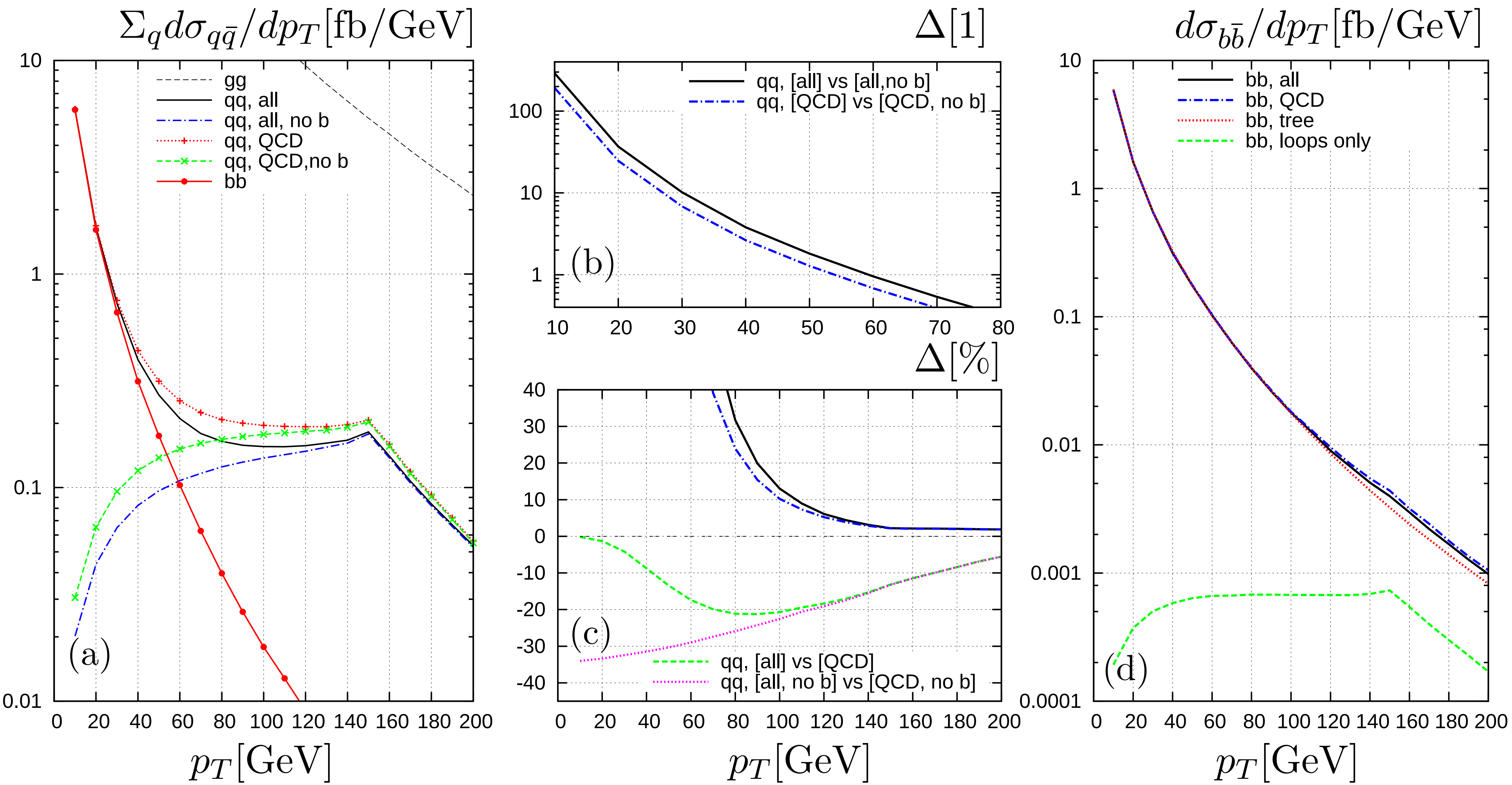
$p_{T,\mathrm{jet}}$ distribution : quark–gluon scattering ($m_H = 120$ GeV)



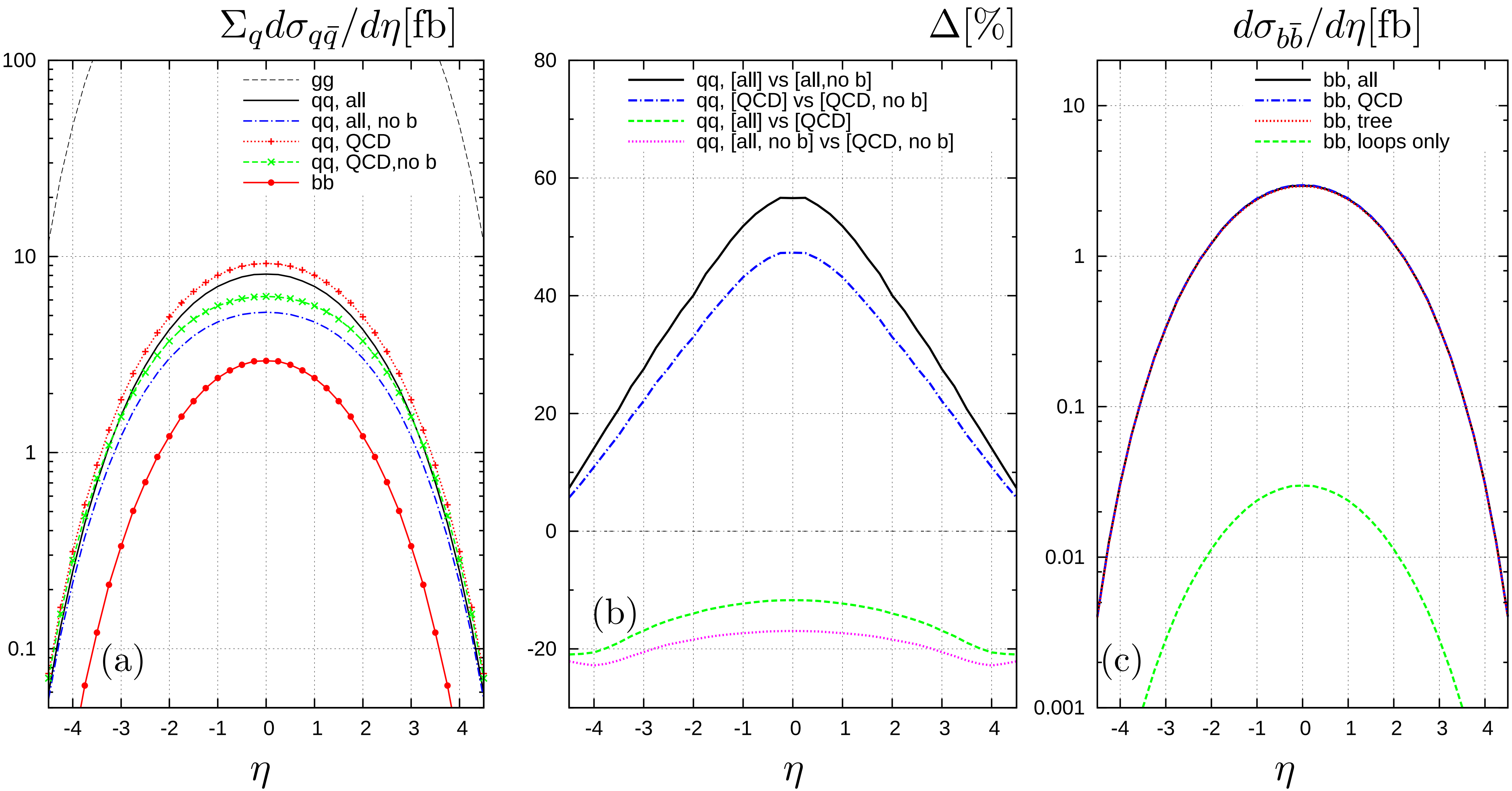
η_{jet} distribution : quark–gluon scattering $(m_H = 120\,\text{GeV})$



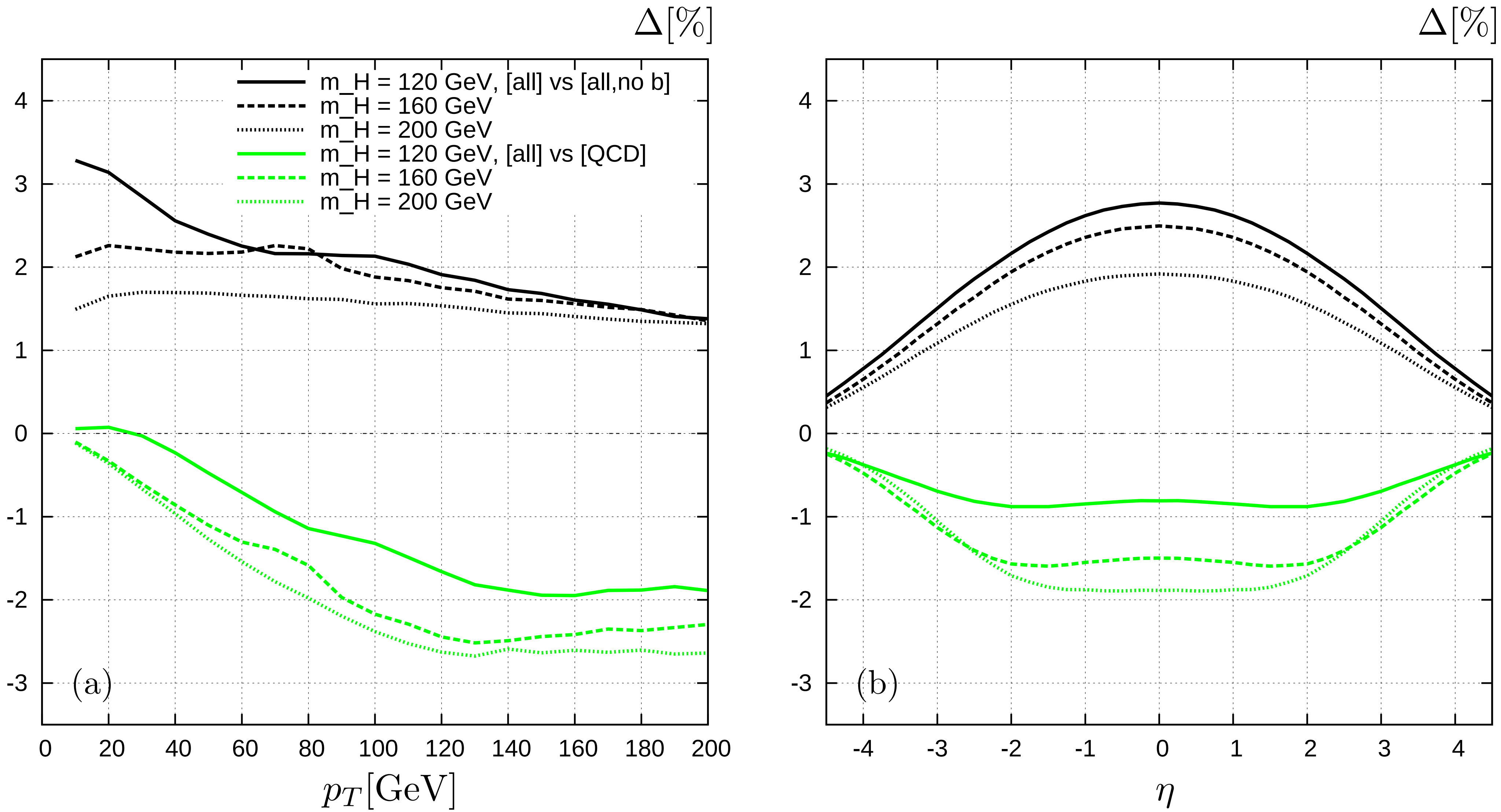
$p_{T,\mathrm{jet}}$ distribution : $q\bar{q}$ annihilation $(m_H = 120\,\mathrm{GeV})$



$\eta_{\rm jet}$ distribution : $q\bar{q}$ annihilation ($m_H = 120$ GeV)

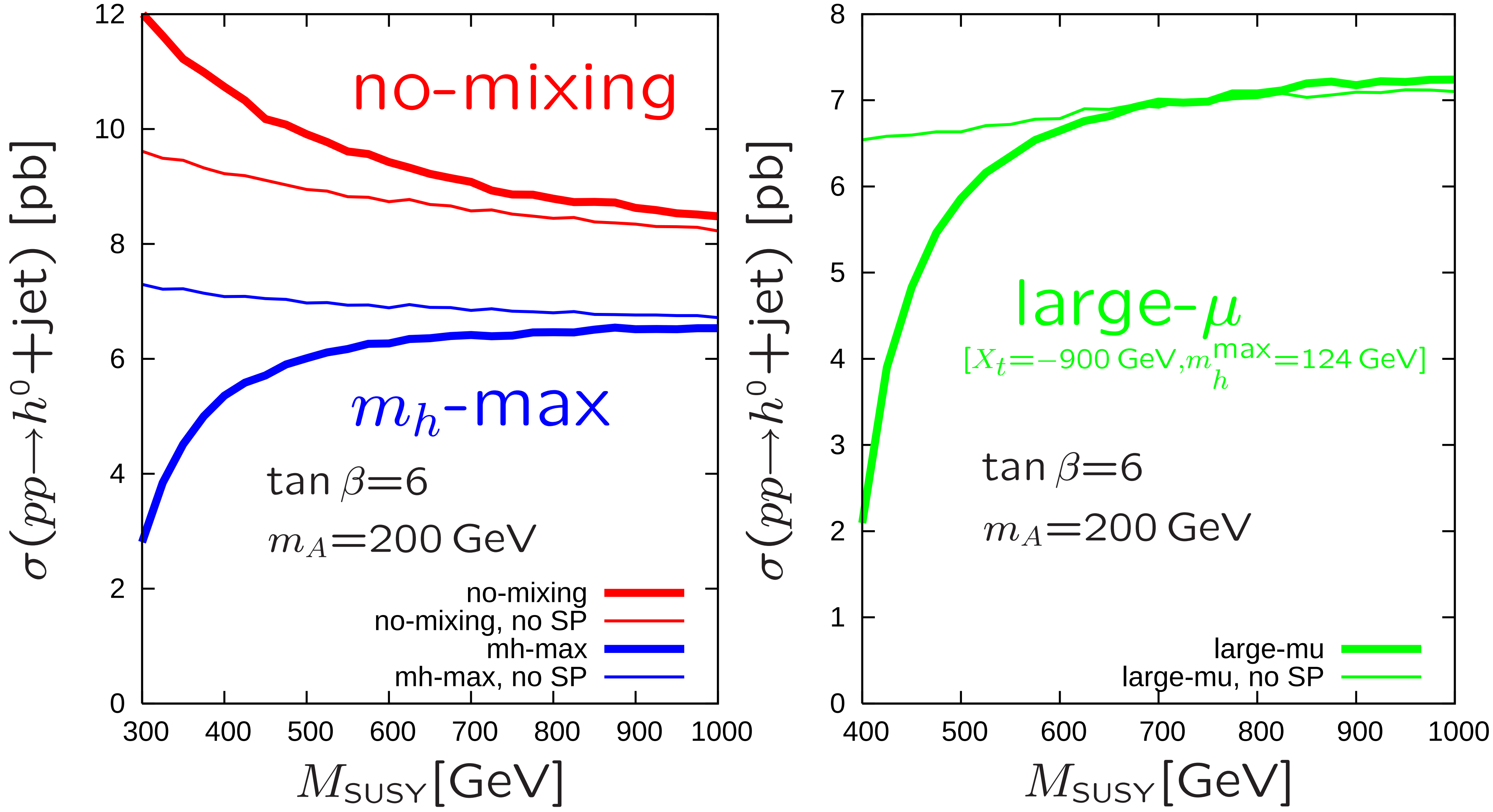


effects on the of the total Higgs + Jet distributions: $(m_H = 120\,\mathrm{GeV})$



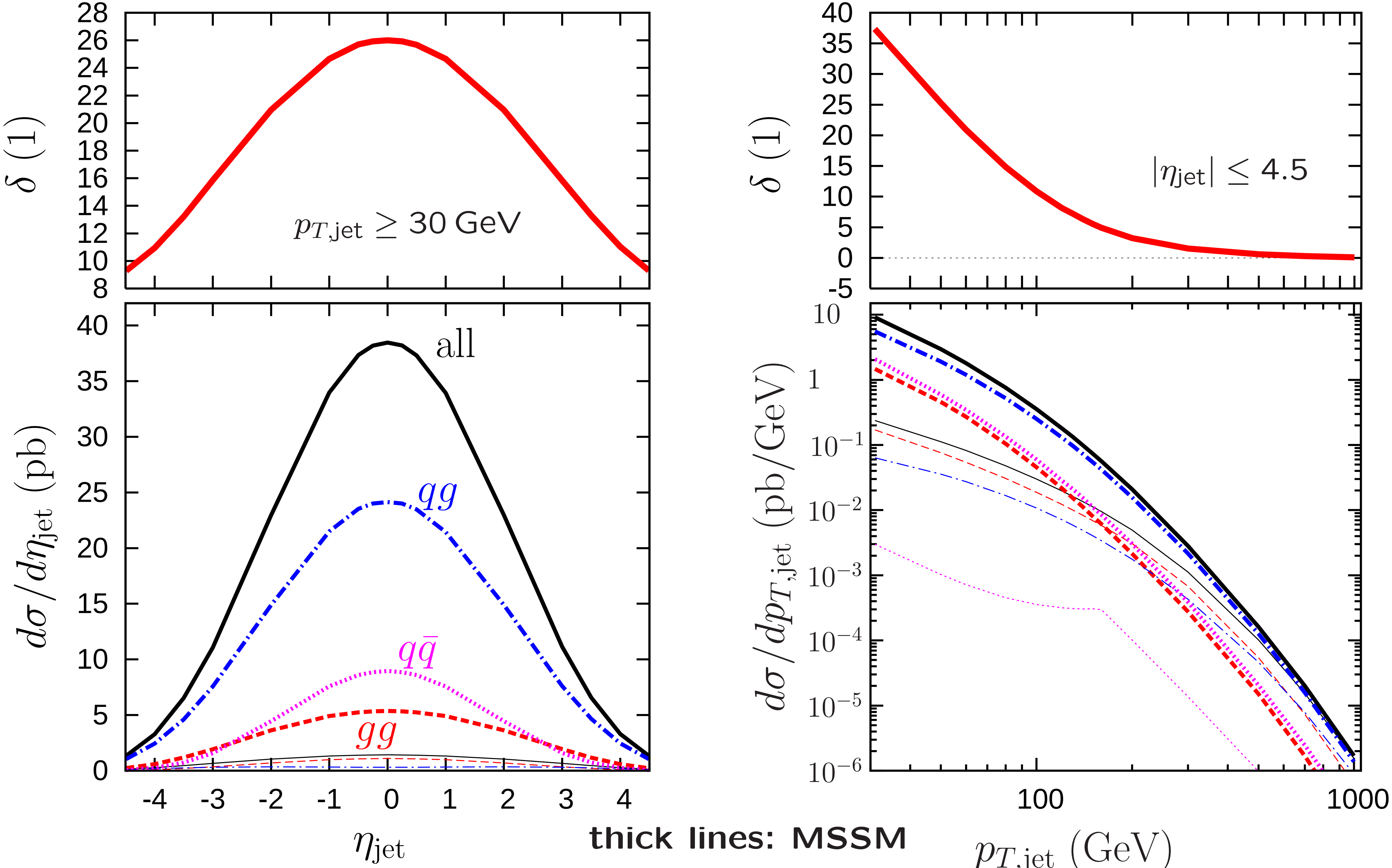
– MSSM Results

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



$p_{T,\text{jet}}$- and η_{jet}-dependence, low-m_A case (bottom processes dominate):

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

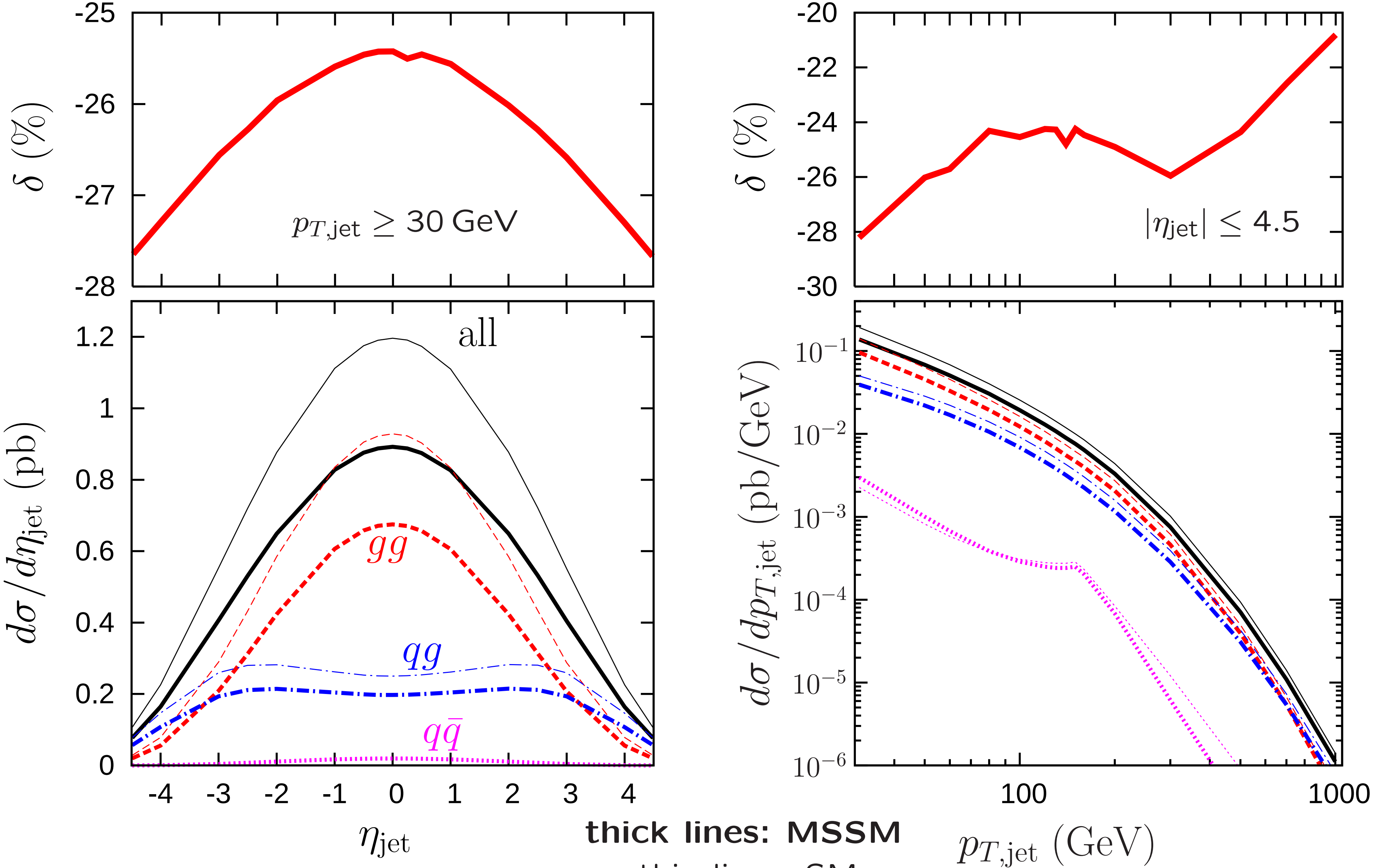


thick lines: MSSM

thin lines: SM

$p_{T,\mathrm{jet}}$- and η_{jet}-dependence, high-m_A case (loop-ind. processes dominate)

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



thick lines: MSSM

thin lines: SM

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.

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

- 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.

- 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.
  $\longrightarrow$ a superpartner of different spin exists for each particle

- couplings are correlated
  $\longrightarrow$ e.g. scalar 4-point int. $\longleftrightarrow$ gauge couplings

- superpartners have the same mass
  $\longrightarrow$ 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

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

→ designed to avoid large Flavour Canging Neutral Currents (FCNC)

consequences of R-parity conservation:

- all interactions involve an *even* number of superpartners
  → superpartners can only be pair-produced

- the lightest superpartner (LSP) is stable
  → the LSP is a candidate for dark matter

– SM extensions

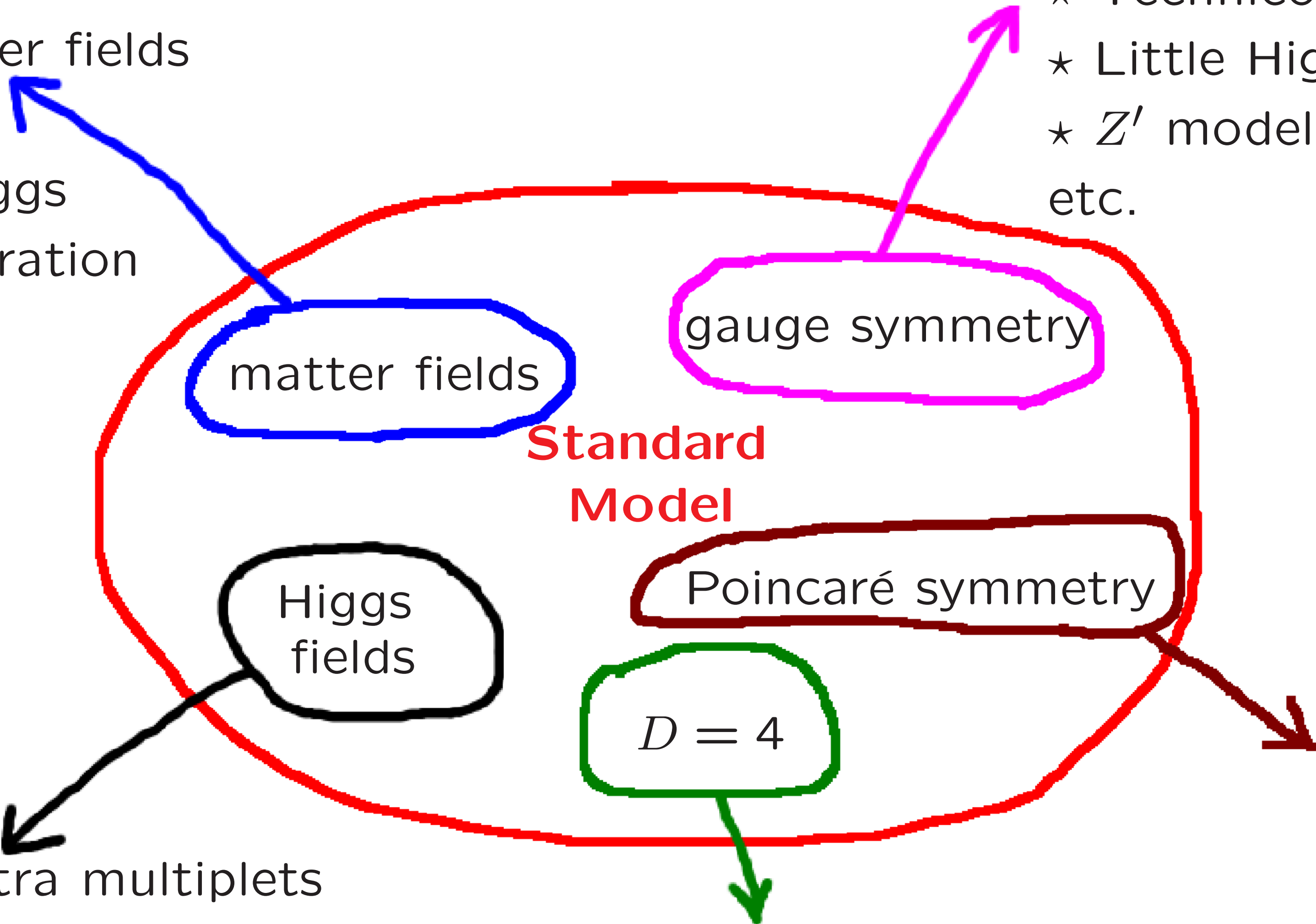
SM extensions: what is anticipated ?

extra gauge groups
- ⋆ GUT
- ⋆ Technicolor
- ⋆ Little Higgs models
- ⋆ Z' models

etc.

extra matter fields
- ⋆ SUSY
- ⋆ Little Higgs
- ⋆ 4th generation

etc.



supersymmetry
- ⋆ MSSM
- ⋆ NMSSM,...

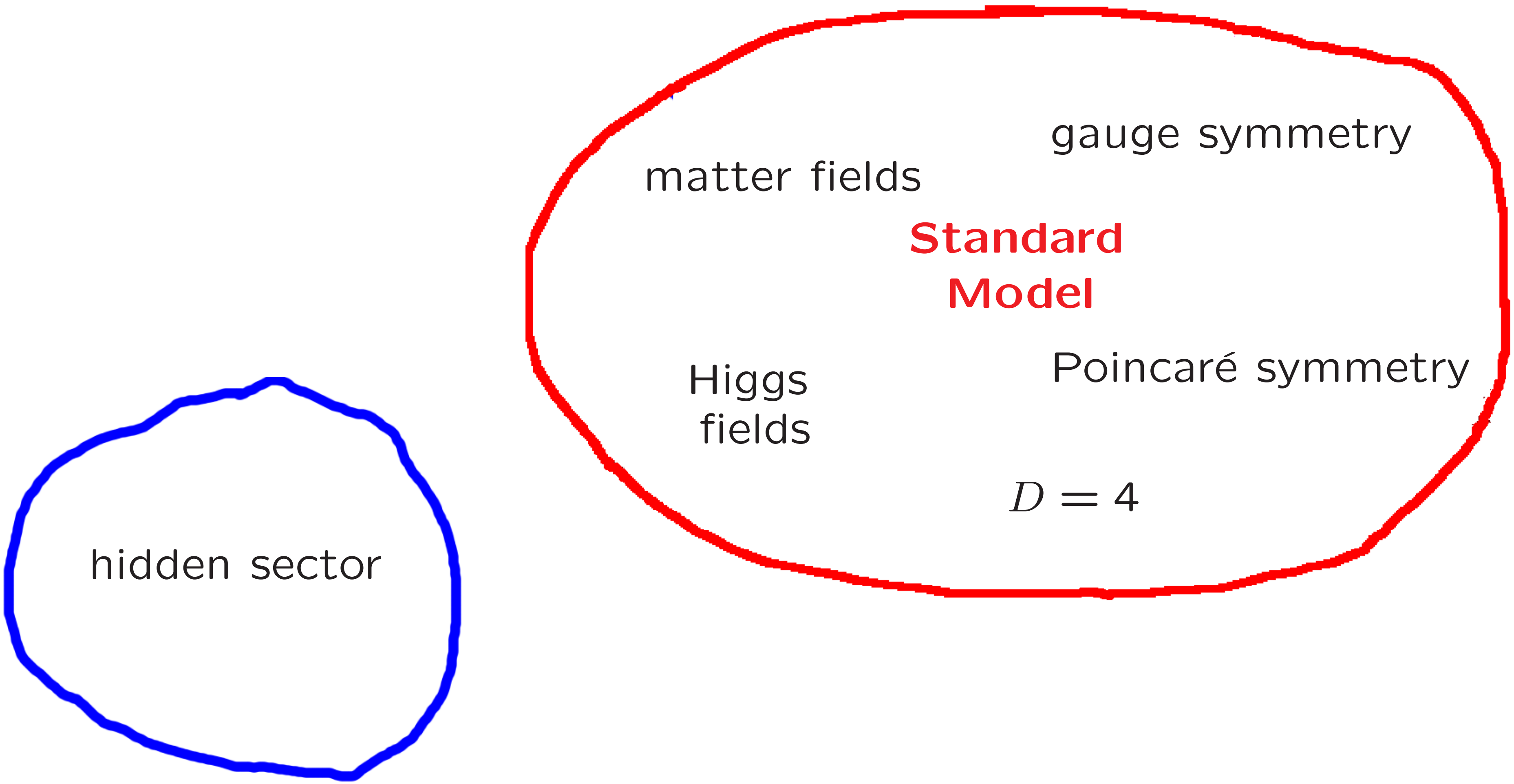
etc.

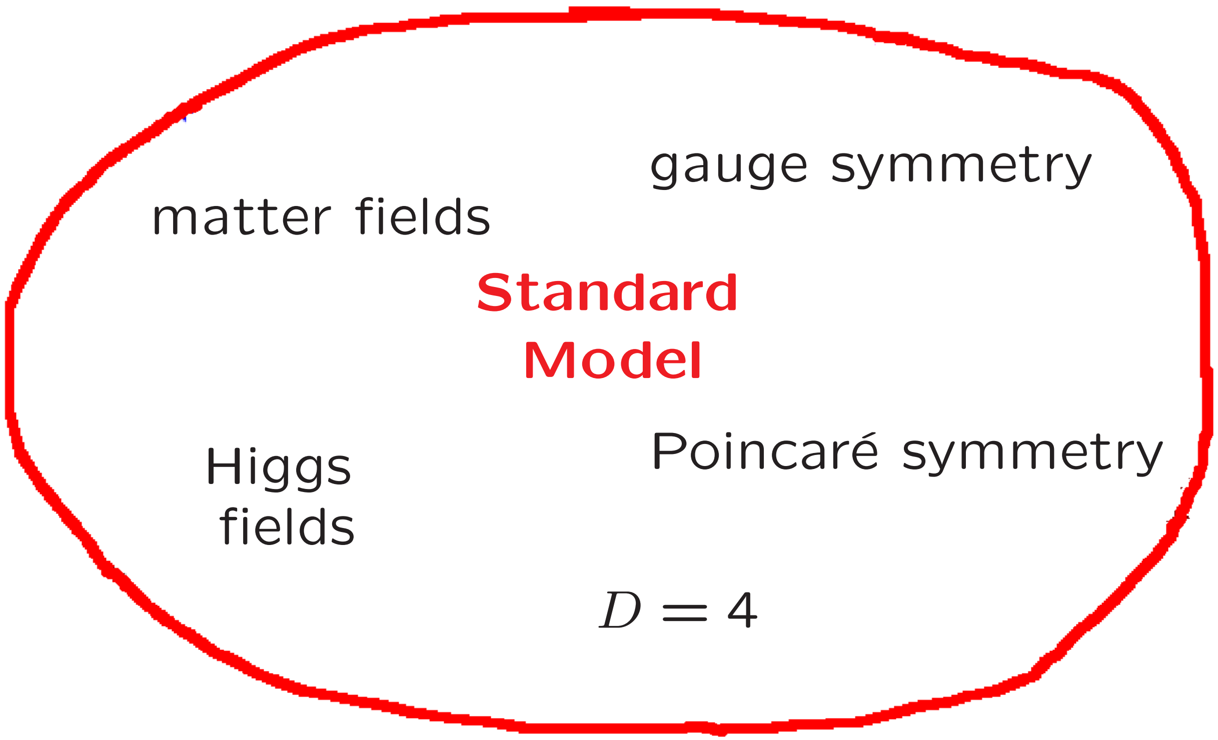
change/extra multiplets
- ⋆ SUSY
- ⋆ Little Higgs
- ⋆ Higgs triplet models

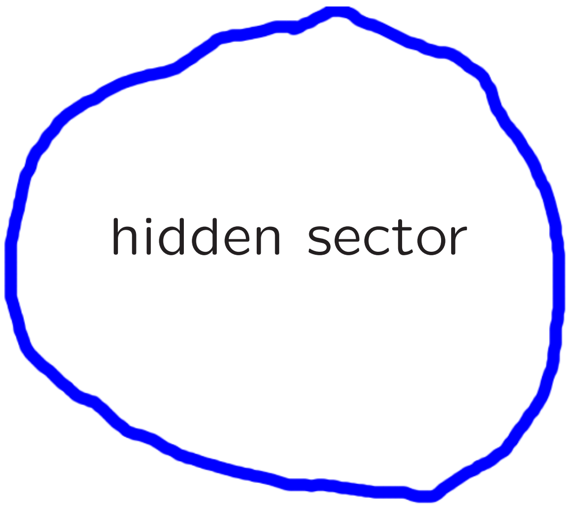
etc.

extra dimensions
- ⋆ universal ED
- ⋆ Randall-Sundrum

etc.


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





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

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