Phenomenology of Higgs Bosons

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

outline :

- How to find Higgs Bosons ?
- Higgsstrahlung
- Higgs + high-p_T Jet in the SM (MSSM)
- HiggsBounds

- 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

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

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

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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.

– Why Higgs Bosons ?

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

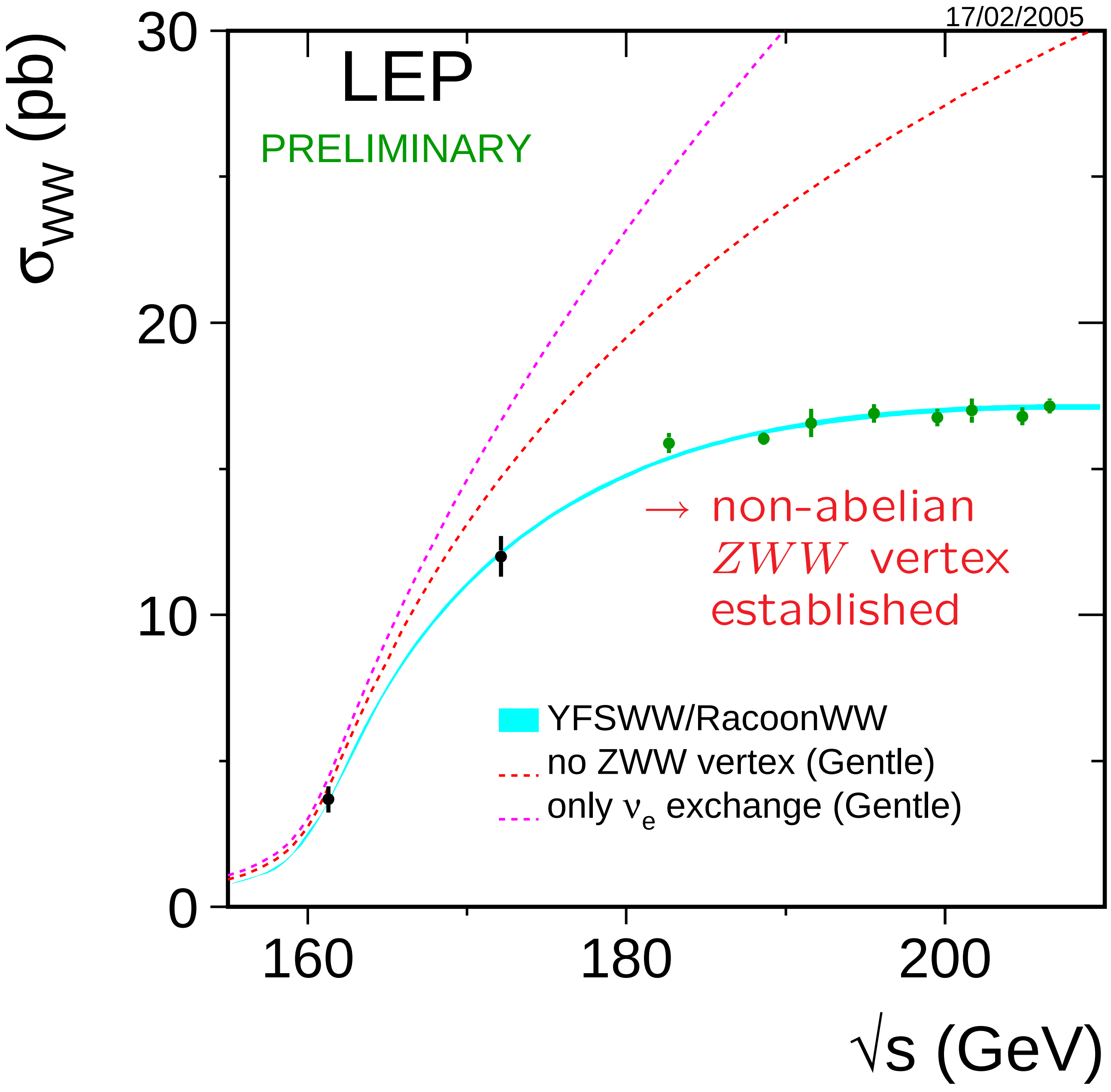
solution: **spontaneous symmetry breaking (SSB)**:

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

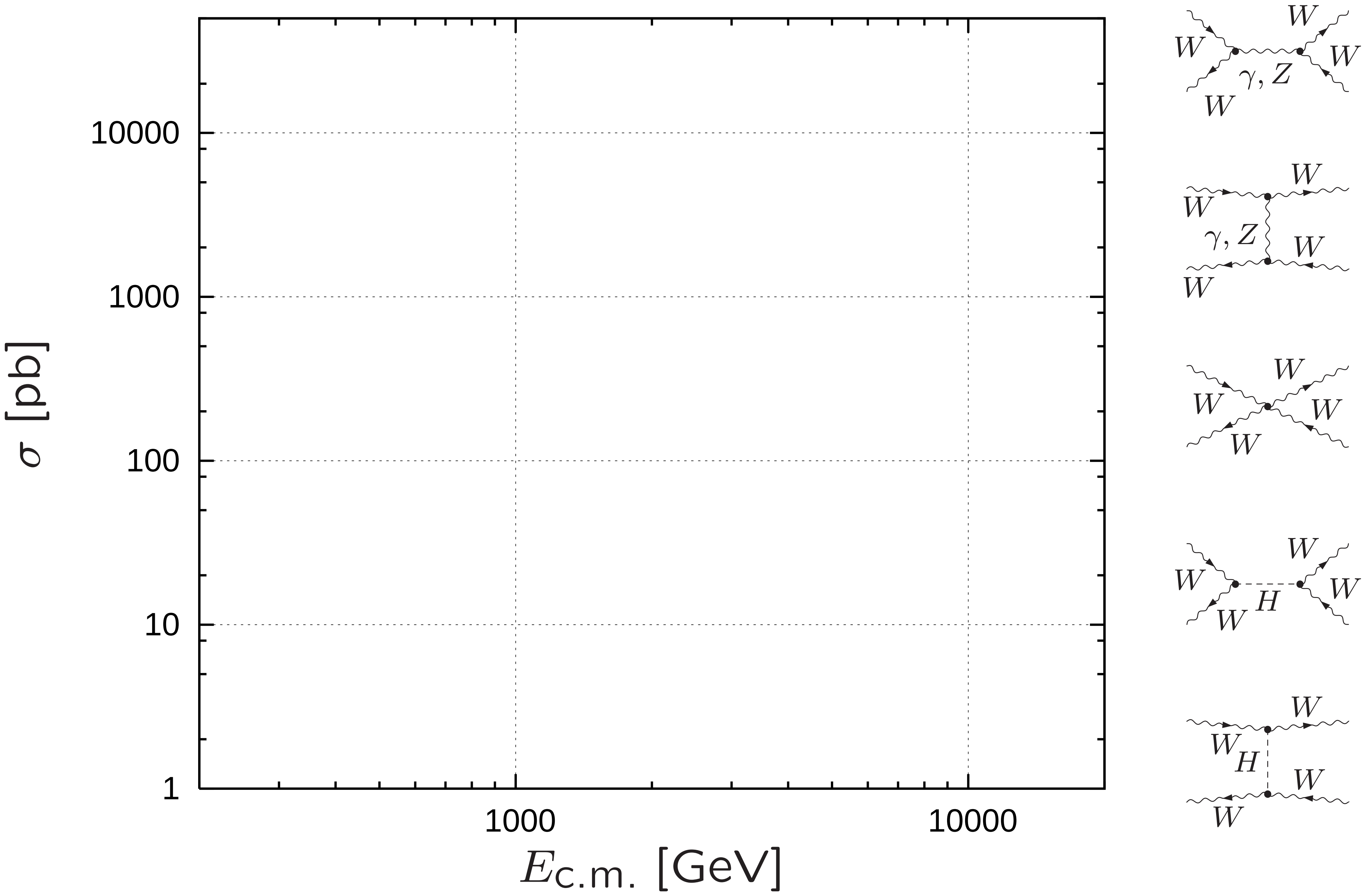
SSB can be realised by

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

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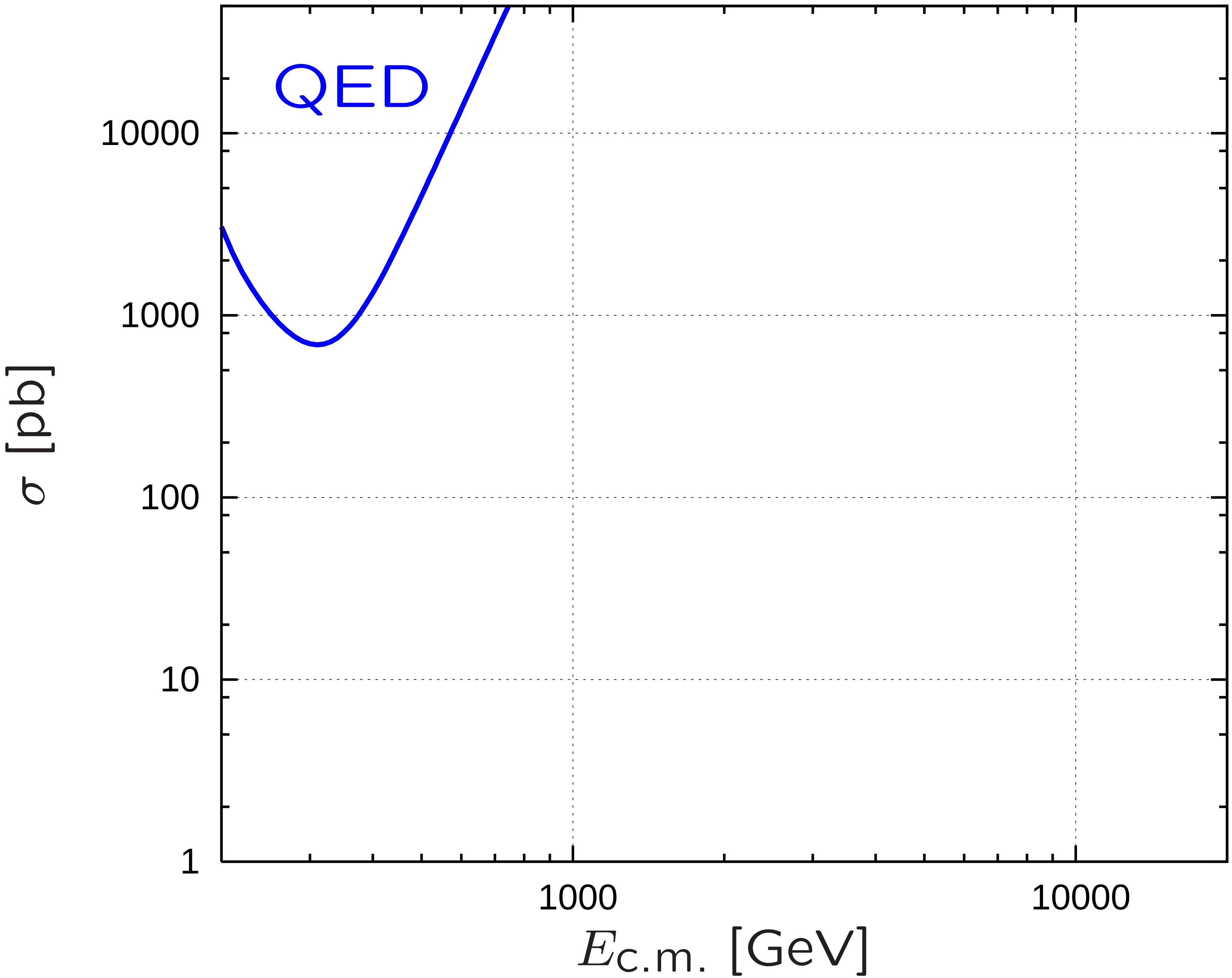

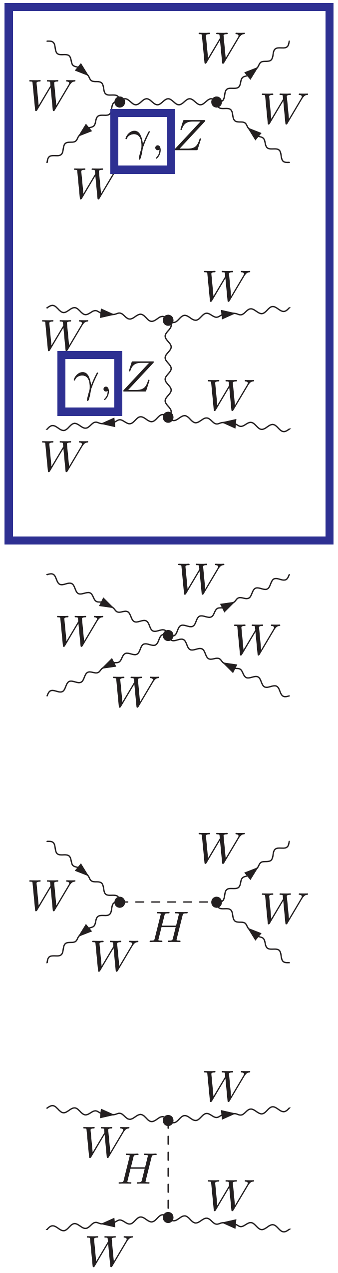

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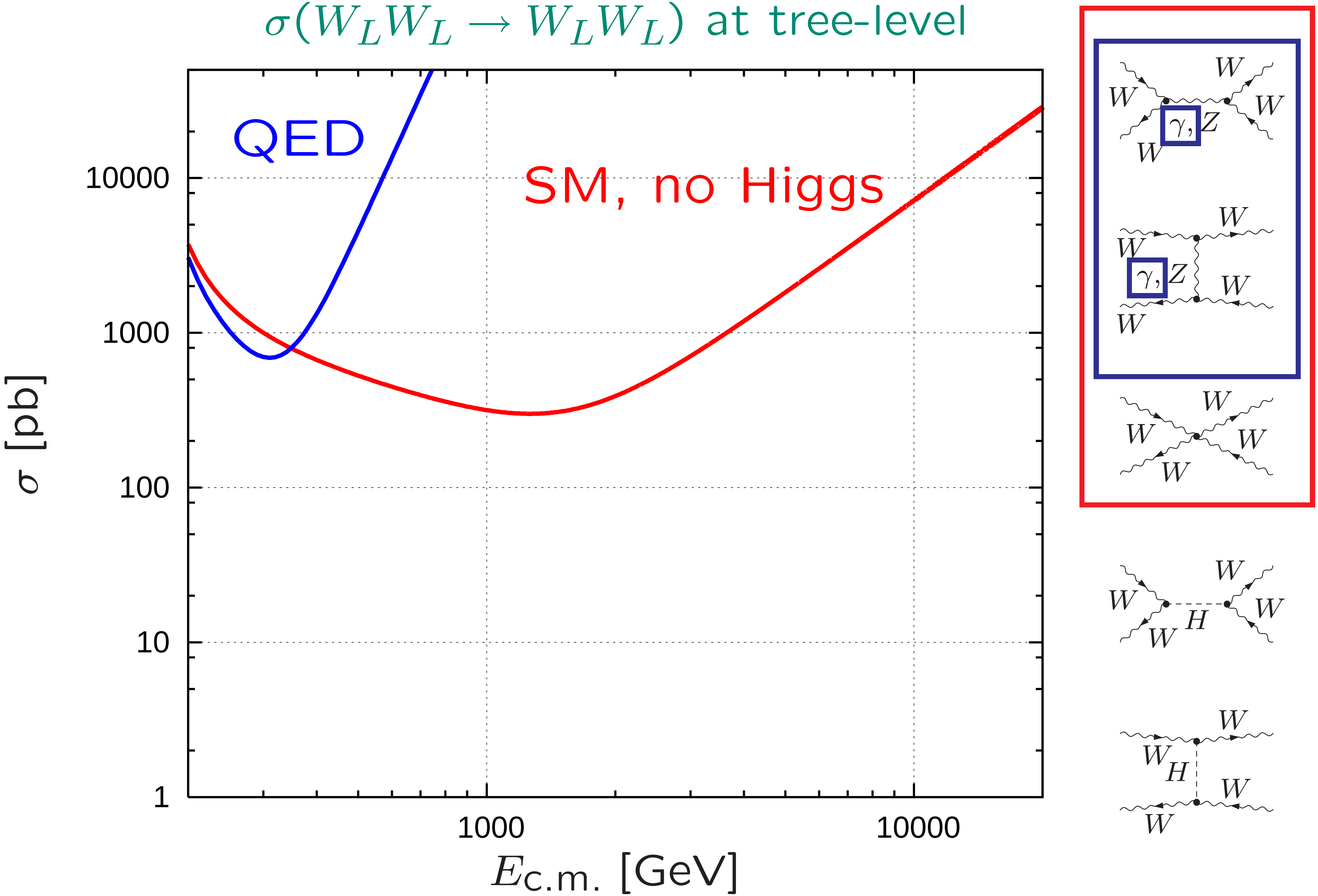
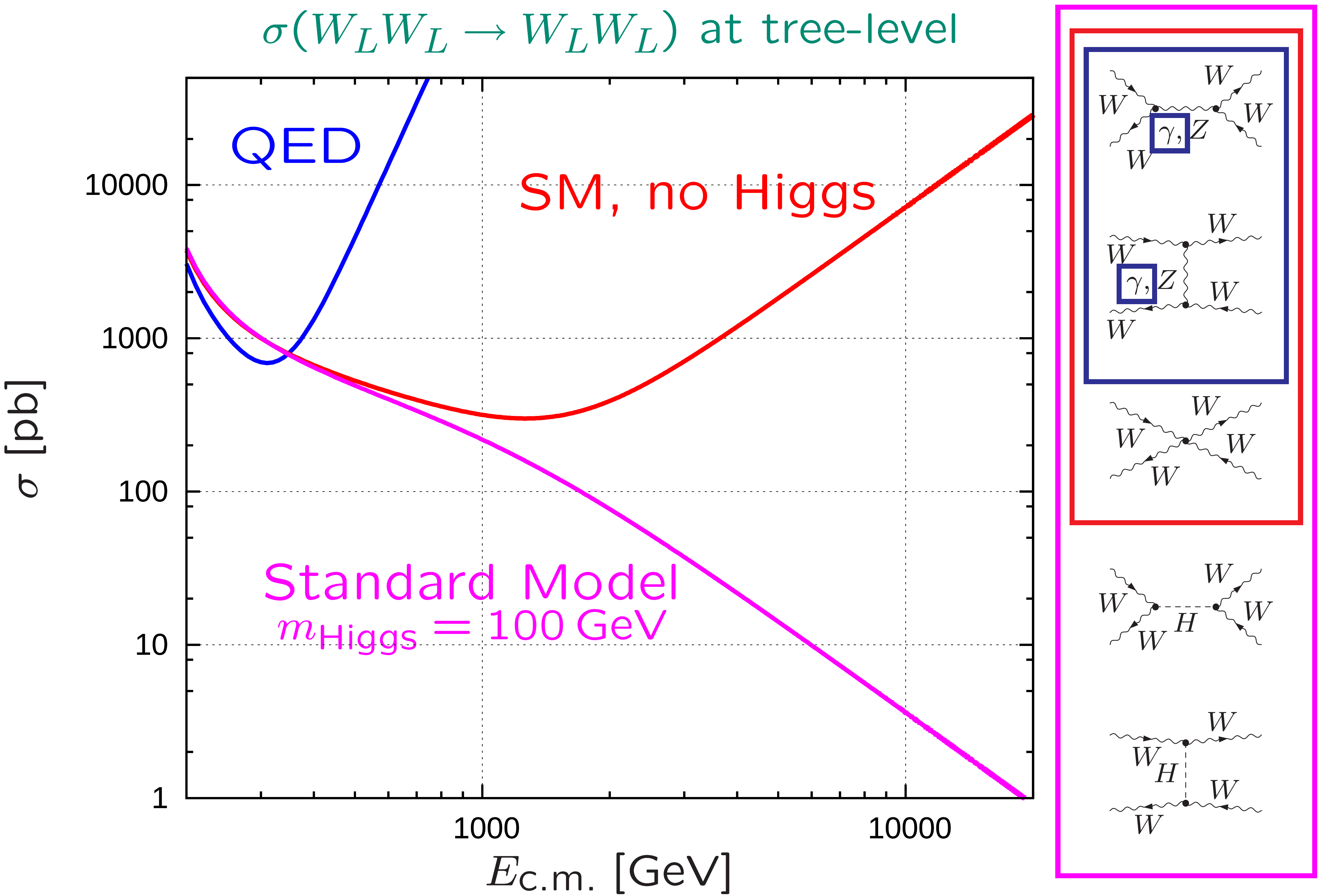


[How to find Higgs Bosons ?, Why Higgs Bosons ?]

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



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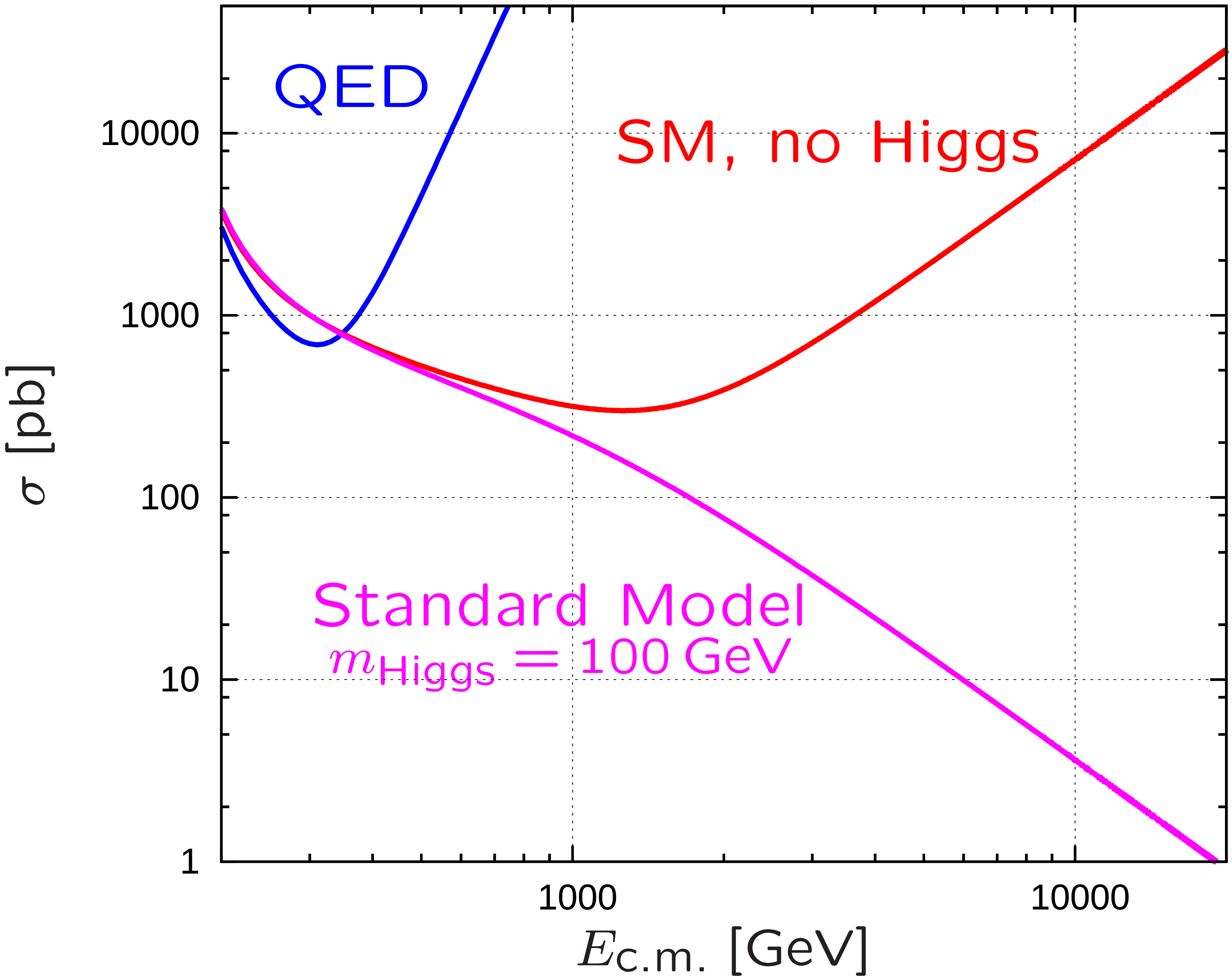


- SM may be applicable up to very high energy.
- If no Higgs exists: new phenomena around 1 TeV expected.

– 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

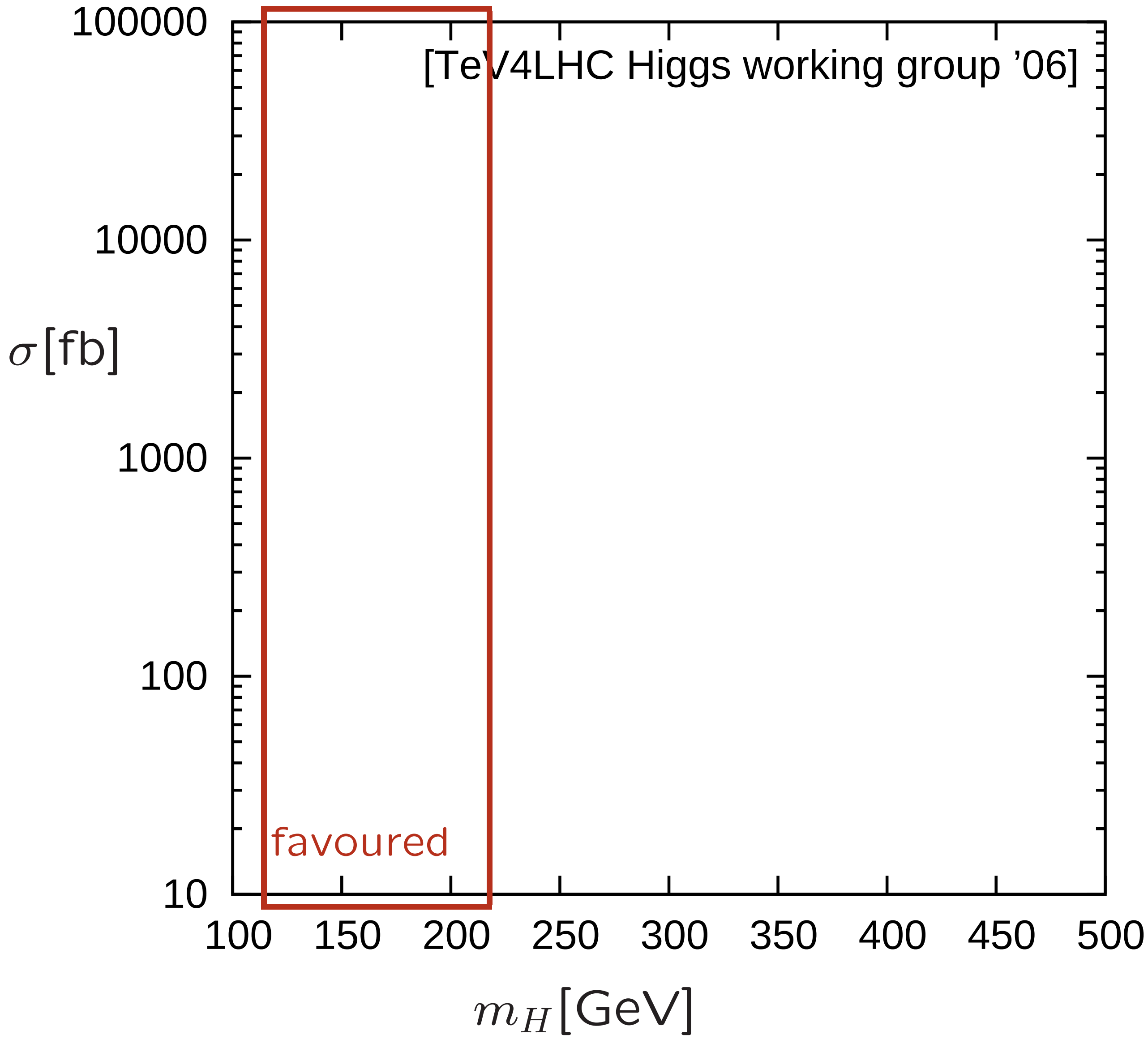
  - the electroweak rho-parameter
    $\rho_{\text{exp.}} = \frac{m_W}{\cos\theta_W m_Z} \approx 1$ up to a few per mille
  - absence of flavour changing neutral currents (FCNC).
  - upper bounds on Higgs signal cross sections
    from negative direct search results (LEP, Tevatron)

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

– Higgs Production

important SM Higgs production processes @ the LHC : $\longrightarrow$ consider:

a) Higgs couplings $\propto$ mass. b) Ordinary matter is very light. c) Huge # of gluon collisions.



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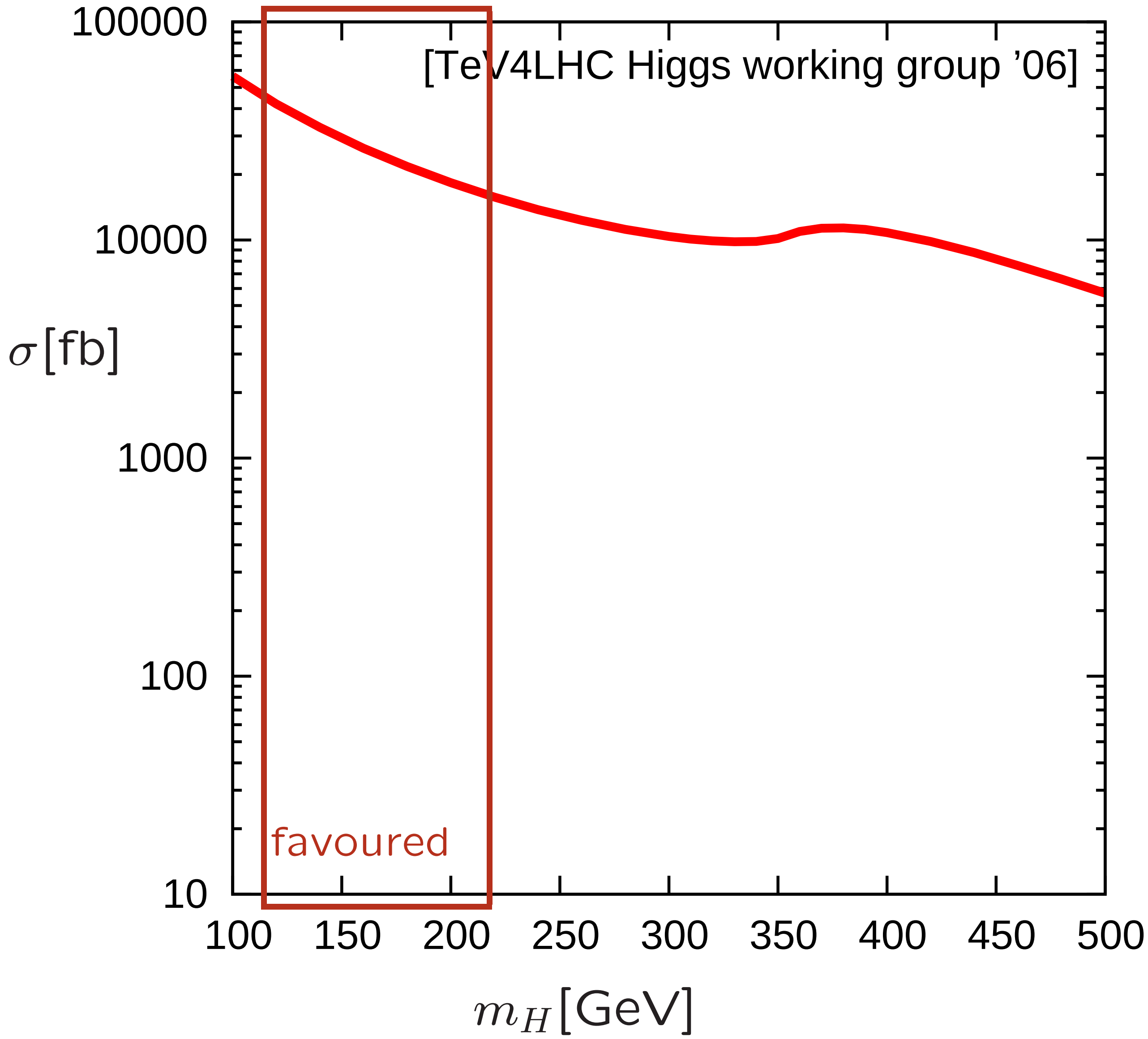
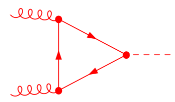


gluon fusion, $gg \to H$



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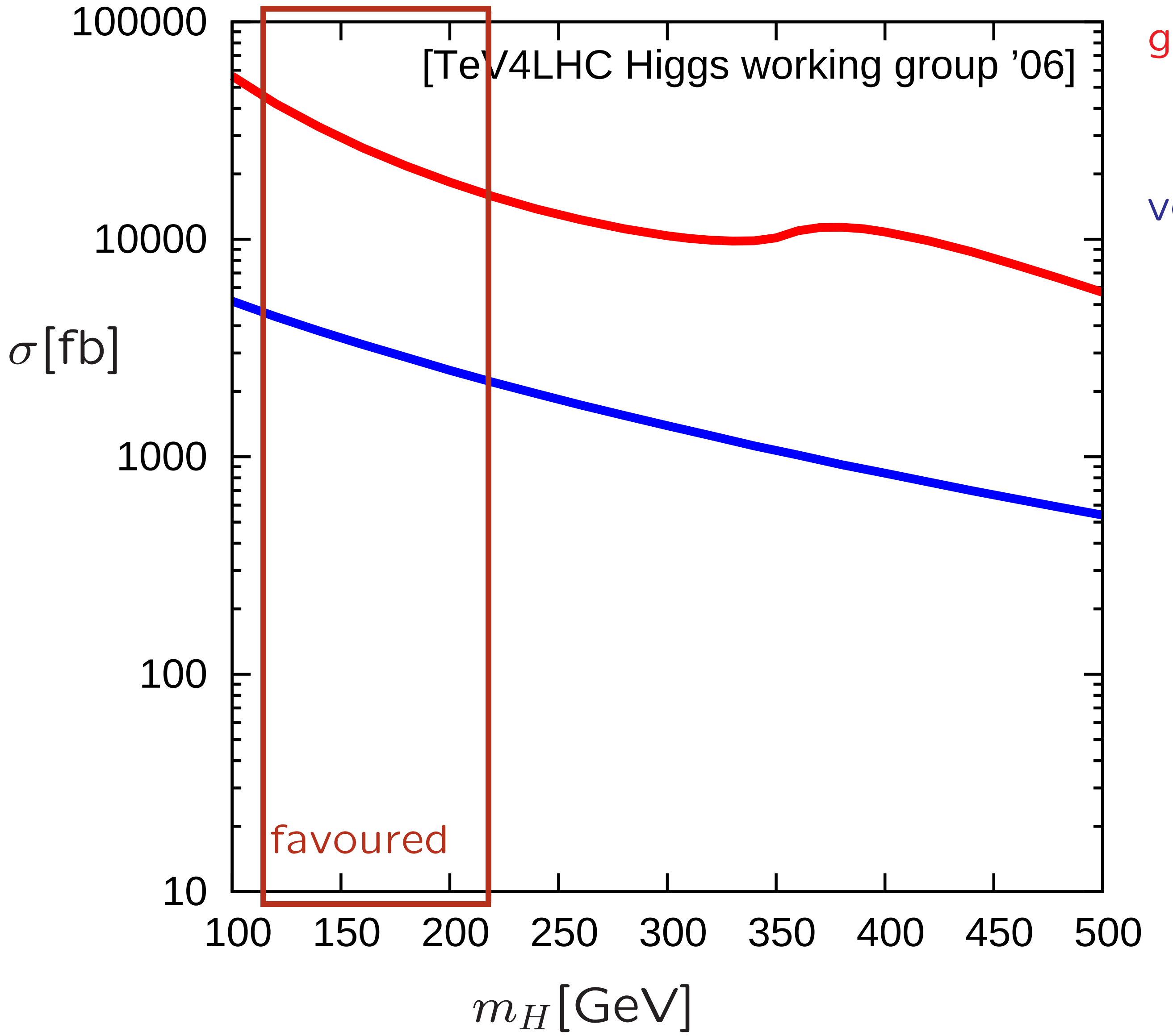

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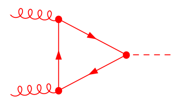
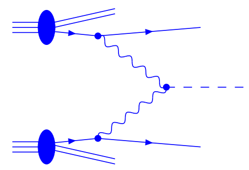


vector boson fusion, $qq \to qqH$



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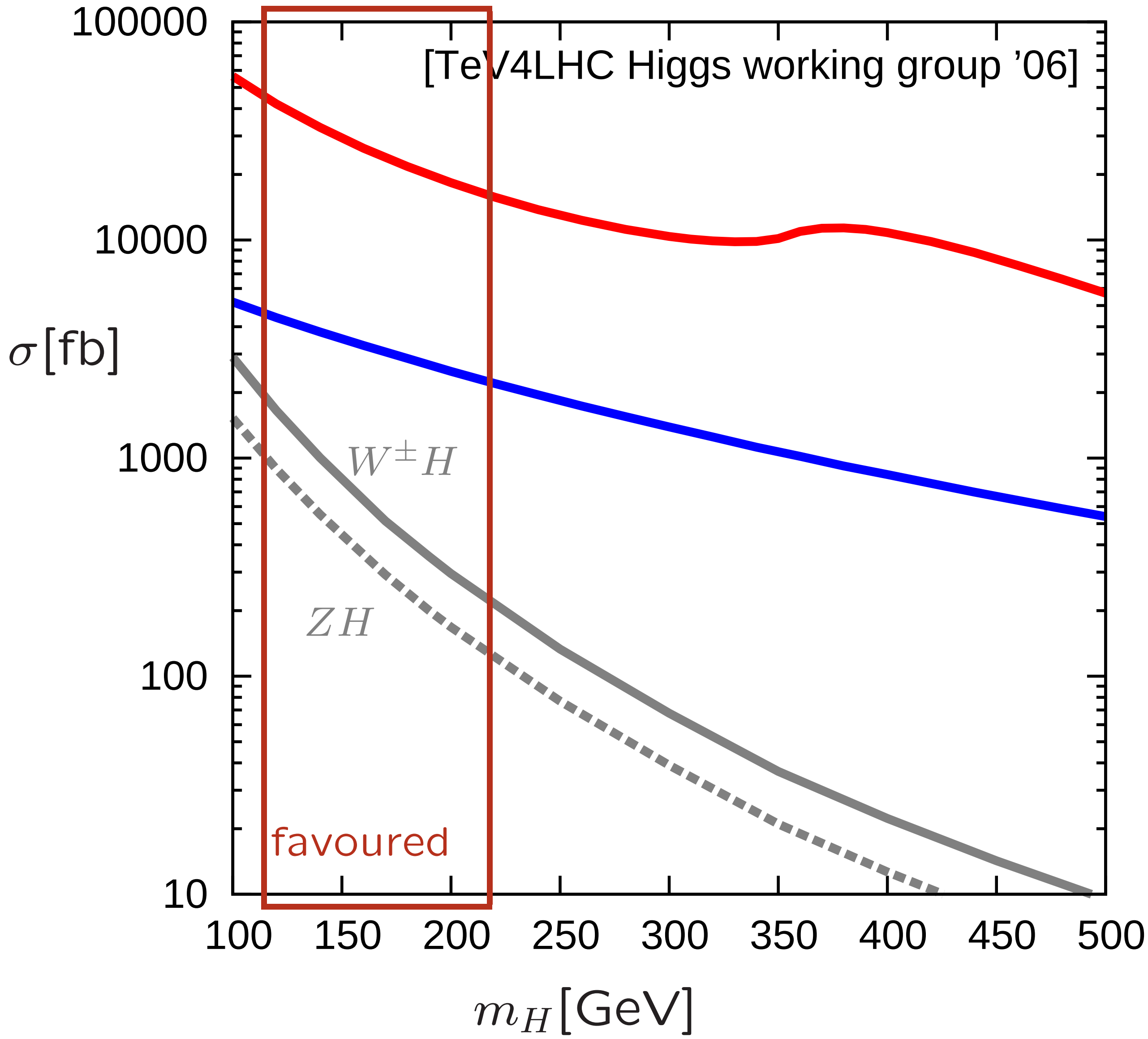

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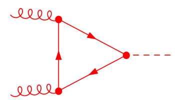

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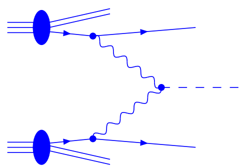
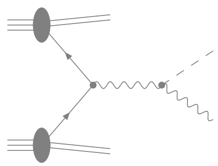


Higgs strahlung, $q\bar{q}' \to VH$



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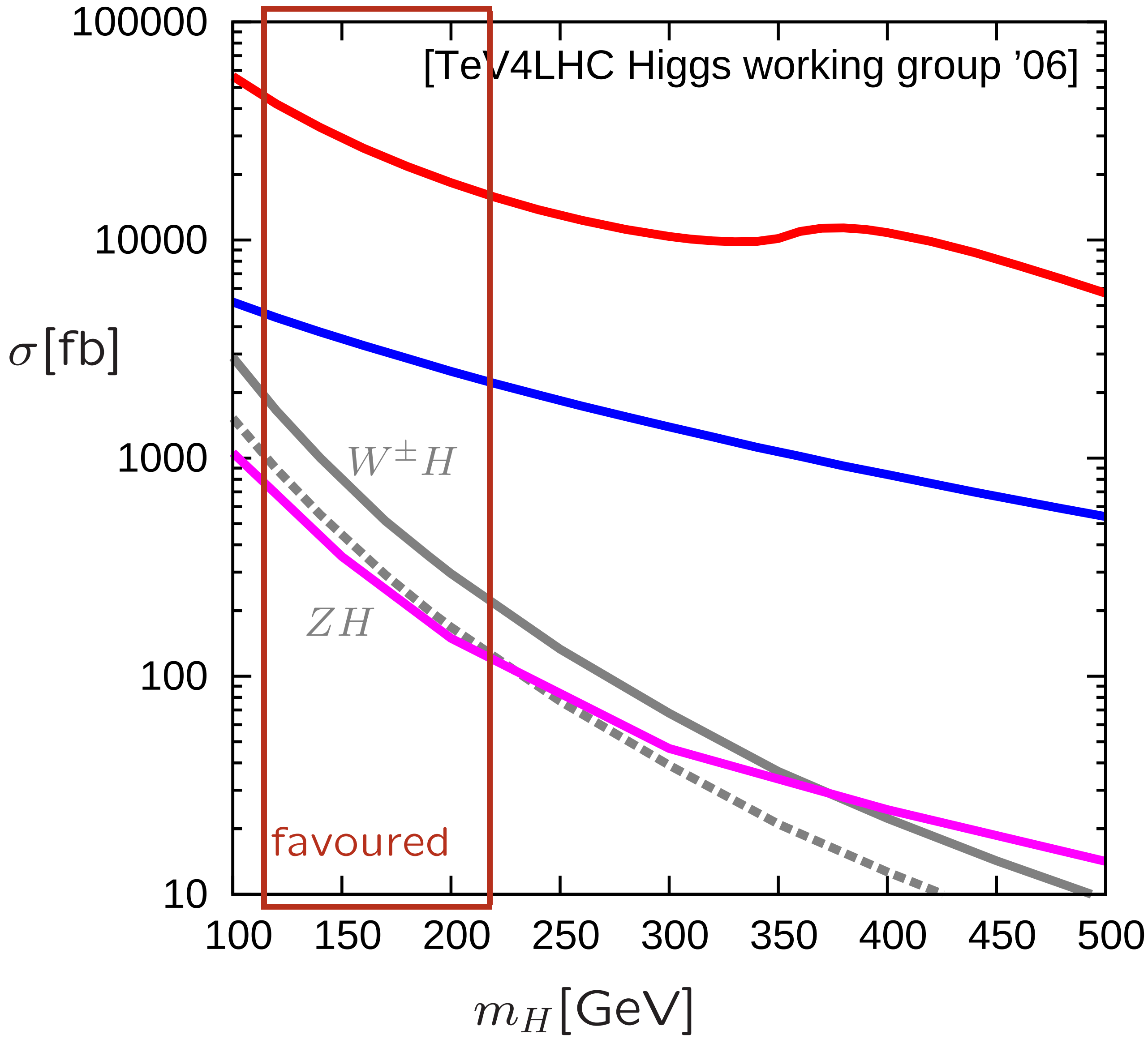

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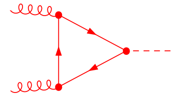

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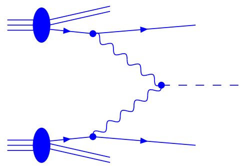

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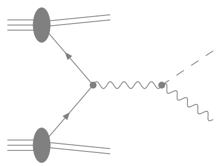
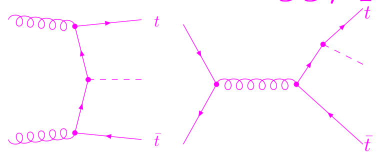


$t\bar{t}H$ production, $gg/q\bar{q} \to t\bar{t}H$



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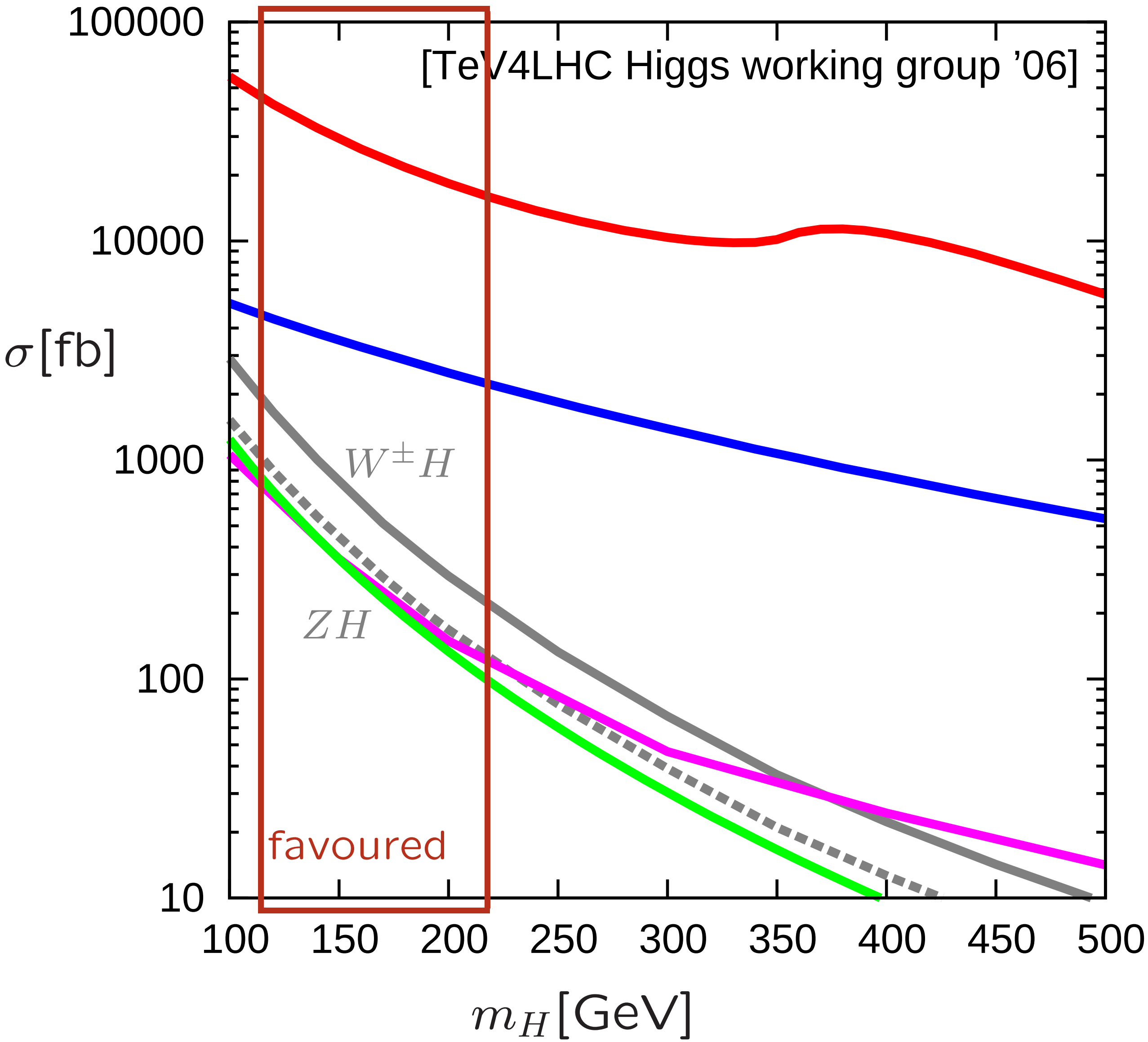
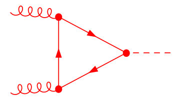
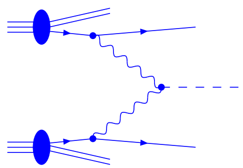


gluon fusion, $gg \rightarrow H$



vector boson fusion, $qq \rightarrow qqH$



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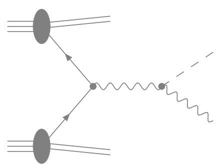

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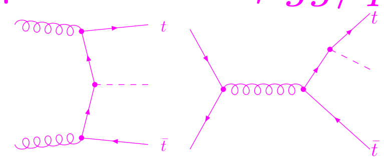
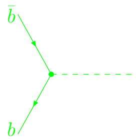


$b\bar{b}$ annihilation, $b\bar{b} \rightarrow H$

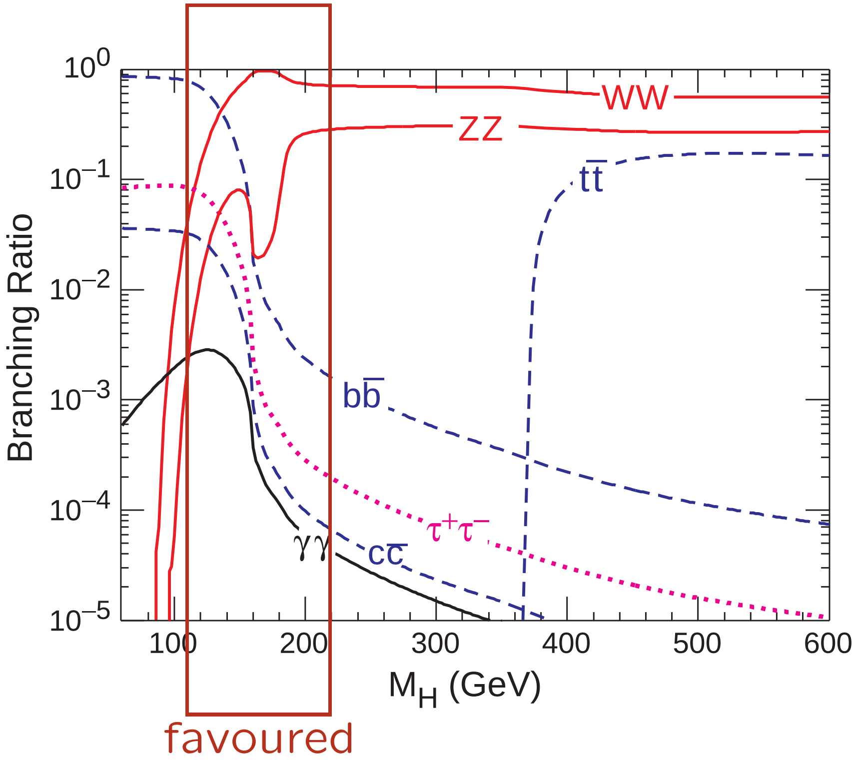


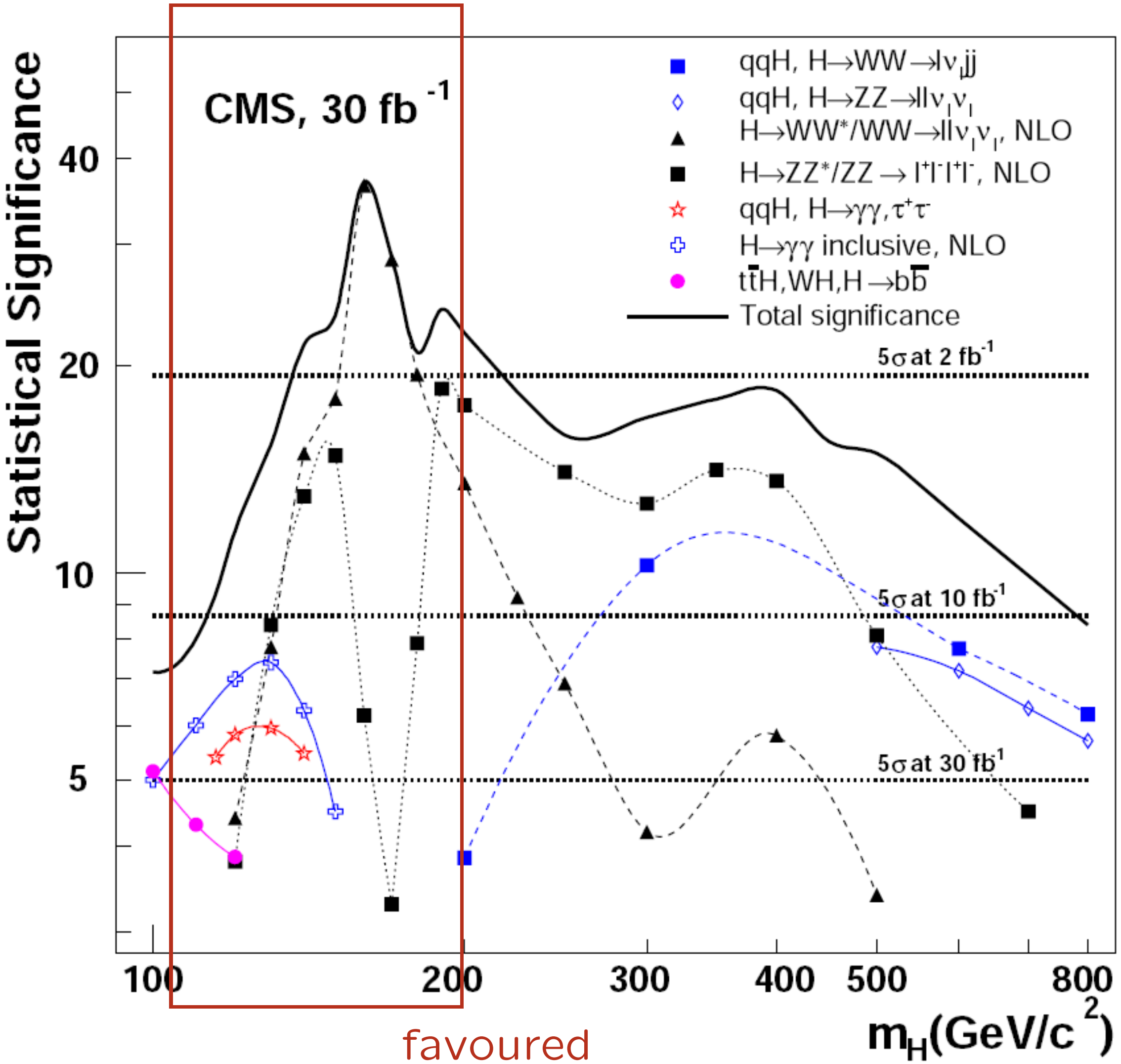
– Higgs Detection

essential for Higgs discovery is:

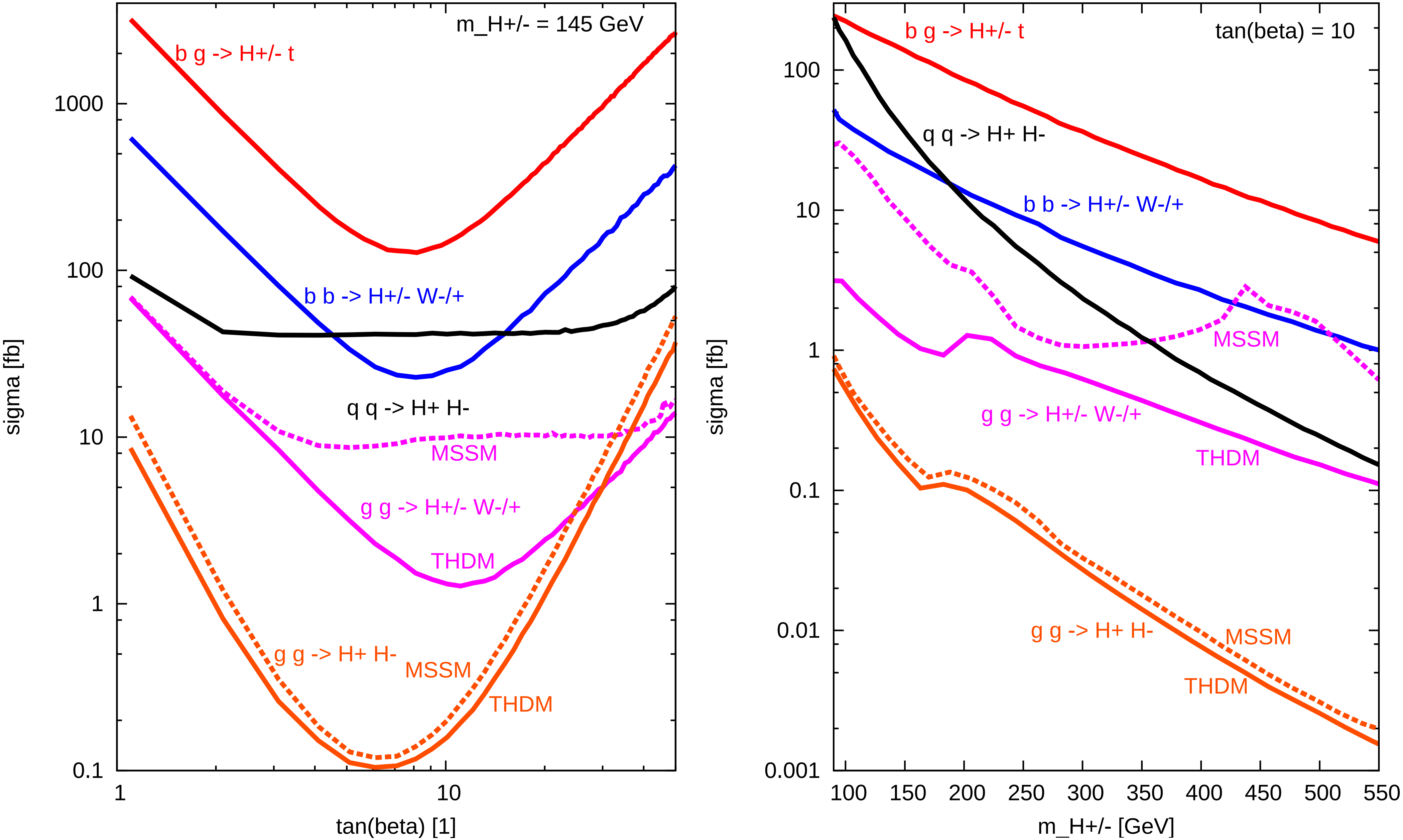
[production rate] × [decay branching ratio] × [detection efficiency]

note!
Higgs events need to be silhouetted against *huge* amount of non-Higgs events

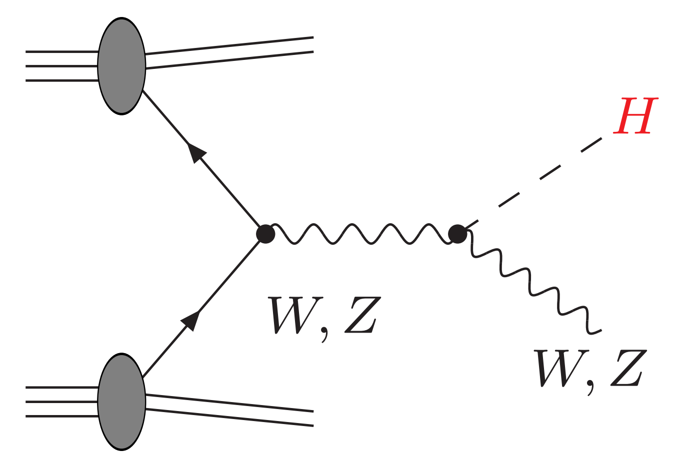




Predictions: charged Higgs cross sections @ **LHC**:

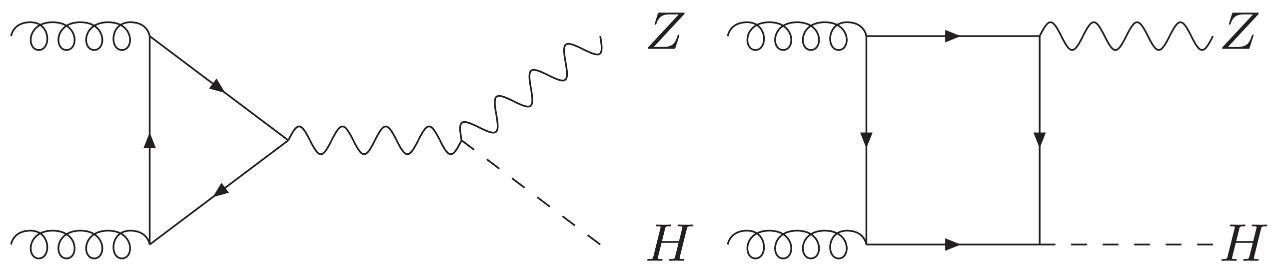


- Higgsstrahlung

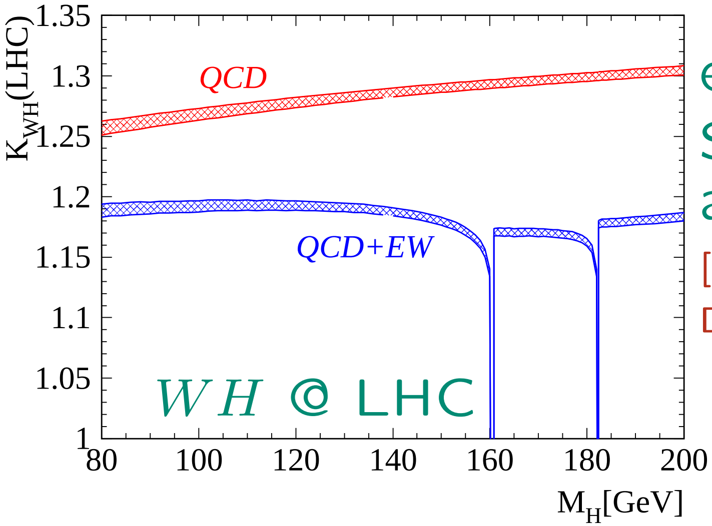


Higgs strahlung, $q\bar{q}' \to VH$

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;

status of theory predictions:

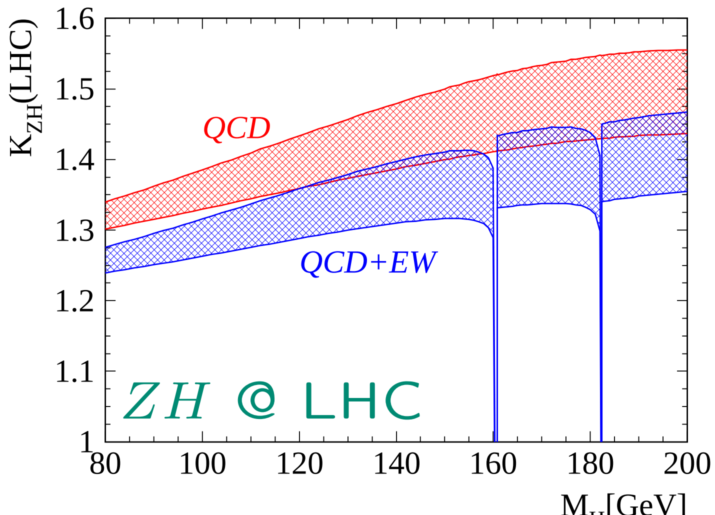
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

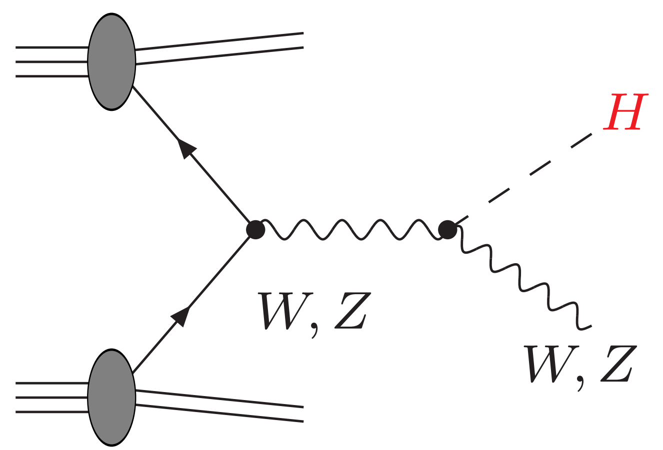
SM, NNLO QCD [OBr, Djouadi, Harlander '03]

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

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



[Higgsstrahlung,]



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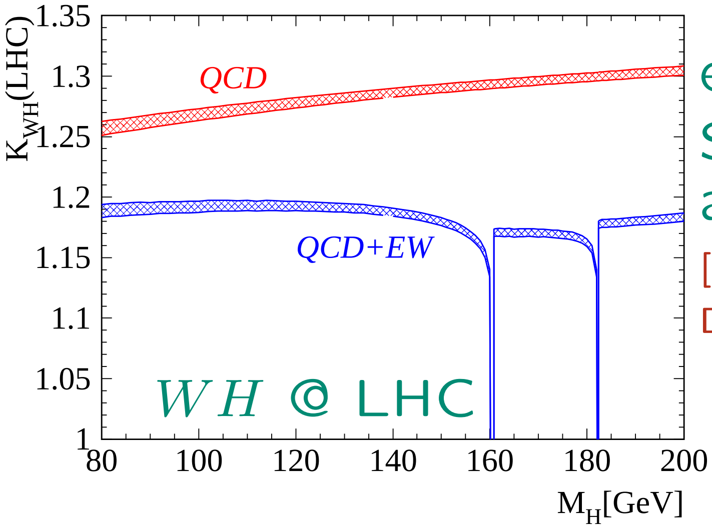

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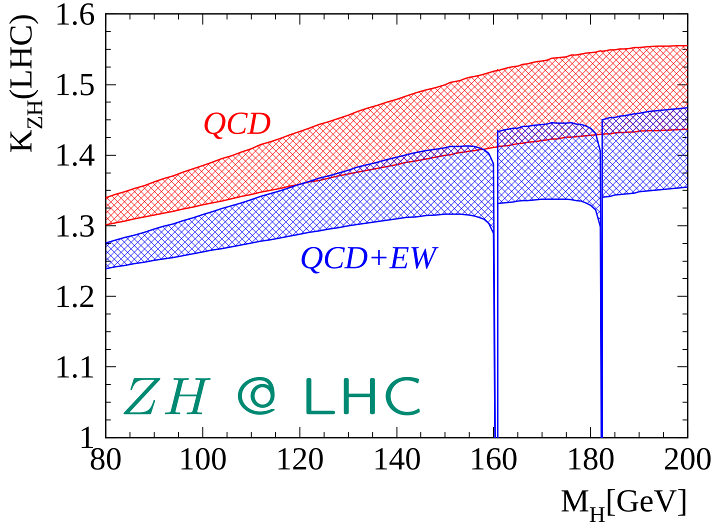


- most precisely known Higgs production process at hadron colliders
- results regularly used by Tevatron collaborations
- recently, we provided updated predictions for cross sections and uncertainties for the ATLAS collaboration

  $\to$ ongoing effort within the LHC Higgs Cross Section Working Group

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

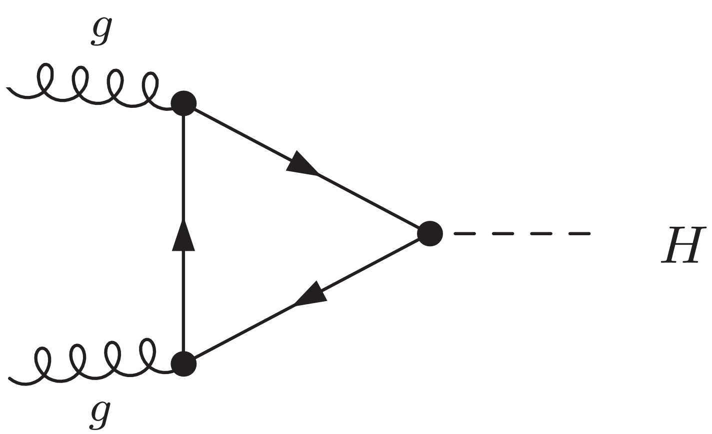
• Higgs + high-p_T Jet in the SM (MSSM)

– Motivation

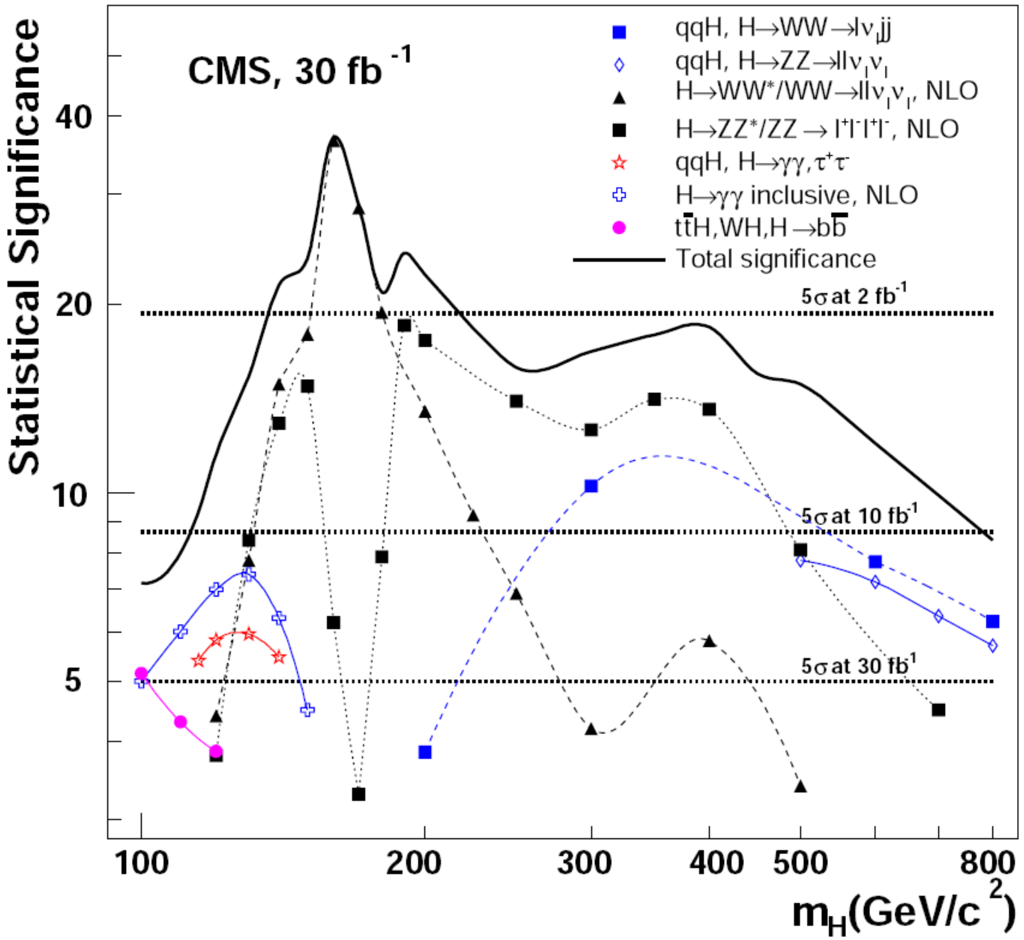
Finding a 100 – 140 GeV SM Higgs is challenging.

The main discovery channel is $H \to \gamma\gamma$ (rare decay) via gluon fusion.

$gg \to H$:



$H \to \gamma\gamma$



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]

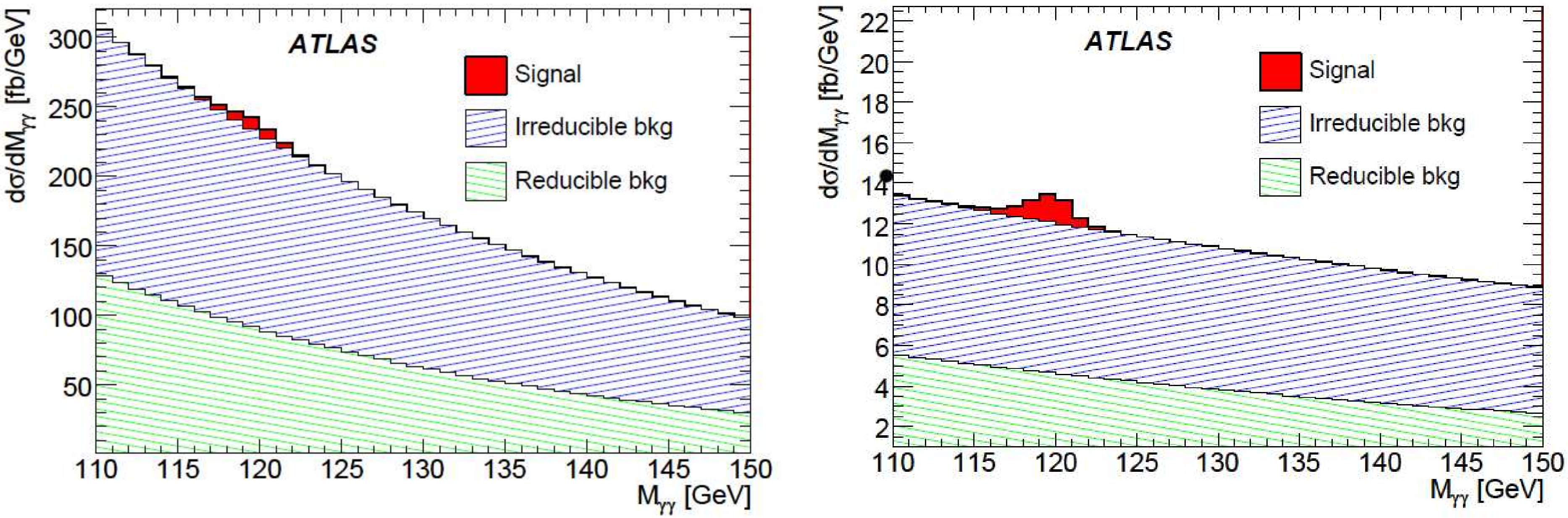
NLO QCD $\mathcal{O}(\alpha_S^4\alpha)$: [de Florian, Grazzini, Kunszt '99]

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

simulations show:

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

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



[ATLAS expected performance 2008]

The Higgs + Jet cross section prediction:

– Current theoretical accuracy:

NLO QCD accuracy (in large m_t approx.) $\propto$ 10% (scale variation)
[de Florian, Kulesza, Vogelsang '05]

– How to improve it? (→ other 10%-ish effects?)

- 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:
  * QCD: beyond the large m_t approx.
  * QCD: effects of non-zero m_b

  } normally not present in MC event generators

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

– New LO Contributions in the SM

Previous Study [Keung, Petriello '09]

SM Higgs p_T distribution:

1. with finite quark mass effects (m_t, m_b) in one-loop QCD amplitude:
   $\rightarrow$ already included in [..., OBr, Hollik '03; '07]

2. with electroweak one-loop effects

3. validity of the large m_t approximation

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

– New LO Contributions in the SM

This Study [OBr '10]

SM Higgs p_T and η_{jet} distribution:

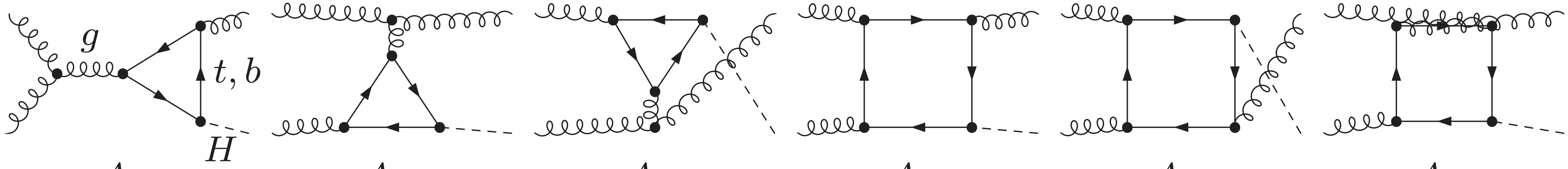
1. with finite quark mass effects (m_t, m_b) in one-loop QCD amplitude:
   $\longrightarrow$ already included in [..., OBr, Hollik '03; '07]

2. with electroweak one-loop effects

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

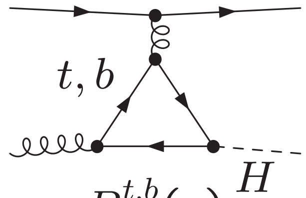
Gluon & Light Quark (u, d, s, c) QCD Contribution : $\mathcal{O}(\alpha_S^3 \alpha)$

gluon fusion, $gg \longrightarrow Hg$



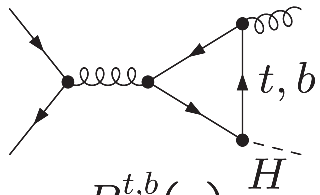
$A_{t,b}$ $A_{t,b}$ $A_{t,b}$ $A_{t,b}$ $A_{t,b}$ $A_{t,b}$

quark gluon scattering, $qg \longrightarrow Hq$



$B_{qg}^{t,b}(q)$

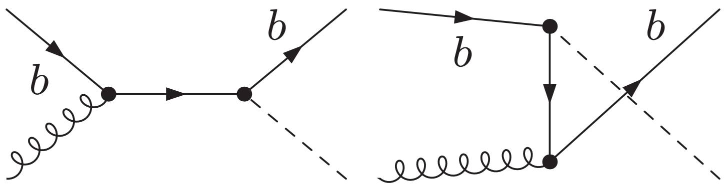
quark anti-quark annihilation, $q\bar{q} \longrightarrow Hg$



$B_{q\bar{q}}^{t,b}(q)$

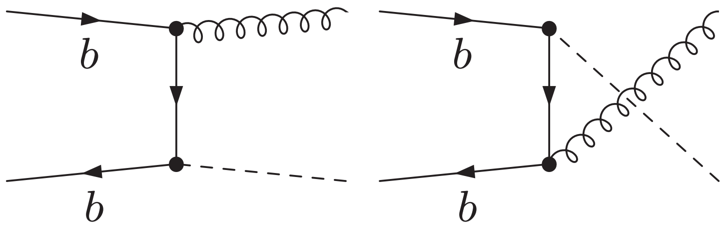
Bottom Quark QCD Contribution : $\mathcal{O}(\alpha_S \alpha)$

quark gluon scattering, $bg \to Hb$



$D_{qg}(b)$ $D_{qg}(b)$

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

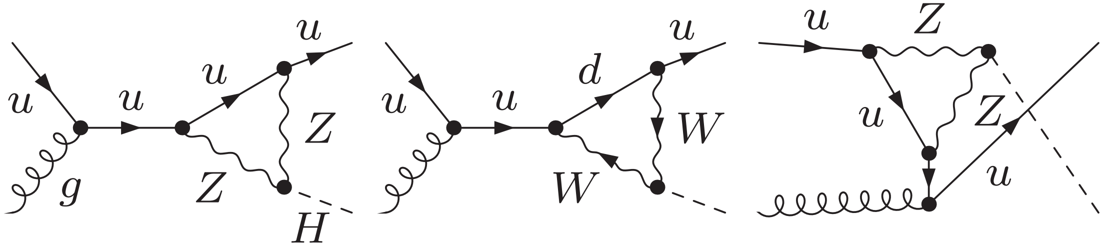


$D_{q\bar{q}}(b)$ $D_{q\bar{q}}(b)$

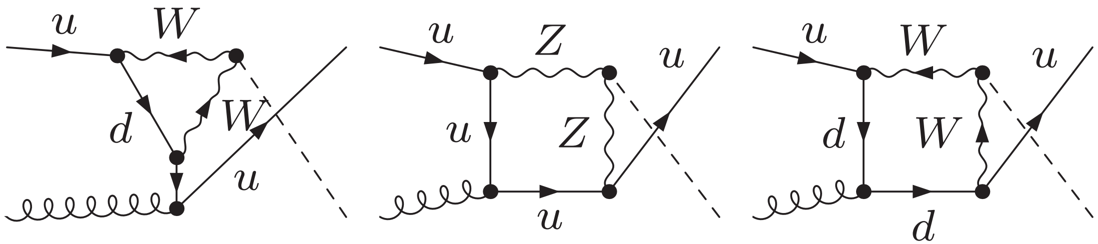
Light Quark (u, d, s, c) EW Contribution : $\mathcal{O}(\alpha_S \alpha^3)$

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

quark gluon scattering, $qg \longrightarrow Hq$



$C_{qg}(u)$ $C_{qg}(u)$ $C_{qg}(u)$



$C_{qg}(u)$ $C_{qg}(u)$ $C_{qg}(u)$

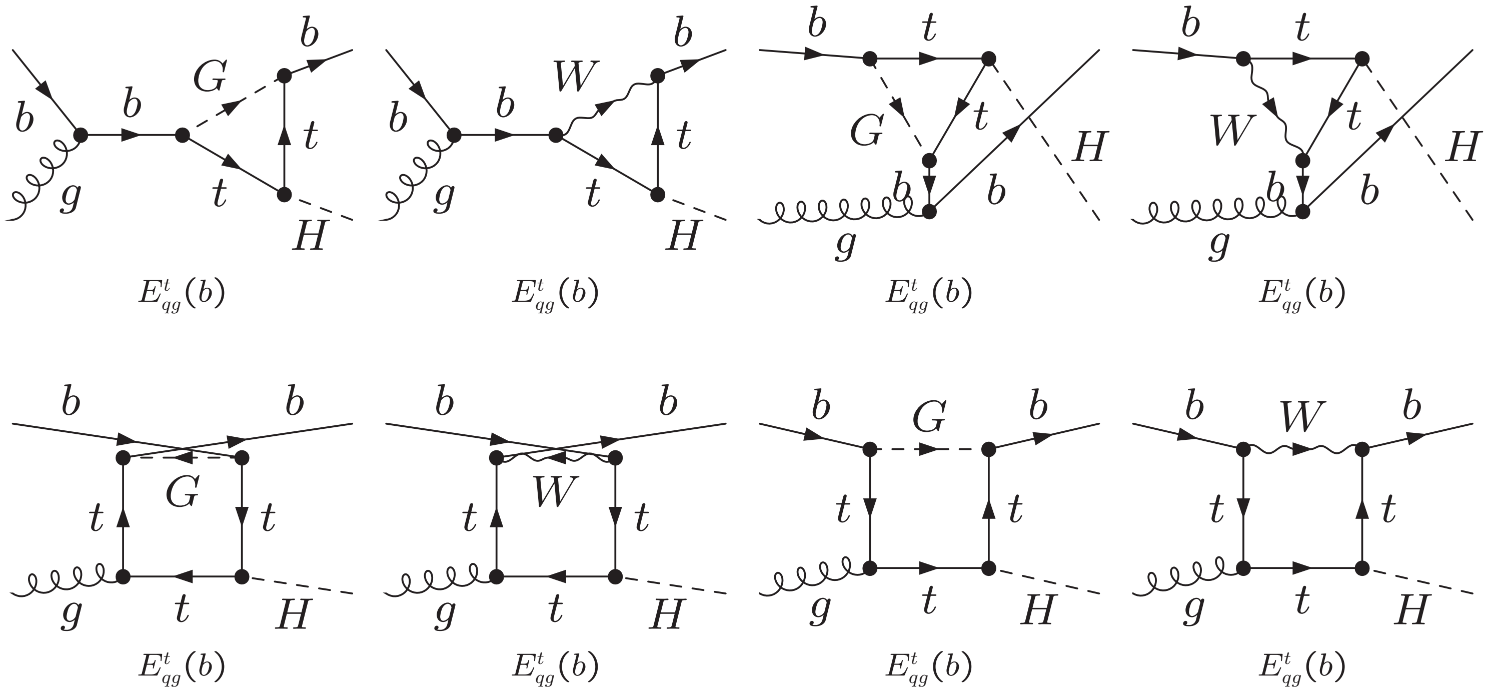
quark anti-quark annihilation, $q\bar{q} \longrightarrow Hg$

crossed diagrams

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

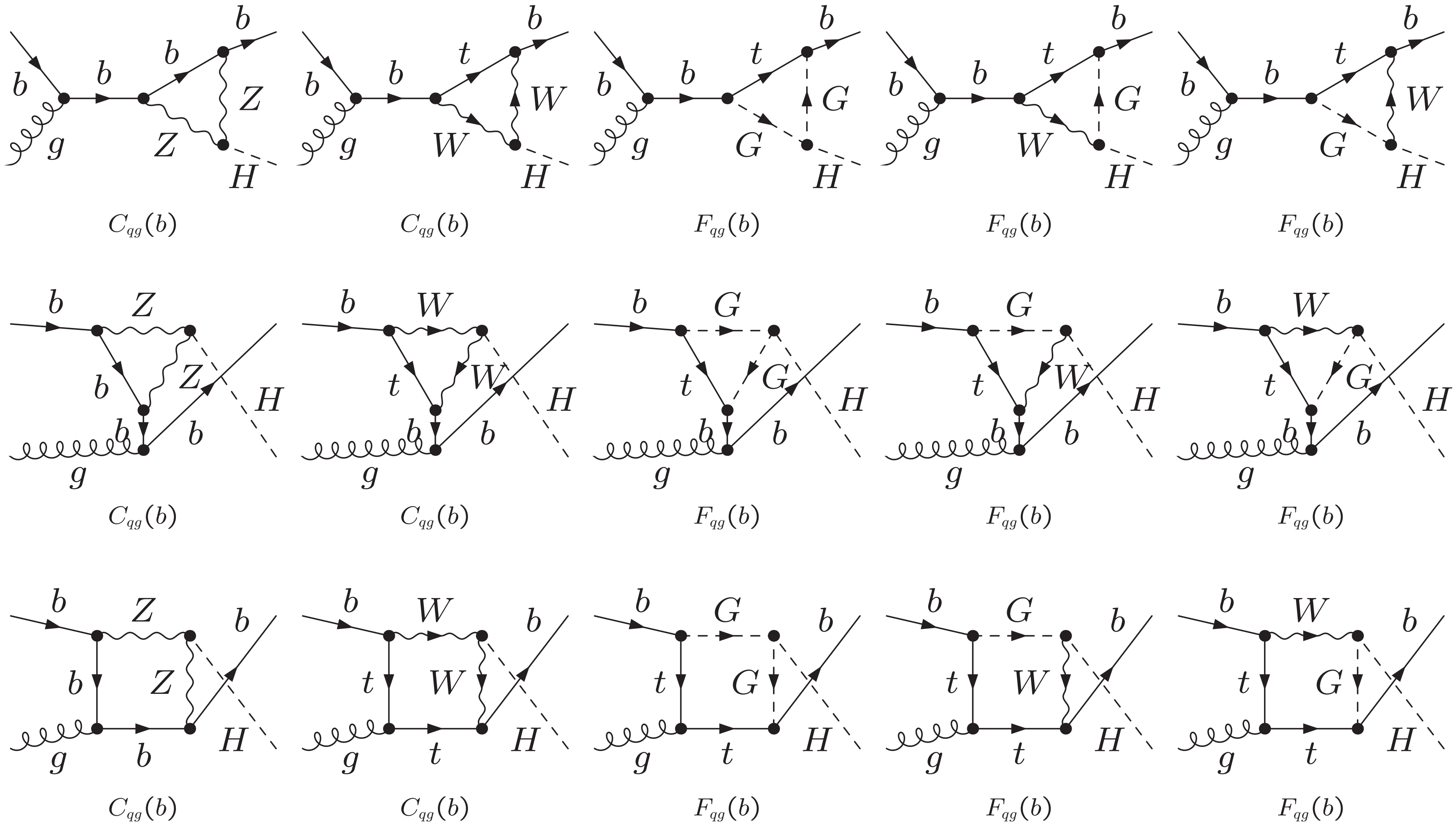
[Mrenna, Yuan '96]

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]

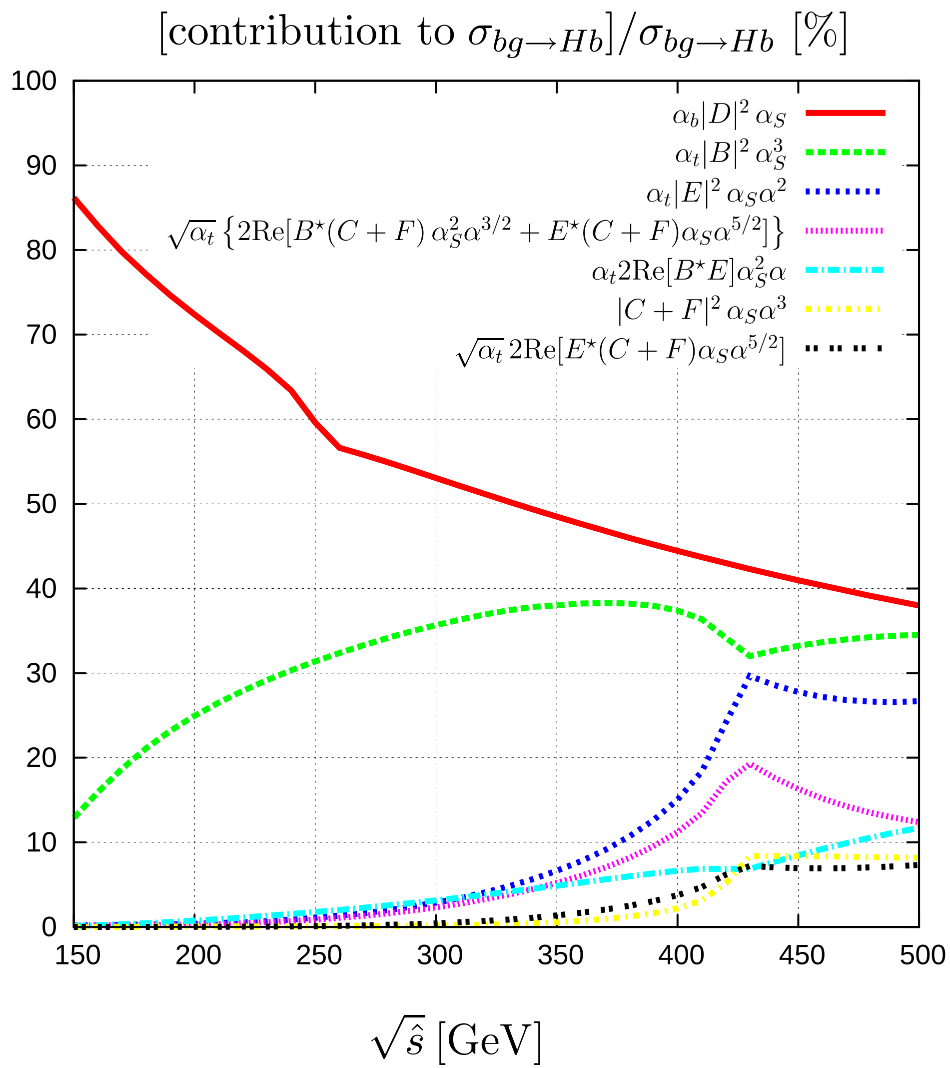
quark gluon scattering, $bg \to Hb$, $\mathcal{O}(\alpha_S \alpha^3)$ "non α_t"



new calculational approach: respect the hierarchy of Yukawa couplings

$(\alpha_t = 3.9 \cdot 10^{-2},\ \alpha_b = 2.3 \cdot 10^{-6})$

example: contributions to bottom gluon scattering ($m_H = 120\,\mathrm{GeV}$)



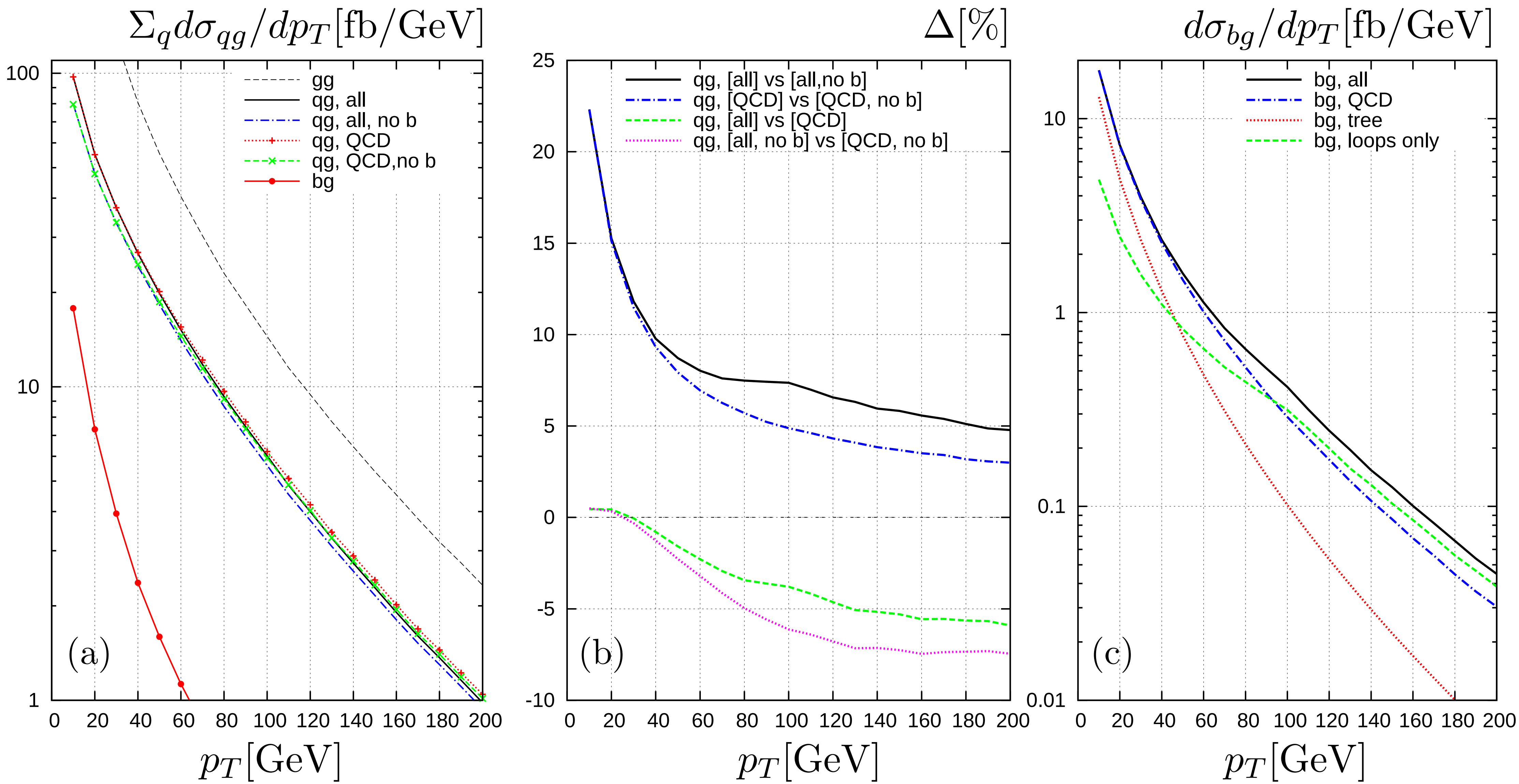
$$\sigma_{bg\to Hb} \propto |\mathcal{M}_{qg}(b)|^2/(4\pi)^4 =$$
$$\alpha_b\left\{ |D_{qg}(b)|^2\alpha_S \right\}(4\pi)^{-2}$$
$$+\,\alpha_t\left\{ |B_{qg}{}^t(b)|^2\alpha_S^3 \right.$$
$$+\,2\mathrm{Re}\left[B^\star_{qg}{}^t(b)E_{qg}{}^t(b)\right]\alpha_S^2\alpha$$
$$\left. +\,|E_{qg}{}^t(b)|^2\alpha_S\alpha^2\right\}$$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

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

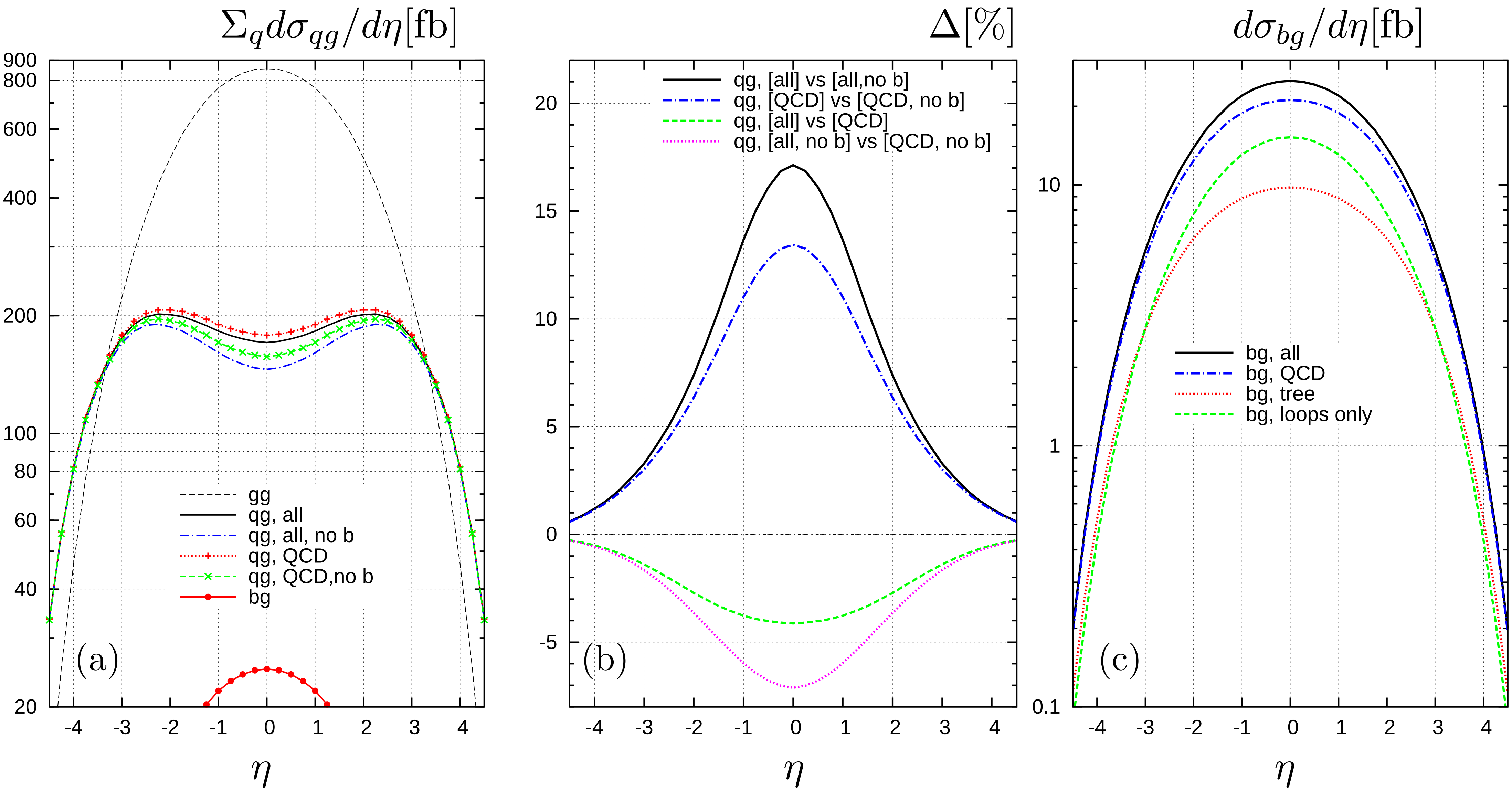
$$\frac{d\sigma(S,p_{T,\text{jet}})}{dp_{T,\text{jet}}}, \; |\eta_{\text{jet}}| < 4.5$$

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

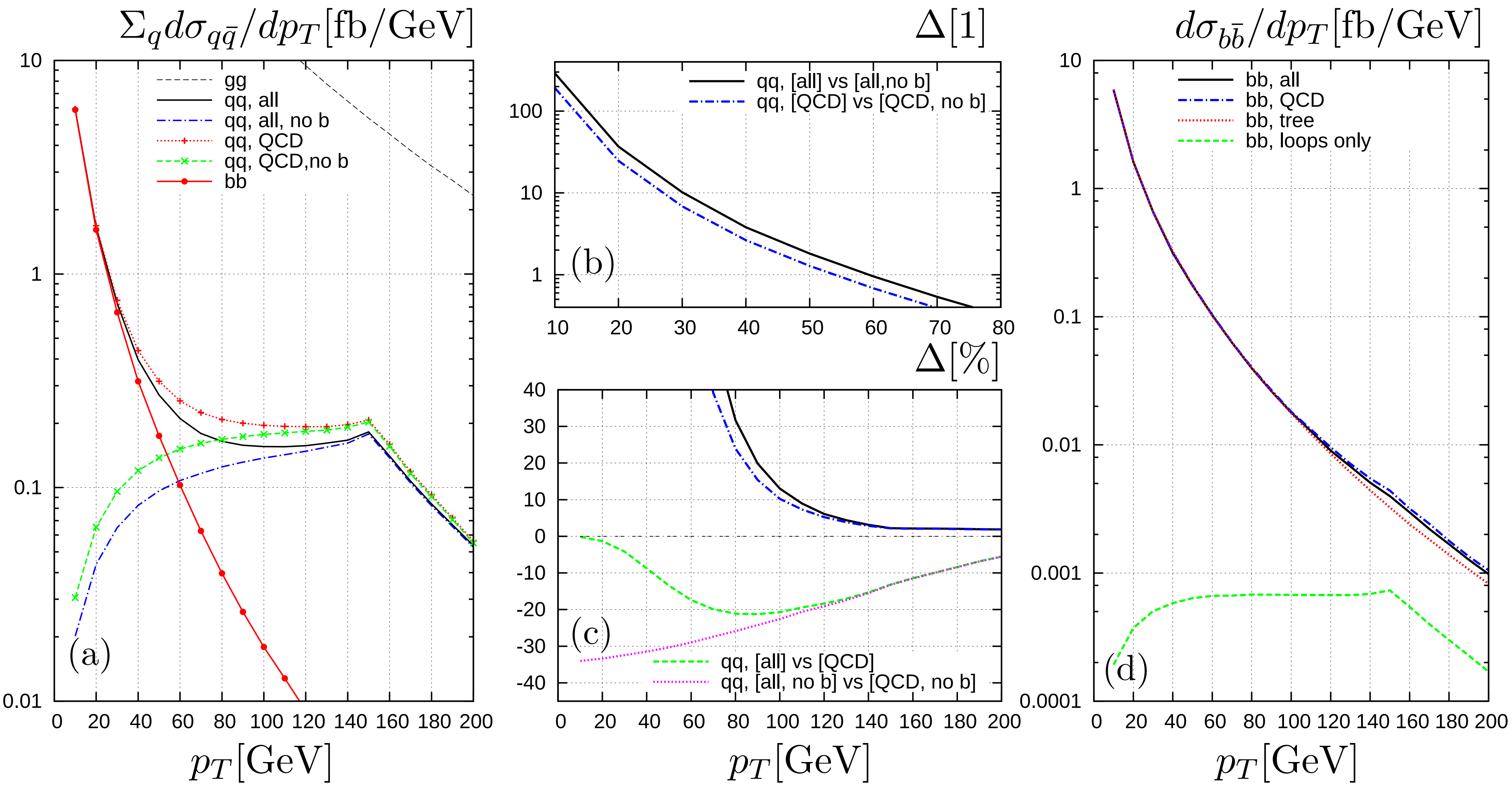
$p_{T,\mathrm{jet}}$ distribution : quark–gluon scattering ($m_H = 120\,\mathrm{GeV}$)



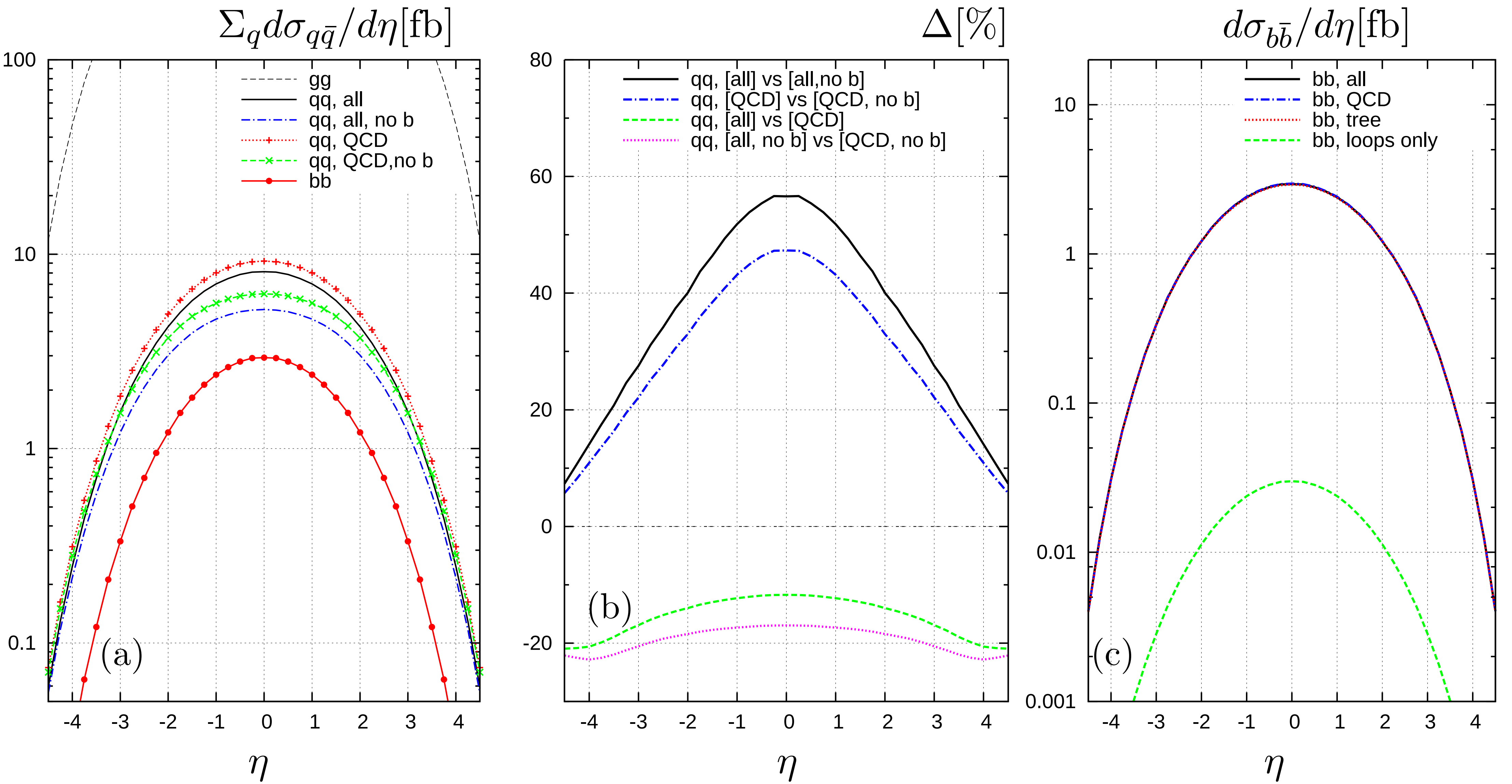
η_{jet} distribution : quark–gluon scattering ($m_H = 120\,\text{GeV}$)



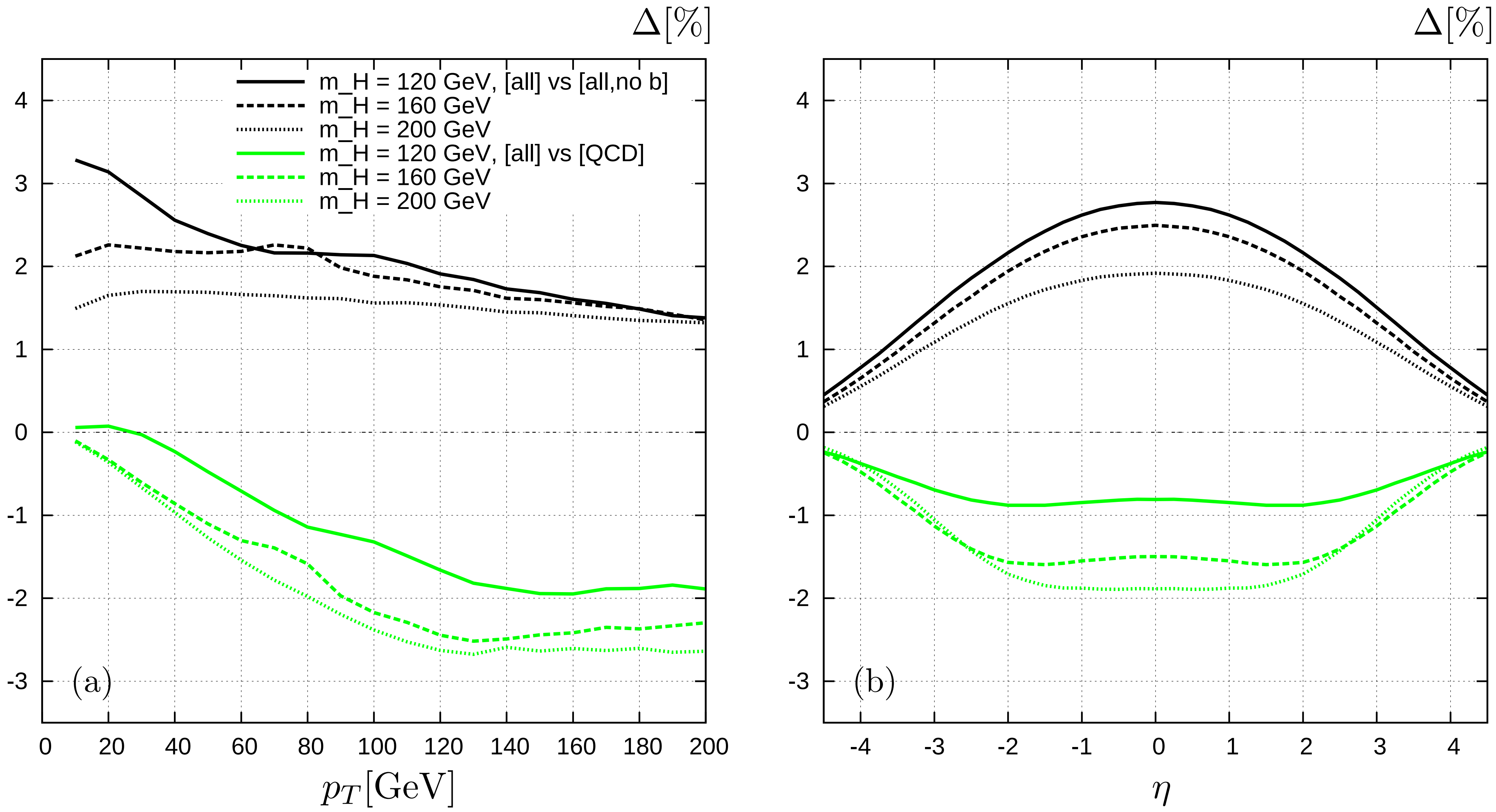
$p_{T,\mathrm{jet}}$ distribution : $q\bar{q}$ annihilation ($m_H = 120\,\mathrm{GeV}$)



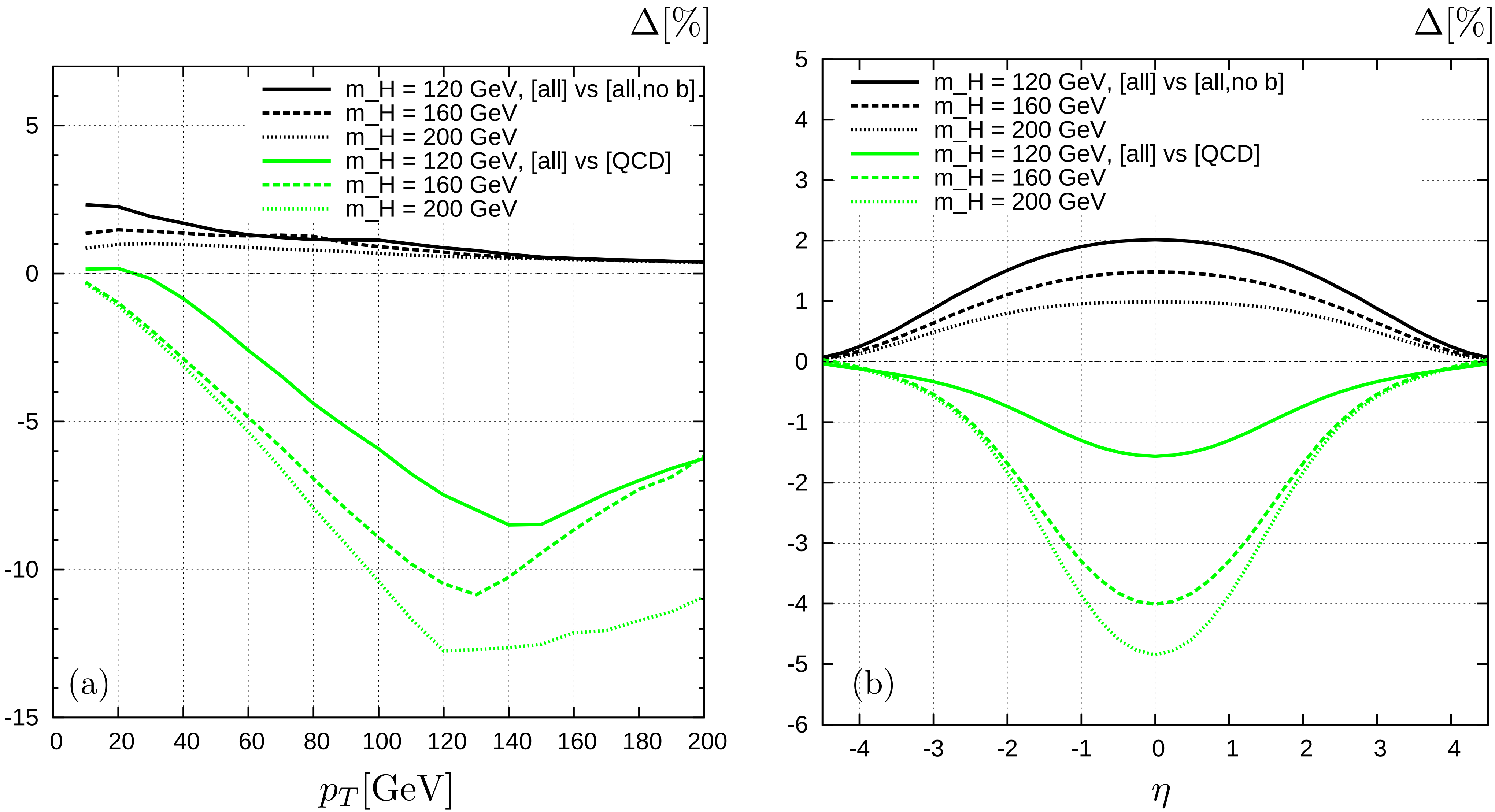
$\eta_{\rm jet}$ distribution : $q\bar{q}$ annihilation ($m_H = 120$ GeV)



effects on the of the total Higgs + Jet distributions ($m_H = 120\,\mathrm{GeV}$)
for the LHC ($\sqrt{s} = 10\,\mathrm{TeV}$):



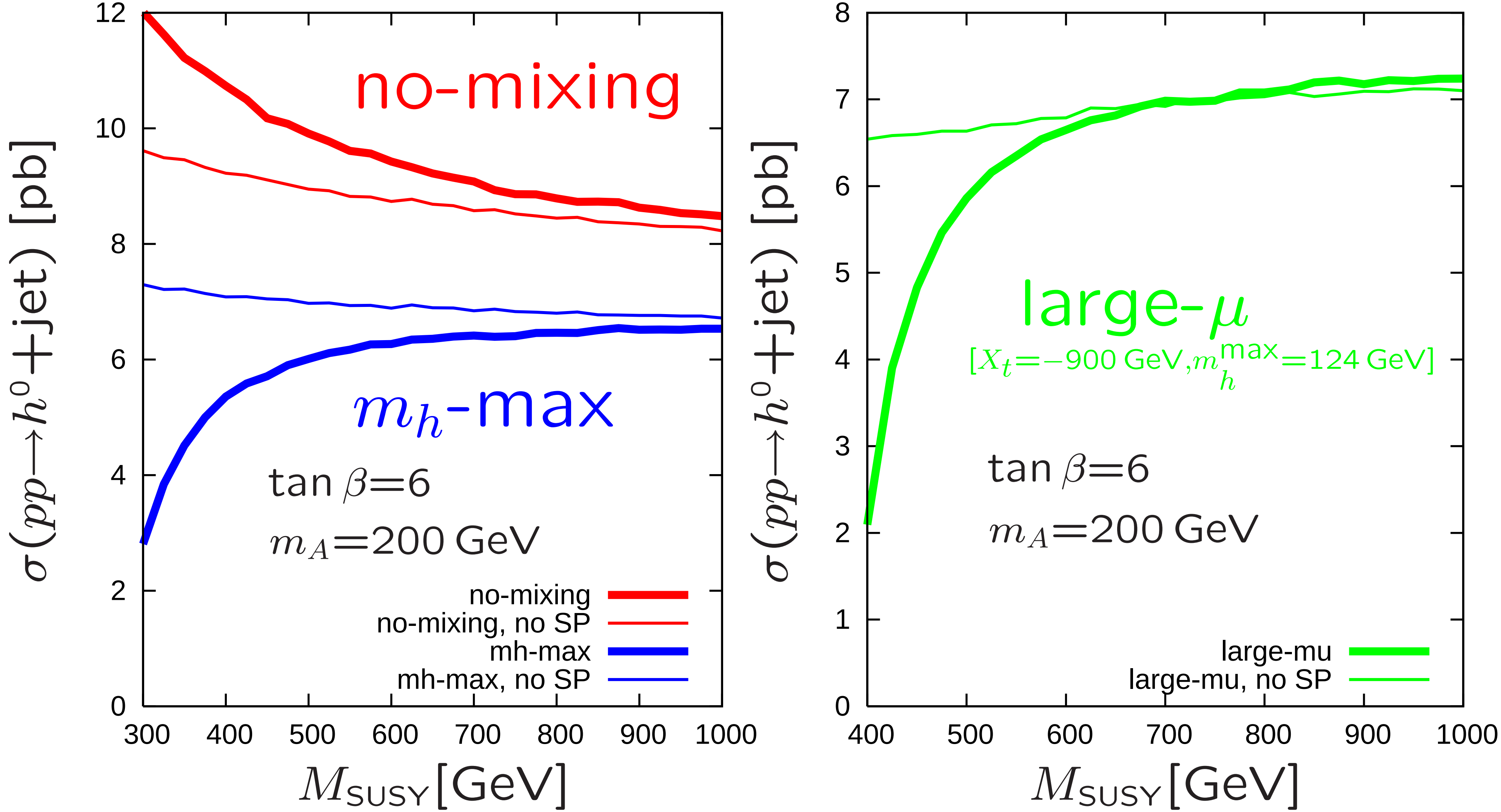
effects on the of the total Higgs + Jet distributions: ($m_H = 120\,\mathrm{GeV}$)
for the Tevatron ($\sqrt{s} = 1.96\,\mathrm{TeV}$):



– MSSM: SUSY-QCD Results* [OBr, Hollik '03 & '07]

* Electroweak LO contributions in the MSSM are currently work in progress.

dependence on squark mass scale M_{SUSY} for three MSSM scenarios:



- HiggsBounds

– What is HiggsBounds? [Bechtle, OBr, Heinemeyer, Weiglein, Williams '08]

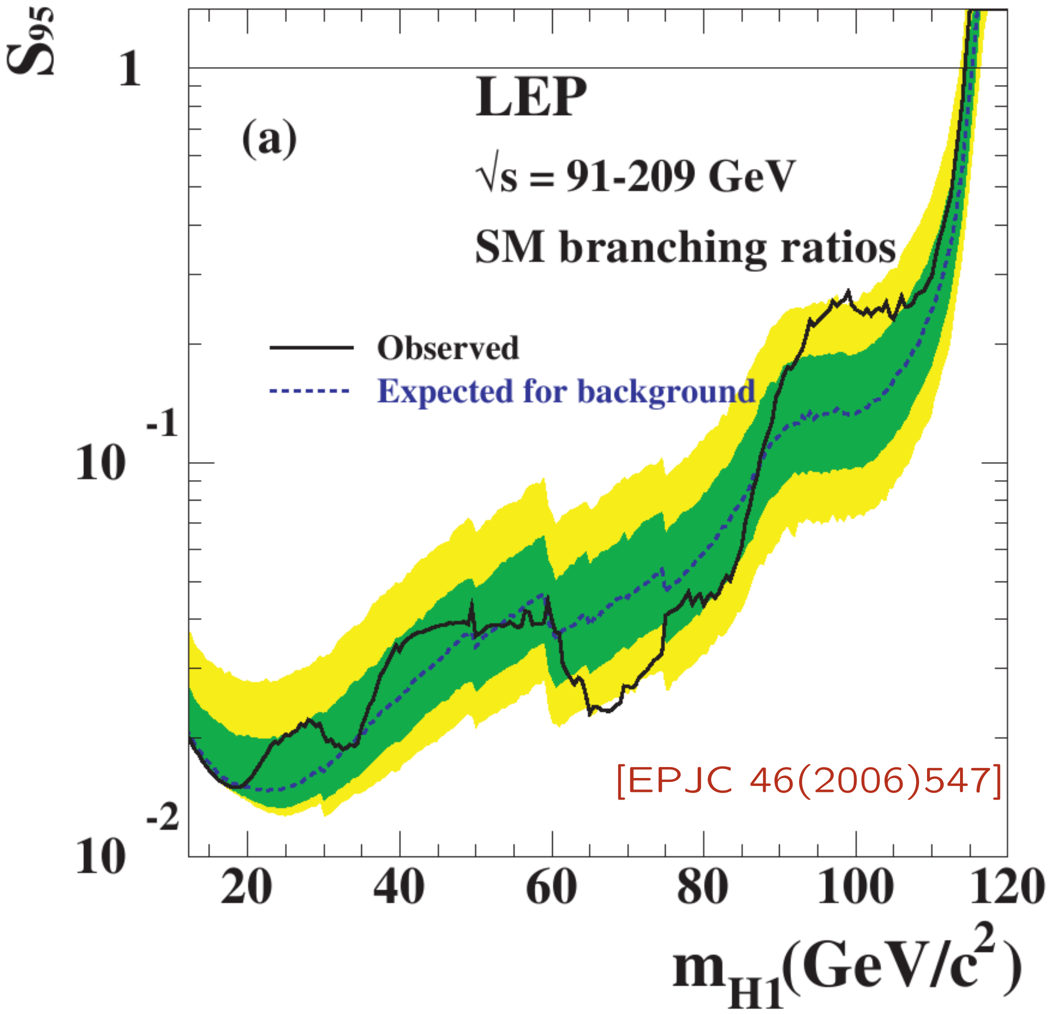
Tool to test models with arbitrary Higgs sectors against exclusion bounds from LEP and the Tevatron.

- Higgs search @ LEP/Tevatron:
  → non-observation of Higgs signals turned into 95% C.L. limits on ...
  a) ... cross sections of 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) ... cross sections of combinations of signal topologies,
  e.g. SM, MSSM combined limits.
  → many individual publications, not convenient to use *all* of them

- HiggsBounds:
  * access to all relevant Higgs exclusion limits in 3 ways: command line, subroutines (Fortran 77/90), web: `www.ippp.dur.ac.uk/HiggsBounds`
  * statistical significance of analyses used (via expected limits)
  * required model input: # of Higgs bosons h_i , m_{h_i}, $\Gamma_{\rm tot}(h_i)$, $\mathrm{BR}(h_i \to \ldots)$, production cross section ratios (wrt reference values)

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

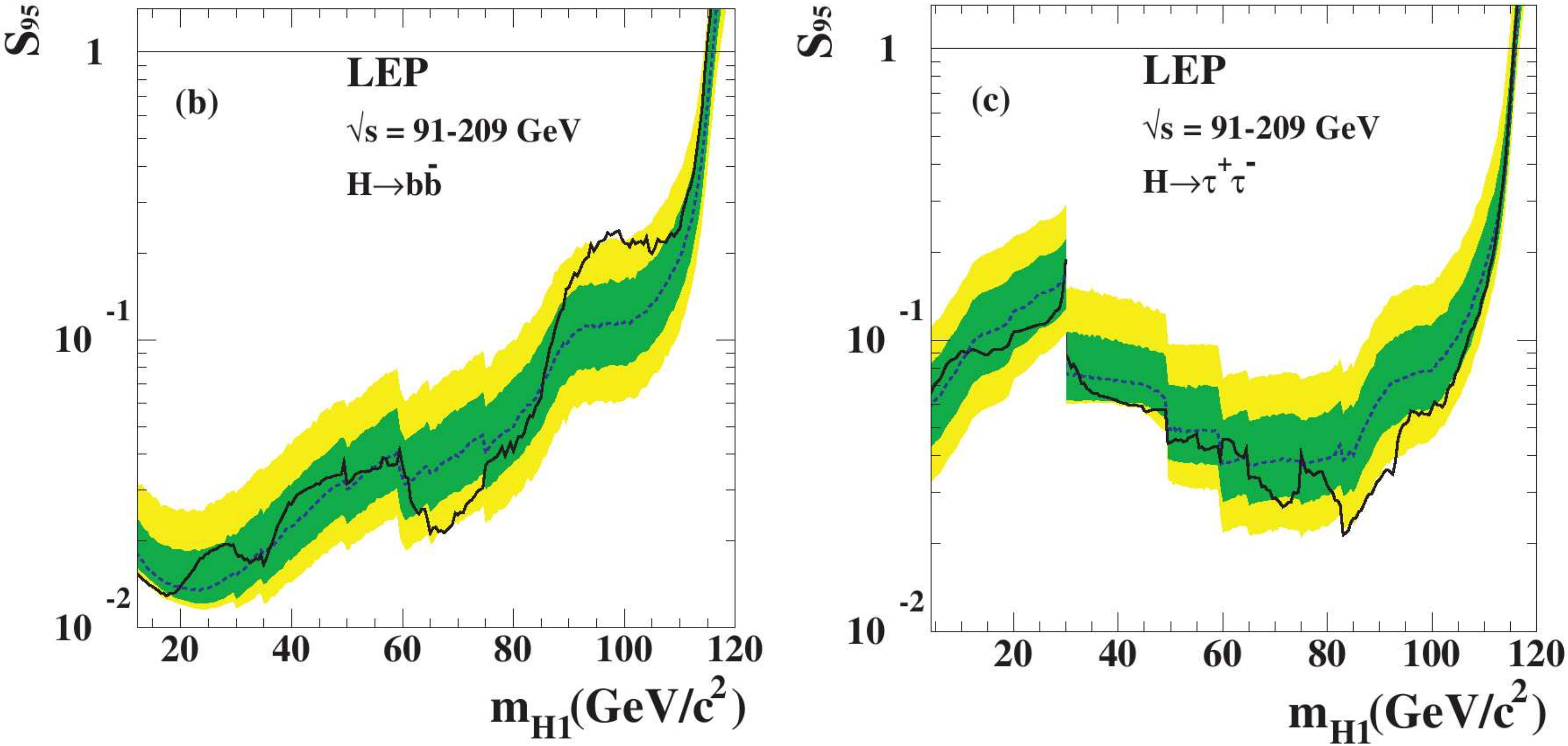
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\text{min}}(m_{H1})$$

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

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

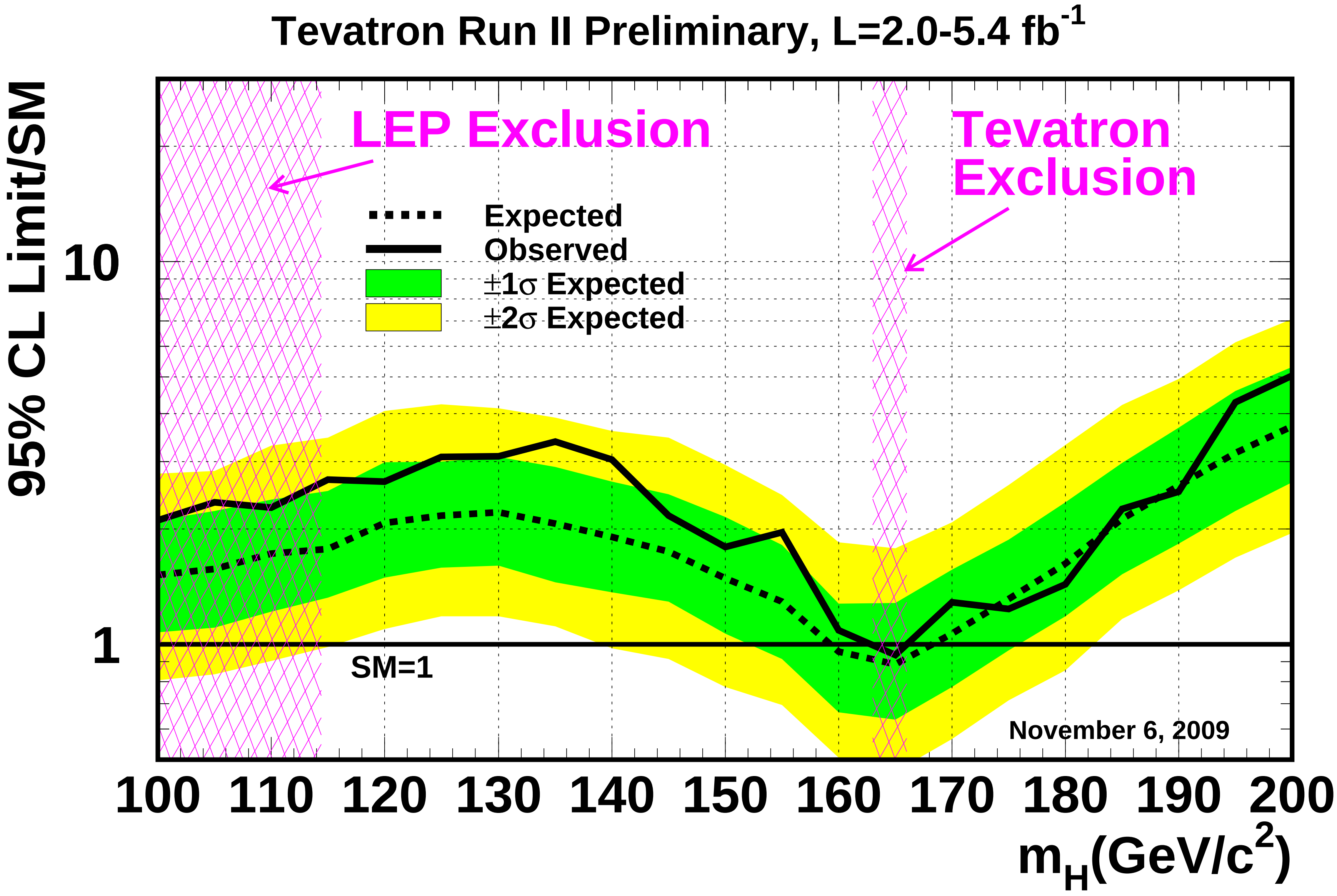
example 2: LEP single topology limits, assuming HZ production and ...

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]



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. $e^+e^- \to (h_k)Z \to$ (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; $e^+e^- \to h_k Z, h_k \to$ hadrons, ...)

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

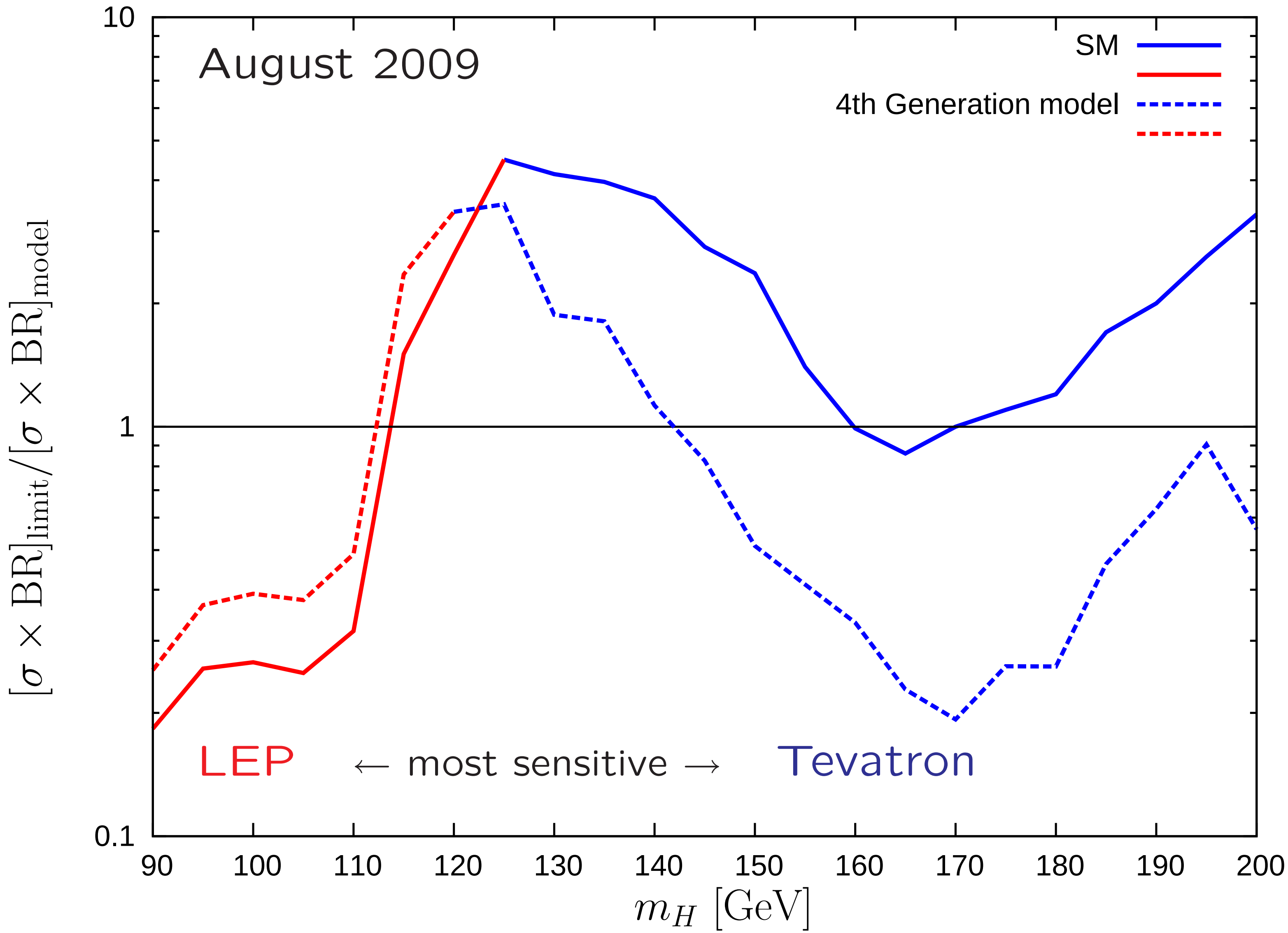
search topology X (analysis)	reference ($\star$=publ.)
$p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{\text{miss.}}$ (CDF with 3.6 [1.0] fb^{-1})	CDF note 9891 [CDF '08]*
$p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{\text{miss.}}$ (DØ with 2.1 [0.93] fb^{-1})	D0 note 5586 [DØ '08]*
$p\bar{p} \to H/HW/HZ/H$ via VBF, $H \to \tau^+\tau^-$ (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.

– Applications

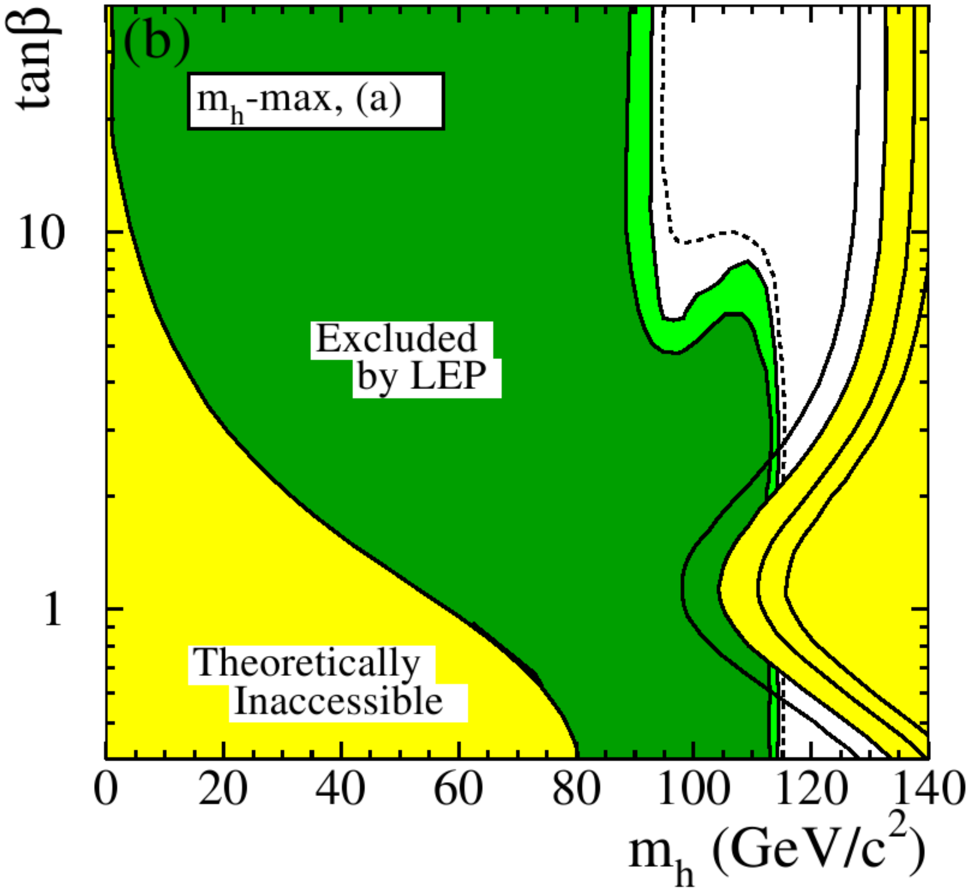
application 1: SM versus Fourth Generation Model exclusion

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

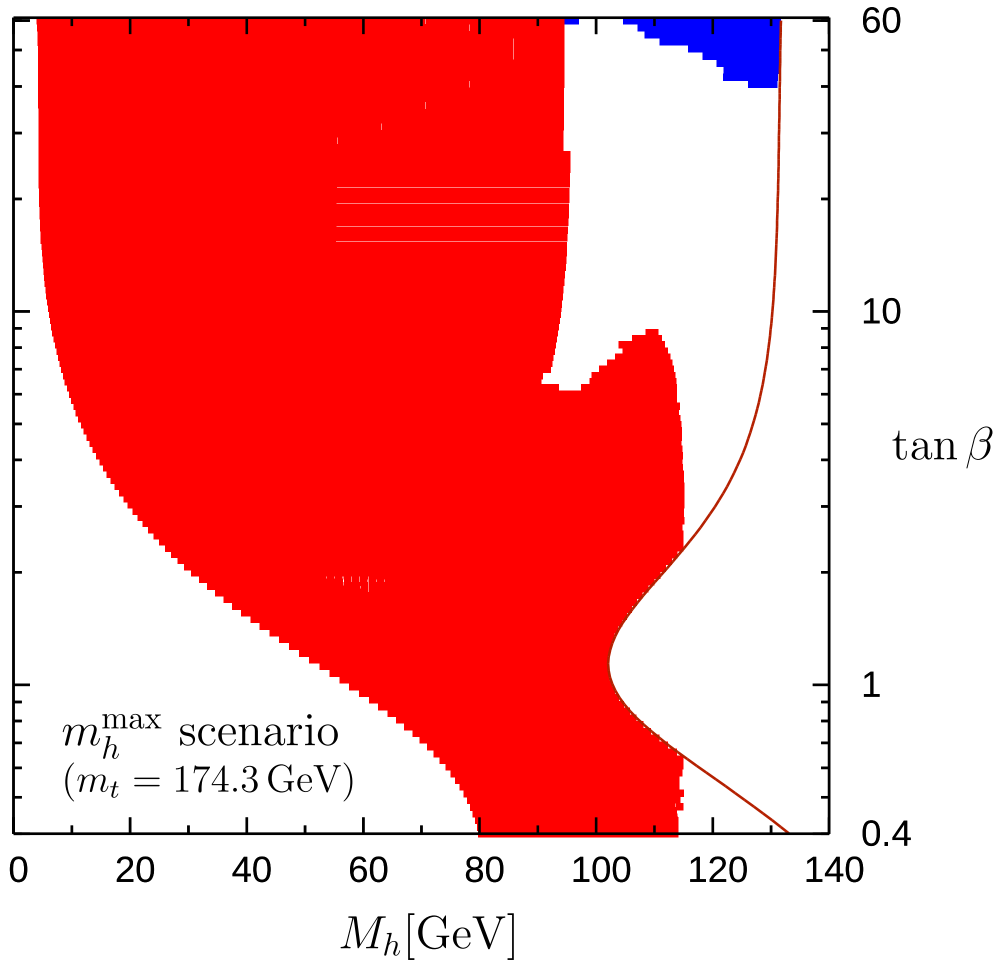


application 2: MSSM benchmark scenarios, exclusion update

a) [EPJC 46(2006)547]

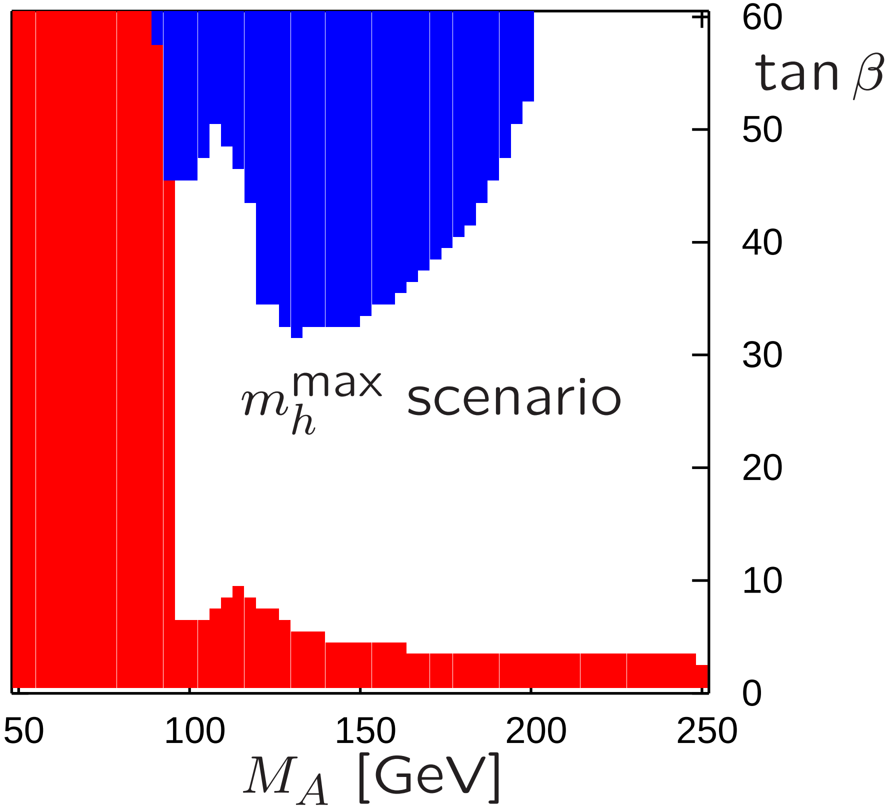


b) HiggsBounds
with: new m_t, impoved m_h prediction, Tevatron data included (■)

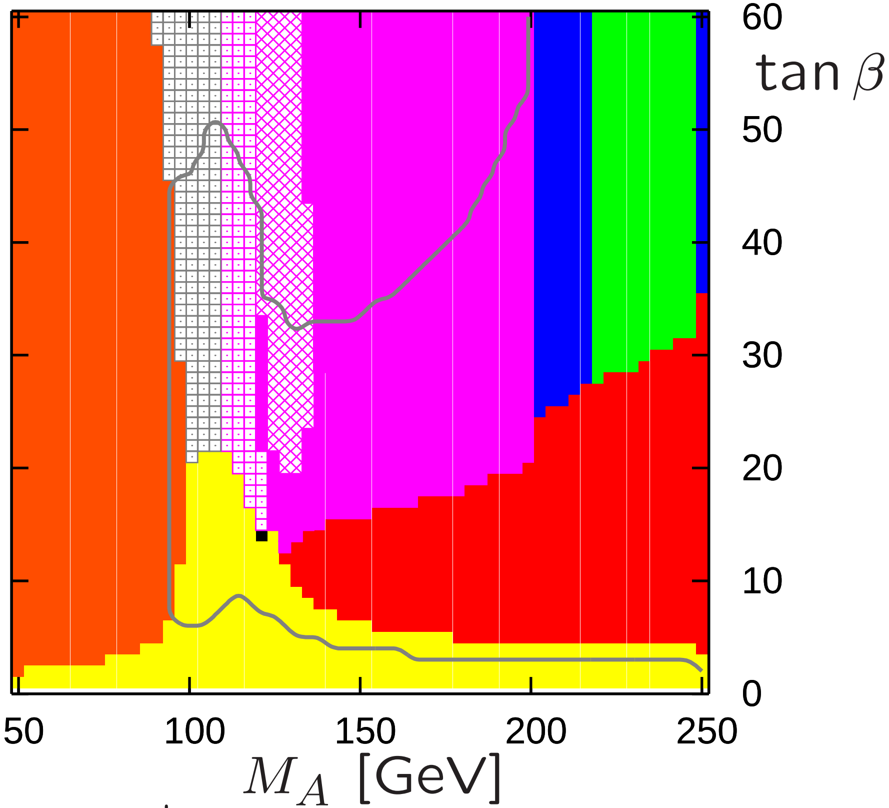


application 2: MSSM benchmark scenarios, exclusion update (August 2009)

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

– There is one graviscalar in 5d: the radion φ

– Higgs – radion mixing via the interaction

$$\mathcal{L} = -\xi\sqrt{-g_{\text{ind}}}\, R(g_{\text{ind}})\, \Phi^{\dagger}\Phi$$

with g_{ind}: induced 4d metric, R: Ricci scalar.

$\longrightarrow$ Radion φ and physical Higgs h mix to form two mass eigenstates

– φ coupling to massive fermions and gauge bosons $\propto$ mass, but

$\star$ $\varphi\, b\bar{b}$ coupling suppressed wrt SM Higgs

$\star$ $\varphi\, gg$ coupling enhanced wrt SM Higgs

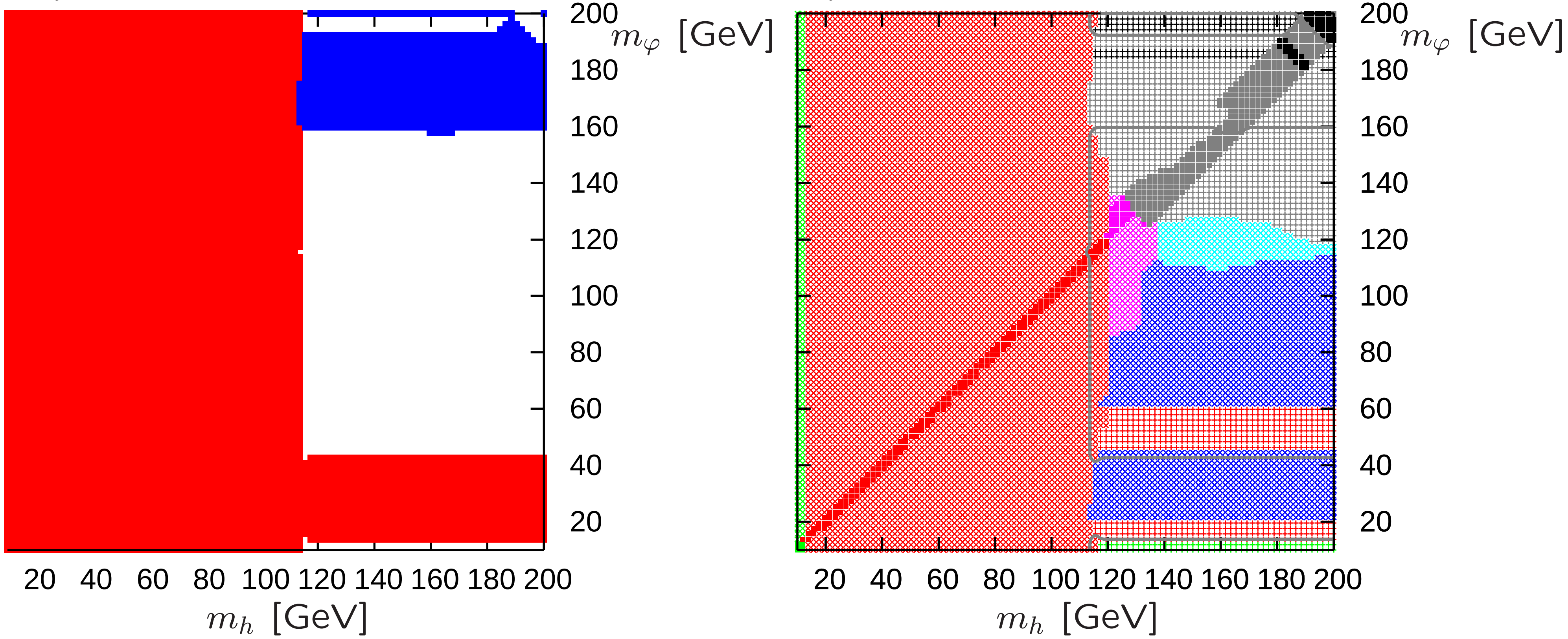
$\star$ $\varphi\, \gamma\gamma$ coupling suppressed wrt SM Higgs

$\longrightarrow$ two scalars in the spectrum with modified couplings compared to the SM Higgs boson

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).

  $\longrightarrow$ `www.ippp.dur.ac.uk/HiggsBounds/`

- 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
  – inclusion of LEP analyses with $H \to$ invis., $H \to$ hadrons, 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.

- 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

– Higgs + Jet: Numerical Results, Tevatron

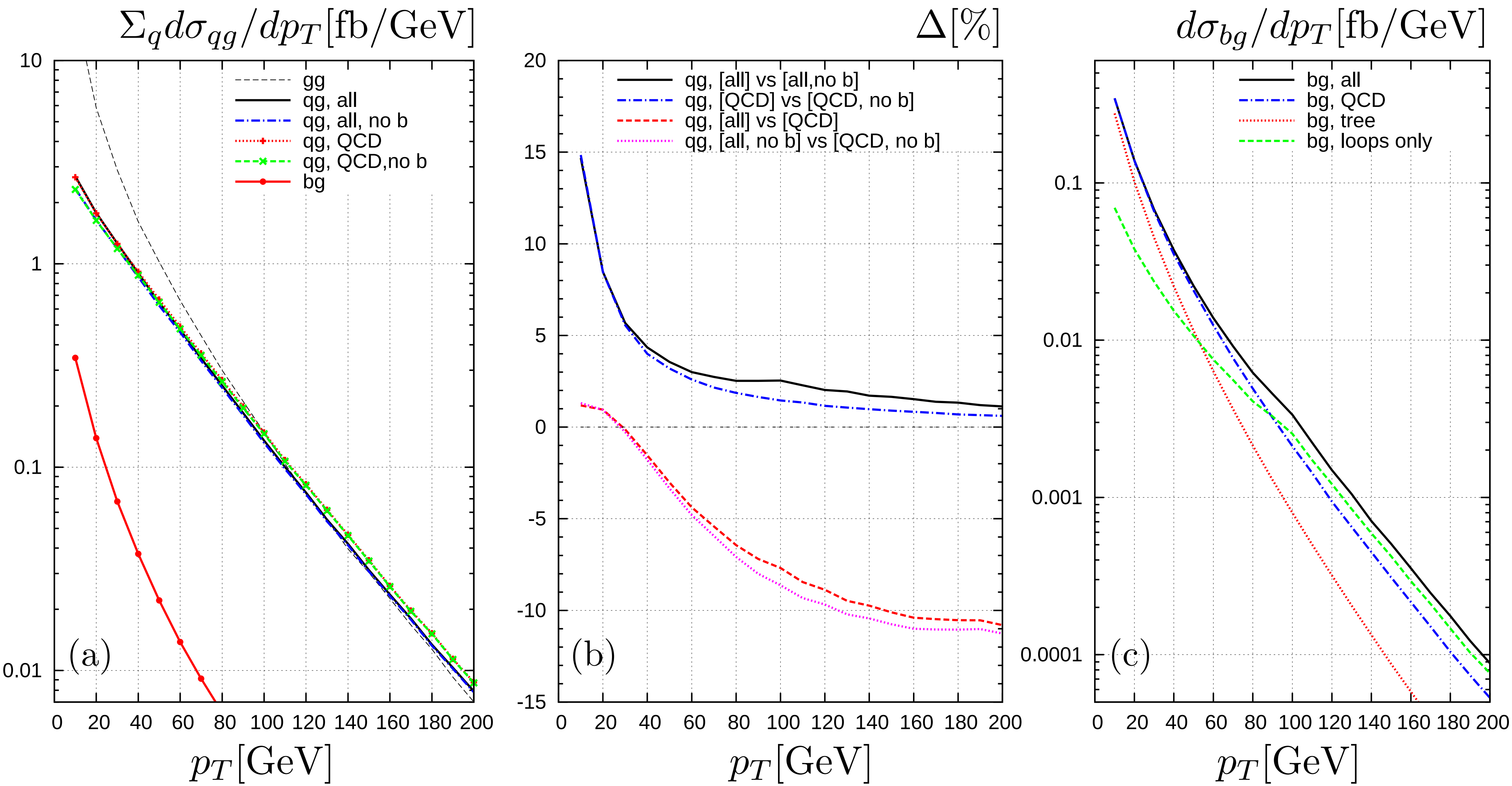
– Higgs + Jet: Numerical Results, Tevatron

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

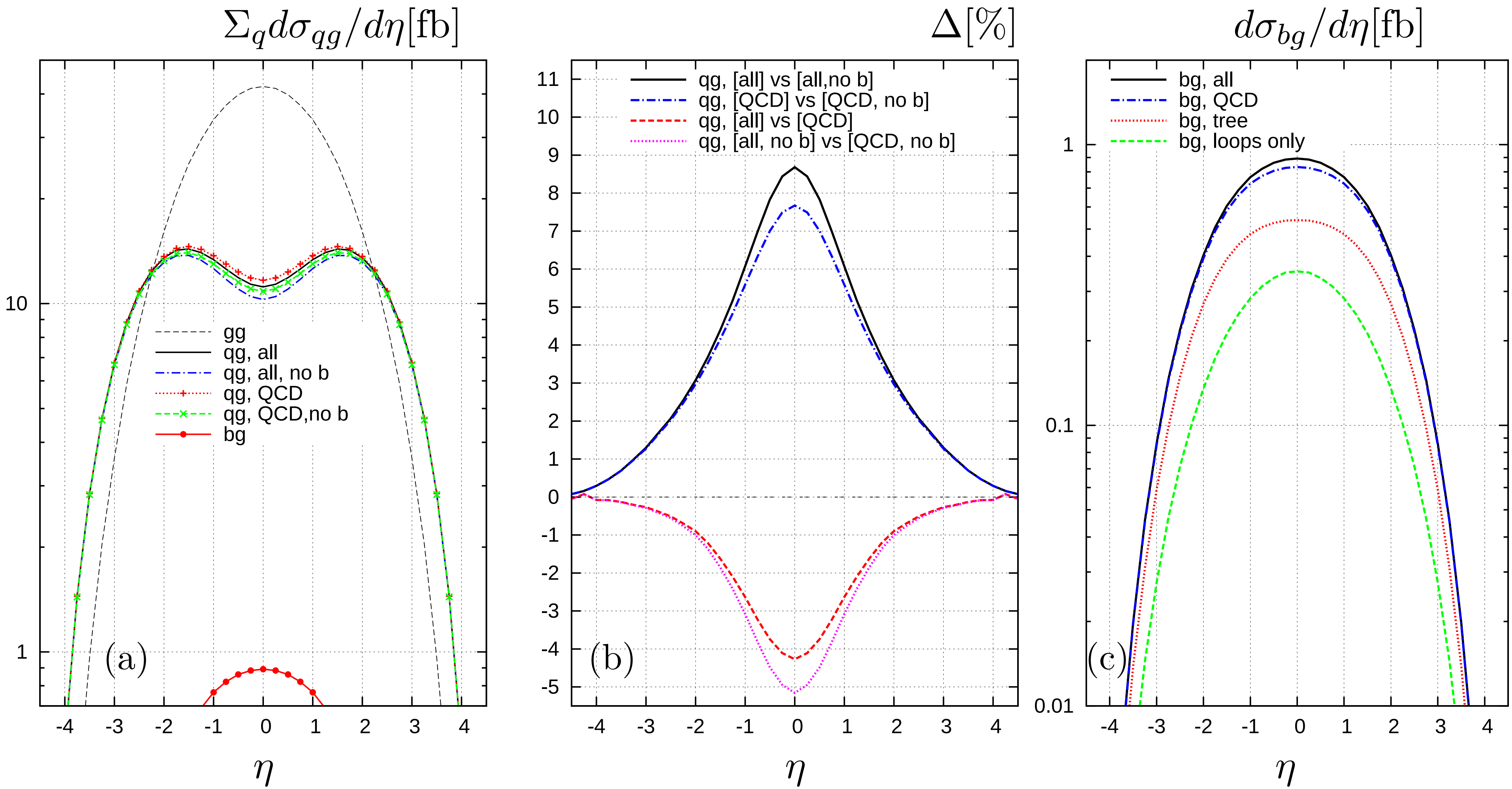
$$\frac{d\sigma(S,p_{T,\text{jet}})}{dp_{T,\text{jet}}}, \;\; |\eta_{\text{jet}}| < 2.5$$

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

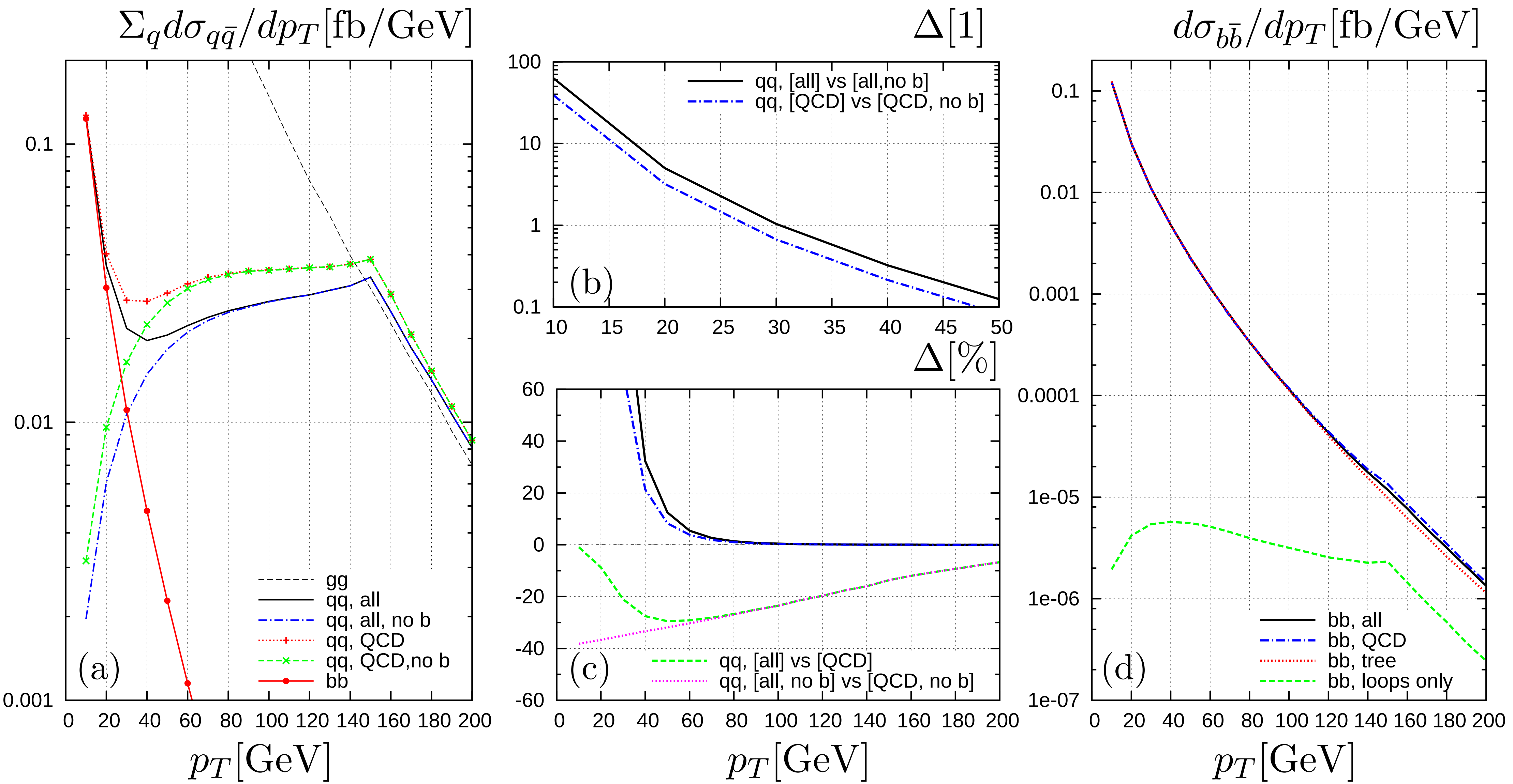
$p_{T,\text{jet}}$ distribution : quark–gluon scattering ($m_H = 120\,\text{GeV}$)



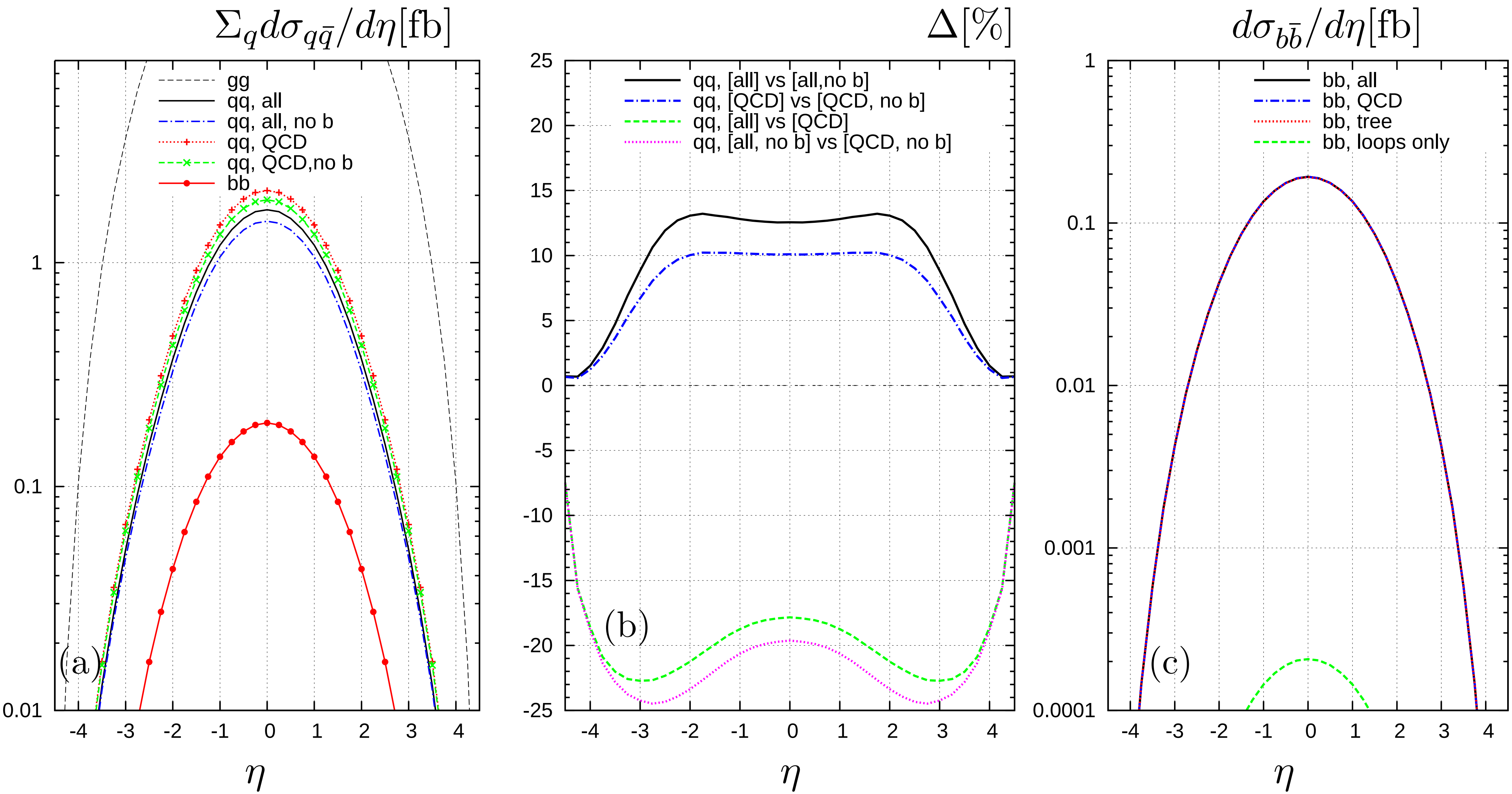
$\eta_{\rm jet}$ distribution : quark–gluon scattering ($m_H = 120\,$GeV)



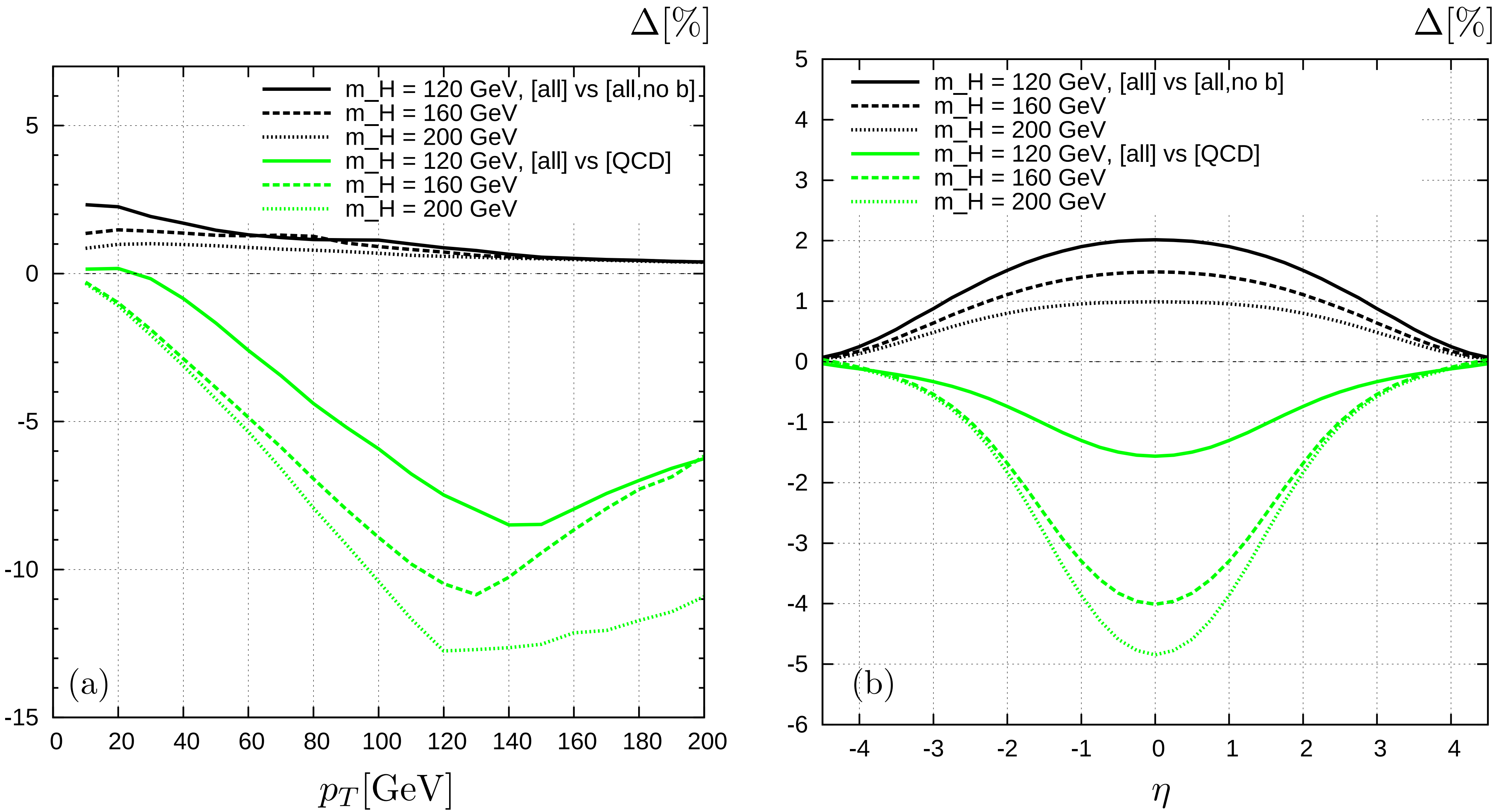
$p_{T,\mathrm{jet}}$ distribution : $q\bar{q}$ annihilation ($m_H = 120\,\mathrm{GeV}$)



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



effects on the of the total Higgs + Jet distributions: ($m_H = 120$ GeV)



– 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

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

$\longrightarrow$ 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

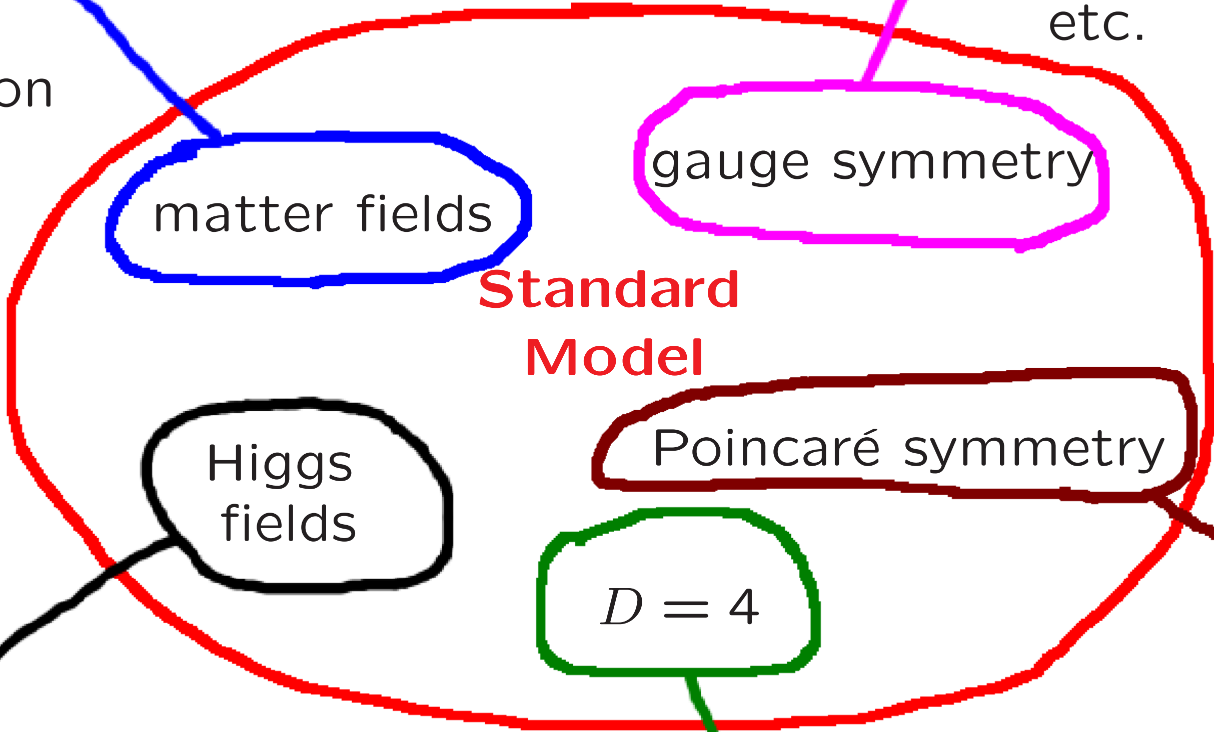
- ⋆ GUT
- ⋆ Technicolor
- ⋆ Little Higgs models
- ⋆ Z' models

etc.

extra matter fields

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

etc.



supersymmetry

- ⋆ MSSM
- ⋆ NMSSM,...

etc.

change/extra multiplets

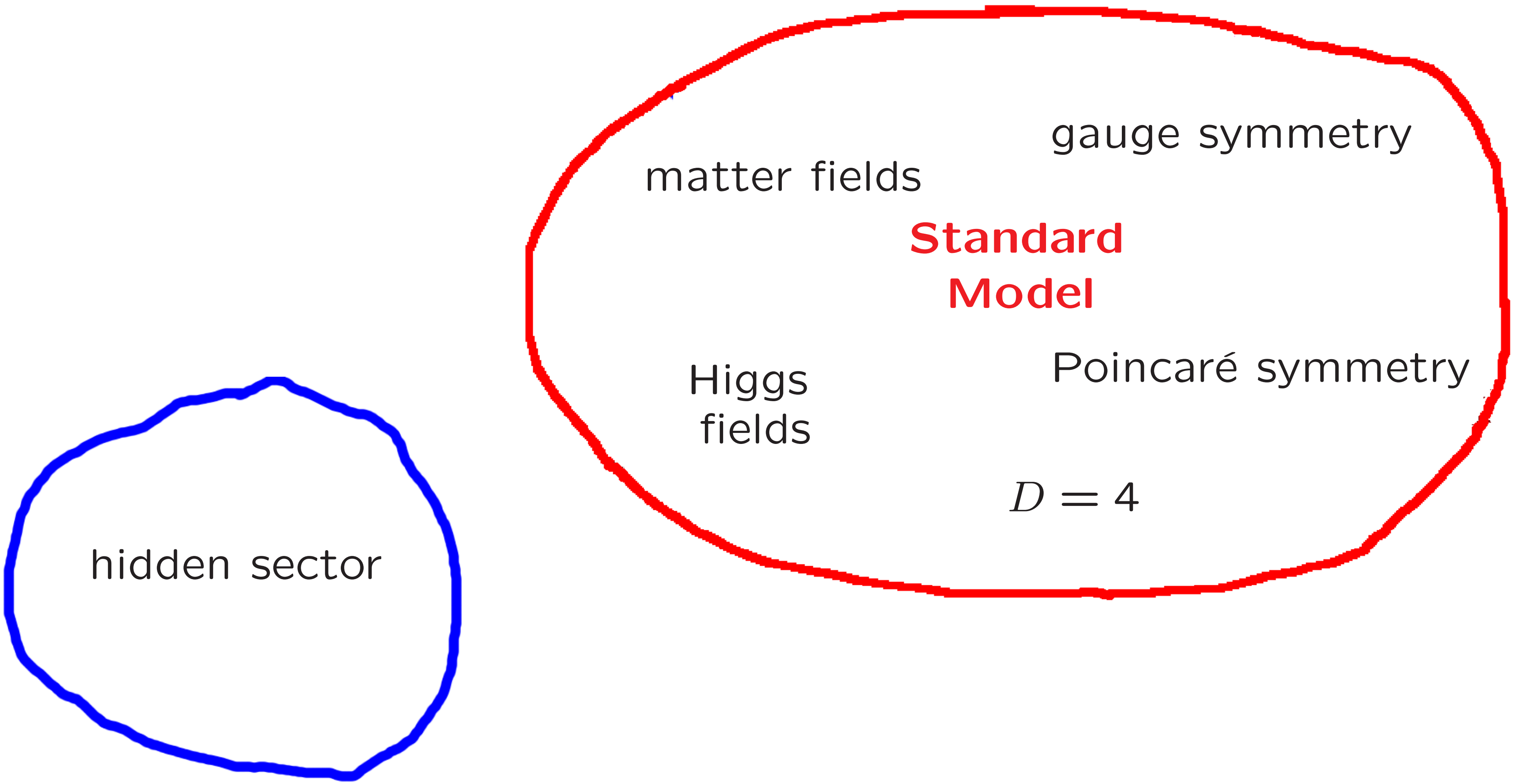
- ⋆ SUSY
- ⋆ Little Higgs
- ⋆ Higgs triplet models

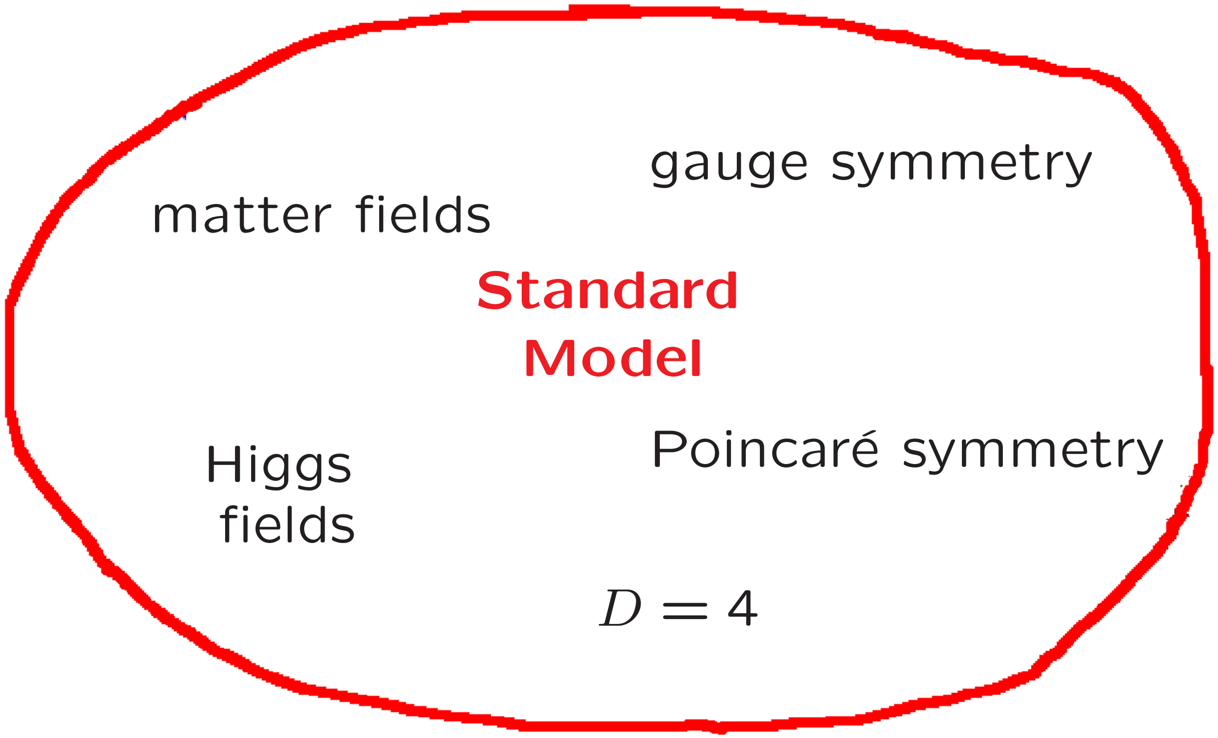
etc.

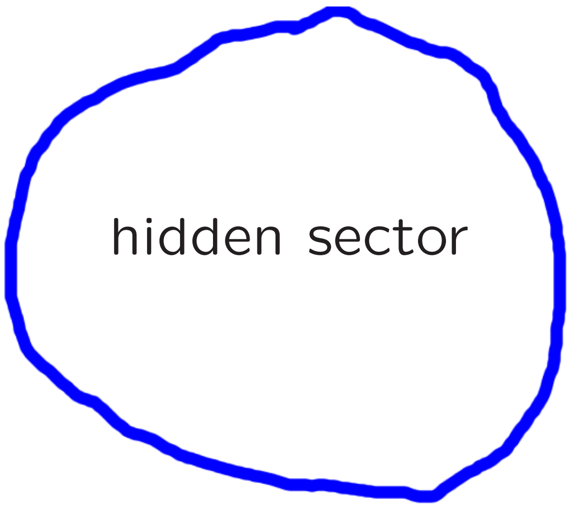
extra dimensions

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