Higgs Bosons and Other New Phenomena

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

outline :

- Electroweak Interaction, Higgs Bosons & beyond
  - The Origin of the Electroweak Interaction
  - The Higgs Boson: What is it good for?
  - How to find Higgs Bosons?
  - What else to expect at the LHC?
- Selected Projects
  - SM Higgsstrahlung (NNLO QCD)
  - HiggsBounds
  - Randall-Sundrum scalar sector constrained
  - New physics in $\gamma\gamma/WW/ZZ$ production

- Electroweak Interaction, Higgs Bosons & beyond

– The Origin of the Electroweak Interaction

■ Beta decay 1911:

Hahn, Meitner: observation : $n \to p\, e^-$ + missing energy

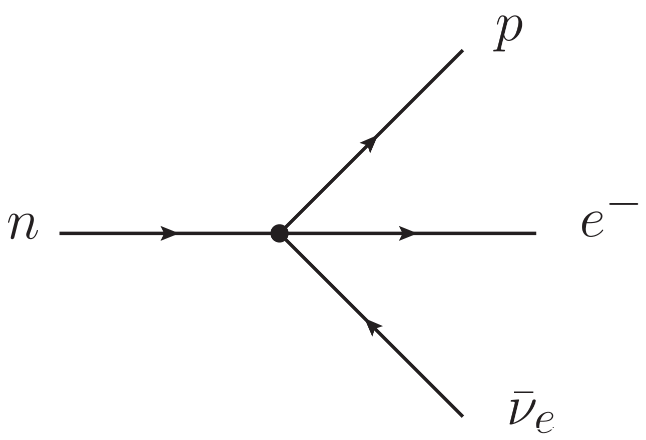
Puzzle:

- continuous energy spectrum of electrons observed
- discrete spectrum expected (energy difference between n and p state)

Bohr: energy is *really* missing   Pauli (1930): $n \to p\, e^-$ + neutrino

(very weakly interacting)

Fermi (1934): “Fermi Model”



- short-range interaction
- good description for energies well below $G_F^{-1/2} \approx 300\,\mathrm{GeV}$ or equivalently length scales well above $\approx 10^{-18} m$ [$=$ 0.001 × size of atomic nuclei].
- but: bad high energy behaviour

– The Origin of the Electroweak Interaction

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Fermi (1934): "Fermi Model" : improvements

Lee, Yang, Wu (1957): Parity violation in weak interactions

Marshak, Sudarshan (1957) [Feynman, Gell-Mann]: $V - A$ theory

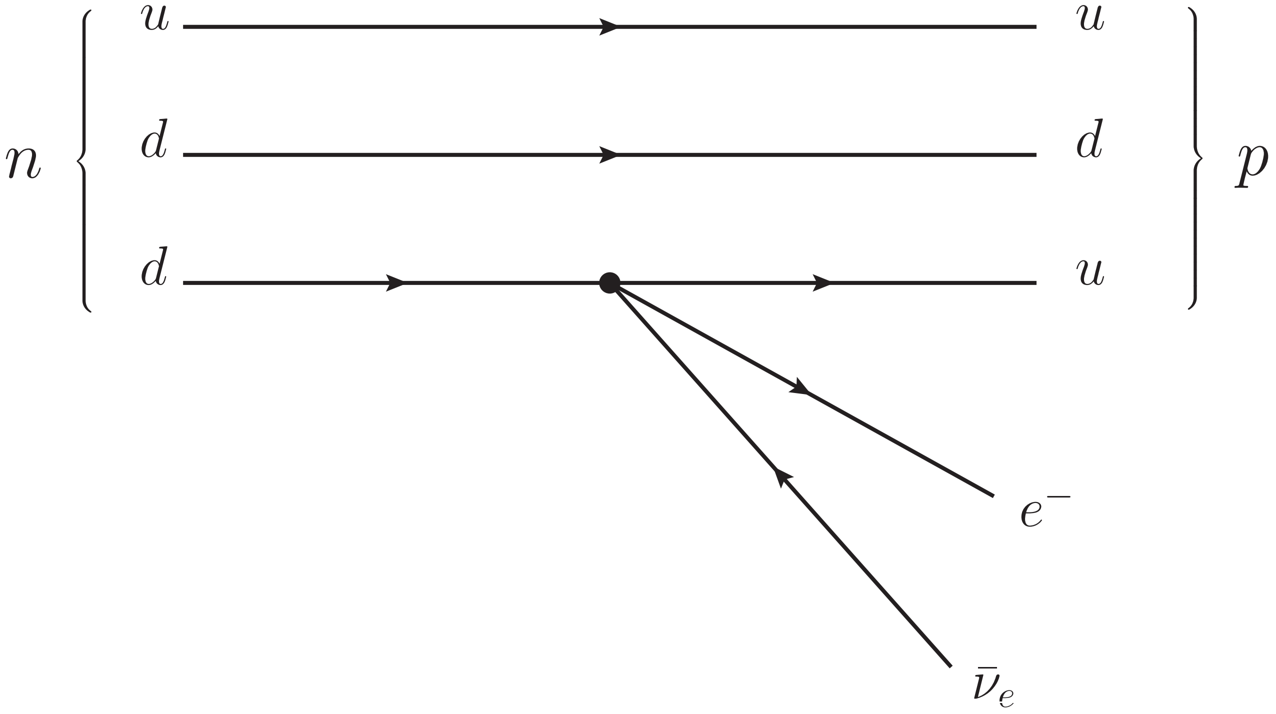
$$\mathcal{L} \propto G_F[\bar\psi_A \underbrace{(\gamma_\mu - \gamma_\mu\gamma_5)}_{V-A} \psi_B][\bar\psi_C \underbrace{(\gamma^\mu - \gamma^\mu\gamma_5)}_{V-A} \psi_D]$$

$$\propto G_F[\bar\psi_A\gamma_\mu P_L\psi_B][\bar\psi_C\gamma^\mu P_L\psi_D] \text{ with } P_L = \frac{1}{2}(1-\gamma_5)$$

- short-range interaction of left-chiral components

■ Beta decay: current understanding:

Quark parton model [Bjorken, Paschos; Feynman 1969]



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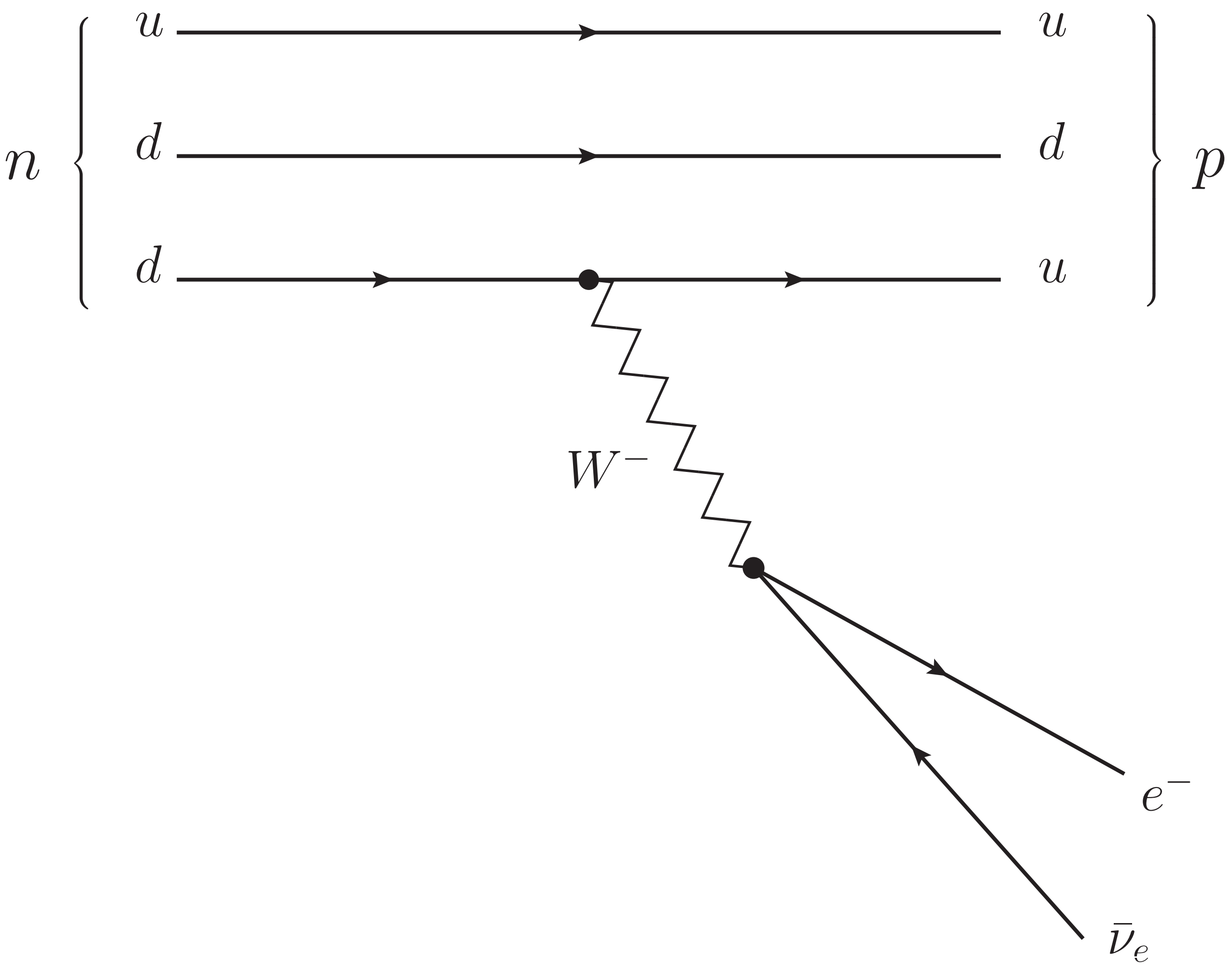

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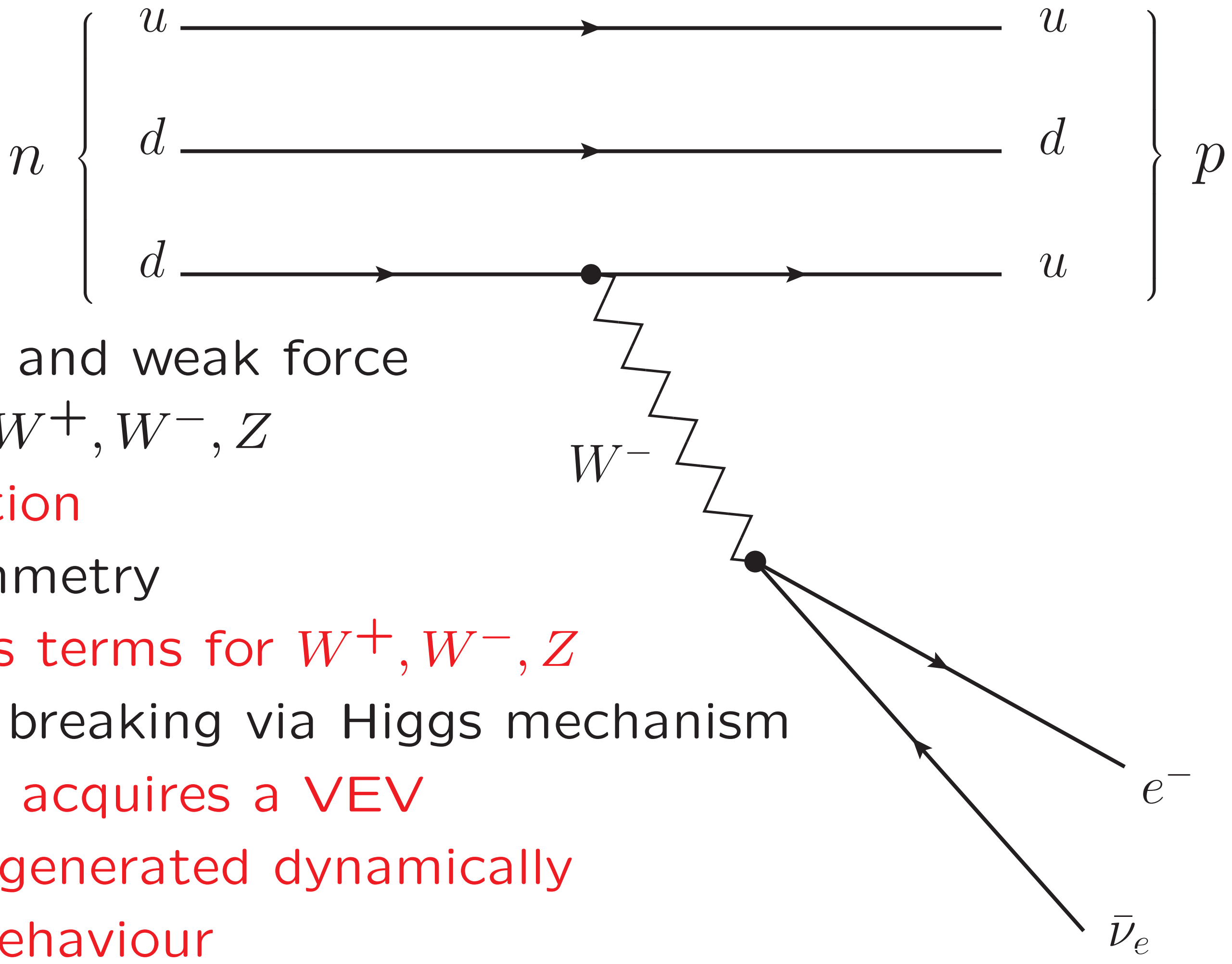

- unification of electrom. and weak force
- massive vector bosons W^+, W^-, Z
  - → short range interaction
- SU(2)×U(1) gauge symmetry
  - → forbids explicit mass terms for W^+, W^-, Z
- spontaneous symmetry breaking via Higgs mechanism
  - → one scalar multiplet acquires a VEV
  - → W^+, W^-, Z masses generated dynamically
  - → good high energy behaviour
  - → theory applicable above 300 GeV ($< 10^{-18} m$)

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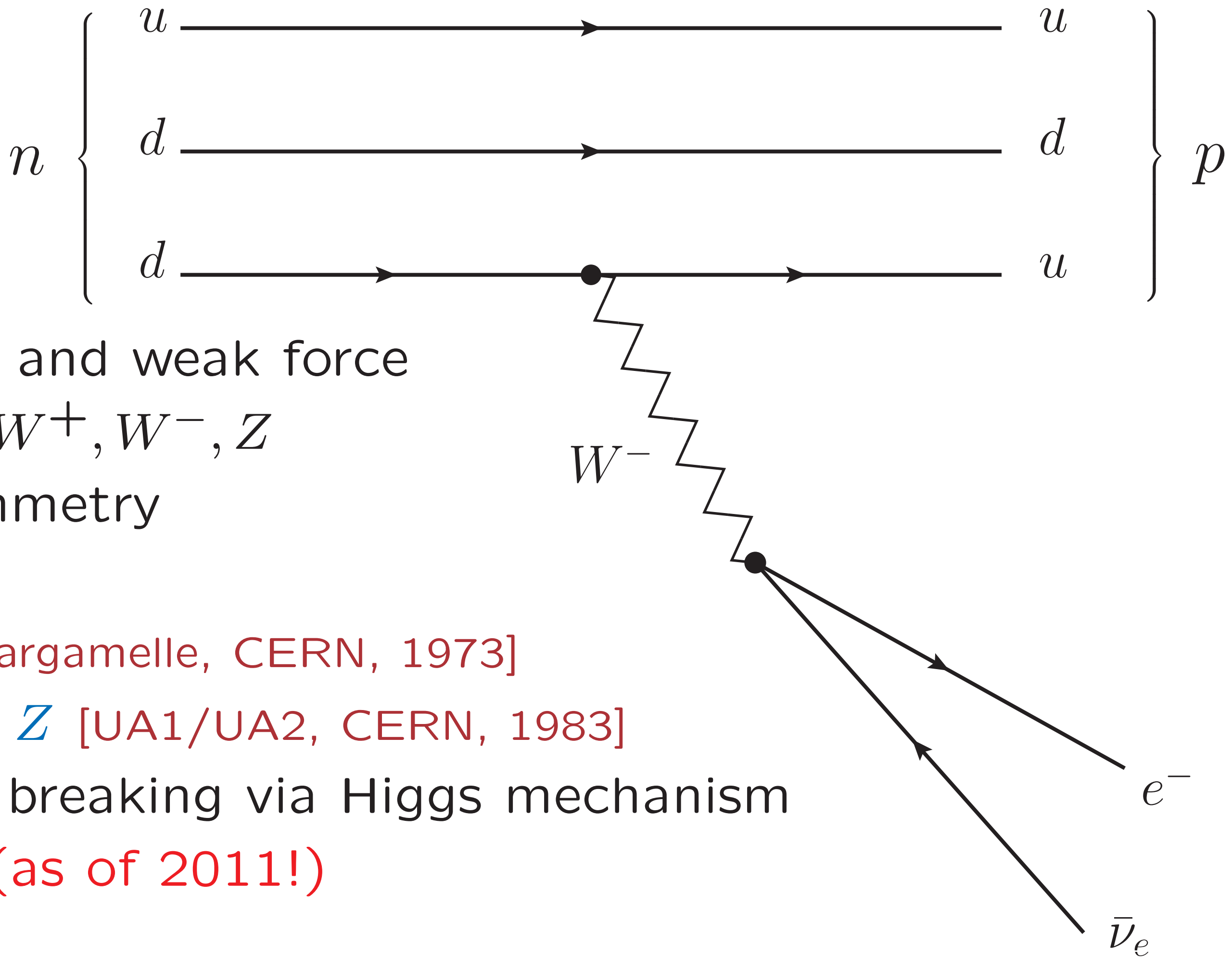
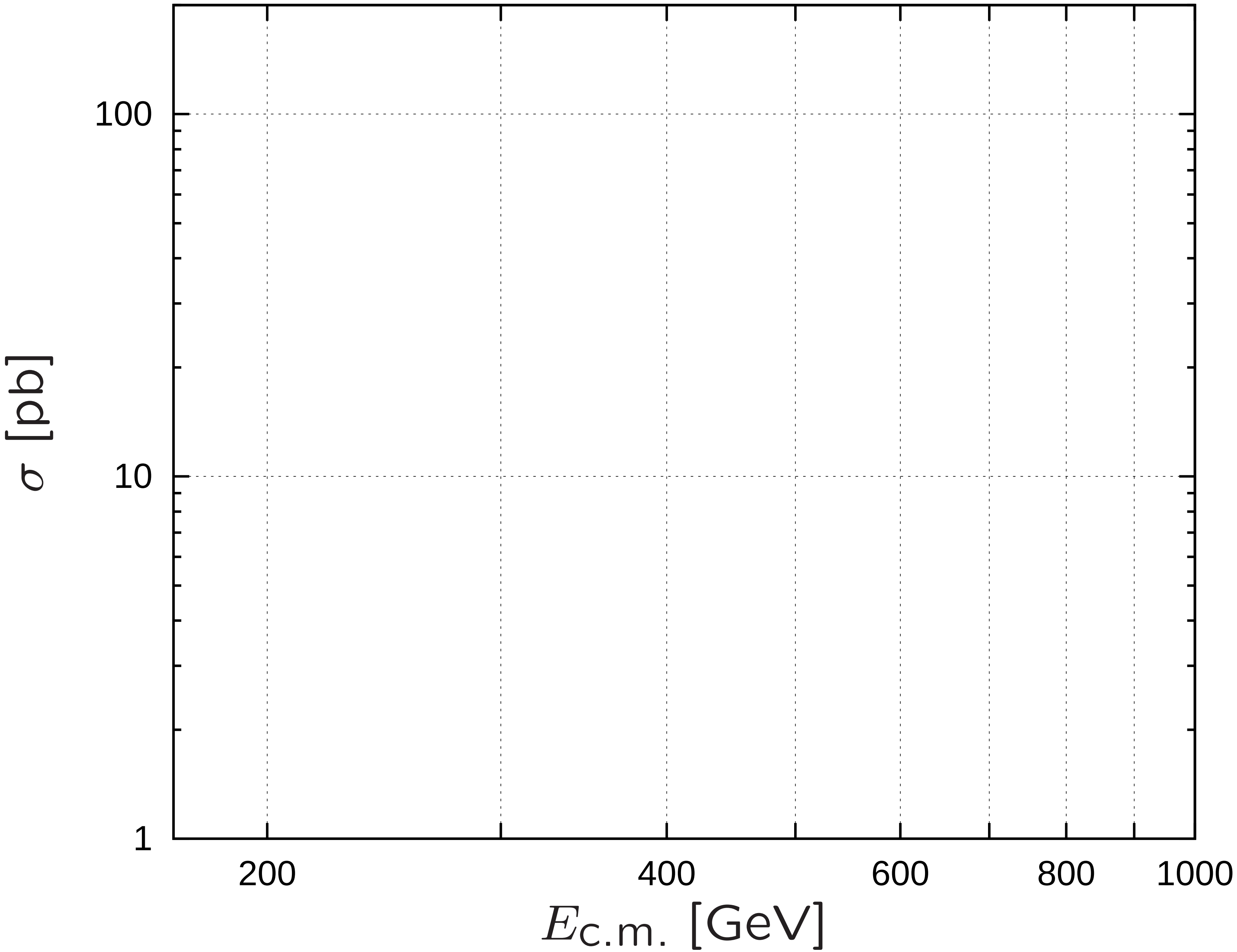
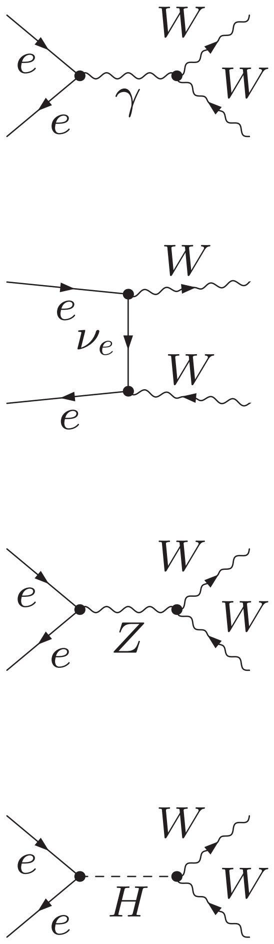


- unification of electrom. and weak force
- massive vector bosons W^+, W^-, Z
- SU(2)×U(1) gauge symmetry
  → confirmations:
  Neutral Currents [Gargamelle, CERN, 1973]
  discovery of W and Z [UA1/UA2, CERN, 1983]
- spontaneous symmetry breaking via Higgs mechanism
  → still open question (as of 2011!)

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





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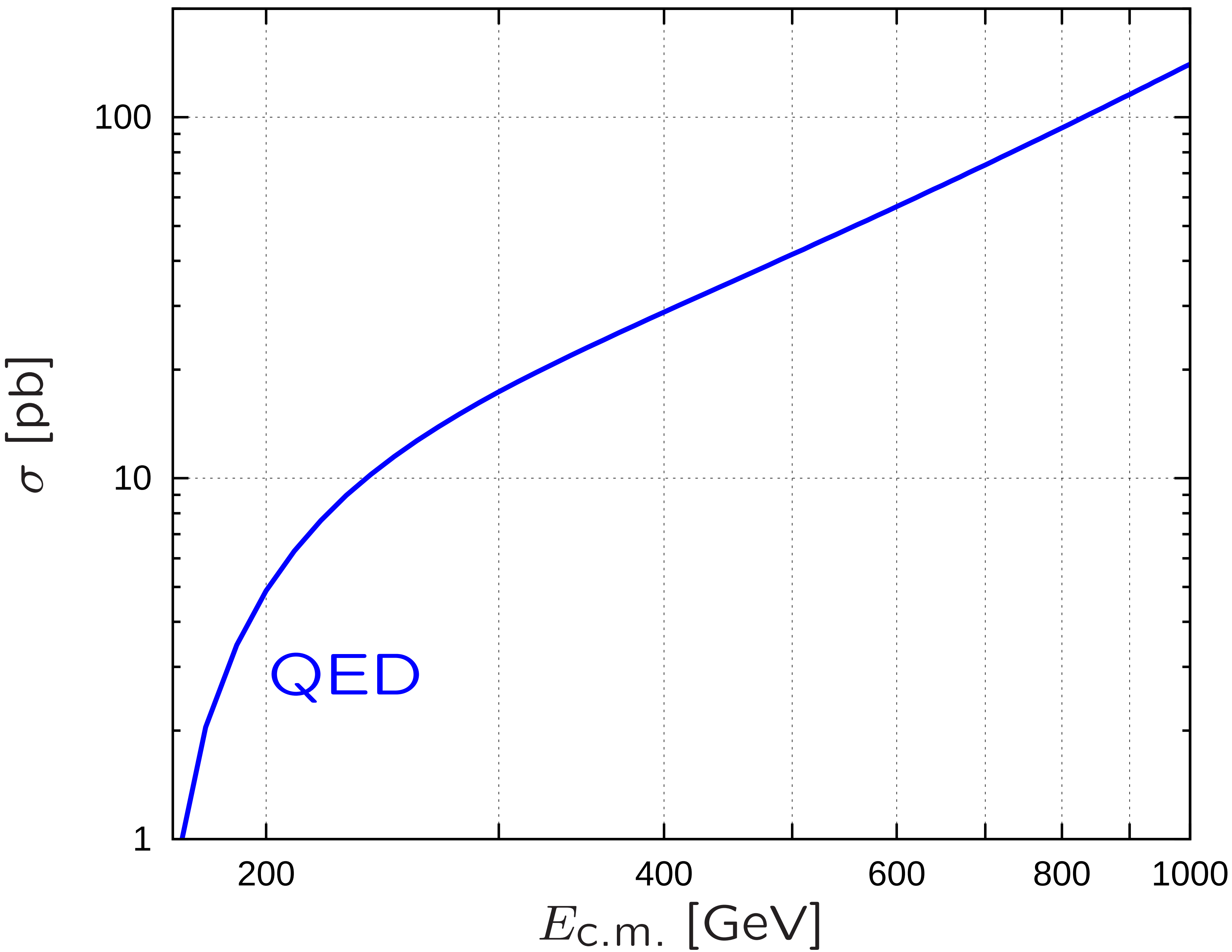

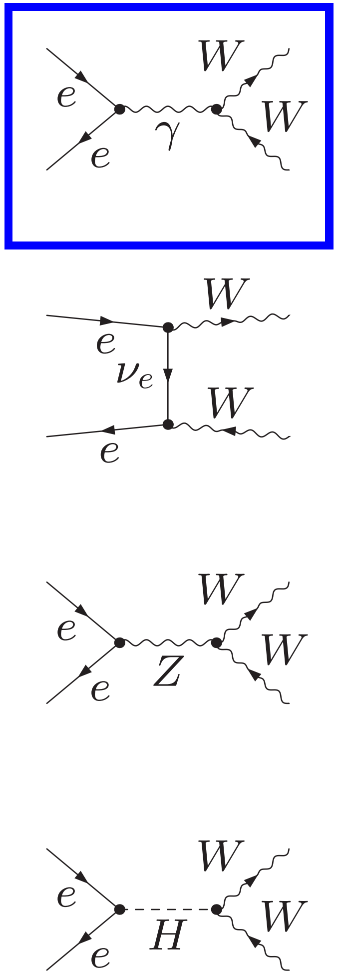

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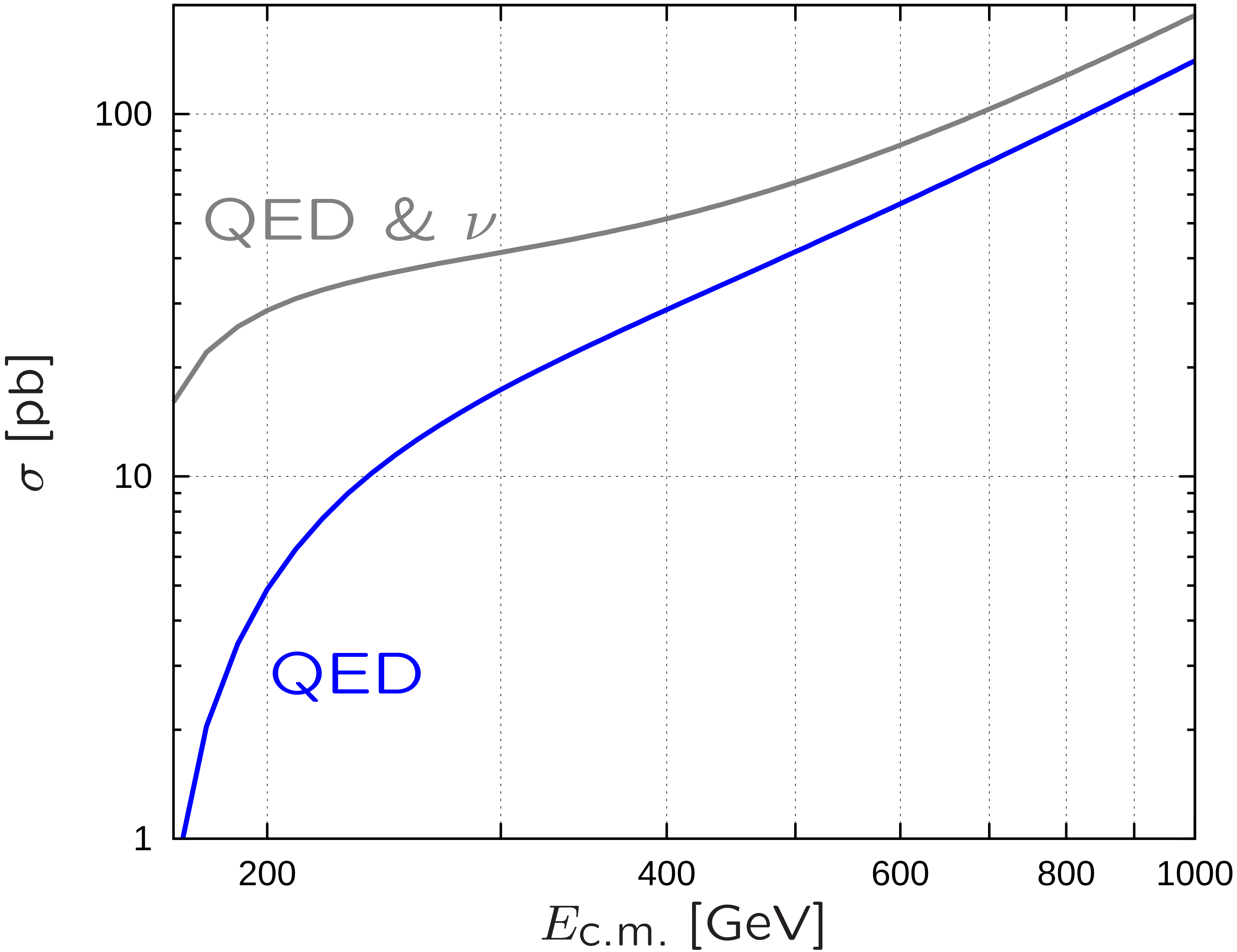

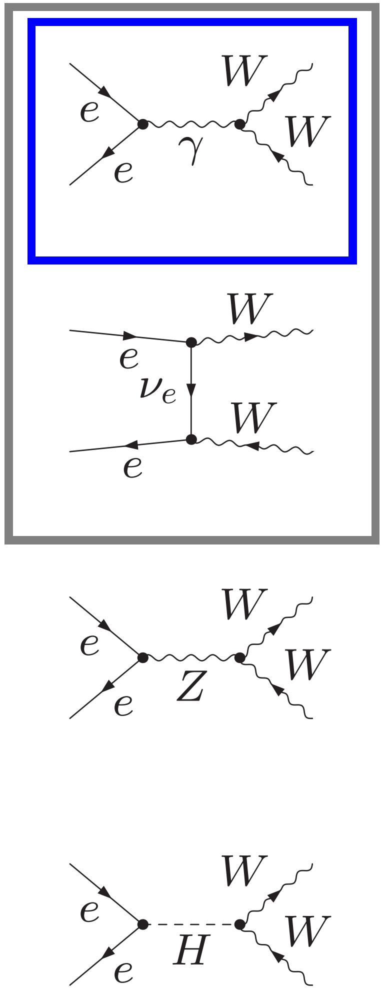

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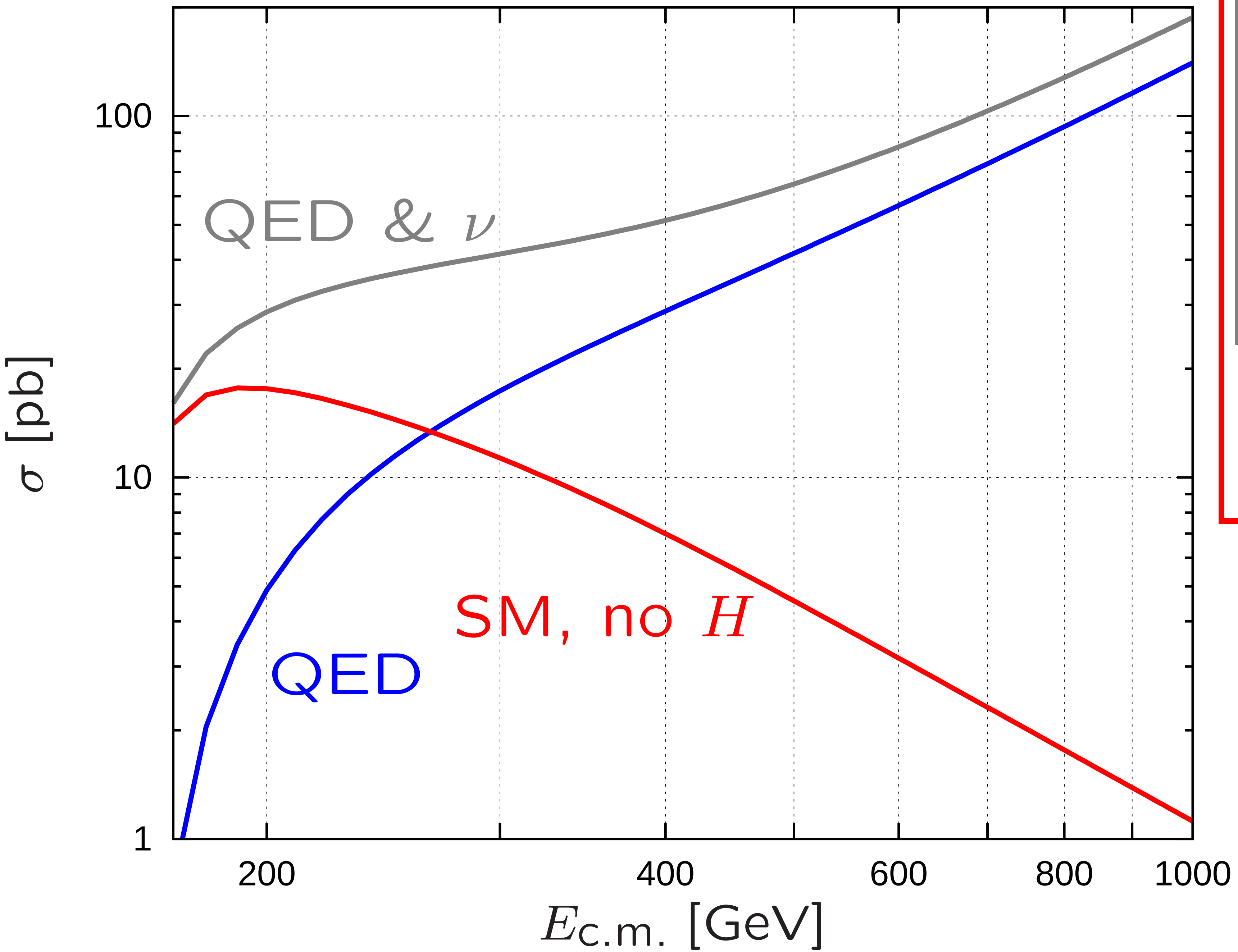

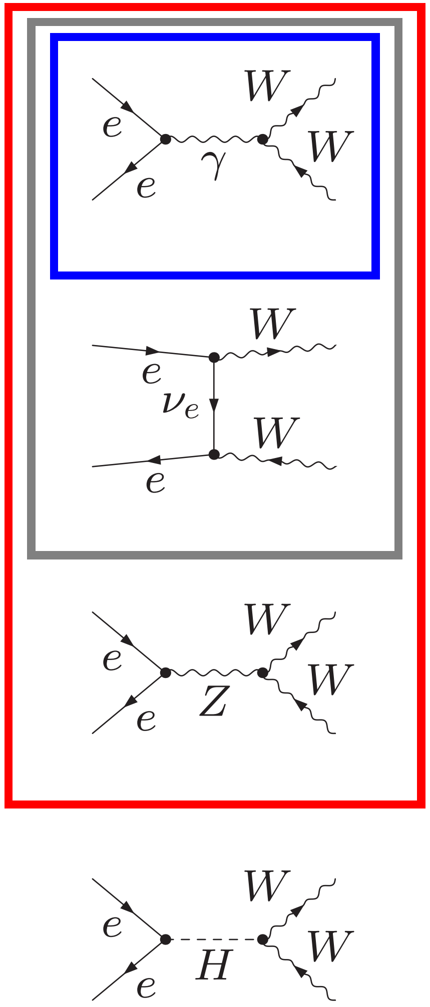

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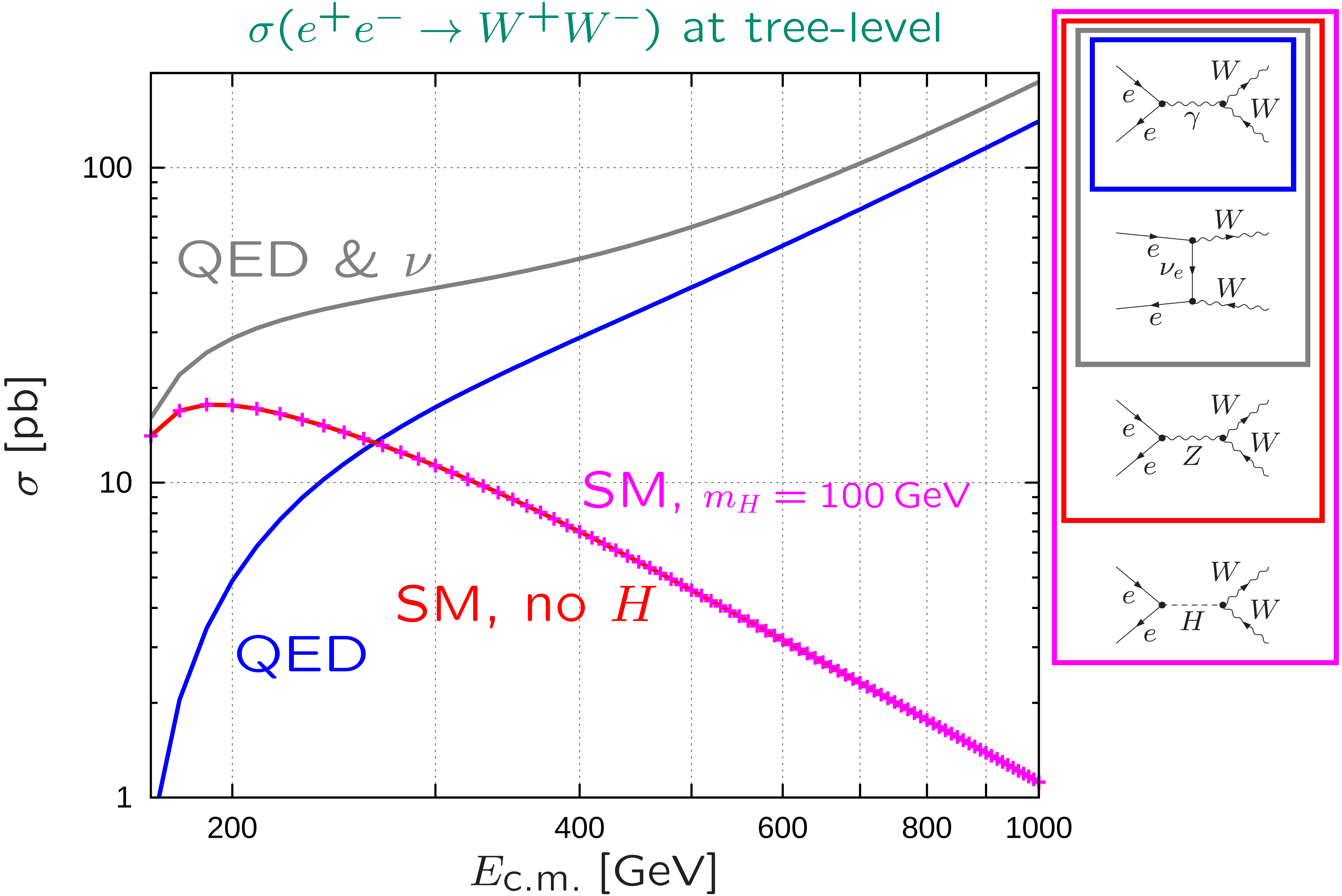
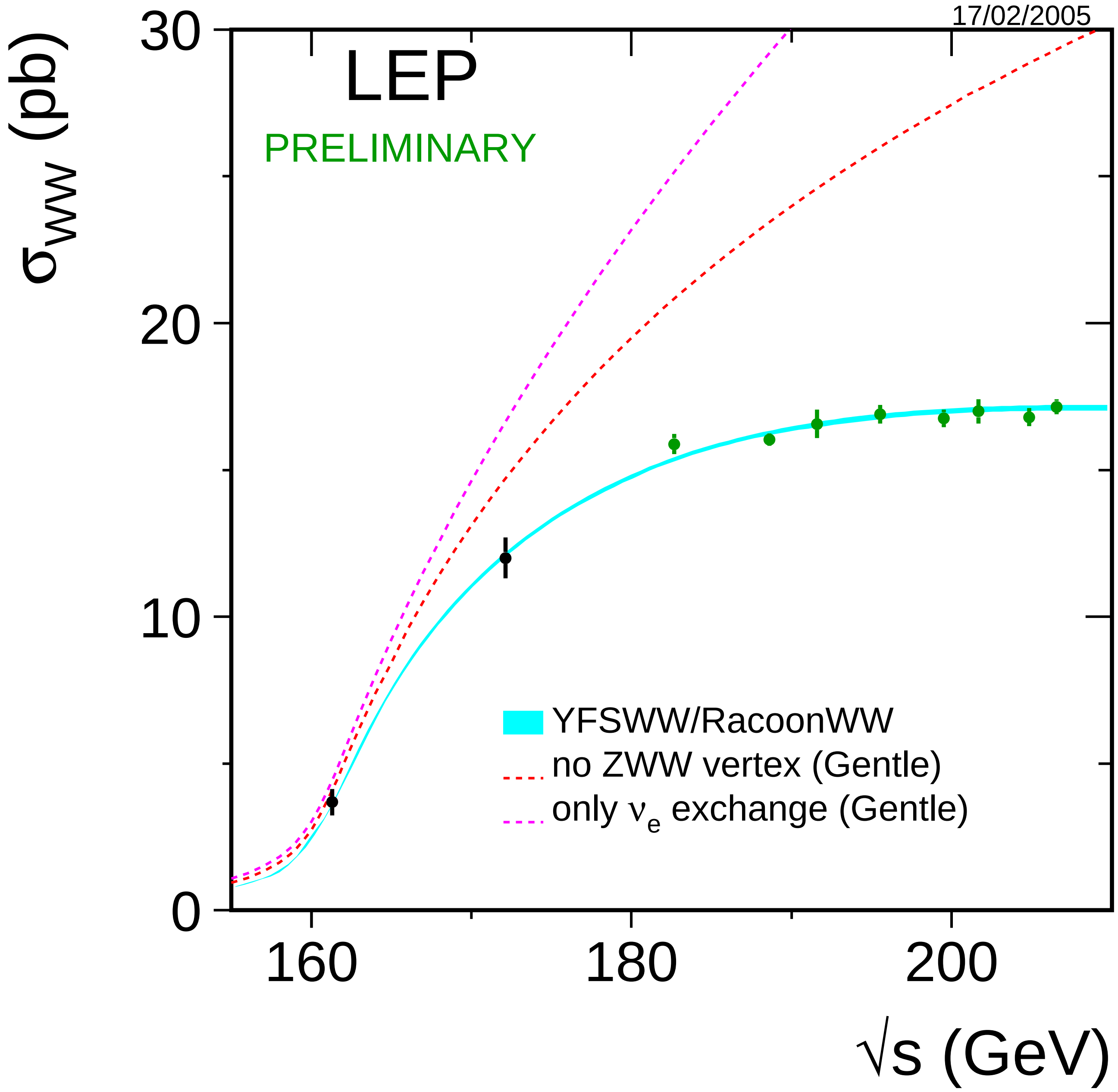


measurement of $\sigma(e^+e^- \to W^+W^-)$ at LEP 2:



– The Higgs Boson: What is it good for?

■ The Higgs mechanism (in the electroweak Standard Model):

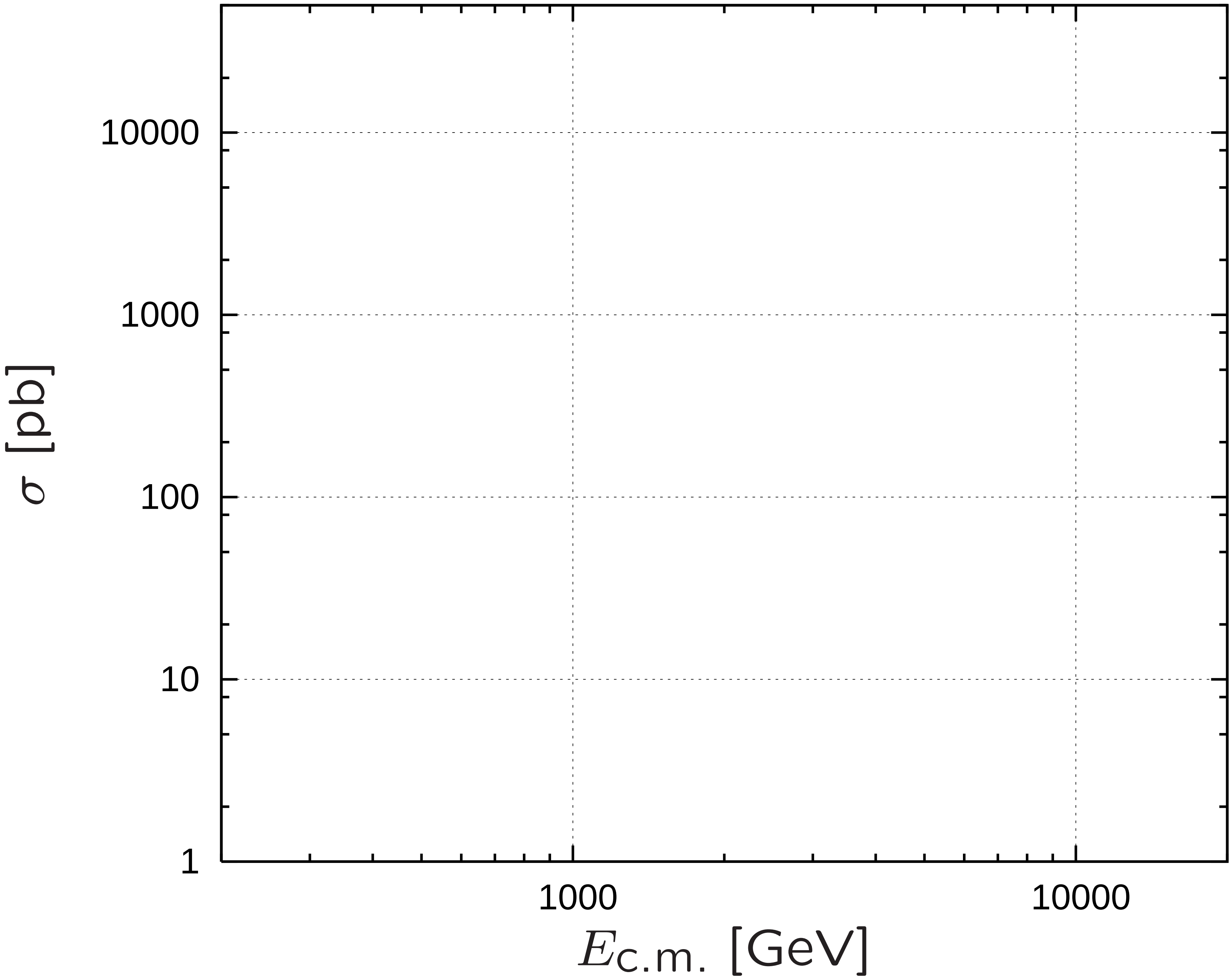
- The Higgs field has 4 components & doesn't vanish in the ground state
- The ground state configuration acts as a medium (background field) with which all particles interact (coupling strength $\propto$ mass)
- 3 components promote Z, W^+, W^- to massive (3 component) vector particles from massless (2 component) ones
- 1 component is an additional physical d.o.f. H → the Higgs boson (coupling strength to other particles $\propto$ mass)

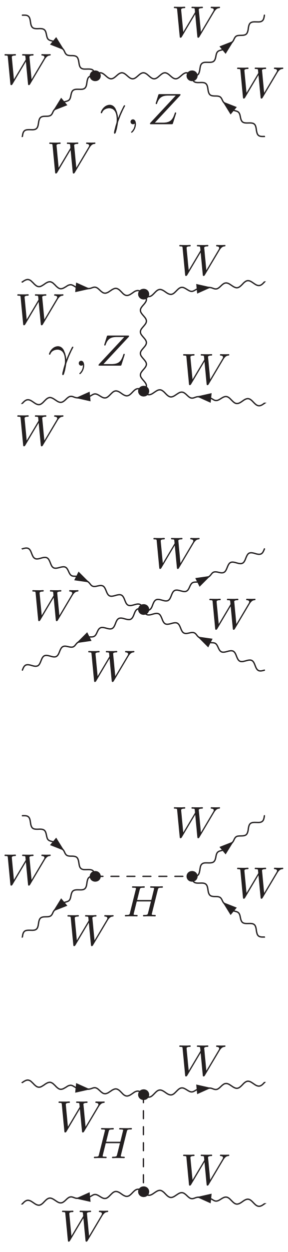
■ The Higgs gives mass to all elementary particles: (e.g. e^-, q, Z, $W^\pm$)

- the Higgs mechanism is a general concept (choice of Higgs field not unique)
- it explains *how* masses arise but not *what* mass values

■ The Higgs cures bad high energy behaviour: (example $W_L W_L$ scattering)

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





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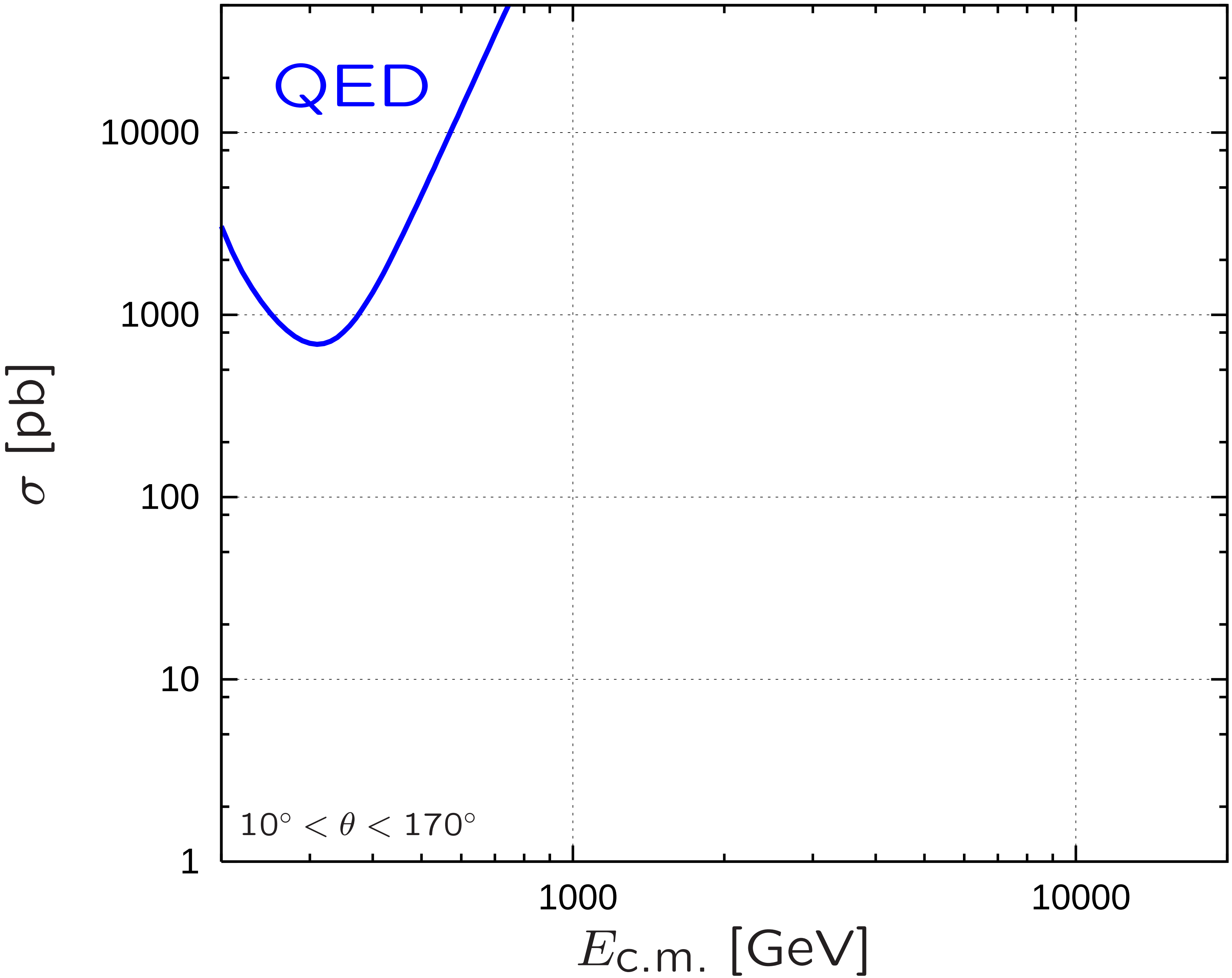

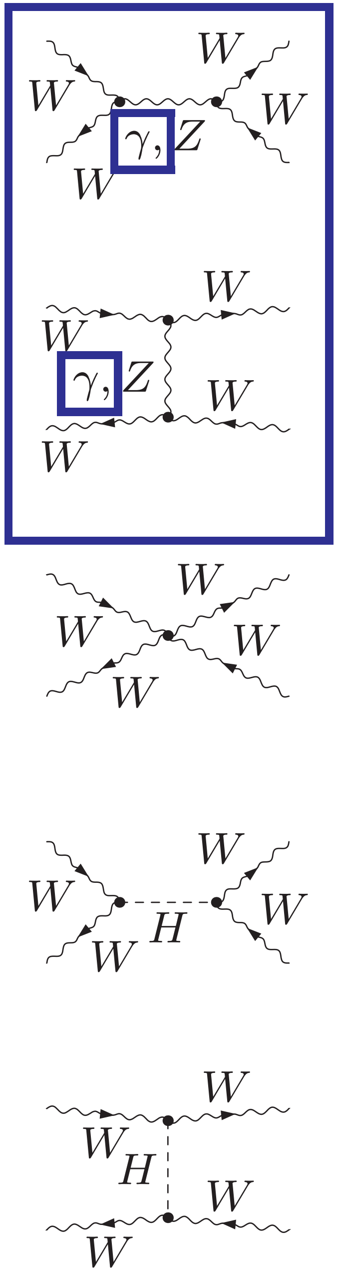

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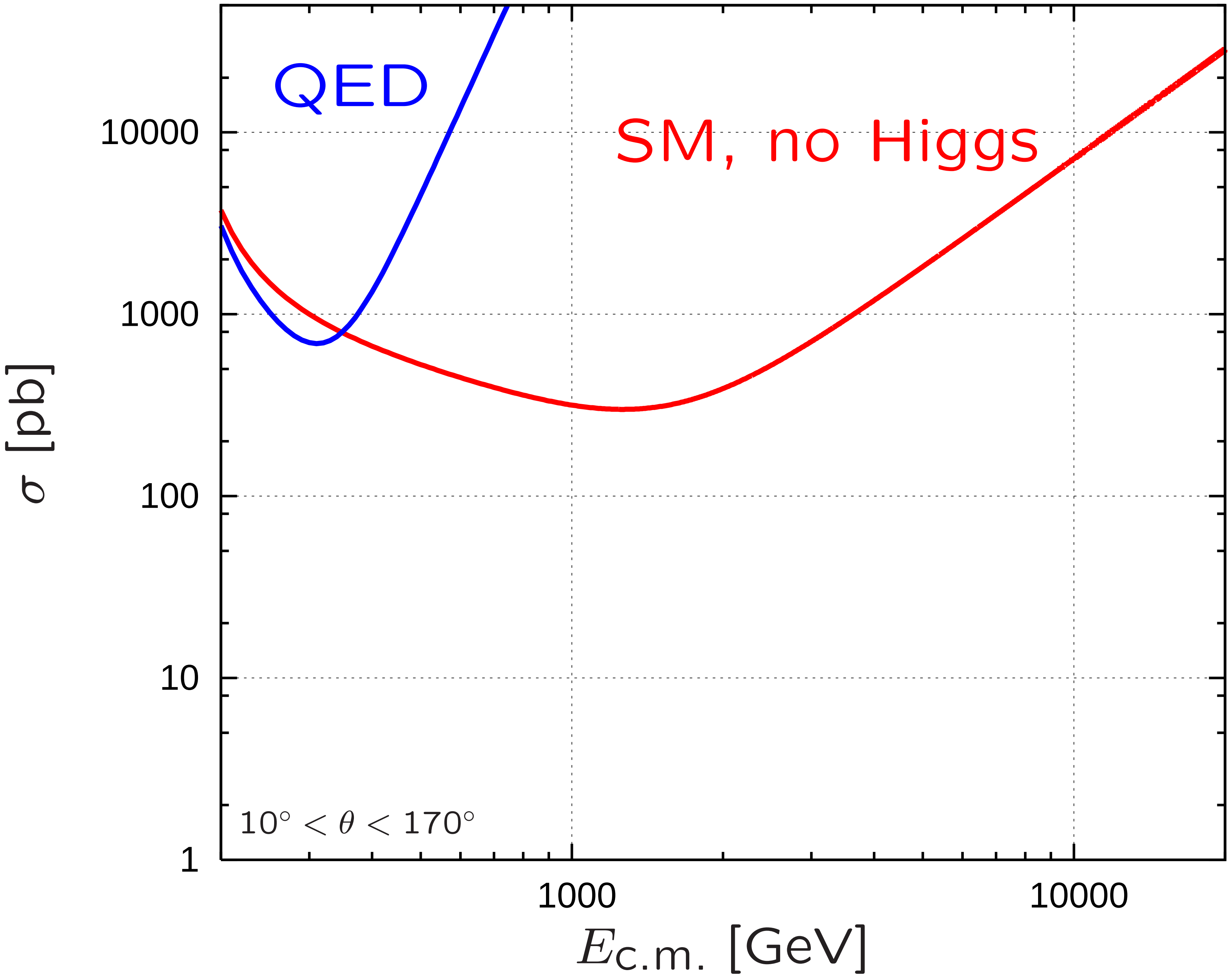

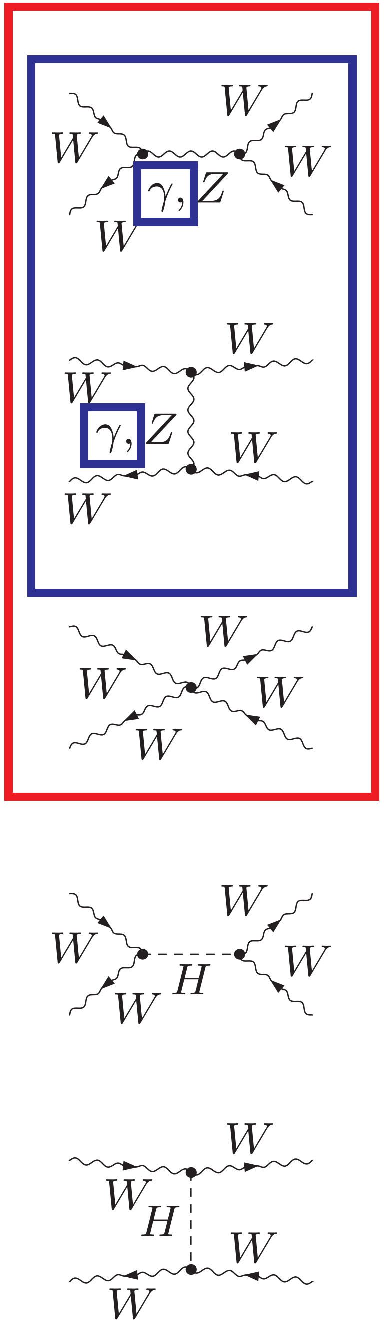

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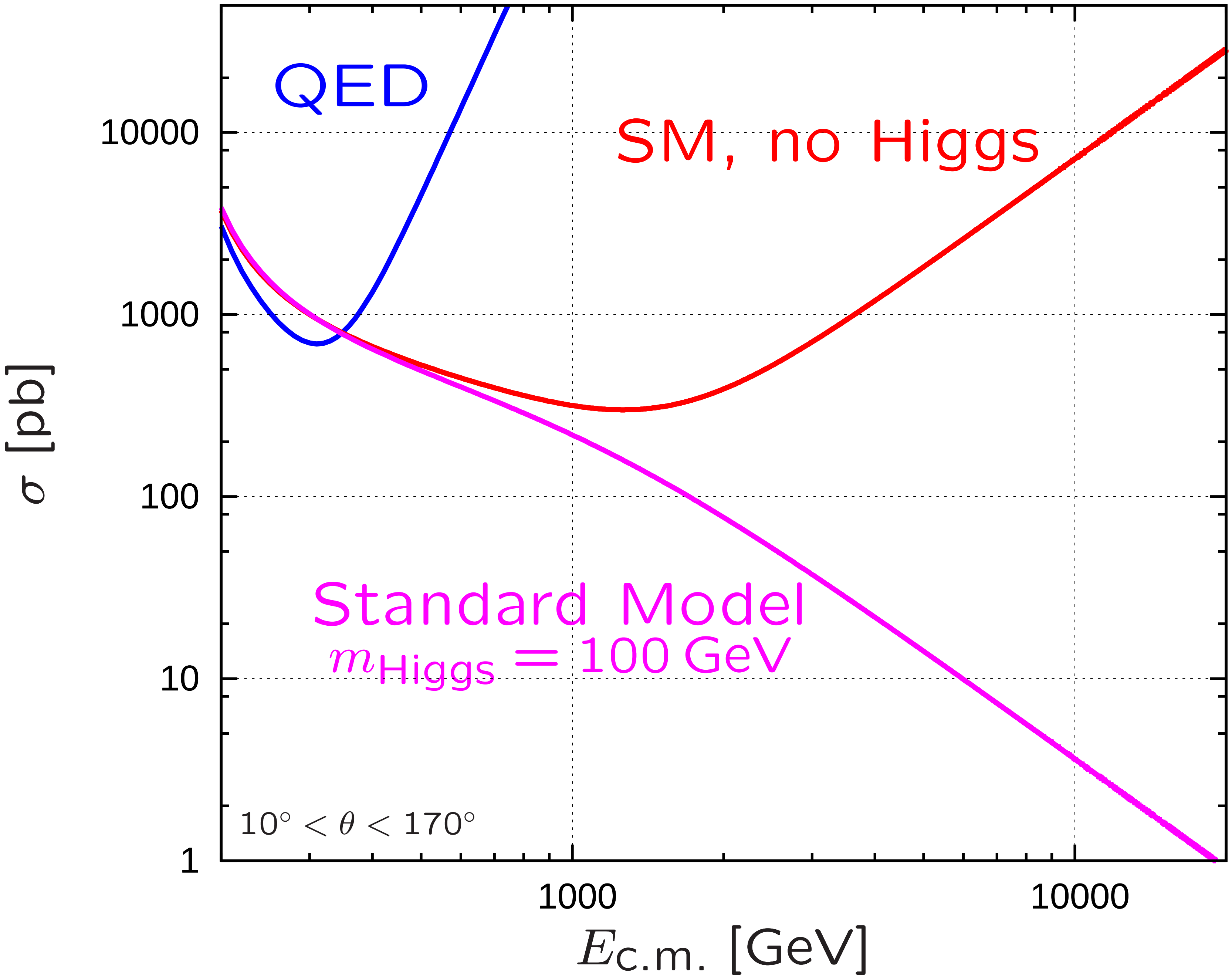

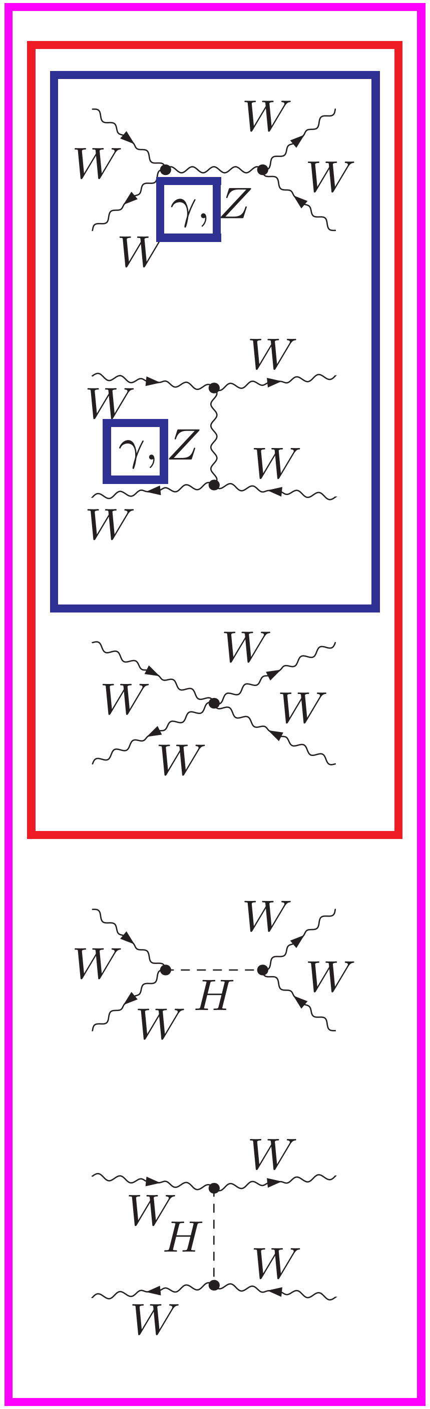

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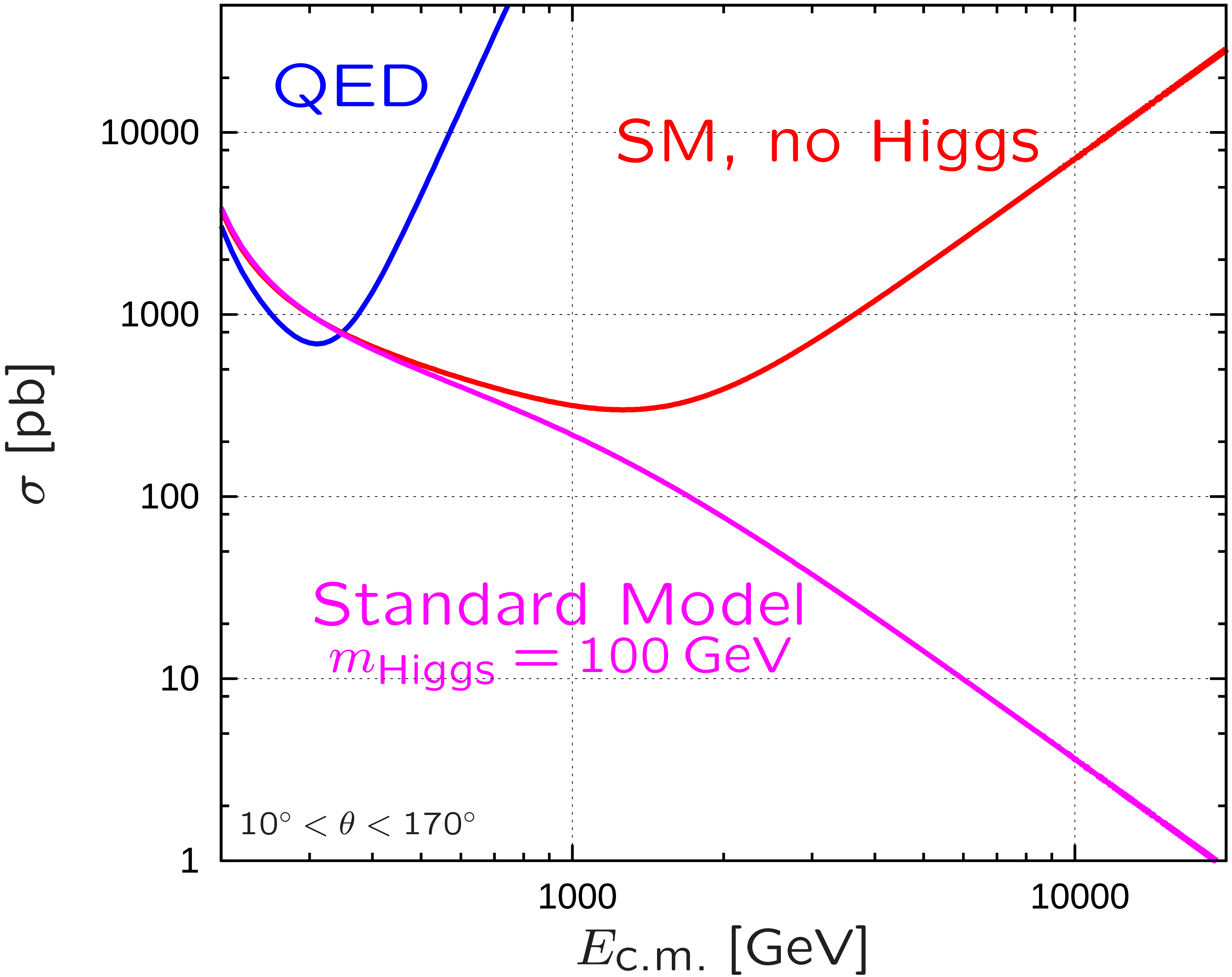


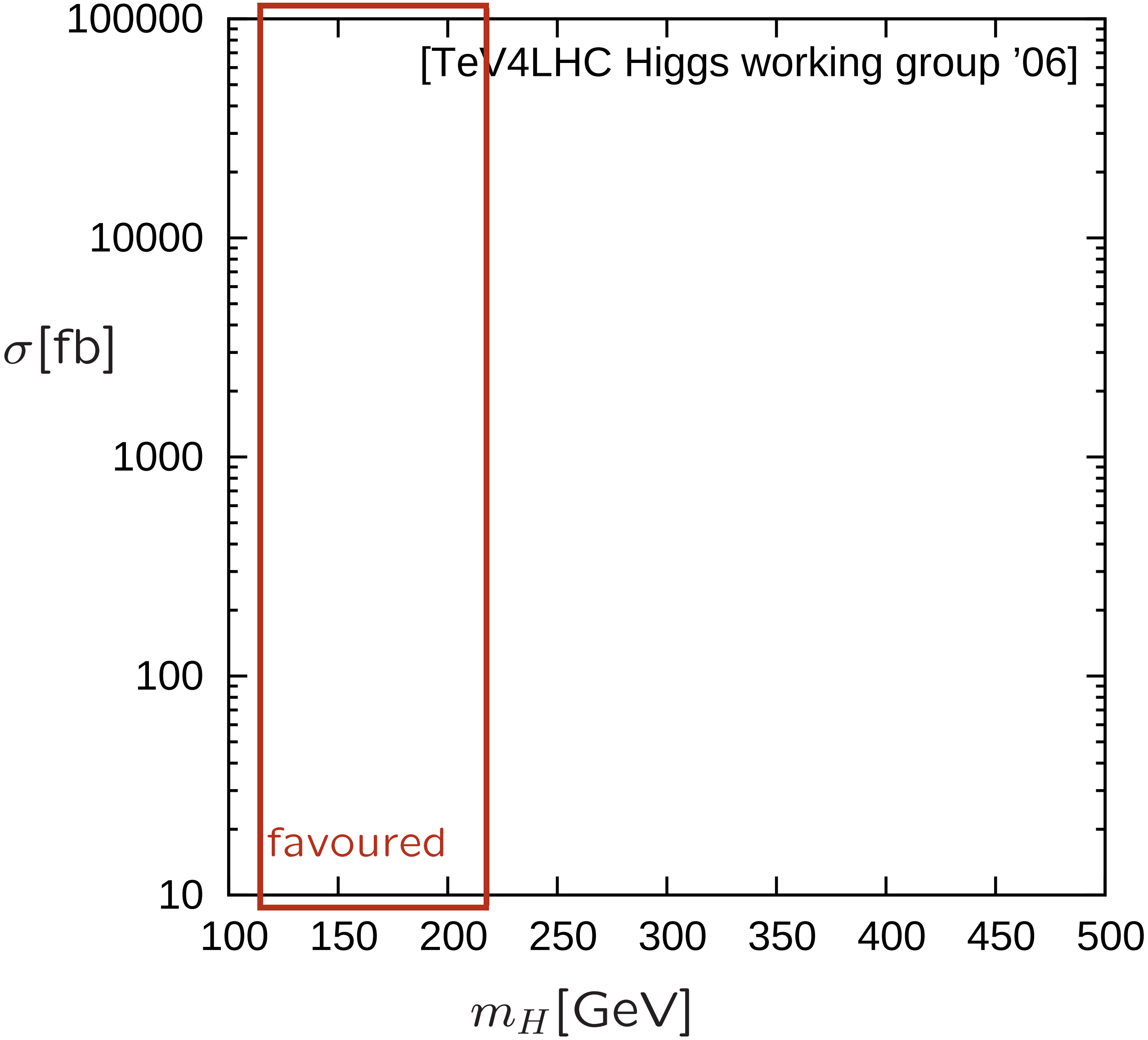
- SM may be applicable up to very high energy.
- If no Higgs exists: new phenomena around 1 TeV expected.

– How to find Higgs Bosons?

■ SM Higgs production @ LHC :

→ consider:

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



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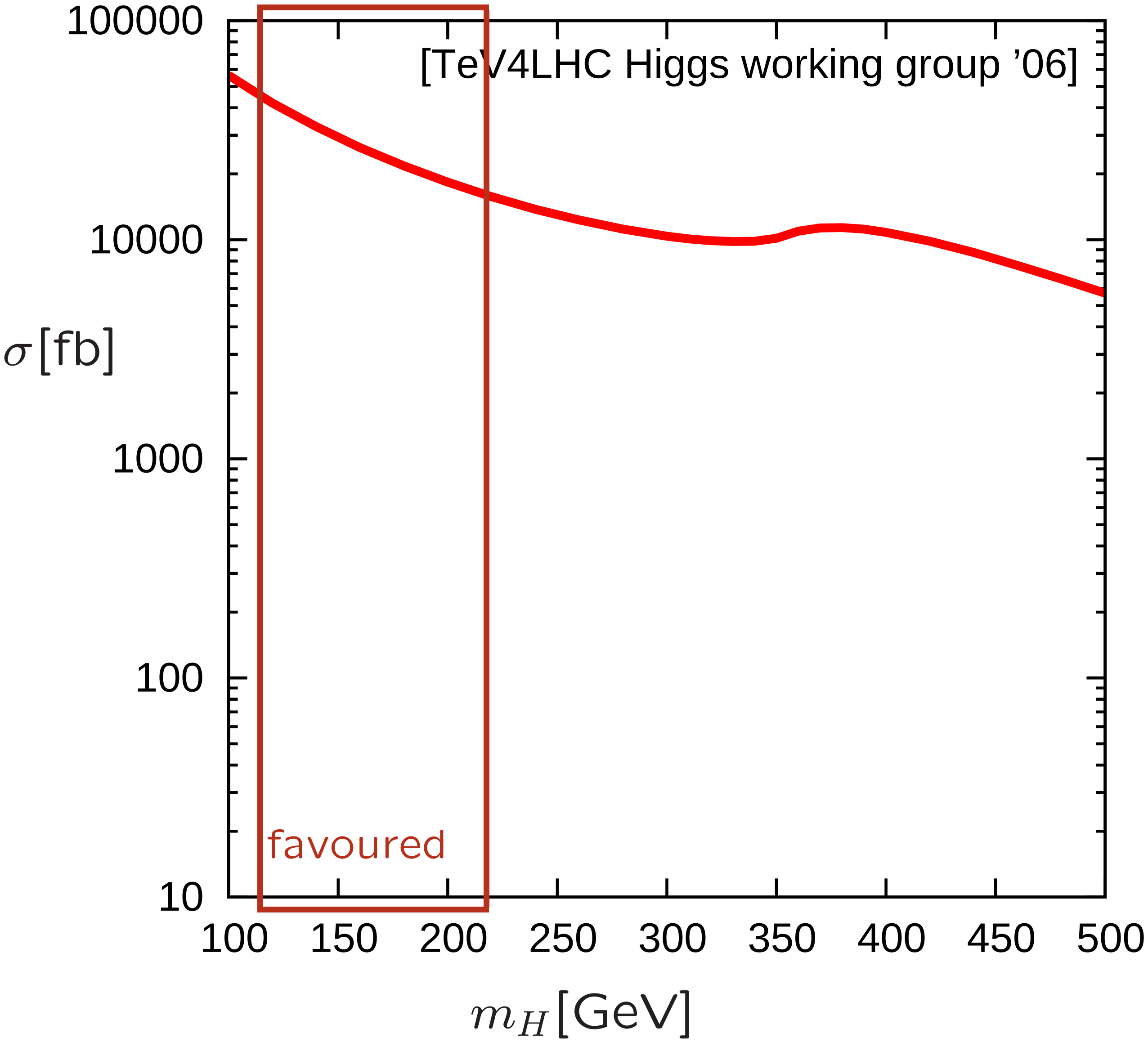
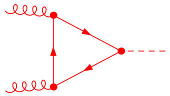


gluon fusion, $gg \to H$



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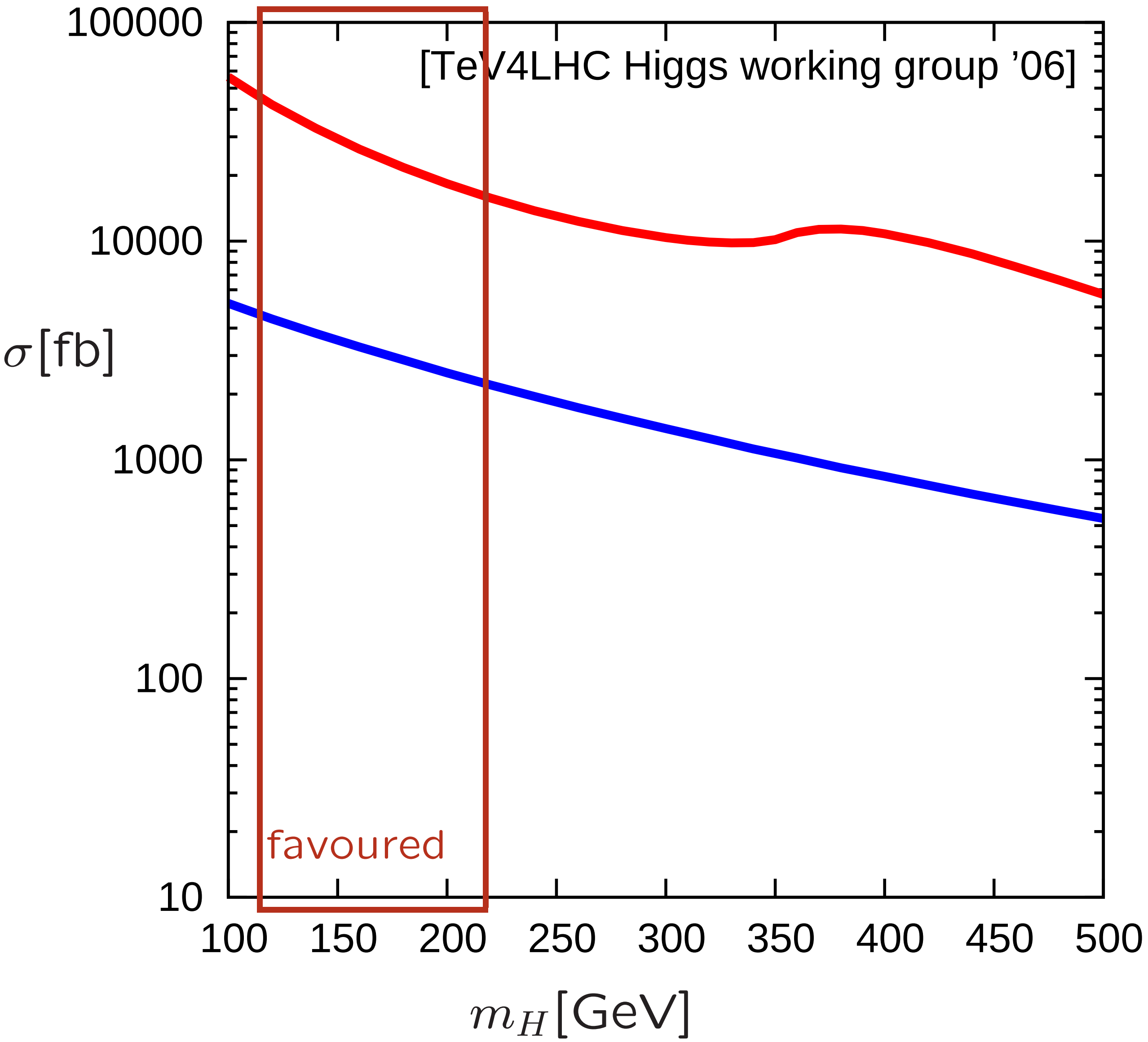

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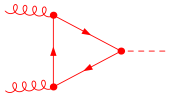
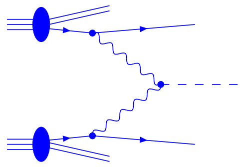


vector boson fusion, $qq \to qqH$



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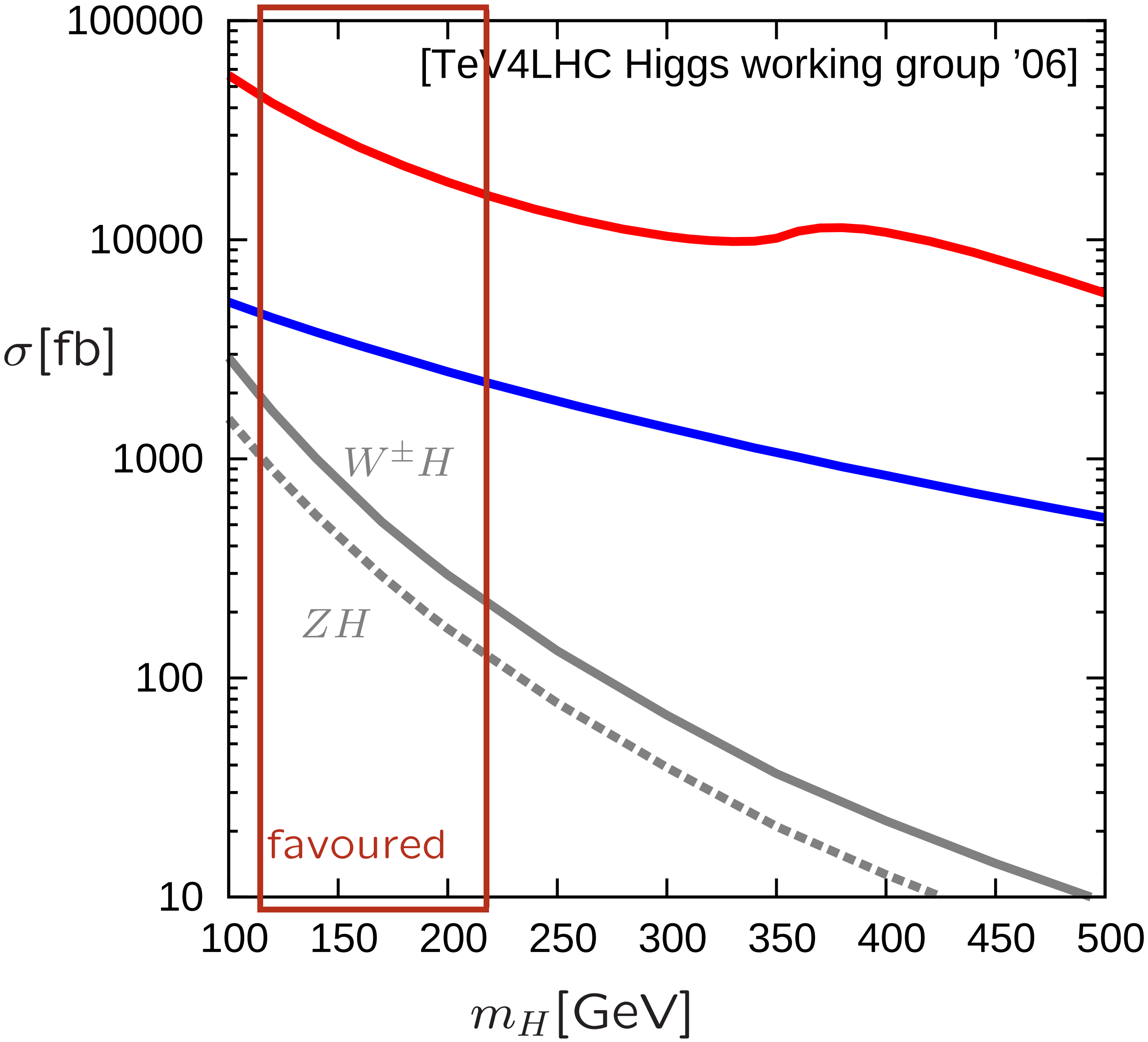

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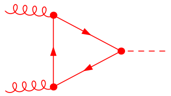

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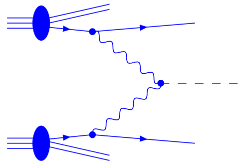
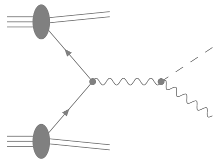


Higgs strahlung, $q\bar{q}' \to VH$



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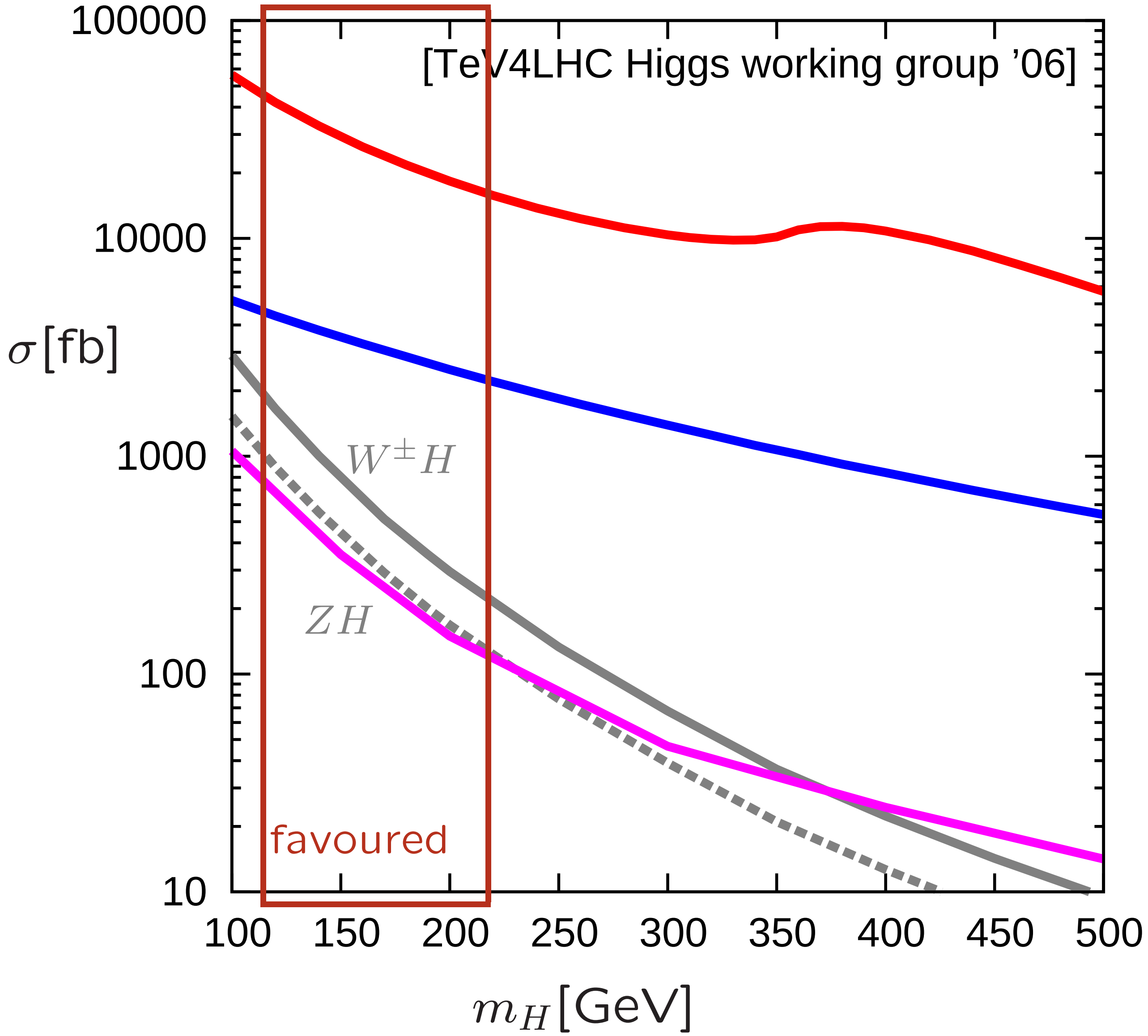

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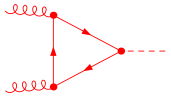

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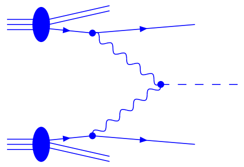

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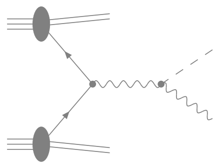
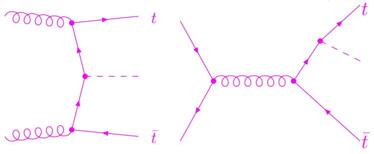


$t\bar{t}H$ production, $gg/q\bar{q} \to t\bar{t}H$



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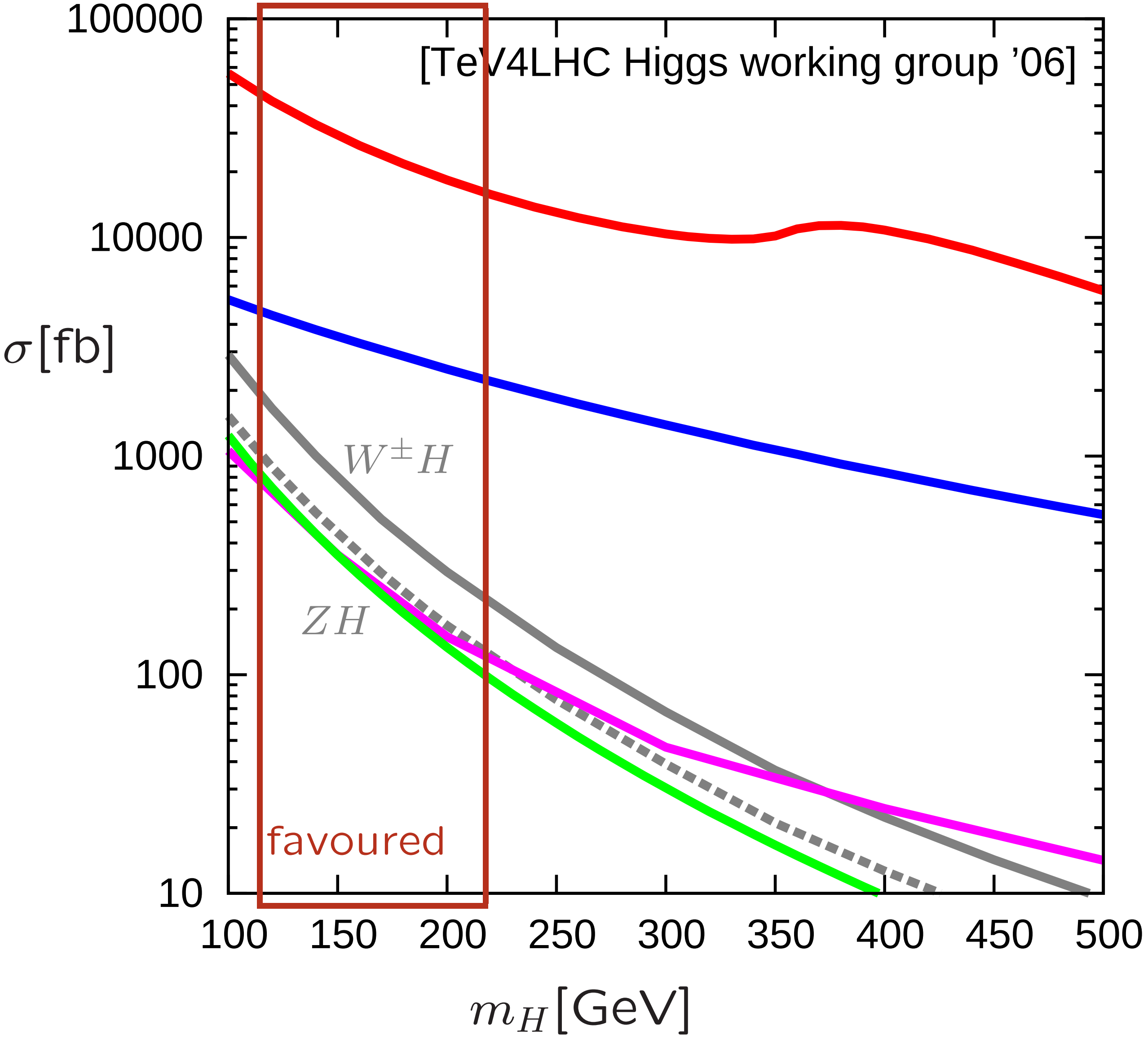

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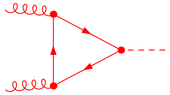

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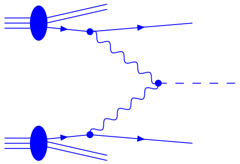

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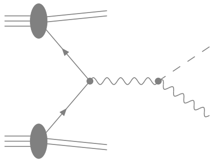

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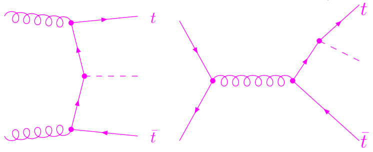
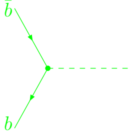


$b\bar{b}$ annihilation, $b\bar{b} \to H$



How to detect Higgs Bosons ?

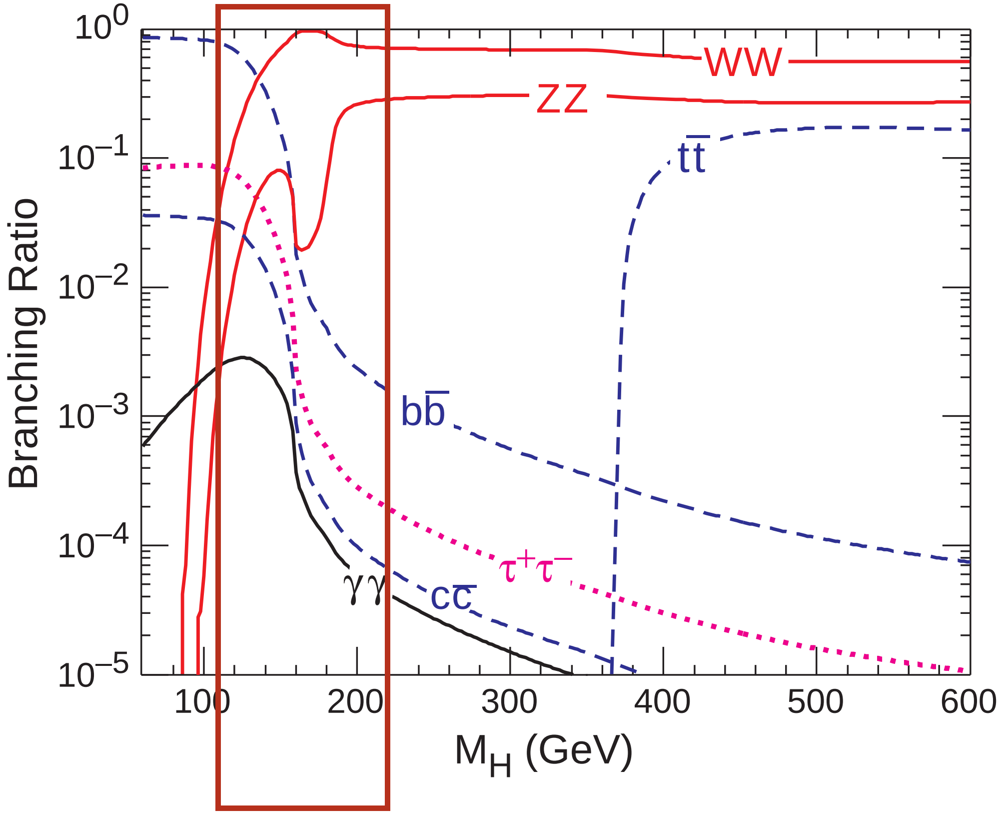
- Essential for Higgs discovery is:

  [production rate]×[decay probability]×[detection efficiency]

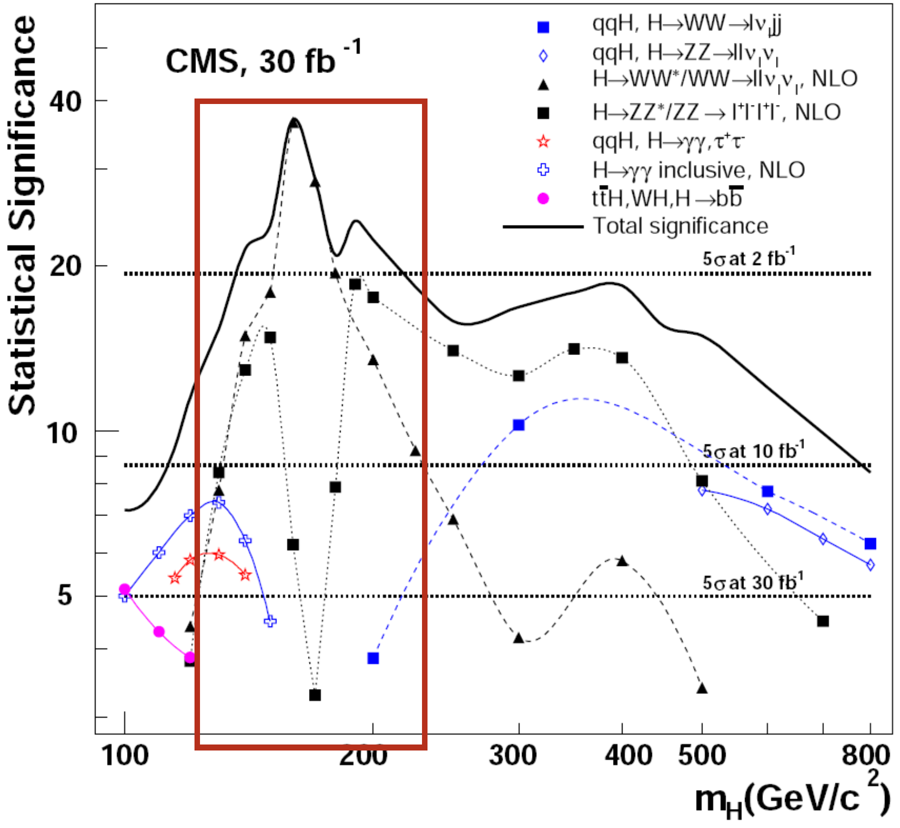
- Higgs events need to be silhouetted against *huge* amount of non-Higgs events

  → e.g. hopeless to see $H \to b\bar{b}$ via gluon fusion

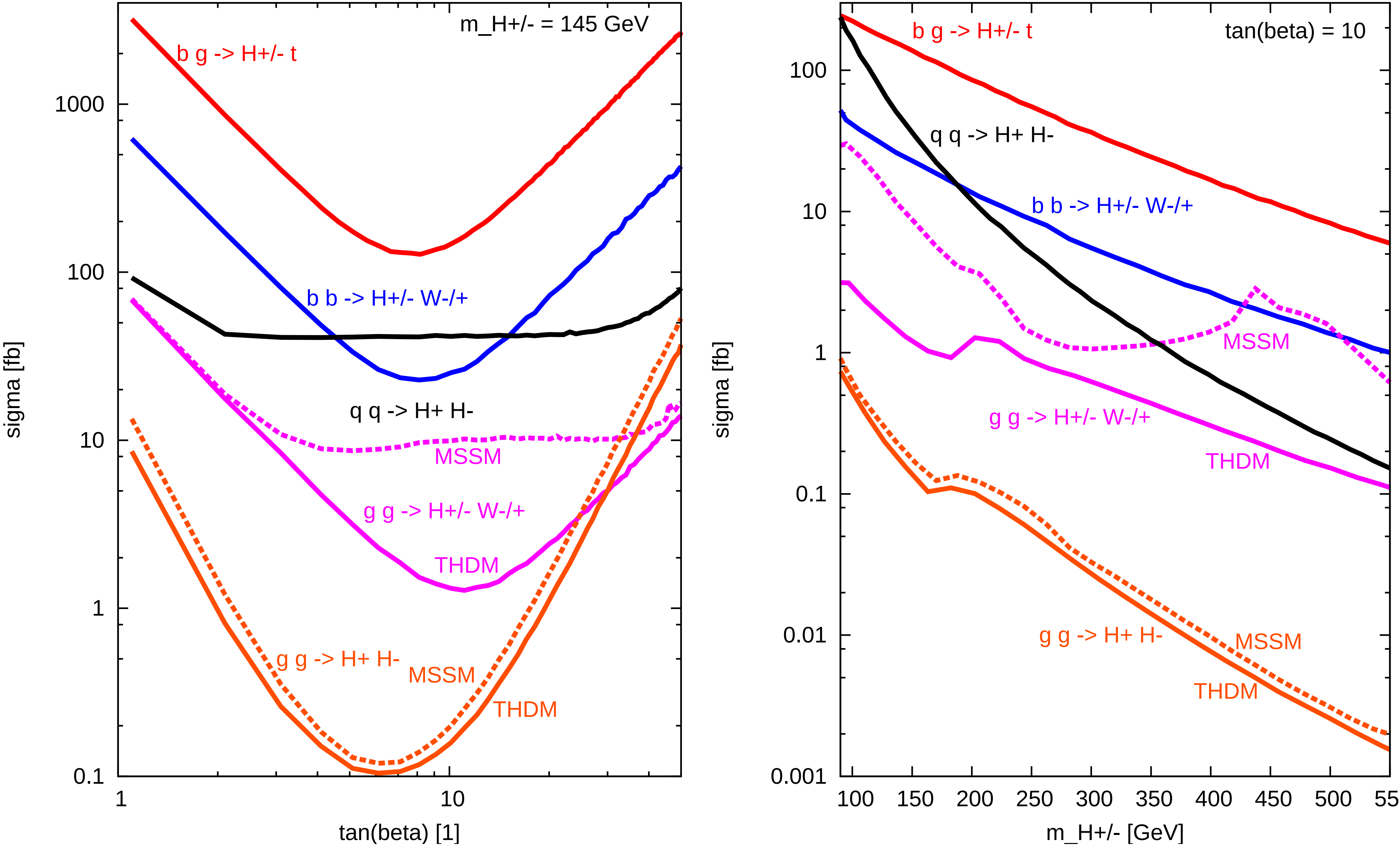
⋆ signal significance for Higgs detection @ LHC:



⋆ SM Higgs decay probability (branching ratio):



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



– What else to expect at the LHC?

■ Naturalness Problem in the Higgs sector

Naturalness ['t Hooft 1980]:

m is a natural small parameter $\Longleftrightarrow$ additional symmetry for $m \to 0$

example : electron mass m_e is a natural small parameter:

- $m_e \to 0 \Longrightarrow$ chiral symmetry
- all quantum corrections to electron self energy $\Sigma_e \propto m_e$
- partial symmetry protects Σ_e from large quantum corrections

counter example : SM Higgs mass m_H is not a natural small parameter

- Higgs Potential: $V_{\text{Higgs}} = -\frac{m_H}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2$
- $m_H \to 0 \Longrightarrow$ no additional symmetry
- Higgs self energy not protected from large quantum corrections

The Naturalness Problem (also often called "the hierarchy problem"):

Assuming the SM is only valid up to some scale Λ (say M_{GUT} or M_{Planck}), quantum corrections to the Higgs self energy are of the order of Λ.
But present observations indicate a value around the electroweak scale Λ_{EW}.

$\Lambda_{\text{EW}} \propto 100\,\text{GeV}$, $M_{\text{GUT}} \propto 10^{15}\,\text{GeV}$ $M_{\text{Planck}} \propto 10^{19}\,\text{GeV}$

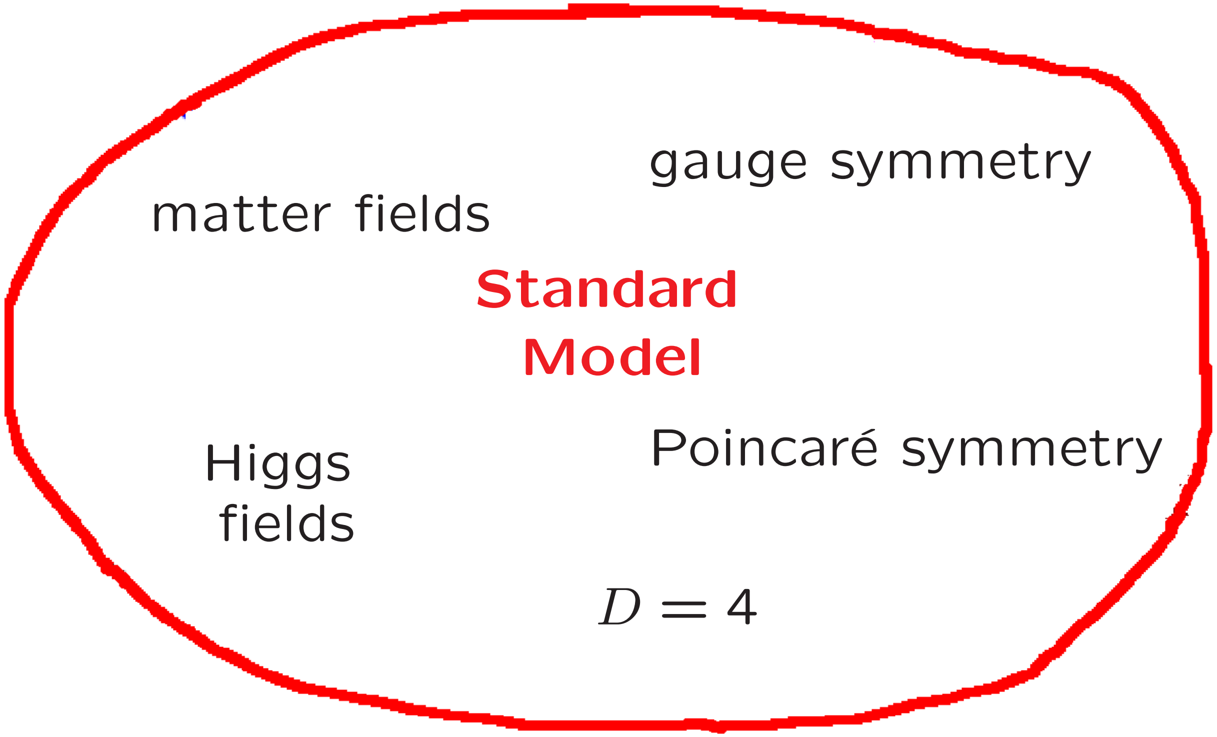
Taking the Naturalness Problem seriously:

What extension of the SM at higher energy scales

could avoid the large quantum corrections

in the Higgs sector?

A broad view on SM extensions



matter fields

gauge symmetry

Standard Model

Higgs fields

Poincaré symmetry

$D = 4$

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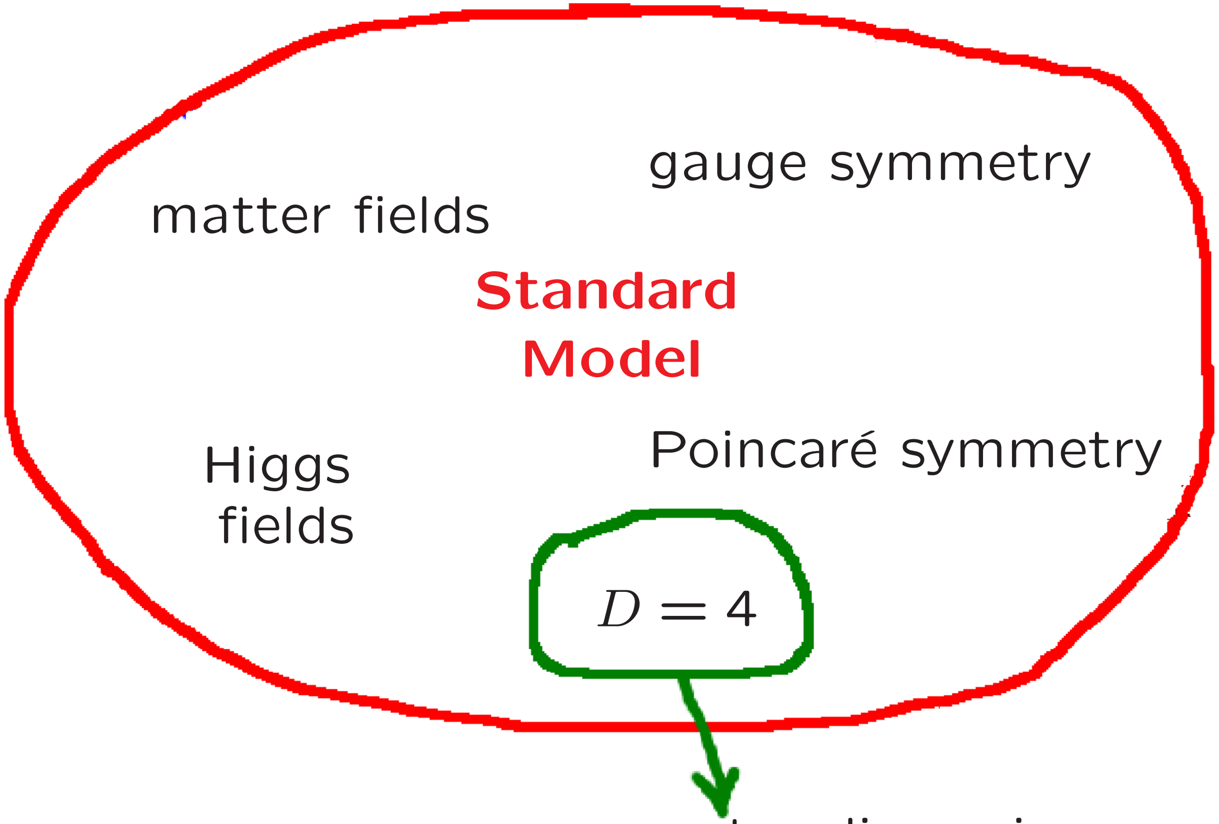

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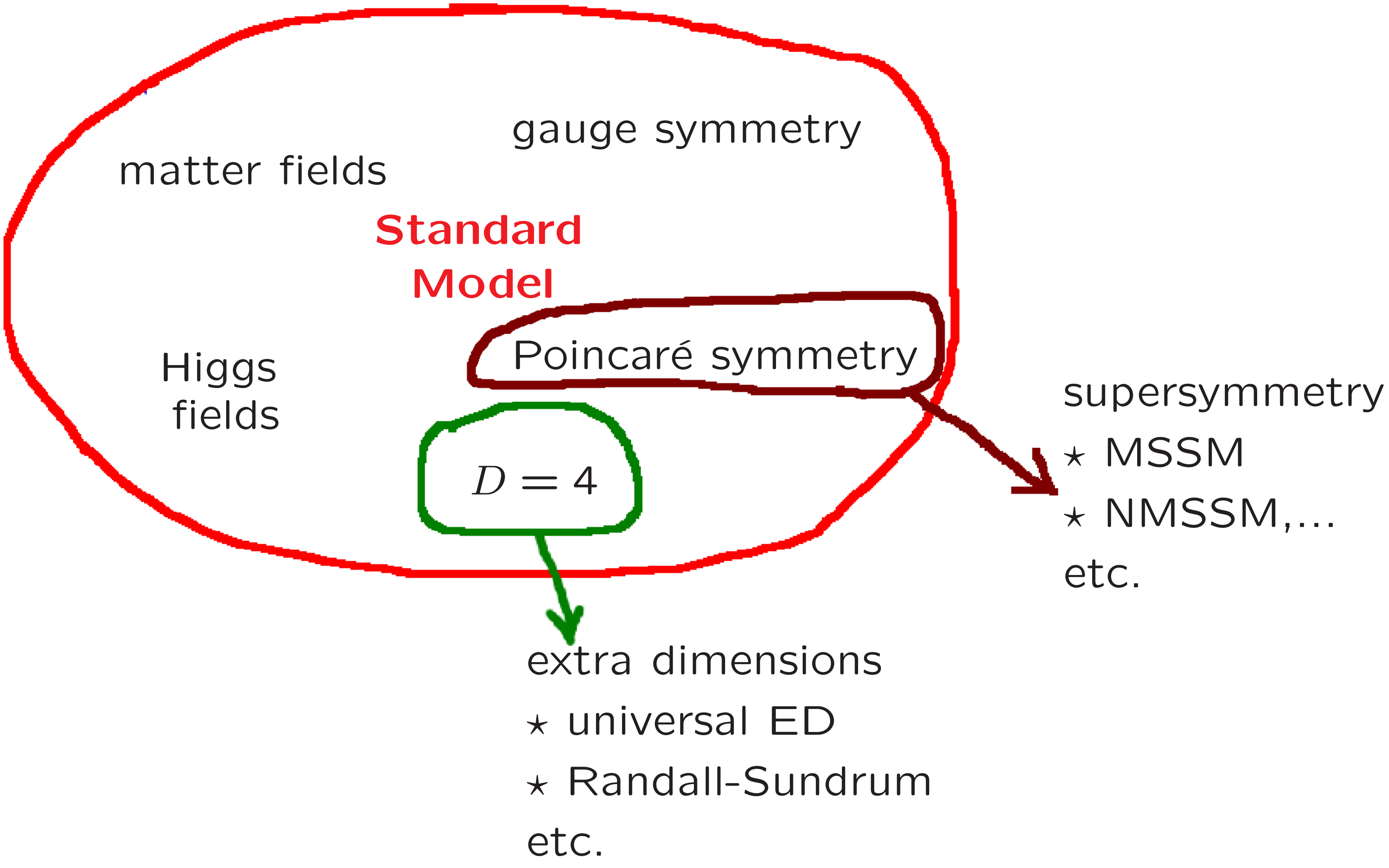
extra dimensions

$\star$ universal ED

$\star$ Randall-Sundrum

etc.

A broad view on SM extensions



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Standard Model

Higgs fields

Poincaré symmetry

$D = 4$

supersymmetry

⋆ MSSM

⋆ NMSSM,...

etc.

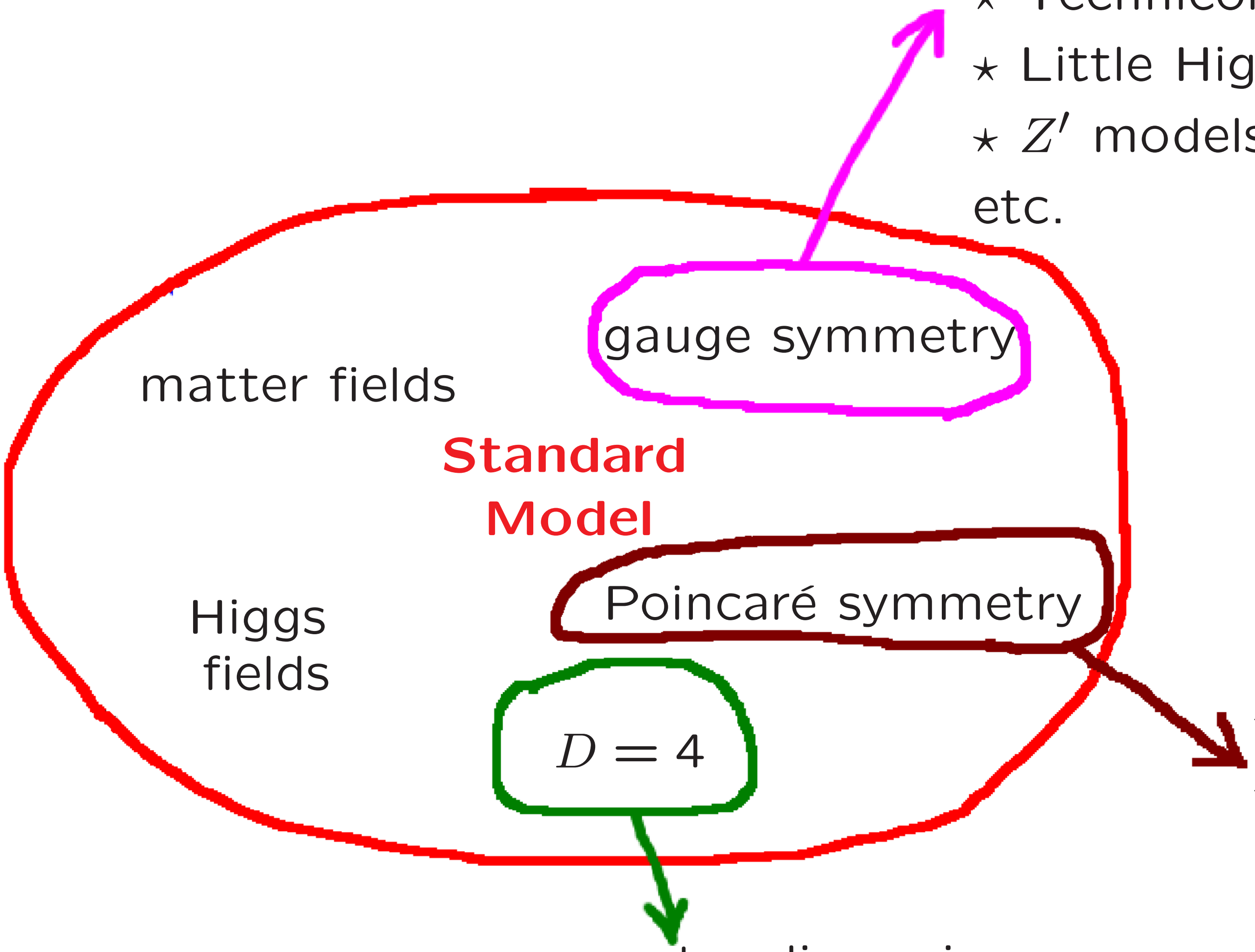
extra dimensions

⋆ universal ED

⋆ Randall-Sundrum

etc.

- A broad view on SM extensions



Standard Model

matter fields

Higgs fields

gauge symmetry

Poincaré symmetry

$D = 4$

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

etc.

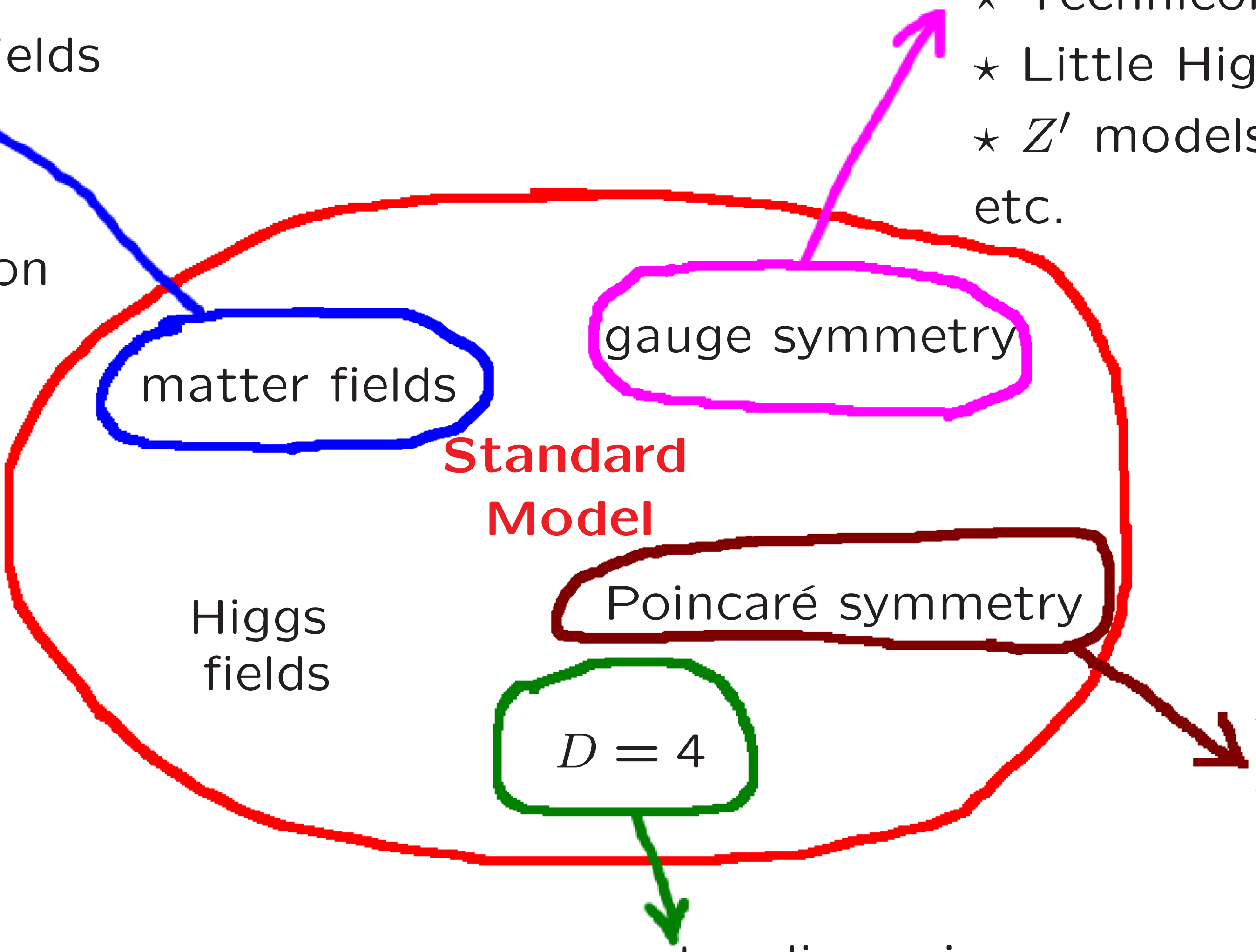
supersymmetry
- ⋆ MSSM
- ⋆ NMSSM,...

etc.

extra dimensions
- ⋆ universal ED
- ⋆ Randall-Sundrum

etc.

A broad view on SM extensions



Standard Model

matter fields

gauge symmetry

Higgs fields

Poincaré symmetry

$D = 4$

extra matter fields

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

etc.

extra gauge groups

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

etc.

supersymmetry

- ⋆ MSSM
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etc.

extra dimensions

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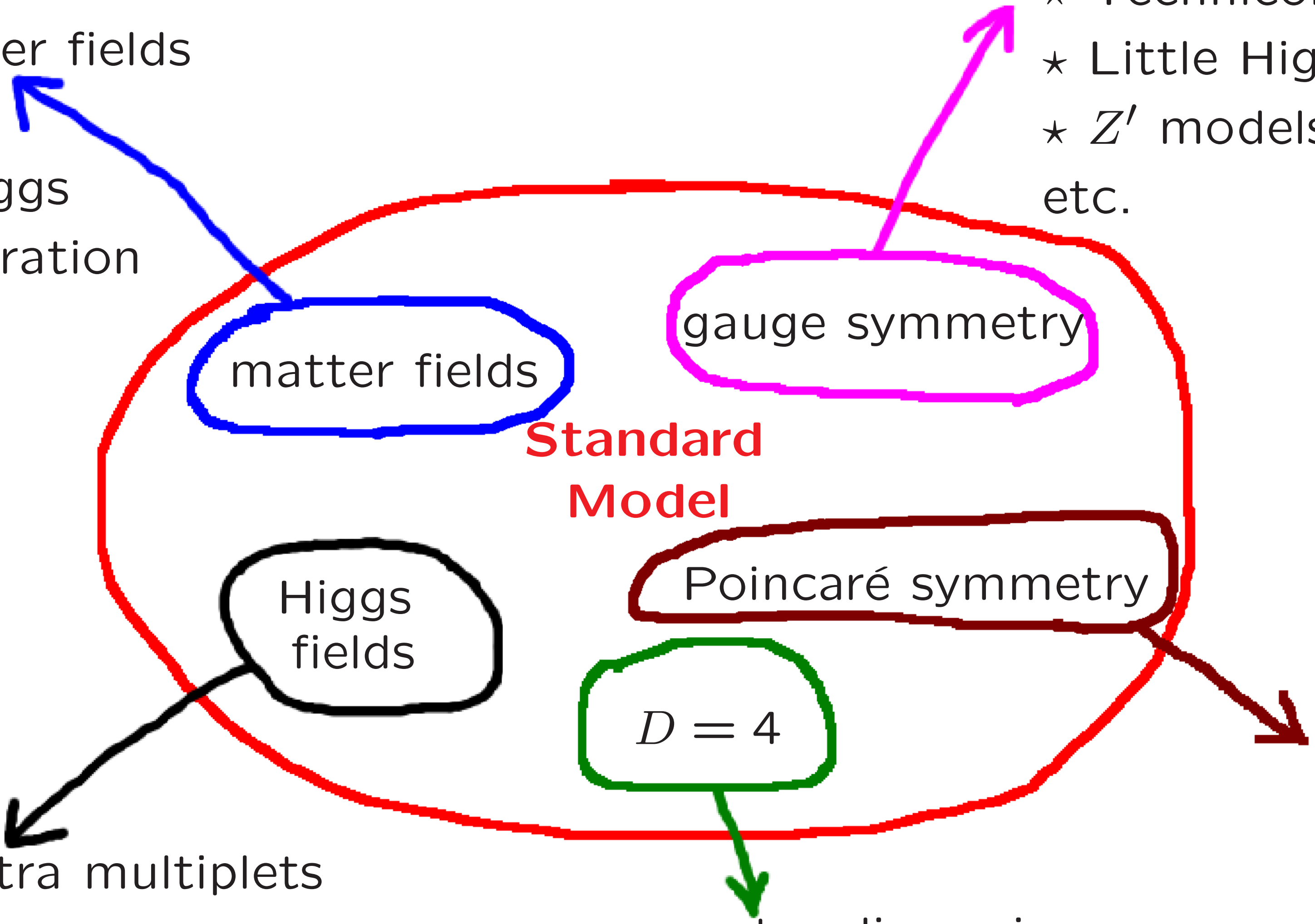
etc.

A broad view on SM extensions



Standard Model

matter fields

gauge symmetry

Higgs fields

Poincaré symmetry

$D = 4$

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

etc.

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

etc.

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

etc.

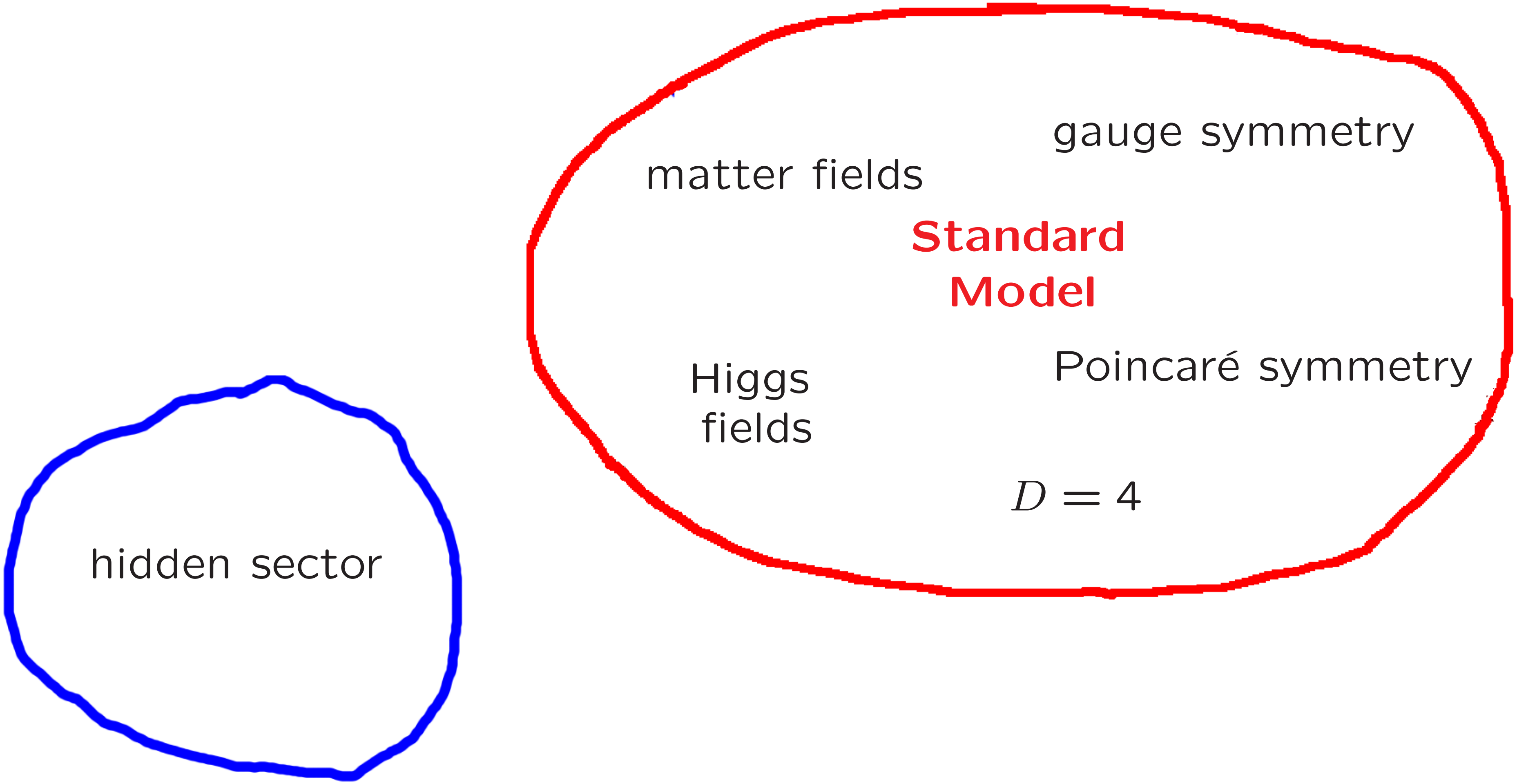
supersymmetry
- ⋆ MSSM
- ⋆ NMSSM,...

etc.

extra dimensions
- ⋆ universal ED
- ⋆ Randall-Sundrum

etc.

A broad view on SM extensions



Standard Model

matter fields

gauge symmetry

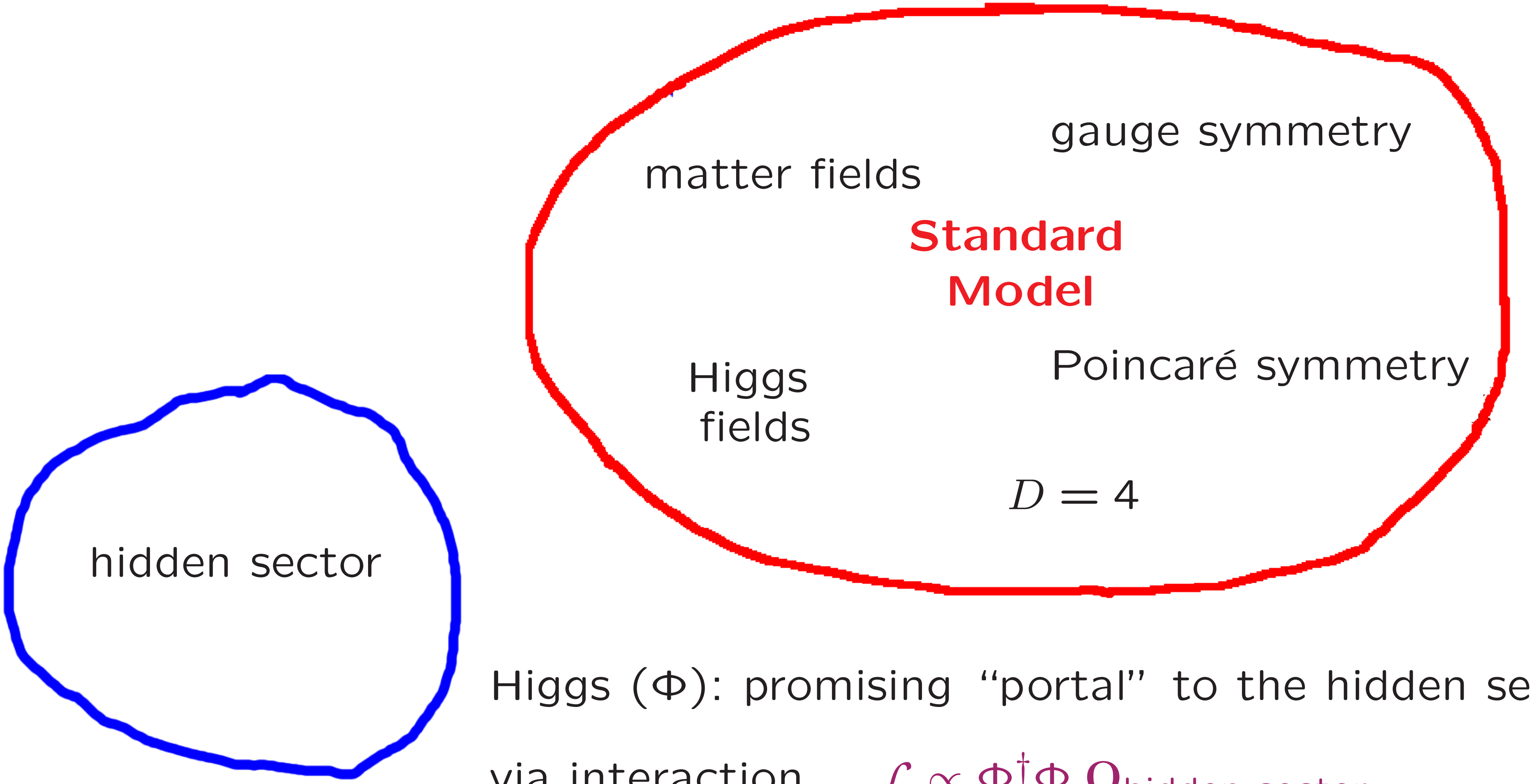
Higgs fields

Poincaré symmetry

$D = 4$

hidden sector

A broad view on SM extensions



matter fields

gauge symmetry

Standard Model

Higgs fields

Poincaré symmetry

$D = 4$

hidden sector

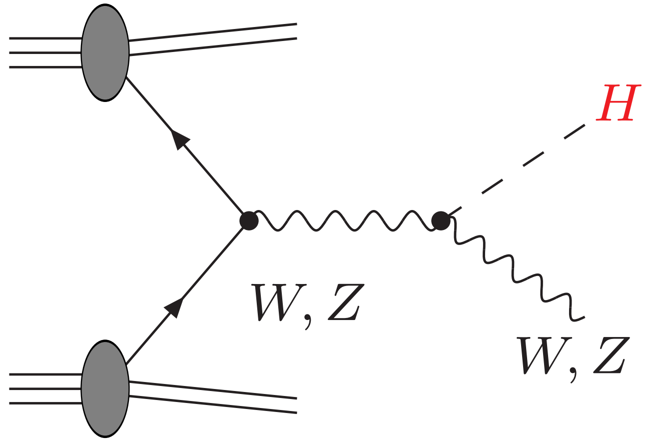
Higgs (Φ): promising “portal” to the hidden sector

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

● Selected Projects

– SM Higgsstrahlung (NNLO QCD)

– SM Higgsstrahlung (NNLO QCD)



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 $\sigma_{\text{NNLO}}(q\bar{q} \to V^\star)$ to evaluate $\sigma(pp \to HV)$.

status of theory predictions:

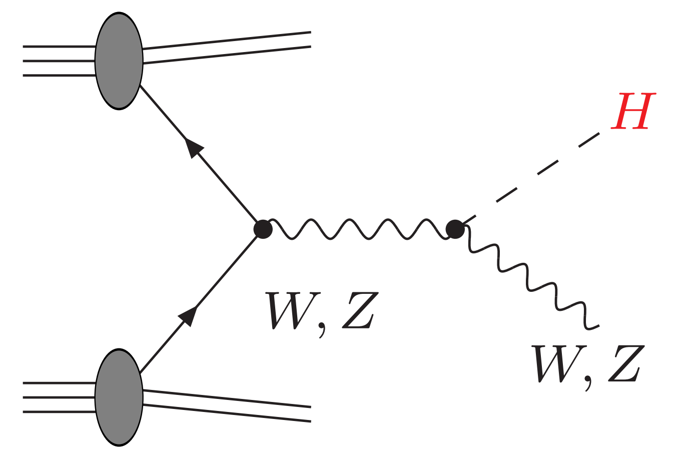
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

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

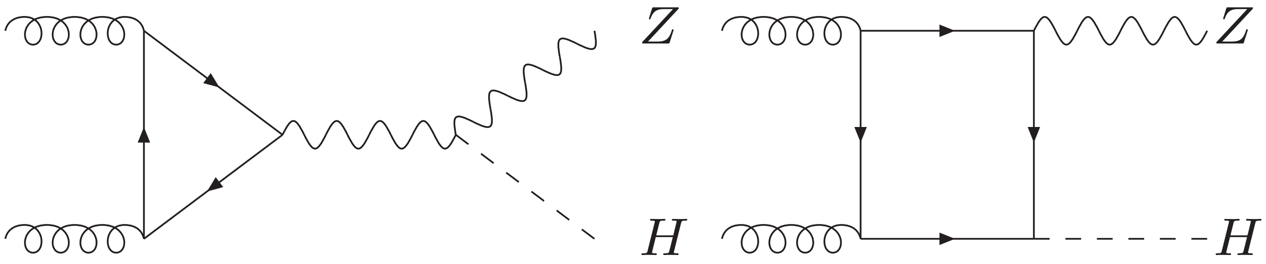
SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

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

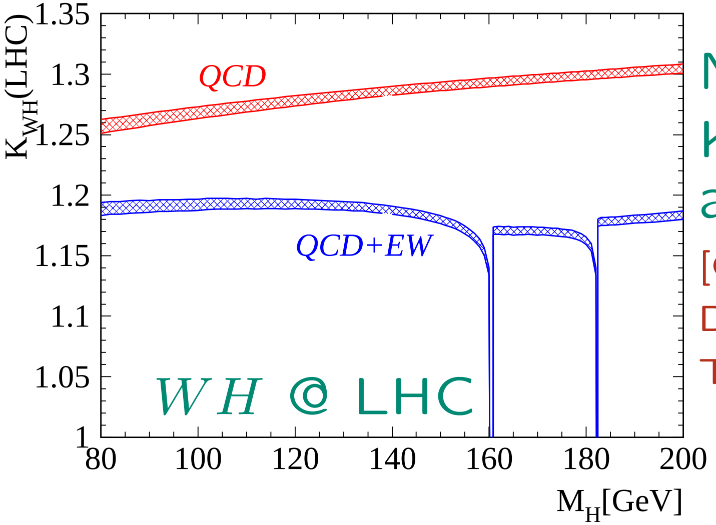


Higgs strahlung, $q\bar{q}' \to VH$

note! additional parton process for ZH @ NNLO



[Dicus, Kao '88; Kniehl '90]



NNLO QCD + NLO EW K-factors and scale uncertainty

[OBr, Ciccolini, Dittmaier, Djouadi, Harlander, Krämer '04; TEV4LHC WG Report '06]

status of theory predictions:

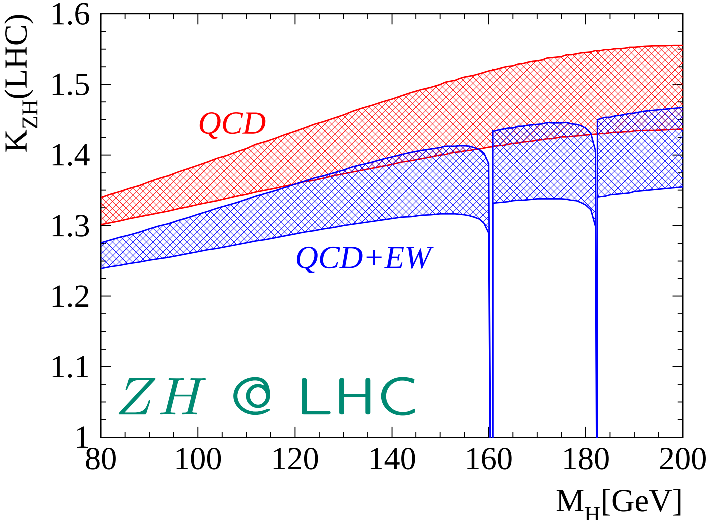
SM, LO [Glashow, Nanopoulos, Yildiz '78]

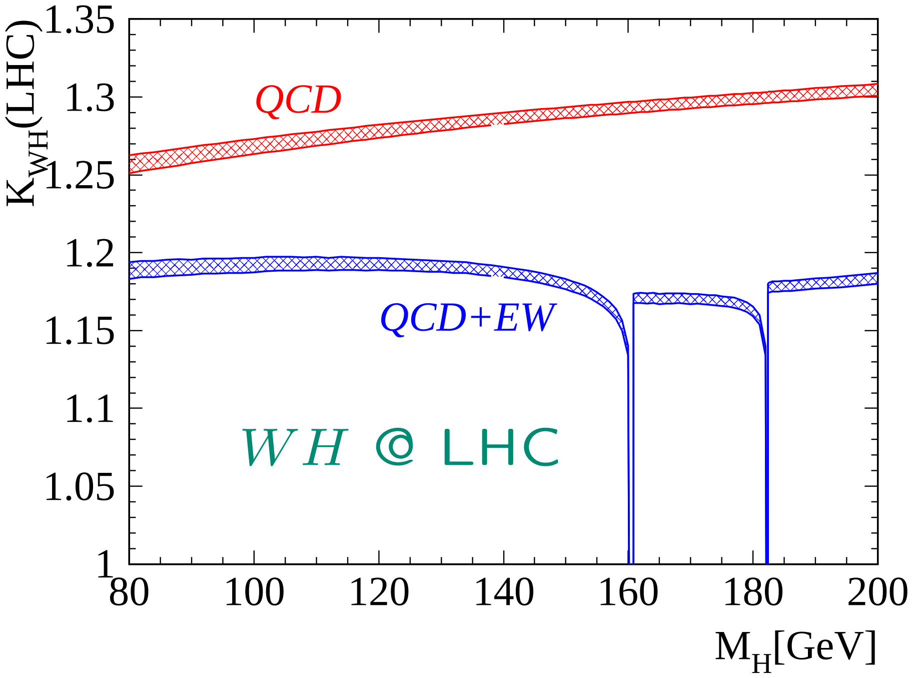
SM, NLO QCD [Han, Willenbrock ' 91]

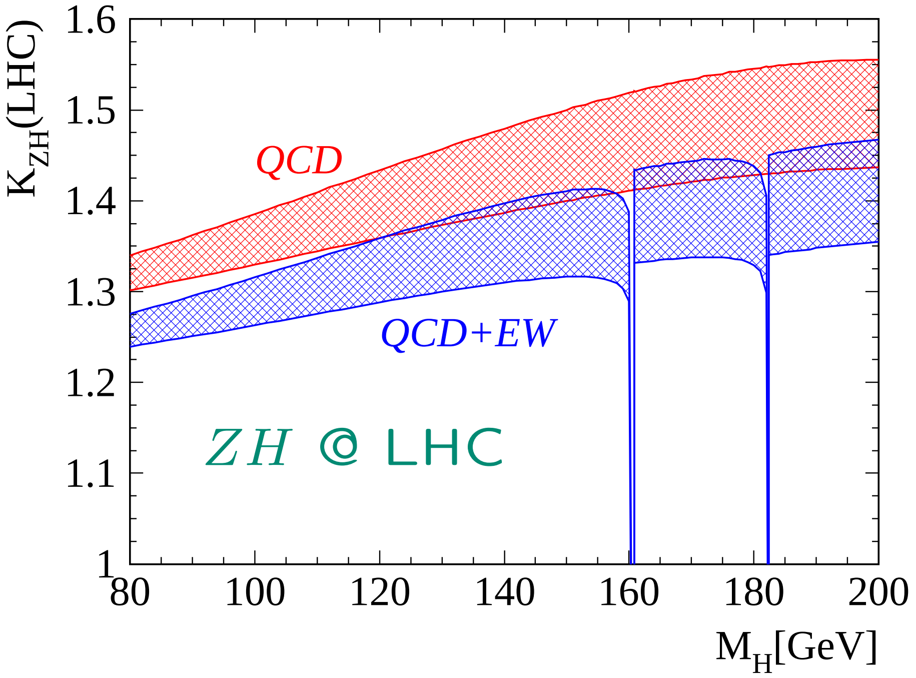
SM, NNLO QCD [OBr, Djouadi, Harlander '03]

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

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







- most precisely known Higgs production process at hadron colliders
- results regularly used by Tevatron collaborations
- recently, we provided updated predictions for total cross sections and uncertainties within the LHC Higgs Cross Section Working Group [CERN Yellow Report 2011]

→ ongoing effort, now focusing on differential distributions

→ code `vh@nnlo` to go public soon [OBr, Harlander, Zirke '11]

Top quark induced corrections

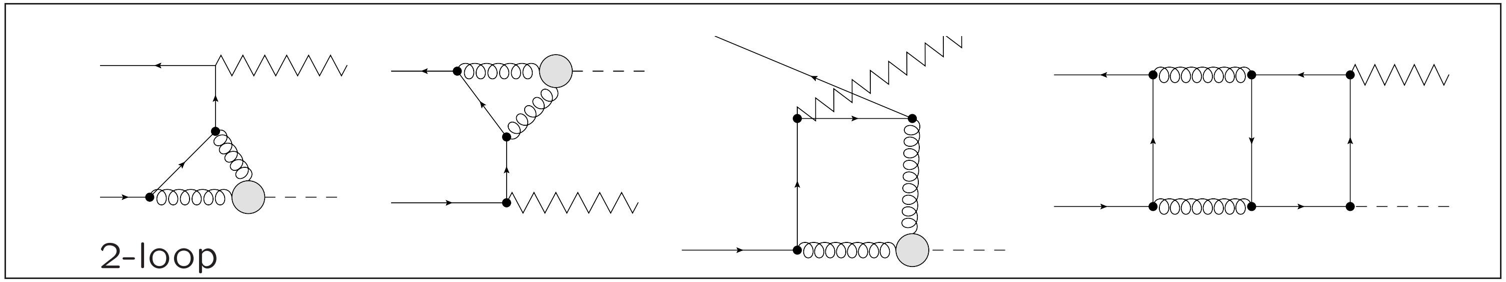
[OBr, Harlander, Wiesemann, Zirke '11]

Unfortunatley, this is not the whole story! :

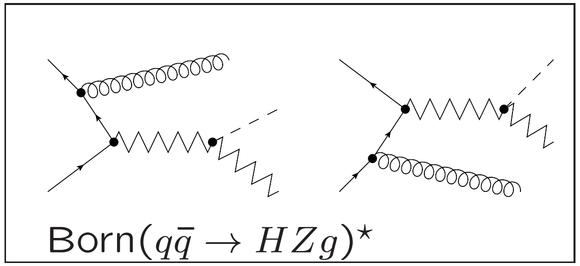
Top quark induced corrections appear at NNLO QCD
and are not Drell-Yan like. → previously overlooked!

- virtual corrections at NNLO to $q\bar{q} \to HZ$: (shaded blob = top quark loop)

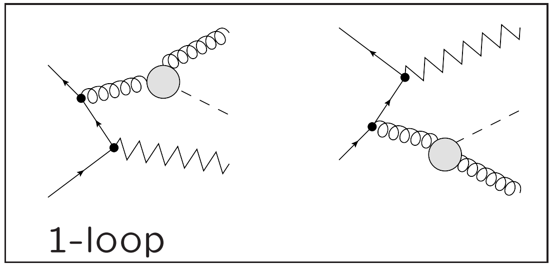
Born($q\bar{q} \to HZ$)*×



- real corrections at NNLO to $q\bar{q} \to HZ$:



×



$+ [qg \to HZq] + [\bar{q}g \to HZ\bar{q}]$

- similar corrections for WH production (and in vector boson fusion too!)
- technical challenge: agreement between two independent calculations using:

  a)... asymptotic expansions b)... effective vertices & tensor reduction
- size of correction ≈ +2% for $m_H = 120\,\text{GeV}$, LHC @ 14 TeV

– HiggsBounds

– HiggsBounds

[Bechtle, OBr, Heinemeyer, Weiglein, Williams '08-'11]

HiggsBounds : tests 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 neutral & charged 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:

`projects.hepforge.org/higgsbounds`

■ implemented analyses 1 :

⋆ neutral Higgs, LEP [HiggsBounds 2.0.0]

$e^+e^- \to h_k Z, h_k \to bb$ or $h_k \to \tau\tau$ [LEP, EPJC46(2006)547)]

$e^+e^- \to h_k Z, h_k \to$ anything [OPAL, EPJC 27(2003)311]

$e^+e^- \to h_k Z, h_k \to$ invisible [hep-ex/0107032], DELPHI [hep-ex/0401022]
L3 [hep-ex/0501033], OPAL [hep-ex/0707.0373]

$e^+e^- \to h_k Z, h_k \to \gamma\gamma$ [LEP, LHWG note 2002-02]

$e^+e^- \to h_k Z, h_k \to$ hadrons [LEP combined limit]

$e^+e^- \to b\bar{b}h_k \to b\bar{b}b\bar{b}$, h_k CP even or odd, DELPHI [hep-ex/0410017]

$e^+e^- \to b\bar{b}h_k \to b\bar{b}\tau\tau$, h_k CP even or odd, DELPHI [hep-ex/0410017], OPAL [hep-ex/0111010]

$e^+e^- \to \tau\tau h_k \to \tau\tau\tau\tau$, h_k CP even or odd, DELPHI [hep-ex/0410017]

$e^+e^- \to h_k Z, h_k \to h_i h_i, h_i \to bb$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k Z, h_k \to h_i h_i, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k, h_i \to bb$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k \to h_i h_i, h_i \to bb$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k \to h_i h_i, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k Z, h_k \to h_i h_i, h_i \to bb, \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k \to bb, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

■ implemented analyses 2 :

⋆ neutral Higgs, Tevatron, single topology [HiggsBounds 2.0.0]

$p\bar{p} \to Zh_k \to llb\bar{b}$, CDF with 5.7 fb^{-1} [CDF note 10235] and with 2.7 fb^{-1} [hep-ex/0908.3534]

$p\bar{p} \to Zh_k \to llb\bar{b}$, D0 with 6.2 fb^{-1} [D0 note 6089]

$p\bar{p} \to Wh_k \to l\nu b\bar{b}$, D0 with 5.3 fb^{-1} [D0 note 6092] and with 1.1 fb^{-1} [hep-ex/0808.1970],
CDF with 5.6 fb^{-1} [CDF note 10217] and with 2.7 fb^{-1} [hep-ex/0906.5613]

$p\bar{p} \to bh_k \to 3b$ jets, CDF with 2.5 fb^{-1} [CDF note 10105],
D0 with 2.6 fb^{-1} [D0 note 5726] and with 1 fb^{-1}[hep-ex/0805.3556]

$p\bar{p} \to$ single $h_k \to WW$,
CDF with 3.0 fb^{-1} [hep-ex/0809.3930], CDF & D0 with 4.8/5.4 fb^{-1} [hep-ex/1005.3216]

$p\bar{p} \to h_k \to \tau\tau$ absolute limits,
D0 with 1 fb^{-1} [hep-ex/0805.2491] and with 2.2 fb^{-1} [D0 note 5740],
CDF with 1.8 fb^{-1} [hep-ex/0906.1014],
CDF & D0 with up to 2.2 fb^{-1} [hep-ex/1003.3363]

$p\bar{p} \to Wh_k \to 3W$, D0 with 3.6 fb^{-1} [D0 note 5873], CDF with 2.7 fb^{-1} [CDF note 7307v3]

$p\bar{p} \to bh_k \to b\tau\tau$,
D0 with 2.7 fb^{-1} [hep-ex/0912.0968, D0 note 5985] and with 4.3 fb^{-1} [D0 note 6083]

$p\bar{p} \to t\bar{t}h_k \to t\bar{t}b\bar{b}$, D0 with 2.1 fb^{-1} [D0 note 5739]

$p\bar{p} \to h_k \to Z\gamma$, D0 with 1.0 fb^{-1} absolute limits [hep-ex/0806.0611]

■ implemented analyses 3 :

⋆ neutral Higgs, Tevatron, combined topologies I [HiggsBounds 2.0.0]

$p\bar{p} \to V h_k \to b\bar{b}$+miss. $E_T (V = W, Z)$ SM combined,

CDF with 5.7 fb^{-1} [CDF note 10212] and with 2.1 fb^{-1} [hep-ex/0911.3935],

D0 with 6.4 fb^{-1} [D0 note 6087] and with 5.2 fb^{-1} [hep-ex/0912.5285]

$p\bar{p} \to h_k + X \to WW + X$ SM combined,

CDF with 5.3 fb^{-1} [CDF note 10102] and with 4.8 fb^{-1} [hep-ex/1001.4468],

D0 with 4.2 fb^{-1} [D0 note 5871] and with 6.7 fb^{-1} [D0 note 6082],

D0 with 5.4 fb^{-1} [hep-ex/1001.4481], CDF & D0 with 4.8-5.4 fb^{-1} [hep-ex/1001.4162]

$p\bar{p} \to h_k \to WW \to ll$, D0 with 3.0 fb^{-1} SM combined [D0 note 5757]

$p\bar{p} \to h_k + X$, CDF & D0 SM combined with 2-4.8 fb $^{-1}$ [hep-ex/0712.2383]

$p\bar{p} \to h_k + X \to \tau\tau$ SM combined,

CDF with 2.0 fb^{-1} [CDF note 9248],

D0 with 4.9 fb^{-1} [D0 note 5845] and with 1.0 fb^{-1} [hep-ex/0903.4800]

$p\bar{p} \to h_k + X$ SM combined, CDF & D0 with 1-2.4 fb^{-1} [hep-ex/0804.3423]

CDF & D0 with 3 fb^{-1} [hep-ex/0808.0534], D0 with 0.44 fb^{-1} [hep-ex/0712.0598]

CDF with 2.0-4.8 fb^{-1} [CDF note 9999], D0 with 2.1-5.4 fb^{-1} [D0 note 6008],

CDF & D0 with 2.1-5.4 fb^{-1} [hep-ex/0911.3930],

CDF & D0 SM with up to 6.7 fb^{-1} [hep-ex/1007.4587]

■ implemented analyses 4 :

⋆ neutral Higgs, Tevatron, combined topologies II [HiggsBounds 2.0.0]

$p\bar{p} \to h_k + X \to bb + X$, CDF with 4 fb^{-1} SM combined [CDF note 10010]

$p\bar{p} \to Vh_k \to VVV \to$ same sign di-lepton(e,mu) (V=W,Z),
D0 with 6.4 fb^{-1} SM combined [D0 note 6091]

$p\bar{p} \to h_k \to \gamma\gamma$ SM combined,
D0 with 4.2 fb^{-1} [D0 note 5858] and with 2.7 fb^{-1} [hep-ex/0901.1887],
CDF with 5.4 fb^{-1} [CDF note 10065]

⋆ charged Higgs, LEP [HiggsBounds 2.0.0]

$e^+e^- \to H^+H^- \to$ 4 jets [LEP, hep-ex/0107031],
$e^+e^- \to H^+H^- \to$ 4 jets [DELPHI, hep-ex/0404012],
$e^+e^- \to H^+H^- \to \tau\nu\tau\nu$ [DELPHI, hep-ex/0404012].

⋆ charged Higgs, Tevatron [HiggsBounds 2.0.0]

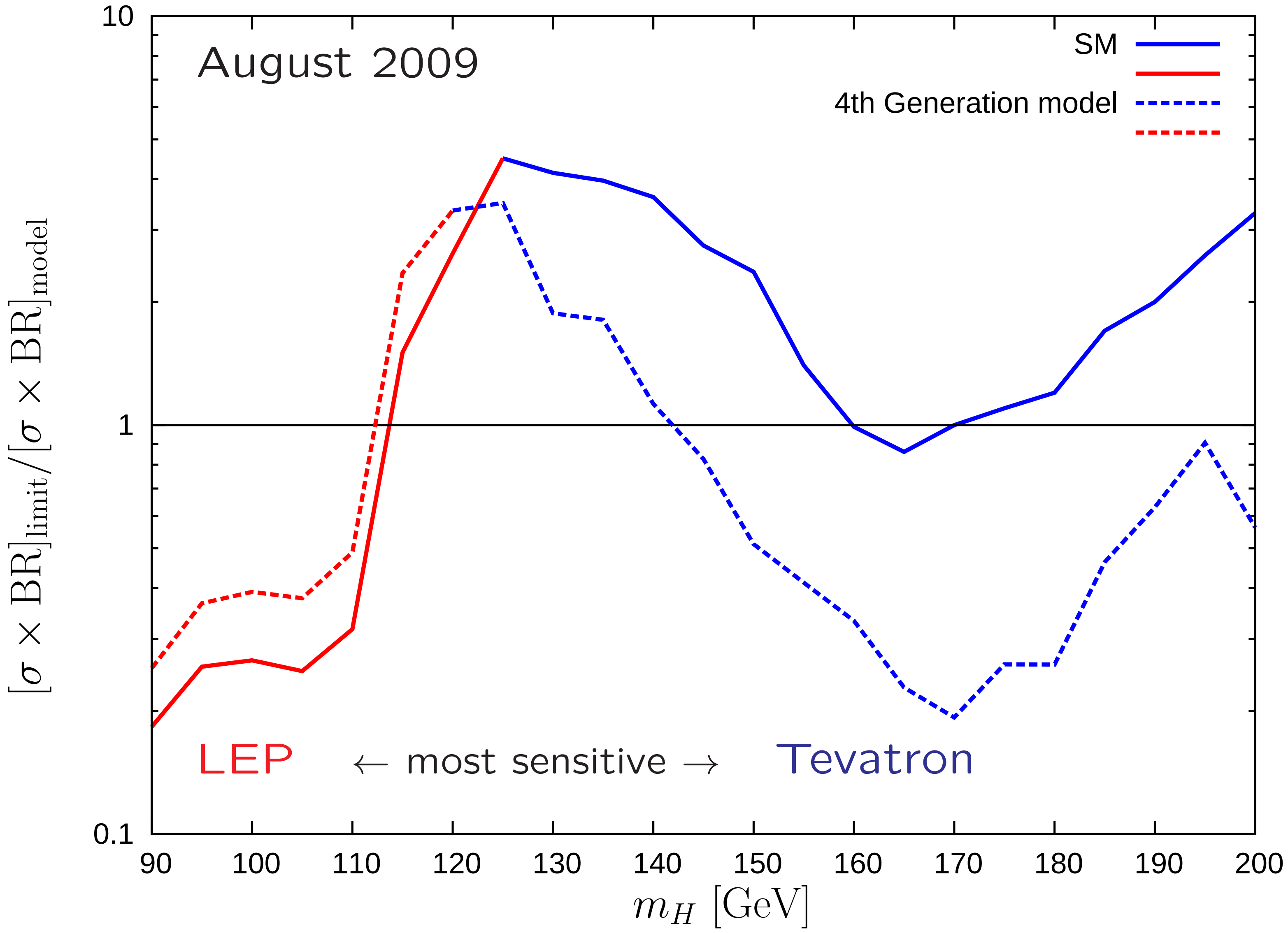
$p\bar{p} \to tt, t \to H + b(\&$ c.c.$), H^+ \to cs$, D0 with 1.0 fb^{-1} [hep-ex/0908.1811],
CDF with 2.2 fb^{-1} [hep-ex/0907.1269]

$p\bar{p} \to tt, t \to H + b(\&$ c.c.$), H^+ \to \tau\nu$, D0 with 1.0 fb^{-1} published [hep-ex/0908.1811]

implemented in total: 82 analyses (29 LEP, 53 Tevatron)

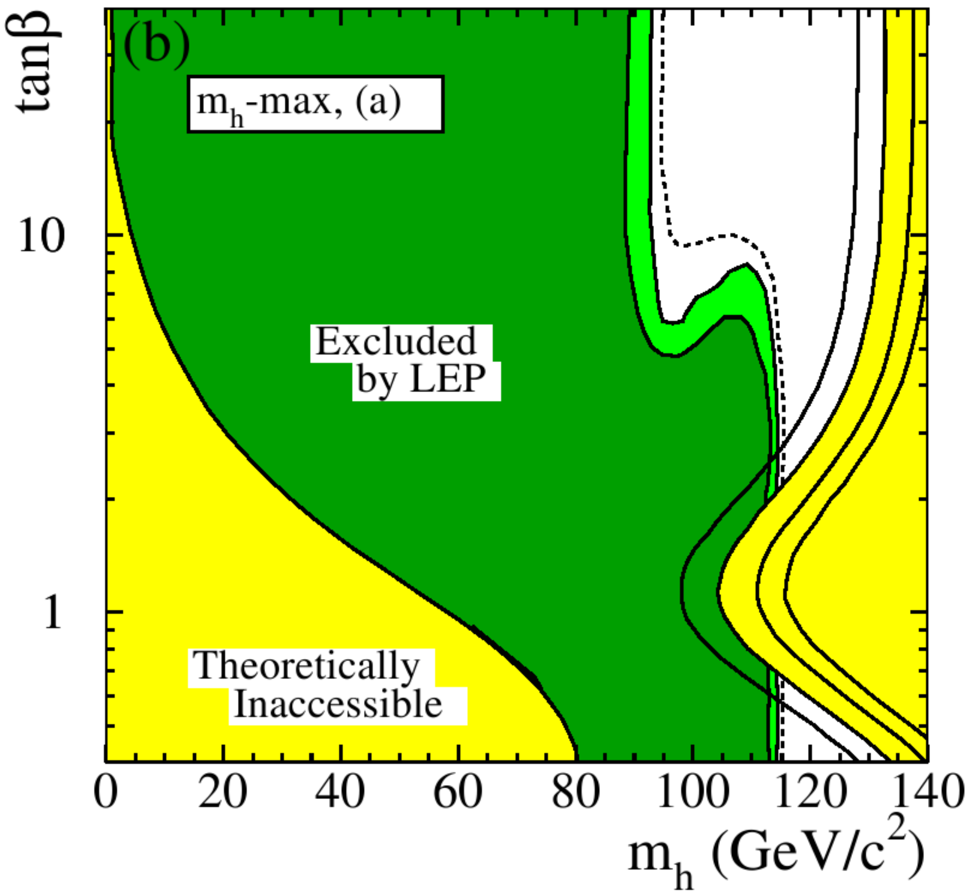
application 1: SM versus Fourth Generation Model exclusion

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



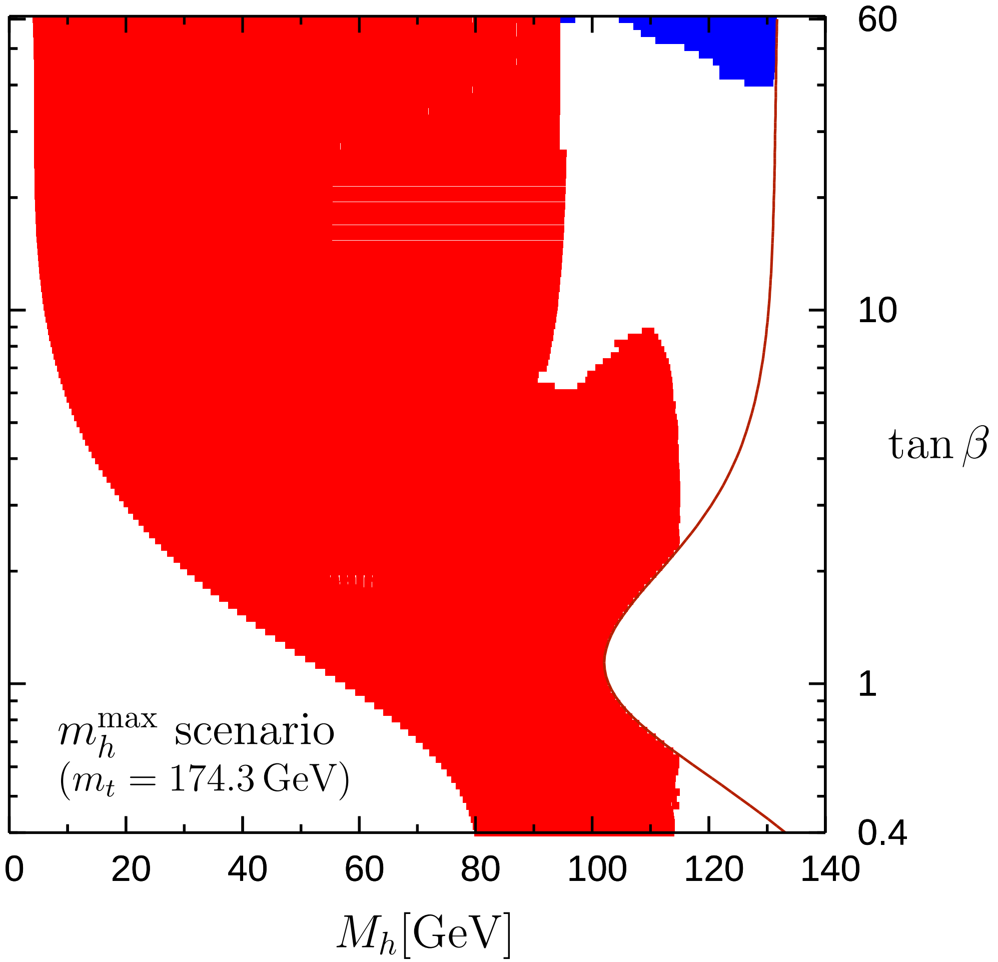
application 2: MSSM benchmark scenarios, exclusion update

a) [EPJC 46(2006)547]



b) **HiggsBounds**

with: new m_t, impoved m_h prediction,
Tevatron data included (🟦)



HiggsBounds: status and outlook

- The code is publicly available since Feb. 2009 (current version: 2.1.1)
  → `projects.hepforge.org/higgsbounds`
  - Tevatron results up to Feb. 2011 included
  - extended functionality ($H^{\pm}$ searches, `onlyP` analyses selection, ...)
  - HiggsBounds 2.0.0 publication accepted by Comput. Phys. Commun.

  very recently: version 3.1.3 beta released

  → includes: LHC data(!), SLHA input option, etc.

- Reception very good ($>$ 100 users). Code used in/by:
  FeynHiggs, CPsuperH, Fittino, MasterCode, 2HDMC, DarkSusy, SuperIso, S. Kraml et al., M. Carena et al., W. Bernreuther et al., ...

- Current work/plans:
  - use CL_{s+b} for given m_H and $\sigma \times$ BR to provide χ^2 (→ model fitting)
  - doubly charged Higgs searches, LEP searches for $m_H < 10\,\text{GeV}$
  - inclusion of width-dependent limits
  - optional addition: SusyBounds (Chargino, Neutralino bounds)

– Randall-Sundrum scalar sector constrained

– Randall-Sundrum scalar sector constrained

■ Randall Sundrum model basics: [Randall, Sundrum '99]

- space has $D = 3 + 1$ dimensions, metric:

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2\,, \quad \phi \in [0, \pi]\,.$$

  Spacetime is a slice of 5d anti-de-Sitter space:
  two boundaries: $\phi = \pi$: IR brane (our 3-space)
  $\phi = 0$: UV brane

- k, r_c are $\mathcal{O}(M_{\mathrm{Pl}})$ with $kr_c \approx 12$.
  This "little hierarchy" can be generated & stabilized [Goldberger, Wise '00]

- resolution of the hierarchy problem: Why is the EW scale $<< M_{\mathrm{Pl}}$?:
  mass parameters in the fundamental 5d model m_0 appear in our visible space as:

$$m = m_0 e^{-kr_c\pi} \approx m_0 10^{-16}\,.$$

- propagating in extra dimension:
  originally: only gravity,
  nowadays: gauge bosons, fermions [EW & flavour observables!]

  But: Higgs needs to be localized on/near IR brane [hierarchy problem!]

■ Randall Sundrum scalar sector:

- There is one graviscalar in 5d: the radion φ
  (typically the lightest new particle to appear)

- 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 on IR brane, R: Ricci scalar.

  → Radion φ and physical Higgs h mix to form two mass eigenstates

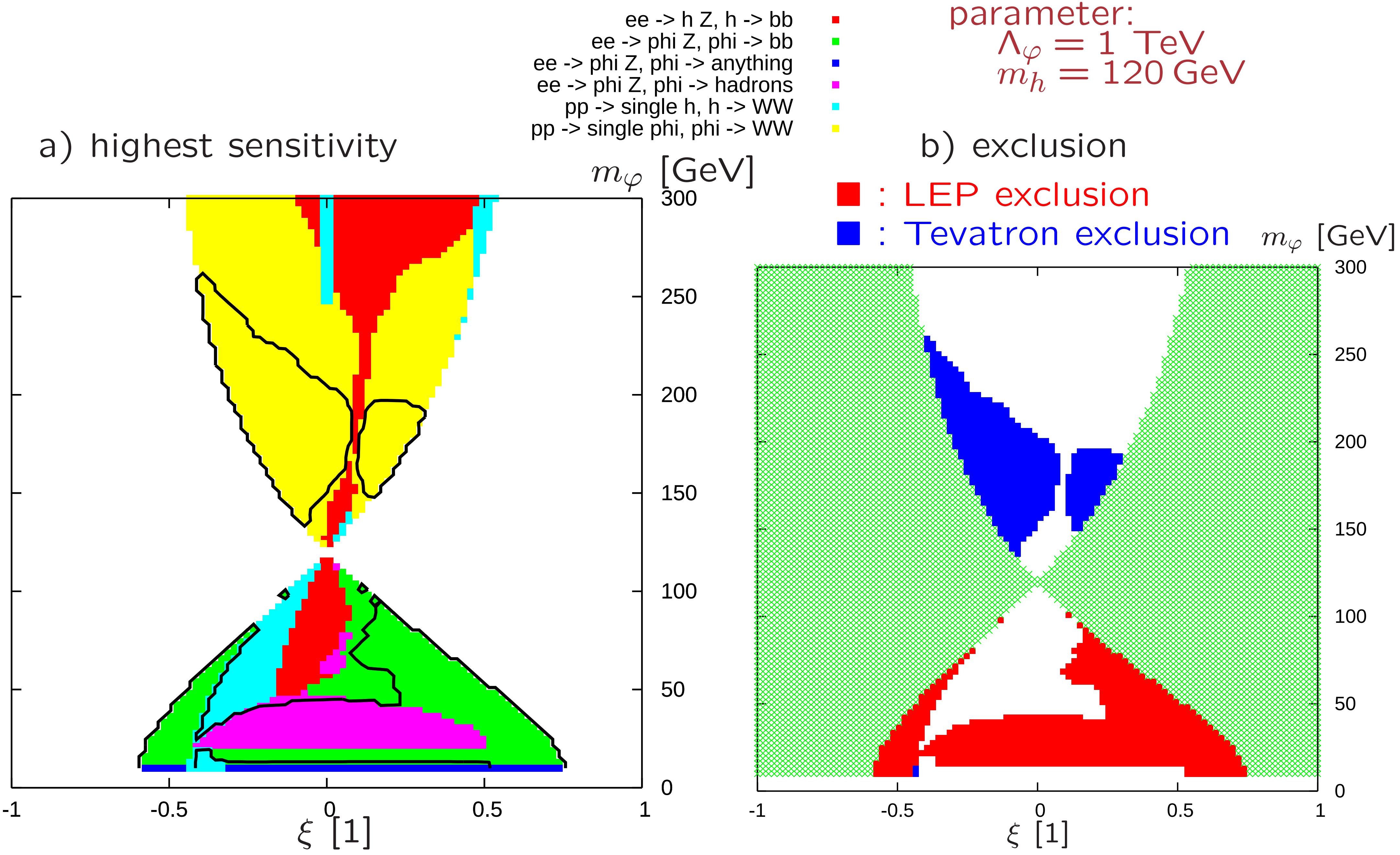
- φ coupling to massive fermions and gauge bosons $\propto$ mass, but
  - ⋆ $\varphi\, b\bar{b}$ coupling suppressed wrt SM Higgs
  - ⋆ $\varphi\, gg$ coupling enhanced wrt SM Higgs
  - ⋆ $\varphi\, \gamma\gamma$ coupling suppressed wrt SM Higgs

→ two scalars in the spectrum with modified couplings
compared to the SM Higgs boson

[Selected Projects, RS scalar sector constrained]

Exclusion range and sensitivity map: $\xi - m_\varphi$ plane

parameter:
$\Lambda_\varphi = 1$ TeV
$m_h = 120$ GeV

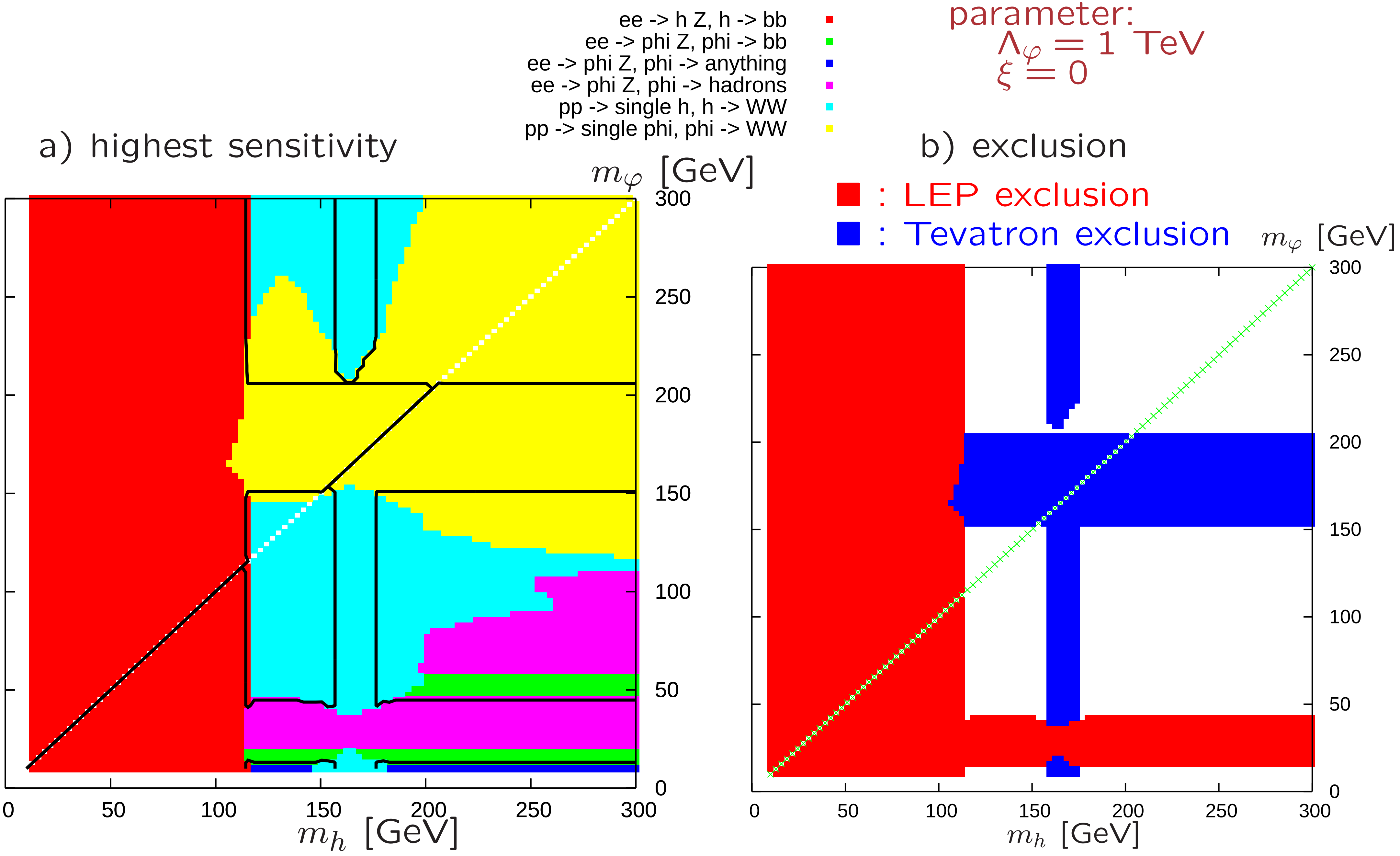


a) highest sensitivity

b) exclusion

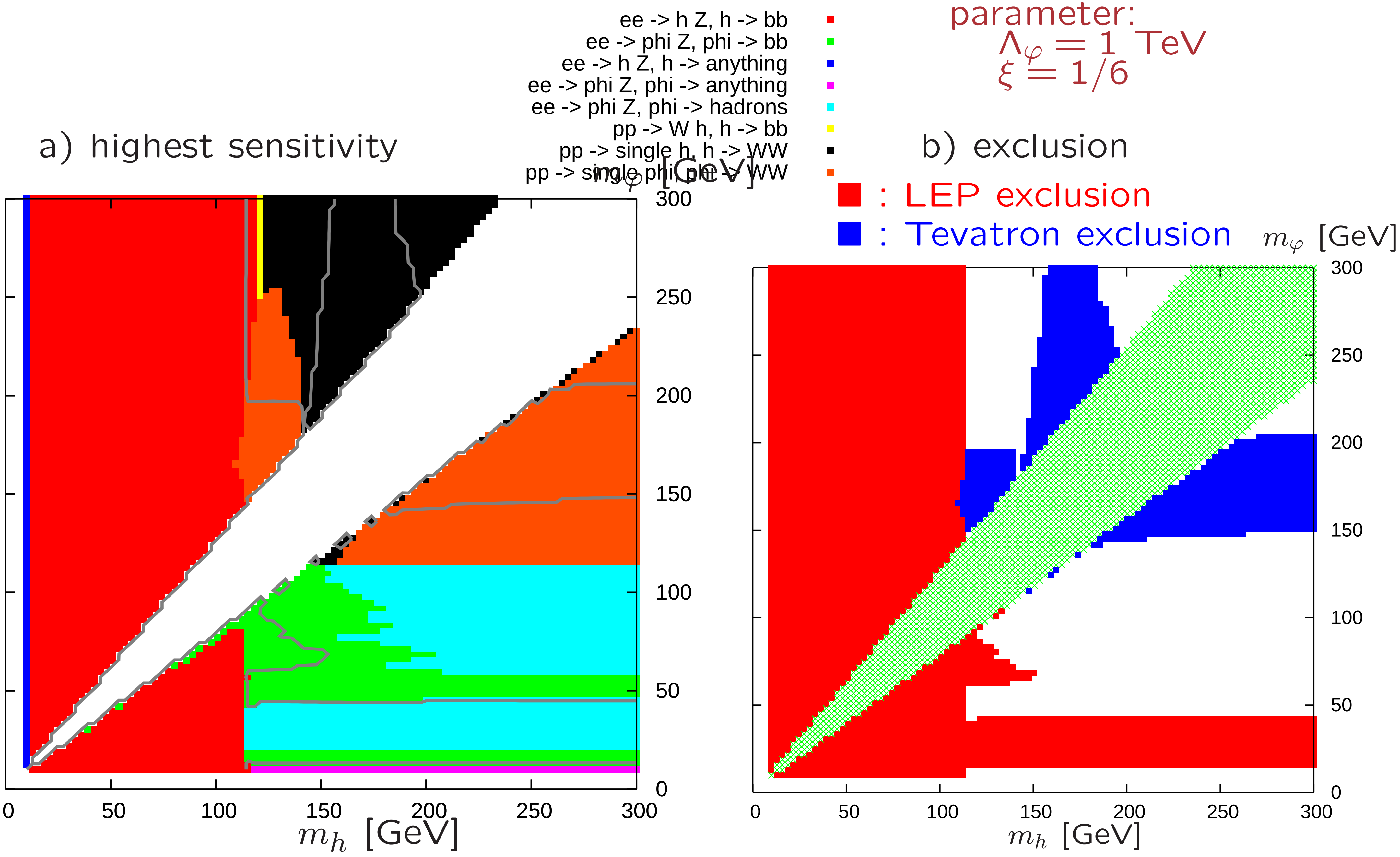
Exclusion range and sensitivity map: $m_h - m_\varphi$ plane

parameter:
$\Lambda_\varphi = 1$ TeV
$\xi = 0$



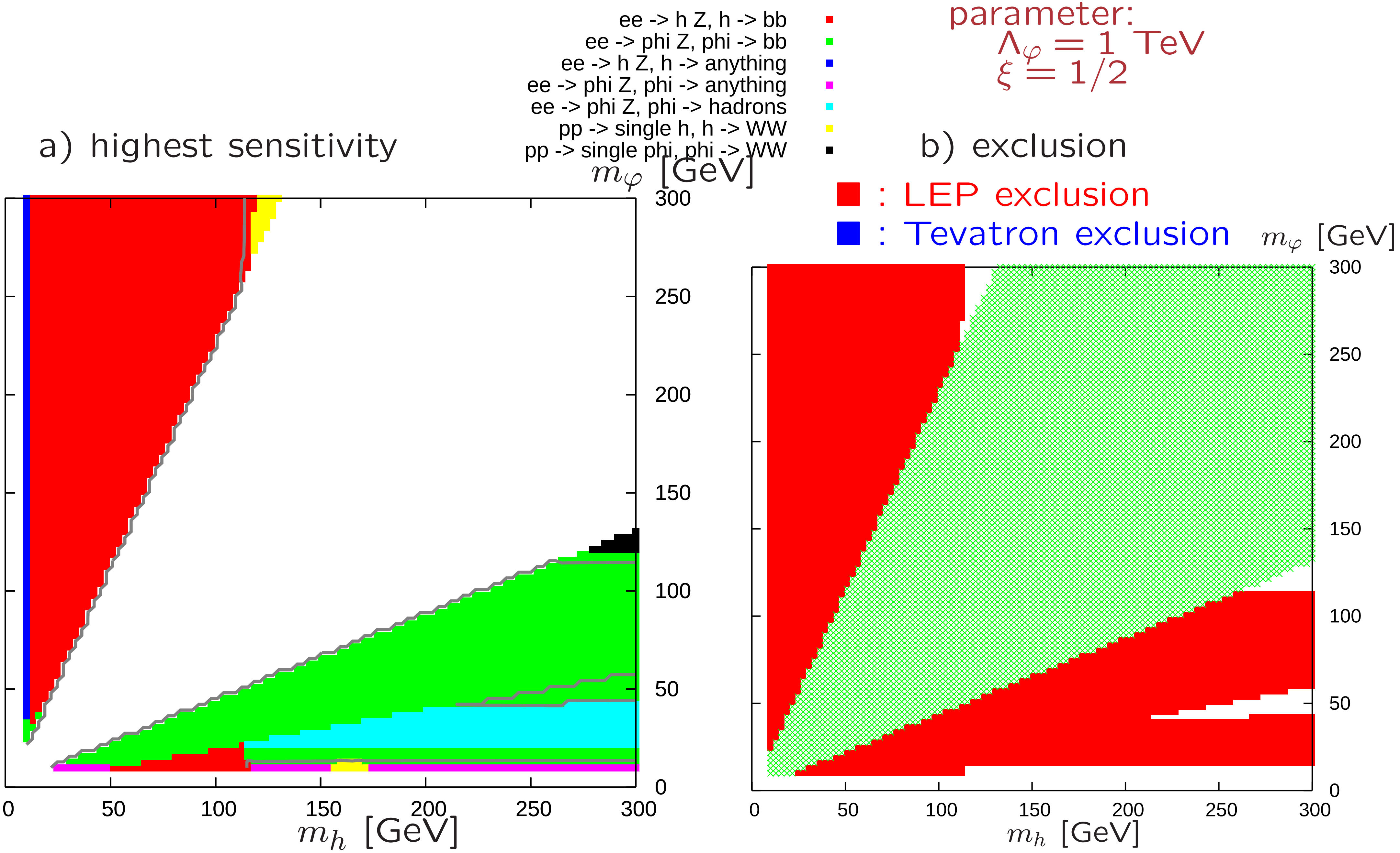
Exclusion range and sensitivity map: $m_h - m_\varphi$ plane

parameter:
$\Lambda_\varphi = 1$ TeV
$\xi = 1/6$



Exclusion range and sensitivity map: $m_h - m_\varphi$ plane

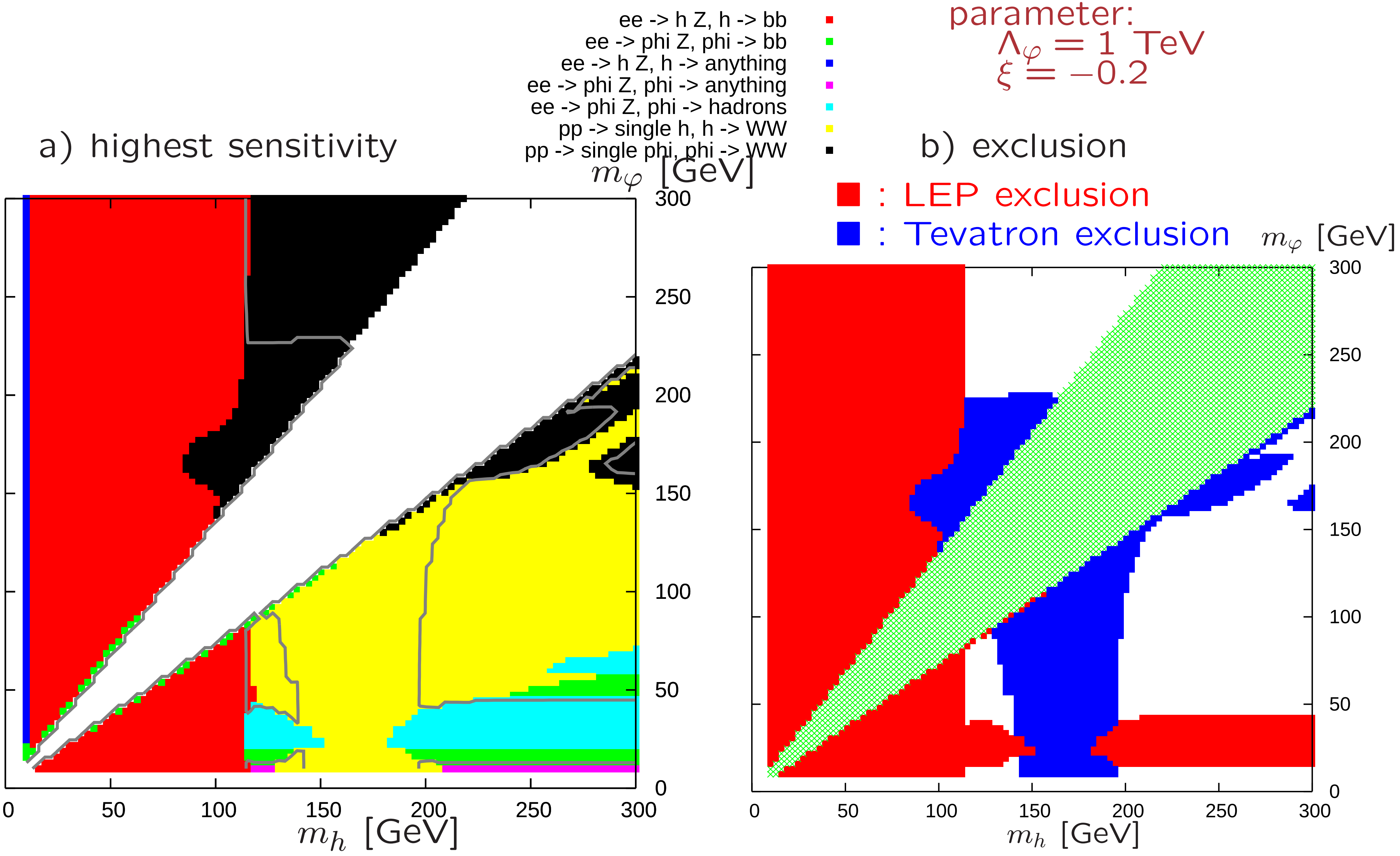
parameter:
$\Lambda_\varphi = 1$ TeV
$\xi = 1/2$


a) highest sensitivity

b) exclusion

Exclusion range and sensitivity map: $m_h - m_\varphi$ plane

parameter:
$\Lambda_\varphi = 1$ TeV
$\xi = -0.2$



a) highest sensitivity

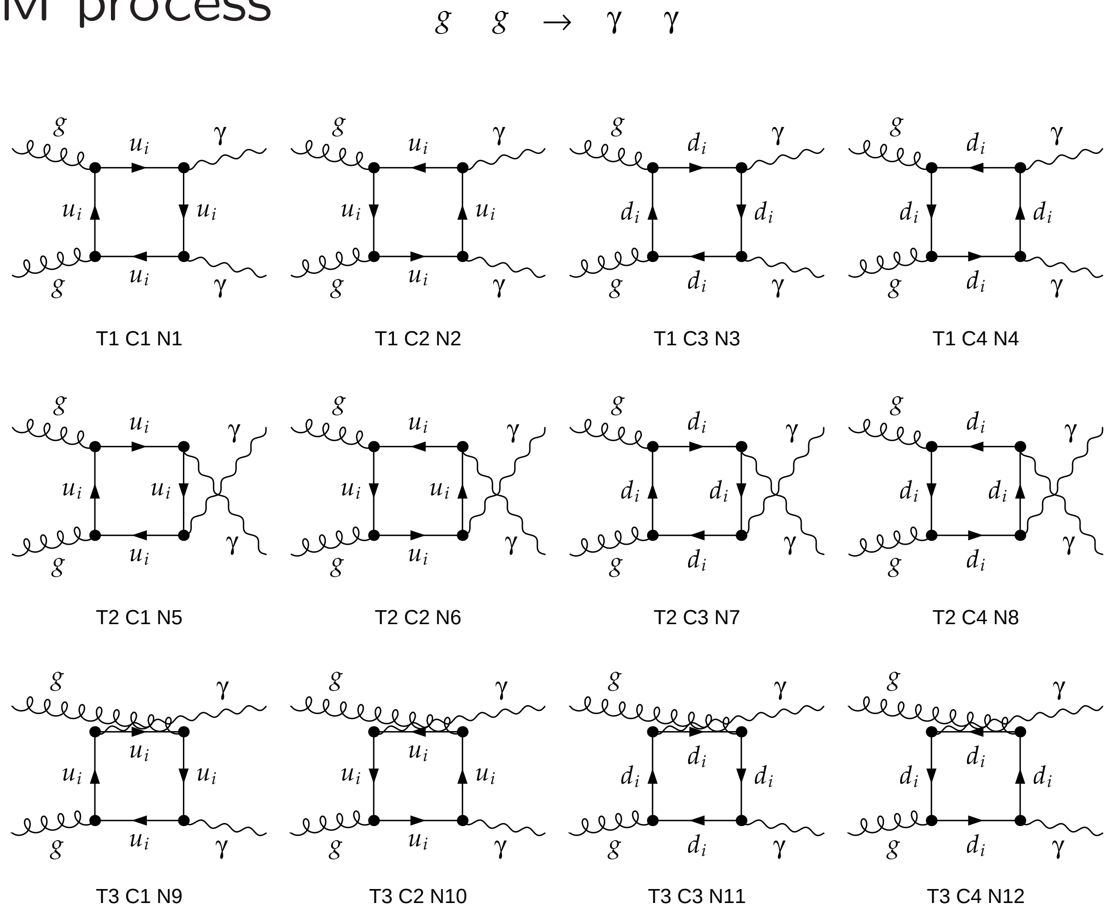
b) exclusion

– New physics in $\gamma\gamma/WW/ZZ$ production

– New physics in $\gamma\gamma/WW/ZZ$ production

■ squark & Kaluza-Klein quark contributions to $gg \to \gamma\gamma$

SM process



In general:

all particles carying colour and electrical charge contribute.

Supersymmetry (MSSM):

– additional contributions by quark superpartners (squarks)

– squark masses $\propto M_{\mathsf{SUSY}}$

Universal Extra Dimensions (UED):

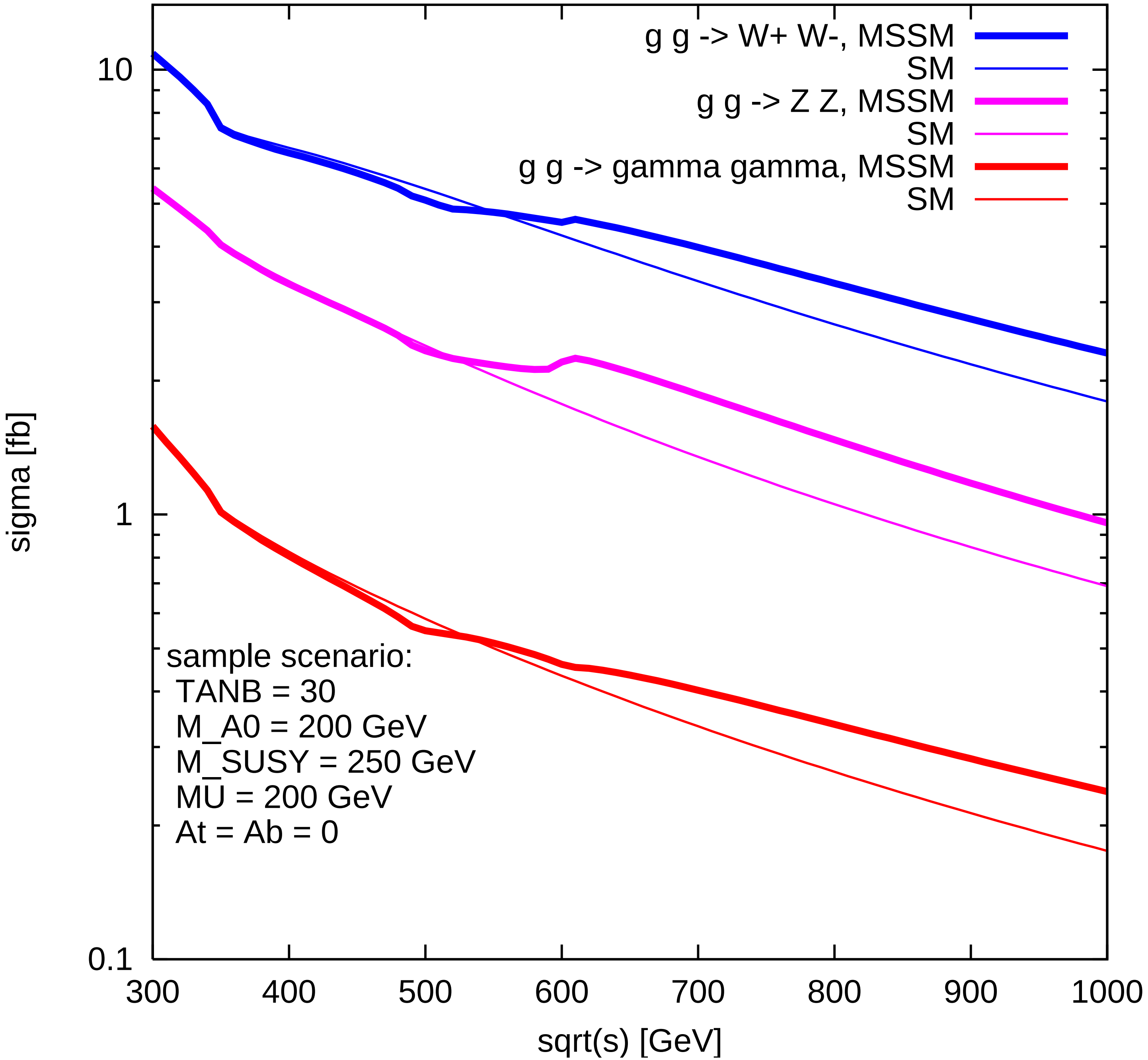
– additional contributions by Kaluza-Klein (KK) excitations of the quarks

– KK quark masses:

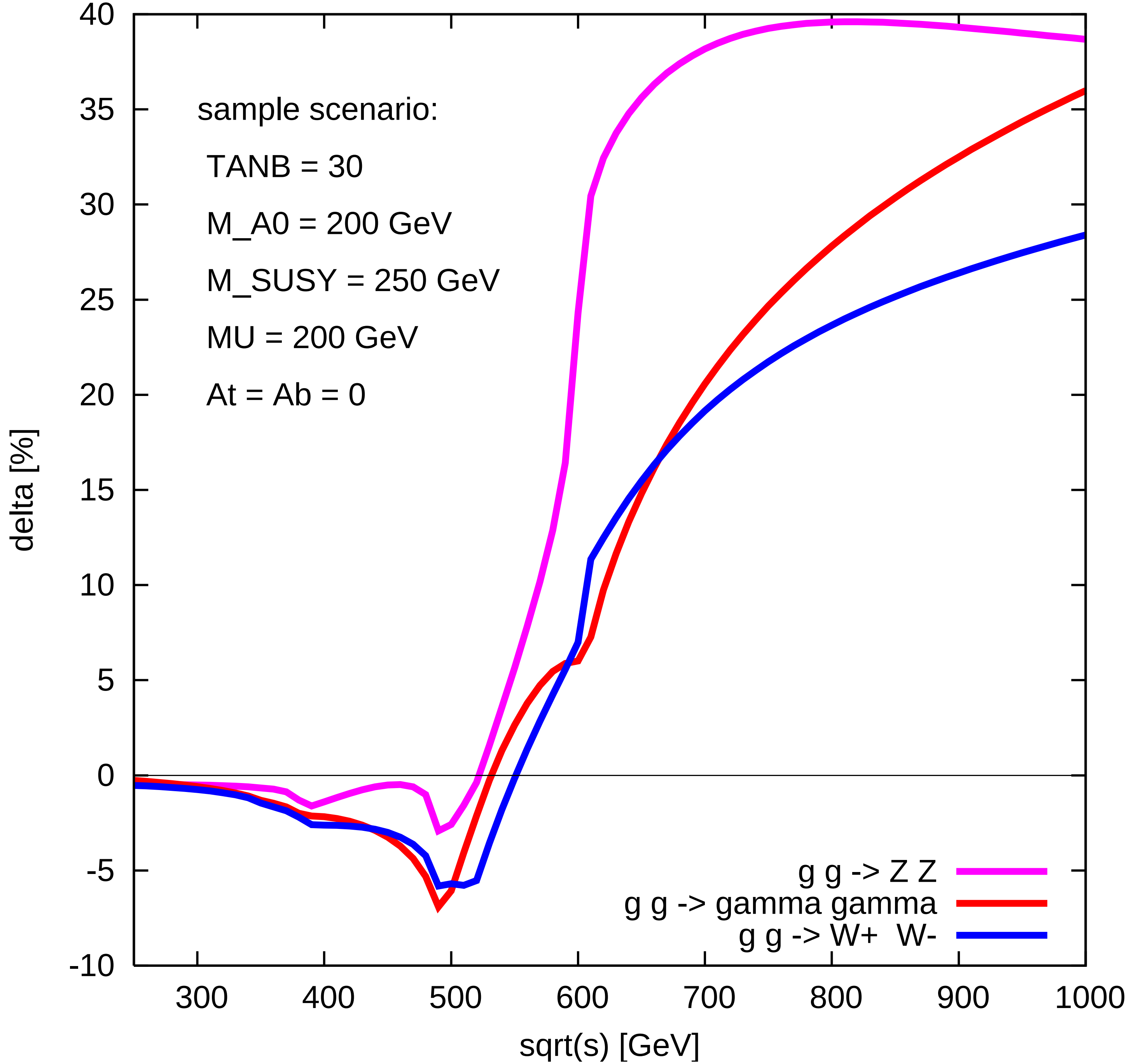
$$m_q^{(n)} = \sqrt{m_q^2 + n^2 m_{\mathsf{KK}}^2} \approx n\, m_{\mathsf{KK}}$$

LHC, $\sigma(gg \to \gamma\gamma/ZZ/W^+W^-)$ in the MSSM:

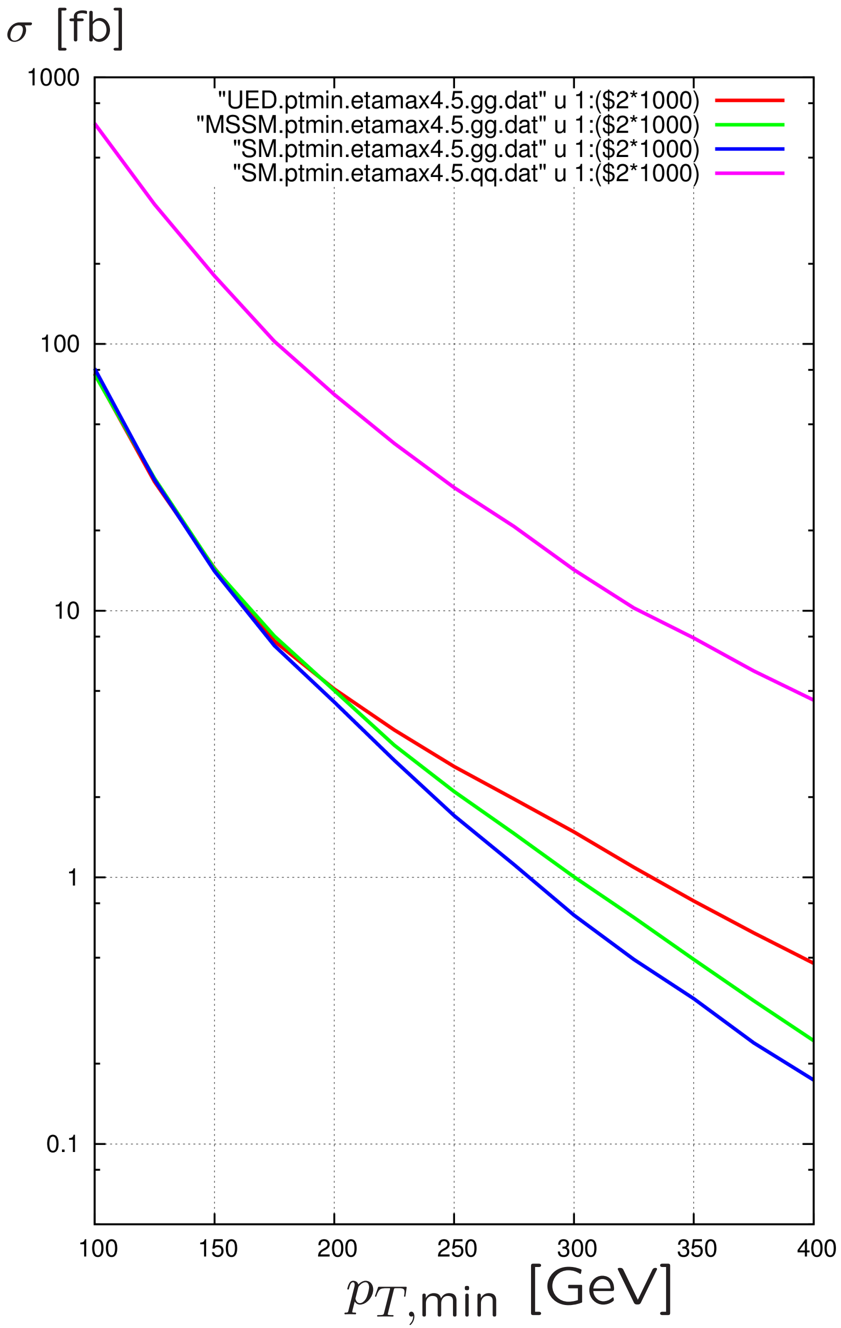
[OBr '11]



LHC, $\sigma(gg \to \gamma\gamma/ZZ/W^+W^-)$: MSSM–SM relative difference: [OBr '11]



LHC(14 TeV), $\sigma(pp \to \gamma\gamma)$: UED/MSSM–SM relative difference: [OBr '11]



cuts:

$p_T > p_{T,\text{min}}$

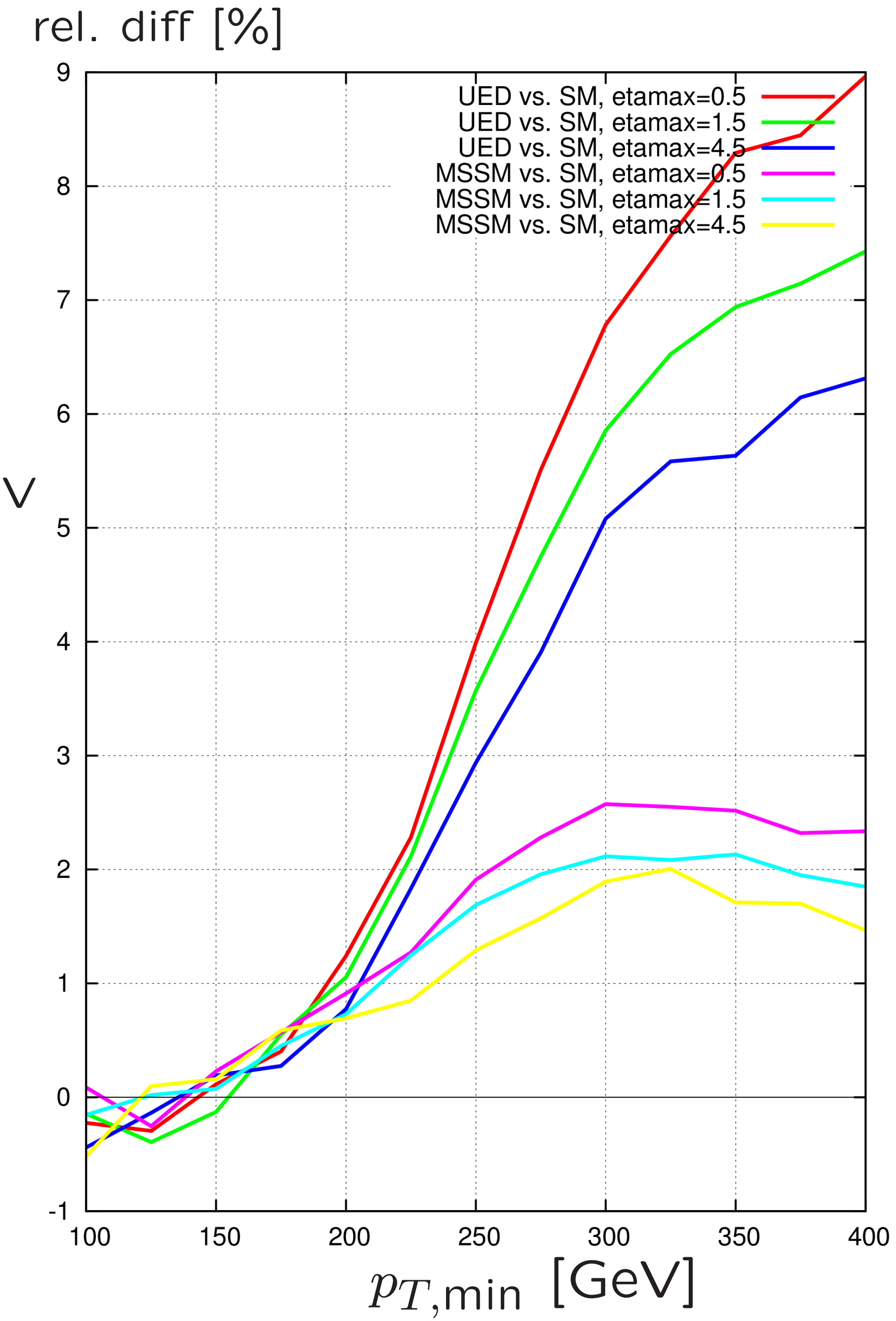
$|\eta| < \eta\text{max}$

MSSM:

$M_{\text{SUSY}} = 250\,\text{GeV}$

UED:

$M_{\text{KK}} = 250\,\text{GeV}$



LHC(14 TeV), $\sigma(pp \to \gamma\gamma)$: UED–SM relative difference: [OBr '11]

cuts:

$p_T > p_{T,\text{min}}$

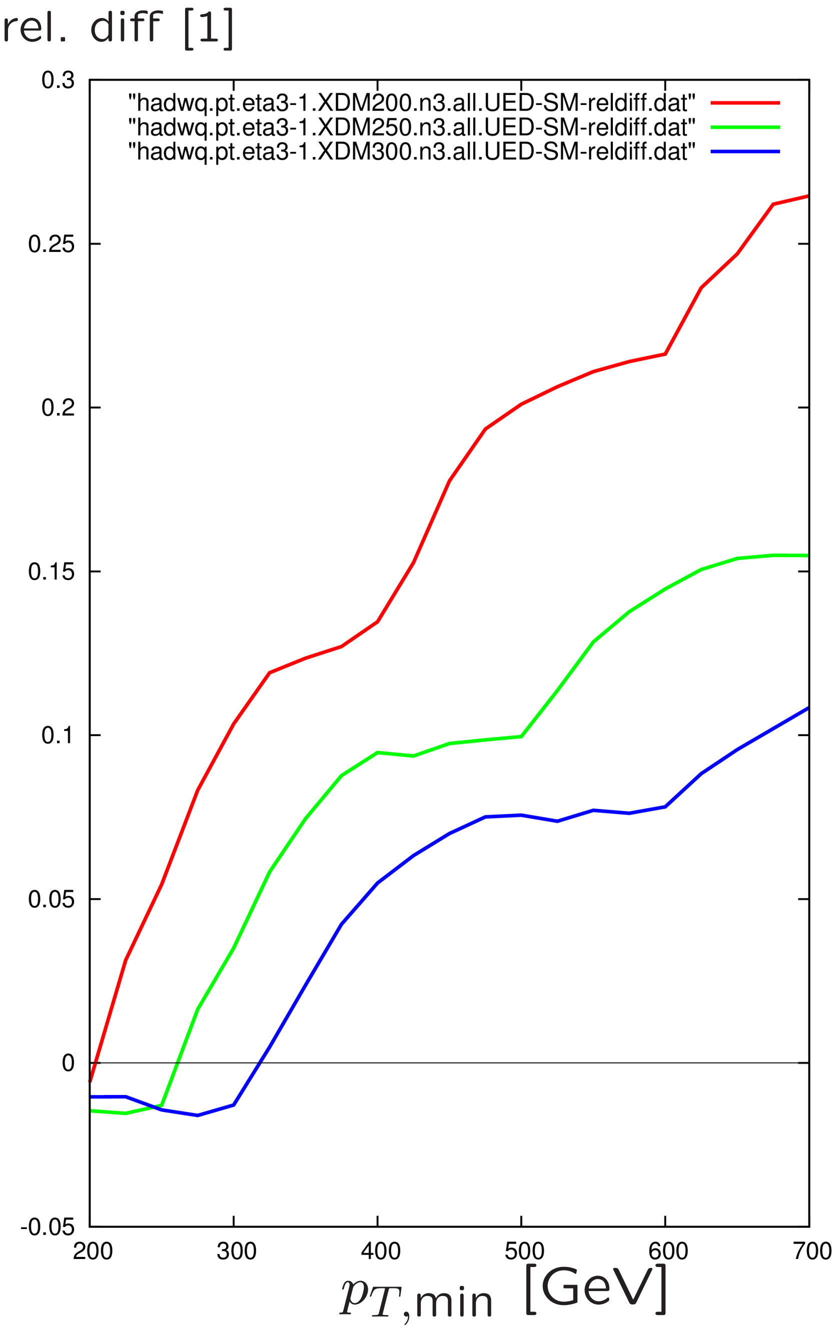
$|\eta| < 1$

UED::

$M_{\text{KK}} = 200$ GeV

$M_{\text{KK}} = 250$ GeV

$M_{\text{KK}} = 300$ GeV



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 Higgsstrahlung is now really known at NNLO QCD accuracy. The impact of this extra corrections is small. Nevertheless, vector boson fusion calculations should also be revisited.
- HiggsBounds: powerful tool for constraining Higgs sectors of new physics models systematically.
- Current Tevatron results rule out additional parts of the Randall-Sundrum model's parameter space (compared to LEP results).
- The di-photon and WW/ZZ production show potential for the discrimination between models. Further investigations are needed.

- 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 $\chi_1^0, \dots, \chi_4^0$

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:

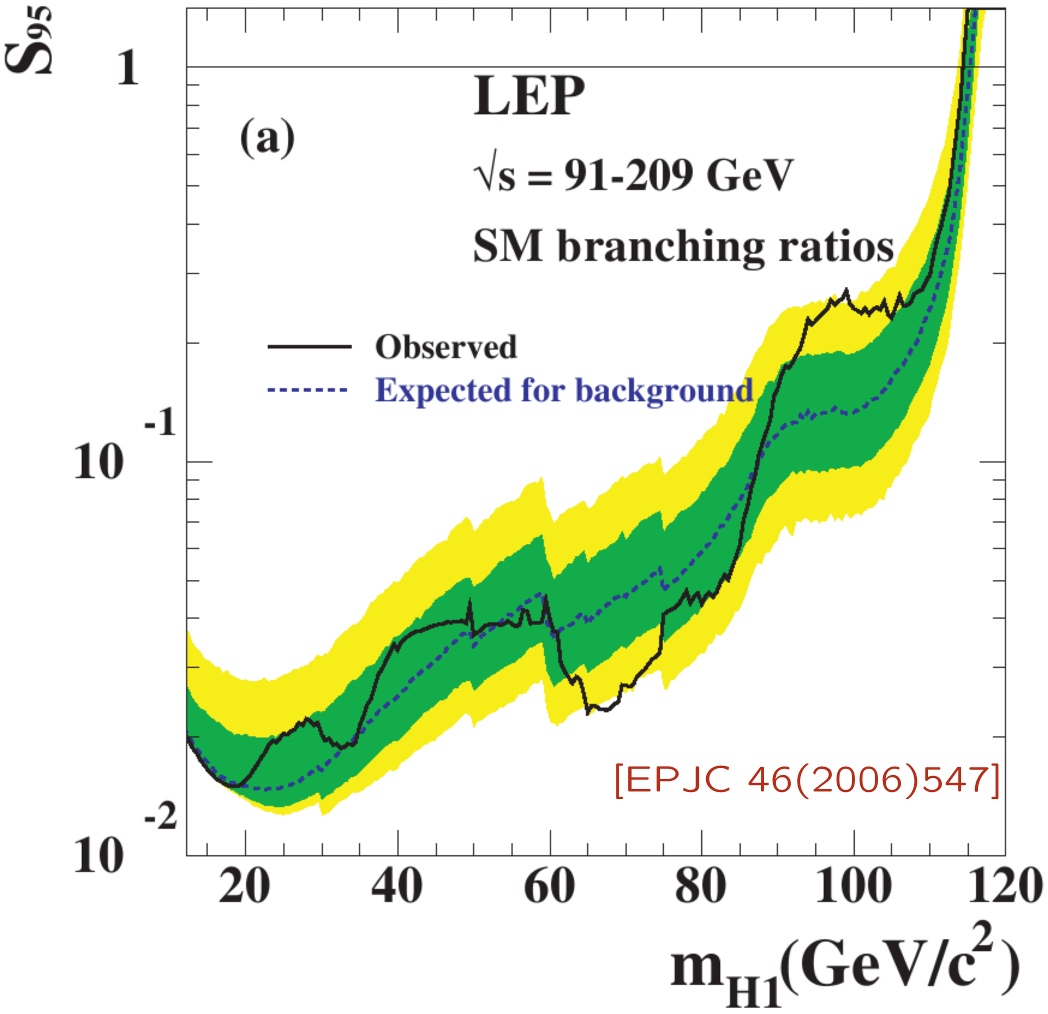
- all interactions involve an *even* number of superpartners
  → superpartners can only be pair-produced

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

– HiggsBounds implementation

Higgs search results: example 1: LEP SM combined limit

exclusion = rejection of the Higgs hypothesis



[EPJC 46(2006)547]

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

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

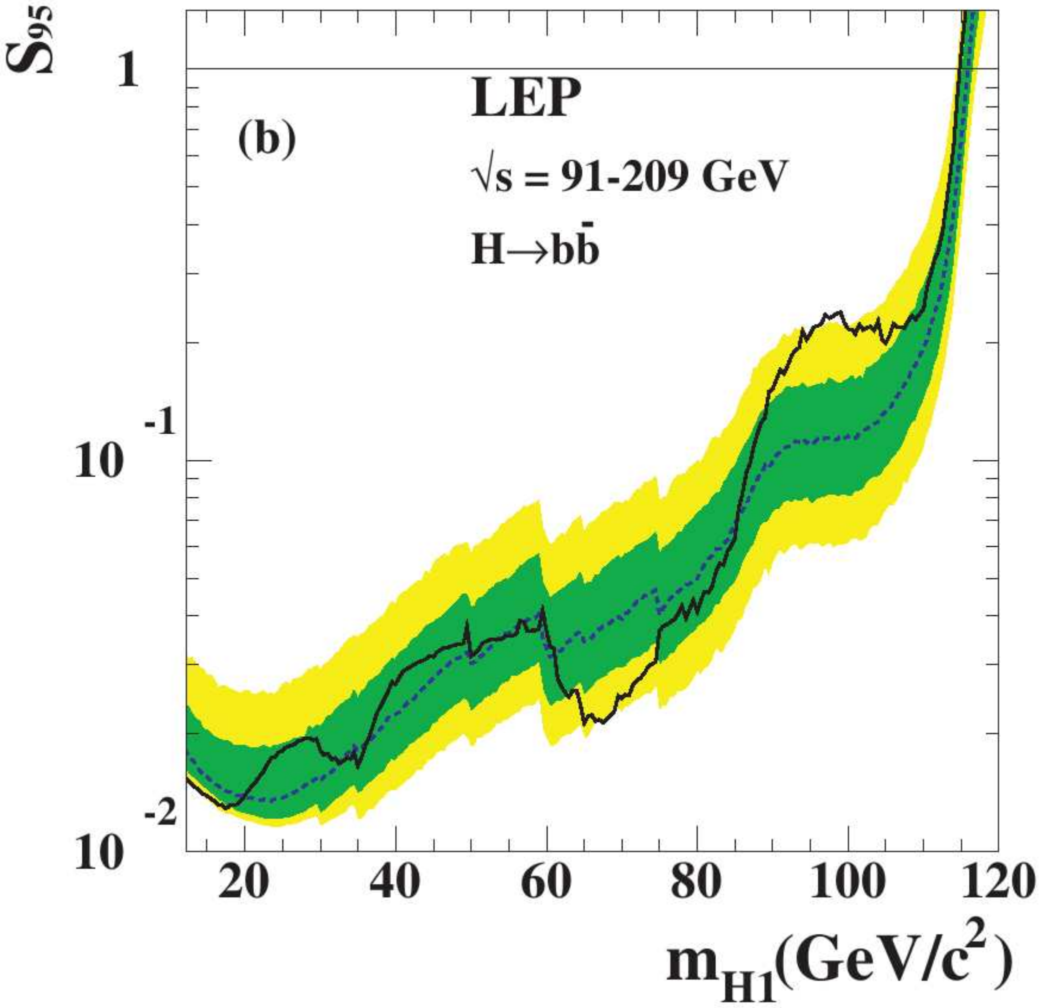
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\text{min}}(m_{H1})$$

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

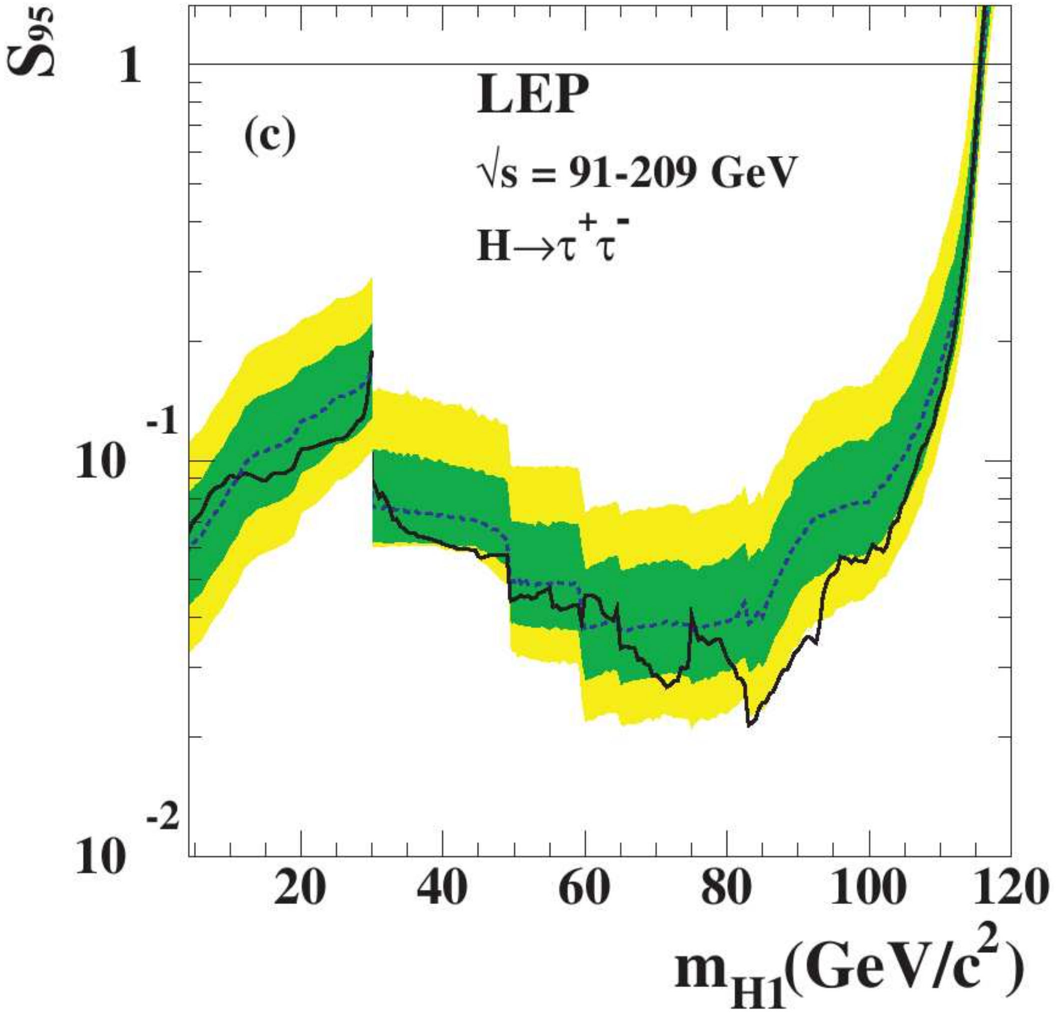
is said to be excluded at the 95% C.L.

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

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

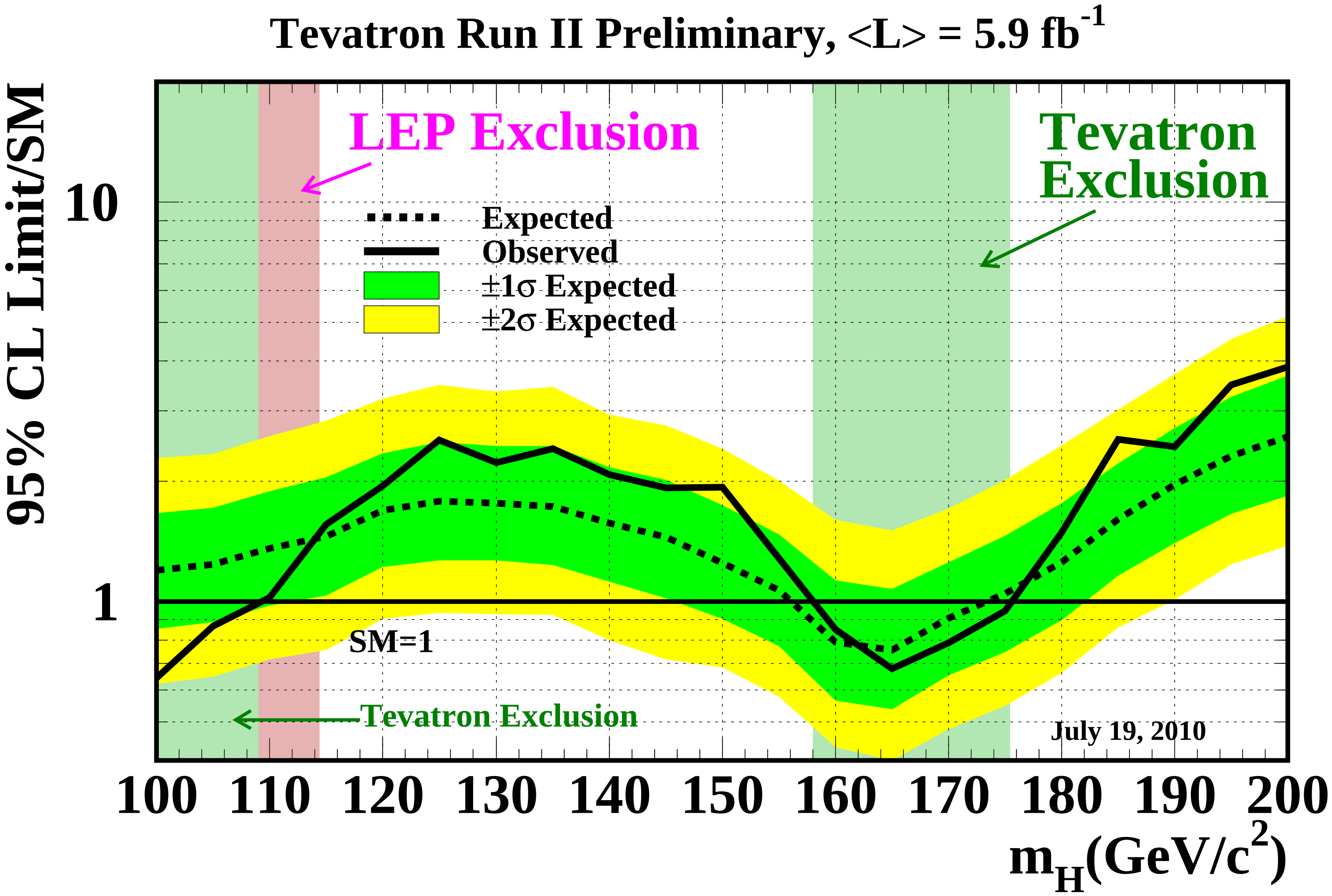


b) ... BR($H \to \tau^+\tau^-$)=1



[EPJC 46(2006)547]

example 3: Tevatron SM combined limit [CDF & DØ '10]



– HiggsBounds implementation

first a definition : **analysis application** X:

application of a certain analysis A_i
to a certain Higgs boson h_k (or a set)

That means: X corresponds to:

- ⋆ a signal topology (or a set),
- ⋆ the corresponding cross section prediction $Q_{\text{model}}(X)$,
- ⋆ observed cross section limit $Q_{\text{observed}}(X)$ of analysis A,
- ⋆ expected cross section limit $Q_{\text{expected}}(X)$ of analysis A.

– HiggsBounds implementation

for an analysis application X:

- 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 the correponding search topology for given Higgs masses + deviations from the reference.

- 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 application at 95% C.L.

→ Problem : how to combine analysis applications
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 application of highest statistical sensitivity.

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

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