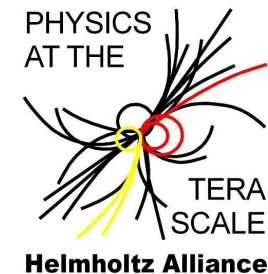


Higgs Bosons and Other New Phenomena

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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)
 - 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:

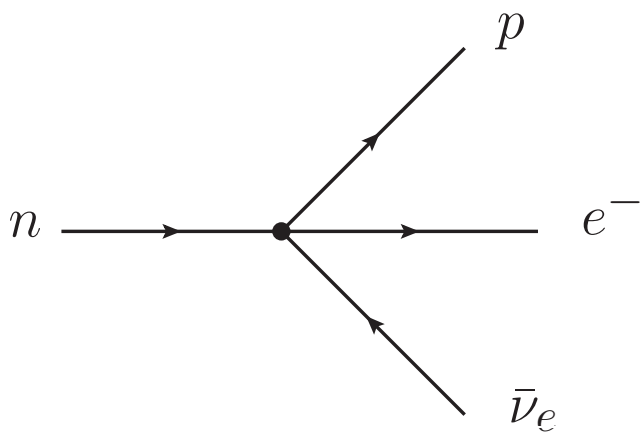
Hahn, Meitner: observation : $n \rightarrow p e^- +$ missing energy

Puzzle:

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

Bohr: energy is *really* missing Pauli (1930): $n \rightarrow p e^- +$ neutrino
(very weakly interacting)

Fermi (1934): “Fermi Model”



- short-range interaction
- good description for energies well below $G_F^{-1/2} \approx 300$ 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

■ Beta decay 1911:

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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

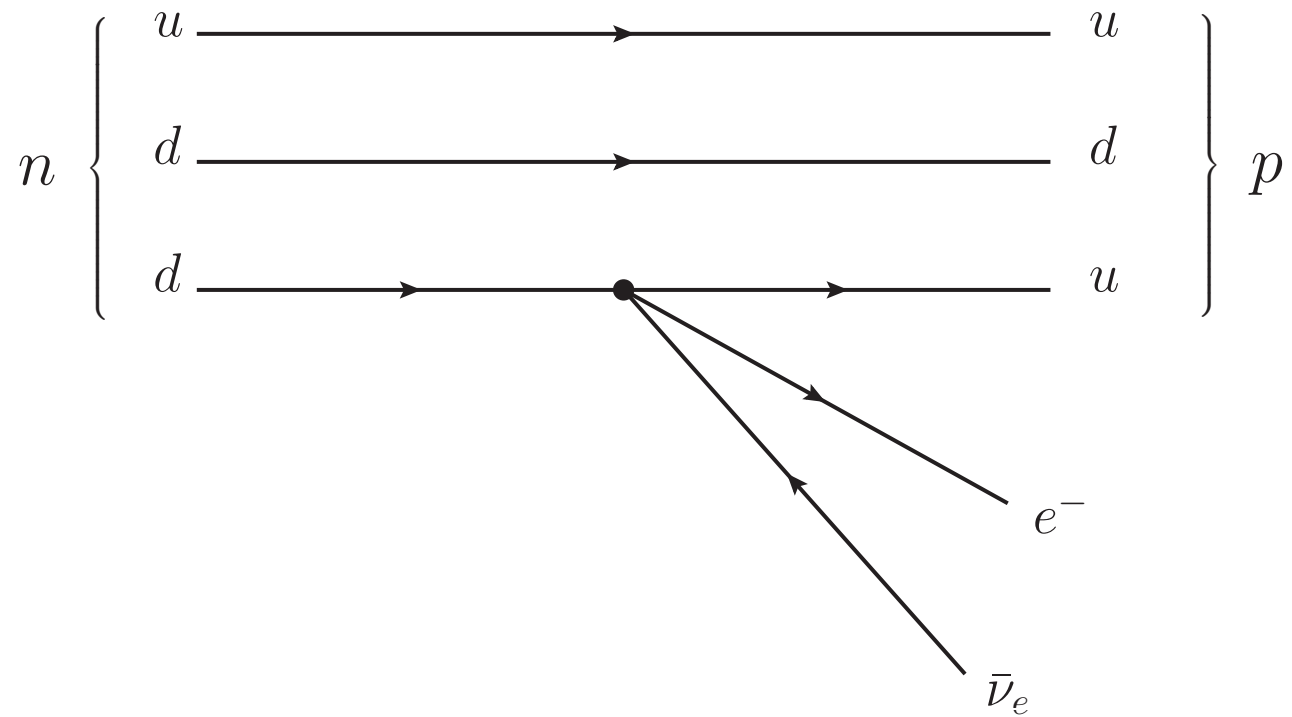
$$\mathcal{L} \propto G_F [\bar{\psi}_A \underbrace{(\gamma_\mu - \gamma_\mu \gamma_5)}_{V-A} \psi_B] [\bar{\psi}_C \underbrace{(\gamma^\mu - \gamma^\mu \gamma_5)}_{V-A} \psi_D]$$

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

- short-range interaction of left-chiral components

■ Beta decay: current understanding:

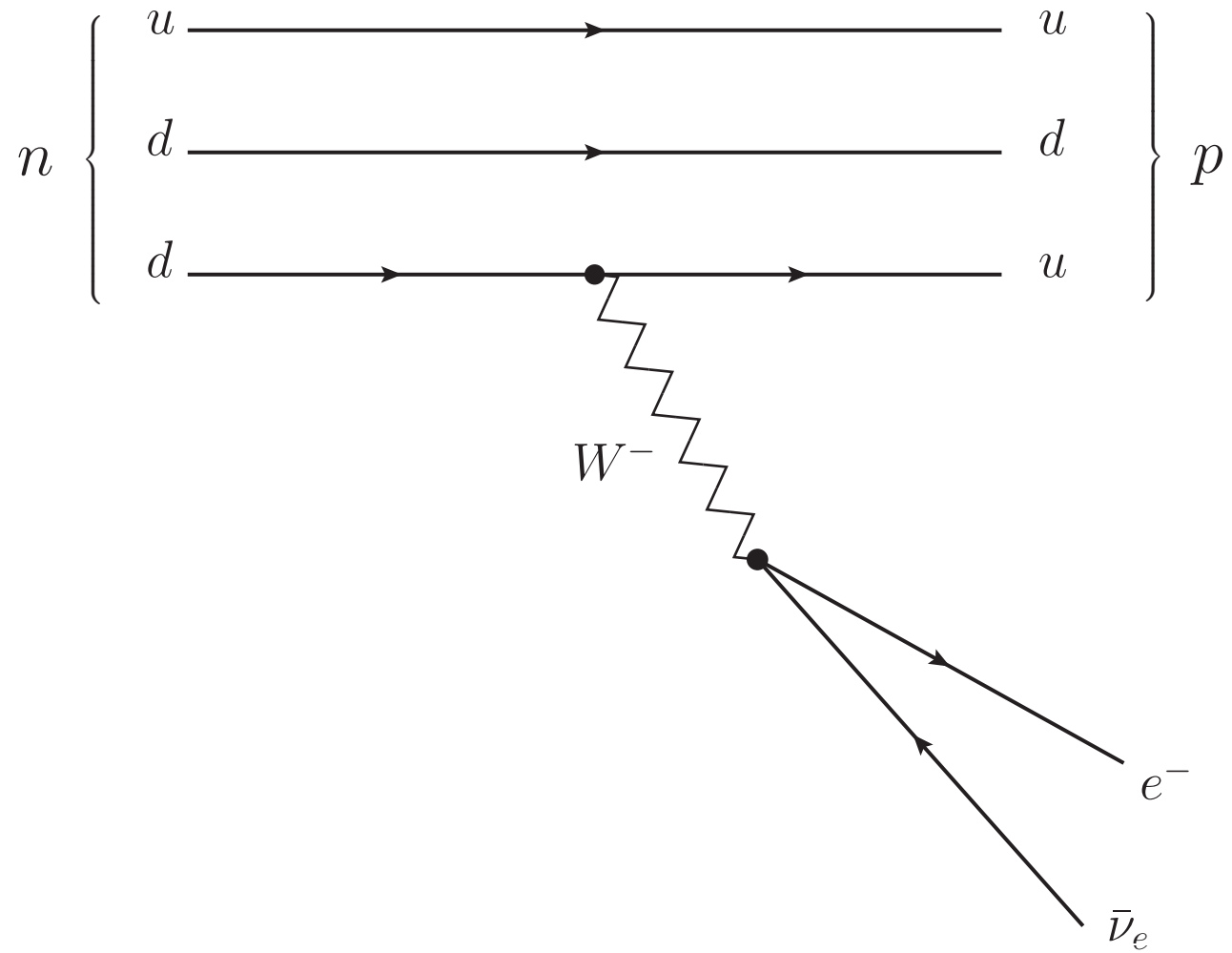
Quark parton model [Bjorken, Paschos; Feynman 1969]



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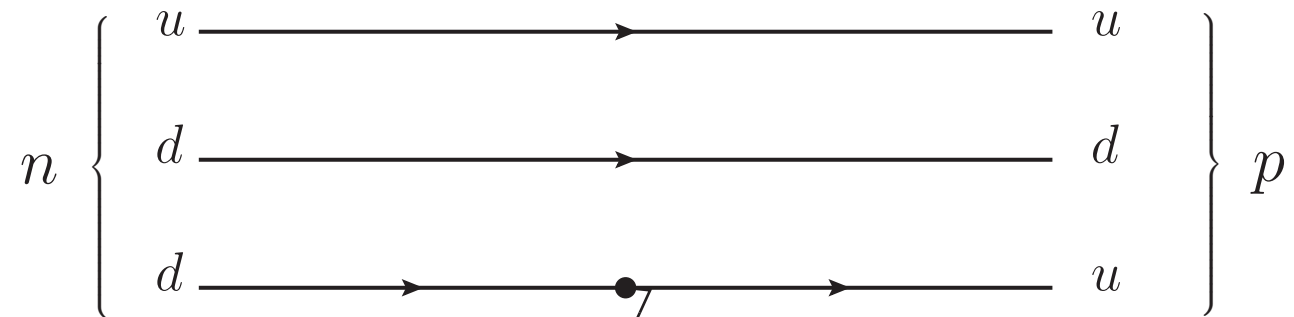
with electroweak interaction [Glashow 1961, Salam 1968, Weinberg 1967]



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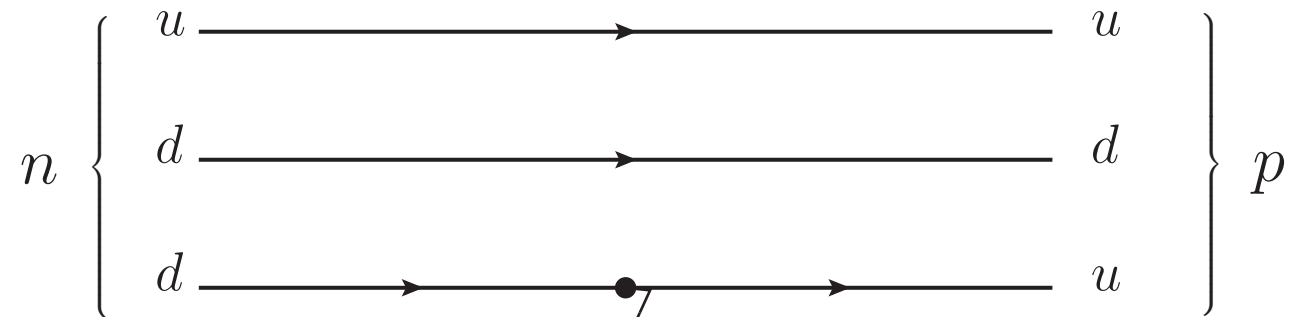


- unification of electrom. and weak force
- massive vector bosons W^+ , W^- , Z
 - short range interaction
- $SU(2) \times U(1)$ gauge symmetry
 - forbids explicit mass terms for W^+ , W^- , Z
- spontaneous symmetry breaking via Higgs mechanism
 - one scalar multiplet acquires a VEV
 - W^+ , W^- , Z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

■ Beta decay: current understanding:

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

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



- unification of electrom. and weak force
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→ confirmations:

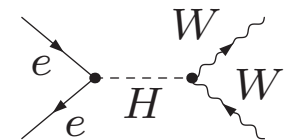
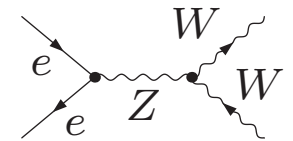
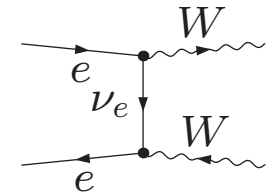
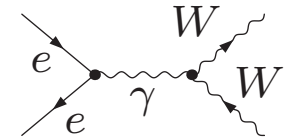
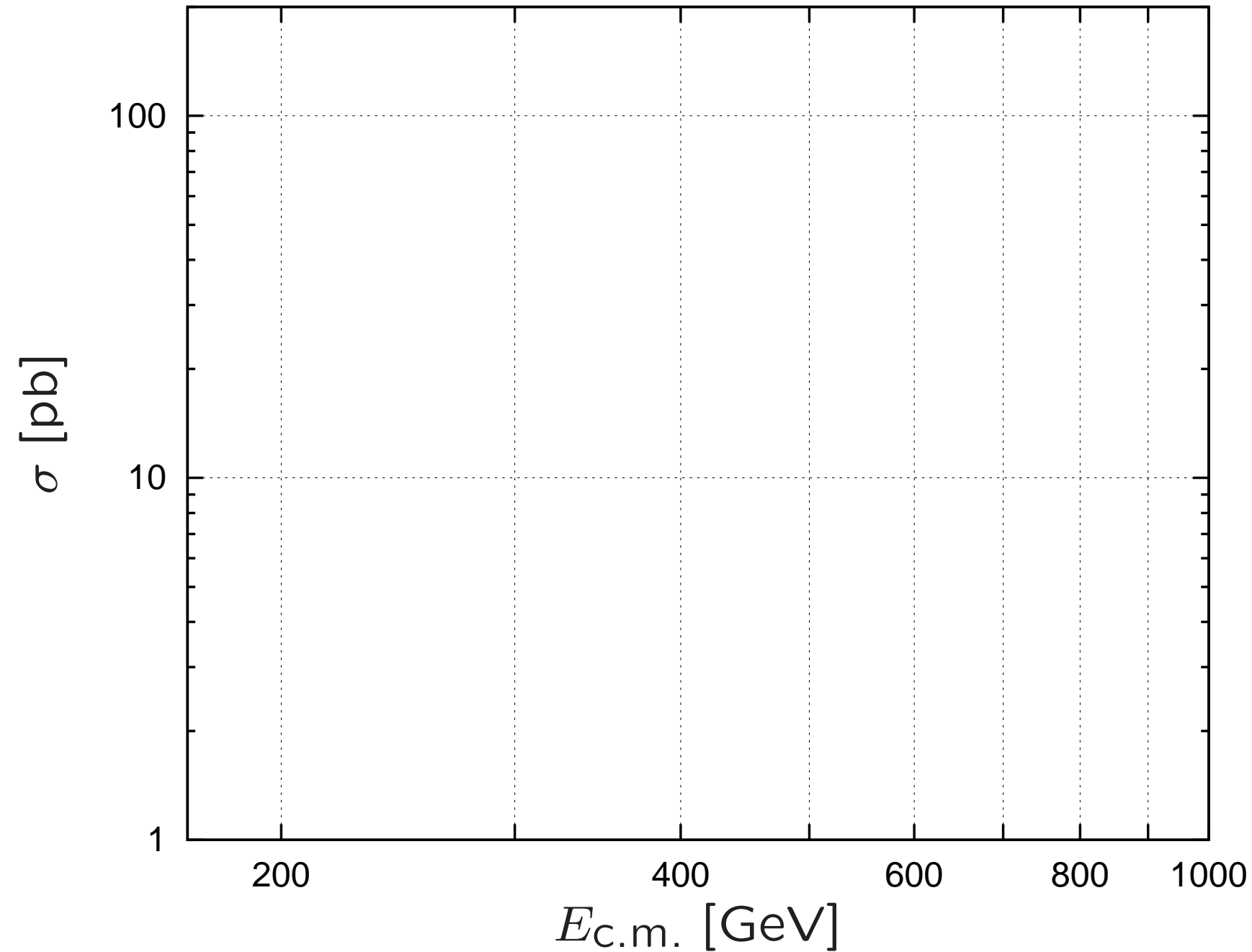
Neutral Currents [Gargamelle, CERN, 1973]

discovery of W and Z [UA1/UA2, CERN, 1983]

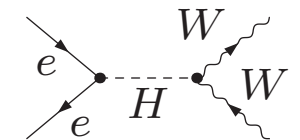
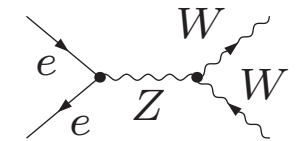
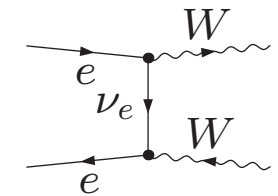
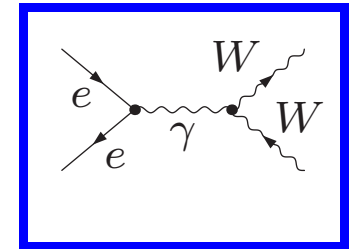
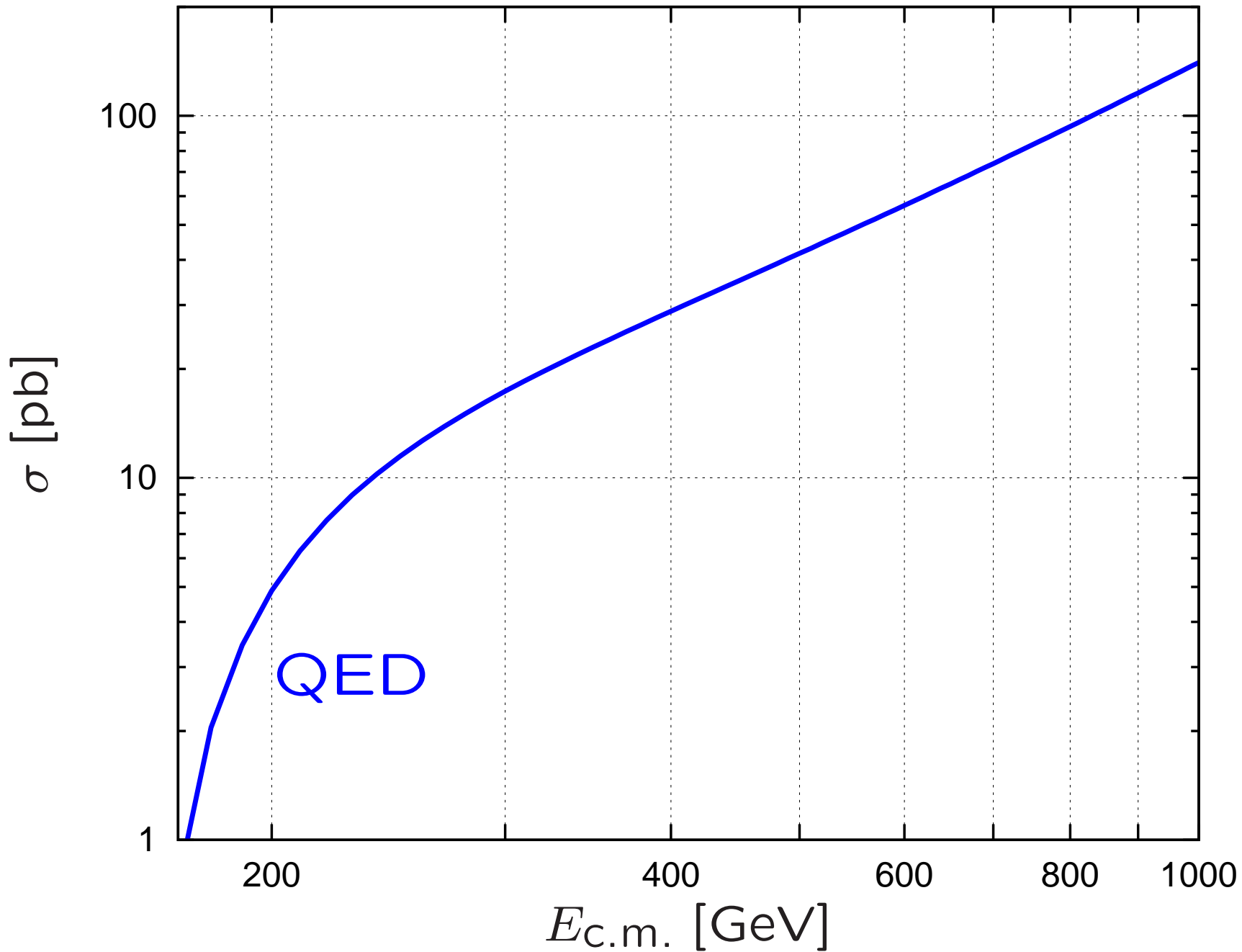
- spontaneous symmetry breaking via Higgs mechanism

→ still open question (as of 2011!)

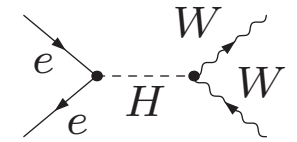
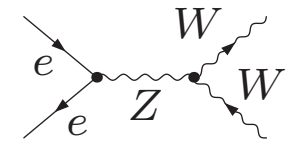
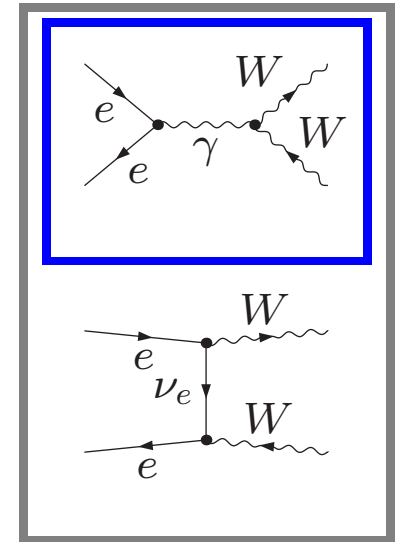
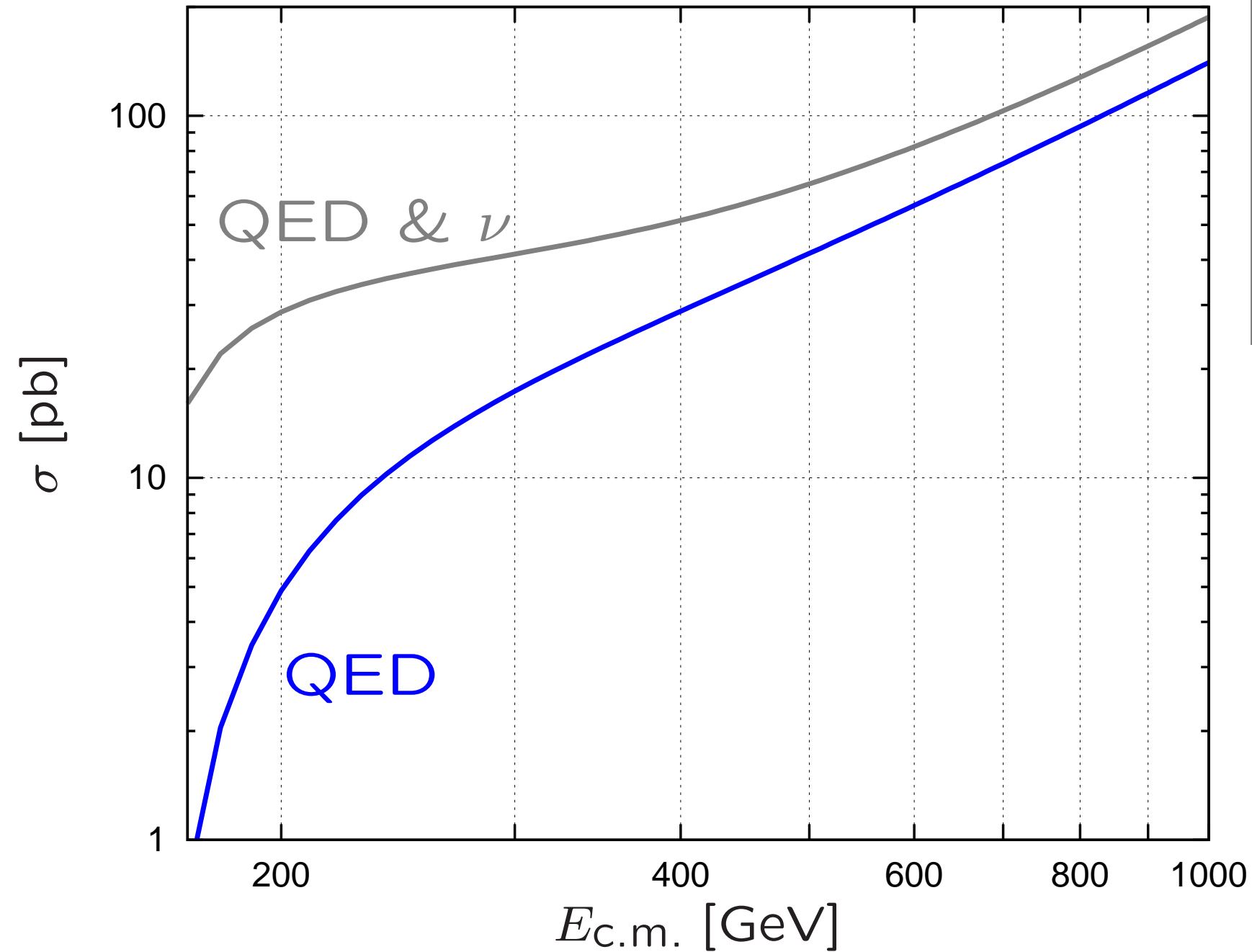
$\sigma(e^+e^- \rightarrow W^+W^-)$ at tree-level



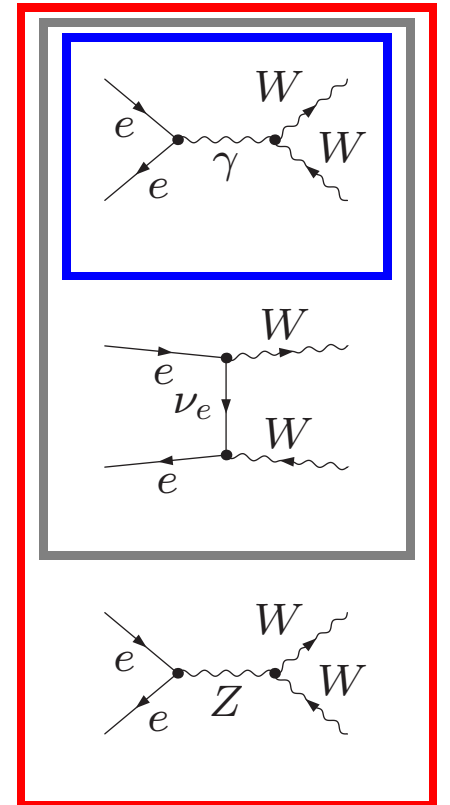
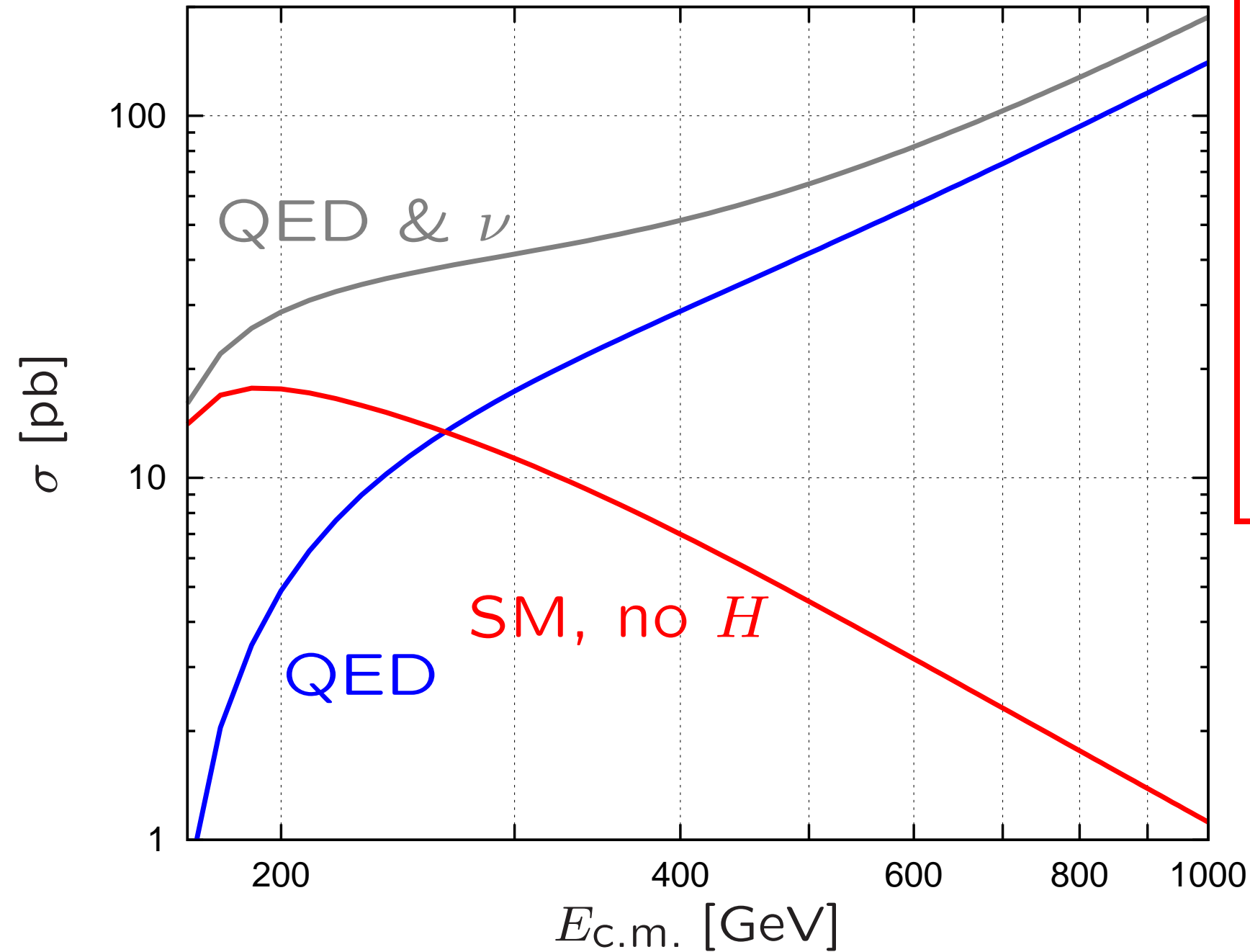
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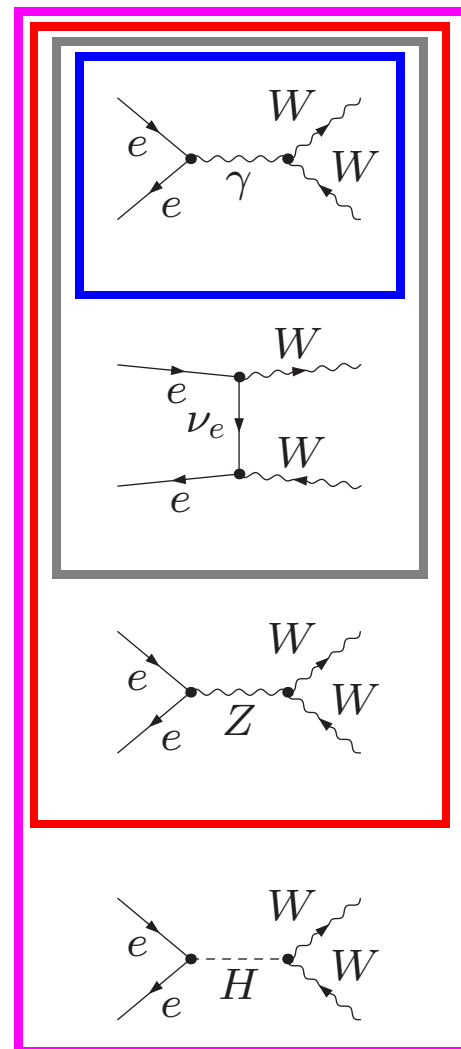
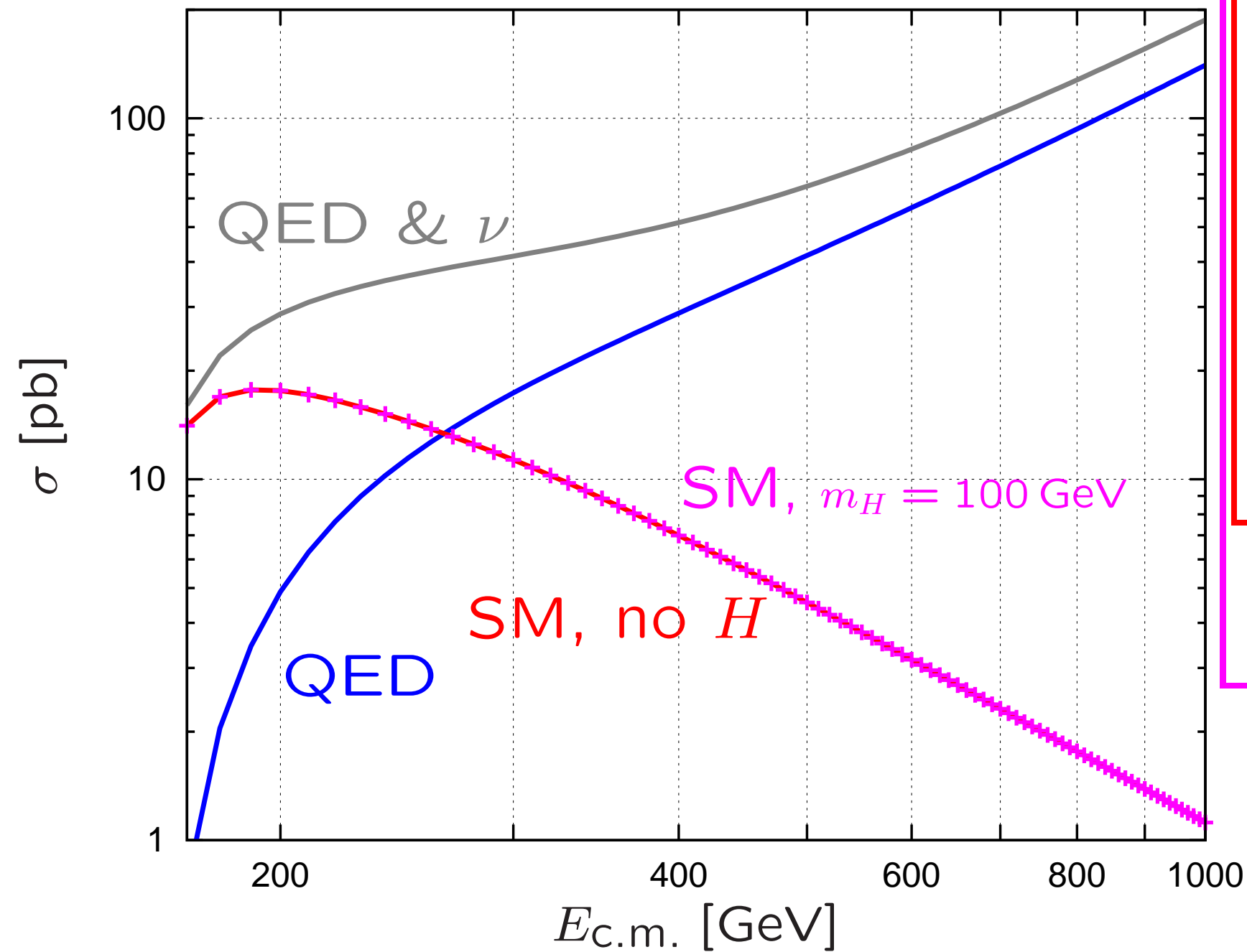
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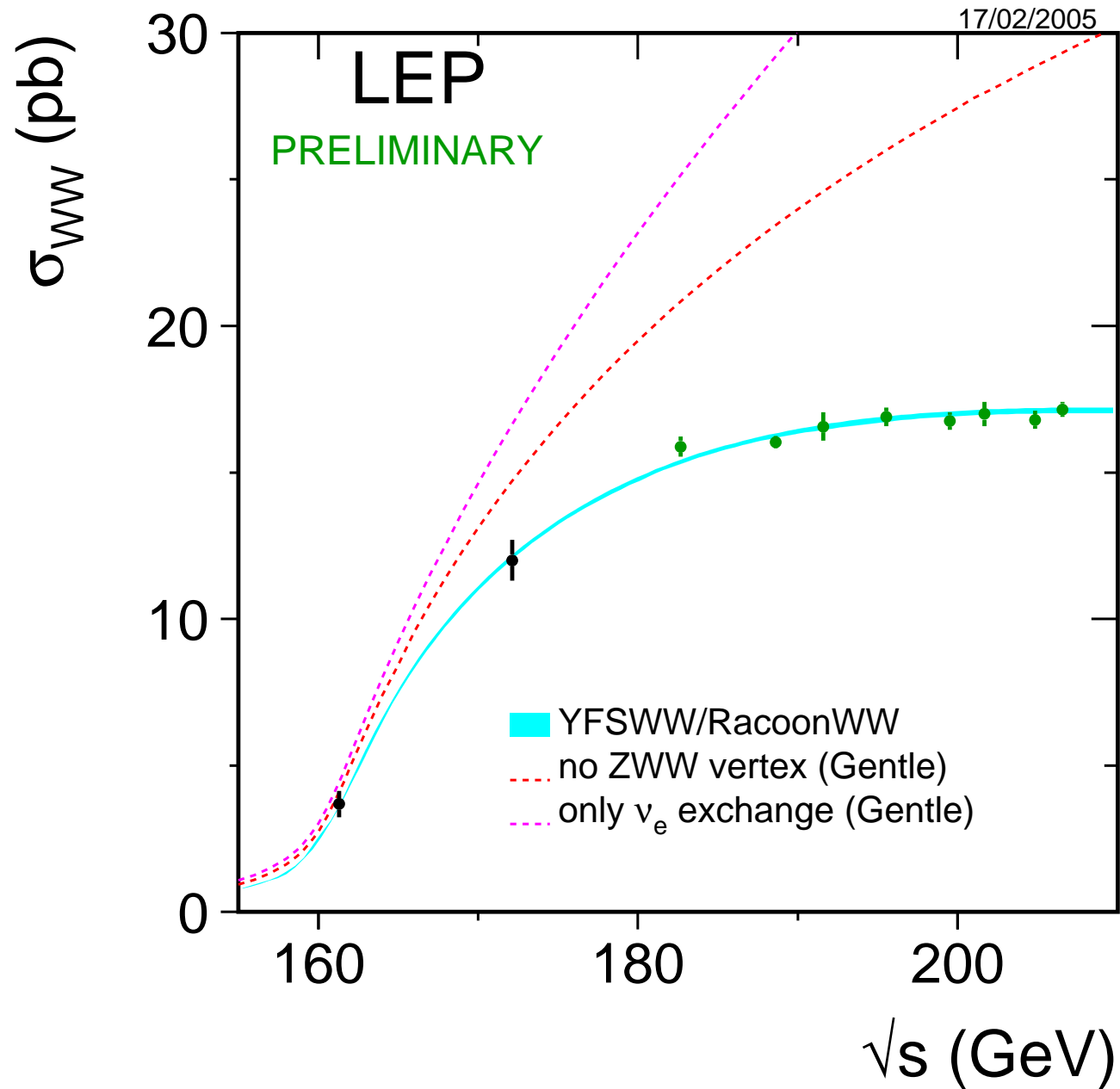
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$\sigma(e^+e^- \rightarrow W^+W^-)$ at tree-level



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



– The Higgs Boson: What is it good for?

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

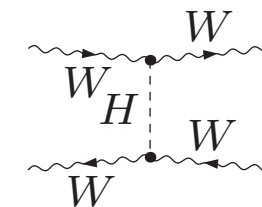
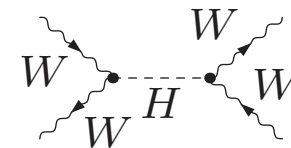
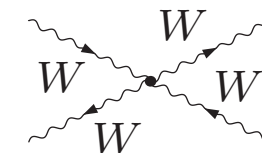
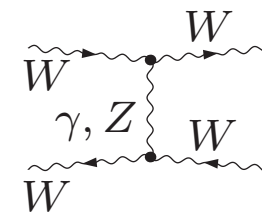
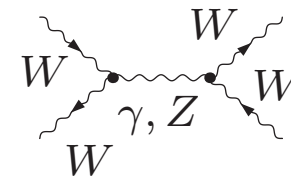
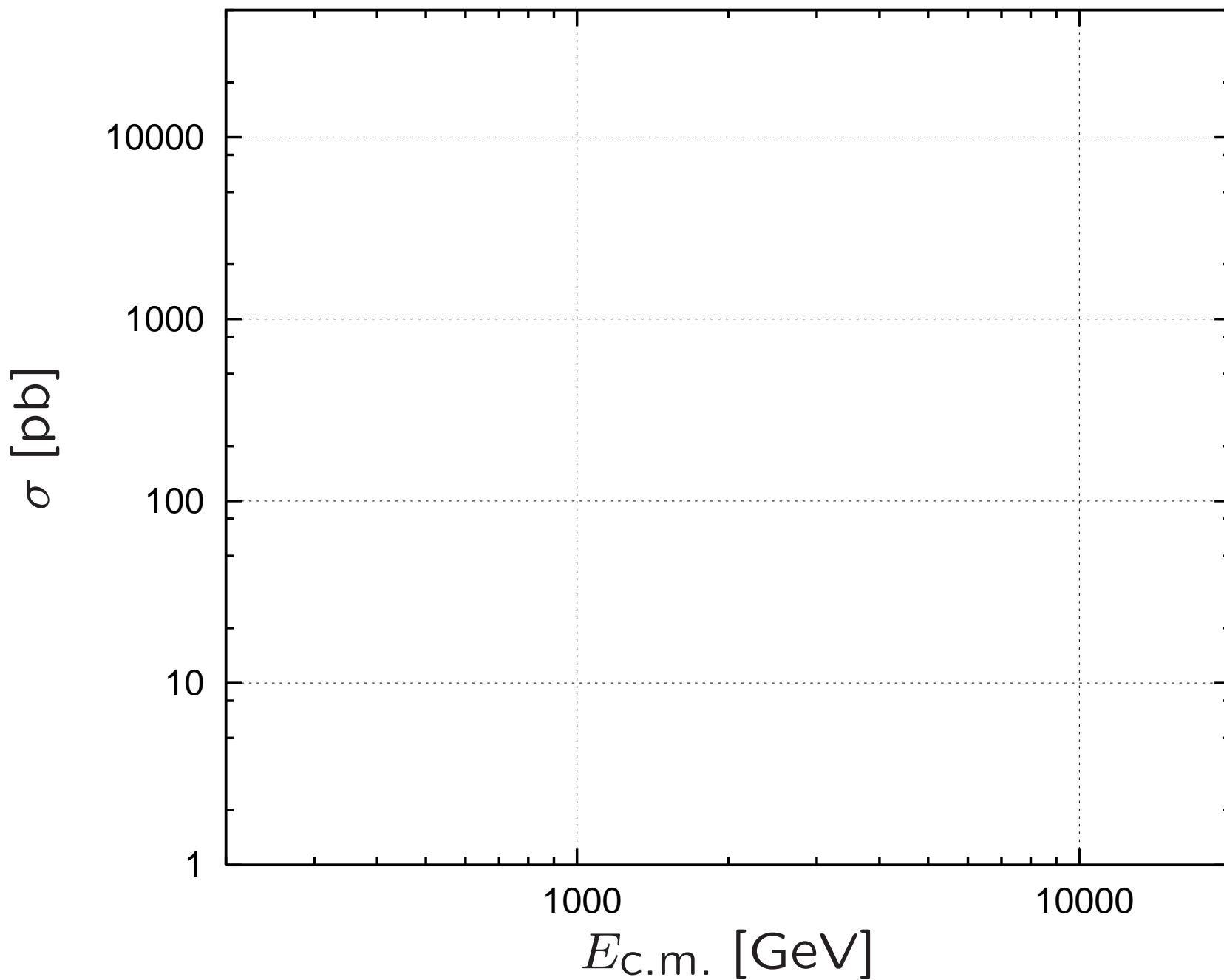
- The Higgs field has **4 components** & doesn't vanish in the ground state
- The **ground state configuration acts as a medium** (background field) with which all particles interact (coupling strength \propto mass)
- **3 components promote Z, W^+, W^- to massive (3 component) vector particles** from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

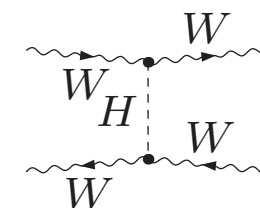
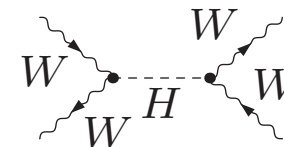
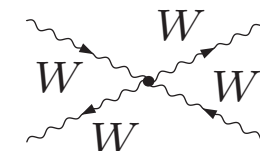
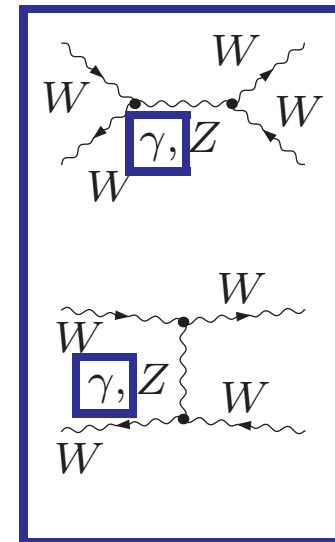
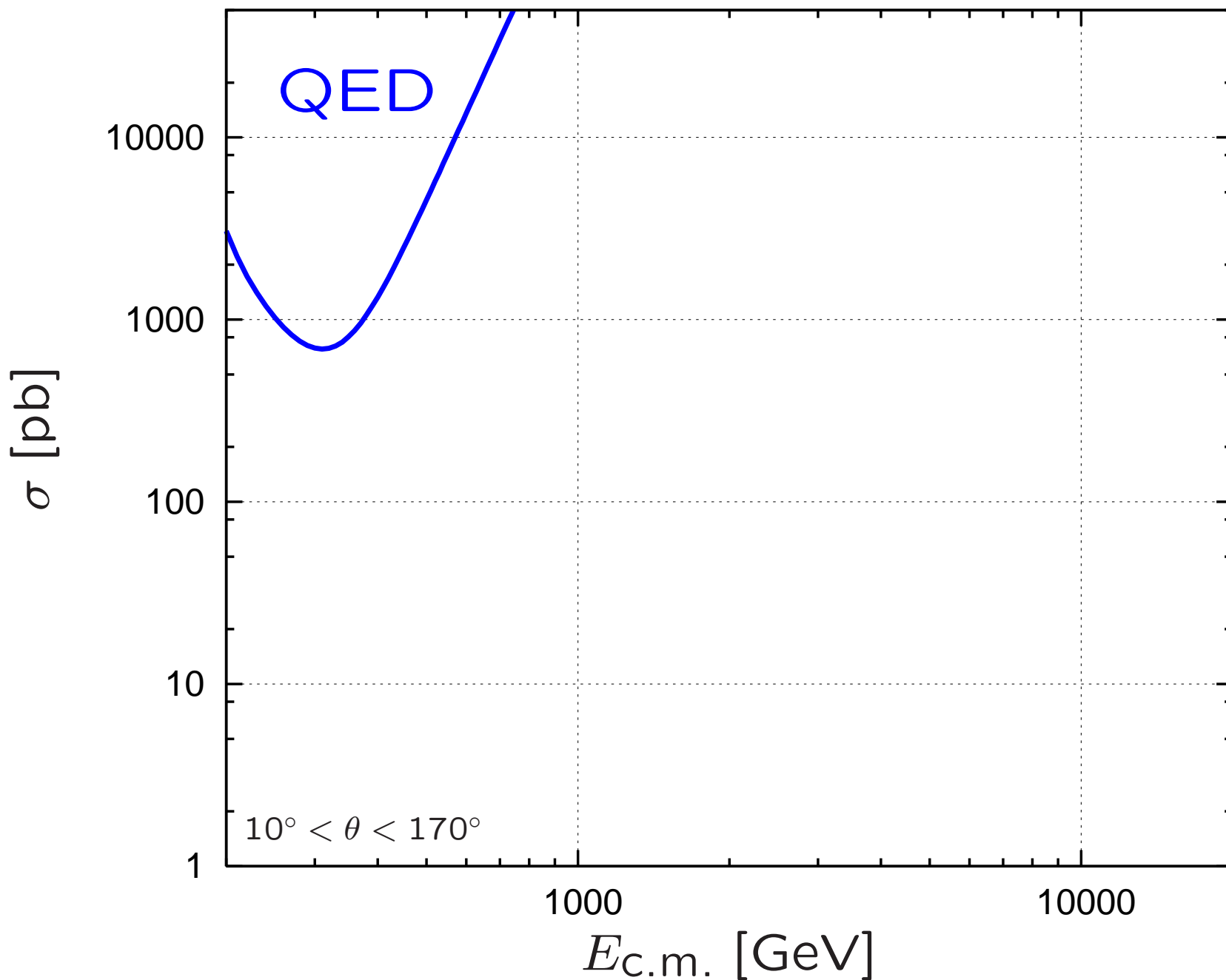
- the Higgs mechanism is a general concept (choice of Higgs field not unique)
- it explains *how* masses arise but not *what* mass values

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

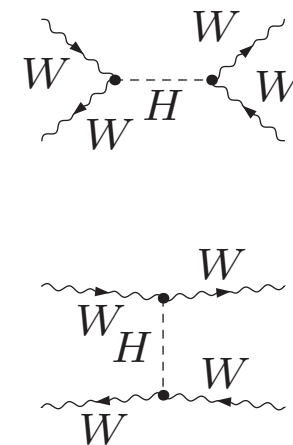
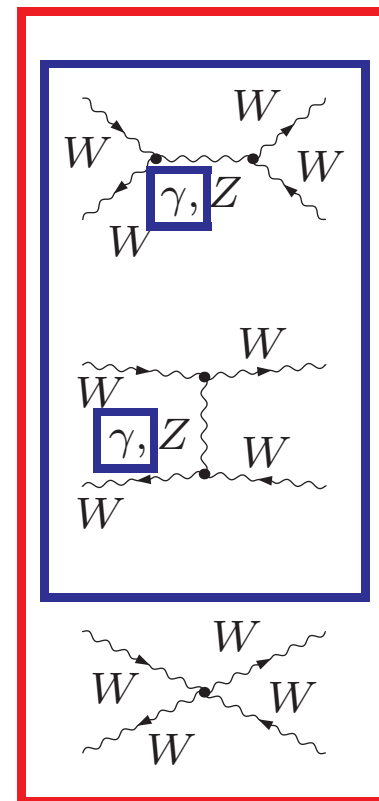
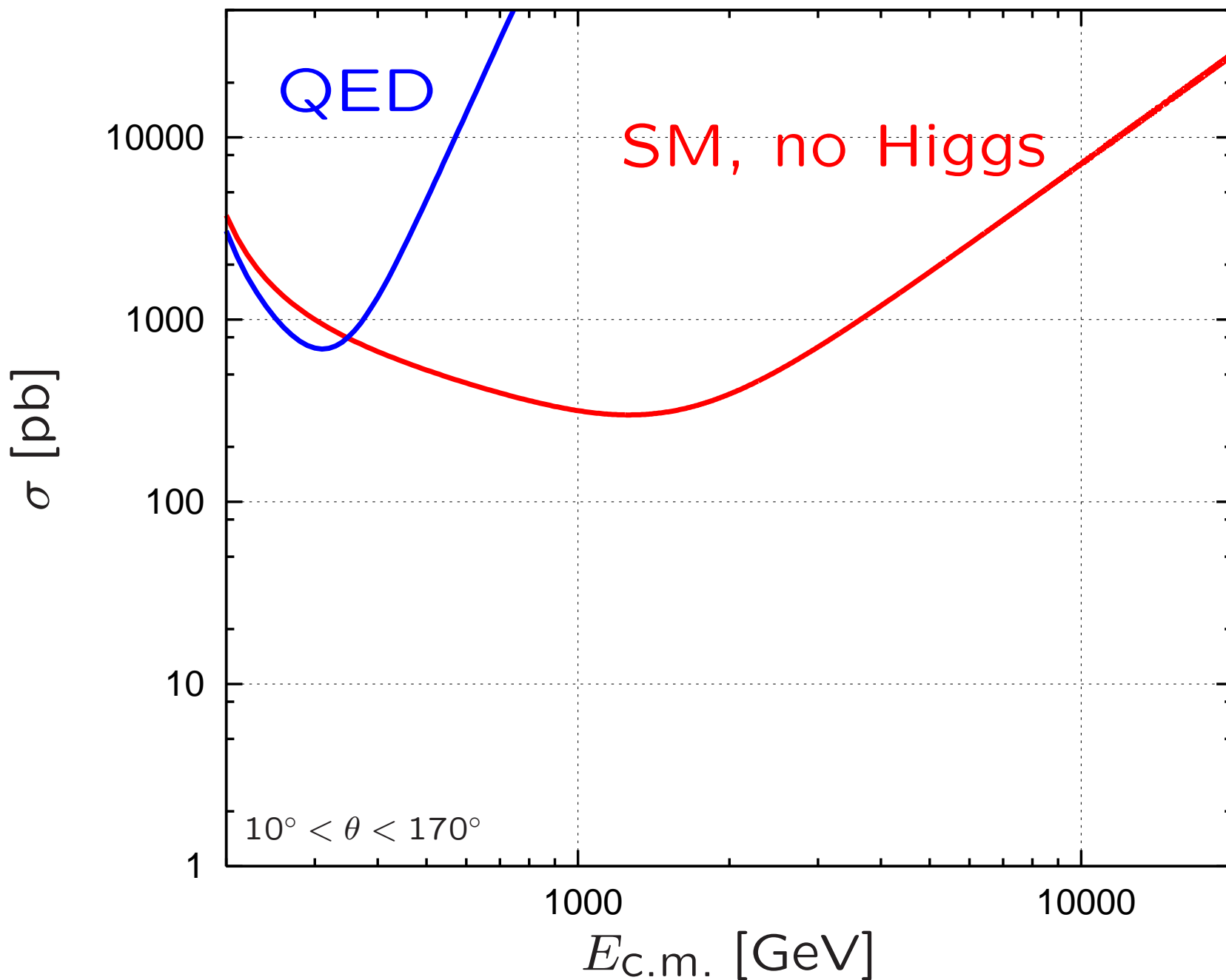
$\sigma(W_L W_L \rightarrow W_L W_L)$ at tree-level



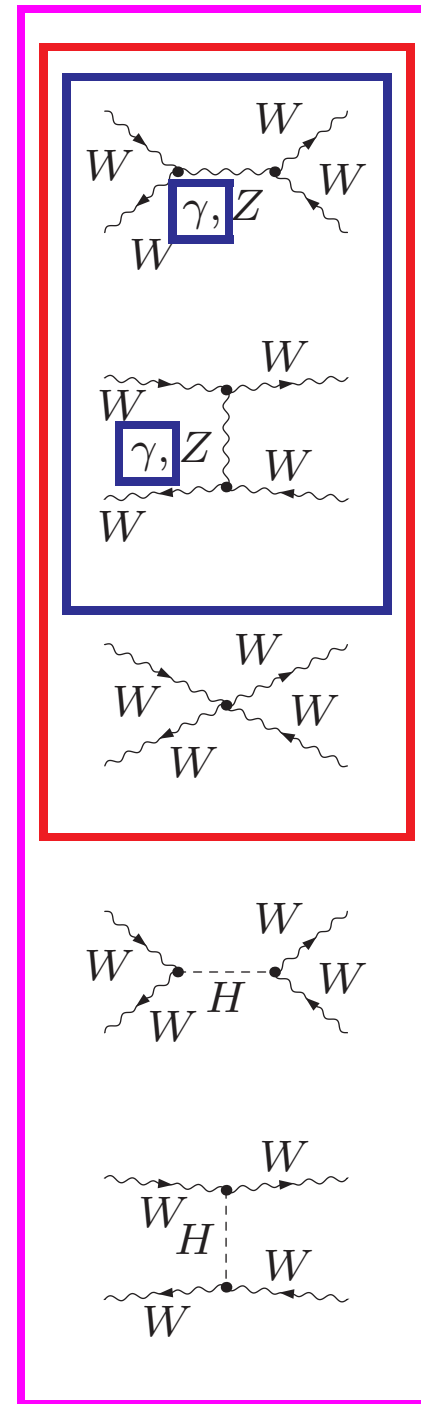
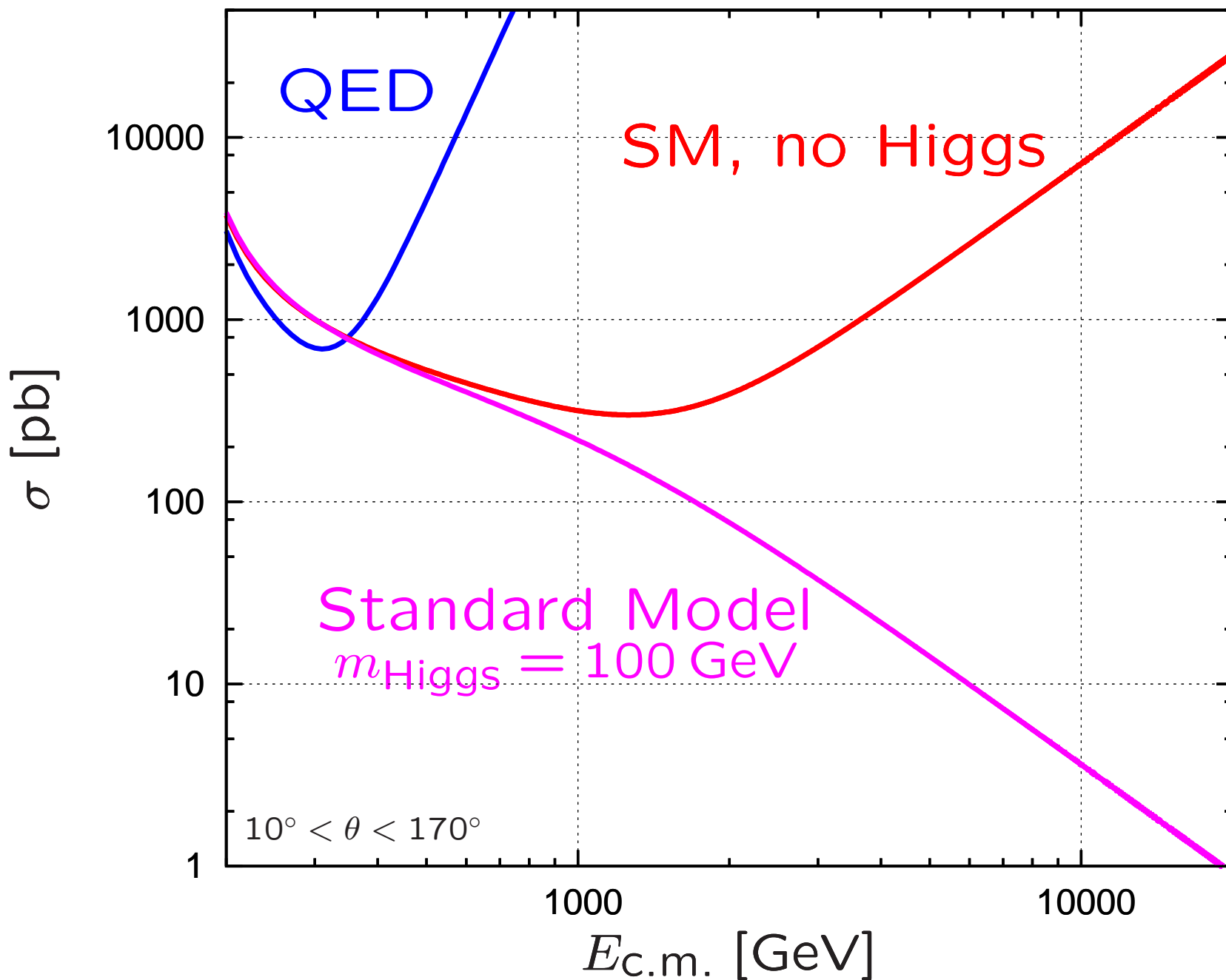
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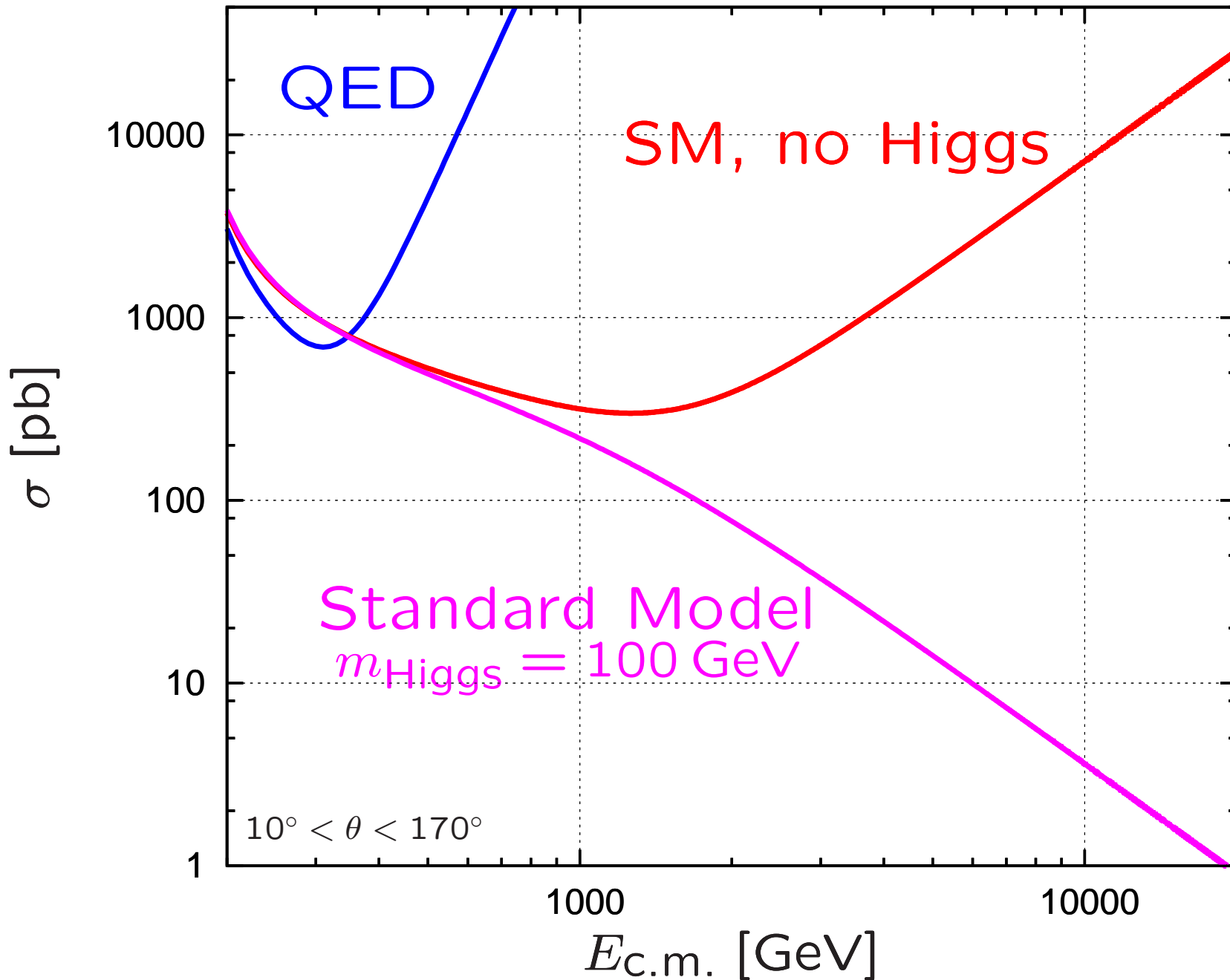
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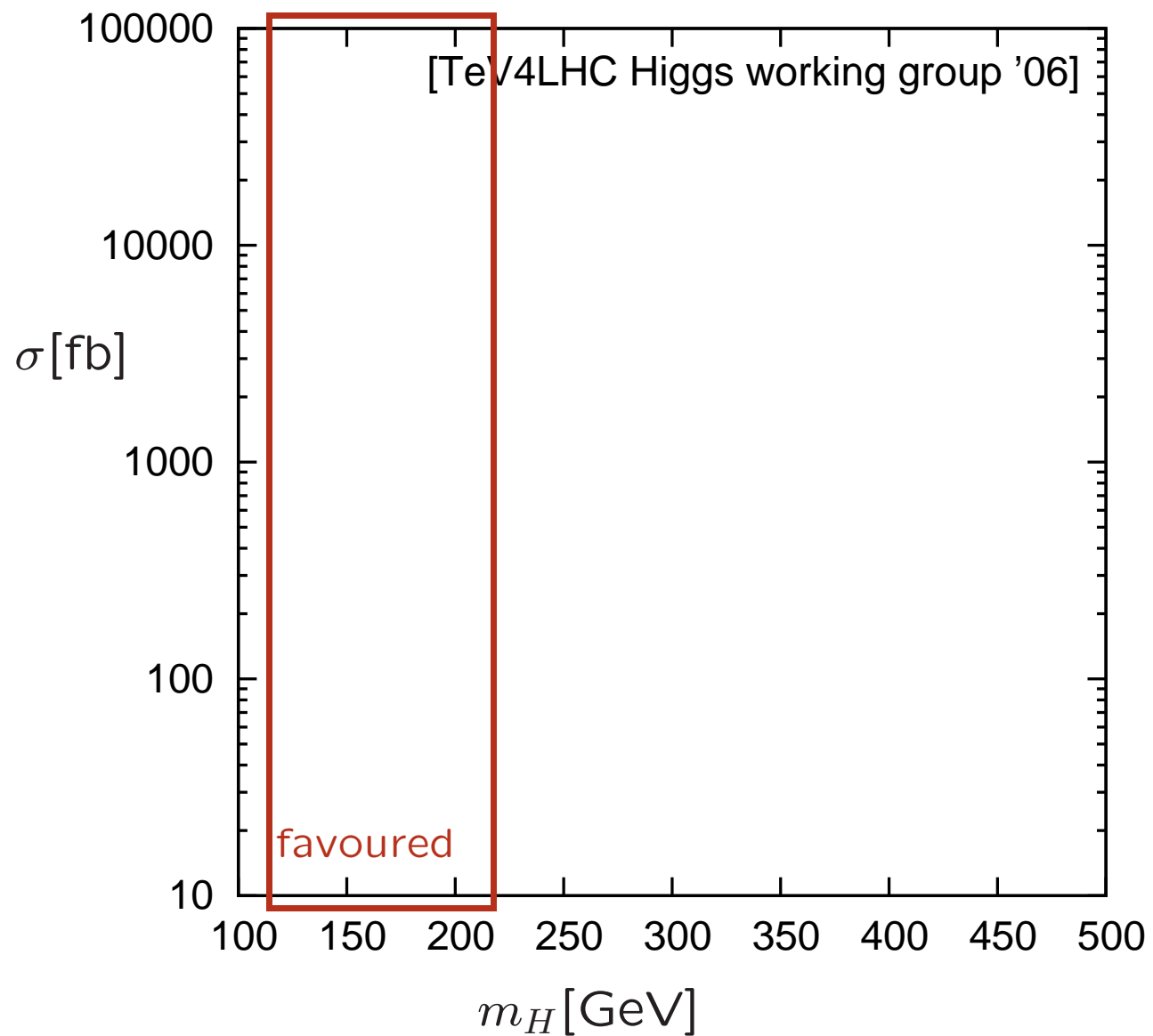
- SM may be applicable up to very high energy.
- If no Higgs exists, new phenomena around 1 TeV expected.

– How to find Higgs Bosons?

■ SM Higgs production @ LHC :

→ consider:

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

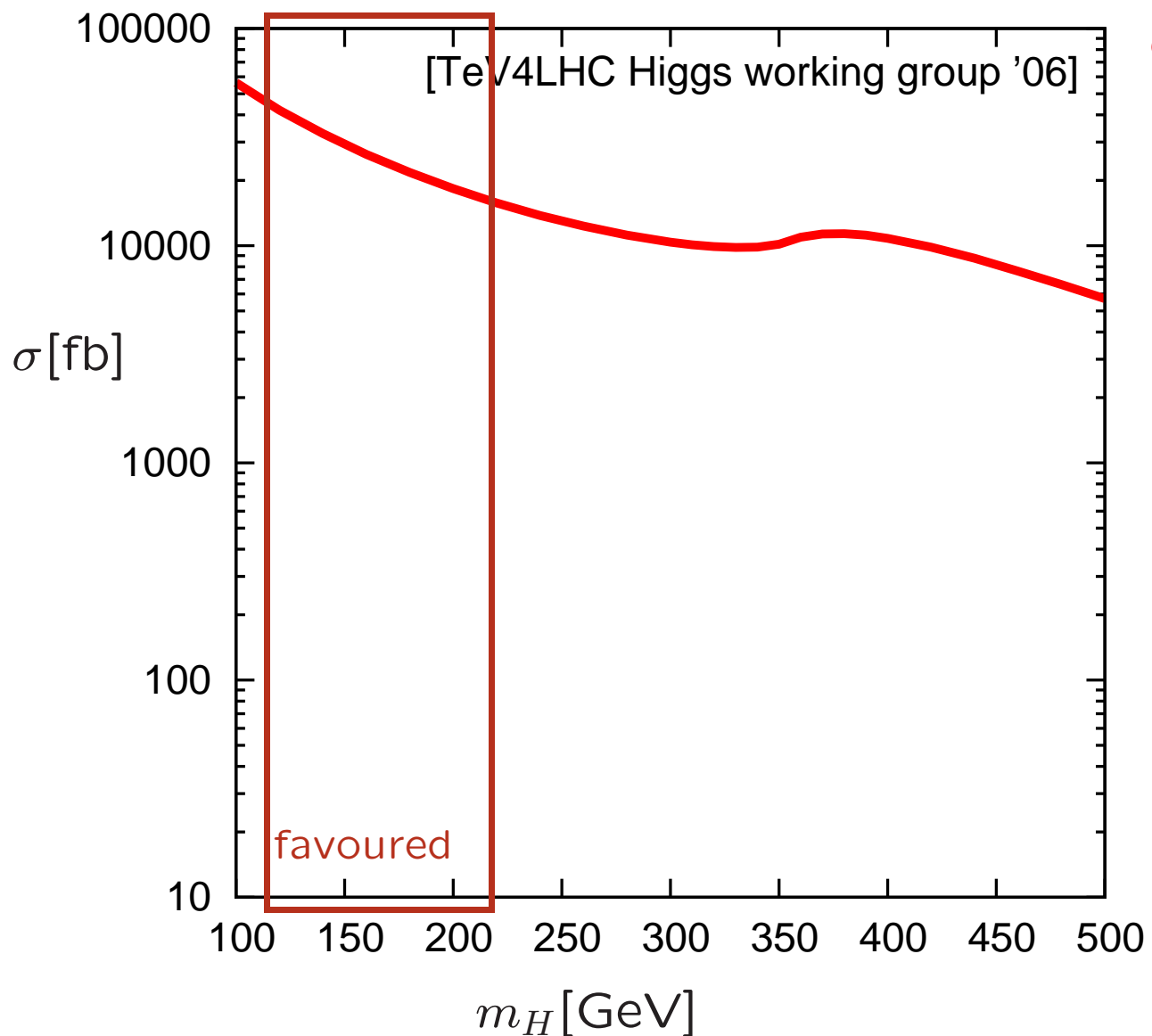


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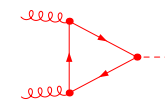
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gluon fusion, $gg \rightarrow H$

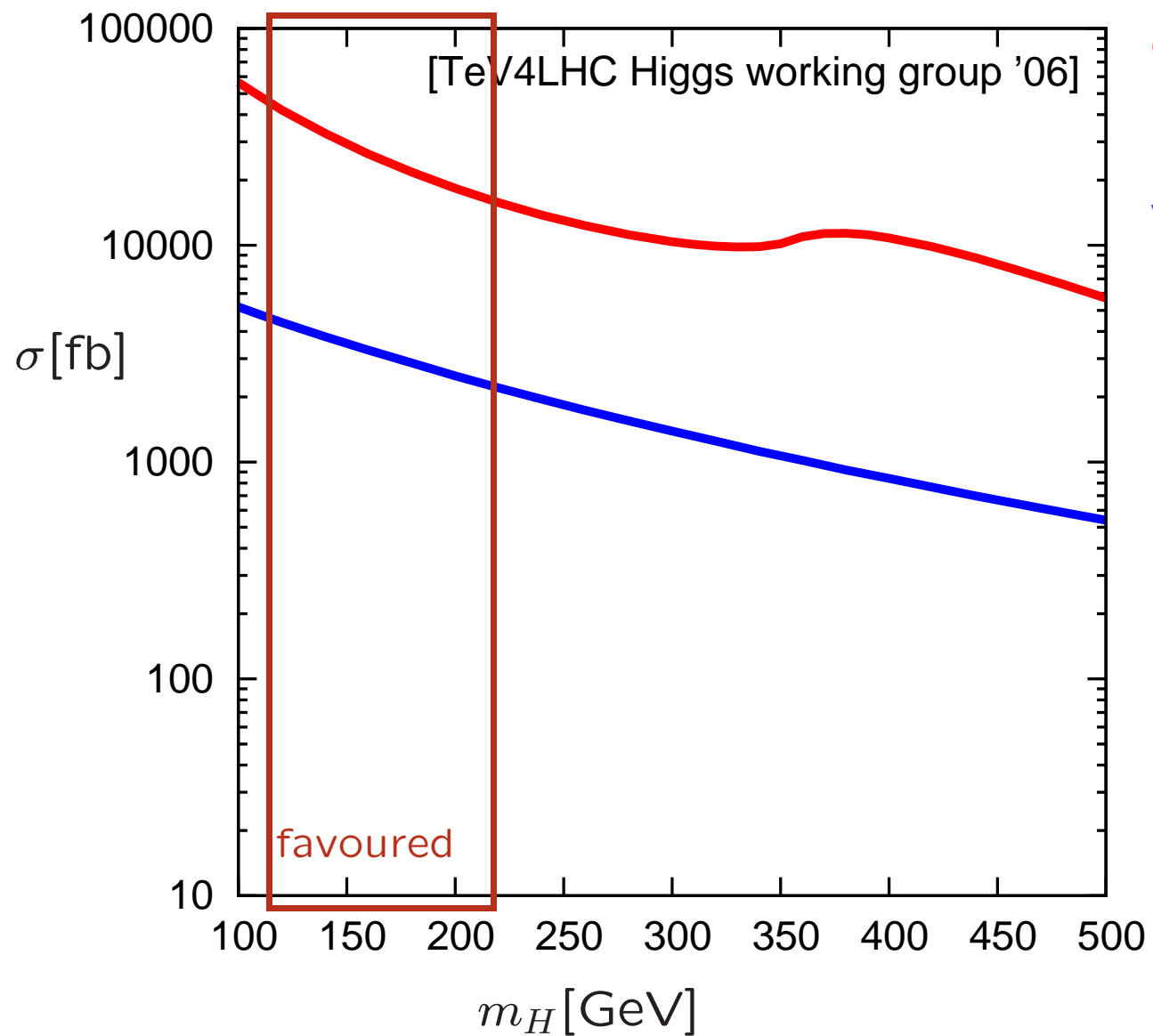


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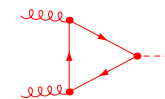
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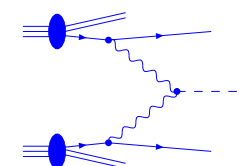
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vector boson fusion, $qq \rightarrow qqH$

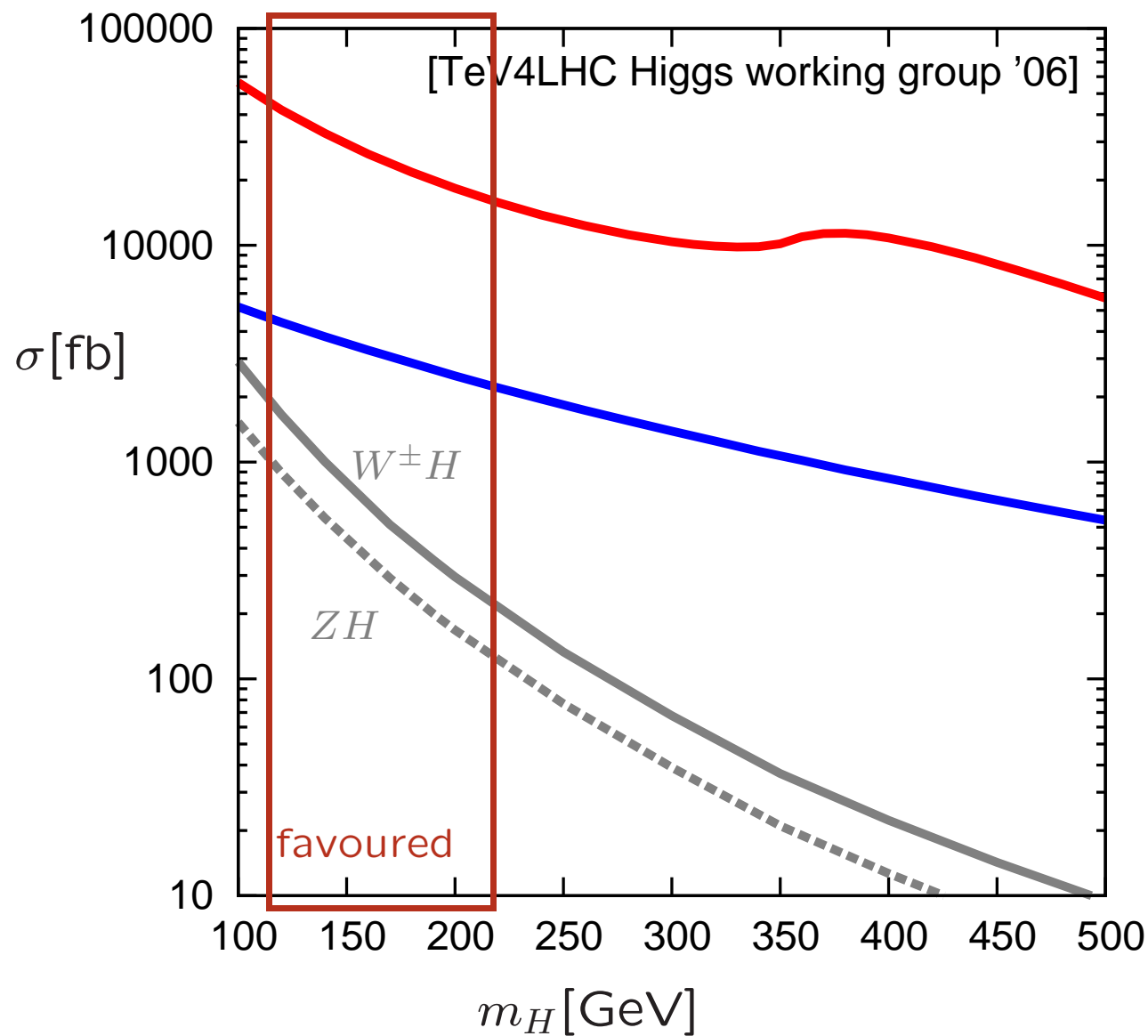


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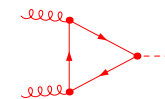
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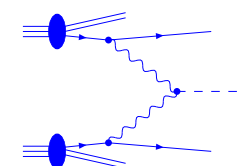
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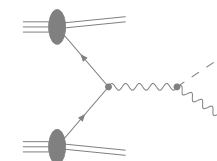
gluon fusion, $gg \rightarrow H$



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

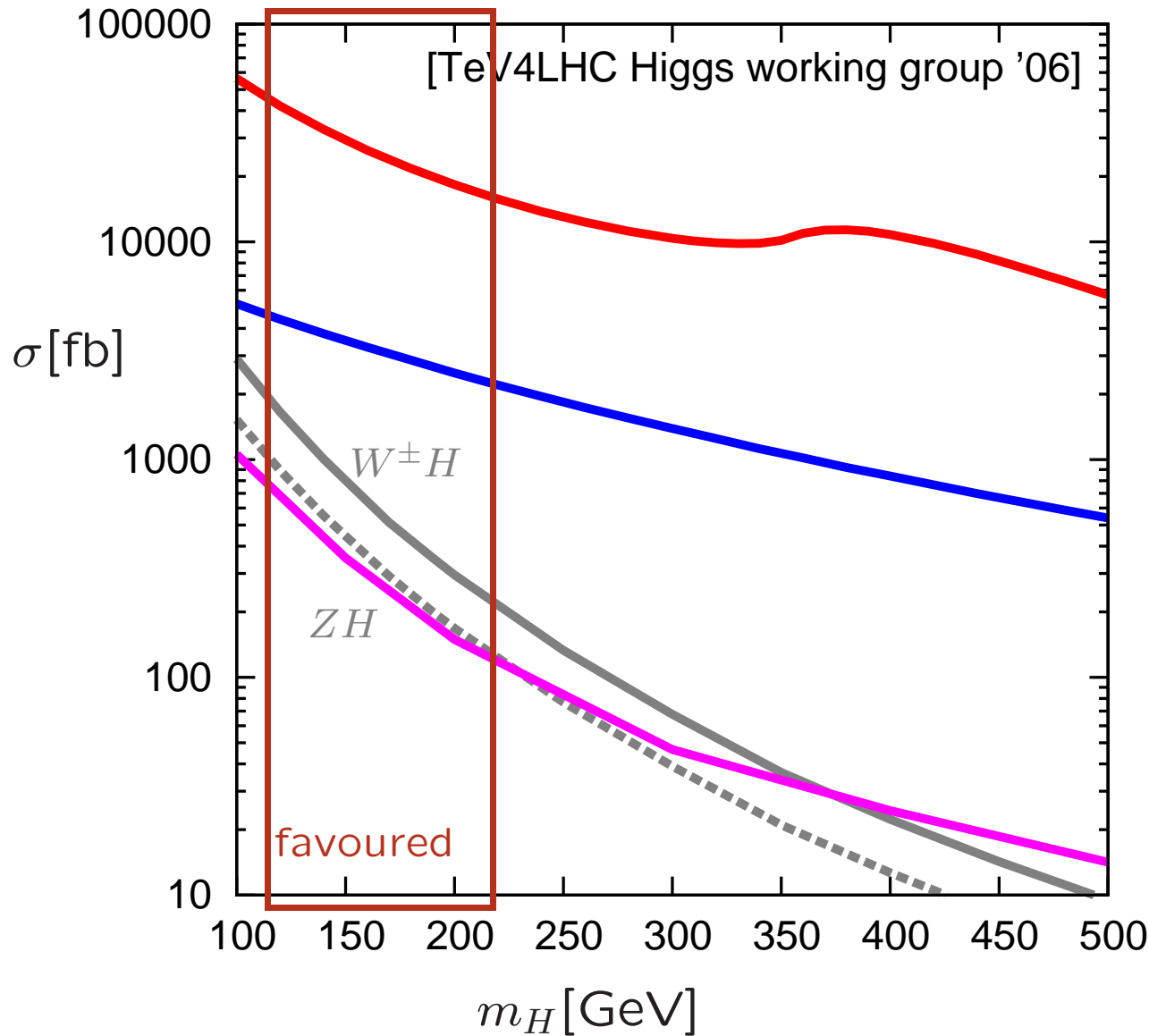


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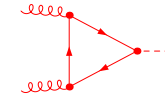
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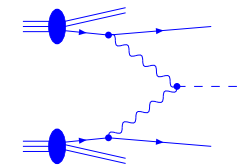
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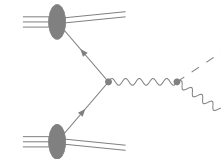
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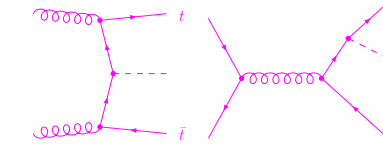
vector boson fusion, $qq \rightarrow qqH$



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



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

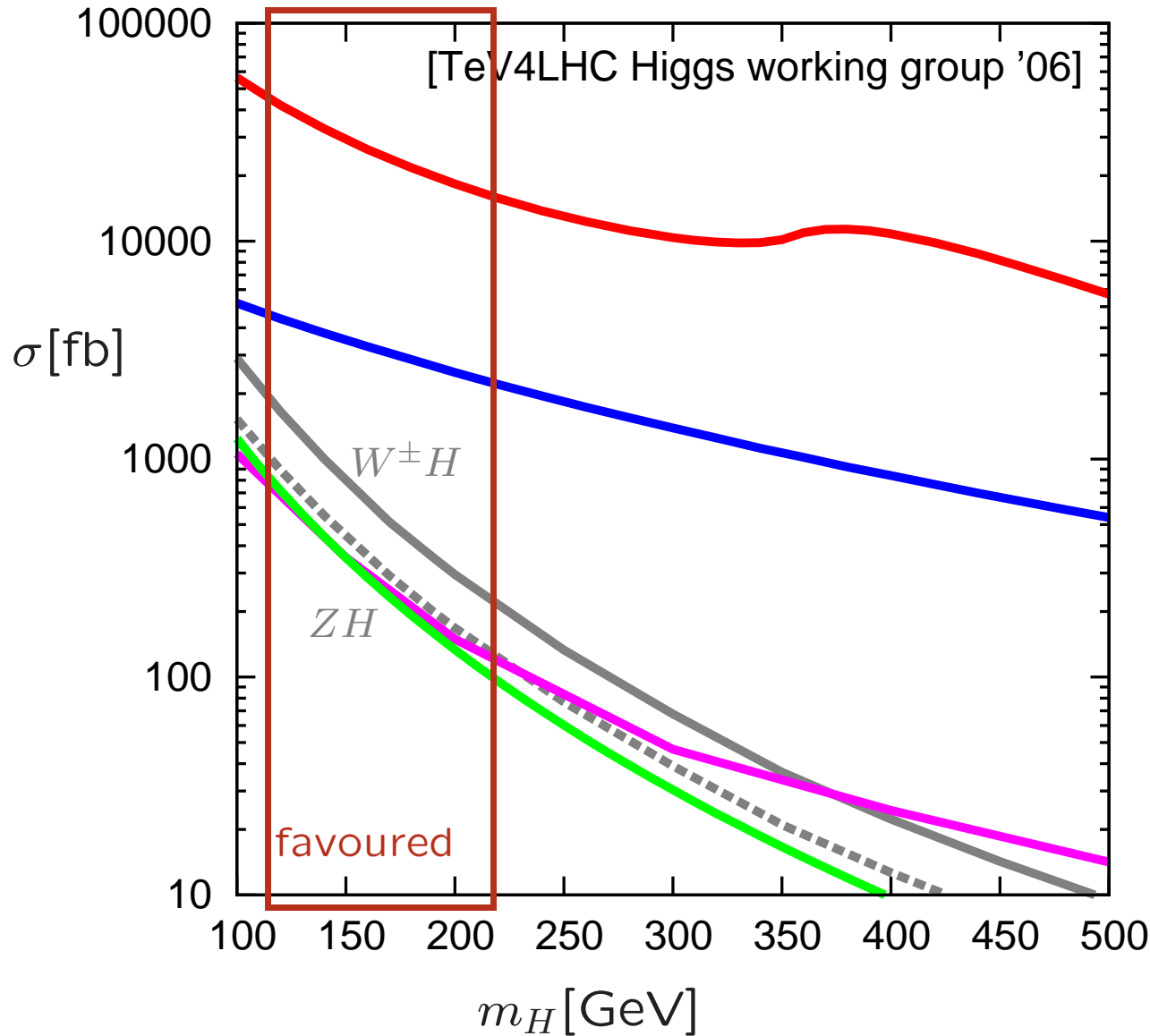


– How to find Higgs Bosons?

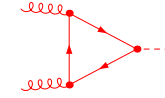
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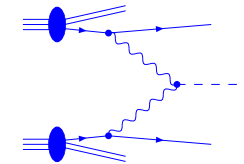
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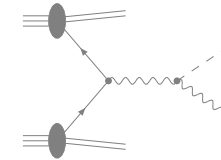
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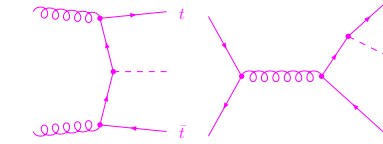
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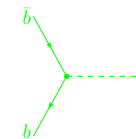
Higgs strahlung, $q\bar{q}' \rightarrow V H$



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



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



How to detect Higgs Bosons ?

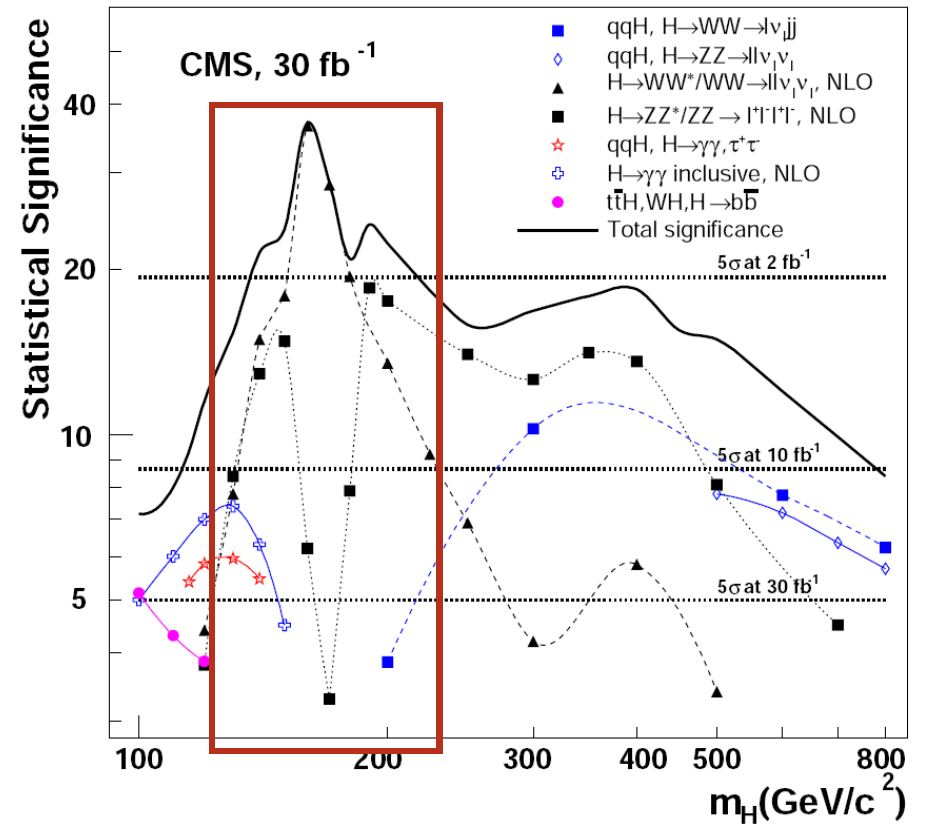
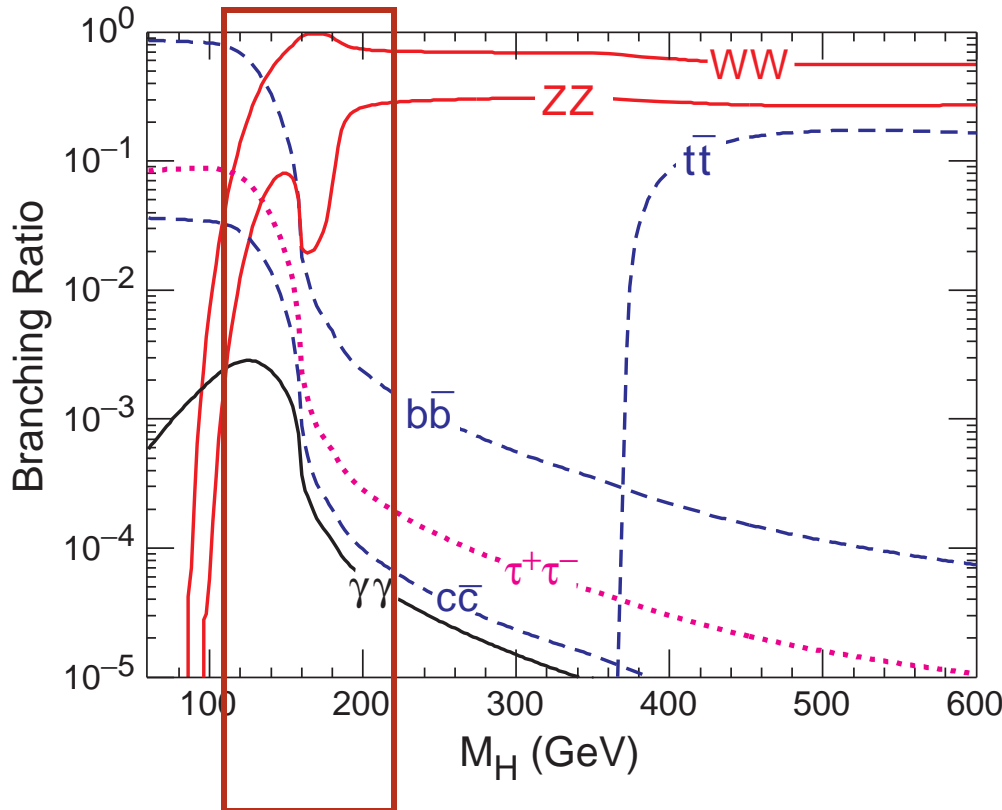
- Essential for Higgs discovery is:

$$[\text{production rate}] \times [\text{decay probability}] \times [\text{detection efficiency}]$$

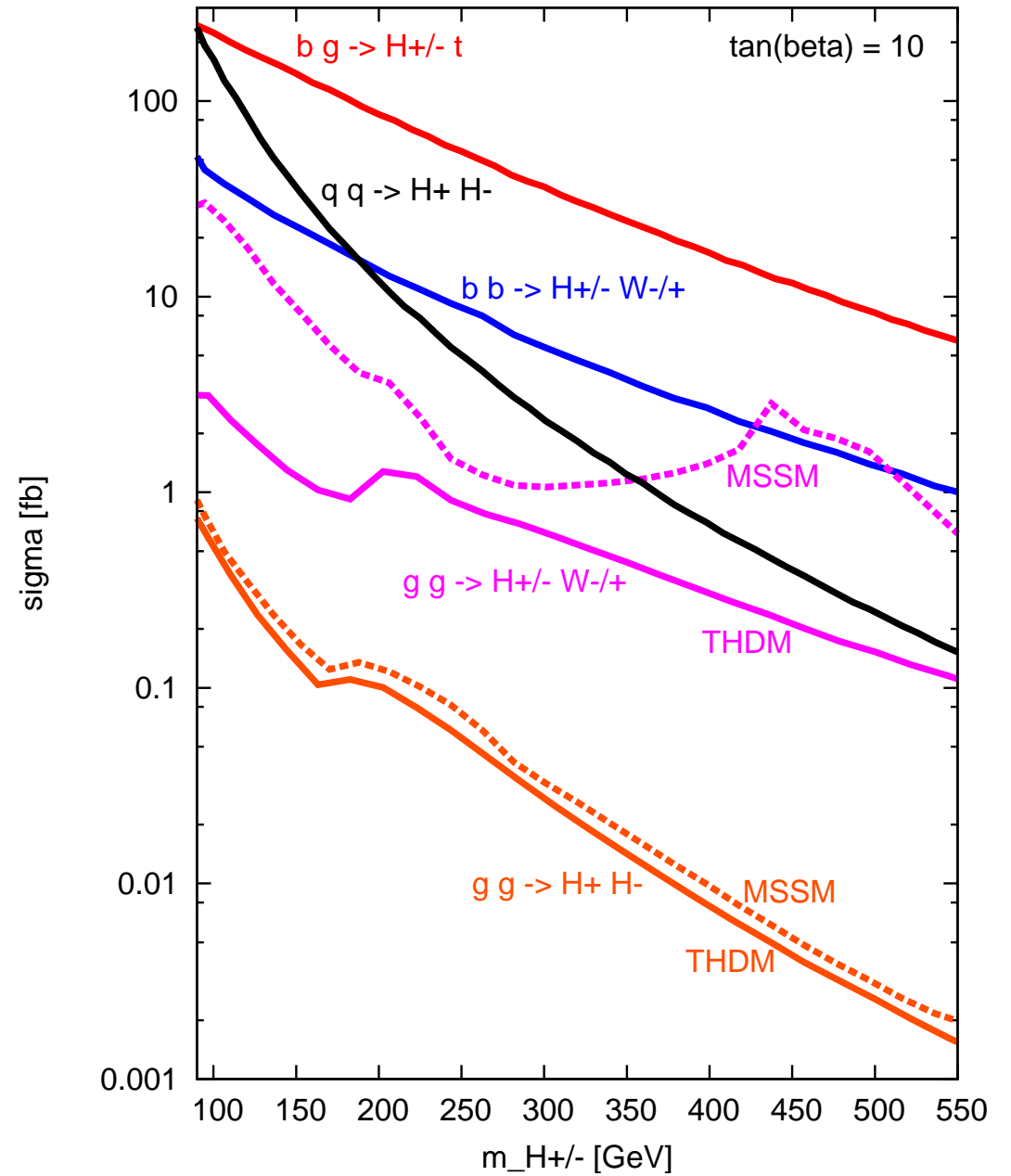
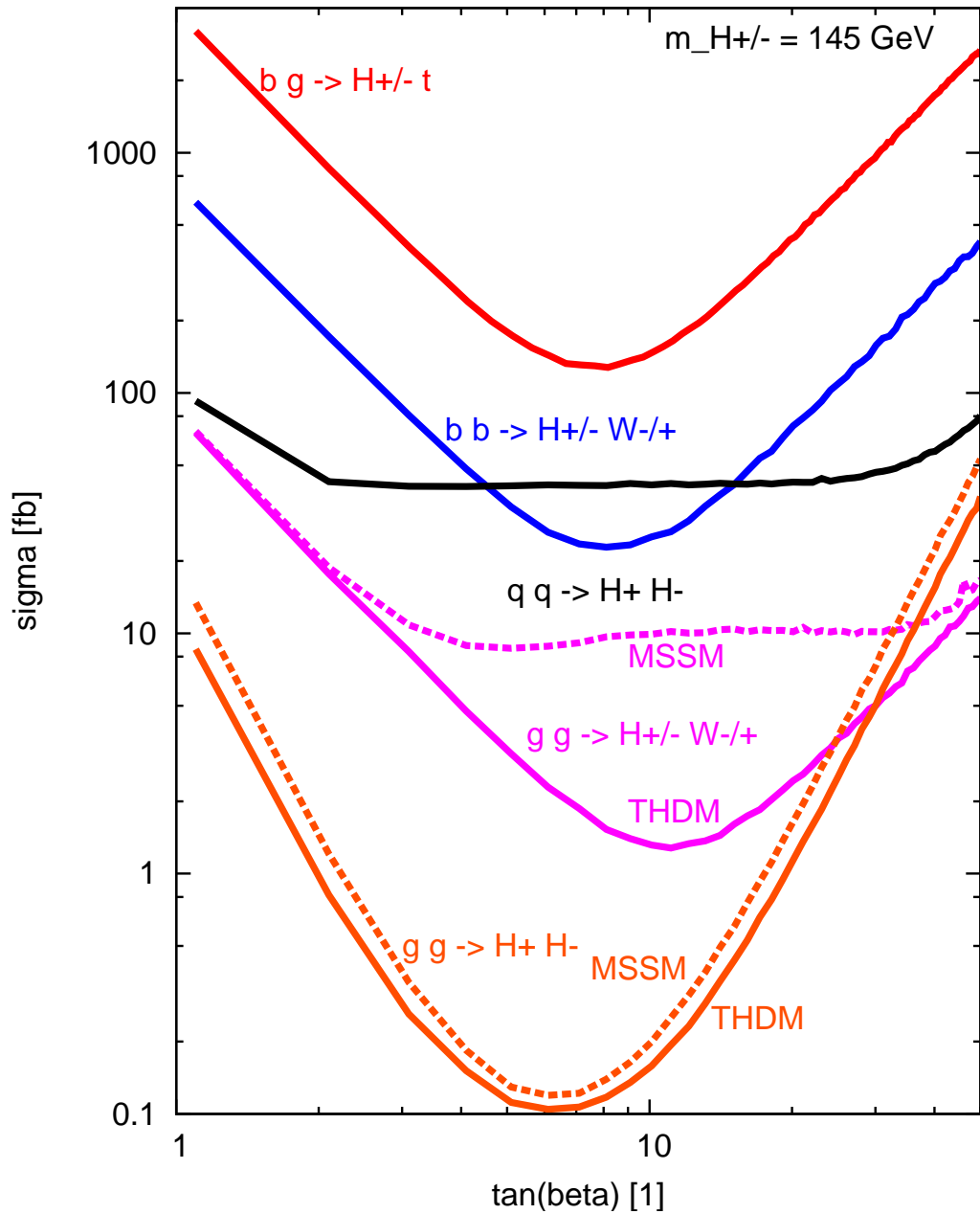
- Higgs events need to be silhouetted against *huge* amount of non-Higgs events
 → e.g. hopeless to see $H \rightarrow b\bar{b}$ via gluon fusion

★ 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 \iff additional symmetry for $m \rightarrow 0$

example : electron mass m_e is a natural small parameter:

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

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

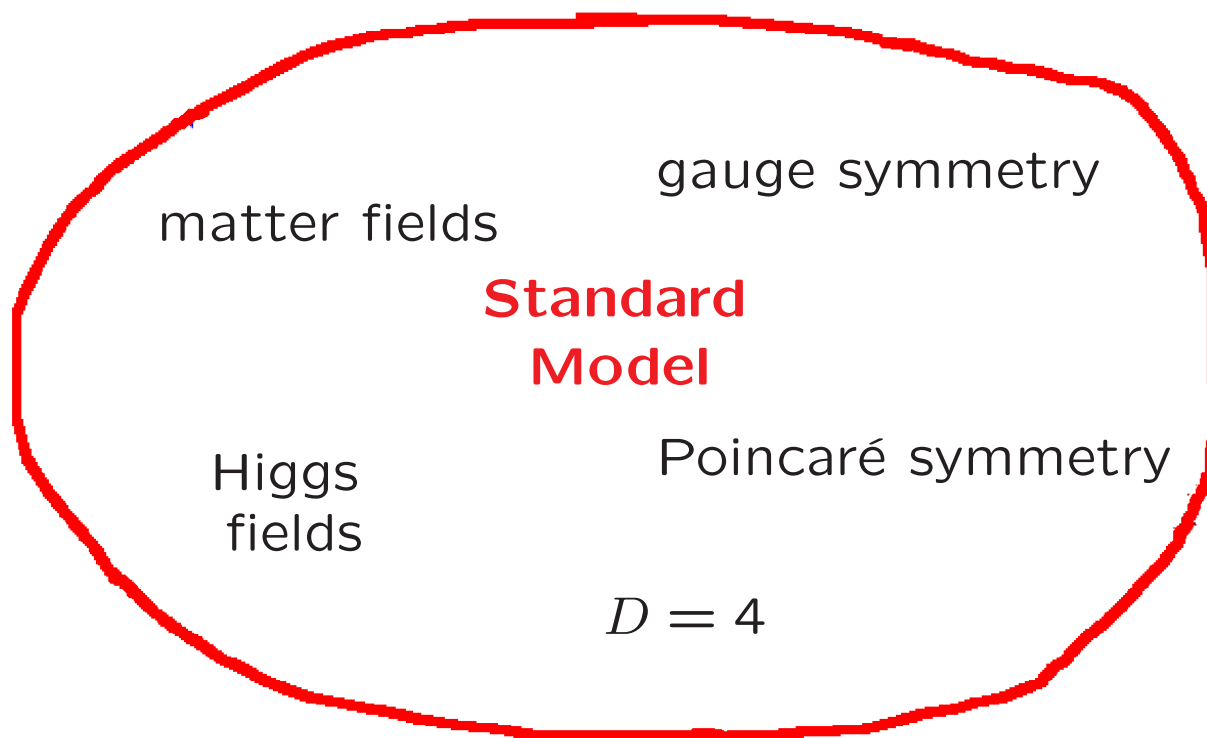
Assuming the SM is only valid up to some scale Λ (say M_{GUT} or M_{Planck}), quantum corrections to the Higgs self energy are of the order of Λ .

But present observations indicate a value around the electroweak scale Λ_{EW} .

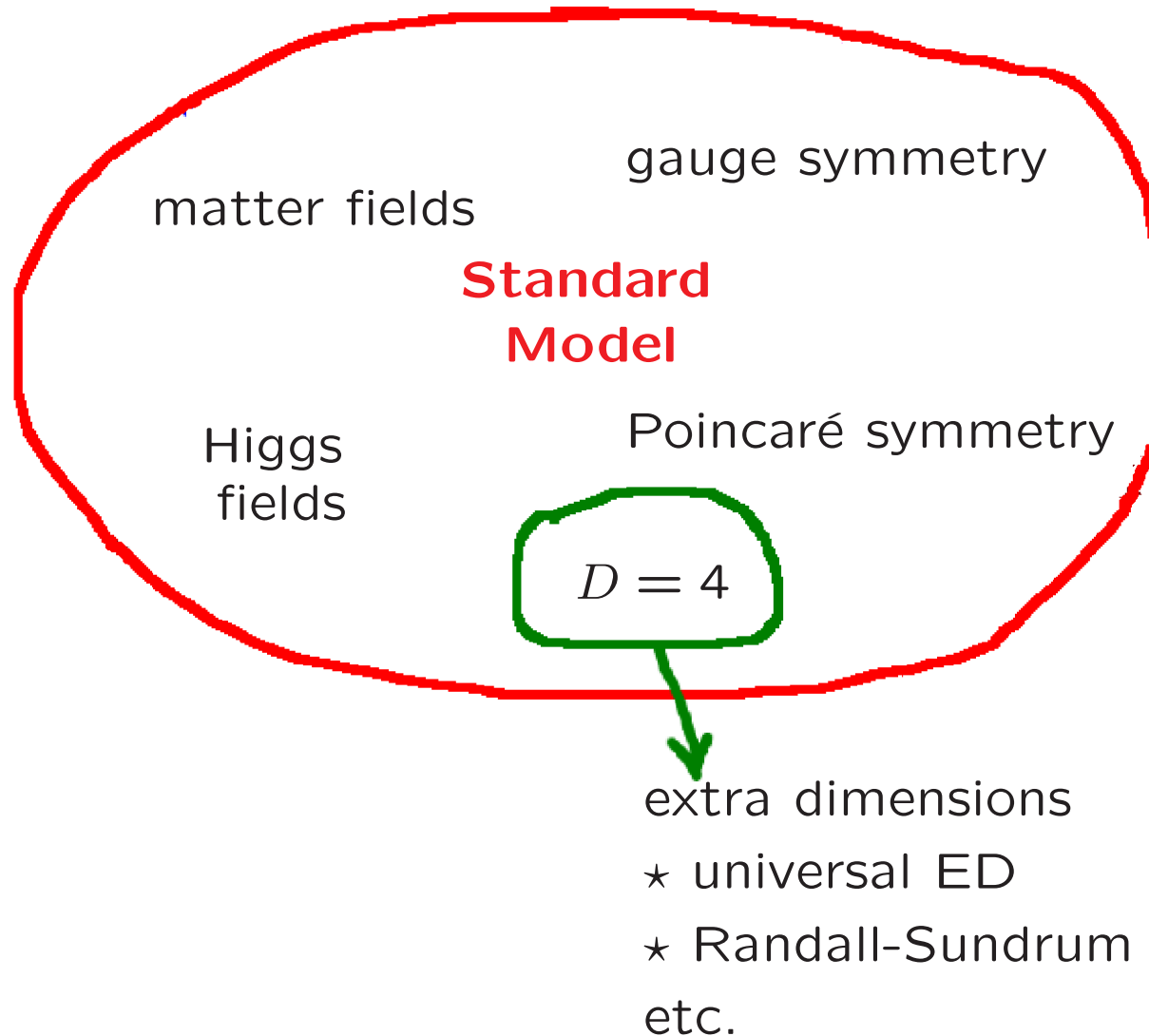
$$\Lambda_{\text{EW}} \propto 100 \text{ GeV}, \quad M_{\text{GUT}} \propto 10^{15} \text{ GeV} \quad M_{\text{Planck}} \propto 10^{19} \text{ GeV}$$

Taking the Naturalness Problem seriously:
What extension of the SM at higher energy scales
could avoid the large quantum corrections
in the Higgs sector?

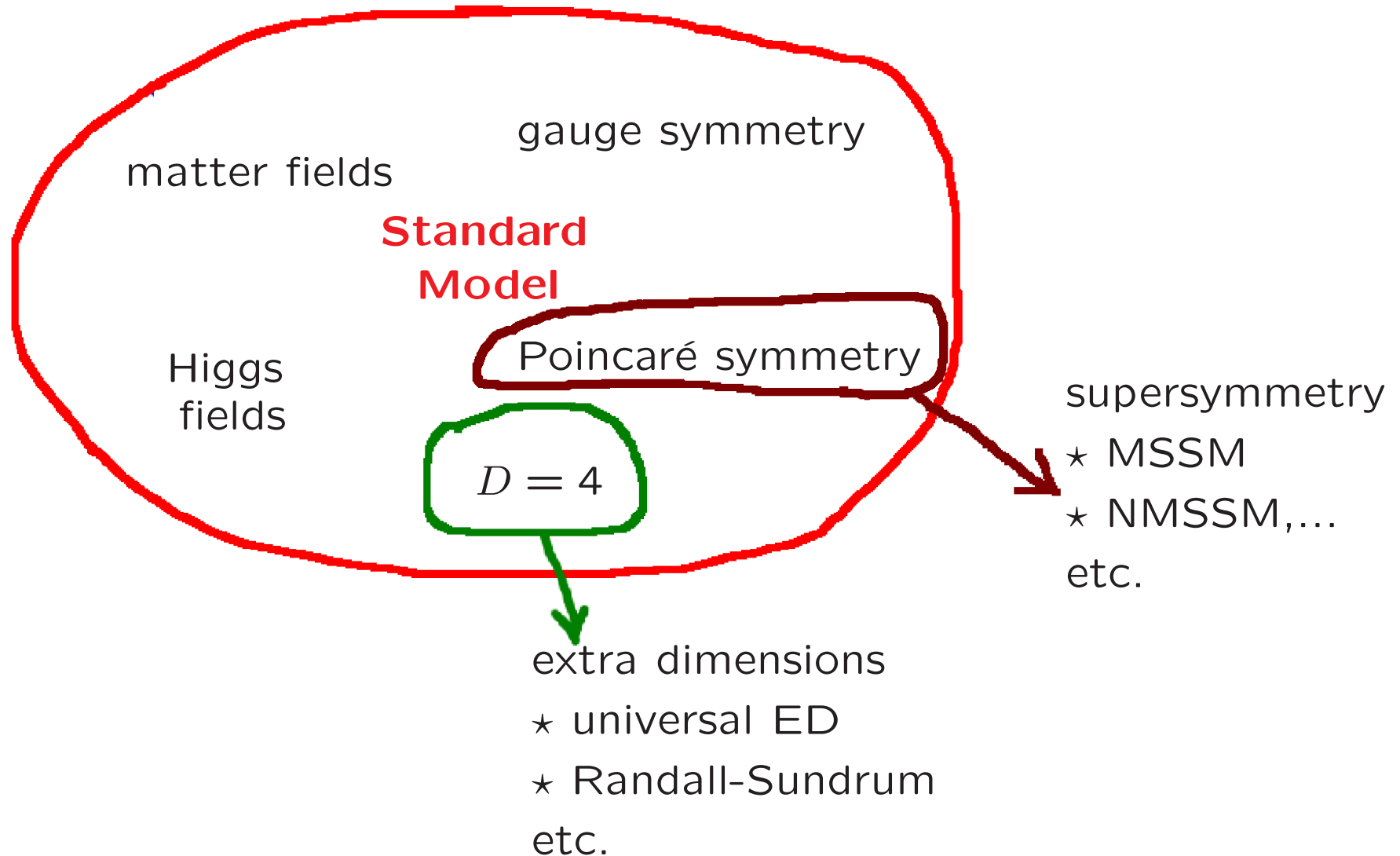
■ A broad view on SM extensions



■ A broad view on SM extensions



■ A broad view on SM extensions



extra gauge groups

★ GUT

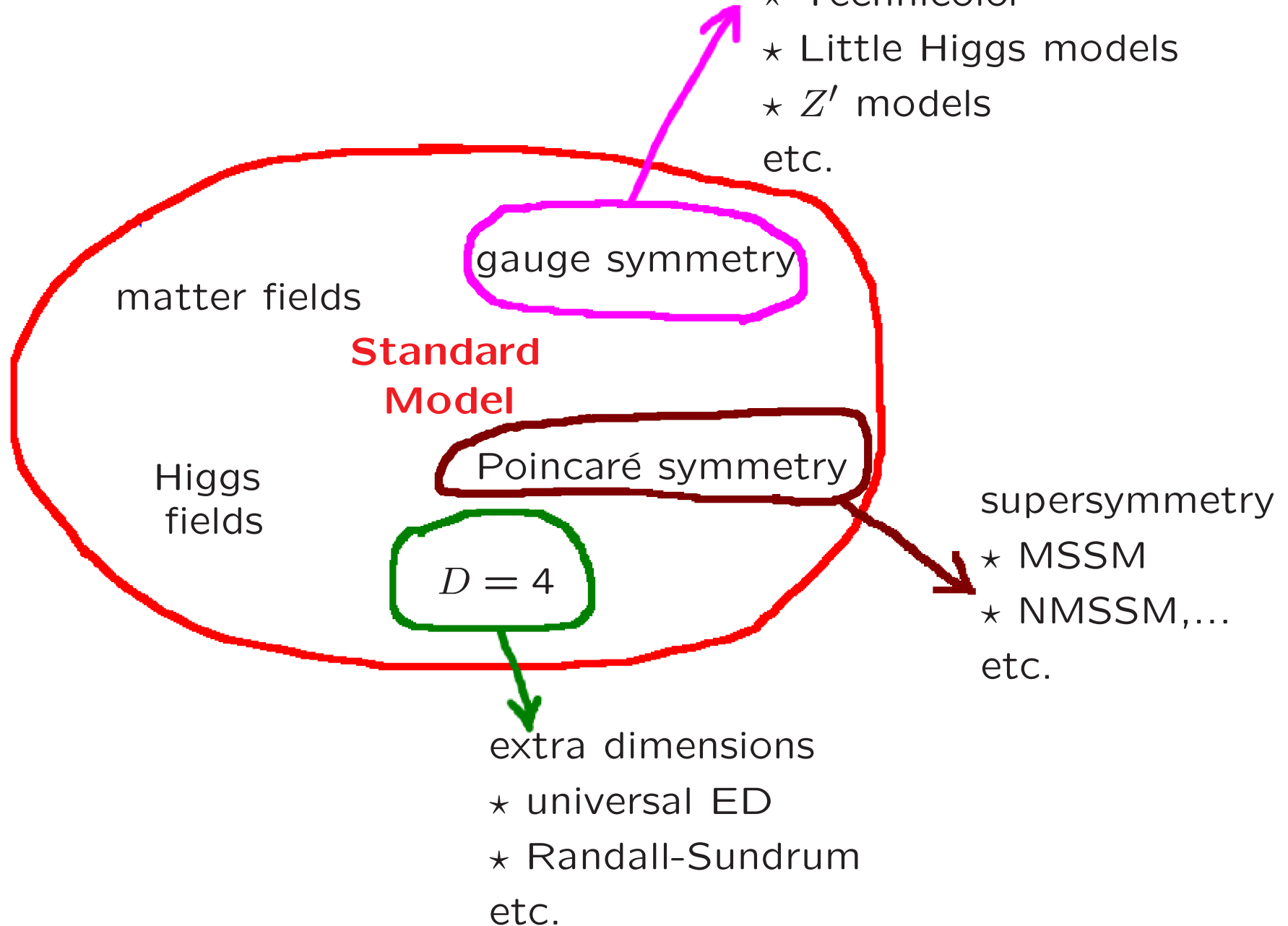
★ Technicolor

★ Little Higgs models

★ Z' models

etc.

■ A broad view on SM extensions



extra gauge groups

★ GUT

★ Technicolor

★ Little Higgs models

★ Z' models

etc.

■ A broad view on SM extensions

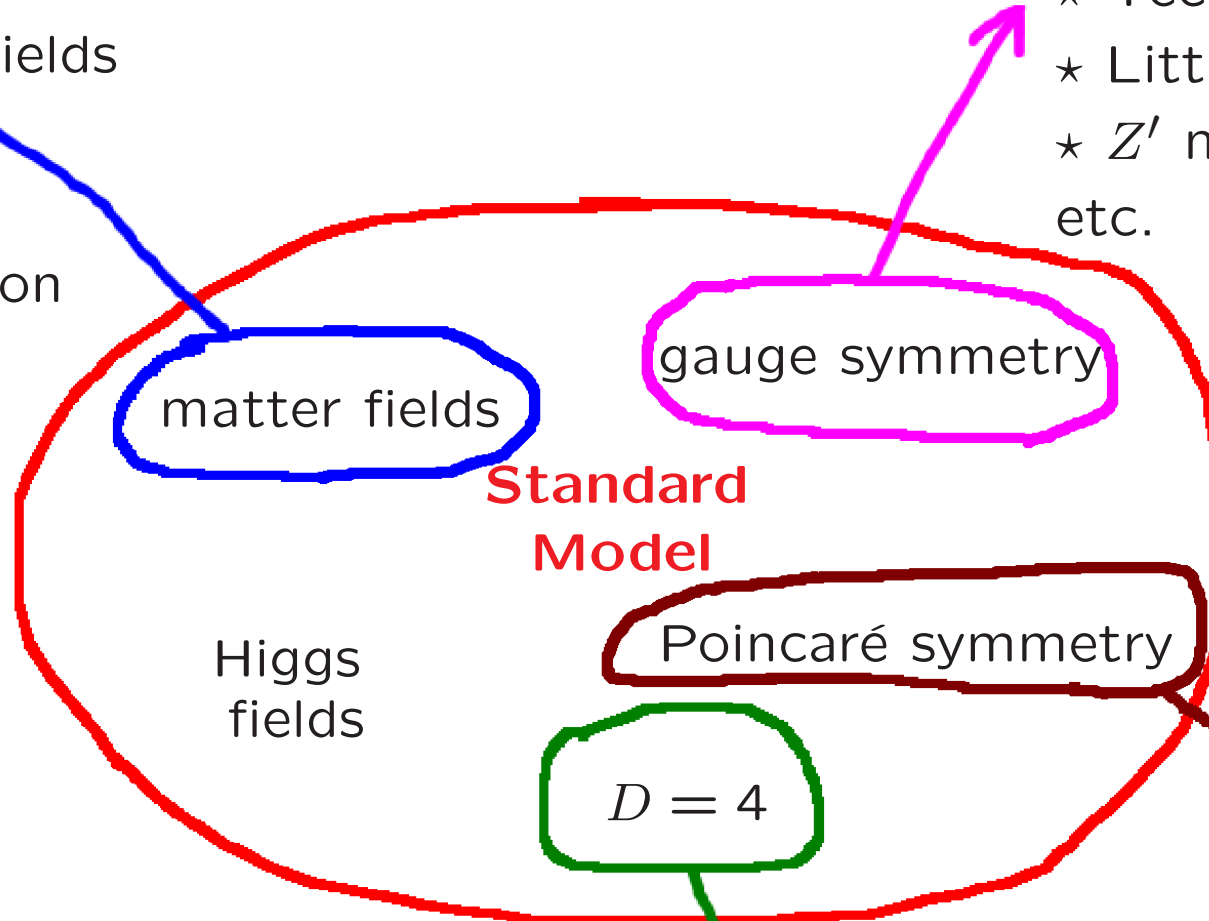
extra matter fields

★ SUSY

★ Little Higgs

★ 4th generation

etc.



supersymmetry

★ MSSM

★ NMSSM,...

etc.

extra dimensions

★ universal ED

★ Randall-Sundrum

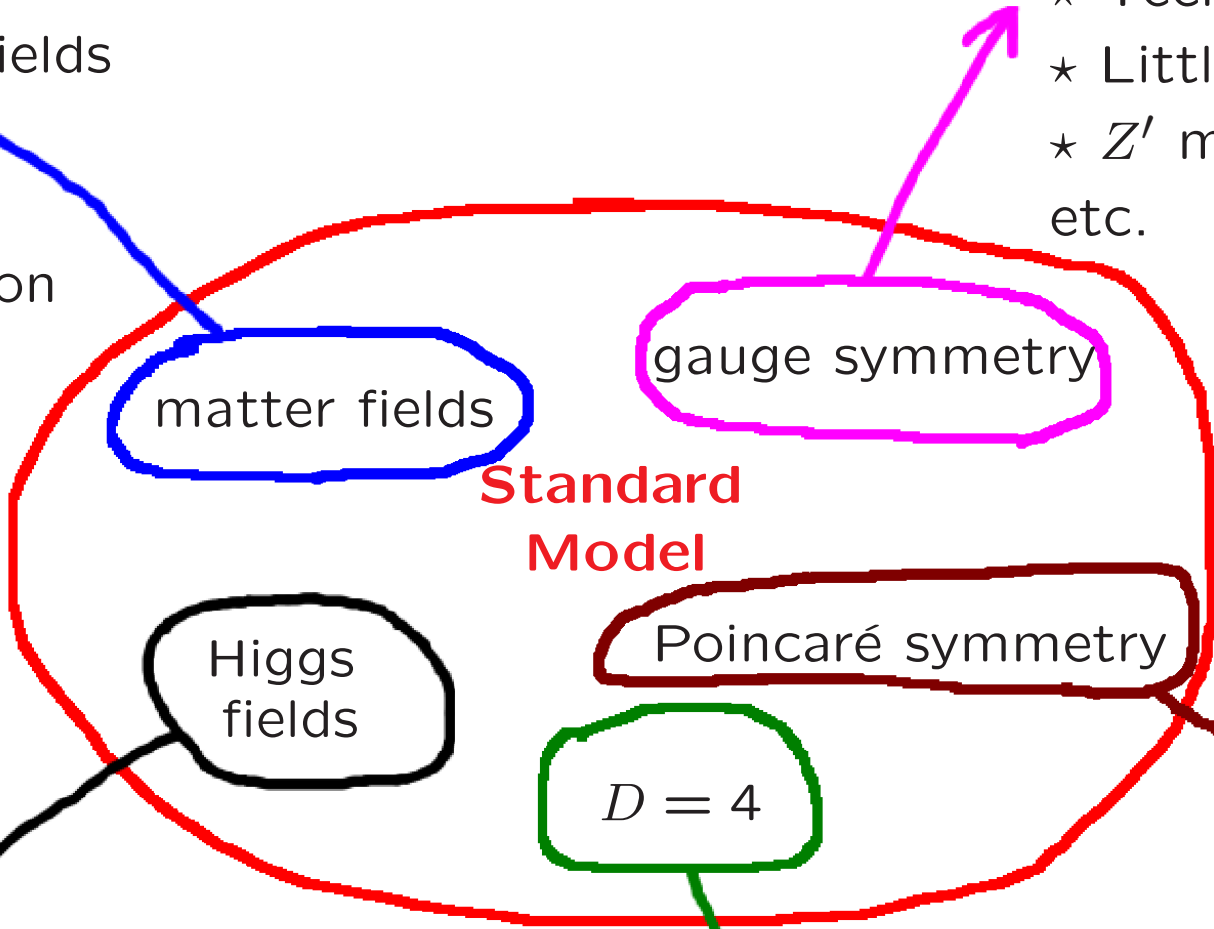
etc.

extra gauge groups

- ★ GUT
- ★ Technicolor
- ★ Little Higgs models
- ★ Z' models
- etc.

■ A broad view on SM extensions

- extra matter fields
- ★ SUSY
 - ★ Little Higgs
 - ★ 4th generation
 - etc.

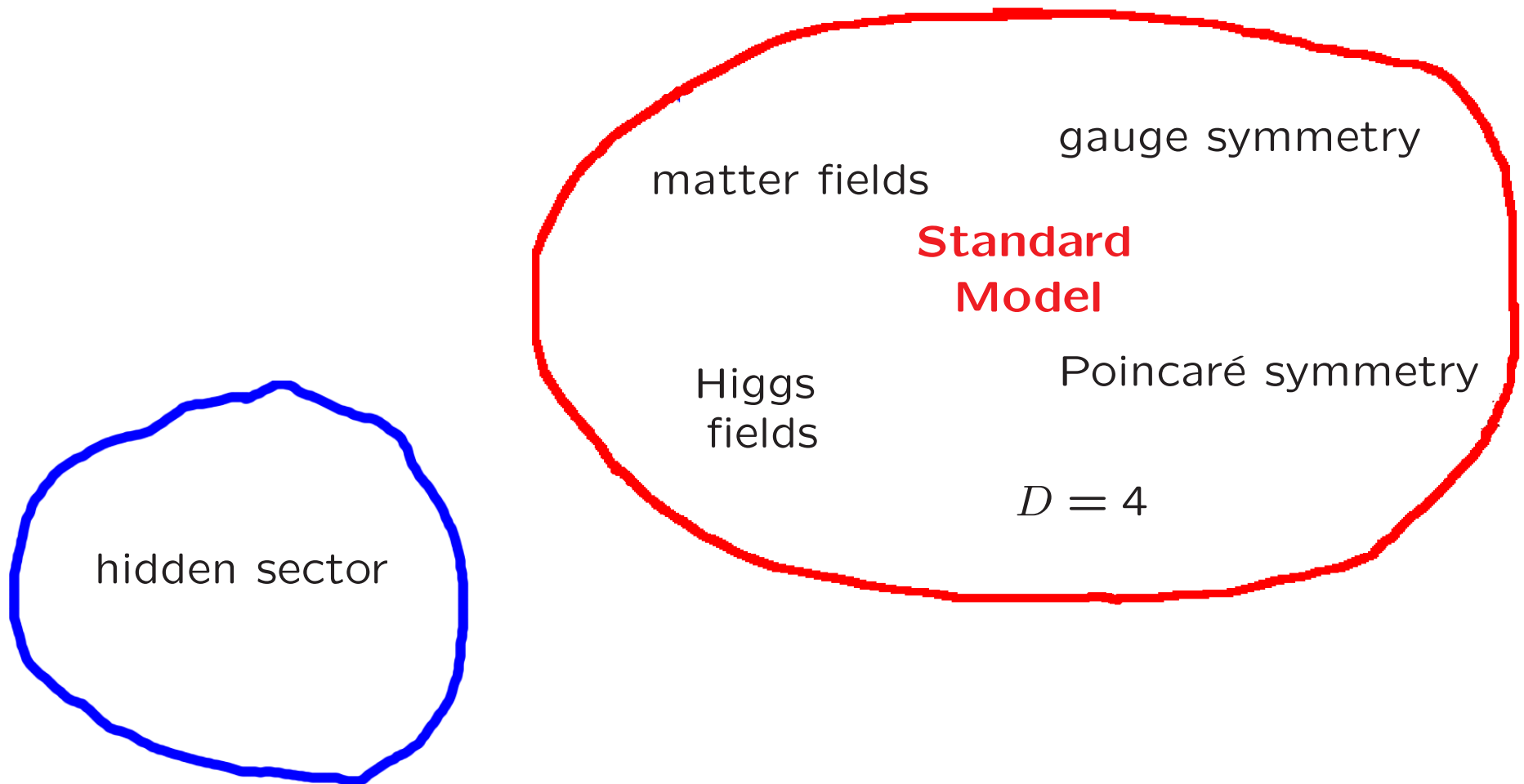


- change/extra multiplets
- ★ SUSY
 - ★ Little Higgs
 - ★ Higgs triplet models
 - etc.

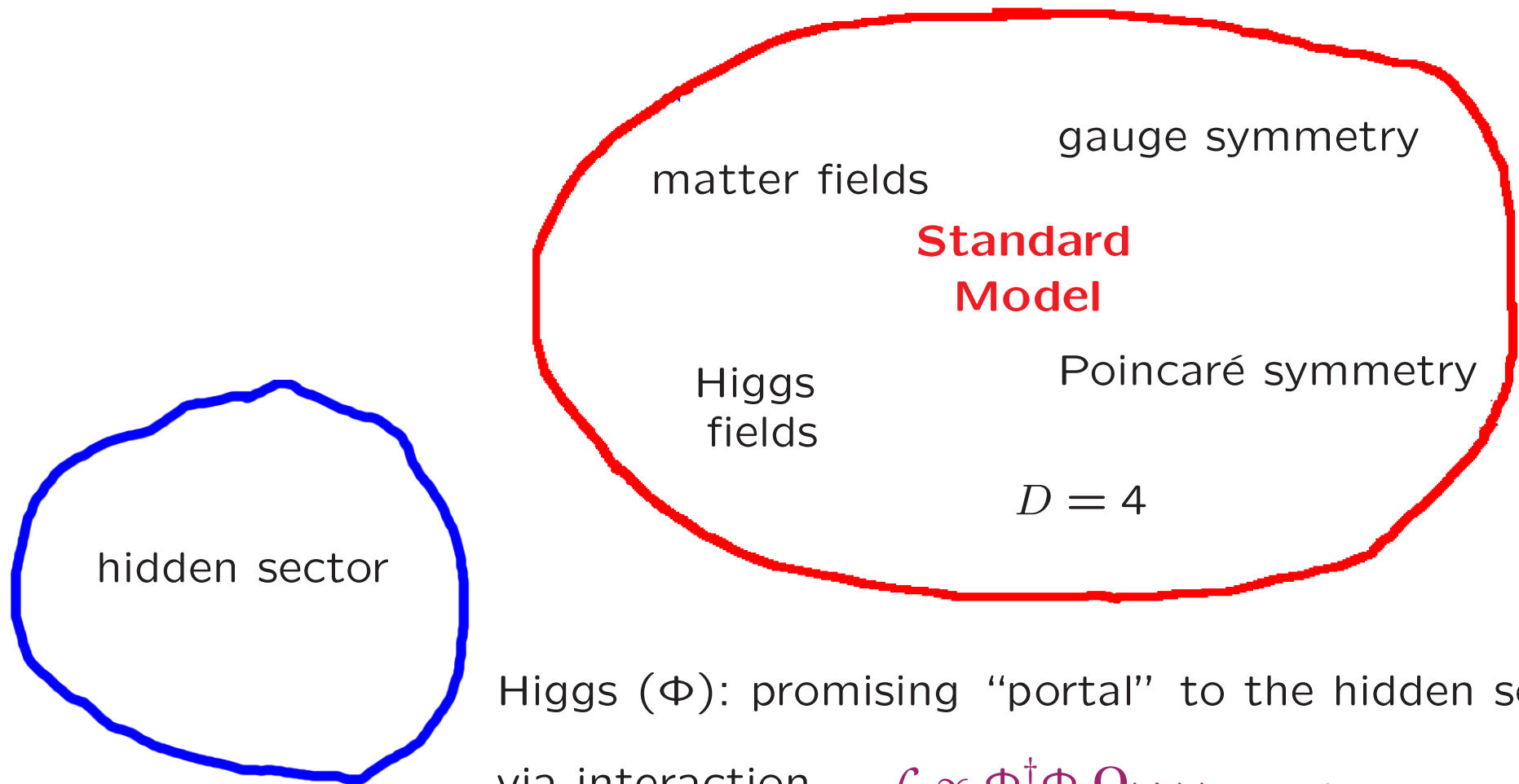
- extra dimensions
- ★ universal ED
 - ★ Randall-Sundrum
 - etc.

- supersymmetry
- ★ MSSM
 - ★ NMSSM,...
 - etc.

■ A broad view on SM extensions



■ A broad view on SM extensions

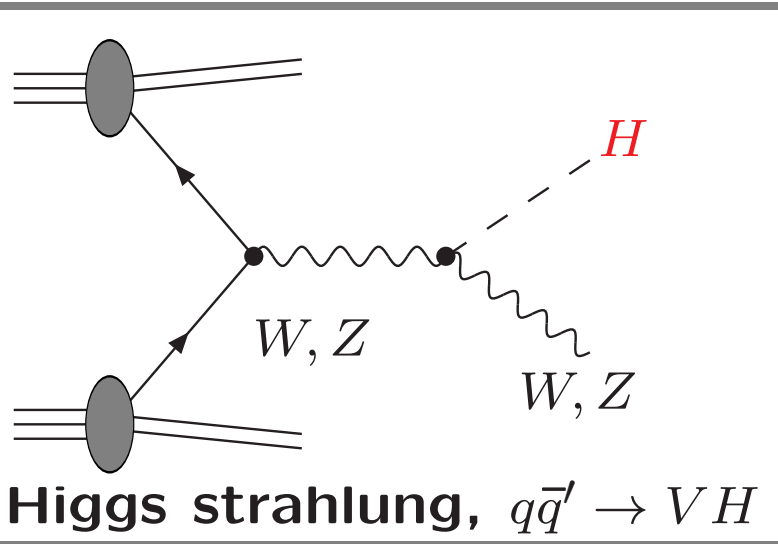


Higgs (Φ): promising “portal” to the hidden sector
via interaction $\mathcal{L} \propto \Phi^\dagger \Phi \mathbf{O}_{\text{hidden sector}}$

- Selected Projects

– SM Higgsstrahlung (NNLO QCD)

– SM Higgsstrahlung (NNLO QCD)



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

Observation 1:

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

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

Observation 2:

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

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

→ Idea : Use $\sigma_{\text{NNLO}}(q\bar{q} \rightarrow V^*)$ to evaluate $\sigma(pp \rightarrow HV)$.

status of theory predictions:

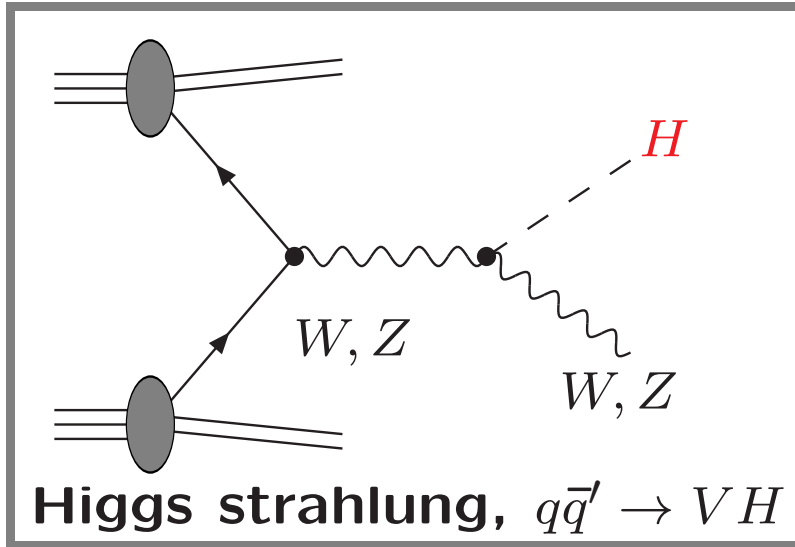
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock '91]

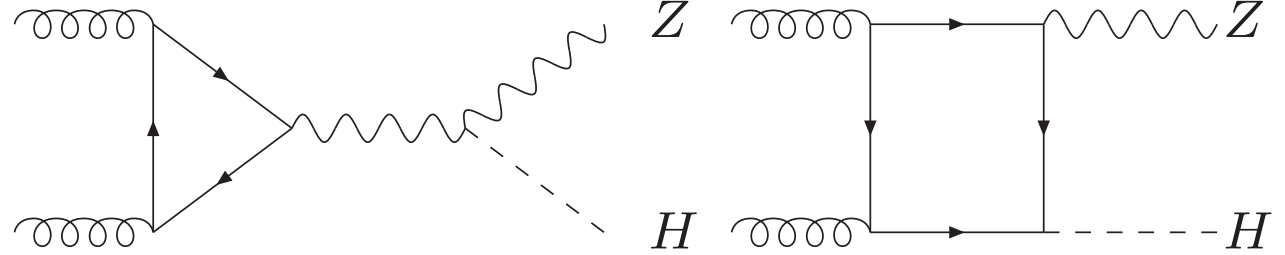
SM, NNLO QCD [OBr, Djouadi, Harlander '03]

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

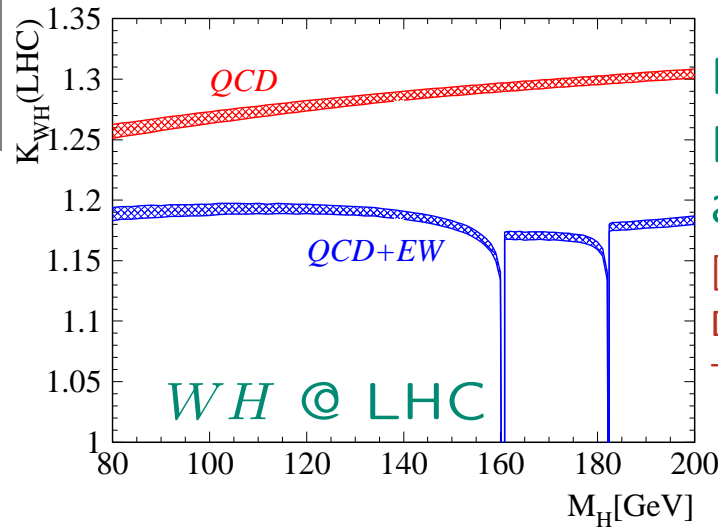
MSSM, NLO SUSY-QCD [Djouadi, Spira '00]



note! additional parton process for ZH @ NNLO

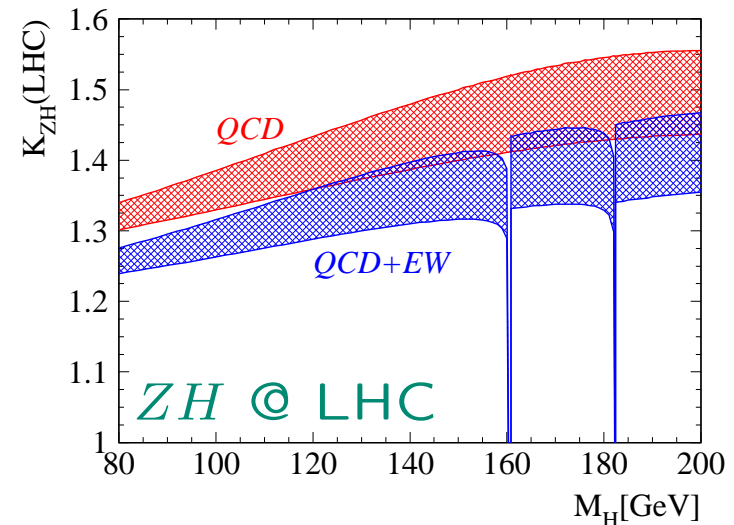


[Dicus, Kao '88; Kniehl '90]



**NNLO QCD + NLO EW
K-factors
and scale uncertainty**

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



status of theory predictions:

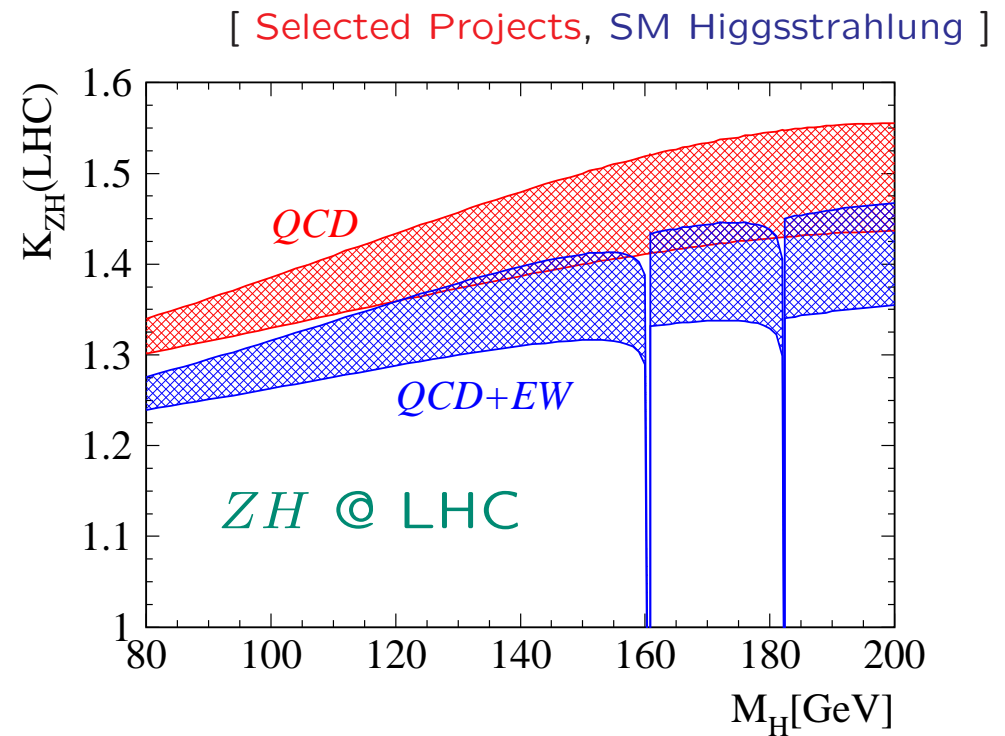
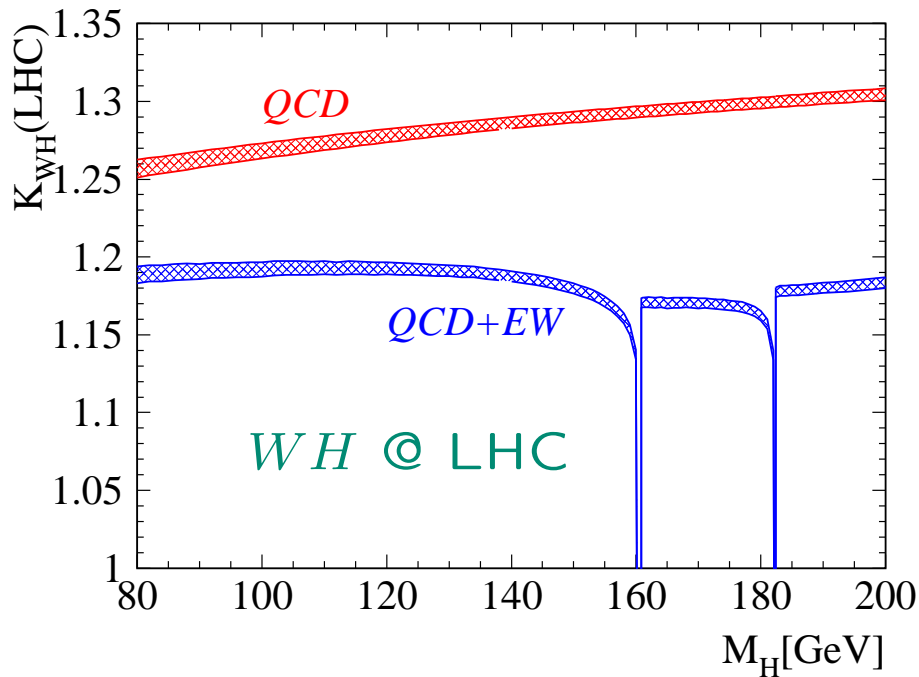
SM, LO [Glashow, Nanopoulos, Yildiz '78]

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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]

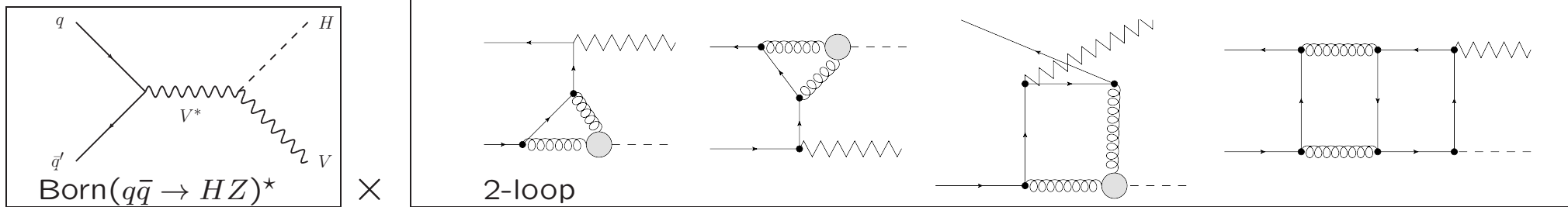
■ Top quark induced corrections

Unfortunately, this is not the whole story! :

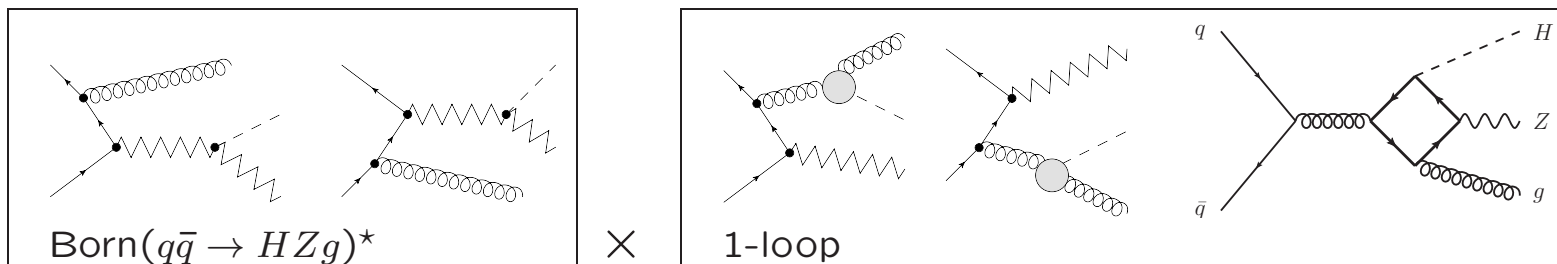
Top quark induced corrections appear at NNLO QCD
and are not Drell-Yan like.

→ previously overlooked!

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



- real corrections at NNLO: ($q\bar{q} \rightarrow HZg$, $qg \rightarrow HZq$, $\bar{q}g \rightarrow HZ\bar{q}$)

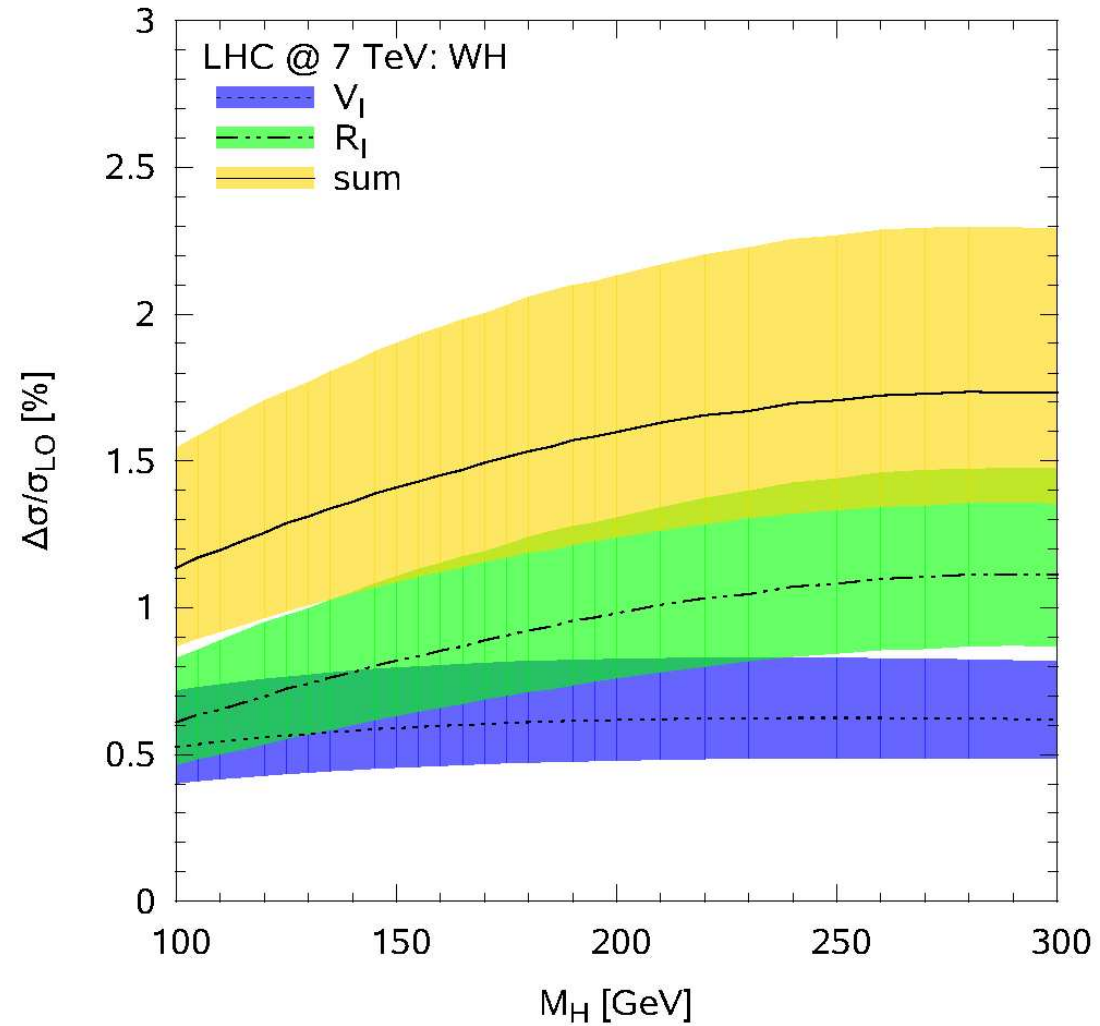
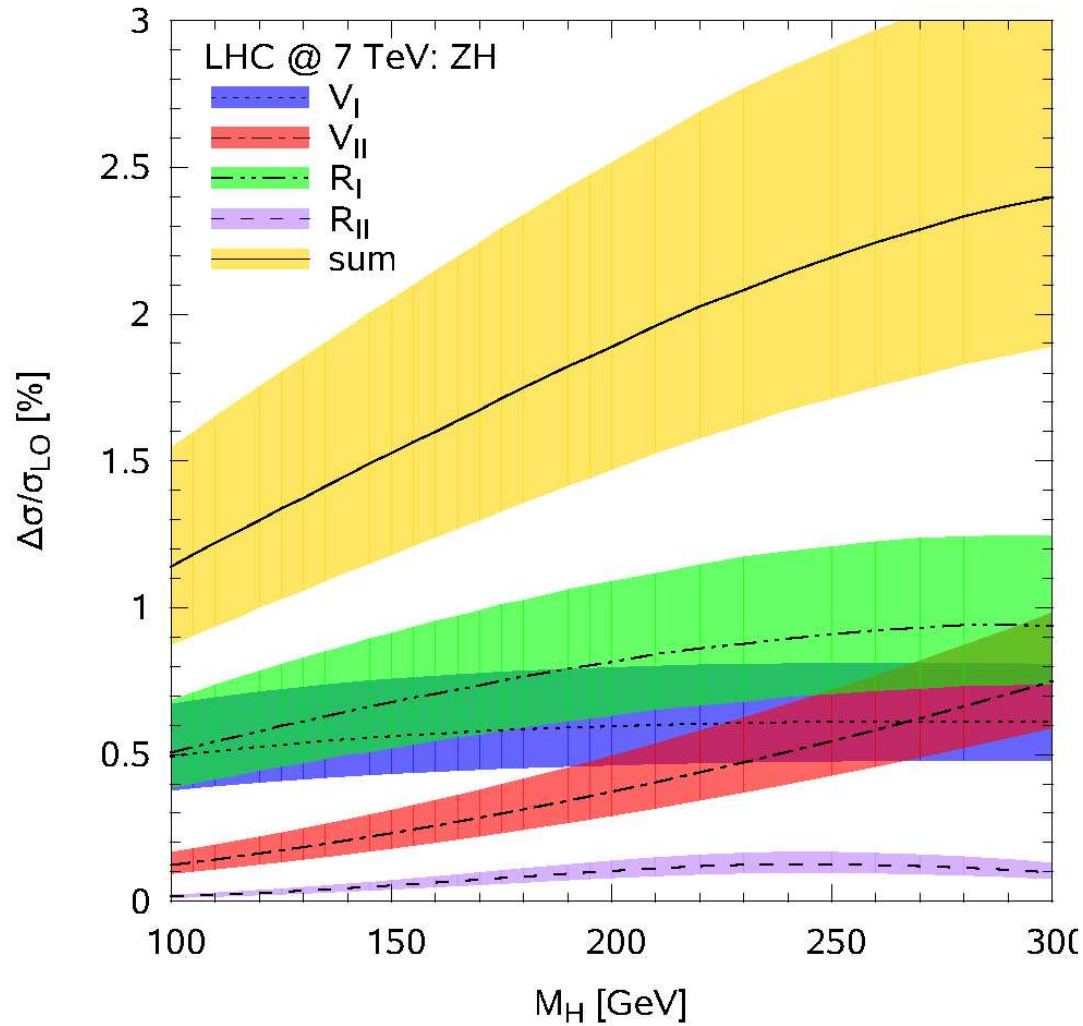


- similar corrections for WH production (and in vector boson fusion too!)
- technical challenges: 1) agreement between two indep. calculations using:
 - ... asymptotic expansions
 - ... effective vertices & tensor reduction
 2) exact calculation of real corrections

■ LHC(7 TeV) results :

ZH

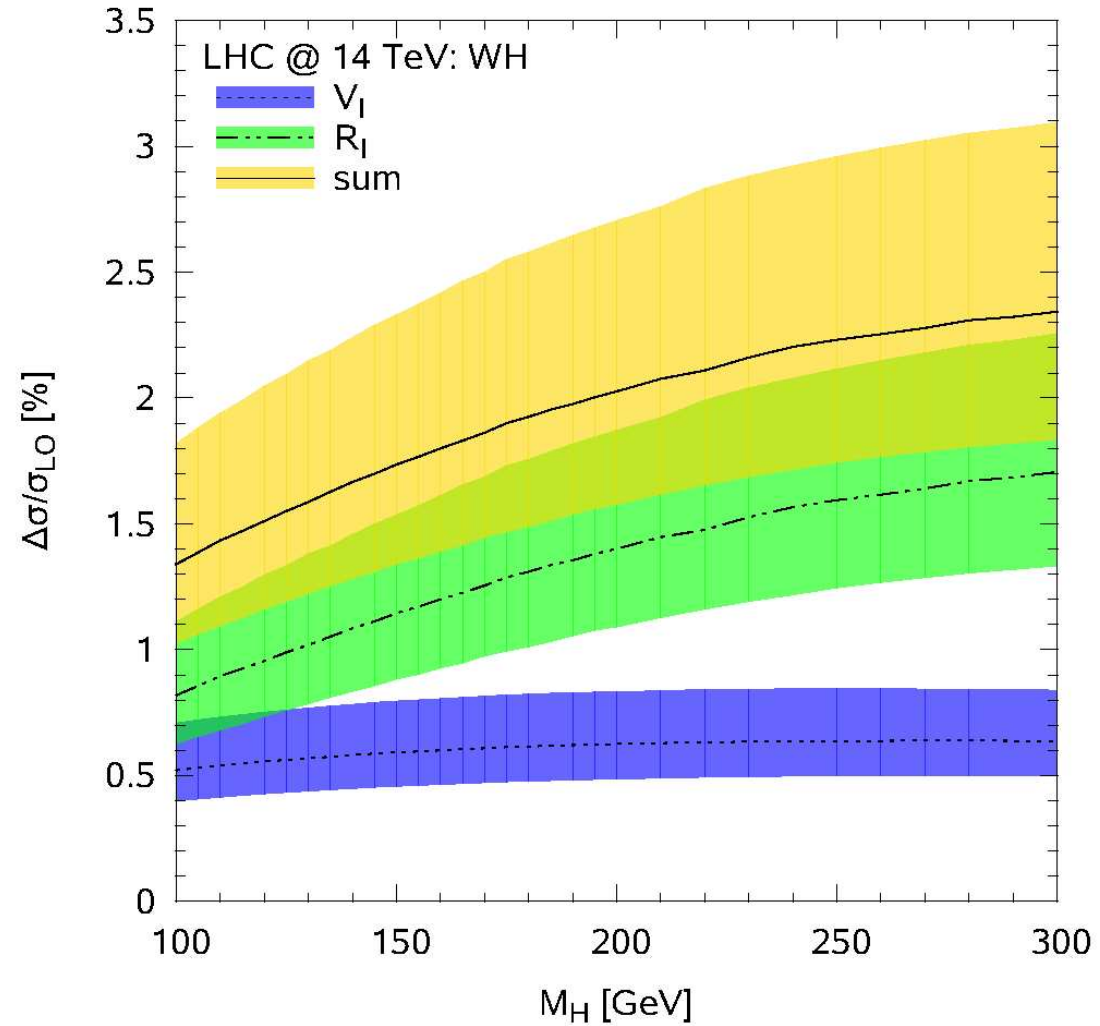
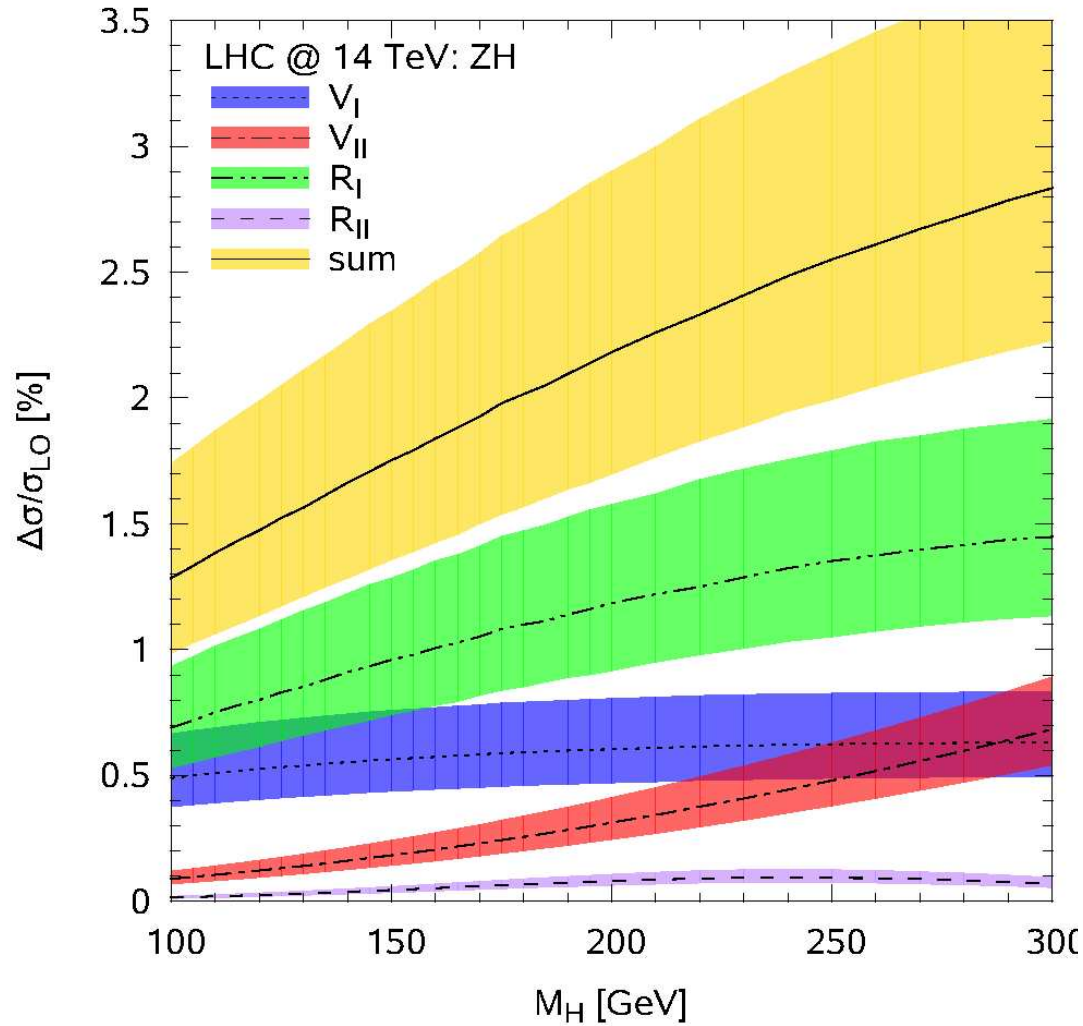
WH



■ LHC(14 TeV) results :

ZH

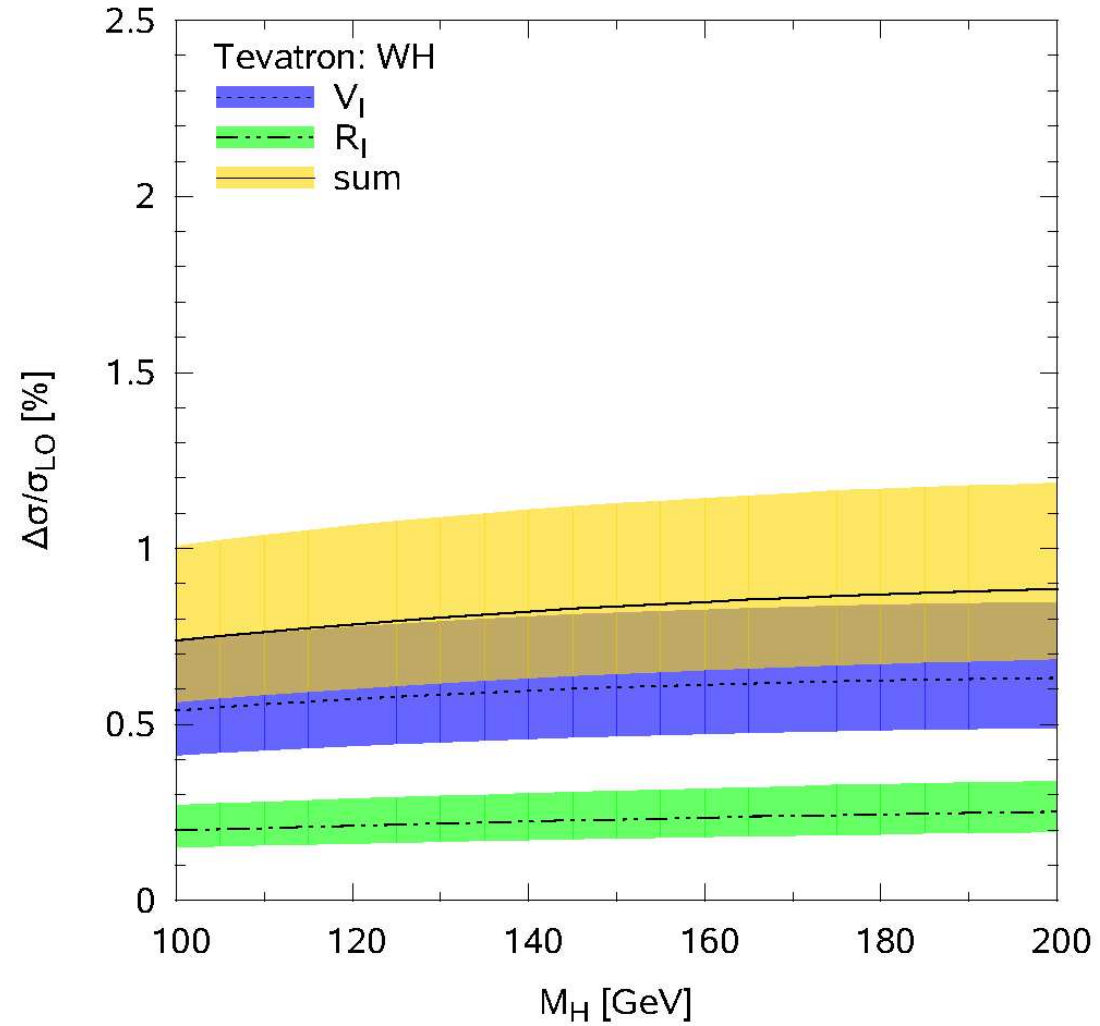
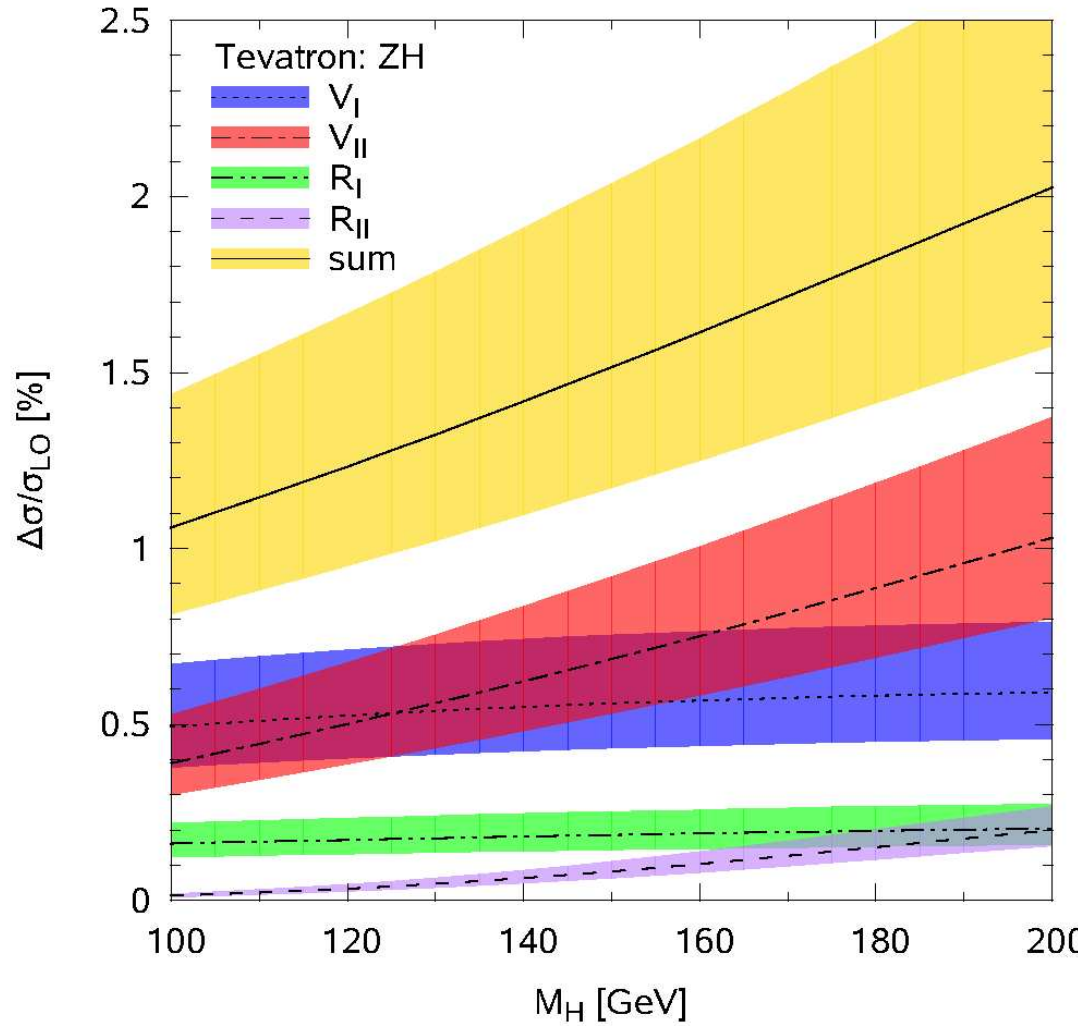
WH



■ Tevatron results :

ZH

WH

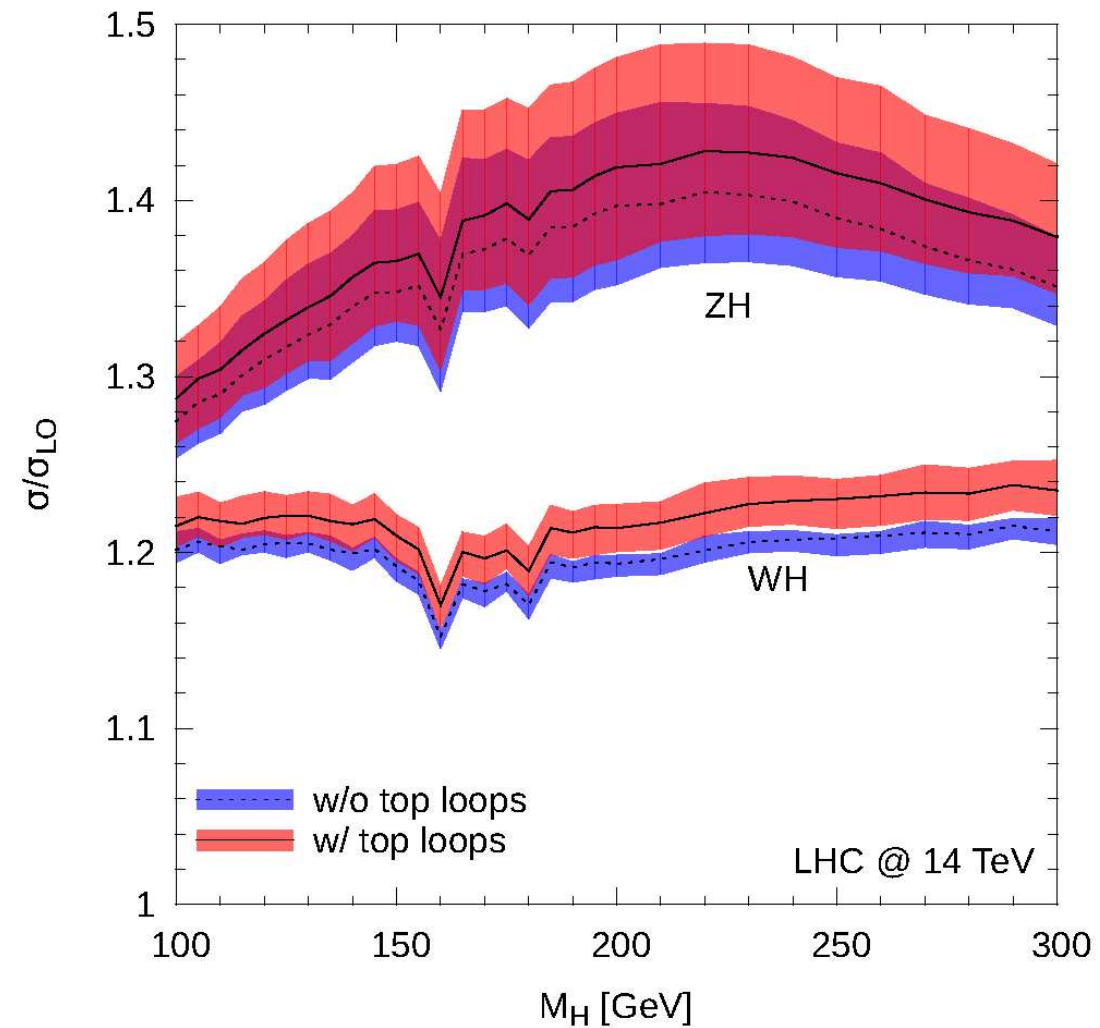
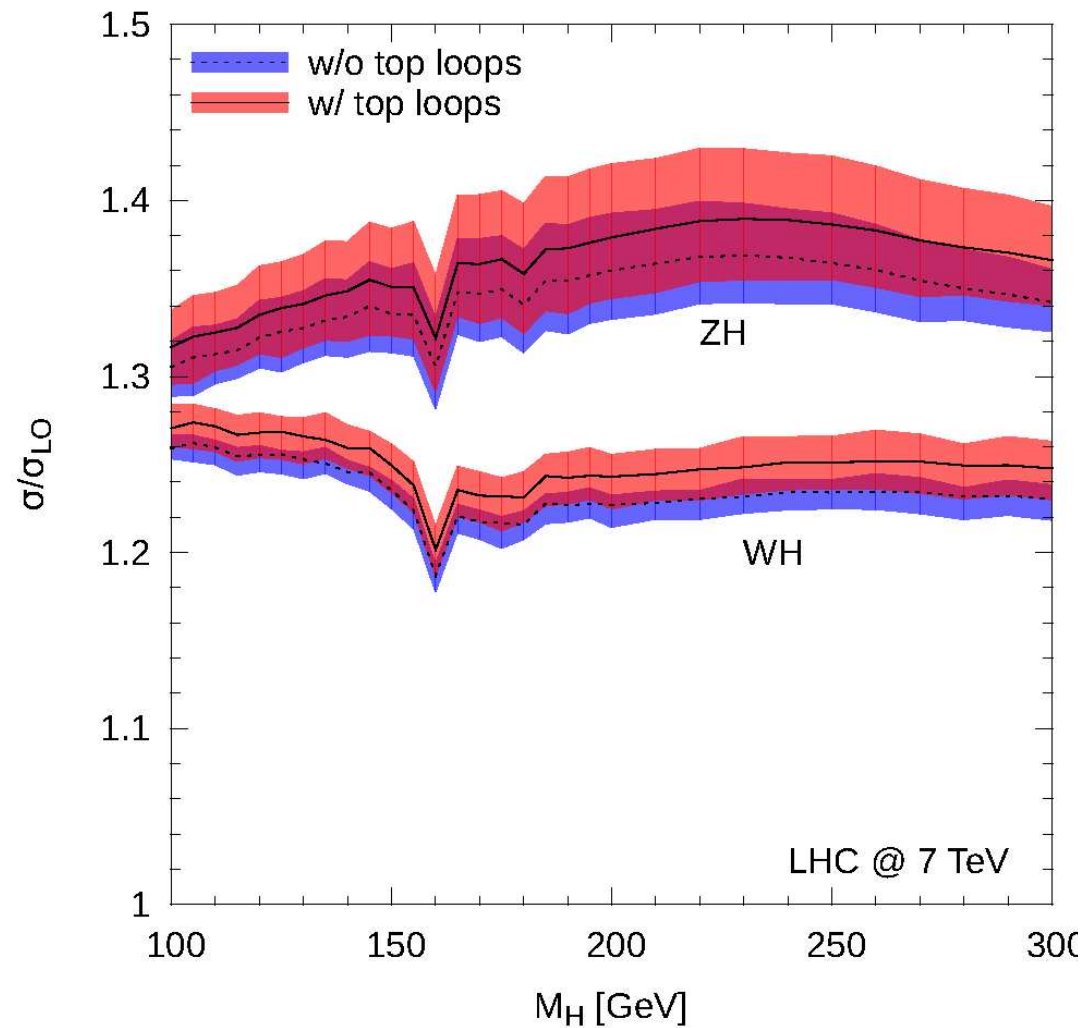


■ LHC results : change in NNLO/LO K -factor

[OBr, Harlander, Wiesemann, Zirke '11]

LHC (7 TeV)

LHC (14 TeV)



- Randall-Sundrum scalar sector constrained

– Randall-Sundrum scalar sector constrained

■ **HiggsBounds** : [Bechtle, OBr, Heinemeyer, Stefaniak, Weiglein, Williams '08-'11]

tests models with arbitrary Higgs sectors against exclusion bounds from direct searches.

- easy access to all relevant Higgs exclusion limits including information not available in the publications. (e.g. expected 95% CL cross section limits)
- 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} , $\Gamma_{\text{tot}}(h_i)$, $\text{BR}(h_i \rightarrow \dots)$,
production cross section ratios (wrt reference values)
- combination of results from LEP, Tevatron and LHC possible
- three ways to use HiggsBounds:
□ command line, □ subroutines (Fortran [77]/90), □ web interface:
projects.hepforge.org/higgsbounds

■ HiggsBounds: status and outlook

- The code is publicly available since Feb. 2009 (current version: 3.5.0 beta)
 - projects.hepforge.org/higgsbounds
 - Tevatron & LHC results up to Lepton-Photon 2011 included
 - extended functionality (H^\pm searches, onlyP analyses selection, ...)
 - HiggsBounds 3.5.0 beta available to download
 - includes: SLHA input option, χ^2 fitting for LEP channels,
optional addition: **SusyBounds** (Chargino, Neutralino bounds)
- Reception very good (> 100 users). Code used in/by:
FeynHiggs, **CPsuperH**, **Fittino**, **MasterCode**, **2HDMC**, **DarkSusy**,
SuperIso, etc.
- Current work/plans:
 - new LHC results after Lepton-Photon 2011
 - searches for fermiophobic models
 - doubly charged Higgs searches, LEP searches for $m_H < 10$ GeV
 - inclusion of width-dependent limits

■ Randall Sundrum model basics:

- 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^{-1} are $\mathcal{O}(M_{\text{Pl}})$ with $kr_c \approx 12$.

This “little hierarchy” can be generated & stabilized [Goldberger, Wise '00]

\Rightarrow fluctuations of r_c : scalar d.o.f φ , gets a VEV Λ_ϕ

- resolution of the hierarchy problem: Why is the EW scale $\ll M_{\text{Pl}}$?:
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 $g_{\text{ind}}(\varphi(x), \dots)$: 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
 - ★ φgg 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

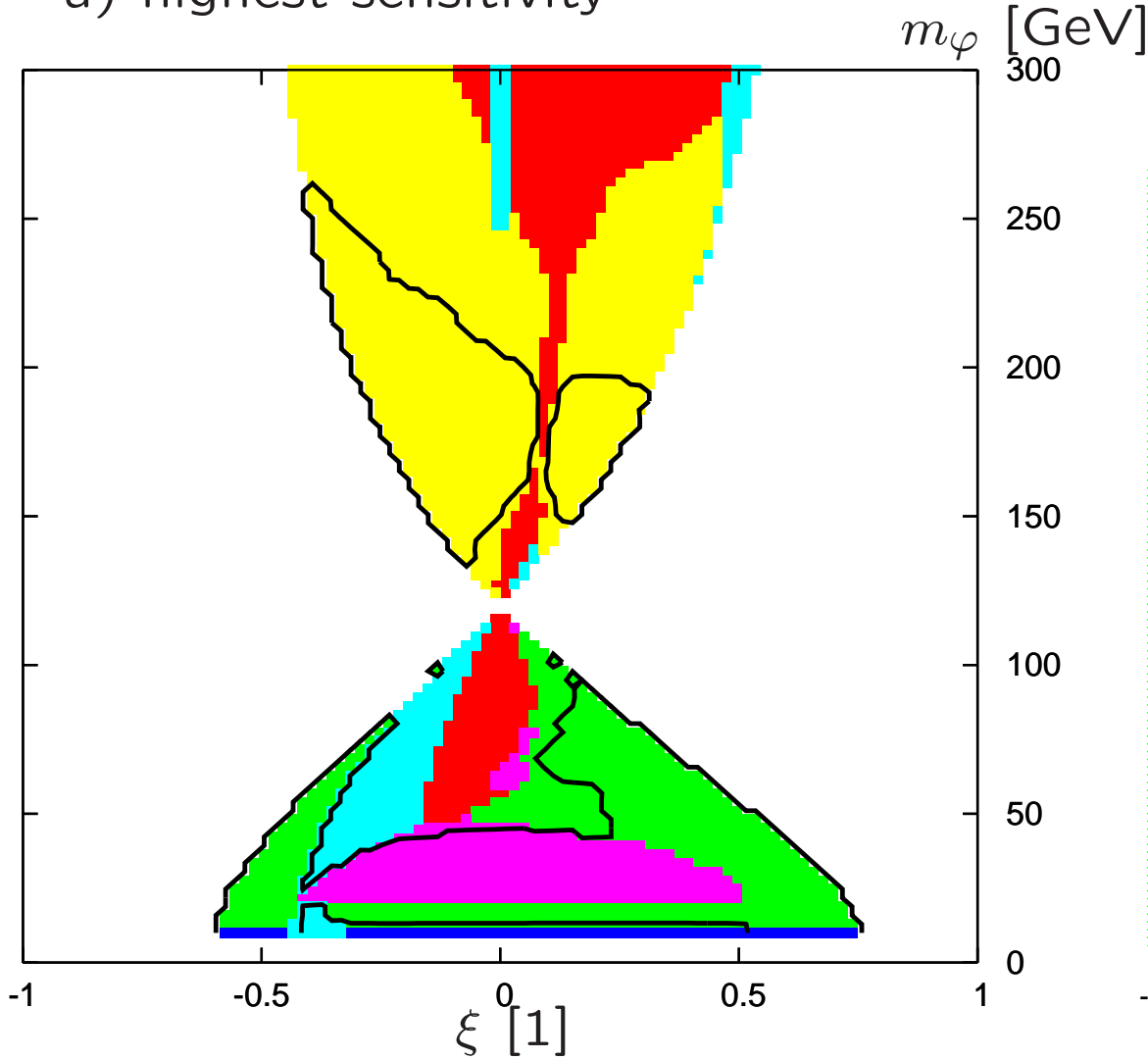
Exclusion range and sensitivity map: $\xi - m_\phi$ plane w/o LHC data (12/2010)

ee \rightarrow h Z, h \rightarrow bb
 ee \rightarrow phi Z, phi \rightarrow bb
 ee \rightarrow phi Z, phi \rightarrow anything
 ee \rightarrow phi Z, phi \rightarrow hadrons
 pp \rightarrow single h, h \rightarrow WW
 pp \rightarrow single phi, phi \rightarrow WW

parameter:

$\Lambda_\phi = 1$ TeV
 $m_h = 120$ GeV

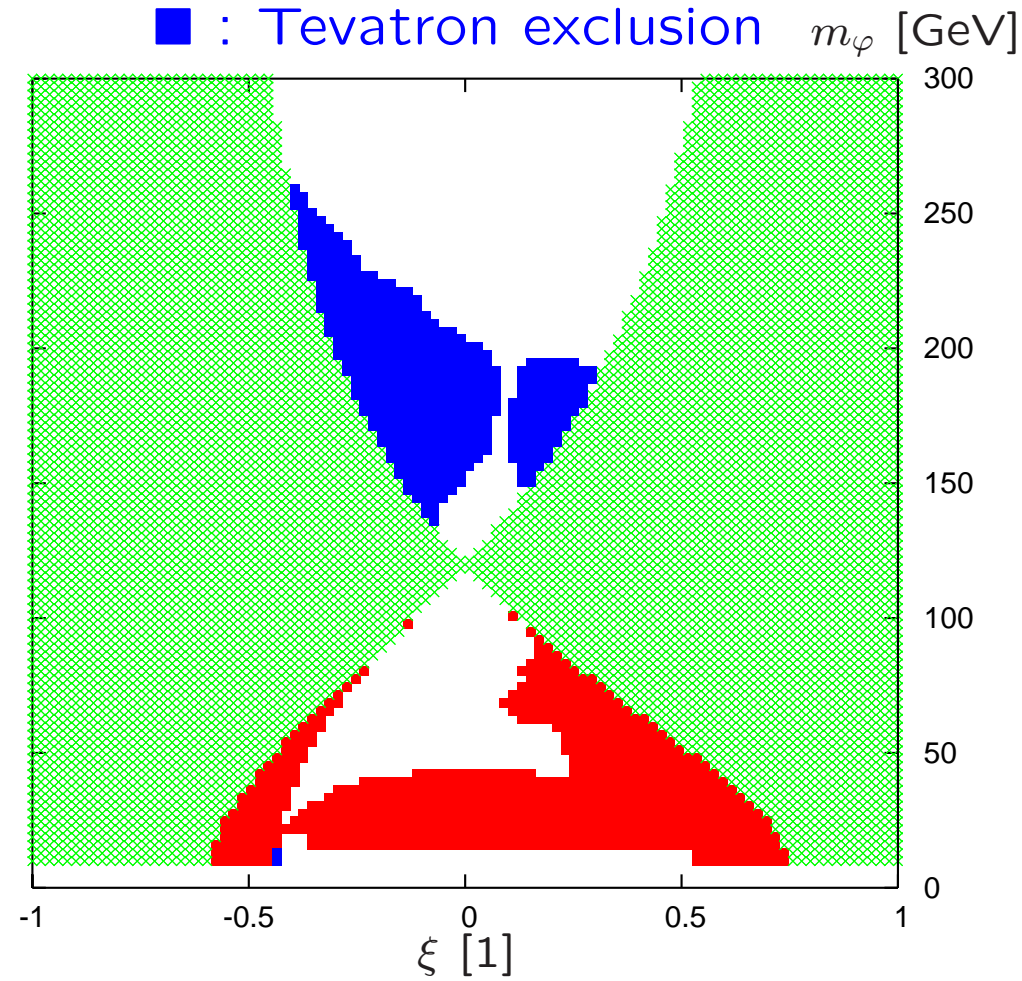
a) highest sensitivity



b) exclusion

■ : LEP exclusion

■ : Tevatron exclusion



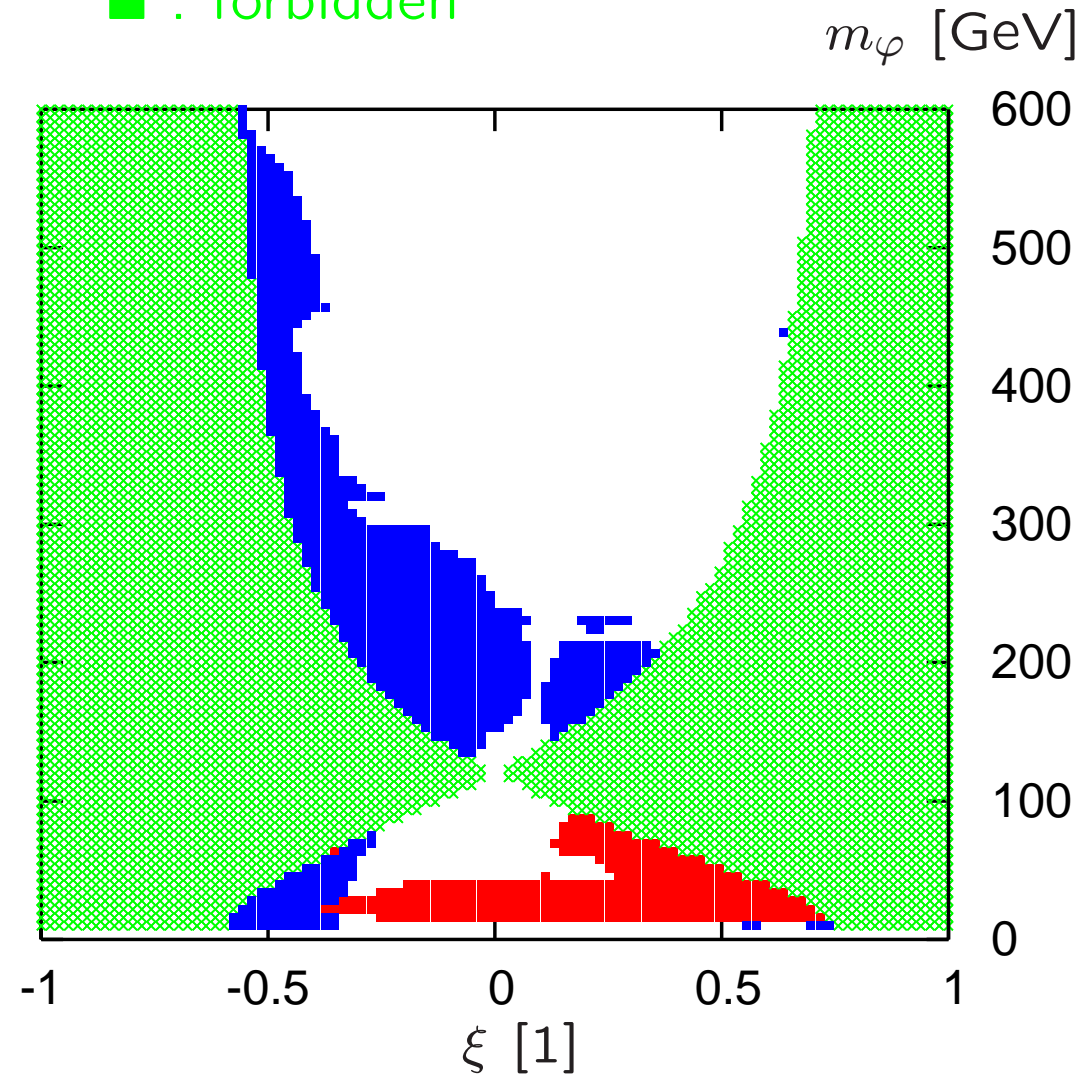
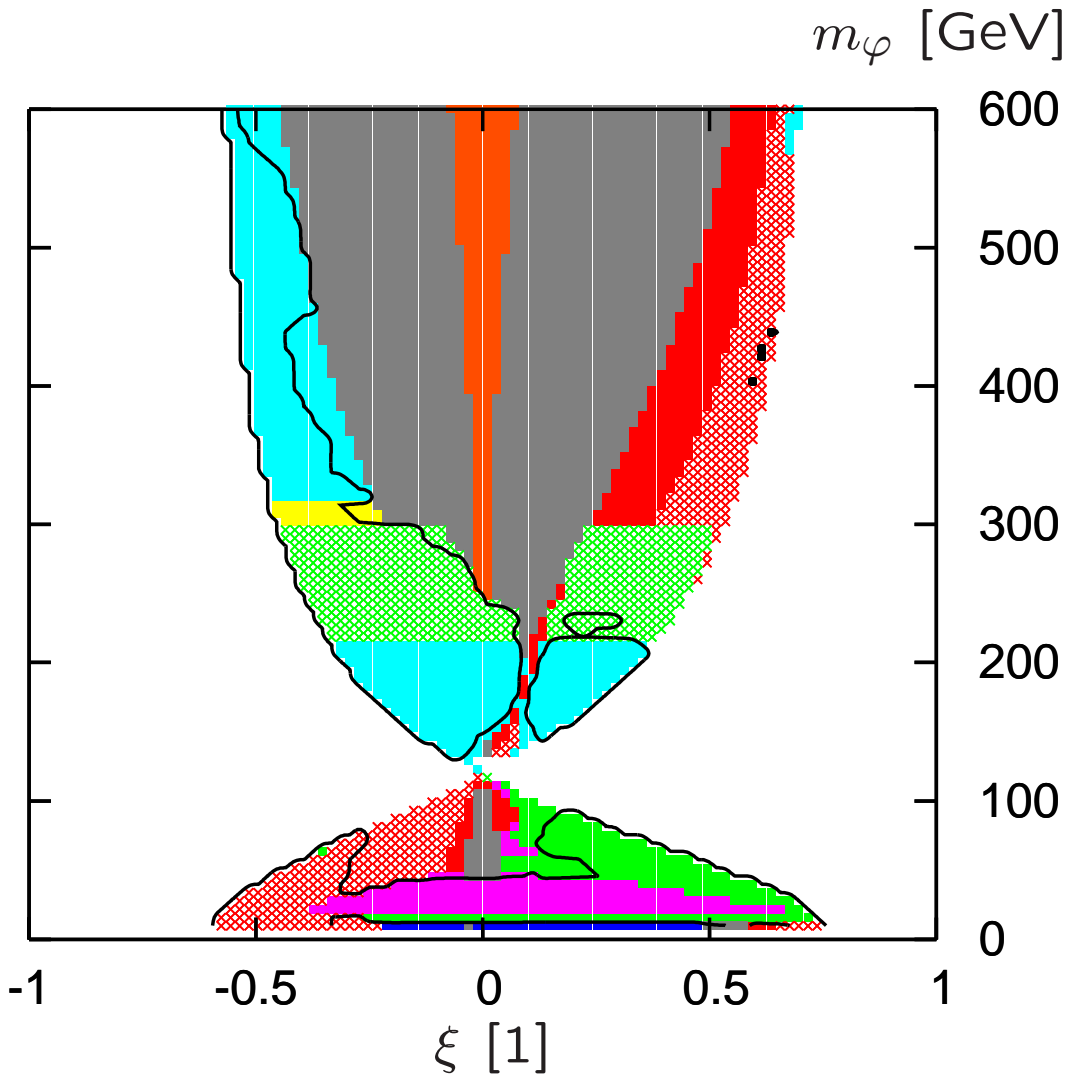
Exclusion range and sensitivity map: $\xi - m_\varphi$ plane with LHC data

parameter: $\Lambda_\varphi = 1 \text{ TeV}$, $m_h = 120 \text{ GeV}$

a) highest sensitivity

b) exclusion

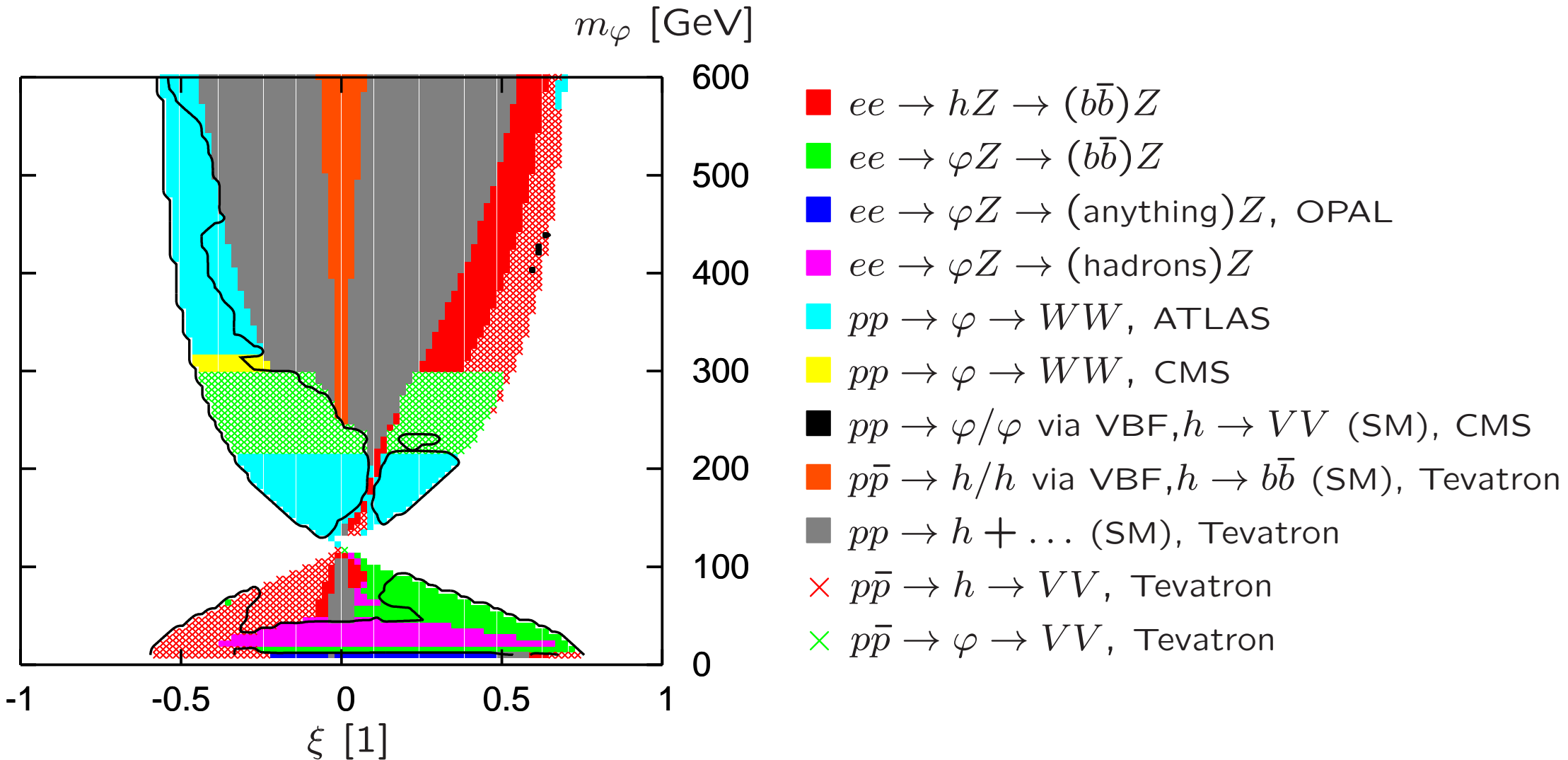
- : LEP exclusion
- : LHC/Tevatron exclusion
- : forbidden



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

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

a) highest sensitivity



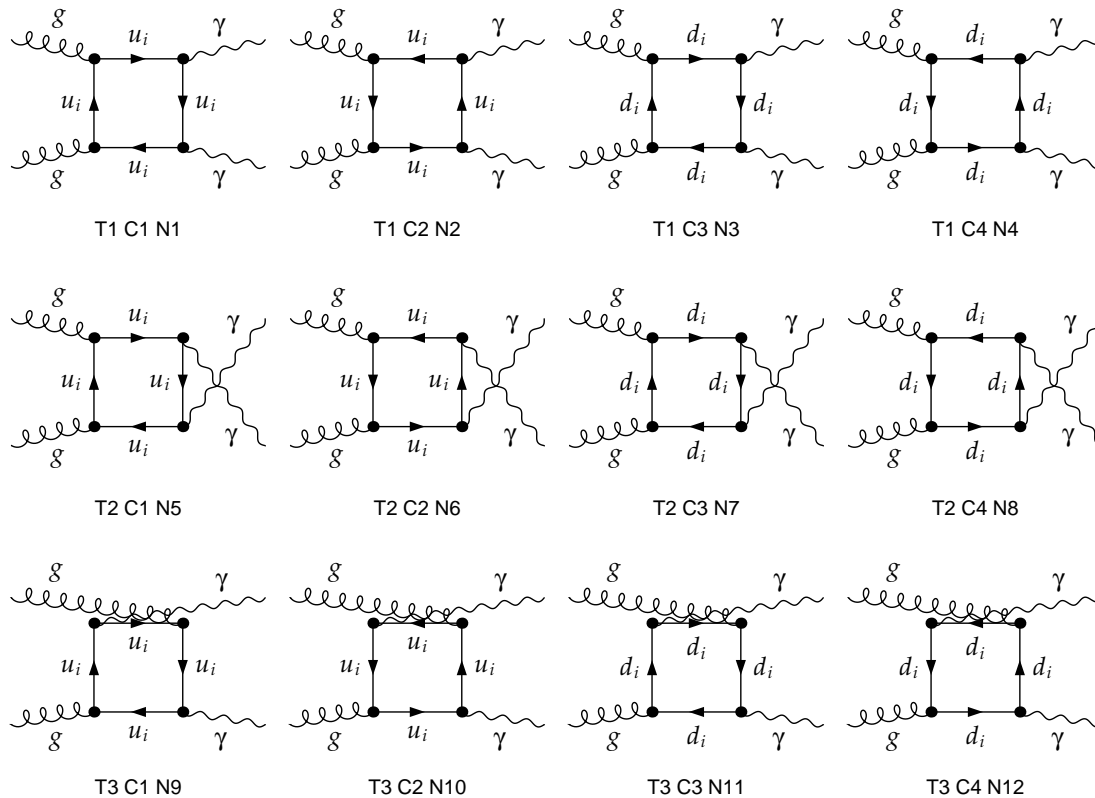
– New physics in $\gamma\gamma/WW/ZZ$ production

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

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

SM process

$$g g \rightarrow \gamma \gamma$$



In general:

all particles carrying colour and electrical charge contribute.

Supersymmetry (MSSM):

- additional contributions by quark superpartners (squarks)
- squark masses $\propto M_{\text{SUSY}}$

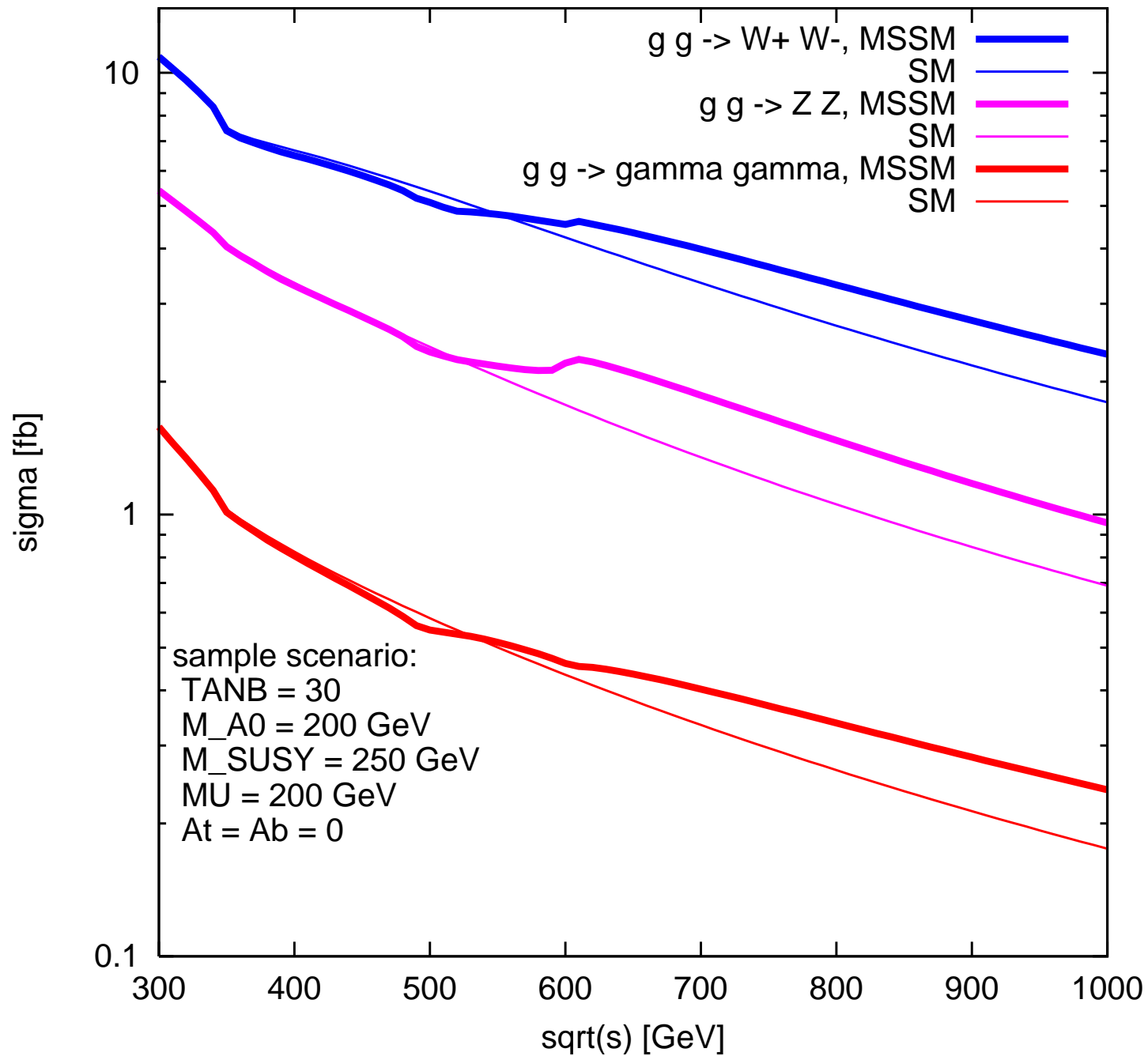
Universal Extra Dimensions (UED):

- additional contributions by Kaluza-Klein (KK) excitations of the quarks
- KK quark masses:

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

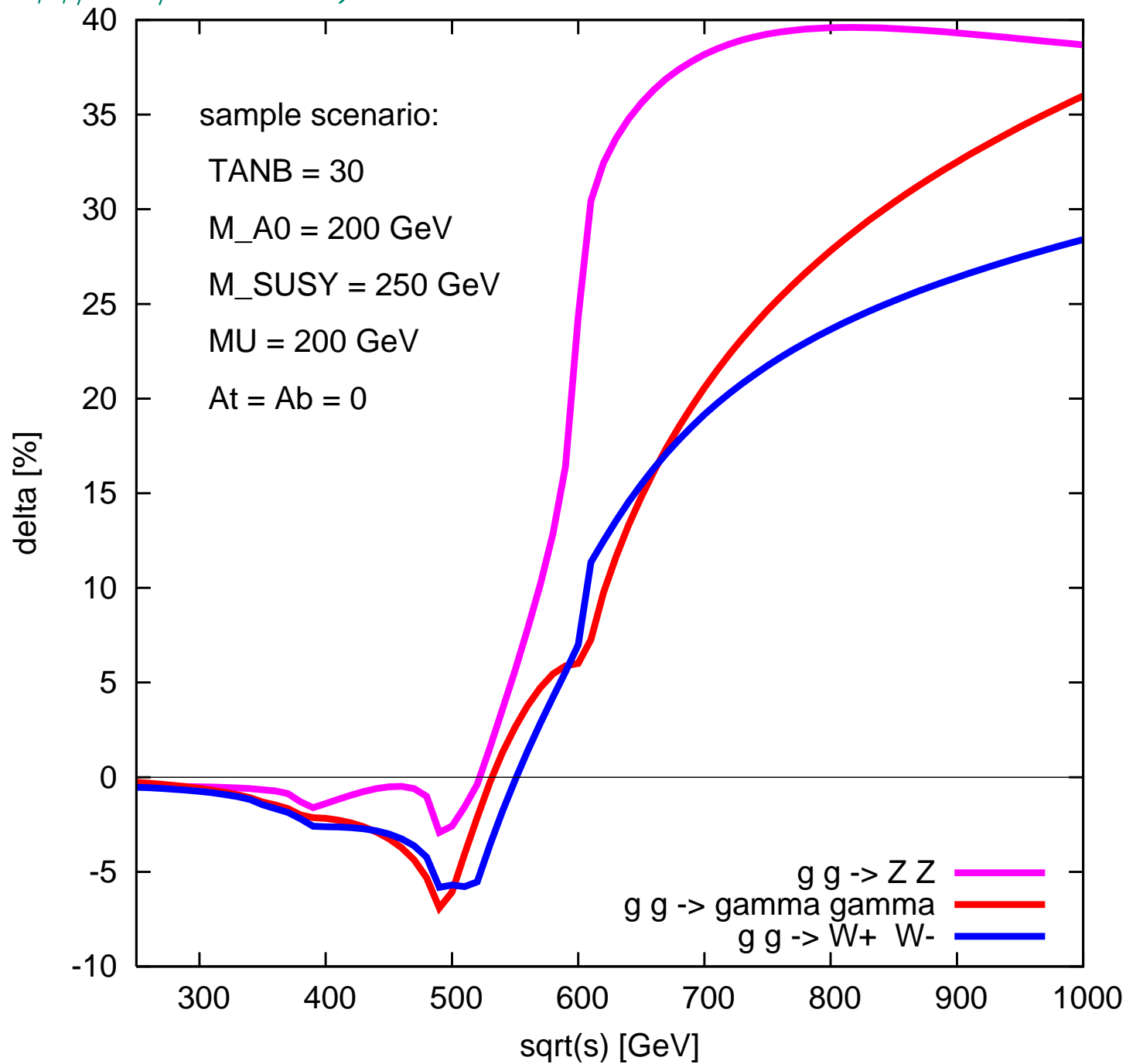
LHC, $\sigma(gg \rightarrow \gamma\gamma/ZZ/W^+W^-)$ in the MSSM:

[OBr '11]

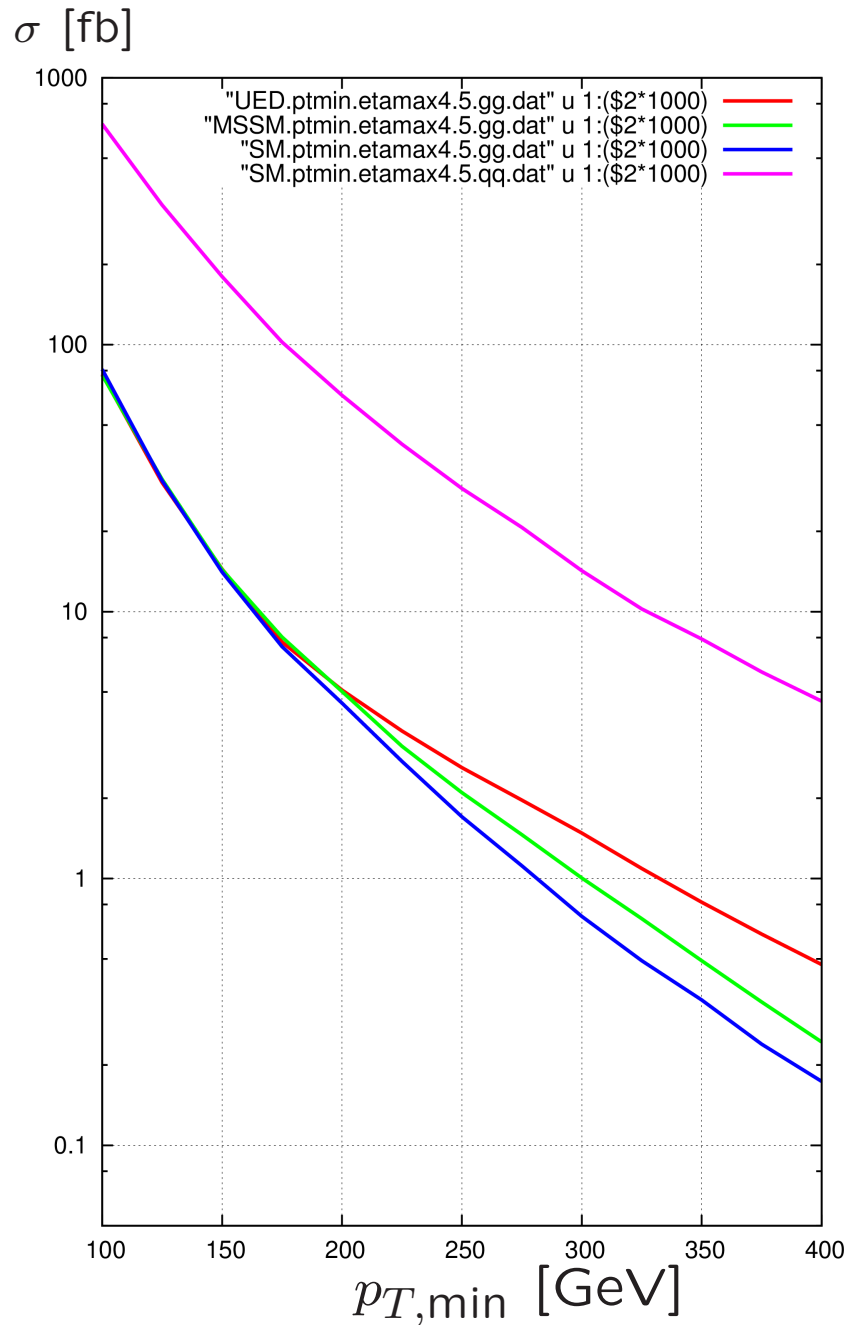


LHC, $\sigma(gg \rightarrow \gamma\gamma/ZZ/W^+W^-)$: MSSM-SM relative difference:

[OBr '11]



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



cuts:

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

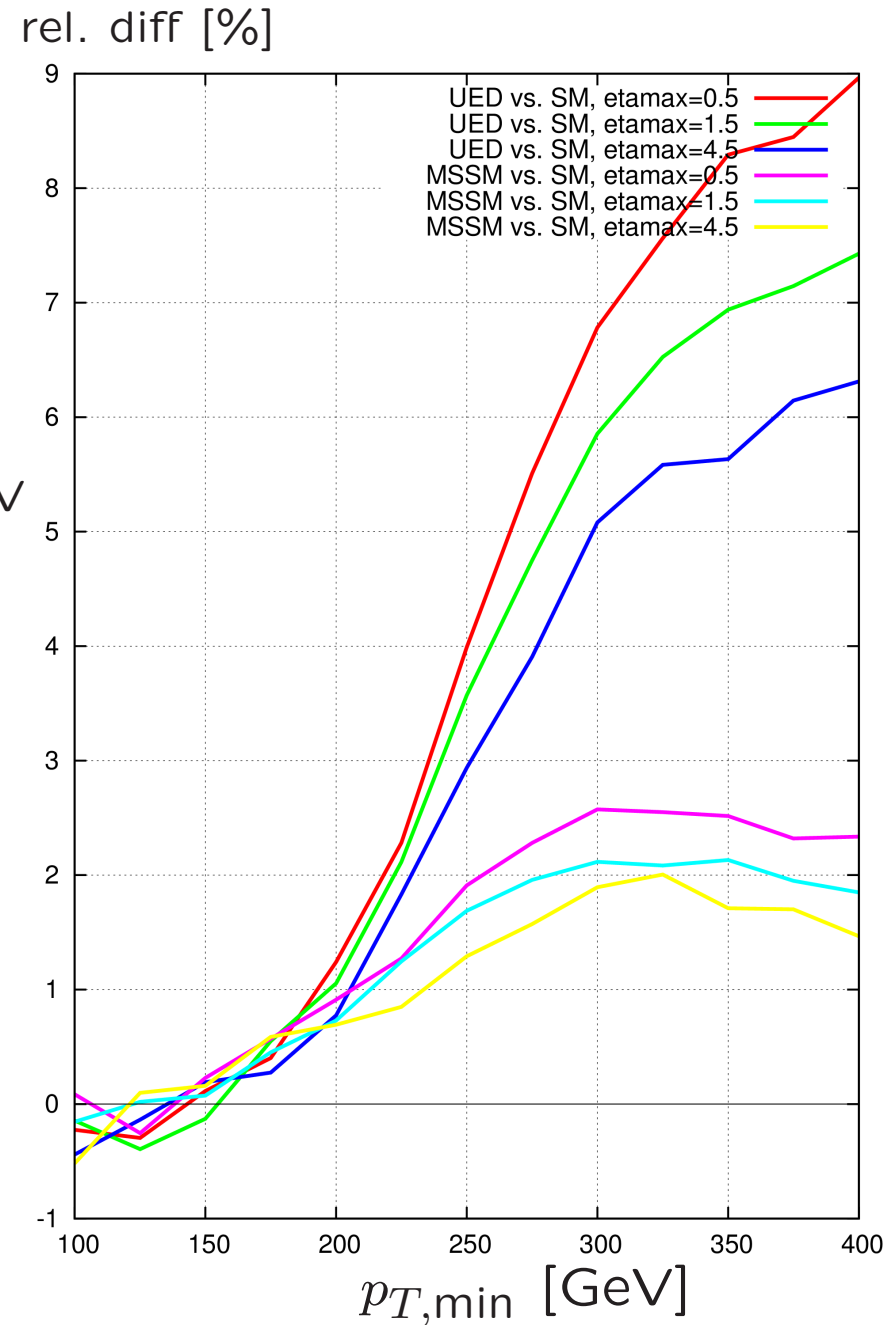
$$|\eta| < \eta_{\max}$$

MSSM:

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

UED:

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

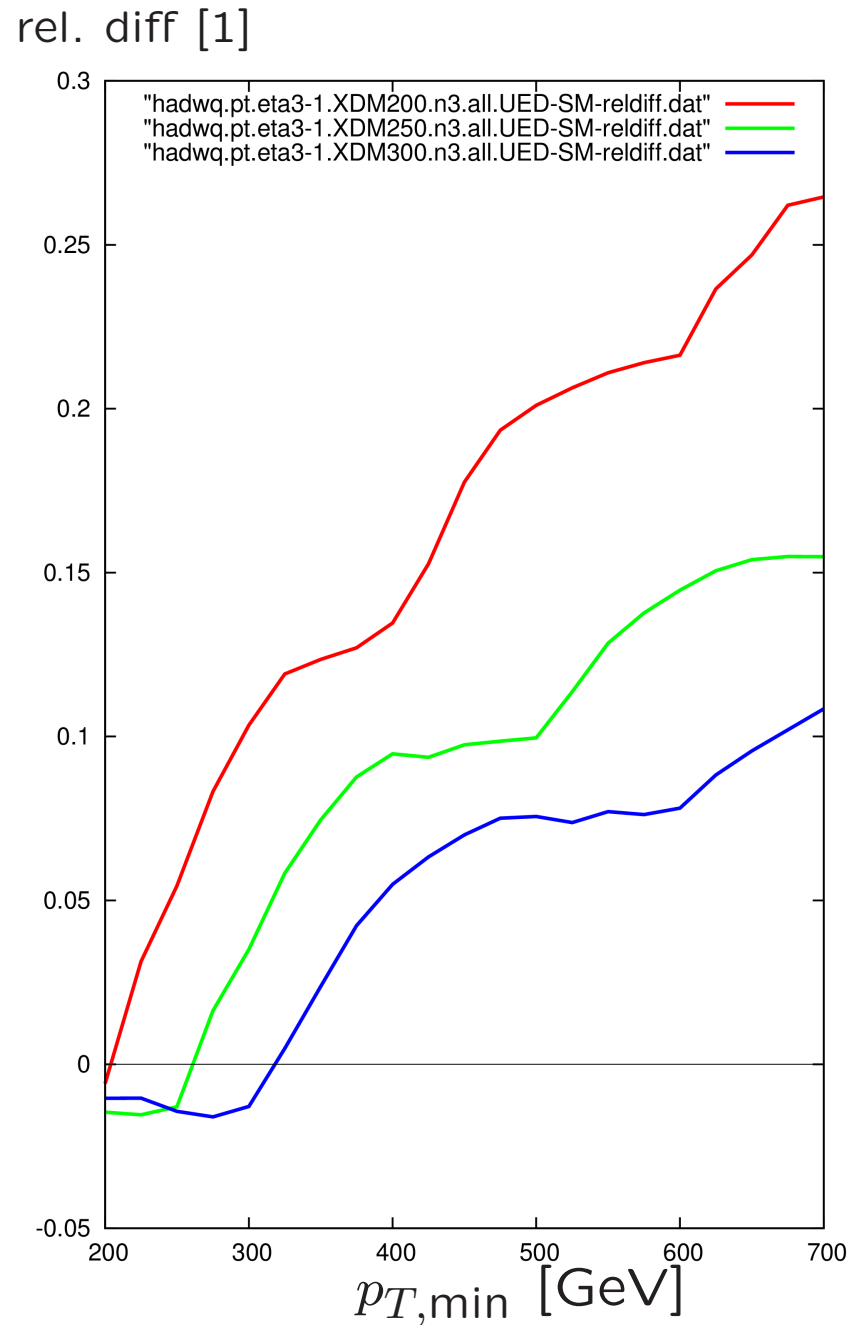


LHC(14 TeV), $\sigma(pp \rightarrow \gamma\gamma)$: UED-SM relative difference:

[OBr '11]

cuts:
 $p_T > p_{T,\min}$
 $|\eta| < 1$

UED::
 $M_{KK} = 200$ GeV
 $M_{KK} = 250$ GeV
 $M_{KK} = 300$ 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. → **Maybe we know more tomorrow!**
- **SM Higgsstrahlung** is now really known at NNLO QCD accuracy. The impact of top-induced corrections is small (adding at most 14 % to the previously known NNLO corrections). Still, SM predictions for vector boson fusion should also be revisited.
- LHC/Tevatron Higgs searches rule out new 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. \leftrightarrow 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 $\left\{ \begin{array}{l} \text{quarks} \\ u, d, s, c, b, t \\ \text{leptons} \\ e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau \end{array} \right.$	$\frac{1}{2}$	sfermions $\left\{ \begin{array}{l} \text{squarks} \\ \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t} \\ \text{sleptons} \\ \tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau \end{array} \right.$	0
gauge bosons G, W^\pm, Z, γ	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** χ_1^\pm, χ_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 Changing Neutral Currents (FCNC)

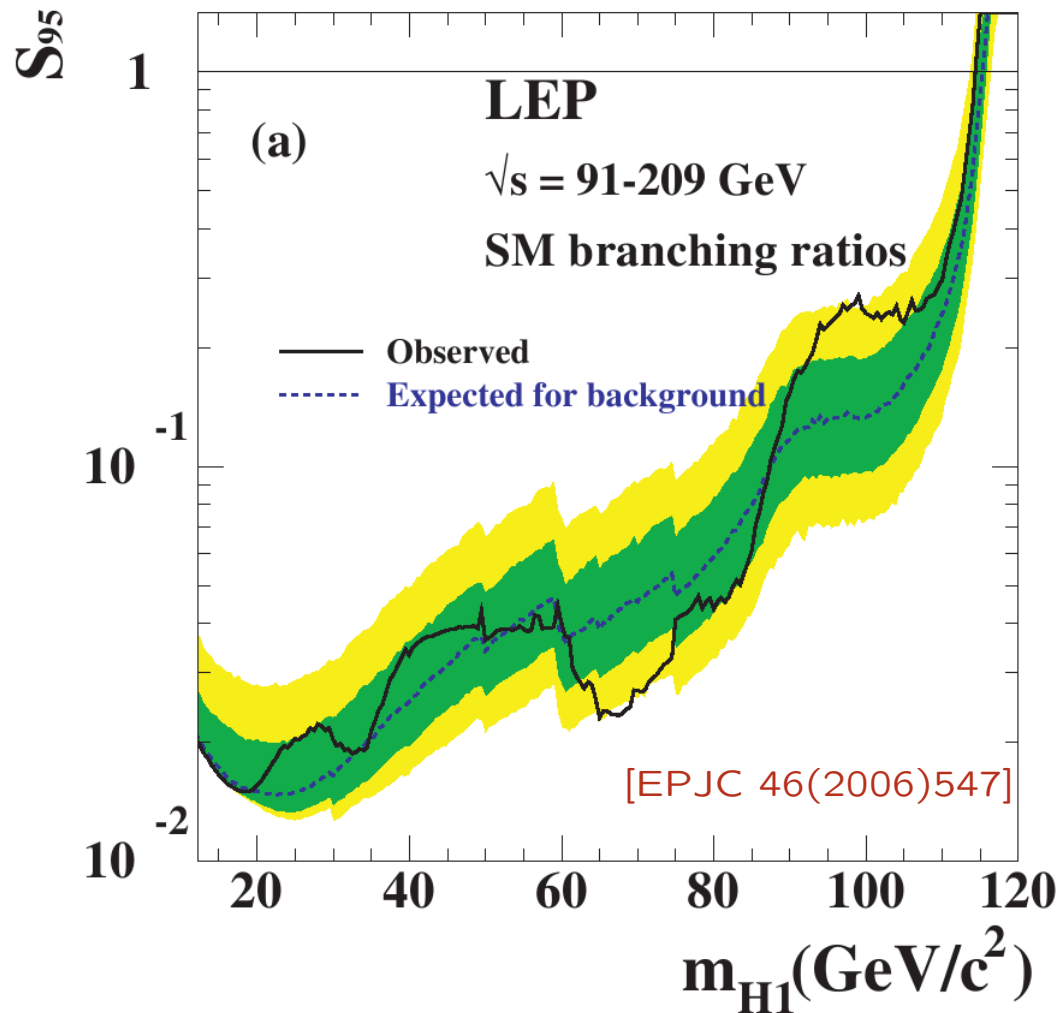
consequences of *R*-parity conservation:

- 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



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

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

A SM-like model with

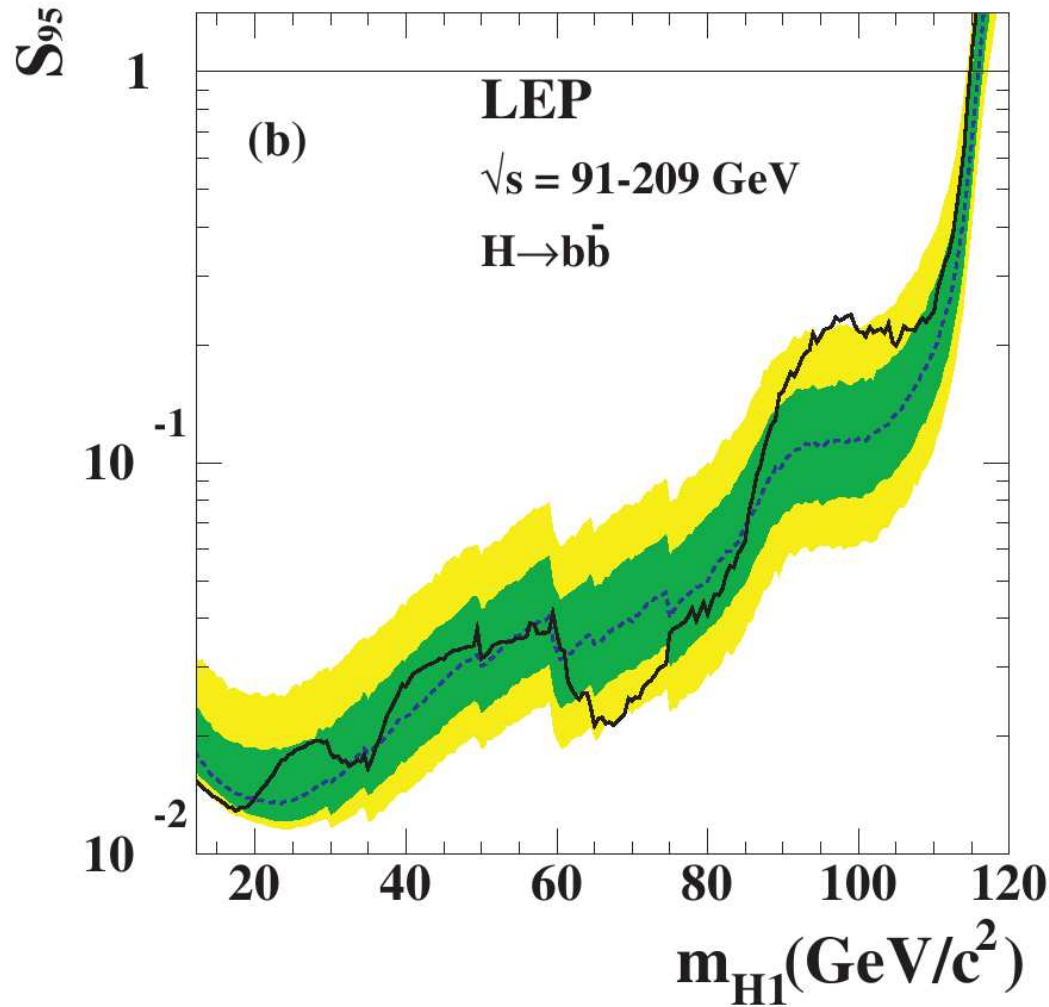
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\min}(m_{H1})$$

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

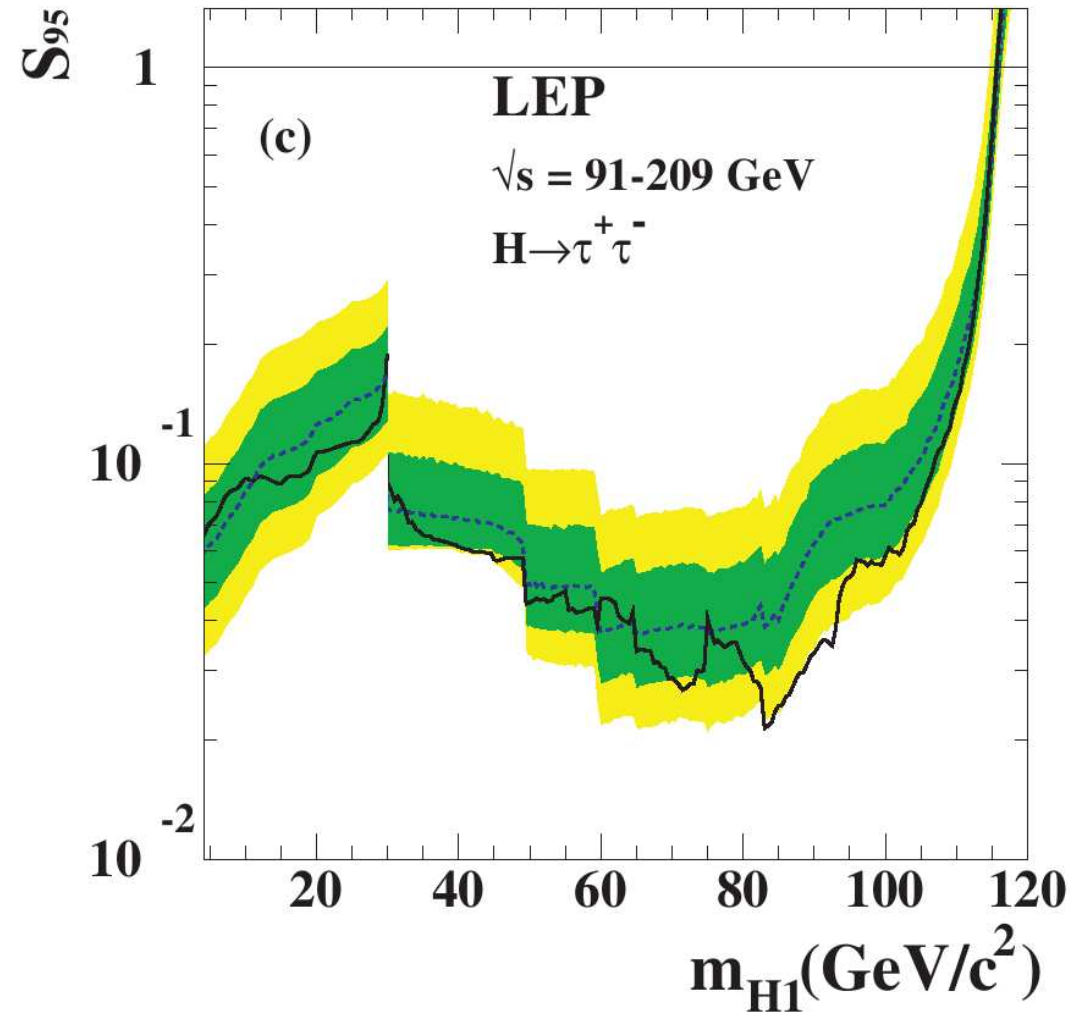
is said to be excluded at the 95% C.L.

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

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

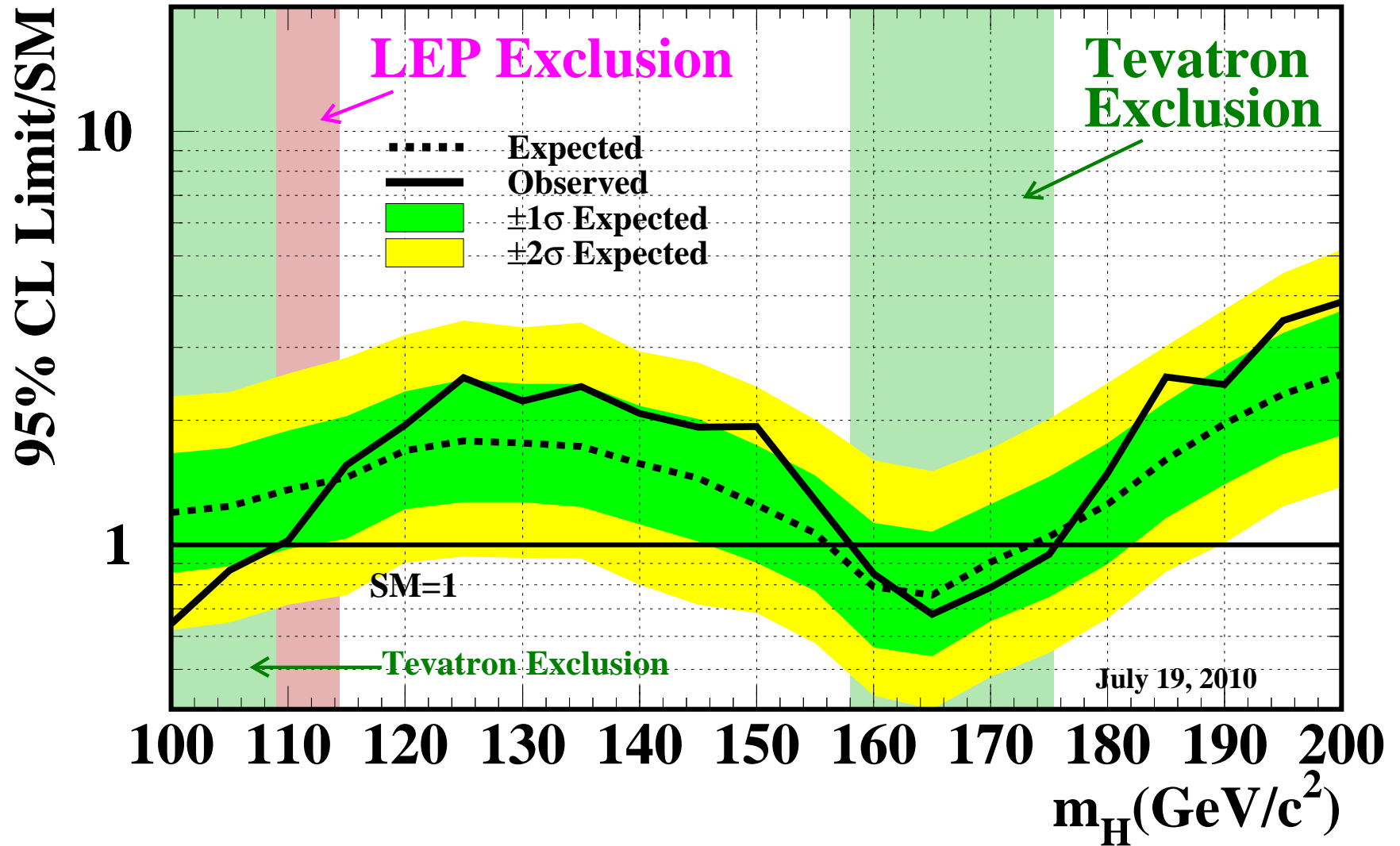


b) ... $\text{BR}(H \rightarrow \tau^+\tau^-)=1$



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

Tevatron Run II Preliminary, $\langle L \rangle = 5.9 \text{ fb}^{-1}$



Considering many analyses for many Higgs bosons:

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 $\bar{\sigma}_{\text{model}}(X)$,
- ★ observed cross section limit $\bar{\sigma}_{\text{observed}}(X)$ of analysis A ,
- ★ expected cross section limit $\bar{\sigma}_{\text{expected}}(X)$ of analysis A .

Basic idea:

for an analysis application X :

- evaluate model prediction

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

of the corresponding search topology for given Higgs masses + deviations from the reference.

- read off the corresponding observed 95% C.L. limit: $\bar{\sigma}_{\text{observed}}(X)$.
- If $\bar{\sigma}_{\text{model}}(X) > \bar{\sigma}_{\text{observed}}(X)$ 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 $\bar{\sigma}_{\text{expected}}(X)$.
- Determine the analysis application X_0 with the highest sensitivity for the signal, i.e. of all X , find X_0 where $\frac{\bar{\sigma}_{\text{model}}(X)}{\bar{\sigma}_{\text{expected}}(X)}$ is maximal.
- If for this analysis application $\bar{\sigma}_{\text{model}}(X_0) > \bar{\sigma}_{\text{observed}}(X_0)$, the model is excluded at 95% C.L. by X_0 .