Supersymmetric Higgs Production via Vector-Boson Fusion

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Phys.Rev.Lett.102:091802,2009 (arXiv:0804.2676 [hep-ph])

Outline

- Vector-Boson Fusion:

  Standard Model (SM) vs.

  Minimal Supersymmetric Standard Model (MSSM)

- SUSY-QCD corrections

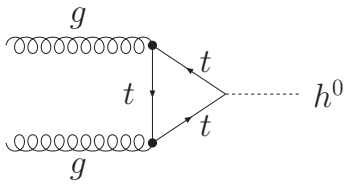
- SUSY-EW corrections

- Numerical Results

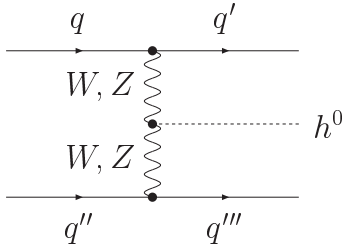
Production Modes

Main (MSSM-)Higgs-boson production modes:

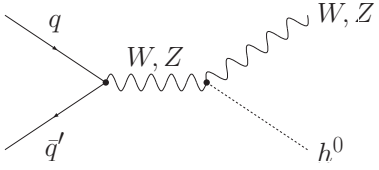
- Gluon-Gluon Fusion



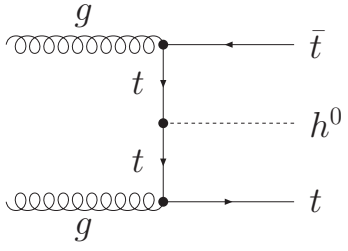
- Vector-Boson Fusion

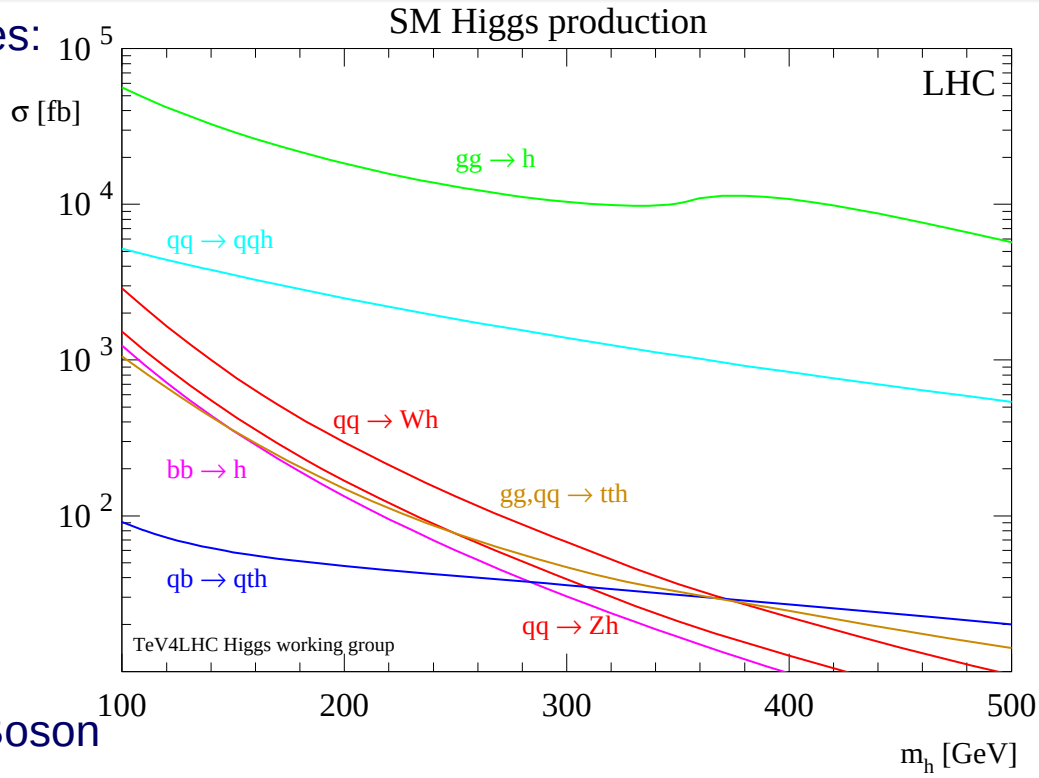


- Associated Production with a Gauge Boson

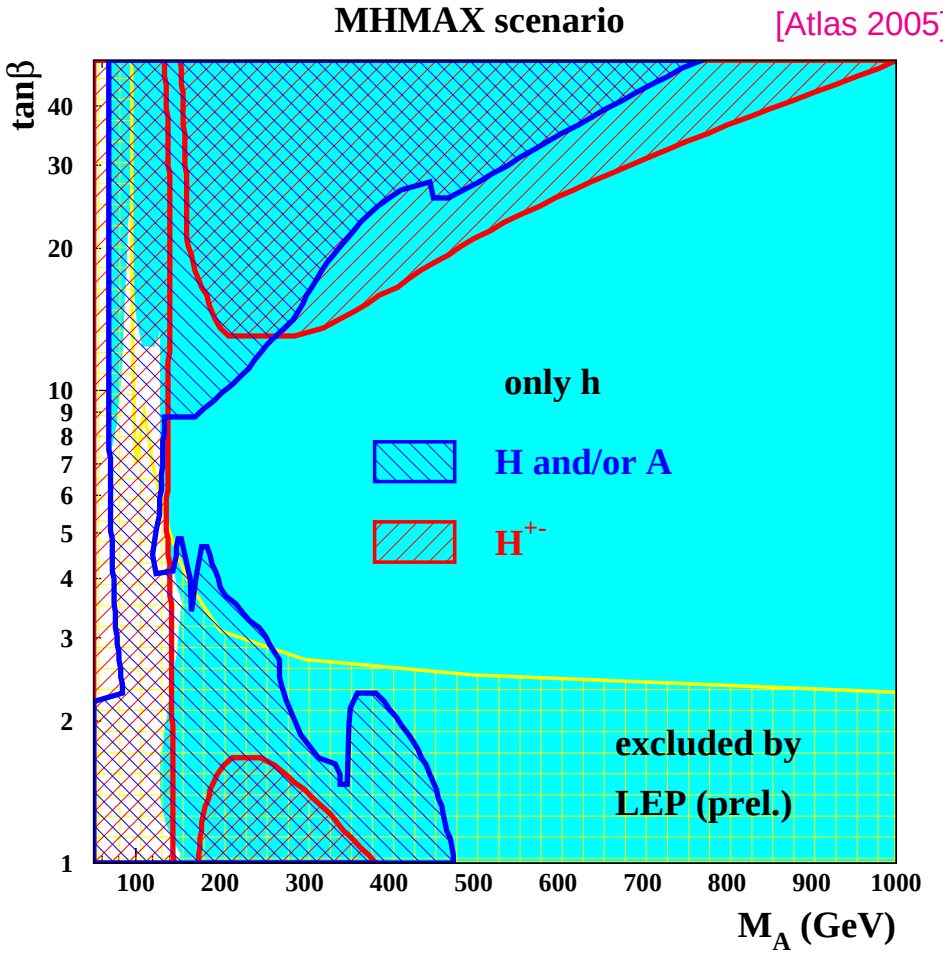


- Associated Production with Top-Quark–Antiquark Pair





LHC Higgs Discovery Potential



Significant region where only one Higgs boson can be found

Which model if $m_H \lesssim 140$ GeV and coupling SM-like?

Can we distinguish SM from MSSM in the Higgs sector by other means?

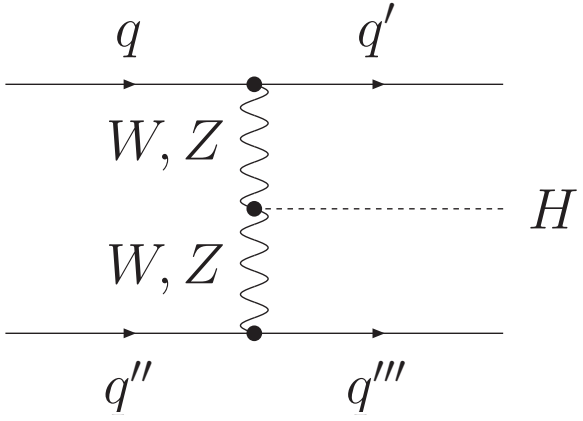
$\Rightarrow$ Loop corrections to Higgs production processes

Higgs Production via Vector Boson Fusion

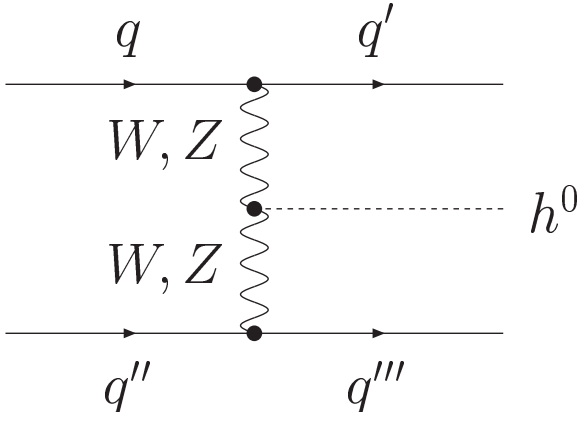
- Second-largest production cross section of Higgs bosons at the LHC (after gluon-gluon fusion)
- Distinct kinematic properties:
  - 2 jets in forward regions of the detector
  - Reduced jet activity in central region
  - central Higgs boson
- Most promising channel for early discovery of the Higgs with $h^0 \longrightarrow \tau^+\tau^-$ decay

[Plehn, Rainwater, Zeppenfeld]

Standard Model (SM):

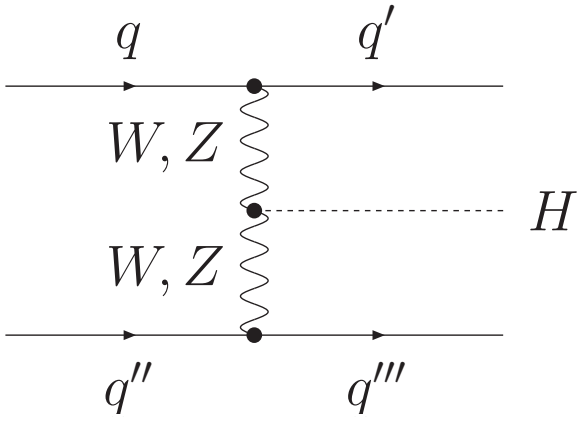


MSSM:

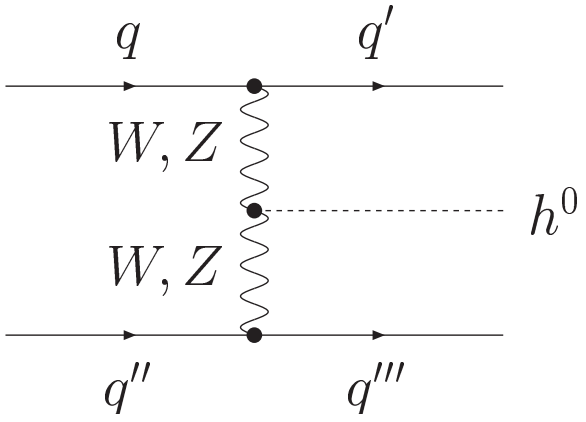


At the Born level

Standard Model (SM):



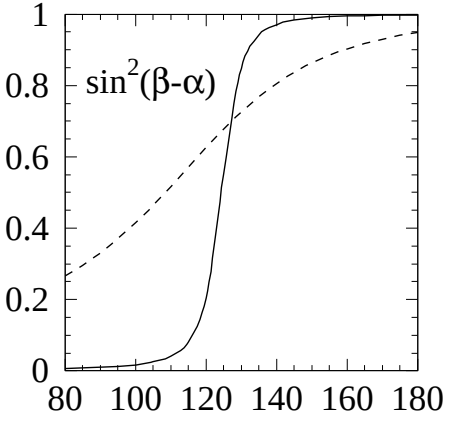
MSSM:

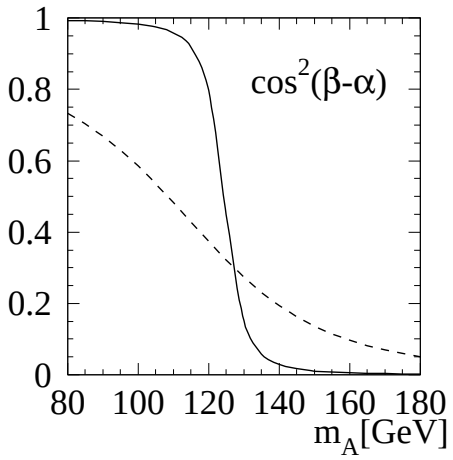


- Replace SM-Higgs boson with (SM-like) MSSM h^0-Boson
- $\Gamma^{MSSM}_{WWh^0,ZZh^0} = \Gamma^{SM}_{WWH,ZZH} \cdot \sin(\beta-\alpha)$

  $\Rightarrow \quad \sigma^{MSSM} = \sigma^{SM} \cdot \sin(\beta-\alpha)^2$

$\alpha =$ mixing angle of CP-even MSSM Higgs bosons; $\tan\beta =$ ratio of Higgs vevs





$$\tan\beta = \begin{cases} 4 & \text{dashed} \\ 30 & \text{solid} \end{cases}$$

[Plehn, Rainwater, Zeppenfeld 1999]

Higher-order corrections

- SM-NLO corrections completely known:
  - QCD: $\mathcal{O}(\alpha_s) \sim 5 - 10\%$

    [Djouadi, Spira, Zerwas; Han, Valencia, Willenbrock]

    [Figy, Oleari, Zeppenfeld; Berger, Campbell]
  - QCD+EW: $\mathcal{O}(\alpha) \sim 5\%$

    [Ciccolini, Denner, Dittmaier]
- Vector-boson-fusion–gluon-gluon interference negligible

  [Andersen, Binoth, Heinrich, Smillie; Bredenstein, Hagiwara, Jäger]
- Estimate of NNLO QCD contributions (gluon-induced processes, small)

  [Harlander, Vollinga, Weber]
- MSSM
  - NLO SUSY-QCD vertex corrections for degenerate squark masses

    [Djouadi, Spira]
  - Complete NLO SUSY contributions

    [Hollik, Plehn, MR, Rzehak]
  - Complete NLO MSSM contributions

    [Figy, Palmer, Weiglein (in preparation)]

Supersymmetry

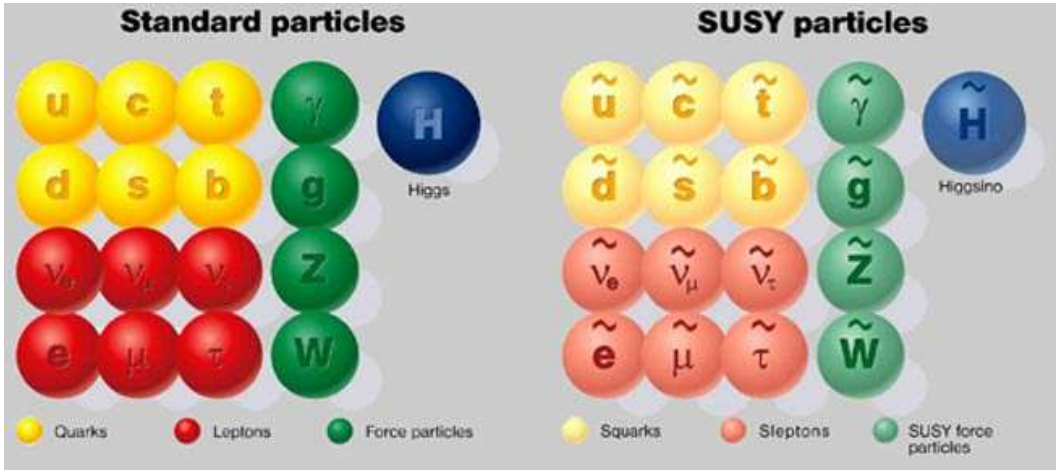
Symmetry between bosons and fermions:

$$Q\,|\text{boson}\rangle = |\text{fermion}\rangle\,; \qquad Q\,|\text{fermion}\rangle = |\text{boson}\rangle$$

Q: Supersymmetry Operator

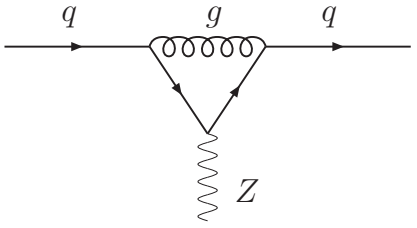
Simplest model: Minimal Supersymmetric Standard Model (MSSM)

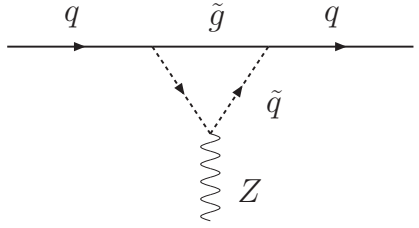
- Supersymmetric partner to each Standard Model particle
- Two Higgs doublets $\Rightarrow$ 5 Higgs bosons (h^0,H^0,A^0,$H^\pm$)
- Particles with same quantum numbers mix
  (e.g. Zino, Photino, 2 neutral Higgsino $\longrightarrow$ 4 Neutralino
  Wino, charged Higgsino $\longrightarrow$ 2 Chargino)



Additional Loop Corrections

- SM is subsector of the full MSSM
- $\Rightarrow$ SM loop corrections form part of the full MSSM set
- R-parity conservation allows separation of SM and SUSY part at one-loop level

(loop consists either of SM 

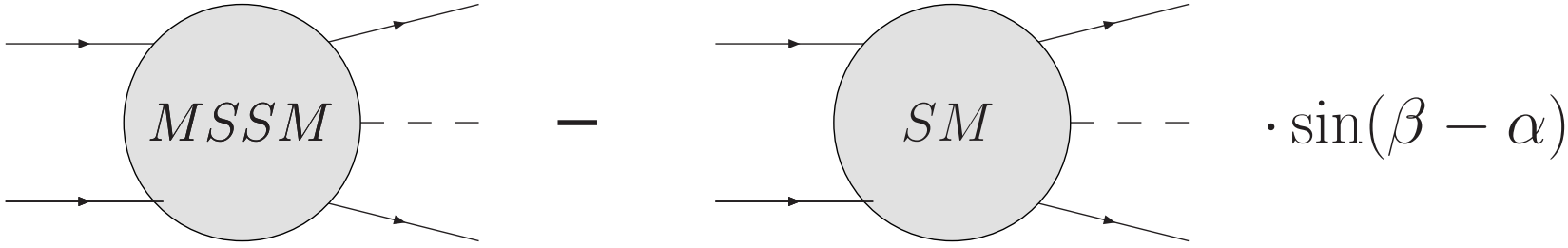
or SUSY 

particles)

- Not completely true in the Higgs sector:
  - MSSM is a (type-II) Two-Higgs doublet model (THDM)
  - Some THDM parameters fixed by SUSY relations
    (e.g. m_{h^0} not a free parameter any longer)
  - Renormalisation in the Higgs sector requires both SM and SUSY part so that divergencies cancel
    (depending on renormalization scheme)
- Split between SM and additional SUSY contribution more difficult

SUSY=MSSM-SM

- SM part (QCD and EW) already calculated
- Simple transfer to MSSM by $\sigma^{SM(MSSM)} = \sigma^{SM} \cdot \sin(\beta - \alpha)^2$
- In the end want one-loop corrections for complete MSSM
- $\Rightarrow$ Subtract SM part from MSSM to obtain additional SUSY contribution



using $m_H^{SM} = m_{h^0}^{MSSM}$

- Subtraction performed on amplitude level
- Cross-check that for non-Higgs couplings this corresponds to just omitting the SM particles

Corrections in the Higgs sector

- In the MSSM at Born level: $m_{h^0} \leq m_Z \approx 91$ GeV
  Large corrections at higher orders: $m_{h^0} \lesssim 135$ GeV $\rightarrow$ need to be taken into account
- Also corrections to Higgs couplings present

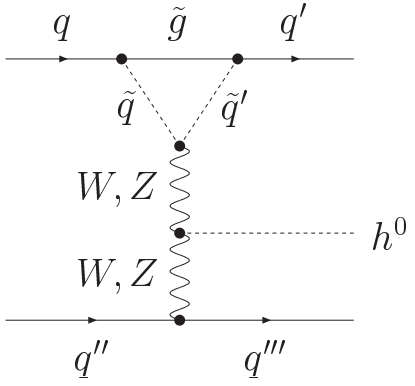
- Effective potential method
  SUBH [Carena, Espinosa, Quiros, Wagner]
  - Corrected couplings automatically from potential
- Feynman-diagrammatic approach
  FEYNHIGGS
  [Hahn, Heinemeyer, Hollik, Rzehak, Weiglein]
  - finite-momentum effects
- $\overline{DR}$ renormalization of Higgs sector requires Z-factors for external on-shell Higgs bosons
  Also higher-order corrections there

	$\Delta\sigma/\sigma(ud \to udh)$	$(\sigma_{\alpha_{\text{eff}}} - \sigma_{\text{full}})/\sigma$
effective theory		
α_{eff}	$-0.389\ \%$	$-0.122\ \%$
full	$-0.266\ \%$	
Feynman diagrams		
α_{eff}	$-0.393\ \%$	$-0.076\ \%$
full	$-0.317\ \%$	
Feynman diagrams, loop-improved Z_{FH}		
α_{eff}	$-0.343\ \%$	$-0.115\ \%$
full	$-0.228\ \%$	

In the following: Feynman diagrams, 1-loop Z-factors

Strong Corrections

Strong ($\mathcal{O}(\alpha_s)$) corrections:



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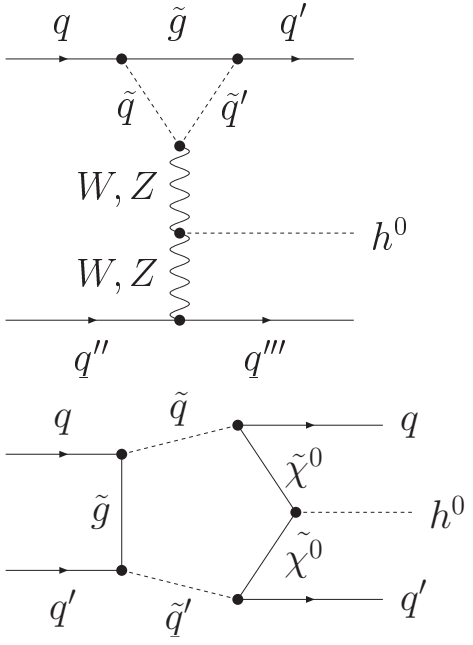

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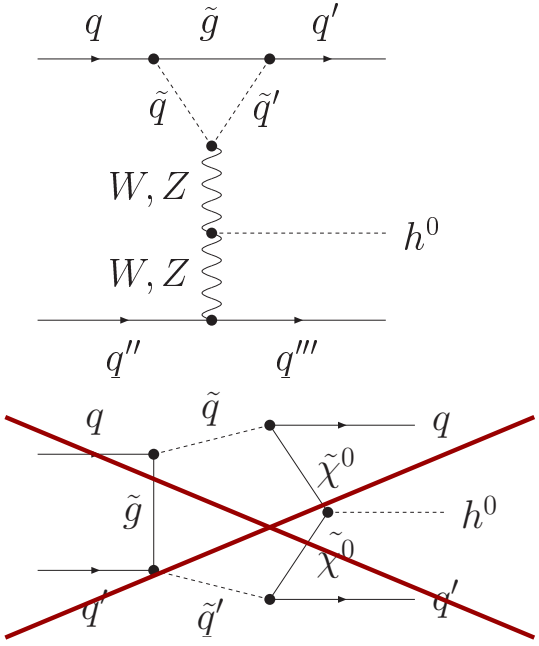

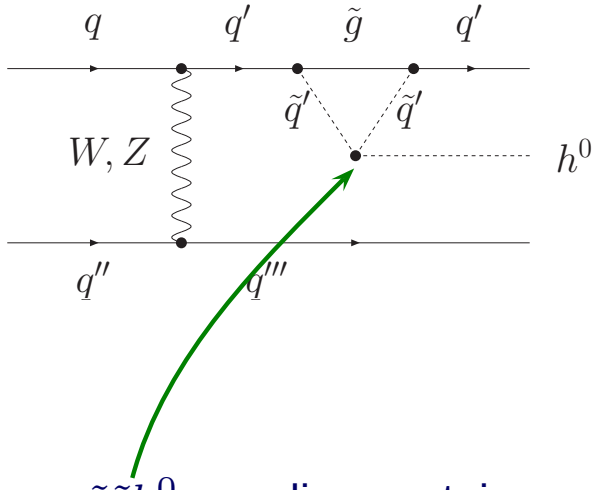

$\tilde{q}\tilde{q}h^0$-coupling contains gauge part (from D-terms)

$\Rightarrow$ Does not vanish even if neglecting Yukawa coupling

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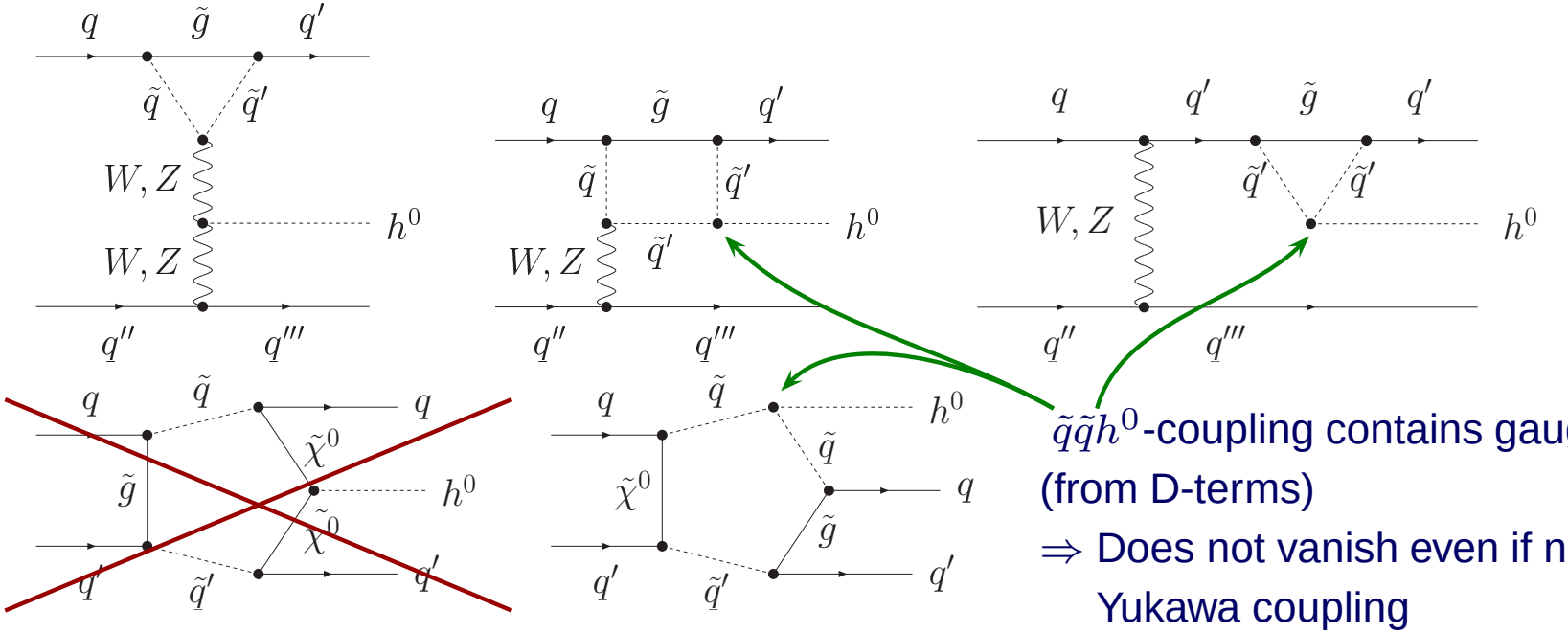

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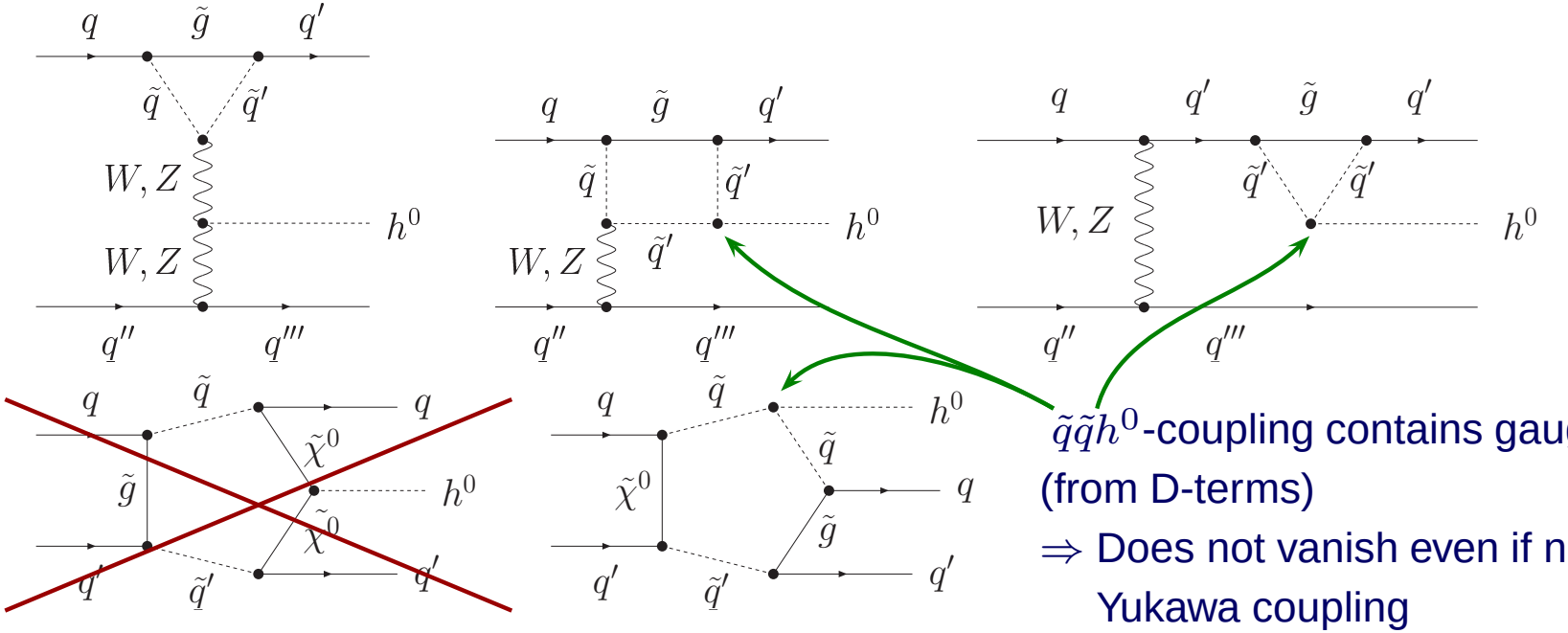

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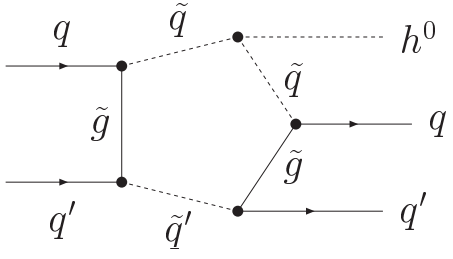
Additional possibility for pentagon diagrams:



$\propto \alpha_s^2 \alpha^2$

With $\alpha_s^2 \sim \alpha$ same order as tree-level

Suppressions

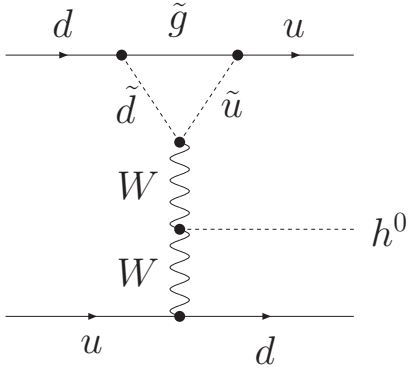
- Size of the strong corrections (Parameter point SPS1a):

	$(\sigma^{\text{one-loop}} - \sigma^{\text{born}})/\sigma^{\text{born}}$	
Vertex corrections	$-1.5 \cdot 10^{-2}\%$	[Djouadi, Spira]
effective qqh^0-Vertex	$5.4 \cdot 10^{-3}\%$	
Box diagrams	$-5.2 \cdot 10^{-3}\%$	
Pentagon diagrams	$-3.1 \cdot 10^{-4}\%$	
total SUSY-QCD corrections	$-1.5 \cdot 10^{-2}\%$	

  $\Rightarrow$ Large suppressions

- Why are the corrections so small:

Vertex Corrections:



- W-coupling purely left-handed
- Quarks approximately massless
- $\Rightarrow$ No chirality flip
- $\Rightarrow$ Trace over fermion line cannot yield $m_{\tilde{g}}$, only kinematic term $\sim m_{h^0}/2$.

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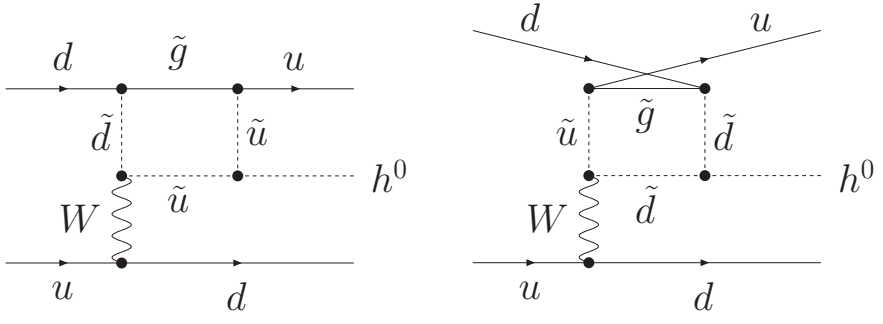

- $\Gamma_{\tilde{q}^\dagger \tilde{q} h^0} \propto T_3 - Q s_W^2$
- $\rightarrow \Gamma_{\tilde{u}^\dagger \tilde{u} h^0} \propto \frac{1}{3} \quad \Gamma_{\tilde{d}^\dagger \tilde{d} h^0} \propto -\frac{5}{12}$
- $\Rightarrow$ Contributions cancel by one order of magnitude
  (up to differences between $\tilde{u}$- and $\tilde{d}$ masses, which are governed by same soft-breaking terms and also small in common SUSY-breaking scenarios).

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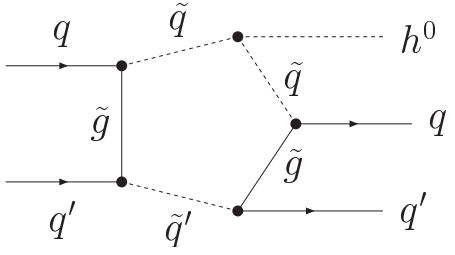
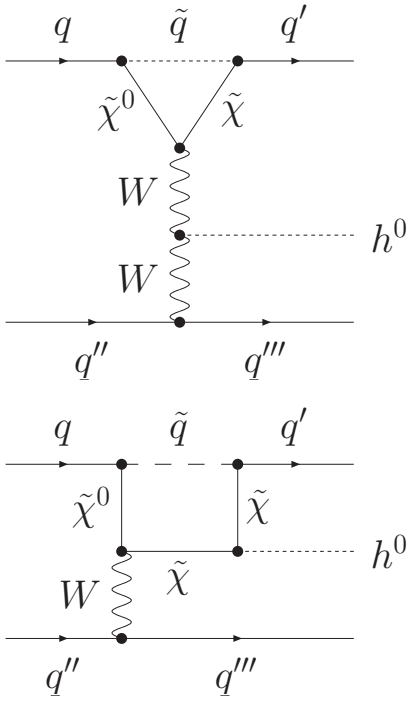


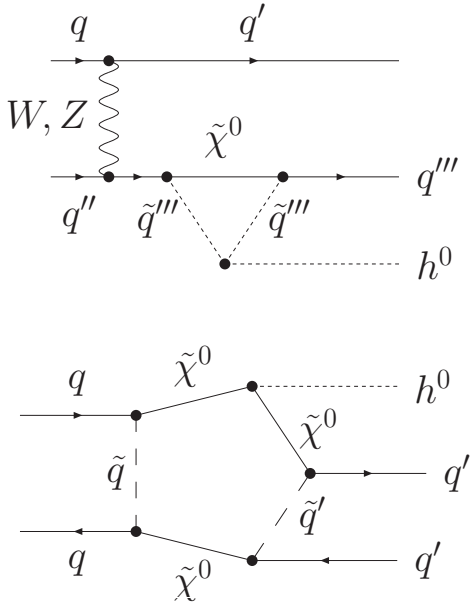
- Large masses in the loop
- Different kinematic structure than tree-level diagram
- $\Rightarrow$ Greatly reduced by kinematic cuts

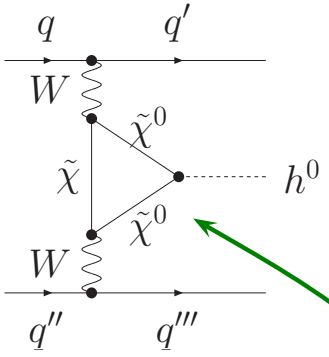
Electro-weak Corrections

Electro-weak ($\mathcal{O}(\alpha)$) corrections:

Any strong diagram with replacement $\tilde{g} \to \tilde{\chi^0}$ $+$







Also corrections to VVh vertex appear

$\Rightarrow$ Additional diagrams lead to more natural size of corrections

Total Corrections

Size of the supersymmetric corrections (Parameter point SPS1a):

diagram	$\Delta\sigma/\sigma$ [%]	diagram	$\Delta\sigma/\sigma$ [%]
$\Delta\sigma \sim \mathcal{O}(\alpha)$		$\Delta\sigma \sim \mathcal{O}(\alpha_s)$	
self energies	0.199		
$qqW + qqZ$	-0.392	$qqW + qqZ$	-0.0148
qqh	-0.0260	qqh	0.00545
$WWh + ZZh$	-0.329		
box	0.0785	box	-0.00518
pentagon	0.000522	pentagon	-0.000308
sum of all $\Delta\sigma/\sigma = -0.484\ \%$			

Numerical Results

Size of the supersymmetric corrections:
(SPS: Set of reference points which probe “typical” parts of the supersymmetric parameter space)

$\Delta\sigma/\sigma$ [%]

	WWh $+ZZh$	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha_s)$	total NLO
SPS1a	-0.329	-0.469	-0.015	-0.484
SPS1b	-0.162	-0.229	-0.006	-0.235
SPS2	-0.147	0.129	-0.002	-0.131
SPS3	-0.146	-0.216	-0.006	-0.222
SPS4	-0.258	-0.355	-0.008	-0.363
SPS5	-0.606	-0.912	-0.010	-0.922
SPS6	-0.226	-0.309	-0.010	-0.319
SPS7	-0.206	-0.317	-0.006	-0.323
SPS8	-0.157	-0.206	-0.004	-0.210
SPS9	-0.094	-0.071	-0.003	-0.074

Again:

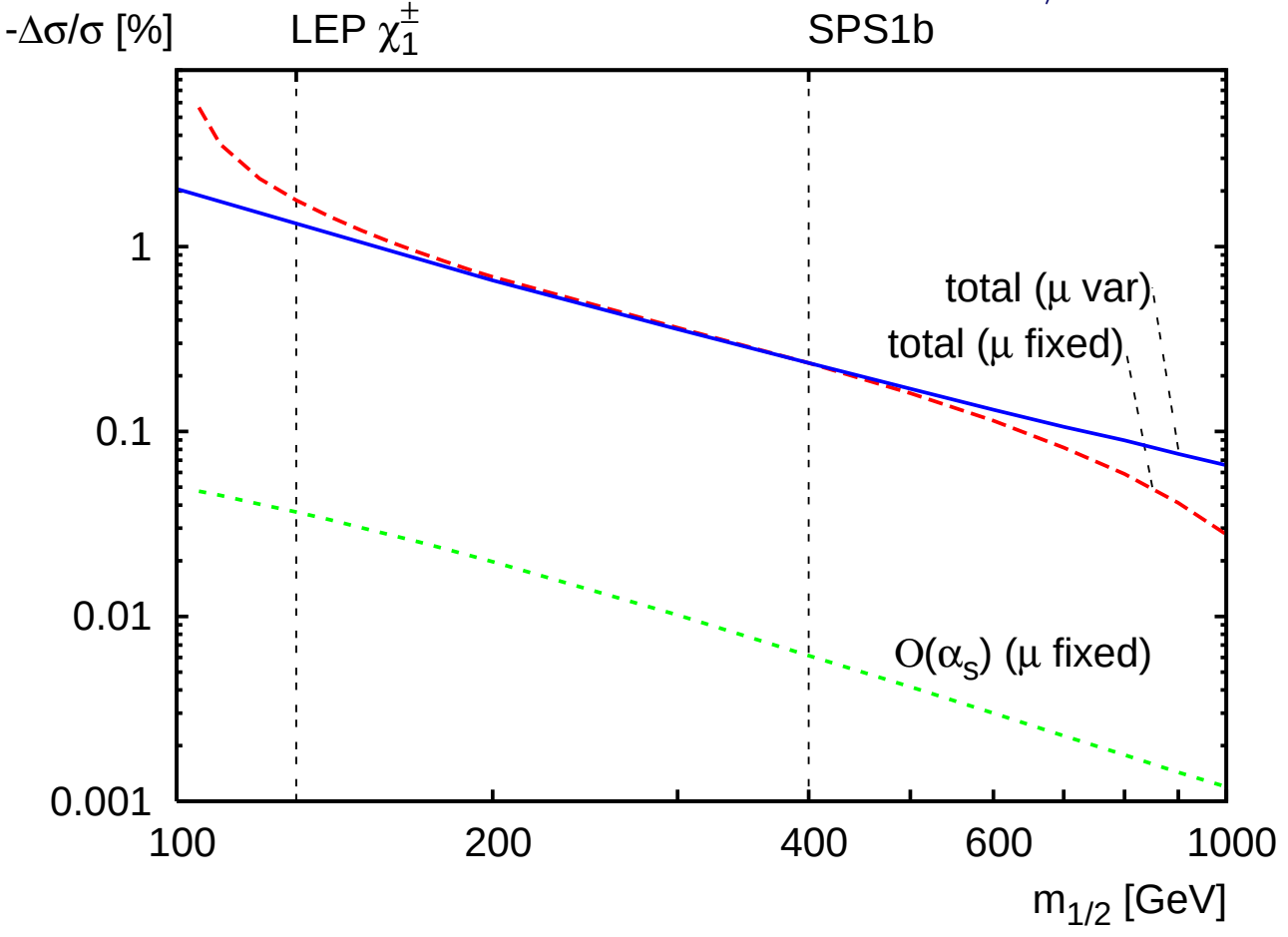
SUSY-QCD corrections tiny

SUSY-EW corrections give main contribution

Typical size less than or around 1%

Mass dependence of the corrections

Starting point: SPS1b → vary GUT scale parameter $m_{1/2}$



- SUSY-QCD strongly suppressed over whole mass range
- Maximal size of corrections in this scenario: -2%
  (most stringent experimental limit from LEP2 chargino bound)
- Can reach up to 4% for parameter points still allowed by direct SUSY searches

Conclusions

- Higgs-boson production via Vector Boson Fusion important discovery mode for the Higgs boson and to study electroweak symmetry breaking

- Supersymmetric diagrams can lead to additional effects beyond simple tree-level factor $\sin(\beta - \alpha)^2$

- Supersymmetric QCD corrections strongly suppressed

- Supersymmetric electro-weak corrections modify cross section on the percent level

BACKUP

Higgs self-couplings

Parameter point SPS1a:

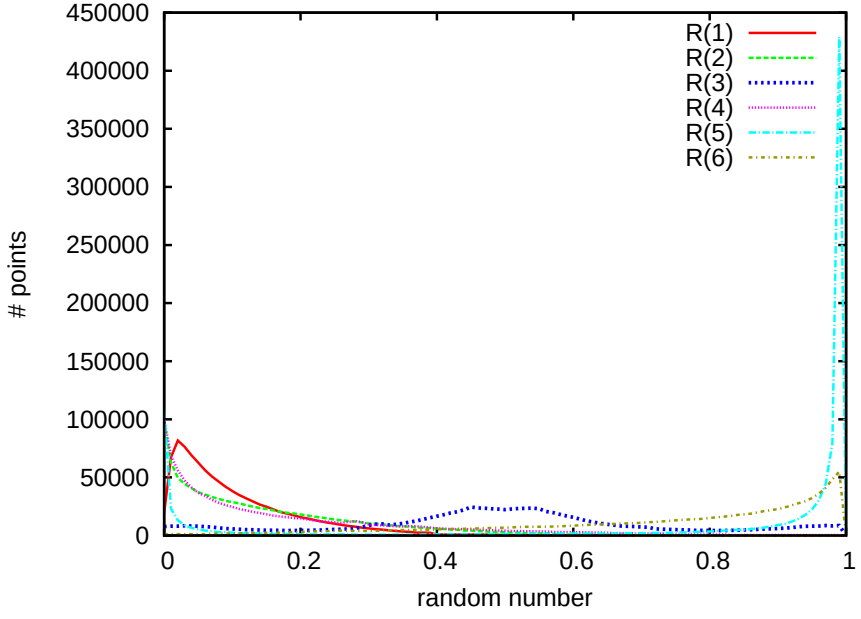
	effective theory		Feynman diagrams	
	α_{eff}	full	α_{eff}	full
λ_{HHH}	0.208	0.198	0.210	0.210
λ_{HHh}	−0.285	−0.275	−0.284	−0.279
λ_{Hhh}	−0.216	−0.219	−0.220	−0.257
λ_{hhh}	0.952	1.503	0.950	1.276
α_{eff}	−0.1132		−0.1158	
m_h	109.8 GeV		111.0 GeV	
m_H	391.5 GeV		391.6 GeV	

Common factor $\frac{-3em_W}{2c_W^2 s_W}$ excluded

Technical Details

52504 individual Feynman diagrams calculated
$\longrightarrow$ impossible without the help of automated tools

- Amplitudes and Fortran code generation: FeynArts, FormCalc [Hahn, Perez-Victoria, Schappacher]
- Hadronic cross sections: HadCalc [MR]
- General-purpose phase-space generator



$\Rightarrow$ Strongly peaked distribution of random points

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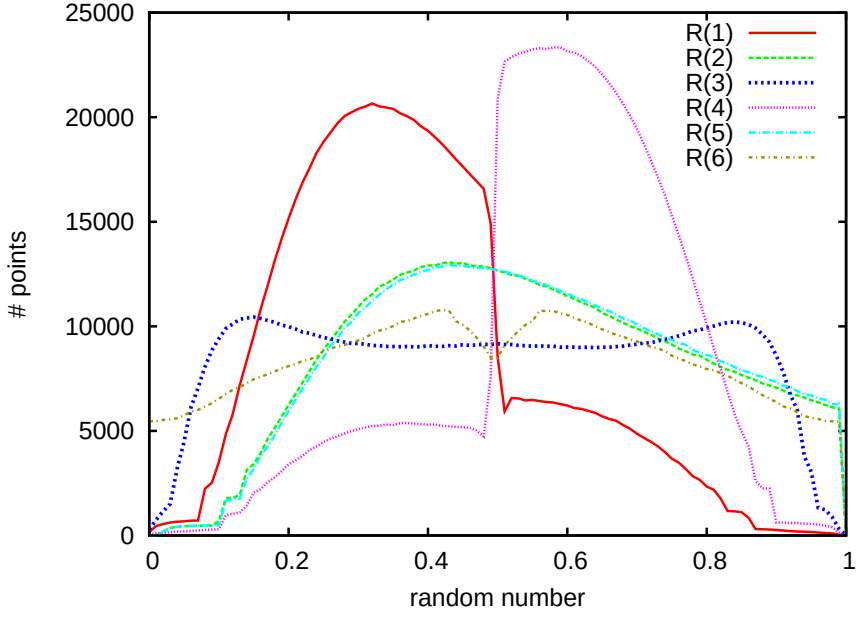
- Hadronic cross sections: HadCalc [MR]
- Specialised phase-space generator [Rainwater, Zeppenfeld]



⇒ Improvement by factor of 10 to obtain similar accuracy

Technical Details

52504 individual Feynman diagrams calculated
$\rightarrow$ impossible without the help of automated tools

- Amplitudes and Fortran code generation:
  FeynArts, FormCalc [Hahn, Perez-Victoria, Schappacher]
- Hadronic cross sections: HadCalc [MR]
- Phase space generator [Rainwater, Zeppenfeld]
  - Train Vegas grid with 10^7 phase space points using tree-level amplitude only
  - Use trained Vegas grid as start point for full evaluation
  - $\Rightarrow$ Additional factor 5 improvement
- Loop integrals: LoopTools [Hahn, MR; v. Oldenborgh]
- Higgs sector: FeynHiggs [Hahn, Heinemeyer, Hollik, Rzehak, Weiglein]