Higgs@LHC

Michael Rauch

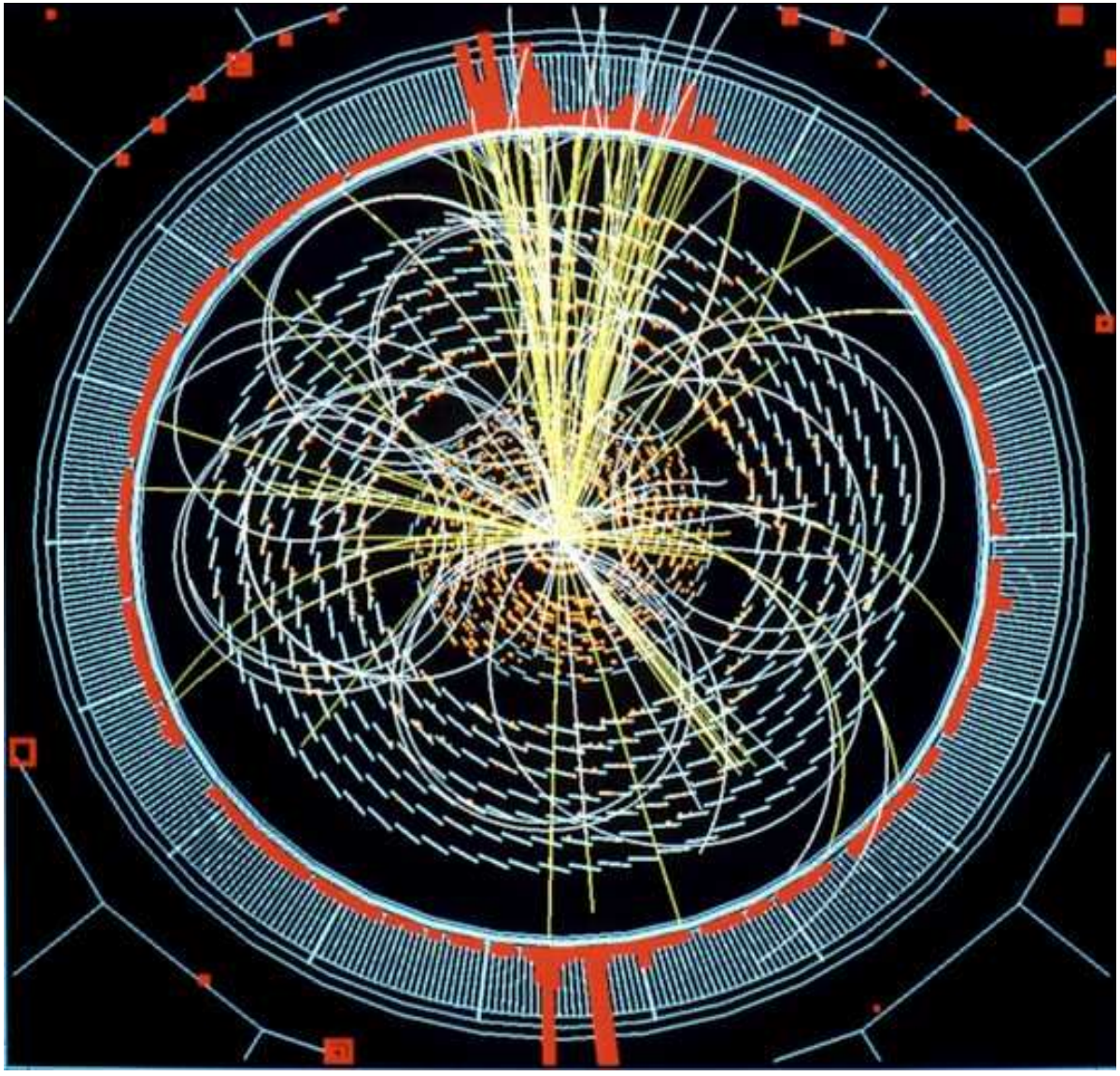
University of Edinburgh

Scottish Universities Physics Alliance (SUPA)

A Higgs event

(Apologies to Colin Daly for deleting him from the picture)

A Higgs event



CMS event $H \to ZZ \to e^+e^-\bar{q}q$

[CMS/CERN]

Production of Supersymmetric Higgs Bosons

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Outline

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

Supersymmetry

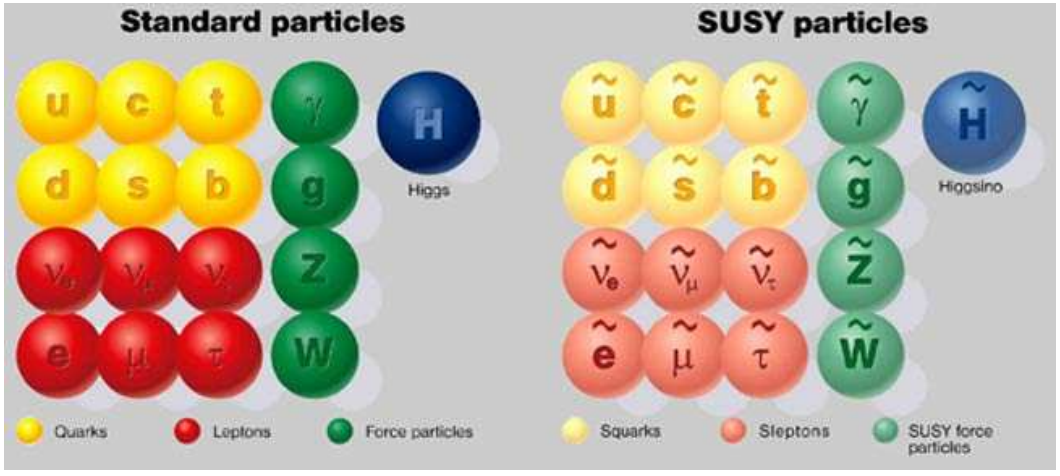
Symmetry between bosons and fermions:

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

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 Higgsino $\rightarrow$ 4 Neutralino)



MSSM Higgs Sector

Two Higgs doublets:

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}\left(\phi_1^0 - i\chi_1^0\right) \\ -\phi_1^- \end{pmatrix}_{(Y=-1)}, \quad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}\left(\phi_2^0 + i\chi_2^0\right) \end{pmatrix}_{(Y=+1)}$$

Physical spectrum:

h^0, H^0: light and heavy CP-even neutral Higgs boson

A^0: CP-odd neutral Higgs boson

$H^\pm$: charged Higgs boson

Two free parameters:

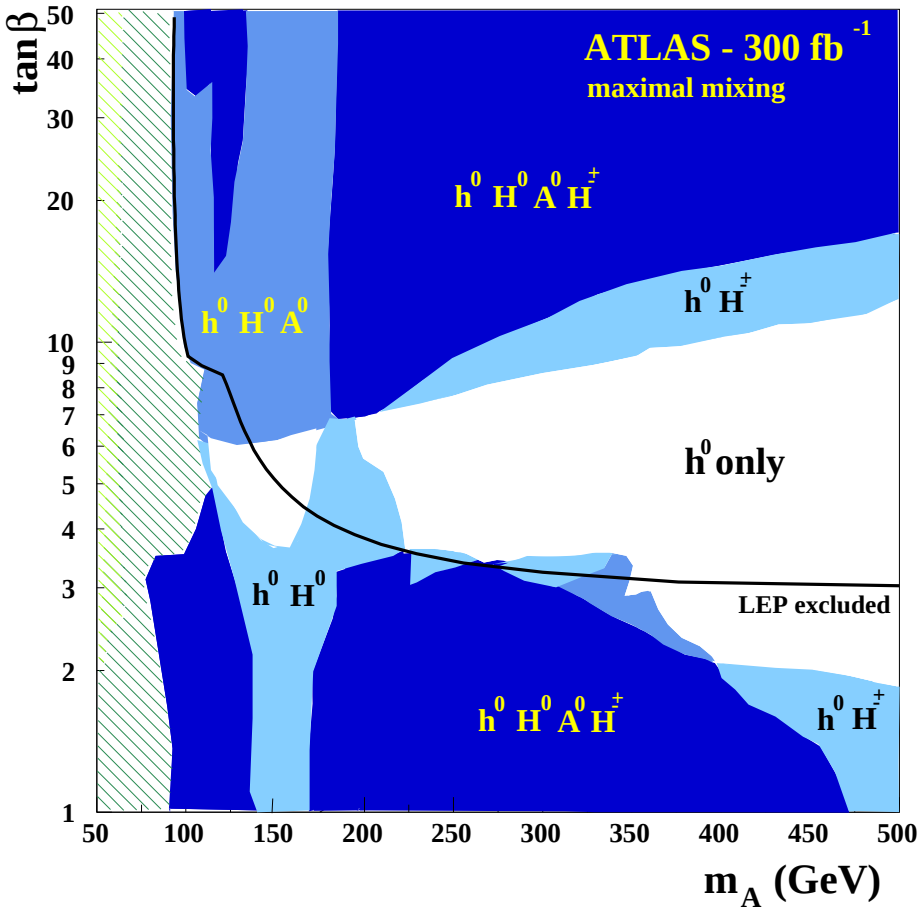
m_A: mass of the CP-odd Higgs boson

$\tan(\beta) = \frac{v_2}{v_1}$: ratio of the Higgs vevs

Prediction: $m_{h^0} \lesssim 140$ GeV

LHC Higgs Discovery Potential

[Atlas TDR 1999]



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?

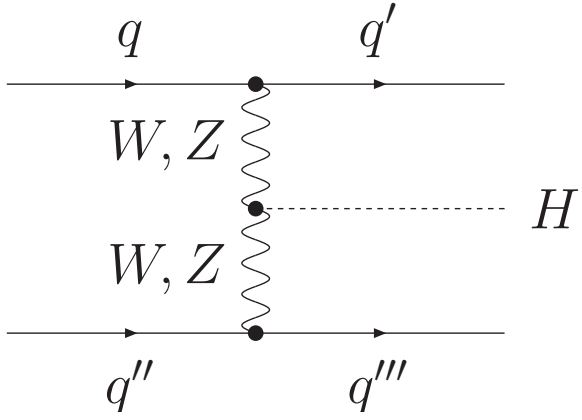
$\Rightarrow$ Loop corrections to Higgs production processes

Higgs Production via Vector Boson Fusion

In the Standard Model

[see Jenni Smillie's talk]

$\sum_{q,q',q'',q'''=u,d,c,s}$



- 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
- NLO corrections completely known

[Djouadi, Spira, Zerwas; Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; Berger, Campbell]

[Ciccolini, Denner, Dittmaier]

- Vector-boson-fusion–gluon-guon interference negligible

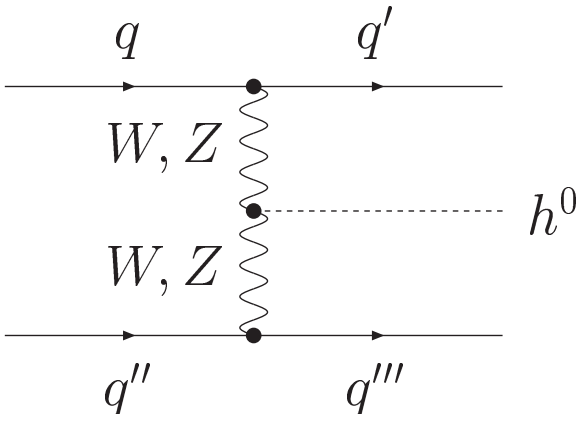
[Andersen, Binoth, Heinrich, Smillie]

[Bredenstein, Hagiwara, Jäger]

Higgs Production via Vector Boson Fusion

In the MSSM at leading order

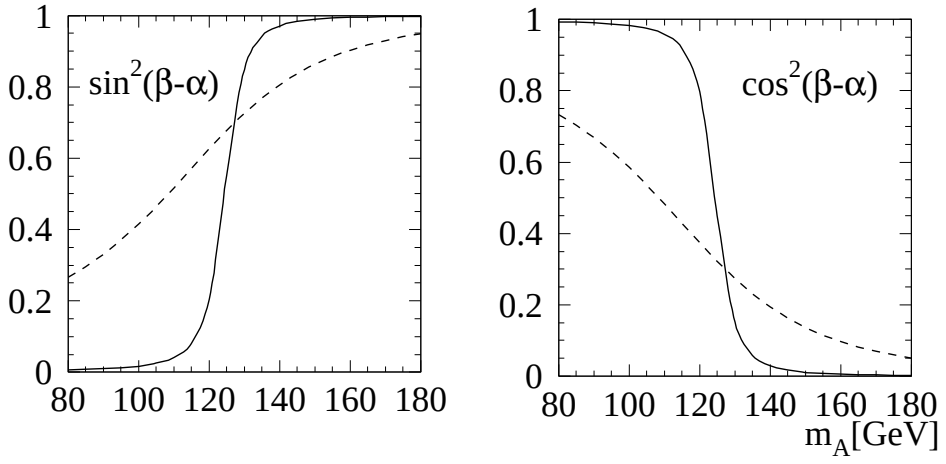
$\sum_{q,q',q'',q'''=u,d,c,s}$



- Replace SM-Higgs boson with (SM-like) MSSM h^0-Boson
- Vector-Boson–Vector-Boson–Higgs coupling modified by
  $\Gamma^{MSSM}_{WWh^0,ZZh^0} = \Gamma^{SM}_{WWH,ZZH} \cdot \sin(\beta - \alpha)$
- Therefore change of total cross section as
  $\sigma^{MSSM} = \sigma^{SM} \cdot \sin(\beta - \alpha)^2$

Corrected Tree-level Result

$$\sigma_0^{MSSM} = \sigma^{SM} \cdot \sin(\beta - \alpha)^2$$



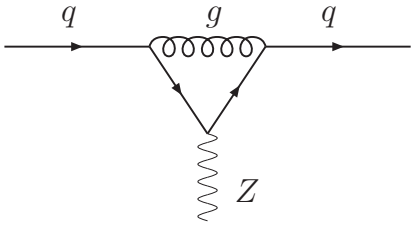
$$\tan\beta = \begin{cases} 4 & \text{dashed} \\ 30 & \text{solid} \end{cases}$$

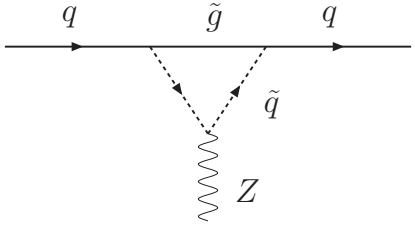
[Plehn, Rainwater, Zeppenfeld 1999]

- $\sin(\beta - \alpha)^2$ close to 1 for large parts of the parameter space
- $\Rightarrow$ Couplings of the h^0 SM-like
- Loop corrections induced by SUSY particles?
- Additional contributions to cross sections

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 

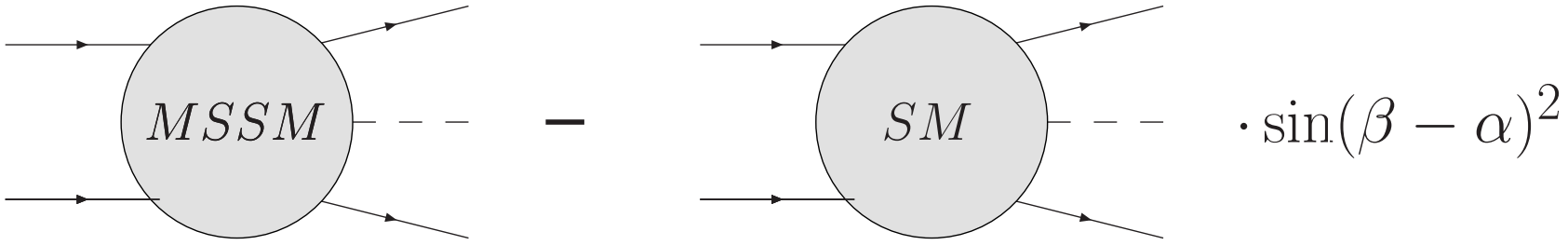
or SUSY 

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

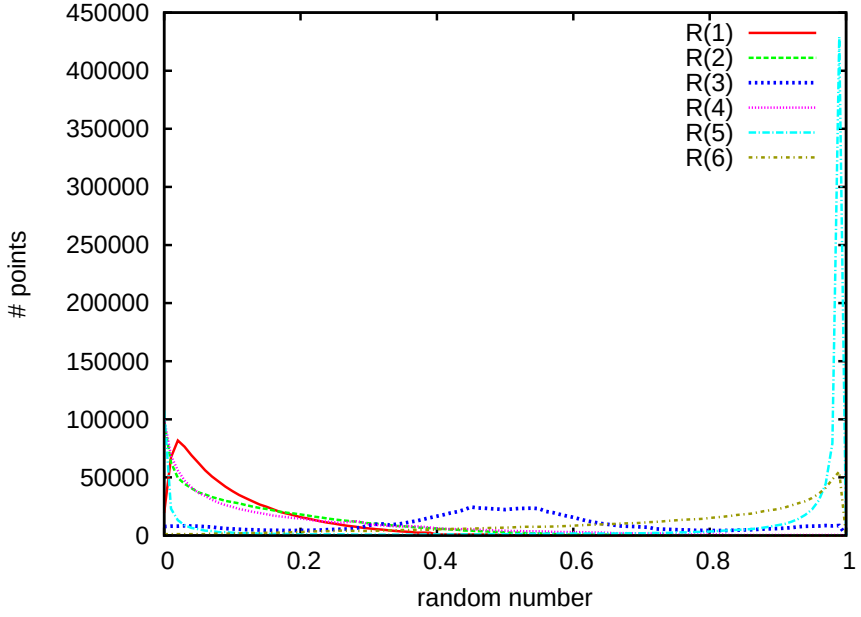
- Subtraction performed on amplitude level
- Cross-check that for non-Higgs couplings this corresponds to just omitting the SM particles

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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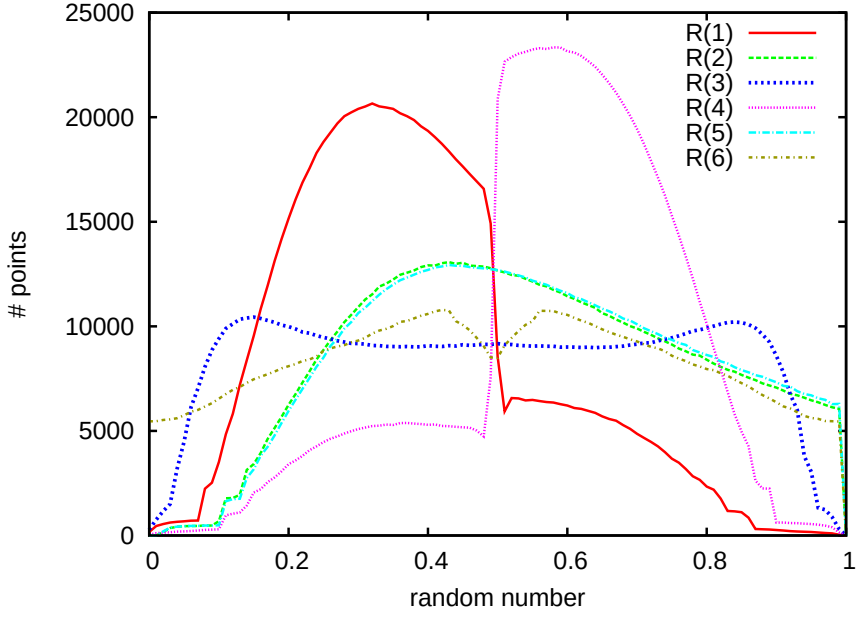
- Specialised phase-space generator [Rainwater, Zeppenfeld]



⇒ Improvement by factor of 10 to obtain similar accuracy

Technical Details

52504 individual Feynman diagrams calculated
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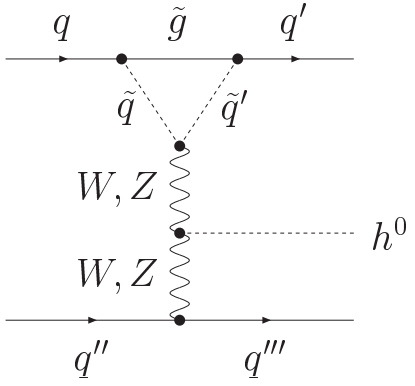
- Amplitudes and Fortran code generation:
  FeynArts, FormCalc [Hahn, Perez-Victoria, Schappacher]
- Hadronic cross sections: HadCalc [MR]
- Phase space generator [Rainwater, Zeppenfeld]
  - Train Vegas grid with 10^7 phase space points using tree-level amplitude only
  - Use trained Vegas grid as start point for full evaluation
  - $\Rightarrow$ Additional factor 5 improvement
- Loop integrals: LoopTools [Hahn, MR; v. Oldenborgh]
- Higgs sector: FeynHiggs [Hahn, Heinemeyer, Hollik, Rzehak, Weiglein]

Strong Corrections

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



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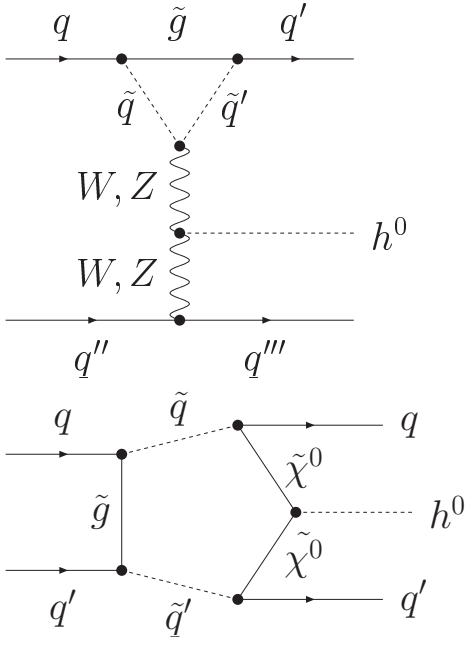

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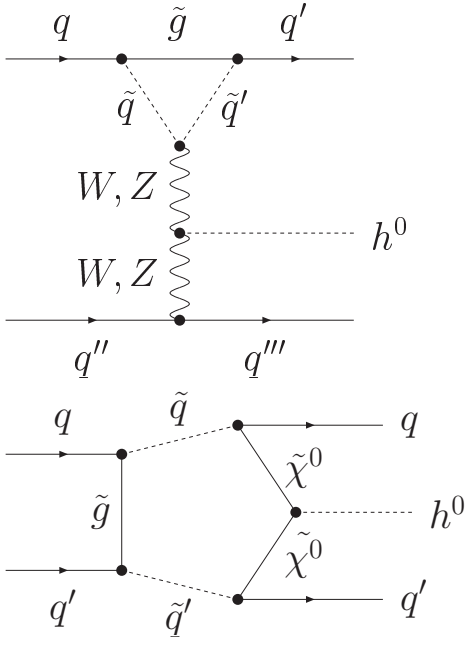

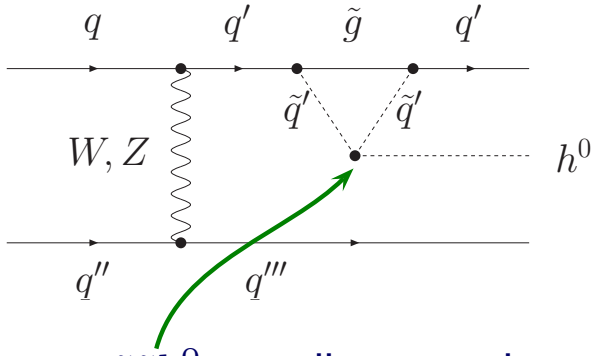

$\tilde{q}\tilde{q}h^0$-coupling contains gauge part (from D-terms)

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

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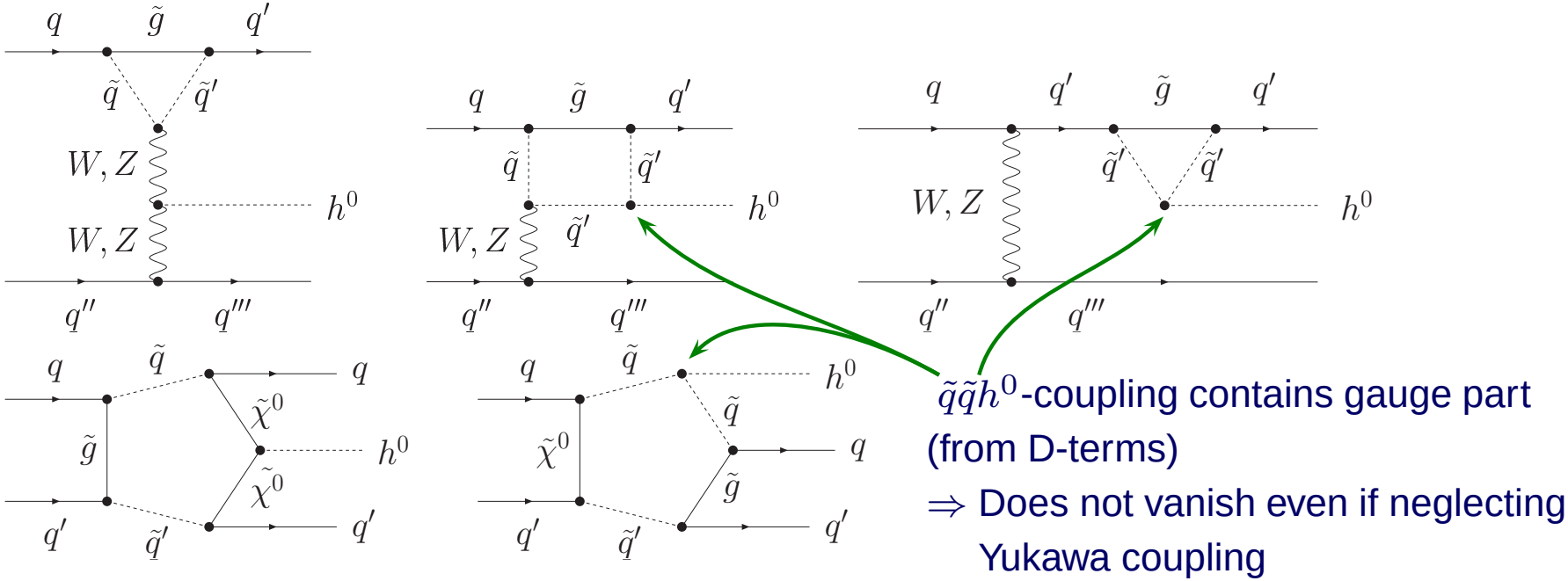

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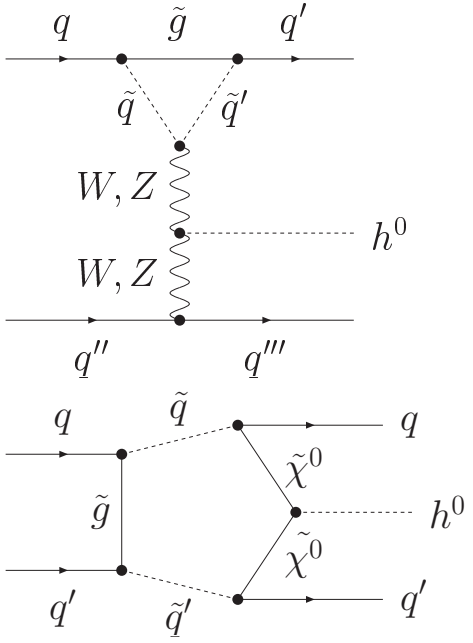

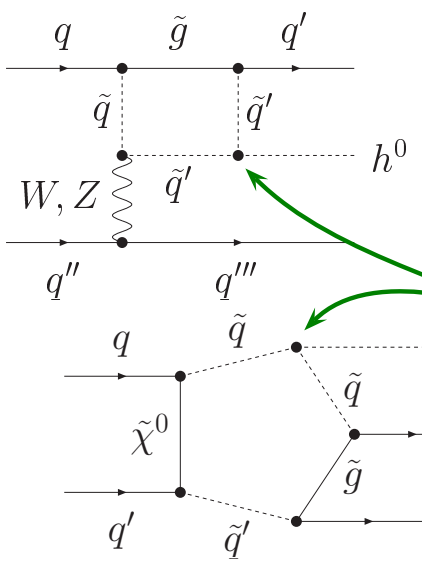

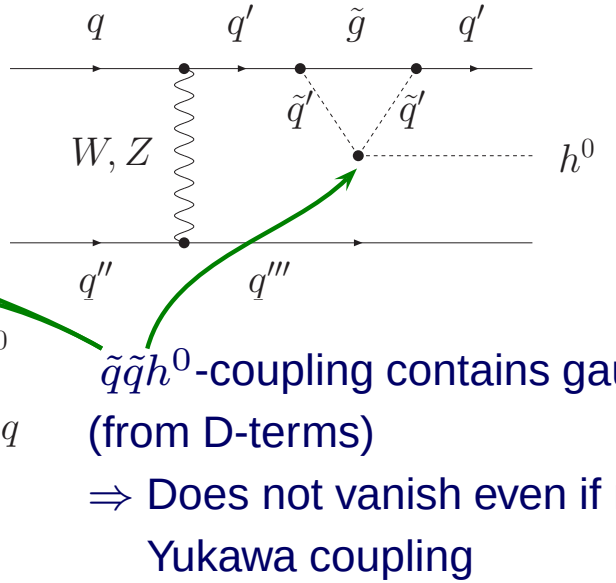

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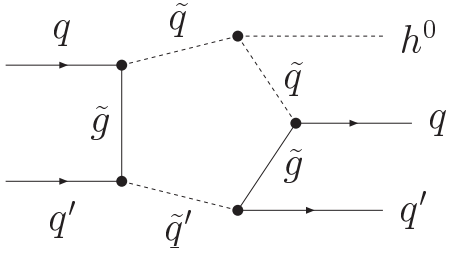
Additional possibility for pentagon diagrams:



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

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

However, not same kinematic structure as tree-level diagram

$\Rightarrow$ Greatly reduced by kinematic cuts

Suppressions

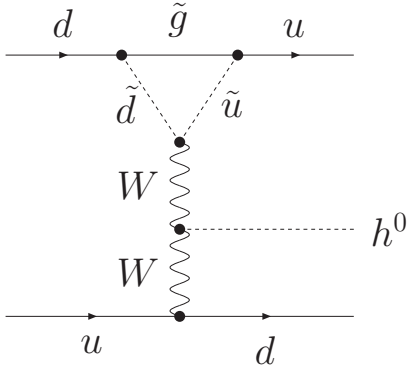
Size of the strong corrections (Parameter point SPA): [Hollik, MR]

	$(\sigma^{\text{one-loop}} - \sigma^{\text{born}})/\sigma^{\text{born}}$
Vertex corrections	$-1.2 \cdot 10^{-2}\%$ [Djouadi, Spira 2000]
effective qqh^0-Vertex	$4.9 \cdot 10^{-3}\%$
Box diagrams	$-4.7 \cdot 10^{-3}\%$
LO Pentagon diagrams	$-1.7 \cdot 10^{-4}\%$
$\mathcal{O}(\alpha_s)$ Pentagon diagrams	$1.9 \cdot 10^{-5}\%$
total SUSY-QCD corrections	$-1.2 \cdot 10^{-2}\%$

$\Rightarrow$ Large suppressions

Why are the corrections so small:

Vertex Corrections:



- W-coupling purely left-handed
- Quarks approximately massless
- $\Rightarrow$ Trace over fermion line cannot yield $m_{\tilde{g}}$, only kinematic term $\sim m_{h^0}/2$.

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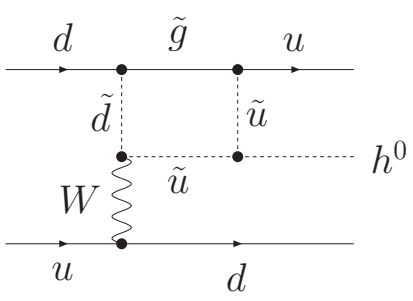
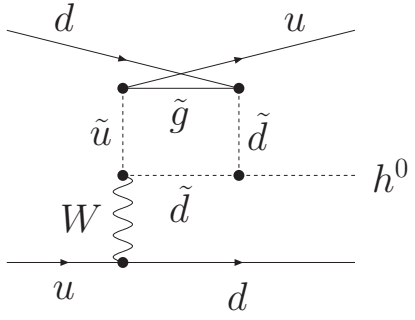
Box diagrams:





$\Gamma_{\tilde{u}^\dagger \tilde{u} h^0} \sim -\Gamma_{\tilde{d}^\dagger \tilde{d} h^0}$

$\Gamma_{\tilde{u}^\dagger \tilde{d} W^+} = \Gamma_{\tilde{d}^\dagger \tilde{u} W^-}$

$\Gamma_{\bar{u} d W^+} = \Gamma_{\bar{d} u W^-}$

$\Rightarrow$ Contributions cancel

(up to differences between $\tilde{u}$- and $\tilde{d}$ masses, which are small in common SUSY-breaking scenarios).

Electroweak Corrections

- Effect of cancellations reduced by additional diagrams without cancellations
- Smaller coupling constant

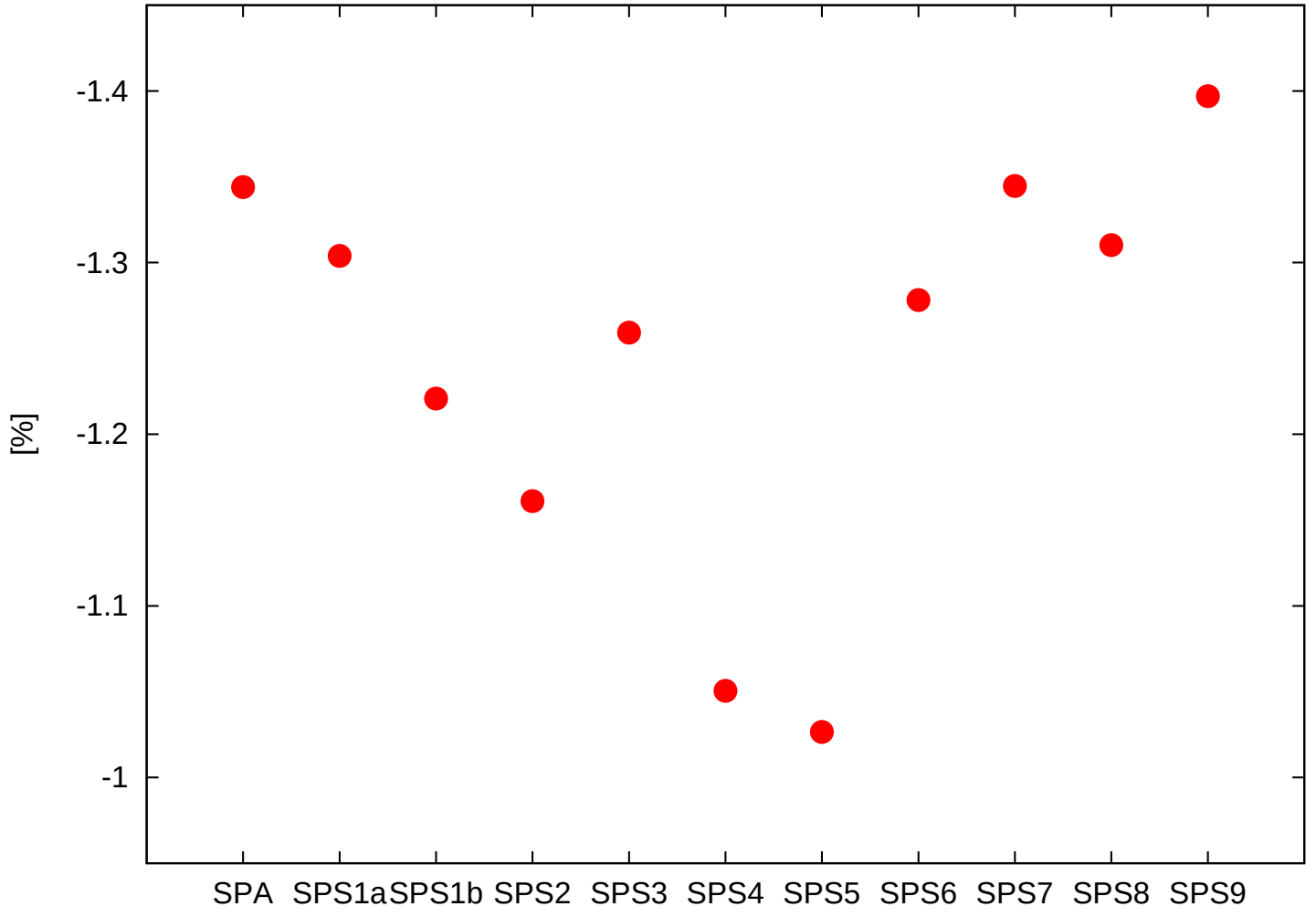
Size of the electroweak corrections (Parameter point SPA): [Hollik, Plehn, MR, Rzehak]

	$(\sigma^{\text{one-loop}} - \sigma^{\text{born}})/\sigma^{\text{born}}$
Self energies	$2.0 \cdot 10^{-1}\,\%$
Vertex corrections	$-1.6\,\%$
effective qqh^0-Vertex	$2.3 \cdot 10^{-2}\,\%$
Box diagrams	$7.2 \cdot 10^{-2}\,\%$
Pentagon diagrams	$4.7 \cdot 10^{-4}\,\%$
total SUSY-EW corrections	$-1.3\,\%$

Significant contributions from VVh^0-vertex

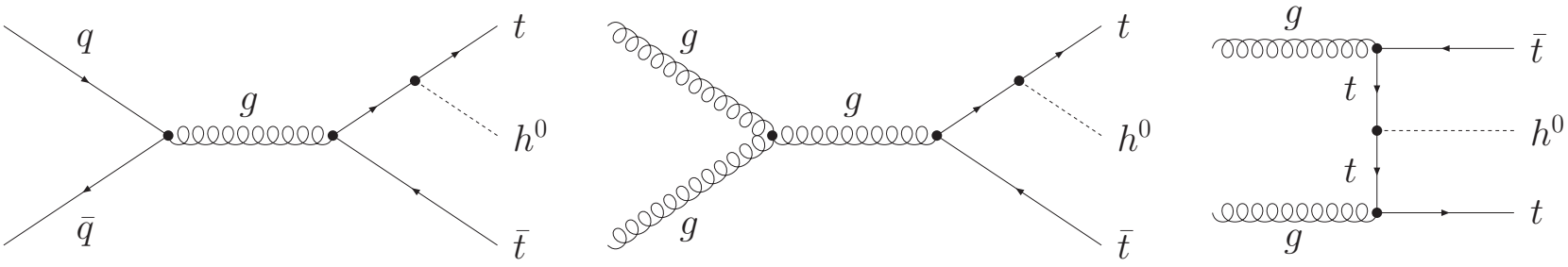
SPS points

Total MSSM contributions for the SPS points



Higgs Production with Top Quarks

- Higgs boson production in association with a top-quark pair
  important process to determine the top-Yukawa coupling
- Detection of the Higgs boson via $h^0 \to \gamma\gamma$ [CMS-TDR]
  (main decay mode $\bar{b}b$ too much background) [Cucciarelli et al.]
- Tree-level diagrams appearing in $t\bar{t}h^0$ production



- SM-QCD corrections already known

[Balazs, He, Yuan; Dicus, Stelzer, Sullivan, Willenbrock 1999]

[Beenakker et al.; Dawson, Orr, Reina, Wackeroth 2001,2003]

[Dittmaier, Krämer, Spira; Dawson, Jackson, Reina, Wackeroth 2004]

- $\Gamma^{MSSM}_{\bar{t}th^0} = \Gamma^{SM}_{\bar{t}tH} \cdot \frac{\cos(\alpha)}{\sin(\beta)}$
- $\Rightarrow$ need SUSY-QCD corrections [Peng et al. 2005; Hollik, MR]

$t\bar{t}h^0$ production

- For the MSSM reference point SPA:

Partonic subprocess	σ_0 [fb]	σ_1 [fb]	Δ_1 [%]
$d\bar{d} \to t\bar{t}h^0$	42.7	37.6	-11.77
$u\bar{u} \to t\bar{t}h^0$	71.9	63.4	-11.81
$s\bar{s} \to t\bar{t}h^0$	7.5	6.6	-11.58
$c\bar{c} \to t\bar{t}h^0$	2.8	2.5	-11.53
$gg \to t\bar{t}h^0$	273.7	264.7	-3.30
$\sum (pp \to t\bar{t}h^0)$	399.0	374.8	-5.96

  where $\Delta_1 = \frac{\sigma_1 - \sigma_0}{\sigma_0}$

- All diagram types must be taken into account
  (in contrast to $b\bar{b}h^0$ production where gluon t-channel dominates)
- S-channel suppression compensated by lower gluon densities at higher x
- Contribution to the total cross section significant

Conclusions

- Higgs-boson production via Vector Boson Fusion important discovery mode for the Higgs boson and to study electroweak symmetry breaking
- Supersymmetric QCD corrections strongly suppressed
- Supersymmetric electro-weak corrections modify cross section on the percent level

- Higgs-boson production in association with top-quarks important channel to study the top-Yukawa coupling
- One-loop SUSY-QCD corrections of several percent
- Need to be taken into account when extracting the top-Yukawa coupling

Backup Slides