Higgs Physics Summary

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Physics at the Terascale
Helmholtz Alliance

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DESY, Hamburg

Outline

- **Higher order calculations - Higgs production and bkg**
  - 2 talks NNLO m_t effects on gg-fusion (Ozeren/Rogal)
  - NLO QCD to $pp \to ttbb$ (Worek)
  - 1-loop MSSM to WBF (Palmer)
  - EW & b-quark contrs to H+jet (Brein)
  - Pseudoscalar decays to WW/ZZ (Wiebusch)
- **Experimental studies**
  - Higgs boson cxns (Warsinsky)
  - MSSM Higgs associated w/ $\phi \to \mu\mu$ (Weber)
  - WH, $H \to bb$ at large p_T (Weiser)
  - WBF in Pythia and Herwig (Hackstein)
- **Computer programs**
  - HiggsBounds (Williams)
- **More on theory calculations**
  - 2-loop $H \to b\bar{b}$ (Reißer)
  - 3-loop Higgs mass corrections (Kant)

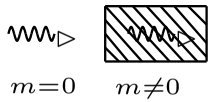
Higgs Physics

Higgs physics at future colliders:
Establish experimentally the Higgs Mechanism

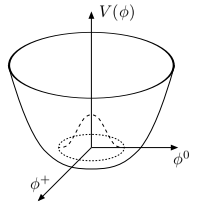
The Higgs mechanism:
Creation of particle masses in a gauge-invariant way

Test of the Higgs mechanism

- Discovery – m
- Spin and CP properties – J^{PC}
- Interaction with the scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X^{(2)}$



- EWSB requires Higgs potential $\leftrightarrow$ $\lambda_{HHH}, \lambda_{HHHH}$



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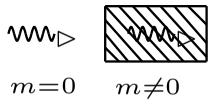

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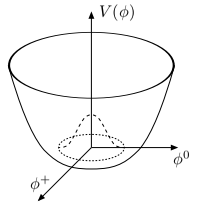

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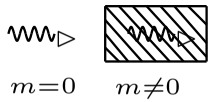

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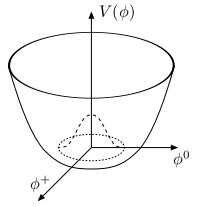

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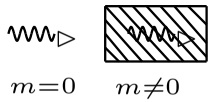

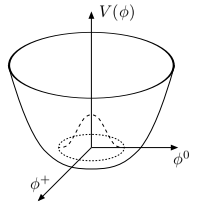

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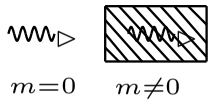
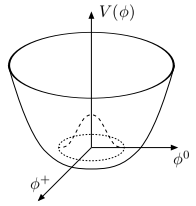




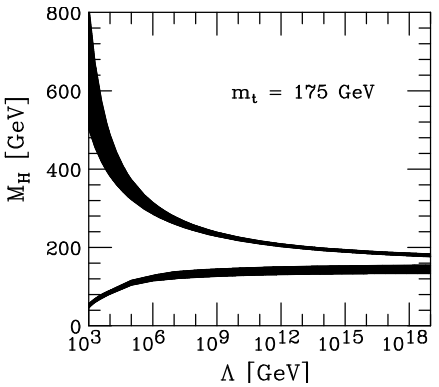
$\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector - $\mathcal{M}$ass $\mathcal{C}$onstraints

- Triviality $\longrightarrow$ upper bound
  Vacuum stability $\longrightarrow$ lower bound

Cabibbo,...;Sher;
Lindner;Hasenfratz,...;
Lüscher, Weisz;
Hambye,...;...

$$\Lambda = 1 \text{ TeV}: \quad 55 \text{ GeV} \lesssim M_H \lesssim 700 \text{ GeV}$$
$$\Lambda_{GUT} = 10^{16} \text{ GeV}: \quad 130 \text{ GeV} \lesssim M_H \lesssim 190 \text{ GeV}$$

Hambye,Riesselmann



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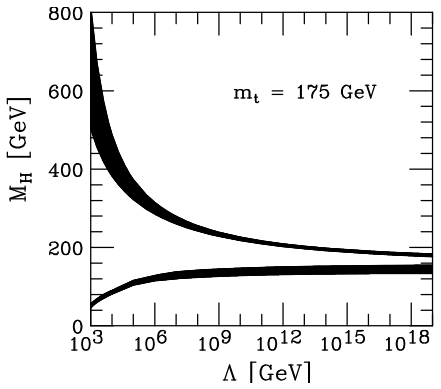
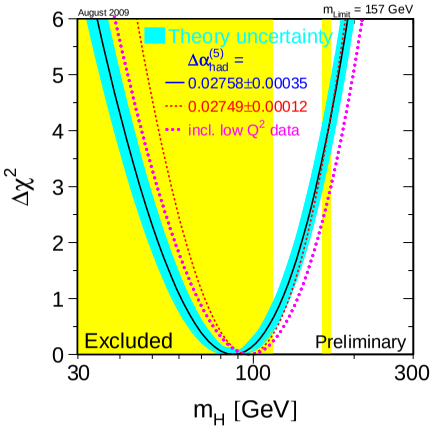


- Fits to electroweak precision data

EWWG

$$M_H = 87^{+35}_{-26} \text{ GeV}, \; M_H \lesssim 186 \text{ GeV} \; @ \; 95\% \text{ CL}$$



LEP Coll.

$\mathcal{SM}$ Higgs Sector - Mass Constraints

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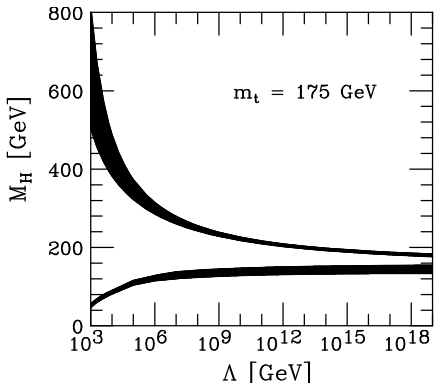

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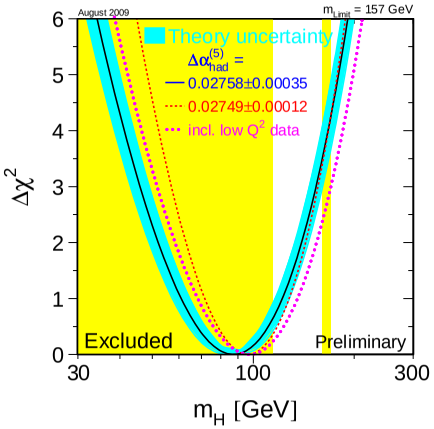
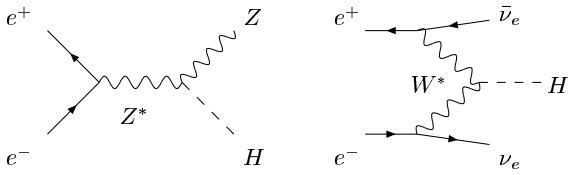


LEP Coll.

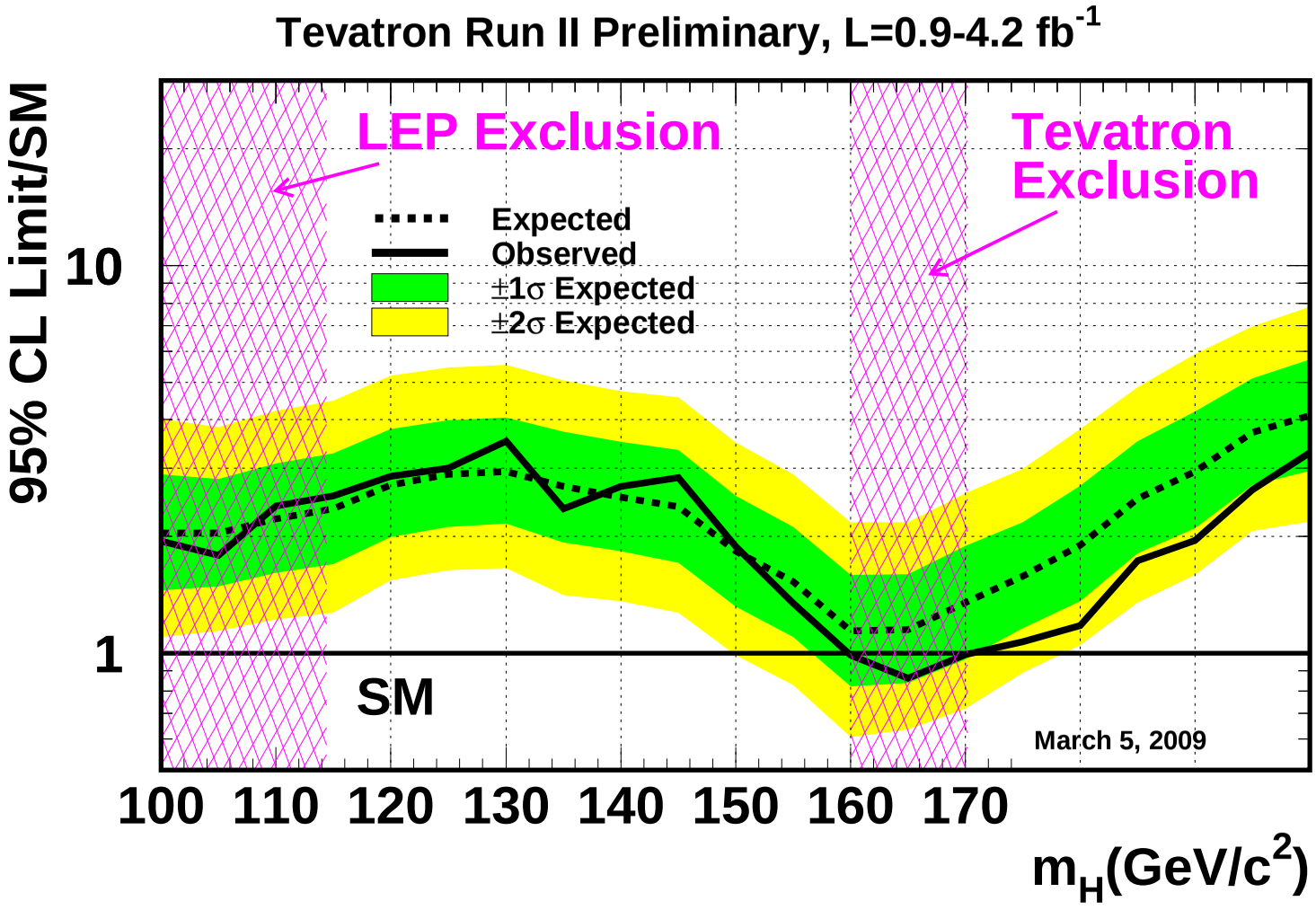
- Direct search @ LEP: $[M_H = 115.3 \text{ GeV}]$

$$M_H > 114.4 \text{ GeV @ 95\% CL}$$

LEP Coll.



$\mathcal{T}$evatron $\mathcal{E}$xclusion



$\mathcal{SUSY}$ $\mathcal{H}$iggs $\mathcal{S}$ector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\overset{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H | neutral, CP-odd A | charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;...

Non-minimal SUSY extensions

Most general SUSY with arbitrary matter content and gauge coupling unification at 10^{17} GeV:

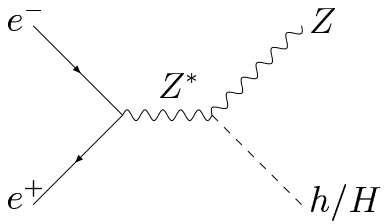
$$M_h \lesssim 200 \text{ GeV}$$ Espinosa,Quiros

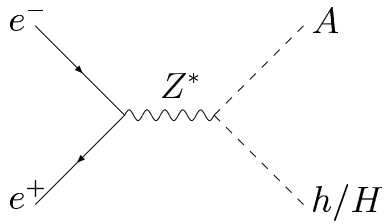
E.g. NMSSM

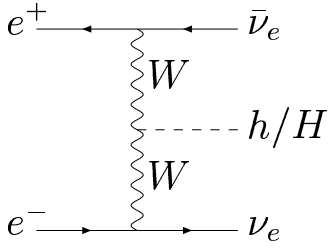
$$M_h^{\text{NMSSM}} \lesssim 142 \text{ GeV}$$ Ellwanger,Hugonie

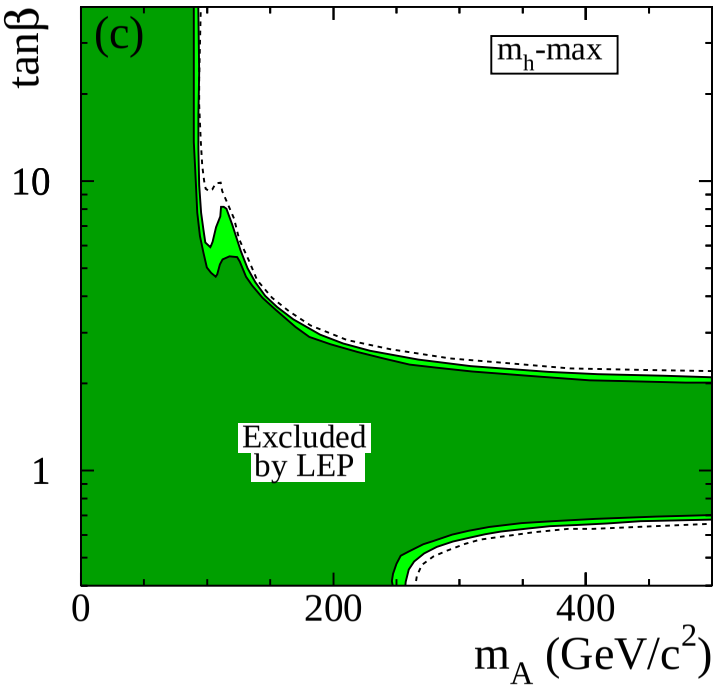
MSSM Higgs Mass Limits

▷ Direct Search at LEP: $e^+e^- \to Z + h/H, A + h/H, \nu_e\bar{\nu}_e + h/H$









$M_{h/H} \gtrsim 91$ GeV

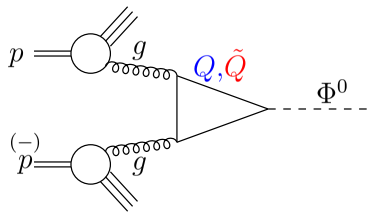
$M_A \gtrsim 91.9$ GeV

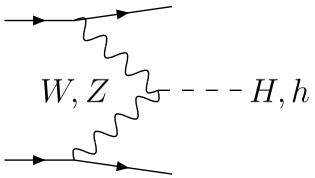
$M_{H^\pm} > 78.6$ GeV

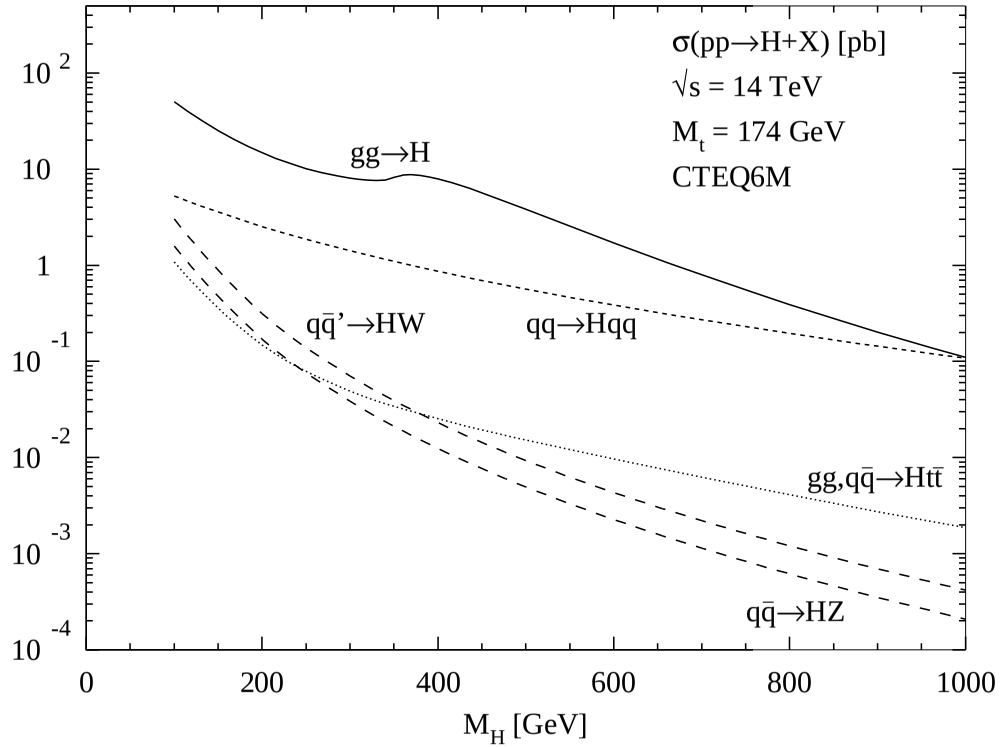
$0.5 < \tan\beta < 2.4$ excluded

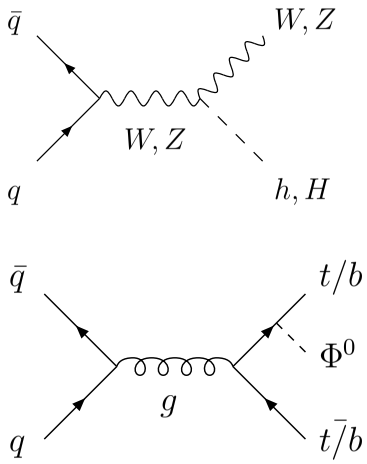
(only in this scenario, $m_t = 174.3$ GeV!)

SM Higgs Boson Produktion at the LHC



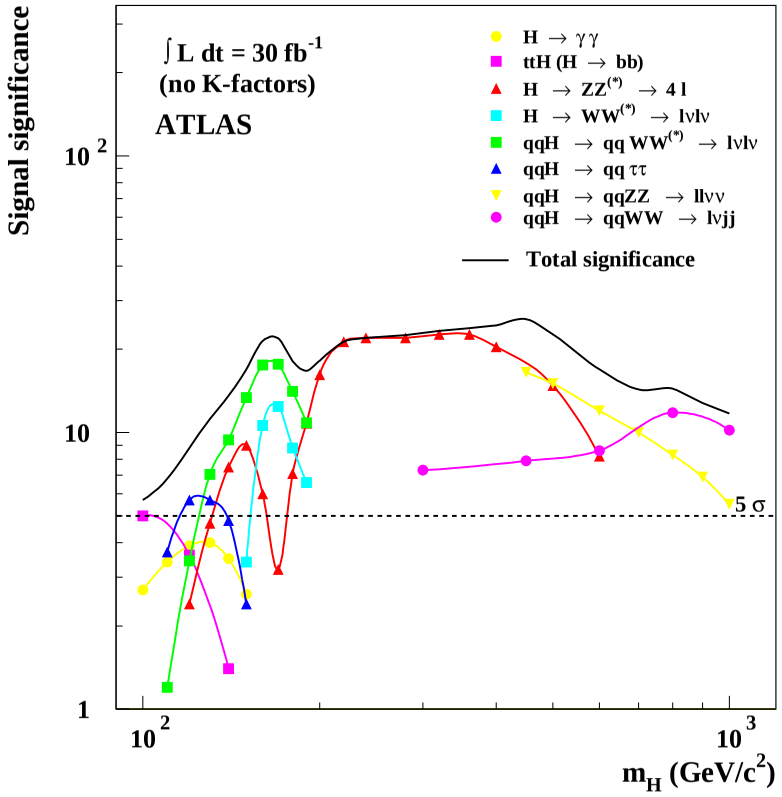




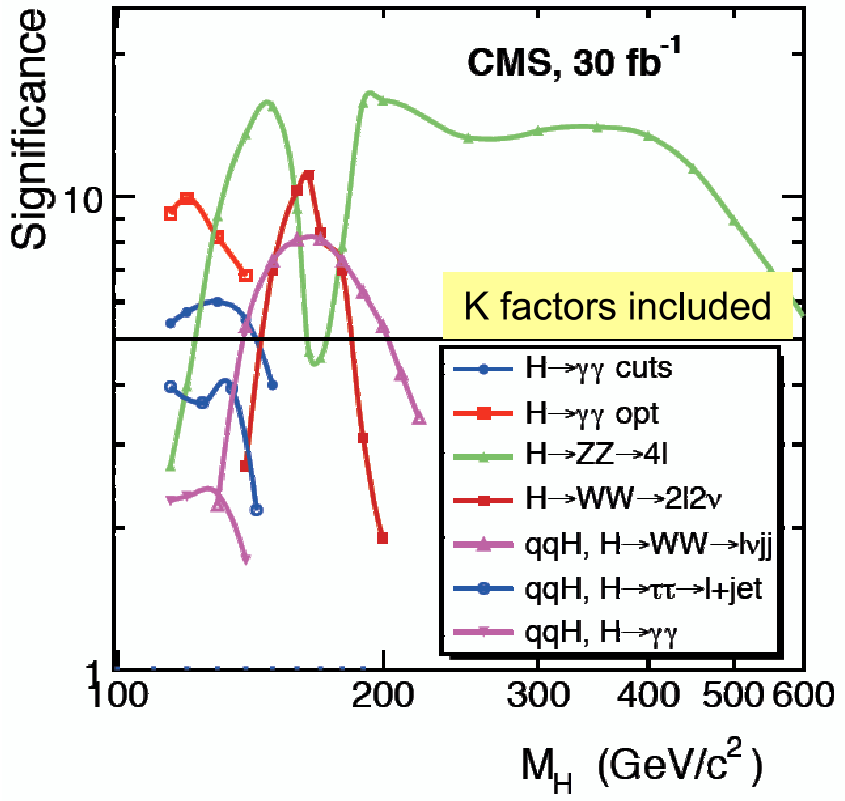


$\mathcal{SM}$ Higgs Boson Search at the $\mathcal{LHC}$

ATLAS



CMS



accuracy: $\delta M_H/M_H \sim 10^{-3}$

MSSM Higgs Boson Search at the LHC

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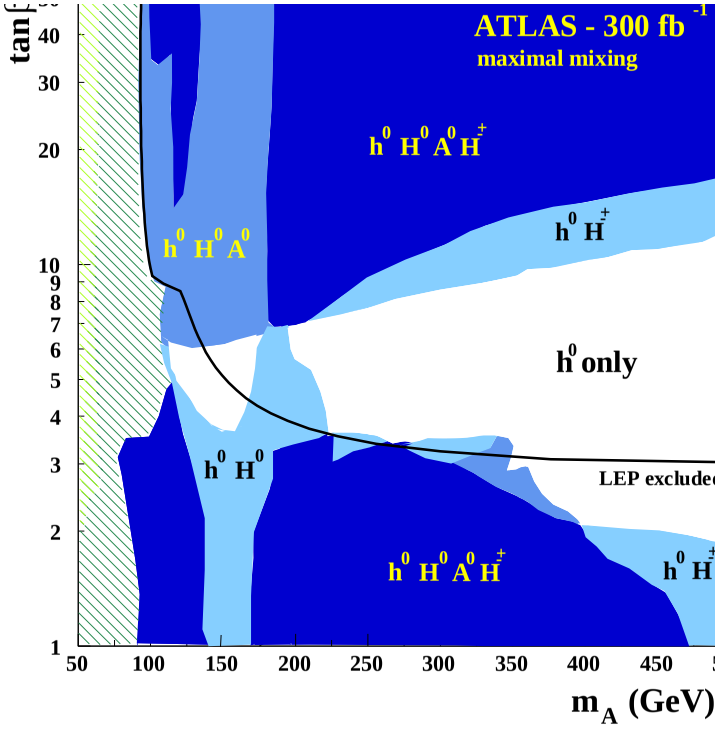

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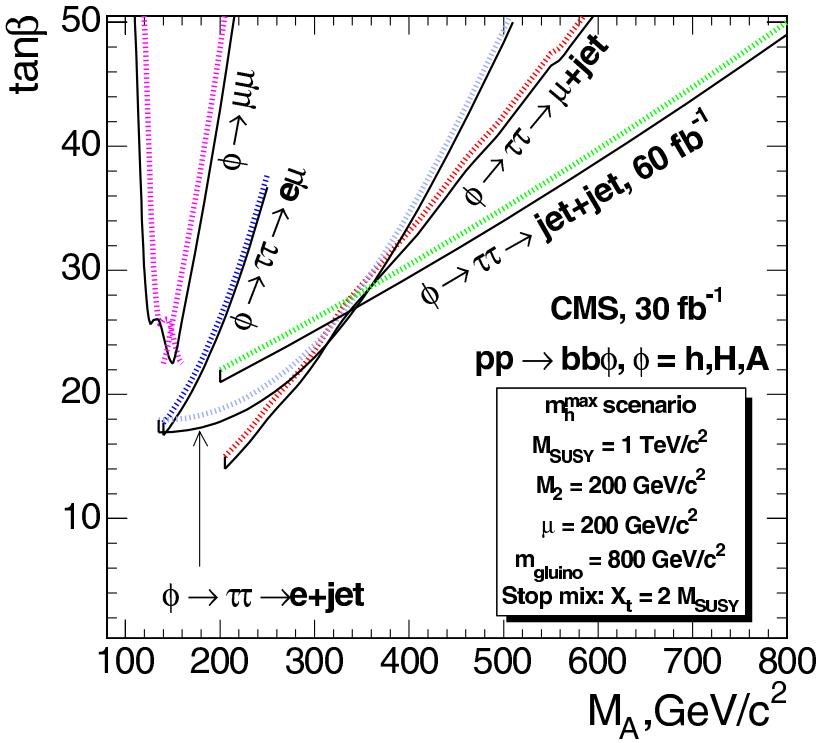

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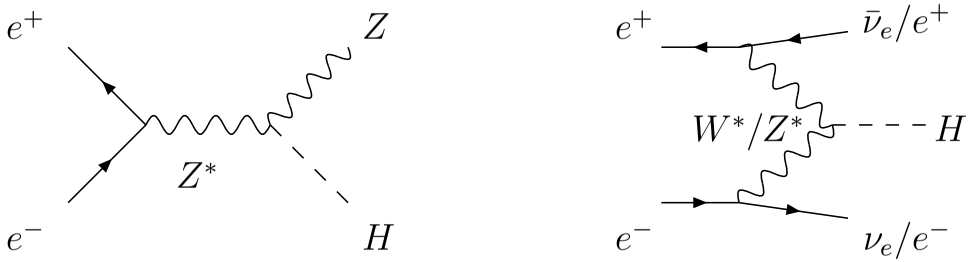
ILC $\mathcal{SM}$ Higgs Boson Production

Production via Higgs-strahlung and VV fusion

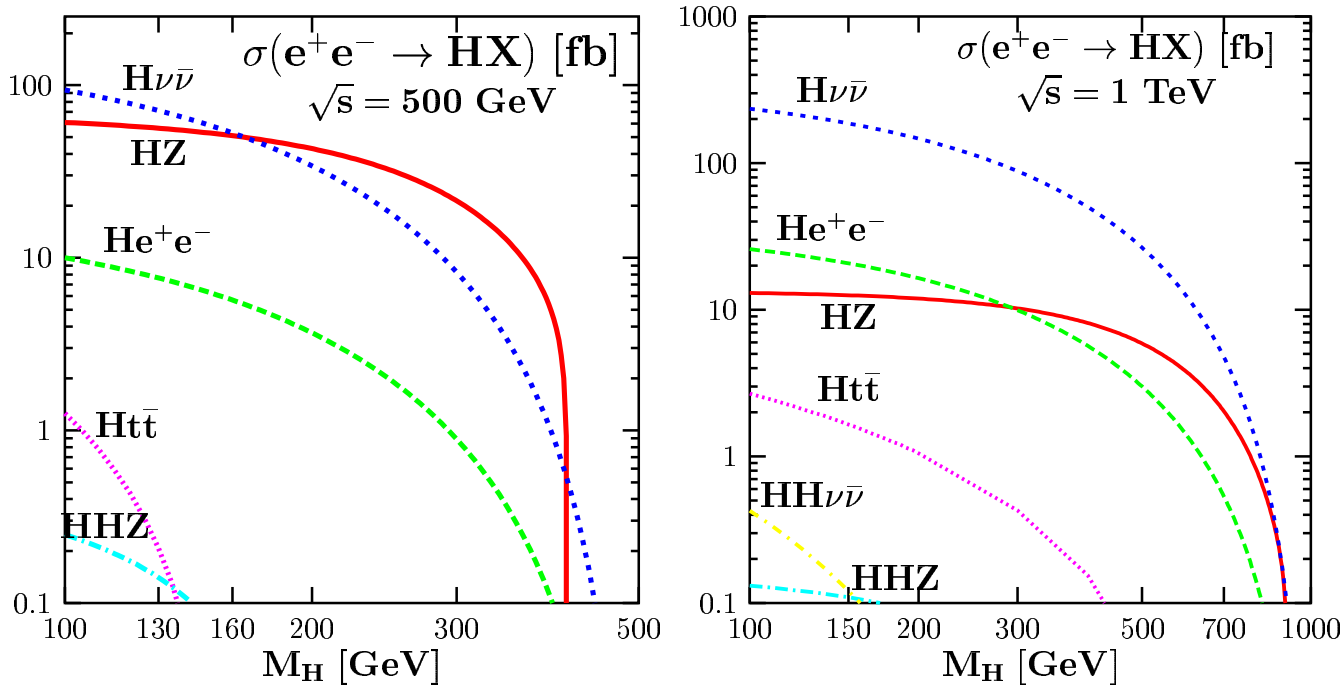


$\sqrt{s} = 500$ GeV

$\int \mathcal{L} = 500$ fb^{-1}

$M_H = 120$ GeV

~ 70000 #/year



Djouadi et al.

NNLO Higgs production via gluon fusion with finite top mass

Kemal Ozeren

Beyond the heavy top limit in the partonic Higgs production at the LHC

Mikhail Rogal

Top mass effects at NNLO

Kemal Ozeren (with R. Harlander) **Mikhail Rogal (with M. Steinhauser, A. Pak)**

- **QCD corrections huge - $\mathcal{O}(100\%)$**

  NLO (effective theory) — Dawson

  NLO (HIGLU) — Spira,Djouadi,Graudenz,Zerwas

  NNLO (effective theory) — Harlander,Kilgore; Anastasiou,Melnikov; Ravindran,Smith,vanNeerven

- **Electroweak**

  Actis,Passarino,Sturm,Uccirati

- **Mixed QCD-Electroweak**

  Anastasiou,Boughezal,Petriello

- **NNLO+NNLL - $\mathcal{O}(\%)$**

  Catani,deFlorian,Grazzini,Nason

- **N^{3}LO threshold enhanced corrections**

  Moch,Vogt;Laenen,Magnea; Ravindran;Kidonakis;Idilbi,Ju,Yuan

- **"π^2-resummation"**

  Ahrens,Becher,Neubert,Yang

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- **How accurate is the effective theory at NNLO?** $\Rightarrow$

- **Perform an asymptotic expansion in** $\frac{1}{m_t}$

$$\sigma = \sum_n \left(\frac{m_H^2}{4m_t^2}\right)^n \sigma_n$$

$*$ first term $\sigma_0 =$ eff. theory result $*$ first non-leading $1/m_t$ term at NLO known Dawson,Kauffman

- **Small** $x = m_H^2/s$**: approach breaks down**

  Match onto the known exact leading small-x result (gg) Marzani,Ball,DelDuca,Forte,Vicini

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- **Comparison NNLO $1/m_t$ expansion with effective theory**

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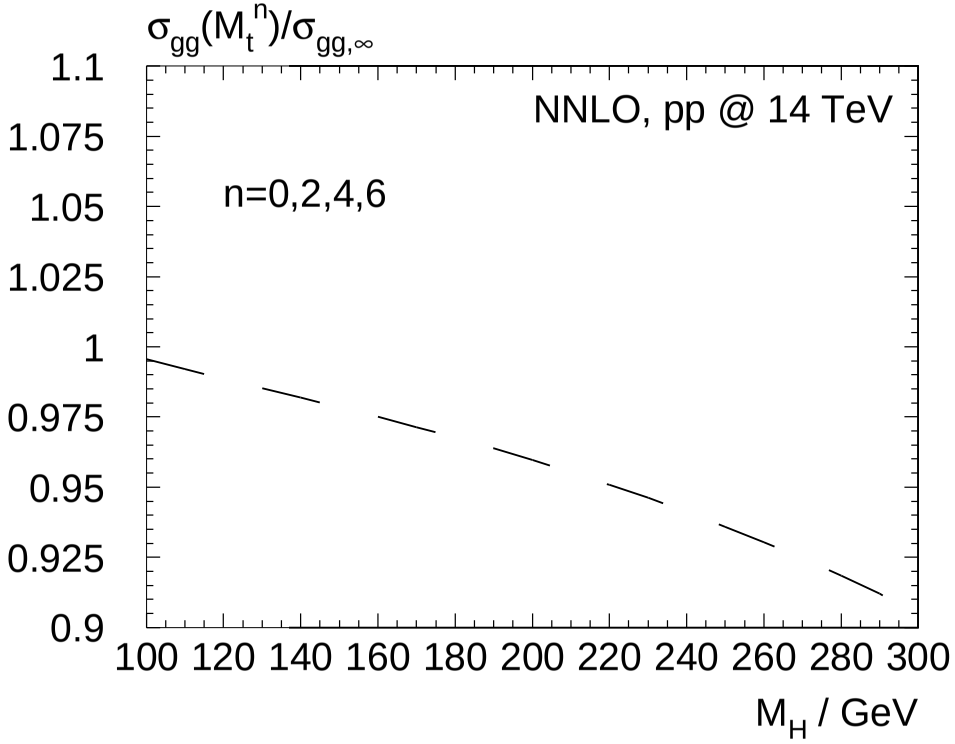

- Top mass effects are small: about 1% $\rightsquigarrow$ effective theory approach justified.
- Agreement between Ozeren et al. and Rogal et al.

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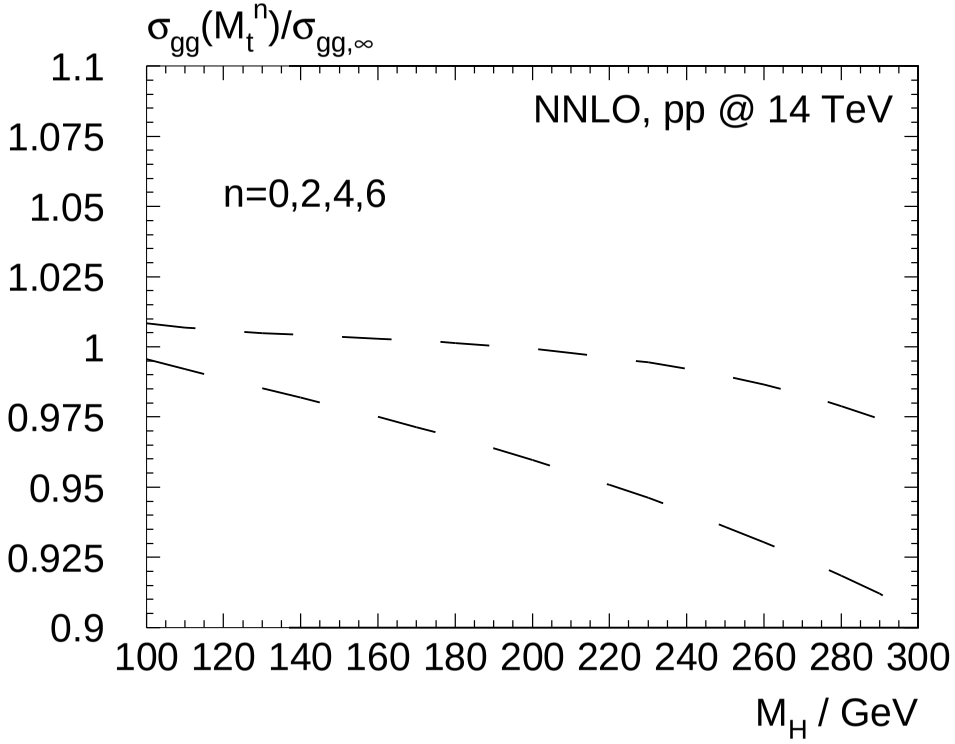

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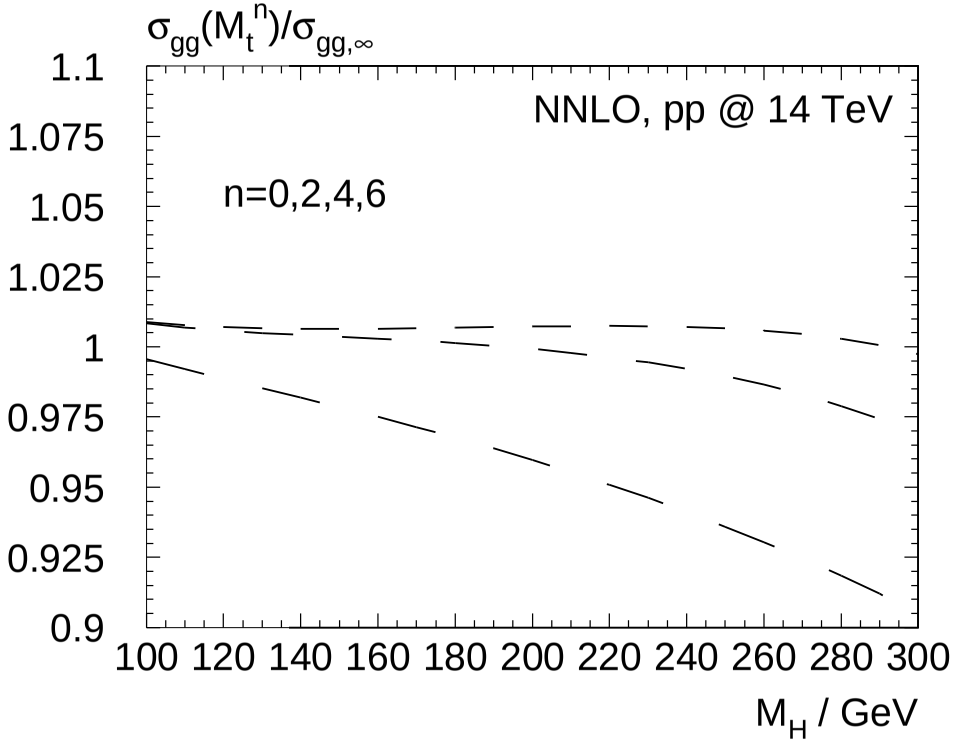

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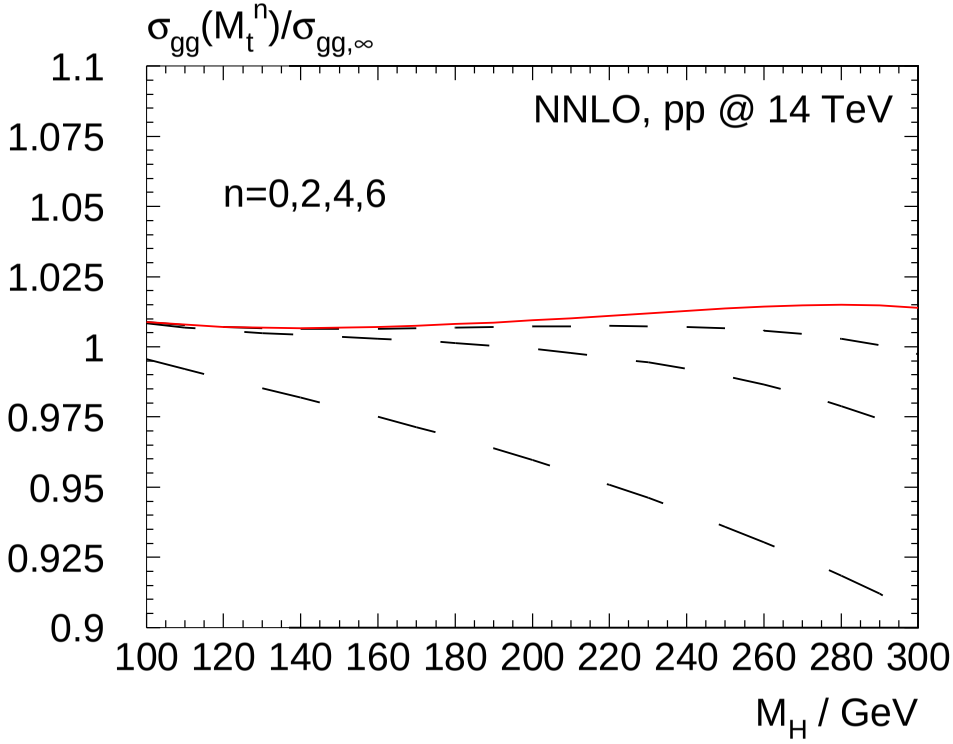

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NLO QCD corrections to $pp \to ttbb$

Malgorzata Worek (with Bevilacqua,Czakon,Papadopoulos,Pittau)

- **Motivation**
  - important bkg to ttH production with $H \to b\bar{b}$
  - analyses with realistic bkgs: signal significance jeopardized if bkgs from $ttbb$, $tt+$ jets not controlled very well

- **NLO $2 \to 4$ particle process** at current technical frontier

- **Fully automatic calculation**
  based on `HELAC-PHEGAS`, `HELAC-1LOOP`, `CUTTOOLS`, `ONELOOP`, `HELAC-DIPOLES`

- **Result**
  - demonstrate power of system in realistic computation with 6 external legs and massive partons
  - Agreement with Feynman diagramatic calculation by Bredenstein,Denner,Dittmaier,Pozzorini

NLO QCD corrections to $pp \longrightarrow ttbb$

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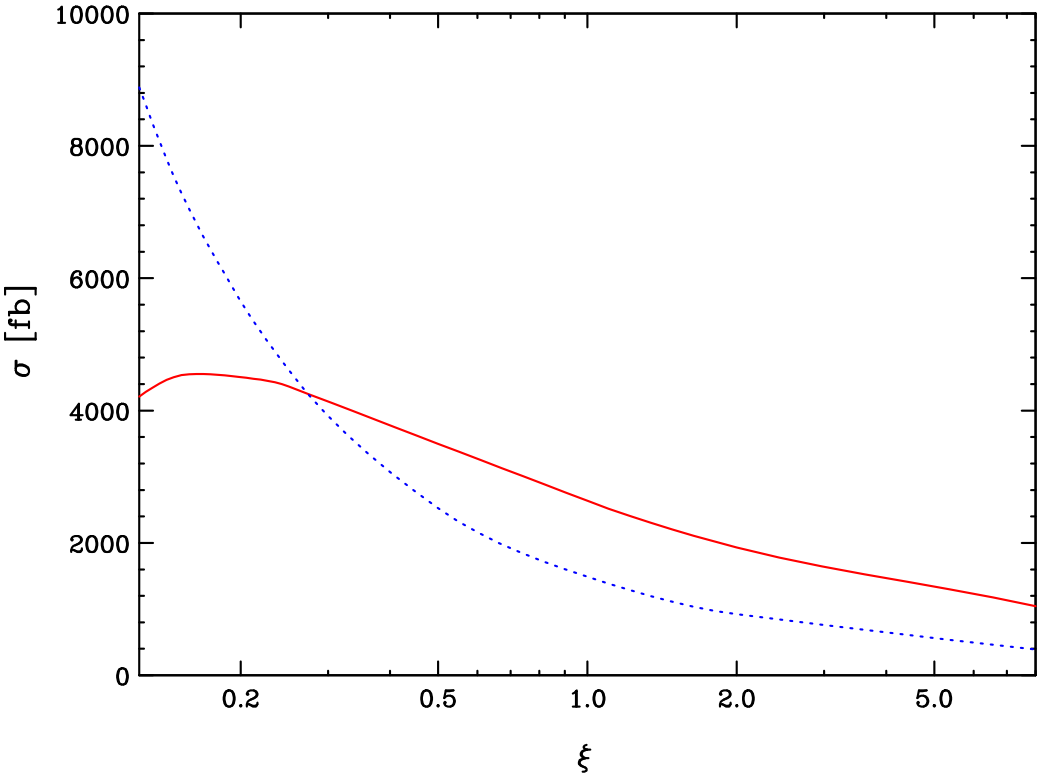


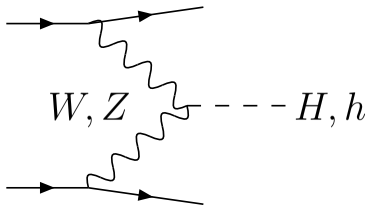
* Scale dependence reduced from 70% at LO to 33% at NLO
* K-factor is large and positive, $K = 1.77$

1-loop MSSM corrections to Higgs production in WBF

Sophy Palmer (with T.Figy,G.Weiglein)

- **Weak boson fusion: second largest SM Higgs production process at LHC**

$$q + q \to q + h - H + q$$



- **Status**

NLO QCD corrections and full SM 1-loop correction calculated and implemented in MC programs — Han,Valencia,Willenbrock; Figy,Oleari,Zeppenfeld; Ciccolini,Denner,Dittmaier

Estimation of $\mathcal{O}(\alpha^3\alpha_S^2)$ contributions — Vollinga

SUSY QCD and SUSY QCD&EW corrections known — Djouadi,Spira; Hollik,Plehn,Rauch,Rzehak

Loop interference effects calculated — Andersen,Binoth,Heinrich,Smillie; Bredenstein,Hagiwara,Jäger

1-loop MSSM corrections to Higgs production in WBF

Sophy Palmer (with T.Figy,G.Weiglein)

- **VBFNLO public MC program:**

Arnold,Bahr,Bozzi,Campanario,Englert,Figy,Greiner,Hackstein,Hankele,Jäger,Klamke,Kubocz,Oleari,Plätzer,Prestel,Worek,Zeppenfeld

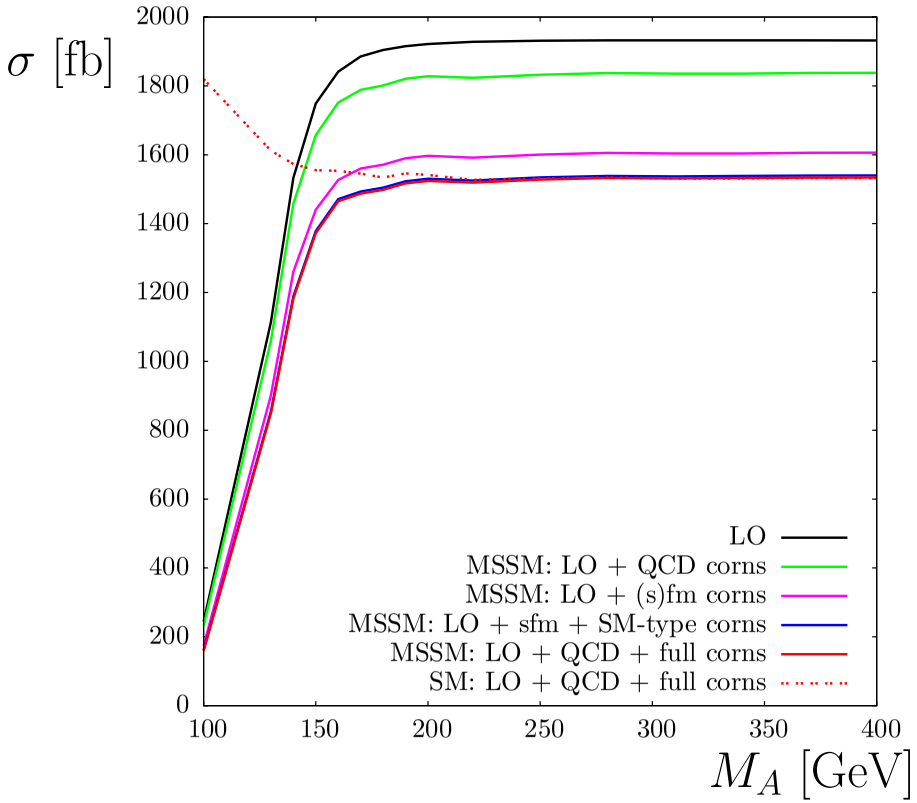
$\longrightarrow$ predictions & distributions for WBF in the SM

$\longrightarrow$ NLO SM QCD corrections included

- **New Corrections to VBFNLO**
  - Full 1-loop SM EW corrections
  - (complex) MSSM: all SM-type corrections, dominant SUSY corrections

1-loop MSSM corrections to Higgs production in WBF

Sophy Palmer (with T.Figy,G.Weiglein)



- EW corrs typically $\mathcal{O}(5\%)$, can be greater than $\mathcal{O}(10\%)$ in non-decoupling regime

Electroweak and Bottom Quark Contributions to Higgs+Jet Production

Oliver Brein

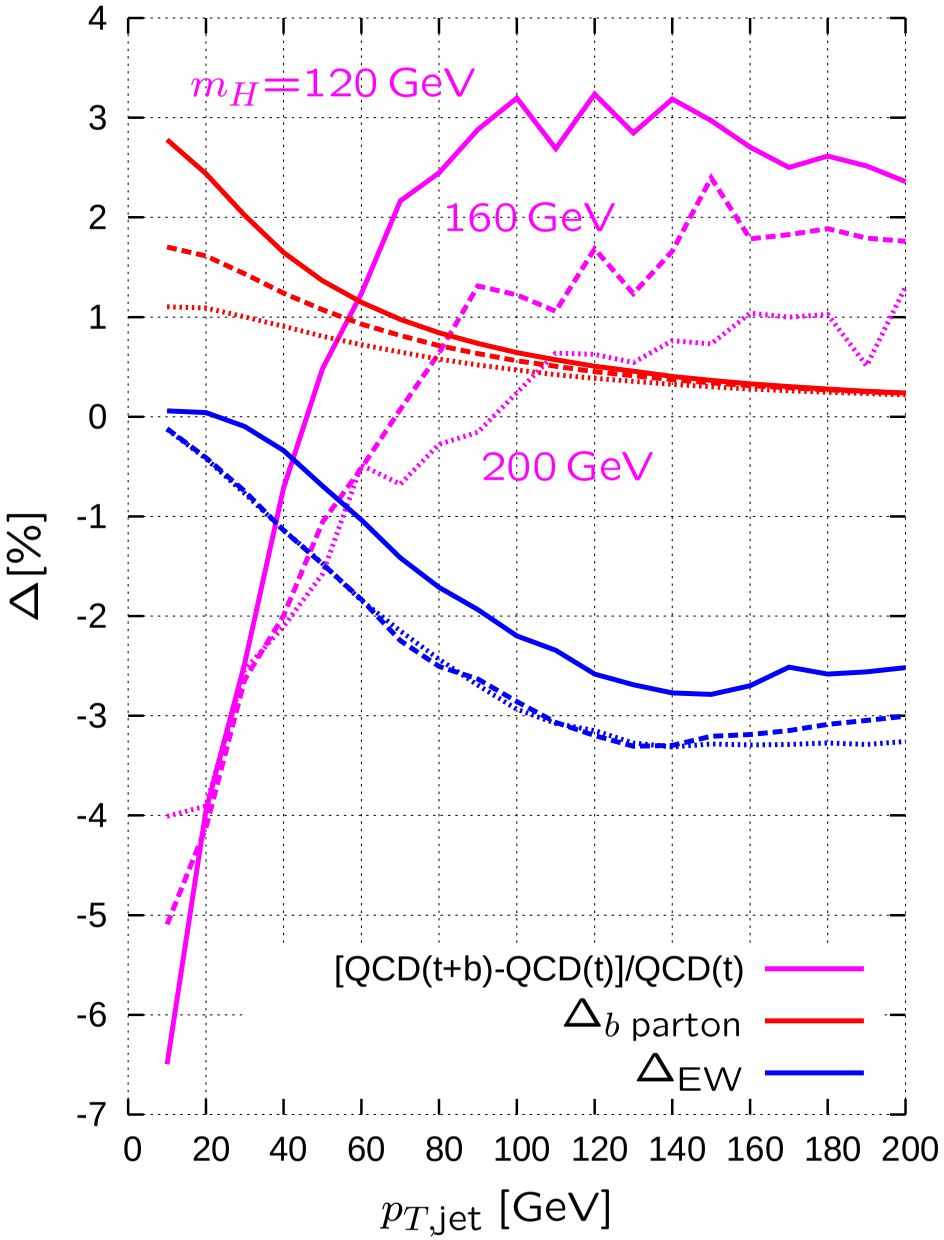
- **Motivation** Low Higgs mass region difficult

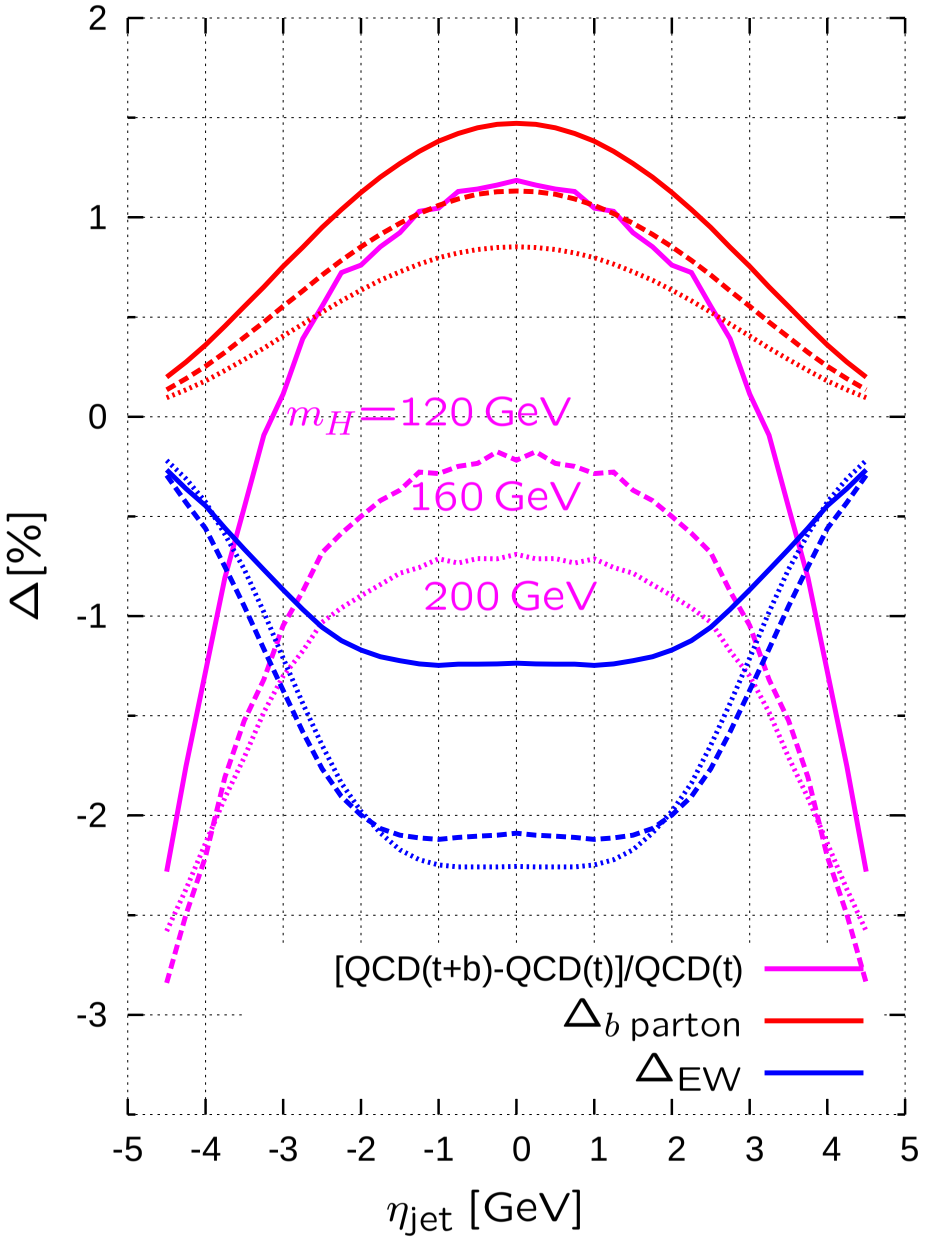
  * study Higgs events w/ high-p_T hadronic jet
  * advantage: richer kinematical structure compared to inclusive production ($\rightarrow$ refined cuts)
  * disadvantage: lower rate than inclusive production

- **LO Contributions to Higgs+ Jet**

  ◦ finite quark mass effects
  ◦ EW loop effects
  ◦ 5-flavour scheme effect

LHC: relative differences in $p_{T,\text{jet}}$- and η_{jet}-distributions ($m_H = 120\,\text{GeV}$) :





Pseudoscalar Higgs Decays into Electroweak Gauge Bosons

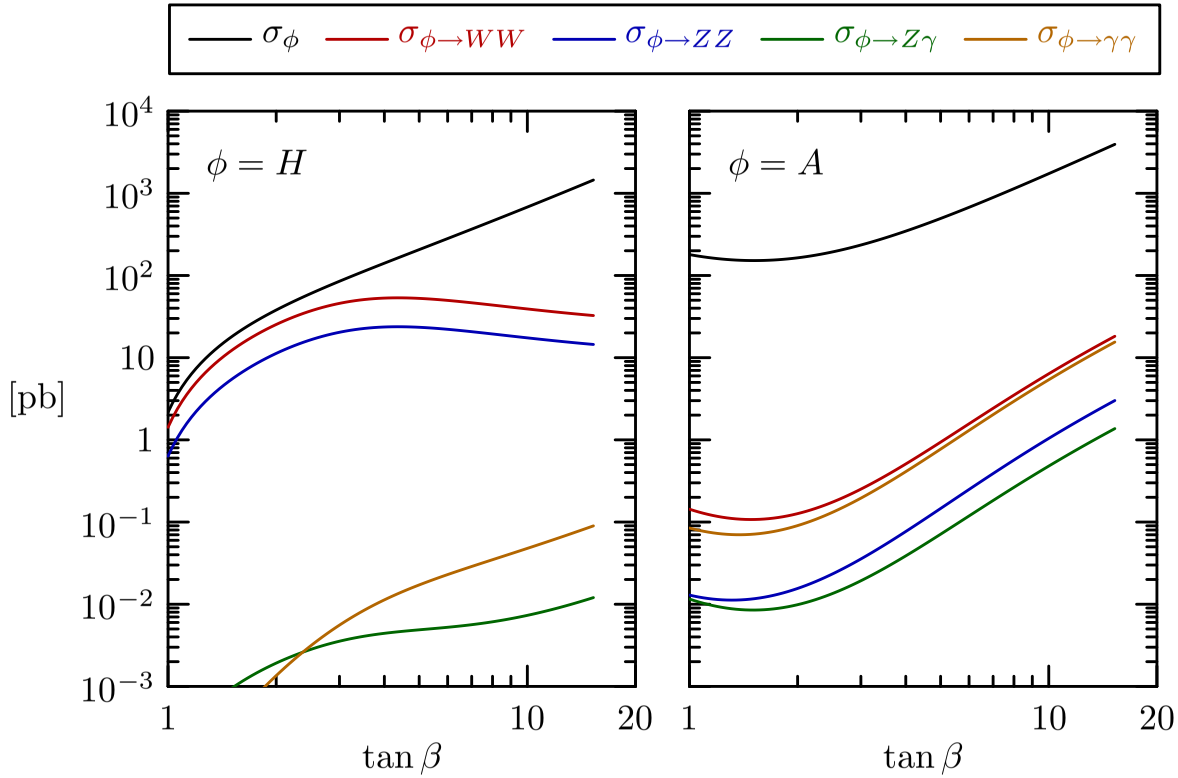
Martin Wiebusch (with W.Bernreuther,P.Gonzalez)

- **Motivation**
  - Higgs $\to WW/ZZ \rightsquigarrow$ very clean signals
  - The Higgs CP eigenvalue of the Higgs can be determined in these decay modes
- **Pseudoscalar Higgs**
  - Models without Higgs sector CP violation: no tree-level couplings between pseudoscalar Higgses and gauge bosons.
  - AVV' couplings must be induced trough fermion loops.
  - BRs usually small
  - But: Higgs-fermion couplings could be large
- **Investigated process** $\sigma(pp \to \phi \to VV')$ in the narrow width approximation for 2HDM, MSSM, 2HDM+4th generation

Pseudoscalar Higgs Decays into Electroweak Gauge Bosons

Martin Wiebusch (with W.Bernreuther,P.Gonzalez)

- **2HDM+4 Cross Sections**



- 4th generation of fermions can greatly enhance $\sigma(pp \to \phi)$, $BR(\phi \to VV')$

Higgs boson cross sections

Markus Warsinsky

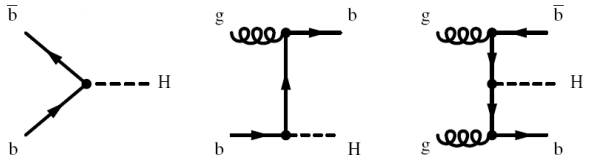
- **Motivation**
  - LHC initially not much sensitivity to Higgs boson(s)
  - But for some parameter space regions, especially MSSM at high $\tan\beta$, early exclusion potential
  - Proper exclusion of a model: also theory uncertainties needed
  - Experimentalists should try to understand, what are the "state of the art" calculations, not only take some tool giving numbers

- **MSSM at large $\tan\beta$: Φbb coupling $\uparrow$**
  - b-associated production becomes important
  - modification of gluon gluon fusion

Higgs boson cross sections

Markus Warsinsky

- bbH-Production

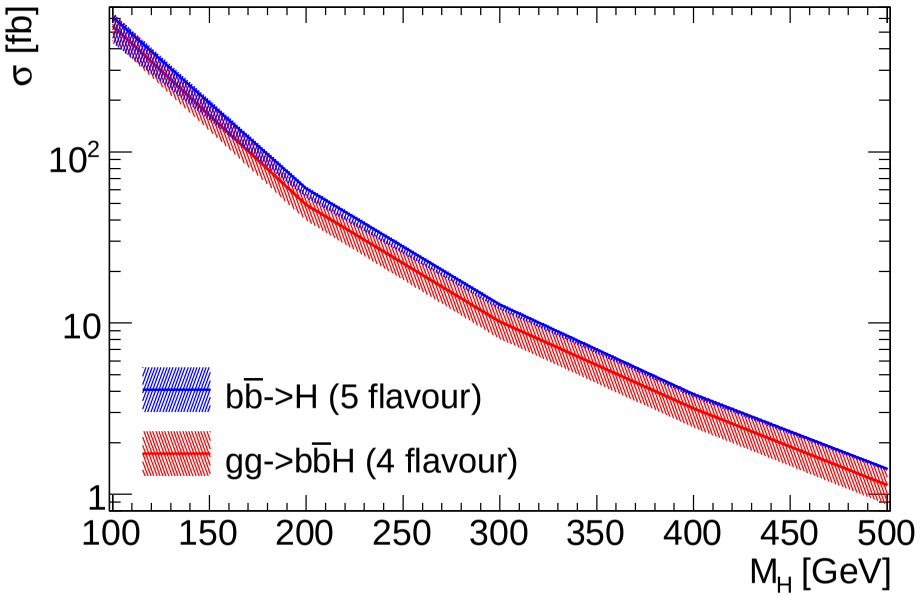


∗ 5 flavour scheme ($b\bar{b} \to H$) (absorbs large logs in pdf, but no details on b-kinematics)

Harlander,Kilgore

∗ 4 flavour scheme ($gg \to b\bar{b}H$) (keeps full mass dependence, but large logs)

Dittmaier,Krämer,Spira;Dawson eal

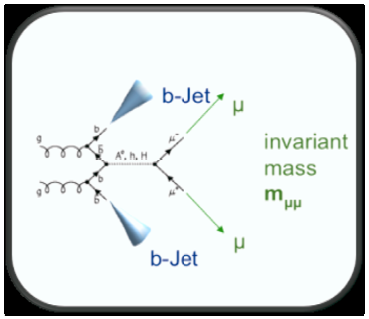


Needs further investigation

Search for neutral MSSM Higgs bosons $h/H/A \to \mu\mu$ @ 1 fb^{-1}

Hendrik Weber (with Anagnostou,Pandoulas,Perieanu,Ostaptschouk)

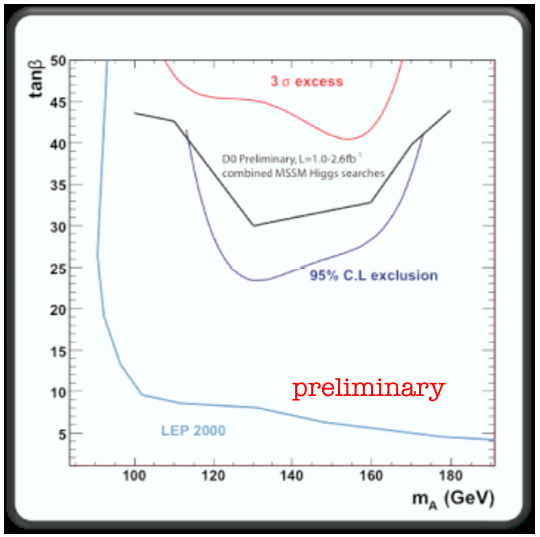
- **Signal**



Signature in the detector

* 2 isolated muons with high p_T
* 2 b-jets with low p_T
* low missing transverse energy

- **Studied backgrounds** Drell-Yan - Irreducible Drell-Yan - top pairs



Potential @ 1 fb^{-1}

* Tevatron exclusion limits significantly improved
* Discovery: needs higher statisitics

The Channel WH, $H \to bb$ at Large Transverse Momenta in ATLAS

Christian Weiser (with G.Piacquadio)

- **Motivation** Low mass Higgs region challenging for discovery $\rightsquigarrow$
  Additional information welcome!
- **Channel WH, $H \to bb$:** very difficult: $S/B = 1.3$ %
- **Idea of J.Butterworth:** select events in which $p_T(H/W) > 200$ GeV $\rightsquigarrow$
  b-quarks in one "fat" jet $\Rightarrow$ strong reduction of bkgs + better acceptance

$$\int \mathcal{L} = 30 \text{ fb}^{-1}\text{: } \frac{S}{\sqrt{B}} = 3.0 \pm 0.3$$

$$S/B \approx 2/3$$

Vector Boson Fusion Higgs in Pythia and Herwig++

Christoph Hackstein (with Krauss,Quast,Zeise,Zeppenfeld)

- **Higgs activities in Karlsruhe**
  - Comparisons of different generators for VBF signal and bkgs, $H \to WW$, $H \to \tau\tau$
  - $Z \to \tau\tau$ bkg modelling w/ hybrid events
  - Full production of boson pair + jet samples for the VBF Higgs group

- **Vector Boson Fusion** 2 hard jets with a big gap between them $\rightsquigarrow$

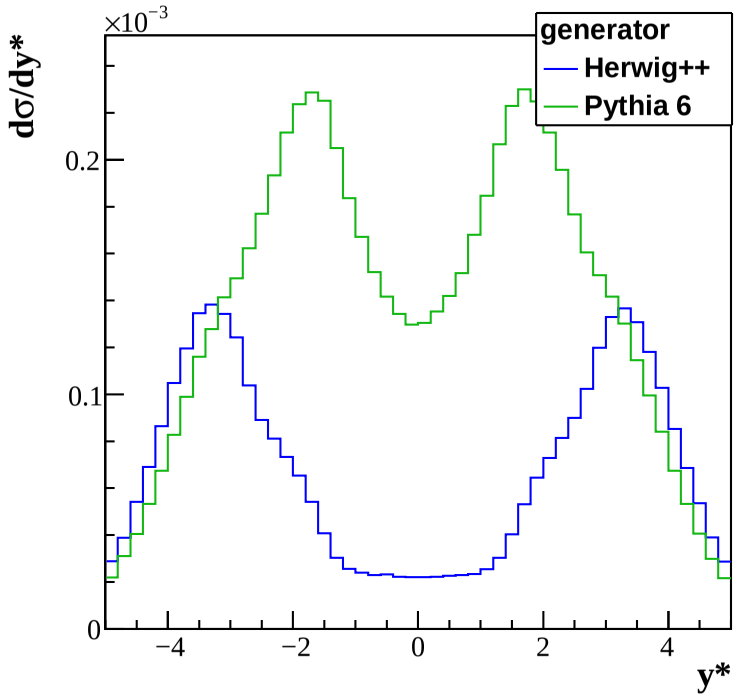
  important to investigate gap after parton shower, hadronization, underlying event

  different generators should be compared for signal and bkgs

Vector Boson Fusion Higgs in Pythia and Herwig++

Christoph Hackstein (with Krauss,Quast,Zeise,Zeppenfeld)

- **Central Jet Veto** veto events with hard central jets plot for $M_H = 120$ GeV



Pythia and Herwig++ differ strongly in the description of jet activity

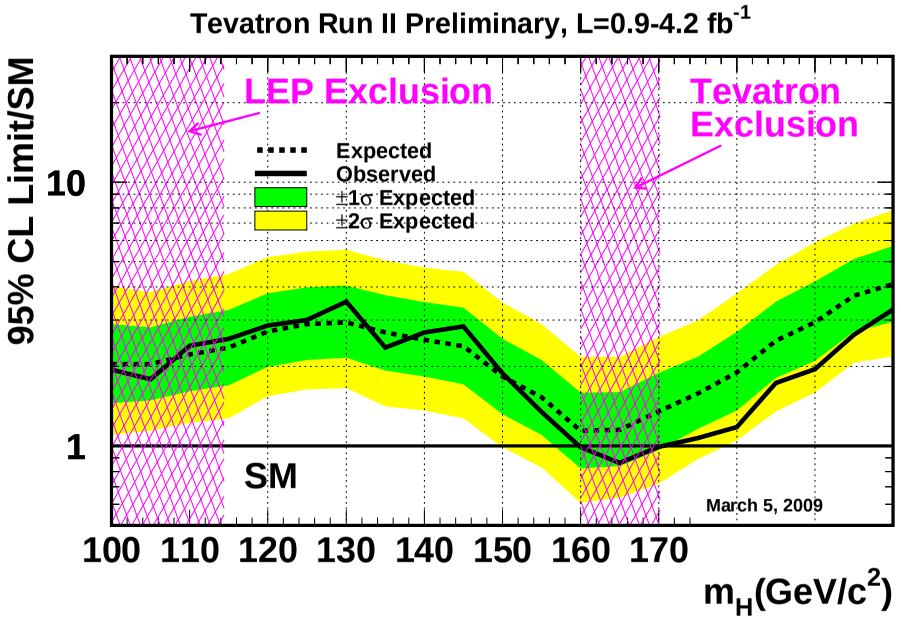
massive partons (top) handled differently by the different shower models

HiggsBounds

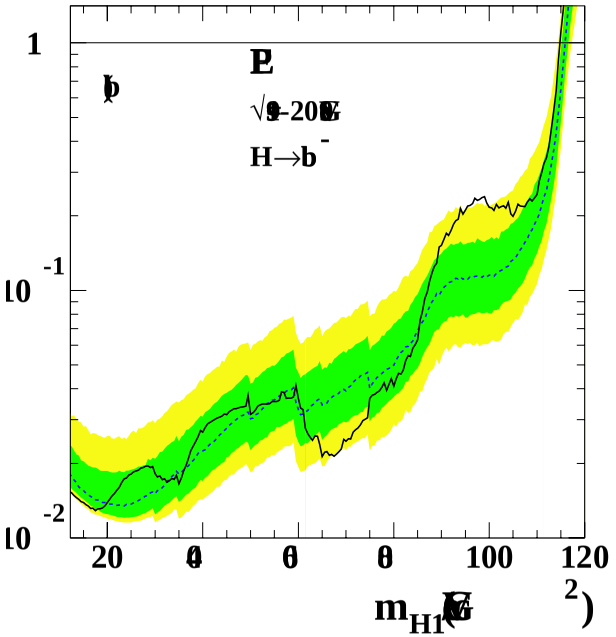
Karina Williams (with Brein,Bechtle,Heinemeyer,Weiglein)

- **Past and present collider Higgs searches:** Restrictions on models.

- **Model-dependent limits**



- **Model-independent limits**



[Eur.Phys.J.C47:547-587,2006]

Which Higgs?

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs

HiggsBounds

Karina Williams (with Brein,Bechtle,Heinemeyer,Weiglein)

- **Is my favourite model excluded?**

- **HiggsBounds (Fortran code):**

  Determines whether a parameter point in a particular model has been excluded at 95% CL by Higgs searches at LEP and Tevatron

$$\frac{(\sigma \times BR)^{\text{model}}}{(\sigma \times BR)^{\text{SM}}} > \frac{(\sigma \times BR)^{\text{obs}}}{(\sigma \times BR)^{\text{SM}}}$$

95 % C.L.

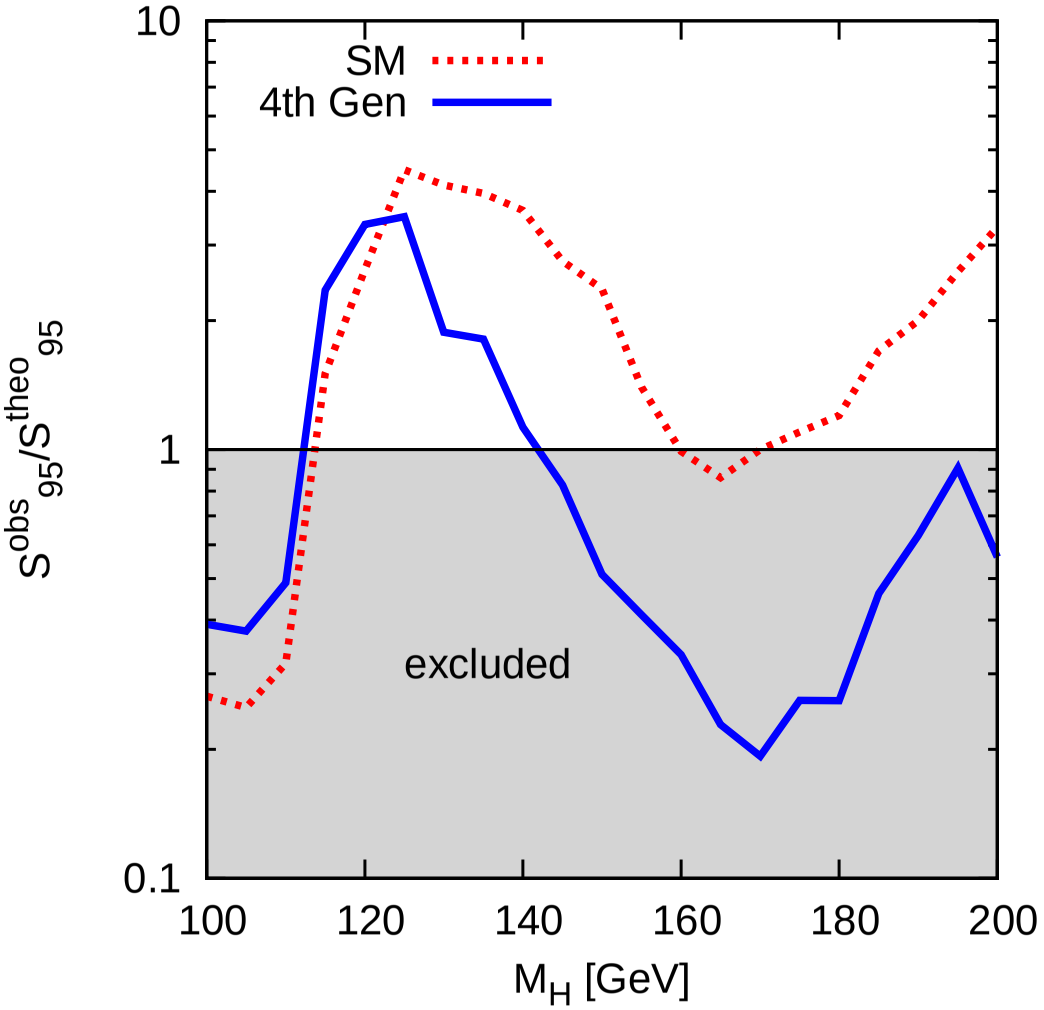
$\Rightarrow$ Model excluded.

- **User provides:** Higgs masses, Γ_{tot}, normalised effective couplings squared, $BR(h_j \to h_i h_i)$ in particular model

- **Webpage:** http://www.ippp.dur.ac.uk/HiggsBounds

Example 1: 4th Generation Model

HiggsBounds 1.2.0 results



Low Energy Theorem in SUSY QCD at 2-loop for $h \to b\bar{b}$

Christoph Reißer (with L.Mihaila)

- **Motivation** $Hb\bar{b}$

  coupling essential for various physical processes windows for new physics through loop effects

- **Effective theory approach** heavy particles "integrated out"

  Full Theory: (SUSY) QCD $\overset{m_i \to \infty}{\longrightarrow}$ Effective Theory: 5-flavor QCD

∗ effective Lagrangian containing Higgs bosons, light fermions, gluons

∗ heavy particle loop effects encoded in coefficients of EFT operators

  QCD: top ◦ SQCD: top, squarks, gluino

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  effective Lagrangian (SM)

  $\mathcal{L}_{\text{eff}} = -\frac{H^0}{v^0} \sum_{i=1}^{5} C_i^0 \mathcal{O}_i'$

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  effective Lagrangian (SM)

  $\mathcal{L}_{\text{eff}} = -\frac{H^0}{v^0} \sum_{i=1}^{5} C_i^0 \mathcal{O}_i'$

- **Decoupling relations** for strong coupling, light quark wave function and mass

- **Renormalization within EFT**

- **Matching effective theory to the full theory**

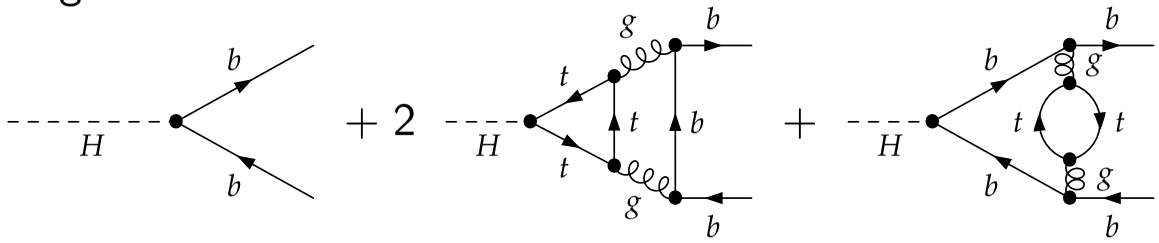
Low Energy Theorem in SUSY QCD at 2-loop for $h \to b\bar{b}$

Christoph Reißer (with L.Mihaila)

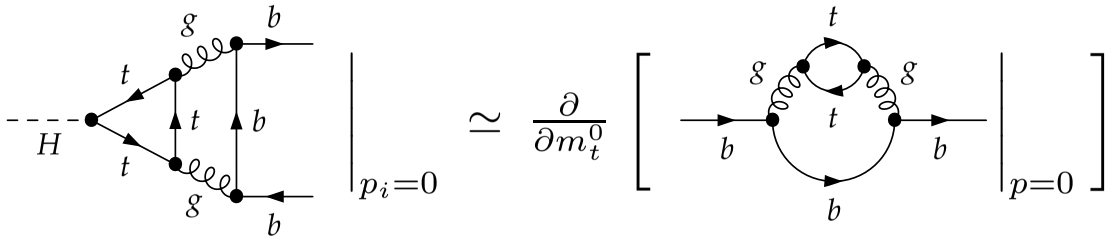
- **Matching effective theory to the full theory**

▷ EFT: tree level diagrams generated by operators $\mathcal{O}_2$, $\mathcal{O}_3$

▷ Full theory diagrams:



- **Low-energy theorem for Higgs interactions** Higgs coupling $\sim$ heavy particle masses



- **Work in progress:** SUSY-QCD 2-loop corrections $\mathcal{O}(1\%)$

Three-loop Corrections to the Mass of the Light Higgs Boson in the MSSM

Philipp Kant (with R.Harlander,L.Mihaila,M.Steinhauser)

- **Motivation** experiment: $\delta M_h \approx 100 - 200$ MeV for light Higgs at LHC
  Need to match this precision!

- **Approach to calculation:**

  ▷ full 3-loop calculation not feasible

  * effective potential approximation ($p^2 = 0$)
  * restrict to t and $\tilde{t}$ loops
  * virtual particles: $t, \tilde{t}, g, \tilde{g}, q, \tilde{q}$

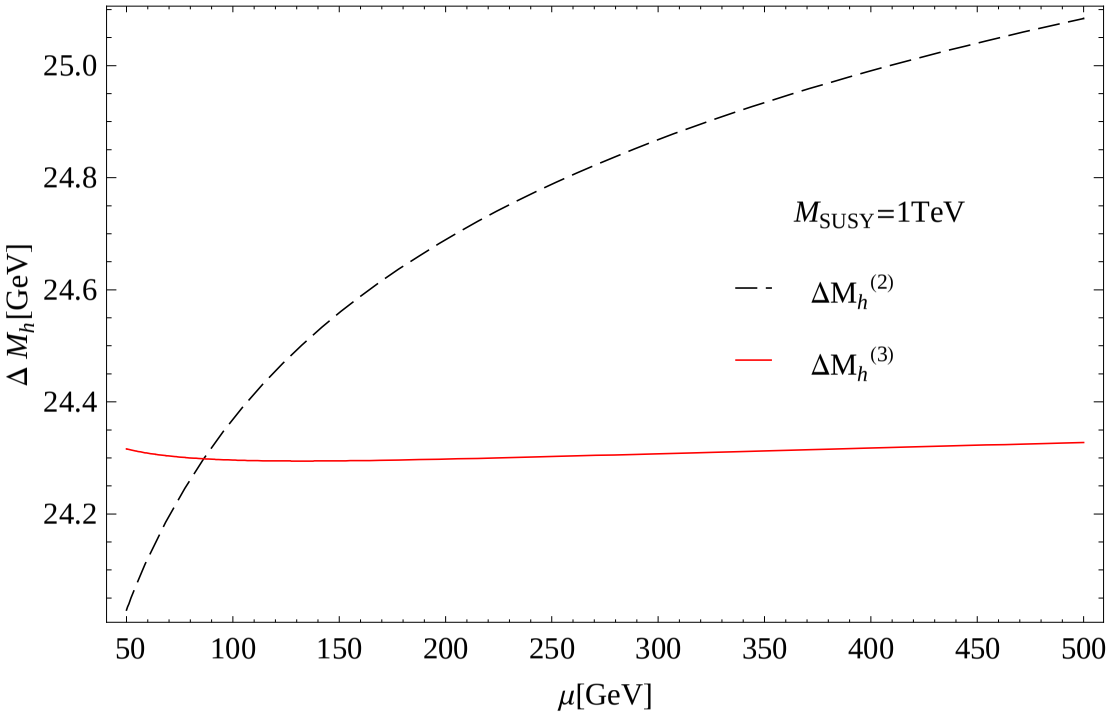
  ▷ Integrals not feasible for arbitrary masses

  * assume fixed hierarchies among superpartner masses
  * asymptotic expansions $\rightsquigarrow$ one-scale integrals

Three-loop Corrections to the Mass of the Light Higgs Boson in the MSSM

Philipp Kant (with R.Harlander,L.Mihaila,M.Steinhauser)

- **Reduced Scale Dependence**



- 3-loop calculation of M_h: effect of $\sim$ 500 MeV $\rightsquigarrow$ cannot be neglected

The Standard Model of Particle Physics

Symmetry group $SU(3) \times SU(2)_L \times U(1)_Y$

I Particle Content ✓

Matter particles:

u	c	t	} Quarks
d	s	b	
ν_e	ν_μ	ν_τ	} Leptons
e	μ	τ	
1.	2.	3.	Family

Interaction particles:

γ	} Bosons
g	
Z	
$W^\pm$	

II Fundamental Forces ✓

Electromagnetic	Photon	
Strong	Gluon	
Weak	W, Z	

III Higgs mechanism Masses of the fundamental particles **?**

The Standard Model of Particle Physics

Symmetry group $SU(3) \times SU(2)_L \times U(1)_Y$

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