UNIVERSITÄT HEIDELBERG
ZUKUNFT
SEIT 1386

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Precision Calculations to Top- and Bottom-Yukawa Couplings within the SM and BSM

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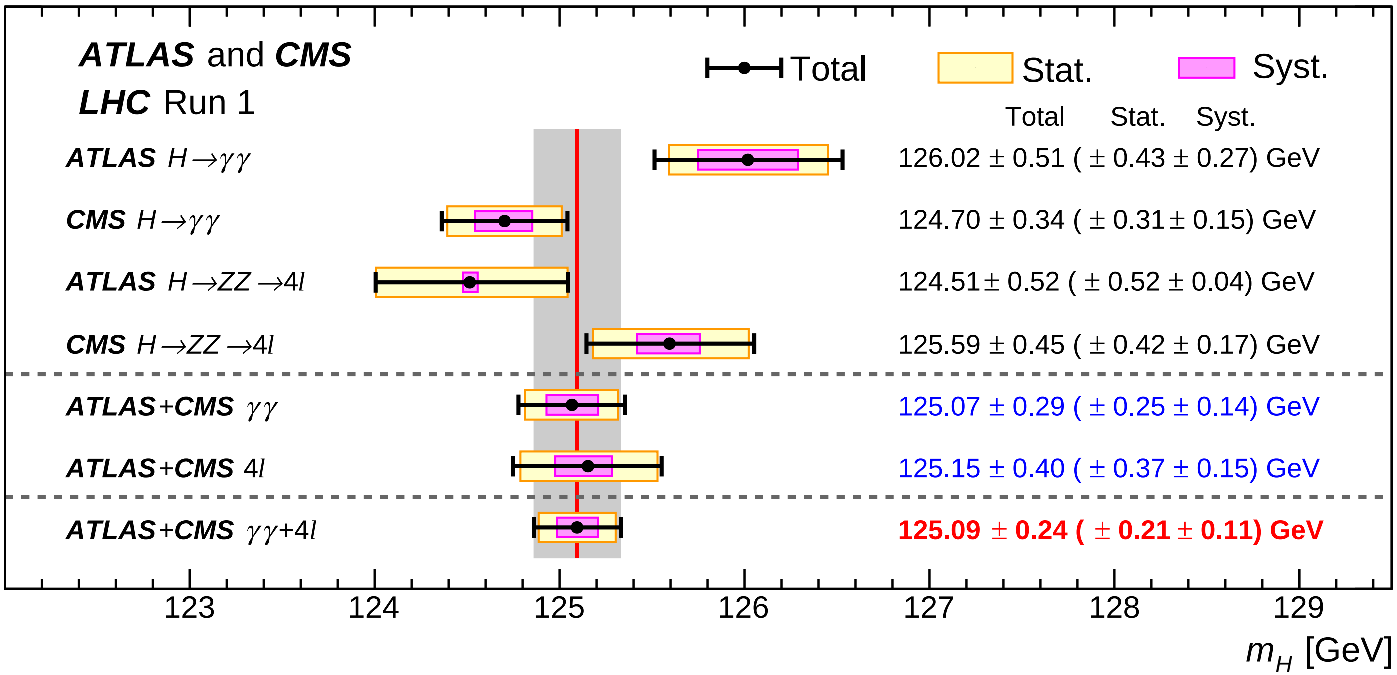
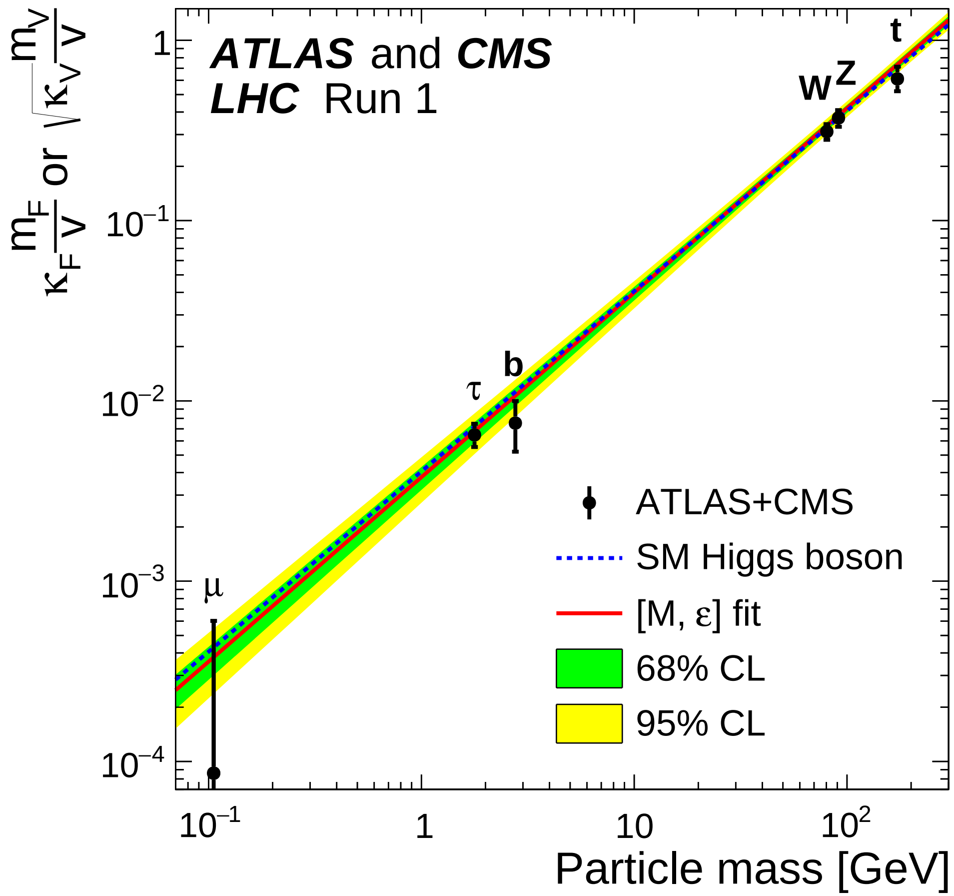
Higgs Properties

- Higgs mass



Higgs Properties

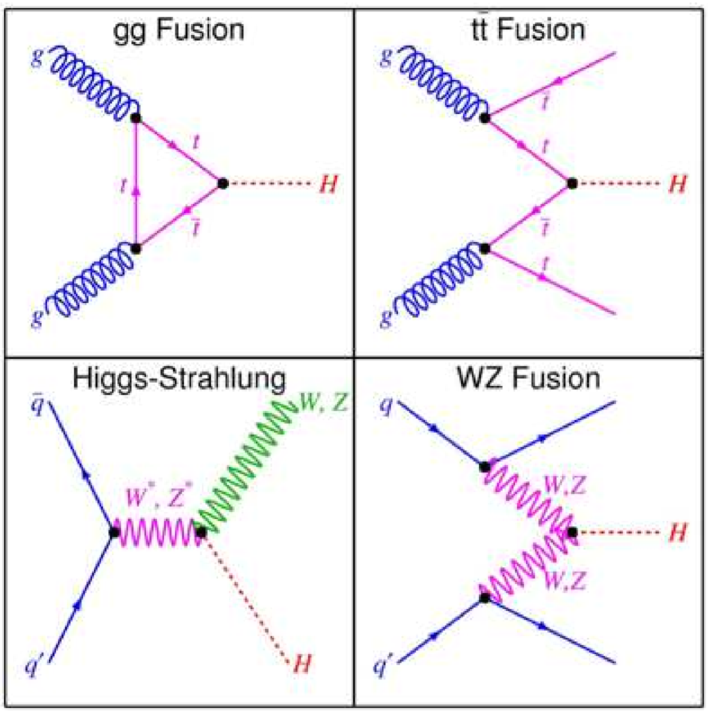
- Higgs couplings

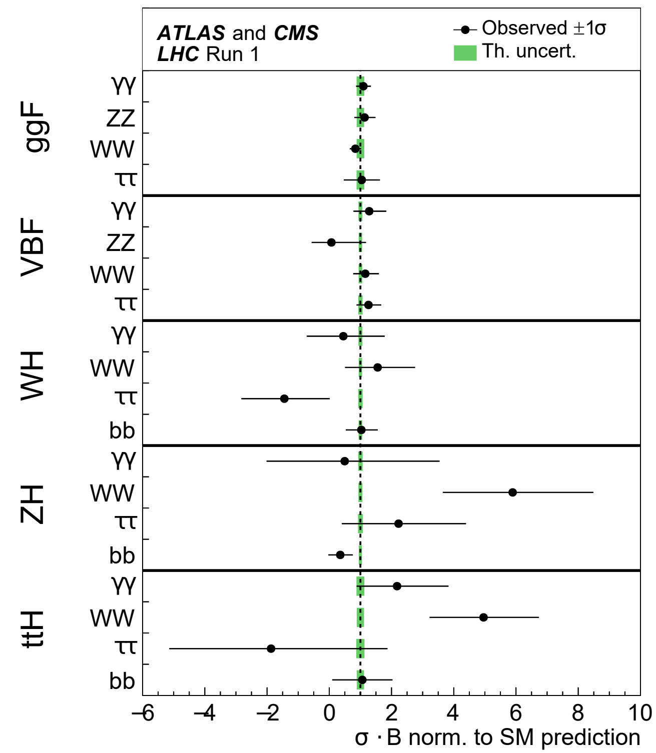


Higgs Properties

- Higgs production and decays

$$\mu = \frac{\sigma \cdot \mathrm{BR(x)}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR(x)}_{\mathrm{SM}}}$$





Higgs Properties

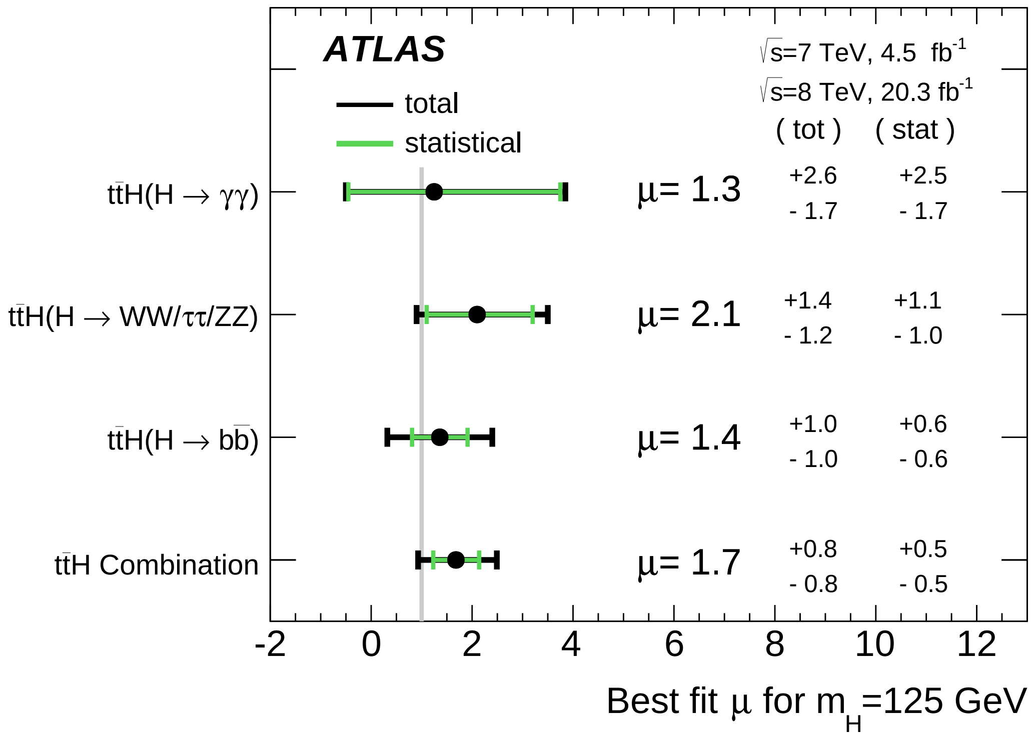
- Conclusions:
  - Excellent agreement between theory and experiment over a wide range of observables
  - New Physics if present manifest at the per-cent level !

α_t at LHC

- Sensitive to New Physics
- Evolution of the Higgs potential
- Determination of the Higgs self-coupling
- Discriminate BSM contribution in **ggH**

α_t at LHC

- indirect: **ggH**; $H \to \gamma\gamma$
- direct: $\sigma(\mathbf{ttH})$; $H \to b\bar{b}$, $H \to \gamma\gamma$, $H \to ZZ$



α_t at LHC

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- indirect: **ggH**; $H \to \gamma\gamma$
- direct: $\sigma(\mathbf{ttH})$; $H \to b\bar{b}$, $H \to \gamma\gamma$, $H \to ZZ$

- Prospects and alternatives for α_t determination:
  - LHC $\sim \mathbf{10}\%$ [Eur. Phys. J C76]
  - sign of α_t from Ht production [Farina, Grojean, Maltoni, Salvioni, Thamm '12]
  - α_t from $pp \to H + \text{jet}$ [Grojean, Salvioni, Schlaffer, Weiler '13]
  - α_t from off-shell Higgs [Azatov, Grojean, Paul, Salvioni '15]
  - HL-LHC or 100 TeV HC $\sim \mathbf{1}\%$ from $t\bar{t}H/t\bar{t}Z$ [Mangano et al '15]

α_t within SM

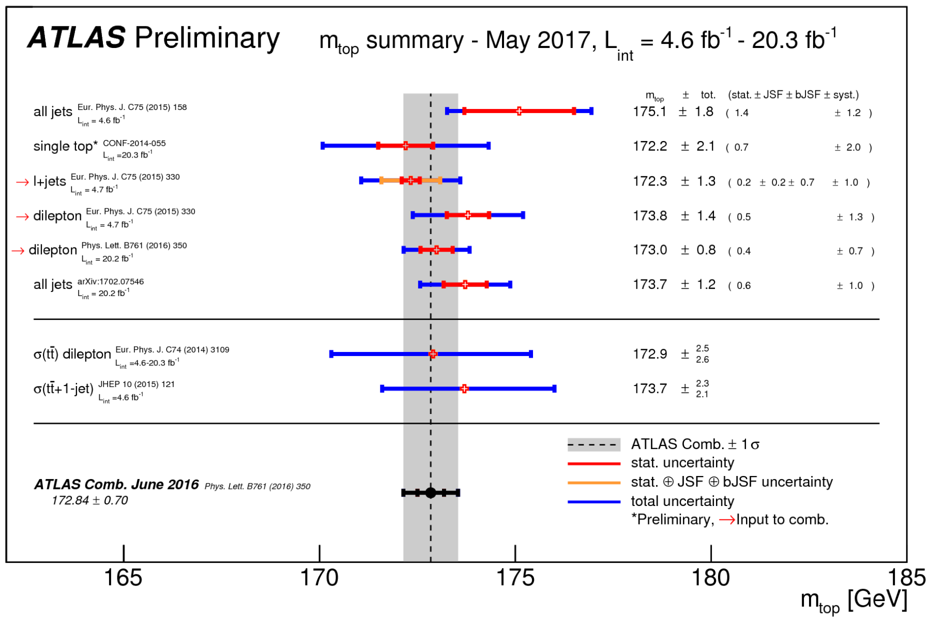
$$\alpha_t(\mu) = 2^{3/2} G_F M_t^2 (1 + \frac{\delta M_t}{M_t} + \Delta r + \delta\beta_{\alpha_t})$$

[Hempfling and Kniehl '94]

- δM_t:
  3-loop QCD[Chetyrkin and Steinhauser'99], [Melnikov and Ritbergen '99];
  4-loop QCD [Marquard et al '15]
  QCD $\times$ EW [Jegerlehner, Kalmykov '03], [Faisst et al '04],[Eiras, Steinhauser '05]
- Δr: $\mathcal{O}(\alpha\alpha_s)$ [Fanchiotti, Kniehl, and Sirlin '92], [Djouadi and Gambino '93]
  $\mathcal{O}(\alpha^2)$ [Buttazzo et al '13]
- 3-loop $\beta\alpha_t$ [Chetyrkin, Zoller '12], [Bednyakov, Pikelner, Velizhanin '12],
  [Herren, L.M., Steinhauser '17]

Top Mass

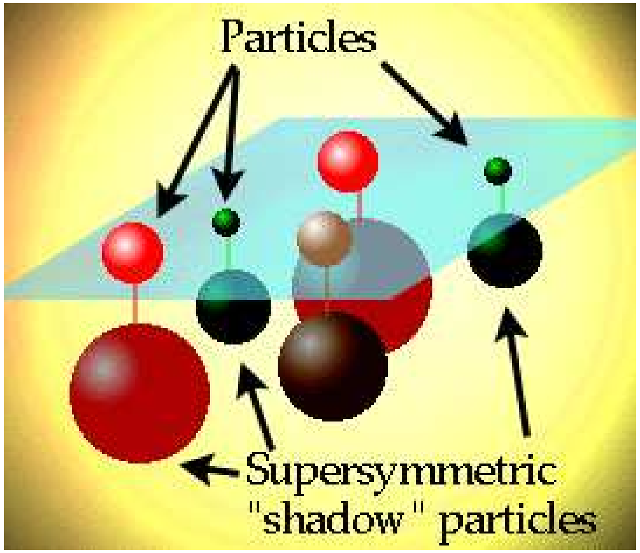
- On-shell top mass measurements



- Running top mass determinations
  - $t\bar{t}$ [Langenfeld, Moch, Uwer '09]
  - $t\bar{t} + j$ [Fuster, Melini, Uwer, Vos '17]
- Relation $\alpha_t \leftrightarrow m_t$ as a probe of EW symmetry breaking

Supersymmetry

- SUSY: symmetry between bosons and fermions



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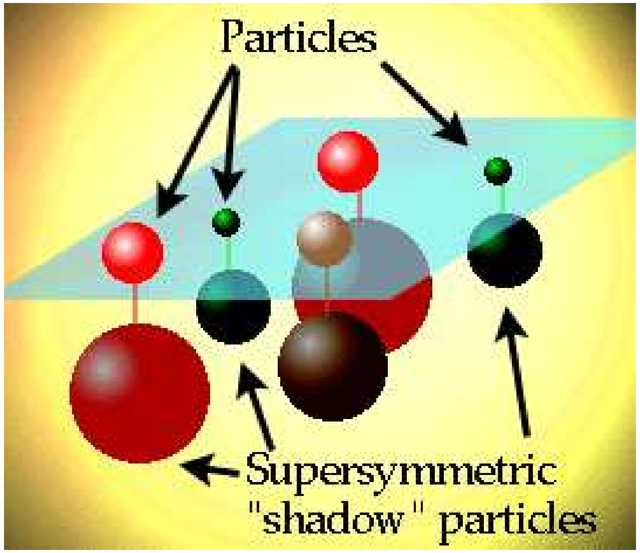

- SUSY must be broken
- $M_{SUSY} \simeq \mathcal{O}(\text{ TeV})$?

Supersymmetry

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- Minimal Supersymmetric extension of SM (MSSM)

	Bosons (spin=0)	Bosons(spin=1)	Fermions
Gauge		gluon W, Z photon	gluino wino, zino photino
Matter	sleptons squarks		leptons quarks
Higgs	Higgses		higgsinos

α_t in the MSSM

- Direct calculation at $\mu \approx M_{\text{SUSY}} \approx 1$ TeV

α_t in the MSSM

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- Direct calculation at $\mu \approx M_{\text{SUSY}} \approx 1$ TeV
  - $\Delta M_{\text{top}}^{\text{MSSM}}$ at 2 loops [S. Martin '04]
    TSIL code [Martin and Robertson '05]

Large logs: $\ln\left(\frac{M_{\text{SUSY}}^2}{M_{\text{top}}^2}\right)$

ΔM_{top}	SM	MSSM ($M_{\text{SUSY}} = 6$ TeV)
1 loop	9.8 GeV	42.3 GeV
2 loops	1.7 GeV	8.2 GeV
3 loops	0.5 GeV	???

To be compared to $\Delta M_{\text{top}}^{\text{exp}} \approx 1$ GeV

α_t in the MSSM

- Direct calculation at $\mu \approx M_{\mathrm{SUSY}} \approx 1$ TeV
- Indirect calculation: resummation of large logs

α_t in the MSSM

- Direct calculation at $\mu \approx M_{\text{SUSY}} \approx 1$ TeV
- Indirect calculation: resummation of large logs
  - SM = effective theory derived from MSSM

$$
\begin{aligned}
\mathcal{L}_{\text{eff}} &= \mathcal{L}_{\text{SM}}^{(6)} + \mathcal{L}_{\text{eff}}^{h} + \ldots\,; \\
\mathcal{L}_{\text{eff}}^{h} &= -\frac{h^{(0)}}{v^{(0)}} \left[C_1^0 \mathcal{O}_1^0 + \sum_{q=u,d,\ldots} \left(C_{2q}^0 \mathcal{O}_{2q}^0 + C_{3q}^0 \mathcal{O}_{3q}^0 \right) + \ldots \right] . \\
\mathcal{O}_1^0 &= \left(G_{\mu,\nu}^a \right)^2 , \\
\mathcal{O}_{2q}^0 &= m_q \bar{q} q \,, \\
\mathcal{O}_{3q}^0 &= \bar{q}(i\not{D} - m_q) q \,.
\end{aligned}
$$

α_t in the MSSM

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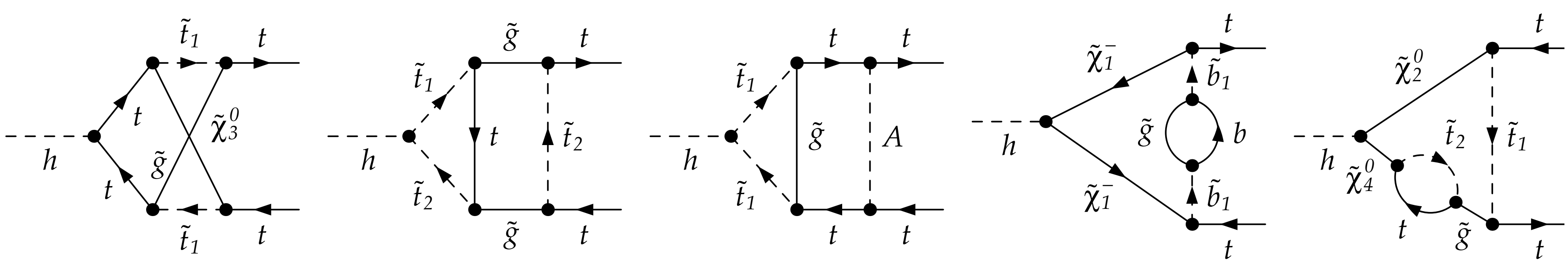
- Direct calculation at $\mu \approx M_{\text{SUSY}} \approx 1$ TeV
- Indirect calculation: resummation of large logs
  - SM = effective theory derived from MSSM

$$\alpha_{\text{t}}^{\text{SM}}(\mu_{\text{dec}}) \quad = \quad \alpha_{\text{t}}^{\text{MSSM}}(\mu_{\text{dec}}) \cdot \zeta_{\alpha_t}(M_{\text{SUSY}}, \mu_{\text{dec}})$$

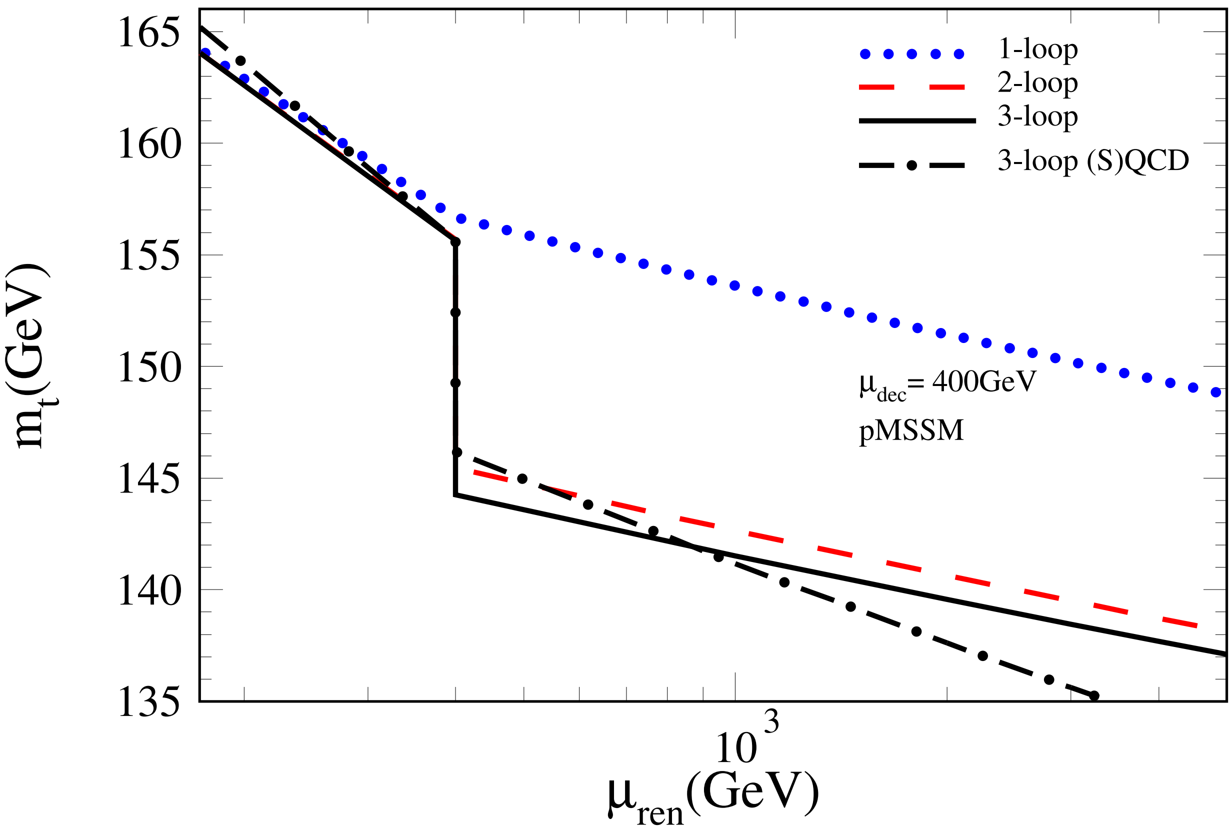
$\zeta_{\alpha_t}(M_{\text{SUSY}}, \mu)$: reduction to 2-loop tadpole MI



[Kunz, L.M., Zerf '14, L.M., Zerf'16]

MSSM Results

pMSSM: $\mu = 2.5$ TeV, $A_t = -4.8$ TeV, $\tan\beta = 10$, $M_A = 1.5$ TeV
$M_{\tilde{g}} = 1$ TeV, $M_Q \simeq M_U \simeq M_D \simeq 2.5$ TeV.



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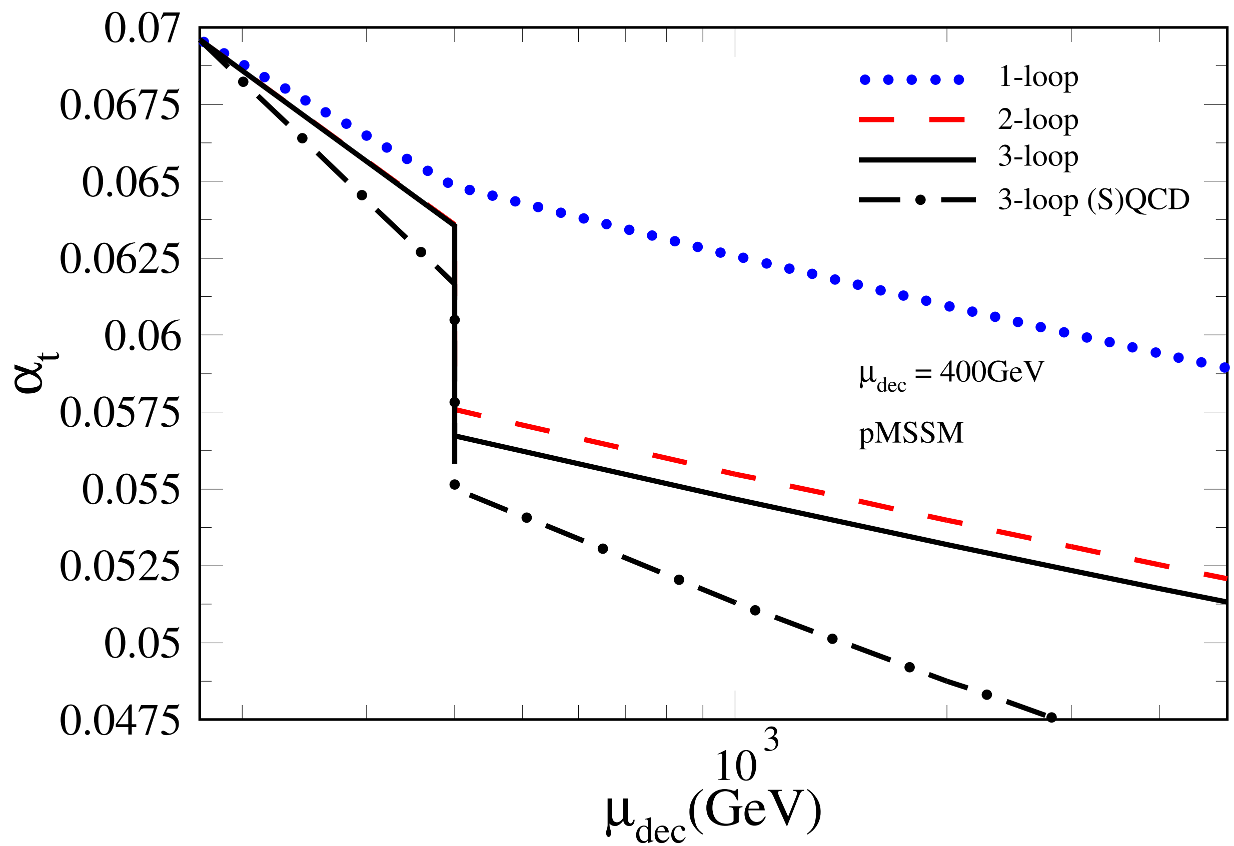

MSSM Results

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- Comparison **SM** vs **MSSM** (pMSSM)

α_t	SM	MSSM
$\alpha_t(\mu = M_t)$	0.070	0.058
$\alpha_t(\mu = 0.4\,\text{TeV})$	0.063	0.056

- Sizeable variation $1\% - 20\%$
- To be compared with the expected LHC precision

α_b at the LHC

- All Higgs branching ratios
- Higgs couplings to down-type fermions
- Search for the New Physics

For $M_H = 125.09$ GeV α_b is derived from $\Gamma(H \to b\bar{b})$

LHC:

- **VBF** $H \to b\bar{b}$
- **VH** $\to b\bar{b}l\nu(ll)(\nu\nu)$

Prospects for α_b determination: $5 - 7\%$

α_b at the LHC

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Theoretical Uncertainties (from [LHC HXSWG 2013])

Partial Width	QCD	Electroweak	Total
$\mathrm{H} \to \mathrm{b\bar{b}/c\bar{c}}$	$\sim 0.1\%$	~ 1–2% for $M_{\mathrm{H}} \lesssim 135\,\mathrm{GeV}$	$\sim 2\%$

α_b at the LHC

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Parametric Uncertainties (from [LHC HXSWG 2013])

Channel	M_{H}[GeV]	Γ[MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t
$\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$	126	2.30	$\pm$ 1. %	$\pm$ 1.1%	$\pm$ 0 %	$<$ 1 %

SM Calculations

- $\mathbf{m}_b^{\overline{\text{MS}}}(m_b) = 4.163 \pm 0.016$ GeV [Kühn et al '09]
- $\Gamma(H \to b\bar{b})$
  - QCD: up to $\mathcal{O}(\alpha_s^4)$ [Gorishnii, Kataev, Larin, and Surguladze '90], [Chetyrkin '96], [Chetyrkin and Steinhauser '97], [Chetyrkin, Kühn and Steinhauser '97], [Harlander and Steinhauser '97],[Baikov, Chetyrkin,Kühn '06]

    first $\mathcal{O}(\alpha_s^5)$ [Liu and Steinhauser '15]

    distributions at $\mathcal{O}(\alpha_s^2)$ [Anastasiou, Herzog, Lazopoulos '12], [Del Duca et al '15]
  - EW: $\mathcal{O}(\alpha)$ [Dabelstein and Hollik '92], [Kniehl '92]
  - QCD $\times$ EW :
    M_t^2-Approximation [Kwiatkowski and Steinhauser '94], [Kniehl and Spira '94], [Chetyrkin, Kniehl, and Steinhauser '97]
    complete QCD $\times$ EW at $\mathcal{O}(\alpha\alpha_s)$ [L.M., Schmidt and Steinhauser '15]

Framework

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- Perturbative Expansion

$$\Gamma(H \to b\bar{b}) \quad = \quad \Gamma^{(0)} \left(1 + \Delta^{(\alpha_s)} + \Delta^{(\alpha)} + \Delta^{(\alpha\alpha_s)} + \ldots\right) \quad \text{with}$$

$$\Gamma^{(0)} \quad = \quad \frac{N_c \alpha m_b^2 M_H}{8 s_W^2 M_W^2} \left(\sqrt{1 - 4m_b^2/M_H^2}\right)^3$$

- Optical Theorem

$$\Gamma(H \to b\bar{b}) \quad = \quad \frac{1}{M_H} \mathrm{Im}\left[\Sigma_H(q^2 = M_H^2 + i\epsilon)\right]$$

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  - Exact 1-loop calculation available [Dabelstein and Hollik '92], [Kniehl '92]
  - $\mathcal{O}(\alpha\alpha_s)$: asymptotic expansions

    Mass scales: $q^2 = M_H^2;\, M_H,\, M_Z,\, M_W,\, M_t$

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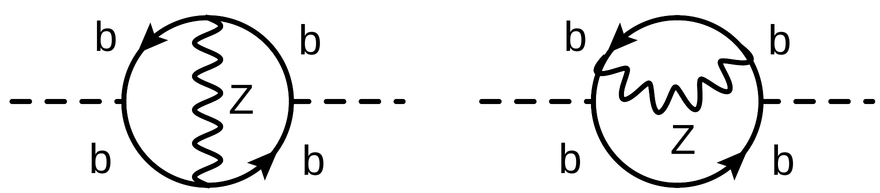
Z-diagrams:



Evaluated for: $q^2 \ll M_Z^2$

Physical limit $q^2 = M_H^2$ obtained via Padé Approximation

Framework

- Optical Theorem

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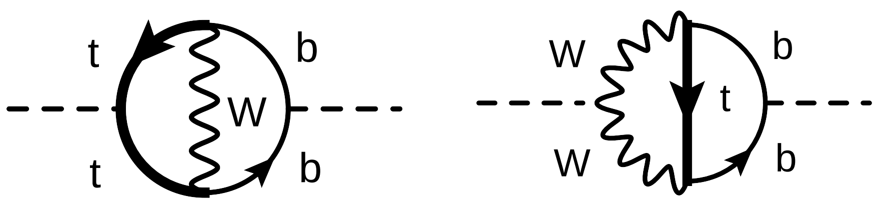
Top- diagrams:



Evaluated for:

$$(A) \qquad M_H^2 \ll 4M_W^2 \ll 4M_t^2\,,$$

$$(B) \qquad M_H^2 \ll 4M_W^2 \approx 4M_t^2\,.$$

SM Results for $\Gamma(H \to b\bar{b})$

	$\Delta^{(\alpha_s)}$	$\Delta^{(\alpha_s^2)}$	$\Delta^{(\alpha_s^3)}$	$\Delta^{(\alpha_s^4)}$
QCD	0.2040	0.0378	0.0020	-0.0014
	$\Delta^{(\mathrm{QED})}$	$\Delta^{(\mathrm{QED},\alpha_s)}$		
QED/QCD	0.0011	0.0001		
	$\Delta^{(\mathrm{weak})}$	$\Delta^{(\mathrm{weak},\alpha_s)}$	$\Delta^{(\mathrm{weak},Z)}$	$\Delta^{(\mathrm{weak},\alpha_s,Z)}$
weak/QCD	-0.0100	-0.0029	-0.0097	-0.0020

- M_t^2-Approximation provides less than 20 % of $\Delta^{(\mathrm{weak},\alpha_s)}$
- Non-factorisable effects

$$\begin{aligned} \Delta^{(\alpha\alpha_s,\mathrm{non-fact.})} &= \Delta^{(\alpha\alpha_s)} - \Delta^{(\alpha)}\Delta^{(\alpha_s)} \\ &= -0.000831(\approx 30\%) \end{aligned}$$

$H \to b\bar{b}$ in the MSSM

1-loop: [Hall, Rattazzi, Sarid '94], [Hempfling '94], ...,

- resummation of the $\tan\beta$-enhanced contributions $\alpha_s^n \tan\beta$
  [Carena et al '00], [Guash, Hafliger, Spira 03], [Dawson et al '11]
- residual theoretical uncertainty $\delta\Gamma(h \to b\bar{b})|_{1-\mathrm{loop}}$ up to 30%

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2-loops: [Noth and Spira '08, '10], [L.M. and Reisser '10]

- approximation: $M_h \ll M_\text{top},\ M_\text{susy}\ \Rightarrow$ effective $\mathcal{L}$ approach
- MSSM $\to$ THDM $\to$ SM
- residual theoretical uncertainty $\delta\Gamma(h \to b\bar{b})|_{2-\text{loop}}$ up to 5%

$$m_b^\text{MSSM}(\mu) \quad = \quad \frac{m_b^\text{SM}(\mu)}{\zeta_{m_b}(\alpha_s, M_\text{SUSY}, m_t, \mu)}$$

$$\zeta_{m_b} = 1 + \delta\zeta_{m_b}^{\tan\beta} + \delta\zeta_{m_b}^\text{rest}\,, \qquad \delta\zeta_{m_b}^{\tan\beta} = 1 + \sum_n \alpha_s^n (A_b - \mu_\text{SUSY}\tan\beta) C_n$$

Conclusions

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- Higgs couplings an essential tool for New Physics searches
- Precise determination of M_h and M_{top} essential for BSM searches