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Precision Calculations of α_t- and α_b within SM and MSSM

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Top-Yukawa Coupling

Motivation

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

α_t at LHC

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

$M_H = 125.09$ GeV	Significance	Reference
ATLAS(125.35 GeV)	2.5 σ	[arXiv:1507.04548]
CMS(125.6 GeV)	3.4 σ	JHEP1409(2014)087

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- Significance $\sim 8.2\sigma$ expected for 3000 fb^{-1}(Run II) ATLAS-CONF-2015-044
- Prospects for α_t determination:
  – LHC $\sim \mathbf{10}\%$ [arXiv:1507.04548]
  – HL-LHC or 100 TeV HC $\sim \mathbf{1}\%$ [arXiv:1507.08169]

α_t within SM

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

[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]
- $\beta\alpha_t$ 3-loop: [Chetyrkin,Zoller '12], [Bednyakov, Pikelner, Velizhanin '12]

SM Results

α_t	NLO	NNLO	N^3LO
QCD	-10%	-2%	-0.7%
EW/QCD	-0.5%	-0.1%	–

$$\begin{aligned} \alpha_t(M_t) &= 0.070 \\ \alpha_t(1\,\text{TeV}) &= 0.054 \end{aligned}$$

α_t in the MSSM

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

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  - $m_{\rm top}^{\rm MSSM}(\mu)/M_{\rm top}^{\rm OS}$ at 2 loops [S. Martin '04]
    TSIL code [Martin and Robertson '05]

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

$\Delta M_{\rm top}$	SM	MSSM ($M_{\rm SUSY} = 6$ 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 $\Delta M_{\rm top}^{\rm exp} \approx 1$ GeV

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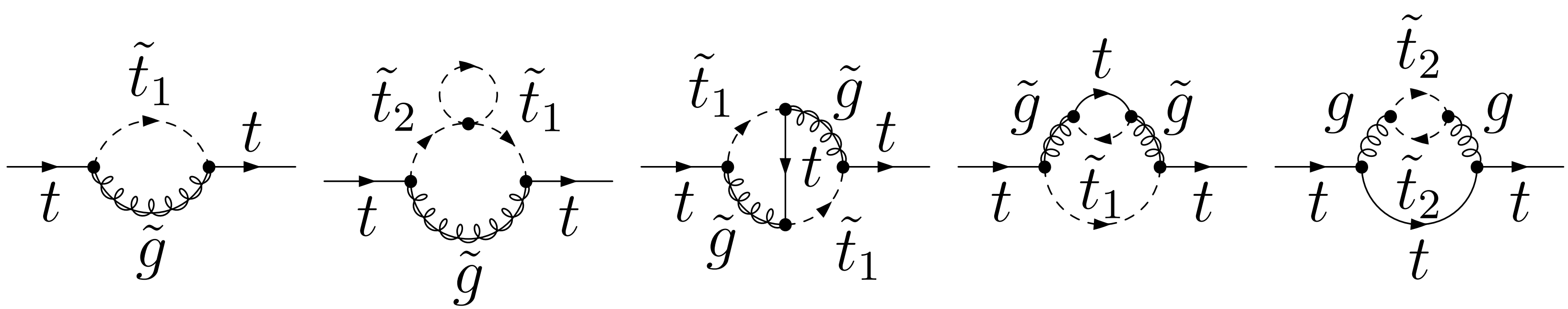
- Indirect calculation: resummation of large logs
  - SM = effective theory derived from MSSM

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

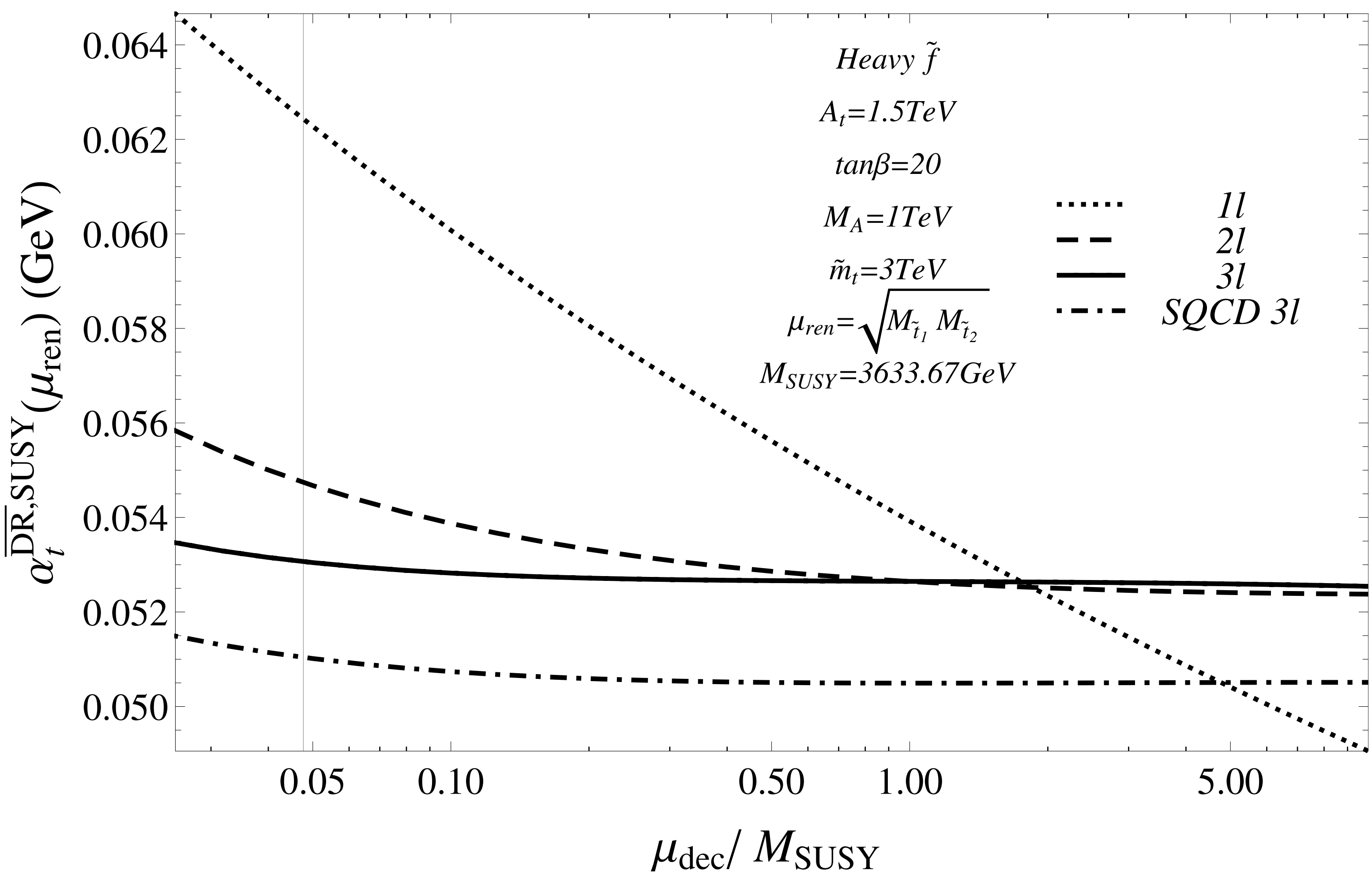
$\zeta_{\alpha_t}(M_{\rm SUSY}, \mu)$: reduction to 2-loop tadpole MI



α_t in the MSSM

- Direct calculation at $\mu \approx M_{\rm SUSY} \approx 1$ TeV
- Indirect calculation: resummation of large logs
  1. $\alpha_t(M_t)$ in SM with max. precision
  2. $\alpha_t(\mu)$ in SM with 3-loop RGE
  3. $\alpha_t(\mu_{\rm dec})$ in MSSM via ζ_{α_t} at 2-loops
  4. $\alpha_t(\mu)$ in MSSM via 3-loop RGE

MSSM Results



MSSM Results

- Comparison **SM** vs **MSSM** (Heavy $\tilde{f}$)

α_t	SM	MSSM
$\alpha_t(\mu = M_t)$	0.070	0.058
$\alpha_t(\mu = 1\,\text{TeV})$	0.054	0.056

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

Bottom-Yukawa Coupling

Motivation

- All Higgs braching 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** $\to b\bar{b}l\nu(ll)(\nu\nu)$

$M_H = 125.09$ GeV	Significance
ATLAS	$1.4\ \sigma$
CMS	$2.1\ \sigma$

Significance $\gtrsim 3\sigma$ expected for $300\,\text{fb}^{-1}$(Run II)
Prospects for α_b determination: $5 - 7\%$

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Theoretical Uncertainties (from [LHC HXSWG 2011])

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

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Parametric Uncertainties (from [LHC HXSWG 2013])

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

SM Calculations

- $\mathbf{m}_b^{\overline{\mathrm{MS}}}(m_b) = 4.163 \pm 0.016$ 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]

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 $\delta\Gamma(h \to b\bar{b})|_{1-\text{loop}}$ up to 30%

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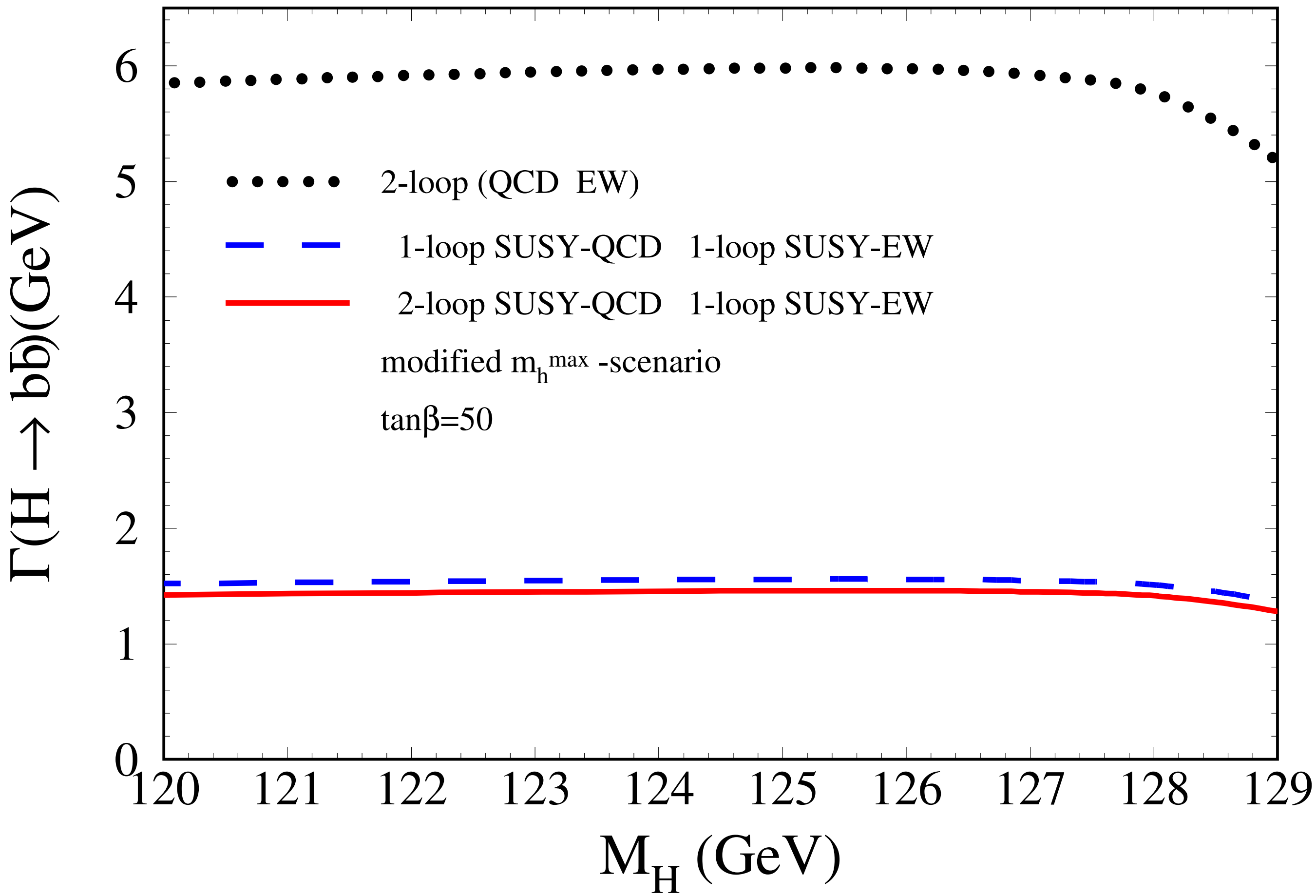
2-loops: [Noth and Spira '08, '10], [L.M. and Reisser '10]

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

MSSM Results

Input: $A_b = 2.5$ TeV, $\tan\beta = 50$, $A_t = 1.5$ TeV, $M_{\mathrm{SUSY}} = 1$ TeV, $m_{\tilde{t}} = 350$ GeV



Summary

- Yukawa couplings to the 3rd generation quarks in the reach of the LHC
- SM vs BSM predictions can be tested with precision measurements from LHC
- Precision required both in theory and experiment