The Higgs p_T as a probe to new physics.

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for the ϕ^*-working group

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Context and Introduction

Chapter 3: ϕ^* distributions for BSM searches

Is ϕ^* more discriminatory of new physics than Higgs p_T?

The set-up

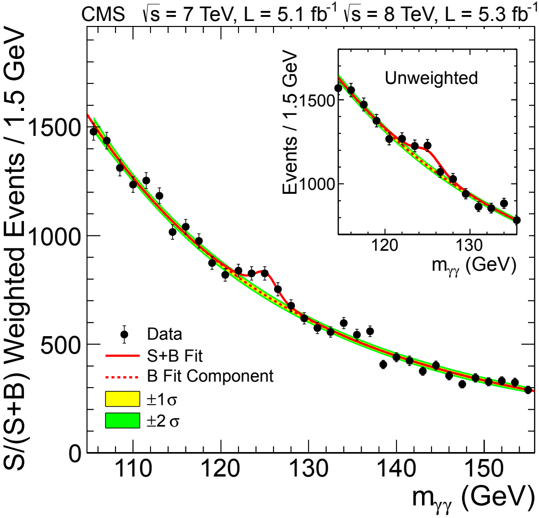
1. Pick your favourite Higgs+1 jet process: $gg \to hg$
2. Add loops from your favourite BSM model: MSSM
3. Pick your favourite MSSM scenario: `lightstop`
4. Study mass effects from BSM loops on the p_T distribution
5. Repeat for ϕ^*

For results see Matias's talk!

Outline

1. Why p_T spectrum?
2. Higgs+1 Jet in the SM
3. Higgs+1 Jet in the MSSM
4. Numerical Results
5. Summary

4th July 2012: Higgs discovery completes the Standard Model?



Open Questions

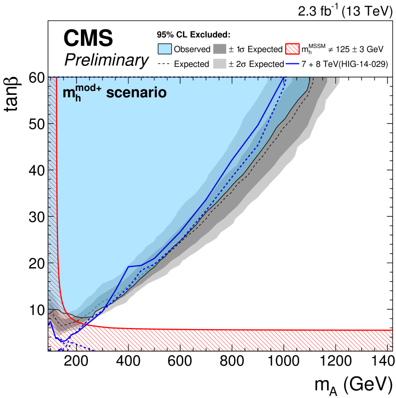
- Unification of gauge couplings?
- Baryon Asymmetry:
  $\Delta N_B - \Delta N_{\bar{B}} \approx 10^9$
  → missing CP violation
- Dark matter
  → stable, weakly interacting,
  $m_{DM} \approx 100$ GeV
- "Unnatural" Higgs mass
- Tiny neutrino masses
- Quantum theory of gravity
- etc etc ...

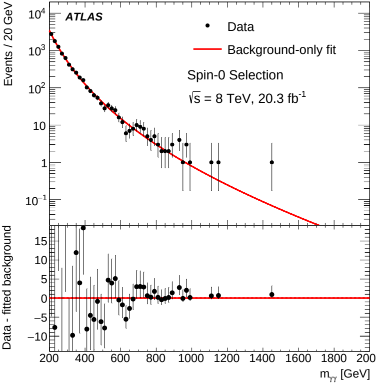
"Frankly, I even find it hard to believe some of the things I've been coming up with."

Searches for new physics

Direct Discovery: Search for new resonances

→ Many blanks and some false leads so far...

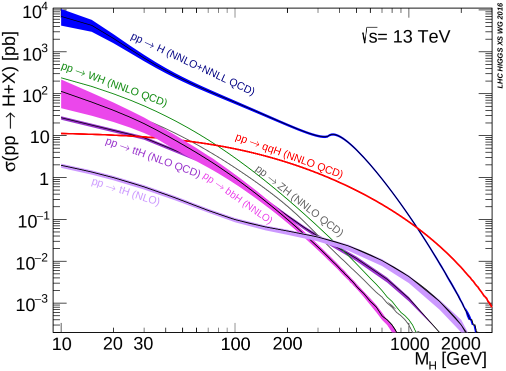




Searches for new physics

Indirect Discovery: Look for deviations from SM predictions in known processes

- Largest contribution to SM Higgs production comes from gluon fusion
- Coupling of gluon to Higgs mediated predominantly by a top loop
- Gluon fusion rate can be altered by modified top Yukawa coupling and/or new coloured/scalar particles



Testing nature of Higgs-gluon interaction and its precise measurement can reveal BSM dynamics

Searches for new physics: Why p_T spectrum?

- Successful EWBG requires new states to generate sizeable potential
- Typically, the states are scalar tops or composite top partners
  - heavy resonances with same quantum no. as top
  - couple strongly to Higgs
- essential to raise Higgs mass (m_h) to "acceptable" levels
- Contributions of new heavy loops ($m_h^2/4m_{\text{loop}}^2 \ll 1$) described by effective gluon-gluon-Higgs interaction:

$$\mathcal{L}_{\text{eff}} = c_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} h$$

$\rightarrow c_g$ quantifies size of interaction, $c_g = 0 \implies$ SM

- Modified Yukawa coupling due to top partners effectively scaled into κ_t
  $\rightarrow \kappa_t = 1 \implies$ SM
- Inclusive gluon fusion cross section cannot disentangle effects of κ_t, c_g

$$\frac{\sigma_{\text{incl}}(\kappa_t, c_g)}{\sigma_{\text{incl}}^{\text{SM}}} \approx (\kappa_t + c_g)^2$$

New physics models: Why p_T spectrum?

Minimal Composite Higgs Model (MCHM)[1]

- In MCHMs, electroweak symmetry is broken dynamically by a strong interaction → based on coset $SO(5)/SO(4)$
- Higgs arises as a pseudo-Nambu-Goldstone boson of the broken symmetry → explains the Higgs mass
- Strong sector contains fermionic resonances which
  - contribute to gluon fusion loop diagram
  - mix with SM fermions and modify top Yukawa coupling
- Contributions to the sum $\kappa_t + c_g$ cancel exactly in a broad class of MCHM:

$$\kappa_t + c_g \approx f_g(\xi),\ \xi \equiv v^2/f^2$$

f is the scale of breaking of global symmetry

Gluon fusion XS is independent of the mass spectrum of new fermionic resonances

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[1] More details in [Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant '14], [Grojean, Salvioni, Schlaffer, Weiler '14] ,[Schlaffer '15]

New physics models: Why p_T spectrum?

Minimal Supersymmetric Standard Model (MSSM)[1]

- In SUSY, the cancellation between the effects of the modification to the gluon-Higgs vertex takes place less generically.
- Assuming MSSM is in decoupling limit, inclusive signal strength is

$$\frac{\Gamma(gg \to h)}{\Gamma(gg \to h)_{\mathrm{SM}}} = (1 + \Delta_t)^2$$

where

$$\Delta_t \approx \frac{m_t^2}{4} \left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{(A_t - \mu / \tan\beta)^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right) \tag{1}$$

- For large values of triliniear coupling of Higgs to the stops A_t, deviations from SM value vanish
- A_t dependent parts of the production cross section respond differently to boosts of Higgs than A_t independent ones

Boosted regime breaks degeneracy

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[1] For a detailed study see:
[Brein Hollik '03], [Langenegger, Spira, Starodumov, Trueb '06],[Bagnaschi, Degrassi, Slavich, Vicini '12], [Harlander, Mantler, Wiesemann '14], [Mantler, Wiesemann '15]

Why p_T spectrum?

Effective description[1]

- Non-trivial structure of Higgs-gluon vertex resolved by introducing scale of large p_T of Higgs → Recoil the Higgs against a jet eg, a gluon
- Higgs p_T contains more information than total cross section:
  - richer kinematical structure
  - shape and maximum and normalization can show deviations from SM
  - allows for refined cuts
- Allowing for $c_g \neq 0$ and $\kappa_t \neq 1$ the differential cross section normalized to SM given by

$$\frac{\sigma(p_T^{\text{cut}})}{\sigma^{\text{SM}}(p_T^{\text{cut}})} = (\kappa_t + c_g)^2 + \delta(p_T^{\text{cut}})\ \kappa_t\ c_g + \epsilon(p_T^{\text{cut}})\ c_g^2$$

with $\sigma(p_T^{\text{cut}}) = \int_{p_T > p_T^{\text{cut}}} dp_T \, \frac{d\sigma}{dp_T}$

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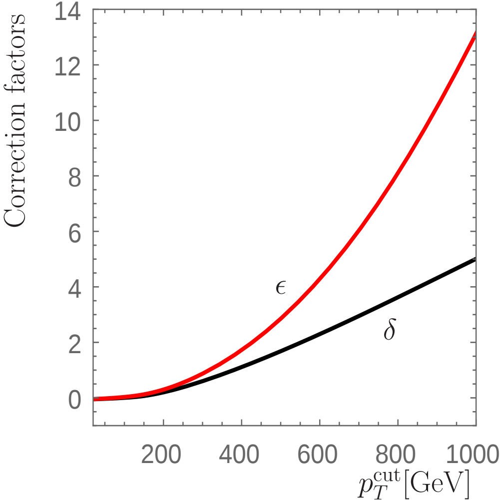
[1] Inclusion of dim 6 operators: [Grojean, Salvioni, Schlaffer, Weiler '14], [Azatov, Paul '14], [Langenegger, Spira, Stebel '15], dim 8 operators: [Harlander, Neumann '13], [Dawson, Zeng '14], High p_T BSM effects in EFT: [Grazzini, Ilnicka, Spira, Wiesemann '16]

Why p_T spectrum?

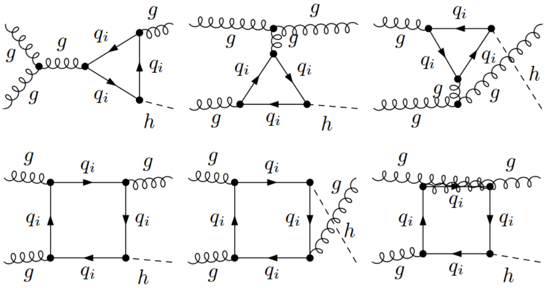
- For small p_T^{cut}, δ, ϵ are small
  - modify the cross section by a few percent
  - less than the uncertainty accepted in inclusive Higgs cross section
- δ, ϵ grow significantly as p_T^{cut} [Harlander, Liebler, Mantler '16], [Grojean et al. '14]
- New physics should show up at high p_T



Measuing the p_T distribution breaks the degeneracy of the inclusive rate and disentangles c_g, κ_t

Higgs+1 jet in the SM

LO contributions to $gg \to gh$ [figures: Brein, Hollik '03]

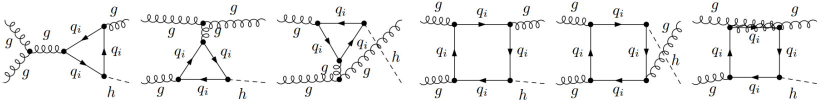


- Higgs production at finite momenta requires additional radiation (g or q)
- Partonic subprocesses contributing to $pp \to h + jet$ are:

$$gg \to hg,\ gq \to h\bar{q},\ \bar{q}g \to h\bar{q},\ q\bar{q} \to hg$$

- Actual breakdown of subprocesses depends on p_T, scale choice, PDFs etc
- Gluon initiated subprocesses dominate
  $\Longrightarrow$ focus on $gg \to hg$ (∼50-70% total rate)

Higgs+1 jet in the SM



- **LO** ($\mathcal{O}(\alpha_s^3)$) results known since ~ 1990: Ellis, Hinchliffe, Soldate, van der Bij '88; Baur, Glover '90
- **NLO** ($\mathcal{O}(\alpha_s^4)$) in HTL came ~ late 90s/early 00s: Schmidt '97; de Florian, Grazzini, Kunszt '99; Ravindran, Smith; Van Neerven '02
  - Estimation of $\mathcal{O}(\alpha_s^4)$ with finite top mass effects: Harlander, Neumann, Oezeren, Wiesemann '12; Neumann, Wiesemann '14
- **NNLO** ($\mathcal{O}(\alpha_s^5)$) results more recent: Boughezal, Caola, Melnikov, Petriello, Schulze '13, '15; Chen, Gehrmann, Glover, Jacquier '15
- Resummation of large logs needed at low p_T:
  - **NLL**: Catani et al.'88; Hinchliffe, Novaes '99; Kauffman '91, '92; Balazs et al. '00; Gerger, Qiu '03; Kulesza et al. '04; Gawron,Kwiecinski '04; Watt et al. '04; Lipatov,Zotov '05
  - **NNLL**: de Florian, Grazzini '00; Catani, de Florian, Grazzini '01; Bozzi, Catani, de Florian, Grazzini '03; Becher, Neubert, Wilhelm '12, '13
  - **N^{3}LL**: Li, Zhu '16; Vladimirov '16
- Resummed results matched to fixed order calculations at high p_T to get predictions for whole p_T range

Higgs bosons in the MSSM

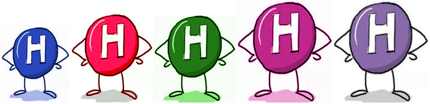
2 Higgs doublets Φ_1 and Φ_2 with $\Phi_i = 1/\sqrt{2}(\phi_i + i\chi_i)$

Physical states

- $\mathcal{CP}$-even: $\phi_1^0, \phi_2^0 \to h, H$
- $\mathcal{CP}$-odd: $\chi_1^0, \chi_2^0 \to A, G$
- charged: $\phi_1^\pm, \phi_2^\pm \to H^\pm, G^\pm$

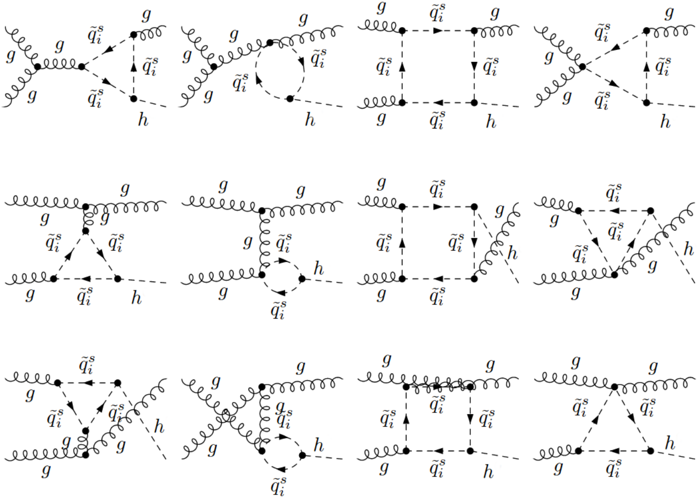
Electroweak Symmetry Breaking → **5 physical Higgs states** $h, H, A, H^\pm$

$$\begin{pmatrix} h \\ H \\ A \\ G \end{pmatrix} = \begin{pmatrix} -s_\alpha & c_\alpha & 0 & 0 \\ c_\alpha & s_\alpha & 0 & 0 \\ 0 & 0 & s_{\beta_n} & c_{\beta_n} \\ 0 & 0 & -c_{\beta_n} & s_{\beta_n} \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ \chi_1^0 \\ \chi_2^0 \end{pmatrix}$$



Higgs+1 jet in the MSSM

LO contributions from squarks to $gg \to gh$ [Brein, Hollik '03]



Higgs+1 jet in the MSSM

- The lightest neutral Higgs h is SM-like in the decoupling limit
- The Higgs+1 jet process is mediated by quarks as well as squarks
  → can lead to potentially large mass effects
- The partonic processes are similar to the SM:
  - gluon fusion $gg \to hg$
  - quark gluon scattering $q(\bar{q})g \to hq(\bar{q})$
  - quark-antiquark annihilation $q\bar{q} \to hg$
- Yukawa couplings of the quarks to the Higgs are different
  → changes overall rate

ϕ		g_u^ϕ	g_d^ϕ	g_V^ϕ
SM	h	1	1	1
MSSM	h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A	$1/\tan\beta$	$\tan\beta$	0

- There are additional super partner loops and additional topologies
  → changes incl. XS and angular distributions

The `lightstop` Scenario

Distributions at LO were plotted using **`MoRe – SusHi`** [sushi.hepforge.org] in conjunction with **`FeynHiggs`** [feynhiggs.de]

`lightstop`:

1. $M_{\text{SUSY}} = 500$ GeV
2. $X_t^{\text{OS}} = 2\ M_{\text{SUSY}}$
3. $|A_t| = |A_b| = |A_\tau| \equiv 1017.5$ GeV
4. $\mu = 350$ GeV
5. $\tan\beta = 20$
6. $M_3 = 1500$ GeV
7. $M_A = 600$ GeV
8. $M_2 = 500$ GeV
9. $M_{\tilde{l}_3} = 1000$ GeV

Variations:

1. $M_{\text{SUSY}} = 600/800$ GeV
2. $X_t^{\text{OS}} = 2\ M_{\text{SUSY}}$
3. $|A_t| = |A_b| = |A_\tau| = X_t + \mu/\tan\beta$
4. $\mu = 350$ GeV
5. $\tan\beta = 20$
6. $M_3 = 1500$ GeV
7. $M_A = 600$ GeV
8. $M_2 = 500$ GeV
9. $M_{\tilde{l}_3} = 1000$ GeV

- Renormalization scales: $\mu_R = \mu_F = M_T/2;\ M_T = \sqrt{m_h^2 + p_T^2}$
- Scale variation: $\{\mu_R, \mu_F\} \in \{M_T/4, M_T/4\}, \{M_T, M_T\}$

The `lightstop` Scenario

Disclaimer:

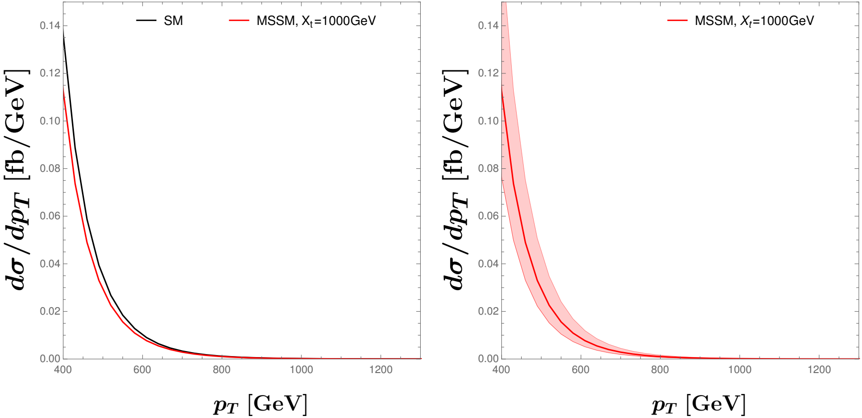
- The **`lightstop`** benchmark points were designed for run I of the LHC in 2013 [Carena et al. '13]
- Bounds on light stops have become tighter
- New MSSM benchmark scenarios compatible with run II are awaited
- Recall eq. (1):

$$\Delta_t = \delta\mathcal{A}_{hgg}/\mathcal{A}_{hgg}^{\mathrm{SM}} \approx \frac{m_t^2}{4m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2)$$

- There is no exact cancellation of stop effects in the total rate
- When $2M_{SUSY} \leq X_t \leq 2.5M_{SUSY}$, the gluon fusion rate is reduced by 10-15 %
- From [Carena et al. '13]: "Reduction similar in magnitude to the ***current*** theoretical uncertainties on the gluon fusion cross section from e.g. the strong coupling constant and parton distribution functions."

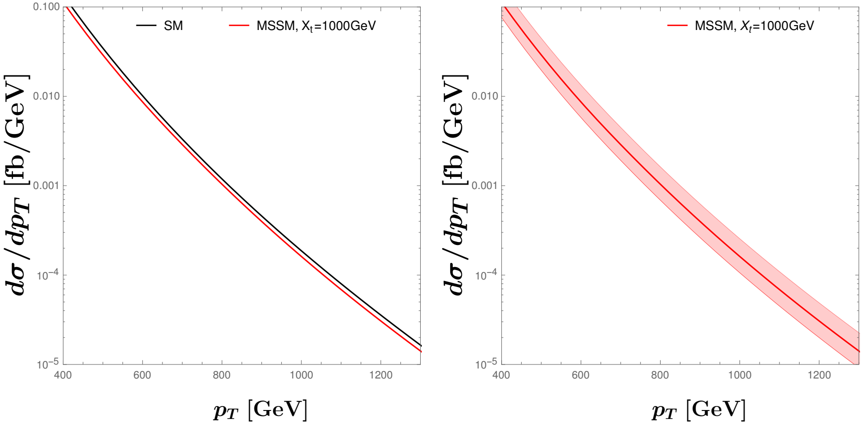
Higgs p_T spectrum in the `lightstop` Scenario

LO differential XS for $gg \to hg$ with massive $t, b, c, \tilde{t}, \tilde{b}$ contributions:



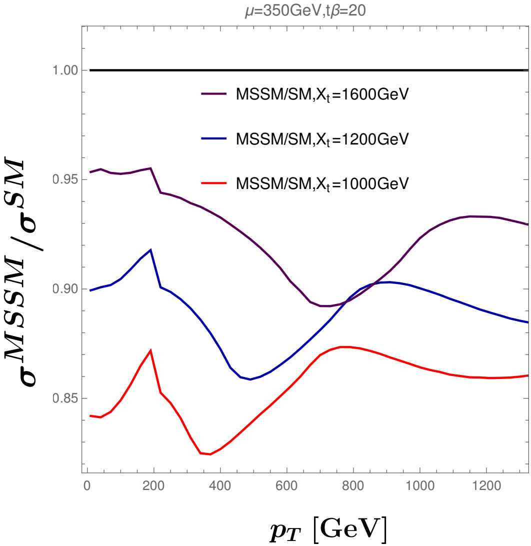
Higgs p_T spectrum in the `lightstop` Scenario

LO differential XS with massive $t, b, c, \tilde{t}, \tilde{b}$ contributions in log scale:



Higgs p_T spectrum in the `lightstop` Scenario

A comparison of MSSM differential XS ($t, b, c, \tilde{t}, \tilde{b}$ in the loops) normalized to the SM (t, b, c) :



Stop masses:

- $m_{\tilde{t}_1} = 625.85\text{GeV}$
  $m_{\tilde{t}_2} = 971.44\text{GeV}$
- $m_{\tilde{t}_1} = 425.07\text{GeV}$
  $m_{\tilde{t}_2} = 771.16\text{GeV}$
- $m_{\tilde{t}_1} = 324.32\text{GeV}$
  $m_{\tilde{t}_2} = 670.44\text{GeV}$

Summary

PROS:

- Mass effects from additional particles in the loop for Higgs+1 jet processes modify the p_T spectrum.
- For the MSSM, we see clear peaks/valleys as the masses of the stops get resolved

CONS:

- Missing higher order calculations contribute significantly to the uncertainties
- Deviations can be smaller than the scale uncertainties
- Exclusion of light squarks in run II $\Longrightarrow$ these deviations would be smaller

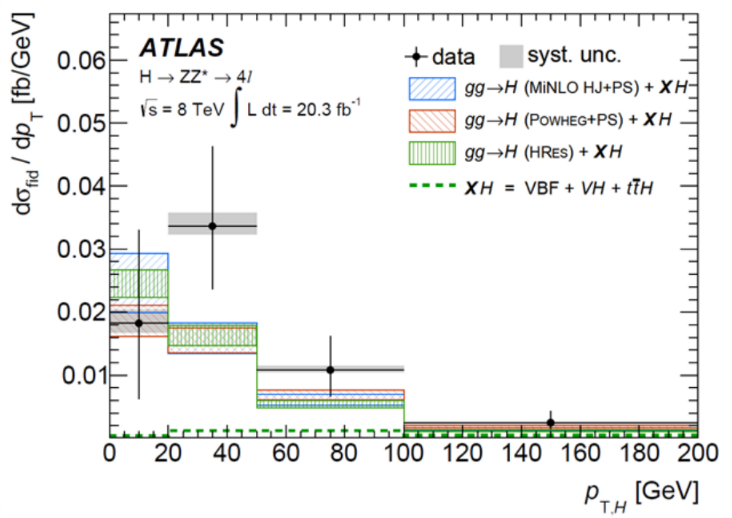
UP NEXT:

- For a study of ϕ^* distributions in the MSSM and a comparison to the p_T spectrum, stay tuned for Matias's talk at 11:30 am today!

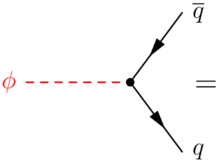
Thank you for your attention!

APPENDIX

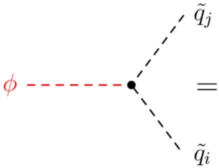
ATLAS results for 8 TeV



Higgs-quark couplings



$= i\frac{m_q}{v} g_q^{\phi}$ and



$= i\frac{m_q^2}{v} g_{\tilde{q},ij}^{\phi}$

$$v = 2m_W/g = 1/\sqrt{\sqrt{2}G_F} = \sqrt{v_d^2 + v_u^2}.$$

ϕ		g_u^{ϕ}	g_d^{ϕ}	g_V^{ϕ}
SM	h	1	1	1
MSSM	h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A	$1/\tan\beta$	$\tan\beta$	0

Higgs-squark couplings

$$g^{\phi}_{\tilde{q},ij} = g^{\phi,\mathrm{EW}}_{\tilde{q},ij} + g^{\phi,\mu}_{\tilde{q},ij} + g^{\phi,\alpha}_{\tilde{q},ij}$$

$$\begin{aligned}
g^{h,\mathrm{EW}}_{\tilde{t},11} &= c^{\mathrm{EW}}_{\tilde{t},1} c^2_{\theta_{\tilde{t}}} + c^{\mathrm{EW}}_{\tilde{t},2} s^2_{\theta_{\tilde{t}}} \\
g^{h,\mathrm{EW}}_{\tilde{t},22} &= c^{\mathrm{EW}}_{\tilde{t},1} s^2_{\theta_{\tilde{t}}} + c^{\mathrm{EW}}_{\tilde{t},2} c^2_{\theta_{\tilde{t}}} \\
g^{h,\mathrm{EW}}_{\tilde{t},12} &= g^{h,\mathrm{EW}}_{\tilde{t},21} = \frac{1}{2}\left(c^{\tilde{t},\mathrm{EW}}_2 - c^{\tilde{t},\mathrm{EW}}_1\right) s_{2\theta_{\tilde{t}}} \\
g^{h,\mu}_{\tilde{t},11} &= -g^{h,\mu}_{\tilde{t},22} = \frac{\mu}{m_t}\frac{\cos(\alpha-\beta)}{s^2_\beta} s_{2\theta_{\tilde{t}}}
\end{aligned}$$

$$\begin{aligned}
g^{h,\mathrm{EW}}_{\tilde{b},11} &= c^{\mathrm{EW}}_{\tilde{b},1} c^2_{\theta_{\tilde{b}}} + c^{\mathrm{EW}}_{\tilde{b},2} s^2_{\theta_{\tilde{b}}} \\
g^{h,\mathrm{EW}}_{\tilde{b},22} &= c^{\mathrm{EW}}_{\tilde{b},1} s^2_{\theta_{\tilde{b}}} + c^{\mathrm{EW}}_{\tilde{b},2} c^2_{\theta_{\tilde{b}}} \\
g^{h,\mathrm{EW}}_{\tilde{b},12} &= g^{h,\mathrm{EW}}_{\tilde{b},21} = \frac{1}{2}\left(c^{\tilde{b},\mathrm{EW}}_2 - c^{\tilde{b},\mathrm{EW}}_1\right) s_{2\theta_{\tilde{b}}} \\
g^{h,\mu}_{\tilde{b},11} &= -g^{h,\mu}_{\tilde{b},22} = -\frac{\mu}{m_b}\frac{\cos(\alpha-\beta)}{c^2_\beta} s_{2\theta_{\tilde{b}}}
\end{aligned}$$

Higgs-squark couplings

$$g^{h,\mu}_{\tilde{t},12} = g^{h,\mu}_{\tilde{t},21} = \frac{\mu}{m_t}\frac{\cos(\alpha-\beta)}{s^2_\beta} c_{2\theta_{\tilde{t}}} \qquad g^{h,\mu}_{\tilde{b},12} = g^{h,\mu}_{\tilde{b},21} = -\frac{\mu}{m_b}\frac{\cos(\alpha-\beta)}{c^2_\beta} c_{2\theta_{\tilde{b}}}$$

$$g^{h,\alpha}_{\tilde{t},11} = \frac{c_\alpha}{s_\beta}\left(2 + \frac{m^2_{\tilde{t}1} - m^2_{\tilde{t}2}}{2m^2_t} s^2_{2\theta_{\tilde{t}}}\right) \qquad g^{h,\alpha}_{\tilde{b},11} = -\frac{s_\alpha}{c_\beta}\left(2 + \frac{m^2_{\tilde{b}1} - m^2_{\tilde{b}2}}{2m^2_b} s^2_{2\theta_{\tilde{b}}}\right)$$

$$g^{h,\alpha}_{\tilde{t},22} = \frac{c_\alpha}{s_\beta}\left(2 - \frac{m^2_{\tilde{t}1} - m^2_{\tilde{t}2}}{2m^2_t} s^2_{2\theta_{\tilde{t}}}\right) \qquad g^{h,\alpha}_{\tilde{b},22} = -\frac{s_\alpha}{c_\beta}\left(2 - \frac{m^2_{\tilde{b}1} - m^2_{\tilde{b}2}}{2m^2_b} s^2_{2\theta_{\tilde{b}}}\right)$$

$$g^{h,\alpha}_{\tilde{t},12} = g^{h,\alpha}_{\tilde{t},21} = \frac{c_\alpha}{s_\beta}\frac{m^2_{\tilde{t}1} - m^2_{\tilde{t}2}}{2m^2_t} s_{2\theta_{\tilde{t}}} c_{2\theta_{\tilde{t}}} \qquad g^{h,\alpha}_{\tilde{b},12} = g^{h,\alpha}_{\tilde{b},21} = -\frac{s_\alpha}{c_\beta}\frac{m^2_{\tilde{b}1} - m^2_{\tilde{b}2}}{2m^2_b} s_{2\theta_{\tilde{b}}} c_{2\theta_{\tilde{b}}}$$

Therein we made use of the abbreviations $s_x = \sin x$ and $c_x = \cos x$ and defined:

$$c^{\mathrm{EW}}_{\tilde{t},1} = -\frac{m^2_Z}{m^2_t}\left(1 - \frac{4}{3}s^2_{\theta_W}\right)\sin(\alpha+\beta) \qquad c^{\mathrm{EW}}_{\tilde{b},1} = \frac{m^2_Z}{m^2_b}\left(1 - \frac{2}{3}s^2_{\theta_W}\right)\sin(\alpha+\beta)$$

$$c^{\mathrm{EW}}_{\tilde{t},2} = -\frac{m^2_Z}{m^2_t}\frac{4}{3}s^2_{\theta_W}\sin(\alpha+\beta) \qquad c^{\mathrm{EW}}_{\tilde{b},2} = \frac{m^2_Z}{m^2_b}\frac{2}{3}s^2_{\theta_W}\sin(\alpha+\beta)$$

Squark Sector

In the MSSM without flavour mixing in the squark sector, squarks $\tilde{q}_{L,R}$ of one generation mix into mass eigenstates $\tilde{q}_{1,2}$.

$$\mathcal{L} \supset -(\tilde{q}_L^\dagger, \tilde{q}_R^\dagger) M_{\tilde{q}}^2 \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix} \qquad \text{with}$$

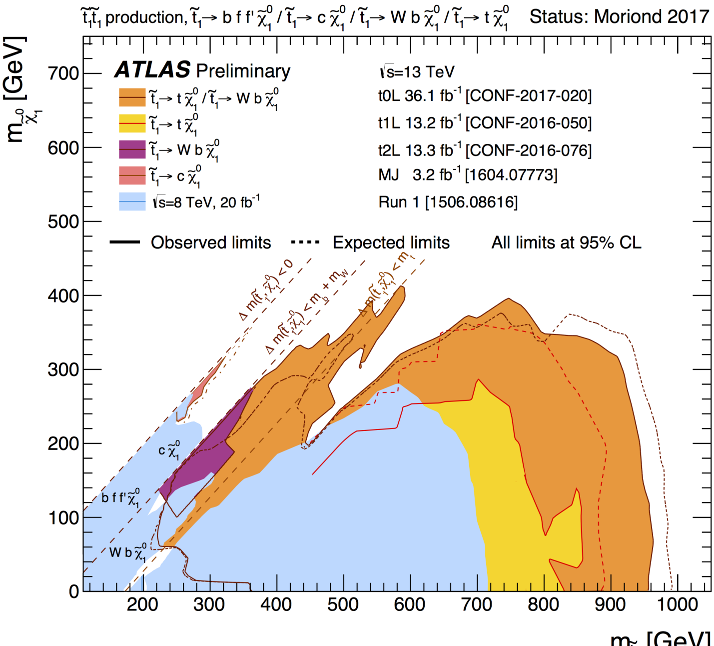
$$M_{\tilde{q}}^2 = \begin{pmatrix} M_{\tilde{q}_L}^2 + m_q^2 + M_Z^2 \cos 2\beta (I_q^3 - Q_q s_W^2) & m_q X_q^* \\ m_q X_q & M_{\tilde{q}_R}^2 + m_q^2 + M_Z^2 \cos 2\beta Q_q s_W^2 \end{pmatrix} . \tag{2}$$

with $X_q := A_q - \mu^* \cdot \{\cot\beta, \tan\beta\}$, where $\cot\beta$ and $\tan\beta$ apply to up- and down-type quarks, respectively.

The soft-breaking masses $M_{\tilde{q}_L}^2$ and $M_{\tilde{q}_R}^2$, the third component of the weak isospin I_q^3, the electric charge Q_q and the mass of the quark m_q are real parameters.

The squark masses (with $m_{\tilde{q}_1} \leq m_{\tilde{q}_2}$) are eigenvalues of the mass matrix.

Higgs-squark couplings



Higgs Sector

The neutral fields of the two Higgs doublets can be decomposed in $\mathcal{CP}$-even (ϕ_1^0, ϕ_2^0) and $\mathcal{CP}$–odd (χ_1^0, χ_2^0) components

$$\begin{aligned} \mathcal{H}_1 &= \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix} = \begin{pmatrix} v_d + \frac{1}{\sqrt{2}}(\phi_1^0 + i\chi_1^0) \\ \phi_1^- \end{pmatrix} \\ \mathcal{H}_2 &= \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_u + \frac{1}{\sqrt{2}}(\phi_2^0 + i\chi_2^0) \end{pmatrix} , \end{aligned} \tag{3}$$

Higgs potential V_H in terms of the neutral Higgs states is given by

$$\begin{aligned} V_H^0 =& (|\mu|^2 + m_{\mathcal{H}_2}^2)|h_u^0|^2 + (|\mu|^2 + m_{\mathcal{H}_1}^2)|h_d^0|^2 \\ & - [m_{12}^2 h_u^0 h_d^0 + h.c.] + \frac{g_1^2 + g_2^2}{8}[|h_u^0|^2 - |h_d^0|^2]^2 \,. \end{aligned}$$