PANIC11

PANIC11 RUTHERFORD CENTENNIAL

19th Particles & Nuclei International Conference

July 24th–29th, 2011 Massachusetts Institute of Technology, Cambridge, MA, USA

Celebrating the centennial of the discovery of the atomic nucleus and the 150th anniversary of MIT

Hosted by the Laboratory for Nuclear Science, MIT

Correlations between High-p_T and Flavour Physics: flavour-violating squark and gluino decays

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Prologue Flavour@High-p_T Interplay

Correlations of high-p_T and flavour physics

How can flavour data help to interprete high-p_T physics ?

What can ATLAS/CMS tell us about flavour ?

Can we ignore flavour when analysing possible

new physics at the electroweak scale?

⇒ CERN workshop on the interplay of flavour and collider physics
Fleischer,Hurth,Mangano see http://mlm.home.cern.ch/mlm/FlavLHC.html

Flavour in the era of the LHC

a Workshop on the interplay of flavour and collider physics

First meeting:

CERN, November 7-10 2005

http://mlm.home.cern.ch/mlm/FlavLHC.html

- BSM signatures in B/K/D physics, and their complementarity with the high-pT LHC discovery potential
- Flavour phenomena in the decays of SUSY particles
- Squark/slepton spectroscopy and family structure
- Flavour aspects of non-SUSY BSM physics
- Flavour physics in the lepton sector
- g-2 and EDMs as BSM probes
- Flavour experiments for the next decade

Local Organizing Committee

International Advisory Committee

5 meetings between 11/2005 and 3/2007

arXiv:0801.1800 [hep-ph] “Collider aspects of flavour physics at high Q”

arXiv:0801.1833 [hep-ph] “B, D and K decays”

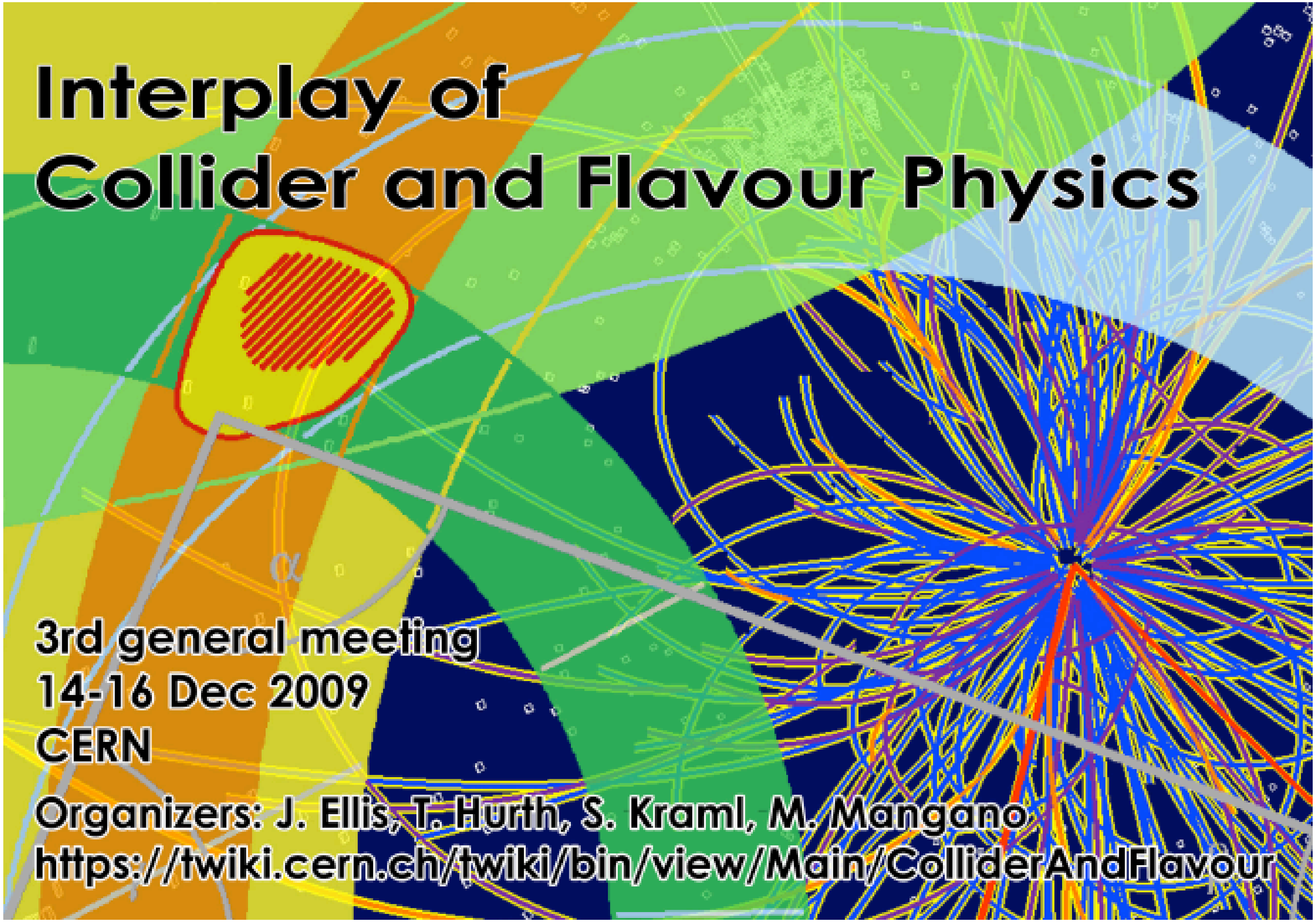
arXiv:0801.1826 [hep-ph] “Flavour physics of leptons and dipole moments”

published in EPJC 57 (2008) 1-492

and in Advances in the Physics of Particles and Nuclei, Vol 29, 480p, 2009

Reference book for flavour in the LHC era

Follow-up working group at CERN



Interplay of
Collider and Flavour Physics

3rd general meeting
14-16 Dec 2009
CERN

Organizers: J. Ellis, T. Hurth, S. Kraml, M. Mangano
https://twiki.cern.ch/twiki/bin/view/Main/ColliderAndFlavour

Ambiguity of new physics scale from flavour data

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathrm{NP}}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}

- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$:

$$c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda_{\mathrm{NP}}^2 \times (\bar{s}\, d)^2 \qquad \Rightarrow \quad \Lambda_{\mathrm{NP}} > 10^4\,\mathrm{TeV}$$

(tree-level, generic new physics)

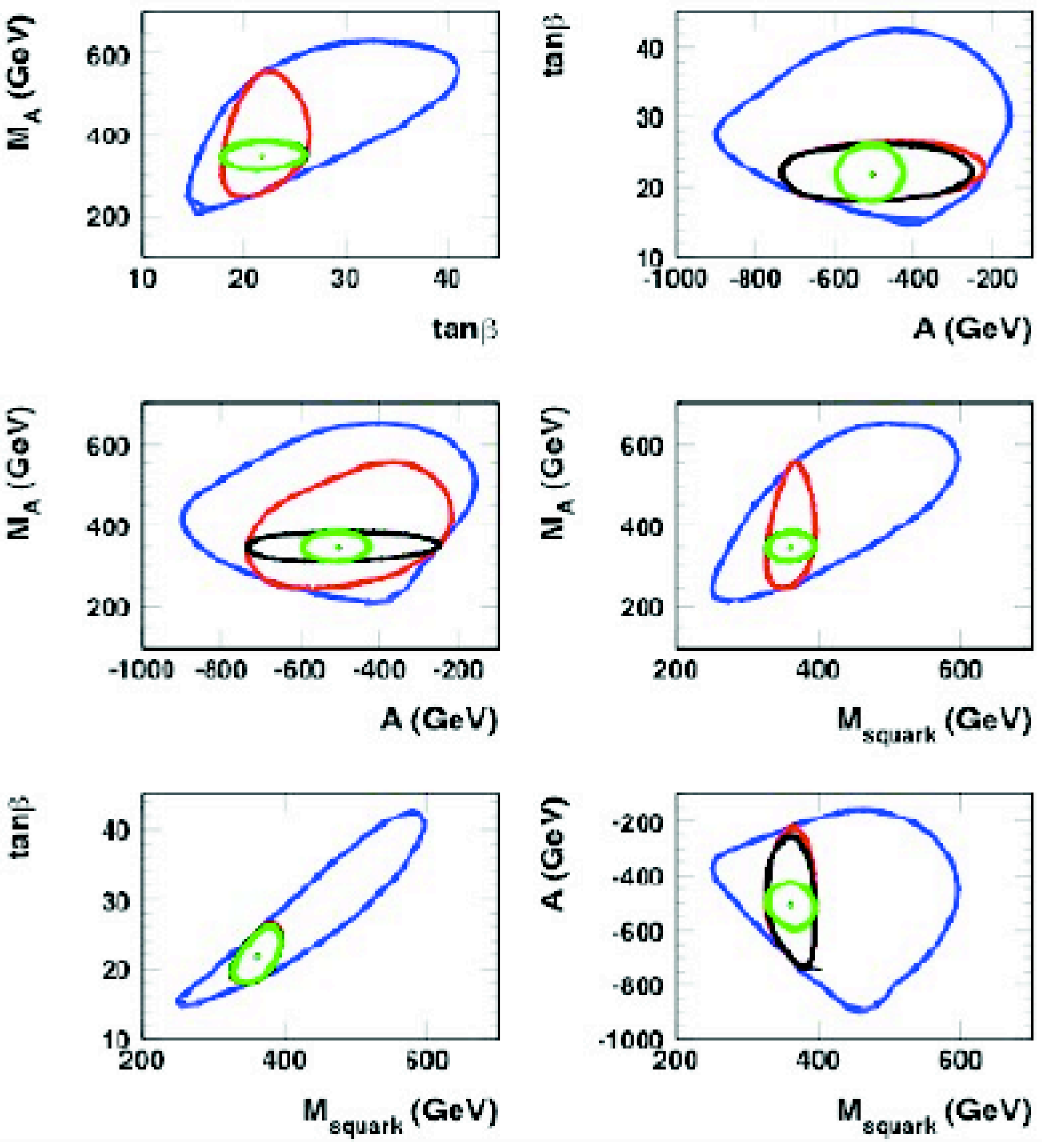
- Natural stabilisation of Higgs boson mass (hierarchy problem)

(i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow$ $\Lambda_{\mathrm{NP}} \leq 1\mathrm{TeV}$

- EW precision data ↔ little hierarchy problem $\Rightarrow$ $\Lambda_{\mathrm{NP}} \sim 3 - 10\mathrm{TeV}$

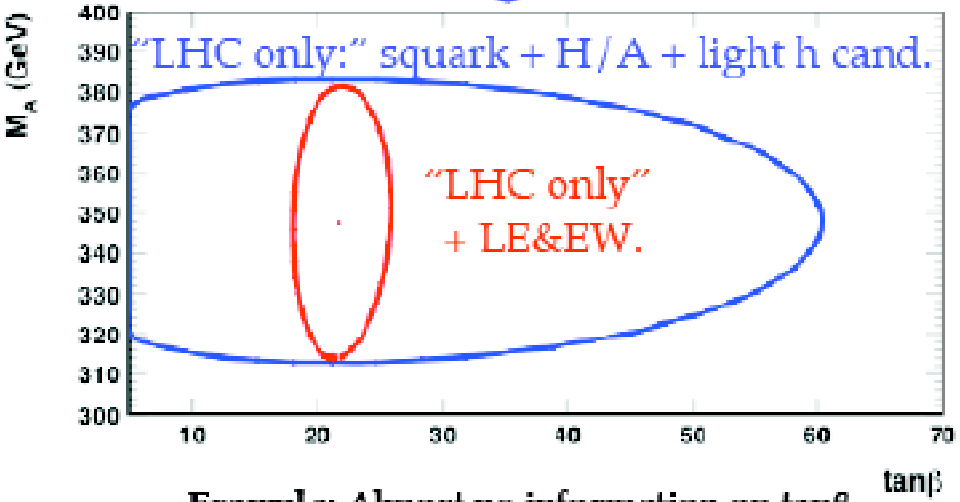
Possible New Physics at the TeV scale has to have a very non-generic flavour structure

Flavour constraints in the cMSSM



LE&EW: low-energy (LE) and EW constraints
LE&EW + squark candidate
LE&EW + squark cand. + H/A cand.
LE&EW + squark + H/A + light h cand.

Including LW&EW constraints facilitates the determination of fundamental MSSM parameters



Example: Almost no information on tanβ without external constraints. Note that a direct measurement of tanβ is very difficult at the LHC

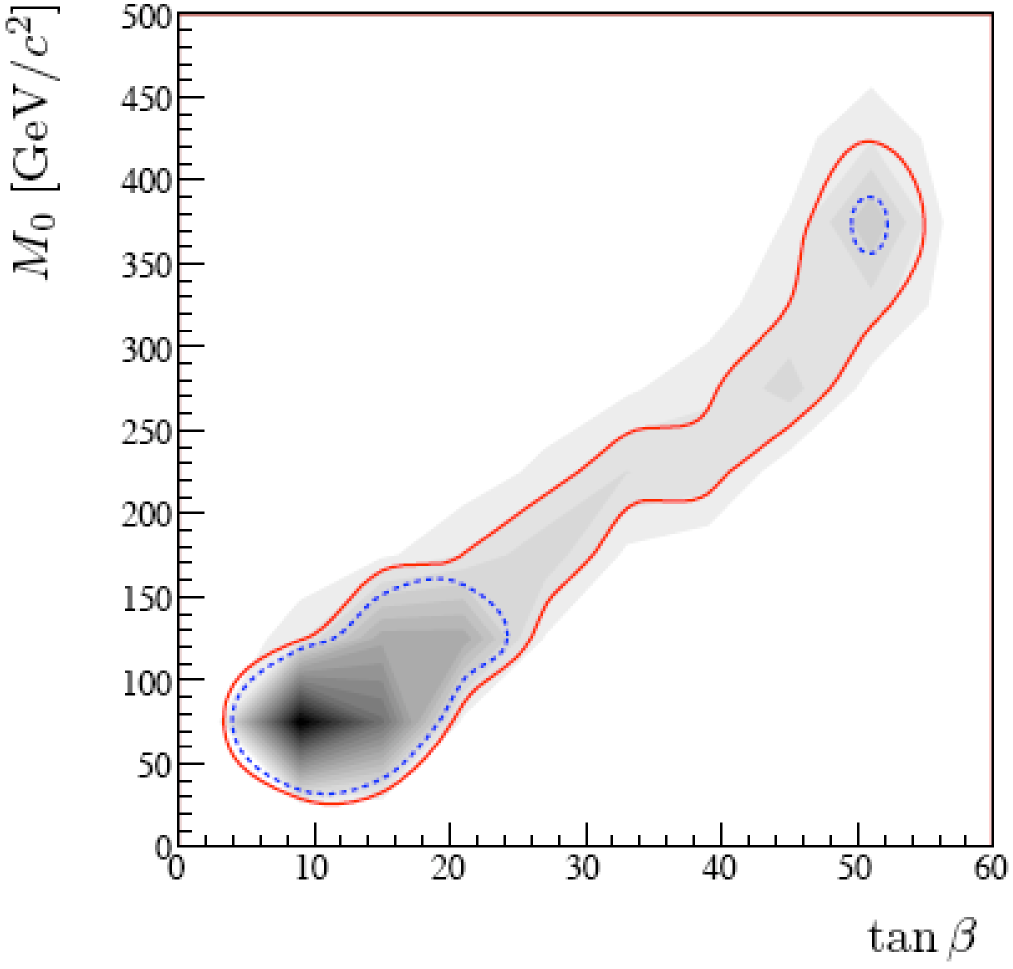
Illustrative Example

Buchmüller et al., arXiv:1106.2529, 1102.4585, 0912.1036, 0907.5568, 0808.4128, 0707.3447

More flavour constraints in the cMSSM

Buchmüller et al.

Multi-parameter χ^2 fit for all CMSSM parameters, $M_0, M_{1/2}, A_0, \tan\beta$



68% (dotted) and

95% (solid) CL

$(g-2)_\mu$, $b \to s\gamma$, Ω_{CDM}

Constraints on the lightest Higgs boson mass

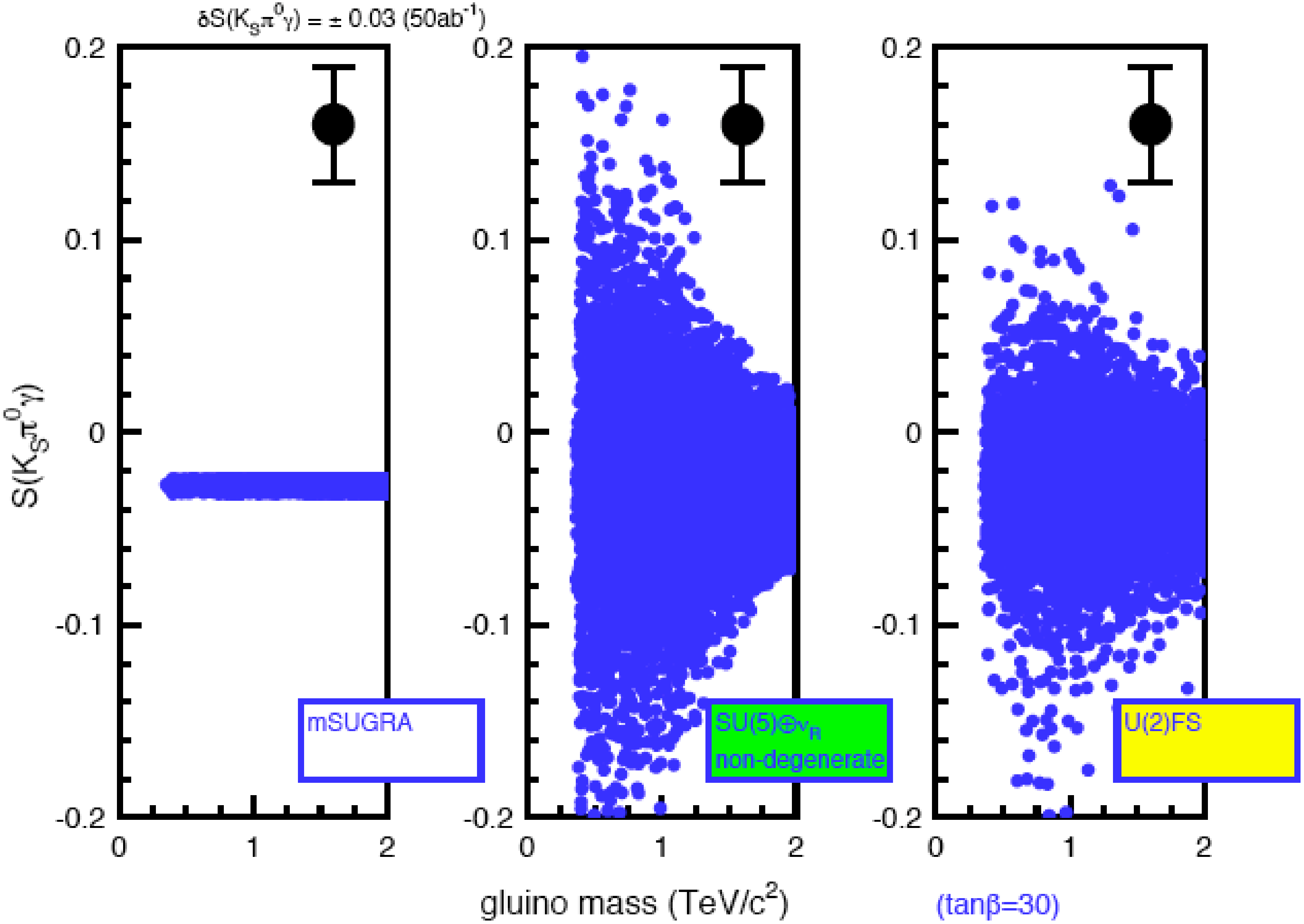
$$m_{\rm h}^{\rm CMSSM} = 110^{+8}_{-10}\ ({\rm exp.}) \pm 3\ ({\rm theo.})\ {\rm GeV}/c^2$$

no restriction on m_h
imposed in the fit

Dynamics of flavour ⇔ mechanism of SUSY breaking

$(BR(b \to s\gamma) = 0$ in exact supersymmetry)

⇒ Discrimination between various SUSY-breaking mechanism



Expected Super-B sensitivity ($50ab^{-1}$) Goto,Okada,Shindou,Tanaka,arXiv:0711.2935

Study lepton flavour at the LHC

Feng et al.,arXiv:0712.0674; see also Gross et al.,arXiv:1001.2883;
Grossman et al.,arXiv:1106.4020

Consider degeneracy and alignment beyond MFV

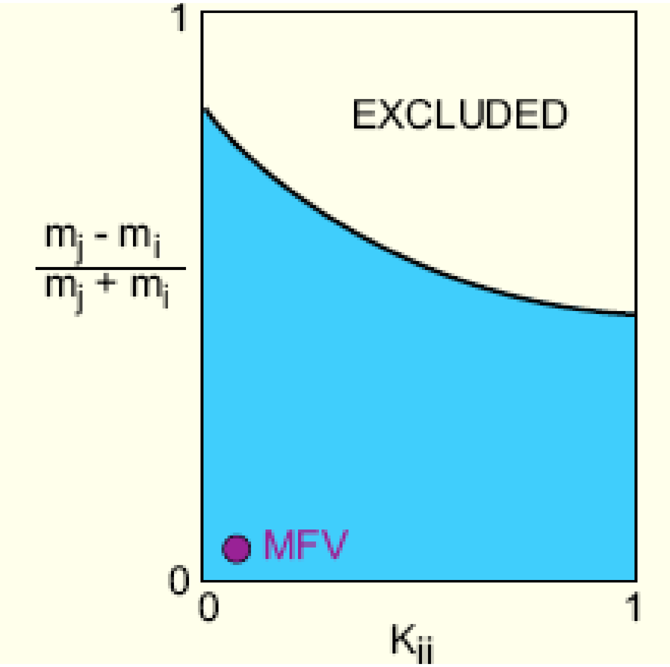
Natural Susy models span a large allowed area in the $(\Delta m^2_{ij}, K_{ij})$ plane.

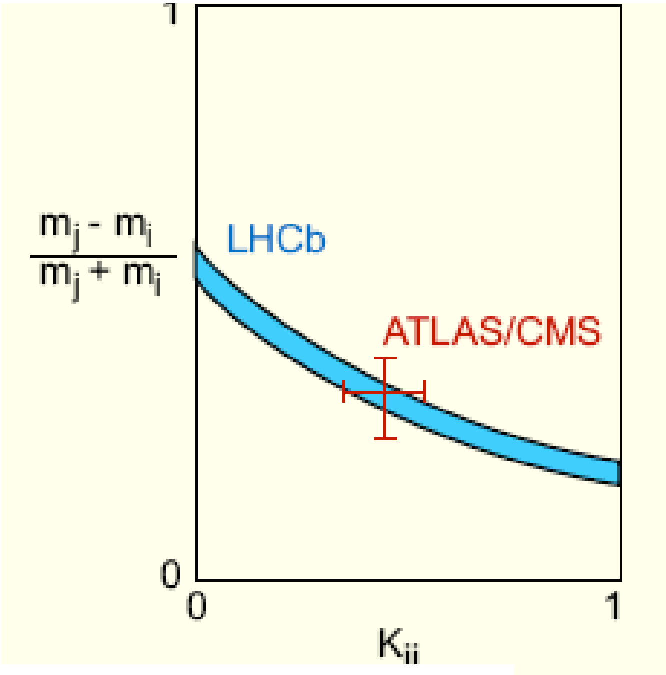
(mass-squared splitting of slepton generations versus their mixing)

FCNC lead to upper bounds for $\Delta m^2_{ij} \times K_{ij}$ only,

$BR(\mu \to e\gamma) \leq 1.2 \times 10^{-11}$, $BR(\tau \to e\gamma) \leq 1.1 \times 10^{-7}$, $BR(\tau \to \mu\gamma) \leq 6.8 \times 10^{-8}$,

while ATLAS/CMS can constrain either or both of the factors.





Measuring slepton masses and mixings at the LHC Feng et al., arXiv:0910.1618

Concrete model: Susy hybrid model (gauge/gravity mediation),
determination of slepton masses and their mixing possible

Flavour-violating squark and gluino decays Hurth, Porod

Can we ignore flavour when analysing possible new physics at the electroweak scale?

Correlations between flavour and high-p_T physics

Example: Supersymmetry

- In the MSSM too many new contributions to flavour violation
  - CKM-induced contributions from H^+, χ^+ exchanges (quark mixing)
  - flavour mixing in the sfermion mass matrix (disalignment)

$\Rightarrow$ Supersymmetric flavour problem

- Squark decays: $\tilde{u}_i \to u_j \tilde{\chi}^0_k \,,\, d_j \tilde{\chi}^+_l \qquad \tilde{d}_i \to d_j \tilde{\chi}^0_k \,,\, u_j \tilde{\chi}^-_l$

  with $i = 1, .., 6$, $j = 1, 2, 3$, $k = 1, .., 4$ and $l = 1, 2$.

- These tree decays are governed by the same mixing matrices as the contributions to flavour violating low-energy observables.

Squark and gluino decays

- $m_{\tilde g} > m_{\tilde q_i}$ $(q = d, u;\ i = 1, \ldots, 6)$ the gluino will mainly decay according to

$$\tilde g \to d_j\, \tilde d_i\,,\ \ \tilde g \to u_j\, \tilde u_i$$

followed by squark decays into neutralino and charginos

$$\tilde u_i \to u_j \tilde\chi^0_k,\, d_j \tilde\chi^+_l\,,\ \ \tilde d_i \to d_j \tilde\chi^0_k,\, u_j \tilde\chi^-_l$$

or into gauge- and Higgs bosons if kinematically allowed

$$\tilde u_i \to Z \tilde u_k\,,\ H^0_r \tilde u_k\,,\ W^+ \tilde d_j\,,\ H^+ \tilde d_j; \qquad \tilde d_i \to Z \tilde d_k\,,\ H^0_r \tilde d_k\,,\ W^- \tilde u_j\,,\ H^- \tilde u_j$$

Due to left-right squark mixing

flavour changing neutral decays into Z-bosons at tree-level

- $m_{\tilde g} < m_{\tilde q_i}$ the squarks decay mainly into a gluino

$$\tilde u_i \to u_j \tilde g\,, \quad \tilde d_i \to d_j \tilde g$$

the gluino decays into charginos and neutralinos

via three-body decays and loop-induced two-body decays

$$\tilde g \to d_j\, d_i\, \tilde\chi^0_k\,,\ u_j\, u_i\, \tilde\chi^0_k\,, \quad \tilde g \to u_j\, d_i\, \tilde\chi^\pm_l\,, \quad \tilde g \to g\, \tilde\chi^0_k$$

Squark mixing

Squark mass matrices ($f = u, d$):

$$\mathcal{M}_f^2 \equiv \begin{pmatrix} M^2_{f,LL} + F_{f\,LL} + D_{f\,LL} & M^2_{f,LR} + F_{f\,LR} \\ \left(M^2_{f,LR}\right)^\dagger + F^*_{f\,RL} & M^2_{f,RR} + F_{f\,RR} + D_{f\,RR} \end{pmatrix}$$

In the super-CKM basis F- and D-terms are flavour diagonal:

$$D_{f\,LL} = (T_{3,f} - e_f \sin^2\theta_W)\cos(2\beta) m_Z^2 \ , \quad D_{f\,RR} = e_f \sin^2\theta_W \cos(2\beta) m_Z^2$$

$$F_{f\,LL,ij} = F_{f\,RR,ij} = m_i^2 \delta_{ij} \ , \quad F_{f\,RL,ij} = -\mu m_i \delta_{ij} (\tan\beta)^{-2T_{3,f}}$$

All flavour violation beyond the CKM in the soft SUSY breaking terms:

$$\begin{aligned} M^2_{d,LL} &= V^\dagger_{CKM} M^2_{u,LL} V_{CKM} = \hat{m}^2_{\tilde{Q}} \equiv V_d^\dagger\, m^2_{\tilde{Q}}\, V_d \,, \\ M^2_{d,RR} &= \hat{m}^2_{\tilde{d}} \equiv U_d^\dagger\, m^{2\,T}_{\tilde{d}}\, U_d \ , \qquad M^2_{u,RR} = \hat{m}^2_{\tilde{u}} \equiv U_u^\dagger\, m^{2\,T}_{\tilde{u}}\, U_u \,, \\ M^2_{d,LR} &= v_1/\sqrt{2}\, \hat{T}_D \equiv v_1/\sqrt{2}\, U_d^\dagger\, T_D^T\, V_d \ , \qquad M^2_{u,LR} = v_2/\sqrt{2}\, \hat{T}_U \equiv v_2/\sqrt{2}\, U_u^\dagger\, T_U^T\, V_u \end{aligned}$$

Observables as functions of the normalized off-diagonal elements:

$$\delta_{LL,ij} = \frac{(M^2_{f,LL})_{ij}}{m^2_{\tilde{q}}} \,, \qquad \delta_{f,RR,ij} = \frac{(M^2_{f,RR})_{ij}}{m^2_{\tilde{f}}} \,, \qquad (i \neq j)$$

Experimental and theoretical constraints

- Vacuum stability constraints
- Electroweak precision data: m_{h_0}, ρ parameter
- Squark Tevatron bounds
- Bounds from flavour observables:
  - Data from K and B_d physics strongly constrain new sources of flavour violation in $s \to d$ and $b \to d$ sector
  - Possibility of sizable new contributions to $b \to s$ remains open.
  - In SUSY- GUTs the large mixing angle in the neutrino sector relates to large mixing in the right-handed b-s sector

$$\begin{array}{lcl}
2.67 < & Br(\bar{B} \to X_s \gamma) \times 10^4 & < 4.29 \\
13.5 < & \Delta M_{B_S}\ ps & < 21.1 \\
1.05 < & BR(\bar{B} \to X_s l^+ l^-)_{\mathrm{low}_{q^2}} \times 10^6 & < 2.15 \\
 & BR(B_s \to \mu^+ \mu^-) \times 10^8 & \leq 5.8
\end{array}$$

Strategy:

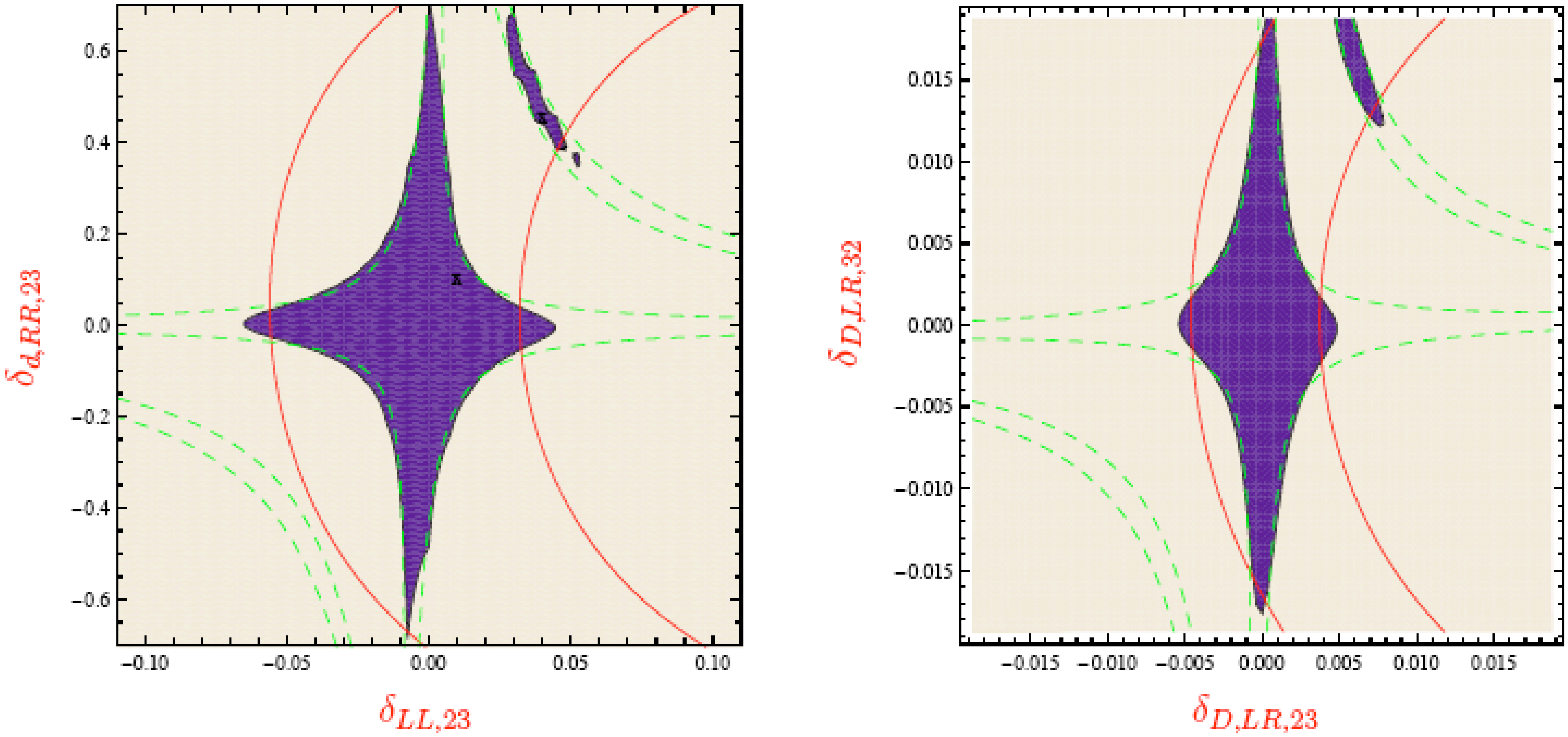
- Take susy benchmark points: SPS1a',γ, and I''
- Vary flavour nondiagonal parameters
  (off-diagonal squark mass entries)
- Use all experimental and theoretical bounds

$\Rightarrow$ Bounds on δ parameters

	SPS1a'	γ	I''
$\delta_{LL,23}$	(-0.05,0.03)	(-0.037,0.005)	(-0.06,0.001)
$\delta_{d,RR,23}$	(-0.43,0.66)	(-0.29,0.48)	(-0.5,0.45)
$\delta_{u,RR,23}$	(-0.7,0.7)	(-0.54,0.43)	(-0.55,0.45)
$\delta_{u,LR,23}$	(-0.16,0.08)	(-0.16,0.06)	(-0.35,0.05)
$\delta_{u,LR,32}$	(-0.7,0.54)	(-0.5,0.2)	(-0.7,0.27)
$\delta_{d,LR,23}$	(-0.0047,0.0046)	(-0.006,0.001)	(-0.01,0.0015)
$\delta_{d,LR,32}$	(-0.019,0.02)	(-0.015,0.015)	(-0.004,0.003)

Assumption used that only one flavour-mixing parameter is present (regions 95% CL.)

Allowed regions for SPS1a'



a) in the $\delta_{d,RR,23}$-$\delta_{LL,23}$

b) in the $\delta_{D,LR,23}$-$\delta_{D,LR,32}$ plane

($b \rightarrow s\gamma$ red lines, ΔM_{B_s} magenta)

Typical results for squark and gluino decays

decaying particle	final states and corresponding branching ratios in % for.					
	I. $\delta_{LL,23} = 0.01, \delta_{D,RR23} = 0.1$			II. $\delta_{LL,23} = 0.04, \delta_{D,RR23} = 0.45$		
$\tilde d_1 \to$ I: $\tilde b_L(\tilde b_R)$	$\tilde\chi^0_1 b$, 4.4 $\tilde u_1 W^-$, 27.7	$\tilde\chi^0_2 b$, 29.8	$\tilde\chi^-_1 t$, 37.0	$\tilde\chi^0_1 s$, 36.8 $\tilde\chi^-_1 t$, 9.6	$\tilde\chi^0_1 b$, 42.2	$\tilde\chi^0_2 b$, 10.9
$\tilde d_2 \to$ I: $\tilde b_R(\tilde b_L, \tilde s_R)$	$\tilde\chi^0_1 s$, 8.0 $\tilde\chi^0_3 b$, 1.1 $\tilde u_1 W^-$, 38.9	$\tilde\chi^0_1 b$, 6.4 $\tilde\chi^0_4 b$, 1.8	$\tilde\chi^0_2 b$, 19.0 $\tilde\chi^-_1 t$, 24.6	$\tilde\chi^0_1 b$, 2.1 $\tilde u_1 W^-$, 33.2	$\tilde\chi^0_2 b$, 27.3	$\tilde\chi^-_1 t$, 34.6
$\tilde d_4 \to$ I: $\tilde s_R(\tilde s_L, \tilde b_R)$	$\tilde\chi^0_1 s$, 9.1 $\tilde\chi^-_1 u$, 2.1	$\tilde\chi^0_1 b$, 6.3 $\tilde\chi^-_1 c$, 47.3	$\tilde\chi^0_2 s$, 25.3 $\tilde u_1 W^-$, 4.8	$\tilde\chi^0_1 d$, 2.3 $\tilde\chi^-_1 c$, 3.0	$\tilde\chi^0_2 d$, 31.7 $\tilde\chi^-_2 u$, 2.3	$\tilde\chi^-_1 u$, 59.7
$\tilde d_5 \to$ I: $\tilde d_L$	$\tilde\chi^0_1 d$, 2.3 $\tilde\chi^-_1 c$, 2.8	$\tilde\chi^0_2 d$, 31.7 $\tilde\chi^-_2 u$, 2.3	$\tilde\chi^-_1 u$, 59.9	$\tilde\chi^0_1 s$, 2.2 $\tilde\chi^-_1 c$, 58.5	$\tilde\chi^0_2 s$, 30.7 $\tilde\chi^-_2 c$, 2.3	$\tilde\chi^-_1 u$, 2.9
$\tilde d_6 \to$ I: $\tilde s_L(\tilde s_R)$	$\tilde\chi^0_1 s$, 3.1 $\tilde\chi^-_1 c$, 58.1	$\tilde\chi^0_2 s$, 30.6 $\tilde\chi^-_2 c$, 2.4	$\tilde\chi^-_1 u$, 2.7	$\tilde\chi^0_1 s$, 19.7 $\tilde\chi^0_4 b$, 2.9 $\tilde g b$, 39.8	$\tilde\chi^0_1 b$, 18.8 $\tilde\chi^-_2 t$, 5.8 $\tilde u_1 W^-$, 5.5	$\tilde\chi^0_3 b$, 2.9 $\tilde g s$, 2.2
$\tilde g \to$	$\tilde u_1 t$, 19.2 $\tilde u_4 u$, 4.2 $\tilde d_1 s$, 1.4 $\tilde d_2 s$, 6.3 $\tilde d_4 s$, 2.3	$\tilde u_2 c$, 8.2 $\tilde u_5 c$, 4.2 $\tilde d_1 b$, 20.6 $\tilde d_2 b$, 9.0 $\tilde d_4 b$, 1.3	$\tilde u_3 u$, 8.3 $\tilde d_3 d$, 8.3 $\tilde d_6 s$, 2.8	$\tilde u_1 t$, 13.5 $\tilde u_4 c$, 2.6 $\tilde d_1 s$, 21.1 $\tilde d_2 b$, 14.0 $\tilde d_4 d$, 2.3	$\tilde u_2 c$, 5.8 $\tilde u_5 u$, 2.6 $\tilde d_1 b$, 22.7 $\tilde d_5 d$, 3.3	$\tilde u_3 u$, 5.8 $\tilde d_3 d$, 5.9

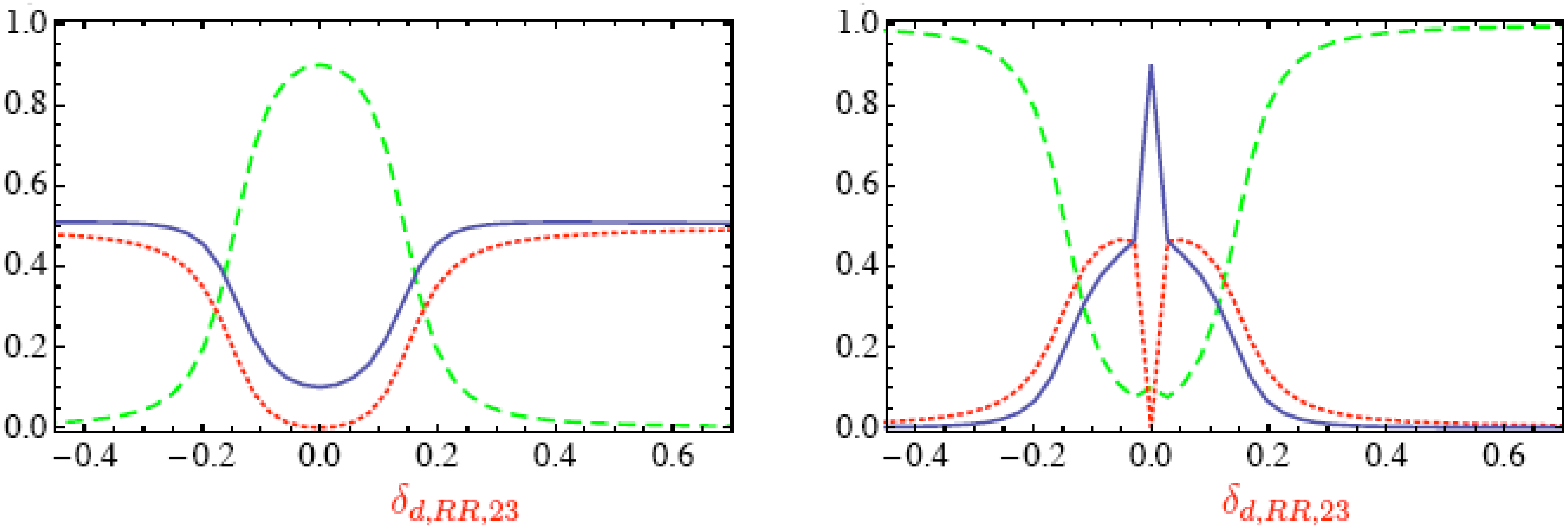
II: $\tilde d_1 \simeq \tilde b_R, \tilde s_R(\tilde b_L)$, $\tilde d_6 \simeq \tilde s_R, \tilde b_R(\tilde b_L)$, $\tilde d_2 \simeq \tilde b_L$, $\tilde d_3 \simeq \tilde d_R$, $\tilde d_4 \simeq \tilde d_L$ and $\tilde d_5 \simeq \tilde s_L$

Squark masses in GeV for SPS1a' and the two points I and II

	$m_{\tilde{d}_1}$	$m_{\tilde{d}_2}$	$m_{\tilde{d}_3}$	$m_{\tilde{d}_4}$	$m_{\tilde{d}_5}$	$m_{\tilde{d}_6}$	$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{u}_4}$	$m_{\tilde{u}_6}$
SPS1a'	506	546	547	547	570	570	367	547	565	586
I. $\delta_{LL,23} = 0.01, \delta_{d,RR,23} = 0.1$	503	525	547	569	570	570	366	547	565	586
II. $\delta_{LL,23} = 0.04, \delta_{d,RR,23} = 0.45$	422	509	547	570	572	641	366	547	565	587

Note that $m_{\tilde{u}_2} \simeq m_{\tilde{u}_3}$ and $m_{\tilde{u}_4} \simeq m_{\tilde{u}_5}$

Composition of a) $\tilde{d}_{i=1}$ and b) $\tilde{d}_{i=2}$ as a function of $\delta_{d,RR,23}$



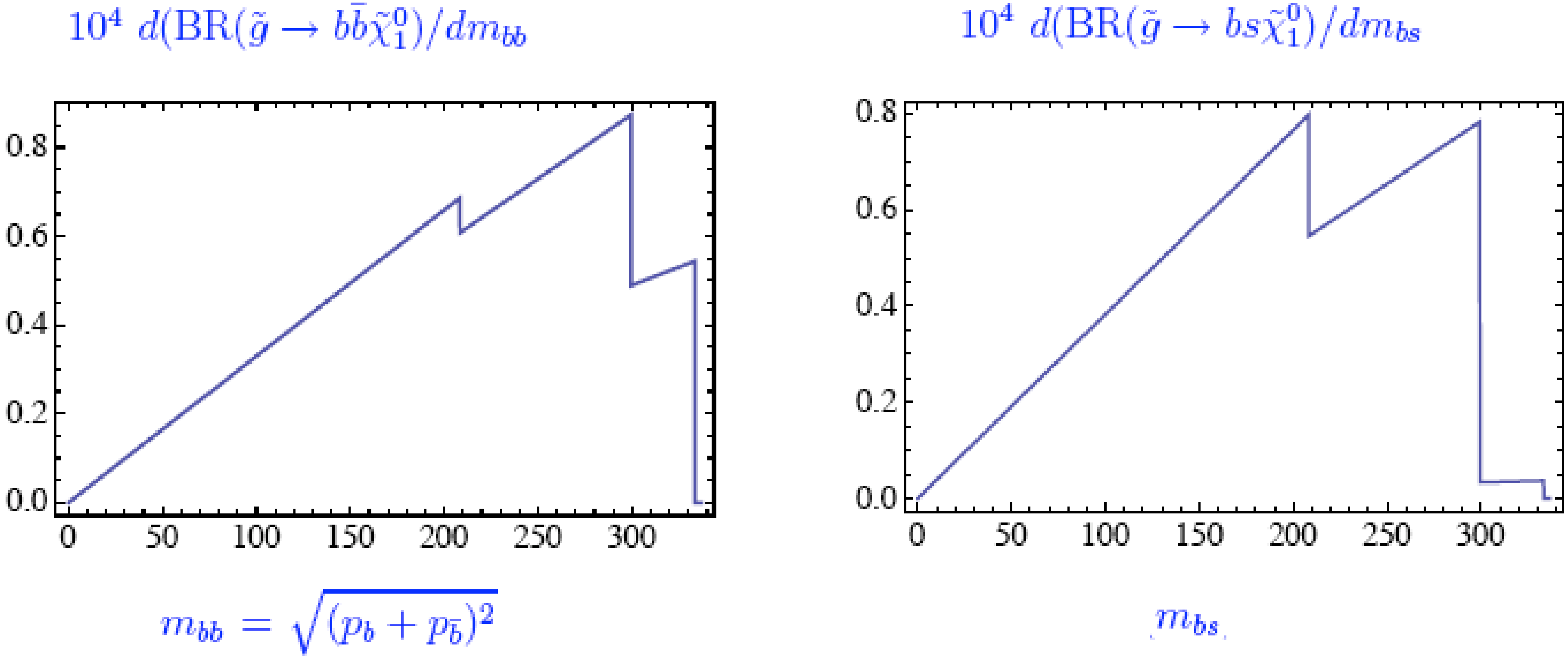
red: $|R^d_{i,\tilde{s}_R}|^2$ **blue:** $|R^d_{i,\tilde{b}_R}|^2$ **green:** $|R^d_{i,\tilde{b}_L}|^2$ $\tilde{d}_k = R^d_{kj}\tilde{d}^{ew}_j$

Impact on LHC and ILC

Flavour tagging at LHC important, but difficult

This can complicate determination of sparticle masses:

$$\tilde{g} \longrightarrow b\tilde{\bar{b}}_j \longrightarrow b\bar{b}\tilde{\chi}^0_k$$



$10^4\ d(\mathrm{BR}(\tilde{g} \to b\bar{b}\tilde{\chi}^0_1)/dm_{bb}$

$10^4\ d(\mathrm{BR}(\tilde{g} \to bs\tilde{\chi}^0_1)/dm_{bs}$

$m_{bb} = \sqrt{(p_b + p_{\bar{b}})^2}$

m_{bs}

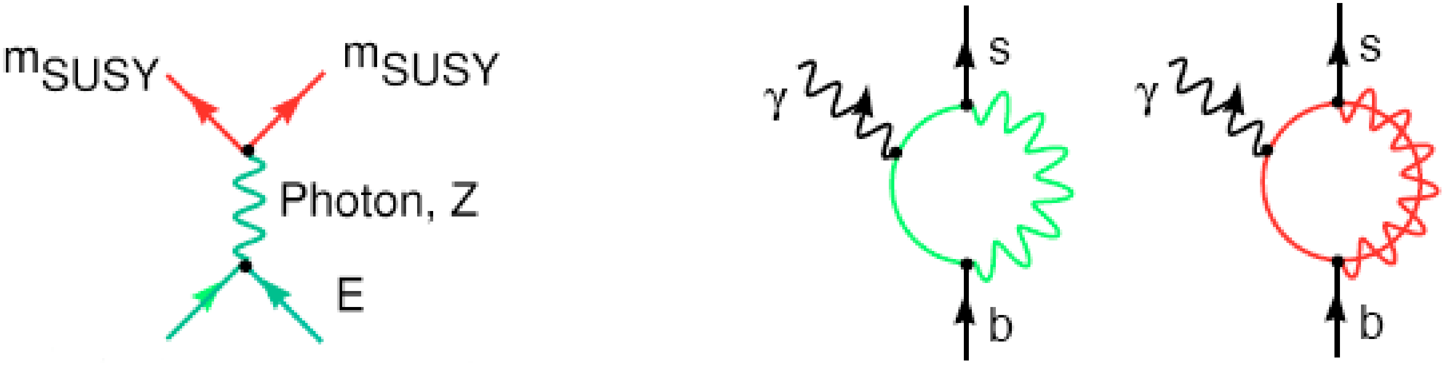
Differential distributions

Additional information from ILC or from Superflavour factory needed !

Epilogue Flavour@high-p_T

Immense potential for synergy and complementarity between high-p_T and flavour physics within the search for new physics

Why?

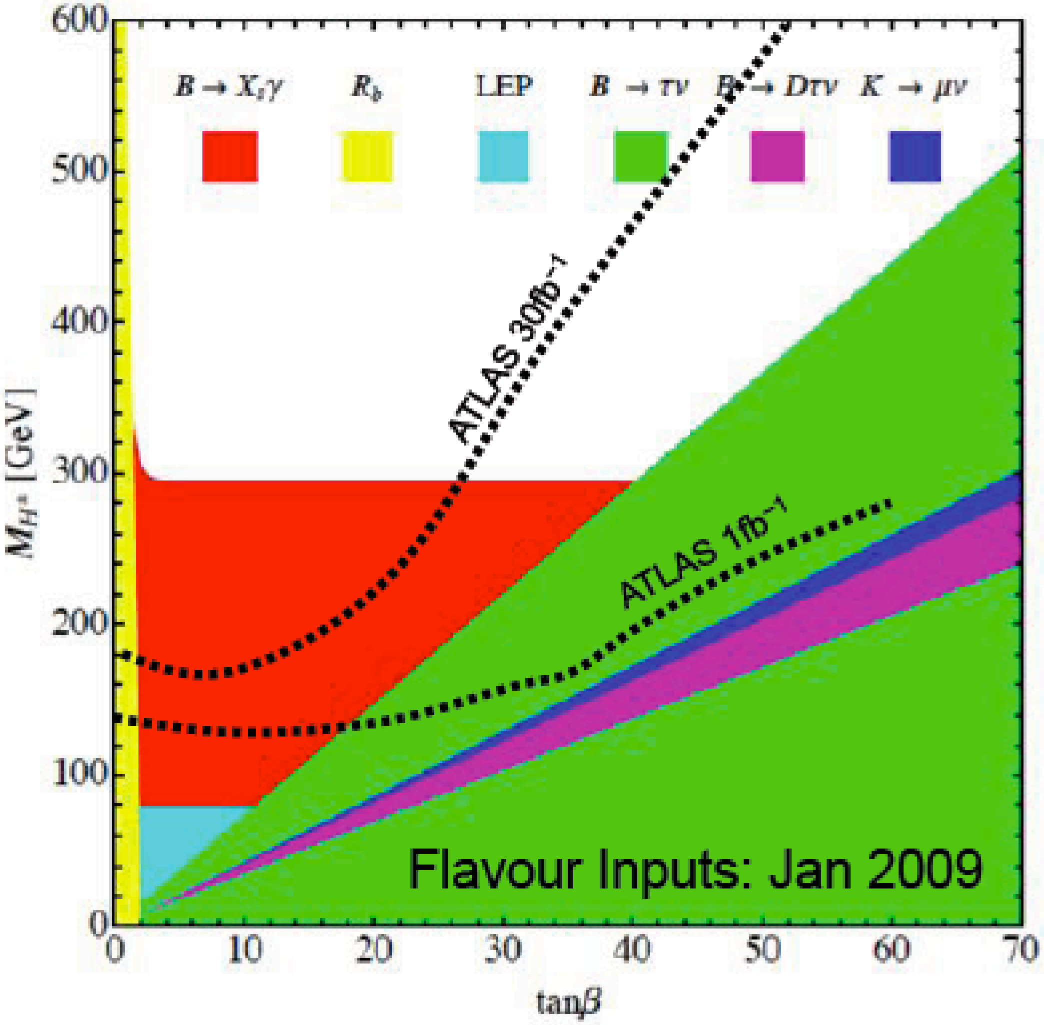


The indirect information will be most valuable when the general nature of new physics will be identified in the direct search, especially when the mass scale of the new physics will be fixed.

$$(C^i_{\text{SM}}/M_W + C^i_{\text{NP}}\,/\Lambda_{\text{NP}} \;) \times \mathcal{O}_i$$

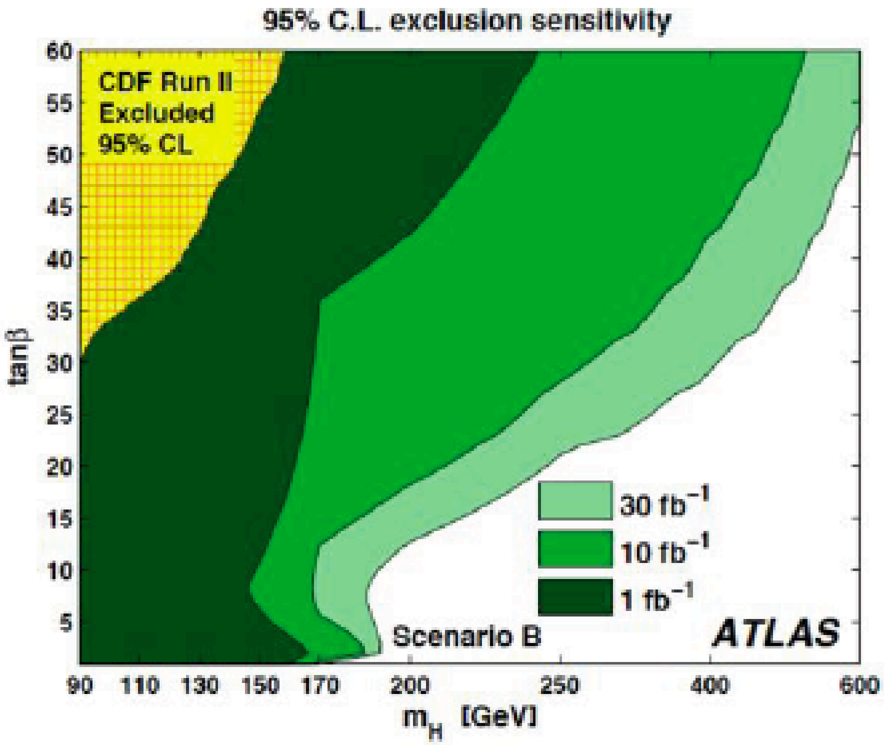
LHC versus flavour constraints

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



U. Haisch 0805.2141
2HDM

Converted constraints expected from ATLAS onto the plot by hand.



Courtesy of Adrian Bevan

LHC versus flavour constraints

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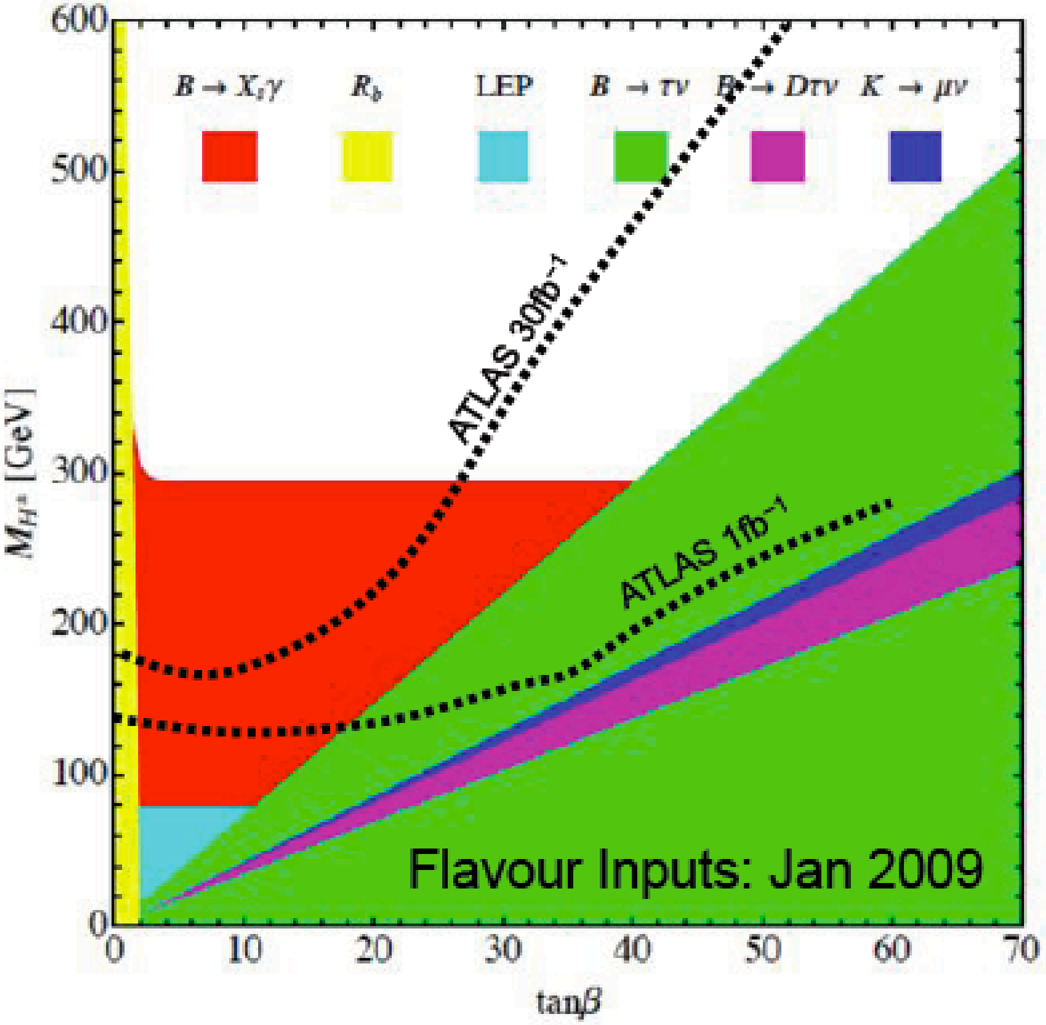

U. Haisch 0805.2141
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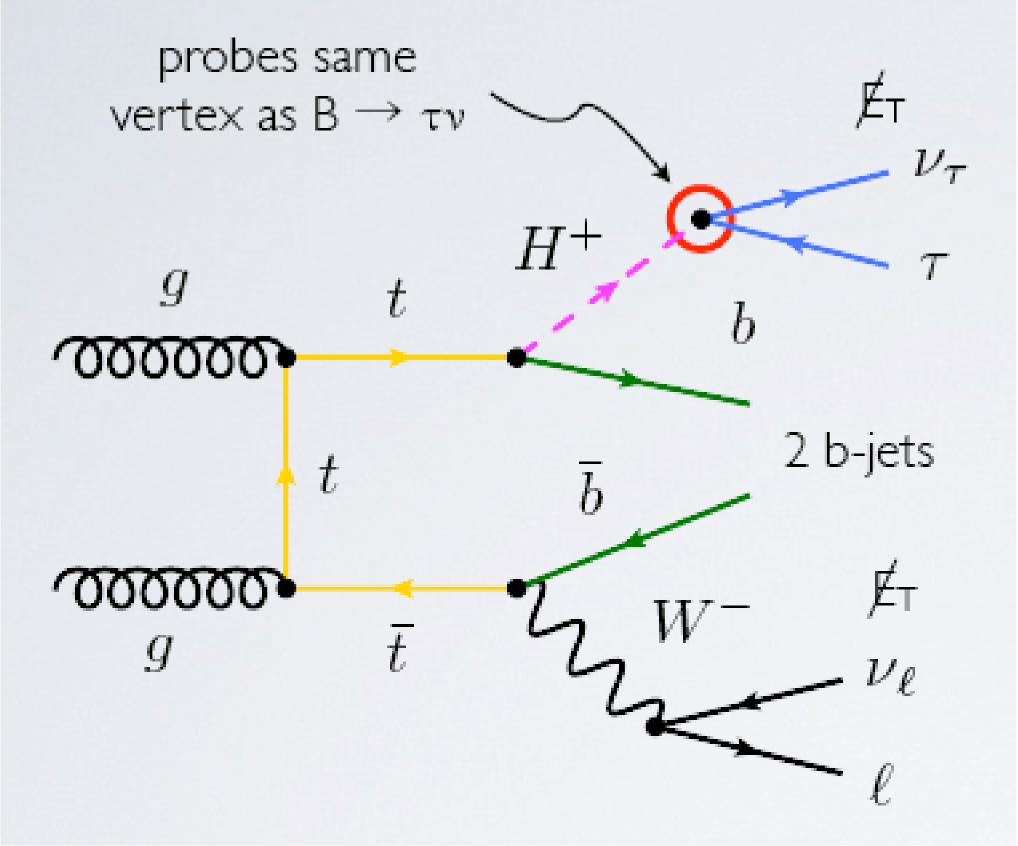

Courtesy of Uli Haisch