Reconstructing Exceptional New Physics

Peter Athron

Contents

- E_6SSM model
- cE_6SSM vs cMSSM
- Mass Spectra
- Phenomenology

Exceptional Supersymmetric Standard Model

[Phys.Rev. D73 (2006) 035009 , Phys.Lett. B634 (2006) 278-284 S.F.King, S.Moretti & R. Nevzorov]

- E_6 inspired model with an extra gauged U(1) symmetry

$$SU(3) \times SU(2) \times U(1)_Y \times U(1)_N \qquad \tan\theta = \sqrt{15}$$

$$U(1)_N = \cos\theta\, U(1)_\chi + \sin\theta\, U(1)_\psi$$

Solves the μ-problem!

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“Inspired” by:

Solves the μ-problem!

$$E_6 \to SO(10) \times U(1)_\psi$$

$$\hookrightarrow SU(5) \times U(1)_\chi$$

$$\hookrightarrow SU(3)_C \times SU(2)_W \times U(1)_Y$$

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$$E_6 \rightarrow SO(10) \times U(1)_\psi$$

$$\hookrightarrow SU(5) \times U(1)_\chi$$

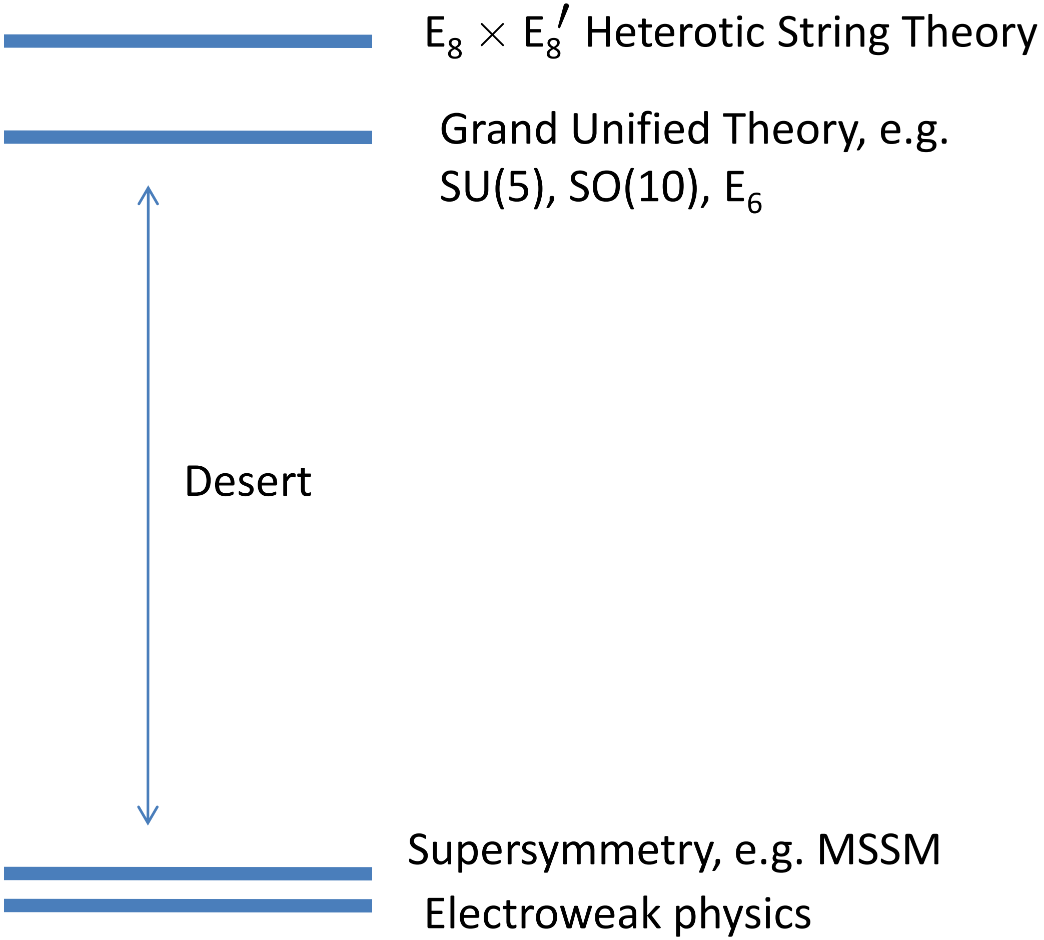
$$\hookrightarrow SU(3)_C \times SU(2)_W \times U(1)_Y$$

- Matter from 3 complete generations of E_6

$\Rightarrow$ automatic cancellation of gauge anomalies

Exceptional New Physics

just beyond the Standard Model



$E_8 \times E_8'$ Heterotic String Theory

Grand Unified Theory, e.g.
SU(5), SO(10), E_6

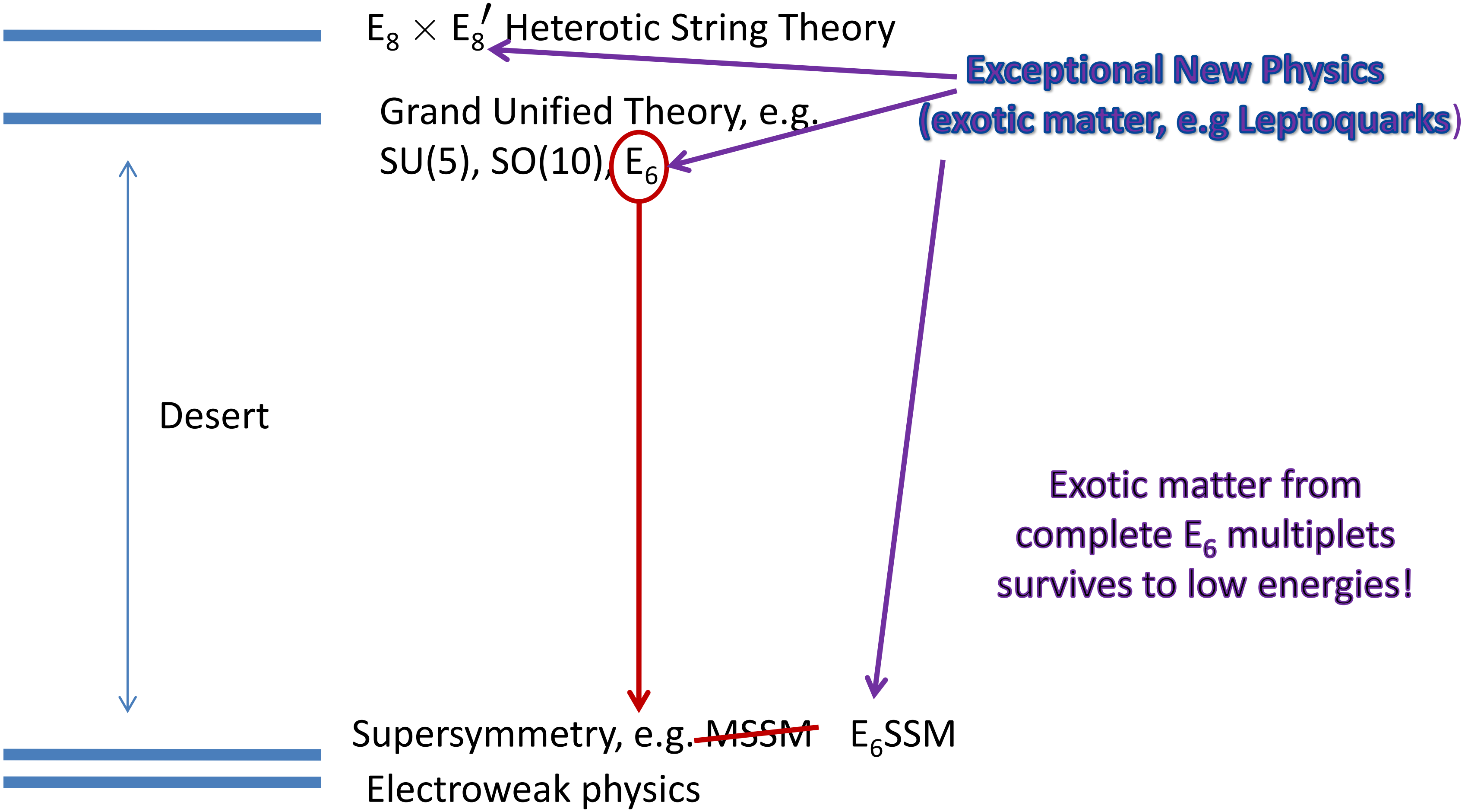
Desert

Supersymmetry, e.g. MSSM

Electroweak physics

Exceptional New Physics

just beyond the Standard Model



$E_8 \times E_8'$ Heterotic String Theory

Grand Unified Theory, e.g.
SU(5), SO(10), E_6

Desert

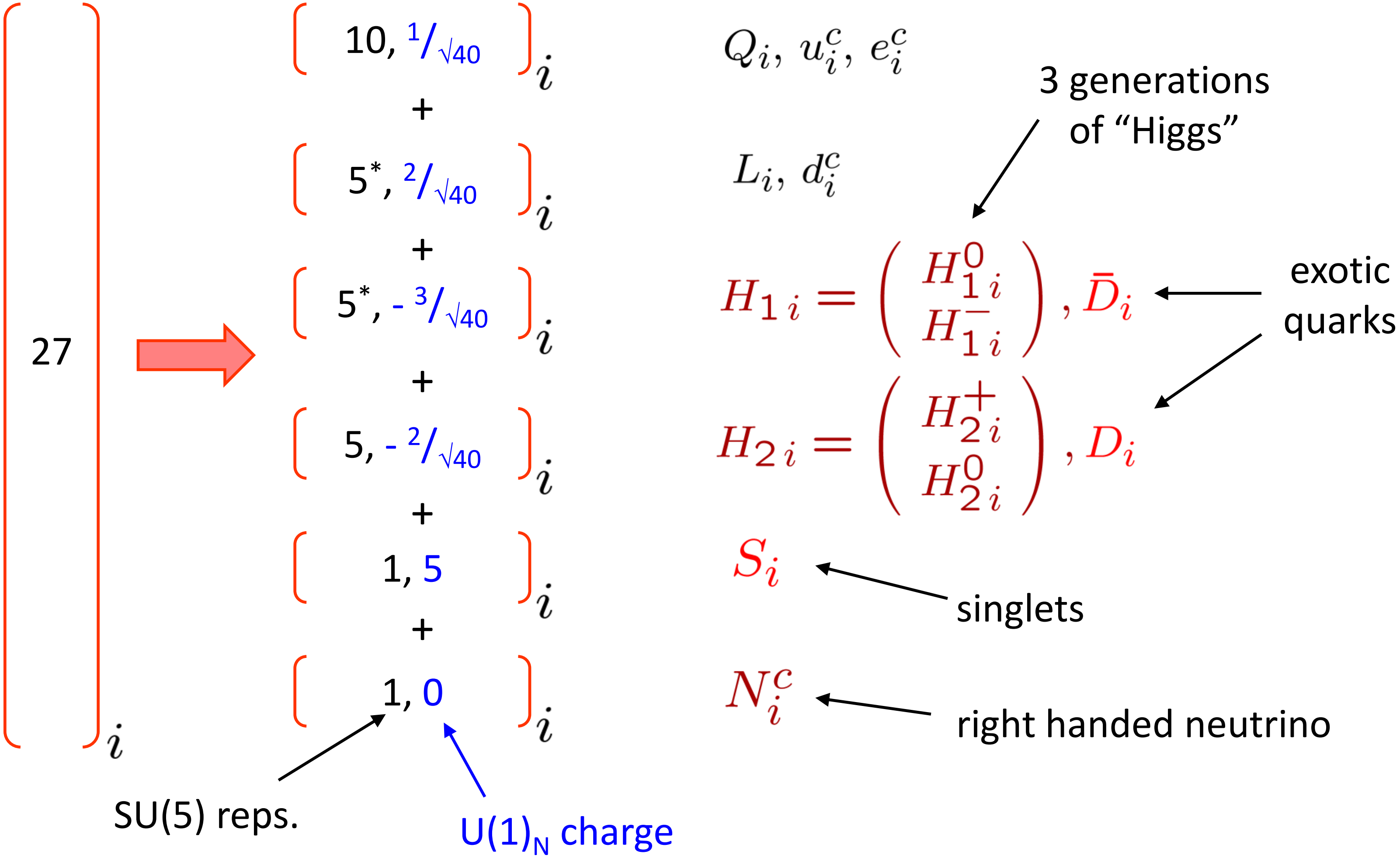
Supersymmetry, e.g. ~~MSSM~~ E_6SSM

Electroweak physics

Exceptional New Physics
(exotic matter, e.g Leptoquarks)

Exotic matter from
complete E_6 multiplets
survives to low energies!

All the SM matter fields are contained in one 27-plet of E_6 per generation.



$$[\,27\,]_i \Rightarrow [\,10, 1/\sqrt{40}\,]_i + [\,5^*, 2/\sqrt{40}\,]_i + [\,5^*, -3/\sqrt{40}\,]_i + [\,5, -2/\sqrt{40}\,]_i + [\,1, 5\,]_i + [\,1, 0\,]_i$$

$Q_i,\ u_i^c,\ e_i^c$

$L_i,\ d_i^c$

$H_{1\,i} = \begin{pmatrix} H_{1\,i}^0 \\ H_{1\,i}^- \end{pmatrix},\ \bar{D}_i$

$H_{2\,i} = \begin{pmatrix} H_{2\,i}^+ \\ H_{2\,i}^0 \end{pmatrix},\ D_i$

S_i

N_i^c

3 generations of “Higgs”

exotic quarks

singlets

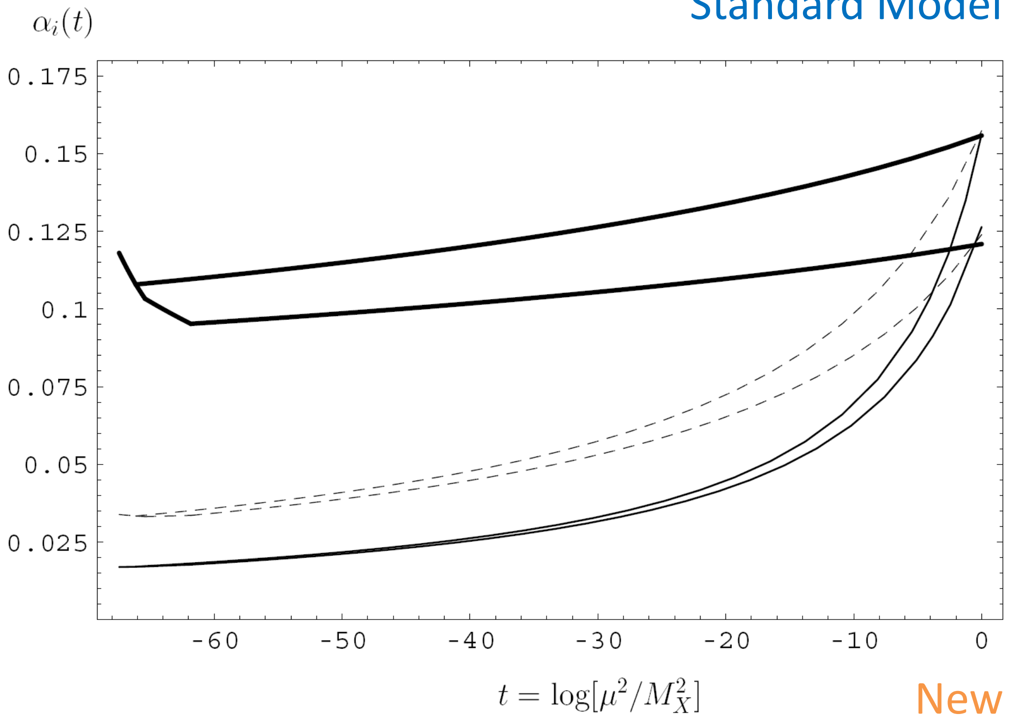
right handed neutrino

SU(5) reps.

$U(1)_N$ charge

Gauge Coupling Unification

Exceptional Supersymmetric Standard Model



- Higgs $\in$ E$_6$ 27plets $\Rightarrow$ relics of $27'$ and $\overline{27}'$, (H' and $\bar{H}'$) .

(for 2step unification without relics see R.Howl, S.F. King PLB 652, 331, JHEP 0801:030)

- Evolution changed dramatically!
- $\beta_s = 0$ at one loop!
- 2-loop and threshold effects important !

New exotic matter!

SU(N) gauge theory

Gauginos

$$b_N = \frac{11}{3}N - \frac{2}{3}N - \frac{1}{3}n_f - \frac{1}{6}n_s$$

U(1) gauge

$$b_1 = -\frac{1}{3}\sum_i Y_i^2$$

Number of fermions

Number of scalars

(matter particles in fundamental representation)

Discrete Symmetries

- **Problem: proton decay**

  - **Solution:** impose Z_2^B or Z_2^L symmety.
    Like R-parity but D is odd, $\tilde{D}$ is even.
    $Z_2^B \Rightarrow$ leptoquarks ; $Z_2^L \Rightarrow$ diquarks.

- **Problem: large Flavour Changing Neutral Currents**,

  - **Solution:** Approximate Z_2^H
    3rd gen Higgs ($H_{1,3}$, $H_{2,3}$ and S_3) : even,
    all others : odd.

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Dropping suppressed term etc. ..

Superpotential

$$\boxed{\begin{aligned} W_{\mathrm{E_6SSM}} \approx\ & \lambda_i S H_{1,i} H_{2,i} + \kappa_i S D_i \bar{D}_i \\ & + h_t H_u Q t^c + h_b H_d Q b^c + h_\tau H_d L \tau^c \end{aligned}}$$

The Constrained E_6SSM

[PA, S.F.King, D.J.Miller, S.Moretti, R.Nevzorov, PRD 80, 035009 (2009), PLB 681, 448-456, (2009)]

- At $M_X \approx 10^{15}$ GeV

$M_{1/2}$	Universal Gaugino Mass
A	Universal trilinear soft mass
m_0	Universal scalar mass

Parameters: $\lambda_i,\ \kappa_i,\ m_0,\ M_{1/2},\ A$

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- Use EWSB Replace soft parameters with $\langle S \rangle = \frac{s}{\sqrt{2}},\ M_Z,\ \tan\beta$

Free Parameters: $\lambda_i,\ \kappa_i,\ s$

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Renormalisation Group Equations (RGEs)

- To connect these high scale conditions with low energies we use RGEs for:
  - Gauge and Yukawa couplings (2 loop).
  - Soft breaking gaugino and trilinear masses (2 loop).
  - Soft scalar masses (1 loop).

cMSSM vs cE$_6$SSM

	cMSSM	cE$_6$SSM
$Q = M_X$	$m_0, M_{1/2}, A, \mu, B\mu$ $g_0, y_t, y_b, y_\tau \cdots$	$m_0, M_{1/2}, A$ $\lambda_i, \kappa_i, g_0, y_t, y_b, y_\tau \cdots$
	↓ RGEs	↓ RGEs
$Q = M_{EW}$	$\frac{\partial V_H}{\partial H_u} = \frac{\partial V_H}{\partial H_d} = 0$ $\lvert\mu\rvert \to M_Z$ $B\mu \to \tan\beta$	$\frac{\partial V_H}{\partial H_u} = \frac{\partial V_H}{\partial H_d} = \frac{\partial V_H}{\partial H_s} = 0$ $\{m_0, M_{1/2}, A\} \to \{M_Z, \tan\beta, s\}$
User Inputs	$m_0, M_{1/2}, A,$ $\tan\beta, sign(\mu)$	$\lambda_i, \kappa_i, \tan\beta, s$

Particle Masses

For full expressions used see [PA, S.F.King, D.J.Miller, S.Moretti, R.Nevzorov, PRD 80, 035009 (2009)]

- Quarks/lepton masses

$$m_i = \frac{y_i(M_S)}{\sqrt{2}} v_j$$

- squarks/slepton masses

(3rd Gen Only)

$$M_i \approx m_i + \frac{y_i(M_S)}{\sqrt{2}} v_j + \triangle_i + \text{mixing}$$

Soft mass

fermion mass

Aux. D-term (inc. new $U(1)_N$ term $\propto s^2$)

- Neutralinos, charginos and gluino:

$$m_{\tilde{\chi}_1^0} \approx M_1$$

$$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx M_2$$

$$m_{\tilde{\chi}_{5,6}^0} \approx M_{Z'}$$

1-loop **shift** to pole (exotics not included)

$$m_{\tilde{g}} \approx M_3 + \triangle_g$$

$$m_{\tilde{\chi}_{3,4}^0} \approx m_{\tilde{\chi}_2^\pm} \approx \mu = \frac{\lambda s}{\sqrt{2}}$$

- Higgs bosons

$$m_{h_1} \approx M_Z + \Delta$$

(Includes two loop contributions)

$$m_{h_2} \approx m_{H^\pm} \approx m_A$$

$$m_{h_3} \approx M_{Z'}$$

- Exotic quarks masses

$$\mu_{D_i} = \frac{\kappa_i(M_S)}{\sqrt{2}} s$$

- Exotic squarks masses

$$M_{D_i} \approx \underset{\underset{\text{Soft mass}}{\nearrow}}{m_{D_i}} + \underset{\underset{\text{fermion mass}}{\uparrow}}{\frac{\kappa_i(M_S)}{\sqrt{2}} s} + \underset{\underset{\text{Aux. D term contribution to mass}}{\uparrow}}{\triangle_D} + \text{mixing}$$

- Inert Higgsino masses

$$m_{\tilde{H}_i} \approx \frac{\lambda_i(M_S)}{\sqrt{2}} s$$

- Inert Higgs masses

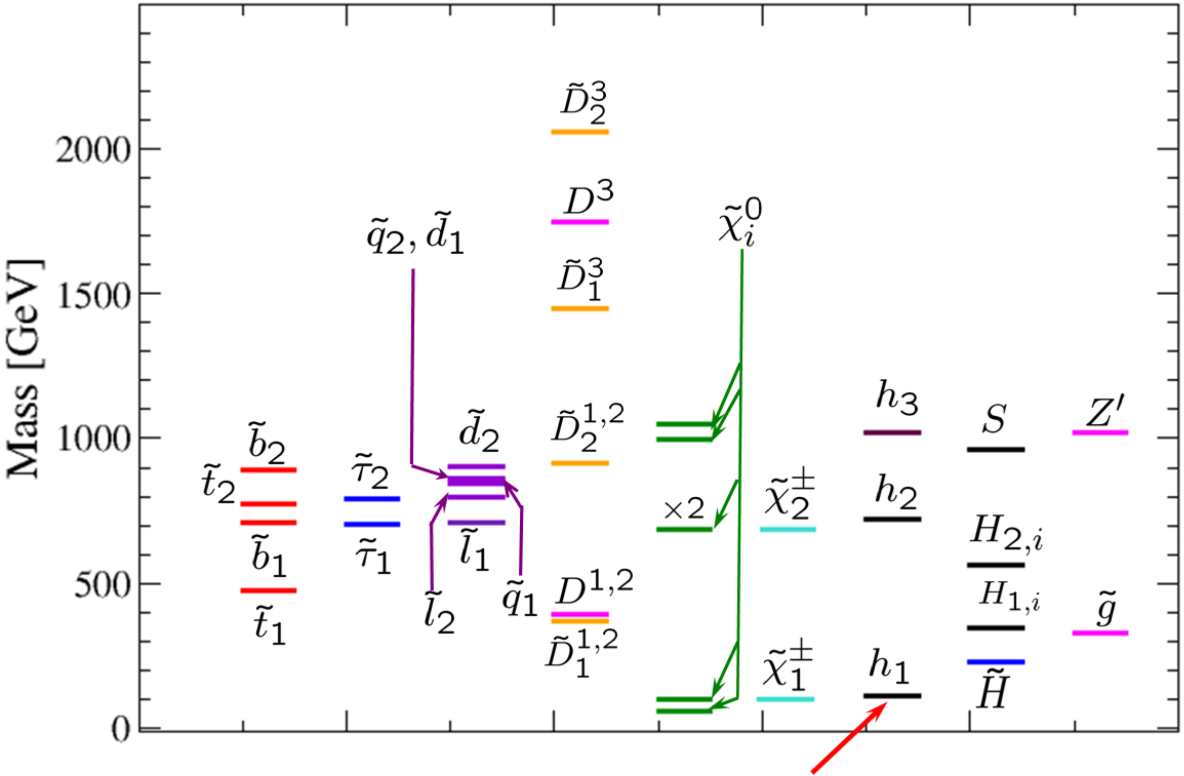
$$\underset{\underset{\text{Soft mass}}{\nearrow}}{m_{H_i}} + \underset{\underset{\text{fermion mass}}{\uparrow}}{\frac{\lambda_i(M_S)}{\sqrt{2}} s} + \underset{\underset{\text{Aux. D term contribution to mass}}{\uparrow}}{\triangle_{H_i}} + \text{mixing}$$

- Exotic Z′ gauge boson

$$M_{Z'} \approx g_1' Q_S s = \frac{5 g_1' s}{\sqrt{40}}$$

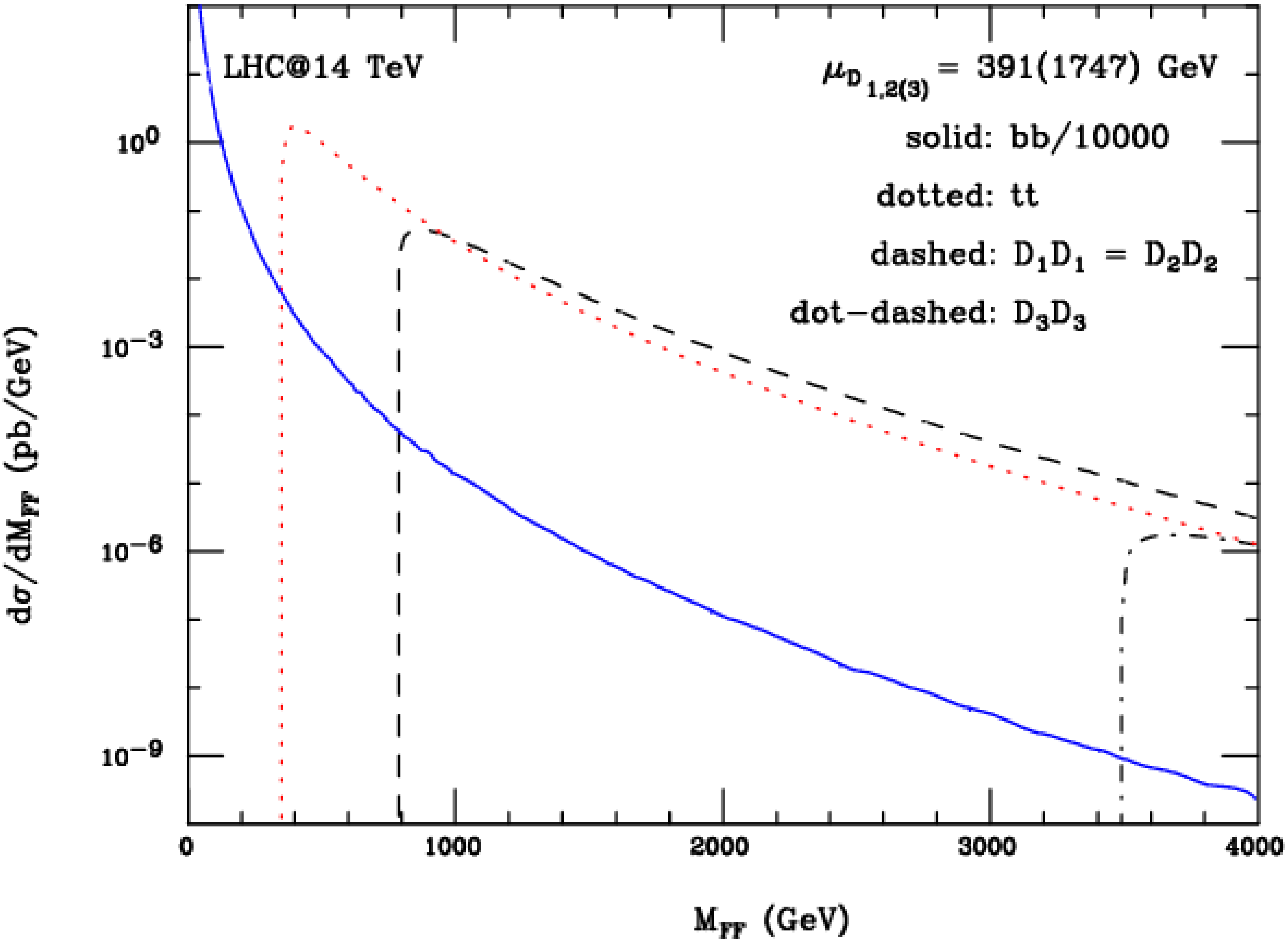
Scenario (Light exotic fermions and scalars)

- Large κ drives electroweak symmetry breaking
- With a universal exotic coupling κ at the GUT scale
  $\Rightarrow$ exotic quarks are always heavy ($\mu_D = \frac{\kappa_i(M_S)}{\sqrt{2}} s$)
- Break κ universality and exotic quarks can be light



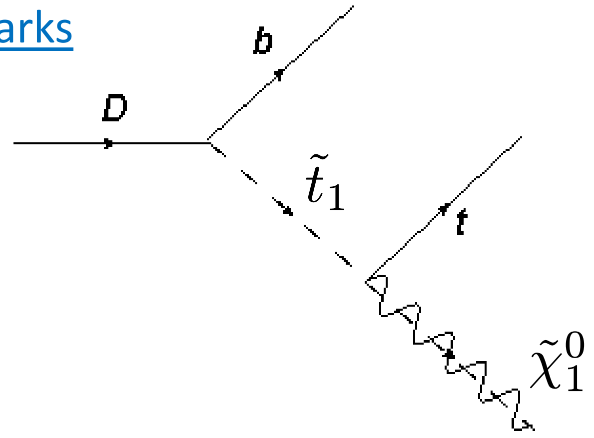
$m_{h_1} = 114$ GeV (approx. two loop)

$$\tan\beta = 10,$$
$$s = 2.7 \text{ TeV},$$
$$M_{1/2} = 358 \text{ GeV},$$
$$m_0 = 623 \text{ GeV},$$
$$A = 757 \text{ GeV}$$
$$\lambda(M_X) = -0.40,$$
$$\lambda_{1,2}(M_X) = 0.1$$
$$\kappa_{1,2}(M_X) = 0.08,$$
$$\kappa_3(M_X) = 0.43$$


LHC@14 TeV
$\mu_{D_{1,2(3)}}$ = 391(1747) GeV
solid: bb/10000
dotted: tt
dashed: $D_1D_1 = D_2D_2$
dot–dashed: D_3D_3
10^0
10^{-3}
10^{-6}
10^{-9}
$d\sigma/dM_{FF}$ (pb/GeV)
0
1000
2000
3000
4000
M_{FF} (GeV)

Exotic Signatures

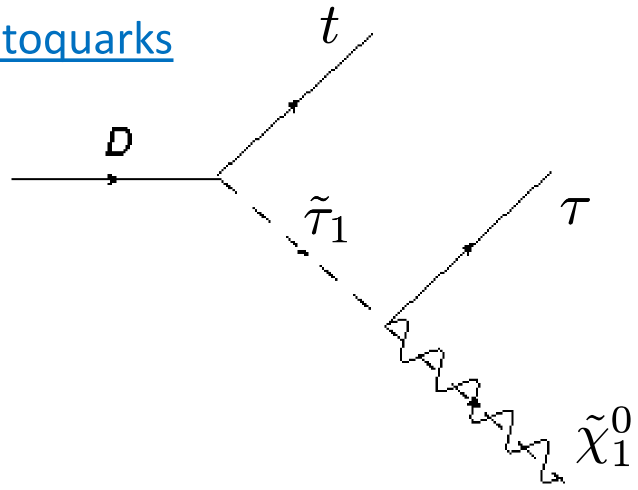
Diquarks



Enhancement of

$$pp \rightarrow t\bar{t}b\bar{b} + E_T^{miss} + X$$

Leptoquarks



$$pp \rightarrow t\bar{t}\tau\bar{\tau} + E_T^{miss} + X$$

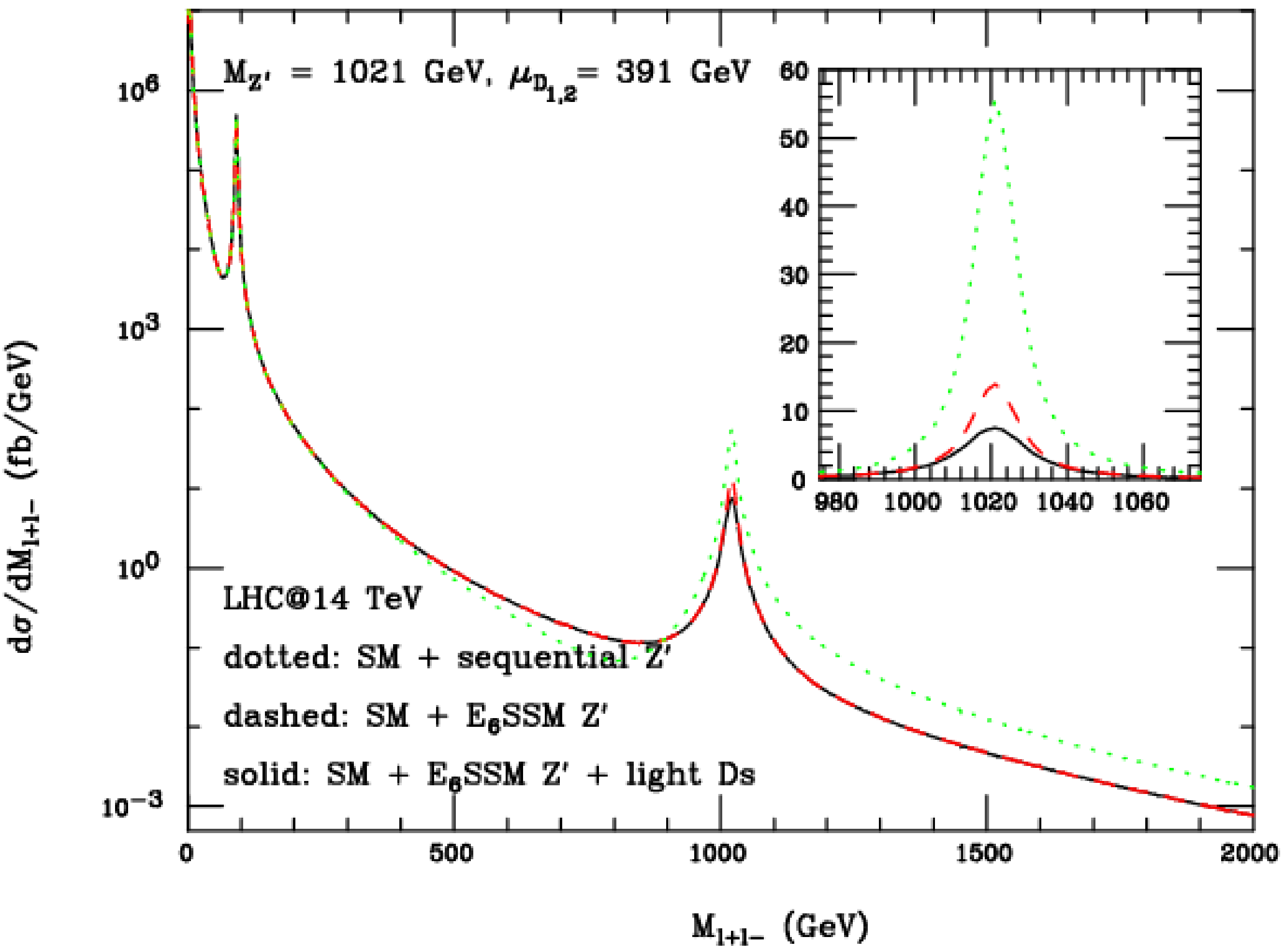
$$pp \rightarrow b\bar{b} + E_T^{miss} + X$$

Scalar partners

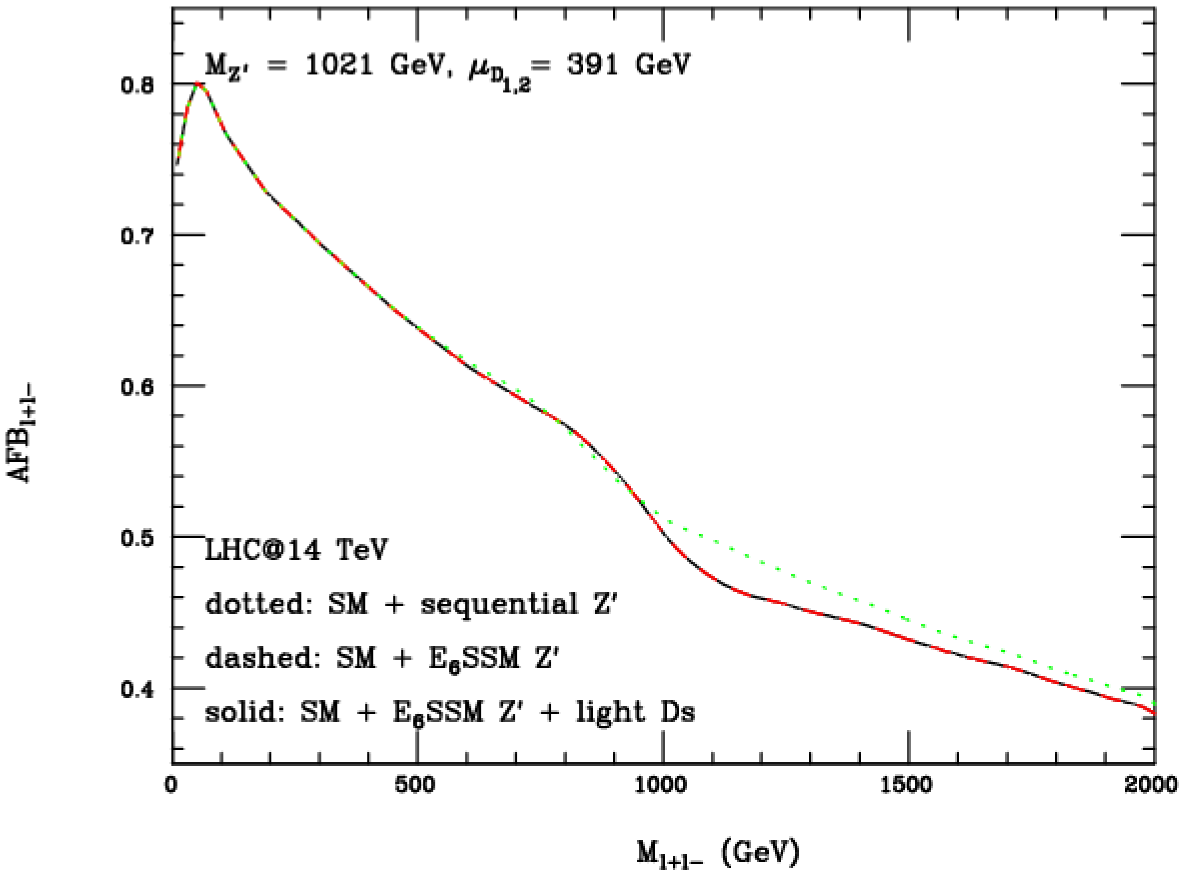
Scalar $\tilde{D}$ similar, but without missing energy from χ_1^0

e.g. $pp \rightarrow t\bar{t}\tau\bar{\tau} + X$

Drell Yan Line Shape



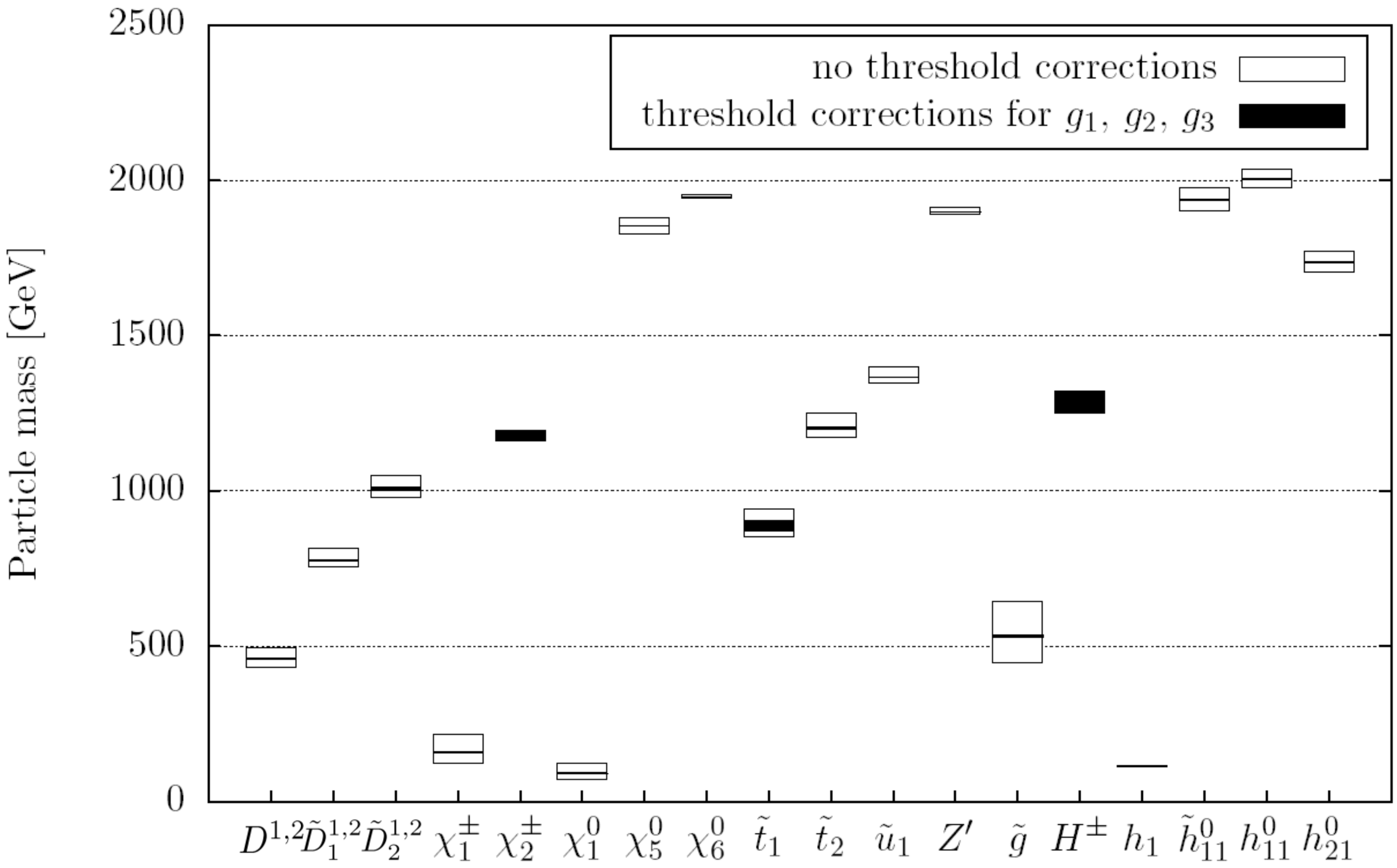
Forward-Backward Asymmetry



Improved precision

[With A. Voigt and D. Stockinger]

- Individual sparticle thresholds included for gauge couplings.
- Large reduction in threshold scale dependence.
- Residual dependence from Yukawa thresholds (adding now)

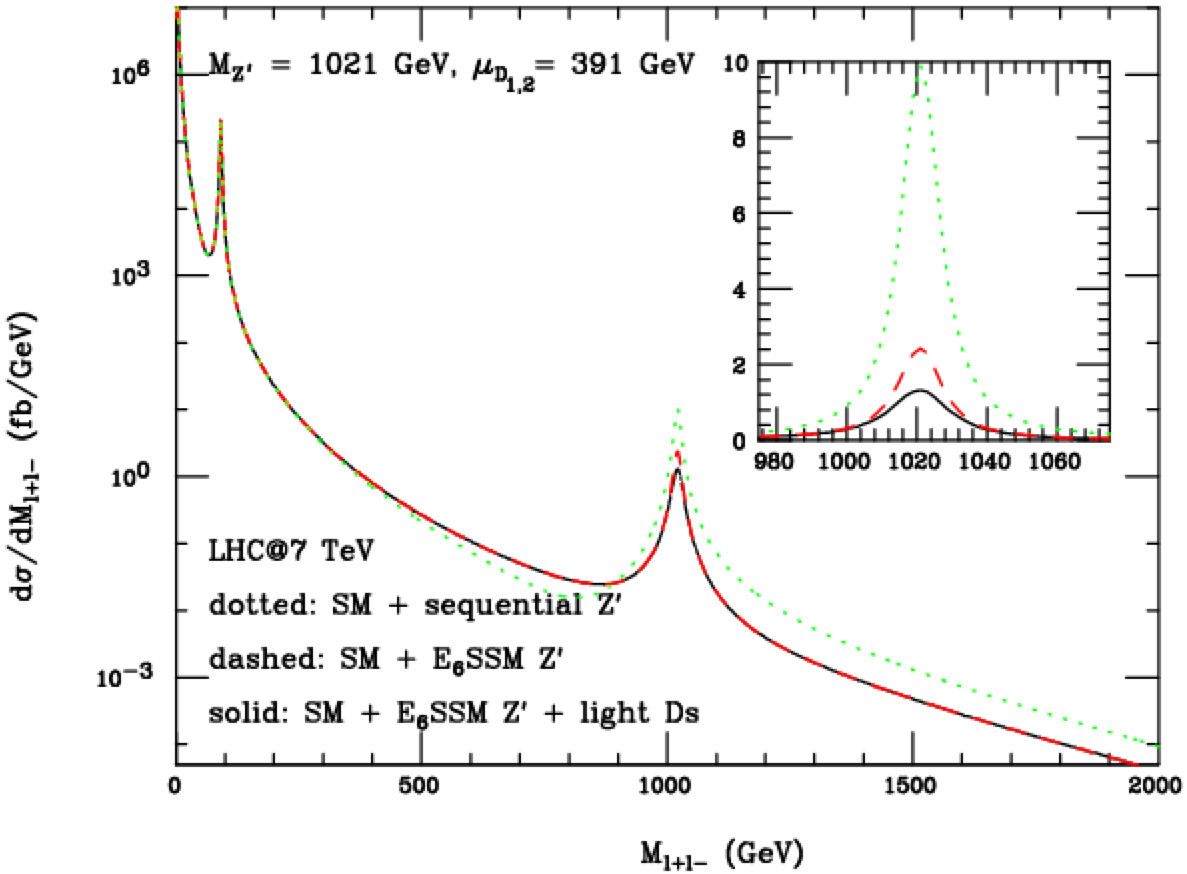


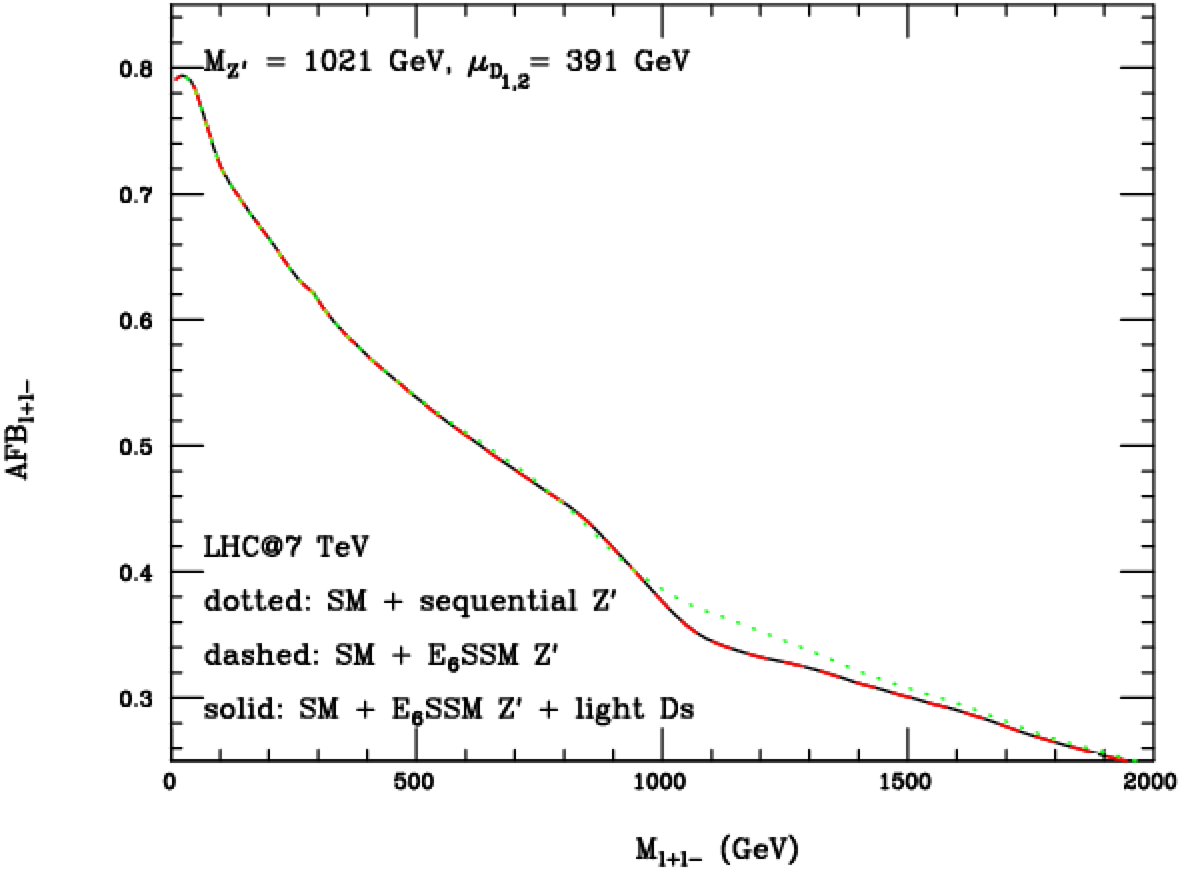
Conclusions

- E_6 / extra U(1) SUSY models, well motivated
- cE_6SSM is an exceptional example.
  - Private cE_6SSM spectrum generator exists. $\Rightarrow$ all mass observables.
  - Precision recently improved. More can be done.
  - General prediction of heavy sfermions and light gluino
- Phenomenology of the cE_6SSM:
  - Exotic quark production cross section,
  - Z' decay widths
  - Forward-backward asymmetry (charge discrimination)

- Extracting cE_6SSM from data:
  - Extremely important ~~if~~ when E_6SSM like signatures are observed.
  - Low energy observables.
  - Cross sections.
  - Incorporation within Fittino / interfacing
  - Lots to do…work in progress…

BACK UP SLIDES


$M_{Z'}$ = 1021 GeV, $\mu_{D_{1,2}}$= 391 GeV
LHC@7 TeV
dotted: SM + sequential Z′
dashed: SM + E_6SSM Z′
solid: SM + E_6SSM Z′ + light Ds
$d\sigma/dM_{l+l-}$ (fb/GeV)
M_{l+l-} (GeV)
10^6
10^3
10^0
10^{-3}
0
500
1000
1500
2000
10
8
6
4
2
0
980
1000
1020
1040
1060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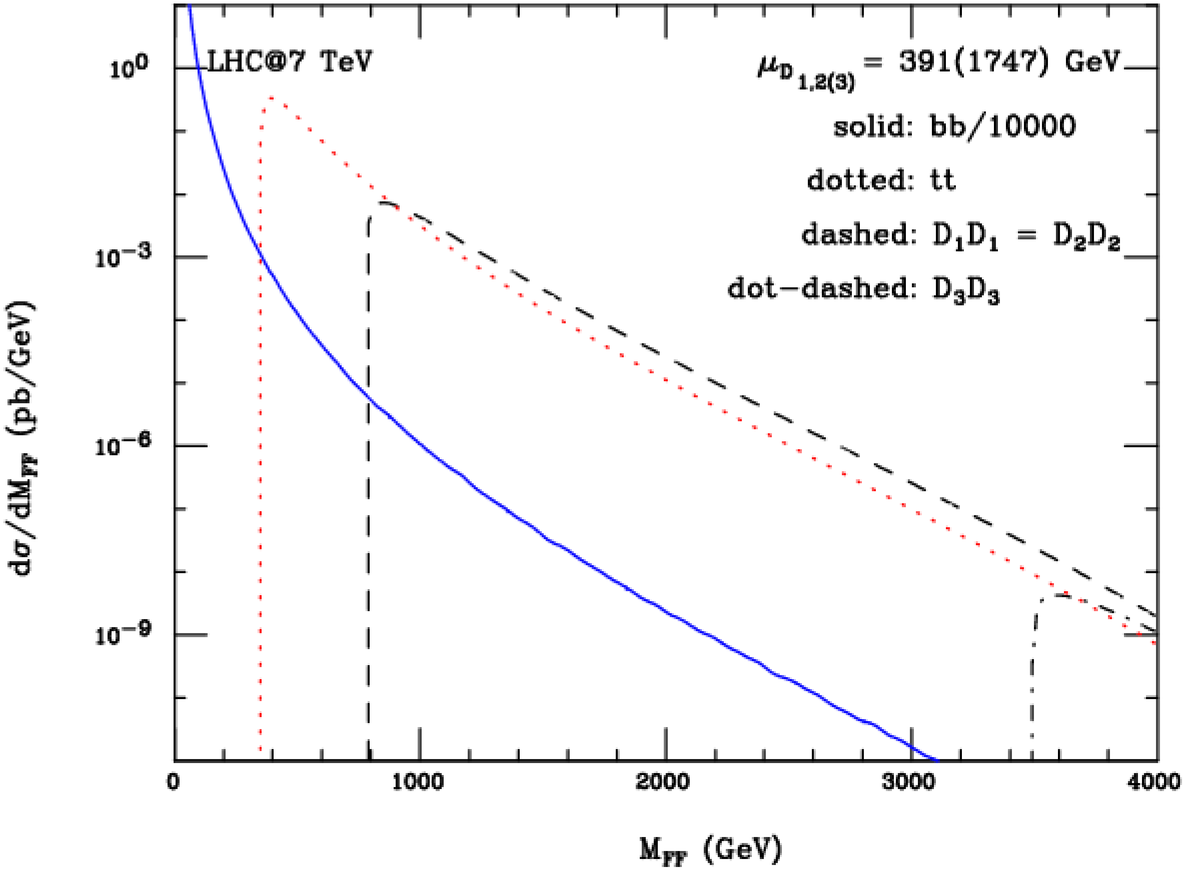
LHC@7 TeV
dotted: SM + sequential Z′
dashed: SM + E_6SSM Z′
solid: SM + E_6SSM Z′ + light Ds
AFB_{l+l-}
M_{l+l-} (GeV)
0.8
0.7
0.6
0.5
0.4
0.3
0
500
1000
1500
2000


LHC@7 TeV
$\mu_{D_{1,2(3)}}$ = 391(1747) GeV
solid: bb/10000
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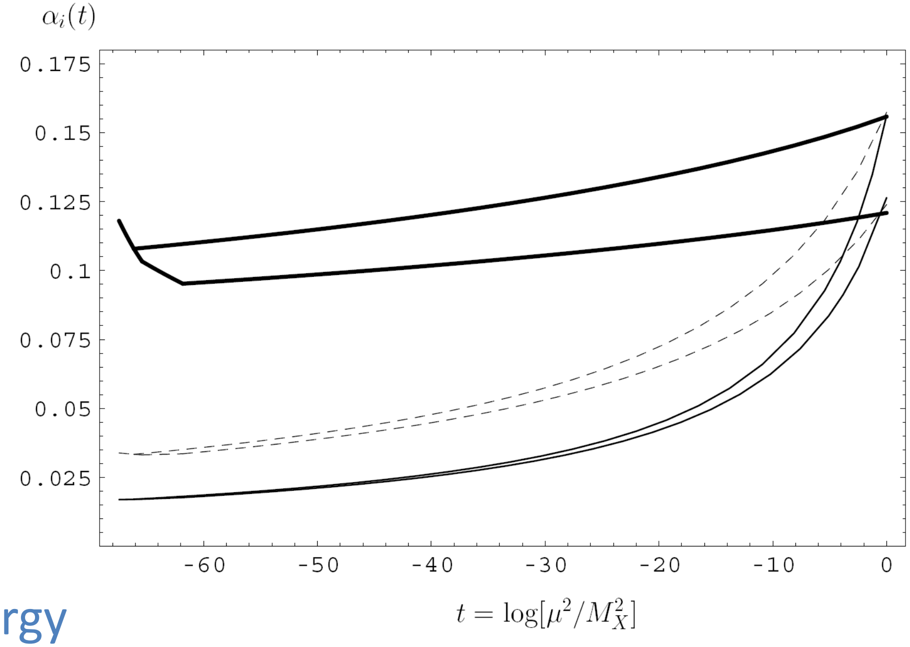
10^0
10^{-3}
10^{-6}
10^{-9}
$d\sigma/dM_{FF}$ (pb/GeV)
0
1000
2000
3000
4000
M_{FF} (GeV)

Threshold Corrections

(In collaboration with Dominik Stockinger and Alexander Voigt)

- Varying $T_{ESSM} \Rightarrow$ 10 -15% effect
- Obstacle for precision calculations
- Solution: include individual sparticle thresholds iteratively.



Full theory

Energy

Particles: Heavy, masses M_i

Light, masses m_i

Couplings: $g''_{ij} M_i M_j \; g'_{ij} m_i M_j$

$g^F_{ij} m_i m_j$

$T_M \leq M_i$

$g^F_{ij} = g^E_{ij} + \zeta_{ij}$

Matching scale

Matching scale

Effective theory

Particles: Light only , masses m_i

Couplings: $g^E_{ij} m_i m_j$

Equate Green's Functions

Energy

Effective coupling

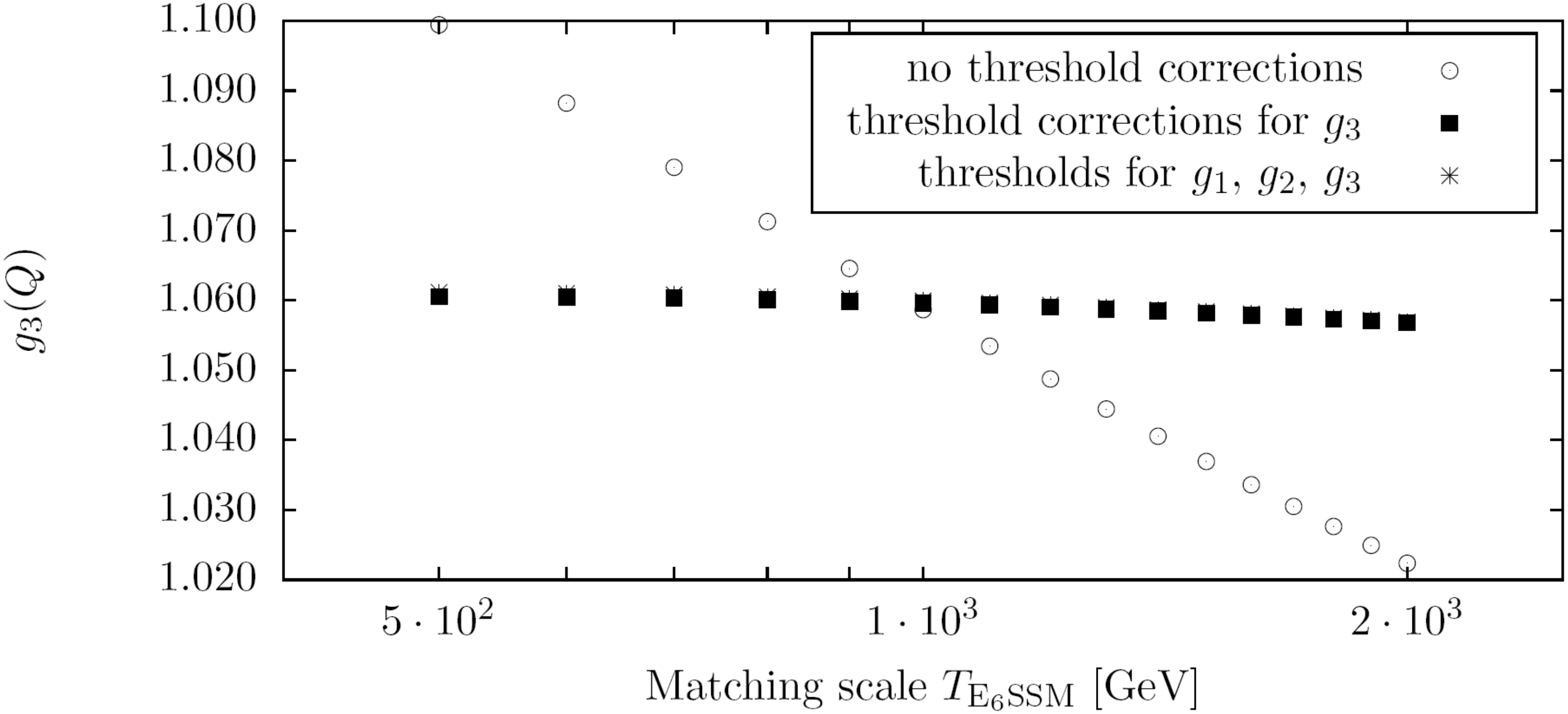
$$\frac{1}{g_i^2} - \frac{1}{\hat{g}_i^2} = C_i - \sum_f \frac{1}{24\pi^2} \ln \frac{m_f}{T} - \sum_s \frac{1}{48\pi^2} \ln \frac{m_s}{T} - \frac{2N}{24\pi^2} \ln \frac{m_{\tilde{g}}}{T}$$

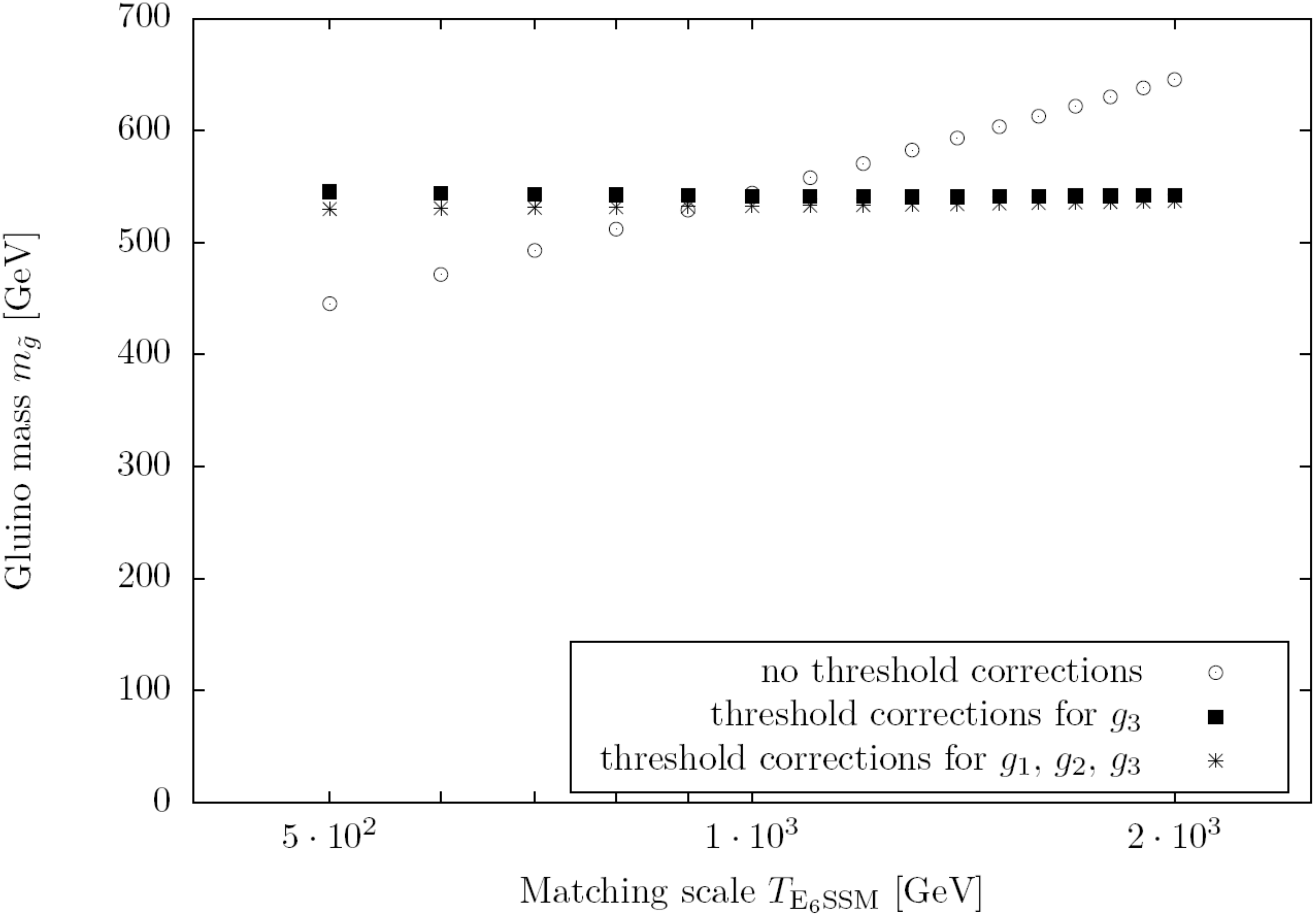
Vanishes for DR-bar couplings

Integrated out fermions

Integrated out scalars

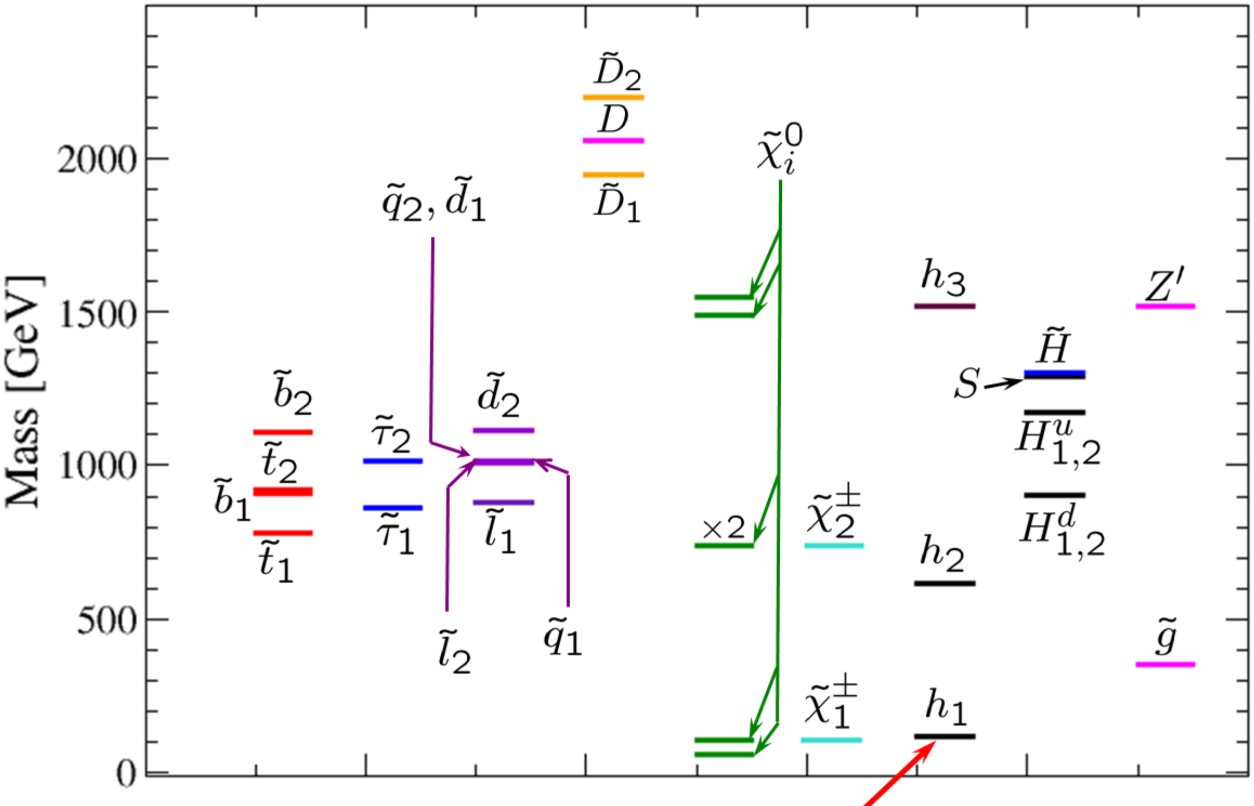
Integrated out gauginos




Gluino mass $m_{\tilde{g}}$ [GeV]
700
600
500
400
300
200
100
0
$5 \cdot 10^2$
$1 \cdot 10^3$
$2 \cdot 10^3$
Matching scale $T_{\mathrm{E_6SSM}}$ [GeV]
no threshold corrections ⊙
threshold corrections for g_3 ■
threshold corrections for g_1, g_2, g_3 ✳

Caution: It is possible all the exotics are heavy and challenging to detect, e.g.

Scenario B (Pessimistic)

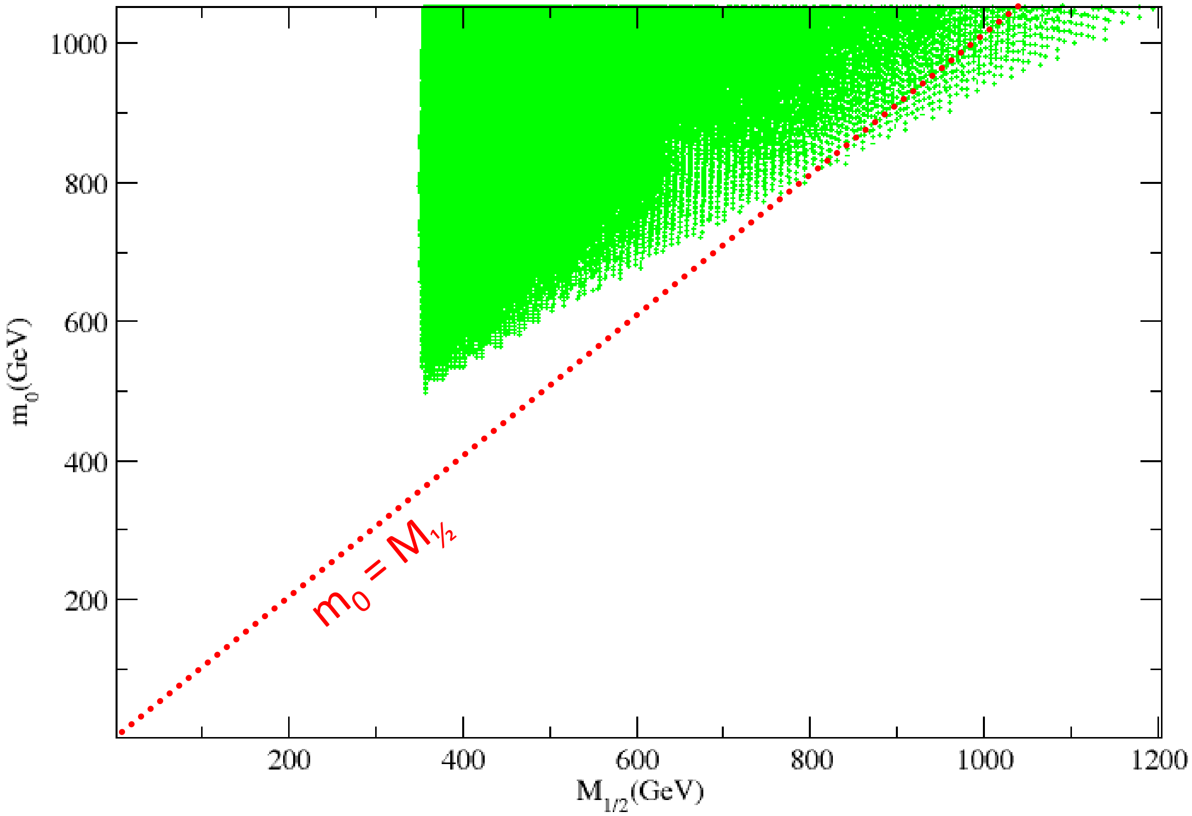


$m_{h_1} = 116$ GeV (approx. two loop)

$$
\begin{aligned}
\tan\beta &= 10, \\
s &= 4.0\ \text{TeV} \\
M_{1/2} &= 389\ \text{GeV}, \\
m_0 &= 725\ \text{GeV}, \\
A &= -1528\ \text{GeV} \\
\lambda(M_X) &= -2.0, \\
\lambda_{1,2}(M_X) &= 2.6 \\
\kappa_{1,2,3}(M_X) &= 2.5,
\end{aligned}
$$

Allowed regions in the m_0 - $M_{½}$ plane

Fix $\tan\beta = 10,$ $\lambda_{1\ 2}$= 0.1, vary λ_3 and $\cdot = \cdot_{1,2,3}$ and s:



: since m_0, $M_{1/2}$ are derived, some possible regions are sparsely populated

- It is possible all the exotics are heavy and challenging to detect

- Even in such a scenario there is still a striking prediction, which is a general result of the cE$_6$SSM.

  - All spectra have a clear hierarchy
  - Gluino is lighter than all sfermions of ordinary matter
  - Strong contrast with typical MSSM scenario
  - Result of the RGE evolution
  - Decay $\tilde{g} \to \bar{q}\tilde{q}^* \to q\bar{q} + E_T^{Miss}$

  - $\Rightarrow$ Appreciable enhancement of:

$$pp \to q\bar{q}q\bar{q} + E_T^{Miss} + X$$