Reconstructing Exceptional New Physics from LHC data

Peter Athron

Contents

- Title is a little aspirational – Not there yet!

- E_6SSM model
- cE_6SSM
- Mass Spectra
- Phenomenology
- Improved Precision

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Road map

- E_6SSM model
- cE_6SSM
- Mass Spectra
- Phenomenology
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Understand the model

What does it look like?

Signatures

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- E_6SSM model
- cE_6SSM

} Understand the model

- Mass Spectra — What does it look like?
- Phenomenology — Signatures
- Improved Precision — parameters ⇔ masses

precision low energy observables

Incorporate within a fitting package, e.g. Fittino

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:

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

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

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

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

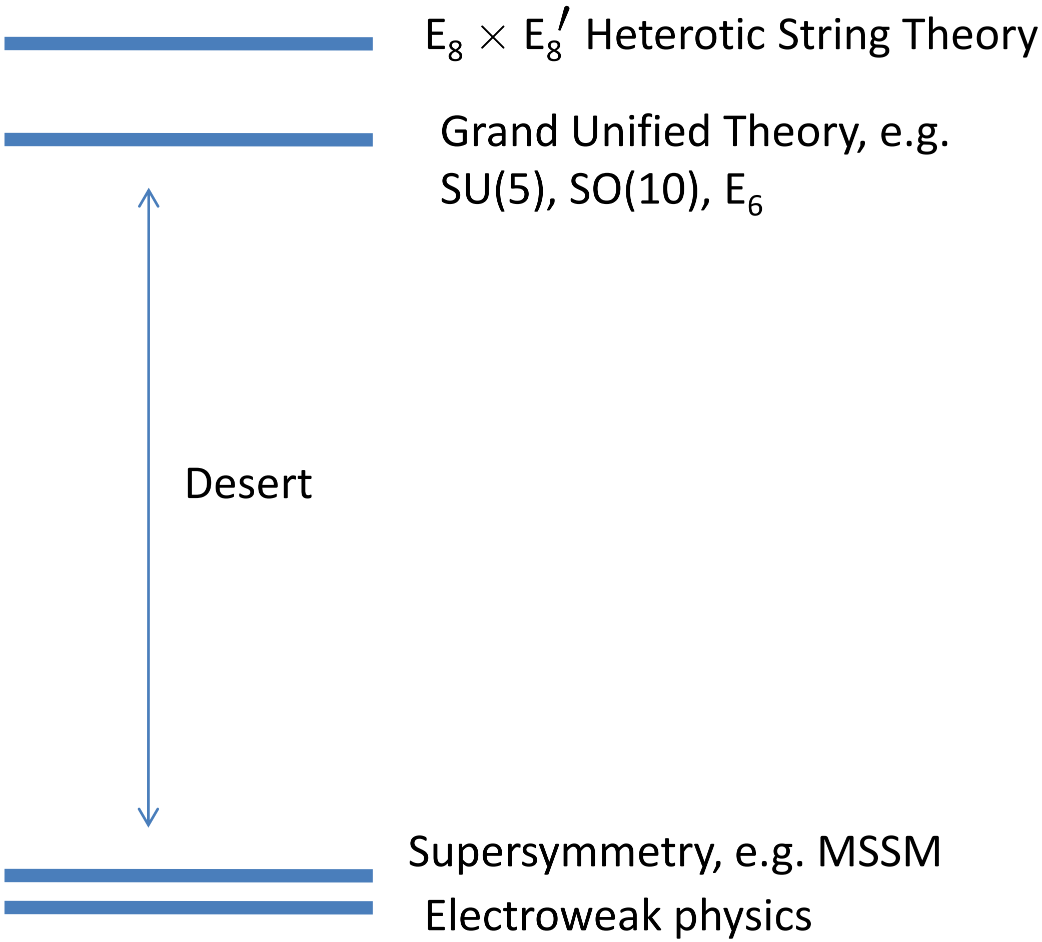
$$\hookrightarrow SU(3)_C \times SU(2)_W \times U(1)_Y$$

- Matter from 3 complete generations of E_6

$\Rightarrow$ automatic cancellation of gauge anomalies

Exceptional New Physics

just beyond the Standard Model



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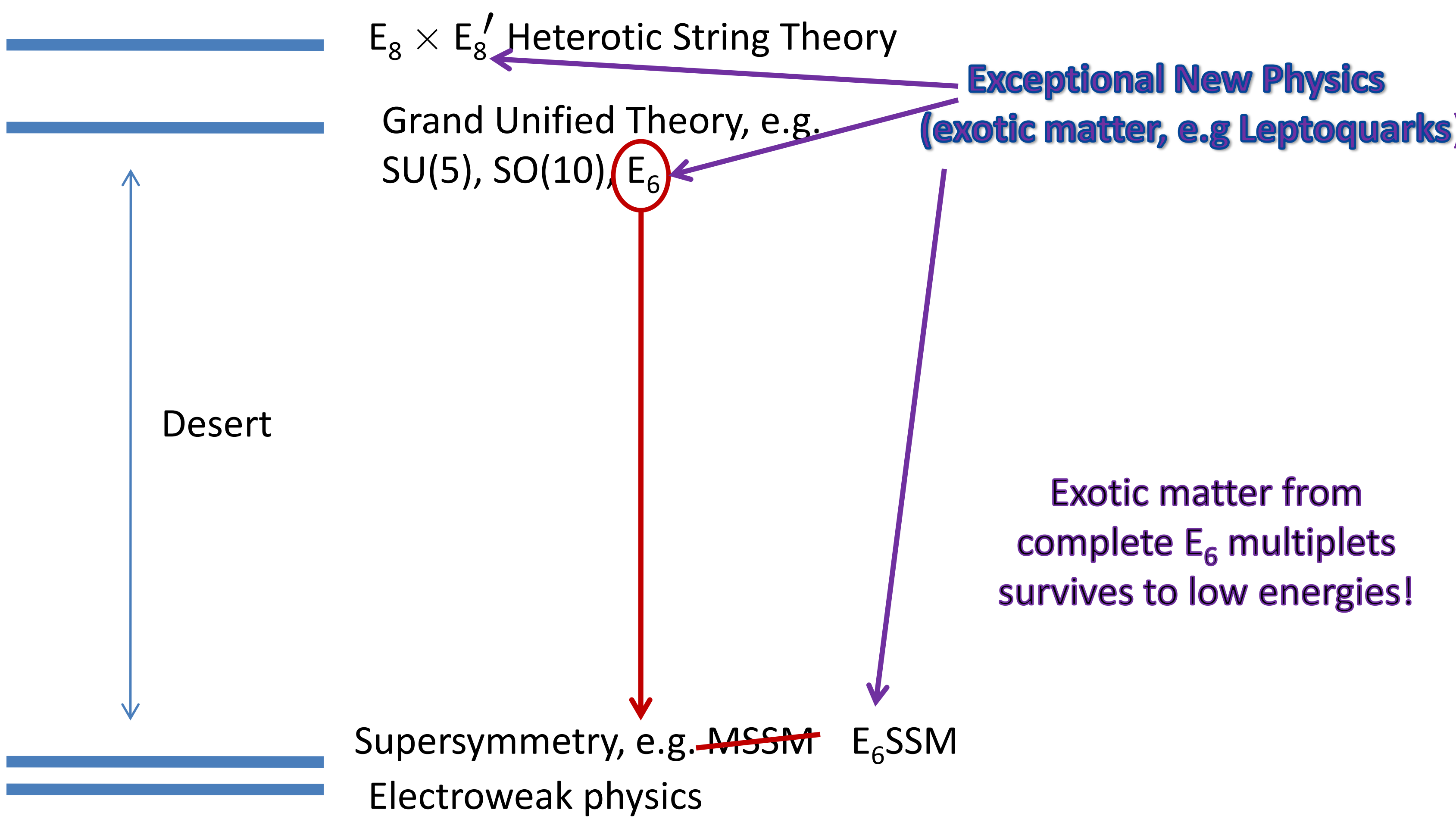


All the SM matter fields are contained in one 27-plet of E_6 per generation.

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

$[10, 1/\sqrt{40}]_i$: $Q_i,\ u_i^c,\ e_i^c$

$[5^*, 2/\sqrt{40}]_i$: $L_i,\ d_i^c$

$[5^*, -3/\sqrt{40}]_i$: $H_{1\,i} = \begin{pmatrix} H^0_{1\,i} \\ H^-_{1\,i} \end{pmatrix},\ \bar{D}_i$

$[5, -2/\sqrt{40}]_i$: $H_{2\,i} = \begin{pmatrix} H^+_{2\,i} \\ H^0_{2\,i} \end{pmatrix},\ D_i$

$[1, 5]_i$: S_i ← singlets

$[1, 0]_i$: N_i^c ← right handed neutrino

3 generations of "Higgs" ($H_{1\,i}$, $H_{2\,i}$)

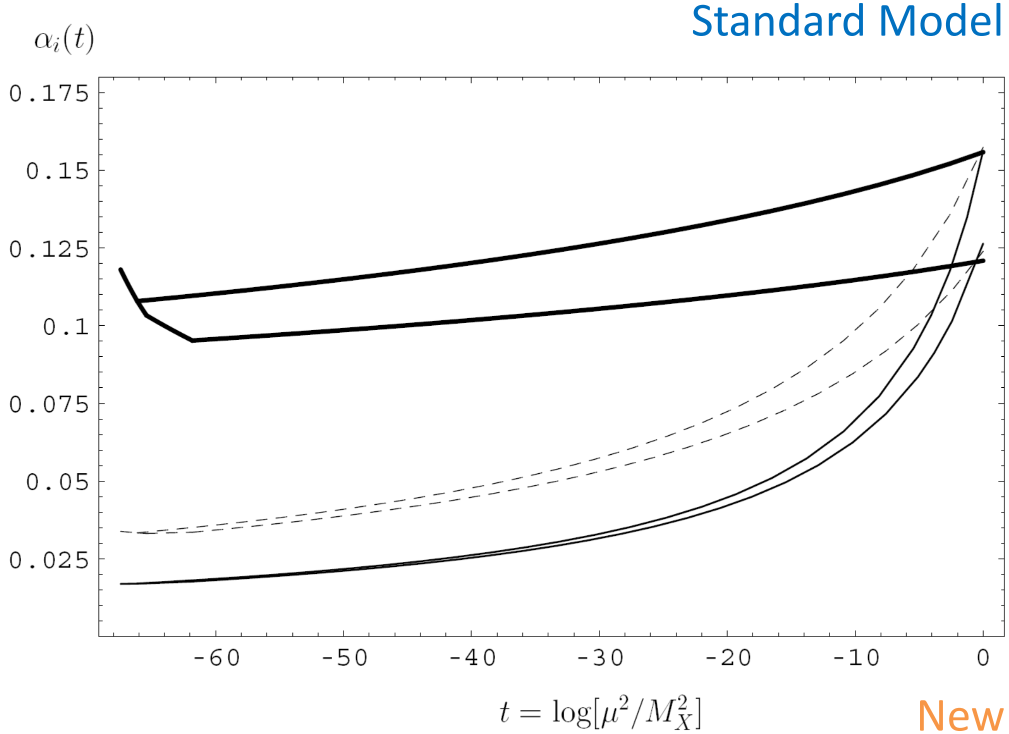
exotic quarks ($\bar{D}_i$, D_i)

SU(5) reps.

$U(1)_N$ charge

Gauge Coupling Unification

Excepional 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 !

SU(N) gauge theory

Gauginos

New exotic matter!

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

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

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

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

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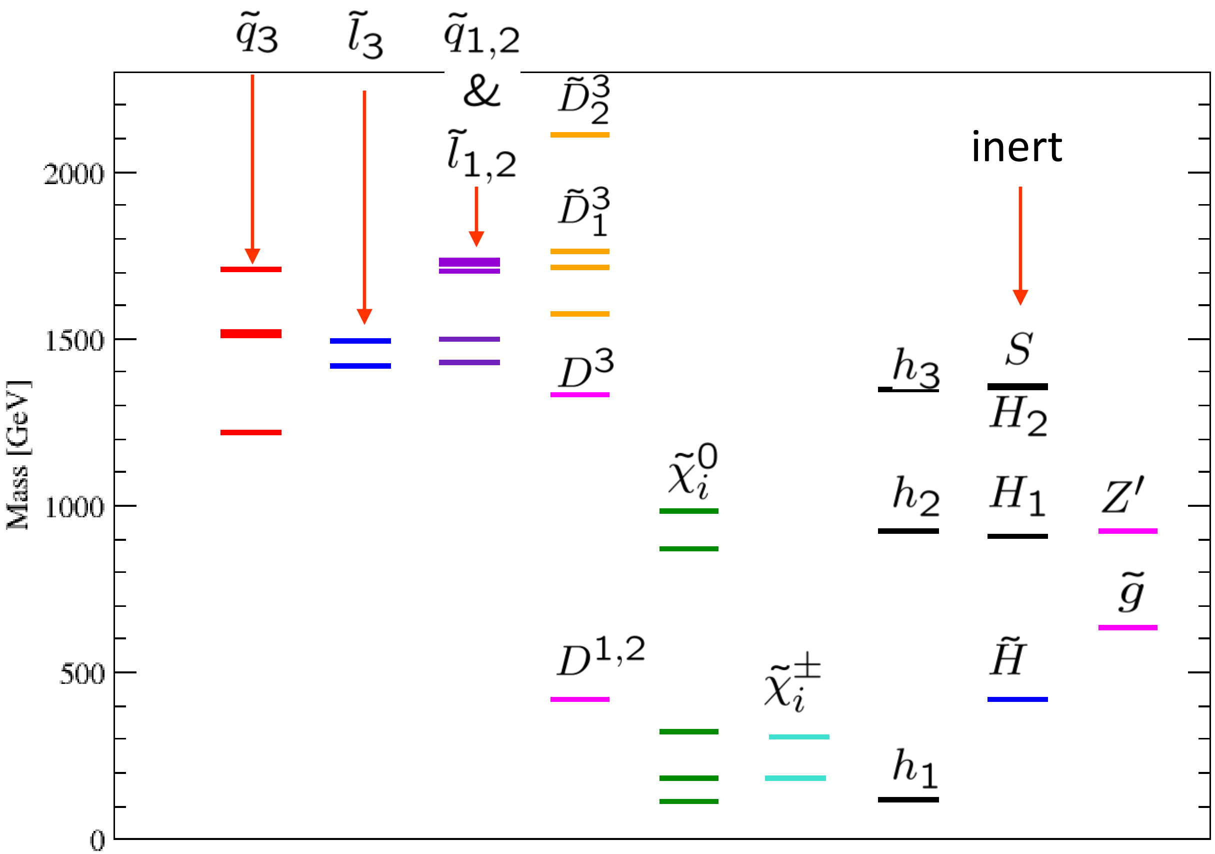
  Free Parameters: $\lambda_i,\ \kappa_i,\ s$

Renormalisation Group Equations (RGEs)

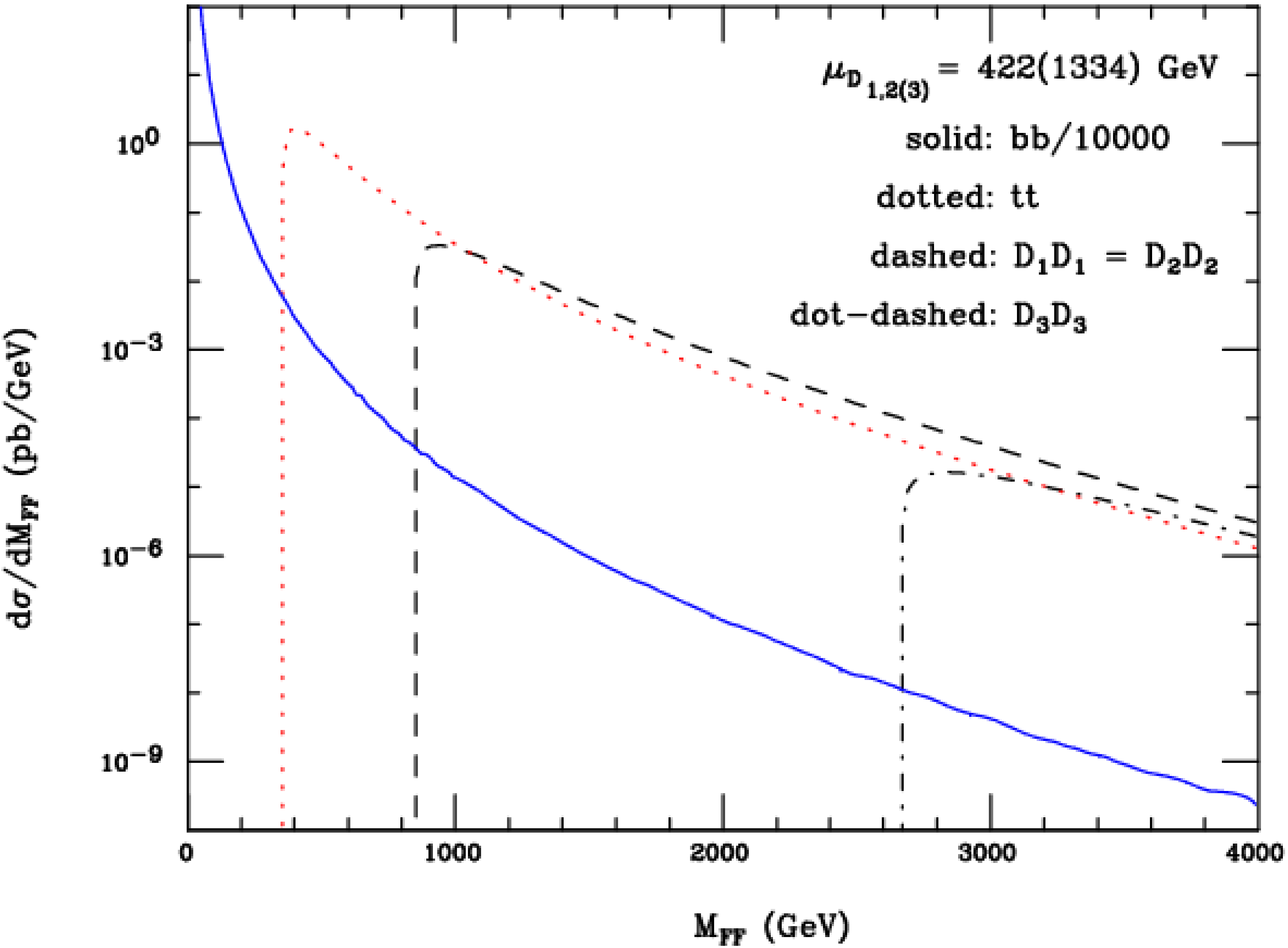
- To connect these high scale conditions with low energies we use RGEs for:
  - Gauge and Yukawa couplings (2 loop).
  - Soft breaking gaugino and trilinear masses (2 loop).
  - Soft scalar masses (1 loop).

Light Z′ Scenario

- Scenario with a sub TeV Z' (926 GeV)
- Heavy sfermions and light gluino (general prediction)
- Light exotic quarks

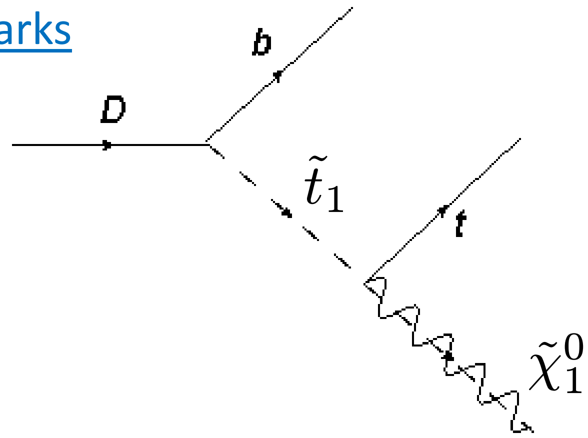


$$\begin{aligned} \tan\beta &= 10, \\ s &= 2.5\text{ TeV}, \\ M_{1/2} &= 728\text{ GeV}, \\ m_0 &= 1387\text{ GeV}, \\ A &= -908\text{ GeV} \\ \lambda(M_X) &= -0.15, \\ \lambda_{1,2}(M_X) &= 0.1 \\ \kappa_{1,2}(M_X) &= 0.08, \\ \kappa_3(M_X) &= 0.28 \end{aligned}$$


$\mu_{D_{1,2(3)}}$ = 422(1334) 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

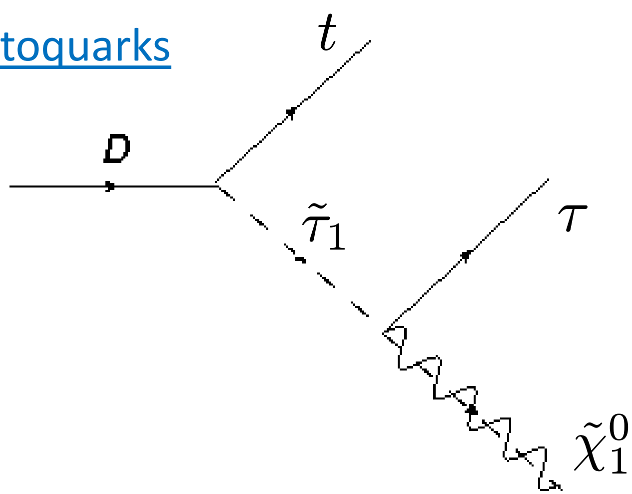
Diquarks



Enhancement of

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

Leptoquarks



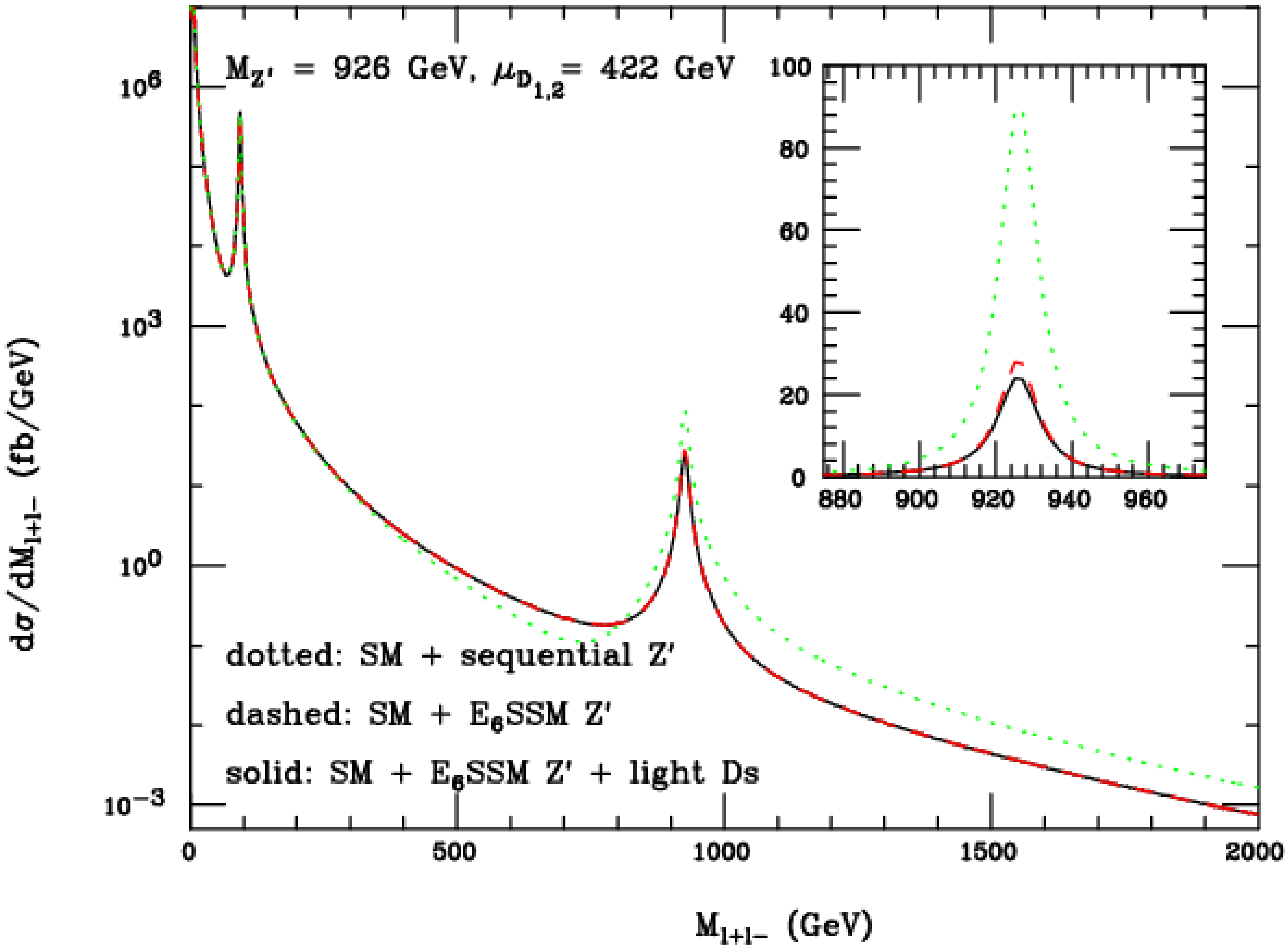
$$pp \to t\bar{t}\tau\bar{\tau} + E_T^{miss} + X$$

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

Scalar partners

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

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


$M_{Z'}$ = 926 GeV, $\mu_{D_{1,2}}$ = 422 GeV
10^6
10^3
10^0
10^{-3}
0
500
1000
1500
2000
$d\sigma/dM_{l^+l^-}$ (fb/GeV)
$M_{l^+l^-}$ (GeV)
dotted: SM + sequential Z′
dashed: SM + E_6SSM Z′
solid: SM + E_6SSM Z′ + light Ds
100
80
60
40
20
0
880
900
920
940
960

Exotic Phenomenology

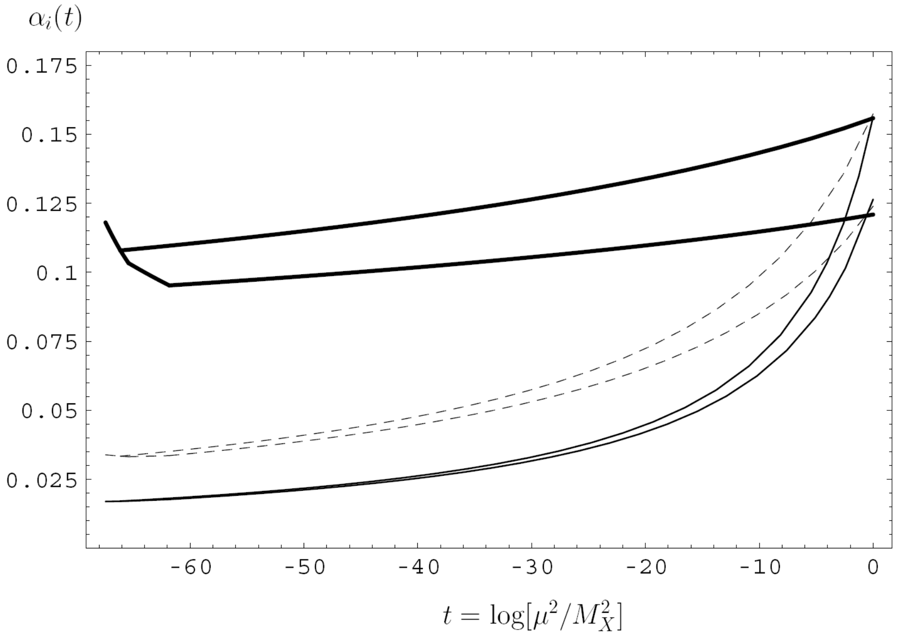
- Sub-TeV Z' not (yet!) ruled out in cE_6SSM.
  - Sfermions heavy in such scenarios
  - Light Exotics - Diquarks/Leptoquarks, singlinos and higgsinos - possible
  - Observation from Drell-yan production.
  - Exotic matter could make a detctable contribution here

- Exotic quark production comparable with $t\bar{t}$
  - Could give striking signature
  - More phenomenological studies important

Threshold Corrections

(In collaboration with Dominik Stockinger and Alexander Voigt)

- Varying $T_{ESSM} \Rightarrow$ 10 -15% effect



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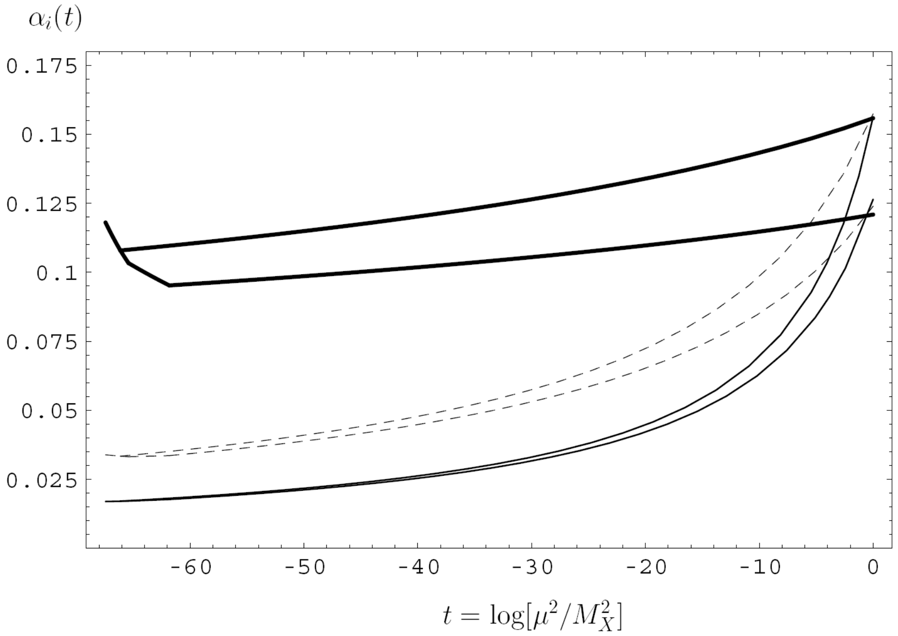
- Solution: include individual sparticle thresholds iteratively.



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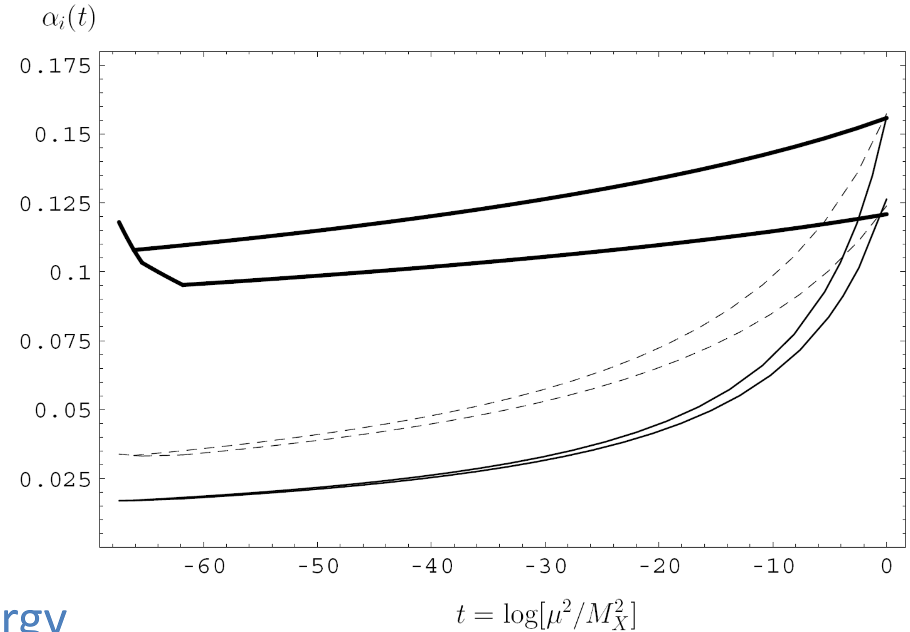


Full theory

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: $g^E_{ij} m_i m_j$

Energy

Equate Green's Functions

Effective coupling

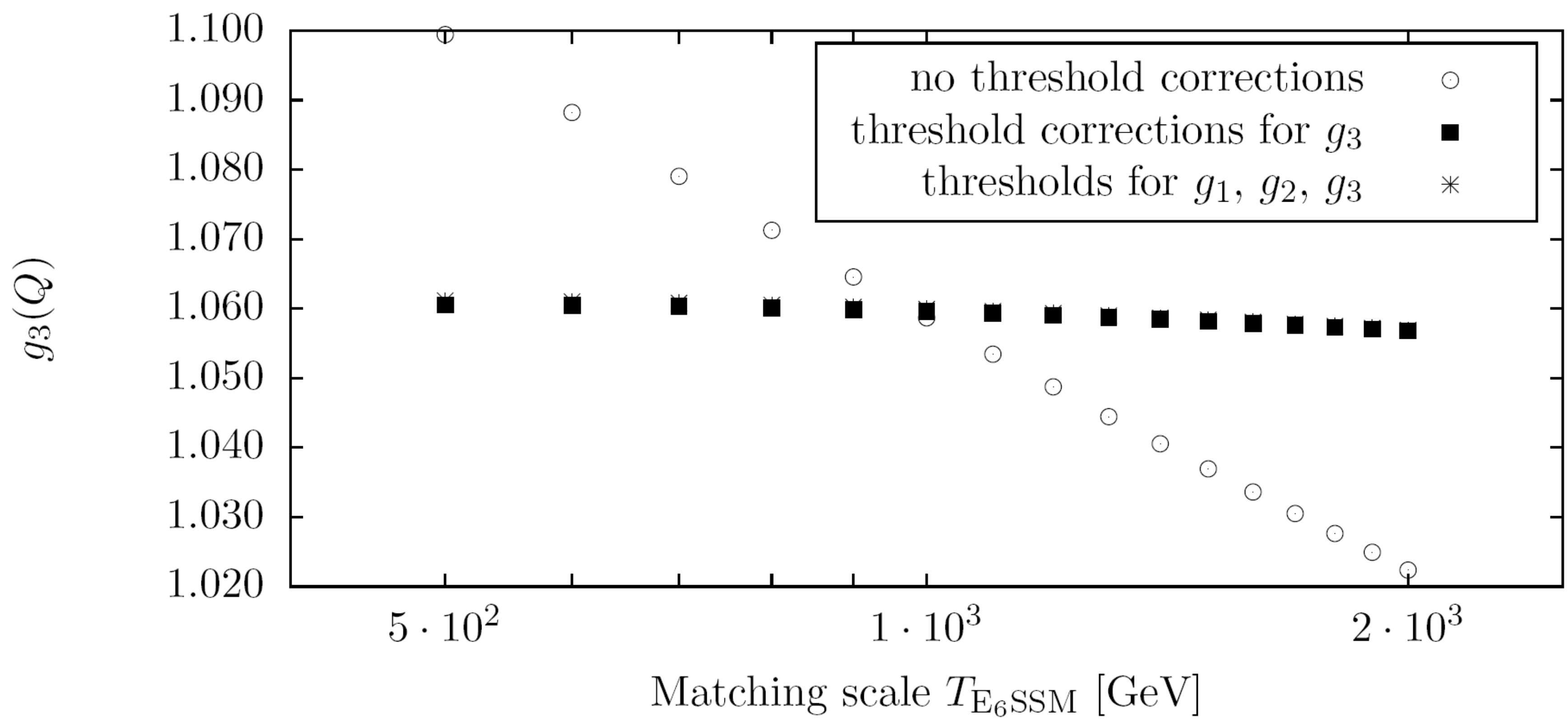
$$\frac{1}{g_i^2} - \frac{1}{\hat{g}_i^2} = C_i - \sum_f \frac{1}{24\pi^2} \ln \frac{m_f}{T} - \sum_s \frac{1}{48\pi^2} \ln \frac{m_s}{T} - \frac{2N}{24\pi^2} \ln \frac{m_{\tilde{g}}}{T}$$

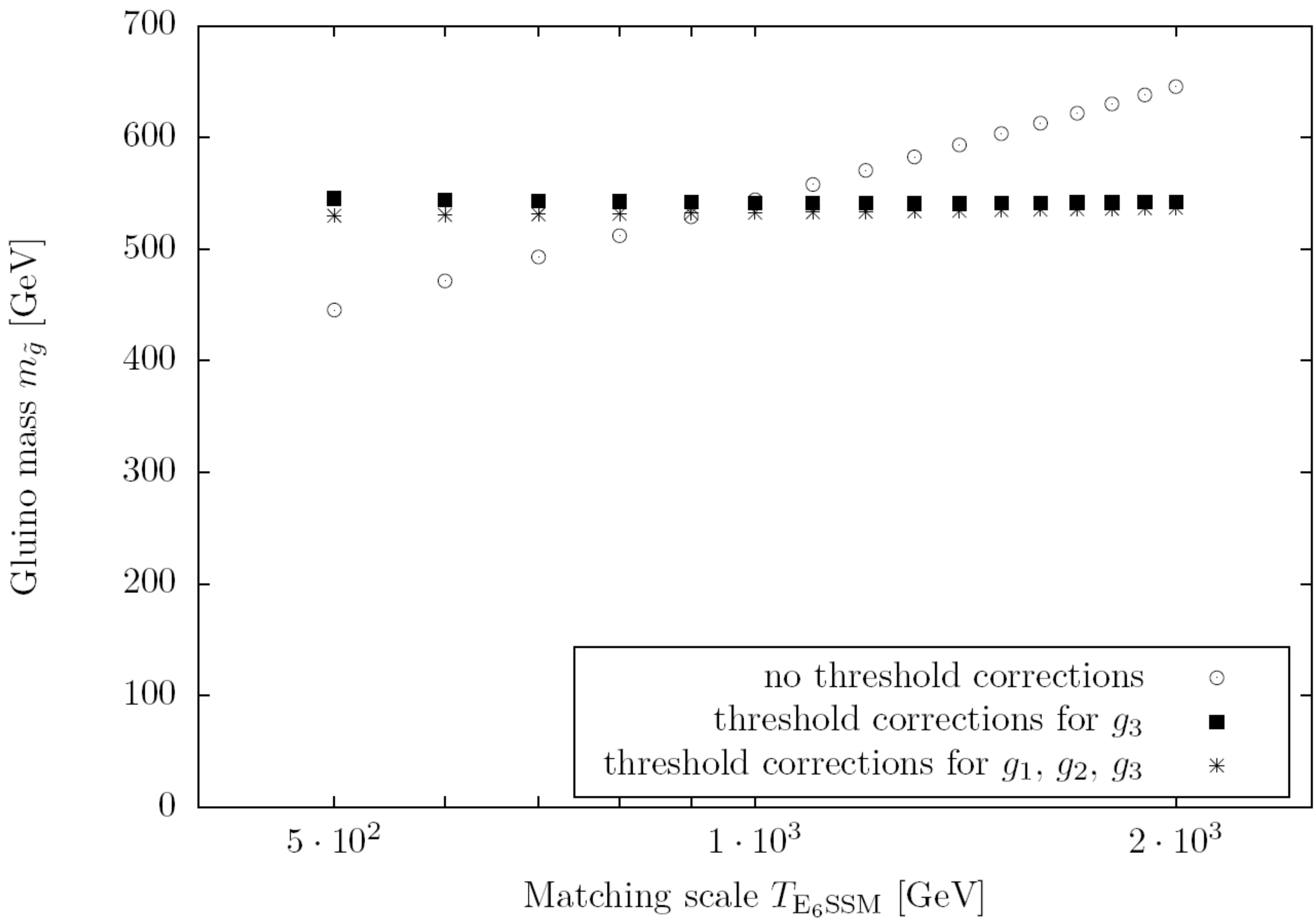
Vanishes for DR-bar couplings

Integrated out fermions

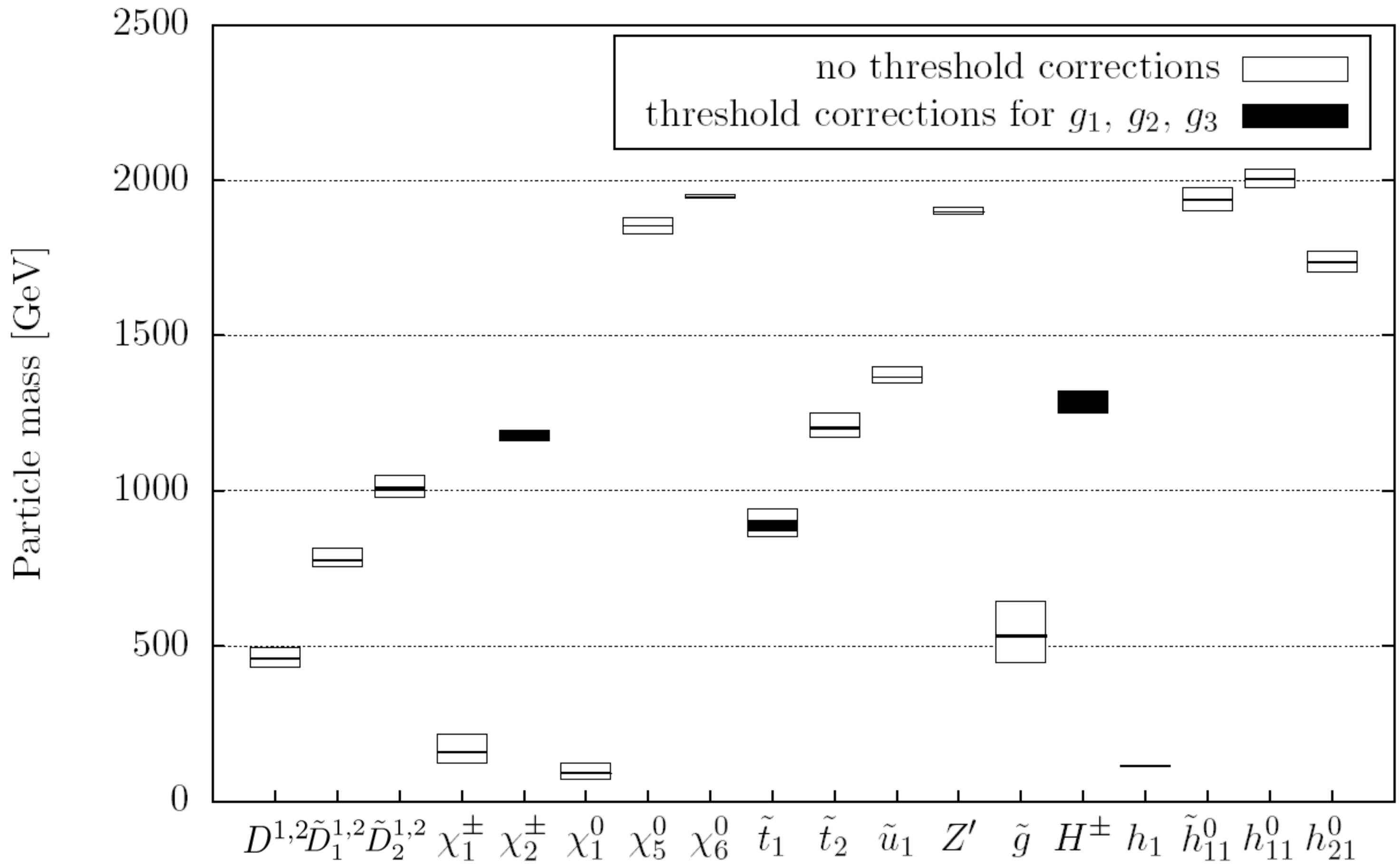
Integrated out scalars

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



- Threshold Corrections important for precision.
  - Individual sparticle thresholds included for gauge couplings.
  - Large reduction in threshold scale dependence.
  - Residual dependence from Yukawa thresholds (coming soon)

Conclusions

- E_6 / extra U(1) SUSY models, (e.g. cE_6SSM) well motivated
  - cE6SSM investigated ,parameter space explored.
  - General prediction of heavy sfermions and light gluino
- Phenomenology of the cE_6SSM:
  - If light exotics can be copiously produced, viable scenarios shown .
  - Z’ can give rise to striking signatures. Impact of the exotics could be visible. Sfermions contribution low in considered point.

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  - Individual sparticle thresholds added for gauge couplings.
  - Threshold scale dependence significantly reduced.
  - Residual dependence shows that Yukawa threshold corrections important
  - Many other corrections, e.g. shifts to pole, two loop scalar mass RGEs…

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- Extracting cE_6SSM from data:
  - Extremely important if E_6SSM like signatures are observed.

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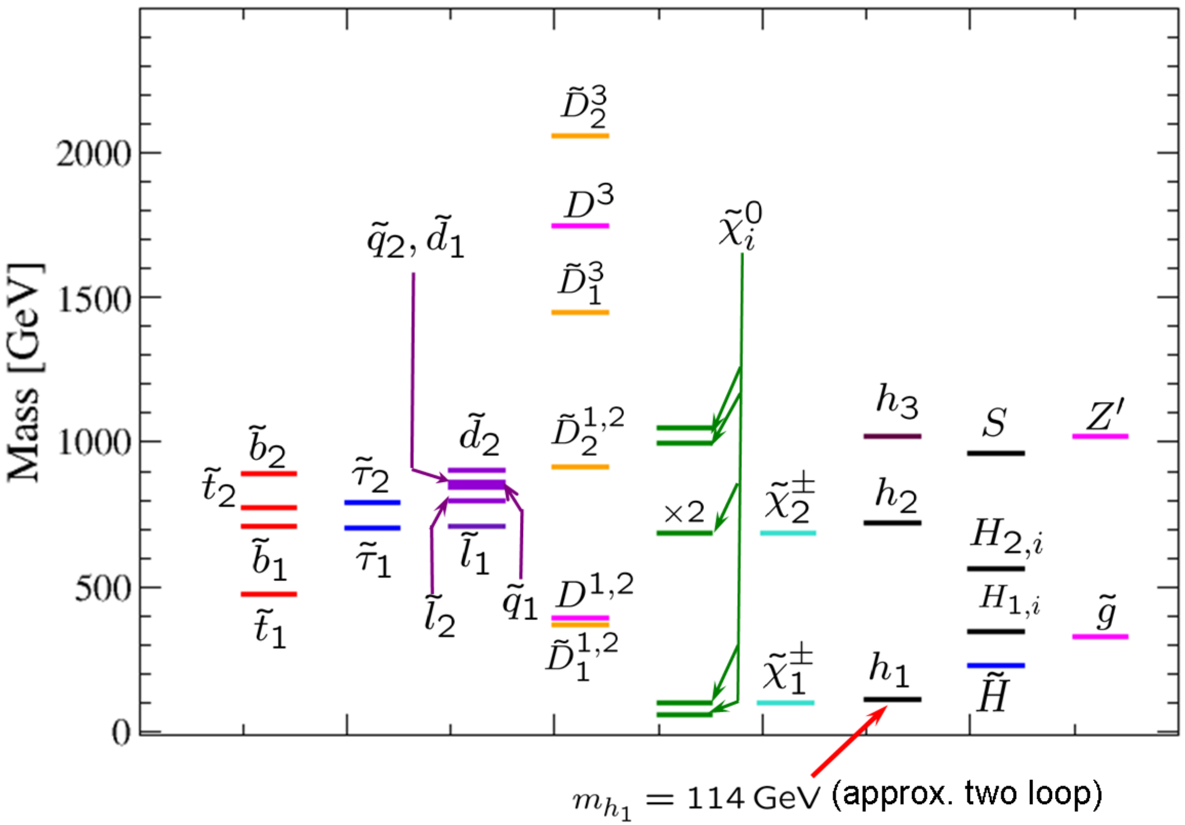
- Extracting cE_6SSM from data:
  - Extremely important ~~if~~ when E_6SSM like signatures are observed
  - Lots to do…work in progress…

BACK UP SLIDES

Scenario (Light exotic fermions and scalars)

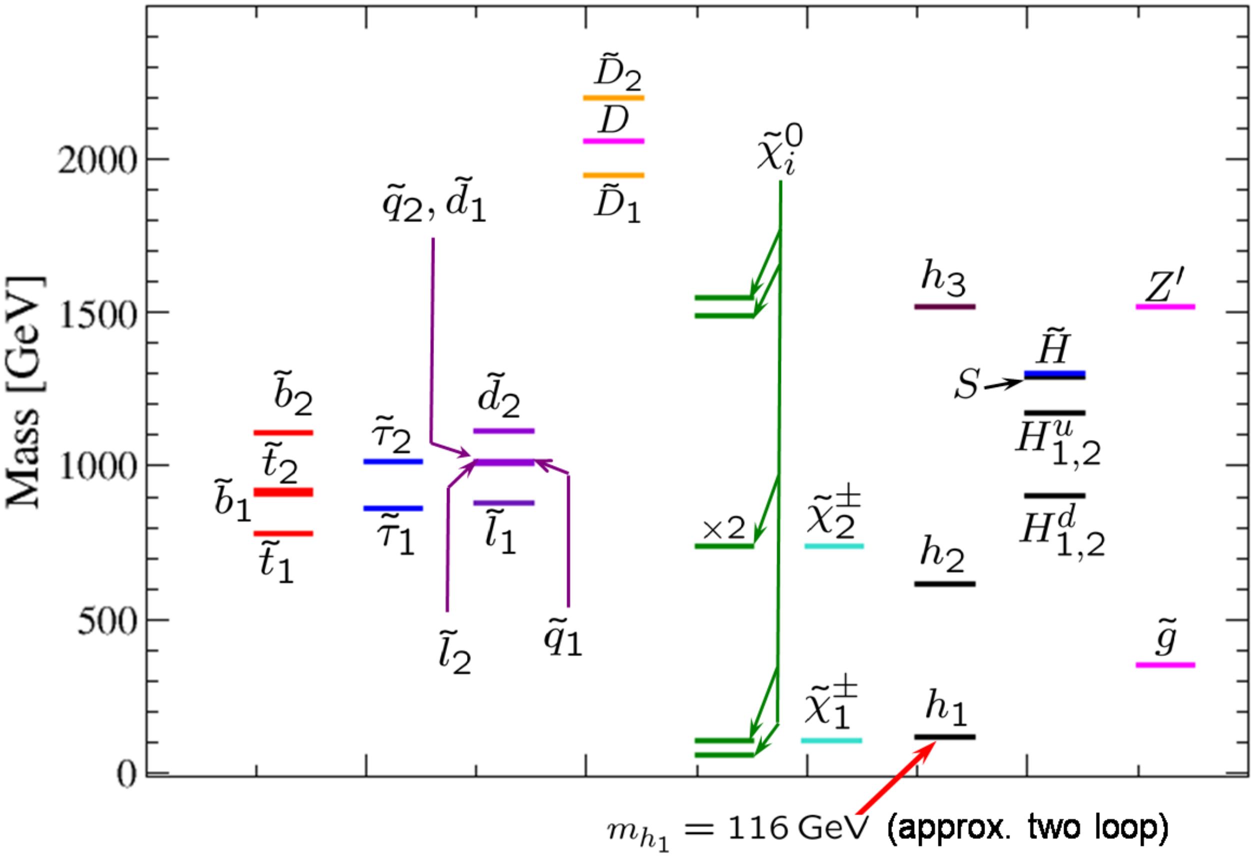
- Large κ drives electroweak symmetry breaking
- With a universal exotic coupling κ at the GUT scale
  $\Rightarrow$ exotic quarks are always heavy $\left(\mu_D = \frac{\kappa_i(M_S)}{\sqrt{2}} s\right)$
- Break κ universality and exotic quarks can be light



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

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

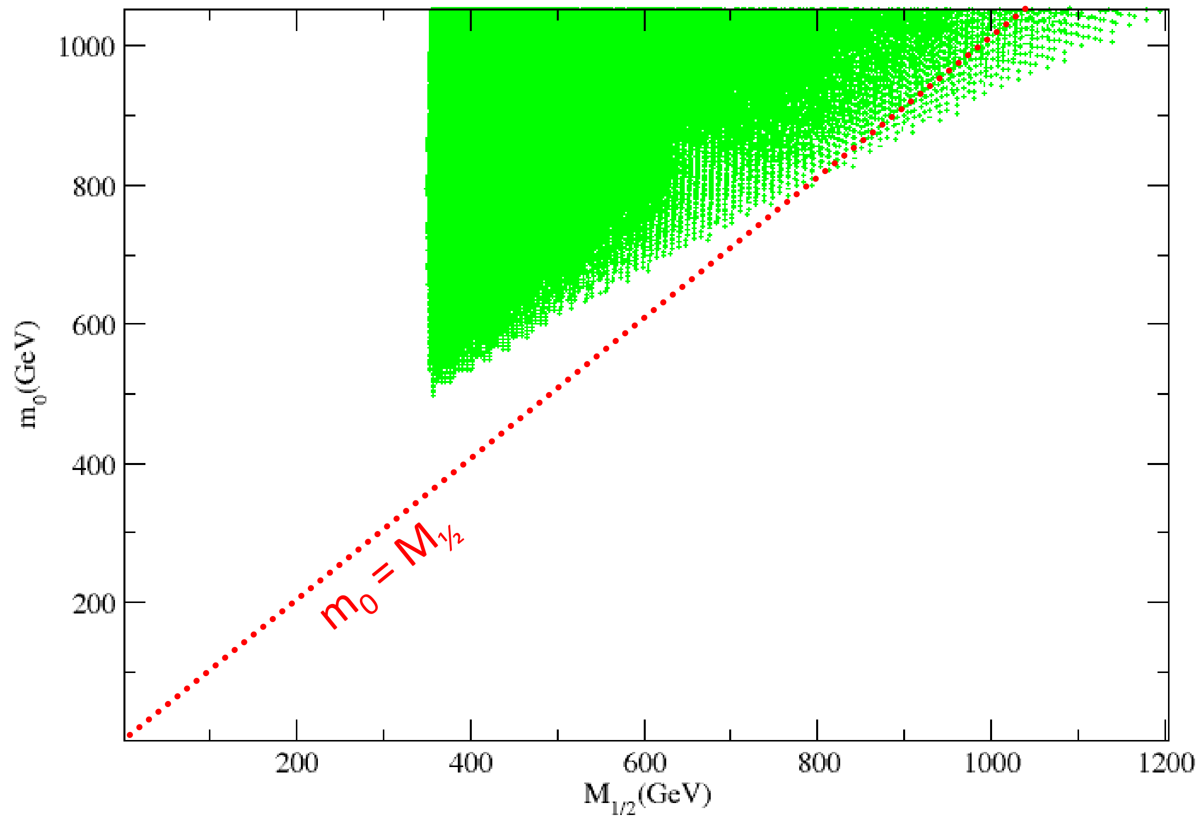
Scenario B (Pessimistic)



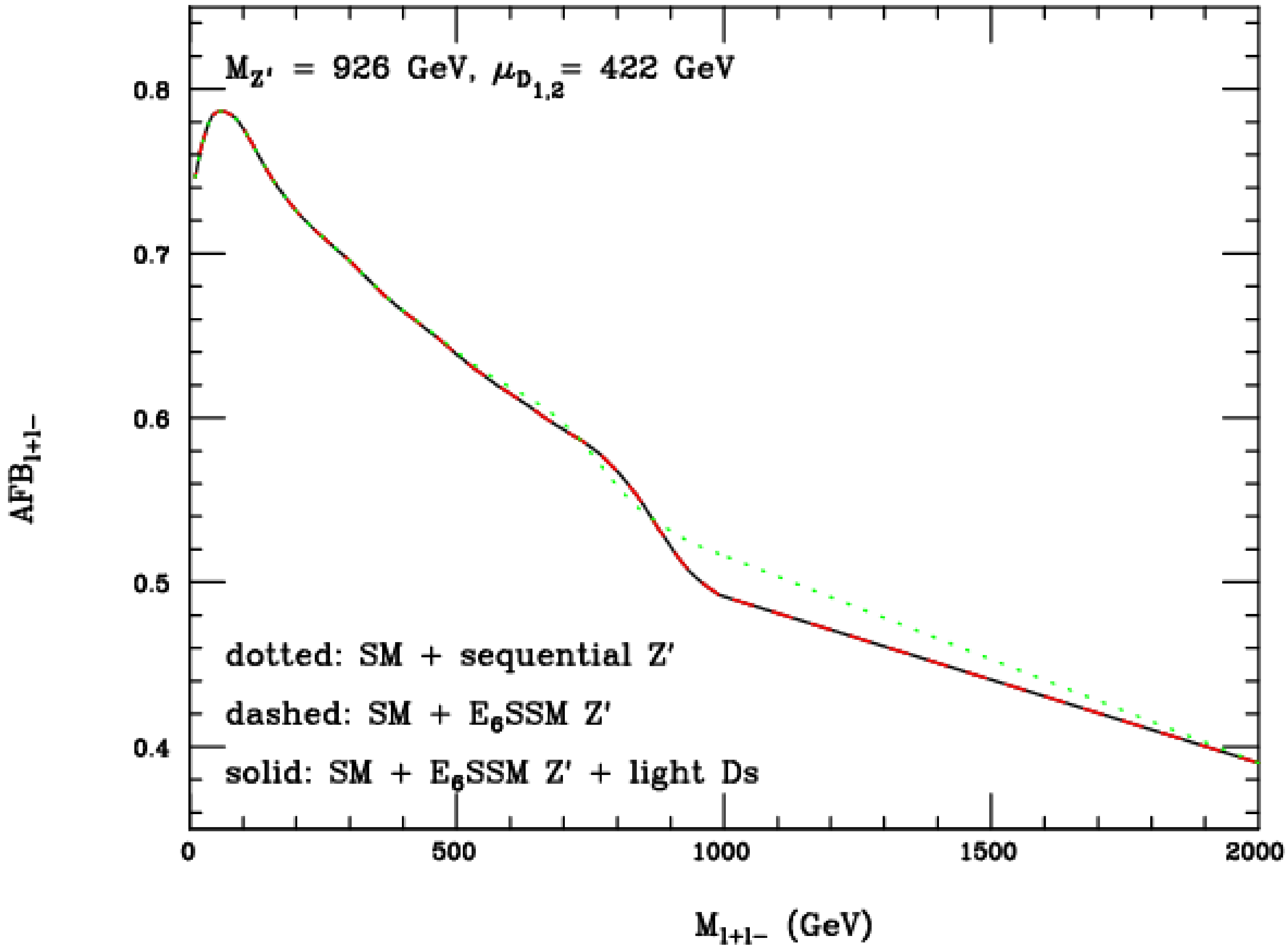
$$\tan\beta = 10,$$
$$s = 4.0\ \text{TeV}$$
$$M_{1/2} = 389\ \text{GeV},$$
$$m_0 = 725\ \text{GeV},$$
$$A = -1528\ \text{GeV}$$
$$\lambda(M_X) = -2.0,$$
$$\lambda_{1,2}(M_X) = 2.6$$
$$\kappa_{1,2,3}(M_X) = 2.5,$$

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:



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



M_Z' = 926 GeV, μ_D1,2 = 422 GeV
0.8
0.7
0.6
0.5
0.4
AFB_l+l−
dotted: SM + sequential Z′
dashed: SM + E6SSM Z′
solid: SM + E6SSM Z′ + light Ds
0
500
1000
1500
2000
M_l+l− (GeV)

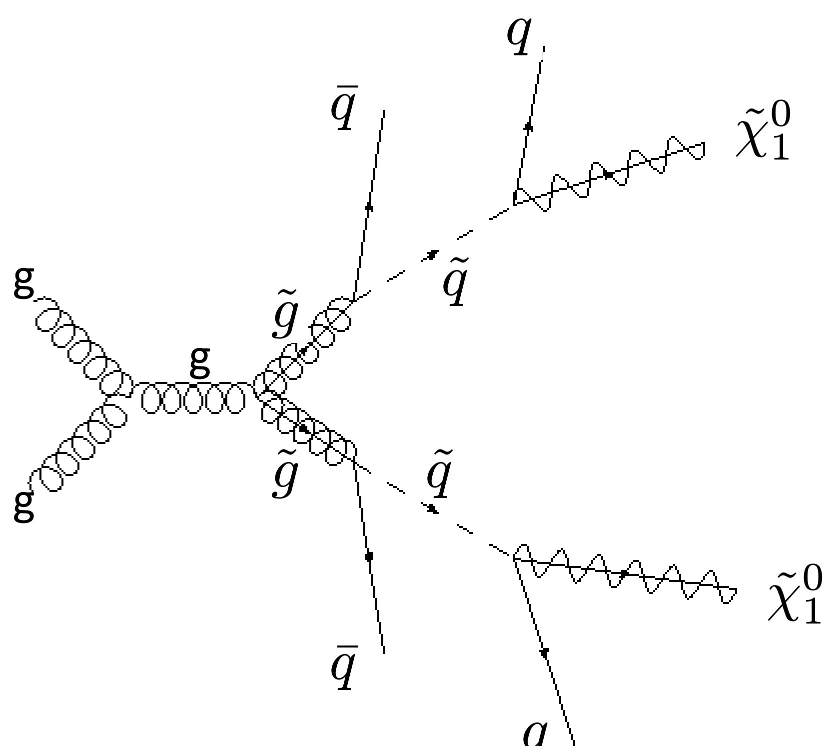
- It is possible all the exotics are heavy and challenging to detect

- 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:

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



E_6SSM Superpotential

- Imposing $Z_2^{B/L}$ and Z_2^H

$$W_{\mathrm{E_6SSM}} \to \lambda_i \hat{S}(\hat{H}_{1i}\hat{H}_{2i}) + \kappa_i \hat{S}(\hat{D}_i\hat{\overline{D}}_i) + f_{\alpha\beta}\hat{S}_\alpha(\hat{H}_d\hat{H}_{2\beta})$$
$$+\tilde{f}_{\alpha\beta}\hat{S}_\alpha(\hat{H}_{1\beta}\hat{H}_u) + \frac{1}{2}M_{ij}\hat{N}_i^c\hat{N}_j^c + \mu'(\hat{H}'\hat{\overline{H}}')$$
$$+h_{4j}^E(\hat{H}_d\hat{H}')\hat{e}_j^c + h_{4j}^N(\hat{H}_u\hat{H}')\hat{N}_j^c + W_{\mathrm{MSSM}}(\mu=0)$$

- To ensure only 3rd gen. gets vevs, we choose:

$$\kappa_i \sim \lambda_3 \geq \lambda_{1,2} \gg f_{\alpha\beta}, \tilde{f}_{\alpha\beta}, h_{4j}^E, h_{4j}^N.$$

- Further integrating out super heavy, right handed neutrinos, and dropping μ' which decouples, leaves:

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