Single-sector gauge mediation, warped extra dimensions, and the Large Hadron Collider

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EFT & UT

- Warped extra dimension models:
  much studied over last few years.
  [Randall, Sundrum 99, ...]
- Alternative to CMSSM, mSUGRA,....
- AdS/CFT interpretation of these models:
  very attractive (but not exactly rigorous).
  [Arkani-Hamed, Porrati, Randall 00;
  Rattazzi, Zaffaroni 00]
- Extra dim'l th's are nonrenorm'ble $\Rightarrow$ EFT.
- Q's: How to complete in UV?
  Give more rigor to AdS/CFT map?
  Model-bldg. insight from underlying th. (UT)?

EFT & UT

- Best candidate string/M-th.
- AdS spacetime solns now exist.
  (warped string = flux background
  = N_c D3's backreaction)
- They realize AdS/CFT (firm footing).
- Our goal:
  marry warped string constructions
  & warped phen'l models.

AdS/CFT correspondence

- Nontrivial YM dynamics (="CFT") takes on a gravitational meaning (="AdS").
- Everybody has heard about $AdS_5 \times S^5$.
- A far more interesting example is the Klebanov-Strassler construction [00].
- It is based on the Klebanov-Witten construction:

$$AdS_5 \times T^{1,1}.$$

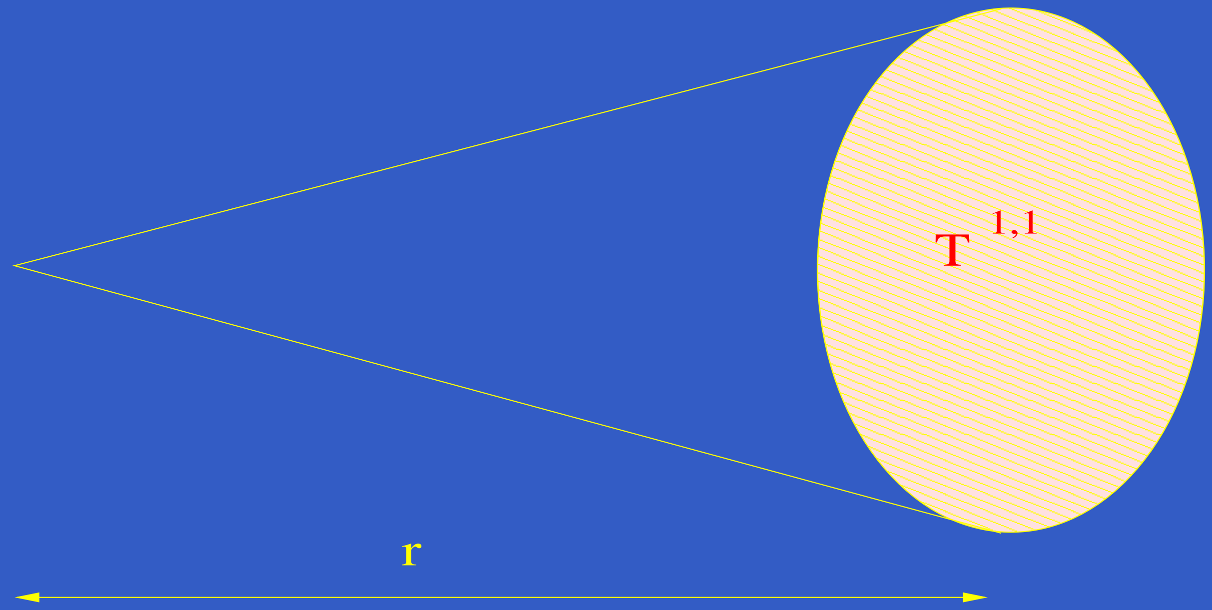
- KW dual gauge theory: $\mathcal{N} = 1$ SCFT.

Conifold

- Type IIB theory is formulated on:

  4d Minkowski $\times$ conifold.

- The conifold has a cone-like geometry, with $T^{1,1}$ base:



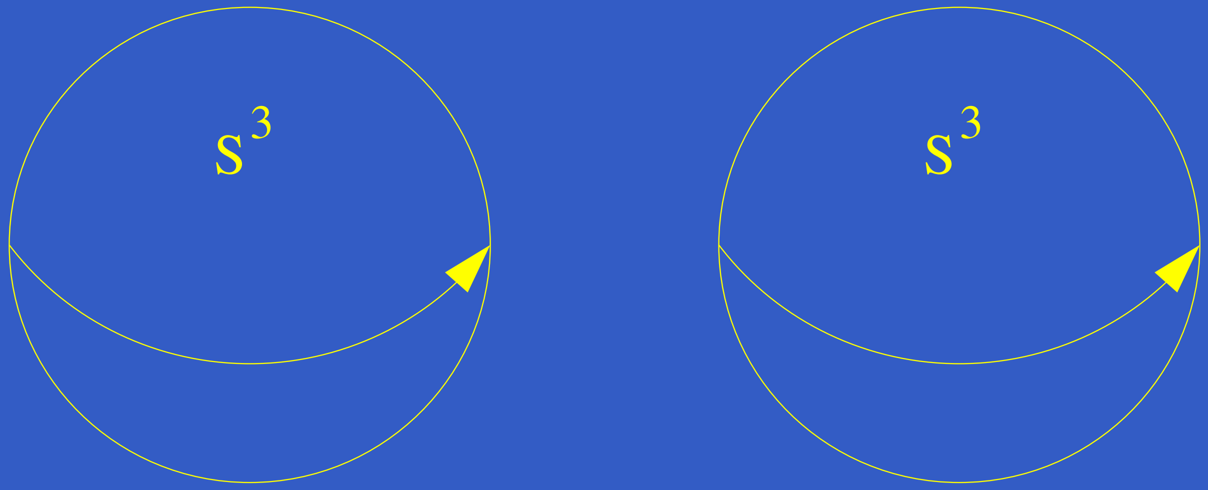
Conifold

- $T^{1,1}$ is a quotient manifold:

$$T^{1,1} = [SU(2) \times SU(2)]/U(1)$$

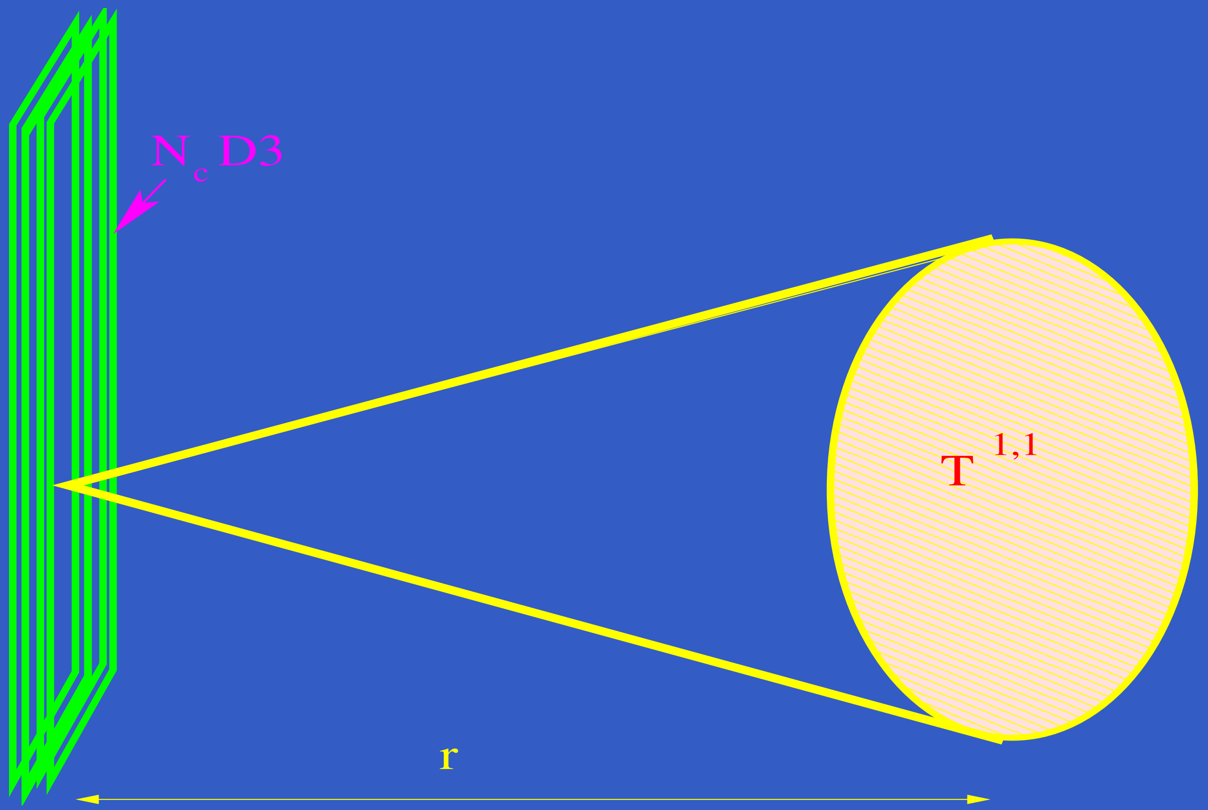
- The "$1, 1$" denotes the $U(1)$ quotient:

$$H = (\sigma_3 \otimes \mathbf{1}) + (\mathbf{1} \otimes \sigma_3).$$



Warping spacetime

- N_c D3's at tip.
- Gravitating $\Rightarrow$ backreact on geometry, warp it.
- Geometry $\rightarrow AdS_5 \times T^{1,1}$.



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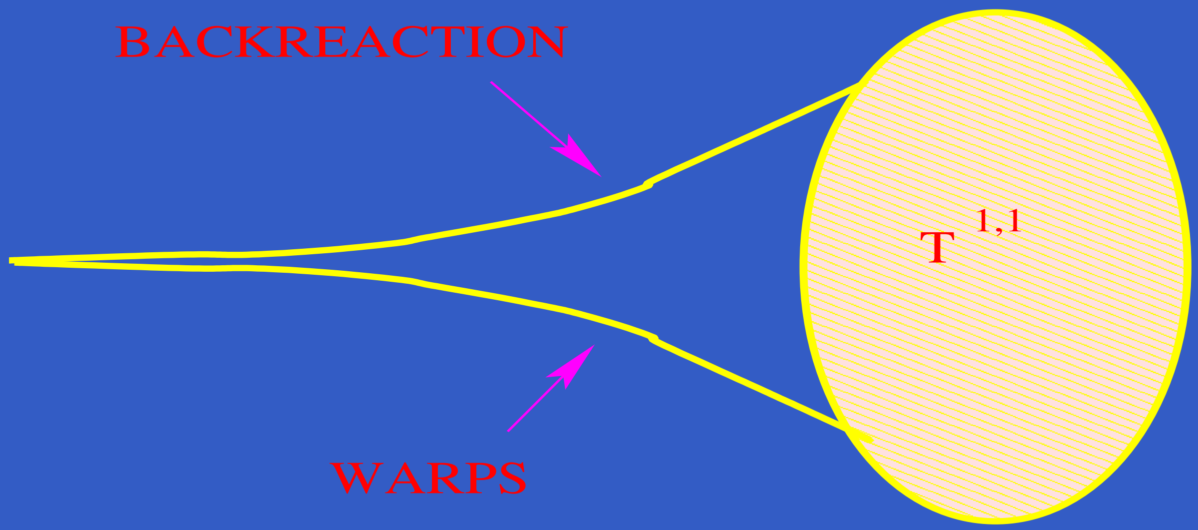


Advantage of $T^{1,1}$

Comparison, $AdS_5 \times X_5$

5d space X_5	S^5	$T^{1,1}$
Killing spinors	32	8
dual FT	$\mathcal{N} = 4$ SCFT	$\mathcal{N} = 1$ SCFT

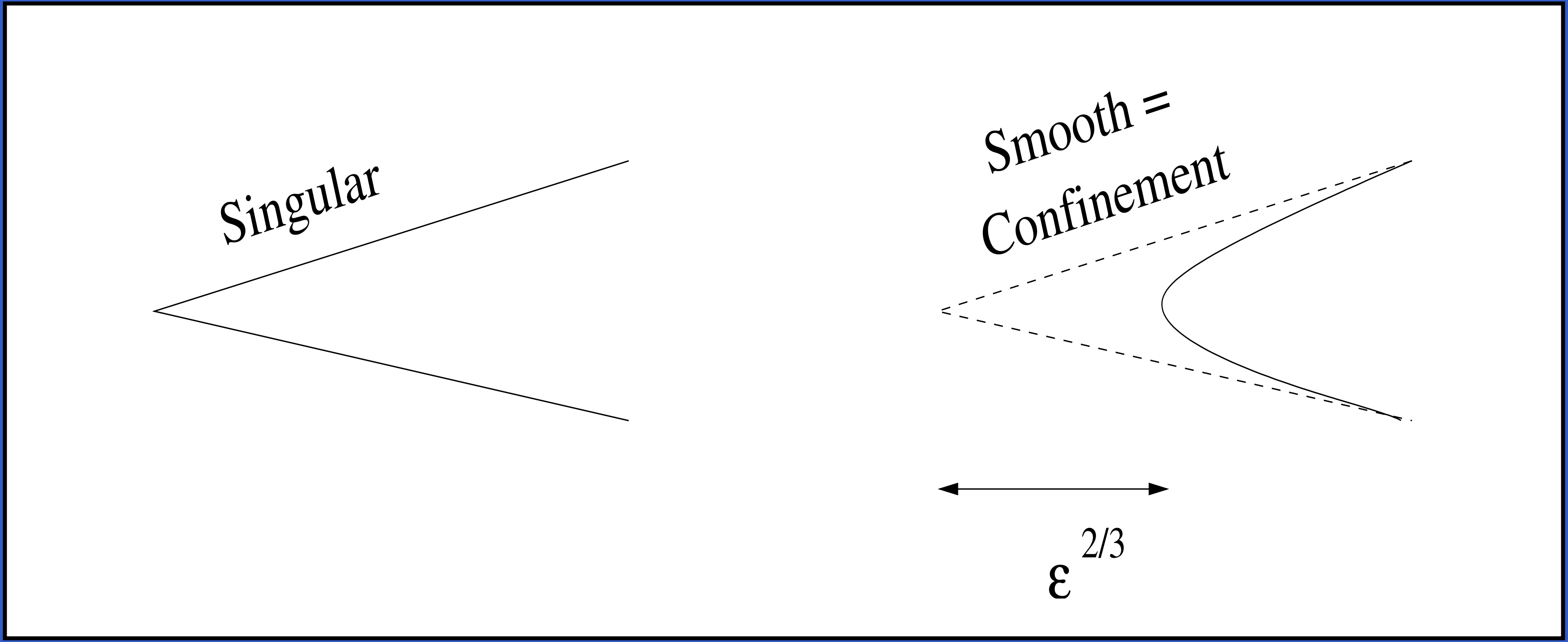
Progress! ... Goal is softly broken $\mathcal{N} = 1$ SUSY.

Singularity at the tip

- There is a singularity at the tip of the conifold.
- In the dual gauge theory, this is reflected by the absence of an IR cutoff.

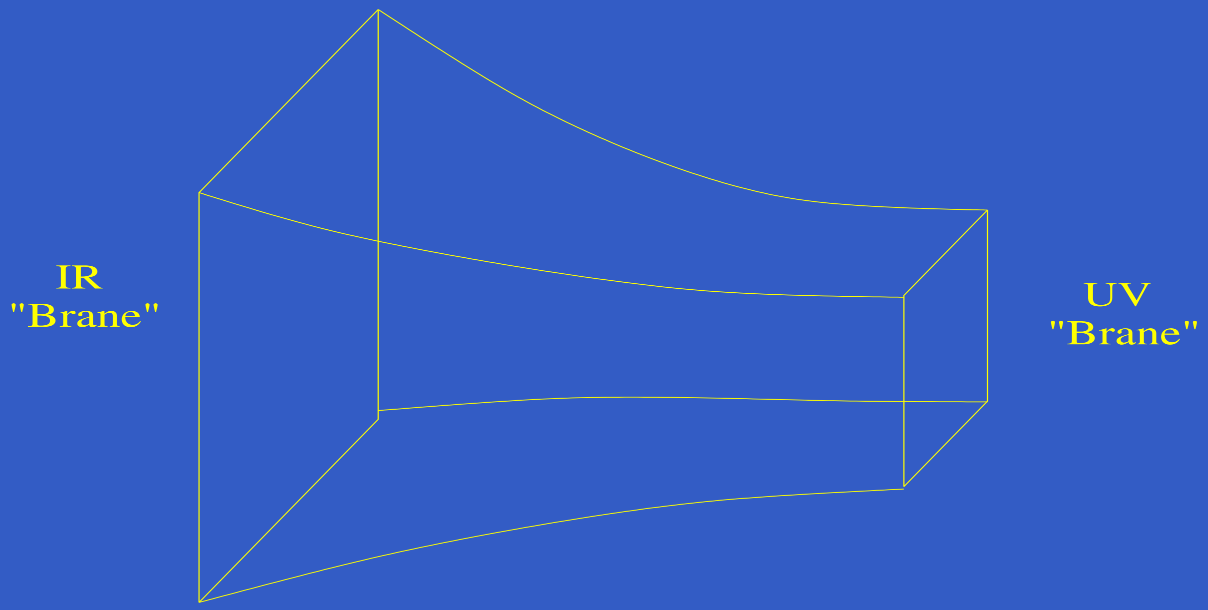
Singularity resolution

- Klebanov-Strassler resolve the singularity with the deformed conifold.
- They show that it is equivalent to confinement in the IR of the dual gauge theory.



Conformal symmetry breaking

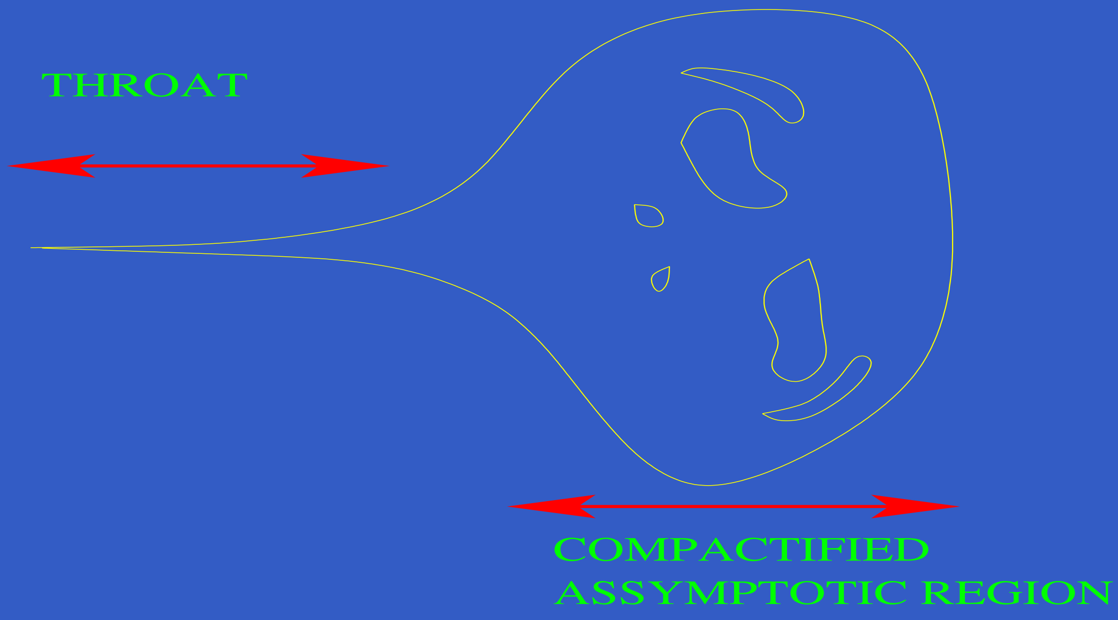
- On the gravity side of the duality, this breaks half the Killing spinors.
- On the gauge theory side, this breaks the fermionic conformal charges, reducing to $\mathcal{N} = 1$ SUSY gauge theory.
- Now we are “very close” to the real world.
- I.e., semi-realistic susy AdS_5 models.



D7 probes = flavors

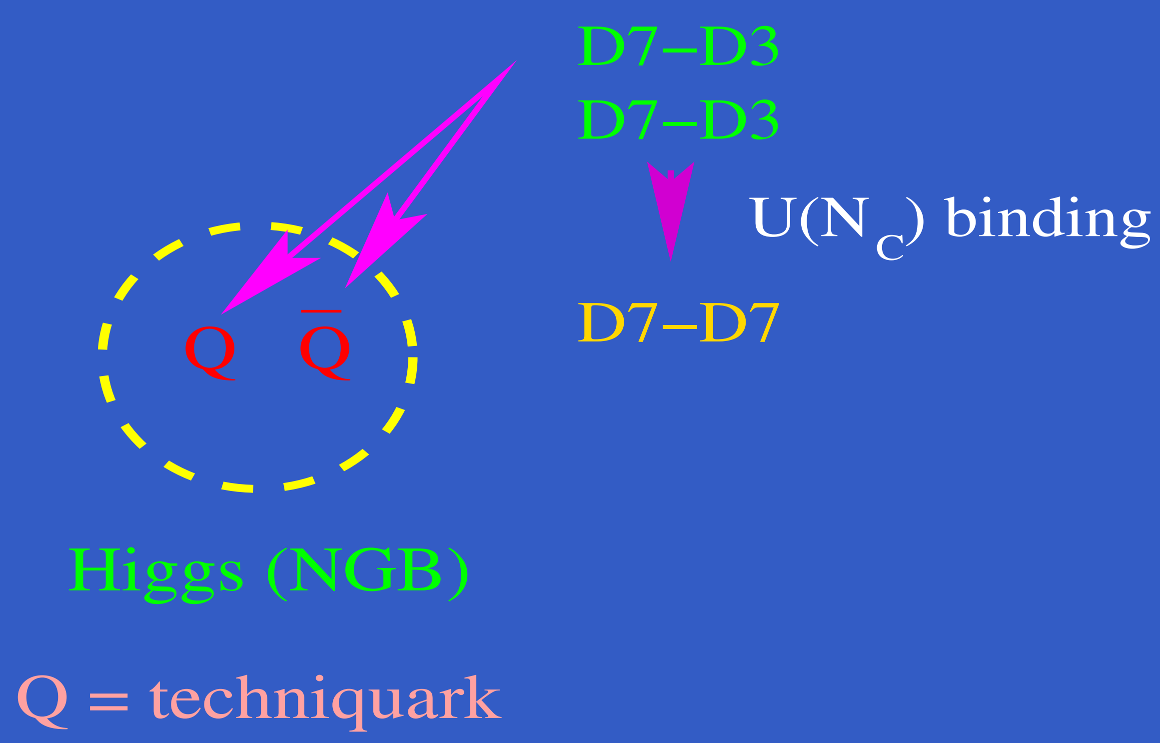
- Introduction of N_f D7 probe branes allows for a weakly coupled $U(N_f)$ gauge theory in the dual.

$$g_f^2 \sim (\text{volume})^{-1}.$$



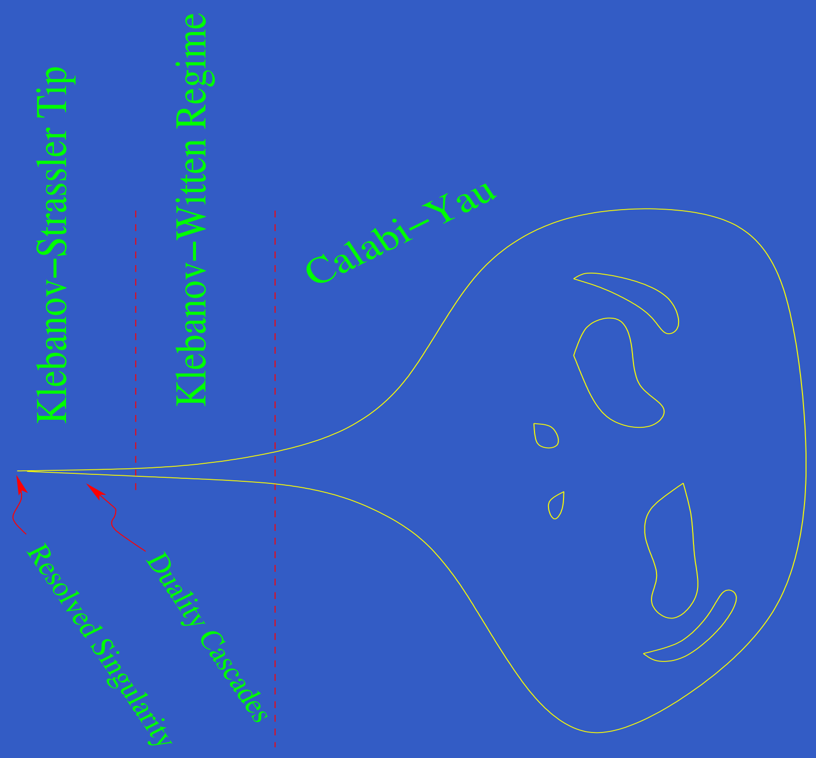
D7 probes = flavors

- Embed D7s $\longrightarrow$ "techniquarks" of dual gauge theory.
- Bound states $\Rightarrow$ models w/ compositeness + SUSY.



Noncompact $\rightarrow$ compact CY

- Recent studies of the low-E EFT (4d, 5d):
  - Sakai, Sonnenschein 03
  - Kuperstein 04
  - Levi, Ouyang 05
  - Gherghetta, JG 06 [$\star$]
  - Acharya, Benini, Valandro 06
- In [$\star$]: include UV regulator.
- METHOD: Giddings, Kachru, Polchinski 02.
- Cap conifold w/ compact Calabi-Yau...



- The CY and the KS tip are, respectively, to be thought of as refinements of the UV and IR branes of, say, Randall-Sundrum 1.

WEDs with MSSM/SUSY-brkg in bulk

- Now I discuss applications of these ideas.

GOAL: String-inspired, realistic low-E theory.

- The models are:
  - MSSM in bulk.
  - Deformed AdS_5.
- SUSY breaking: use non-supersymmetric variants of KS string refinement.
  [Borokhov, Gubser 02;
  Kuperstein, Sonnenschein 03]

RS1

- Slice of AdS_5:

$$ds_5^2 = A^2(z)\left(-dt^2 + d\vec{x}^2 + dz^2\right),$$
$$A^2(z) = \frac{1}{z^2}.$$

- 1+3 dim's: t, $\vec{x}$.
- 5th dim.: $1 \leq z \leq z_{\mathrm{IR}}$.
- Warp factor: $A^2(z)$ (units of AdS curvature).
- UV brane: $z_{\mathrm{UV}} = 1$.
- IR brane: $z_{\mathrm{IR}} = m_P/(0.1 \text{ to } 10\ \mathrm{TeV})$.

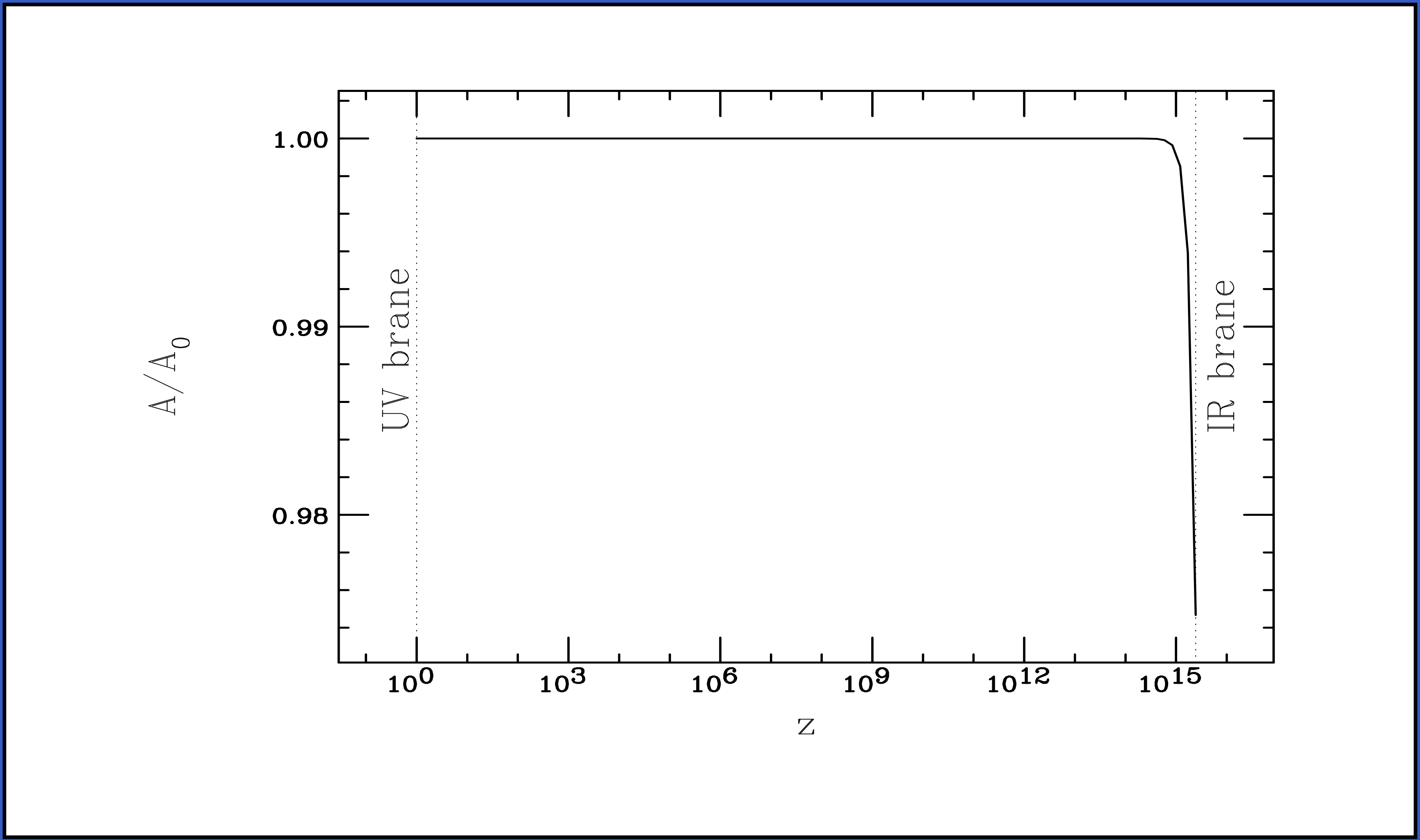
Deforming AdS_5

- Deform AdS according to the dim'l reduc. of Kup.-Sonn. soln.:

$$ds_5^2 = A^2(z)\left(-dt^2 + d\vec{x}^2 + dz^2\right),$$
$$A^2(z) = \frac{1}{z^2}\left(1 - \epsilon \cdot (z/z_{\text{IR}})^4\right).$$

- Domain: $1 \le z \le z_{\text{IR}}$.
- Dial 1: $\epsilon \sim 0.1$. [$\epsilon = 0.05$ in following.]
- Dial 2: $z_{\text{IR}} = m_P/$(1-100 TeV).
- SUSY lim.: $\epsilon \to 0$.
- Interpretation: DSB in the $SU(N_c)$.

A few per cent violence in the IR: Will it matter?



* Ratio deformed/undeformed warp factor. *

* Unchanged except very near IR brane. *

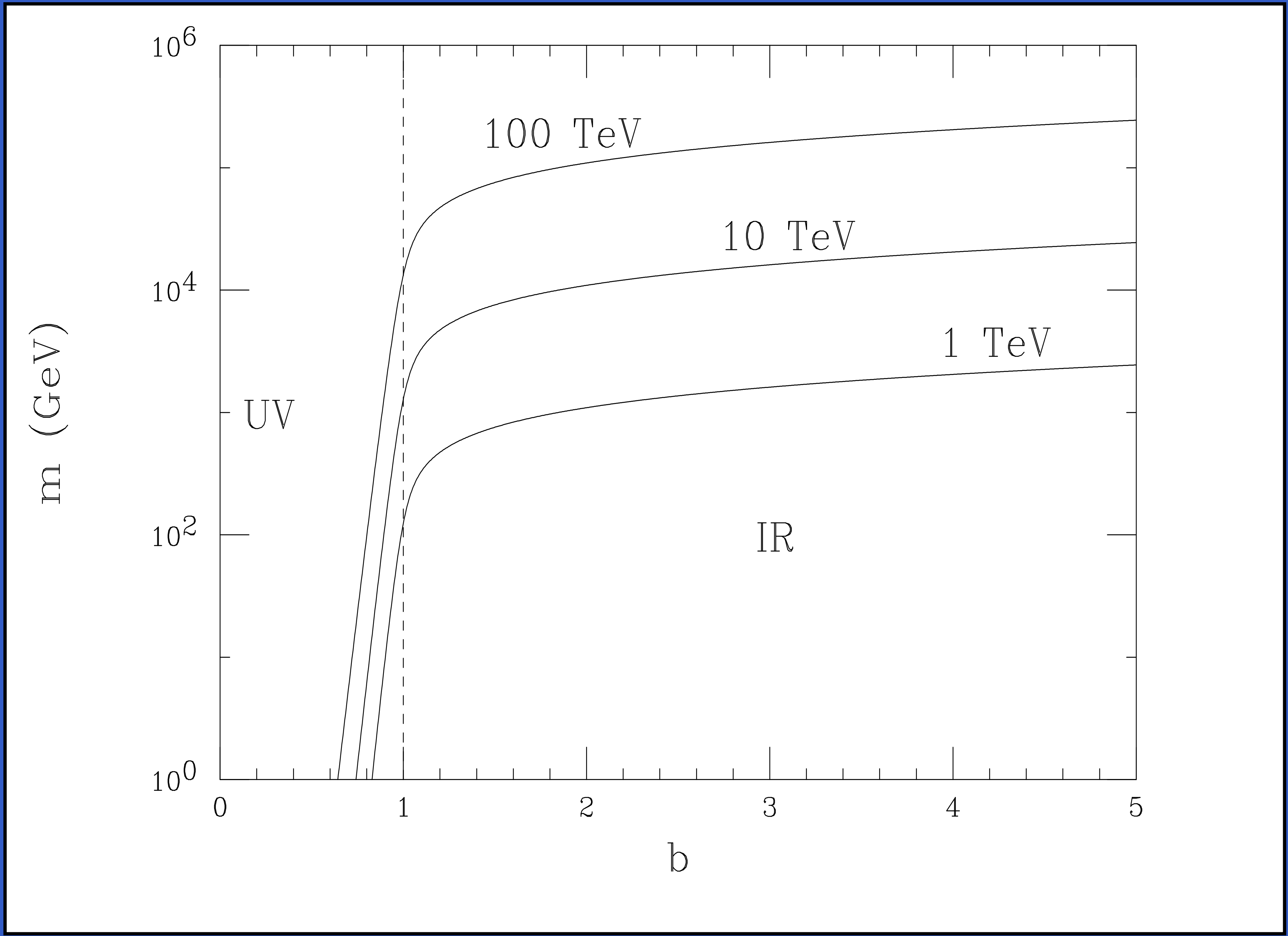
Scalars

- Solutions parameterized by boundary mass b.
- LO profile $\sim z^{b-1}$, unchanged.
- Zero modes lifted:

$$\tilde{m} \approx \sqrt{\epsilon(b-1)(b+10)}\, z_{\text{IR}}^{-1} \quad (b>1)$$
$$\tilde{m} \approx \sqrt{\epsilon(1-b)(b+10)}\, (z_{\text{IR}})^{b-2} \quad (0<b<1)$$

- KK modes still $\sim \pi / z_{\text{IR}}$.

Masses of quasi-zeromode scalars



Fermions

- Exact zeromodes persist.

$$0 = (\gamma^\alpha \partial_\alpha + \gamma_5 \partial_z + cA)\,\hat{\psi}, \quad \hat{\psi} \equiv A^2 \psi,$$
$$f_\pm = N_\pm A^{-2}(z) \exp\left(\mp c \int_1^z dz'\, A(z')\right).$$

- Profile virtually unchanged:

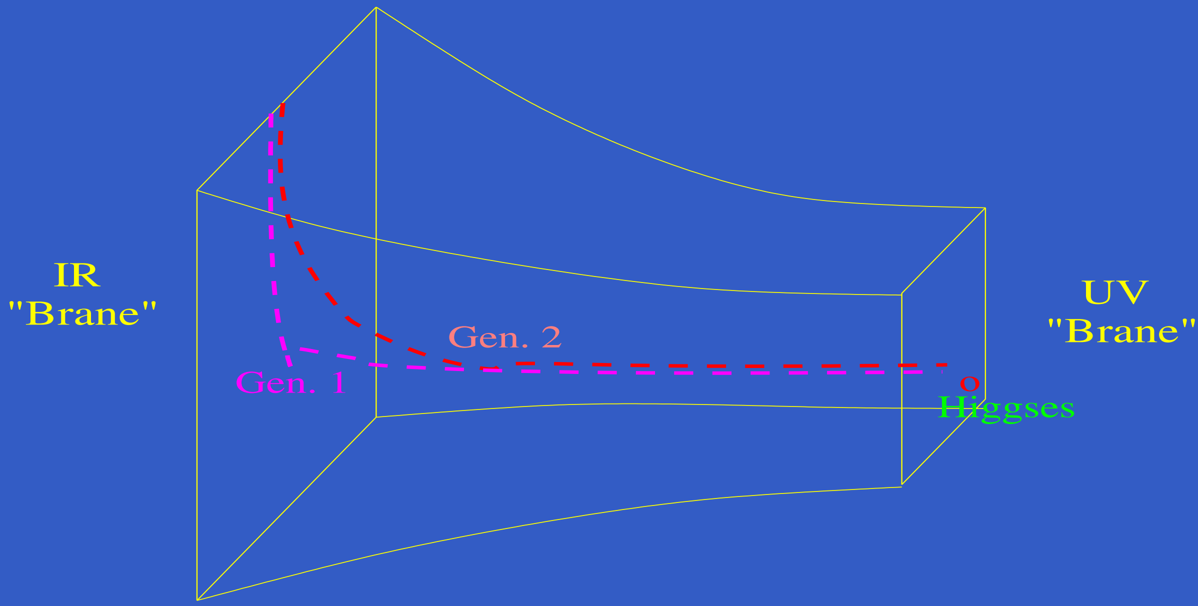
$$N_\pm z^{\frac{1}{2} \mp c_\pm} \left[1 + \frac{\epsilon z^4}{4 z_{\text{IR}}^4}(1 - \frac{1}{2} c_\pm)\right].$$

- $m = 0$'s protected by chiral symmetries.
- $\Rightarrow$ massless gauginos.
- Z_2 projection $\rightarrow$ chiral/$\mathcal{N} = 1$ light spectrum.

Generational hierarchies

- Higgses at UV brane (why? ... later.).
- Dial 3: Bulk fermion masses $c_{L,R}$.
- Use profiles $\sim z^{\frac{1}{2}-c_L},\ z^{\frac{1}{2}+c_R}$ for ferm. hier.

$$Y_{4d} = \frac{1}{2} Y_{5d} \sqrt{\frac{1-2c_L}{z_{\text{IR}}^{1-2c_L}-1}} \sqrt{\frac{1+2c_R}{z_{\text{IR}}^{1+2c_R}-1}}\ .$$



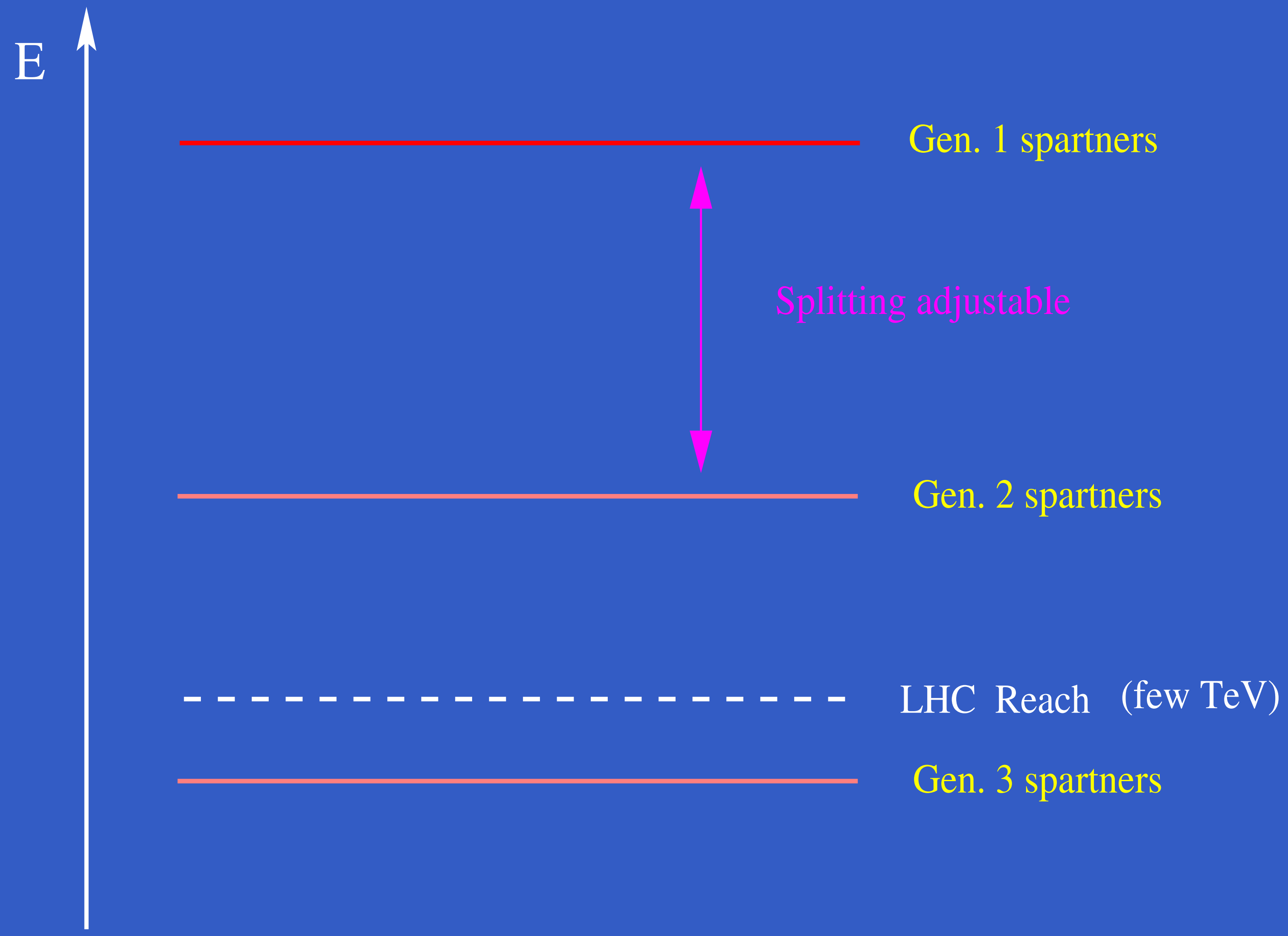
Scalar-fermion correlation

- SUSY implies boundary scalar mass b:

$$b = \frac{3}{2} - c_L.$$

- $\mathcal{O}(\epsilon)$ deviations in this relation $\rightarrow$ $\mathcal{O}(\epsilon^2)$ mass/profile corrections ... neglect.
- Scalar/fermion profiles approx. same.
- $\Rightarrow$ scalar partners of light fermions IR localized $(b > 1)$, [HEAVY]
- partners of heavy fermions UV localized $(b < 1)$. [LIGHT]

Scalars: INVERTED HIERARCHY [worried? ... good.]



Gen. 1 & 2 scalars beyond LHC reach.

Dual interpretation

- IR-localized generations 1 & 2 $\Rightarrow$ composite.
- Scalars feel the SUSY-breaking strong dynamics directly.

$$\tilde{m}_\phi \sim \Lambda_{SU(N)} \sim m_{KK}$$

- Fermions protected by chiral symmetry.

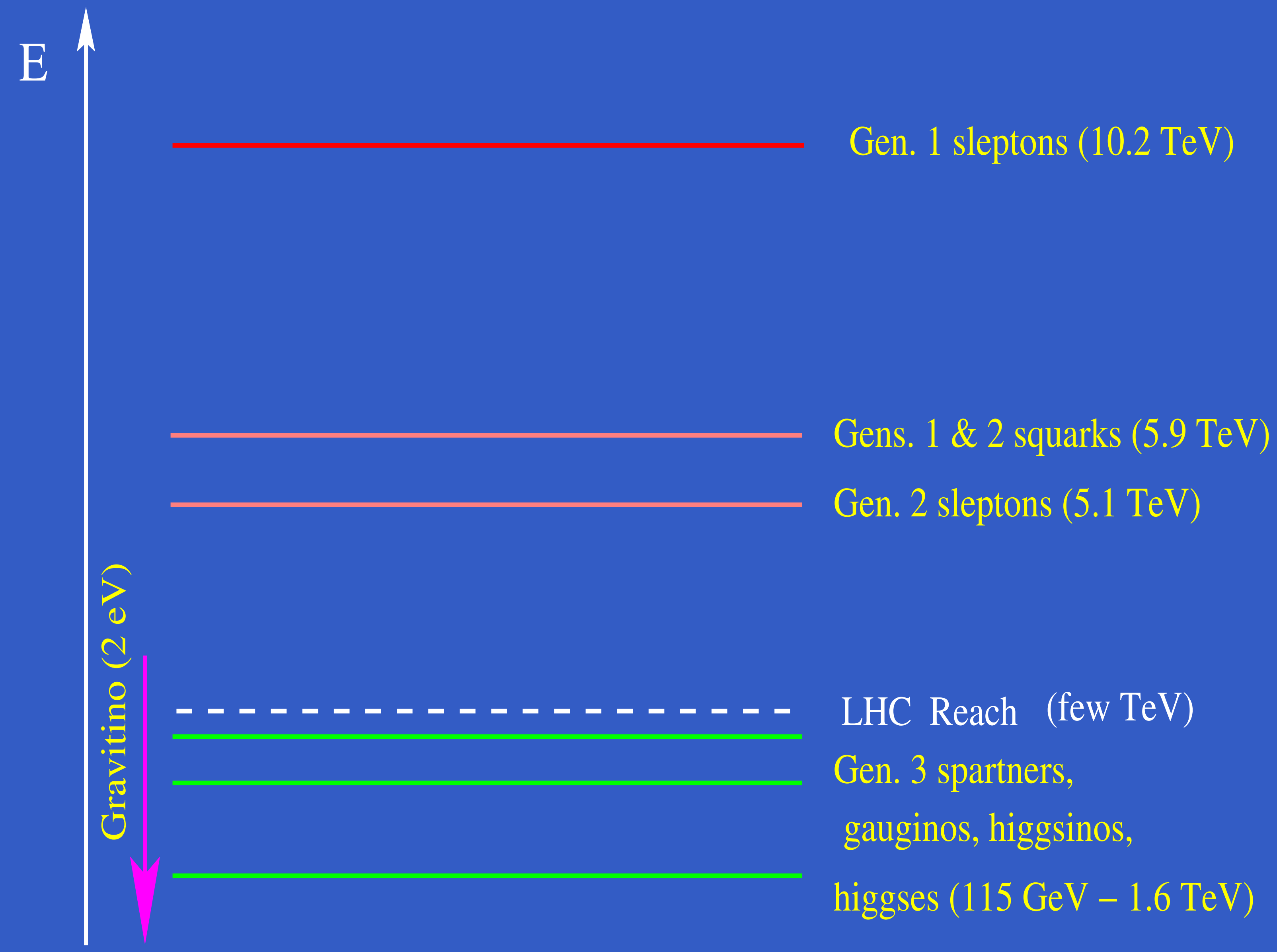
Third generation, higgses, gauginos

- Composite 1st & 2nd generations $\longrightarrow$ messengers with F-terms:

$$F \sim \tilde{m}_\phi \Lambda_{SU(N)}$$

- Equivalent to "single-sector" dynamical SUSY-breaking.
  [Arkani-Hamed, Luty, Terning 97-98]
- Third generation elementary $\Rightarrow$ only feel SM gauge mediation.
- Similarly for Higgses and gauginos.
- Gravity dual of 1-loop gaugino mass: G_3 flux background.

Example spectrum



Example spectrum

$\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_{eL}$	10160, 10150, 10160 GeV
$\tilde{\mu}_L$, $\tilde{\mu}_R$, $\tilde{\nu}_{\mu L}$	5145, 5130, 5145 GeV
$\tilde{d}_L$, $\tilde{d}_R$, $\tilde{u}_L$, $\tilde{u}_R$	5905, 5885, 5970, 5890 GeV
$\tilde{s}_L$, $\tilde{s}_R$, $\tilde{c}_L$, $\tilde{c}_R$	5905, 5885, 5970, 5890 GeV
$\tilde{g}$	1615 GeV
$\tilde{b}_1$, $\tilde{b}_2$, $\tilde{t}_1$, $\tilde{t}_2$	1354, 1369, 1253, 1369 GeV
$\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\nu}_{\tau L}$	511, 630, 633 GeV
$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$	478, 593 GeV
$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$	288, 480, 511, 598 GeV
h^0, A^0, H^0, $H^{\pm}$	115, 646, 646, 651 GeV
$\tilde{G}$	2.35 eV

FCNC constraints

- Nondegenerate squarks very dangerous.
- We keep gen. 1 vs. 2 squarks degenerate.
- $\Rightarrow$ little 1-2 hierarchy (m_c/m_u) in 5d Yukawas.
- Gen. 1-3 and 2-3 mixing constraints $\Rightarrow$ KK scale cannot be too large.
- Still solve BIG hierarchies,
  e.g. m_t/m_e,
  w/ localization!

FCNC's [vs. Ciuchini et al., hep-ph/0702144]

$\lvert\delta^d\rvert$	model	95% CL (bound)	experiment
12/LL	2.1×10^{-4}	1.4×10^{-2}	
12/RR	2.1×10^{-4}	9.0×10^{-3}	
12/LR	8.5×10^{-12}	9.0×10^{-5}	
12/RL	4.9×10^{-13}	9.0×10^{-5}	
13/LL	2.2×10^{-2}	9.0×10^{-2}	Δm_B, β
13/RR	2.1×10^{-2}	7.0×10^{-2}	Δm_B, β
13/LR	3.6×10^{-8}	1.7×10^{-2}	
13/RL	5.1×10^{-11}	1.7×10^{-2}	
23/LL	1.6×10^{-1}	1.6×10^{-1}	$b \to sX$, Δm_{B_s}
23/RR	1.6×10^{-1}	2.2×10^{-1}	$b \to sX$, Δm_{B_s}
23/LR	2.6×10^{-7}	4.5×10^{-3}	
23/RL	6.4×10^{-9}	6.0×10^{-3}	

Tachyonic stop/sbottom constraint

- Consider $d\tilde{m}^2_{Q3}/dt$, w/ gen. 1 & 2 squarks at scale Λ.
- 1-loop:

$$\beta^{(1)}_{\tilde{m}^2_{Q3}} \approx -\frac{\alpha_s}{4\pi}\frac{32}{3}M_3^2 \quad \text{(IR} \nearrow\text{)}.$$

- 2-loop:

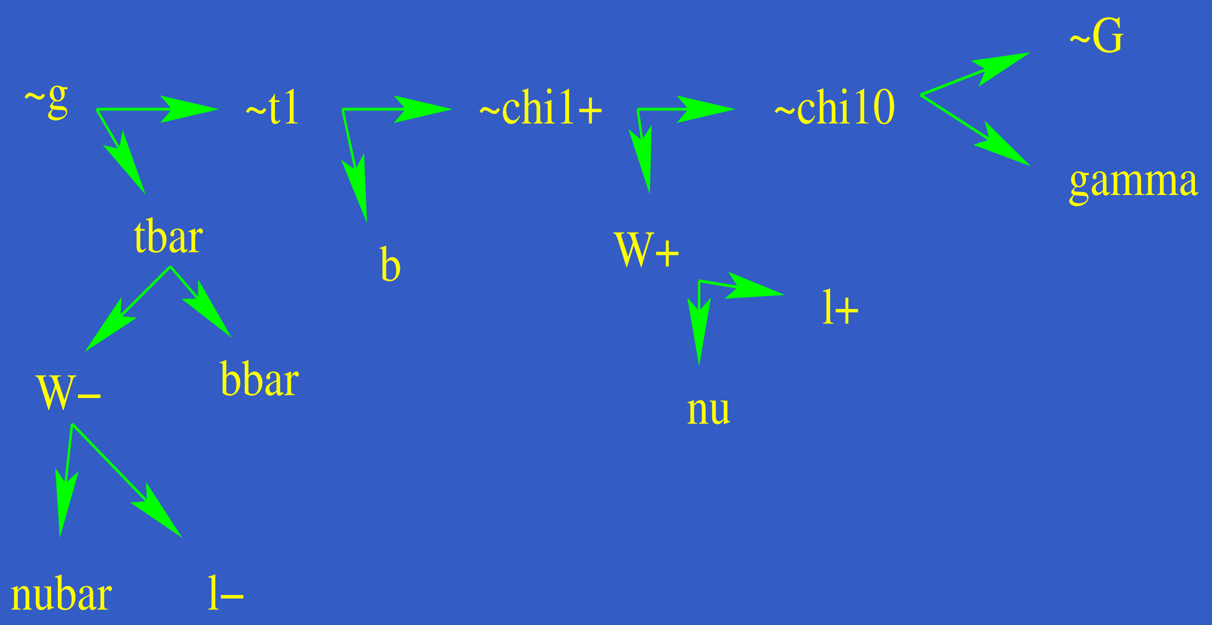
$$\beta^{(2)}_{\tilde{m}^2_{Q3}} \approx \frac{\alpha_s^2}{(4\pi)^2}\frac{4\cdot 32}{3}\Lambda^2 \quad \text{(IR} \searrow\text{)}.$$

- $\tilde{m}^2_{Q3}(\text{TeV}) > 0$ constraint:

$$(\sqrt{\pi/\alpha_s(\Lambda)} \approx 6): \quad \Lambda \lesssim 6M_3.$$

LHC predictions

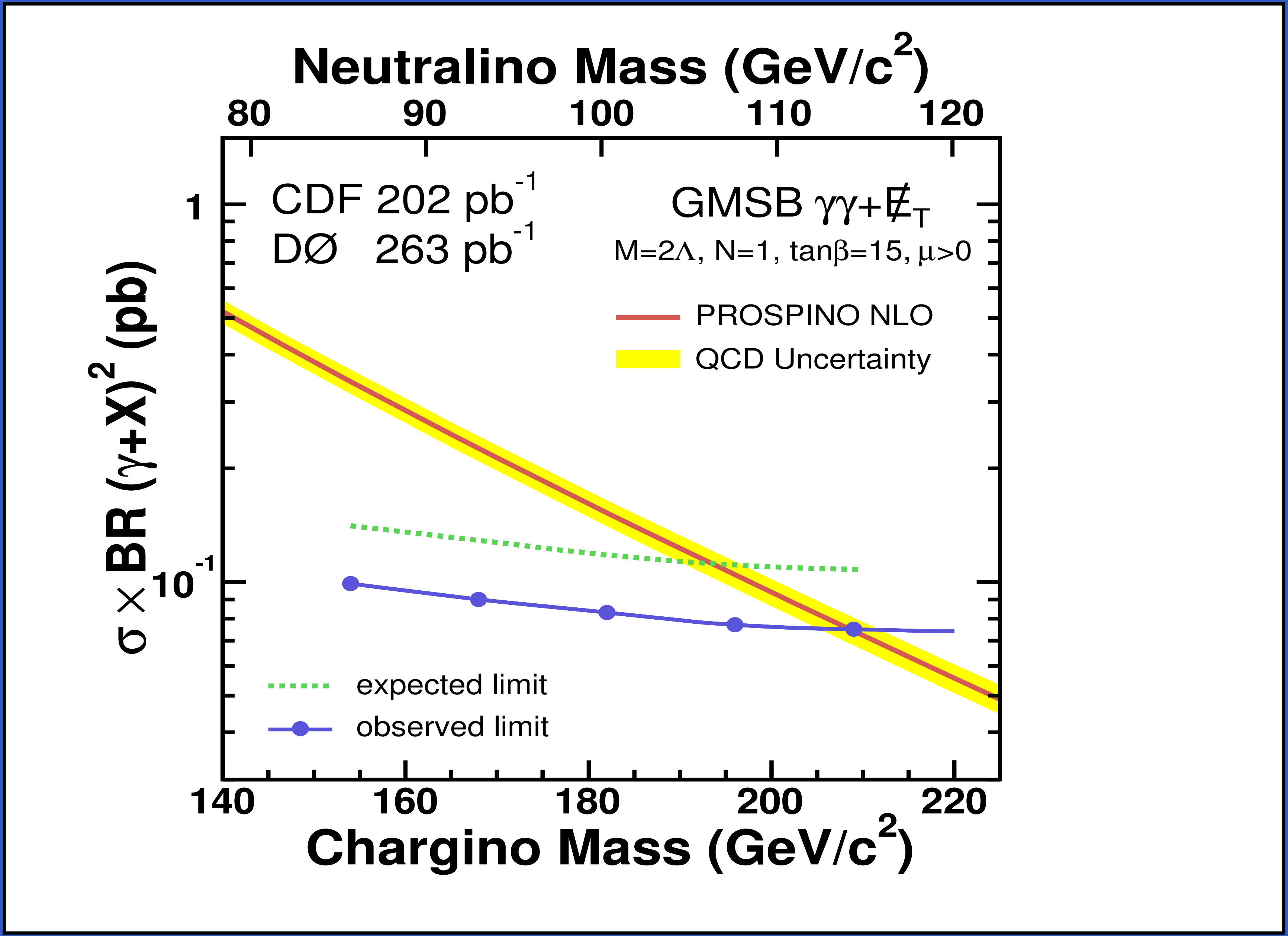
- Typical cascade decay from $gg \to \tilde{g}\tilde{g}$:



- The $\tilde{\chi}_1^0$ decays give rise to the distinctive signal:

$$p\bar{p} \to \gamma\gamma + \not{E}_T + X.$$

Limit from $p\bar{p} \to 2\gamma + \not{E}_T$ [Tevatron 2005]



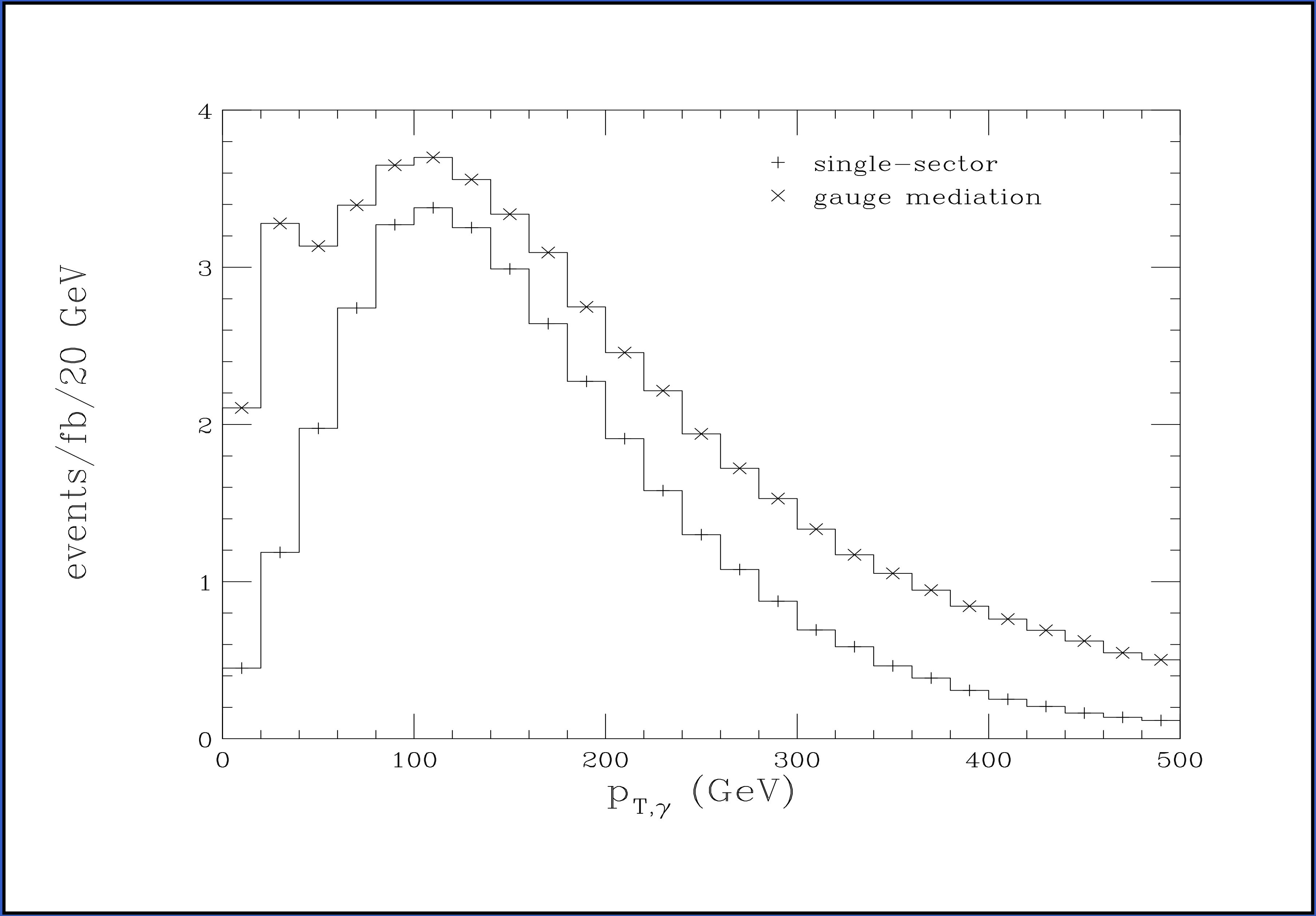
$\gamma\gamma + \not{E}_T$ in our model

- At Tevatron energy 1.96 TeV, PYTHIA says: $\sigma \times BR = 2.5 \times 10^{-5}$ pb ~ 0 events at DØ+CDF w/ 2 fb^{-1}.
- No constraint.

$\gamma\gamma + \not{E}_T$ in our model

- At LHC energy 14 TeV, PYTHIA says:
  $\sigma \times BR = 3.5 \times 10^{-2}$ pb.
- 1000 times the rate of Tevatron!
- Obtain ~ 35 events w/ 1 fb^{-1} ($\sim$ 1st year).
- Backgrounds larger at LHC:
  Will we see the signal?
- Compare to gauge mediation.

Compare to GMED



Backgrounds

- Real:

$$pp \to \{gg, q\bar{q}\} \to \gamma\gamma,$$

- Fake: (mainly $j \sim \pi^0$):

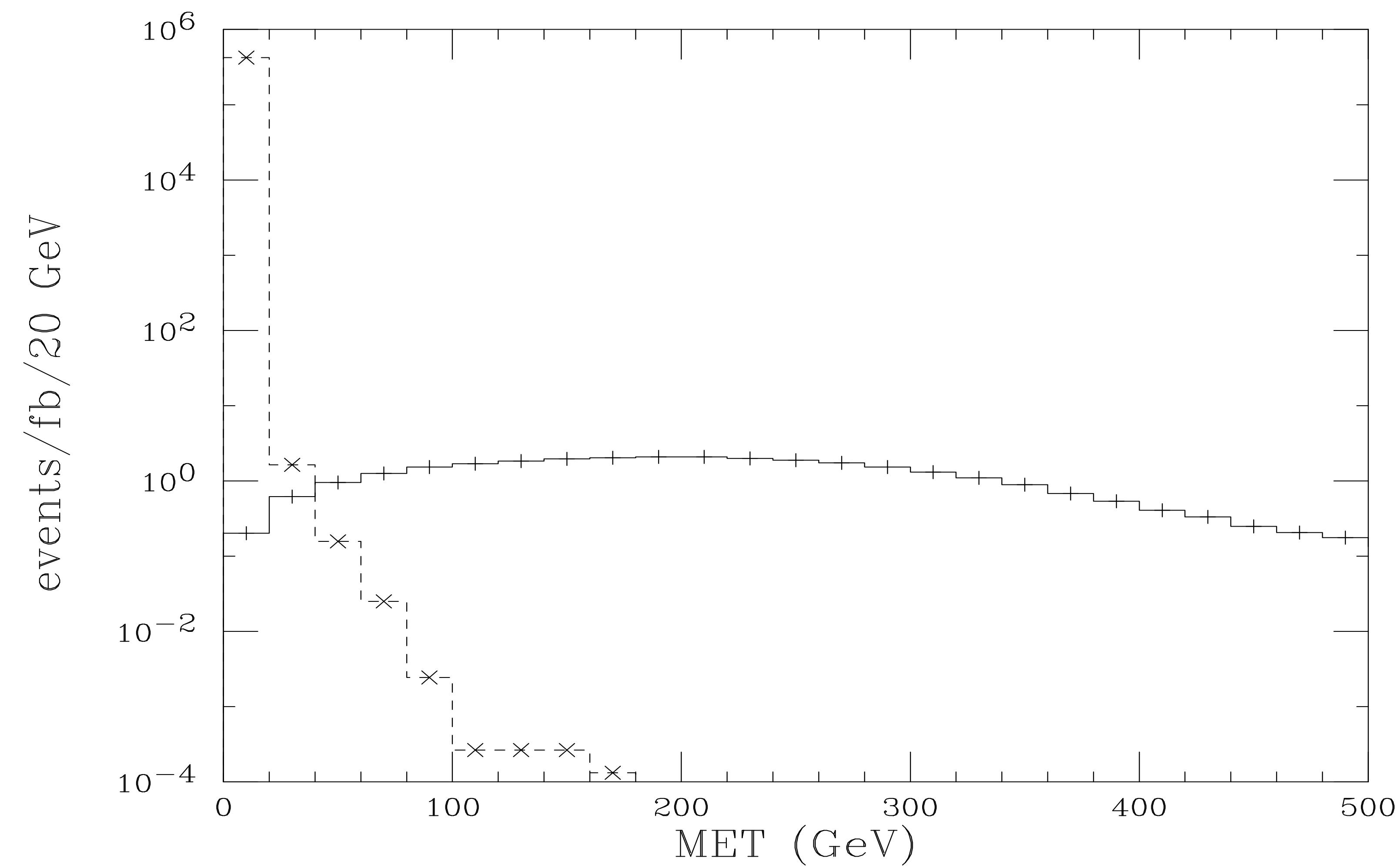
$$pp \to \gamma\, j_{\text{fake}}, \quad pp \to j_{\text{fake}}\, j_{\text{fake}}.$$

channel	$\gamma\gamma$	γj	jj
cross section	0.15 μb	0.12 mb	55 mb

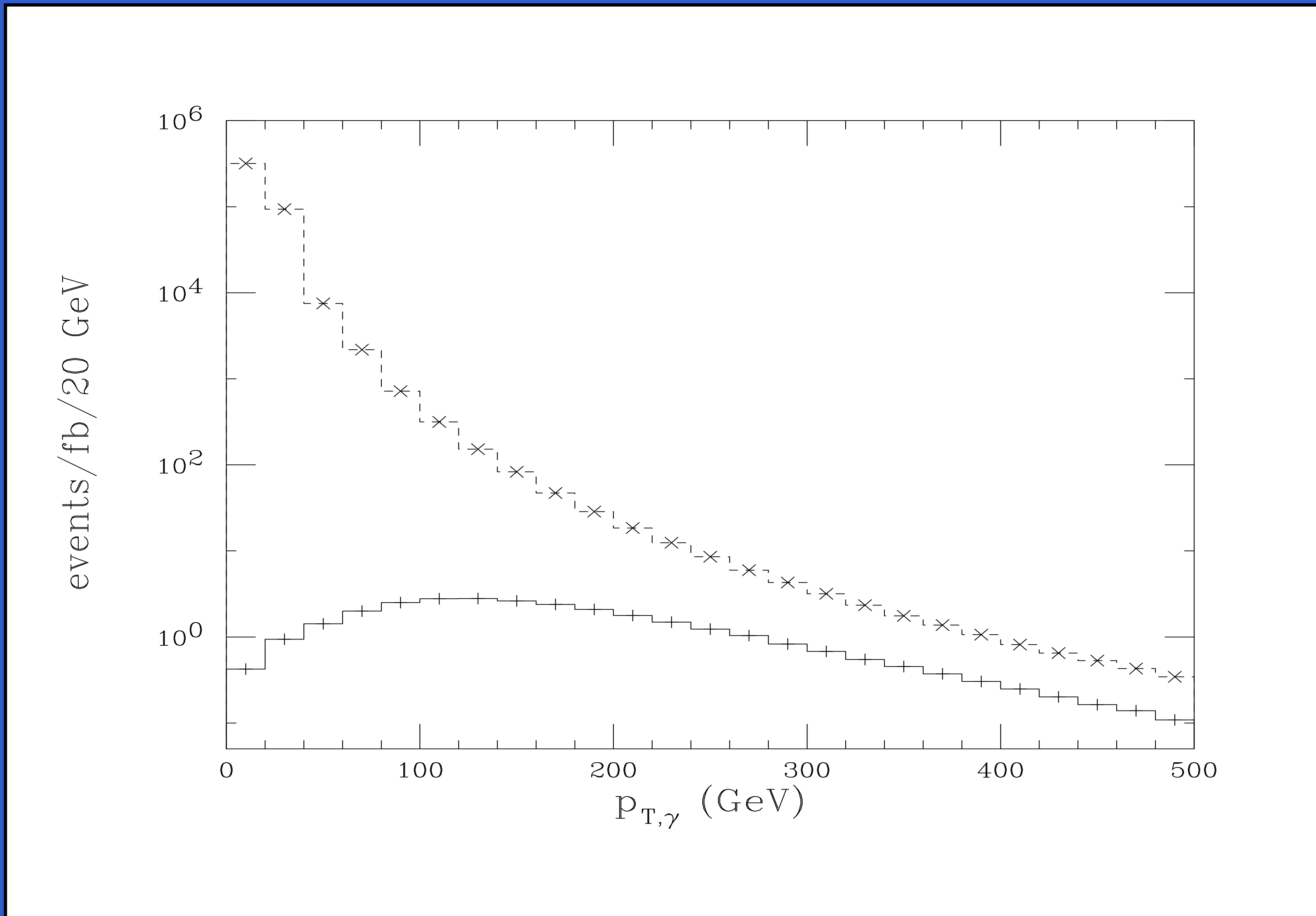
- Comparable since

$$j_{\text{fake}}/j \sim 10^{-3}$$

MET [SUSY = solid, SM($\gamma\gamma$) = dashed]



pT [SUSY = solid, SM($\gamma\gamma$) = dashed]



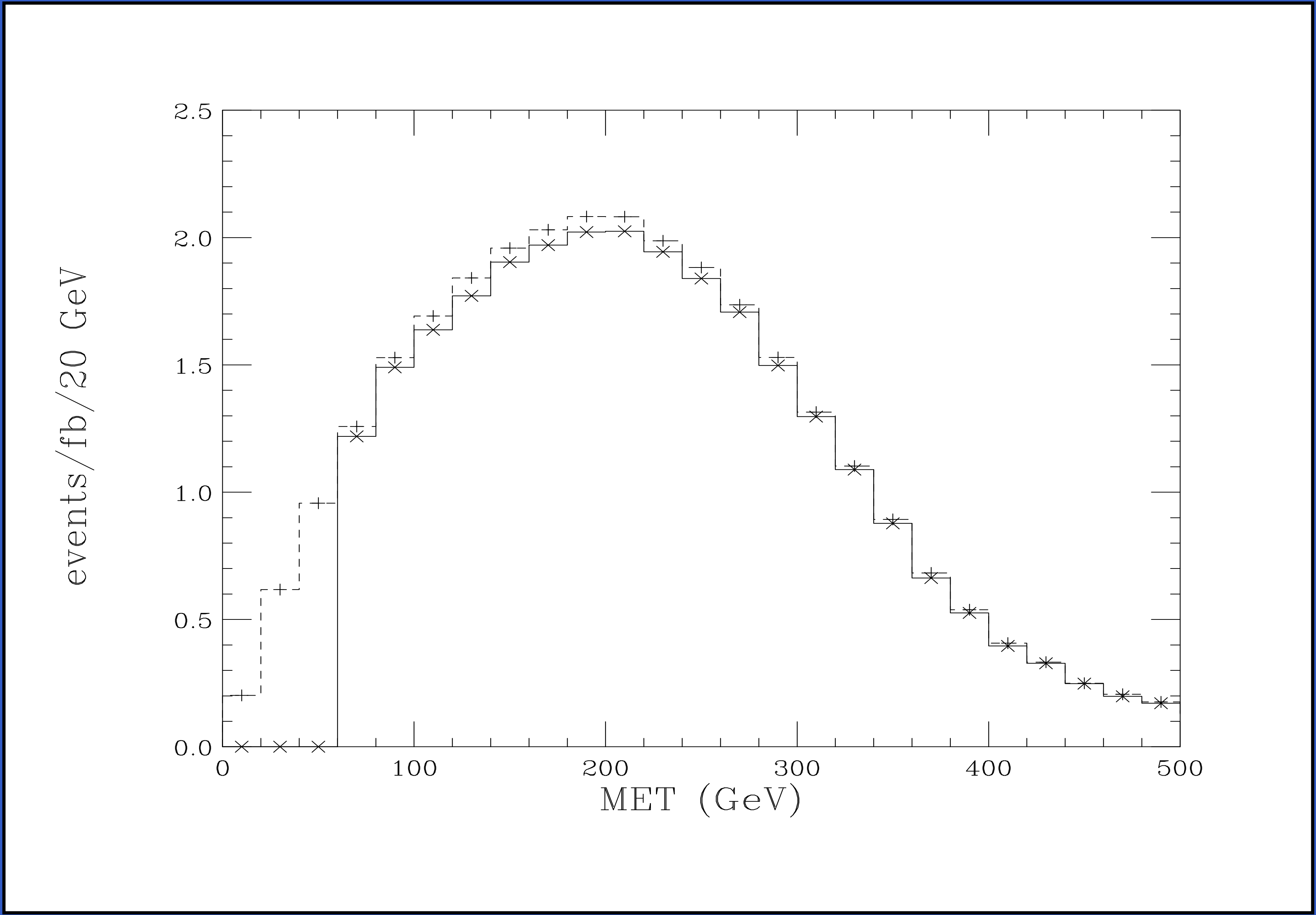
Cuts

- Distributions suggest:

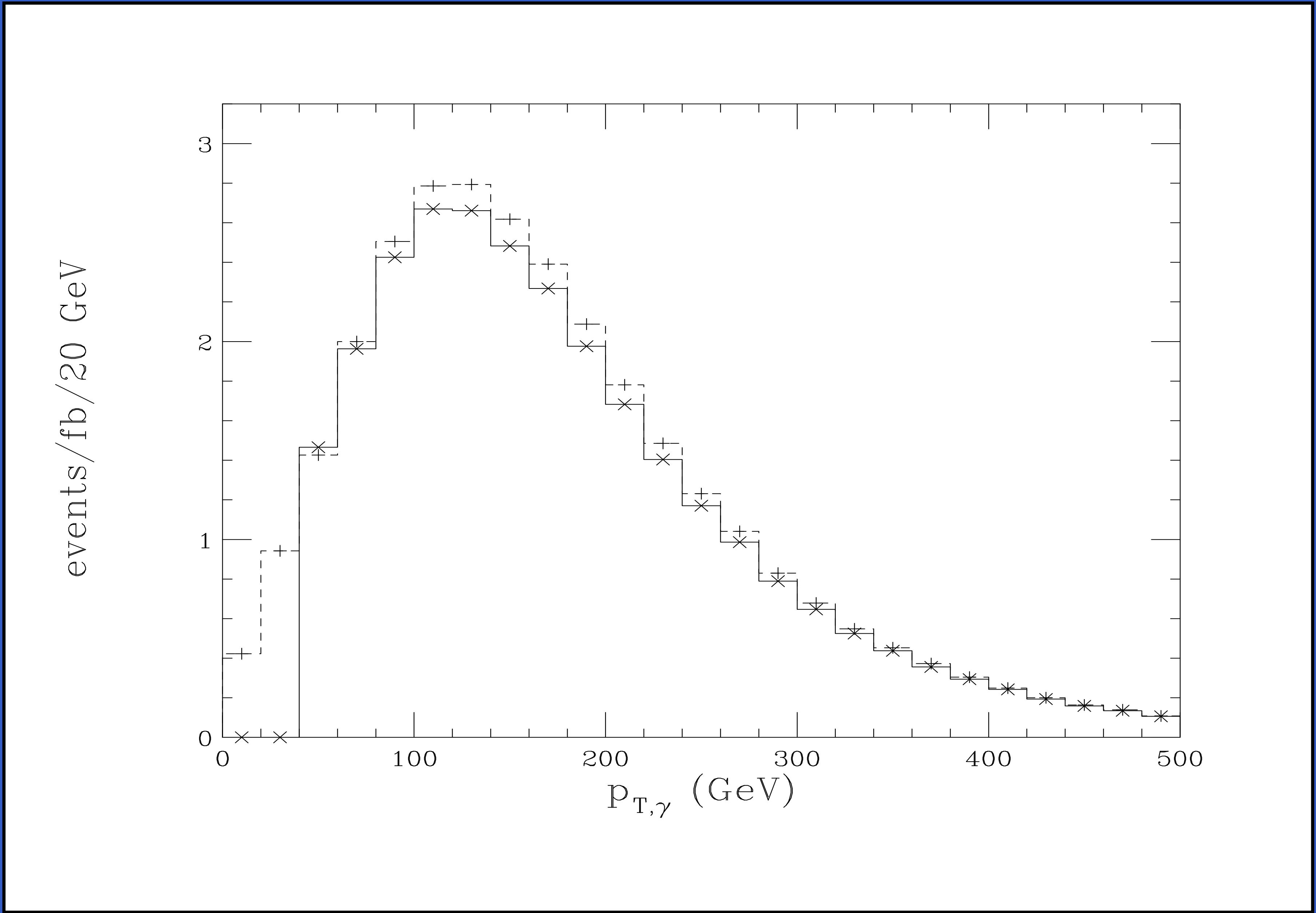
$$p_{T,\gamma} \geq 40 \text{ GeV}, \qquad \not{E}_T \geq 60 \text{ GeV}$$

- Don't lose much signal.
- Background eliminated.

MET (signal) [w/ cuts = solid, w/o cuts = dashed]



pT (signal) [w/ cuts = solid, w/o cuts = dashed]



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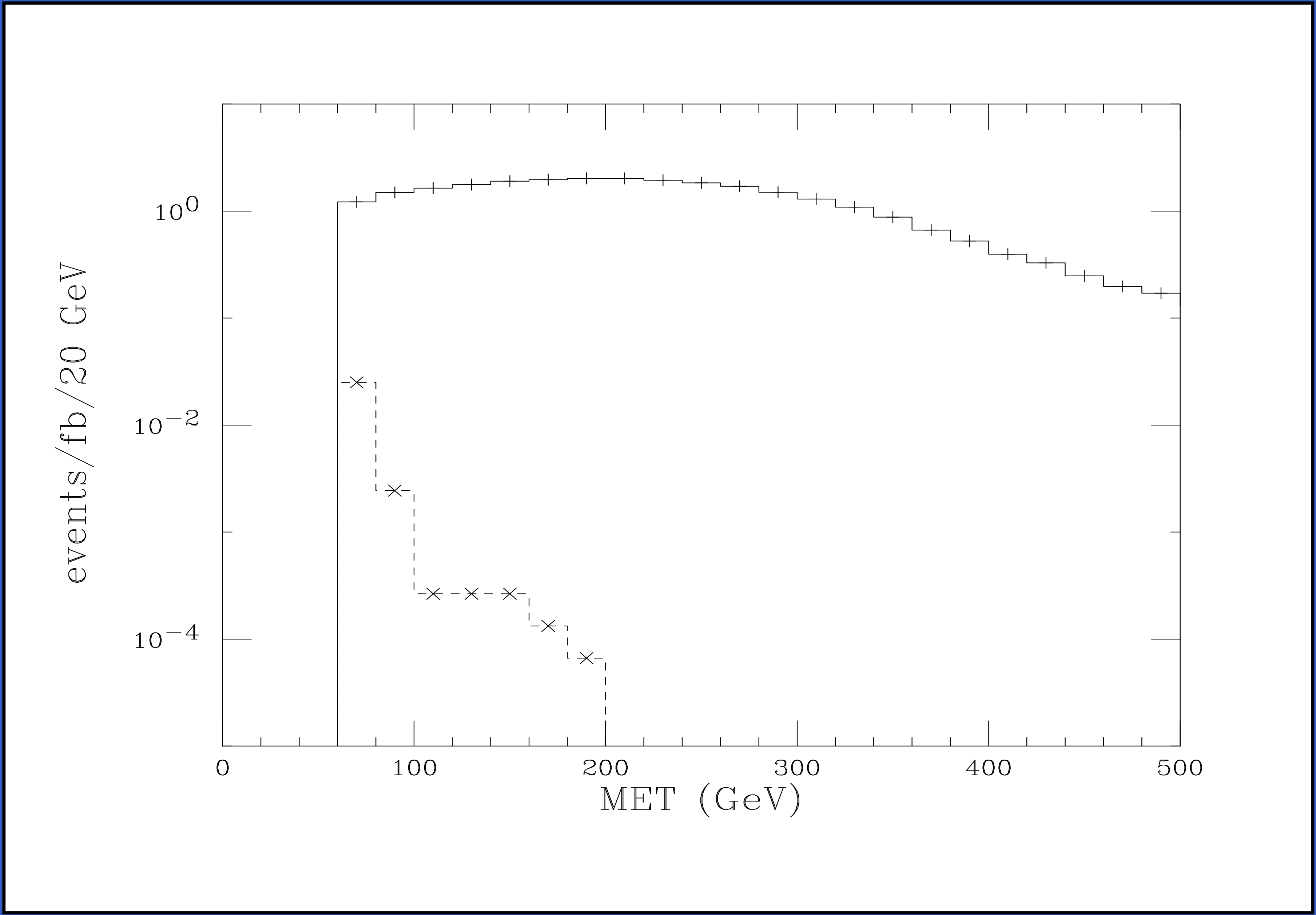
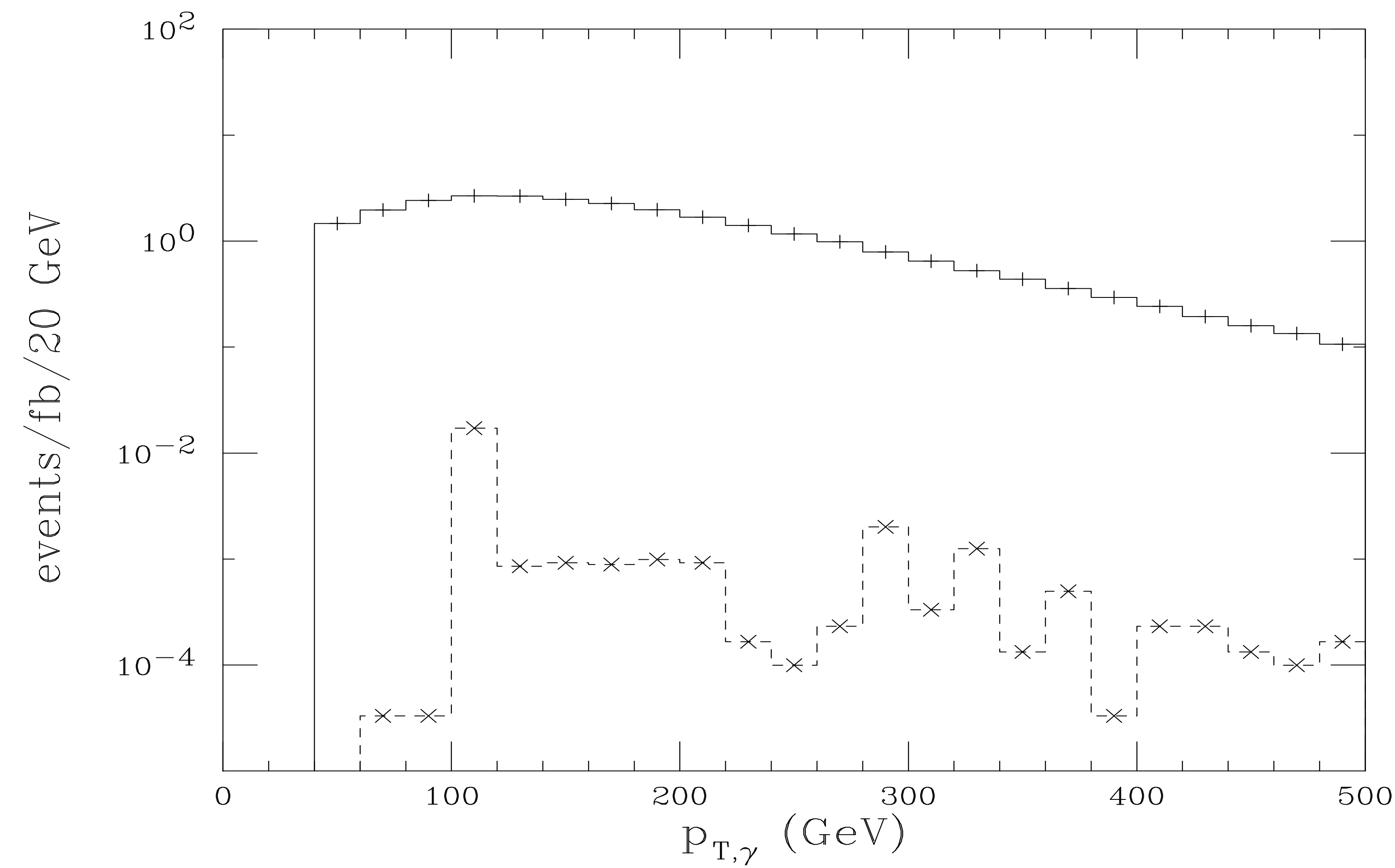


pT w/cuts [SUSY = solid, SM($\gamma\gamma$) = dashed]



Summary w/cuts

Integrated Luminosity	SUSY	SM 2γ	SM 2γ + fakes
1 fb^{-1}	27.6	0.0285	$\lesssim 0.1$
10 fb^{-1}	276	0.285	$\lesssim 1$

Why Higgses on UV brane?

- Suppose $H_{1,2} \longrightarrow$ IR brane.
- Gen. 1 & 2 UV localized.
- Gauge mediated $\tilde{m}_{1,2}, M_i\ (i = 1, 2, 3) \sim$ 1 TeV $\Rightarrow$ KK scale 100 TeV.
- No SUSY at IR end $\rightarrow$ problems...

Why Higgses on UV brane?

- 2HDM many new parameters: 3 m^2's, 7 λ's.
- Many new sources of FCNC's.
- Hierarchy problem:
  - Gen. 3 now IR localized $\to$ 100 TeV $\tilde{m}_3$.
  - KK modes 100 TeV.
  - Unsuppressed coupling to Higges for both.
  - Recall $\lambda_t \sim 1$ and $\Delta m^2_{h^0} \sim \ln(\tilde{m}_t/m_t)$.
  - Destabilizes EW scale.

Predictive

- The mass scale of Gen. 1,2 sfermions are fixed by the quark and lepton masses and two additional parameters ($z_{\rm IR}$, ϵ).
- The rest of the spartners are fixed by three other parameters ($F,\ N_{\rm mess.},\ \tan\beta$).

Conclusions

- Gravitational dual for single-sector models.
- A single parameter (ϵ) for SUSY-breaking in bulk.
- Lower rates distinguish model from gauge mediation.
- Backgrounds negligible w/ simple cuts.
- BIGGEST CONSTRAINTS:
  - FCNC's and
  - tachyonic squarks.