The Implication of F-theory GUTs for LHC

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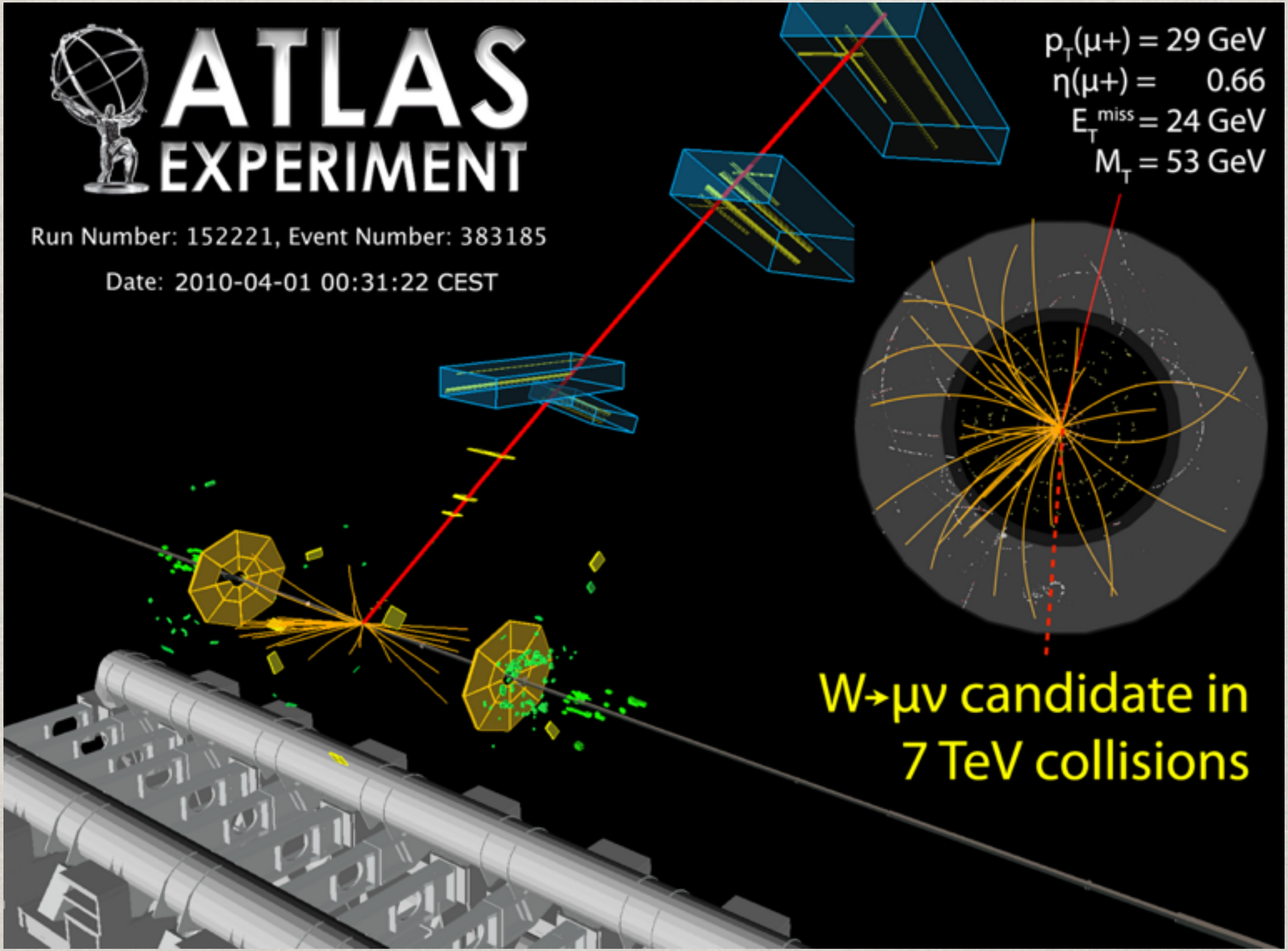
arXiv:1001.4084, w/ J. Heckman and C. Vafa
arXiv:0903.3609, w/ J. Heckman, G. Kane and C. Vafa

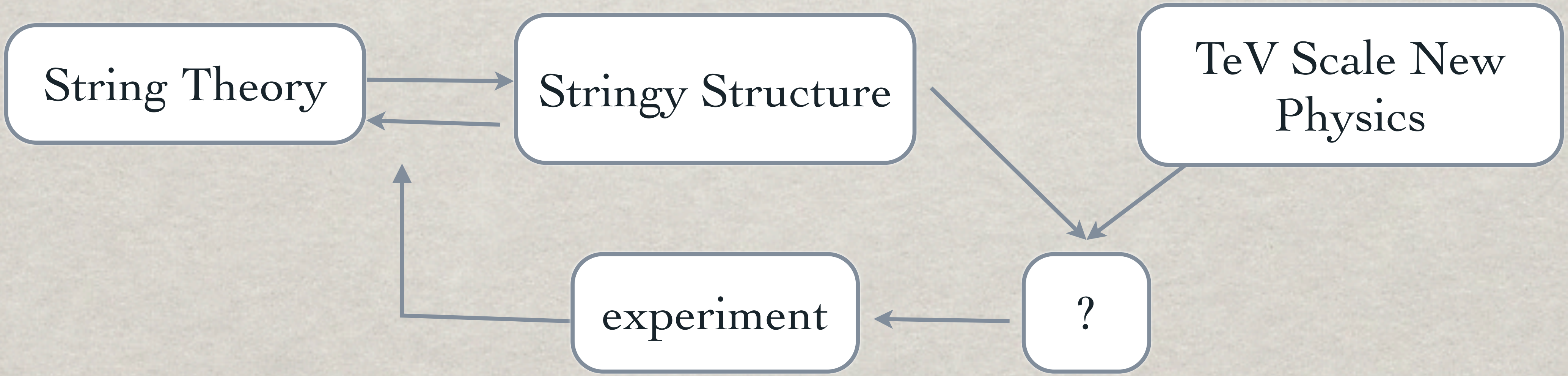
SVP meeting, KITP May 2010


ATLAS EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+)$ = 29 GeV
$\eta(\mu+)$ = 0.66
E_T^{miss} = 24 GeV
M_T = 53 GeV
W→μν candidate in
7 TeV collisions

STRING PHENO @ THE LHC AGE

The more phenomenological approach:

- New Physics Scenario + Ingredient from string compactification + Pheno. Constraints is already stringent
- Focusing on models which could be seen and tested in near future

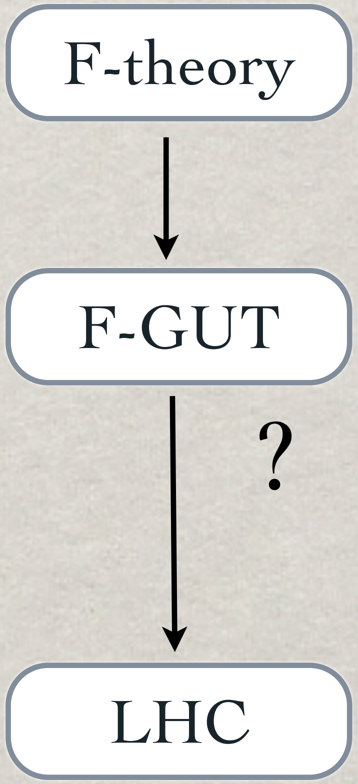


Focus on the F-theory GUT model

[C. Beasley, J. Heckman and C. Vafa]
and many others: V. Bouchard, S. Cecotti, M. Cheng, J. Conlon, J. Marsano, F. Quevedo, N. Saulina, S. Schafer-Nameki, J. Seo, A. Tavanfar, T. Watari, M. Wijnholt . . . . . .

Plan of my talk

- What are the ingredients for F-GUT
- SUSY breaking and U(1)$_{PQ}$ deformation
- LHC signals and searching strategy


F-theory

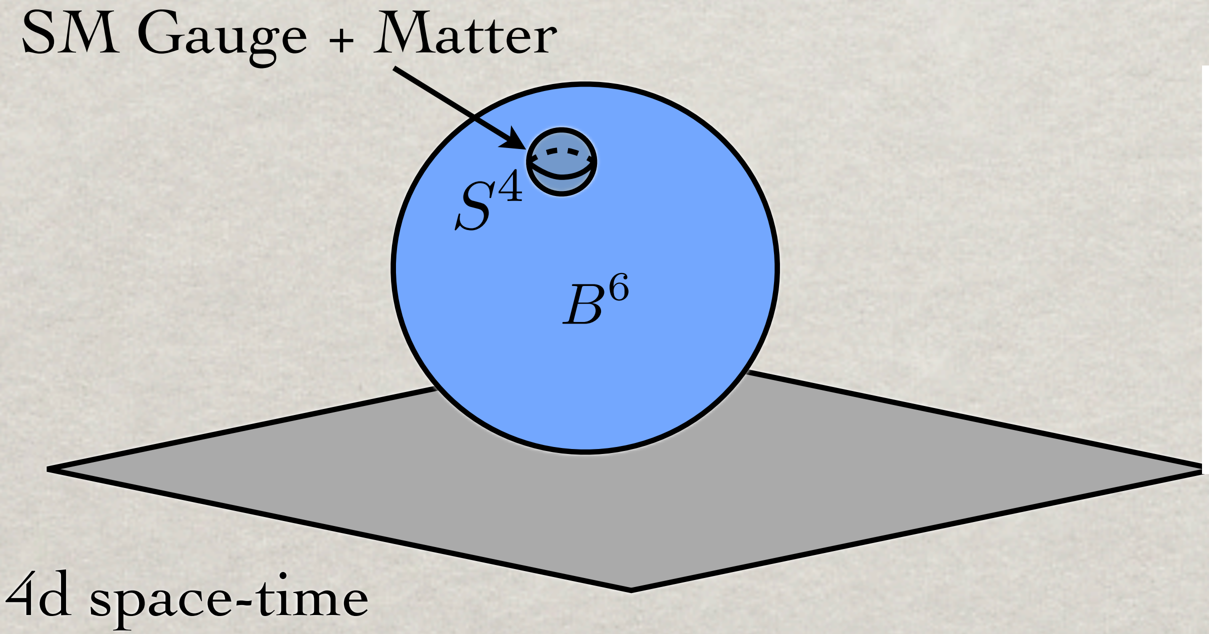
F-GUT

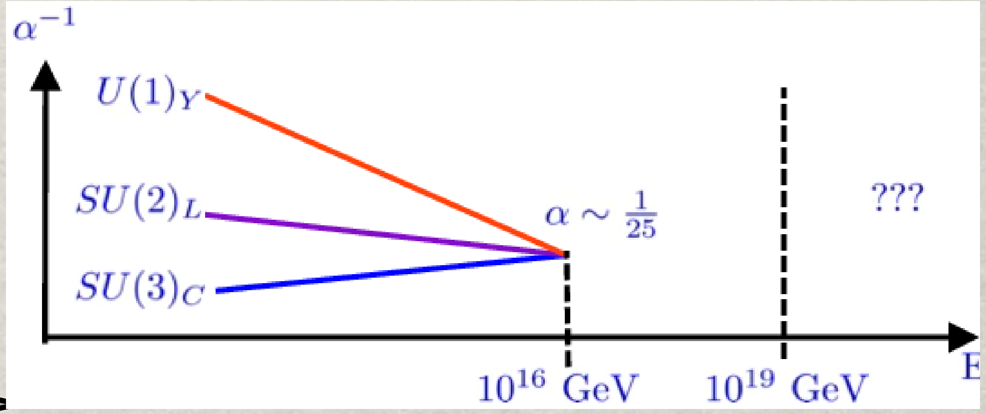
?

LHC

LOCAL MODEL

- Focusing on the UV motivated gauge theories -- Local models gravity can be decoupled $M_{GUT}/M_{pl} \sim 10^{-3}$
- Requiring GUT and decoupling limit severely restrict the model

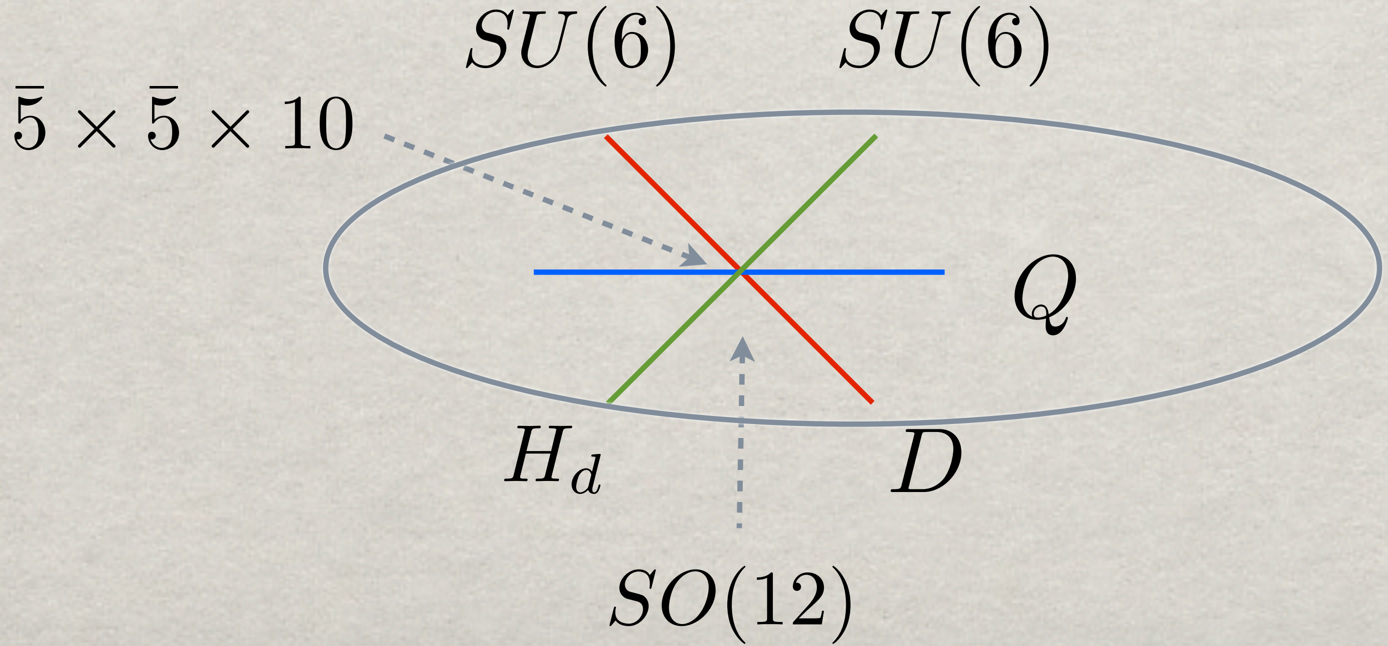




F-THEORY INGREDIENTS FOR MODEL BUILDING

- Gauge fields --> ADE Singularity $S^4 \times C^2/\Gamma_{ADE}$
- Matter fields --> Curve with enhanced symmetry
- Yukawa --> Point with enhanced symmetry

	Total dim	Internal dim
Gravity	10	6
Gauge	8	4
Matter	6	2
Yukawa	4	0



E8 POINT UNIFICATION

- Hierarchical CKM matrices
- μ term from the vev of a GUT singlet
- U(1)$_{\text{PQ}}$ symmetry
- Right-handed Neutrino

Heckman and Vafa, arXiv:0811.2417
Heckman,Tavanfar and Vafa, arXiv:0906.0581

E8 enhanced symmetry

min. number of geometric ingredients necessary

- E8 breaking pattern

$$E_8 \supset SU(5)_{GUT} \times SU(5)_{\perp}$$

broken by U(1) flux to
$SU(3) \times SU(2) \times U(1)$

broken to U(1)s by geometry

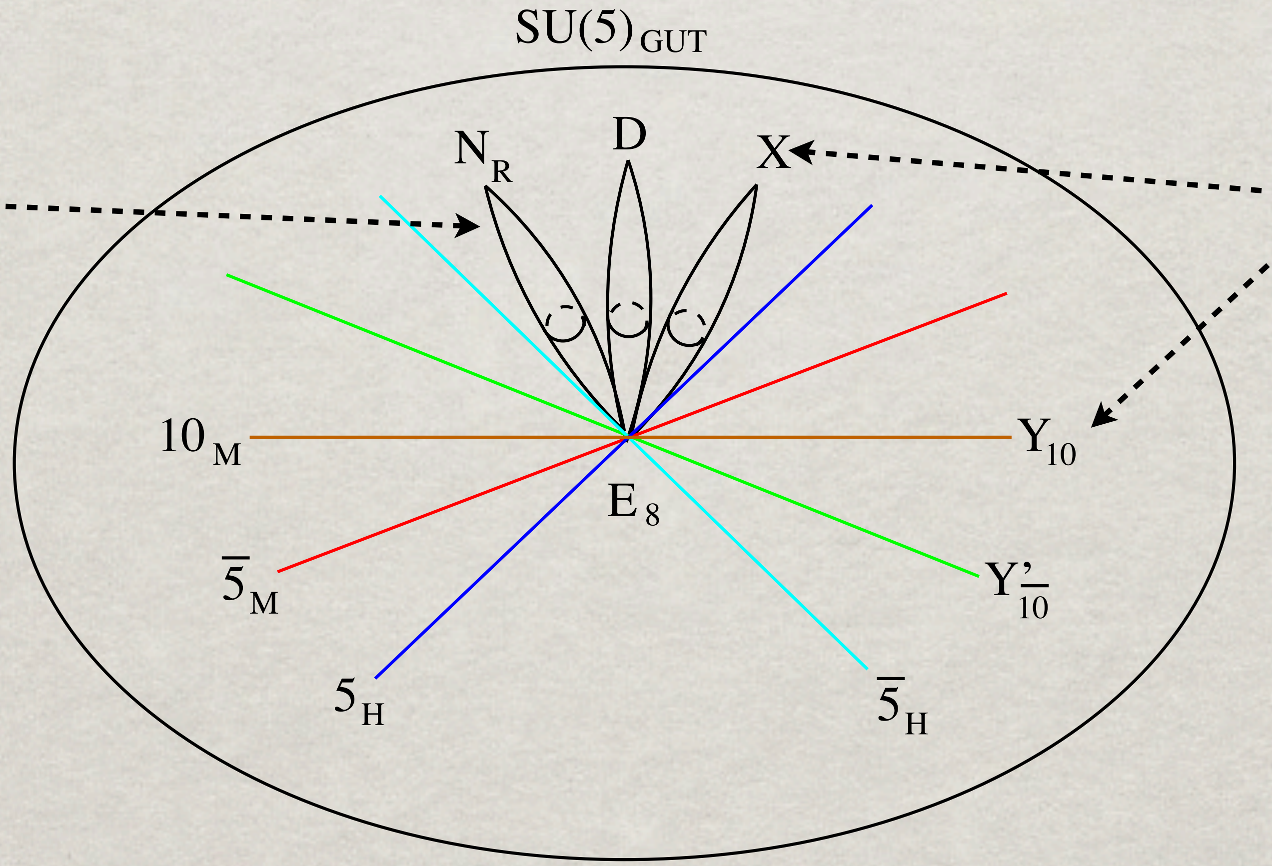
E8 POINT UNIFICATION

- Majorana Neutrino Scenario ⟵ min. scenario
  - Extra matter $10 \oplus \overline{10}$
  - Only one U(1) survive, PQ charge fixed

	$\overline{5}_M$	10_M	5_H	$\overline{5}_H$	$X^\dagger$	N_R
Majorana $U(1)_{PQ}$	$+2$	$+1$	-2	-3	$+5$	0

- Dirac Neutrino Scenario
  - Two U(1)'s : $U(1)_{PQ}$ $U(1)_\chi$

MINIMAL E8 MODEL



GUT singlets

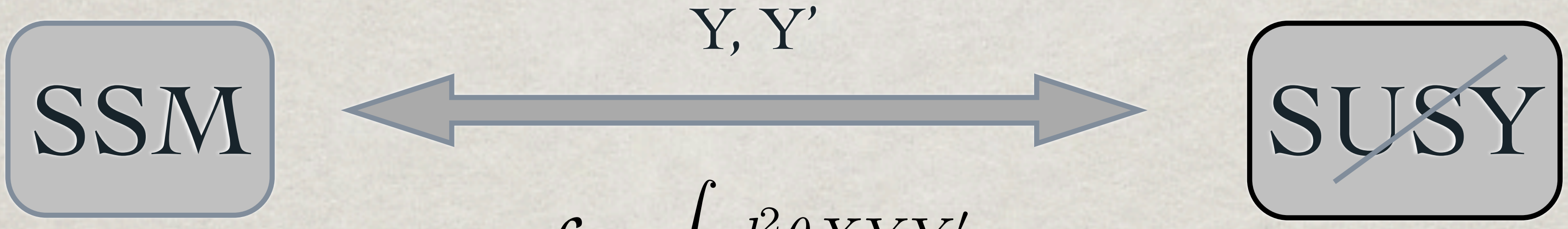
What are these for?

Minimal E8 model

~~SUSY~~ AND MEDIATION

- Extra GUT multiplet + Singlet ⟶ Gauge mediation is natural in F-GUTs.

- Basic Picture



Y, Y’

SSM

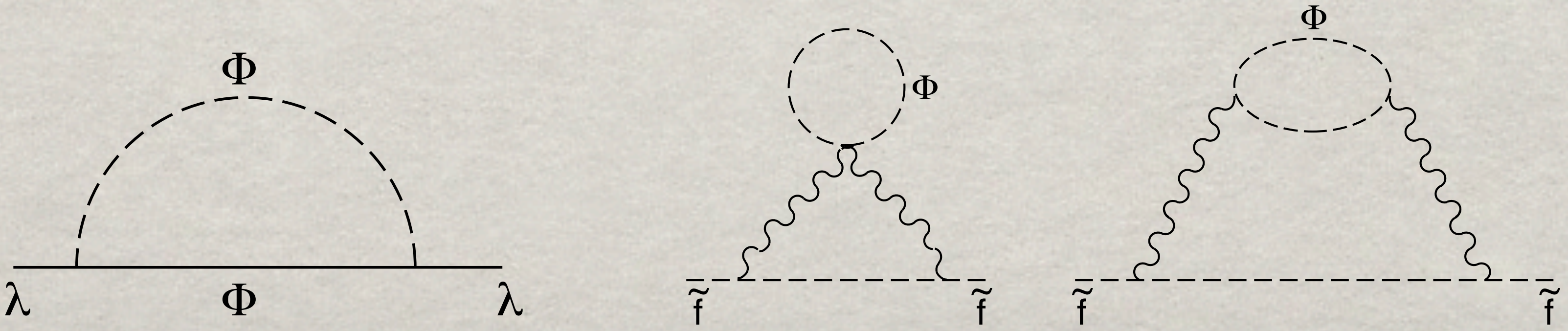
~~SUSY~~

$$\mathcal{L} \sim \int d^2\theta XYY'$$

$$\langle X \rangle = M + \theta^2 F$$

- Soft mass $m_{soft} \sim \frac{\alpha}{4\pi}\frac{F}{M}$

- In almost all cases, messengers are in $10 \oplus \overline{10}$



$\mu/B\mu$ PROBLEM

- EWSB in MSSM $B, \mu \sim M_{EW}$
- In F-GUTs, PQ charge of X forbid $\int d^2\theta X H_u H_d$
- D-term contribution to μ term

$M_X \sim 10^{15}$ GeV

$$\int d^4\theta \frac{X^\dagger H_u H_d}{M_X} \text{(from integrating out KK modes of X)}$$

$$\Longrightarrow \mu \sim \frac{\bar{F}}{M_X}, \quad \text{require } \mu \sim 10^2\text{GeV} \Longrightarrow \boxed{F \sim 10^{17}\text{GeV}^2}$$

- Bμ term:

$$\int d^4\theta \frac{X^\dagger X X^\dagger H_u H_d}{M_X^3} \Longrightarrow B\mu \sim \frac{M|F|^2}{M_X^3} = \frac{M}{M_X}\left|\frac{F}{M_X}\right|^2$$

$$\frac{B\mu}{\mu} \sim \frac{M}{M_X}\mu$$ ← smaller than μ if M < Mx

M. Ibe and R. Kitano, JHEP 0708:016,2007
J. Marsano, N.Saulina S. Schafer-Nameki, J. Heckman and Vafa
……

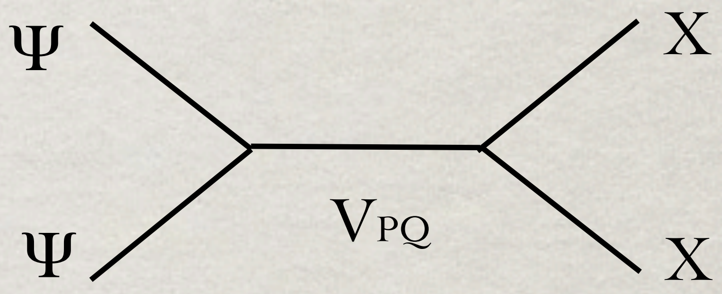
U(1)PQ AND AXION

- U(1)PQ gauge boson can obtain mass through Stueckelberg mechanism
- Below M_{PQ} , global U(1)PQ $\longrightarrow$ broken by $\langle X \rangle = M$
- *M* set the axion decay constant $10^9 \text{ GeV} < M < 10^{12} \text{ GeV}$
- Take soft mass to be ~TeV $\longrightarrow \frac{F}{M} \sim 10^5 \text{ GeV} \longrightarrow \boxed{M \sim 10^{12} \text{ GeV}}$
- In fact both *M* and F-term can be generated through Fayet-Polonyi potential
  --Mild tuning of the flux needed to achieve necessary hierarchy

J. Marsano, N.Saulina S. Schafer-Nameki, J. Heckman and Vafa

U(1)PQ INDUCED SOFT MASSES

Integrate out heavy PQ gauge boson



$$\mathcal{L} \supset -g^2_{_{PQ}} e_X e_\Psi \int d^4\theta \frac{X^\dagger X \Psi^\dagger \Psi}{M^2_{PQ}}$$

Additional contribution to the scalar mass $m^2_{soft} = m^2_{mGMSB} + q_\Psi \Delta^2_{PQ}.$

$$\Delta^2_{PQ} \sim g^2_{_{PQ}} \frac{F^2_X}{M^2_{PQ}}$$

$$\Delta_{PQ} \sim \mathcal{O}(100) \text{ GeV}$$

	10_M	$\bar{5}_M$	5_H	$\bar{5}_H$
q_{Majorana}	$-4/5$	$-8/5$	$+8/5$	$+12/5$

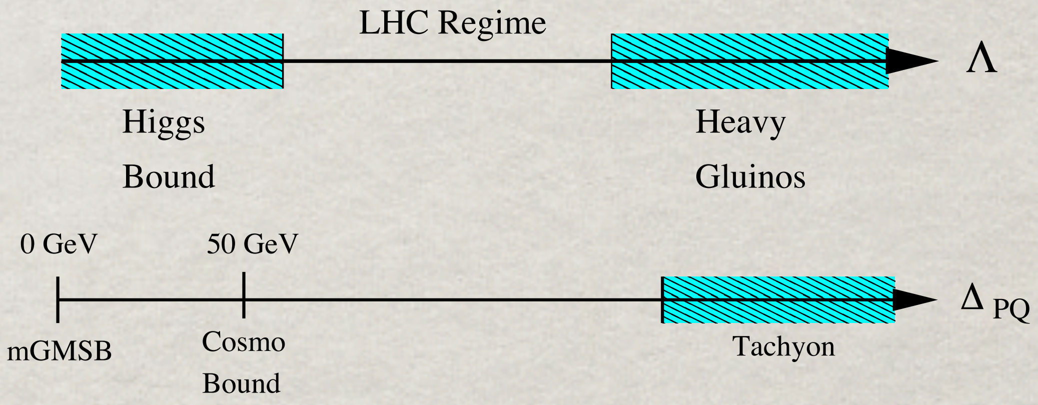
Cosmological constraint

$$\Delta_{PQ} \gtrsim 50 \text{ GeV}$$

Negative sign -> Lower $m_{\tilde{q}}, m_{\tilde{l}}$

SOFT TERMS AT LOW ENERGY

- GMSB + PQ deform. set BC @ M_{mess}
- Effective Parameters for Pheno Study:
  - Λ ($\Lambda \equiv F/M$) and Δ_{PQ}
  - N_{10} = 1, 2 (N_5=3,6)
  - $B\mu$ =0 @ $M_{mess} \sim 10^{12}$ GeV
    -- fix tanβ at low scale



- RG evolving of soft parameters down to TeV scale

DETAIL FEATURE IN SOFT TERMS

- Gaugino Mass $m_{gaugino} \sim N_{10}\frac{\alpha}{4\pi}\Lambda$

No PQ shift

- Scalar Mass

$$m^2_{scalar} = \hat{m}^2_{scalar} + e_\Phi \Delta^2_{PQ}$$

$$\hat{m}_{scalar} \sim \sqrt{N_{10}}\frac{\alpha}{4\pi}\Lambda$$

$$m = \widehat{m}\sqrt{1 - \frac{\Delta^2_{PQ}}{\widehat{m}^2}},$$

  - Small for squark
  - Large for sleptons -> largest for lightest stau

THE LSP

- Gravitino mass: $m_{\tilde{G}} \sim \frac{F}{M_p} \sim 10 - 100 MeV$

Heckman,Tavanfar and Vafa, arXiv:0812.3155

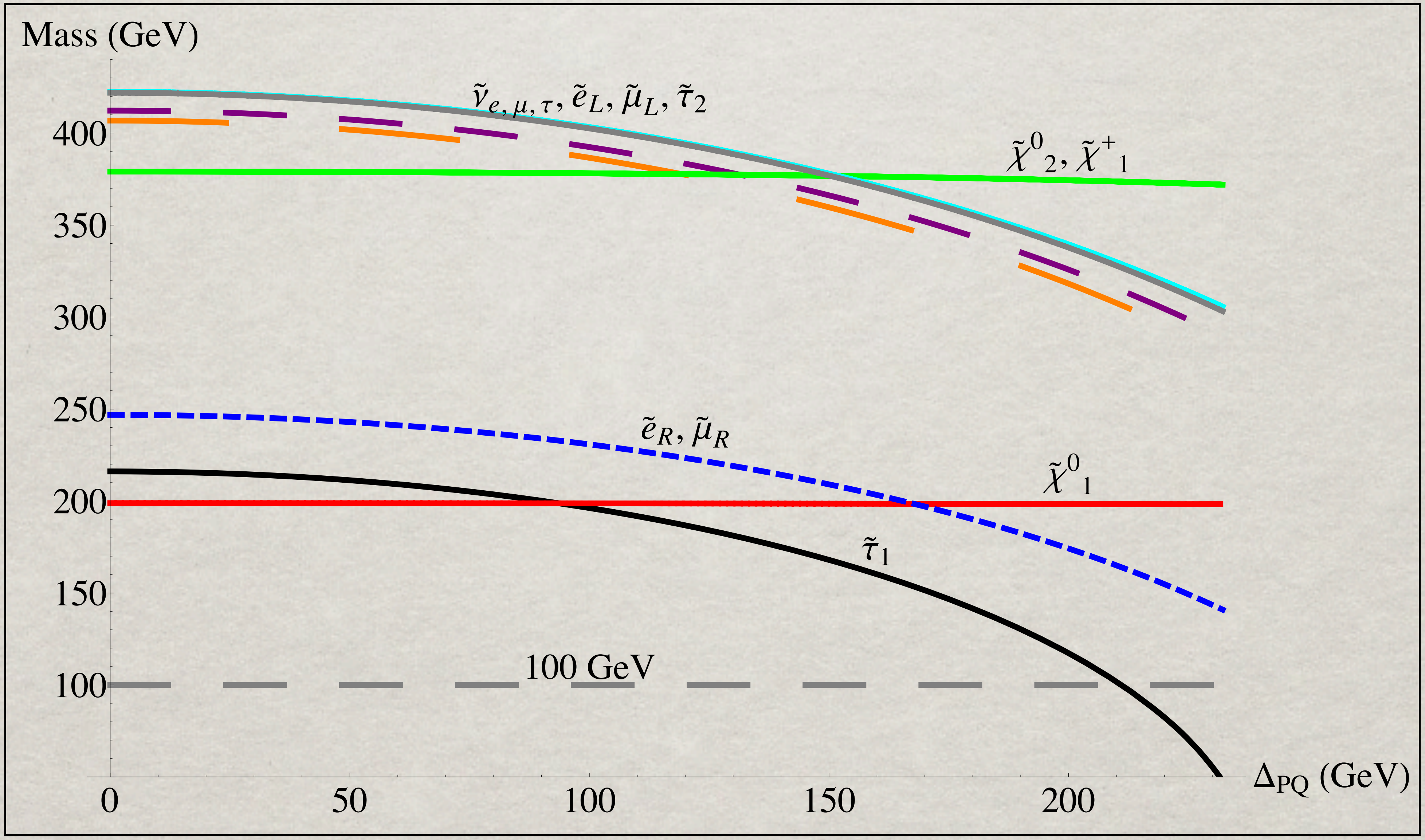
- NLSP decay to Gravitino

$$\Gamma(\tilde{\psi} \to \tilde{G} + \psi) \sim \frac{m_{NLSP}^5}{F_X^2}$$

- NLSP is quasi-stable, lifetime : one sec - an hour

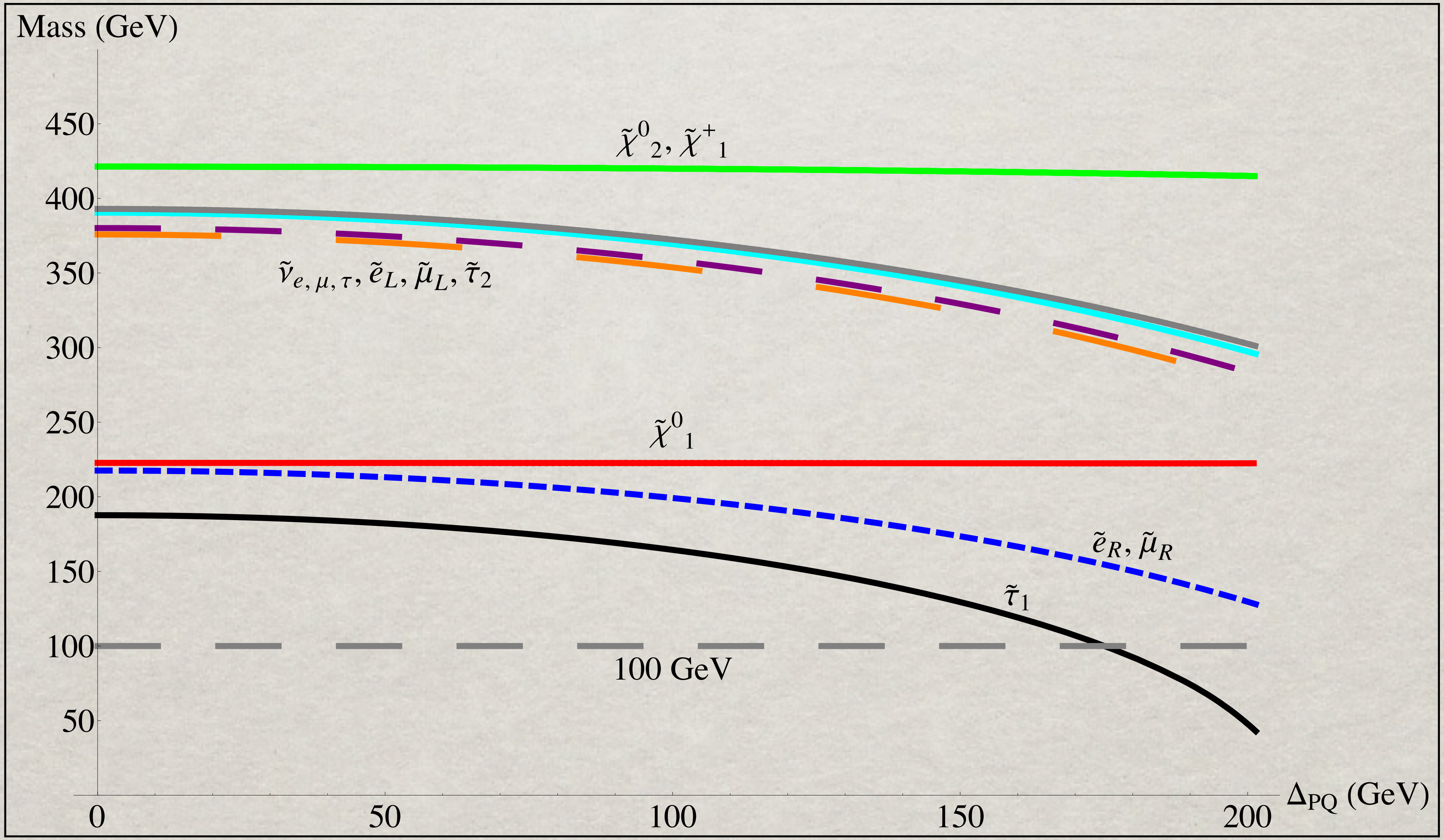
Δ_{PQ} AND SLEPTON MASS

-- **N_{10}=1, Λ = 50 TeV**

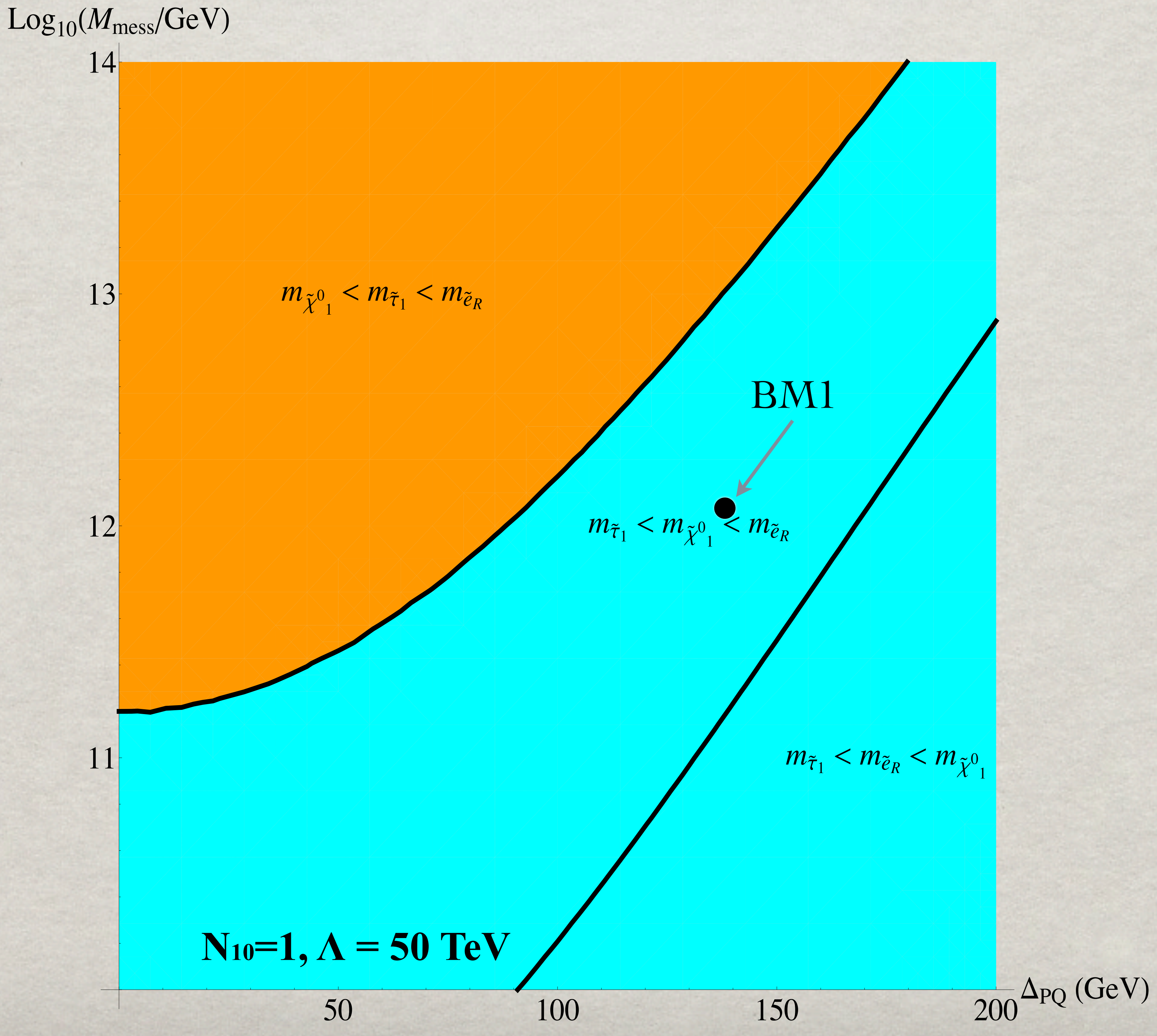


Δ_{PQ} AND SLEPTON MASS

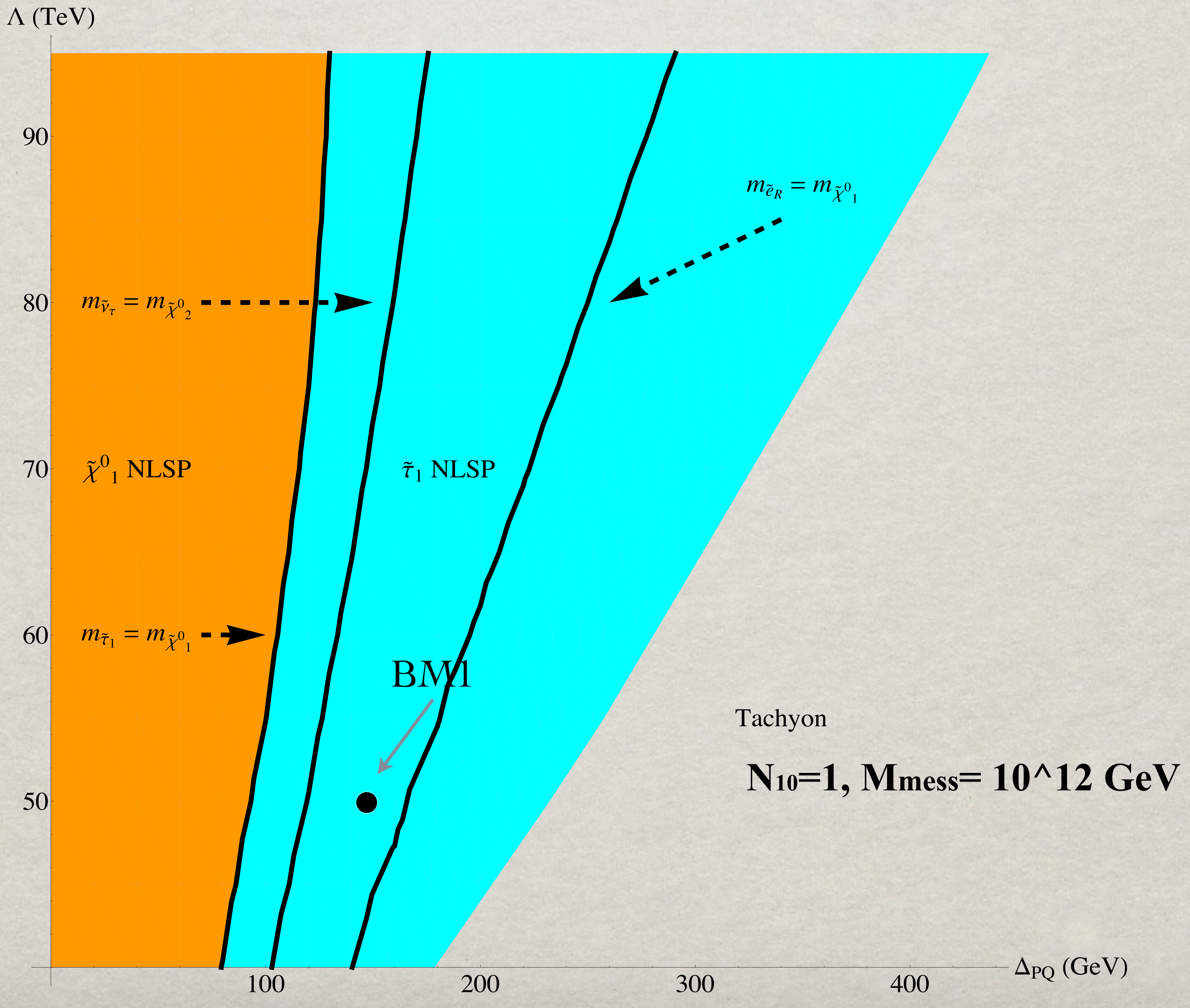
-- N_{10}=2, Λ = 53 TeV



NLSP -- STAU / BINO

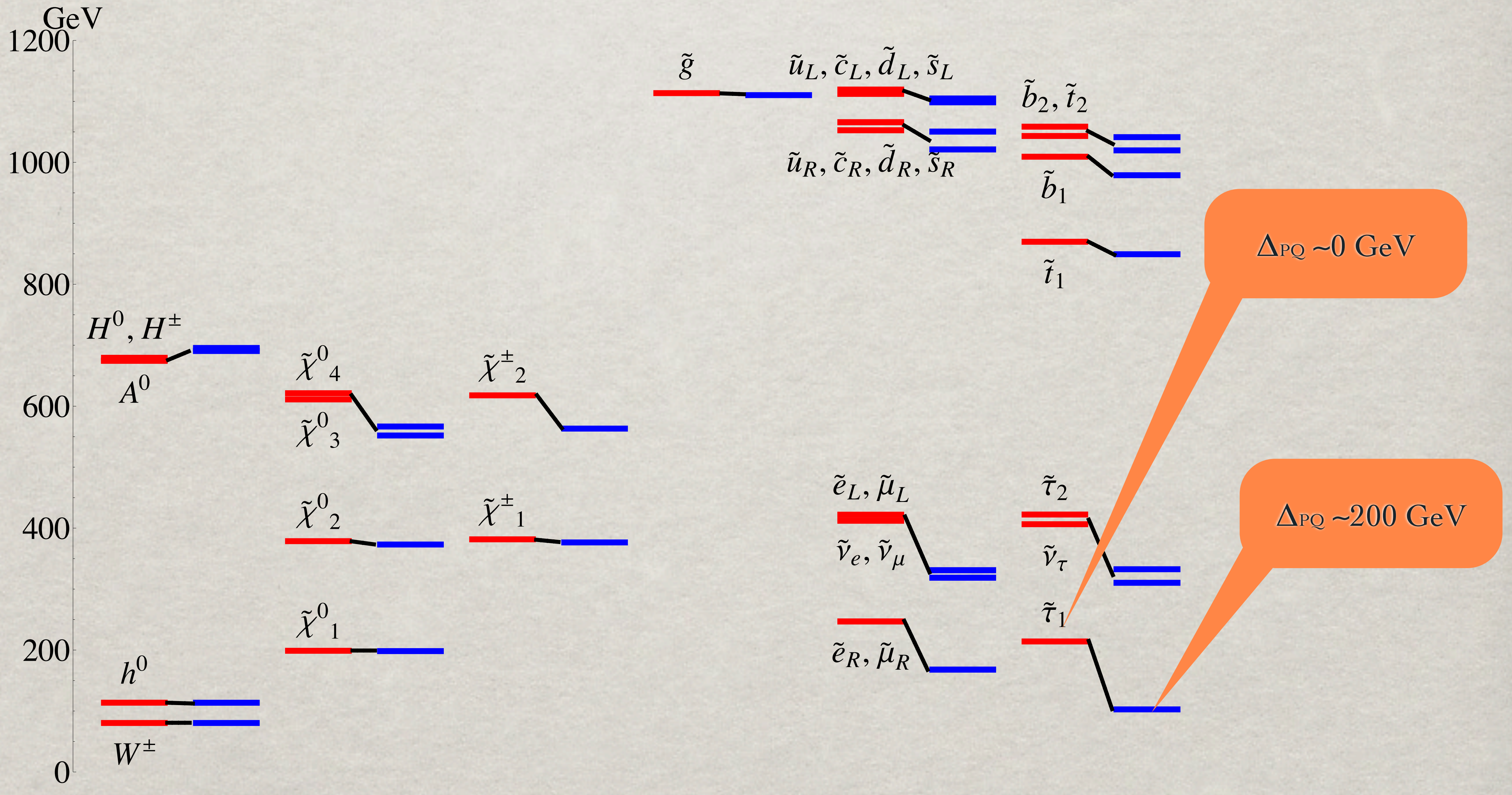


NLSP -- STAU / BINO



THE WHOLE SPECTRUM

N_{10}=1, Λ = 50 TeV (Benchmark 1)

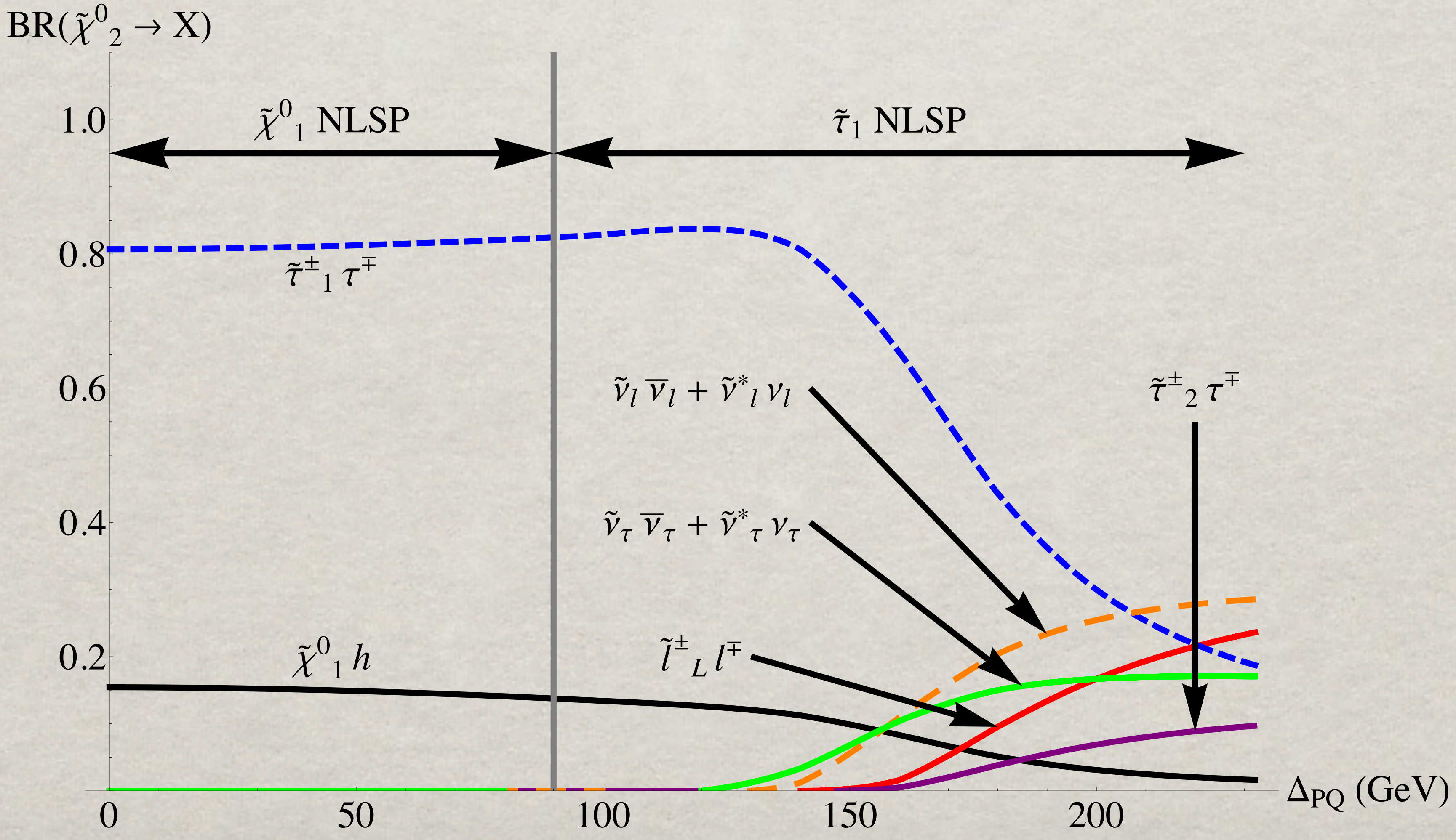


Δ_{PQ} ~0 GeV

Δ_{PQ} ~200 GeV

EFFECTS ON SPARTICLE DECAY

- Squarks and gluino decay not sensitive to Δ_{PQ}
- Neutralino and chargino decay change significantly



DIFFERENCE FROM OTHER MODELS

- Although a deformation of mGMSB, it is narrow and less studied region of parameter space

- Qualitative comparison with mGMSB and mSUGRA

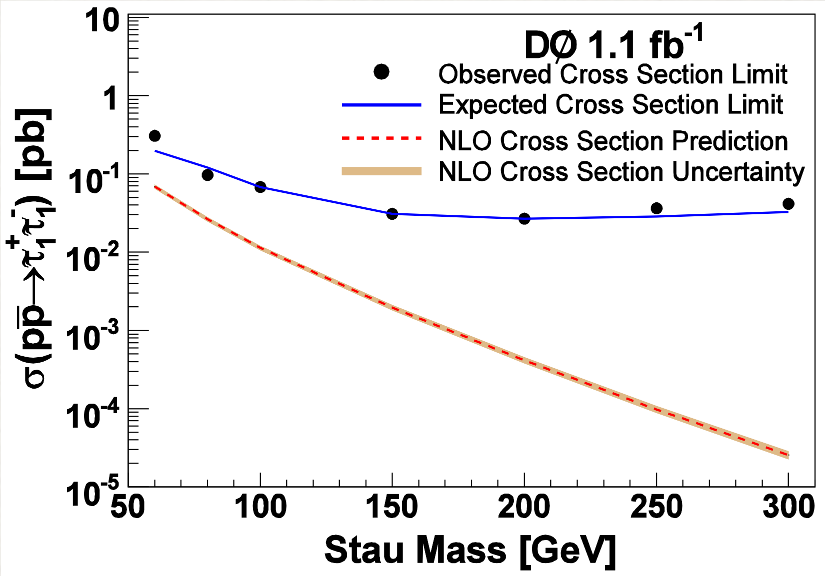
	low scale mGMSB	FGUT	mSUGRA
~~SUSY~~ scale	10^5 GeV	$10^8 - 10^9$ GeV	10^{11} GeV
LSP	Gravitino	Gravitino	χ_1
NLSP	short-live χ_1 or stau	long-lived stau	short-live χ_2 or stau
Signal	γ +$\cancel{Et}$+jets	heavy "muon"	$\cancel{Et}$+jets

WHAT CAN WE SEE AT LHC?

- Rest of the Talk: Focus on stau NLSP scenario
- Main Questions:
    - How staus are produced and detected at LHC ?
    - What are the signals? How they depends on F-GUT parameters?
    - What is the prospect for discovery?
    - Can we identify F-GUTs?

LONG-LIVED STAU SEARCH IN THE PAST

or Charged Heavy Massive Particle(CHAMP)



LEP II: m >100GeV

LEPSUSYWG/02-05.1

D0: 2 isolated μ w/ pt> 20 GeV

PRL 102, 161802(2009)

No Mass limit on stau!

CDF: 1 isolated μ with pt > 40 Gev

T. Aaltonen et al. PRL103, 021802 (2009)

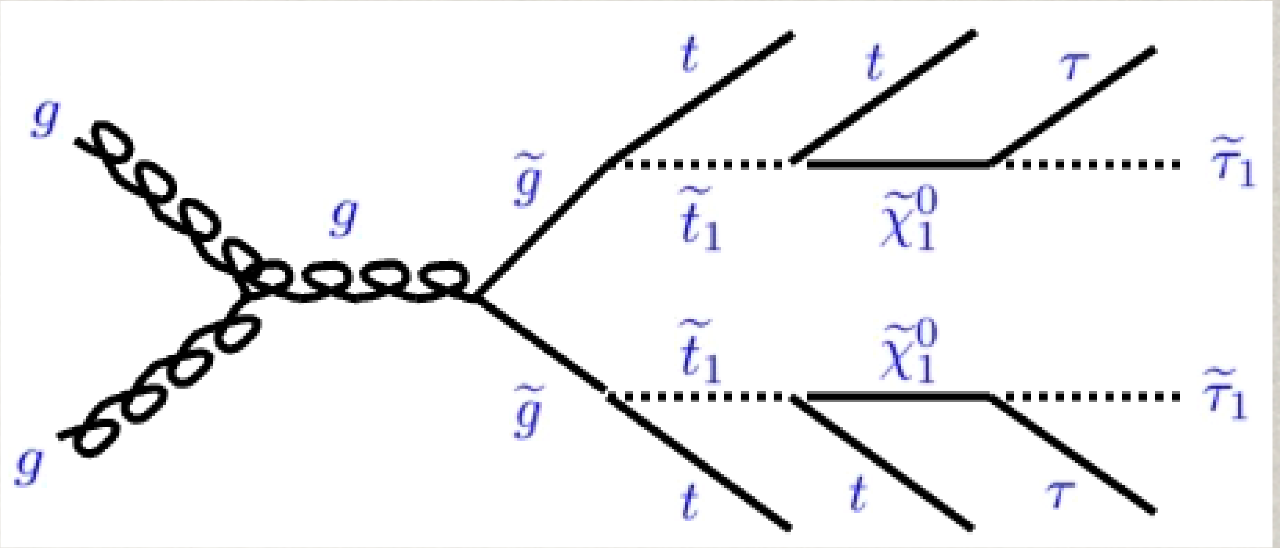
σ<10fb at 95% C.L

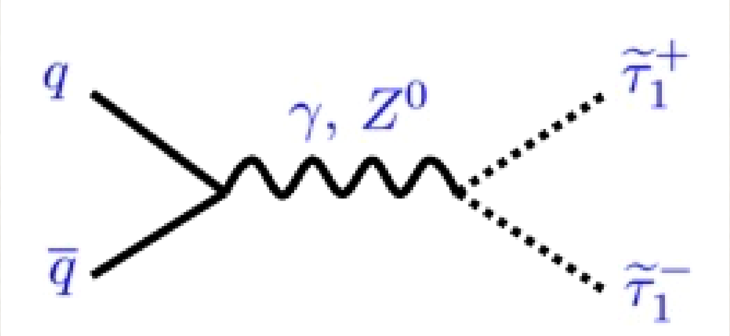
P. Achard et al., Phys. Lett. B 517, 75 (2001).

Limit on the stau mass is model dependent (depend on other sparticle mass)
For FGUTs, m > 100 GeV

STAU PRODUCTION IN LHC

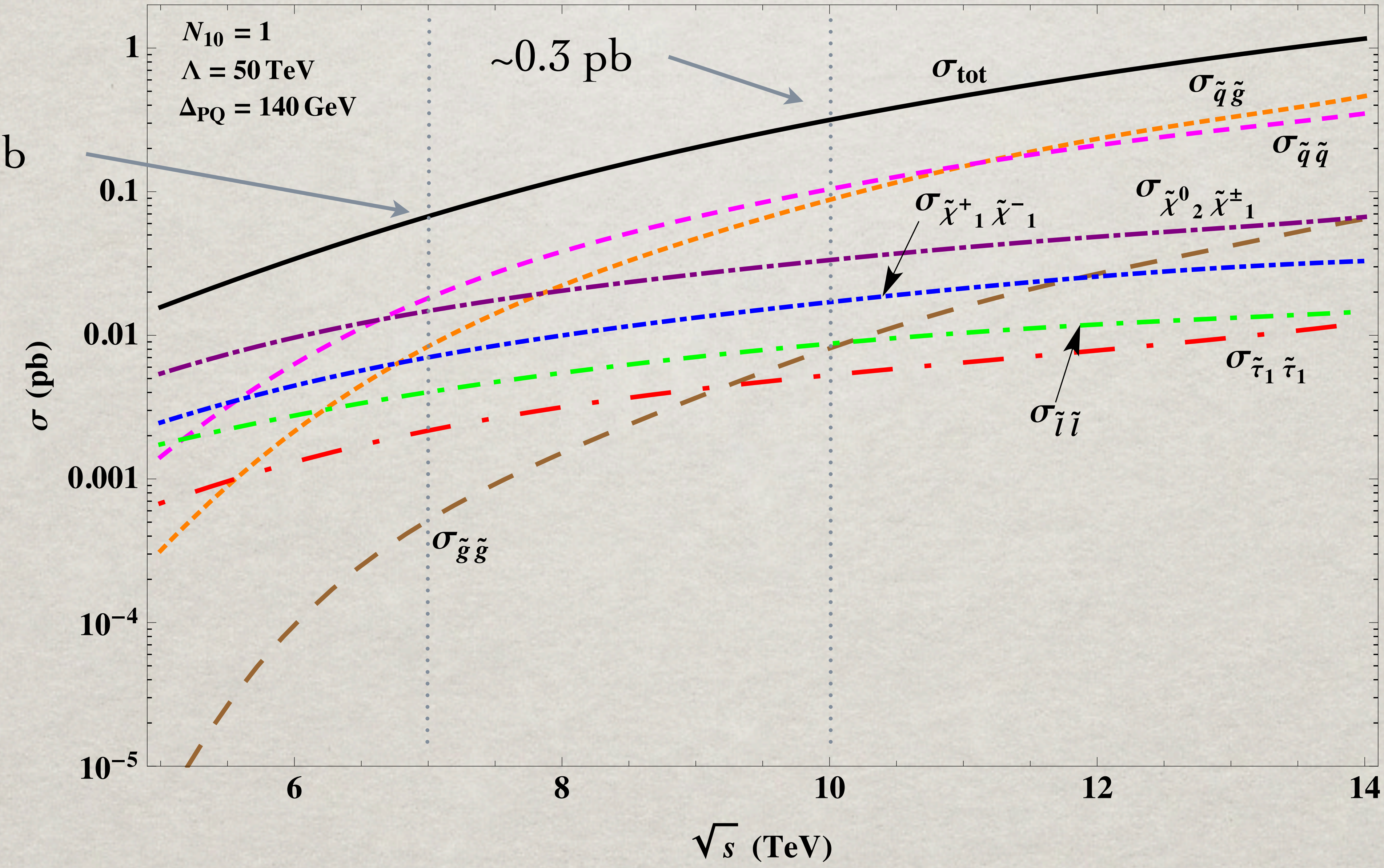
- Superpartners are produced in pair <-- R-parity
- Cascade Decays
- All SUSY events : 2 stau + X
- NO LARGE MISSING ENERGY





PRODUCTION RATE @ LHC

LO cross section from Pythia



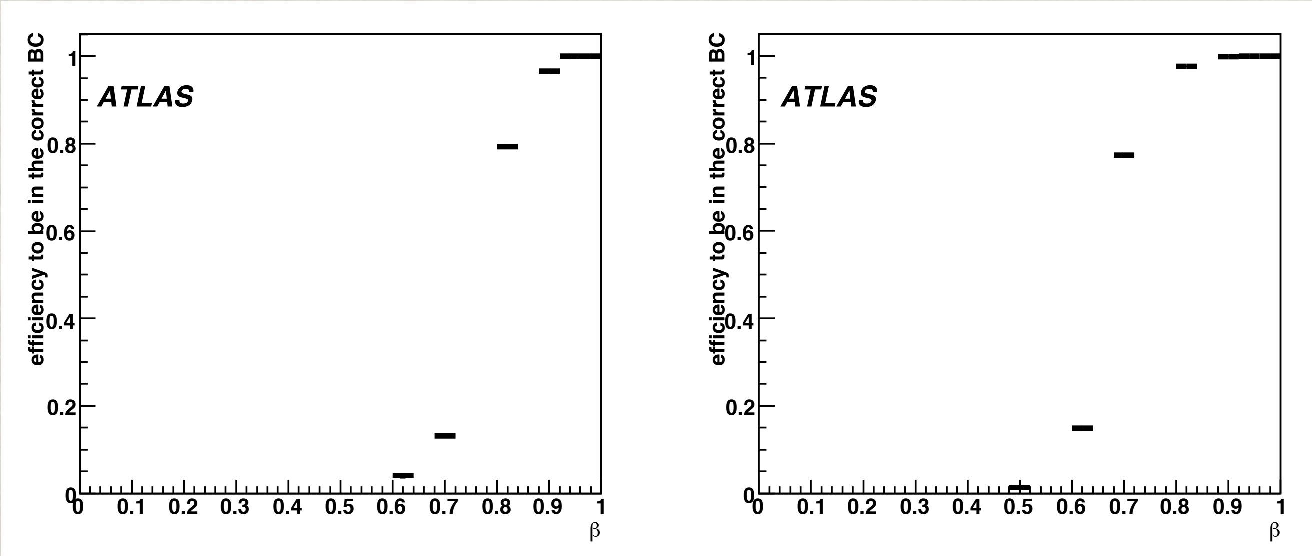
~0.07 pb

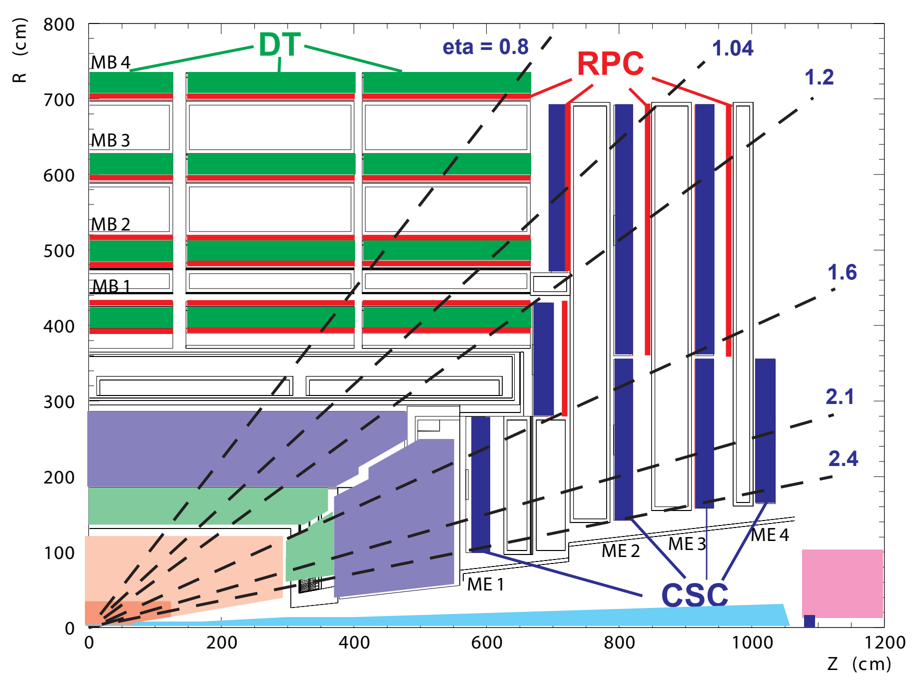
~0.3 pb

DETECTOR AND TRIGGER

- Muon trigger (efficiency drop very fast below $\beta = 0.8$)

- Muons w/ low velocity($\beta < 0.6$) are not trigger by Muon trigger would reach the muon chamber too late, out of Bunch Crossing time 25ns





- jet + $\not{E}t$ trigger (independent of the stau velocity)

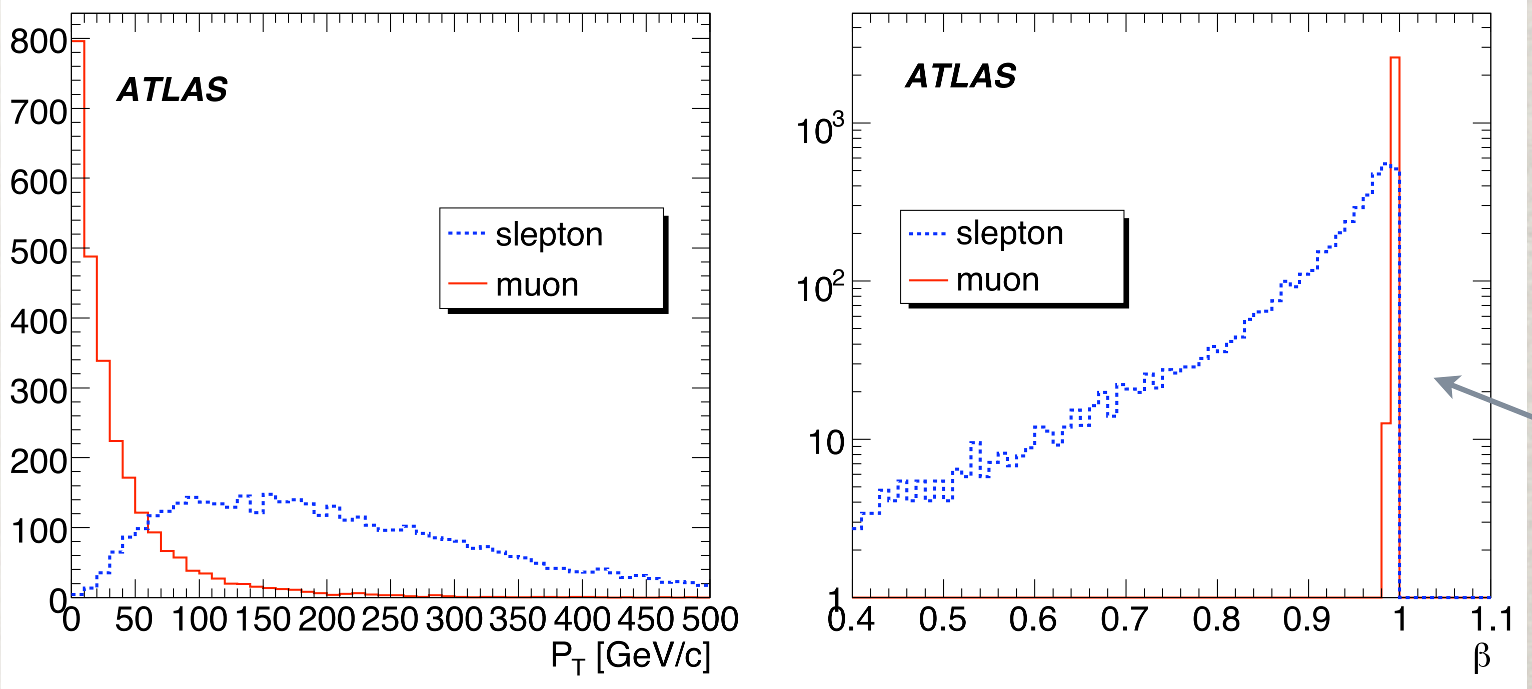
Low velocity stau can be explored using MDT (Monitored Drift Chamber) data in off-line analysis

HOW TO ISOLATE STAUS

- Triggered as a muon, but much more energetic !
- Heavy --> expect low velocity (β)
  - Time-of-flight measurement in muon chamber
  - dE/dx measurement in Calorimeter $\frac{dE}{dx} \propto \left(\frac{Q}{\beta}\right)^2$

recently using fast-moving
stau also proposed

Jie Chen and T. Adams
arXiv:0909.3157 [hep-ph]



Muon and Stau can be isolated
using β cut

Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics
arXiv:0901.0512

SIMULATION

- Consider stau candidate with $0.6 < \beta < 0.91$, pass the muon trigger with 100% efficiency

- Detector resolution of stau velocity and momentum

$$\frac{\sigma_\beta}{\beta} = 0.028\beta, \quad \frac{\sigma_p}{p} = \frac{k_1 p}{\text{GeV}} \oplus k_2\sqrt{1 + \frac{m_{\tilde{\tau}}^2}{p^2}} \oplus \frac{k_3 \text{ GeV}}{p}$$

$k_1 = 0.0118\%$, $k_2 = 2\%$ and $k_3 = 89\%$

- Event Generation - Pythia + basic detector effects

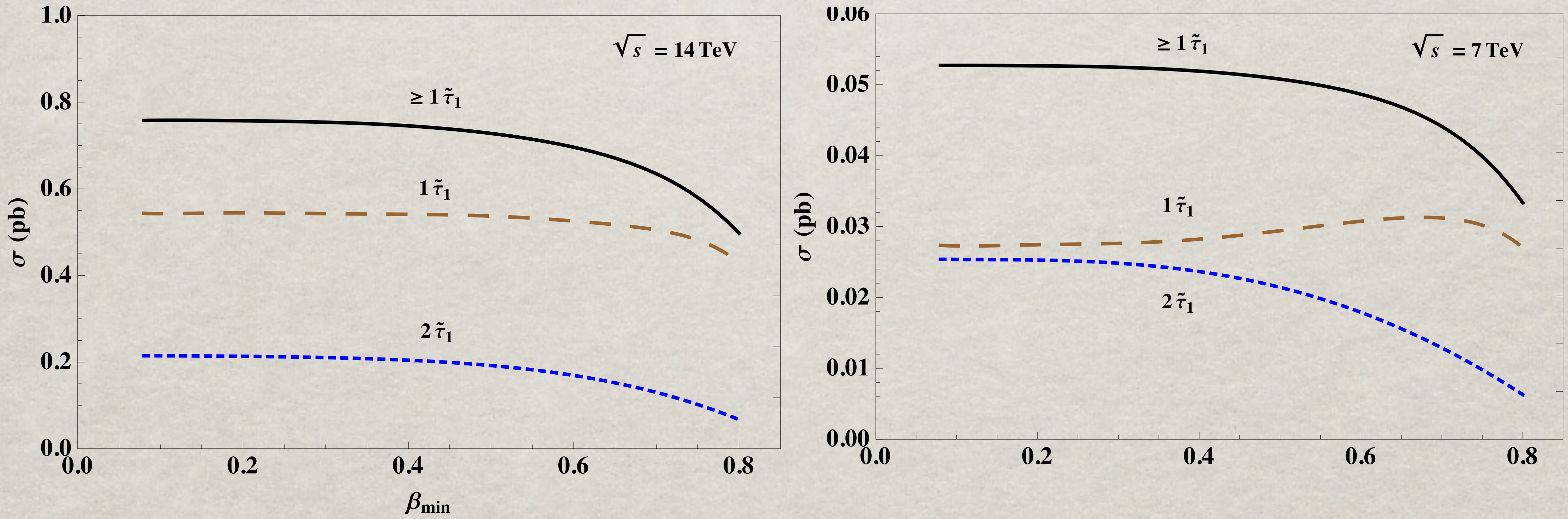
- leptons: e/mu w/ $P_t > 10$ GeV and $|\eta| < 2.5$ + stau with $\beta > 0.91$

- jets: $P_t > 50$GeV and $\eta < 2.5$

SIGNAL - INCLUSIVE STAU($\tilde{\tau}$ + X)

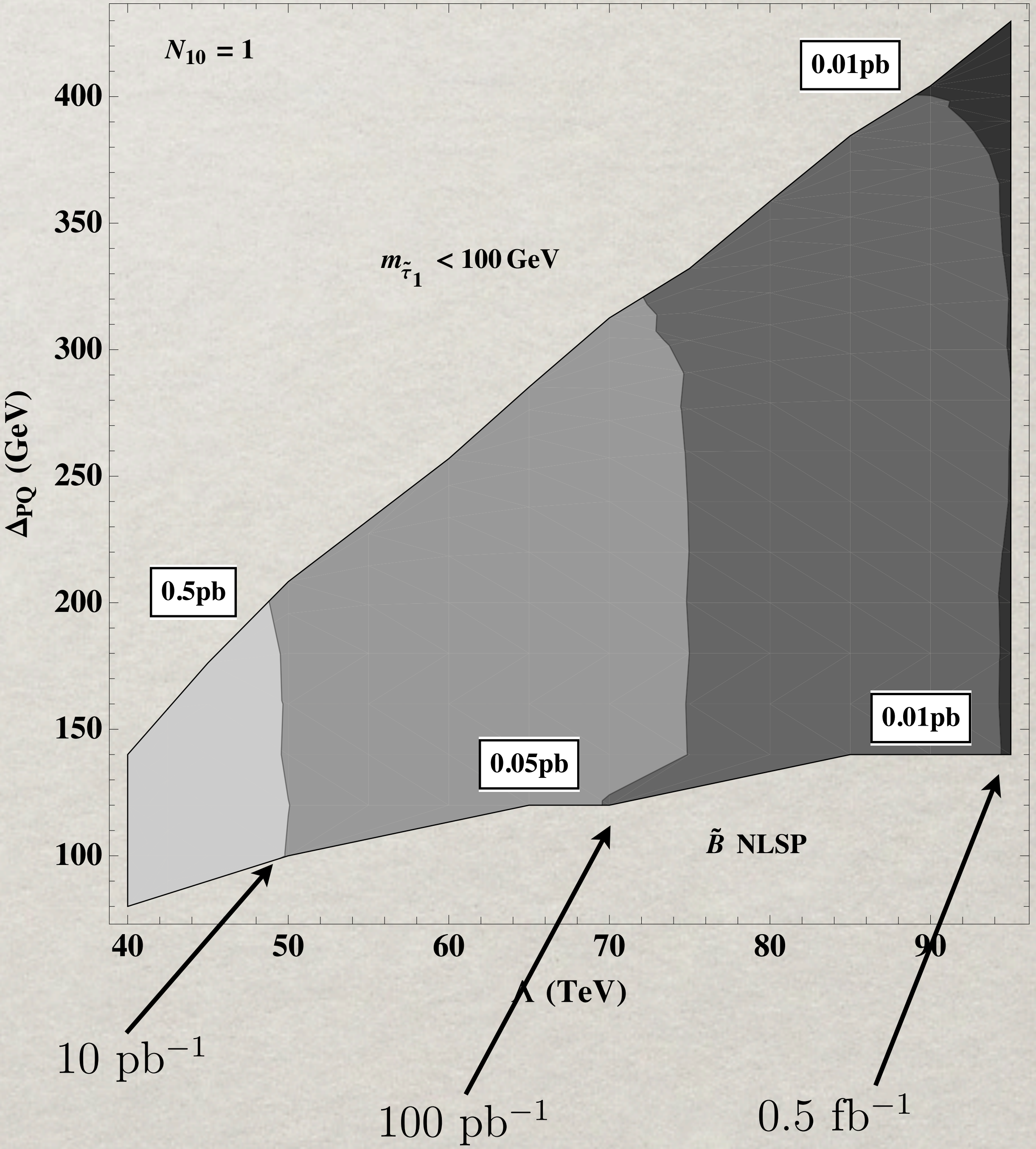
1. At least one stau candidate
2. ≥1 jet w/ Pt >50GeV and $\not{E}t$ >50GeV(Trigger-level)
3. Effective Mass > 800 GeV

$$m_{eff} = \sum_{i=1}^{min(4,N_{jet})} p_T^{jet,i} + \sum_{i=1}^{min(2,N_{\mu})} p_T^{\mu,i} .$$



DISCOVERY POTENTIAL @ 14 TEV

- Cross section contours in (Λ, Δ_{PQ})
- SM bkg negligible(take to be 1) discovery <=> σ L > 5
- For the best case, only need ~ 10 pb^{-1}
- For CM Energy 7 TeV, need ~ 100 pb^{-1}



10 pb^{-1}

100 pb^{-1}

0.5 fb^{-1}

DISCOVERY POTENTIAL @ 14 TEV

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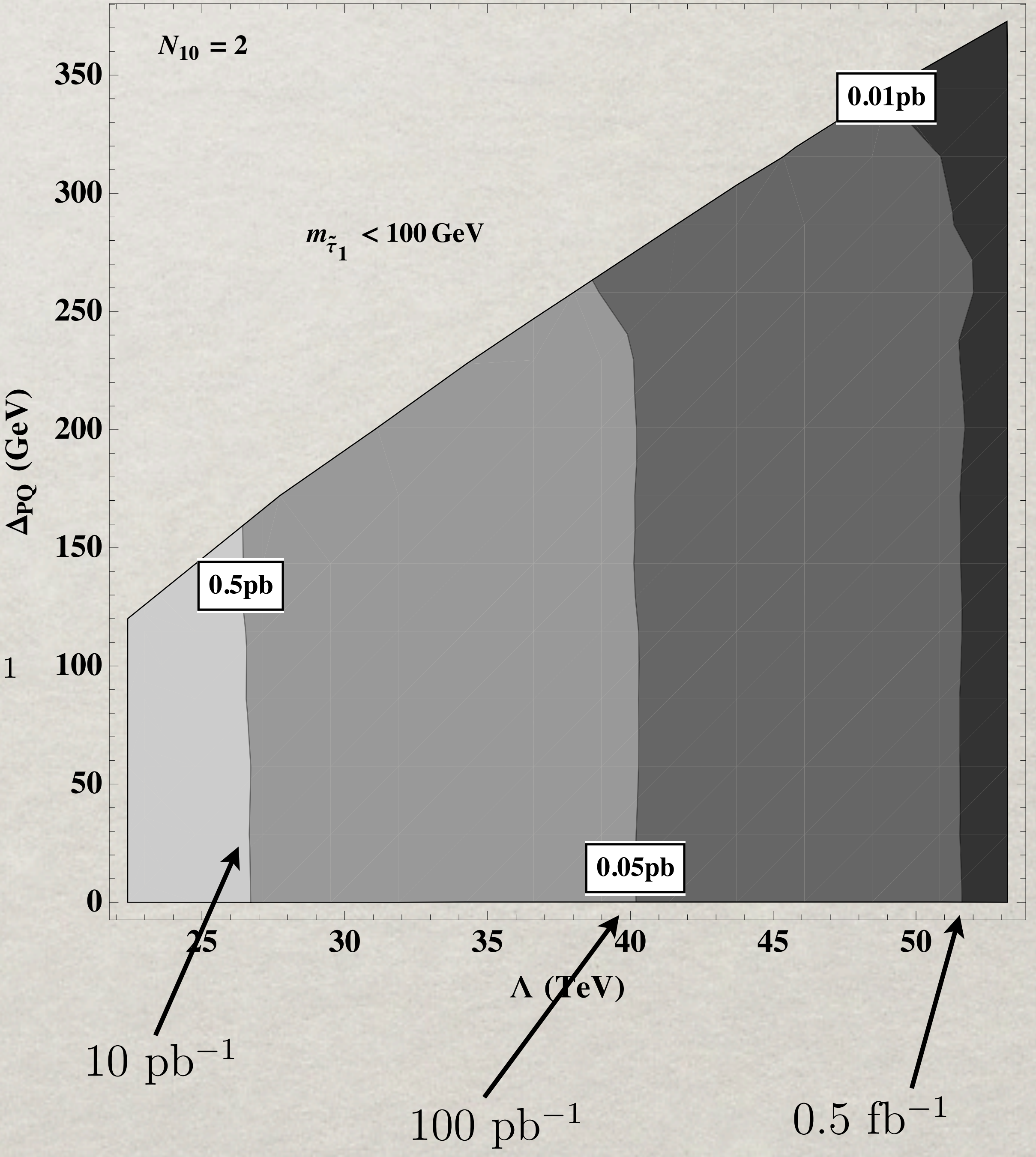
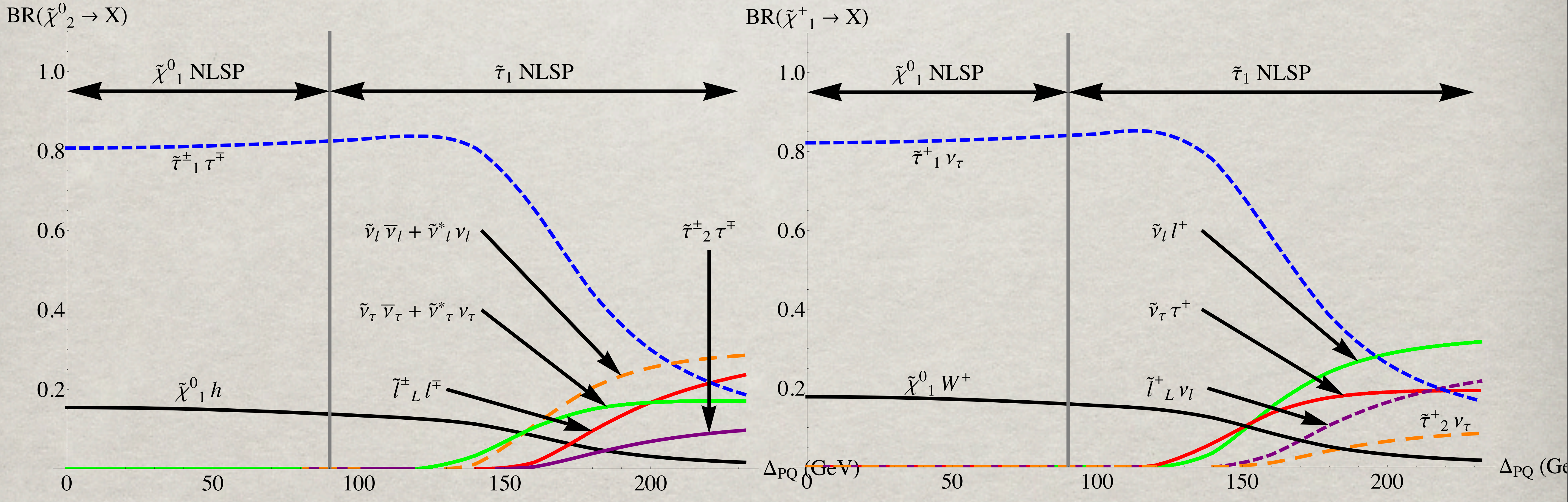


OTHER CHANNELS - ($\tilde{\tau}$ + LEPTONS)

- Lots of leptons from cascade decay
- Increase with PQ deformation

$$\begin{aligned}\chi_2^0 &\rightarrow \tilde{l}+l\rightarrow 2l+\tau+\tilde{\tau},\\ &\quad\ \tilde{\nu}+\nu\rightarrow 2\nu+\tau+\tilde{\tau},\\ &\quad\ \tilde{\tau}+\tau\\ \chi_1^\pm &\rightarrow \tilde{\tau}+\nu_\tau,\\ &\quad\ \tilde{\nu}+\tau\rightarrow\tilde{\tau}+2\tau+\nu\end{aligned}$$



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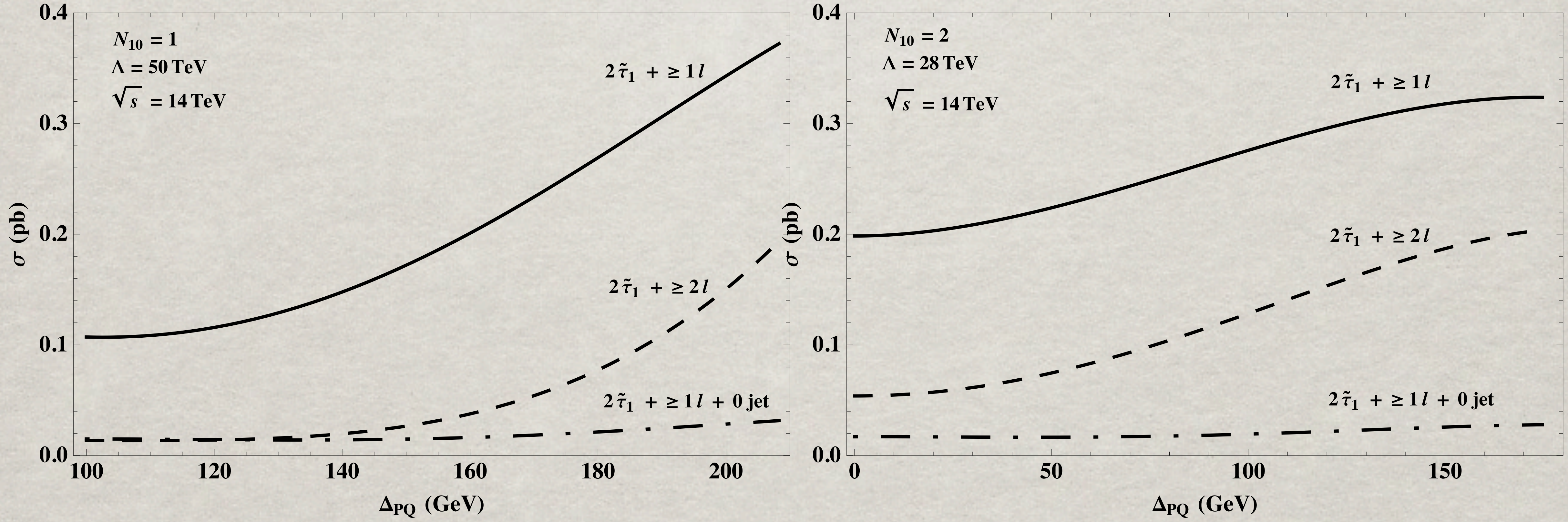
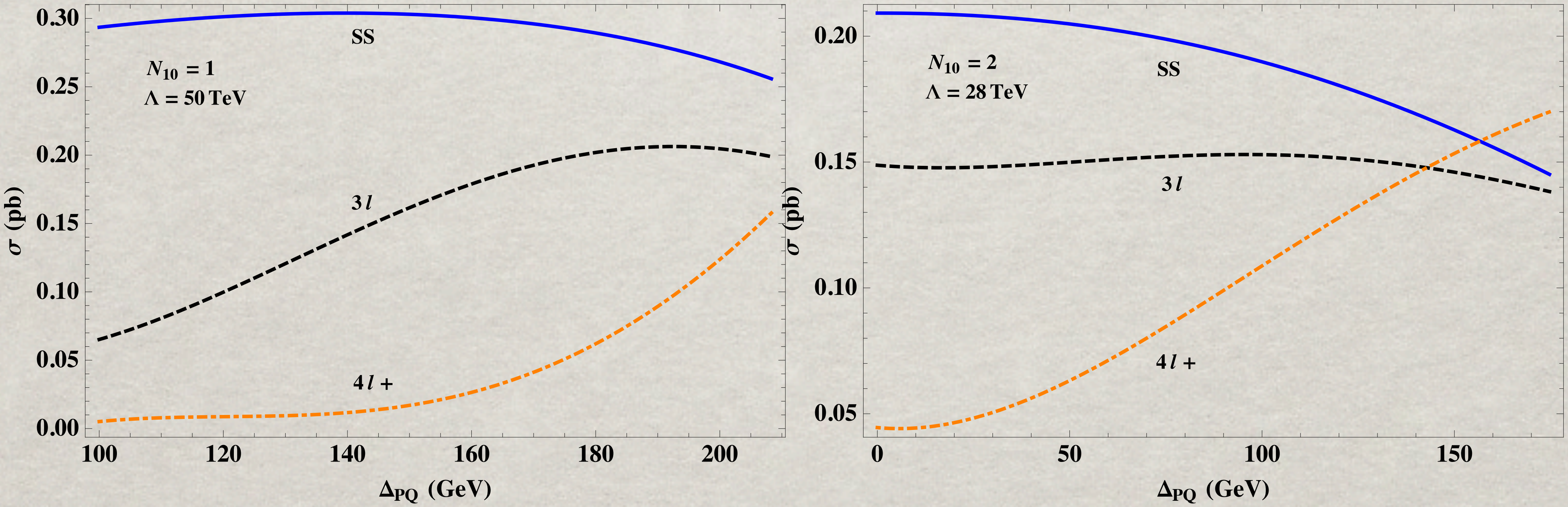
\chi_2^0 &\rightarrow \tilde{l} + l \rightarrow 2l + \tau + \tilde{\tau}, \\
&\quad \tilde{\nu} + \nu \rightarrow 2\nu + \tau + \tilde{\tau}, \\
&\quad \tilde{\tau} + \tau \\
\chi_1^\pm &\rightarrow \tilde{\tau} + \nu_\tau, \\
&\quad \tilde{\nu} + \tau \rightarrow \tilde{\tau} + 2\tau + \nu
\end{aligned}$$



INCLUSIVE “MUON”

- Hard leptons + jets, where no isolation of stau is necessary.
- SM Background can reduced by hard cuts
  - At least two hard leptons with $p_T > 100$ GeV
  - At least two hard jets with $p_T > 150$ GeV.

- $\beta > 0.67$, $p_T > 20$ GeV and $|\eta| < 2.5$
- SS: A pair of same-sign isolated leptons.
- $3l$: Three isolated lepton candidates.
- $4l+$: Four or more isolated lepton candidates.



IS IT F-GUTS?

Once long-lived stau is confirmed (from the tau rich events), there are only few possible scenarios, e.g. minimal GMSB models

Two major ways:

- superpartner masses
  -- measurement can be done at the LHC
  - very few number of parameters
    -- measuring mass of squark and gluino fix N_{10} and **Λ;** measuring other mass give additional checks
- susy breaking scale
  -- measure the lifetime of stau

very challenging at LHC

Non-collider approach: staus produced by neutrino-nucleon interaction and detected by Neutrino telescope

Albuquerque, Burdman, Chacko, Phys.Rev.Lett.92:221802,2004

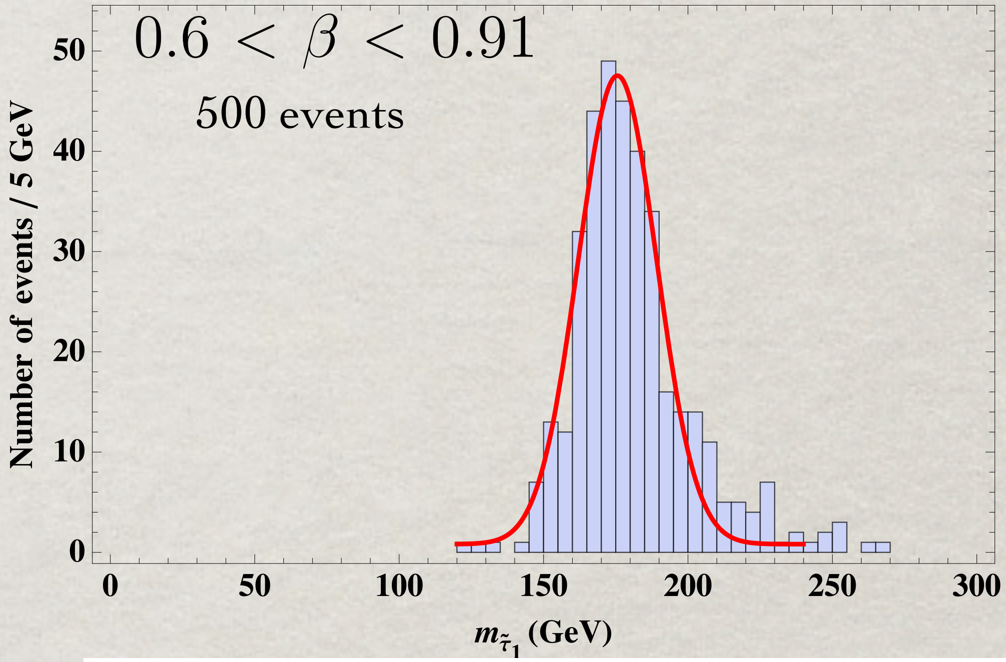
MEASURING MASS

- Generally much easier compare to conventional SUSY model -- No $\not{E}t$
- Stau mass can be constructed from the measured momentum and velocity. Better precision if selecting low velocity stau

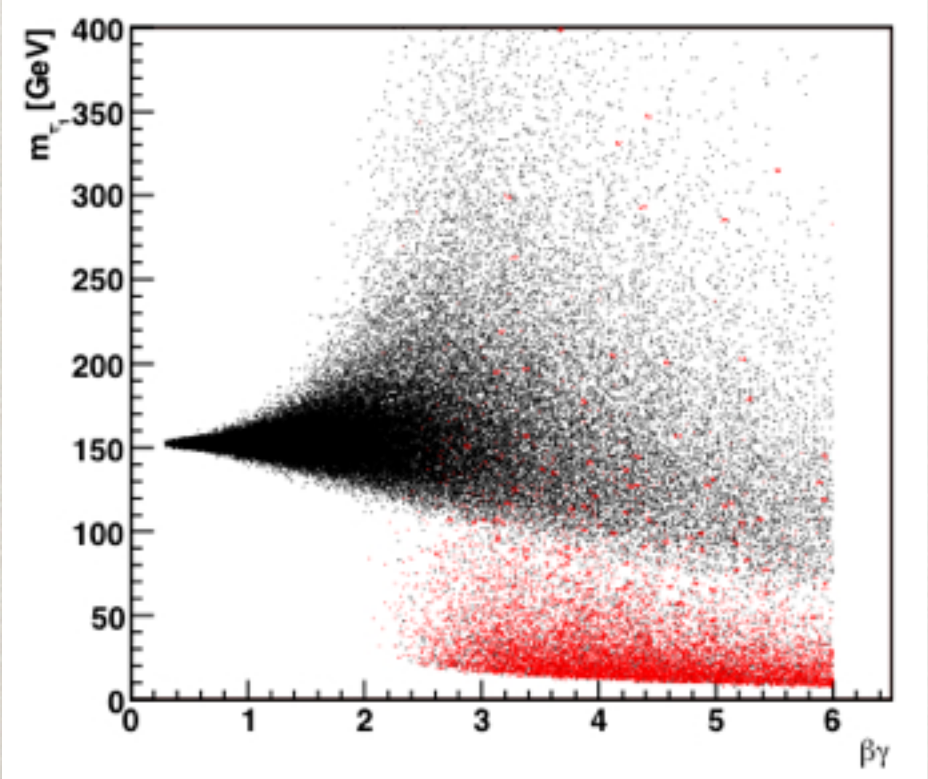
$$m_{\tilde{\tau}_1} = \frac{p}{\beta\gamma}$$

$$m_{\tilde{\tau}}^{\breve{f}it} = 175.59 \pm 0.47 \text{ GeV}$$

$$m_{\tilde{\tau}}^{true} = 175 \text{ GeV}$$

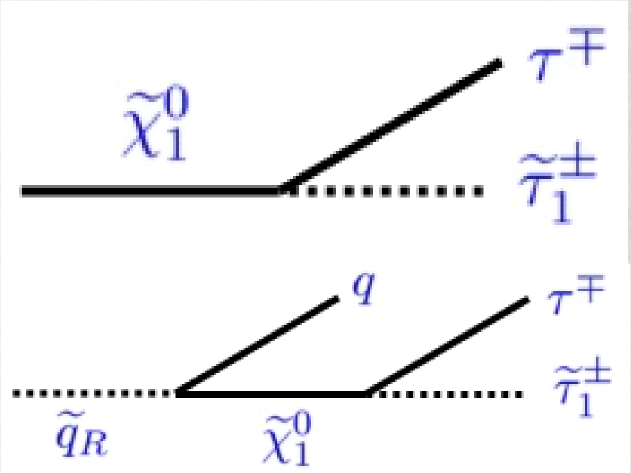


Hinchliffe Paige ’98, Ellis etal ’06



MEASURING MASS

Other masses can be constructed by selecting proper final-state particles



Construct Invariant Mass distribution

With 30 inv fb, the following precision can be achieved

$$\Delta m_{\tilde{\tau}_1} = 0.021 \text{ GeV}, \ \Delta m_{\tilde{\nu}_\tau} = 1.2 \text{ GeV}, \ \Delta m_{\tilde{l}_L} = 2.0 \text{ GeV}$$
$$\Delta m_{\tilde{\chi}_1^0} = 0.9 \text{ GeV}, \ \Delta m_{\tilde{\chi}_2^0} = 2.0 \text{ GeV},$$
$$\Delta m_{\tilde{q}_R} = 2.8 \text{ GeV}, \ \Delta m_{\tilde{q}_L} = 3.7 \text{ GeV}, \ \Delta m_{\tilde{b}_1} = 57.7 \text{ GeV}.$$

Hinchliffe Paige ’98, Ellis etal ’06
Ibe Kitano ’07, Ito Kitano Moroi ’09

EXAMPLE

N_{10}=1, Λ = 50 TeV
Δ_{PQ}=140GeV

- Compare F-GUT Benchmark with mGMSB

- Vary mGMSB parameters:

  $M_{mess},\ \Lambda,\ \sqrt{F},\ \tan\beta$

- Distinguishing models is possible
  -- require large luminosity

parameter	$\mathrm{Maj}^{(1)}_{\mathrm{mid}}$	mGMSB1	mGMSB2
M_{mess}	10^{12}	10^{12}	2×10^{9}
$\sqrt{F}$	2.2×10^{8}	2.2×10^{8}	10^{7}
$\tan\beta$	24.05	34.7	24.5
$m_{\tilde{g}}$	1112	1113	1116
$m_{\tilde{\chi}_1^0}$	198.6	199.0	199.3
$m_{\tilde{\chi}_2^0}$	377.1	379.4	378.0
$m_{\tilde{\chi}_1^\pm}$	380.3	382.3	381.2
$m_{\tilde{u}_L}$	1106	1112	1102
$m_{\tilde{u}_R}$	1059	1066	1063
$m_{\tilde{t}_1}$	857.6	866.7	898.1
$m_{\tilde{t}_2}$	1050	1047	1059
$m_{\tilde{b}_1}$	997.2	982.2	1014
$m_{\tilde{b}_2}$	1032	1032	1046
$m_{\tilde{e}_L,\tilde{\mu}_L}$	383.0	421.7	382.2
$m_{\tilde{\nu}_e,\tilde{\nu}_\mu}$	372.5	412.1	371.6
$m_{\tilde{e}_R,\tilde{\mu}_R}$	214.3	246.9	204.9
$m_{\tilde{\tau}_1}$	175.0	174.8	174.7
$m_{\tilde{\nu}_\tau}$	366.1	400.4	367.7
$m_{\tilde{\tau}_2}$	384.0	422.3	385.1
m_h	114.3	114.3	113.8
m_A	693.1	614.2	623.4

very close

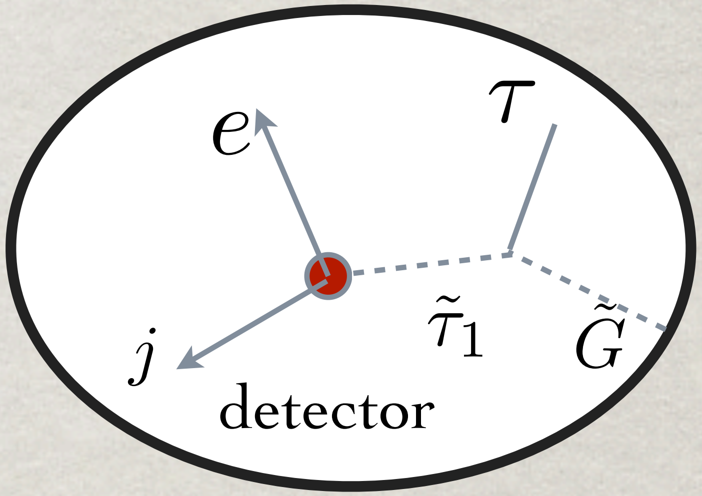
different

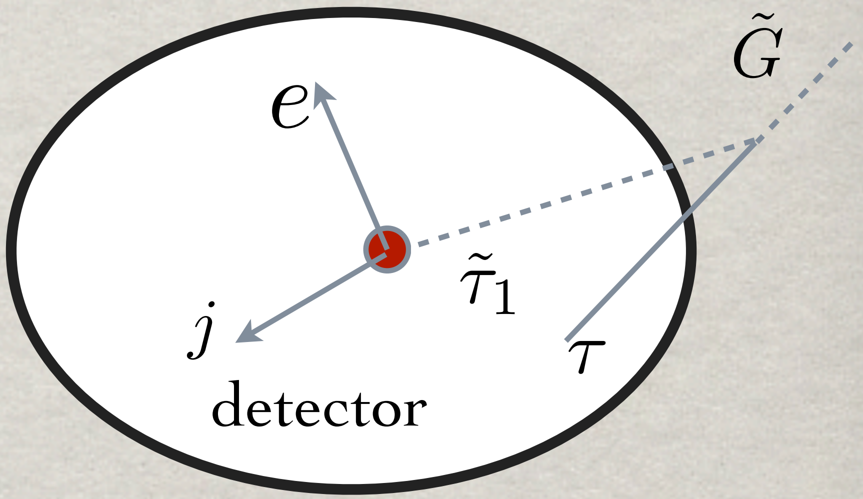
fixed

STOPPED STAU?

- Low velocity stau can be stopped
  - Inside detector: stau decay not correlated with the bunch crossing, difficult to trigger (with normal trigger)
    with modified trigger see **Asai, Hamaguchi and Shirai, Phys.Rev.Lett.103:141803,2009**
  - Outside detector:
    - External detector, e.g. Water Tank -- require lifetime long enough
    - Stau trapped in Cavern Material decaying back to detector

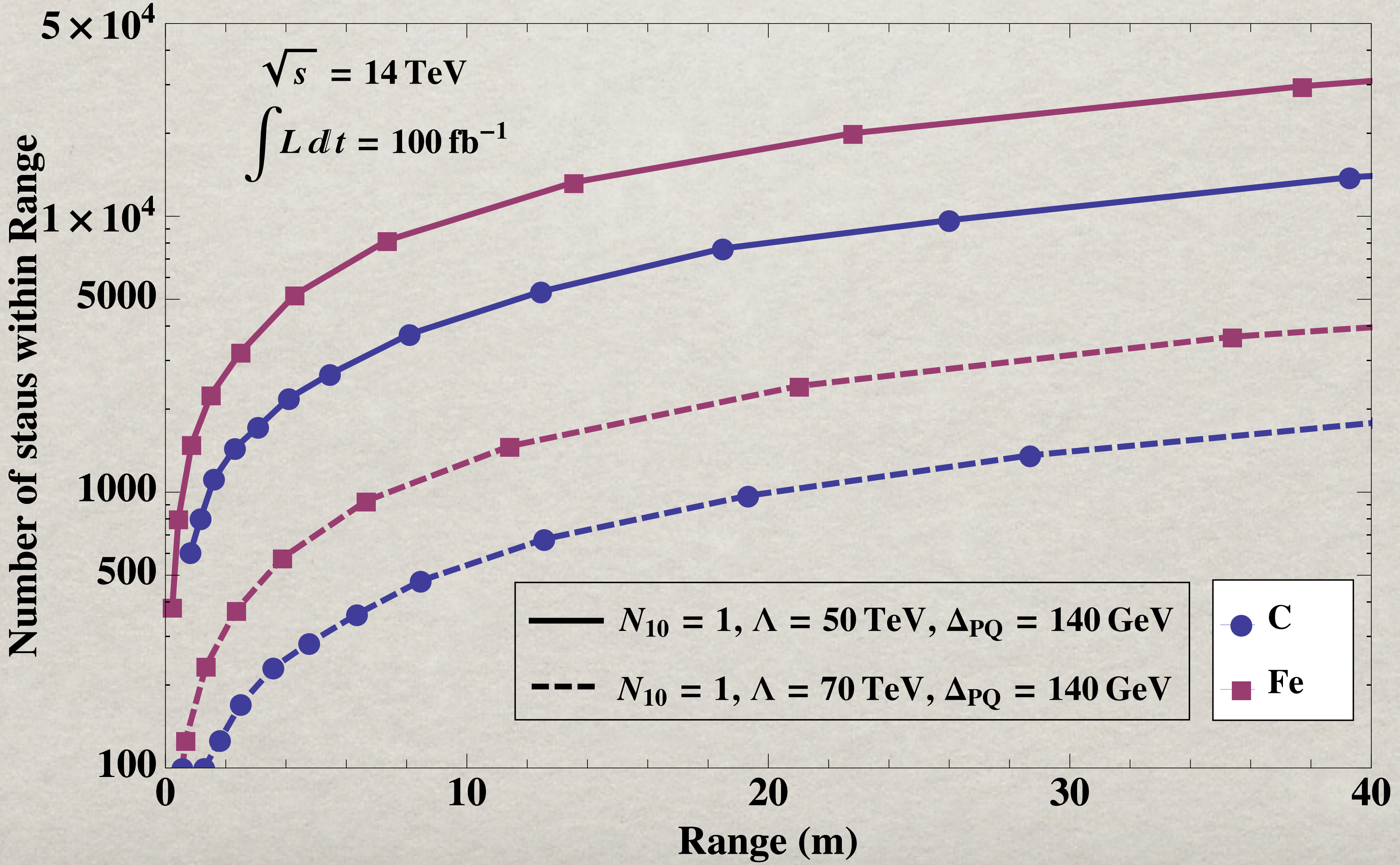
Buchmuller etal ’04
Feng and Smith ’04
De Roeck etal ’05
Hamaguchi etal ’04, ’06,’09





STOPPED STAU?

The faction of low velocity stau is small --> need large luminosity



CONCLUSION

- F-GUTs is a rigid frameworks for SUSY GUTs -- just enough to fit various aspects of phenomenological ingredient
- Embedding of GMSB in the framework is natural and predicative
- It can be tested at the LHC within a few years
- It also interesting to see if these local construction can be globally consistent.