Post-LHC RPV SUSY

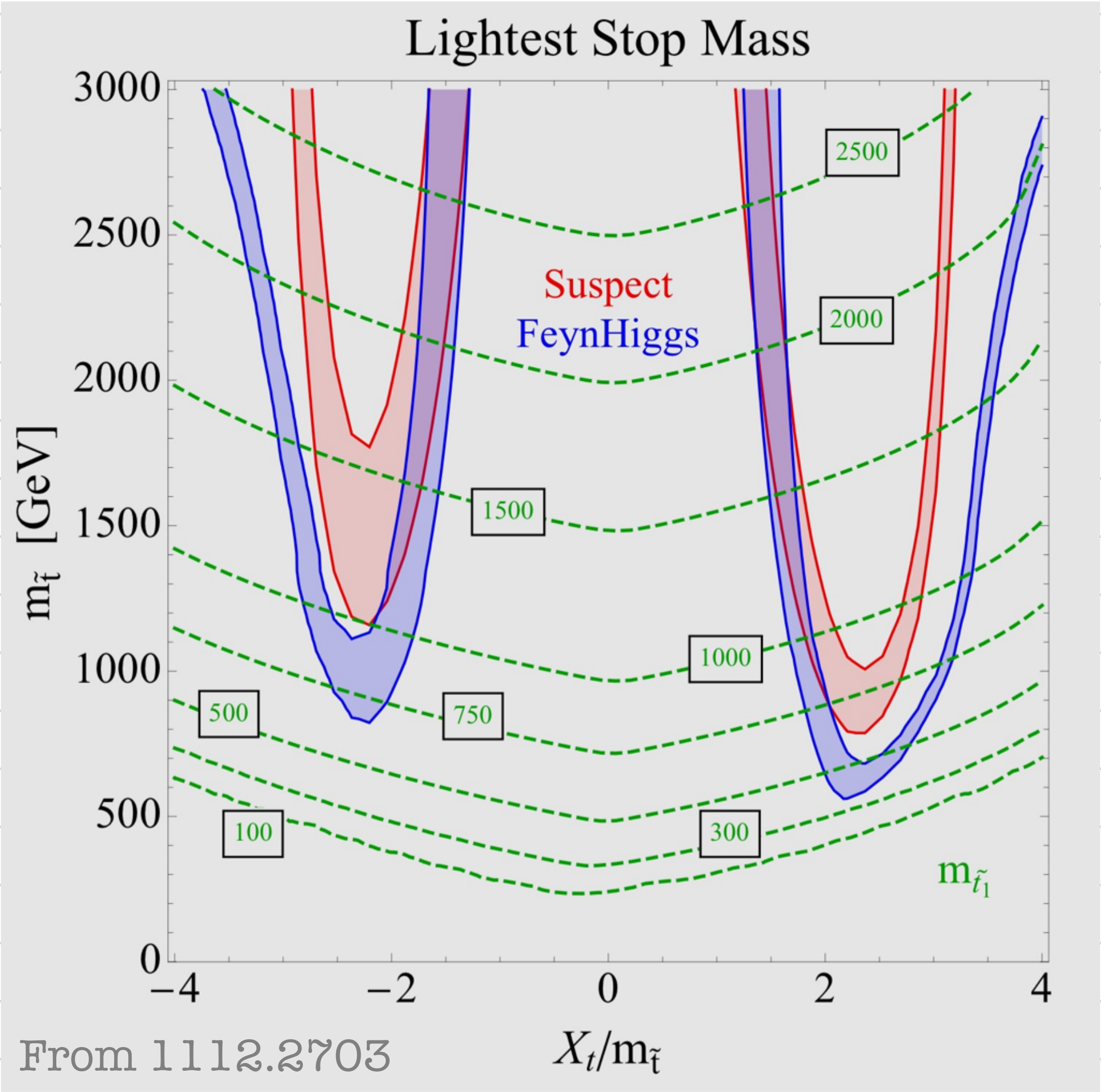
Roberto Franceschini
(University of Maryland)

- ArXiv:1301.3637 with R. Mohapatra
- ArXiv:1212.3622 with R. Torre

125 GeV BOSON DISCOVERY AND SUSY

$m_h = 125$ GeV $\gg m_Z$

POSSIBLE IN THE MSSM
BUT REQUIRES LARGISH SOFT MASSES



→ NON-MINIMAL MODELS

The PARTICLE ZOO

Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS & beyond!

Can't decide? Order a Particle Pack!

View Cart	Add to Cart He's the one everyone wants to meet, and with recent events, it looks like we finally get to meet him. Higgs Boson is also part of the Boson 5-Pack. Approximately 14 oz/388 grams; 5.5 inches/15 cm across. For ages 5 and up as it contains small parts.

HIGGS BOSON

H

The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland, which collides particles at 99.99% the speed of light, will detect the elusive Higgs Boson

$10.49 PLUS SHIPPING

LIGHT HEAVY

Wool felt, fleece with gravel fill for maximum mass.

HIGGS BOSON

The PARTICLE ZOO

The Particle Zoo: Subatomic Particle plushies

www.particlezoo.net/individual_pages/shop_higgsboson.html

The PARTICLE ZOO

Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS & beyond!

Can't decide? Order a Particle Pack!

Add to Cart

View Cart

He's the one everyone wants to meet, and with recent events, it looks like we finally get to meet him. Higgs Boson is also part of the Boson 5-Pack.

Approximately 14 oz/388 grams; 5.5 inches/15 cm across.
For ages 5 and up as it contains small parts.

HIGGS BOSON H

The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland, which collides particles at 99.99% the speed of light, will detect the elusive Higgs Boson

~~$1[illegible]9~~ 20.000 $ EACH

LIGHT ●●●●●●●●●●●●◐ HEAVY

Wool felt, fleece with gravel fill for maximum mass.

HIGGS BOSON

The PARTICLE ZOO

The PARTICLE ZOO

Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS & beyond!

IF YOU WANT SUPERSYMMETRIC PARTNER (SUSY) PARTICLES...

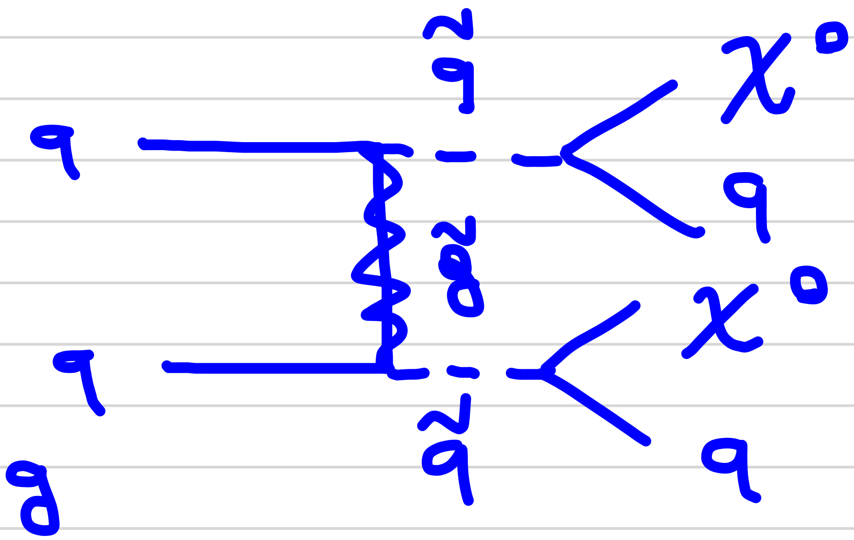
I was going to offer particle plushies which were larger and heavier than the regular squishies to include the as-yet-unobserved supersymmetric partners: the *wino*, *zino*, *photino*, *Higgsino*, *selectron*, *stop quark* and so on. However, these would be prohibitively expensive to ship overseas and given the small amount of requests, I decided to do the following:

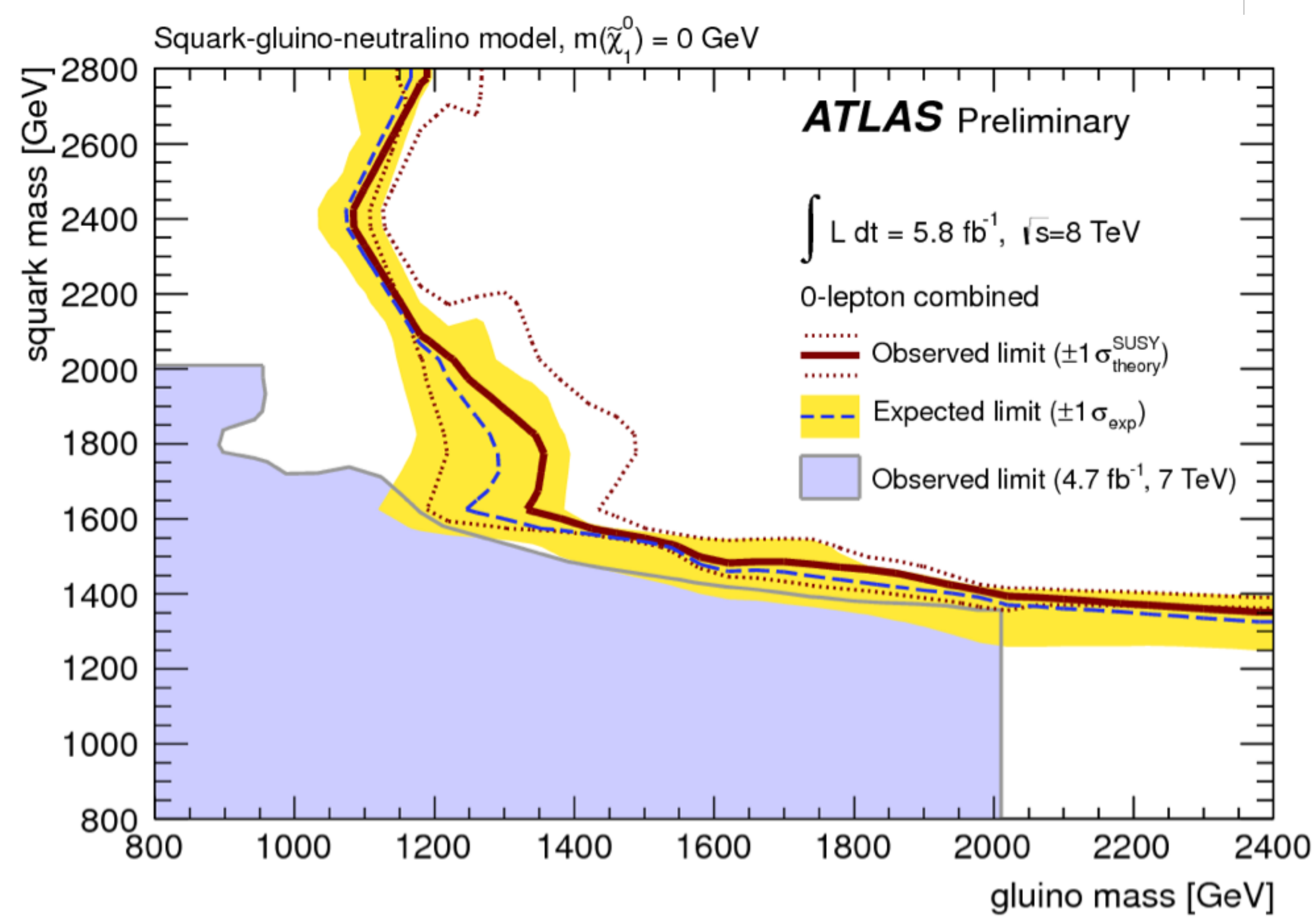
If you would like any or all of the SUSY particles, I will make them the same size as the regular particles, but fill them with gravel to represent their enormous mass. This means the heavier particles like the Higgs, top quark, etc., would be identical except for the tag. If you wanted to use the plushies to demonstrate the difference in mass between SUSY particles and the standard model particles, I would suggest ordering the "Universe-in-a-Box" to represent standard particles. They are 1/3 size and so the "regular" particles will be large next to them. Please email me at particle @ particlezoo.net if you would like to order any SUSY particles.

NO SIGNAL FROM SUPERPARTNERS

SEARCHES IN FINAL STATES jets + leptons + photons + mET

MISSING TRANSVERE ENERGY IS ASSUMED FROM THE PRODUCTION OF INVISIBLE χ^0





χ^0 IS THE DM CANDIDATE

$m_{SUSY} > \text{TeV}$

SUSY ALTERNATIVES : DIRAC GLUINO

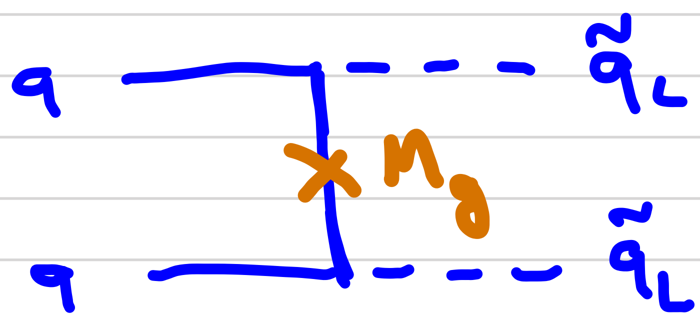
GIVE MASS TO THE GAUGINOS INTRODUCING A_i <u>DIRAC PARTNER</u>

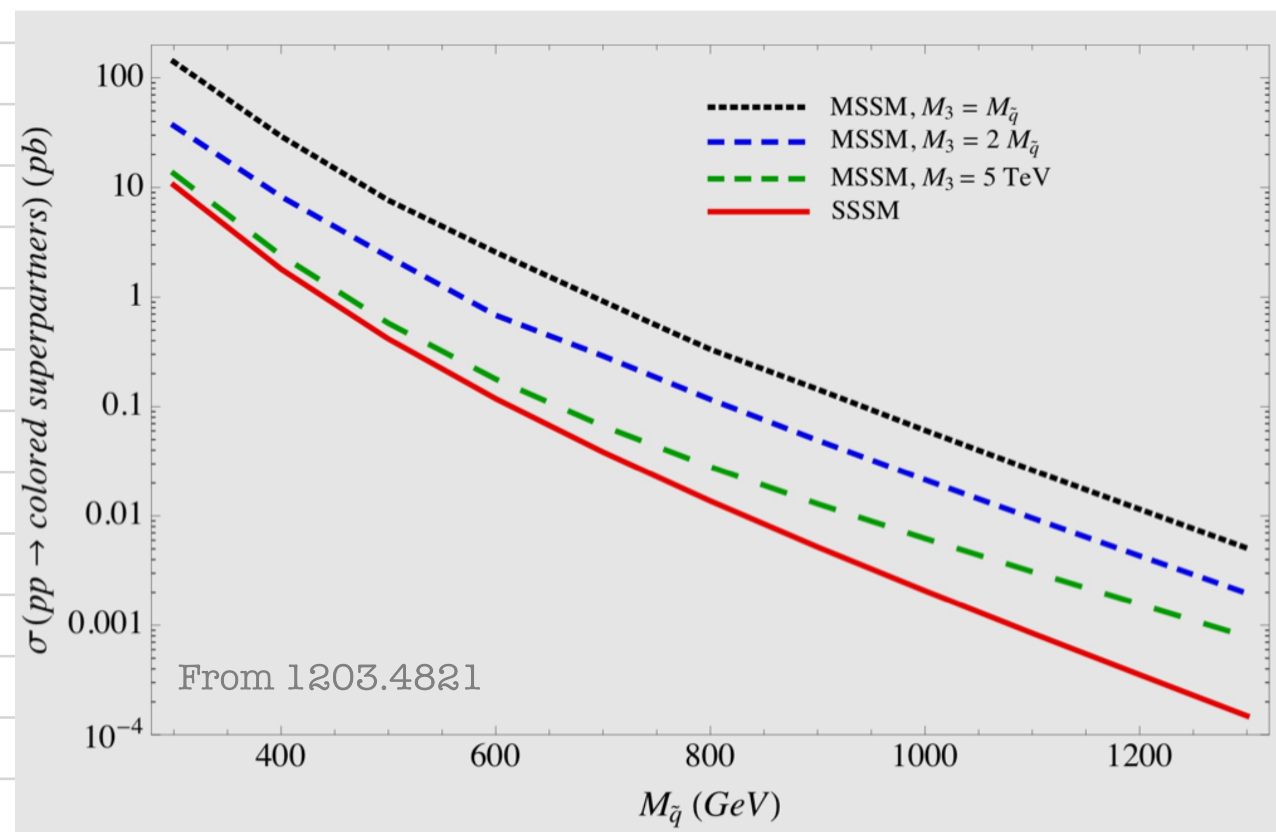
$$\int d^2\theta \, \frac{1}{M} A_i W'_{i,\alpha} W^\alpha \longrightarrow m_D A_i \tilde{\lambda}_i \qquad m_D \sim \frac{D}{M}$$

- DIRAC GLUINO

$$pp \to \tilde{q}_L \tilde{q}_L , \tilde{q}_R \tilde{q}_R , \tilde{q}_L \tilde{q}_R$$

AT HIGH $m_{\tilde{q}}$ $\quad qq \to \tilde{q}\tilde{q}$





GAUGINO PARTNERS PHENOMENOLOGY $\qquad A_3 \longrightarrow jj$

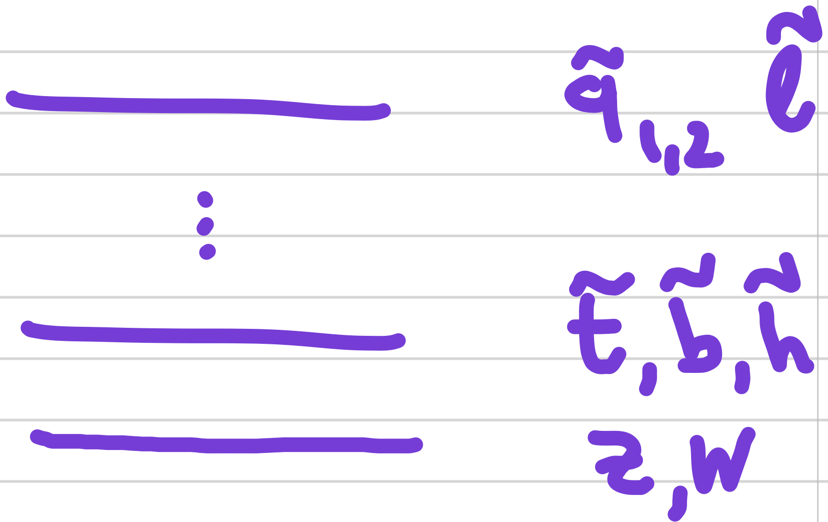
SUSY ALTERNATIVES: EFFECTIVE SUSY

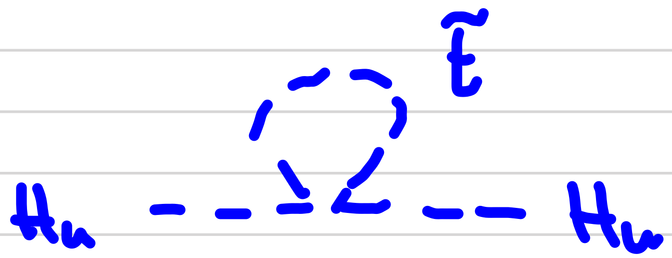
- "NATURAL" SUSY

  ONLY FEW SUPER PARTNERS

  $\tilde{t}, \tilde{b}, \tilde{g}, \tilde{h}$ ARE CRUCIAL

  TO STABILIZE THE WEAK SCALE





$$\delta m_{H_u}^2 \propto \frac{1}{16\pi^2} y_t^2 \, m_{\tilde{t}}^2$$

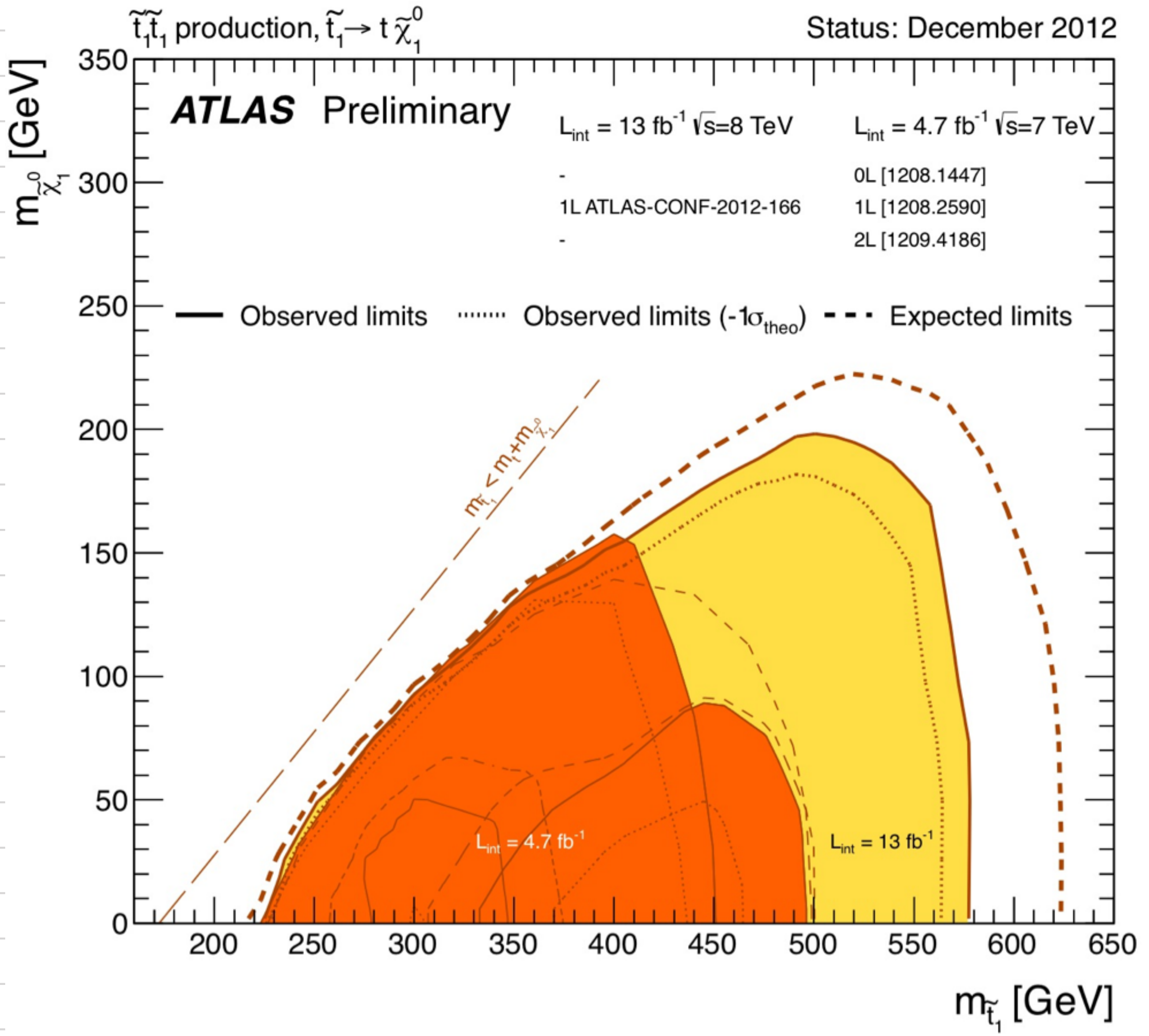
EXPERIMENTAL CHALLENGE

SEARCHES ARE MORE DIFFICULT

HEAVY FLAVOR FINAL STATES

LARGER MULTIPLICITIES, SOFTER OBJECTS

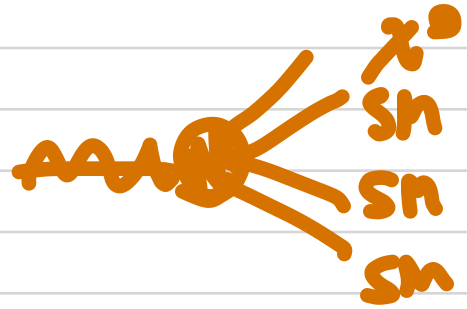
CHALLENGE ACCEPTED!



SUSY ALTERNATIVES: COMPRESSED/STEALTH

REDUCE THE AMOUNT OF mET

- LARGER MULTIPLICITY



1212.1456,1302.1870

- MORE DEGENERATE INVISIBLE PARTICLES $m_{\tilde{\psi}} = m_{\psi} + m_{\chi}$

OR $m_{\tilde{\psi}} = m_{\psi}$ if $m_{\chi} = 0$

ZERO MOMENTUM IN THE χ^0

SUSY ALTERNATIVES: R-PARITY VIOLATION

GAUGE INVARIANCE ALLOWS NEW YUKAWA INTERACTIONS

$$W_{RPV} = \lambda'' u^c d^c d^c + \lambda' Q L d^c + \lambda L L e^c + \mu' L H_u$$

- ALL THE MASSIVE SUSY PARTICLES DECAY INTO SM STATES

- NO BSM SOURCE OF mET

MUCH WEAKER LIMITS:

1211.4025; 1202.6616; 1302.2146;1209.0764,1212.1446,1307.1355

PAIR PROD.

$\tilde{g} \to jjj$

$\tilde{g} \to Q\tilde{Q} \to \ell^+\ell^+ + X,\ \ell^-\ell^+ + X,\ \ell + \text{jets},\ \ell + b + \text{jets}$

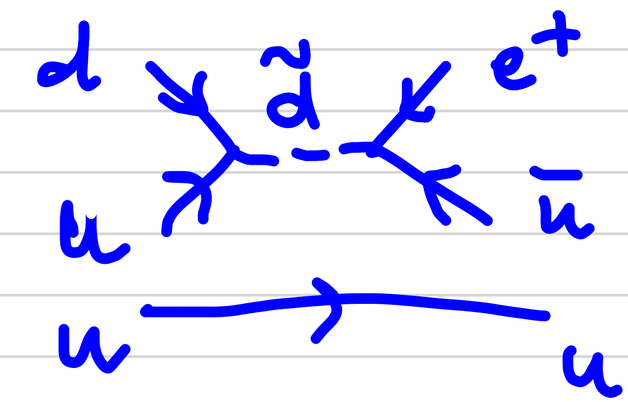
$\tilde{q} \to jj$

AT THIS STAGE ALL THESE OPTIONS ARE WORTH BEING CONSIDERED

WHY NOT RPV?

$$W_{RPV} = \lambda'' u^c d^c d^c + \lambda' Q L d^c + \lambda L L e^c + \mu' L H_u$$

- LEPTONIC & BARYONIC NUMBER VIOLATION
- PROTON DECAY $\lambda'' \cdot \lambda' < 10^{-24}$



- WIMP DARK MATTER IS NO LONGER STABLE
- UNIFICATION IS HARDER TO ACHIEVE $W_{RPV} \approx 10\,\bar{5}\,\bar{5}$

hep-ph/9704339
1305.7034

- VERY SMALL COUPLINGS

R-PARITY IS NOT BARYON NUMBER

- PROTON DECAYS VIA HIGHER DIM OPERATORS

$W^{(5)} = \frac{1}{M} u^c u^c d^c e^c$ MEDIATES PROTON DECAY TOO FAST EVEN FOR $M \sim M_{GUT}$

IN LOW-SCALE MODELS R-PARITY IS NOT ENOUGH

"EFFECTIVE" SUSY

TYPICALLY INVOLVES LOW-SCALES OF SUSY MEDIATION

⇓

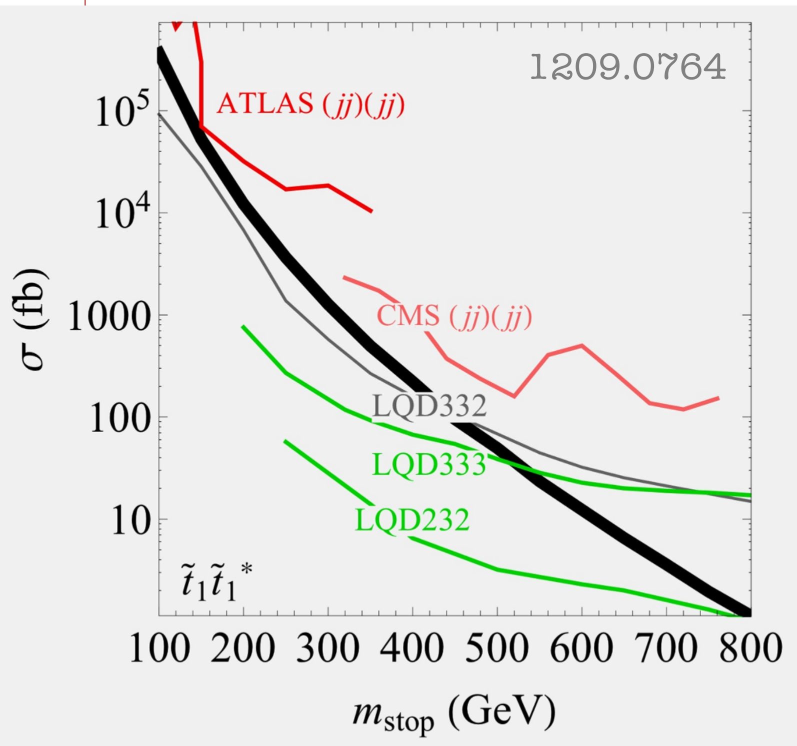
PROTON DECAY BECOMES A UV ISSUE

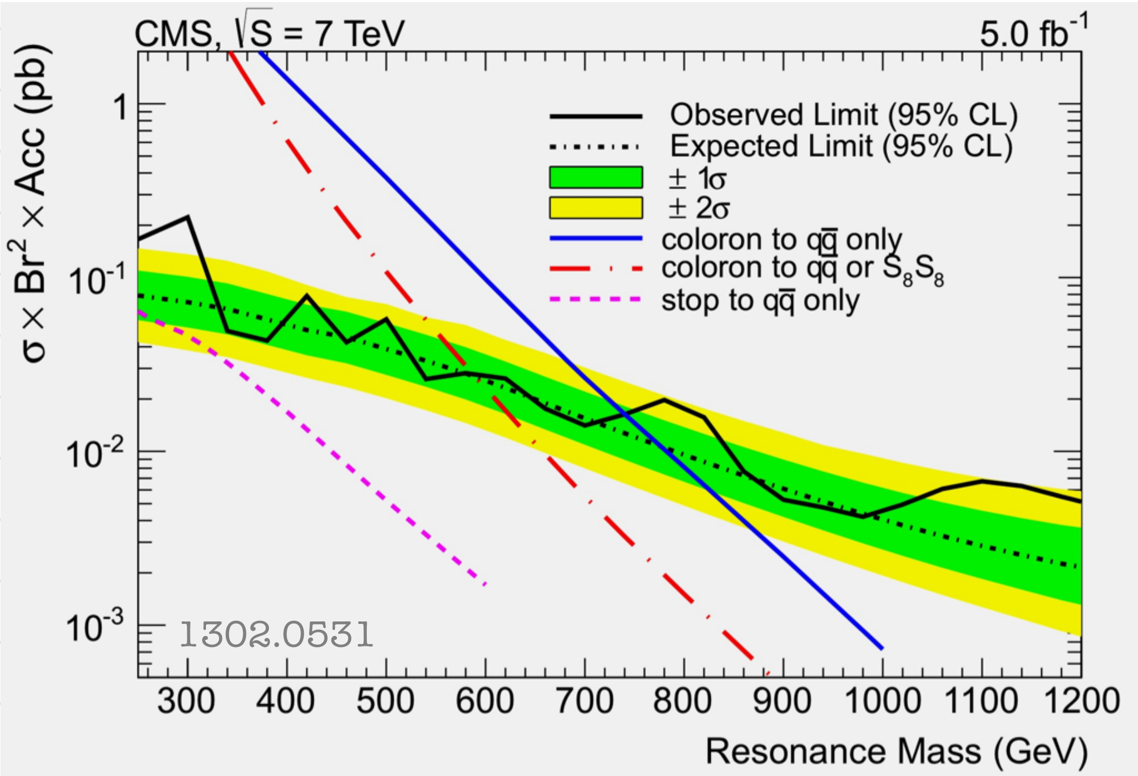
WHY RPV?

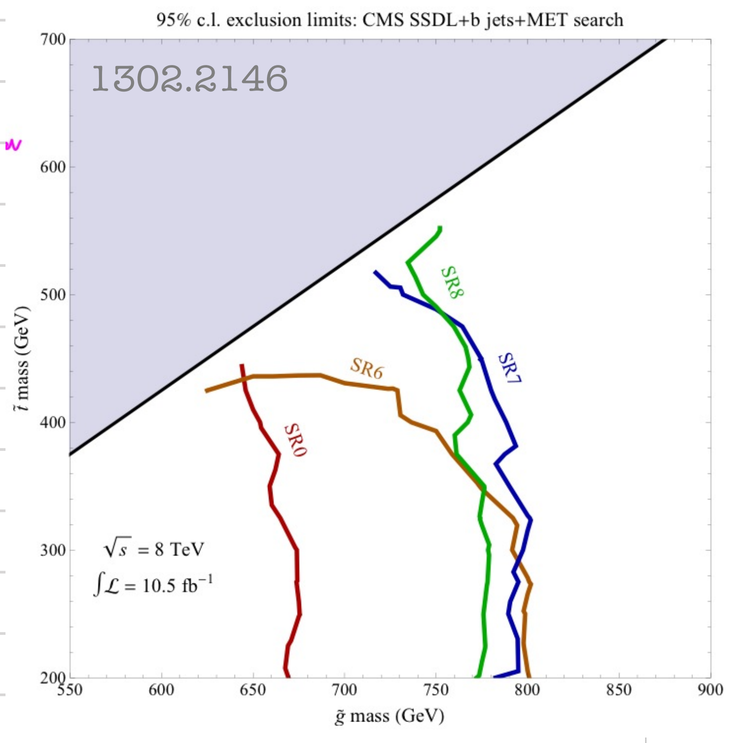
PHENOMENOLOGY IS DISTINCT: REDUCED MISSING ENERGY
RESONANCES $g \to jjj$, $\tilde{q} \to jj$
META-STABLE, MESINO-OSCILLATION

NATURAL SUSY: RPV LESS CONSTRAINED THAN RPC

LIMITS ON PAIR PRODUCTION



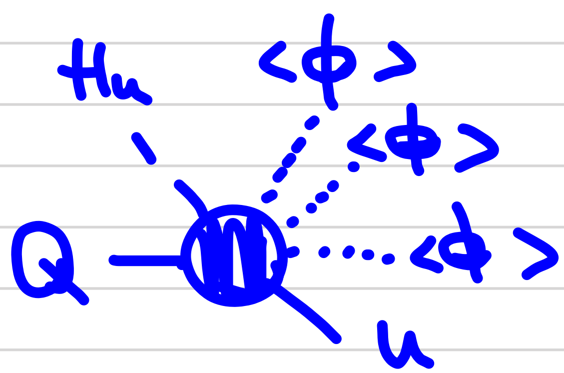




... STILL THE FLAVOR STRUCTURE
AND THE SIZE OF THE COUPLINGS
LOOKS SPECIAL

GAUGED FLAVOR SYMMETRIES

- THE YUKAWA COUPLINGS OF THE SM BREAK A LARGE SYMMETRY
  $SU(3)_{Q,L,u,d,e,\nu}$
- THE PATTERN OF YUKAWAS/MASSES/MIXING IS EXPLAINED BY A GAUGED FLAVOR SYMMETRY



$$y_{SM} \sim \frac{\langle\phi\rangle^n}{M^n}$$

- FLAVOR GAUGE BOSONS HAVE MASS $m_\rho \sim \langle\phi\rangle \sim y_{SM}$

$$\frac{1}{m_\rho^2}\bar{\psi}_a\psi_b\bar{\psi}_c\psi_d \qquad \text{FCNC} \sim \frac{1}{m_\rho^2} \sim \frac{1}{m_{light}}$$

$$m_\rho > 10^5\ \text{TeV}$$

SUSY of Grinstein, Redi, Villadoro

BEREZHIANI '83, '85
1009.2049

FLAVOR DYNAMICS CAN BE AT A MUCH LOWER SCALE IF

$$m_{light} \sim \frac{1}{M_{heavy}} \sim \frac{1}{m_\rho}$$

"seesaw-like"

MSSM FIELDS: $Q, L, u^c, d^c, e^c, \nu^c$

FLAVOR GROUP: $SU(3)_{Q,L,u^c,d^c,e^c,\nu^c}$

EXOTIC FIELDS: U, U^c, D, D^c (TO CANCEL FLAVOR ANOMALIES)

- EACH MSSM FIELD IS A FUNDAMENTAL OF HIS OWN SU(3)
- $U^c, D^c \sim 3^*$ $SU(3)_Q$ $\quad U, D \sim 3$ $SU(3)_{u^c,d^c}$

W^{MSSM}_{RPV} is FORBIDDEN BY THE FLAVOR SYMMETRY

$$W^{EXO}_{RPV} = \tilde{\lambda}'' U^c D^c D^c$$

1212.4860

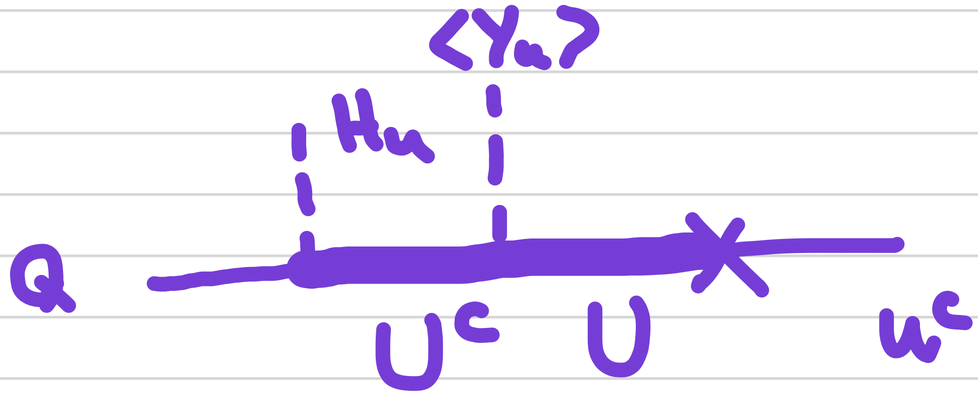
$$W = \lambda'_u U U^c Y_u + \mu_u U u^c + \lambda_u Q H_u U^c$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(3)_Q$	$SU(3)_{u^c}$	$SU(3)_{d^c}$	$SU(3)_L$	$SU(3)_{e^c}$	$SU(3)_{\nu^c}$
Q	3	2	$\frac{1}{3}$	3					
u^c	3^*		$-\frac{4}{3}$		3^*				
d^c	3^*		$\frac{2}{3}$			3^*			
U	3		$\frac{4}{3}$		3				
U^c	3^*		$-\frac{4}{3}$	3^*					
D	3		$-\frac{2}{3}$			3			
D^c	3^*		$\frac{2}{3}$	3^*					
L		2	-1				3		
e^c			2					3^*	
ν^c			0						3^*
E			-2					3	
E^c			2				3^*		
N			0						3
N^c			0				3^*		
H_u		2	1						
H_d		2	-1						
Y_u				3	3^*				
$\bar{Y}_u$				3^*	3				
Y_d				3		3^*			
$\bar{Y}_d$				3^*		3			
Y_ℓ							3	3^*	
$\bar{Y}_\ell$							3^*	3	
Y_ν							3		3^*
$\bar{Y}_\nu$							3^*		3

ANOMALY FREE

$$W = \lambda'_u U U^c Y_u + \mu_u U u^c + \lambda_u Q H_u U^c$$

KRNJAIC, STOLARSKI
1212.4860



$$\mathcal{M}_u = \begin{pmatrix} 0 & \mu_u \\ \lambda_u v & \lambda'_u \langle Y_u \rangle \end{pmatrix}$$

$$\theta_R = \frac{\mu_u}{\lambda'_u \langle Y_u \rangle} \sim \frac{1}{\lambda_u} \frac{m_{SM}}{v}$$

FLAVOR BLIND $\underline{\mu_u}, \lambda_u, \lambda'_u$

$$W_{RPV}^{MFV} = \lambda'' U^c D^c D^c \rightarrow \lambda'' u^c d^c d^c$$

$$Y_{SM} \sim \frac{\lambda_u \mu_u}{\lambda'_u \langle Y_u \rangle}$$

$$\lambda''_{ijk} \sim V_{il} \frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \epsilon_{ljk}$$

HIERARCHY OF SM YUKAWAS FROM INVERSE HIERARCHY OF MASSES OF FLAVOR BOSONS

HIERARCHY OF RPV COUPLINGS FROM HIERARCHY OF SM FERMIONS MASSES

$$\lambda''_{ijk} \sim V^{\text{ckm}}_{il} \frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \epsilon_{ljk}$$

	bs	bd	ds
t	1.46×10^{-7}	3.97×10^{-8}	2.05×10^{-8}
c	1.76×10^{-8}	4.8×10^{-9}	5.81×10^{-12}
u	2.4×10^{-10}	3.17×10^{-12}	3.83×10^{-15}

KRNJAIC, STOLARSKI 1212.4860

Csáki et al. 1111.1235

- RPV COUPLINGS ARE PREDICTED

  UP TO AN OVERALL FACTOR

  (RATIO OF COUPLINGS AND $SU(2)_W$ VEVs)

  VERY SMALL COUPLINGS FROM THE SMALL MIXINGS BETWEEN MSSM AND THE RPV SECTOR

- FLAVOR DYNAMICS CAN BE LOW-SCALE

  FLAVOR PARTNERS OF THE TOP ARE THE LIGHTEST

- λ' QLD RPV CANNOT BE GENERATED

  Q AND L ARE CHARGED UNDER DIFFERENT GROUPS

PARTIAL COMPOSITENESS + SUSY

1205.5803
KEREN-ZUR et al

$$\lambda_i \psi_i^{SM} \mathcal{O}_i \qquad \psi_{SM} \text{———} \mathcal{O}_i$$

$\mathcal{O}_i$ OF DIMENSION $\Delta_i = \frac{5}{2} + \delta_i$

$$\lambda_i = g_\rho \epsilon_i = \lambda_i(\Lambda_{UV}) \left(\frac{m_\rho}{\Lambda_{UV}}\right)^{\delta_i}$$

$$Y_{ij} \sim \epsilon_{Q_i} \epsilon_{u_j}$$

- NEARLY MARGINAL INTERACTIONS GENERATE THE LARGE MASSES (m_{top})
- TO REPRODUCE CKM $\quad \frac{\epsilon_{Q_1}}{\epsilon_{Q_2}} \sim \lambda \quad \frac{\epsilon_{Q_2}}{\epsilon_{Q_3}} \sim \lambda^2$

$$\mathcal{O}_{u^c} \mathcal{O}_{u^c} \mathcal{O}_{d^c} \xrightarrow{\text{mixing}} \lambda'' u^c d^c d^c$$

$$\lambda''_{ijk} \sim \epsilon_{u_i} \epsilon_{d_j} \epsilon_{d_k} \sim \frac{\epsilon_{q_3}}{\epsilon_{q_i}} \frac{\epsilon_{q_3}}{\epsilon_{q_j}} \frac{\epsilon_{q_3}}{\epsilon_{q_k}} (\epsilon_{u_3})^3 \frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3}$$

RF, MOHAPATRA 2013

SO FAR

$$\lambda_{BNV}\, u_i^c d_j^c d_k^c \sim \frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3}$$

ALTHOUGH DIFFERENT CKM STRUCTURES

IS THIS ALL THAT ONE CAN DO ?

THE TWO MODELS HAVE VERY SIMILAR LSP PHENO

$$BR(\tilde{t} \to bj) \simeq 99\%$$

CRUCIAL FOR THE DETECTION OF A LIGHT $\tilde{t}$

SUSY LEFT-RIGHT GAUGED FLAVOR

- EMBED $SU(2)\times U(1)$ IN A $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ BROKEN BY $\langle \chi \rangle$
- RIGHT-HANDED SM FIELDS IN DOUBLETS
- GAUGE THE FLAVOR GROUP

$$SU(3)_{Q_L} \times SU(3)_{Q_R} \times SU(3)_{\ell_L} \times SU(3)_{\ell_R}$$

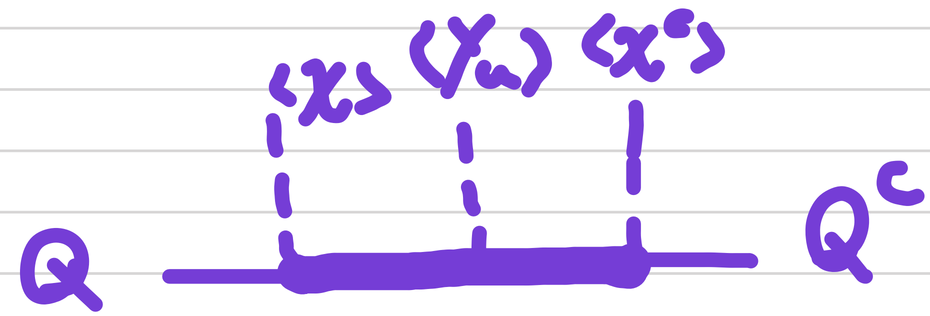
	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	$SU(3)_{Q_L}$	$SU(3)_{Q_R}$	$SU(3)_{\ell_L}$	$SU(3)_{\ell_R}$
Q	3	2		$\frac{1}{3}$	3			
Q^c	3^*		2	$-\frac{1}{3}$		3^*		
U	3			$\frac{4}{3}$		3		
U^c	3^*			$-\frac{4}{3}$	3^*			
D	3			$-\frac{2}{3}$		3		
D^c	3^*			$\frac{2}{3}$	3^*			
L		2		-1			3	
L^c			2	1				3^*
E				-2				3
E^c				2			3^*	
N				0				3
N^c				0			3^*	
$\chi, \bar{\chi}$		2		± 1				
$\chi^c, \bar{\chi}^c$			2	± 1				
Y_u					3	3^*		
$\bar{Y}_u$					3^*	3		
Y_d					3	3^*		
$\bar{Y}_d$					3^*	3		
Y_ℓ							3	3^*
$\bar{Y}_\ell$							3^*	3
Y_ν							3	3^*
$\bar{Y}_\nu$							3^*	3

ANOMALY FREE

$SU(3)_{QL}\times SU(3)_{QR}\times SU(3)_{LL}\times SU(3)_{LR}$ L-R

$$W=\lambda_u\left(Q\chi U^c+Q^c\chi^c U\right)$$
$$+\ \lambda_d\left(Q\bar{\chi}D^c+Q^c\bar{\chi}^c D\right)$$
$$+\lambda_u' Y_u\, UU^c+\lambda_d' Y_d\, DD^c$$

NO "μ-TERMS"



$$M_d=\frac{\lambda_d^2}{\lambda_d'}\frac{v_L v_R}{\langle\hat{Y}_d\rangle}\qquad M_u=\frac{\lambda_u^2}{\lambda_u'}\frac{v_L v_R}{V_{am}^{\dagger}\hat{Y}_u V_{am}}$$

$$\theta^{u,d}_{L,R}=\frac{\lambda v_{L,R}}{\lambda' Y_{u,d}}\qquad v_L\ll v_R\ll\langle\hat{Y}_{u,d}\rangle$$

$$\theta^{u_i}\sim\frac{m_{u_i}}{m_t}$$

$$W^{Exo}_{RPV}=\lambda''\left(UDD+U^cD^cD^c\right)$$

↓ MIXING

$$W^{MSSM}_{RPV}=\lambda''\,u^c d^c d^c$$

$$\lambda''_{ijk}\sim V^{am}_{il}\frac{m_{u_i}m_{d_j}m_{d_k}}{m_t^3}\,\epsilon_{ljk}$$

$SU(3)_{V,q} \times SU(3)_{V,\ell}$

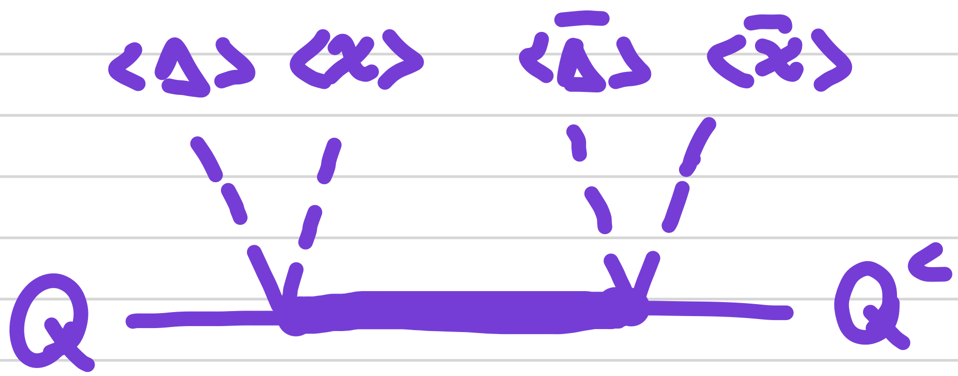
	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	$SU(3)_{V,q}$	$SU(3)_{V,\ell}$
Q	3	2		$\frac{1}{3}$	3	
Q^c	3^*		2	$-\frac{1}{3}$	3^*	
U	3			$\frac{4}{3}$	3^*	
U^c	3^*			$-\frac{4}{3}$	3	
D	3			$-\frac{2}{3}$	3^*	
D^c	3^*			$\frac{2}{3}$	3	
L		2		-1		3
L^c			2	1		3^*
E				-2		3^*
E^c				2		3
N				0		3^*
N^c				0		3
$\chi, \bar{\chi}$		2		± 1		
$\chi^c, \bar{\chi}^c$			2	∓ 1		
Δ_u					6	
$\bar{\Delta}_u$					6^*	
Δ_d					6	
$\bar{\Delta}_d$					6^*	
Δ_ℓ						6
$\bar{\Delta}_\ell$						6^*
Δ_ν						6
$\bar{\Delta}_\nu$						6^*

- ANOMALY FREE
- $\Delta \sim 6$ OF FLAVOR GROUP

$SU(3)_{V,q} \times SU(3)_{V,\ell}$

$$W \supset \frac{\lambda_d}{\Lambda}\left(Q\,\chi\,D^c\,\Delta_d + Q^c\chi^c D\,\bar{\Delta}_d\right) + M_D\,D D^c$$

MASS TERM (WITHOUT FLAVON VEV)



$$m_{d,SM} \sim \frac{\lambda_d^2}{\Lambda^2}\frac{v_L v_R \langle \Delta_d\rangle^2}{M_D}$$

$$\theta_{L,R} \sim \frac{\lambda_d}{\Lambda}\frac{v_{L,R}\langle \Delta_d\rangle}{M_D} \sim \sqrt{\frac{m_{d,SM}}{v_{R,L}}\,\frac{v_{L,R}}{M_D}}$$

$$W^{EXO}_{RPV} = \tilde{\lambda}''\left(UDD + U^c D^c D^c\right) + \tilde{\lambda}\left(LLE^c + L^c L^c E^c\right)$$

$\Downarrow$

$$W^{MSSM}_{RPV} = \lambda''\, u^c d^c d^c + \lambda\, L L e^c$$

- SEPARATE BNV, LNV

$$W^{\text{MSSM}}_{\text{RPV}} = \lambda'' u^c d^c d^c + \lambda L L e^c$$

- SEPARATE BNV, LNV
- DIFFERENT DEPENDENCE ON THE SM MASSES

$$\lambda''_{ijk} \sim V^{\text{ckm}}_{il} \left(\frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \right)^{1/2} \epsilon_{ljk}$$

$$\theta_{L,R} \sim \sqrt{\frac{m_{d,SM}}{v_{R,L}} \frac{v_{L,R}}{M_D}}$$

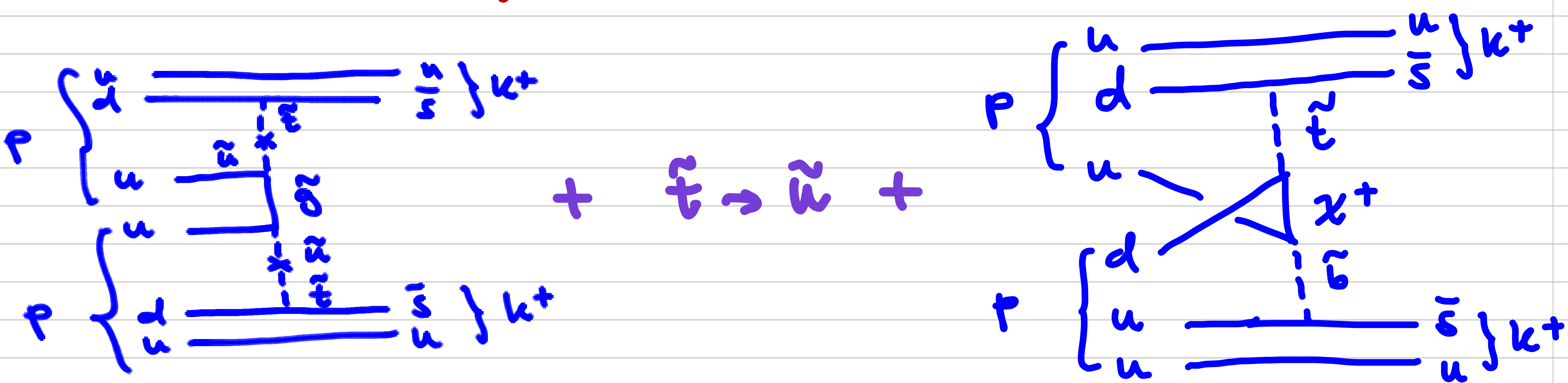
	bs	bd	ds
t	3.94×10^{-5}	4.38×10^{-5}	1.43×10^{-4}
c	6.22×10^{-5}	6.93×10^{-5}	5.3×10^{-7}
u	1.55×10^{-5}	8.35×10^{-7}	6.39×10^{-9}

MORE PROMPT DECAYS

- SIMILARLY LNV $\lambda \sim \left(\frac{m_e}{m_t} \right)^{1/2}$
- $m_f^{SM} \sim \langle \text{FLAVON} \rangle$

"NORMAL" HIERARCHY OF FLAVOR GAUGE BOSONS

LIMITS: $pp \to K^+K^+$ $\tau > 1.7 \times 10^{32}$ years



SQUARK FV

FLAVOR CONSERVING

$$A_{FC} \sim \frac{1}{m_{\tilde{g}}}\left(\frac{1}{m_{\tilde{q}}}\right)^4 \left(\frac{m_u m_d m_s}{m_s}\right)^{\mu} V_{td}^2$$

$\mu = 1$ or 2

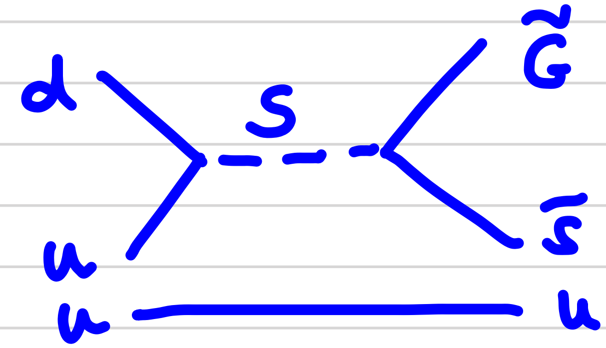
$$\tau_{pp \to KK}(\mu = 1) \sim 10^{34}\, y$$

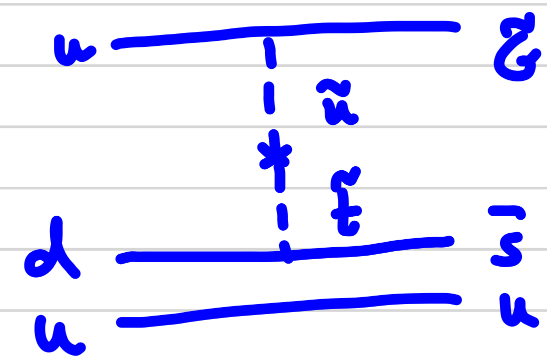
$n - \bar{n}$

proton decay $p \to K^+ \nu$ $\tau > 10^{33}$ y

hep-ph/9611285

$p \to K^+ \tilde{G}$





$$A_{FV} \sim \frac{1}{m_{\tilde{q}}^2} \frac{1}{m_{3/2} M_{pl}} V_{td} \left(\frac{m_d m_s}{m_t}\right)^{\mu} \delta_{13}$$

$$\tau \sim 10^{33}\,y \left(\frac{m_{3/2}}{\mathrm{KeV}} \frac{0.01}{\delta_{13}}\right)^2 \qquad \mu = 2$$

$$\tau \sim 10^{33}\,y \left(\frac{m_{3/2}}{\mathrm{MeV}} \frac{0.01}{\delta_{13}}\right)^2 \qquad \mu = 1$$

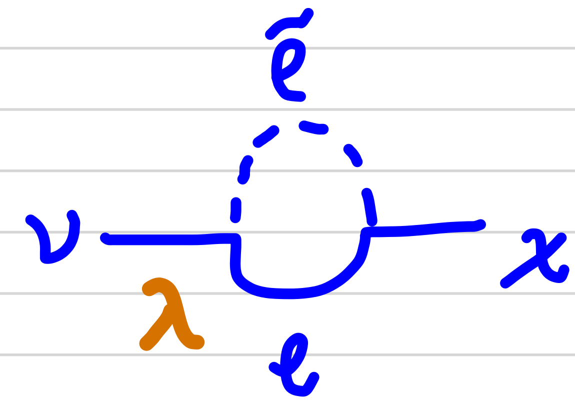
proton decay $p \to K^+ \nu$ $\tau > 10^{33}\,y$

$p \to K^+ \nu$

$$W^{MSSM}_{RPV} \supset \lambda_{ijk} L_i L_j e^c_k$$

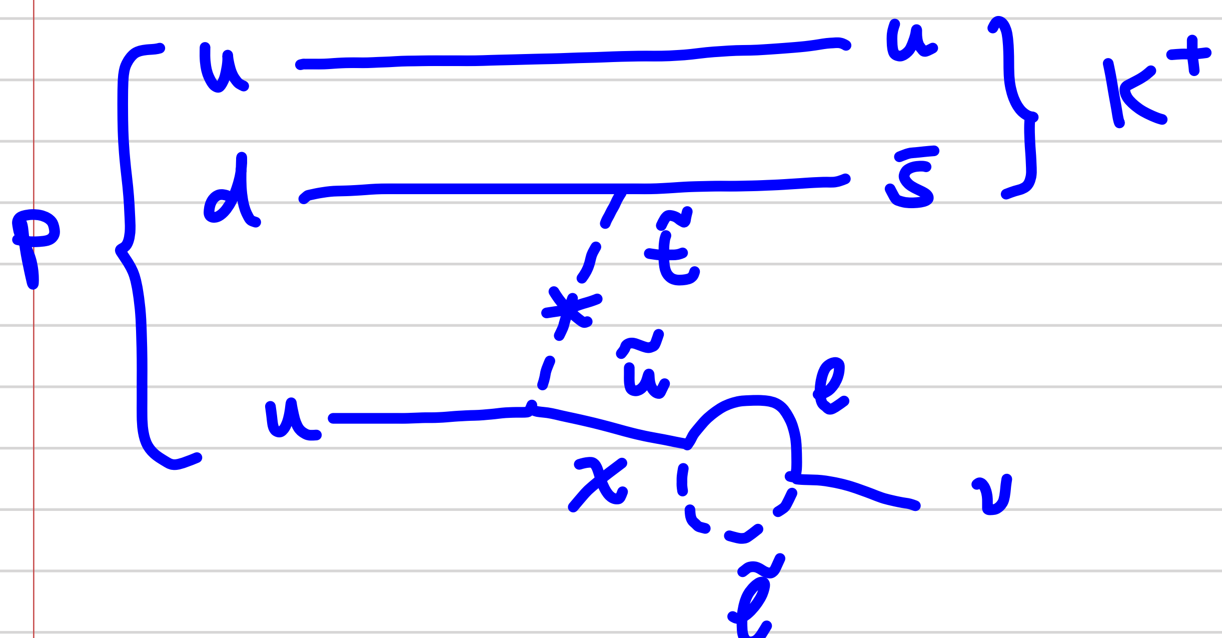
$$\lambda \sim \frac{m_{e_k}}{m_t}$$

IN THE MODEL $SU(3)_{V,q} \times SU(3)_{V,\ell}$



LNV GIVES $\nu - \chi^0$ MIXING

1302.0004



$$A \sim \frac{\lambda}{16\pi^2} \delta_{13} V_{tb} \left(\frac{m_d m_s}{m_t^2}\right)^{1/2} \frac{1}{m_{\tilde{q}}^2 m_\chi}$$

- THE RPV FLAVOR STRUCTURE IS PREDICTED IN TERMS OF SM MASS RATIOS AND CKM

$$\lambda''_{ijk} \sim V^{\alpha k n}_{il} \left(\frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \right)^{\mu} \epsilon_{ljk}$$

- AN OVERALL FACTOR IS TYPICALLY NOT FIXED

$\mu = 1$ $\quad Br(\tilde{t} \to bd + bs) \simeq \underline{99\%}$

$SU(3)_{Q,L,d,u,e,\nu}$
$SU(3)_{Q,Q^c,L,L^c}$
PARTIAL COMPOSITENESS

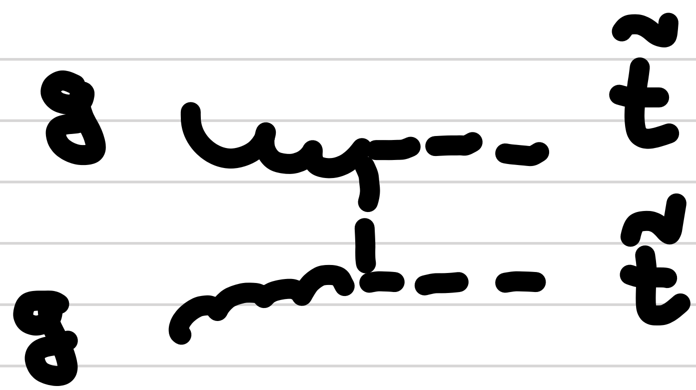
$\mu = 1/2$ $\quad Br(\tilde{t} \to bd + bs) \simeq \underline{14\%}$ $\quad SU(3)_{V,q,e}$

DECAY RATES IN HEAVY FLAVOR OF THE STOP/SBOTTOM LSP

$pp \to \tilde{t}\tilde{t} \to$ jets

RF, TORRE 2012

Tevatron + LEP $m_{\tilde{t}} > 100$ GeV



$\tilde{t} \to jj$

CHALLENGING ESPECIALLY FOR LIGHT $\tilde{t}$

- IN GENERAL FULLY HADRONIC SIGNALS HAVE LARGE BACKGROUNDS FROM

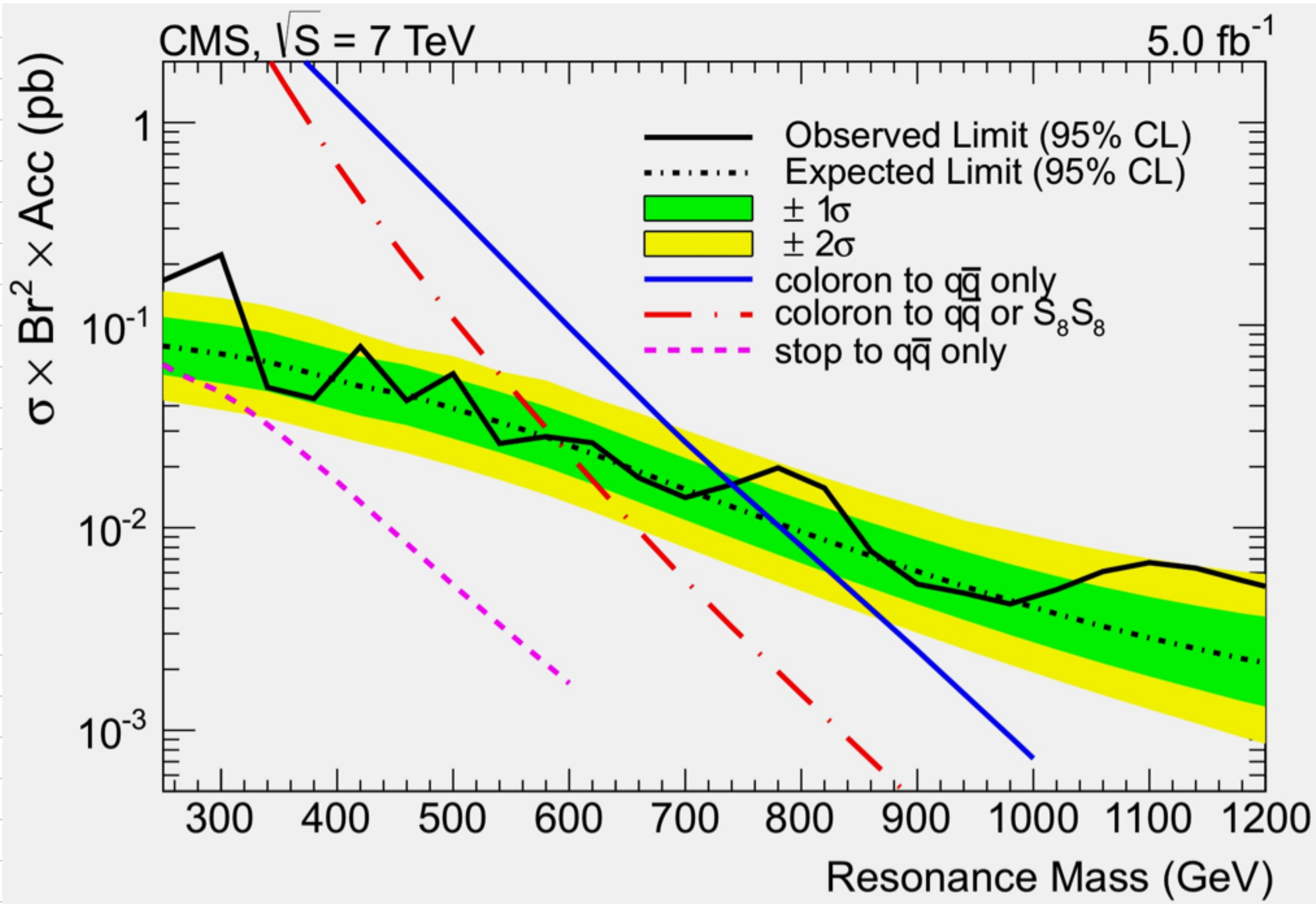
QCD MULTI-JET BACKGROUND

- EVEN TRIGGERING IS AN ISSUE

4 jet $p_T > 85$ GeV @ LHC 8
4 jet $p_T > 45$ GeV "parked"
b-trigger

- $t \to bq$ $q = d, s$

PROVIDES EXTRA HANDLES B-TAG (TRIGGER & ANALYSIS)

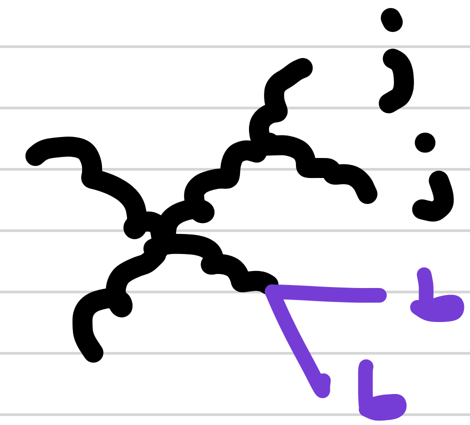


CMS, $\sqrt{S}$ = 7 TeV
5.0 fb^{-1}
$\sigma \times Br^2 \times Acc$ (pb)
1
10^{-1}
10^{-2}
10^{-3}
Observed Limit (95% CL)
Expected Limit (95% CL)
$\pm$ 1σ
$\pm$ 2σ
coloron to $q\bar{q}$ only
coloron to $q\bar{q}$ or S_8S_8
stop to $q\bar{q}$ only
300
400
500
600
700
800
900
1000
1100
1200
Resonance Mass (GeV)

- $pp \to \tilde{t}\tilde{t} \to bbqq$

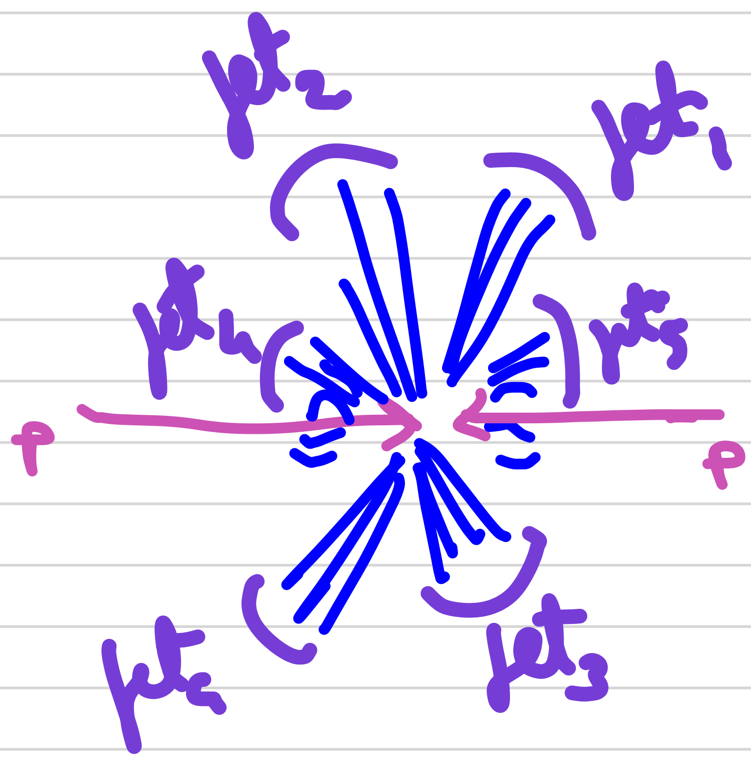
  b-tag $\epsilon \sim 66\%$ $\phi < 10^{-2}$

- $pp \to jets$ QCD $\epsilon \ll 1$ BECAUSE ONE FLAVOR



- $pp \to t\bar{t} \to bbqqqq$

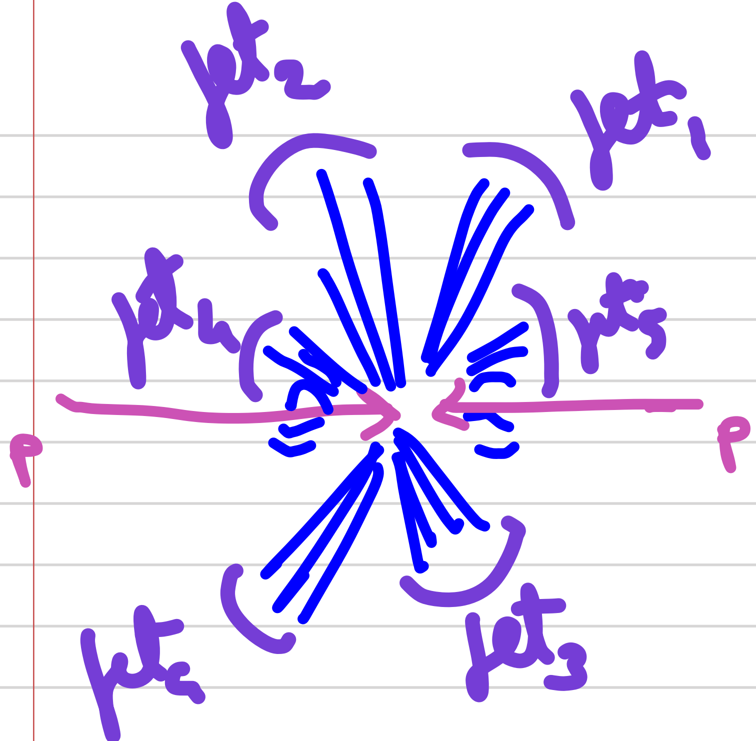
- DOUBLE RESONANCE STRUCTURE



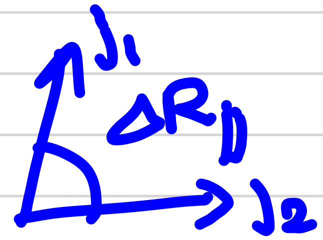
$\tilde{t} = jet_k \, jet_i$

$\tilde{t} = jet_p \, jet_q$

- IDENTIFICATION OF THE CANDIDATE RESONANCE $\tilde{t}$



$$m_{\tilde{q}}^2 \simeq p_{T_{j_1}} p_{T_{j_2}} \Delta R_{jj}^2$$



$$\Delta R \sim \frac{m}{p_T}$$

$$p_T \sim m_{\tilde{q}}$$
$$\Delta R \simeq 1$$

- PAIRING BY MINIMIZING $|1 - \Delta R_{ij}| + |1 + \Delta R_{kl}|$
- RESONANCE CANDIDATES WITH SIMILAR MASS δ_m
- HARD vs FORWARD PROCESS

$\cos\theta^*$ large angle small angle

- MASS OF THE SIGNAL HAS LITTLE SENSITIVITY TO ΔR

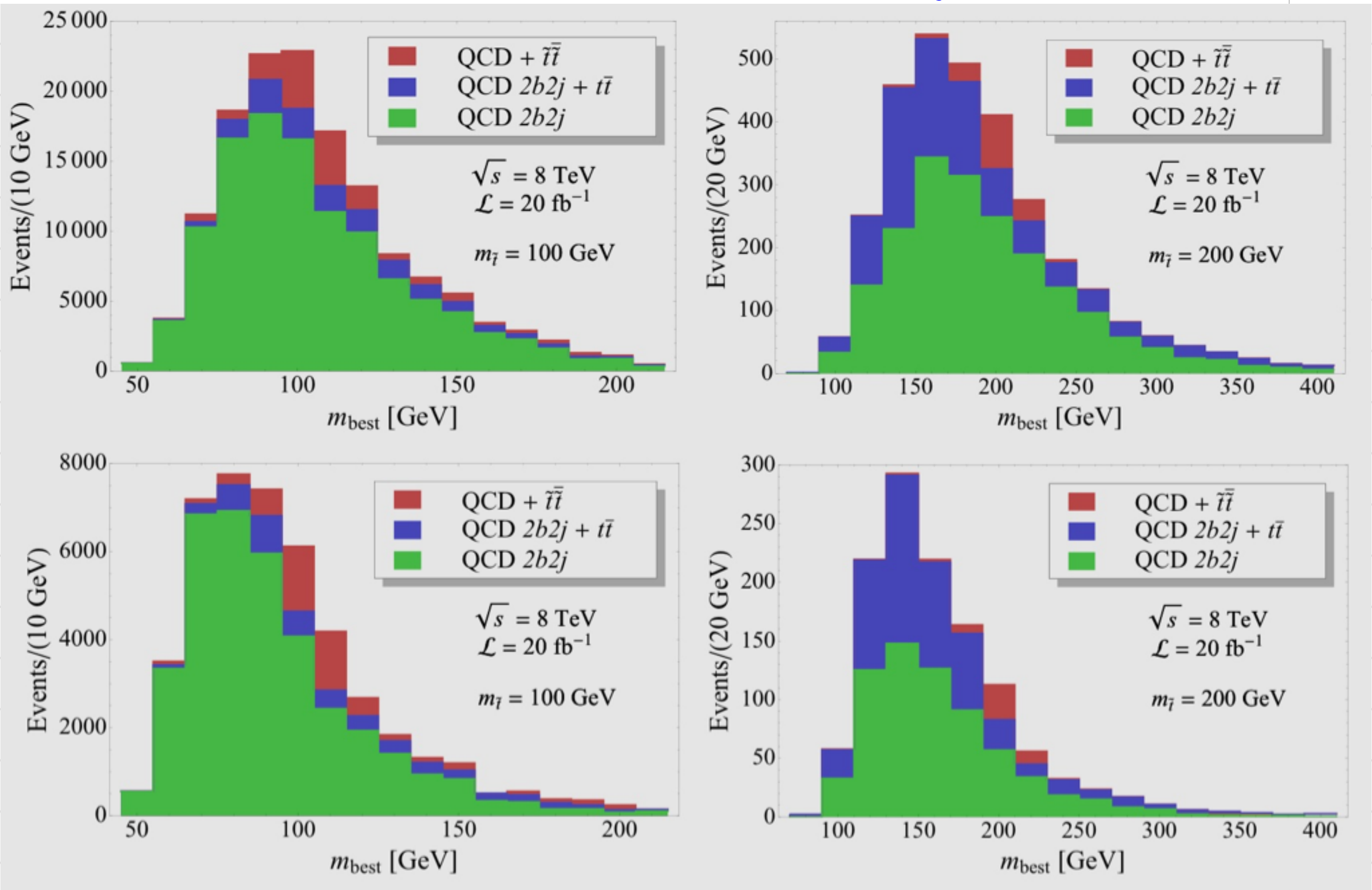
LOOK INSIDE THE CANDIDATE RESONANCES $(\Delta R_{12} + \Delta R_{34})/2$

$$p_{T,j} > \frac{m_{\tilde{t}}}{2}\,, \qquad |\eta_j| < 2.8\,, \qquad \Delta R_{jj} > 0.7\,,$$
$$\delta_m < 0.075\,, \qquad |\cos\theta^*| < 0.4\,, \quad \Delta R_{\text{best}} < 1.5\,,$$
$$\Delta\eta_{\text{best}} < 0.8\,.$$

$m_{\tilde{t}} = 100$ GeV $\qquad m_{\tilde{t}} = 200$ GeV

ENFORCING LOOSELY COLLINEAR JETS IN THE RESONANCE CANDIDATE

ENFORCING MORE COLLINEAR JETS IN THE RESONANCE CANDIDATE



$\mathcal{L} = 20/\text{fb}$ $\sqrt{s} = 8$ TeV $\longrightarrow$ $m_{\tilde{t}}$ UP TO 200 GeV

CONCLUSIONS AND OUTLOOK

- RPV STILL CAN HAVE SUB-TeV SUPER PARTNERS

- PROTON DECAY IS <u>NOT</u> AUTOMATICALLY SAVED BY R-PARITY IN LOW SCALE MODELS

- BREAKING OF GAUGED FLAVOR SYMMETRIES CONNECTED TO THE SIZE OF RPV COUPLINGS

$$W_{RPV} = \lambda''_{ijk} u^c_i d^c_j d^c_k$$

$$\lambda''_{ijk} \sim V^{ckm}_{il} \left(\frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \right)^{\mu} \epsilon_{ljk}$$

$\mu = 1, \frac{1}{2}$

·) CHALLENGING LIGHT SQUARK SCENARIO

$\tilde{g}, \tilde{h}, \tilde{q}_3$

$\tilde{t}_R$

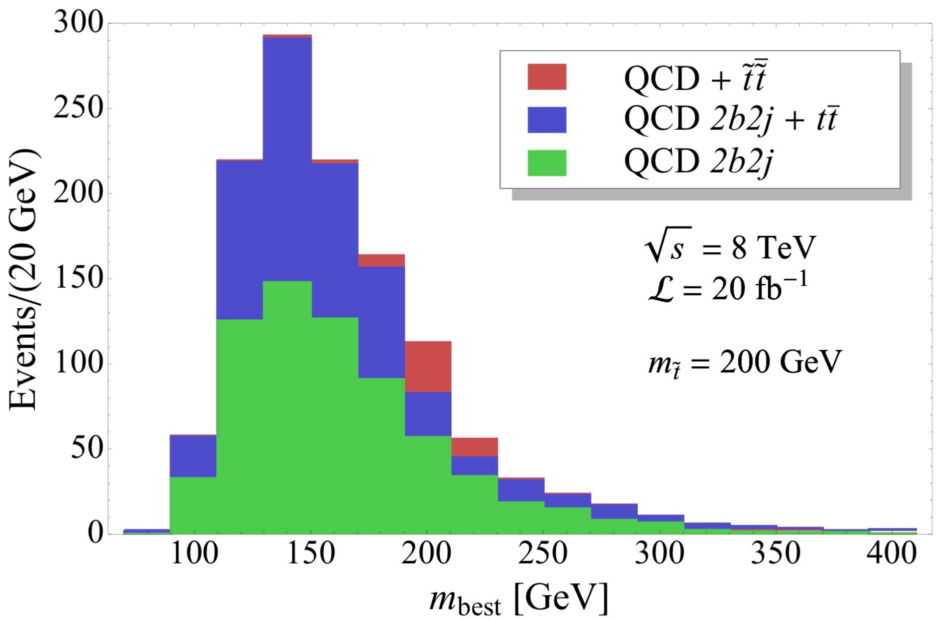
PAIR STOP PRODUCTION $\tilde{t} \to qq$

- $Br(\tilde{t} \to bd + bs) \simeq$ 99% — $SU(3)_{Q,L,d,u,e,\nu}$; $SU(3)_{Q,Q^c,L,L^c}$; PARTIAL COMPOSITENESS ... } $\mu = 1$

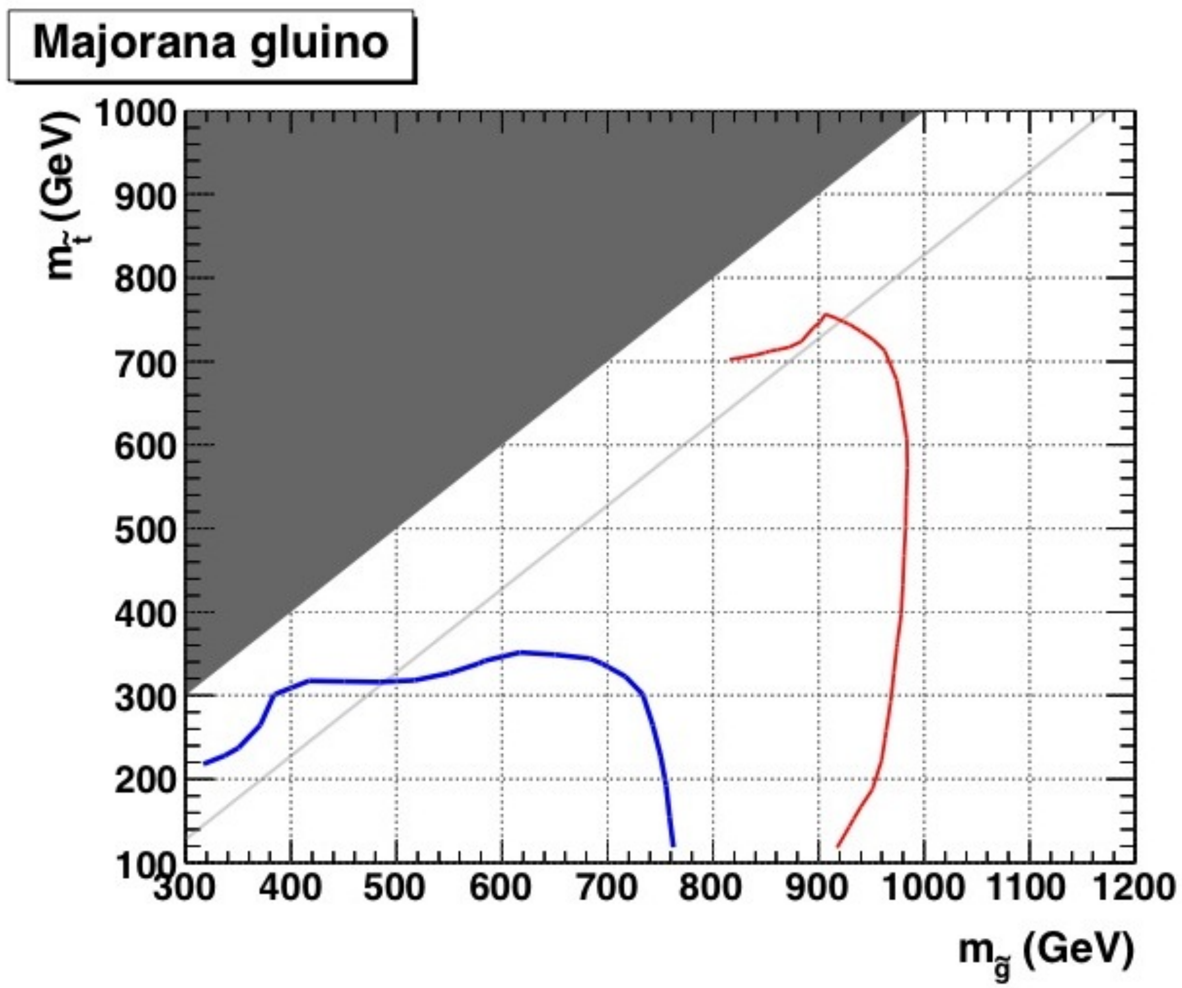
- $Br(\tilde{t} \to bd + bs) \simeq$ 14% — $SU(3)_{V,q,e}$ $\mu = \frac{1}{2}$

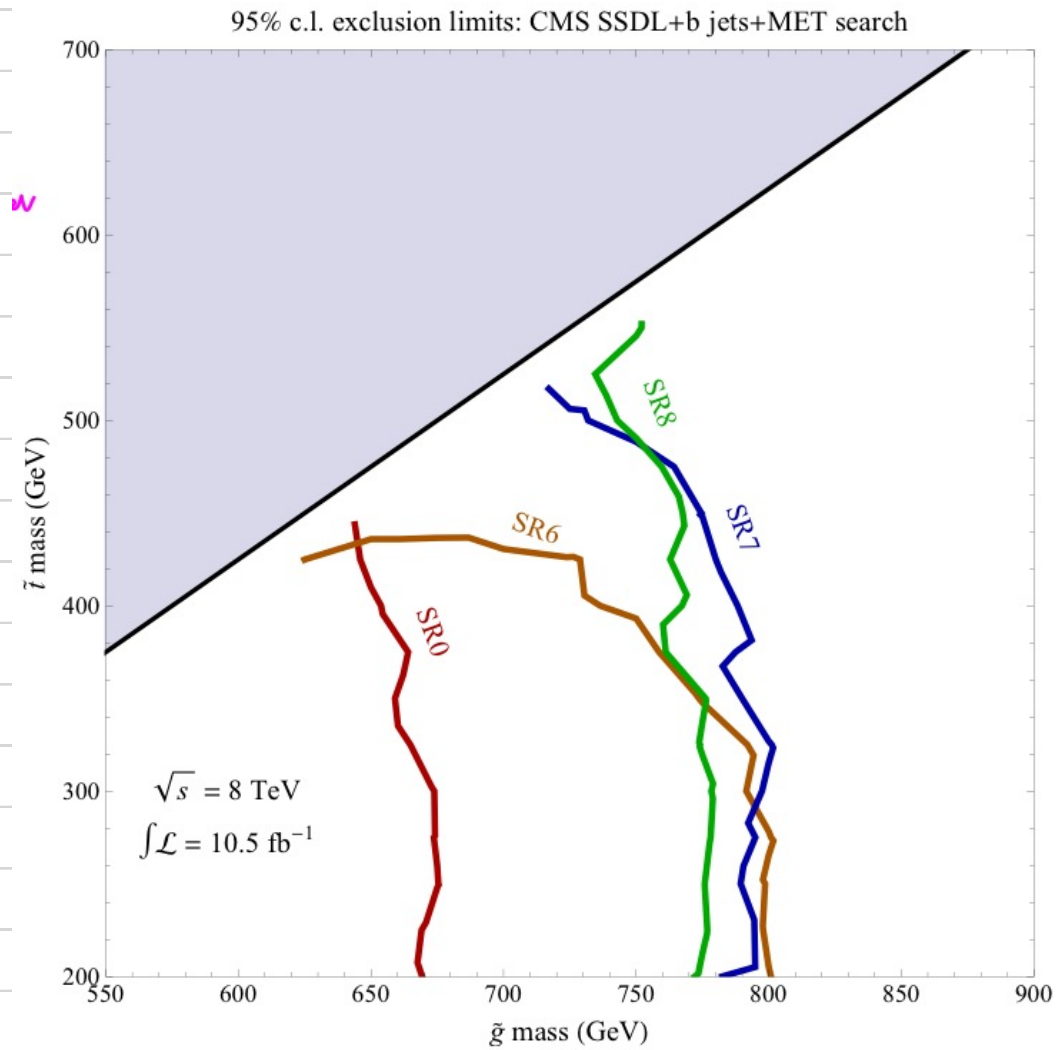
- LHC CAN TELL

$pp \to \tilde{t}\tilde{t} \to b\bar{b}q\bar{q}$

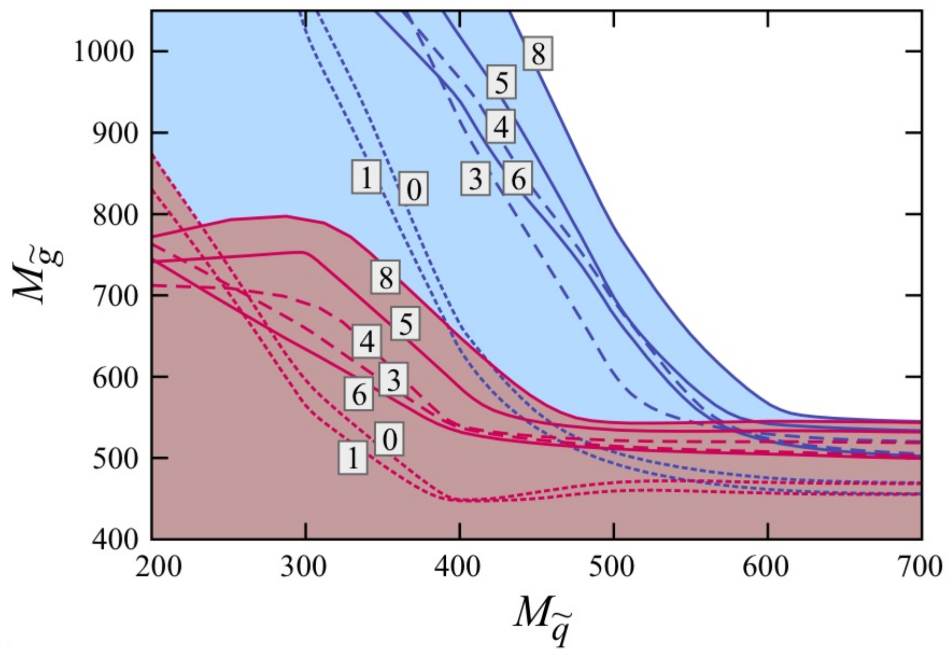


SAME SIGN DILEPTONS (+b)

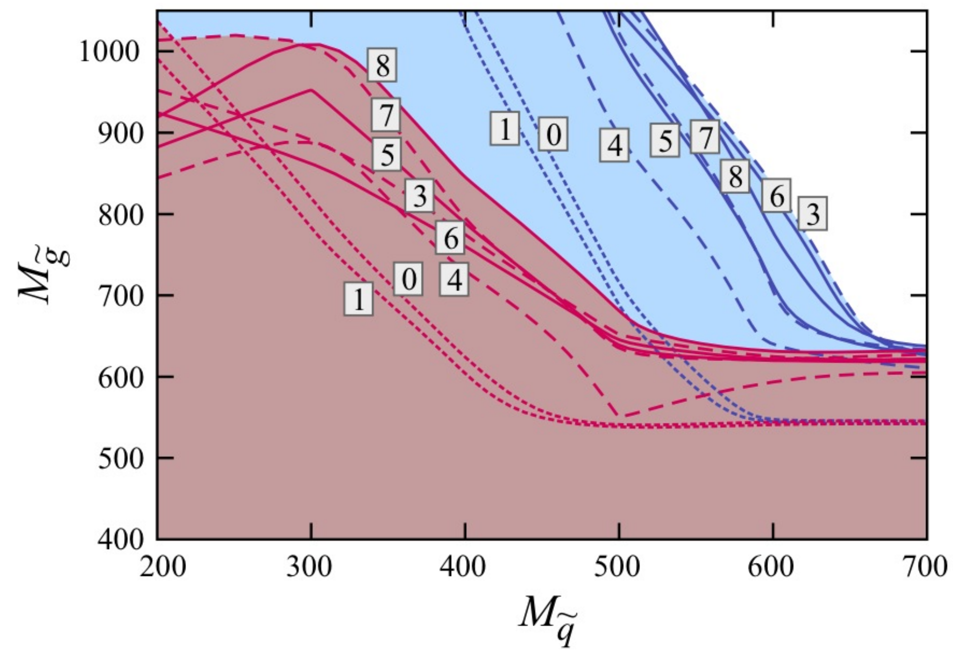




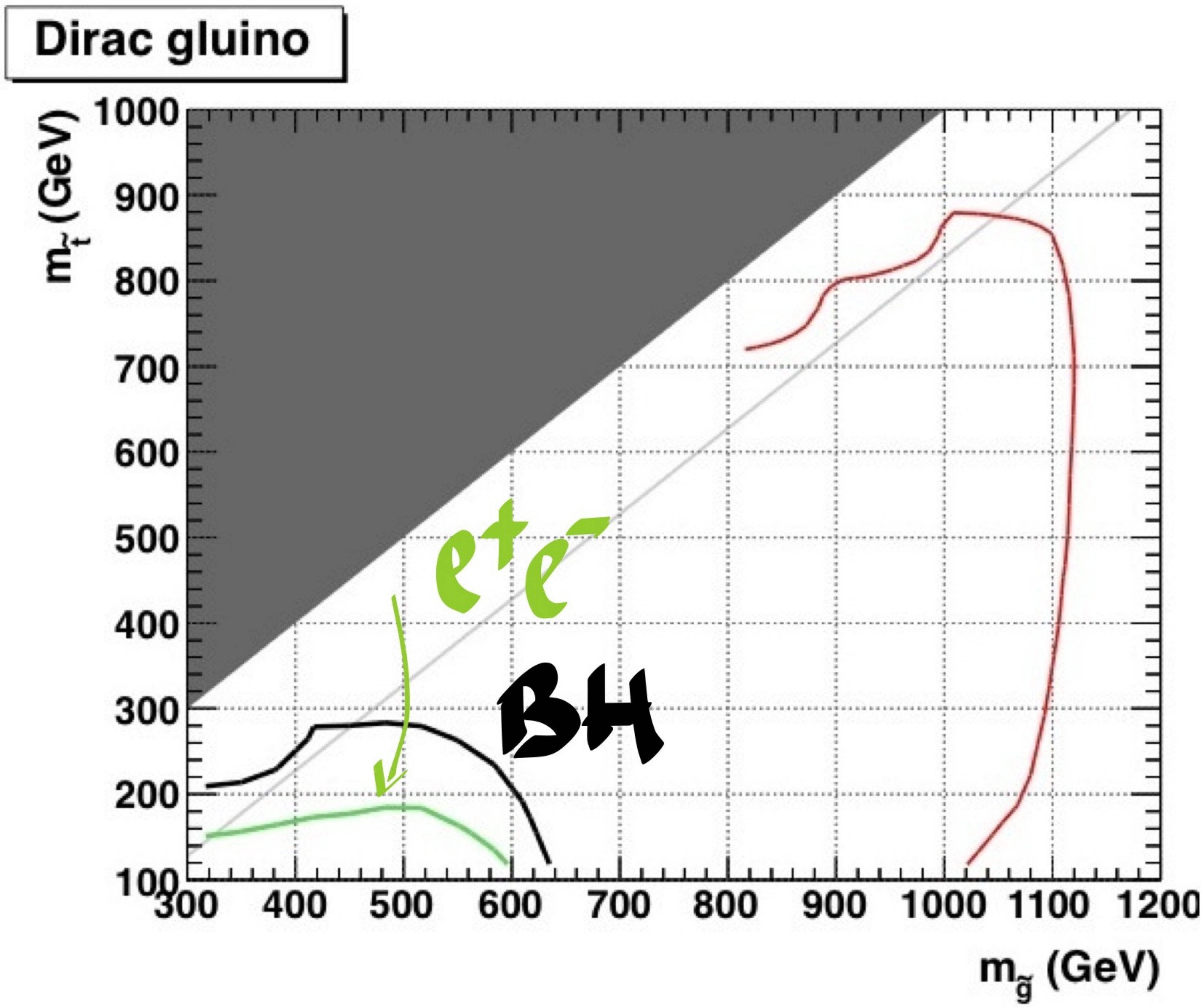
Full MFV



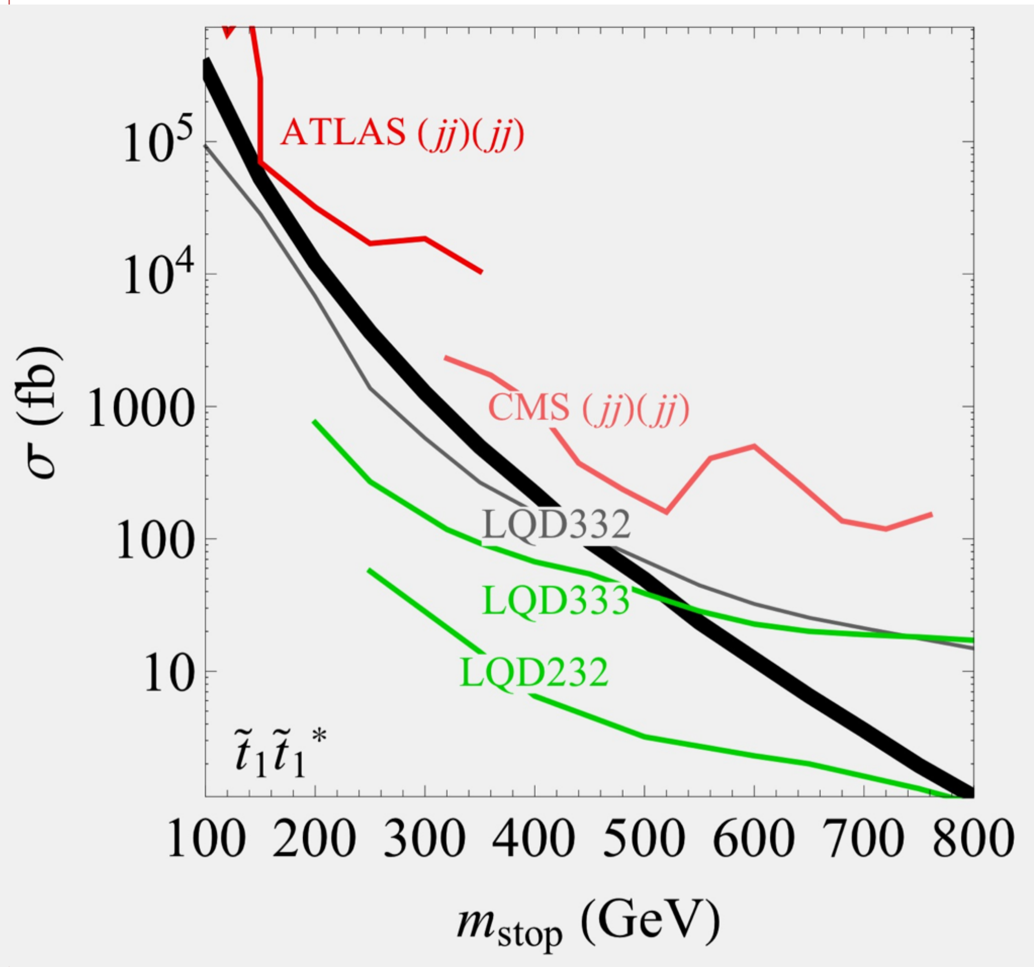
Holomorphic MFV

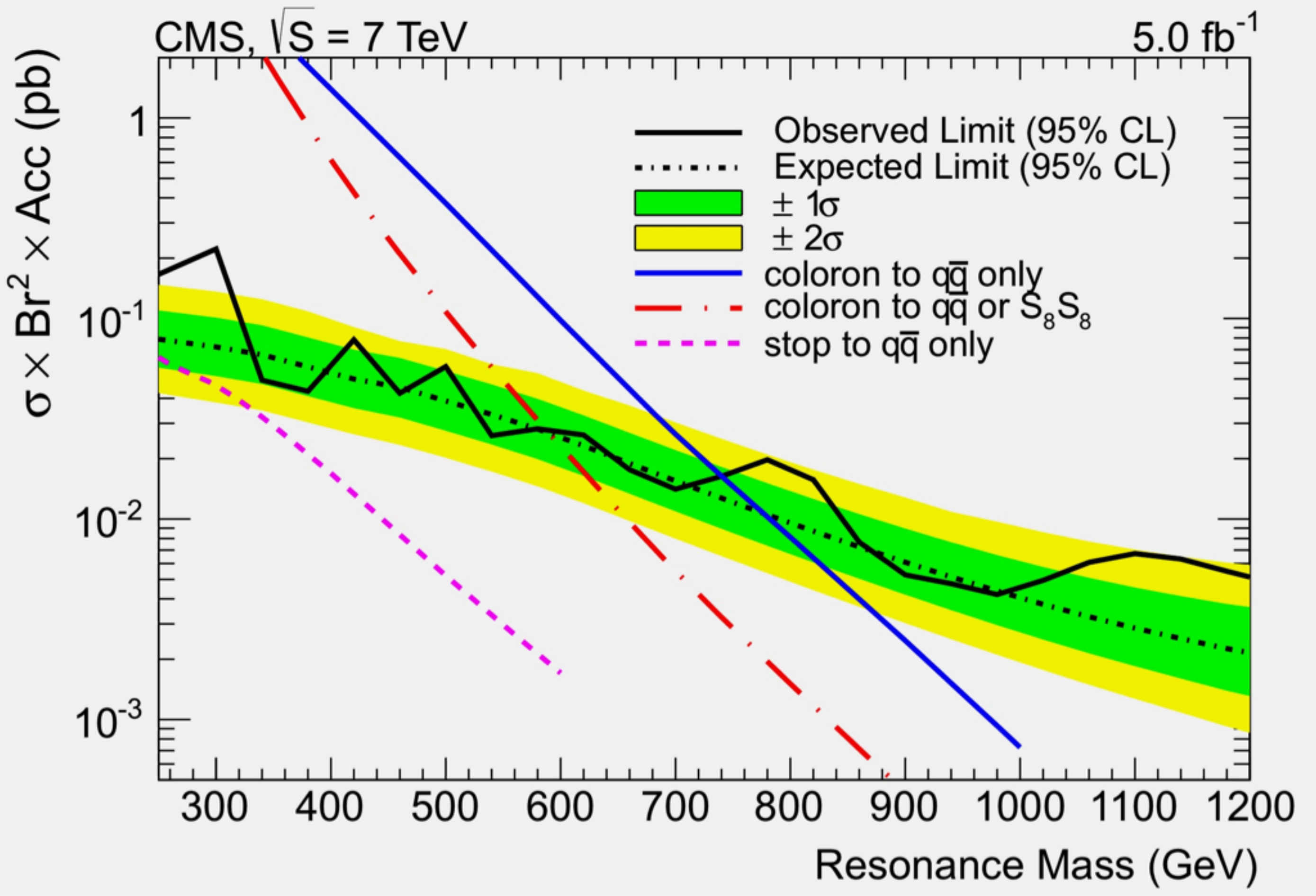


DIRAC GLUINO

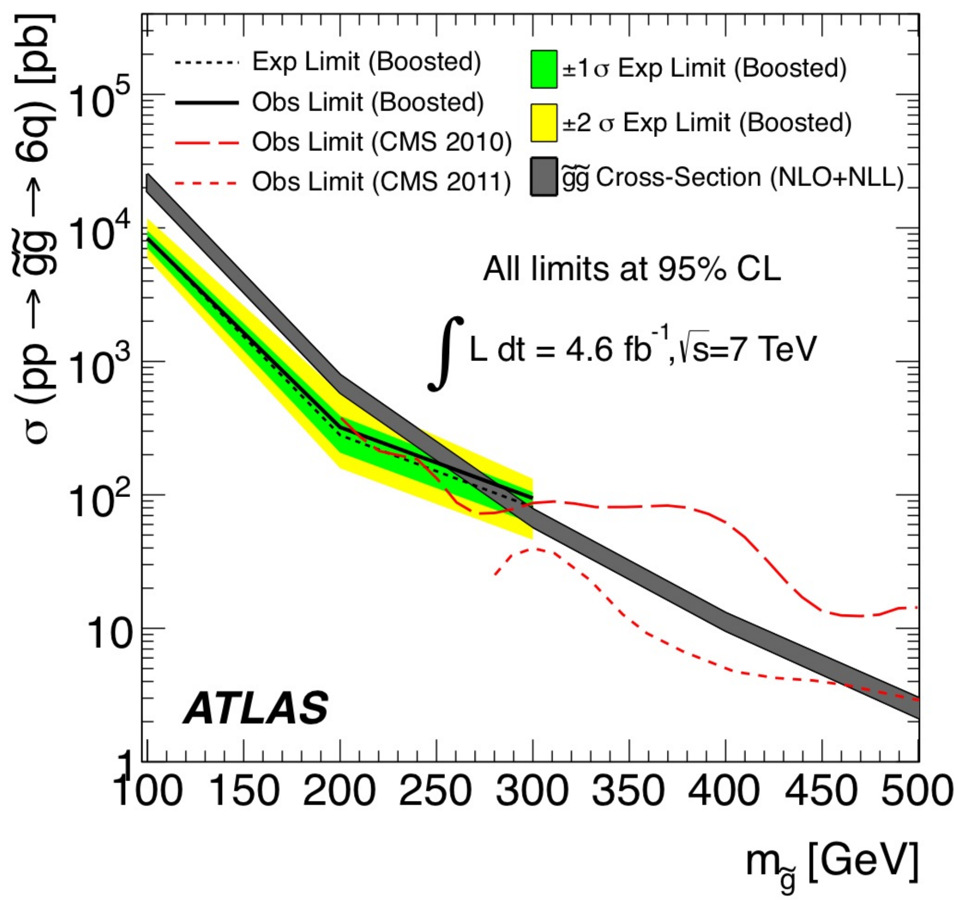


PAIRED DIJET $\tilde{q} \rightarrow jj$





PAIRED $\tilde{g} \to jjj$



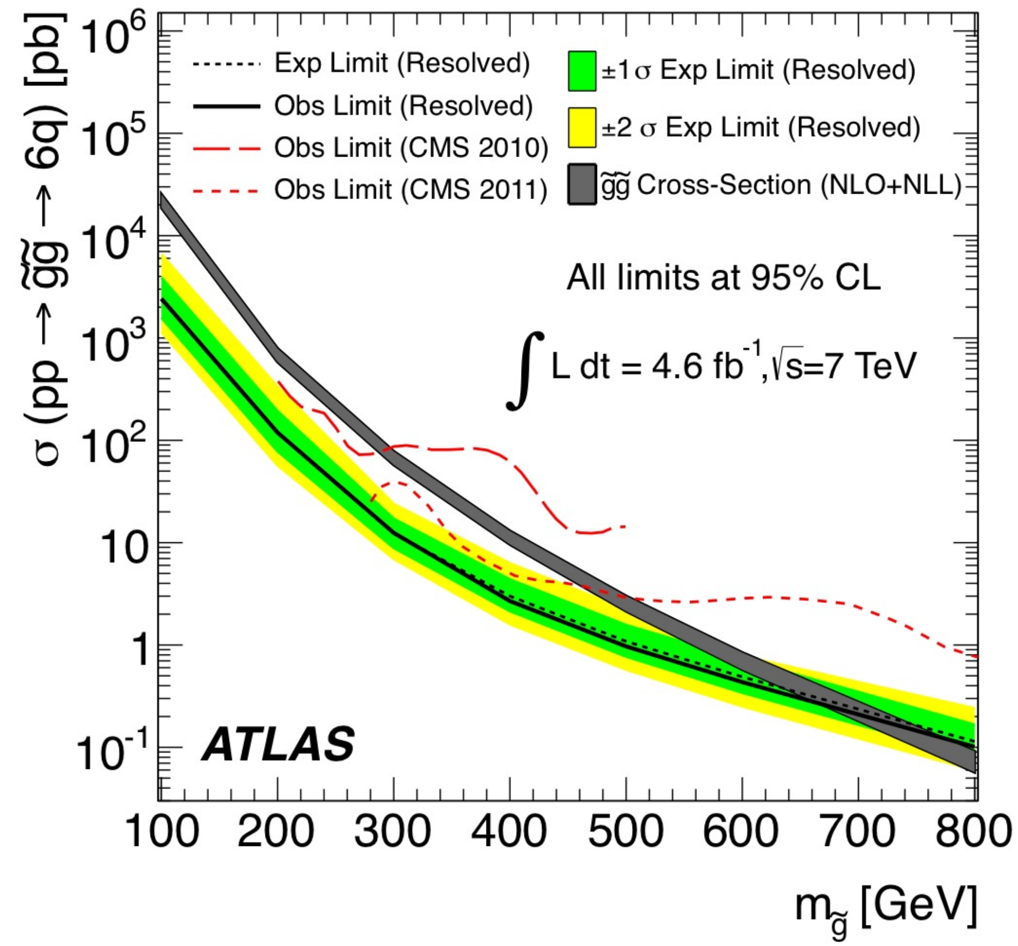


Figure 6. The expected and observed 95% confidence limit
channel. The published CMS results using 35 pb^{-1} of 2010 d
shown for comparison.

idence limits are shown for the resolved analyses
$^{-1}$ of 2010 data and using 5 fb^{-1} of 2011 data are

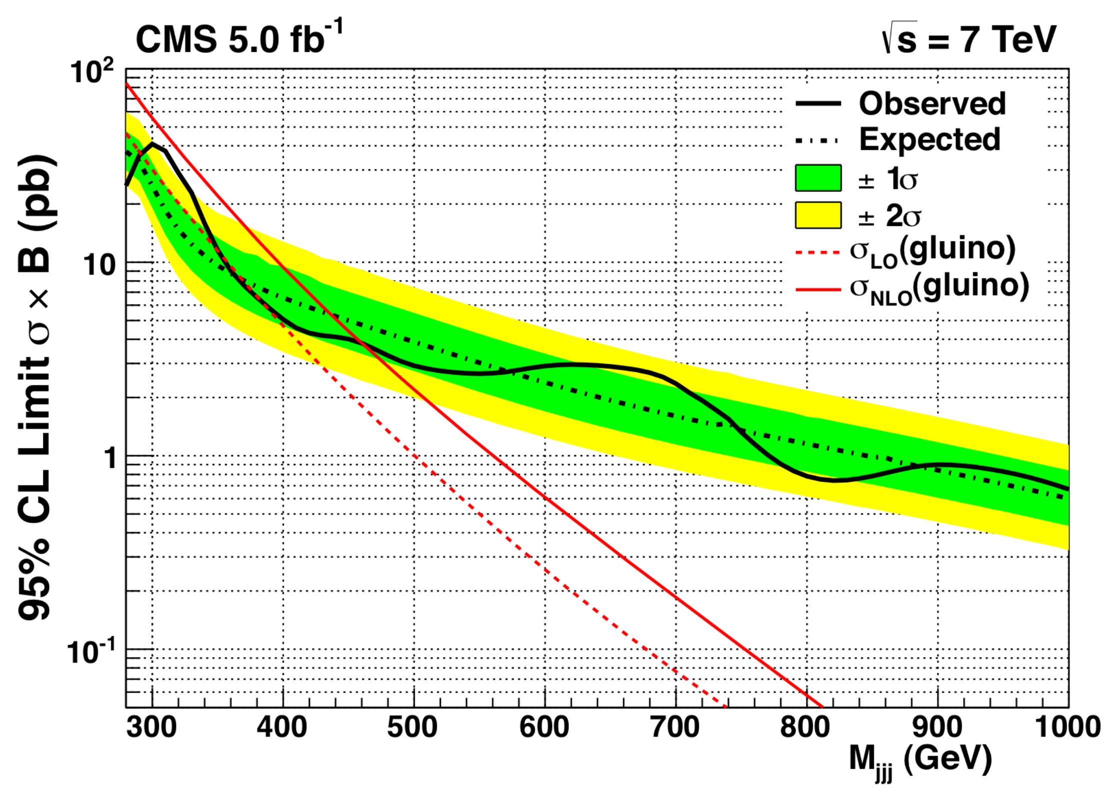


Figure 4: Observed and expected 95% CL upper limits on the cross section times branching fraction for gluino pair production followed by RPV decay of each gluino to three light-flavored quark jets. Also shown are the $\pm1\sigma$ and $\pm2\sigma$ bands on the expected limit, as well as the theoretical LO and NLO cross sections for gluino production, assuming a branching fraction of a

HIGH MULTIPLICITY FINAL STATES

$\tilde{g} \rightarrow$ many jets 1207.5787

- SUBSTRUCTURE BY ACCIDENT, JET MASS OBSERVABLES 1212.1456, 1302.1870

$$W_{RPV} = \lambda''_{ijk}\, u_i^c d_j^c d_k^c$$

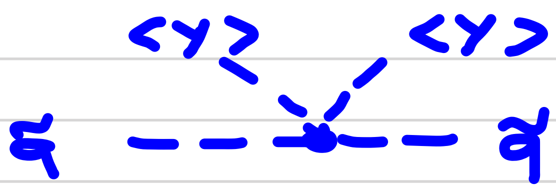
$$\lambda''_{ijk} \sim V_{il}^{ckm} \left(\frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \right)^{\mu} \epsilon_{ljk}$$

$\mu = 1, \frac{1}{2}$

- $m_p \sim m_{f,SM}^{\pm 1}$
- $pp \to k^+ k^+$ $\quad p \to k^+ \nu$ $\quad n - \bar{n}$ $\quad$ OK FOR THE EXPECTED λ''_{ijk}

$\perp$

- $Br(\tilde{t} \to bd + bs) \simeq 99\%$ $\quad$ $SU(3)_{Q,L,d,u,e,\nu}$, $SU(3)_{Q,Q^c,L,L^c}$, PARTIAL COMPOSITENESS $\Big\}\ \mu = 1$
- $Br(\tilde{t} \to bd + bs) \simeq 14\%$ $\quad$ $SU(3)_{V,q,e}$ $\quad \mu = \frac{1}{2}$
- LHC CAN TELL $\quad pp \to \tilde{t}\tilde{t} \to b\bar{b}q\bar{q}$
- SUSY BREAKING FOR A COMPLETE ANALYSIS OF FV
- SPARTICLE SPECTRUM



$\sim \delta_{flavor}$

- FLAVOR-AWARE SUSY BREAKING MEDIATION