LHCphenOnet

LIGHT RPV STOPS HIDING IN LHC DATA

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(former fellow of LHCPhenoNet)

05 December 2013

based on R. Franceschini and RT, 1212.3622 [hep-ph]

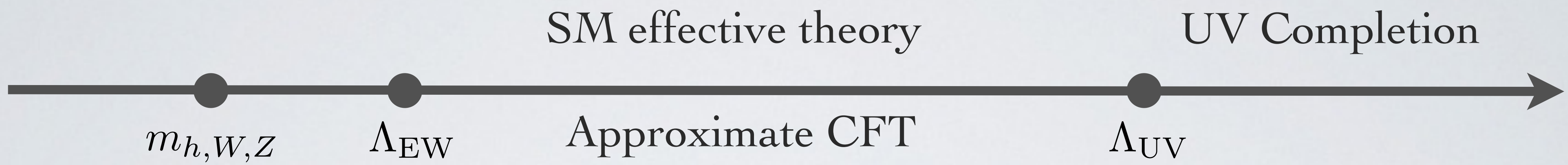
OUTLINE

- Introduction & Natural SUSY
- R-parity and its breaking
- Pair production of stops: signal vs background
- Conclusions

Left out

- Model building for R-parity violation

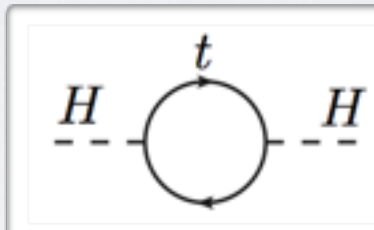
NATURALNESS IN THE SM



1. All deformations of the CFT are either irrelevant, marginal or very close to marginal (e.g. QCD)
2. The relevant deformations can be forbidden by symmetries (e.g. fermion masses forbidden by chiral symmetry)
3. The relevant deformations are tuned to be small

$$\Delta\mathcal{L}_{\mathrm{SM}}^{\mathrm{rel}} = c\Lambda_{\mathrm{UV}}^2 H^\dagger H$$

$$m_h^2 = c\Lambda_{\mathrm{UV}}^2 + \delta m_h^2$$



$$\delta m_h^2 = -\frac{y_t^2}{16\pi^2}\Lambda_{\mathrm{UV}}^2$$

- The sensitivity of the Higgs mass on physics at the scale Λ_{UV} is given by

$$\Delta \gtrsim \left(\frac{125\ \mathrm{GeV}}{m_h}\right)^2 \left(\frac{\Lambda_{\mathrm{UV}}}{400\ \mathrm{GeV}}\right)^2$$

- If we believe in some "naturalness"

$$\Delta \lesssim 100 \quad \Longrightarrow \quad \Lambda_{\mathrm{UV}} \lesssim 4\ \mathrm{TeV}$$

- This is the ONLY argument to expect new physics related to EWSB at the TeV scale!

NATURALNESS IN THE SM

SM effective theory — UV Completion

$m_{h,W,Z}$ — $\Lambda_{\rm EW}$ — Approximate CFT — $\Lambda_{\rm UV}$

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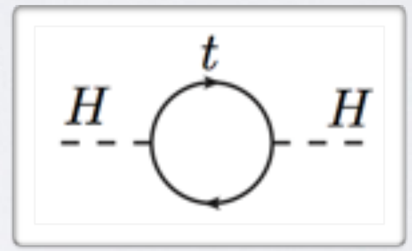

$$\delta m_h^2 = -\frac{y_t^2}{16\pi^2}\Lambda_{\rm UV}^2$$

- The sensitivity of the Higgs mass on physics at the scale $\Lambda_{\rm UV}$ is given by

Natural CH ⇓ Light top partners ←

$$\Delta \gtrsim \left(\frac{125\ \text{GeV}}{m_h}\right)^2 \left(\frac{\Lambda_{\rm UV}}{400\ \text{GeV}}\right)^2$$

→ Natural SUSY ⇓ Light stops

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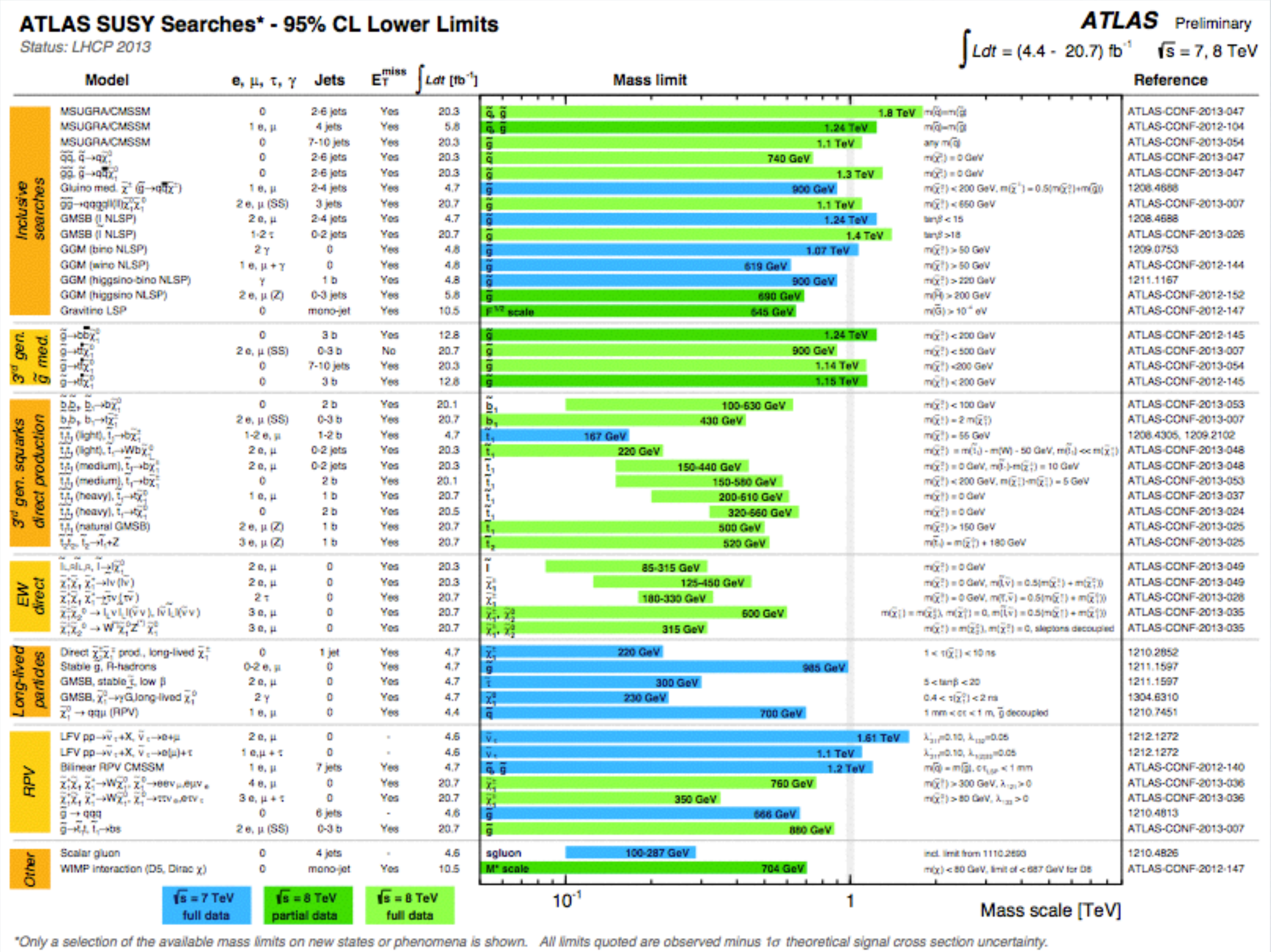
THE HEALTH OF SUSY



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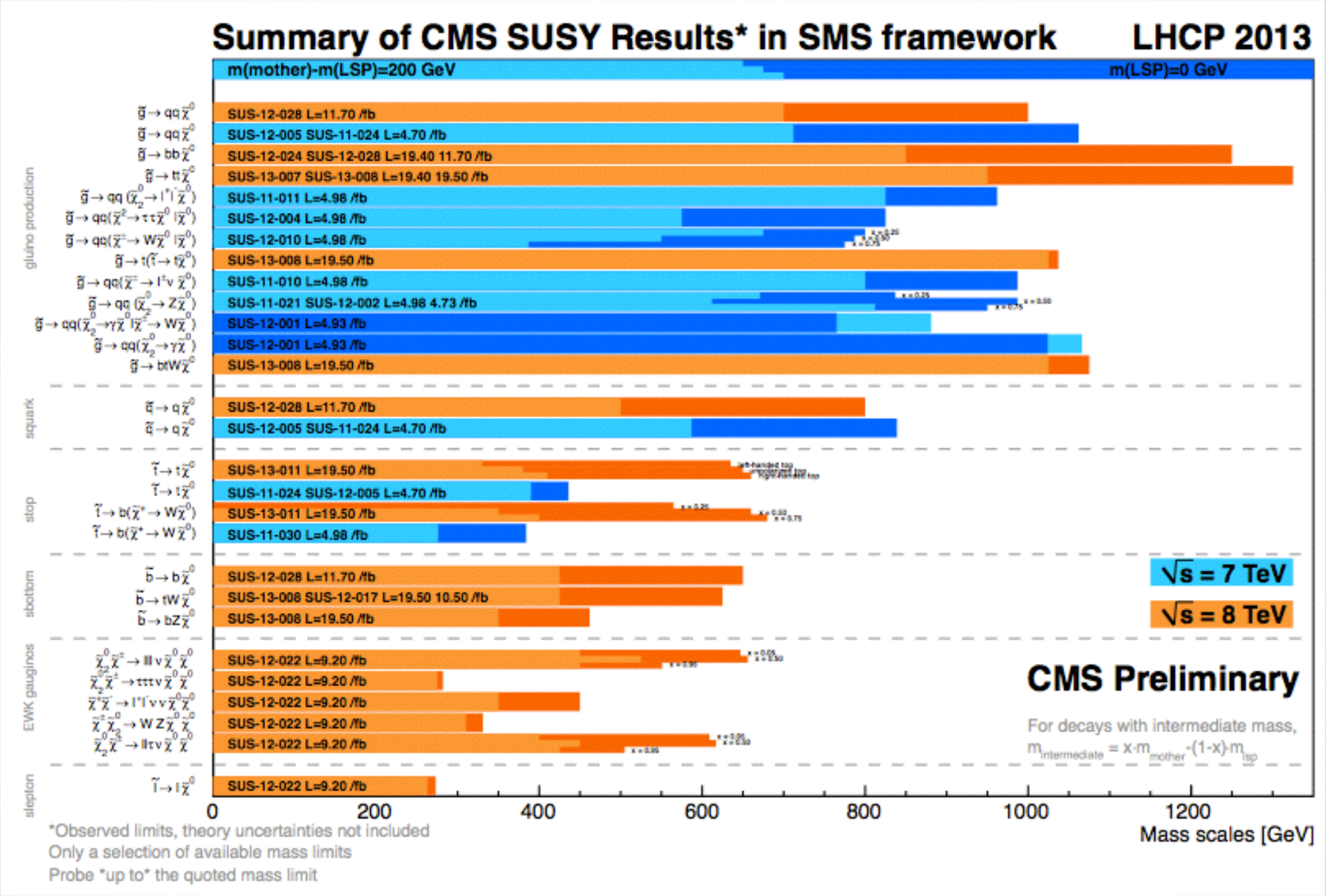
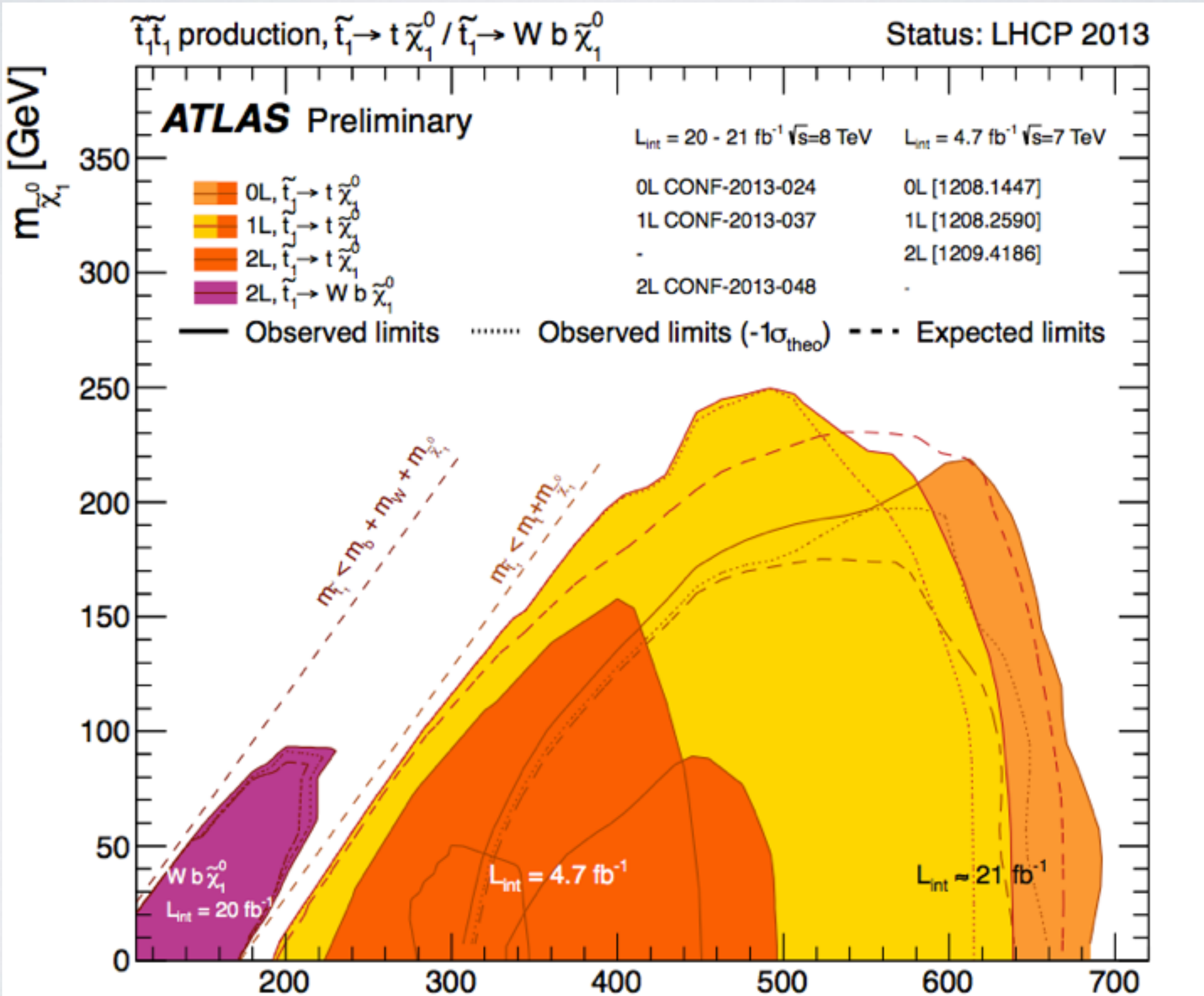


STOP SEARCHES

- The LHC7/8 has put very strong bounds on third generation squarks



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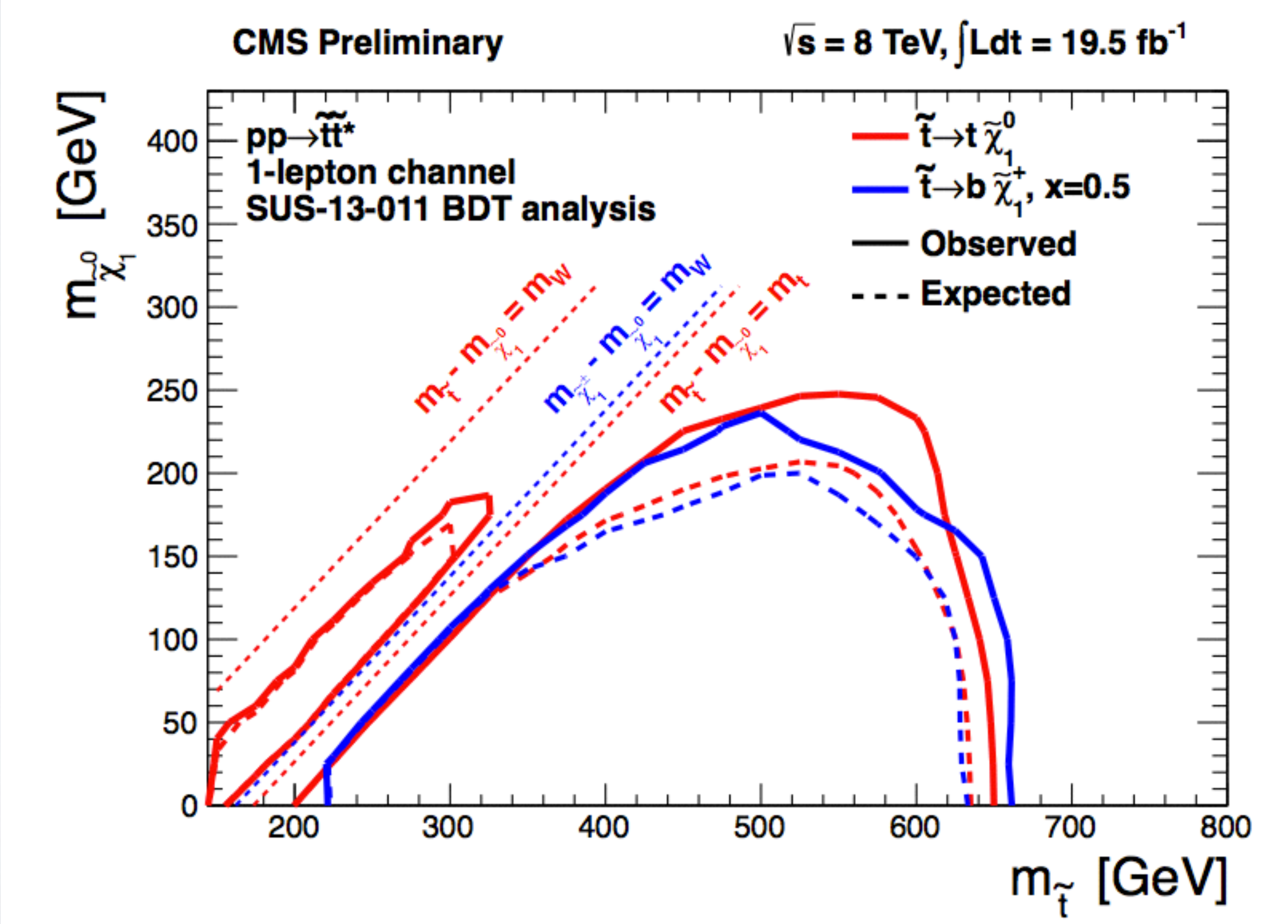
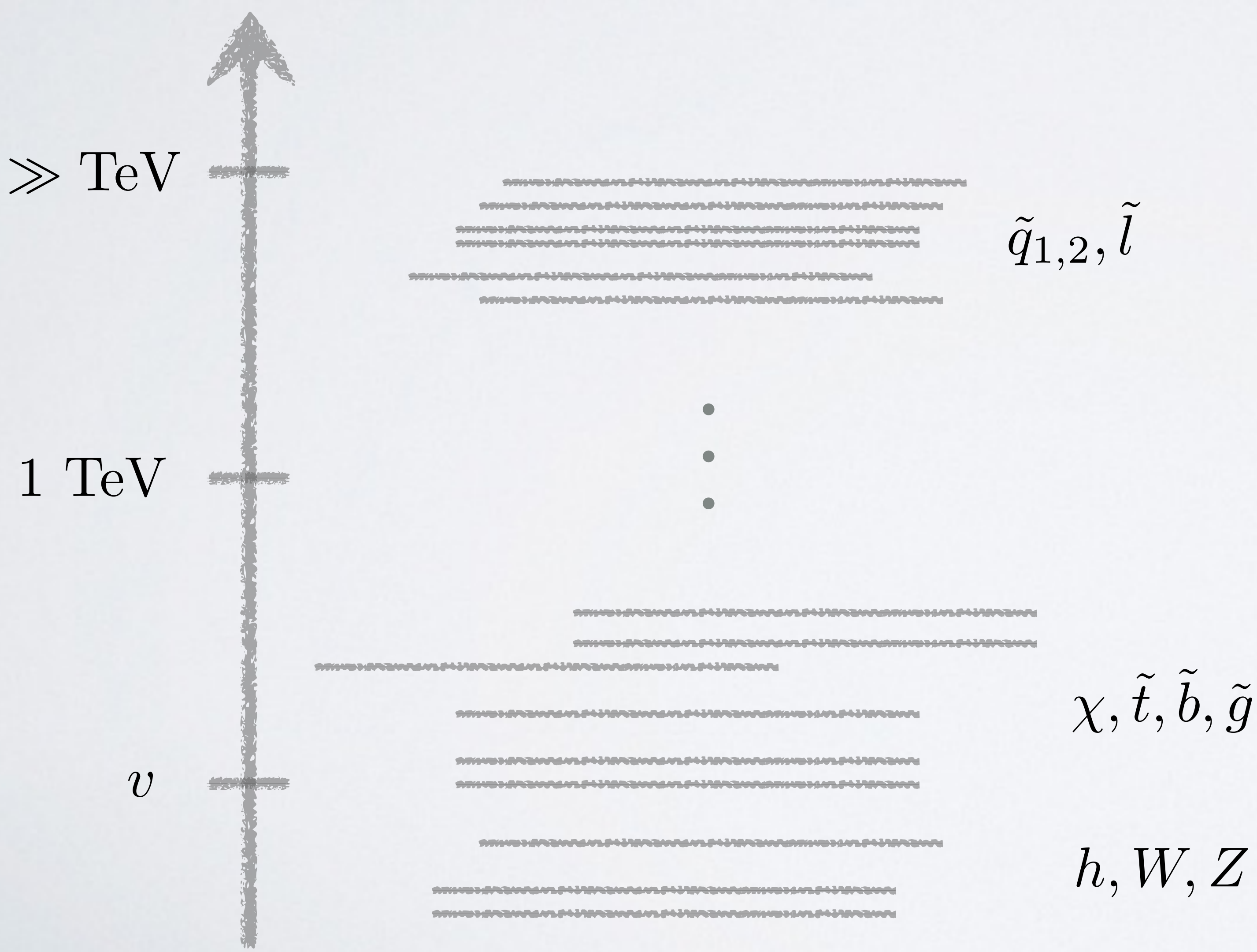


MSSM --> NATURAL SUSY

- We still want to insist on naturalness and on supersymmetry
- We are interested in an effective SUSY model describing only the physics relevant for the LHC
- These ingredients require only a part of the SUSY spectrum to be at the TeV scale and possible new physics to become relevant at some scale $\Lambda_{\rm UV}$ possibly not far above the TeV scale



Typical signatures:

- Heavy flavored final states
- Less missing energy
- Large multiplicities

Alternatives

- Stealth SUSY
- RPV
- ....

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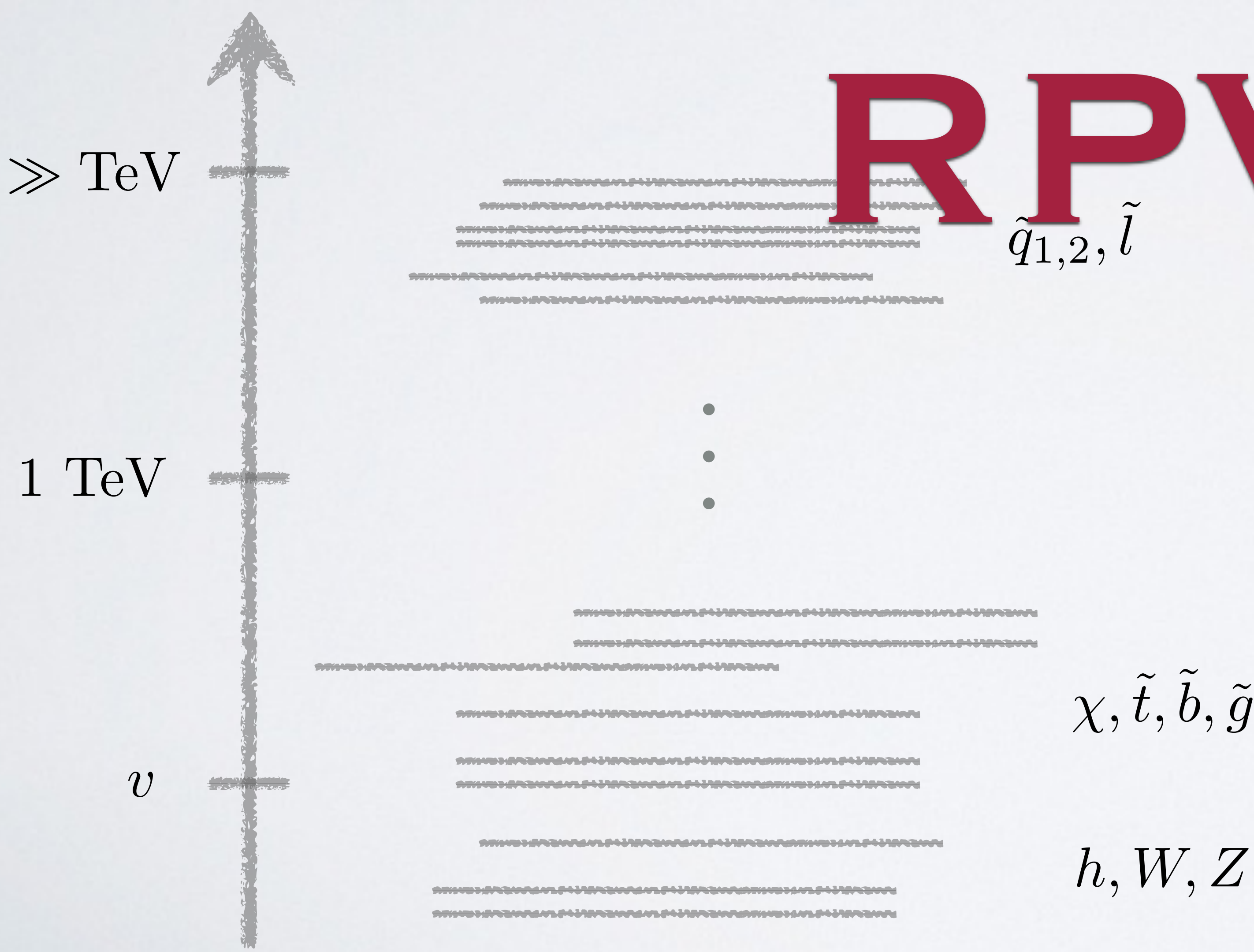

RPV

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Alternatives

- Stealth SUSY
- RPV
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WHY RPV?... WHY NOT?

- In the SM B and L conservation is accidental while in the MSSM gauge invariant, local operators that violate B and L can be written at the renormalizable level

$$W_{\not{B}} = \frac{1}{2}\lambda''_{ijk}U_i^c D_j^c D_k^c$$
$$W_{\not{L}} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk}L_i L_j E_k^c + \frac{1}{2}\lambda'_{ijk}L_i Q_j D_k^c$$

Dreiner hep-ph/9707435
Barbier et al. hep-ph/0406039

- There is a total of 9+27+9 new Yukawas ($\lambda, \lambda', \lambda''$) and 3 new mass parameters (μ_i)
- The mixings μ_i can be diagonalized away with a suitable field redefinition and is unphysical if no soft terms are present
- When SUSY is broken however, the mixing will reappear in the dim=2 ~~SUSY~~ soft terms generating RPV mass terms
- To forbid these operators a symmetry called R-parity is required, where

$$R_P = (-1)^{2S+3(B-L)}$$

- SM particles have even R-parity while superpartners, i.e. squarks, sleptons, higgsinos and gauginos have odd R-parity

WHY RPV?... WHY NOT?

- Giving up with R-parity generates a lot of problems

1. B and L violation
2. Proton decay ($\lambda'' \cdot \lambda' < 10^{-24}$)
3. Experimental constraints (charged current universality, masses of ν_e ,$0\nu 2\beta$ decay, atomic parity violation, $\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$, $D^0 - \bar{D}^0$ mixing, $n - \bar{n}$ oscillation, di-nucleon decay, $\Gamma(\pi \to e\bar{\nu})/\Gamma(\pi \to \mu\bar{\nu})$, $\mathrm{BR}(D^+ \to \bar{K}^{0*}\mu^+\nu_\mu)/\mathrm{BR}(D^+ \to \bar{K}^{0*}e^+\nu_e)$, $\mathrm{BR}(\tau \to \pi\nu_\tau)$, ν_μ DIS)

- However R-parity is not enough to forbid B and L violating HDO and in effective SUSY models one could expect the scale that suppresses these operators to be lower than the GUT scale

$$W_{\mathrm{HDO}} \supset \frac{k}{\Lambda_{p\text{-decay}}} UUDE$$

- In this case proton decay becomes an issue even with R-parity for $\Lambda_{p\text{-decay}} < M_{\mathrm{GUT}}$
- In the framework of Natural SUSY RPV is less constrained than RPC
- RPV provides very peculiar phenomenology (due to the absence of MET)
- However, some model building to predict the couplings and the flavor structure is necessary (e.g. MFV, gauged flavor symmetry, partial compositeness, etc.) *Berenzhiani 1985, Grinstein, Redi, Villadoro 1009.2049, Krnjaic, Stolarski 1212.4860, Csaki, Grossman, Heidenreich 1111.1239, Karen-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi 1205.5803, Franceschini, Mohapatra 1301.3637, Csaki, Heidenreich 1302.0004*

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- Considering only B breaking but not L breaking the main bounds are the following

$\lvert\lambda''_{uds}\rvert < O(10^{-5})$	$NN \to K^+K^+$	$\lvert\lambda''_{cdb}\lambda''_{csb}\rvert < O(10^{-3})$	$K - \bar{K}$ oscillation
$\lvert\lambda''_{udb}\rvert < O(10^{-2})$	$n - \bar{n}$ oscillation	$\lvert\lambda''_{tdb}\lambda''_{tsb}\rvert < O(10^{-3})$	$K - \bar{K}$ oscillation
$\lvert\lambda''_{tds}\rvert < O(10^{-1})$	$n - \bar{n}$ oscillation	$\lvert\lambda''_{ids}\lambda''_{idb}\rvert < O(10^{-1})$	$B^+ \to K^0\pi^+$
$\lvert\lambda''_{tdb}\rvert < O(10^{-1})$	$n - \bar{n}$ oscillation	$\lvert\lambda''_{ids}\lambda''_{isb}\rvert < O(10^{-3})$	$B^- \to \phi\pi^-$

$\lambda'' < 3 \times 10^{-7}$ for $m_{\tilde{f}} \sim 1$ TeV cosmological bound

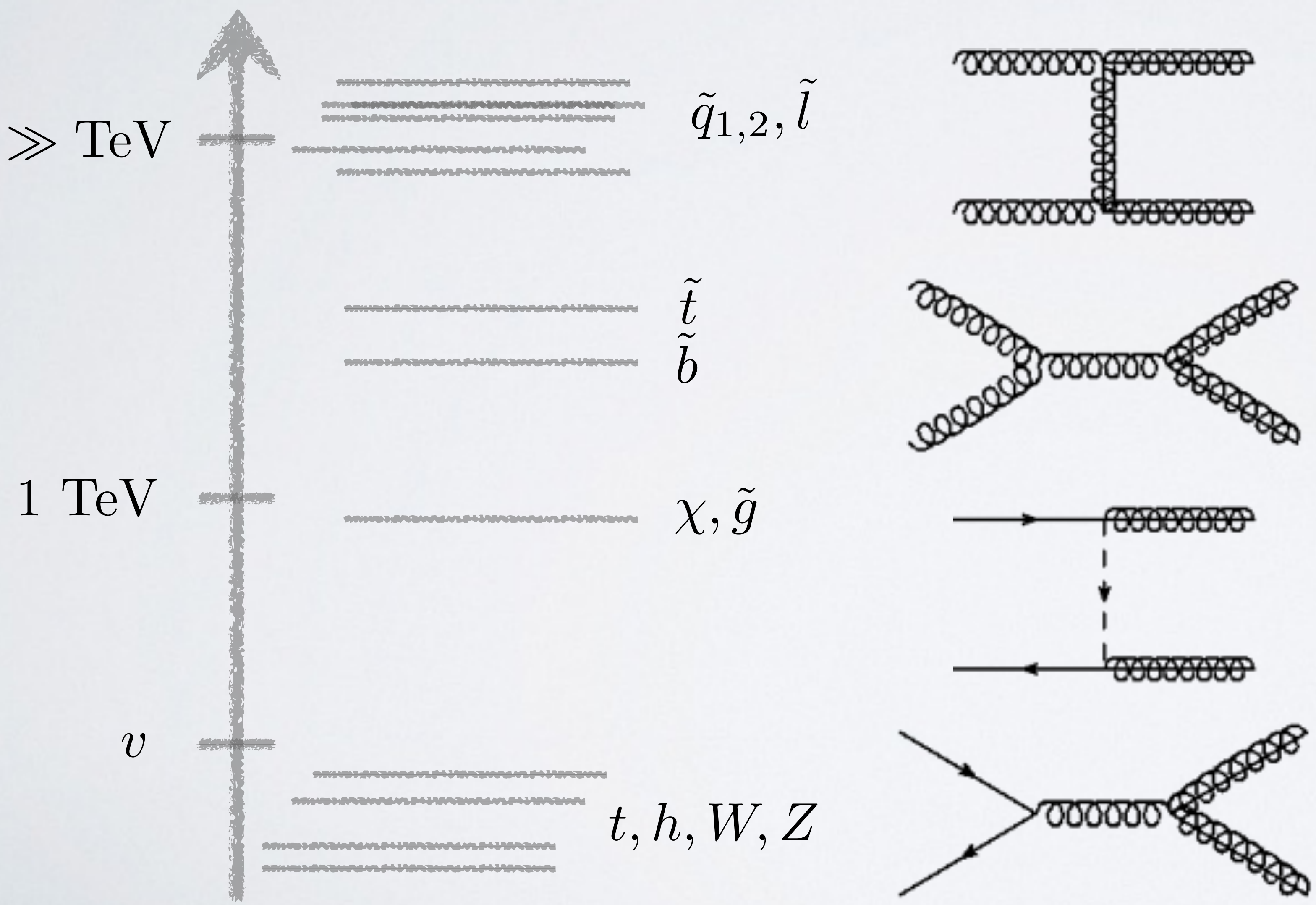
Barbier et al. hep-ph/0406039
Di Luzio, Nardecchia, Romanino 1305.7034

- Unification has been usually considered an issue but recently a natural solution has been presented in the context of SO(10) with an adjoint vev along T_{3R} or $B - L$ ***(Di Luzio, Nardecchia, Romanino 1305.7034)***

- The absence of a stable LSP also implies the lack of a WIMP DM candidate but solutions are possible (axions)

SIGNATURES

- Collider signatures of RPV strongly depend on the spectrum (light states and LSP)
- Leptonic RPV more constrained due to many leptons in final states
- Hadronic RPV gives more "jetty" final states and therefore is less constrained
- We focus on hadronic RPV (L conservation can still protect proton decay)
- QCD pair production of colored superpartners ($\tilde{g}\tilde{g}$, $\bar{\tilde{b}}\tilde{b}$, $\bar{\tilde{t}}\tilde{t}$) main prod. mechanism



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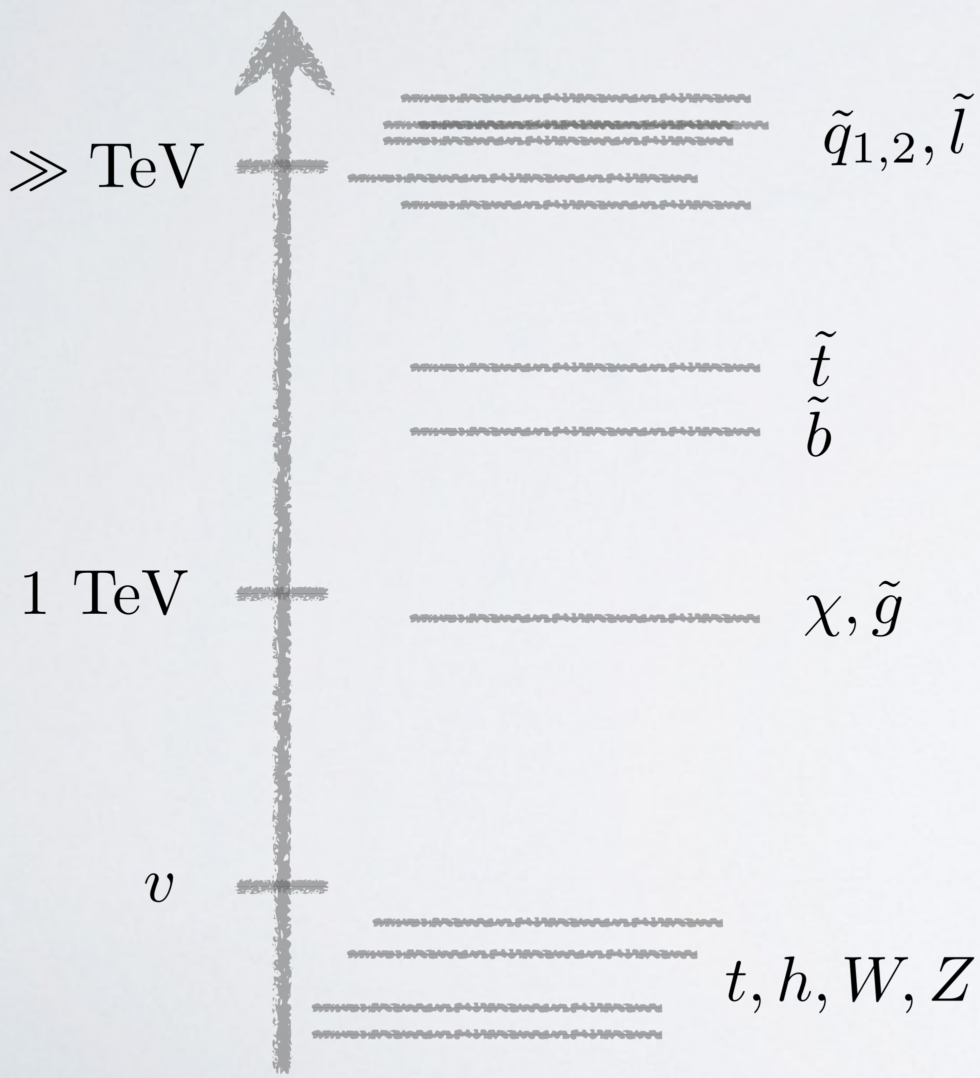

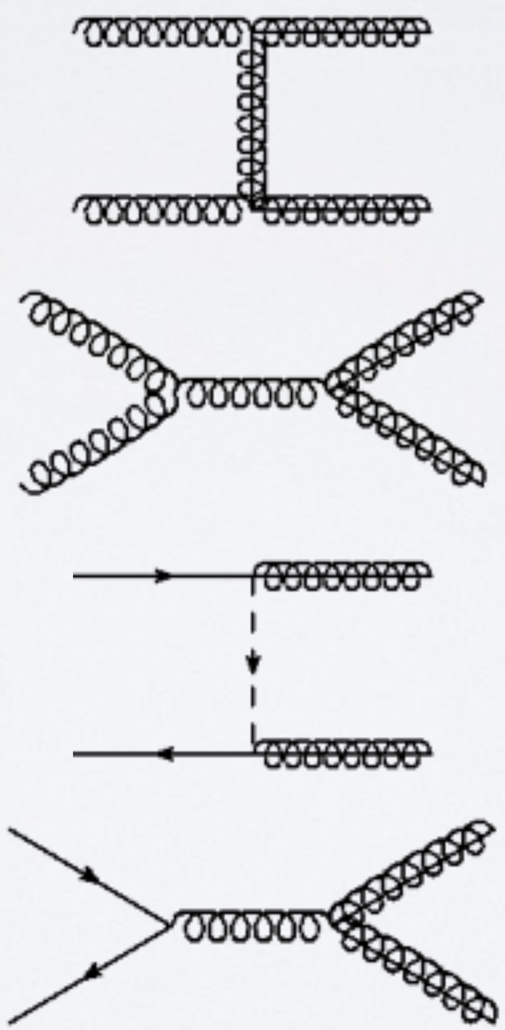

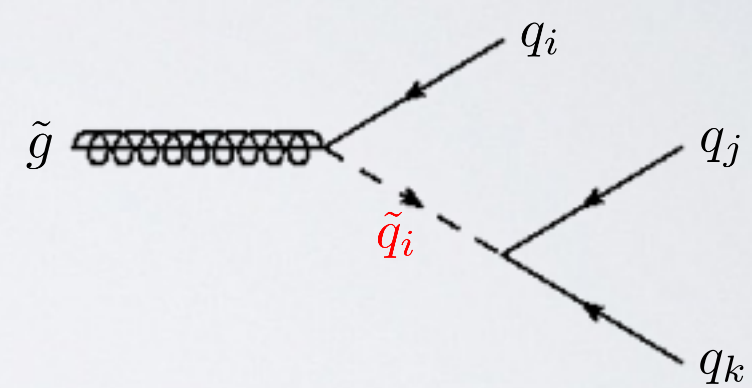

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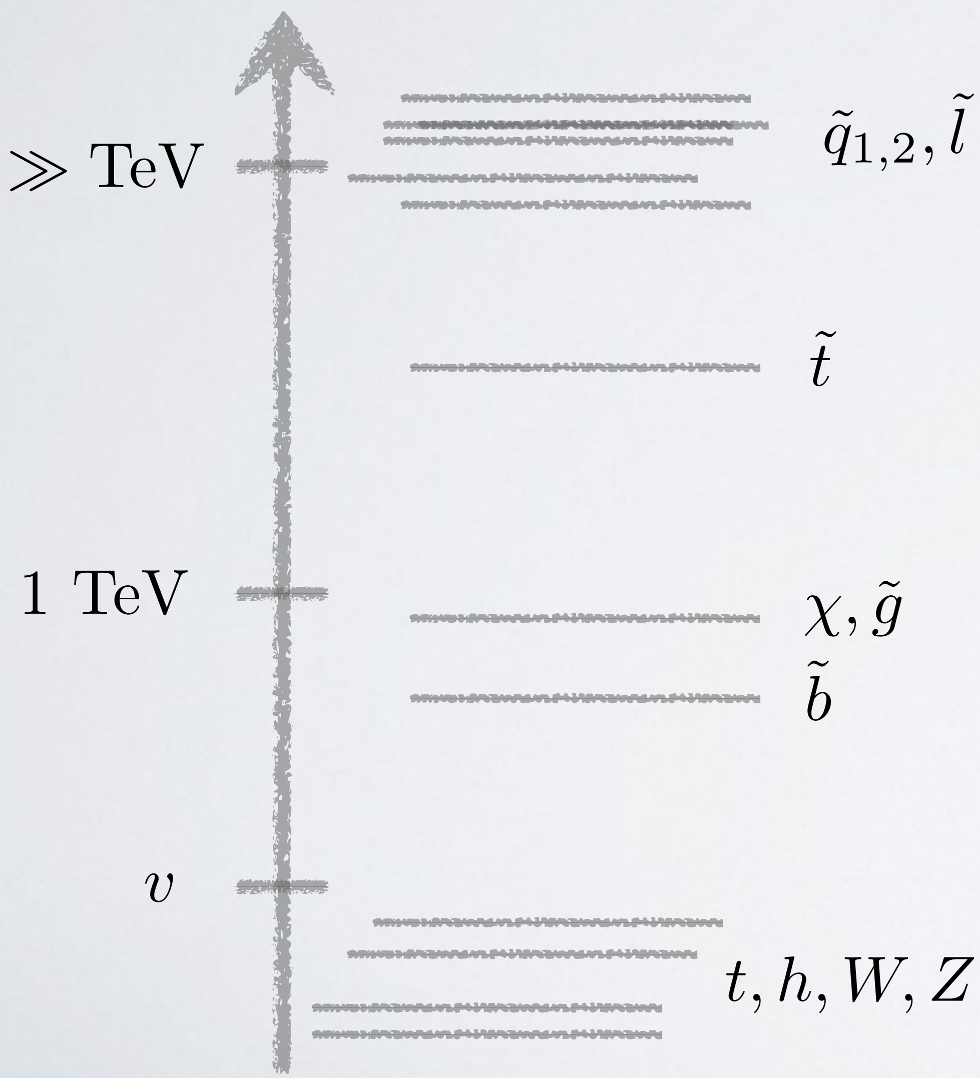

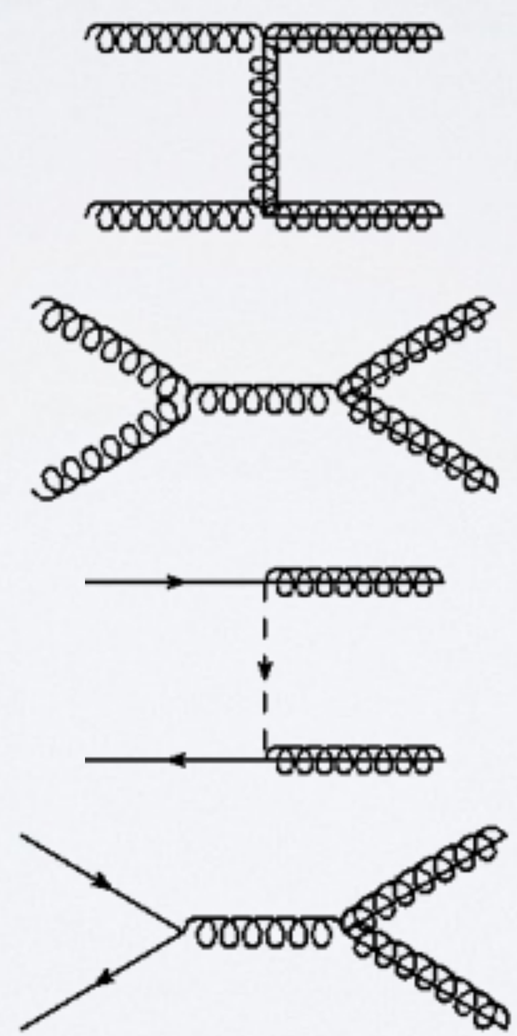

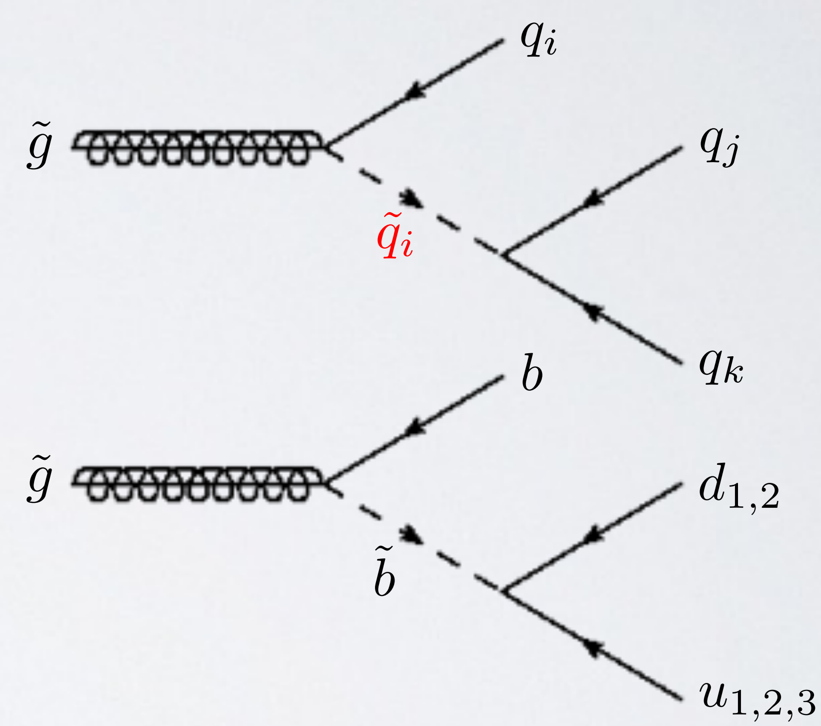

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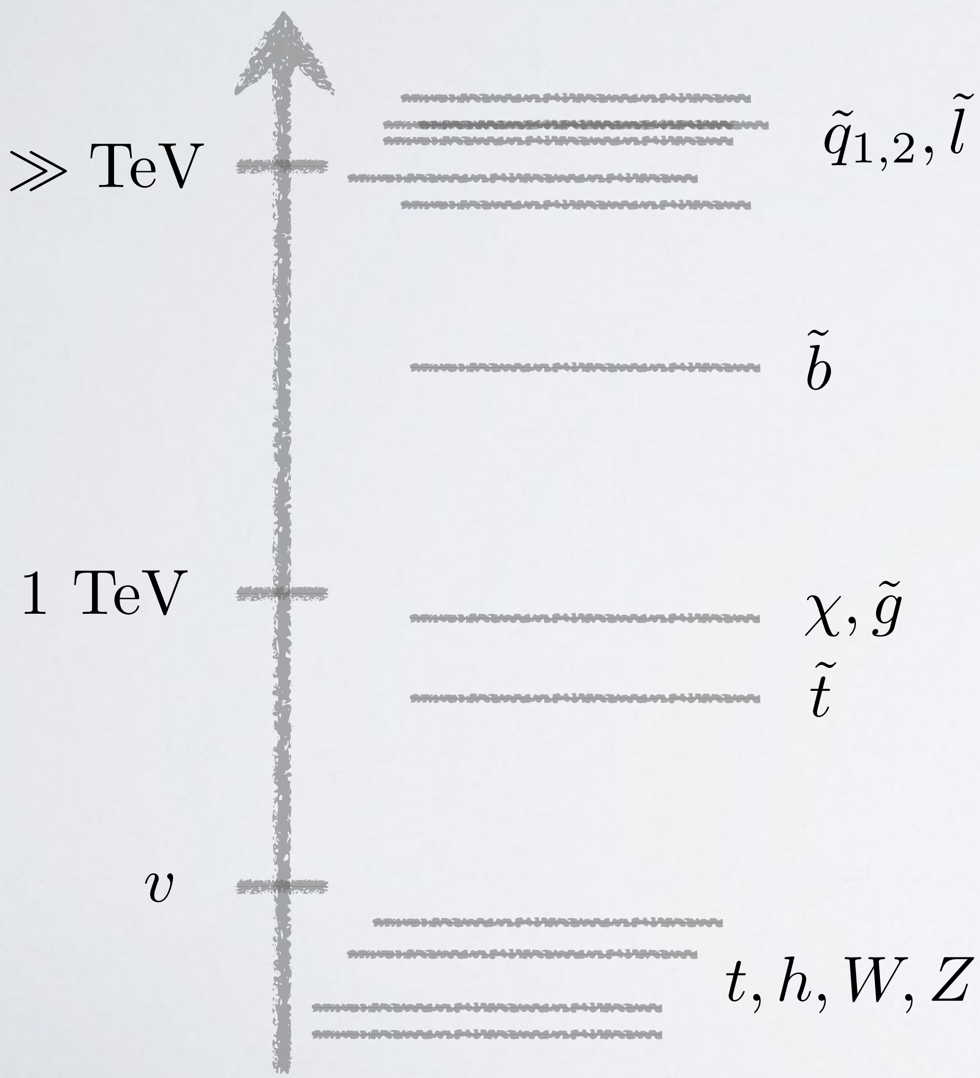

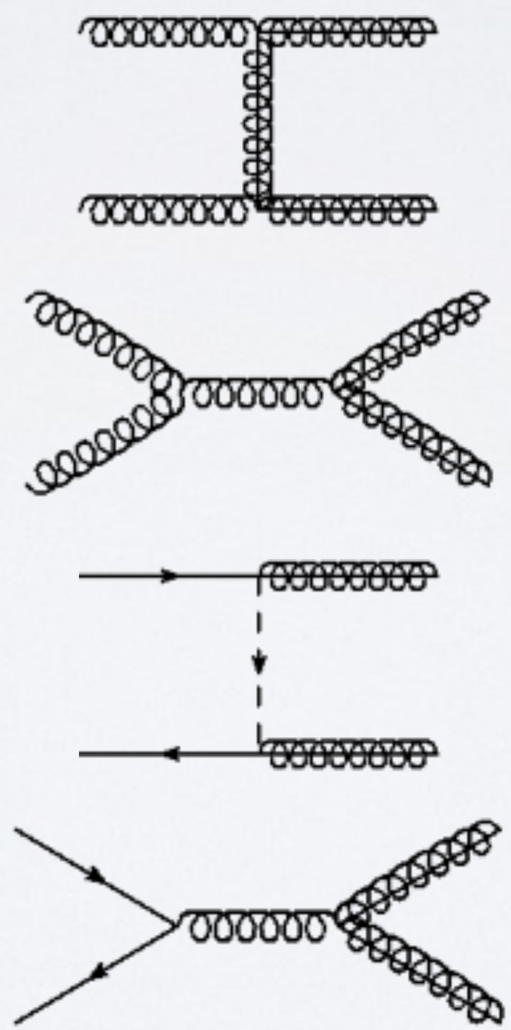

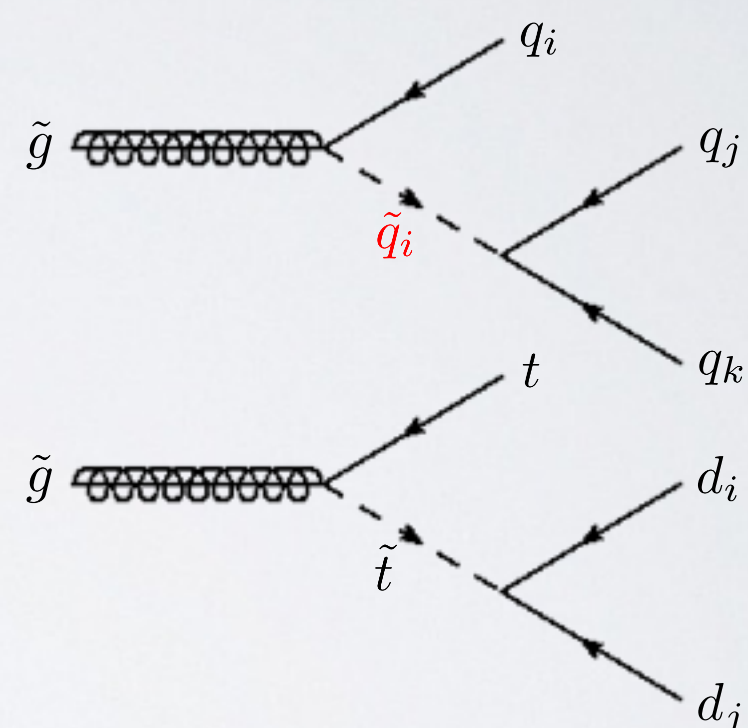

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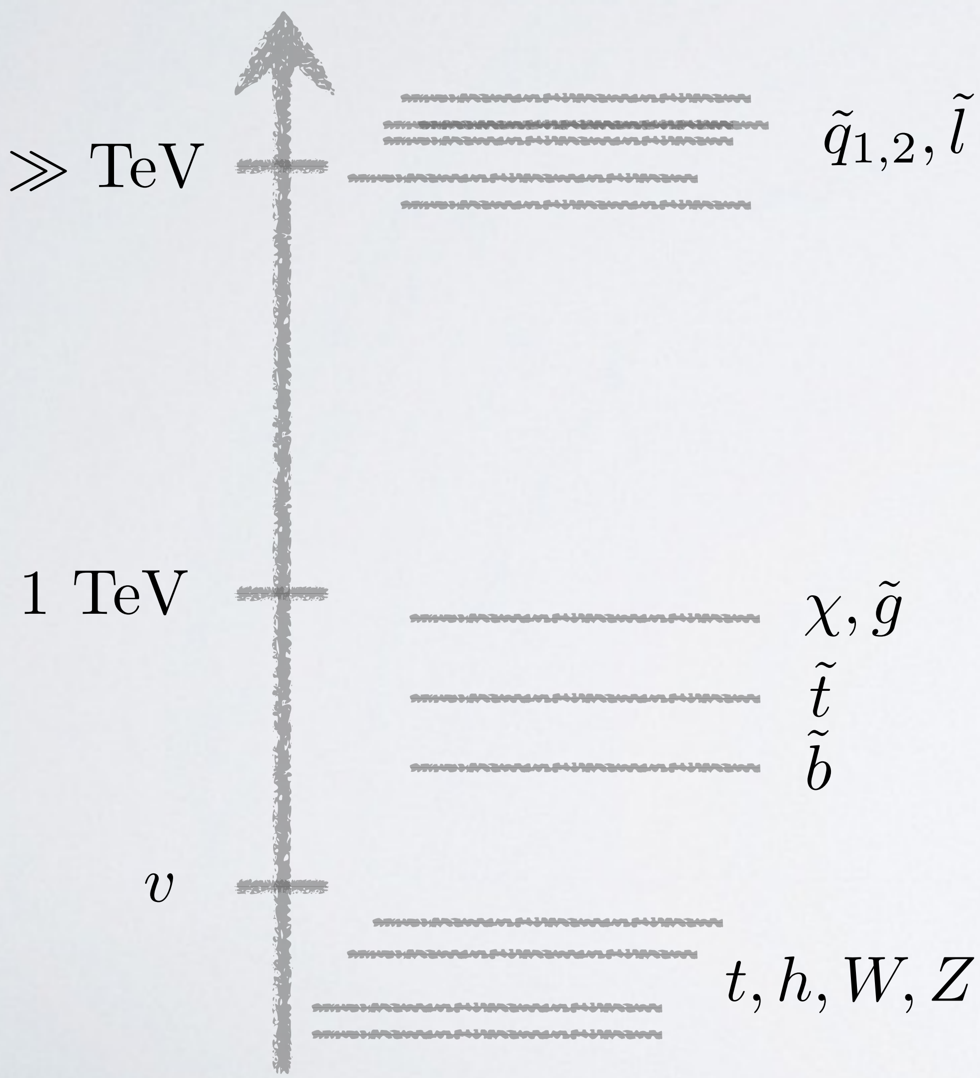

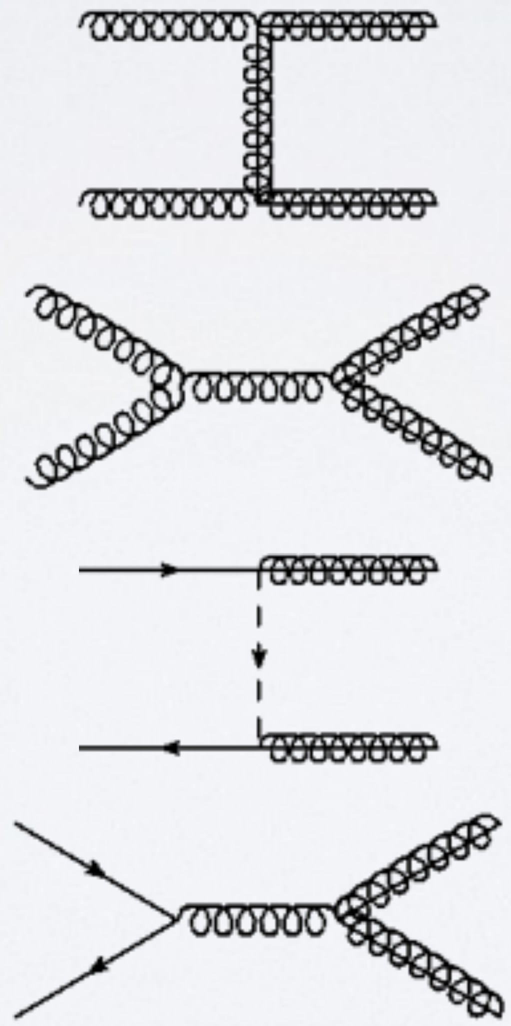

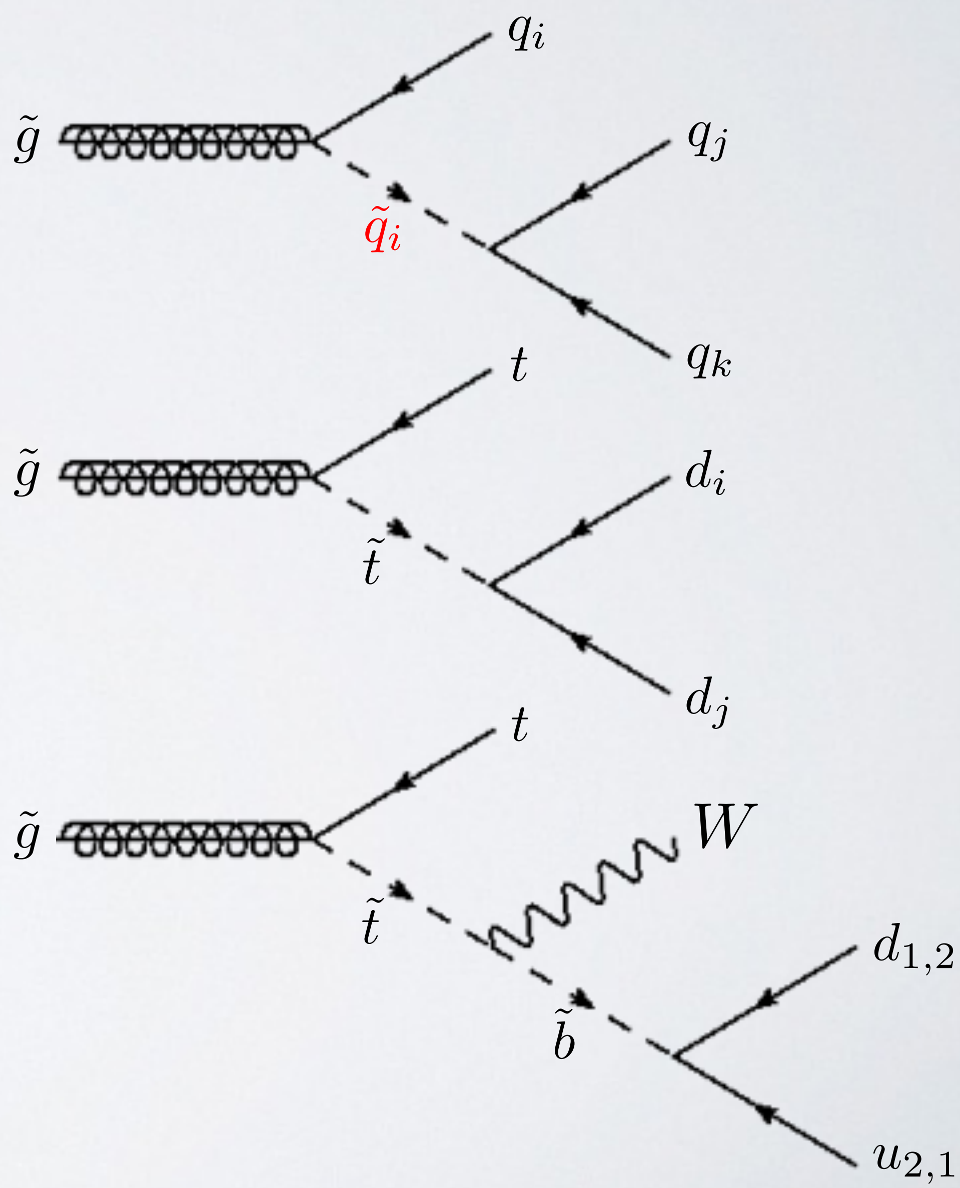

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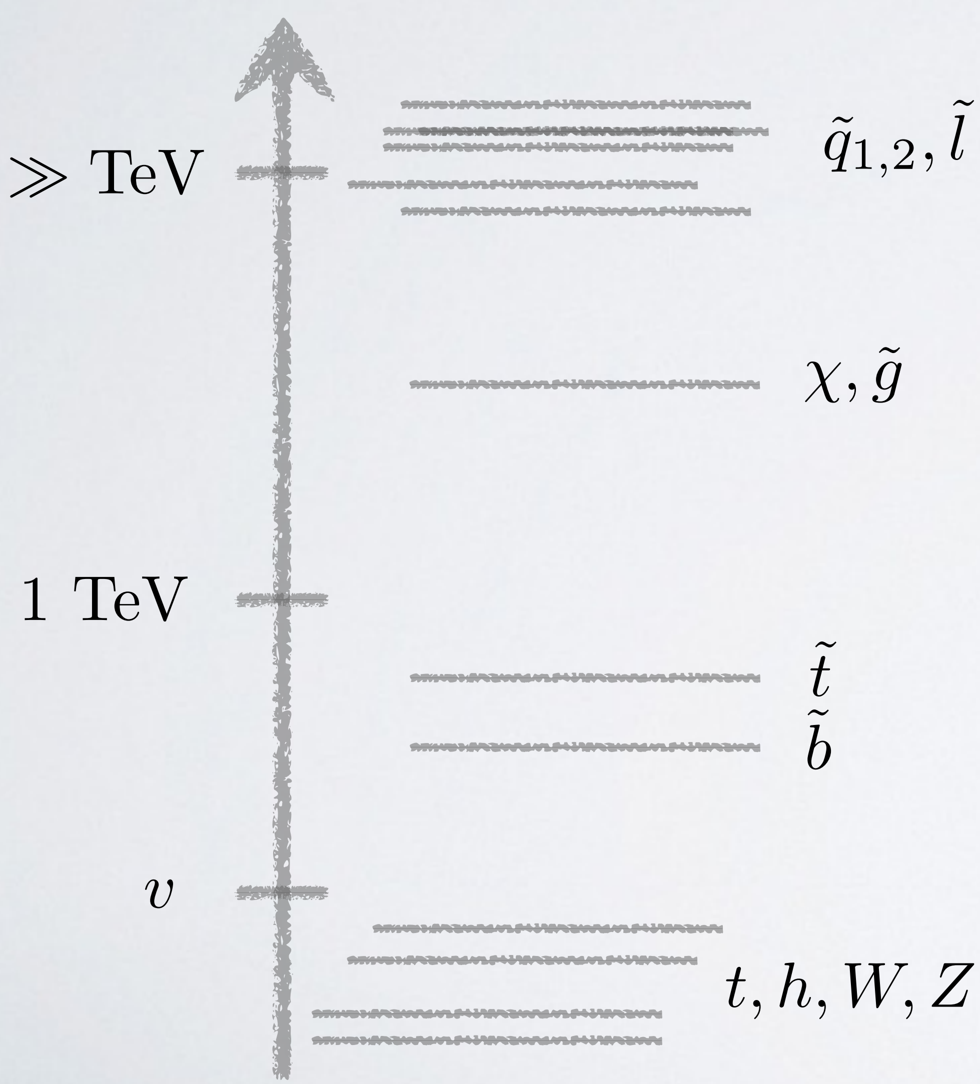

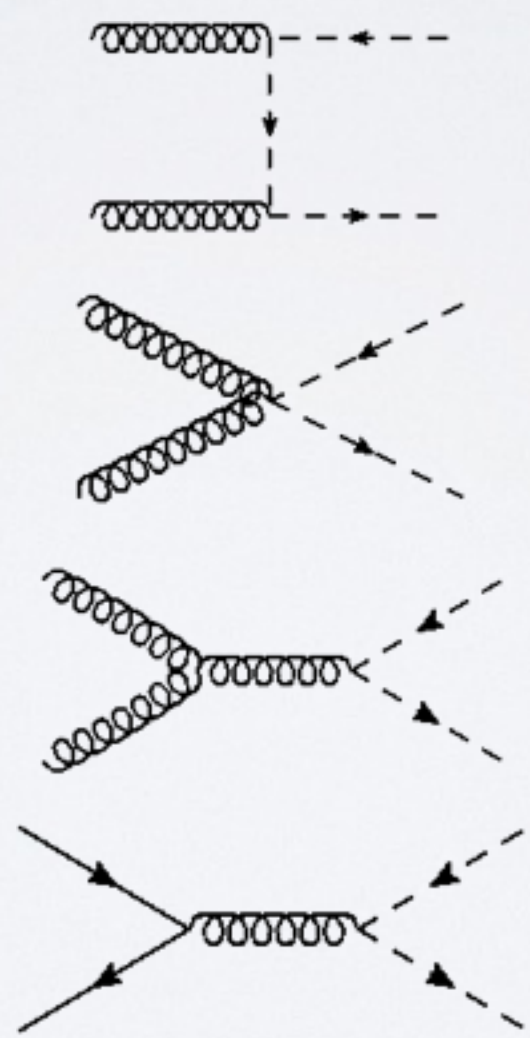

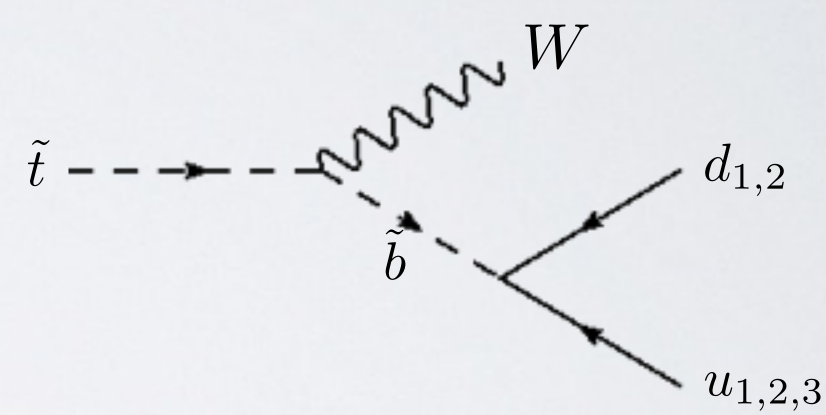

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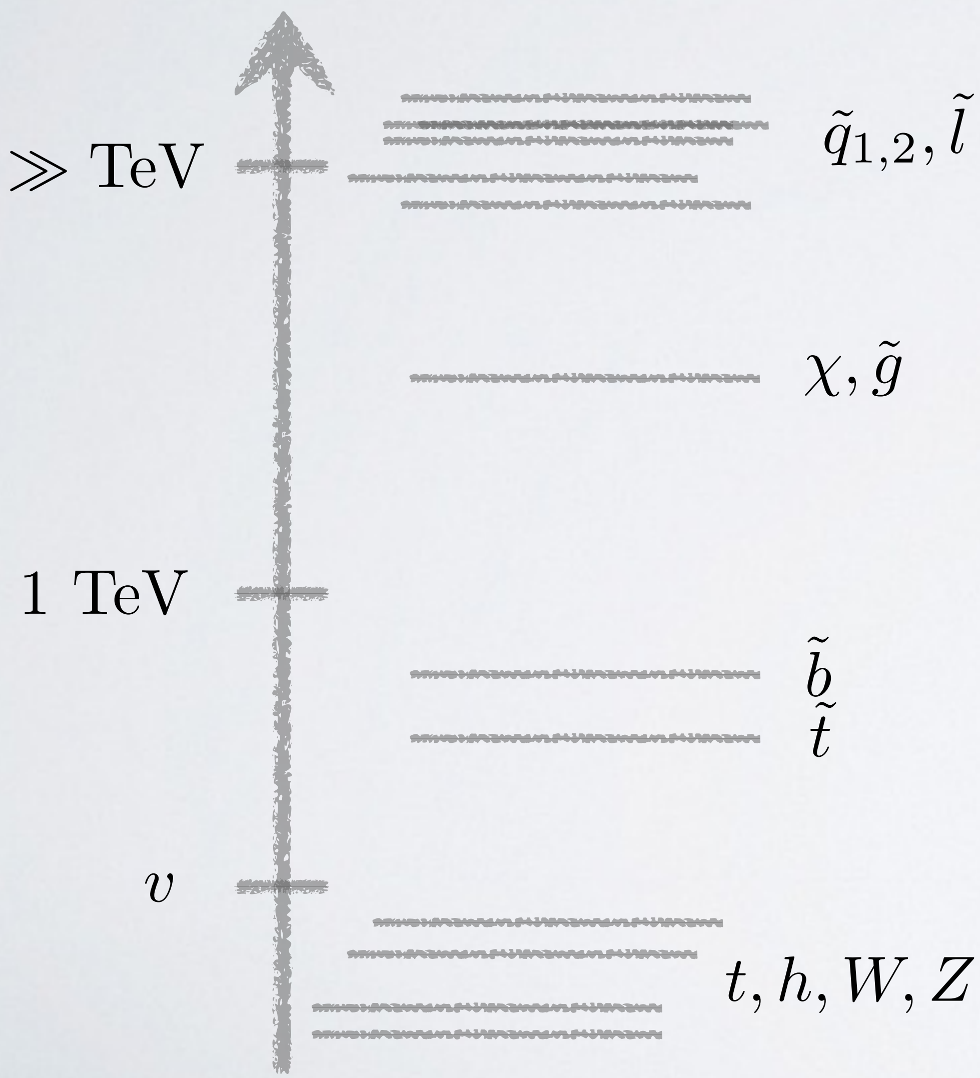

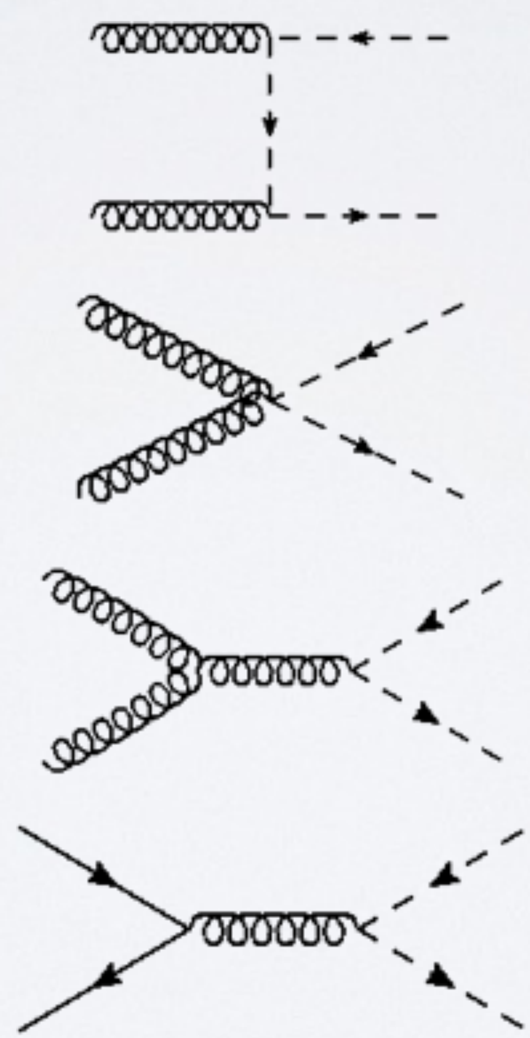

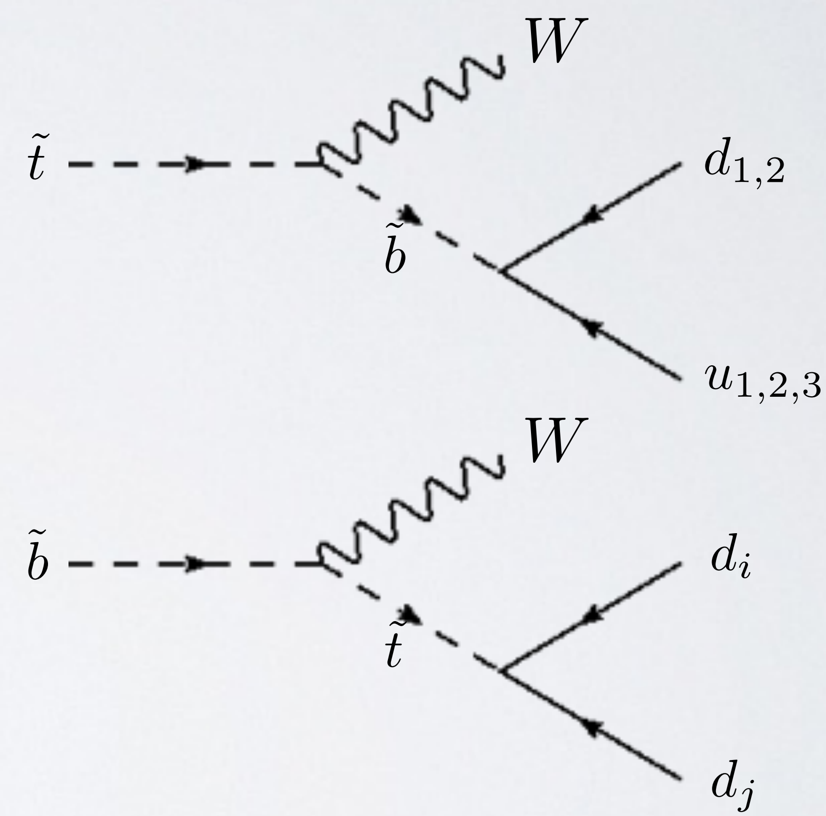

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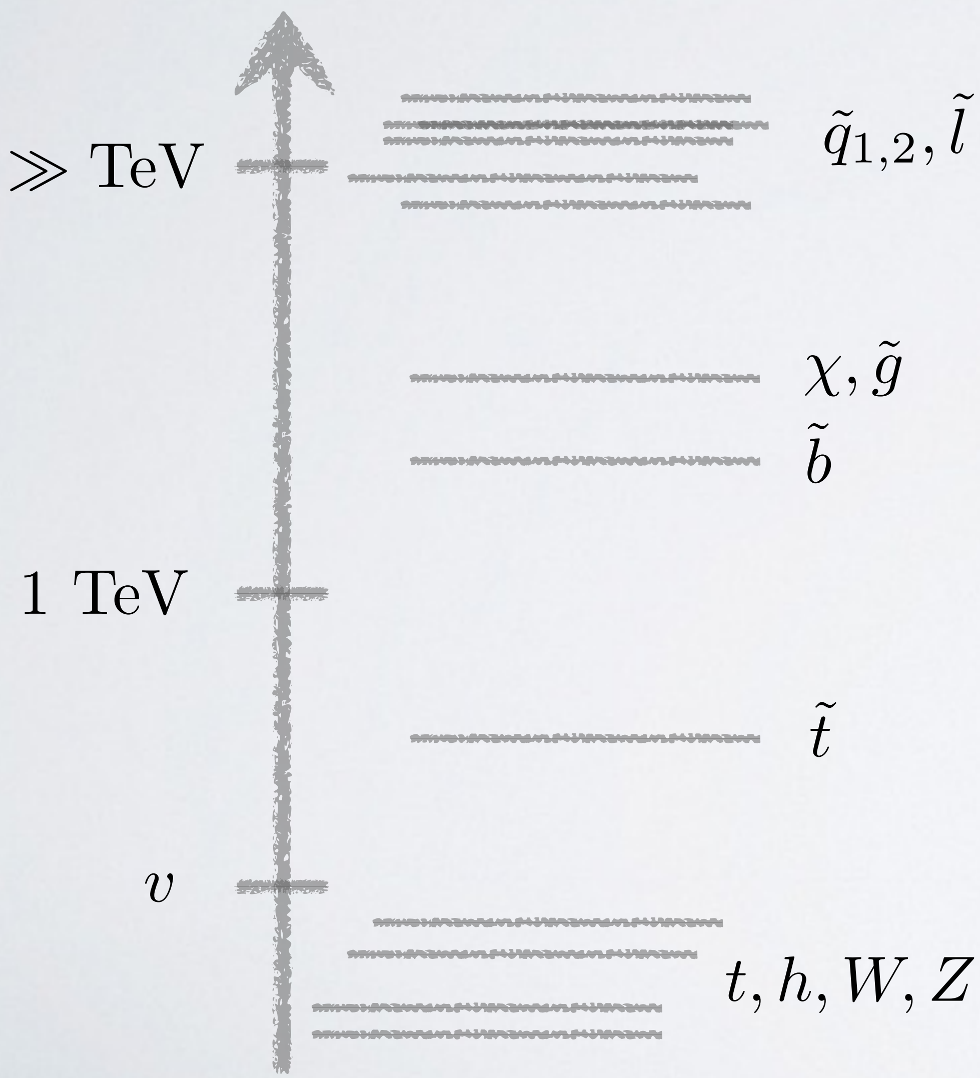

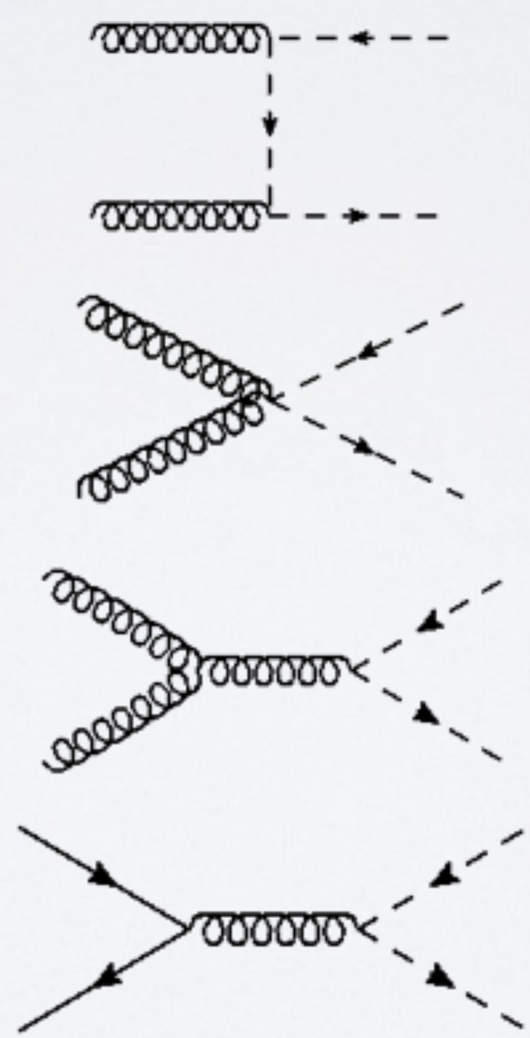

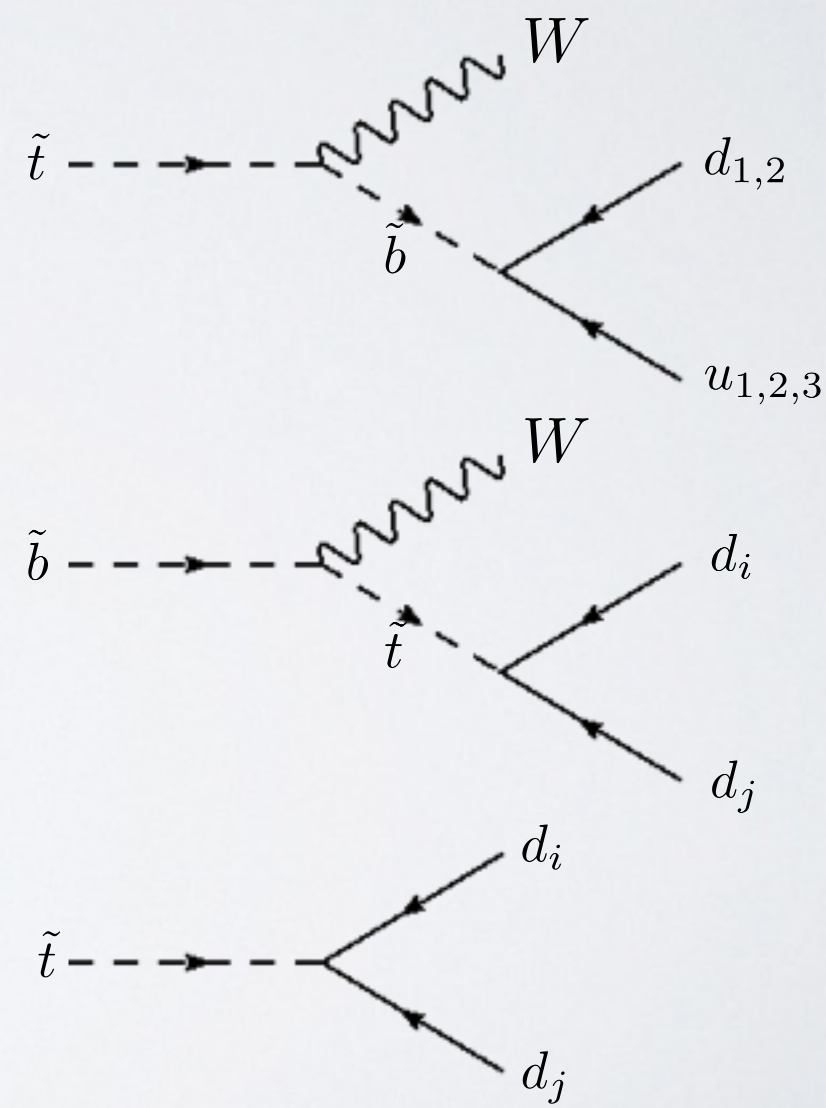

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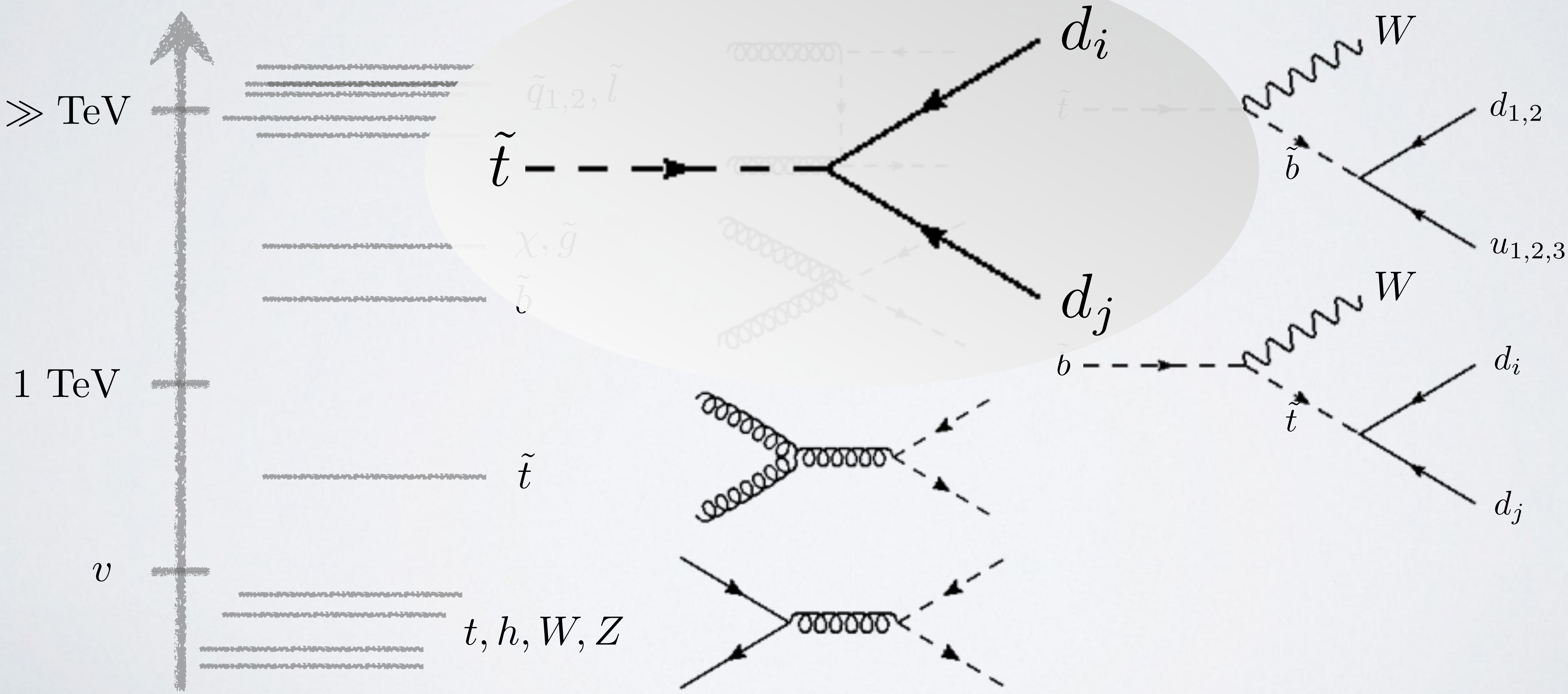
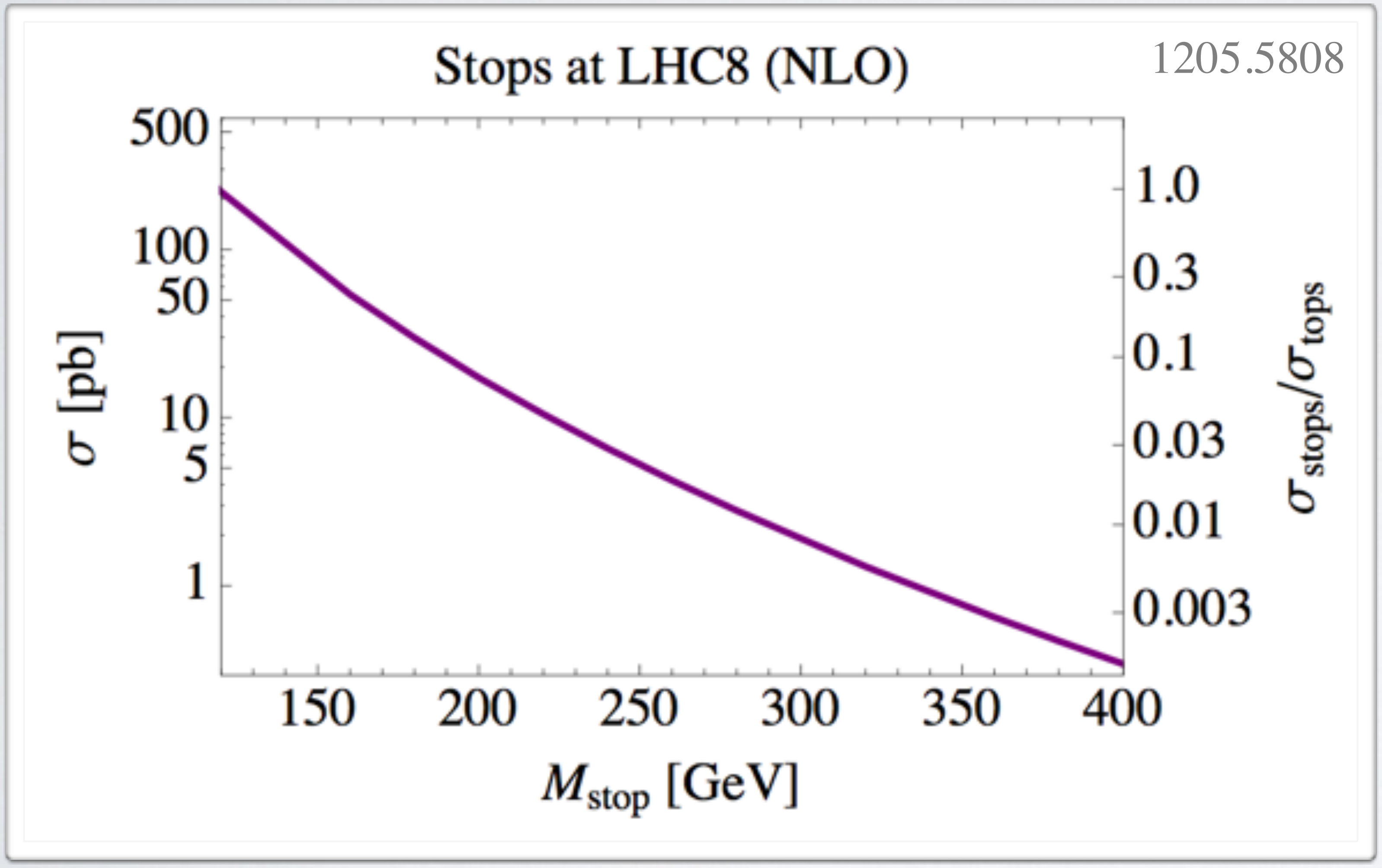
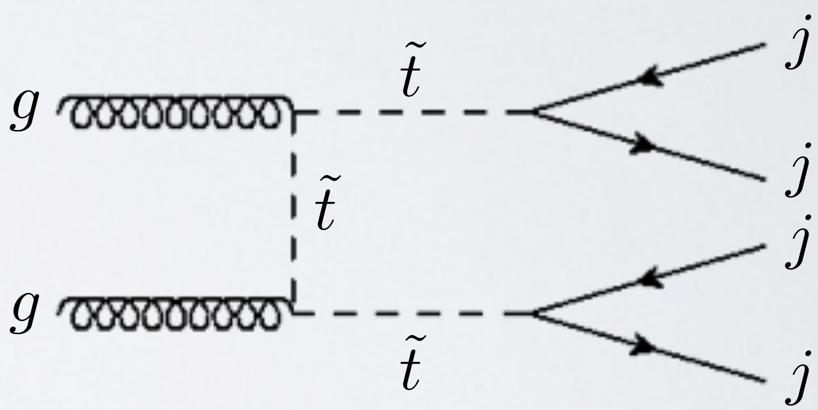


STOP PAIR PRODUCTION

- We have seen that RPV couplings are bounded to be very small
- Single production of superpartners is therefore strongly suppressed
- Pair production however depends only on QCD interactions and it's fixed by the color quantum numbers





STOP RPV DECAY

- The stop BRs into different flavor di-quark final states are model dependent
- The structure of the baryon number violating couplings λ'' is given, in explicit constructions with gauged flavor symmetry, by the expression

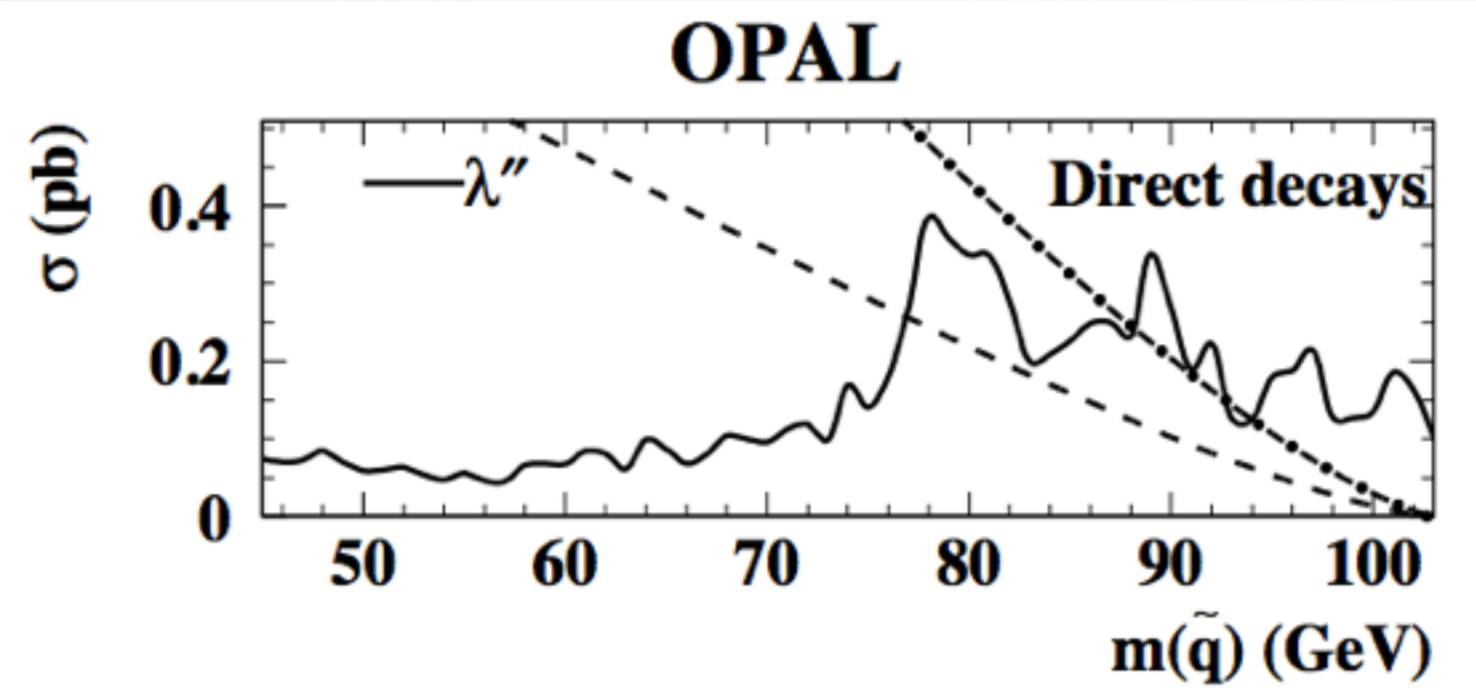
$$\lambda'' \sim V_{il}^{\mathrm{CKM}} \left(\frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \right)^{\mu} \epsilon_{ljk}$$

- This expression depends only on CKM matrix elements, quark masses and a model dependent parameter μ (the overall factor is a free parameter)

$\mu = 1$	$\mathrm{BR}\left(\tilde{t} \to bd + bs\right) \approx 99\%$	$SU(3)_{Q,L,d,u,e,\nu}$ $SU(3)_{Q,Q^c,L,L^c}$ Partial Compositeness	*Csaki, Grossman, Heidenreich 1111.1239* *Krnjaic, Stolarski 1212.4860* *Karen-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi 1205.5803*
$\mu = \frac{1}{2}$	$\mathrm{BR}\left(\tilde{t} \to bd + bs\right) \approx 14\%$	$SU(3)_{V,q,l}$	*Franceschini, Mohapatra 1301.3637*

- For small BRs into heavy flavors searches are very difficult, but assuming large BRs into heavy flavors stop pair production can be observed at the LHC

CURRENT LIMITS: LEP + TEVATRON

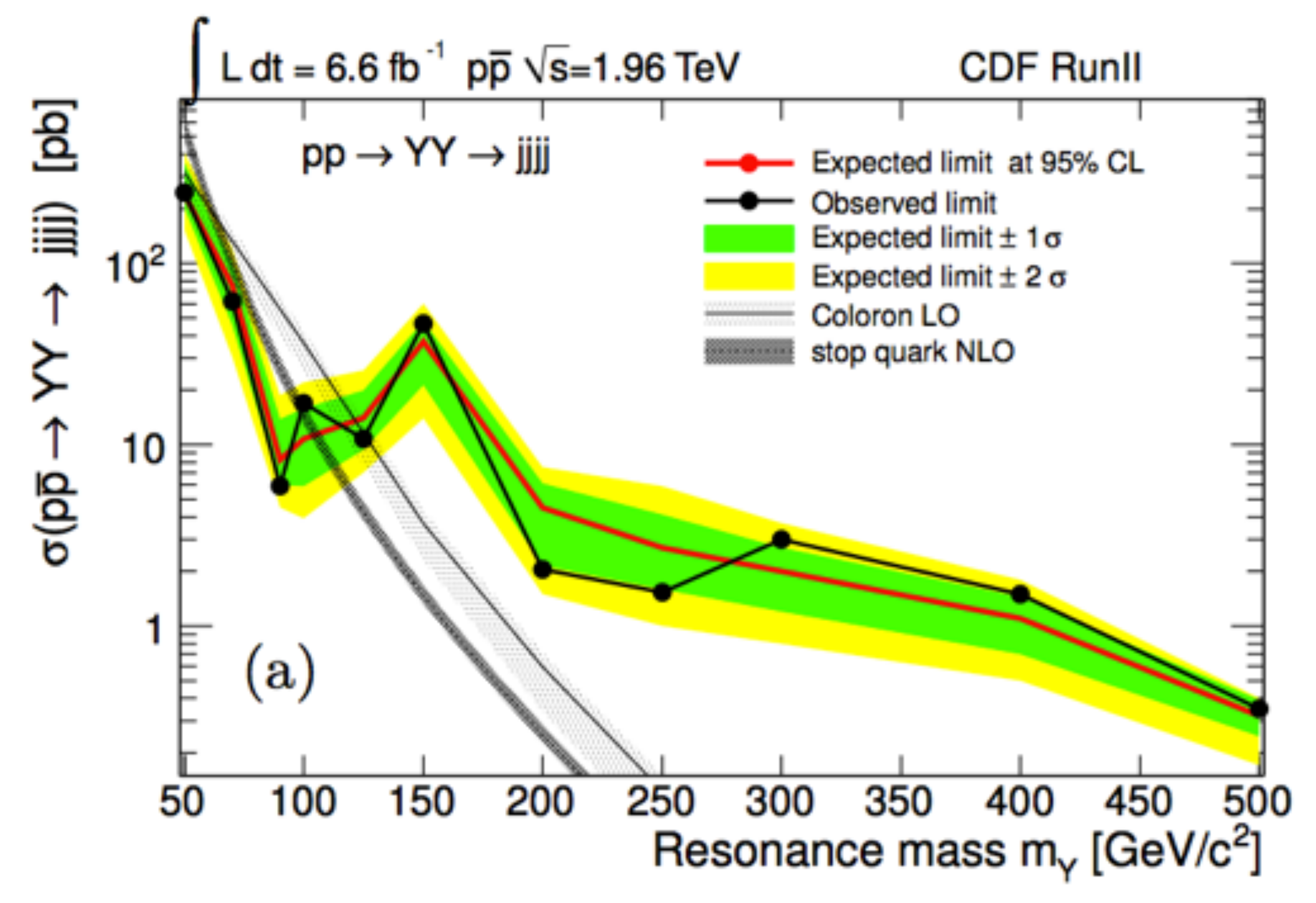


- Searches at LEP have set a bound *(OPAL Collaboration hep-ex/0310054)*

$$m_{\tilde{t}}(\theta_{\tilde{t}} = 0.98) \geq 77 \text{ GeV}$$
$$m_{\tilde{t}}(\theta_{\tilde{t}} = 0) \geq 88 \text{ GeV}$$

- Tevatron (CDF) has an analysis setting a stronger bound *(CDF Collaboration 1303.2699 hep-ex)*

$m_{\tilde{t}} \leq 50$ GeV $\qquad m_{\tilde{t}} \geq 100$ GeV

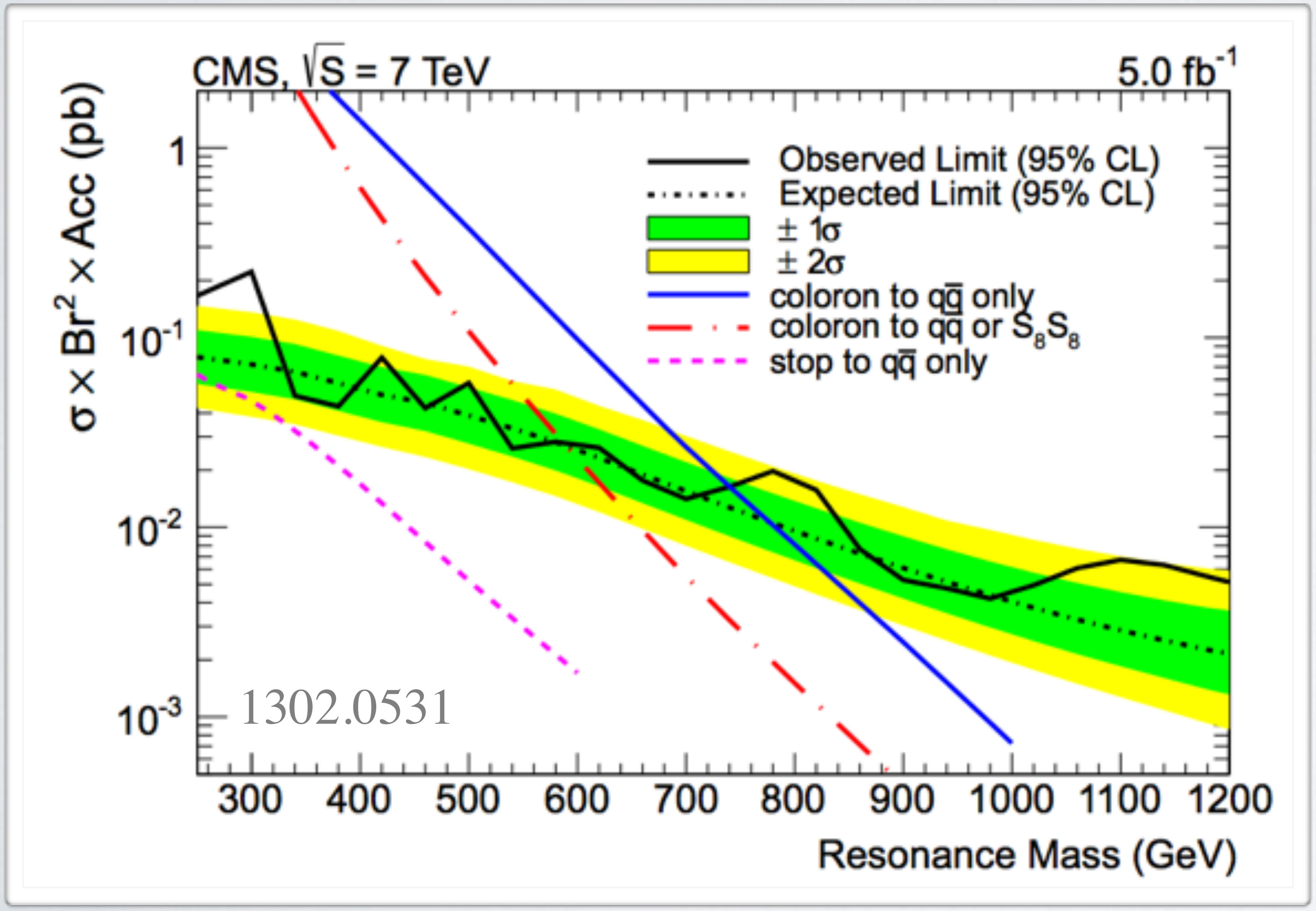


CURRENT LIMITS: LHC

- Together, LEP and Tevatron have set a bound

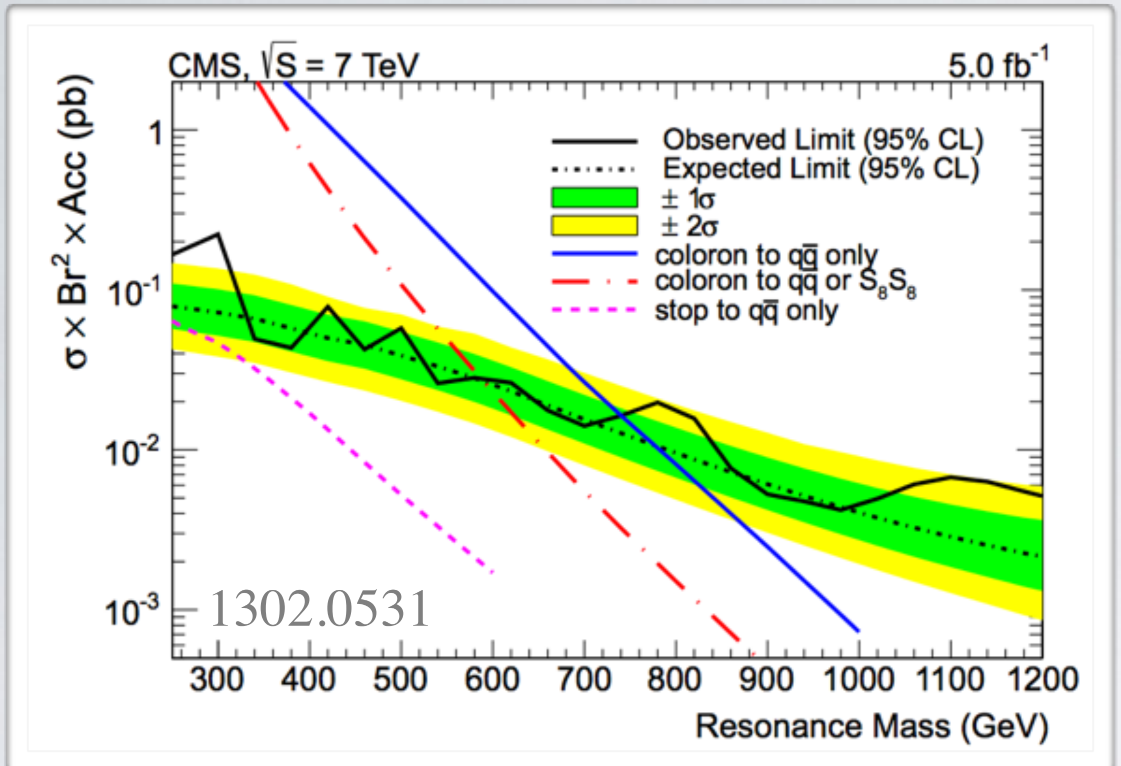
$$m_{\tilde{t}} \geq 100 \text{ GeV}$$

- ATLAS and CMS have presented searches for pair produced colored resonances decaying to 4j (colorons and sgluons) and recently have also focused on stops



- The LHC is not yet sensitive to the stop pair production CS in the present analyses
- The background is huge, and heavy flavor tagging is crucial in this case
- We will show that exploiting b-tagging LHC data can already exclude stops in the very light mass region (at the heart of naturalness)

SKETCH OF THE ANALYSES



Mass pairing: $\delta_m = \dfrac{|m_{ab} - m_{cd}|}{m_{ab} + m_{cd}}$

Main cuts: at least 4j with

$p_{T\,j} > 110$ GeV

$|\eta_j| < 2.5$

$\Delta R_{jj} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \geq 0.7$

$\delta_m < 0.075$

$\Delta = \sum_{i=1,2} (p_T)_i - |m_{ab} - m_{bc}| > 25$

Ang. pairing: $\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1|$

Main cuts: at least 4j with

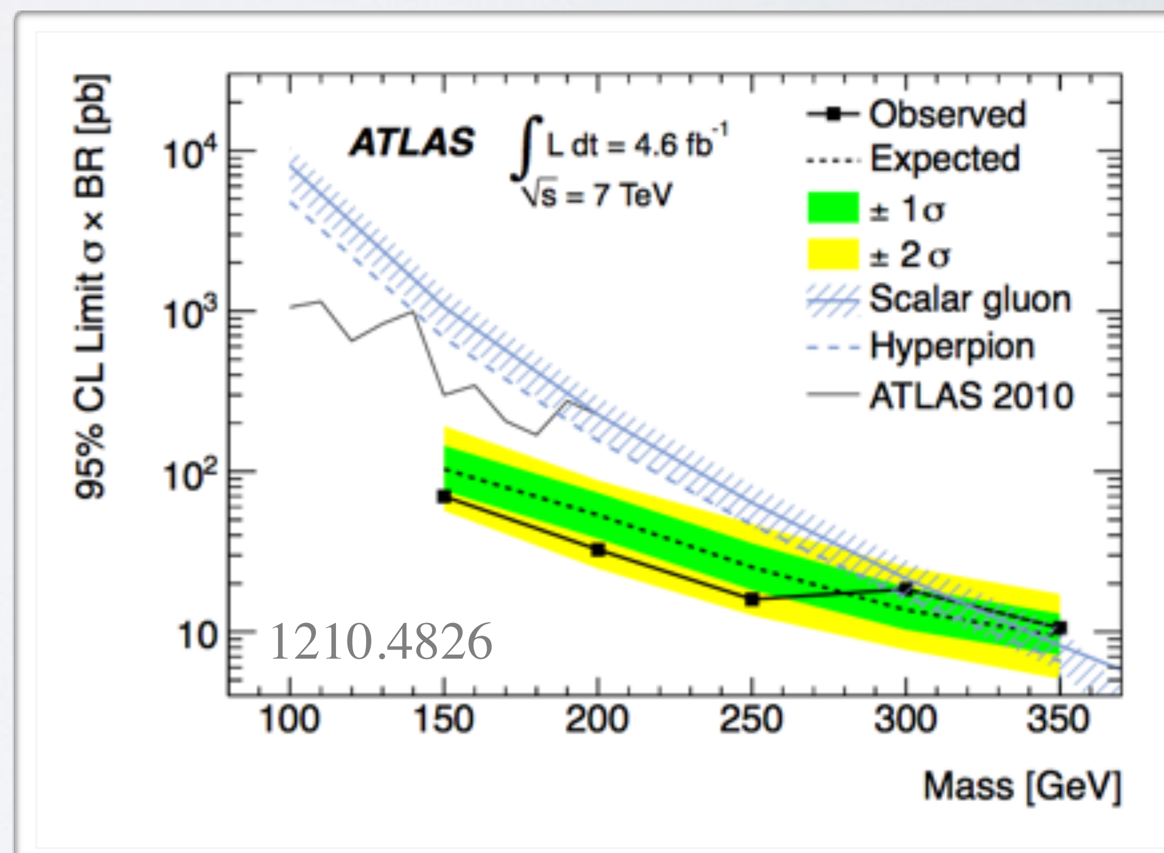
$p_{T\,j} > 80$ GeV

$|\eta_j| < 1.4$

$\Delta R_{jj} > 0.6 \qquad \Delta R_{\text{pairs}} < 1.6$

$\delta_m < 0.15$

$|\cos\theta^*| = \dfrac{|p^{\text{cm}}_{z\,a} + p^{\text{cm}}_{z\,b}|}{|\mathbf{p}^{\text{cm}}_a + \mathbf{p}^{\text{cm}}_b|} < 0.5$



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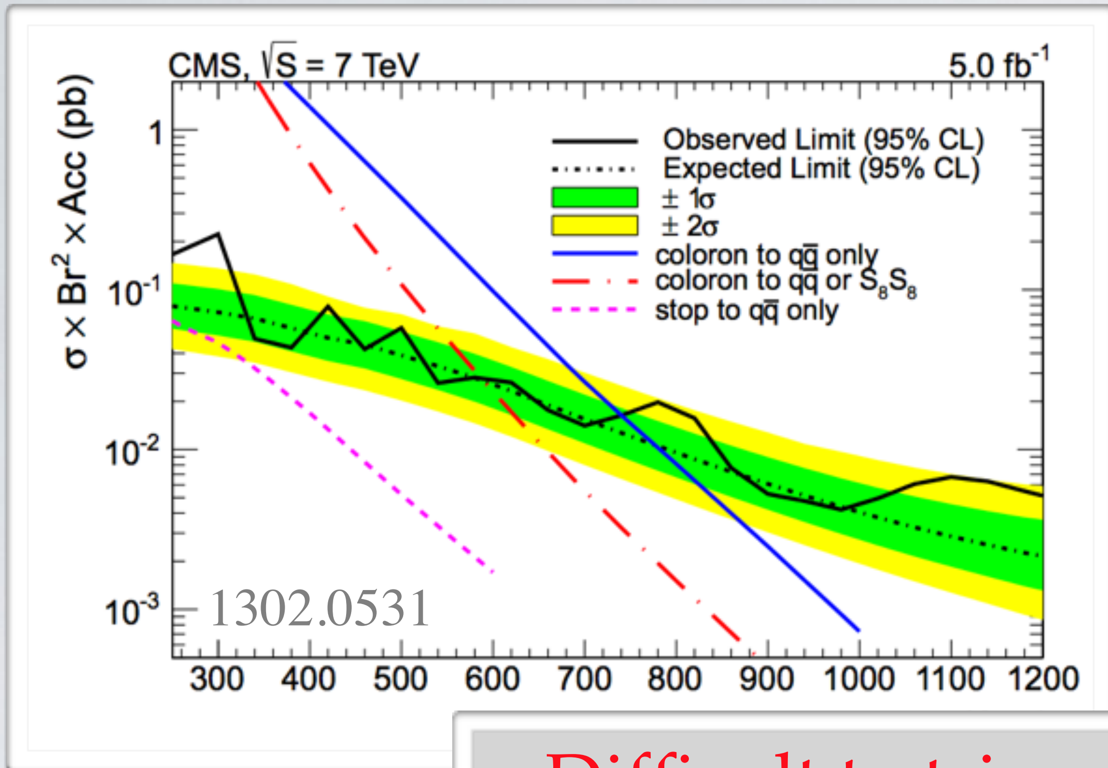

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Difficult to trigger on events with low pT jets

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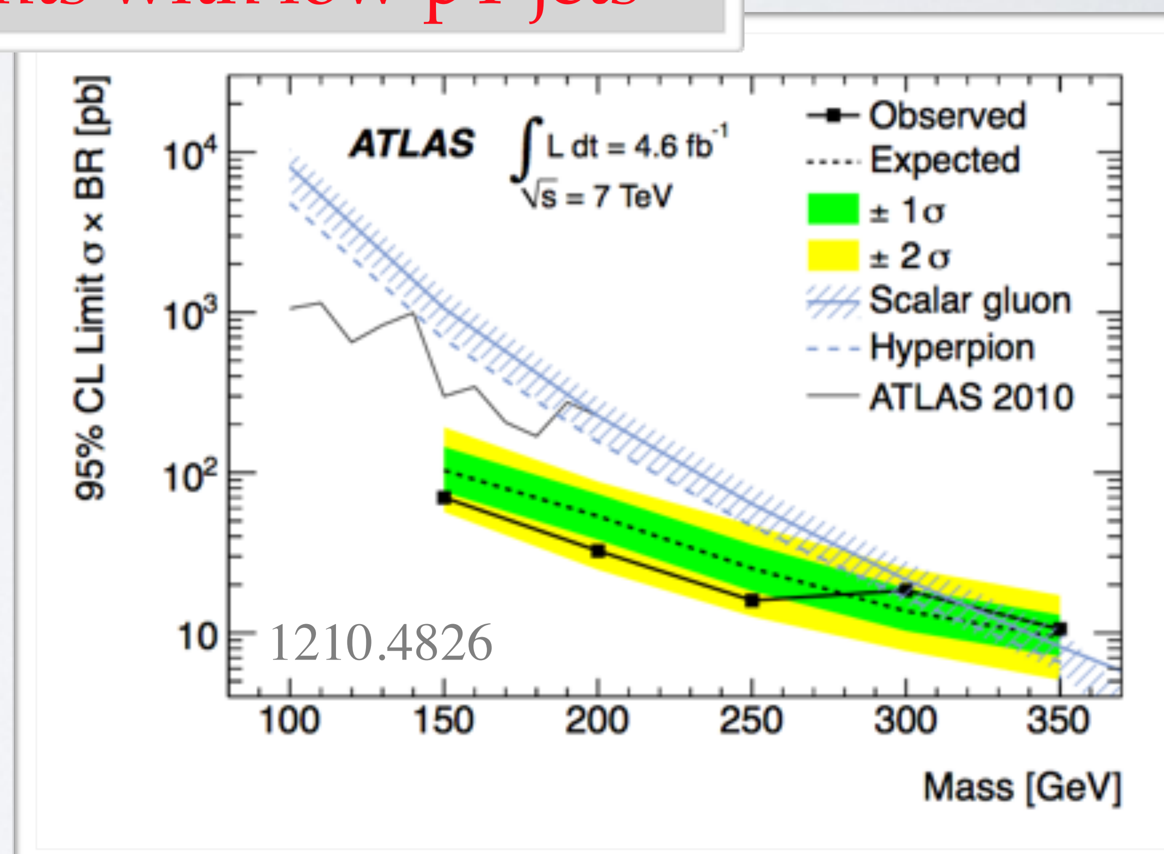
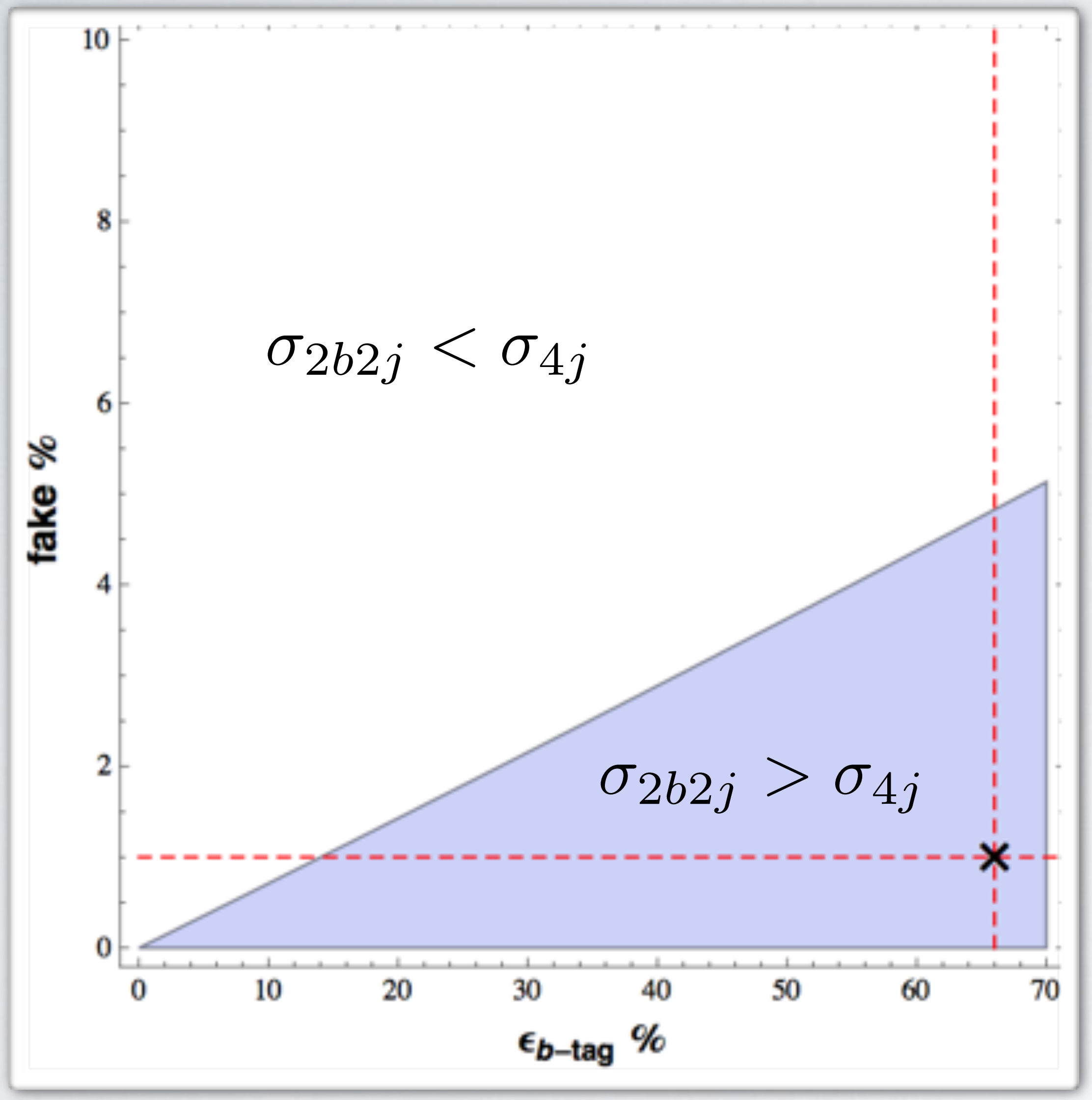


B-TAGGING

- Online b-tagging can help in reducing the pT threshold for the recorded jets!



	0 b-tag	1 b-tag	2 b-tag
$\sigma_{4j}^{(8\text{TeV})}$	320 nb	12.8 nb	192 pb
$\sigma_{2b2j}^{(8\text{TeV})}$	8.8 nb	5.8 nb	3.8 nb

MG5 with selections $p_T > 35$ GeV, $|\eta| < 3.5$, $\Delta R > 0.4$

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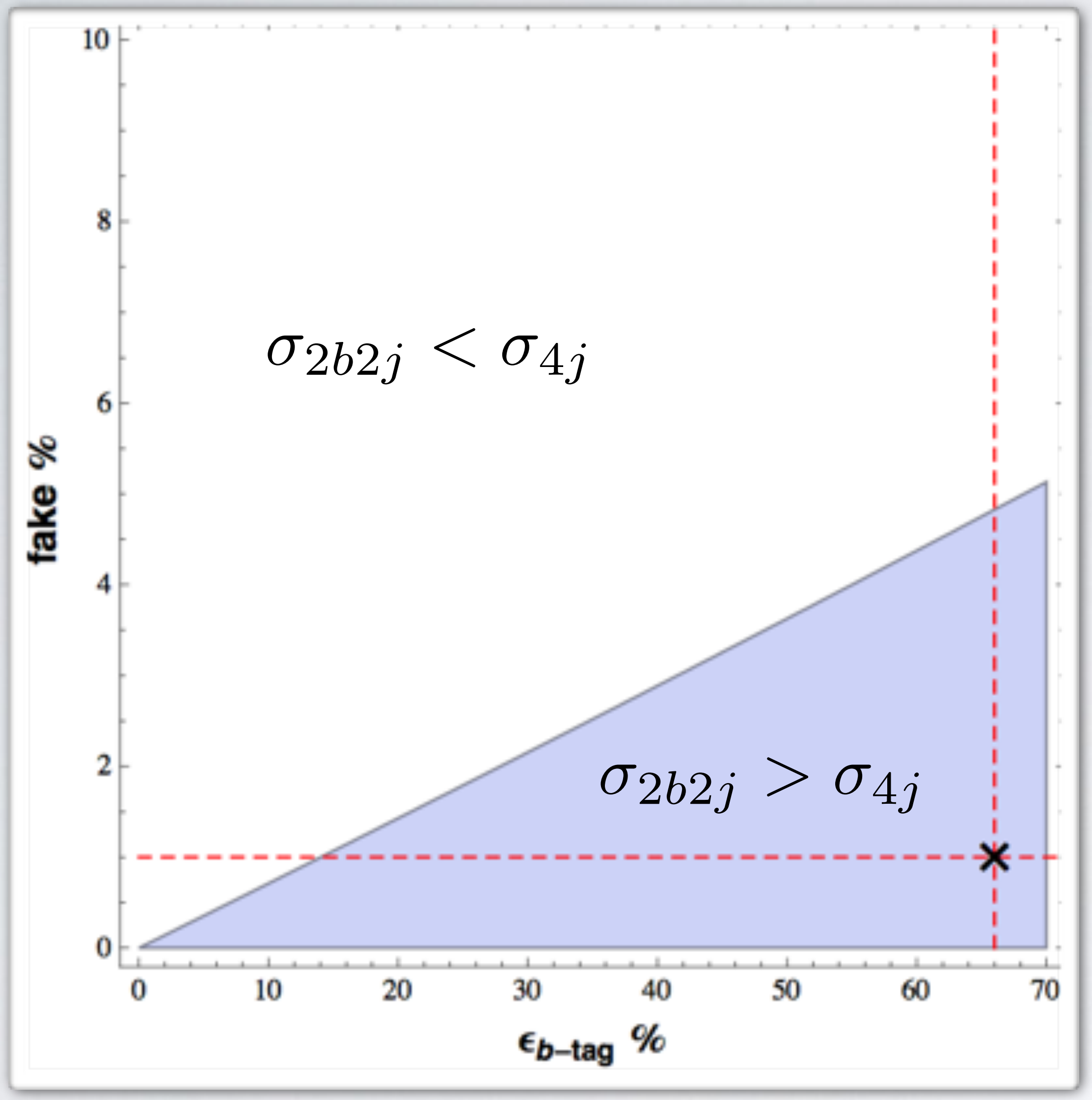

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- We can reduce main background from the 4j to the 2b2j, i.e. a factor of ~40 smaller
- Assuming the interesting events have been recorded with the ATLAS and CMS 2012 triggers, then using (offline) b-tagging the relevant backgrounds for our final state are

$$pp \to 2b2j \qquad pp \to t\bar{t} \left(\sigma_{t\bar{t}}^{(8\text{TeV})} = 135 \text{ pb}\right)$$

OUR ANALYSIS

- We aim to identify the stops signal as a bump in the $m_{\rm best}$ distribution
- After studying the effect of a cut based analysis using all the different kinematic variables defined by the CMS and ATLAS collaborations, we identify the following kinematic variables as the most relevant to optimize S/B

$$\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1|$$

$$\delta_m = \frac{|m_{ab} - m_{cd}|}{m_{ab} + m_{cd}}$$

$$m_{\rm best} = \frac{m_{ab} + m_{cd}}{2}$$

$$\Delta\eta_{\rm best} = \frac{|\Delta\eta_{ab}| + |\Delta\eta_{cd}|}{2}$$

$$\cos\theta^* = \frac{p^{\rm cm}_{z\,a} + p^{\rm cm}_{z\,b}}{|\mathbf{p}^{\rm cm}_a + \mathbf{p}^{\rm cm}_b|} = \frac{p^{\rm cm}_{z\,c} + p^{\rm cm}_{z\,d}}{|\mathbf{p}^{\rm cm}_c + \mathbf{p}^{\rm cm}_d|}$$

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- The relevant kinematic quantities crucially depend, especially for signal, on smearing effects due to showering and detector
- To get a reasonable estimate of the signal and background distributions in these variables we made a full simulation chain
  - MadGraph5 @LO (CTEQ6L1)
  - Pythia 8 (parton shower)
  - Fastjet 2 (anti-k_T with $R = 0.6$)
  - Delphes 2.0 (detector simulation)

OUR ANALYSIS

- We aim to identify the stops signal as a bump in the m_{best} distribution
- After studying the effect of a cut based analysis using all the different kinematic variables defined by the CMS and ATLAS collaborations, we identify the following kinematic variables as the most relevant to optimize S/B

$$\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1| \qquad \delta_m = \frac{|m_{ab} - m_{cd}|}{m_{ab} + m_{cd}}$$

$$m_{\text{best}} = \frac{m_{ab} + m_{cd}}{2} \qquad \Delta\eta_{\text{best}} = \frac{|\Delta\eta_{ab}| + |\Delta\eta_{cd}|}{2}$$

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Validated vs ATLAS analysis (4j) 1110.2693 with 30% level agreement after all selections!

CUT OPTIMIZATION

For very boosted jets we have

$$m_{\tilde{t}}^2 \approx p_{T_{j_1}} p_{T_{j_2}} \Delta R_{j_1 j_2}^2$$

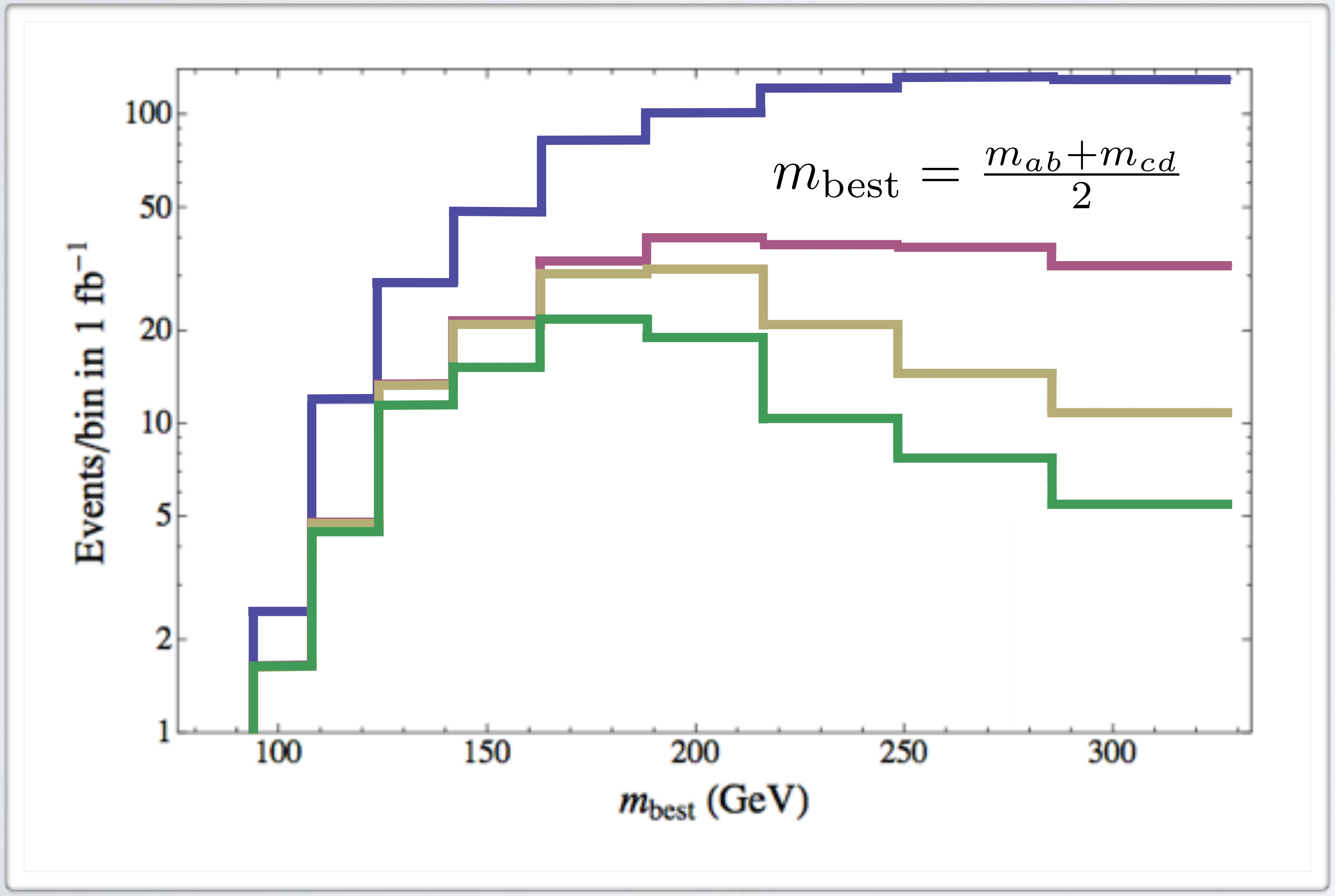
$$\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1|$$

We identify these selections to optimize S/B

$p_{T\,j} > \frac{m_{\tilde{t}}}{2}$ $\quad |\eta| < 2.8$ $\quad \Delta R_{jj} > 0.7$

$\delta m < 0.075$ $\quad |\cos\theta^*| < 0.4$ $\quad \Delta R_{\rm best} < 1.5$

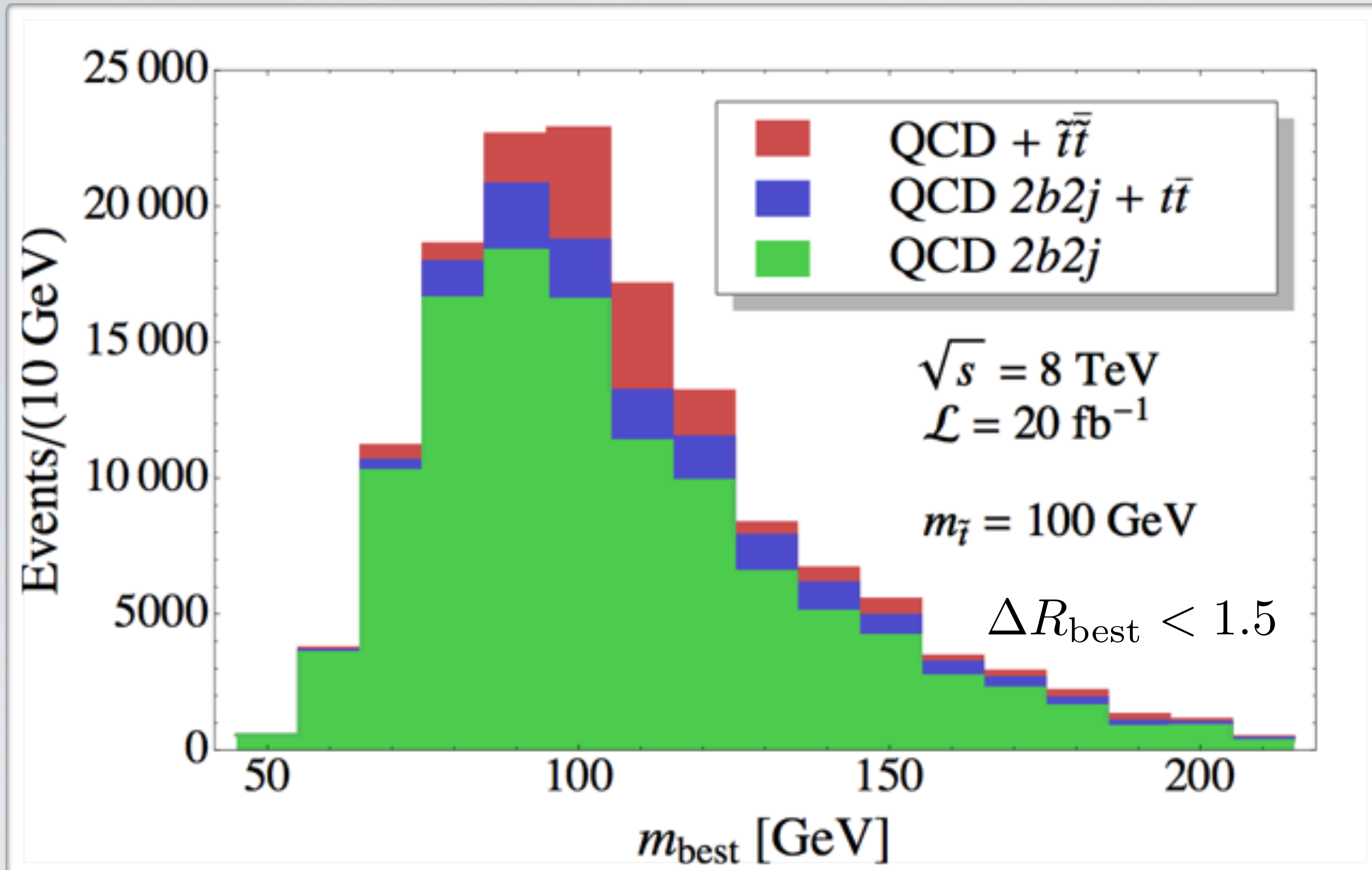
$\Delta\eta_{\rm best} < 0.8$



The combined effect of the $\Delta R_{\rm best}$ and $\Delta\eta_{\rm best}$ cuts is to move the peak of the background distribution toward smaller values of $m_{\rm best}$

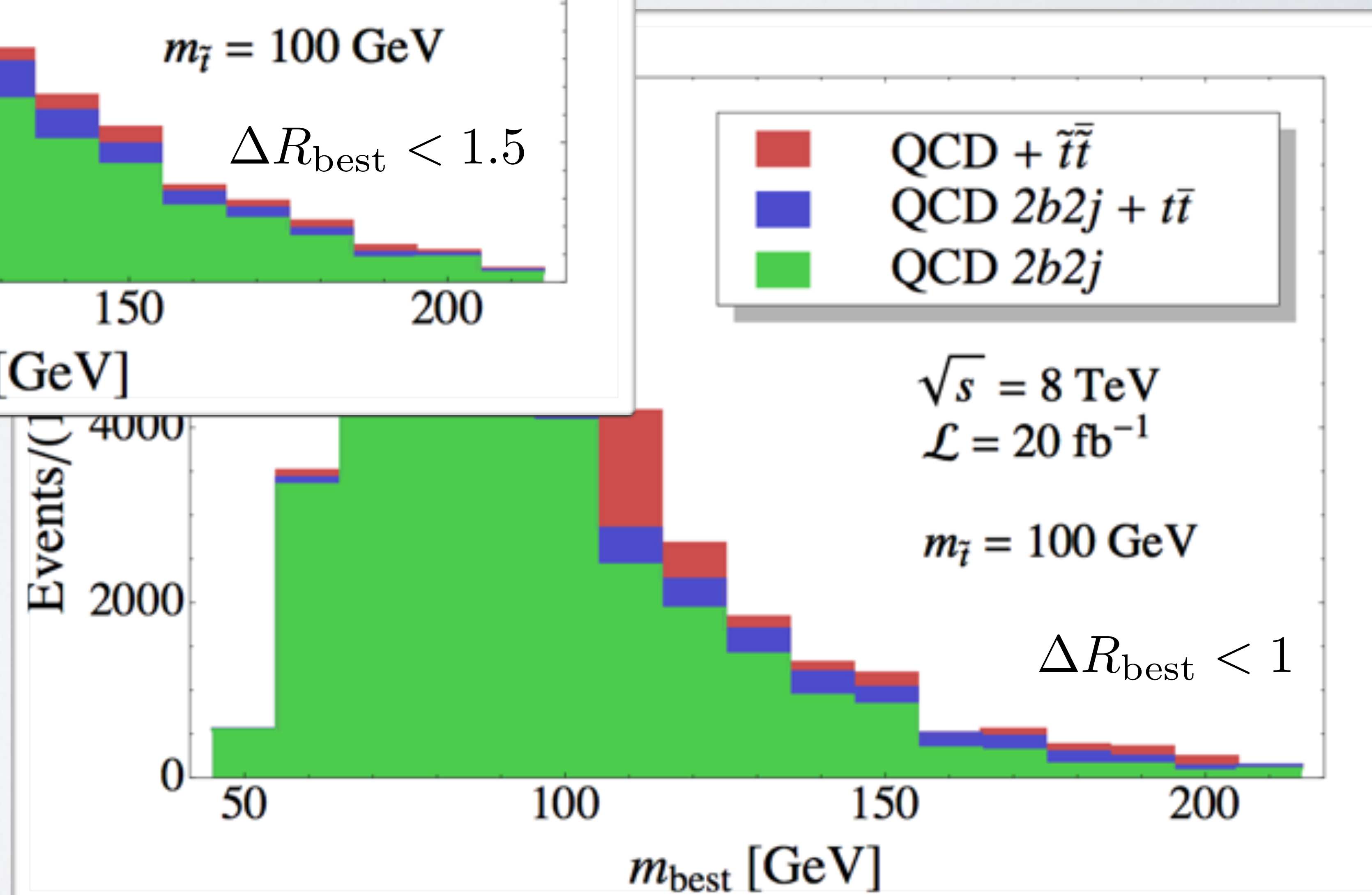
Therefore using these angular variables we can hope to see the stop signal as a bump on a smoothly falling background

RESULTS: 100 GEV STOPS



Several bins with large S/B

Discovery possible at the LHC provided events with small jet pT have been recorded (maybe some "parked" data?)



Harder $\Delta R_{\rm best}$ cut pushed the BG peak toward lower masses and forces the signal to bump on the smoothly falling background

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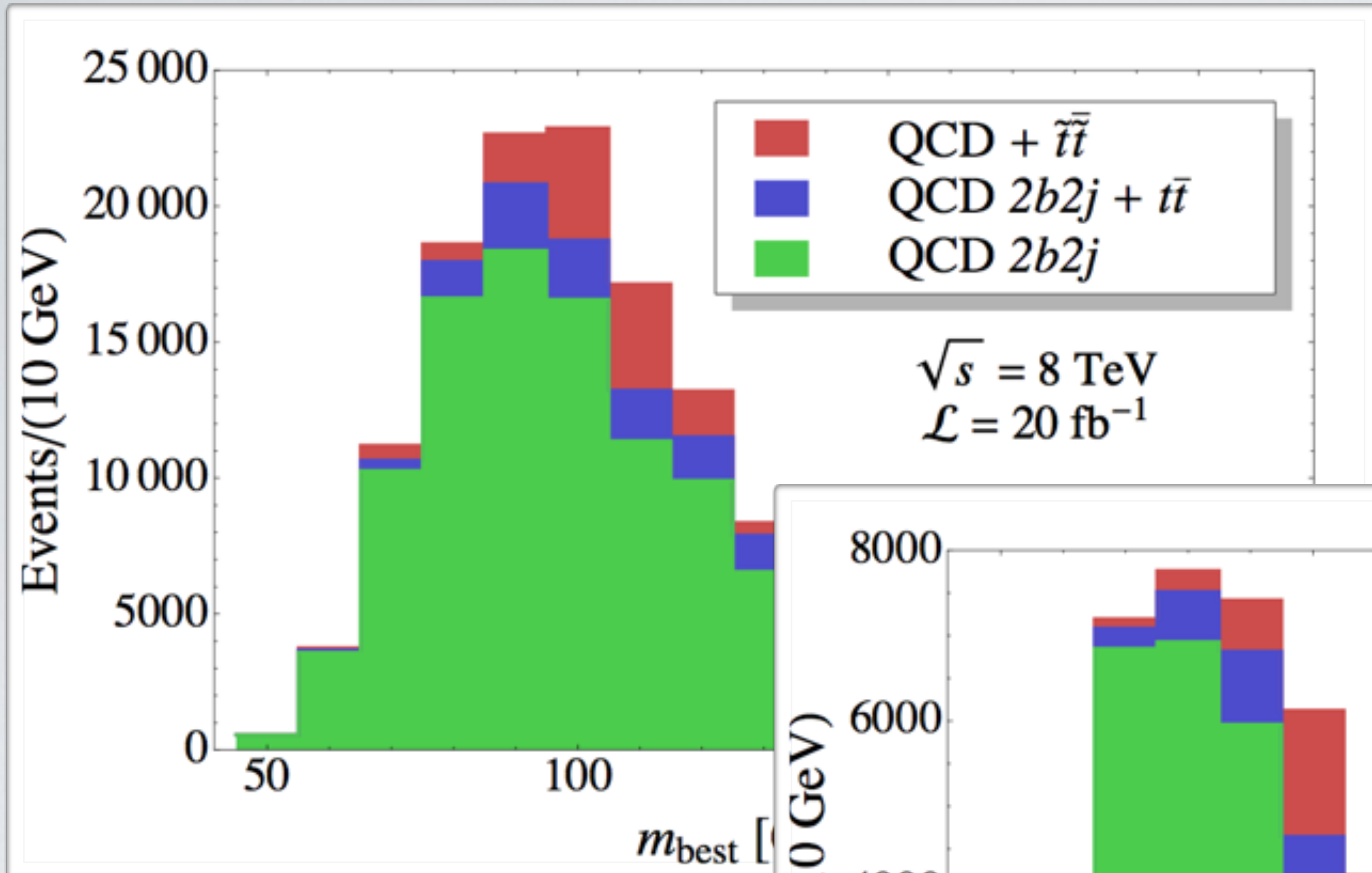

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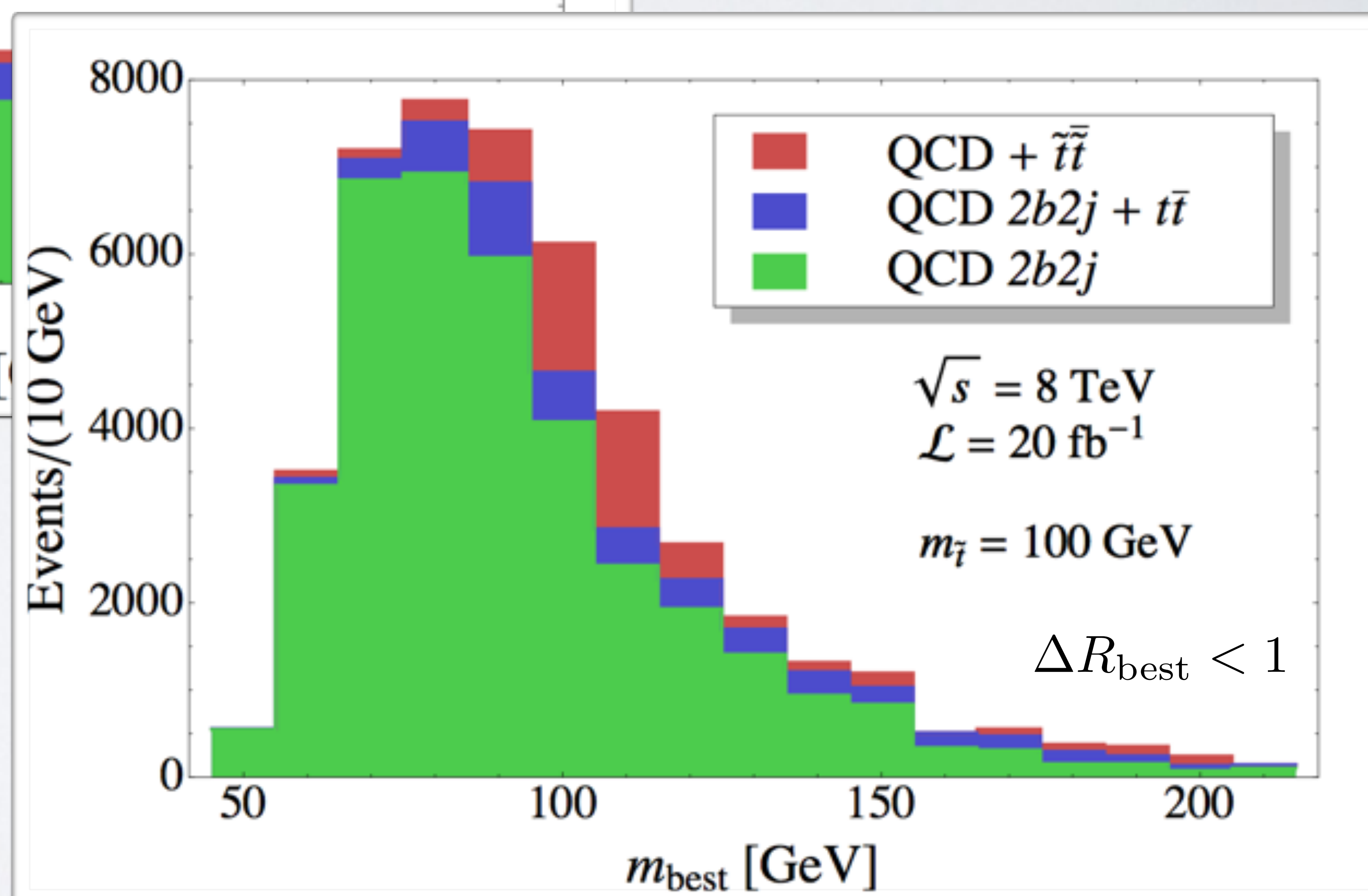

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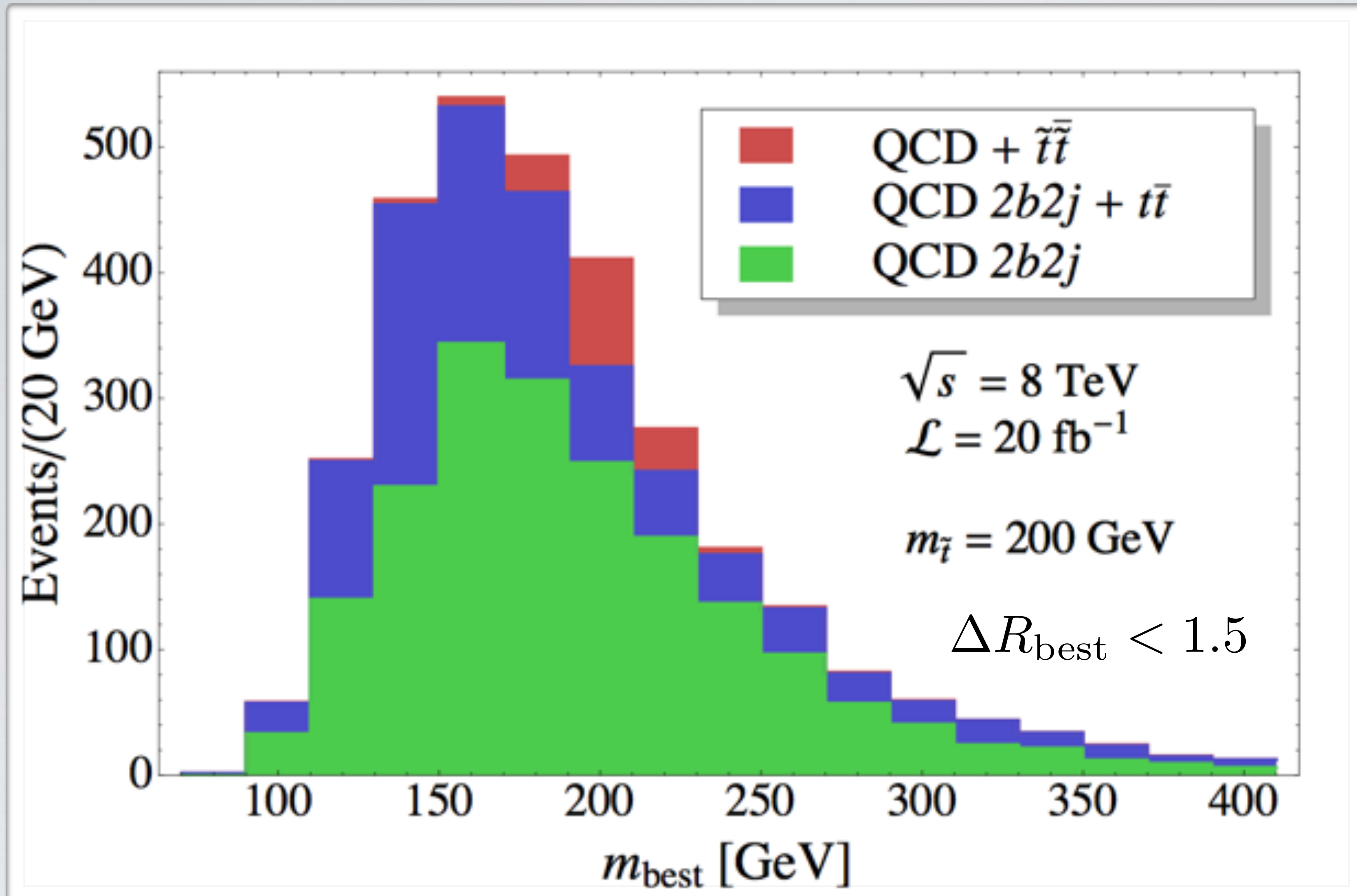
RESULTS: 200 GEV STOPS



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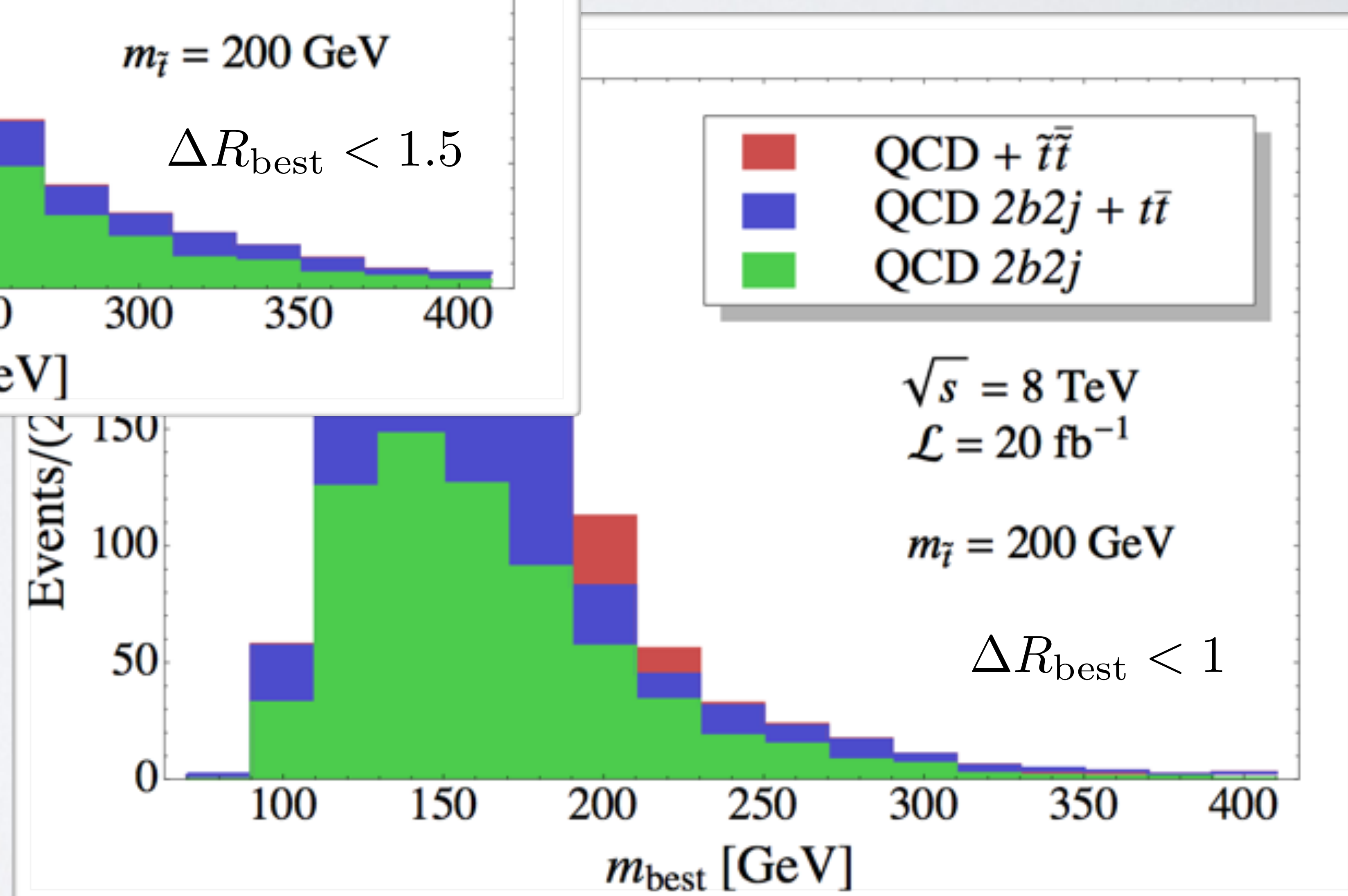

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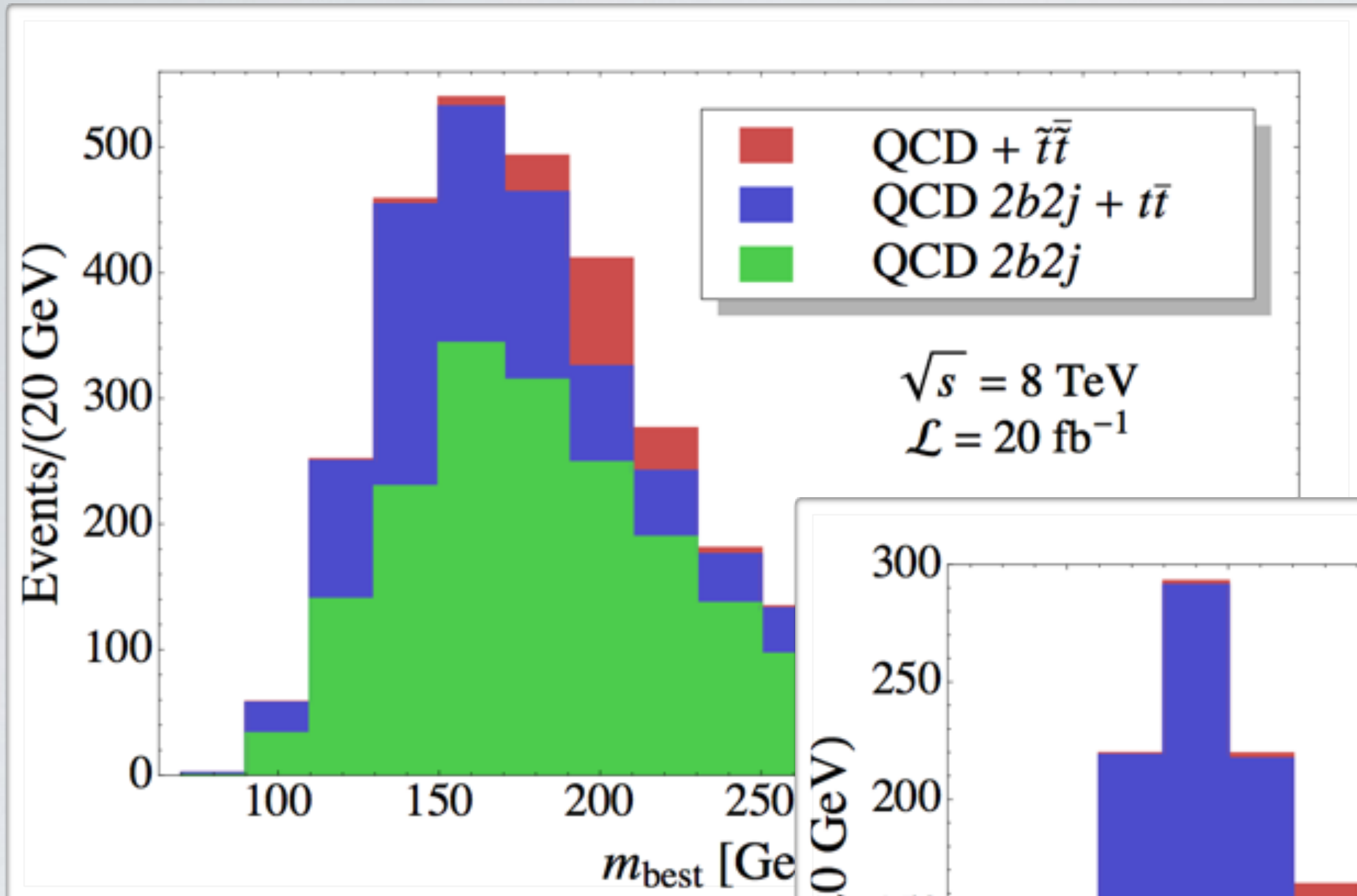

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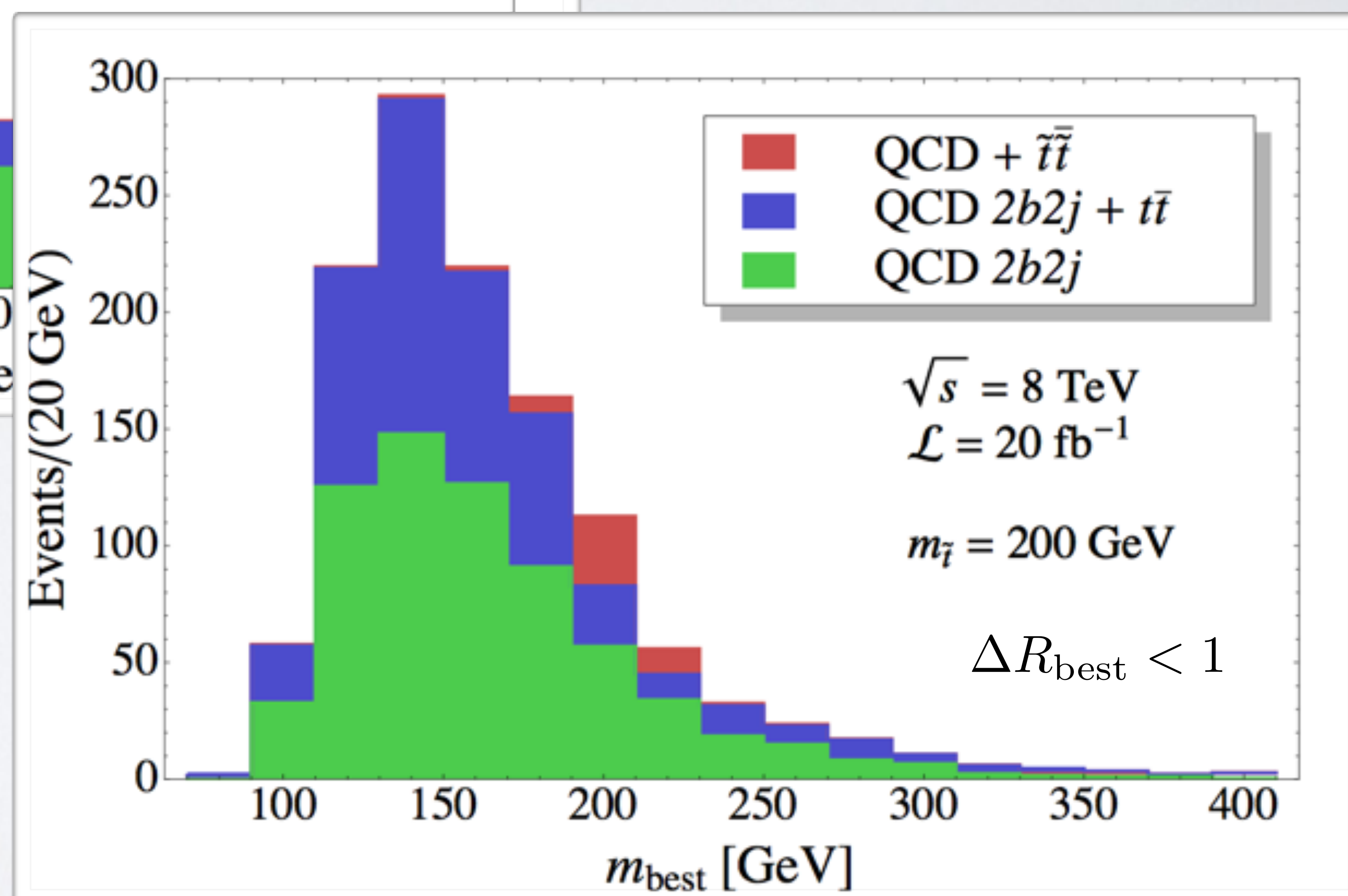

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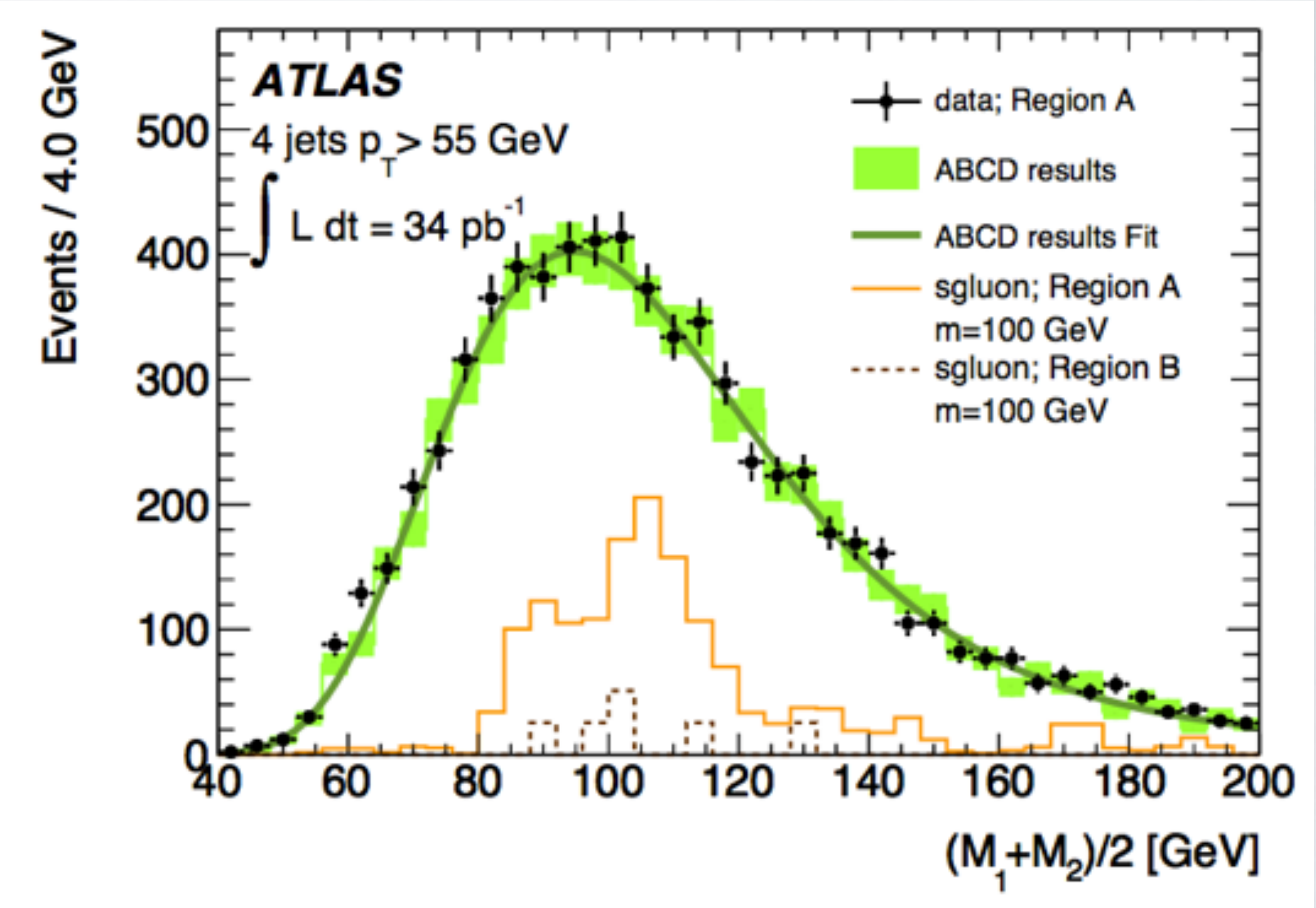
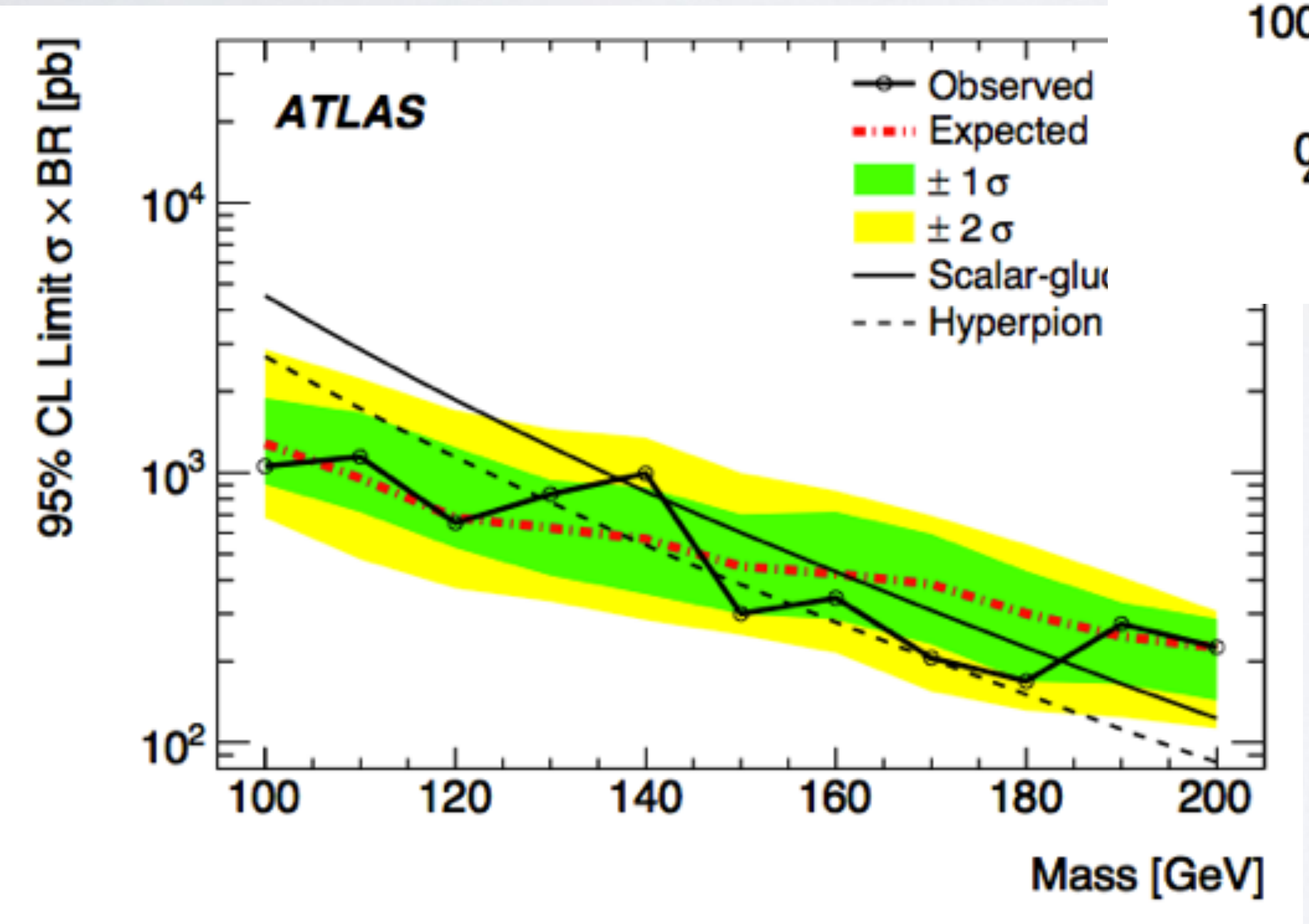
HOW ROBUST IS OUR PREDICTION?

- One may argue that the signal can hardly be extracted from the BG for our S/B
- We can simply check the S/B which allows discovery/exclusion by comparing with an experimental analysis





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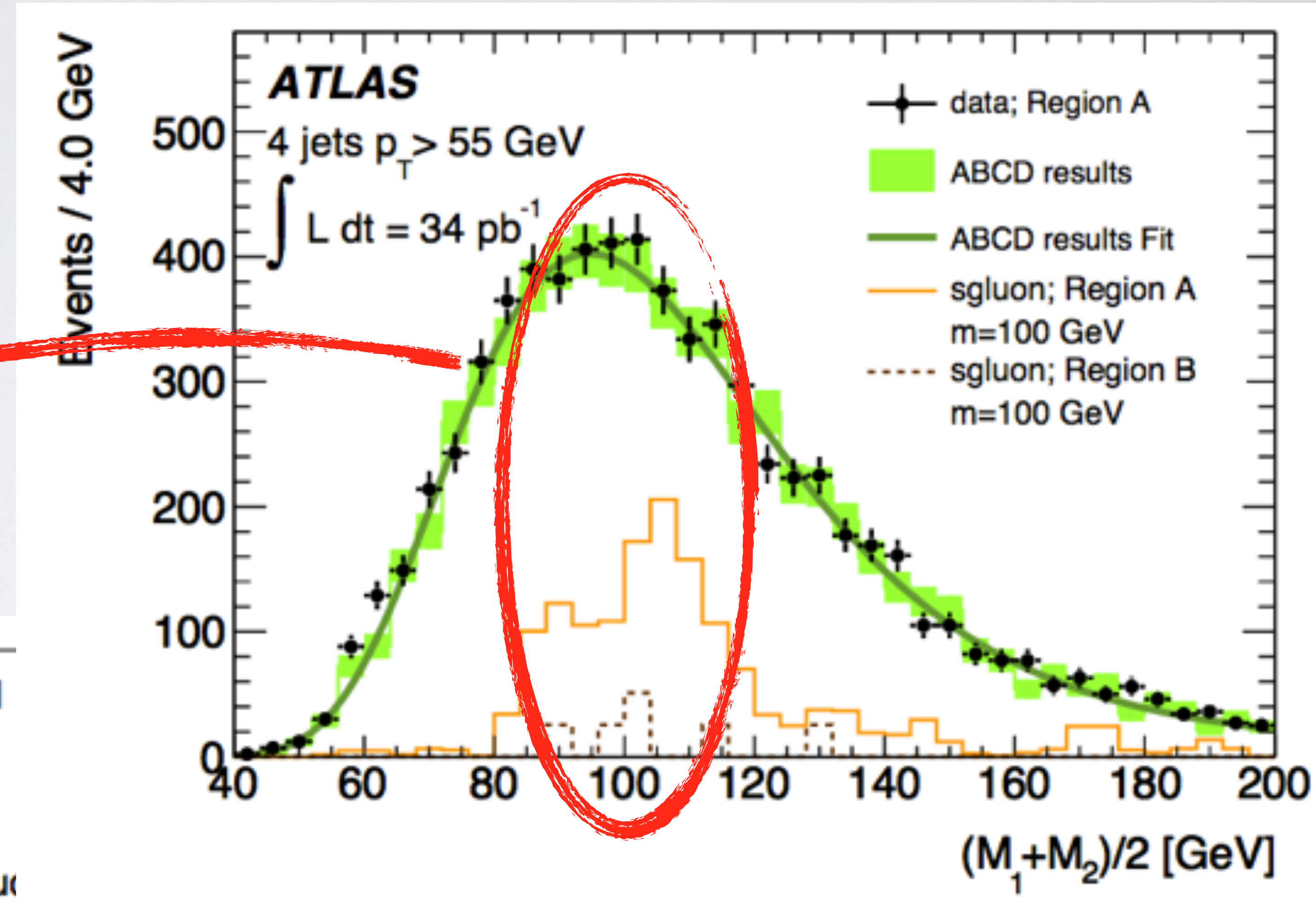

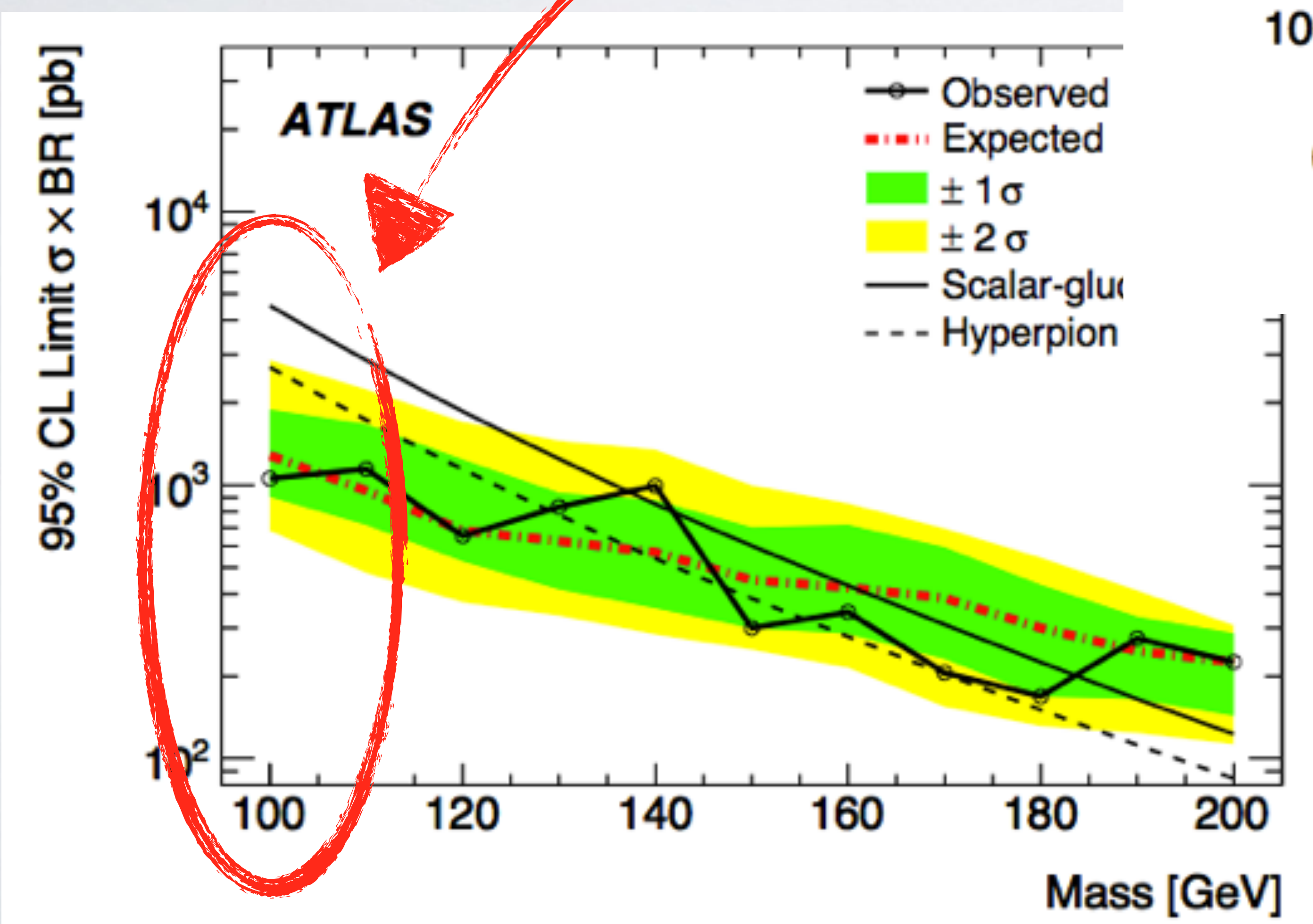

- With S/B~0.5 they can exclude the sgluon CS by a factor of 4÷5

They are sensitive to S/B~0.1 with an analysis very similar to ours!

CONCLUSION

- If we take Naturalness as a driving principle, then a new “LHC paradox” adds up to the “LEP paradox” to require non-minimal models
- Insisting on Naturalness and Supersymmetry and in the attempt of building an effective SUSY model, *R*-parity is probably not enough to guarantee proton stability and looking for RPV physics can be motivated
- RPV SUSY is characterized by the absence of large MET and its phenomenology is strikingly different from the RPC one
- We studied the pair production of stops in the Natural region (where the stop mass is very close to the top-quark one) assuming large BR into heavy flavor final states (motivated by RPV model building)
- We pointed out the importance of using online b-tagging to keep low pT thresholds in the trigger for multi-jet final states in order to cover all the region down to the present bound on RPV stops
- Using b-tagging and suitable angular selections we concluded that light RPV stops can be discovered even with the data already collected in the first run of the LHC

THANK YOU