LIGHT RPV STOPS HIDING IN THE LHC DATA

Riccardo Torre
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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

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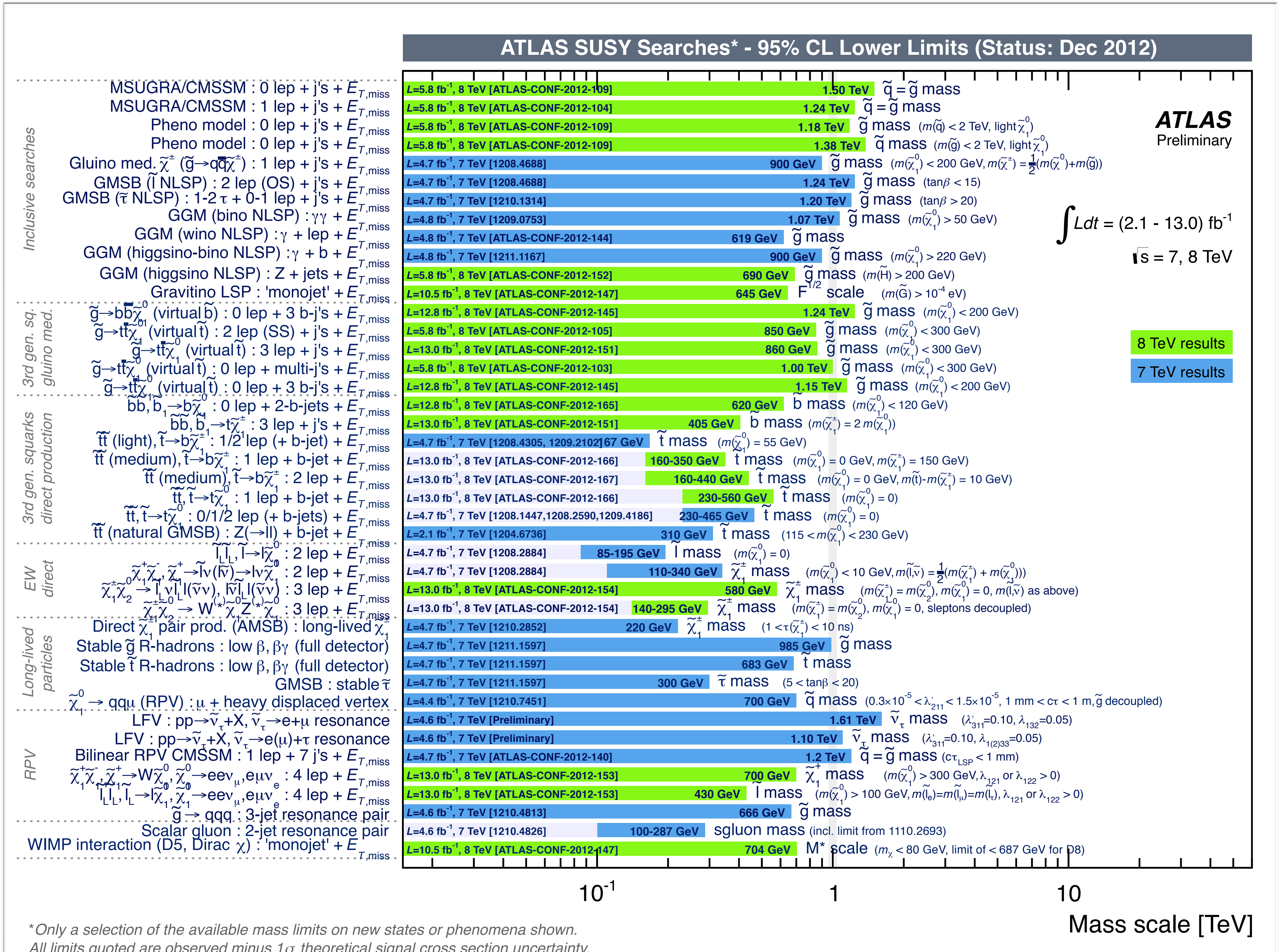
Left out

- Model building for R-parity violation

THE HEALTH OF SUSY



Freitag, 24. Mai 13

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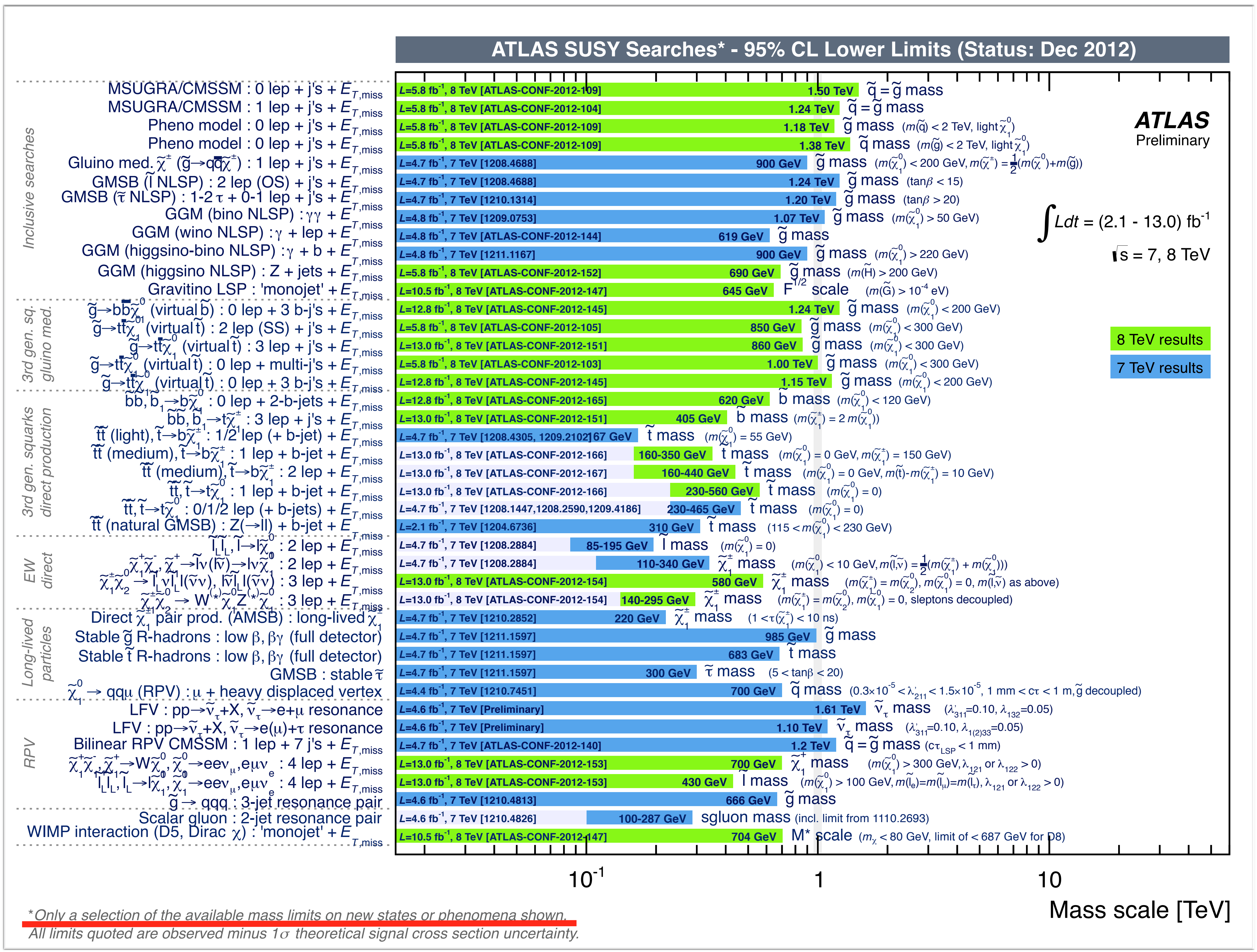
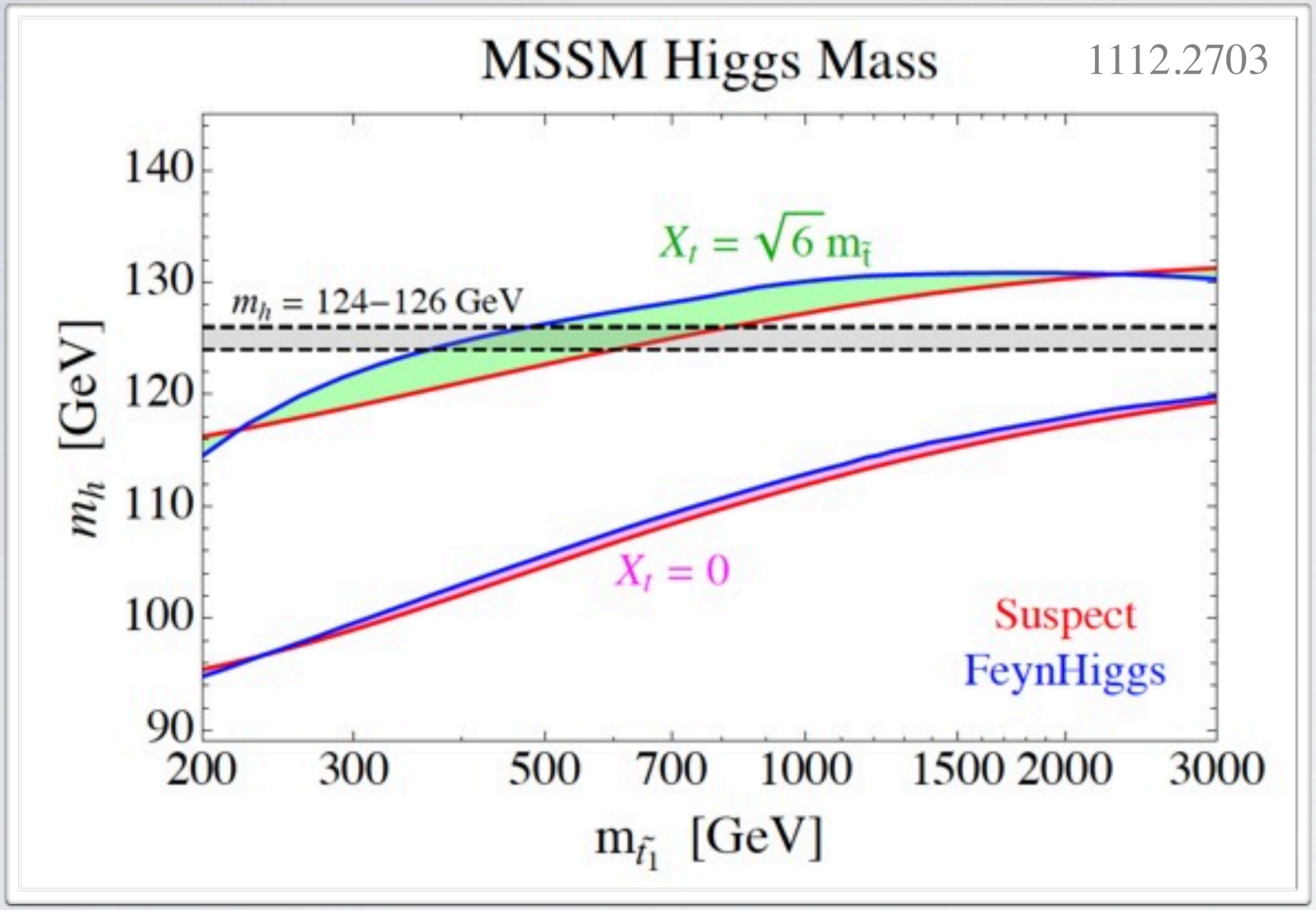


THE HIGGS VS THE MSSM



$$m_h \sim 125.5 \text{ GeV}$$

$$\Downarrow$$

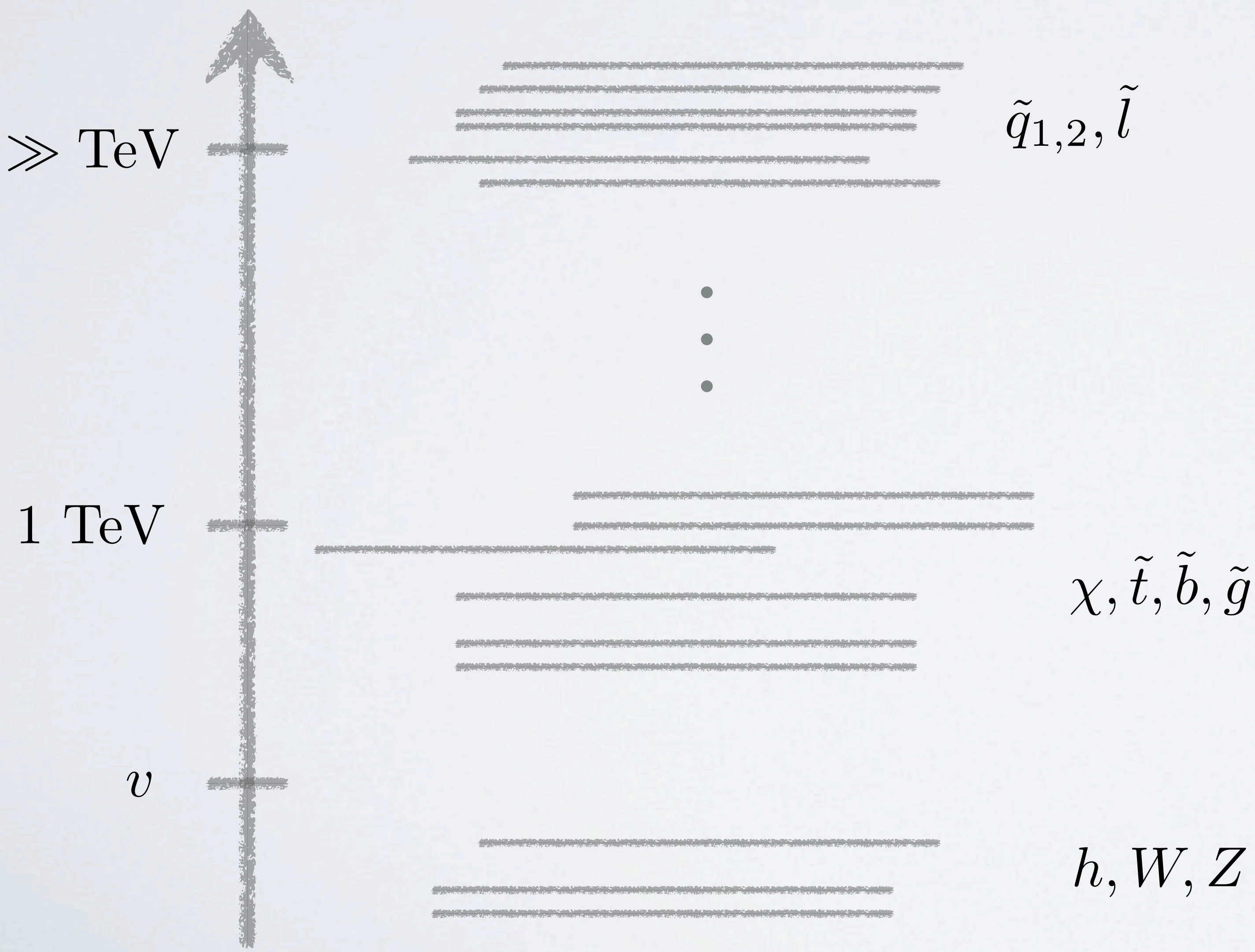
Large stop masses

Close to maximal stop mixing

- The light Higgs boson and the negative results in the searches for superpartners point toward a non-minimal scenario
- A plethora of possible models, so which criterion to follow?

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 Λ_{UV} not far above the TeV scale



Typical signatures:

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

Alternatives

- Split SUSY
- Stealth SUSY
- RPV
- ....

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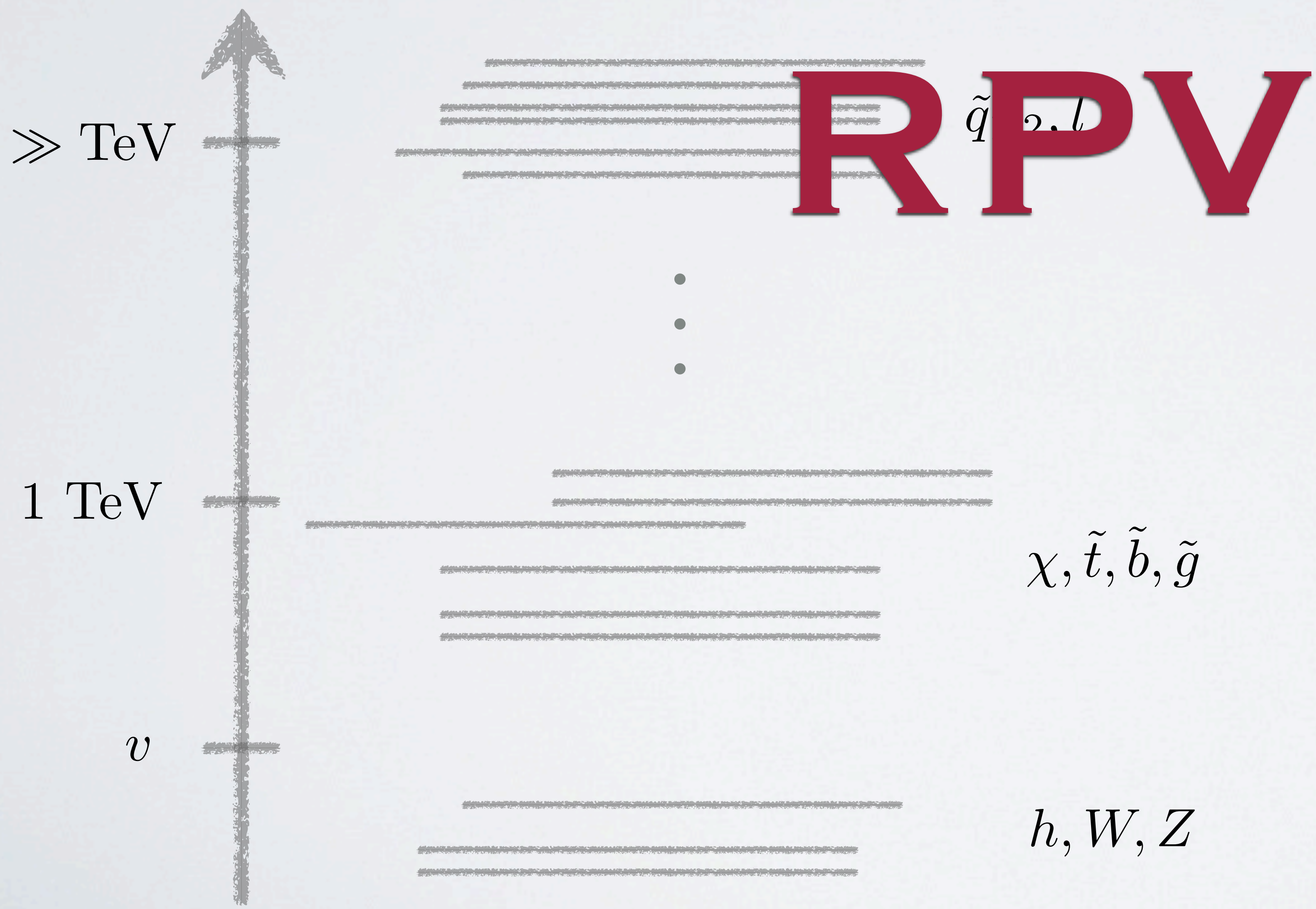

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WHY RPV?... WHY NOT?

- 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

$$W_{\not B} = \lambda'' UDD$$
$$W_{\not L} = \lambda LLE + \lambda' QLD + \mu' LH_d$$

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

- 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
- There are problems giving-up with R-parity

1. B and L violation
2. Proton decay ($\lambda'' \cdot \lambda' < 10^{-24}$)
3. WIMP DM candidate
4. Experimental constraints (charged current universality, masse 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, heavy nucleon decay, $\Gamma(\pi \to e\bar{\nu}) / \Gamma(\pi \to \mu\bar{\nu})$, $\mathrm{BR}(D^+ \to \bar{K}^{0*}\mu^+\nu_\mu) / \mathrm{BR}(D^+ \to \bar{K}^{0*}e^+\nu_e)$, $\mathrm{BR}(\pi \to \pi\nu_\tau)$, ν_μ DIS)

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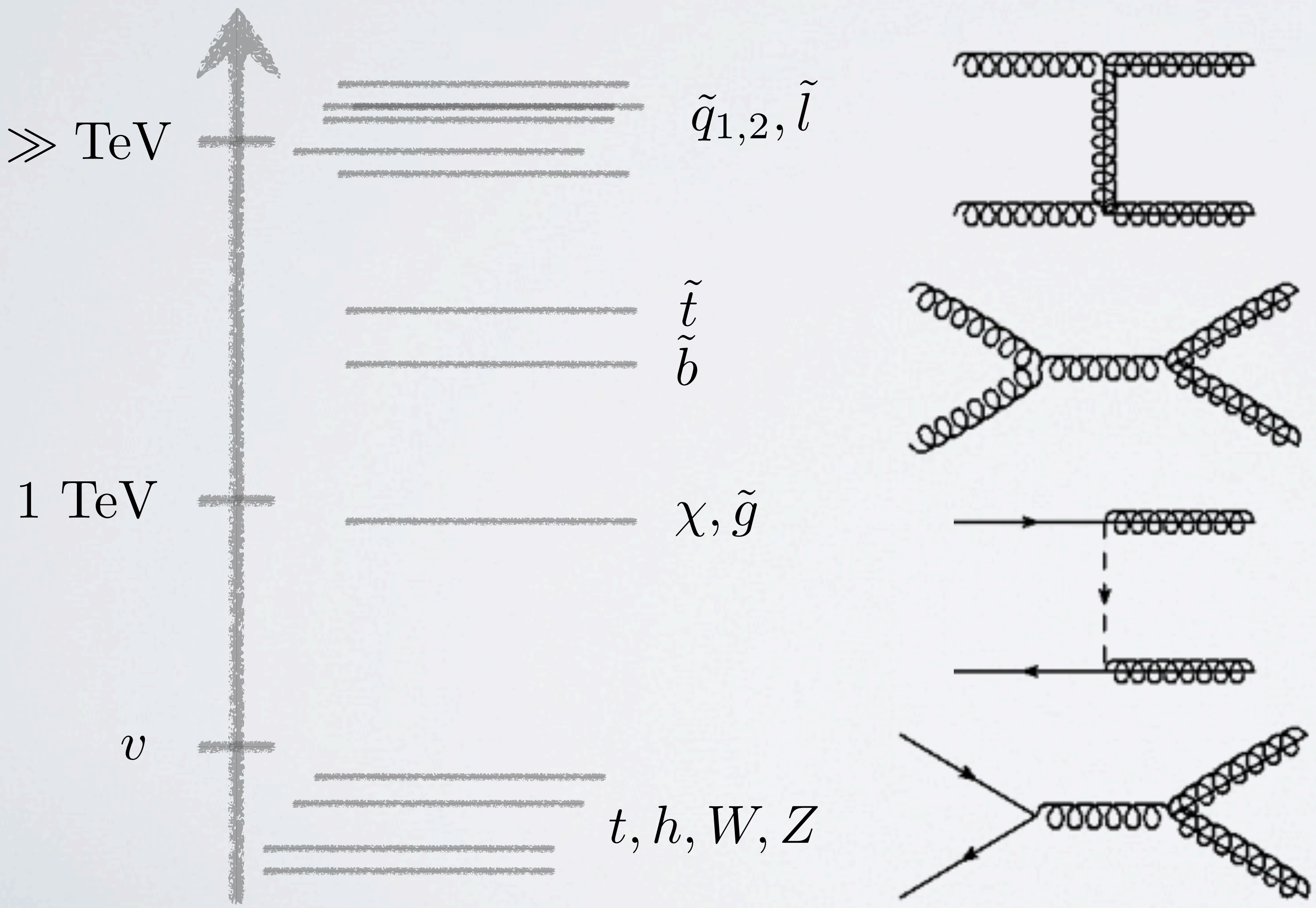
- However R-parity is not enough to forbid B and L violating HDO and in effective models one could expect the scale that suppresses these operators to be lower than the GUT scale

$$W_{\mathrm{HDO}} \supset \frac{k}{\Lambda_{\mathrm{RPV}}} UUDE$$

- In this case proton decay becomes an issue even with R-parity for $\Lambda_{\mathrm{RPV}} < M_{\mathrm{GUT}}$
- 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. gauged flavor symmetry, partial compositeness) *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*

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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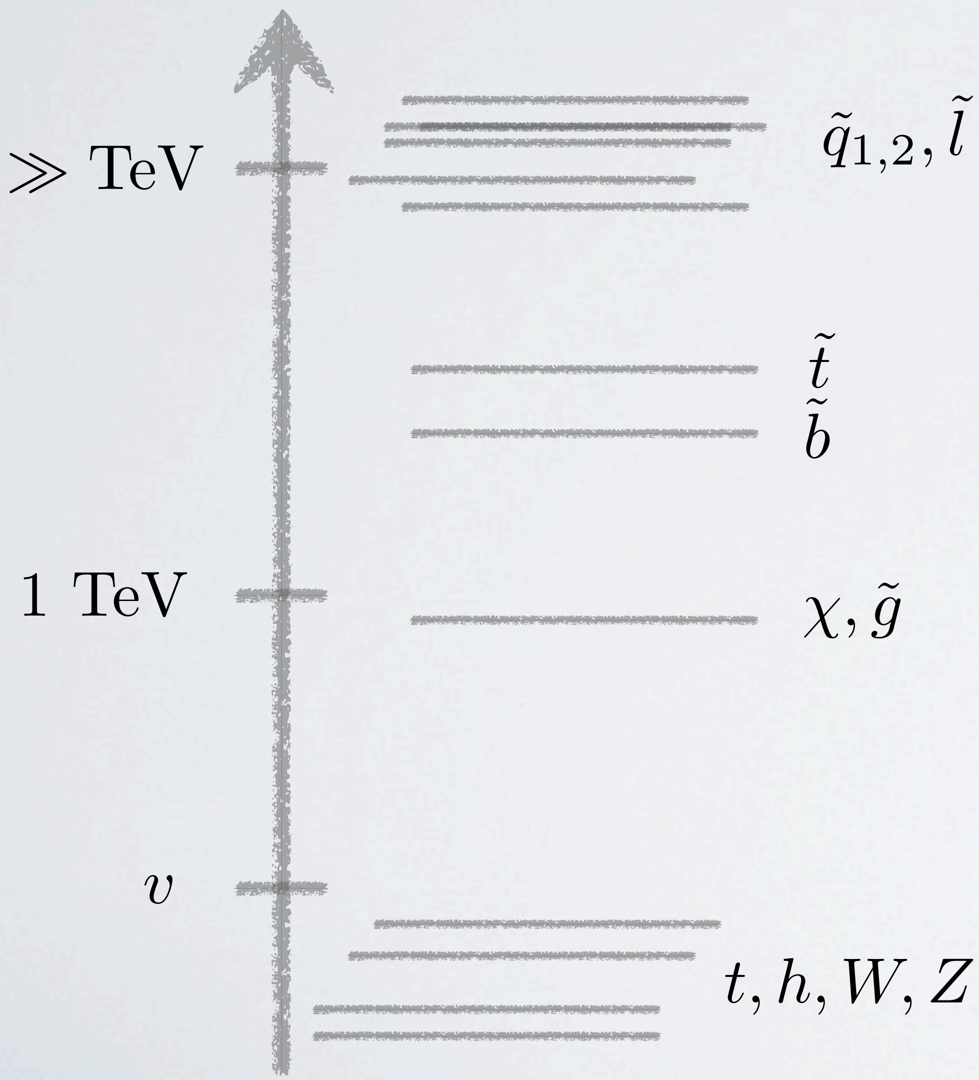

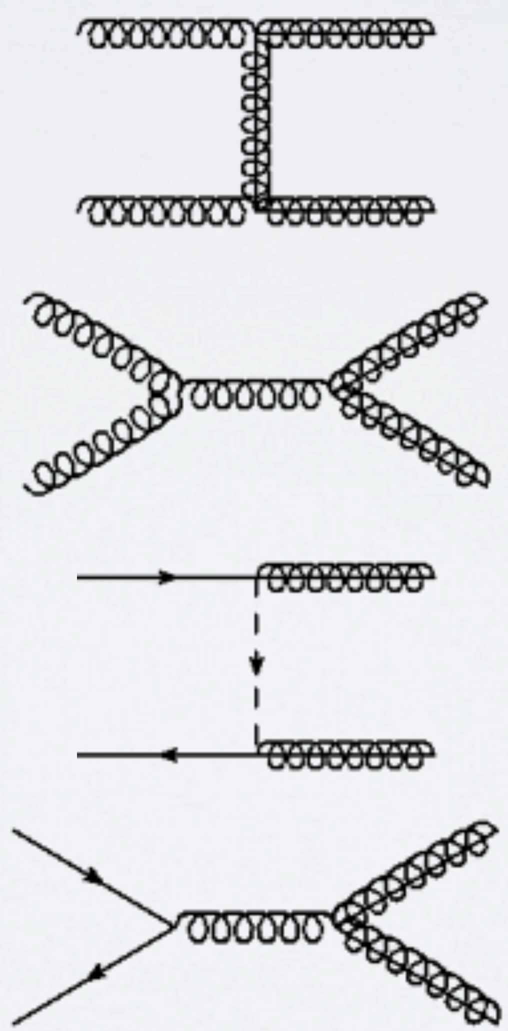

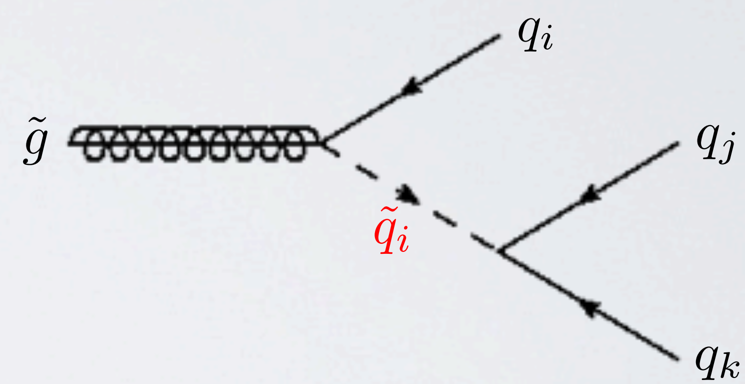

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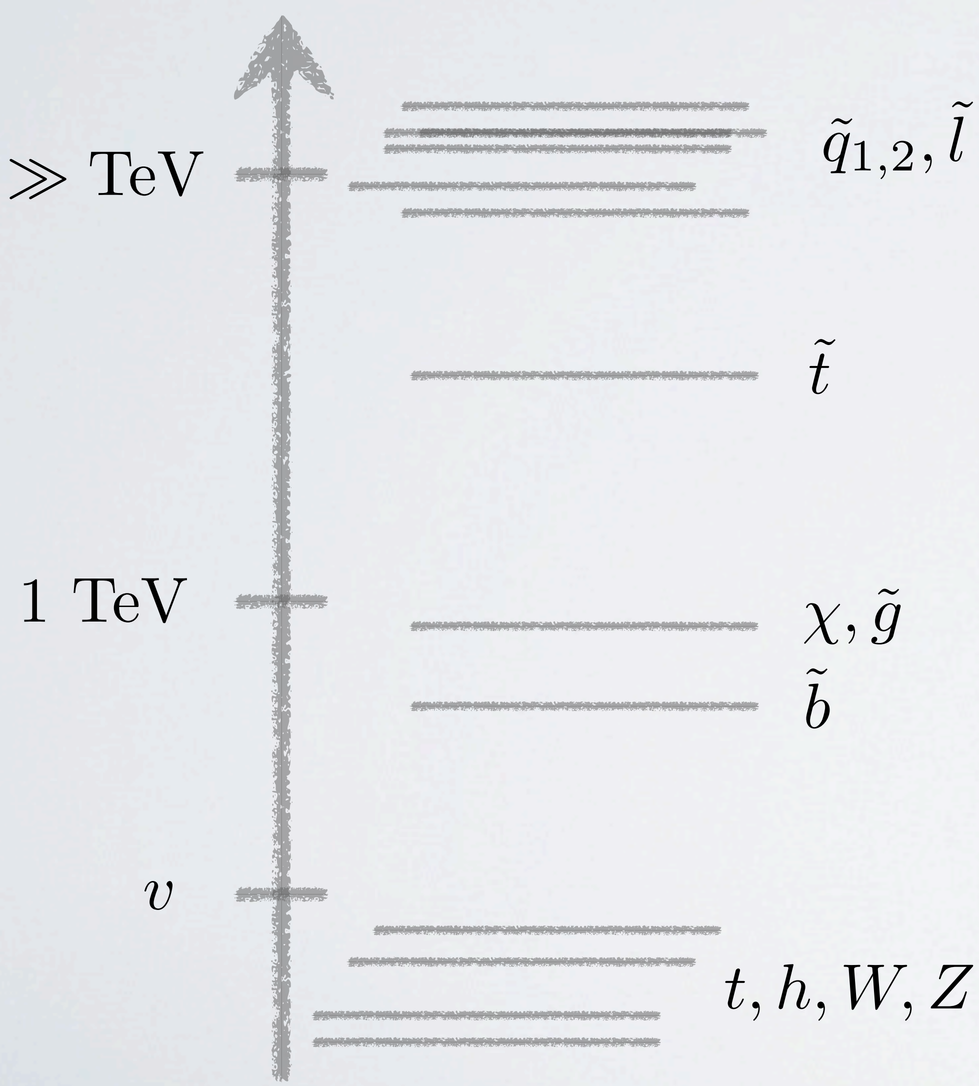

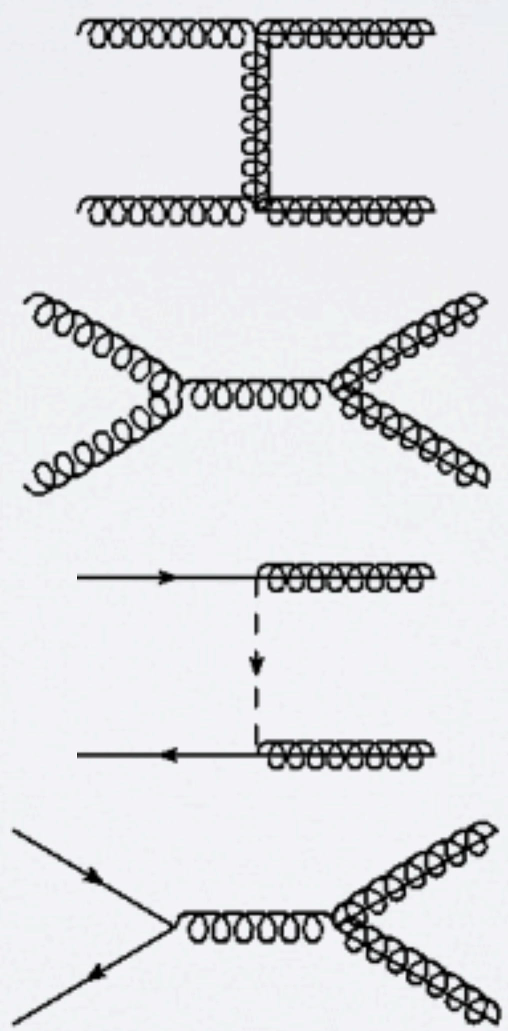

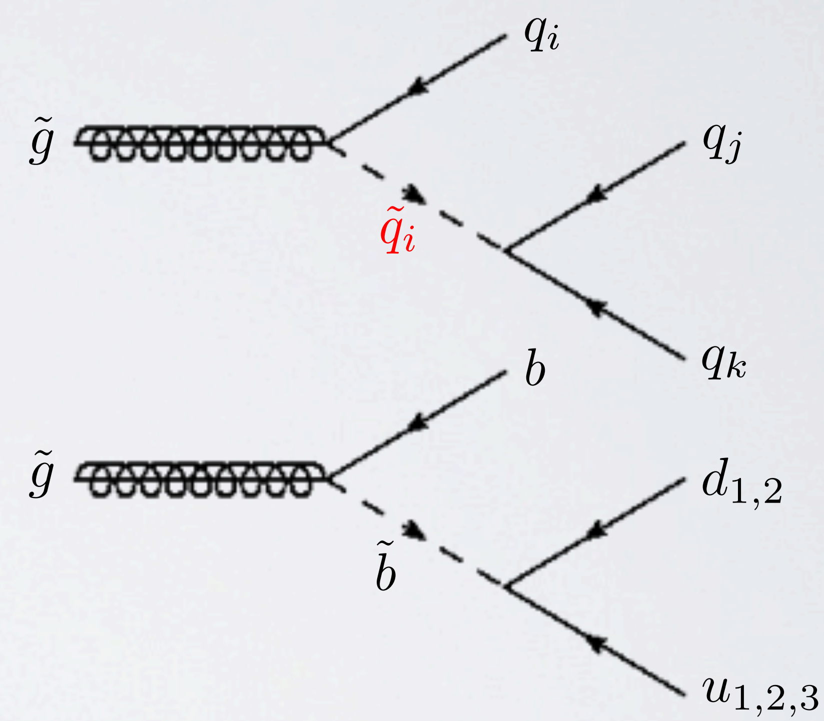

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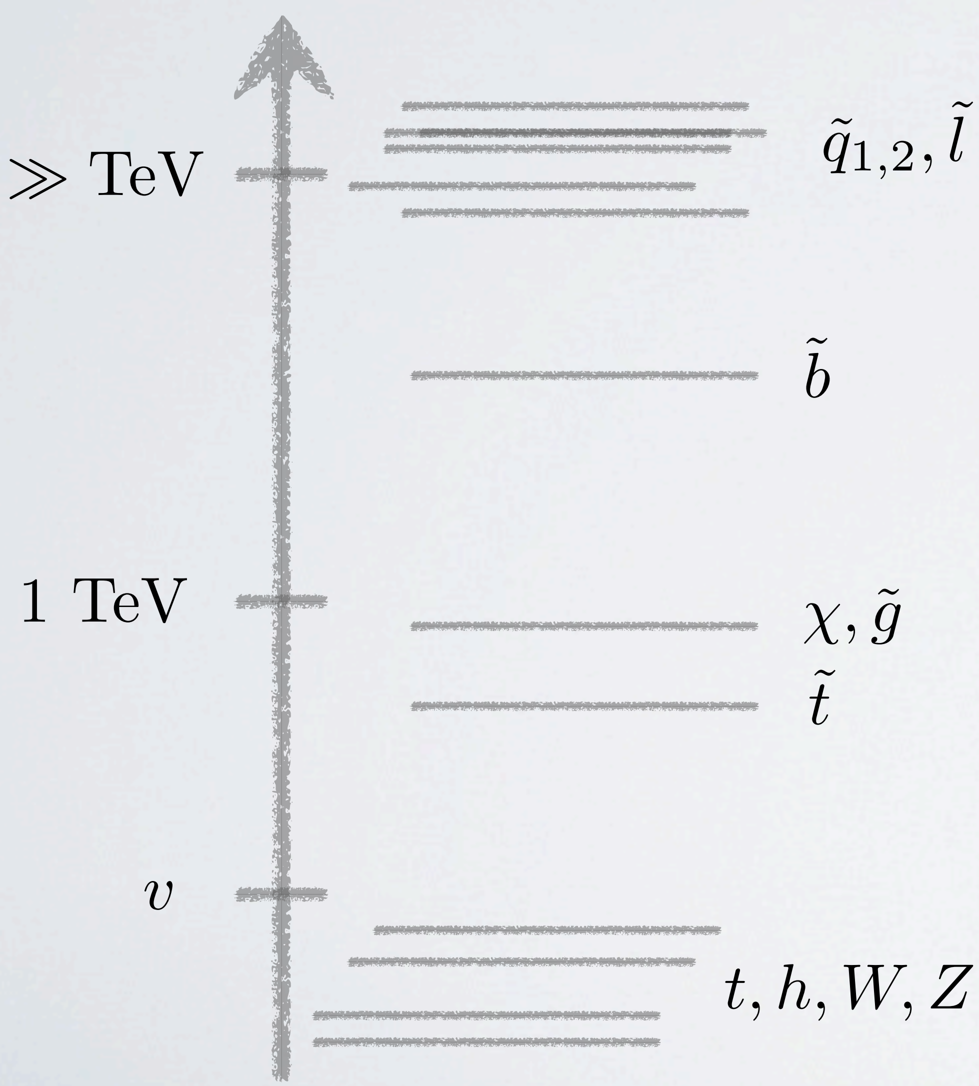

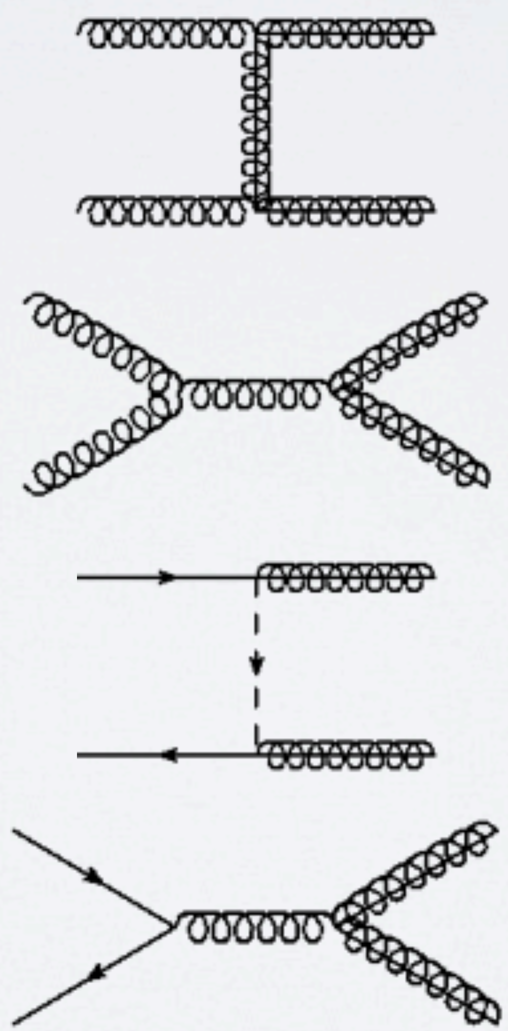

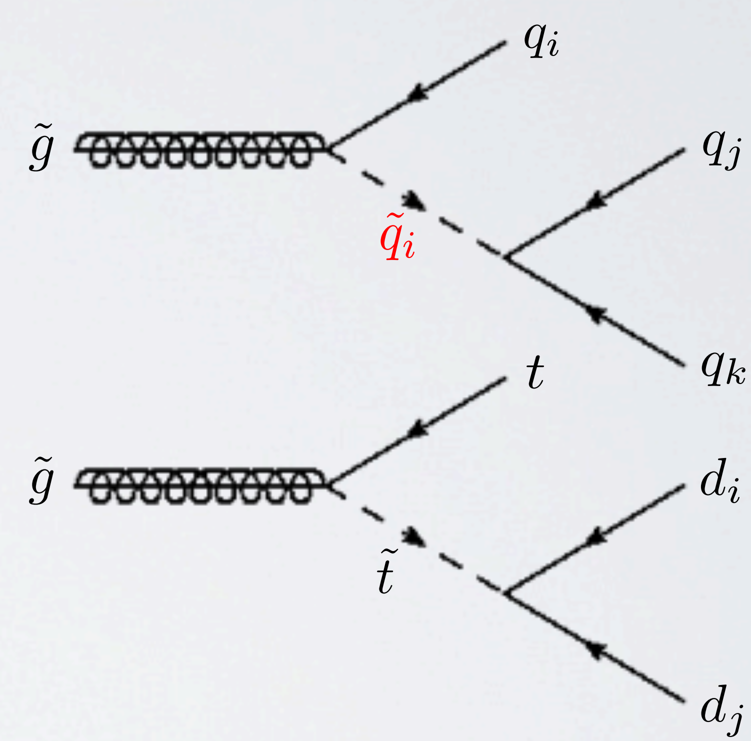

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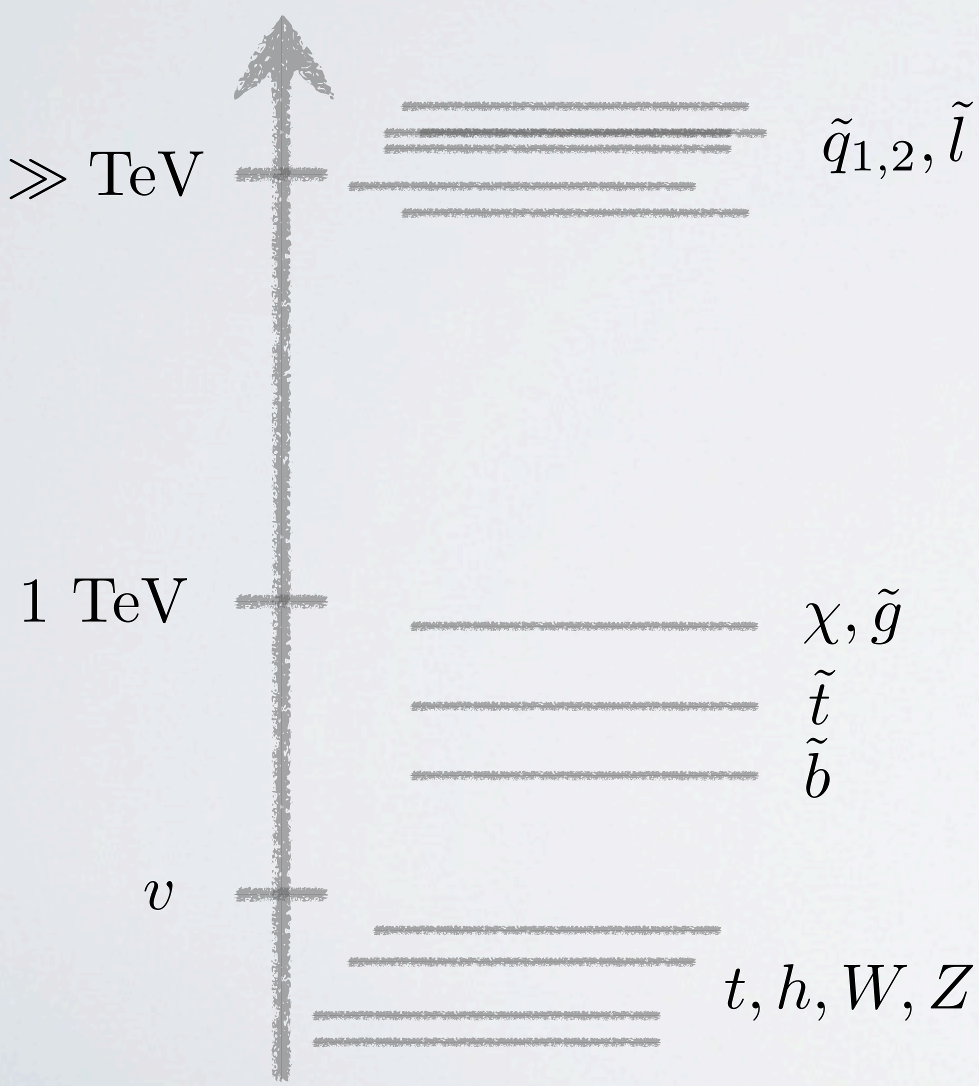

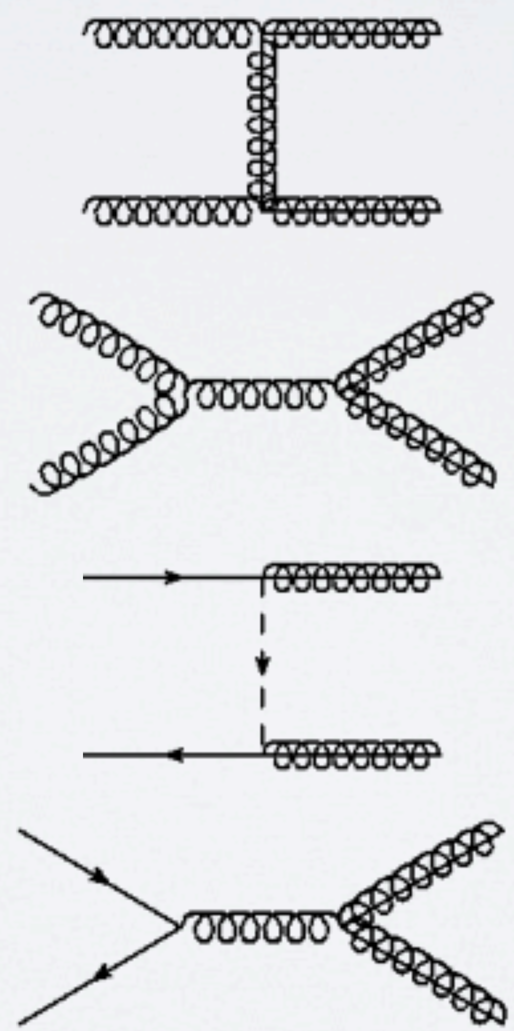

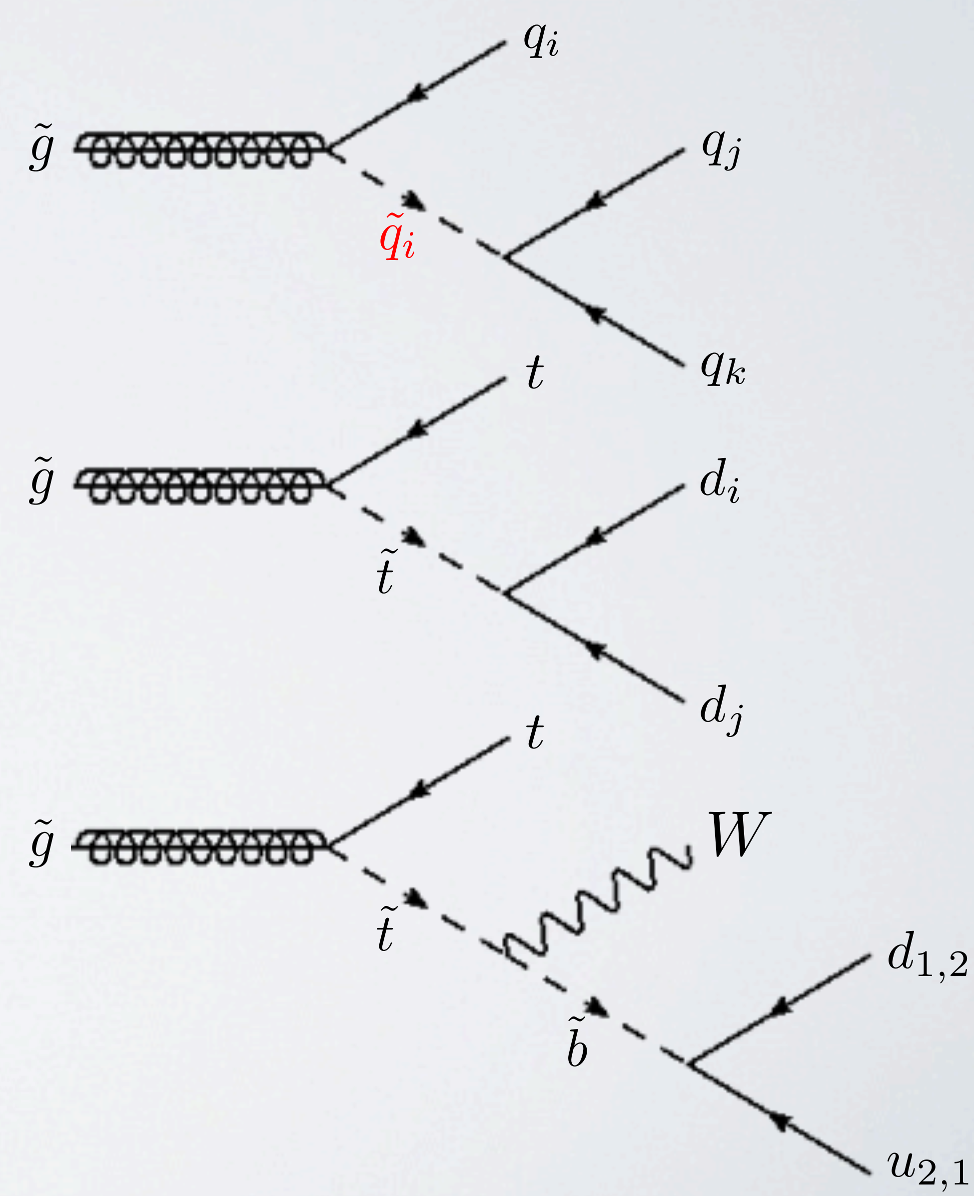

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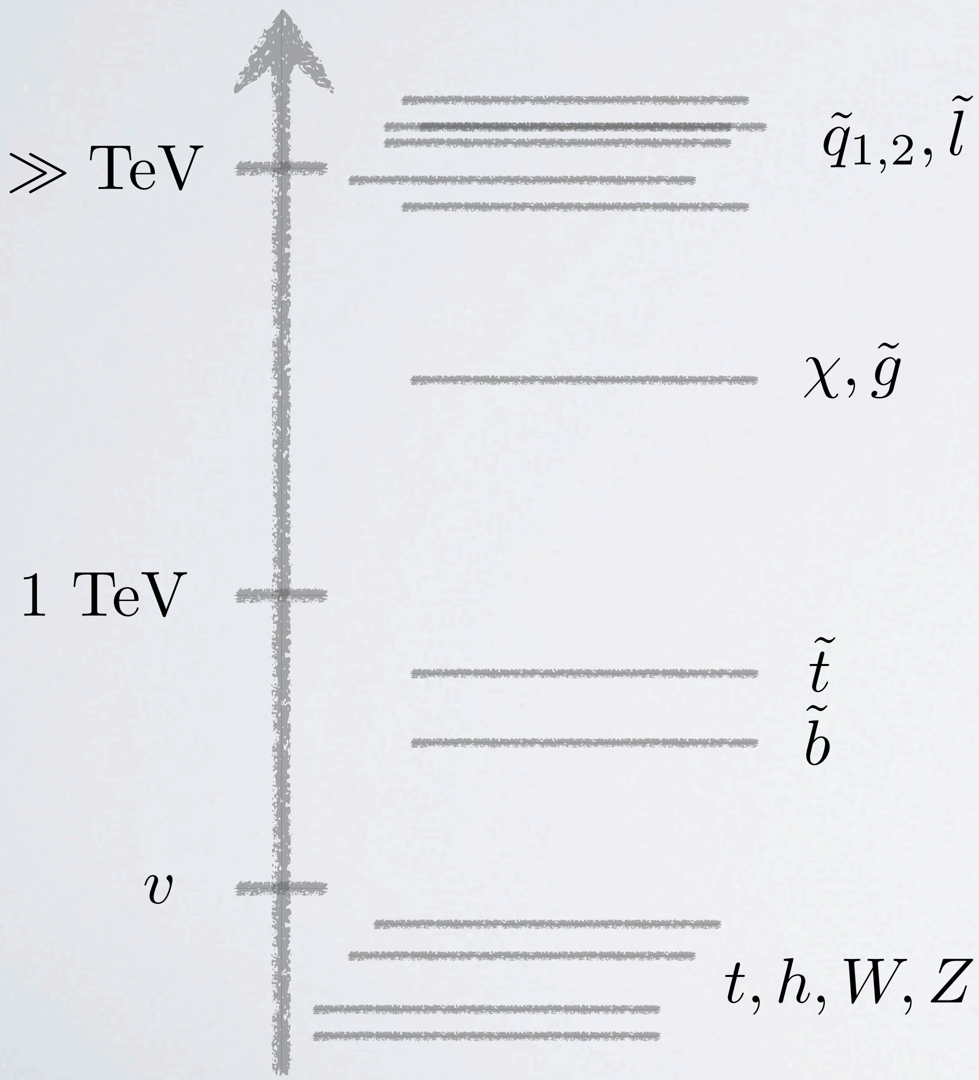

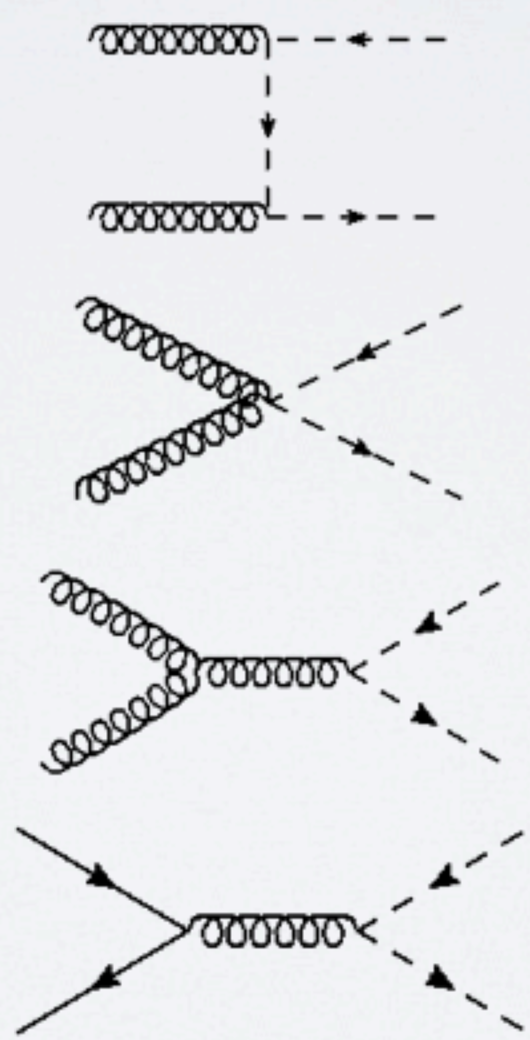

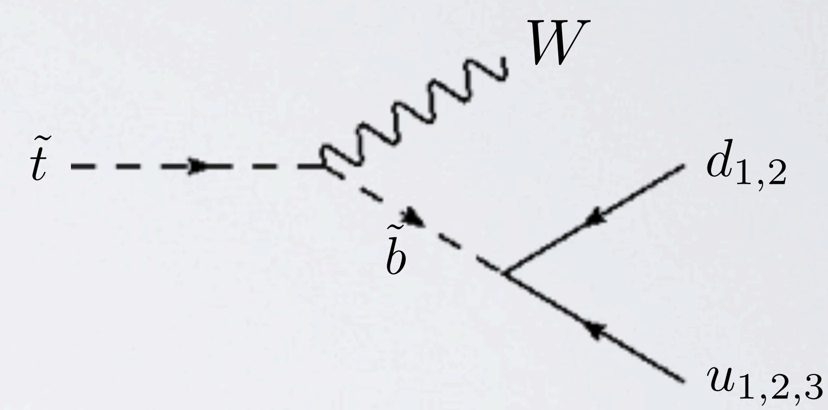

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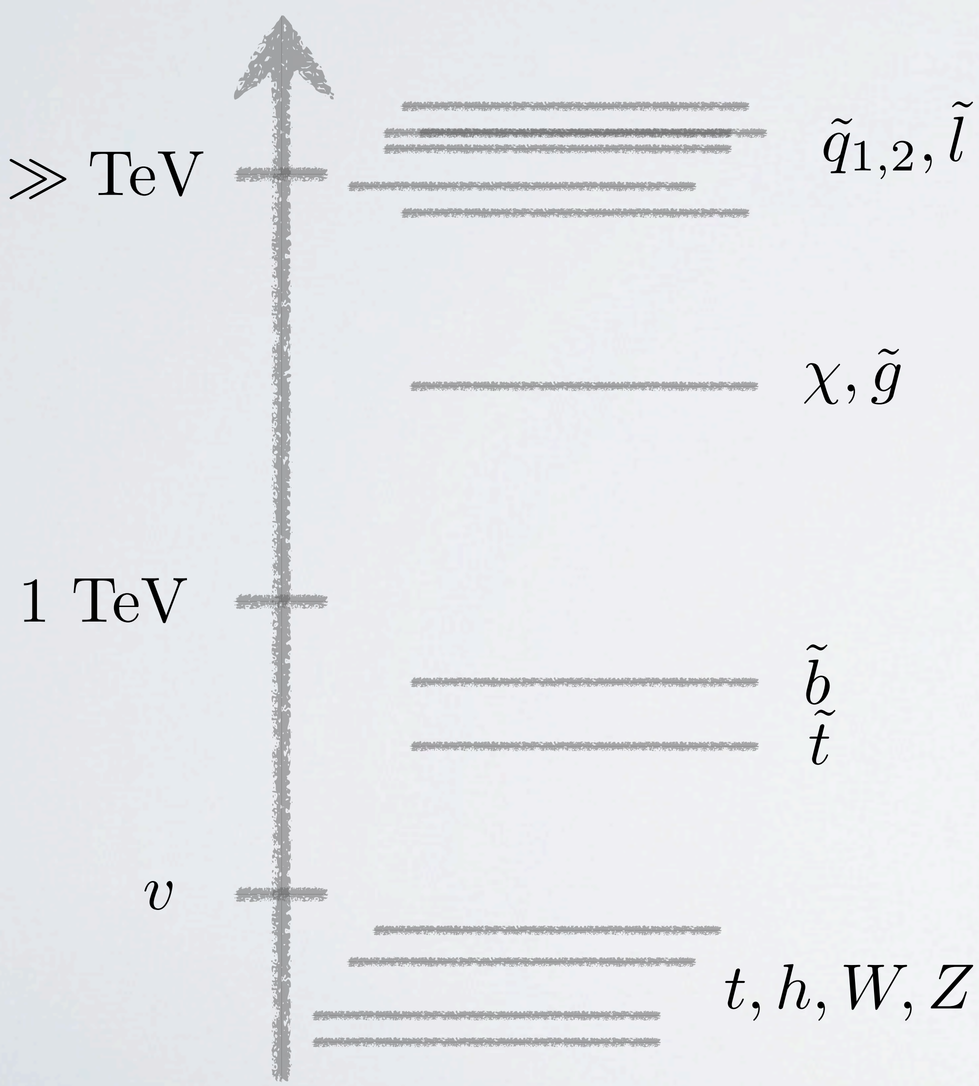

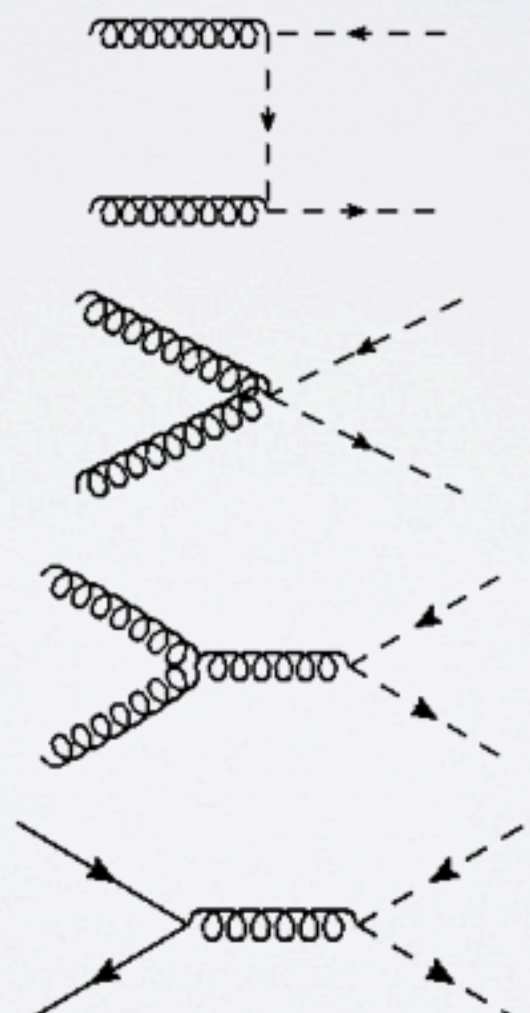

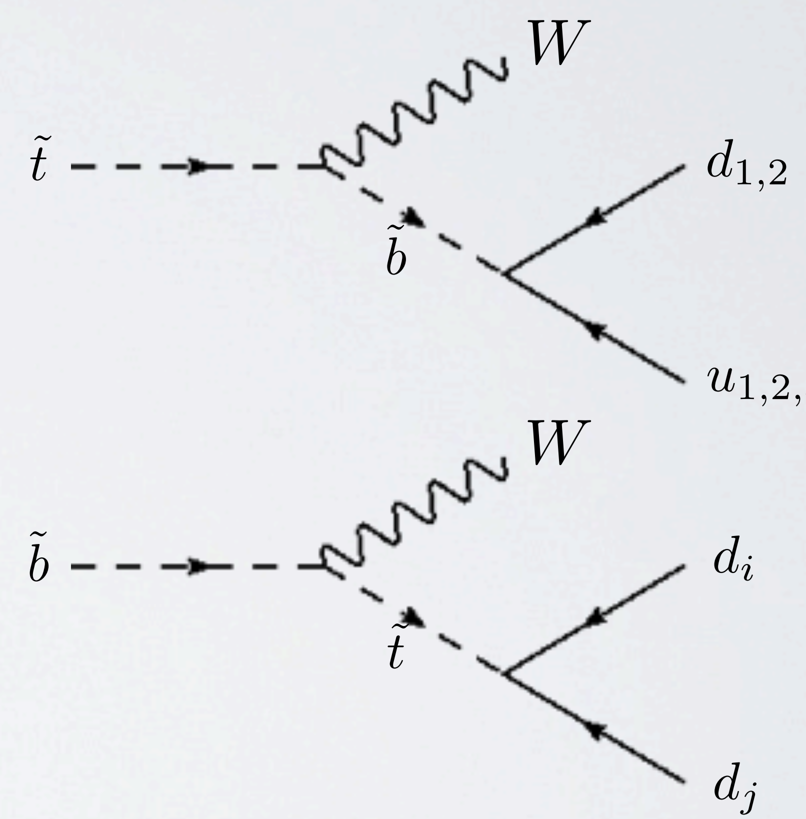

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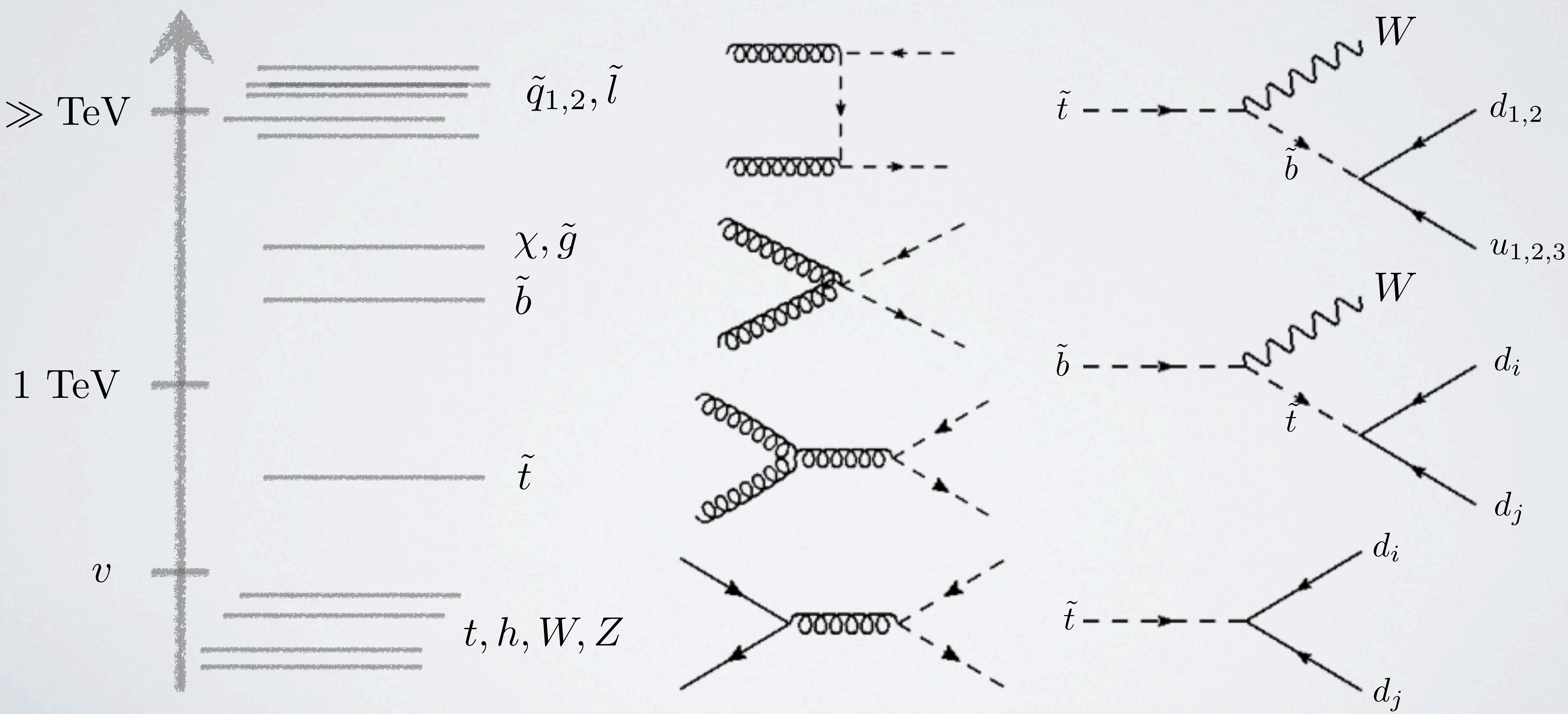

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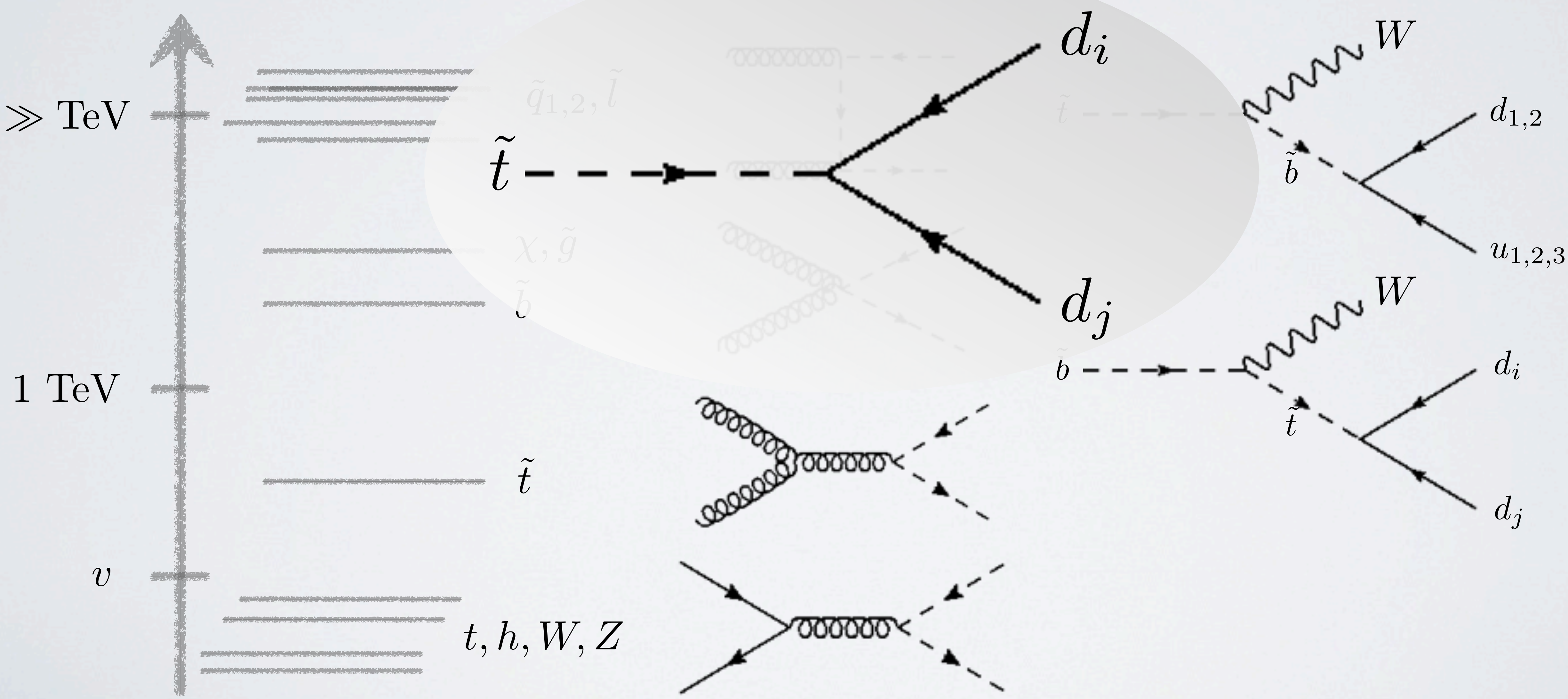

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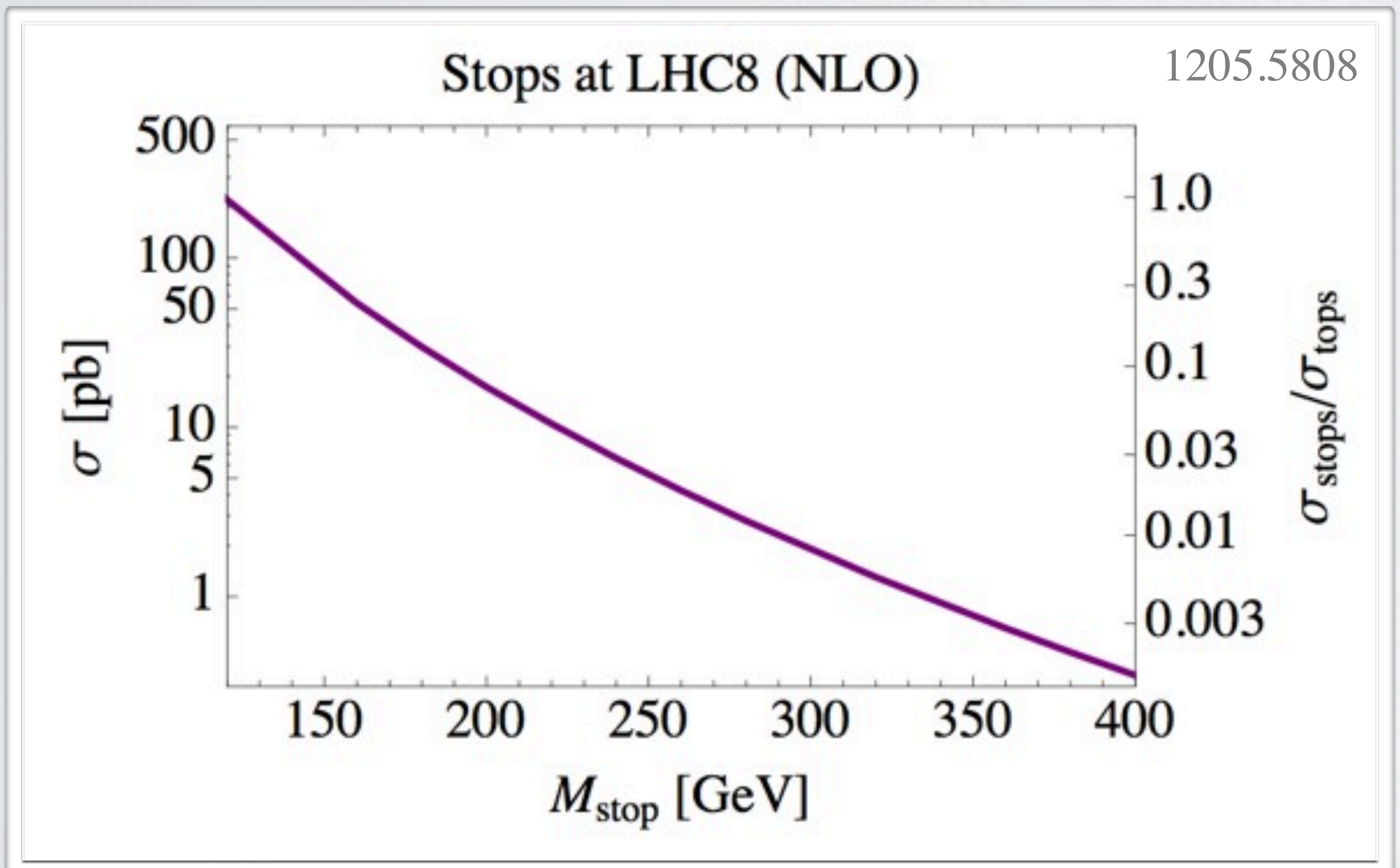
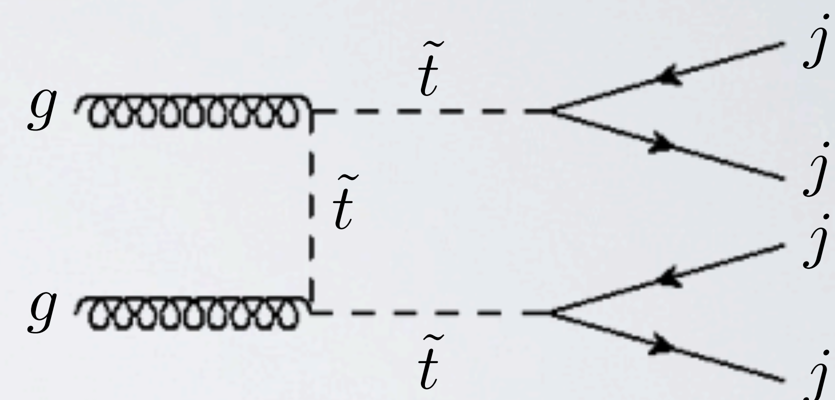
STOP PAIR PRODUCTION

- 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 strong quantum numbers





- 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

STOP 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

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

- 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*

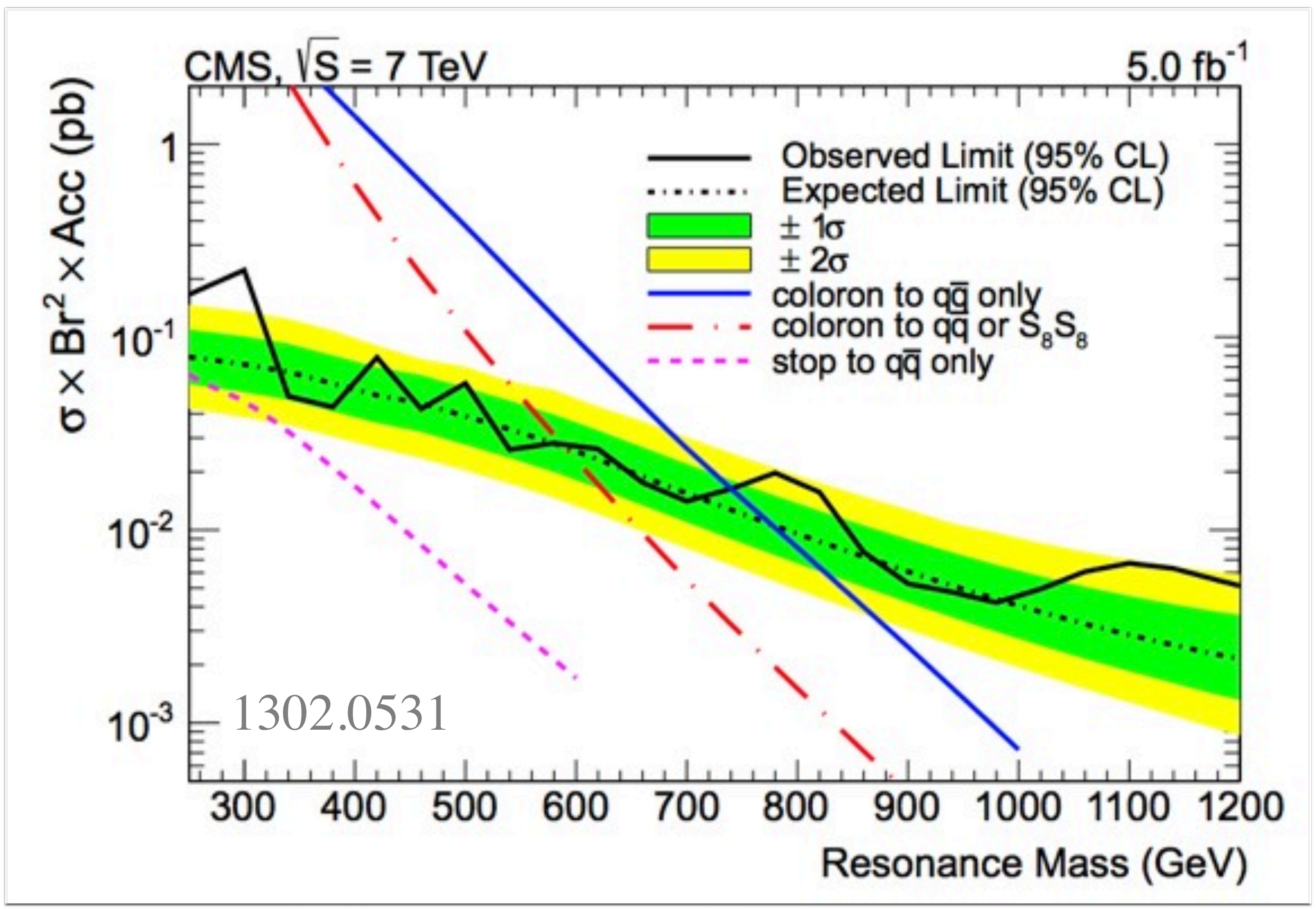
- For small BRs into heavy flavors searches are very difficult, but assuming large BRs into heavy flavors stop pair production can be observed at the LHC

CURRENT LIMITS

- Searches at LEP and Tevatron have set a bound

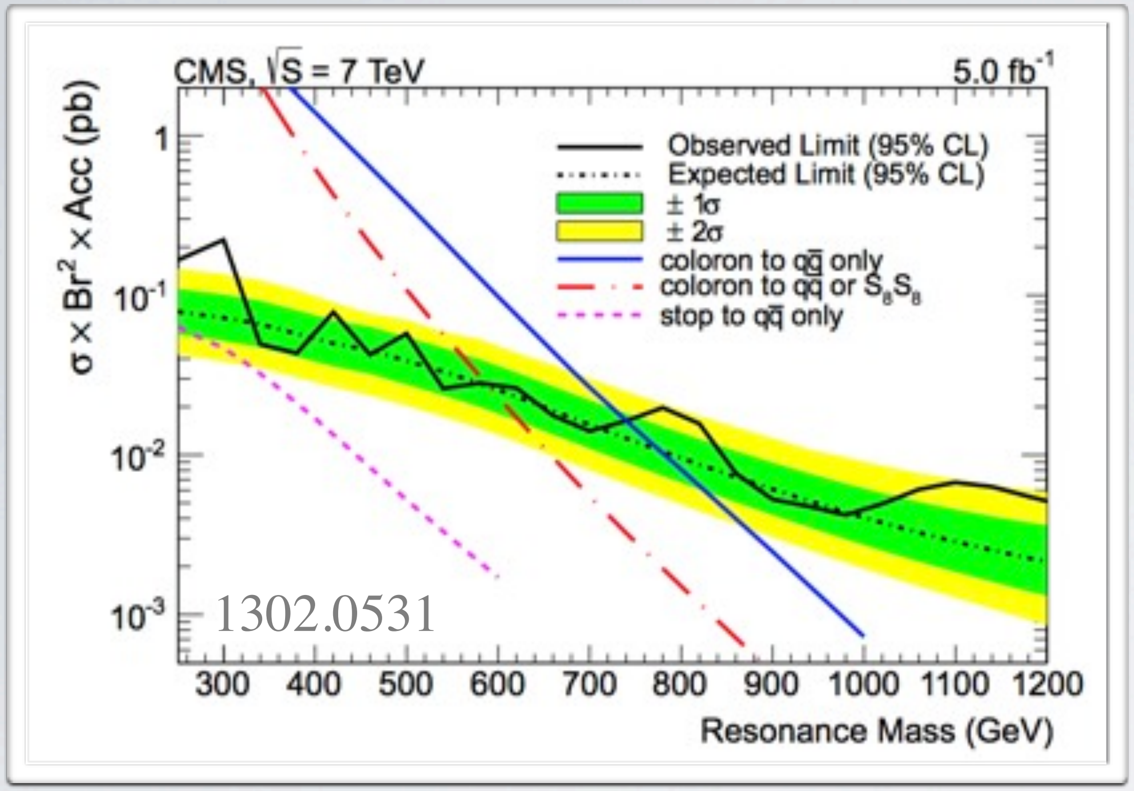
$$m_{\tilde{t}} \geq 100\ \text{GeV}$$

- 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 with b-tagging techniques LHC data can already exclude stops in the very light mass region (at the hearth 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

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

$|\eta_j| < 2.5$

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

$\delta_m < 0.075$

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

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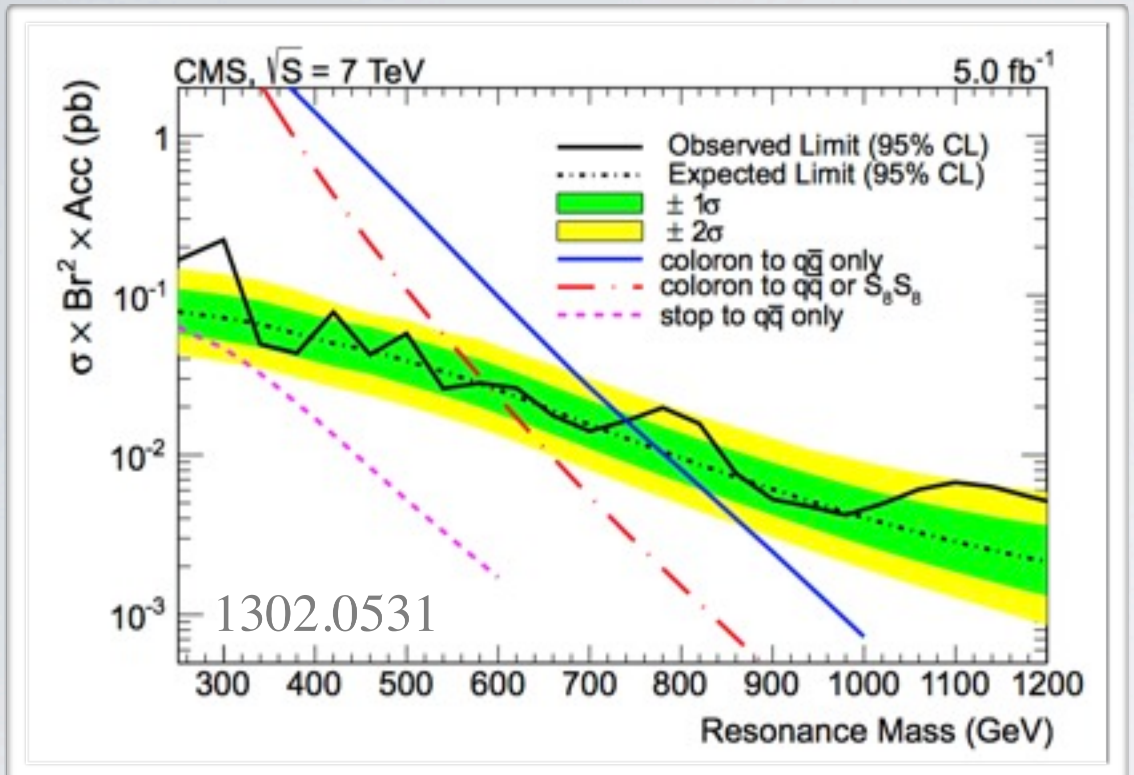

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Ang. pairing: $\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1|$

Main cuts: at least 4j with

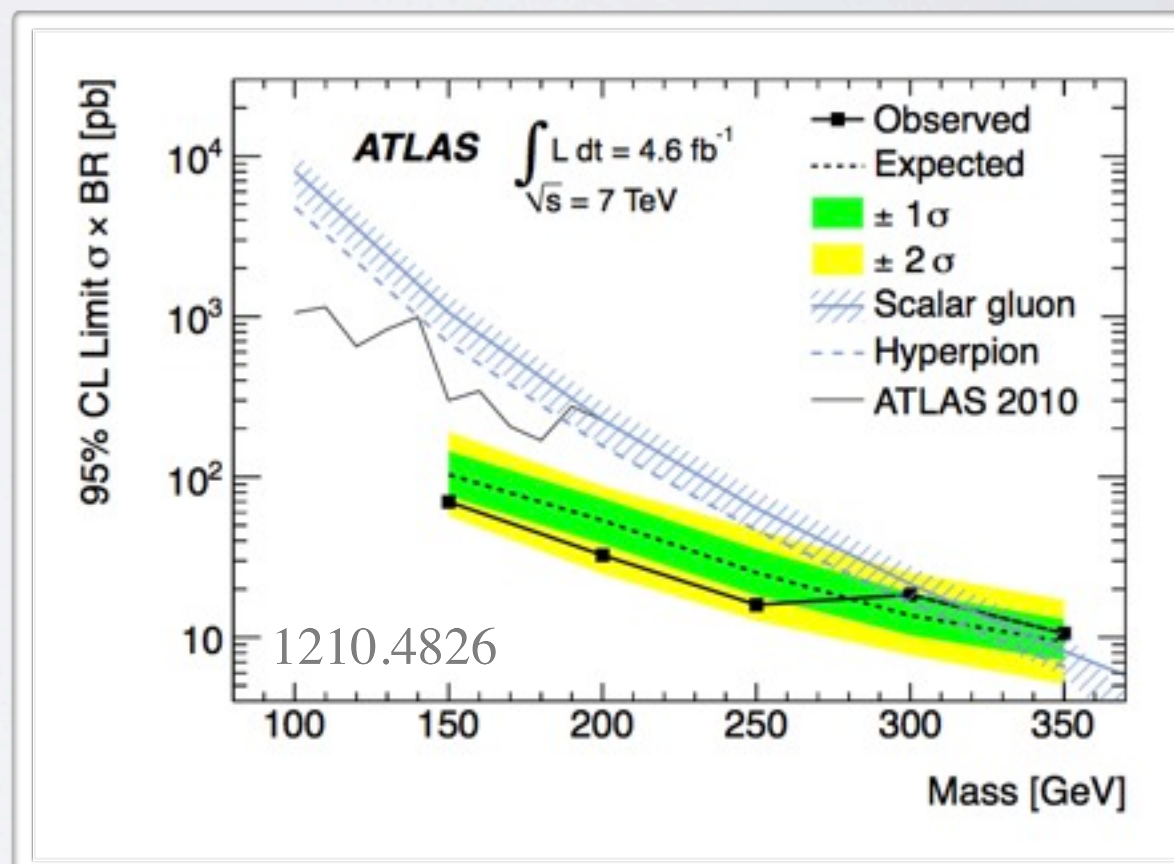
$p_{T\,j} > 80$ GeV

$|\eta_j| < 1.4$

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

$\delta_m < 0.15$

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



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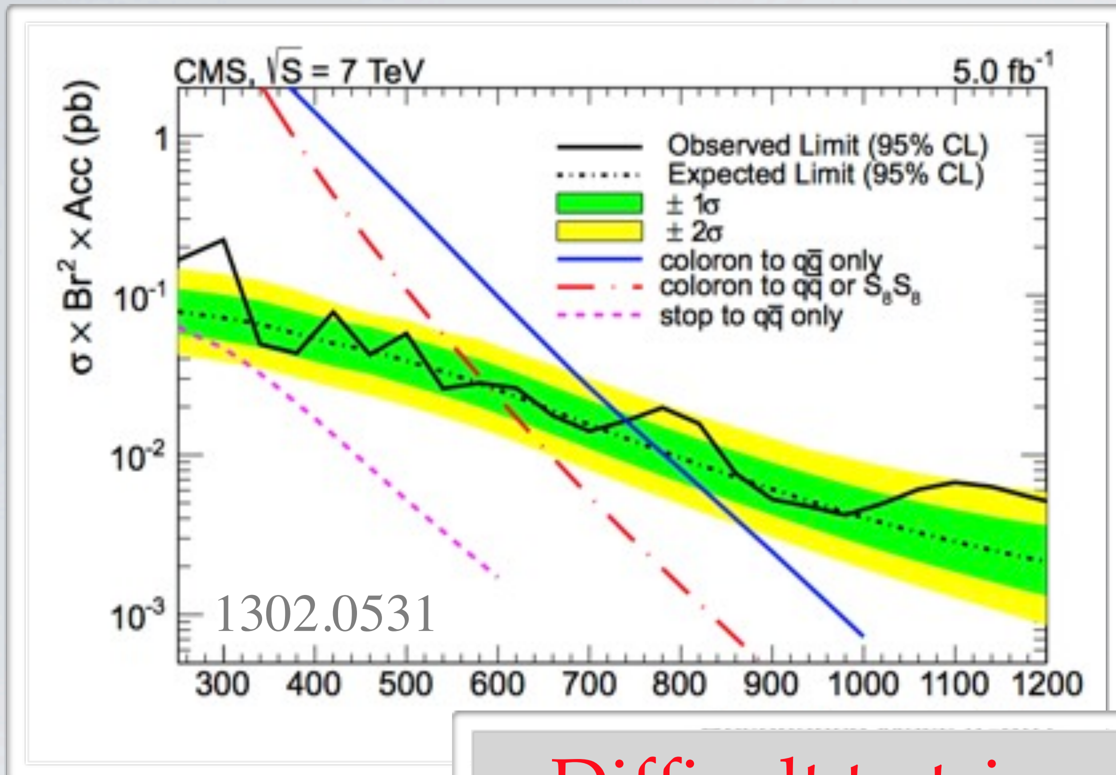

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Difficult to trigger on events with low pT jets

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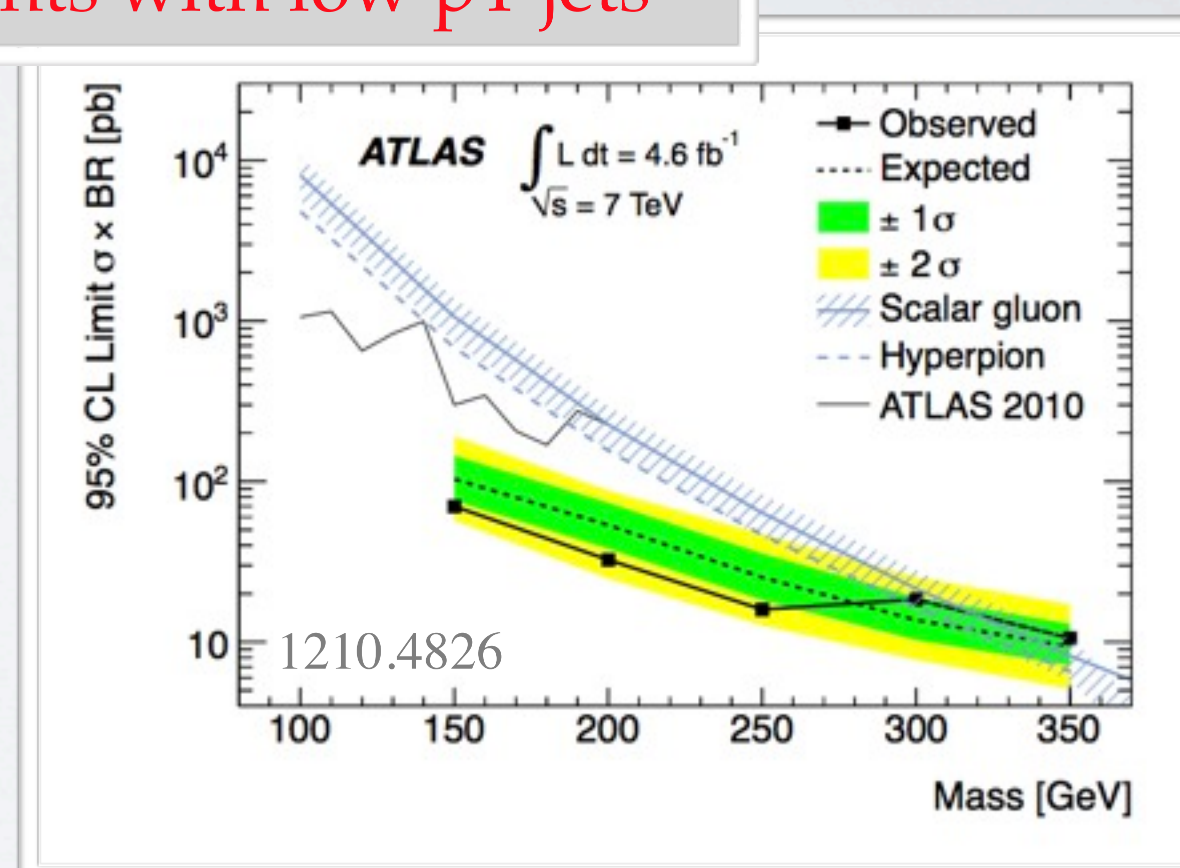

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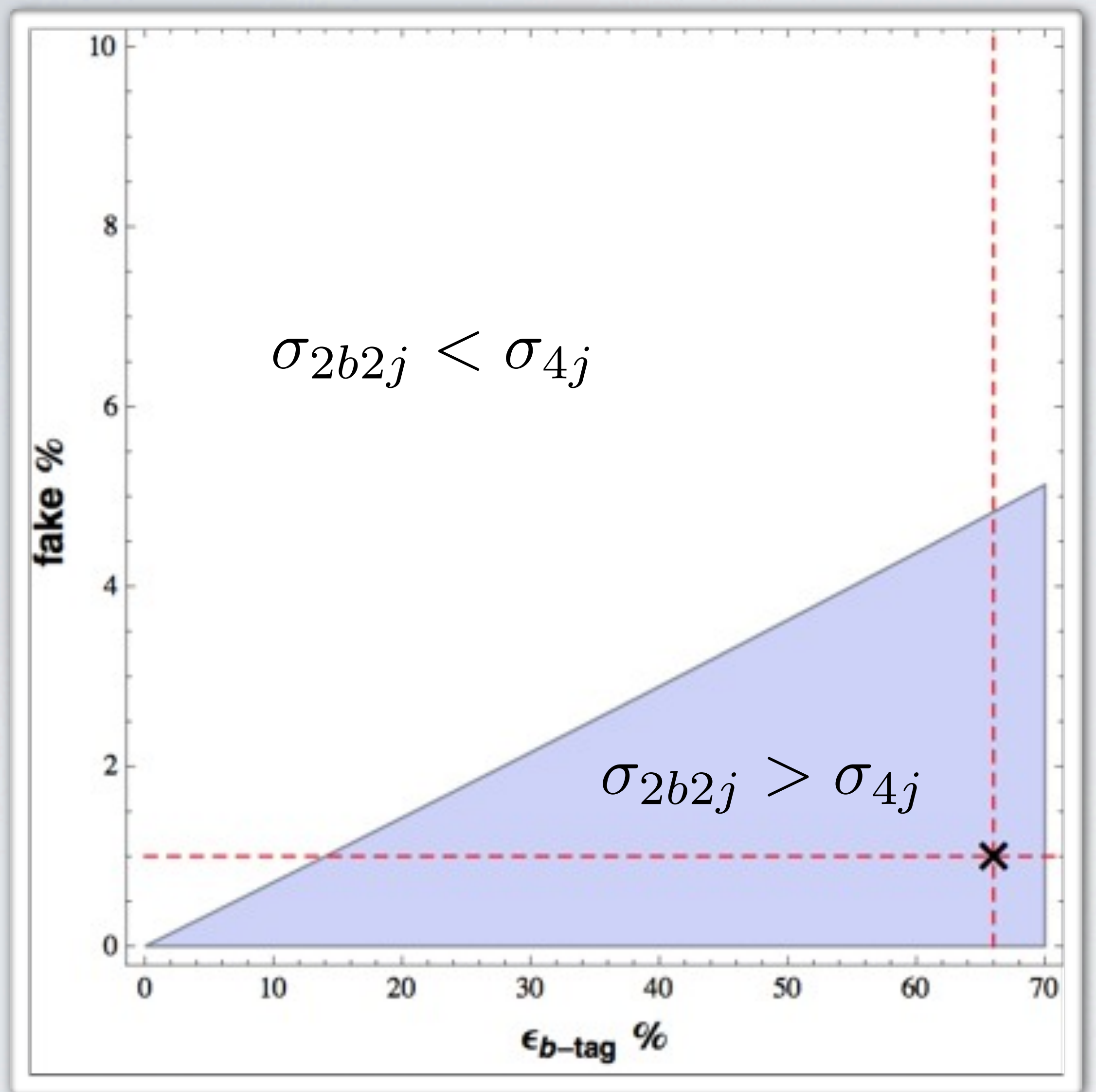
B-TAGGING

- 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, $|\eta| < 3.5$, $\Delta R > 0.4$

	0 b-tag	1 b-tag	2 b-tag
$\sigma_{4j}^{(8\text{TeV})}$	5 nb	200 pb	3 pb
$\sigma_{2b2j}^{(8\text{TeV})}$	136 pb	90 pb	59 pb

MG5 with selections $p_T > 75$ GeV, $|\eta| < 3.5$, $\Delta R > 0.4$

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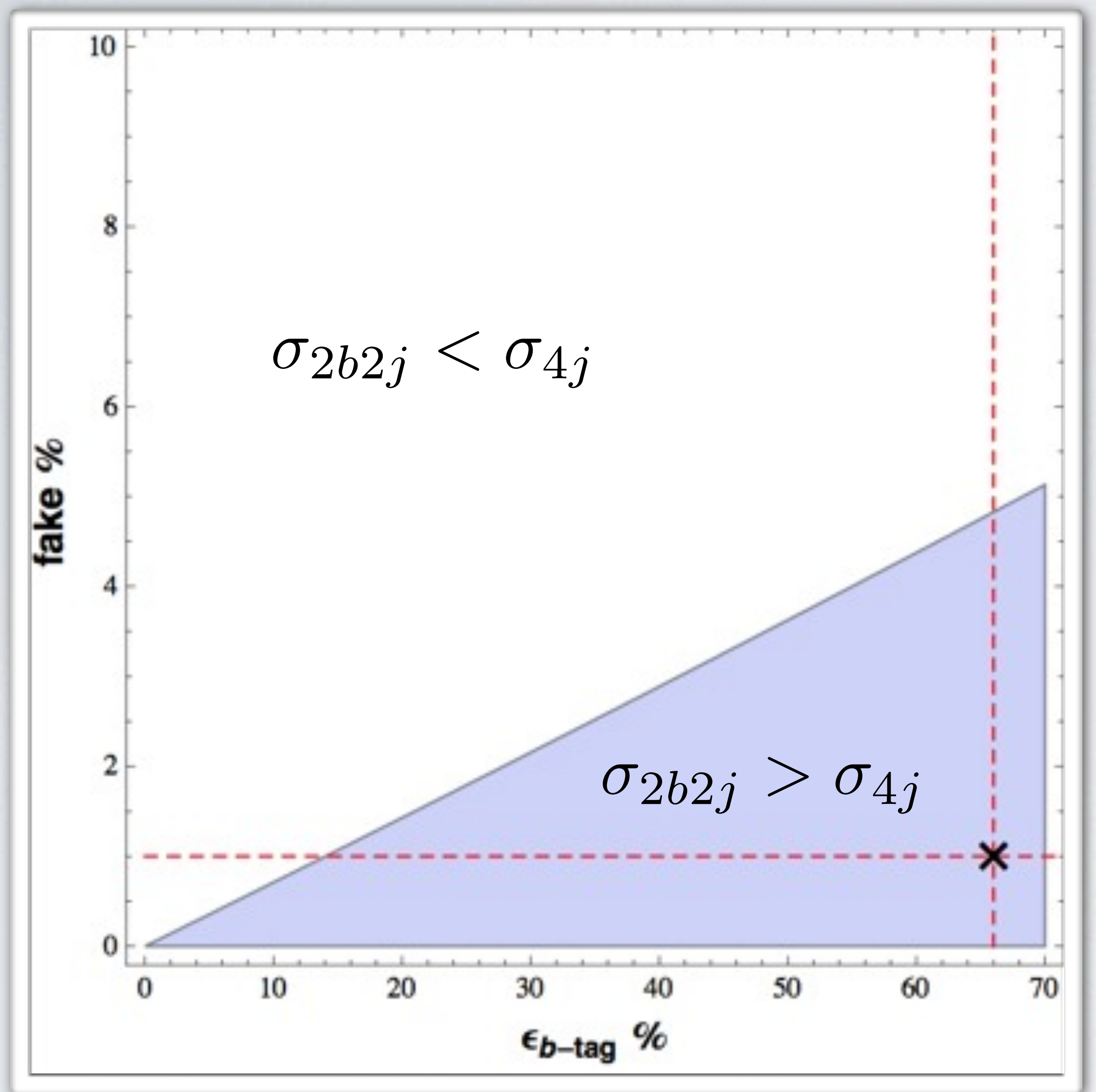

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MG5 with selections $p_T > 35$ GeV, $|\eta| < 3.5$, $\Delta R > 0.4$

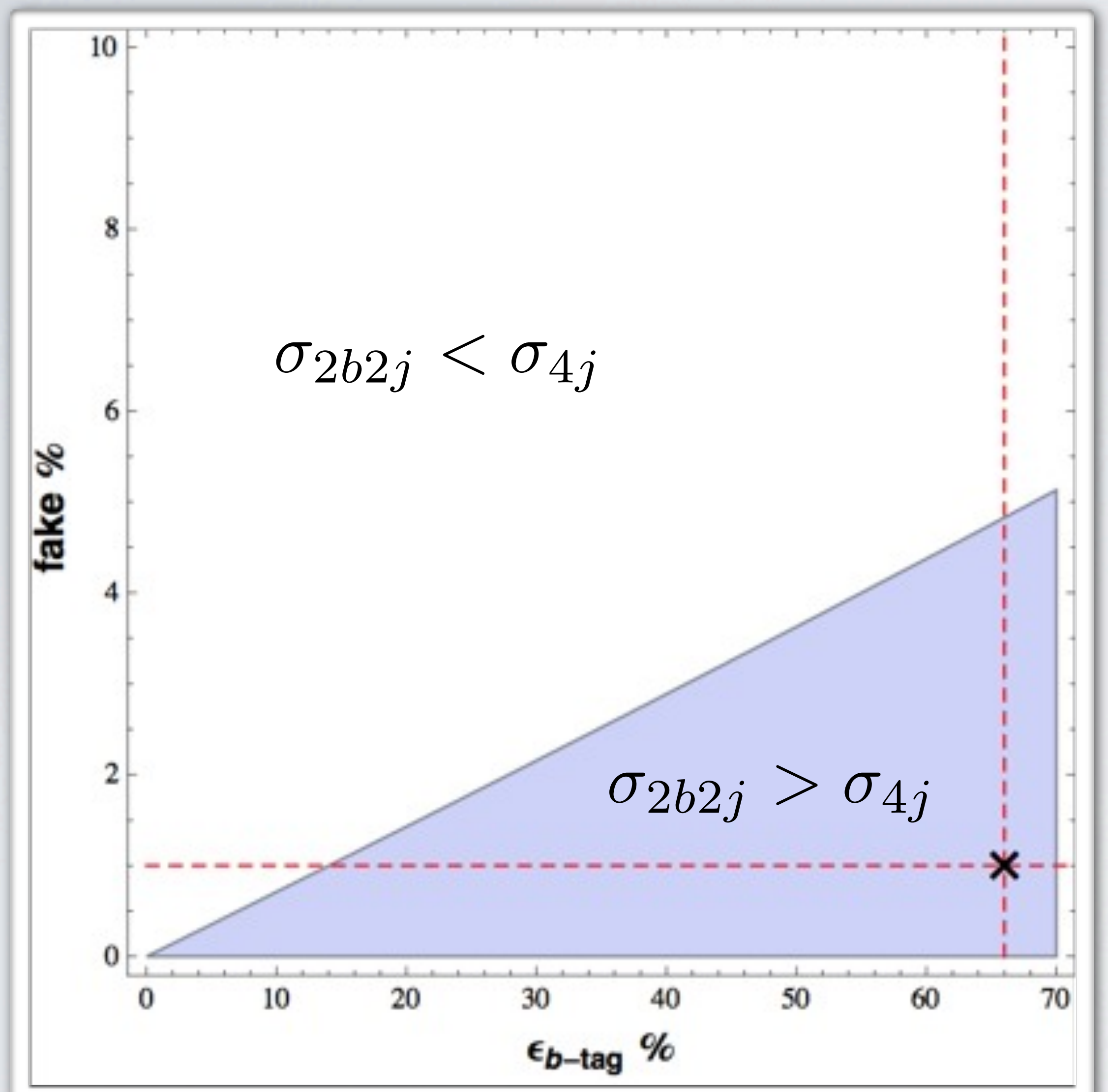
	0 b-tag	1 b-tag	2 b-tag
$\sigma_{4j}^{(8\text{TeV})}$	5 nb	200 pb	3 pb
$\sigma_{2b2j}^{(8\text{TeV})}$	136 pb	90 pb	59 pb

MG5 with selections $p_T > 75$ GeV, $|\eta| < 3.5$, $\Delta R > 0.4$

- We can reduce main background from the 4j to the 2b2j, i.e. a factor of 36 smaller

B-TAGGING

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



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- We can reduce main background from the 4j to the 2b2j, i.e. a factor of 36 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

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

OUR ANALYSIS

- We aim at 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

$$\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1| \qquad \Delta\phi_{\rm best} = \frac{\Delta\phi_{ab} + \Delta\phi_{cd}}{2}$$

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

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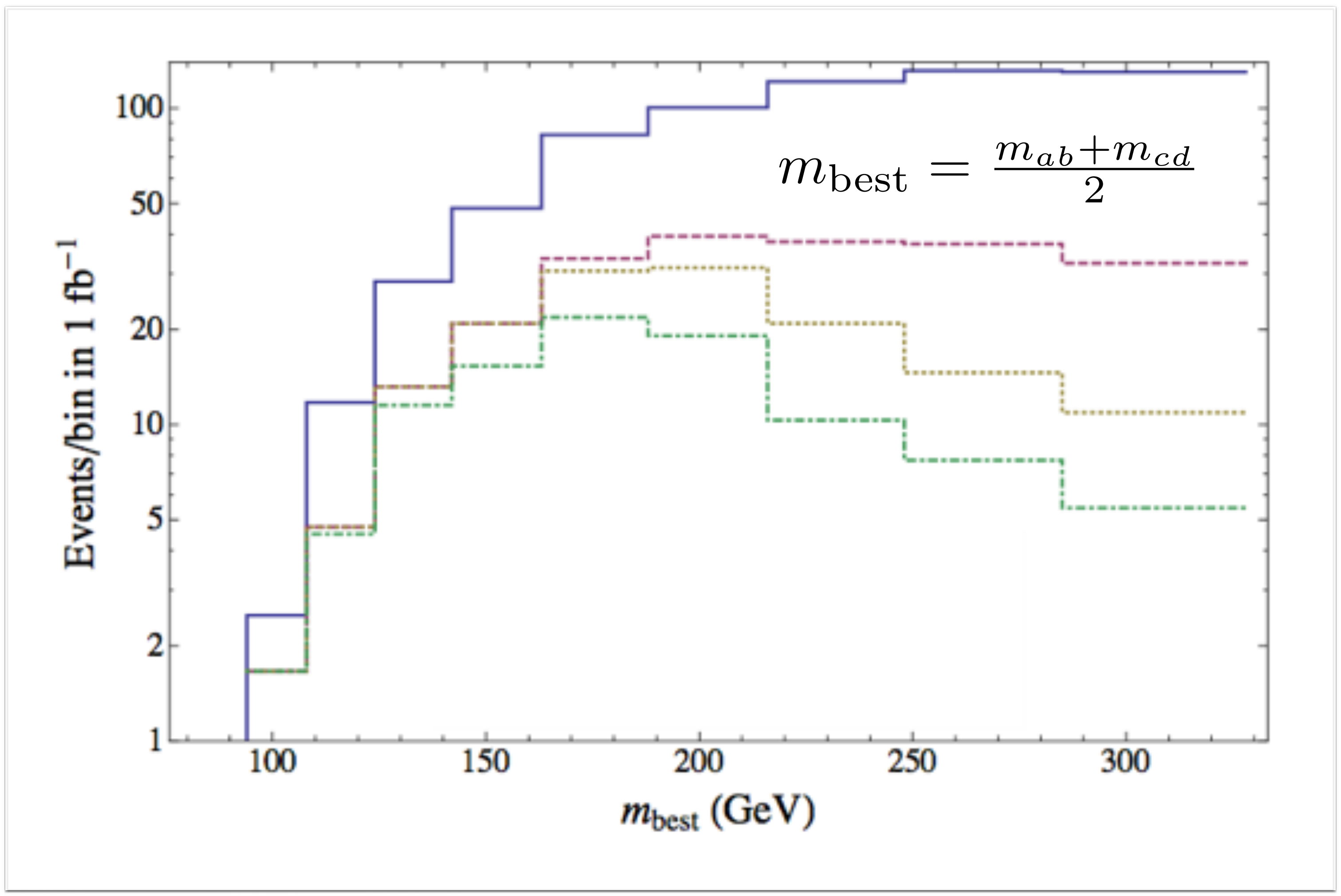
For very boosted jets we have

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



Freitag, 24. Mai 13

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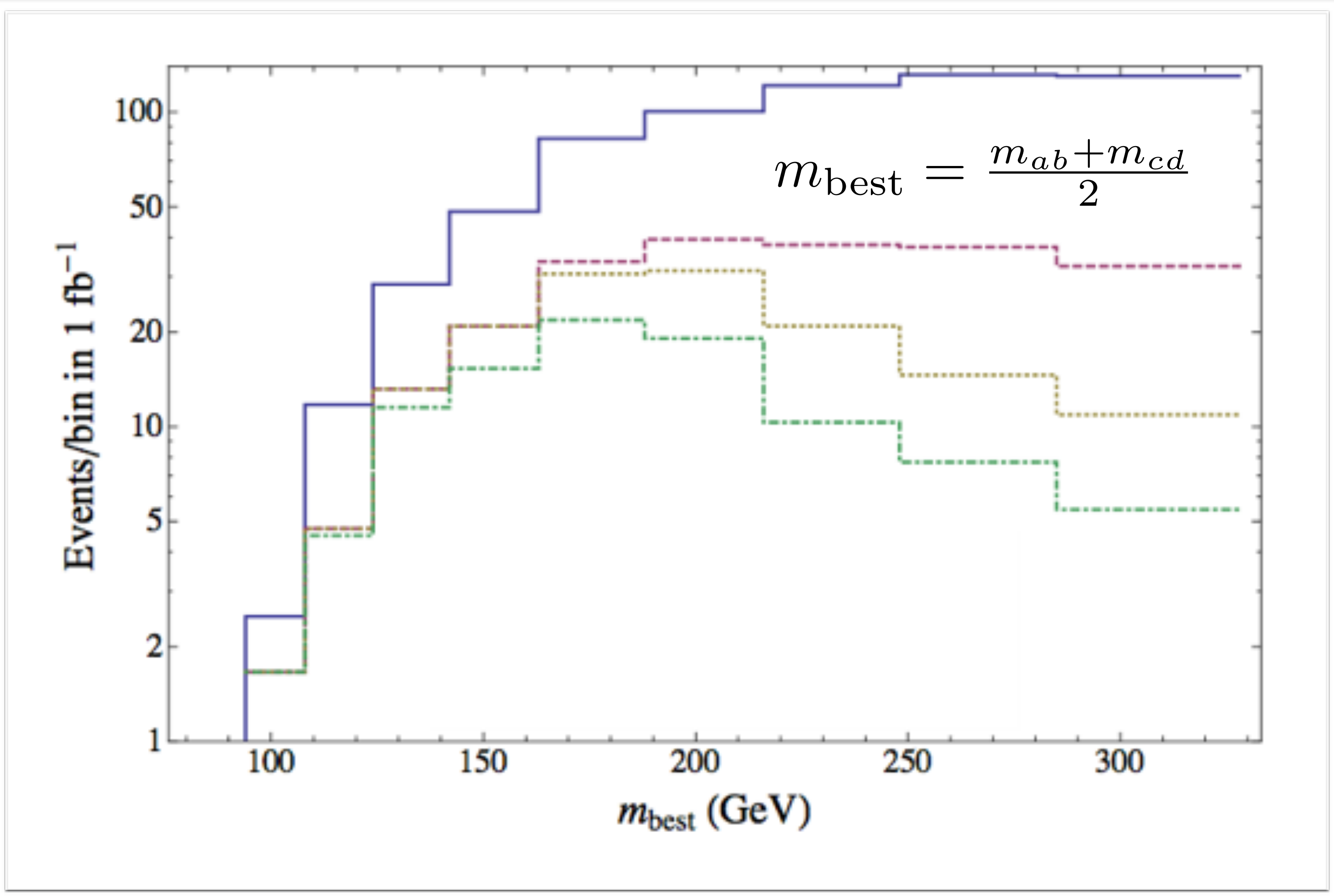

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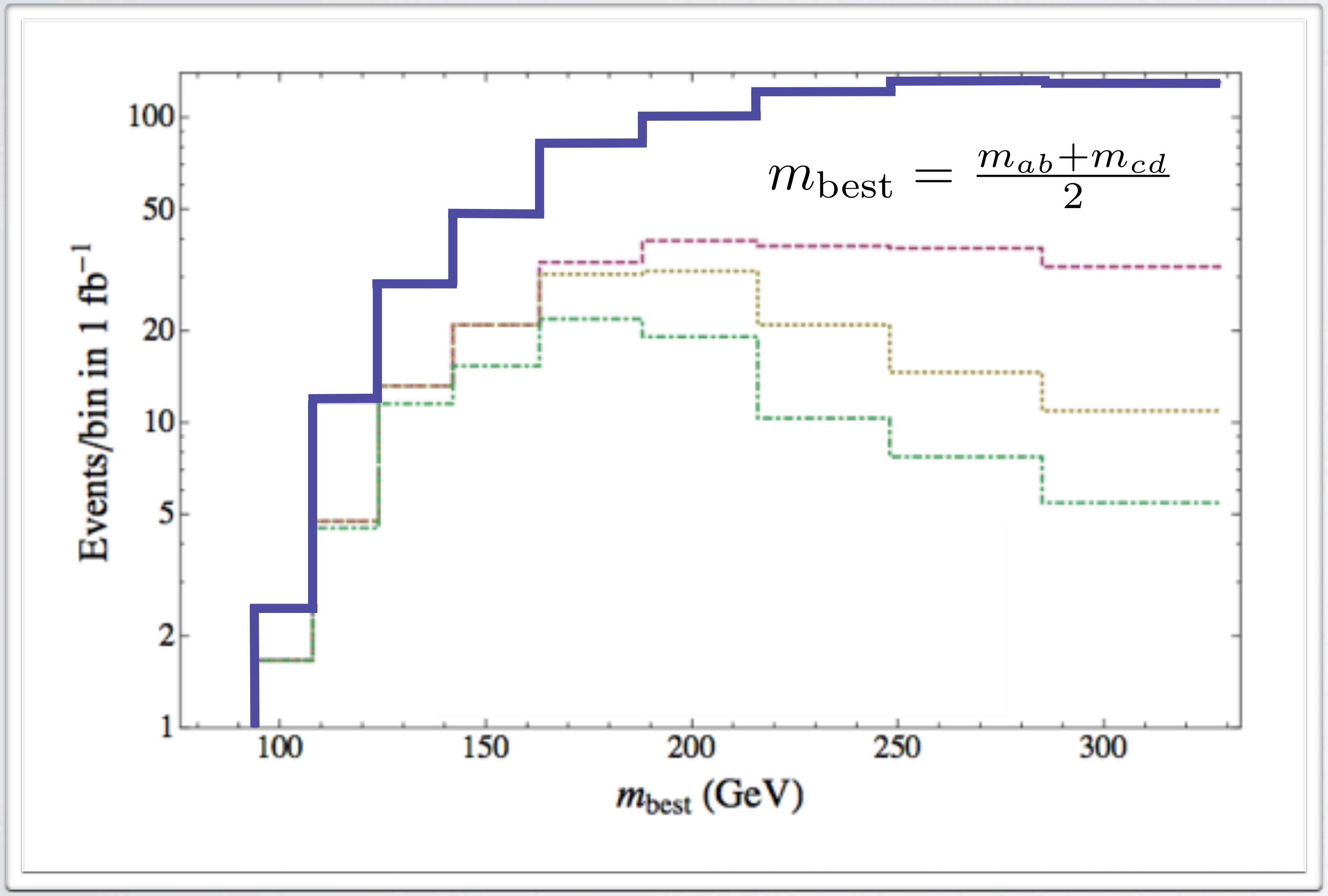
$p_{T\,j} > \frac{m_{\tilde{t}}}{2}$ $\quad |\eta| < 2.8$ $\quad \Delta R_{jj} > 0.7$

$\delta m < 0.075$



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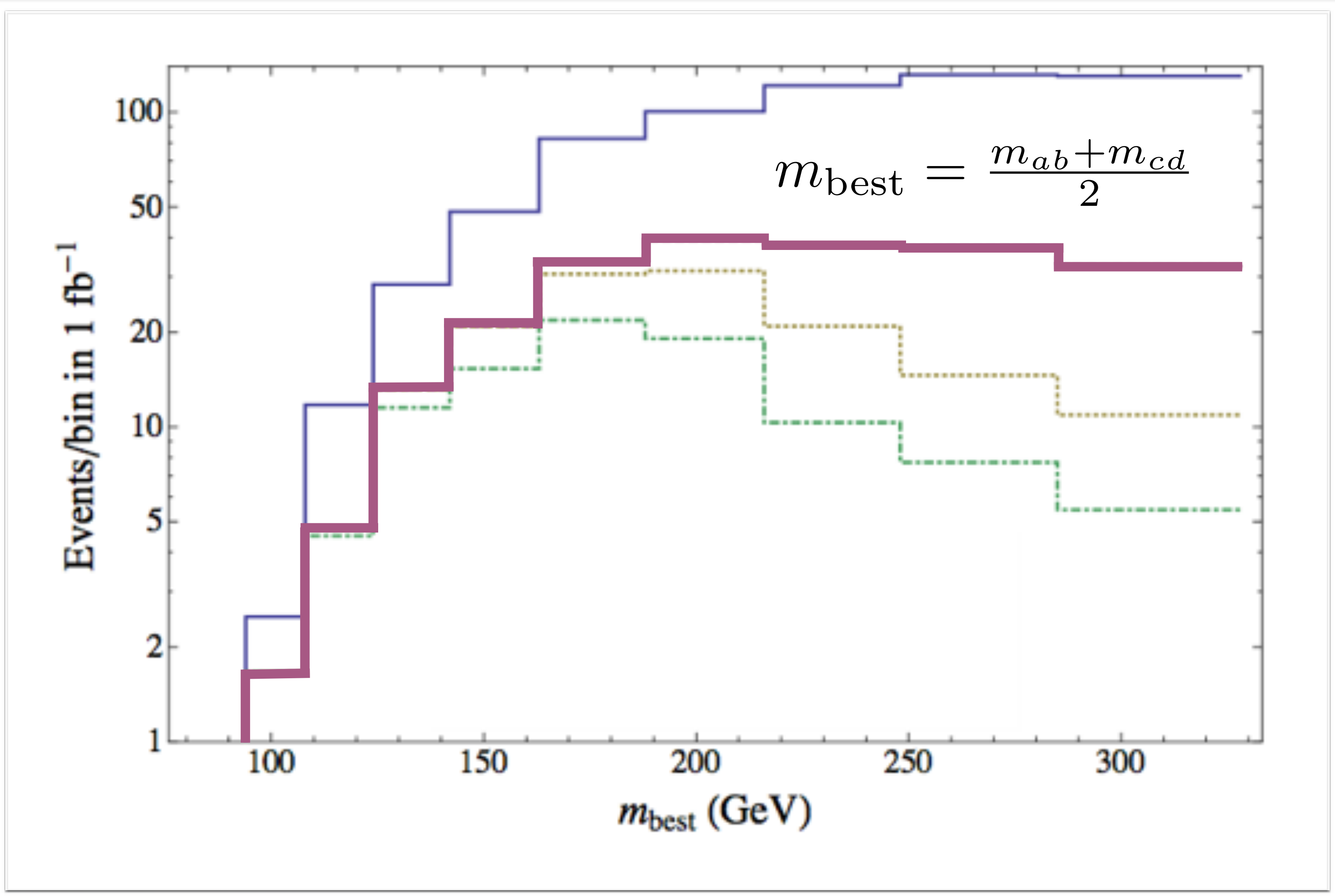

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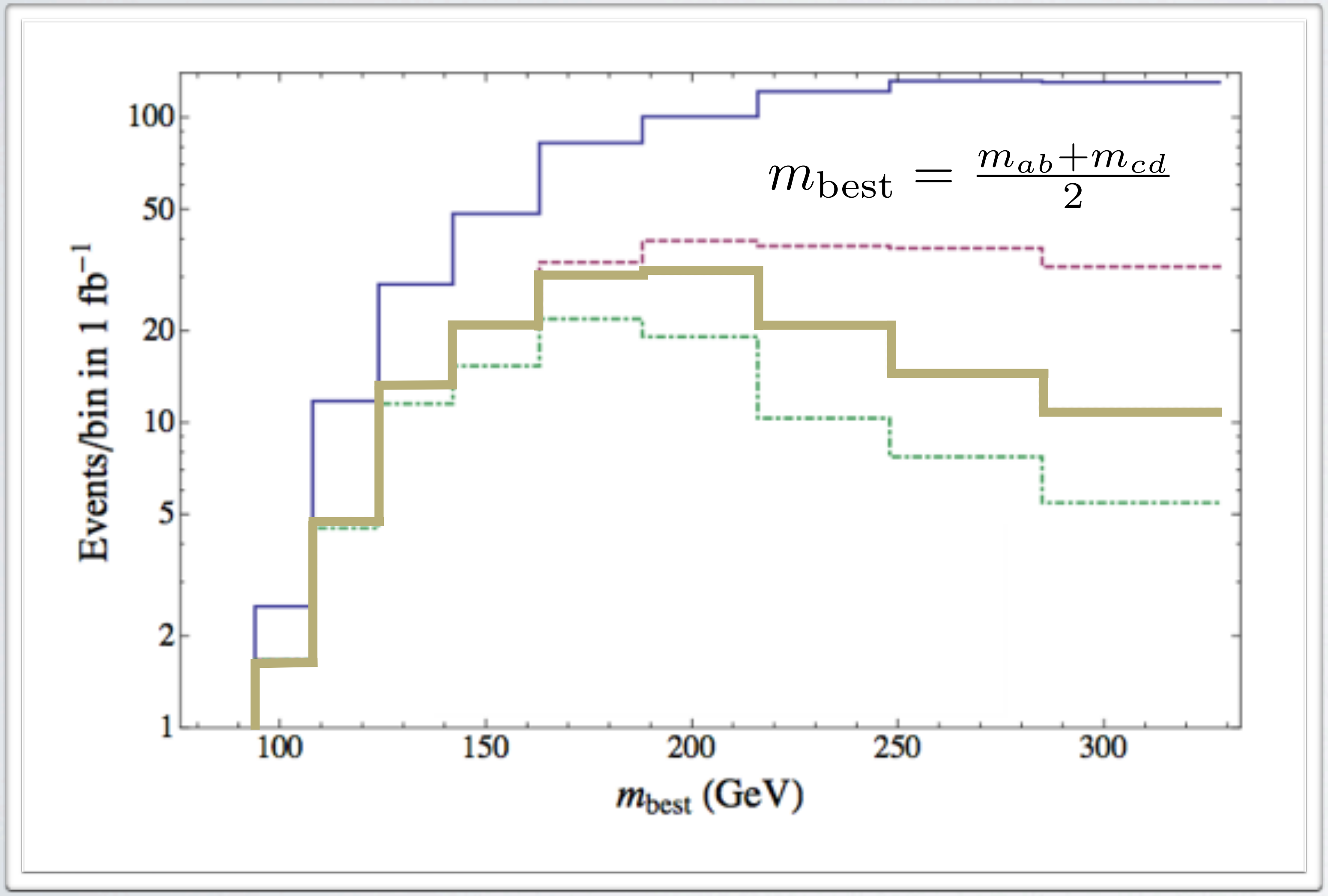

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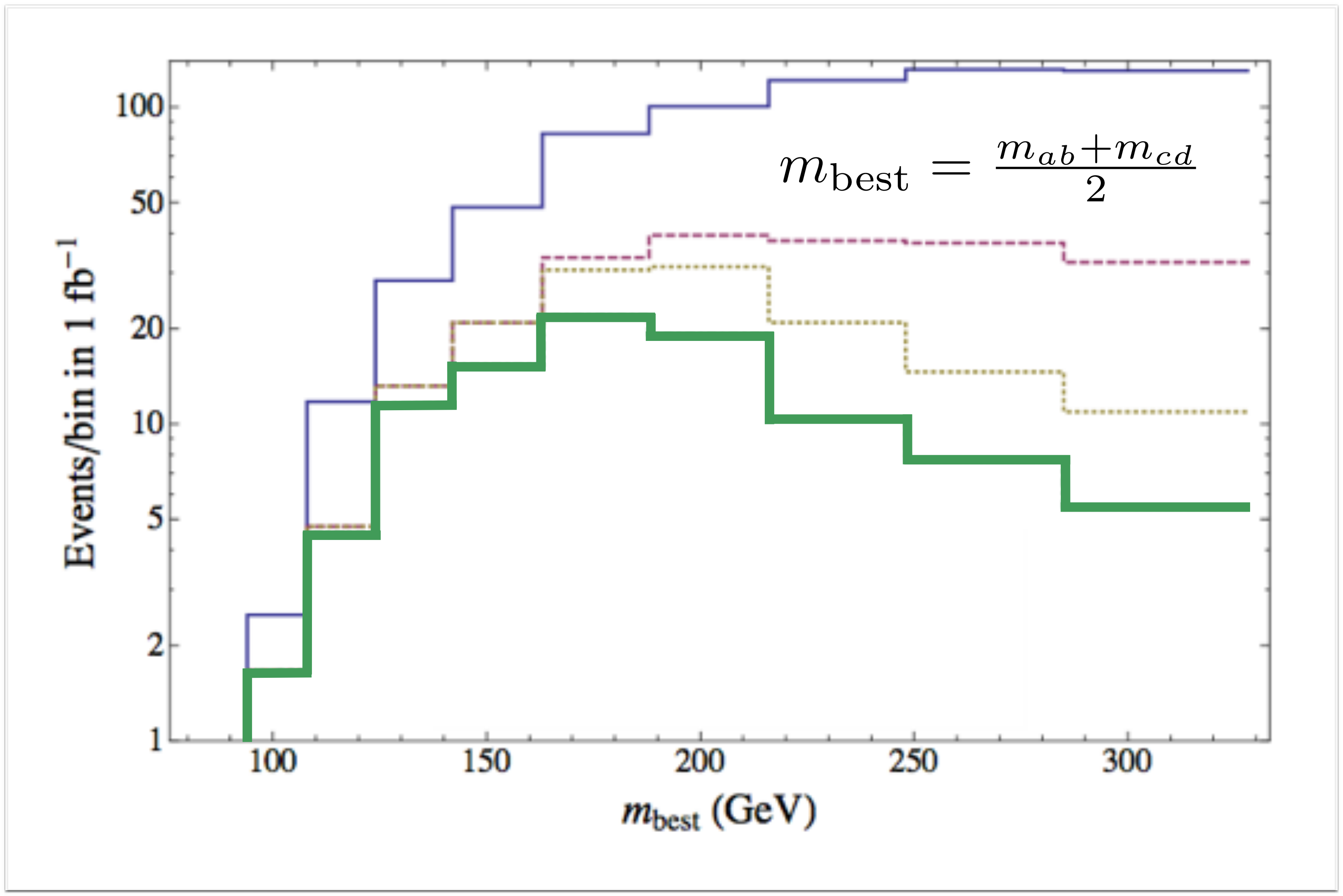

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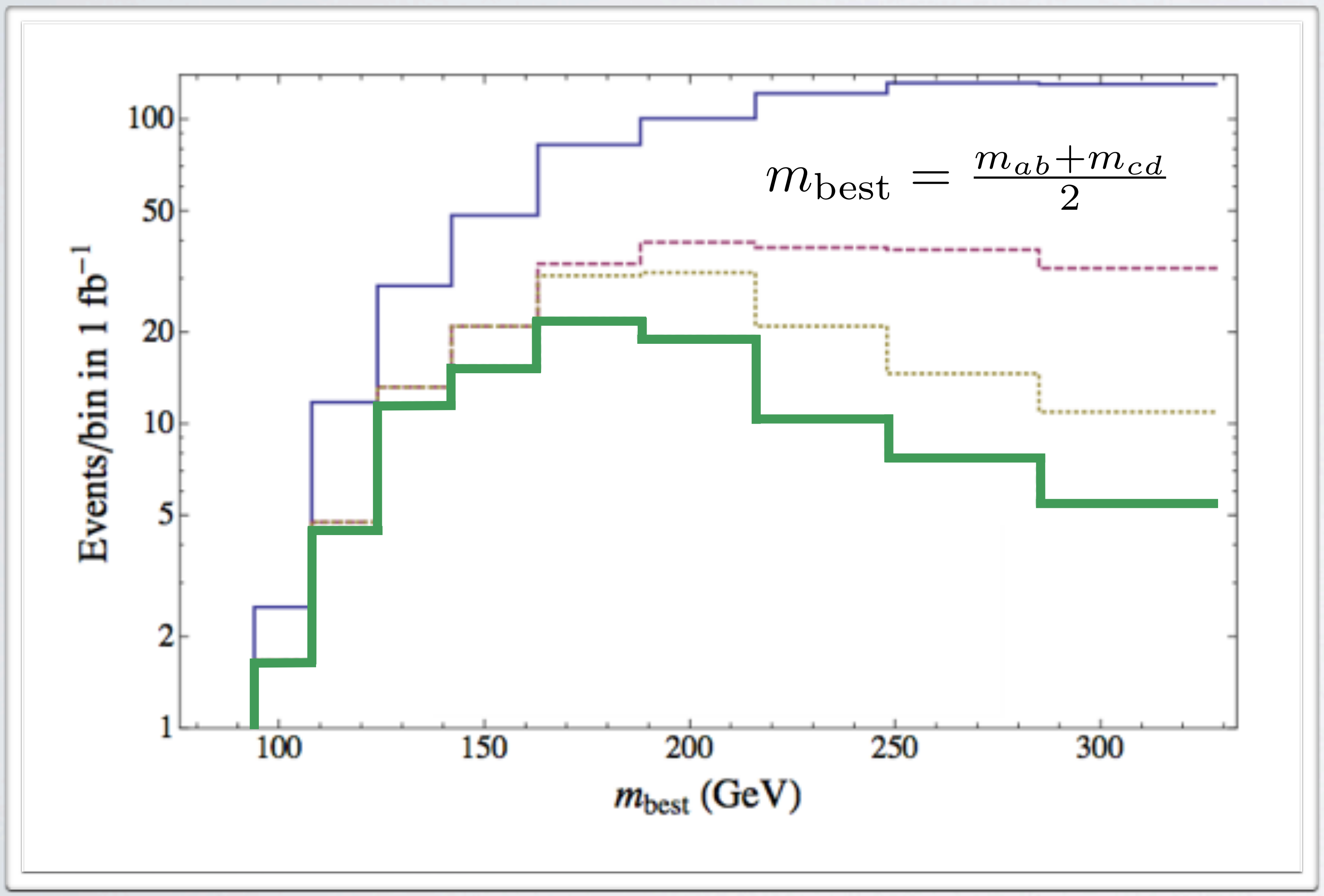

The combined effect of the $\Delta R_{\rm best}$ and $\Delta\eta_{\rm best}$ cuts is to move the peak of the background distribution toward smaller values of $m_{\rm best}$

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

CUT EFFICIENCIES LHC@8TEV

	$m_{\tilde{t}} = 100$ GeV - ΔR *pairing*								
	$\tilde{t}\bar{\tilde{t}}$ (314 pb)			QCD $b\bar{b}jj$ (8826 pb)[a]			$t\bar{t}$(135 pb)		
Selection	$\epsilon^{(1)}$	ϵ	$\epsilon_{i\to i+1}$	$\epsilon^{(1)}$	ϵ	$\epsilon_{i\to i+1}$	$\epsilon^{(1)}$	ϵ	$\epsilon_{i\to i+1}$
$\eta < 2.8$	0.81	0.81	-	0.82	0.82	-	0.88	0.88	-
$p_T > 50$ GeV	0.16	0.16	0.19	0.15	0.15	0.18	0.38	0.38	0.43
$\Delta R > 0.7$	0.78	0.15	0.95	0.79	0.14	0.96	0.85	0.36	0.94
b-tags $= 2$	0.44	0.064	0.44	0.44	0.062	0.44	0.44	0.15	0.44
$\delta_m < 0.075$	0.13	0.010	0.16	0.11	0.0085	0.14	0.15	0.026	0.17
$\|\cos\theta^*\| < 0.4$	0.33	0.0047	0.46	0.19	0.0021	0.24	0.36	0.026	0.45
$\Delta\eta_{\rm best} < 0.8$	0.31	0.0030	0.64	0.23	0.00077	0.38	0.37	0.0069	0.60
$\Delta R_{\rm best} < 1.5$	0.25	0.0025	0.85	0.19	0.00063	0.82	0.31	0.0056	0.81
$\Delta R_{\rm best} < 1$	0.031	0.00080	0.32	0.030	0.00020	0.32	0.043	0.0016	0.28

[a]This QCD cross section is computed taking $p_T > 35$ GeV, $|\eta| < 3.5$ and $\Delta R > 0.4$ for the matrix element computation.

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	$m_{\tilde{t}} = 200$ GeV - ΔR *pairing*								
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Selection	$\epsilon^{(1)}$	ϵ	$\epsilon_{i\to i+1}$	$\epsilon^{(1)}$	ϵ	$\epsilon_{i\to i+1}$	$\epsilon^{(1)}$	ϵ	$\epsilon_{i\to i+1}$
$\eta < 2.8$	0.16	0.16	-	0.94	0.036	-	0.88	0.88	-
$p_T > 100$ GeV	0.026	0.026	0.16	0.13	0.13	0.14	0.0031	0.31	0.035
$\Delta R > 0.7$	0.15	0.035	0.95	0.88	0.12	0.93	0.85	0.027	0.87
b-tags $= 2$	0.44	0.011	0.44	0.44	0.52	0.44	0.44	0.012	0.44
$\delta_m < 0.075$	0.036	0.0031	0.29	0.12	0.0072	0.14	0.15	0.0015	0.13
$\lvert\cos\theta^*\rvert < 0.4$	0.096	0.0018	0.57	0.25	0.0021	0.29	0.36	0.00066	0.45
$\Delta\eta_{\text{best}} < 0.8$	0.078	0.0013	0.73	0.29	0.00084	0.41	0.38	0.00044	0.66
$\Delta R_{\text{best}} < 1.5$	0.075	0.0011	0.85	0.26	0.00071	0.84	0.31	0.00038	0.86
$\Delta R_{\text{best}} < 1$	0.012	0.00031	0.29	0.046	0.00025	0.35	0.043	0.00019	0.49

[b]This QCD cross section is computed taking $p_T > 75$ GeV, $|\eta| < 3.5$ and $\Delta R > 0.4$ for the matrix element computation.

CUT EFFICIENCIES LHC@8TEV

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$\Delta R_{\rm best} < 1$	0.031	0.00080	0.32	0.030	0.00020	0.32	0.043	0.0016	0.28

$S/B \sim 12\%$

[a] This QCD cross section is computed taking $p_T > 35$ GeV, $|\eta| < 3.5$ and $\Delta R > 0.4$ for the matrix element computation.

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$\eta < 2.8$	0.16	0.16	-	0.94	0.036	-	0.88	0.88	-
$p_T > 100$ GeV	0.026	0.026	0.16	0.13	0.13	0.14	0.0031	0.31	0.035
$\Delta R > 0.7$	0.15	0.035	0.95	0.88	0.12	0.93	0.85	0.027	0.87
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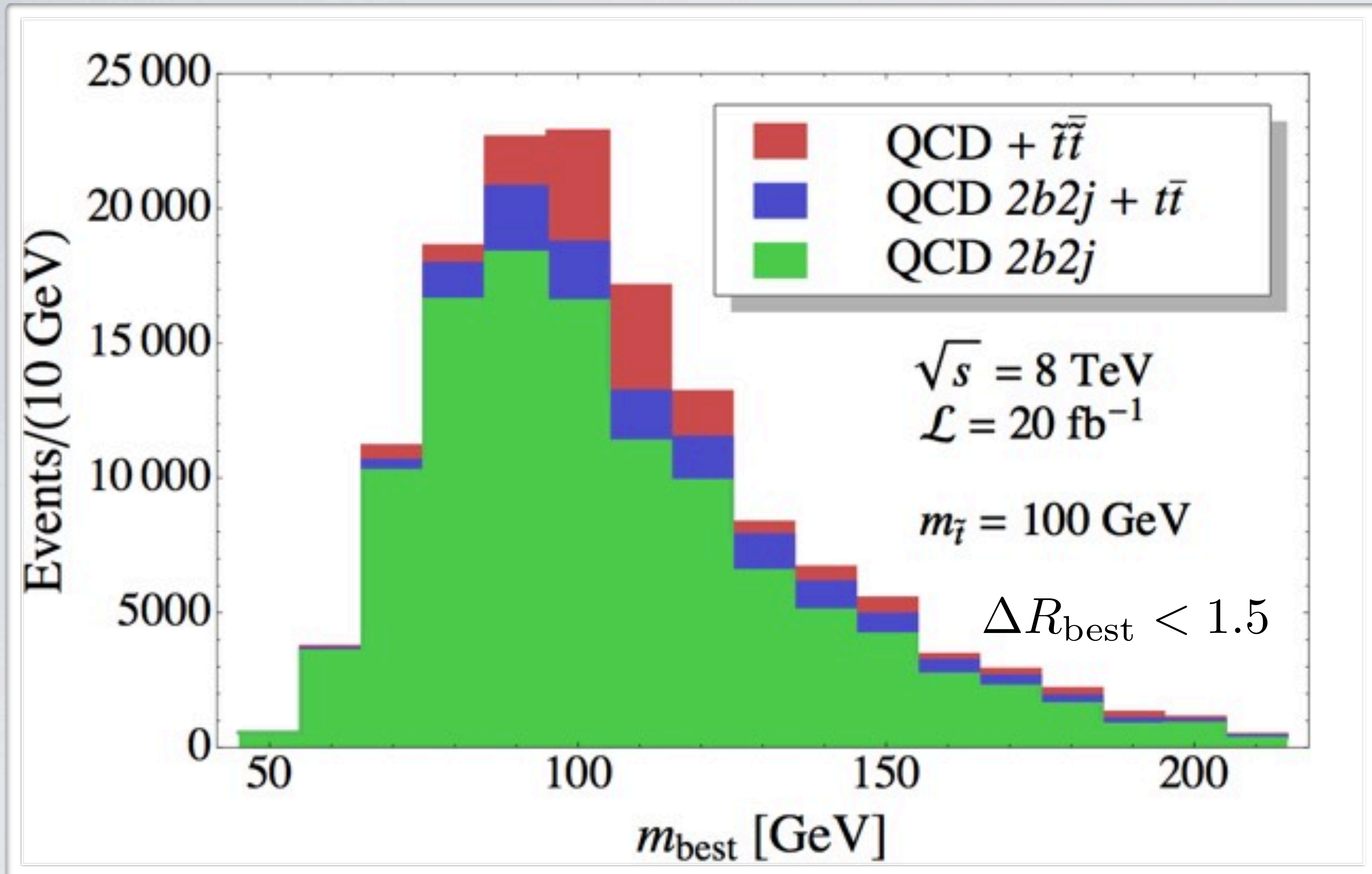
$\Delta\eta_{\rm best} < 0.8$	0.078	0.0013	0.	[illegible]	[illegible]	0.41	0.38	0.00044	0.66
$\Delta R_{\rm best} < 1.5$	0.075	0.0011	0.85	0.26	0.00071	0.84	0.31	0.00038	0.86
$\Delta R_{\rm best} < 1$	0.012	0.00031	0.29	0.046	0.00025	0.35	0.043	0.00019	0.49

$S/B \sim 7\%$

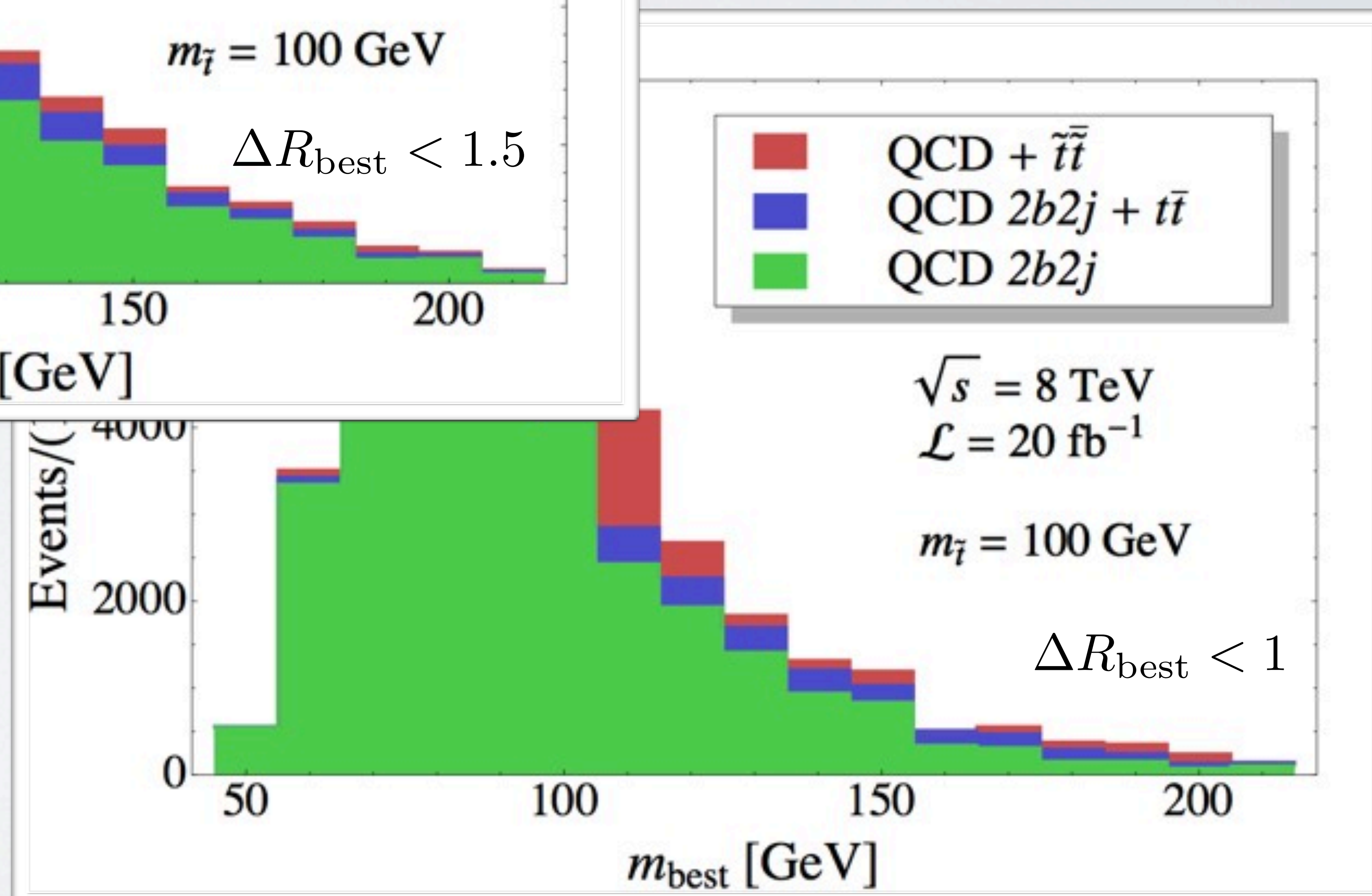
[b] This QCD cross section is computed taking $p_T > 75$ GeV, $|\eta| < 3.5$ and $\Delta R > 0.4$ for the matrix element computation.

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 ΔR_{best} cut forces the signal to bump on the smoothly falling background

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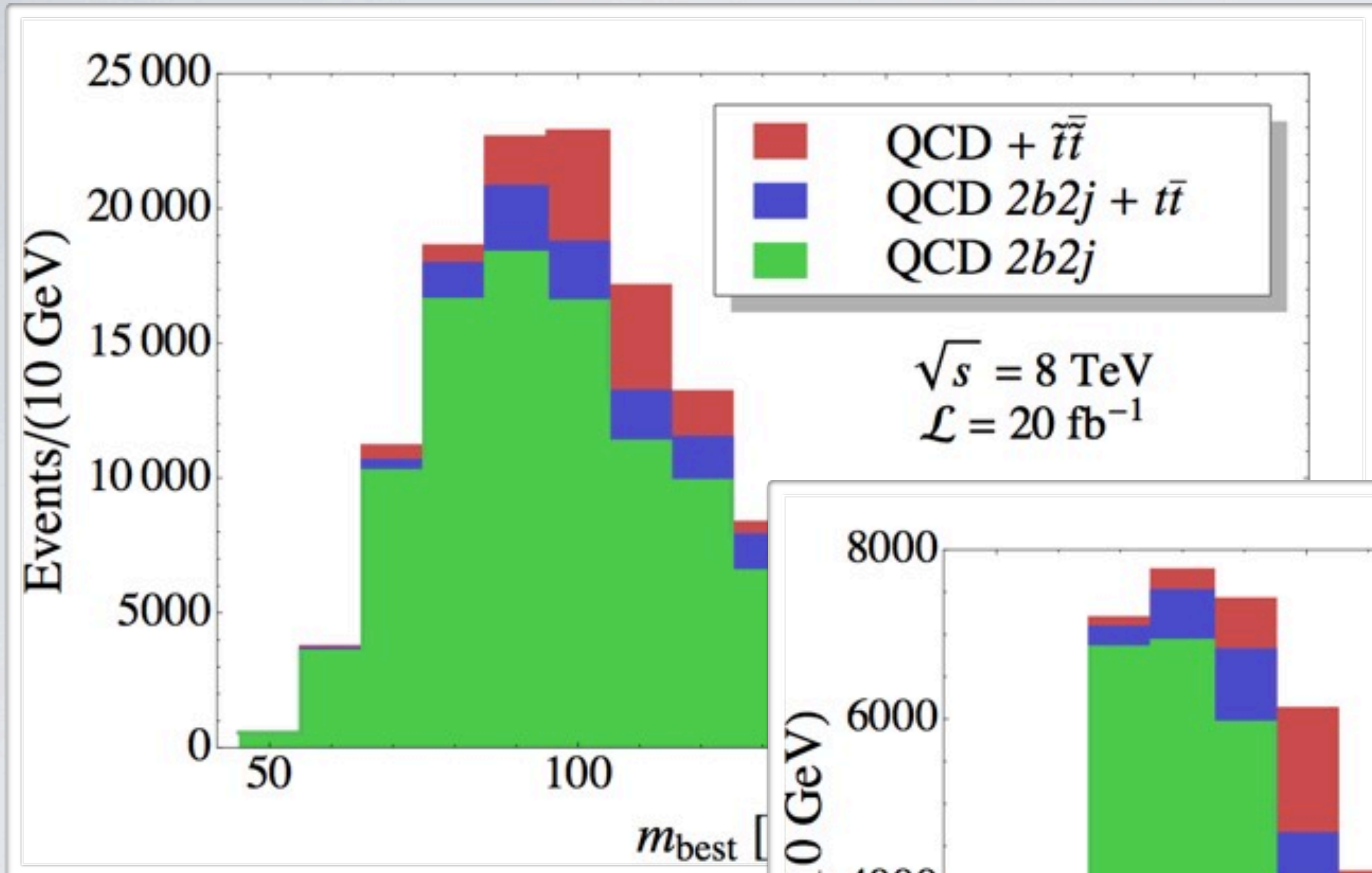

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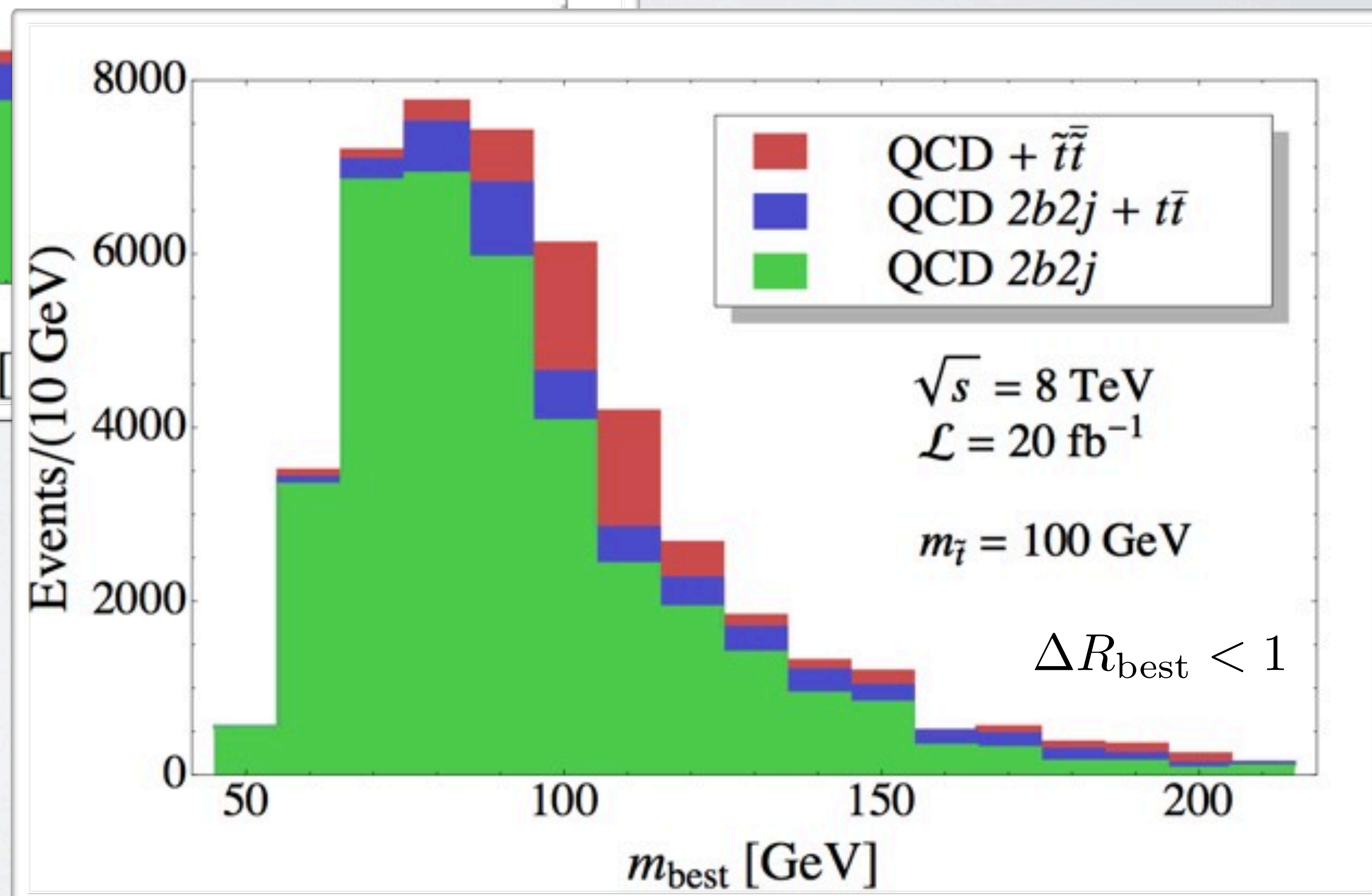
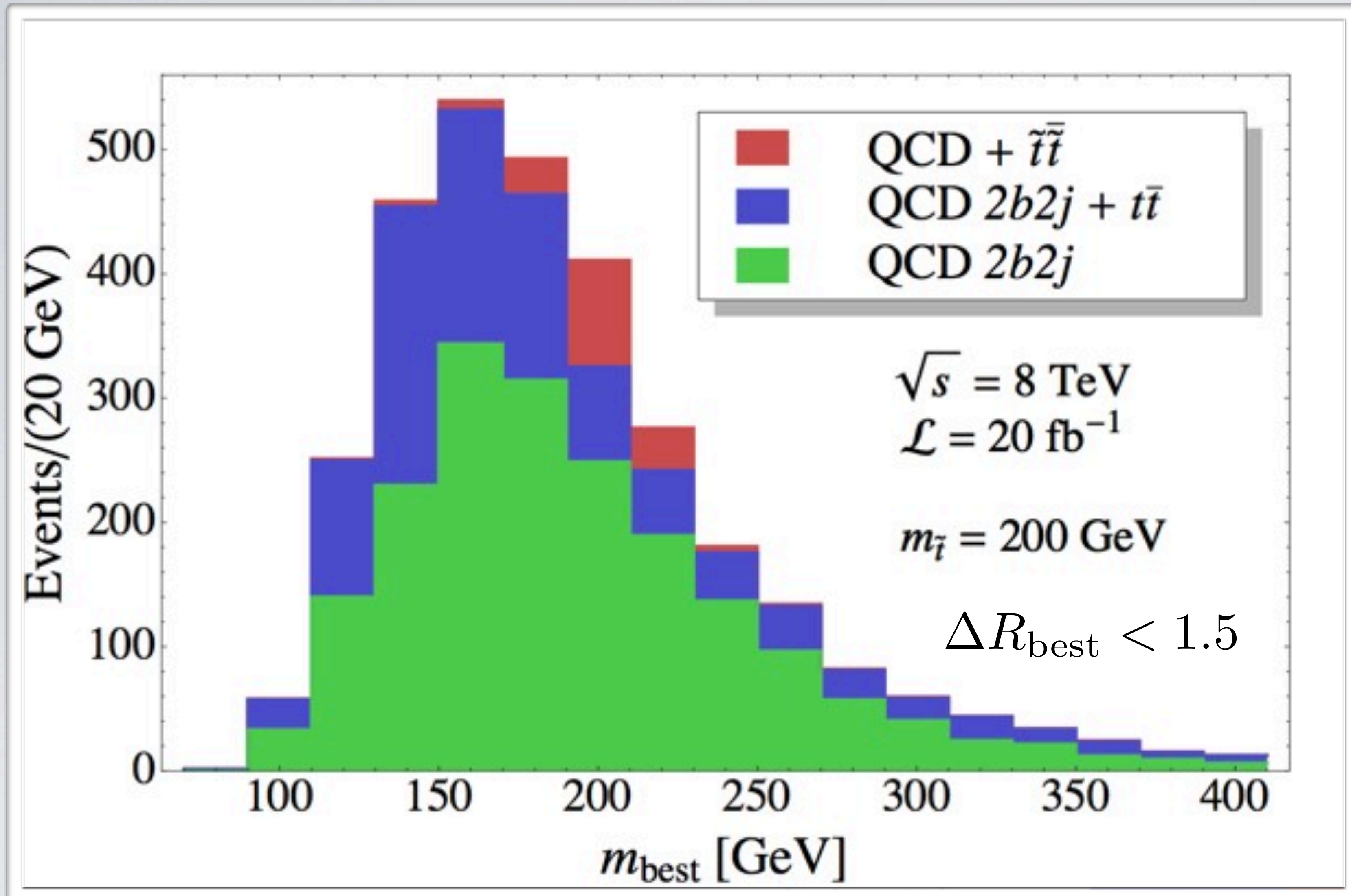


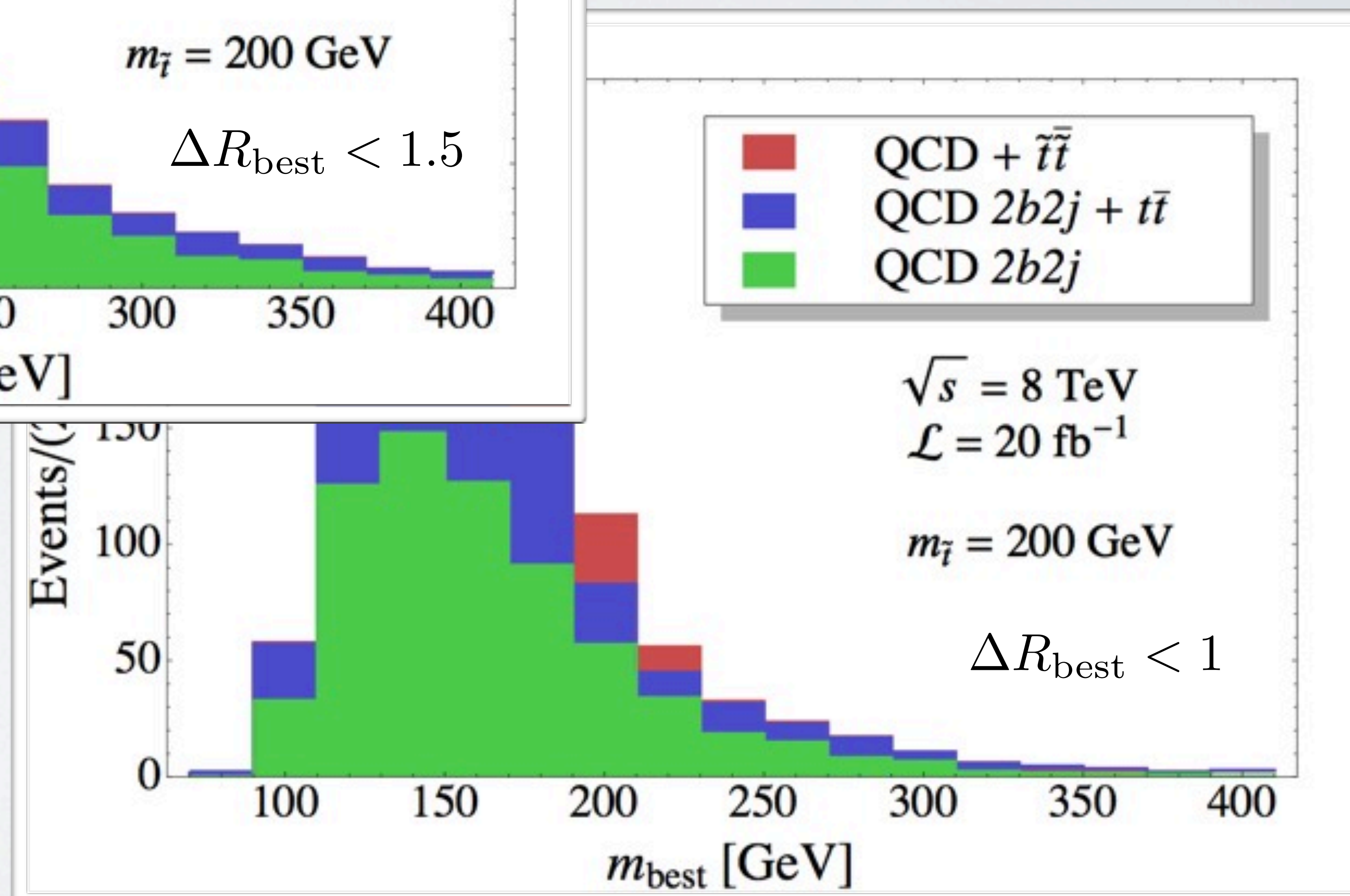
Harder ΔR_{best} cut forces the signal to bump on the smoothly falling background

RESULTS: 200 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?)



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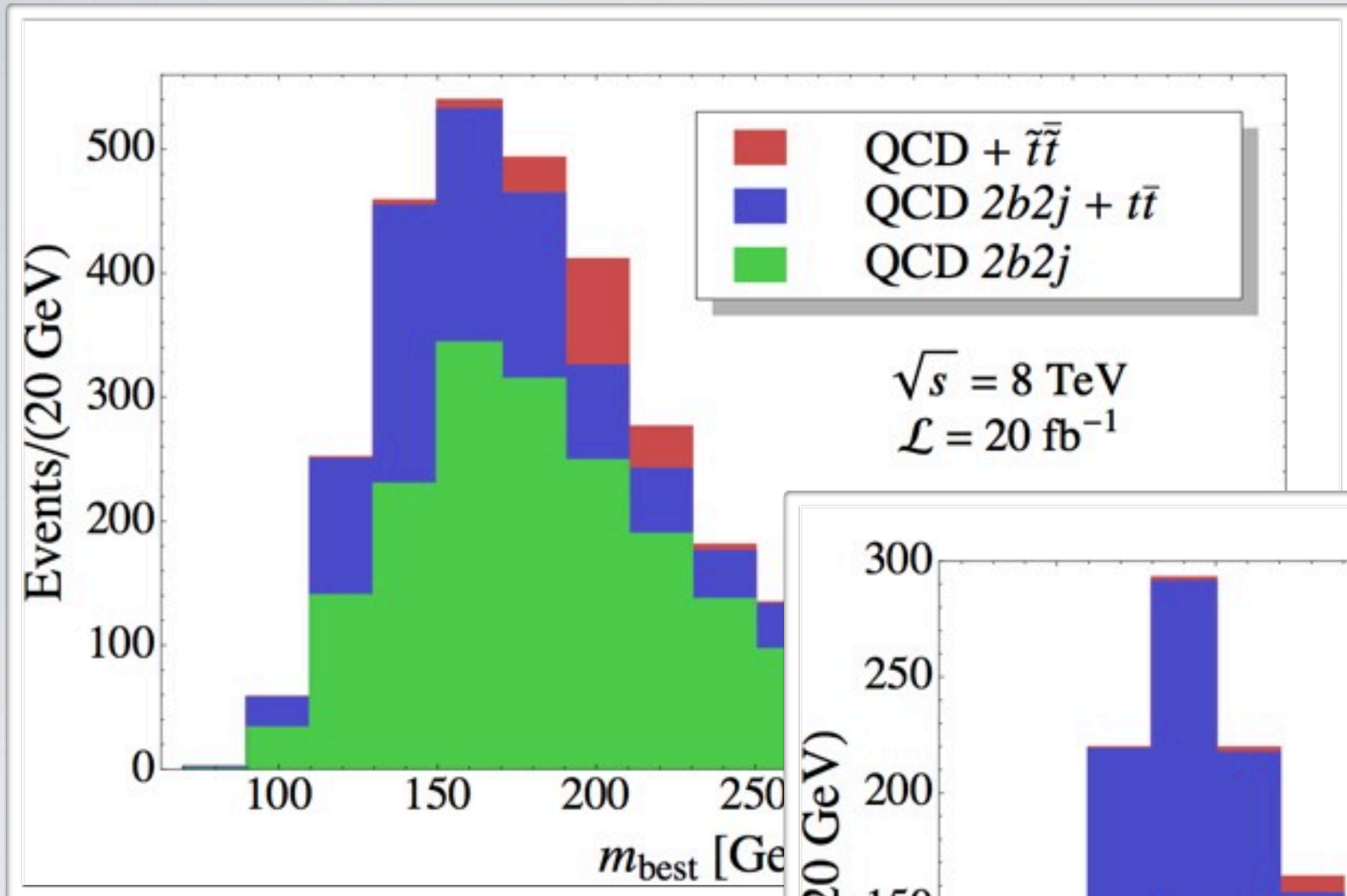

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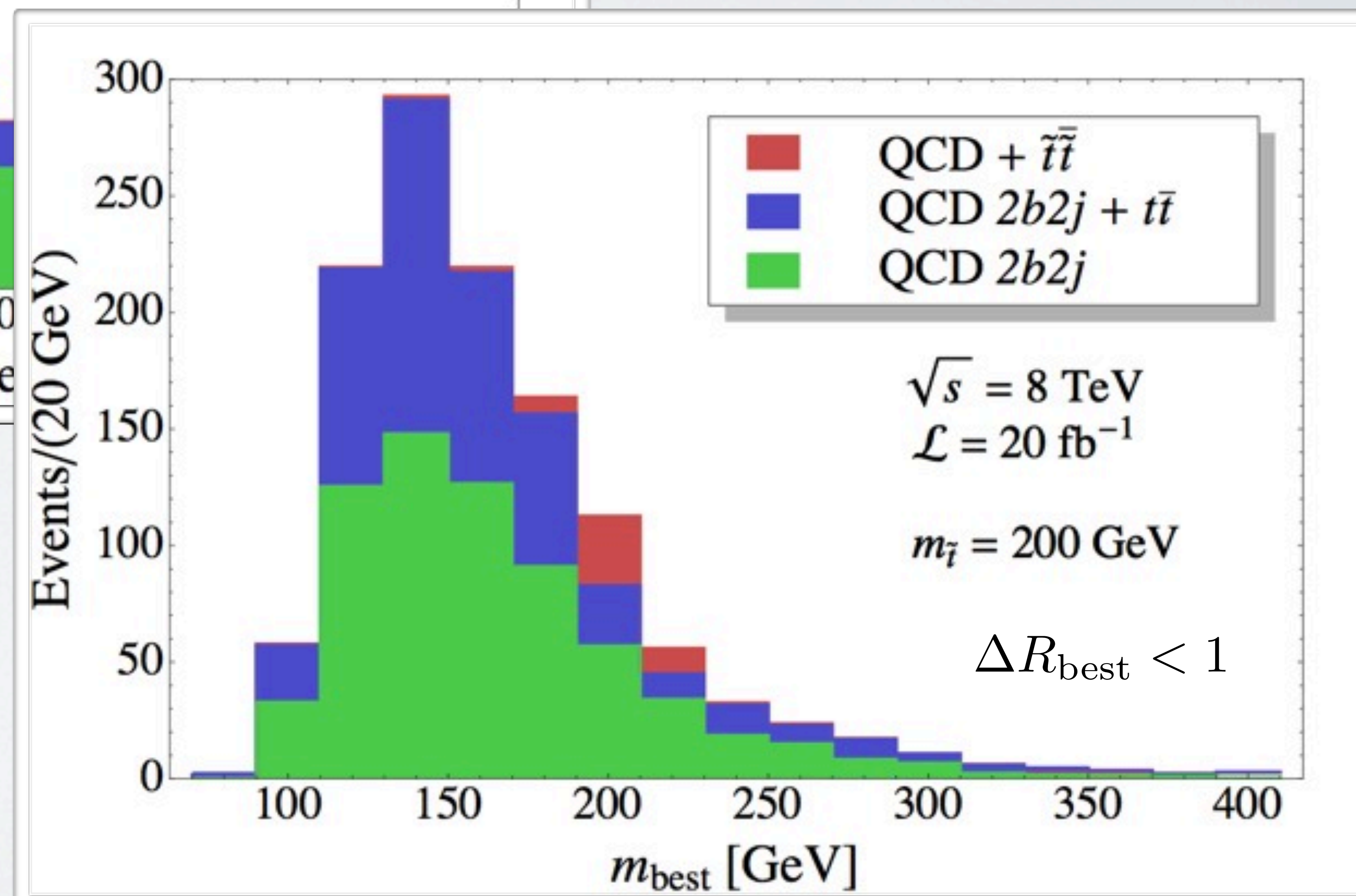

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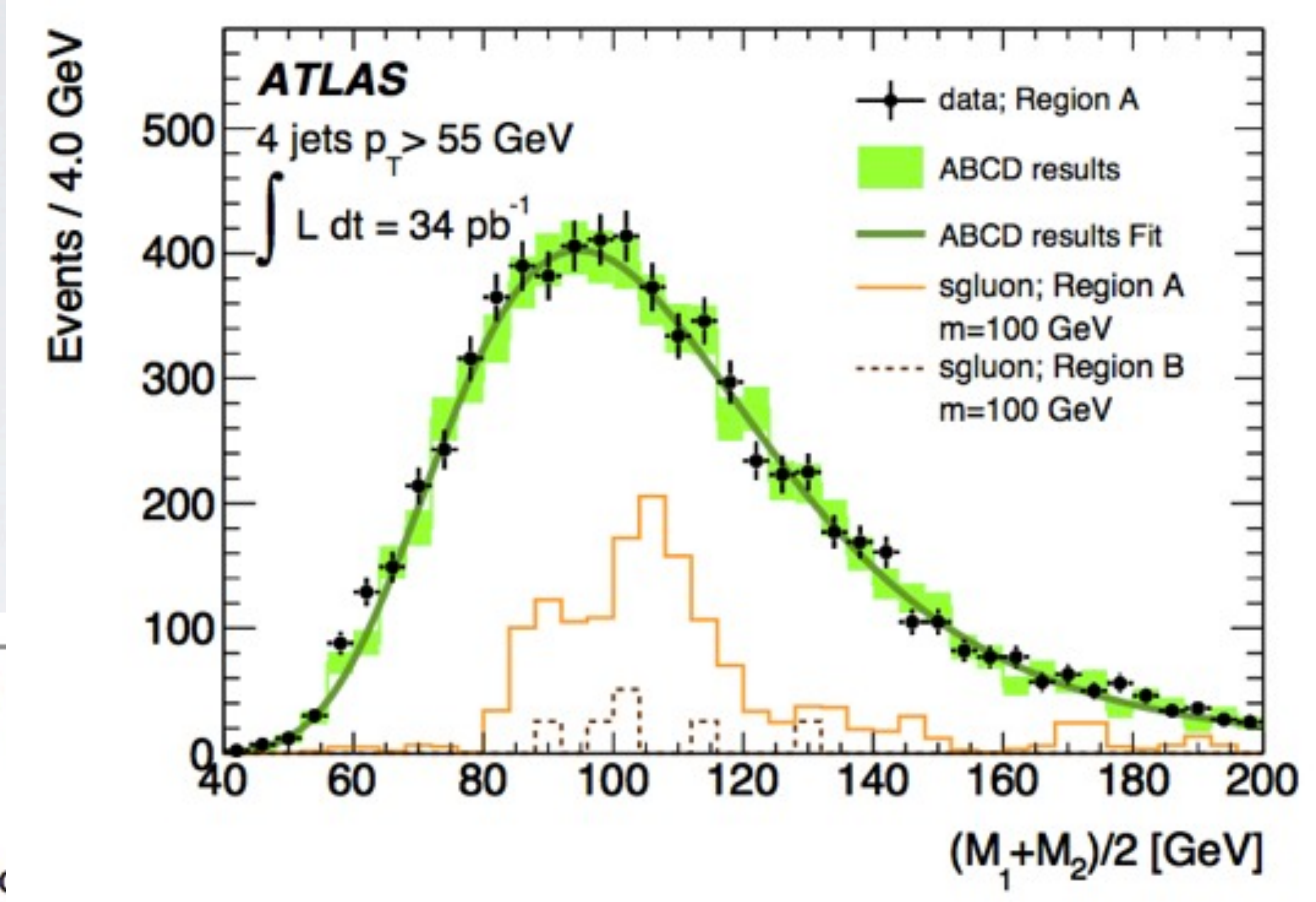
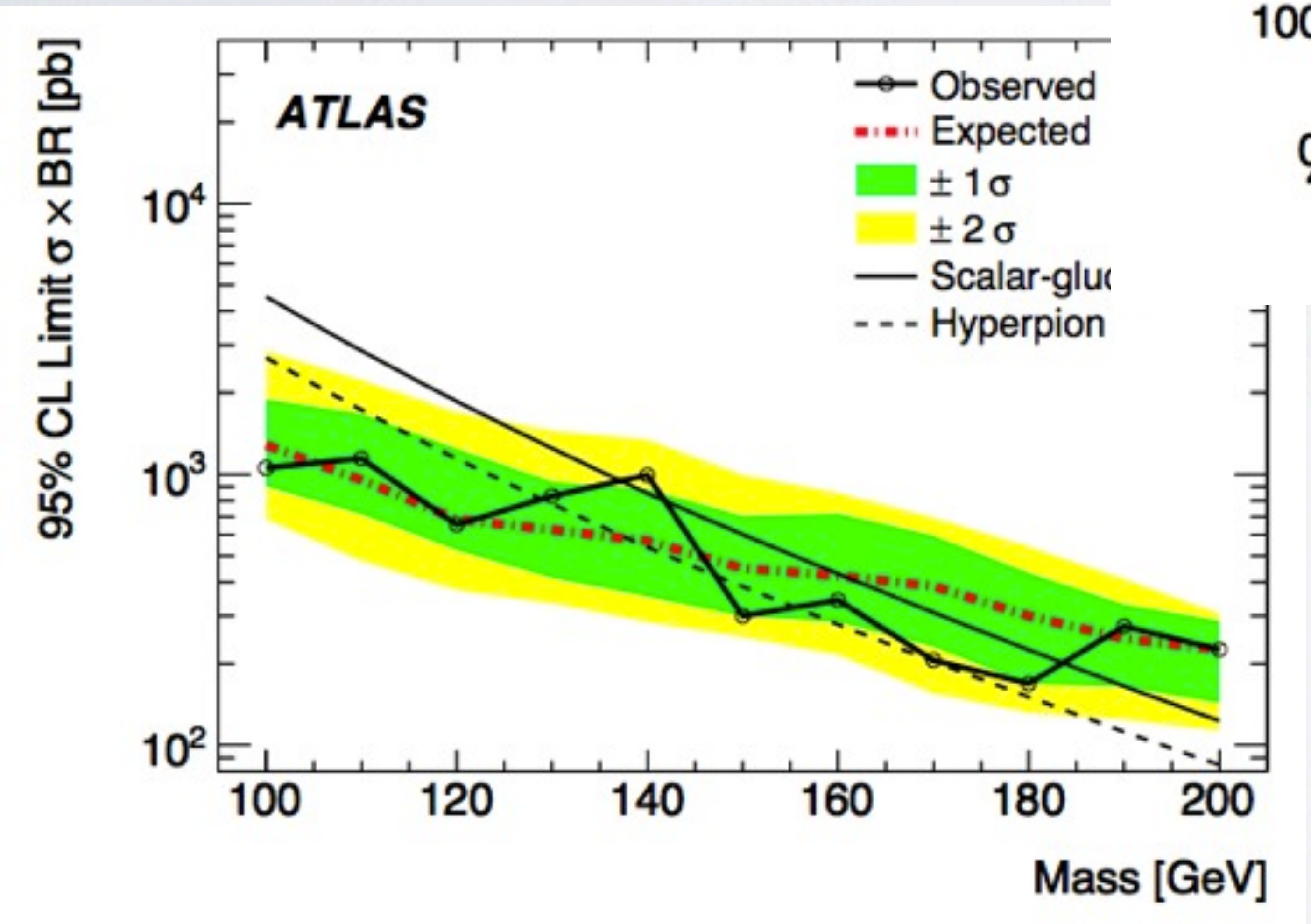
HOW ROBUST IS OUR PREDICTION?

- One may argue that the signal can hardly been 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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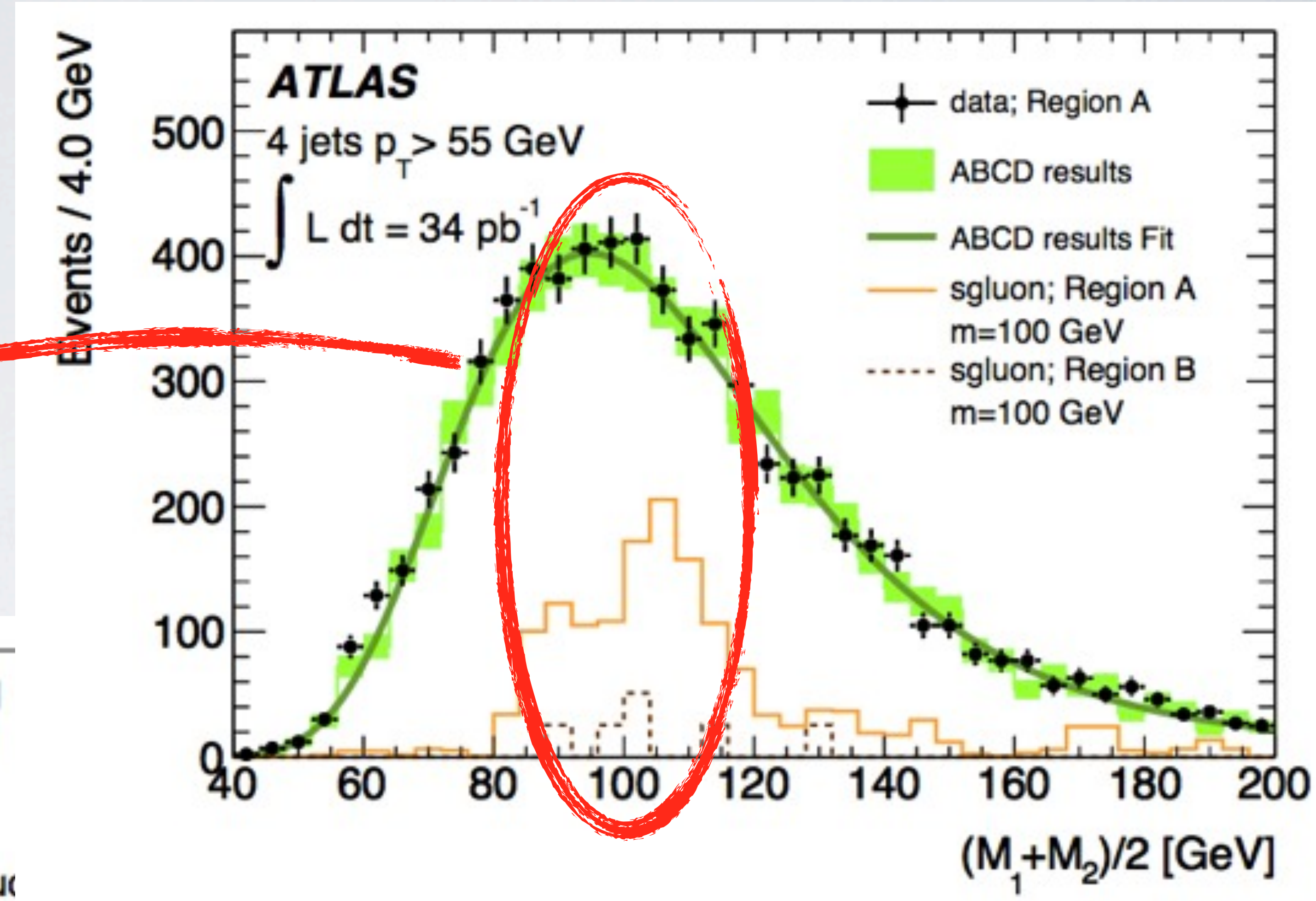

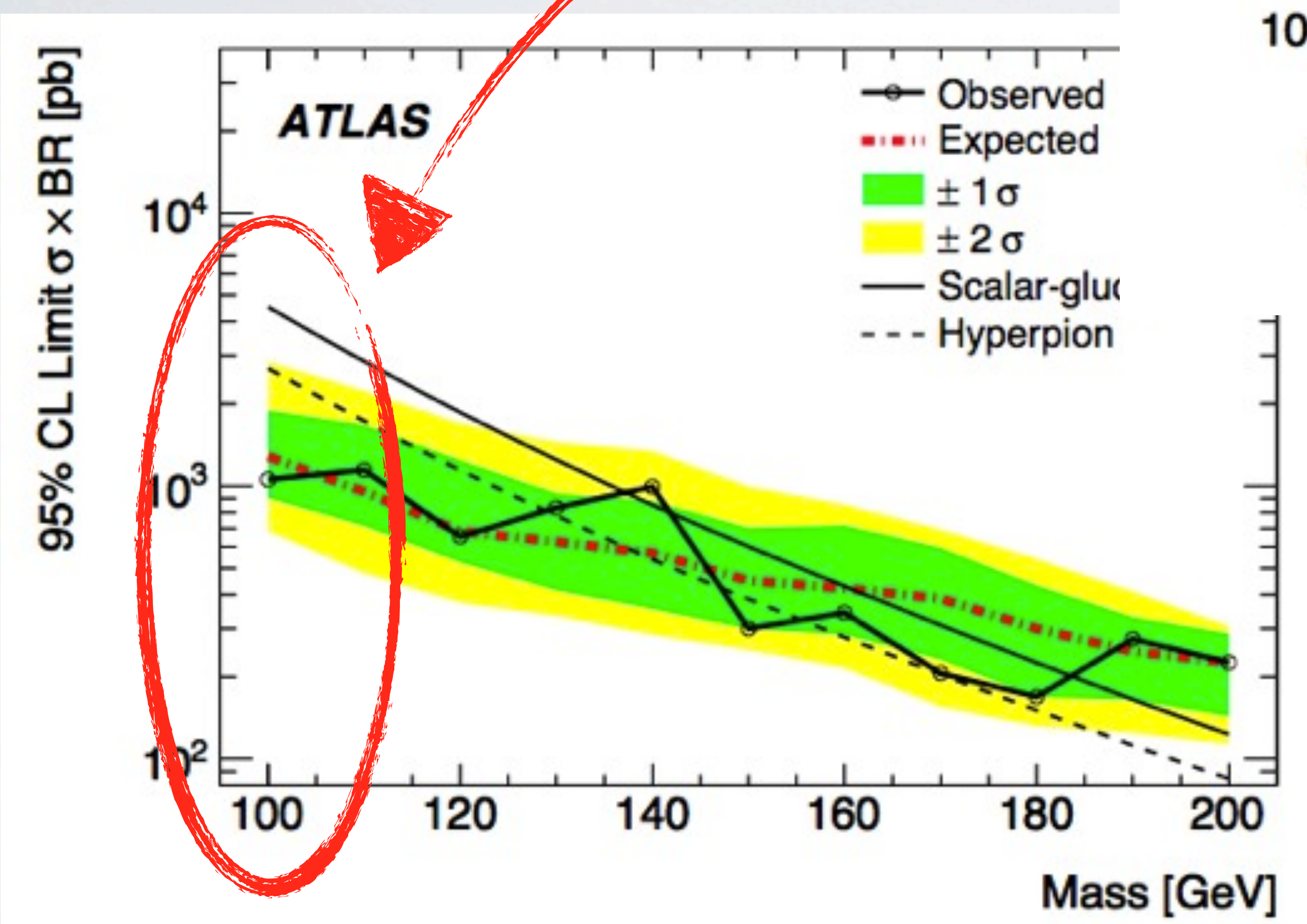

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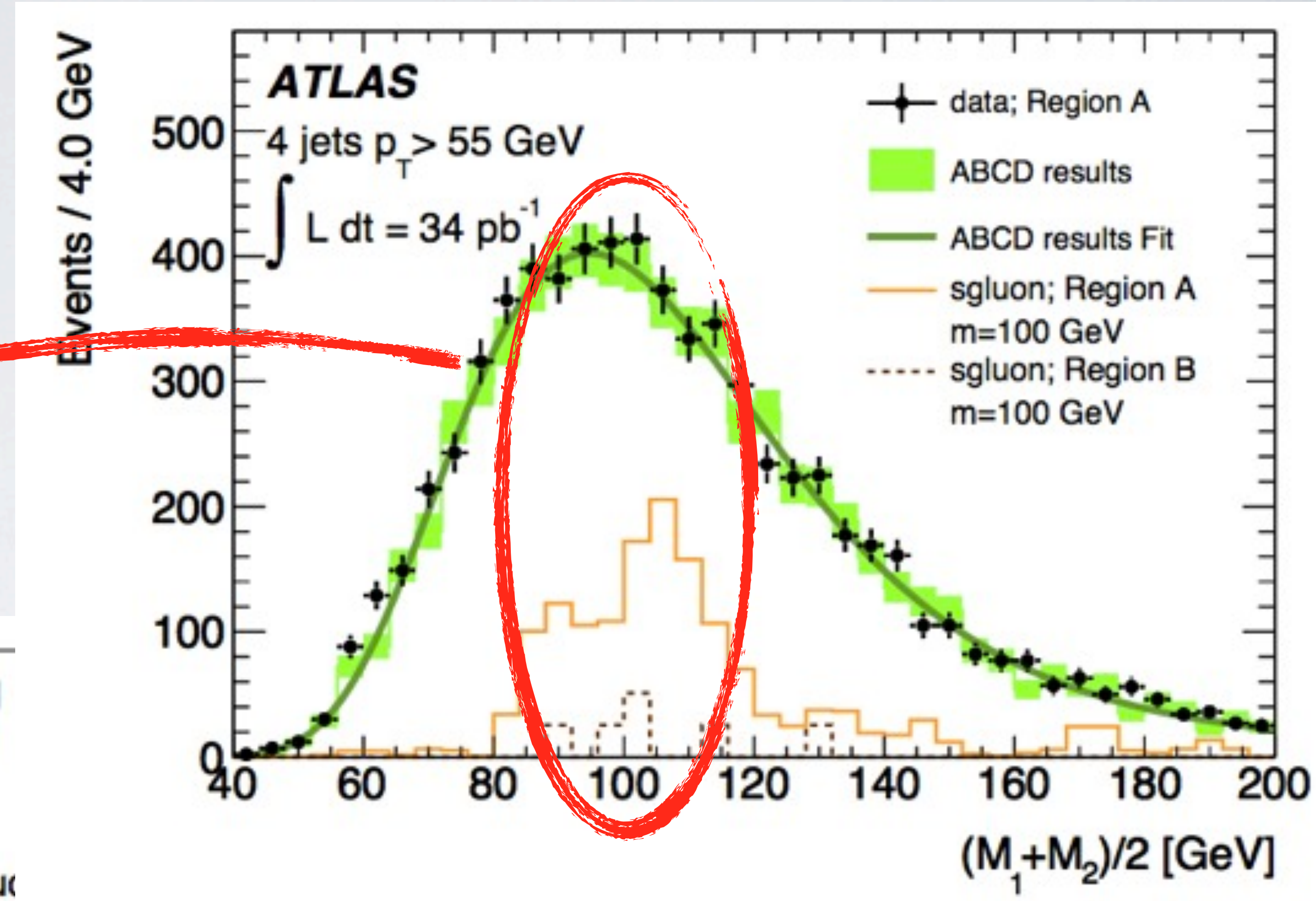

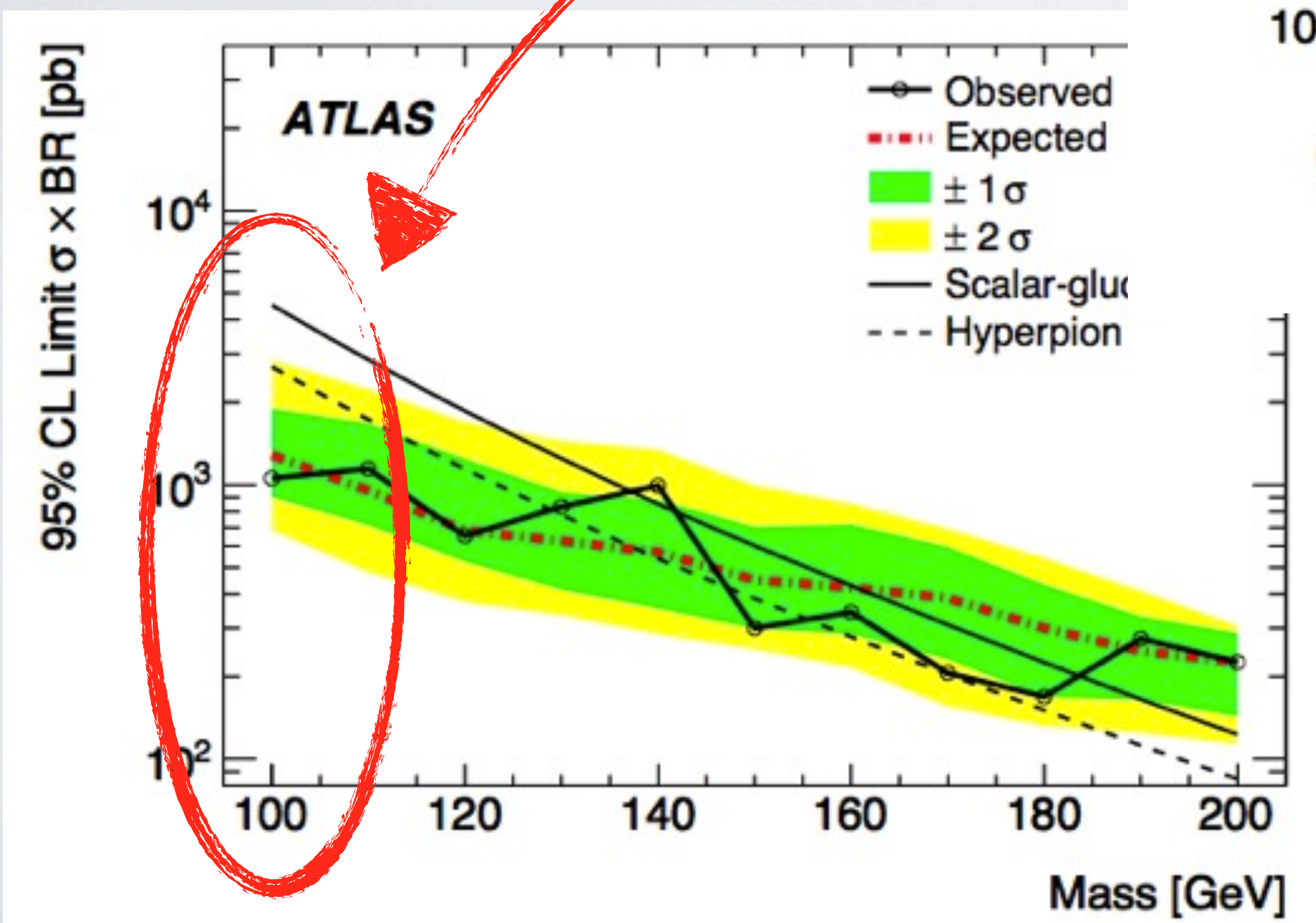

- With S/B~0.5 they can exclude the sgluon CS by a factor of 4/5

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

CONCLUSION

- If we take Naturalness as a first 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 (in effective SUSY models)
- 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 based on gauged flavor symmetries)
- We pointed out the importance of using online b-tagging to keep low pT thresholds in the trigger for multi-jet final states
- 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