The Status of GMSB after 1/fb at the LHC

David Shih
Rutgers University

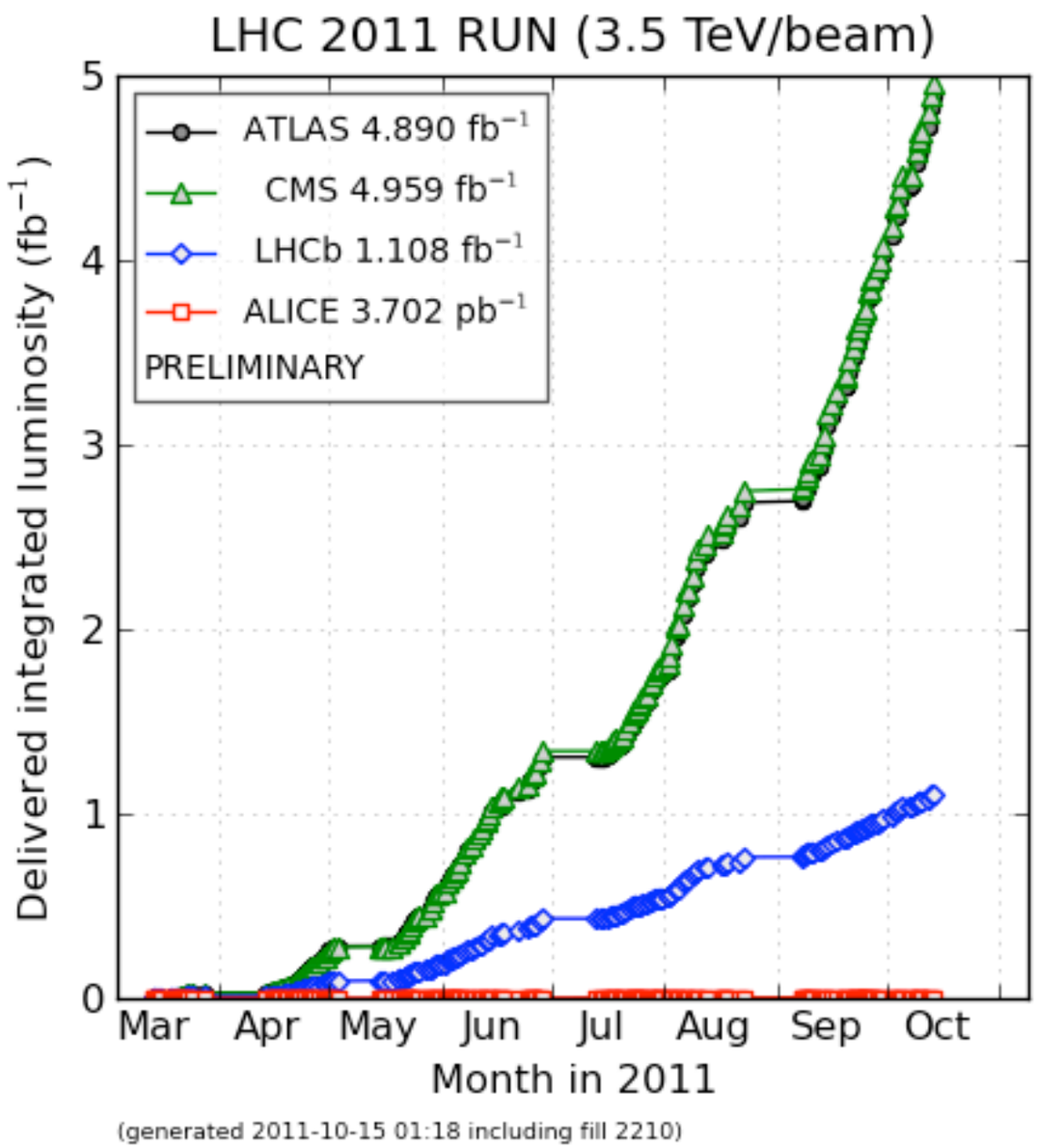
Work in progress with Yevgeny Kats, Patrick Meade, and Matt Reece

Also based on:

Meade, Reece & DS (0911.4130, 1006.4575)
Ruderman & DS (1009.1665, 1103.6083)
Kats & DS (1106.0030)

Current Status of the LHC

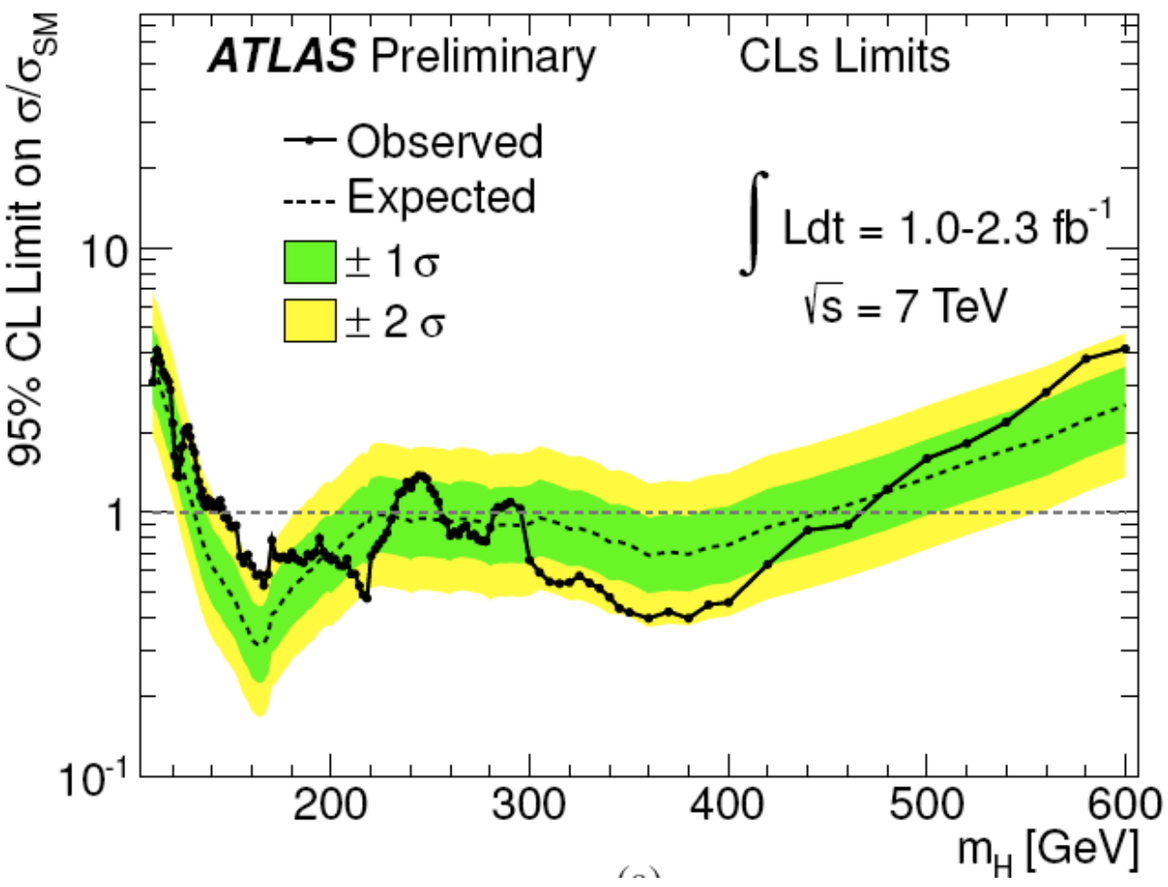
In 2011, the LHC experiments have been collecting data at an astounding rate -- nearly 5/fb already and growing!

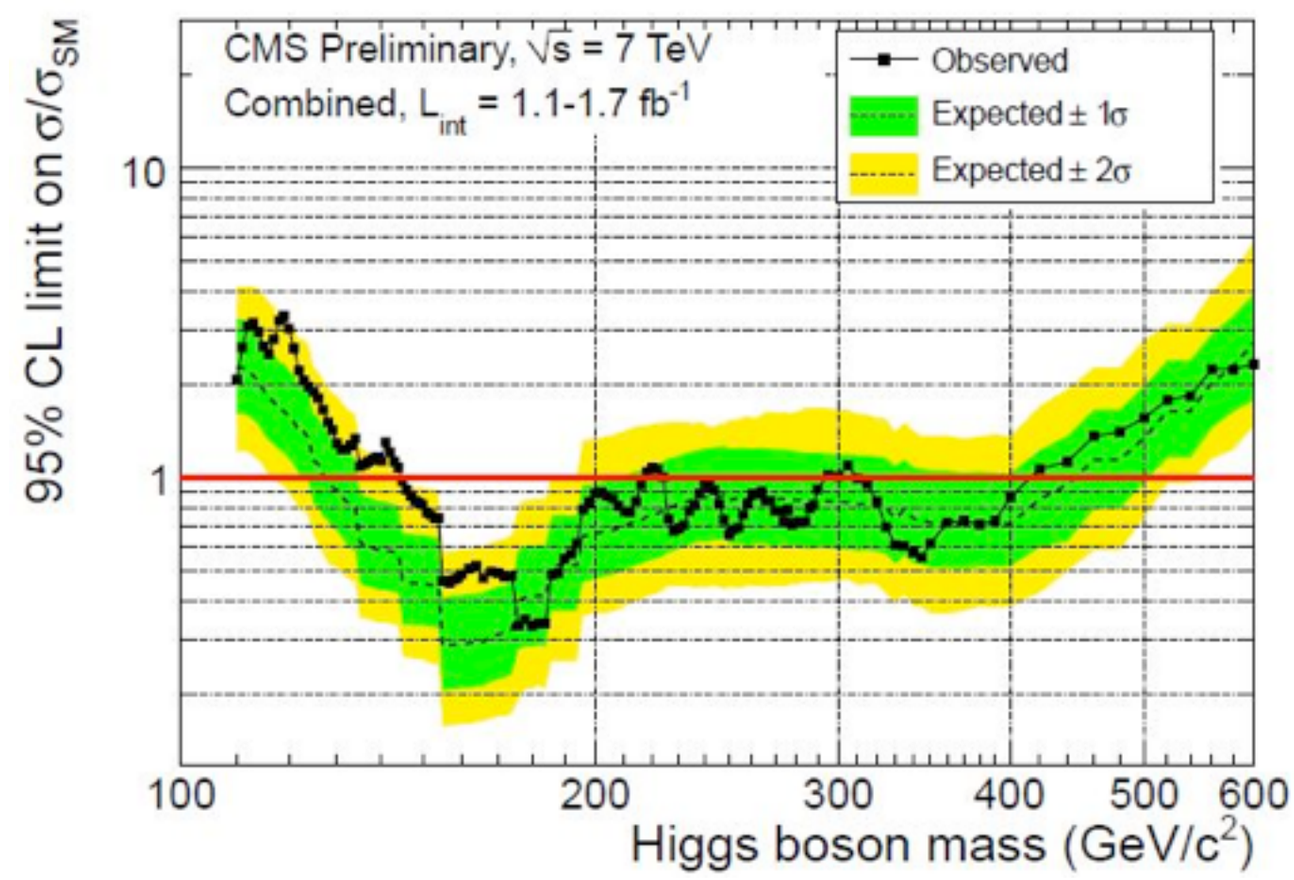


Current Status of the LHC

So far, no signs of new physics.

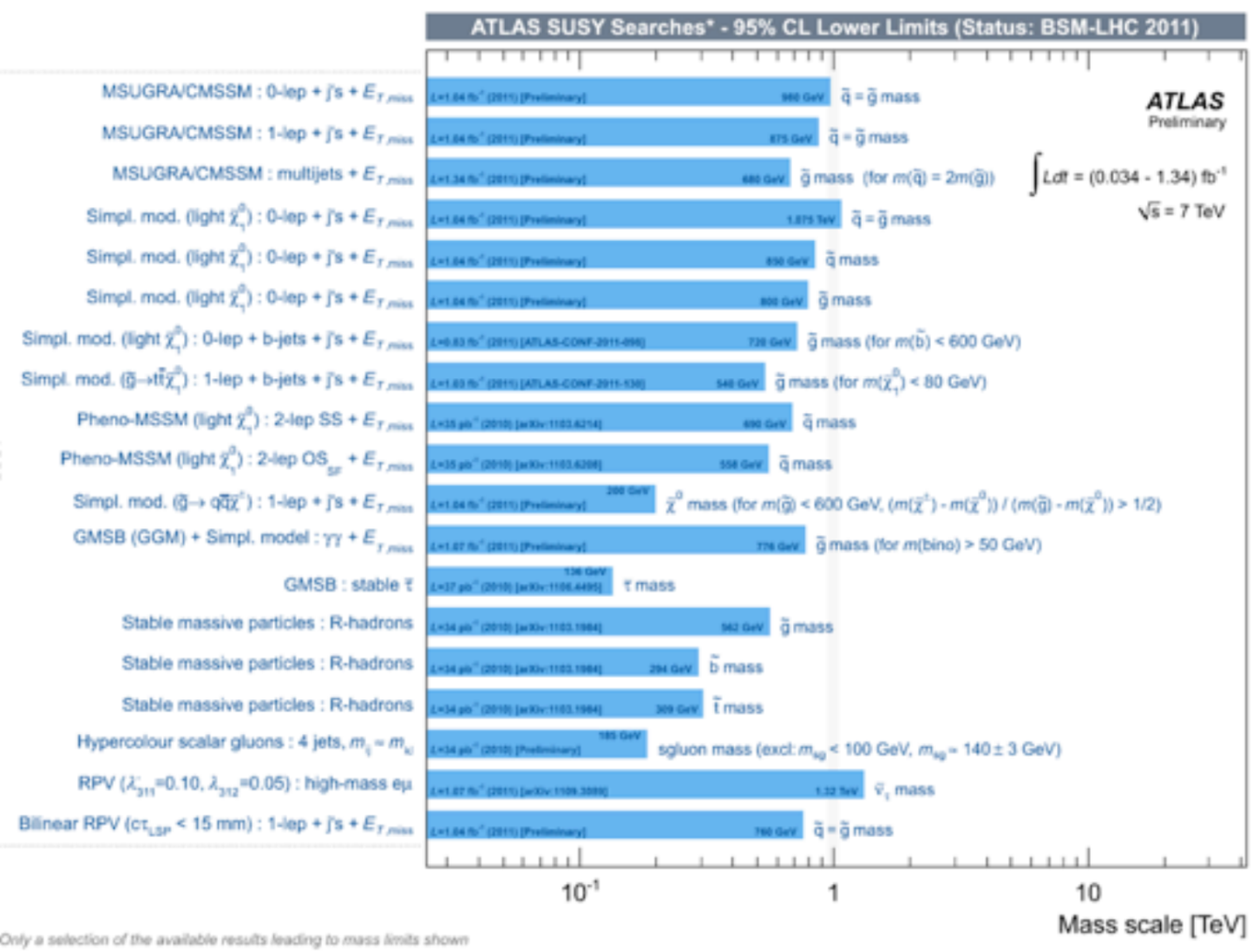
In particular, no signs of the Higgs....

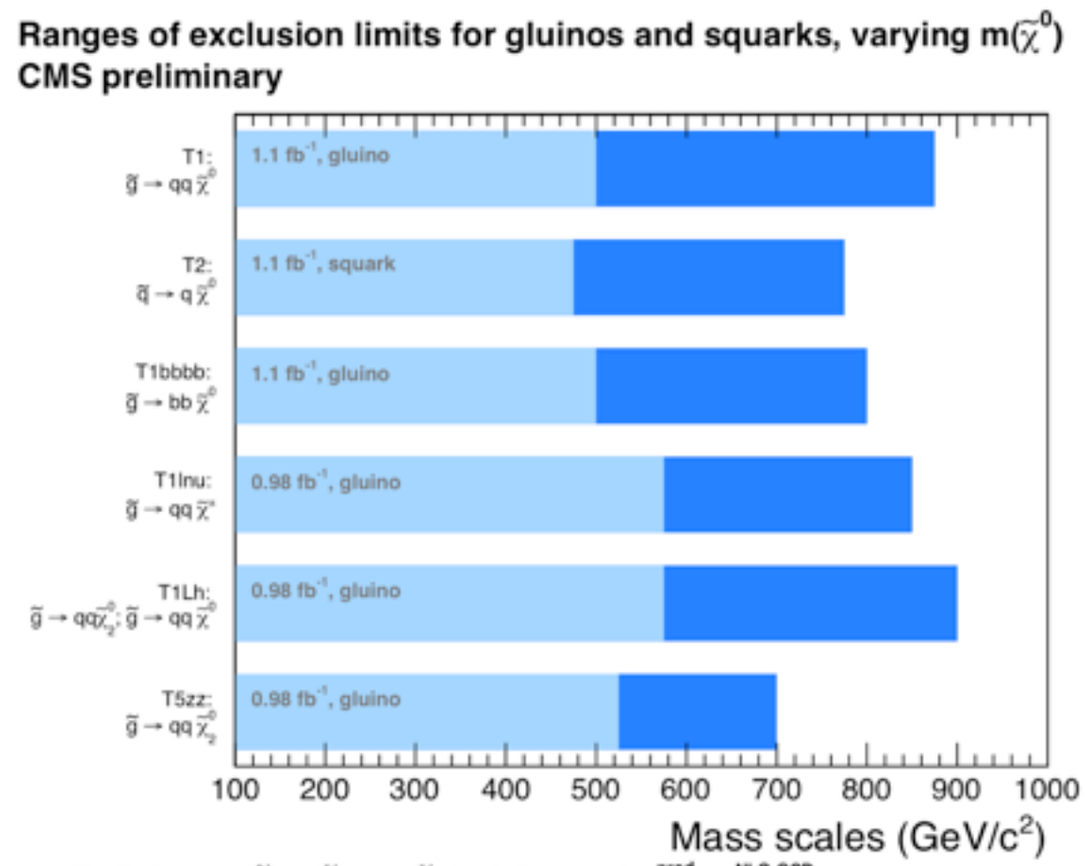




Current Status of the LHC

... and no signs of SUSY:





For limits on $m(\tilde{g})$, $m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{prod} = \sigma^{NLO\text{-}QCD}$.

$m(\tilde{\chi}^\pm), m(\tilde{\chi}_2^0) = \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})$-200 GeV/c^2 (light blue).

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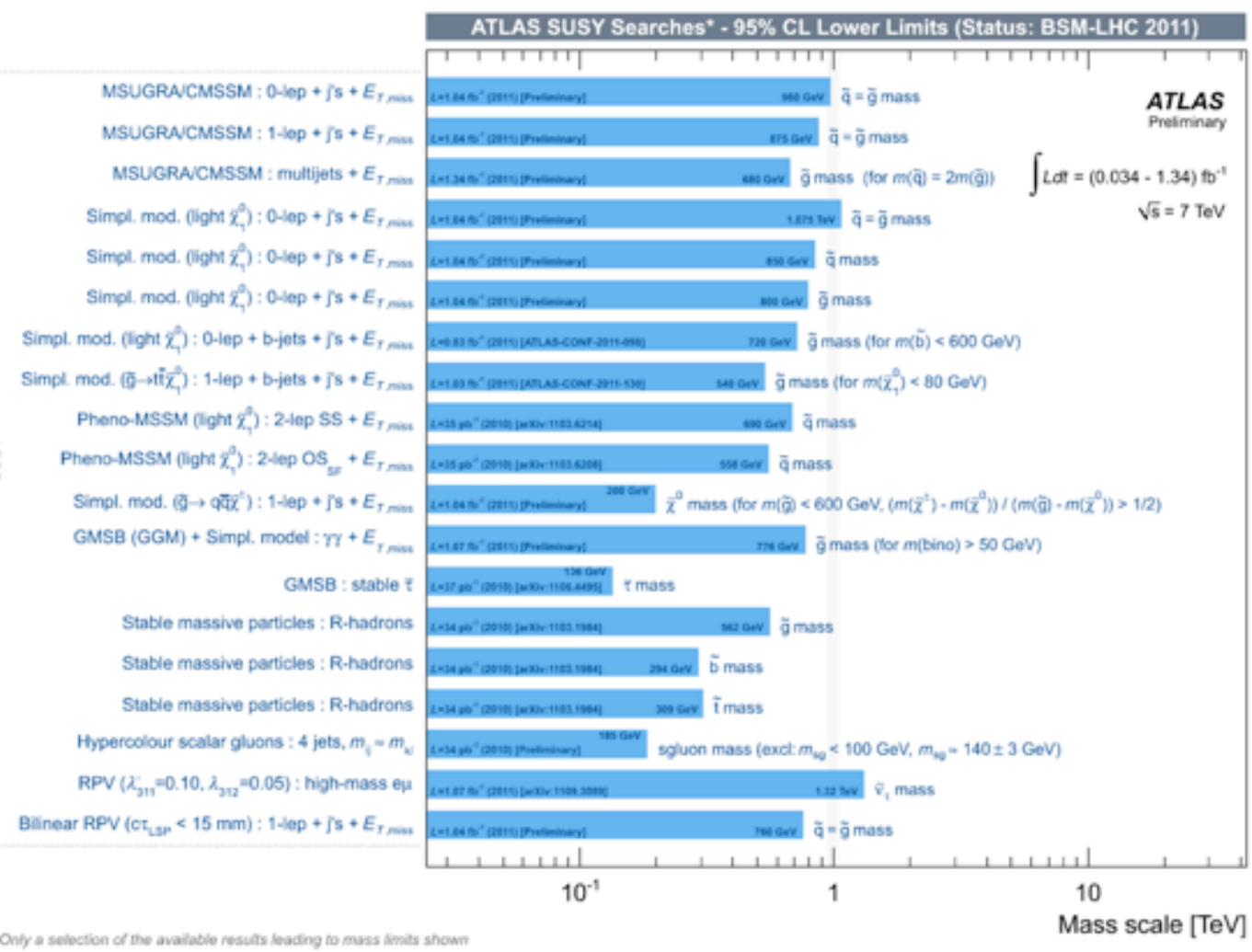

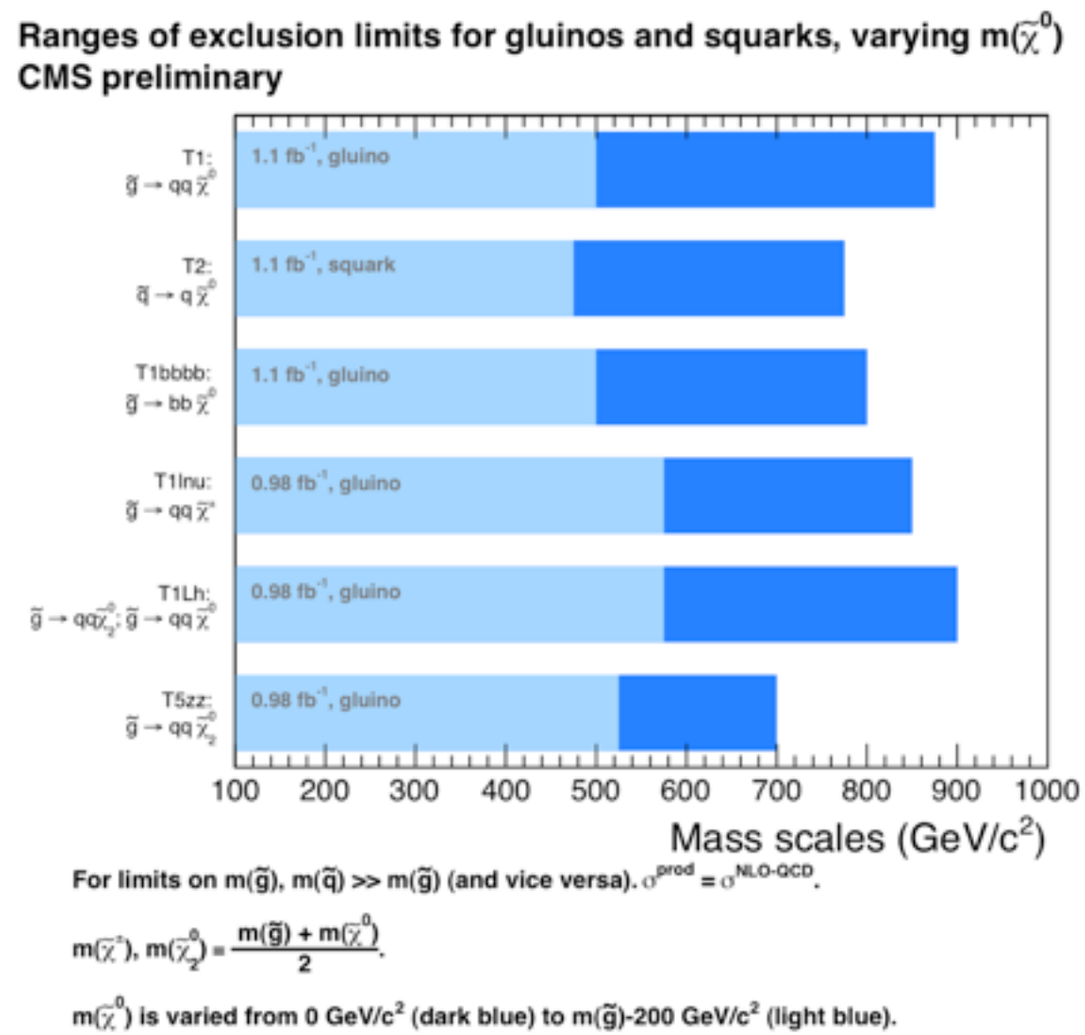

Should we be concerned???

Today's Talk

- In today's talk, I will take you on a guided tour of the latest SUSY searches from the LHC.
- We will focus on their implications for low-scale SUSY-breaking scenarios (General Gauge Mediation).
- As we'll see, studying signatures of GGM naturally leads one to consider most (all?) of the LHC SUSY searches
  -- GGM is a "signature generating machine"
  -- There is a lot more to GMSB phenomenology than photons!!
- GGM provides a nice unifying framework with which to understand all the different LHC results!

First, let us set the stage...

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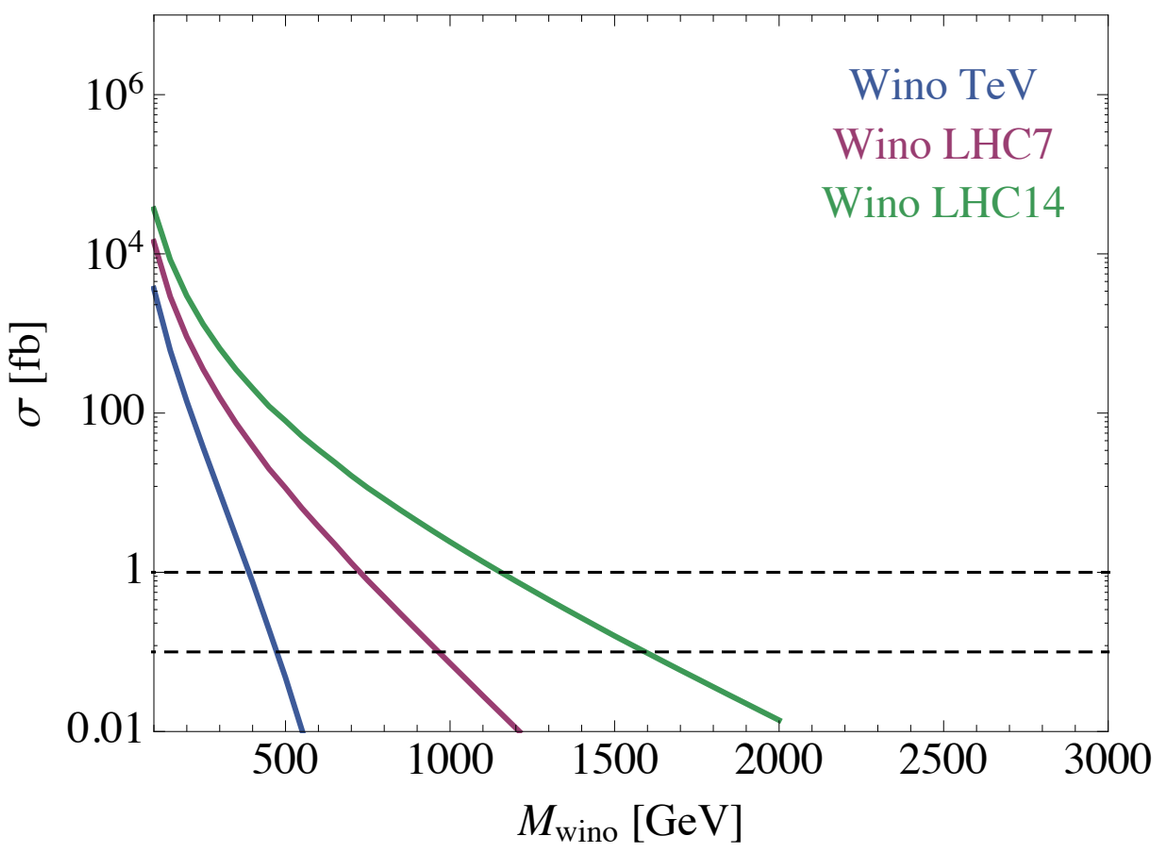

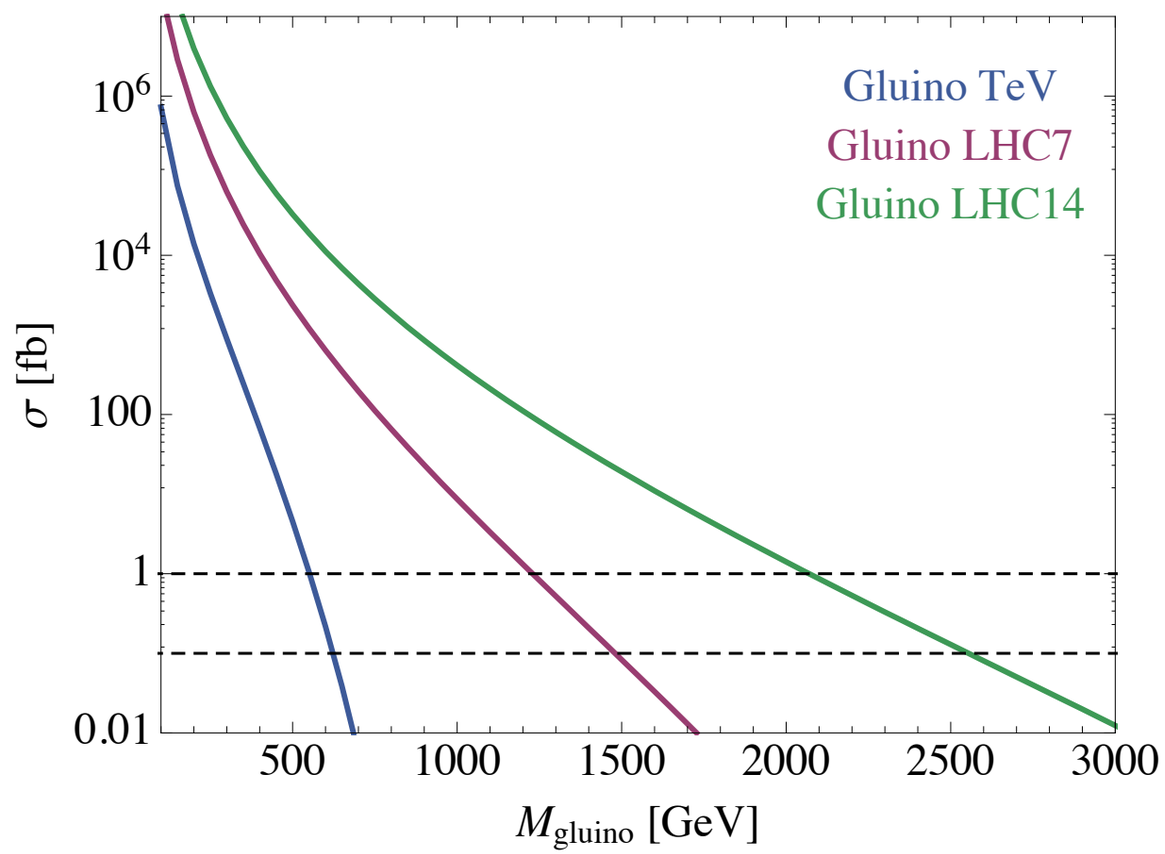

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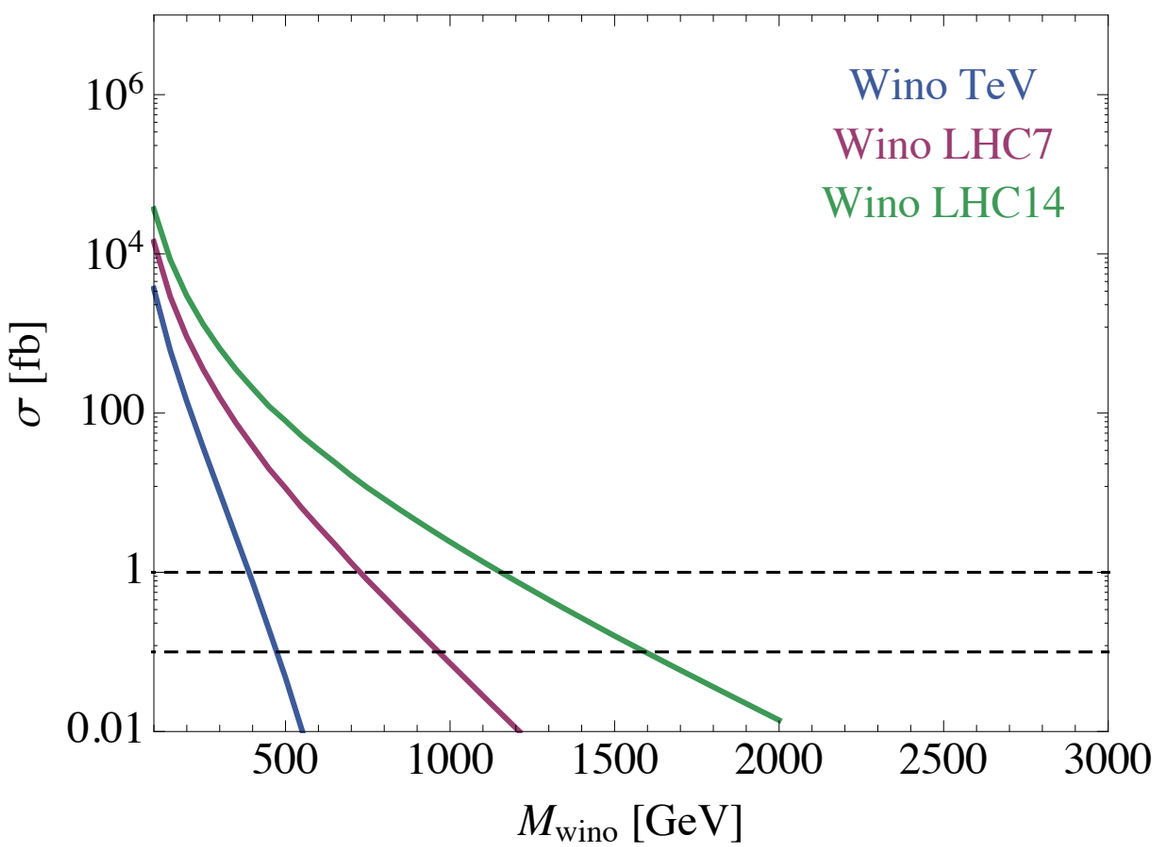

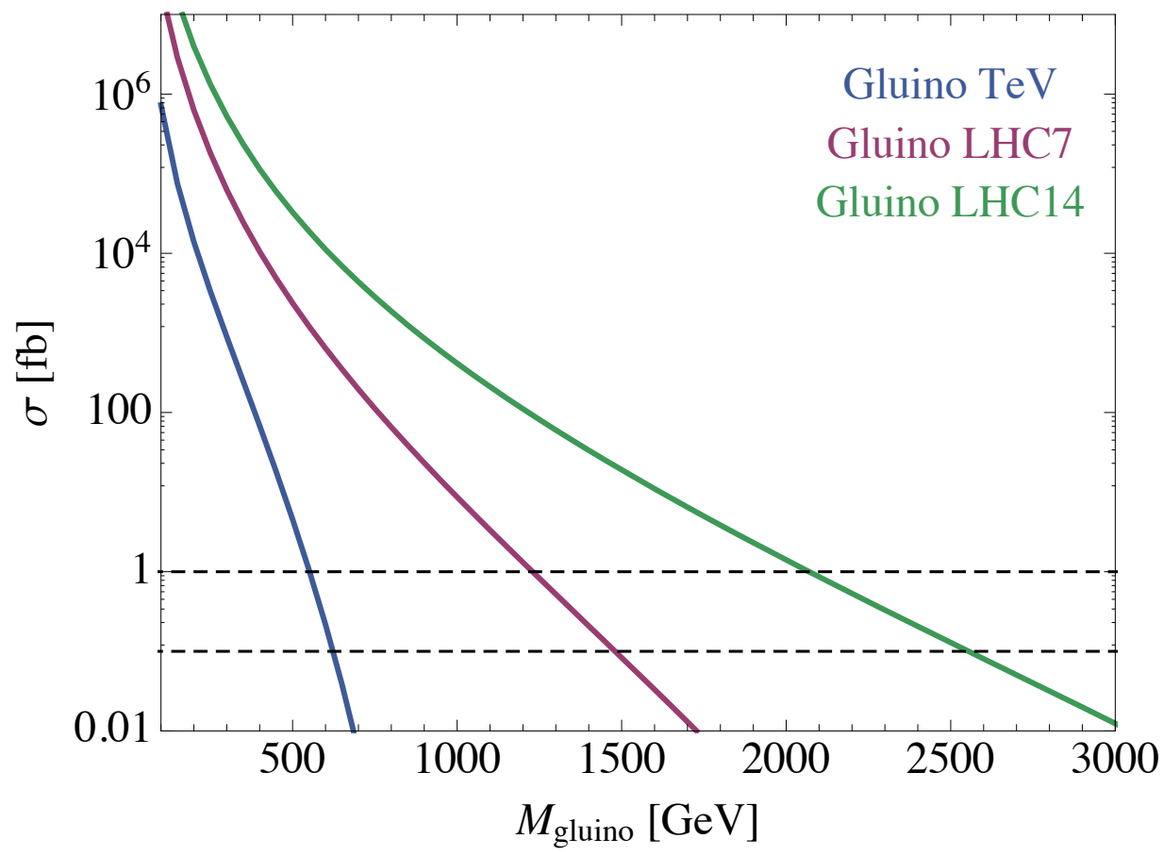

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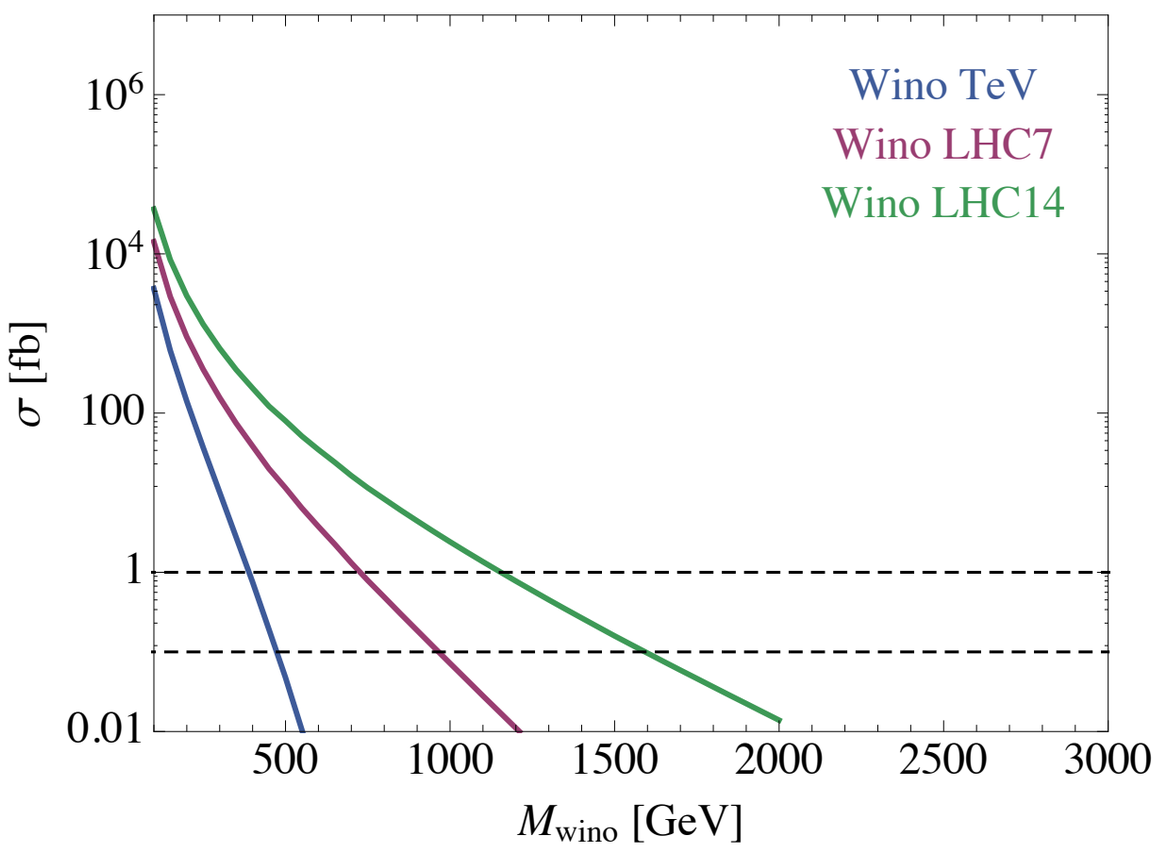

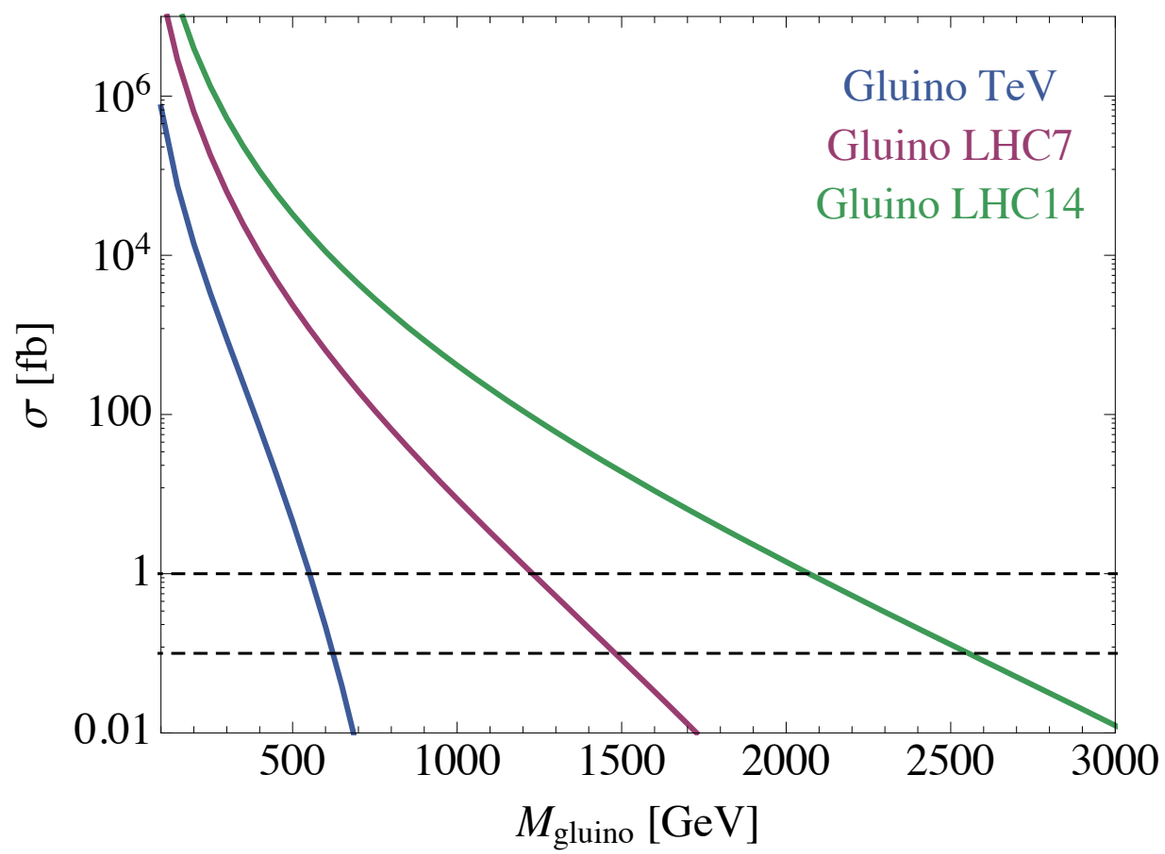

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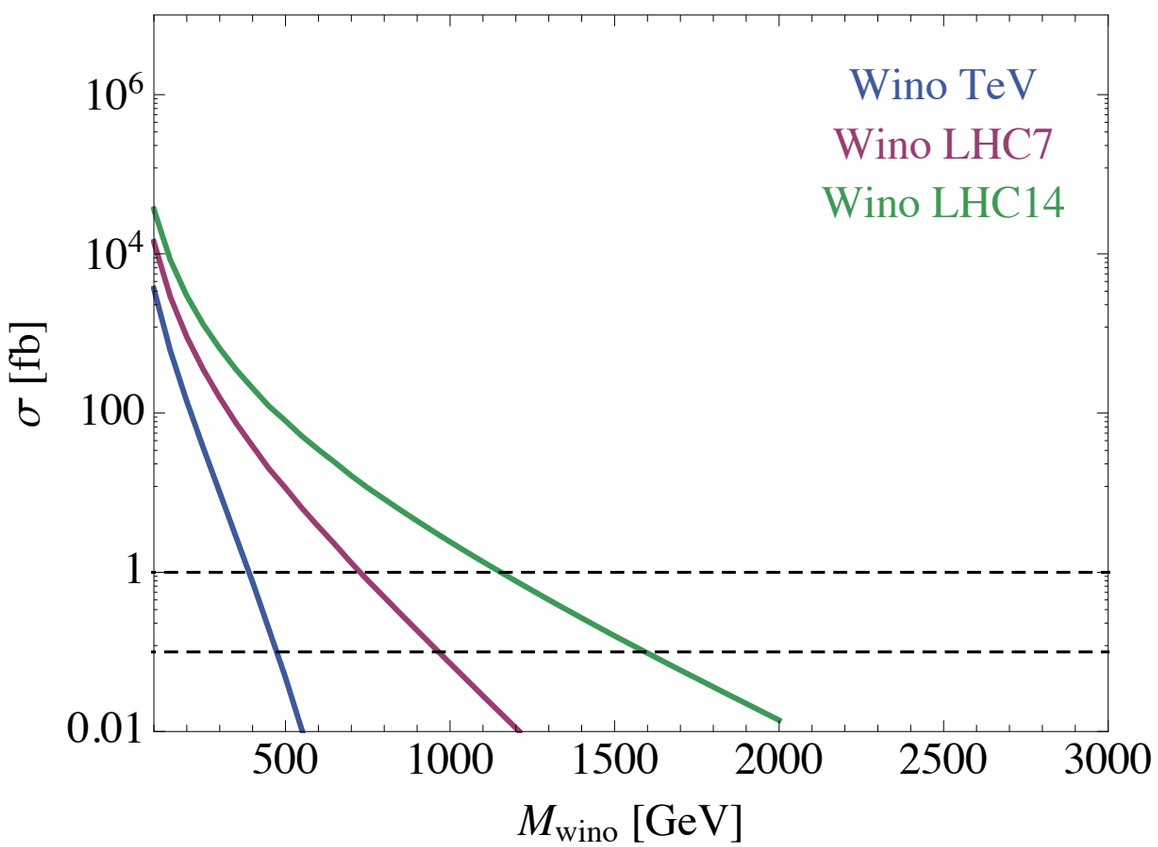

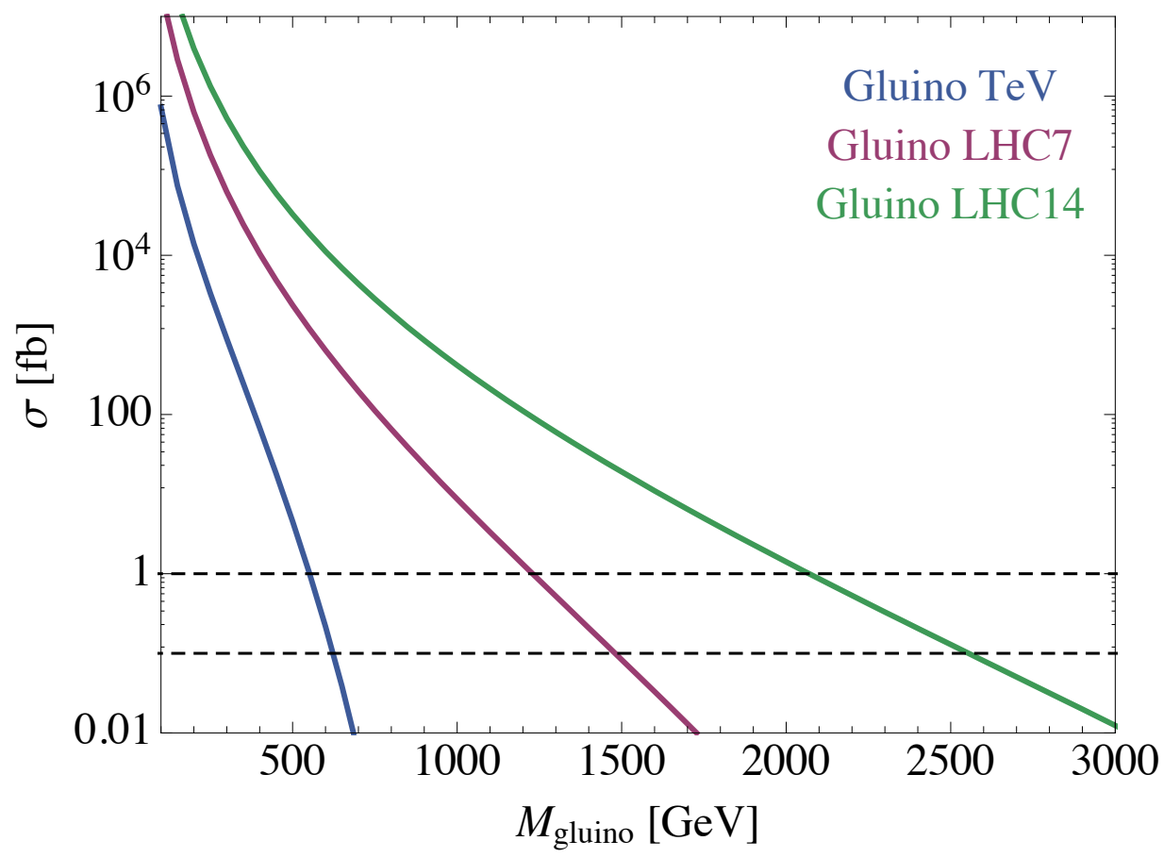

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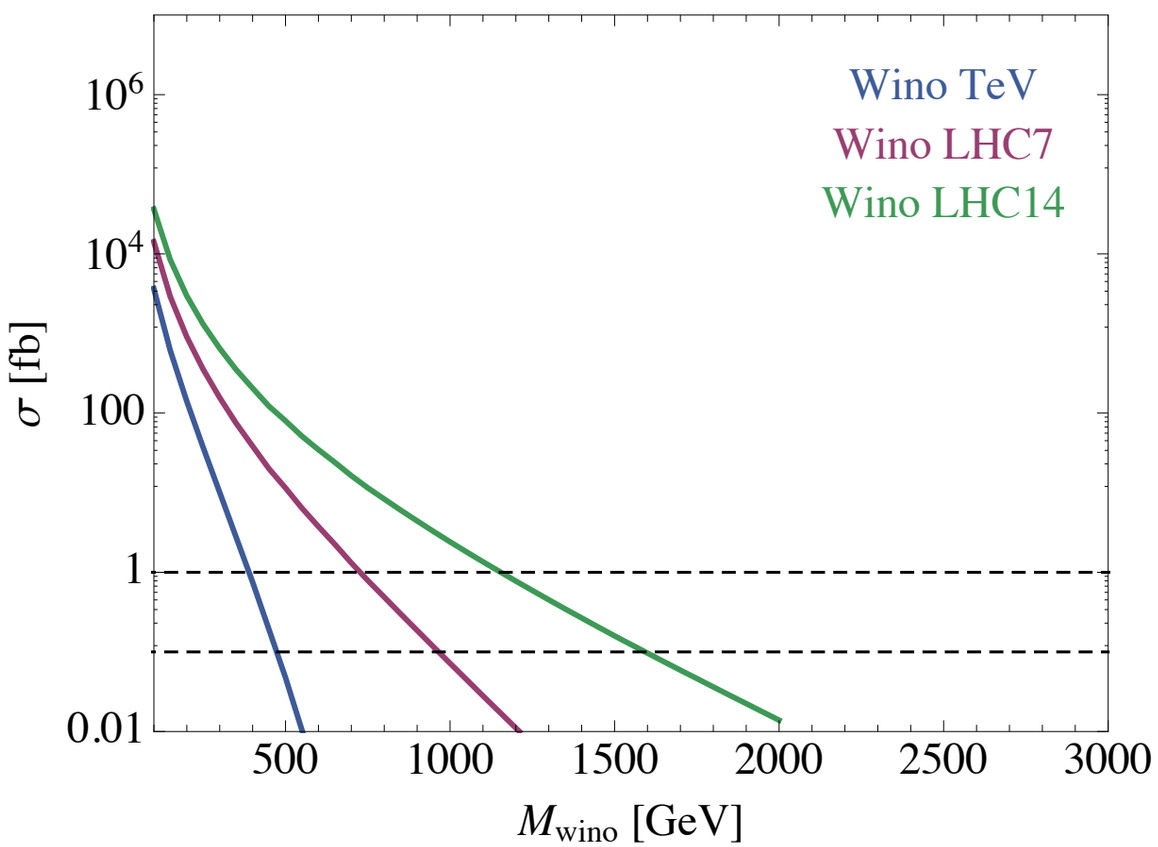

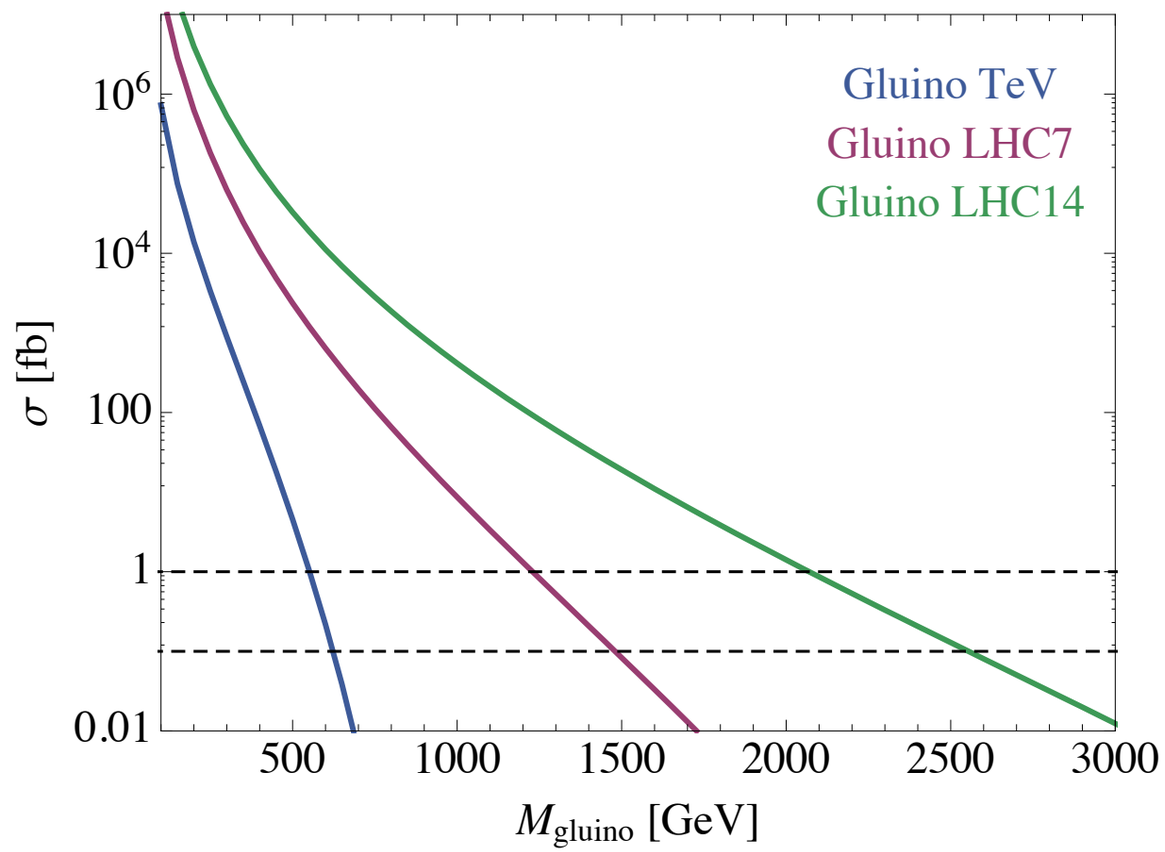

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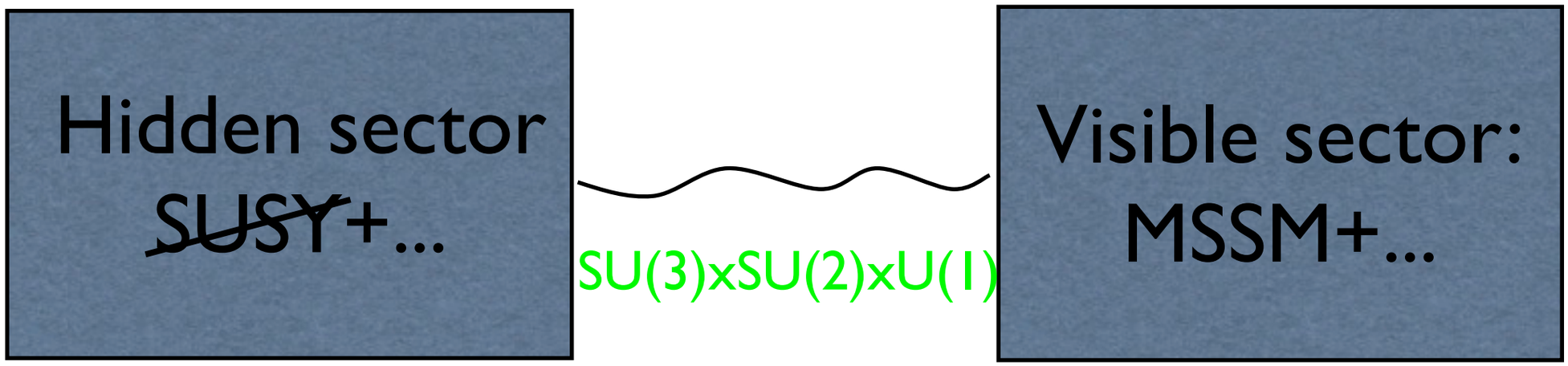
Yardstick with which to measure the current progress

Gauge Mediation



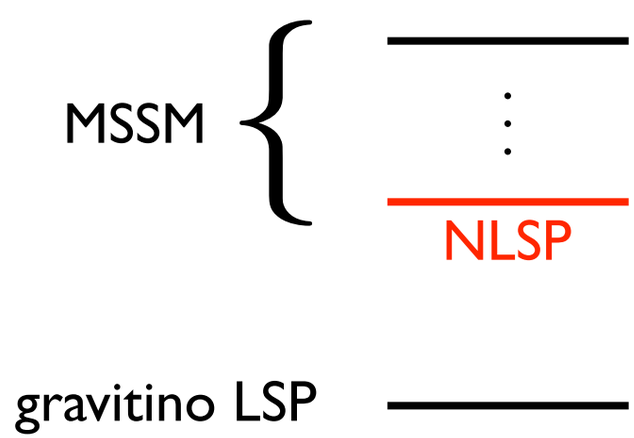
- Gauge mediation is a very attractive scenario for the MSSM:
  - Solves SUSY flavor problem
  - Calculable framework
- Recently, a model-independent framework for GMSB was formulated, and the full parameter space was understood:
- "General Gauge Mediation" (Meade, Seiberg & DS; Buican, Meade, Seiberg & DS)
- LHC searches are now being designed with GGM in mind!

The NLSP

- Gravitino LSP is a universal prediction of gauge mediation models:

$$m_{3/2} = \frac{F}{\sqrt{3}M_{pl}} \quad (\sim \mathrm{eV} - \mathrm{GeV})$$

- Lightest MSSM sparticle becomes the next-to-lightest superpartner (NLSP).



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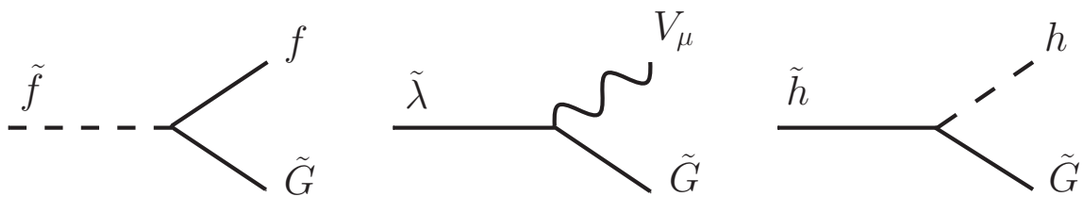

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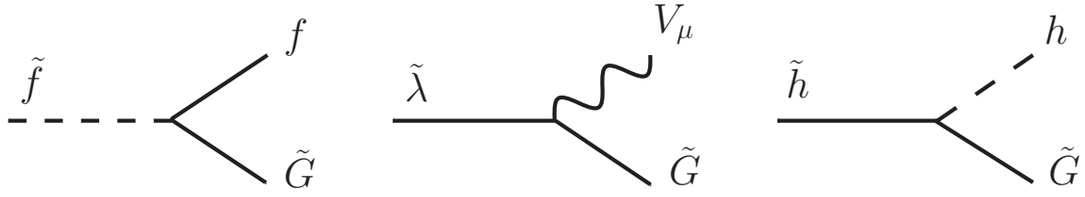

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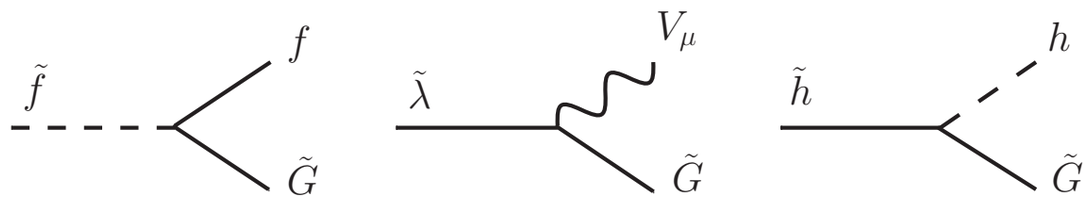

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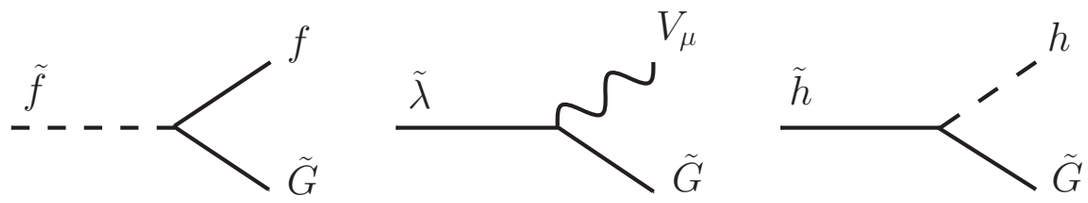

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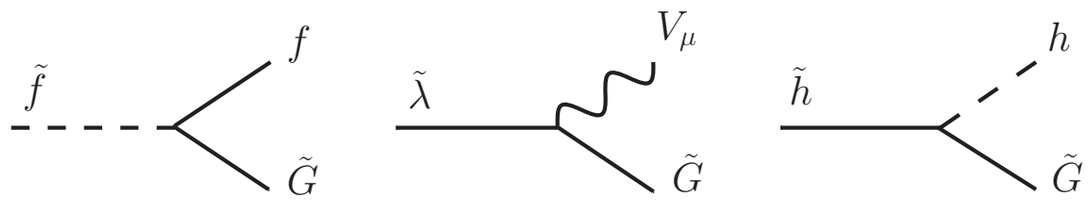

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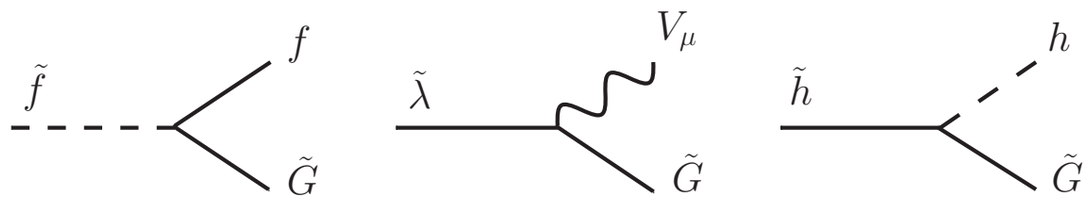

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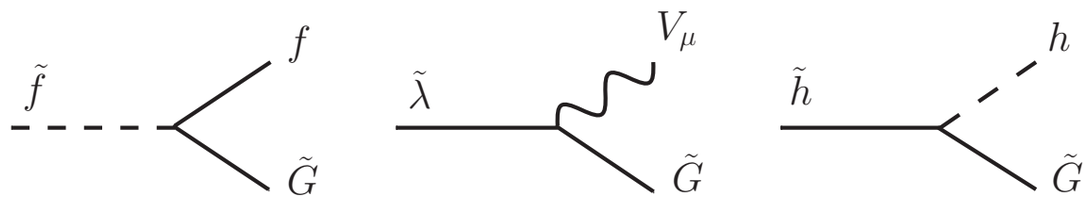

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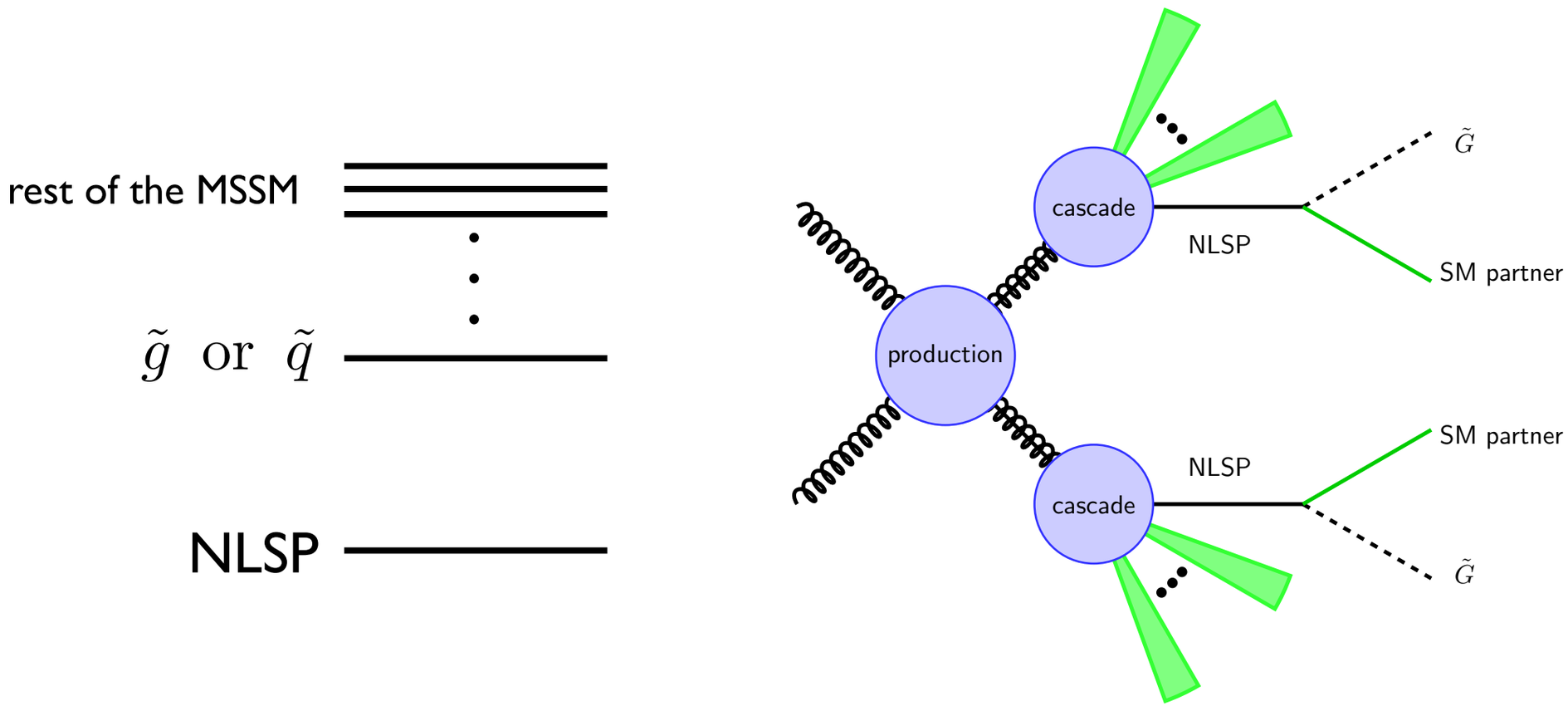
- Considering all possible NLSP decays leads to many different final states!

The rest of the talk

- In the rest of the talk, I will give an overview of the current LHC searches, as seen through the lens of GGM.
- Our modus operandi:
  - Simulate signal events using public codes for spectrum generation (SoftSUSY and SDECAY), process generation (Pythia), jet clustering (FastJet), and NLO cross sections (Prospino).
  - Filter through homemade detector simulation (basic geometric acceptance, lepton isolation).
  - Validate on benchmark model points / grids provided by public experimental references.
  - Using experimentally-estimated backgrounds, derive limits on "simplified" GMSB scenarios (minimal spectra for production and decay).

More on our minimal spectra

- We will focus on the minimal spectra for production and decay.



- Will show limits in 2D (M_{gluino} vs M_{NLSP} and M_{gluino} vs M_{squark} with fixed M_{NLSP}).

- Parametrize phenomenology with physical masses, not unphysical model parameters!!

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Relevant LHC Searches

Analysis	Collaboration	Luminosity (fb^{-1})	Ref
jets+MET	ATLAS	1	[26]
	CMS	1.1	[27]
with α_T	CMS	1.1	[28]
6-8 jets+MET	ATLAS	1.34	[29]
b-jets+MET	ATLAS	0.833	[30]
	CMS	1.1	[31]
SS dileptons+MET	CMS	0.98	[33]
lepton+jets+MET	ATLAS	1.04	[34]
	CMS	1.1	[35]
lepton+b-jets+MET	ATLAS	1.03	[36]
$Z(\ell^+\ell^-)$+jets+MET	CMS	0.98	[37]
$\gamma\gamma$+MET	ATLAS	1.07	[38]
	CMS	1.1	[40]
γ+jets+MET	CMS	1.1	[40]
$\gamma+\ell$+MET	CMS	0.035	[41]

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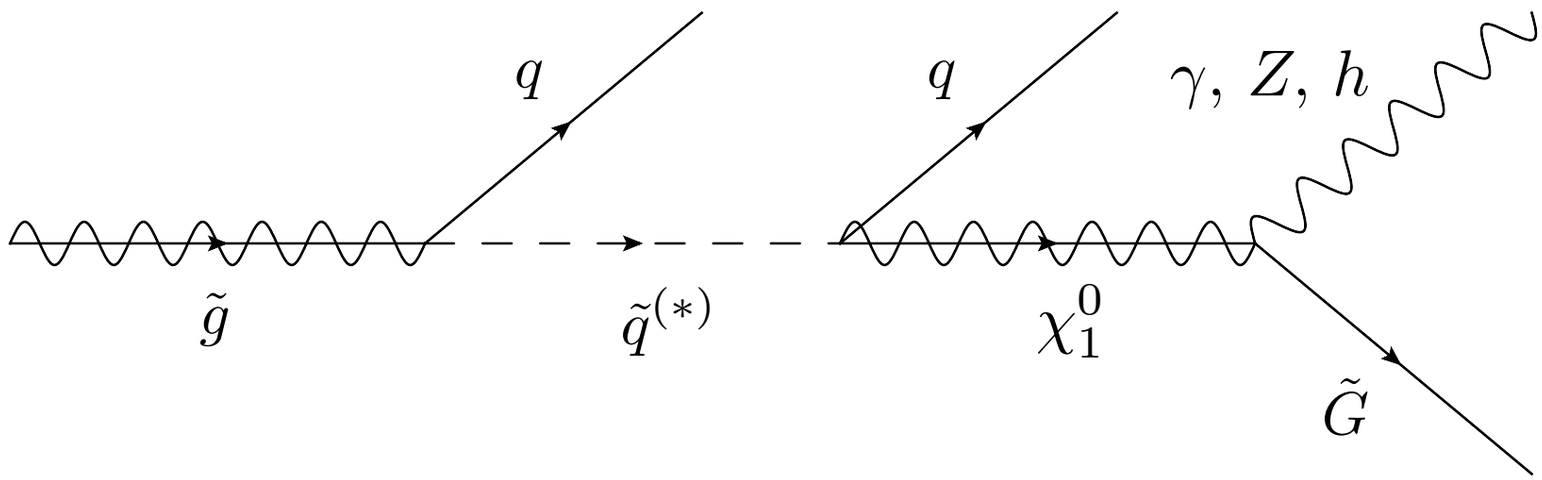

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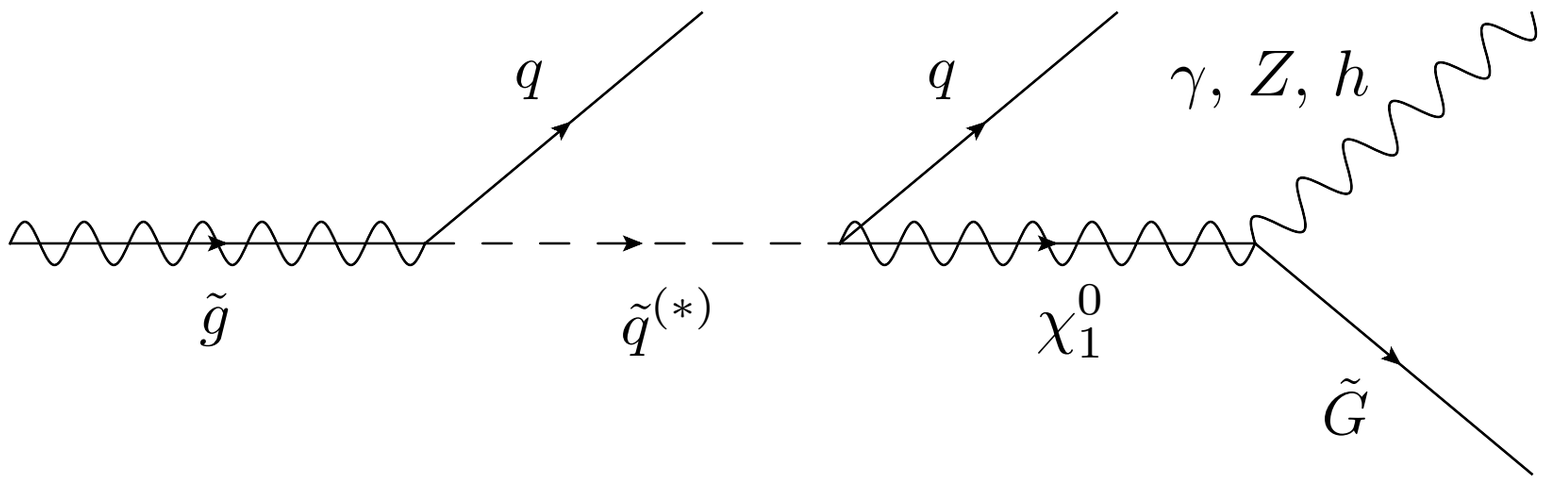

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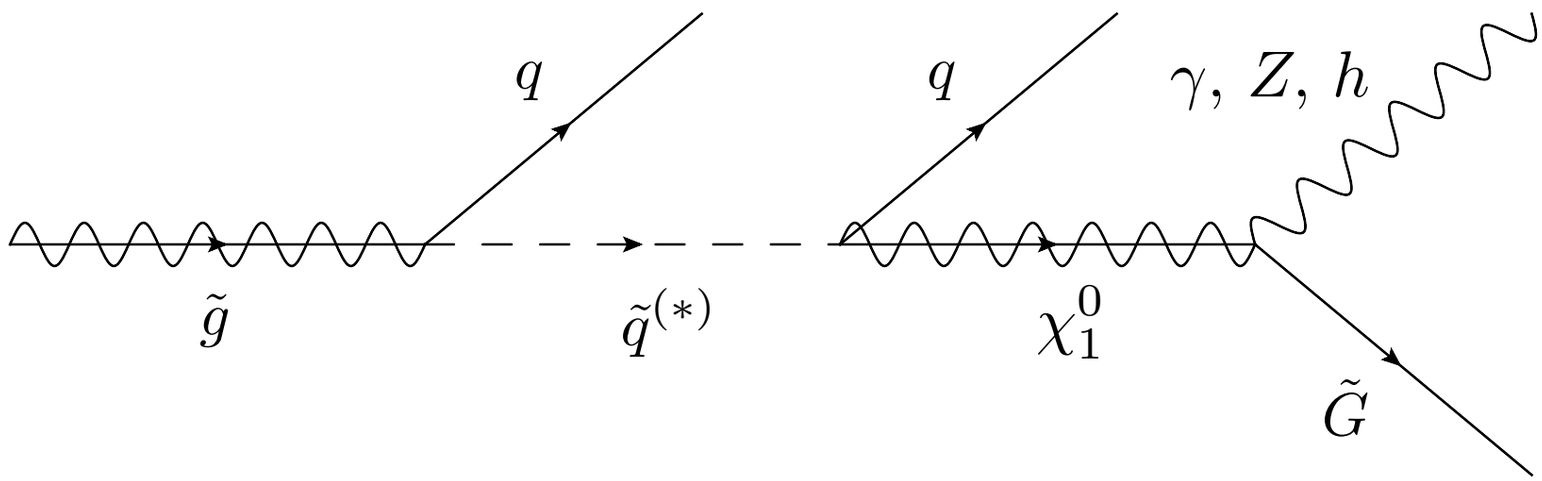

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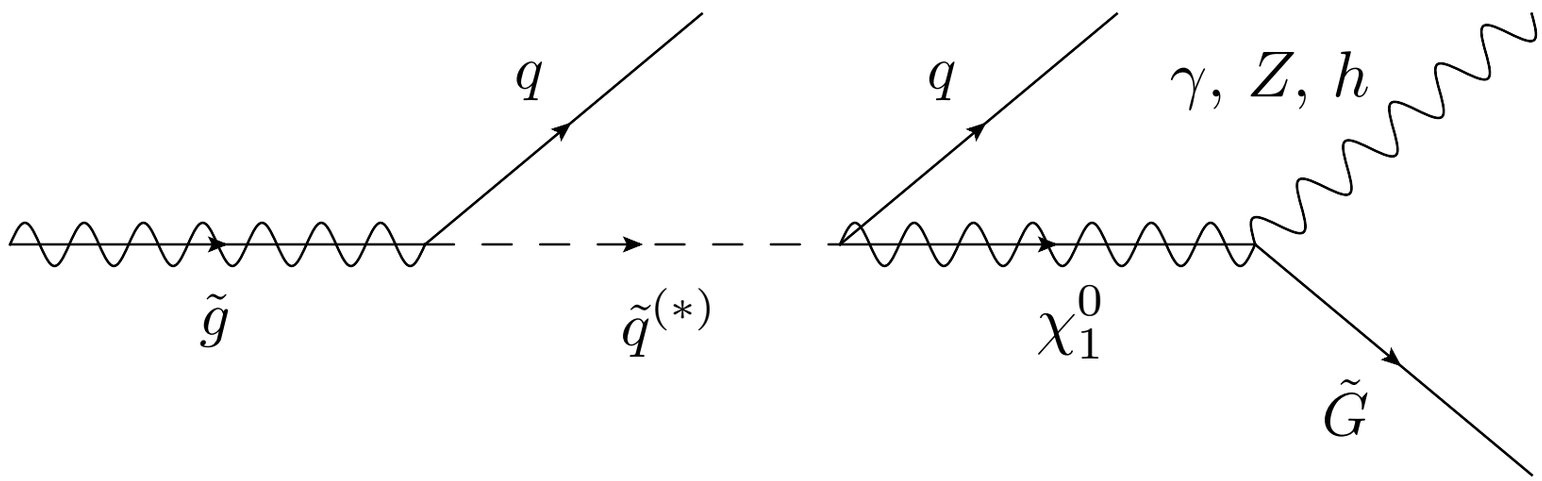

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  - Z-rich Higgsino NLSP — ZZ+MET

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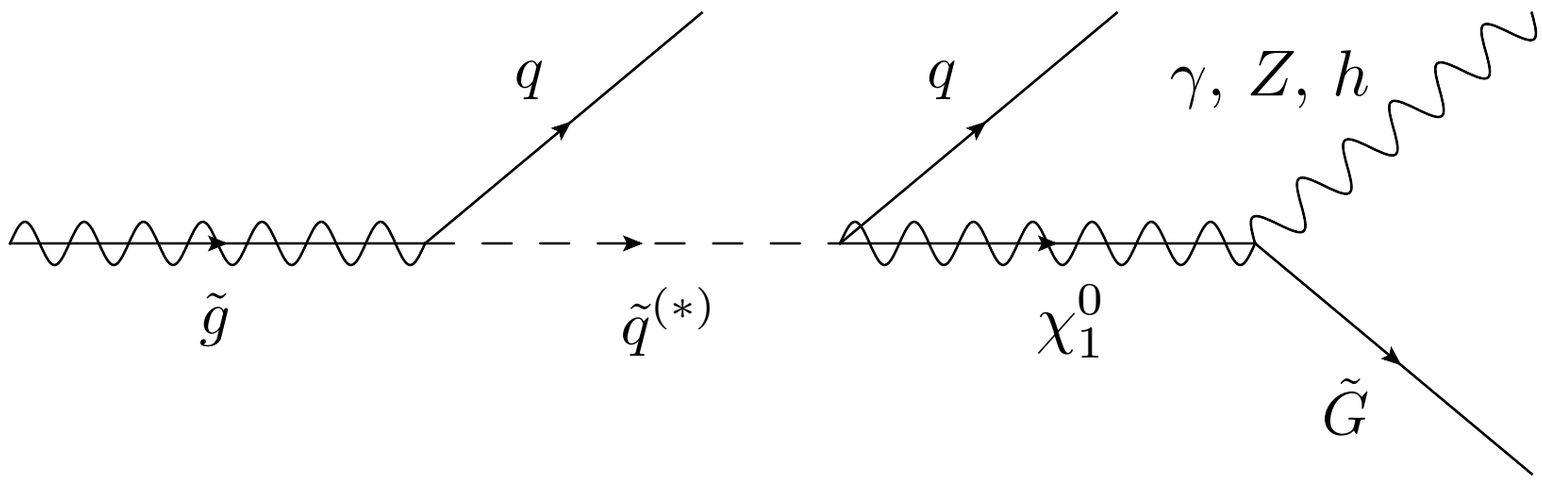

- Focus on simplifying gauge eigenstate limits:
  - Bino NLSP — γγ+MET
  - Z-rich Higgsino NLSP — ZZ+MET
  - h-rich Higgsino NLSP — hh+MET

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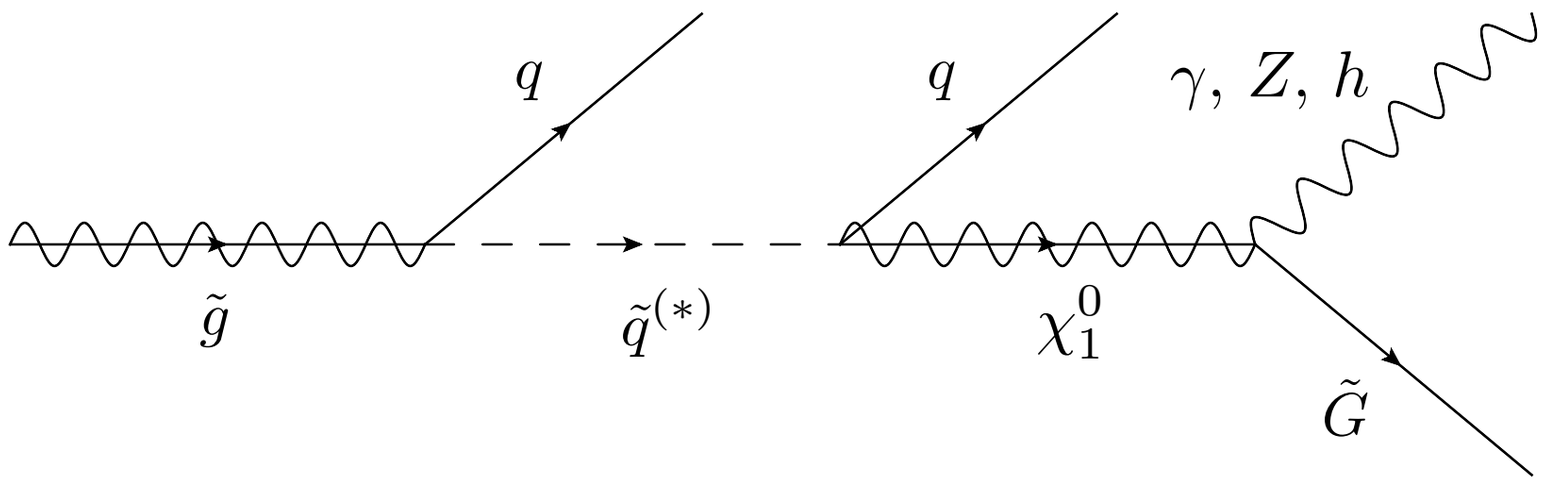
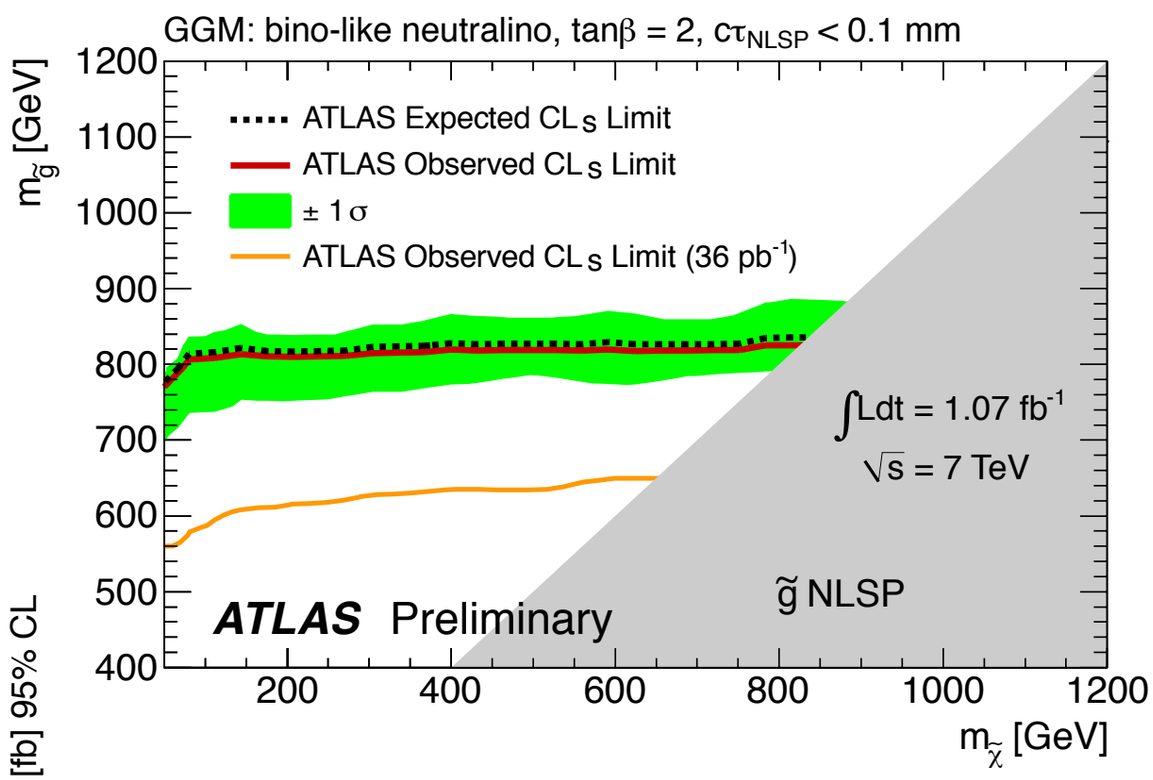
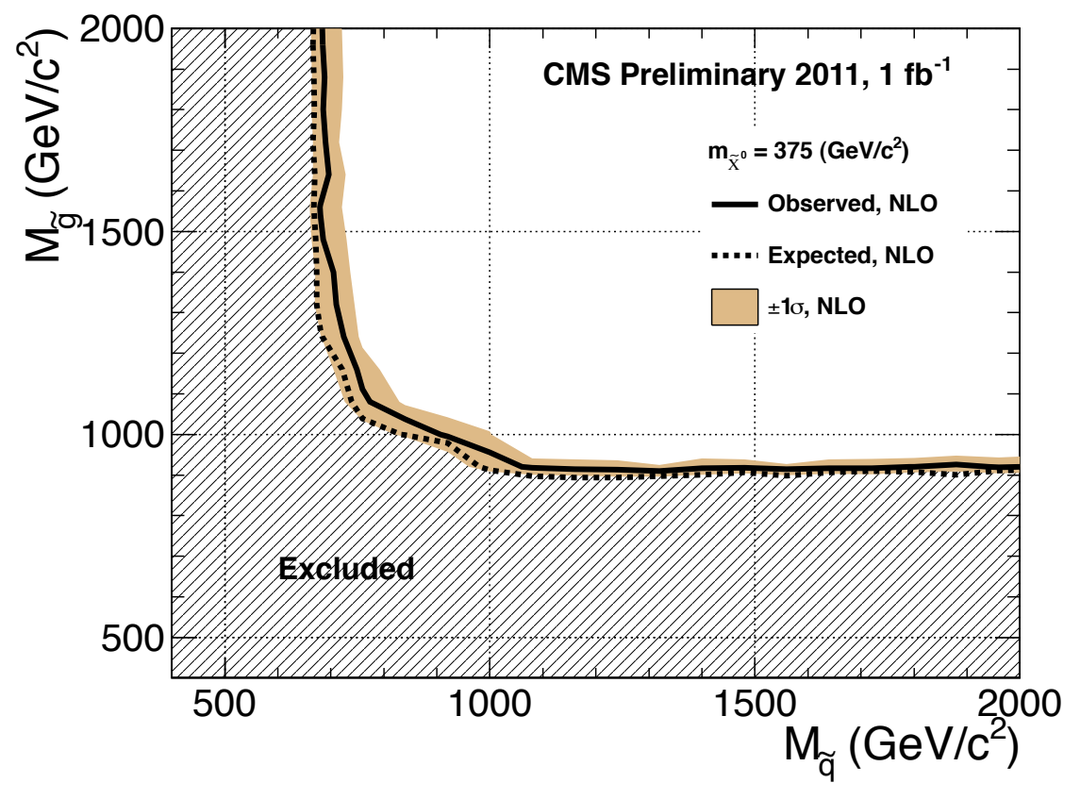


- Focus on simplifying gauge eigenstate limits:
  - Bino NLSP — γγ+MET
  - Z-rich Higgsino NLSP — ZZ+MET
  - h-rich Higgsino NLSP — hh+MET
  - Wino (co-)NLSP — γγ+MET, γZ+MET, ZZ+MET, γW+MET, ZW+MET

γγ+MET and Bino NLSP

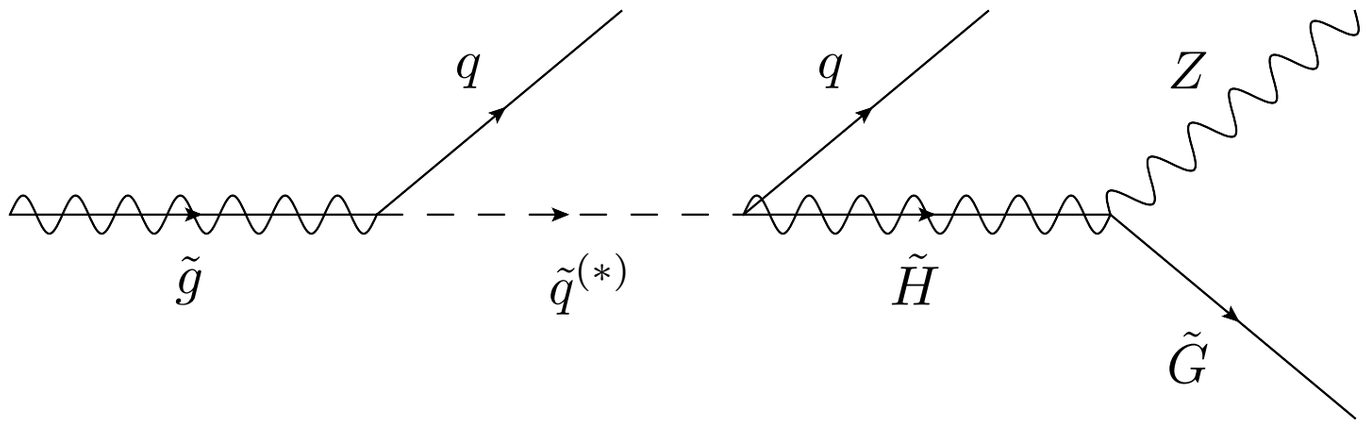
- Bino NLSP => the most well-known GMSB signature: γγ+MET
- Latest searches with ~ 1/fb by CMS (CMS-SUS-11-009) and ATLAS (ATL-PHYS-SLIDE-2011-523)





CMS and ATLAS are now expressing their results in GGM-motivated simplified parameter spaces! (Ruderman & DS)

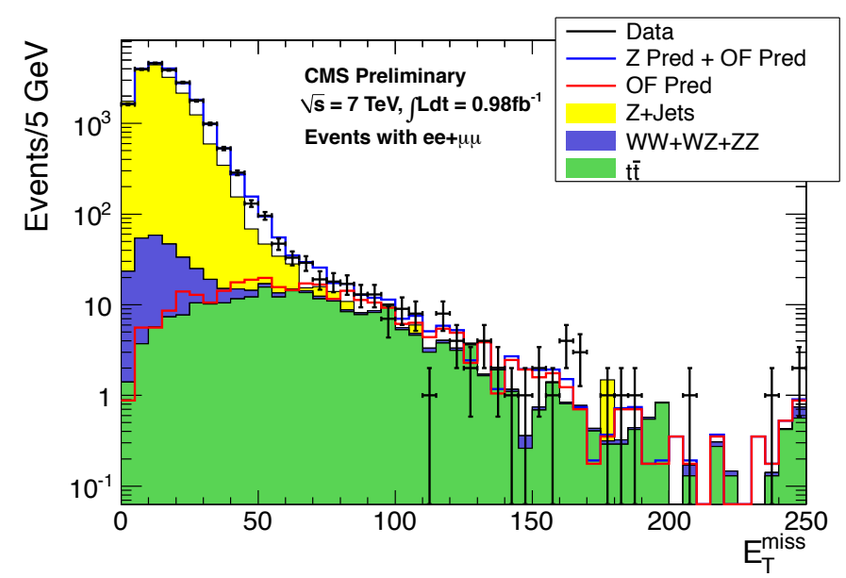
Z-rich Higgsino NLSPs



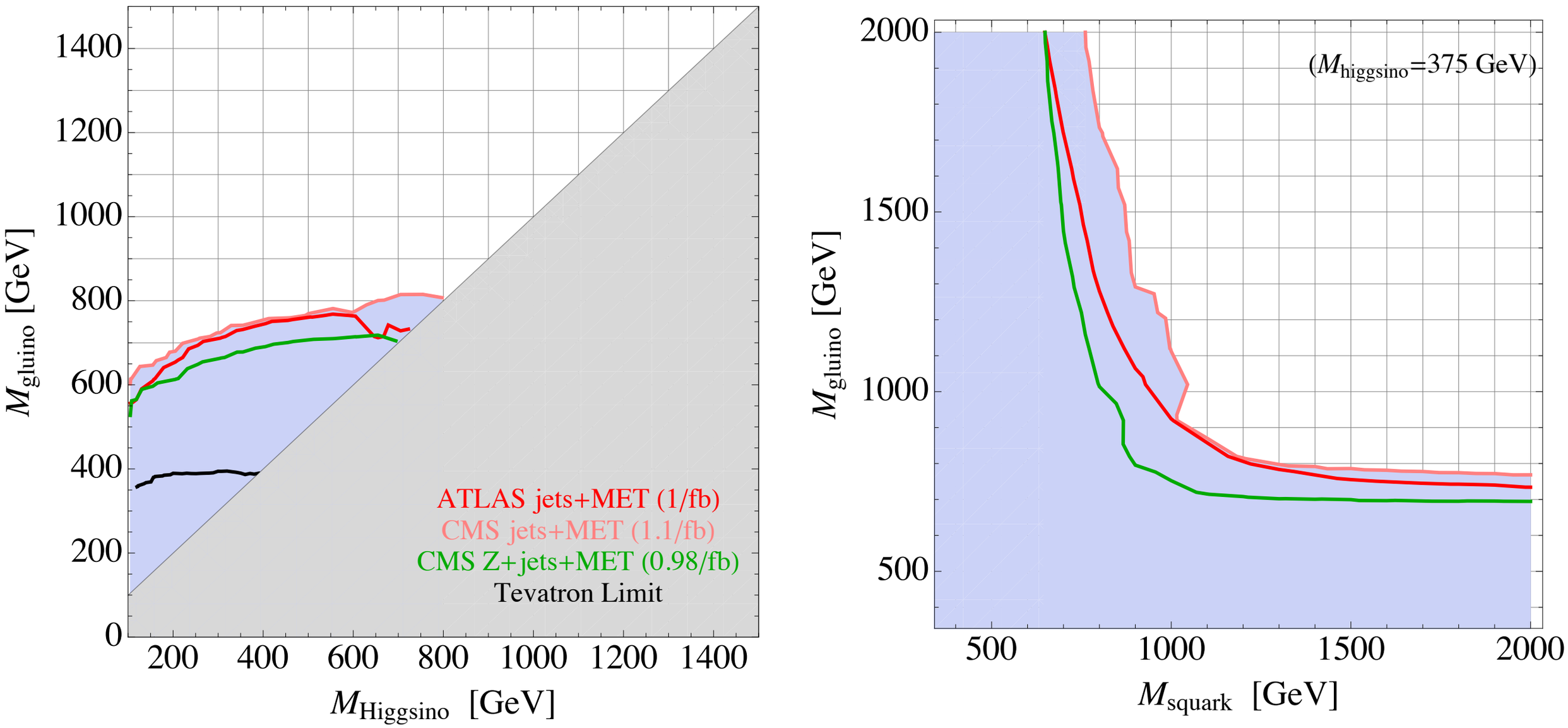
- If the NLSP is a Higgsino which decays primarily to Z's, Z(ll)+jets+MET should be a good channel.
  (Matchev & Thomas; Meade, Reece & DS; Ruderman & DS)
- Latest search by CMS with 0.98/fb (CMS-PAS-SUS-11-017)

≥2 jets with pT>30
e+e- or mu+mu- with pT>20 and 81<minv<101

	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV
Z Pred	$5.1 \pm 1.0 \pm 0.8$	$0.09 \pm 0.04 \pm 0.01$
$t\bar{t}$ Pred	$50.6 \pm 2.8 \pm 4.6$	$3.2 \pm 0.7 \pm 0.3$
Prediction	$55.7 \pm 3.0 \pm 4.6$	$3.3 \pm 0.7 \pm 0.3$
Data	**57 (25,32)**	**4 (1,3)**
UL	20	5.9



Exclusion Contours for Z−rich Higgsino NLSP



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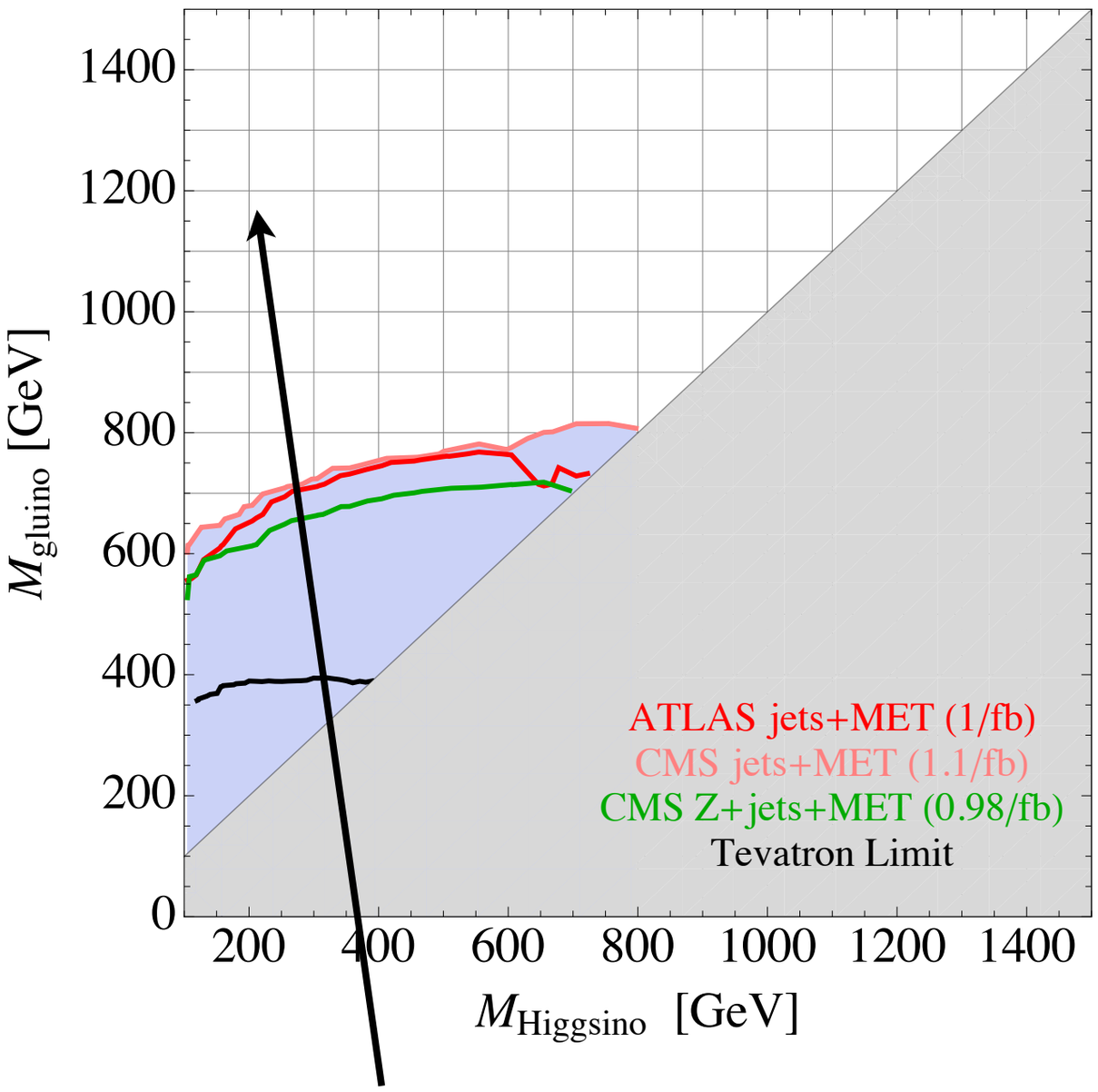

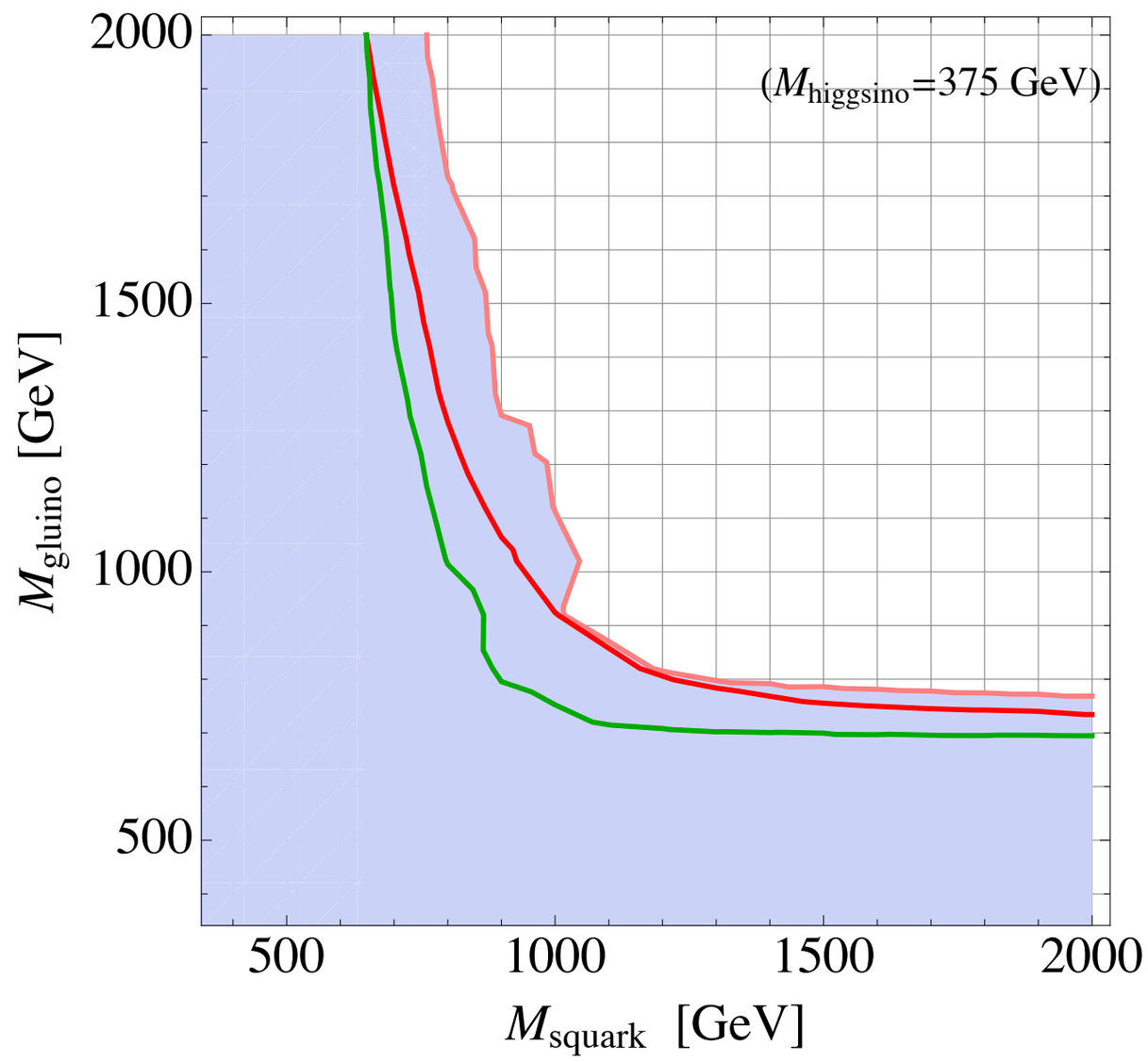

Cannot yet see direct Higgsino production.
Might need softer cuts plus more data.

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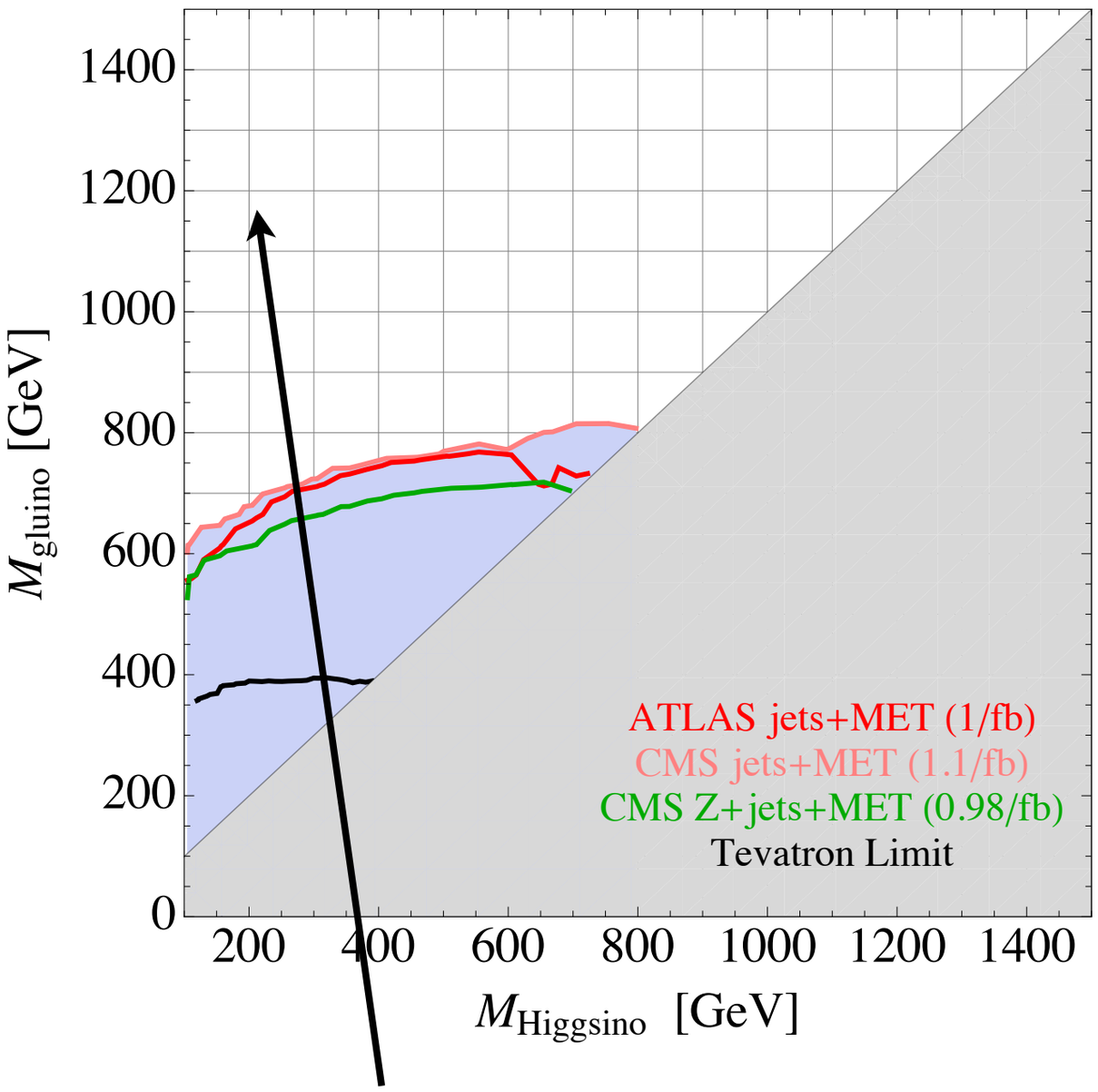
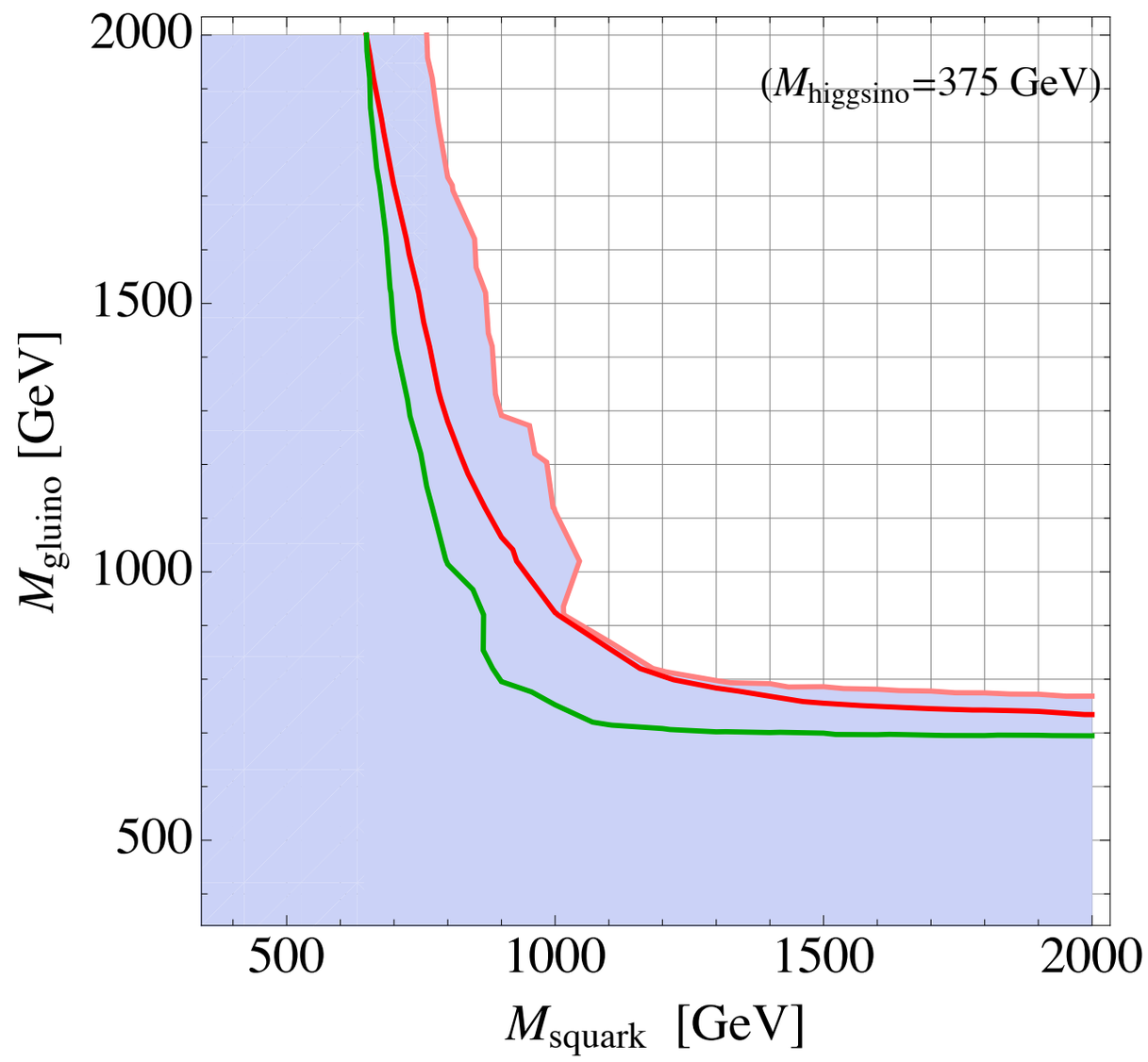
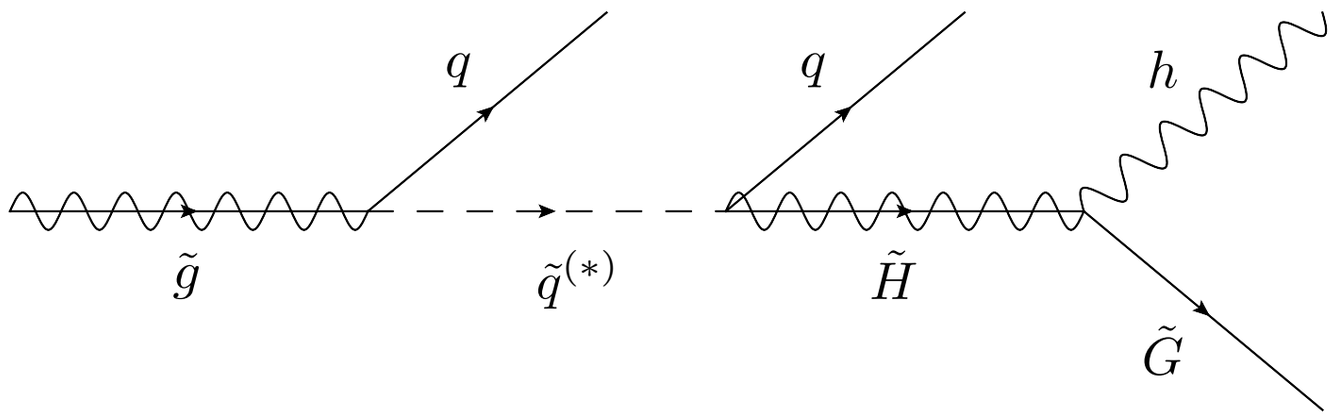




Cannot yet see direct Higgsino production.
Might need softer cuts plus more data.

ttbar is a dominant background.
MT2 with leptons might be helpful...

h-rich Higgsino NLSP



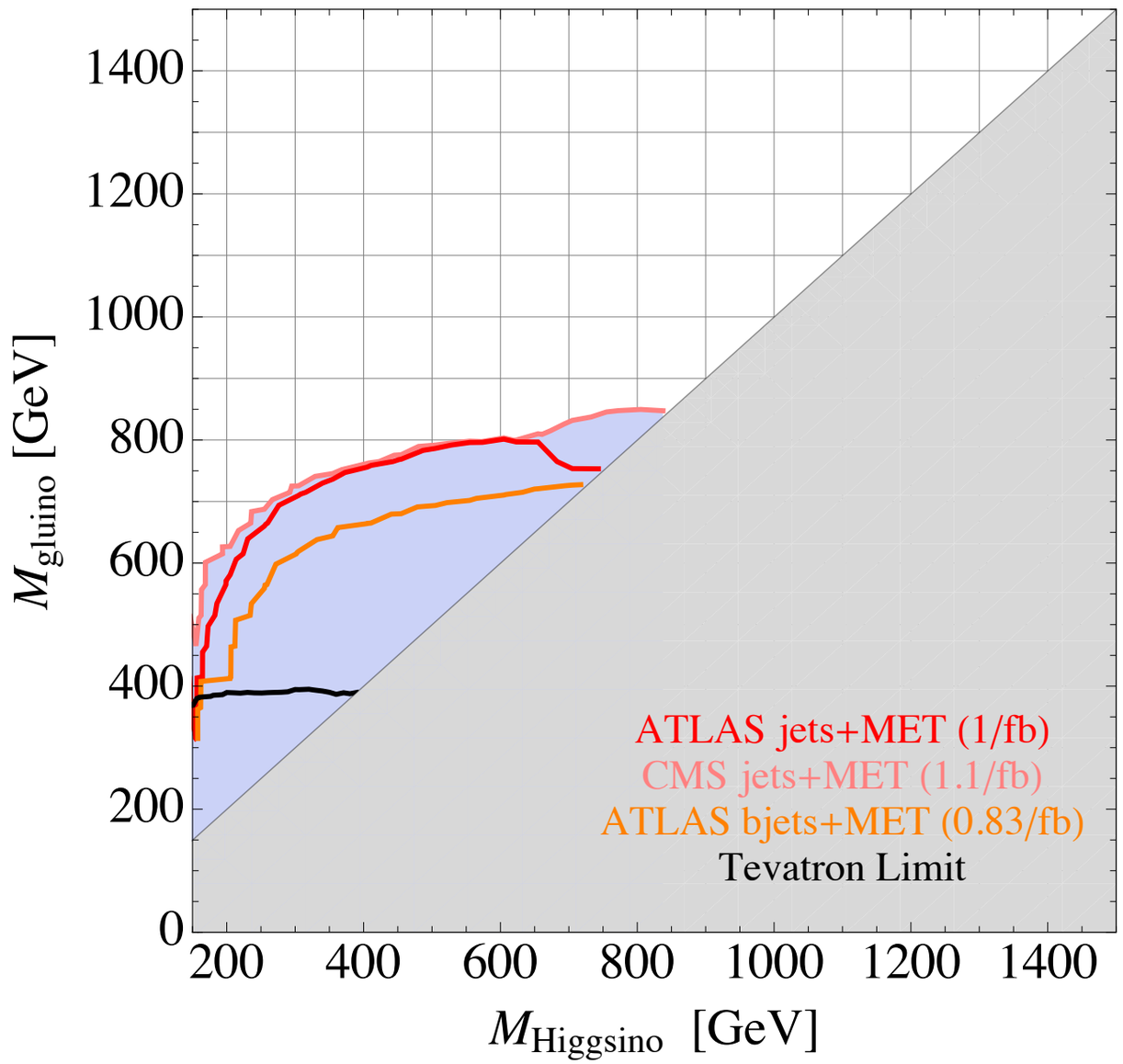
- Higgsino NLSP can also decay primarily to h's. Then bjets+MET is a relevant final state.

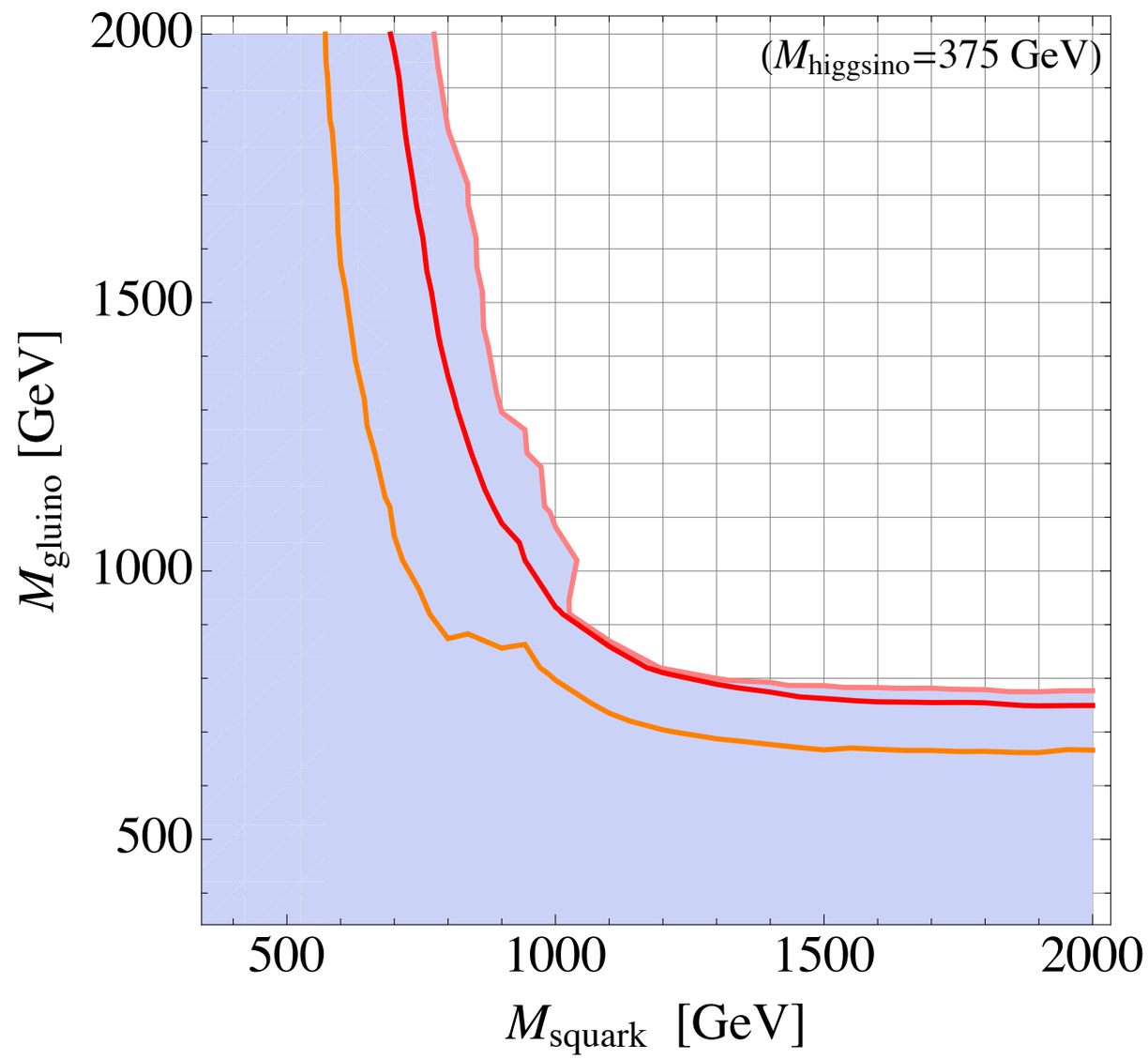
- Latest search by ATLAS with 0.83/fb (ATLAS-CONF-2011-098)

≥1 jet with pT>130, ≥2 additional jets with pT>50
MET > 130, MET/m_{eff} > 0.25, $\Delta\phi_{min}$>0.4

Sig. Reg.	Data (0.83 fb^{-1})	Top	W/Z	QCD	Total
3JA (1 btag m_{eff} >500 GeV)	361	221^{+82}_{-68}	121 ± 61	15 ± 7	356^{+103}_{-92}
3JB (1 btag m_{eff} >700 GeV)	63	37^{+15}_{-12}	31 ± 19	1.9 ± 0.9	70^{+24}_{-22}
3JC (2 btag m_{eff} >500 GeV)	76	55^{+25}_{-22}	20 ± 12	3.6 ± 1.8	79^{+28}_{-25}
3JD (2 btag m_{eff} >700 GeV)	12	$7.8^{+3.5}_{-2.9}$	5 ± 4	0.5 ± 0.3	$13.0^{+5.6}_{-5.2}$

Exclusion Contours for h−rich Higgsino NLSP





Degraded sensitivity at low NLSP mass -- MET is being squeezed out! (interesting contrast with Z-rich case)

jets+MET again does slightly better than the more specialized bjets+MET.

Largely due to systematic errors in b-tagging. Will this be improved with more data?

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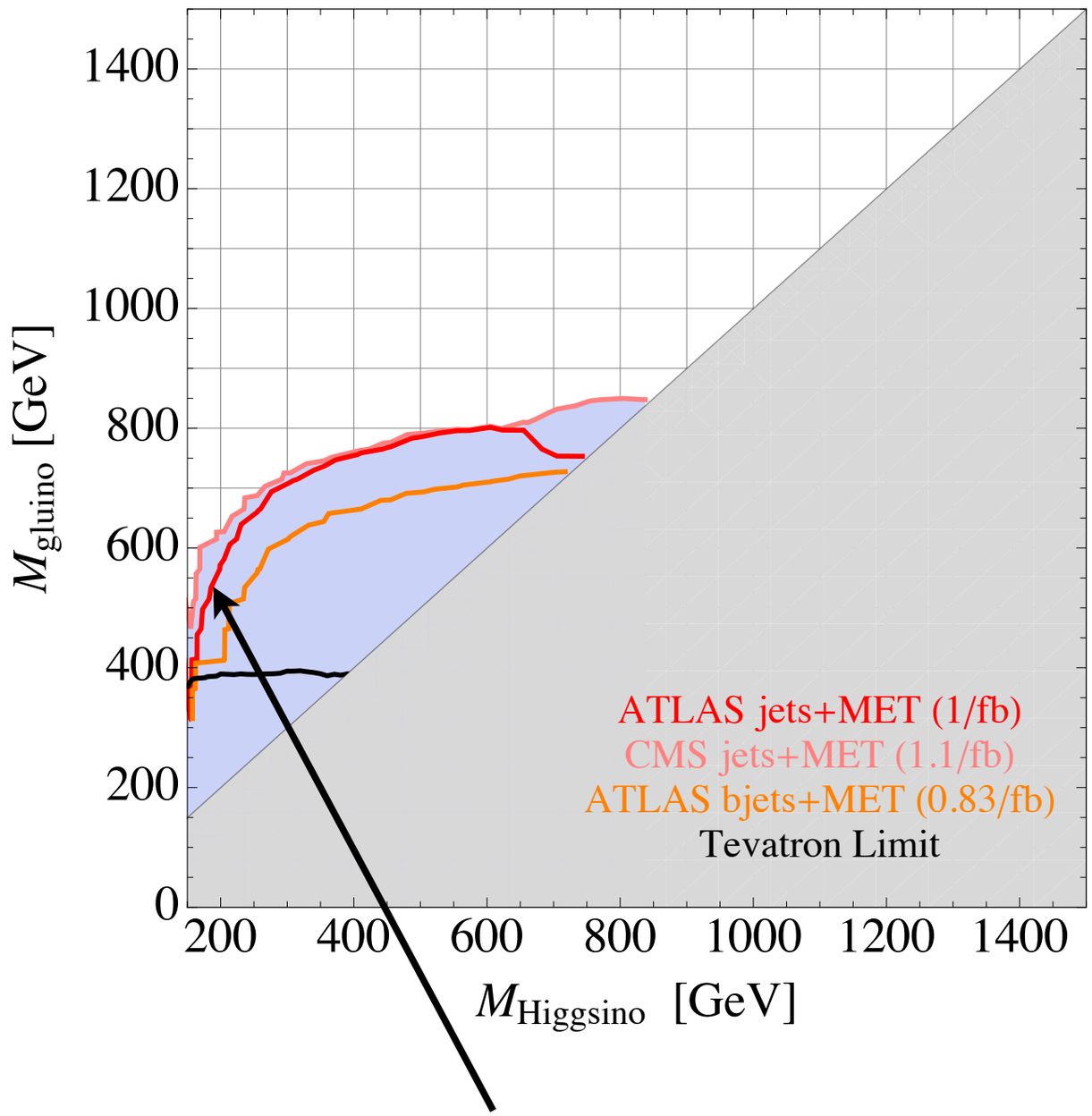

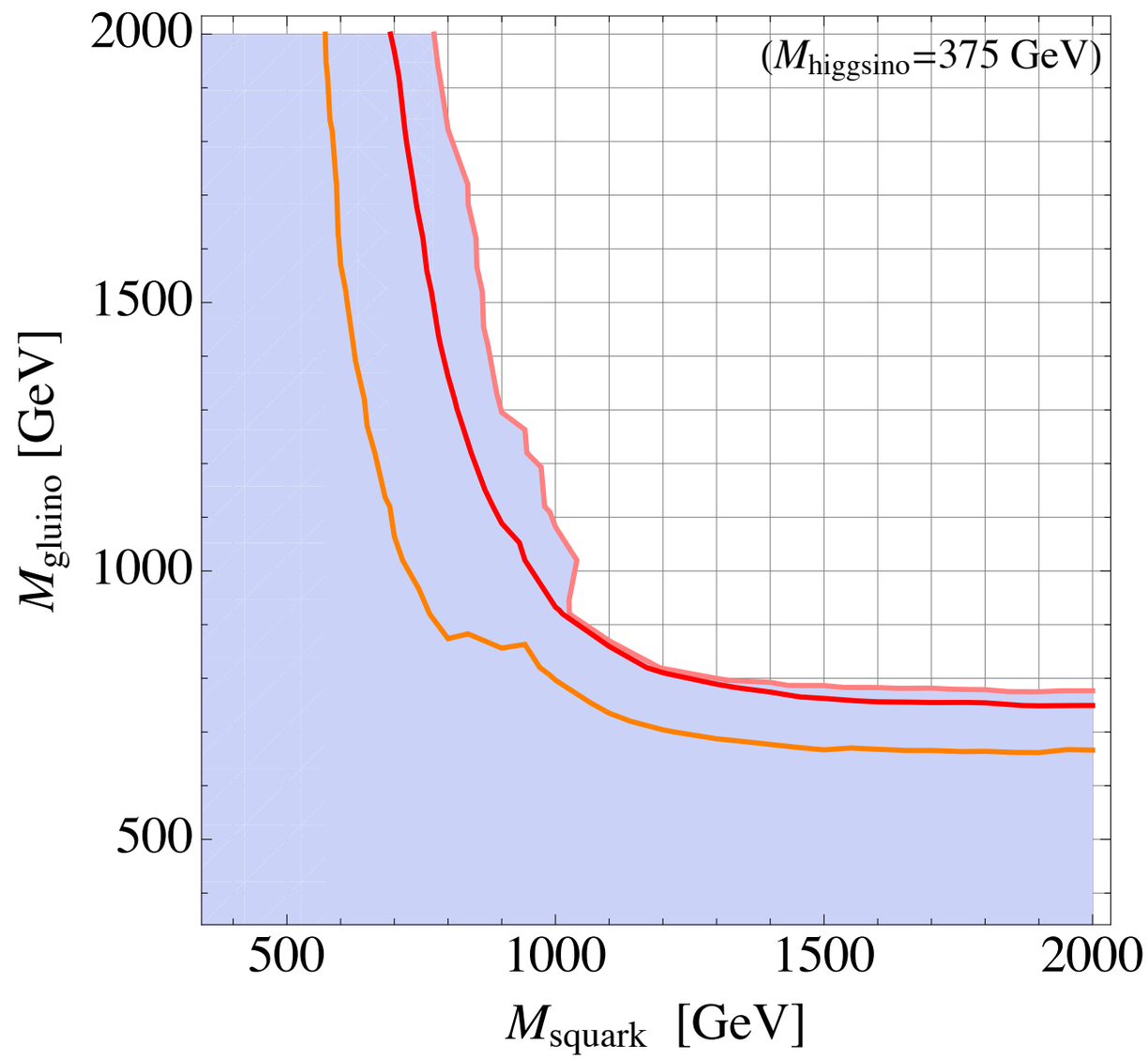

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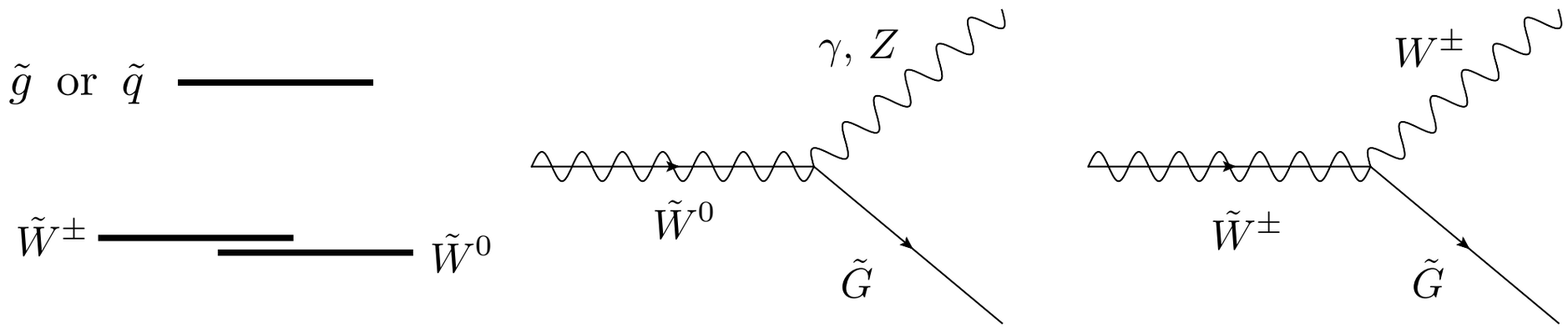
Wino co-NLSP



- Finally, for neutralino NLSPs, the last scenario is "Wino co-NLSP" (Meade, Reece & DS; Ruderman & DS)
- Here a wino-like chargino and neutralino are extremely degenerate and become co-NLSPs.
- Many interesting final states to consider!
  - jets+MET
  - l+jets+MET
  - Z+jets+MET
  - γ+l+MET
  - γγ+MET
  - γ+jets+MET

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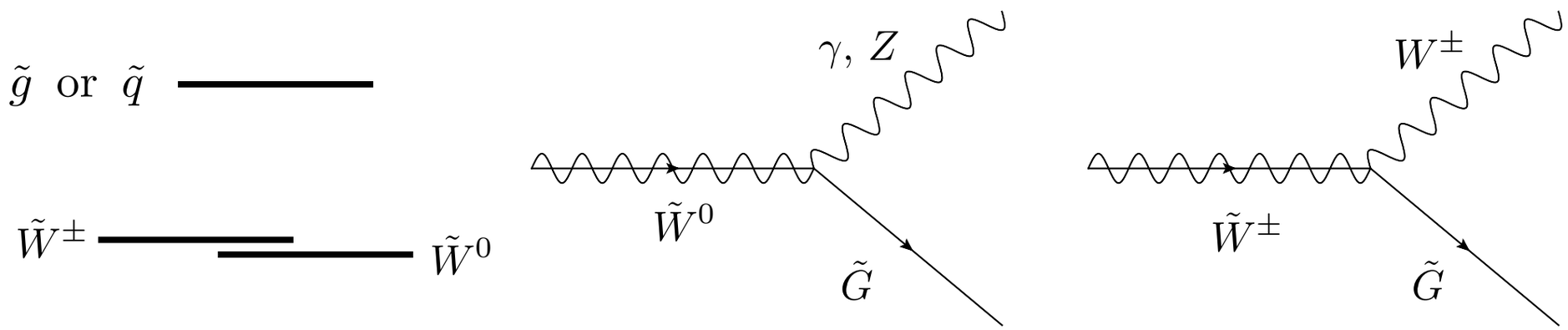

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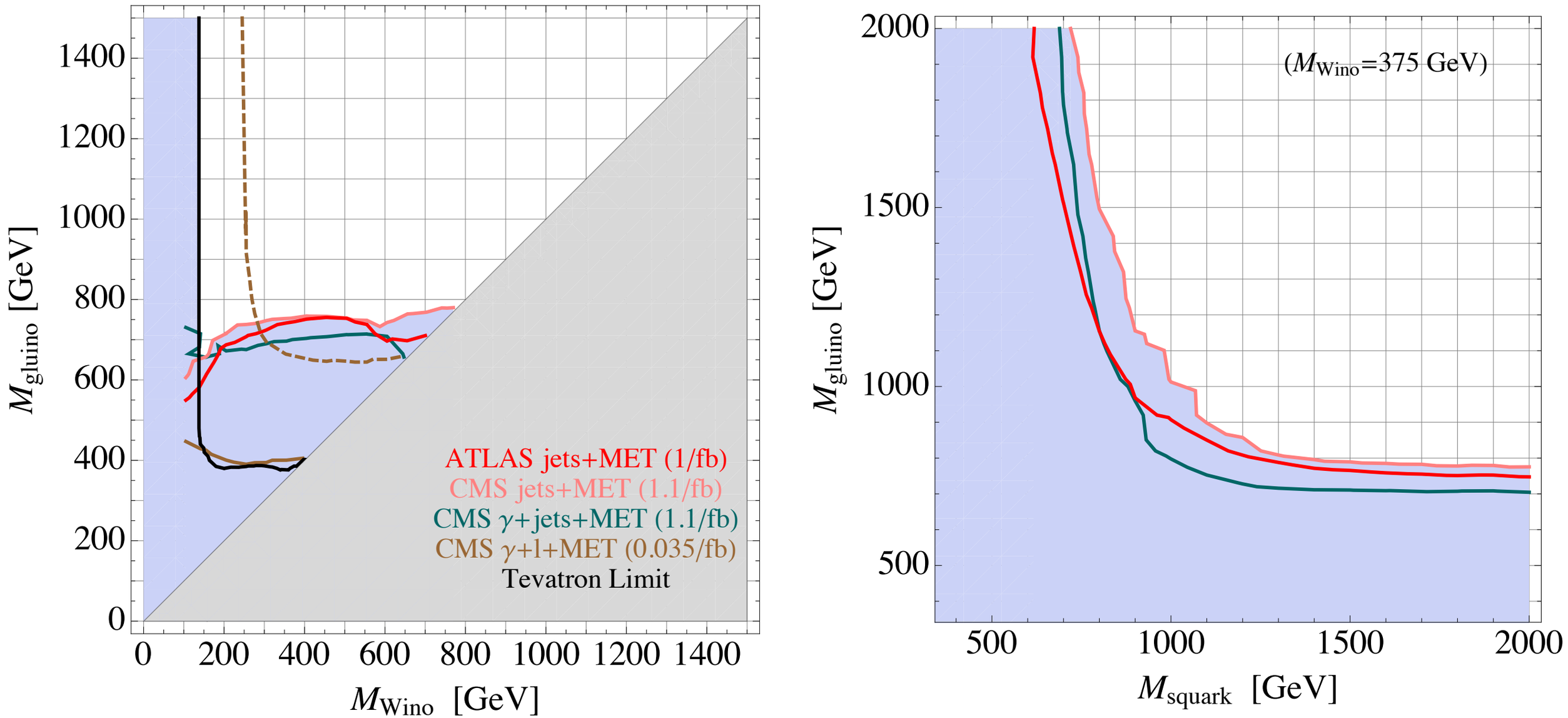
- Many interesting final states to consider!
  - jets+MET
  - l+jets+MET
  - Z+jets+MET
  - γ+l+MET ← First ever dedicated analysis by CMS with 0.035/fb (1105.3152)!
  - γγ+MET
  - γ+jets+MET

Exclusion Contours for Wino NLSP



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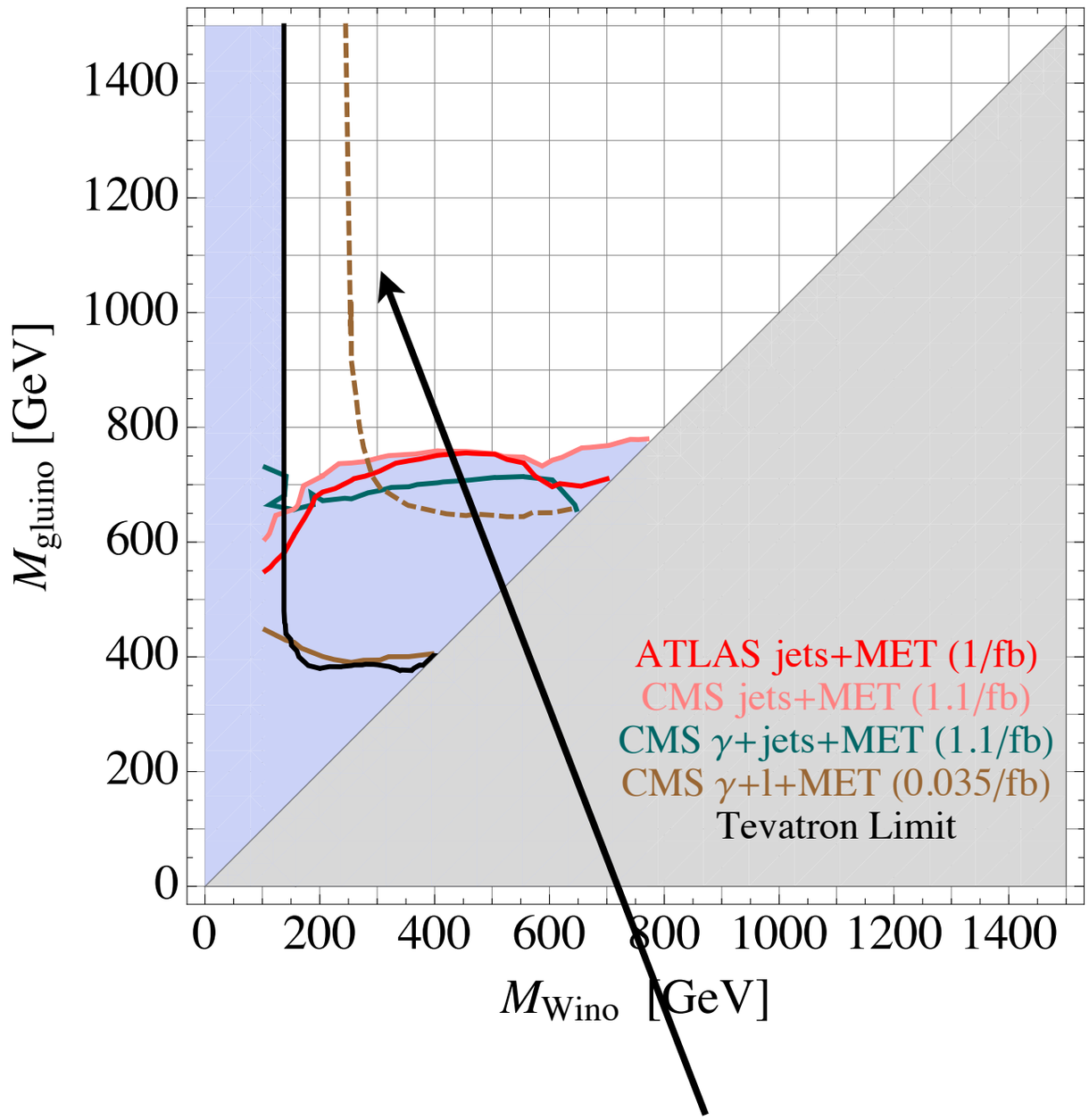

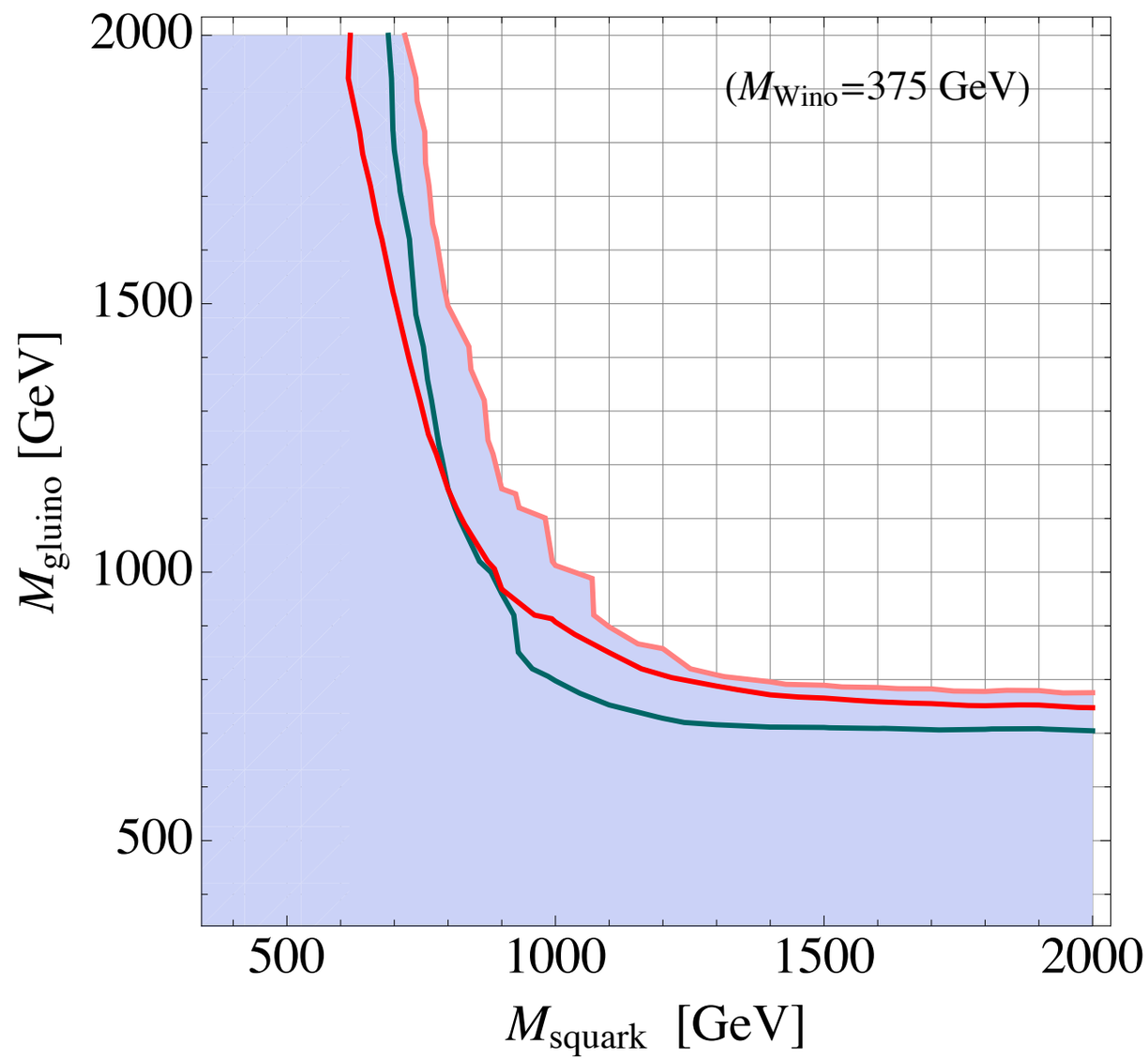

With 1/fb, lγ+MET could start to see direct wino production!

Slepton NLSPs

Slepton co-NLSP

(Ruderman & DS)

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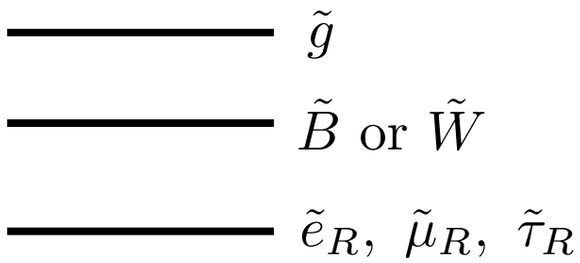
- Next, we come to the slepton (co-)NLSP scenario:



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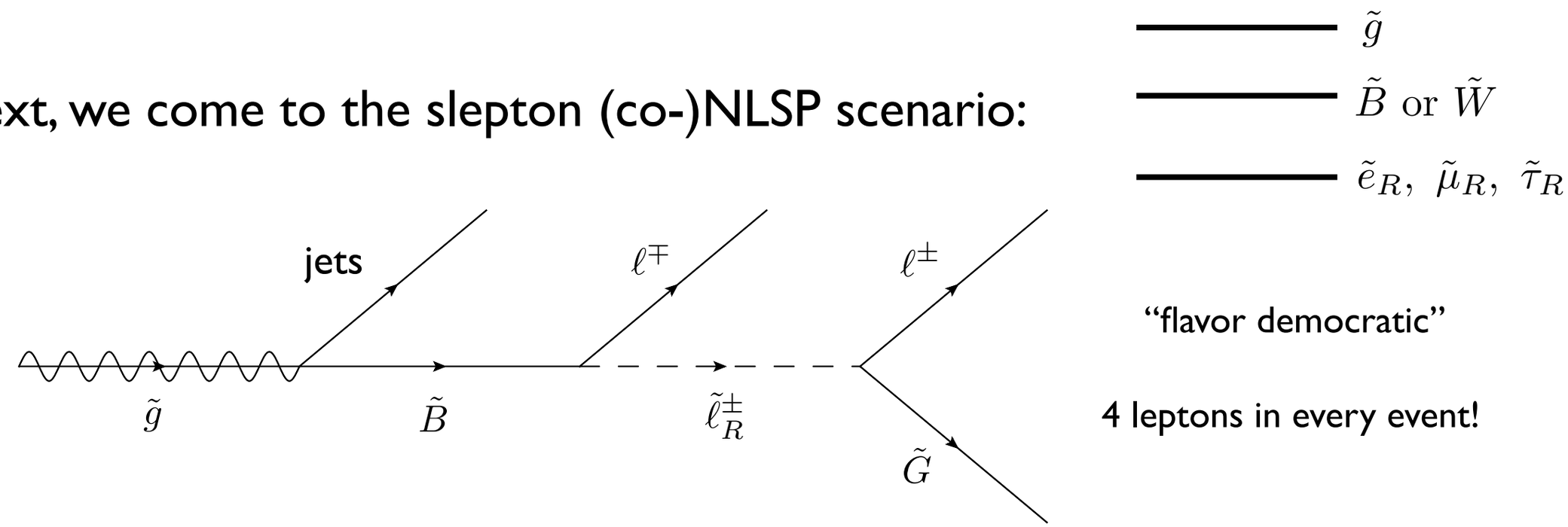

"flavor democratic"

4 leptons in every event!

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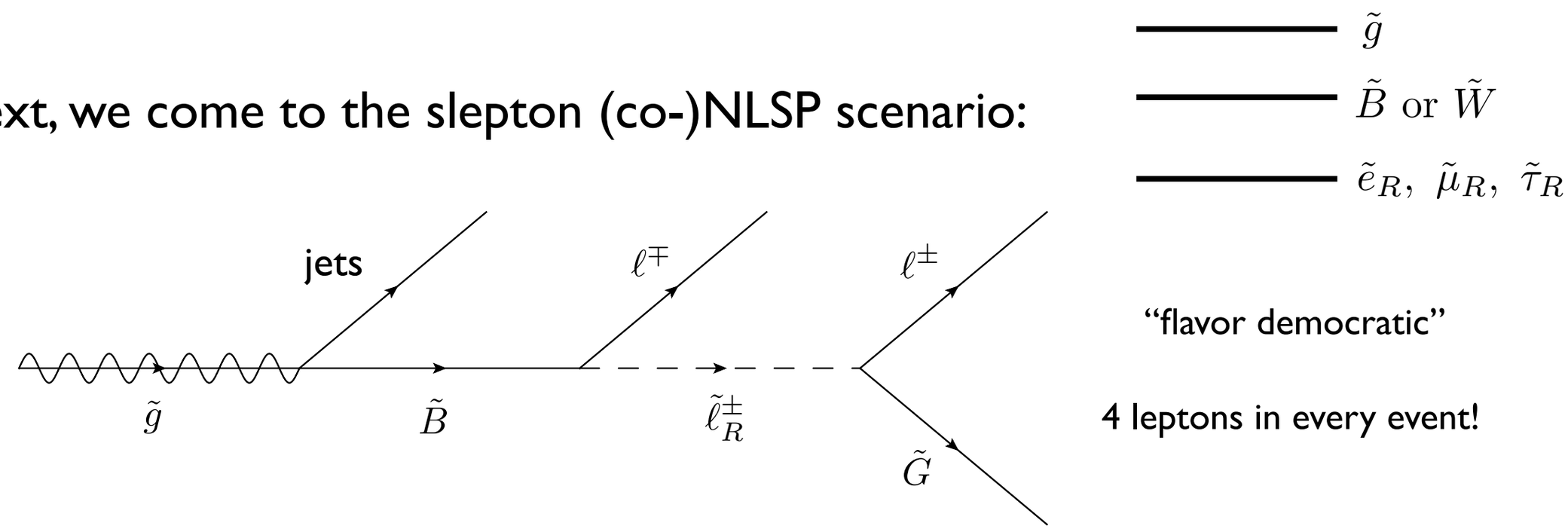

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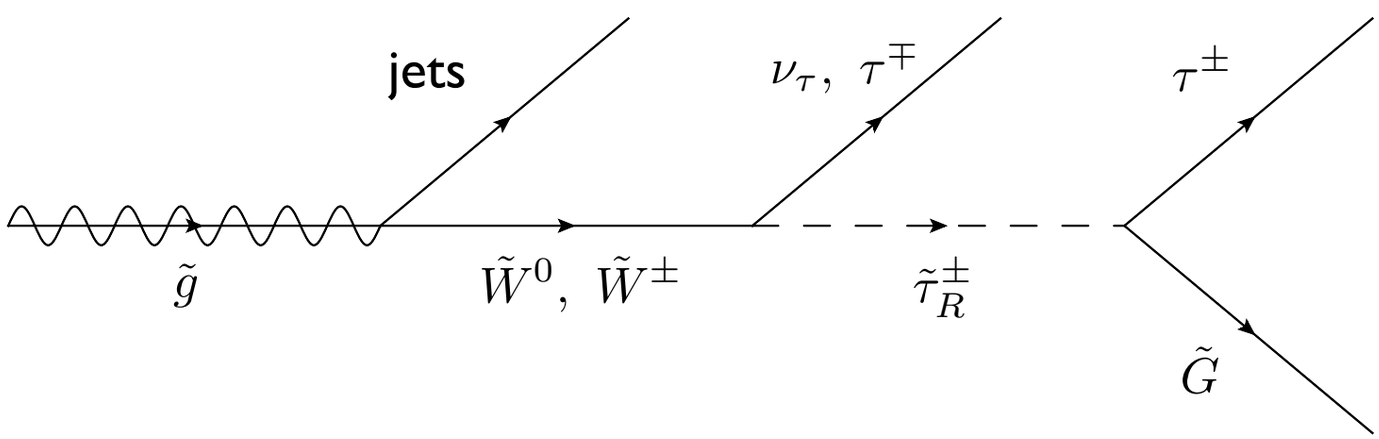

"tau-rich"

2-4 taus in every event!

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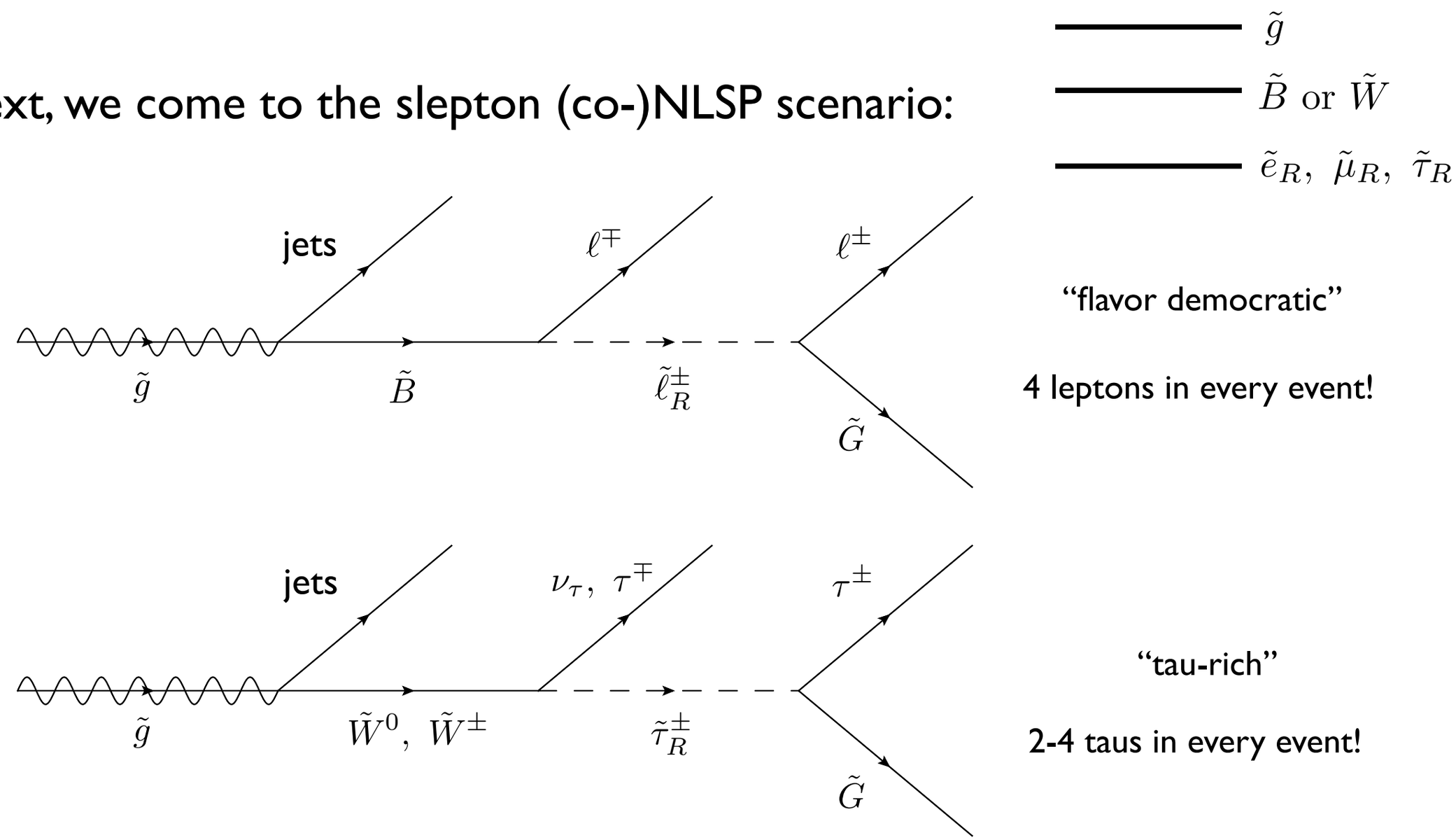
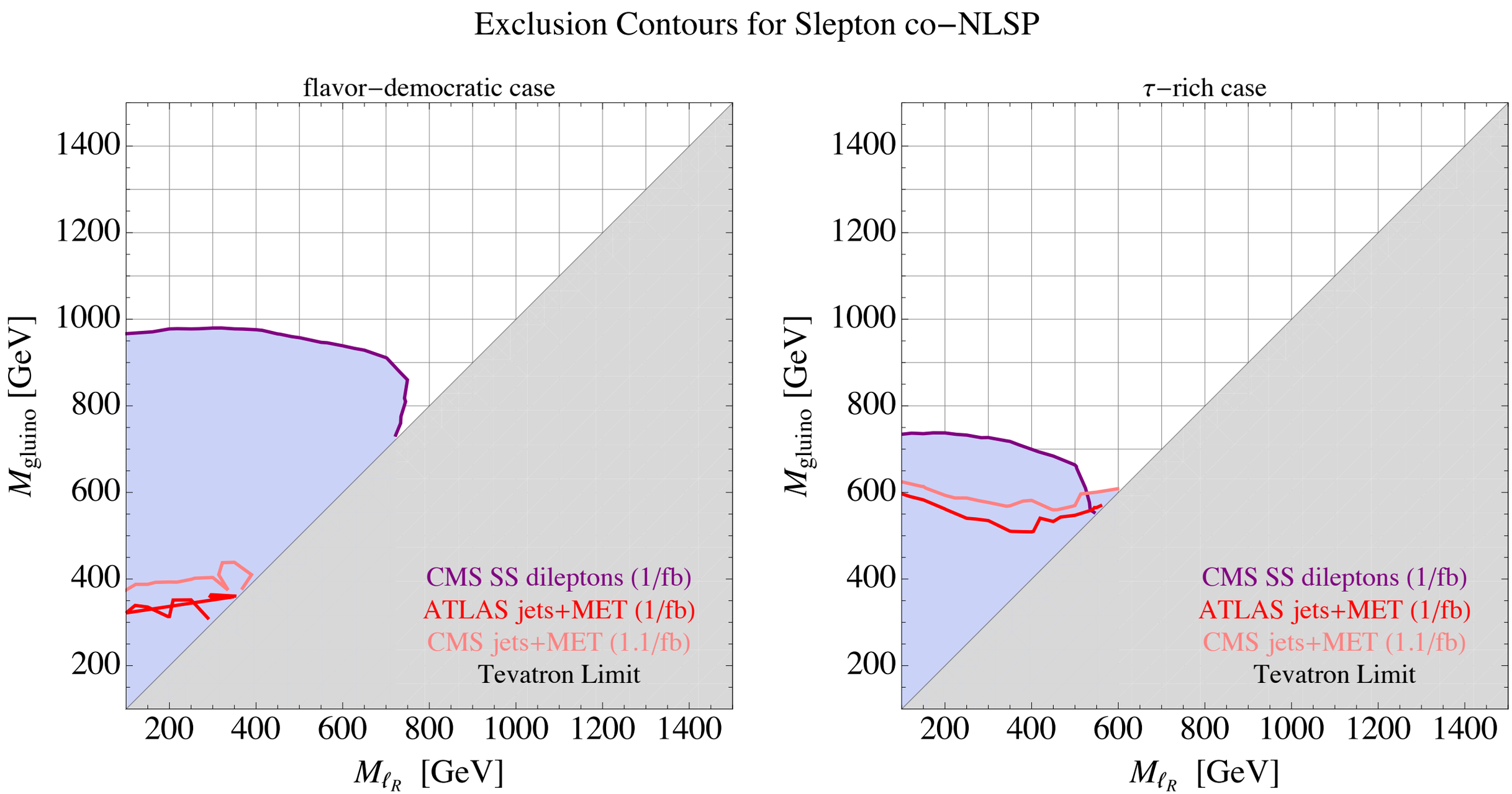


- Here SS dileptons+MET and multileptons+MET are ideal search channels



Limit on flavor-democratic case extremely strong -- comparable to γγ+MET for Bino NLSP. Limits on tau-rich case are weaker but still significant.

SS dileptons is a very clean and powerful channel!

Sneutrino co-NLSP

(Katz & Tweedie)

$\tilde{g}$

$\tilde{B}$ or $\tilde{H}$

$\tilde{e}_L,\ \tilde{\mu}_L,\ \tilde{\tau}_L$

$\tilde{\nu}_e,\ \tilde{\nu}_\mu,\ \tilde{\nu}_\tau$

$$m_{\tilde{\ell}_L} - m_{\tilde{\nu}_\ell} = \frac{m_W^2(-\cos(2\beta))}{m_{\tilde{\ell}_L} + m_{\tilde{\nu}_\ell}}$$

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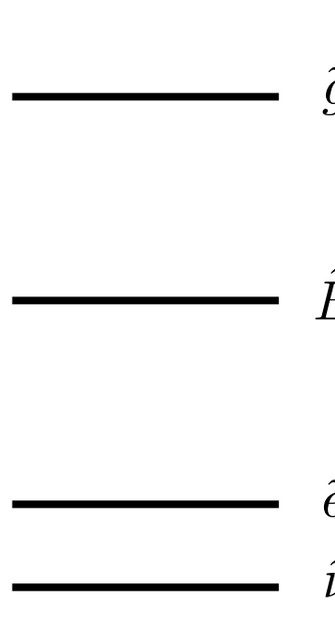
- Finally, there is also the sneutrino co-NLSP scenario. Here the NLSP decay is invisible, so one has to look for decays of heavier states:



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$$\tilde{e}_L, \; \tilde{\mu}_L, \; \tilde{\tau}_L \qquad m_{\tilde{\ell}_L} - m_{\tilde{\nu}_\ell} = \frac{m_W^2(-\cos(2\beta))}{m_{\tilde{\ell}_L} + m_{\tilde{\nu}_\ell}}$$

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$\tilde{\ell}_L \to \tilde{\nu}_\ell + W^*$

$\tilde{e}_L, \; \tilde{\mu}_L, \; \tilde{\tau}_L$

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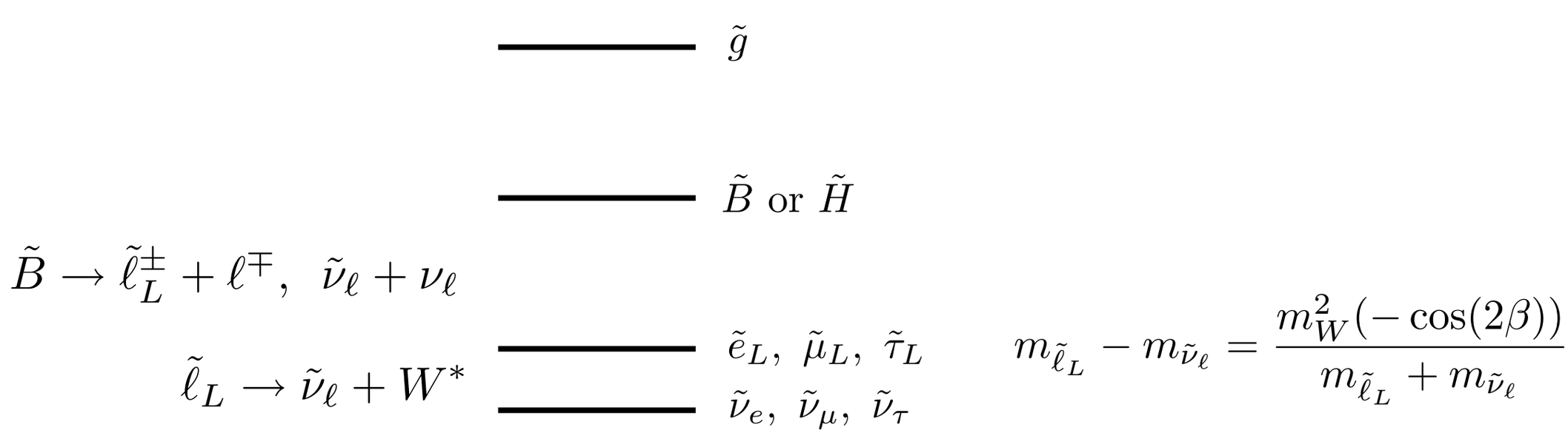
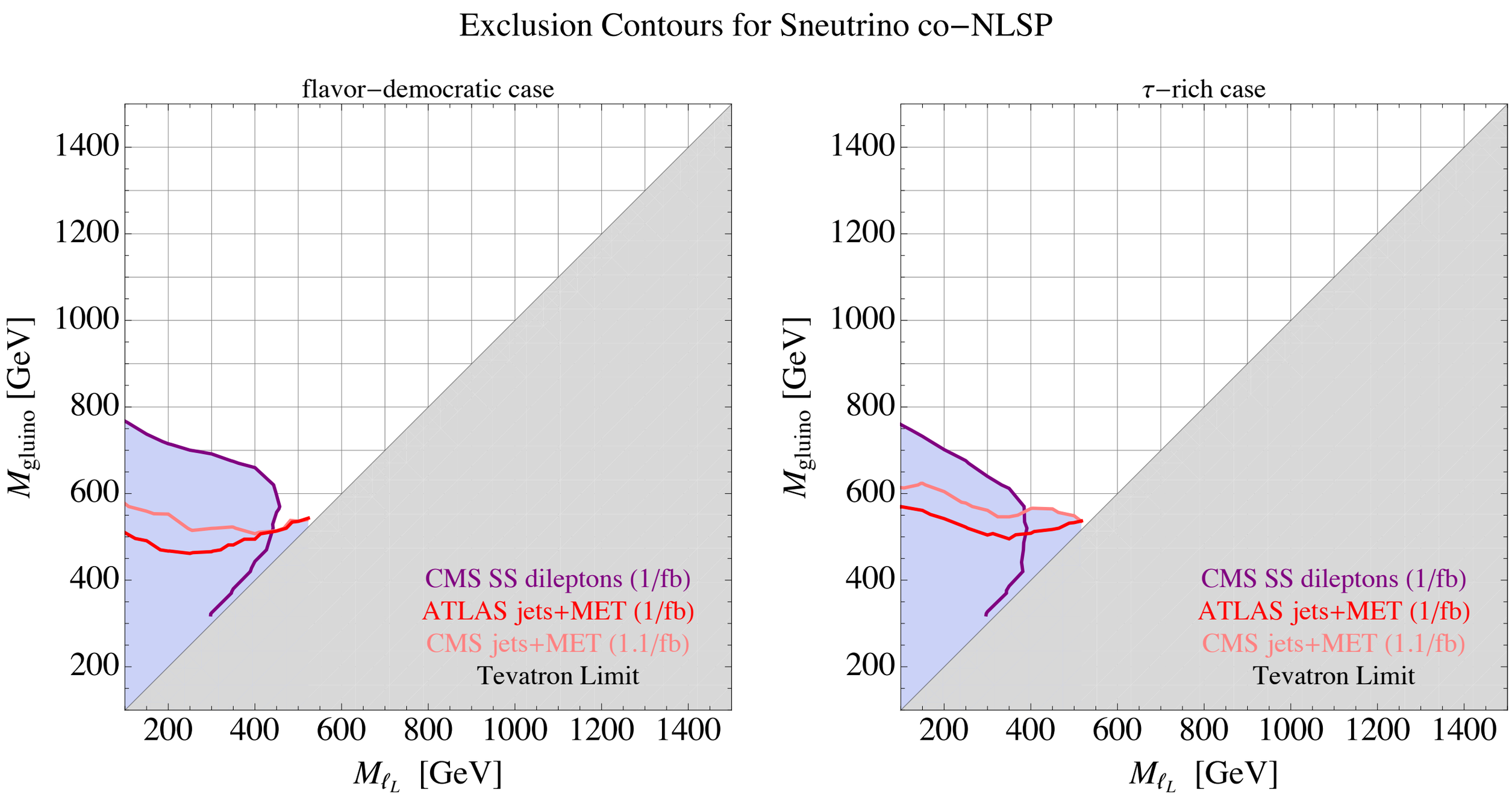


- Very similar signatures to slepton co-NLSP, but with an important difference: fewer and softer leptons.

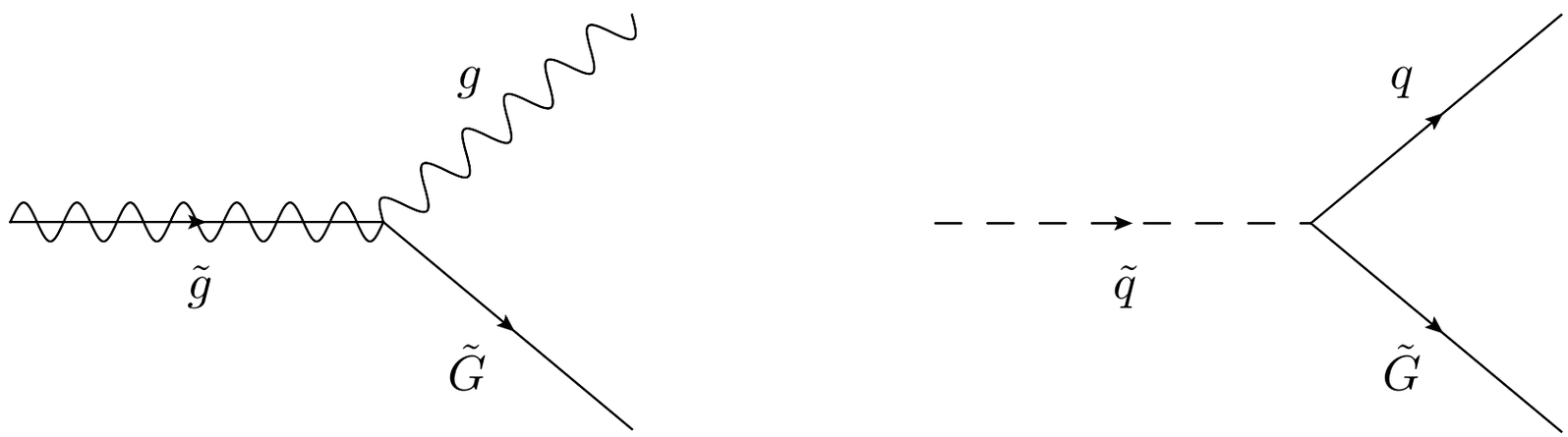


Limits are much weaker than for slepton co-NLSP!

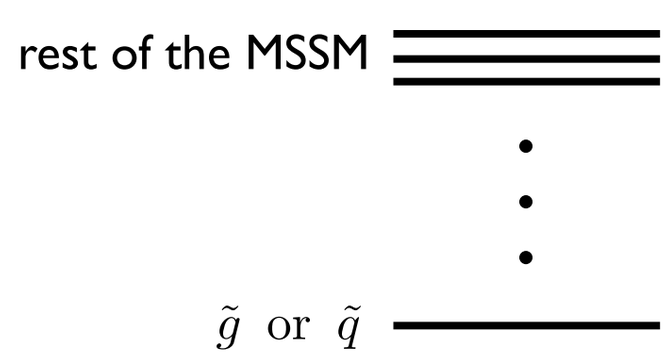
Colored NLSPs

Gluino/Squark NLSP

- Decays directly to q+gravitino and g+gravitino. Jets+MET!



- Rest of the spectrum becomes irrelevant. Can set limits on NLSP mass directly.



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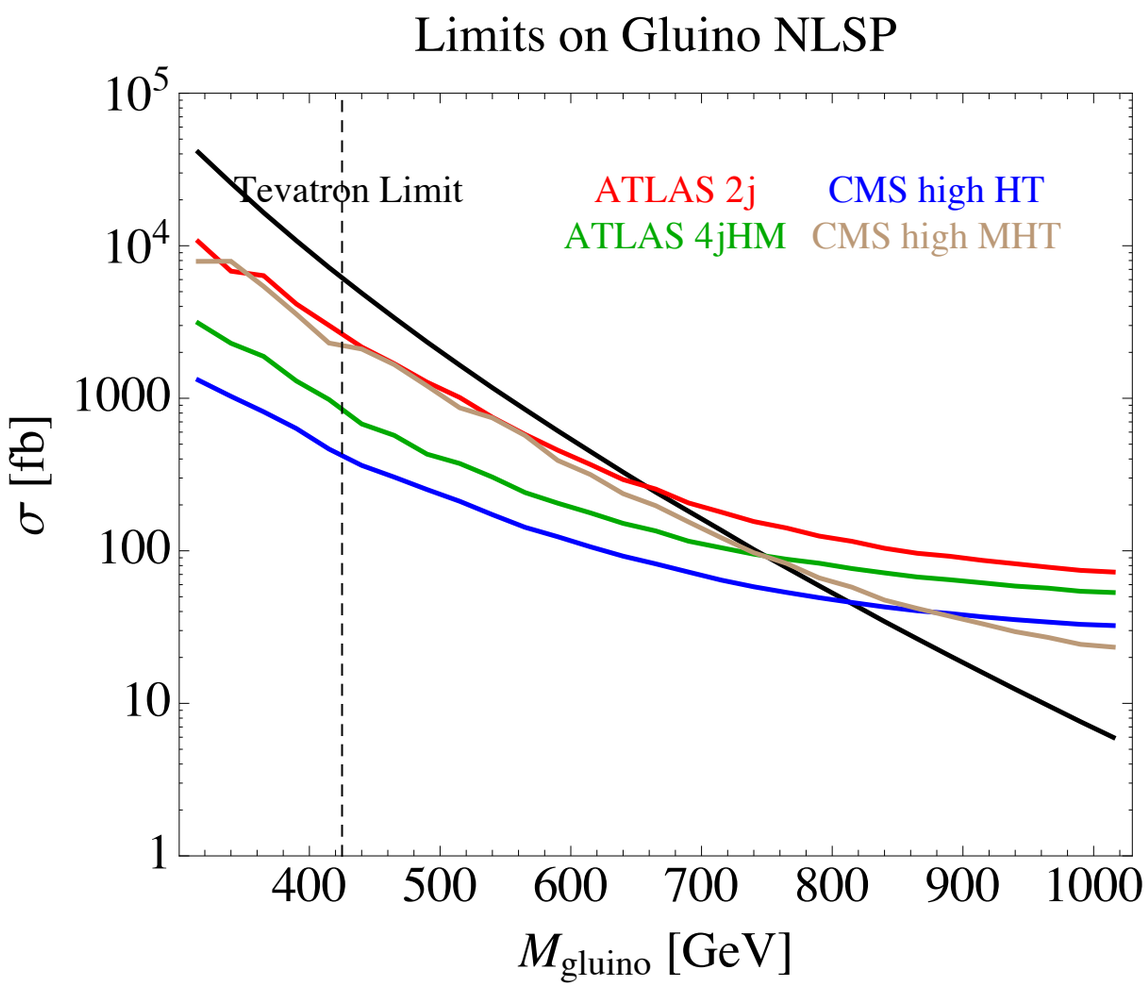
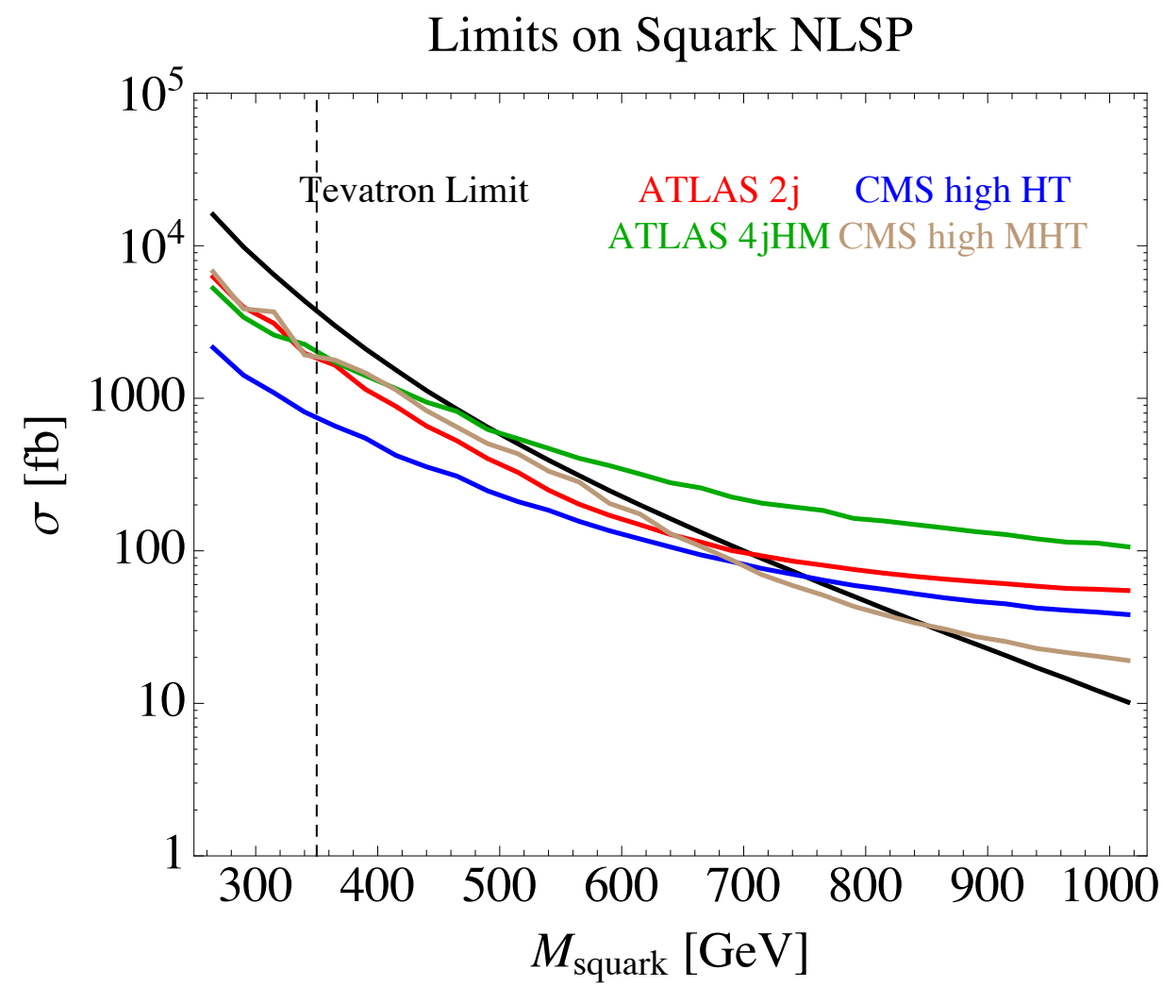
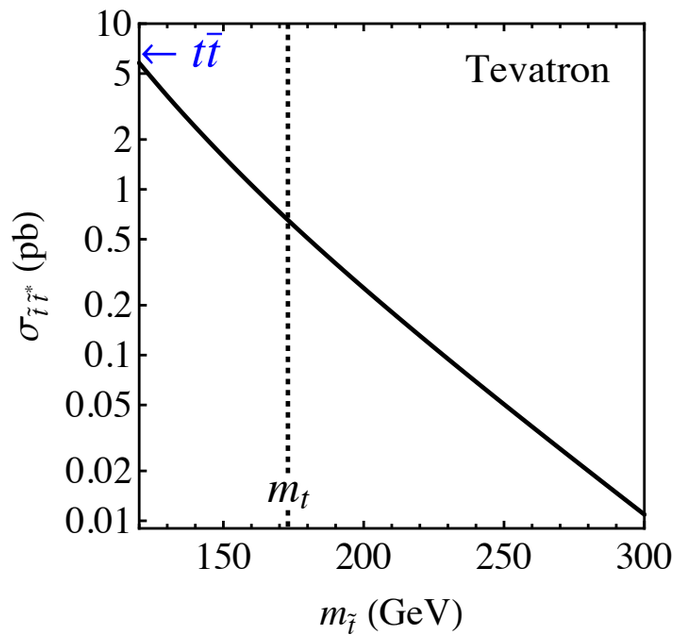
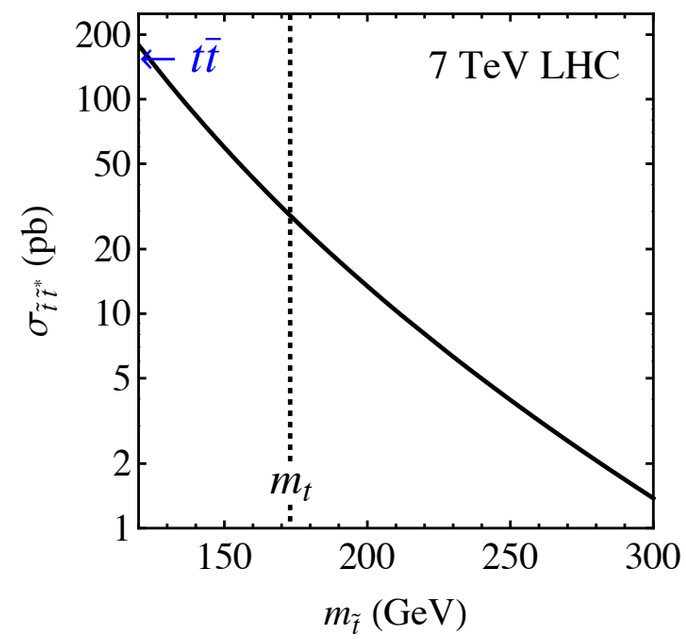




- Comments:
  - Interesting differences between gluino & squark NLSP due to ISR/FSR
  - Nevertheless, best limits are comparable: m_{NLSP} > 800-850 GeV

Stop NLSP





- An interesting special case is stop NLSP. Degenerate squark NLSP is strongly excluded, but a single stop can be much lighter.
  - Stop is generically lighter than other squarks, due to L-R splitting and RG running.
  - Light stops are well-motivated by the little hierarchy problem.
  - The rate for pair production of a single stop is much smaller than ttbar.
- How light can the stop be? Can it even be lighter than the top?

Stop NLSP

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- Stop NLSP signature very similar to ttbar. $\tilde{t} \to t + \tilde{G}, \qquad \tilde{t} \to Wb\tilde{G}$

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  - ATLAS search for fermionic top partners in ttbar+MET

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  - ATLAS search for fermionic top partners in ttbar+MET
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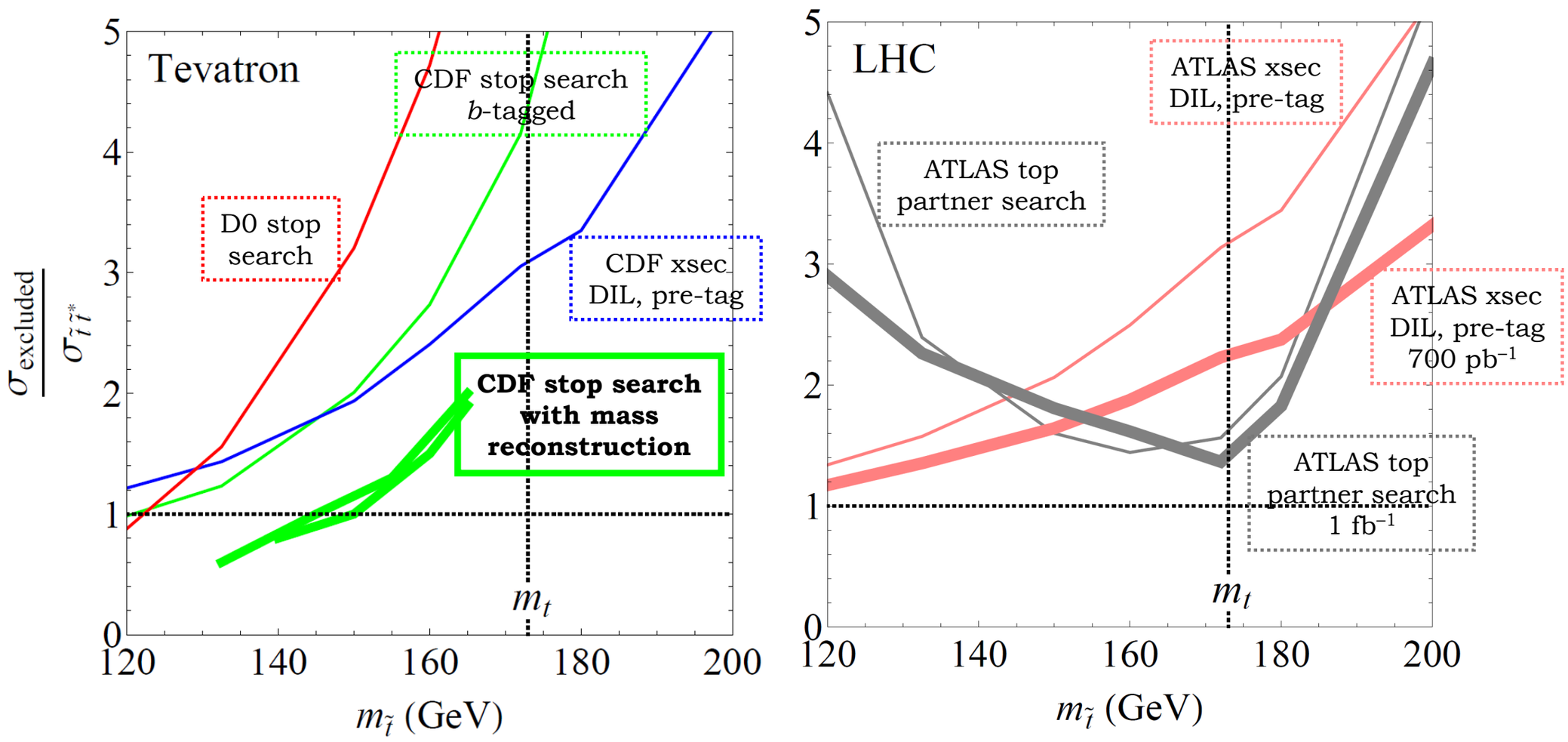
- Potential difficulties include:
  - Huge ttbar background (7.5 pb vs < 1pb at Tevatron; 150 pb vs <~50 pb at LHC)
  - Softer bjets and MET for light stops compared to ttbar

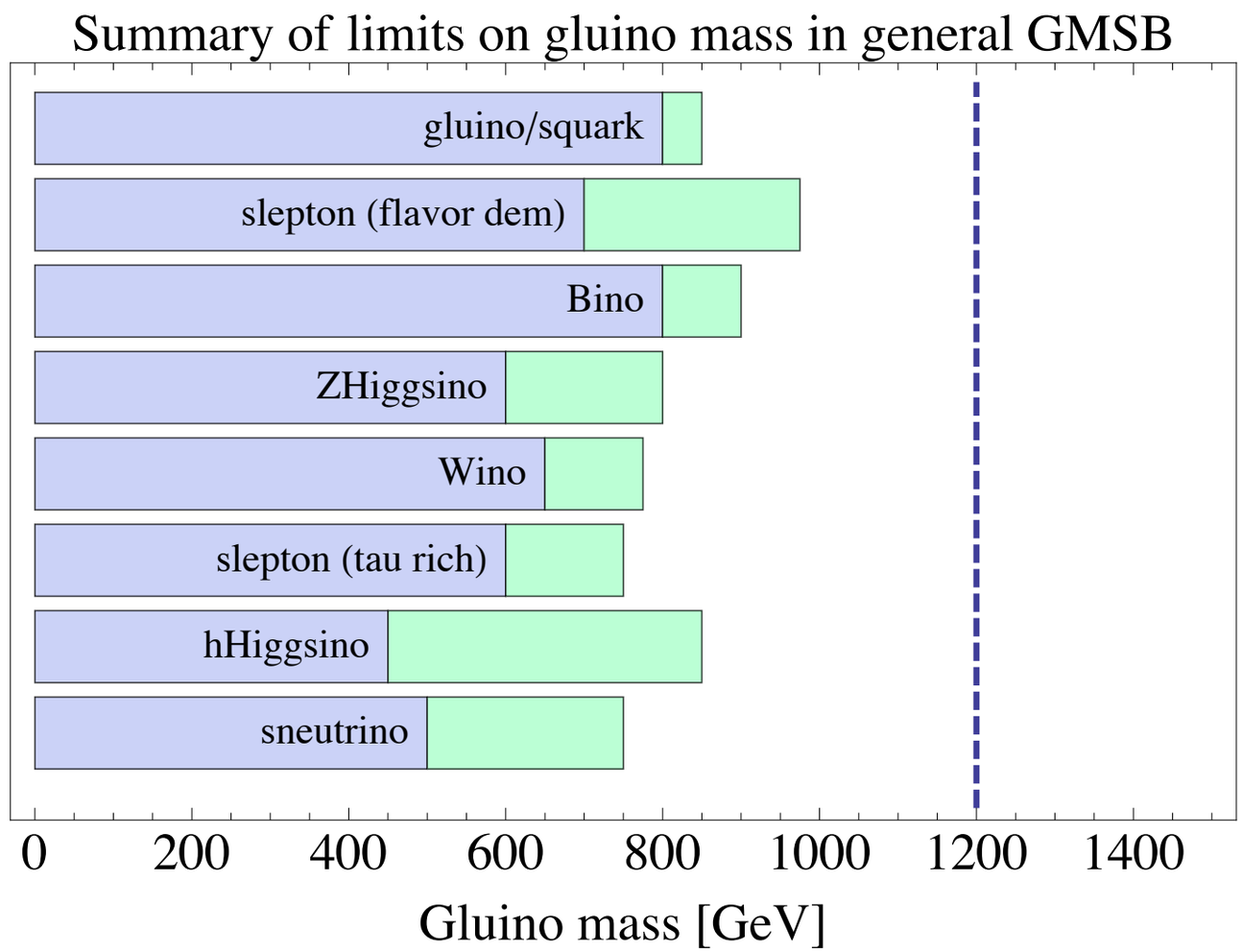
Stop NLSP

- Our results (Kats & DS 1106.0030)



Stop could still be lighter than the top!!

Summary



- We have reviewed the current status of LHC SUSY searches.
- GMSB with promptly decaying NLSPs is fairly well-covered by jets+MET and more specialized searches. In the cleanest channels, we are already approaching the "kinematic limit" of LHC @ 7 TeV.

Future Directions

- Where to expect the greatest progress?
  - 3rd generation (taus, bottoms, and tops)
  - Electroweak production
  - Squeezed spectra
  - Multiple decay modes
- We have not discussed:
  - Scenarios with long-lived NLSPs (detector stable or displaced decays). Detector stable case well-covered; displaced decays are still unexplored (!!)
  - Scenarios without MET such as R-parity violation
- Sadly, SUSY was not "right around the corner." But there is still much more discovery potential remaining at the LHC. Exciting times are ahead!!

The End

The scale of SUSY-breaking

- Gravitino mass: $m_{3/2} = \dfrac{F}{\sqrt{3} M_{pl}}$

- Sparticle masses: $m_{soft}^2 = \kappa^2 \left(\dfrac{F}{M}\right)^2 \sim \mathrm{TeV}$ M = "Messenger scale"

Gauge mediation	Gravity mediation	Anomaly mediation
$M \ll M_{pl}$	$M \sim M_{pl}$	$M \sim M_{pl}$
$\kappa \sim \dfrac{\alpha}{4\pi}$	$\kappa \sim 1$	$\kappa \sim \dfrac{\alpha}{4\pi}$

"Low scale SUSY-breaking"

Gravitino LSP. No WIMP DM. Calculable. Solves SUSY flavor problem.

"High scale SUSY-breaking"

Neutralino or sneutrino LSP. WIMP dark matter possible. Generally not calculable. Can have severe SUSY flavor problem.

Jets+MET

- Latest searches with 1/fb by ATLAS (1109.6572) and CMS (SUS11004)

ATLAS

Signal Region	≥ 2-jet	≥ 3-jet	≥ 4-jet	High mass
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 130	> 130	> 130	> 130
Leading jet p_{T}	> 130	> 130	> 130	> 130
Second jet p_{T}	> 40	> 40	> 40	> 80
Third jet p_{T}	–	> 40	> 40	> 80
Fourth jet p_{T}	–	–	> 40	> 80
$\Delta\phi(\mathrm{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$	> 0.4	> 0.4	> 0.4	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	> 500/1000	> 1100

CMS

baseline	≥3 jets, pT>50 HT>350, MHT>200
medium HT & MHT	baseline + HT>500, MHT>350
high HT	baseline + HT>800
high MHT	high HT + HT>800, MHT>500

Explicit lepton veto in both analyses.
Secretly photon veto in both as well!

Jets+MET

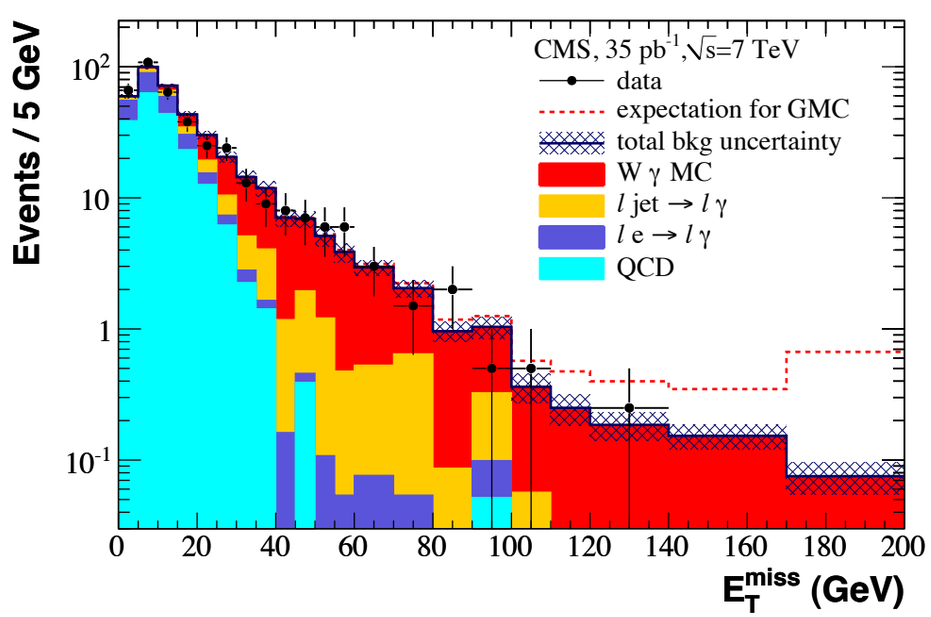
- Both ATLAS and CMS saw no evidence for new physics.

Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, m_{eff} > 500 GeV	≥ 4-jet, m_{eff} > 1000 GeV	High mass
Z/γ+jets	32.5 ± 2.6 ± 6.8	25.8 ± 2.6 ± 4.9	208 ± 9 ± 37	16.2 ± 2.1 ± 3.6	3.3 ± 1.0 ± 1.3
W+jets	26.2 ± 3.9 ± 6.7	22.7 ± 3.5 ± 5.8	367 ± 30 ± 126	12.7 ± 2.1 ± 4.7	2.2 ± 0.9 ± 1.2
$t\bar{t}$+ single top	3.4 ± 1.5 ± 1.6	5.6 ± 2.0 ± 2.2	375 ± 37 ± 74	3.7 ± 1.2 ± 2.0	5.6 ± 1.7 ± 2.1
QCD jets	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.74 ± 0.14 ± 0.51	2.10 ± 0.37 ± 0.83
Total	62.3 ± 4.3 ± 9.2	55 ± 3.8 ± 7.3	984 ± 39 ± 145	33.4 ± 2.9 ± 6.3	13.2 ± 1.9 ± 2.6
Data	58	59	1118	40	18

	Baseline (H_{T} >350 GeV) ($\not{H}_{\mathrm{T}}$ >200 GeV)	Medium (H_{T} >500 GeV) ($\not{H}_{\mathrm{T}}$ >350 GeV)	High H_{T} (H_{T} >800 GeV) ($\not{H}_{\mathrm{T}}$ >200 GeV)	High $\not{H}_{\mathrm{T}}$ (H_{T} >800 GeV) ($\not{H}_{\mathrm{T}}$ >500 GeV)
$Z \to \nu\bar{\nu}$ from γ+jets	$376 \pm 12 \pm 79$	$42.6 \pm 4.4 \pm 8.9$	$24.9 \pm 3.5 \pm 5.2$	$2.4 \pm 1.1 \pm 0.5$
$t\bar{t}/W \to e, \mu + X$	$244 \pm 20^{+30}_{-31}$	$12.7 \pm 3.3 \pm 1.5$	$22.5 \pm 6.7^{+3.0}_{-3.1}$	$0.8 \pm 0.8 \pm 0.1$
$t\bar{t}/W \to \tau_h + X$	$263 \pm 8 \pm 7$	$17 \pm 2 \pm 0.7$	$18 \pm 2 \pm 0.5$	$0.73 \pm 0.73 \pm 0.04$
QCD	$31 \pm 35^{+17}_{-6}$	$1.3 \pm 1.3^{+0.6}_{-0.4}$	$13.5 \pm 4.1^{+7.3}_{-4.3}$	$0.09 \pm 0.31^{+0.05}_{-0.04}$
Total background	928 ± 103	73.9 ± 11.9	79.4 ± 12.2	4.6 ± 1.5
Observed in data	986	78	70	3

l+γ+MET

- First dedicated analysis by CMS with 0.035/fb (1105.3152). (Not a well-explored final state! Only one other previous search, at CDF with 1/fb.)
- Selection:
  - At least one lepton with pT>20 GeV
  - At least one photon with pT>30 GeV
  - MET>100 GeV



	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 100$ GeV
$W\gamma$	1.68 ± 0.42	1.40 ± 0.37
jet$\rightarrow \gamma$	0.02 ± 0.02	0.10 ± 0.09
e $\rightarrow \gamma$	0.04 ± 0.03	0.09 ± 0.04
QCD	0.00 ± 0.00	0.00 ± 0.00
Total background	1.74 ± 0.43	1.59 ± 0.39
data	1	1
	(eγ)	(μγ)

Slepton co-NLSP

- Latest SS dileptons search by CMS with 0.98/fb (CMS-PAS-SUS-11-010)

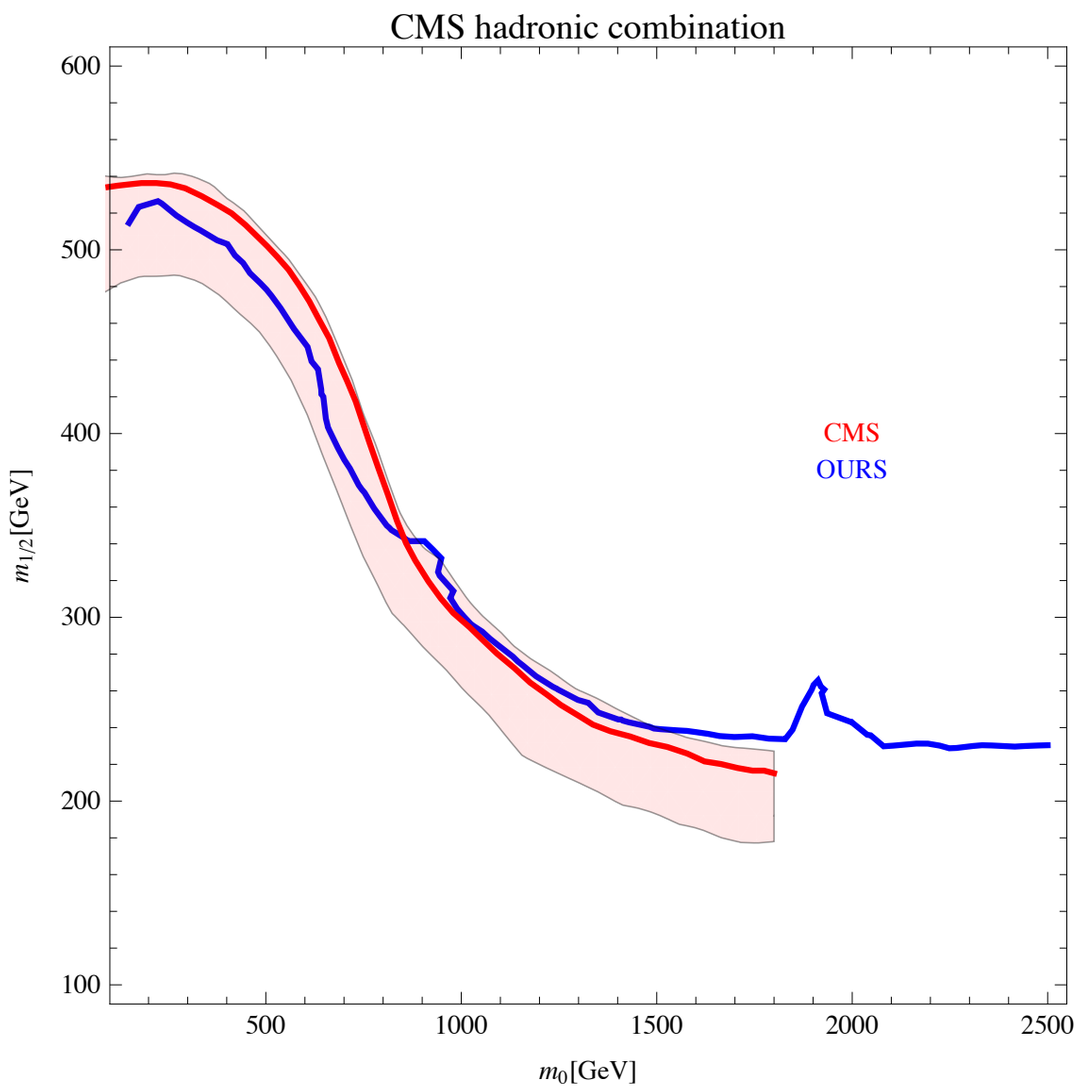
high pT baseline

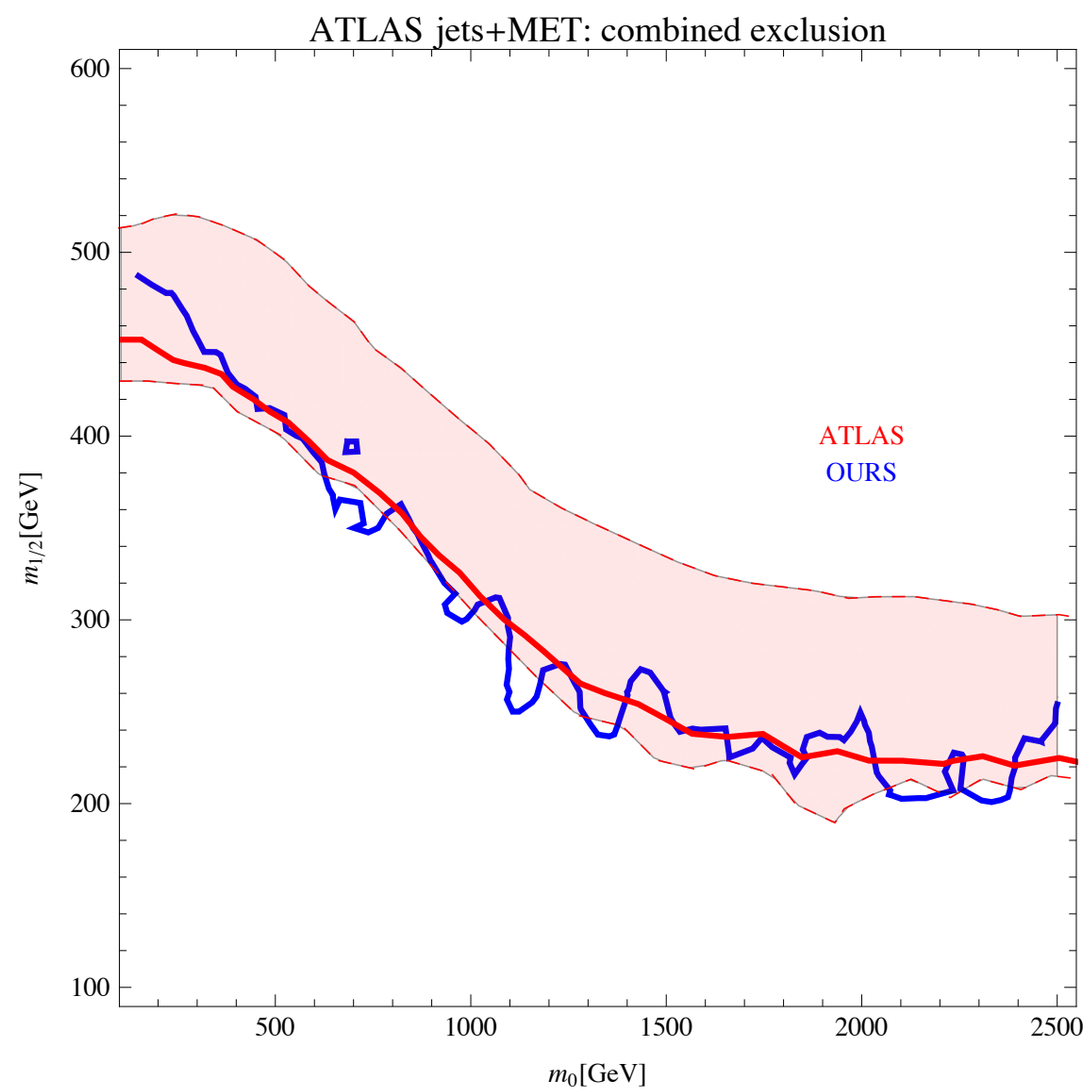
Search Region (minimum H_T/E_T^{miss})	ee	$\mu\mu$	eμ	Total	95% CL UL yield
Region 1 (400/120)					
Predicted background by (A1)	0.4 ± 0.3	0.4 ± 0.3	0.7 ± 0.4	1.4 ± 0.7	
Predicted background by (A2)	0.7 ± 0.5	0.4 ± 0.3	0.4 ± 0.3	1.4 ± 0.7	
Observed	0	0	0	0	3.0
Region 2 (400/50)					
Predicted background by (A1)	1.4 ± 0.8	1.3 ± 0.8	1.3 ± 0.6	4.0 ± 1.7	
Predicted background by (A2)	1.5 ± 0.8	0.8 ± 0.4	1.0 ± 0.5	3.3 ± 1.2	
Observed	1	2	2	5	7.5
Region 3 (200/120)					
Predicted background by (A1)	1.2 ± 0.7	1.5 ± 0.8	1.8 ± 0.8	4.5 ± 1.9	
Predicted background by (A2)	1.3 ± 0.7	1.8 ± 0.8	1.8 ± 0.7	4.9 ± 1.8	
Observed	0	2	1	3	5.2
Region 4 (80/100)					
Predicted background by (A1)	2.5 ± 1.2	2.6 ± 1.2	4.9 ± 2.2	10 ± 4	
Predicted background by (A2)	2.4 ± 1.0	3.6 ± 1.6	4.4 ± 1.6	10 ± 4	
Observed	3	2	2	7	6.0

tau baseline

Search Region (minimum H_T/E_T^{miss})	$e\tau$	$\mu\tau$	$\tau\tau$	Total	95% CL UL yield
Region 1 (400/120)					
Predicted background	1.1 ± 0.4	1.8 ± 1.4	0.0 ± 0.2	2.9 ± 1.7	
Observed	1	2	0	3	5.8

Some validation plots





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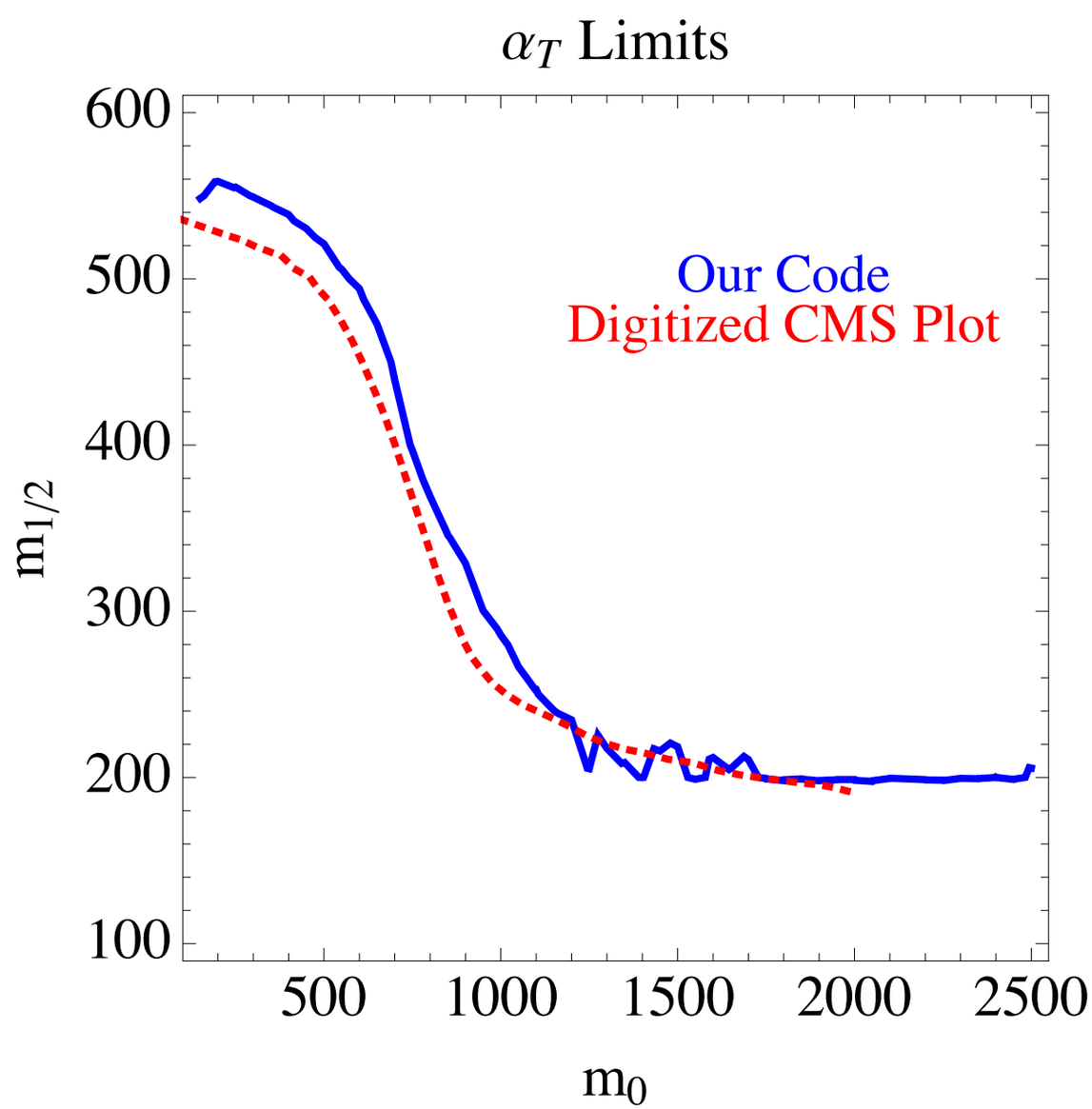

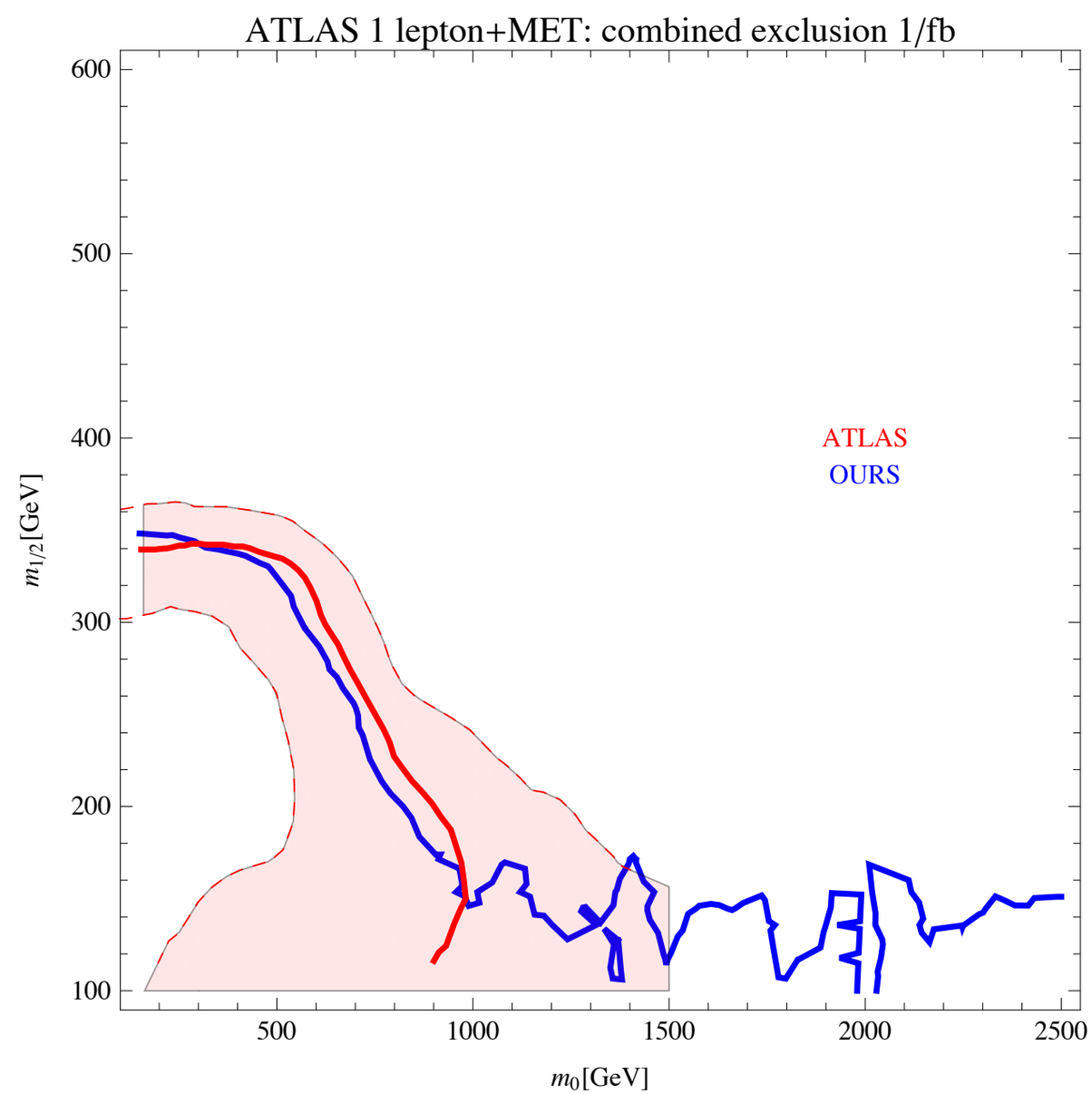

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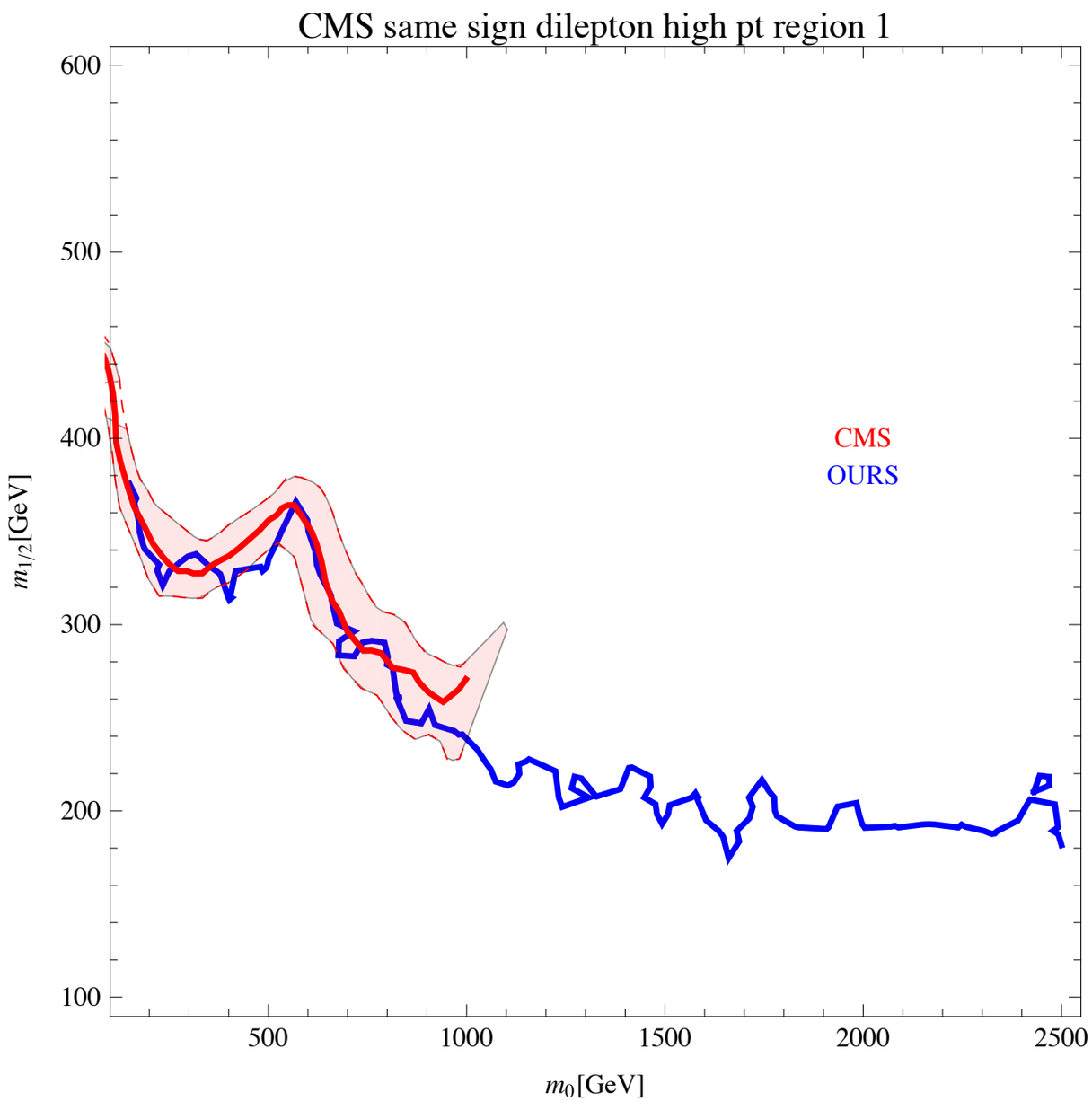
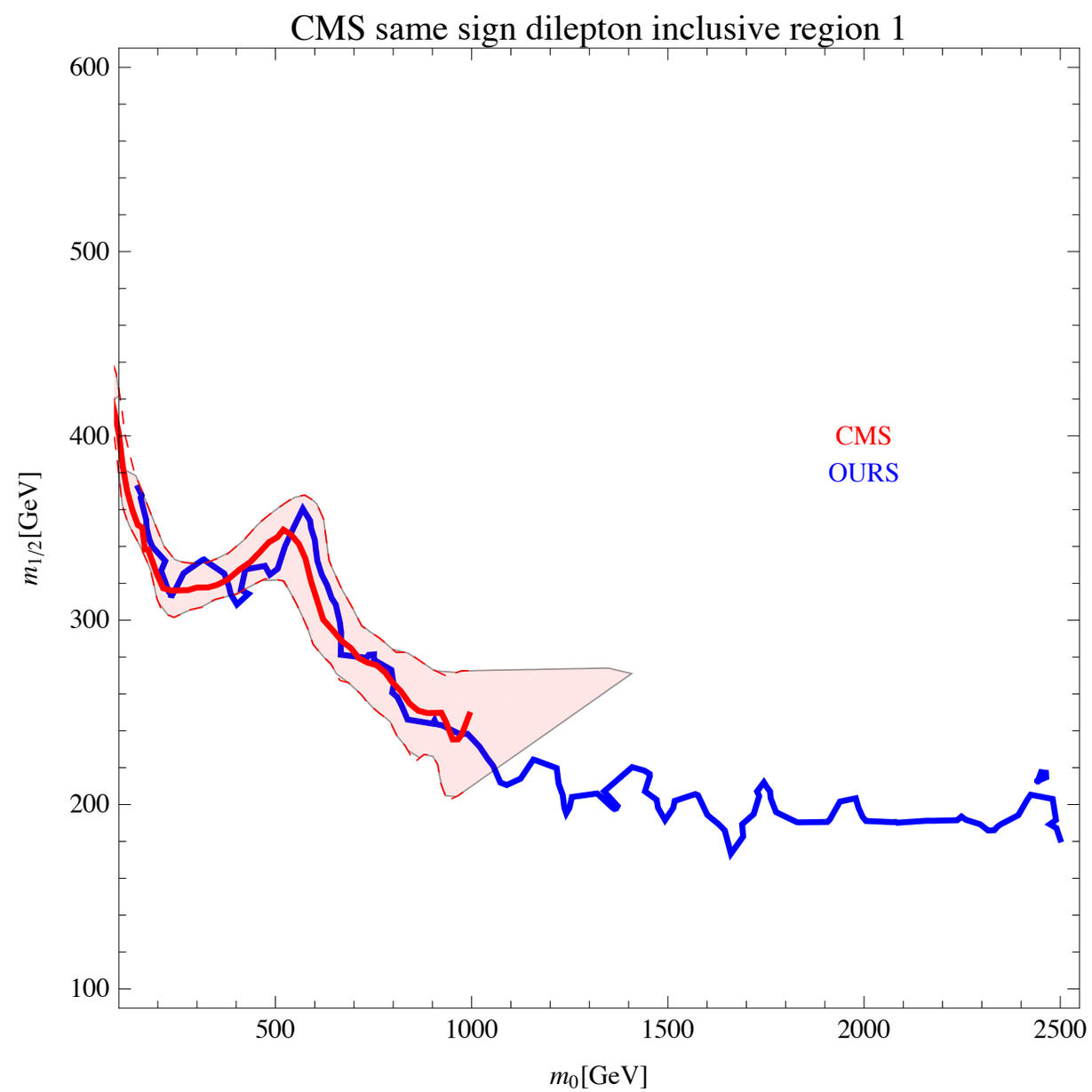
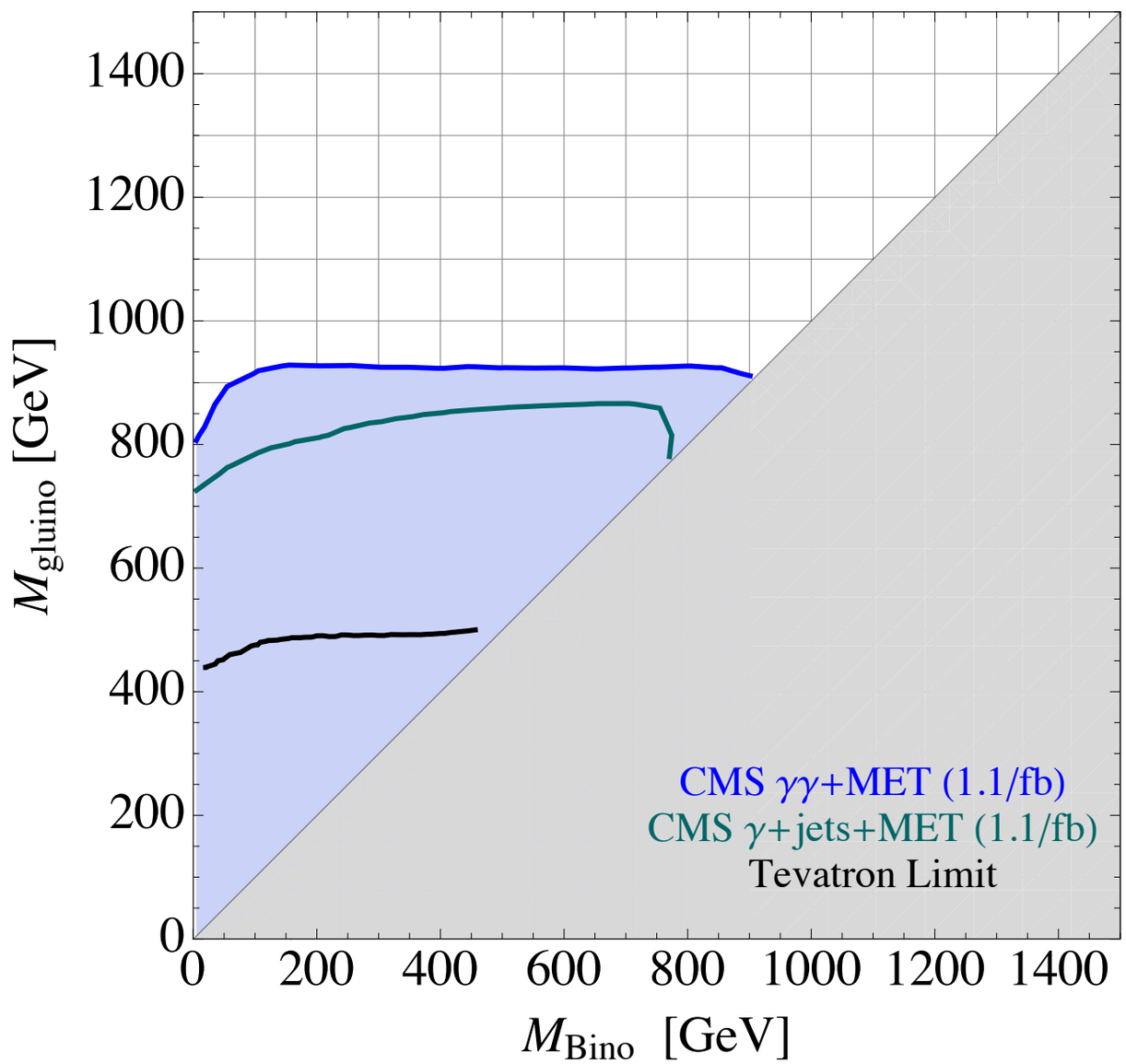
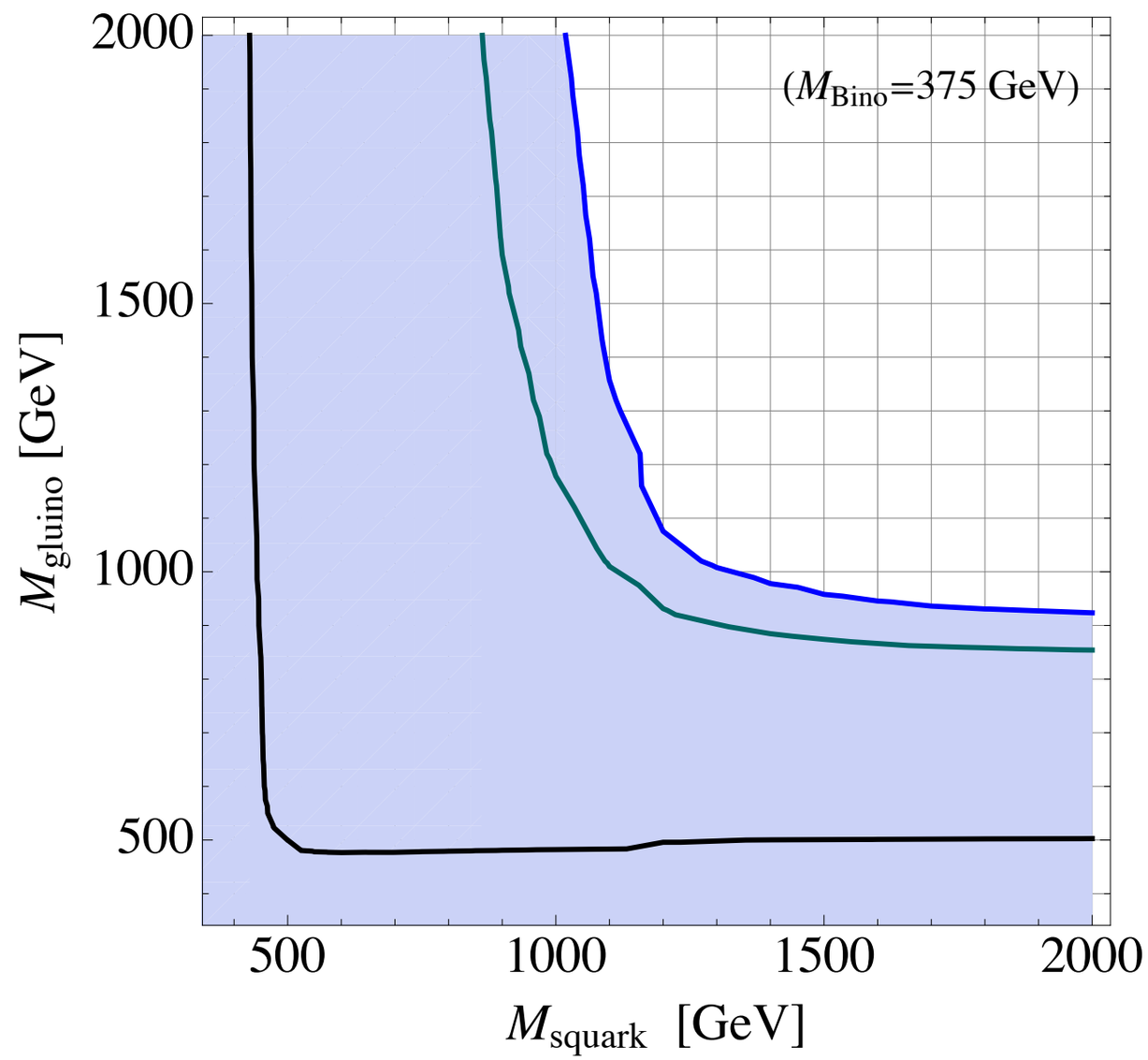




Exclusion Contours for Bino NLSP





Discrepancy with squark production?

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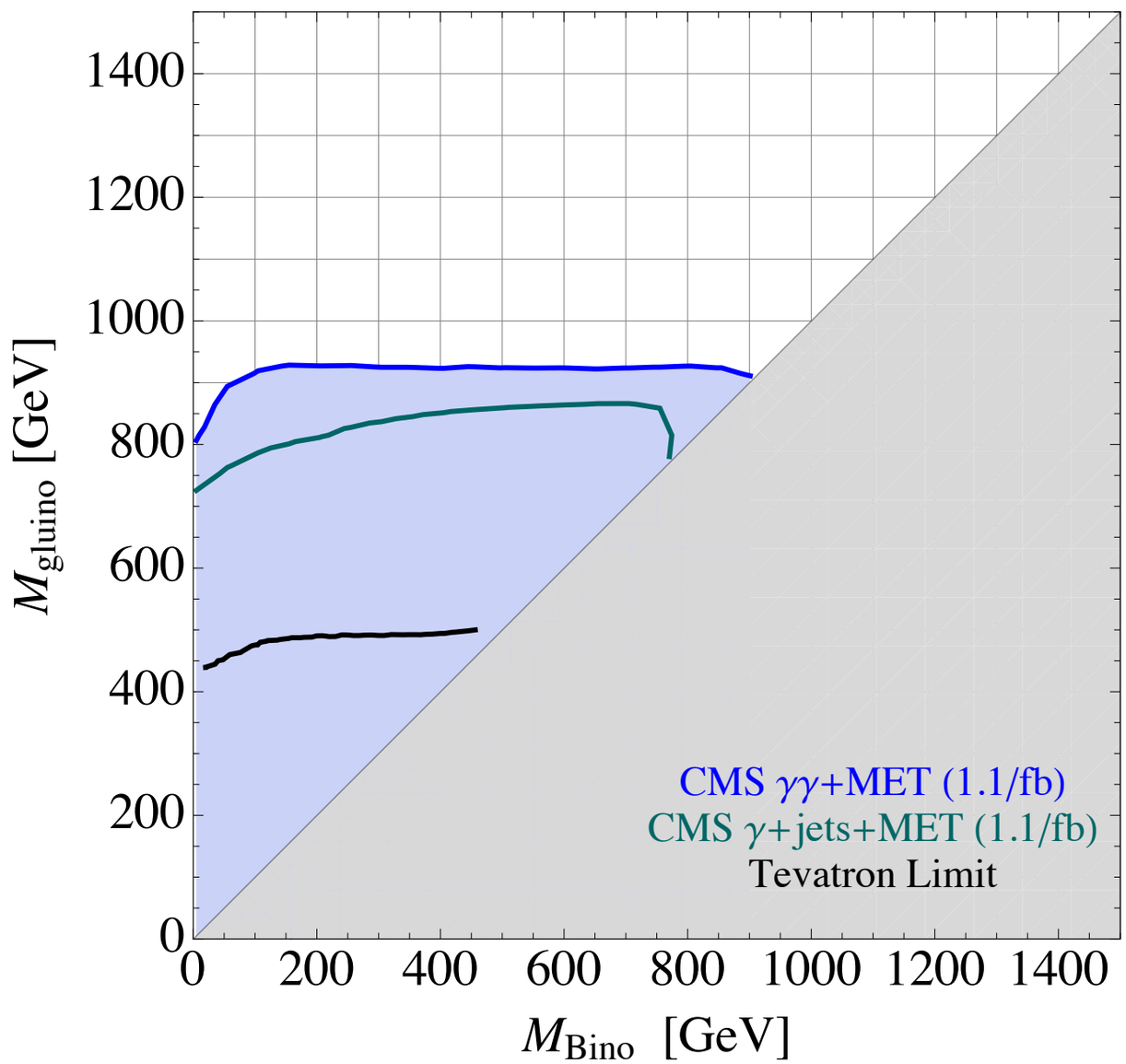

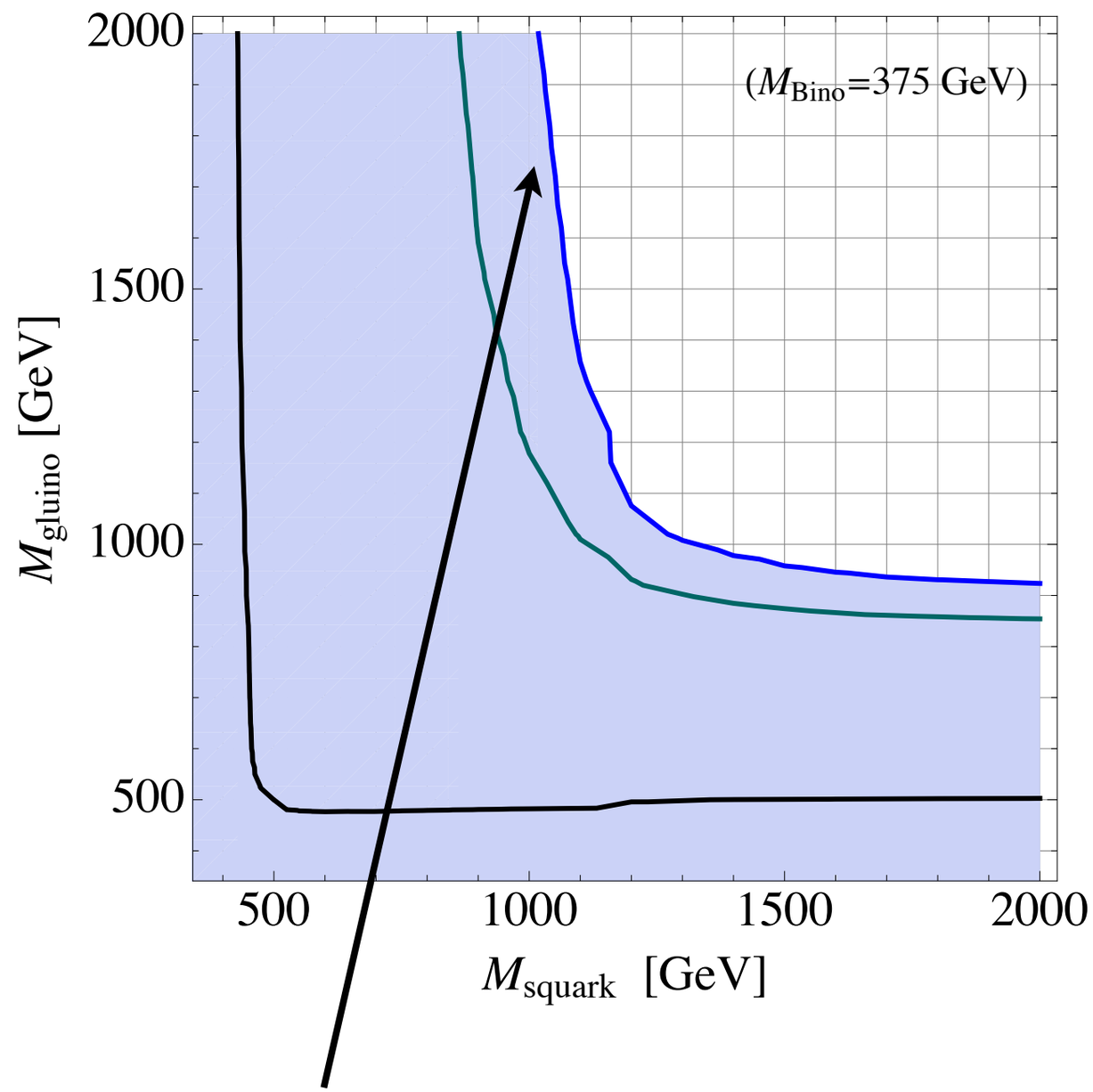

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