Constraining compressed supersymmetry using leptonic signatures

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based on: arXiv:1206.6767

CERN 15/7/2012

Introduction

- SUSY is one of the most promising candidates of beyond the SM

  ameliorating hierarchy problem, dark matter, gauge coupling unification, ...

Hierarchy problem and LHC:

$$(\text{weak scale})^2 \simeq m_H^2(\text{bare}) + \Delta m_H^2$$

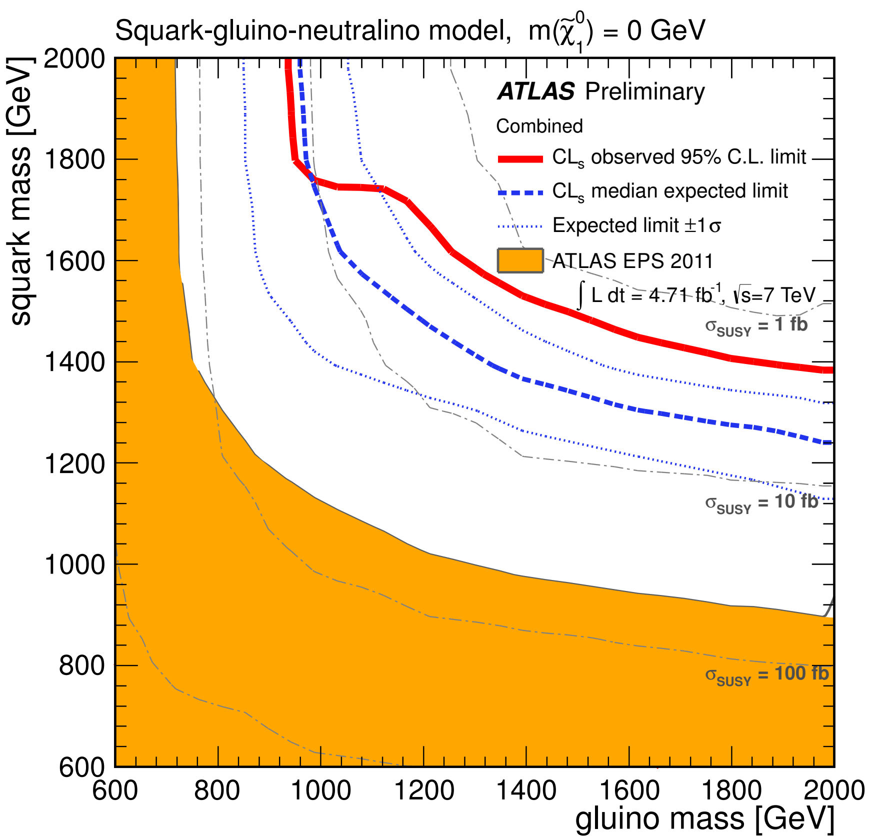
SM: $\Delta m_H \sim \Lambda \; (\sim 10^{19}\,\text{GeV})$ ⇨ *very precise tuning on m_H(bare)*

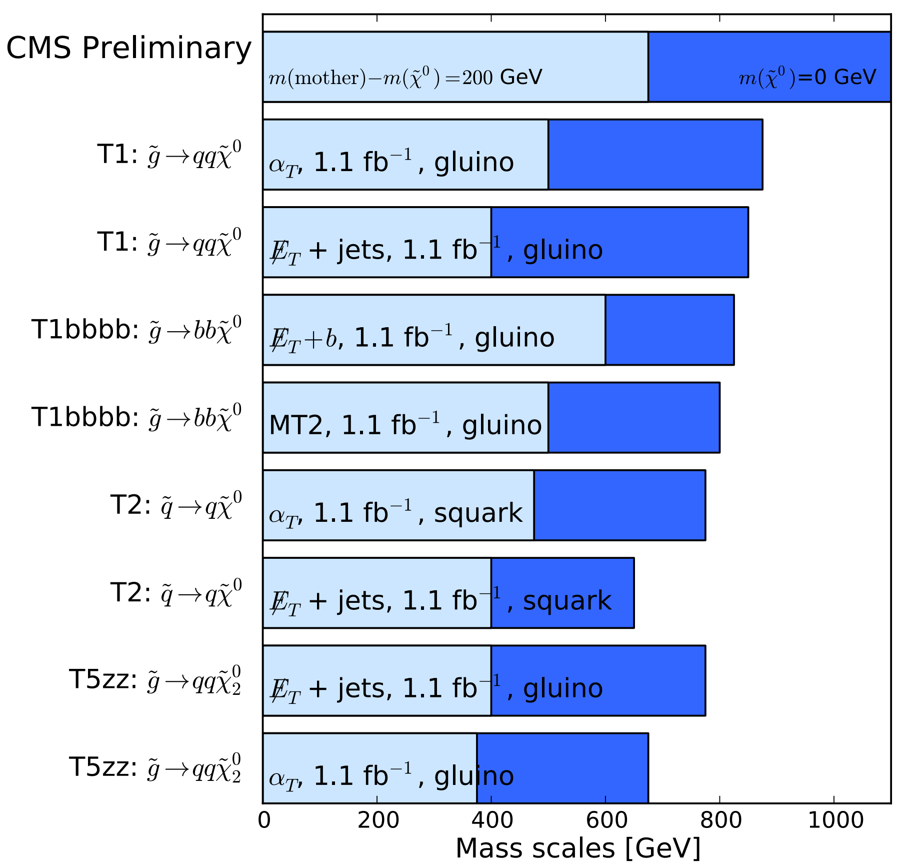
SUSY: $\Delta m_H \sim m_{\text{SUSY}} \; (m_{\tilde{t}}, m_{\tilde{g}}, \cdots)$ ⇨ *no fine tuning if $m_{SUSY} \sim m_{weak}$*

SUSY should be seen at the LHC

Is light SUSY possible?

- Constraint from direct SUSY searches $(\mathrm{jets} + \not{E}_T)$:

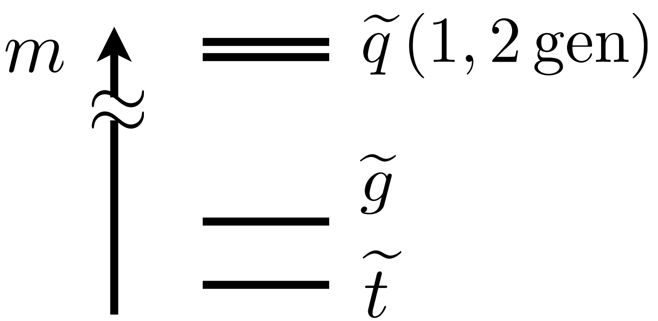




$$m_{\tilde{q}}, m_{\tilde{g}} \gtrsim 1\,\mathrm{TeV}$$

Where is SUSY hidden?

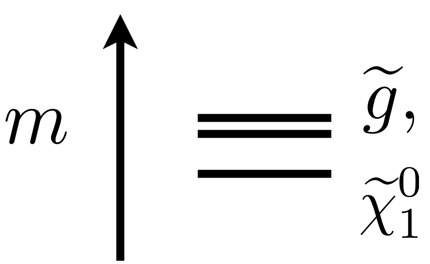
Split generation



- small cross sections of stop and gluino productions
- large # of final particles --> smaller p_T, $\not{E}_T$

$$\tilde{g} \to \tilde{t}t \to 2b + 4j + \widetilde{\chi}_1^0$$

Compressed spectrum

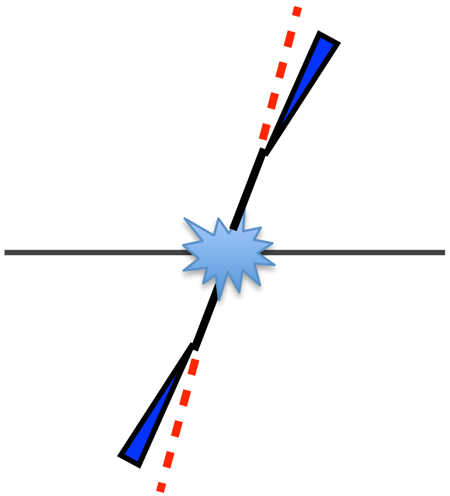


- small jet p_T

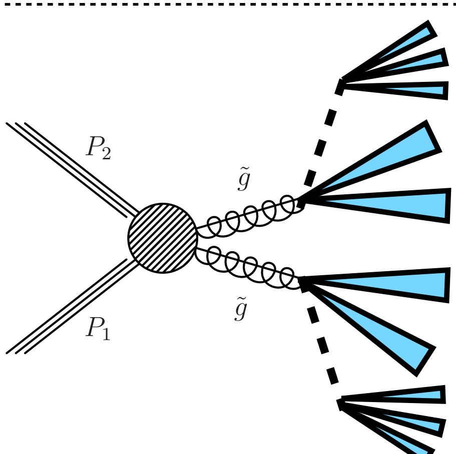
  $p_T \sim m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$

- small $\not{E}_T$

  (LSPs are back-to-back and cancel each other in $\not{E}_T$)



RPV



- small $\not{E}_T$

  (LSPs decay to SM particles)

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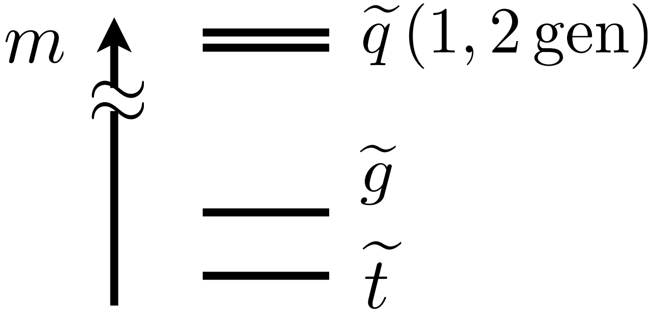
Split generation



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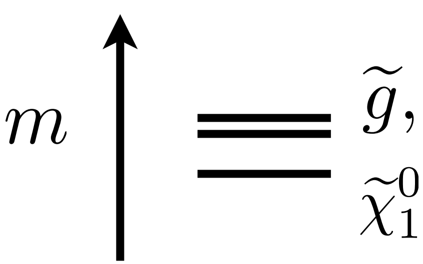

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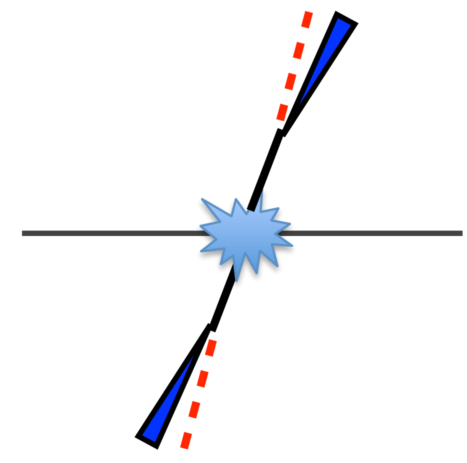

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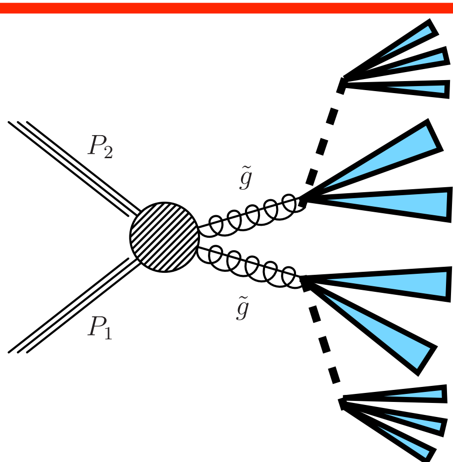


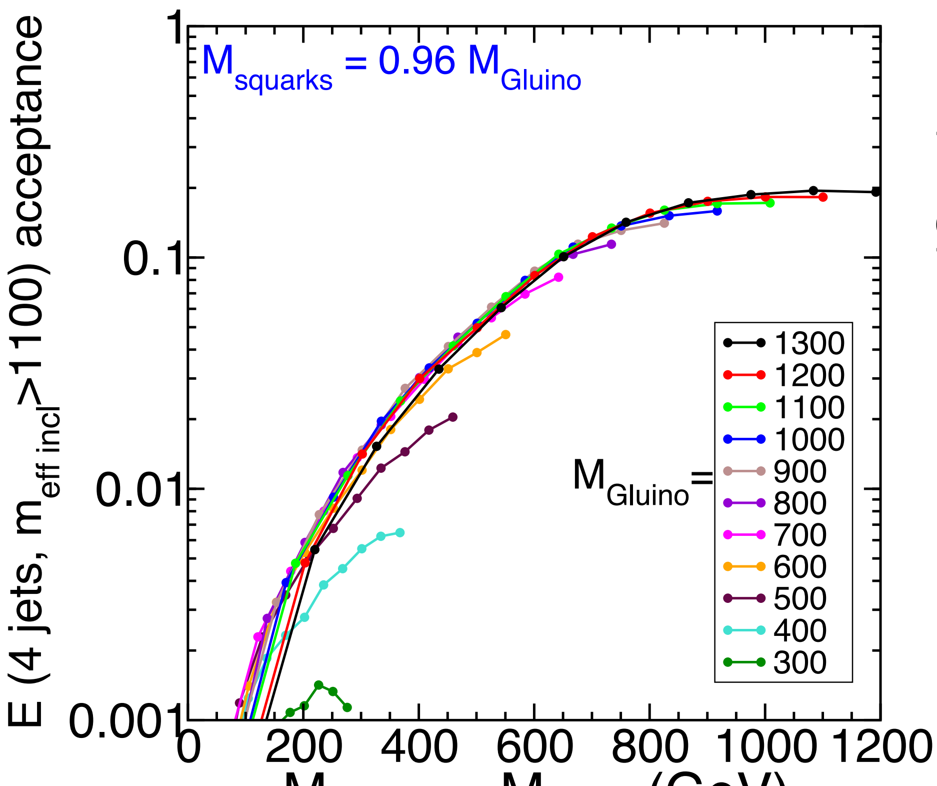
- small $\not{E}_T$

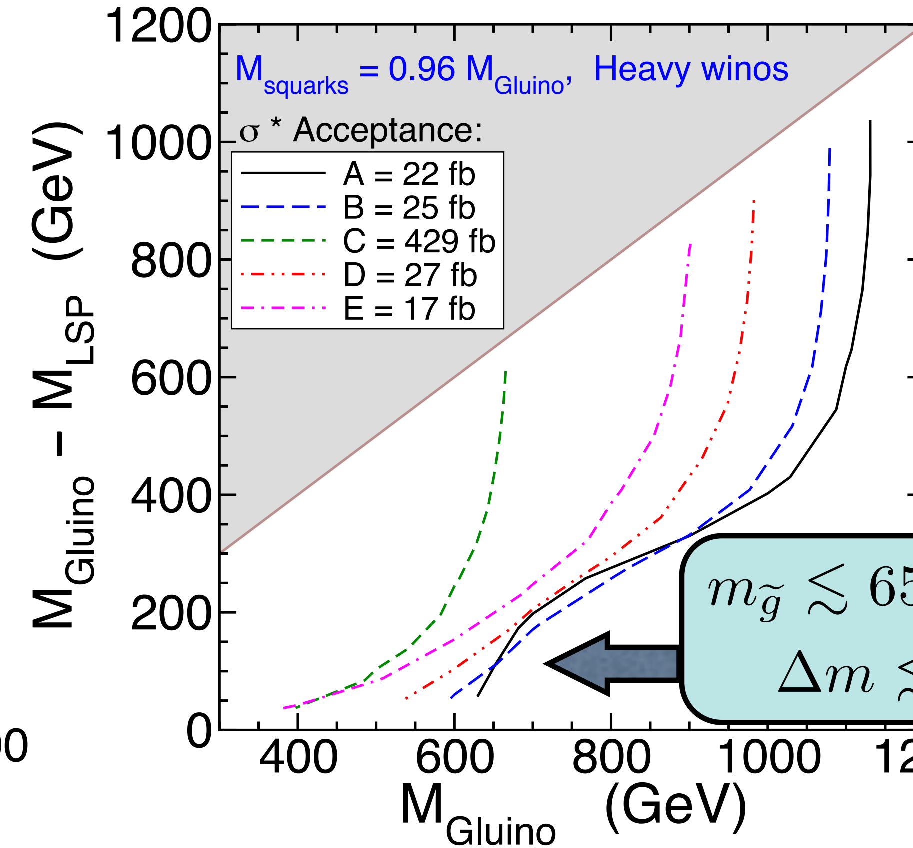
  (LSPs decay to SM particles)

Compressed SUSY vs. multi-jet + $\not{E}_T$ searces

T.J.LeCompte, S.P.Martin Phys.Rev. D85

	A	B	C	D	E
Leading jet p_T [GeV]	> 130	> 130	> 130	> 130	> 130
Number of jets n	≥ 2	≥ 3	≥ 4	≥ 4	≥ 4
$p_T(j_n)$ [GeV]	> 40	> 40	> 40	> 40	> 80
m_{eff} [GeV]	> 1000	> 1000	> 500	> 1000	> 1100
$E_T^{\text{miss}}/m_{\text{eff}}$	> 0.3	> 0.25	> 0.25	> 0.25	> 0.2
ATLAS $\sigma \times$ Acc [fb]	< 22	< 25	< 429	< 27	< 17





$m_{\tilde{g}} \lesssim 650\,\text{GeV}$ for $\Delta m \lesssim 100\,\text{GeV}$

Leptonic searches

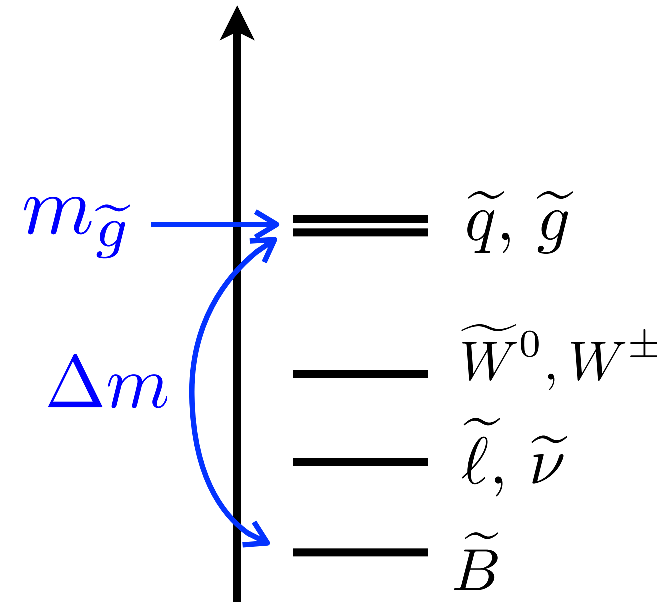
- Large p_T and E_T^{miss} cut kill a lot of signal events in compressed SUSY models.
- For leptonic searches, the p_T and E_T^{miss} cuts are much milder.

ATLAS multi-lepton searches: arXiv:1110.6189, arXiv:1204.5638, ATLAS-CONF-2012-001

signal region	2OS	2SS	3LEP	4LEP
N(lep)	= 2 (OS)	= 2 (SS)	= 3	>= 4
leading μ (e) p_T (GeV)	> 20 (25)	> 20 (25)	> 20 (25)	> 20 (25)
E_T^{miss} (GeV)	> 250	> 100	> 50	> 50
dilpton mass (GeV)	> 12	> 12	> 20	> 20
luminosity (fb^{-1})	1.04	1.04	2.06	2.06

- If squarks and gluino decay into leptons in compressed SUSY models, leptonic searches can be used to constrain such models.

Simplified model



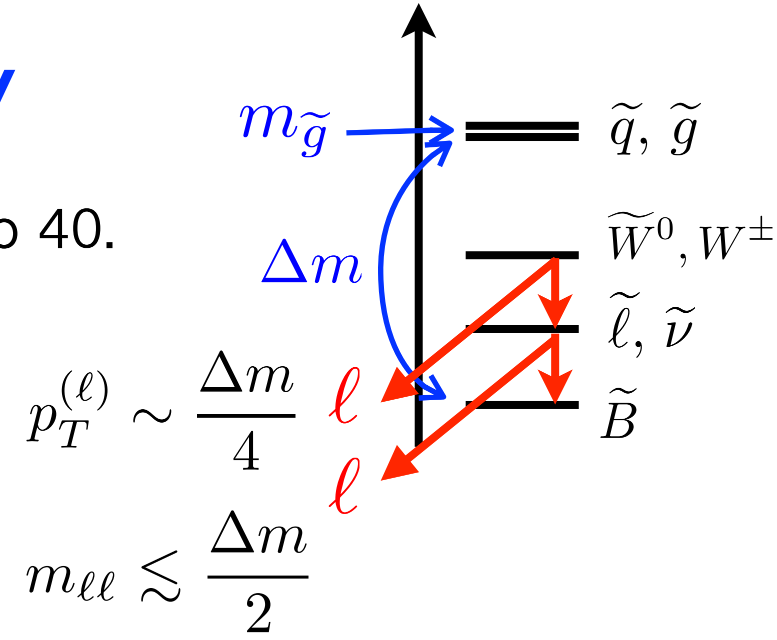
- 3rd gen. sfermions and higssinos are decoupled.
- $\widetilde{\chi}_1^0 \simeq \widetilde{B},\ \widetilde{\chi}_2^0 \simeq \widetilde{W}^0,\ \widetilde{\chi}_1^{\pm} \simeq \widetilde{W}^{\pm}$
- $m_{\widetilde{q}} \simeq m_{\widetilde{g}}$
- $m_{\widetilde{W}} = \dfrac{m_{\widetilde{g}} + m_{\widetilde{\chi}_1^0}}{2},\ m_{\widetilde{\ell}} = \dfrac{m_{\widetilde{W}} + m_{\widetilde{\chi}_1^0}}{2}$

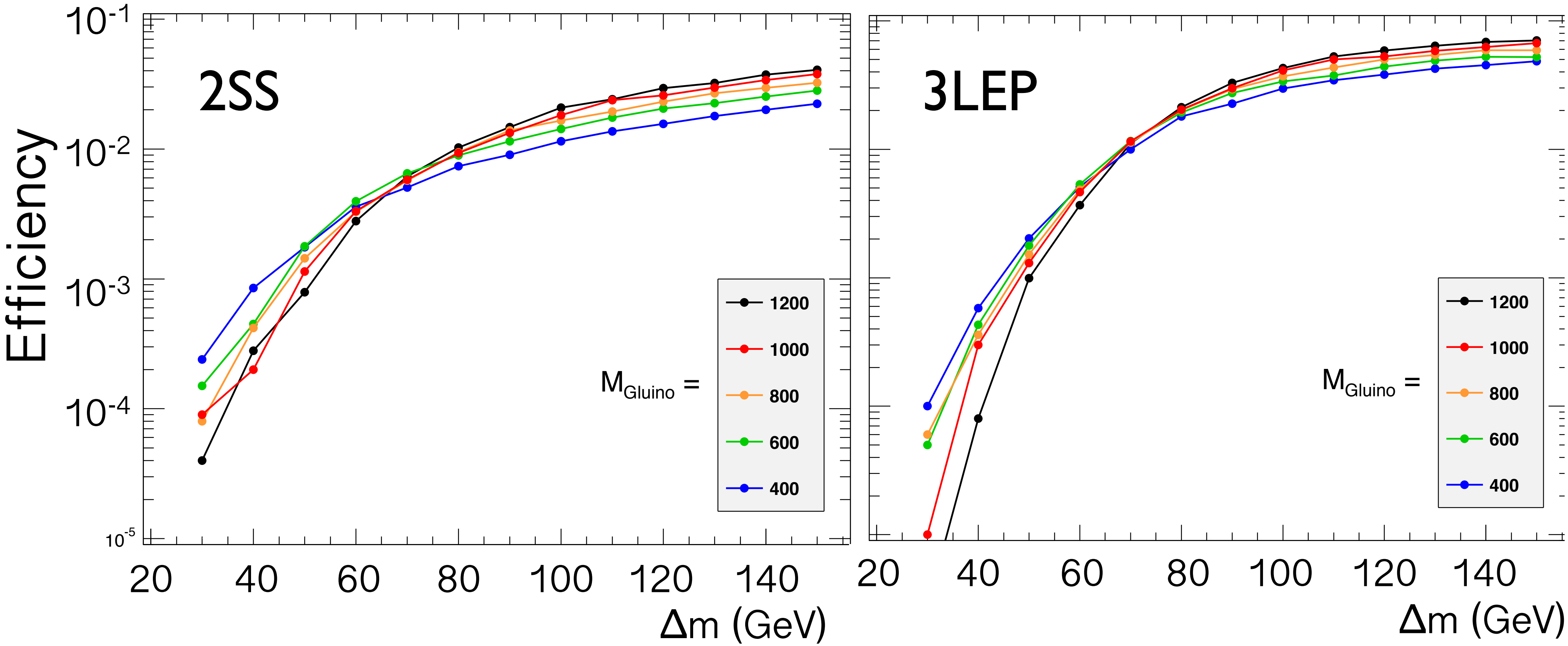
$$
\begin{aligned}
&\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}^{\pm}\ell^{\mp} q \to \ell^{\pm}\ell^{\mp} q \tilde{\chi}_1^0 && BR = 33\% \ , \\
&\tilde{q}_L \to \tilde{\chi}_1^{\pm} q \to \tilde{\ell}^{\pm}\nu_\ell q \,(\tilde{\nu}_\ell \ell^{\pm} q) \to \ell^{\pm}\nu_\ell q \tilde{\chi}_1^0 && BR = 67\% \ , \\
&\tilde{g} \to \tilde{\chi}_2^0 qq \to \tilde{\ell}^{\pm}\ell^{\mp} qq \to \ell^{\pm}\ell^{\mp} qq \tilde{\chi}_1^0 && BR \simeq 16\% \ , \\
&\tilde{g} \to \tilde{\chi}_1^{\pm} qq \to \tilde{\ell}^{\pm}\nu_\ell qq \,(\tilde{\nu}_\ell \ell^{\pm} qq) \to \ell^{\pm}\nu_\ell qq \tilde{\chi}_1^0 && BR \simeq 33\% \ .
\end{aligned}
$$

- Event generation: **Herwig++**, Detector simulation: **Delphes**

Efficiency

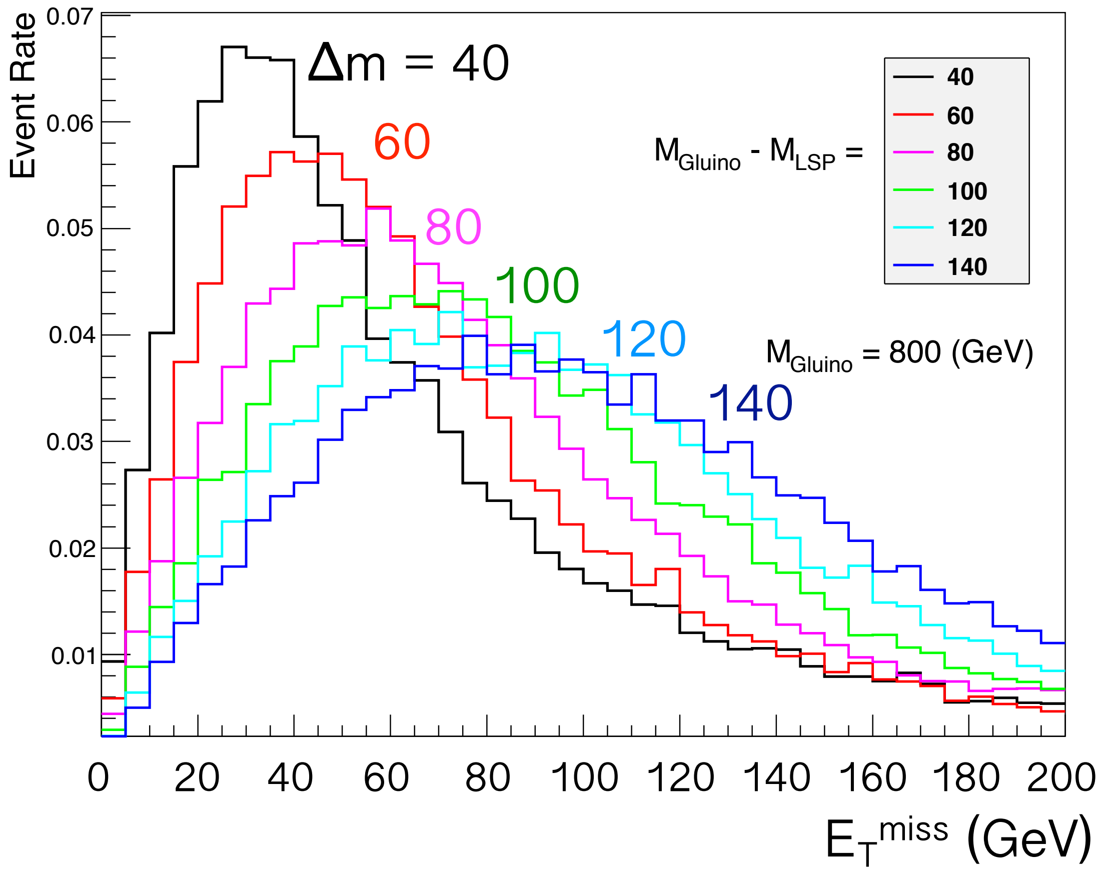
- The efficiencies drop quickly from Δm=100 to 40.
- The efficiency hardly depends on $m_{\tilde{g}}$





E_T^{miss}

- Neutrinos appear in the SUSY decay chains associated with charged leptons.
- E_T^{miss} distributions peak around (2/3)*Δm and have long tails.



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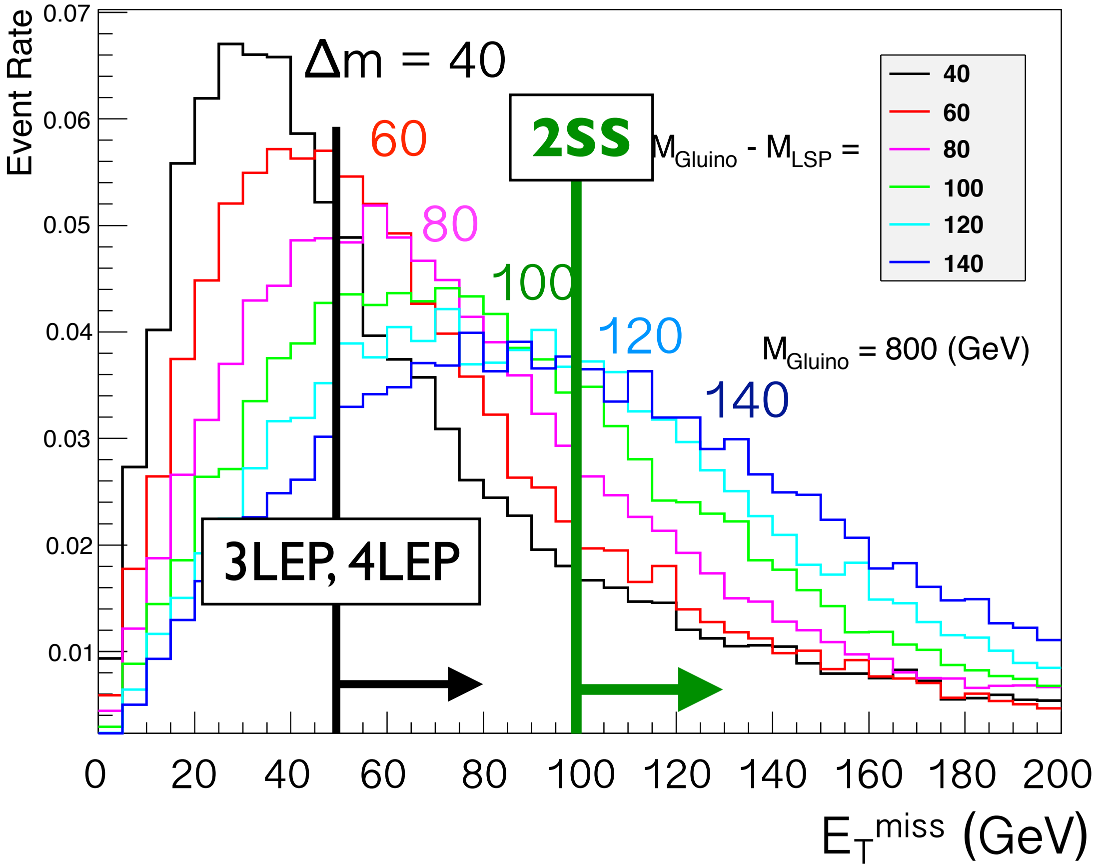

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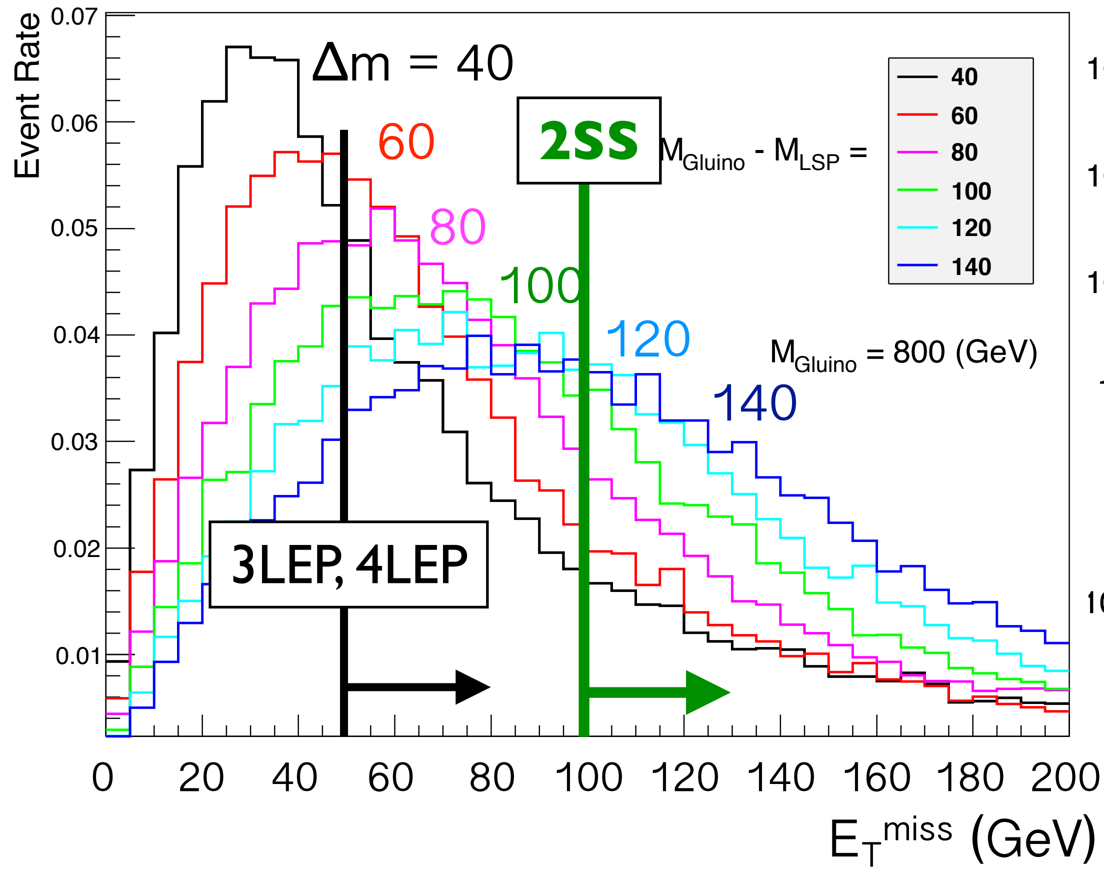

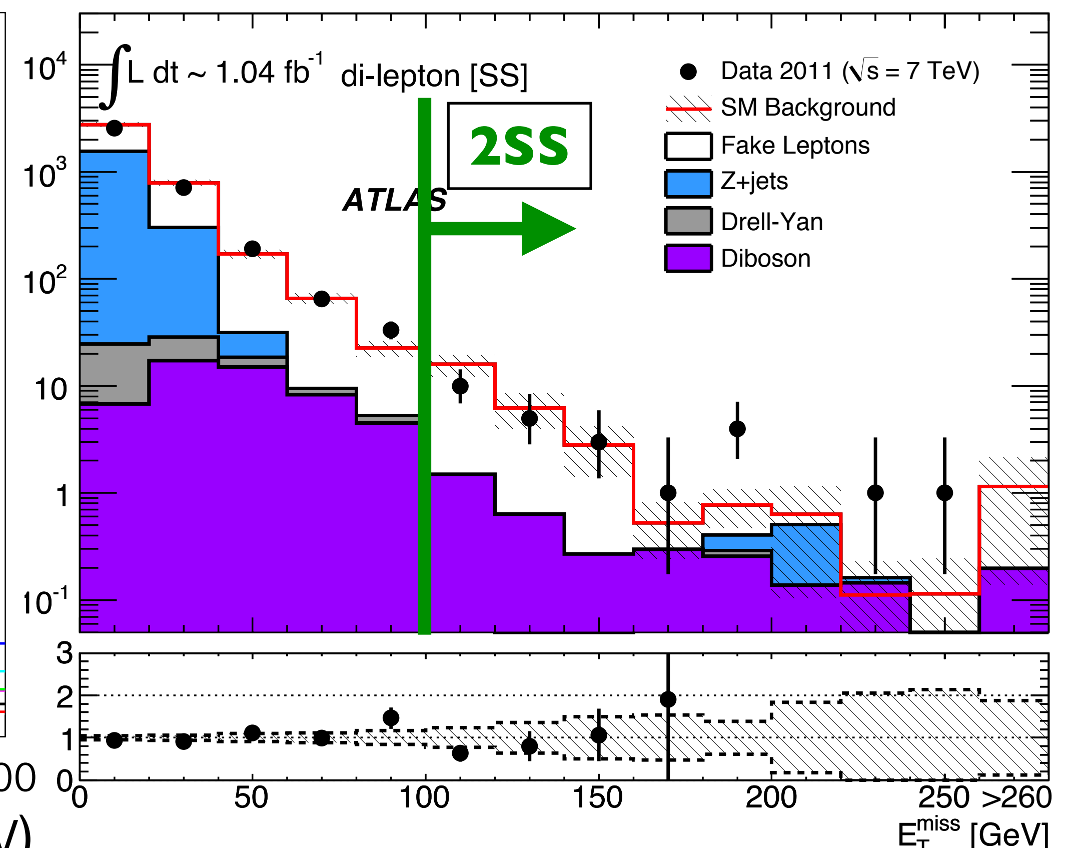

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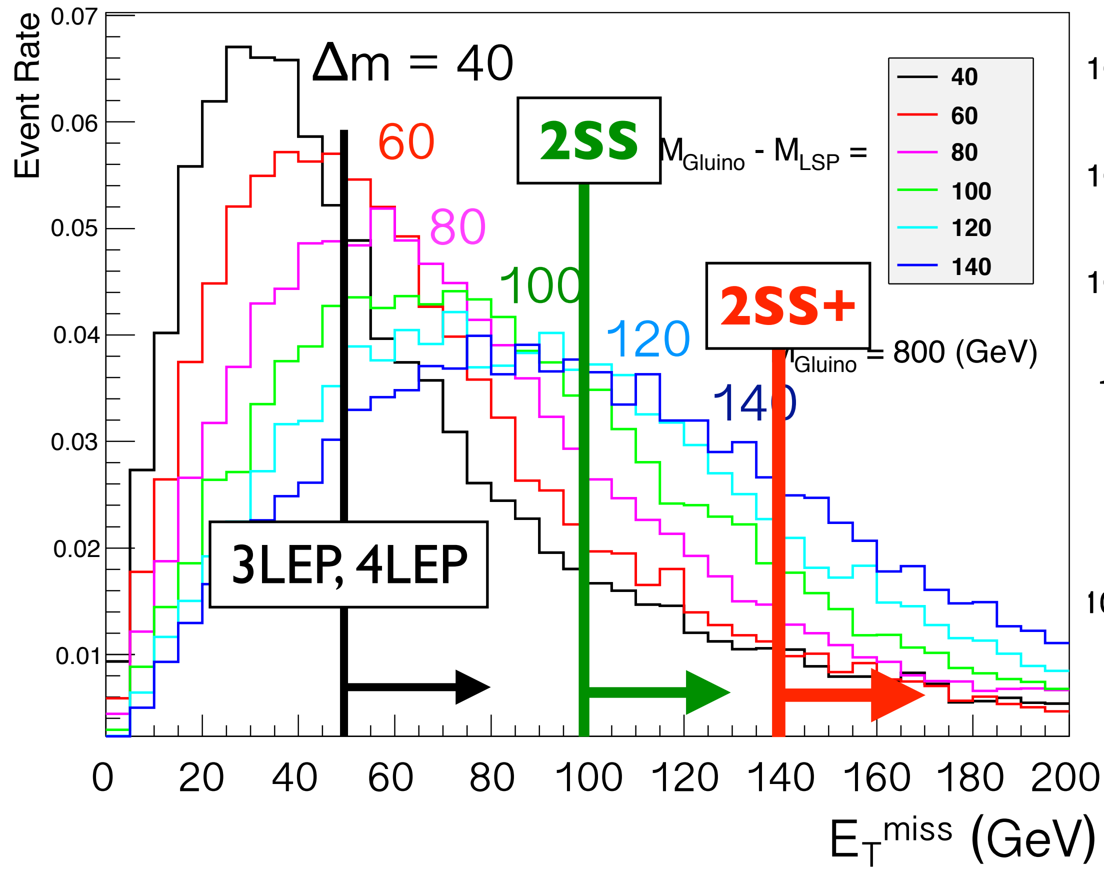
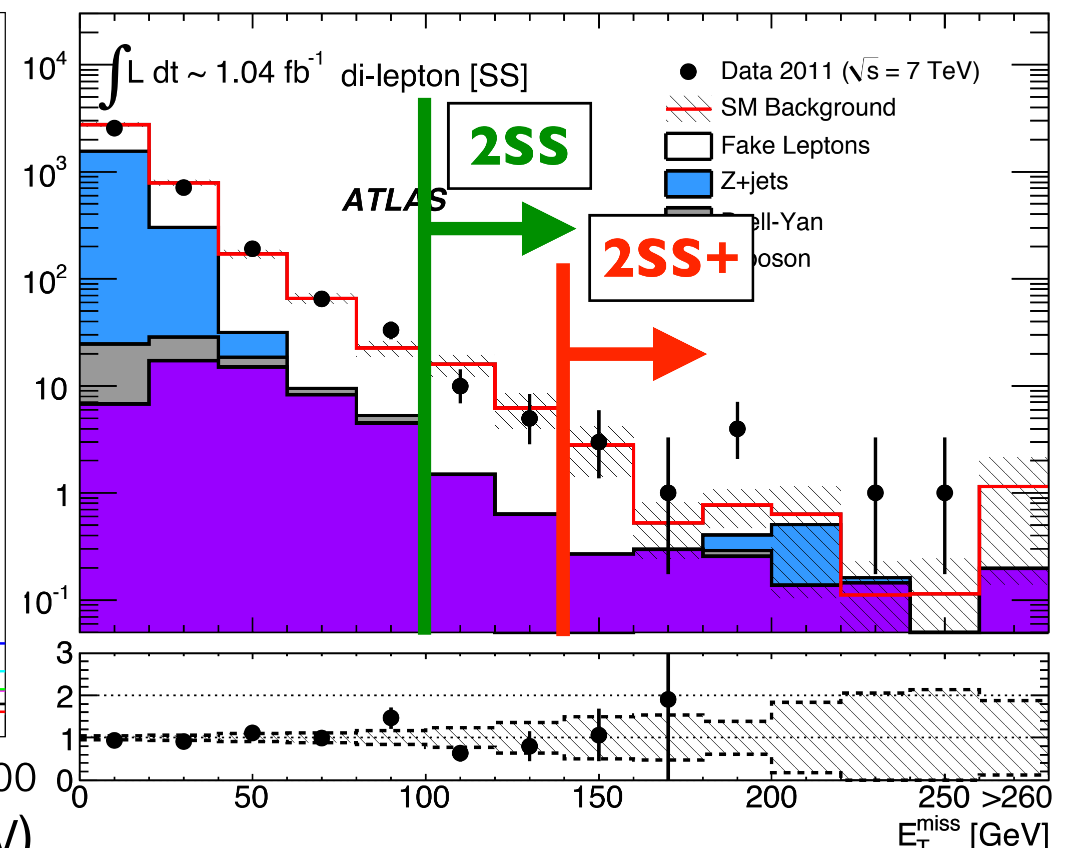
- If E_T^{miss} cut is raised to 140 from 100 GeV in 2SS, 80% of the BG is removed, but reduction on the signal is only 30% (Δm ~ 70).





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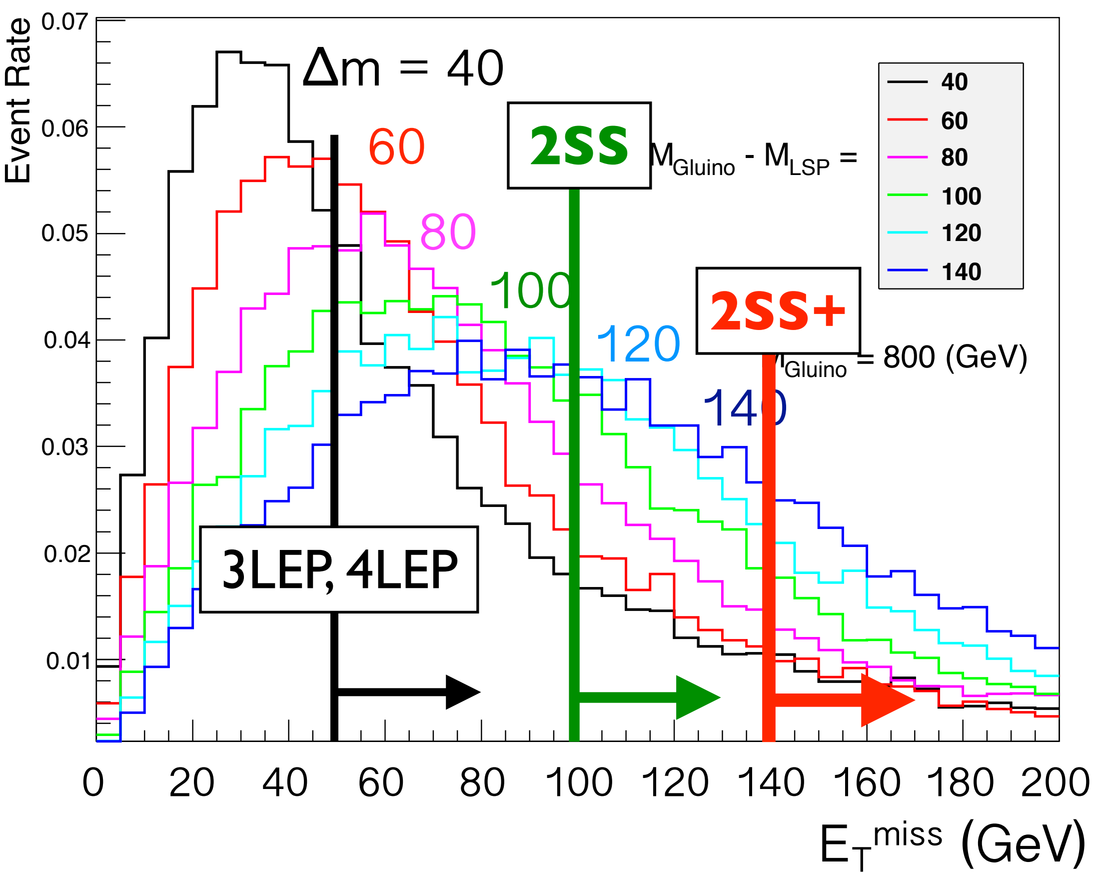
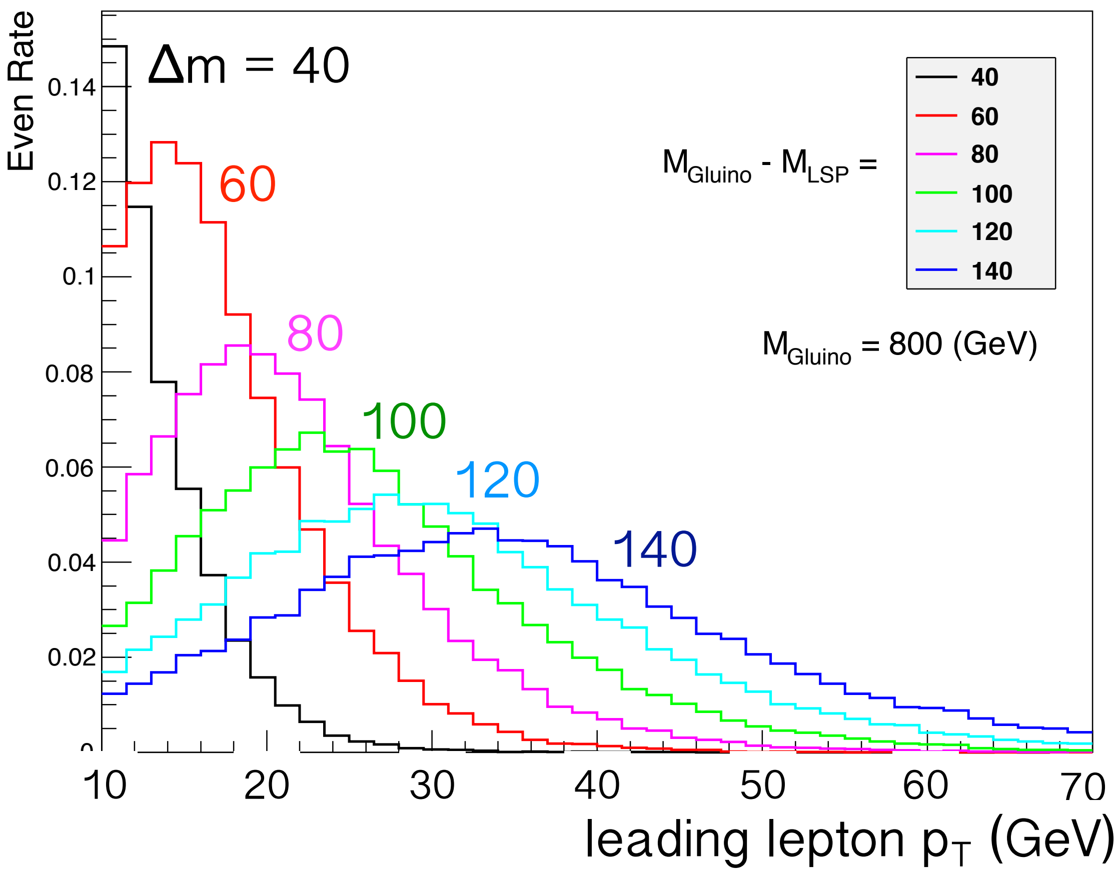
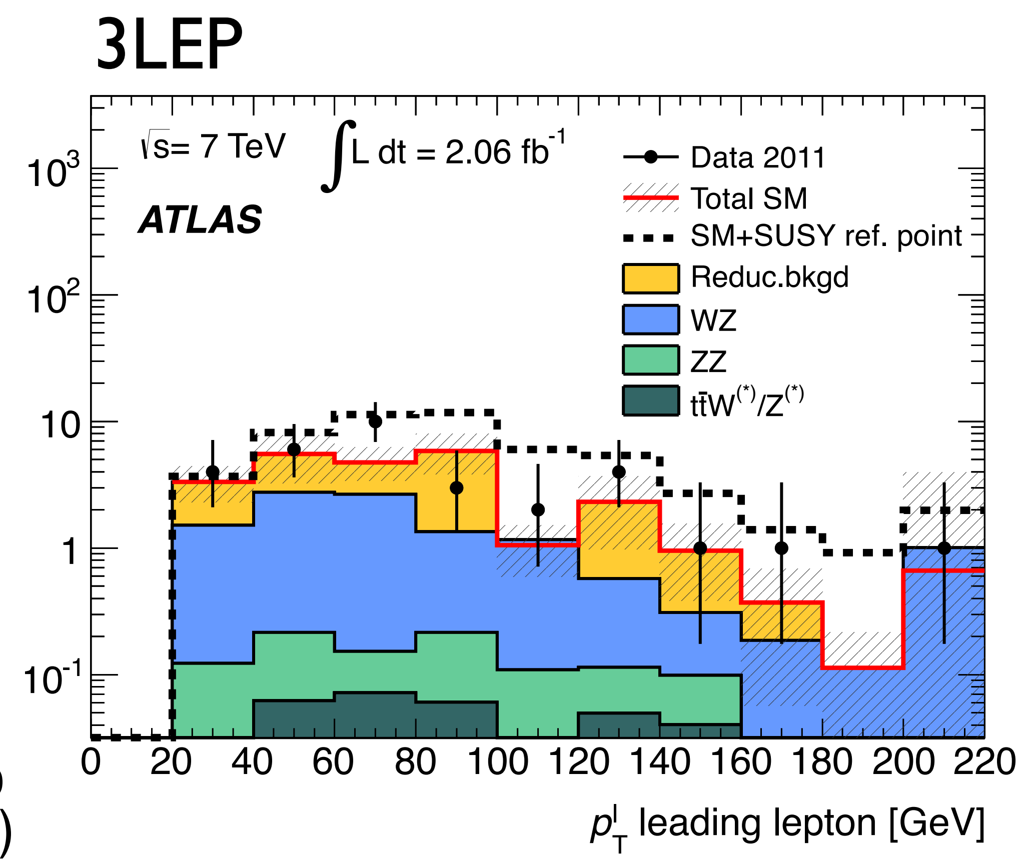


signal region	2SS	2SS+
N(lep)	= 2 (SS)	= 2 (SS)
leading μ (e) p_T	> 20 (25)	> 20 (25)
E_T^{miss} (GeV)	> 100	> 140
dilpton mass (GeV)	> 12	> 12
luminosity (fb^{-1})	1.04	1.04
expected BG	32.6 ± 7.9	6.4 ± 1.6
observed	25	10
σ_{vis}^{bound} (95% CL)	14.8 fb	10.9 fb

leading lepton p_T

- p_T^{lep} distributions peak around $\Delta m/4$, and quickly fall off towards the high p_T region.
- The p_T cut of 20 (25) for μ (e) is the limiting factor of the analysis for the small Δm.





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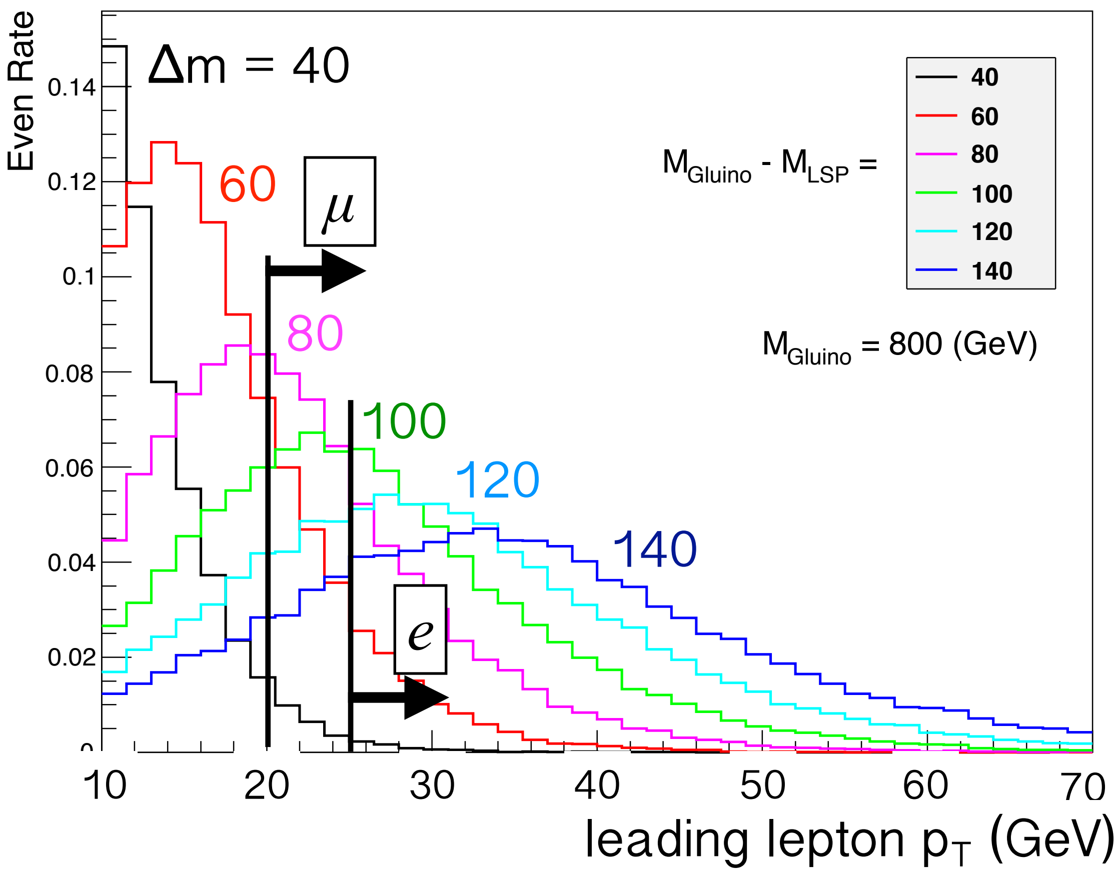

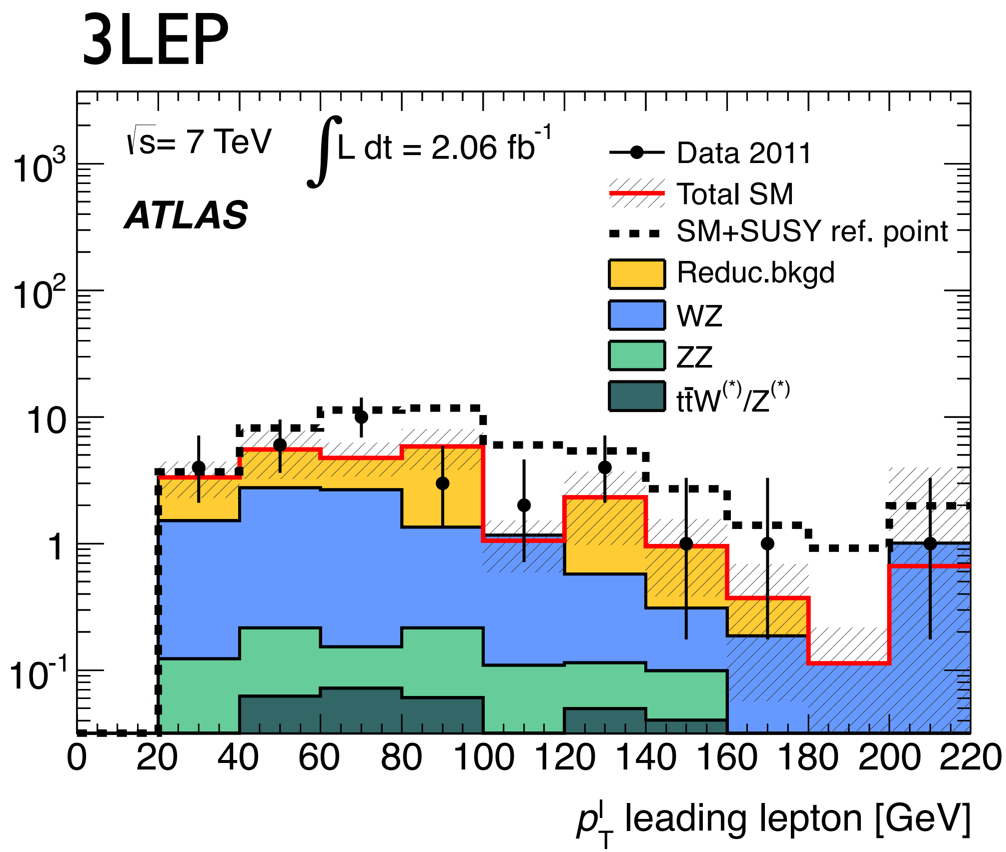

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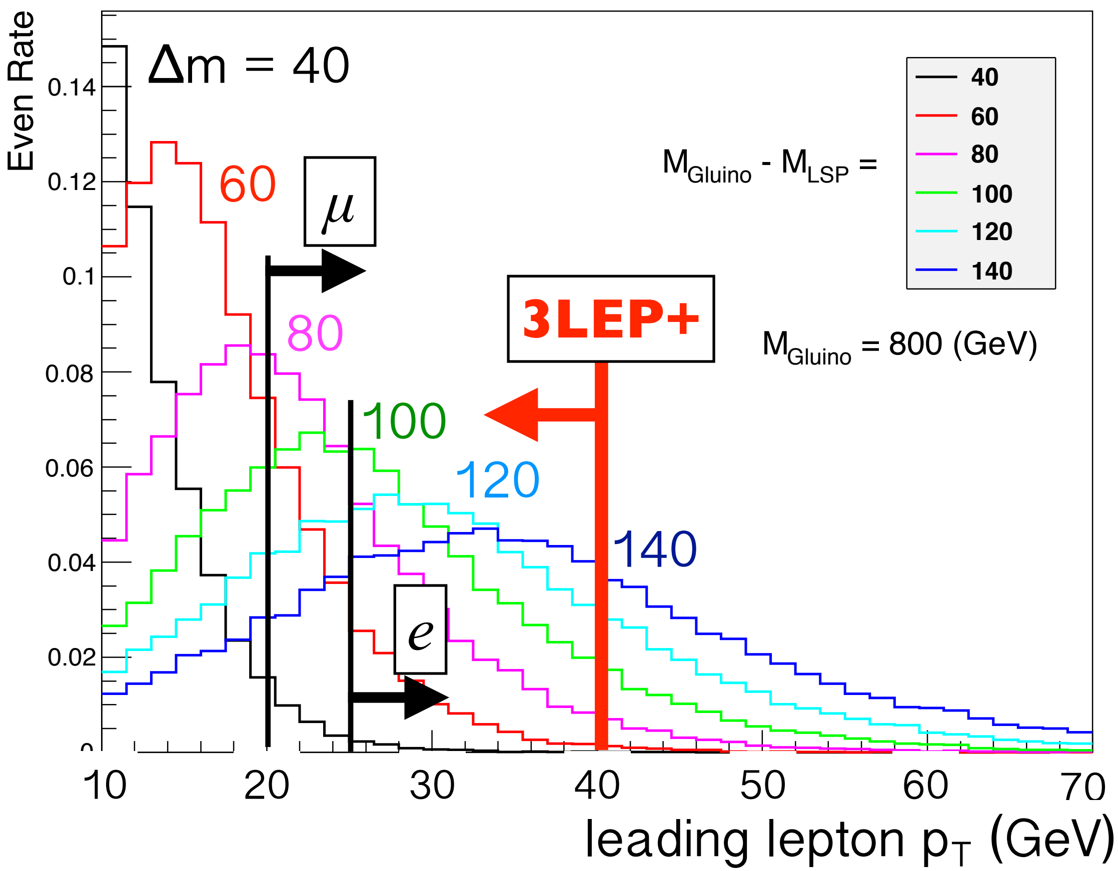
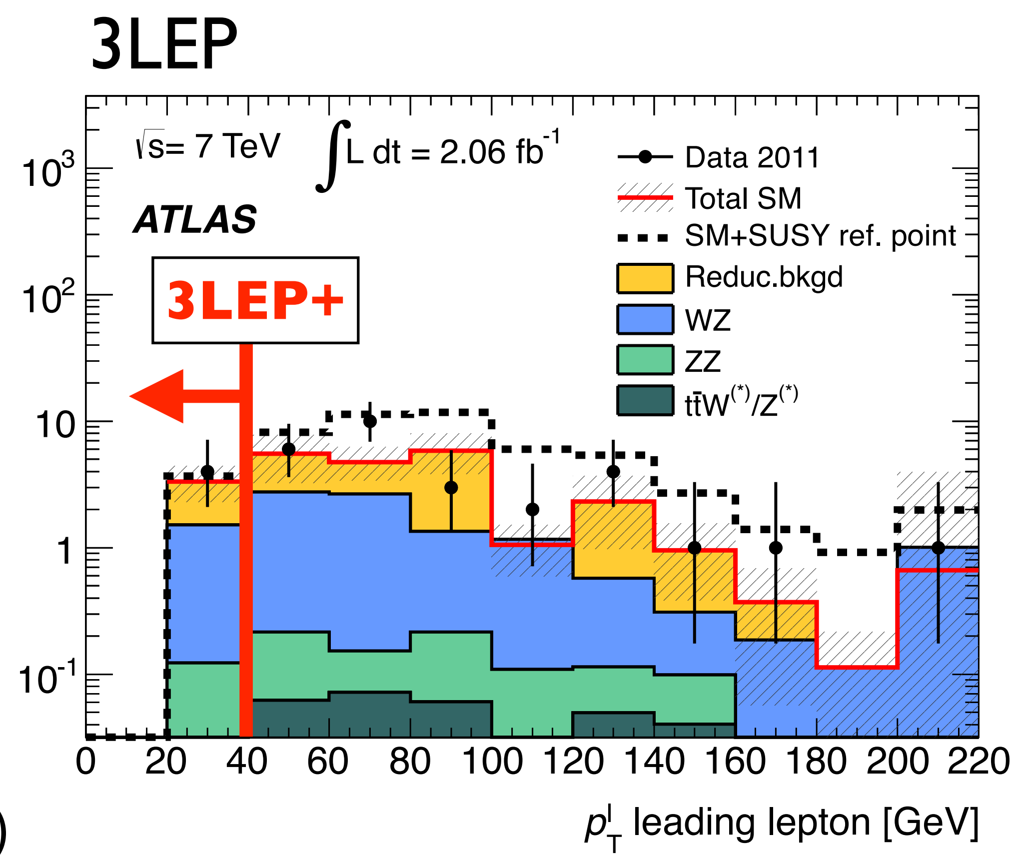
- If a low pT cut of 40GeV is added in 3LEP, 90% of the BG is removed, but reduction on signal is only 50% (Δm ~ 140).





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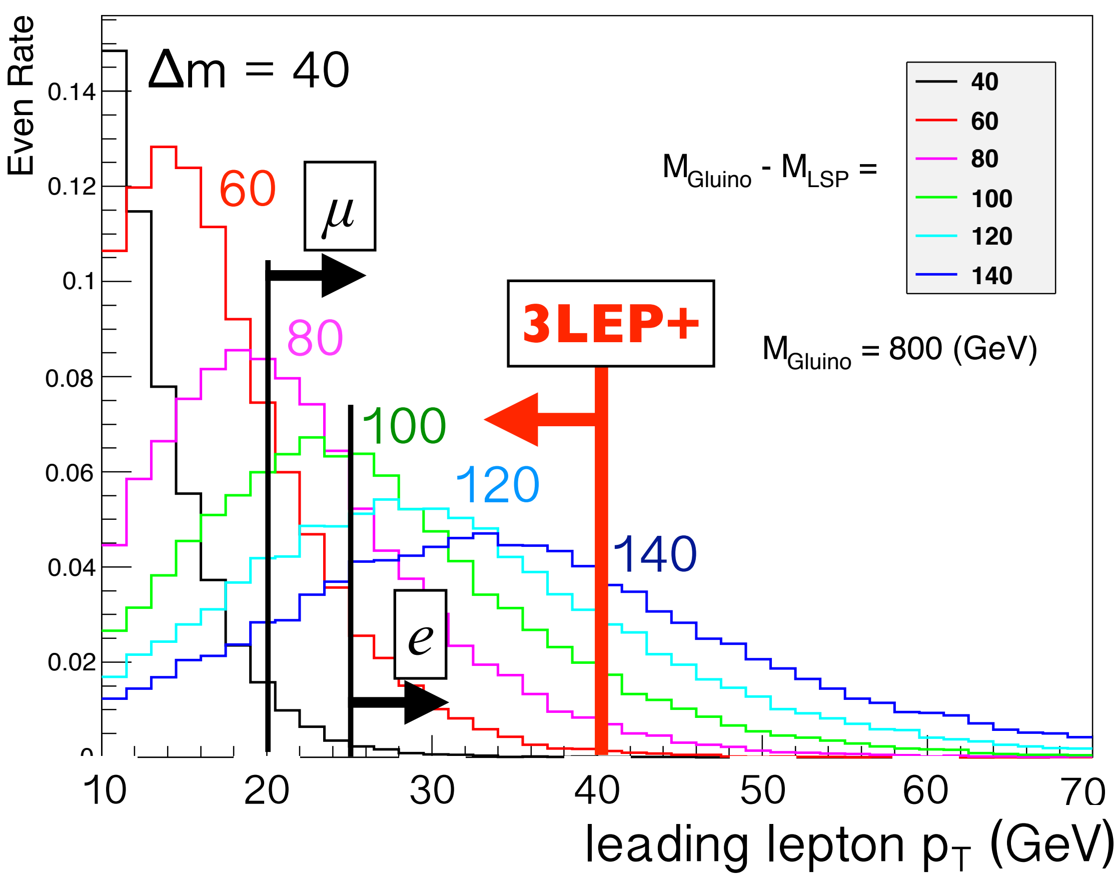
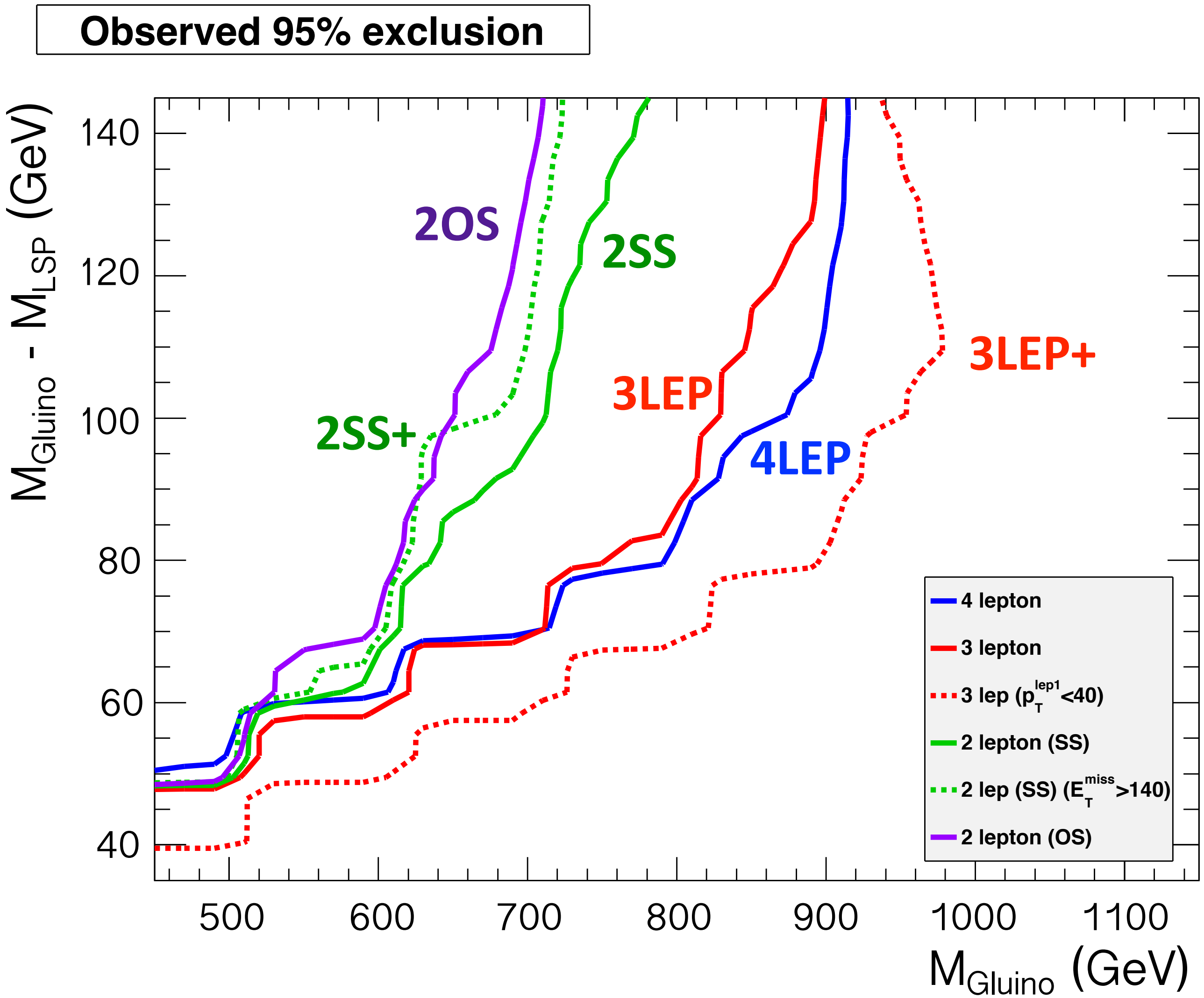


signal region	3LEP	3LEP+
N(lep)	= 3	= 3
leading μ (e) p_T	> 20 (25)	> 20 (25), <40
E_T^{miss} (GeV)	> 50	> 50
dilpton mass	> 20	> 20
luminosity (fb^{-1})	2.06	2.06
expected BG	26 ± 5	3.3 ± 0.6
observed	32	4
σ_{vis}^{bound} (95%)	10.0 fb	3.3 fb

Exclusion

- m_{Gluino} > 900GeV if Δm > 100GeV, m_{Gluino} > 500GeV if Δm > 50GeV.
- New 3LEP+ significantly extends the exclusion limit.
- New 2SS+ does not extend the limit because of an excess in the signal region.



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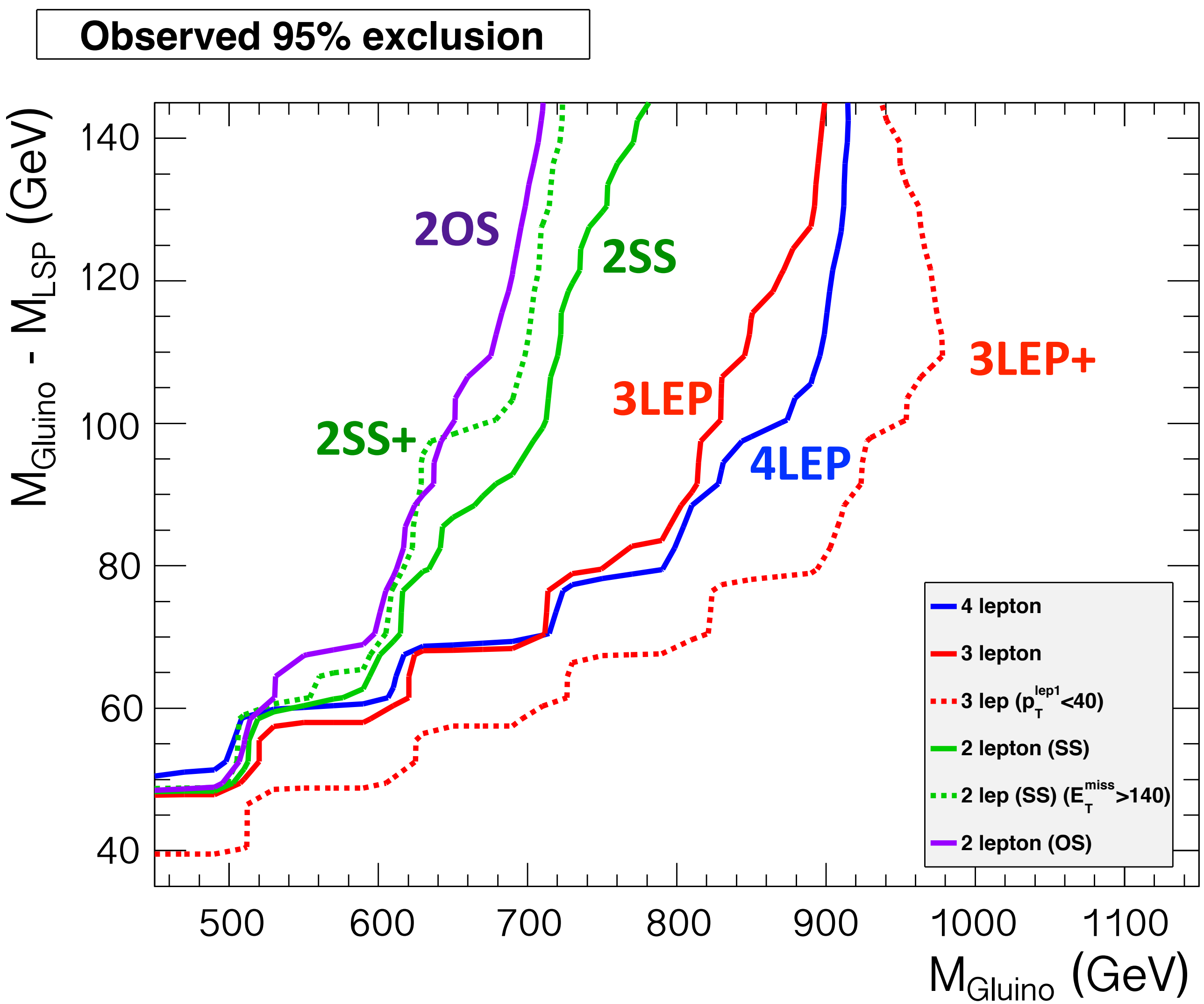

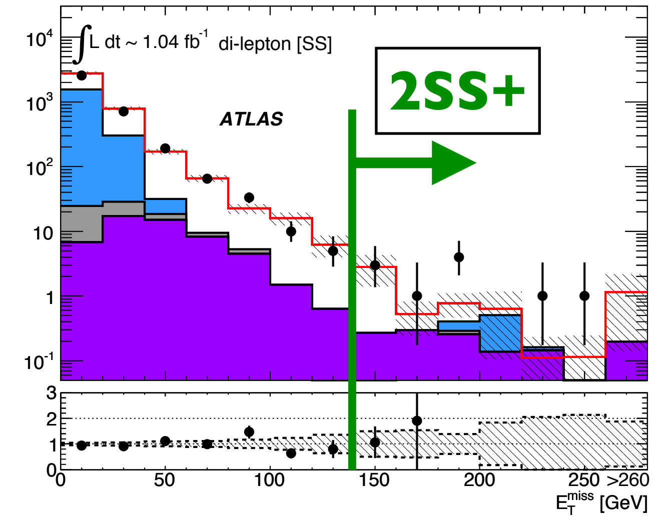

SR	2SS	2SS+
BG^{exp}	32.6±7.9	6.4±1.6
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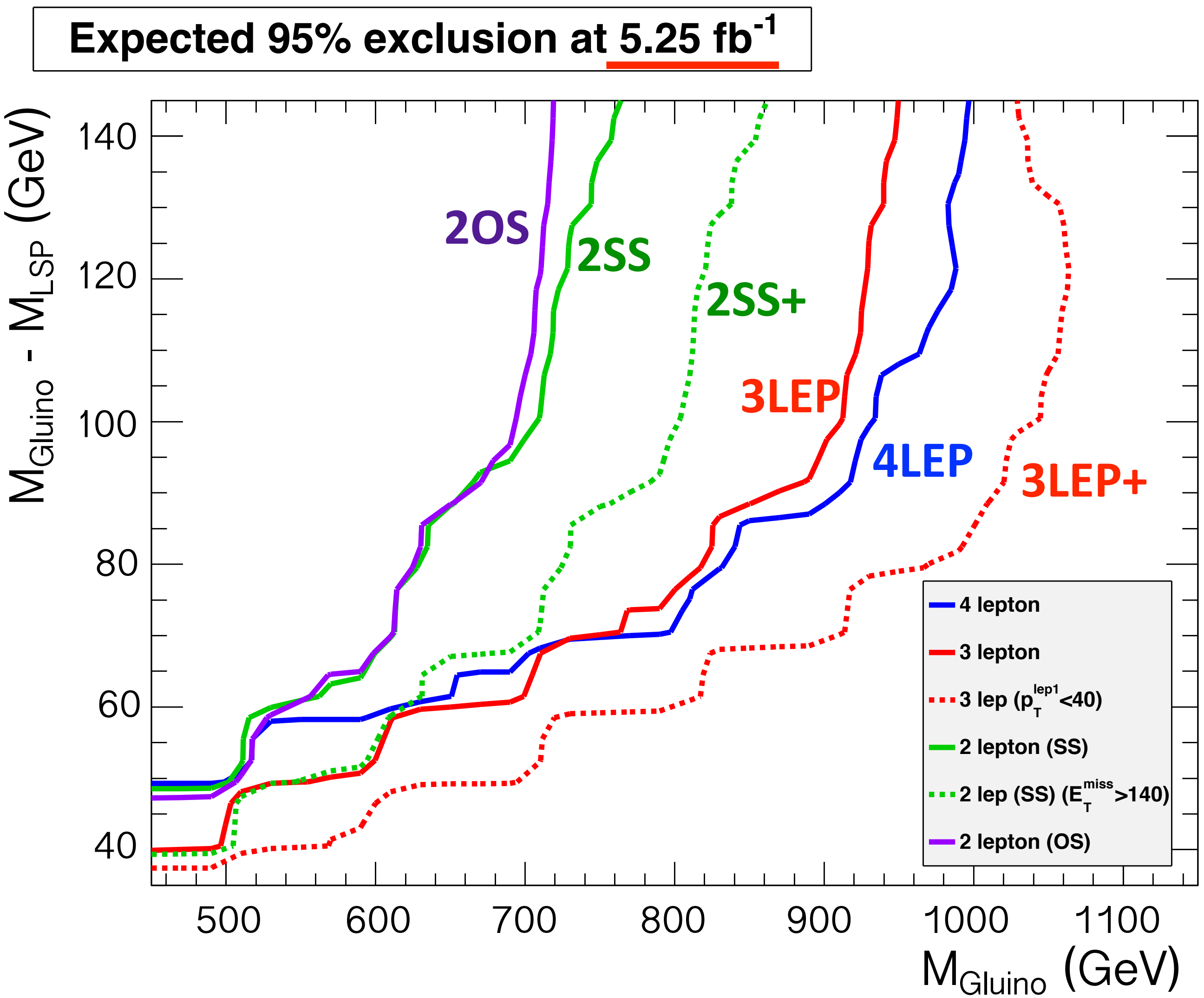


5.25/fb projection:

- m_{Gluino}>1TeV if Δm>80GeV
- m_{Gluino}>600GeV if Δm>50GeV

Summary

• Compressed SUSY models still provide an interesting possibility to accommodate naturalness to direct SUSY search constraints.

• In such a model, if squarks and gluino have sizeable leptonic branching ratios, multi-lepton searches can be used to constrain the model.

• In our simplified model, the bound on the gluino/squark mass is:

$m_{g/q}$ > 900 (500) GeV for Δm > 100 (50) GeV.

Application to the other model

- The estimated mass limits are not applicable to models with different cross sections and branching ratios.

- The visible cross section may be decomposed as:

$$\sigma_{\rm vis}^{(i)} = \sum_{a\to X, b\to Y} \sigma_{ab} \cdot B_{a\to X} \cdot B_{b\to Y} \cdot \epsilon_{a\to X, b\to Y}^{(i)}$$

$$\begin{aligned} a, b &: \text{ SUSY particles} \\ X, Y &: \text{ decay processes} \\ \sigma_{ab} &: \text{ cross section of } a, b \text{ production} \\ B_{a\to X} &: \text{ branching ratio of } a \to X. \\ \epsilon_{a\to X, b\to Y}^{(i)} &: \text{ efficiency of signal region } (i) \end{aligned}$$

- The event simulation and detector simulation are required only to calculate the efficiencies.

Application to the other model

- The estimated mass limits are not applicable to models with different cross sections and branching ratios.

- The visible cross section may be decomposed as:

requires MC simulation

$$\sigma^{(i)}_{\text{vis}} = \sum_{a\to X, b\to Y} \sigma_{ab} \cdot B_{a\to X} \cdot B_{b\to Y} \cdot \boxed{\epsilon^{(i)}_{a\to X, b\to Y}}$$

a, b: SUSY particles

X, Y: decay processes

σ_{ab}: cross section of a, b production

$B_{a\to X}$: branching ratio of $a \to X$.

$\epsilon^{(i)}_{a\to X, b\to Y}$: efficiency of signal region (i)

- Only efficiencies require the MC simulation to be estimated.

- Visible cross section can be estimated without doing MC simulation if the efficiencies are known.

- We define three types of decay processes as:

$$
\begin{aligned}
(a \rightarrow X) = \quad & \widetilde{\chi}_2^0: \quad \widetilde{q}/\widetilde{g} \rightarrow \widetilde{\chi}_2^0 + \text{jets} \rightarrow \ell^+\ell^-\widetilde{\chi}_1^0 + \text{jets} \\
& \widetilde{\chi}_1^\pm: \quad \widetilde{q}/\widetilde{g} \rightarrow \widetilde{\chi}_1^\pm + \text{jets} \rightarrow \ell\nu\widetilde{\chi}_1^0 + \text{jets} \\
& \widetilde{\chi}_1^0: \quad \widetilde{q}/\widetilde{g} \rightarrow \widetilde{\chi}_1^0 + \text{jets}
\end{aligned}
$$

- Considering both decay chains, relevant signal regions are identified for each event process, XY:

$$
\begin{aligned}
XY = \quad & \tilde{\chi}_2^0\tilde{\chi}_1^0 \Longrightarrow \text{2OS;} \\
& \tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \Longrightarrow \text{2OS, 2SS;} \\
& \tilde{\chi}_1^\pm\tilde{\chi}_2^0 \Longrightarrow \text{3LEP (2OS, 2SS);} \\
& \tilde{\chi}_2^0\tilde{\chi}_2^0 \Longrightarrow \text{4LEP (3LEP, 2OS, 2SS);} \\
& \tilde{\chi}_1^0\tilde{\chi}_1^0,\ \tilde{\chi}_1^\pm\tilde{\chi}_1^0 \Longrightarrow \text{less than 2 leptons.}
\end{aligned}
$$

$\epsilon^{(i)}_{XY}$ in % $\quad (m_{\tilde{q}/\tilde{g}} = 800\,\mathrm{GeV})$

Δm (GeV)		50	60	70	80	100	120	140
2OS	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$	0.21	0.53	0.87	1.30	1.9	2.6	3.0
	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	0.18	0.41	0.61	0.82	1.07	1.29	1.34
	$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.18	0.27	0.37	0.42	0.52	0.53	0.48
	$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	0.26	0.70	1.31	1.85	3.52	4.43	4.33
2SS	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$	0.79	2.23	4.40	7.00	12.93	18.24	22.34
	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	0.38	0.88	1.46	2.00	3.16	4.22	5.25
	$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.36	0.70	1.03	1.28	1.28	2.12	2.08
2SS+	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$	0.55	1.54	2.79	4.63	7.76	9.23	11.70
	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	0.25	0.56	0.89	1.18	1.82	2.11	2.80
	$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.25	0.46	0.63	0.78	0.63	1.03	1.00
3LEP	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	0.16	0.73	2.16	4.41	10.39	14.75	17.33
	$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.43	1.58	4.01	7.70	12.35	15.91	18.03
3LEP+	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	0.15	0.71	2.05	4.07	8.57	10.17	8.83
	$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.42	1.55	3.87	7.01	10.18	10.53	8.23
4LEP	$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.28	1.24	3.73	8.50	15.76	18.83	23.61

caveats:

- Contributions from other processes are neglected.

$$\text{e.g. } \tilde{g} \to \tilde{t}^{(*)} t^{(*)} \to \ell\ell\nu\nu bb\chi_1^0$$

- Efficiencies vary about factor of 2-5 btw $m_{g/q}$ = 400 to 1200GeV depending on Δm.

- Efficiencies differ if the assumption

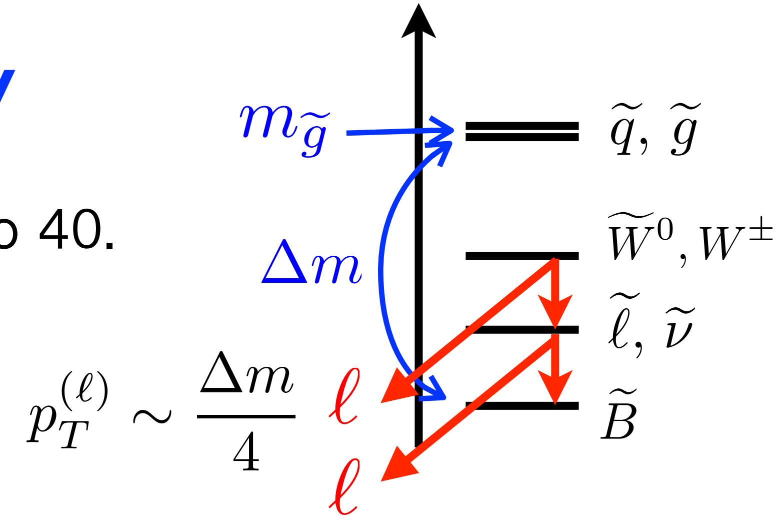
$$m_{\widetilde{W}} = \frac{m_{\tilde{g}} + m_{\tilde{\chi}_1^0}}{2}, \quad m_{\tilde{\ell}} = \frac{m_{\widetilde{W}} + m_{\tilde{\chi}_1^0}}{2}$$

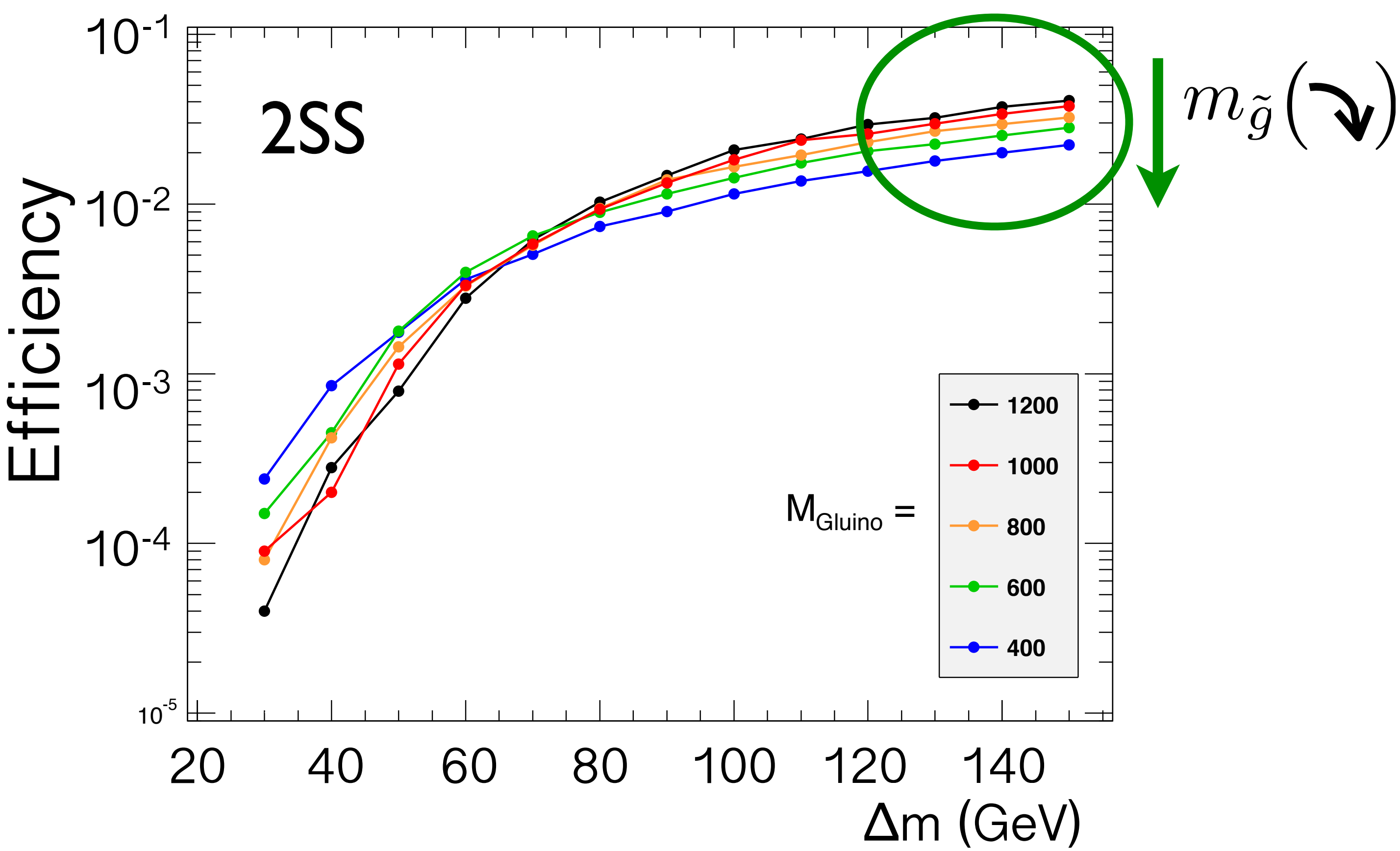
is relaxed. We have checked the efficiencies do not change much in the events with wino decaying to leptons through three body decays.

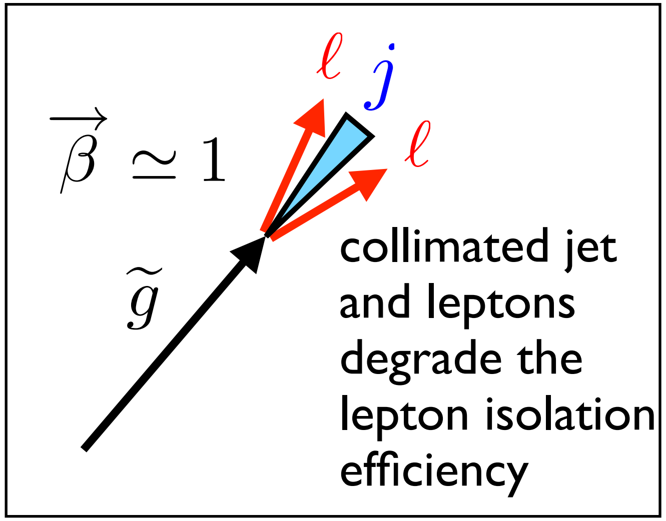
$$\boxed{\sigma^{(i)}_{\mathrm{vis}} \sim \sum_{a\to X, b\to Y} \sigma_{ab} \cdot B_{a\to X} \cdot B_{b\to Y} \cdot \epsilon^{(i)}_{a\to X, b\to Y}(\Delta m)}$$

Efficiency

- The efficiencies drop quickly from Δm=100 to 40.
- The efficiency hardly depends on $m_{\tilde{g}}$







Efficiency

- The efficiencies drop quickly from Δm=100 to 40.
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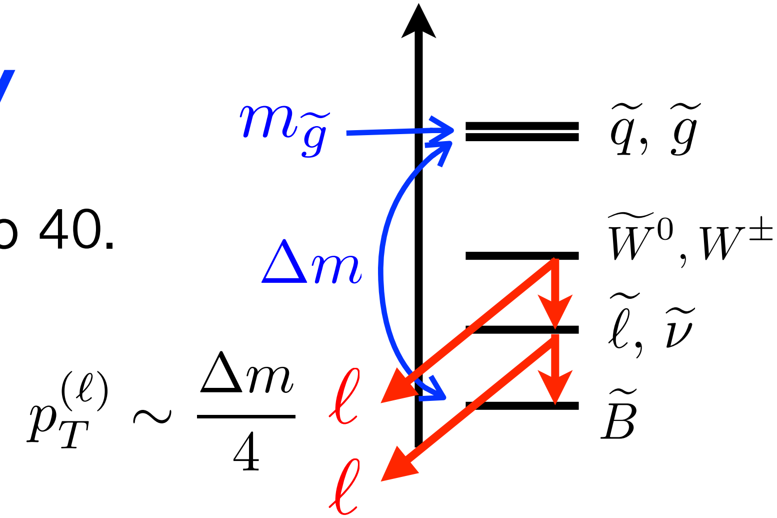
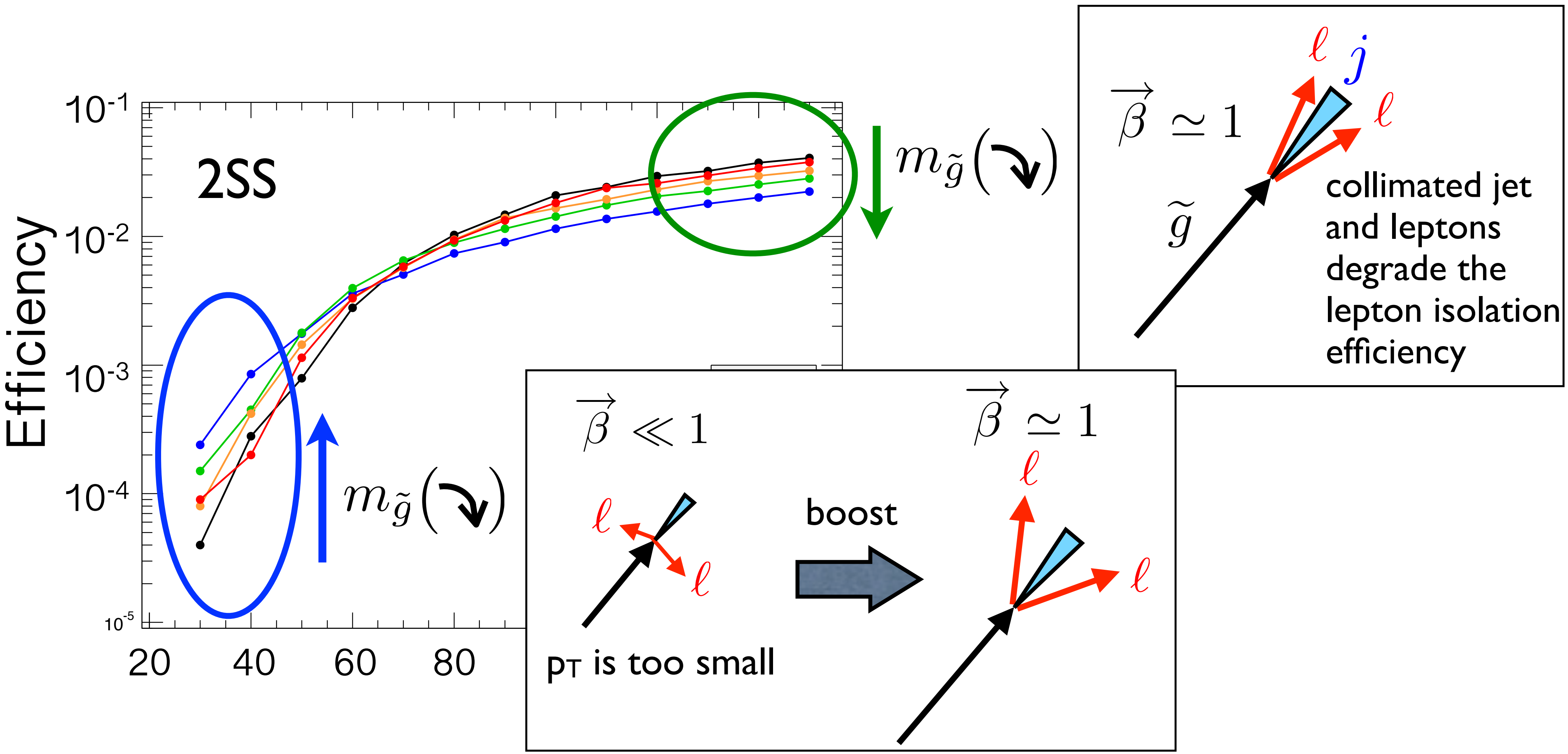
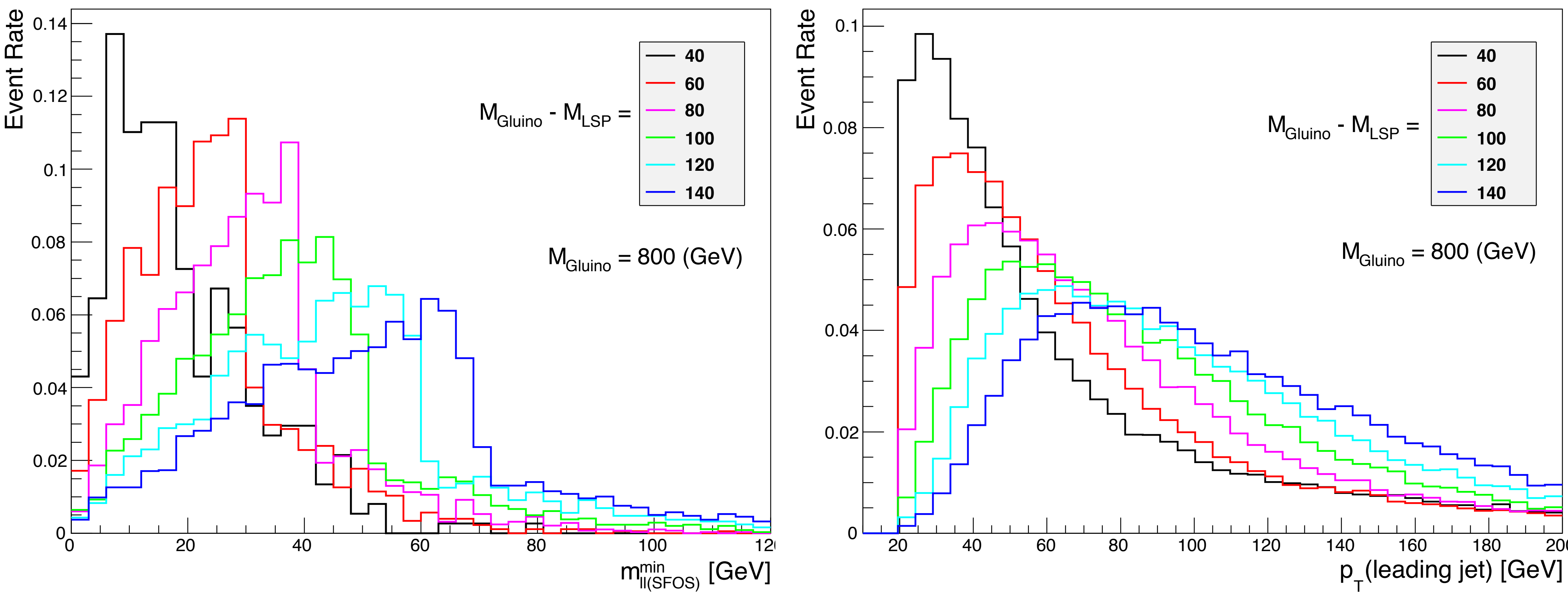
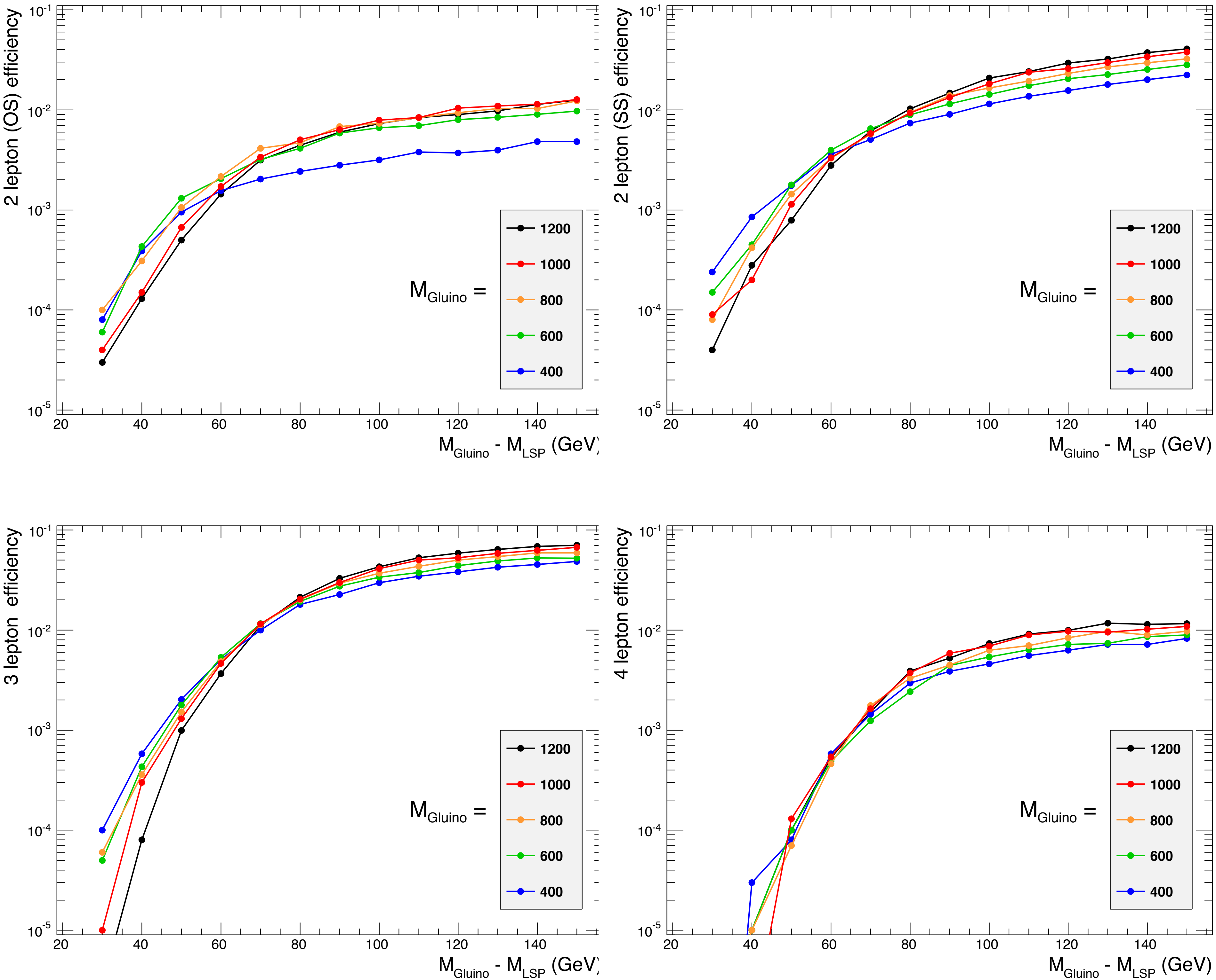






Event Rate
M_Gluino - M_LSP =
40
60
80
100
120
140
M_Gluino = 800 (GeV)
m^min_ll(SFOS) [GeV]
Event Rate
M_Gluino - M_LSP =
40
60
80
100
120
140
M_Gluino = 800 (GeV)
p_T(leading jet) [GeV]

mother particle	$\tilde{\ell}^{\pm}$	$\tilde{\chi}_2^0$	$\tilde{\chi}_1^{\pm}$		$\tilde{q}_R$	$\tilde{q}_L$		$\tilde{g}$		
decay mode	$\tilde{\chi}_1^0 \ell^{\pm}$	$\tilde{\ell}^{\pm} \ell^{\mp}$	$\tilde{\ell}^{\pm} \nu_{\ell}$	$\tilde{\nu}_{\ell} \ell^{\pm}$	$\tilde{\chi}_1^0 q$	$\tilde{\chi}_2^0 q$	$\tilde{\chi}_1^{\pm} q$	$\tilde{\chi}_1^0 qq$	$\tilde{\chi}_2^0 qq$	$\tilde{\chi}_1^{\pm} qq$
$BR(\%)$	100	100	50	50	100	33	67	50.5	16.5	33.0


2 lepton (OS) efficiency
2 lepton (SS) efficiency
3 lepton efficiency
4 lepton efficiency
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
20 40 60 80 100 120 140
$M_{Gluino} - M_{LSP}$ (GeV)
M_{Gluino} =
1200
1000
800
600
400

Let $n^{(i)}_{s/b}$ and $\sigma^{(i)}_{s/b}$ be the number of expected events and the systematic error for signal/background in the signal region i, respectively. The number of expected events can then be written as

$$\lambda^{(i)}(\delta_b, \delta_s) = n_b^{(i)}(1 + \delta_b \sigma_b^{(i)}) + n_s^{(i)}(1 + \delta_s \sigma_s^{(i)}) \,, \tag{5.1}$$

where δ_b and δ_s are nuisance parameters, which parametrise the actual size of the systematic errors. Assuming that the number of observed events follows Poisson distribution and systematic errors have Gaussian probability distribution, the probability of observing n events is given by

$$P(n, n_b^{(i)}, n_s^{(i)}) = \int_{-1/\sigma_s^{(i)}}^{\infty} d\delta_s \int_{-1/\sigma_b^{(i)}}^{\infty} d\delta_b \frac{e^{-\lambda^{(i)}}(\lambda^{(i)})^n}{n!} e^{-\frac{1}{2}(\delta_s^2 + \delta_b^2)} \,. \tag{5.2}$$

Note that the lower limits on the integration ranges are set to assure that the number of signal and background events are positive. If an experiment observes $n_o^{(i)}$ events, the p-value for the signal plus background hypothesis and that for the background only hypothesis are obtained as

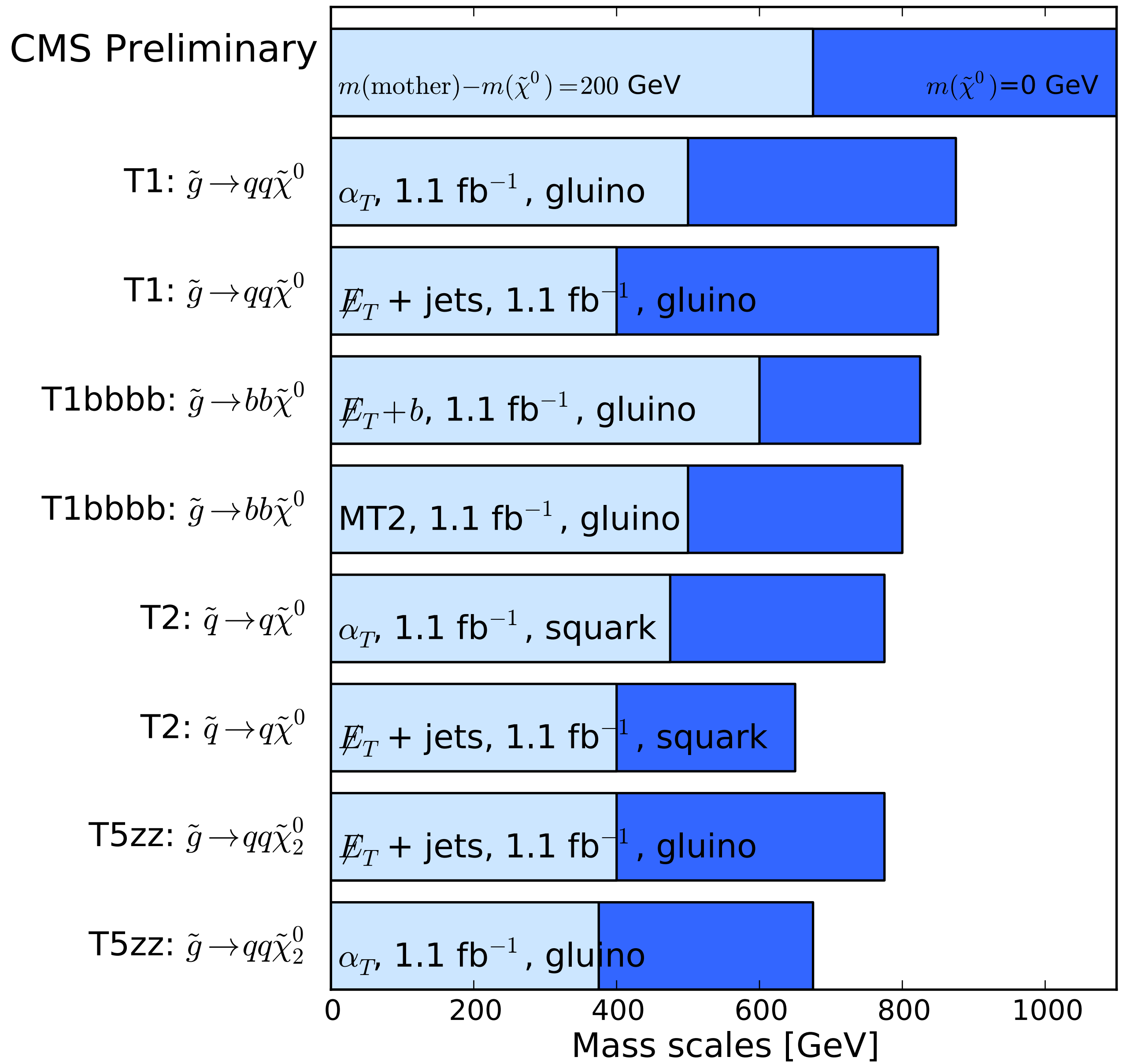
$$p_{s+b}(n_o^{(i)}) = \sum_{n=0}^{n_o^{(i)}} P(n, n_b^{(i)}, n_s^{(i)}) \qquad \text{and} \qquad p_b(n_o^{(i)}) = \sum_{n=n_o^{(i)}}^{\infty} P(n, n_b^{(i)}, 0) \,, \tag{5.3}$$

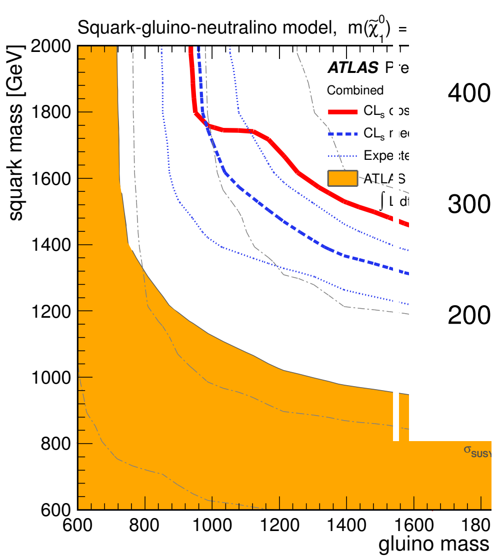
respectively. Finally, the CL_s variable is defined as

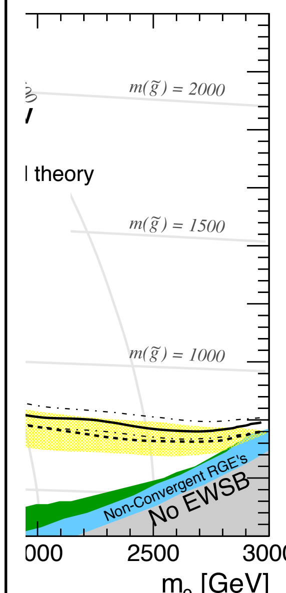
$$CL_s = \frac{p_{s+b}}{1 - p_b} \,. \tag{5.4}$$

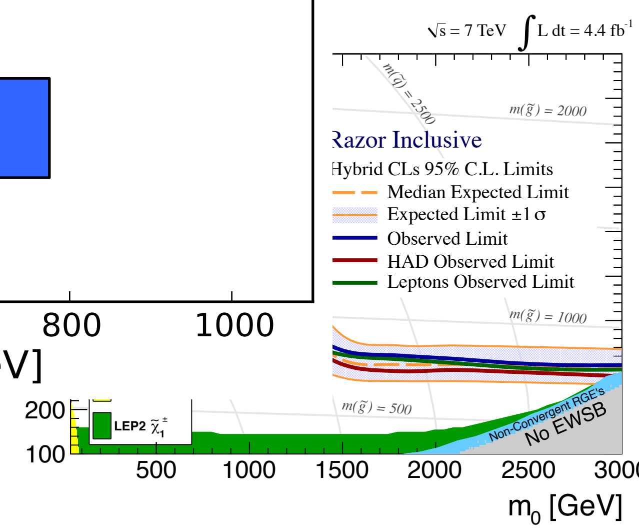
Is light SUSY possible?

- Constraint fr

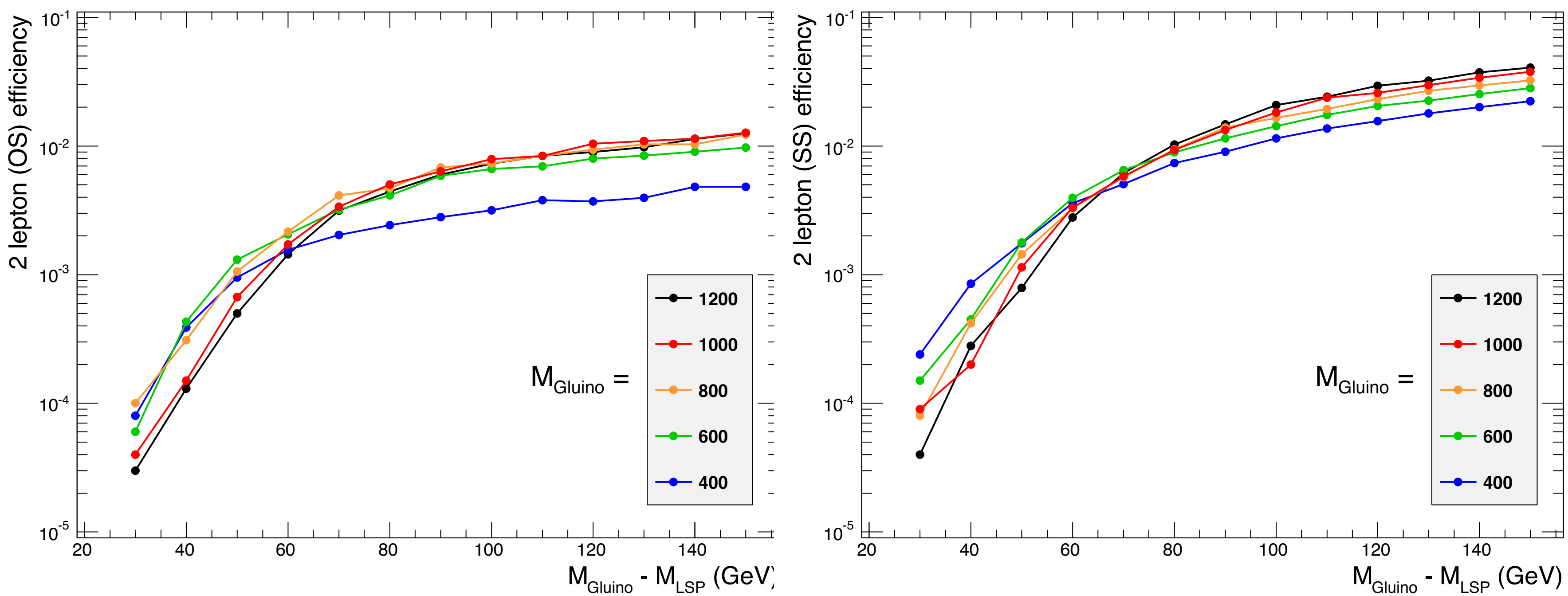








signal region	2OS	2SS	3LEP	4LEP
N(lep)	= 2 (OS)	= 2 (SS)	= 3	>= 4
leading e (μ) p_T (GeV)	> 20 (25)	> 20 (25)	> 20 (25)	> 20 (25)
E_T^{miss} (GeV)	> 250	> 100	> 50	> 50
dilpton mass (GeV)	> 12	> 12	> 20	> 20
luminosity (fb^{-1})	1.04	1.04	2.06	2.06



signal region	2OS	2SS	3LEP	4LEP
N(lep)	= 2 (OS)	= 2 (SS)	= 3	>= 4
leading e (mu) p_T (GeV)	> 20 (25)	> 20 (25)	> 20 (25)	> 20 (25)
dilpton mass (GeV)	> 12	> 12	> 20	> 20
luminosity (fb^{-1})	1.04	1.04	2.06	2.06