Search for the low-lying SUSY spectrum at the LHC consistent with the recent muon $g-2$ result

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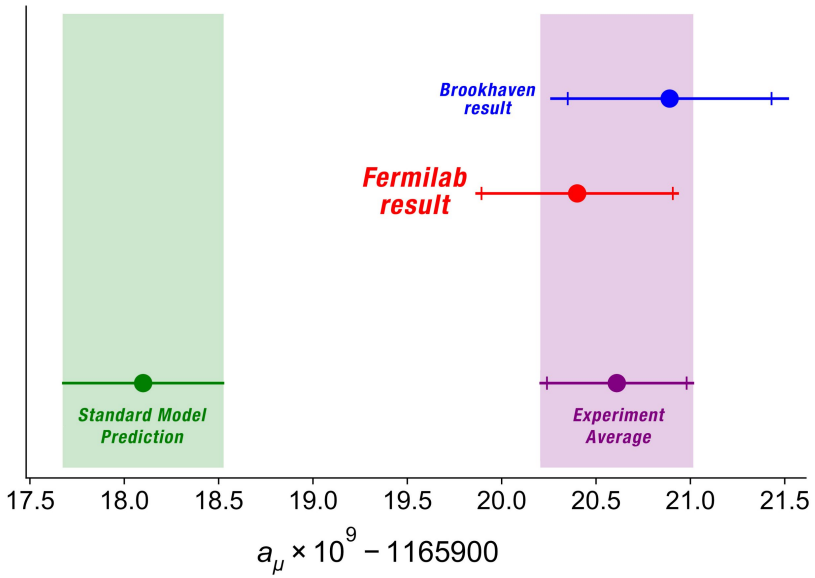
Table of Contents

Fermilab E989 experiment has measured $a_\mu = (g-2)_\mu/2$ with an unprecedented accuracy so that

$$a_\mu^{\rm exp} = 116592040(54) \times 10^{-11}$$

B. Abi *et al.* [Muon g-2], Phys. Rev. Lett. **126**, no.14, 141801 (2021)

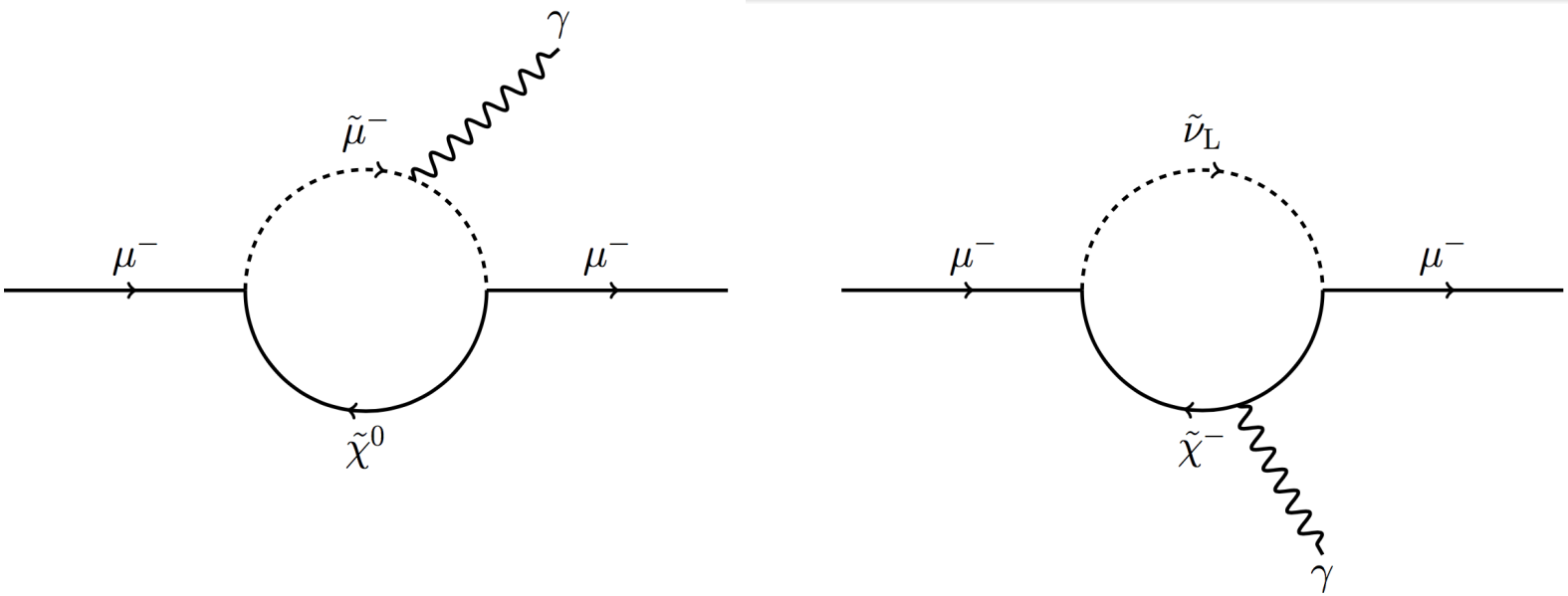


The difference between the combined Fermilab and Brookhaven (FB) result and the SM result is

$$\Delta a_\mu^{\rm FB} = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-11},$$

which is a 4.2σ deviation of experiment from the SM result

Electroweak SUSY corrections



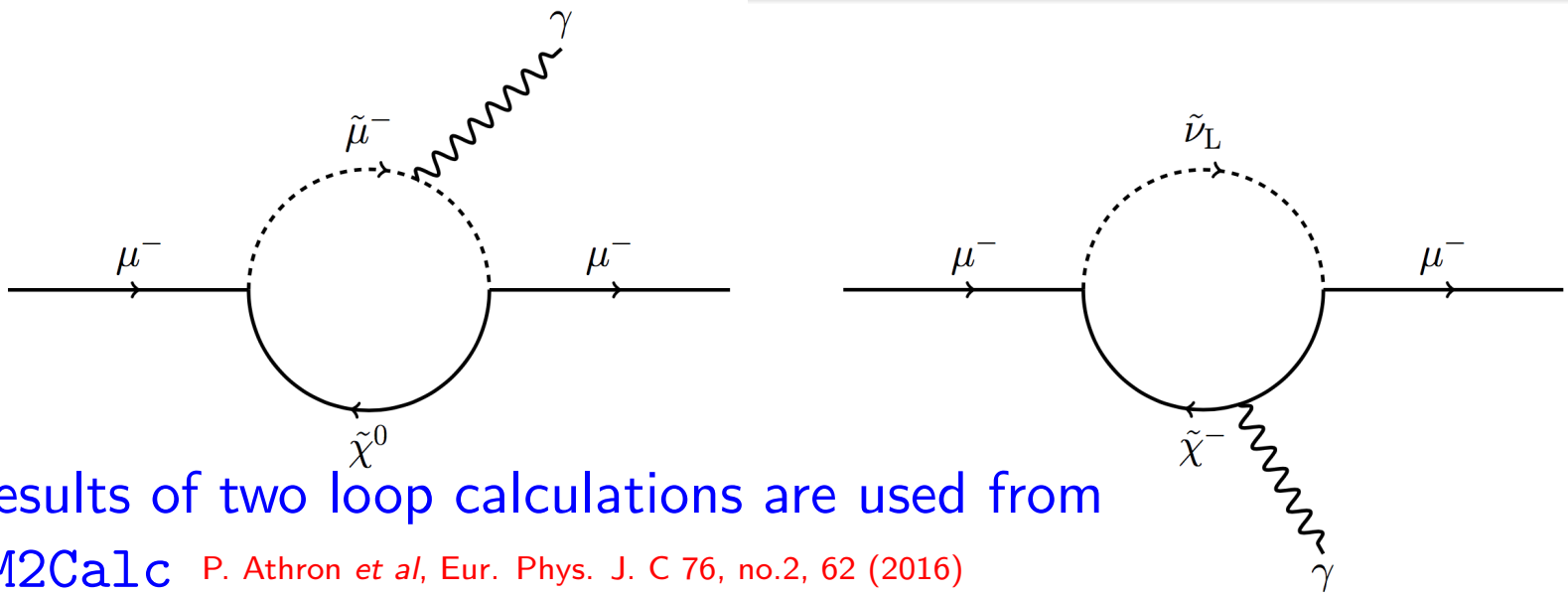
SUGRA unified models can generate SUSY loop corrections to $(g-2)_\mu$

$$a_\mu^{\chi^0} = \frac{m_\mu \alpha_{\rm EM}}{4\pi \sin^2\theta_W} \sum_{j=1}^{4}\sum_{k=1}^{2} \frac{1}{m_{\tilde{\chi}_j^0}} \left[{\rm Re}(\eta_{\mu j}^k) F_1\left(\frac{m^2_{\tilde{\mu}_k}}{m^2_{\tilde{\chi}_j^0}}\right) + \frac{m_\mu}{6 m_{\tilde{\chi}_j^0}} X_{\mu j}^k F_2\left(\frac{m^2_{\tilde{\mu}_k}}{m^2_{\tilde{\chi}_j^0}}\right)\right]$$

T. Ibrahim and P. Nath, Phys. Rev. D 62, 015004 (2000)

$$a_\mu^{\chi^+} = \frac{m_\mu \alpha_{EM}}{4\pi \sin^2\theta_W} \sum_{i=1}^{2} \frac{1}{m_{\chi_i^+}} \left[{\rm Re}(\kappa_\mu U_{i2}^* V_{i1}^*) F_3\left(\frac{m^2_{\tilde{\nu}}}{m^2_{\tilde{\chi}_i^+}}\right) + \frac{m_\mu}{6 m_{\chi_i^+}} (|\kappa_\mu U_{i2}^*|^2 + |V_{i1}|^2) F_4\left(\frac{m^2_{\tilde{\nu}}}{m^2_{\tilde{\chi}_i^+}}\right)\right]$$

Electroweak SUSY corrections



Results of two loop calculations are used from

`GM2Calc` P. Athron *et al*, Eur. Phys. J. C 76, no.2, 62 (2016)

SUGRA unified models can generate SUSY loop corrections to $(g-2)_\mu$

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SUGRA models

- SUGRA high scale model is characterized by five input parameters: m_0 , A_0 , $m_{1/2}$, $\tan\beta$, $\mathrm{sgn}(\mu)$. Gaugino sector may be relaxed so one can easily allow for coannihilation

$$m_0, \quad A_0, \quad \boxed{m_1, \quad m_2, \quad m_3}, \quad \tan\beta, \quad \mathrm{sgn}(\mu)$$

- RGE running down to the electroweak scale will generate the entire MSSM sparticle spectrum
- How are the SUGRA input parameters constrained following the recent $g-2$ result?
- Can the resulting SUSY spectrum be observable at the LHC?

Scan with an artificial neural network (ANN)

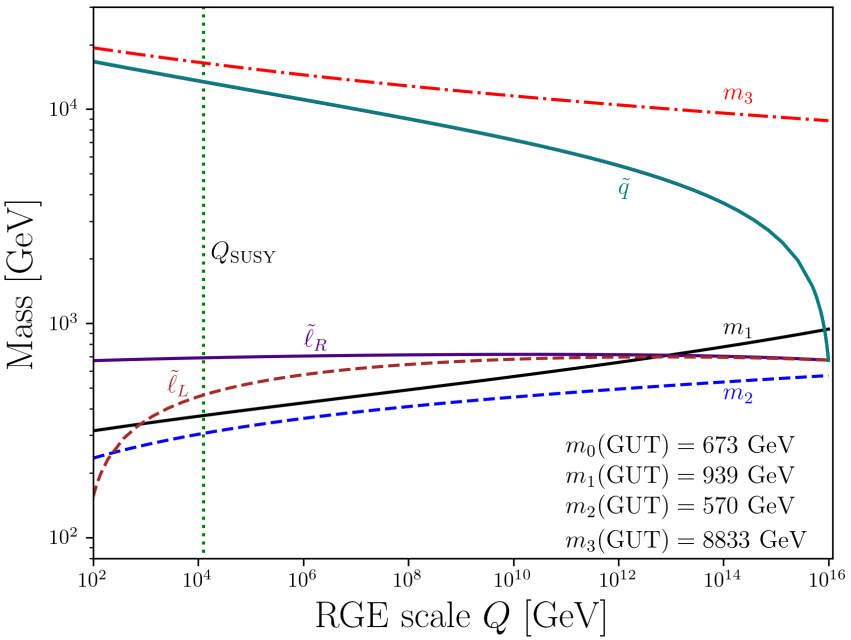
- We scan the SUGRA parameter space using an ANN
- The ANN has three layers with 25 neurons per layer. It constructs the likelihood of a point using the three constraints on the Higgs mass, DM relic density and muon $g-2$, i.e.,

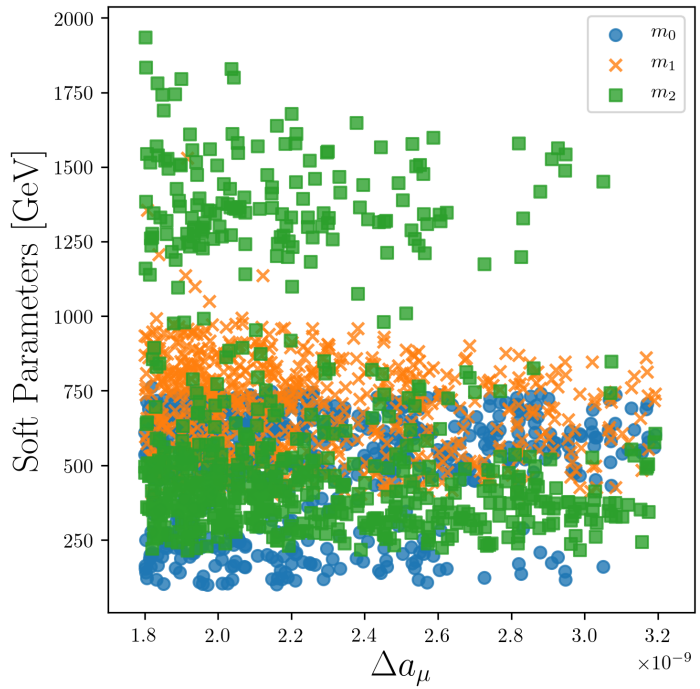
$$m_{h^0} = 125 \pm 2 \text{ GeV},$$
$$\Omega h^2 < 0.126,$$
$$\Delta a_\mu = (2.87 \pm 0.97) \times 10^{-9}.$$

- It is observed that the allowed regions of the parameter space are those where **gluino-driven radiative breaking of the electroweak symmetry** occurs

RGE running and soft parameters consistent with $(g-2)_\mu$

[AA, M. Klasen, P. Nath and R. M. Syed, [arXiv:2107.06021 [hep-ph]]].

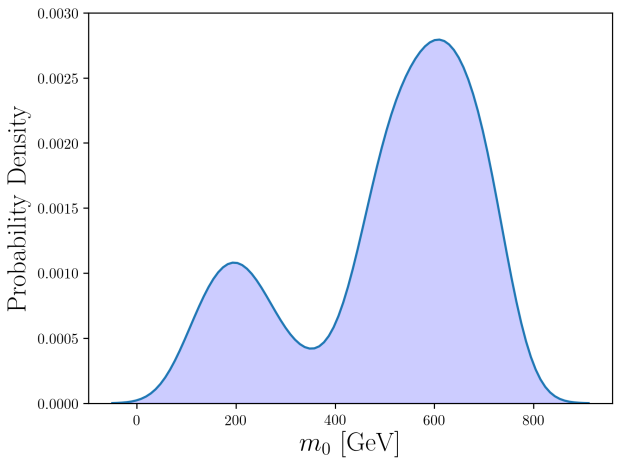


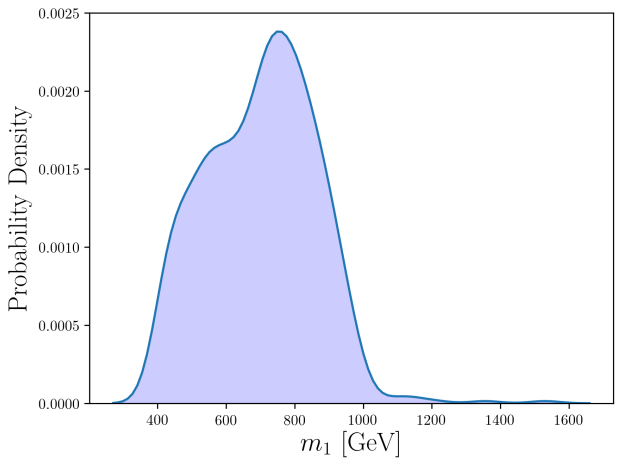


Gluino-driven EWSB: Large m_3 leading to heavy colored sector particles

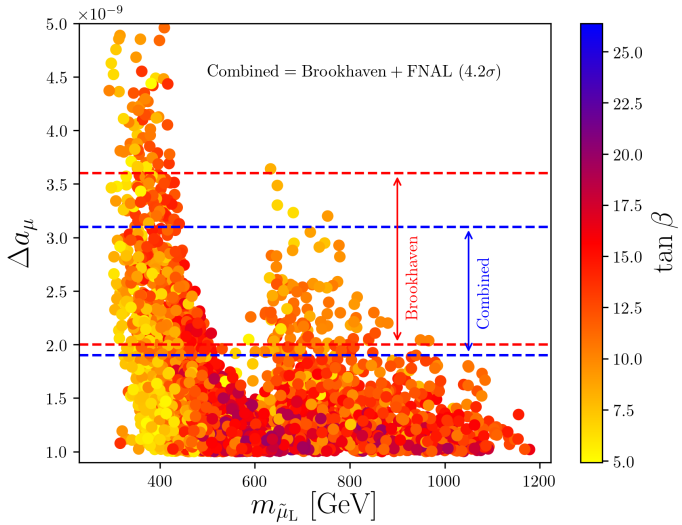
The electroweak sector remains light and within reach of the LHC

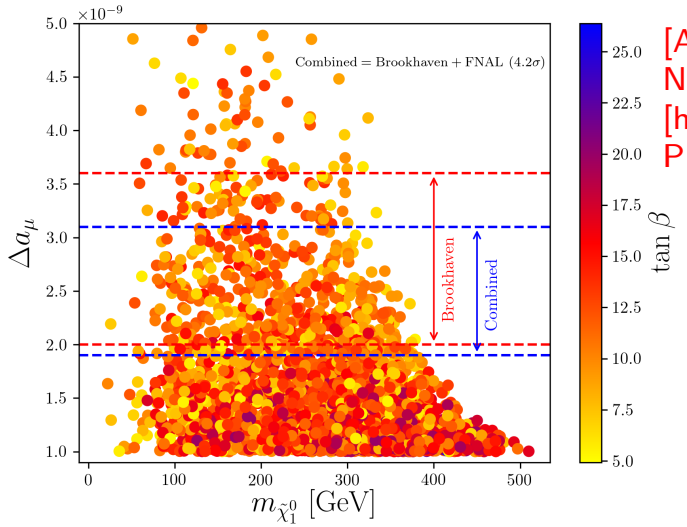
Input parameters and sparticle spectrum





Consistent with: Higgs boson mass, DM relic density, DM direct detection experiments and LHC limits on sparticles





[AA, M. Klasen and P. Nath, [arXiv:2104.03839 [hep-ph]] (to appear in PRD)].

The light sparticle spectrum falls in 3 classes of mass hierarchies:

(A): Here $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ are essentially degenerate, and $\tilde{\tau}_1$ is the NLSP. This leads to the mass hierarchy $\boxed{m_{\tilde{\tau}_1} < m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm} < m_{\tilde{\ell}}}$

(B): Here there is a reversal in the hierarchy for the first two inequalities, i.e., between $\tilde{\tau}_1$ and $\tilde{\chi}_2^0$ or $\tilde{\chi}_1^\pm$

$$m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm} < m_{\tilde{\tau}_1} < m_{\tilde{\ell}},$$
$$m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^0} < m_{\tilde{\tau}_1} < m_{\tilde{\ell}},$$
$$m_{\tilde{\chi}_1^\pm} < m_{\tilde{\tau}_1} < m_{\tilde{\chi}_2^0} < m_{\tilde{\ell}}.$$

(C): In this case the sleptons are lighter than $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ while the stau is the NLSP. Thus here we have $\boxed{m_{\tilde{\tau}_1} < m_{\tilde{\ell}} < m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm}}$

- We select the set of benchmarks

	Model	h^0	$\tilde{\ell}_L$	$\tilde{\ell}_R$	$\tilde{\nu}_L$	$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	Ωh^2	$\Delta a_\mu (\times 10^{-9})$
(A)	(a)	123.0	508.1	762.0	502.3	331.9	324.2	404.3	0.004	2.11
(B)	(b)	123.4	305.0	463.0	295	251.7	237.4	237.6	0.002	2.33
	(c)	123.7	346.8	511.9	338.0	240.3	205.6	205.8	0.001	2.67
	(d)	125.3	422.8	763.8	415.7	370.4	337.3	337.6	0.003	2.14
(C)	(e)	124.5	628.7	402.2	623.6	338.3	326.8	998.4	0.082	1.94
	(f)	123.4	722.8	262.9	718.2	206.5	195.5	1038.4	0.103	2.57
	(g)	123.9	856.4	327.4	852.4	243.5	240.1	1227	0.016	1.94

- LHC production and decay

$$\left.\begin{aligned} pp &\to \tilde{\ell}_{L/R}\tilde{\ell}_{L/R} \to \ell^+\ell^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \\ pp &\to \tilde{\nu}_L\tilde{\nu}_L \to \tilde{\chi}_1^+\tilde{\chi}_1^-\ell^+\ell^- \\ pp &\to \tilde{\nu}_L\tilde{\ell}_L \to \tilde{\chi}_1^0\tilde{\chi}_1^+\ell^+\ell^- \end{aligned}\right\} \text{SFOS leptons} + \text{MET}$$

- We use a deep neural network (DNN) to train the signal and background events using a set of kinematic variables

$$E_{\mathrm{T}}^{\mathrm{miss}},\quad p_{\mathrm{T}}(j_1),\quad p_{\mathrm{T}}(\ell_1),\quad p_{\mathrm{T}}(\ell_2),\quad p_{\mathrm{T}}^{\mathrm{ISR}},\quad M_{\mathrm{T2}},\quad M_{\mathrm{T}}^{\mathrm{min}},\quad m_{\ell\ell},$$
$$\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\ell},\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}),\quad \Delta\phi_{\mathrm{min}}(\mathbf{p}_{\mathrm{T}}(j_i),\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}),$$

where $M_{\mathrm{T}}^{\mathrm{min}} = \mathrm{min}[m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell_1},\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell_2},\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})]$

- The DNN employed has three dense hidden layers with 128 neurons per layer and tanh as an activation function to define the output neurons given the input values [TMVA: P. Speckmayer, A. Hocker, J. Stelzer and H. Voss, J. Phys. Conf. Ser. 219, 032057 (2010)]
- We consider two signal regions: SR-2ℓ1j (one non-b-tagged jet) and SR-2ℓ2j (at least two non-b-tagged jets)

Kinematic cuts

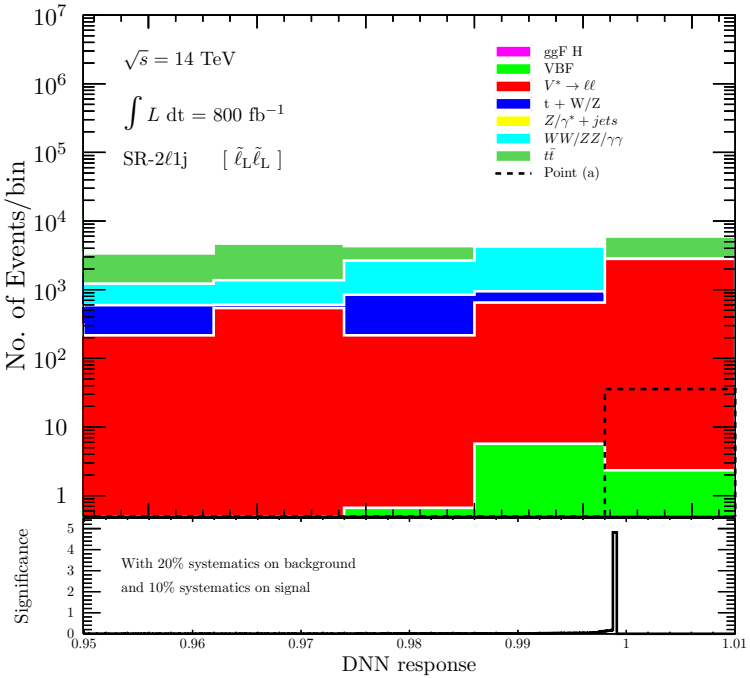
Cuts are customized for HL-LHC and HE-LHC

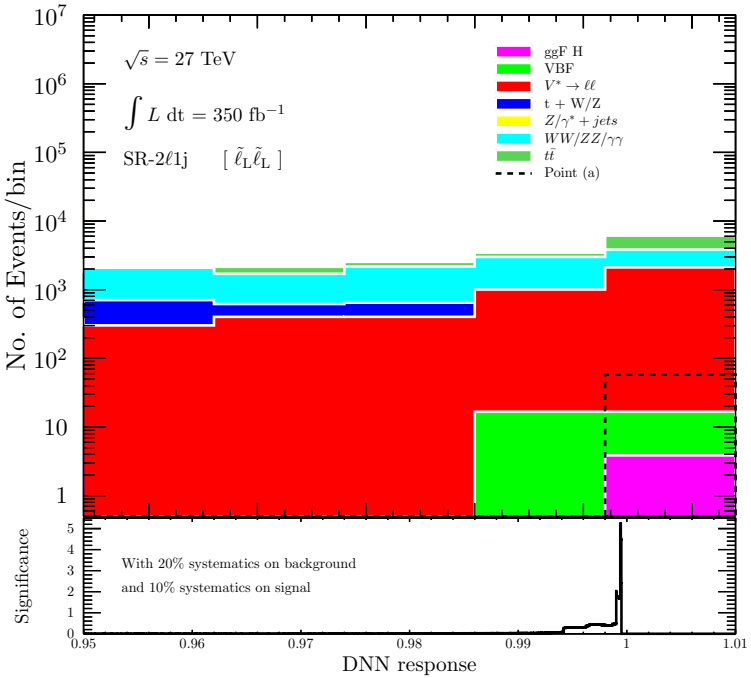
Observable	(b), (c), (d)	(a)	(e), (f), (g)	(b), (c), (d)	(a)	(e), (f), (g)
	Preselection criteria (SR-2ℓ2j)			Preselection criteria (SR-2ℓ1j)		
N_ℓ (SFOS)	2			2		
$N_{\text{jets}}^{\text{non-b-tagged}}$	≥ 2			1		
$p_T(j_1)$ [GeV]	> 20			> 20		
$p_T(\ell_1)$ (electron, muon) [GeV]	$> 15, > 10$			$> 15, > 10$		
E_T^{miss} [GeV]	> 100			> 100		
	Analysis cuts			Analysis cuts		
$m_{\ell\ell}$ [GeV] $>$	136 (110)	150	150 (110)	110	120	150
$E_T^{\text{miss}}/\mathbf{p}_{\text{T}}^{\ell} >$	1.9 (2.8)	-	-	1.0	-	-
$\Delta\phi_{\min}(\mathbf{p}_{\text{T}}(j_i), \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad] $>$	-	0.85 (1.5)	-	-	0.85 (1.5)	-
$p_T(\ell_2)$ [GeV] $>$	-	-	190 (370)	-	-	190 (300)
M_{T2} [GeV] $>$	- (140)	- (120)	200 (300)	130 (230)	100	200 (300)
DNN response $>$	0.95	0.95	0.95	0.95	0.95	0.95

Signal and background distributions 1/2

Distributions of S and B for the di-slepton channel and signal region SR-2ℓ1j at 14 TeV and 27 TeV

[20% systematics included in the background and 10% in the signal]

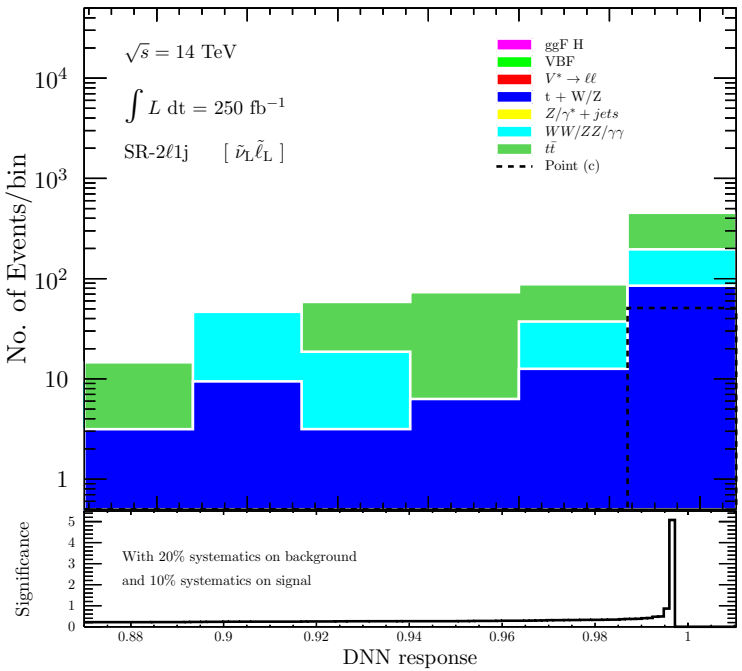


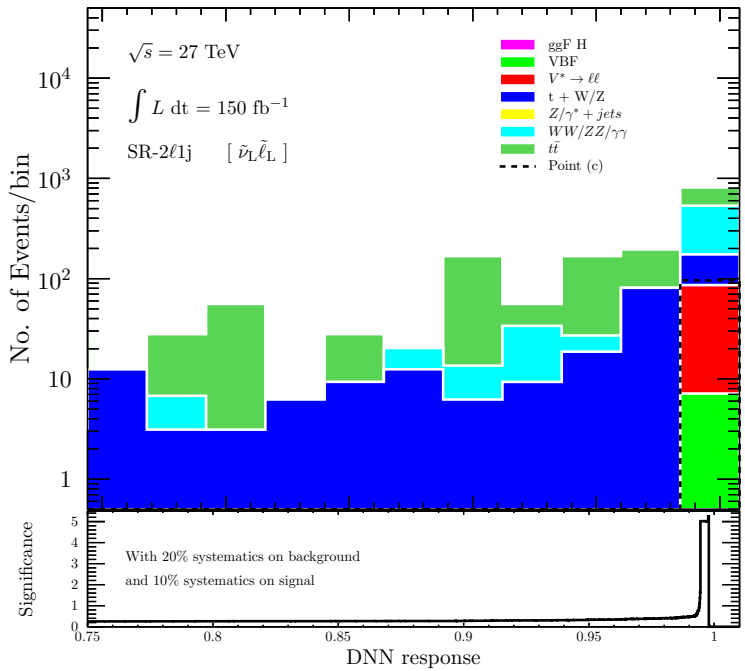


Signal and background distributions 2/2

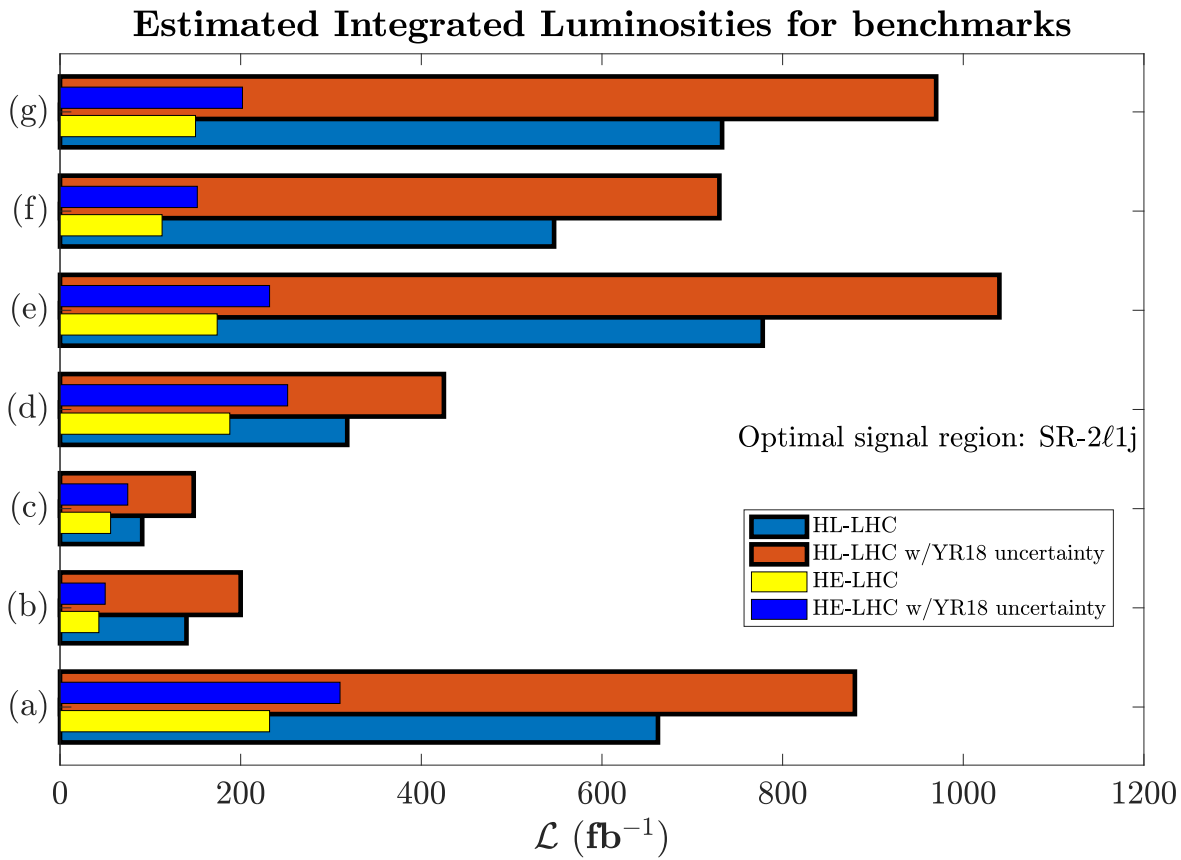
Distributions of S and B for the sneutrino-slepton channel and signal region SR-2ℓ1j at 14 TeV and 27 TeV

[20% systematics included in the background and 10% in the signal]





Integrated luminosities for the combined channels



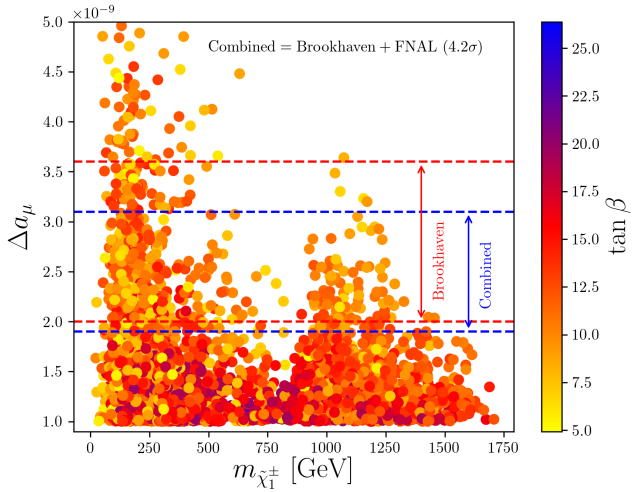
Benchmarks (b) and (c) require 200 fb^{-1} and 148 fb^{-1} at 14 TeV. The rest require more than 400 fb^{-1} but are all within the reach of HL-LHC. Much smaller integrated luminosities are required for HE-LHC

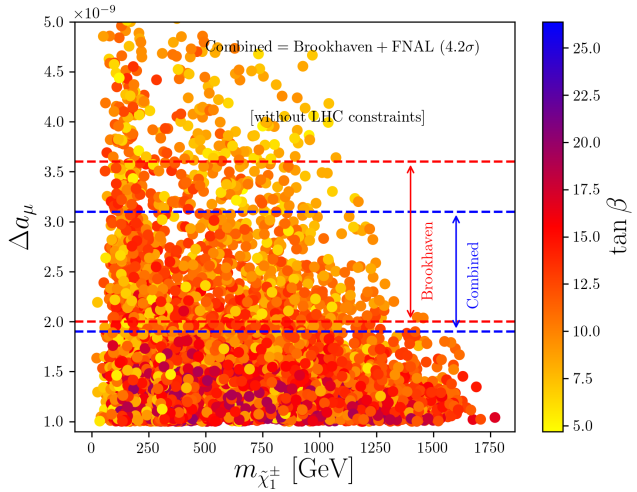
Conclusions

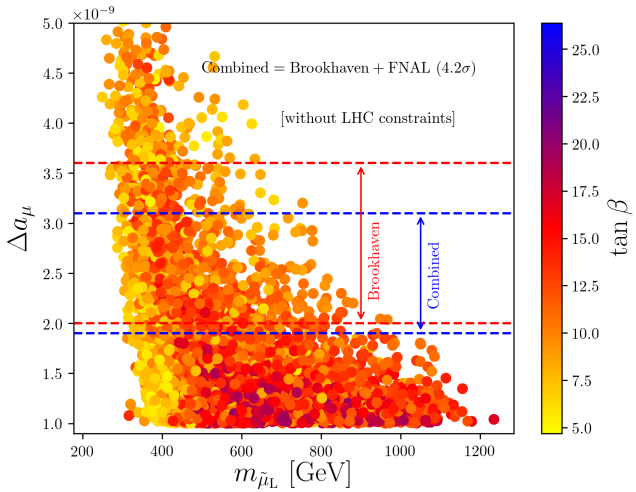
- A scan of the SUGRA parameter space using ML while imposing the recent $(g-2)_\mu$ result naturally leads to the case of gluino-driven EWSB
- The colored sparticles are heavy while the electroweak sector is low-lying and within reach of the LHC
- The mean light sparticle masses are: $m_{\tilde{\chi}_1^0} \sim 235$ GeV, $m_{\tilde{\chi}_1^\pm} \sim 445$ GeV, $m_{\tilde{\ell}_\mathrm{L}} \sim 480$ GeV, $m_{\tilde{\ell}_\mathrm{R}} \sim 590$ GeV, $m_{\tilde{\nu}_\mathrm{L}} \sim 470$ GeV and $m_{\tilde{\tau}_1} \sim 300$ GeV
- We studied slepton and sneutrino pair production as well as slepton-sneutrino associated production
- Some benchmarks can be discovered in the next run of HL-LHC while lower integrated luminosities are required at HE-LHC

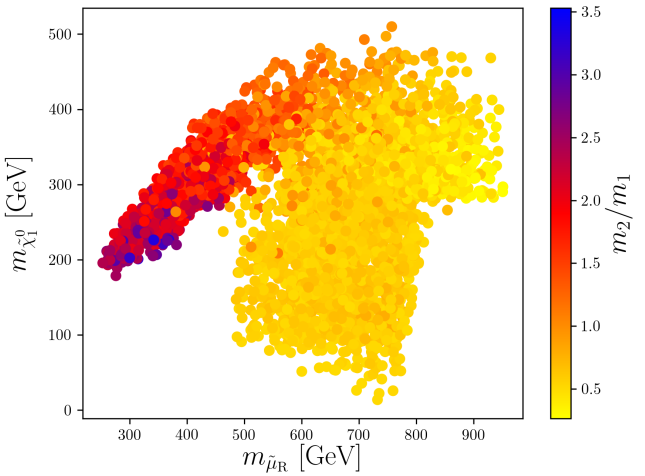
BACKUP SLIDES

Results of the scan with ANN









The left and right smuon masses at one loop so that

$$m^2_{\tilde{\mu}_{\rm L}} = m_0^2 + m_\mu^2 + C_1 m_1^2 + C_2 m_2^2 + \left(-\frac{1}{2} + \sin^2\theta_W\right) M_Z^2 \cos(2\beta)$$

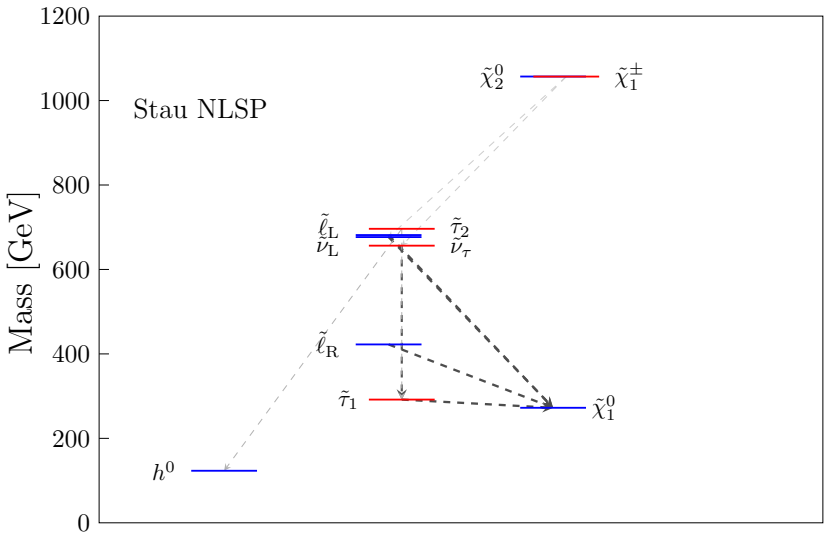
$$m^2_{\tilde{\mu}_{\rm R}} = m_0^2 + m_\mu^2 + 4 C_1 m_1^2 - \sin^2\theta_W M_Z^2 \cos(2\beta)$$

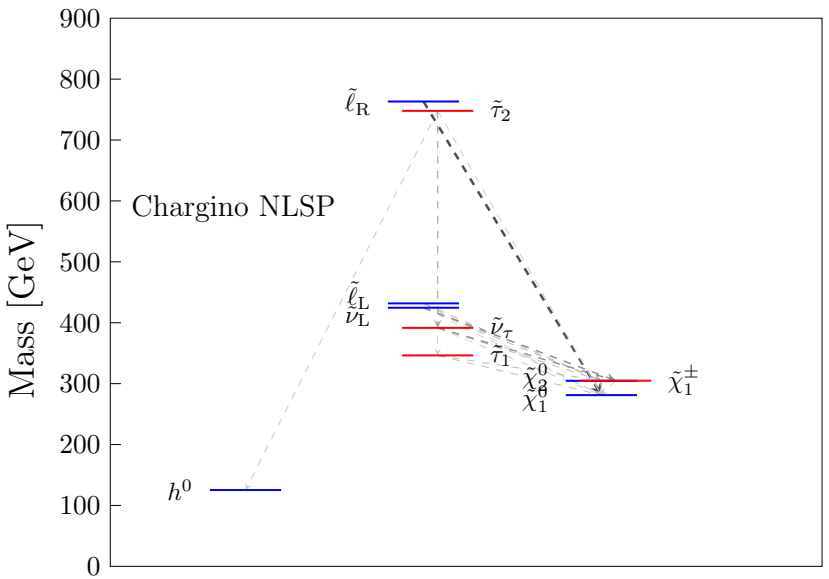
Here $C_1 = \frac{3}{10}\tilde{\alpha}_G f_1$, $C_2 = \frac{3}{2}\tilde{\alpha}_G f_2$, where $\tilde{\alpha}_G = \alpha_G/(4\pi)$, $f_k(t) = t(2 + b_k\tilde{\alpha}_G t)/(1 + b_k\tilde{\alpha}_G t)^2$, $t = \ln(M_G^2/Q^2)$ and $(b_1, b_2) = (33/5, 1)$. Thus

$$\boxed{m^2_{\tilde{\mu}_{\rm R}} - m^2_{\tilde{\mu}_{\rm L}} = 3m_1^2 C_1 - m_2^2 C_2 + \left(\frac{1}{2} - 2\sin^2\theta_W\right) M_Z^2 \cos(2\beta)}$$

Using $\alpha_1 \sim 0.016, \alpha_2 = 0.033, \alpha_G \sim 0.04$ and $M_G \sim 1.2 \times 10^{16}$ GeV gives $C_1 \approx 0.16$ and $C_2 \approx 0.23$. Thus one finds that typically the right smuon has a larger mass than the left smuon unless $m_2 \gtrsim 1.24 m_1$ (with the assumed input)

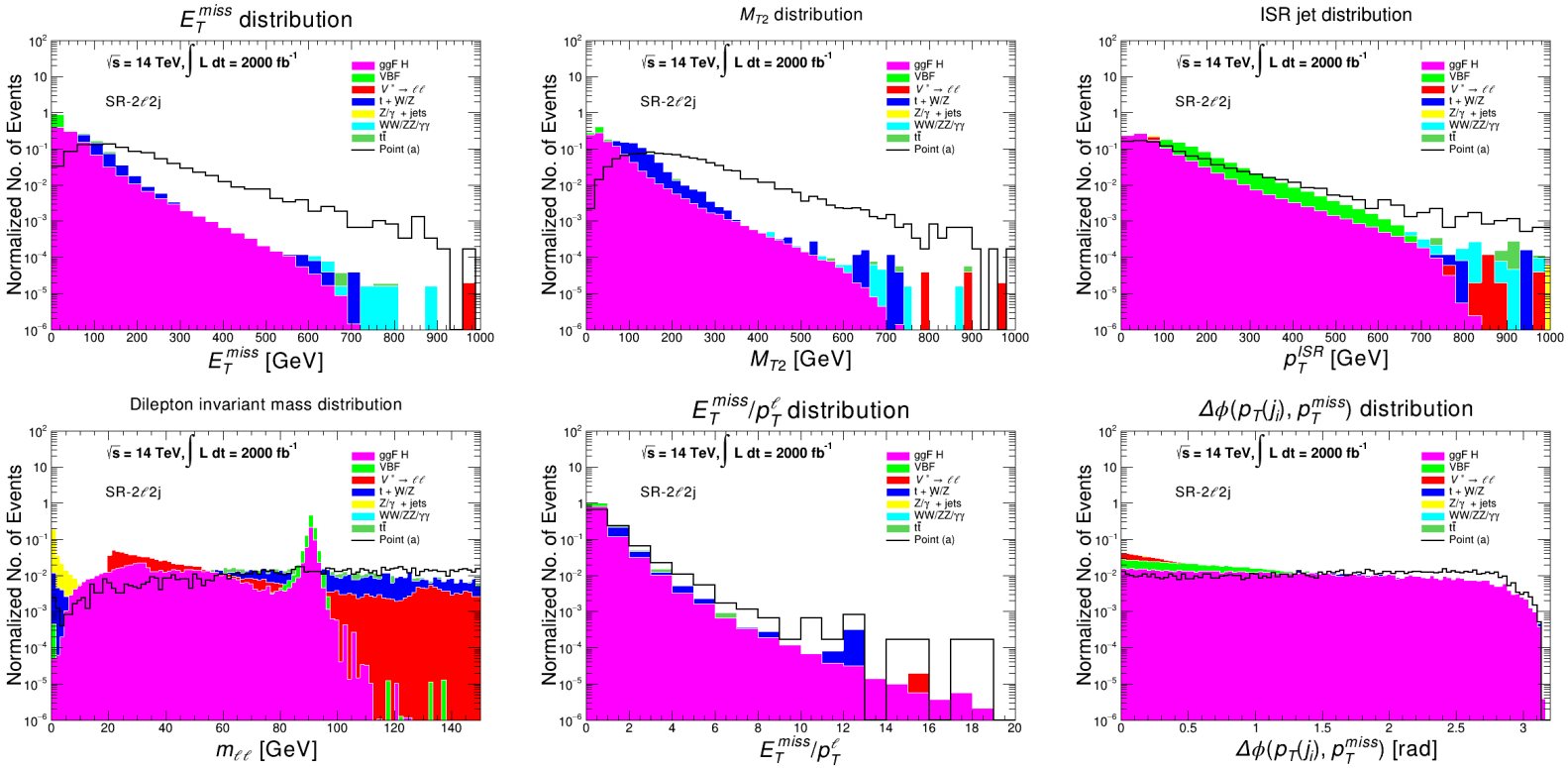
Sparticle spectrum and branching ratios





Model	$\tilde{\ell}_L \to \ell\tilde{\chi}_1^0$	$\tilde{\ell}_L \to \ell\tilde{\chi}_2^0$	$\tilde{\ell}_L \to \nu_\ell\tilde{\chi}_1^\pm$	$\tilde{\ell}_R \to \ell\tilde{\chi}_1^0[\tilde{\chi}_2^0]$	$\tilde{\nu}_L \to \tilde{\chi}_1^+\ell^-$	$\tilde{\nu}_L \to \tilde{\chi}_1^0\nu_\ell$
(a)	22%	26%	52%	100% [-]	51%	24%
(b)	31%	7%	62%	- [100%]	62%	30%
(c)	31%	6%	63%	- [100%]	62%	31%
(d)	31%	6%	63%	- [100%]	63%	32%
(e)	100%	-	-	100% [-]	-	100%
(f)	100%	-	-	100% [-]	-	100%
(g)	100%	-	-	100% [-]	-	100%

Kinematic variables used for training DNN



We use the signal significance $Z = \dfrac{S}{\sqrt{S + B + (\delta_S S)^2 + (\delta_B B)^2}}$

to determine the required integrated luminosity for discovery

- We determine the angle between the dilepton system and each non-b-tagged jet in the event, i.e., $\Delta\phi(p_T(j_i), p_T^{\ell})$
- If an event has exactly two jets with $p_T(j_1)$ and $p_T(j_2)$, respectively, then
  1. if $\Delta\phi(p_T(j_1), p_T^{\ell}) < \Delta\phi(p_T(j_2), p_T^{\ell})$, both are tagged as non-ISR jets
  2. if $\Delta\phi(p_T(j_1), p_T^{\ell}) > \Delta\phi(p_T(j_2), p_T^{\ell})$, then the subleading jet is tagged as non-ISR and the leading one will be an ISR jet
- If an event has more than two jets, then we select *up to two* jets that are closest to the dilepton system and tag them as non-ISR (possible jets arising from the decay of the SUSY system) and the rest are classified as ISR jets

  The largest number of events correspond to the case of one ISR and one non-ISR jet per event. Moreover, one can get as many as six ISR jets in an event but with a low event count while a larger number of events have no ISR jets.

LHC production cross sections

Table: The aNNLO+NNLL production cross-sections of slepton pair ($\tilde{\ell} = \tilde{e}, \tilde{\mu}$) and sneutrino pair as well as slepton associated production with a sneutrino at $\sqrt{s} = 14$ TeV and $\sqrt{s} = 27$ TeV for our benchmarks. The cross section is in fb.

Model	$\sigma(pp \to \tilde{\ell}_L \tilde{\ell}_L)$		$\sigma(pp \to \tilde{\ell}_R \tilde{\ell}_R)$		$\sigma(pp \to \tilde{\nu}_L \tilde{\ell}_L)$		$\sigma(pp \to \tilde{\nu}_L \tilde{\nu}_L)$	
	14 TeV	27 TeV	14 TeV	27 TeV	14 TeV	27 TeV	14 TeV	27 TeV
(a)	1.084	4.515	0.057	0.335				
(b)	9.810	30.80	0.656	2.54	41.78	127.80	10.52	33.10
(c)	5.805	19.31	0.417	1.72	24.40	78.97	4.94	15.10
(d)	2.486	9.188	0.056	0.332	10.44	37.47	2.10	7.21
(e)	0.388	1.915	1.22	4.32				
(f)	0.188	1.065	6.91	20.15				
(g)	0.074	0.506	2.87	9.22				

Estimated integrated luminosity for discovery

Table: The estimated integrated luminosities, in fb^{-1}, for discovery of our benchmarks at 14 TeV and 27 TeV after combining all production channels and including systematics in the signal and background.

Model	SR-2ℓ1j		SR-2ℓ2j	
	$\mathcal{L}$ at 14 TeV	$\mathcal{L}$ at 27 TeV	$\mathcal{L}$ at 14 TeV	$\mathcal{L}$ at 27 TeV
(a)	880	310	1262	694
(b)	200	50	1860	715
(c)	148	75	1887	1320
(d)	425	252	$\cdots$	2804
(e)	1040	232	1738	1194
(f)	730	152	2074	689
(g)	970	202	$\cdots$	1031

The 27 TeV collider: HE-LHC

- The High Energy LHC (HE-LHC) is a possible candidate as the next generation pp collider at CERN
- Uses the existing LHC ring with 16 T FCC magnets replacing the current 8.3 T ones
- Center-of-mass energy boosted to 27 TeV with a design luminosity ~ 5 times that of the HL-LHC
- This set up necessarily means that a larger part of the parameter space of supersymmetric models beyond the reach of the 14 TeV collider will be probed