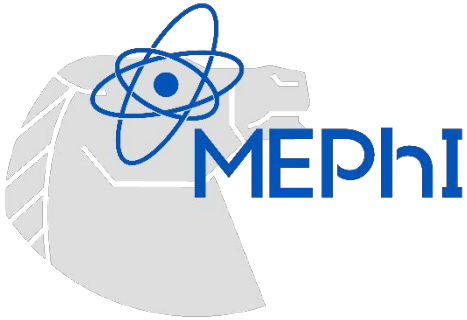


Pair gravitino production at the LHC

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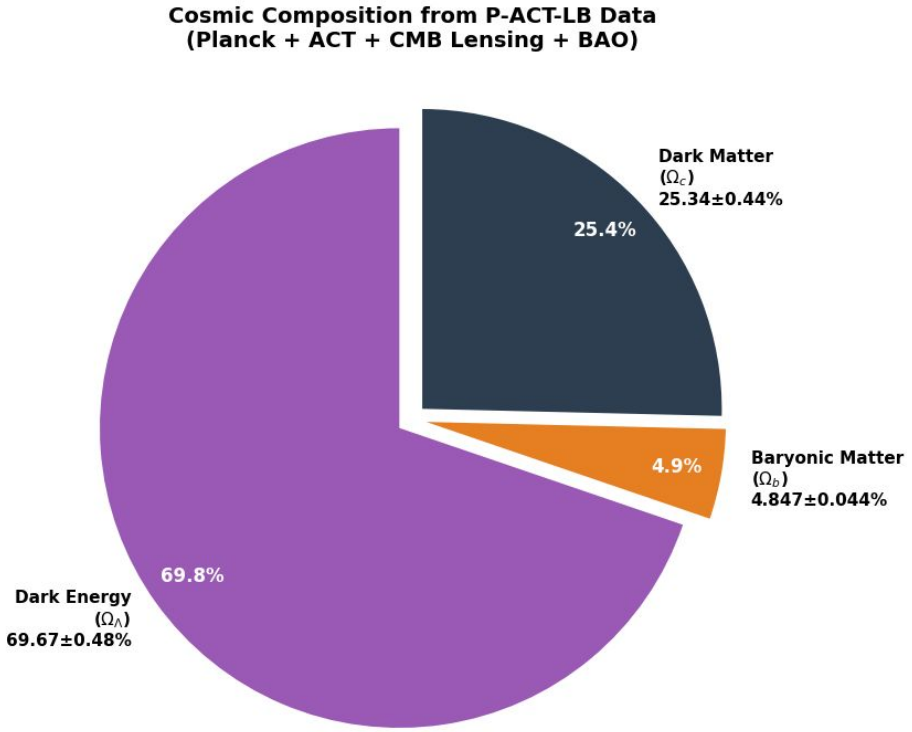
M. Savina savina@cern.ch

Warm dark matter

The most popular cosmology model - Lambda CDM: include dark energy, cold dark matter (CDM) and baryon matter.

Warm dark matter (WDM) - decouples (goes out of thermodynamic equilibrium) while still relativistic, but by the time of the transition from the RD (radiation-dominated) to the MD (matter-dominated) stage, it has become non-relativistic.

Unlike CDM, WDM particles still possess significant velocities at the stage of structure formation, so the classical ideal fluid approximation is not applicable. Non-ideal effects lead to important phenomena such as the suppression of perturbations on small scales.



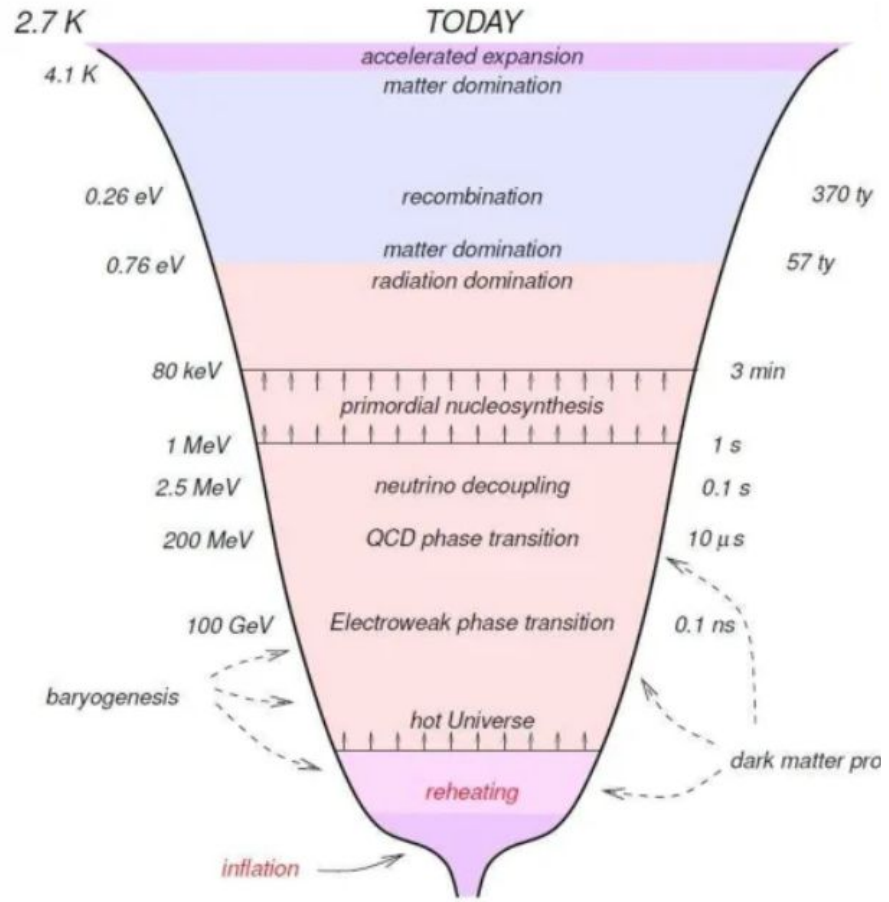
P.1. Composition of the Universe in the ΛCDM model from the combined analysis of DESI and Planck data.[1]

Warm dark matter

Why warm dark matter?

- missing satellite problem [2]
- casp-core problem[3-4]
- too big to fail problem[5-7]

Joint analysis of strong gravitational lensing and Milky Way satellites sets a 95% lower limit on WDM particle mass 9.7 keV* . [8-9]
In the model under consideration, the gravitino (LSP) serves as a warm dark matter candidate with a mass of 10 keV.



P.2. Timeline of the evolution of the Universe: temperature and energy as a function of time.

1. [9]. Nadler, E. O., Birrer, S., Gilman, D., (2021). Dark matter constraints from a unified analysis of strong gravitational lenses and Milky Way satellite galaxies. The Astrophysical Journal, *917*(1), 7.

Minimal Supersymmetric Standart Model (MSSM)

Superfield	Bosons		Fermions		$SU(3)$	$SU(2)$	$U_Y(1)$
Vector							
G^a	gluon	g^a	gluino	$\tilde{g}^a$	8	0	0
V^k	weak	$W^k\ (W^{\pm}, Z)$	wino, zino	$\tilde{w}^k\ (\tilde{w}^{\pm}, \tilde{z})$	1	3	0
V'	hypercharge	$B\ (\gamma)$	bino	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter							
L_i	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
E_i		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
Q_i	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	1/3
U_i		$\tilde{U}_i = \tilde{u}_R$		$U_i = u_R^c$	3^*	1	$-4/3$
D_i		$\tilde{D}_i = \tilde{d}_R$		$D_i = d_R^c$	3^*	1	2/3
Higgs							
H_1	Higgs	$\tilde{H}_1$	Higgsino	$\tilde{H}_1$	1	2	-1
H_2		$\tilde{H}_2$		$\tilde{H}_2$	1	2	1

graviton G, $s = 2$, $m = 0 \rightarrow$ gravitino $\tilde{G}$, $s = 3/2$, $m_{3/2} = \dfrac{F_0}{\sqrt{3}M_{Pl}}$

Neutralino — superposition of higgsinos, bino and zino.
Changino — superposition of wino and charged higgsino

Symmetry between fermions and bosons:

- Generalization of the Poincaré algebra by adding new generators Q^I_α, $\bar{Q}^I{}_{\dot{\alpha}}$ d their comutation equations; group element seems like: $G(x^\mu, \theta, \bar{\theta}) = e^{i(-x^\mu P_\mu + \theta Q + \bar{\theta}\bar{Q})}$
- SUSY generators (supercharges): transform boson ↔ fermion;

$$[P_m, Q^I_\alpha] = 0, \quad [P_m, \bar{Q}^I_{\dot{\alpha}}] = 0,$$
$$[J_{mn}, Q^I_\alpha] = -i(\sigma_{mn})_\alpha{}^\beta Q^I_\beta, \quad [J_{mn}, \bar{Q}^I_{\dot{\alpha}}] = i(\tilde{\sigma}_{mn})_{\dot{\alpha}}{}^{\dot{\beta}} \bar{Q}^I_{\dot{\beta}},$$
$$\{Q^I_\alpha, Q^J_\beta\} = \epsilon_{\alpha\beta} Z^{IJ}, \quad \{\bar{Q}^I_{\dot{\alpha}}, \bar{Q}^J_{\dot{\beta}}\} = \epsilon_{\dot{\alpha}\dot{\beta}} \bar{Z}^{IJ},$$
$$\{Q^I_\alpha, \bar{Q}^J_{\dot{\alpha}}\} = 2(\sigma^m)_{\alpha\dot{\alpha}} P_m \delta^{IJ},$$

Gravitino — gauge field, appears as a result of local sypersymmetry(SUGRA) breaking and gets mass by “eating” goldstino.

GMSB

Supersymmetry has to be broken, and since in the MSSM there are no fields that have non-zero vacuum expectation values, the following sectors are introduced:

1. Hidden sector (SUSY breaking occurs in this sector)
2. Visible (Matter) sector
3. Messengers (transmit SUSY breaking from the hidden sector to the visible sector)

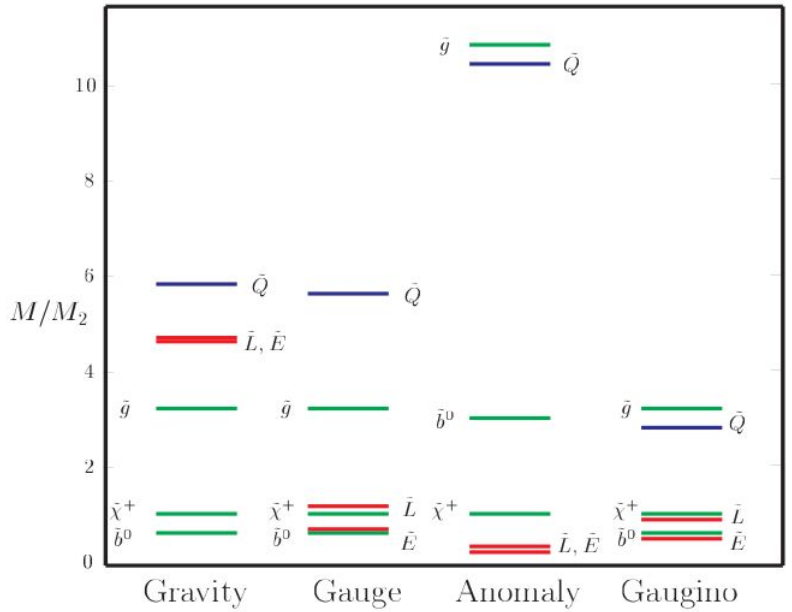
Transmition of spontaneous SUSY breaking from hidden to visible sector:

- Gravity mediated
- Gauge mediated
- Anomaly mediated
- Gaugino mediated

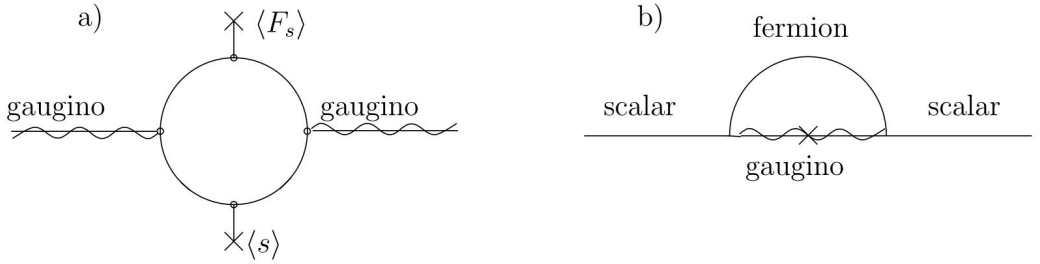
Gauge mediated supersymmetry breaking (GMSB):
In hidden sector — only superfield X:

$$< X >=< x > +F\theta^2$$

$\mathcal{L}_{Yukava} \propto XS\bar{S}$, where $S, \bar{S}$ - messengers fields.



P.3. Typical mass spectra for different SUSY breaking mechanisms[10]

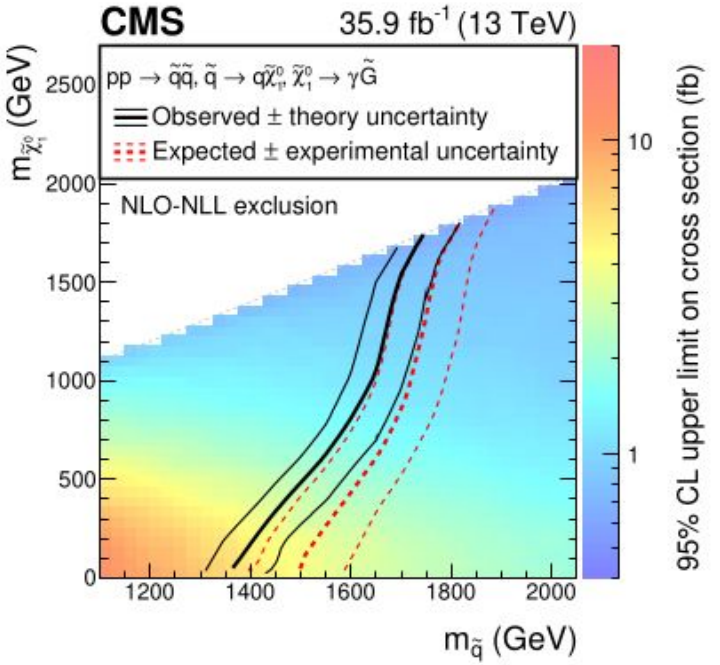


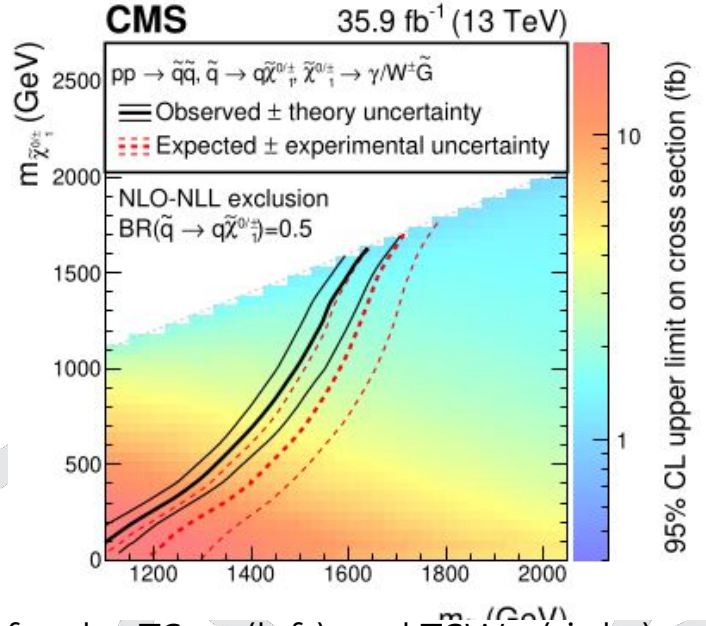
P.4. a) Gauginos get masses via diagrams with loops of messenger fields. b) A typical diagram contributing to soft masses of MSSM scalars; [11]

CMS results for prompt production signature of pair gravitino production (1 eV)

Key results of searching for gauge-mediated SUSY with photons and missing transverse momentum in 35.9 fb^{-1} of 13 TeV CMS [12] data is presented for bino-wino-like neutralino decays to photons and gravitinos, optimized for both electroweak and strong production scenarios:

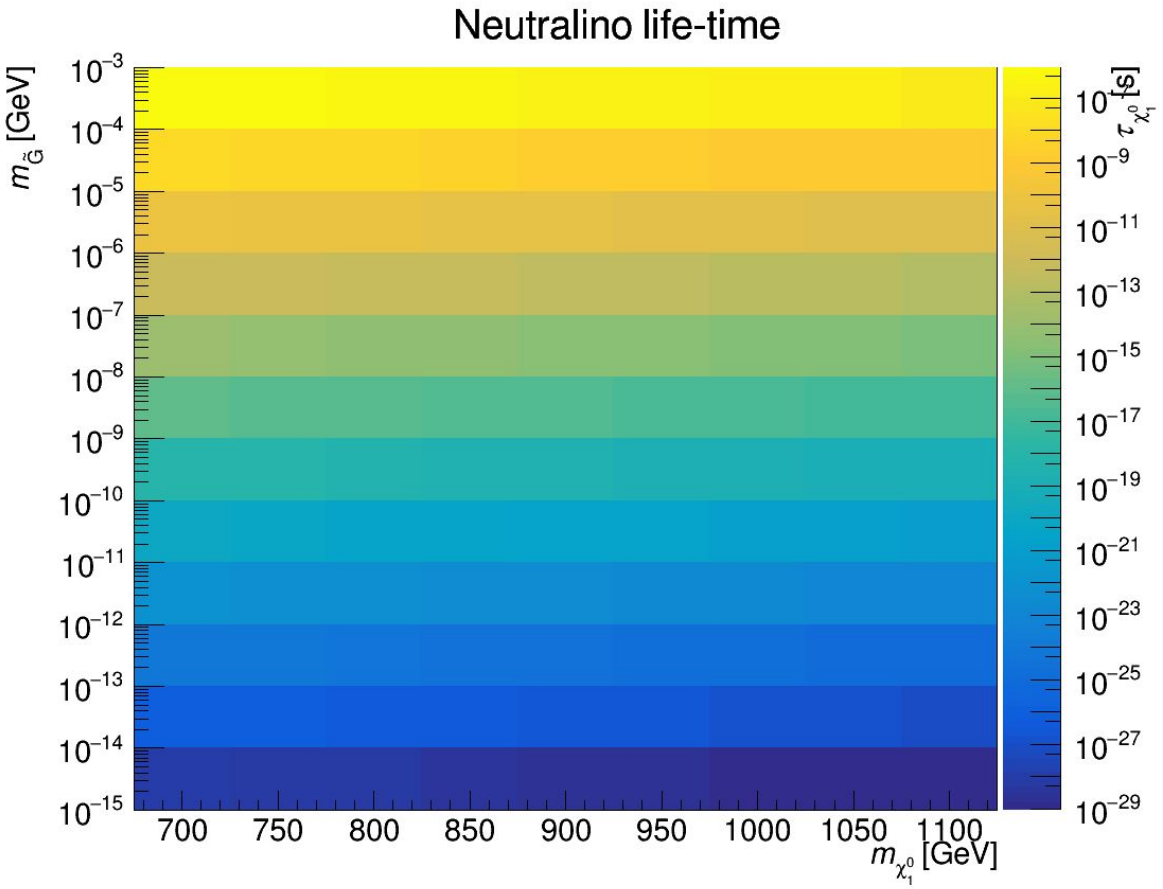
1. No deviation from SM – Data agree with standard model expectations; no evidence of new physics.
2. EWK gaugino production (general gauge mediation): for similar wino and bino masses → masses below 980 GeV are excluded at 95% CL, improving the previous limit by 270 GeV.
3. EWK simplified models:
   - TChiWg scenario → NLSP mass < 780 GeV excluded
   - TChiNg scenario → NLSP mass < 950 GeV excluded
   - Strong production (gluinos, squarks):
   - Gluinos (T5gg, T5Wg): excluded up to 2100 GeV
   - Squarks (T6gg, T6Wg): excluded up to 1750 GeV





P.5. The 95% CL limits for the T6gg (left) and T6Wg (right) SMS models in the squark neutralino/chargino mass plane

Modeling pair production cross-section with MadGraph5



P.6. Neutralino life-time scan from gravitino and neutralino mass

For models with a gravitino mass greater than 0.1 keV, the neutralino (NLSP) decay length exceeds 1 μm, hence the event signatures become long-lived, while the upper limit on the gravitino mass (for LLP signatures) from the decay length is 1 MeV.

$$\Gamma_{\chi_1^0} \propto \frac{m_{\chi_1^0}^5}{m_{\tilde{G}}^2 M_{Pl}^2}$$

Modeling pair production cross-section with MadGraph5

	General gauge mediated (GGM) SUSY	Simplified supersymmetric model
strong channel	–	+
weak channel	+	+
squarks, gluino, sleptons masses	$m_u = m_d = m_e = m_H = 8$ TeV	$m_e = m_h = 8$ TeV $m_u = m_d = m_g = 1.5$ TeV
neutralinos	$\tilde{\chi}_3^0, \tilde{\chi}_4^0 : m > 2.5$ TeV $m_{\tilde{\chi}_2^0} > m_{\tilde{\chi}_1^0}$ $\Delta = 250$ GeV	$\tilde{\chi}_3^0, \tilde{\chi}_4^0 : m > 2.5$ TeV $m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$
charginos	$m_{\tilde{\chi}_2^\pm} > 2.5$ TeV $m_{\tilde{\chi}_1^\pm} < 2.5$ TeV	$m_{\tilde{\chi}_2^\pm} > 2.5$ TeV $m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$
decays	$\tilde{\chi}_3^0/\tilde{\chi}_4^0 \not\to \tilde{\chi}_2^0, \tilde{\chi}_1^0$ $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0$	$\tilde{\chi}_3^0/\tilde{\chi}_4^0 \not\to \tilde{\chi}_2^0, \tilde{\chi}_1^0$ $\tilde{\chi}_2^0 \not\to \tilde{\chi}_1^0$ $(m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0})$ $\tilde{\chi}_1^0 \to \tilde{G}$ $\tilde{g}\tilde{g} \to \tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{g}\tilde{g} \to \tilde{\chi}_1^0\tilde{\chi}_1^\pm$

T.2. Main characteristic of GGM и SSM models

MSSM free parameters:

- Three gauge couplings
- The matrices of the Yukawa couplings
- The Higgs field mixing parameter
- The soft supersymmetry breaking parameters.

GMSB free parameters:

- The Higgs field mixing parameter
- Messengers scale
- Gaugino and squark masses

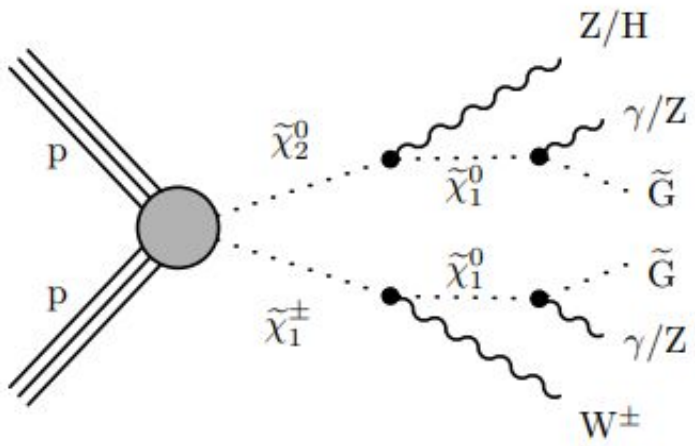
GGM free parameters:

- First and second neutralino mass

SSM free parameters:

- Gluino\squark mass and first neutralino mass

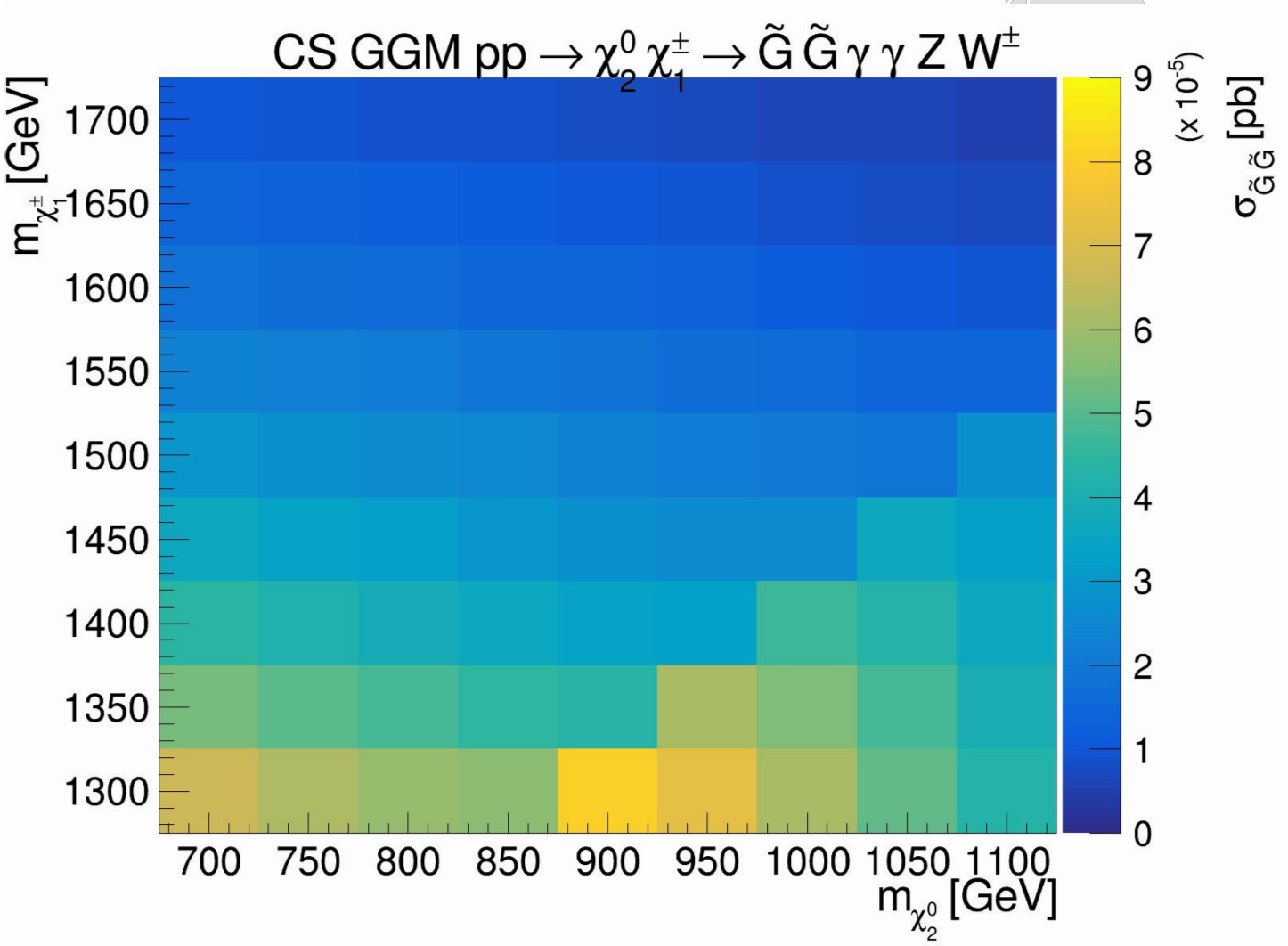
GGM. Channel 1



For full integrated luminosity (L) for LHC 3 runs events number of pair gravitino production:

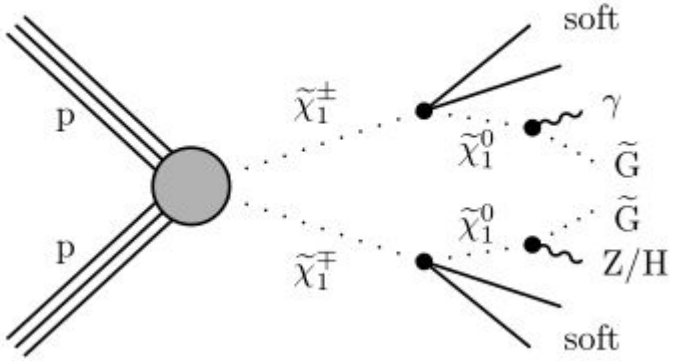
$$L_{CMS} = 300[fb^{-1}]$$

$$N_{\tilde{G}\tilde{G}} = L_{CMS}\sigma_{\tilde{G}\tilde{G}} = 3 \div 30$$



P.7. Cross-sectoon scan of pair gravitino production at the LHC

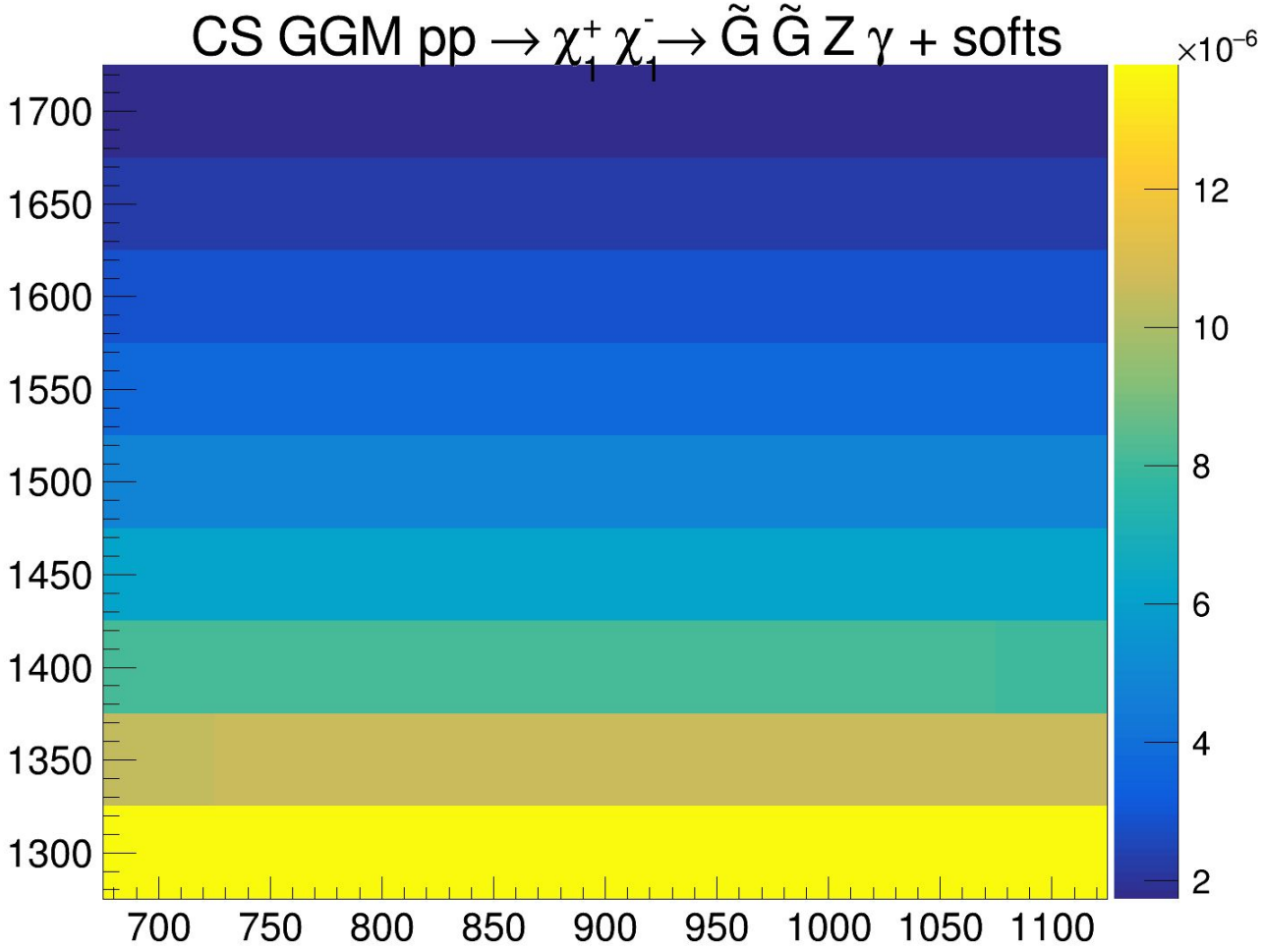
GGM. Channel 2



For full integrated luminosity (L) from LHC 3 runs events number of pair gravitino production:

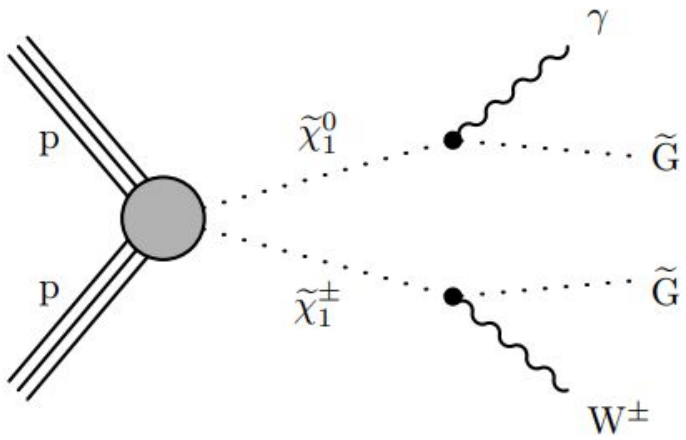
$$L_{CMS} = 300[fb^{-1}]$$

$$N_{\tilde{G}\tilde{G}} = L_{CMS}\sigma_{\tilde{G}\tilde{G}} = 1 \div 3$$



P.8. Cross-sectoon scan of pair gravitino production at the LHC

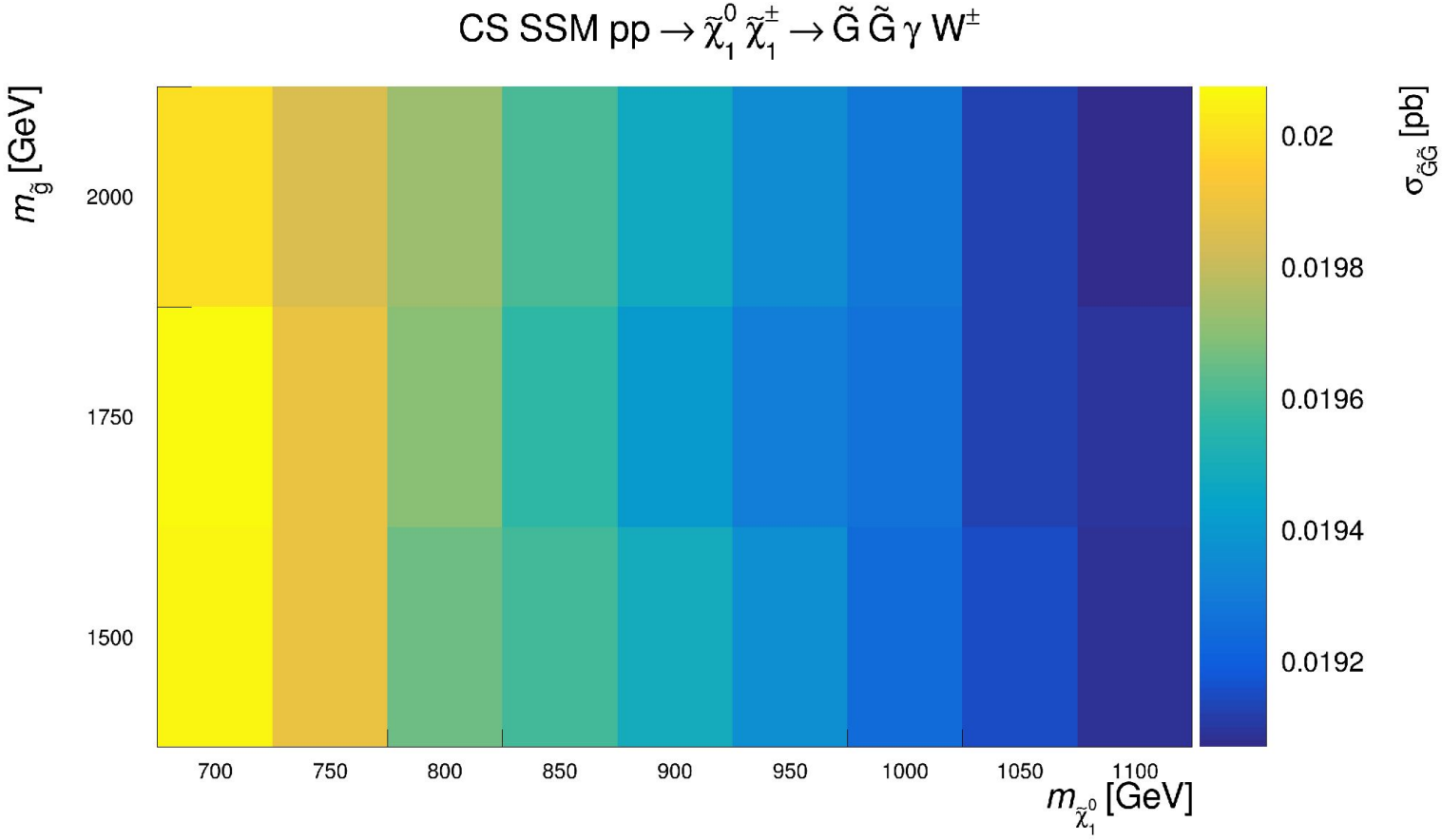
SSM (TChiWg).Weak channel.



For full integrated luminosity (L) from LHC 3 runs events number of pair gravitino production:

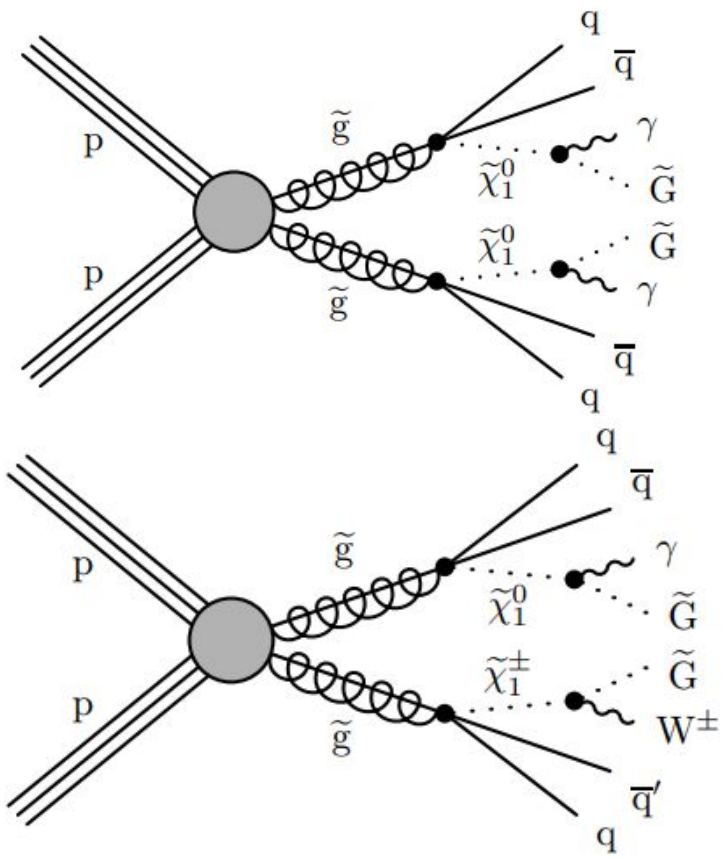
$$L_{CMS} = 300[fb^{-1}]$$

$$N_{\tilde{G}\tilde{G}} = L_{CMS}\sigma_{\tilde{G}\tilde{G}} \approx 6 \times 10^4$$



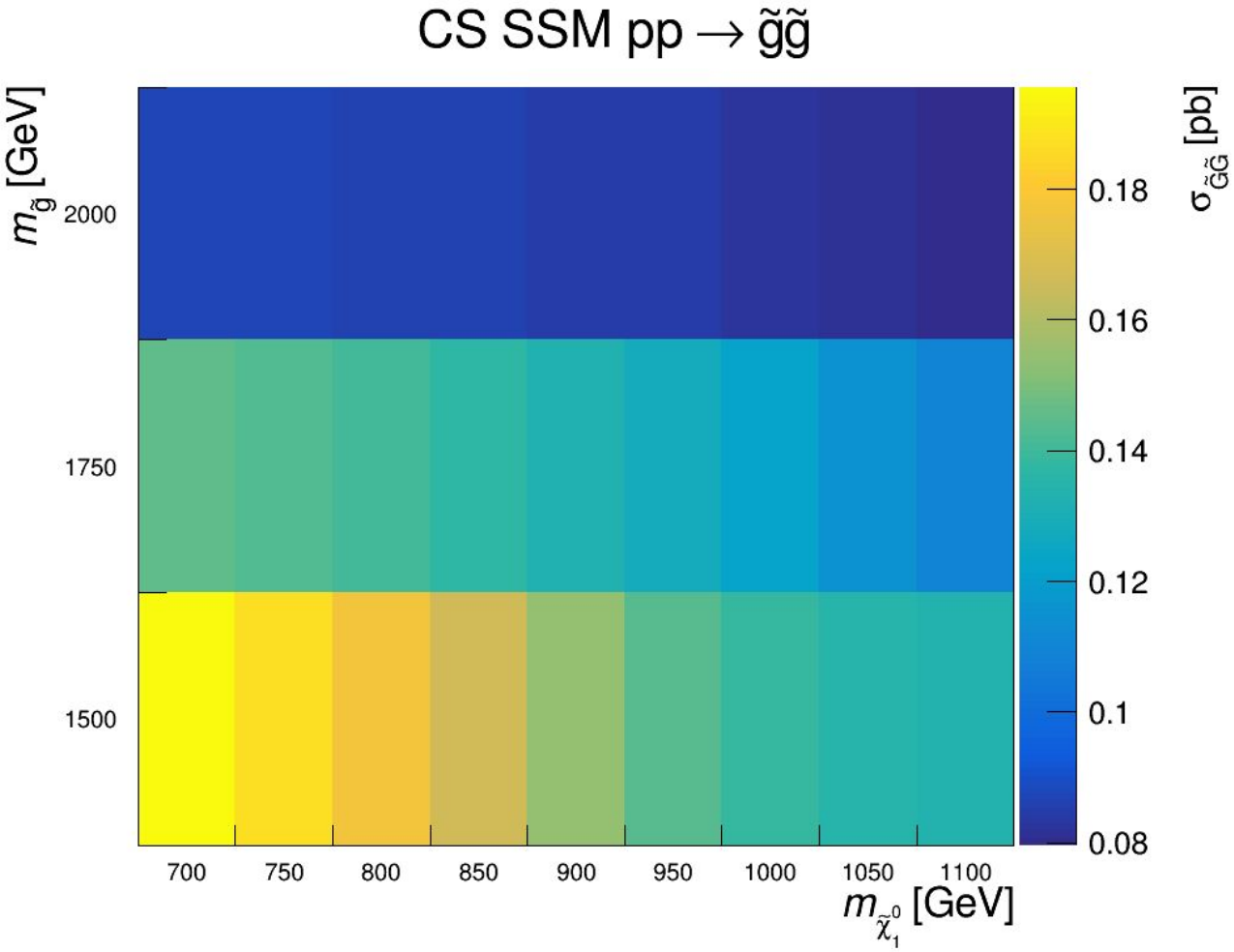
P.9. Cross-sectoon scan of pair gravitino production at the LHC

SSM (T5gg&T5Wg). Strong channel 1.



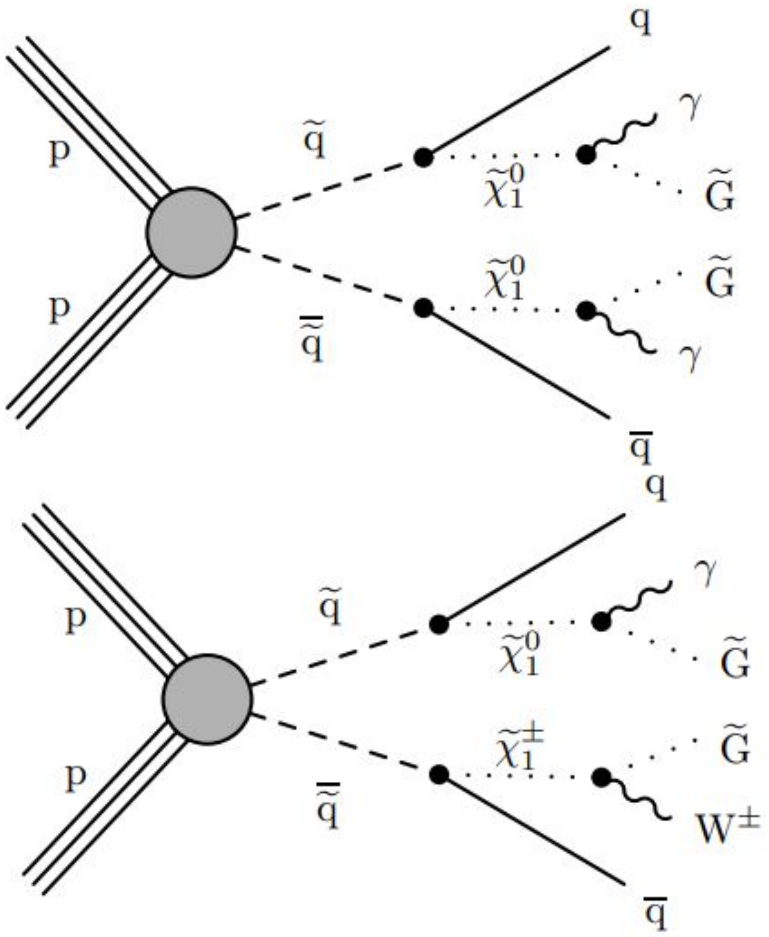
$$L_{CMS} = 300[fb^{-1}]$$

$$N_{\tilde{G}\tilde{G}} = L_{CMS}\sigma_{\tilde{G}\tilde{G}} = 2 \times 10^3 \div 6 \times 10^4$$



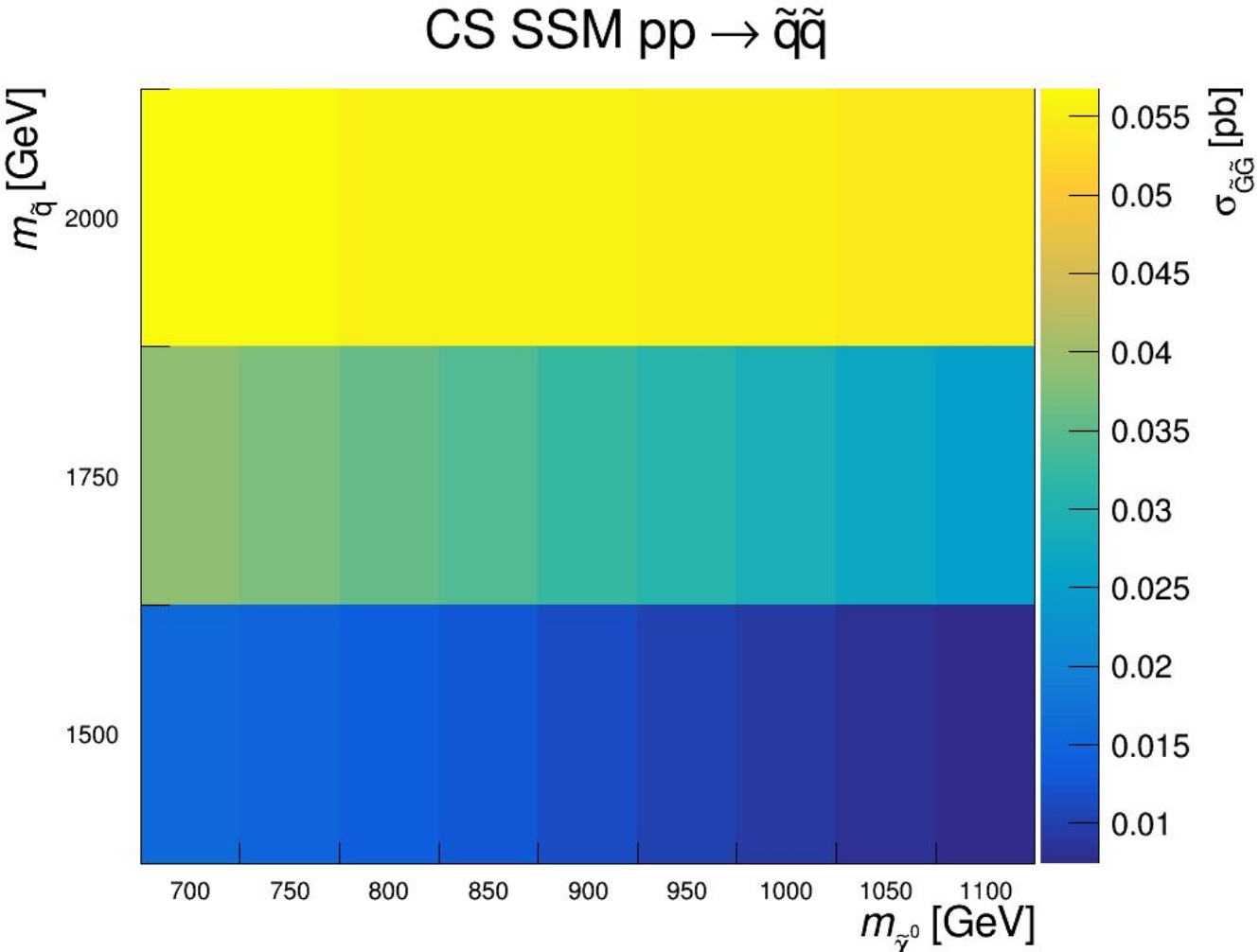
P.10. Cross-sectoon scan of pair gravitino production at the LHC

SSM (T6gg&T6Wg). Strong channel 2.



$$L_{CMS} = 300[fb^{-1}]$$

$$N_{\tilde{G}\tilde{G}} = L_{CMS}\sigma_{\tilde{G}\tilde{G}} = 3 \times 10^2 \div 6 \times 10^3$$



P.11. Cross-sectoon scan of pair gravitino production at the LHC

Event selection

Model type	Model	Signature
GGM	GGM1	$p_T^{miss} + 2\gamma + 2\ell^{\pm} + \ell'$
	GGM2	p_T^{miss} + soft jets + $\gamma + 2\ell^{\pm}$
SSM	TChiWg	$p_T^{miss} + \gamma + \ell$
	T5gg	p_T^{miss} + 4 jets + 2γ or 4 jets + $\gamma + \ell$
	T6gg	p_T^{miss} + 2 jets + 2γ or 2 jets + $\gamma + \ell$

T.2. Interesting signature for pair gravitino production

Characteristic	Prompt signatures	Long-lived particles (LLP) signatures
Decay length ($c\tau$)	$c\tau \lesssim 10^{-6}$ m	$c\tau \in [10^{-6}; 10^{1}]$ m
SM examples	W, Z, t-quarks, Higgs boson	Kaons, B-hadrons, muons (stable)
Analysis challenges	Large QCD background masking the signal	Reconstruction complexity but low SM background

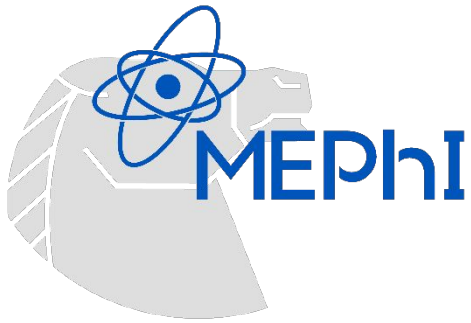
T.3. Prompt VS LLP signatures comparison

Conclusions

An analysis of the observability of gravitino pair production at the LHC has been performed for models with gauge-mediated supersymmetry breaking (GMSB). Astronomical constraints on the mass of warm dark matter particles, for which gravitinos are a plausible candidate, have also been taken into account. Two models of the supersymmetry mass spectrum were considered.

- For General Gauge Mediation (GGM), the expected number of events over three LHC runs ranges from 4 to 33.
- For SSM (symplified supersymmetric models), the expected number of events ranges from 60,000 to 126,000.

Model	**Events number**
General gauge mediation	4 - 33
SSM (TChiWg)	60.000
SSM (T5gg&T5Wg)	2.000-60.000
SSM (T6gg&T6Wg)	300-6.000



Thanks for your attention



Links

1. DESI Collaboration. (2025). DESI 2024 VI: Cosmological constraints from the measurements of baryon acoustic oscillations. Journal of Cosmology and Astroparticle Physics, *2025*(02), 021. https://doi.org/10.1088/1475-7516/2025/02/021
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10. Kazakov, D. I. (2000). Beyond the Standard Model (In search of supersymmetry). CERN Yellow Report, CERN-2001-003, 125-198. https://doi.org/10.5170/CERN-2001-003.125
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