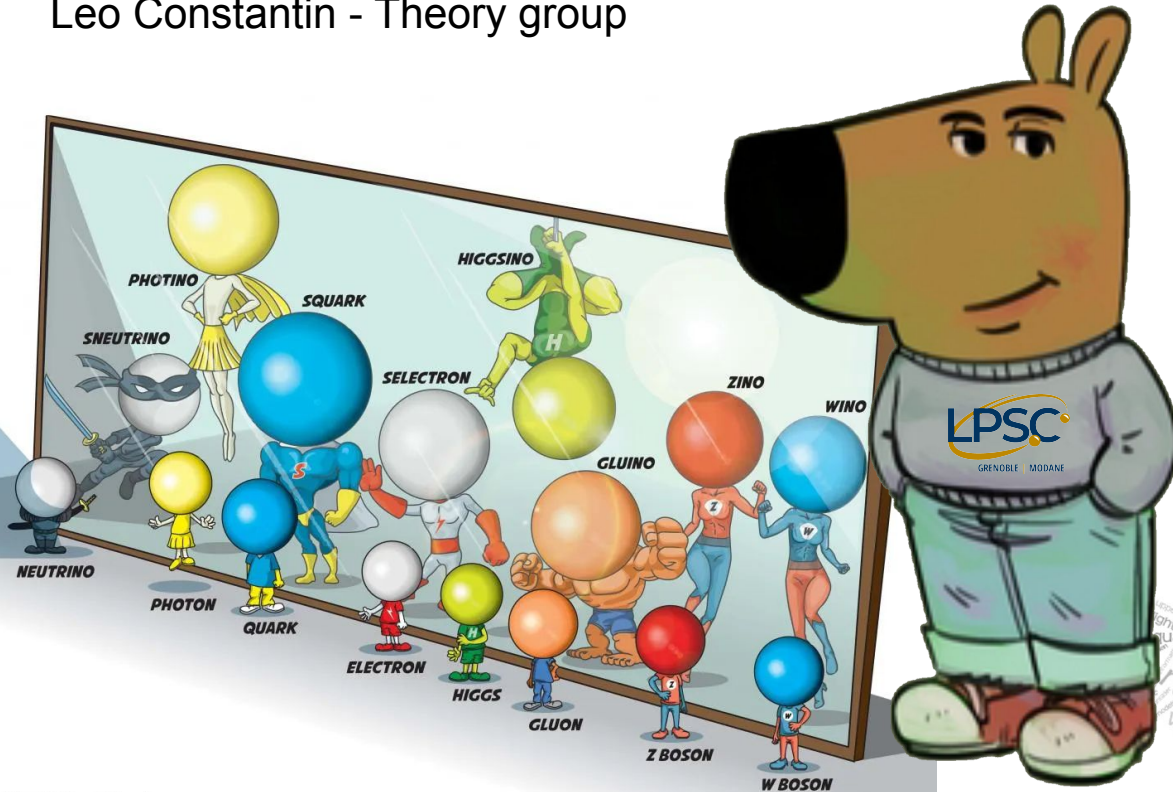


Tools and methods to investigate new physics.

Leo Constantin - Theory group



The standard model : content and higgs discovery

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS (left side of the table)

LEPTONS (left side of the table)

SCALAR BOSONS (right side of the table)

Gauge Bosons / Vector Bosons (right side of the table)

-Very successful theory of particle physics

-Ingredients :

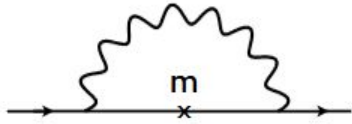
Relativity, Quantum mechanics, Gauge invariance

-Internal symmetries : $SU(3)_C \times SU(2)_L \times U(1)_Y$

Higgs discovery in 2012 , what's next ???

Why would we go beyond : naturalness and hierarchy

Fermion



$$\delta m \propto m \ln\left(\frac{\Lambda}{m}\right)$$

The mass of a fermion is protected by chiral symmetry



Scalar



$$\delta m^2 \propto \Lambda^2$$

The Higgs (or any scalar) mass is quadratically sensitive to new physics scale !!!!



Why would we go beyond : naturalness and hierarchy



$$m_H^2(\text{phys}) \sim m_{H\text{bare}}^2 + \frac{c}{16\pi^2} \Lambda^2$$

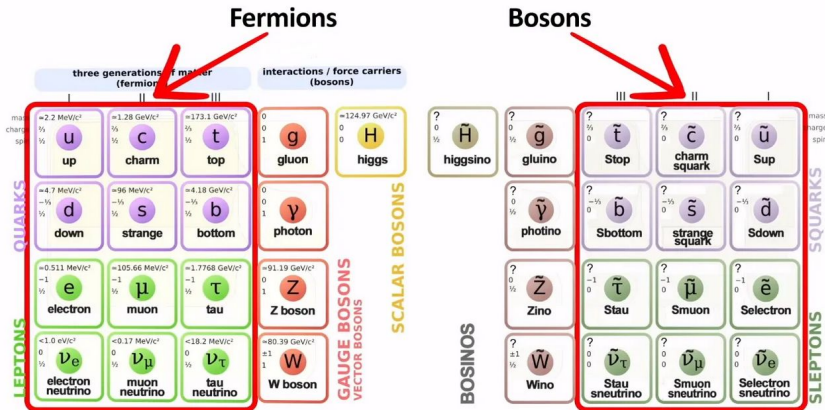
Need fine tuning to achieve the right cancellation

A natural extension : SUSY phenomenology and naturalness

- Cool symmetry between bosons and fermions, $Q|\text{Boson}\rangle = |\text{Fermion}\rangle$, $Q|\text{Fermion}\rangle = |\text{Boson}\rangle$.

Particles and their superpartners enter loops with opposite sign : no more quadratic divergence

$$m_H^2(\text{phys}) \sim m_{H\text{bare}}^2 + \cancel{\frac{c}{16\pi^2} \Lambda^2}$$

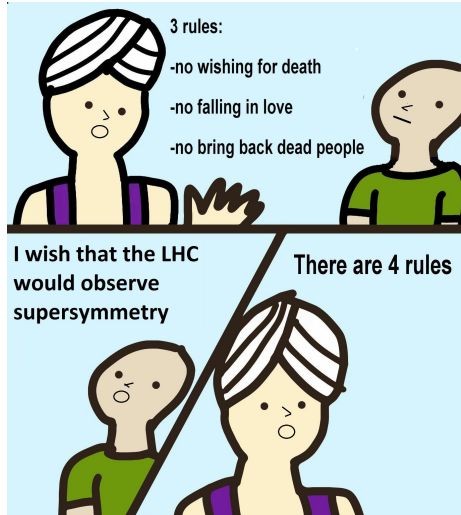


Gauge bosons superpartners mix together :

Neutralinos $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$

Charginos $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$

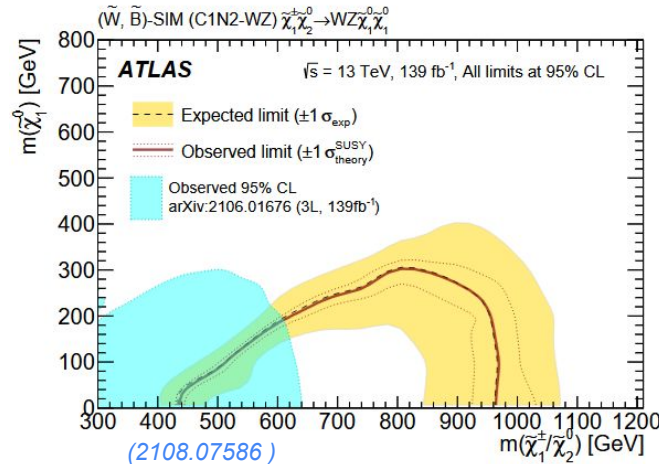
Probing BSM with direct searches



-Different final states can be investigated to probe SUSY at LHC.

-No evidence so far : where is SUSY ?

- Experiments interpret their results as Simplified Models (SMS) : effective model assuming for a handful of particles and decay modes.



SMS example : production of 2 superpartners decaying in a specific channel

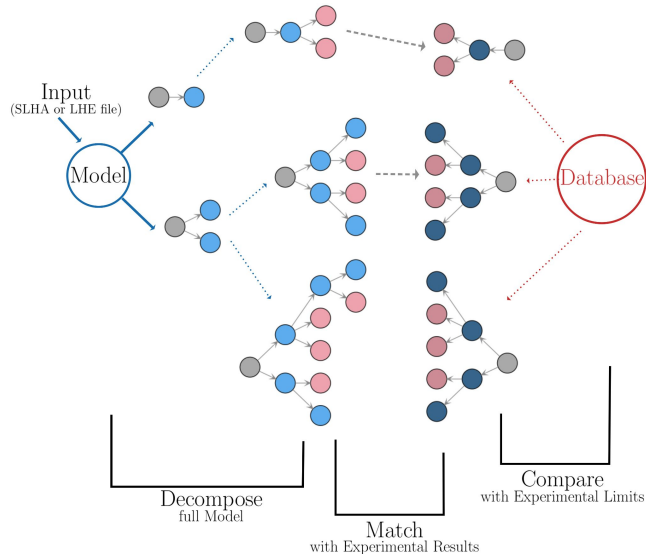
$$\tilde{W} / \tilde{B} (\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow WZ)$$

Reinterpretation with SModelS



SModelS : public tool for reinterpreting SMS results from the LHC. Uses CMS and ATLAS results

- Fast (no event simulation / no recast !), thus well suited for parameter scans.
- Not as precise as recasting (interpolation of efficiencies, conservative results).
- Large collection of results (limited by the available SMS results)



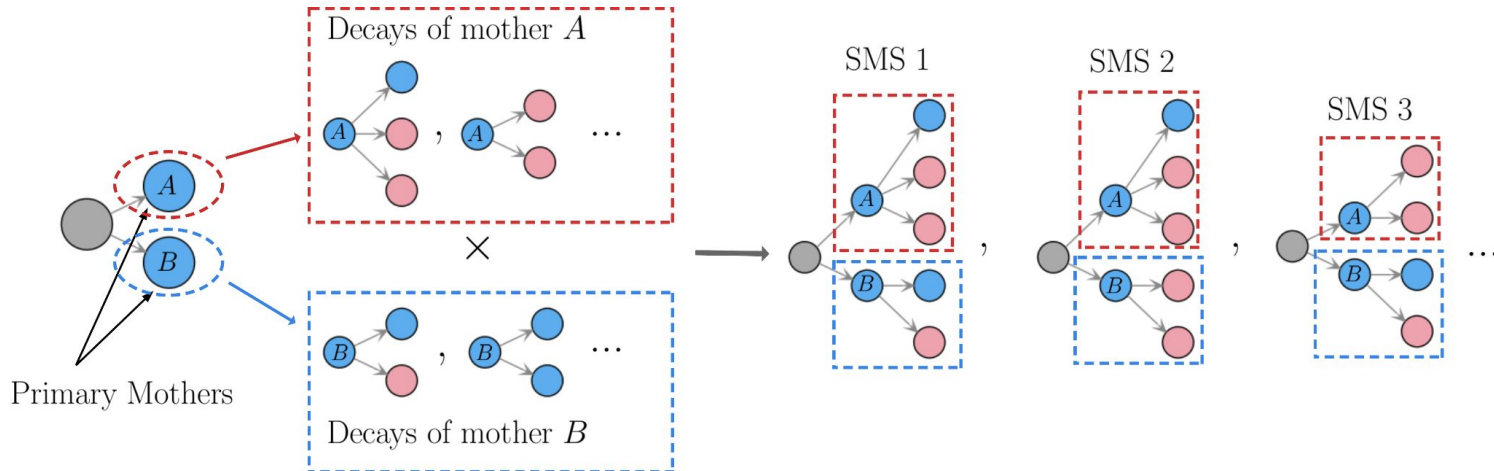
Latest version 3.1.1 :
126 SMS topologies
127 analyses (36 Run 1, 91 Run 2)
64 CMS, 63 ATLAS

Reinterpretation with SModelS



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ATLAS pMSSM study and comparison

ATLAS : reinterpretation of their searches by recasting their analyses on a scan of points.



Parameter	Min	Max	Note
$M_{\tilde{L}_1} (=M_{\tilde{L}_2})$	10 TeV	10 TeV	Left-handed slepton (first two gens.) mass
$M_{\tilde{R}_1} (=M_{\tilde{R}_2})$	10 TeV	10 TeV	Right-handed slepton (first two gens.) mass
$M_{\tilde{L}_3}$	10 TeV	10 TeV	Left-handed stau doublet mass
$M_{\tilde{R}_3}$	10 TeV	10 TeV	Right-handed stau mass
$M_{\tilde{Q}_1} (=M_{\tilde{Q}_2})$	10 TeV	10 TeV	Left-handed squark (first two gens.) mass
$M_{\tilde{U}_1} (=M_{\tilde{U}_2})$	10 TeV	10 TeV	Right-handed up-type squark (first two gens.) mass
$M_{\tilde{D}_1} (=M_{\tilde{D}_2})$	10 TeV	10 TeV	Right-handed down-type squark (first two gens.) mass
$M_{\tilde{Q}_3}$	2 TeV	5 TeV	Left-handed squark (third gen.) mass
$M_{\tilde{U}_3}$	2 TeV	5 TeV	Right-handed top squark mass
$M_{\tilde{D}_3}$	2 TeV	5 TeV	Right-handed bottom squark mass
M_1	-2 TeV	2 TeV	Bino mass parameter
M_2	-2 TeV	2 TeV	Wino mass parameter
μ	-2 TeV	2 TeV	Bilinear Higgs boson mass parameter
M_3	1 TeV	5 TeV	Gluino mass parameter
A_t	-8 TeV	8 TeV	Trilinear top coupling
A_b	-2 TeV	2 TeV	Trilinear bottom coupling
A_τ	-2 TeV	2 TeV	Trilinear τ -lepton coupling
M_A	0 TeV	5 TeV	Pseudoscalar Higgs boson mass
$\tan \beta$	1	60	Ratio of the Higgs vacuum expectation values

ATLAS consider 8 Run 2 analyses.

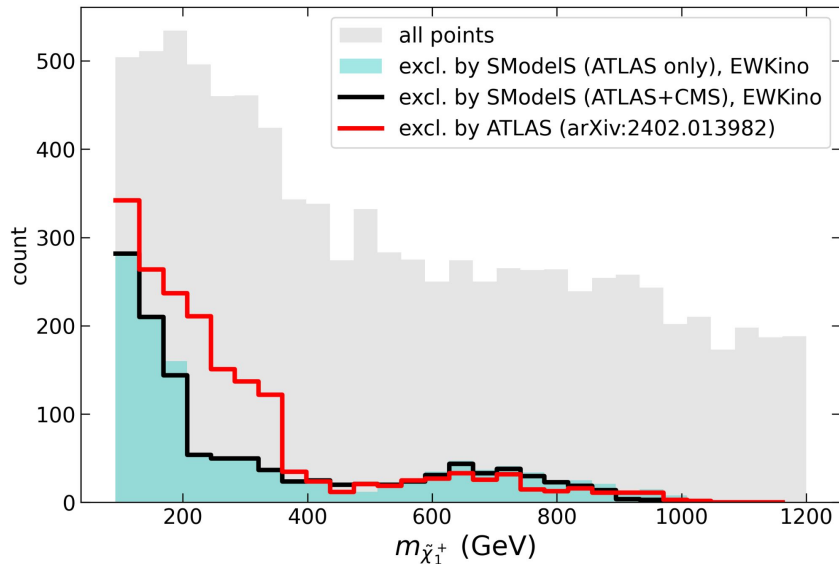
Most sensitive analysis conclude on the exclusion status of the point.

That's exactly the type of study SModelS is built for !

Type	Analysis	In SModelS
0 leptons	SUSY-2018-41	YES
1 lepton + 2 b-jets	SUSY-2019-08	YES
2 leptons + 0 jets	SUSY-2018-32	YES
2 leptons + Jets	SUSY-2018-05	YES
3 leptons on shell	SUSY-2019-09	YES
3 leptons off shell	SUSY-2018-02	SUSY-2017-03
Compressed	SUSY-2018-16	YES
Disappearing Track	SUSY-2018-19	SUSY-2016-06
h \rightarrow invisible constraint	HIGG-2021-05	NO
CP odd Higgs Boson constraint	HIGG-2018-57	NO

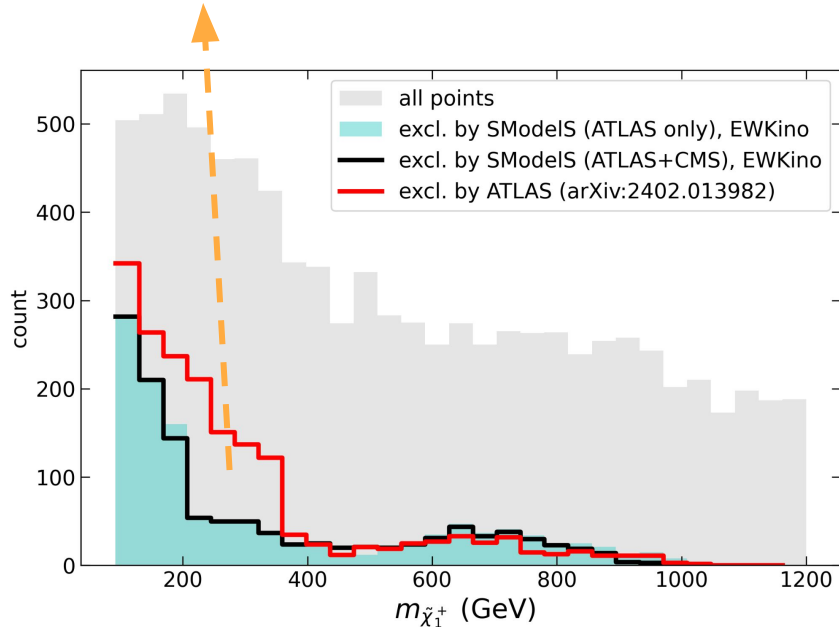
ATLAS pMSSM study and comparison : results

- Good agreement between SModelS and ATLAS
- Good agreement between ATLAS and CMS
- 200 - 400 GeV: disappearing track search (36 fb⁻¹ results in SModelS)



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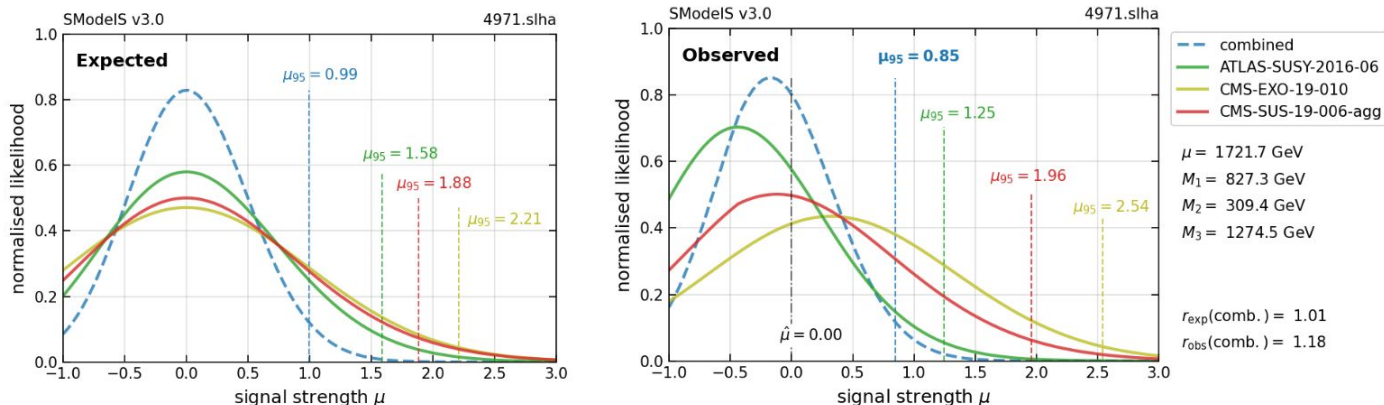


- Under exclusion
 - ▶ Disappearing track search
 - ▶ Topologies not available and complex decays not constrained
- Over exclusion
 - ▶ Overestimation of the exclusion of an analysis in SModelS (ATLAS-SUSY-2018-41): 166 points concerned

Going further : analysis combination and full database use

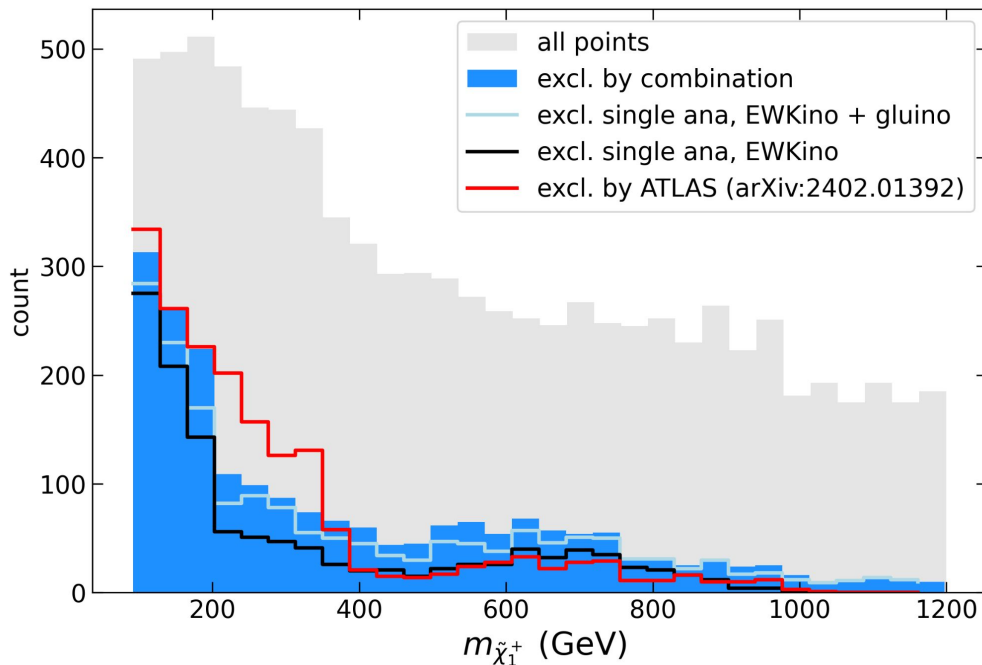
We can combine uncorrelated analyses in SModelS to reduce statistical fluctuations and include different topologies.

37 analyses available for combination on this scan (24 ATLAS, 13 CMS).
We retain the combination that maximize the expected sensitivity.



- We add gluino production because we have results in the database for this.
- We then combine over the whole database.

Results at each step of this study



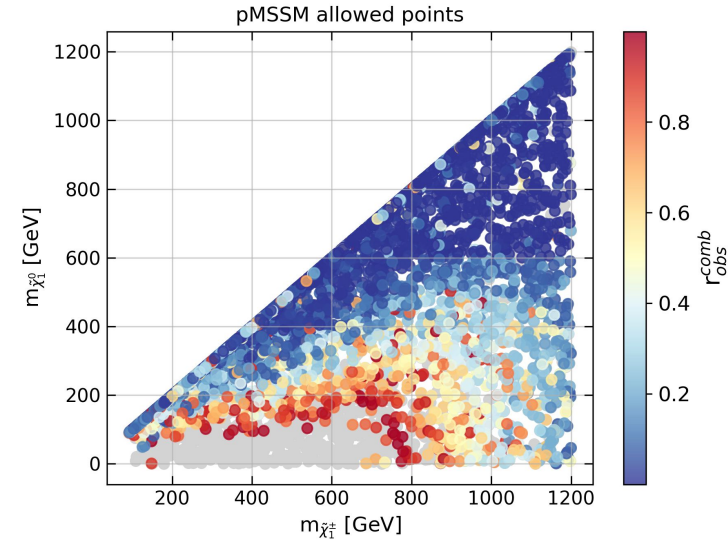
	bino-like LSP	non-bino LSP
Total number of points after filtering	3034	5919
Number of points excluded by:		
1. ATLAS in arXiv:2402.01392	529 (17%)	1271 (21%)
2. ATLAS EWKino results in SModelS	575 (19%)	687 (12%)
3. all EWKino results in SModelS	539 (18%)	662 (11%)
4. full database	666 (22%)	1030 (17%)
5. full DB with analysis combination	847 (28%)	1184 (20%)

- Significant exclusion enhancement when adding gluino production
- Significant enhancement when combining analyses as well

Allowed parameter space : the best we can do so far to valorize experimental results

We can draw the allowed parameter space of the pMSSM :

- Lot of room for susy realization even at light scale !
- Red-orange points in range to be more thoroughly tested in the futur



So Far :

- SModelS well suited for scans, good agreement with ATLAS.
- Need for the right material to properly implement searches in the database.
- Proof that combination of analyses has a significant impact on the coverage.

$$r = \frac{\sigma^{BSM}}{\sigma_{95}}$$

Probing BSM with indirect searches : an Effective Field Theory approach to new physics

$$\mathcal{O}_{LeQu}^{(3)}$$

$$\mathcal{O}_{HeD}$$

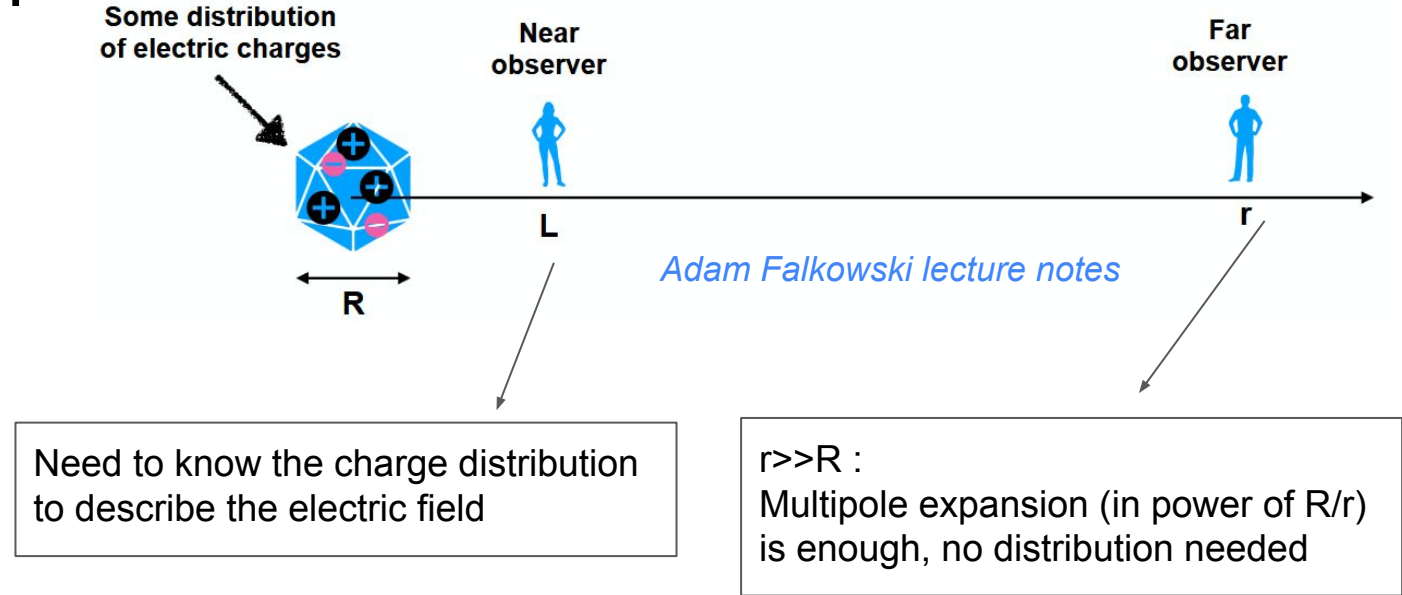


$$\mathcal{O}_{H\tilde{W}}$$

$$\mathcal{O}_W$$

$$\mathcal{O}_{ee}$$

What is EFT ?



In our case, new physics at large scale manifest itself at our scale in operators such as :

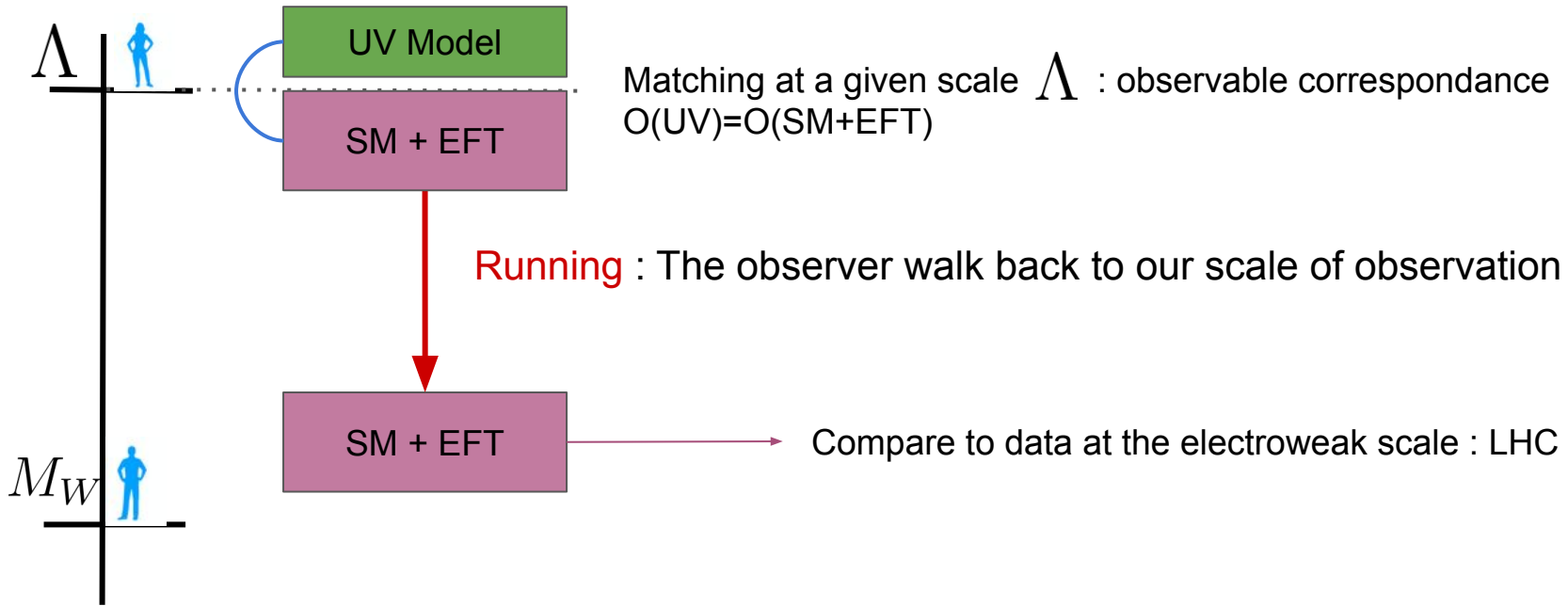
$$(H^\dagger H)^6$$

$$(\bar{e}_R^p \gamma_\mu e_R^q) (\bar{e}_R^r \gamma^\mu e_R^s)$$

$$\epsilon^{IJK} W_\nu^{I\mu} W_\rho^{J\nu} W_\mu^{K\rho}$$

Without the knowledge of the actual new physics !

The Effective Field Theory approach in particle physics



The beginning of the big tools era in EFT

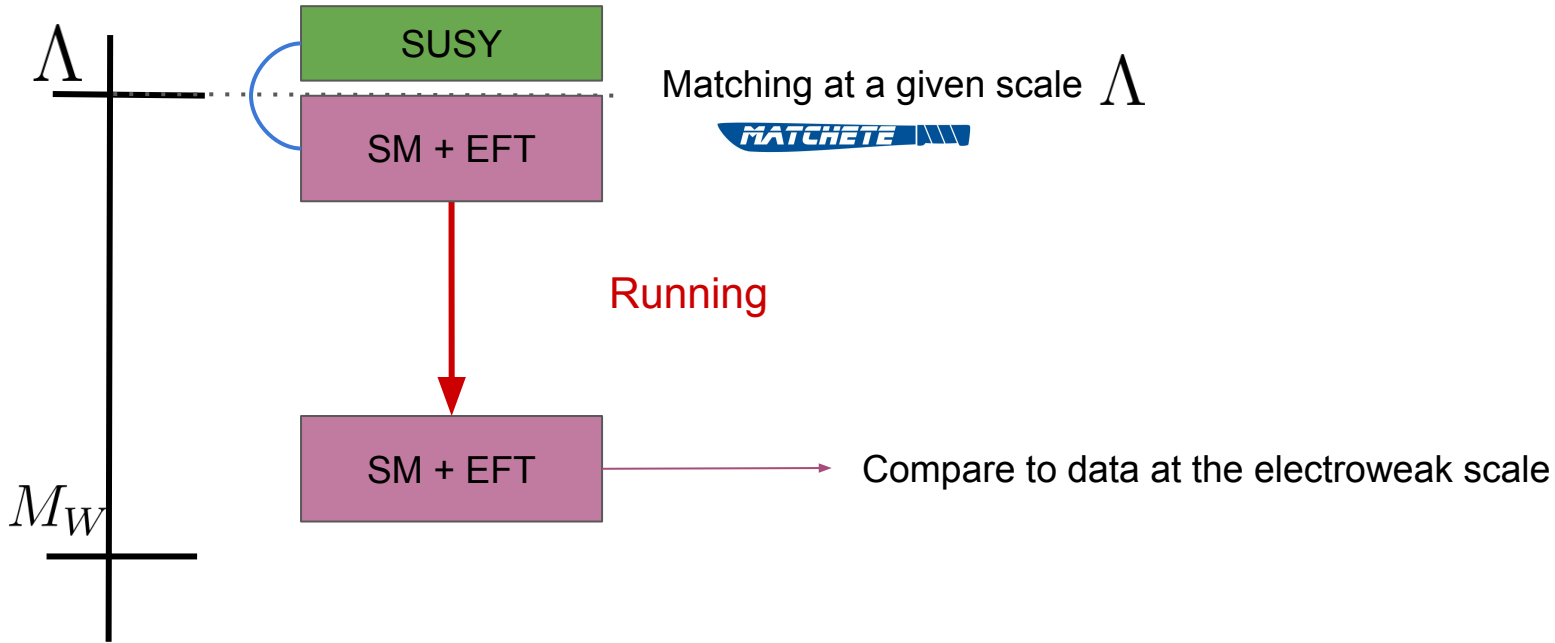
We enter an era where EFT tools now allows to do some tasks that would be impossible to do by hand :
Automated matching, generating operator basis, Running of operators ..



Goal : concrete use of these tools for SUSY

The Effective Field Theory approach in particle physics

An example of a possible scenario :



Possibility of retaining some SUSY fields in the EFT : Light Higgsinos ?

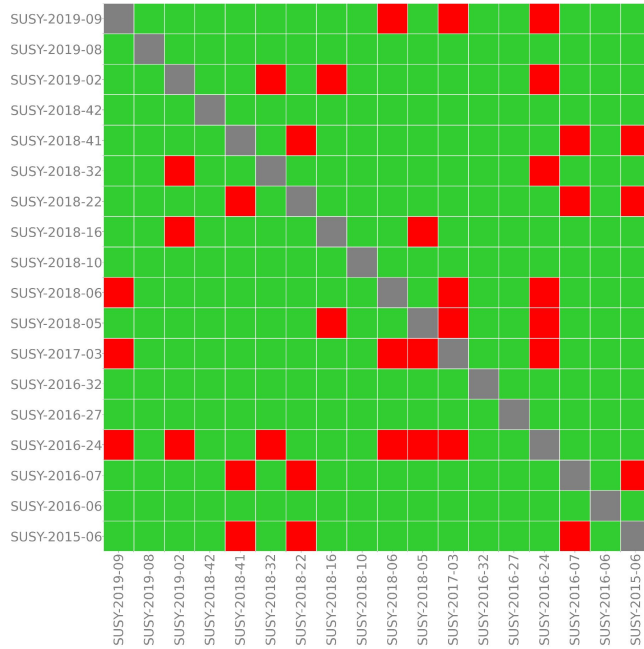
Summary

- Tools play a central role in exploring physics beyond the Standard Model.
- SModelS allow to scrutinize the parameter space of a model at low cost by using the Simplified model results provided by the experiments.
- Good agreement with ATLAS which increases as new analysis are implemented in the database.
- Analysis combination has a significant impact on the coverage of the pMSSM.
- The EFT community has come up with tools that open new paths to be explored, especially for SUSY.

Thanks !

Combination of uncorrelated analyses : matrix

ATLAS, 13 TeV



Combination matrix for ATLAS

Mixing matrix for the electroweakinos

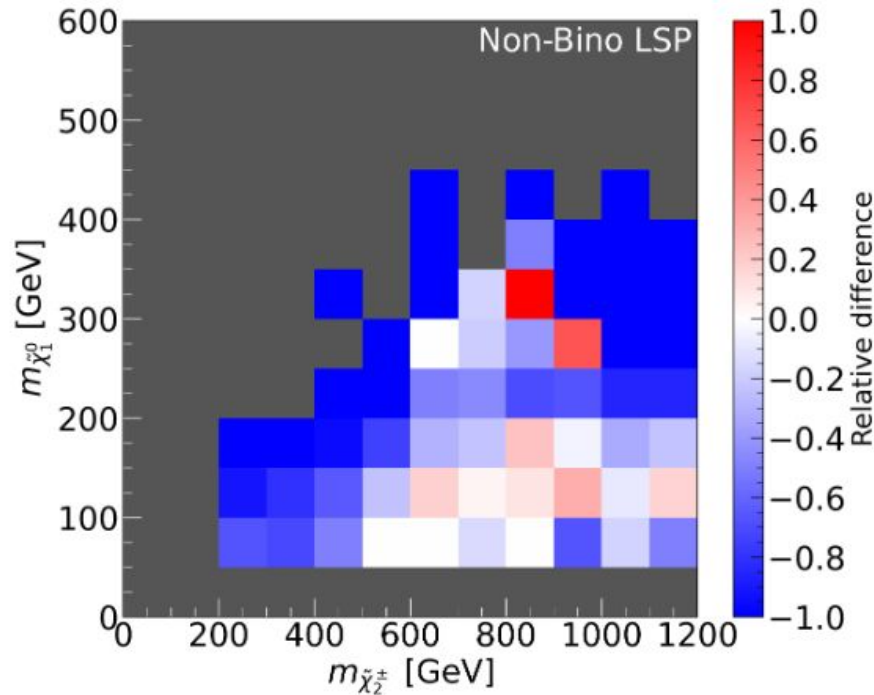
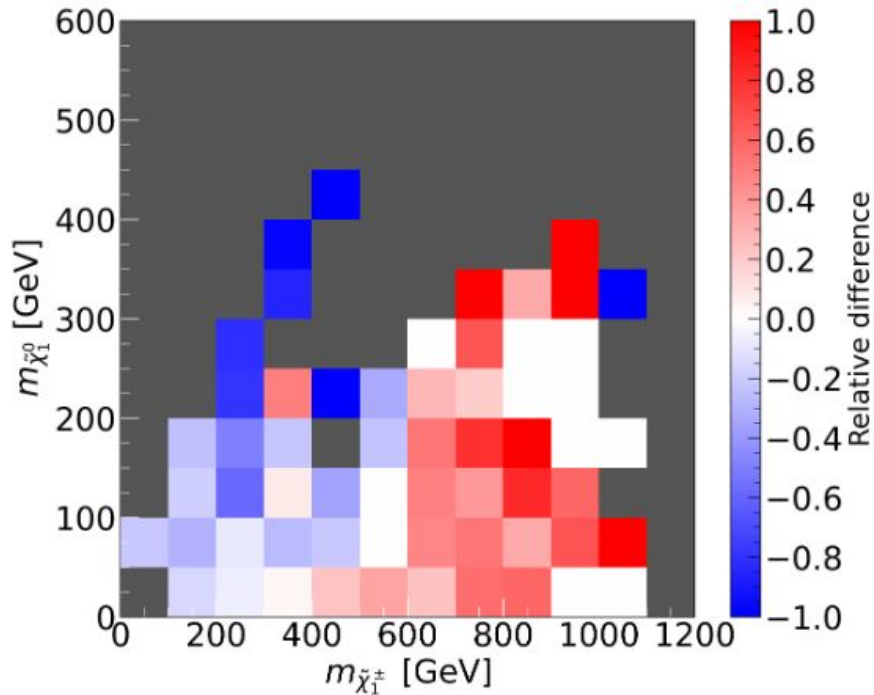
$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

$$\mathcal{M}_C = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}, \quad \mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}$$

$$(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$$

$$(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$$

Plots of $\frac{\text{SModelS exc.} - \text{ATLAS exc.}}{\text{ATLAS exc.}}$



- Under exclusion
 - ▶ Disappearing track search
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Using the full database

