

An abstract, high-contrast image featuring a complex, layered geometric pattern in shades of blue and white. The pattern consists of overlapping, curved, and faceted shapes that resemble crystalline structures or mathematical surfaces. The overall effect is one of depth and complexity, with light and shadow creating a sense of three-dimensional space.

International Workshop

# **PROBLEMS OF MODERN MATHEMATICAL PHYSICS**

BLTP JINR, Dubna, Russia

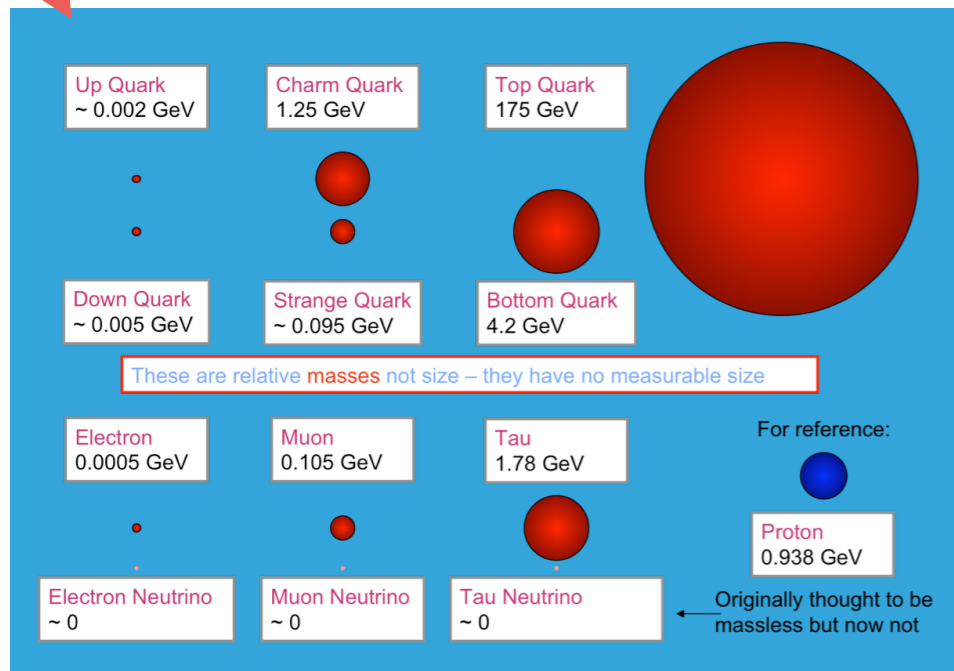
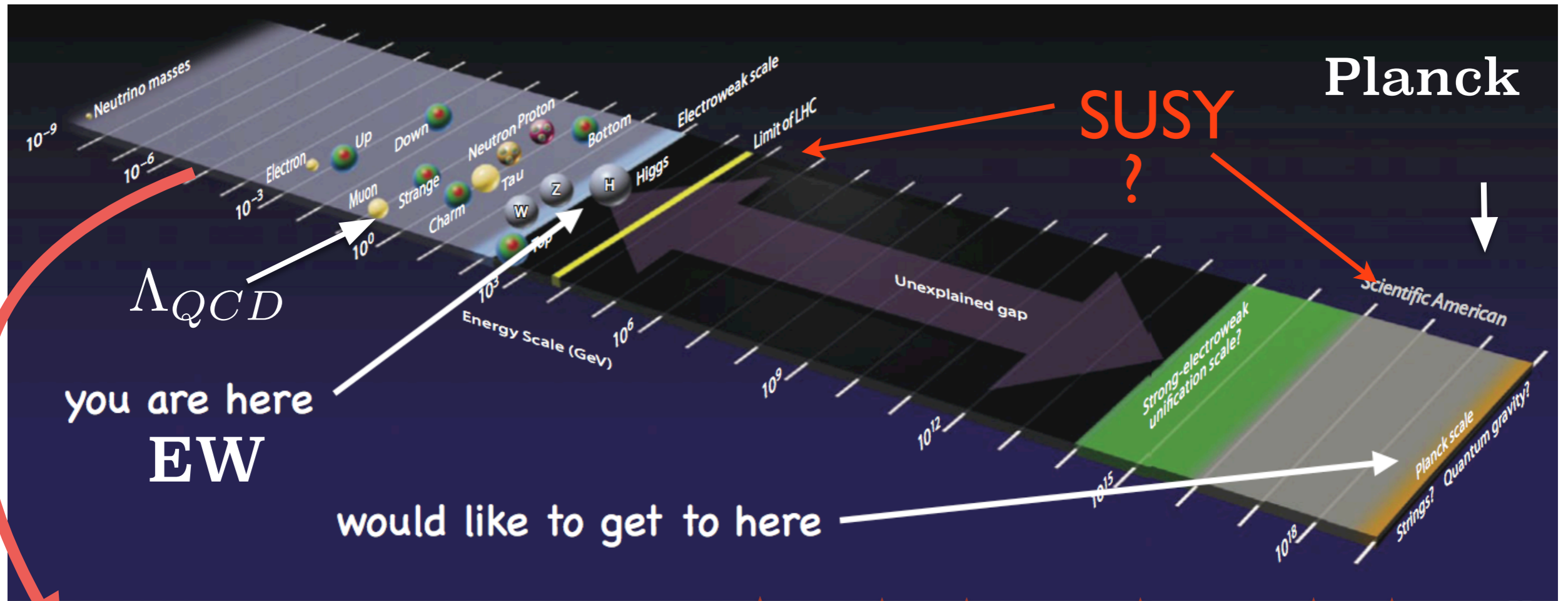
19 - 23 February, 2024

## **SUPERSYMMETRY IN PARTICLE PHYSICS**

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**DMITRY KAZAKOV**  
**JINR(DUBNA)**

# IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?



## NEW SYMMETRIES

## SUPERSYMMETRY

Supersymmetry is an extension of the Poincare symmetry of the SM

## Poincare Algebra

$$\begin{aligned}
 [P_\mu, P_\nu] &= 0, \\
 [P_\mu, M_{\rho\sigma}] &= i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho), \\
 [M_{\mu\nu}, M_{\rho\sigma}] &= i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho})
 \end{aligned}$$

## Super Poincare Algebra

 $Q_i, \bar{Q}_i$ 

$$\begin{aligned}
 [Q_\alpha^i, P_\mu] &= [\bar{Q}_{\dot{\alpha}}^i, P_\mu] = 0, \\
 [Q_\alpha^i, M_{\mu\nu}] &= \frac{1}{2}(\sigma_{\mu\nu})_\alpha^\beta Q_\beta^i, & [\bar{Q}_{\dot{\alpha}}^i, M_{\mu\nu}] &= -\frac{1}{2}\bar{Q}_{\dot{\beta}}^i(\bar{\sigma}_{\mu\nu})^{\dot{\beta}}_{\dot{\alpha}},
 \end{aligned}$$

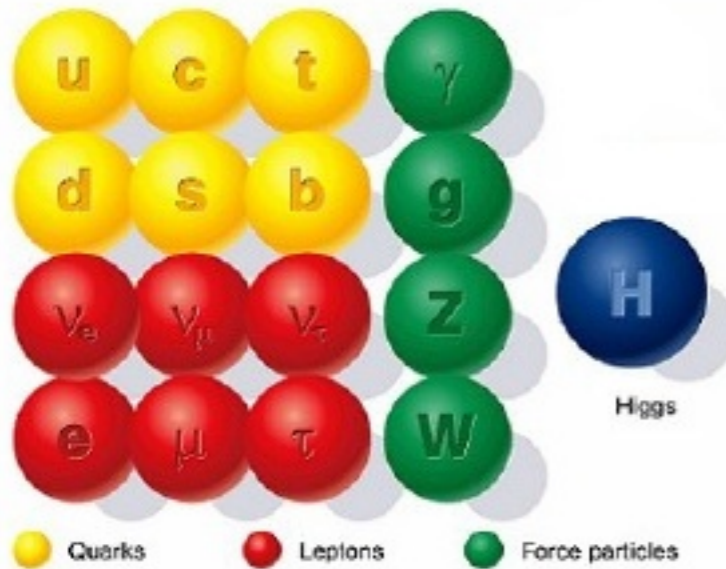
$$\{Q_\alpha^i, \bar{Q}_{\dot{\beta}}^j\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot{\beta}} P_\mu$$

$$\{Q_\alpha^i, Q_\beta^j\} = 2\epsilon_{\alpha\beta} Z^{ij}, \quad Z^{ij} = Z_{ij}^+$$

$$\{\bar{Q}_{\dot{\alpha}}^i, \bar{Q}_{\dot{\beta}}^j\} = -2\epsilon_{\dot{\alpha}\dot{\beta}} Z^{ij}, \quad [Z_{ij}, \text{anything}] = 0,$$

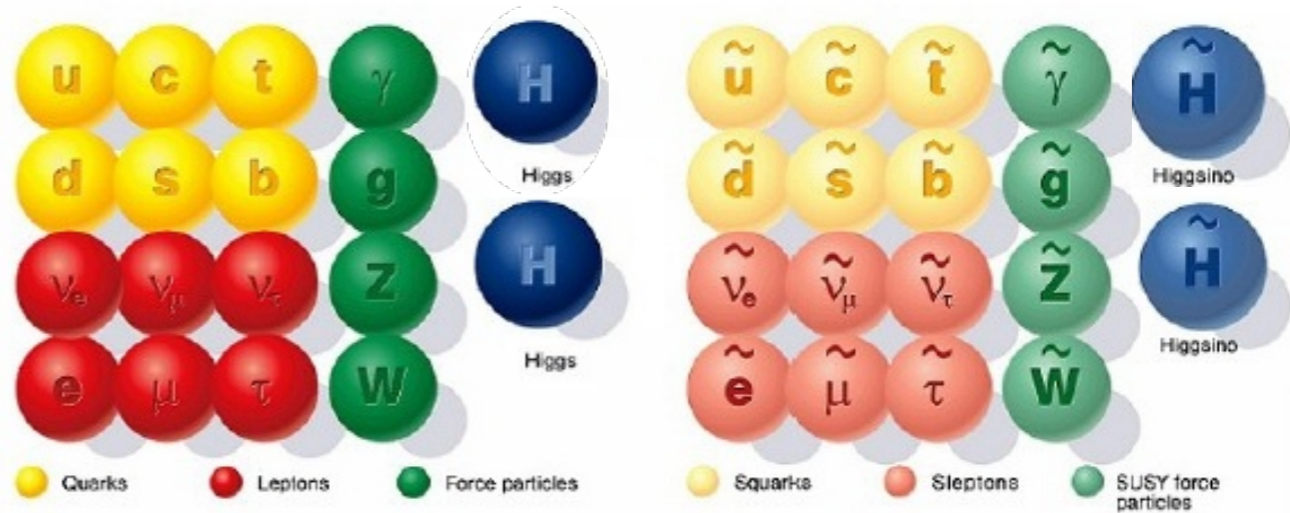
$$\alpha, \dot{\alpha} = 1, 2 \quad i, j = 1, 2, \dots, N.$$

Supersymmetry is a dream of a unified theory of all particles and interactions



Standard particles

## SUPERSYMMETRY



Standard particles

SUSY particles

## Why SUSY?

- Unification with gravity!
- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle

• Unification with gravity!

$$\{Q_\alpha^i, \bar{Q}_\beta^j\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\beta} P_\mu \Rightarrow \{\delta_\varepsilon, \bar{\delta}_{\bar{\varepsilon}}\} = 2(\varepsilon\sigma^\mu\bar{\varepsilon})P_\mu$$

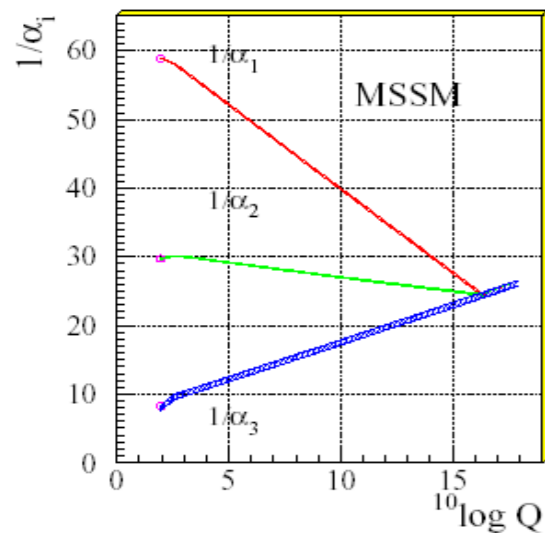
$\varepsilon = \varepsilon(x)$  local coordinate transf.  $\Rightarrow$  (super)gravity

**Local supersymmetry = general relativity !**

Supersymmetry is a dream of a unified theory of all particles and interactions

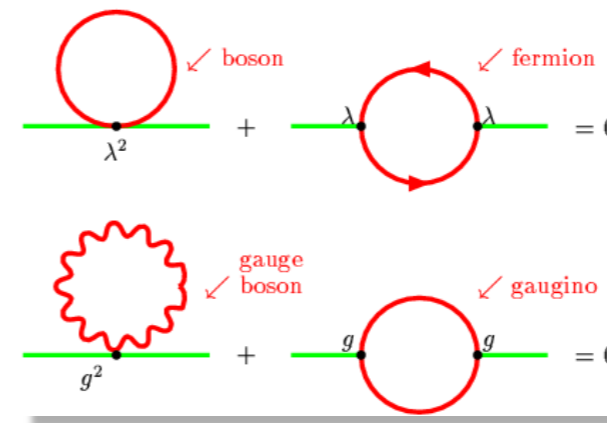
## Why SUSY?

### Unification of the gauge couplings



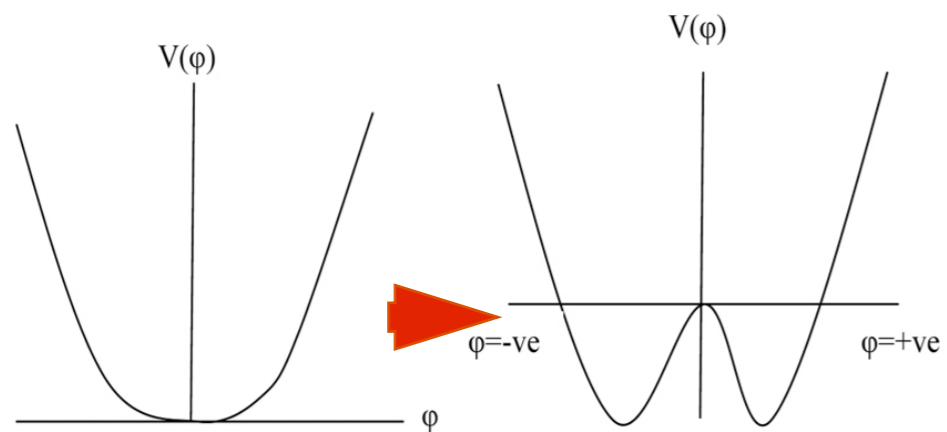
The basis of a grand Unified Theory

### Solution of the hierarchy problem



Cancellations of corrections and stabilization of the Higgs potential

### Explanation of the EW symmetry violation



Fig(a): Before symmetry breaking

Fig(b): After symmetry breaking

### Provided the DM particle

$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

Neutralino=DM

Violation of symmetry comes from radiative corrections

Bosons and Fermions come in pairs

$(\varphi, \psi)$

$(\tilde{\lambda}, A_\mu)$

$(\tilde{g}, g)$

Spin 0

Spin 1/2

Spin 1/2

Spin 1

Spin 3/2

Spin 2

scalar

chiral  
fermion

majorana  
fermion

vector

gravitino

graviton

# THE PARTICLE CONTENT OF THE MSSM

Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$		
Gauge			<i>gluino</i> $\tilde{g}^a$						
$\mathbf{G}^a$	gluon	$g^a$			8	0	0		
$\mathbf{V}^k$	Weak	$W^k (W^\pm, Z)$	<i>wino, zino</i> $\tilde{w}^k (\tilde{w}^\pm, \tilde{z})$		1	3	0		
$\mathbf{V}'$	Hypercharge	$B (\gamma)$	<i>binos</i> $\tilde{b}(\tilde{\gamma})$		1	1	0		
Matter									
$\mathbf{L}_i$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1		
$\mathbf{E}_i$					$\tilde{E}_i = \tilde{e}_R$	$E_i = e_R$	1	1	2
$\mathbf{N}_i$					$\tilde{N}_i = \tilde{\nu}_R$	$N_i = \nu_R$	1	1	0
$\mathbf{Q}_i$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	1/3		
$\mathbf{U}_i$					$\tilde{U}_i = \tilde{u}_R$	$U_i = u_R^c$	3*	1	-4/3
$\mathbf{D}_i$					$\tilde{D}_i = \tilde{d}_R$	$D_i = d_R^c$	3*	1	2/3
Higgs									
$\mathbf{H}_1$	Higgses	$H_1$	higgsinos	$\tilde{H}_1$	1	2	-1		
$\mathbf{H}_2$					$H_2$	$\tilde{H}_2$	1	2	1
$\mathbf{S}$	Singlet	$s$	singlino	$s$	1	1	0		

MSSM

$$R = (-1)^{3(B-L)+2S}$$

The Usual Particle :  $R = + 1$   
 SUSY Particle :  $R = - 1$

B - Baryon Number  
 L - Lepton Number  
 S - Spin

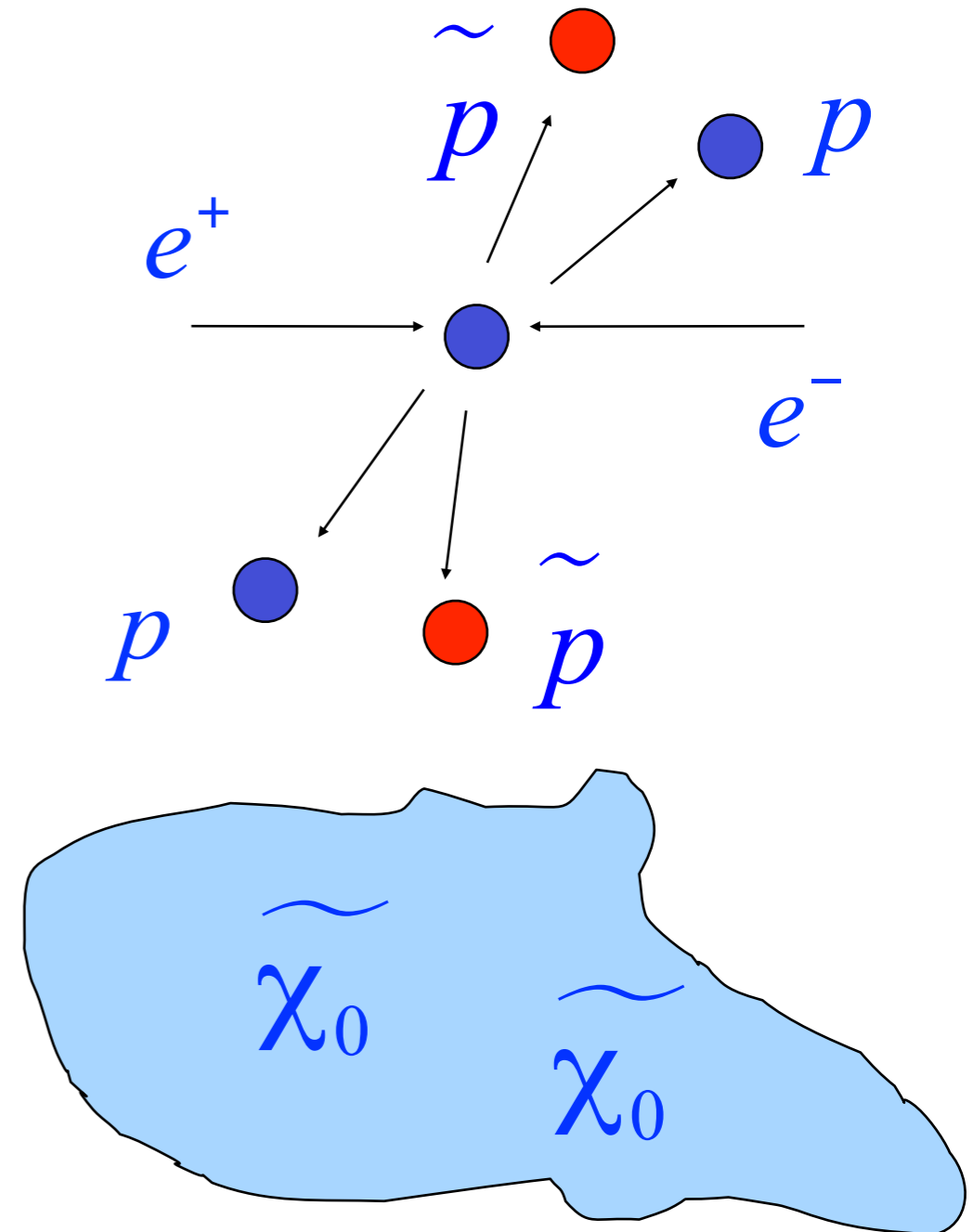
## The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable



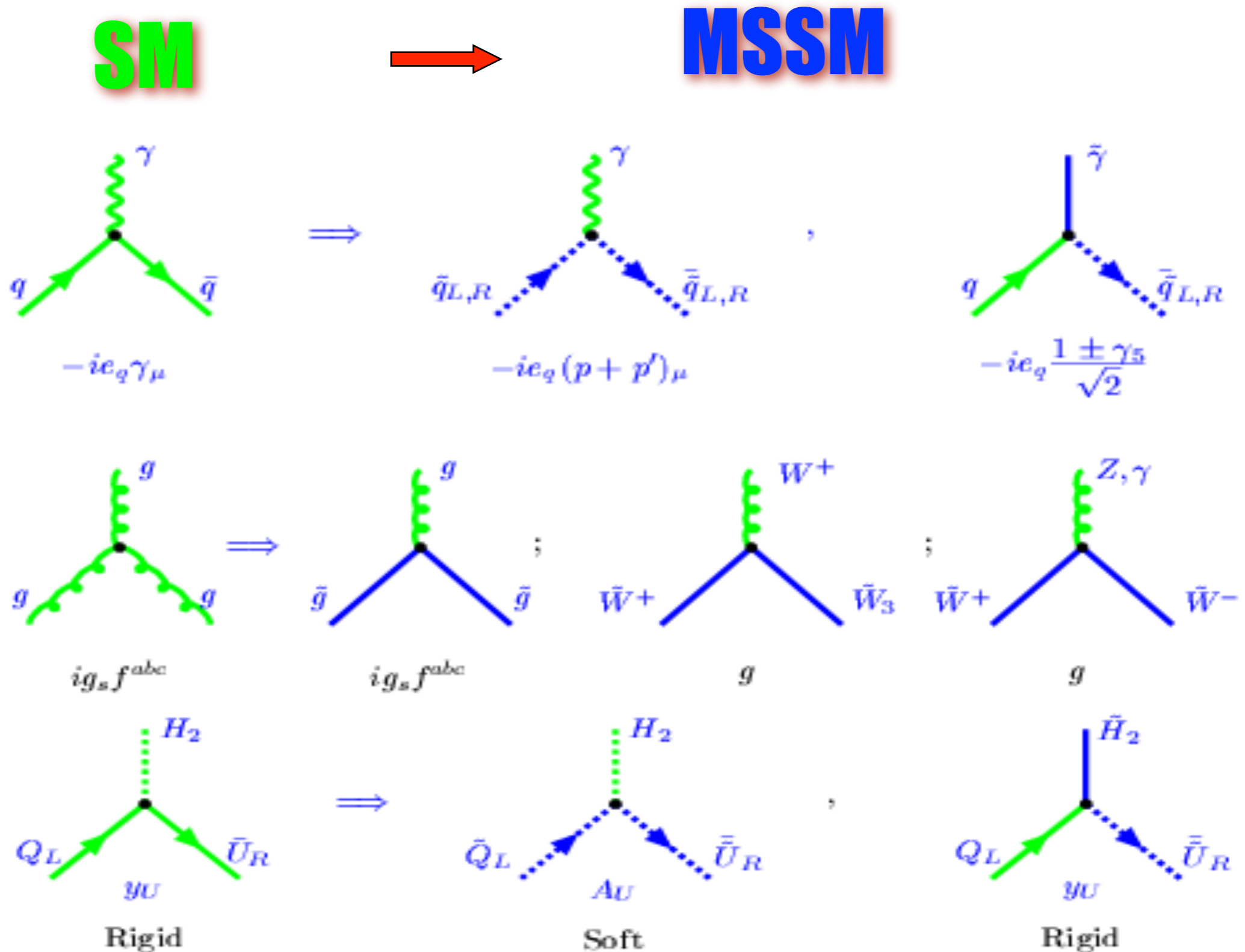
- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino)
- It can survive from the Big Bang and form the Dark matter in the Universe

$\tilde{\chi}_0$

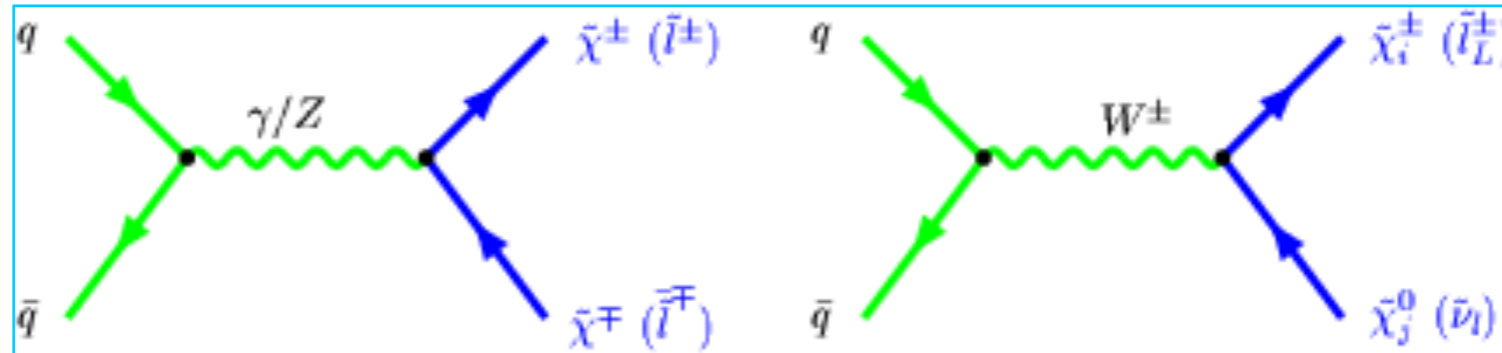




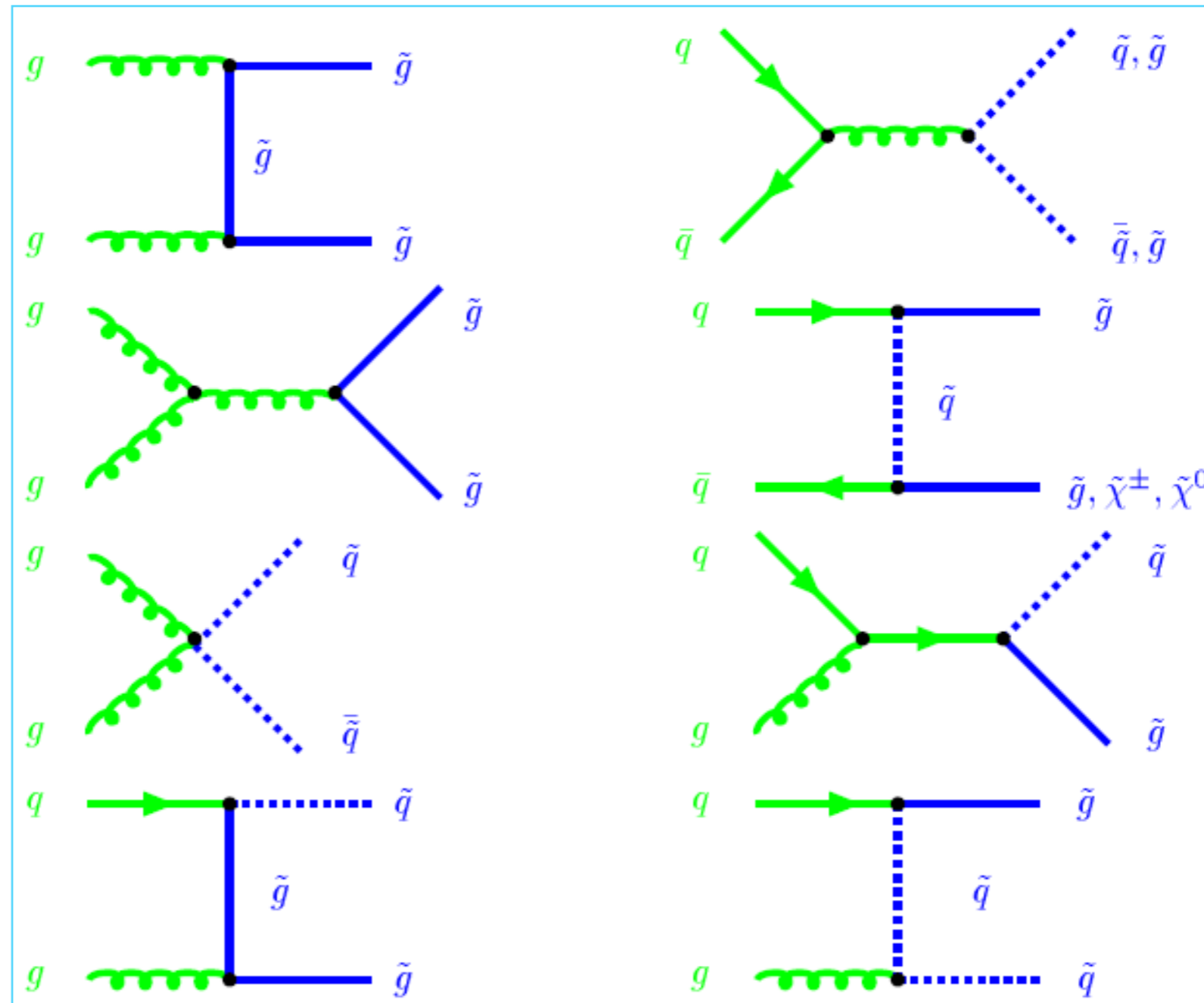
## Vertices



Annihilation



Quark-gluon Fusion

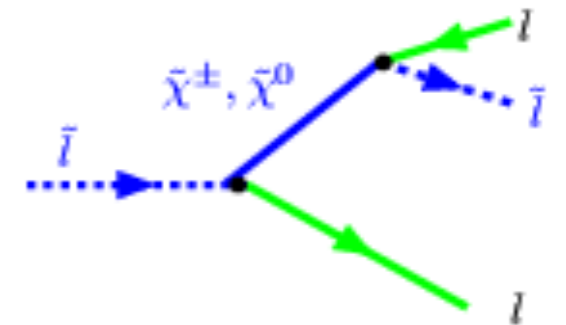
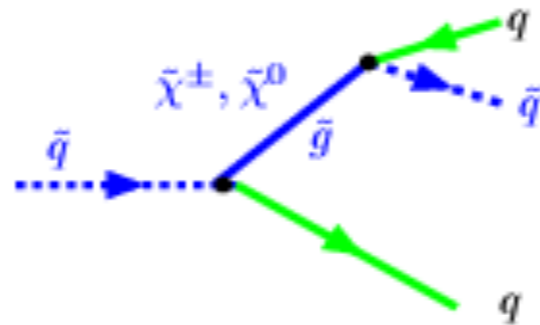


squarks

$$\tilde{q}_{L,R} \rightarrow q + \tilde{\chi}_i^0$$

$$\tilde{q}_L \rightarrow q' + \tilde{\chi}_i^\pm$$

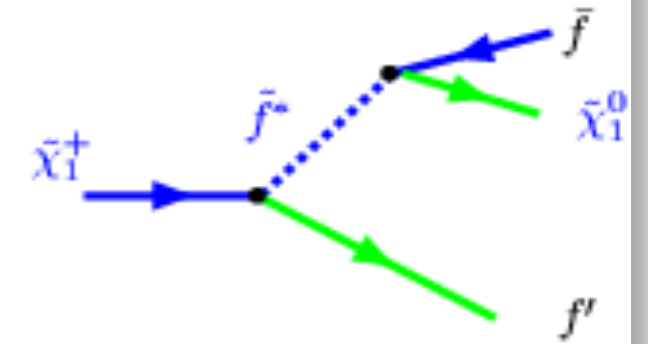
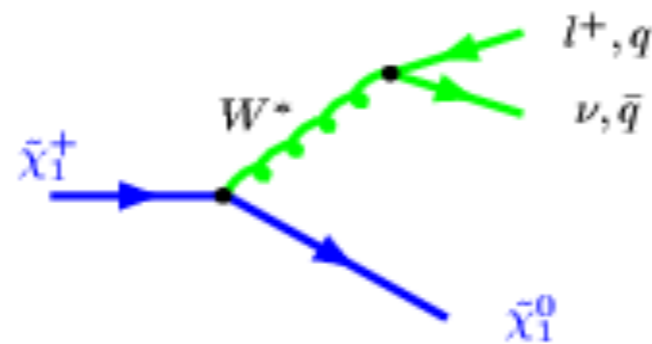
$$\tilde{q}_{L,R} \rightarrow q + g$$



sleptons

$$\tilde{l} \rightarrow l + \tilde{\chi}_i^0$$

$$\tilde{l}_L \rightarrow \nu_l + \tilde{\chi}_i^\pm$$



chargino

$$\tilde{\chi}_i^\pm \rightarrow e + \nu_e + \tilde{\chi}_i^0$$

$$\tilde{\chi}_i^\pm \rightarrow q + q' + \tilde{\chi}_i^0$$

neutralino

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + l^+ + l^-$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + q + q'$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^\pm + l^\pm + \nu_l$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + \nu_l + \bar{\nu}_l$$

Final states

$$l^+ l^- + \cancel{E}_T$$

$$2 \text{ jets} + \cancel{E}_T$$

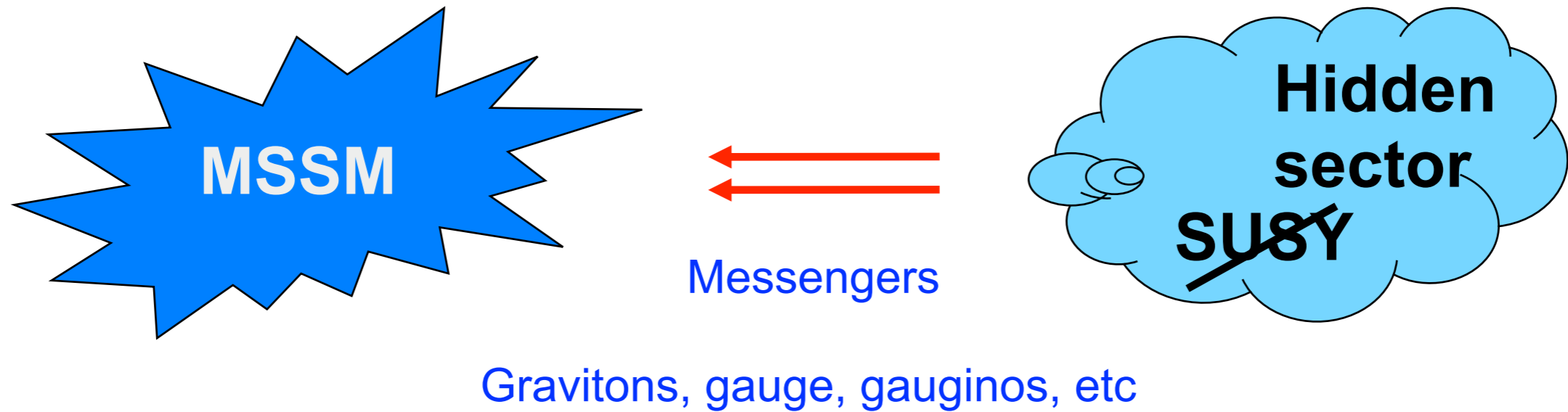
$$\gamma + \cancel{E}_T$$

$$\cancel{E}_T$$

gluino

$$\tilde{g} \rightarrow q + \bar{q} + \tilde{\gamma}$$

$$\tilde{g} \rightarrow g + \tilde{\gamma}$$



Breaking via F and D terms in a hidden sector

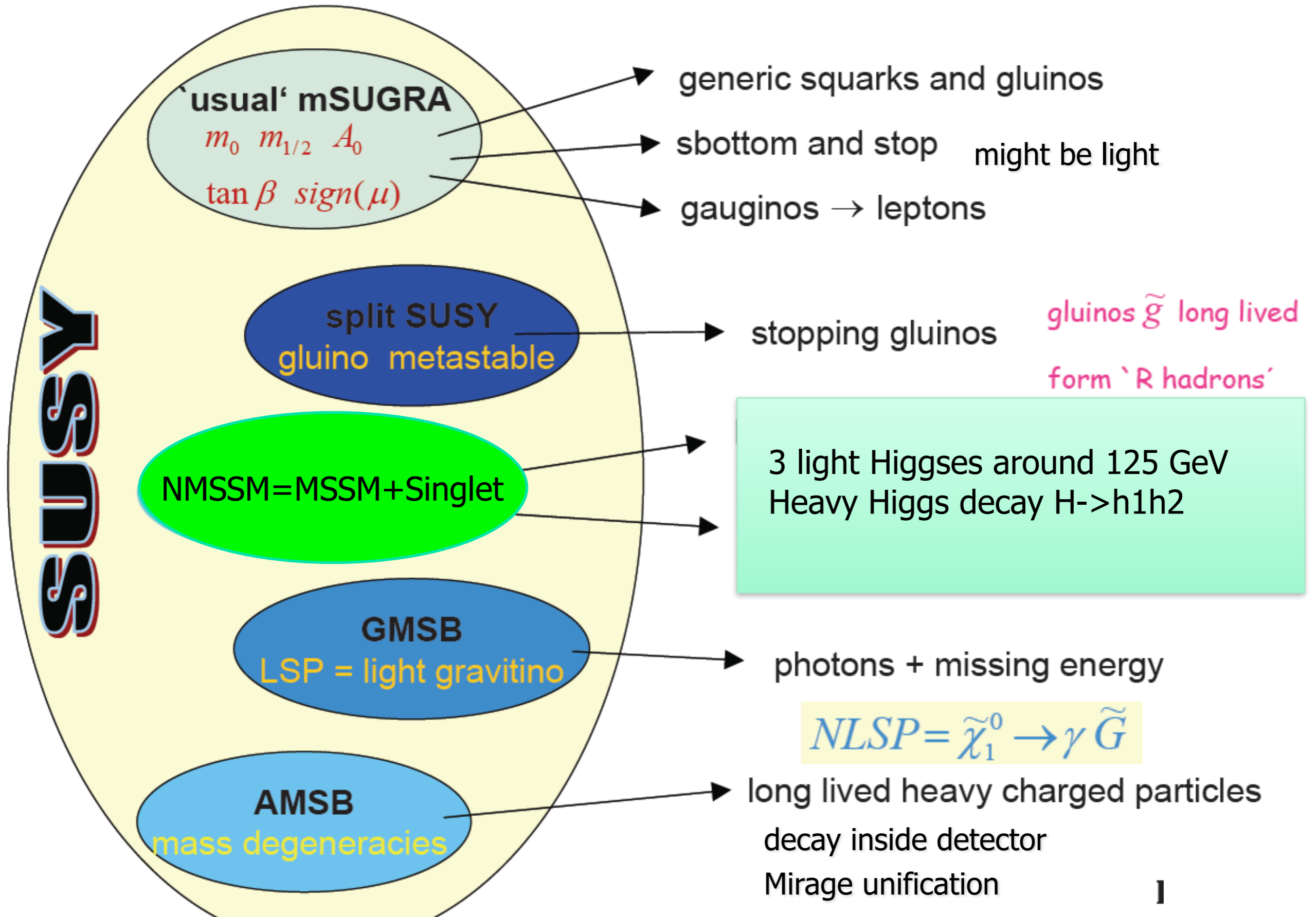
$$-L_{Soft} = \sum_{\alpha} M_{\alpha} \tilde{\lambda}_{\alpha} \tilde{\lambda}_{\alpha} + \sum_i m_{0i}^2 |A_i|^2 + \sum_{ijk} A_{ijk} A_i A_j A_k + \sum_{ij} B_{ij} A_i A_j$$

↑
↑
↑
↑

gauginos
scalar fields

Over 100 of free parameters !

# SUSY Models and Signatures



**Particle Phys**

- Direct production at colliders at high energies

- Indirect manifestation at low energies

Rare decays (  $B_s \rightarrow s\gamma$ ,  $B_s \rightarrow \mu^+\mu^-$ ,  $B_s \rightarrow \tau\nu$  )  
g-2 of the muon

- Search for long-lived SUSY particles

**Astro Phys**  
**(if SUSY DM)**

- Relic abundancy of Dark Matter in the Universe

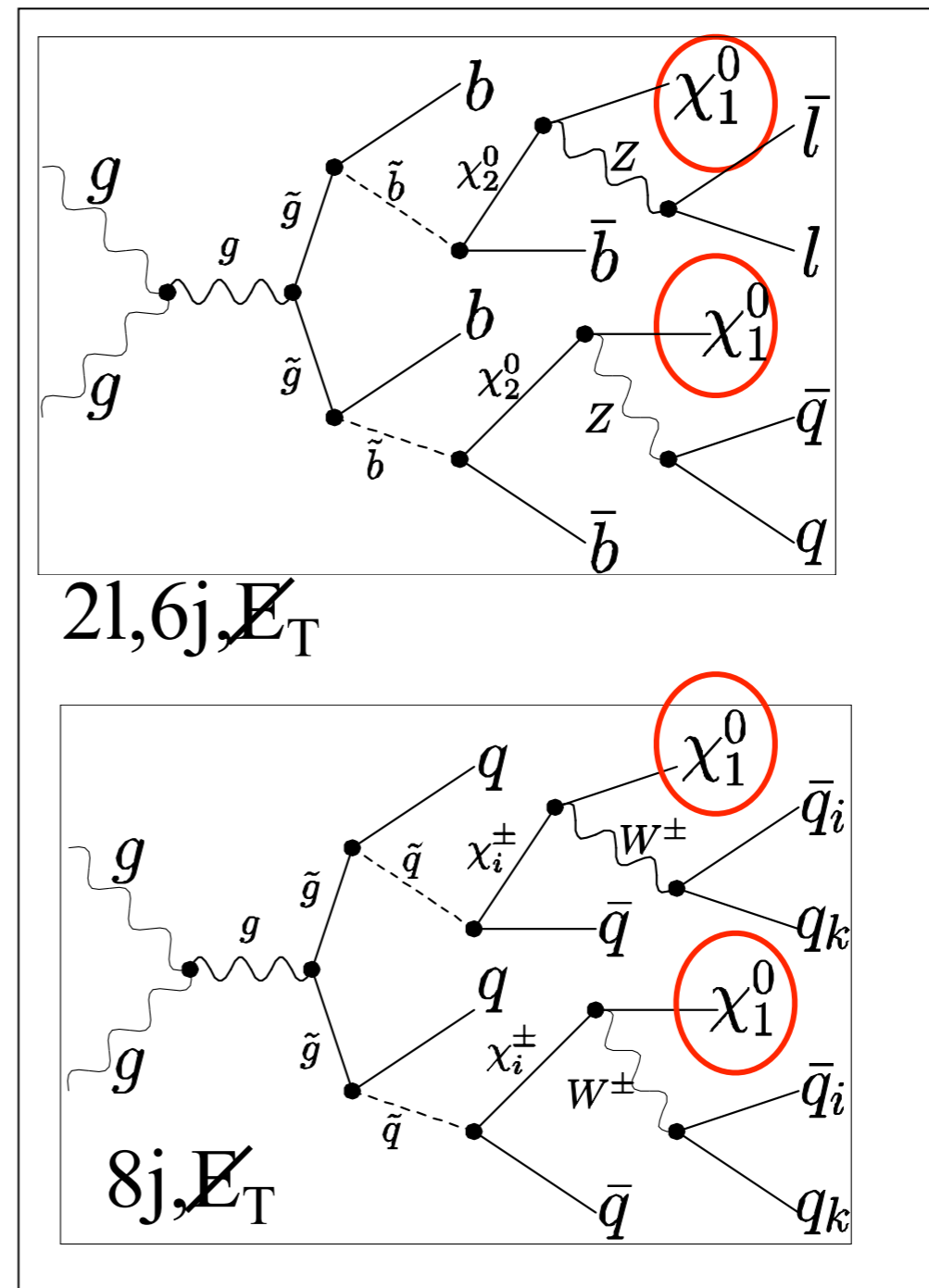
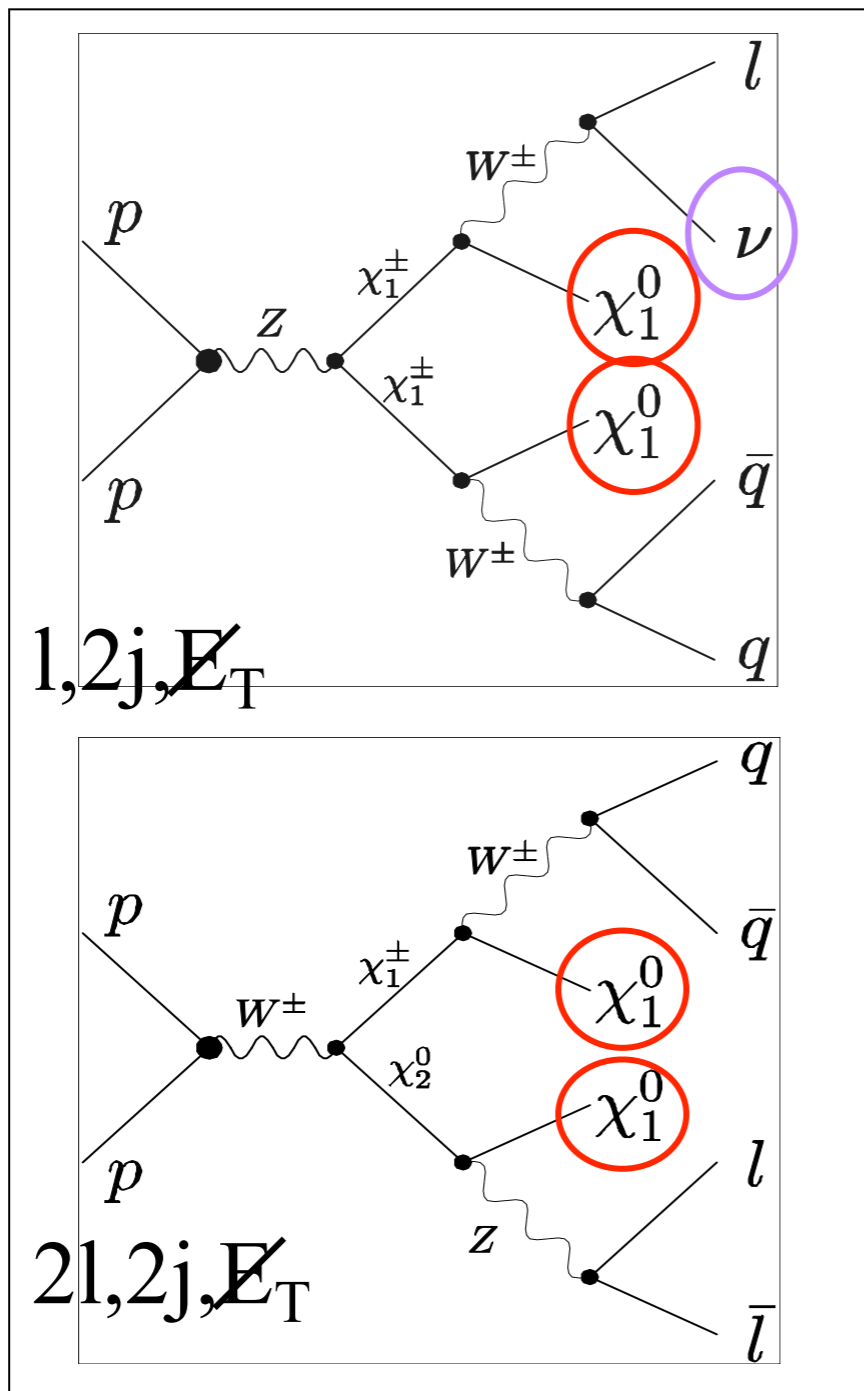
- DM annihilation signal in cosmic rays

- Direct DM interaction with nucleons

Nothing so far ...

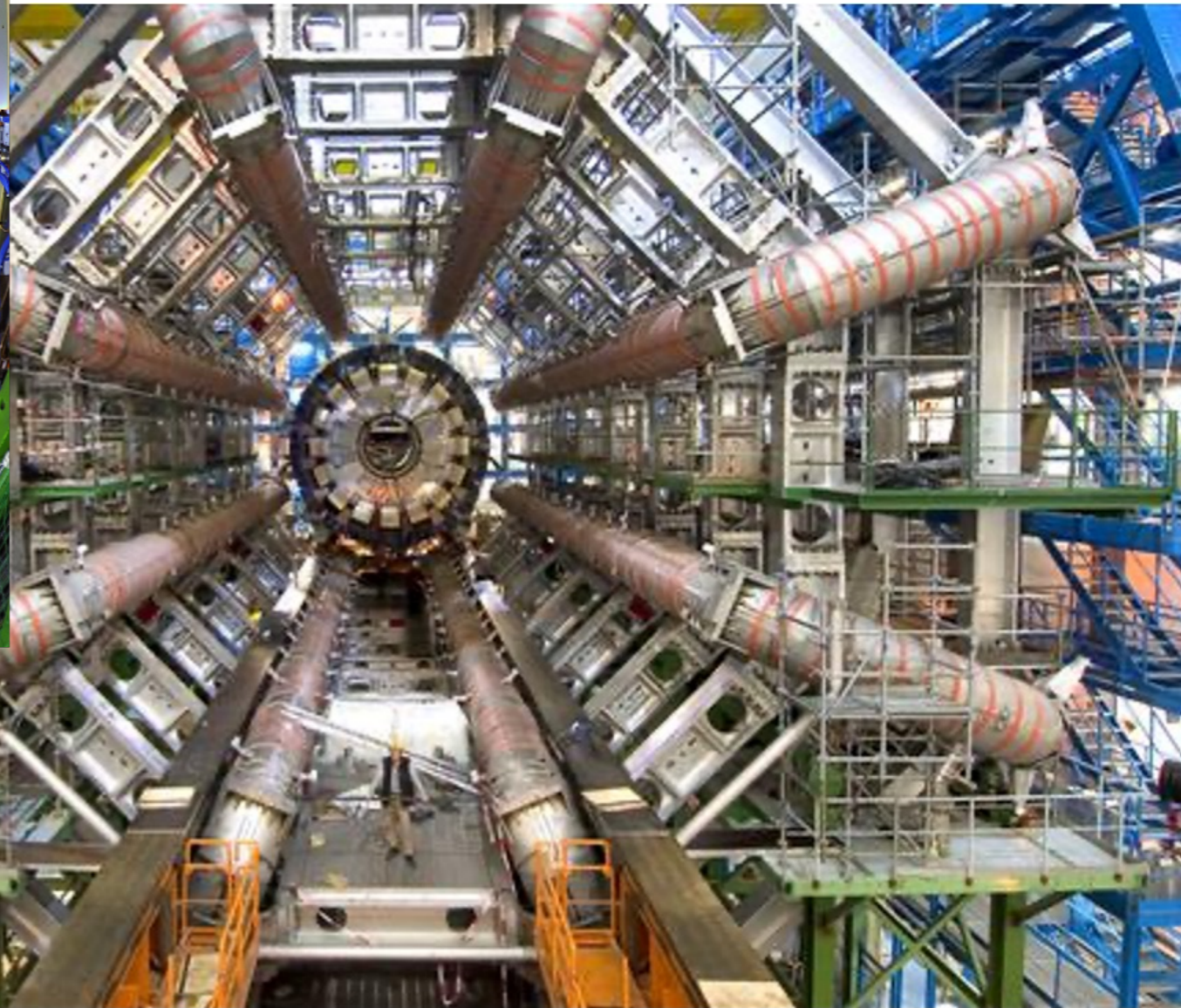
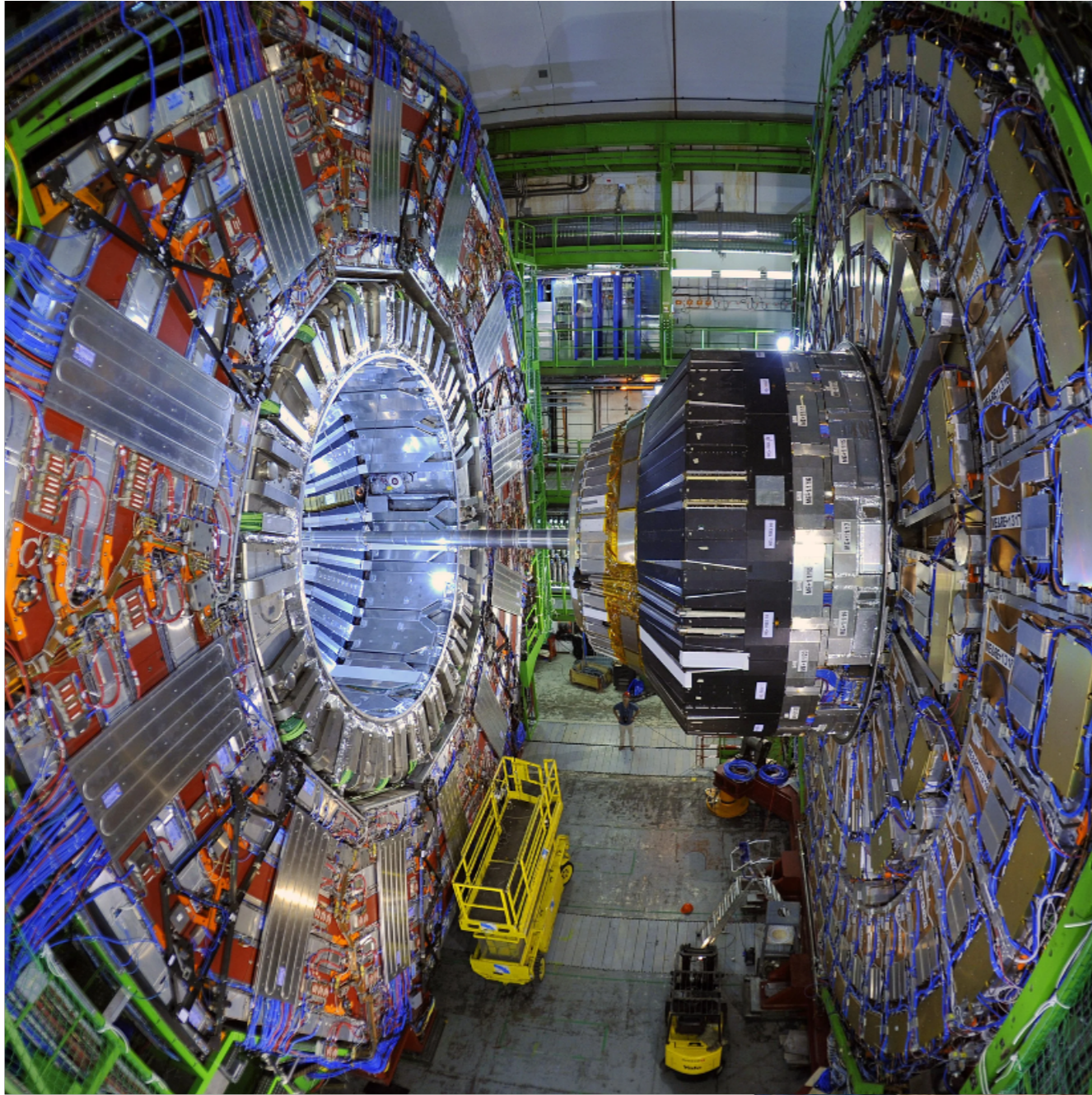
# CREATION AND DECAY OF SUPERPARTNERS IN CASCADE PROCESSES @ LHC

*weak int's*



*Strong int's*

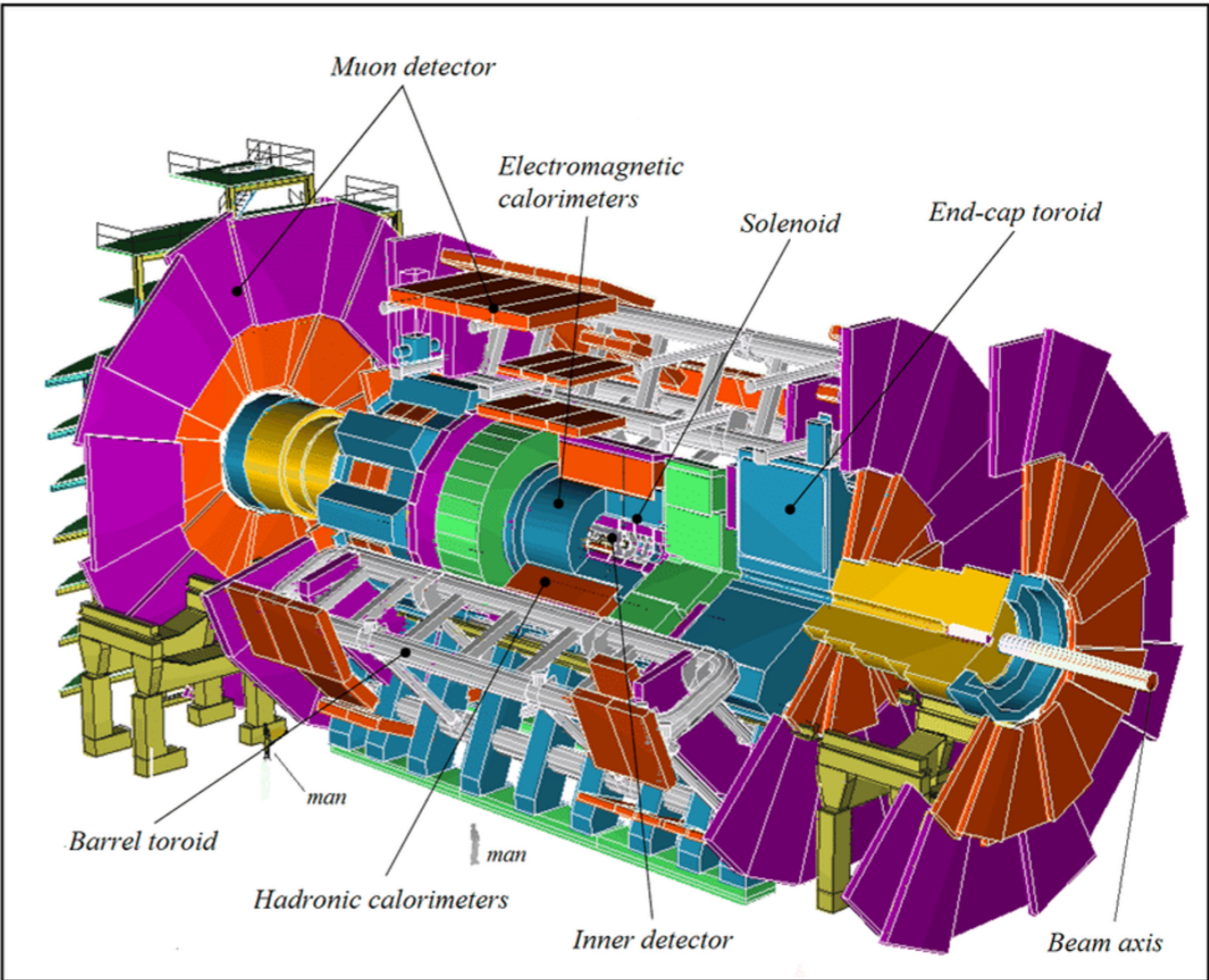
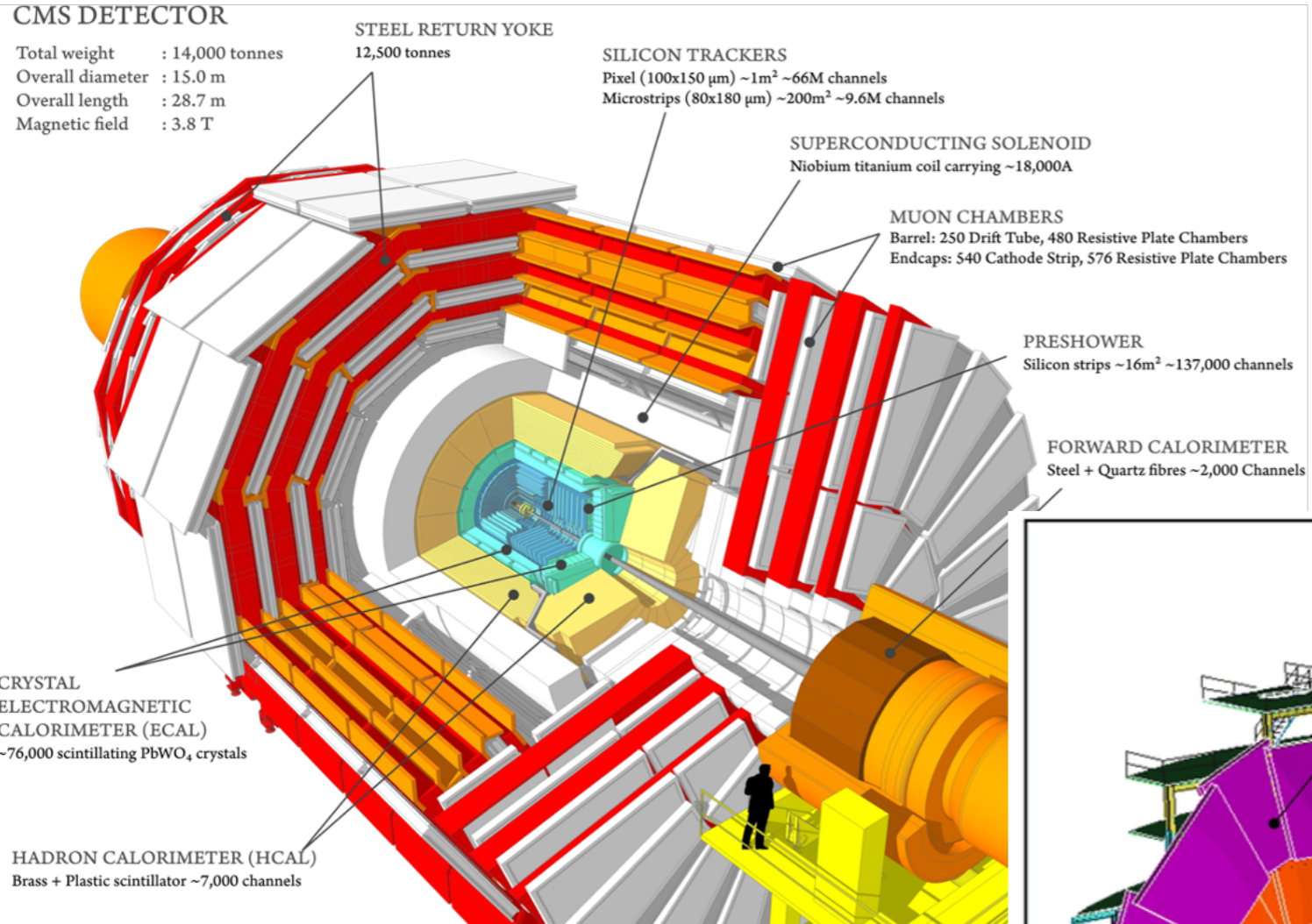
Typical SUSY signature: Missing Energy and Transverse Momentum





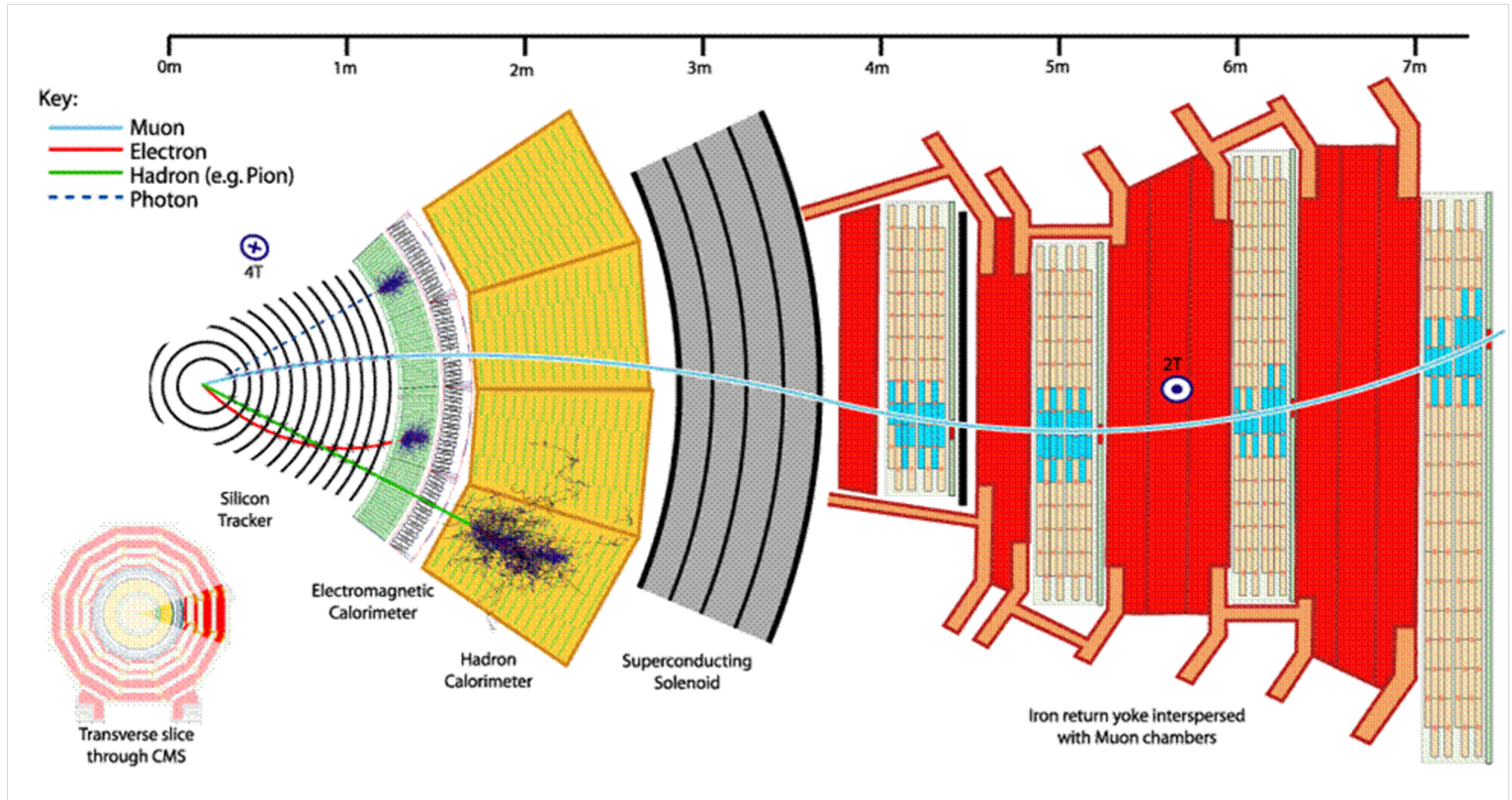
## CMS DETECTOR

Total weight : 14,000 tonnes  
 Overall diameter : 15.0 m  
 Overall length : 28.7 m  
 Magnetic field : 3.8 T



# TYPICAL EVENT SIGNATURE

“The standard” signature, CMS example



## Two ways to present and analyse data:

### 1. High energy input:

introduce universal parameters at high energy scale (GUT)

Example  $m_0, m_{1/2}, A_0, \tan \beta$  of MSSM

Advantage: small number of universal parameters for all masses

Disadvantage: strictly model dependent (MSSM, NMSSM, etc)

### 2. Low energy input:

use low energy parameters like masses of superpartners

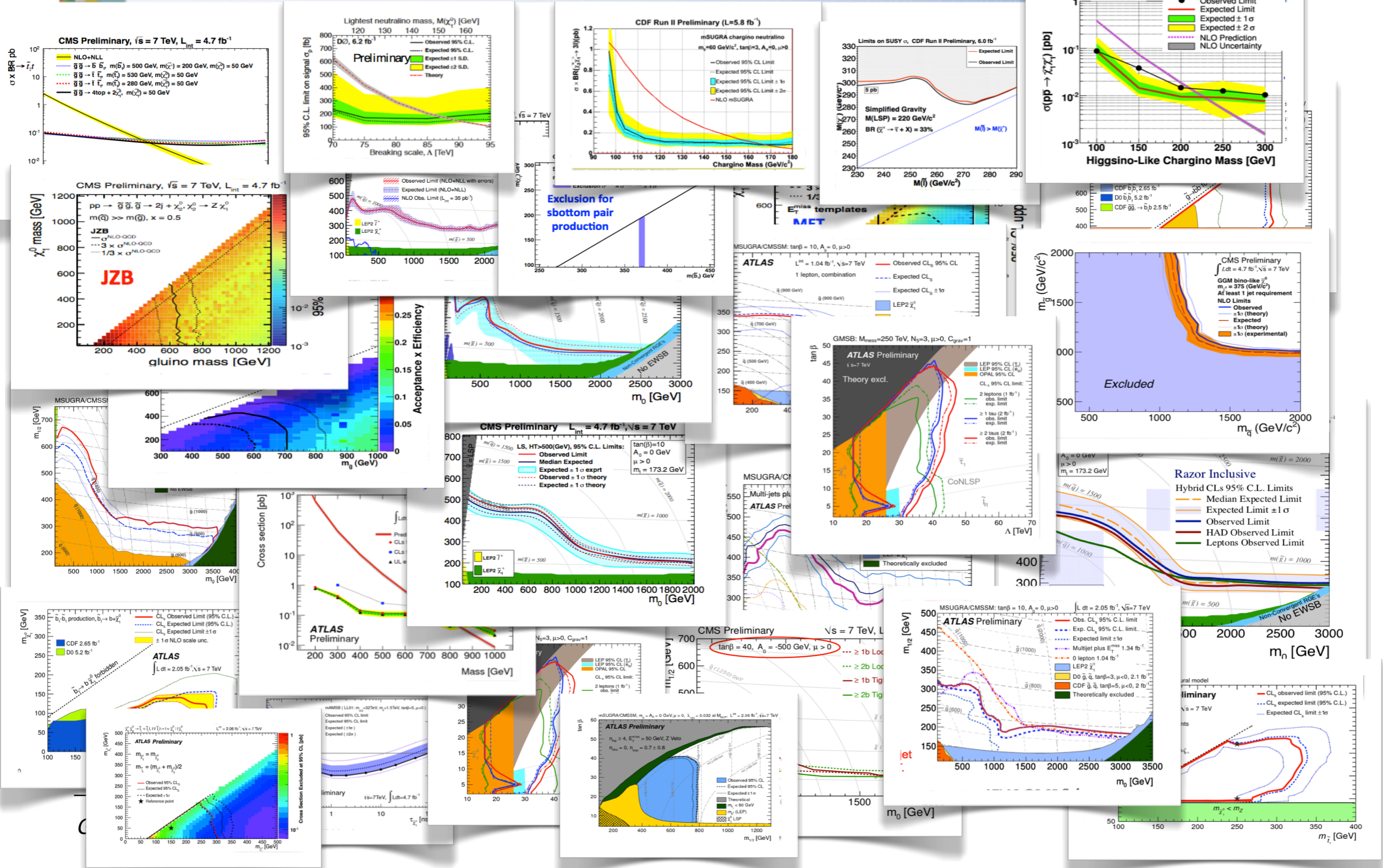
Example  $\tilde{m}_g, \tilde{m}_q, \tilde{m}_\chi$  or  $m_A, \tan \beta$

Advantage: less model dependent

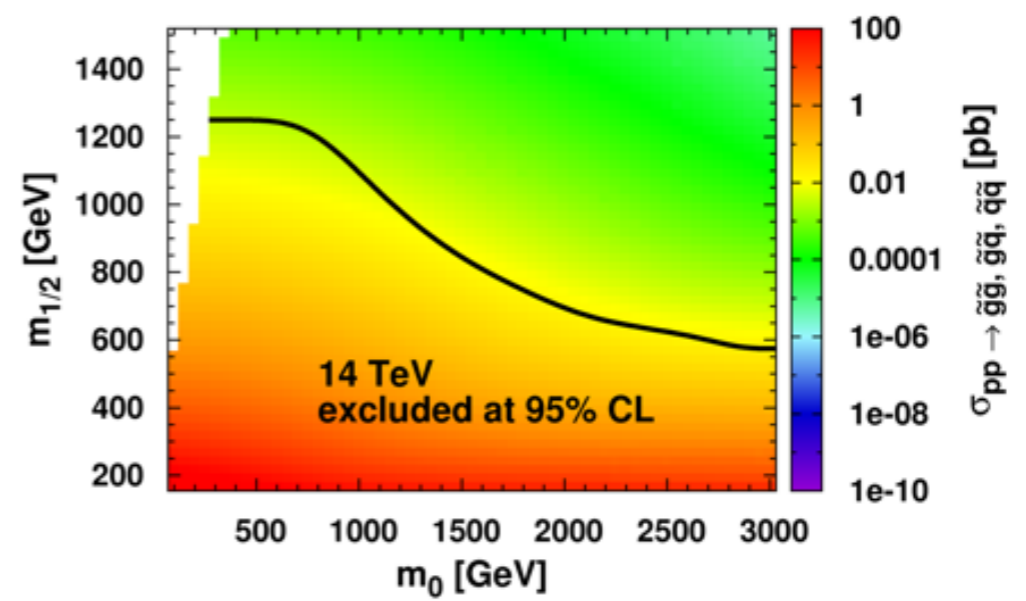
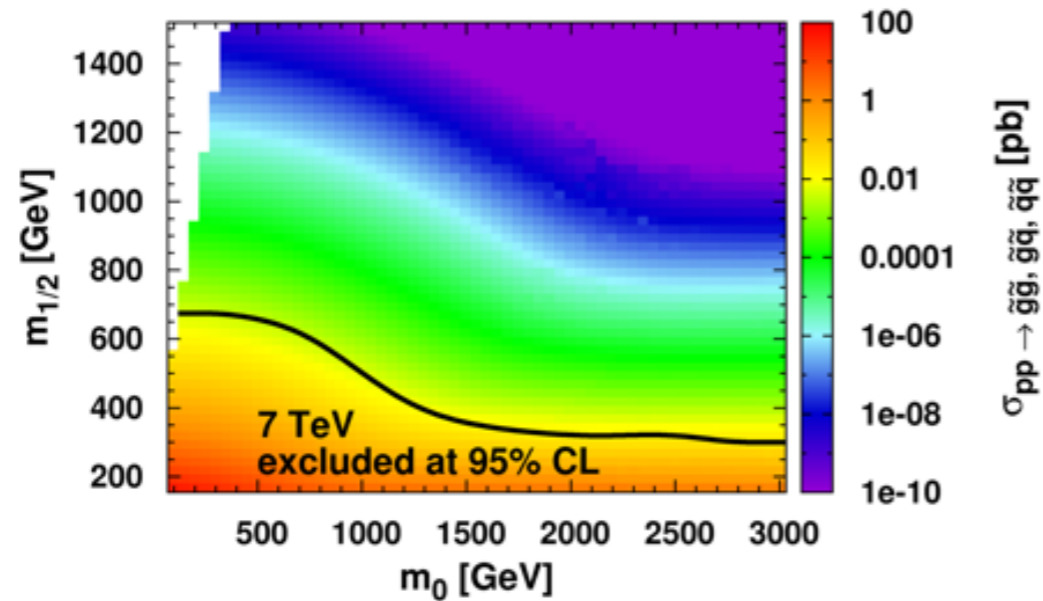
Disadvantage: many parameters, process dependent

Both approaches are used

# SUSY searches



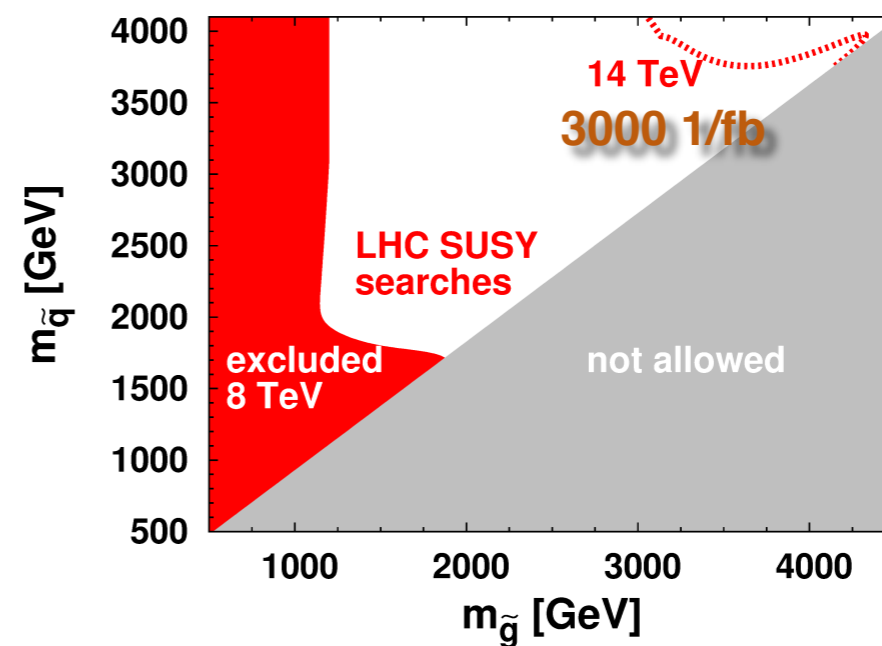
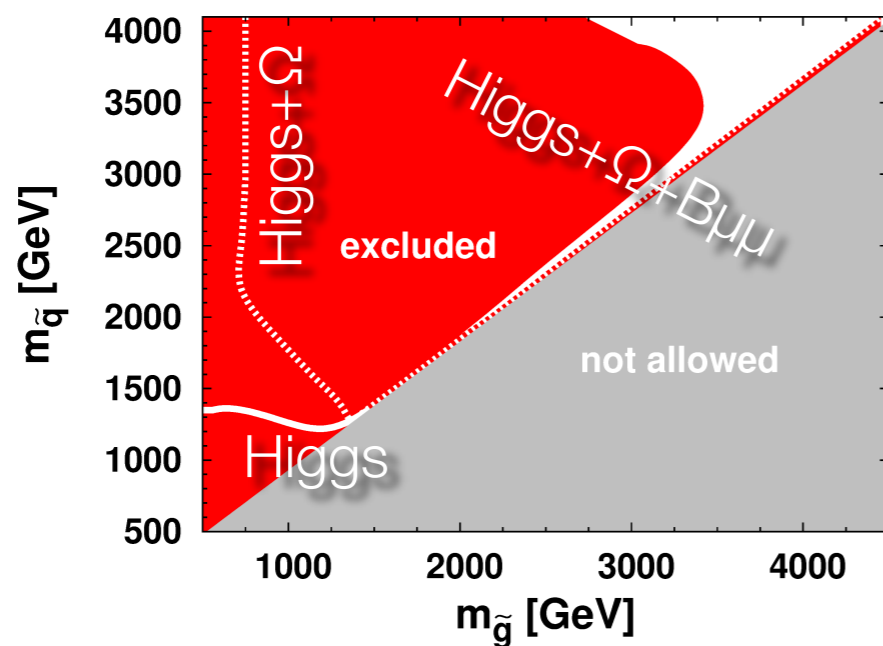
# WHAT IS THE LHC REACH?



Universal scenario

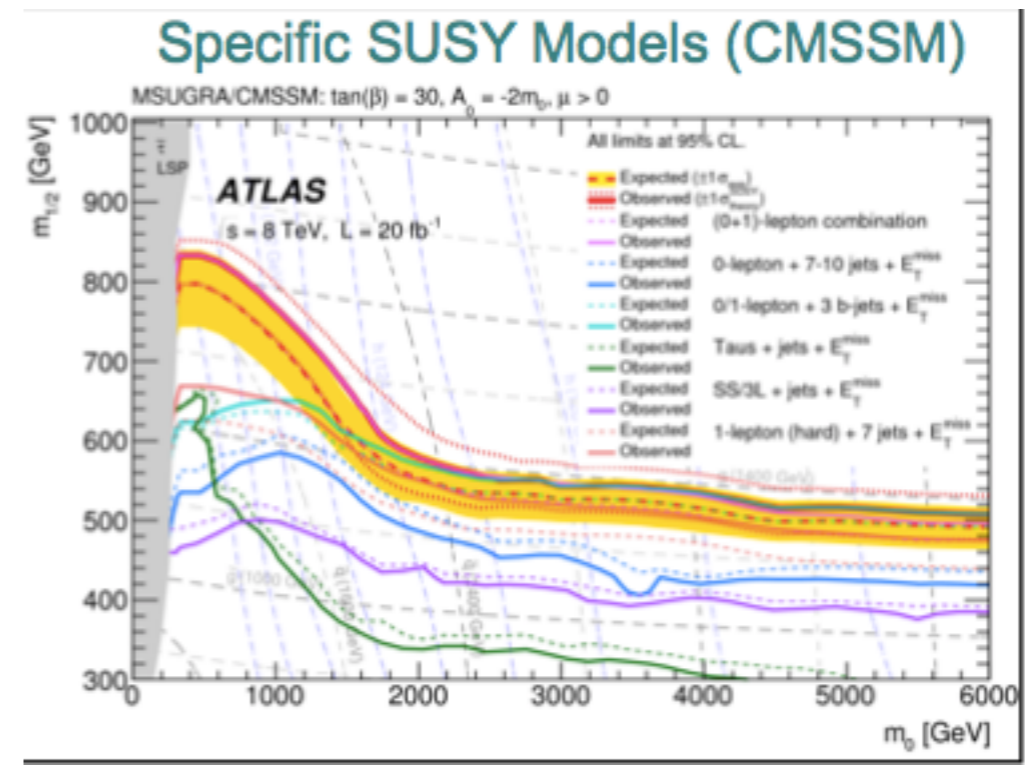
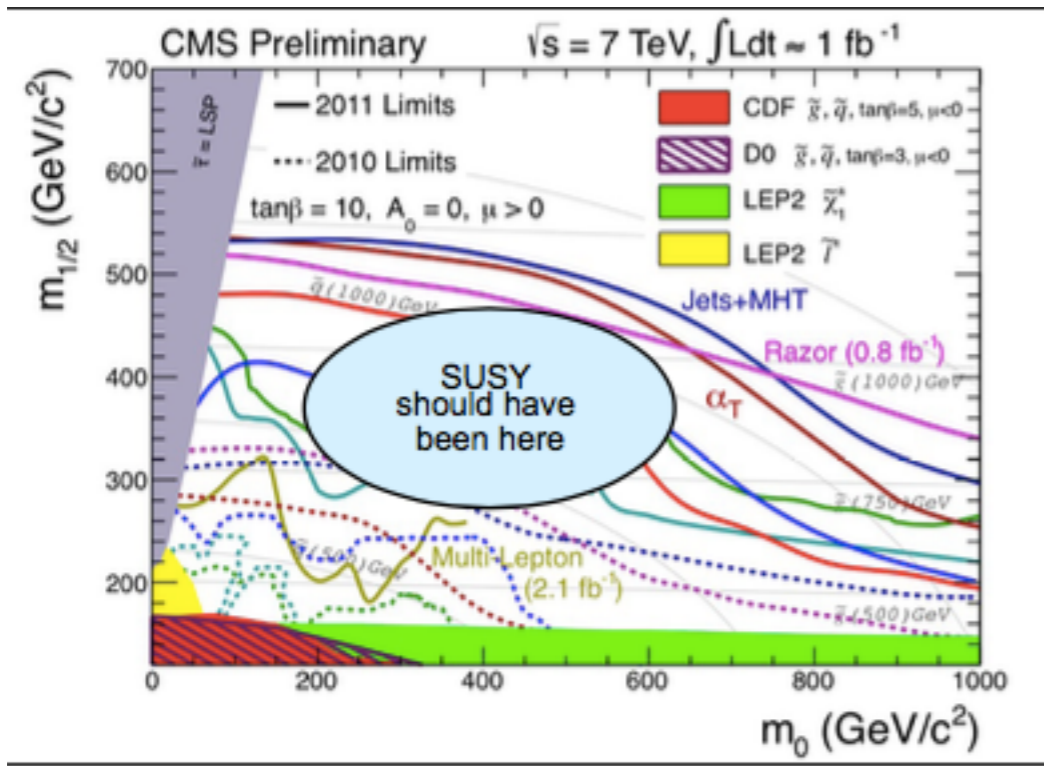
CMSSM

NMSSM

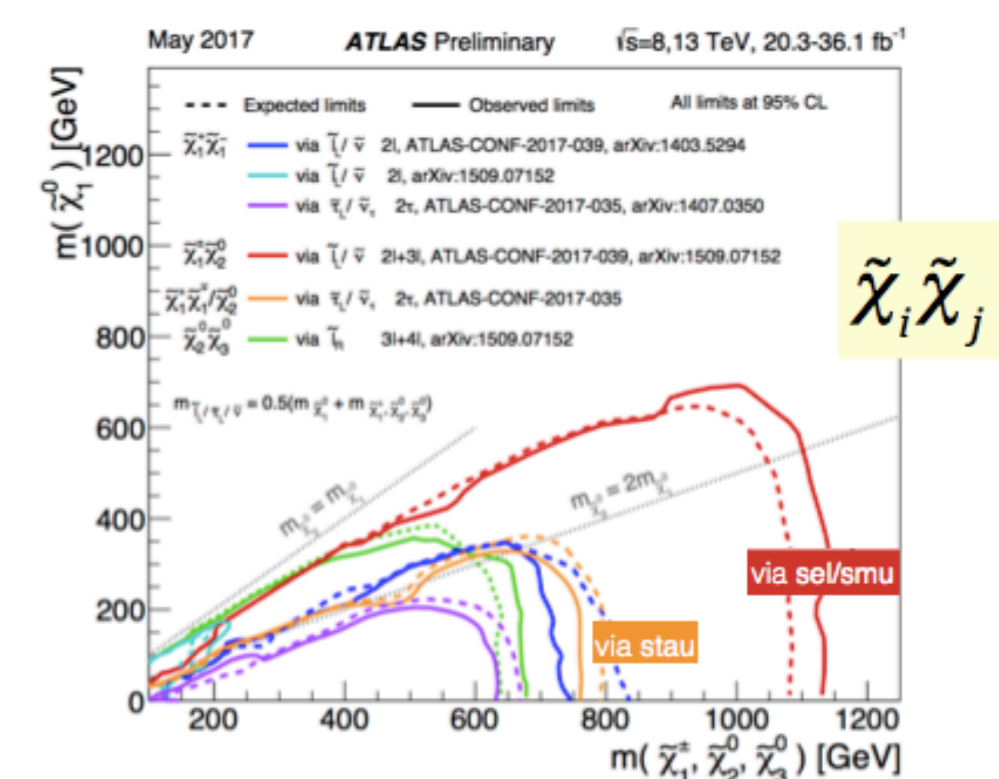
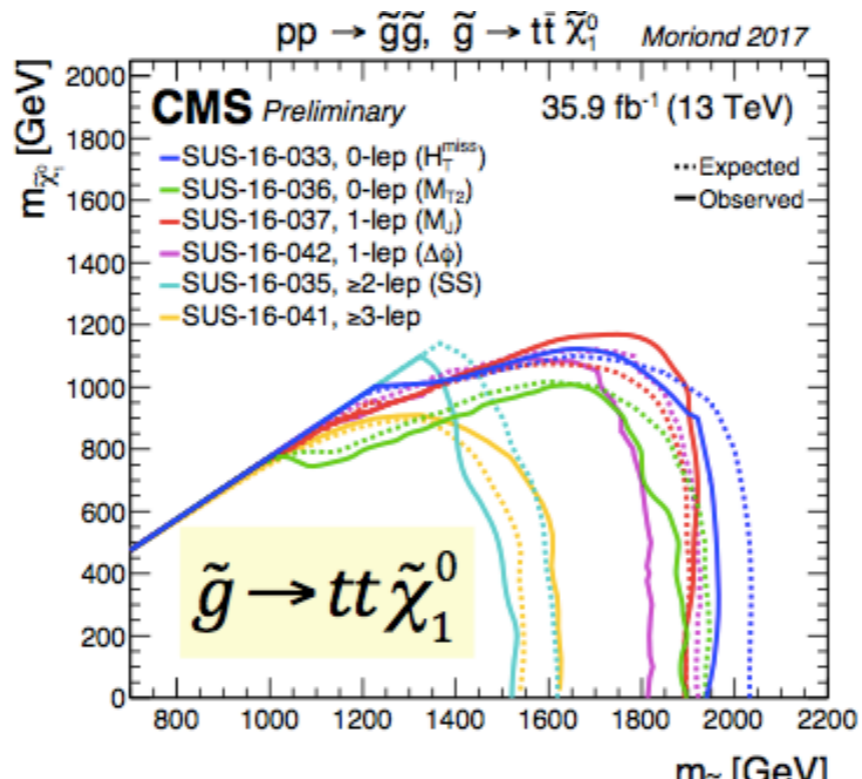
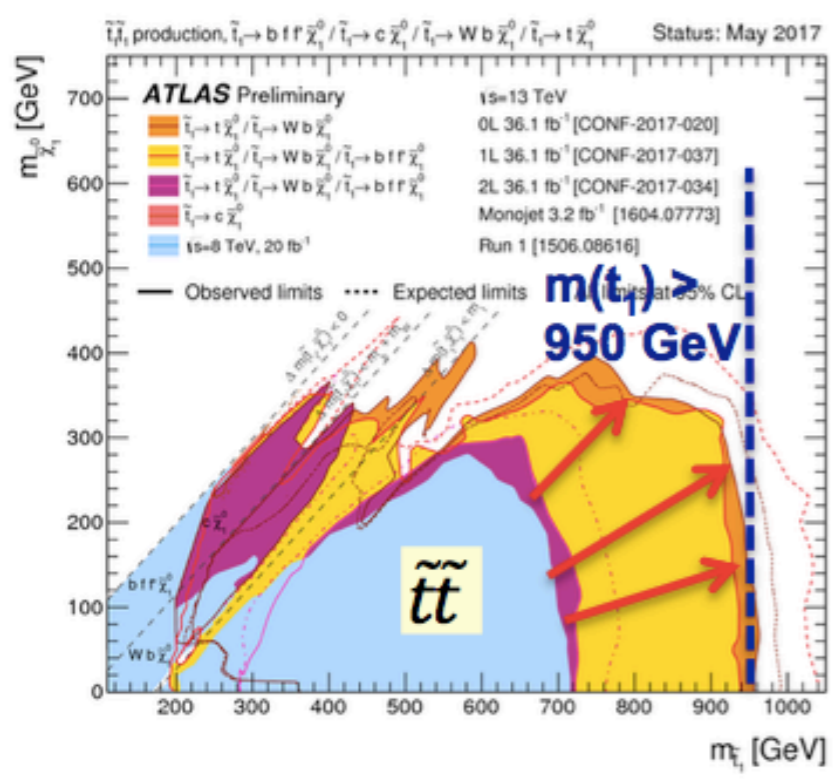


Masses of superpartners

# WHAT IS THE LHC REACH NOW?



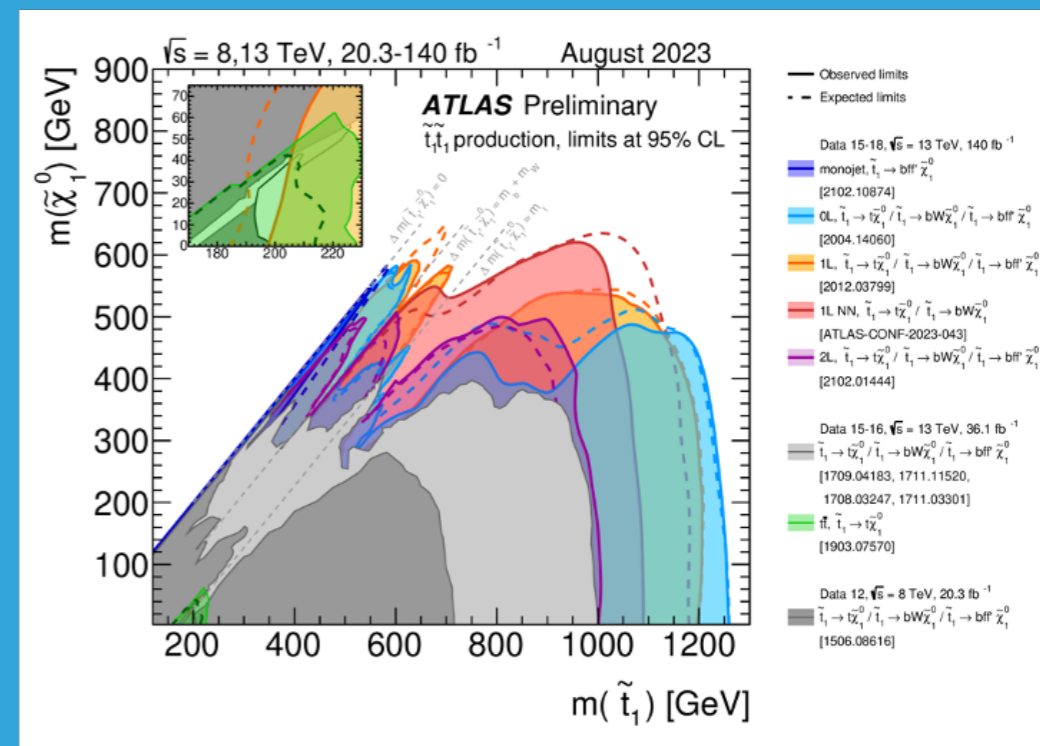
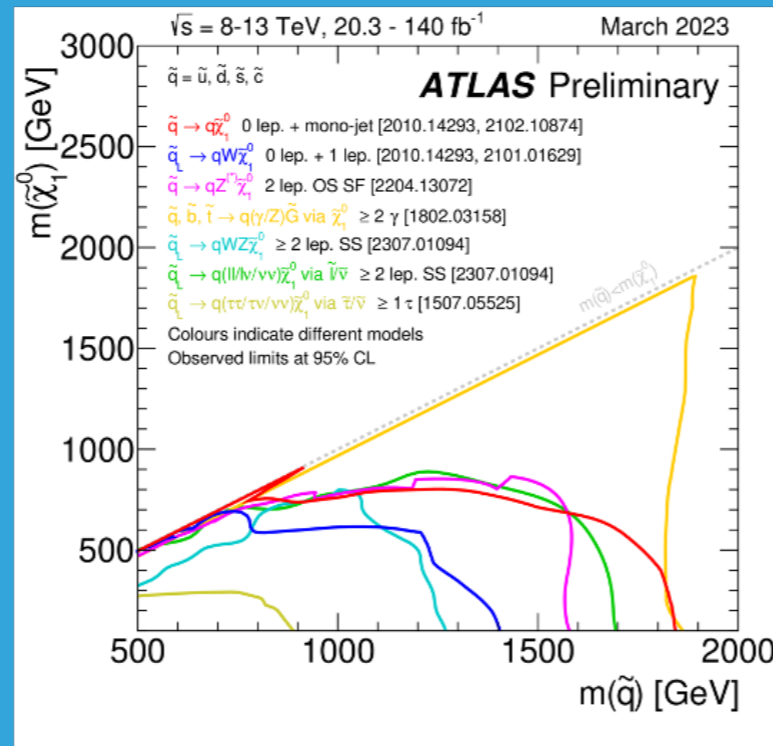
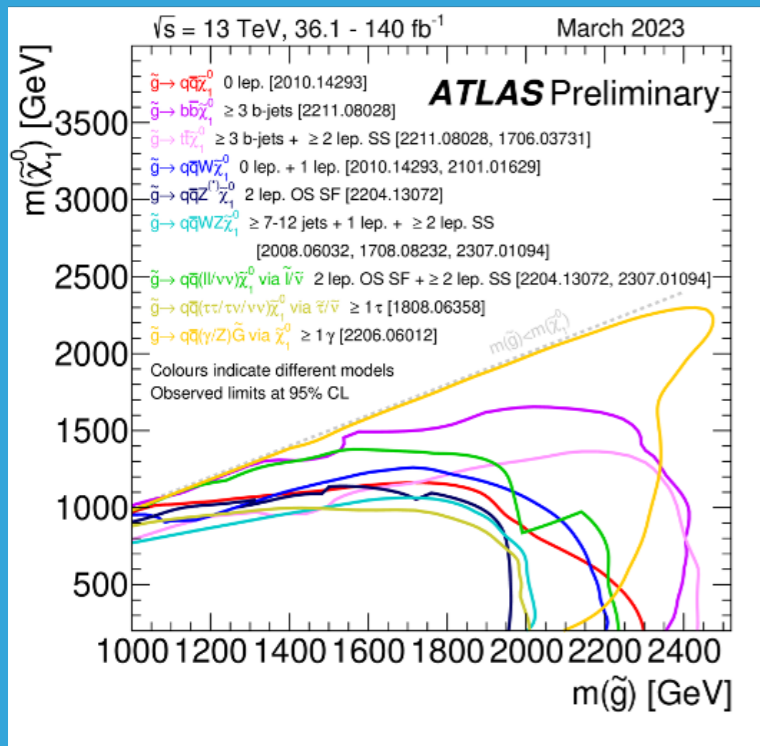
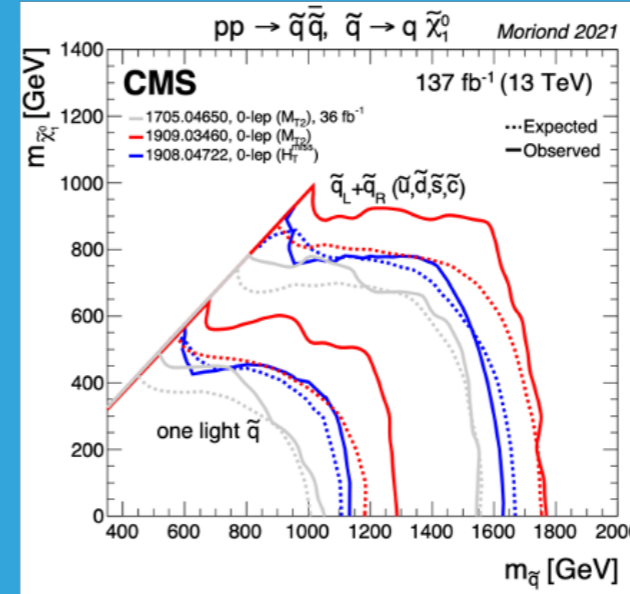
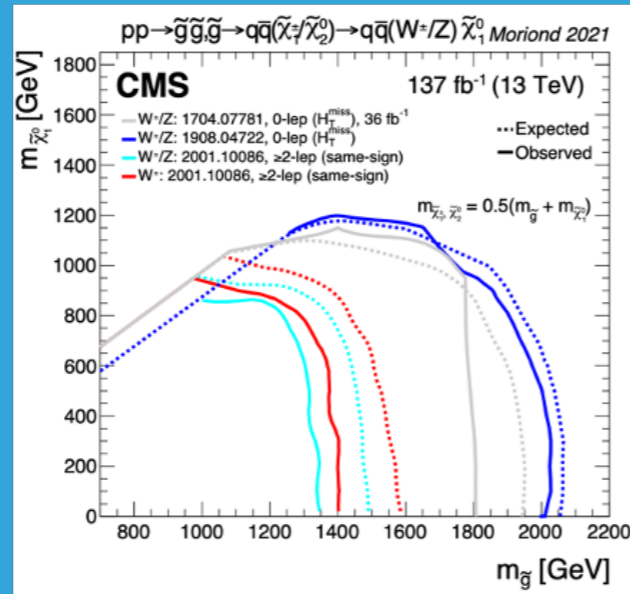
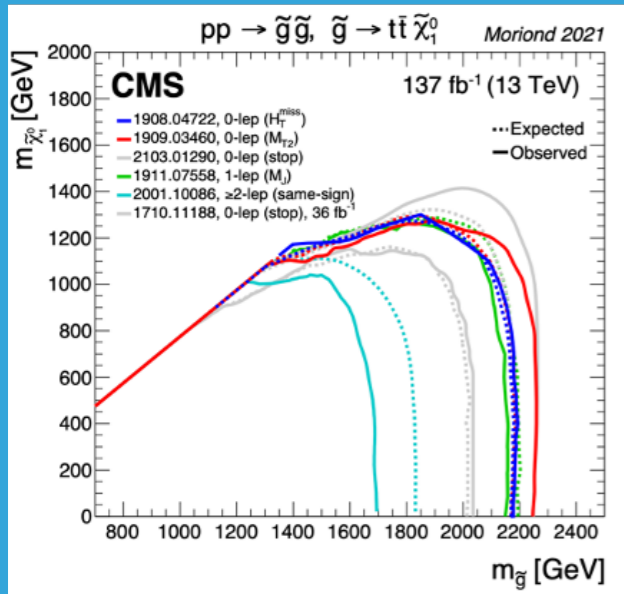
## Universal parameters

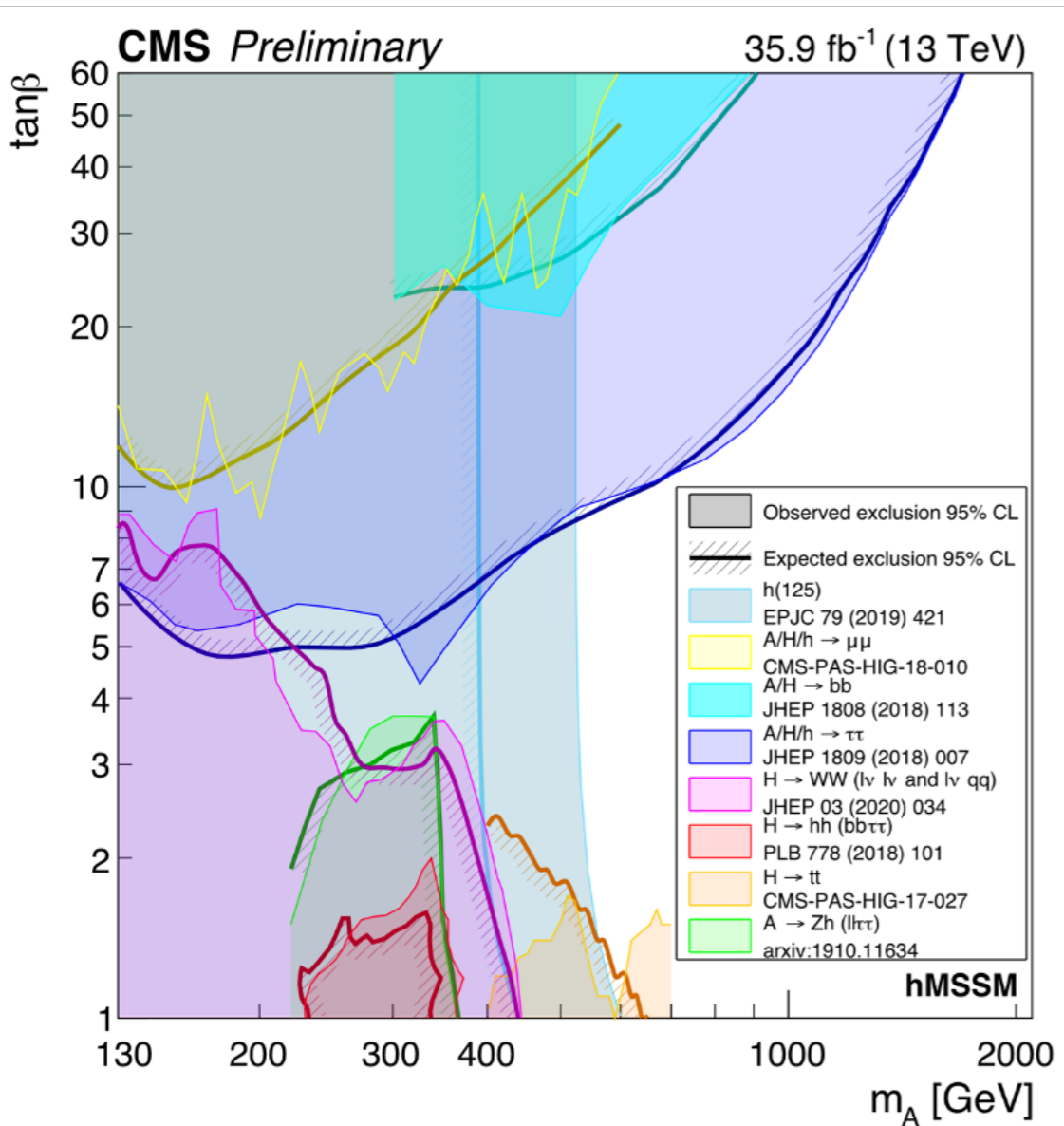


## Masses of superpartners

# RECENT LHC LIMITS ON MSSM '23 23

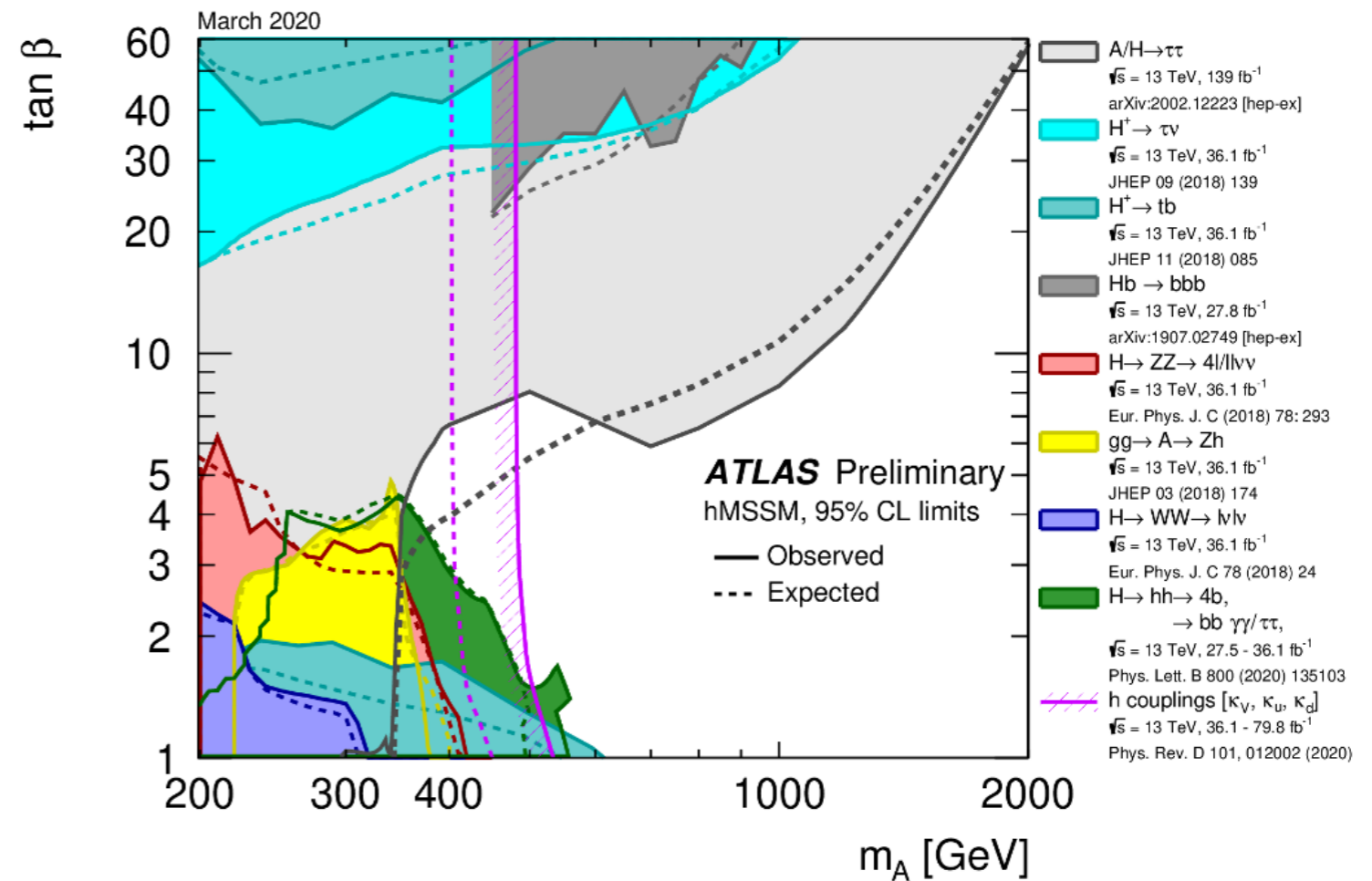
## RUN2 LHC limits on MSSM, ATLAS&CMS





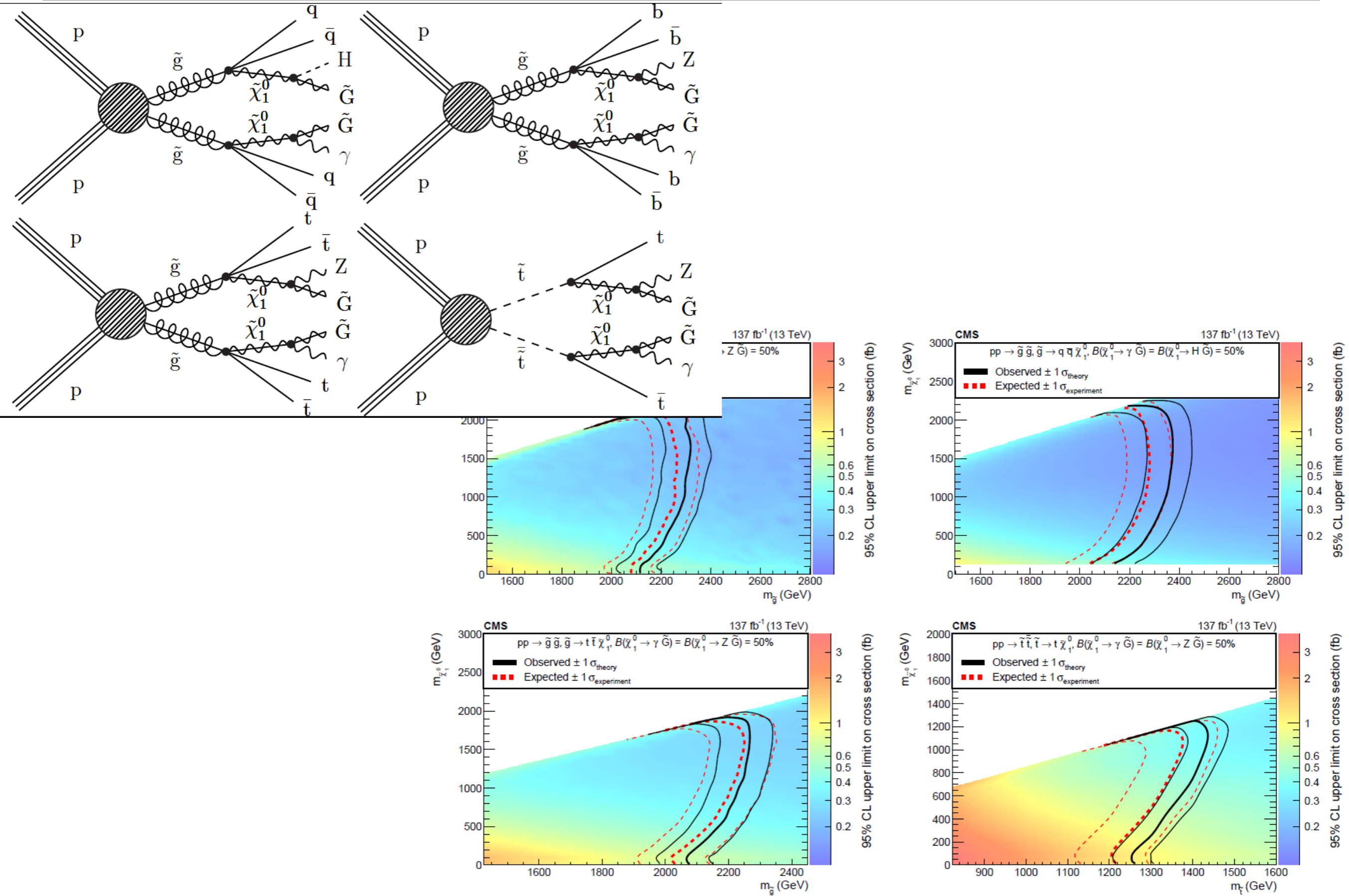
## 2HDM hMSSM combined results, RUN2

Much more details see in a talk by [Adam Bailey](#)  
 (+ comprehensive list of analyses for ATLAS & CMS)

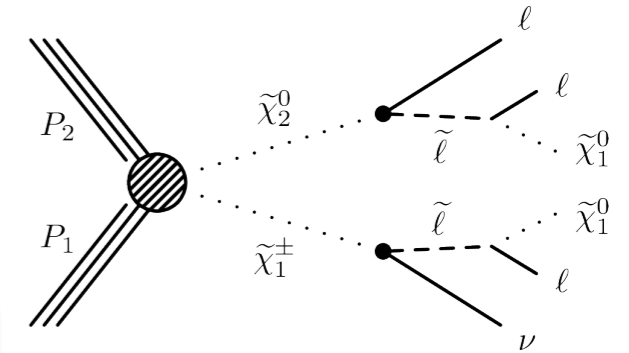




# RUN2 LHC LIMITS ON GMSB MSSM, CMS



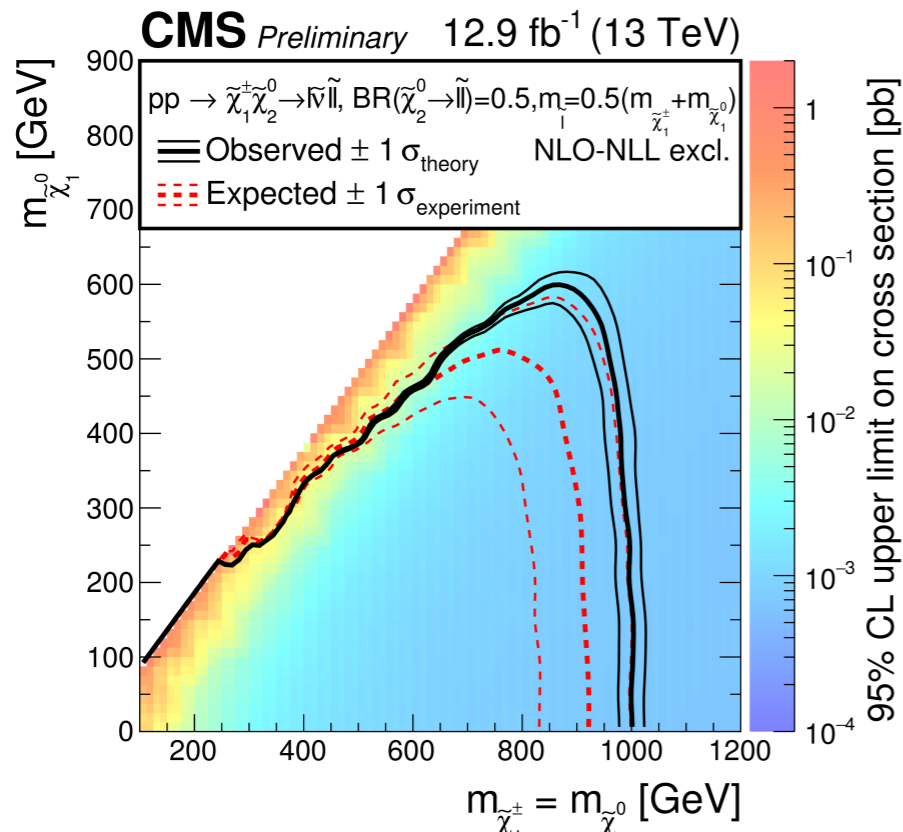
## Chargino / neutralino production



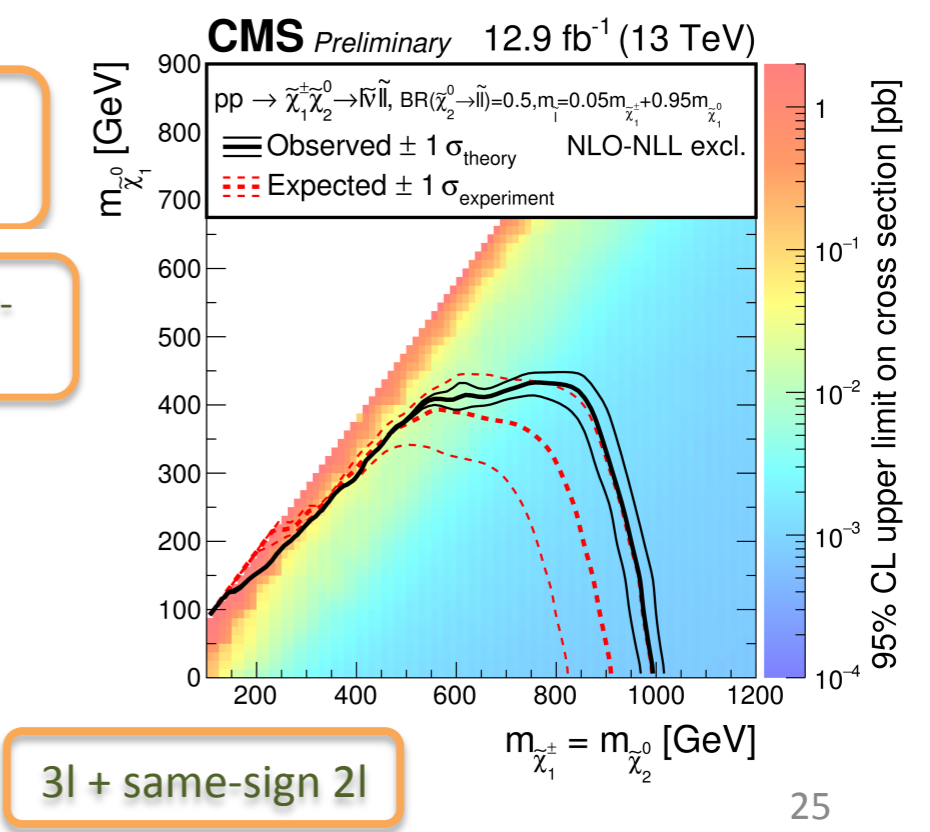
### Direct production of “electroweakino” pairs

- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

## No light EWkinos



Effect of change in intermediate slepton mass



3l + same-sign 2l

# ATLAS AND CMS SUSY Limits, 2023

Search Category	Signature	Channels	Decay	Reference	Limit (TeV)	Notes	Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	$0 e, \mu$	2-6 jets	$E_T^{miss}$	140	$\tilde{q}$ [1x, 8x Degen.] 1.0, 1.85	$m(\tilde{\chi}_1^0) < 400$ GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{miss}$	140	$\tilde{q}$ [8x Degen.] 0.9	$m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	2102.10874
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	$0 e, \mu$	2-6 jets	$E_T^{miss}$	140	$\tilde{g}$ 2.3	$m(\tilde{\chi}_1^0) = 0$ GeV	2010.14293
						Forbidden 1.15-1.95	$m(\tilde{\chi}_1^0) = 1000$ GeV	2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	$1 e, \mu$	2-6 jets		140	$\tilde{g}$ 2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	$E_T^{miss}$	140	$\tilde{g}$ 2.2	$m(\tilde{\chi}_1^0) < 700$ GeV	2204.13072
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	$0 e, \mu$	7-11 jets	$E_T^{miss}$	140	$\tilde{g}$ 1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032
		SS $e, \mu$	6 jets		140	$\tilde{g}$ 1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	2307.01094
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{u}\tilde{\chi}_1^0$	$0-1 e, \mu$	3 b	$E_T^{miss}$	140	$\tilde{g}$ 2.45	$m(\tilde{\chi}_1^0) < 500$ GeV	2211.08028
		SS $e, \mu$	6 jets		140	$\tilde{g}$ 1.25	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	1909.08457
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	$0 e, \mu$	2 b	$E_T^{miss}$	140	$\tilde{b}_1$ 1.255	$m(\tilde{\chi}_1^0) < 400$ GeV	2101.12527
						$\tilde{b}_1$ 0.68	$10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$	$0 e, \mu$	6 b	$E_T^{miss}$	140	$\tilde{b}_1$ Forbidden	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1908.03122
		$2 \tau$	2 b	$E_T^{miss}$	140	$\tilde{b}_1$ 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	$0-1 e, \mu$	$\geq 1$ jet	$E_T^{miss}$	140	$\tilde{t}_1$ 1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	$1 e, \mu$	3 jets/1 b	$E_T^{miss}$	140	$\tilde{t}_1$ Forbidden	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799, ATLAS-CONF-2023-043
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	$1-2 \tau$	2 jets/1 b	$E_T^{miss}$	140	$\tilde{t}_1$ Forbidden	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	$0 e, \mu$	2 c	$E_T^{miss}$	36.1	$\tilde{t}_1$ 0.85	$m(\tilde{\chi}_1^0) = 0$ GeV	1805.01649
	$0 e, \mu$	mono-jet	$E_T^{miss}$	140	$\tilde{t}_1$ 0.55	$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	2102.10874	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	$1-2 e, \mu$	1-4 b	$E_T^{miss}$	140	$\tilde{t}_1$ 0.067-1.18	$m(\tilde{\chi}_2^0) = 500$ GeV	2006.05880
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 + Z$	$3 e, \mu$	1 b	$E_T^{miss}$	140	$\tilde{t}_1$ Forbidden	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880
EW direct	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via WZ	Multiple $\ell$ /jets	$\geq 1$ jet	$E_T^{miss}$	140	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ 0.96	$m(\tilde{\chi}_1^0) = 0$ , wino-bino	2106.01676, 2108.07586
		$ee, \mu\mu$		$E_T^{miss}$	140	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ 0.205	$m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^+\tilde{\chi}_1^+$ via WW	$2 e, \mu$		$E_T^{miss}$	140	$\tilde{\chi}_1^+$ 0.42	$m(\tilde{\chi}_1^0) = 0$ , wino-bino	1908.08215
	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via Wh	Multiple $\ell$ /jets		$E_T^{miss}$	140	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ Forbidden	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^+\tilde{\chi}_1^+$ via $\tilde{\chi}_1/\tilde{\nu}$	$2 e, \mu$		$E_T^{miss}$	140	$\tilde{\chi}_1^+$ 1.0	$m(\tilde{\chi}_1^0) = 0$ , wino-bino	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	$2 \tau$		$E_T^{miss}$	140	$\tilde{\tau}$ [ $\tilde{\tau}_R, \tilde{\tau}_{R,L}$ ] 0.34, 0.48	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2023-029
	$\tilde{\chi}_{1,R}\tilde{\chi}_{1,R}, \tilde{\chi}_1 \rightarrow \ell\tilde{\chi}_1^0$	$2 e, \mu$	0 jets	$E_T^{miss}$	140	$\tilde{\chi}_1$ 0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215
		$ee, \mu\mu$	$\geq 1$ jet	$E_T^{miss}$	140	$\tilde{\chi}_1$ 0.26	$m(\tilde{\chi}_1^0) = 0$	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	$0 e, \mu$	$\geq 3$ b	$E_T^{miss}$	140	$\tilde{H}$ 0.94	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$	To appear
		$4 e, \mu$	0 jets	$E_T^{miss}$	140	$\tilde{H}$ 0.55	$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	2103.11684
		$0 e, \mu$	$\geq 2$ large jets	$E_T^{miss}$	140	$\tilde{H}$ 0.45-0.93	$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	2108.07586
		$2 e, \mu$	$\geq 2$ jets	$E_T^{miss}$	140	$\tilde{H}$ 0.77	$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 0.5$	2204.13072
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{miss}$	140	$\tilde{\chi}_1^\pm$ 0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^\pm$ 0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{miss}$	140	$\tilde{g}$ 2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx		$E_T^{miss}$	140	$\tilde{g}$ [ $\tau(\tilde{g}) = 10$ ns]	$m(\tilde{\chi}_1^0) = 100$ GeV	2205.06013
	Displ. lep		$E_T^{miss}$	140	$\tilde{e}, \tilde{\mu}$ 0.7	$\tau(\tilde{\ell}) = 0.1$ ns	2011.07812	
	pixel dE/dx		$E_T^{miss}$	140	$\tilde{\tau}$ 0.34, 0.36	$\tau(\tilde{\ell}) = 0.1$ ns	2011.07812	
						$\tau(\tilde{\ell}) = 10$ ns	2205.06013	
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell \rightarrow \ell\ell\ell$	$3 e, \mu$		$E_T^{miss}$	140	$\tilde{\chi}_1^+/\tilde{\chi}_1^0$ [ $BR(Z\tau)=1, BR(Ze)=1$ ] 0.625, 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\nu\nu$	$4 e, \mu$	0 jets	$E_T^{miss}$	140	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ [ $\lambda_{133} \neq 0, \lambda_{123} \neq 0$ ] 0.95, 1.55	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$		$\geq 8$ jets		140	$\tilde{g}$ [ $m(\tilde{\chi}_1^0) = 50$ GeV, 1250 GeV] 1.6, 2.25	Large $\lambda'_{112}$	To appear
	$\tilde{u}, \tilde{t} \rightarrow \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s$		Multiple		36.1	$\tilde{t}$ [ $\lambda'_{223} = 2e-4, 1e-2$ ] 0.55, 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow b\tilde{b}s$		$\geq 4b$		140	$\tilde{t}$ Forbidden	$m(\tilde{\chi}_1^0) = 500$ GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$		$2 \text{ jets} + 2 b$		36.7	$\tilde{t}_1$ [ $qg, b\tilde{s}$ ] 0.42, 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$	$2 e, \mu$	2 b		36.1	$\tilde{t}_1$ 1.0, 0.4-1.45	$BR(\tilde{t}_1 \rightarrow b\tilde{e}/b\tilde{\mu}) > 20\%$	1710.05544
		$1 \mu$	DV		136	$\tilde{t}_1$ [ $1e-10 < \lambda'_{233} < 1e-8, 3e-10 < \lambda'_{233} < 3e-9$ ] 1.0, 1.6	$BR(\tilde{t}_1 \rightarrow q\tilde{\mu}) = 100\%, \cos\phi_t = 1$	2003.11956
$\tilde{\chi}_1^+/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s, \tilde{\chi}_1^+ \rightarrow b\tilde{b}s$	$1-2 e, \mu$	$\geq 6$ jets		140	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	2106.09609	

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

10<sup>-1</sup> 1 Mass scale [TeV]

## “The non-standard” (Long-Lived Particle) signatures

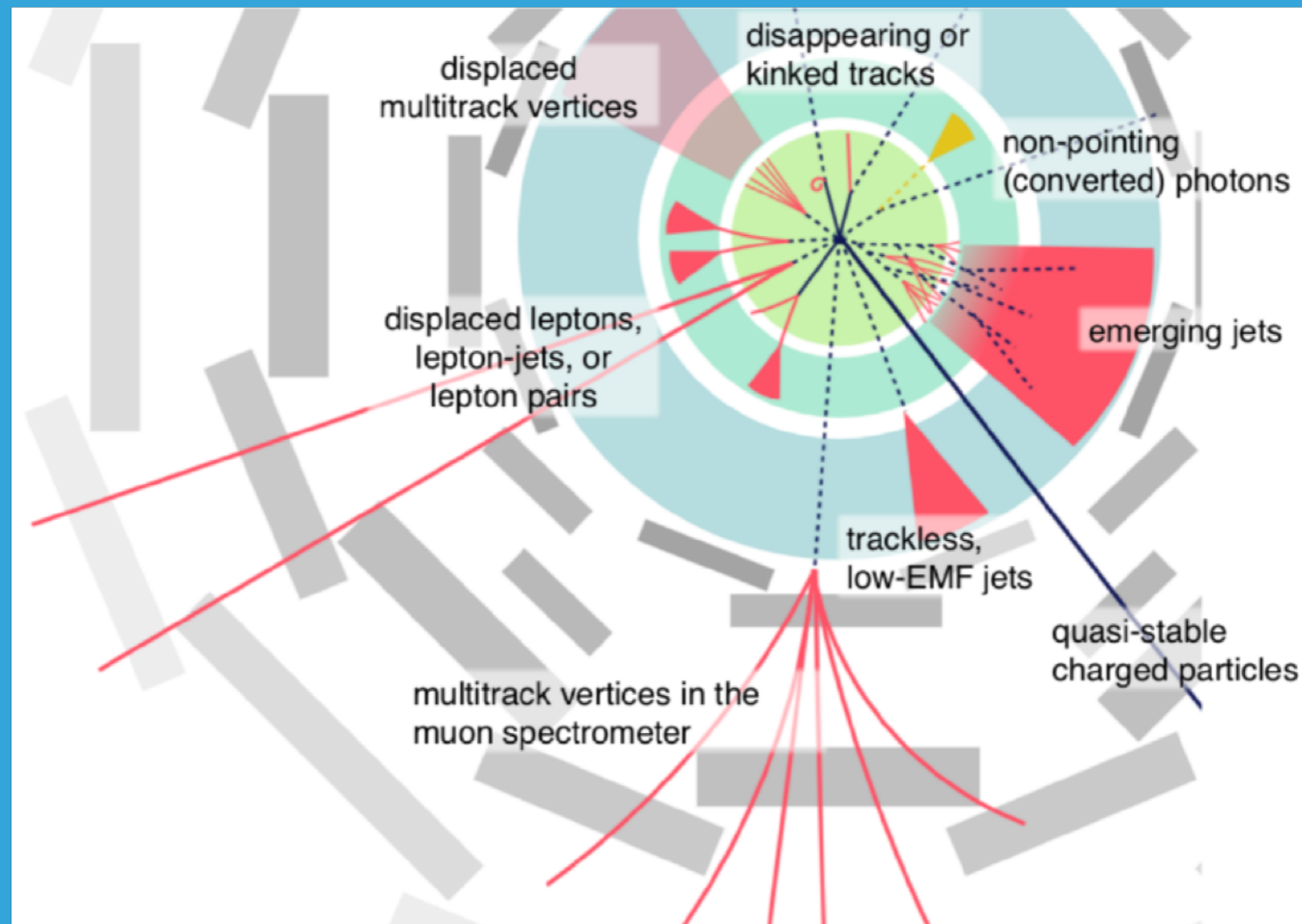
### LLP:

a proper lifetime  $\tau_0$  is greater than or comparable to the characteristic size of the (sub)detectors

✓ small  $\tau_0$  that comparable to the inner tracker size, no displaced tracks → “standard” prompt decay

✓ intermediate  $\tau_0$  → LLP

✓ very large/infinite large  $\tau_0$  → stable particles, “standard” MET signatures

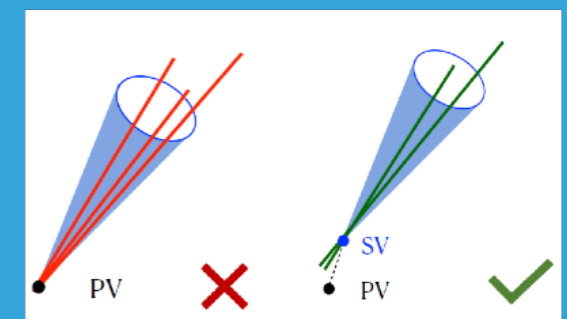
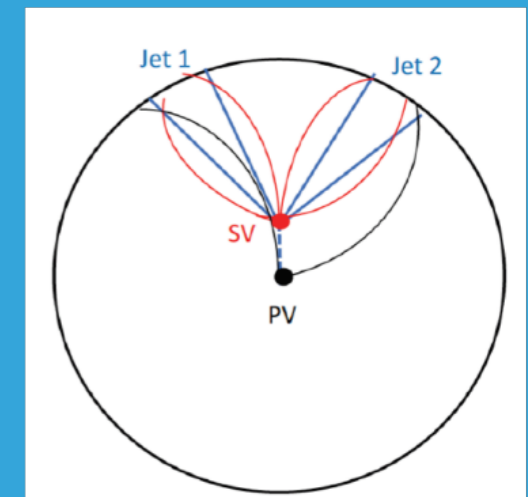


Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper:  
arXiv:1903.04497

LLP theory motivations:  
arXiv:1806.07396

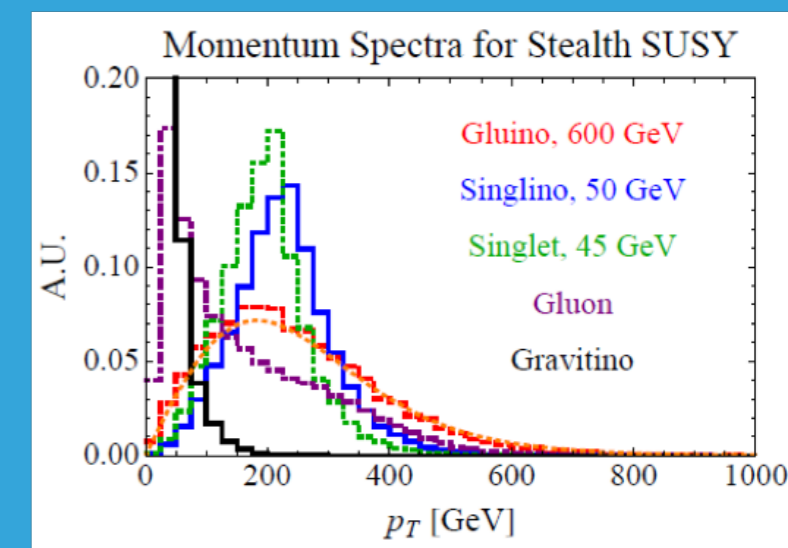
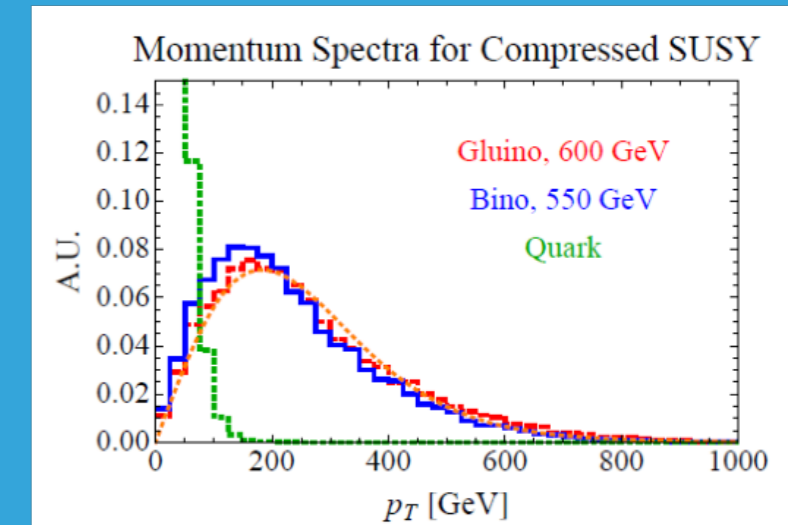
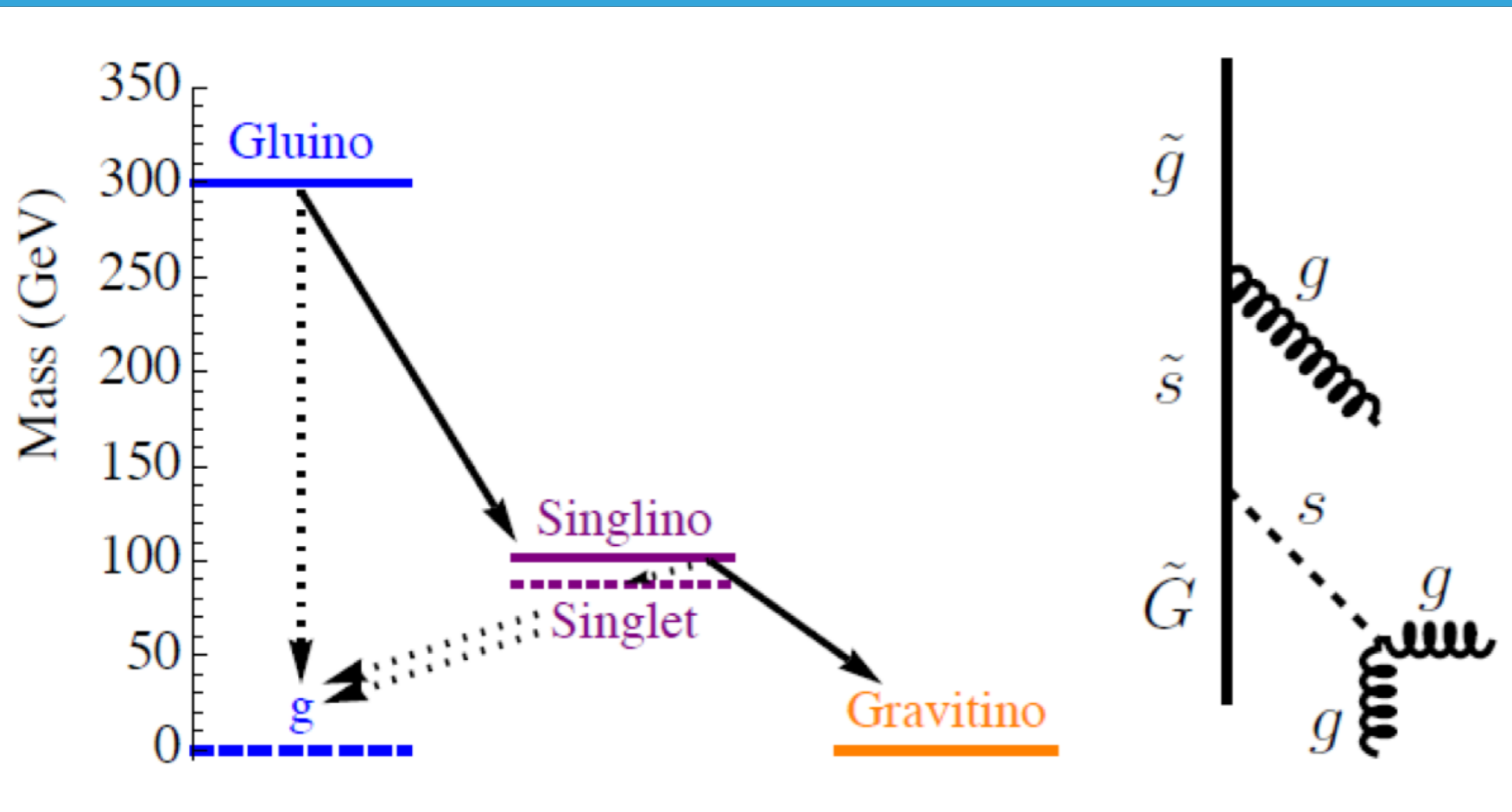
displaced jets/leptons



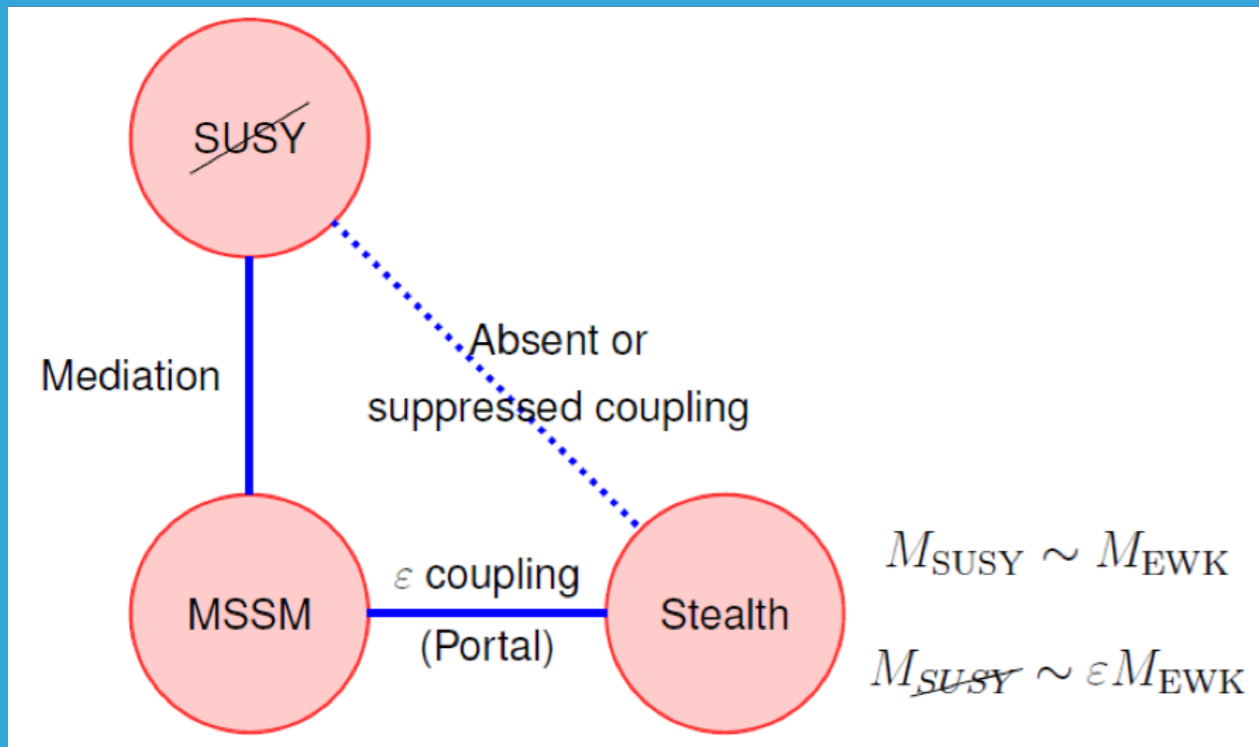
# Stealth supersymmetry model

## Stealth supersymmetry idea

SUSY is natural, low-scale SUSY breaking, hidden sector with one chiral singlet superfield (singlino/singlet). The lightest supersymmetric particle – gravitino (GMSB), LOSP decay to gravitino through a hidden sector. R-odd singlino, R-even singlet. Masses in a hidden sector of order the EW scale, states approximately supersymmetric – mass splitting is much smaller than masses, states are **closely degenerated by masses**. Suppression of large missing  $E_T$  (connected with gravitino).



## Stealth supersymmetry idea



SUSY breaking – low-scale vs high-scale (large soft mass contributions to the stealth sector),  $m_{X_1 X_2}$

Soft SUSY\_breaking B-term (or  $M_{Pl}$  suppression in SUGRA)

$$\mathcal{L} \supset \int d^2\theta m (1 + \theta^2 m_{3/2}) X_1 X_2 \supset m_{3/2} m X_1 X_2$$

$$\delta m = m - \sqrt{m^2 - B} \approx \frac{B}{2m} \quad \text{splitting of about 10 GeV,}$$

$$B = m_{3/2} m \quad \longrightarrow \quad m_{3/2} \lesssim 2\delta m \lesssim 20 \text{ GeV}$$

Stealth masses of about the EW scale – accident or common underlying physics? **Small  $B_\mu$ /dynamically generated masses**

GMSB decay width

$$\Gamma(\tilde{g} \rightarrow g\tilde{G}) = \frac{m_{\tilde{g}}^5}{48\pi M^2 m_{\tilde{G}}^2} = 1.1 \times 10^{-9} \text{ GeV} \left( \frac{m_{\tilde{g}}}{250 \text{ GeV}} \right)^5 \left( \frac{m_{\tilde{G}}}{1 \text{ eV}} \right)^{-2}$$

will be modified by new hidden sector

SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

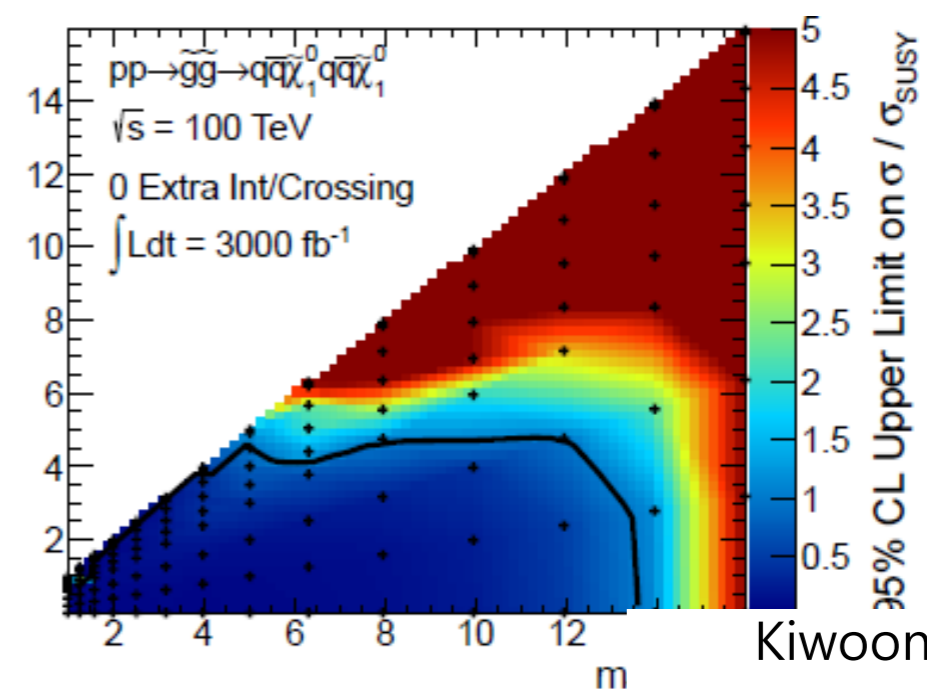
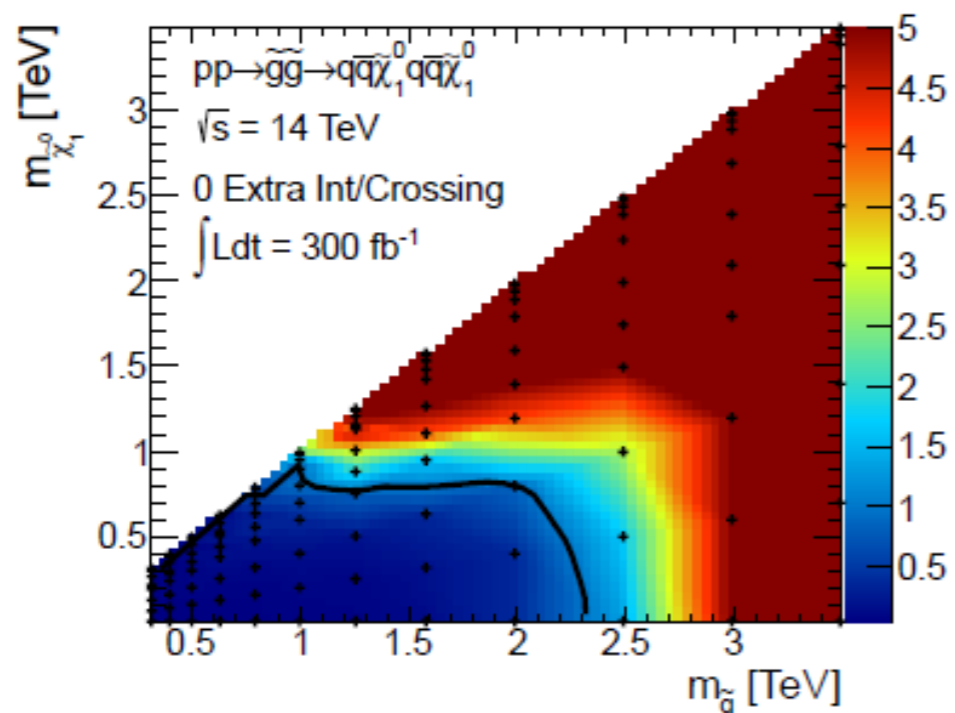


\* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, '13

100 TeV collider



Kiwoon Choi

(ICHEP 2016, Chicago)

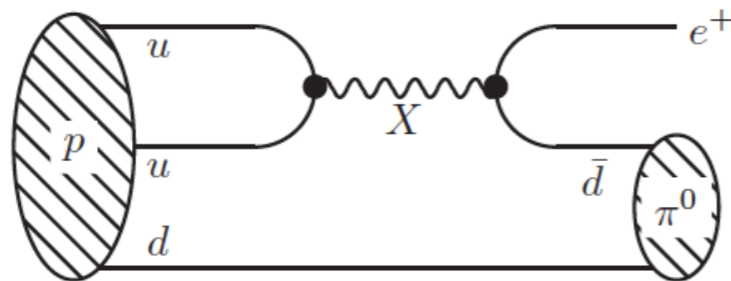
## Crucial points:

- SUSY leads to unification
- SUSY solves the hierarchy problems for GUTs
- No GUT without SUSY

## New properties:

- Later unification - higher GUT scale
- Longer proton life-time  $\tau \sim M_{GUT}^4$
- New modes of proton decay

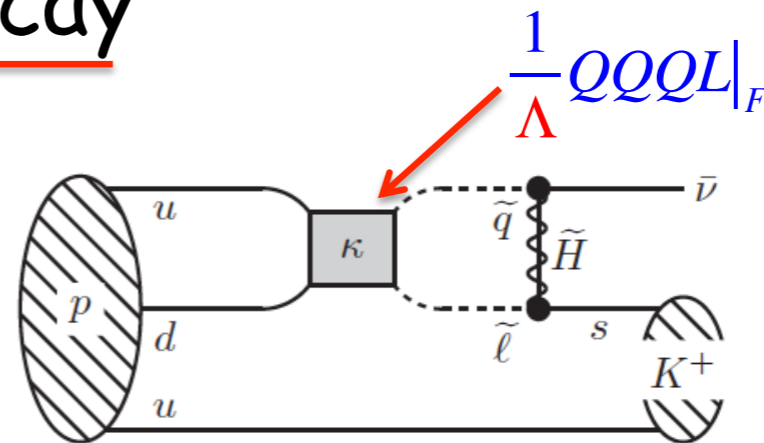
## SUSY GUTS - Nucleon decay



(a) Dimension 6.

$$p \rightarrow \pi^0 + e^+$$

$$\tau_{p \rightarrow e^+ \pi^0} > 1 \times 10^{34} \text{ yrs}, M_X > 10^{16} \text{ GeV}$$



(b) Dimension 5.

$$p \rightarrow K^+ + \bar{\nu}$$

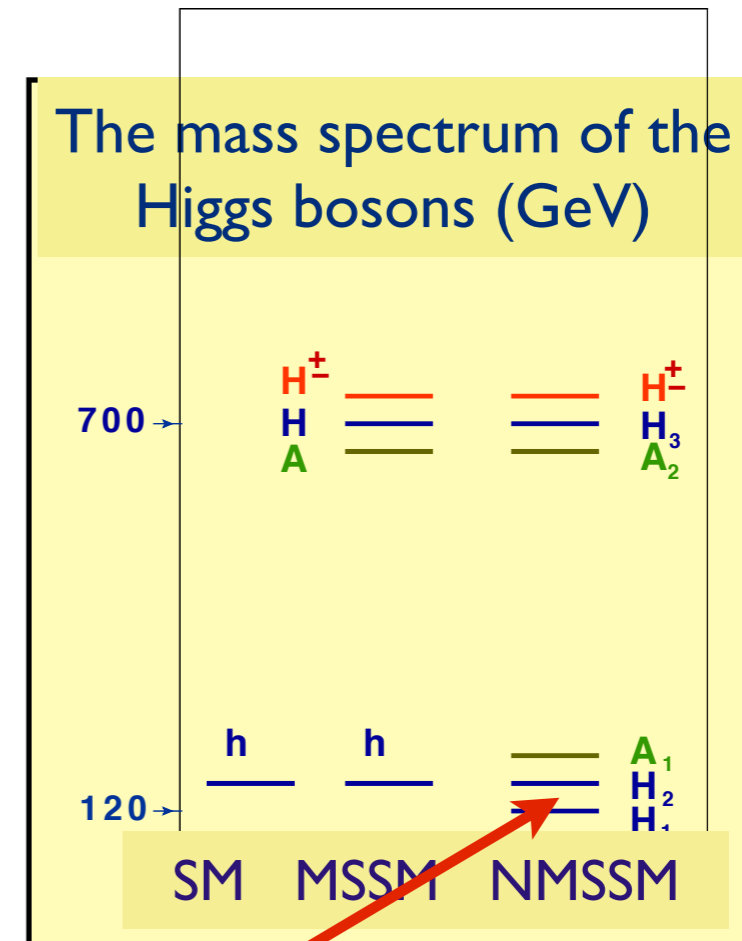
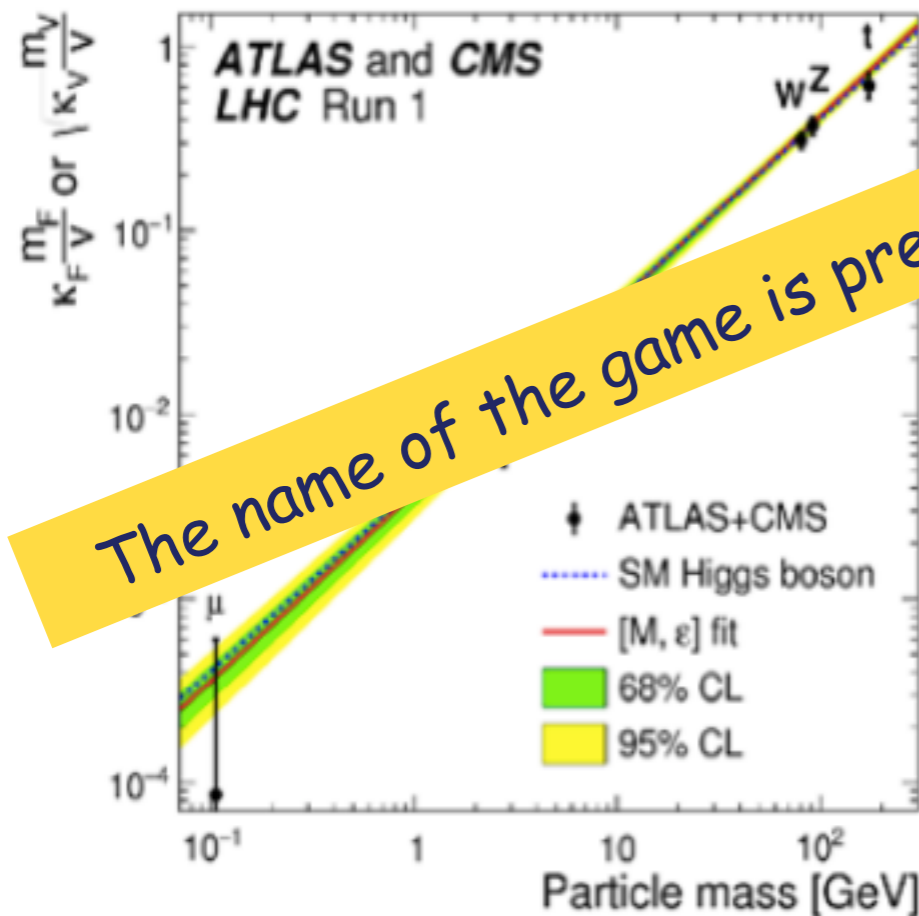
$$\tau_{p \rightarrow K^+ \bar{\nu}} > 3.3 \times 10^{33} \text{ yrs}$$



How to probe?

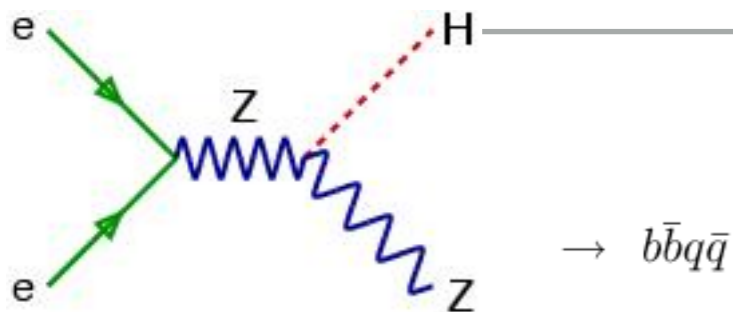
- Probe deviations from the SM Higgs couplings

- Perform direct search for additional scalars



We may have found one of these states

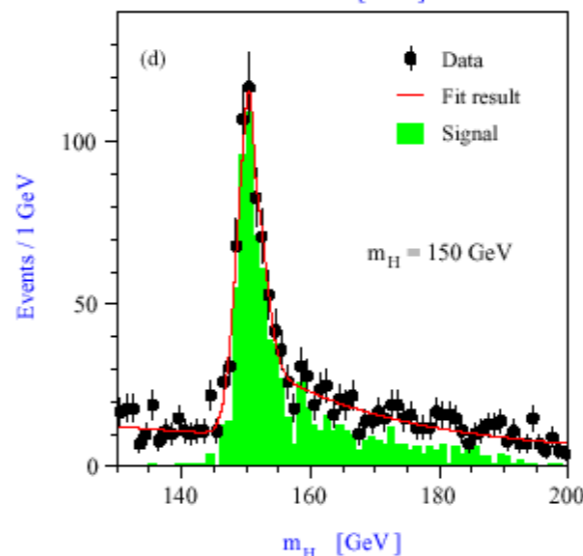
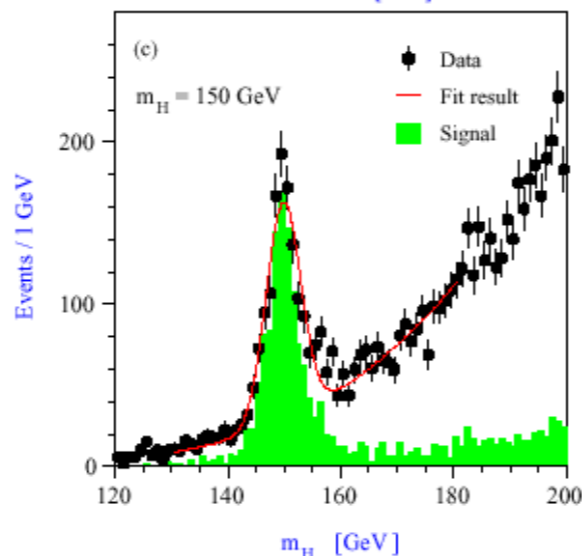
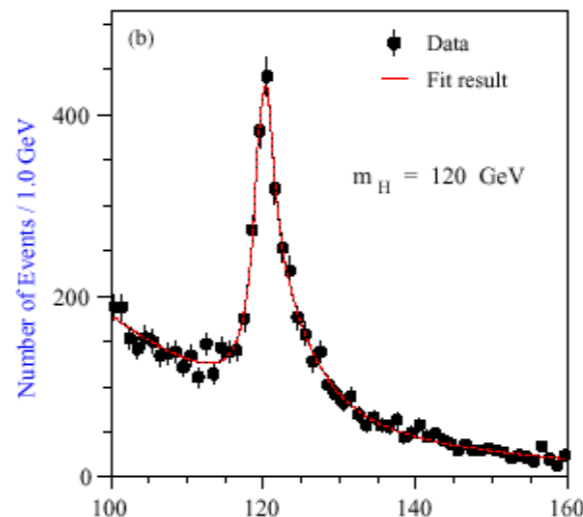
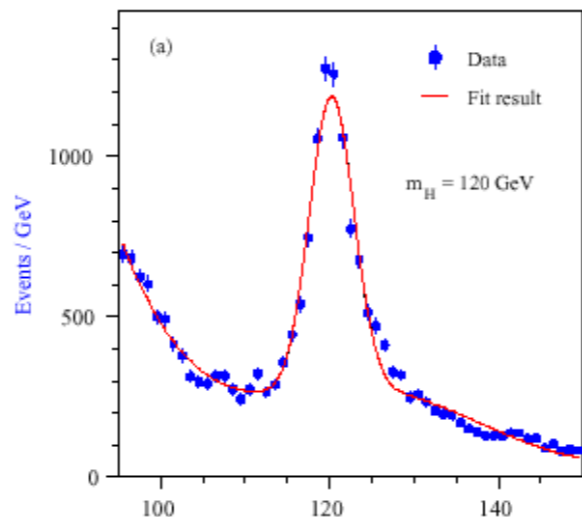
One has to check the presence or absence of heavy Higgs bosons



$ee \rightarrow HZ$  diff. decay channels

Int Linear Collider

$\rightarrow W^+W^-q\bar{q}$



$\rightarrow q\bar{q}l^+l^-$

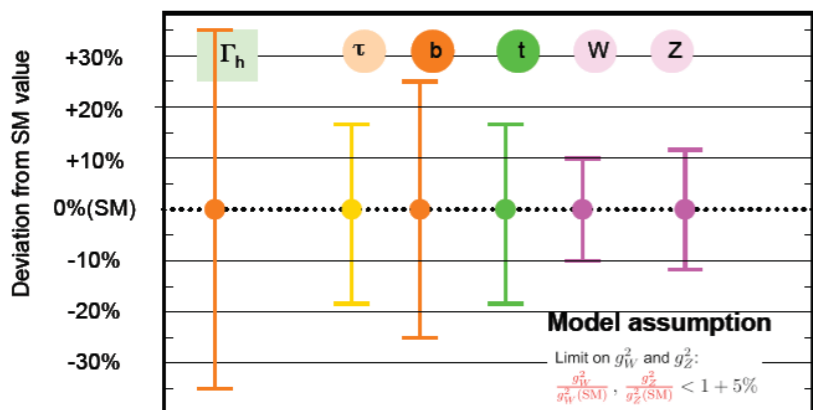
$\Delta m_H = 40 \text{ MeV}$

$\rightarrow W^+W^-l^+l^-$

$\Delta m_H = 70 \text{ MeV}$

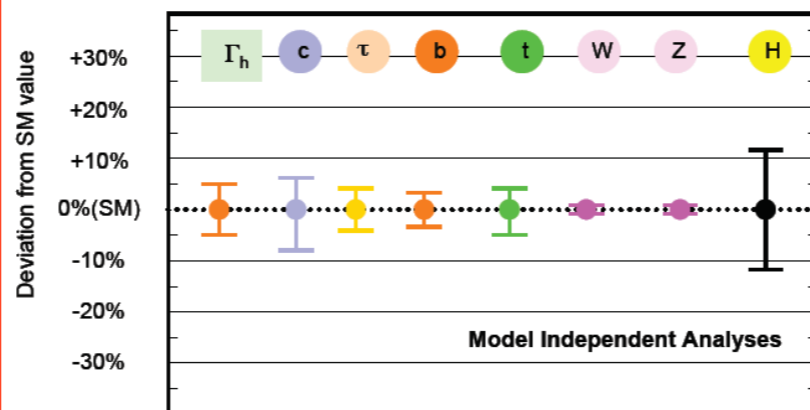
## Coupling Precision

LHC 300 fb<sup>-1</sup> x 2



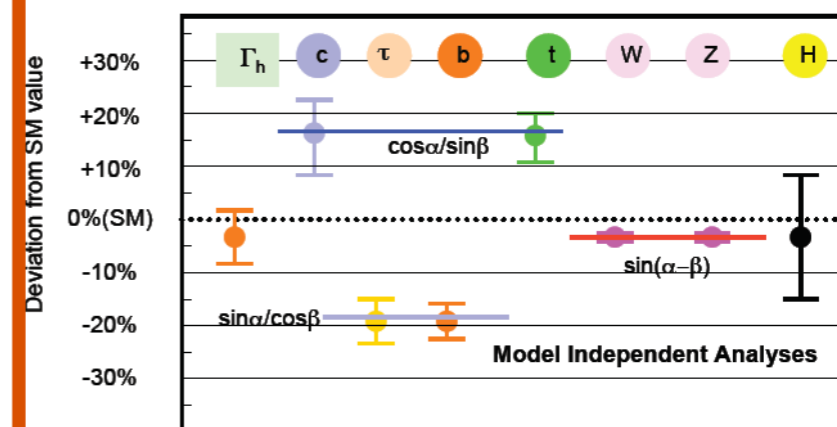
## Coupling Precision

ILC



## SUSY or 2HDM

ILC



# CONCLUDING REMARKS

- ☑ LHC experiments are at the front line of mystery land: be patient
- ☑ No sign of supersymmetry so far
- ☑ More involved scenarios are under study
- ☑ High luminosity LHC will have much more possibilities
- ☑ SUSY might be much heavier (?!)
- ☑ SUSY might be irrelevant in particle physics (!?)



What the future may bring?