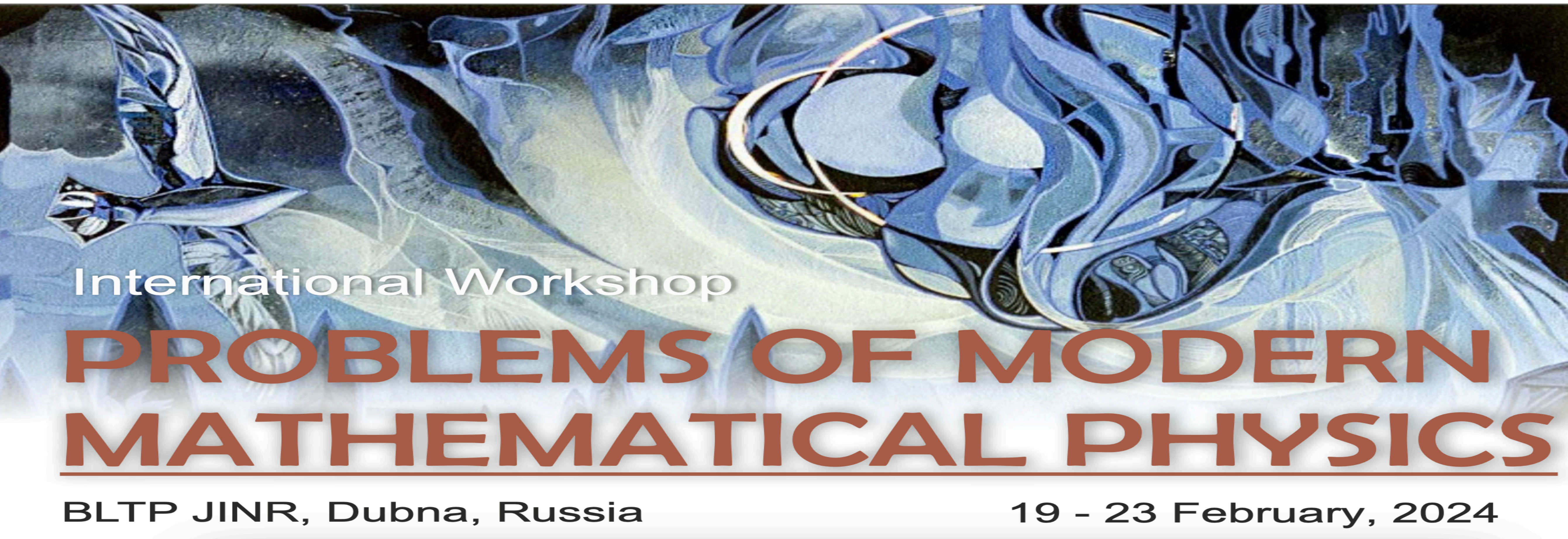
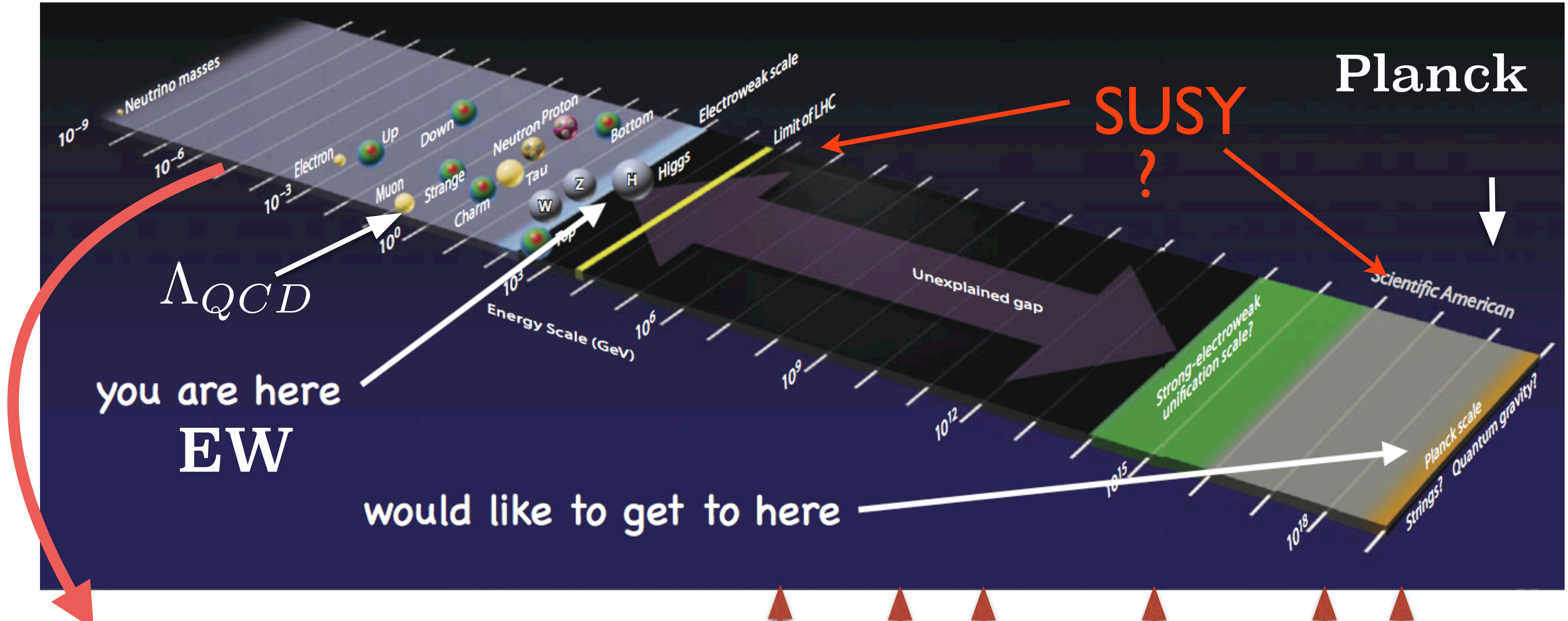
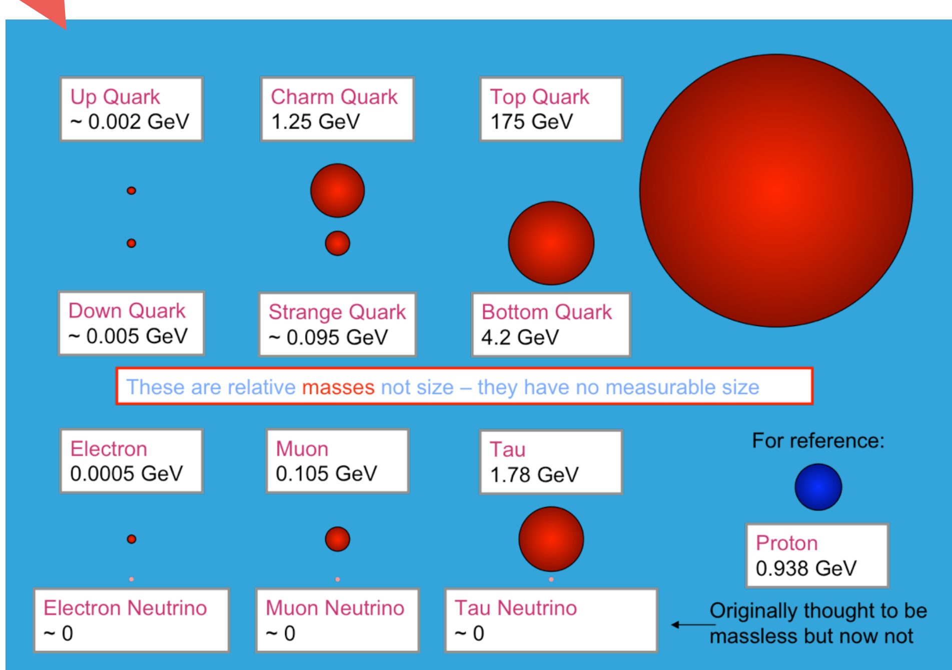


SUPERSYMMETRY IN PARTICLE PHYSICS

DMITRY KAZAKOV
JINR(DUBNA)

IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?





?

Vacuum Stab ~ 10^{11} GeV

Majorana scale ~ 10^{12} GeV

GUT scale ~ 10^{16} GeV

String scale ~ 10^{18} GeV

Planck scale ~ 10^{19} GeV

?

NEW SYMMETRIES

SUPERSYMMETRY

Supersymmetry is an extension of the Poincare symmetry of the SM

Poincare Algebra

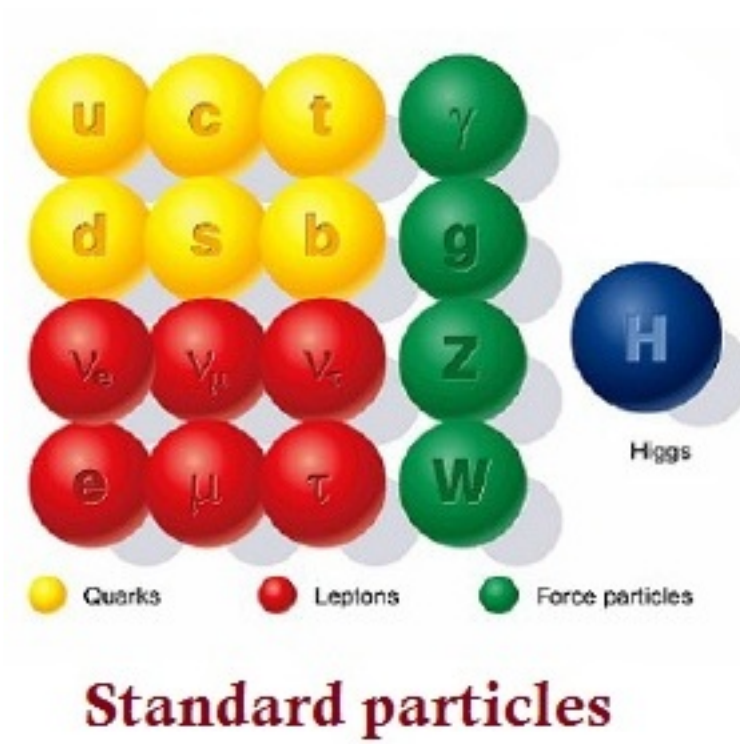
$$[P_\mu, P_\nu] = 0,$$
$$[P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),$$
$$[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho})$$

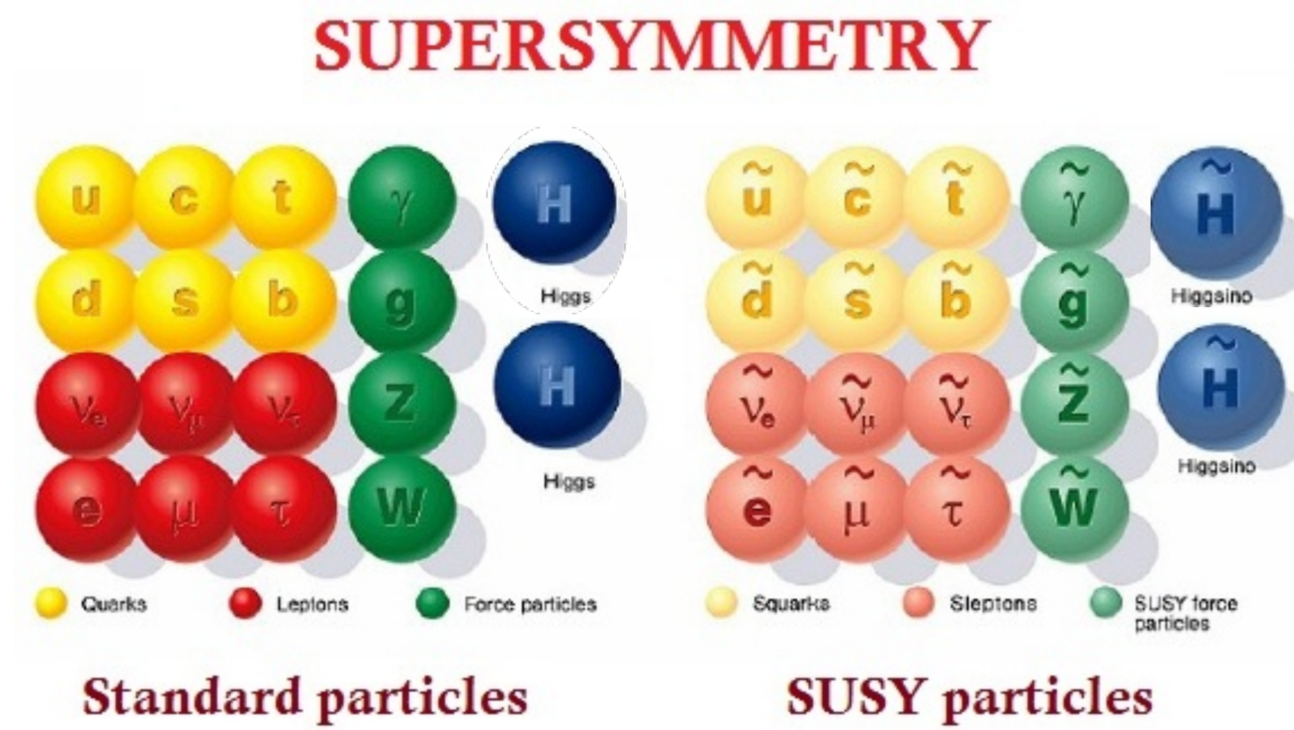
Super Poincare Algebra $\quad Q_i,\ \bar{Q}_i$

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,$$
$$[Q^i_\alpha, M_{\mu\nu}] = \frac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta, \qquad [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\frac{1}{2}\bar{Q}^i_{\dot\beta}(\bar\sigma_{\mu\nu})^{\dot\beta}_{\dot\alpha},$$
$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$
$$\{Q^i_\alpha, Q^j_\beta\} = 2\epsilon_{\alpha\beta}Z^{ij}, \qquad Z^{ij} = Z^+_{ij},$$
$$\{\bar{Q}^i_{\dot\alpha}, \bar{Q}^j_{\dot\beta}\} = -2\epsilon_{\dot\alpha\dot\beta}Z^{ij}, \qquad [Z_{ij}, anything] = 0,$$
$$\alpha, \dot\alpha = 1, 2 \qquad i, j = 1, 2, \ldots, N.$$

MOTIVATION FOR SUSY IN PARTICLE PHYSICS

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





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!

$$\{Q^i_\alpha, \overline{Q}^j_\beta\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\beta} P_\mu \quad \Rightarrow \quad \{\delta_\varepsilon, \overline{\delta}_{\overline{\varepsilon}}\} = 2(\varepsilon\sigma^\mu\overline{\varepsilon})P_\mu$$

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

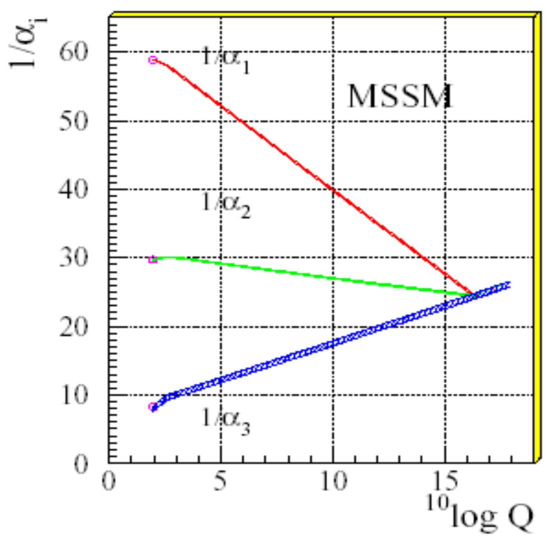
Local supersymmetry = general relativity !

MOTIVATION FOR SUSY IN PARTICLE PHYSICS

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

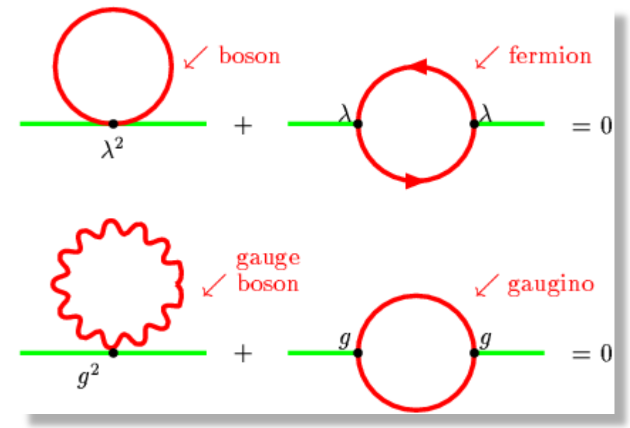
Why SUSY?

Unification of the gauge couplings



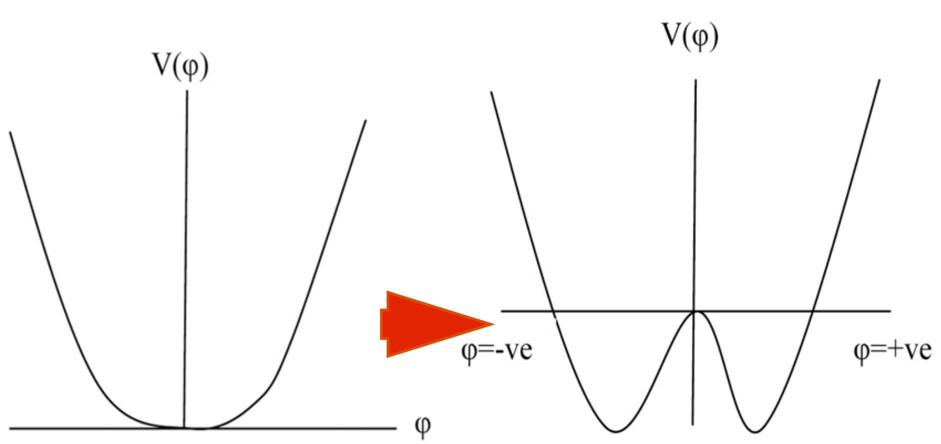
The basis of a grand Unified Theory

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

Violation of symmetry comes from radiative corrections

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

THE SIMPLEST (N=1) SUSY MULTIPLETS

Bosons and Fermions come in pairs

(φ,ψ)		$(\tilde{\lambda}, A_\mu)$		$(\tilde{g}, g)$	
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					
$\mathbf{G^a}$	gluon g^a	*gluino* $\tilde{g}^a$	8	0	0
$\mathbf{V^k}$	Weak W^k $(W^\pm, Z)$	*wino, zino* $\tilde{w}^k$ $(\tilde{w}^\pm, \tilde{z})$	1	3	0
$\mathbf{V'}$	Hypercharge B (γ)	*bino* $\tilde{b}(\tilde{\gamma})$	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

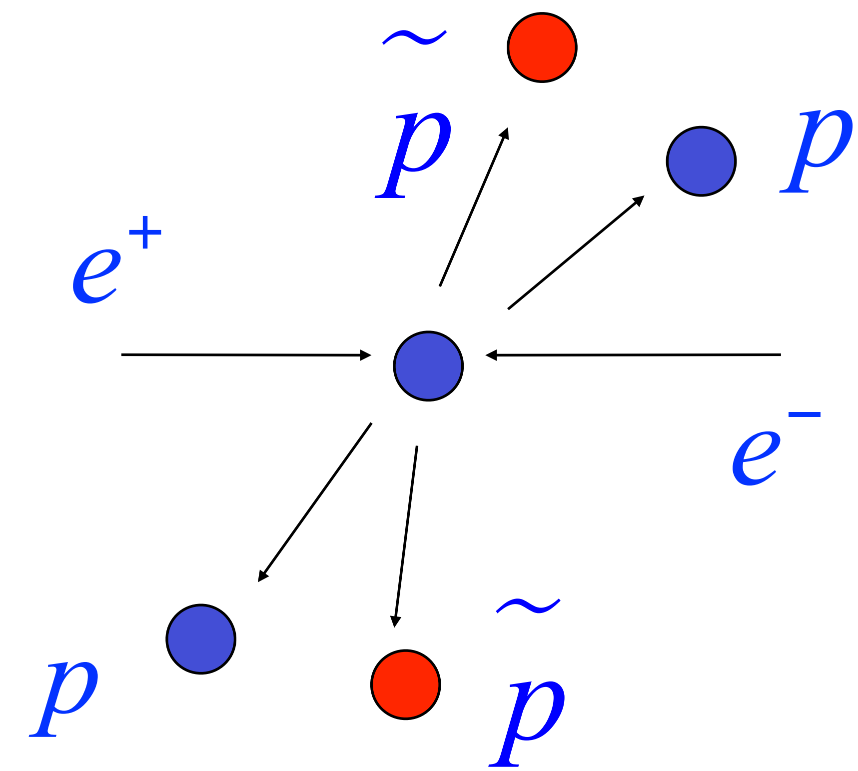
NMSSM

THE R-PARITY

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

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

B - Baryon Number
L - Lepton Number
S - Spin

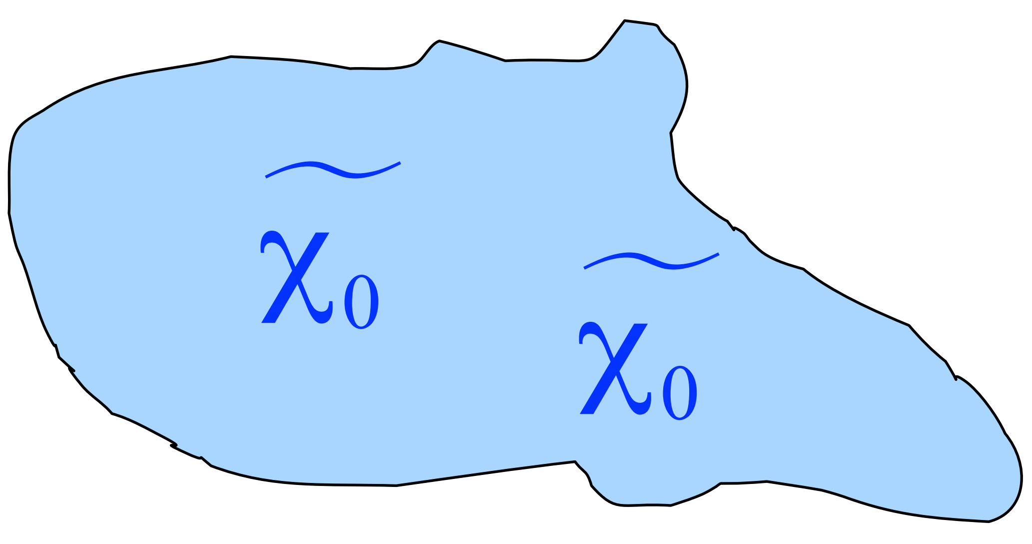


The consequences:

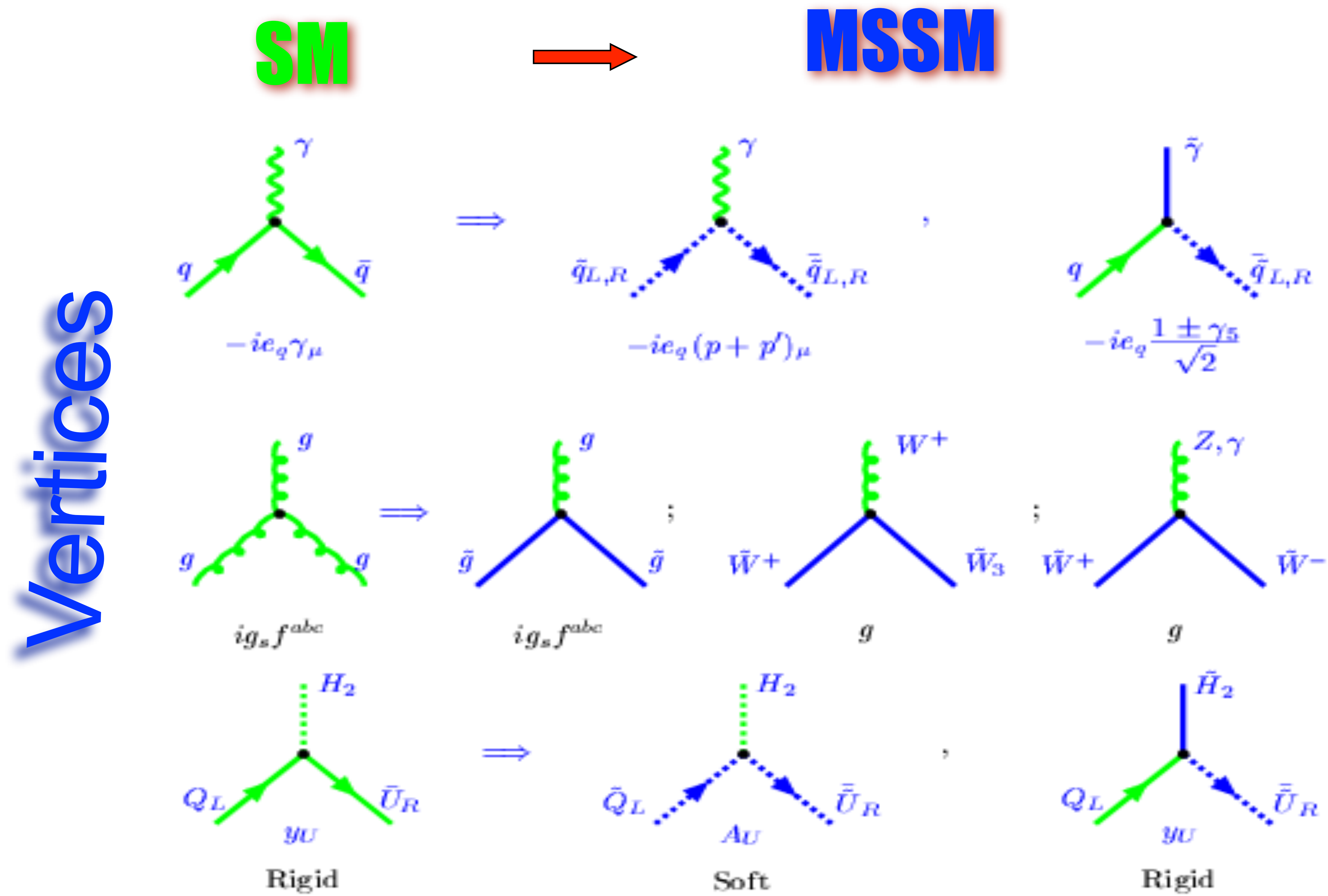
- The superpartners are created in pairs
- The lightest superparticle is stable

⬇

- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\widetilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe

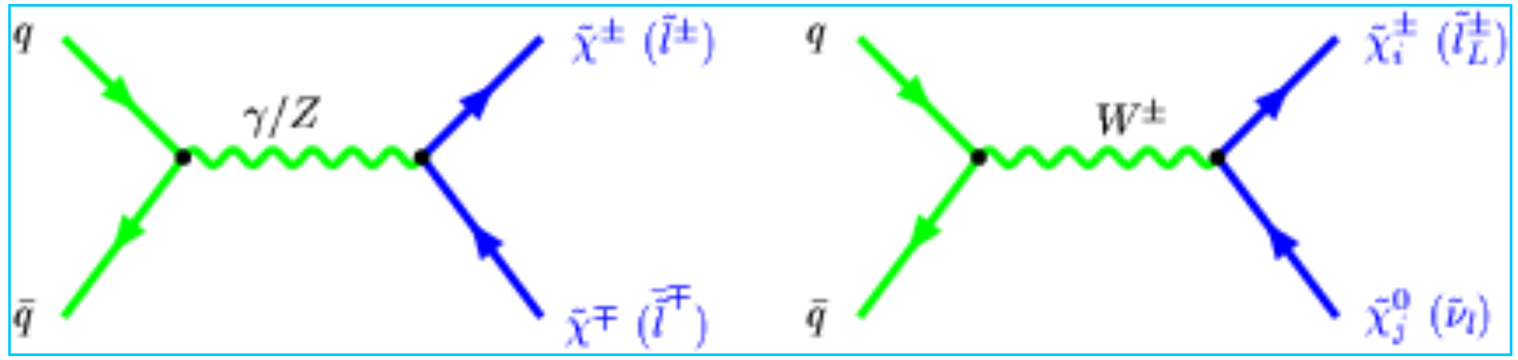


THE INTERACTIONS IN THE MSSM

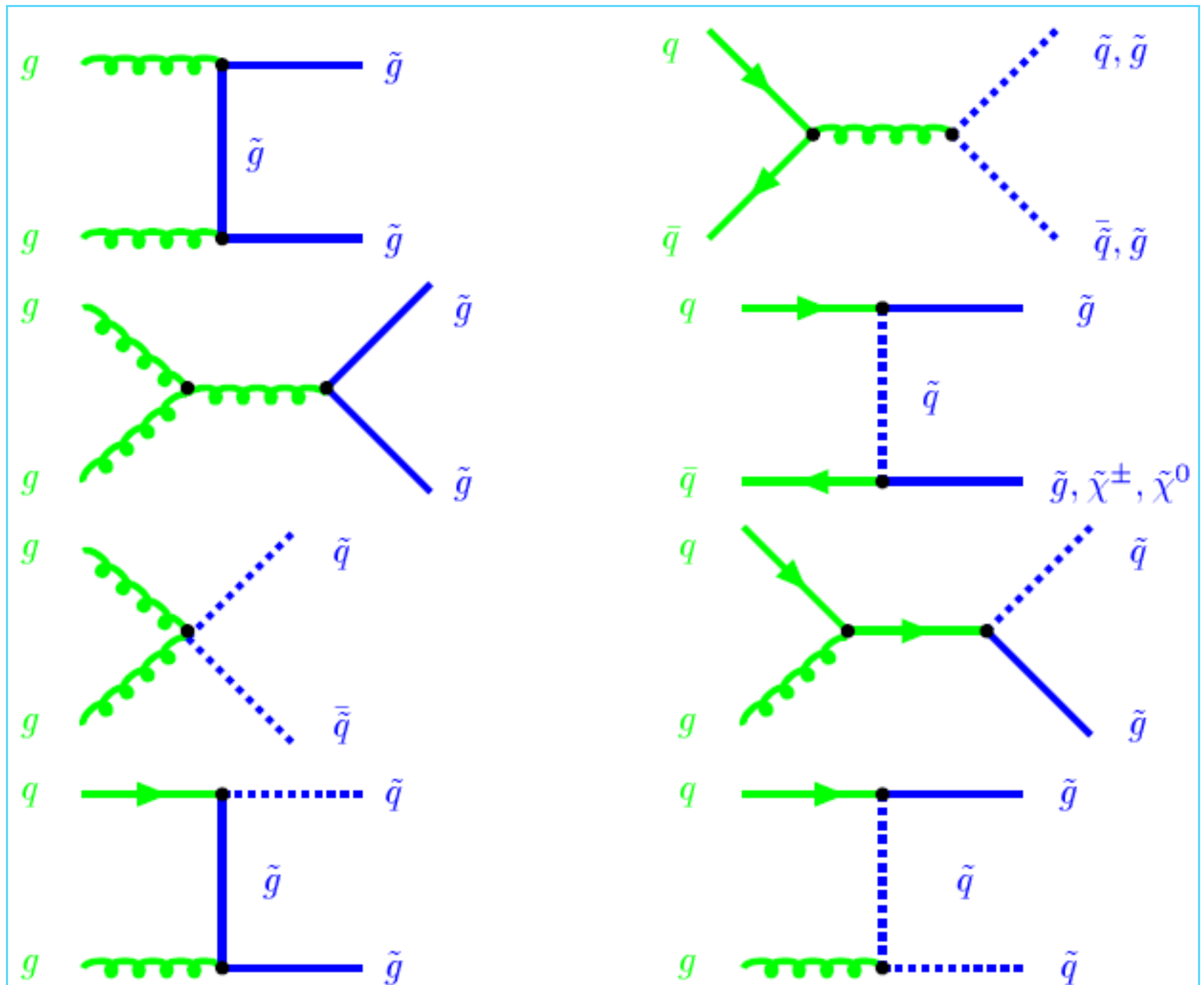


SUPERPARTNERS PRODUCTION AT THE LHC

Annihilation



Quark- gluon Fusion



THE DECAY OF SUPERPARTNERS

squarks

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

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

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

sleptons

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

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

chargino

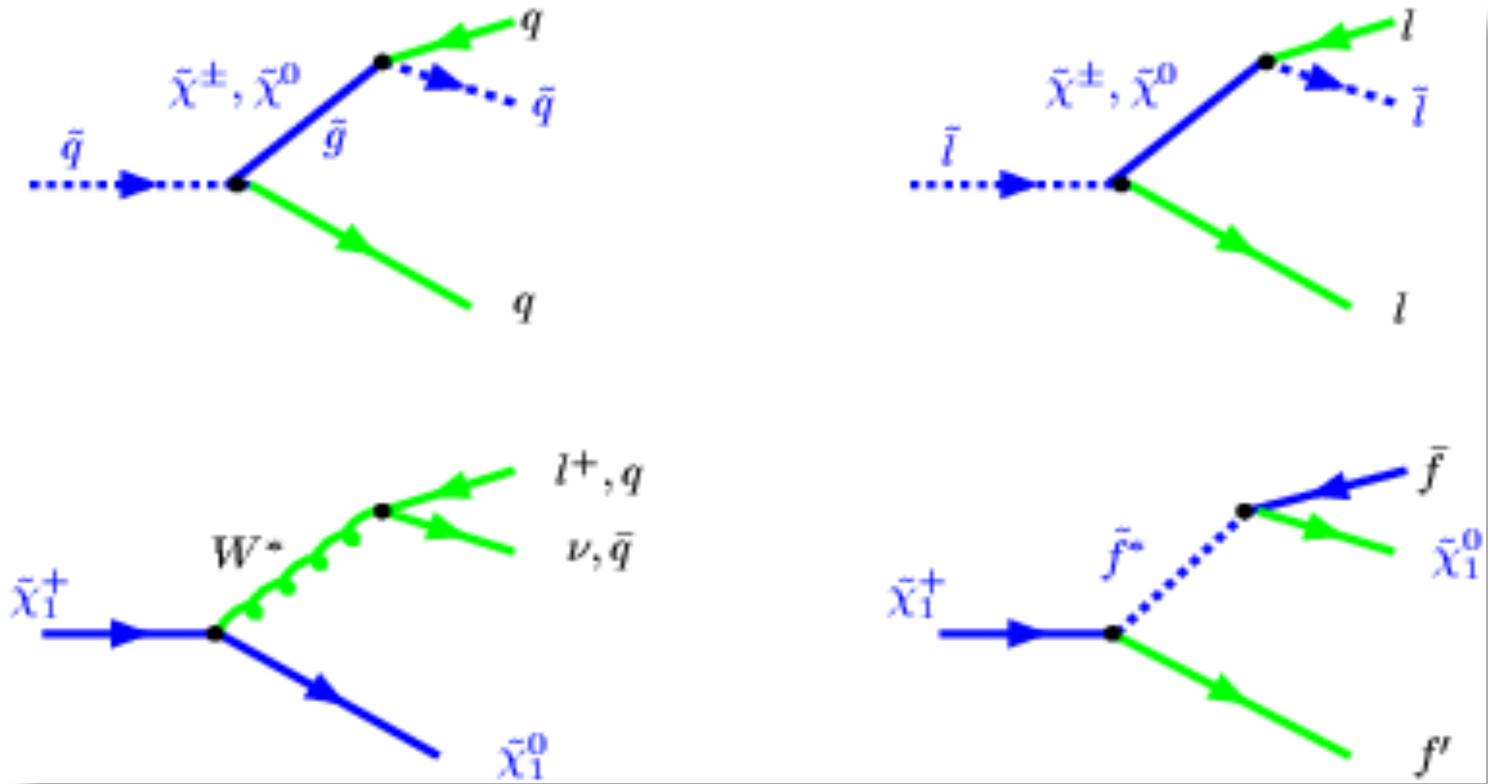
$$\tilde{\chi}_i^{\pm} \to e + \nu_e + \tilde{\chi}_i^0$$

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

gluino

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

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



neutralino

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

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

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

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

Final states

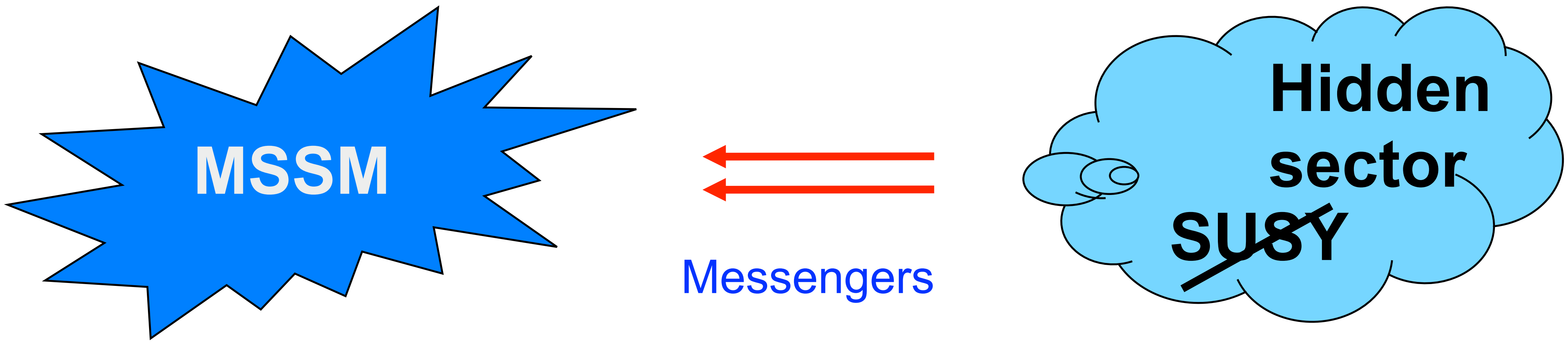
$$l^+ l^- + \not{E}_T$$

$$2 \text{ jets } + \not{E}_T$$

$$\gamma + \not{E}_T$$

$$\not{E}_T$$

SOFT BUSY BREAKING



Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

$$-L_{Soft} = \sum_{\alpha} M_i \widetilde{\lambda}_i \widetilde{\lambda}_i + \sum_{i} m_{0i}^2 \, | A_i |^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

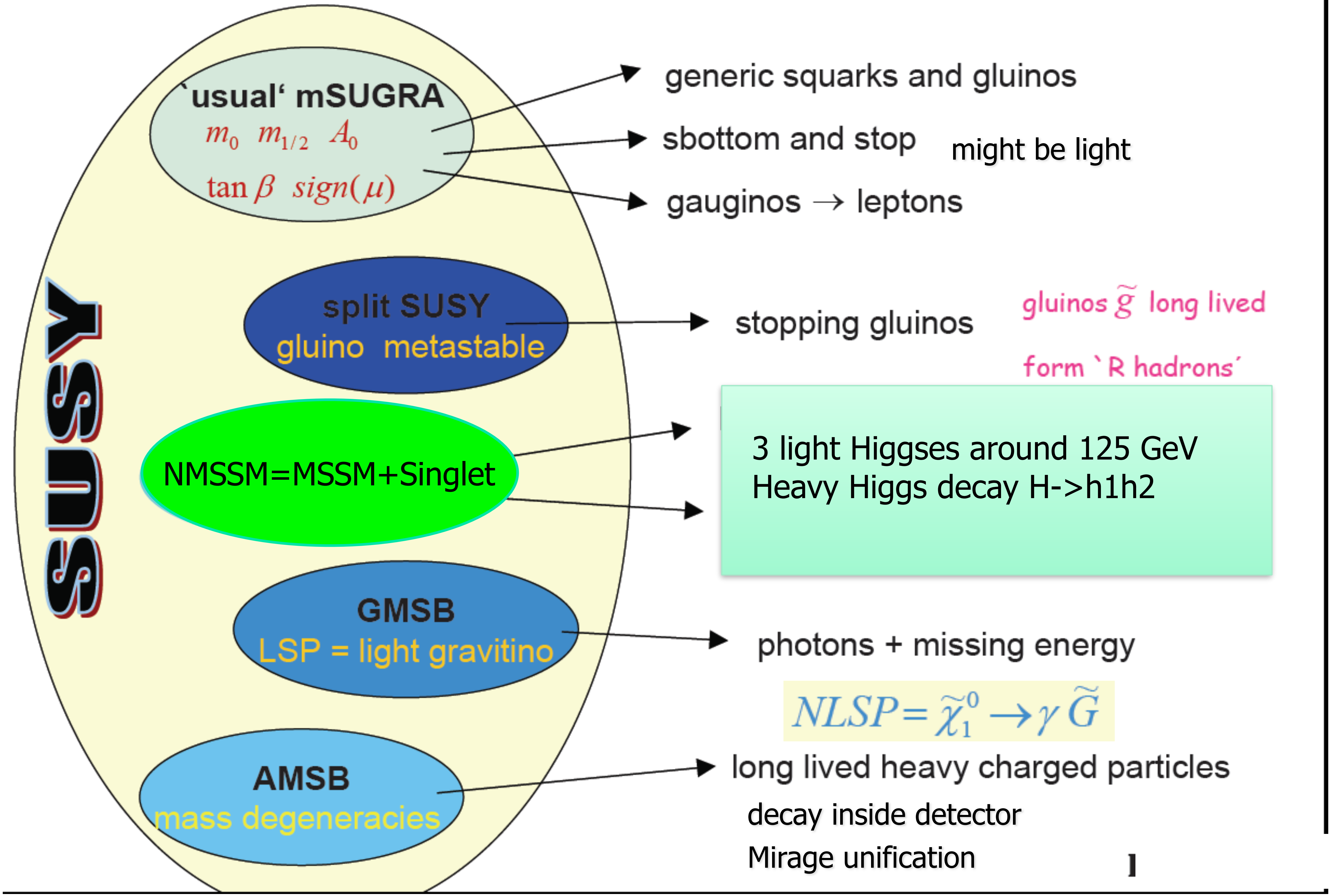
gauginos

scalar fields

Over 100 of free parameters !

SUSY Models and Signatures

T.Hebbeker



SEARCH FOR SUSY MANIFESTATION

Particle Phys

- Direct production at colliders at high energies
- Indirect manifestation at low energies
  - Rare decays ($B_s \to s\gamma,\ B_s \to \mu^+\mu^-, B_s \to \tau\nu$)
  - g-2 of the muon
- Search for long-lived SUSY particles

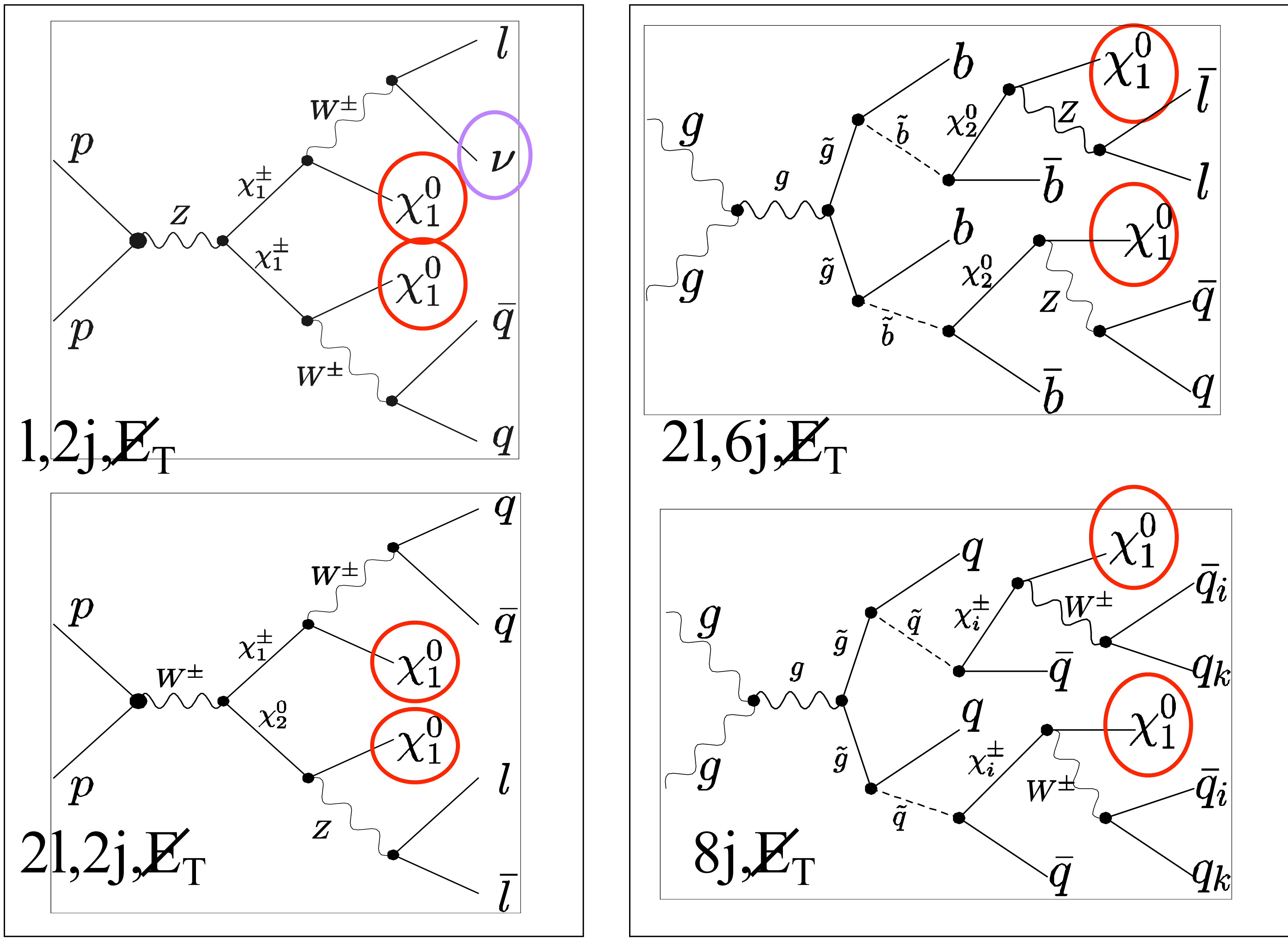
Astro Phys (if SUSY DM)

- 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

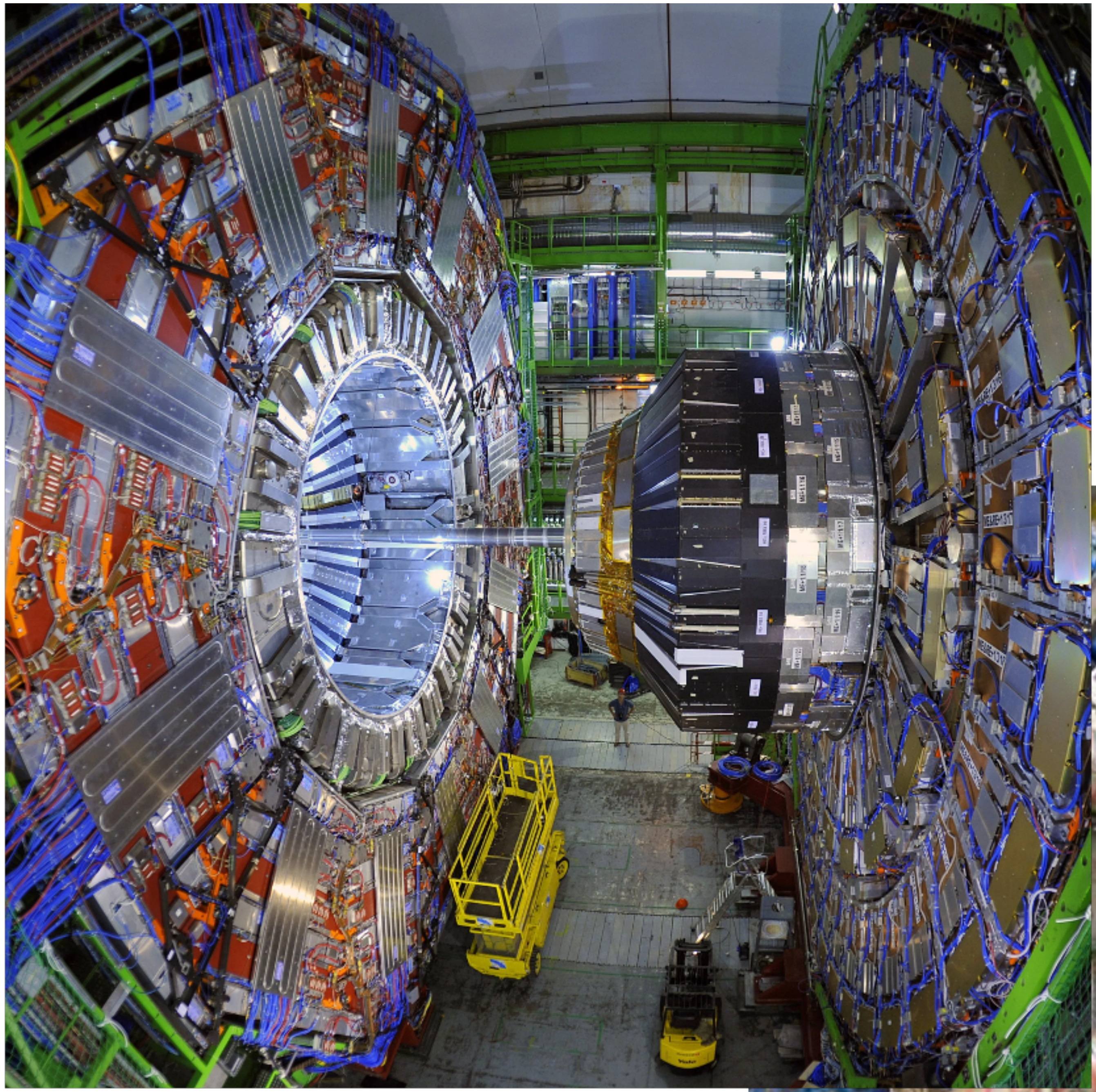
weak int's

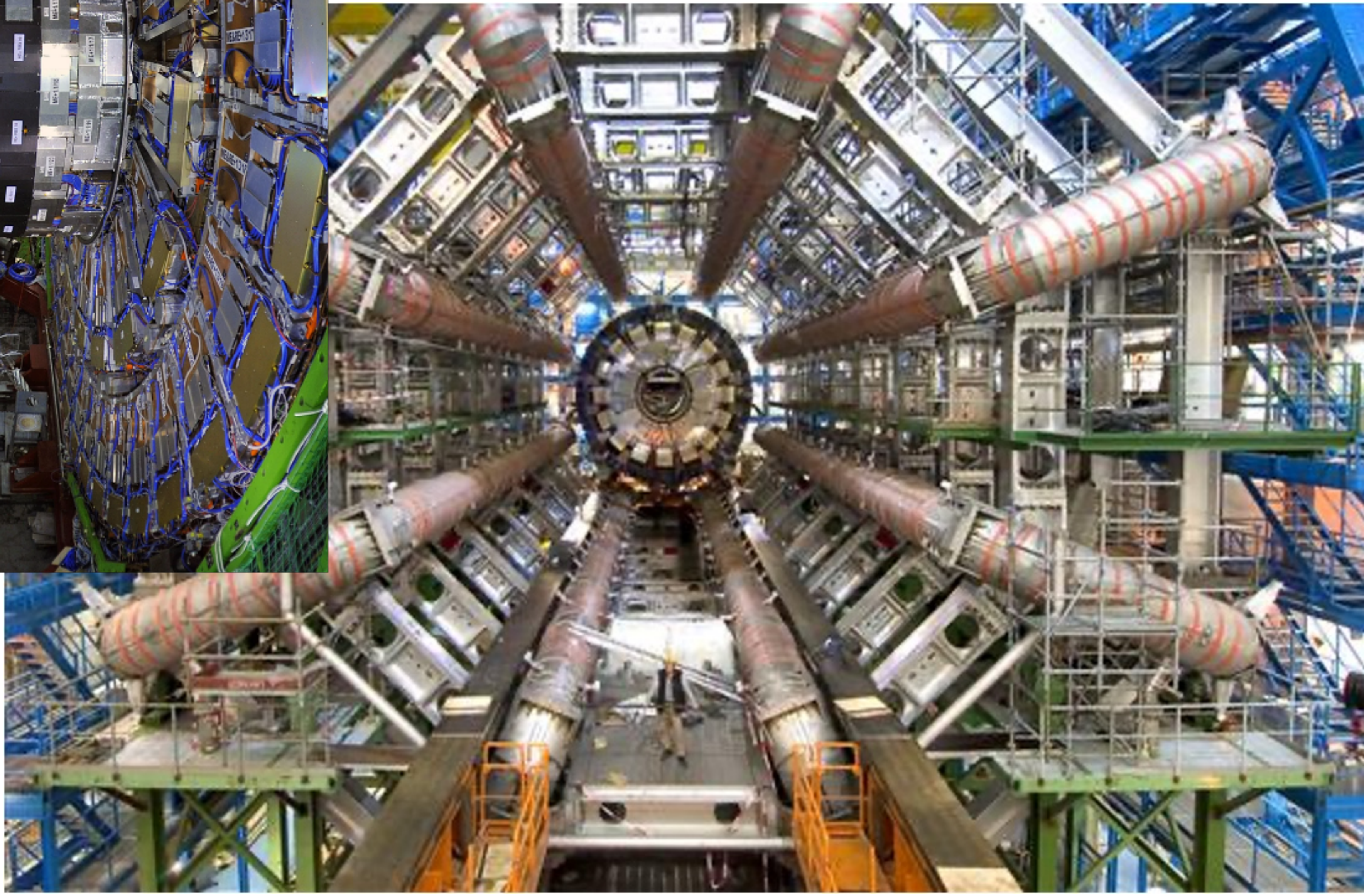


Strong int's

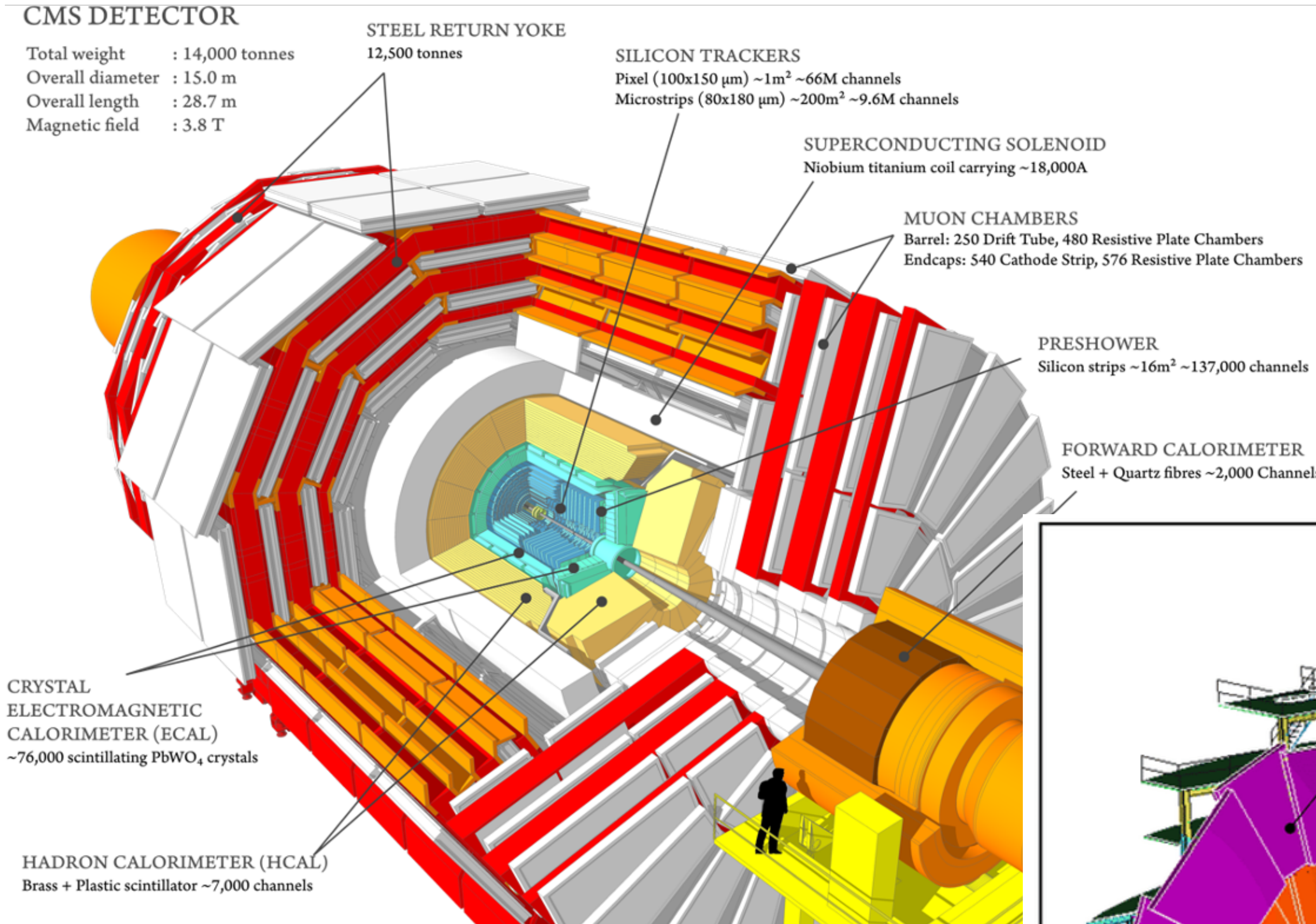
Typical SUSY signature: Missing Energy and Transverse Momentum

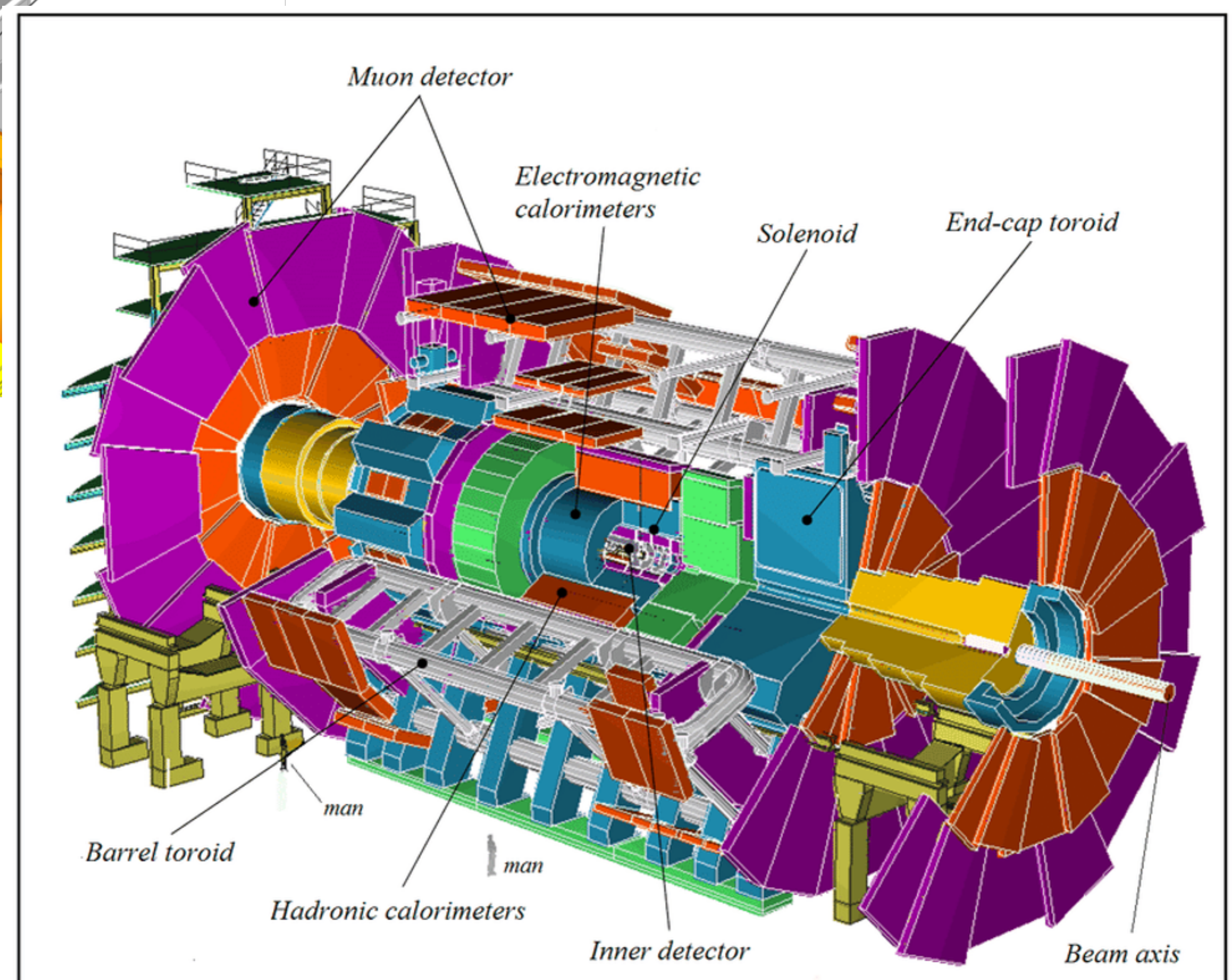
DETECTOR CONFIGURATIONS AT THE LHC: CMS & ATLAS





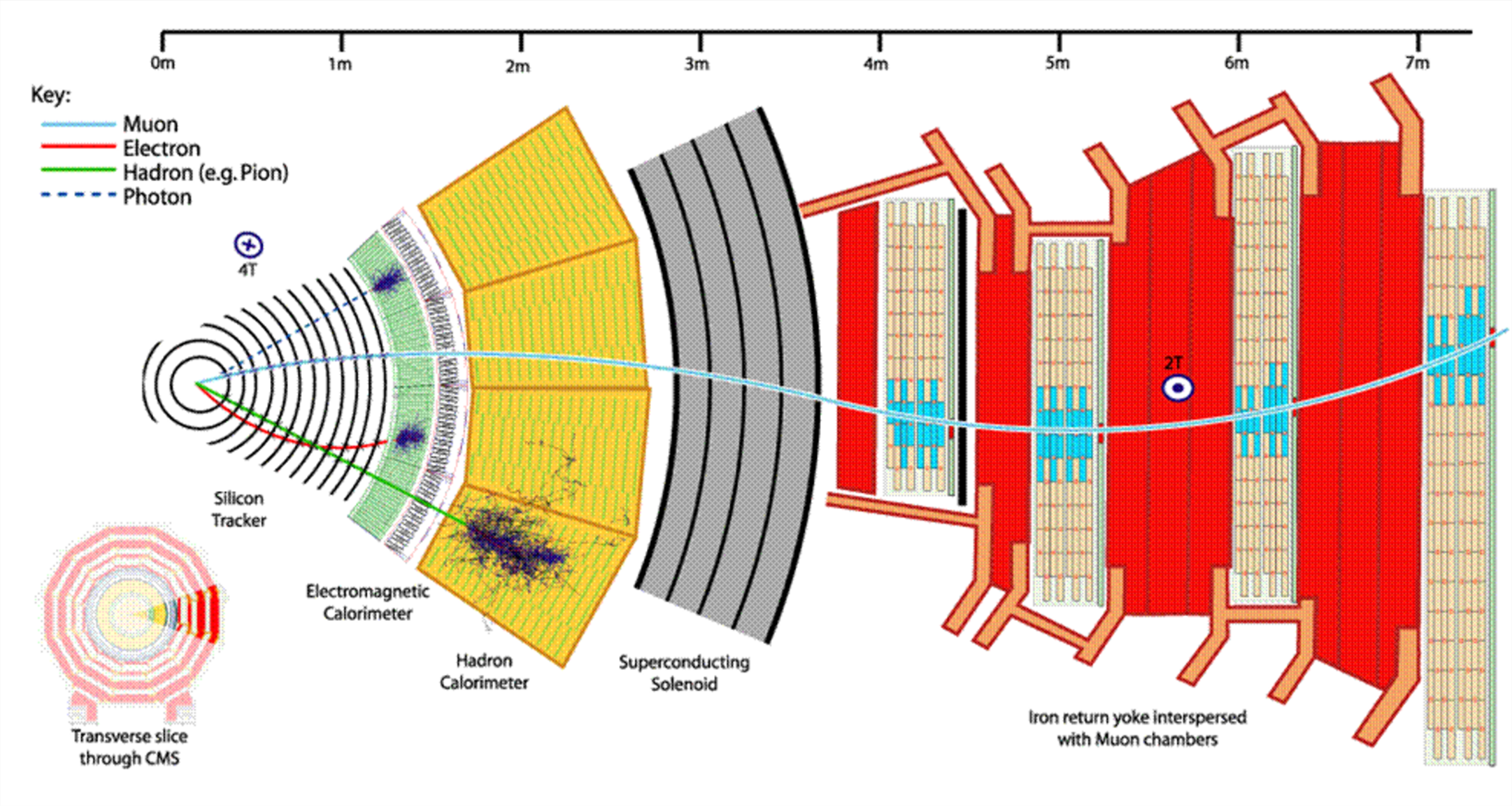
DETECTOR CONFIGURATIONS AT THE LHC: CMS & ATLAS





TYPICAL EVENT SIGNATURE

"The standard" signature, CMS example



EXP AND THEOR FRAMEWORK

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

Advandage: small number of universal parameters for all masses
Disadvantage: strictly model dependent (MSSM, NMSSM, etc)

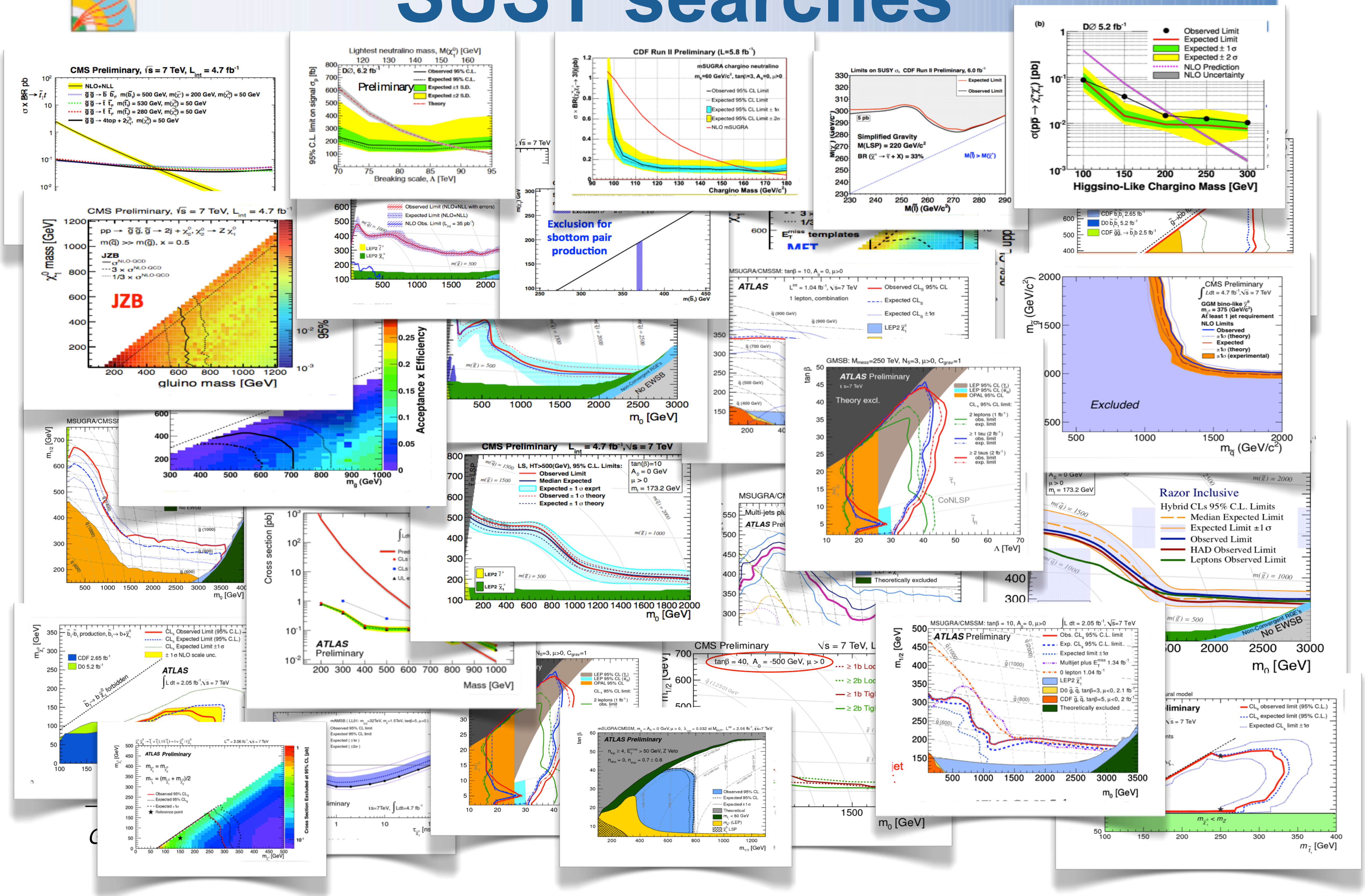
2. Low energy input:
use low energy parameters like masses of superpartners
Example $\tilde{m}_g, \; \tilde{m}_q, \; \tilde{m}_\chi$ or $m_A, \tan\beta$

Advandage: less model dependent
Disadvantage: many parameters, process dependent

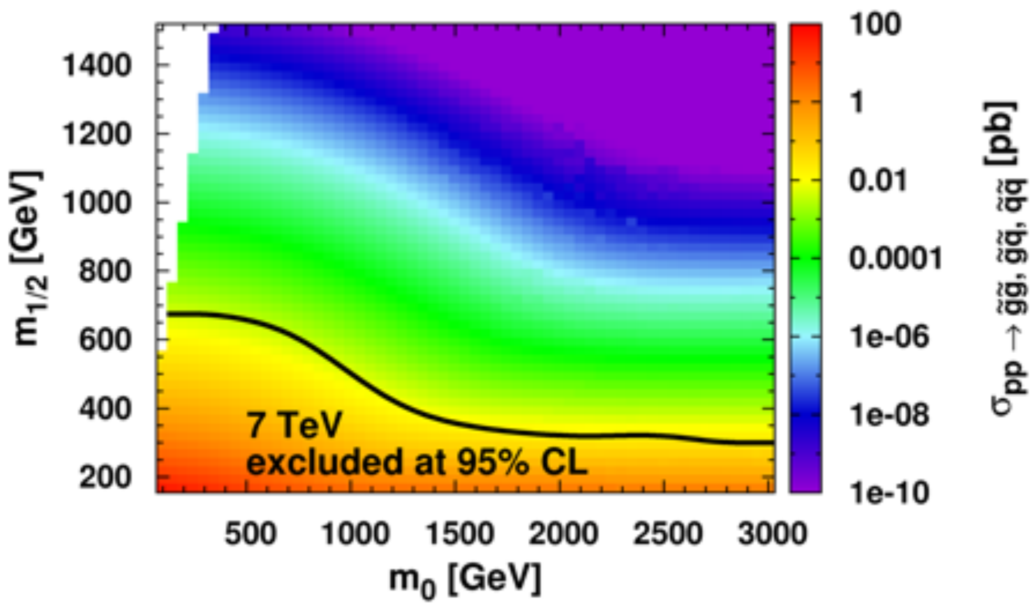
Both approaches are used

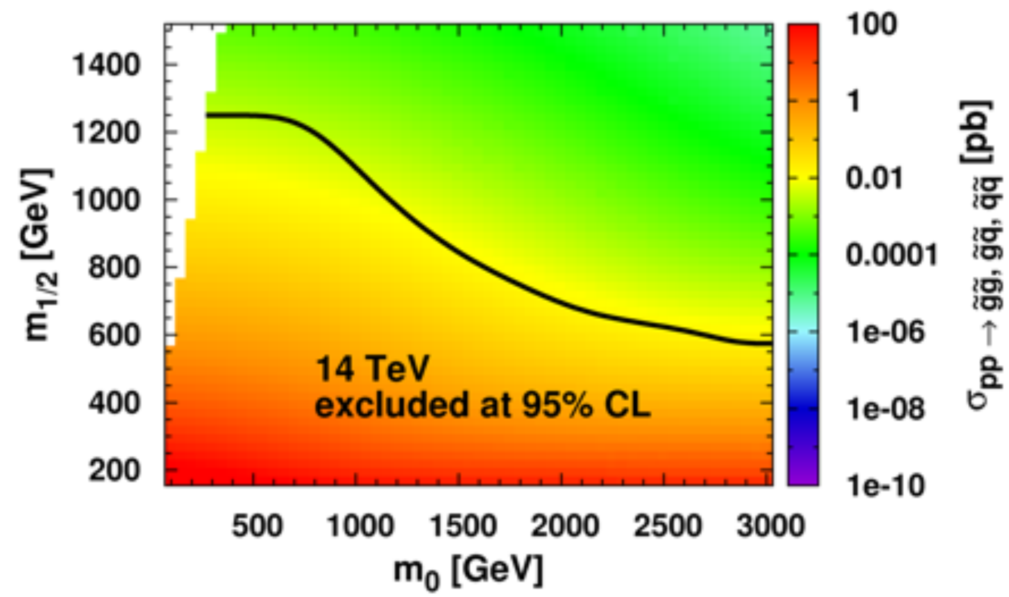
Guido Tonelli

SUSY searches



WHAT IS THE LHC REACH?

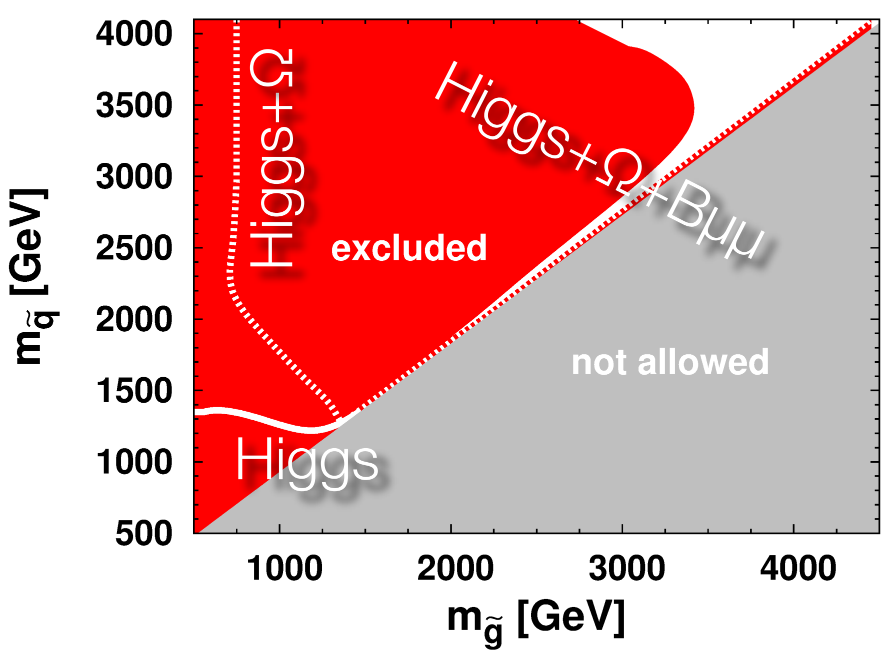


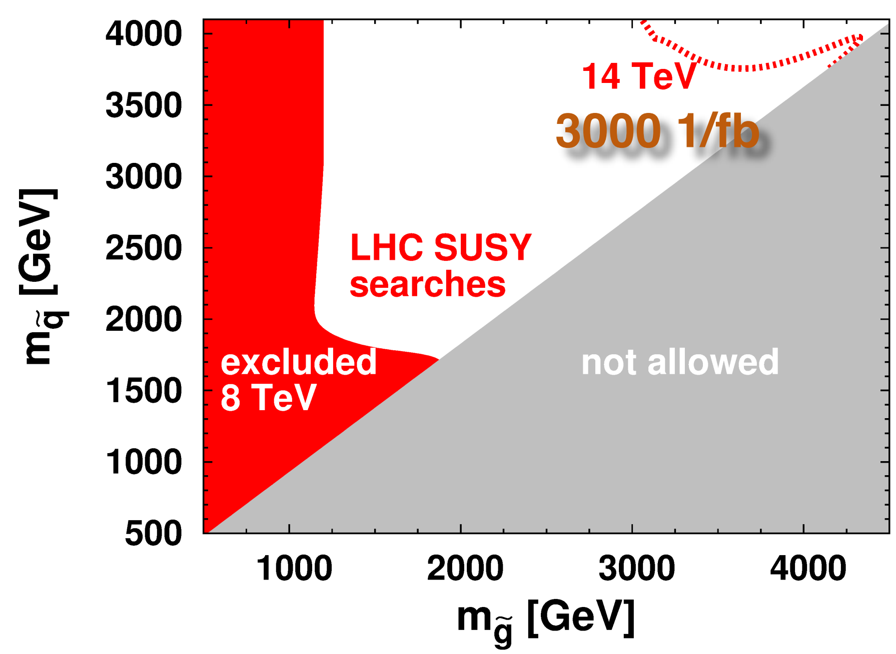


Universal scenario

CMSSM

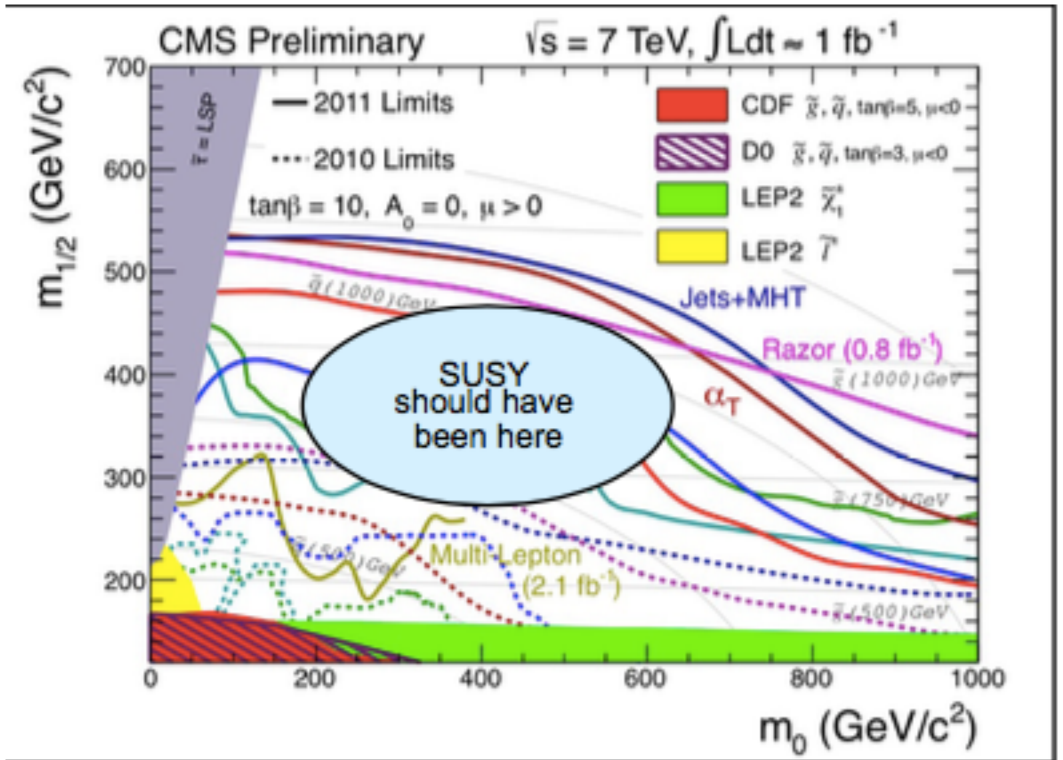
NMSSM

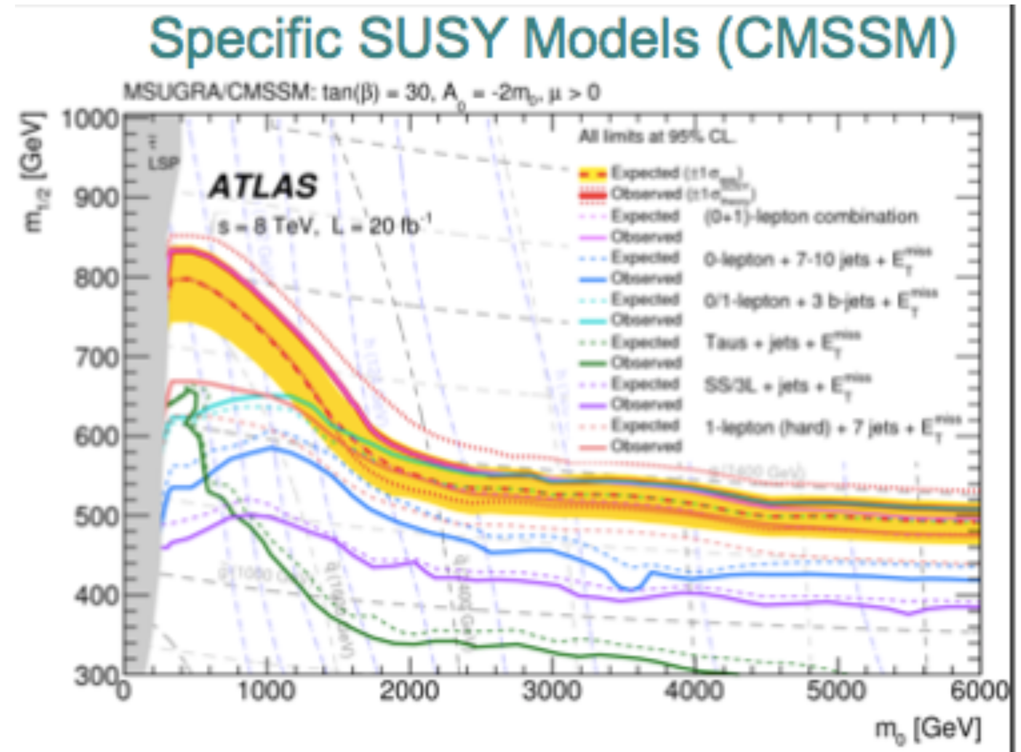




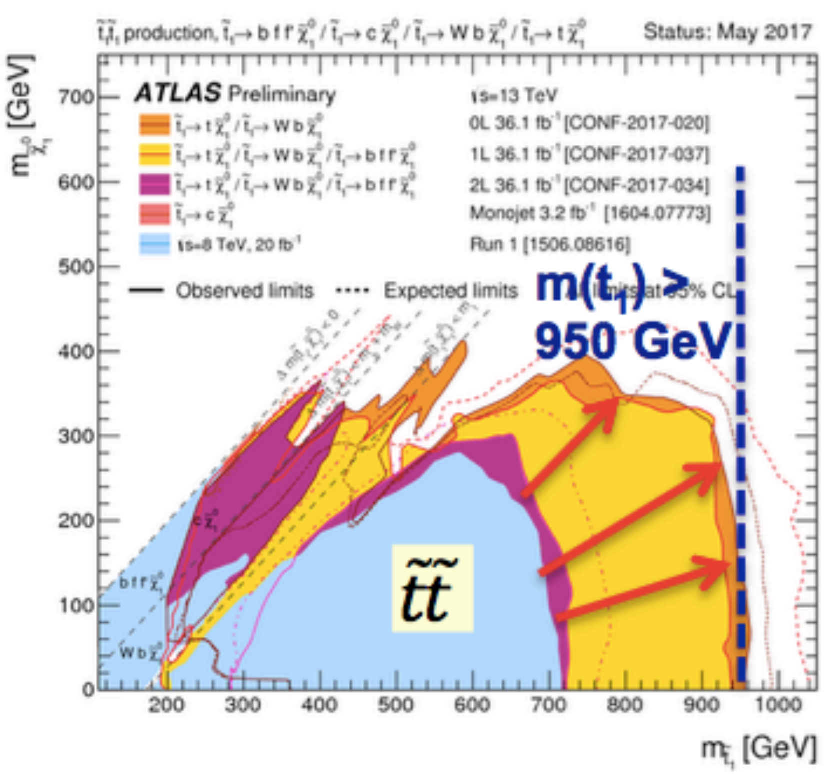
Masses of superpartners

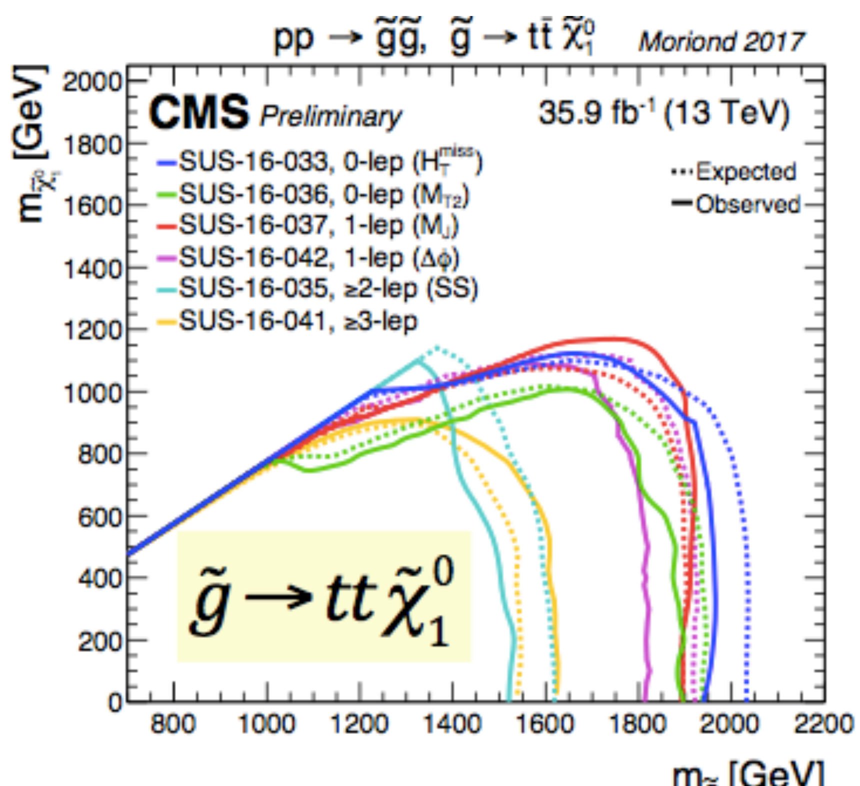
WHAT IS THE LHC REACH NOW?

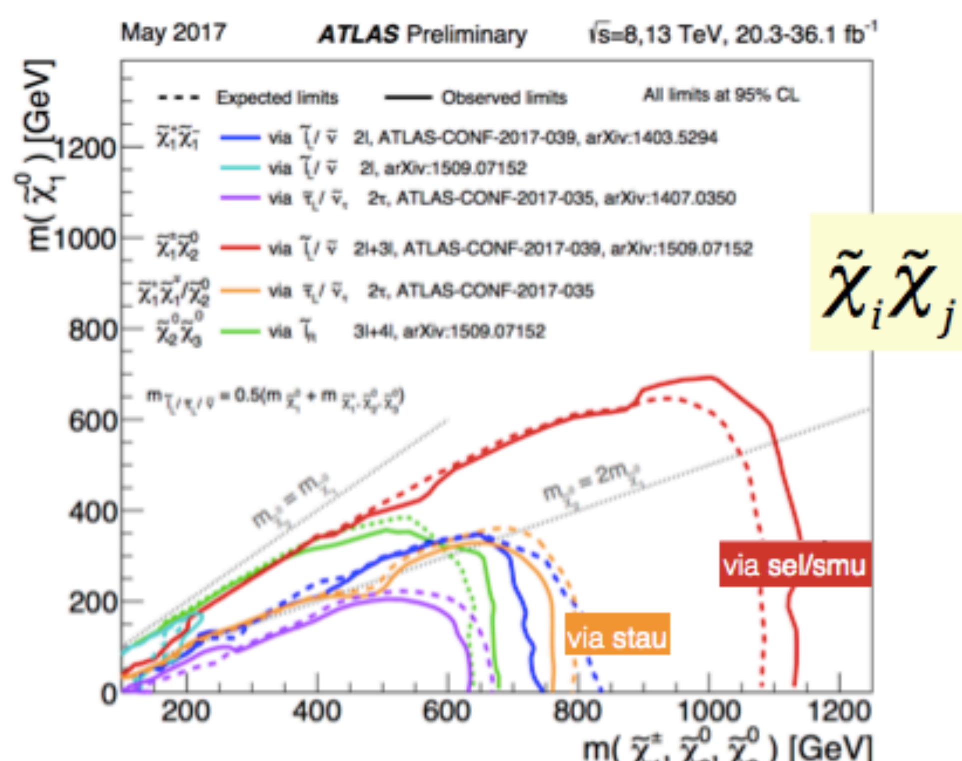




Universal parameters



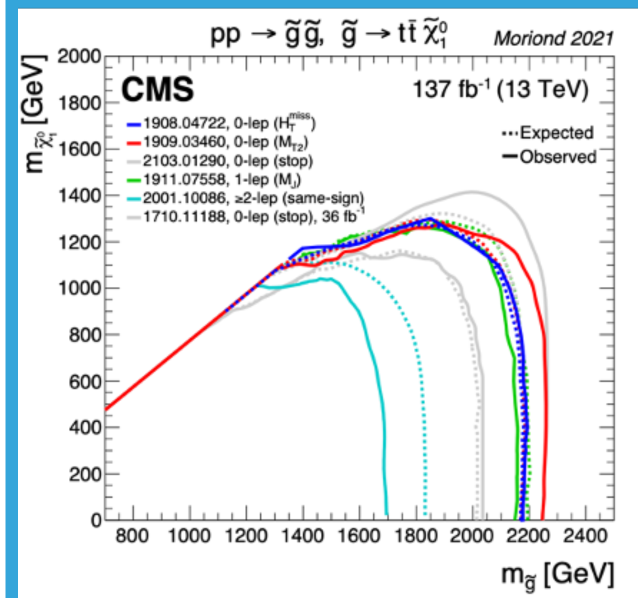


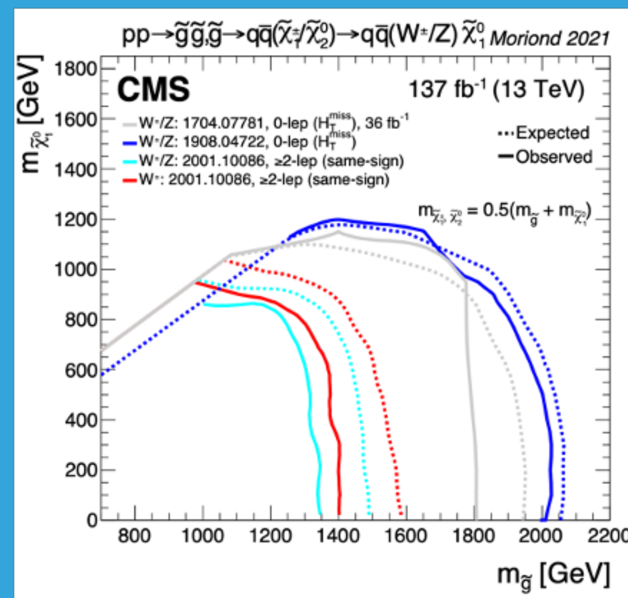


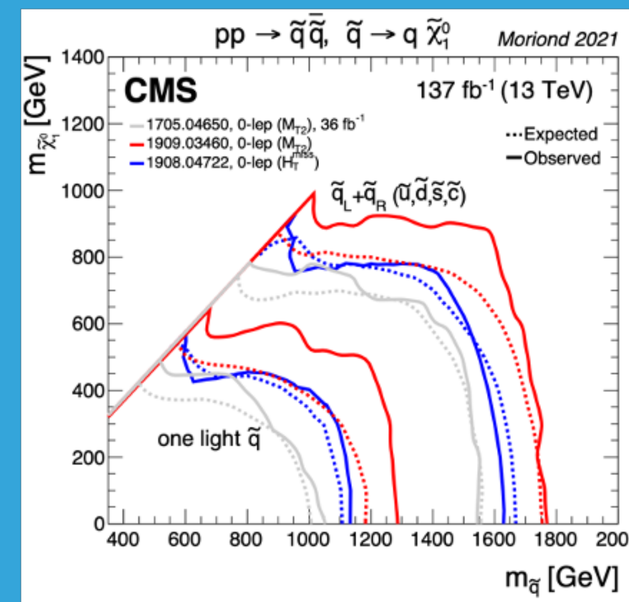
Masses of superpartners

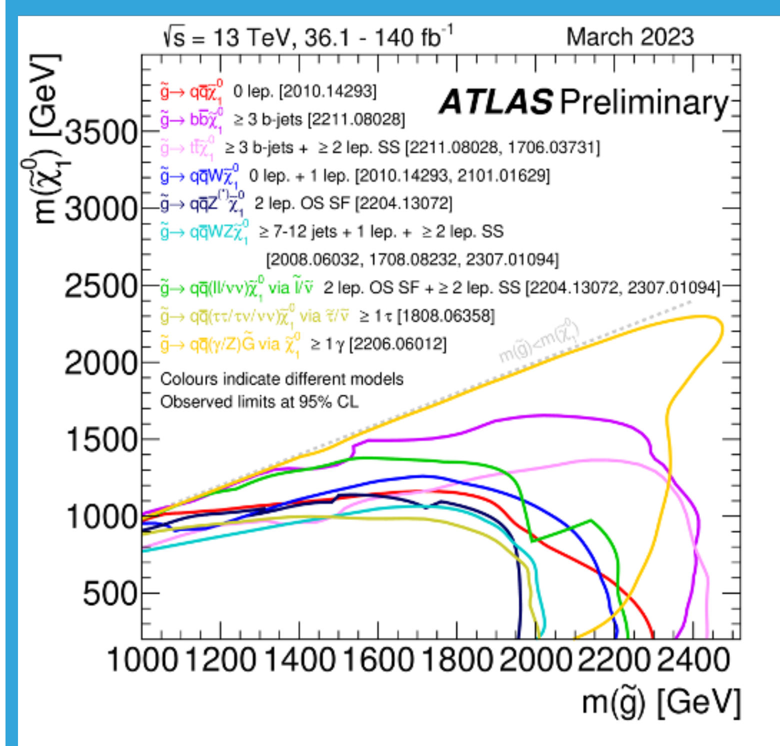
RECENT LHC LIMITS ON MSSM '23

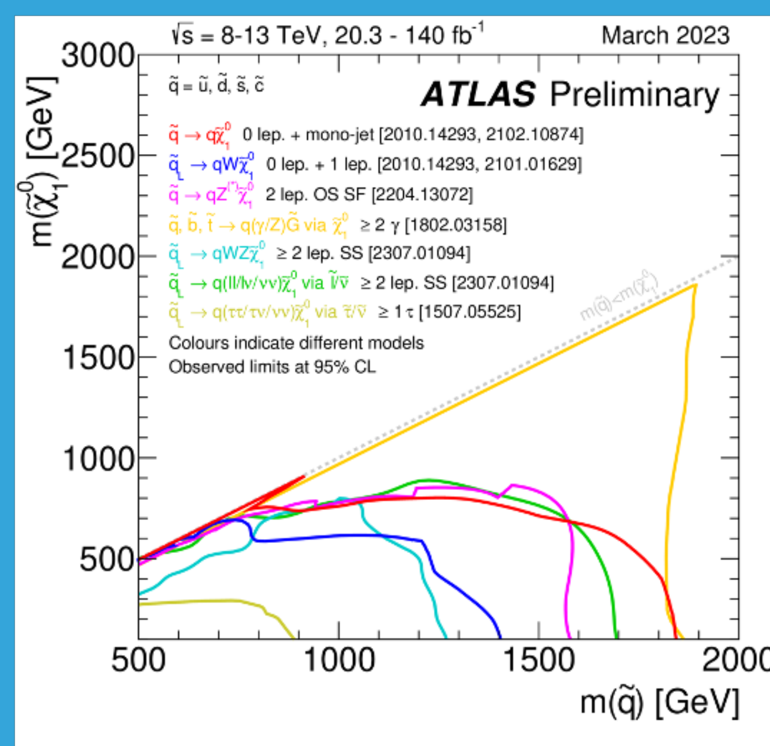
RUN2 LHC limits om MSSM, ATLAS&CMS

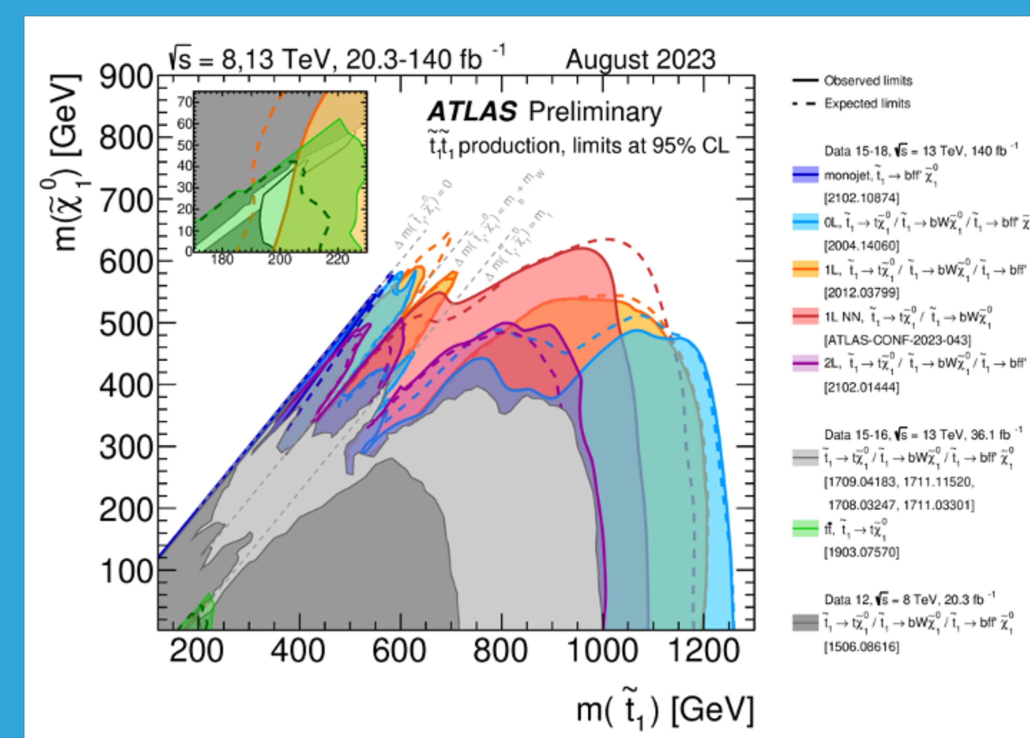




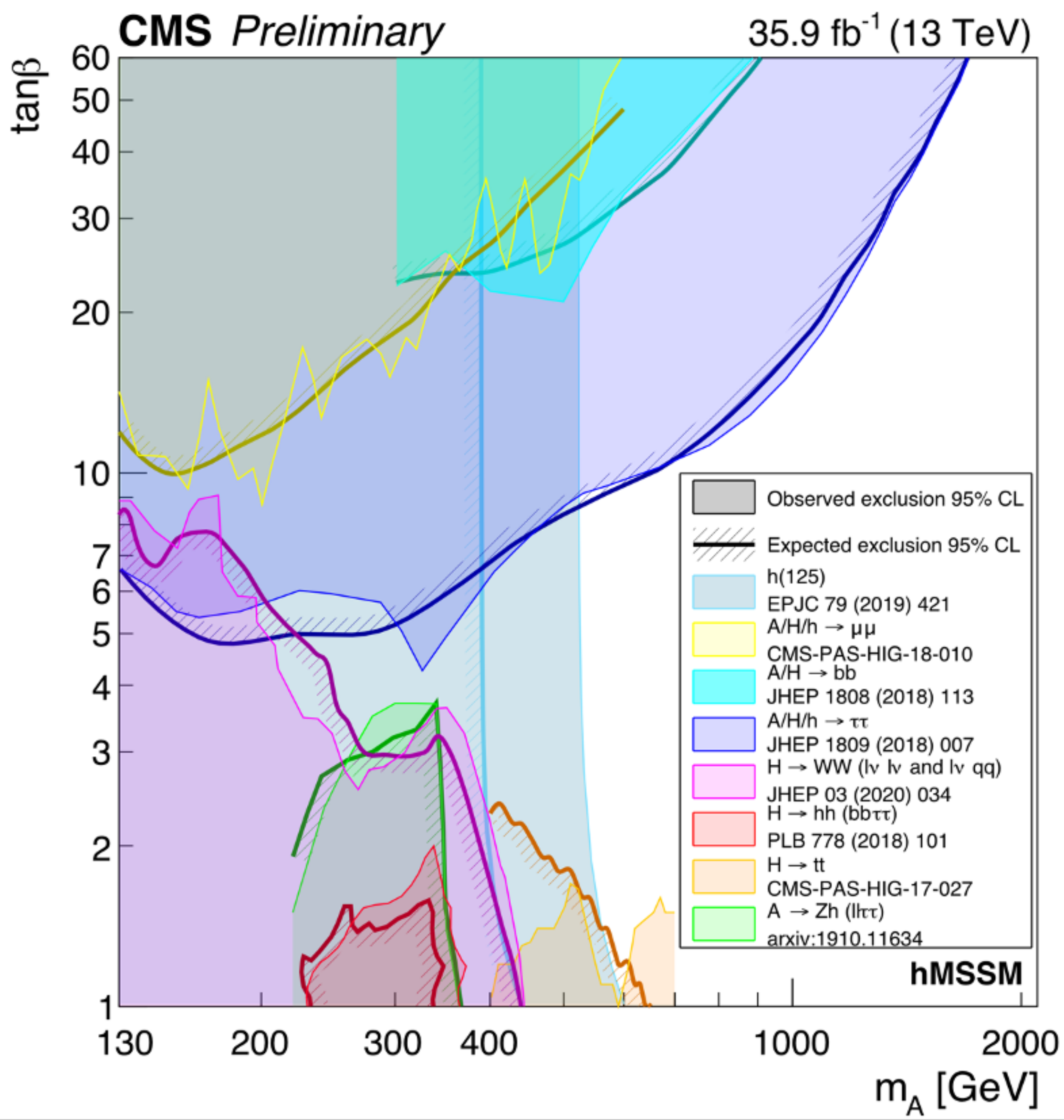






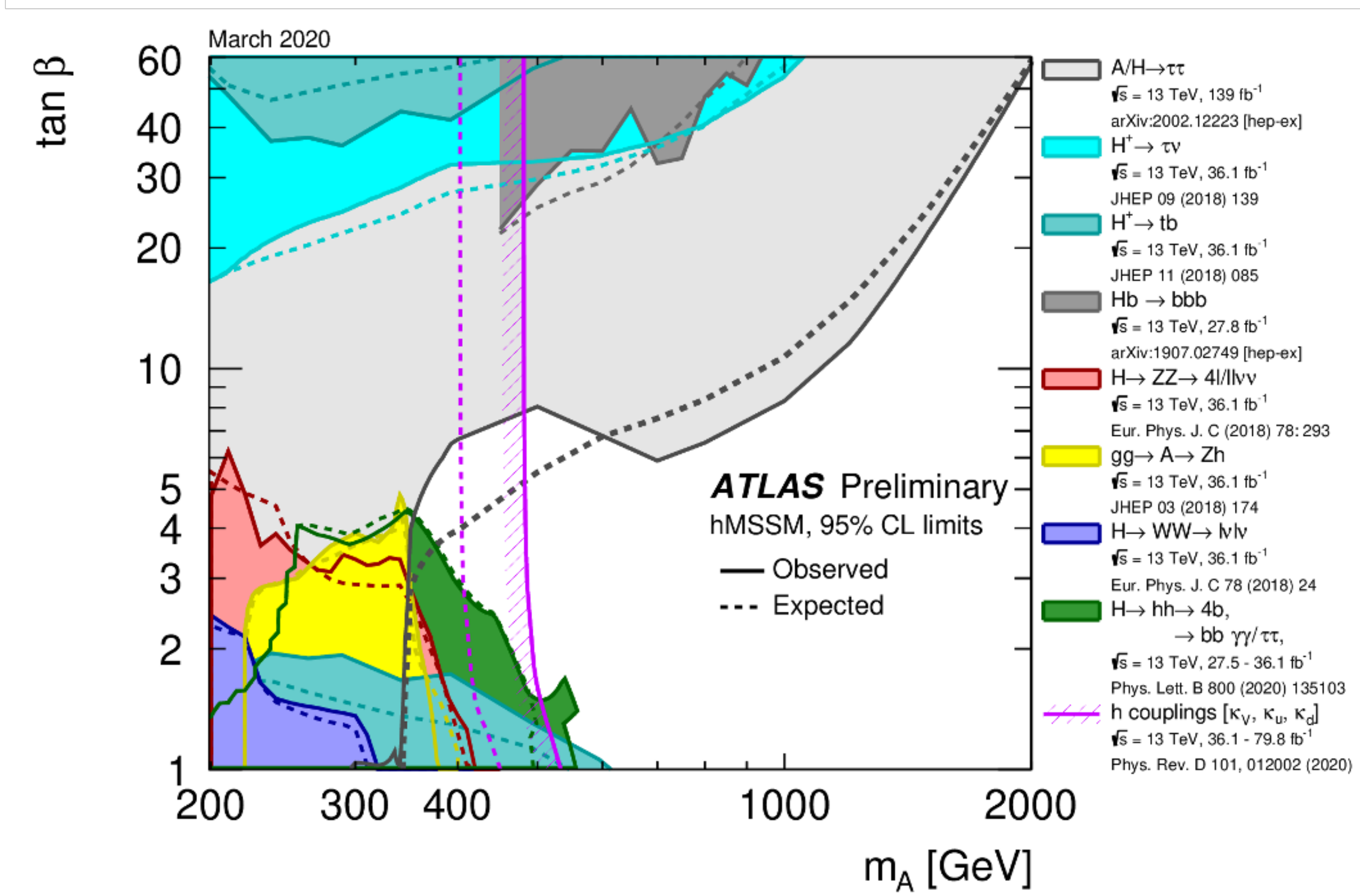


2HDM AND HMSSM LIMITS, RUN2

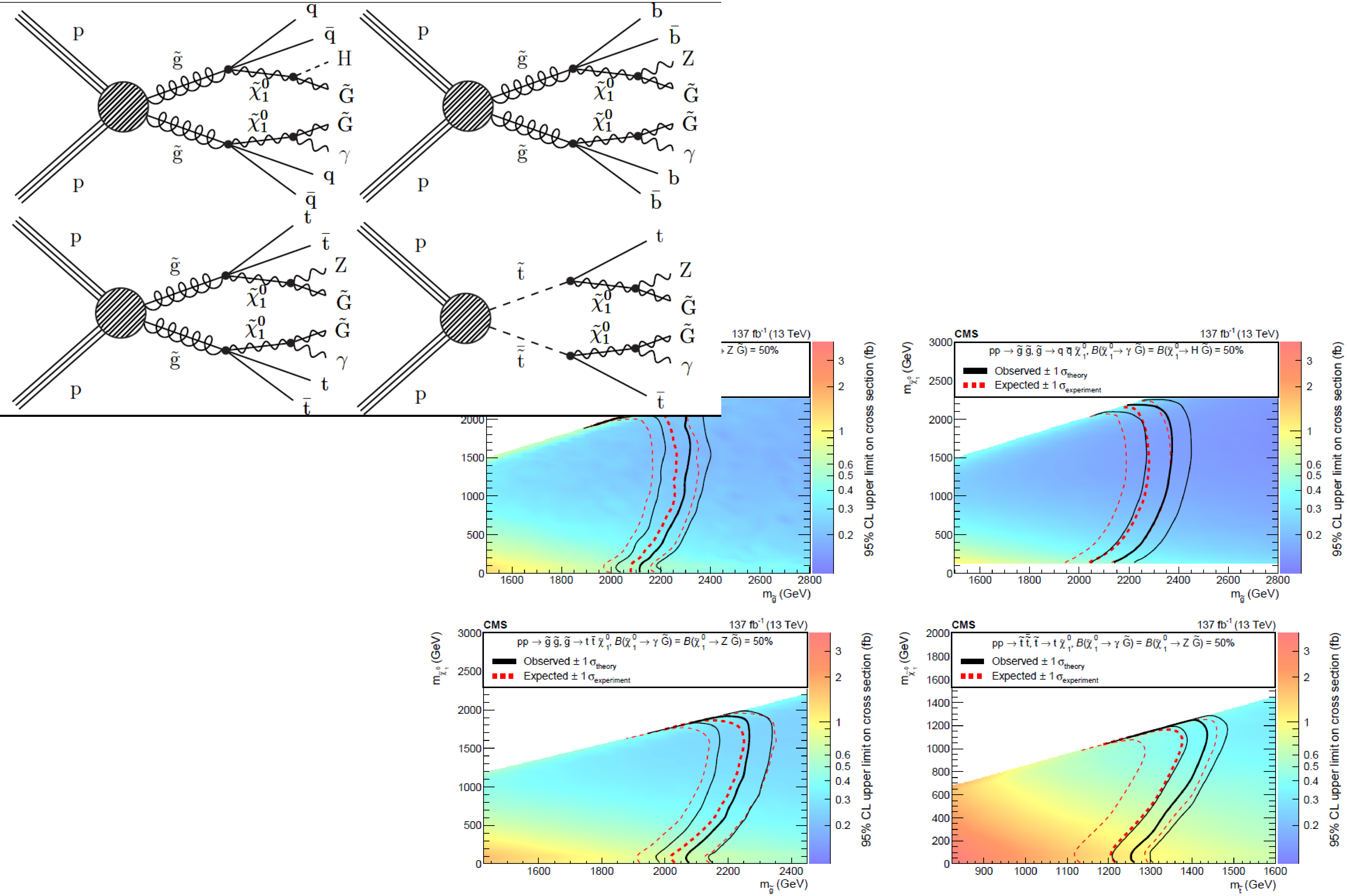


2HDM hMSSM combined results, RUN2

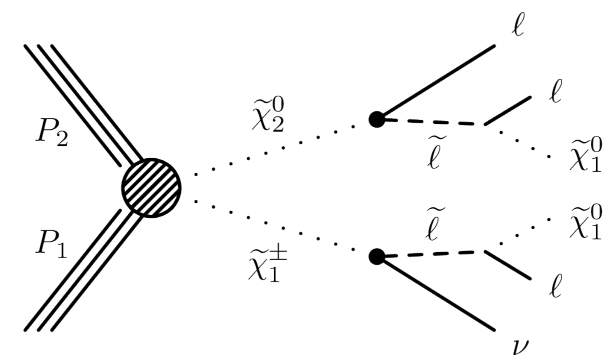
Much more details see in a talk by Adam Bailey
(+ comprehensive list of analyses for ATLAS & CMS)



RUN2 LHC LIMITS ON GMSB MSSM, CMS



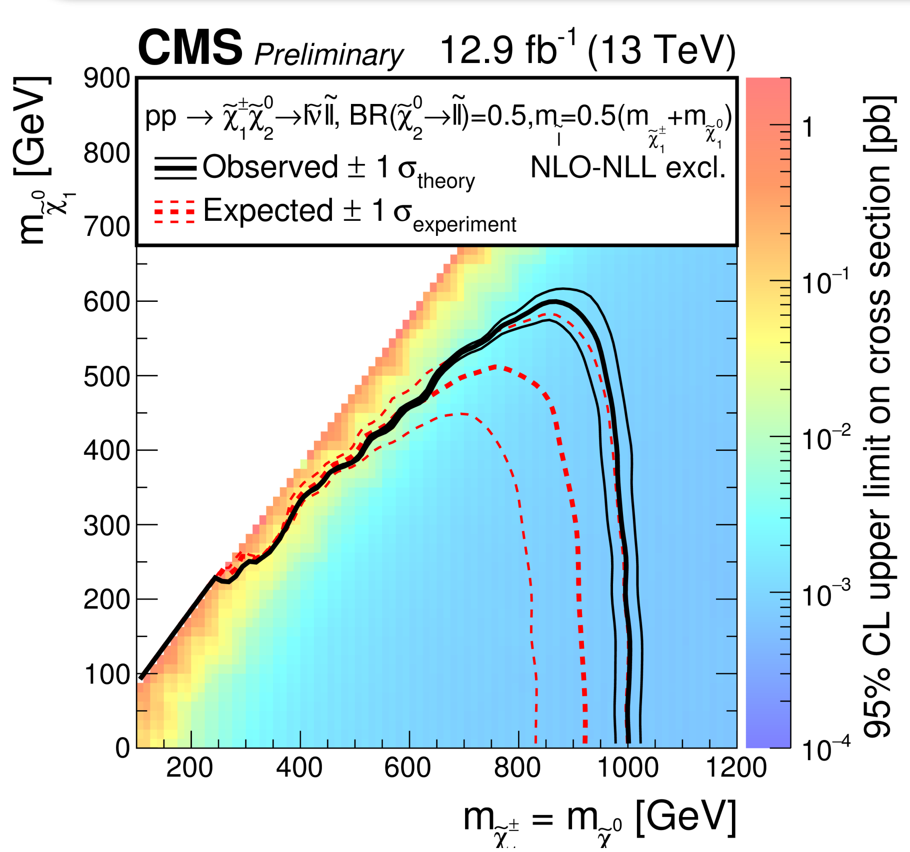
Chargino / neutralino production



Direct production of "electroweakino" pairs

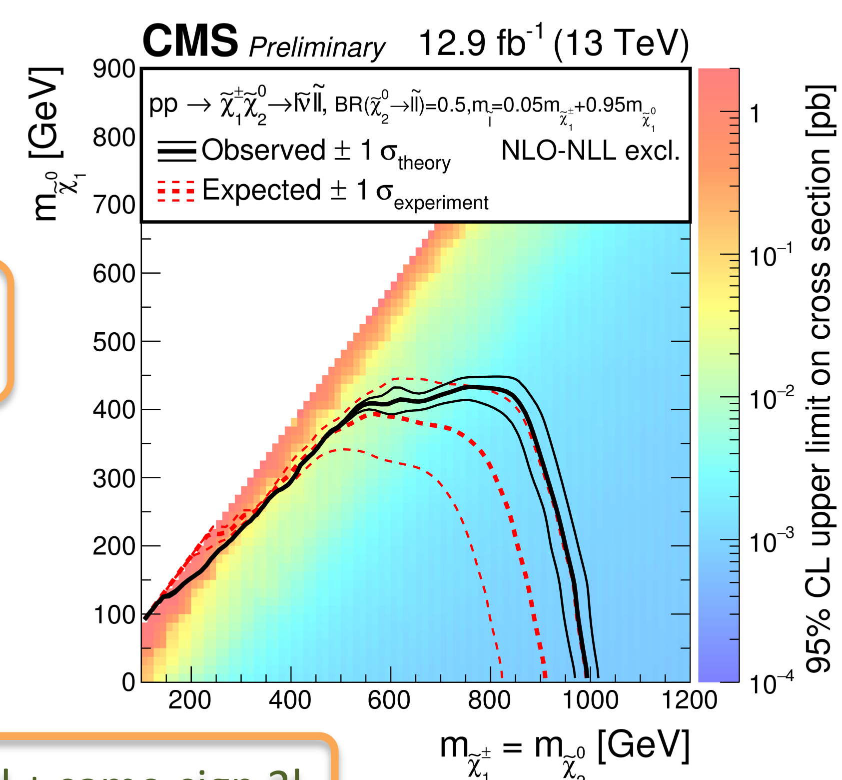
- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

No light EWkinos



Effect of change in intermediate slepton mass

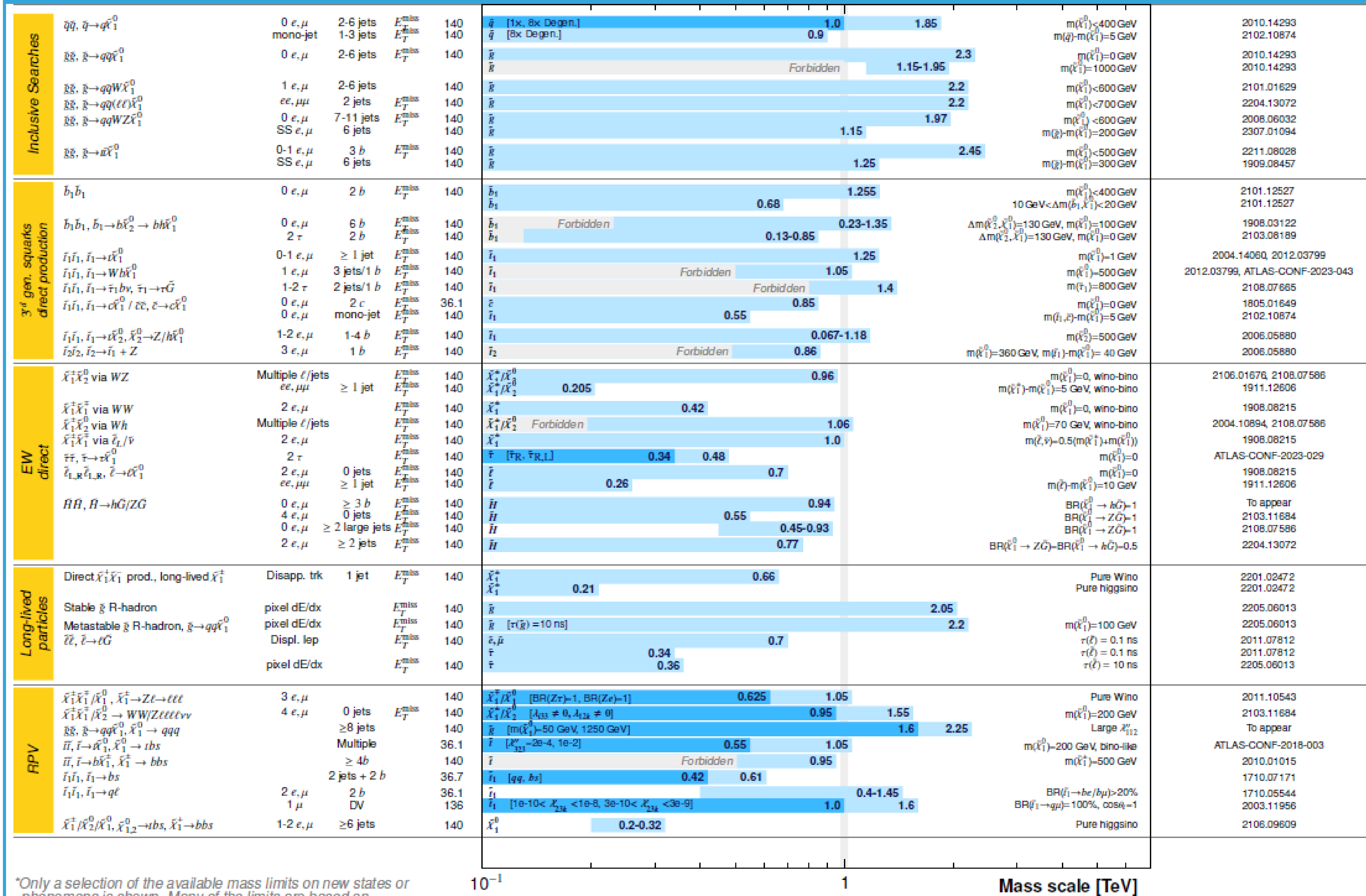
↔



3l + same-sign 2l

ATLAS AND CMS LIMITS 2023

ATLAS/CMS SUSY Limits, 2023



LONG LIVED PARTICLES

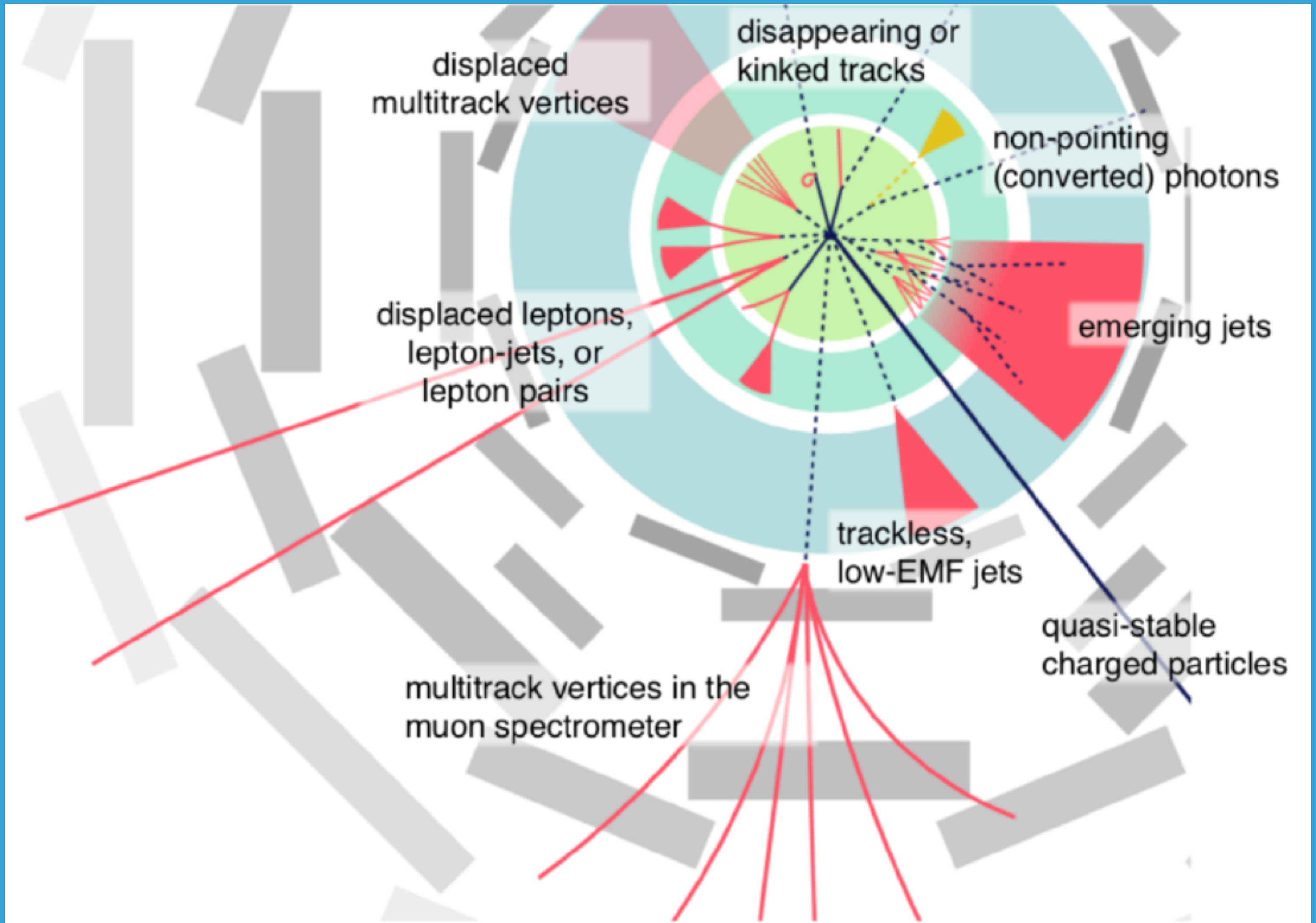
"The non-standard" (Long-Lived Particle) signatures

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

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

✓ intermediate $c\tau_0$ → LLP

✓ very large/infinite large $c\tau_0$ → stable particles, "standard" MET signatures

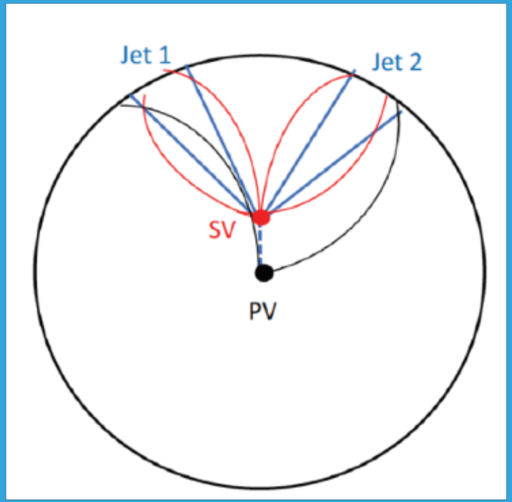


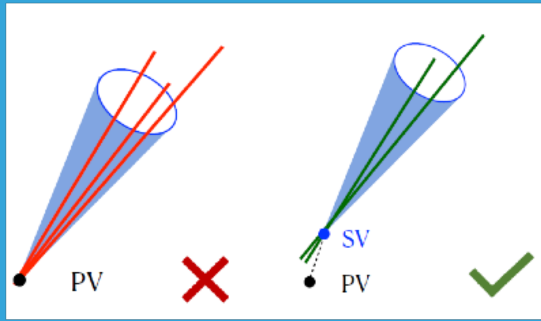
Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper: arXiv:1903.04497

LLP theory motivations: arXiv:1806.07396

displaced jets/leptons

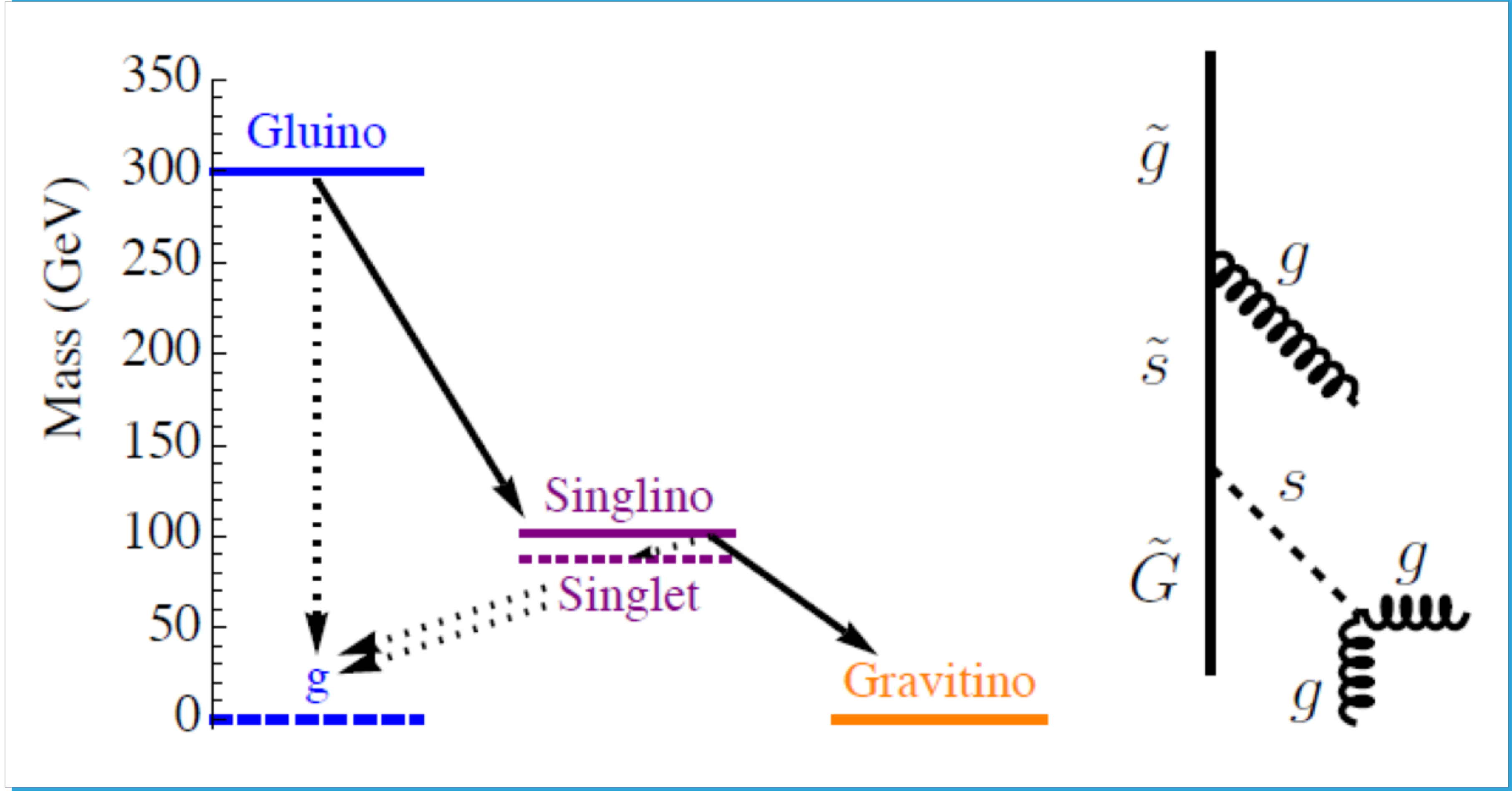


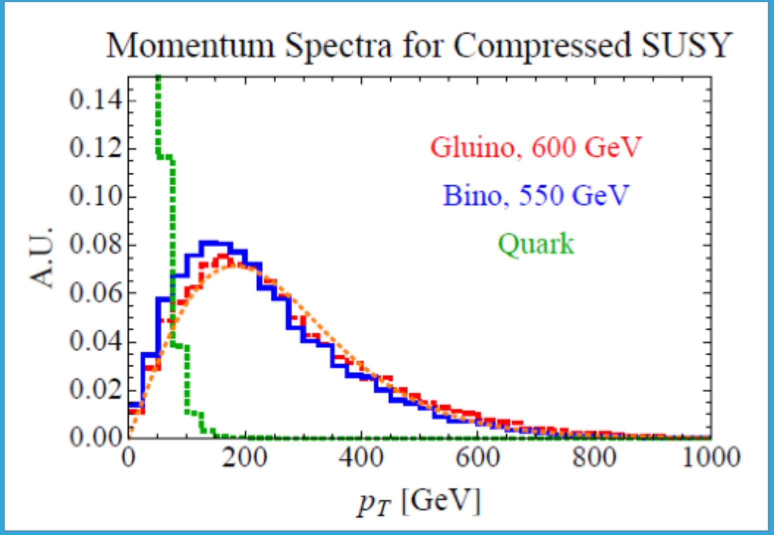


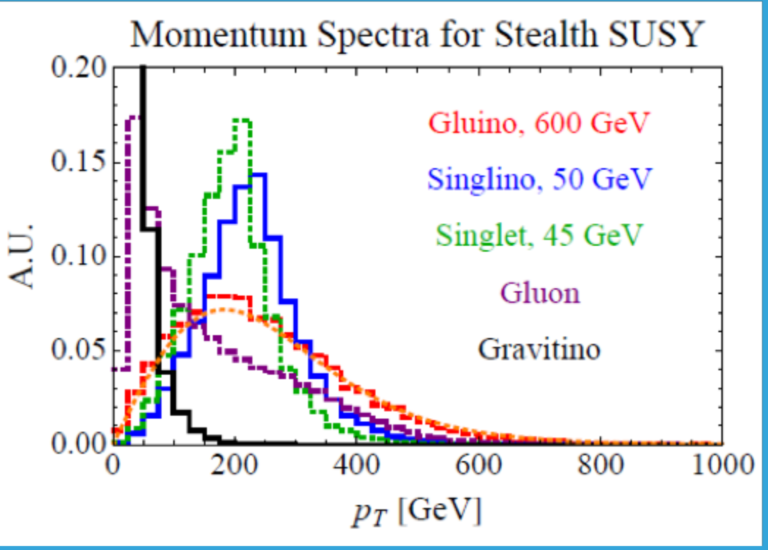
Stealth supersymmetry model

Stealth supersymmetry idea

SUSY is natural, low-scale SUSY breaking, hidden sector with one chiral singlet supefield (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).

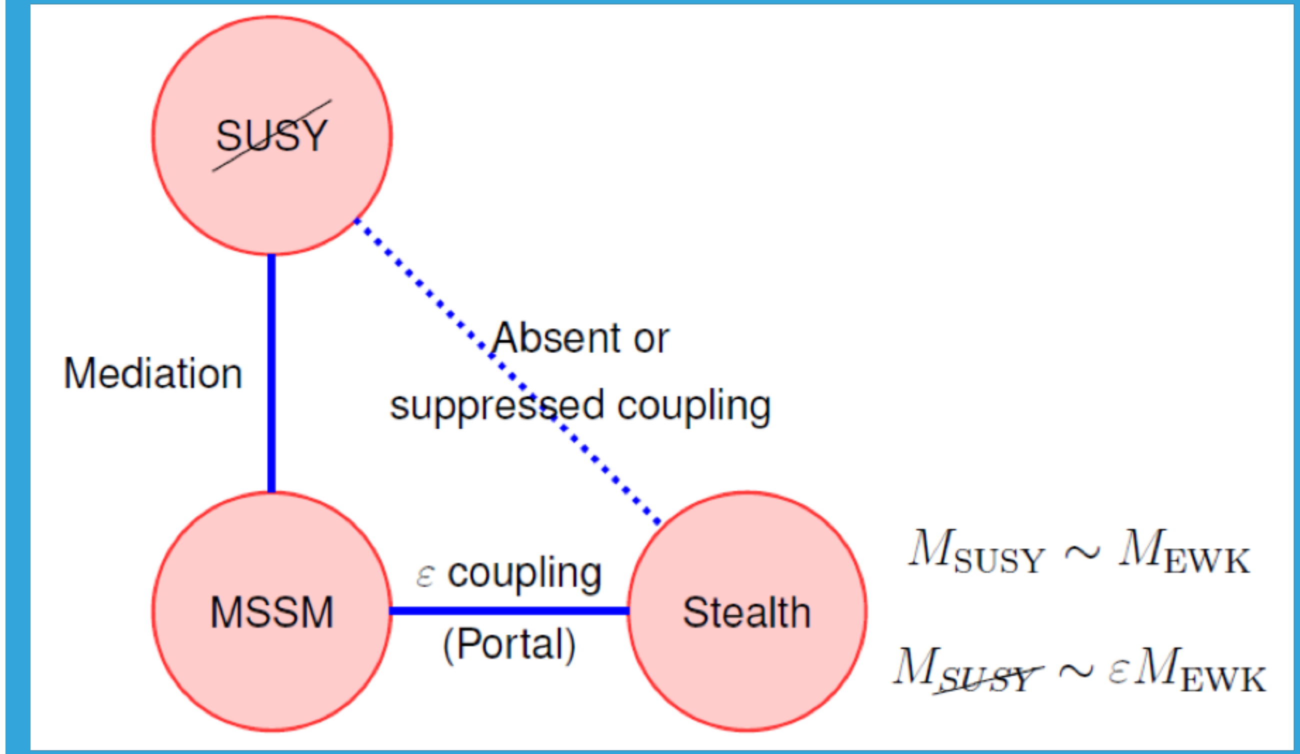






Stealth supersymmetry idea

Stealth supersymmetry idea



SUSY breaking – low-scale vs high-scale (large soft mass contributions to the stealth sector), mX_1X_2

Soft SUSY_breaking B-term (or M_{Pl} suppression in SUGRA)

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

$$\delta m = m - \sqrt{m^2 - B} \approx \frac{B}{2m}$$

splitting of about 10 GeV,

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

Stealth masses of about the EW scale – accident or common underlying physics? Small Bμ/dynamically generated masses

GMSB decay width

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

will be modified by new hidden sector

FUTURE SUSY SEARCHES

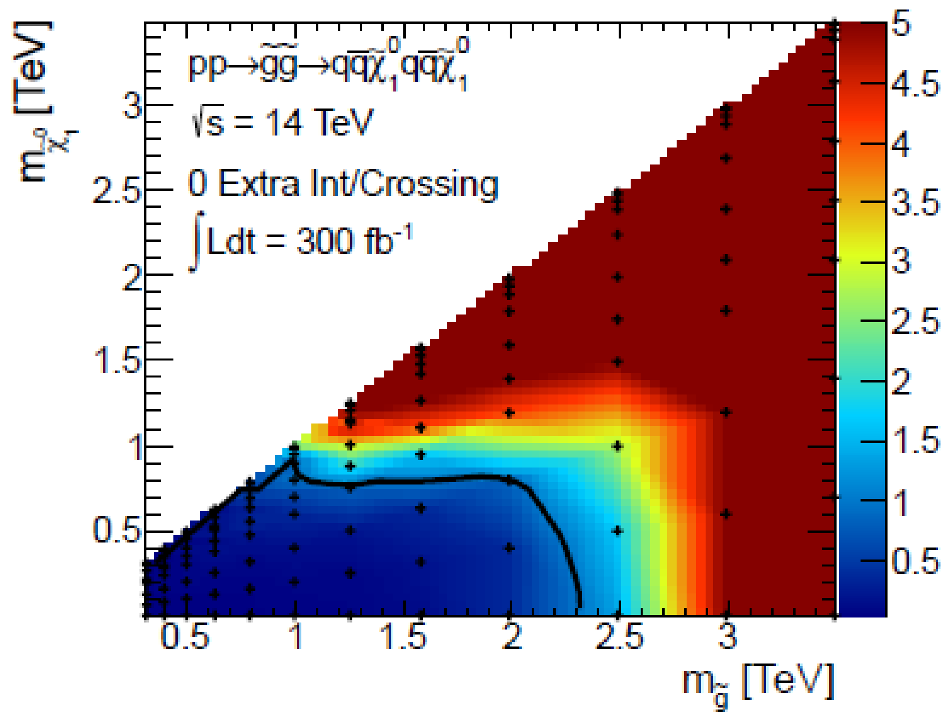
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

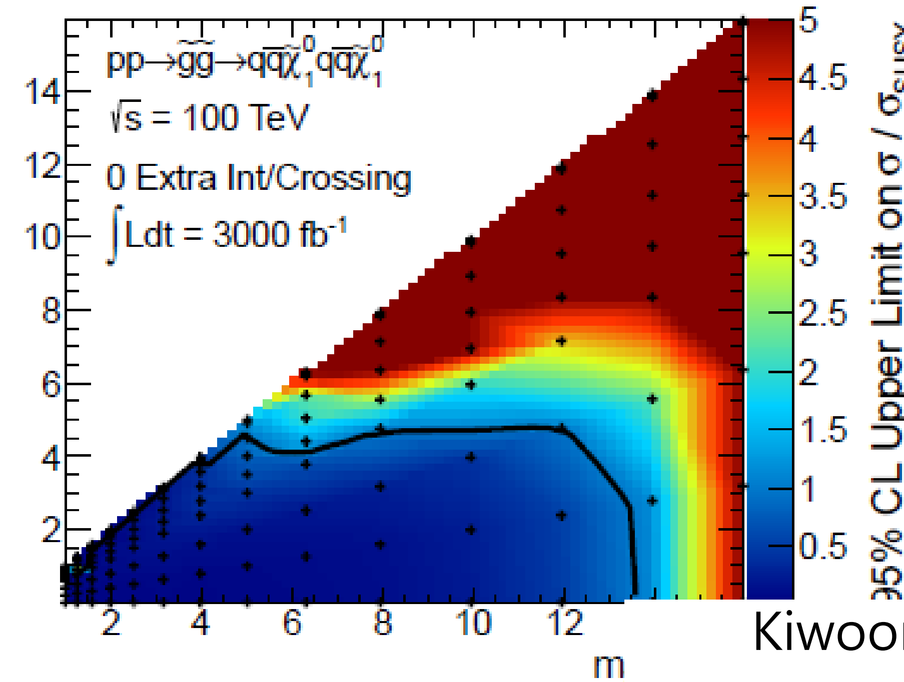
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, '13

100 TeV collider





Kiwoon Choi

(ICHEP 2016, Chicago)

SUSY GUT

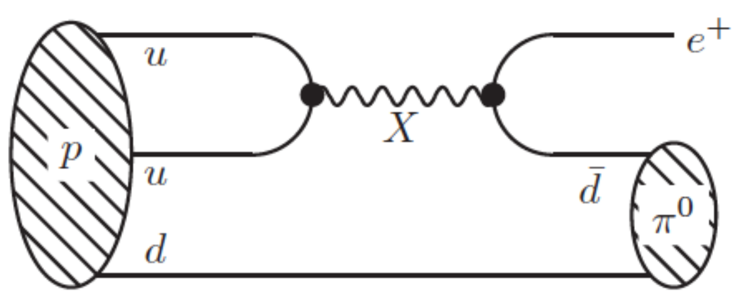
Crucial points:

- 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

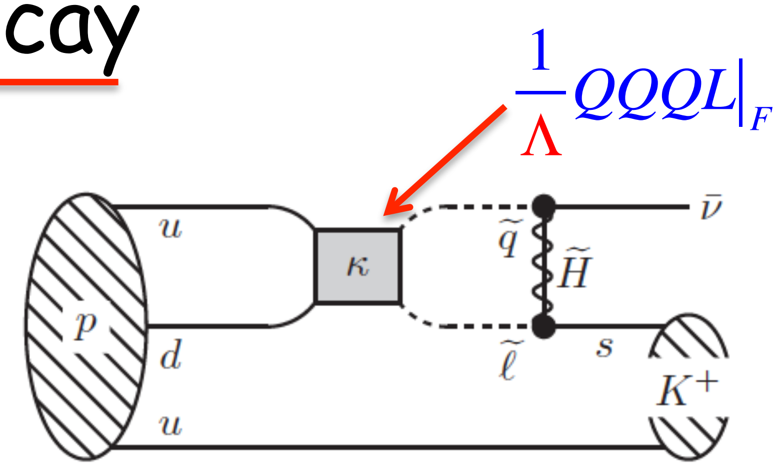
SUSY GUTS - Nucleon decay



(a) Dimension 6.

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

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



(b) Dimension 5.

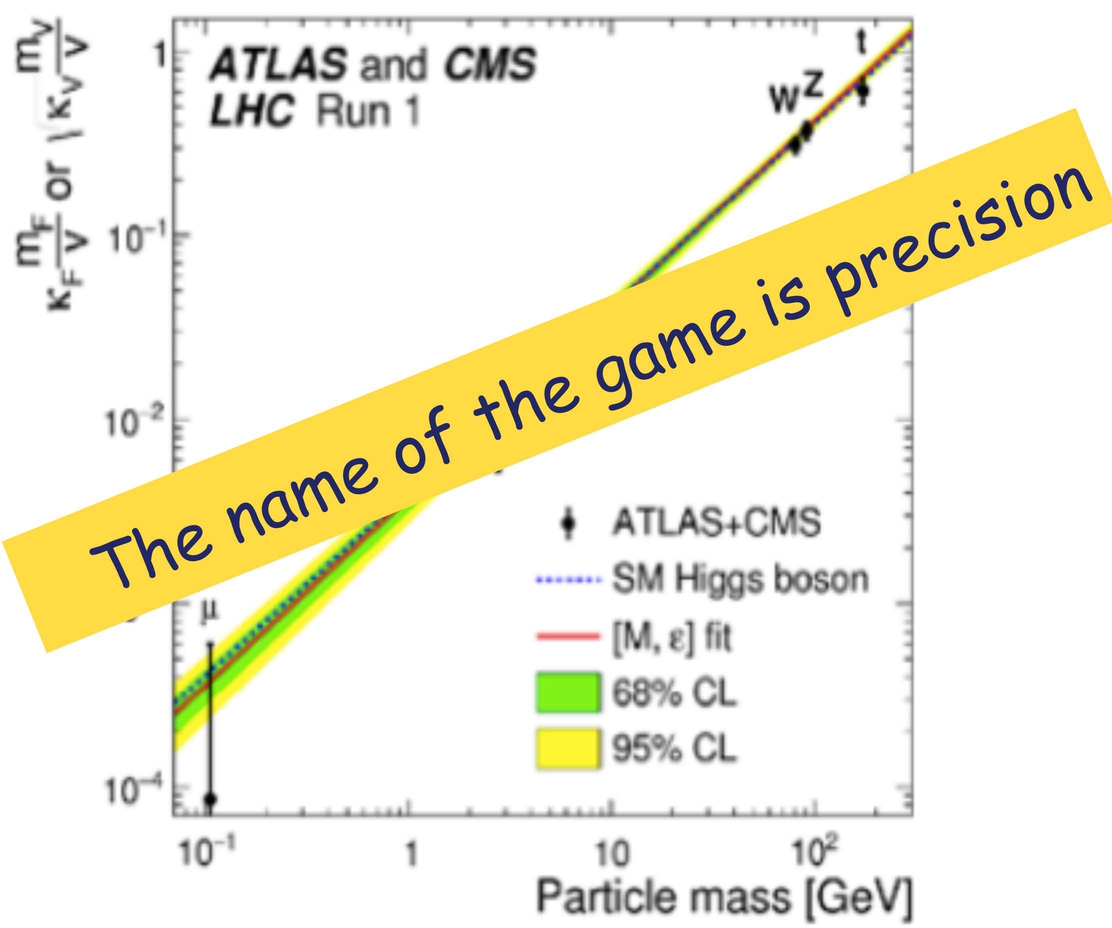
$$p \to K^+ + \bar{\nu}$$

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

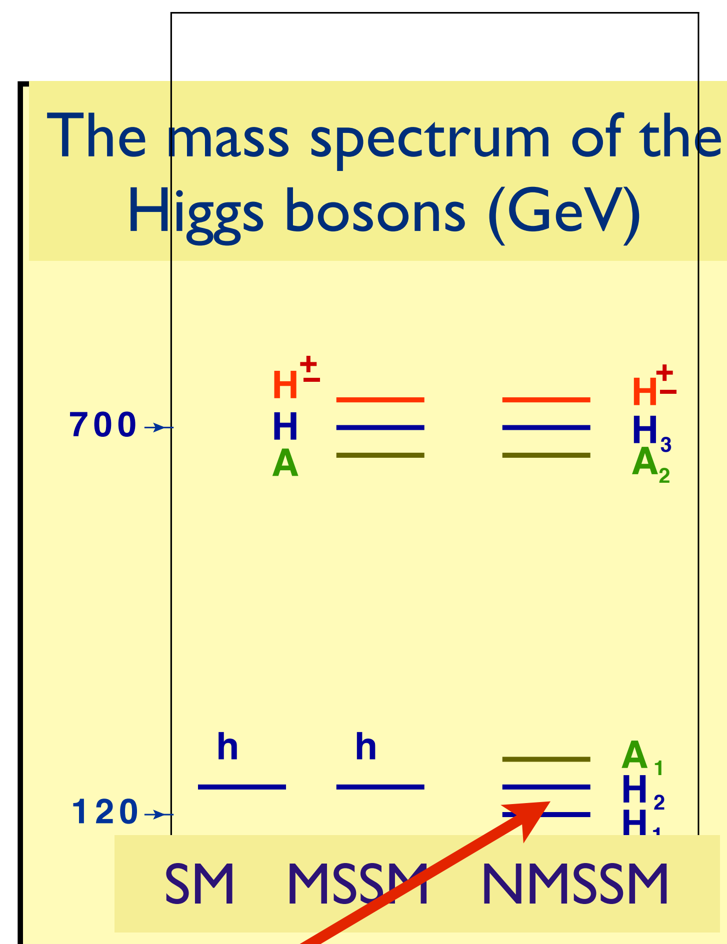
EXTENDED HIGGS SECTOR

How to probe?

- Probe deviations from the SM Higgs couplings



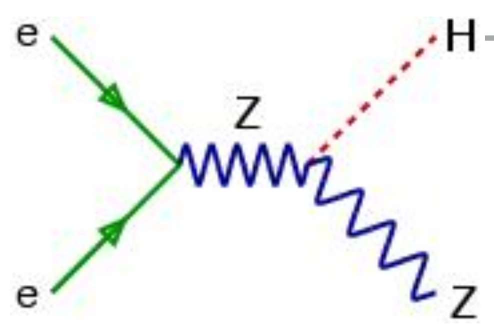
- Perform direct search for additional scalars



We may have found one of these states

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

PRECISION PHYSICS OF THE HIGGS BOSONS



$\rightarrow b\bar{b}q\bar{q}$

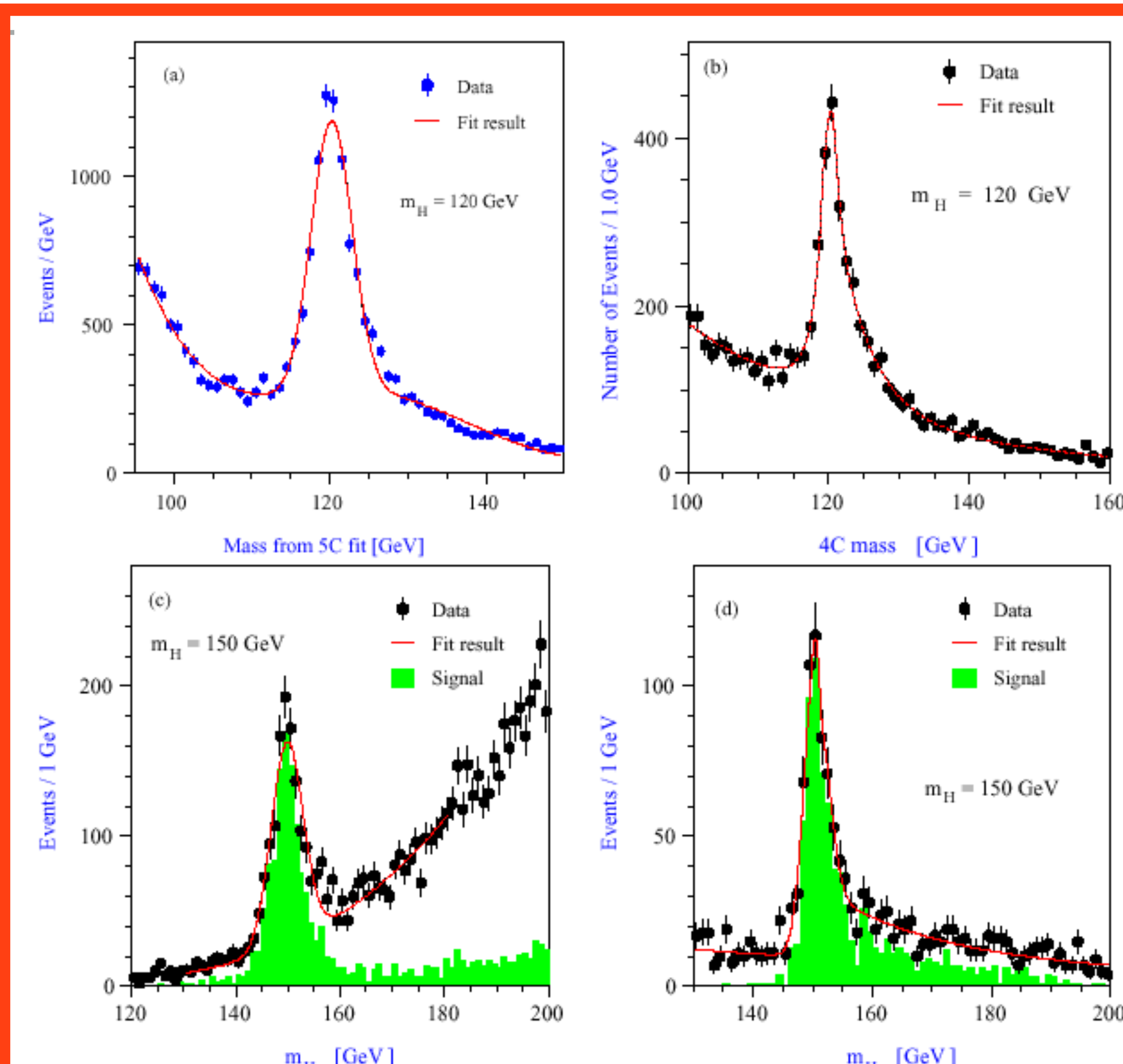
$\rightarrow q\bar{q}\ell^+\ell^-$

ee -> HZ diff. decay channels

Int Linear Collider

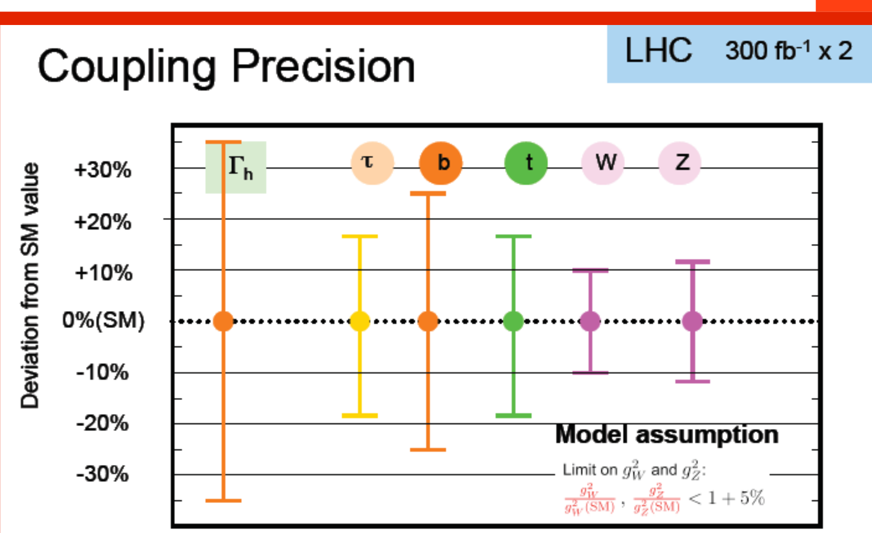
$\rightarrow W^+W^-q\bar{q}$

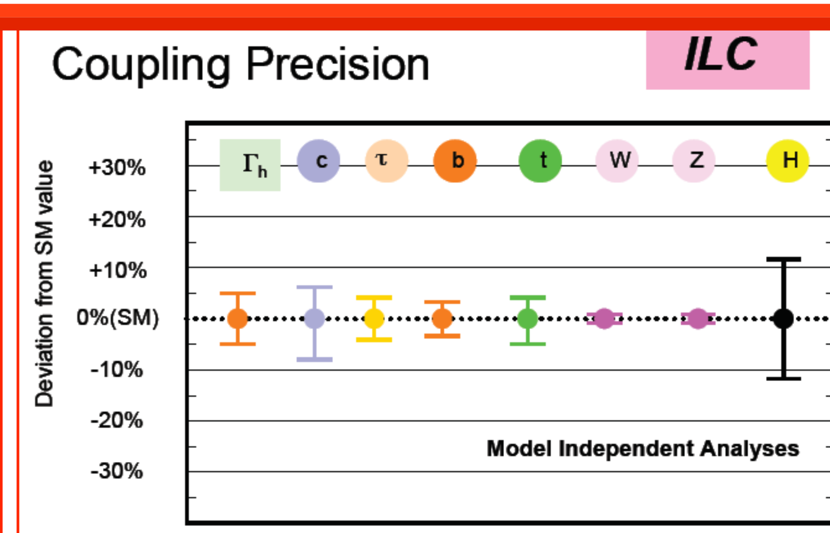
$\rightarrow W^+W^-\ell^+\ell^-$

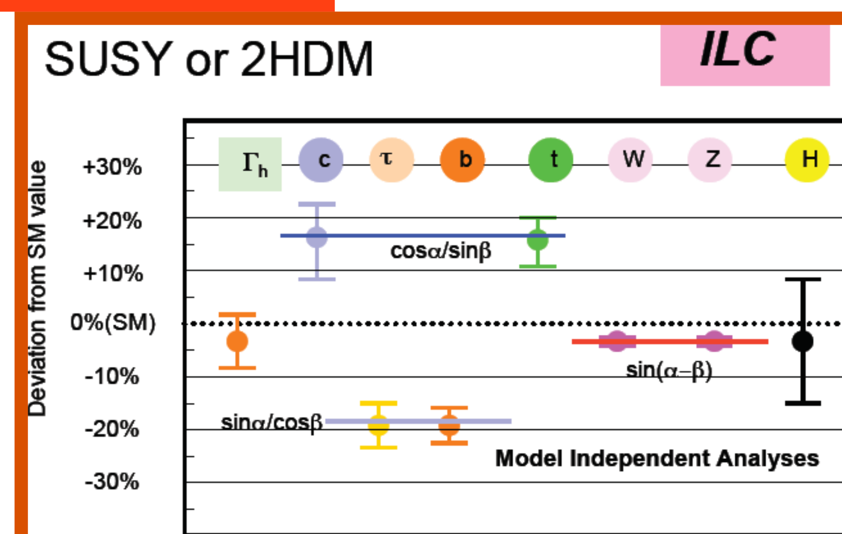


Δm_H = 40 MeV

Δm_H = 70 MeV







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?