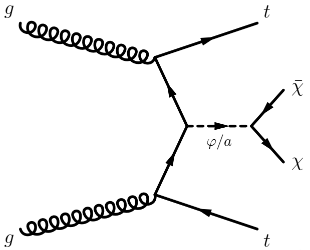
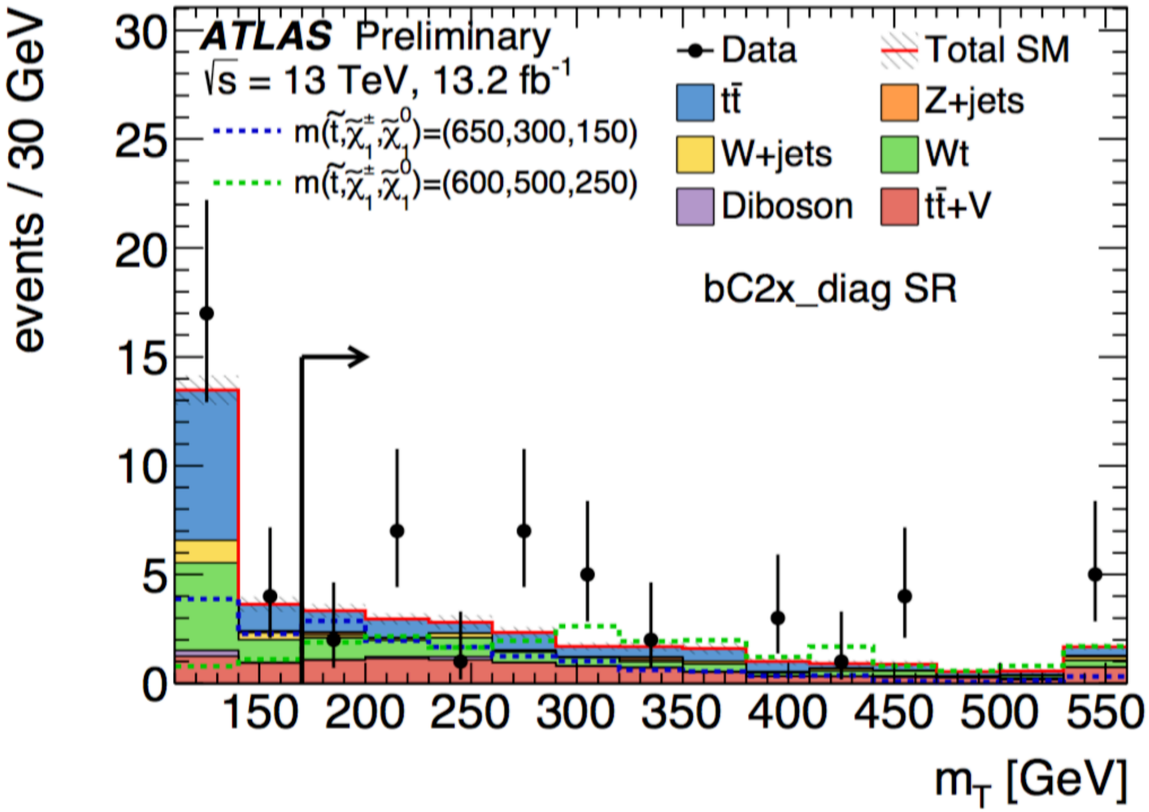
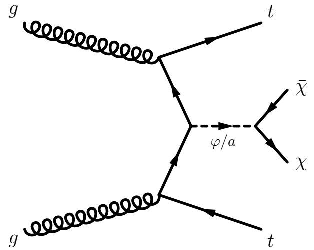


Transverse mass



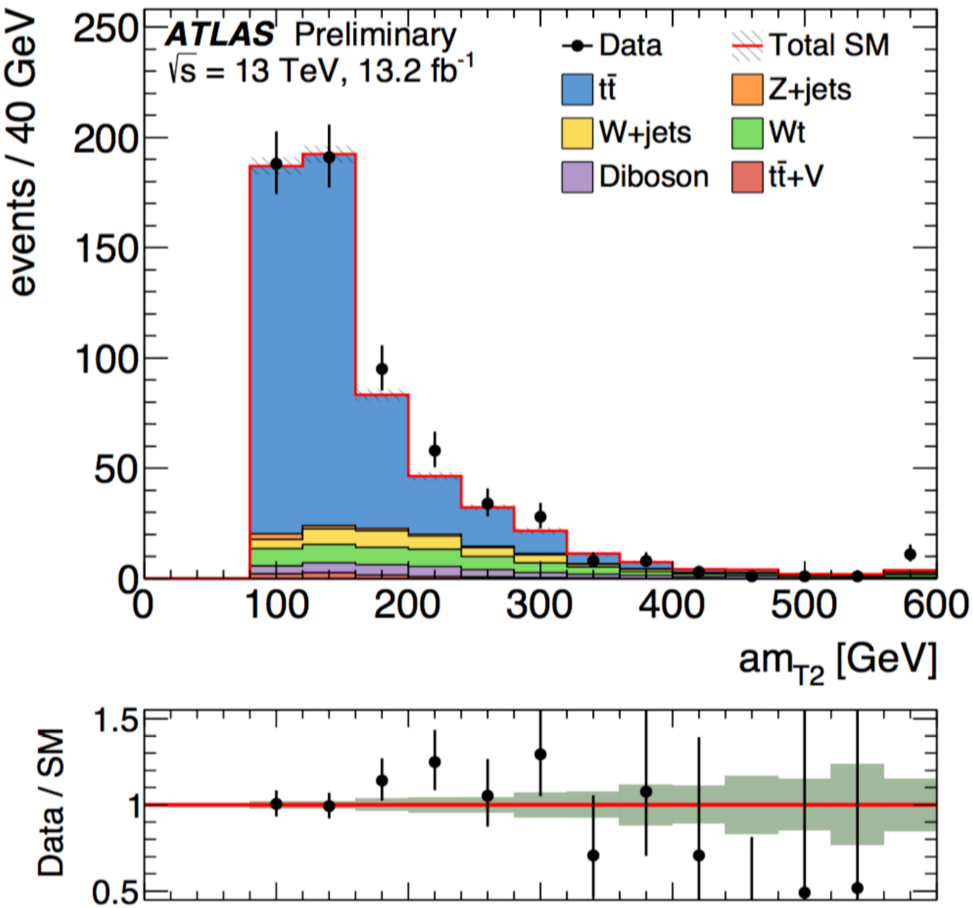
$$m_T^2 = 2p_T^{lep} E_T^{miss}[1 - \cos(\Delta\phi)]$$

Rejects W+jets and top pairs decaying semi-leptonically

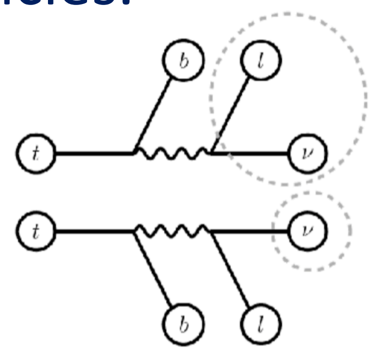


Transverse mass

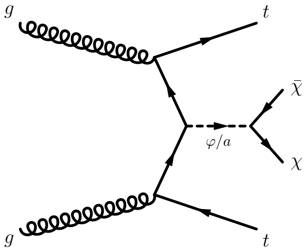
$$m_{T2}^2(\vec{p}_T^{\,l1}, \vec{p}_T^{\,l2}, \vec{p}_T^{\,miss}) = \min_{\vec{p}_T^{\,miss1} + \vec{p}_T^{\,miss2} = \vec{p}_T^{\,miss}} \{\max[m_T^2(\vec{p}_T^{\,l1}, \vec{p}_T^{\,miss1}), m_T^2(\vec{p}_T^{\,l2}, \vec{p}_T^{\,miss2})]\}$$



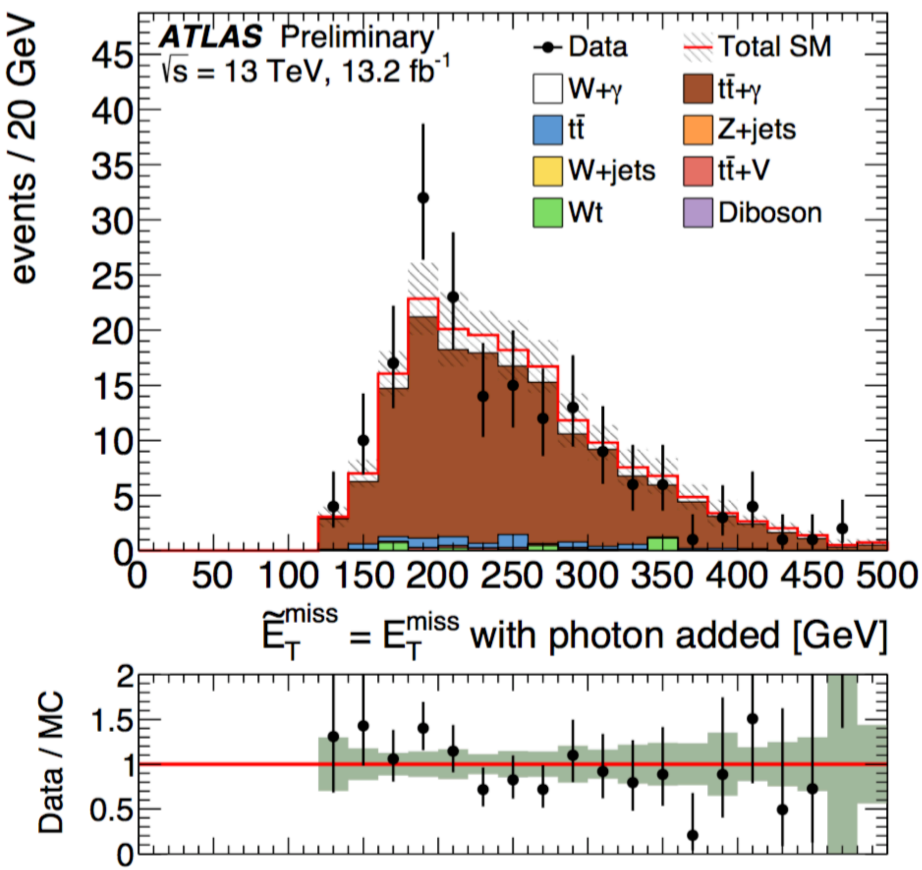
Generalisation of the transverse mass for systems with two invisible particles.



The generalized version for asymmetric decays (am_{T2}) is used here.



From ttγ to ttZ



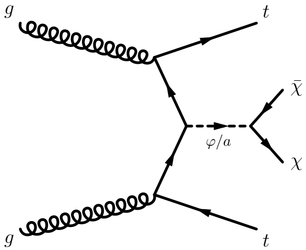
A CR using *Z* boson decays to charged leptons is not feasible

- small branching ratio
- limited dataset available

ttγ can be used for a data-driven approach.

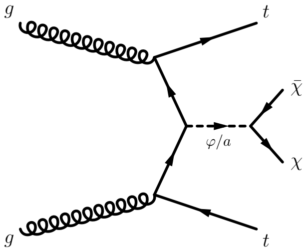
- Select high-p_T γ

The highest-p_T photon is vectorially added to p_T^{miss} and this sum is used to construct $\tilde{E}_T^{miss}$

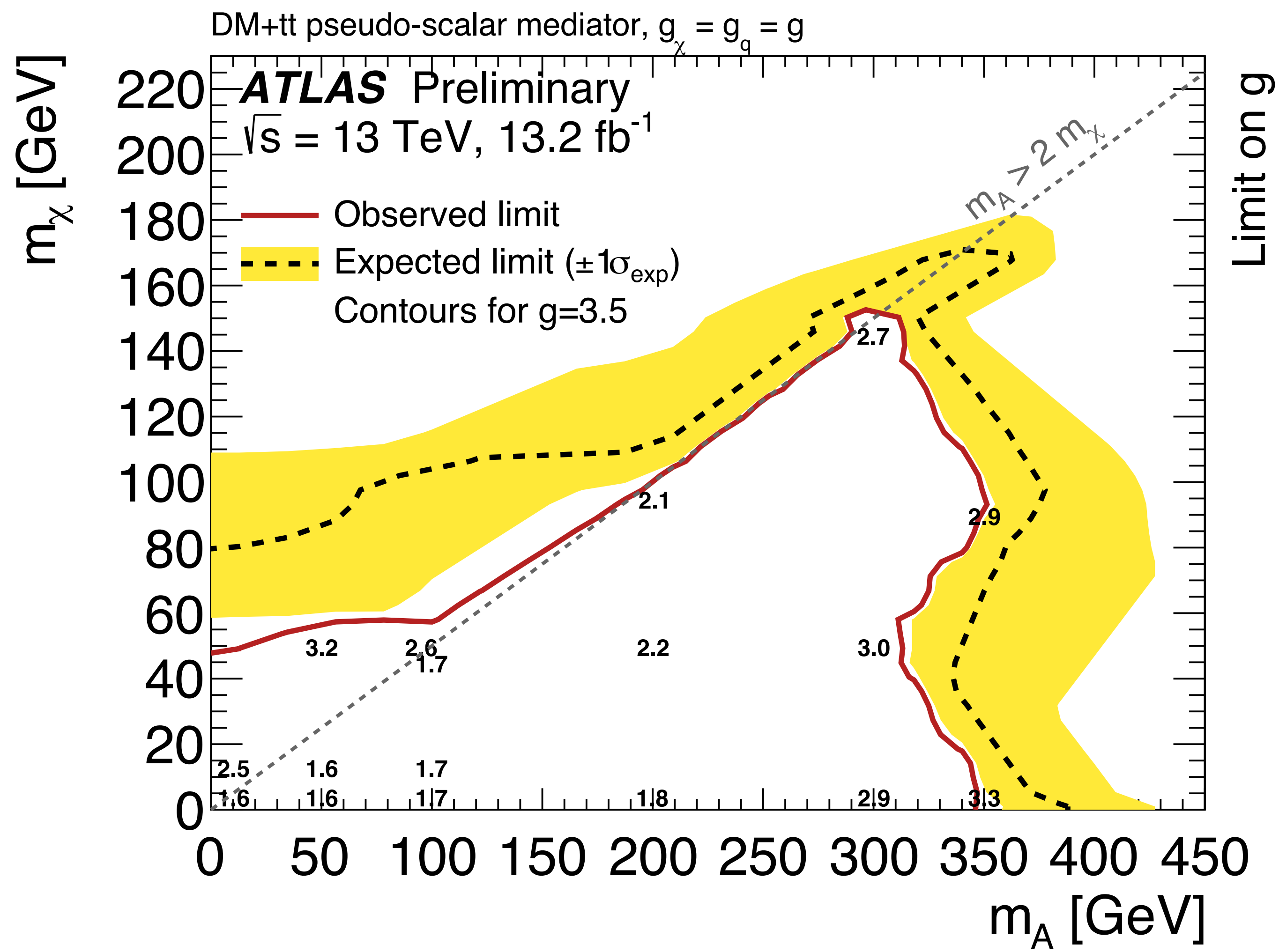


Results

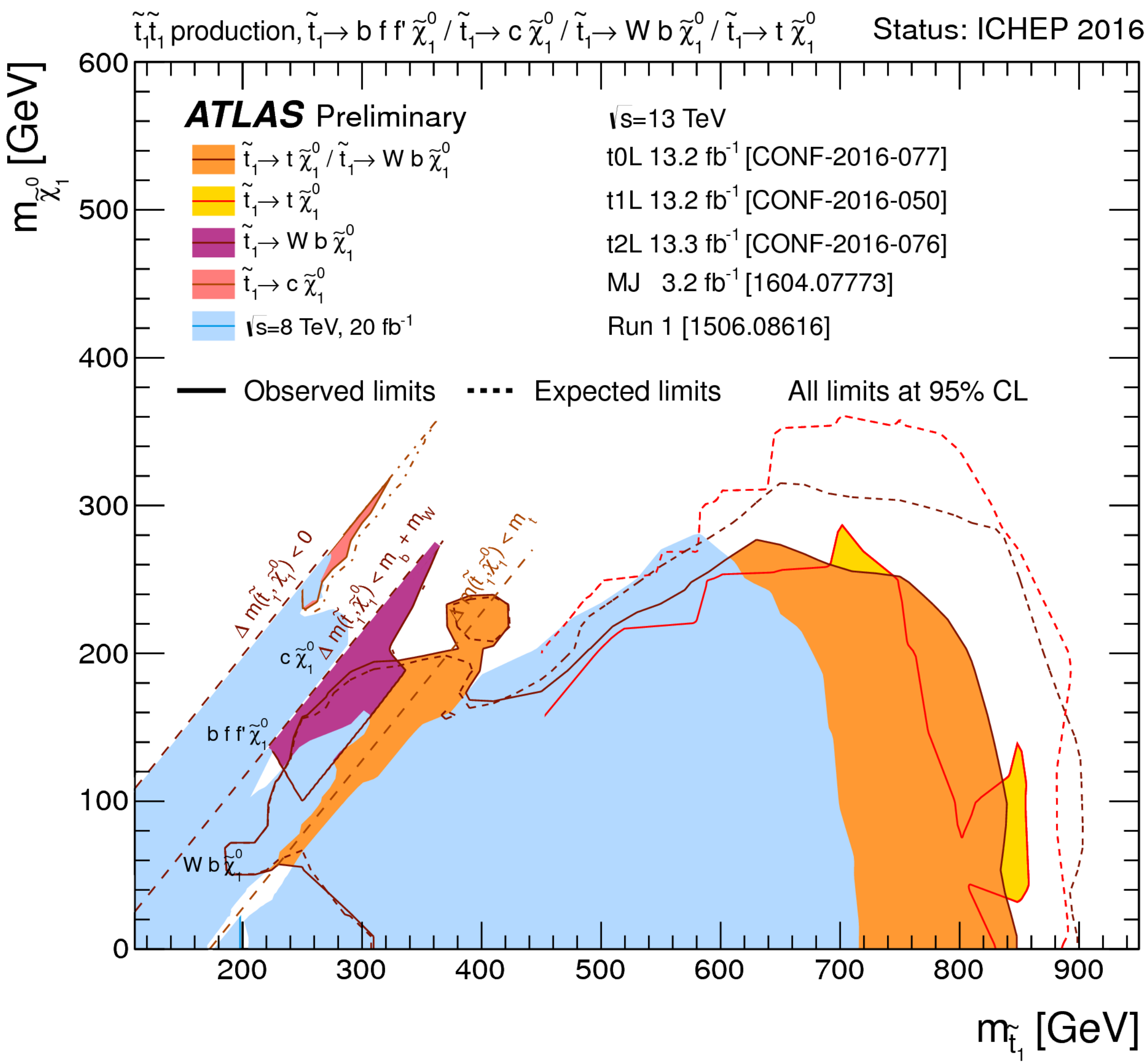
Signal region	SR1	tN_high	bC2x_diag	bC2x_med	bCbv	DM_low	DM_high
Observed	37	5	37	14	7	35	21
Total background	24 ± 3	3.8 ± 0.8	22 ± 3	13 ± 2	7.4 ± 1.8	17 ± 2	15 ± 2
$t\bar{t}$	8.4 ± 1.9	0.60 ± 0.27	6.5 ± 1.5	4.3 ± 1.0	0.26 ± 0.18	4.2 ± 1.3	3.3 ± 0.8
W+jets	2.5 ± 1.1	0.15 ± 0.38	1.2 ± 0.5	0.63 ± 0.29	5.4 ± 1.8	3.1 ± 1.5	3.4 ± 1.4
Single top	3.1 ± 1.5	0.57 ± 0.44	5.3 ± 1.8	5.1 ± 1.6	0.24 ± 0.23	1.9 ± 0.9	1.3 ± 0.8
$t\bar{t} + V$	7.9 ± 1.6	1.6 ± 0.4	8.3 ± 1.7	2.7 ± 0.7	0.12 ± 0.03	6.4 ± 1.4	5.5 ± 1.1
Diboson	1.2 ± 0.4	0.61 ± 0.26	0.45 ± 0.17	0.42 ± 0.20	1.1 ± 0.4	1.5 ± 0.6	1.4 ± 0.5
Z+jets	0.59 ± 0.54	0.03 ± 0.03	0.32 ± 0.29	0.08 ± 0.08	0.22 ± 0.20	0.16 ± 0.14	0.47 ± 0.44
$t\bar{t}$ NF	1.03 ± 0.07	1.06 ± 0.15	0.89 ± 0.10	0.95 ± 0.12	0.73 ± 0.22	0.90 ± 0.17	1.01 ± 0.13
W+jets NF	0.76 ± 0.08	0.78 ± 0.08	0.87 ± 0.07	0.85 ± 0.06	0.97 ± 0.12	0.94 ± 0.13	0.91 ± 0.07
Single top NF	1.07 ± 0.30	1.30 ± 0.45	1.26 ± 0.31	0.97 ± 0.28	–	1.36 ± 0.36	1.02 ± 0.32
$t\bar{t} + W/Z$ NF	1.43 ± 0.21	1.39 ± 0.22	1.40 ± 0.21	1.30 ± 0.23	–	1.47 ± 0.22	1.42 ± 0.21
p_0 (σ)	0.012 (2.2)	0.26 (0.6)	0.004 (2.6)	0.40 (0.3)	0.50 (0)	0.0004 (3.3)	0.09 (1.3)
$N^{\text{limit}}_{\text{non-SM}}$ exp. (95% CL)	$12.9^{+5.5}_{-3.8}$	$5.5^{+2.8}_{-1.1}$	$12.4^{+5.4}_{-3.7}$	$9.0^{+4.2}_{-2.7}$	$7.3^{+3.5}_{-2.2}$	$11.5^{+5.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N^{\text{limit}}_{\text{non-SM}}$ obs. (95% CL)	26.0	7.2	27.5	9.9	7.2	28.3	15.6



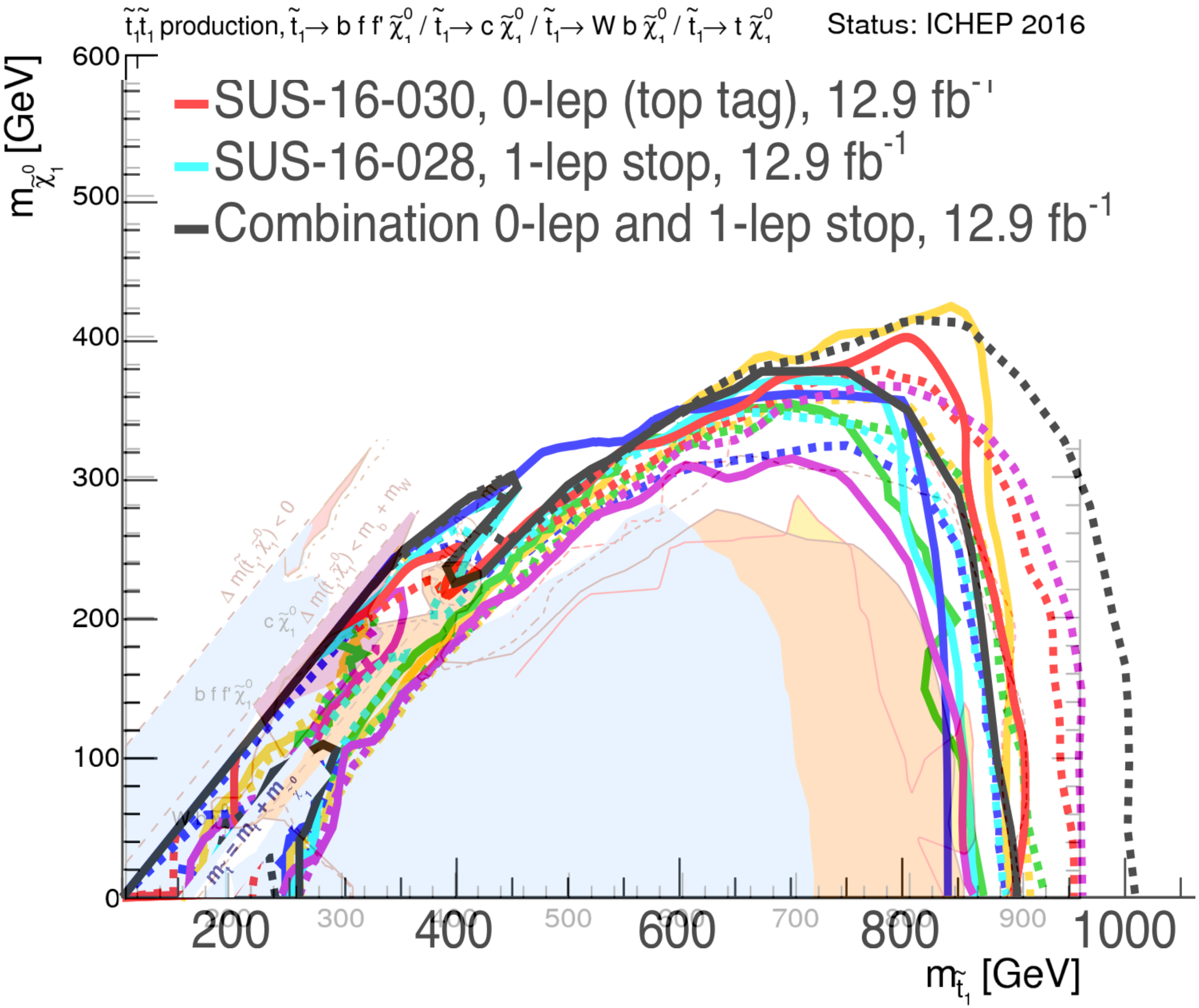
Interpretation



Summary of ATLAS results



… and CMS

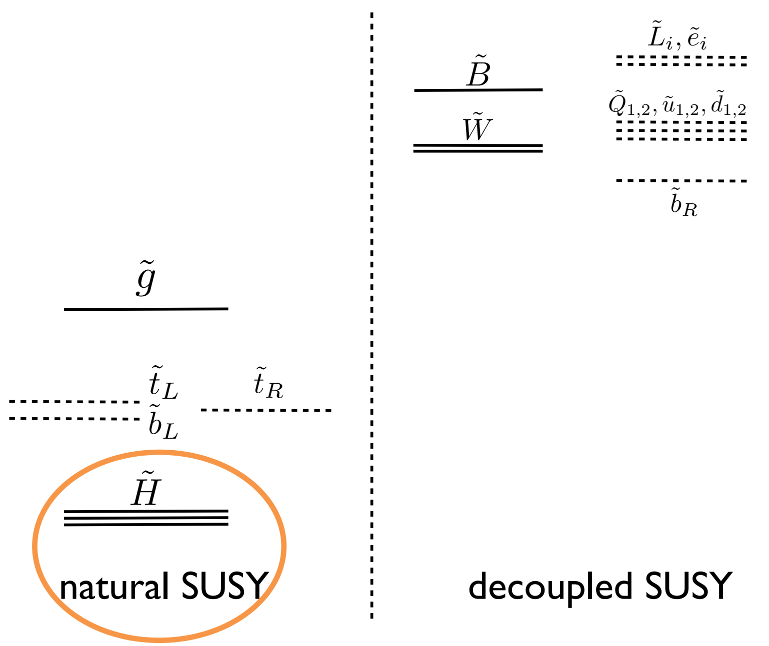


$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
Status: ICHEP 2016
SUS-16-030, 0-lep (top tag), 12.9 fb^{-1}
SUS-16-028, 1-lep stop, 12.9 fb^{-1}
Combination 0-lep and 1-lep stop, 12.9 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
100
200
300
400
500
600
200
400
600
800
1000

Next steps

While dark matter searches are still far away from being able to probe the nominal parameters of their theory, we might be soon hitting the bottom of the natural SUSY spectrum at the LHC.

M.Papucci, J.Ruderman, A. Weiler
hep-ph:1110.6926



- ***Gluinos* and *stops*** (and *sbottoms)* around the TeV

Could be out of the LHC reach!

A new hunt is starting:

- Two *higgsinos*, i.e. one chargino and two neutralinos of a few hundred GeV

Summary

The analysis of 13 TeV data of ATLAS and CMS continues
to constrain Beyond Standard Model physics:

- 95% CL exclusion limits are set within various phenomenological assumptions

Even if the results have been found consistent with Standard Model expectations, the search continues:

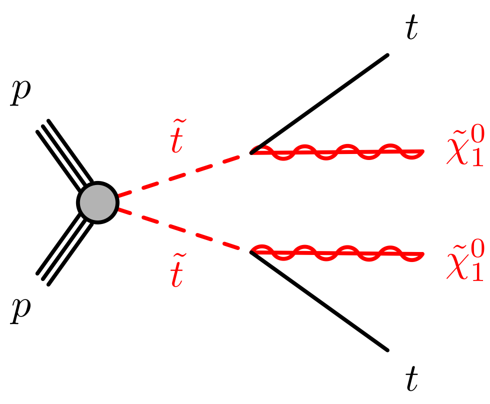
- **Exciting results ahead with the full 2015+2016 dataset**

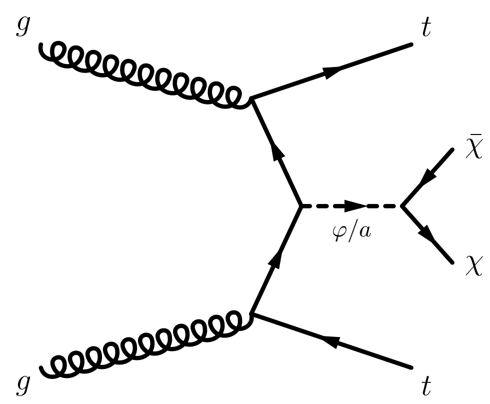
- **Discovering** something new is an important step
- Finding out **what** we have discovered is
  even more interesting!

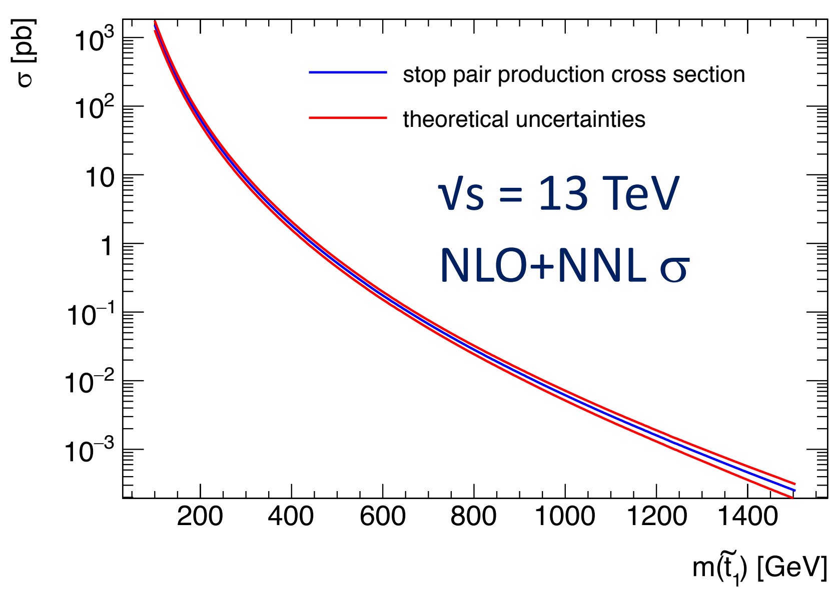
Perhaps not what we think!

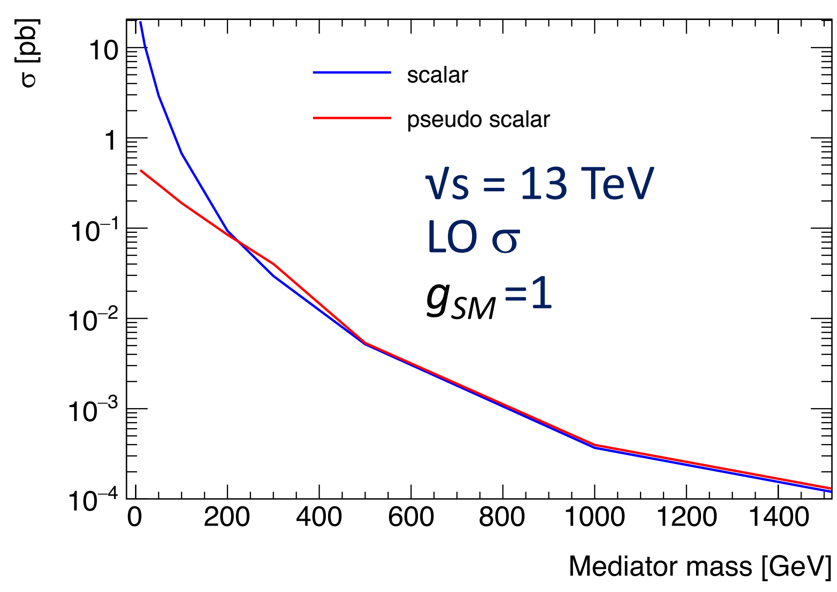
THANKS FOR YOUR ATTENTION!

Process Sensitivity



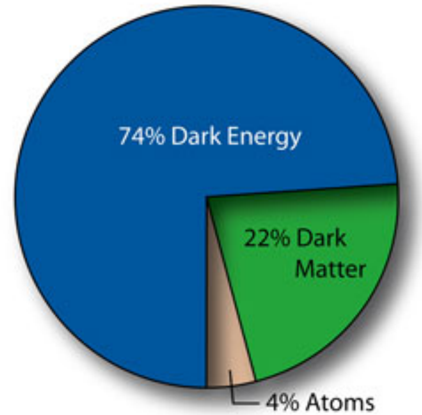






Dark Matter

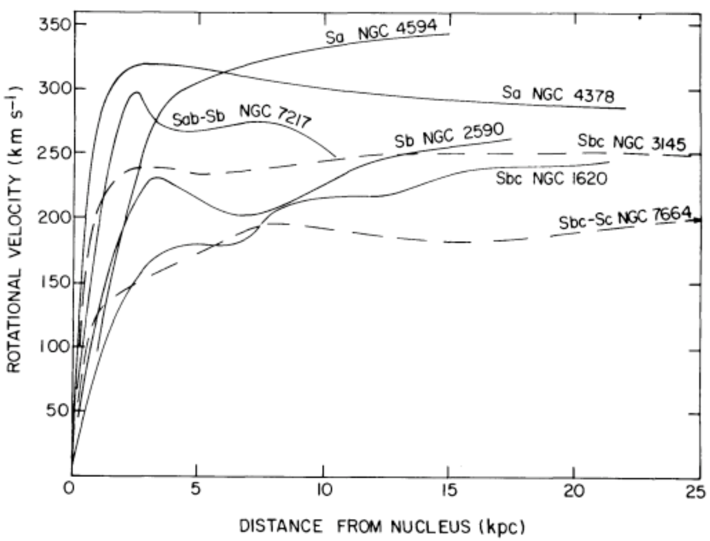
Atoms ~4-5% of total energy in the universe

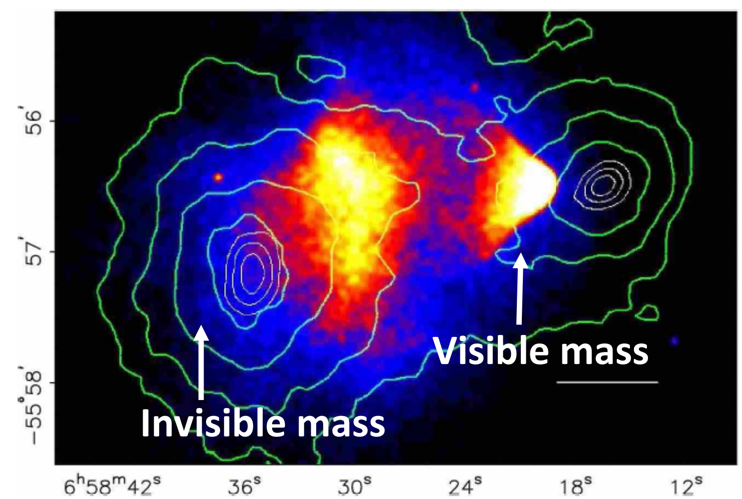


Evidence for Dark Matter from:

- Rotation curves of galaxies
- Galaxy cluster collisions
- Microwave background radiation

We don't know anything about it except it interacts **gravitationally** and is **stable.**

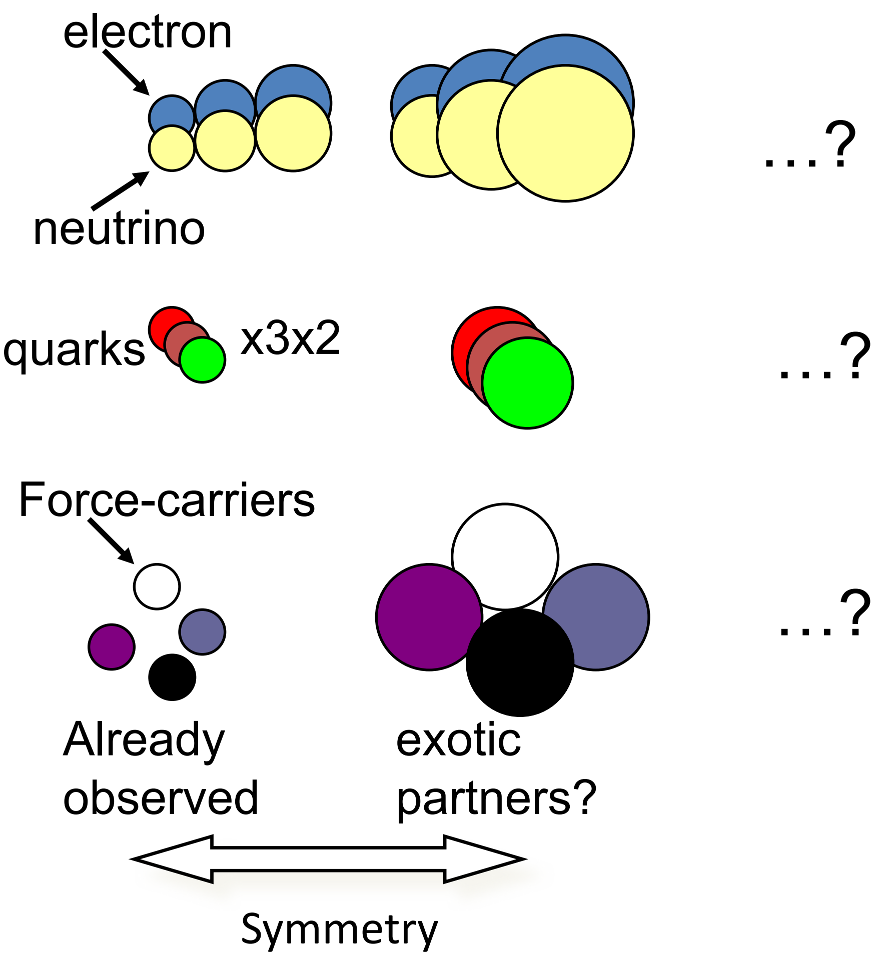




Candidates

New particles by a symmetry:

- **Supersymmetry**
  - Relationship between particles with spins differing by ½
- **Spatial symmetry**
  - With extra dimensions
- **Gauge symmetry**
  - Extra force interactions (and often matter particles)



Natural SUSY

Naturalness provides a useful criterion to address the status of SUSY at the electroweak scale.

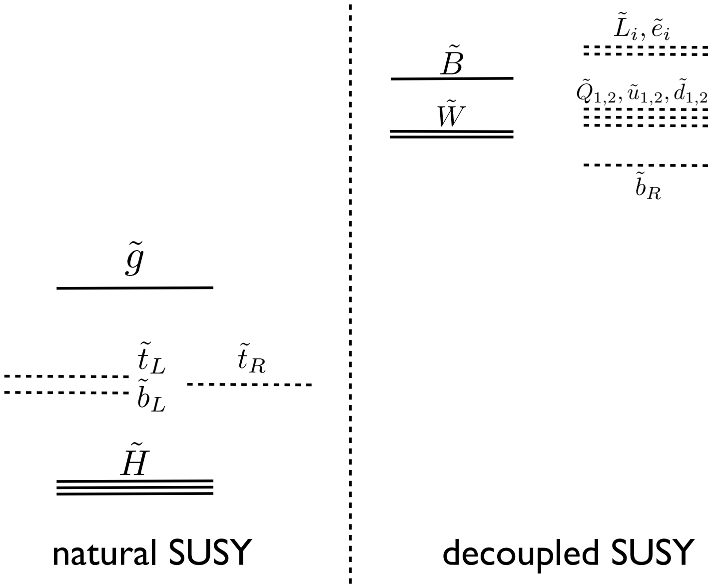
- **The naturalness requirement is summarized by the following relation in the Minimal Supersymmetric Standard Model (MSSM)**

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_H^2$$

If the superpartners are too heavy, contributions to the right-hand side must be tuned against each other to achieve electroweak symmetry breaking at the observed energy scale.

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right)$$

$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2 \ln^2\left(\frac{\Lambda}{TeV}\right)$$



M.Papucci, J.Ruderman, A. Weiler
hep-ph:1110.6926

In a natural theory we expect:

- Two *higgsinos*, i.e. one chargino and two neutralinos of a few hundred GeV ($\mu \cong m_Z$ at tree level)
- ***stop* and *sbottoms*** up to several hundred GeV (1-loop radiative corrections)
- *Gluinos* up to a few TeV (2-loop radiative corrections)

R-Parity

- **R-parity** R = (-1)$^{3B+L+2S}$ is a discrete multiplicative symmetry.
  - **SUSY particles must be produced in pairs**
  - The Lightest Supersymmetric Particle (LSP) is stable (dark matter candidate)

L-number violating terms

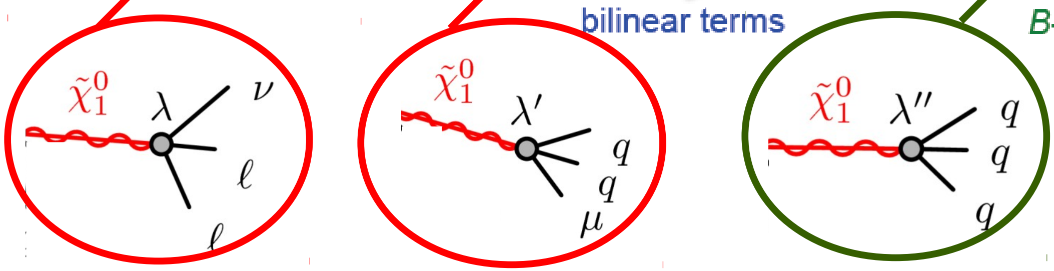
The MSSM potential

$$W_{\not{R}p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

bilinear terms

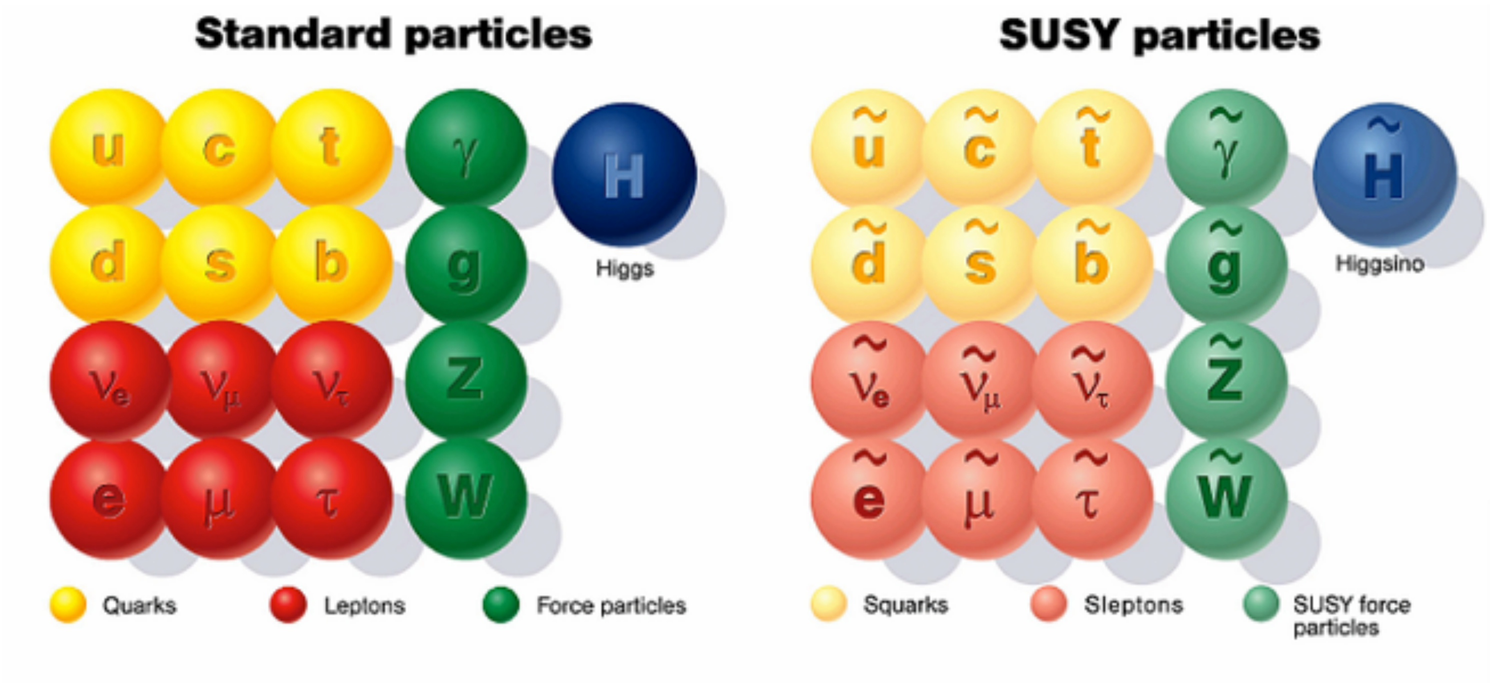
B-number violating terms

RPV couplings λ,λ',λ''



- No reason to assume conservation of R-parity
  - Can constrain proton decay with lepton or baryon violating SUSY, but not both
  - LSP decays → no dark matter candidate
  - **non-prompt decays** if λ couplings are small

Supersymmetry



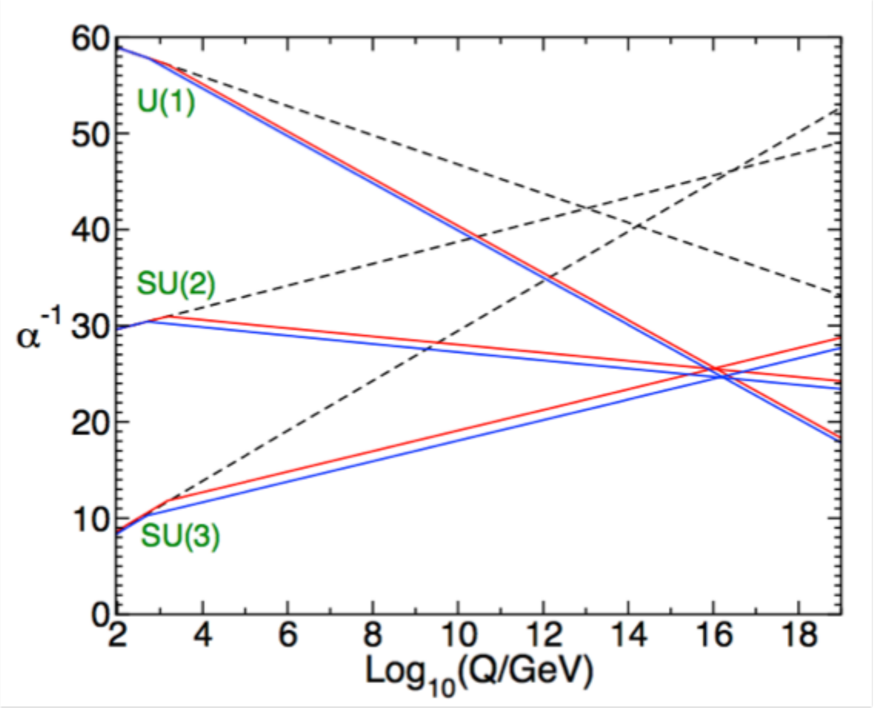
$$W^{\pm}\ W^{0}\ B \overset{mixing}{\rightarrow} W^{\pm}\ Z\ \gamma$$

$$\tilde{H}_u^0\ \tilde{H}_d^0\ \tilde{W}^0\ \tilde{B}^0 \overset{mixing}{\rightarrow} \tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$$ neutralinos

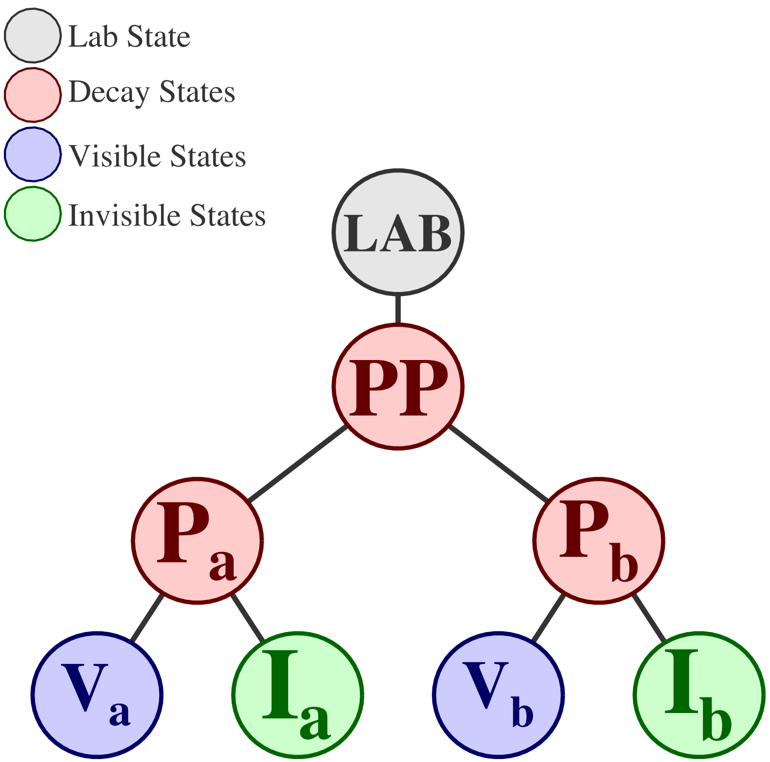
$$\tilde{H}_u^+\ \tilde{H}_d^-\ \tilde{W}^+\ \tilde{W}^- \overset{mixing}{\rightarrow} \tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^{\pm}$$ charginos

SUSY fixes gauge unification

- Predicts gauge unification
  - Modifies RGE's
  - Step towards deeper understanding of the universe



Concept



Building the decay system:

- determine the mass of the invisible system, *m*I: the smallest Lorentz-invariant mass consistent with the inputs that will accommodate the subsequent boosts and also prevent the states *I*i from becoming tachyonic.
- boost from the lab to the *PP* frame: rapidity of the visible and invisible systems are equal. This choice results in our choice of the *PP*, or COM, frame being a longitudinally boost invariant (also forces the mass of the *PP* system, *m*V +I , to take its minimum value)
- the boosts to each of their individual reference frames: assumption that *m*Va = *m*Vb, be equal in magnitude and anti-parallel (observables subsequently defined are contra-boost invariant which means, as in the case for the longitudinal boost invariance, that they are effectively insensitive (on average) to the fact that this boost from *PP* (COM) to *P*i is not the *true* boost.

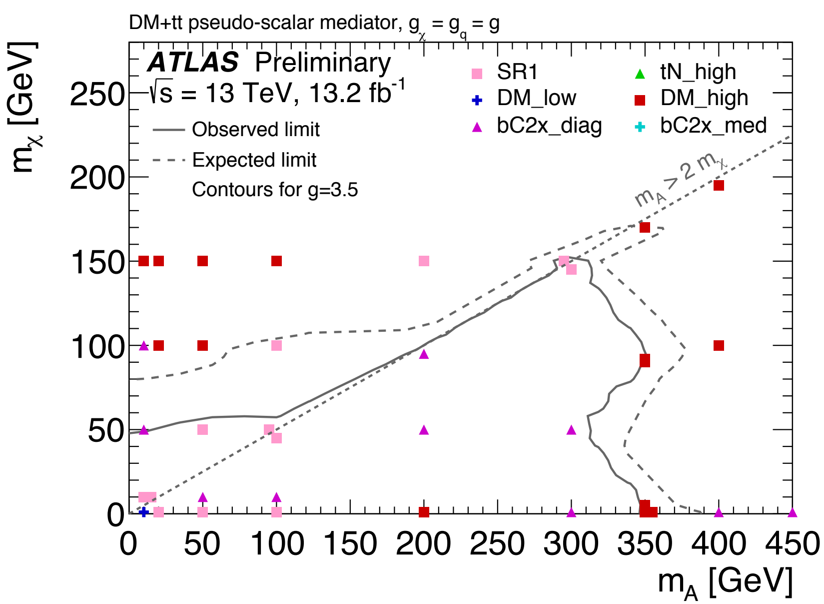
3 body (2L)

Common selection	
Lepton flavour	SF, DF
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV] (SF only)	>10
R_{p_T}	>0.5
$1/\gamma_{R+1}$	>0.8
$\Delta\phi_\beta^R$	$> 0.85 \lvert\cos\theta_b\rvert + 1.8$

Region specific	SR_W^{3-body}	SR_t^{3-body}
b-jet multiplicity	= 0	> 0
M_Δ^R [GeV]	> 95	> 110

Signal Region	SR^{hadMT2}_{Low}	SR^{hadMT2}_{High}	SR_W^{3-body}-SF	SR_W^{3-body}-DF	SR_t^{3-body}-SF	SR_t^{3-body}-DF	DM-SRL	DM-SRH
Total background expectation	13.6	6.8	12	5.3	4.7	3.7	6.4	2.27
Total background systematic	50%	58%	34%	41%	41%	41%	36%	26%
Jet energy scale	–	–	16%	23%	17%	9%	6%	4%
Jet energy resolution	–	–	2%	10%	2%	11%	3%	5%
E_T^{miss} modelling	1%	1%	–	–	–	–	2%	1%
MC statistical uncertainties	3%	5%	13%	20%	13%	25%	5%	–
Diboson theoretical uncertainties	–	–	10%	12%	2%	<1%	–	1%
top theoretical uncertainties	30%	29%	17%	22%	34%	30%	10%	23%
$t\bar{t}$- Wt interference	22%	27%	–	–	–	–	–	–
Diboson fitted normalisation	–	–	15%	3%	2%	<1%	–	–
$t\bar{t}$ fitted normalisation	1%	1%	1%	1%	2%	2%	1%	–
Wt fitted normalisation	26%	26%	–	–	–	–	–	–
$t\bar{t}$ V fitted normalisation	–	–	–	–	–	–	14%	18%
Fake and non-prompt lepton	4%	6%	3%	6%	<1%	15%	–	–
Luminosity	1%	1%	1%	1%	1%	1%	1%	1%

SR selections (1L)



Common event selection	
Trigger	E_T^{miss} trigger
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons
Jets	at least two signal jets, and $\lvert\Delta\phi(\mathrm{jet}_i, \vec{p}_T^{miss})\rvert > 0.4$ for $i \in \{1,2\}$
Hadronic τ veto*	veto events with a hadronic τ decay and $m_{T2}^{\tau} < 80$ GeV

Variable	SR1	tN_high
Number of (jets, b-tags)	(≥ 4, ≥ 1)	(≥ 4, ≥ 1)
Jet $p_T >$ [GeV]	(80 50 40 40)	(120 80 50 25)
E_T^{miss} [GeV]	> 260	> 450
$E_{T,\perp}^{miss}$ [GeV]	–	> 180
$H_{T,sig}^{miss}$	> 14	> 22
m_T [GeV]	> 170	> 210
am_{T2} [GeV]	> 175	> 175
topness	> 6.5	–
m_{top}^{χ} [GeV]	< 270	–
$\Delta R(b, \ell)$	< 3.0	< 2.4
Leading large-R jet p_T [GeV]	–	> 290
Leading large-R jet mass [GeV]	–	> 70
$\Delta\phi(\vec{p}_T^{miss}, 2^{nd}$large-R jet)	–	> 0.6

Variable	bC2x_diag	bC2x_med	bCbv
Number of (jets, b-tags)	(≥ 4, ≥ 2)	(≥ 4, ≥ 2)	(≥ 2, $= 0$)
Jet $p_T >$ [GeV]	(70 60 55 25)	(170 110 25 25)	(120 80)
b-tagged jet $p_T >$ [GeV]	(25 25)	(105 100)	–
E_T^{miss} [GeV]	> 230	> 210	> 360
$H_{T,sig}^{miss}$	> 14	> 7	> 16
m_T [GeV]	> 170	> 140	> 200
am_{T2} [GeV]	> 170	> 210	–
$\lvert\Delta\phi(\mathrm{jet}_i, \vec{p}_T^{miss})\rvert (i = 1)$	> 1.2	> 1.0	> 2.0
$\lvert\Delta\phi(\mathrm{jet}_i, \vec{p}_T^{miss})\rvert (i = 2)$	> 0.8	> 0.8	> 0.8
Leading large-R jet mass [GeV]	–	–	[70, 100]
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	–	–	> 1.2

Variable	DM_low	DM_high
Number of (jets, b-tags)	(≥ 4, ≥ 1)	(≥ 4, ≥ 1)
Jet $p_T >$ [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,sig}^{miss}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{miss}, \mathrm{jet}_i))(i \in \{1-4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8	–