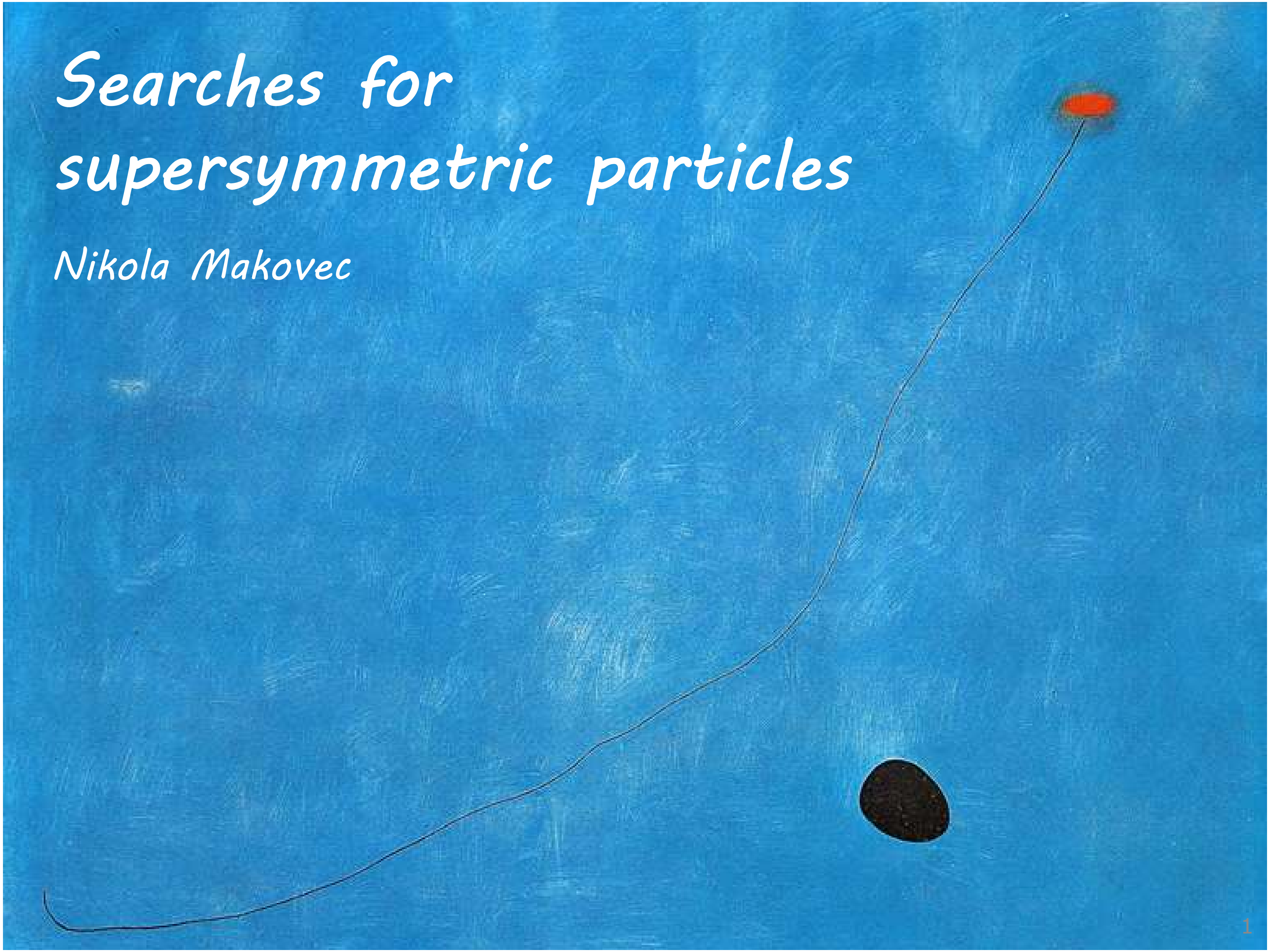
Searches for supersymmetric particles

Nikola Makovec



Outline and References

Outline

1. Phenomenology
2. Squarks and gluinos searches
3. A detailed example: the 0 lepton analysis
4. Searches for additional Higgs bosons

References

- A Supersymmetry Primer
    - S. Martin
    - hep-ph/9709356

- Supersymmetry part I and II
    - PDG review
    - http://pdg.lbl.gov/2018/reviews/rpp2018-rev-susy-1-theory.pdf
    - http://pdg.lbl.gov/2018/reviews/rpp2018-rev-susy-2-experiment.pdf

- Weak-scale Supersymmetry
    - H. Baer and X. Tata
    - Cambridge, 2006

Phenomenology

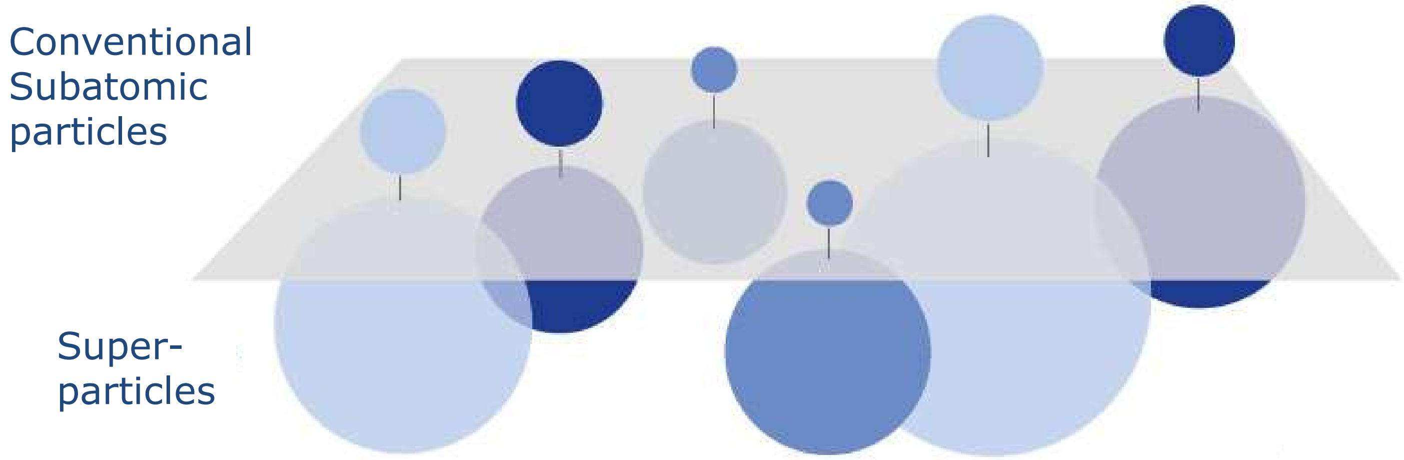
Supersymmetry

Supersymmetry (SUSY): a symmetry between bosons and fermions

It is the unique extension of the Poincaré algebra

- P_μ (translations)
- $M_{\mu\nu}$ (rotations and boosts)
- Q_α (SUSY transformation)

$$\{Q_\alpha, Q_\beta\} = (\gamma^\mu)_{\alpha\beta} P_\mu$$

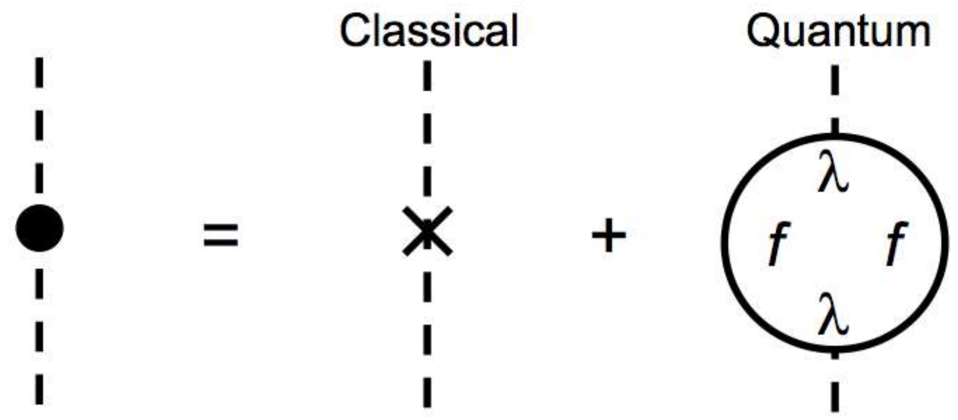


Every SM particle has a SUSY partner with identical quantum numbers except for spin

SUSY scale could be anywhere from 0 up to M_{Pl} but…

Weak scale supersymmetry

1. Solves the Higgs naturalness problem



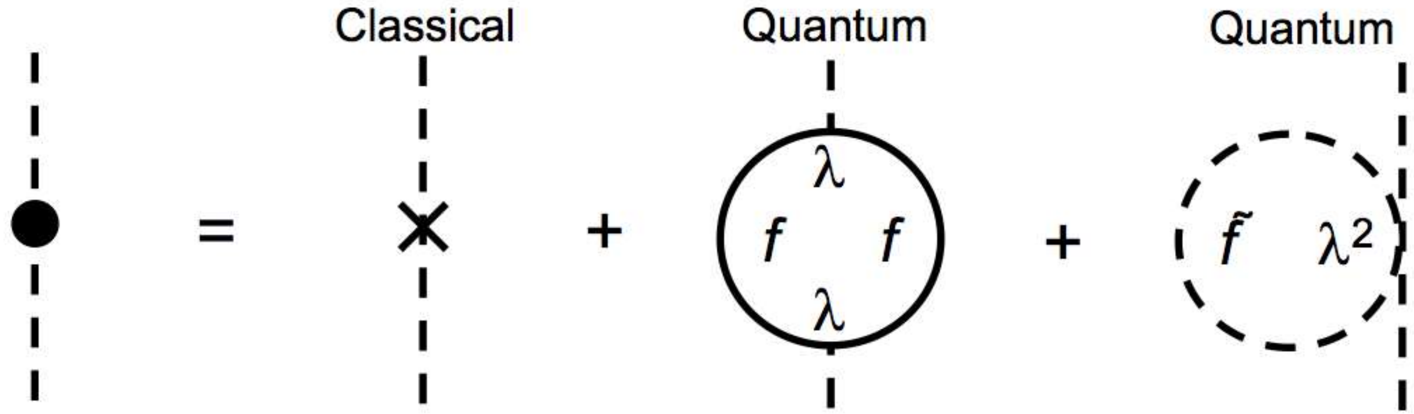
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

= 125GeV

= $O(10^{38})$GeV

Weak scale supersymmetry

1. Solves the Higgs naturalness problem



$$m_h^2 = (m_h^2)_0 - \underbrace{\frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2}_{0}$$

Weak scale supersymmetry

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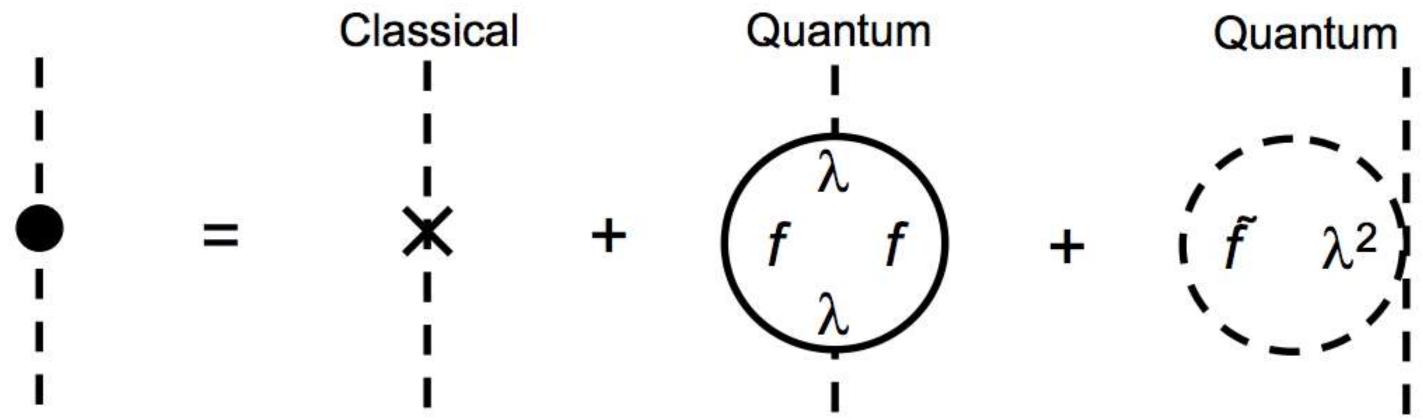


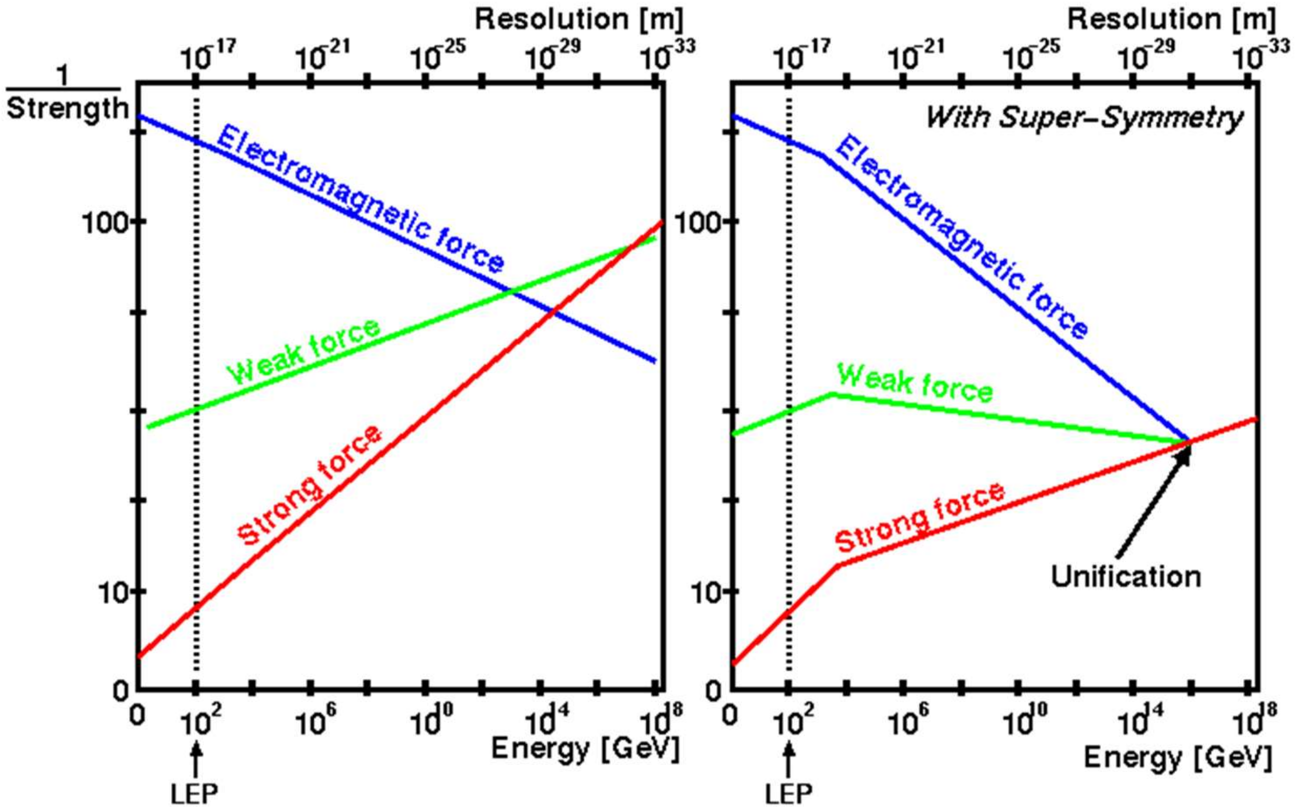
$$m_h^2 = (m_h^2)_0 - \underbrace{\frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2}$$

$$+ \frac{1}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_h)$$

Broken SUSY still provides a solution to the hierarchy problem
if superparticles have mass at the TeV scale or below

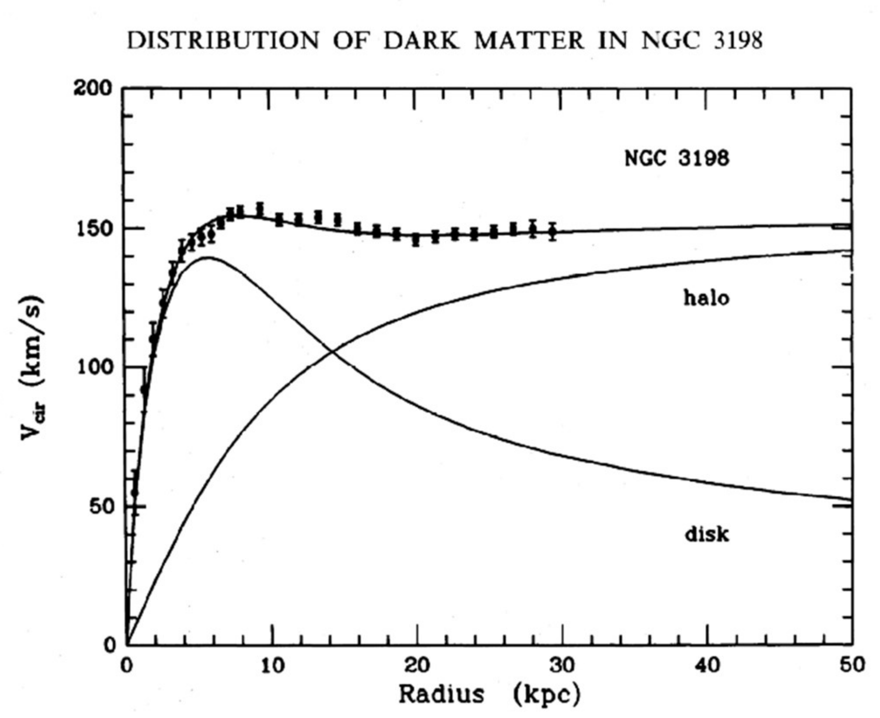
Weak scale supersymmetry

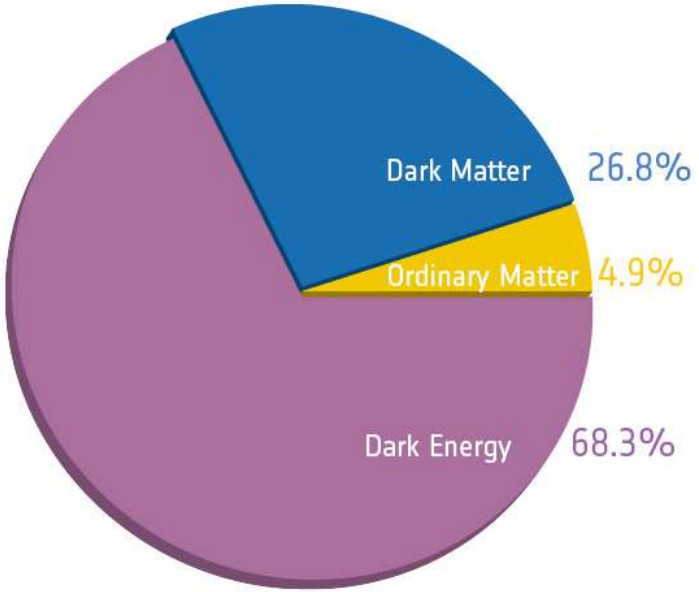
1. Solves the Higgs naturalness problem
2. Opens the door to GUT



Weak scale supersymmetry

1. Solves the Higgs naturalness problem
2. Opens the door to GUT
3. Provides a Dark Matter candidate





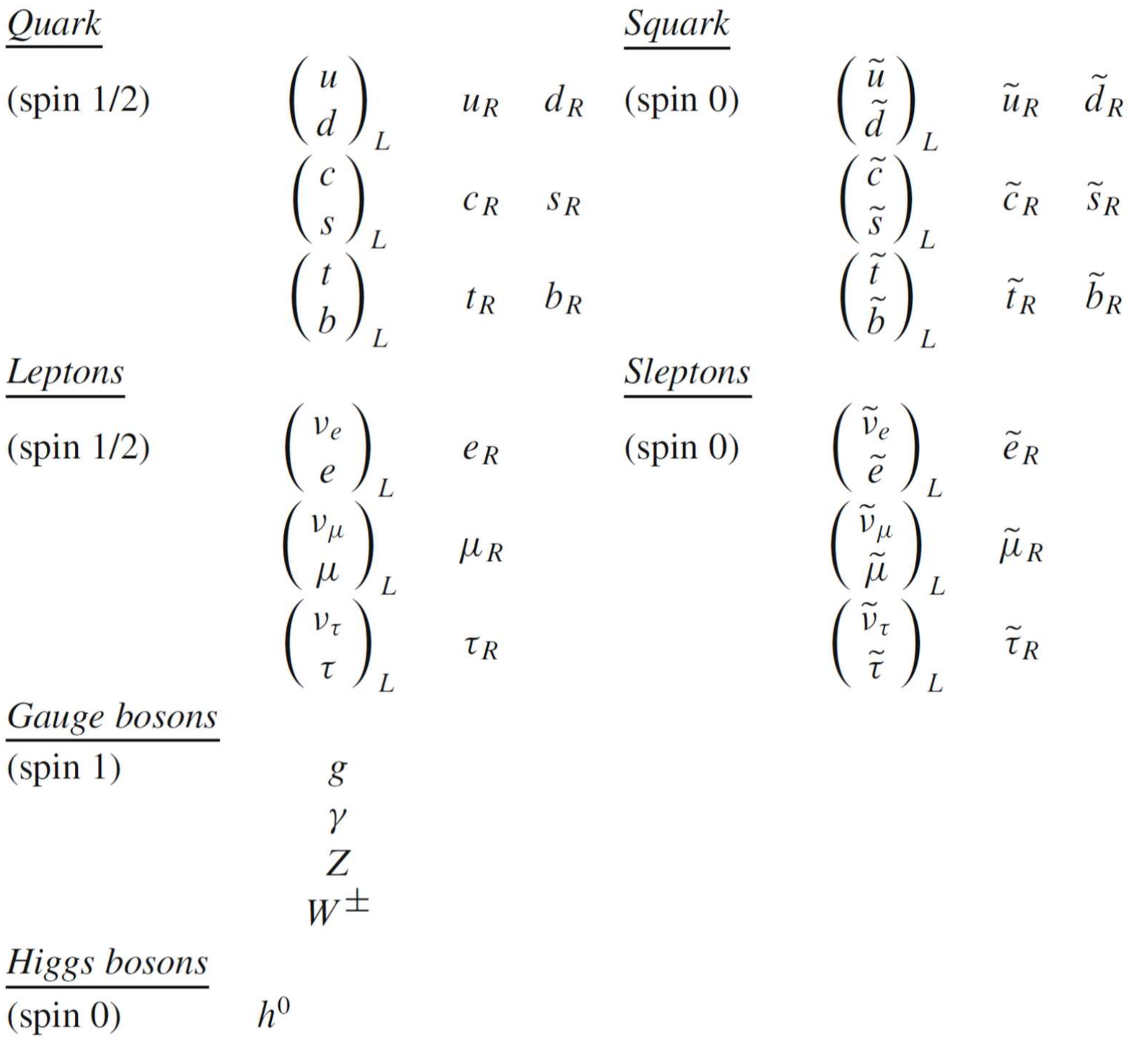
Planck

Minimal Supersymmetric Standard Model (MSSM)

Quark			
(spin 1/2)	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	c_R	s_R
	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	t_R	b_R
Leptons			
(spin 1/2)	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	e_R	
	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	μ_R	
	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	τ_R	
Gauge bosons			
(spin 1)	g		
	γ		
	Z		
	$W^\pm$		
Higgs bosons			
(spin 0)	h^0		

Particles and Fundamental Interactions, Braibant et al

Minimal Supersymmetric Standard Model (MSSM)



Quark				*Squark*			
(spin 1/2)	$\begin{pmatrix}u\\d\end{pmatrix}_L$	u_R	d_R	(spin 0)	$\begin{pmatrix}\tilde{u}\\\tilde{d}\end{pmatrix}_L$	$\tilde{u}_R$	$\tilde{d}_R$
	$\begin{pmatrix}c\\s\end{pmatrix}_L$	c_R	s_R		$\begin{pmatrix}\tilde{c}\\\tilde{s}\end{pmatrix}_L$	$\tilde{c}_R$	$\tilde{s}_R$
	$\begin{pmatrix}t\\b\end{pmatrix}_L$	t_R	b_R		$\begin{pmatrix}\tilde{t}\\\tilde{b}\end{pmatrix}_L$	$\tilde{t}_R$	$\tilde{b}_R$
Leptons				*Sleptons*			
(spin 1/2)	$\begin{pmatrix}\nu_e\\e\end{pmatrix}_L$	e_R		(spin 0)	$\begin{pmatrix}\tilde{\nu}_e\\\tilde{e}\end{pmatrix}_L$	$\tilde{e}_R$	
	$\begin{pmatrix}\nu_\mu\\\mu\end{pmatrix}_L$	μ_R			$\begin{pmatrix}\tilde{\nu}_\mu\\\tilde{\mu}\end{pmatrix}_L$	$\tilde{\mu}_R$	
	$\begin{pmatrix}\nu_\tau\\\tau\end{pmatrix}_L$	τ_R			$\begin{pmatrix}\tilde{\nu}_\tau\\\tilde{\tau}\end{pmatrix}_L$	$\tilde{\tau}_R$	
Gauge bosons							
(spin 1)	g						
	γ						
	Z						
	$W^\pm$						
Higgs bosons							
(spin 0)	h^0						

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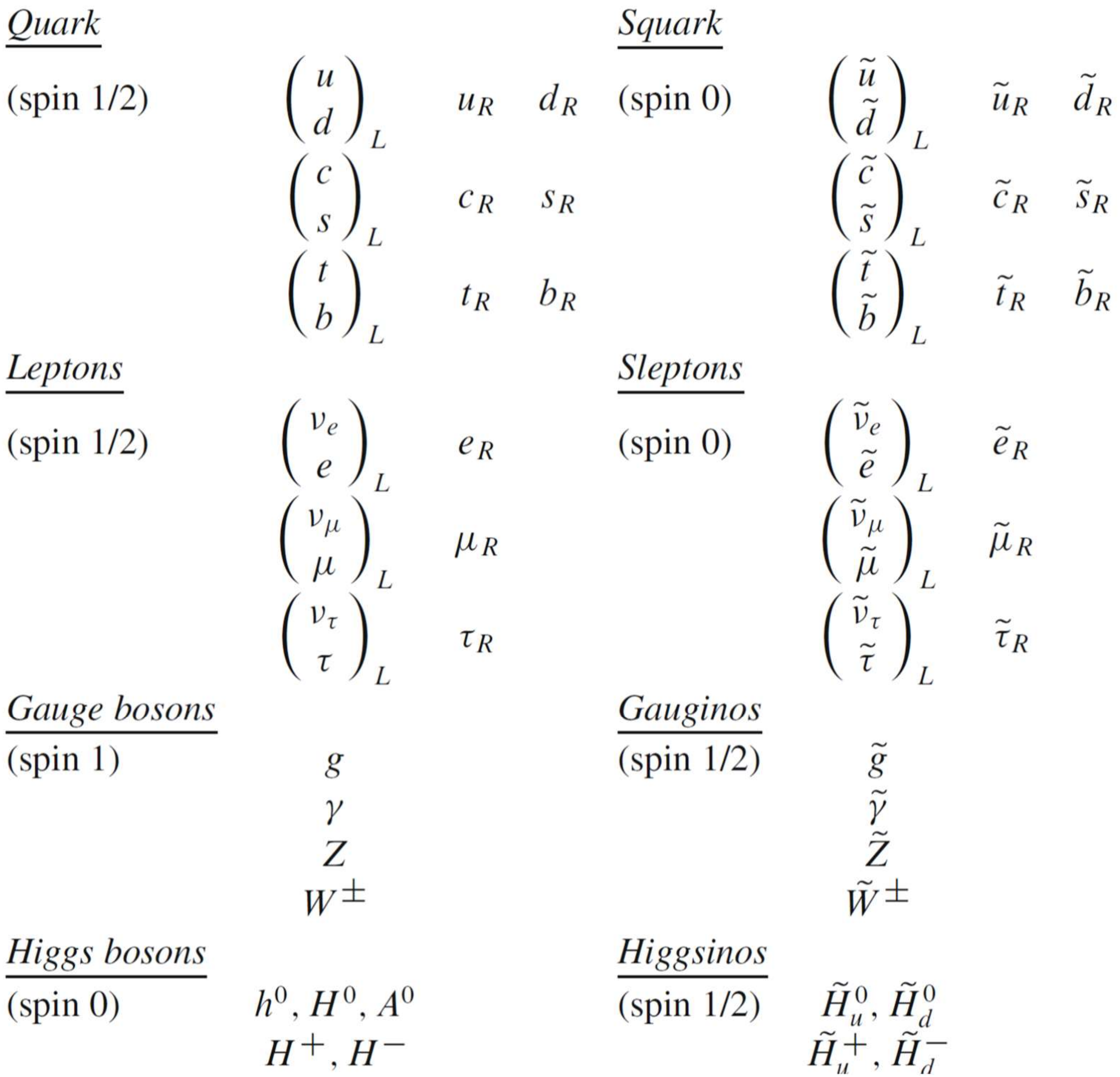

Quark				*Squark*			
(spin 1/2)	$\begin{pmatrix}u\\d\end{pmatrix}_L$	u_R	d_R	(spin 0)	$\begin{pmatrix}\tilde{u}\\\tilde{d}\end{pmatrix}_L$	$\tilde{u}_R$	$\tilde{d}_R$
	$\begin{pmatrix}c\\s\end{pmatrix}_L$	c_R	s_R		$\begin{pmatrix}\tilde{c}\\\tilde{s}\end{pmatrix}_L$	$\tilde{c}_R$	$\tilde{s}_R$
	$\begin{pmatrix}t\\b\end{pmatrix}_L$	t_R	b_R		$\begin{pmatrix}\tilde{t}\\\tilde{b}\end{pmatrix}_L$	$\tilde{t}_R$	$\tilde{b}_R$
Leptons				*Sleptons*			
(spin 1/2)	$\begin{pmatrix}\nu_e\\e\end{pmatrix}_L$	e_R		(spin 0)	$\begin{pmatrix}\tilde{\nu}_e\\\tilde{e}\end{pmatrix}_L$	$\tilde{e}_R$	
	$\begin{pmatrix}\nu_\mu\\\mu\end{pmatrix}_L$	μ_R			$\begin{pmatrix}\tilde{\nu}_\mu\\\tilde{\mu}\end{pmatrix}_L$	$\tilde{\mu}_R$	
	$\begin{pmatrix}\nu_\tau\\\tau\end{pmatrix}_L$	τ_R			$\begin{pmatrix}\tilde{\nu}_\tau\\\tilde{\tau}\end{pmatrix}_L$	$\tilde{\tau}_R$	
Gauge bosons				*Gauginos*			
(spin 1)	g			(spin 1/2)	$\tilde{g}$		
	γ				$\tilde{\gamma}$		
	Z				$\tilde{Z}$		
	$W^\pm$				$\tilde{W}^\pm$		
Higgs bosons				*Higgsinos*			
(spin 0)	h^0, H^0, A^0			(spin 1/2)	$\tilde{H}_u^0, \tilde{H}_d^0$		
	H^+, H^-				$\tilde{H}_u^+, \tilde{H}_d^-$		

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Minimal Supersymmetric Standard Model (MSSM)

Quark				*Squark*				
(spin 1/2)	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R	(spin 0)	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L$	$\tilde{u}_R$	$\tilde{d}_R$	
	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	c_R	s_R		$\begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix}_L$	$\tilde{c}_R$	$\tilde{s}_R$	
	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	t_R	b_R		$\begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}_L$	$\tilde{t}_R$	$\tilde{b}_R$	
Leptons				*Sleptons*				
(spin 1/2)	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	e_R		(spin 0)	$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e} \end{pmatrix}_L$	$\tilde{e}_R$		
	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	μ_R			$\begin{pmatrix} \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix}_L$	$\tilde{\mu}_R$		
	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	τ_R			$\begin{pmatrix} \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}_L$	$\tilde{\tau}_R$		
Gauge bosons				*Gauginos*				
(spin 1)	g			(spin 1/2)	$\tilde{g}$			
	γ				$\tilde{\gamma}$			Neutralinos
	Z				$\tilde{Z}$			$\longrightarrow \quad \chi^0_{1,2,3,4}$
	$W^\pm$				$\tilde{W}^\pm$			$\{\tilde{\gamma}, \tilde{Z}, \tilde{H}^0_u, \tilde{H}^0_d\}$
Higgs bosons				*Higgsinos*				Charginos
(spin 0)	h^0, H^0, A^0			(spin 1/2)	$\tilde{H}^0_u, \tilde{H}^0_d$			$\longrightarrow \quad \chi^\pm_{1,2}$
	H^+, H^-				$\tilde{H}^+_u, \tilde{H}^-_d$			$\{\tilde{W}^\pm, \tilde{H}^\pm\}$

Particles and Fundamental Interactions, Braibant et al

Minimal Supersymmetric Standard Model (MSSM)

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	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	c_R	s_R		$\begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix}_L$	$\tilde{c}_R$	$\tilde{s}_R$	
	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	t_R	b_R		$\begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}_L$	$\tilde{t}_R$	$\tilde{b}_R$	$\longrightarrow$ $\tilde{t}_{1,2}, \tilde{b}_{1,2}$
Leptons				*Sleptons*				
(spin 1/2)	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	e_R		(spin 0)	$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e} \end{pmatrix}_L$	$\tilde{e}_R$		
	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	μ_R			$\begin{pmatrix} \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix}_L$	$\tilde{\mu}_R$		
	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	τ_R			$\begin{pmatrix} \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}_L$	$\tilde{\tau}_R$		$\longrightarrow$ $\tilde{\tau}_{1,2}$
Gauge bosons				*Gauginos*				
(spin 1)	g			(spin 1/2)	$\tilde{g}$			
	γ				$\tilde{\gamma}$			Neutralinos
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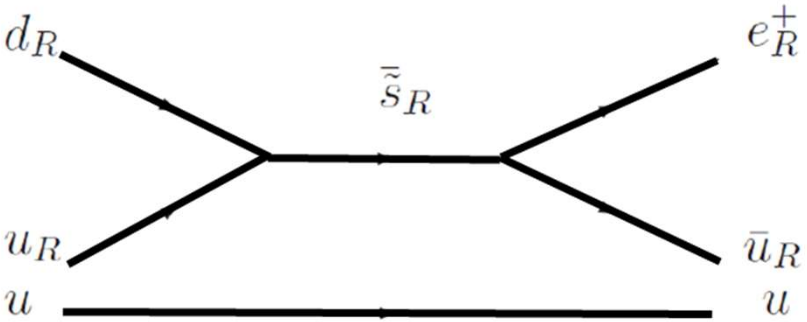
	$W^\pm$				$\tilde{W}^\pm$			$\{\tilde{\gamma}, \tilde{Z}, \tilde{H}^0_u, \tilde{H}^0_d\}$
Higgs bosons				*Higgsinos*				Charginos
(spin 0)	h^0, H^0, A^0			(spin 1/2)	$\tilde{H}^0_u, \tilde{H}^0_d$			$\longrightarrow$ $\chi^\pm_{1,2}$
	H^+, H^-				$\tilde{H}^+_u, \tilde{H}^-_d$			$\{\tilde{W}^\pm, \tilde{H}^\pm\}$

Particles and Fundamental Interactions, Braibant et al

R-parity: a new quantum number

General supersymmetric lagrangian violates leptonic and baryonic numbers



Solution: new symmetry postulated

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

+1 for particles

-1 for superparticles

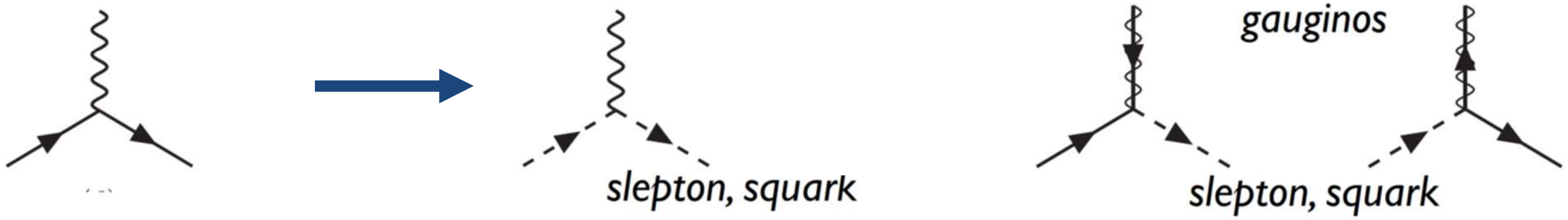
If R-parity is conserved:

- No B and L violation by construction
- SUSY particles created in pairs at colliders
- Lightest Supersymmetric Particle (LSP) stable
- LSP is a natural dark matter candidate if neutral and interacts weakly

$\Rightarrow$ Missing transverse energy signature at LHC

SUSY diagrams

Because of the symmetry, SUSY diagrams are obtained from SM ones adding tilde on two of the particles. Examples:



SUSY diagrams

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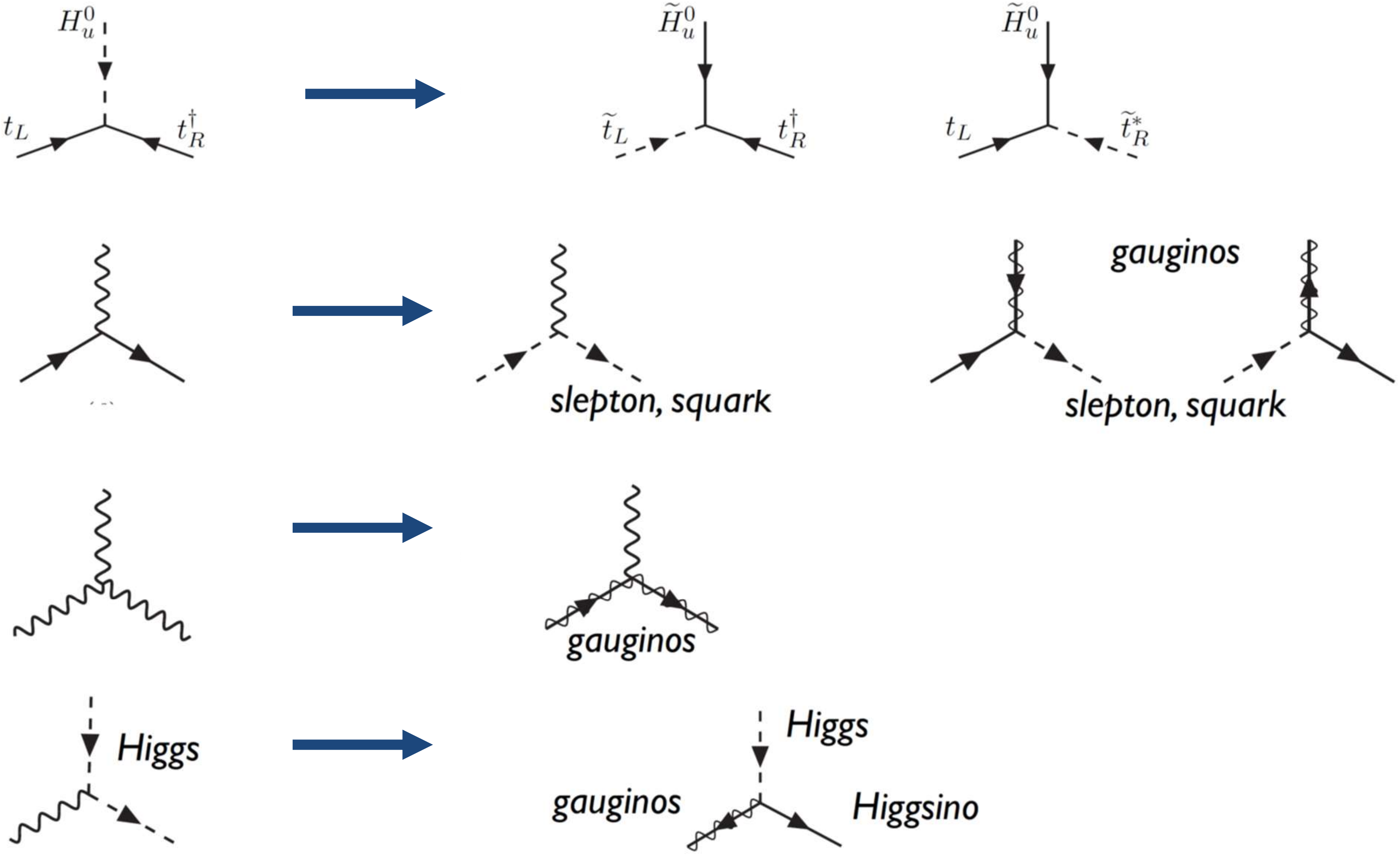


Soft supersymmetry breaking

We don't know how SUSY is broken, but soft SUSY breaking effects can be parameterized in the Lagrangian without introducing new quadratic (Λ^2) divergences → 105 free parameters but they are constraints by the experiments since they could induce flavour changing neutral currents (FCNC) or CP violation at an unacceptable level

$$L_{soft} \;=\; -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)$$

M_{soft} ~1TeV

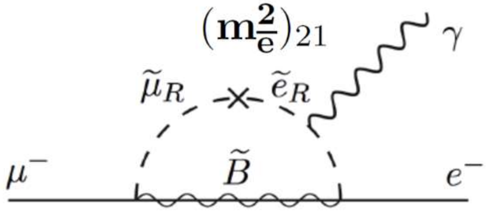
Soft supersymmetry breaking

$$L_{soft} = -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}\right)$$

$$-\underbrace{\tilde{Q}^\dagger\,\mathbf{m}^2_{\mathbf{Q}}\,\tilde{Q} - \tilde{L}^\dagger\,\mathbf{m}^2_{\mathbf{L}}\,\tilde{L}}_{\text{Left handed}} - \underbrace{\tilde{\bar{u}}\,\mathbf{m}^2_{\bar{\mathbf{u}}}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m}^2_{\bar{\mathbf{d}}}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m}^2_{\bar{\mathbf{e}}}\,\tilde{\bar{e}}^\dagger}_{\text{Right handed}}$$

mQ, mL, mu, md, me are 3x3 matrices in Flavour

M_{soft} ~1TeV



$\mu^- \to e^-\gamma$

Not observed experimentally
→ constraints on mass matrix

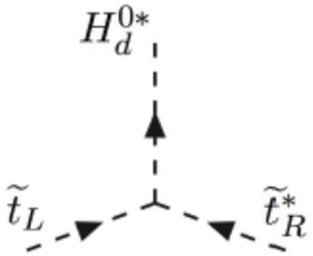
Soft supersymmetry breaking

$$L_{soft} \;=$$

$$-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right)$$

A-terms result in L-R sfermion mixing, proportional to fermion Yukawa
Each of a_u, a_d, a_e is a complex 3 × 3 matrix in family space, with dimensions of [mass]

Trilinear couplings example:



Soft supersymmetry breaking

$$L_{soft} \;=$$

$$- m^2_{H_u} H^*_u H_u - m^2_{H_d} H^*_d H_d - (b H_u H_d + \text{c.c.}) \,.$$

Contributions to the Higgs potential

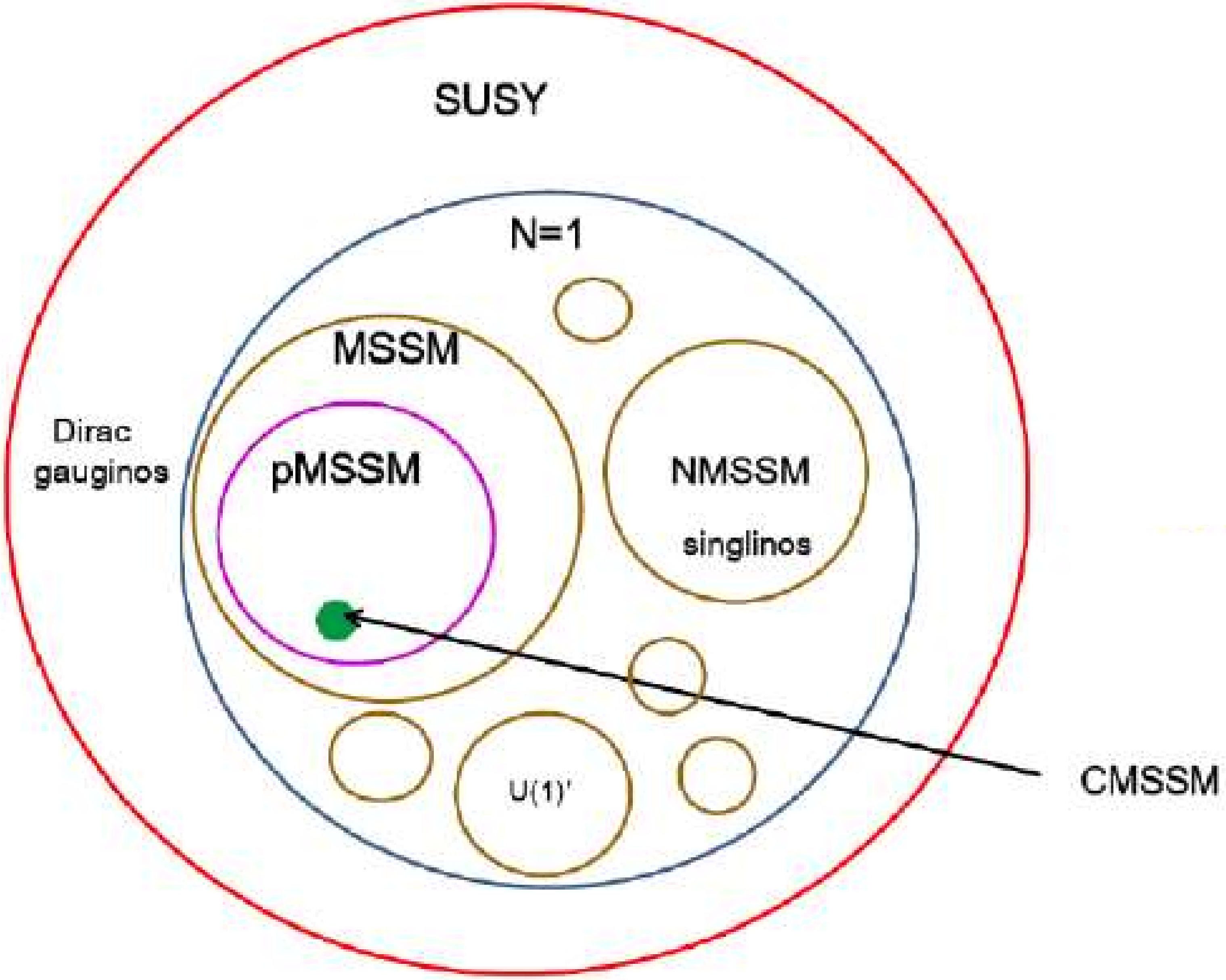
Soft supersymmetry breaking

We don't know how SUSY is broken, but soft SUSY breaking effects can be parameterized in the Lagrangian without introducing new quadratic (Λ^2) divergences → 105 free parameters but they are constraints by the experiments since they could induce flavour changing neutral currents (FCNC) or CP violation at an unacceptable level

$$\begin{aligned} L_{soft} \;=\; & -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}\right) \\ & -\left(\tilde{\bar{u}}\,\mathbf{a_u}\,\tilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\,\tilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\,\tilde{L}H_d + \text{c.c.}\right) \\ & -\tilde{Q}^\dagger\,\mathbf{m_Q^2}\,\tilde{Q} - \tilde{L}^\dagger\,\mathbf{m_L^2}\,\tilde{L} - \tilde{\bar{u}}\,\mathbf{m_{\bar{u}}^2}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m_{\bar{e}}^2}\,\tilde{\bar{e}}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,. \end{aligned}$$

Soft SUSY breaking terms should be merely viewed as a parametrization of our ignorance and can be used as an effective lagrangian from which to derive phenomenology

Supersymmetric models



pMSSM

The MSSM has 105 new parameters

- 8 parameters in the gaugino/higgsino sector (3 real and 5 phases)
- 21 sfermion masses
- 36 real mixing angles to define the sfermion mass eigenstates,
- 40 CP-violating phases that can appear in sfermion interactions.

Reflect our ignorance on SUSY breaking

Most of these are new flavor violation parameters or CP violating phases

Phenomenologically more "viable" models can be defined by making some further assumptions :

- All the soft SUSY breaking parameters are real and therefore there is no new source of CP violation in addition to the one from the CKM matrix
- The matrices for the sfermion masses and for the trilinear couplings are all diagonal implying the absence of flavor changing neutral current (FCNC) at tree level
- The soft susy breaking masses and trilinear couplings of the first and second sfermion generations are the same at low energy to cope with some severe constrains such as for example from neutral kaon mixing

pMSSM

The pMSSM has 19 parameters instead of 105 for the MSSM

- 3 wino/bino/gluino mass: $M_{1,2,3}$
- 10 squark/slepton soft masses
- Ratio of Higgs vevs: tanβ
- Pseudo-scalar Higgs mass: m_A
- Higgsino mass parameter: μ
- 3 trilinear couplings for the 3rd gen : $A_{t,b,\tau}$

A comprehensive study of the 19-parameter pMSSM is computationally expensive

Can reduce the number of parameters to 10 by assuming

- a common squark mass parameter for the first two generations,
- a common squark mass parameter for the third generation
- a common slepton mass parameter
- a common third generation A parameter.

cMSSM (aka mSuGra)

Top-down approach

- Model of SUSY breaking inspired by gravity mediation
- Impose boundary conditions at high energy scale
- Predict phenomenology at the EWK scale (renormalisation group equation)

Five parameters

GUT scale:

Scalar masses (*m0*)

Gaugino masses (*m1/2*)

Trilinear couplings (*A0*)

Low-energy:

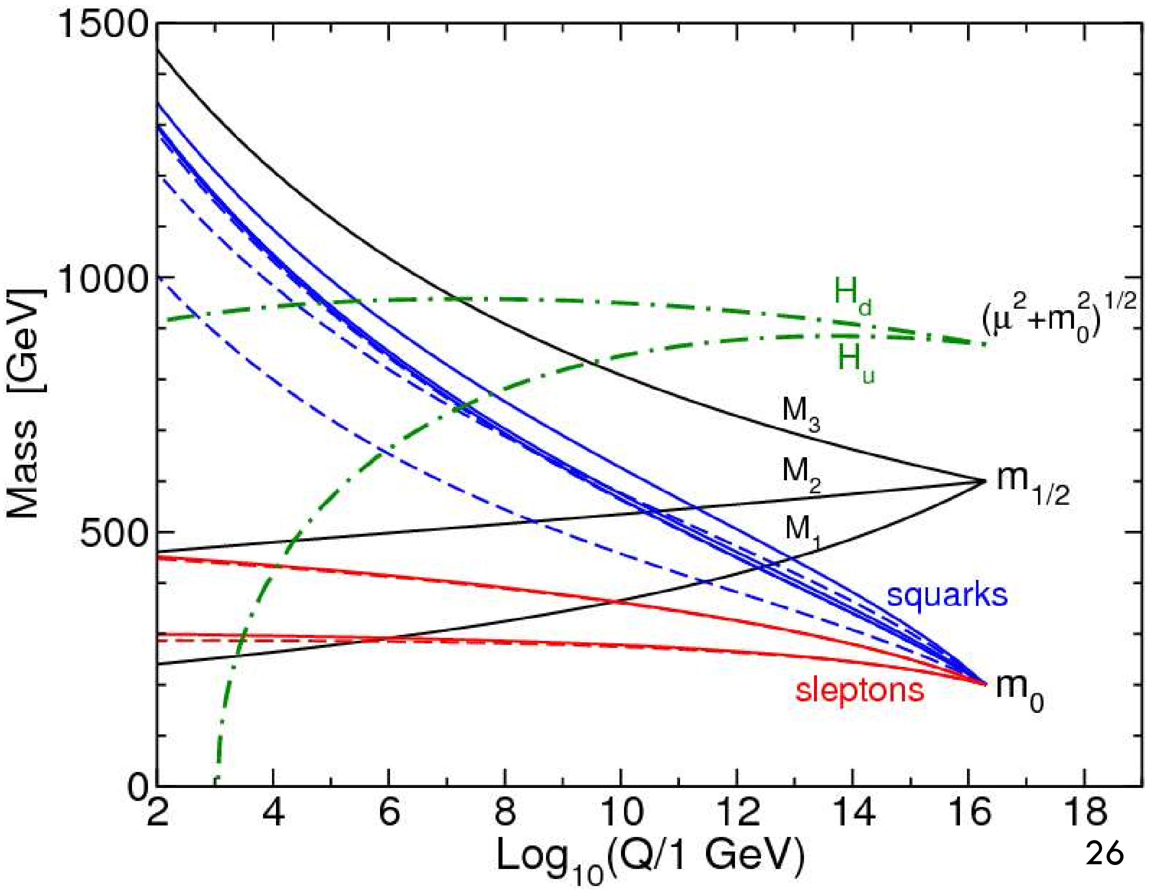
tanβ and sign(μ)

At EW scale:

M3:M2:M1~7:2:1

$m_{slepton} < m_{squark}$

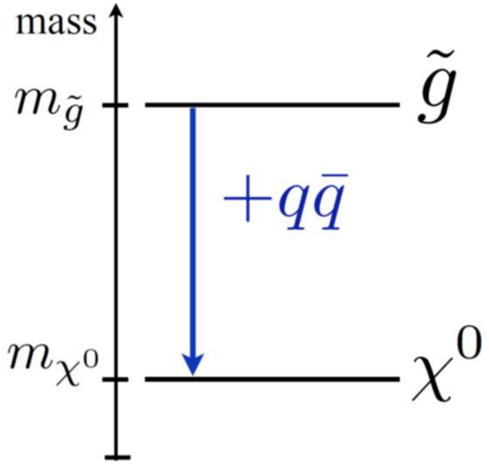
$\mu^2 + m^2_{Hu} < 0$



Simplified models

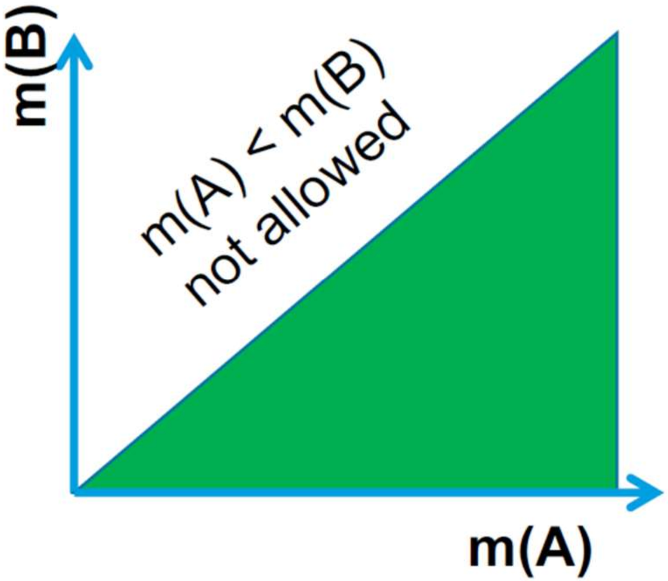
From all sparticles consider only 2 or 3, decouple all others, force a specific decay mode(s) (with fixed Branching Ratio)

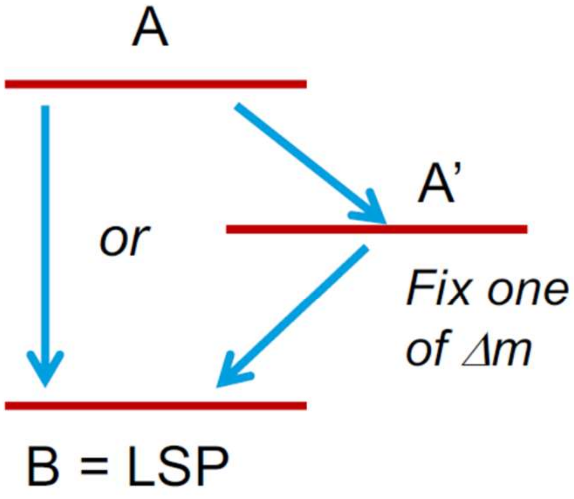
$$\mathcal{L}_{\text{int}} = \frac{\lambda_i^2}{M_i^2}\tilde{g} q_i \bar{q}_i \chi^0 + \text{ h.c.}$$



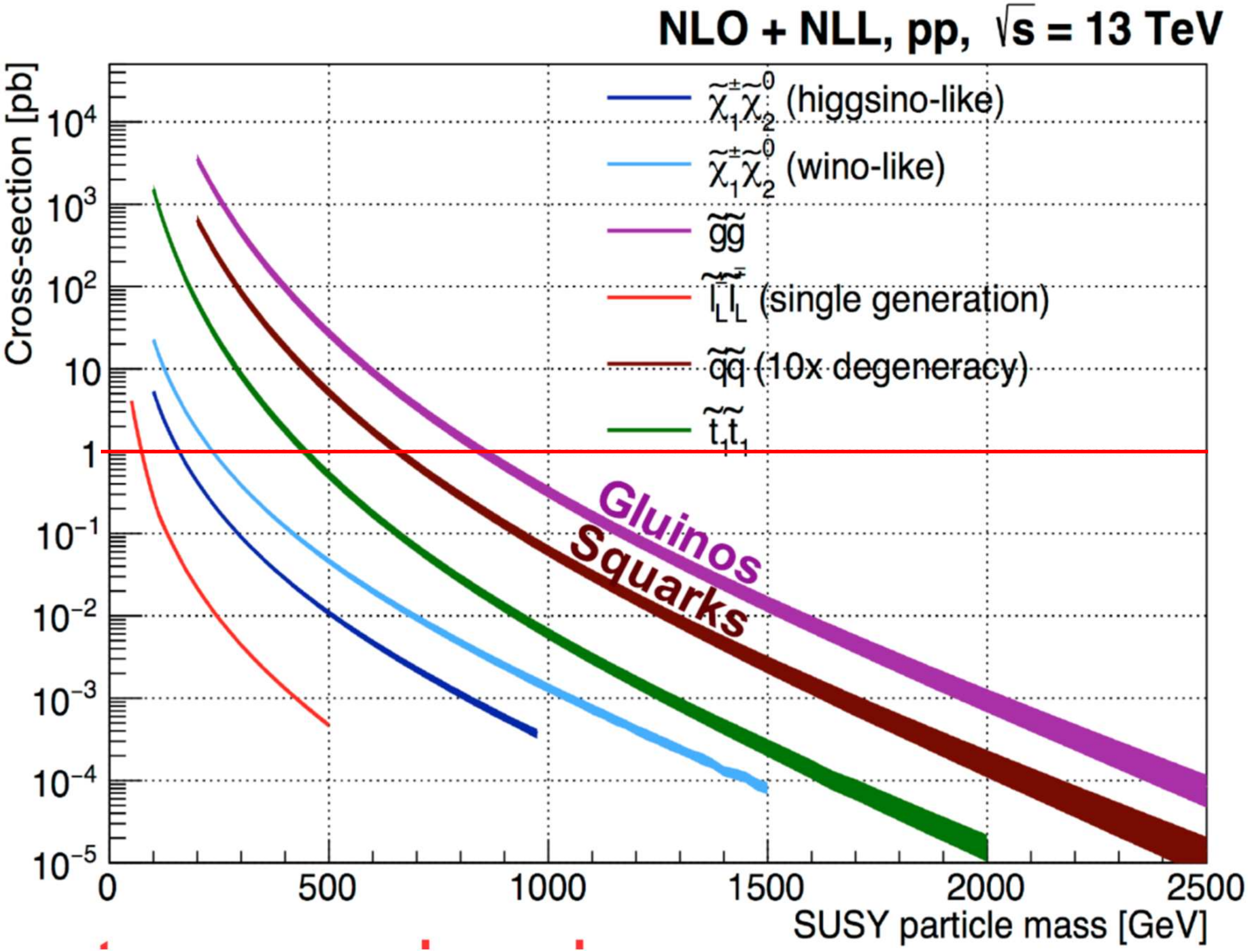
Assumptions on the chirality and nature of particle involved

Not always realistic but nice tool for analysis optimisation and display results

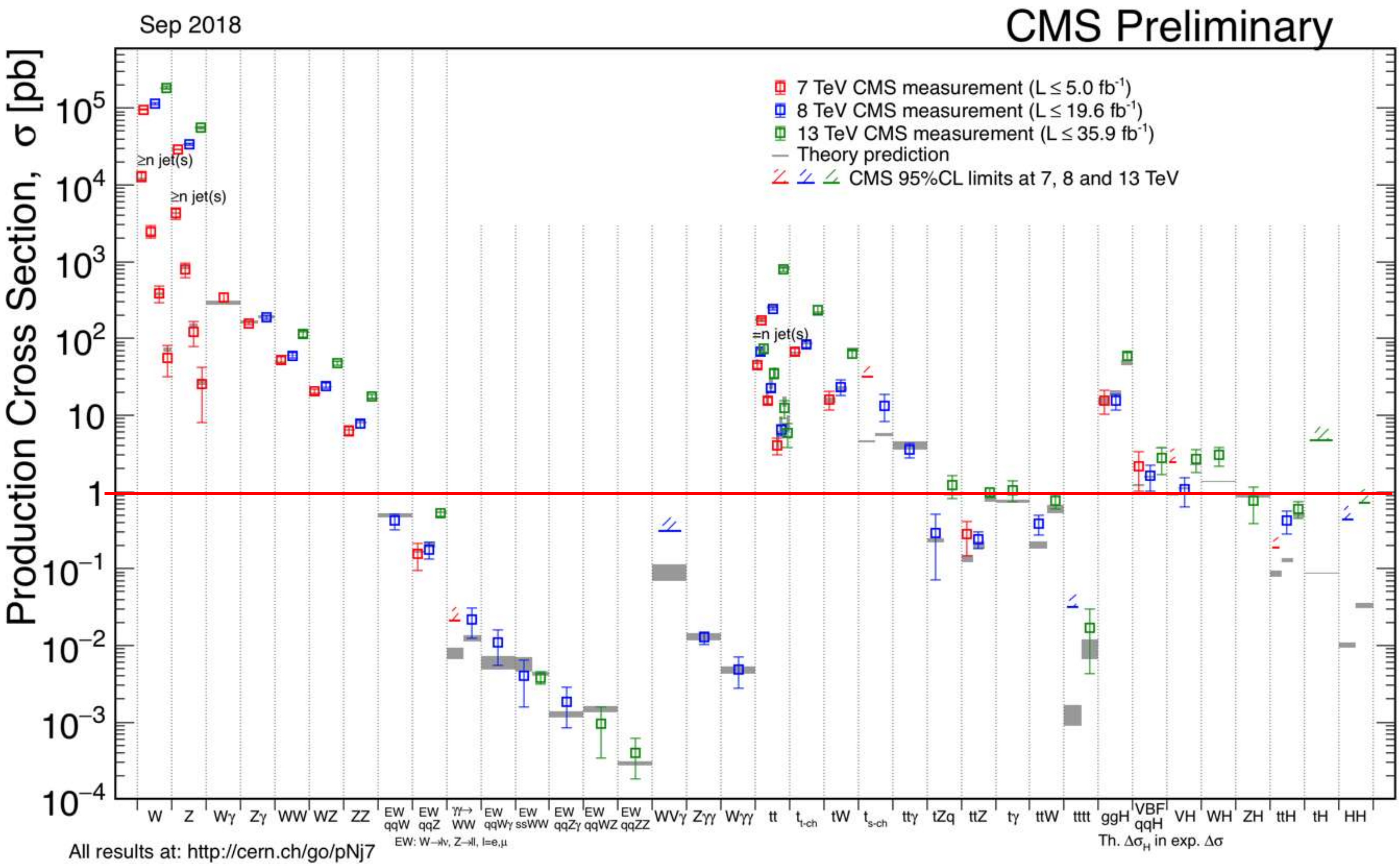




SUSY production at the LHC

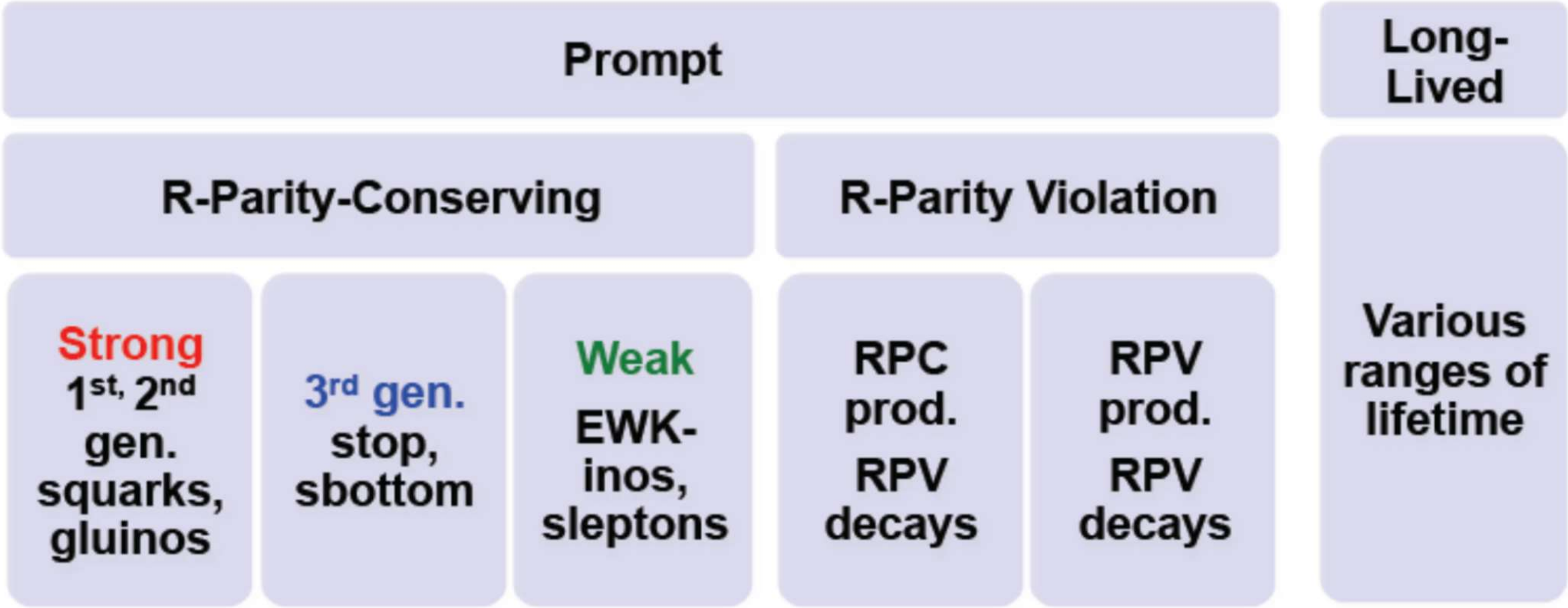


But remember



Search strategy

Search strategy designed to provide coverage for a broad class of SUSY models



Prompt

R-Parity-Conserving

Strong **1st, 2nd gen. squarks, gluinos**

3rd gen. **stop, sbottom**

Weak **EWK-inos, sleptons**

R-Parity Violation

RPC prod. **RPV decays**

RPV prod. **RPV decays**

Long-Lived

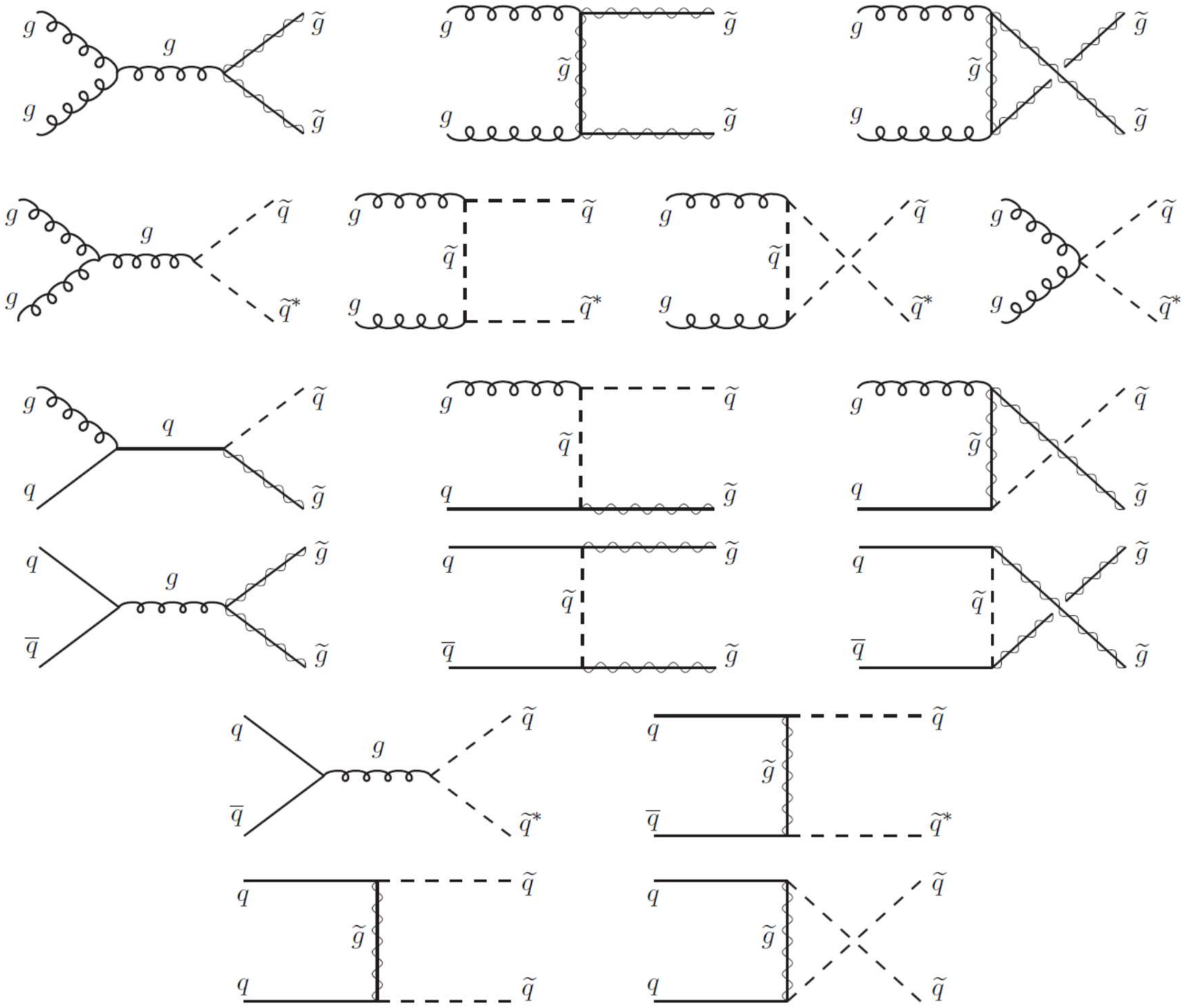
Various ranges of lifetime

Image credit: M. D'Onofrio

+Additional Higgs boson searches

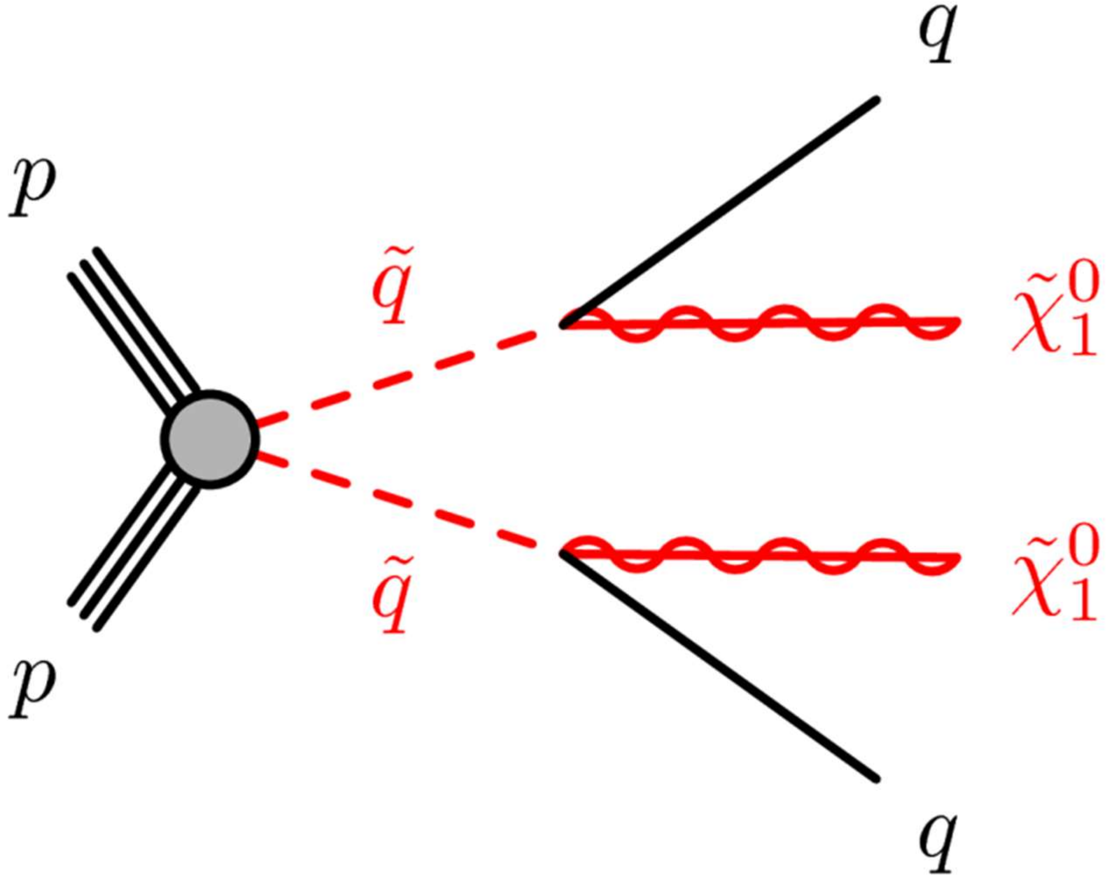
Squarks and gluinos

Squarks and gluinos production



Squarks decays

If m_{squark}>m $_{gluino}$, then the squark decays to a gluino and a quark via strong interation otherwise weak interaction:



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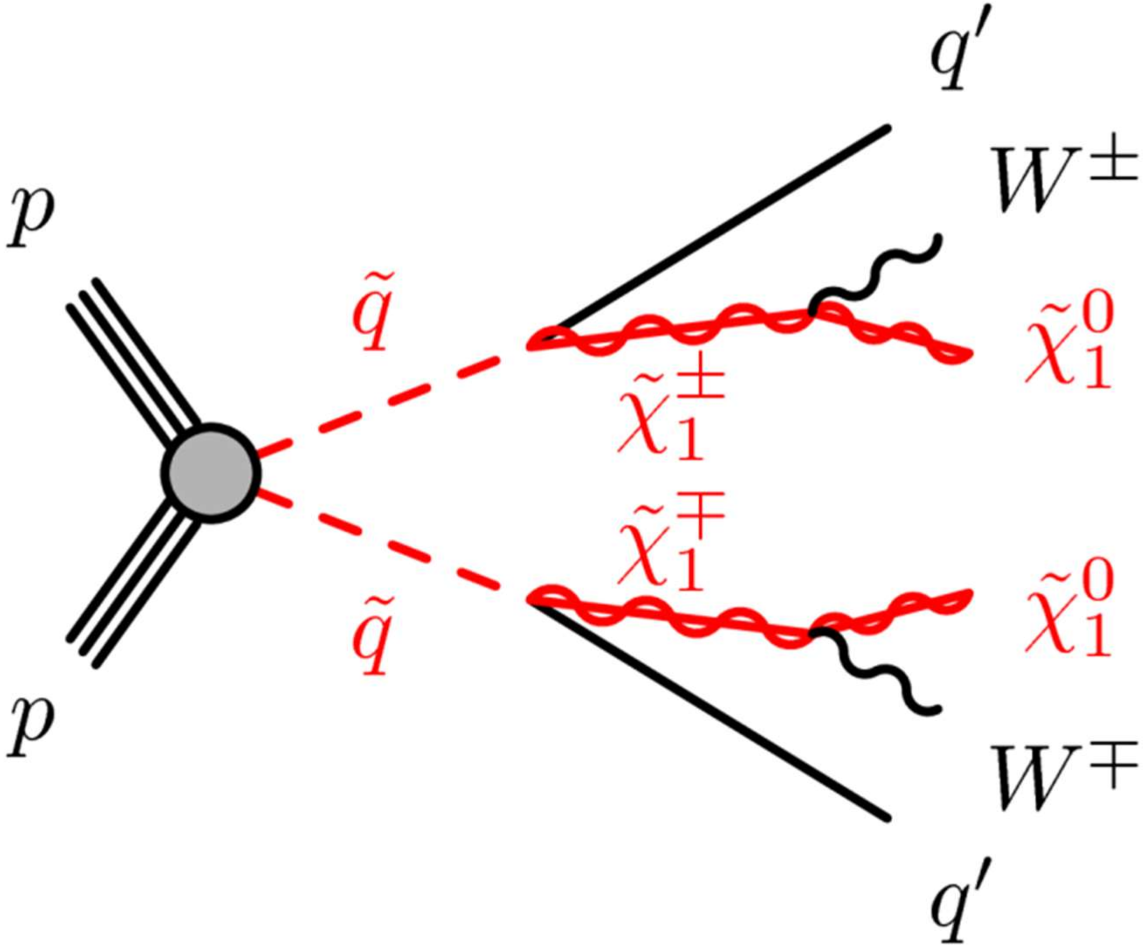

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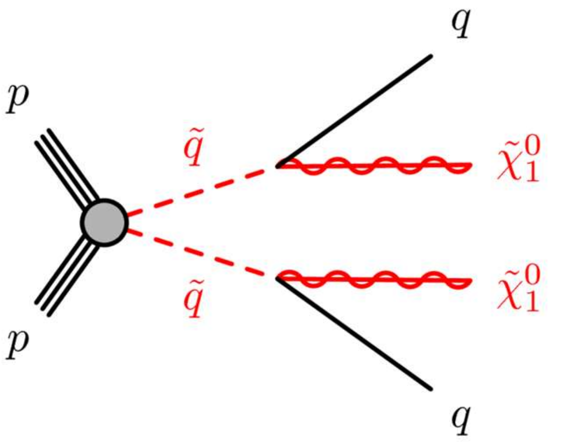
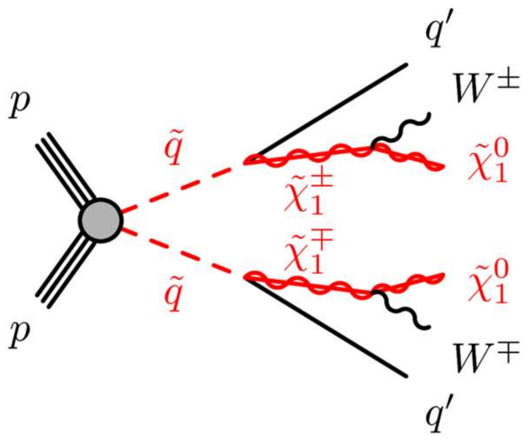
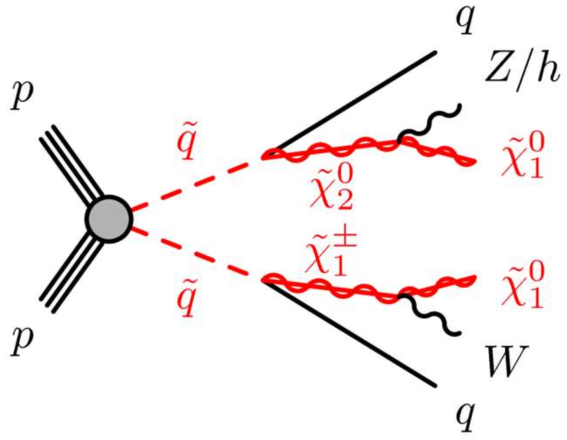
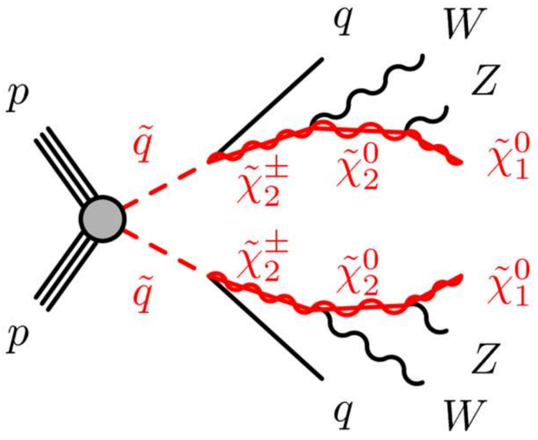




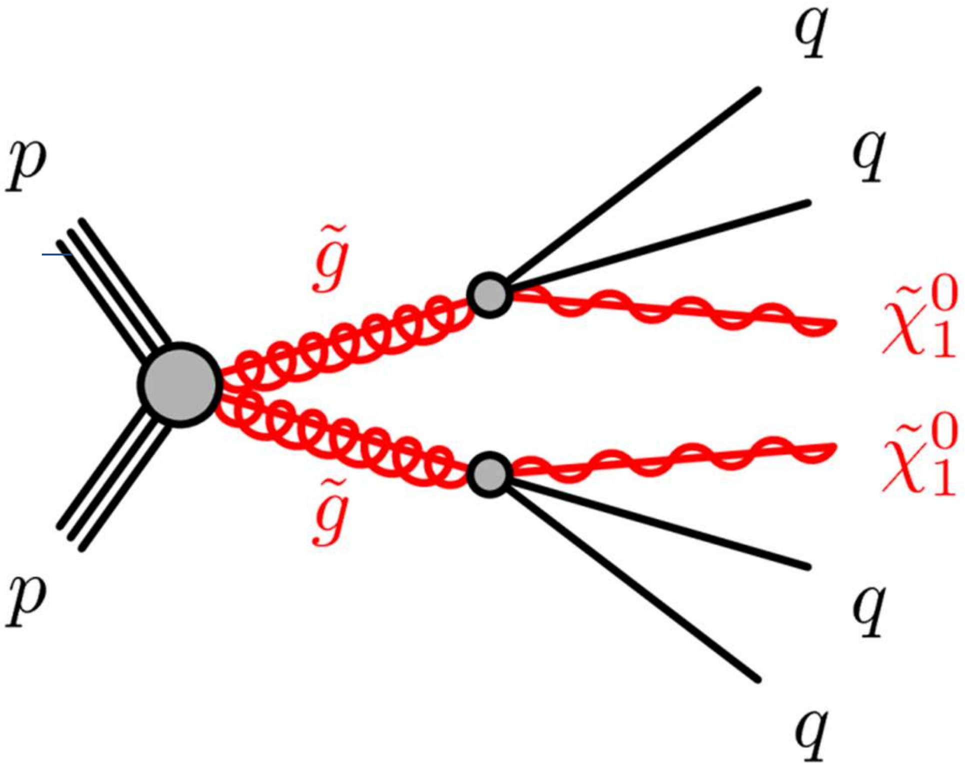




Note: Intermediate particles can be offshell, asymmetric decays also possible!

Gluino decays

The gluino only interacts via strong interaction, so the decay is to squark-quark. If $m_{squark}>m_{gluino}$ then the squark will be virtual and one will have a 3-body decay:



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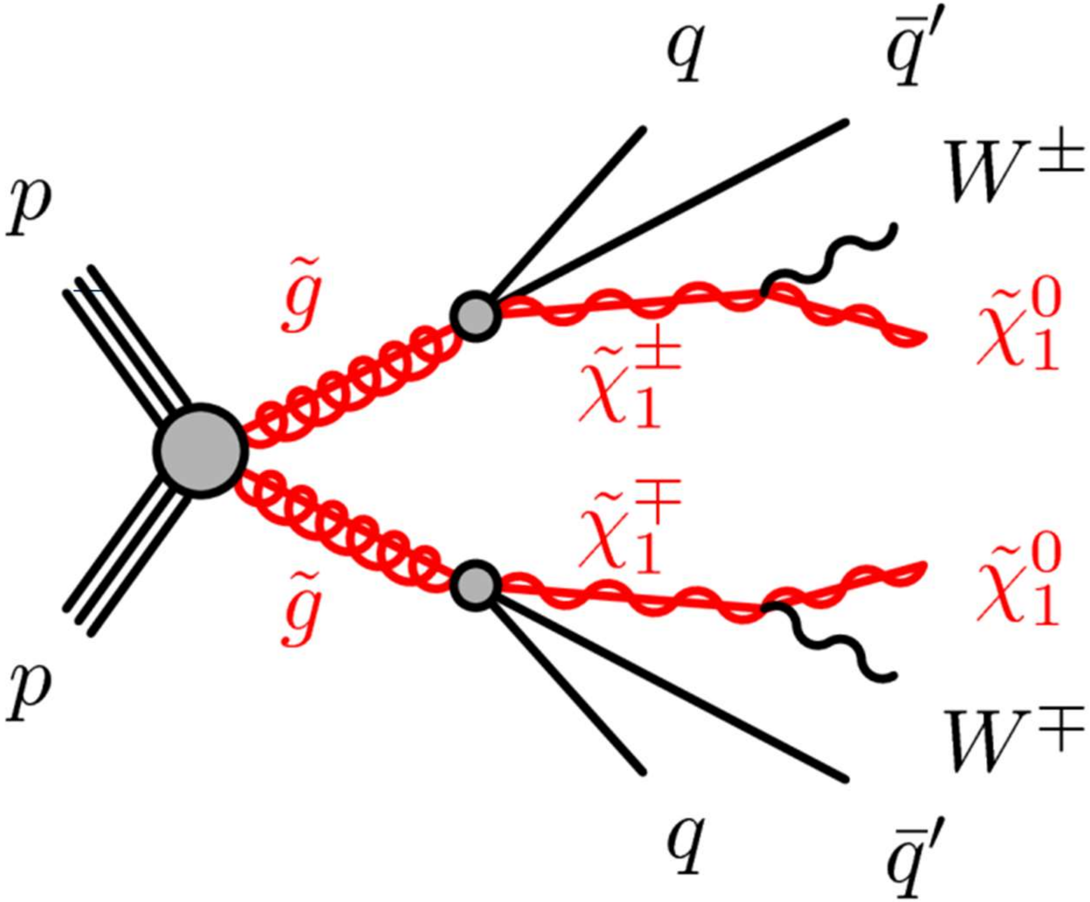

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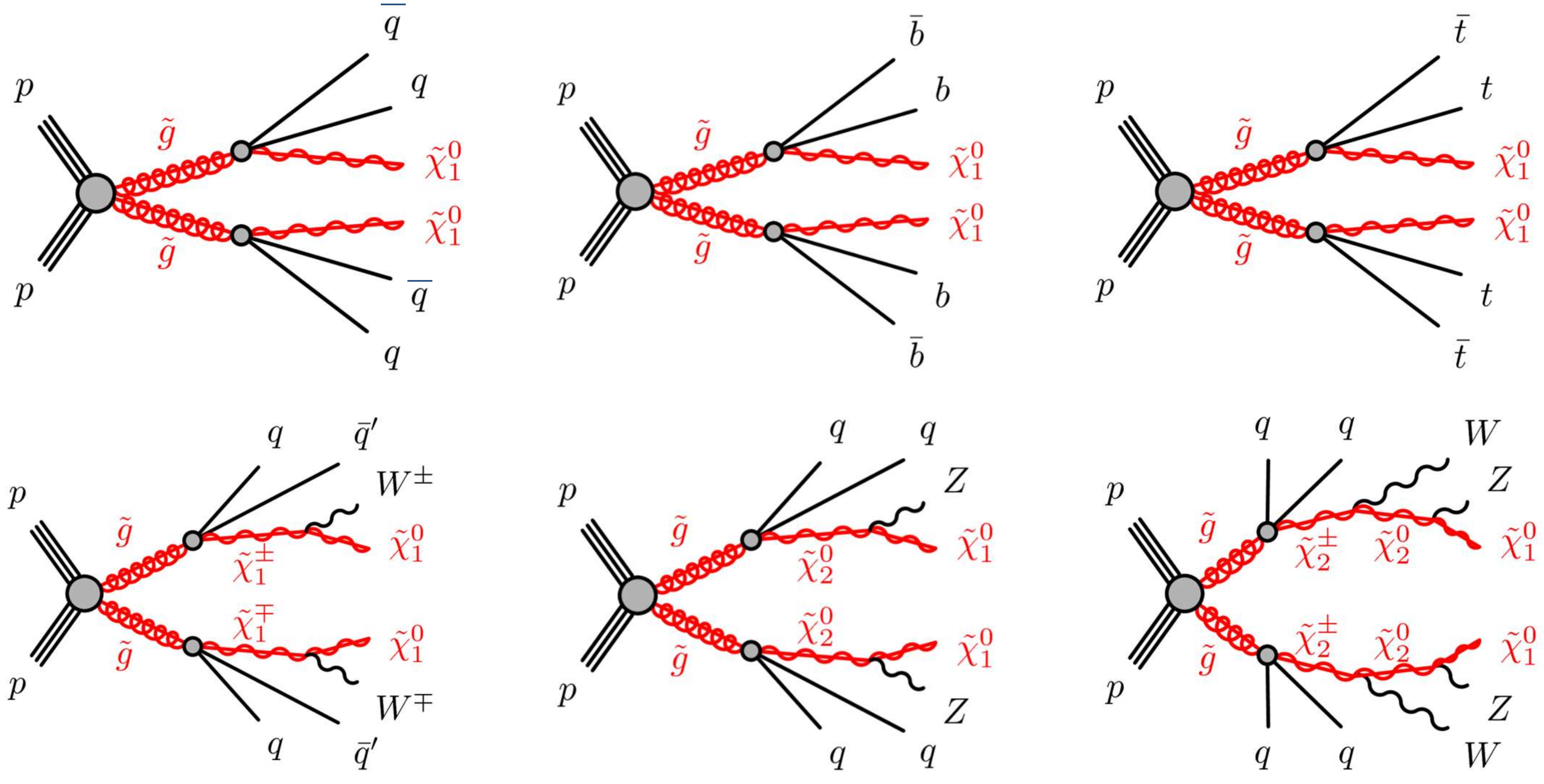
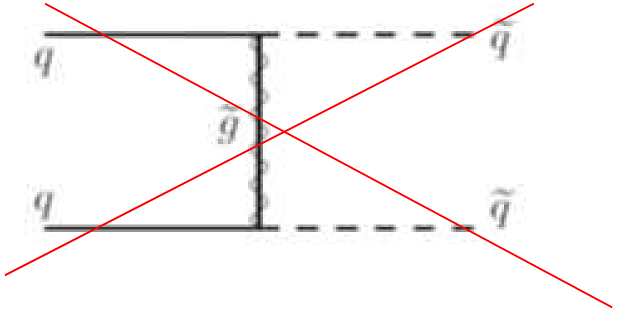


Rq: Intermediate particles can be offshell, asymmetric decays also possible!

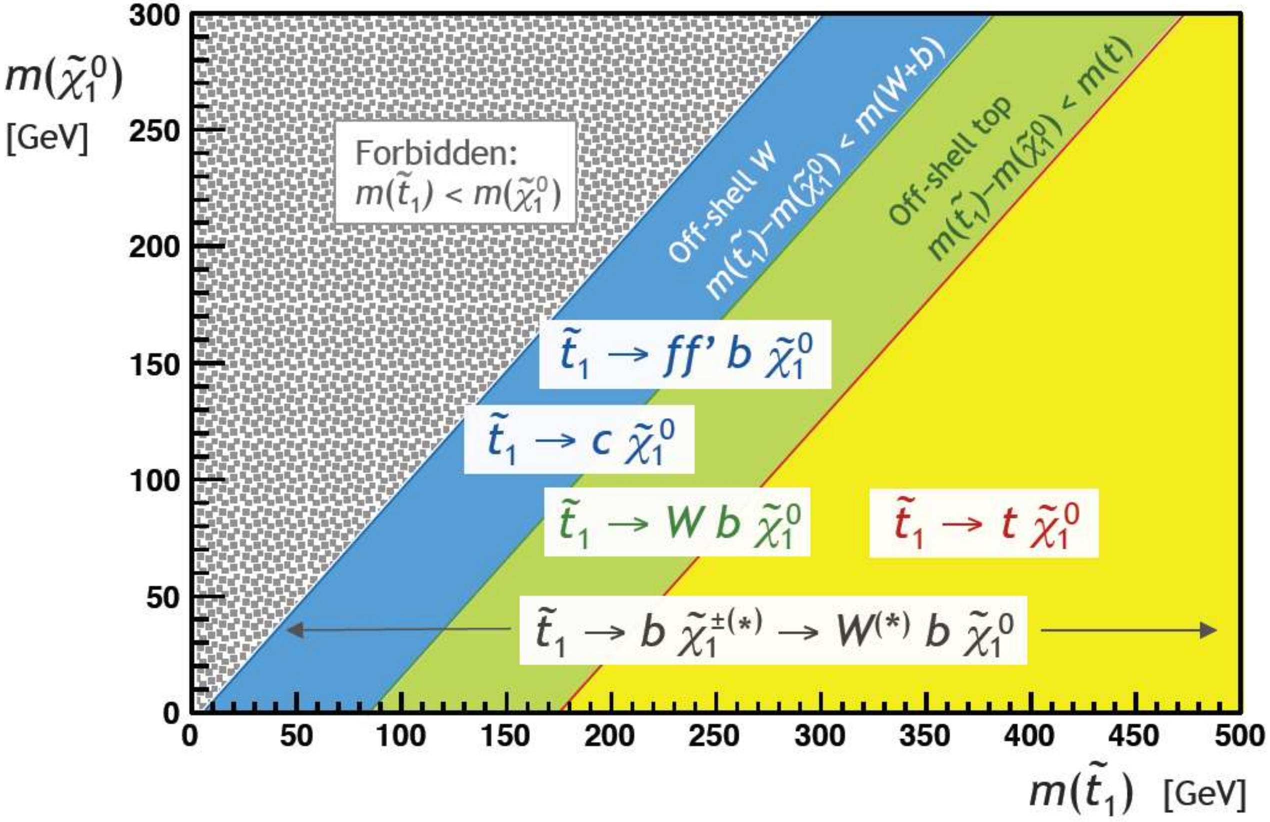
Stop

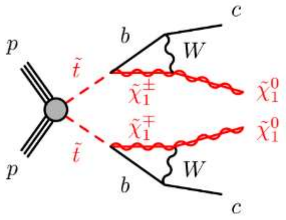
Thanks to the mixing, the lightest stop can be the lightest squarks

Lowest cross-section (no top in proton)



Large spectrum of possible stop decays:

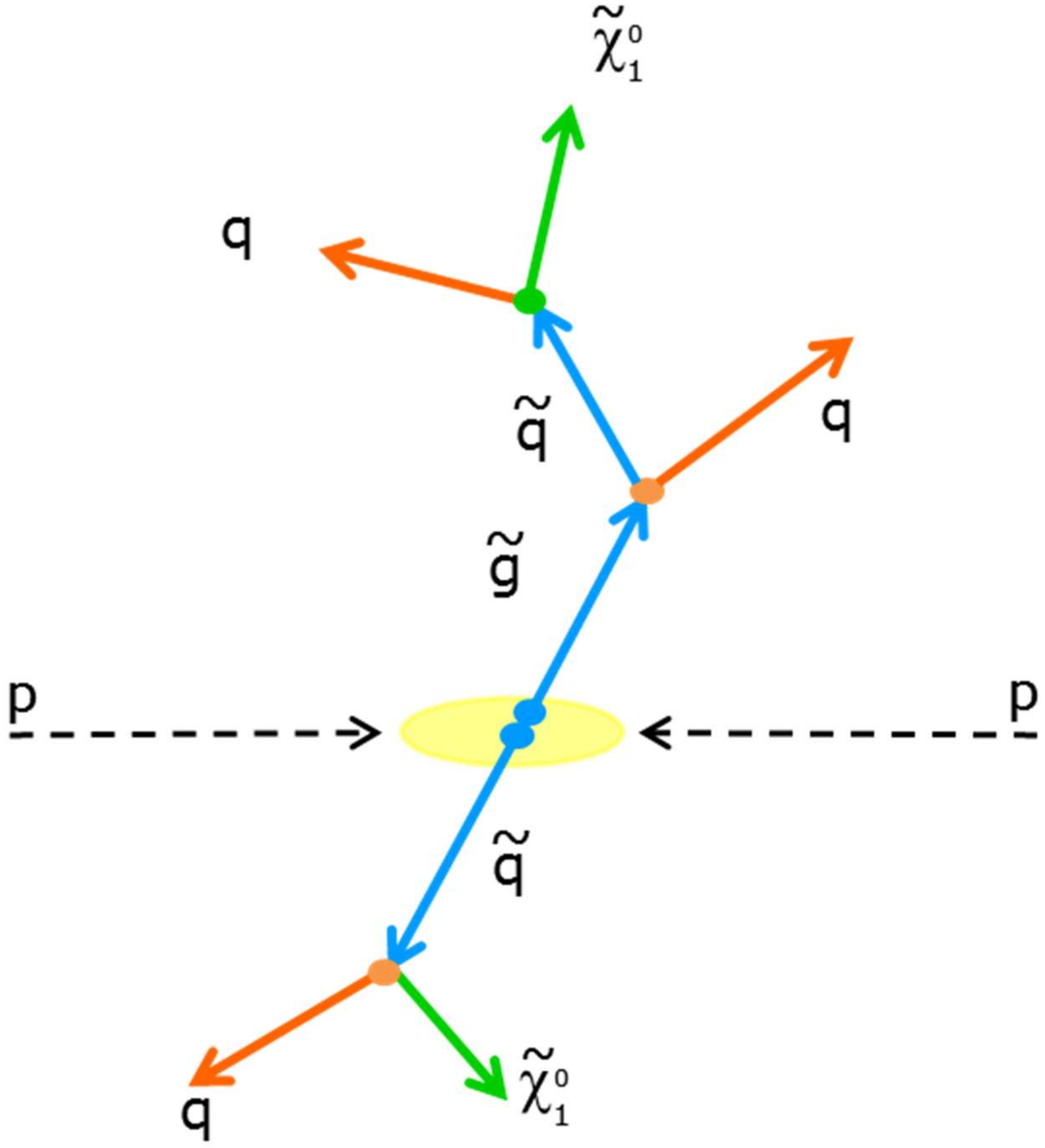




A detailed example: OL analysis

arXiv:1405.7875

OL analysis

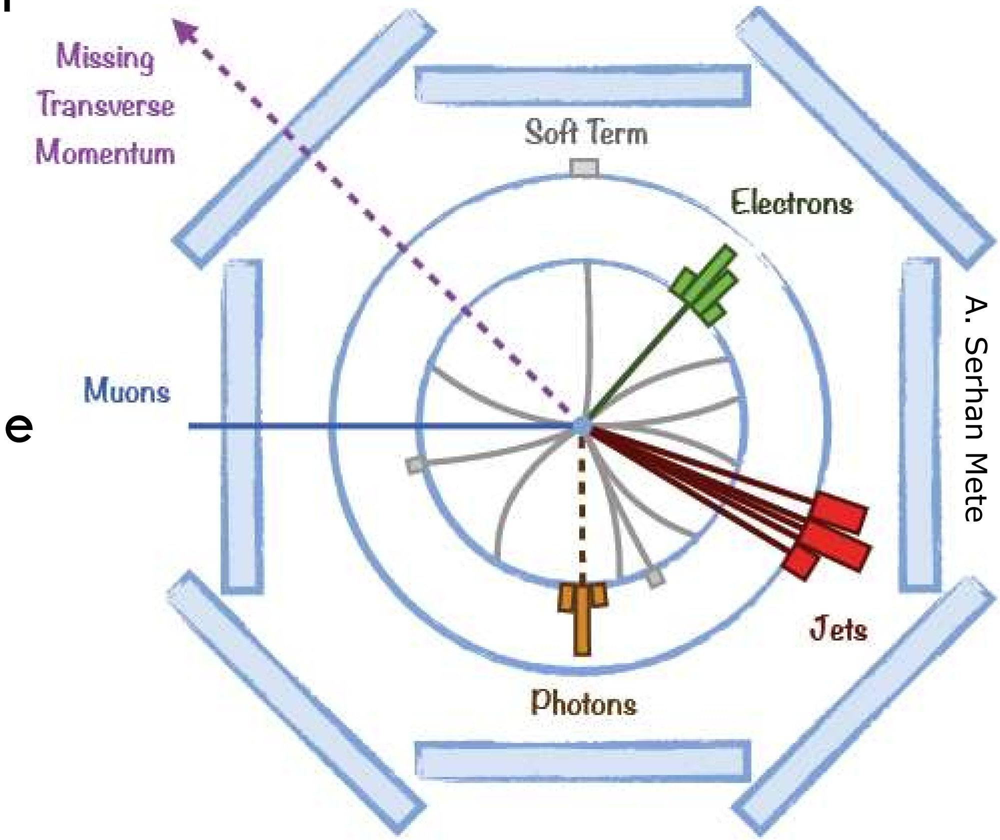


Missing transverse energy

Missing transverse energy (MET) can indicate the presence of neutrinos or other non-interacting particles (ex: lsp neutralino)

It is calculated as the negative of the vectorial sum of all of the objects reconstructed in the event:

$$\overrightarrow{MET} = -\sum_{objects} \vec{p}_T$$



A. Serhan Mete

Trigger

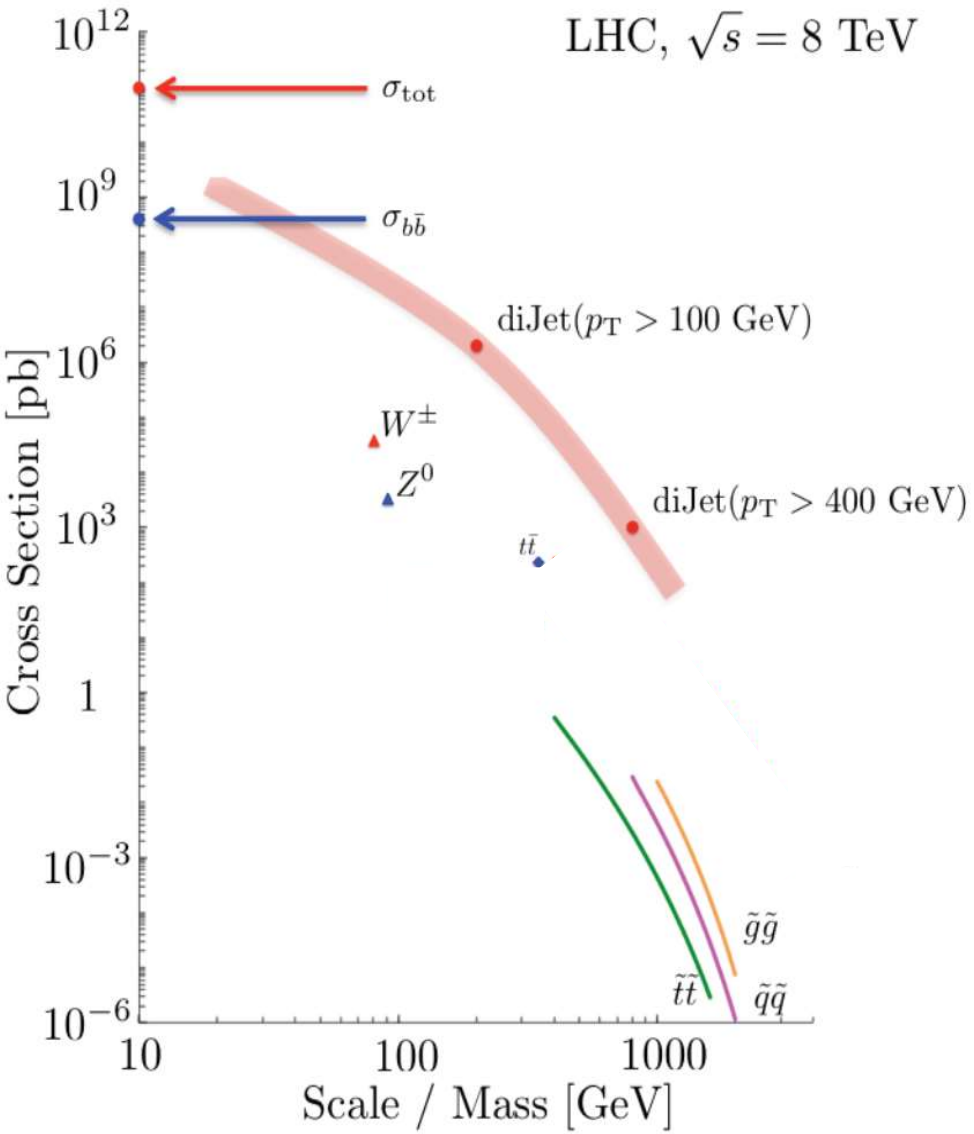
Signal swamped by SM background:

- Need a first selection online (trigger)

Jet+MET trigger

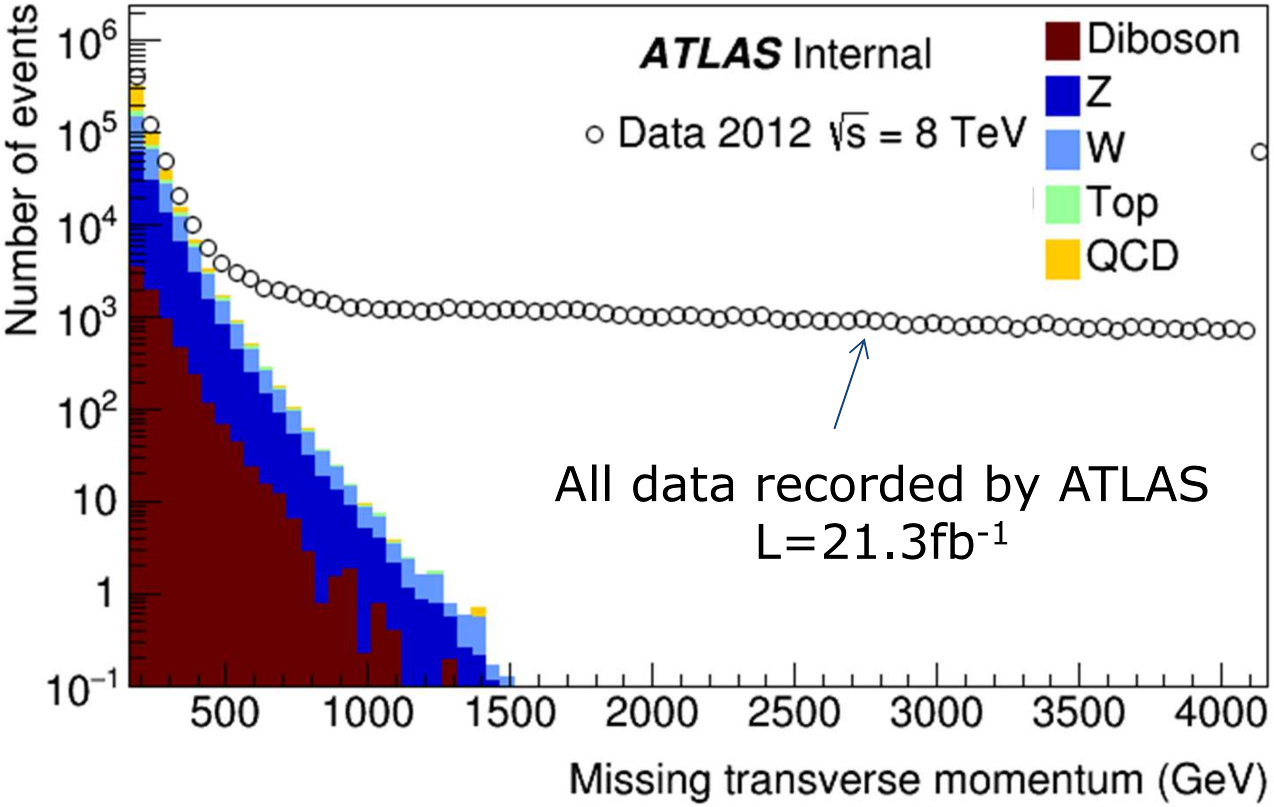
Fully efficient with respect the following offline cuts:

- Leading jet pt>130GeV
- MET>160GeV



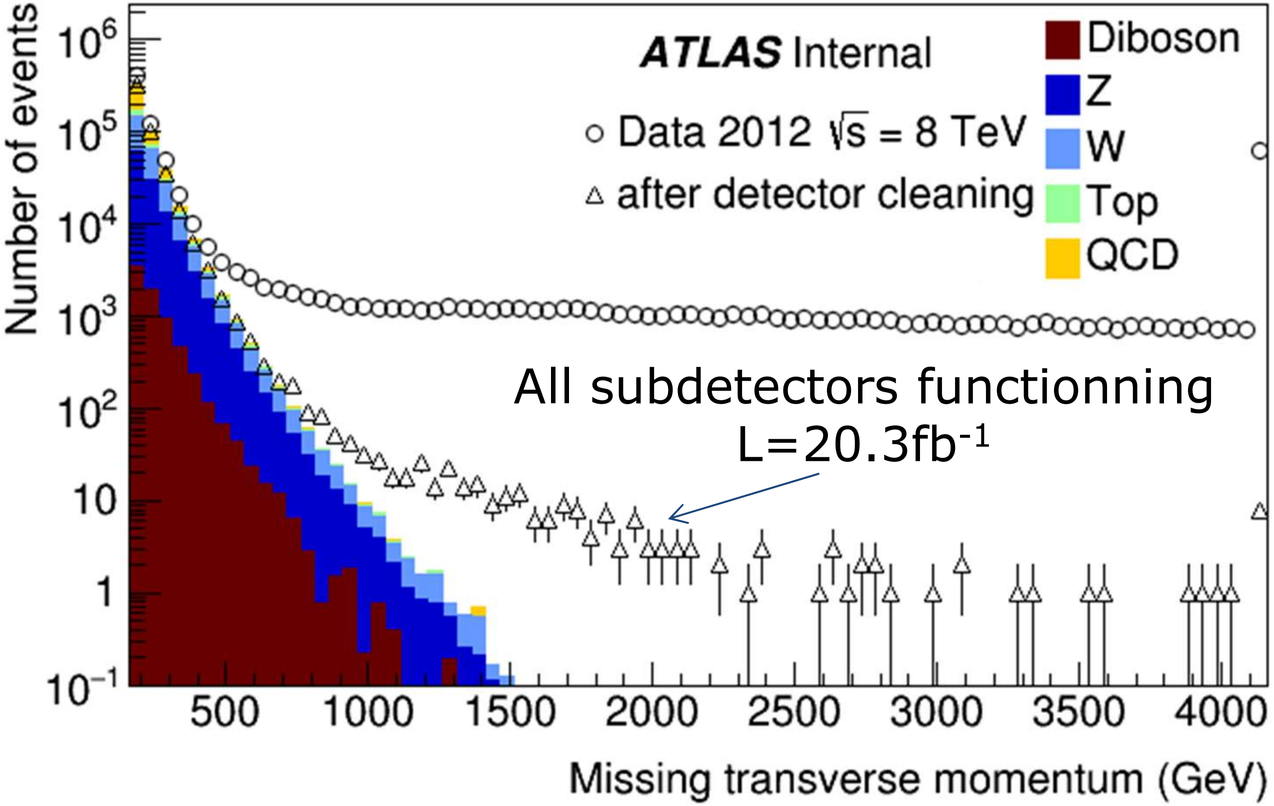
Missing transverse energy

Events without lepton



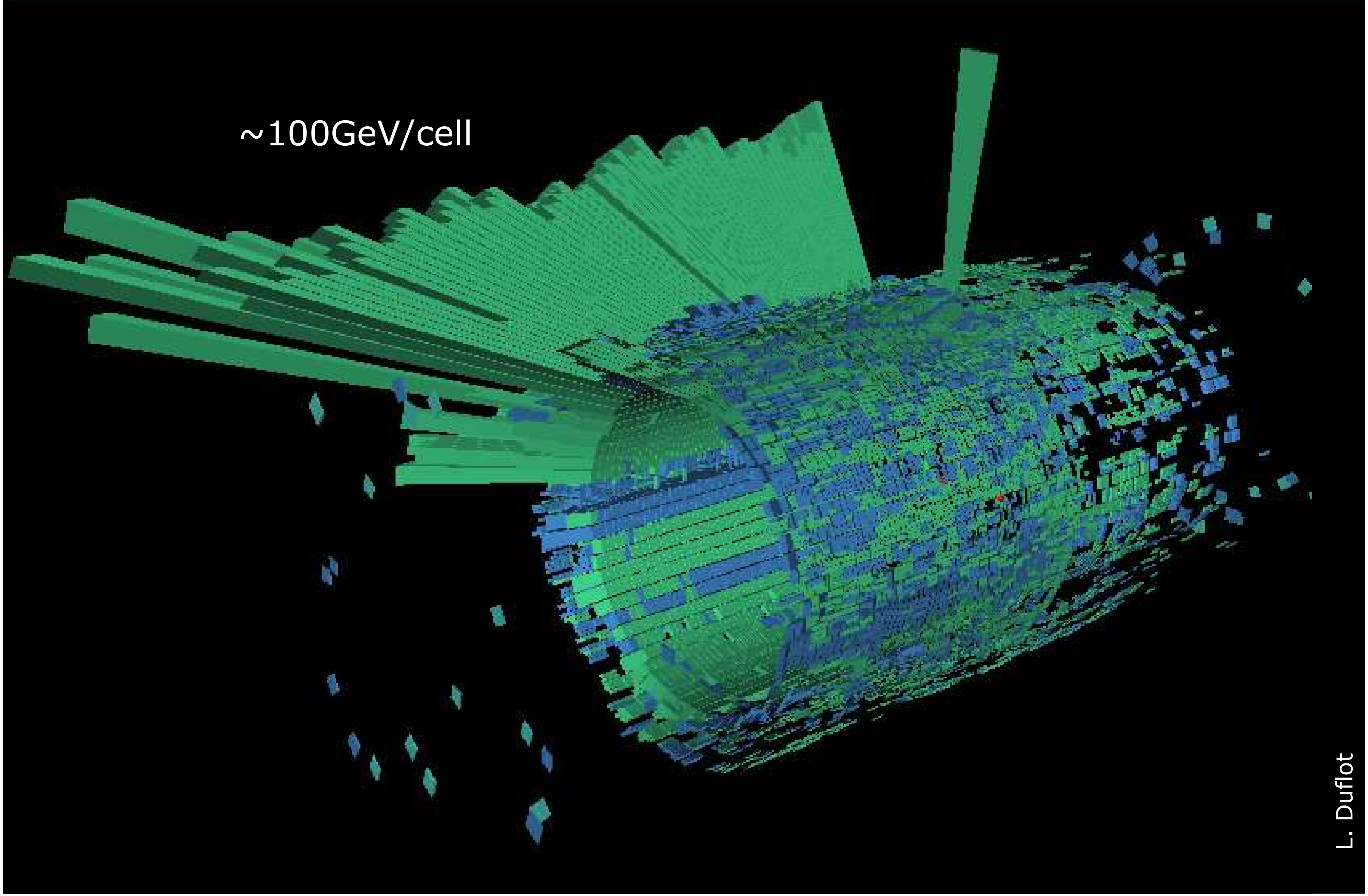
All data recorded by ATLAS
L=21.3fb^{-1}

Missing transverse energy



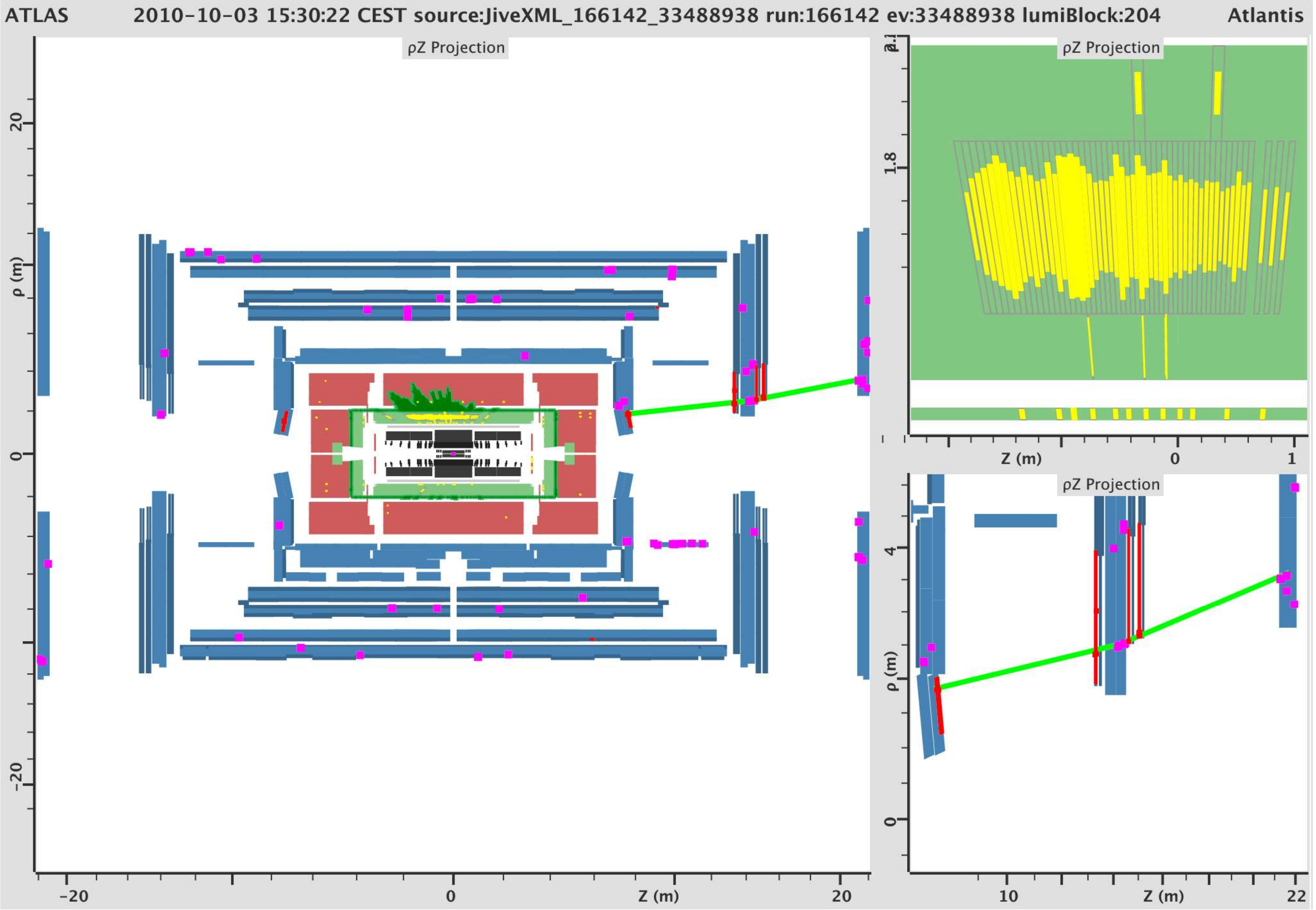
All subdetectors functionning
L=20.3fb^{-1}

Calorimeter large scale coherent noise



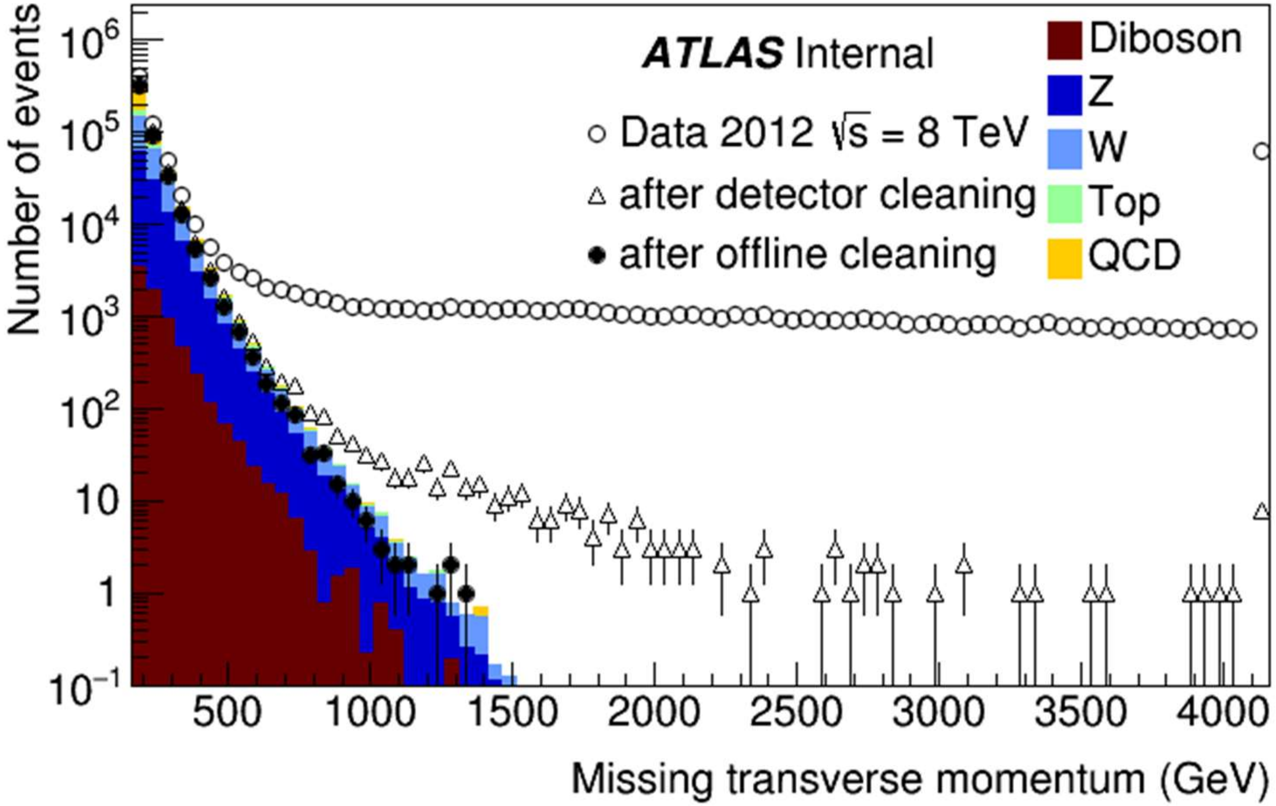
L. Duflot

Beam induced background



Missing transverse energy

Reject events with at least one Looser bad jet with pT>20GeV
or with at least one Tight bad jet with pT>100GeV

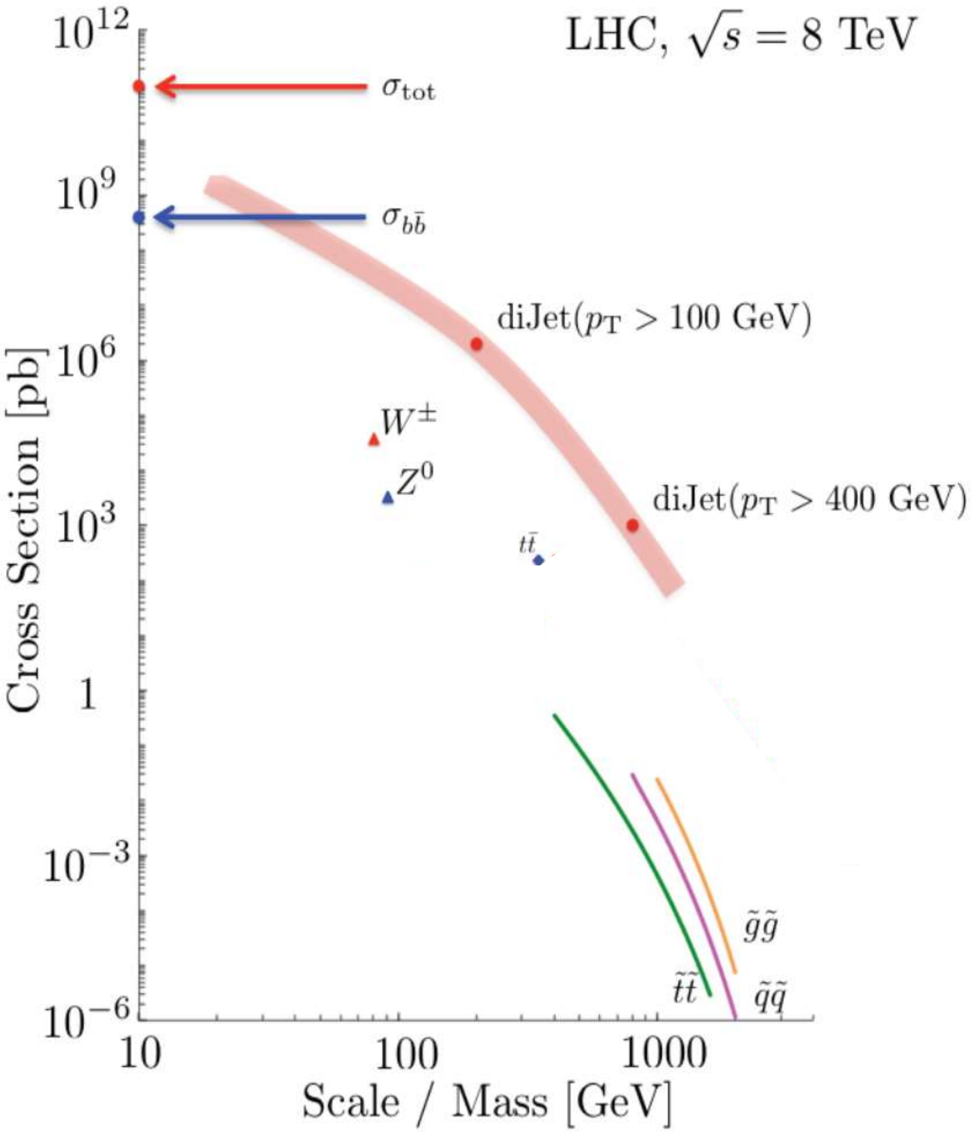


No more unphysical tail!

Background

- Veto events with electrons and muons with pT>10GeV

- Main background:
  - **Z→νν+jets**: irreducible background, dominant at low jet multiplicity
  - **W+jets**: mainly coming from W→τν decay
  - **Top**: mainly pair production with W→τν decay, dominant at high jet multiplicity
  - **Diboson**: small (<10%) estimated from MC
  - **Multijets**: negligible thanks to harsh cuts to reject it

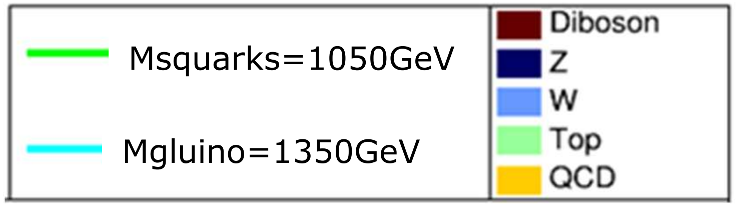


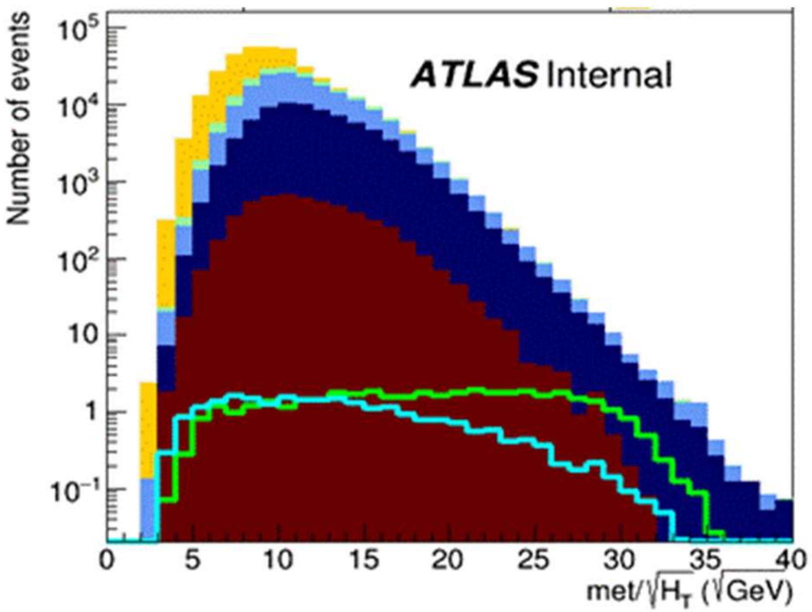
Discriminating variables

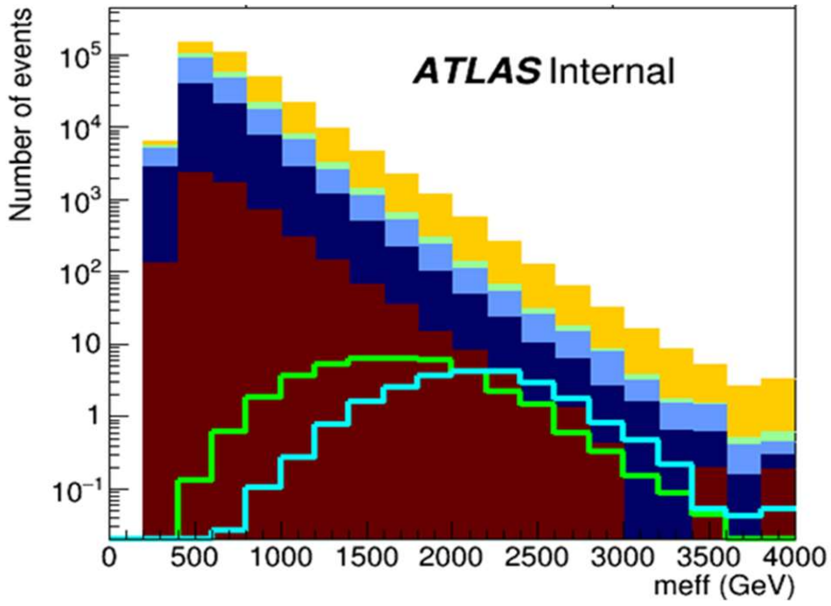
$$M_{eff} = H_T + E_T^{miss}$$

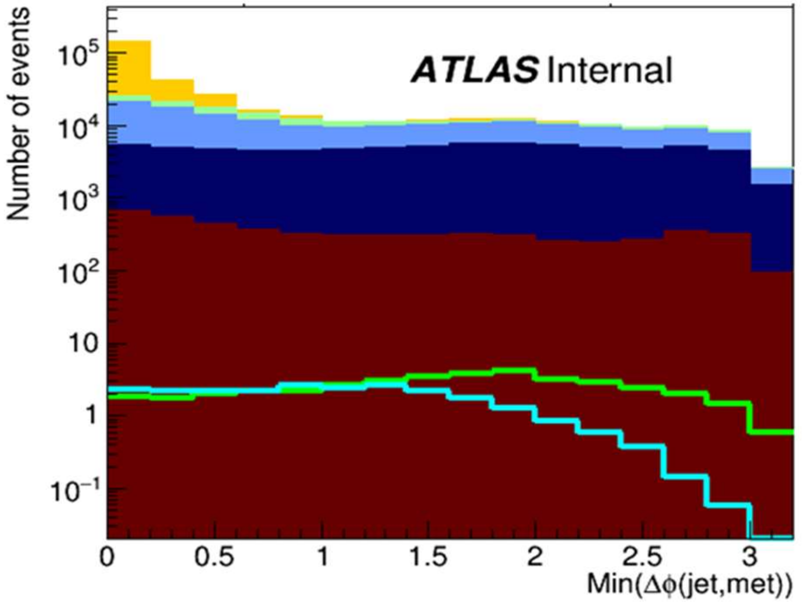
$$H_T = \sum_{jets\ pT>40GeV} p_T^{jets}$$

Massless lsp

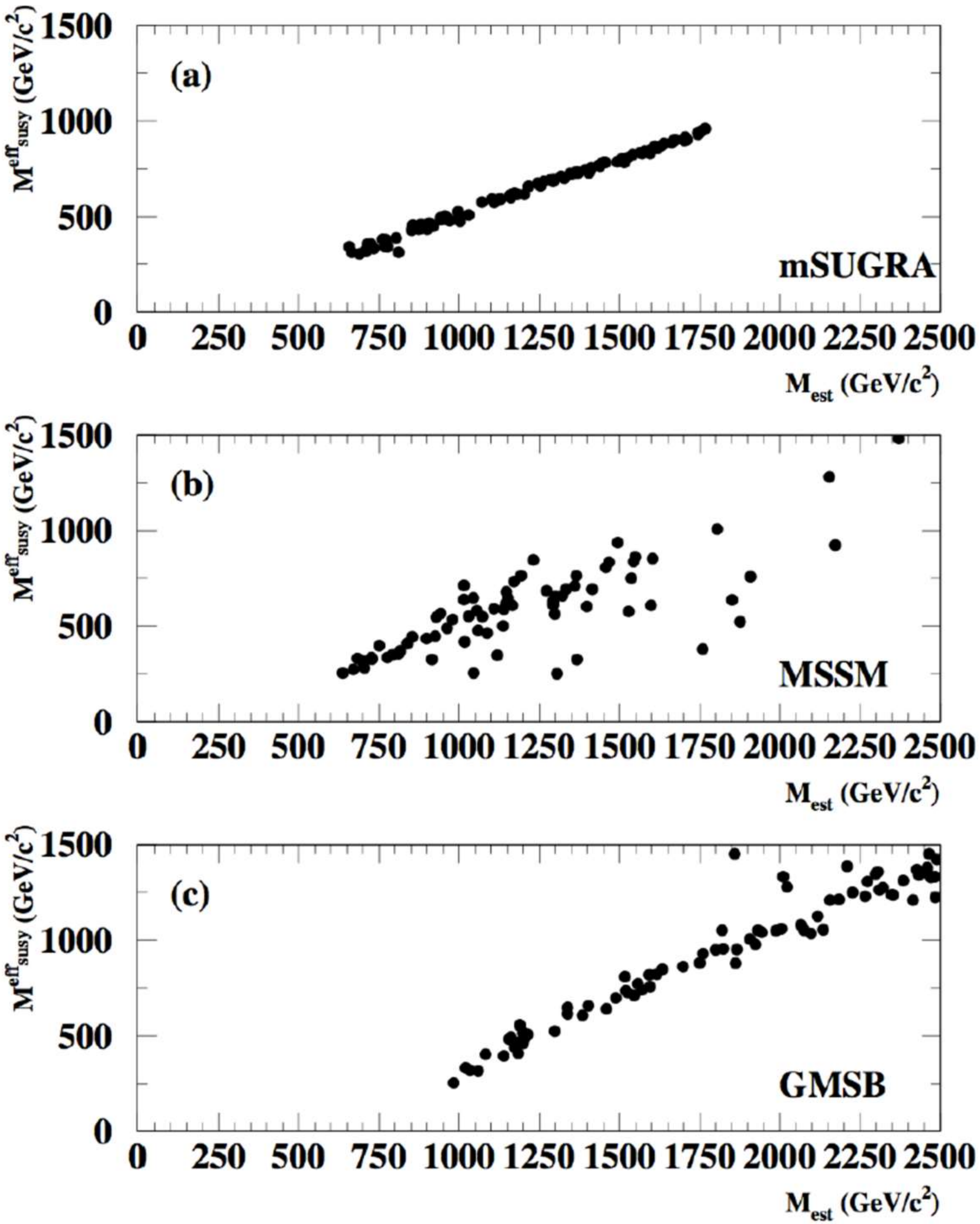








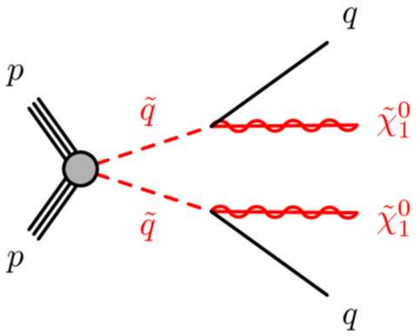
Effective mass

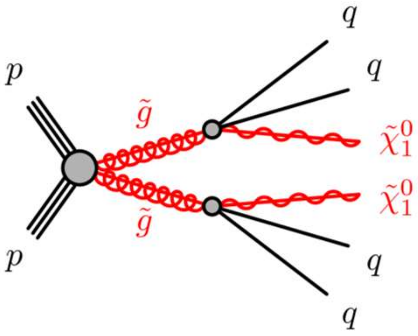


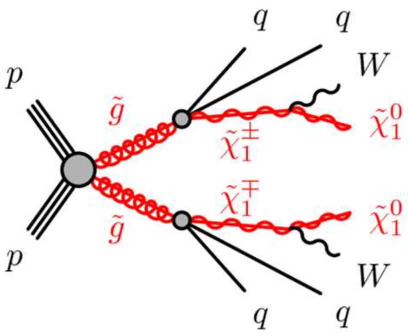
Signal regions

$$M_{eff} = H_T + E_T^{miss} \qquad H_T = \sum_{jets\ pT>40GeV} p_T^{jets}$$

Requirement	Channel														
	2j				3j	4j					5j	6j			
	2jl	2jm	2jt	2j(W)		4j(W)	4jl-	4jl	4jm	4jt		6jl	6jm	6jt	6jt+
Targetted signal	$\tilde{q}\tilde{q}$ direct			$\tilde{g}\tilde{g}$ one-step	$\tilde{g}\tilde{g}$ direct	$\tilde{q}\tilde{q}$ one-step	$\tilde{q}\tilde{q}$ direct		$\tilde{q}\tilde{g}$ & $\tilde{g}\tilde{g}$		$\tilde{q}\tilde{q}$ one-step	$\tilde{g}\tilde{g}$ one-step			NUHM
$\Delta\phi(j_{1,2,(3)}, E_{\mathrm{T}}^{\mathrm{miss}}) >$	0.4														
$\Delta\phi(j_{i>3}, E_{\mathrm{T}}^{\mathrm{miss}}) >$	–					0.2									
W candidates	–			$2\ W \to j$ 60<m(W)<100 GeV	–	$W \to j +$ $W \to jj$ 60<m(W)<100 GeV	–								
$E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{H_T} >$	8	15	15				10	10							
$E_{\mathrm{T}}^{\mathrm{miss}} / m_{\mathrm{eff}}(Nj) >$				0.25	0.3	0.35			0.4	0.25	0.2	0.2	0.2	0.25	0.15
$m_{\mathrm{eff}}(\mathrm{incl.})$ [GeV] >	800	1200	1600	1800	2200	1100	700	1000	1300	2200	1200	900	1200	1500	1700







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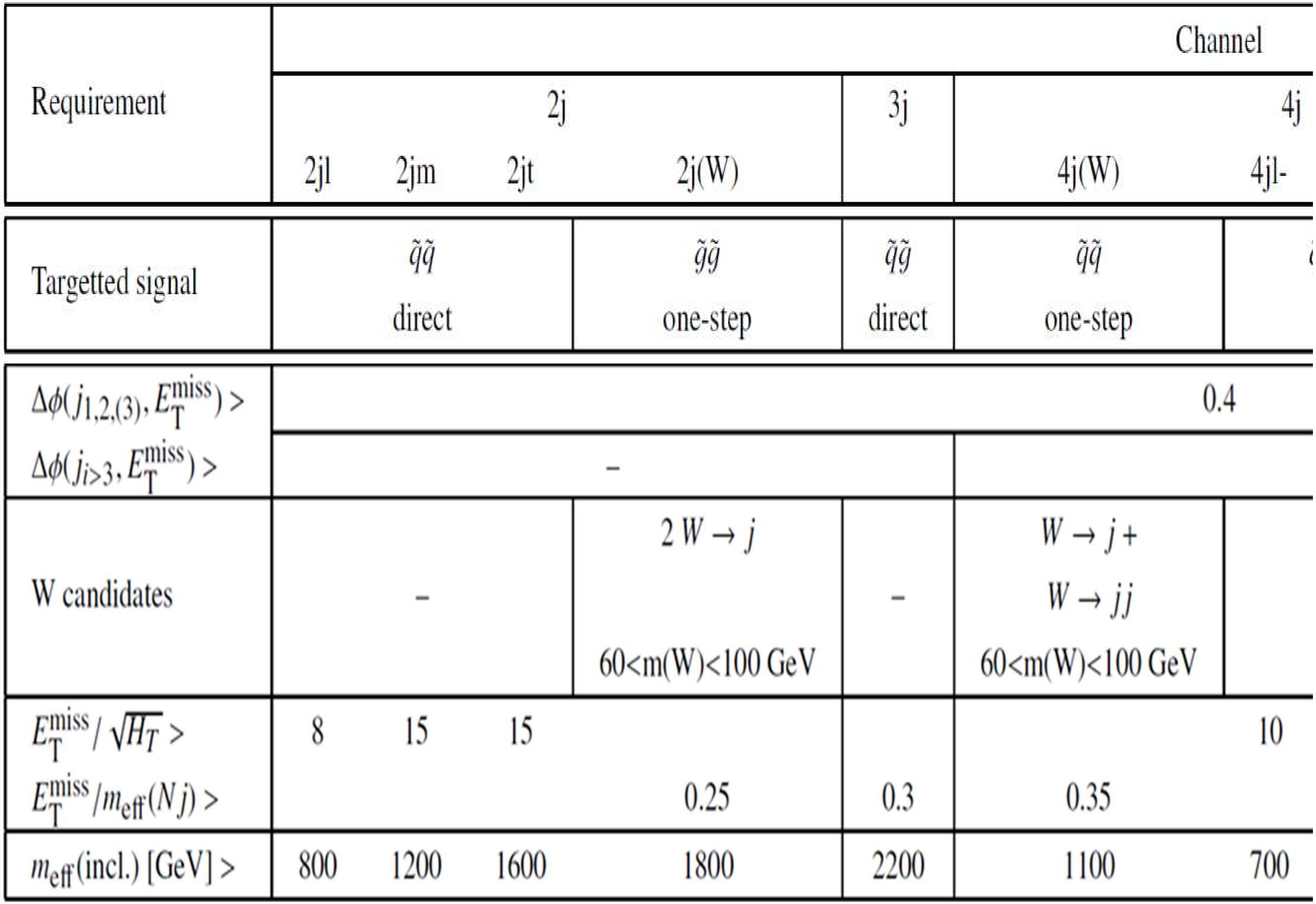

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Targetted signal	$\tilde{q}\tilde{q}$ direct			$\tilde{g}\tilde{g}$ one-step	$\tilde{q}\tilde{g}$ direct	$\tilde{q}\tilde{q}$ one-step	$\tilde{q}\tilde{q}$ direct		$\tilde{q}\tilde{g}$ & $\tilde{g}\tilde{g}$		$\tilde{q}\tilde{q}$ one-step		$\tilde{g}\tilde{g}$ one-step		NUHM
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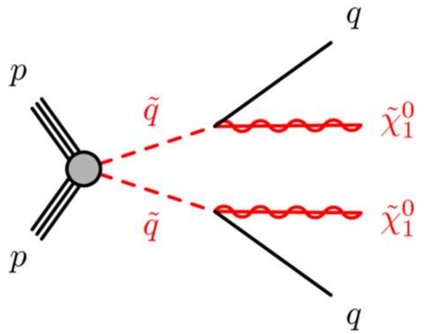

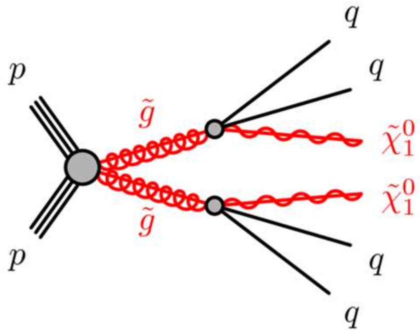

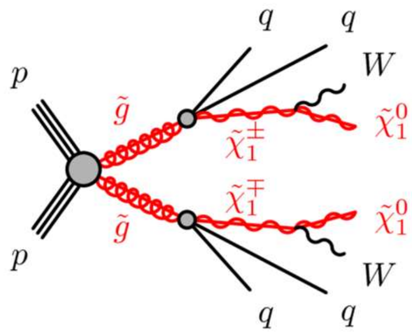

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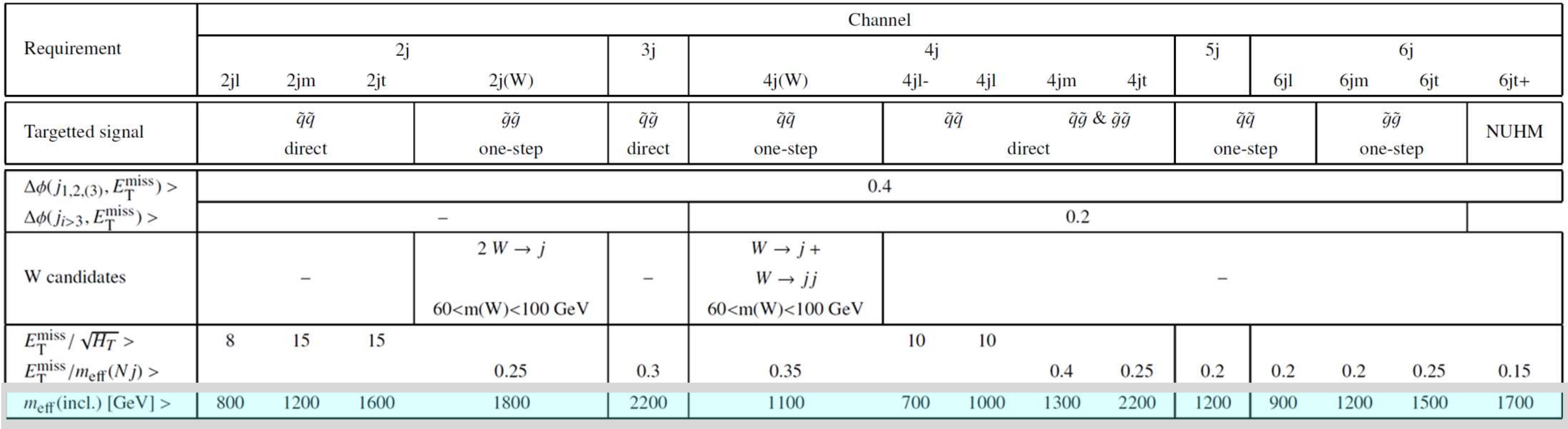

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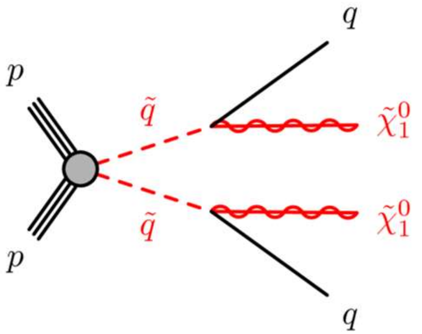

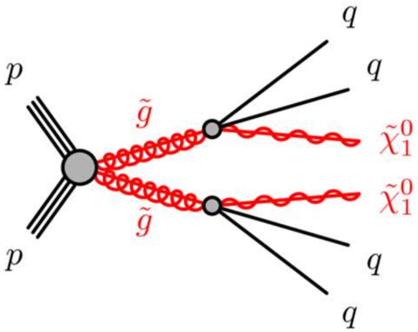

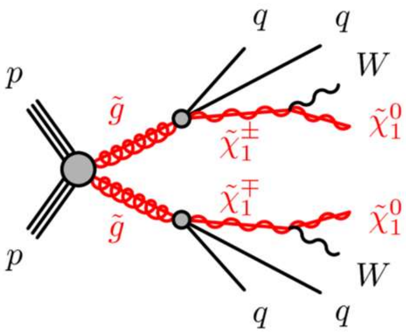

Signal regions

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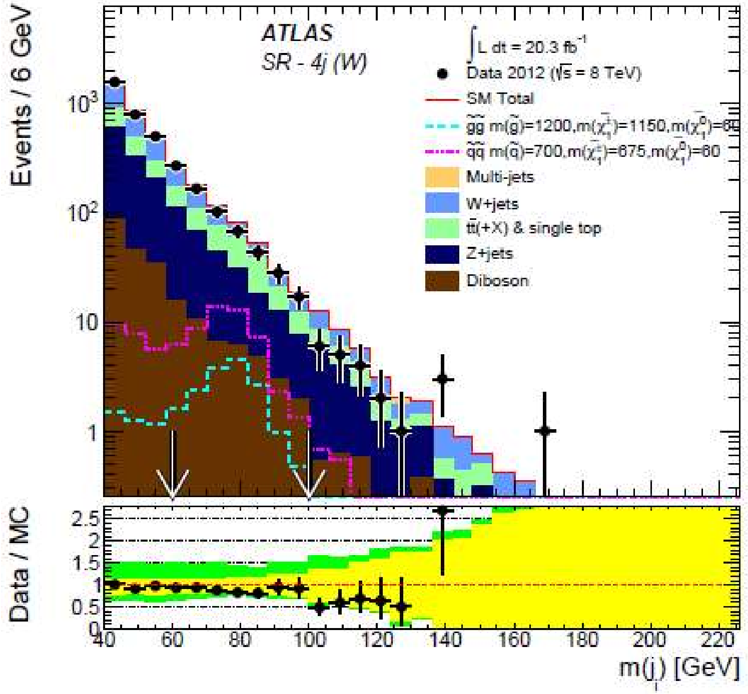

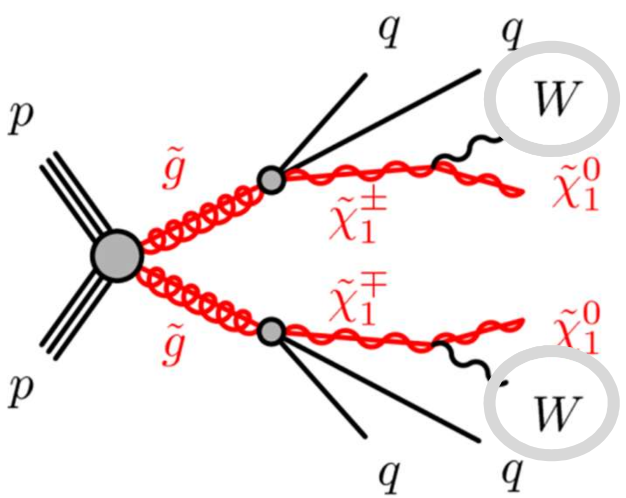

Zνν background prediction

$$N_{Z\nu\nu}^{pred} = N_{Z\nu\nu}^{MC}$$

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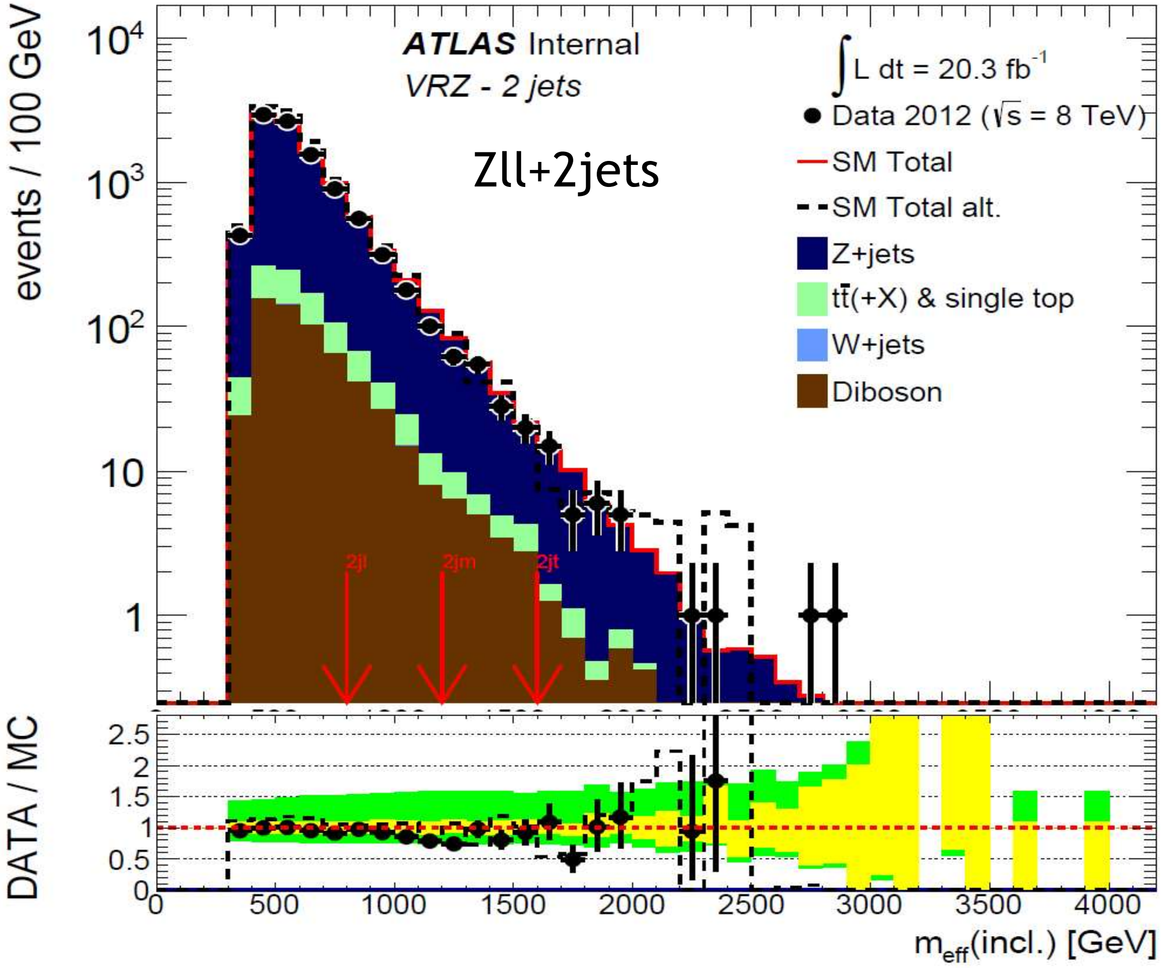


$$meff' = met' + H_T = \left|\overrightarrow{met} + \overrightarrow{p_T^{Zll}}\right| + H_T$$

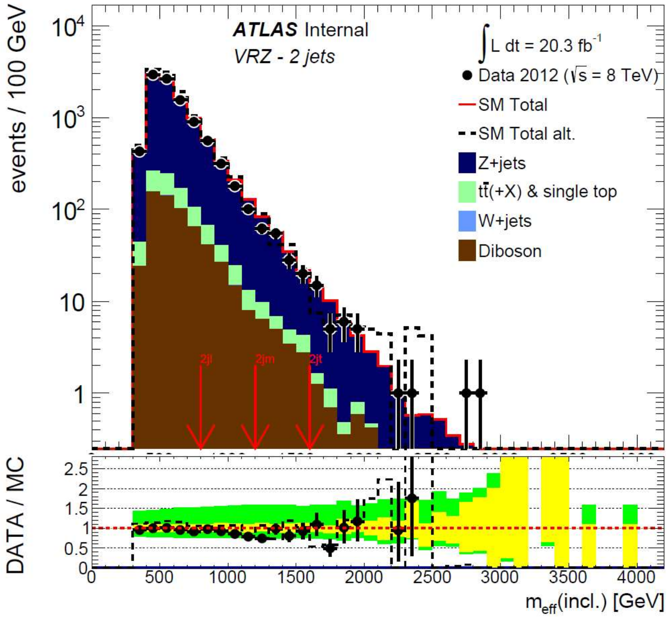
Zνν background prediction

$$N^{pred}_{Z\nu\nu} = N^{MC}_{Z\nu\nu} \times \frac{N^{data}_{Zll}}{N^{MC}_{Zll}}$$

scale factor

Zll+2jets

- Renormalize the MC to data in dedicated control regions
- Control regions are orthogonal to the SR (by inverting cuts) but have kinematical cuts close to SR



$$meff' = met' + H_T = \left|\overrightarrow{met} + \overrightarrow{p_T^{Zll}}\right| + H_T$$

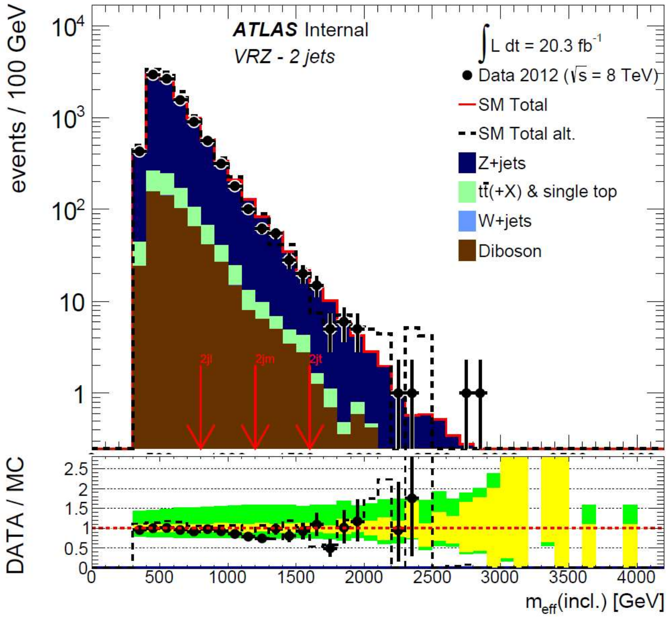
Zνν background prediction

$$N^{pred}_{Z\nu\nu} = N^{data}_{Zll} \times \frac{N^{MC}_{Z\nu\nu}}{N^{MC}_{Zll}}$$

transfer factor

Zll+2jets

- Renormalize the MC to data in dedicated control regions
- Control regions are orthogonal to the SR (by inverting cuts) but have kinematical cuts close to SR
- Systematic uncertainties which are correlated between CR and SR largely cancel out in the transfer factor
- Zll are statistically limited



$$meff' = met' + H_T = \left|\overrightarrow{met} + \overrightarrow{p_T^{Zll}}\right| + H_T$$

Likelihoods

The background can also be constrained by the data using a control region where the number of events is noted m

$$L(n,m \mid \mu,b) = \frac{(\mu s+b)^n e^{-(\mu s+b)}}{n!} . \frac{(\tau b)^m e^{-\tau b}}{m!}$$

$$b_{CR} = \tau b = \frac{b}{TF}$$

$$\hat{b} = TF.m_{meas.}$$

Here b is treated as a nuisance parameter.

If $b_{CR}=\tau b \neq m_{meas}$, need to adjust b to maximize the likelihood.

In general, there should also be also an uncertainty on τ

One can also introduce equivalently the background strengh parameter (μ_bb)

$$L(n,m \mid \mu,\mu_b) = \frac{(\mu.s+\mu_b.b)^n e^{-(\mu.s+\mu_b.b)}}{n!} . \frac{(\mu_b.b_{CR})^m e^{-\mu_b.b_{CR}}}{m!}$$

$$\hat{\mu}_b = \frac{m_{meas.}}{b_{CR}}$$

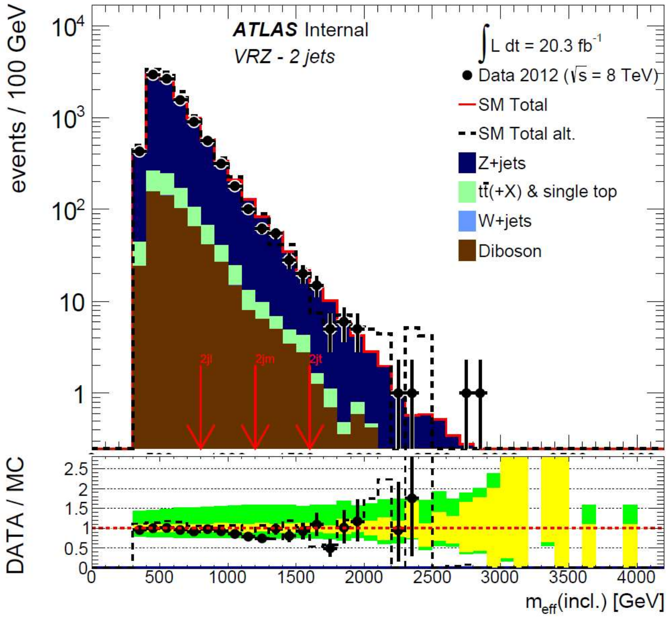
There should also be also an uncertainty on b and b_{CR} which should be highly correlated.

Zνν background prediction

Zll+2jets

$$N^{pred}_{Z\nu\nu} = N^{MC}_{Z\nu\nu} \times \frac{N^{data}_{Zll}}{N^{MC}_{Zll}}$$

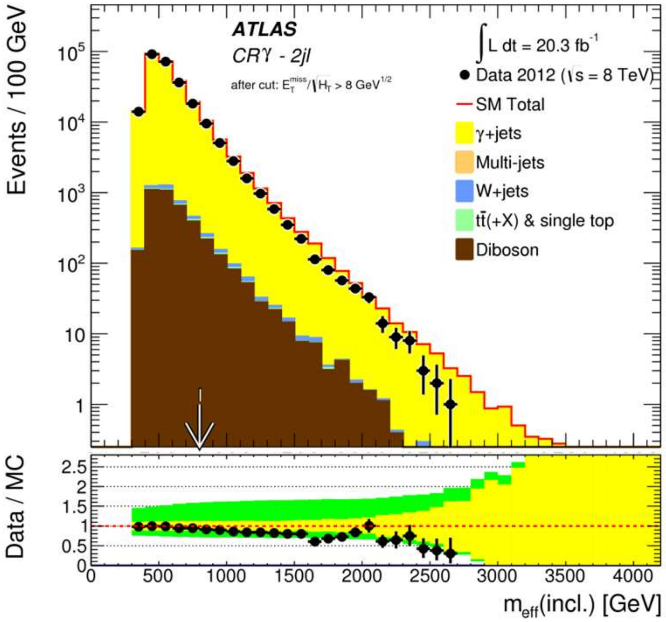
- Renormalize the MC to data in dedicated control regions
- Control regions are orthogonal to the SR (by inverting cuts) but have kinematical cuts close to SR
- Systematic uncertainties which are correlated between CR and SR largely cancel out in the transfer factor
- Zll are statistically limited



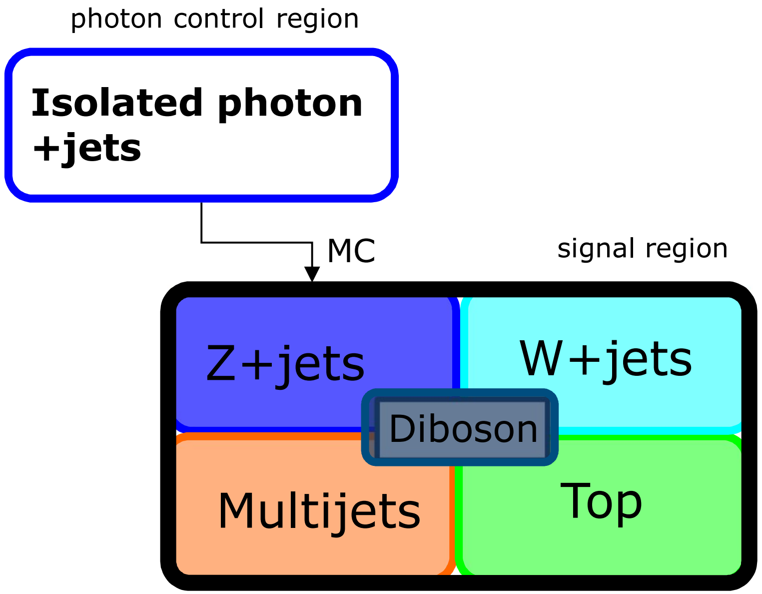
γ+2jets

$$N^{pred}_{Z\nu\nu} = N^{MC}_{Z\nu\nu} \times \frac{N^{data}_{\gamma+jets}}{N^{MC}_{\gamma+jets}}$$

- The process γ+jets has much larger statistics
- But massless boson and different couplings
- Transfer factors theoretically understood at the 5-10% level



Background estimation strategy



photon control region

Isolated photon +jets

MC

signal region

Z+jets

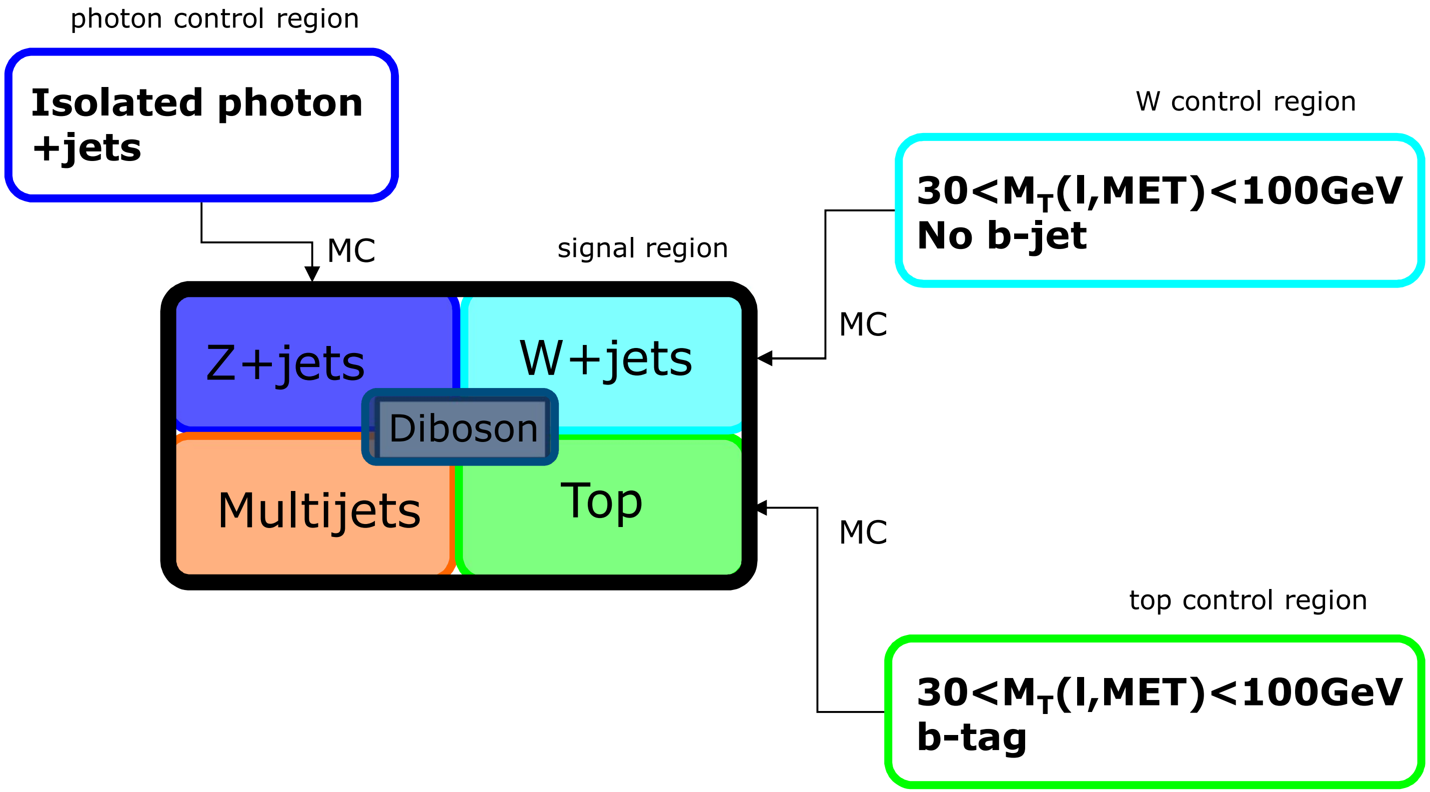
W+jets

Diboson

Multijets

Top

Background estimation strategy



photon control region

Isolated photon +jets

MC

signal region

Z+jets

W+jets

Diboson

Multijets

Top

W control region

$30<M_T(l,MET)<100GeV$ No b-jet

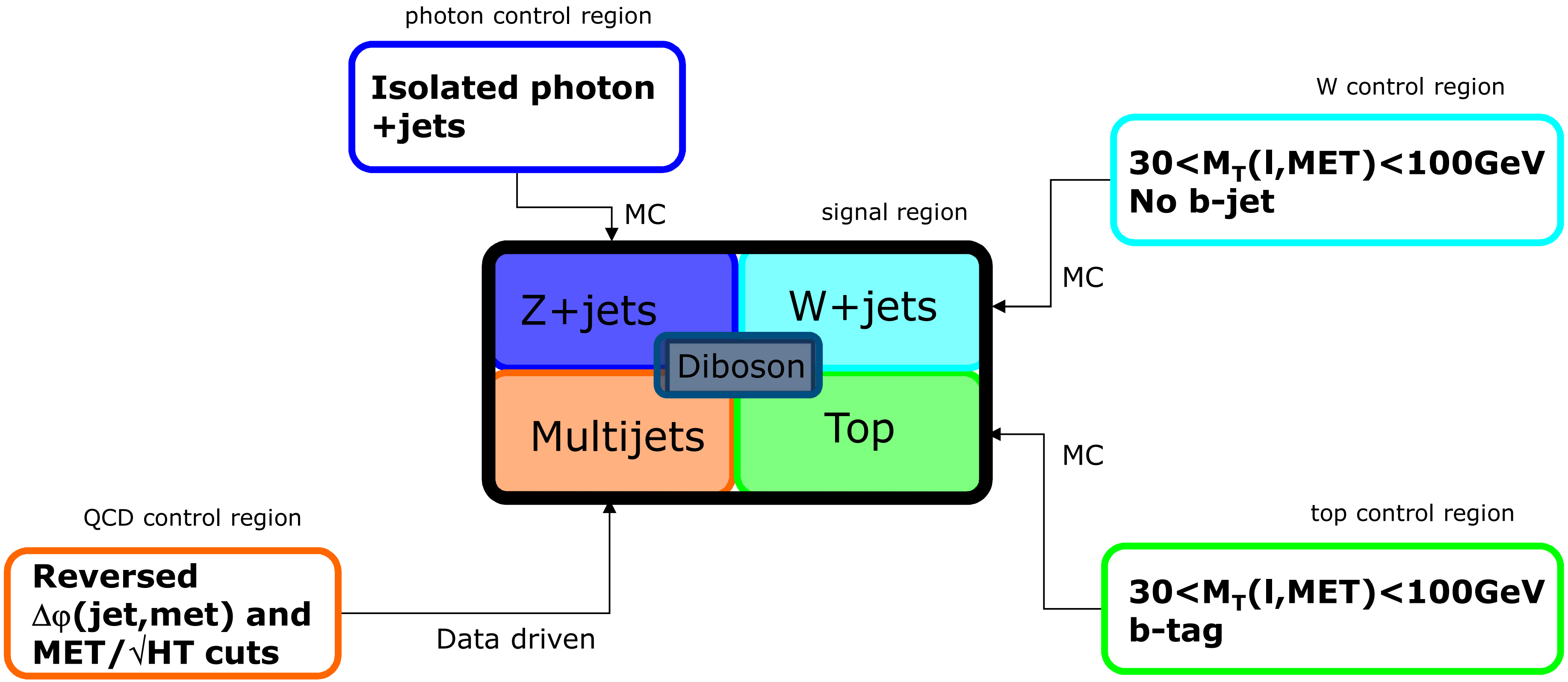
MC

MC

top control region

$30<M_T(l,MET)<100GeV$ b-tag

Background estimation strategy



photon control region

Isolated photon +jets

MC

signal region

Z+jets

W+jets

Diboson

Multijets

Top

W control region

$30<M_T(l,MET)<100$GeV
No b-jet

MC

MC

top control region

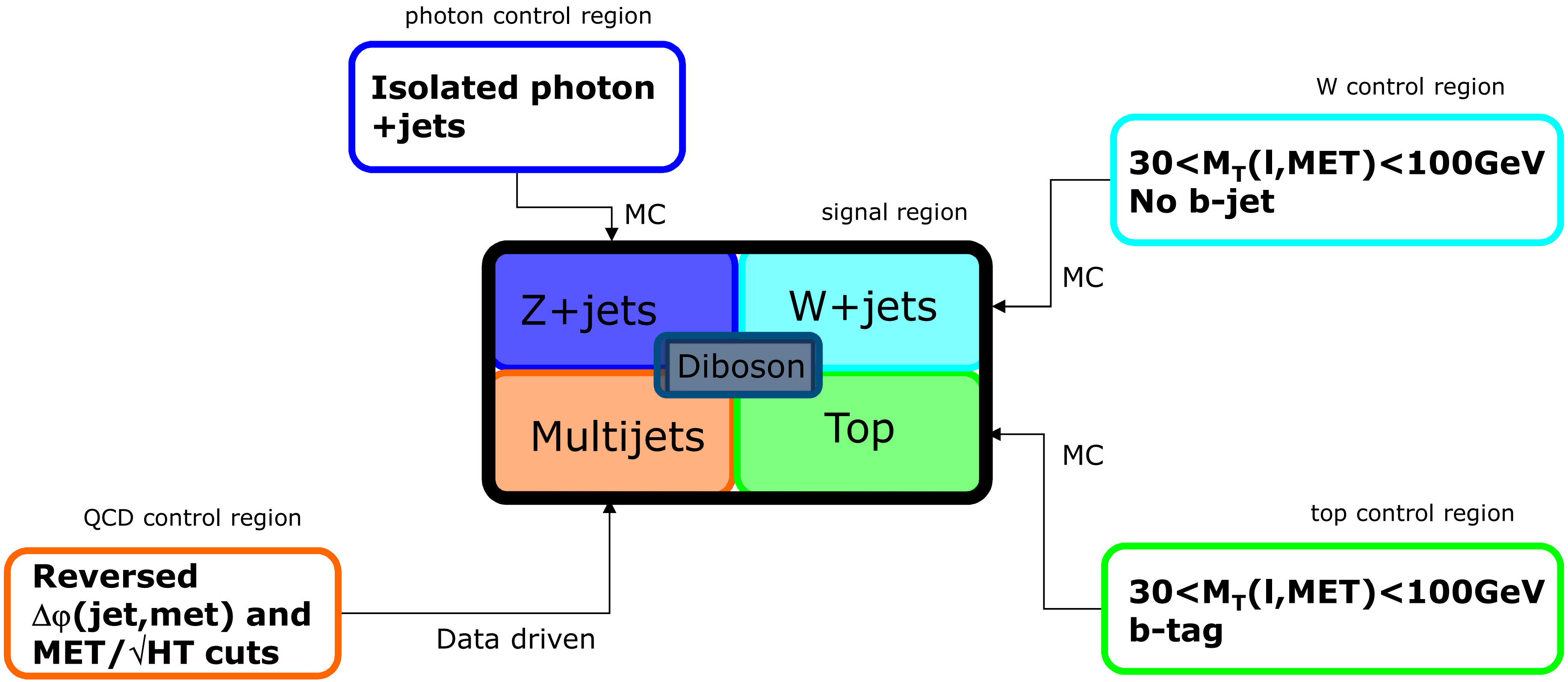
$30<M_T(l,MET)<100$GeV
b-tag

QCD control region

Reversed
$\Delta\varphi$(jet,met) and
MET/$\sqrt{}$HT cuts

Data driven

Background estimation strategy



photon control region

Isolated photon +jets

MC

signal region

Z+jets

W+jets

Diboson

Multijets

Top

W control region

$30<M_T(l,MET)<100GeV$
No b-jet

MC

MC

top control region

$30<M_T(l,MET)<100GeV$
b-tag

QCD control region

Reversed
$\Delta\varphi$(jet,met) and
MET/$\sqrt{}$HT cuts

Data driven

Fitting strategy

A global likelihood fit for the normalization of each background from the 4 control regions is simultaneously performed separately for each signal region.

- Background cross contamination in control regions automatically taken into account

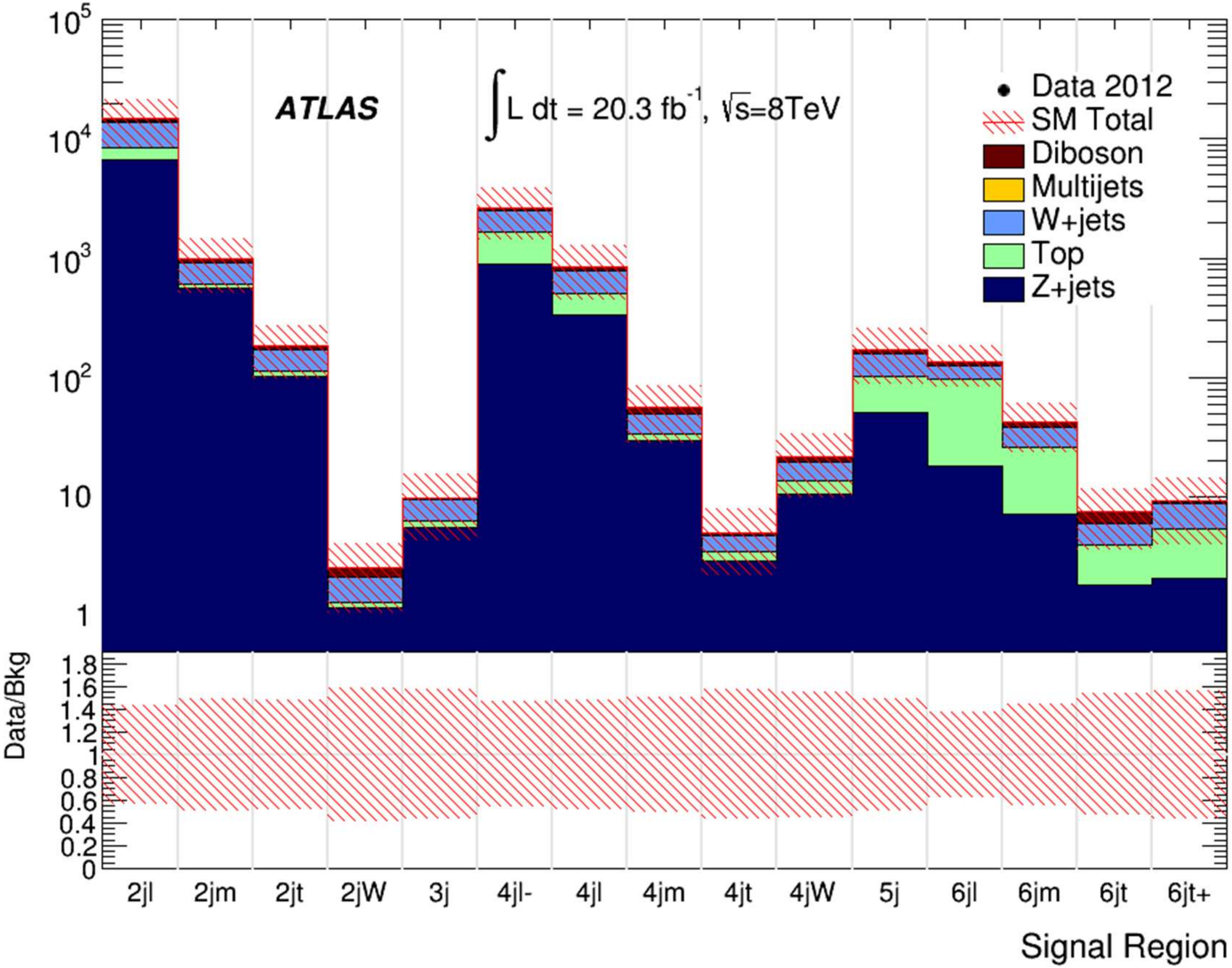
$$L(\boldsymbol{n},\boldsymbol{\theta}^0|\boldsymbol{\mu},\boldsymbol{s},\boldsymbol{b},\boldsymbol{\theta}) = P(n_s|\lambda_s(\boldsymbol{\mu},\boldsymbol{s},\boldsymbol{b},\boldsymbol{\theta}))) \times \prod_{r\in CRs} P(n_r|\lambda_r(\boldsymbol{\mu},\boldsymbol{s},\boldsymbol{b},\boldsymbol{\theta})) \times \prod_{j\in SUs} G(\theta_j^0,\theta_j)$$

avec $$\lambda_i(\boldsymbol{\mu},s_i,\mathbf{b_i},\boldsymbol{\theta}) = s_i(\boldsymbol{\theta})\cdot\mu_s + \sum_{j\in bkg} b_{i,j}(\boldsymbol{\theta})\cdot\mu_j$$

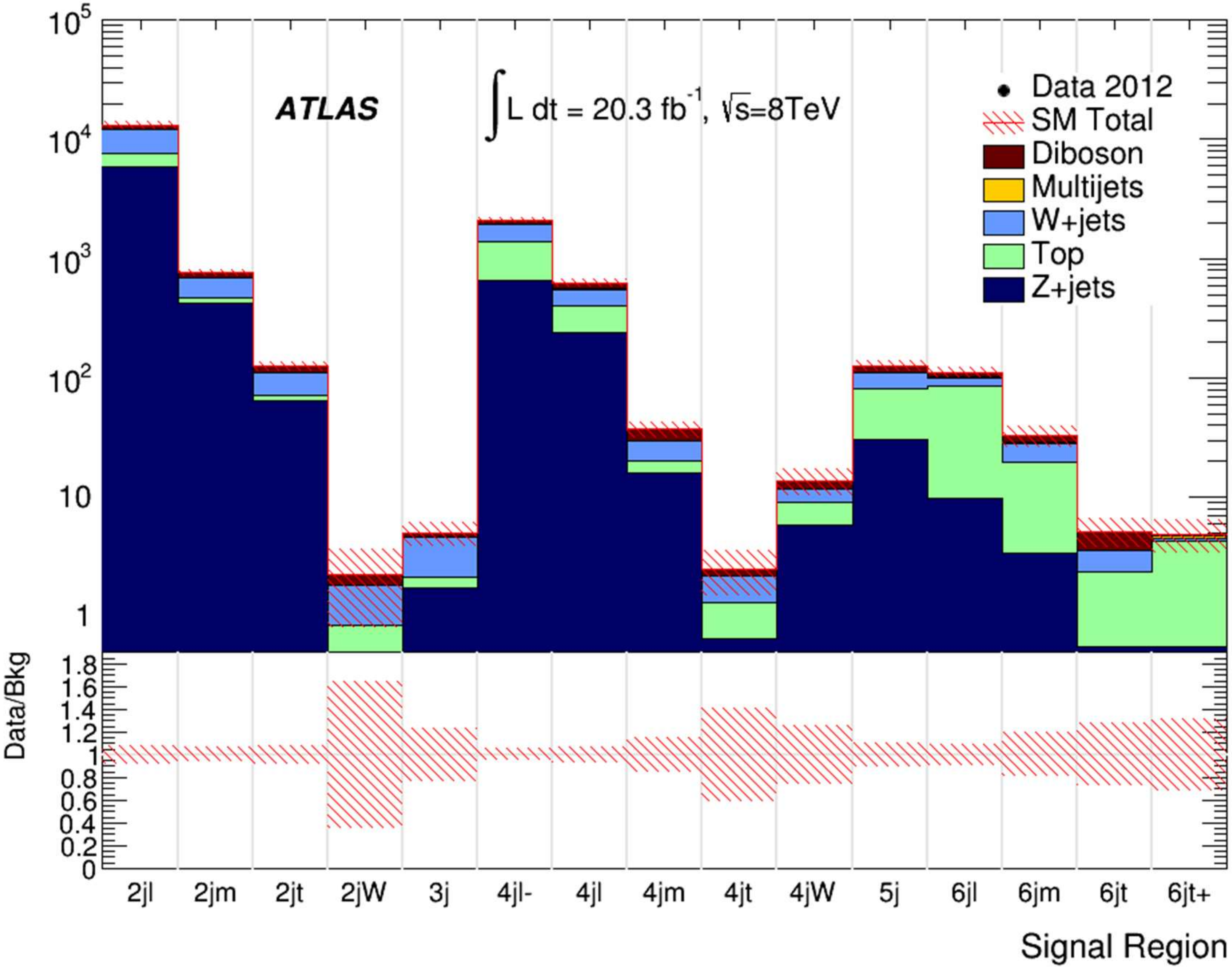
Systematics:

- Cancellation of the main systematics thanks to semi data driven technique
- JES, JER: 1 to 12%
- Theory: 5 to 20%
- Statistics in CR: 1 to 30%

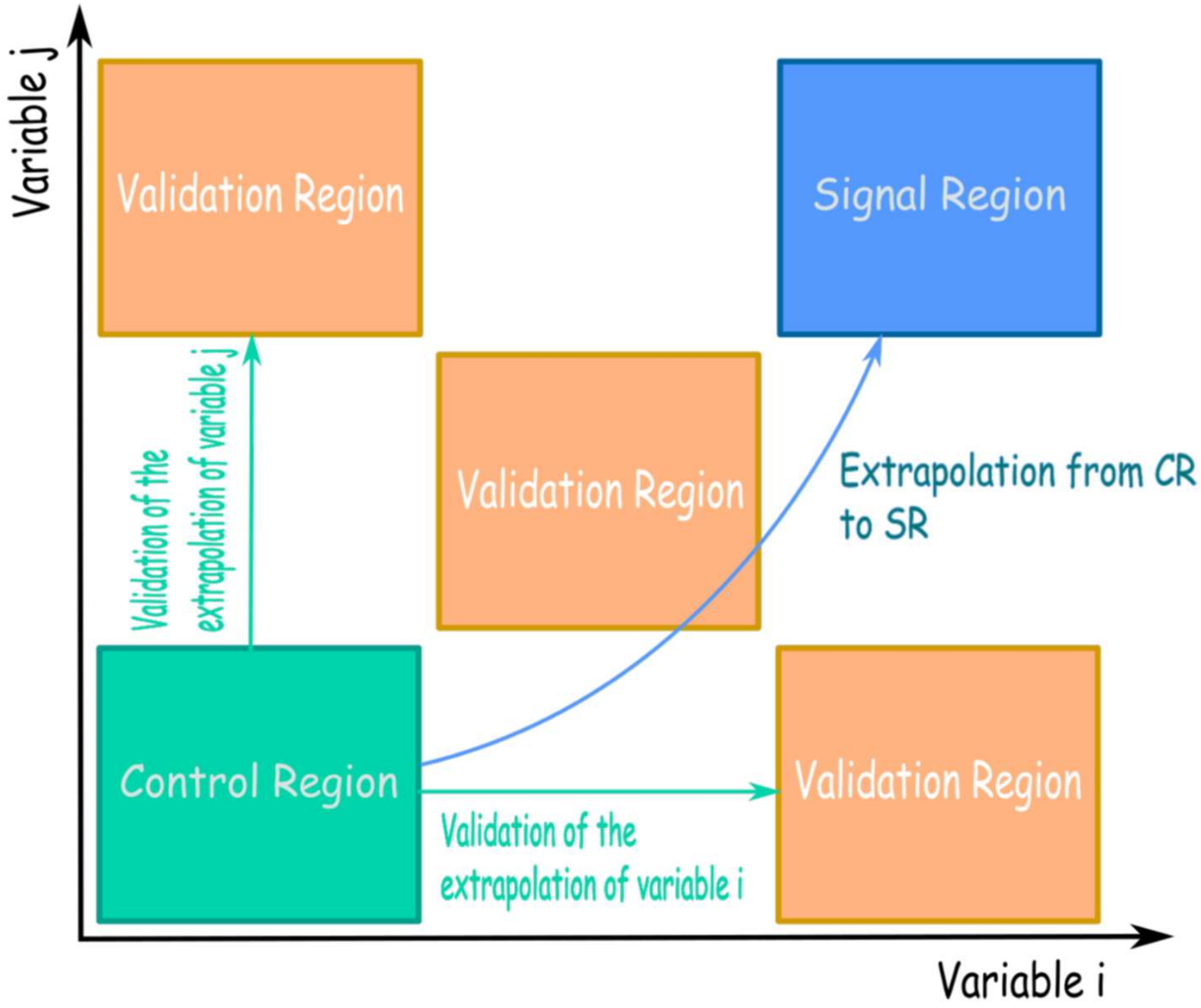
MC background prediction



Fitted background prediction



Validation regions



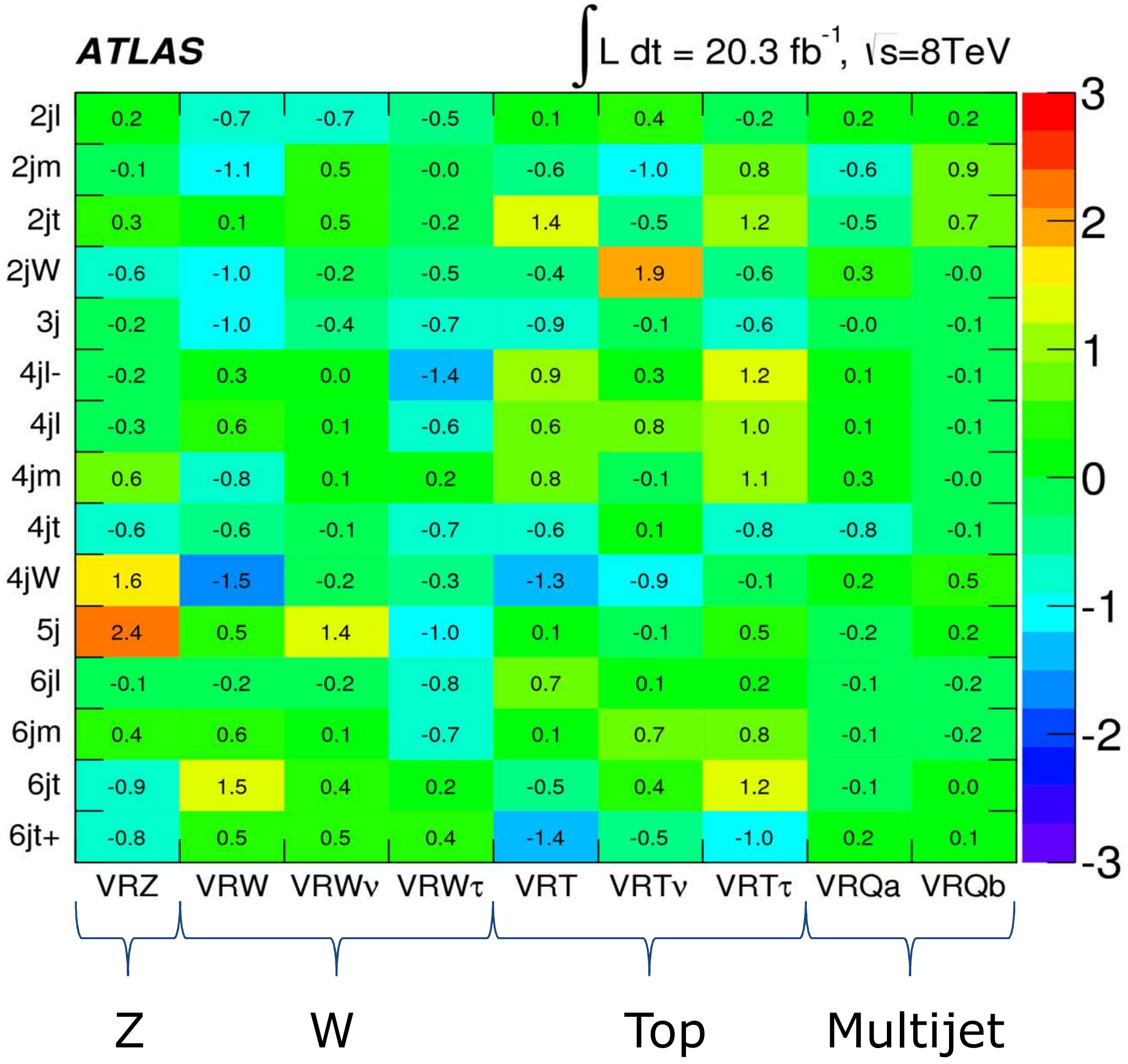
Validation regions

Several validation regions were designed to validate the background prediction

Pull:

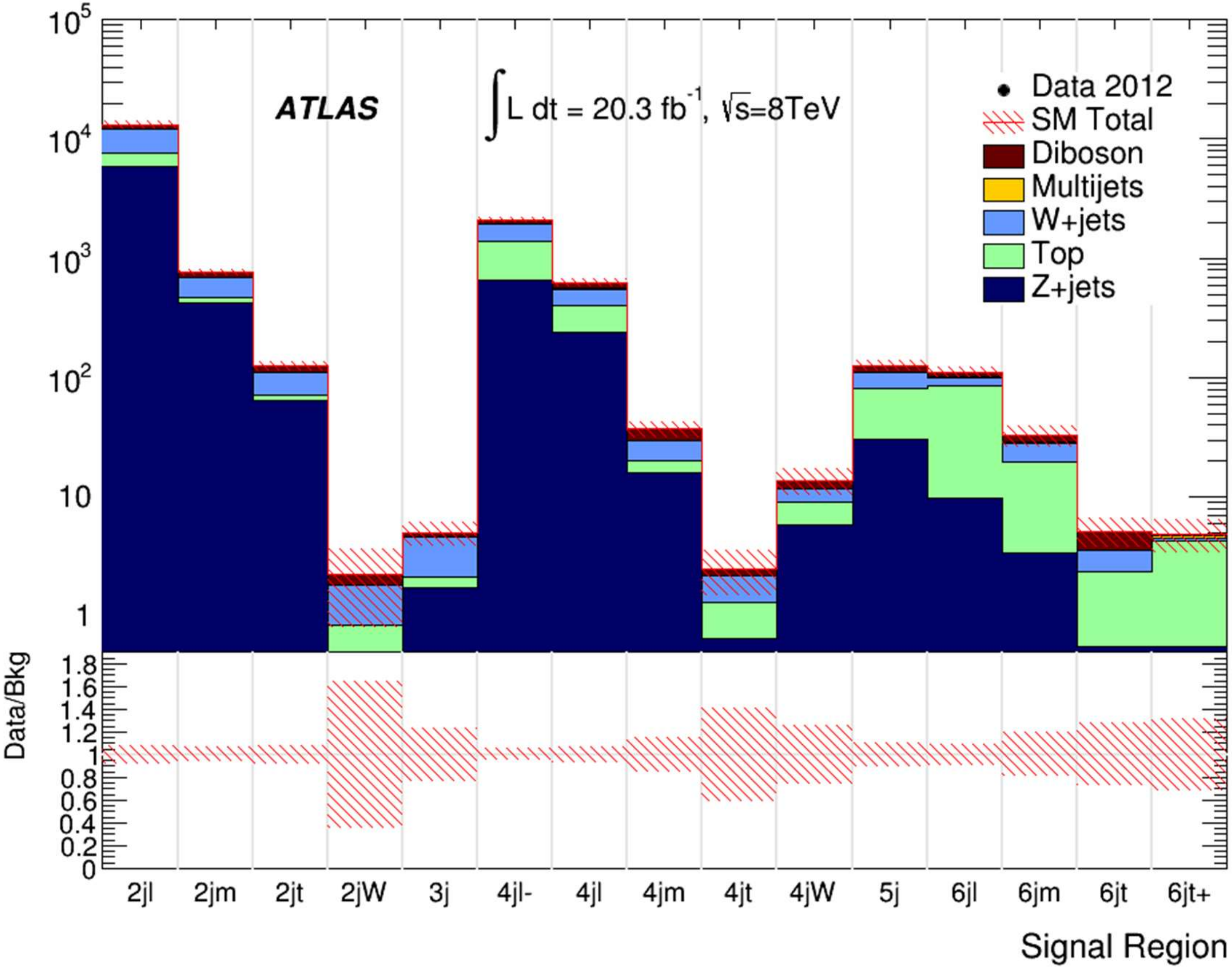
$$\frac{n_{obs}-n_{pred}}{\sigma}$$

Good agreement between data and the prediction!

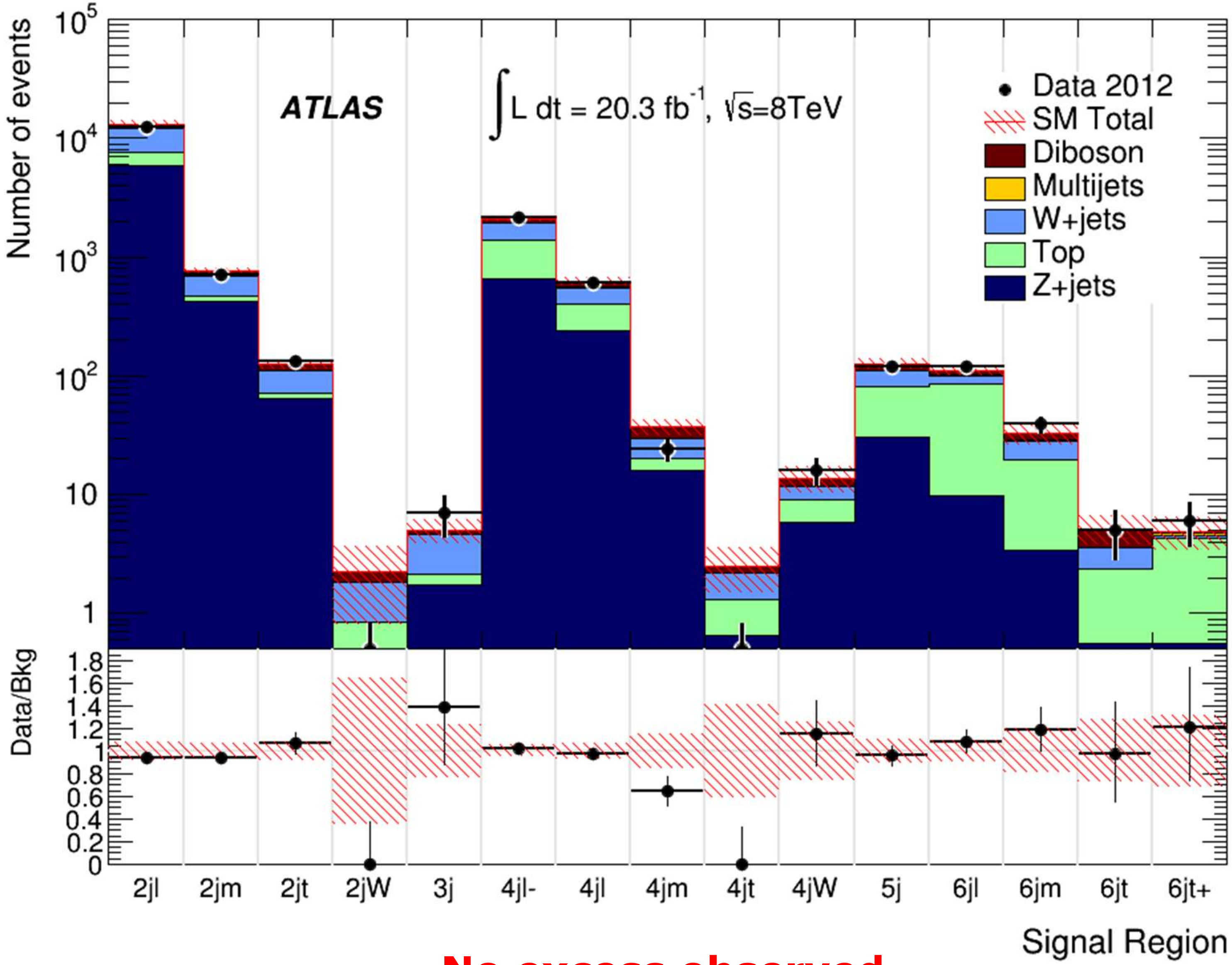


	VRZ	VRW	VRWν	VRWτ	VRT	VRTν	VRTτ	VRQa	VRQb
2jl	0.2	-0.7	-0.7	-0.5	0.1	0.4	-0.2	0.2	0.2
2jm	-0.1	-1.1	0.5	-0.0	-0.6	-1.0	0.8	-0.6	0.9
2jt	0.3	0.1	0.5	-0.2	1.4	-0.5	1.2	-0.5	0.7
2jW	-0.6	-1.0	-0.2	-0.5	-0.4	1.9	-0.6	0.3	-0.0
3j	-0.2	-1.0	-0.4	-0.7	-0.9	-0.1	-0.6	-0.0	-0.1
4jl-	-0.2	0.3	0.0	-1.4	0.9	0.3	1.2	0.1	-0.1
4jl	-0.3	0.6	0.1	-0.6	0.6	0.8	1.0	0.1	-0.1
4jm	0.6	-0.8	0.1	0.2	0.8	-0.1	1.1	0.3	-0.0
4jt	-0.6	-0.6	-0.1	-0.7	-0.6	0.1	-0.8	-0.8	-0.1
4jW	1.6	-1.5	-0.2	-0.3	-1.3	-0.9	-0.1	0.2	0.5
5j	2.4	0.5	1.4	-1.0	0.1	-0.1	0.5	-0.2	0.2
6jl	-0.1	-0.2	-0.2	-0.8	0.7	0.1	0.2	-0.1	-0.2
6jm	0.4	0.6	0.1	-0.7	0.1	0.7	0.8	-0.1	-0.2
6jt	-0.9	1.5	0.4	0.2	-0.5	0.4	1.2	-0.1	0.0
6jt+	-0.8	0.5	0.5	0.4	-1.4	-0.5	-1.0	0.2	0.1

Fitted background prediction

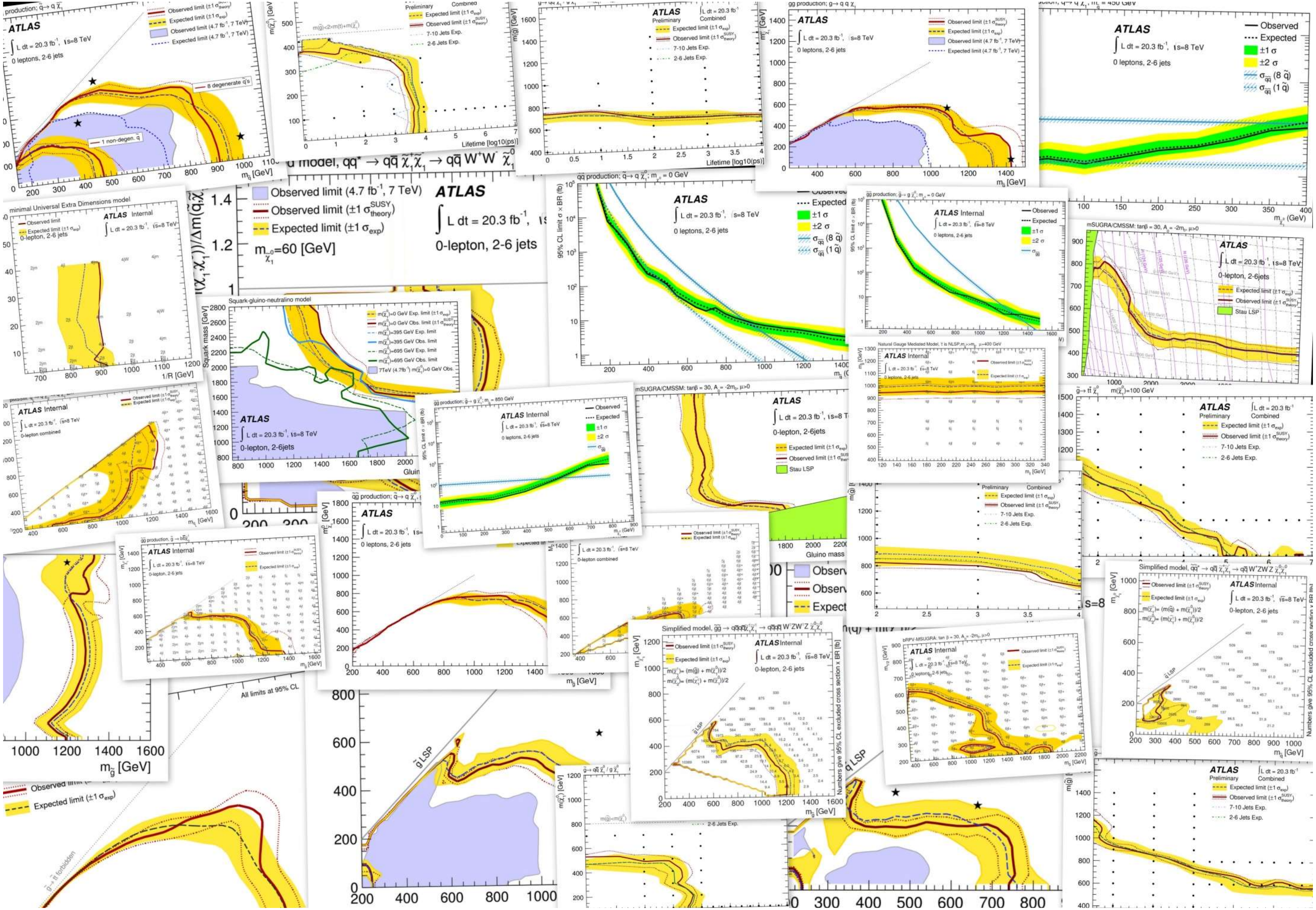


Results

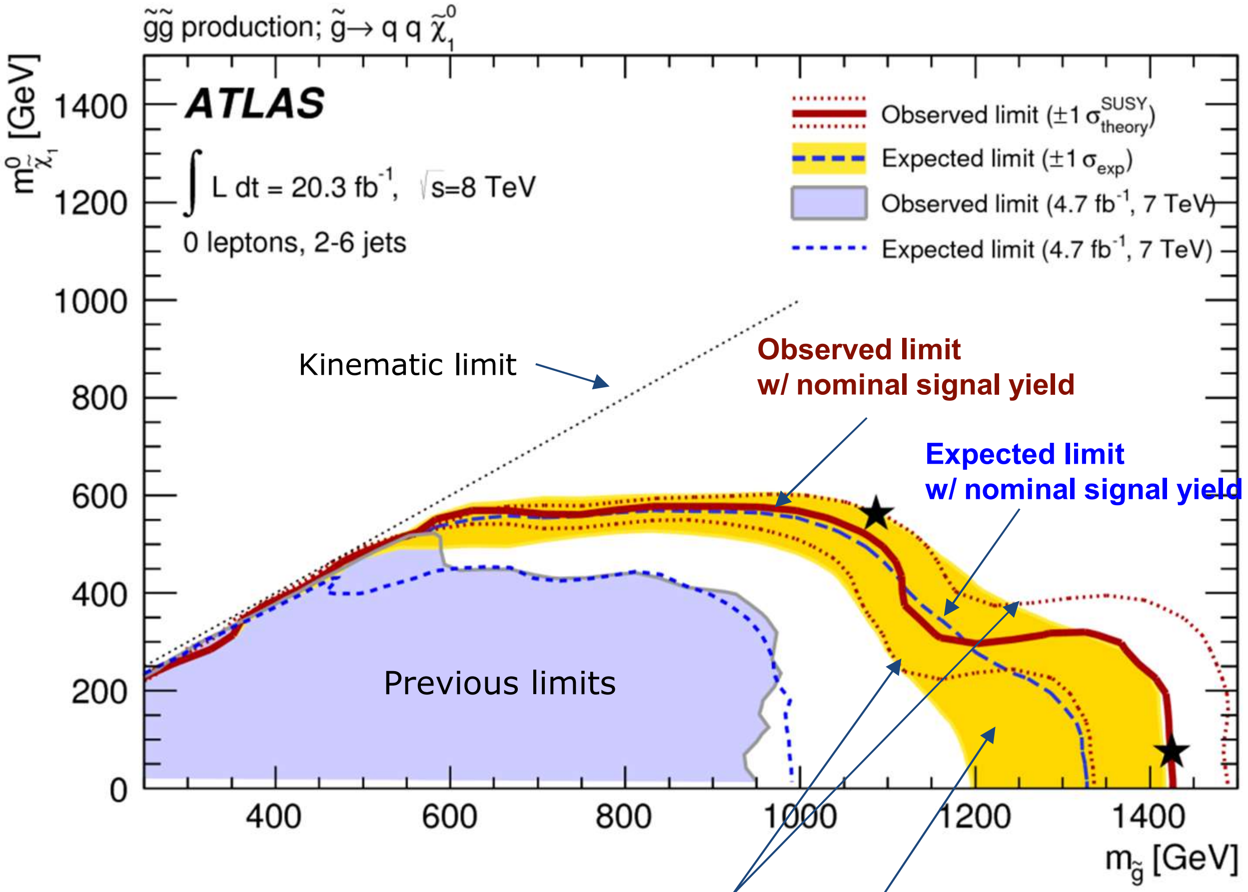


No excess observed

Limits


ATLAS
∫ L dt = 20.3 fb⁻¹, √s=8 TeV
0 leptons, 2-6 jets
Observed limit (±1 σ_theory^SUSY)
Expected limit (±1 σ_exp)
Observed limit (4.7 fb⁻¹, 7 TeV)
Expected limit (4.7 fb⁻¹, 7 TeV)
8 degenerate q̃'s
1 non-degen. q̃
m_g̃ [GeV]
Lifetime [log10(ps)]
Preliminary
Combined
7-10 Jets Exp.
2-6 Jets Exp.
Observed
Expected
±1 σ
±2 σ
σ_qq̃ (8 q̃)
σ_qq̃ (1 q̃)
m_χ̃₁⁰=60 [GeV]
0-lepton, 2-6 jets
minimal Universal Extra Dimensions model
1/R [GeV]
Squark-gluino-neutralino model
Squark mass [GeV]
Gluino mass
7TeV (4.7fb⁻¹) m(χ̃₁⁰)=0 GeV Obs.
95% CL limit σ × BR (fb)
mSUGRA/CMSSM: tanβ = 30, A₀ = -2m₀, μ>0
Stau LSP
Natural Gauge Mediated Model
Simplified model, g̃g̃ → qq̄qq̄ χ̃₁^± χ̃₁^± → qq̄qq̄ W^±ZW^±Z χ̃₁⁰χ̃₁⁰
Numbers give 95% CL excluded cross section x BR [fb]
bRPV-mSUGRA: tan β = 30, A₀ = -2m₀, μ>0
All limits at 95% CL
g̃ LSP
g̃→ tt̄ forbidden
ATLAS Internal
0-lepton combined

Interpretation



Kinematic limit

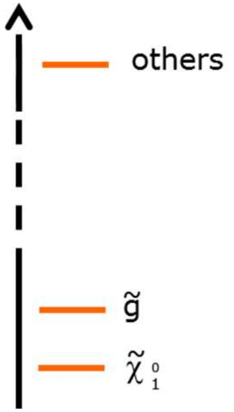
Observed limit
w/ nominal signal yield

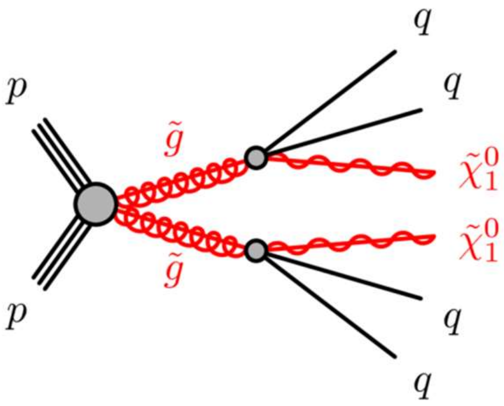
Expected limit
w/ nominal signal yield

Previous limits

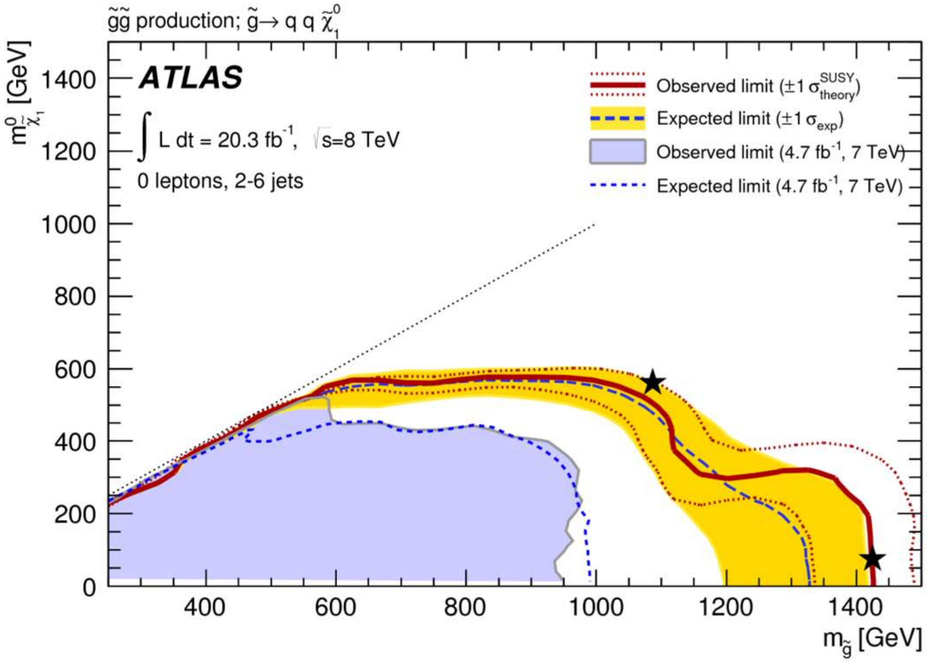
Observed limit w/ ±1σ theory shifted signal yield

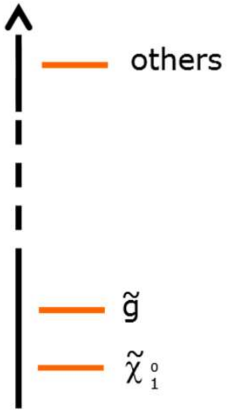
±1σexp uncertainty on the
Expected limit

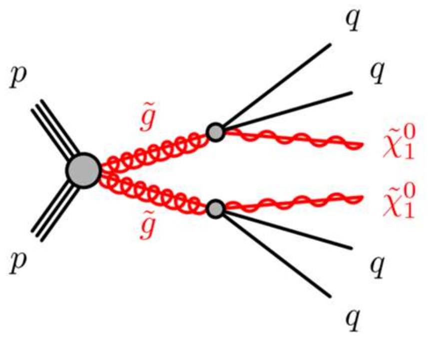


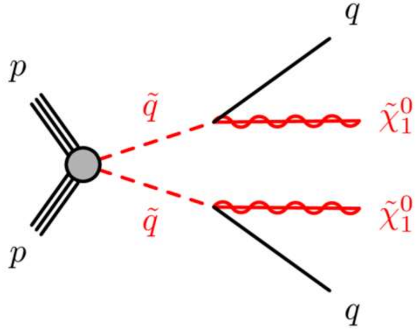


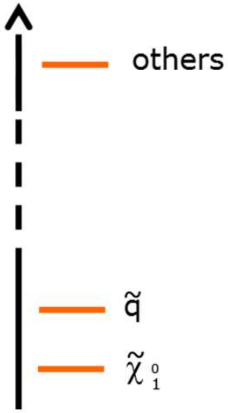
Interpretation

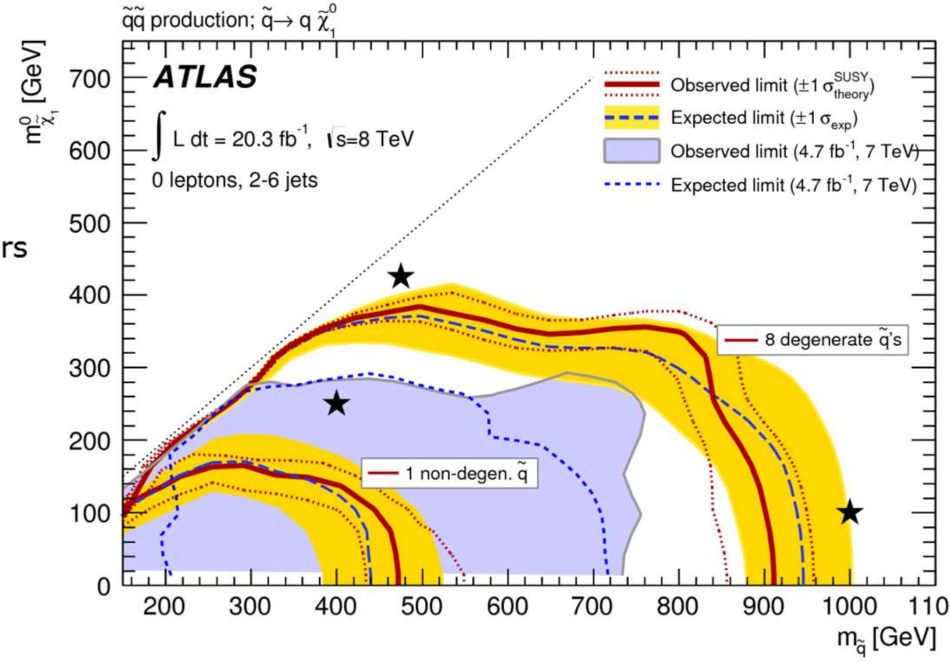




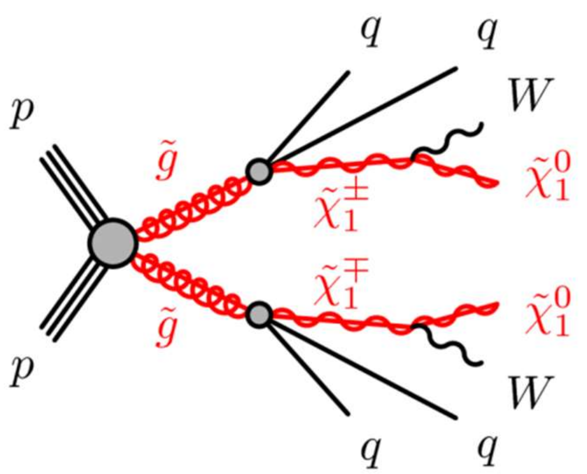


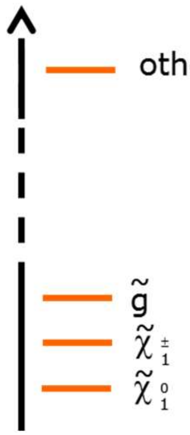




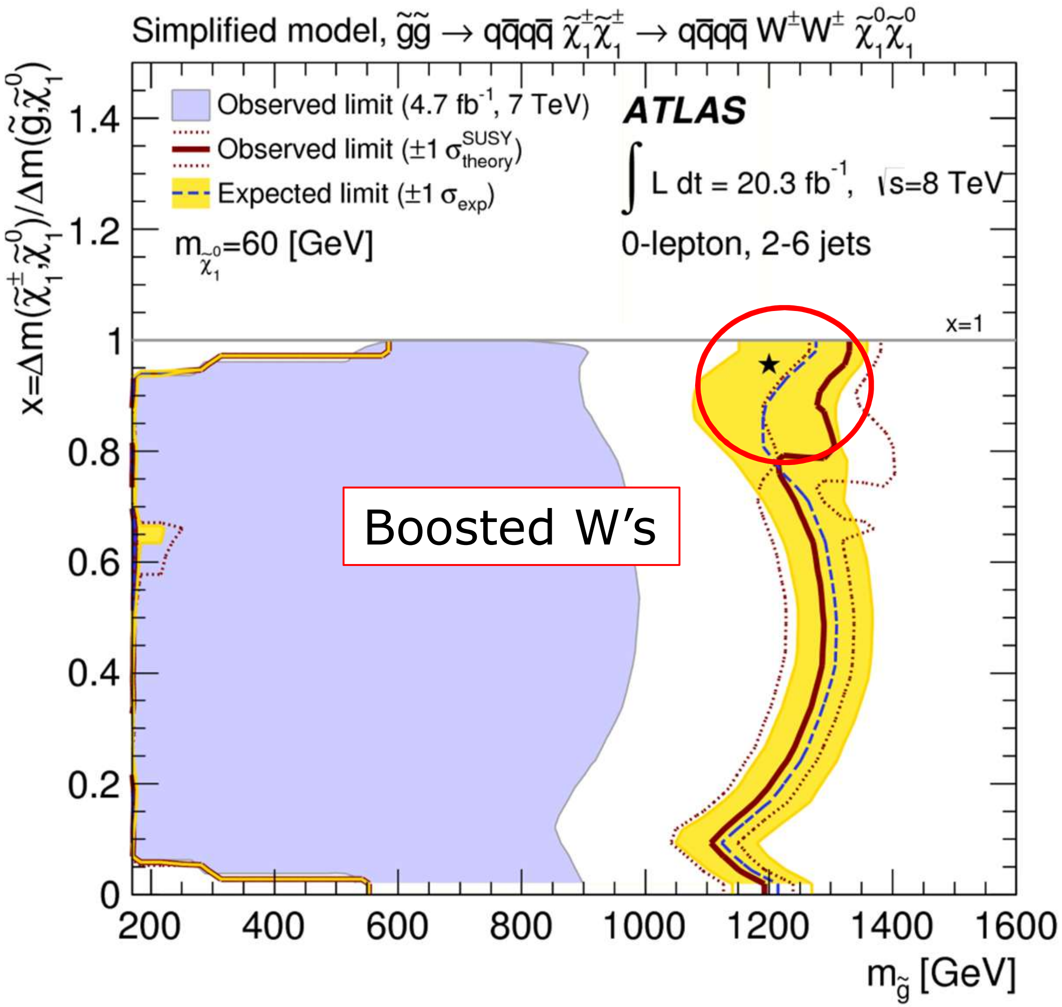


Interpretation



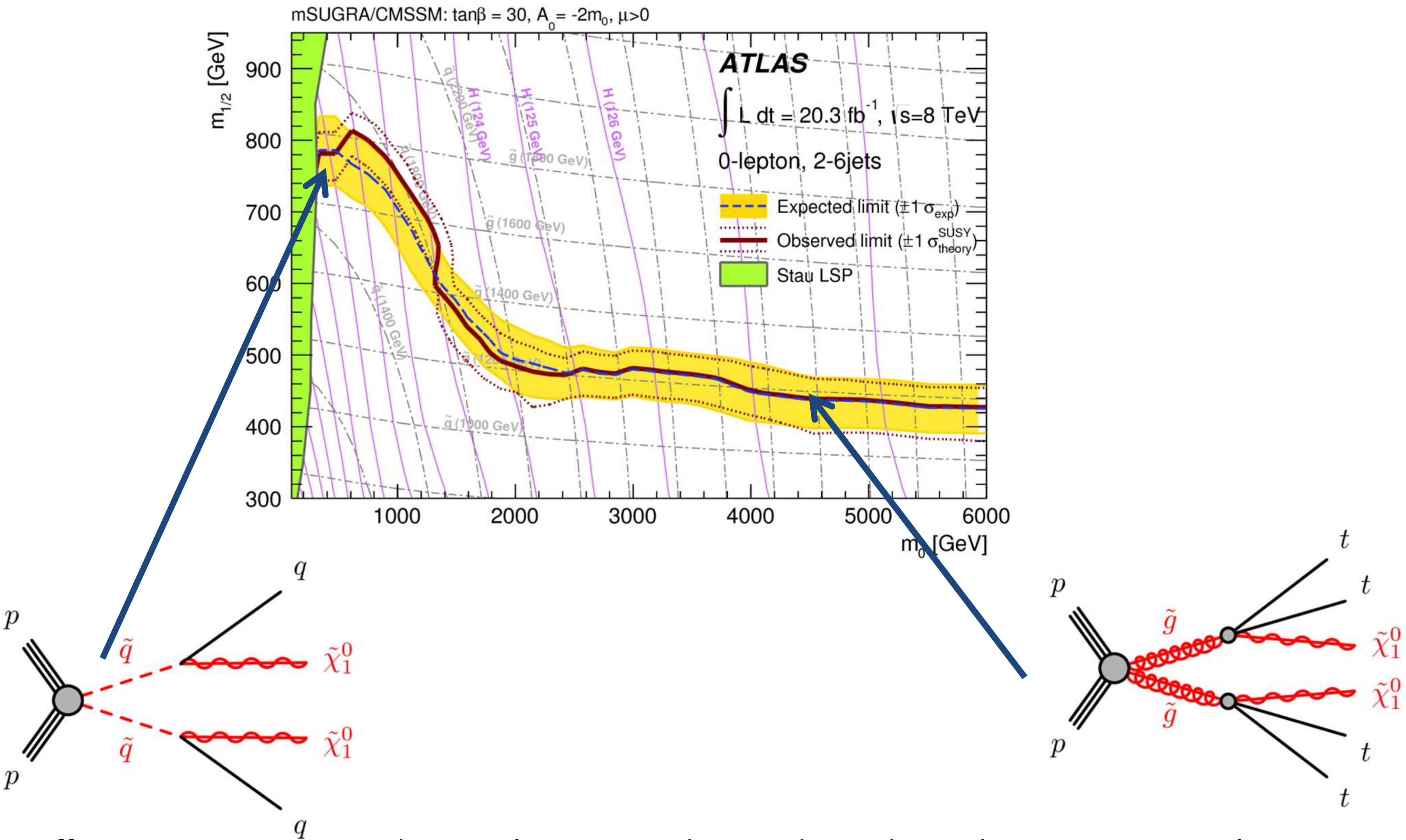


$$x=\Delta m(\tilde{\chi}_1^{\pm},\tilde{\chi}_1^0)/\Delta m(\tilde{g},\tilde{\chi}_1^0)$$



Boosted W’s

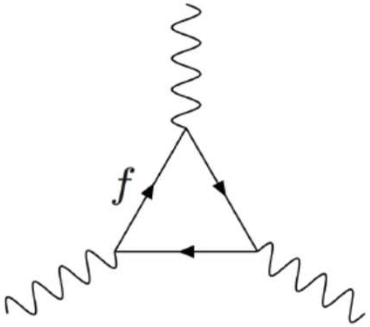
mSugra



Different processes contribute, relative contribution depends on the parameters values

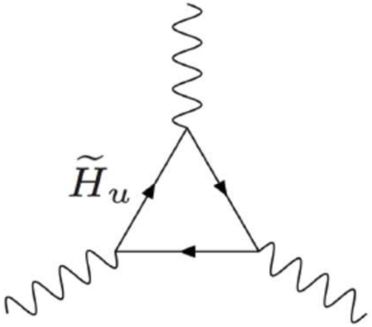
Additional Higgs bosons

Why 2 Higgs doublets?



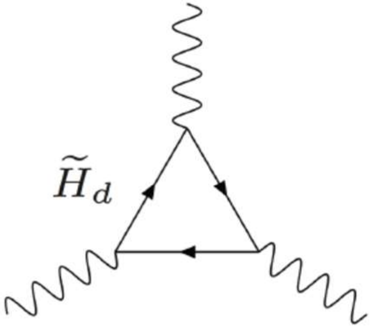
$$\sum_{SM\ \ fermions} Y_f^3 = 0$$

anomaly cancellation
Miracle of the standard model



$$\left(\frac{1}{2}\right)^3$$

Now in SUSY we got at least
one new fermion, the Higgsino



$$\left(-\frac{1}{2}\right)^3$$

Need a Higgsino with
Y=-1/2 to avoid anomalies

This new anomaly cancels if and only if both the $\tilde{H}_u$ and $\tilde{H}_d$ Higgsinos exist.

The masses of the up-quarks $(\mathrm{u,c,t})$ arise from coupling with H_u

The masses of the down-quarks $(\mathrm{d,s,b})$ arise from coupling with H_d

2 Higgs doublets
needed!

Tl

C. Clément

MSSM Higgs sector

Higgs sector in SUSY contains two scalar doublets ⇒ 5 Higgs

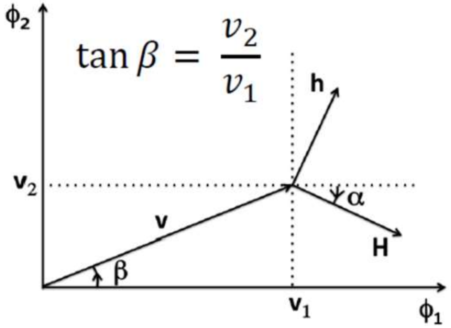
- neutral, CP-even: h, H
- neutral, CP-odd: A
- charged H^+,H^-

$$v^2 = v_u^2 + v_d^2 \qquad \tan\beta = \frac{v_u}{v_d}$$

At tree level two free parameters: m_A and tanβ

$$\begin{aligned}
m_{H^\pm}^2 &= m_A^2 + m_W^2 \\
m_{H,\,h}^2 &= \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right) \\
\tan\alpha &= \frac{-(m_A^2 + m_Z^2)\sin 2\beta}{(m_Z^2 - m_A^2)\cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}}
\end{aligned}$$

$$\begin{aligned}
H^0 &= \mathrm{Re}(H_\mathrm{d}^2)\cos\alpha + \mathrm{Re}(H_\mathrm{u}^1)\sin\alpha, \\
h^0 &= -\mathrm{Re}(H_\mathrm{d}^2)\sin\alpha + \mathrm{Re}(H_\mathrm{u}^1)\cos\alpha, \\
A^0 &= \mathrm{Im}(H_\mathrm{d}^2)\sin\beta + \mathrm{Im}(H_\mathrm{u}^1)\cos\beta,
\end{aligned}$$



Decoupling limit ($m_A >> m_Z$)

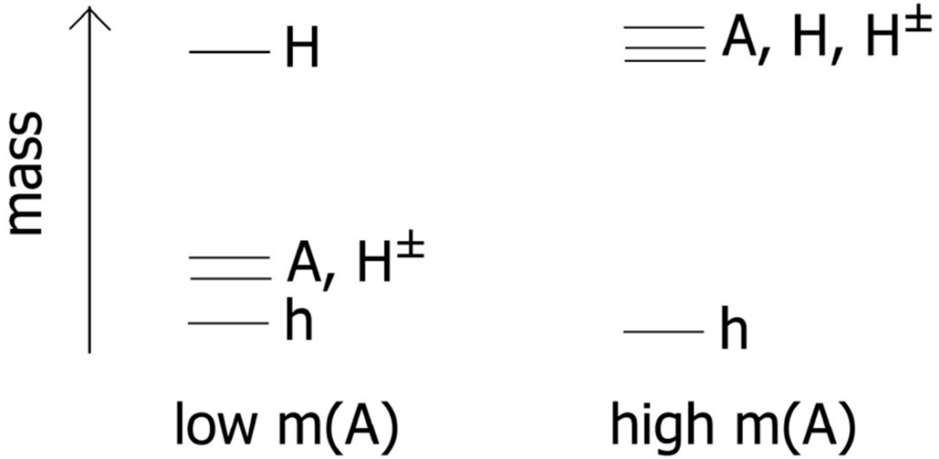
$$m_h^2 \simeq m_Z^2 \cos^2 2\beta \,,$$

$$m_H^2 \simeq m_A^2 + m_Z^2 \sin^2 2\beta \,,$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2 \,,$$

$$\cos^2(\beta - \alpha) \simeq \frac{m_Z^4 \sin^2 4\beta}{4m_A^4} << 1$$

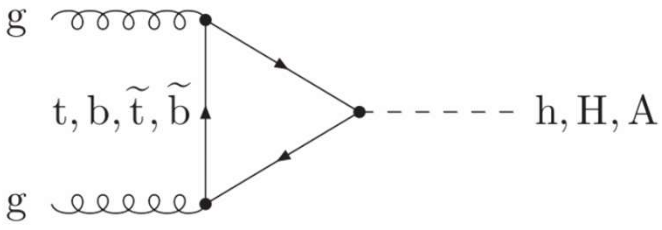
(alignment limit)



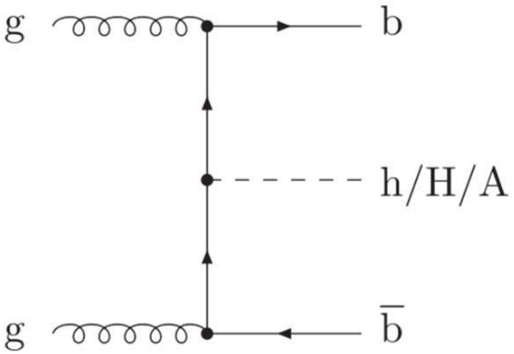
Neutral Higgs production modes

Two main production modes:

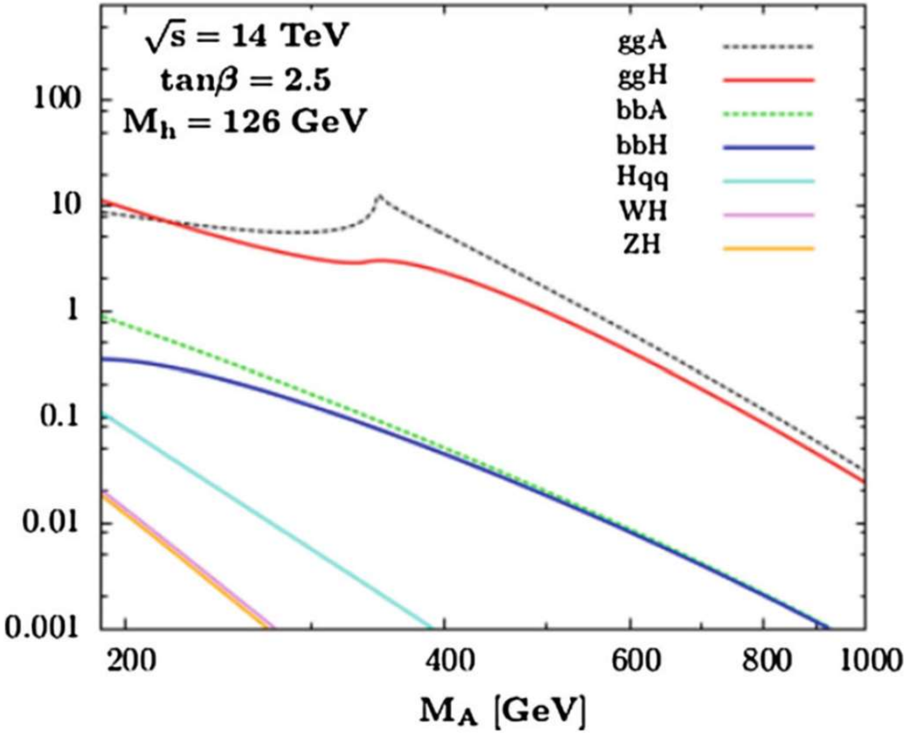
- gg→ ϕ ϕ=(h/H/A)



- bbϕ (enhanced at large tanβ)



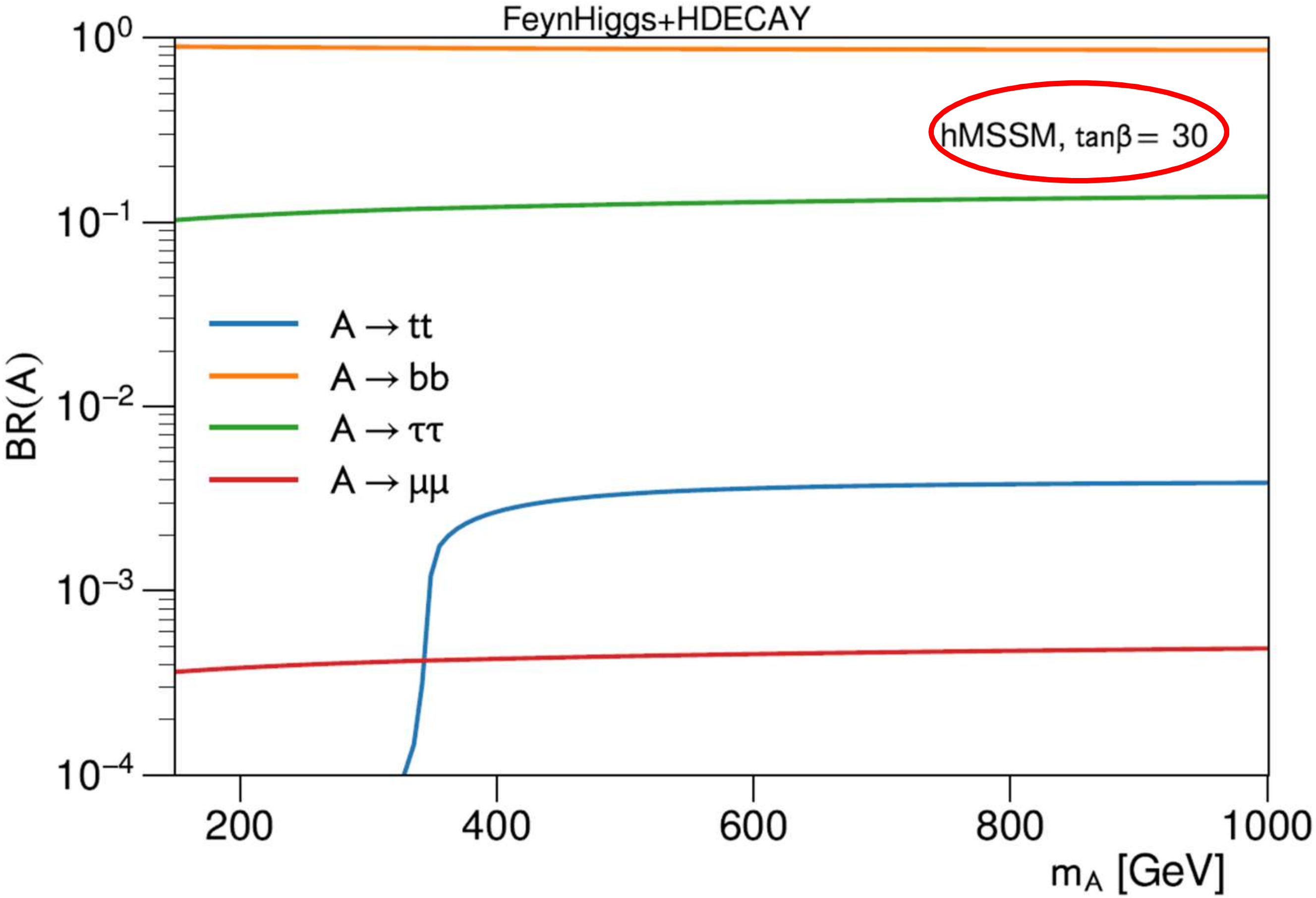
	g_{VV}	g_{uu}	$g_{dd,\ell\ell}$
A	0	$\cot\beta$	$\tan\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$



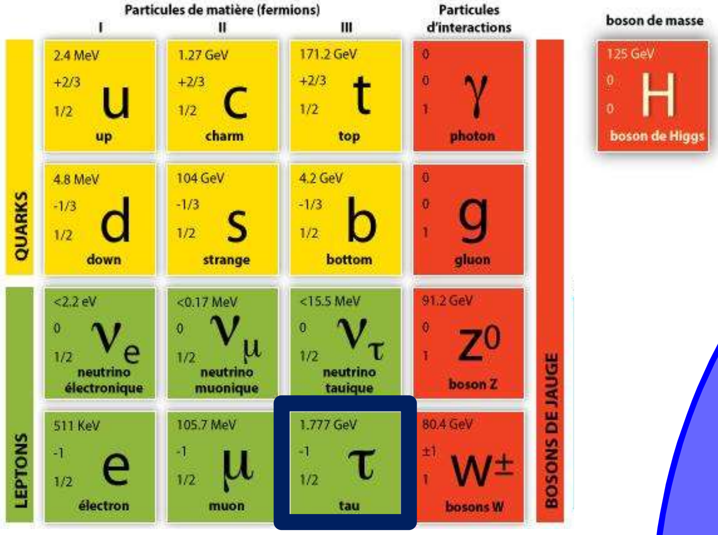
Neutral Higgs decay modes

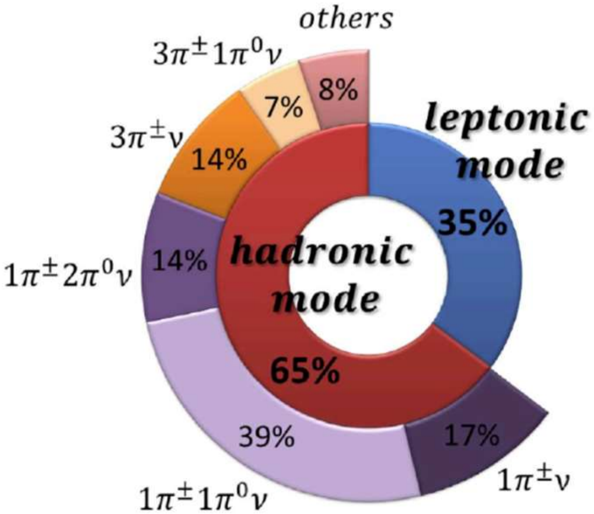
Neutral Higgs ϕ=H,A decay modes at m(A/H) > 350 GeV :

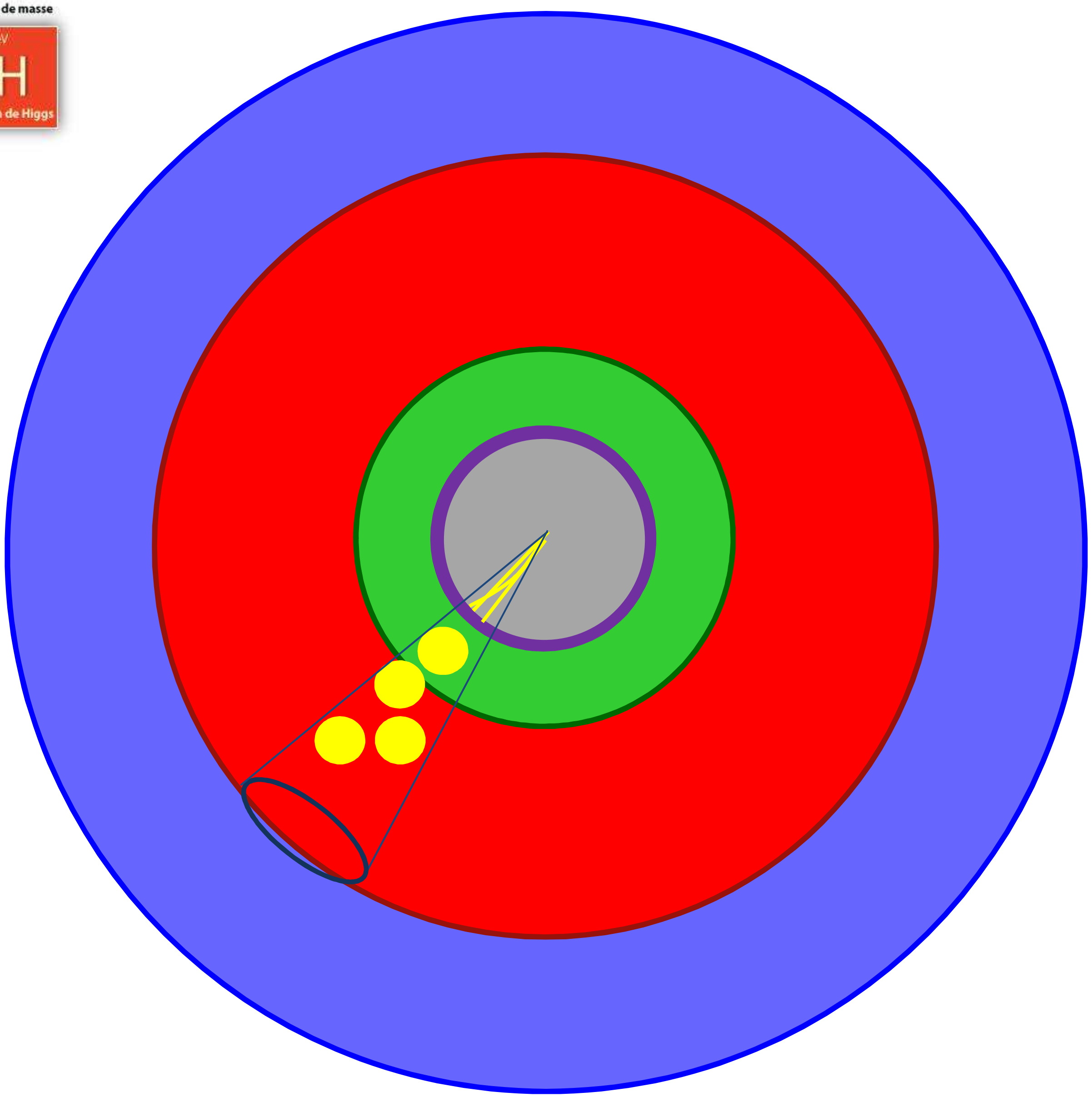
- BR(ϕ→bbar)
- BR(ϕ→ττ)
- BR(ϕ→tt) (enhanced at low tanβ)



τ lepton







Hadronic τ: narrow jet with one or three tracks

Search for A/H$\rightarrow\tau\tau$

Signature: 2 isolated high leptons (e, μ ,τ_h)

- eμ, e τ_h, $\mu\tau_h$, $\tau_h\tau_h$

Background:

- Dominated by τ mis-identification: Multijets, W+jets,…
- Z->$\tau\tau$ is not so large in the high mass region

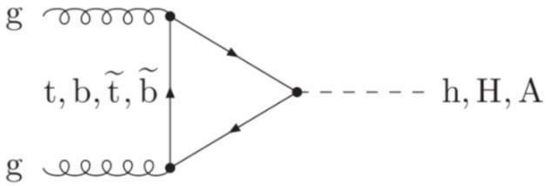
16 categories for sensitivity optimization

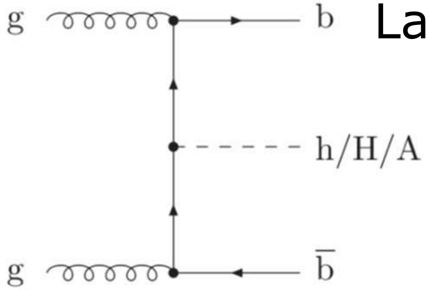
Signal extraction based on:

$$m_T^{\text{tot}} = \sqrt{m_T^2(p_T^{\tau_1}, p_T^{\tau_2}) + m_T^2(p_T^{\tau_1}, p_T^{\text{miss}}) + m_T^2(p_T^{\tau_2}, p_T^{\text{miss}})}$$

$$m_T = \sqrt{2\, p_T\, p_T' \, [1 - \cos(\Delta\phi)]}.$$

Search for A/H→ττ

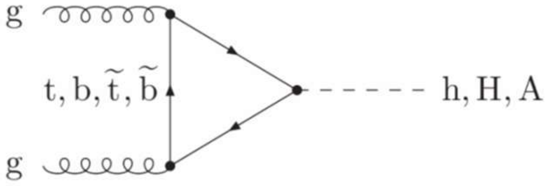


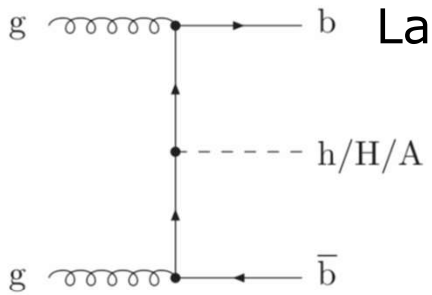


Large tanβ

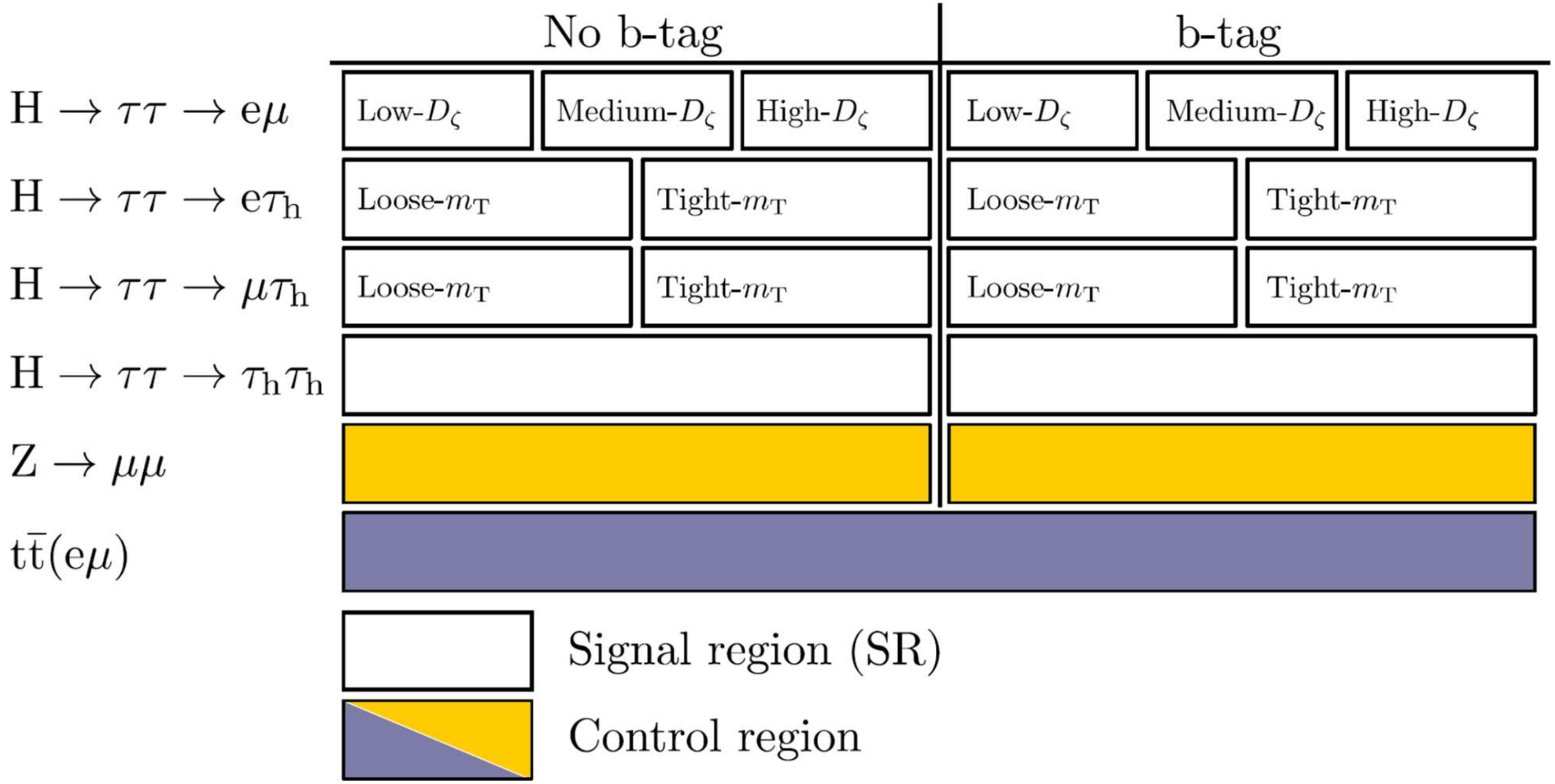
<table>
<tr><th></th><th colspan="6">No b-tag</th><th colspan="6">b-tag</th></tr>
<tr><td>$H \to \tau\tau \to e\mu$</td><td colspan="2">Low-D_ζ</td><td colspan="2">Medium-D_ζ</td><td colspan="2">High-D_ζ</td><td colspan="2">Low-D_ζ</td><td colspan="2">Medium-D_ζ</td><td colspan="2">High-D_ζ</td></tr>
<tr><td>$H \to \tau\tau \to e\tau_h$</td><td colspan="3">Loose-m_T</td><td colspan="3">Tight-m_T</td><td colspan="3">Loose-m_T</td><td colspan="3">Tight-m_T</td></tr>
<tr><td>$H \to \tau\tau \to \mu\tau_h$</td><td colspan="3">Loose-m_T</td><td colspan="3">Tight-m_T</td><td colspan="3">Loose-m_T</td><td colspan="3">Tight-m_T</td></tr>
<tr><td>$H \to \tau\tau \to \tau_h\tau_h$</td><td colspan="6"></td><td colspan="6"></td></tr>
</table>

Search for A/H→ττ





Large tanβ

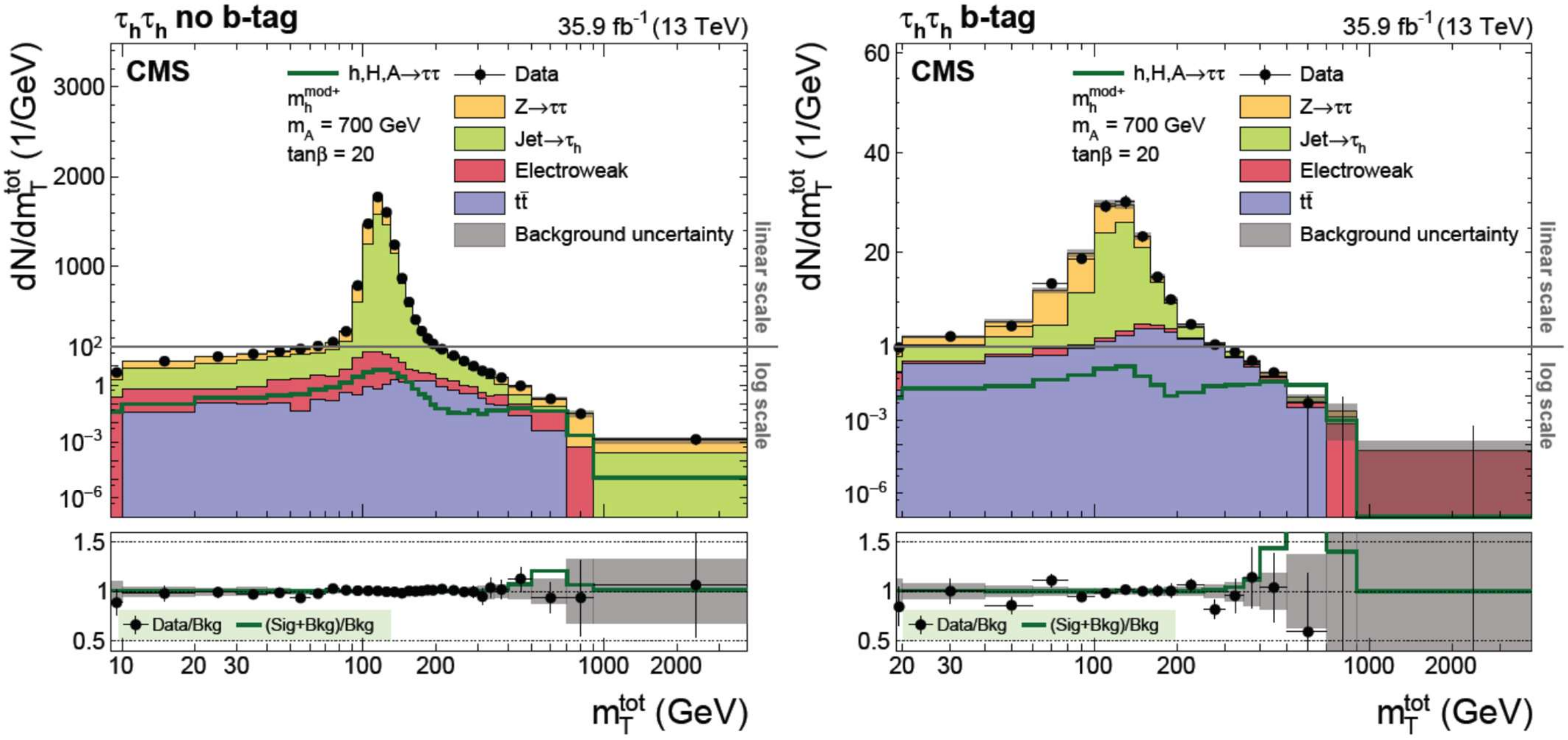


	No b-tag			b-tag		
$H \to \tau\tau \to e\mu$	Low-D_ζ	Medium-D_ζ	High-D_ζ	Low-D_ζ	Medium-D_ζ	High-D_ζ
$H \to \tau\tau \to e\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \mu\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \tau_h\tau_h$	☐			☐		
$Z \to \mu\mu$	🟨			🟨		
$t\bar{t}(e\mu)$	🟪					

☐ Signal region (SR)

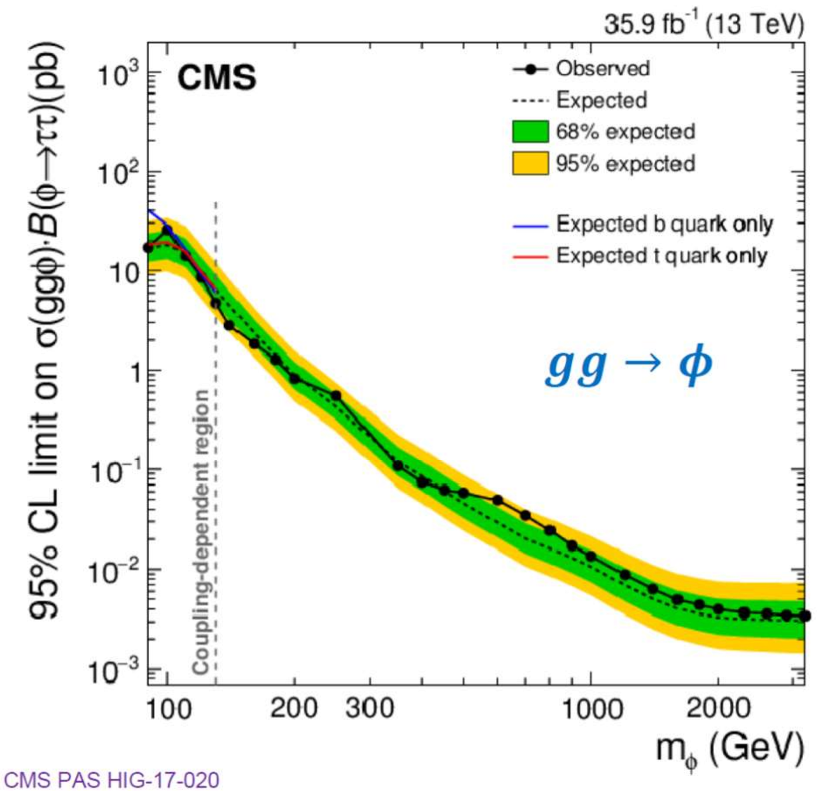
🟪🟨 Control region

Search for A/H→ττ

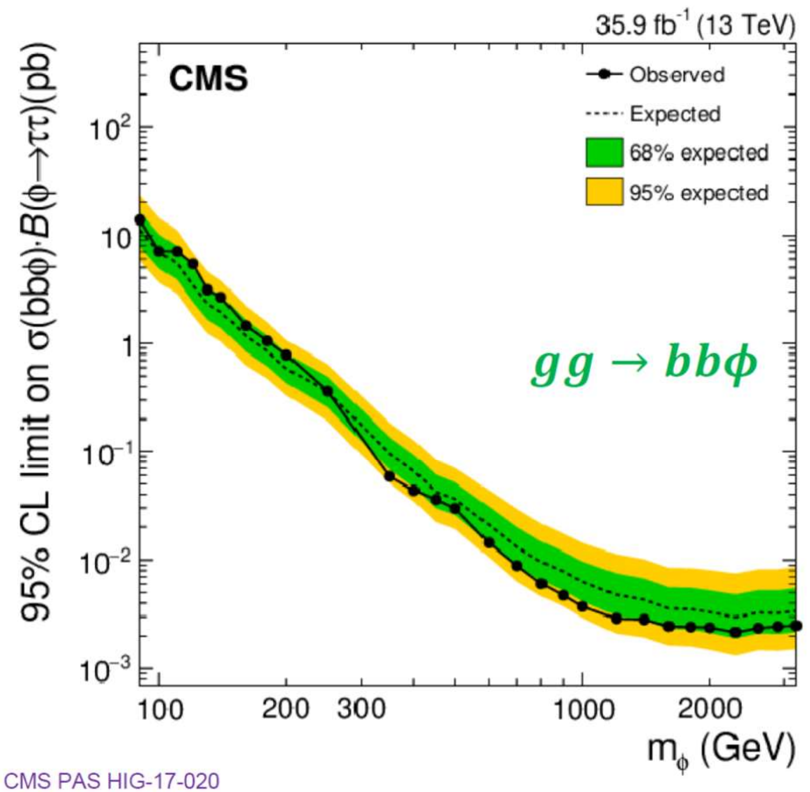


Search for A/H→ττ

- **Model-independent** exclusion limits for $gg \to \phi$ and $gg \to bb\phi$:
  - All categories and final states combined together
  - Limits cover a **large range** of m_ϕ
  - **No significant excess** with respect to background expectations

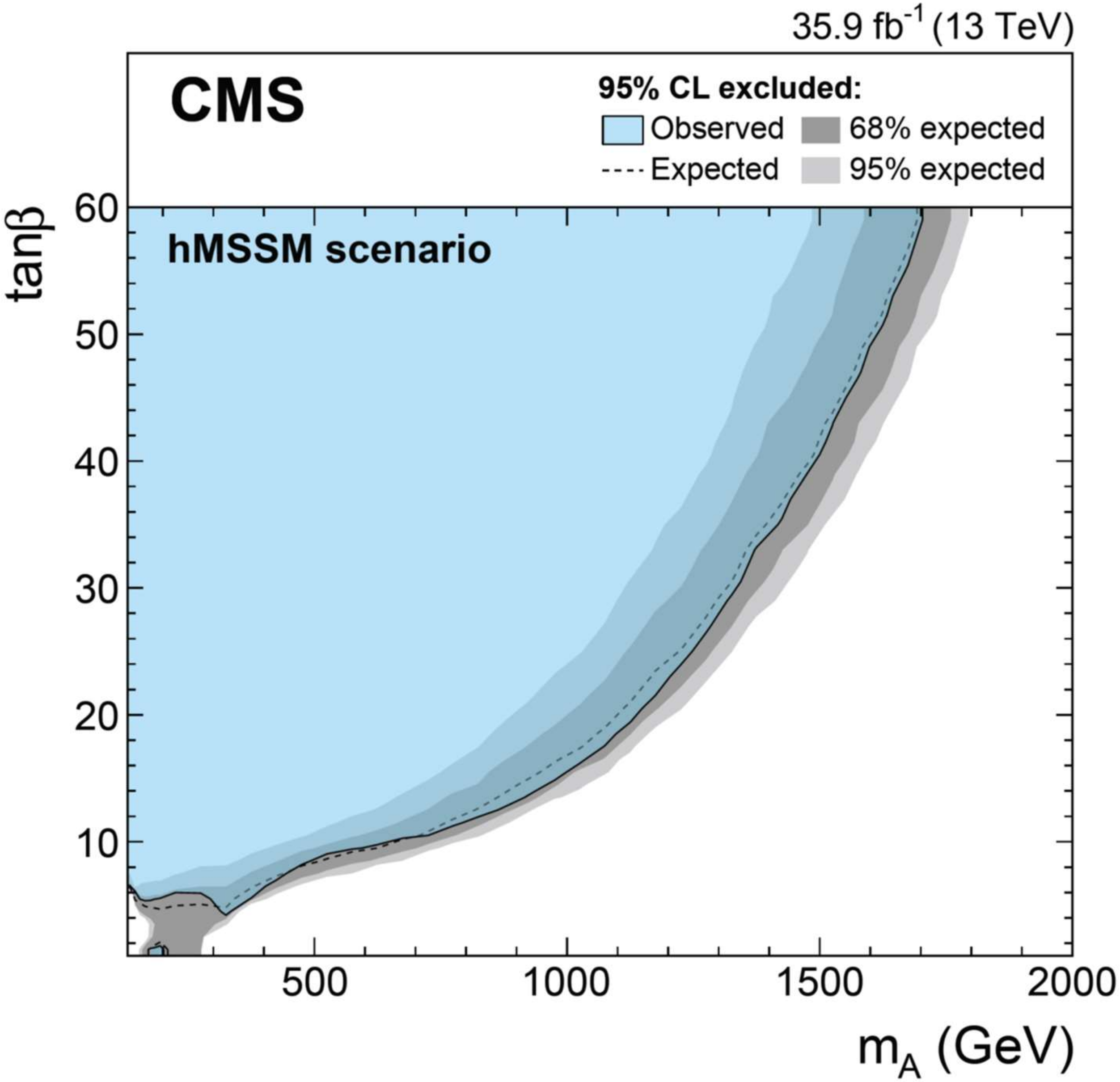


CMS PAS HIG-17-020

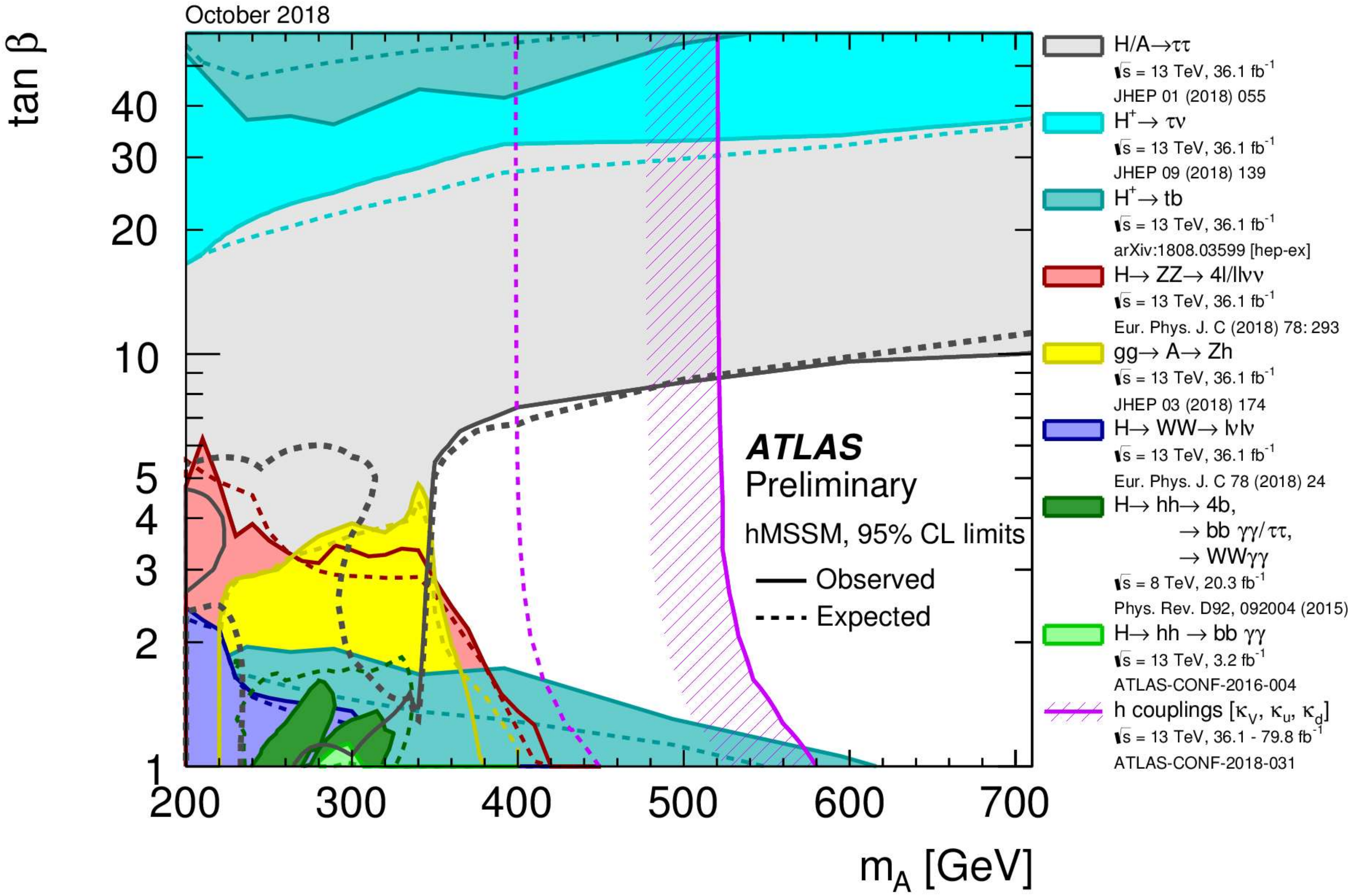


CMS PAS HIG-17-020

Search for A/H→ττ



Summary


October 2018
tan β
40
30
20
10
5
4
3
2
1
200
300
400
500
600
700
m_A [GeV]
ATLAS
Preliminary
hMSSM, 95% CL limits
Observed
Expected
H/A→ττ
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 01 (2018) 055
H^+→ τν
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 09 (2018) 139
H^+→ tb
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
arXiv:1808.03599 [hep-ex]
H→ ZZ→ 4l/llνν
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C (2018) 78: 293
gg→ A→ Zh
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 03 (2018) 174
H→ WW→ lνlν
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 78 (2018) 24
H→ hh→ 4b,
→ bb γγ/ττ,
→ WWγγ
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D92, 092004 (2015)
H→ hh → bb γγ
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
ATLAS-CONF-2016-004
h couplings [κ_V, κ_u, κ_d]
$\sqrt{s}$ = 13 TeV, 36.1 - 79.8 fb^{-1}
ATLAS-CONF-2018-031


That's all Folks!

Exercise

Assuming R-parity with the photino as the LSP and all other sparticles decoupled:

- Draw Feynman diagrams for squarks and gluinos production at the LHC
- Draw Feynman diagrams for squarks and gluinos decays

Exercise

Assuming R-parity conservation, show that

1. SUSY particles must be produced in pairs
2. One SUSY particle (except the LSP) must always contains exactly one SUSY particle in its Decay products
3. The LSP is stable

1)

$$SM + SM \rightarrow SUSY + SUSY$$

$$R = (+1) \times (+1) = (-1) \times (-1)$$

2)

$$SUSY \rightarrow SUSY + SM + SM + \ldots$$

$$R = (-1) = (-1) \times (+1) \times (+1)$$

3)

$$LSP \not\rightarrow SUSY + SM + SM + \ldots$$

$$R = (-1) = (-1) \times (+1) \times (+1)$$

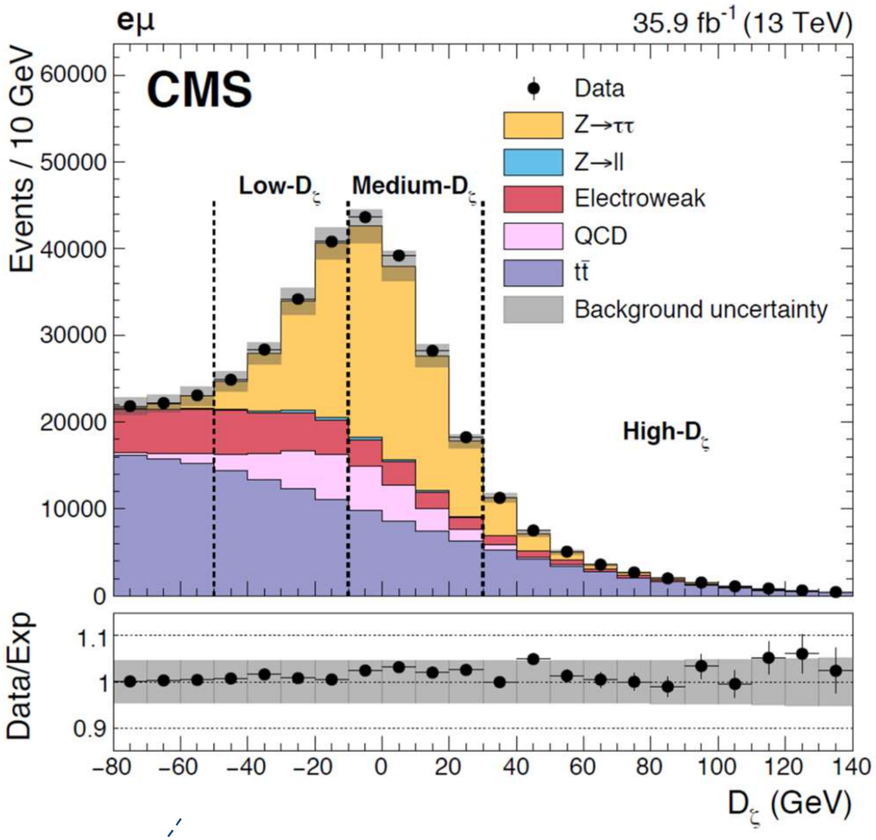
not possible because no lighter SUSY particle

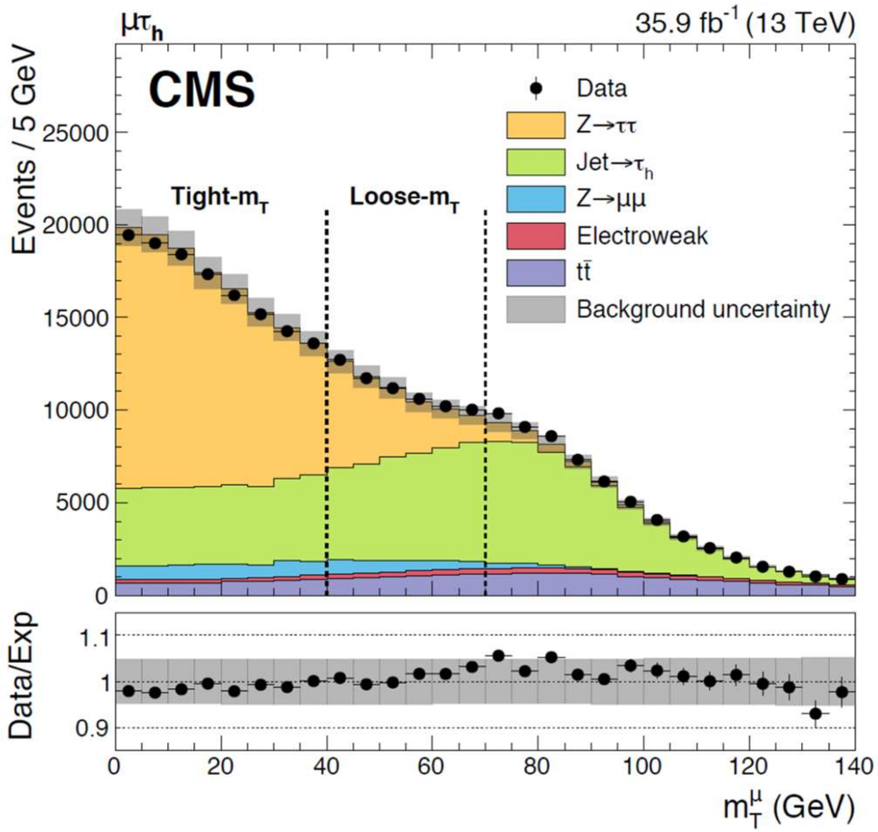
$$LSP \not\rightarrow SM + SM + \ldots$$

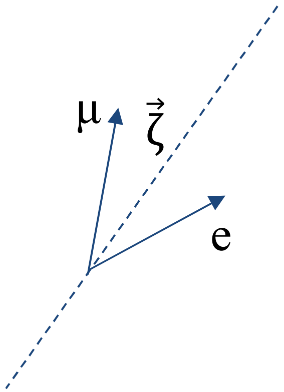
$$R = (-1) \neq (+1) \times (+1)$$

not possible because R-parity must be conserved

Search for A/H→ττ







$$D_\zeta = p_\zeta^{\text{miss}} - 0.85\, p_\zeta^{\text{vis}}$$

$$p_\zeta^{\text{miss}} = \vec{p}_{\text{T}}^{\text{miss}} \cdot \hat{\zeta};$$

$$p_\zeta^{\text{vis}} = \left(\vec{p}_{\text{T}}^{\text{e}} + \vec{p}_{\text{T}}^{\mu}\right) \cdot \hat{\zeta}$$

$$m_{\text{T}}^{\text{e}(\mu)} = \sqrt{2\, p_{\text{T}}^{\text{e}(\mu)}\, p_{\text{T}}^{\text{miss}}\, (1 - \cos\Delta\phi)}$$

Search for A/H→ττ

Background process	Misidentification	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$H \to \tau\tau$ (SM)		MC	MC	MC	MC
$Z \to \tau\tau$		MC†	MC†	MC†	MC†
$Z \to \ell\ell$	$\ell \to \tau_h$	MC	MC	MC	MC
	$\text{Jet} \to \tau_h$		F_F	F_F	F_F
Diboson+single t	$\tau/\ell \to \tau_h$	MC	MC	MC	MC
	$\text{Jet} \to \tau_h$		F_F	F_F	F_F
$t\bar{t}$	$\tau/\ell \to \tau_h$	MC†	MC†	MC†	MC†
	$\text{Jet} \to \tau_h$		F_F	F_F	F_F
W+jets	$\text{Jet} \to \tau_h$	MC	F_F	F_F	F_F
QCD multijet production	$\text{Jet} \to \tau_h$	CR	F_F	F_F	F_F

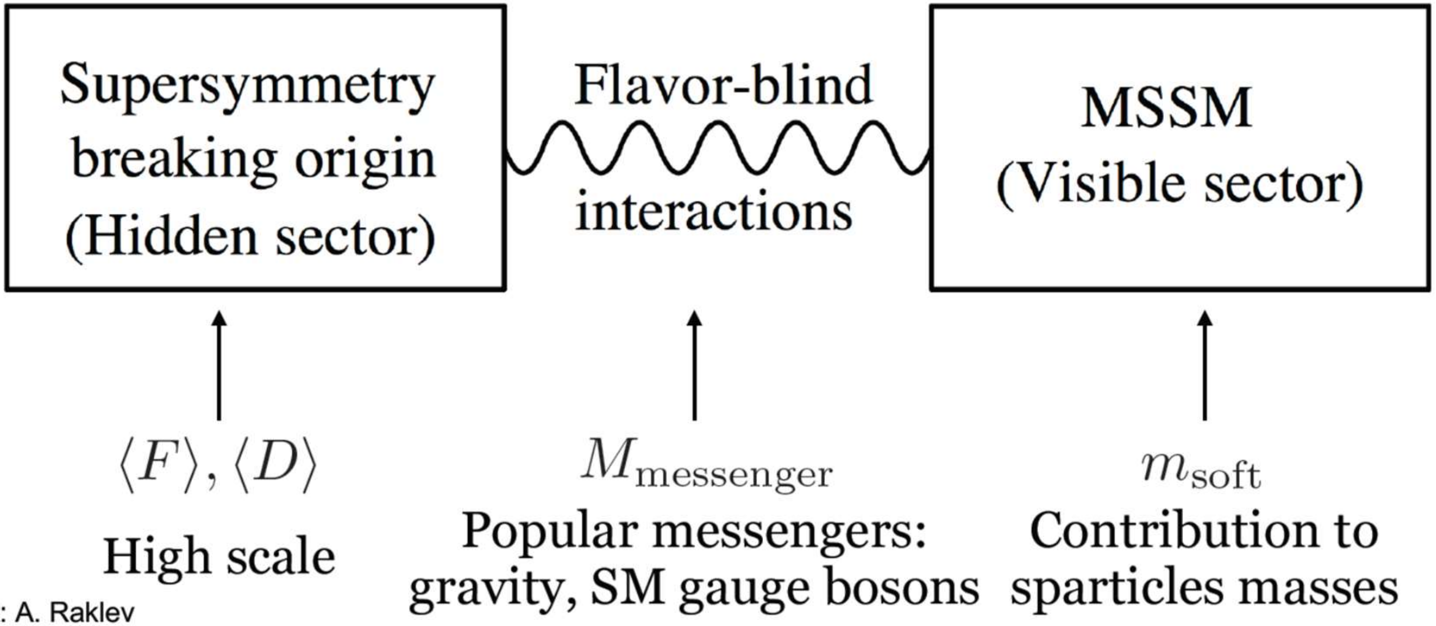
† Normalization from control region in data.

Supersymmetry breaking

The existence of soft susy breaking terms have been justified in the context of spontaneously broken local supersymmetry i.e. spontaneouly broken supergravity

The spontaneous breaking occurs in a so called 'hidden sector' at high energy scale and is transmitted to a so called 'visible sector' at lower energy scale (SM particles and susy partners) via some interactions (messengers) :

- gravitational interactions ⇒ e.g. **MSUGRA, AMSB**
- new gauge interactions ⇒ e.g. **Gauge Mediated SUSY Breaking i.e. GMSB**



Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

MSSM (Visible sector)

$\langle F \rangle, \langle D \rangle$

High scale

$M_{\text{messenger}}$

Popular messengers: gravity, SM gauge bosons

m_{soft}

Contribution to sparticles masses

Image credit: A. Raklev

Squarks and sleptons masses

- Obtaining physical masses implies diagonalization of the mass matrices coming from the original Lagrangian
- To treat the sfermions in complete generality we would have to consider arbitrary mixing and diagonalize

1. a 6×6 mass matrix for the up-type squarks $(\tilde{t}_L, \tilde{t}_R, \tilde{c}_L, \tilde{c}_R, \tilde{u}_L, \tilde{u}_R)$
2. a 6×6 mass matrix for the down-type squarks $(\tilde{b}_L, \tilde{b}_R, \tilde{s}_L, \tilde{s}_R, \tilde{d}_L, \tilde{d}_R)$
3. a 6×6 mass matrix for the charged sleptons $(\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\mu}_L, \tilde{\mu}_R, \tilde{e}_L, \tilde{e}_R)$
4. a 3×3 mass matrix for sneutrinos $(\tilde{\nu}_\tau, \tilde{\nu}_\mu, \tilde{\nu}_e)$

Fortunately most of mixing angles are small in viable models and the Yukawa couplings for the first and second generations are negligible. We end up with 7 unmixed pairs

$$(\tilde{c}_L, \tilde{c}_R), (\tilde{u}_L, \tilde{u}_R), (\tilde{s}_L, \tilde{s}_R), (\tilde{d}_L, \tilde{d}_R), (\tilde{\mu}_L, \tilde{\mu}_R), (\tilde{e}_L, \tilde{e}_R), (\tilde{\nu}_\mu, \tilde{\nu}_e)$$

and 3 **mixing** pairs (due to sizable Yukawa coupling)

$$(\tilde{t}_L, \tilde{t}_R), (\tilde{b}_L, \tilde{b}_R), (\tilde{\tau}_L, \tilde{\tau}_R)$$

Squark masses

Obtaining physical masses implies diagonalization of the mass matrices coming from the original Lagrangian

Fortunately most of mixing angles are small in viable models and the Yukawa couplings for the first and second generations are negligible

For the stop:

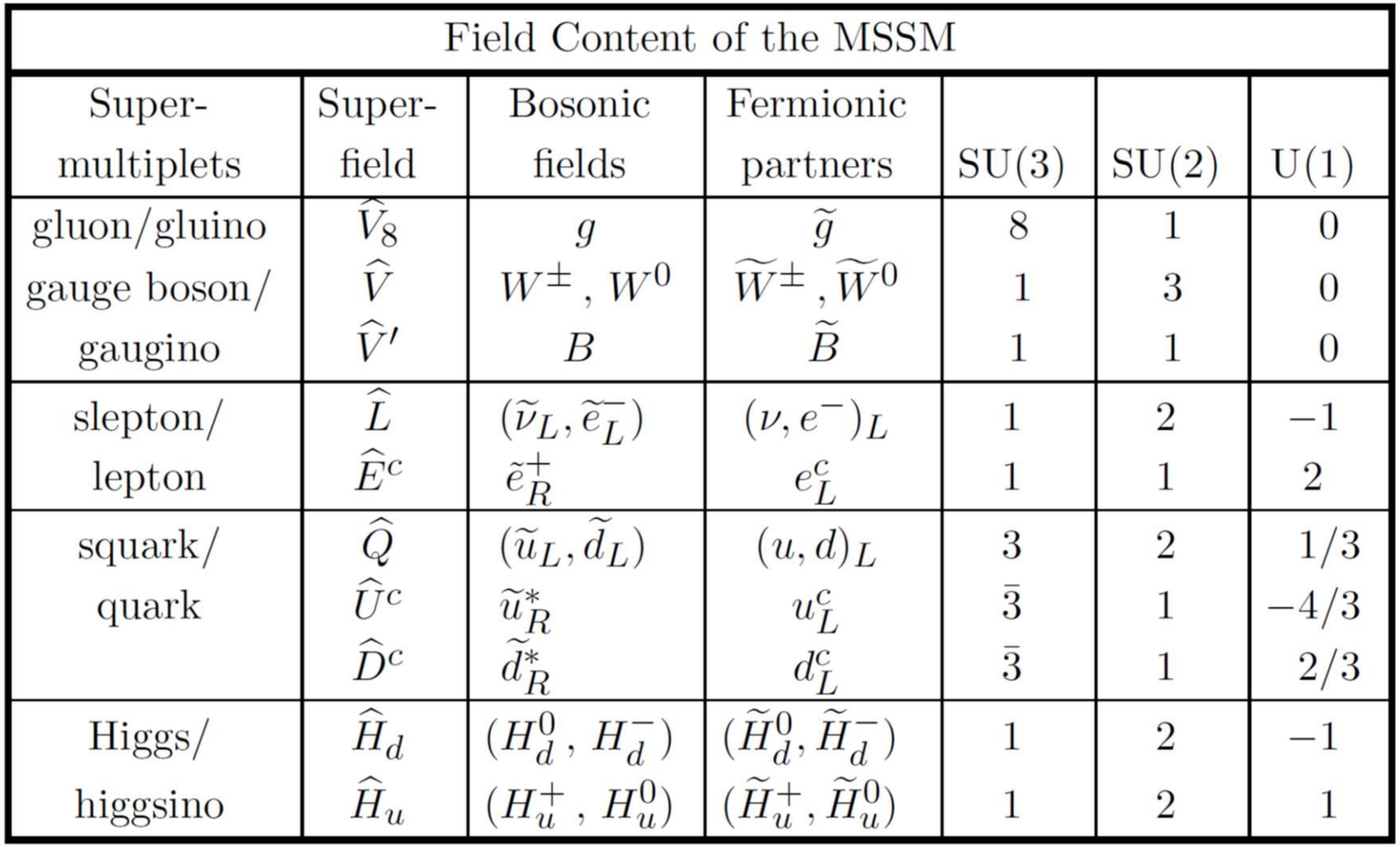
$$\mathcal{L}_{stop-mass} = -\left(t_L^* \quad t_R^*\right)\begin{pmatrix} m^2_{\tilde{Q}_3} + m_t^2 + \Delta_{\tilde{u}_L} & \frac{v}{\sqrt{2}}\sin\beta\,(a_t - y_t\mu\cot\beta) \\ \frac{v}{\sqrt{2}}\sin\beta\,(a_t - y_t\mu\cot\beta) & m^2_{\tilde{t}_R} + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}\begin{pmatrix} t_L \\ t_R \end{pmatrix}.$$

where $\Delta_{\tilde{u}_{L,R}}$ is an $SU(2)_L \times U(1)_y$ D-term ($\Delta_{\phi_{L,R}} = M_Z^2(T_{3\phi_{L,R}} - Q_{\phi_{L,R}}\sin^2\theta_W)\cos 2\beta$)

$$\begin{aligned} m^2_{\tilde{t}_1,\,\tilde{t}_2} &= \frac{1}{2}\Bigg[\left(m^2_{\tilde{Q}_3} + m^2_{\tilde{t}_R} + 2m_t^2 + \Delta_{u_L} + \Delta_{u_R}\right) \\ &\mp \sqrt{\left(m^2_{\tilde{Q}_3} - m^2_{\tilde{t}_R} + \Delta_{u_L} - \Delta_{u_R}\right)^2 + 2v^2\sin^2\beta\,(a_t - y_t\mu\cot\beta)^2}\Bigg] \end{aligned}$$

Weak SUSY

Minimal Supersymmetric Standard Model (MSSM)



Field Content of the MSSM						
Super-multiplets	Super-field	Bosonic fields	Fermionic partners	SU(3)	SU(2)	U(1)
gluon/gluino	$\widehat{V}_8$	g	$\widetilde{g}$	8	1	0
gauge boson/	$\widehat{V}$	$W^{\pm}, W^0$	$\widetilde{W}^{\pm}, \widetilde{W}^0$	1	3	0
gaugino	$\widehat{V}'$	B	$\widetilde{B}$	1	1	0
slepton/	$\widehat{L}$	$(\widetilde{\nu}_L, \widetilde{e}^-_L)$	$(\nu, e^-)_L$	1	2	−1
lepton	$\widehat{E}^c$	$\tilde{e}^+_R$	e^c_L	1	1	2
squark/	$\widehat{Q}$	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	1/3
quark	$\widehat{U}^c$	$\widetilde{u}^*_R$	u^c_L	$\bar{3}$	1	−4/3
	$\widehat{D}^c$	$\widetilde{d}^*_R$	d^c_L	$\bar{3}$	1	2/3
Higgs/	$\widehat{H}_d$	(H^0_d, H^-_d)	$(\widetilde{H}^0_d, \widetilde{H}^-_d)$	1	2	−1
higgsino	$\widehat{H}_u$	(H^+_u, H^0_u)	$(\widetilde{H}^+_u, \widetilde{H}^0_u)$	1	2	1

Higgs sector extended to 5
Higgs bosons: h, H, A, H±

$$\tilde{H}^0_u\ \tilde{H}^0_d\ \tilde{W}^0\ \tilde{B}^0 \longrightarrow \tilde{\chi}^0_1\ \tilde{\chi}^0_2\ \tilde{\chi}^0_3\ \tilde{\chi}^0_4$$

$$\tilde{H}^+_u\ \tilde{H}^-_d\ \tilde{W}^+\ \tilde{W}^- \xrightarrow[\text{EW symmetry breaking}]{} \tilde{\chi}^{\pm}_1\ \tilde{\chi}^{\pm}_2$$

Charginos and neutralinos masses

(i) Neutral components → Neutralinos

$$\mathcal{L}_{neutral} = -\frac{1}{2}\left(\tilde{B} \quad \tilde{W}^0 \quad \tilde{H}_d^0 \quad \tilde{H}_u^0\right) \underbrace{\begin{pmatrix} M_1 & 0 & -g'v_d/2 & g'v_u/2 \\ 0 & M_2 & gv_d/2 & -gv_u/2 \\ -g'v_d/2 & gv_d/2 & 0 & -\mu \\ g'v_u/2 & -gv_u/2 & -\mu & 0 \end{pmatrix}}_{M_\chi} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix} + h.c. \, ,$$

Mass eigenstates, the neutralinos, obtained after diagonalization

$$diag\left(m_{\tilde{\chi}_1^0} \, , \quad m_{\tilde{\chi}_2^0} \, , \quad m_{\tilde{\chi}_3^0} \, , \quad m_{\tilde{\chi}_4^0}\right) \, ,$$

(ii) Charged components → Charginos

$$\mathcal{L}_{charged} = -\frac{1}{2}\left[\left(\tilde{W}^+ \quad \tilde{H}_u^+\right) \mathbf{C}^\mathbf{T} \begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix} + \left(\tilde{W}^- \quad \tilde{H}_d^-\right) \mathbf{C} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}\right] + h.c. \qquad (55)$$

with the mass matrix of the charged components given by

$$\mathbf{C} = \begin{pmatrix} M_2 & gv_u/2 \\ gv_d/2 & \mu \end{pmatrix} . \qquad (56)$$

where the eigenstates are the charginos $\chi_1^\pm$ and $\chi_2^\pm$.

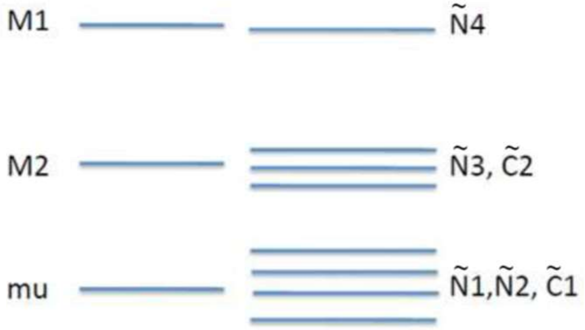
Charginos and neutralinos masses

Bino case
Open Spectra

Wino case
Degenerate spectra

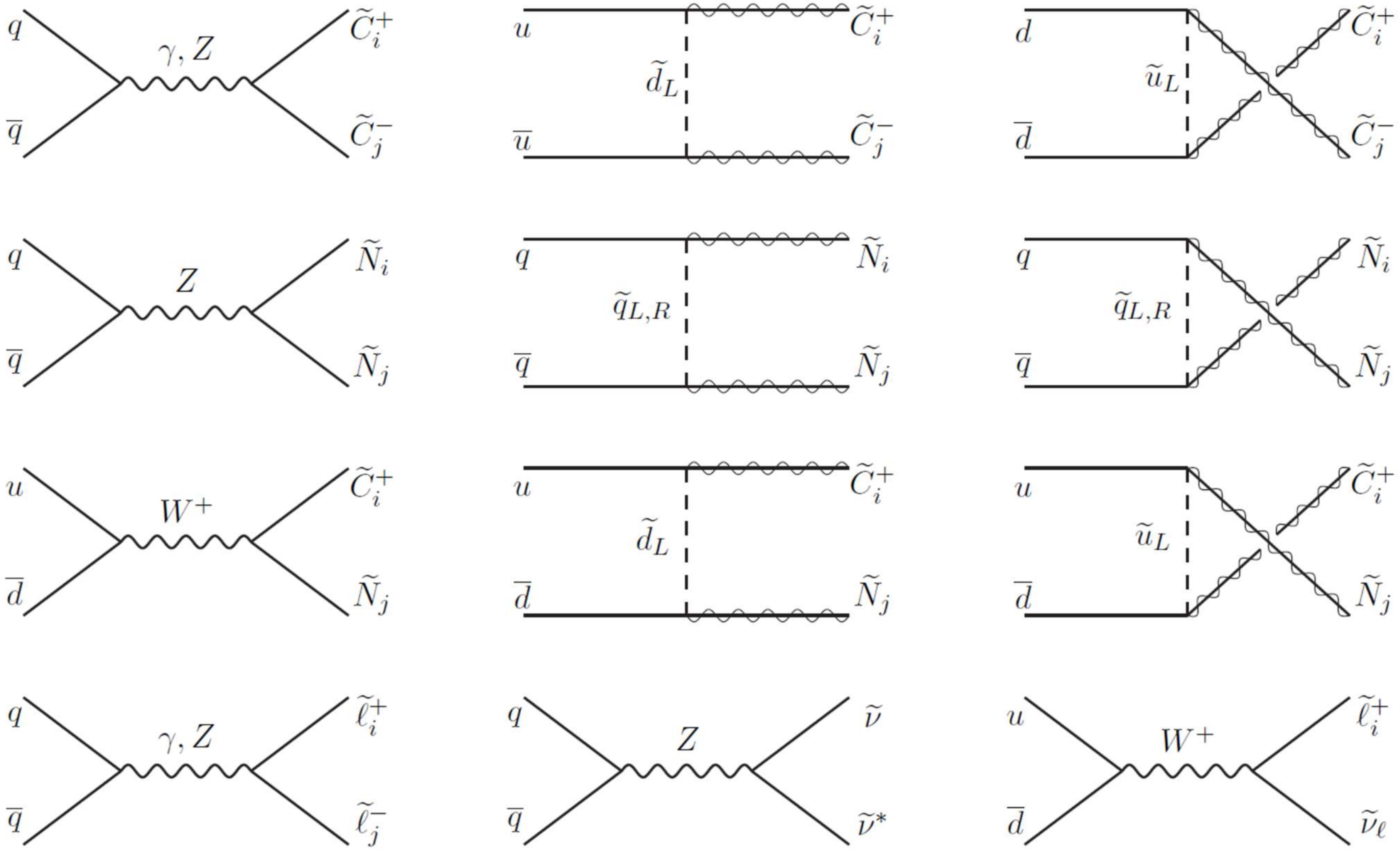
Long-lived particles

Higgsino case
Compressed spectra



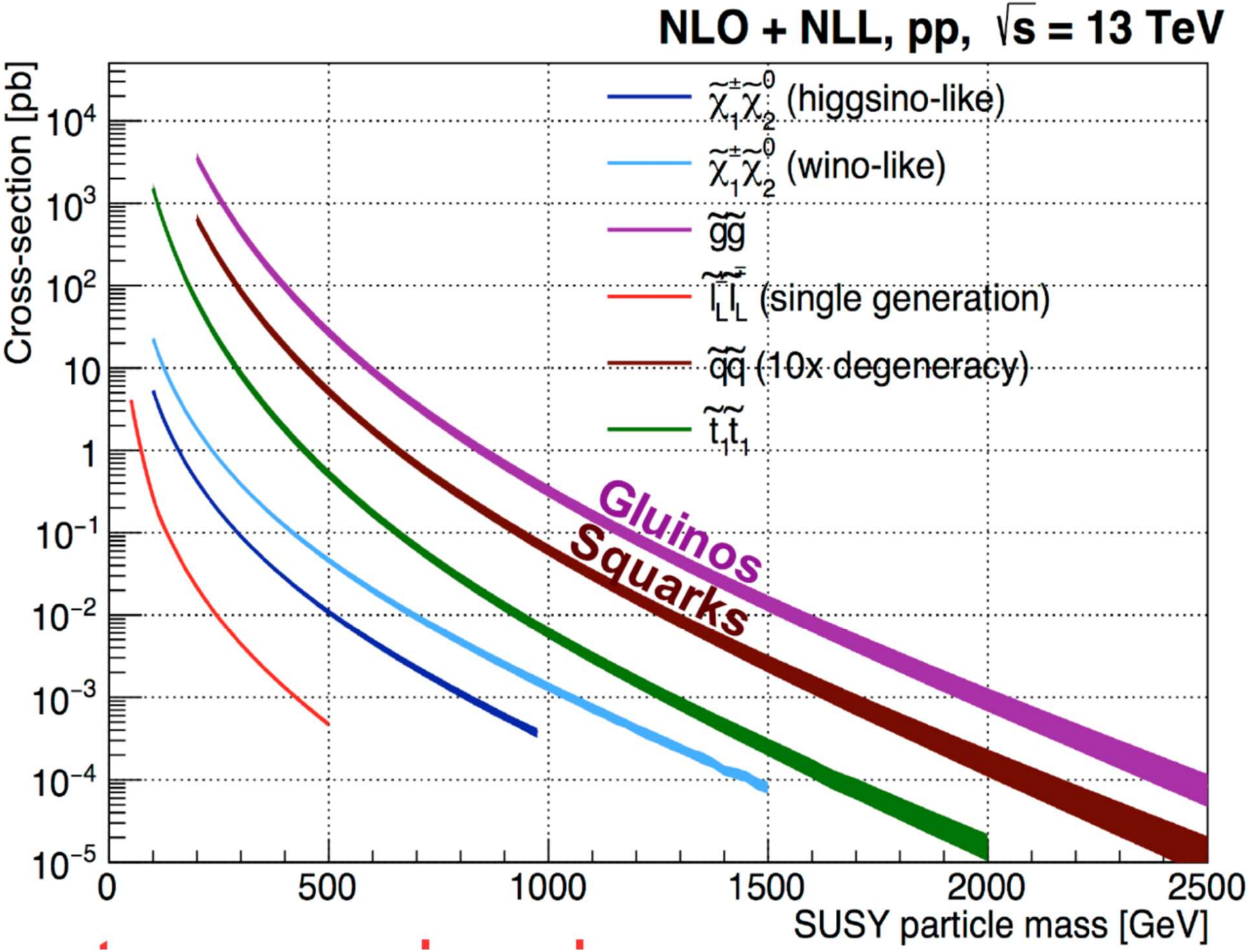
Very challenging
(low MET and soft decay products)

Electroweak production



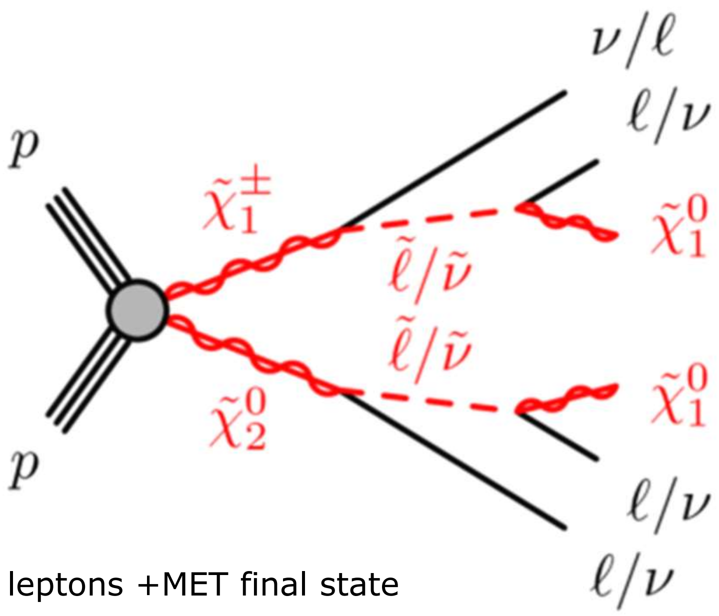
Rare processes at the LHC: only quarks in the initial state
At least two vertices involving the electromagnetic or weak coupling

Cross-section



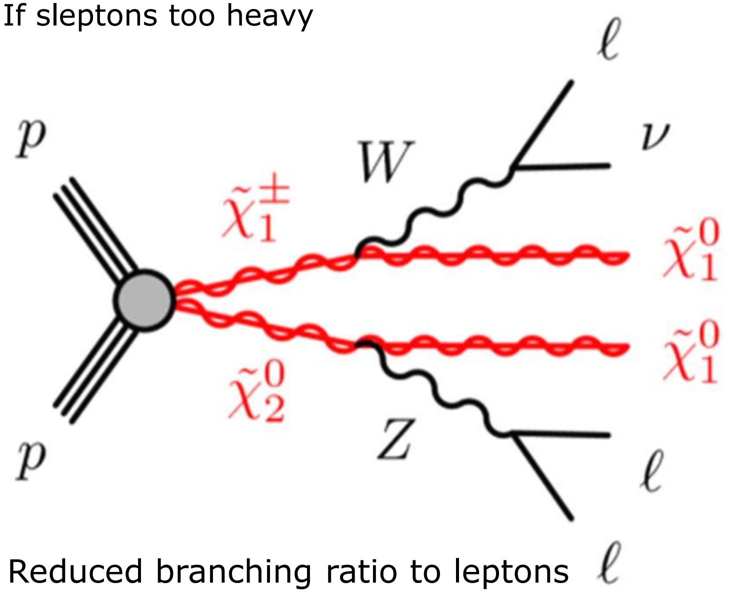
Decays

Bino case
Open Spectra

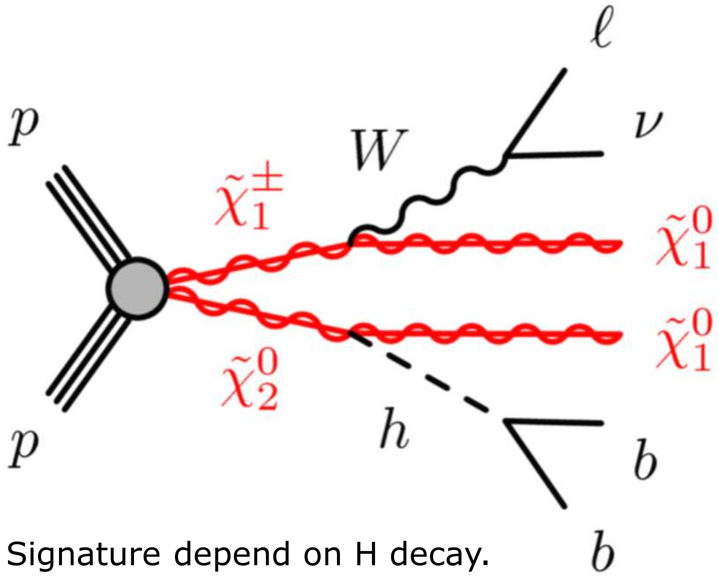


3 leptons +MET final state

If sleptons too heavy



Reduced branching ratio to leptons



Signature depend on H decay.

Multilepton search

arXiv:1709.05406

- *To face the small cross-section the analysis is subdivided into* ***several categories:***
  - **2 same-sign $\ell_{(e,\mu)}$ / $3\ell_{(e,\mu)}$ / 3ℓ with 1 or 2 τ_h / > 3ℓ with at max 2 τ_h**
- ***Signal regions: bins in kinematic variables (**E_T^{miss} **,** $M_T(\ell, E_T^{miss})$***, $p_T(\ell\ell)$, $M_{T2}(\ell,\ell)$****)**
  - *discriminate from SM bkg and increase sensitivity to different sparticle mass hierarchies*
- *It uses* ***single/double lepton triggers*** *(offline p_T > 25/20 - 15/10 GeV)*
  - *doesn't cover the quasi-degenerate region of phase space, but it goes down to* **E_T^{miss} 50 GeV**
- *Events with* ***at least one b-tag jet are rejected***
- ***Main residual backgrounds:***

WZ production

External and internal conversions

Non-prompt leptons (W+Jets, ttbar, DY+Jets)

rare SM processes ZZ/H, VVV or ttV

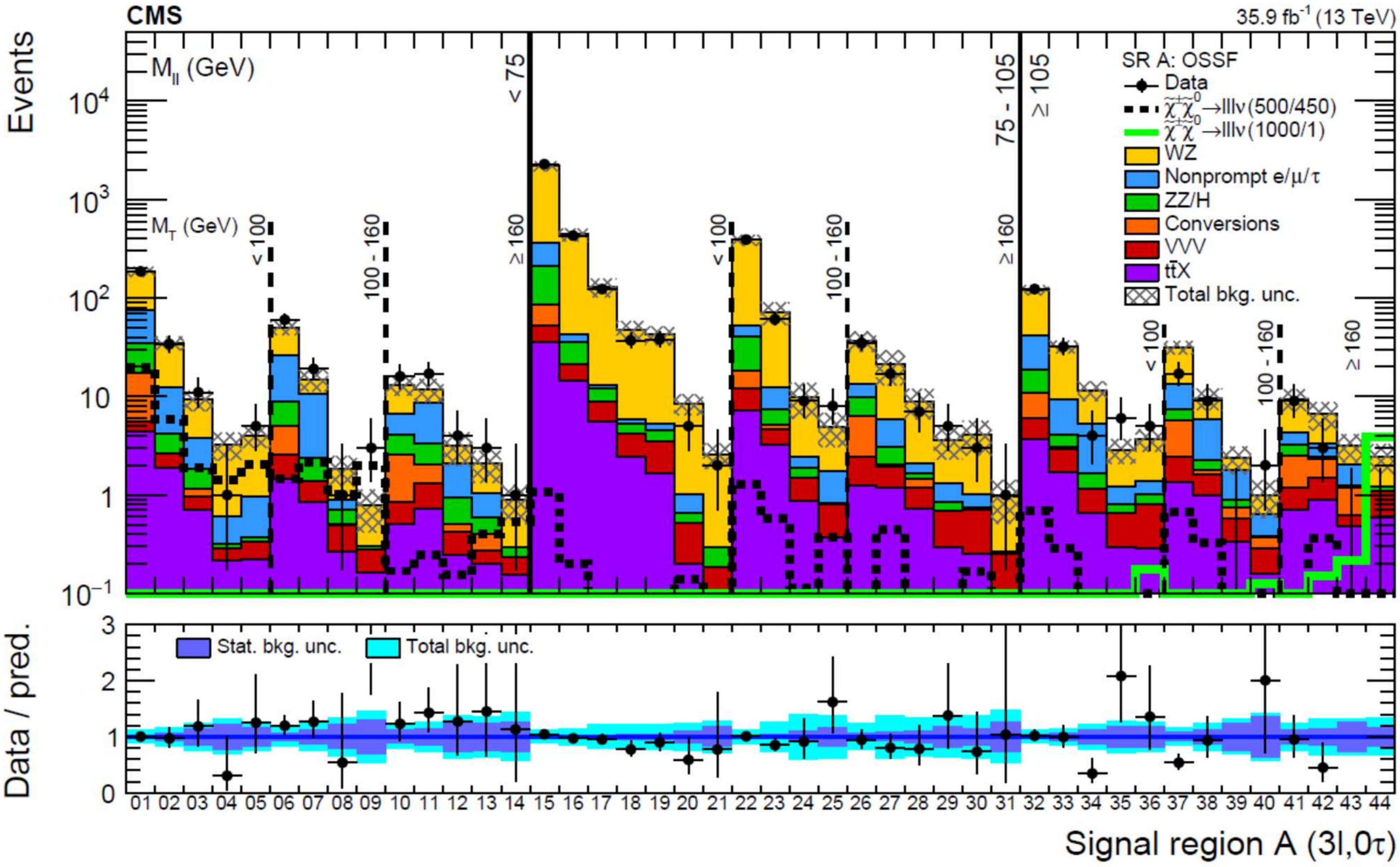
charge mis-identification

* $$(M_T = \sqrt{2E_T^{miss} p_T^{\ell} \left(1 - \cos\left(\Delta\phi\right)\right)})$$

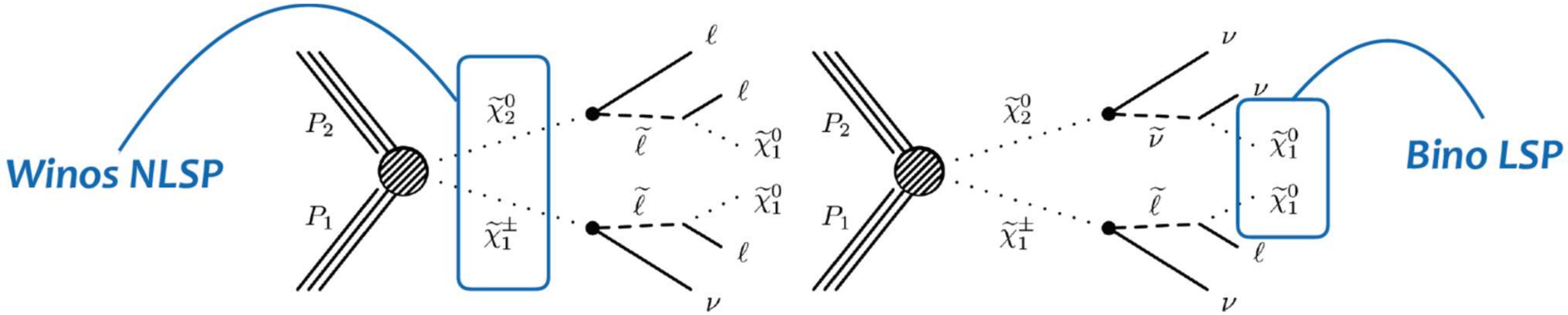
** $$M_{T2}^2 = \min_{\vec{p}_{T1}^{miss} + \vec{p}_{T2}^{miss} = \vec{p}_T^{miss}} \left[\max\{ M_T^2(\vec{p}_T^{\ell_1}, \vec{p}_{T1}^{miss}), M_T^2(\vec{p}_T^{\ell_2}, \vec{p}_{T2}^{miss}) \} \right]$$

Multilepton search

Results for three light leptons (**OSSF pair**)



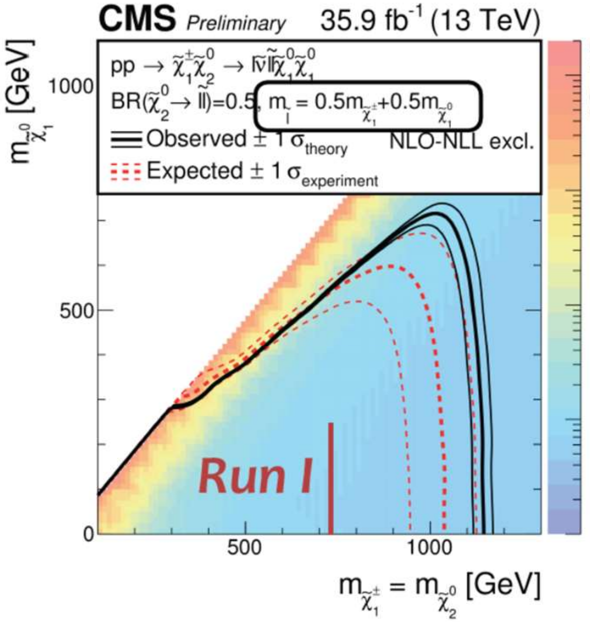
Multilepton search: light sleptons



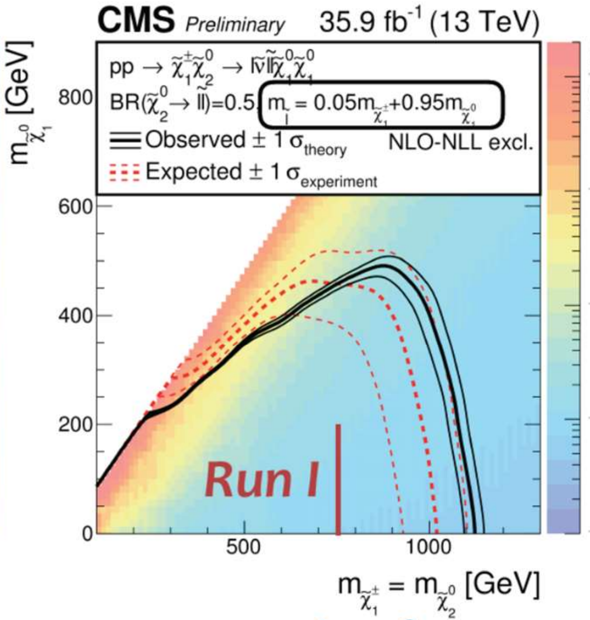
Winos NLSP

Bino LSP

Flavour democratic scenario



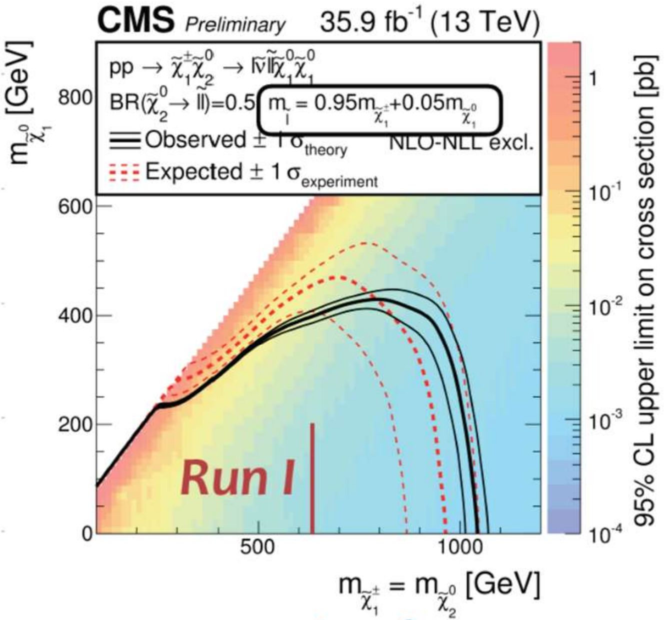
3ℓ(e,μ) with OSSF pair



2 same-sign ℓ(e,μ)

3ℓ(e,μ) with OSSF pair

$m_{\tilde{l}} = 0.05m_{\tilde{\chi}_1^\pm} + 0.95m_{\tilde{\chi}_1^0}$

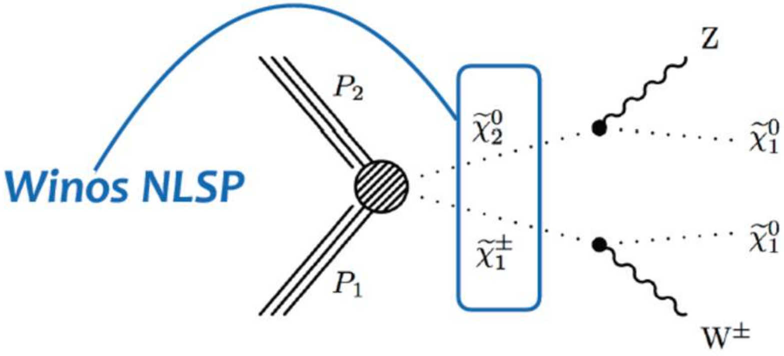


2 same-sign ℓ(e,μ)

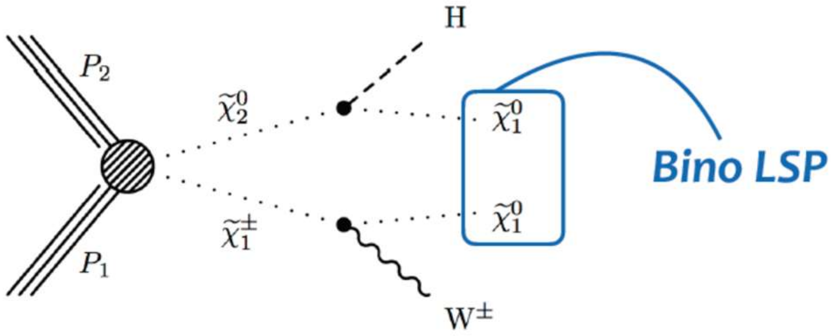
3ℓ(e,μ) with OSSF pair

$m_{\tilde{l}} = 0.95m_{\tilde{\chi}_1^\pm} + 0.05m_{\tilde{\chi}_1^0}$

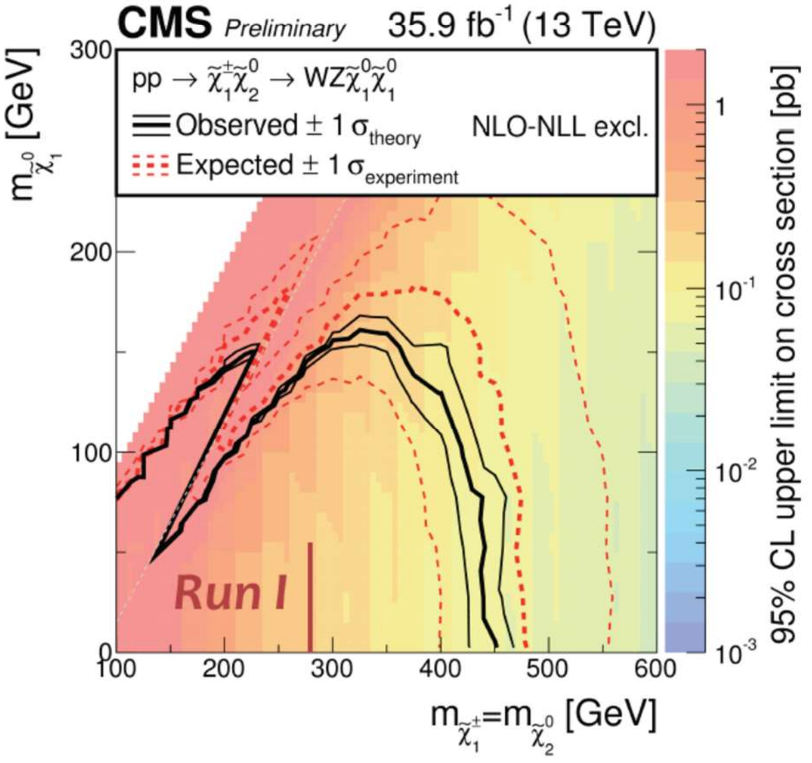
Multilepton search: heavy sleptons



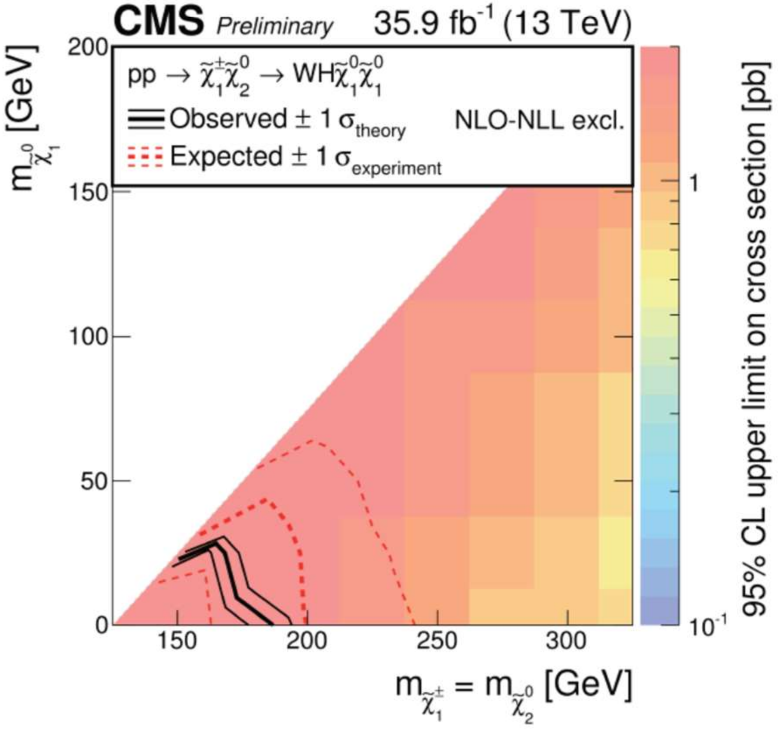
Winos NLSP



Bino LSP



3ℓ(e,μ) with OSSF pair



all final states

C. Botta

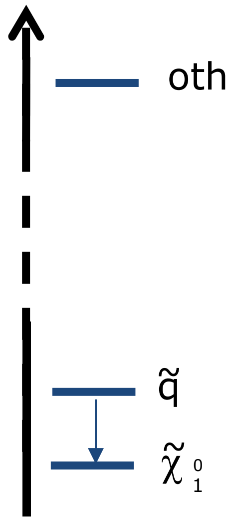
pMSSM interpretation

Simplified vs realistic models

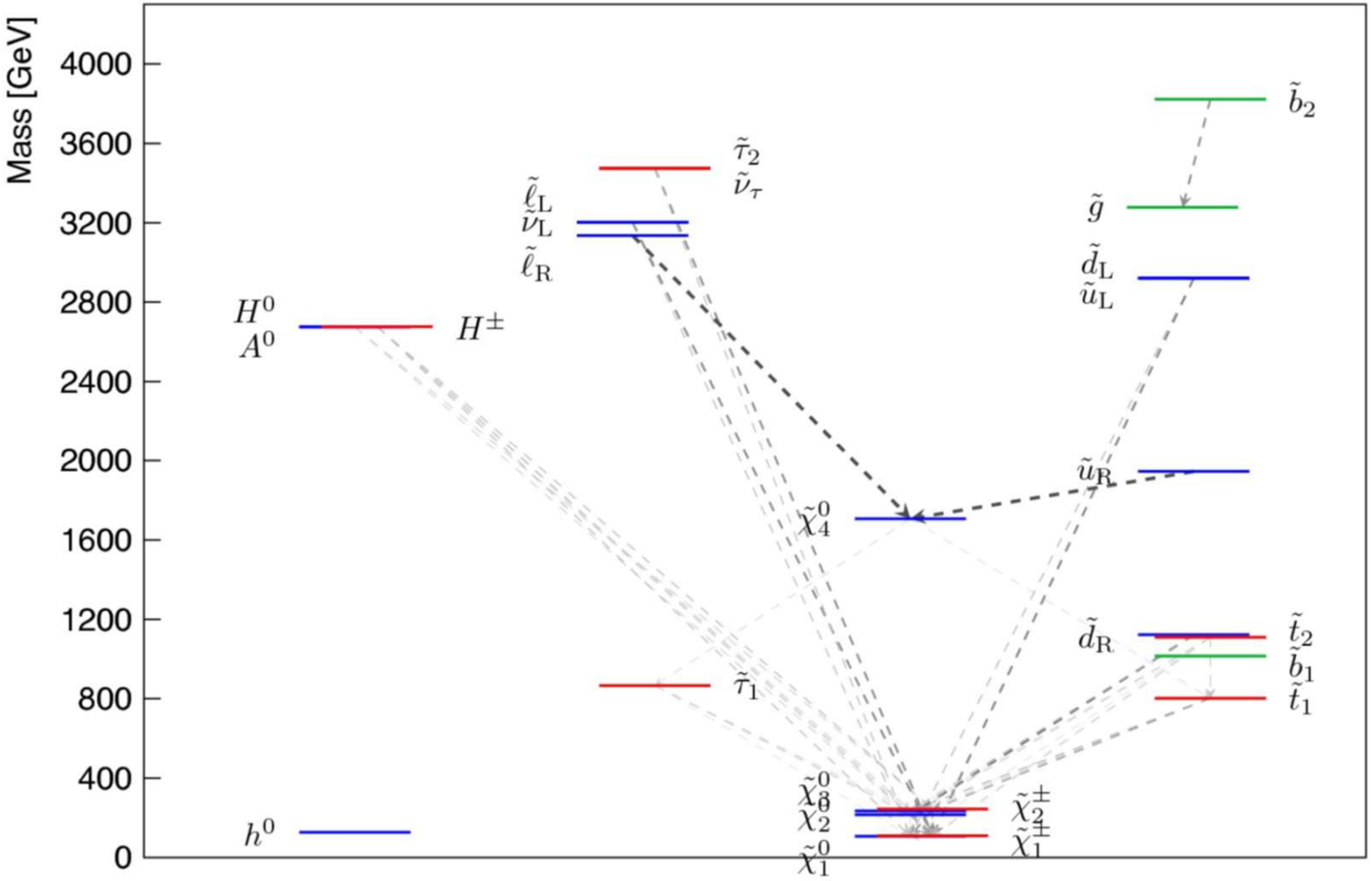
Most searches interpret results in terms of simplified models

These consider a single production and decay process

Not representative of more complex SUSY phenomenology



vs



pMSSM

Assumptions:

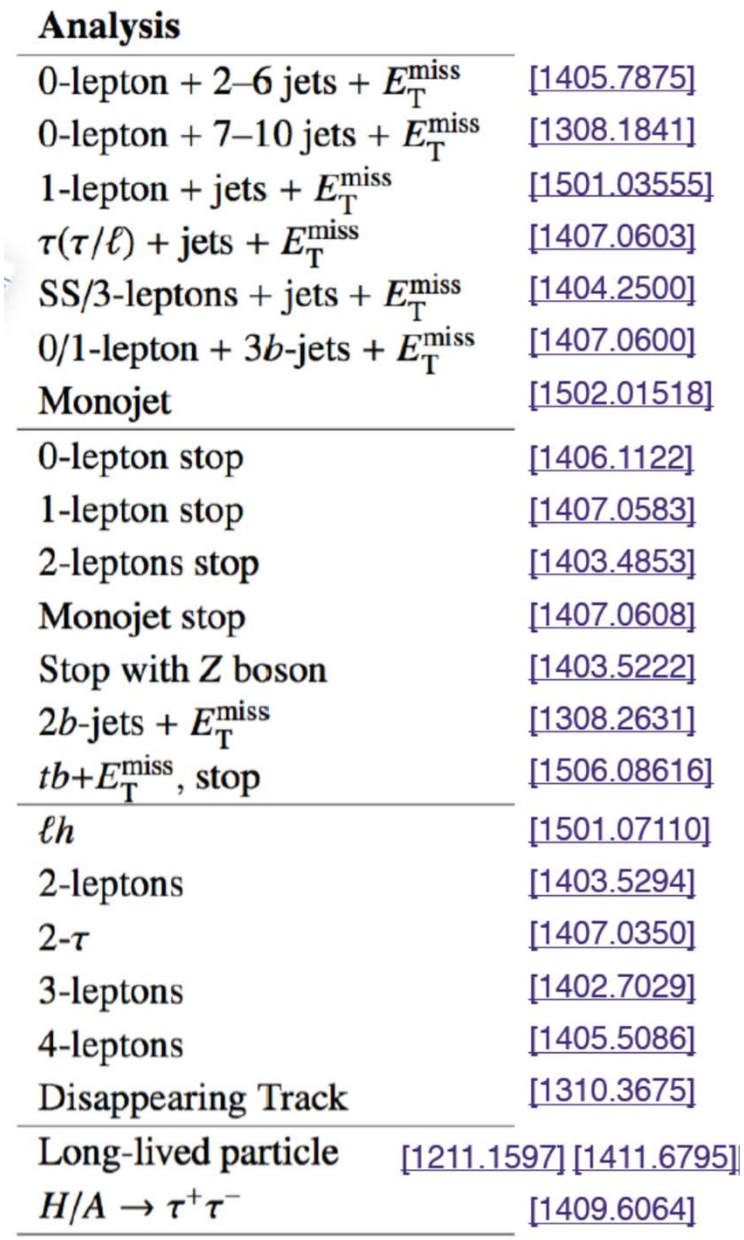
- 1st gen. sfermion degenerate with corresponding 2nd gen. sfermion
- No CP violation beyond CKM
- No FCNC
- Lightest neutralino as LSP

The pMSSM has 19 parameters instead of 105 for the MSSM

- 3 wino/bino/gluino mass: $M_{1,2,3}$
- 10 squark/slepton soft masses
- Ratio of Higgs vevs: $\tan\beta$
- Pseudo-scalar Higgs mass: m_A
- Higgsino mass parameter: μ
- 3 trilinear couplings for the 3rd gen : $A_{t,b,\tau}$

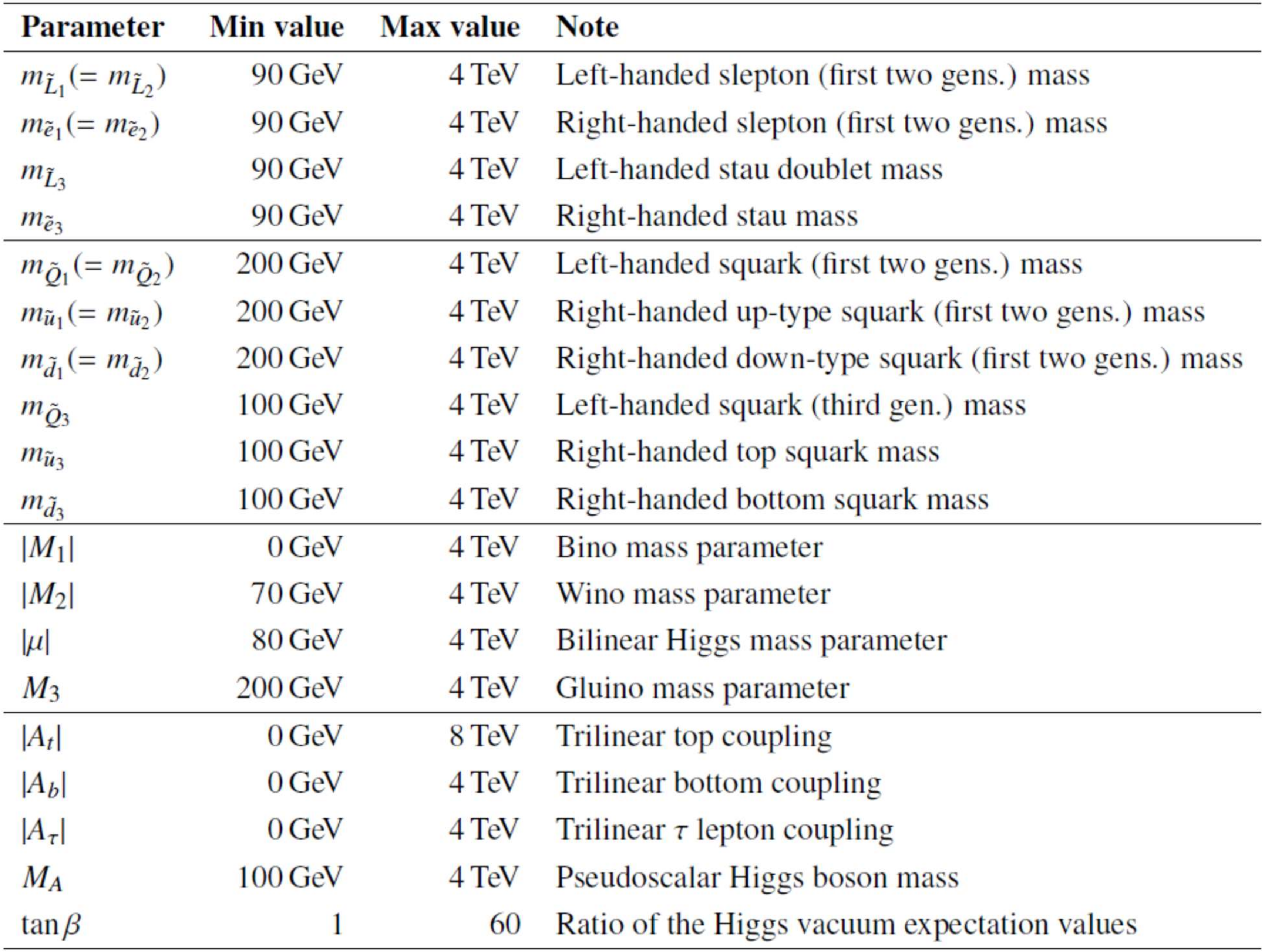
Strategy

1. Scan pMSSM space
   - A cartesian grid in 19-D is not possible (4^{19}=300 billion) so we need to **sample the parameter space** randomly
   - Sampled from uniform distributions in the 19 parameters with ranges chosen w.r.t existing exclusions and LHC reach
2. Find points that are not excluded by other constraints dq
   - 300 000/500 millions
3. Generate samples and obtain new exclusion limits for each analysis using full simulation when needed
4. Determine overall status of points based on all analysis results



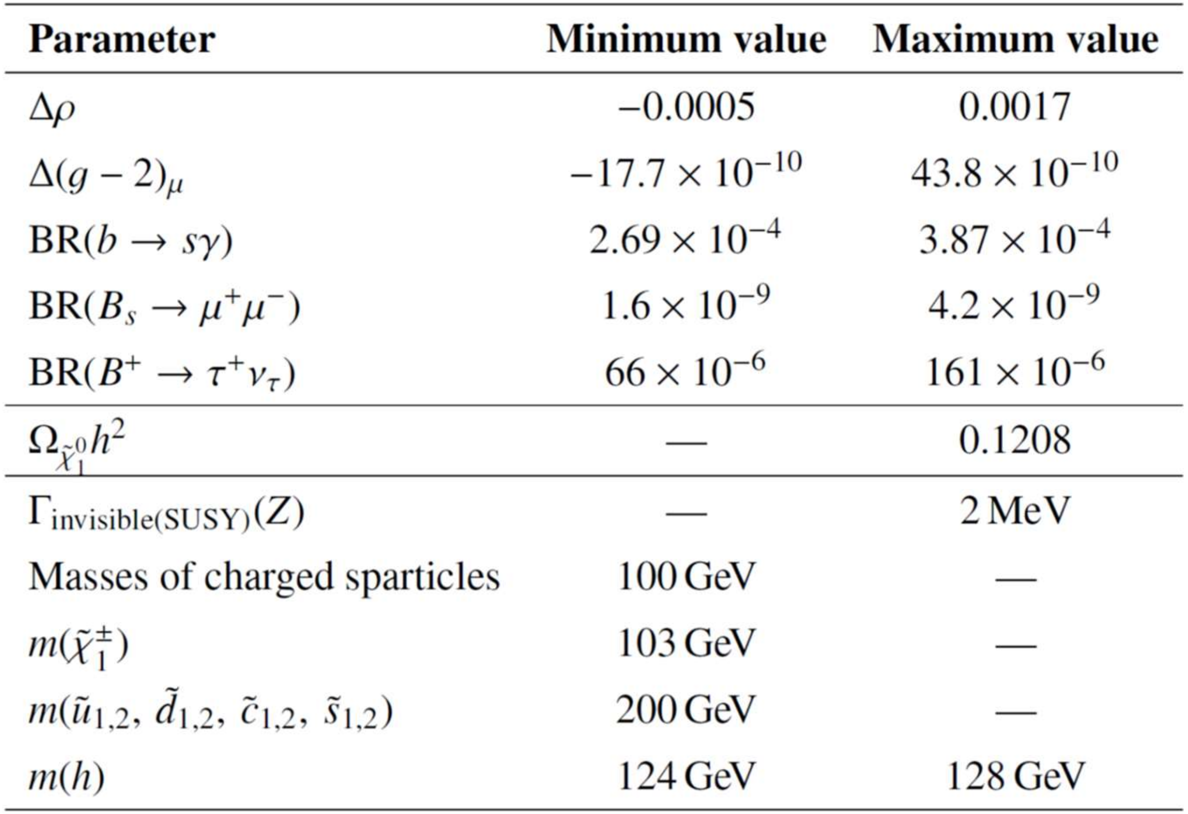
Analysis	
0-lepton + 2–6 jets + E_T^{miss}	[1405.7875]
0-lepton + 7–10 jets + E_T^{miss}	[1308.1841]
1-lepton + jets + E_T^{miss}	[1501.03555]
$\tau(\tau/\ell)$ + jets + E_T^{miss}	[1407.0603]
SS/3-leptons + jets + E_T^{miss}	[1404.2500]
0/1-lepton + 3b-jets + E_T^{miss}	[1407.0600]
Monojet	[1502.01518]
0-lepton stop	[1406.1122]
1-lepton stop	[1407.0583]
2-leptons stop	[1403.4853]
Monojet stop	[1407.0608]
Stop with Z boson	[1403.5222]
2b-jets + E_T^{miss}	[1308.2631]
tb+E_T^{miss}, stop	[1506.08616]
ℓh	[1501.07110]
2-leptons	[1403.5294]
2-τ	[1407.0350]
3-leptons	[1402.7029]
4-leptons	[1405.5086]
Disappearing Track	[1310.3675]
Long-lived particle	[1211.1597] [1411.6795]
$H/A \to \tau^+\tau^-$	[1409.6064]

Parameters



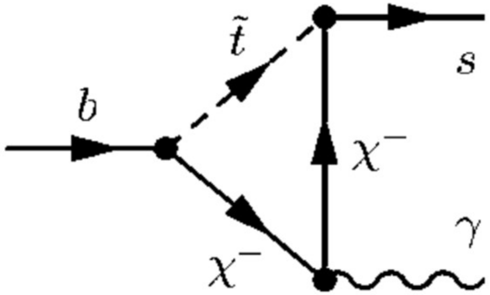
Parameter	Min value	Max value	Note
$m_{\tilde{L}_1}(= m_{\tilde{L}_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1}(= m_{\tilde{e}_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde{Q}_1}(= m_{\tilde{Q}_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1}(= m_{\tilde{u}_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1}(= m_{\tilde{d}_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\|M_1\|$	0 GeV	4 TeV	Bino mass parameter
$\|M_2\|$	70 GeV	4 TeV	Wino mass parameter
$\|\mu\|$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\|A_t\|$	0 GeV	8 TeV	Trilinear top coupling
$\|A_b\|$	0 GeV	4 TeV	Trilinear bottom coupling
$\|A_\tau\|$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

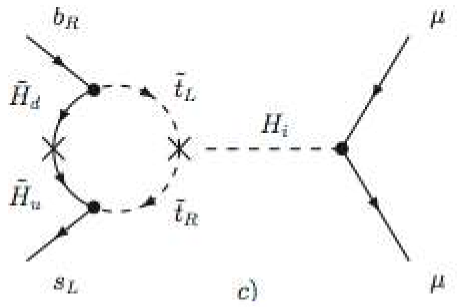
Constraints

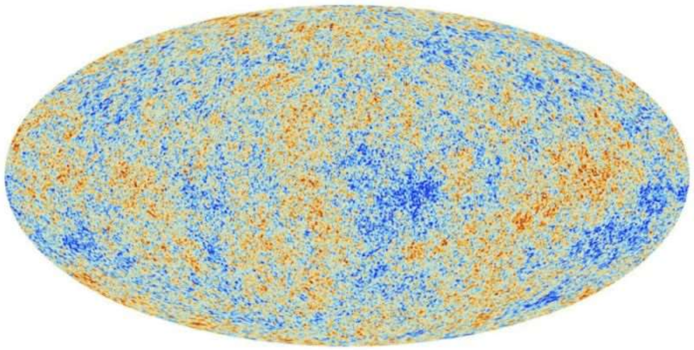


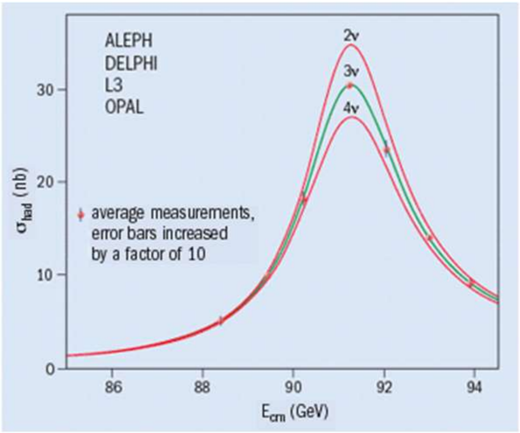
Parameter	Minimum value	Maximum value
$\Delta\rho$	-0.0005	0.0017
$\Delta(g-2)_\mu$	-17.7×10^{-10}	43.8×10^{-10}
$\mathrm{BR}(b \to s\gamma)$	2.69×10^{-4}	3.87×10^{-4}
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	1.6×10^{-9}	4.2×10^{-9}
$\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$	66×10^{-6}	161×10^{-6}
$\Omega_{\tilde{\chi}_1^0} h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	2 MeV
Masses of charged sparticles	100 GeV	—
$m(\tilde{\chi}_1^\pm)$	103 GeV	—
$m(\tilde{u}_{1,2},\ \tilde{d}_{1,2},\ \tilde{c}_{1,2},\ \tilde{s}_{1,2})$	200 GeV	—
$m(h)$	124 GeV	128 GeV

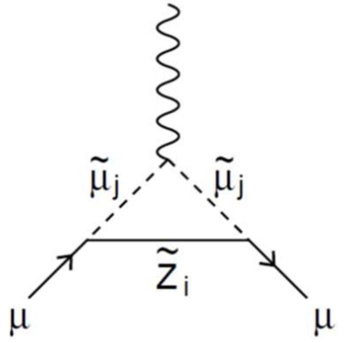
$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$$









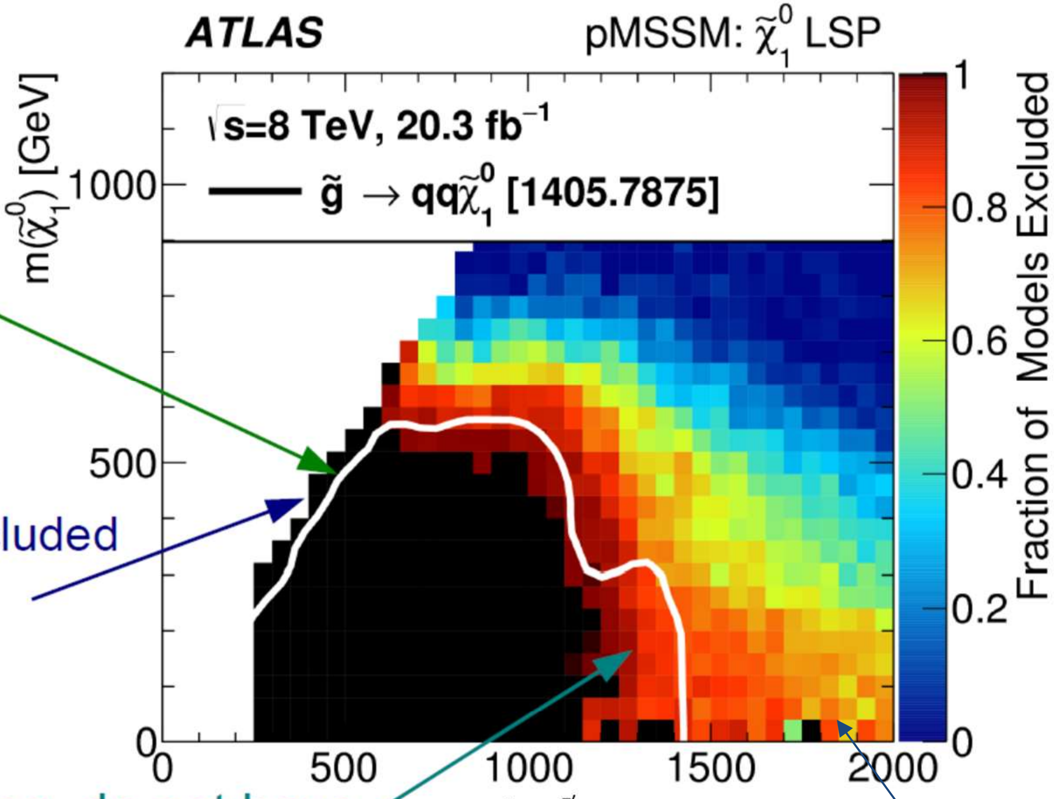


Gluinos

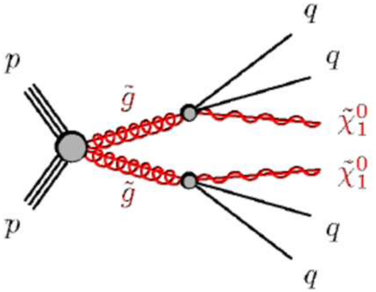
Present results as fraction of excluded models as a function of various parameters, such as sparticle masses

- Black means 100% excluded – white is no models generated

Exclude almost all models with $m(\tilde{g})<1$ TeV and $m(\tilde{\chi}_1^0)<0.5$ TeV

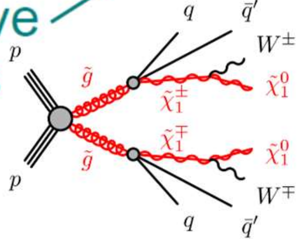


Good agreement with the gluino simplified model limit from 0-lepton + 2-6 jets E_t^{miss} analysis



Diagonal excluded by mono-jet analysis

For heavier gluinos, do not have 100% exclusion due to models with intermediate sparticles

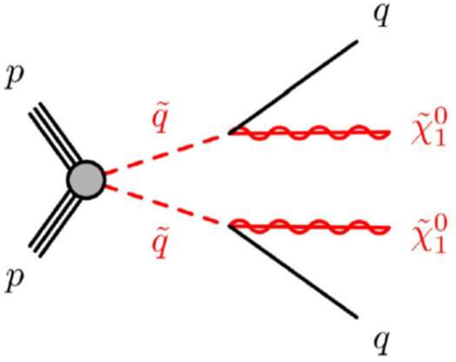


Band of sensitivity for model with $\chi_1^\pm \rightarrow$ wino-like LSP model from disappearing track search

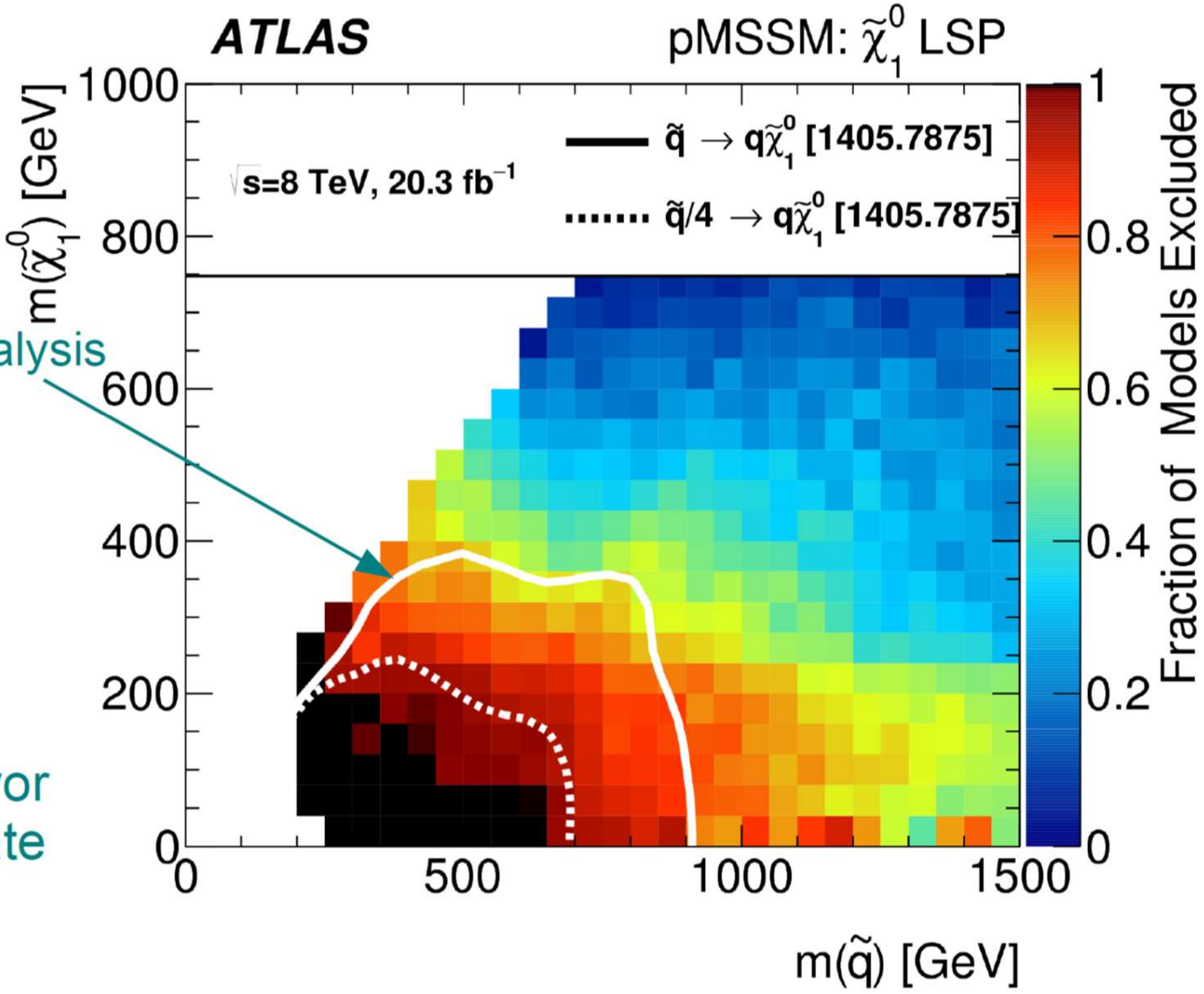
Squarks

For light-flavor squarks, only m($\tilde{q}$)<250 GeV fully excluded

Not in agreement with simplified model limit from 0-lepton + 2-6 jets E_t^{miss} analysis

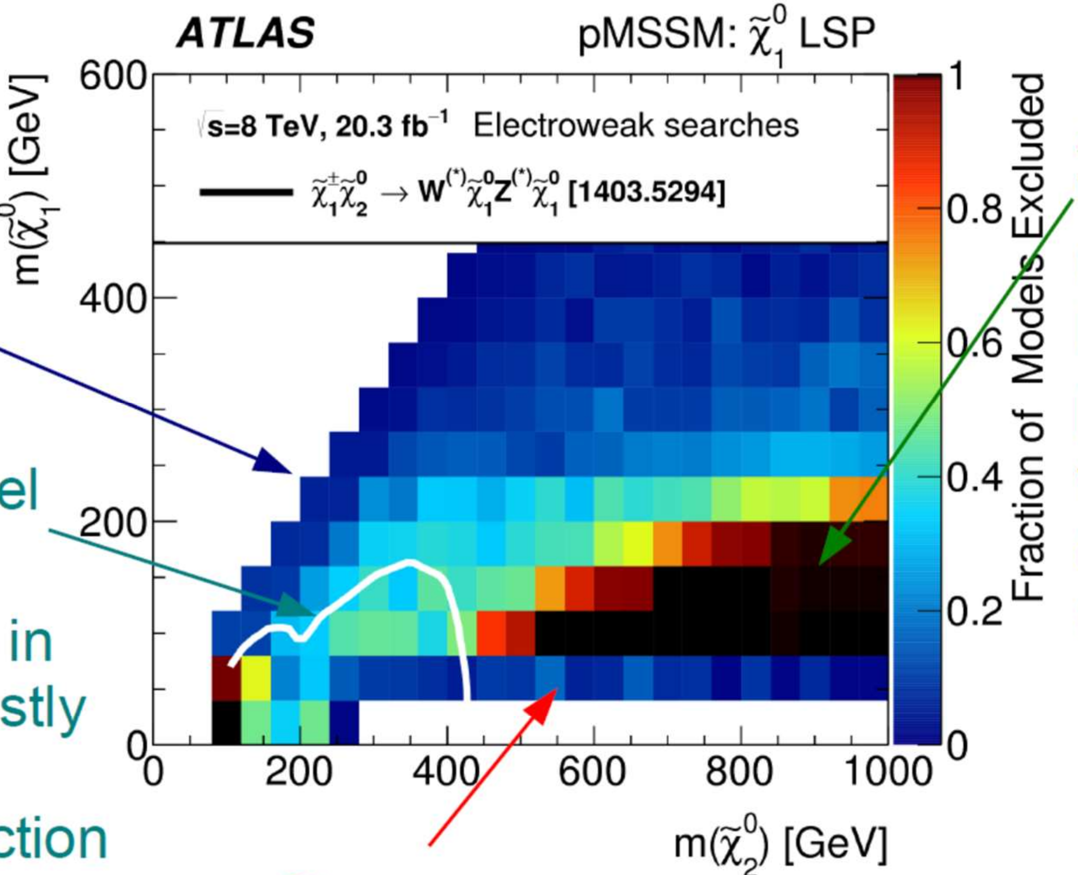


Due to not all 8 light-flavor squarks being degenerate in the pMSSM



Electroweakinos

Electroweakino exclusion complicated due to strong dependence on the nature of LSP (Bino, Wino and Higgsino admixture)



Diagonal dominated by Higgsino-like LSP – poorly excluded

Simplified model assumes $\tilde{\chi}_2^0$ is pure Wino, but in our models mostly Higgsino with lower cross section and thus worse exclusion

Almost all Wino LSP models with long-lived $\tilde{\chi}_1^+$

Lifetime largest when Bino and Higgsinos are heavy

m($\tilde{\chi}_1^0$)<100 GeV is all Bino LSP as light charginos are excluded by LEP

Exclusion Strength per Analysis

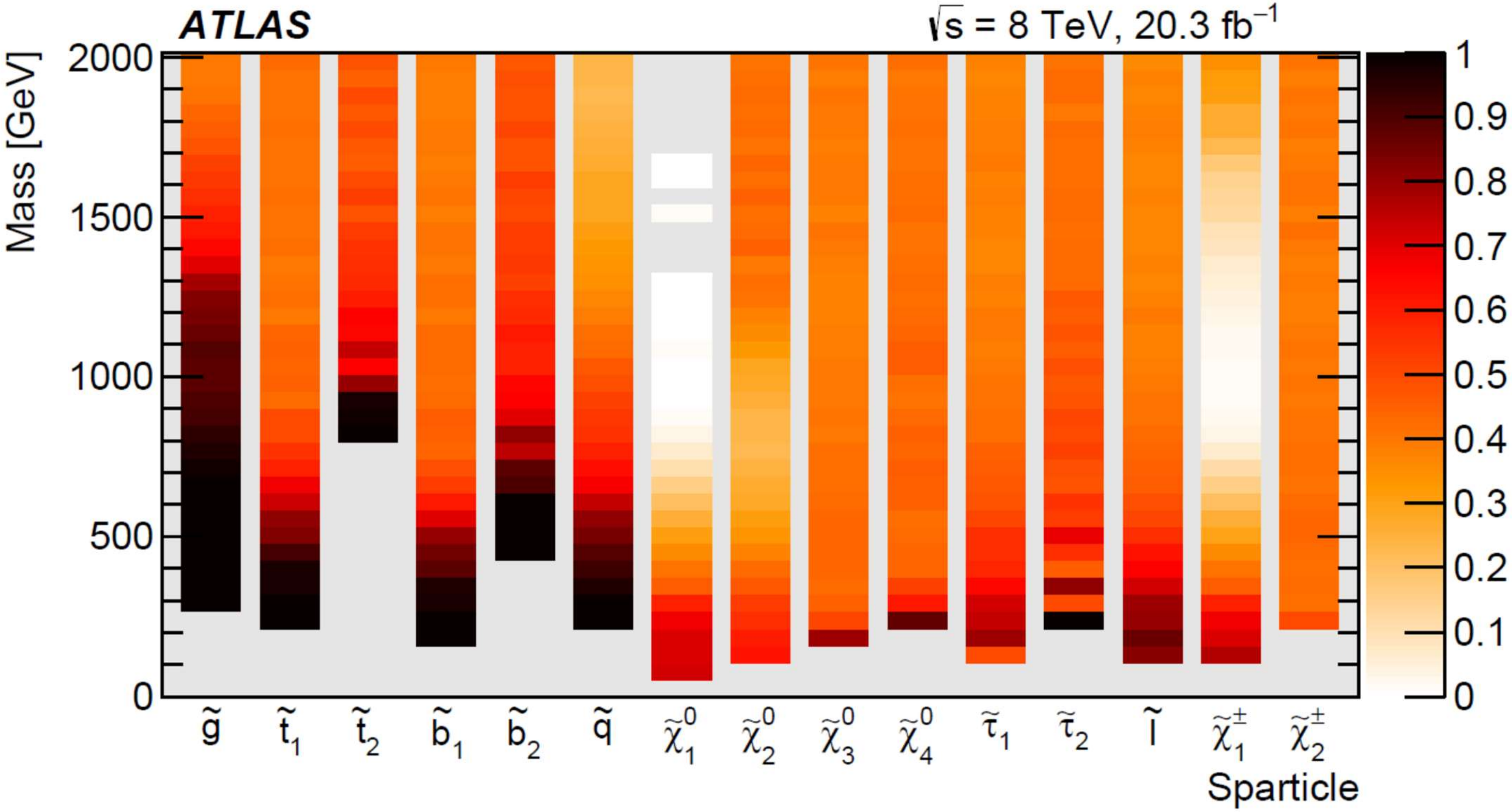
Can also compare strength of different analysis for these pMSSM models

Absolute fractions very dependent on pMSSM scan range, but gives idea of relative sensitivity

Split by LSP type (dominant $\tilde{\chi}_1^0$ component)

Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{miss}	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + E_T^{miss}	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
$tb+E_T^{miss}$, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

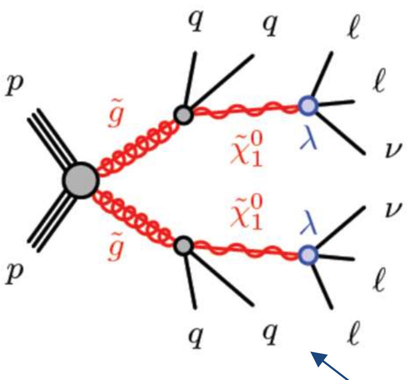
Conclusion

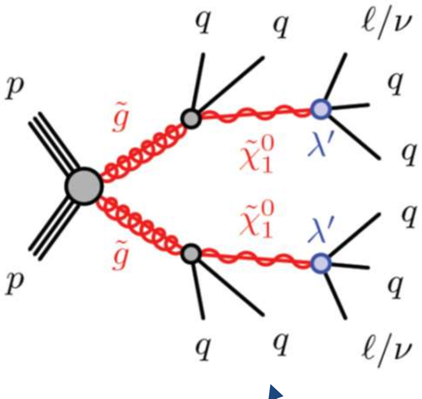

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Mass [GeV]
2000
1500
1000
500
0
$\tilde{g}$
$\tilde{t}_1$
$\tilde{t}_2$
$\tilde{b}_1$
$\tilde{b}_2$
$\tilde{q}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_2^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_4^0$
$\tilde{\tau}_1$
$\tilde{\tau}_2$
$\tilde{l}$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_2^\pm$
Sparticle
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

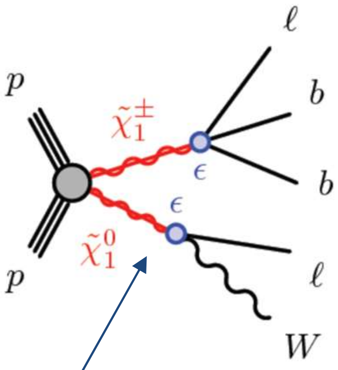
Other searches

R-parity violation

arXiv:1710.07171

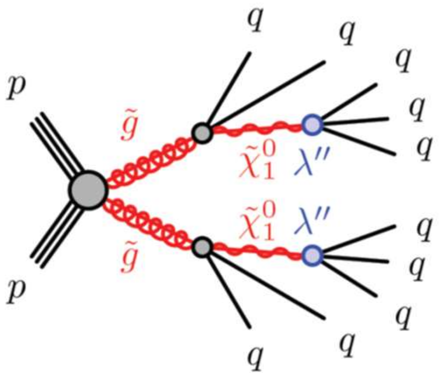






$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^i L_i H_u$$

$$W_{\Delta \mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$$

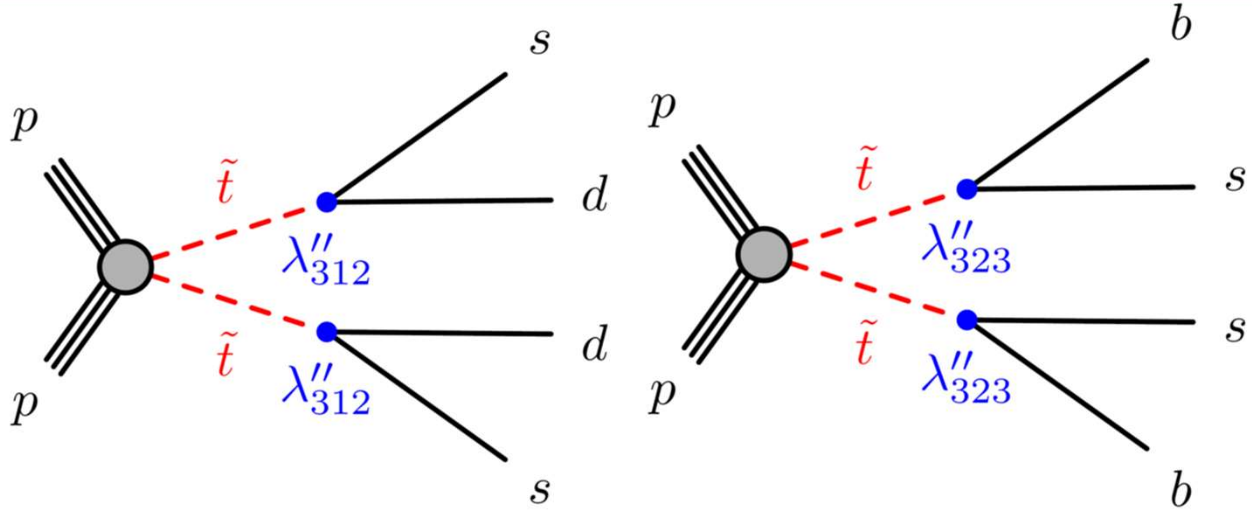


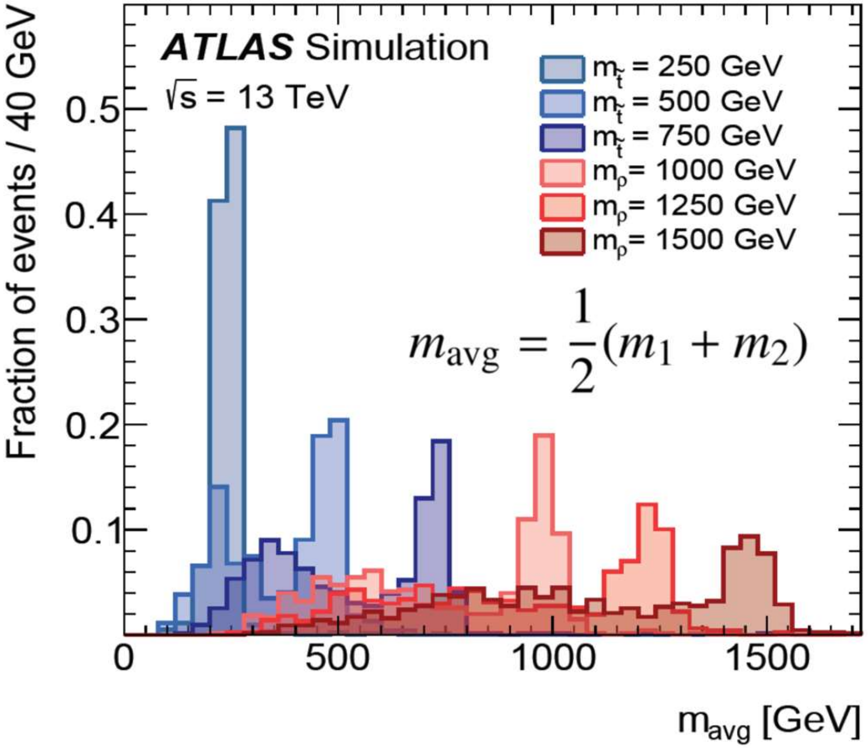
RPV allows for new terms in the superpotential and thus allows for new interactions

Proton decay prevents violation of L and B, but allows violation of L or B

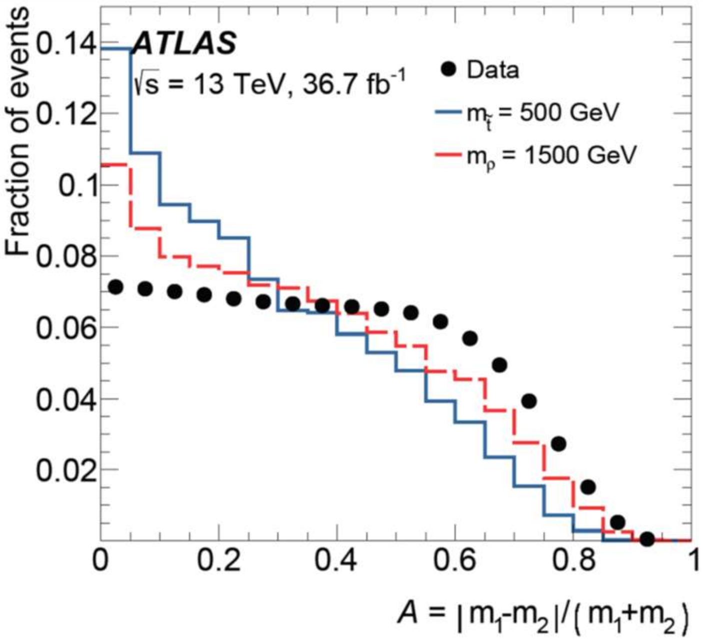
RPV leads to new collider search strategies

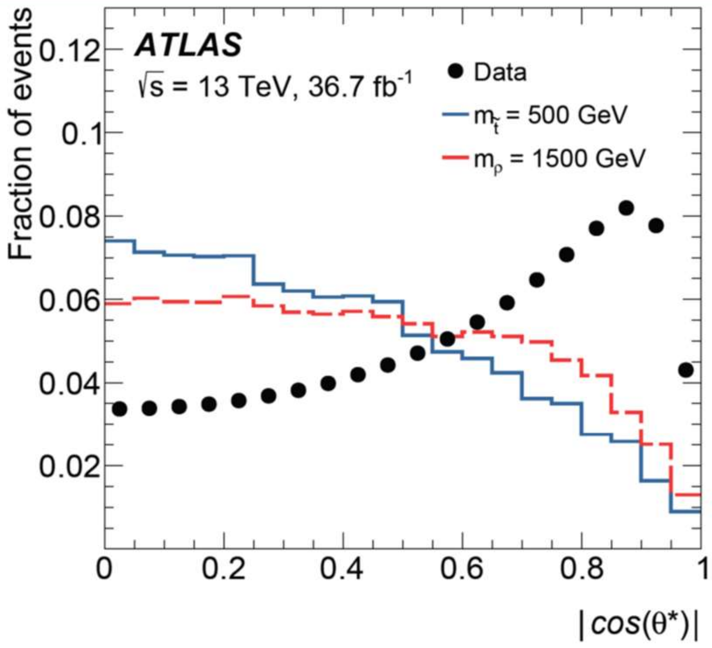
RPV: dijet resonance pairs

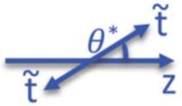


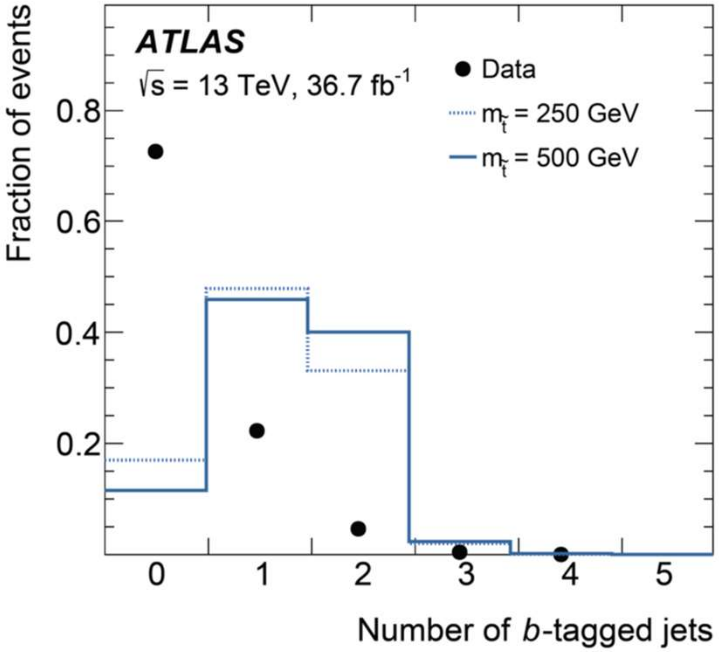


RPV: dijet resonance pairs

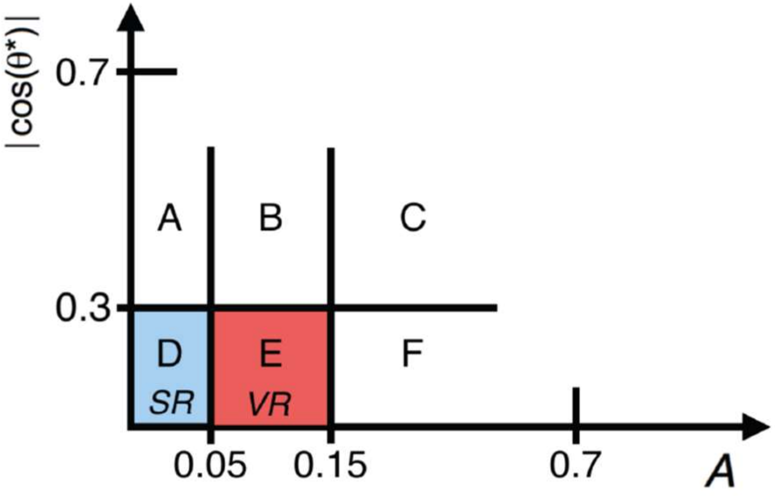




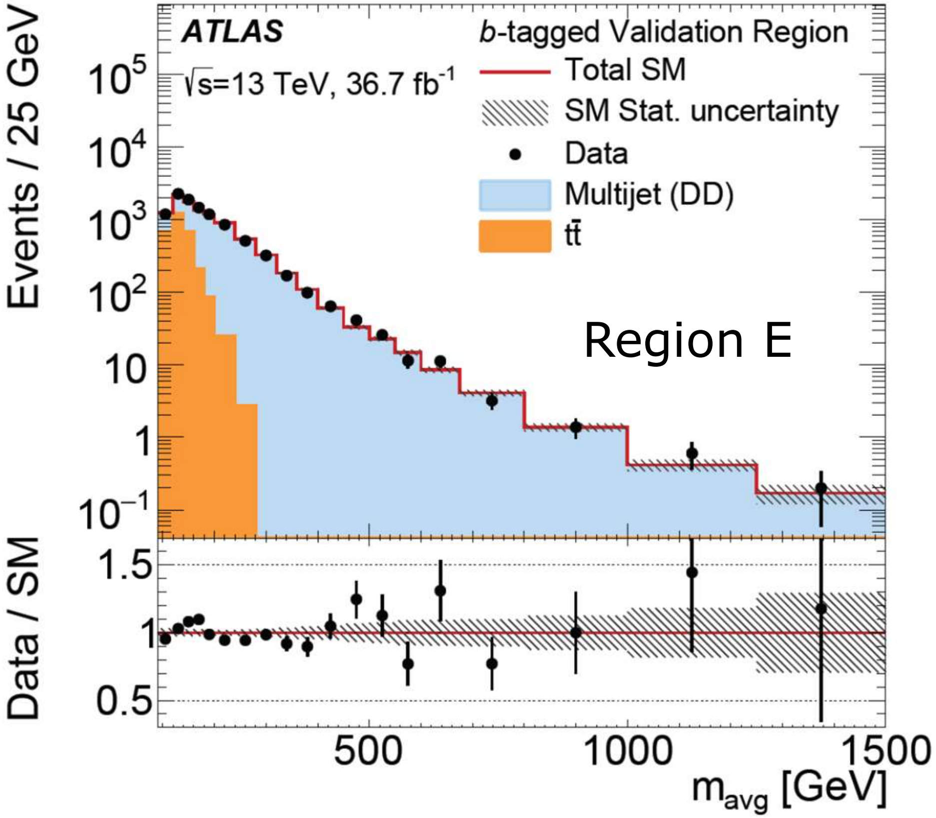




RPV: dijet resonance pairs



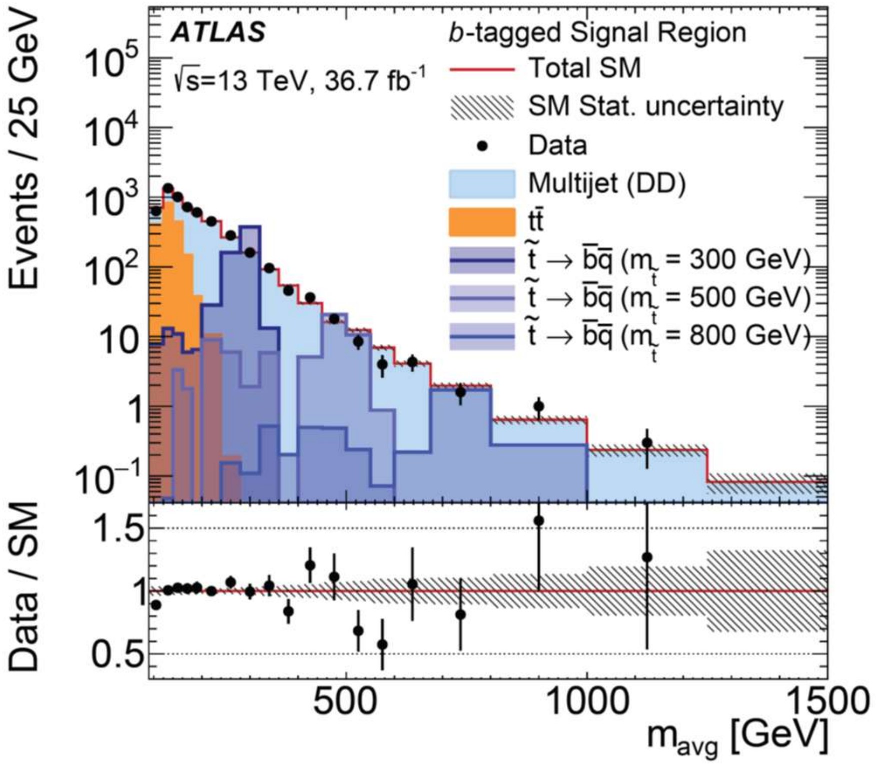
$$N_\mathrm{D} = N_\mathrm{A} \times N_\mathrm{F} / N_\mathrm{C}$$

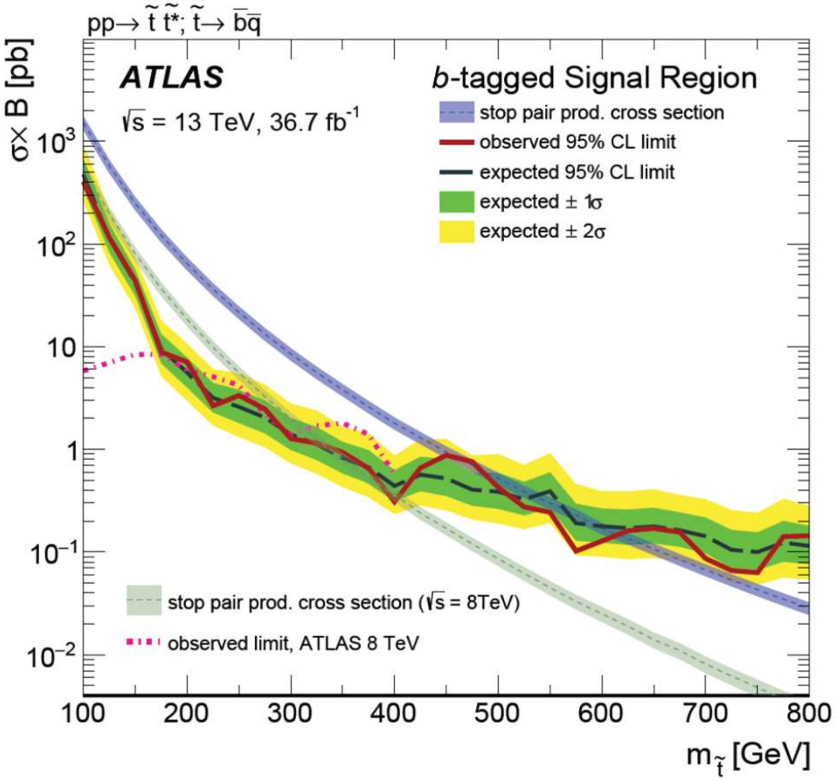


Assumptions:

- Variables not correlated
- No signal contribution in regions different other than D

RPV: dijet resonance pairs





Long-Lived Particles (LLP)

arXiv:1810.12602

$$\tau^{-1} = \Gamma = \frac{1}{2m_X} \int d\Pi_f |\mathcal{M}(m_X \to \{p_f\})|^2$$

There are many ways SUSY particles could be long lived

- Decay through heavy virtual particles
- Small decay phase space (ex: small Δm between NLSP and LSP)
- Small couplings (ex: decay to gravitino or small RPV coupling)

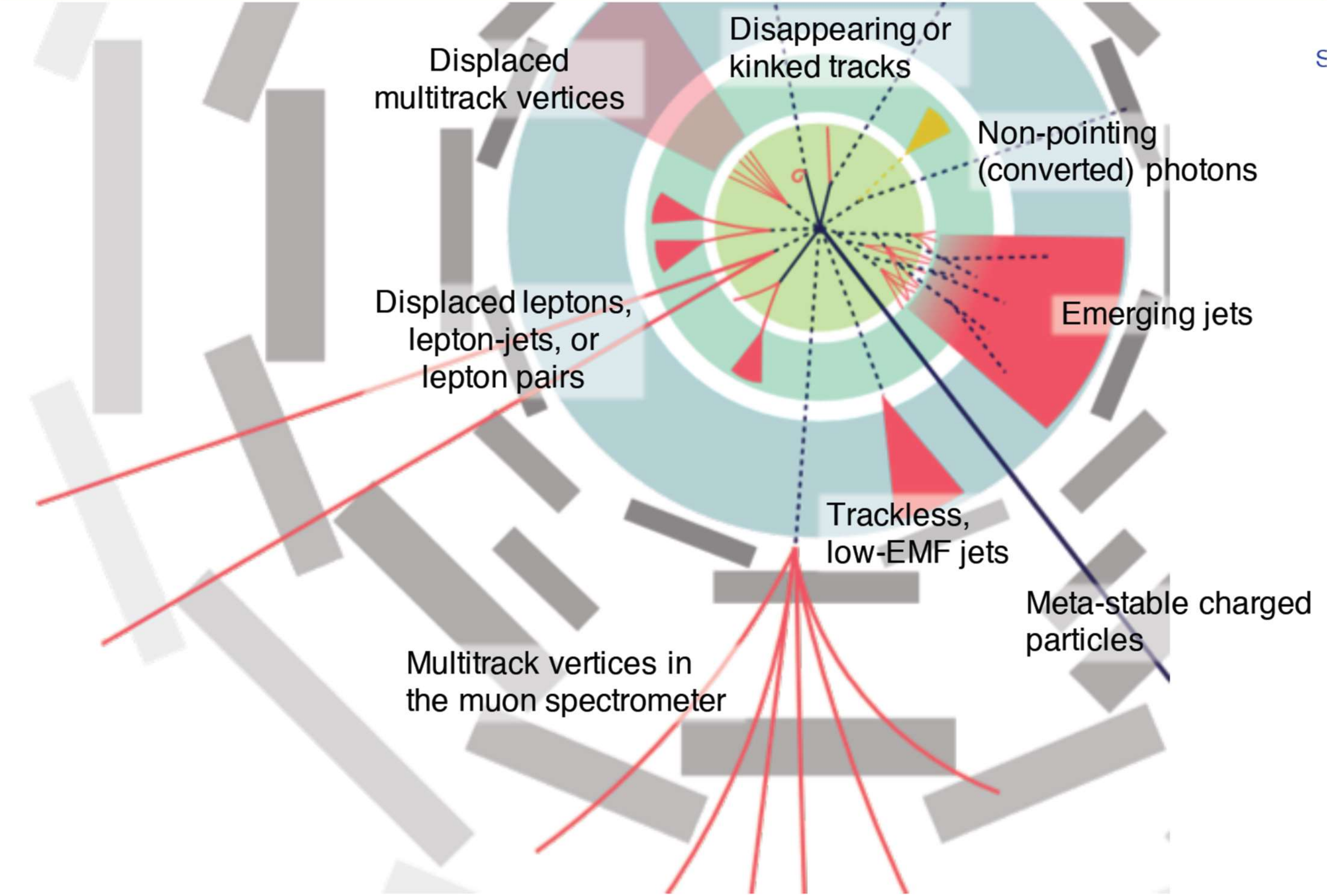
Experimentally very diverse

→ depends on particle's properties: life-time, charge, decay

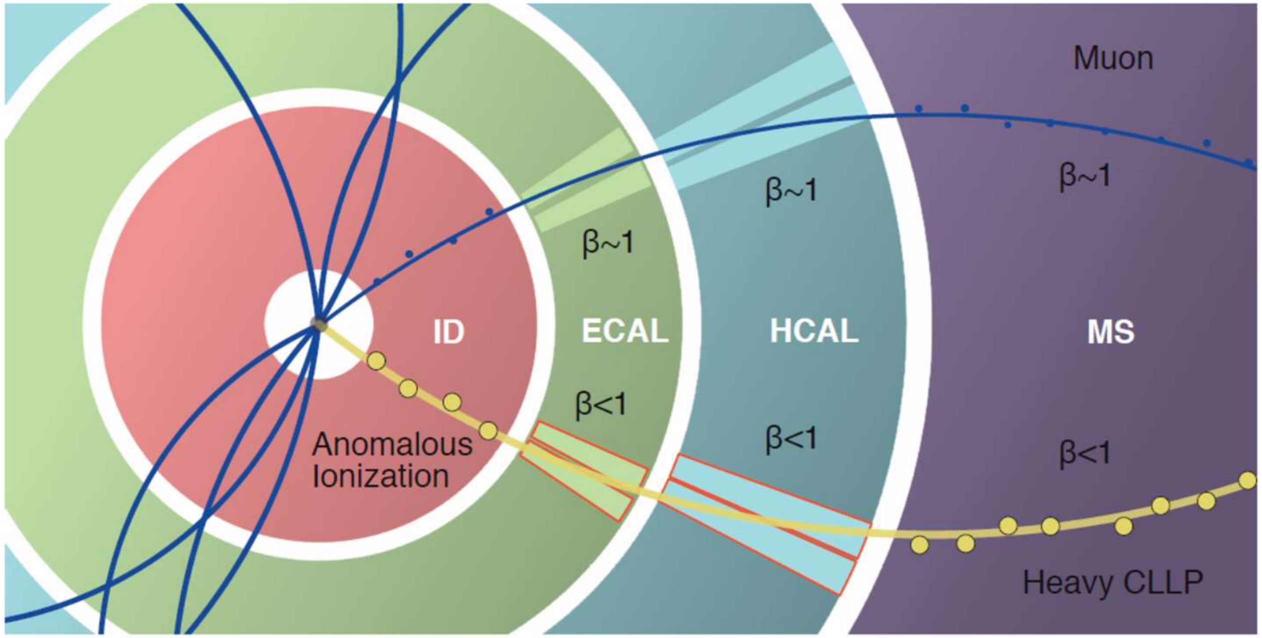
- Decay within detector
  - Life-time < O(10 ns) highly displaced vertices, kinked tracks, disappearing tracksO
- Outside detector
  - Undetectable if neutral
  - Highly ionizing (dE/dx)slow (time-of-flight)
- Decay out-of-time (wrt collision)

Mean decay length = γcτ
γ = Lorentz boost
c = speed of light
τ = mean life-time

Long-Lived Particles (LLP)



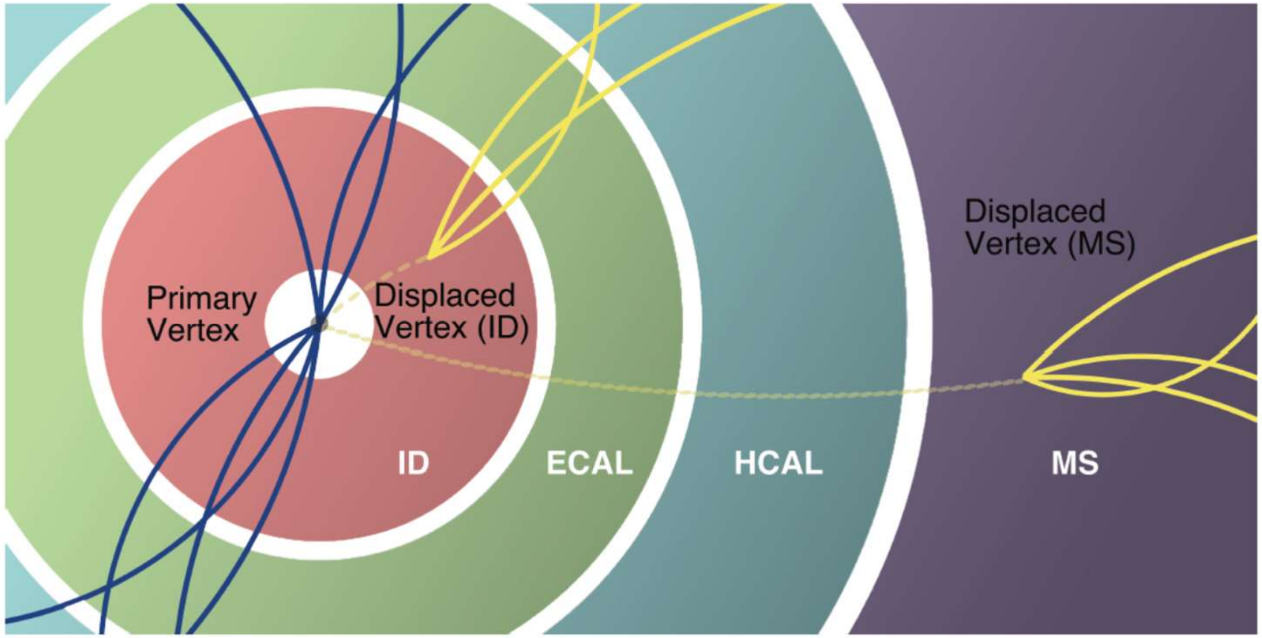
Long-Lived Particles (LLP)



Anomalous ionisation

$$\left\langle \frac{dE}{dx} \right\rangle \sim -\frac{z^2}{\beta^2} \cdot \left[\ln\left(\frac{\beta^2}{(1-\beta^2)}\right) - \beta^2 + C \right]$$

A charged LLP that is slow-moving (β<1) or has charge greater than 1 can be identified via anomalously large using for instance pixel detectors



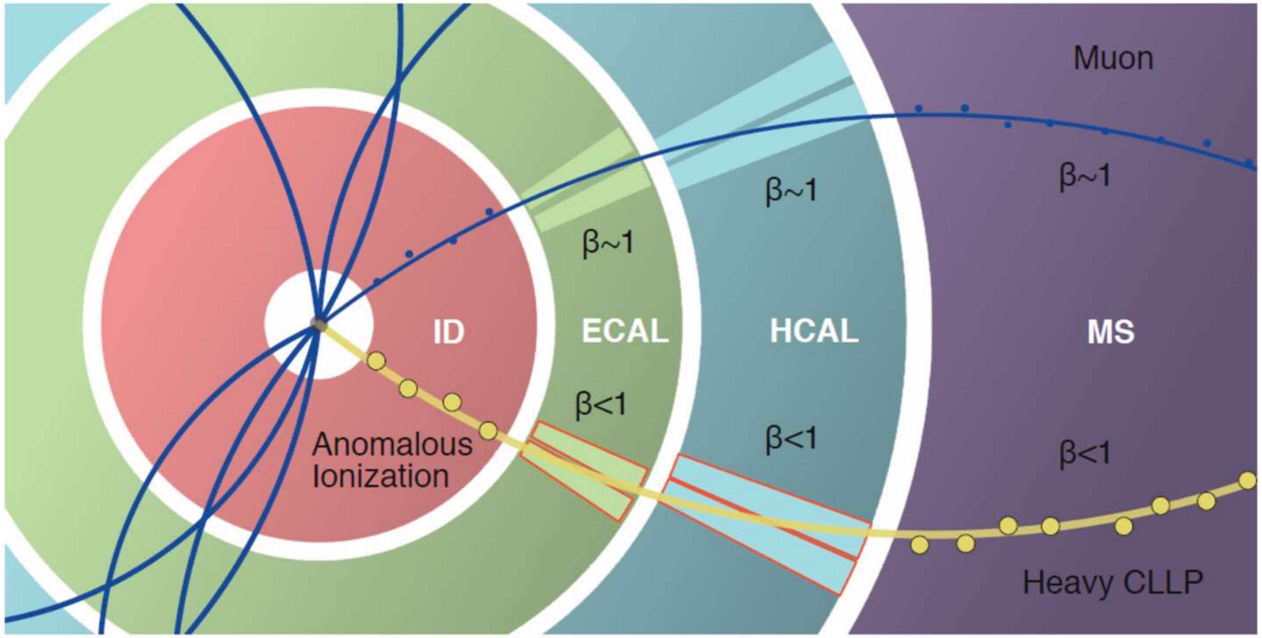
Displaced objects

- Tracks
- Vertices
- Calorimeter deposits

→ Need dedicated reconstruction algorithms

LLP can be stopped in the detector and decays long afterwards (τ>10ns)

Long-Lived Particles (LLP)



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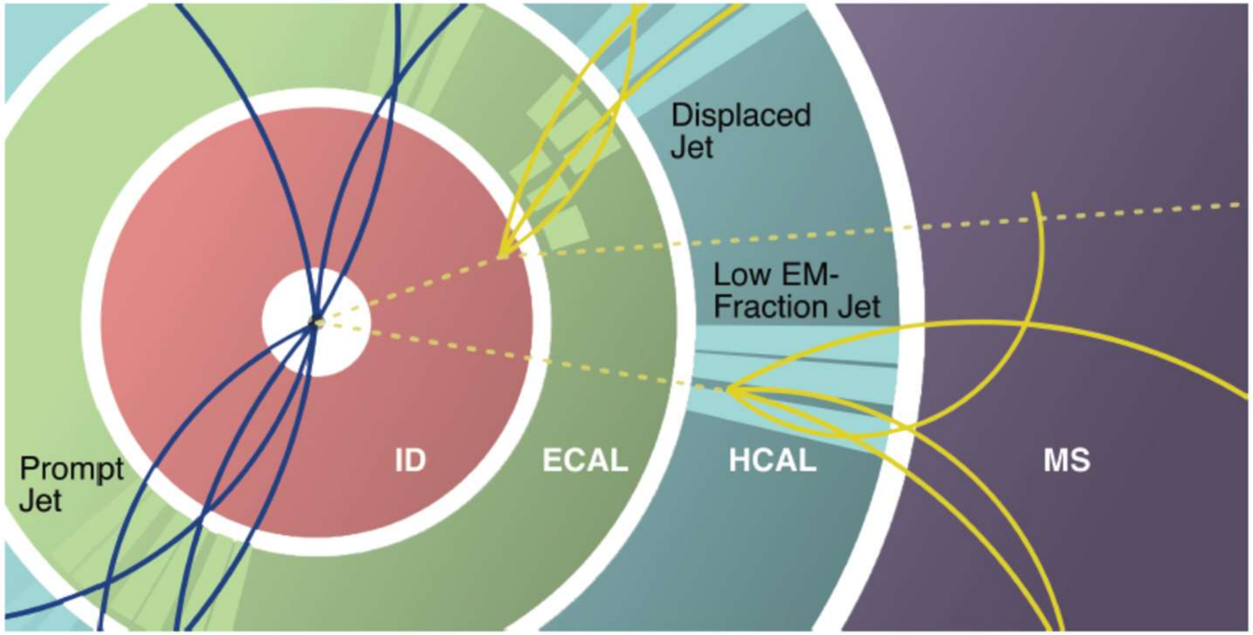

Displaced objects

- Tracks
- Vertices
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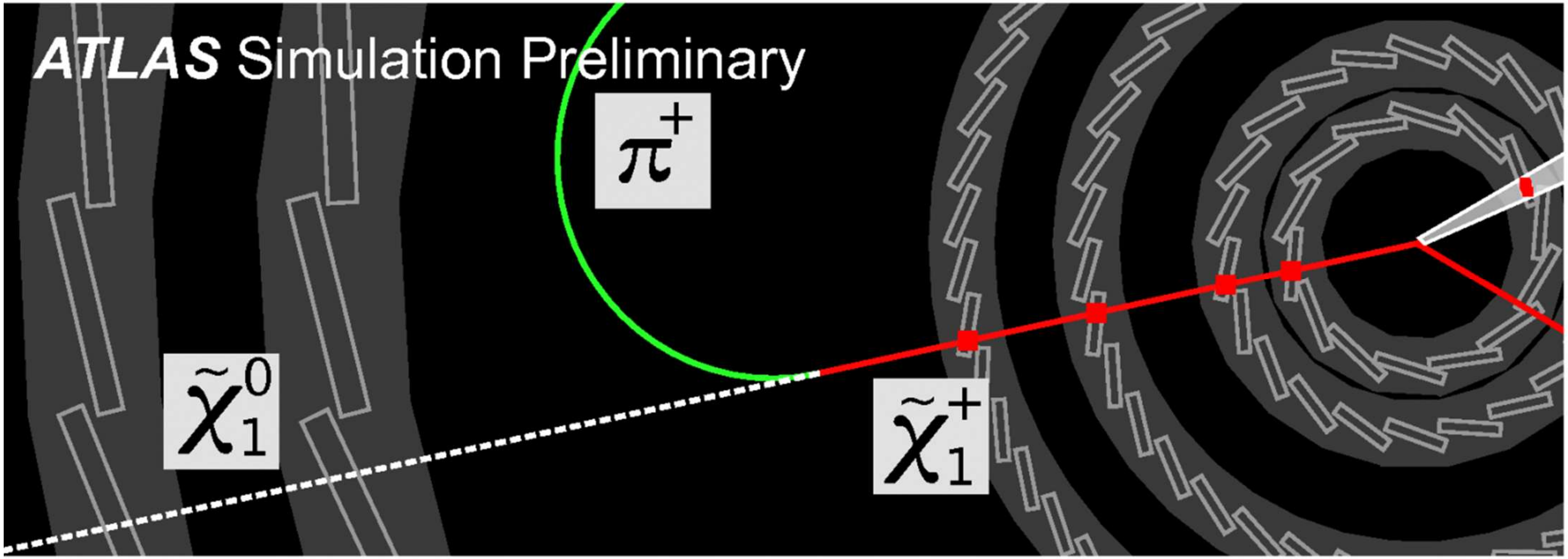
LLP can be stopped in the detector and decays long afterwards (τ>10ns)

Long-Lived Particles (LLP)

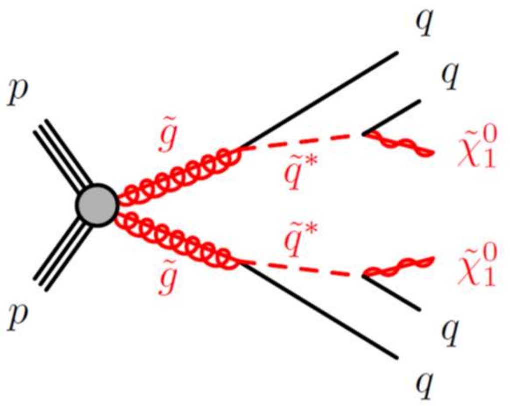
Disappearing tracks



LLP: stopped gluinos

Split SUSY (unnatural model): very heavy scalars but the Higgs weak scale mass gauginos and in particular the gluinos:

$$\Gamma^{-1} \sim \left(\frac{m_S}{10^3\ \mathrm{TeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \times 10^{-4}\ \mathrm{ns}$$

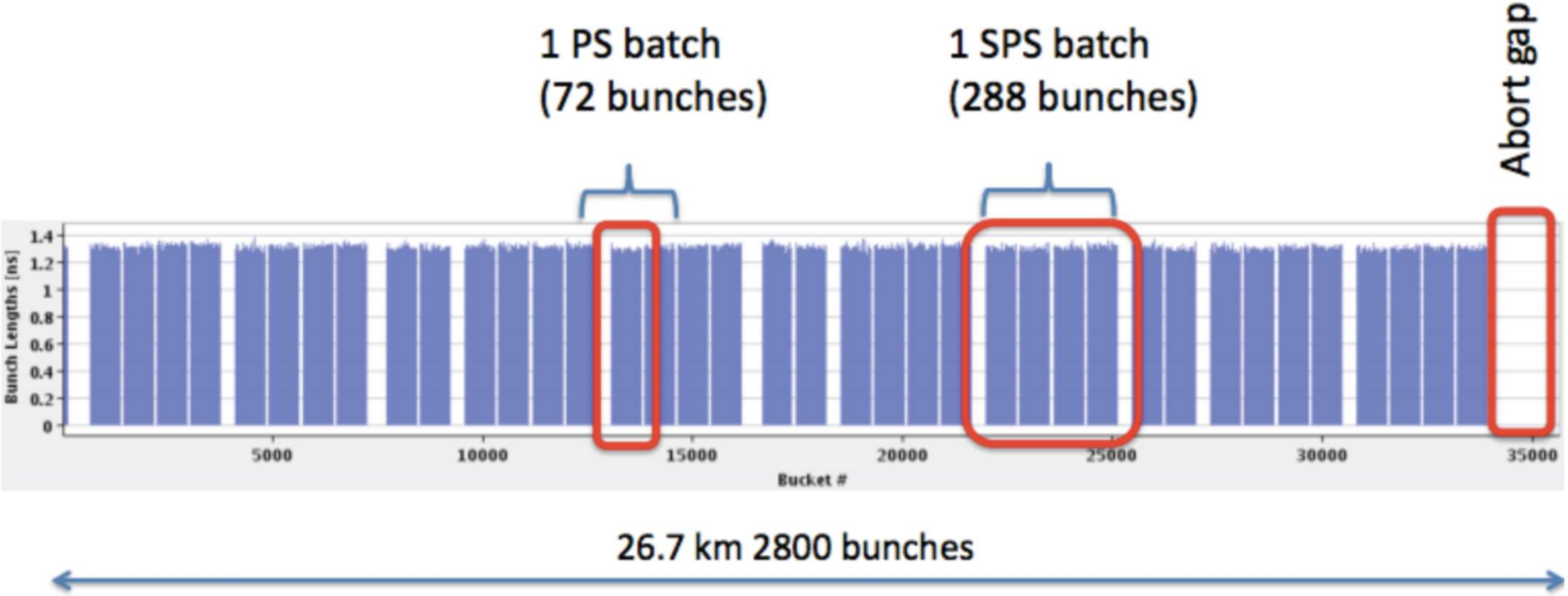


- $m_S > 10^3$GeV: the gluino is long lived and hadronize into a color-singlet state known as R-hadron ($g\tilde{g}, q\bar{q}\tilde{g}, qqq\tilde{g}$) before decaying
- $m_S > 10^6$GeV: it travels macroscopic distances before decaying
- $m_S > 10^7$GeV: it typically decays outside the detector or is stopped in the detector material
- $m_S > 10^{13}$GeV: it is effectively stable, since it has a lifetime longer than the age of the universe

R-hadrons that decay inside the detector can be detected via displaced or delayed decays, as well as disappearing tracks

LLP: stopped gluinos

Stopped gluinos generally can give rise to a detector signal that occurs after the triggering and readout time windows associated with the collision that produced the LLP→ search for them in gaps in the proton bunch train



3564 possible slots for protons but only a fraction is filled

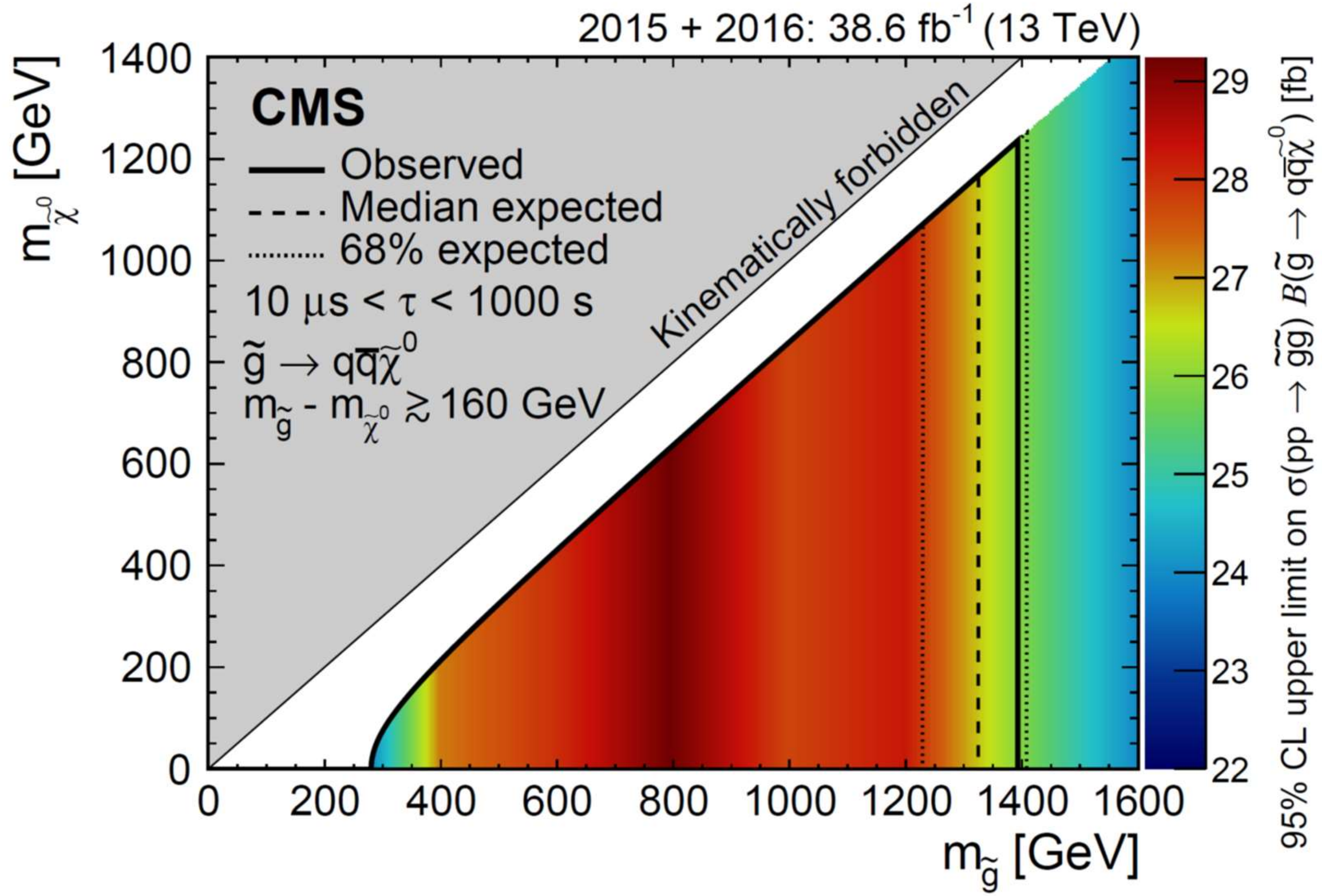
LLP: stopped gluinos

Signature: High energetic jets in absence of collisions

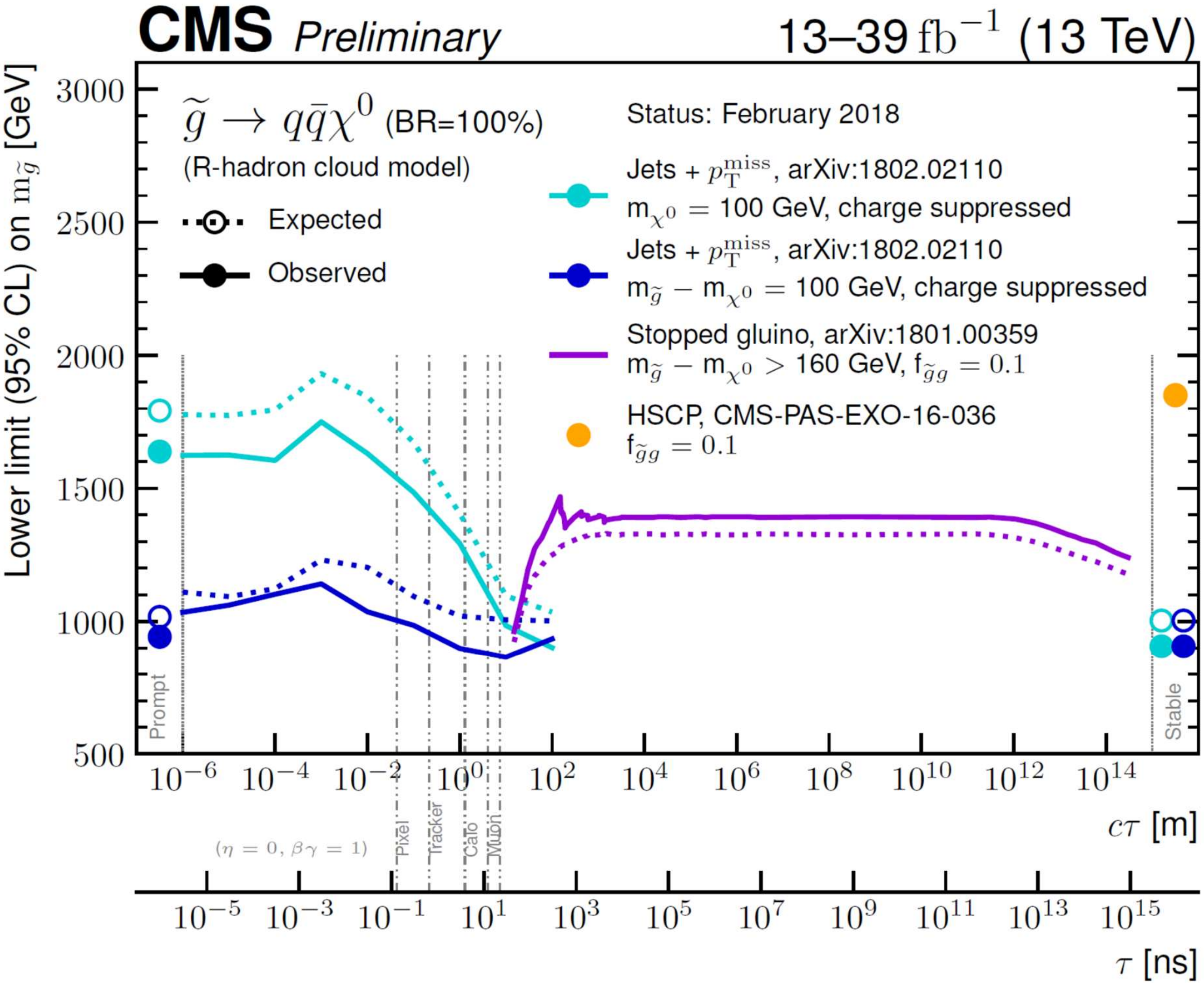
Background: calorimeter noise, cosmics and beam halo

Sensitivity: Massive particles with lifetimes 10 µs - 1000 s

No excess observed



Gluinos (R-hadron)



Exercise 1

Assuming R-parity conservation, show that

1. SUSY particles must be produced in pairs
2. One SUSY particle (except the LSP) must always contains exactly one SUSY particle in its Decay products
3. The LSP is stable