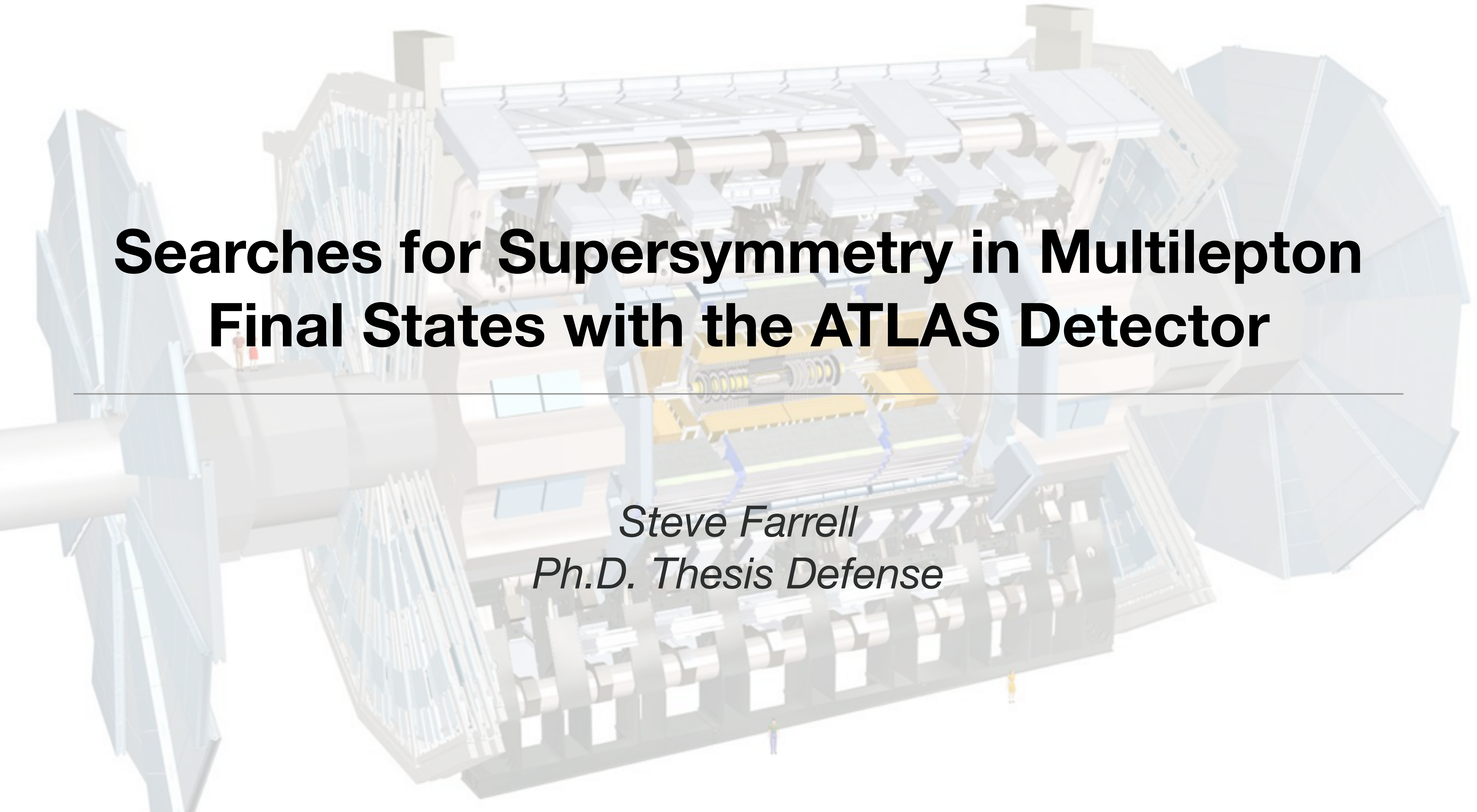

Searches for Supersymmetry in Multilepton Final States with the ATLAS Detector

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Ph.D. Thesis Defense

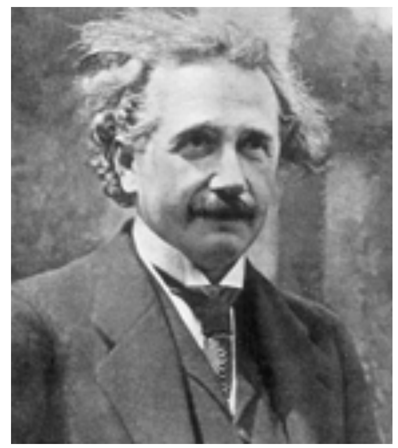
University *of* California · Irvine

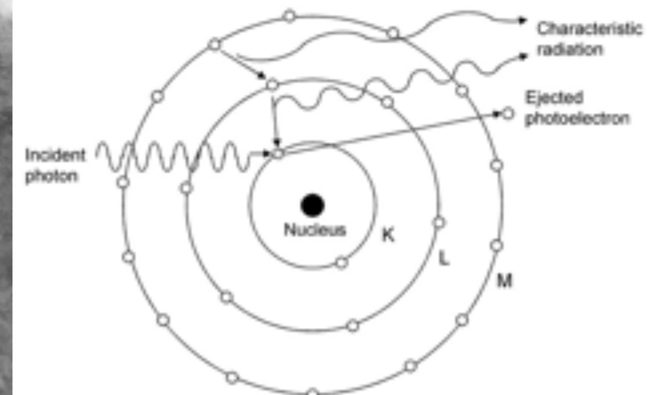
Introduction

- The field of (particle) physics is constantly looking to reinvent itself

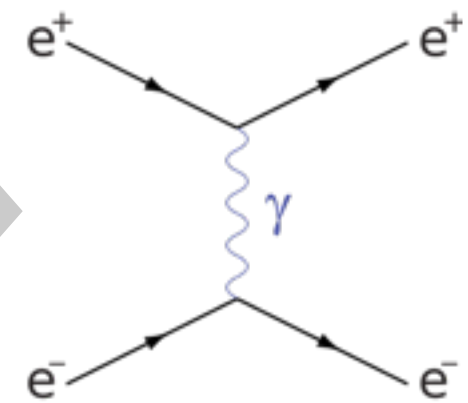
Classical mechanics

Relativity and quantum mechanics





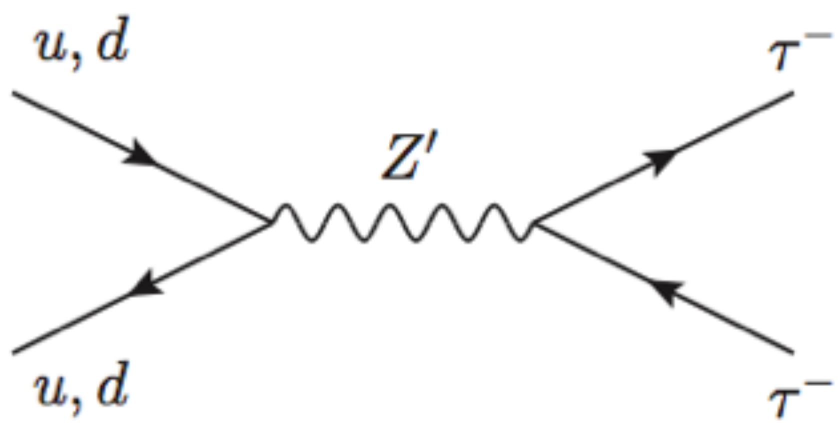
Quantum field theory



- We now have a nice working model of elementary particle particles
  - but we know it is not complete
- We have some guiding principles in searches for new physics
  - Namely, symmetries!

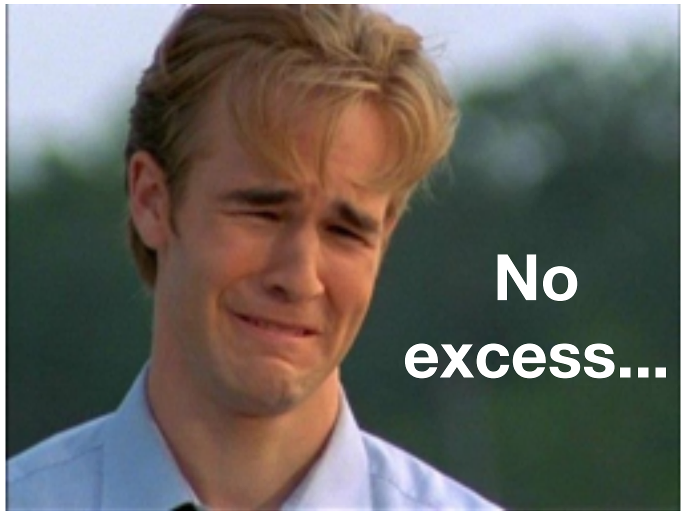
How do we look for new physics?

- New symmetries usually come with new particles
- These particles can be produced in collisions at the LHC



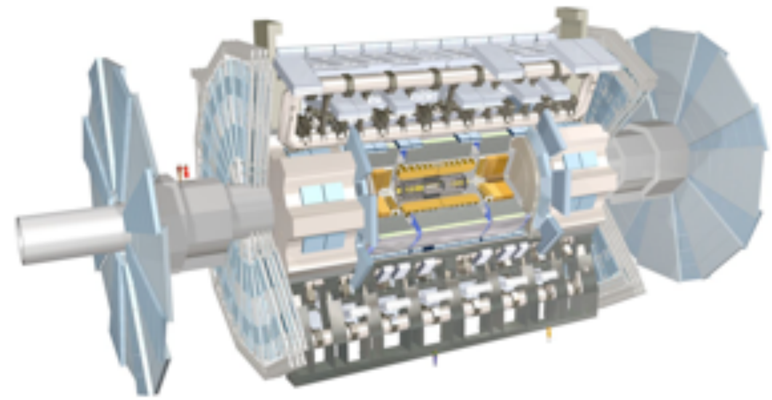
- How do we find them?
  - Understand the signature
  - Tune an event selection
  - Look for an excess in the data

- What if we don't see anything new?
  - Cry a little
  - Set limits on new physics models



How have I contributed?

- I work on the ATLAS experiment and analyze LHC data



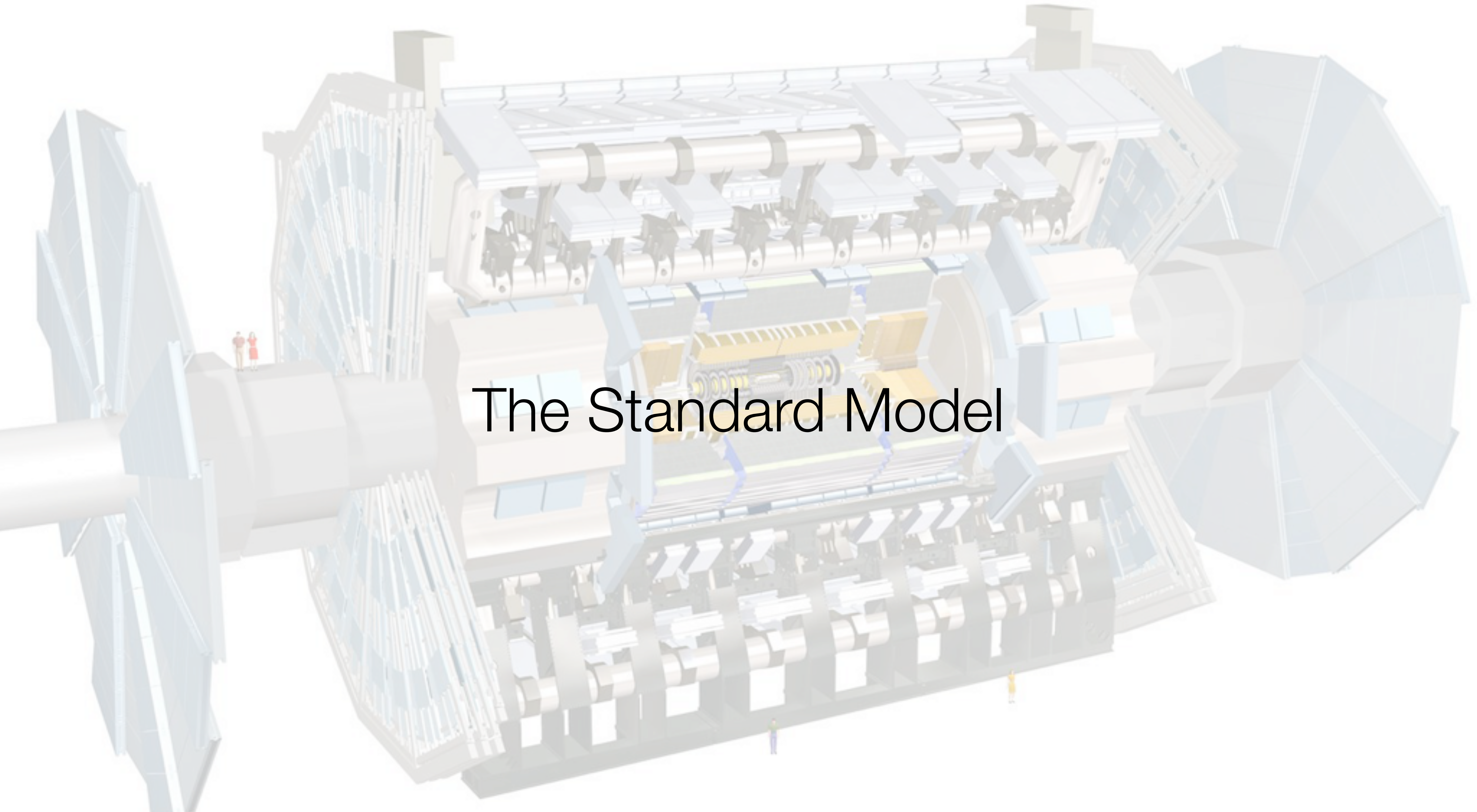
- Searches for supersymmetry
  - **Three-lepton electroweak analysis**
    - Common analysis software
    - Object and event selection
    - Background studies and estimation

    Public results
    2 papers with 2011 data
    2 conference results with 2012 data
    1 paper in internal review
  - **Four-lepton analysis (electroweak and R-parity violation)**
    - Common analysis software
    - Object selection
    - Background estimation

    Public results
    1 paper with 2011 data
    1 conference result with 2011 data
    2 conference results with 2012 data
- Data quality studies and monitoring

Contents of this Defense

- Part I - Theory
  - The Standard Model of Particle Physics
    - Its content and flaws
  - Supersymmetry
    - Theoretical and experimental features
- Part II - Experimental Apparatus
  - The ATLAS Experiment
    - The LHC, the detector, and particle reconstruction
- Part III - Data Analysis
  - A Search for Electroweak SUSY in the Three-Lepton Channel
  - A Search for RPV and RPC SUSY in the Four-Lepton Channel
- Conclusions

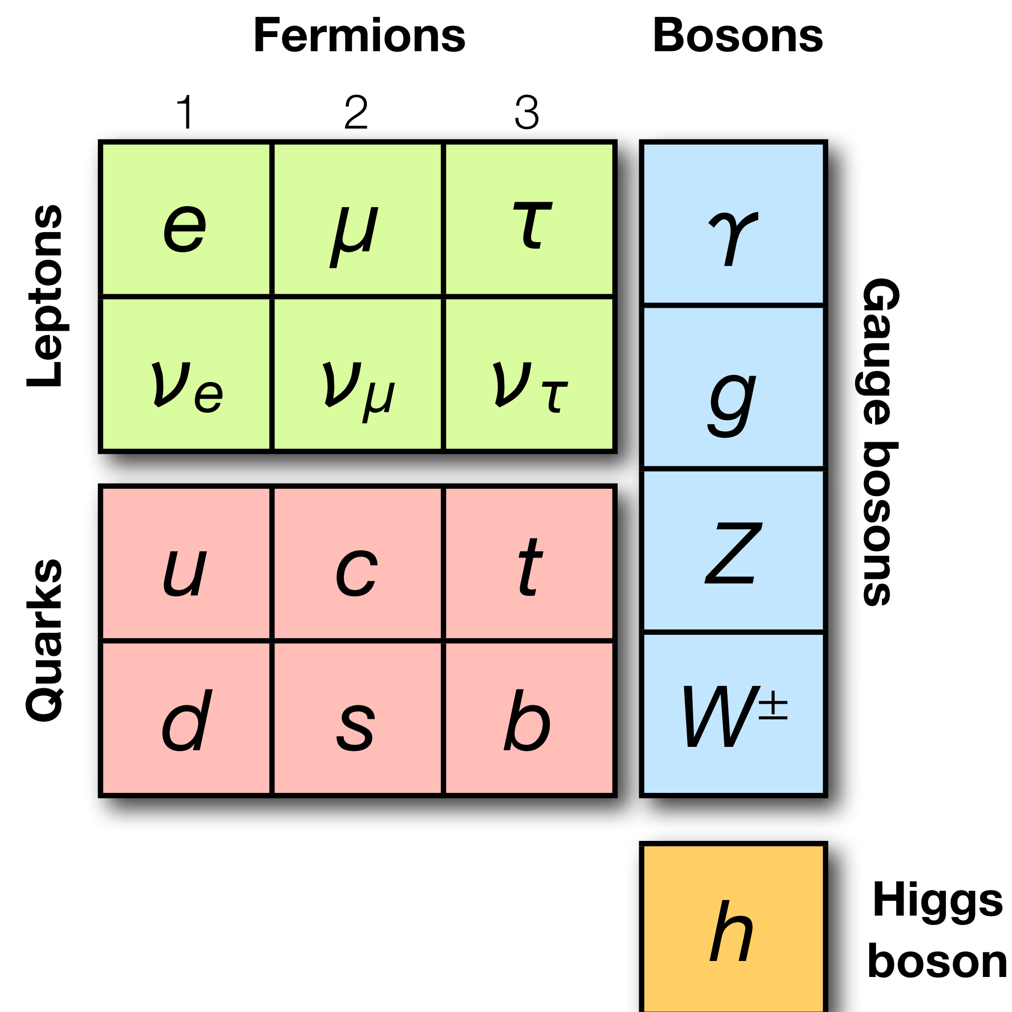


The Standard Model

Overview of the Standard Model

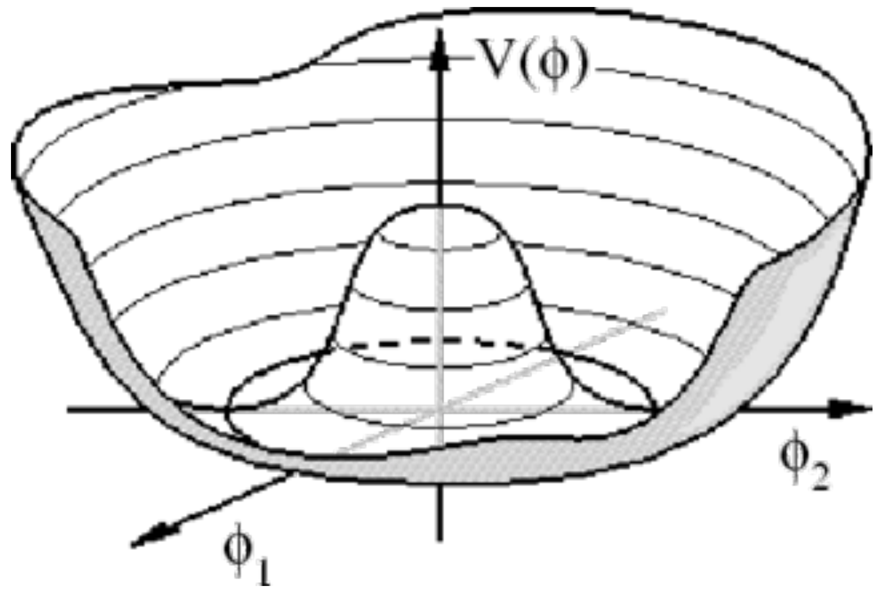
- A quantum field theory describing *fermions* and *bosons*
- Three generations of leptons and quarks
- Three fundamental interactions arising from gauge symmetry

$$\underset{\textbf{8 gluons}}{\underset{\downarrow}{SU(3)_C}} \times \underset{\textbf{3 W bosons}}{\underset{\downarrow}{SU(2)_L}} \times \underset{\textbf{B boson}}{\underset{\downarrow}{U(1)_Y}}$$



- One scalar boson, the Higgs boson, responsible for electroweak symmetry breaking
  - Now discovered at the LHC!

Electroweak Symmetry Breaking



- Higgs boson potential is shaped like the bottom of a wine bottle
- The Higgs has a nonzero vacuum expectation value (VEV), which breaks the electroweak symmetry.
- Results in mass terms for the quarks, charged leptons, and electroweak gauge bosons

massless W^1, W^2, W^3, B $\longrightarrow$ (massive $W^{\pm}, Z$) + (massless γ)

Problems with the Standard Model

- Theoretical issues
    - No description of gravity
    - The hierarchy problem
- Conflicting experimental evidence

Neutrino mass

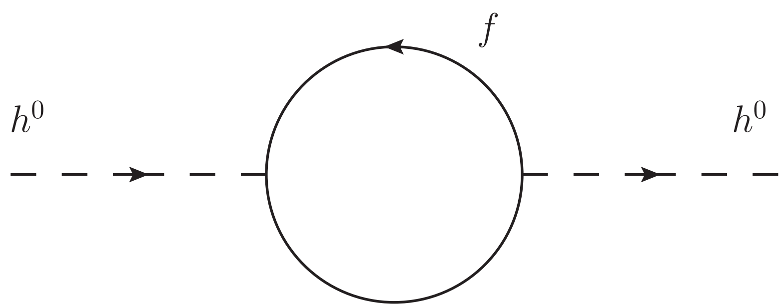
Dark matter

Dark energy

- Aesthetic issues
    - Why only three generations of fermions?
    - Why are there 19 free parameters?

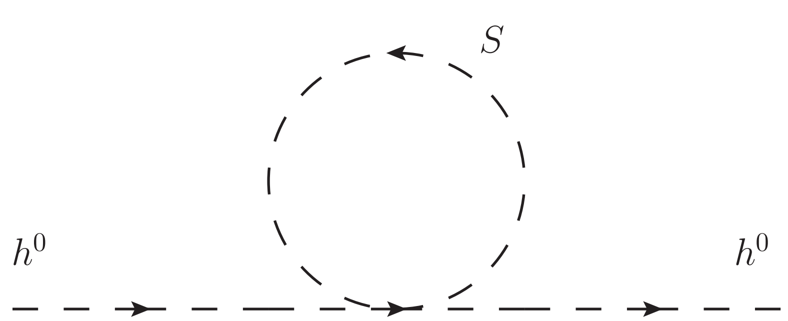
The Hierarchy Problem

- Quantum corrections to the Higgs mass involve fermion loops which diverge, proportional to the squared cutoff scale of the integral:

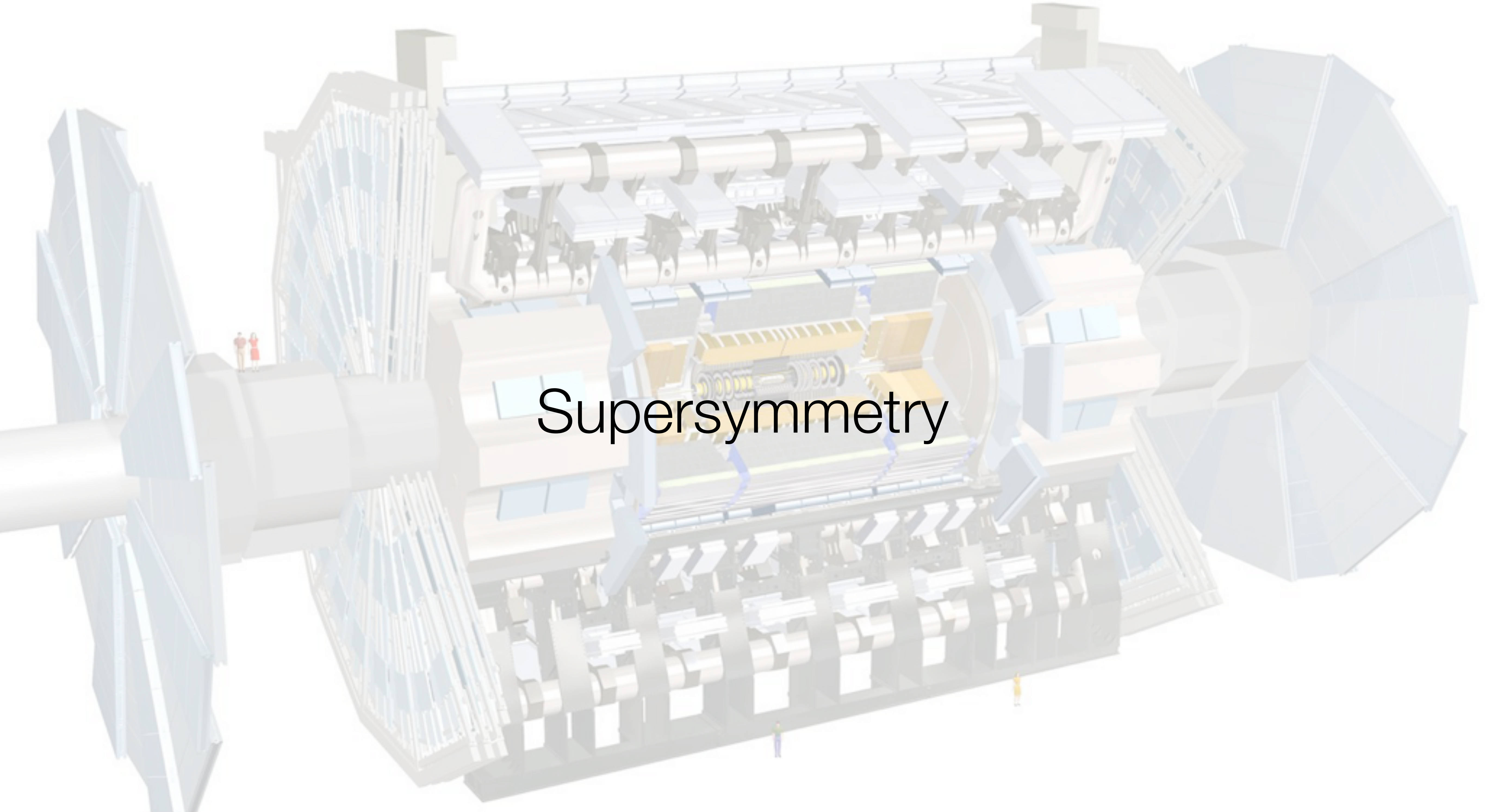


$\Delta m^2 \sim \Lambda^2$

- Miraculous fine tuning is necessary to keep the Higgs down at 125 GeV, unless some new symmetry (wink, wink) can fix it
- A corresponding scalar particle with the same coupling strength will give a negative contribution which cancels the one above:



- By introducing new partner particles for each contributing SM particle with spin differing by 1/2, the Higgs mass is stabilized



Supersymmetry

General Features of Supersymmetry

- A symmetry of nature which relates fermions and bosons
- Fields are grouped into supermultiplets with equal number of fermionic and bosonic degrees of freedom
- To make the Standard Model supersymmetric, each SM particle must get a new partner particle

- Some common attractive features of SUSY models
  - They can solve the hierarchy problem
  - The gauge couplings can be made to unify at some high scale
  - They can provide a candidate for Dark Matter (under R-parity)

The Minimal Supersymmetric Standard Model

- Minimal particle content to be supersymmetric and consistent with the SM
- The SM fermions get scalar sfermion partners: the squarks and sleptons
  - Same chiral structure as the SM
- The gauge bosons get fermion partners, the gauginos
- ***Two*** Higgs doublets in the MSSM with fermion partners, the higgsinos

Chiral supermultiplets

Names		Spin-0	Spin-1/2
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$
sleptons, leptons	L	$(\tilde{\nu}_L, \tilde{e}_L)$	(ν_L, e_L)
	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$
Higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$
	H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$

Vector supermultiplets

Names	Spin-1/2	Spin-1
gluinos, gluons	$\tilde{g}$	g
winos, W bosons	$\widetilde{W}^\pm, \widetilde{W}^0$	$W^\pm, W^0$
bino, B boson	$\widetilde{B}$	B

R-parity

- The General MSSM contains terms which violate lepton and baryon number:

$$W_{\mathrm{RPV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2$$

- This allows for proton decay!
- One can disallow these terms by introducing a discrete symmetry, *R*-parity:

$$R\text{-}parity = (-1)^{2S+3B+L} = \begin{cases} +1 & \text{for ordinary particles} \\ -1 & \text{for super-partners} \end{cases}$$

- The lightest superpartner (LSP) is then stable!
  - WIMP dark matter candidate

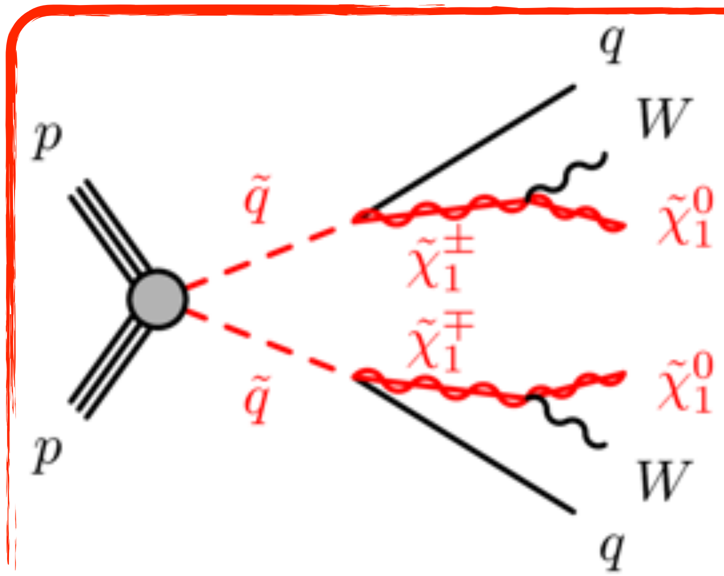
Breaking the Symmetry

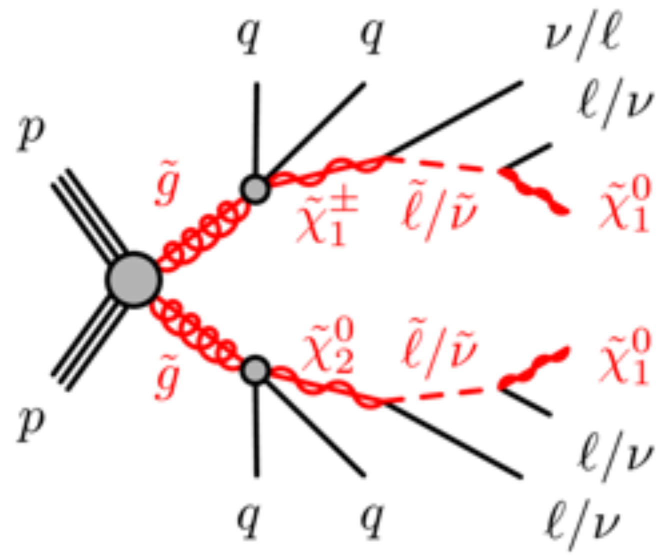
- Unbroken SUSY predicts sparticles with ***the same mass*** as their SM-counterparts
- These sparticles would have been found by now
  - SUSY must be spontaneously broken!
- How to break SUSY
  - Assume a specific breaking mechanism
    - Several ideas have been studied extensively
  - Parametrize our ignorance
    - Explicitly write down the SUSY-breaking terms; results in ***105 free parameters!***
- Mixing can occur
  - The gauginos and higgsinos mix to form the *charginos* and *neutralinos*:

$$\tilde{\chi}_1^{\pm}, \ \tilde{\chi}_2^{\pm} \qquad\qquad \tilde{\chi}_1^0, \ \tilde{\chi}_2^0, \ \tilde{\chi}_3^0, \ \tilde{\chi}_4^0,$$

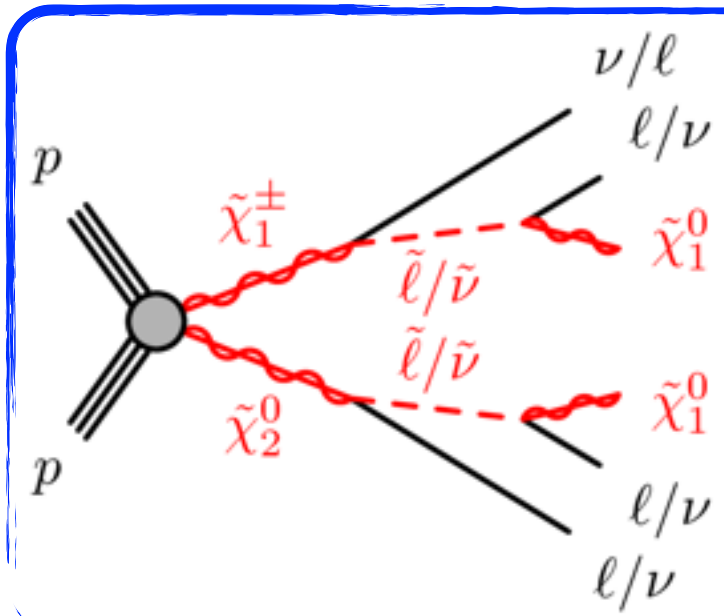
Experimental Features of Supersymmetry - RPC

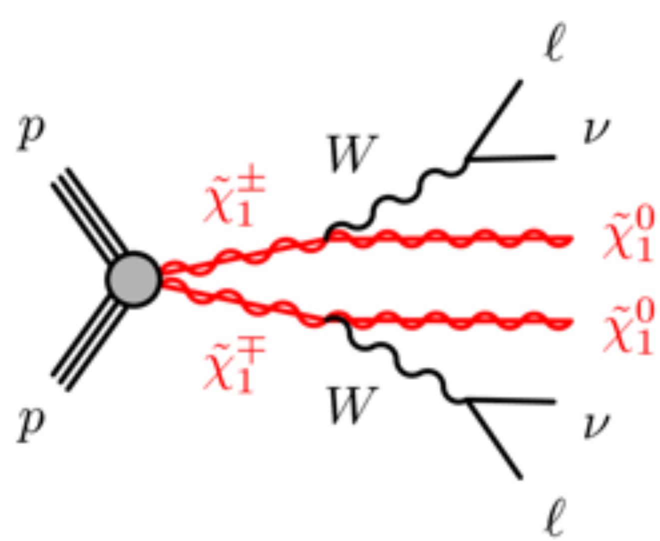
- **General features**
  - Many-body final states
  - Missing transverse momentum from LSPs





- **Strong production**
  - High cross sections
  - Decays with jets, leptons, bosons

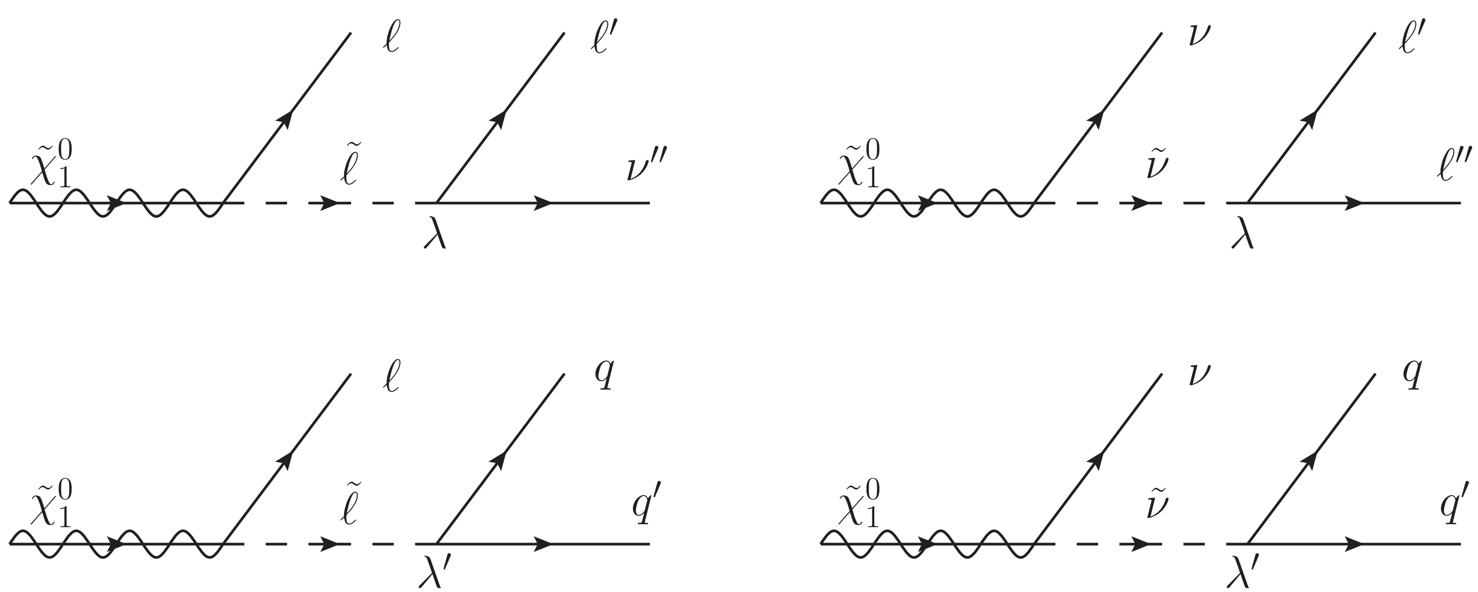




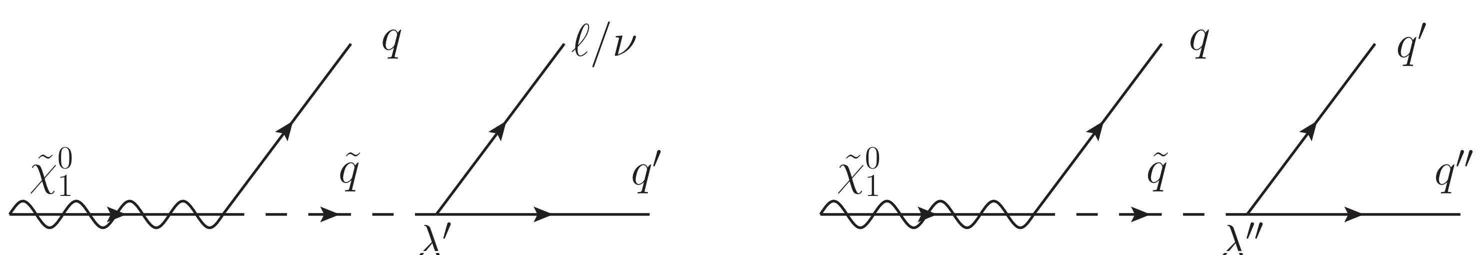
- **Electroweak production**
  - Low hadronic activity
  - Decays with bosons and leptons

Experimental Features of Supersymmetry - RPV

- **General features**
  - Production modes can be the same as the RPC models
  - The LSP can promptly decay via couplings violating lepton or baryon number

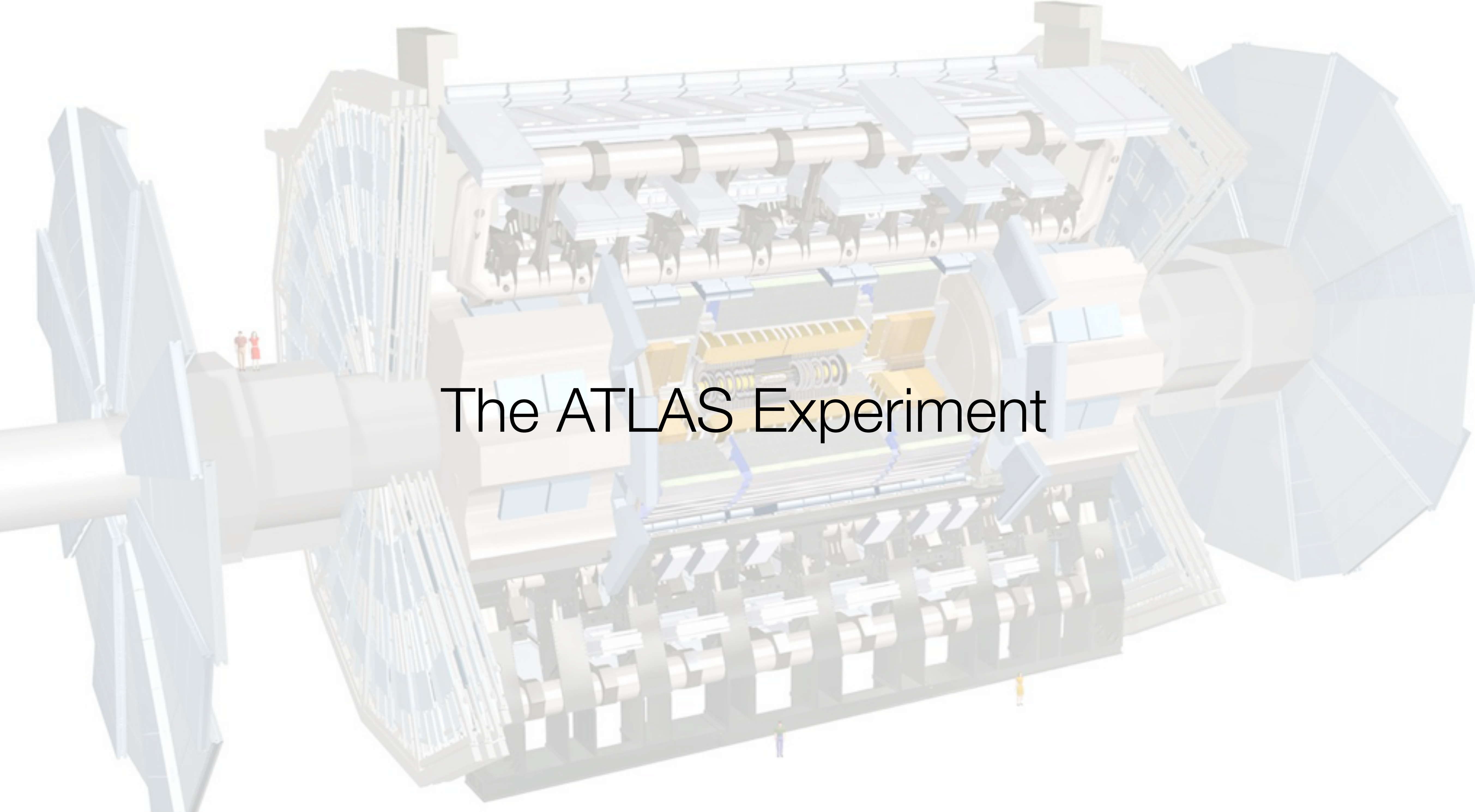


- **λ and λ' couplings violate lepton number**
  - High lepton and quark multiplicity final states

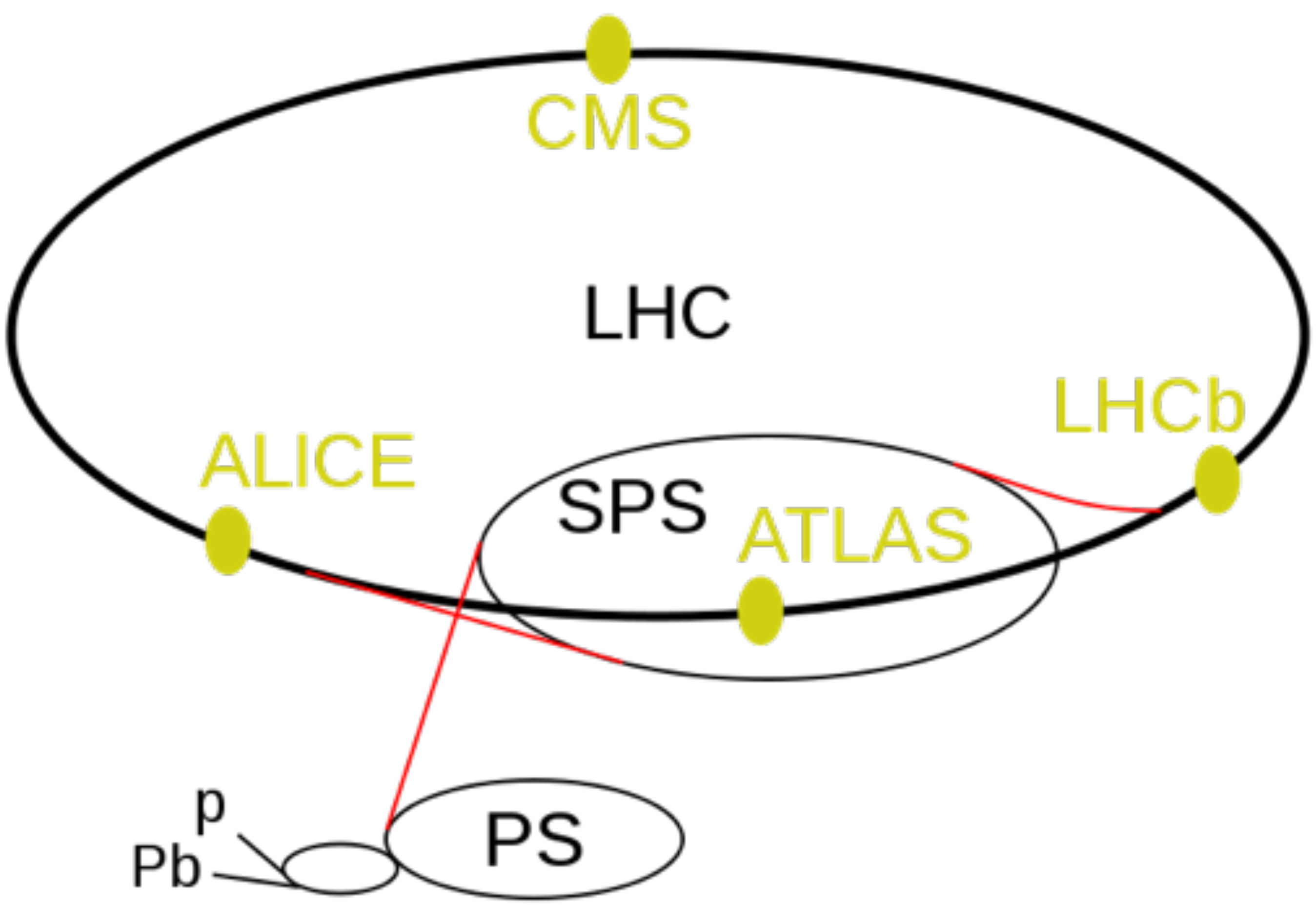


- **λ" couplings violate baryon number**
  - High jet multiplicity

The ATLAS Experiment



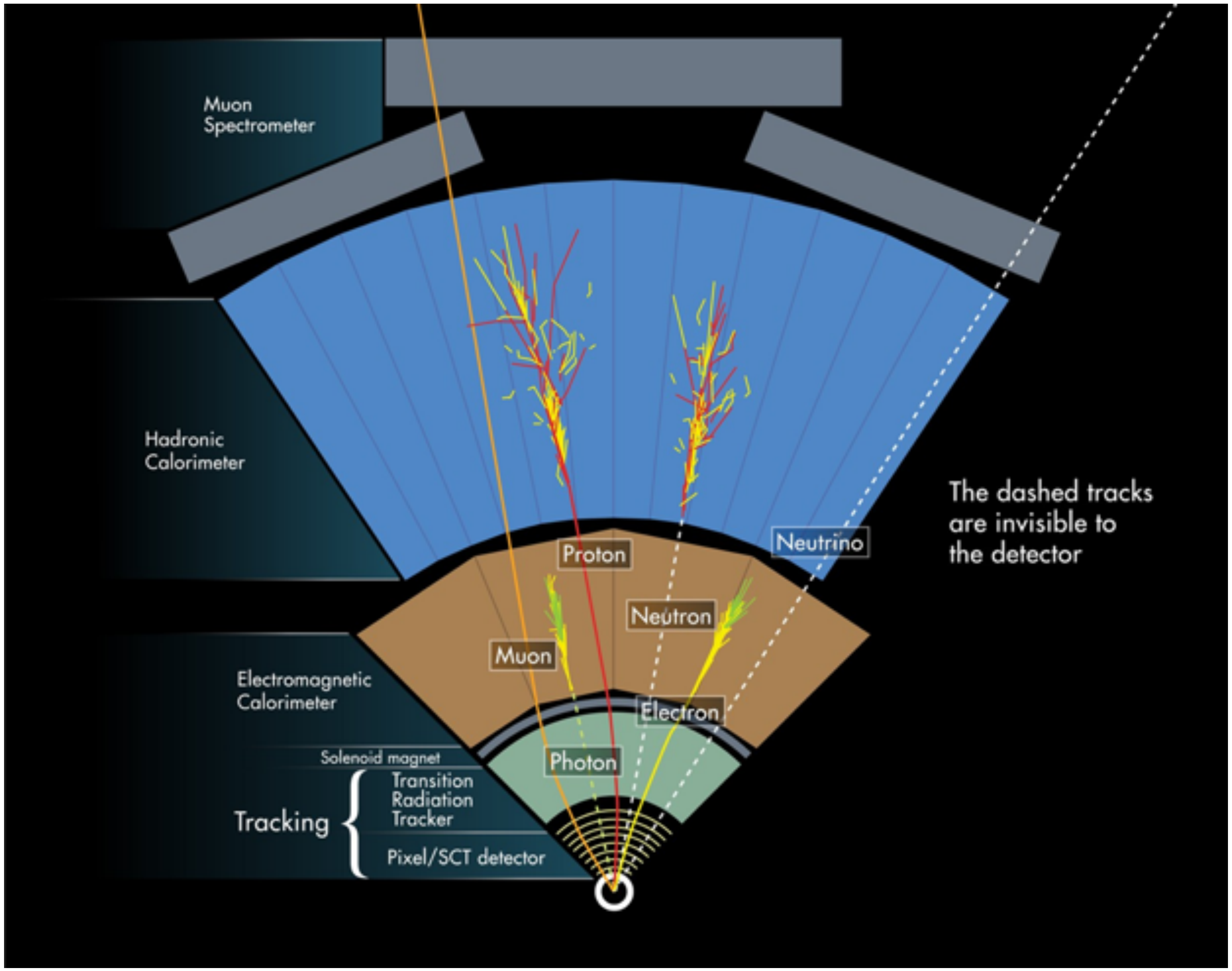
The Large Hadron Collider

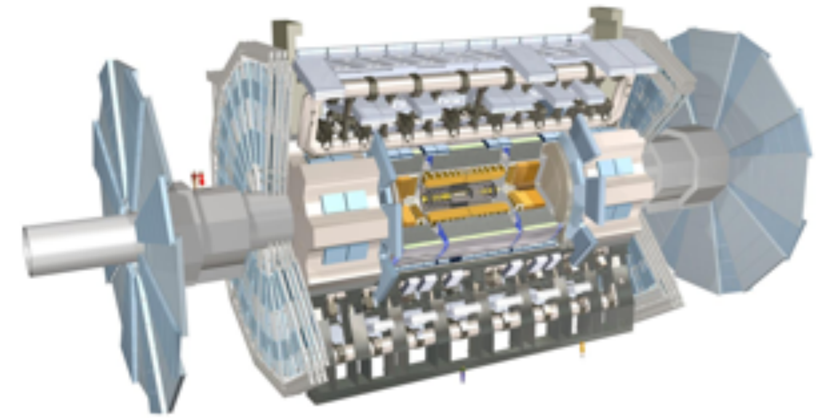


- Highest energy collider in the world
- Collides protons (p-p), lead ions (Pb-Pb), or both (p-Pb)
- Proton beams composed of bunches of $\sim 10^{11}$ protons with 50 ns spacing in 2012
- Two general purpose detectors: ATLAS and CMS
- Heavy ion experiment: ALICE
- B-physics experiment: LHCb

***pp* collision energy:**
7 TeV in 2011,
8 TeV in 2012,
13-14 TeV in (2015?)

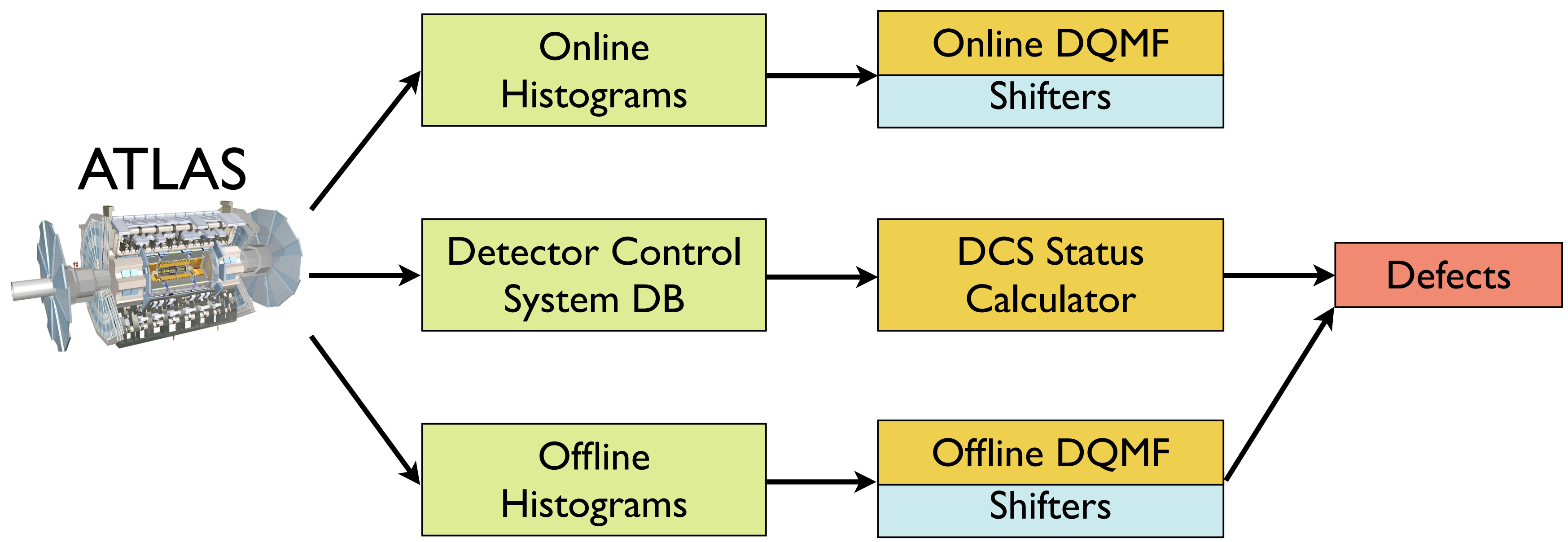
The ATLAS Detector





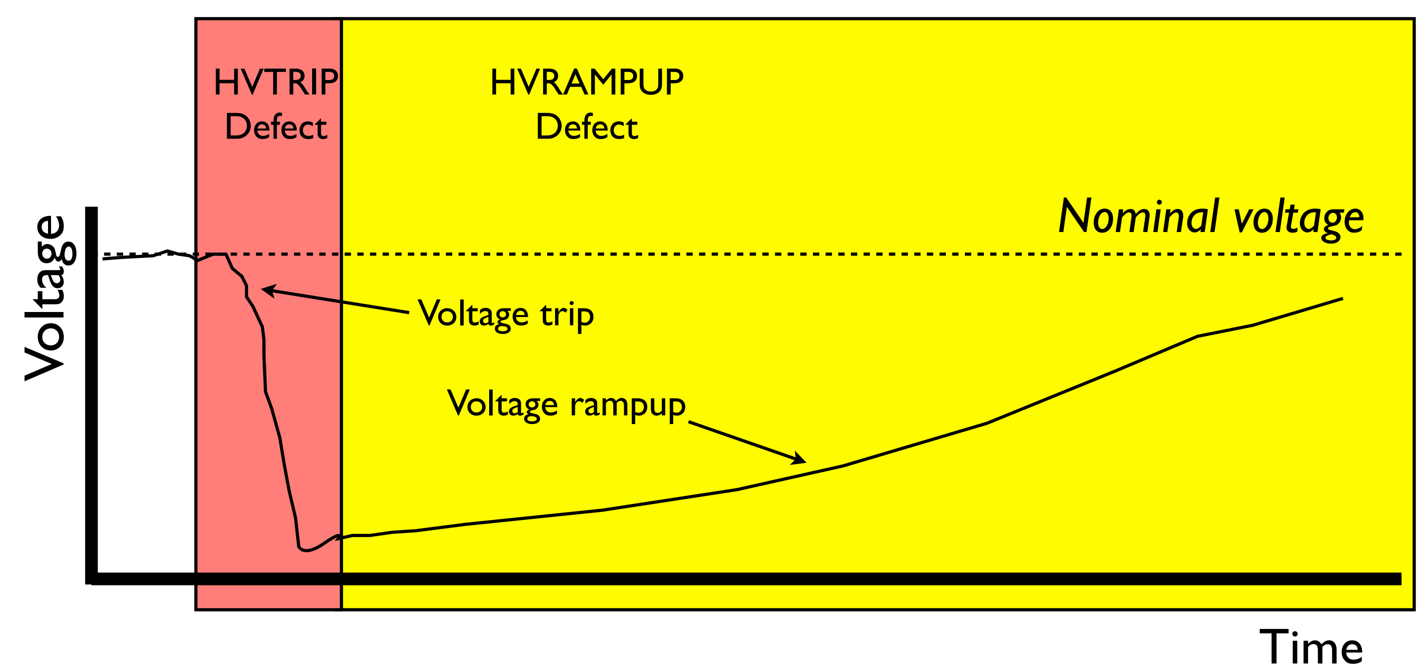
- Large general purpose detector comprised of several specialized subdetectors
- Inner detector measures charged particle tracks
- Calorimeters measure electromagnetic and hadronic showers
- Muon spectrometer measures muon tracks
- A 3-level trigger system selects interesting events

Data Quality



- Analyses depend on the quality of the data
  - It is essential to have a robust assessment framework
- Data quality is represented by *defects*
  - **Primary defects** represent specific detector problems
  - **Virtual defects** represent high-level logical combinations of primary defects

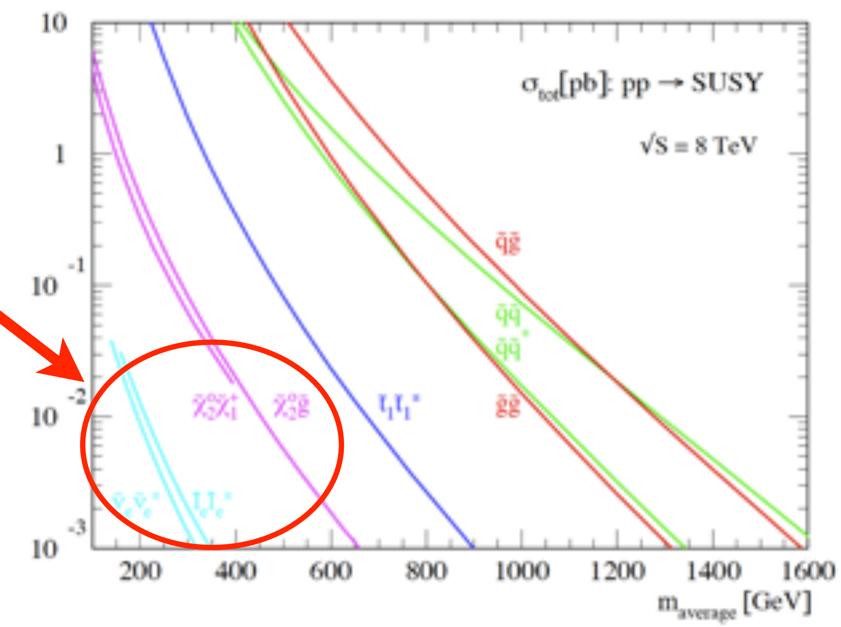
LAr high-voltage trip and ramp-up defects

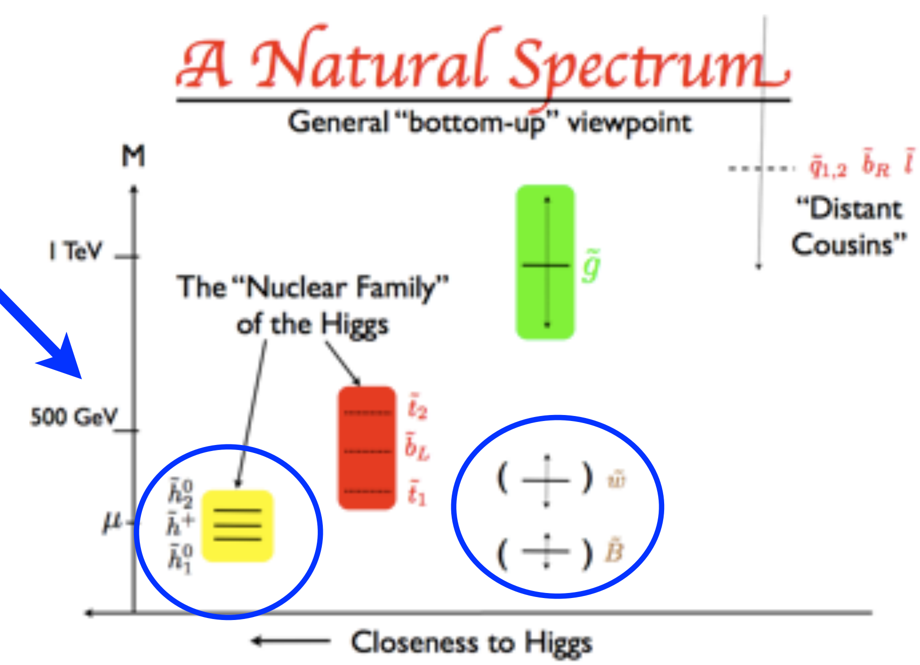


Analysis: Electroweak SUSY in the Three-Lepton Channel

Motivation

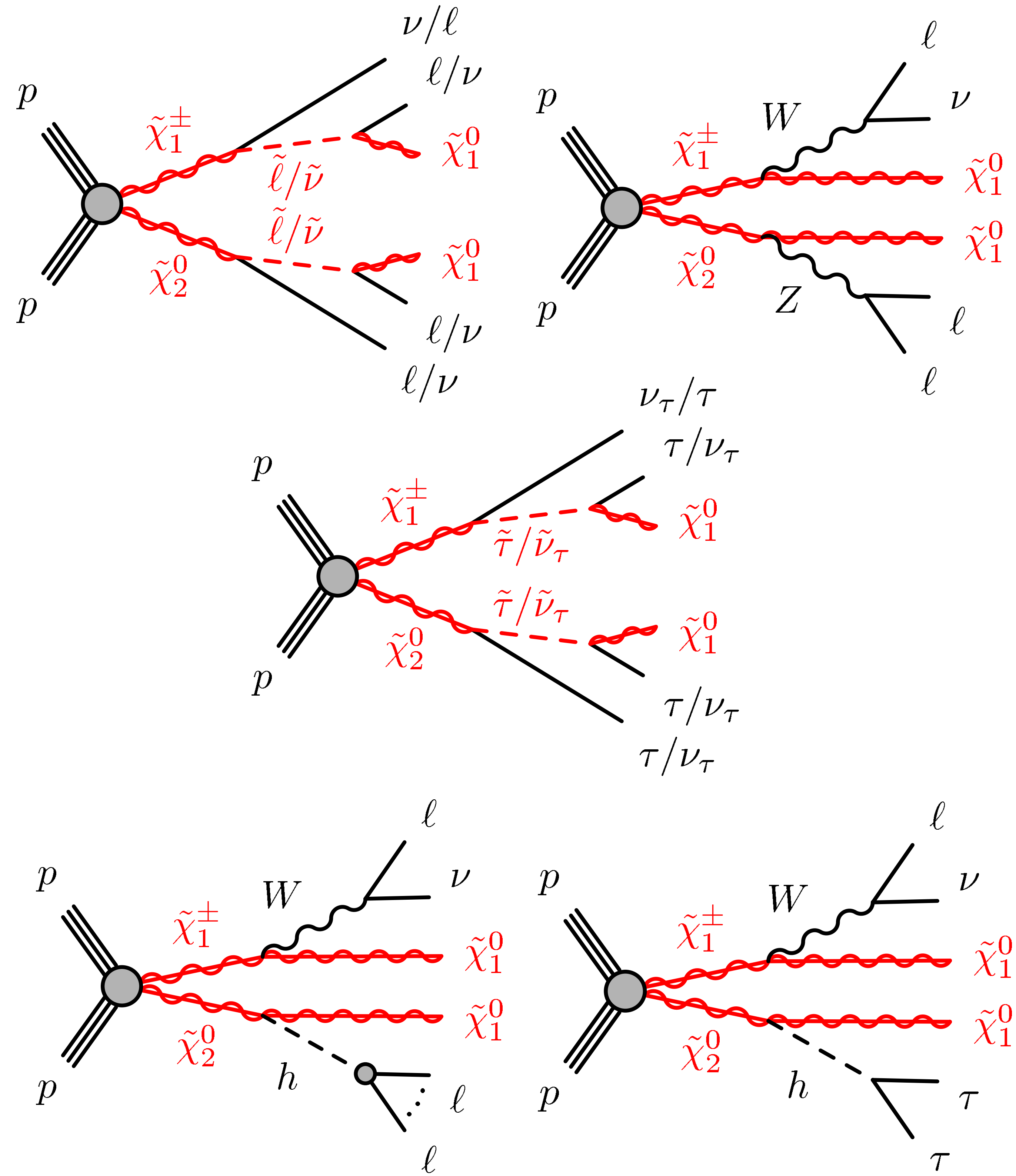
- Squark and gluino mass limits are already at the TeV scale
  - EWK production might be the dominant SUSY process at the LHC
- Natural SUSY prefers light gauginos and higgsinos
  - EWK searches complementary to 3rd gen squark searches
- EWK production can give multi-lepton signatures with low hadronic activity
  - Low Standard Model background





Signals: simplified models

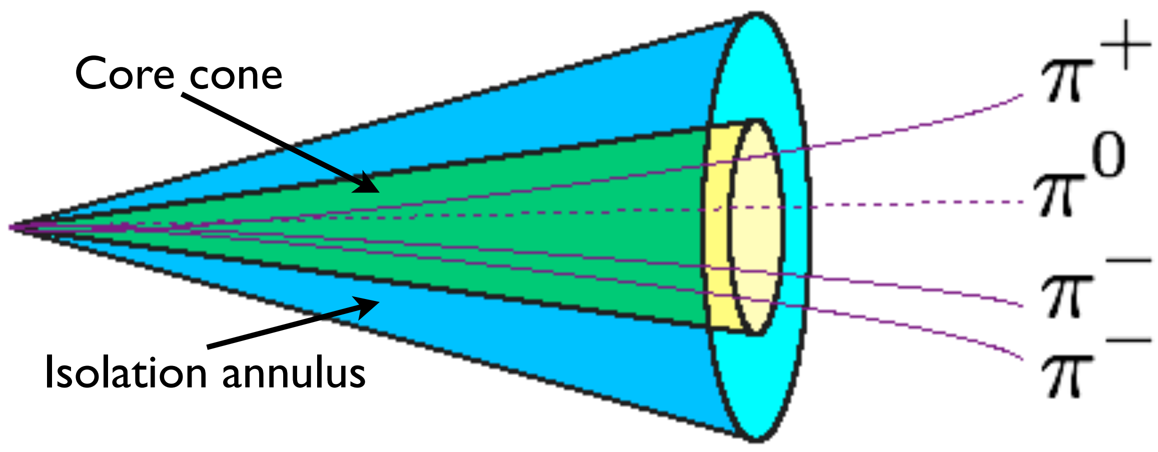
- Direct production of chargino1-neutralino2 (C1N2) with several decay modes
  - Intermediate sleptons/sneutrinos (flavor democratic)
  - Intermediate W and Z bosons (on-shell and off-shell)
  - Intermediate staus/tau-sneutrinos
  - Intermediate W and h bosons
    - Higgs decays to taus, WW, and ZZ included
- Technical details
  - C1, N2 mass degenerate
  - Slepton, sneutrino mass degenerate
    - Set halfway between C1/N2 and N1



Object Reconstruction and Selection

- Electrons
  - Combination of ID track and calorimeter shower
  - $p_T > 10$ GeV
  - Isolation criteria
  - Impact parameter criteria
- Muons
  - Combination of ID track and muon spectrometer track
  - $p_T > 10$ GeV
  - Isolation criteria
  - Impact parameter criteria
- Jets
  - Hadronic calorimeter shower clusters and ID tracks
  - $p_T > 20$ GeV
  - b-jets tagged by looking for a displaced vertex (80% efficient)
- Missing transverse energy (MET)
  - Calculated by summing all energy deposits in the calorimeters
  - Corrected for reconstructed electrons, muons, and photons

Object Reconstruction and Selection - Taus



Tau decays

- 65% to hadrons
  - 50% to 1-prong
  - 15% to 3-prong
- 35% to leptons

- Hadronic tau reconstruction is seeded by jets
  - Tracks and clusters inside the core cone are associated to the tau
    - X-prong refers to number of charged hadron tracks
  - Tracks and clusters in the isolation annulus are used to discriminate against jets
- *Boosted decision trees* are used to distinguish between taus, jets, and electrons
  - Uses shower shape variables and decay-vertex coordinates
- $p_T > 20$ GeV
- 1-prong or 3-prong

Event Selection

- Events are selected that have three leptons and *zero* b-tagged jets
- Kinematic variables are used in several signal regions to distinguish the SUSY signals from the SM background
  - Invariant mass of two leptons
    - Same-flavor opposite-sign (SFOS)
    - Lepton and tau
    - Tau and tau
  - Missing transverse energy
  - Transverse mass
    - Kinematic endpoint for particle decaying to 1 visible, 1 invisible
  - M_{T2} (stransverse mass)
    - Generalization of transverse mass to 2 particles decaying
  - Lepton and tau p_T

Signal regions are classified by lepton channel: 0, 1, or 2 hadronic taus

Signal Regions

- **SR0a** - Light lepton SR *binned* in M_{SFOS}, MET, and M_T (20 bins), targeting decays with sleptons and WZ
- **SR0b** - Light lepton SR targeting Wh with h→ll+x
- **SR1SS** - SS light leptons + 1 tau SR targeting Wh
- **SR2a** - 1 light lepton + 2 tau SR targeting staus
- **SR2b** - 1 light lepton + 2 tau SR targeting Wh

SR	SR0a	SR0b	SR1SS	SR2a	SR2b
ℓ flavor/sign	SFOS-ℓ	$\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	$\tau^{\pm}\ell^{\mp}\ell^{\mp}$	$\tau\tau\ell$	$\tau^{\pm}\tau^{\mp}\ell$
Z boson	binned	–	veto (ee)	–	–
b-jet	veto	veto	veto	veto	veto
$E_{\mathrm{T}}^{\mathrm{miss}}$	binned	> 50	> 50	> 50	> 60
m_{T}	binned	–	–	–	–
m_{T2}	–	–	–	> 100	–
p_{T}^{ℓ}	–	> 20	> 30	–	–
$\min(\Delta\phi(\ell^{\pm}, \ell^{\mp}))$	–	≤ 1.0	–	–	–
$\sum p_{\mathrm{T}}^{\ell}$	–	–	> 70	–	–
$\sum p_{\mathrm{T}}^{\tau}$	–	–	–	–	> 110
$m_{\ell\tau}$	–	–	< 120	–	–
$m_{\tau\tau}$	–	–	–	–	70–120

SR0a bins defined in backup

Background Modeling

- **Irreducible background: processes with 3 real, isolated leptons**
  - Diboson WZ and ZZ
  - Triboson
  - ttbar + W/Z

Modeled with Monte Carlo

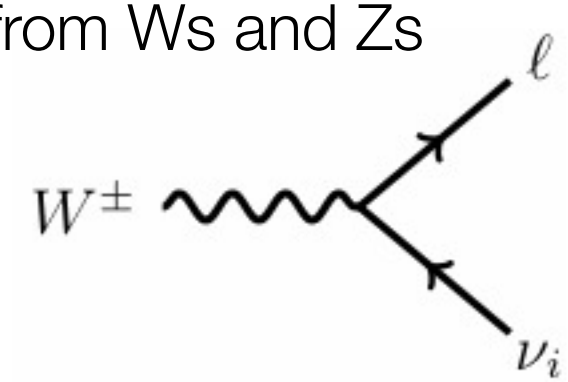
- **Reducible background: process with 1 or 2 fake leptons**
  - W+jets, Z+jets
  - ttbar, single top
  - WW

Modeled with Matrix Method

- Reducible background with 3 fake leptons is *negligible*

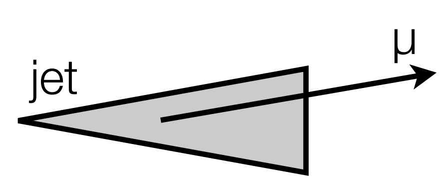
Real leptons

prompt leptons coming from Ws and Zs

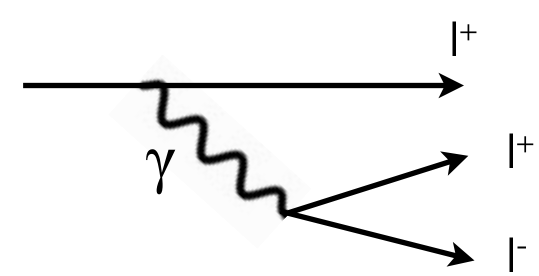


Fake leptons

HF/LF fakes from jets



Conversion leptons from photon radiation



The Matrix Method Fake Lepton Estimate

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon}_2 & \epsilon_1\bar{f}_2 & f_1\bar{\epsilon}_2 & f_1\bar{f}_2 \\ \bar{\epsilon}_1\epsilon_2 & \bar{\epsilon}_1 f_2 & \bar{f}_1\epsilon_2 & \bar{f}_1 f_2 \\ \bar{\epsilon}_1\bar{\epsilon}_2 & \bar{\epsilon}_1\bar{f}_2 & \bar{f}_1\bar{\epsilon}_2 & \bar{f}_1\bar{f}_2 \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

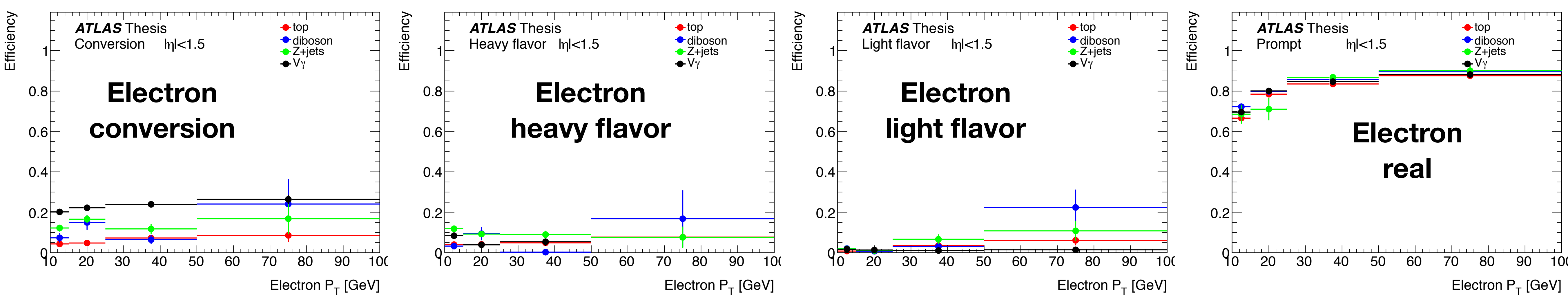
$$\bar{\epsilon}_i = 1 - \epsilon_i$$
$$\bar{f}_i = 1 - f_i$$

- Relates object quality properties to the real and fake composition
- Number of tight (T) and loose (L) leptons related to number of real (R) and fake (F) leptons in terms of
  - probability for a real lepton to be tight (ϵ) or only loose ($1-\epsilon$)
  - probability for a fake lepton to be tight (f) or only loose (1-f)
- Leading light lepton is not used in the matrix equation *(hence 4x4 matrix)*
  - Background dominated by leading real lepton + softer fakes
- Inversion of equation gives the estimate of events with 1 or 2 fake leptons:

$$N_{Fake \rightarrow TT} = \epsilon_1 f_2 \times N_{RF} + f_1\epsilon_2 \times N_{FR} + f_1 f_2 \times N_{FF}$$

Matrix Method Technicalities

- Tight and loose selections must be chosen to ensure good separation between real and fake efficiency
  - Otherwise matrix method is unstable!
  - **Loose definition of electrons and muons**
    - Remove the isolation and impact parameter cuts
  - **Loose definition of taus**
    - Remove the BDT criteria
- Real and fake efficiencies can depend on type, process, and object/event kinematics:



- Monte Carlo samples do not generally get the fake efficiencies correct

Matrix Method Efficiencies

- How to parametrize the complicated efficiencies?
  - Use data and MC to combine all relevant information
  - Construct weighted average efficiencies for each signal region

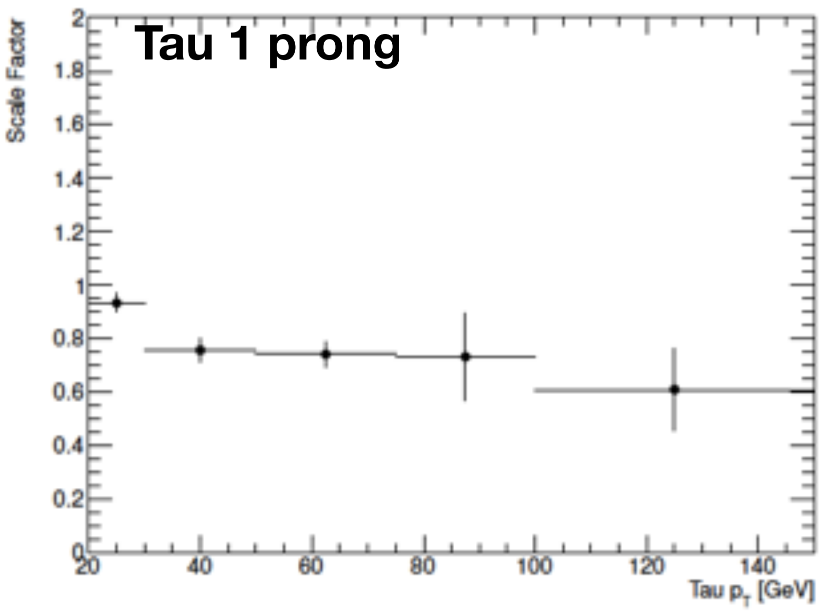
$$f_{XR} = \Sigma_{i,j}(f^{ij} \times sf^{i} \quad \times R^{ij}_{XR})$$

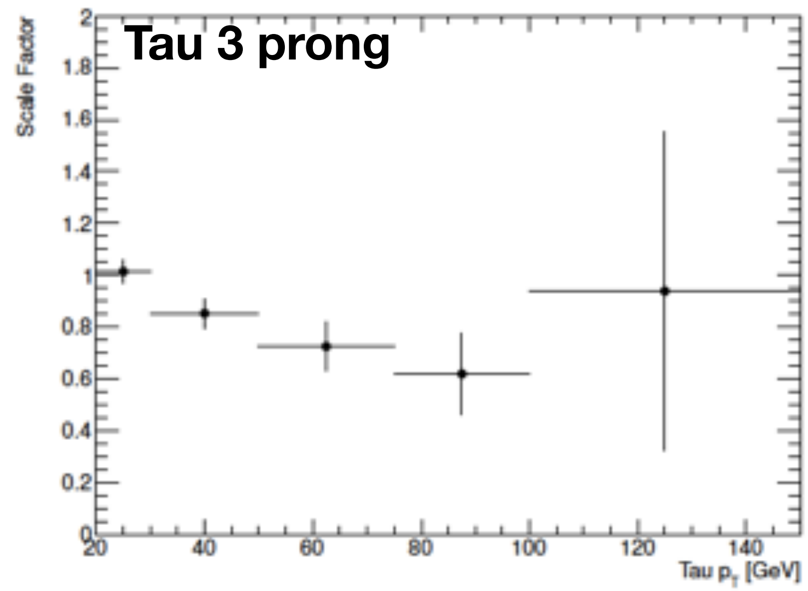
$$\epsilon_{XR} = \Sigma_{j}\ (\epsilon^{j} \quad \times sf^{Real} \times P^{j}_{XR})$$

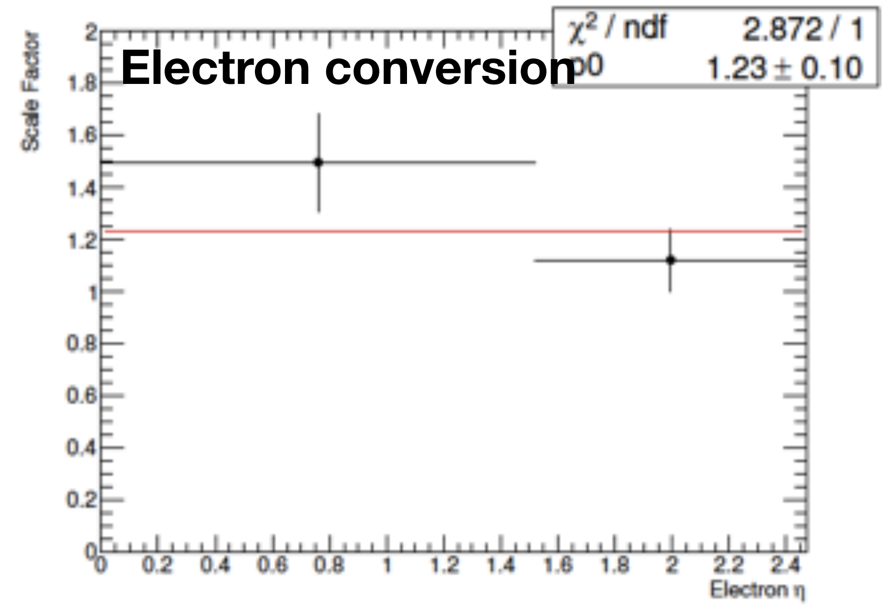
- Weighted average efficiencies are calculated with
  - Efficiencies per type and process (f^{ij} and ϵ^{j}), extracted from MC
  - Scale factors (sf^{i}) to correct the efficiencies for data/MC differences
  - Fractions (R^{ij}, P^{j}) of each type and process in each signal region, from MC

Matrix Method Efficiency Scale Factors

$$sf_{\mu}^{HF} = 0.89 \pm 0.03 \qquad sf_{e}^{HF} = 0.74 \pm 0.04$$

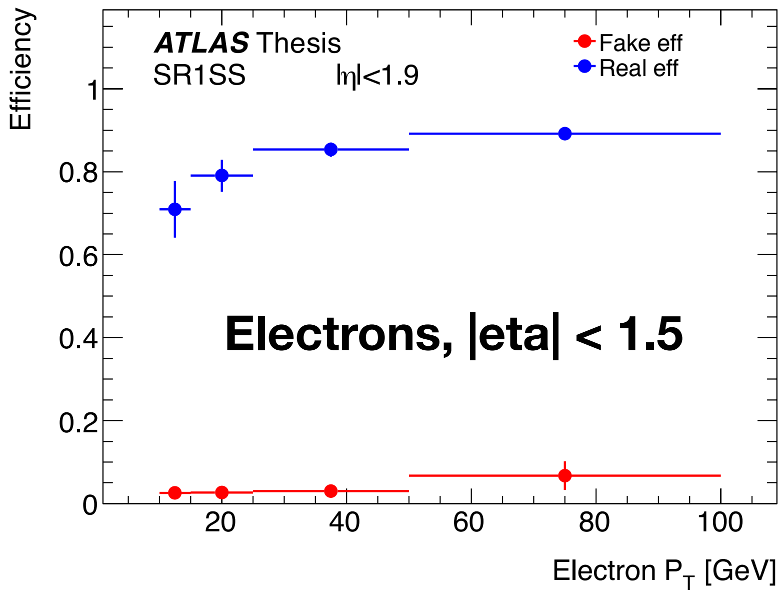


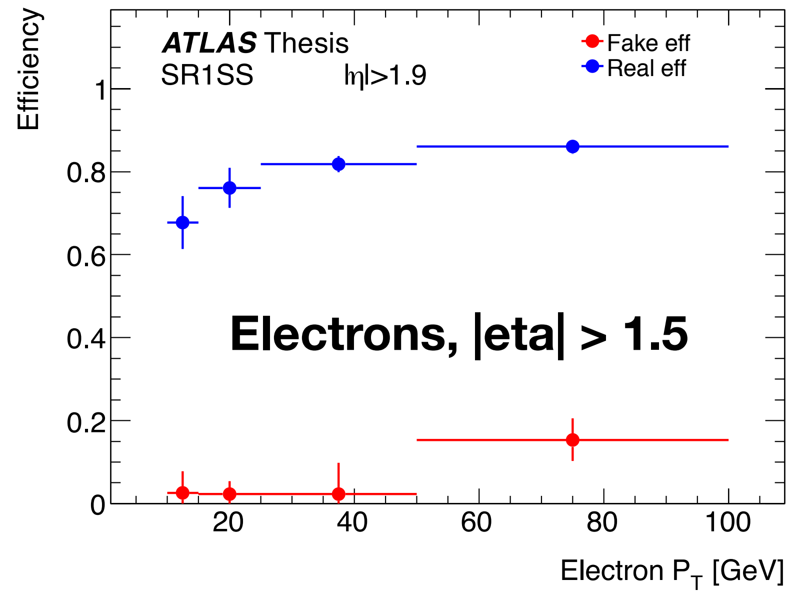


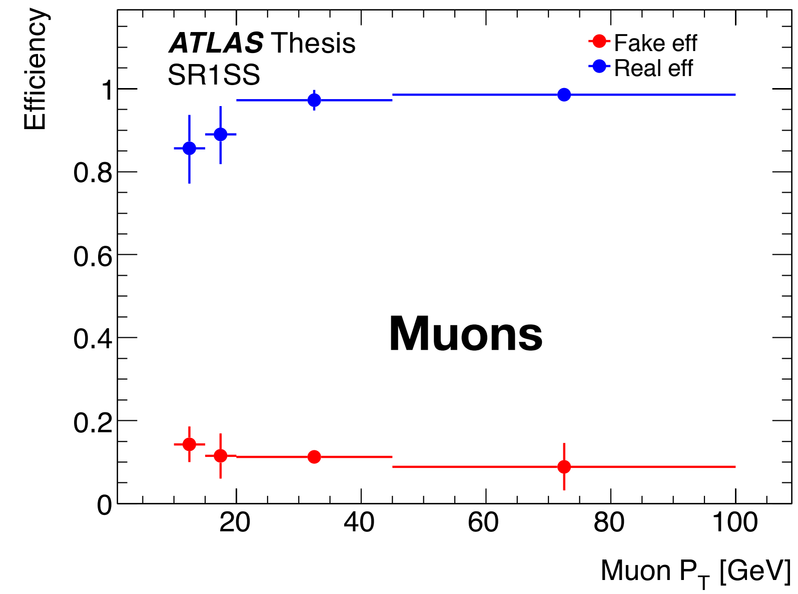


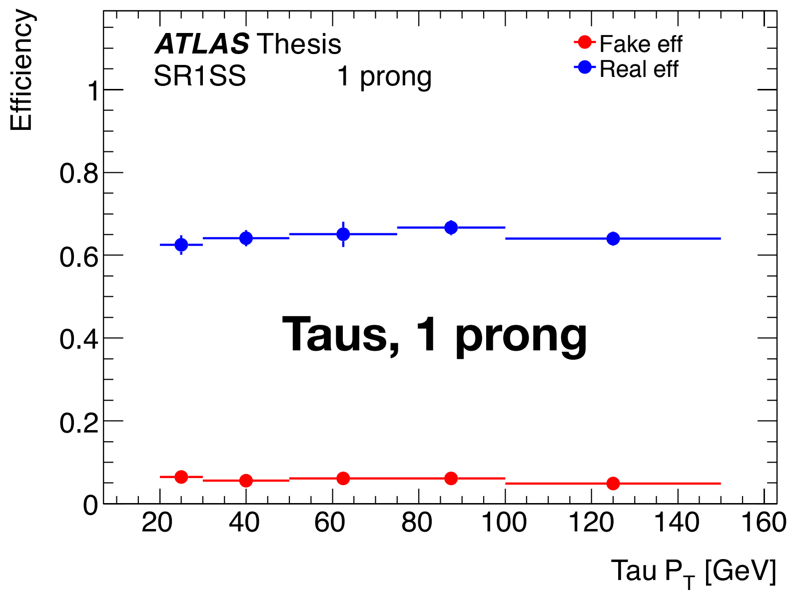
- **Scale factors are calculated as the ratio of efficiencies in data over MC**
- Heavy flavor SF for light leptons are measured in a bb control region
- Electron conversion SF measured in Z→μμ+e control region
- Tau fake SFs measured in W+jets control region
- Real efficiency SFs also measured, but observed to be ~1

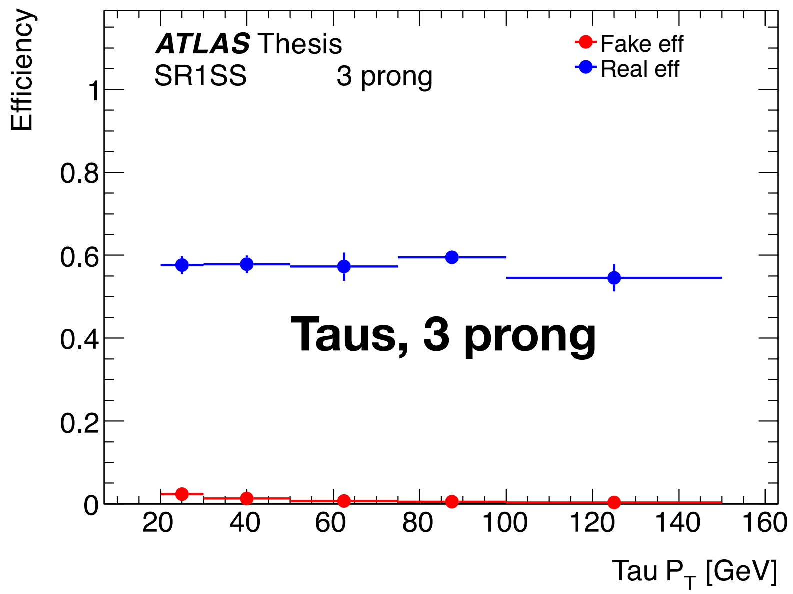
Weighted Average Efficiencies for SR1SS











Uncertainties

	SR0a Z request		SR0a Z veto		SR0b	
Leading	Cross-section	6.84%	Generator	11.33%	Cross-section	26.23%
Sub-leading	Generator	6.31%	Cross-section	9.60%	stat	11.31%
	Trigger	4.65%	MM elec FR	4.65%	Generator	8.05%
	Luminosity	2.60%	Trigger	3.96%	Trigger	3.08%
	JER	2.32%	MM muon FR	3.33%	Luminosity	1.72%
	SR1SS		SR2a		SR2b	
Leading	stat	6.86%	stat	9.86%	stat	8.89%
Sub-leading	Cross-section	6.01%	Generator	4.07%	MM tau FR	4.26%
	MM tau FR	5.47%	MM tau FR	3.64%	Tau ID SF	2.38%
	Trigger	2.90%	Cross-section	2.20%	Cross-section	2.13%
	Generator	2.19%	JES	1.96%	Trigger	1.64%

- Only the dominant uncertainties are listed, which include
  - Uncertainties on the MC simulation: statistics, cross-sections, generator dependence, trigger simulation
  - Uncertainties on the matrix-method fake prediction: electron, muon, and tau fake rate uncertainties

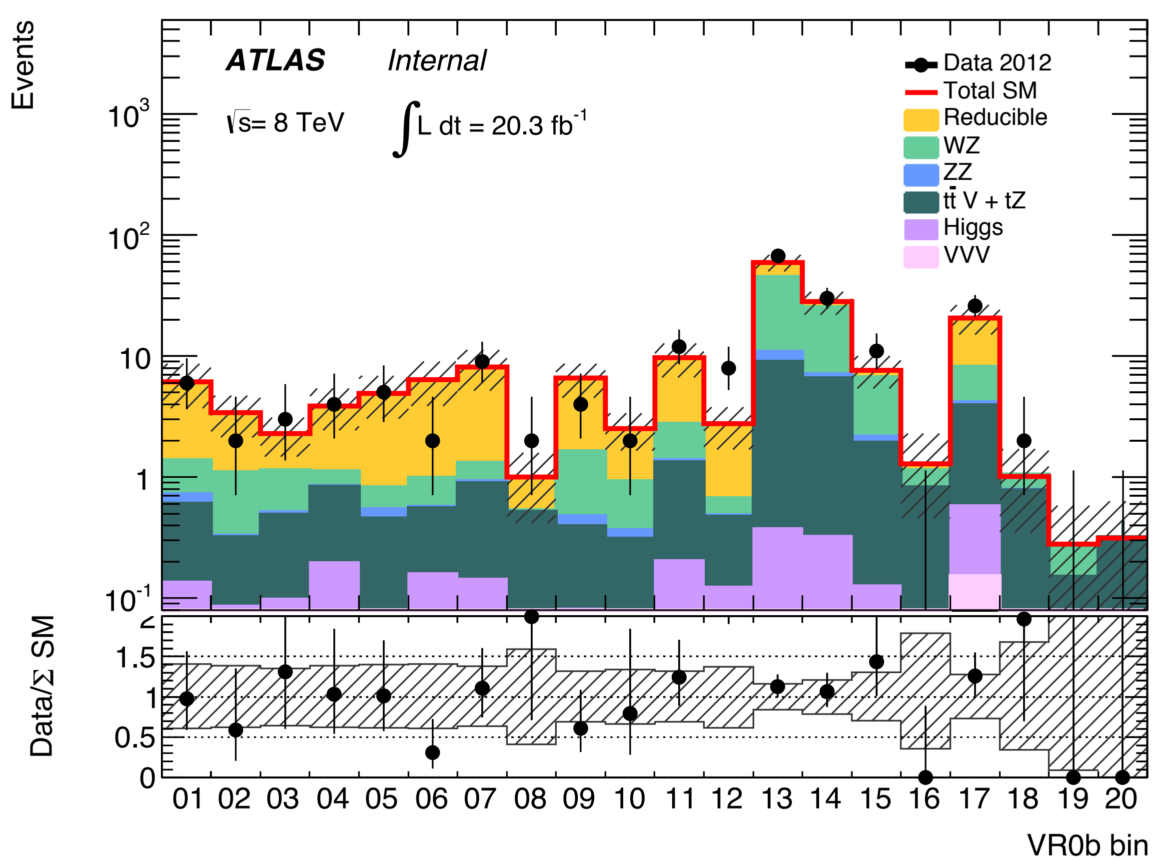
Background Validation

	Channel	Z boson	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	N(b-jets)	Target process
VR0noZa	$\ell^{\pm}\ell^{\mp}\ell'$	m_{SFOS} & $m_{3\ell}$ veto	35–50	–	WZ^{*}, $Z^{*}Z^{*}$, Z^{*}+jets
VR0noZb	$\ell^{\pm}\ell^{\mp}\ell'$	m_{SFOS} & $m_{3\ell}$ veto	> 50	$== 1$	$t\bar{t}$
VR0Za	$\ell^{\pm}\ell^{\mp}\ell'$	request	35–50	–	WZ, Z+jets
VR0Zb	$\ell^{\pm}\ell^{\mp}\ell'$	request	> 50	$== 1$	WZ
VR0b	$\ell^{\pm}\ell^{\mp}\ell'$	binned	binned	$== 1$	WZ, $t\bar{t}$
VR1SSa	$\ell^{\pm}\ell^{\pm}\tau$	–	35–50	–	WZ, Z+jets
VR1SSb	$\ell^{\pm}\ell^{\pm}\tau$	–	> 50	$== 1$	$t\bar{t}$
VR2a	$\ell\tau\tau$	–	35–50	–	W+jets, Z+jets
VR2b	$\ell\tau^{\pm}\tau^{\mp}$	–	> 50	$== 1$	$t\bar{t}$

- Validation regions are designed to test the modeling of various background processes
- VR0b is a light lepton binned region, with the same bins as SR0a

Background Validation

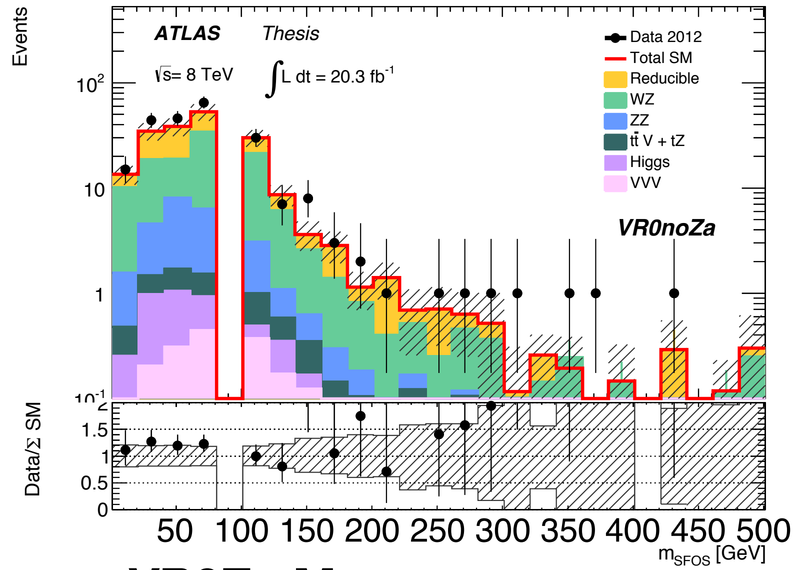
Sample	WZ	ZZ	Top+V	VVV	Higgs	Fake	Σ SM	Data
VR0noZa	91^{+12}_{-12}	19^{+4}_{-4}	$3.211^{+1.010}_{-0.970}$	$1.9^{+1.9}_{-1.9}$	$2.7^{+1.3}_{-1.3}$	73^{+20}_{-17}	191^{+24}_{-22}	228
VR0Za	471^{+47}_{-47}	48^{+7}_{-7}	$10.1^{+2.3}_{-2.2}$	$0.7^{+0.7}_{-0.7}$	$2.7^{+1.5}_{-1.5}$	261^{+70}_{-63}	794^{+86}_{-80}	792
VR0noZb	$10.5^{+1.8}_{-2.0}$	$0.62^{+0.12}_{-0.12}$	$9.5^{+3.1}_{-3.1}$	$0.35^{+0.36}_{-0.36}$	$1.5^{+1.0}_{-1.0}$	47^{+15}_{-13}	69^{+15}_{-14}	79
VR0Zb	58^{+7}_{-7}	$2.6^{+0.4}_{-0.4}$	18^{+4}_{-4}	$0.18^{+0.18}_{-0.18}$	$0.71^{+0.29}_{-0.29}$	19^{+5}_{-5}	98^{+10}_{-10}	110
VR1SSa	$14.6^{+1.9}_{-1.9}$	$1.76^{+0.29}_{-0.28}$	$0.9^{+0.9}_{-0.9}$	$0.4^{+0.4}_{-0.4}$	$0.57^{+0.34}_{-0.34}$	71^{+9}_{-9}	89^{+10}_{-9}	82
VR1SSb	$1.99^{+0.35}_{-0.35}$	$0.138^{+0.028}_{-0.028}$	$2.8^{+1.3}_{-1.3}$	$0.08^{+0.08}_{-0.08}$	$0.5^{+0.5}_{-0.5}$	$22.7^{+2.8}_{-2.8}$	$28.2^{+3.2}_{-3.2}$	26
VR2a	$14.3^{+2.4}_{-2.5}$	$1.8^{+0.4}_{-0.4}$	$1.0^{+0.7}_{-0.7}$	$0.12^{+0.12}_{-0.12}$	$0.6^{+0.4}_{-0.4}$	630^{+9}_{-12}	648^{+10}_{-13}	656
VR2b	$1.9^{+0.4}_{-0.4}$	$0.12^{+0.04}_{-0.04}$	$1.7^{+0.7}_{-0.7}$	$0.06^{+0.07}_{-0.07}$	$0.5^{+0.5}_{-0.5}$	162^{+6}_{-8}	166^{+6}_{-8}	158



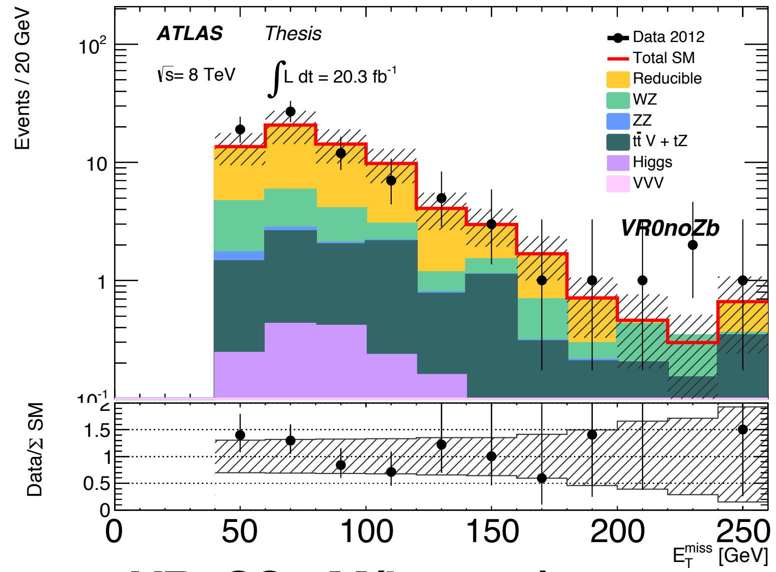
- Nice agreement in the VRs

Background Validation

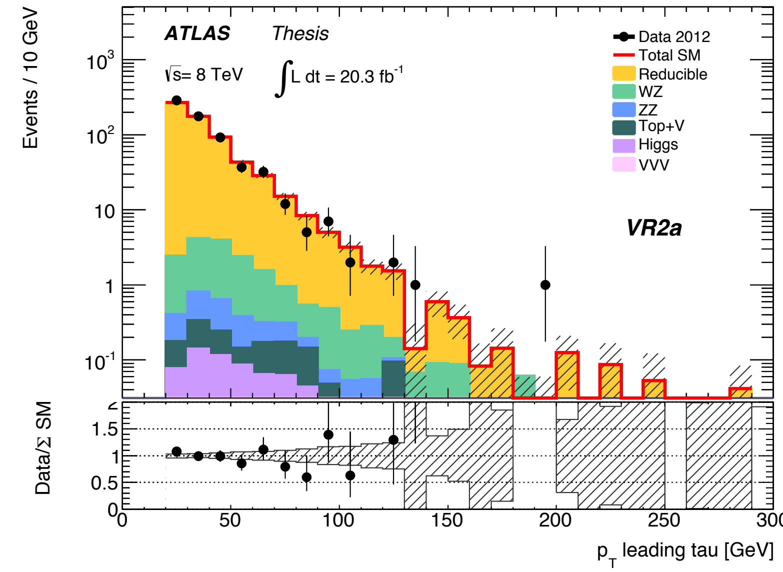
VR0noZa M_{SFOS}



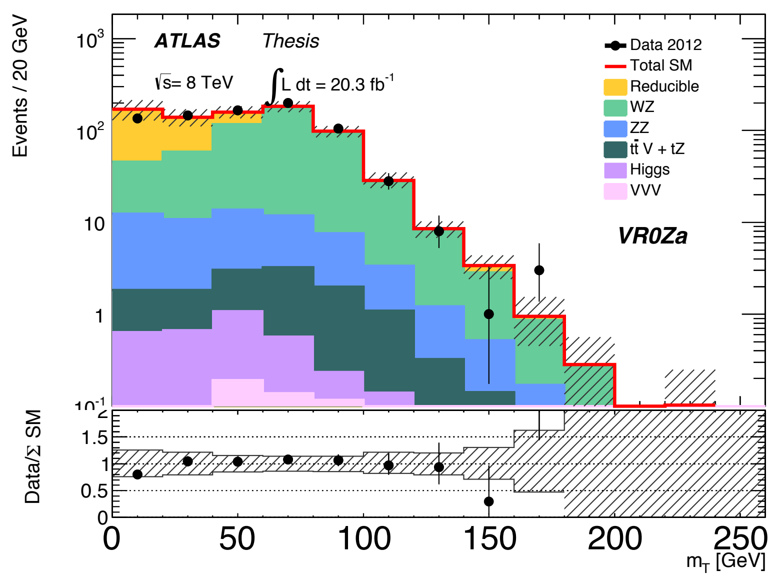
VR0noZb MET



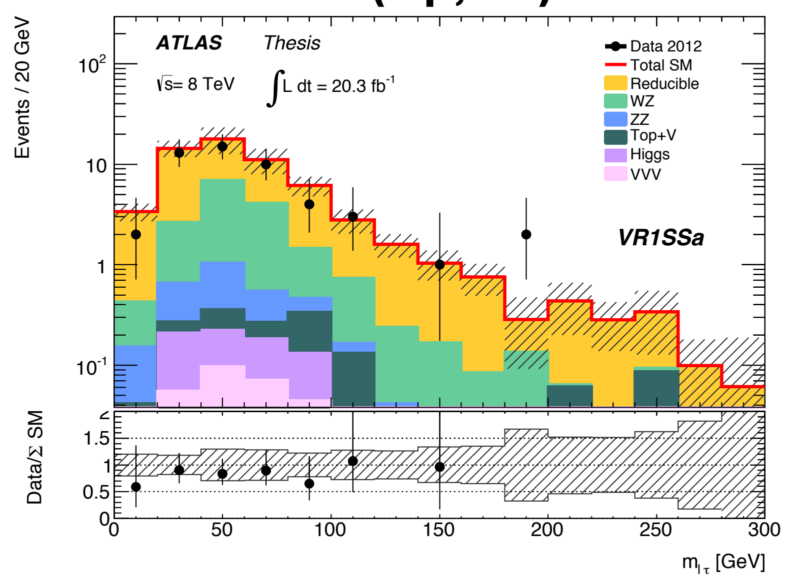
VR2a leading tau p_T



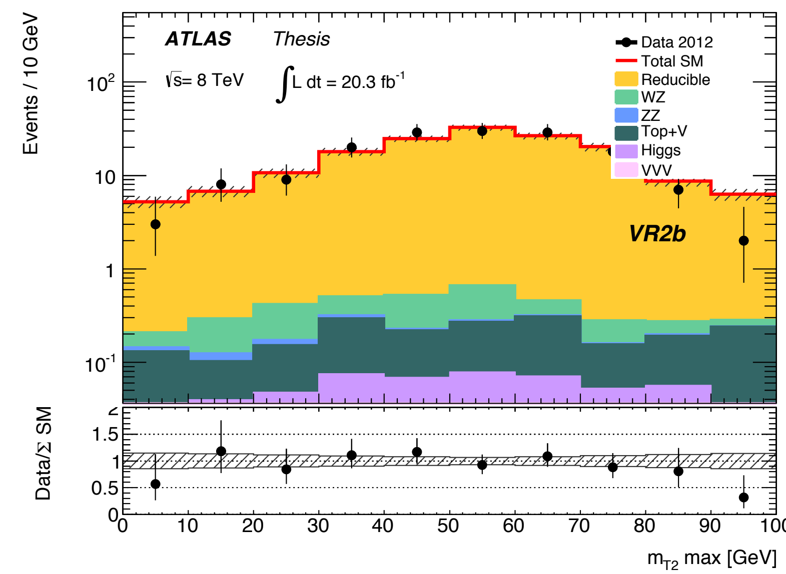
VR0Za M_T



VR1SSa M(lep,tau)



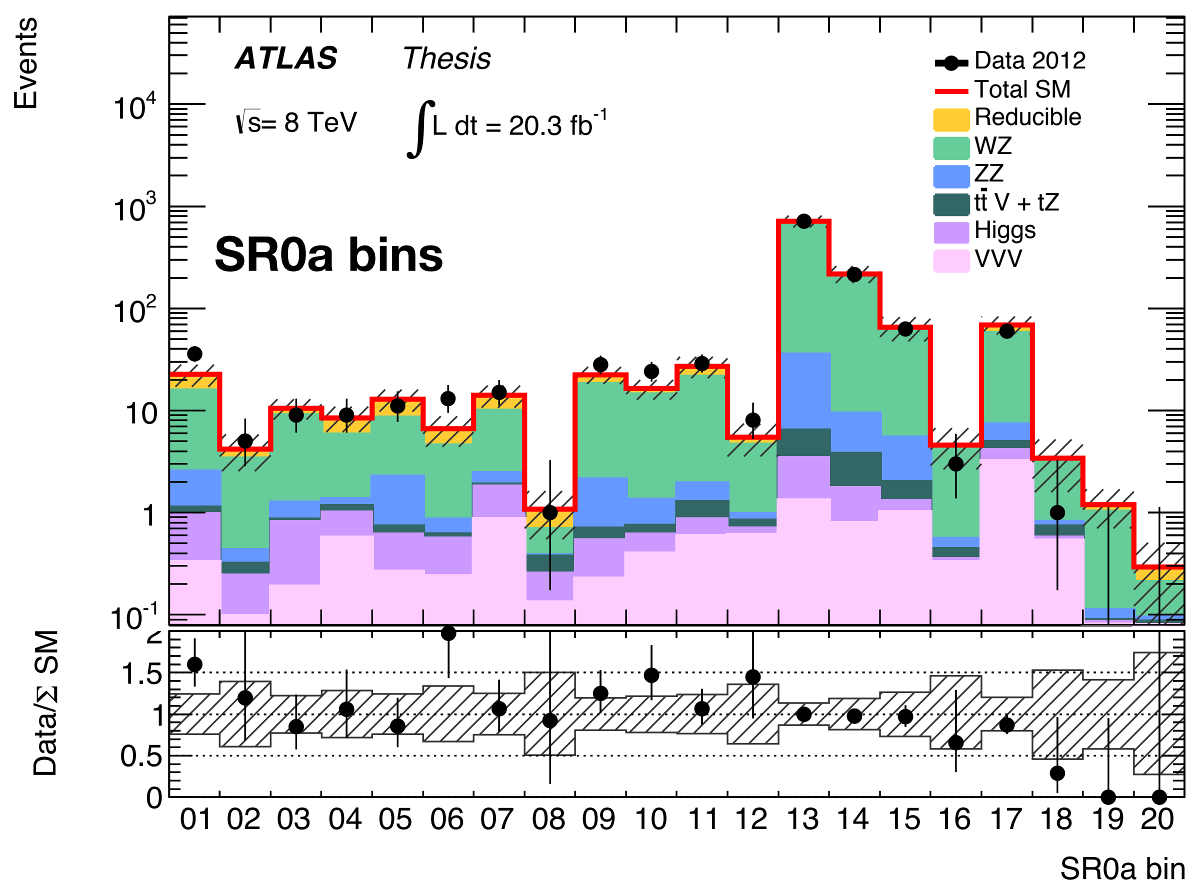
VR2b M_{T2}



- Nice agreement in the kinematic shapes

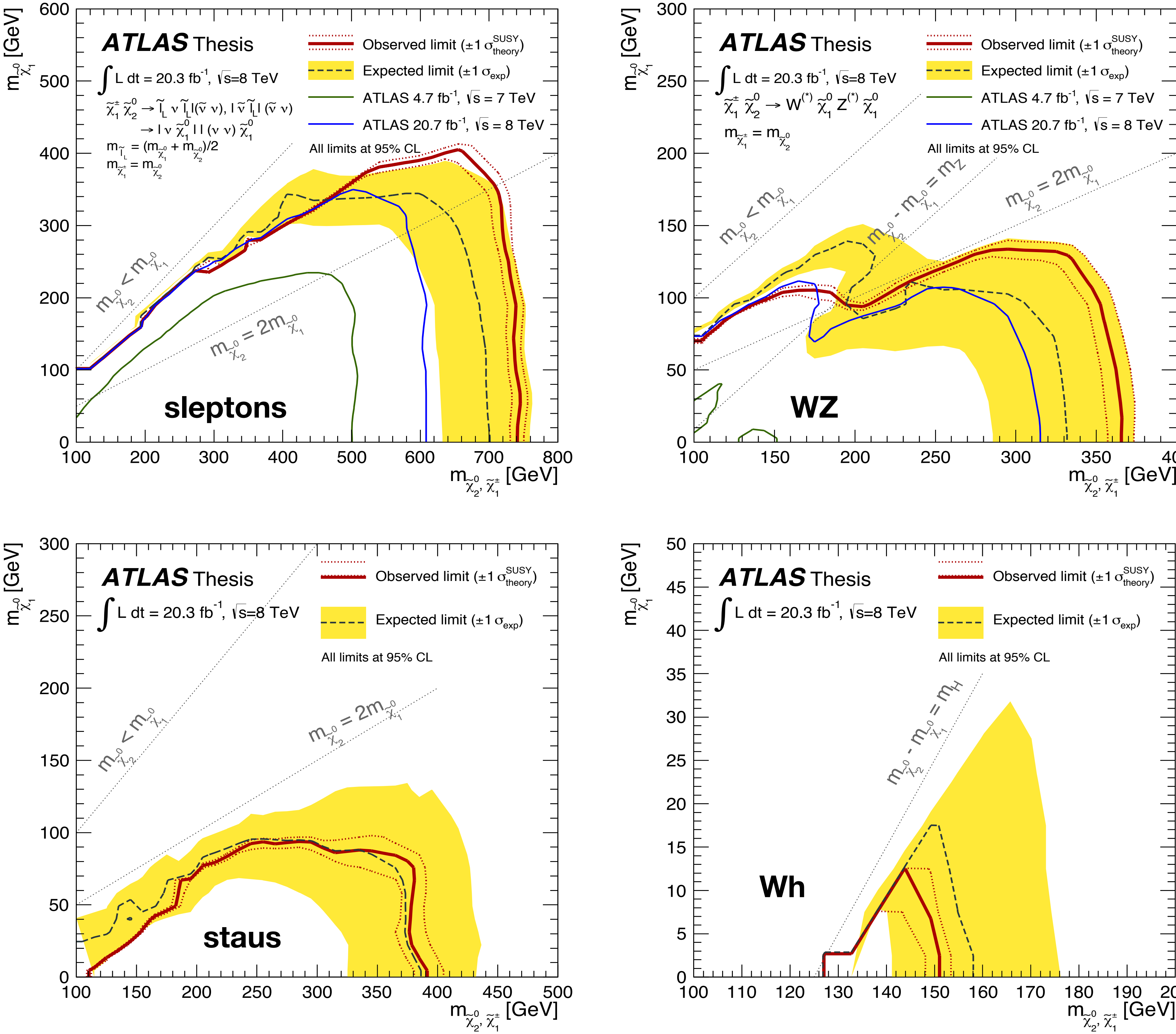
Signal Region Results

Sample	3-Prompt Lepton Background	Fake Lepton Background	Σ SM	Data
SR0b	$2.8^{+1.3}_{-1.3}$	$1.5^{+0.5}_{-0.5}$	$4.2^{+1.4}_{-1.4}$	3
SR1SS	$5.9^{+1.4}_{-1.4}$	$4.5^{+0.9}_{-0.9}$	$10.4^{+1.7}_{-1.7}$	13
SR2a	$1.5^{+0.5}_{-0.6}$	$5.1^{+0.7}_{-0.7}$	$6.6^{+0.8}_{-0.9}$	6
SR2b	$1.2^{+0.4}_{-0.4}$	$4.9^{+0.7}_{-0.7}$	$6.1^{+0.8}_{-0.8}$	5

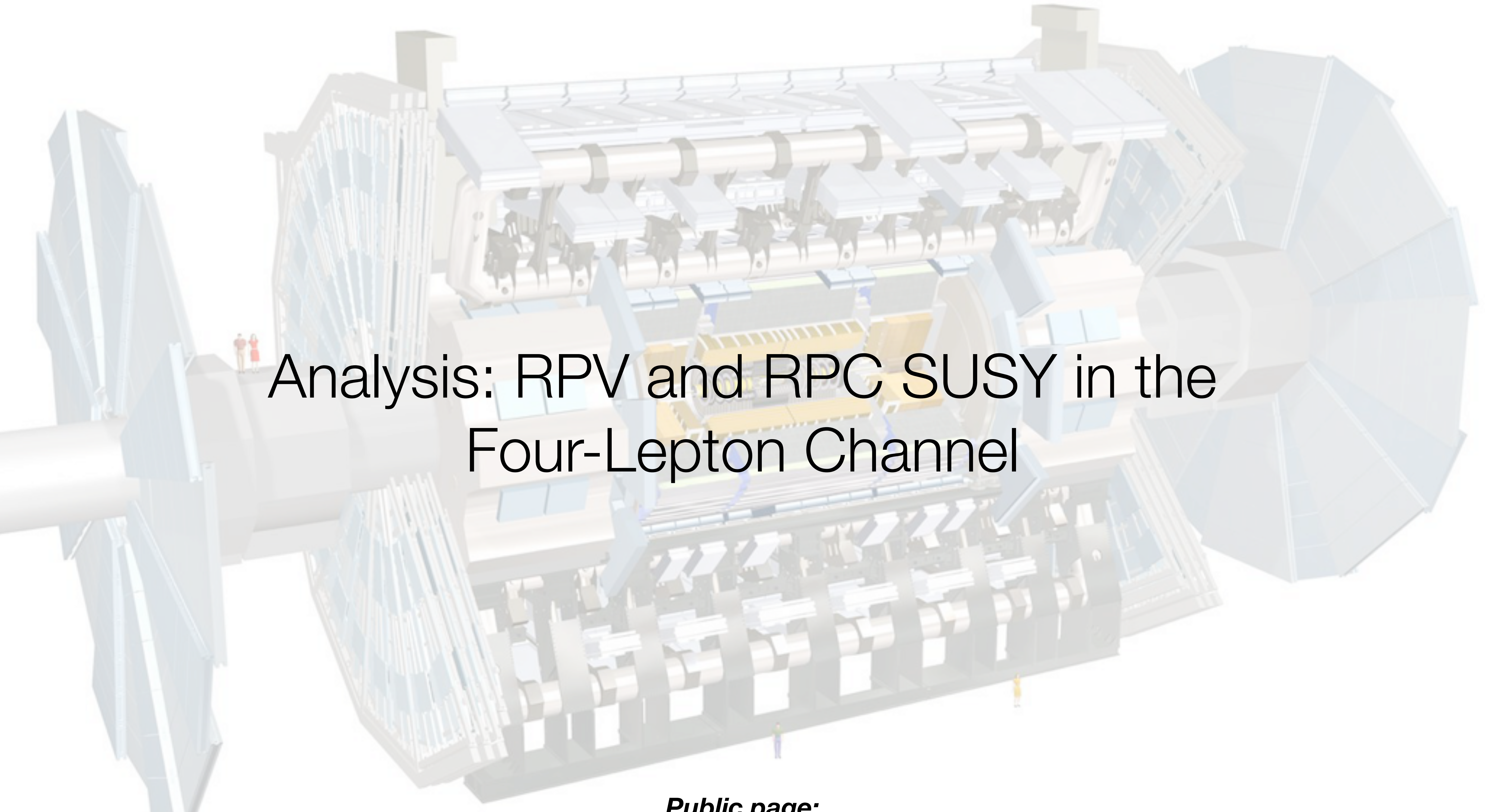


- Good agreement with the Standard Model prediction
- No evidence for supersymmetry

Statistical Interpretation



- 95% exclusion contours in the diagrams with intermediate sleptons, staus, WZ, and Wh
- Slepton and WZ models show significant improvement over previous public result
- New limits with staus and Wh will contribute strongly to combinations with other channels



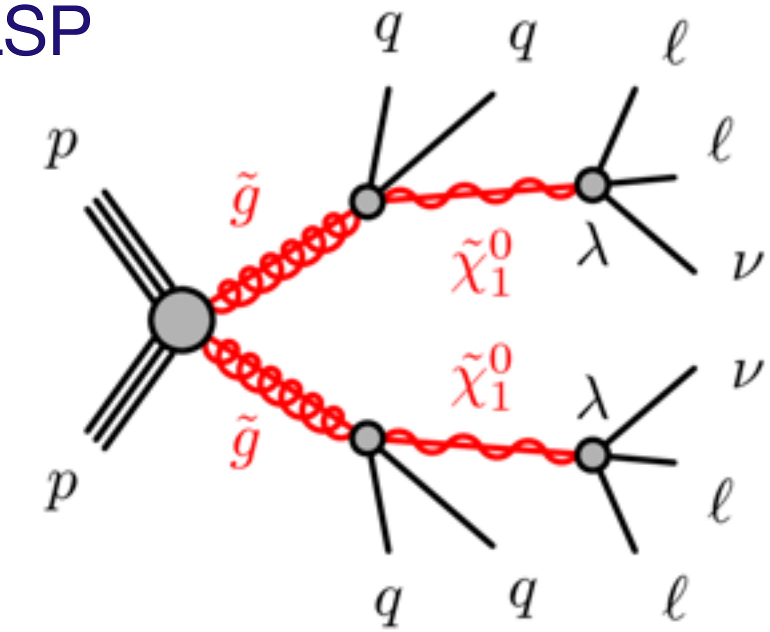
Analysis: RPV and RPC SUSY in the Four-Lepton Channel

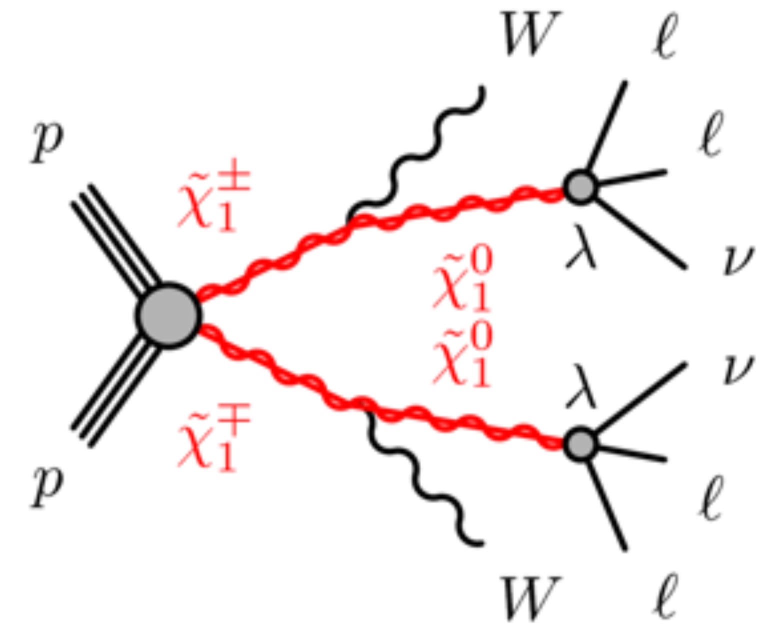
Public page:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-036/

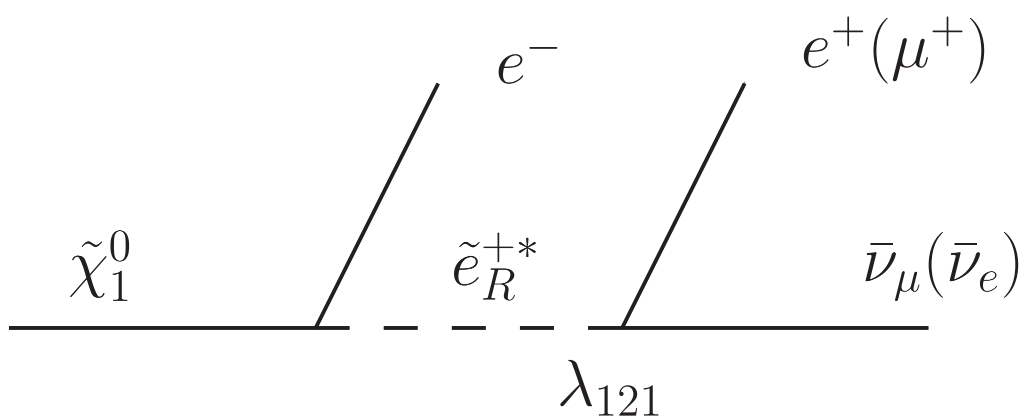
Signal Models: RPV SUSY

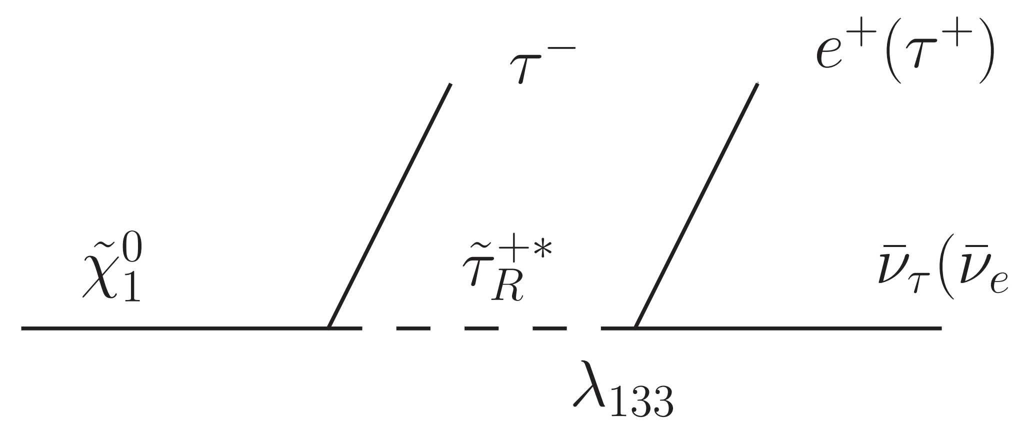
- RPC pair production of NLSP
    - Gluino or Wino





- Bino-like neutralino LSP decays promptly via λ_{121} and λ_{133}
    - λ_{133} enriched in taus

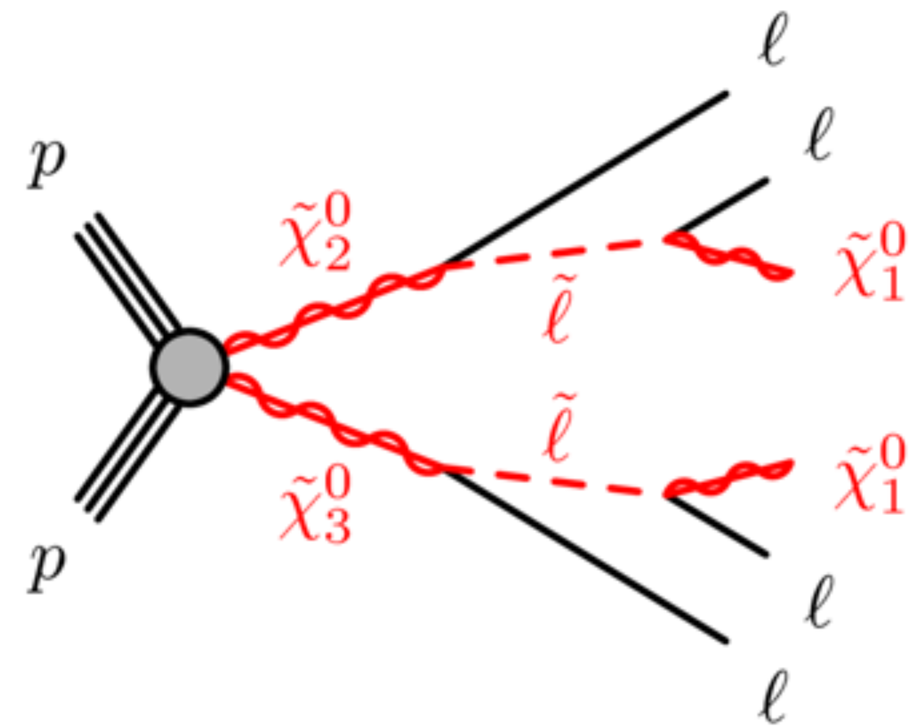


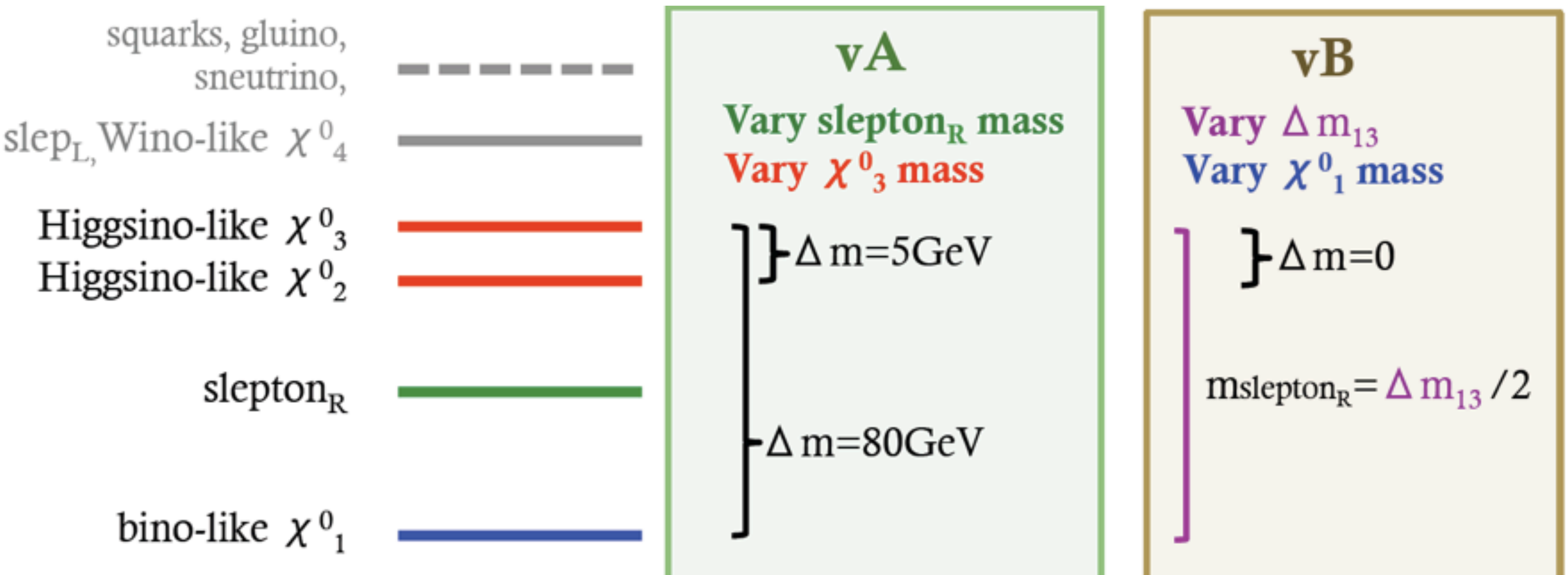


- Final states with 4-6 charged leptons, some MET from neutrinos, and jets (in gluino production)

Signal Models: RPC N2N3 production

- N2N3 production and decay via right-handed sleptons
- Final state with 4 leptons (e,μ) and MET from the LSPs





Event Selection

SR	N(ℓ)	N(τ)	Z veto	$E_{\mathrm{T}}^{\mathrm{miss}}$		m_{eff}
SR0noZa	$\geq$4	$\geq$0	$(\ell^+\ell^-)$, $(\ell^+\ell^- + \ell)$, $(\ell^+\ell^- + \ell^+\ell^-)$	>50		–
SR0noZb	$\geq$4	$\geq$0	$(\ell^+\ell^-)$, $(\ell^+\ell^- + \ell)$, $(\ell^+\ell^- + \ell^+\ell^-)$	>75	or	>600
SR1noZ	=3	$\geq$1	$(\ell^+\ell^-)$, $(\ell^+\ell^- + \ell)$	>100	or	>400

- Three signal regions with zero or one hadronic taus, Z-vetoes, and cuts on the MET or m_{eff}:

$$m_{\mathrm{eff}} = E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{\mathrm{leptons}} p_{\mathrm{T}}^{\ell} + \sum_{\mathrm{jets\ with\ } p_{\mathrm{T}} > 40\ \mathrm{GeV}} p_{\mathrm{T}}^{\mathrm{jet}}$$

Background Modeling

- Similar to the three-lepton analysis
- Backgrounds with four prompt leptons modeled with MC
  - ZZ, Higgs, ZWW, ttbar+Z
- Backgrounds with one or two fake leptons modeled with the *weighting method*
  - Processes with one fake: WZ, WWW, ttbar+W
  - Processes with two fake: Z, WW, ttbar
- Backgrounds with three or more fake leptons are *negligible*

The Weighting Method

- A simplified version of the matrix method which relies solely on a fake ratio:

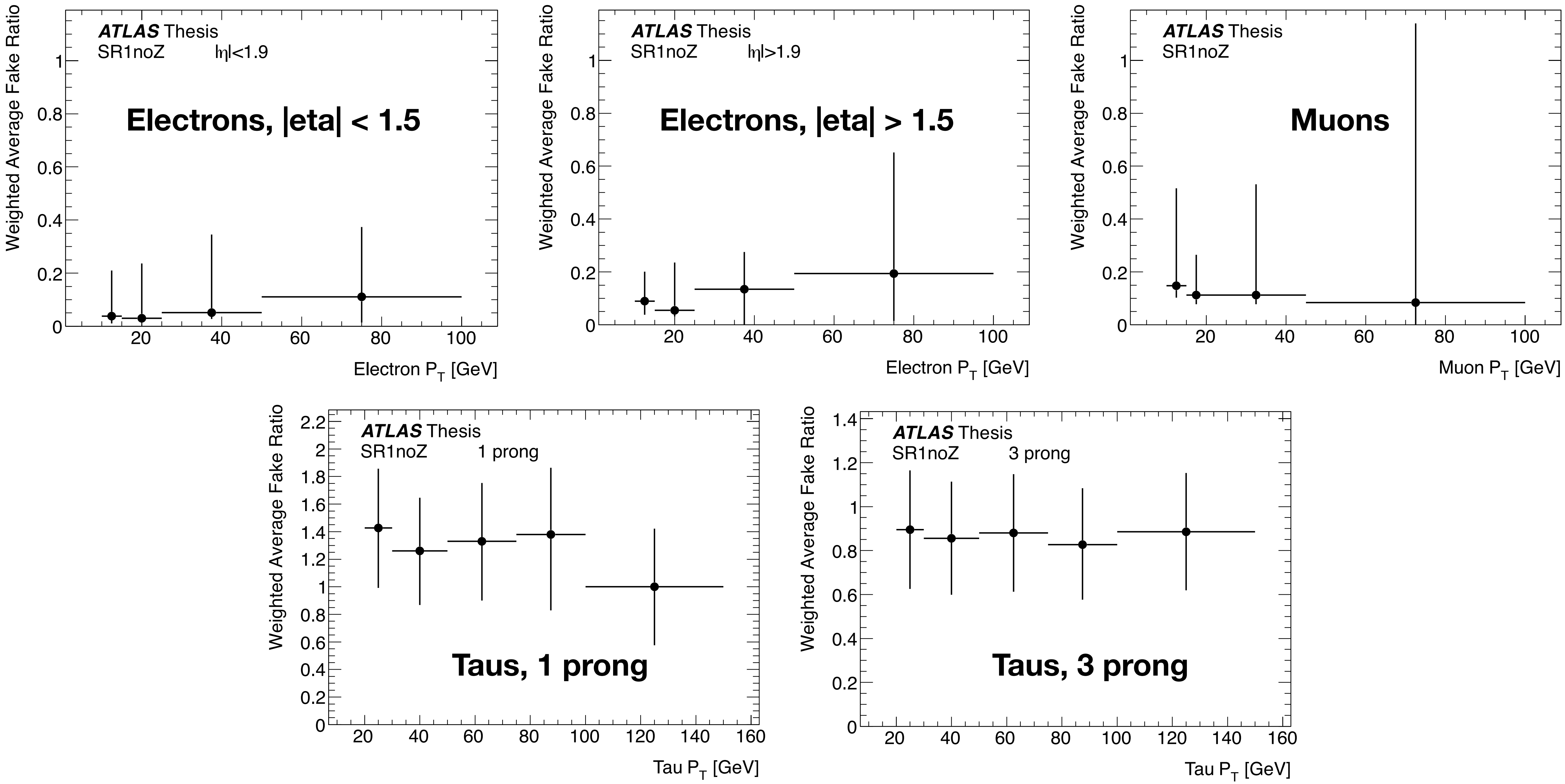
$$F = f/\bar{f}, \qquad \bar{f} = 1 - f$$

- The fake estimate is extrapolated to the signal region from a selection with one or two loose leptons using the fake ratios:

$$N_{fake} = [N_{data}(3T + 1L) - N_{MC,4L}(3T + 1L)] \times F$$
$$- [N_{data}(2T + L_1 + L_2) - N_{MC,4L}(2T + L_1 + L_2)] \times F_1 \times F_2$$

- The second term removes the double counting of events with two fake leptons
- Weighted average fake ratios are used, parametrized in the same way as the three-lepton analysis

Weighted Average Fake Ratios in SR1noZ



Background Validation

VR	N(ℓ)	N(τ)	SFOS pair	Z boson	E_T^{miss}	m_{eff}	dominant bkg.
VR0noZ	$\geq$4	$\geq$0	–	veto	<50	<400	Z^*Z^*
VR0Z	$\geq$4	$\geq$0	require	require	<50	-	ZZ
VR1noZ	==3	$\geq$1	–	veto	<50	<400	Z^*Z^*, WZ, Z+jets
VR1Z	==3	$\geq$1	require	require	<50	-	ZZ, WZ, Z+jets

- Validation regions with zero or one tau validate the background modeling in the signal regions

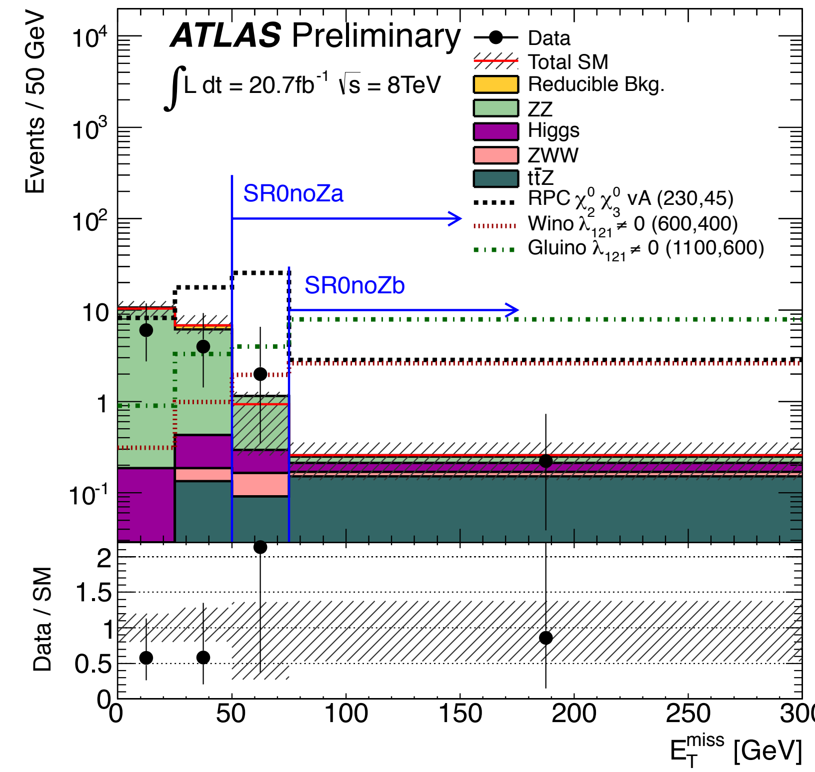
Sample	VR0noZ	VR1noZ	VR0Z	VR1Z
ZZ	7.2 ± 3.6	1.45 ± 0.30	167 ± 38	8.0 ± 1.2
ZWW	0.031 ± 0.031	0.027 ± 0.027	0.35 ± 0.35	0.10 ± 0.10
$t\bar{t}Z$	$0^{+0.05}_{-0}$	$0^{+0.10}_{-0}$	1.5 ± 0.7	0.18 ± 0.14
Higgs	0.17 ± 0.05	0.23 ± 0.05	4.5 ± 0.9	0.64 ± 0.16
MC Bkg.	7.4 ± 3.6	1.70 ± 0.34	173 ± 39	8.9 ± 1.4
Fake Bkg.	$0.3^{+0.7}_{-0.3}$	7.9 ± 3.6	$2.0^{+2.6}_{-2.0}$	28 ± 10
Total Bkg.	7.7 ± 3.4	9.6 ± 3.6	175 ± 37	37 ± 10
Data	3	10	201	31

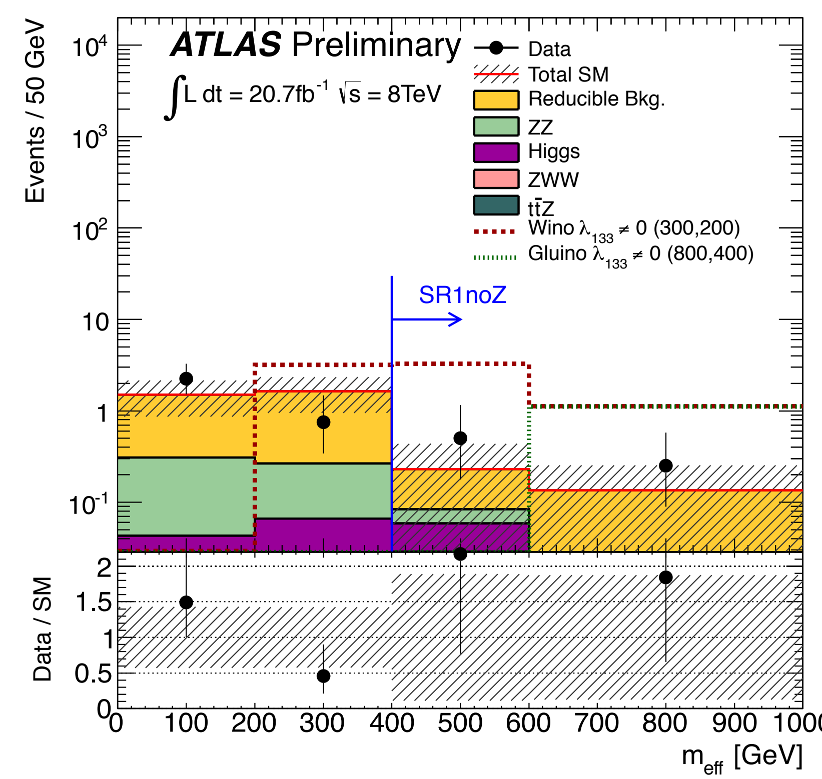
- Good agreement is observed

Signal Region Results

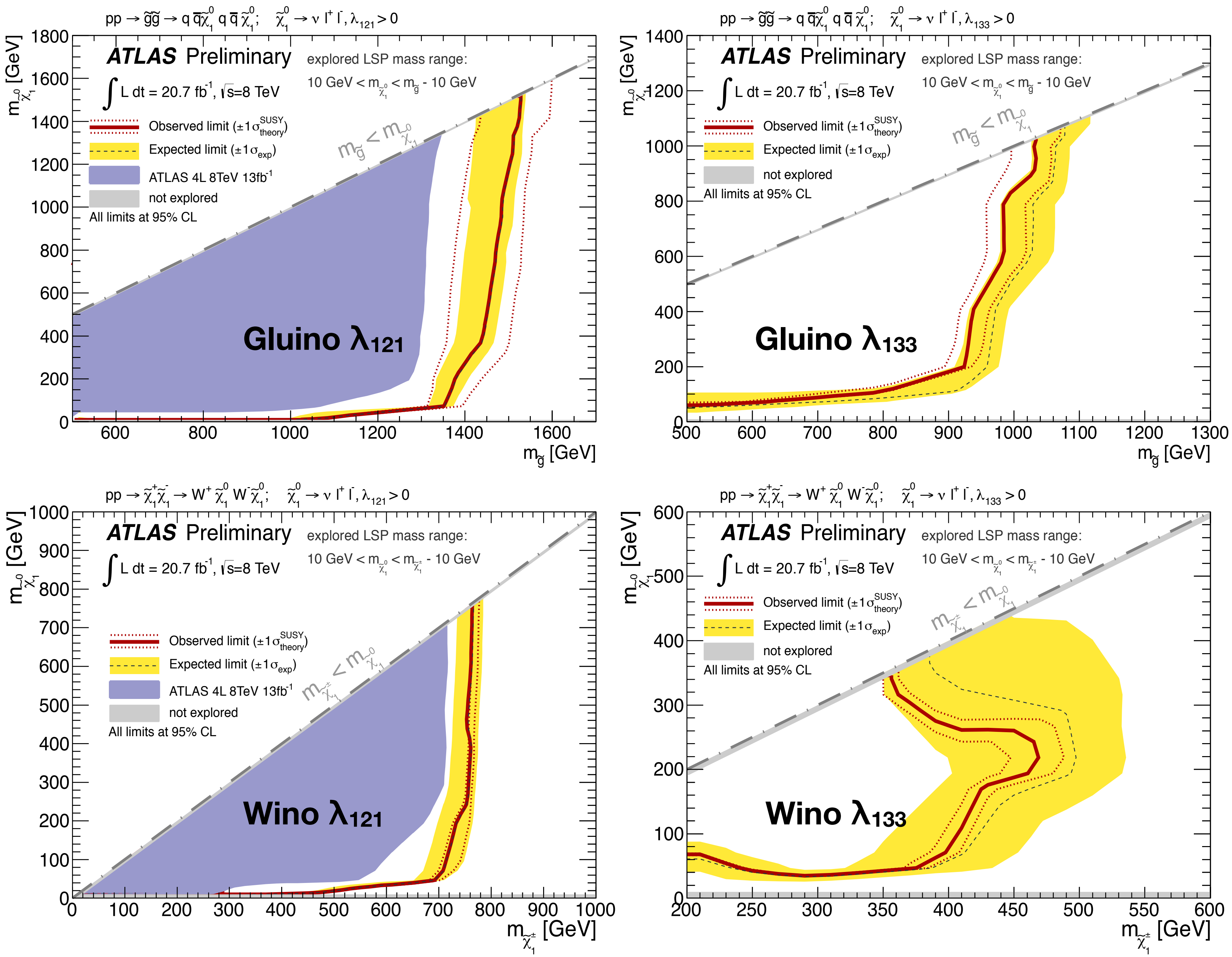
Sample	SR0noZa	SR0noZb	SR1noZ
ZZ	0.6 ± 0.5	0.50 ± 0.26	0.19 ± 0.05
ZWW	0.12 ± 0.12	0.08 ± 0.08	0.05 ± 0.05
$t\bar{t}Z$	0.73 ± 0.34	0.75 ± 0.35	0.16 ± 0.12
Higgs	0.26 ± 0.07	0.22 ± 0.07	0.23 ± 0.06
MC 4-prompt Bkg.	1.7 ± 0.8	1.6 ± 0.6	0.62 ± 0.21
Fake Lepton Bkg.	$0^{+0.16}_{-0}$	$0.05^{+0.14}_{-0.05}$	1.4 ± 1.3
Total Bkg.	1.7 ± 0.8	1.6 ± 0.6	2.0 ± 1.3
Data	2	1	4
p_0-value	0.29	0.5	0.15

- Good agreement with the Standard Model prediction
- No evidence for supersymmetry



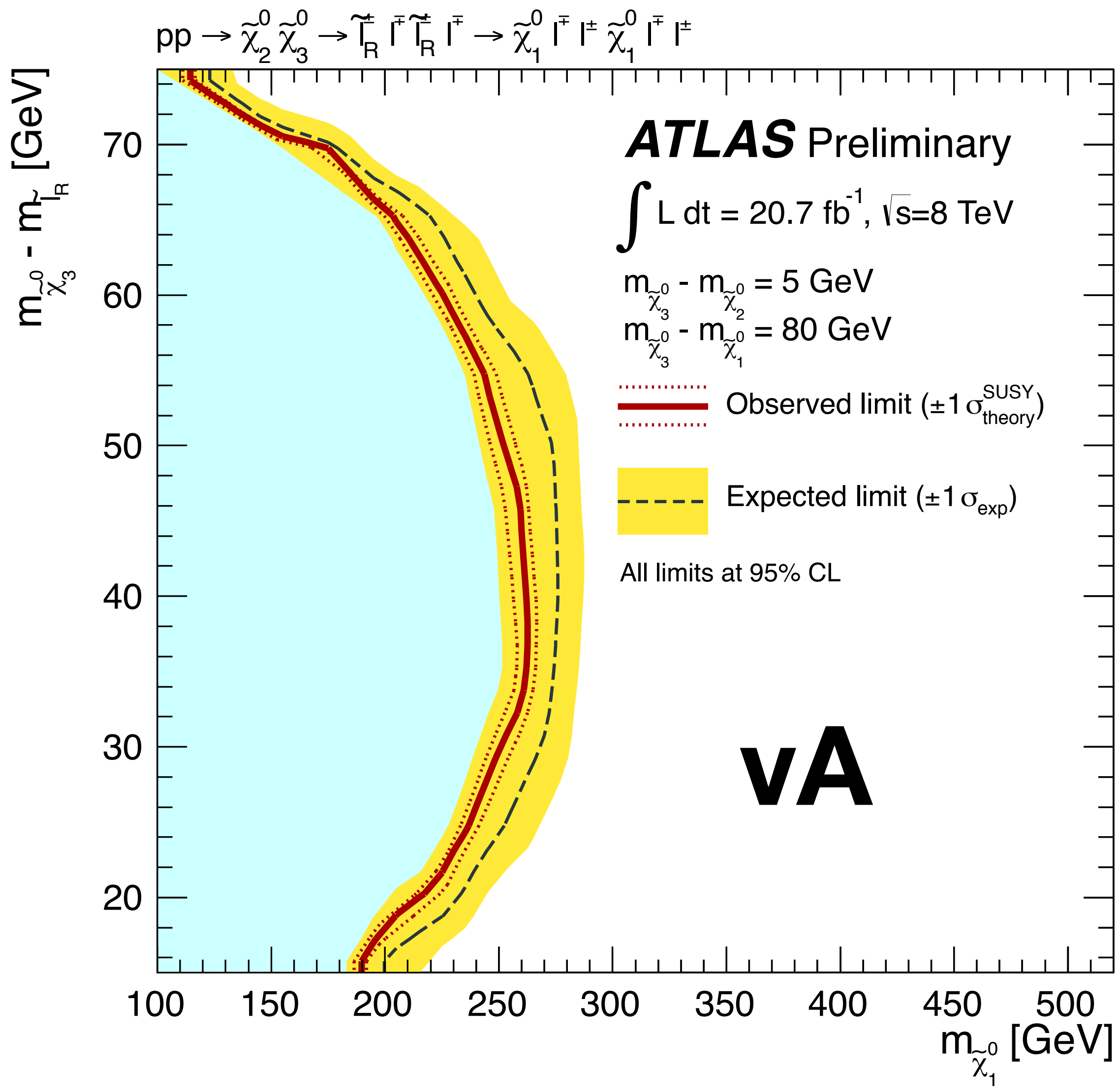


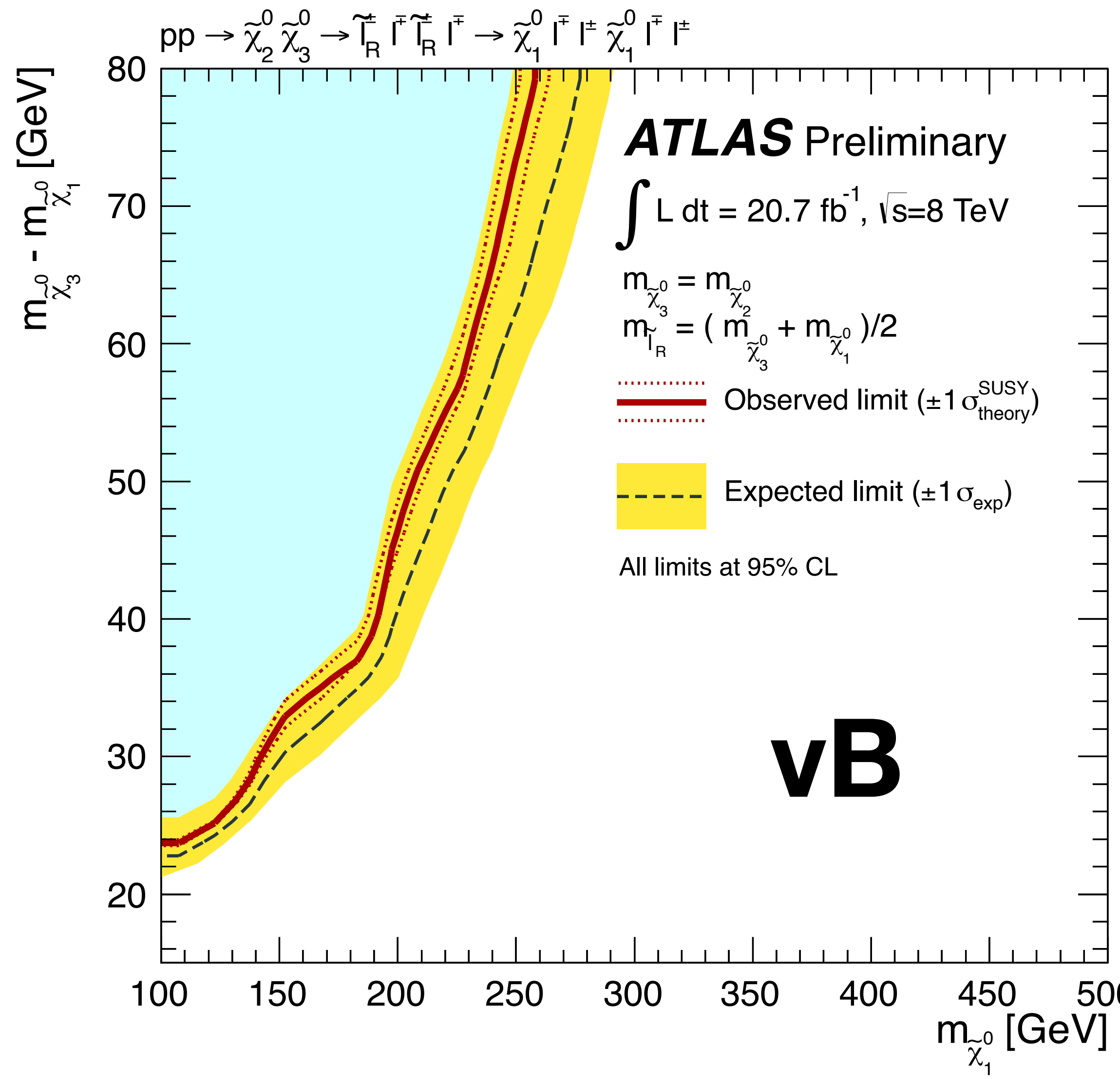
Statistical Interpretation: RPV models



- 95% exclusion contours in the RPV simplified models
- λ_{121} models show good improvement over previous ATLAS result
- New λ_{133} models have good exclusion

Statistical Interpretation: N2N3 models



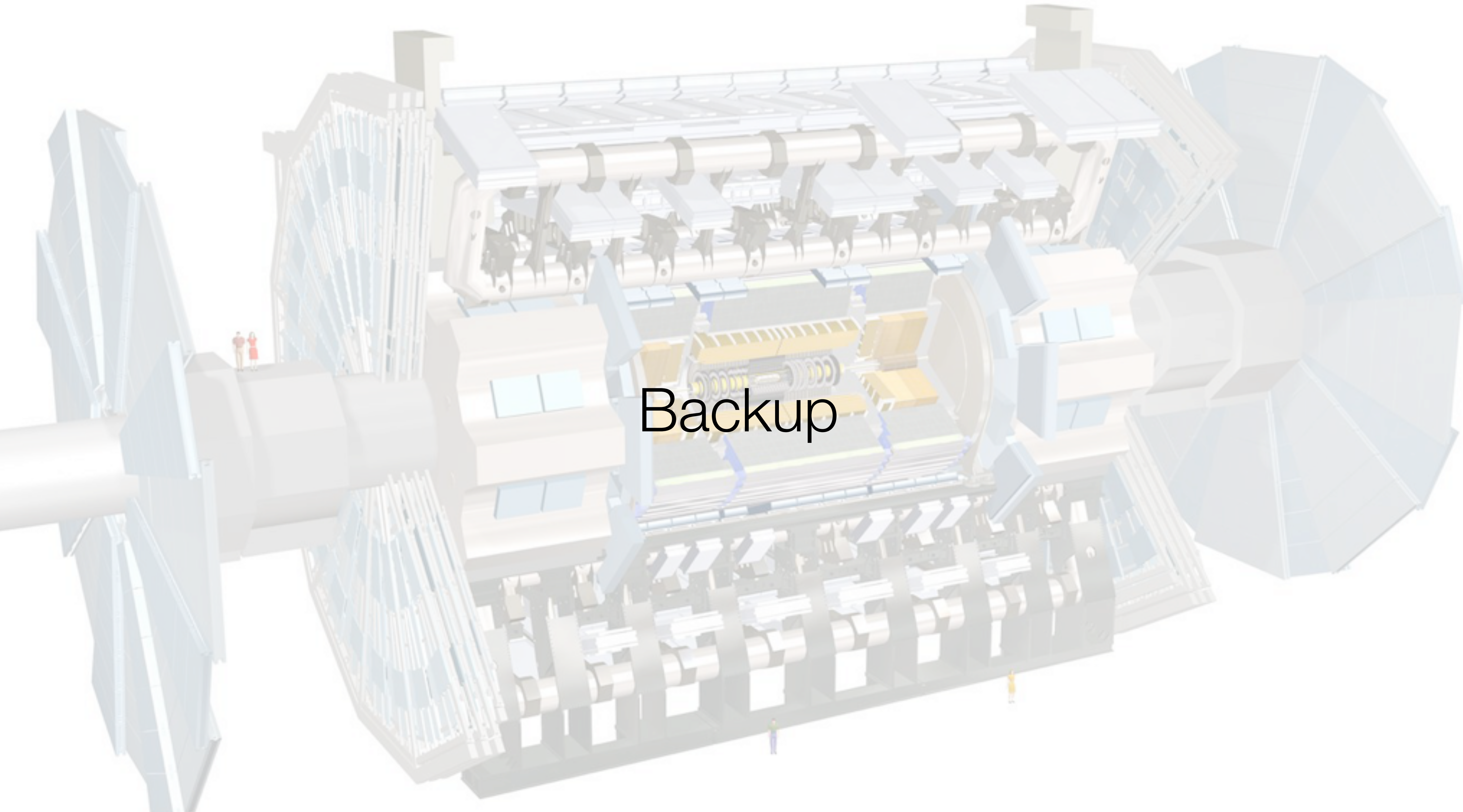


- 95% exclusion contours in the N2N3 simplified models
- Reminder
    - vA: varies slepton and N3 masses
    - vB: varies (m1-m3) and LSP masses

Conclusion

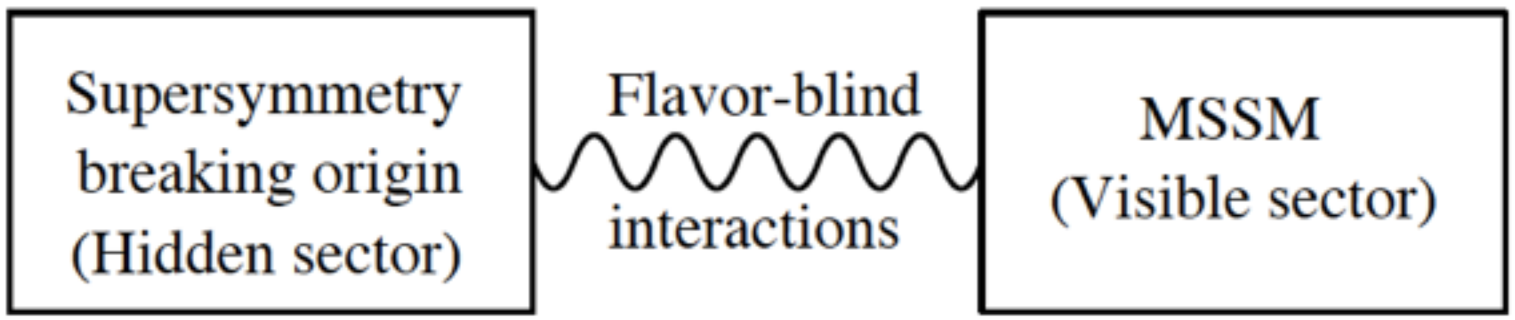
- Searches for supersymmetry in the three- and four-lepton channels have been carried out using 8 TeV proton-proton collision data from the ATLAS detector
- In all cases, no evidence for supersymmetry has been found; observed data agrees well with the Standard Model predictions
- Three-lepton analysis
  - Limits have been placed on chargino-neutralino production with simplified models and the pMSSM (not shown), considering cases with intermediate sleptons, SM gauge bosons, and the Higgs boson
- Four-lepton analysis
  - Limits have been placed on RPV simplified models with gluino and wino NLSP for λ couplings
  - Limits have been place on neutralino pair production and decay via right-handed sleptons with simplified models

Backup



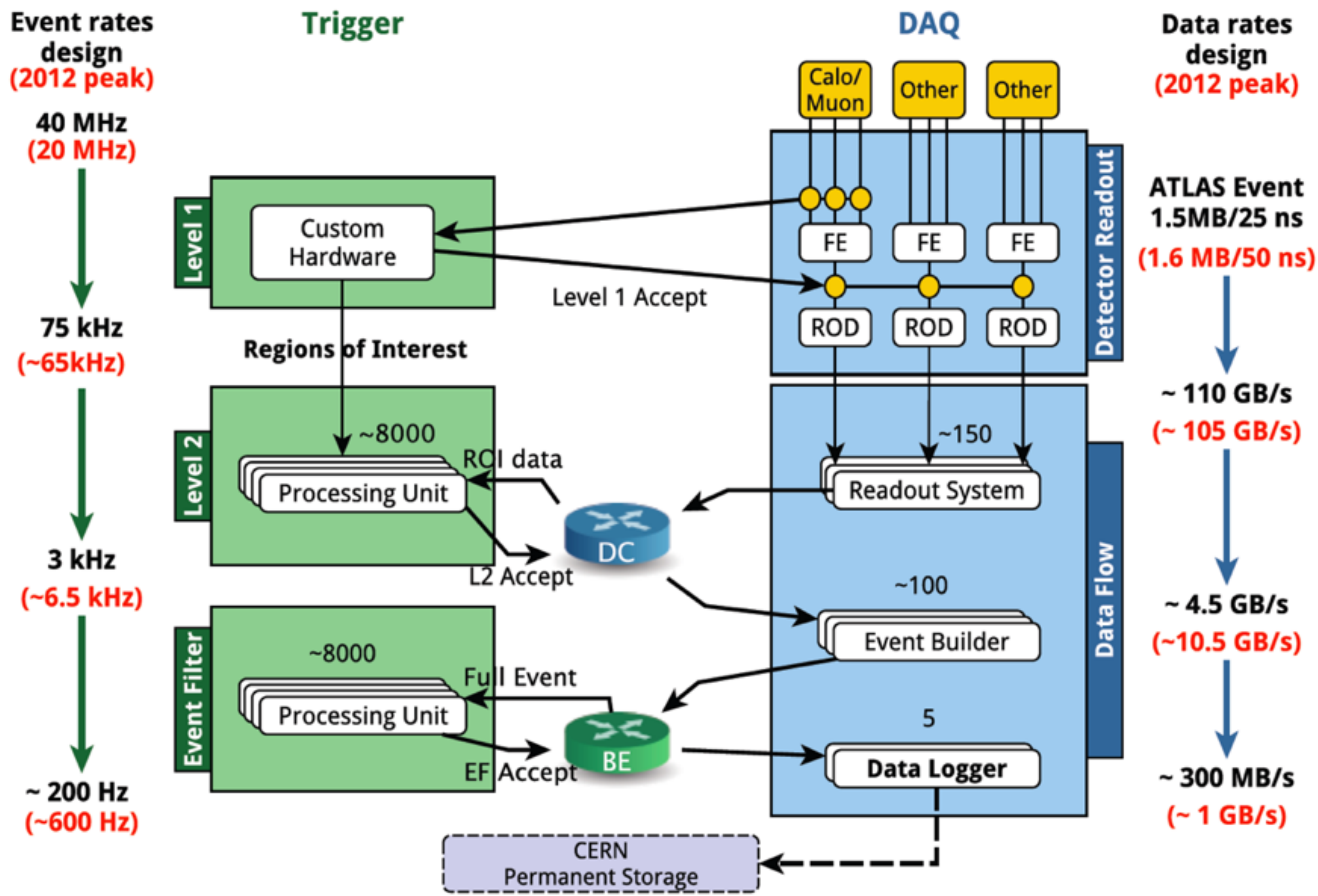
Breaking Supersymmetry

- No sparticles have been found --> SUSY must be a broken symmetry
- As with the electroweak case, SUSY should be spontaneously broken

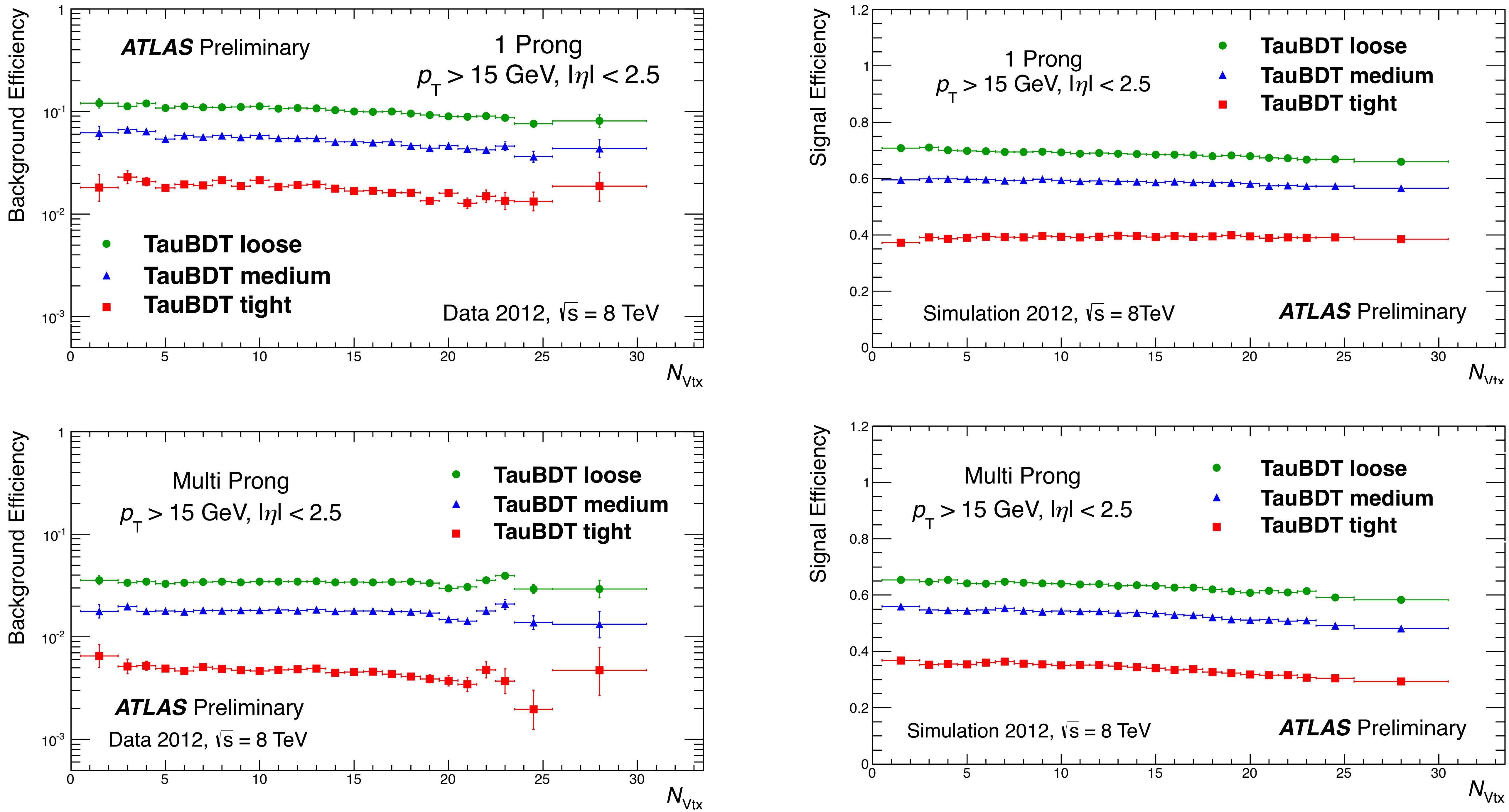


- It is common to assume that SUSY is broken in some hidden sector of fields which couple very weakly to the SM via messengers:
  - via gravitational interactions
  - via gauge interactions
  - via anomalies
- These models can be extremely predictive (mSUGRA has only 5 parameters)
- If we instead simply parametrize our ignorance, we get ***105 free parameters***

ATLAS Trigger and Data Acquisition



Tau Identification



Trigger chains

Trigger	Detail	offline threshold [GeV]
Isolated e	EF_el_EF_e24vhi_medium1	25
Isolated μ	EF_mu24i_tight	25
ee	EF_2e12Tvh_loose1	14,14
	EF_e24vh_medium1_e7_medium1	25,10
$\mu\mu$	EF_2mu13	14,14
	EF_mu18_tight_mu8_EFFS	18,10
$e\mu$	EF_e12Tvh_medium1_mu8	14,10
	EF_mu18_tight_e7_medium1	18,10

Three-Lepton Event Selection: decays with sleptons and WZ

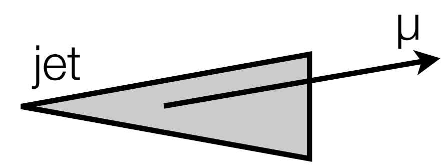
- To improve on previously published results, a binned signal region is used, **SR0a**
- Three light leptons
- Binned in
  - Same-flavor opposite-sign (SFOS) mass
  - Transverse mass
  - Missing transverse energy
- B-jet veto applied

m_{SFOS}	m_{T}	$E_{\mathrm{T}}^{\mathrm{miss}}$	3ℓ Zveto	SR bin
12–40	0–80	50–90		1
		90–∞		2
	80–∞	50–75		3
		75–∞		4
40–60	0–80	50–75	yes	5
		75–∞		6
	80–∞	50–135		7
		135–∞		8
60–81.2	0–80	50–75	yes	9
	80–∞	50–75		10
	0–110	75–∞		11
	110–∞	75–∞		12
81.2–101.2	0–110	50–90	yes	13
		90–∞		14
	110–∞	50–135		15
		135–∞		16
101.2–∞	0–180	50–210		17
	180–∞	50–210		18
	0–120	210–∞		19
	120–∞	210–∞		20

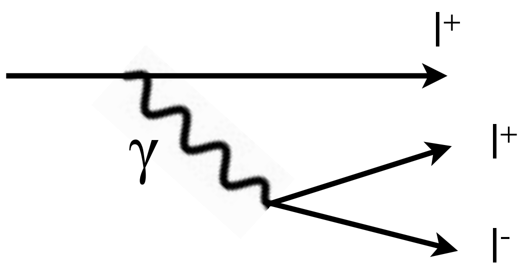
Sources of fake leptons

- ***Electrons and Muons***
  - **Heavy flavor fake** - A real electron from the semi-leptonic decay of a B-hadron inside a jet
    - Non-prompt, non-isolated
  - **Light flavor fake** - Either from a semi-leptonic decay of a light-flavor quark, or simply a jet mis-reconstructed as an electron
    - Non-isolated
  - **Conversion fake** - Radiated photon converted into electron-positron pair
    - Non-prompt
- ***Taus***
  - **Light flavor fake** - a hadronic quark or gluon jet mis-reconstructed as a tau
  - **Heavy flavor fake** - A b-jet mis-reconstructed as a tau due to the displaced vertex
  - **Conversion/electron fake** - an electron mis-reconstructed as a tau

HF/LF fakes from jets



Conversion leptons from photon radiation



Signals: phenomenological MSSM (pMSSM)

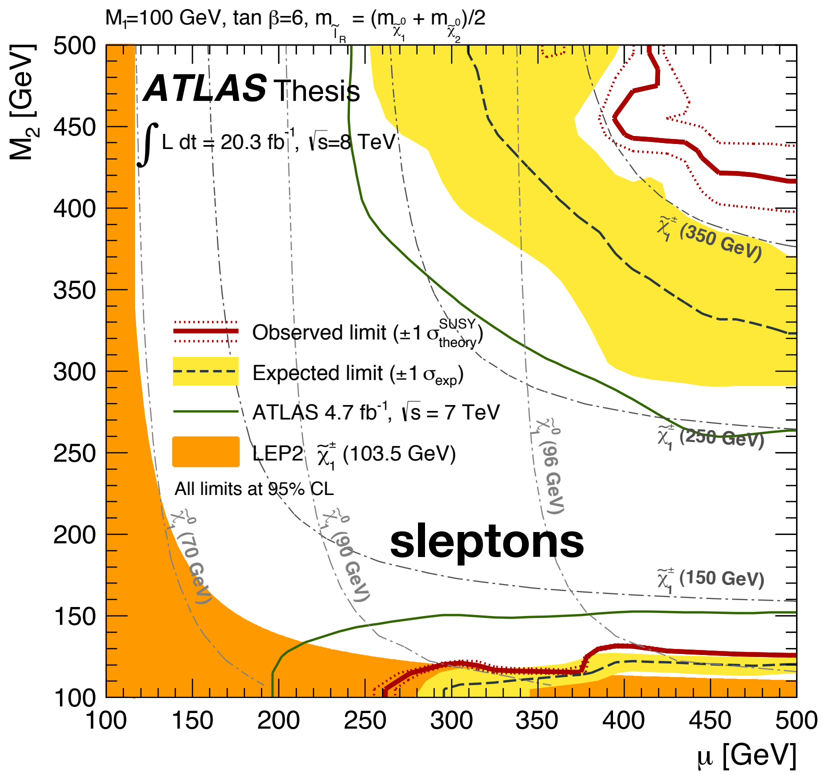
- Explicit assumptions used to reduce the number of free parameters in the MSSM → **19 parameters**
  - CP conservation to remove phases
  - Minimal flavor violation to kill off-diagonal elements in mass matrices
  - Negligible tri-linear couplings for 1st, 2nd generations
  - Degenerate 1st, 2nd generation sfermion masses
- Additional choices → **3 parameters**
  - Lightest Higgs mass set at 125 GeV
  - Ratio of Higgs VEVs, tanβ, is set to 6, 10, or 50
  - Slepton mass set depending on model
- Remaining parameters
  - M1 = U(1) gaugino mass
  - M2 = SU(2) gaugino mass
  - μ = Higgsino mass

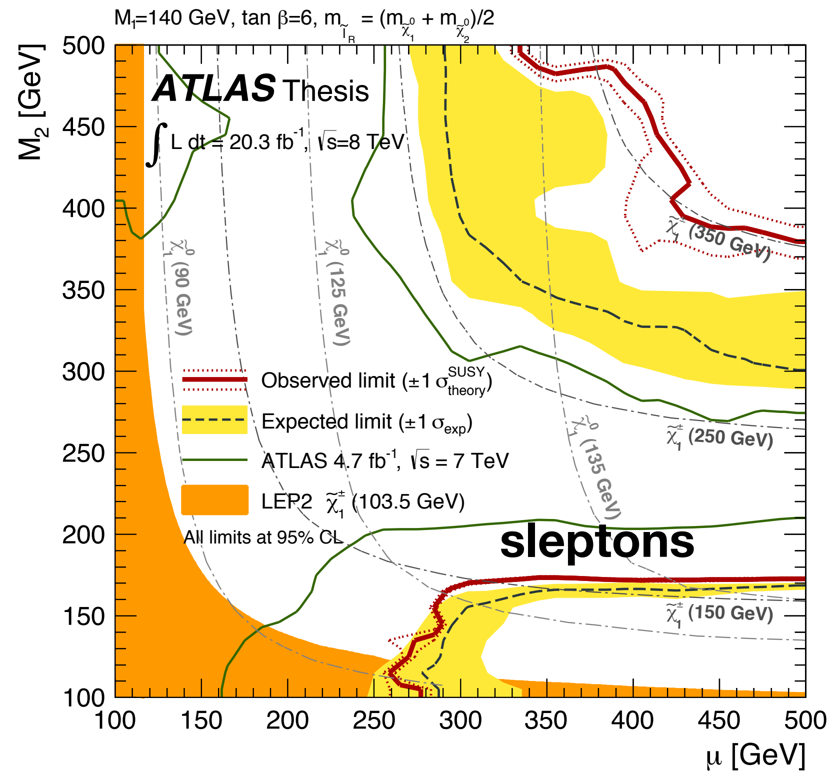
Decays via right-handed sleptons
- Low tanB = 6
- M1 = 100/140/250 GeV

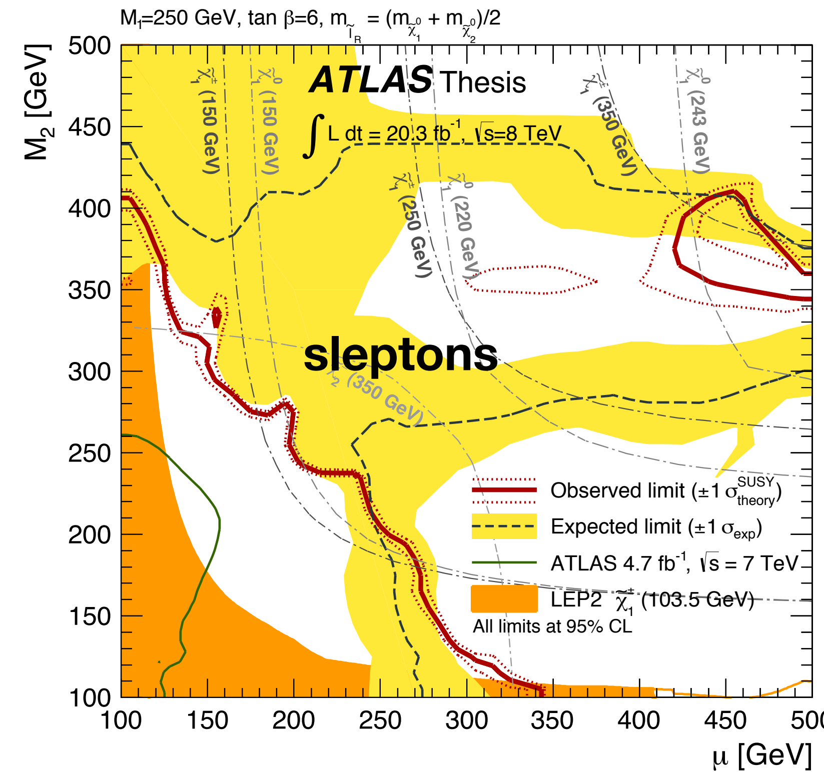
Decays via W/Z/h
- Low tanβ = 10
- M1 = 50 GeV

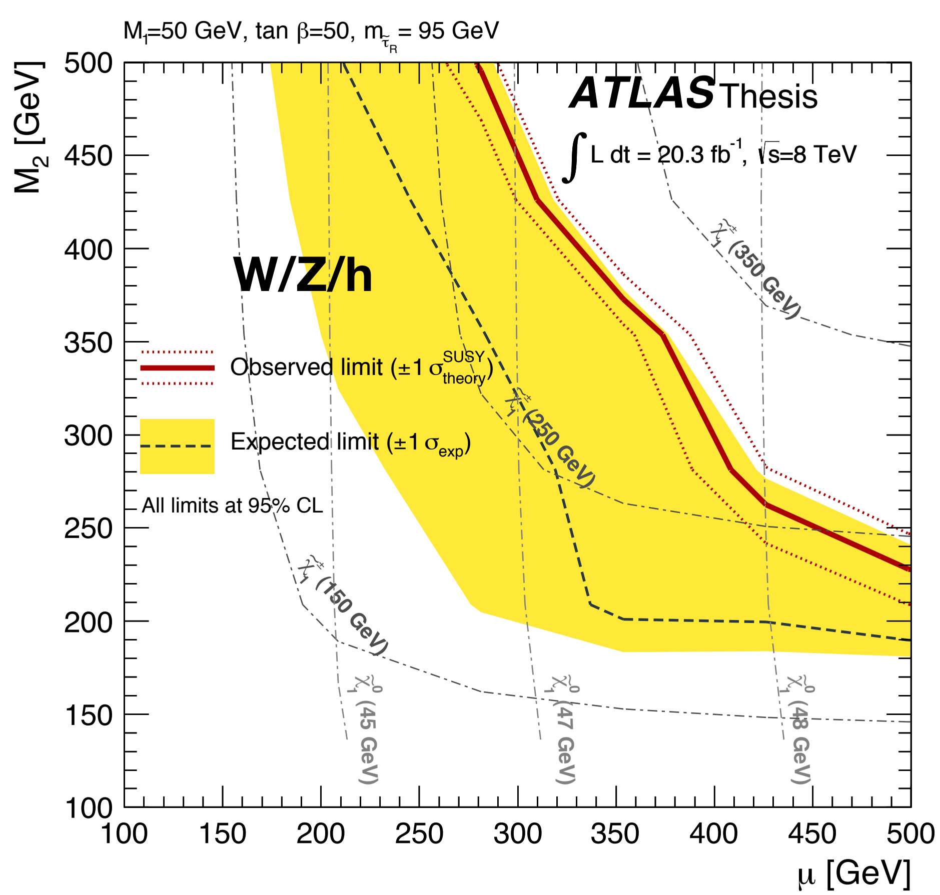
Decays via right-handed staus
- High tanβ = 50
- M1 = 50 GeV
  - Fixed stau mass
- M1 = 75 GeV
  - Stau halfway between C1,N2 and N1

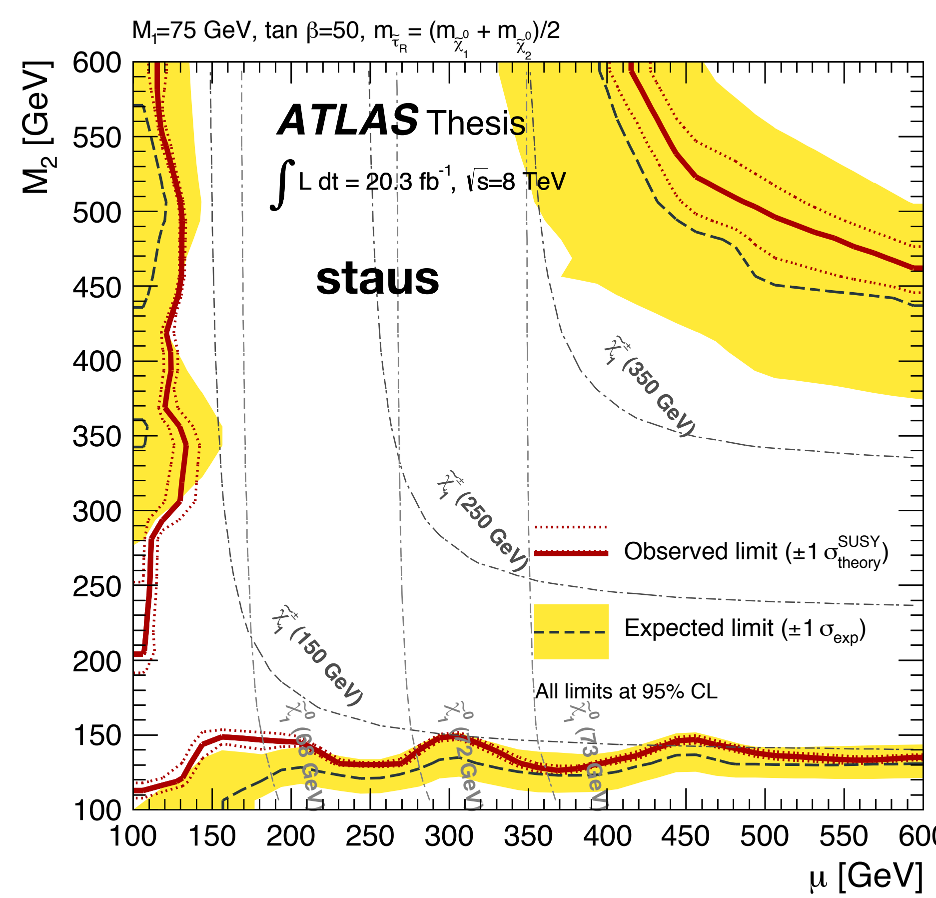
Three-Lepton Limits in pMSSM









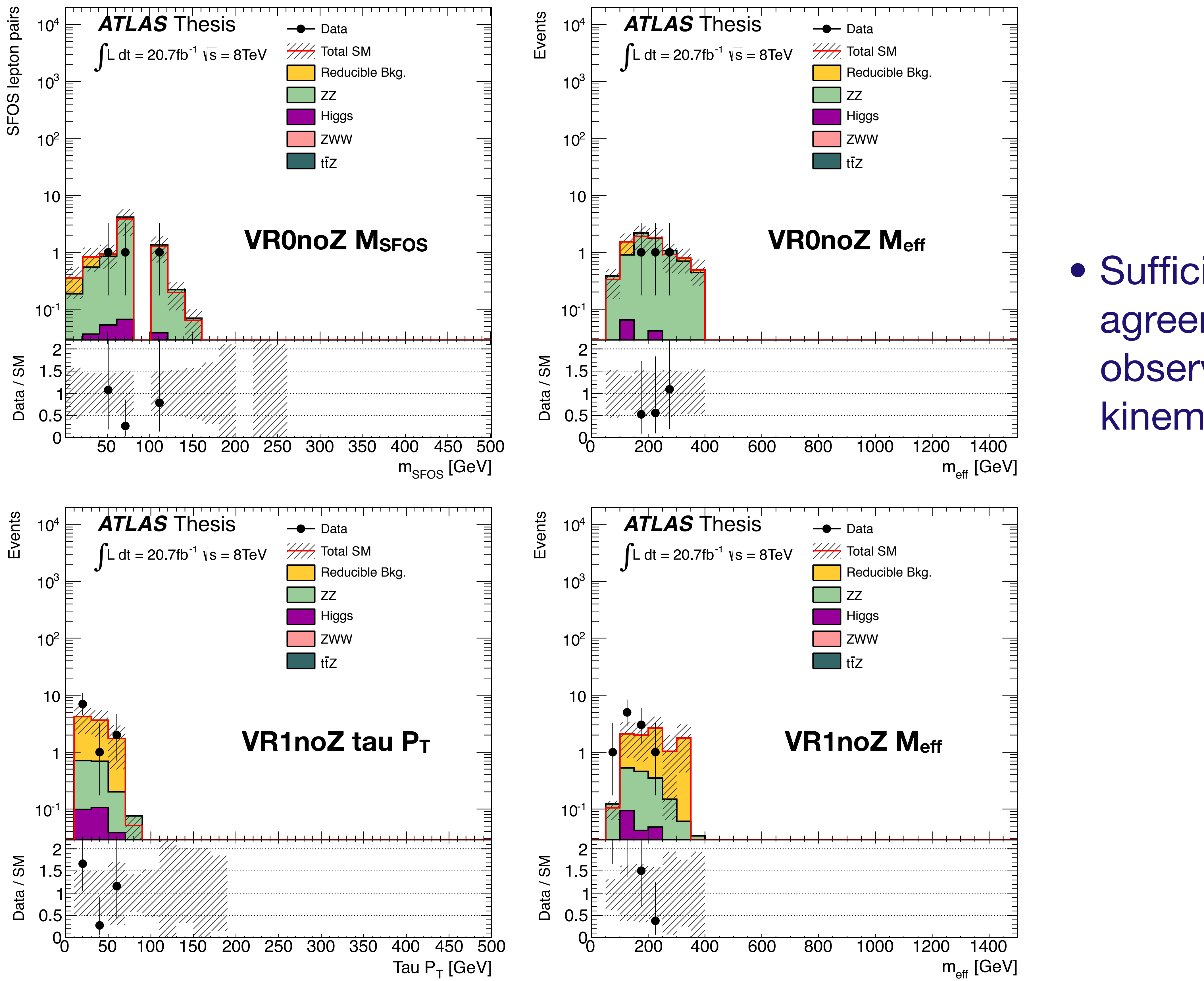


Four-Lepton Uncertainties

	SR0noZa		SR0noZb		SR1noZ	
Leading	Fake Ratio	38%	Cross Section	23%	MC Statistics	60%
Subleading	Generator	33%	Generator	22%	Fake Ratio	21%
	Cross Section	25%	Fake Ratio	20%	Cross Section	3%
	MC Statistics	16%	MC Statistics	16%	JER	2%

- Only the dominant uncertainties are listed, which include
  - Uncertainties on the MC simulation: statistics, cross sections, generator dependence
  - Uncertainties on the weighting method from the fake ratio calculation

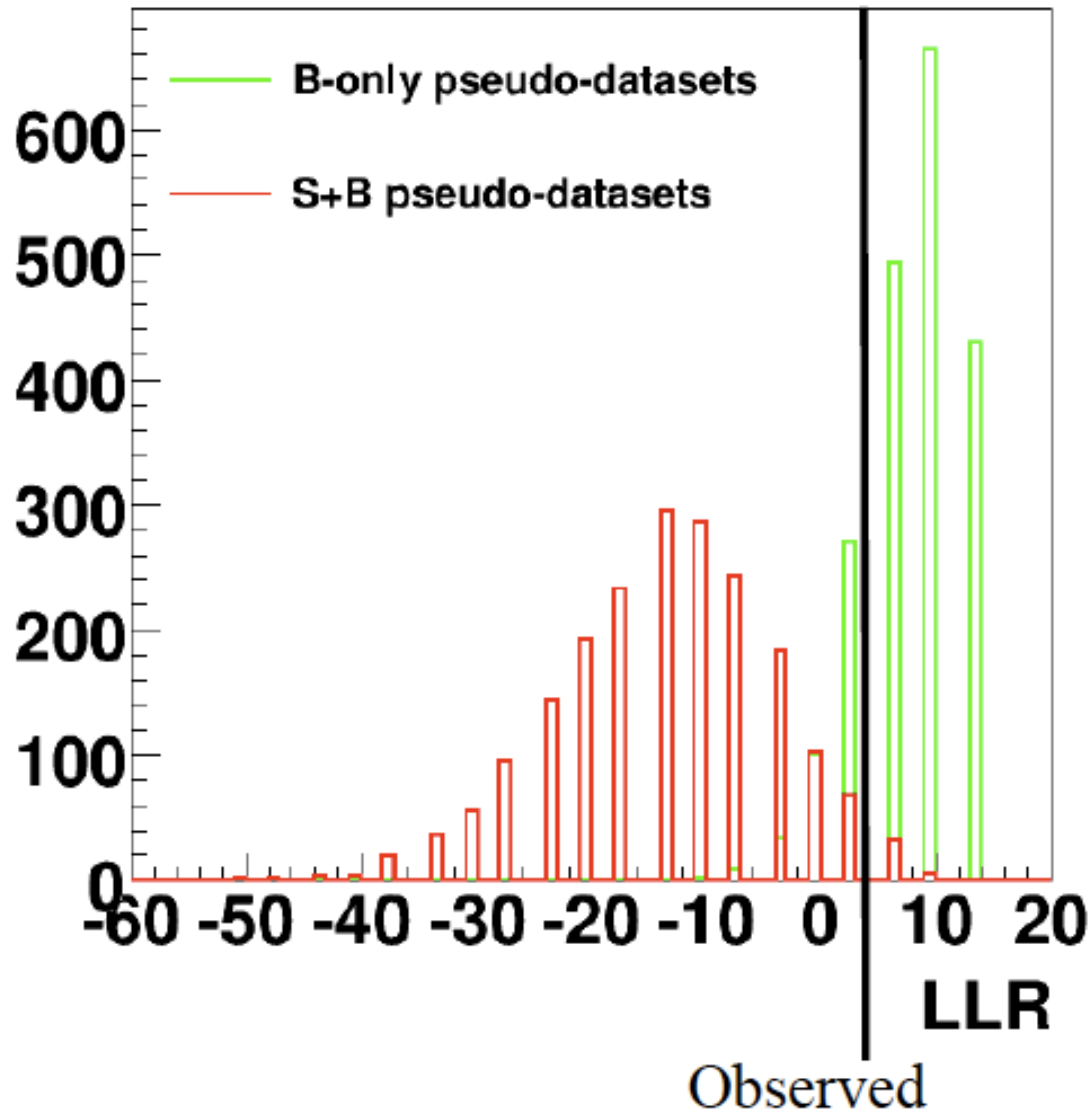
Four-Lepton Background Validation



- Sufficient agreement observed in the kinematic shapes

CL_S: A Modified Frequentist Approach to Limits

- Make ensemble of pseudo-experiments for S+B and B only.
- Determine log-likelihood ratio (LLR) for each pseudo-experiment
- Integrate red above observed to obtain $CL_{s+b} = 0.052$
- Integrate green above observed to get $CL_b = 0.93$
- $CL_s = CL_{s+b} / CL_b = 0.055$
- Excluded at 95% confidence if $CL_s < 0.05$



http://www-d0.fnal.gov/~schwier/talks/seminars/Ud0Statistics2010.pdf