Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the *W*-boson mass in $\sqrt{s}$ = 13 TeV *pp* collisions with the ATLAS detector

arXiv:2209.13935v1 [hep-ex]

Richard Hildebrandt, 19.06.23

Supervisor: Michael Holzbock

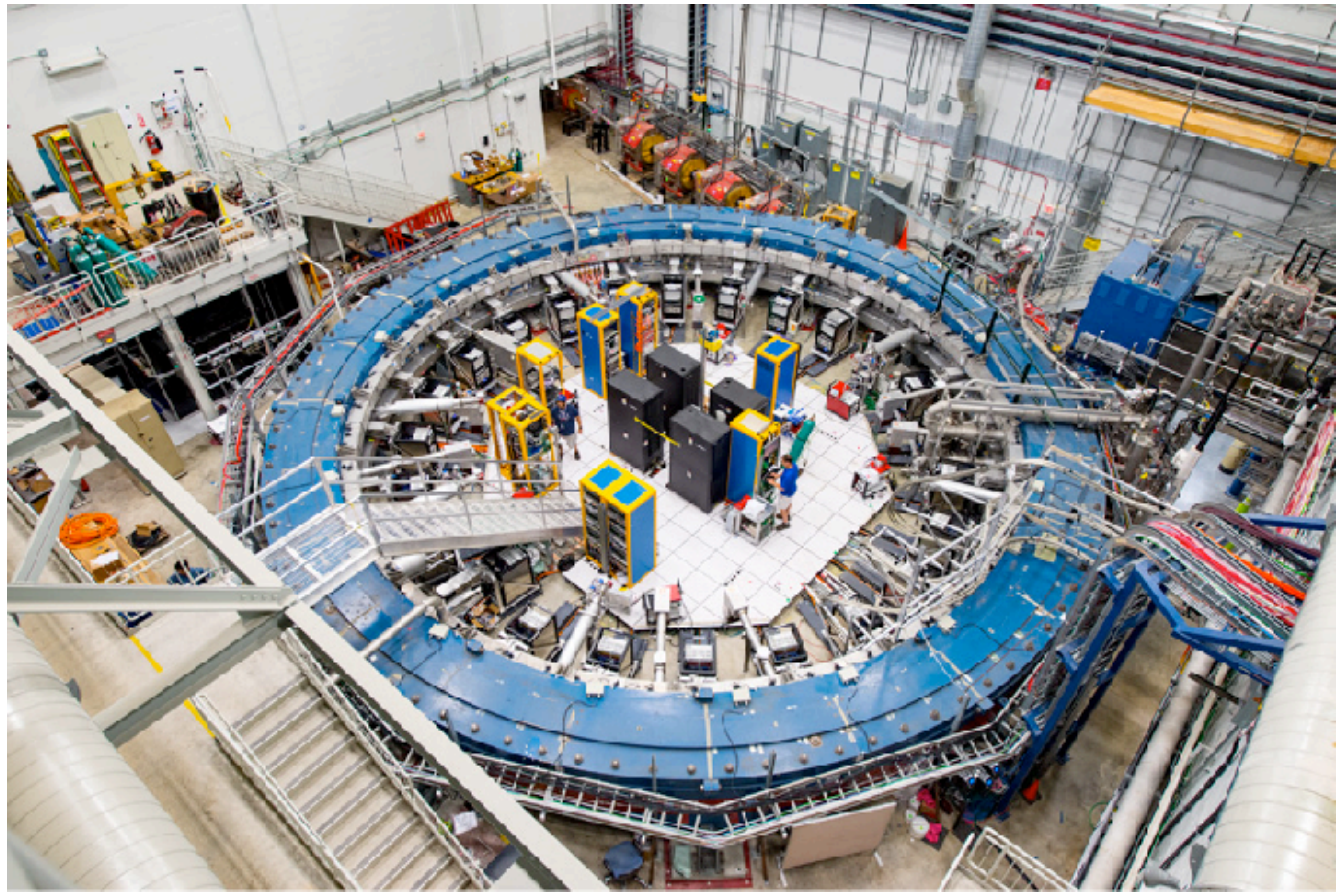
Outline:

1. Motivation
2. Theoretical Background
3. Event Selection
4. Background Estimation
5. Uncertainties
6. Results

New Physics Motivation

Muon g-2 Anomaly

- g-factor in $\boldsymbol{\mu} = g\frac{e}{2m}\mathbf{S}$ dimensionless proportionality factor between spin magnetic moment and spin angular moment
- Anomalous magnetic moment $a_\mu = \frac{g-2}{2}$
- Recent measurements at Fermi-Lab
- Muons decay into positrons and neutrinos
- Measuring the rate and energy of positrons allows computing the g-factor

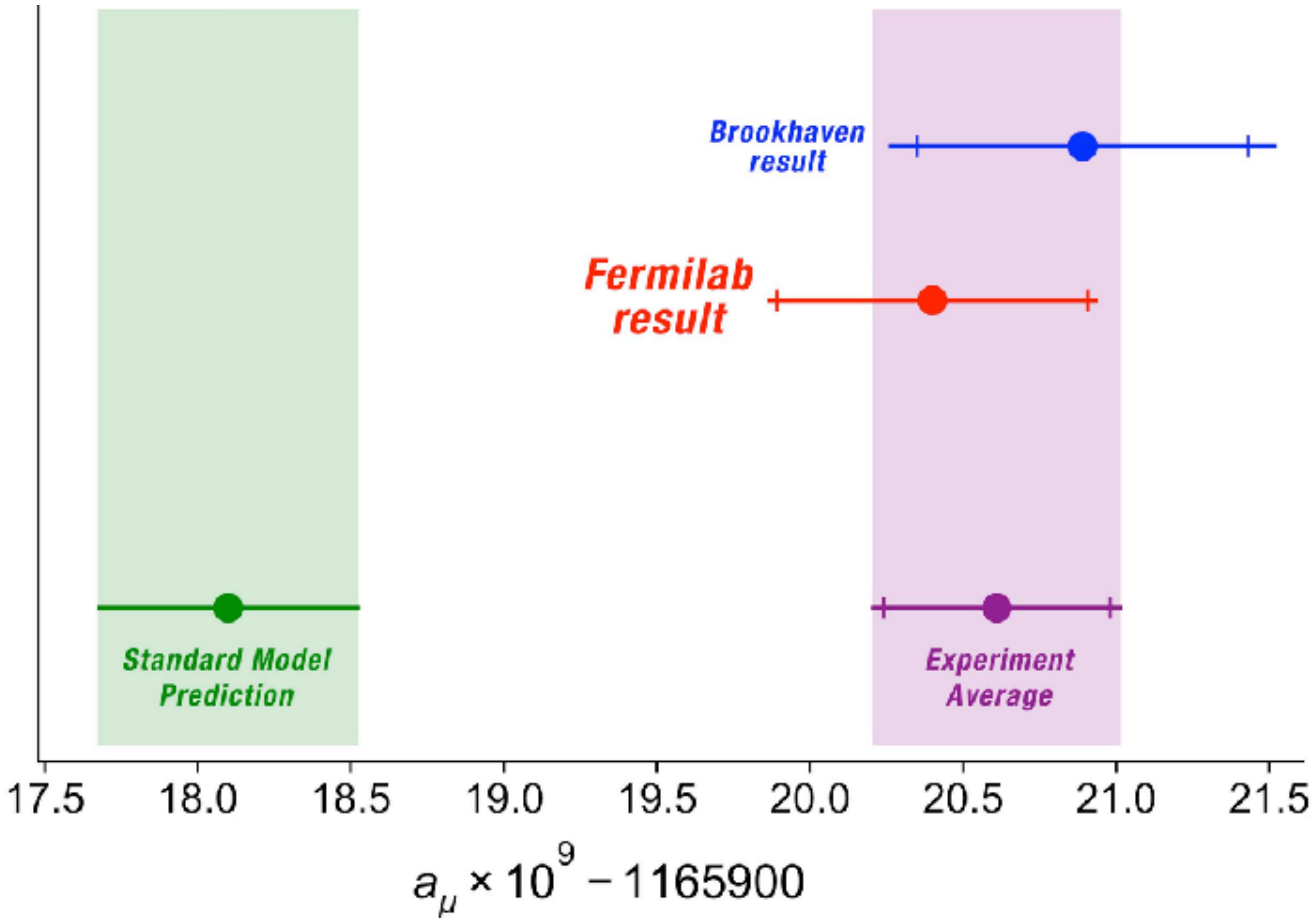


https://vms.fnal.gov/asset/detail?recid=1950114

New Physics Motivation

Muon g-2 Anomaly

- combined experimental results differ from SM predictions by 4.2σ
- non sufficient SM corrections hint at new physics



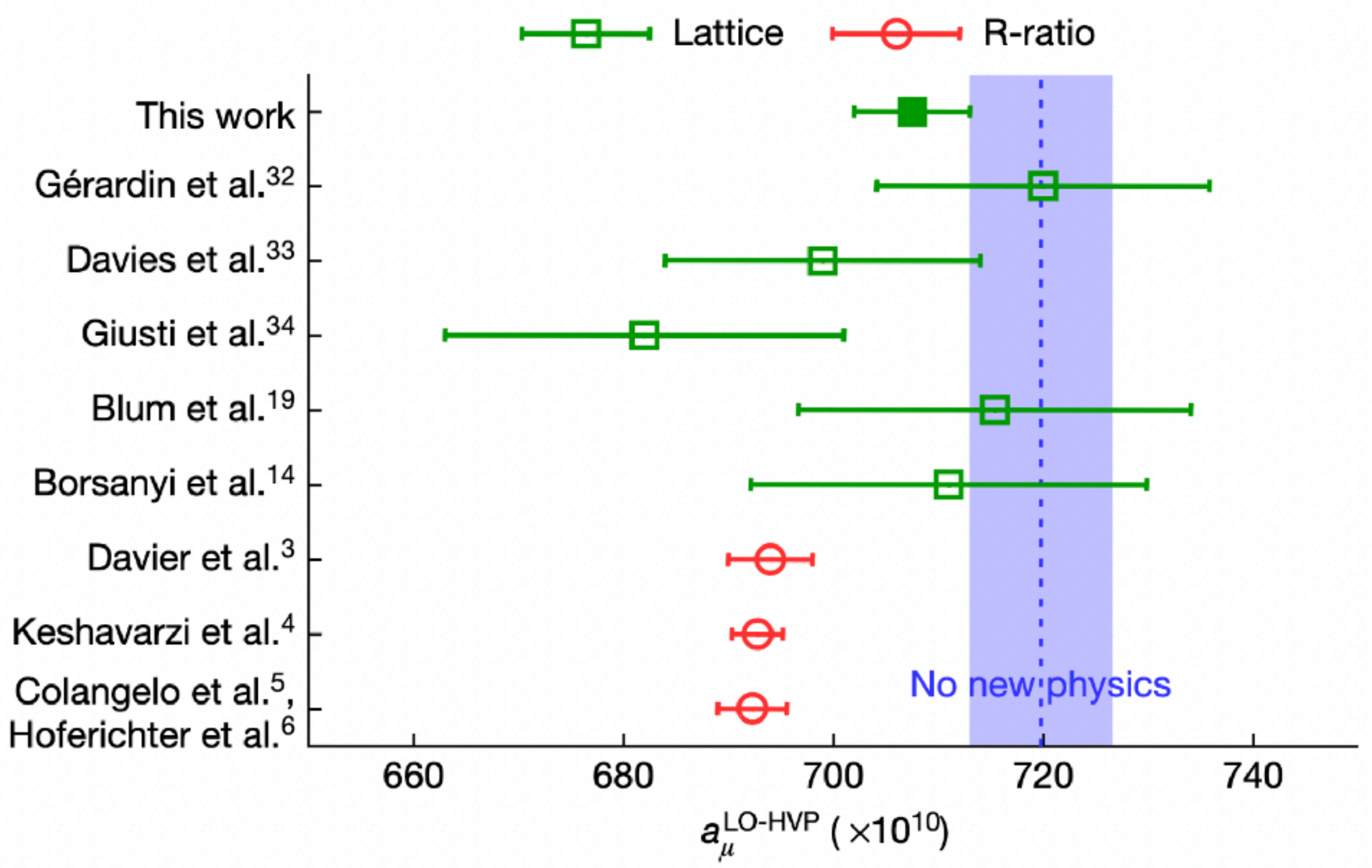
https://news.fnal.gov/wp-content/uploads/2021/04/Muon-g-2-results-plot.jpg

New Physics Motivation

Muon g-2 Anomaly

- Different theoretical approaches to compute corrections to a_μ

- Lattice QCD calculations can be closer to the experimental result, but vary a lot throughout different attempts



https://www.nature.com/articles/s41586-021-03418-1/figures/3

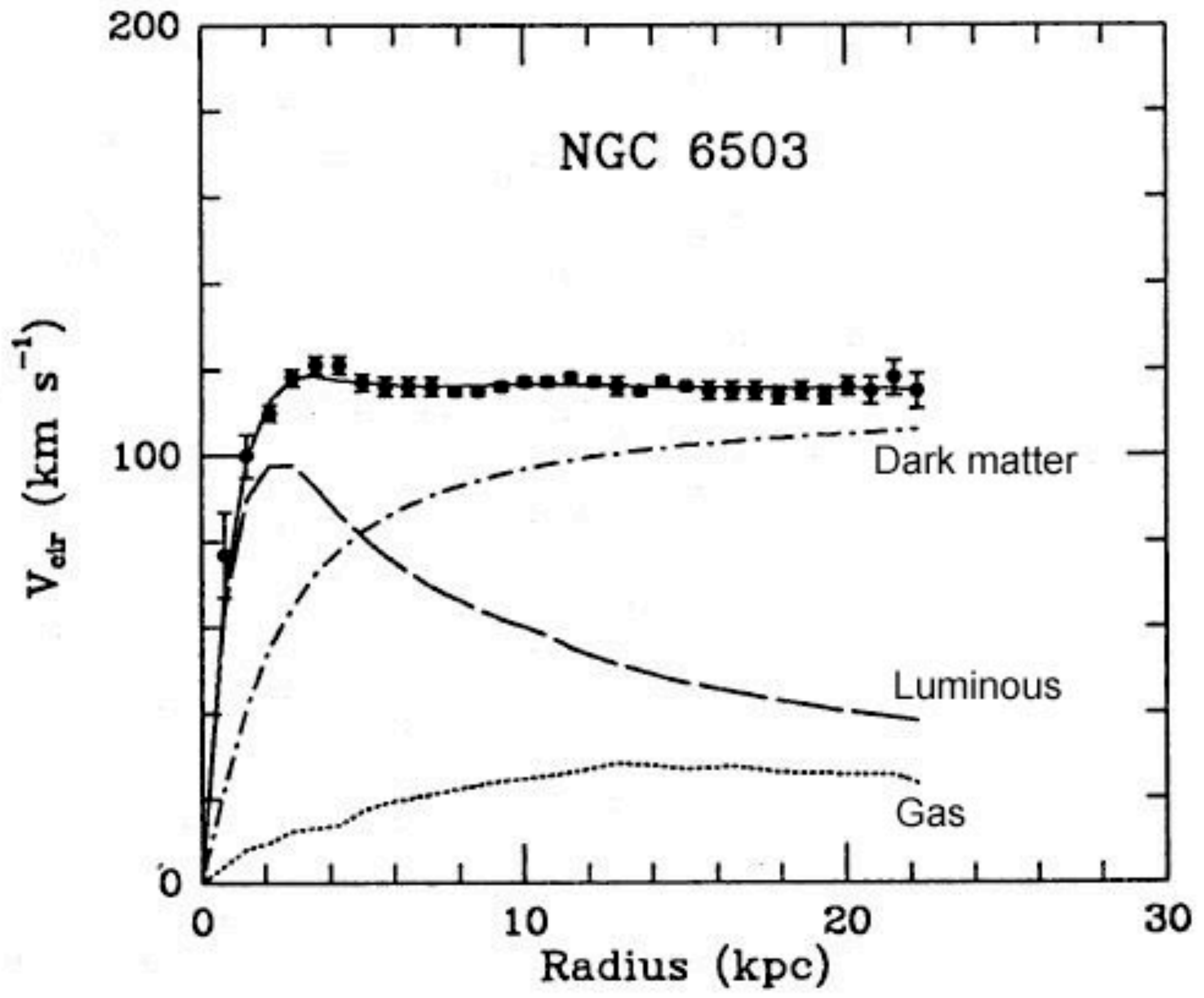
New Physics Motivation

Dark Matter

- Observable matter decreases rapidly with increasing radius in galaxies
- Inconsistent with constant rotation speed

→ There need to be unobservable stable particles that make up the „Dark Matter“

- SM does not provide a suitable candidate
  → needs extension

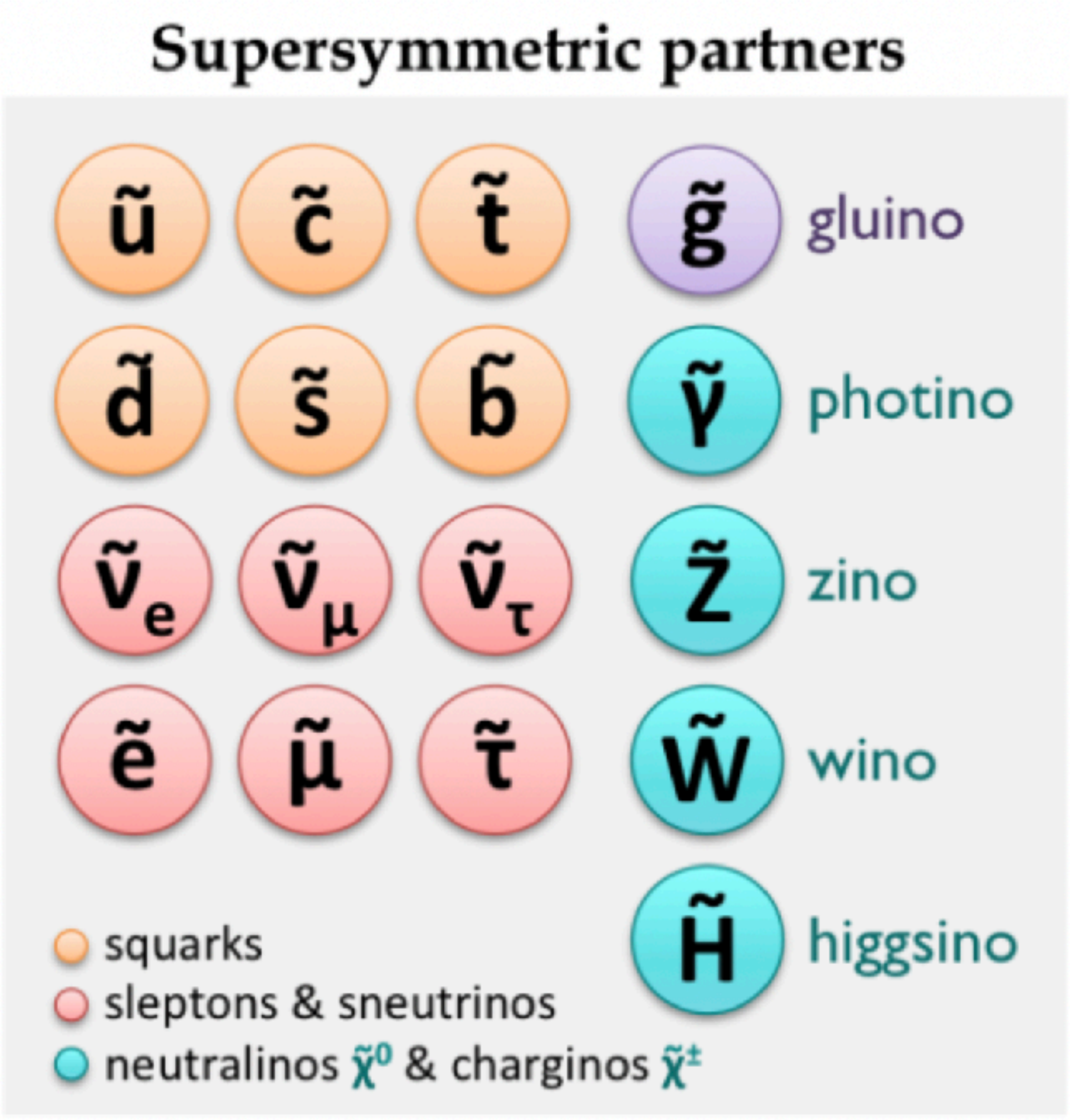


http://www.astro-photography.net/images/NGC%206503%20rotation%20curve%20annotated.jpg

Supersymmetry (SUSY)

- Predicts a set of new particles
- Minimal Supersymmetric Standard Model (MSSM) introducing minimal number of additional particles
- Mirror image of SM relating bosons and fermions → partners differ in spin by 1/2
- Unbroken SUSY would predict particles with same mass as SM counterparts

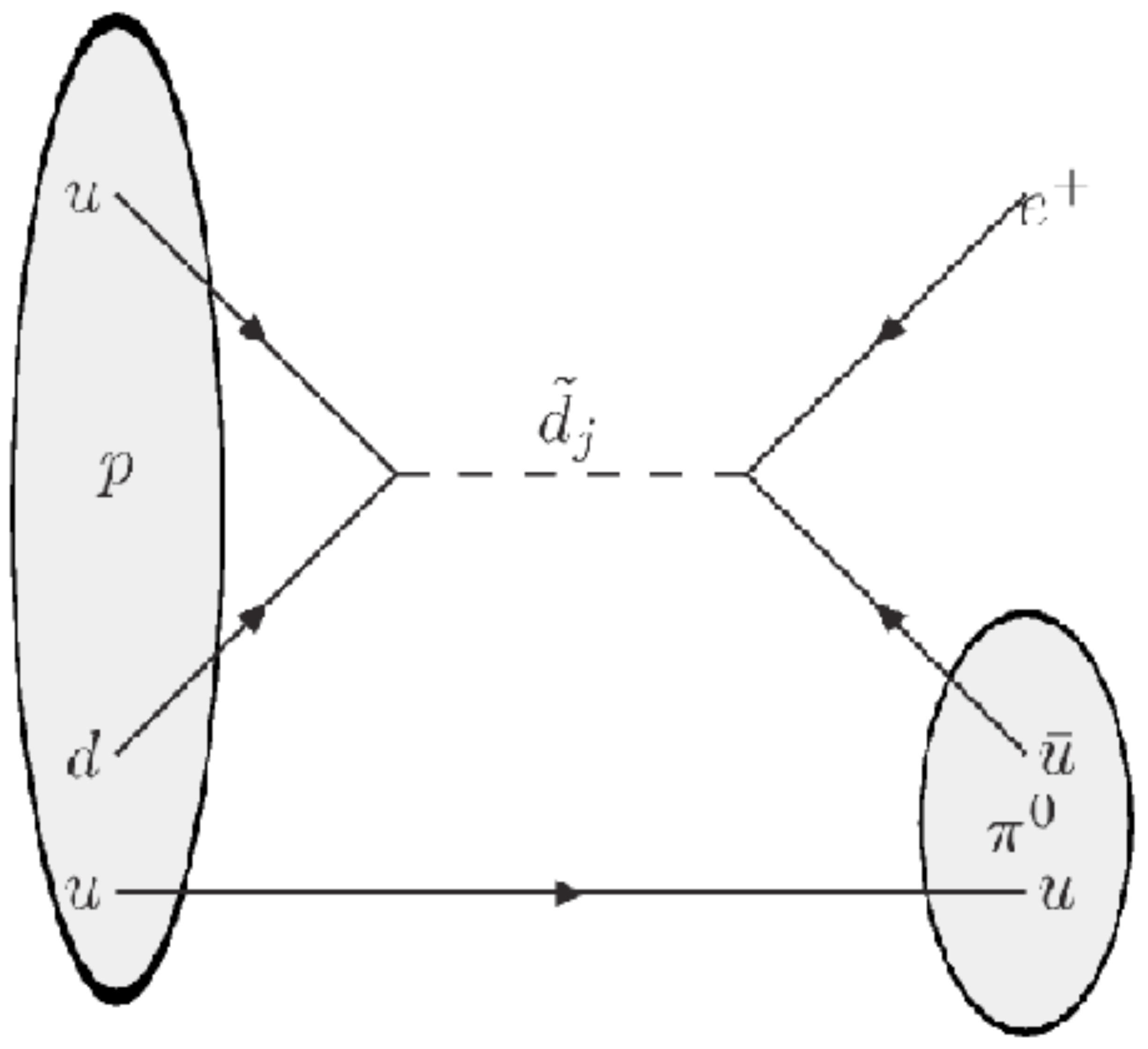
→SUSY has to be softly broken to allow higher masses



https://ific.uv.es/sct/images/susy_particles.png

MSSM Requirements

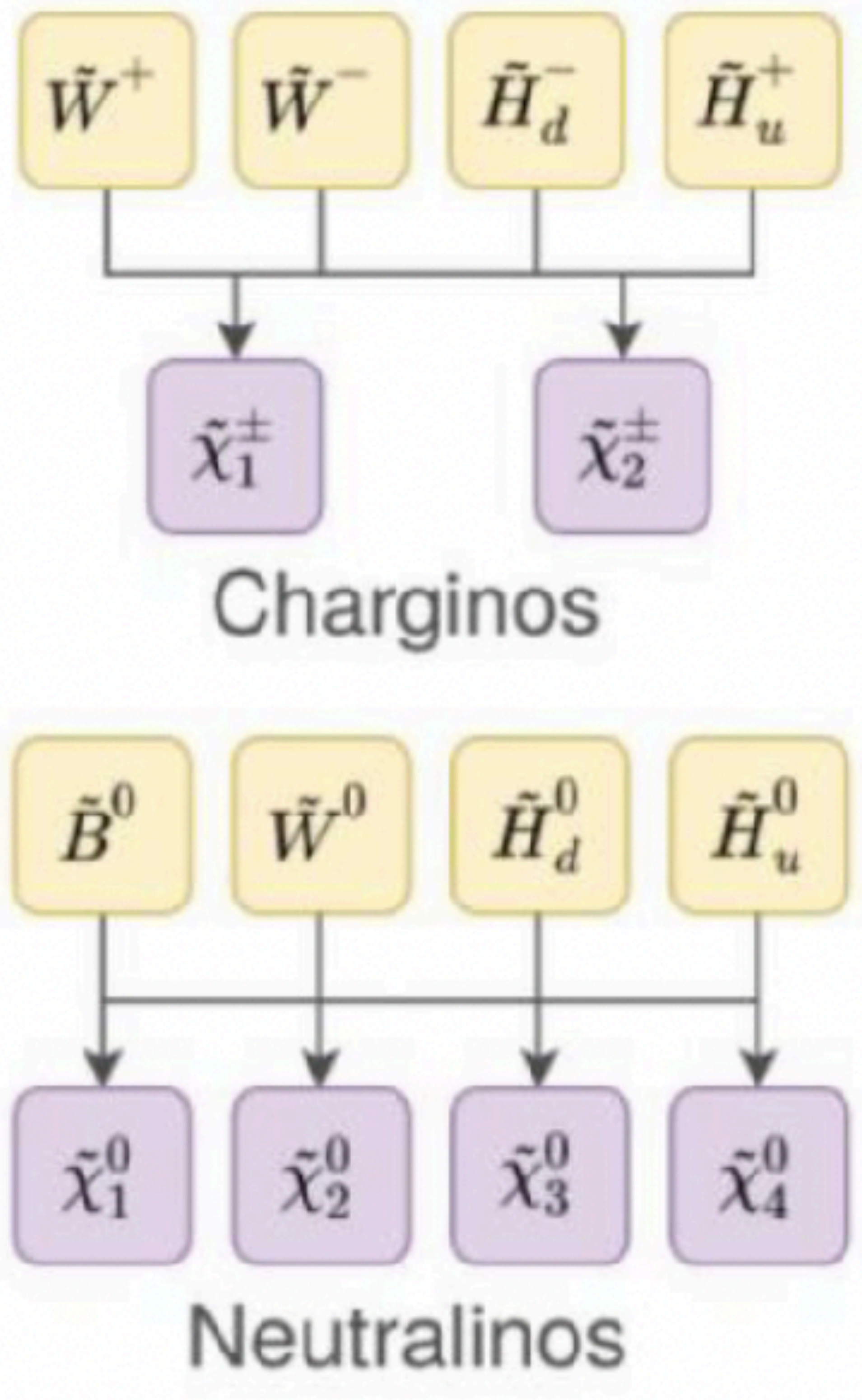
- In SUSY it is possible to add baryon- and lepton-number violating terms, which can lead to short time proton decays (experimentally ~10^{34} years)
- Typically R-Parity conservation is required via a new quantum number: $P_R = (-1)^{3(B-L)+2s}$, yielding 1 for SM and -1 for SUSY particles
- Implications:
    - SUSY particles can only be produced in pairs
    - Lightest supersymmetrical particle (LSP) is stable



https://cds.cern.ch/record/2214349/files/

Relevant SUSY Particles

- MSSM requires two higgs-doublets (down-type and up-type)
- Particles we focus on:
  - Sleptons (selectron and smuon)
  - Chargino (mix of charged winos and higgsinos)
  - Neutralino (mix of neutral binos, winos and higgsinos)

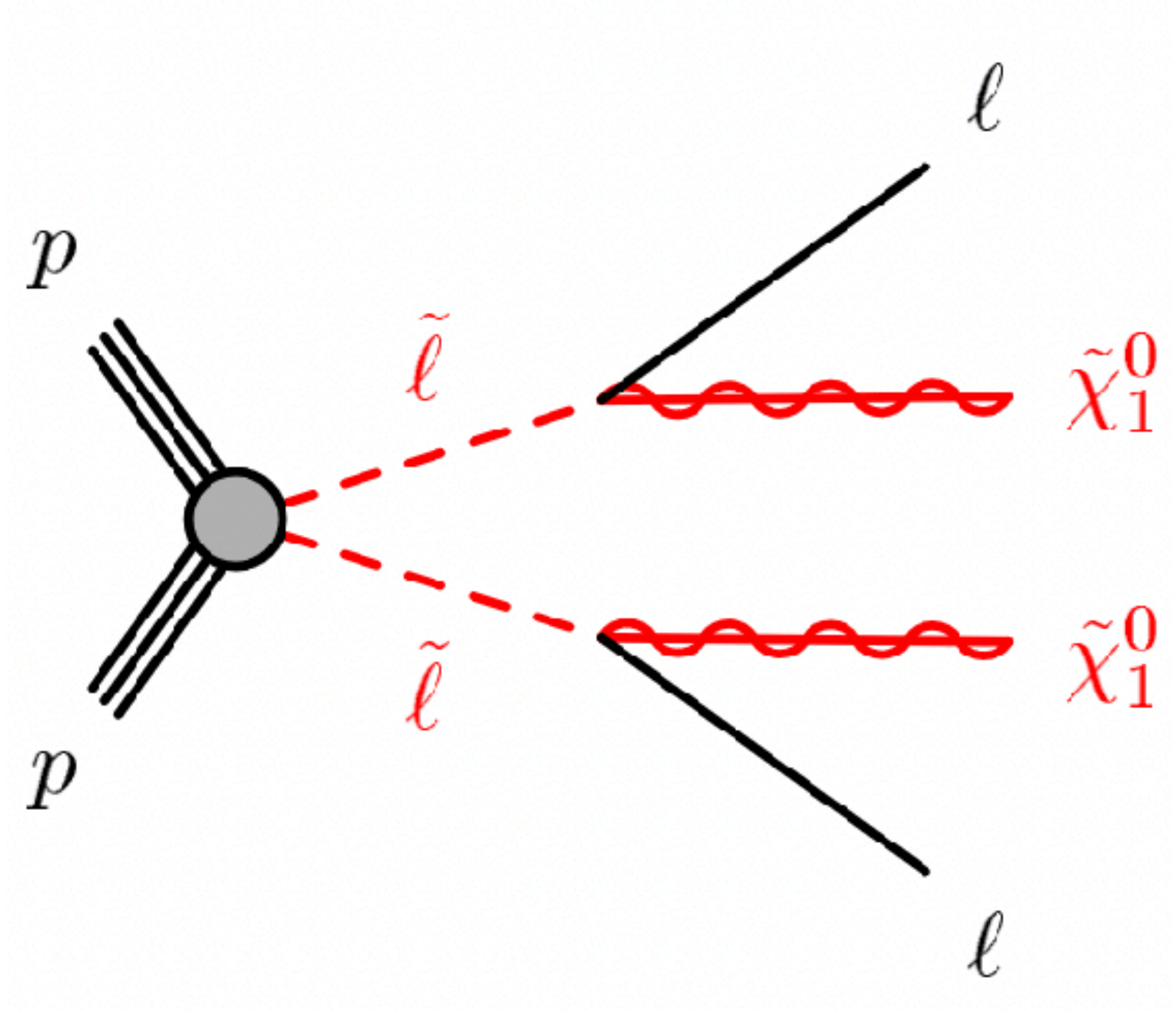


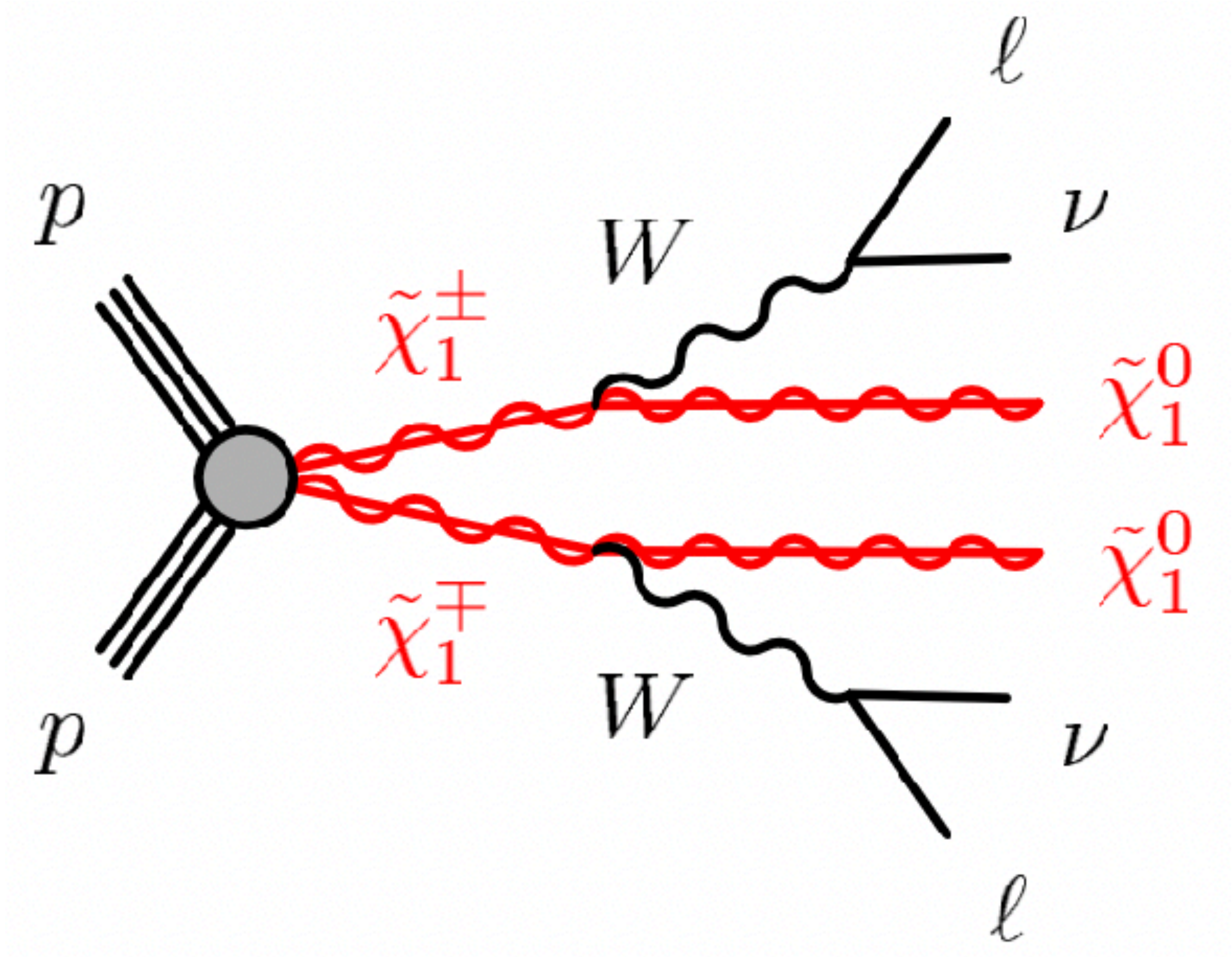
Considered SUSY Scenarios

- 2 supersymmetric simplified models:

slepton: $pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell + \tilde{\chi}_1^0\tilde{\chi}_1^0$

chargino: $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \to \ell\ell + \nu\nu + \tilde{\chi}_1^0\tilde{\chi}_1^0$



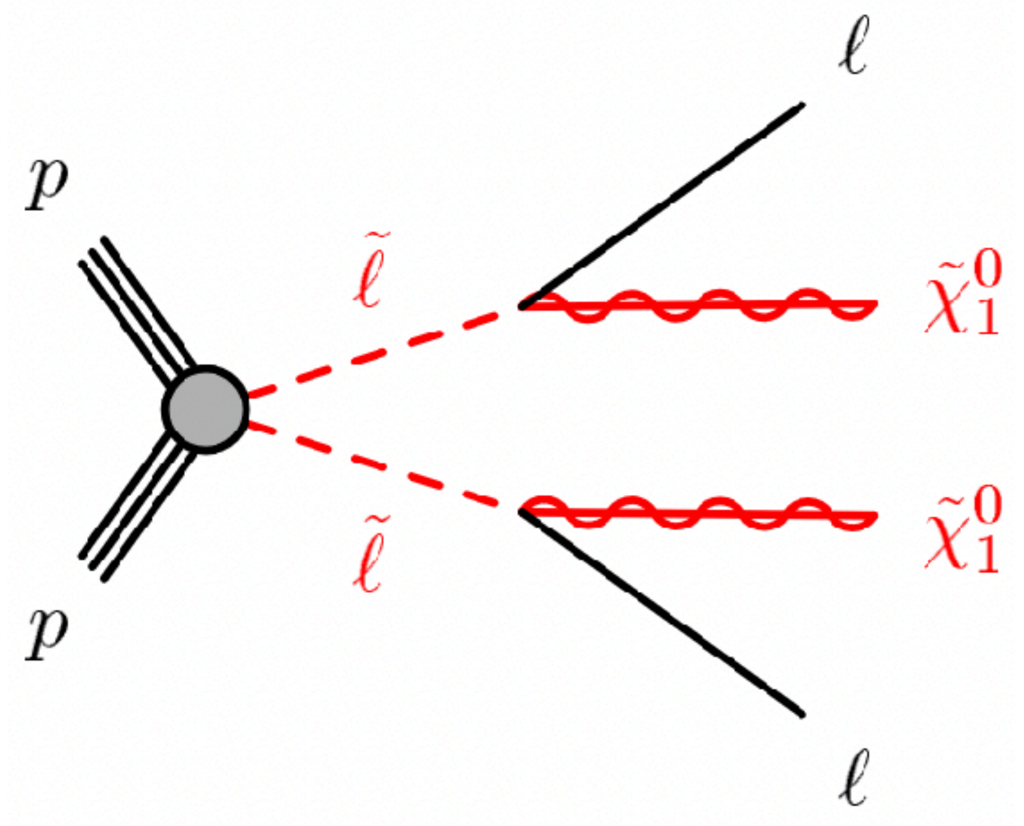


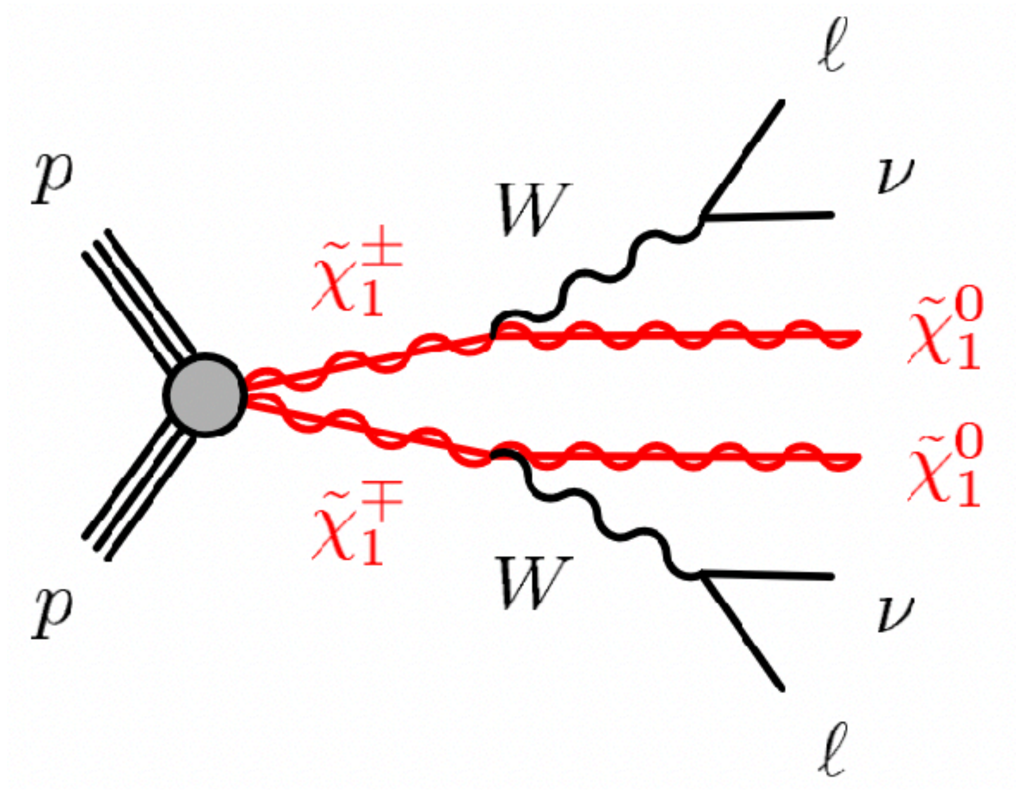
Considered SUSY Scenarios

- The visible final state consists of two leptons in both models, electrons and muons are considered

- Lepton flavour conservation requires same flavour lepton final state for the slepton model but allows both same and different flavor leptons for the chargino model
  $\rightarrow$ different analysis strategies for each model

- Sparticle masses are only free parameters, focus on mass splittings $m(\tilde{\ell}) - m(\tilde{\chi}_1^0)$ and $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$ near $m(W)$

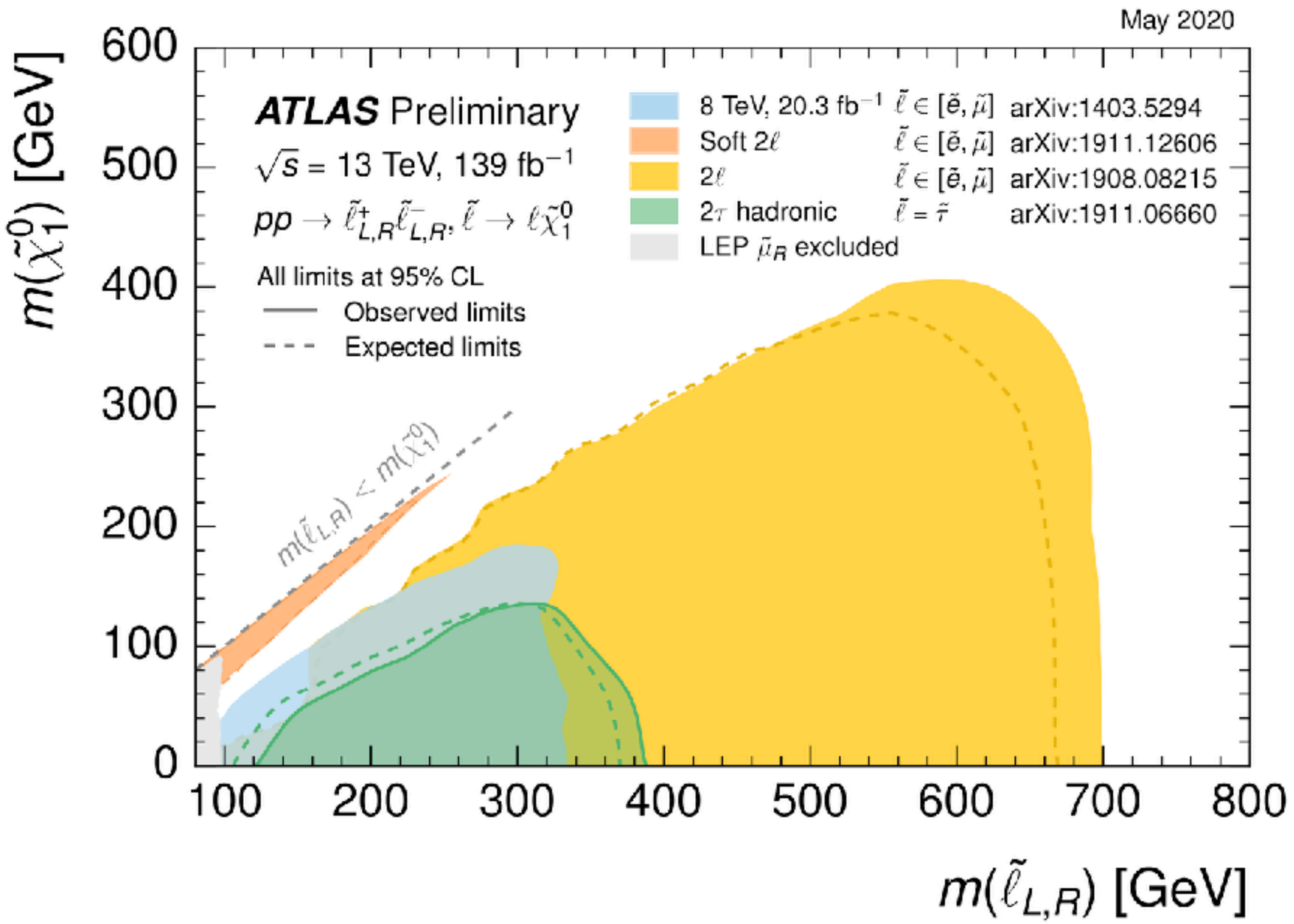




Already Examined Regions

Slepton Search

- Colored regions are searches from previous papers
- Regions with light neutralinos mostly analyzed already
- Still a gap at ~50GeV

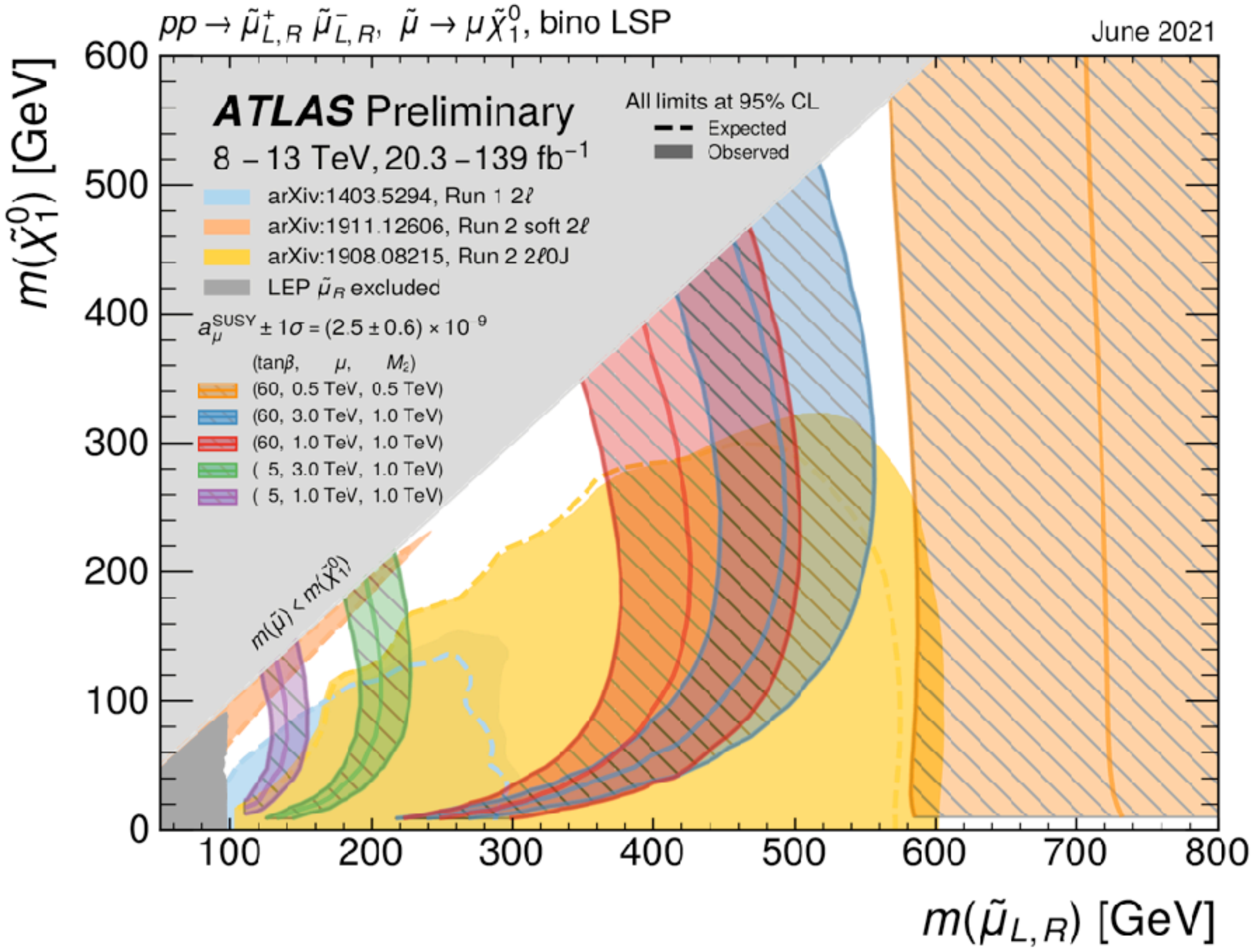


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_EWSummary_directsleptons/ATLAS_SUSY_EWSummary_directsleptons.png

Unexamined Regions

Motivation

- Hatched bands display mass regions compatible with the g-2 anomaly
- Worthwhile to close the gap
- This paper takes the same Run 2 dataset and aims to improve the sensitivity at the border region



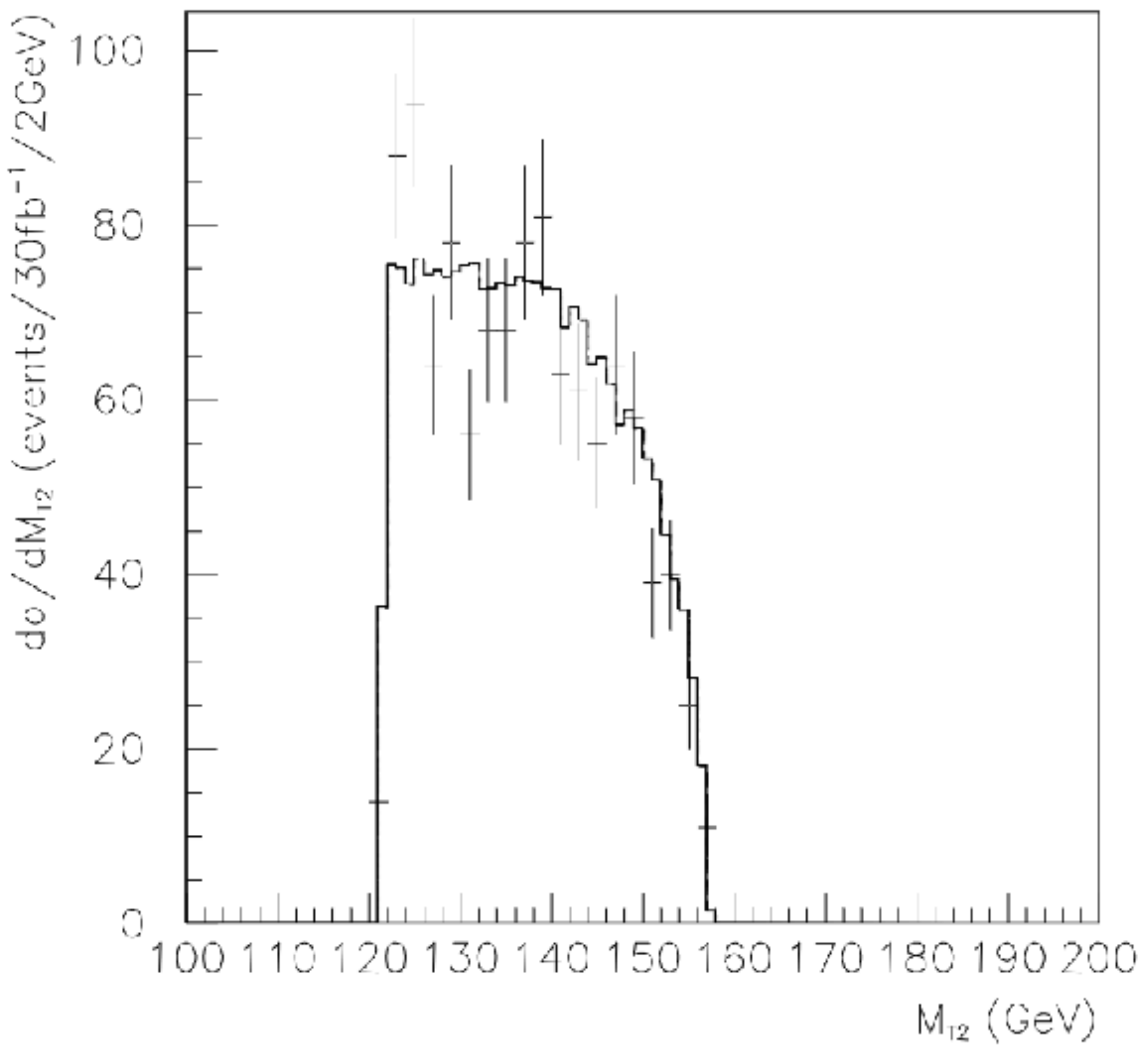
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-019/fig_15.png

Important Kinematic Variables

Stransverse Mass

- Useful for events with two invisible particles
- Transverse mass: $m_{\mathrm{T}}^2 = 2p_{\mathrm{T}}q_{\mathrm{T}}(1 - \cos(\Delta\phi))$
- $m_{\mathrm{T2}}(\mathbf{p}_{\mathrm{T},1}, \mathbf{p}_{\mathrm{T},2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) = \min_{\mathbf{q}_{\mathrm{T},1}+\mathbf{q}_{\mathrm{T},2}=\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}} \{\max[m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T},1}, \mathbf{q}_{\mathrm{T},1}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T},2}, \mathbf{q}_{\mathrm{T},2})]\}$
- Gives an upper bound on the mass of the parent of the pair produced particles
- Masses of invisible particles are free parameters and set to 100 GeV, so one is using a variable denoted as m_{T2}^{100}

$$pp \to X + \tilde{l}_R^+\tilde{l}_R^- \to X + l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$
$$m(\tilde{l}) = 157.1 \text{ GeV}, m(\tilde{\chi}) = 121.5 \text{ GeV}$$



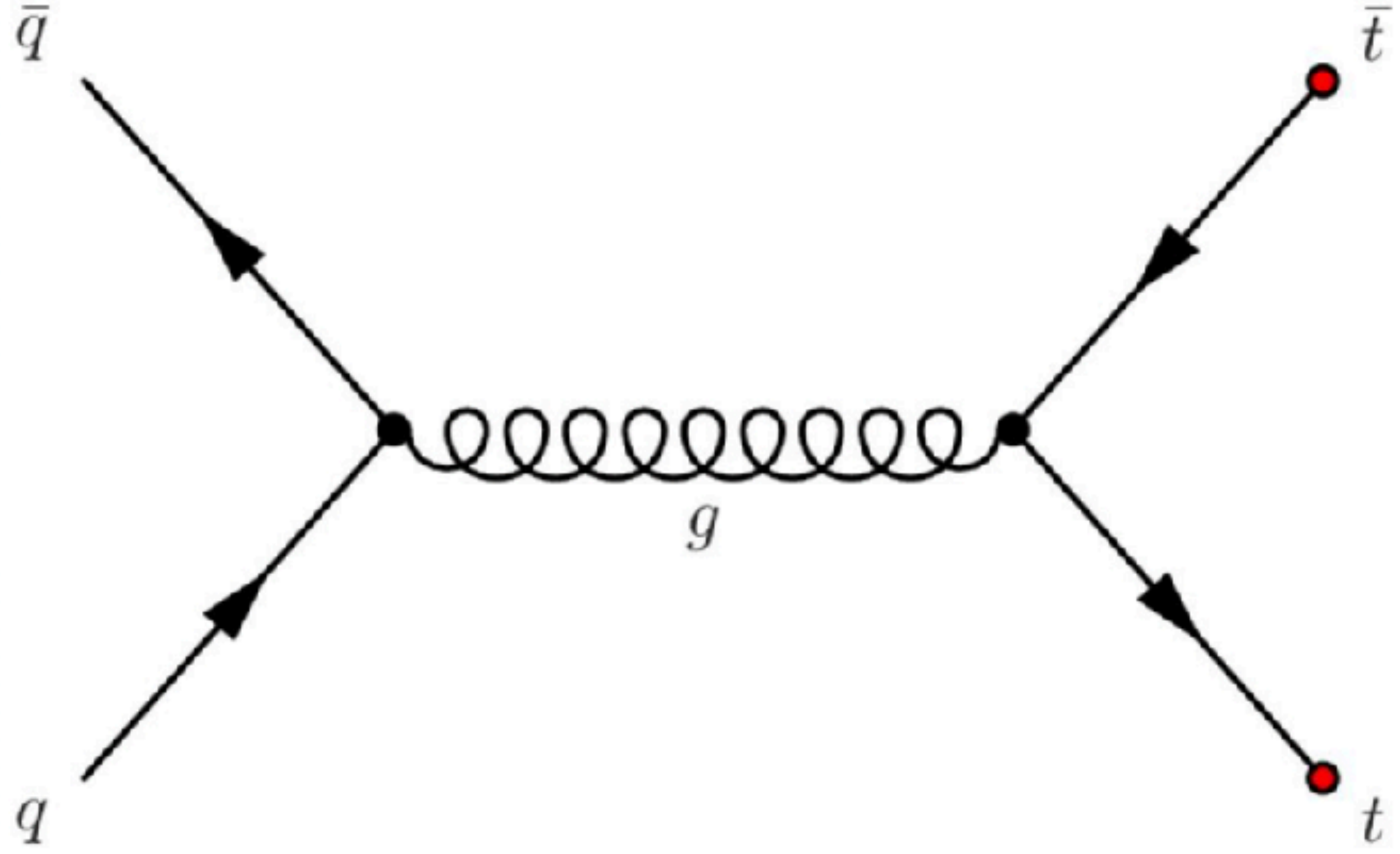
https://arxiv.org/pdf/hep-ph/9906349.pdf

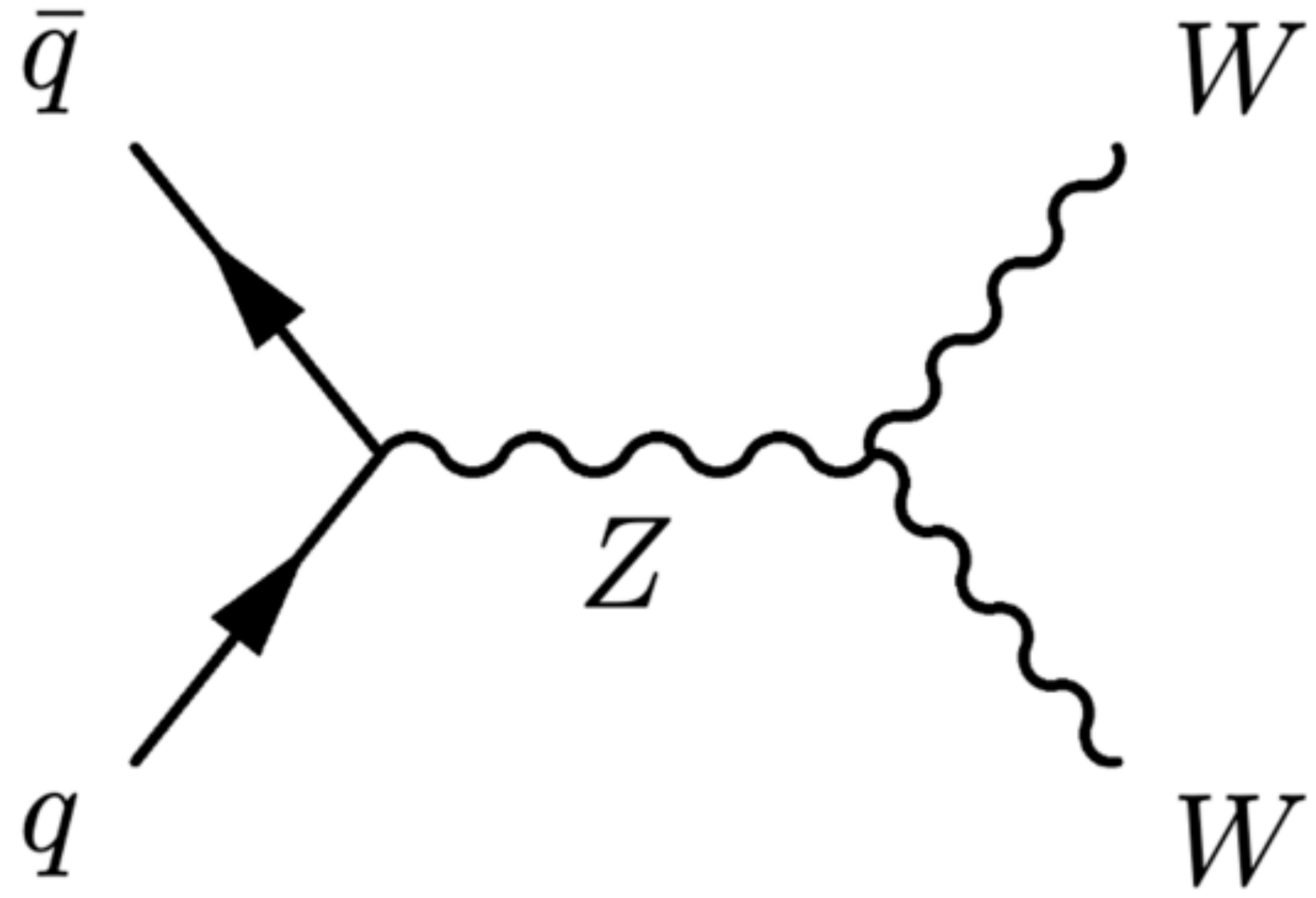
Other Kinematic Variables

- $\cos\theta^{*}_{\ell\ell} = \tanh(\Delta\eta_{\ell\ell}/2)$ is a measure for the polar angle between incoming quark and the produced sparticle
- $E_{\mathrm{T}}^{\mathrm{miss}}$ significance helps to discriminate between events with $E_{\mathrm{T}}^{\mathrm{miss}}$ arising from invisible particles or poorly measured particles, the $\mathbf{p}_{\mathrm{T}}$ resolution and identification inefficiencies

SM Backgrounds

- Irreducible backgrounds with prompt leptons
  - Dominated by $t\bar{t}$ and diboson (VV) events
- Reducible backgrounds from fake/non-prompt (FNP) leptons

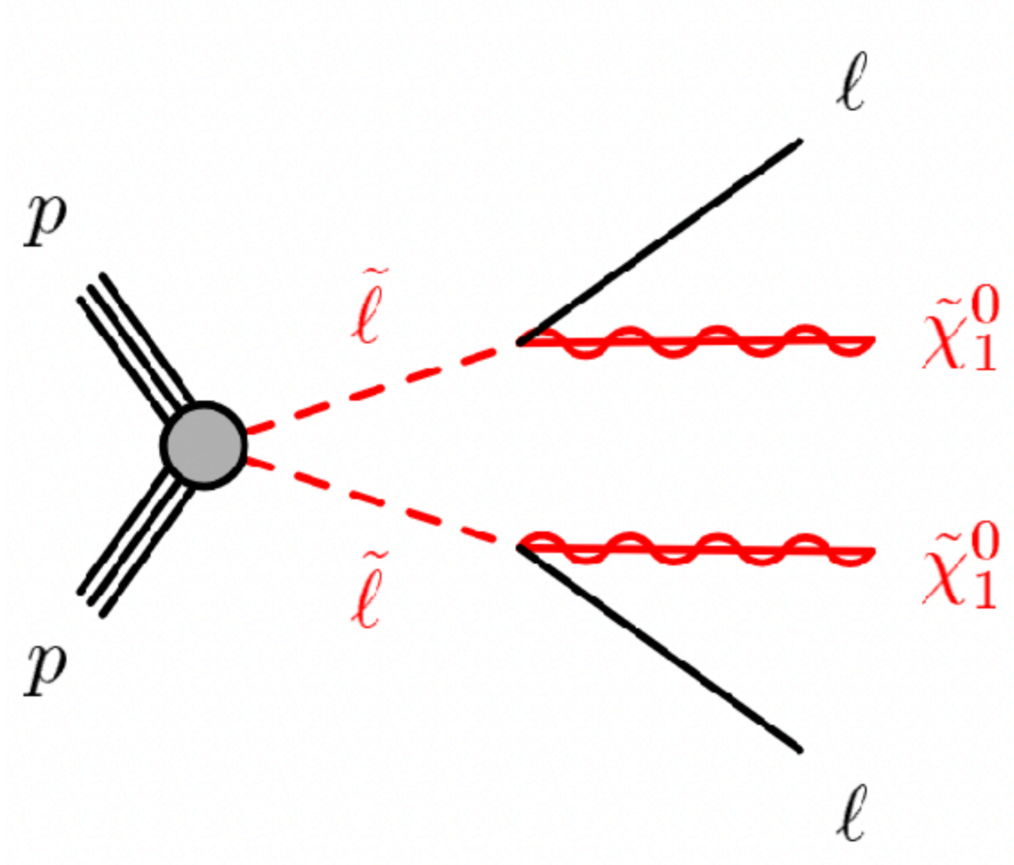


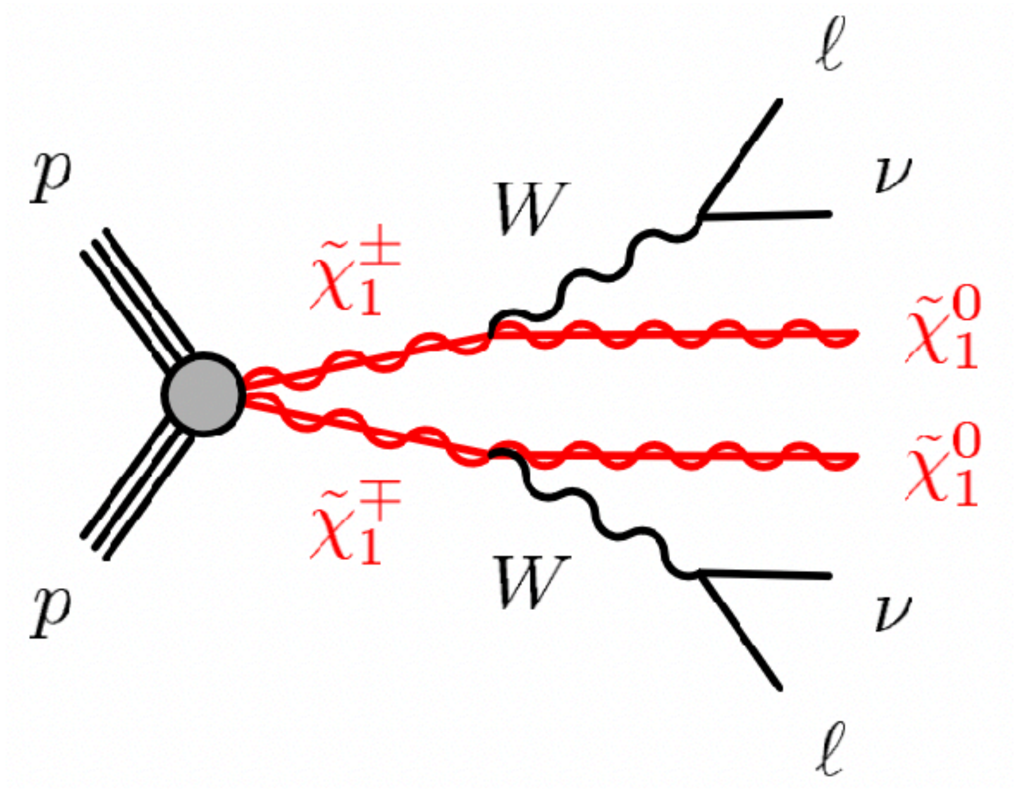


Event Selection

Preselection

- LHC Run 2 data set with single lepton trigger thresholds (around 20-300 GeV)
- Oppositely charged signal leptons with $p_{\mathrm{T},\ell_1} > 27$ GeV, $p_{\mathrm{T},\ell_2} > 9$ GeV and invariant mass $m_{\ell\ell} > 11$ GeV
- Same Flavour (SF) and Different Flavour (DF) event categorization
- SF events: $|m_{\ell\ell}$ - 91 GeV$| > 15$ GeV, reducing *VZ* and *Z*+jets backgrounds
- No more than one jet





Event Selection

Slepton Model

- Requirements:
    - SF opposite charge leptons
    - No b-tagged jets (to reduce $t\bar{t}$ and single-top backgrounds)
    - Signal regions (SR) divided into 0J and 1J (multiplicity of non b-tagged jets)
- SR binned in m_{T2}, increases sensitivity to different mass splitting scenarios

Signal region (SR)	SR-0J	SR-1J
$n_{b\text{-tagged jets}}$	$= 0$	
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	>7	
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 1$
$p_{\mathrm{T}}^{\ell_1}$ [GeV]	> 140	> 100
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	> 20	> 50
$m_{\ell\ell}$ [GeV]	> 11	> 60
$p_{\mathrm{T,boost}}^{\ell\ell}$ [GeV]	< 5	-
$\lvert\cos\theta^{*}_{\ell\ell}\rvert$	< 0.2	< 0.1
$\Delta\phi_{\ell,\ell}$	> 2.2	> 2.8
$\Delta\phi_{\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}},\ell_1}$	> 2.2	-
Binned SRs		
m_{T2}^{100} [GeV]	$\in[100,105)$ $\in[105,110)$ $\in[110,115)$ $\in[115,120)$ $\in[120,125)$ $\in[125,130)$ $\in[130,140)$ $\in[140,\infty)$	
Inclusive SRs		
m_{T2}^{100} [GeV]	$\in[100,\infty)$ $\in[110,\infty)$ $\in[120,\infty)$ $\in[130,\infty)$ $\in[140,\infty)$	

Classification of Chargino Events

BDT Classifier Training

- Decision trees used to classify events into signal, background VV, background top and background other with a certain probability based on a set of kinematic variables ($p_{\mathrm{T}}^{\ell_1}, p_{\mathrm{T}}^{\ell_2}, E_{\mathrm{T}}^{\mathrm{miss}}, m_{\mathrm{T2}}, m_{\ell\ell}, \Delta\phi_{\mathrm{boost}}, \Delta\phi_{\mathrm{p_T^{miss}},\ell_1}, \Delta\phi_{\mathrm{p_T^{miss}},\ell_2}, \cos\theta^*_{\ell\ell}, E_{\mathrm{T}}^{\mathrm{miss}}$)

- Gradient Boosted Decision Trees (BDT) uses a machine learning technique where a chain of trees tries to minimize the error of the previous tree

- MC samples of signal and SM background are split into training and test set and further categorized into SF and DF events, the BDT classifier is trained on the two training sets and tested on the statistically independent test sets

Event Selection

Chargino Model

- Both SF and DF opposite-charge lepton signals are allowed
- Requirements:
    - Veto against b-tagged jets (reducing $t\bar{t}$ and t backgrounds)
    - Also non-b-tagged jet veto

Signal region (SR)	SR-DF	SR-SF
$n_{b\text{-tagged jets}}$	= 0	
$n_{\text{non-}b\text{-tagged jets}}$	= 0	
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	>8	
m_{T2} [GeV]	>50	
BDT-other		< 0.01
Binned SRs		
BDT-signal	∈(0.81,0.8125]	∈(0.77,0.775]
	∈(0.8125,0.815]	∈(0.775,0.78]
	∈(0.815,0.8175]	∈(0.78,0.785]
	∈(0.8175,0.82]	∈(0.785,0.79]
	∈(0.82,0.8225]	∈(0.79,0.795]
	∈(0.8225,0.825]	∈(0.795,0.80]
	∈(0.825,0.8275]	∈(0.80,0.81]
	∈(0.8275,0.83]	∈(0.81,1]
	∈(0.83,0.8325]	
	∈(0.8325,0.835]	
	∈(0.835,0.8375]	
	∈(0.8375,0.84]	
	∈(0.84,0.845]	
	∈(0.845,0.85]	
	∈(0.85,0.86]	
	∈(0.86,1]	
Inclusive SRs		
BDT-signal	∈(0.81,1]	∈(0.77,1]
	∈(0.81,1]	
	∈(0.82,1]	
	∈(0.83,1]	
	∈(0.84,1]	
	∈(0.85,1]	
		∈(0.77,1]
		∈(0.78,1]
		∈(0.79,1]
		∈(0.80,1]

Background Estimation

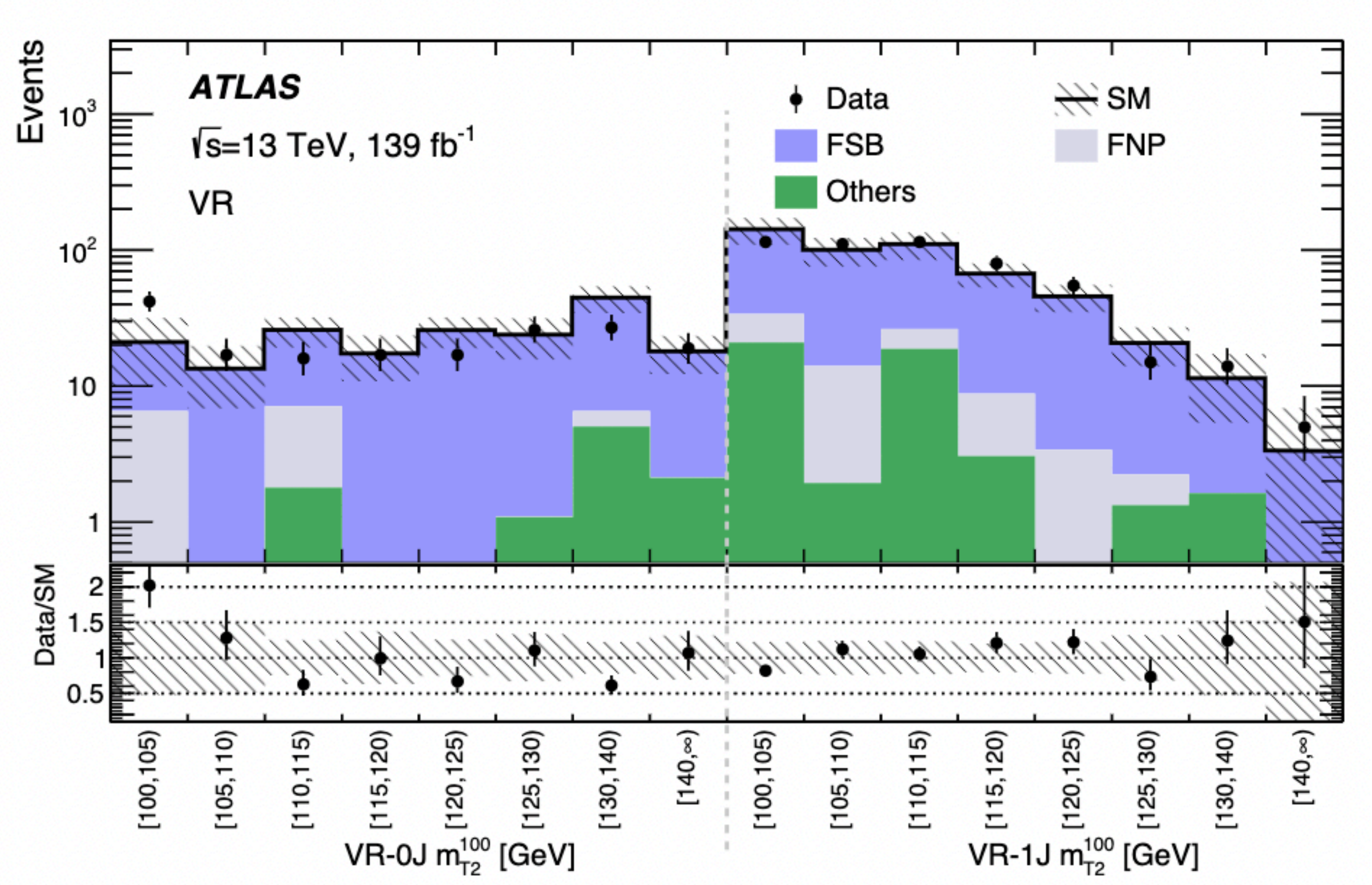
Slepton Model FSB

- Data-driven technique
- SF channel (e^+e^-, $\mu^+\mu^-$) and DF channel ($e\mu$)
- Slepton model only produces SF opposite sign (SFOS) signatures
- Main background processes produce SF and DF leptons with same probability
- Flavour Symmetric Background (FSB) estimation uses DF channel to predict background in the SF channel

Background Estimation

Slepton Model

- FSB used to estimate SF Background
- FNP background are estimated via detection efficiencies of prompt leptons in different Control Regions (CR) via the „matrix method“
- Validation Region (VR) uses same selection as SR, but with inverted $|\cos\theta^*_{\ell\ell}|$
- Data is consistent with expectation



Background Estimation

Chargino Model

- Control regions (CR) enriched in the two dominating backgrounds VV and top are used to normalize MC
- CR-top allows b-jet to enrich in top-quark processes
- CR-VV requires higher BDT-VV
- Moving into VRs via increasing signal BDT requirement or reestablishing b-jet veto

Control region (CR)	CR-VV		CR-top	
E_T^{miss} significance	> 8			
m_{T2} [GeV]	> 50			
$n_{\text{non-}b\text{-tagged jets}}$	= 0			
Leptons flavour	DF	SF	DF	SF
$n_{b\text{-tagged jets}}$	= 0	= 0	= 1	= 1
BDT-other	-	< 0.01	-	< 0.01
BDT-signal	$\in (0.2, 0.65]$	$\in (0.2, 0.65]$	$\in (0.5, 0.7]$	$\in (0.7, 0.75]$
BDT-VV	> 0.2	> 0.2	-	-
BDT-top	< 0.1	< 0.1	-	-

Validation region (VR)	VR-VV-DF	VR-VV-SF	VR-top-DF	VR-top-SF	VR-top0J-DF	VR-top0J-SF
E_T^{miss} significance	> 8					
m_{T2} [GeV]	> 50					
$n_{\text{non-}b\text{-tagged jets}}$	= 0					
$n_{b\text{-tagged jets}}$	= 0	= 0	= 1	= 1	= 0	= 0
BDT-other	-	< 0.01	-	< 0.01	-	< 0.01
BDT-signal	$\in (0.65, 0.81]$	$\in (0.65, 0.77]$	$\in (0.7, 1]$	$\in (0.75, 1]$	$\in (0.5, 0.81]$	$\in (0.5, 0.77]$
BDT-VV	> 0.2	> 0.2	-	-	< 0.15	< 0.15
BDT-top	< 0.1	< 0.1	-	-	-	-

Systematic Uncertainties

Slepton Model

- Dominating contributions:
  - Statistical uncertainty (limited event counts)
  - Flavour symmetric background (FSB) estimation
  - FNP estimation

Region m_{T2} [GeV]	SR-0J $\in[100,\infty)$	SR-1J $\in[100,\infty)$
Total background expectation	76	78
MC and FSB statistical uncertainties	14%	13%
FSB estimate	9%	9%
FNP leptons	5%	4%
$Z/\gamma^*(\rightarrow \ell\ell)$+jets theoretical uncertainties	< 1%	3%
E_T^{miss} modelling	2.3%	< 1%
Jet energy scale	< 1%	< 1%
Jet energy resolution	< 1%	1%
b-tagging	< 1%	< 1%
Lepton modelling	1%	< 1%
Total systematic uncertainty	17%	17%

Systematic Uncertainties

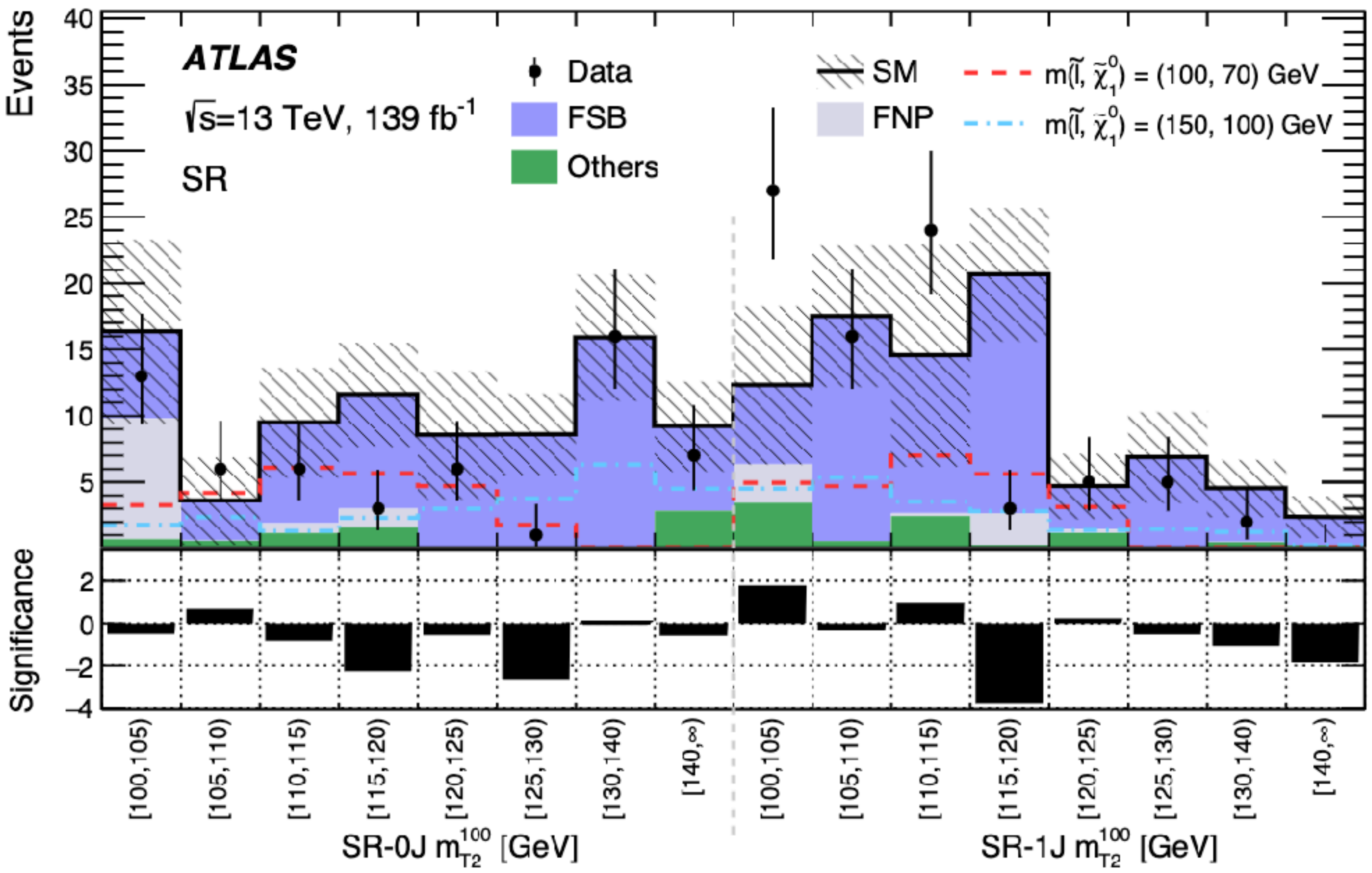
Chargino Model

- Dominant contributions:
  - Modelling $E_{\mathrm{T}}^{\mathrm{miss}}$ (Pile-Up etc.)
  - Modelling and extrapolating diboson events
  - Modelling of jet energies

Region	$\mathrm{SR}^{\text{-DF BDT-signal}\in(0.81,1]}_{\text{-SF BDT-signal}\in(0.77,1]}$
Total background expectation	630
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	9.1%
Diboson theoretical uncertainties	5.8%
Jet energy scale	5.2%
VV normalization	3.6%
Jet energy resolution	1.7%
MC statistical uncertainties	1.7%
Lepton modelling	1.2%
Top theoretical uncertainties	1%
$t\bar{t}$ normalization	1%
FNP leptons	0.8%
b-tagging	0.7%
$Z/\gamma^{*}(\rightarrow \ell\ell)$+jets theoretical uncertainties	0.04%
Total systematic uncertainty	12%

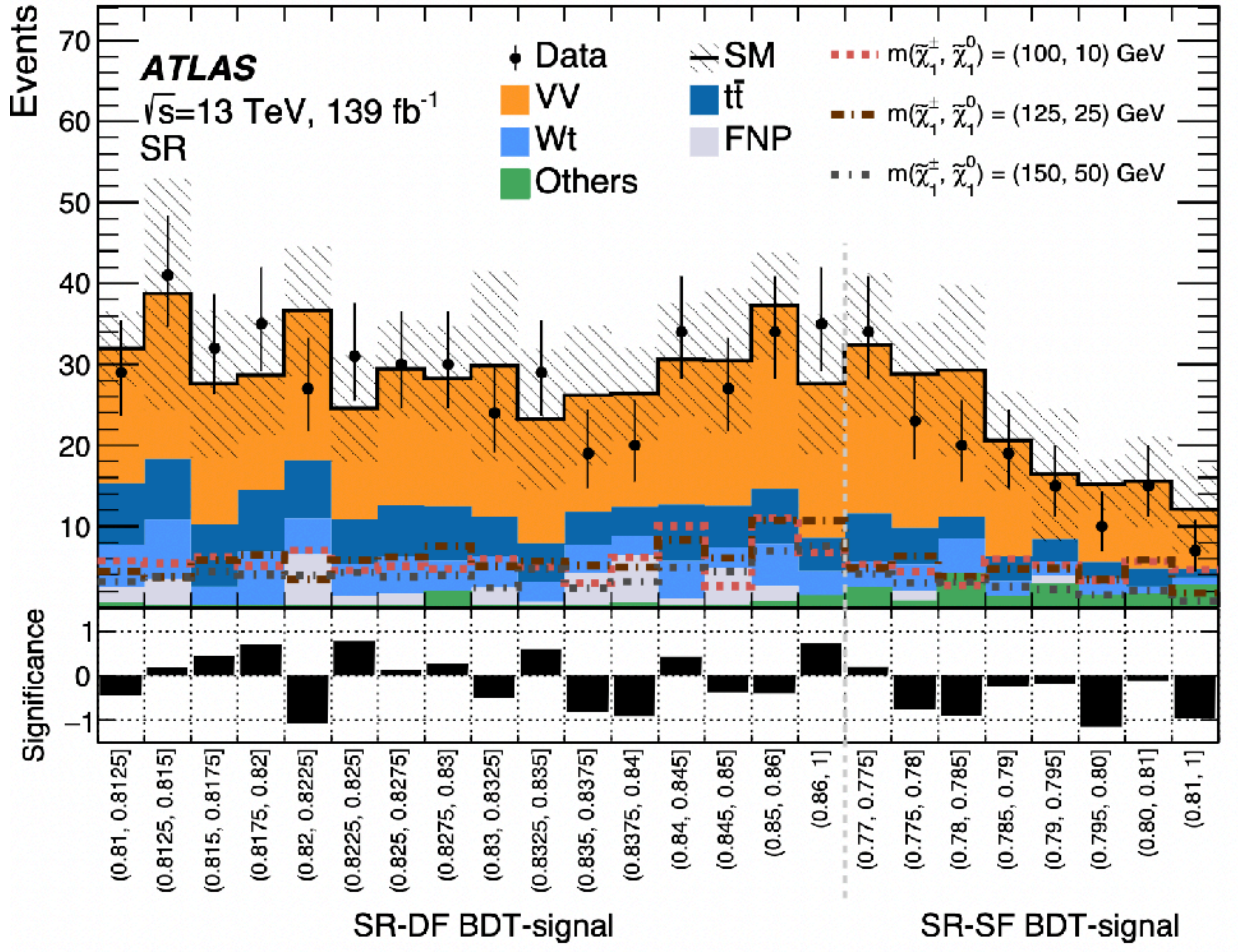
Slepton Results

- Dashed lines give signal expectation for different sparticle masses
- Large discrepancies strictly correlated with statistical fluctuation in DF events used for FSB estimation
- Consistent with SM prediction



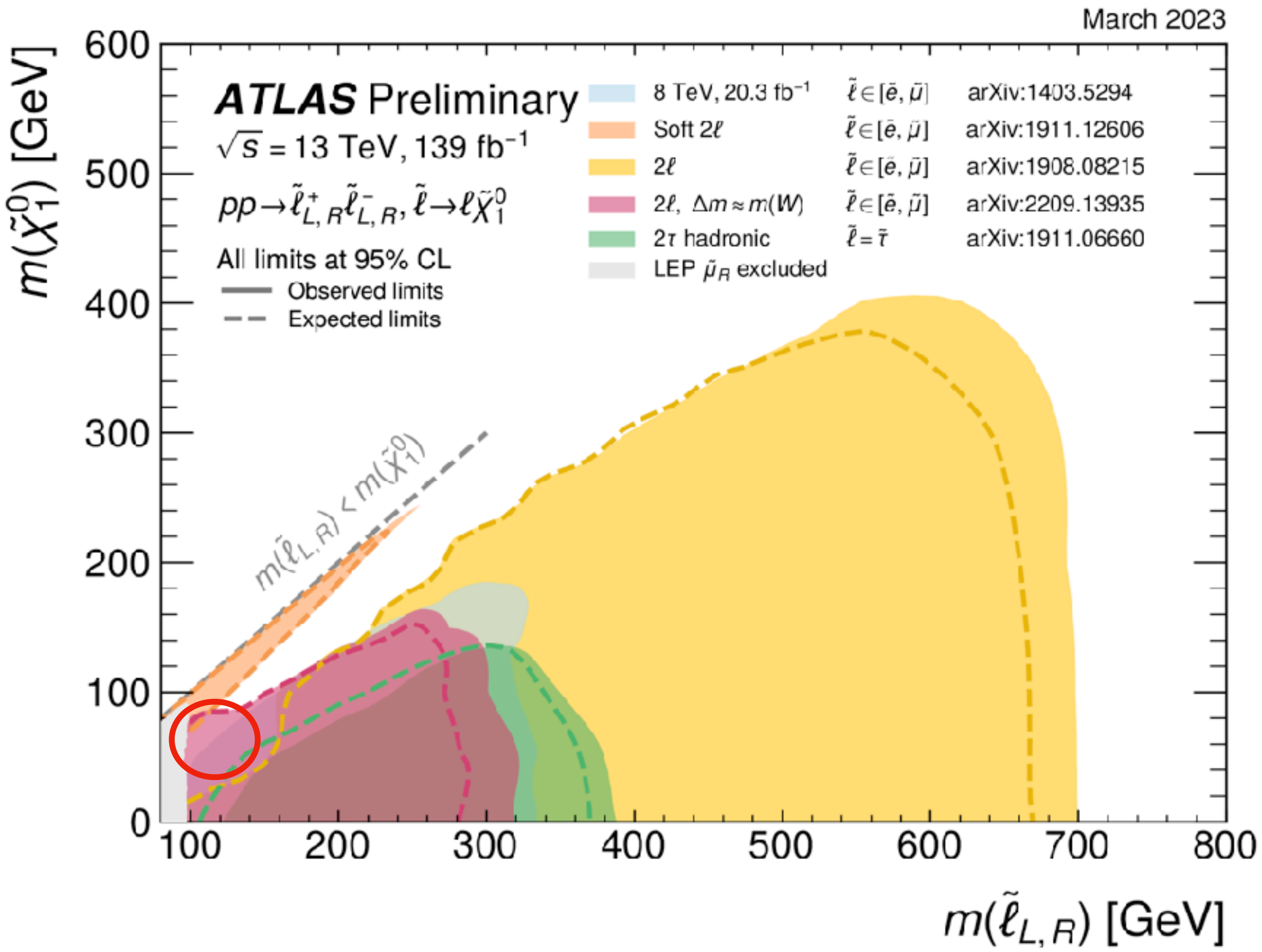
Chargino Results

- No significant deviation from SM Background Predictions



Conclusion

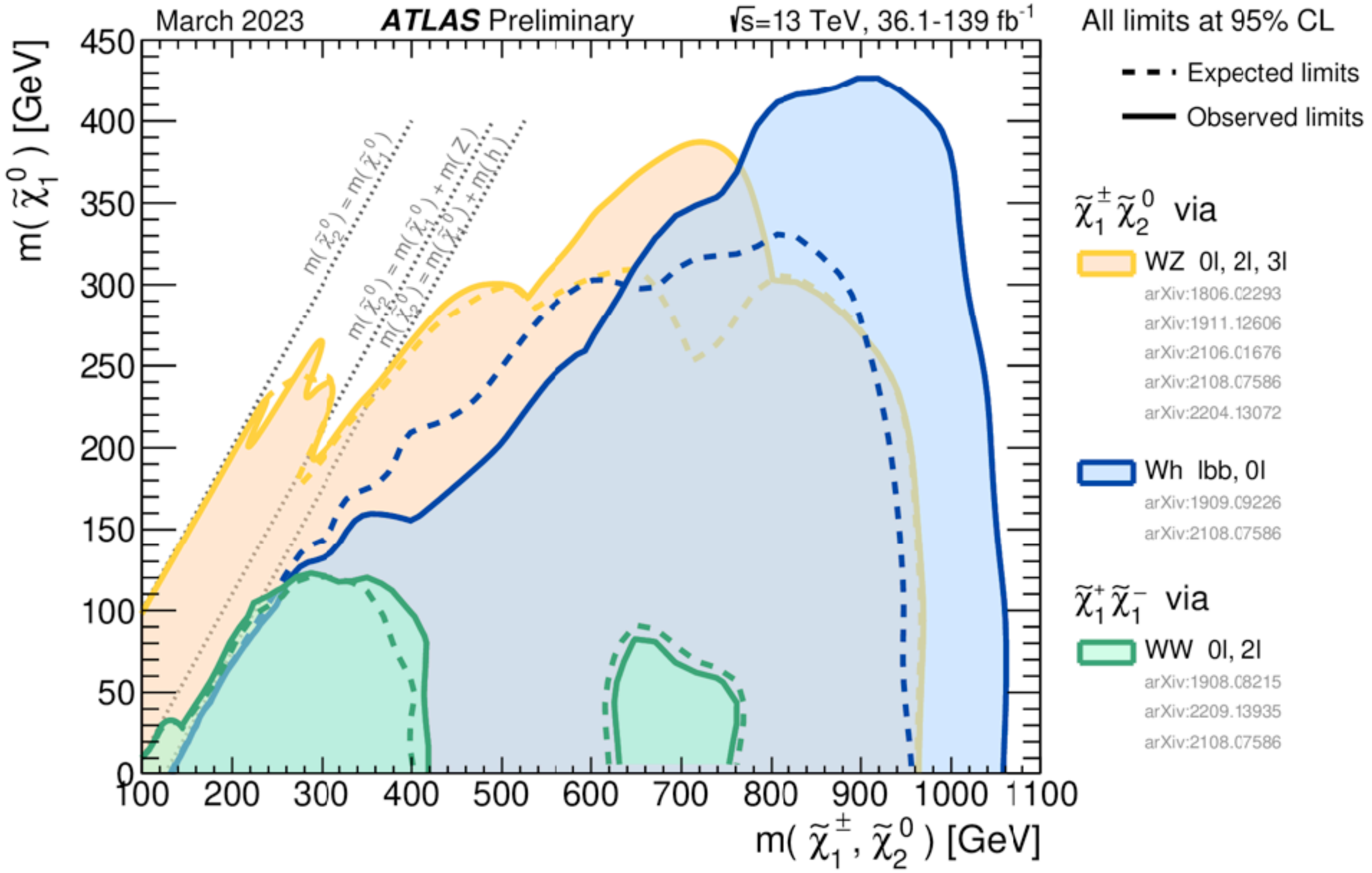
- Only small unexplored region developed
- Data consistent with SM
- Slepton masses up to 150 GeV with mass splittings of 50 GeV are excluded with 95% CL



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-005/fig_15.png

Chargino Search Areas

- Chargino masses up to 140 GeV with mass splittings as low as 100 GeV are excluded with 95% CL



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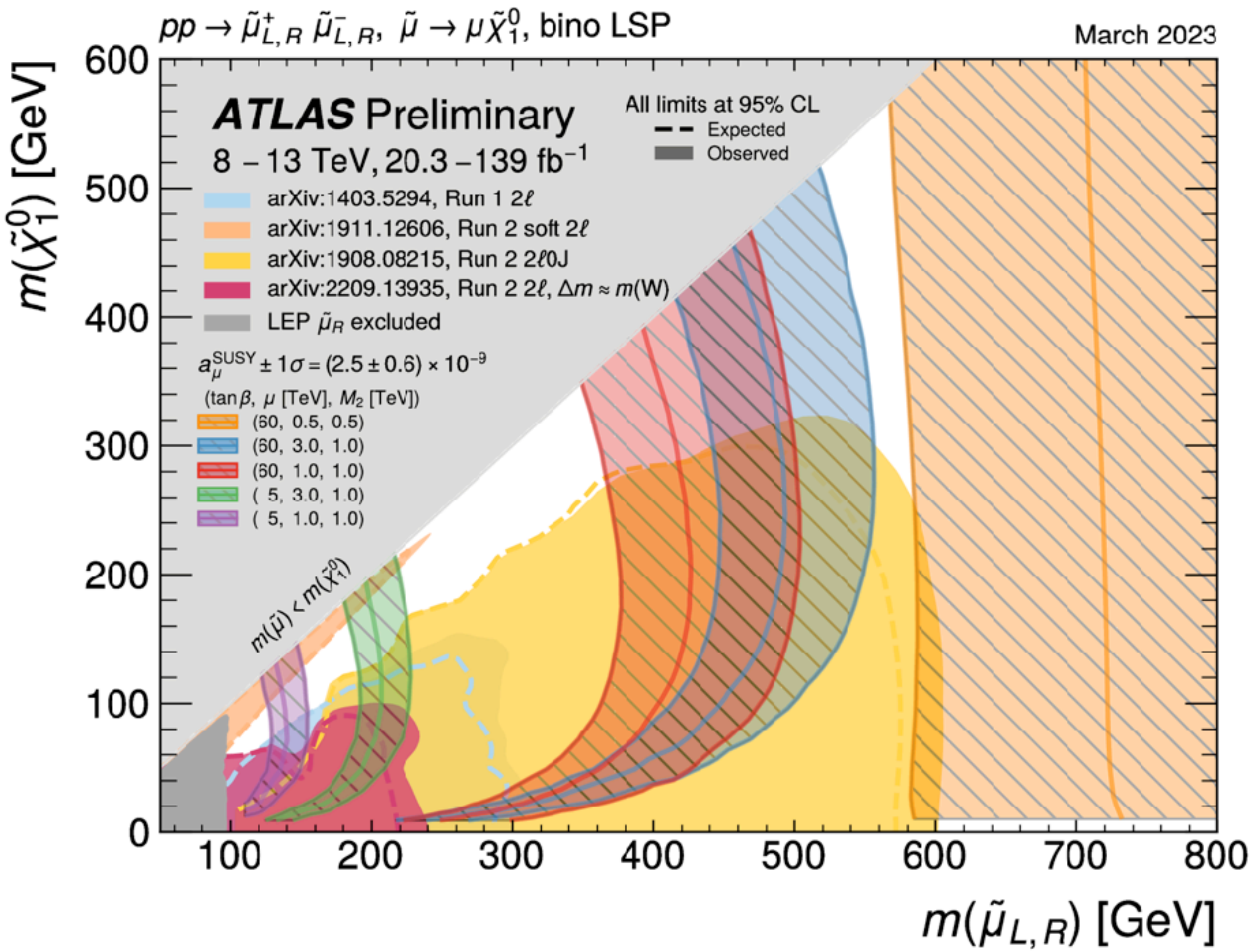
Smuon Search respectively

- No further exploration of the band regions



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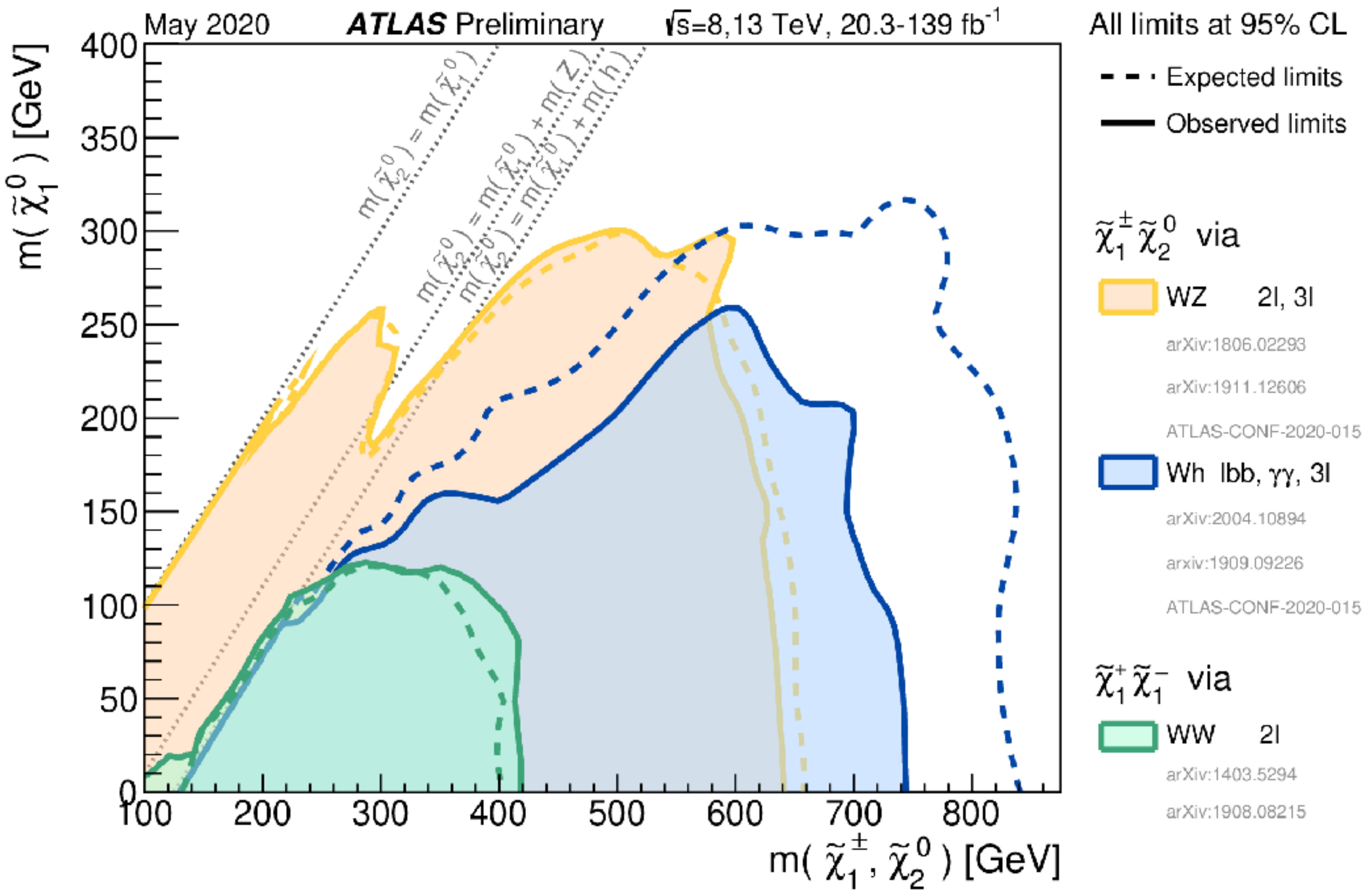
Backup Slides

Old Chargino Searches



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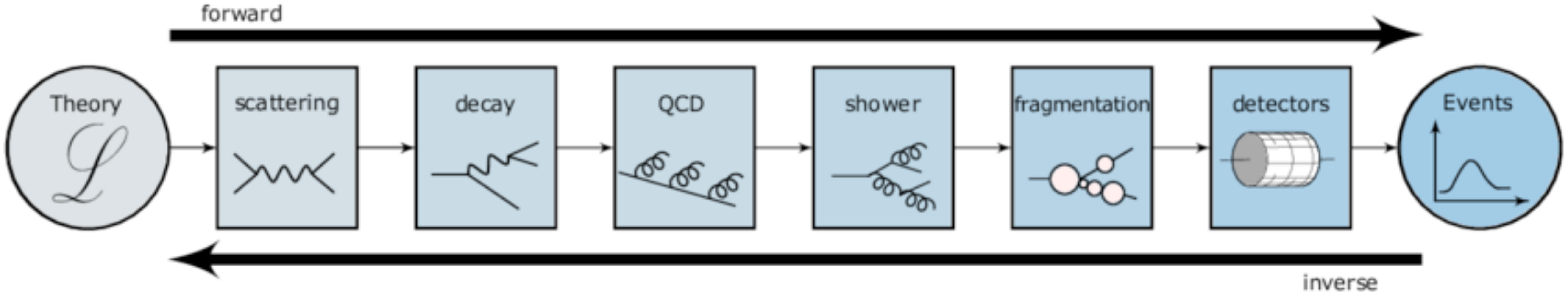
FSB Estimation Formula

- $N_{\mathrm{SF}}^{\mathrm{expected}} = 0.5 \cdot \left(\kappa + \frac{1}{\kappa}\right) \cdot \alpha \cdot N_{\mathrm{DF}}$ with $\kappa = \sqrt{\frac{N_{\mu^+\mu^-}}{N_{e^+e^-}}}$ and $\alpha = \sqrt{\frac{\epsilon_{\mu\mu}^{\mathrm{trig}}\epsilon_{ee}^{\mathrm{trig}}}{\epsilon_{e\mu}^{\mathrm{trig}}}}$

MC Process



https://www.researchgate.net/figure/Illustration-of-the-LHC-simulation-chain-The-forward-direction-is-discussed-in-Secs-2_fig1_370186980