“Elusive & Exclusive - Highlights from Recent SUSY Searches with ATLAS”

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DPNC Seminar

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University of Geneva, Switzerland

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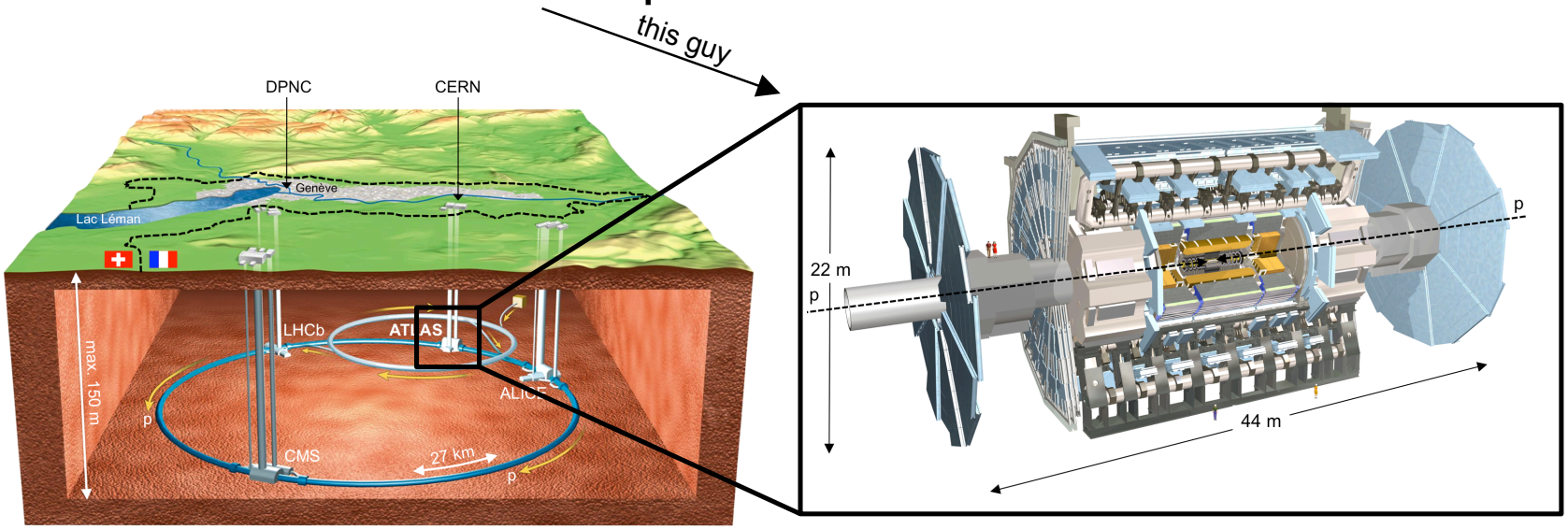
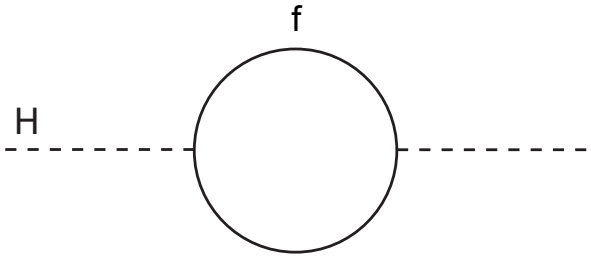
Outline

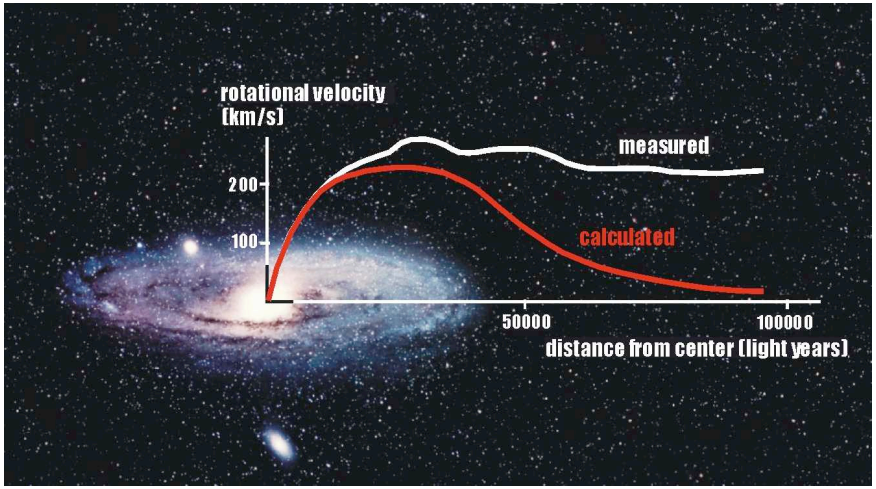
- What I will be talking about:
  - Motivation to still search for *elusive* SUSY
  - 3 select ATLAS searches (*exclusive or excessive*?)
  - Outlook to the future
- What I will not be talking about (lack of time):
  - Details of detector performance ☹



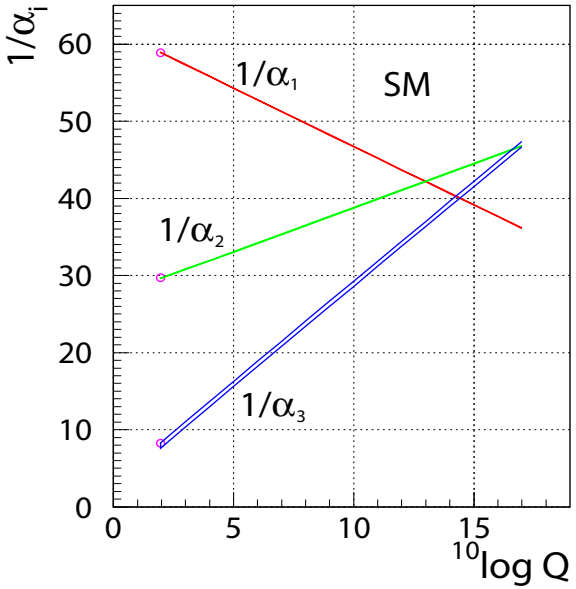
Open Questions of the Standard Model

- **Hierarchy problem**: Higgs mass subject to quadratically divergent loop corrections.
  → Unnatural fine-tuning





- **Dark matter:** Cosmological data suggest presence of dark matter → No explanation within Standard Model



- **Grand unification:** Standard Model coupling constants do not unify at high scales.
  → SM does not imply a Grand Unified Theory

Never tired of analogies…

http://www.quantumdiaries.org

"The Higgs has a snowman's chance in hell"

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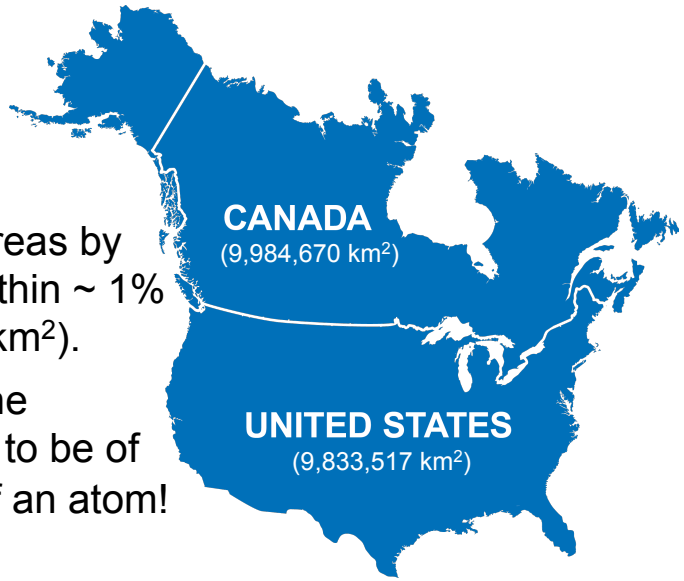
Surface areas by chance within ~ 1% (151,153 km^2).

Imagine the difference to be of the size of an atom!



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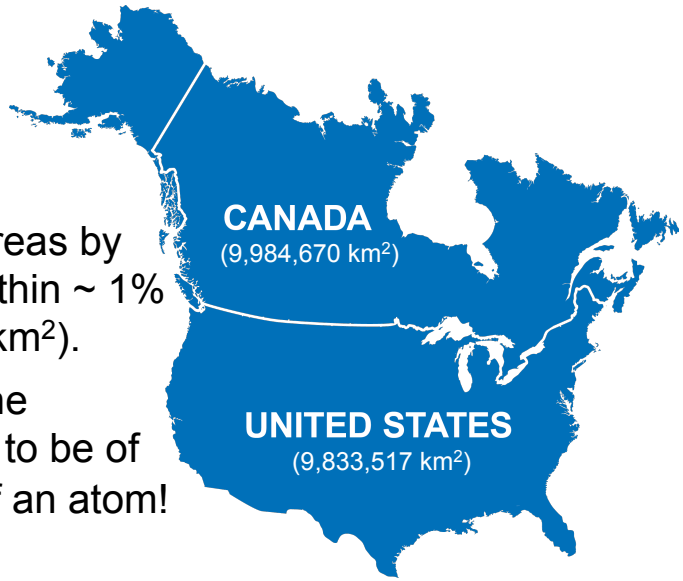

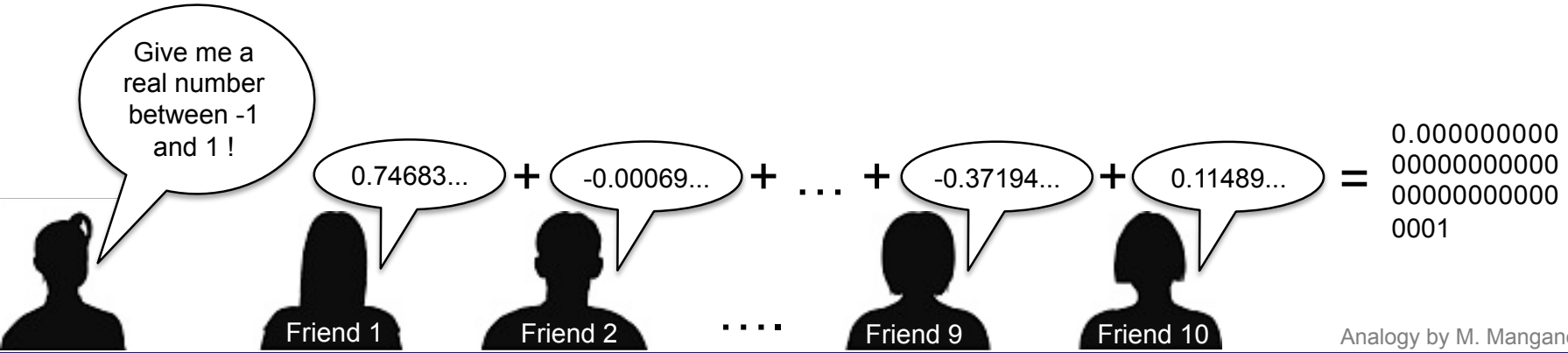

Analogy by M. Mangano

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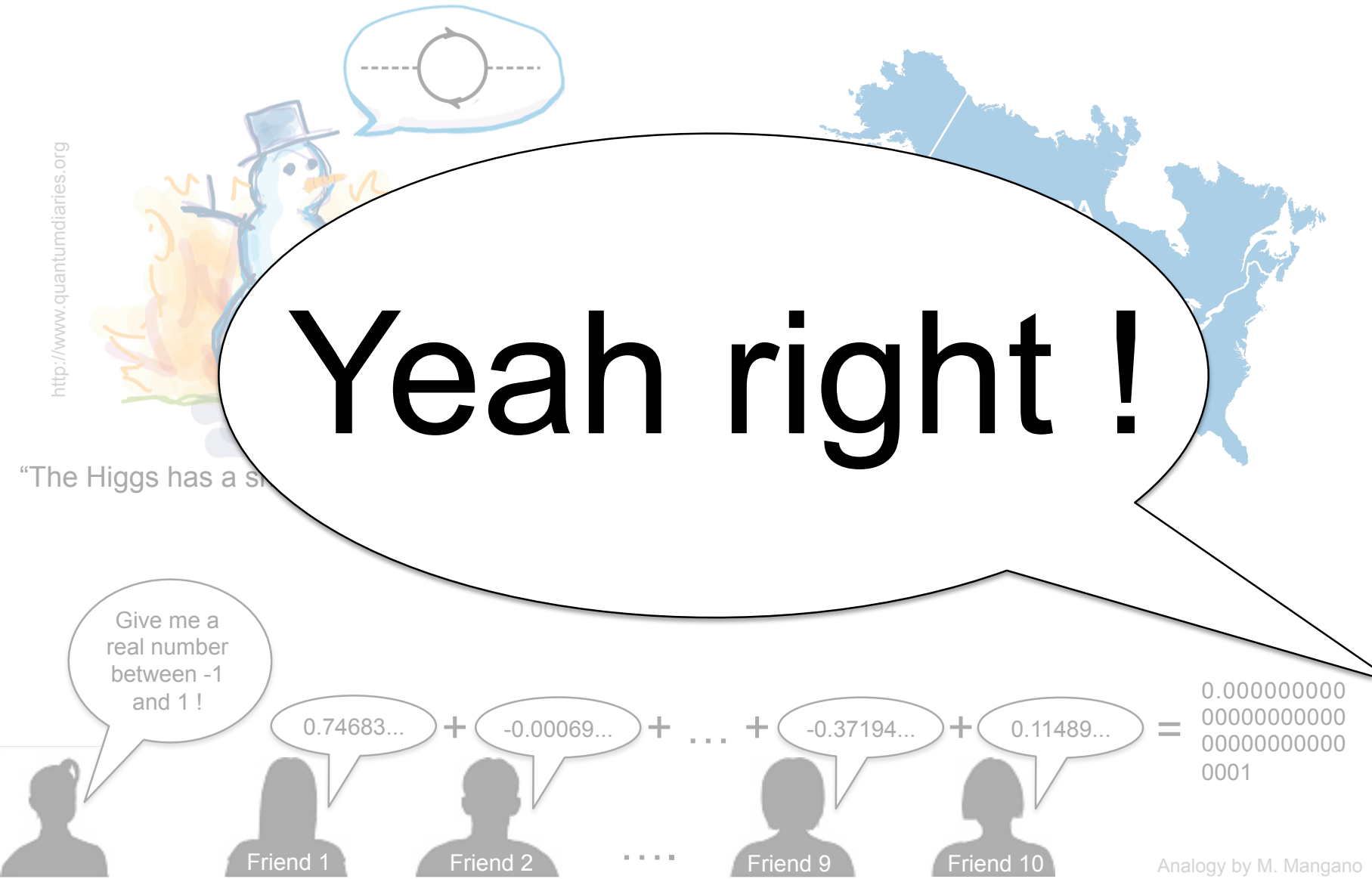


We need… Supersymmetry (SUSY)

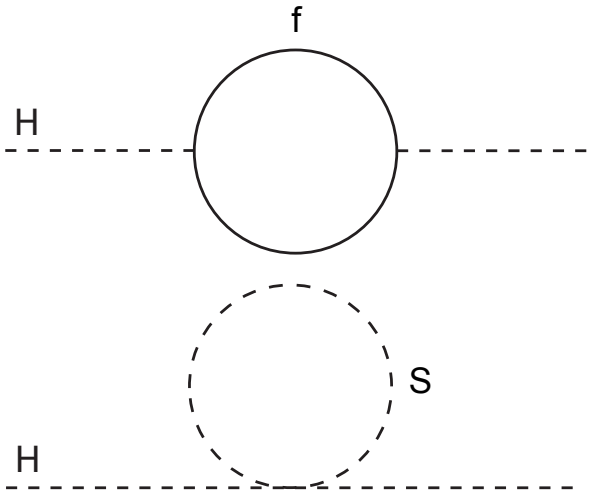
- Fundamental symmetry between fermions and bosons introducing a set of new partner particles to the SM particles with half-spin difference.

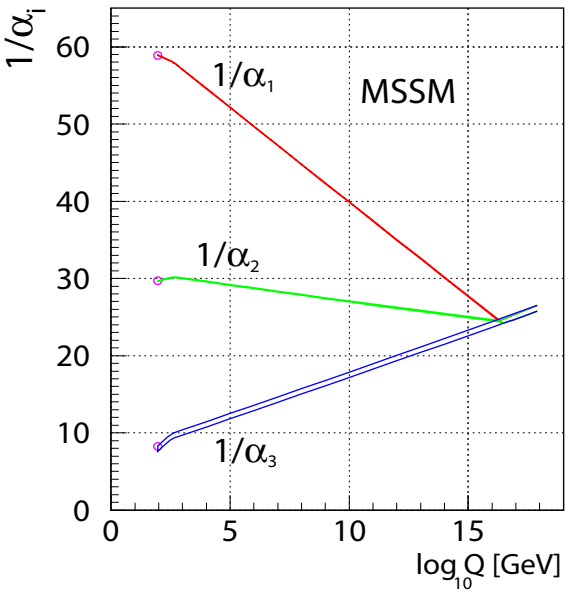
✓ Opposite-sign loop corrections from SUSY particles. Quadratic divergencies cancel. → No (little) fine-tuning.

✓ If R-parity conserved: Lightest SUSY Particle (LSP) stable. → Natural candidate for dark matter.

R-parity = $(-1)^{3(B-L)+2s}$
- SM particles: +1
- SUSY particles: -1

✓ Unification of gauge couplings at $M_{GUT} \approx 10^{16}$ GeV

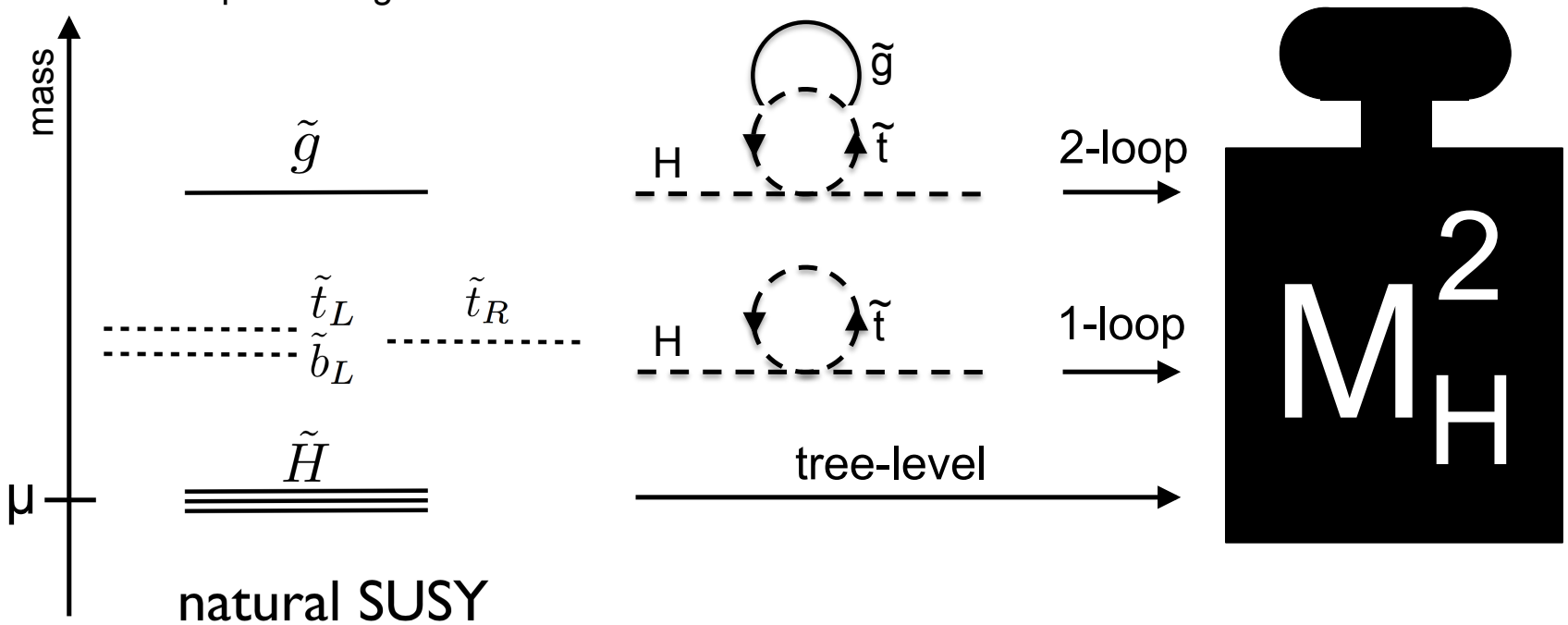




Not just any SUSY… **Natural** SUSY

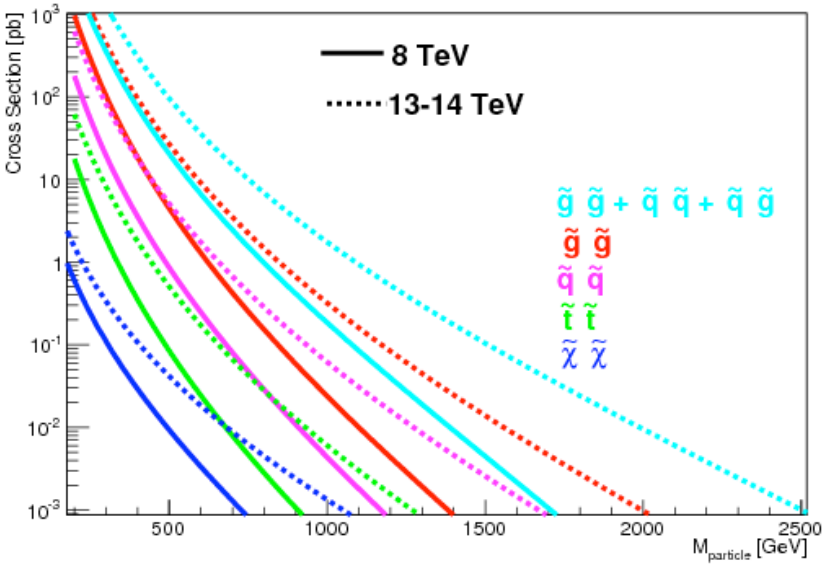
- Higgs boson discovery and strong experimental bounds have put vanilla SUSY under pressure
- Search efforts focus around "Natural SUSY" (e.g. arXiv:1110.6926) as a possible (the last?) way out
- Within the MSSM stop and gluino masses enter at **1 and 2 loop level** into the Higgs mass matrix, the Higgsino mass parameter μ **at tree level**!

→ Requires relatively **light gluinos, stops, higgsinos**, remaining SUSY particles decoupled at high masses

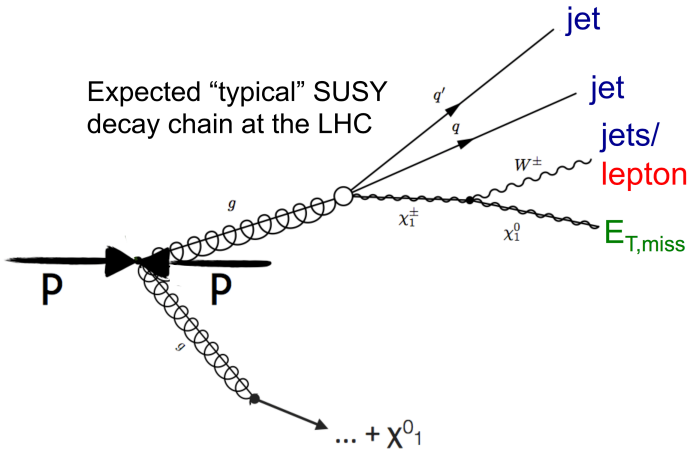


How to search for SUSY at the LHC

- If SUSY particles exist at LHC accessible energies and R-parity is conserved:
  - Pair-production
  - Direct or cascade decays to the stable lightest SUSY particle (LSP).
- Experimental signature of inclusive searches:
  - Significant missing transverse energy (E_T^{miss})
  - Multiple high-p_T jets
  - Other objects, e.g. leptons, photons
- Search strategy @ 13 TeV:
  - → Early data: Gluino & 1st/2nd generation squark searches have the largest potential due to high cross-sections (increase)
  - → Beyond ~ 10fb^{-1}: Searches for third generation squarks start to exceed Run-1 sensitivity
  - → The future: Electro-weak SUSY searches need large amounts of data due to low cross-sections



[http://inspirehep.net/record/1326406]



Searches discussed in this Seminar

- If SUSY particles exist at LHC accessible energies and R-parity is conserved:
  - Pair-production
  - Direct or cascade decays to the stable lightest SUSY particle (LSP)
- Experimental signature of inclusive searches:
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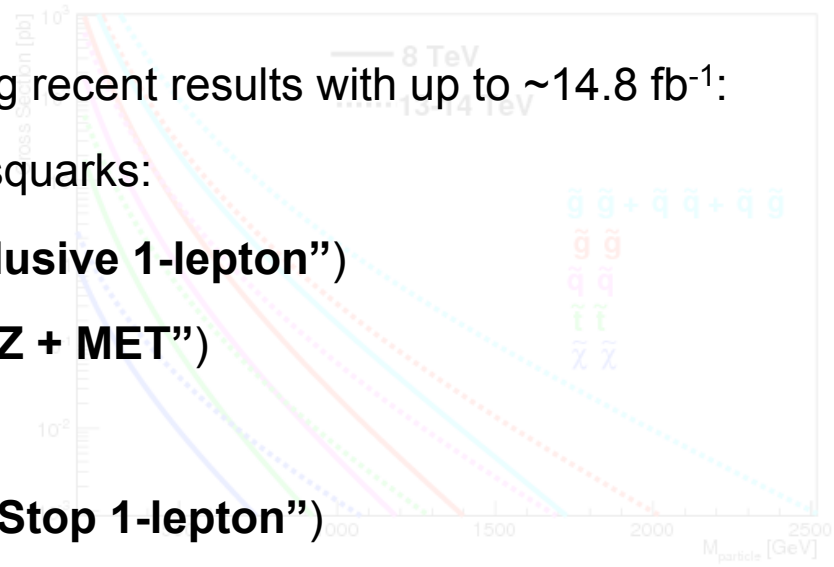

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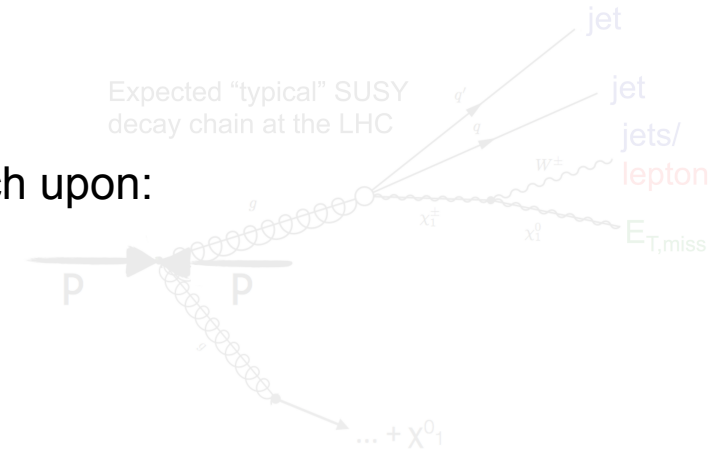
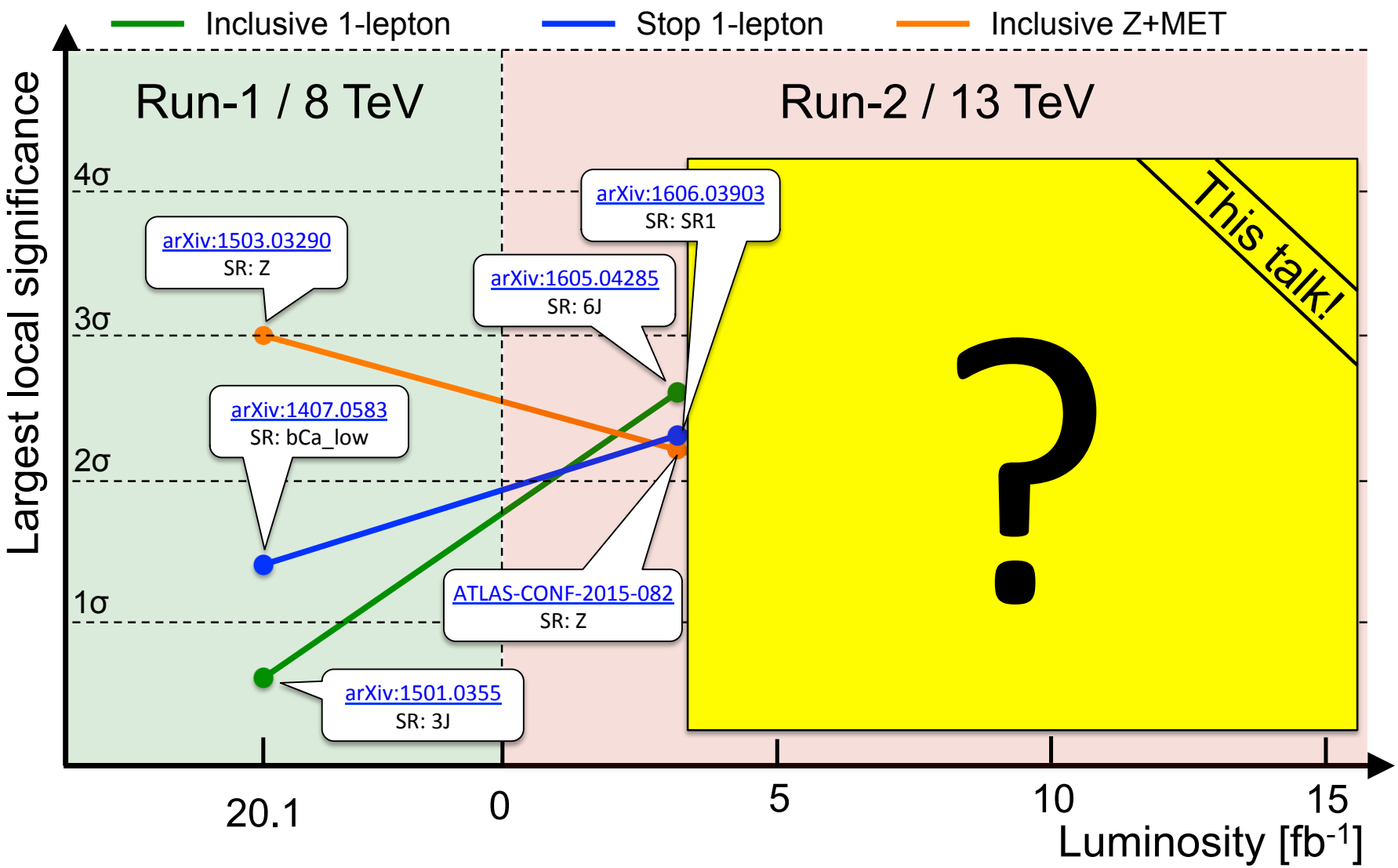


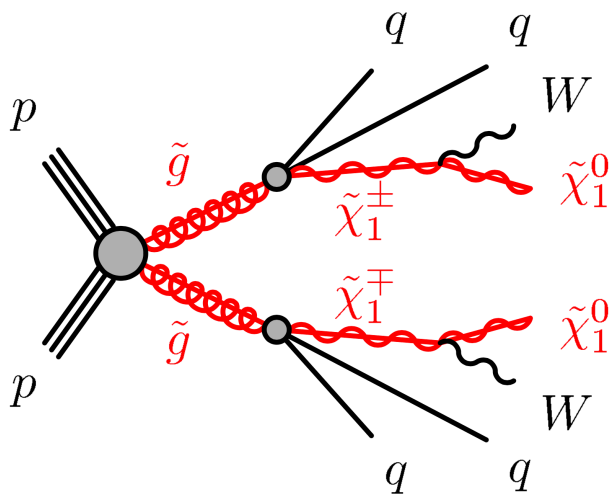
- Will present a selection of 3 interesting recent results with up to ~14.8 fb^{-1}:
  - Inclusive searches for gluinos & squarks:
    - ➢ 1-lepton + jets + $E_{T,miss}$ (**"Inclusive 1-lepton"**)
    - ➢ Z + jets + $E_{T,miss}$ (**"Inclusive Z + MET"**)
  - 3rd generation quarks:
    - ➢ 1-lepton + (b-)jets + $E_{T,miss}$ (**"Stop 1-lepton"**)
  - Outlook to electro-weak searches
- Important areas of activity that I will not touch upon:
  - R-parity violating models
  - Long-lived particles

What happened so far…



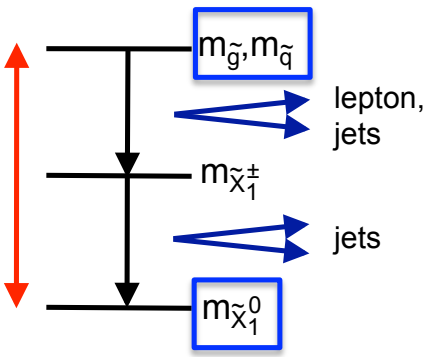
Inclusive 1-lepton Search

- Target final state: **1 lepton (soft/hard) + jets + E_T^{miss}**
- Benchmark scenario:
  - Simplified model with gluino production and 1-step decay via chargino to LSP (100% branching ratio)
  - Simplified model parameter space defined in terms of three parameters: **gluino / squark mass, neutralino mass, mass ratio parameter x**



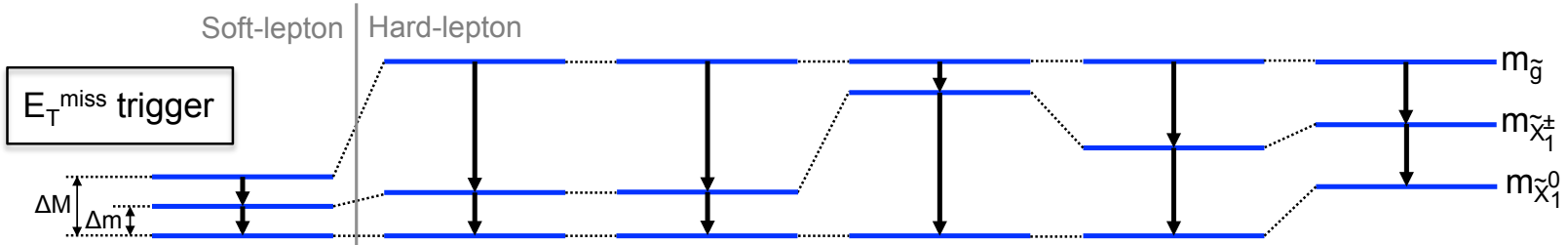
(+ equivalent squark production models)

$$x = \frac{m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}_1^0}}{m_{\tilde{g}/\tilde{q}} - m_{\tilde{\chi}_1^0}}$$

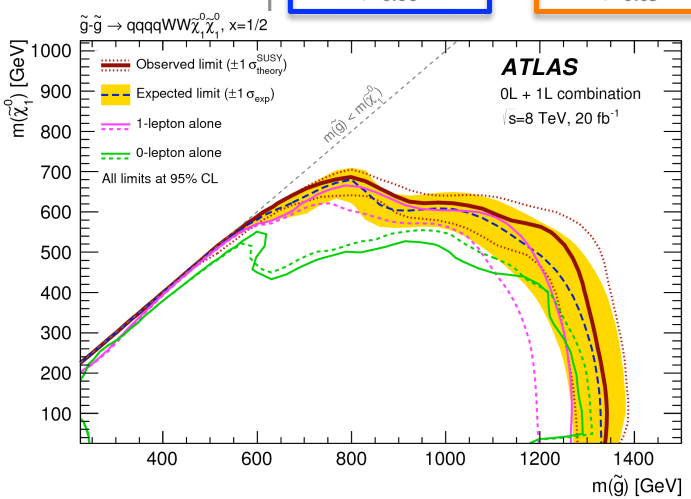


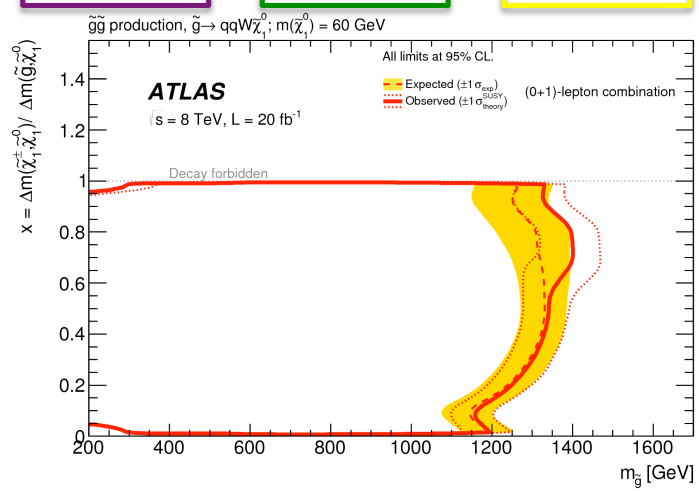
- Define **two model planes** to probe optimal slices of parameter space
  - ($m_{\tilde{g}/\tilde{q}}$, $m_{\tilde{\chi}_1^0}$) with fixed mass ratio parameter x = ½
  - ($m_{\tilde{g}/\tilde{q}}$, mass ratio parameter x) with $m_{\tilde{\chi}_1^0}$ fixed to 60 GeV

Inclusive 1-lepton: Gluino Signal Regions



	GG 2J	GG 4J low-x	GG 4J low-x b-veto	GG 4J high-x	GG 6J high-mass	GG 6J bulk	
N_{lep} (preselected)	= 1	= 1					N_{lep} (preselected)
p_T^ℓ (GeV)	[7(6), 35]	> 7(6)	> 7(6)	> 35	> 35	> 35	p_T^ℓ (GeV)
N_{jet}	≥ 2	≥ 4	≥ 4	≥ 4	≥ 6	≥ 6	N_{jet}
p_T^{jet1} (GeV)	> 200	> 100	> 100	> 400	> 125	> 125	p_T^{jet1} (GeV)
p_T^{jet2} (GeV)	> 30	> 100	> 100	> 30	> 30	> 30	$p_T^{jet2,3}$ (GeV)
m_T (GeV)	> 100	> 100	> 100	[30, 100]	> 30	> 30	p_T^{jet4} (GeV)
E_T^{miss} (GeV)	> 460	-	-	-	> 30	> 30	$p_T^{jet5,6}$ (GeV)
E_T^{miss}/m_{eff}^{inc}	> 0.35	-	= 0	-	-	-	N_{b-jet}
		> 125	> 125	> 475	> 225	> 225	m_T (GeV)
		> 250	> 250	> 250	> 250	> 250	E_T^{miss} (GeV)
		> 2000	> 2000	> 1600	> 2000	> 1000	m_{eff}^{inc} (GeV)
		-	-	> 0.3	> 0.1	> 0.2	E_T^{miss}/m_{eff}^{inc}
		> 0.06	> 0.03	-	> 0.04	> 0.04	Jet aplanarity





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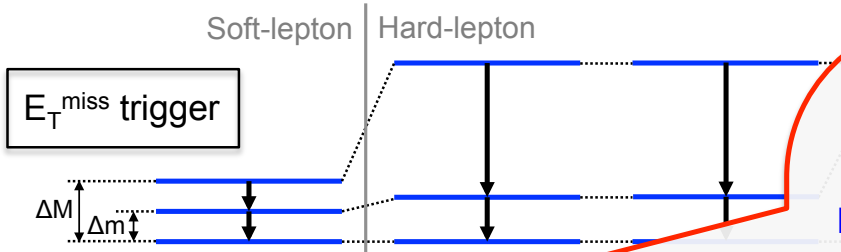

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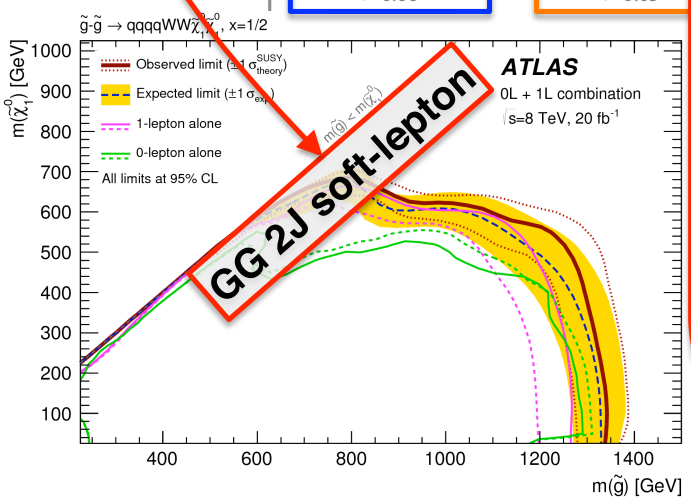
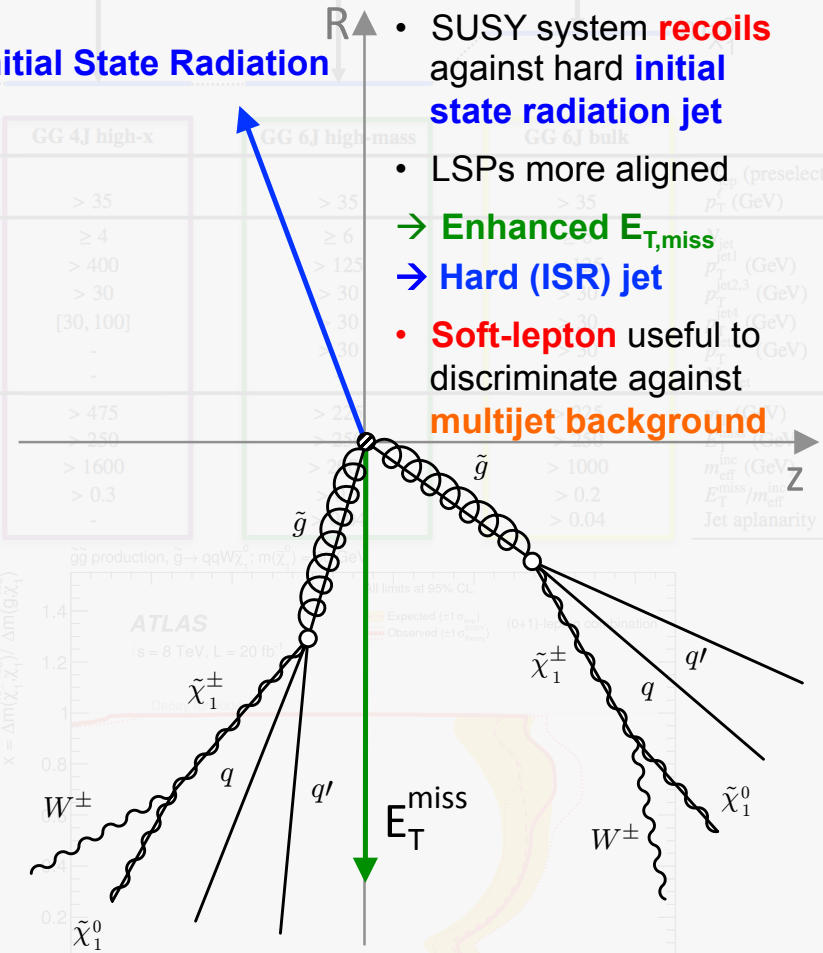
N_{lep} (preselected)	= 1	= 1	= 1	= 1	= 1	= 1
p_T^{ℓ} (GeV)	[7(6), 35]	> 7(6)	> 7(6)	> 35	> 35	> 35
N_{jet}	≥ 2	≥ 4	≥ 4	≥ 4	≥ 6	≥ 6
p_T^{jet1} (GeV)	> 200	> 100	> 100	> 400	> 125	> 125
p_T^{jet2} (GeV)	> 30	> 100	> 100	> 30	> 30	> 30
m_T (GeV)	> 100	> 100	> 100	[30, 100]	-	-
E_T^{miss} (GeV)	> 460	-	> 100	-	> 475	> 250
E_T^{miss}/m_{eff}^{inc}	> 0.35	-	-	-	> 250	> 250
m_{eff}^{inc} (GeV)		> 125	> 125	> 125	> 1600	> 1000
E_T^{miss}/m_{eff}^{inc}		> 250	> 250	> 250	> 0.3	> 0.2
Jet aplanarity		> 2000	> 2000	> 2000	-	> 0.04
		-	-	-		
		> 0.06	> 0.03	> 0.06		



- Targeting small mass differences, difficult to distinguish from SM backgrounds



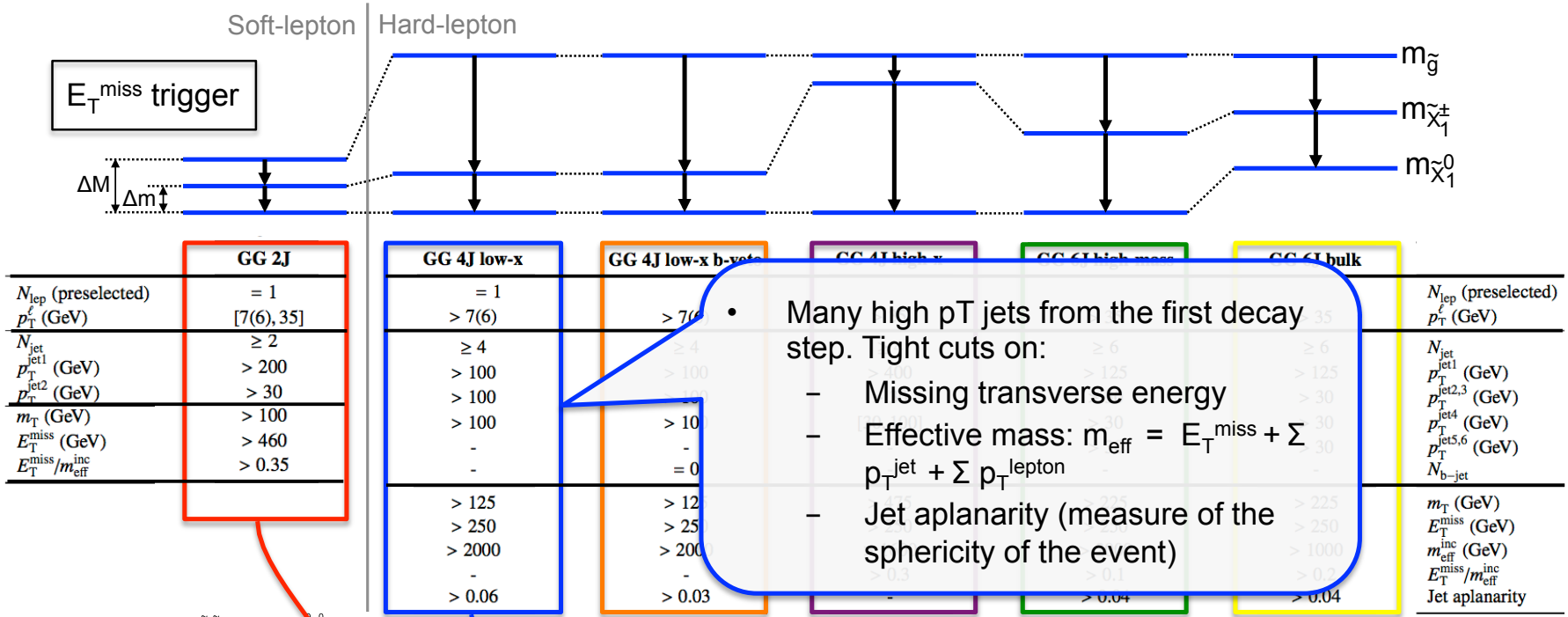
- SUSY system **recoils** against hard **initial state radiation jet**
- LSPs more aligned

→ **Enhanced $E_{T,miss}$**

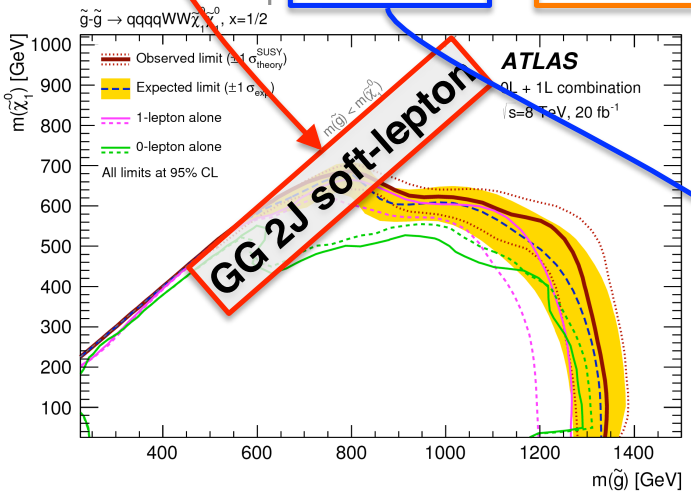
→ **Hard (ISR) jet**

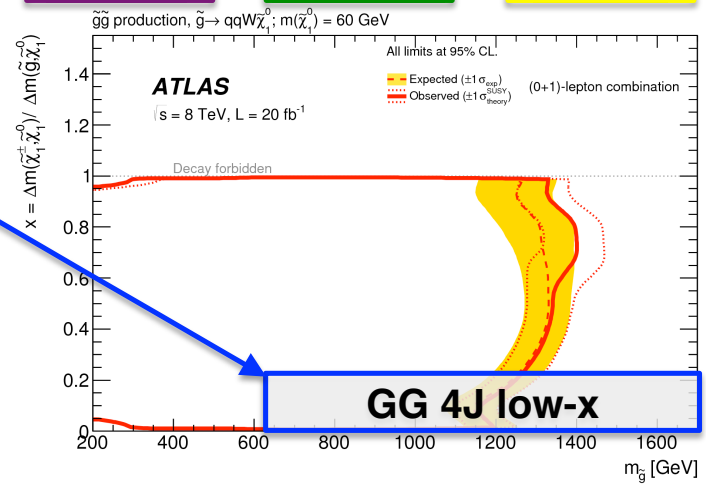
- **Soft-lepton** useful to discriminate against **multijet background**

Inclusive 1-lepton: Gluino Signal Regions



- Many high pT jets from the first decay step. Tight cuts on:
  - Missing transverse energy
  - Effective mass: $m_{eff} = E_T^{miss} + \Sigma\, p_T^{jet} + \Sigma\, p_T^{lepton}$
  - Jet aplanarity (measure of the sphericity of the event)





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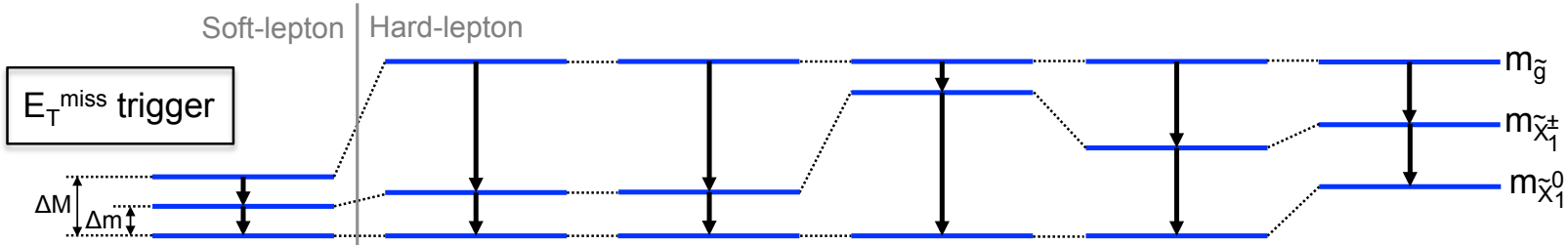

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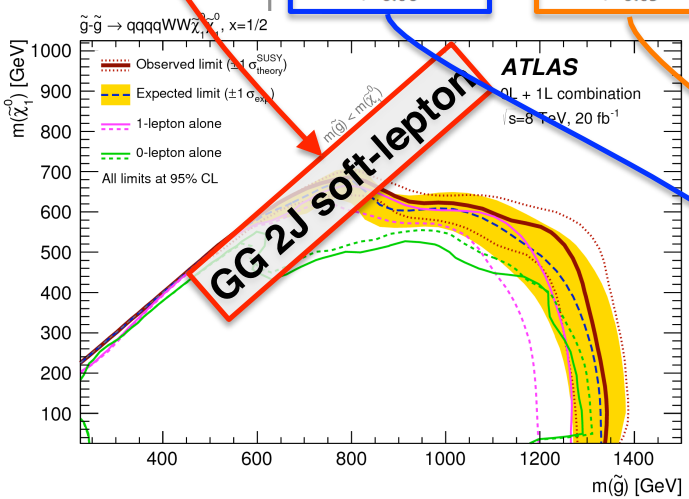
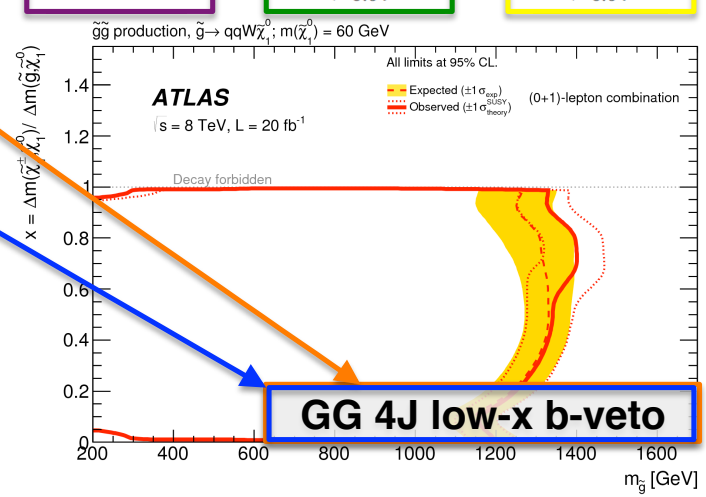
N_{jet}	≥ 2	≥ 4	≥ 4	[illegible]	[illegible]	[illegible]	N_{jet}
p_T^{jet1} (GeV)	> 200	> 100	> 100	> 400	> 225	[illegible]	p_T^{jet1} (GeV)
p_T^{jet2} (GeV)	> 30	> 100	> 100	> 30	[illegible]	[illegible]	$p_T^{jet2,3}$ (GeV)
m_T (GeV)	> 100	> 100	> 100	[30, 100]	[illegible]	> 30	p_T^{jet4} (GeV)
E_T^{miss} (GeV)	> 460	-	-	[illegible]	[illegible]	> 30	$p_T^{jet5,6}$ (GeV)
E_T^{miss}/m_{eff}^{inc}	> 0.35	-	= 0	-	-	-	N_{b-jet}
		> 125	> 125	> 475	> 225	> 225	m_T (GeV)
		> 250	> 250	> 250	> 250	> 250	E_T^{miss} (GeV)
		> 2000	> 2000	> 1600	> 2000	> 1000	m_{eff}^{inc} (GeV)
		-	-	> 0.3	> 0.1	> 0.2	E_T^{miss}/m_{eff}^{inc}
		> 0.06	> 0.03	-	> 0.04	> 0.04	Jet aplanarity

- Same as GG 4J low-x with b-jet veto to enhance sensitivity for exclusion

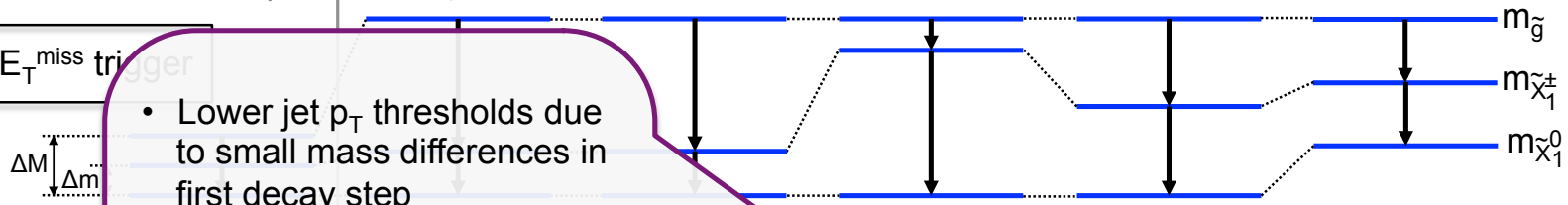




Inclusive 1-lepton: Gluino Signal Regions

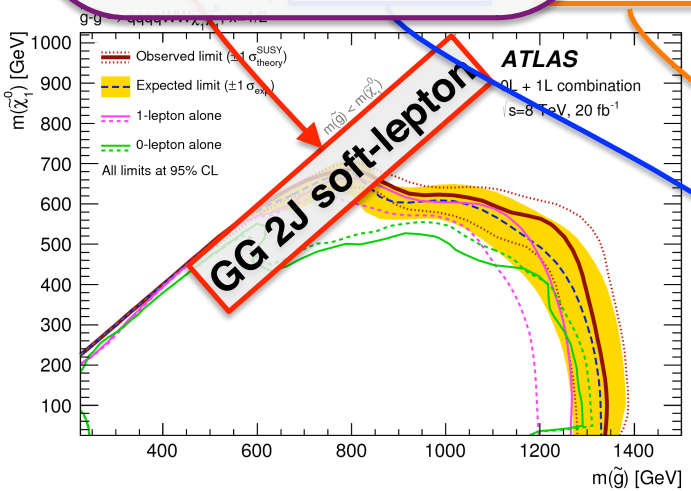
Soft-lepton | Hard-lepton

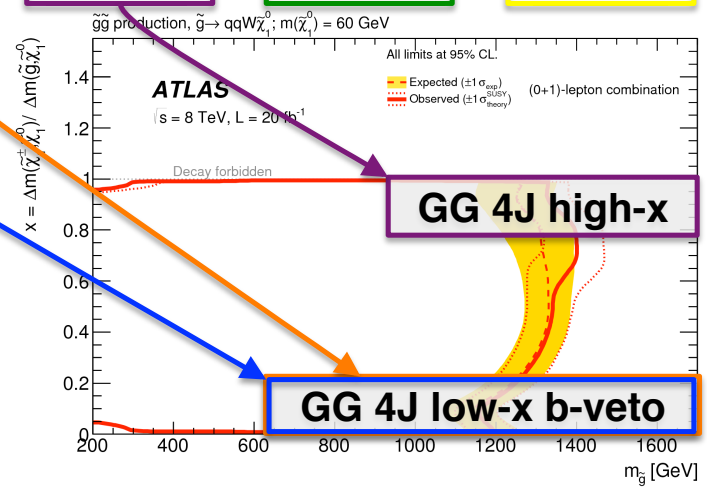
E_T^{miss} trigger



- Lower jet p_T thresholds due to small mass differences in first decay step
- One energetic jet and one hard lepton from second decay step (hadronic / leptonic W decay)
- Tight cut on transverse mass between lepton and E_T^{miss}
- No aplanarity requirement

	GG 4J high-x	GG 6J high-mass	GG 6J bulk	
N_{lep} (preselected)				N_{lep} (preselected)
p_T^ℓ (GeV)	> 7(6)	> 35	> 35	> 35	p_T^ℓ (GeV)
N_{jet}	≥ 4	≥ 4	≥ 6	≥ 6	N_{jet}
p_T^{jet1} (GeV)	> 100	> 400	> 125	> 125	p_T^{jet1} (GeV)
p_T^{jet2} (GeV)	> 100	> 30	> 30	> 30	$p_T^{jet2,3}$ (GeV)
	> 100	[30, 100]	> 30	> 30	p_T^{jet4} (GeV)
	-	-	> 30	> 30	$p_T^{jet5,6}$ (GeV)
	= 0	-	-	-	N_{b-jet}
m_T (GeV)	> 125	> 475	> 225	> 225	m_T (GeV)
E_T^{miss} (GeV)	> 250	> 250	> 250	> 250	E_T^{miss} (GeV)
m_{eff}^{inc} (GeV)	> 2000	> 1600	> 2000	> 1000	m_{eff}^{inc} (GeV)
E_T^{miss}/m_{eff}^{inc}	-	> 0.3	> 0.1	> 0.2	E_T^{miss}/m_{eff}^{inc}
	> 0.03	-	> 0.04	> 0.04	Jet aplanarity





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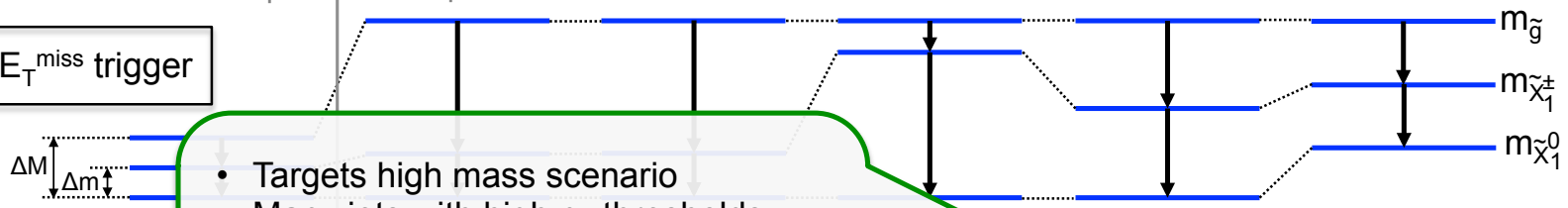
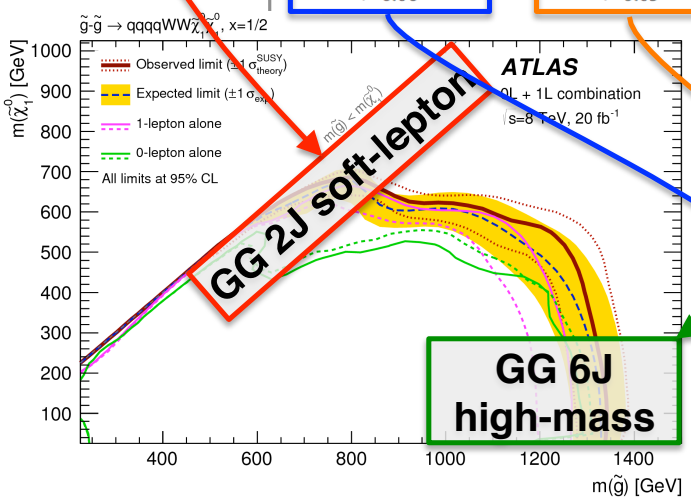
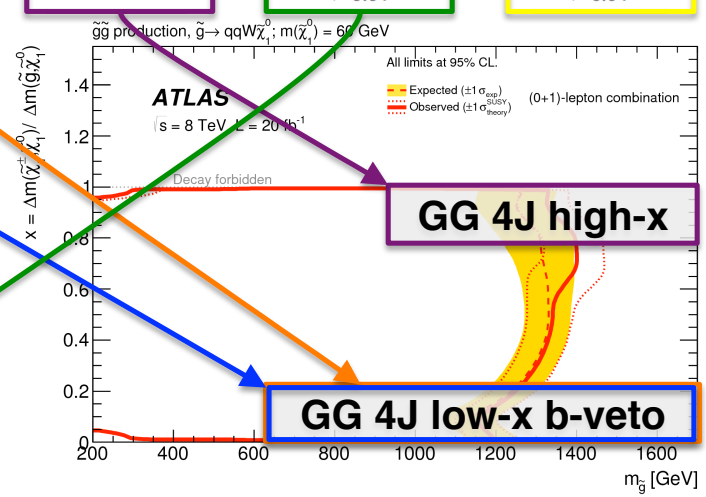


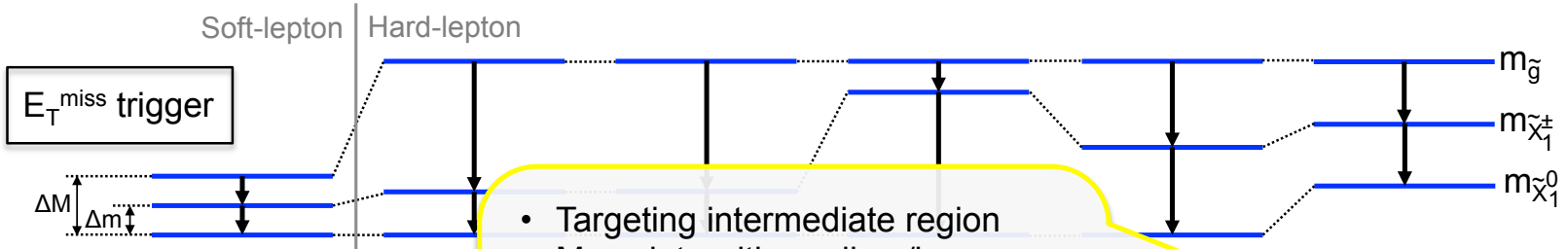
- Targets high mass scenario
- Many jets with high p_T thresholds
- Tight cuts on effective mass: m_{eff} = $E_T^{miss} + \Sigma\, p_T^{jet} + \Sigma\, p_T^{lepton}$
- Aplanarity cut (many high p_T objects in the event)

				GG 6J high-mass	GG 6J bulk	
N_{lep} (preselected)						N_{lep} (preselected)
p_T^{ℓ} (GeV)			> 35	> 35	> 35	p_T^{ℓ} (GeV)
N_{jet}			≥ 4	≥ 6	≥ 6	N_{jet}
p_T^{jet1} (GeV)			> 400	> 125	> 125	p_T^{jet1} (GeV)
p_T^{jet2} (GeV)			> 30	> 30	> 30	$p_T^{jet2,3}$ (GeV)
			[30, 100]	> 30	> 30	p_T^{jet4} (GeV)
m_T (GeV)	> 100	> 100	-	> 30	> 30	$p_T^{jet5,6}$ (GeV)
E_T^{miss} (GeV)	> 460	-	-	-	-	N_{b-jet}
E_T^{miss}/m_{eff}^{inc}	> 0.35	= 0	-			
			> 475	> 225	> 225	m_T (GeV)
	> 125	> 125	> 250	> 250	> 250	E_T^{miss} (GeV)
	> 250	> 250	> 1600	> 2000	> 1000	m_{eff}^{inc} (GeV)
	> 2000	> 2000	> 0.3	> 0.1	> 0.2	E_T^{miss}/m_{eff}^{inc}
	-	-	-	> 0.04	> 0.04	Jet aplanarity
	> 0.06	> 0.03				



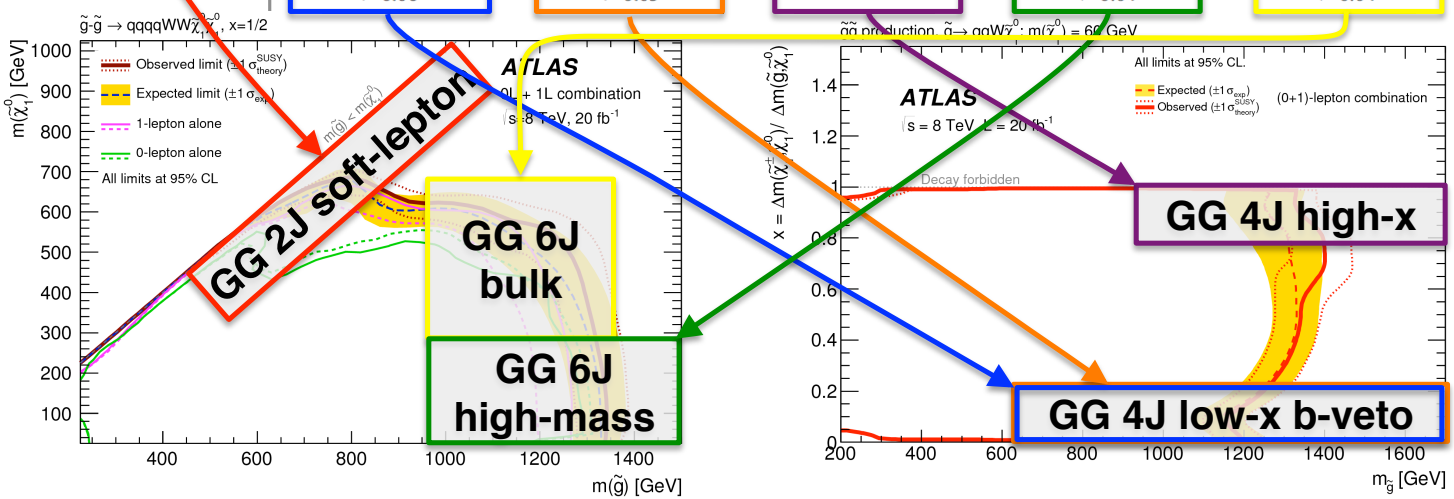


Inclusive 1-lepton: Gluino Signal Regions



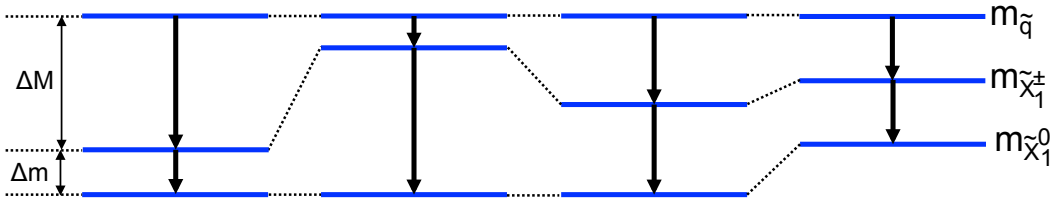
- Targeting intermediate region
- Many jets with medium/loose p_T thresholds
- Medium cuts on all discriminating variables
- 2.6σ data surplus in 3.2fb^{-1}@13TeV result

	GG 2J	GG 4J low-x	GG 4J low-x b-veto	GG 4J high-x	GG 6J high-mass	GG 6J bulk	
N_{lep} (preselected)	= 1	= 1					N_{lep} (preselected)
p_T^ℓ (GeV)	[7(6), 35]	> 7(6)			> 35	> 35	p_T^ℓ (GeV)
N_{jet}	≥ 2	≥ 4		≥ 4	≥ 6	≥ 6	N_{jet}
p_T^{jet1} (GeV)	> 200	> 100		> 400	> 125	> 125	p_T^{jet1} (GeV)
p_T^{jet2} (GeV)	> 30	> 100		> 30	> 30	> 30	$p_T^{jet2,3}$ (GeV)
		> 100		[30, 100]	> 30	> 30	p_T^{jet4} (GeV)
		-		-	> 30	> 30	$p_T^{jet5,6}$ (GeV)
		-	= 0	-	-	-	N_{b-jet}
m_T (GeV)	> 100	> 125	> 125	> 475	> 225	> 225	m_T (GeV)
E_T^{miss} (GeV)	> 460	> 250	> 250	> 250	> 250	> 250	E_T^{miss} (GeV)
m_{eff}^{inc} (GeV)		> 2000	> 2000	> 1600	> 2000	> 1000	m_{eff}^{inc} (GeV)
E_T^{miss}/m_{eff}^{inc}	> 0.35	-	-	> 0.3	> 0.1	> 0.2	E_T^{miss}/m_{eff}^{inc}
		> 0.06	> 0.03	-	> 0.04	> 0.04	Jet aplanarity

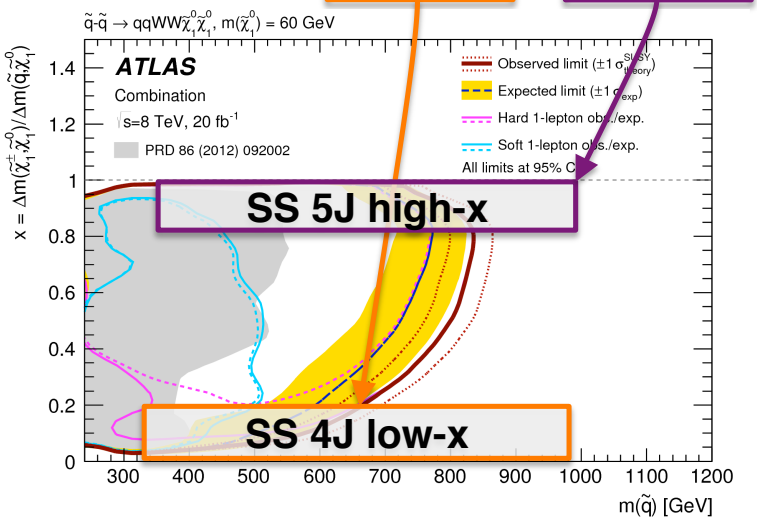


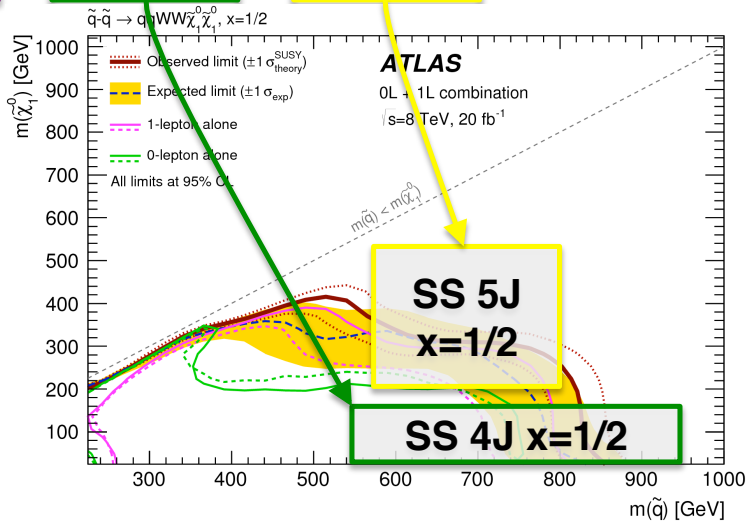
Inclusive 1-lepton: Squark Signal Regions

E_T^{miss} trigger



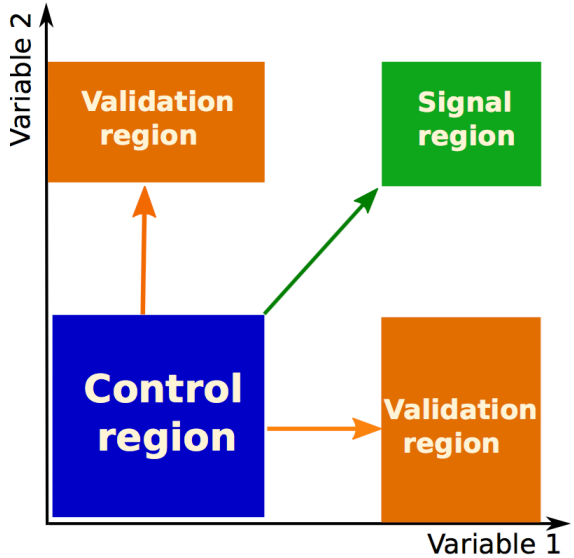
	SS 4J low-x	SS 5J high-x	SS 4J x=1/2	SS 5J x=1/2
N_{lep} (preselected)	= 1	= 1	= 1	= 1
p_T^{ℓ}(GeV)	> 35	> 35	> 35	> 35
N_{jet}	≥ 4	≥ 5	≥ 4	≥ 5
$p_T^{jet1,2}$ (GeV)	> 250	> 30	> 50	> 50
$p_T^{jet3,4}$ (GeV)	> 30	> 30	> 50	> 50
p_T^{jet5} (GeV)	-	> 30	-	> 50
N_{b-jet}	= 0	= 0	= 0	= 0
m_T (GeV)	[150, 400]	> 400	> 175	> 175
E_T^{miss} (GeV)	> 250	> 400	> 300	> 300
m_{eff}^{inc} (GeV)	-	-	> 1200	-
E_T^{miss}/m_{eff}^{inc}	-	-	-	> 0.2
Lepton aplanarity	> 0.03	> 0.03	> 0.08	-

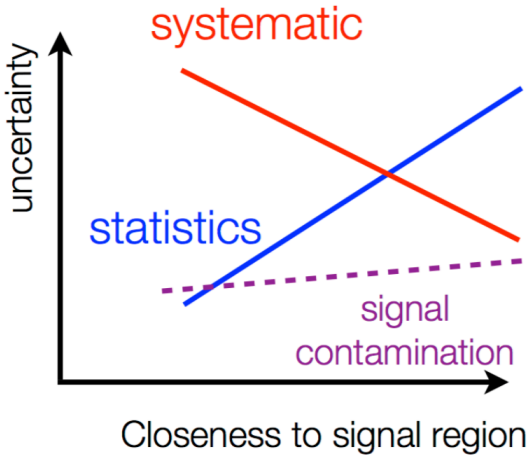




Inclusive 1-lepton: Background Estimation

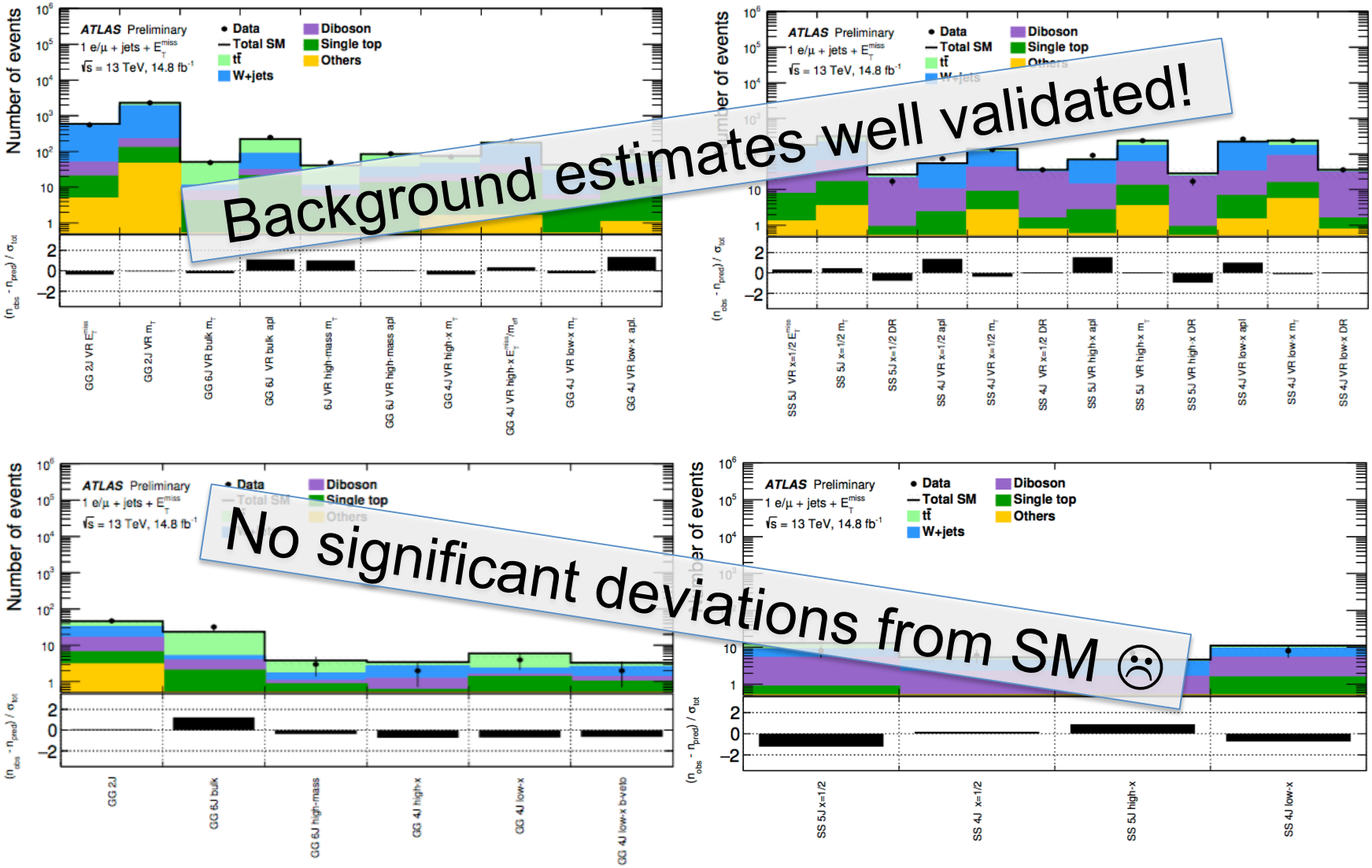
- **Major backgrounds: tt & W+jets (diboson for squark signal regions)**
  - ① Define control regions (CRs) that are enriched in the process of interest & normalise simulation
  - ② Extrapolation based on simulation from CRs to validation regions (VRs) and eventually to the SRs
  - → Optimization of CR and VR selections:
    - Theoretical uncertainties (proximity to the SRs)
    - Statistics in CRs
    - Signal contamination





- **Smaller backgrounds:**
  - tt+V, single-top, (di-boson for gluino signal regions), Z+jets, etc. taken from simulation
  - Fake-lepton background negligible

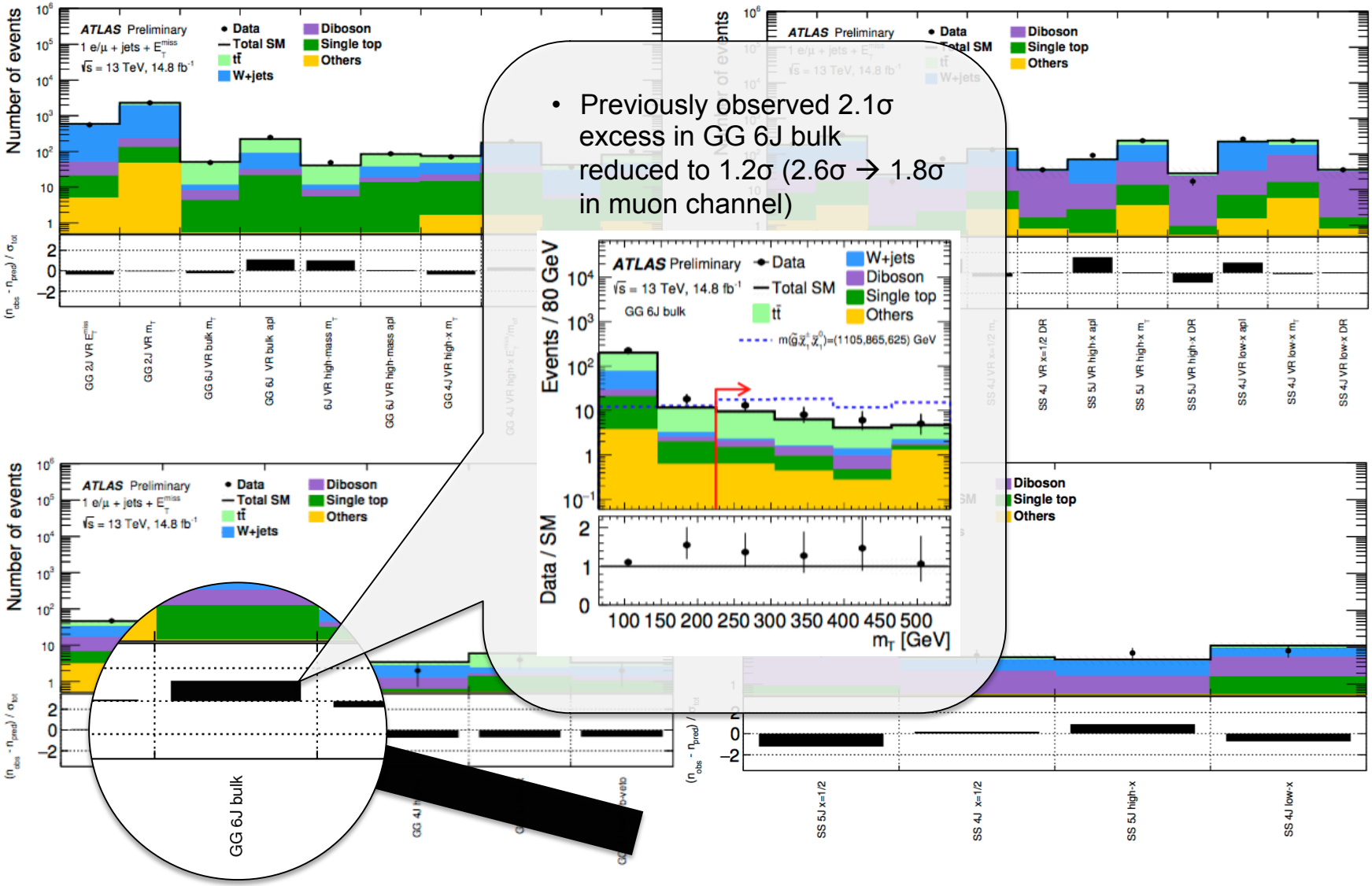
Inclusive 1-lepton: Validation & Results



Background estimates well validated!

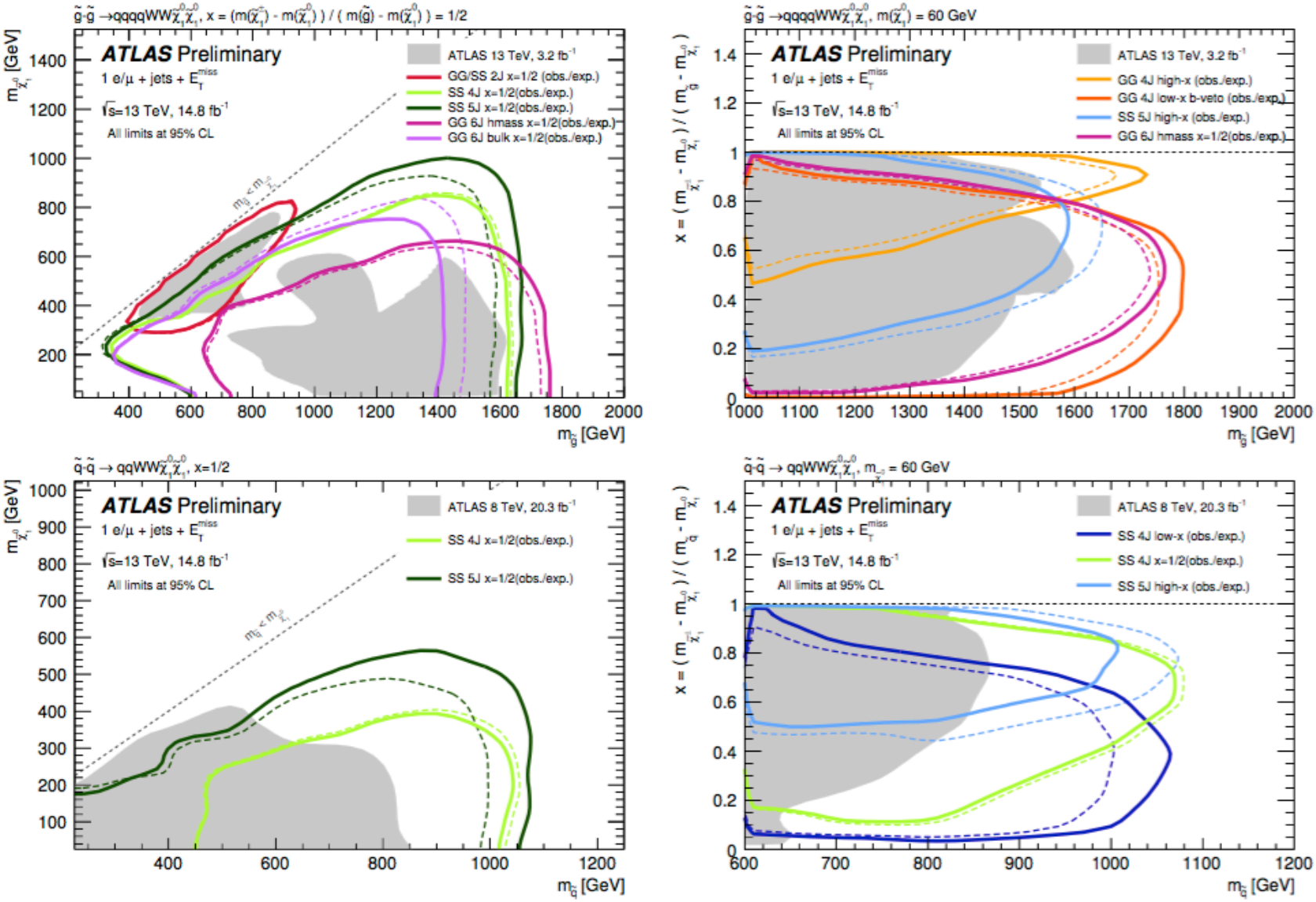
No significant deviations from SM ☹

Inclusive 1-lepton: Validation & Results



- Previously observed 2.1σ excess in GG 6J bulk reduced to 1.2σ (2.6σ → 1.8σ in muon channel)

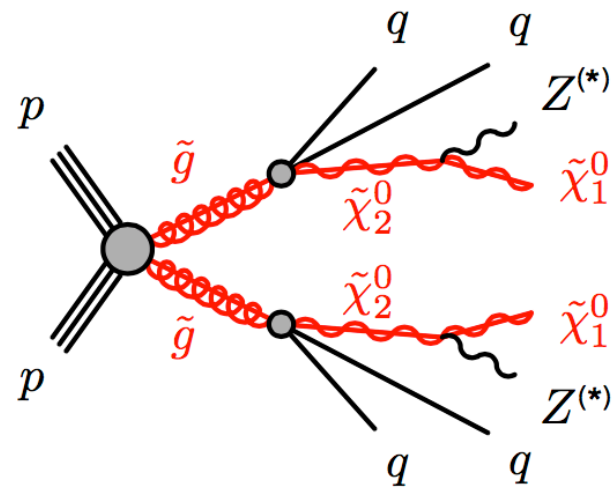
Inclusive 1-lepton: Interpretation

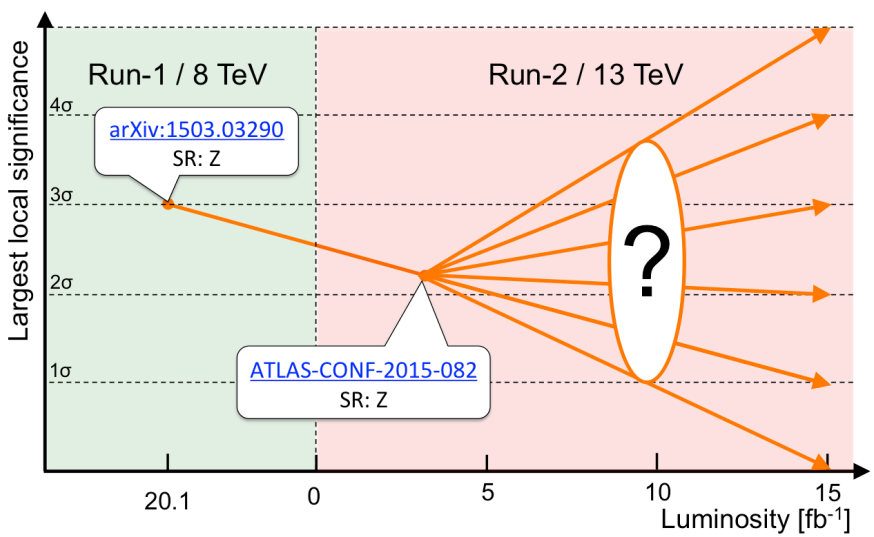


Z+MET Search

- Looking for SUSY models with Z-boson production along the decay chains
- Has been a hot topic for a while following interesting 8 TeV & first 13 TeV results
- Signature: **l^+l^- + jets + $E_{T,miss}$**

Benchmark simplified model





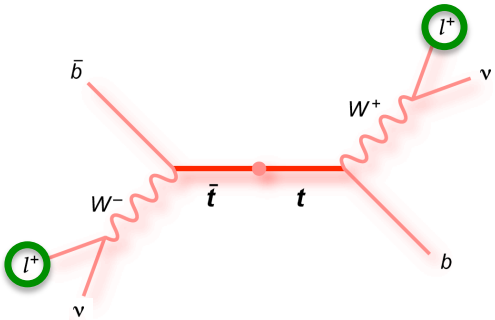
Signal region ("SRZ")

E_T^{miss} [GeV]	H_T^{incl} [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	
> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	
SF/DF	$\Delta\phi(\text{jet}_{12}, p_T^{miss})$	$m_T(\ell_3, E_T^{miss})$ [GeV]	$n_{b\text{-jets}}$	
SF	> 0.4	–	–	

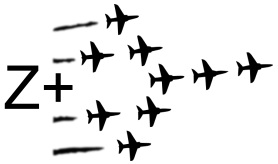
→ SRZ essentially unchanged since Run-1

Z+MET: Backgrounds

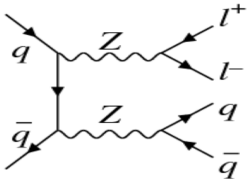
- **Flavour symmetric** background:
  - Backgrounds with ee / μμ final states
  - Dominated by tT (50-70%), Wt, Z → ττ
  - Constitutes **60%** of total backgrounds
  - → Estimated using the so-called **"flavour symmetry" method** based on eμ control sample



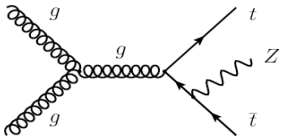
- **Z/gamma* + jets** background:
  - Arises from met mismeasurements
  - Well suppressed due to met requirements (constitutes around **5%** of total background)
  - However: Difficult to model and can mimic signal
  - → Estimated using **photon + jets control sample**



- **WW/ZZ diboson** background:
  - Constitutes **30%** of total backgrounds,
  - → Estimated with **simulation** and cross-checked in validation regions



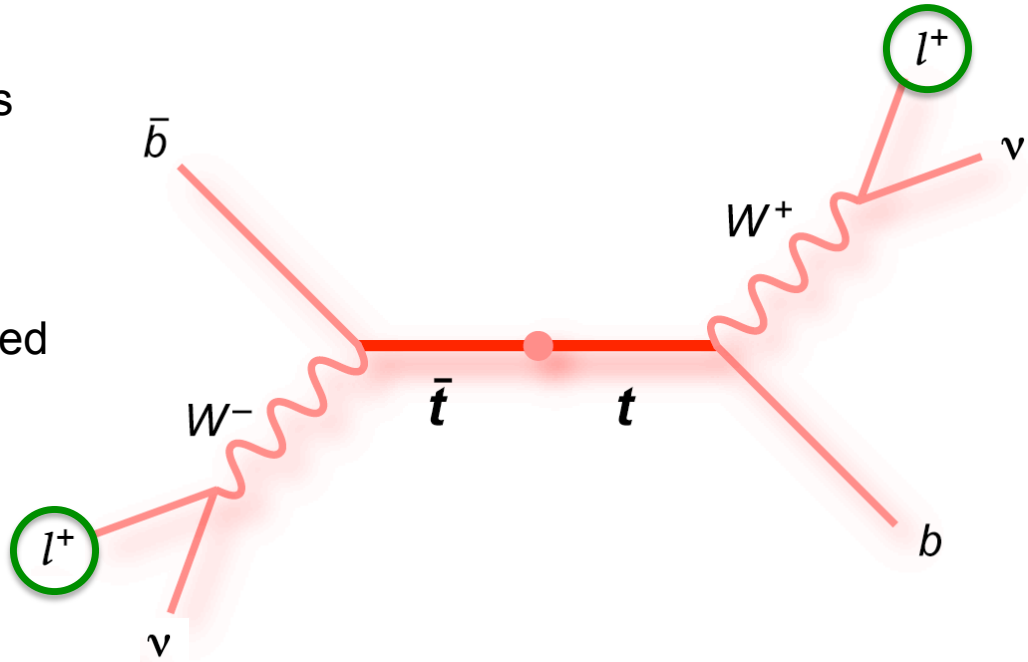
- **Rare top** background (ttW,ttZ,ttWW procceses):
  - Constitutes ~ **5%** of total backgrounds → From **simulation**

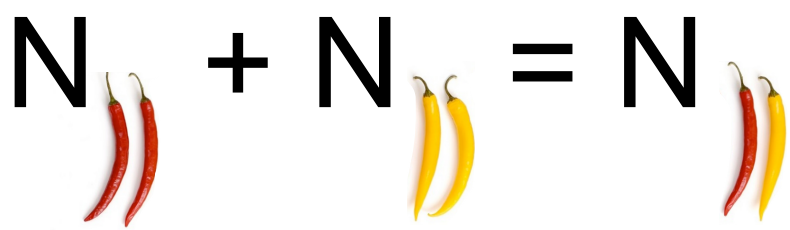


- **Fake / non-prompt lepton** background:
  - **Sub-%** level → Estimated with **data-driven matrix method**

Z+MET: Flavour-Symmetry Method

- Flavour-symmetric backgrounds have 2 leptons from separate W decays
- Estimate background with opposite flavour events based on $N_{ee} + N_{\mu\mu} = N_{e\mu}$
- Apply corrections for:
  - Contamination of **non flavour-symmetric** backgrounds
  - Electron vs. muon **reconstruction and identification** efficiencies
  - Di-electron / di-muon vs. eμ **trigger** efficiencies





Z+MET: Flavour-Symmetry Method

Correction for contamination of non flavour-symmetric processes in eμ control sample

Sum over eμ control data with lepton (p_T,η) – dependent correction factors:

e vs. μ offline reconstruction and identification efficiency

di-e / di-μ vs. eμ trigger efficiencies

Estimated ee/μμ background

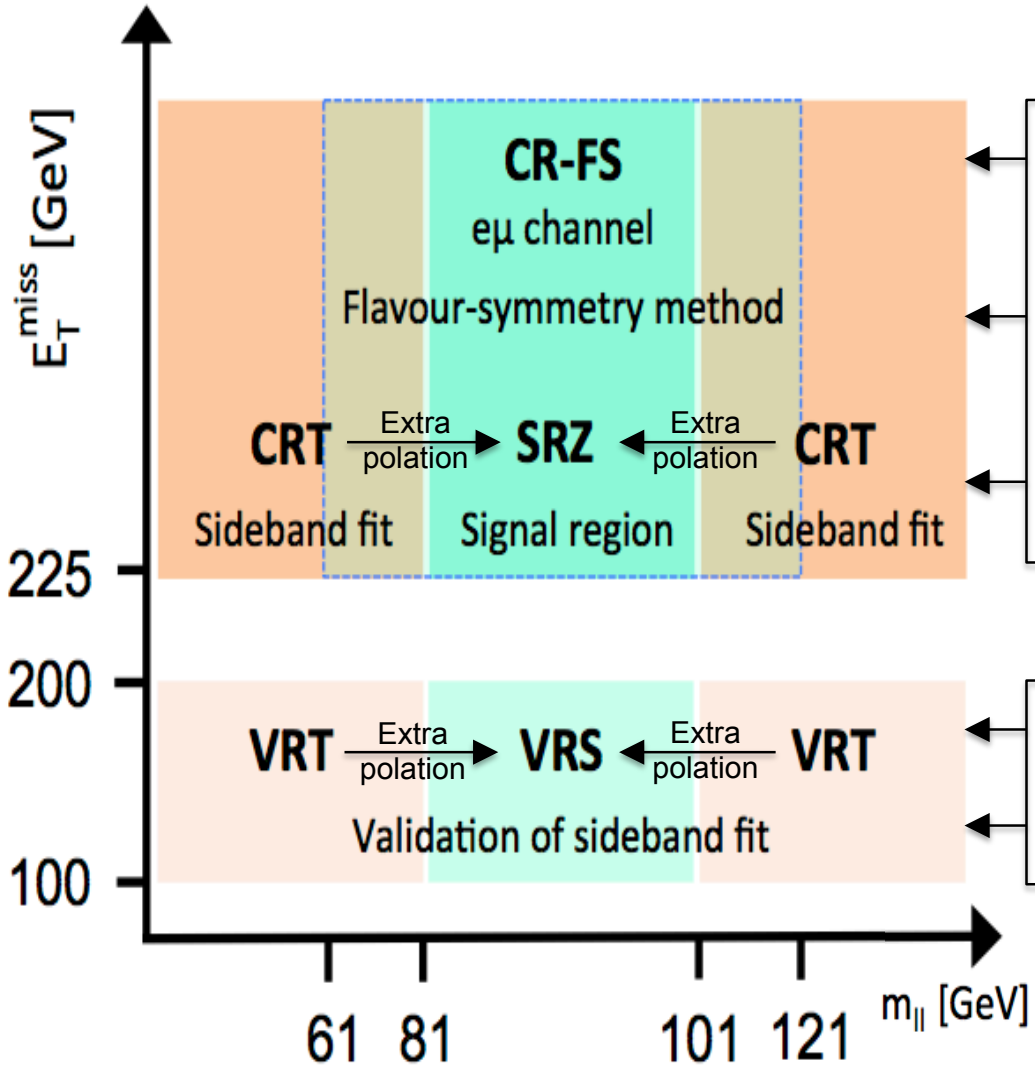
$$N_{ee}^{\text{est}} = \frac{1}{2} \cdot f_{\text{FS}} \cdot f_{Z\text{-mass}} \cdot \sum_{i}^{N_{e\mu}^{\text{data}}} k_e(p_{\text{T}}^{i,\mu}, \eta^{i,\mu}) \cdot \alpha(p_{\text{T}}^{i,\mu}, \eta^{i,\mu}),$$

$$N_{\mu\mu}^{\text{est}} = \frac{1}{2} \cdot f_{\text{FS}} \cdot f_{Z\text{-mass}} \cdot \sum_{i}^{N_{e\mu}^{\text{data}}} k_\mu(p_{\text{T}}^{i,e}, \eta^{i,e}) \cdot \alpha(p_{\text{T}}^{i,e}, \eta^{i,e}),$$

BR correction factor

Fraction in eμ control data that is contained within the SR's invariant mass window (invariant mass window widened in CR to triple control region statistics)

Z+MET: Validation Flavour Symmetry Method



- Perform likelihood fit in Z-mass sidebands (CRT) which is dominated by tT (~75%)
- All BG processes from MC
- tT normalisation floating (norm factor = 0.64)
- Extrapolation of prediction to signal region (CRT → SRZ)

- Fit & flavour symmetry method repeated also in lower MET region to validate extrapolation

→ Excellent agreement in both regions:

Region	Flavour-symmetry	Sideband fit
SRZ	33 ± 4	29 ± 7
VR-S	99 ± 8	92 ± 25

Z+MET: Z/gamma* + jets background

- Exploit similar kinematics between Z+jets and photon+jets events
  → Both have $E_{T,miss}$ from jet mis-measurements

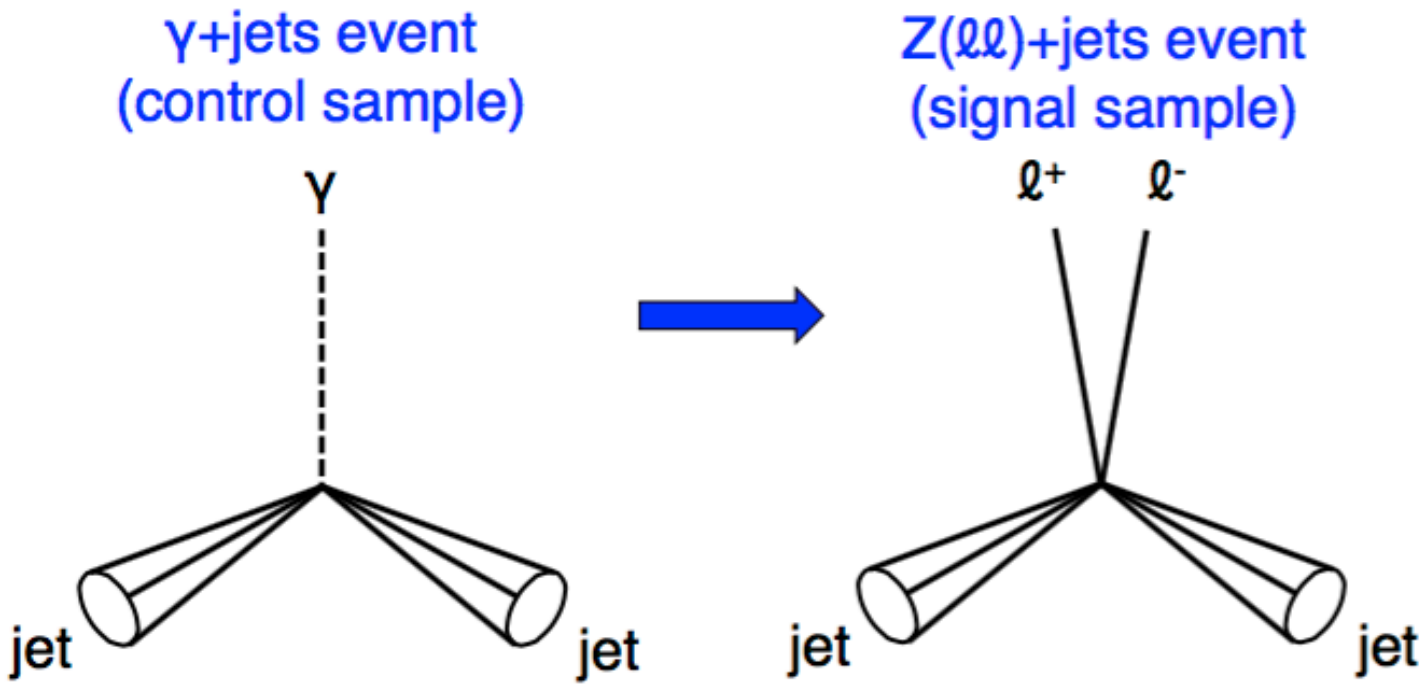
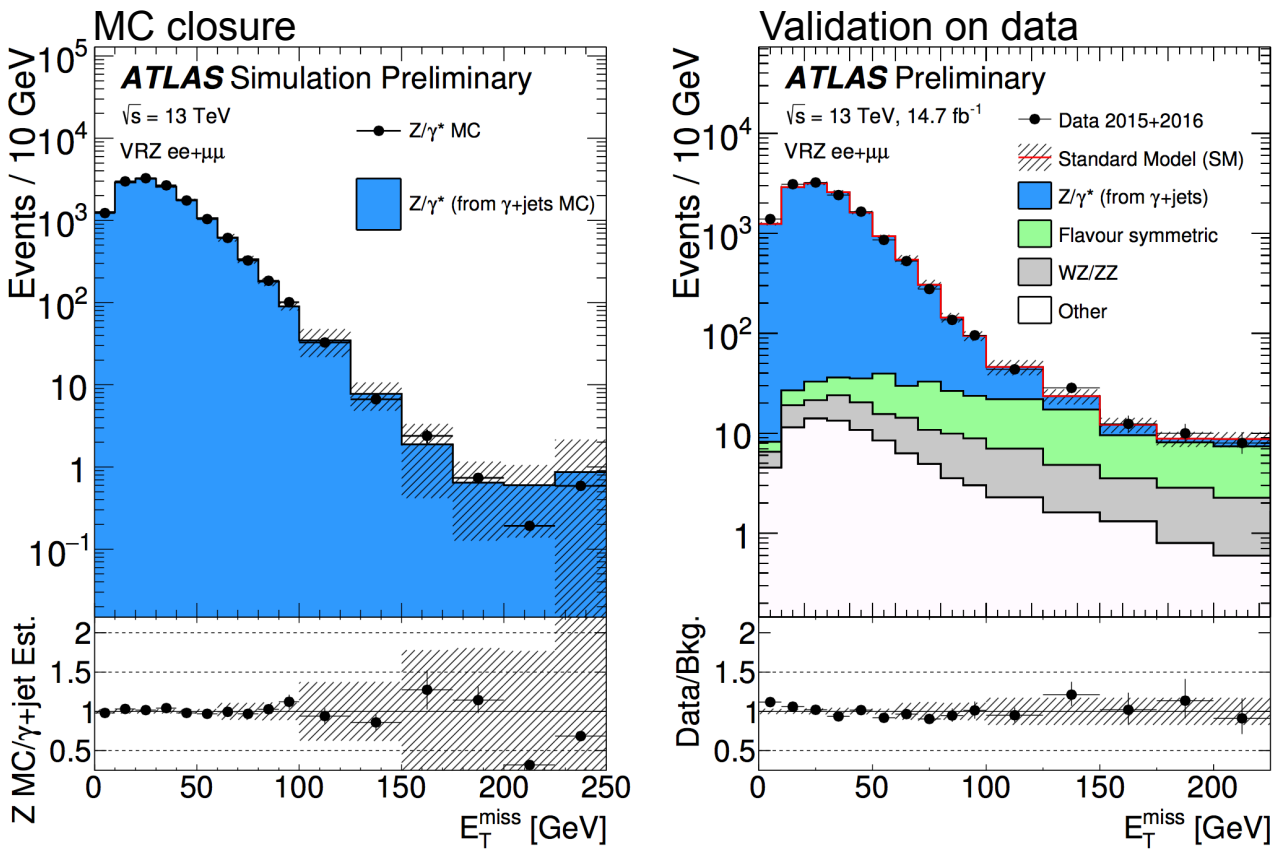


Figure B. Hooberman

- Smearing of photon p_T according to Z → ee or Z → μμ resolution function
- Reweighting of $p_T(\gamma)$ to match $p_T(Z)$

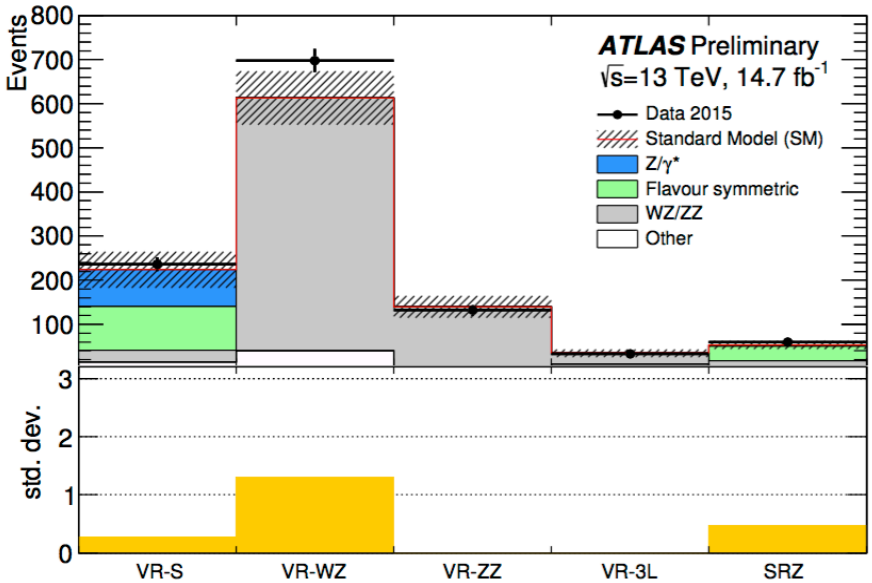
Z+MET: Validation: Z/gamma* + jets

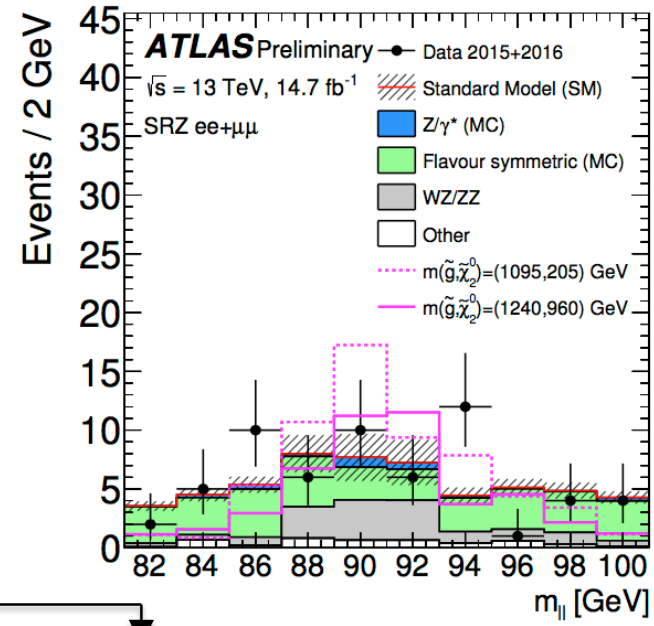
- Validation of predictions in dedicated validation region VRZ:
  - $e^+e^-/\mu^+\mu^-$ leptons, p_T > (50,25) GeV, m_{ll} 81-101 GeV
  - 2 jets, p_T > 30 GeV, H_T > 600 GeV, $\Delta\phi$ (jet$_{1,2}$, $E_{T,miss}$cut) > 0.4



→ Excellent agreement on MC closure test and validation on data

Z+MET: Validation & Results



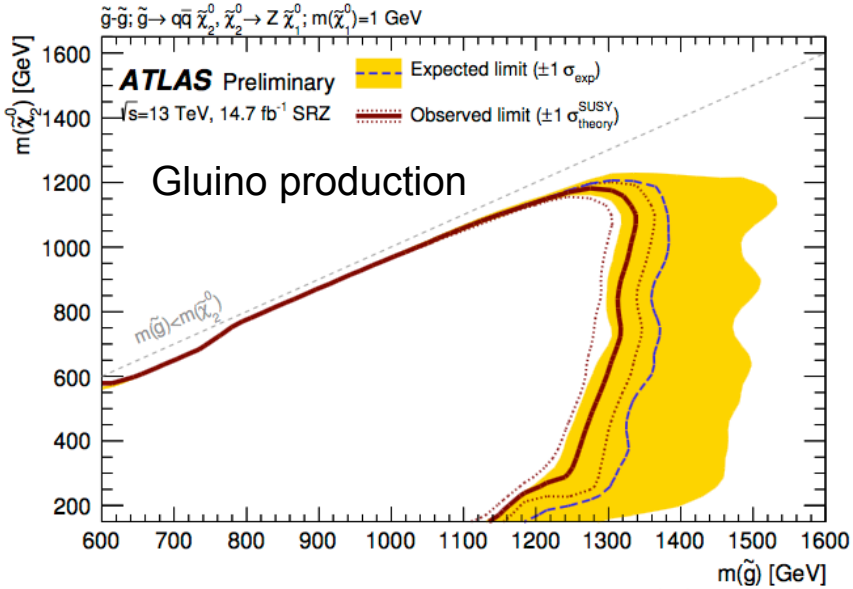


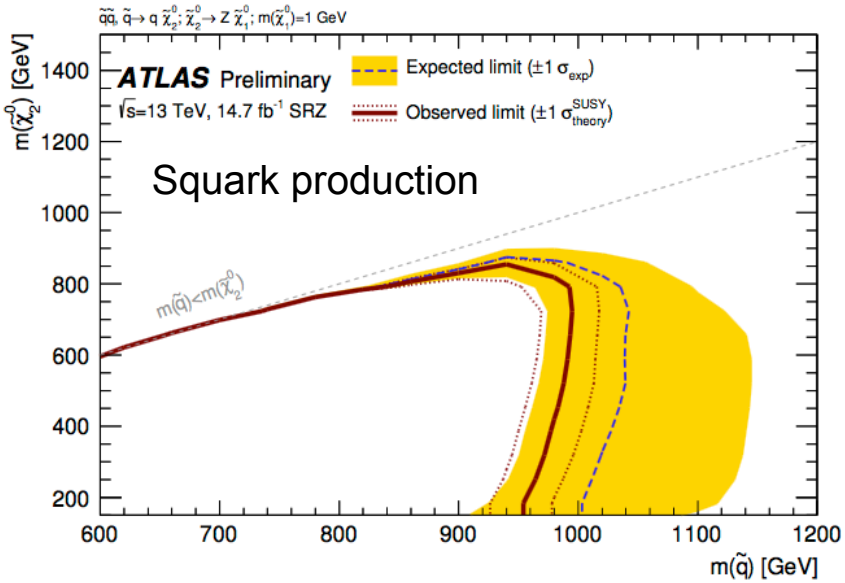
	SRZ	SRZ ee	SRZ $\mu\mu$
Observed events	60	35	25
Total expected background events	53.5 ± 9.3	27.1 ± 5.1	26.8 ± 4.4
Flavour-symmetric ($t\bar{t}$, Wt, WW and $Z \to \tau\tau$) events	33.2 ± 3.9	16.5 ± 2.1	16.7 ± 2.0
$Z/\gamma^* +$ jets events	3.1 ± 2.8	$1.0^{+1.3}_{-1.0}$	2.1 ± 1.4
WZ/ZZ events	14.2 ± 7.7	7.8 ± 4.3	6.4 ± 3.5
Rare top events	2.9 ± 0.8	1.4 ± 0.4	1.5 ± 0.4
Fake lepton events	$0.1^{+0.8}_{-0.1}$	$0.5^{+0.7}_{-0.5}$	$0^{+0.2}$
$p(s = 0)$	0.32	0.15	0.5
Significance (σ)	0.47	1.00	0
Observed (Expected) S^{95}	28.2 ($24.5^{+8.9}_{-6.7}$)	22.0 ($15.8^{+6.5}_{-4.5}$)	12.9 ($14.0^{+5.7}_{-3.9}$)
$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	1.9	1.5	0.88

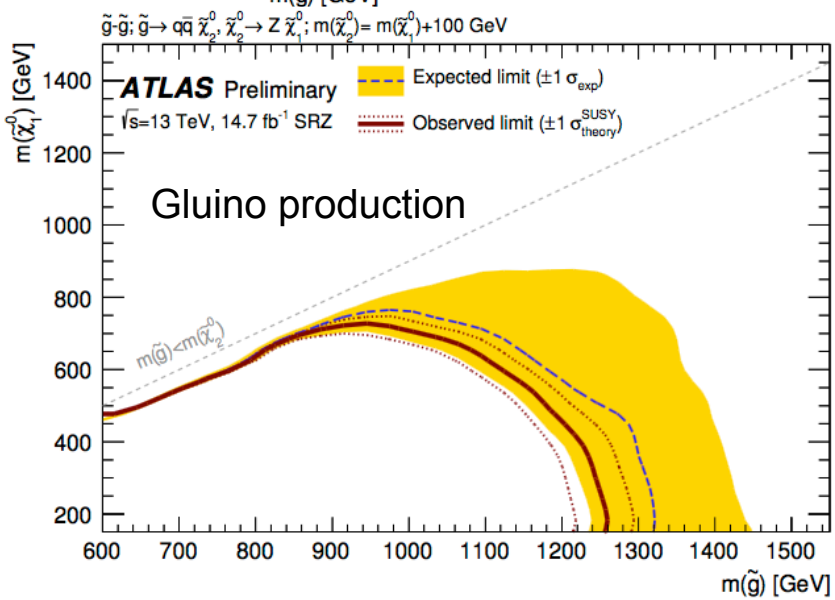
→ **Perfect agreement** with the expectation in the SR

→ The previously observed excess has **disappeared**

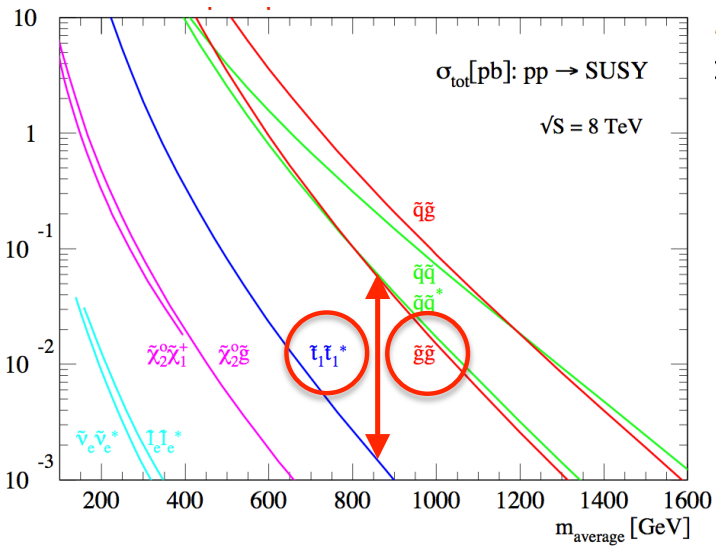
Z+MET: Interpretation

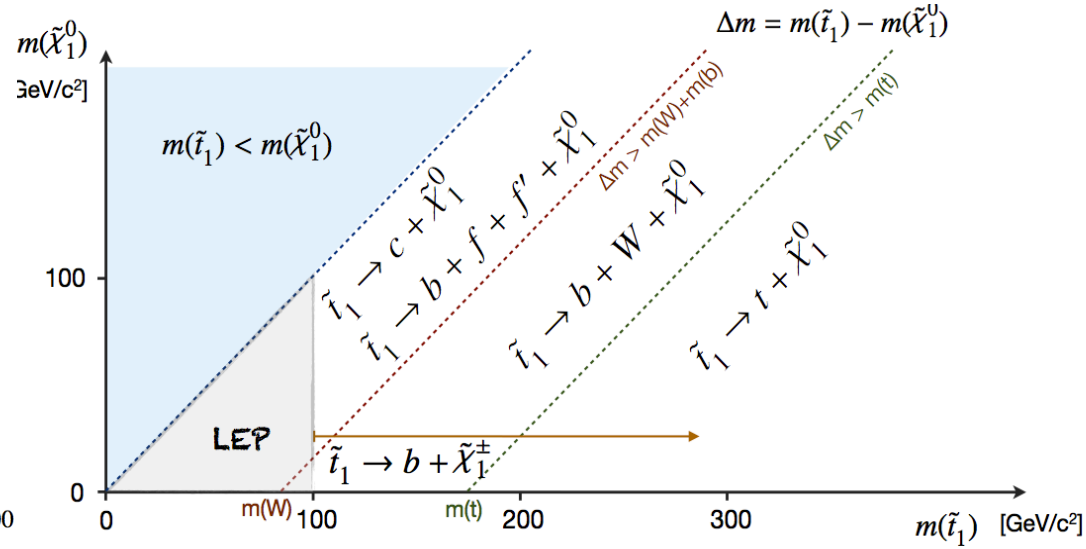






Stop Production & Decay

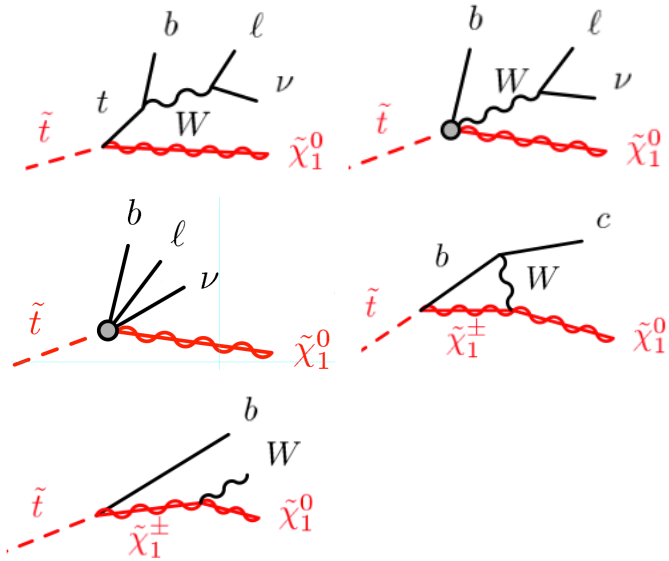




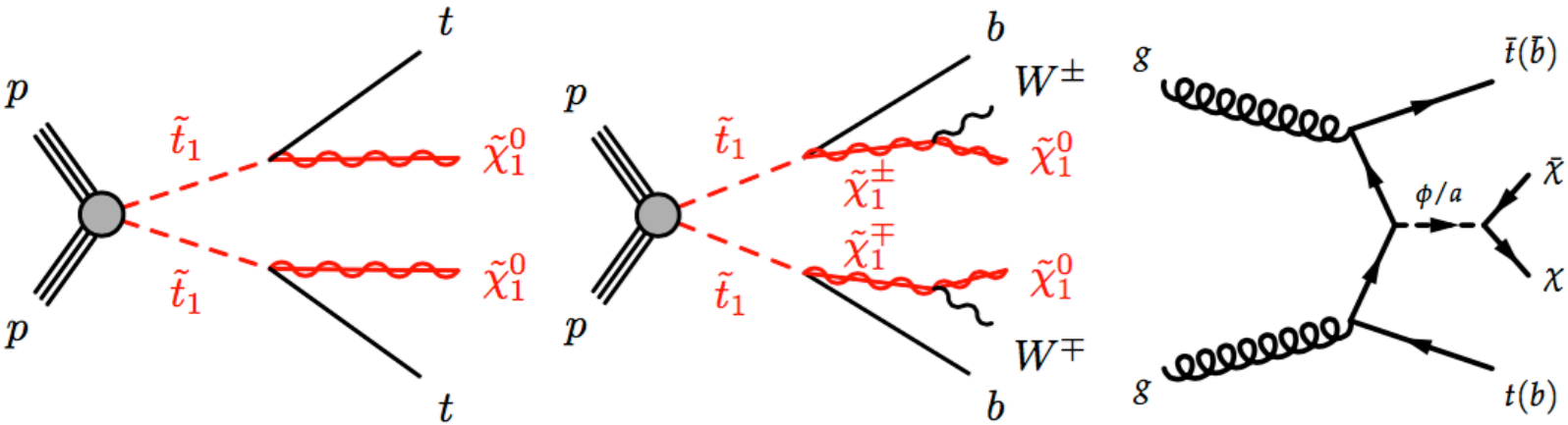
- $\tilde{t}\,\tilde{t}^*$ production:
  - Cross-section suppressed w.r.t. to gluino and light squark production
- Decay modes:
  - Only $\tilde{t}$ and X^0 accessible: $\tilde{t} \to t + X^0$ with on- / off-shell t and W or loop-suppressed decay with charm
  - If $X^\pm$ in reach: $\tilde{t} \to b + X^\pm \to W + X^0$ with on- / off-shell W

→ To cover all interesting ground need searches for **light & heavy** stops

→ Compressed off-shell scenarios require large amounts of data: Not an early search (but competitive 8 TeV results)



Stop 1-lepton Search

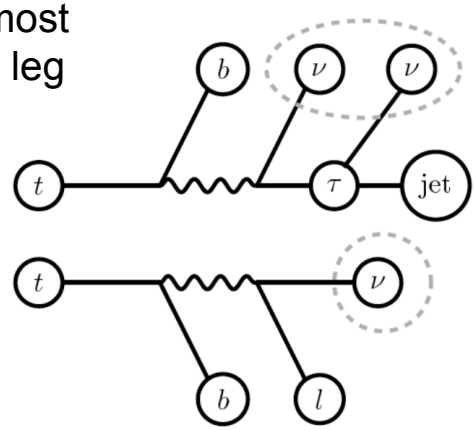


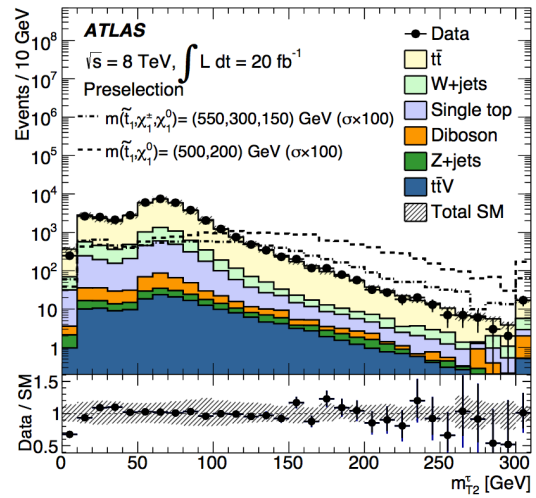
- Latest 13 TeV search considers heavy stop production with stop → top neutralino and stop → b + chargino decays
- In addition dedicated signal regions for dark matter production via spin-0 mediator
- Signature: **1-lepton + (b-)jets + $E_{T,miss}$**

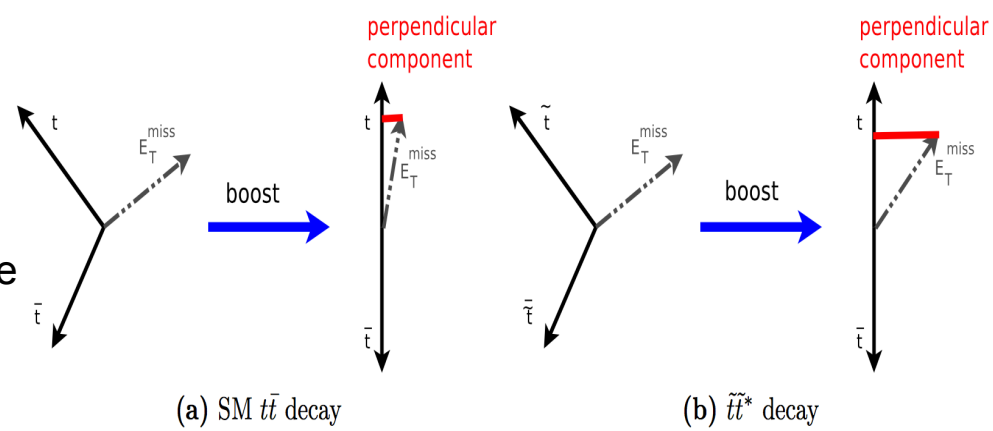
→ First serious direct stop production search with ATLAS @ 13 TeV

Stop 1-lepton: Discriminating Variables

- Standard variables to discriminate against multi-jets (misid. & non-prompt leptons), W+jets & semi-lepton tT: $\mathbf{E_{T,miss}}$, $\mathbf{m_T}$, $\mathbf{\Delta\phi\ (jet_{1,2}, E_{T,miss})}$
- $\mathbf{H_{T,miss}}$ **significance:** Effective against multi-jets
- $\mathbf{m^X_{top}}$**:** Invariant mass of the 3 jets most compatible with hadronic top decay leg
- **Asymmetric** $\mathbf{am_{T2}}$ **and** $\mathbf{m^\tau_{T2}}$**:** Generalization of the transverse mass applied to signatures where two particles are not directly detected: $\mathbf{am_{T2}}$ (dileptonic tT & one lepton not reconstructed), $\mathbf{m^\tau_{T2}}$ (dileptonic tT with hadronic tau).
- **Topness**: χ^2 minimization quantifying the compatibility with a dileptonic tT event where one lepton is not reconstructed.
- $\mathbf{E^{\perp}_{T,miss}}$: In semi-leptonic top decays $E_{T,miss}$ component perpendicular to the top decay leg larger in SUSY events due to $E_{T,miss}$ from LSP.

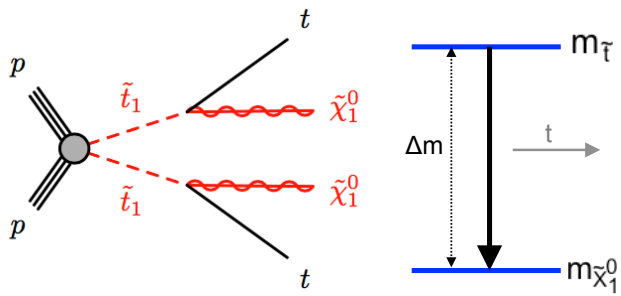






Stop 1-lepton: Signal Regions

- Targets stop → top + LSP



- **SR1**: low mass splitting Δm where all decay products are resolved

  → a 2.3σ excess was observed in this region in the 3.2fb^{-1} @ 13TeV analysis.

- **tN_high**: large mass splitting Δm with very boosted top quarks where decay products are very close by and can be reconstructed in a single jet

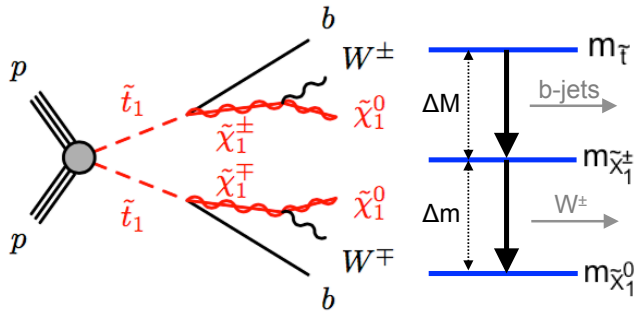
Variable	SR1	tN_high
Number of (jets, b-tags)	($\geq 4, \geq 1$)	($\geq 4, \geq 1$)
Jet $p_T >$ [GeV]	(80 50 40 40)	(120 80 50 25)
E_T^{miss} [GeV]	> 260	> 450
$E_{T,\perp}^{miss}$ [GeV]	–	> 180
$H_{T,sig}^{miss}$	> 14	> 22
m_T [GeV]	> 170	> 210
am_{T2} [GeV]	> 175	> 175
topness	> 6.5	–
m_{top}^{χ} [GeV]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

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

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

Stop 1-lepton: Signal Regions

- Targets stop → b + chargino



- **bC2x_diag** & **bC2x_med**: Covering models with $m_{\chi}^{\pm} = 2*m_{\chi}^{0}$ with small and large mass splittings

- **bCbv**: Designed for models where ΔM is small (10 GeV) & Δm is large
  - Soft b-jets cannot be reconstructed → b-veto to suppress tT
  - W very boosted → W-mass cut on large-R jet mass

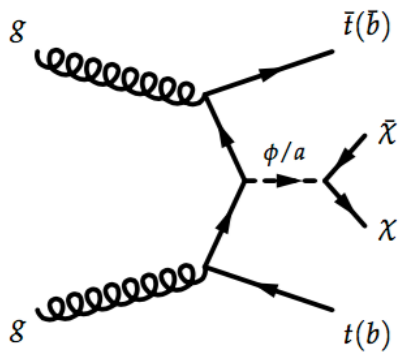
Variable	SR1	tN_high
Number of (jets, b-tags)	($\geq 4, \geq 1$)	($\geq 4, \geq 1$)
Jet $p_T >$ [GeV]	(80 50 40 40)	(120 80 50 25)
E_T^{miss} [GeV]	> 260	> 450
$E_{T,\perp}^{miss}$ [GeV]	–	> 180
$H_{T,sig}^{miss}$	> 14	> 22
m_T [GeV]	> 170	> 210
am_{T2} [GeV]	> 175	> 175
topness	> 6.5	–
m_{top}^{χ} [GeV]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

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

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

Stop 1-lepton: Signal Regions

- Targets dark matter production



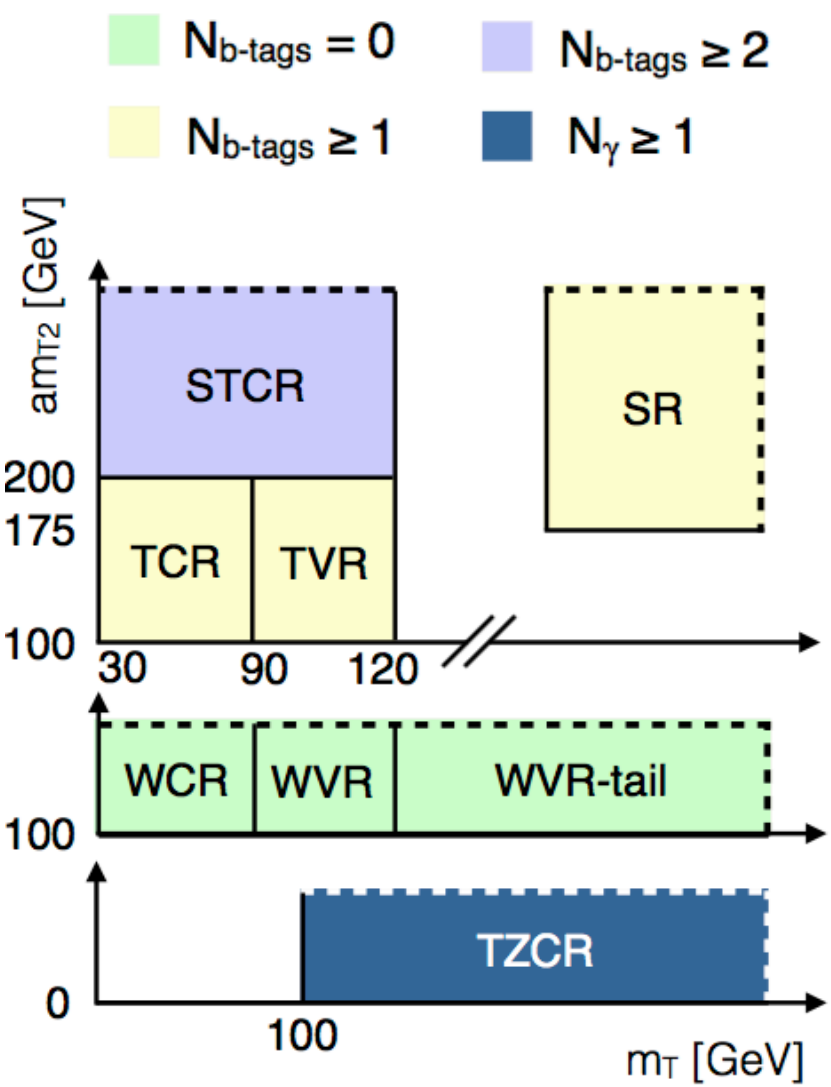
- **DM_low & DM_high**: Designed to be sensitive to low-mass and high-mass dark matter production in associated with top quarks

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

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

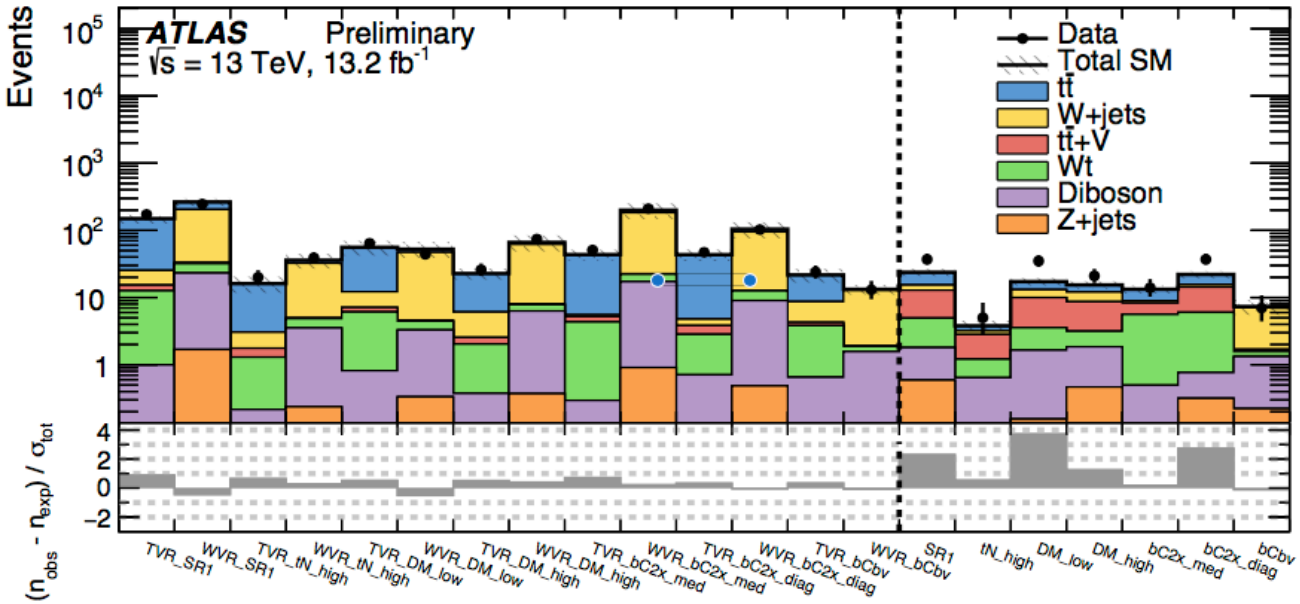
Variable	DM_low	DM_high
Number of (jets, b-tags)	($\geq 4, \geq 1$)	($\geq 4, \geq 1$)
Jet $p_T >$ [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,sig}^{miss}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{miss}, \text{jet}_i))(i \in \{1-4\})$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

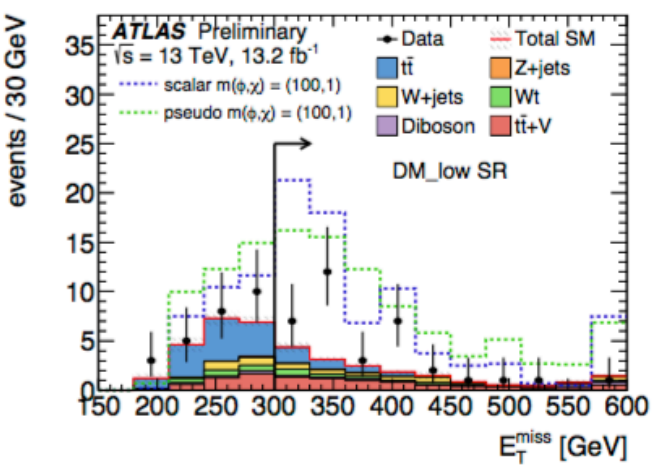
Stop 1-lepton: Background Estimation

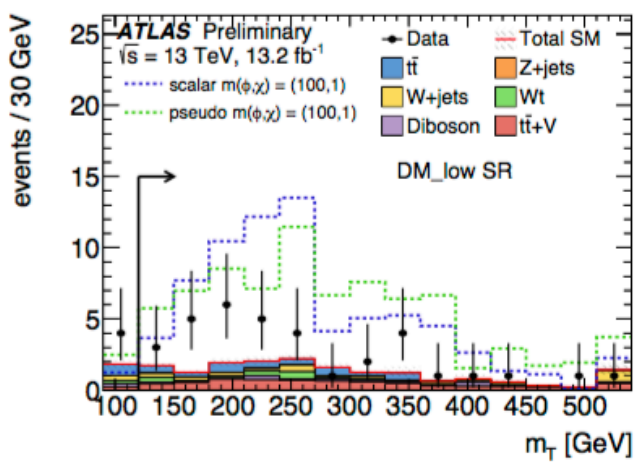


- Dominant backgrounds isolated in dedicated control regions
  - **W+jets / tT → WCR/TCR**:
    - Standard approach of b-veto / 1 b-jet control regions with associated validation regions
    - Purity 75% / 50-90%
  - **Single-top Wt → STCR**:
    - 2 b-jets requirement (additional b from intial state), high am_{T2} since mass from Wb system higher than from top-quark
    - Purity ~ 40-50%
  - **tt+Z(→ vv) → TZCR**:
    - Irreducible background, estimation based on tt+γ events with γ to $E_{T,miss}$ (approximation valid at large boson p_T)
    - Purity ~ 90%

Stop 1-lepton: Validation & Results

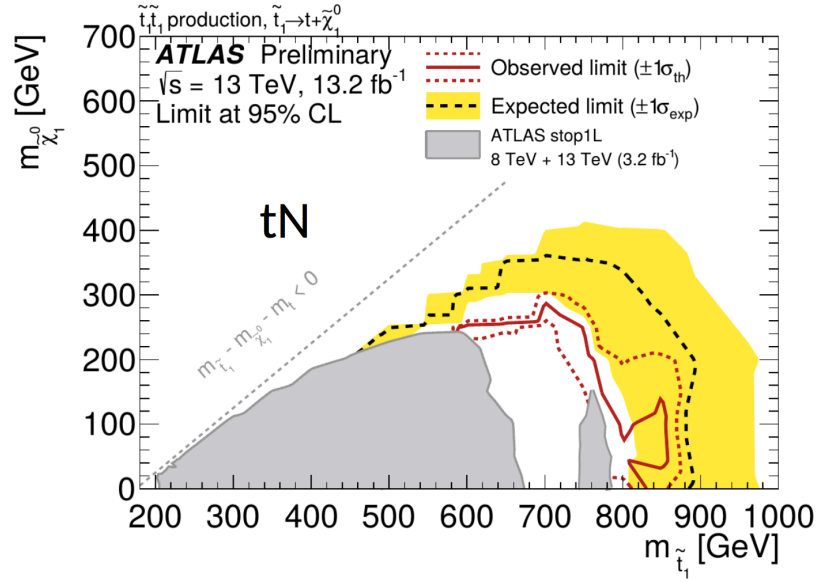


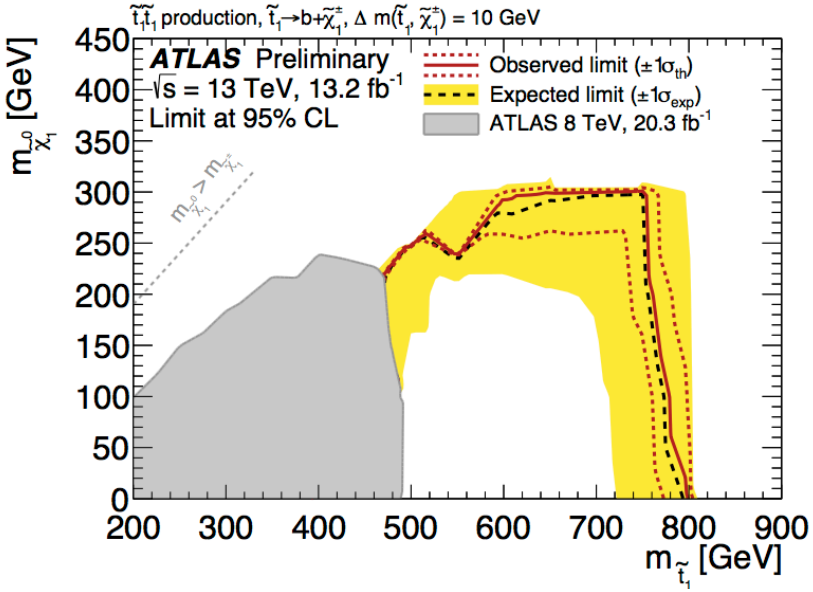


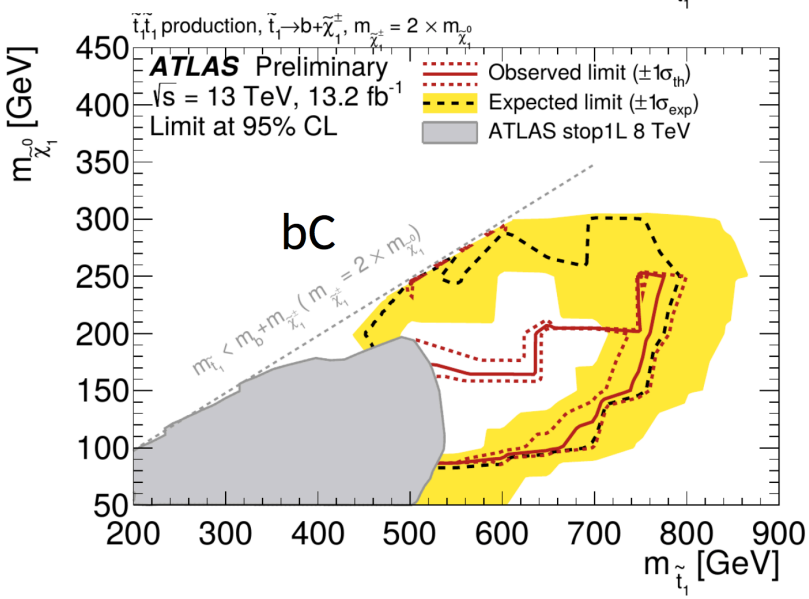


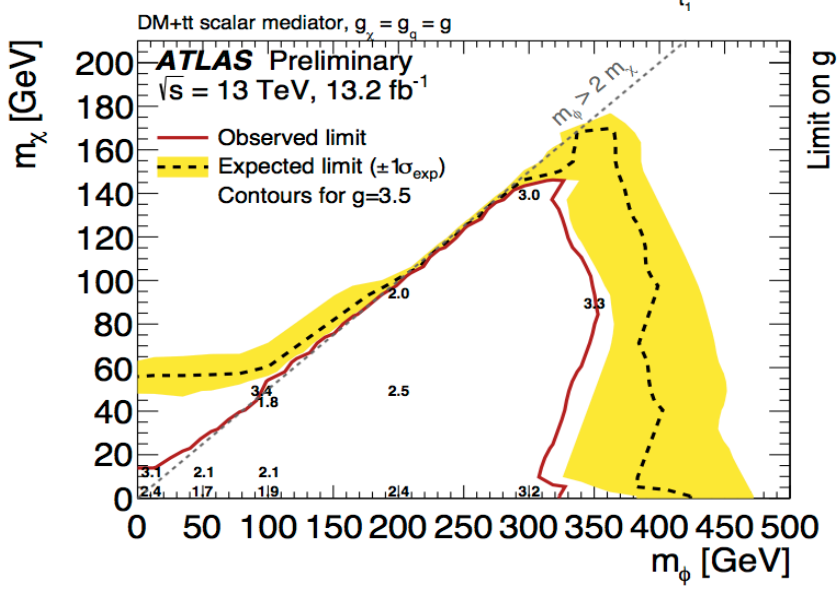
- Excellent agreement in all validation regions
- Deviations of 3.3/2.6/2.2 σ observed in SRs DM_low, bC2x_diag, SR1 → signal regions are correlated
- Small excess of 2.3 from 3.2@13TeV results persists

Stop 1-lepton: Interpretations

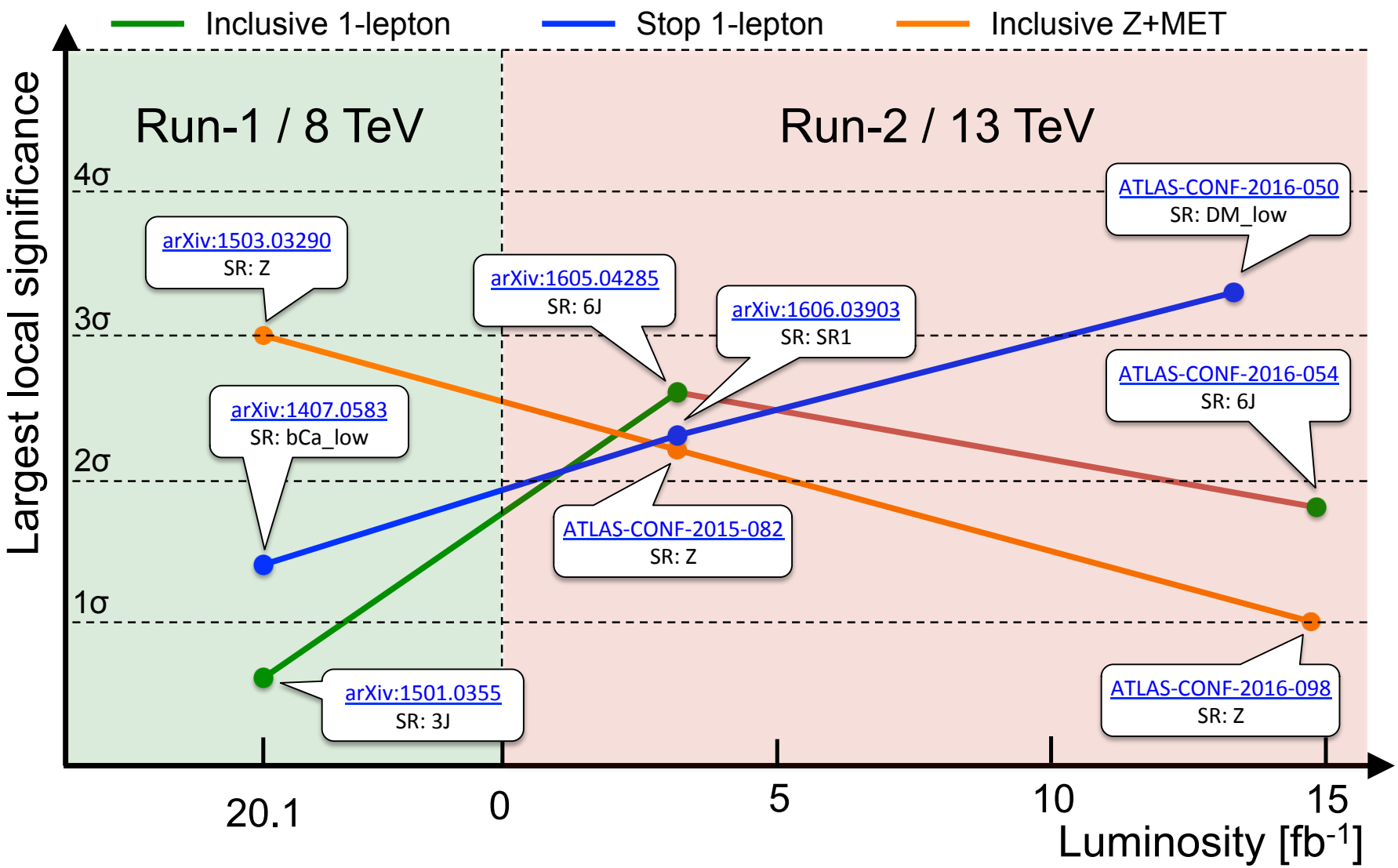






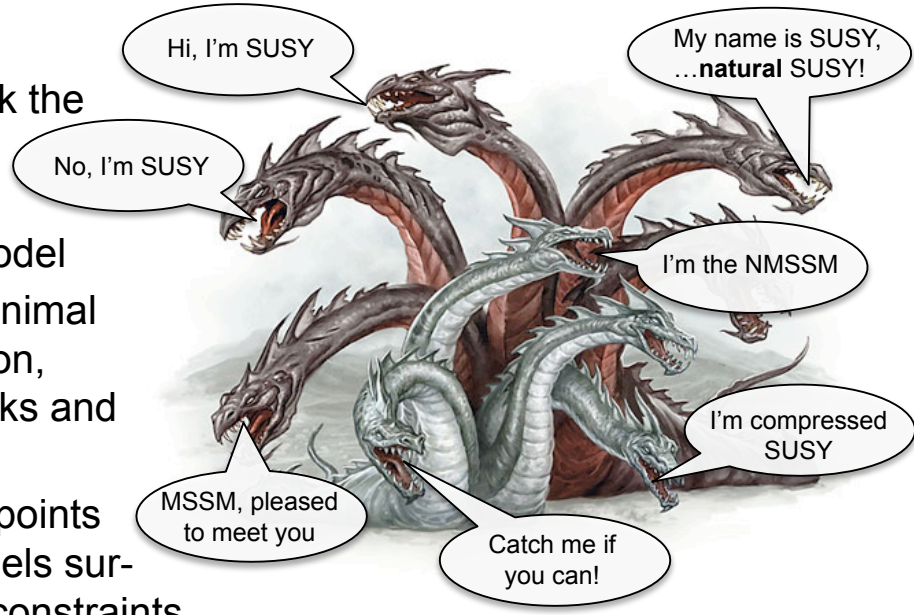


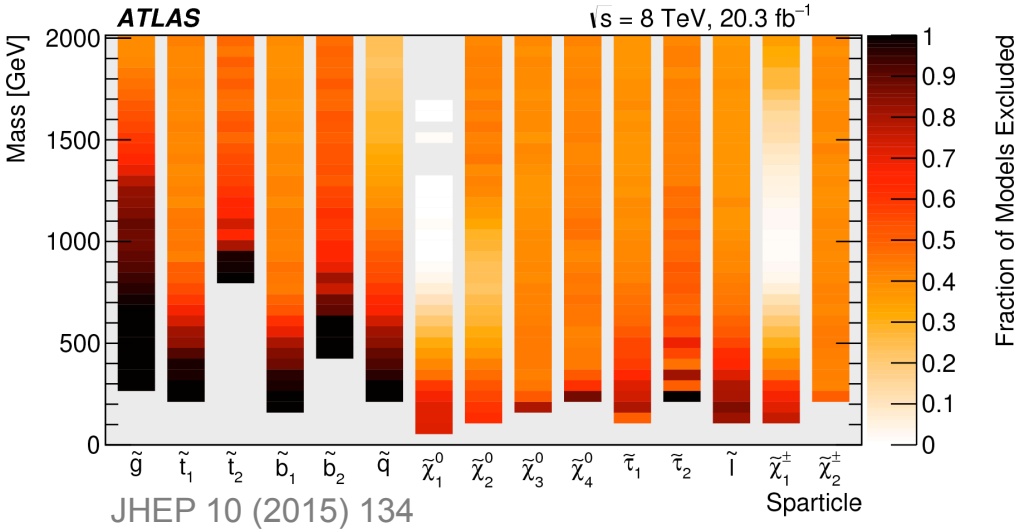
To summarize…



Can we ever kill SUSY?

- SUSY is a **many headed monster**!
- Our currently best attempt to broadly attack the monster are **pMSSM scans**:
  - Reinterpretation of many ATLAS SUSY searches in a 19 parameter pMSSM model
  - Assumptions: R-parity conservation, minimal flavor violation, no additional CP violation, degeneracy of 1st /2nd generation squarks and sleptons
  - For Run-1 result: 500 millions pMSSM points randomly sampled, with ~ 300 000 models surviving theory & non-LHC experimental constraints





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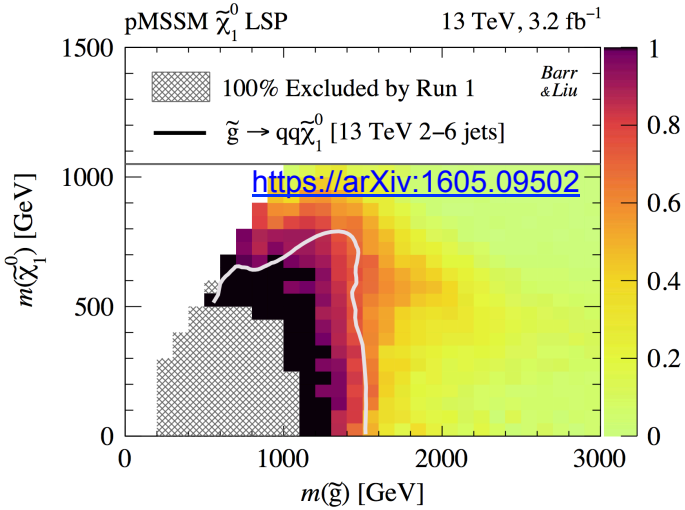
First results on 13 TeV scan: Barr & Liu



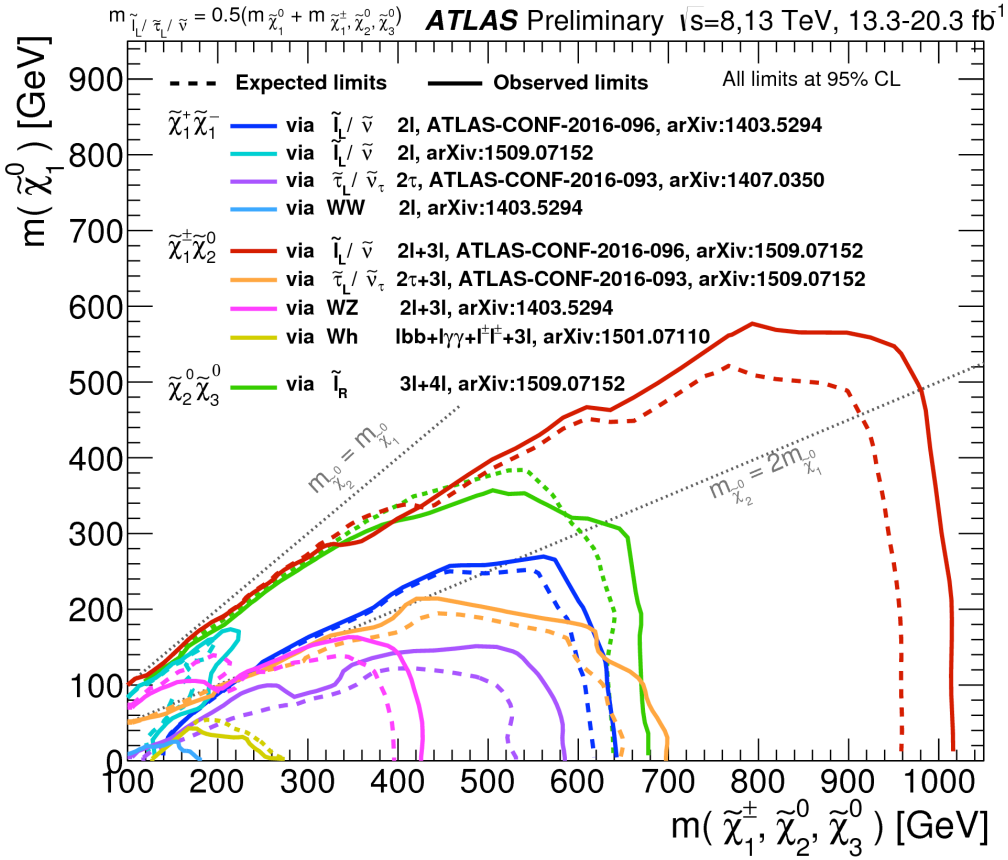
Electro-weak Production

- Electro-weak SUSY searches:
  - The future !
  - Out last chance (?)

- Suppressed production cross-sections for electroweak SUSY particles at hadron colliders thus small signal acceptance

→ Mass limits significantly weaker than in strong production searches

→ Light SUSY still possible ?



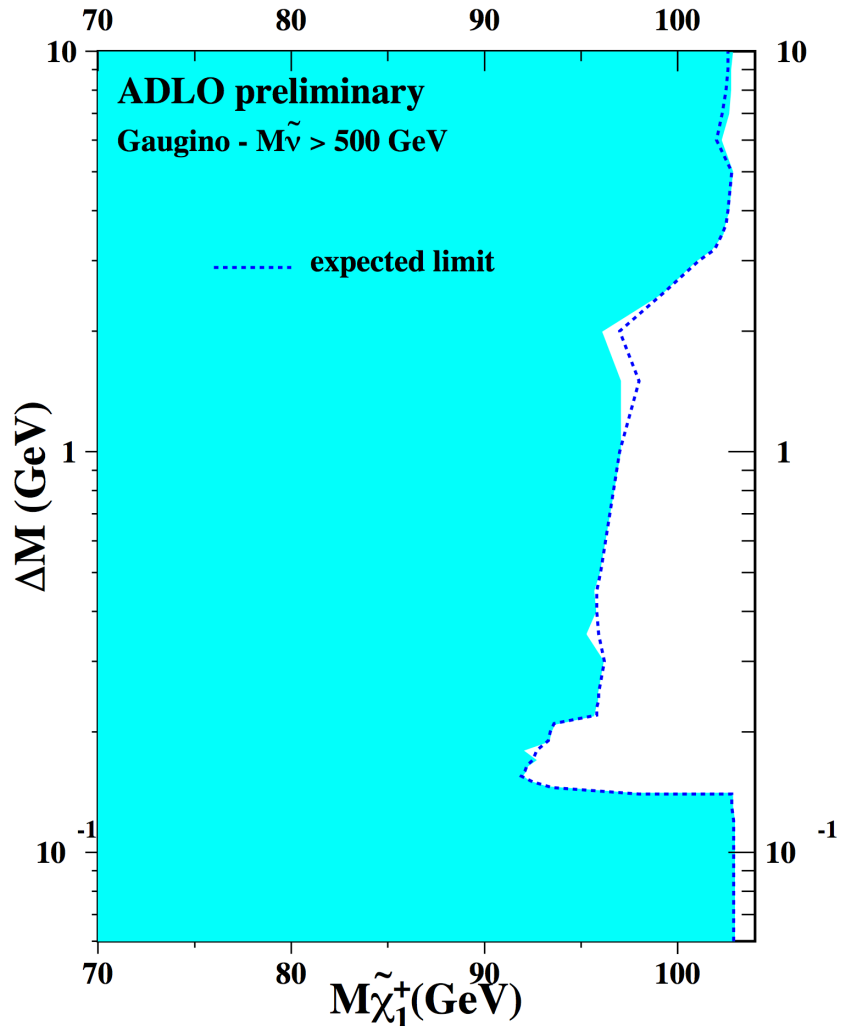
EW direct	$\tilde{l}_{L,R}\tilde{l}_{L,R}, \tilde{l}\to l\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{l}$	90-335 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{l}\nu(l\tilde{\nu})$	2 e,μ	0	Yes	13.3	$\tilde{\chi}_1^\pm$	640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{l},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	$\tilde{\chi}_1^\pm$	580 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2016-093
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{l}_L\nu\tilde{l}_L l(\tilde{\nu}\nu), l\tilde{\nu}\tilde{l}_L l(\tilde{\nu}\nu)$	3 e,μ	0	Yes	13.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	1.0 TeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{l},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	425 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{l}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{l}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{l}_R l$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	635 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{l},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$	115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$	590 GeV	$c\tau$<1 mm	1507.05493

LEP limit still unbeaten!

- Natural SUSY seems **in trouble**:
  - Strong bounds from the LHC on gluinos (~ 2 TeV) and stop (~ 800 GeV)
- No further significant jump in center of mass energy foreseen in a long time thus little prospect of significantly enhanced limits
- Reminder: Higgsino mass parameter μ enters **at tree level** into the Higgs mass matrix!

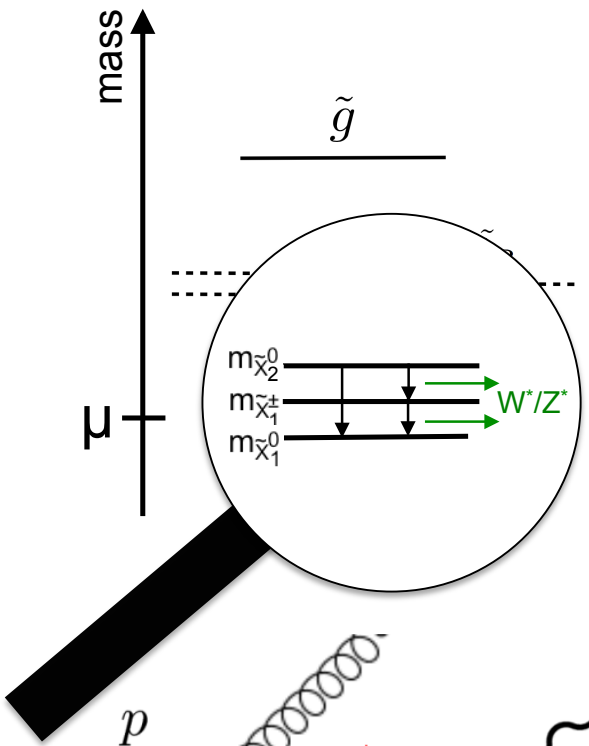
→ Searches for **Higgsinos** at the LHC may be our last experimental window to natural Supersymmetry!

→ LEP limits @ m_χ > 92 GeV are currently still our strongest bounds!

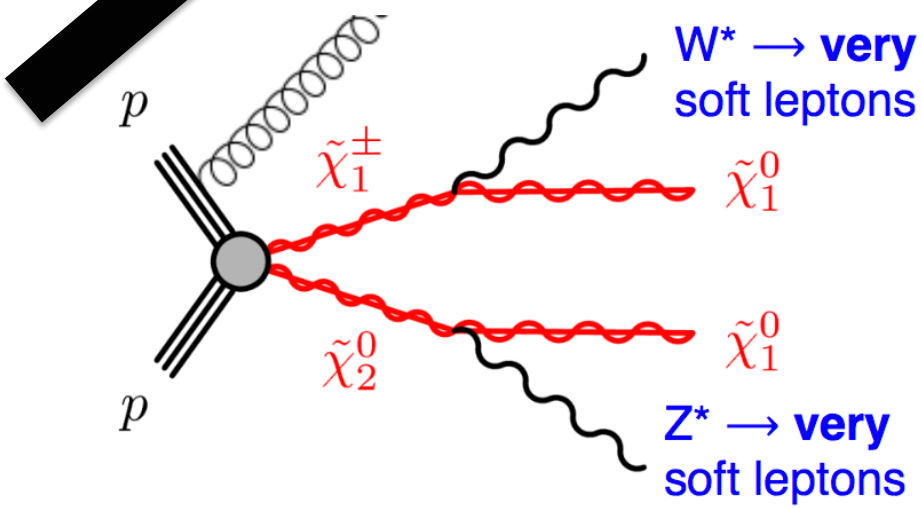


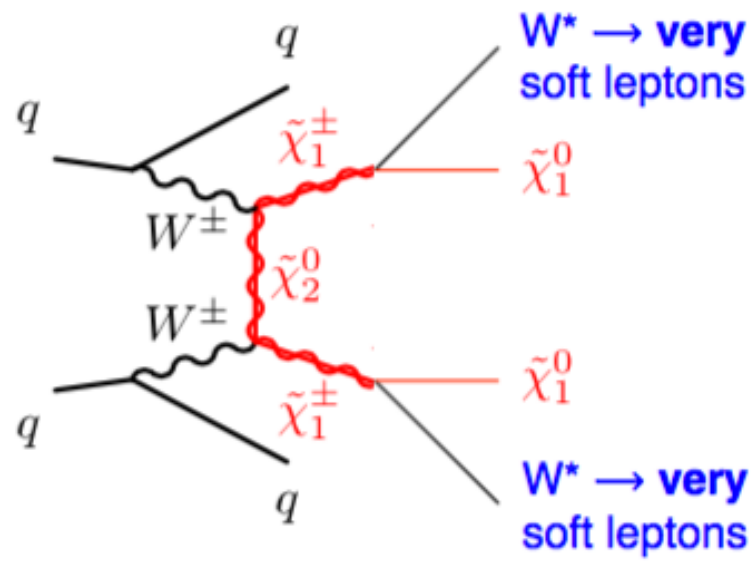
LEP SUSY Working Group:
http://lepsusy.web.cern.ch/lepsusy/Welcome.html

Search Strategies



- Final state:
  - Multiple **very soft leptons** from virtual W/Z decays → Very difficult to distinguish from SM
- Need experimental handles:
  - Initial or final state radiation (jet, photon)
  - VBF

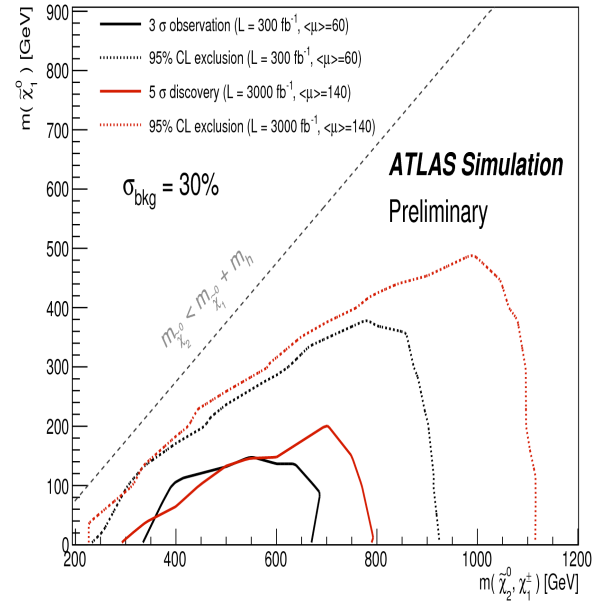




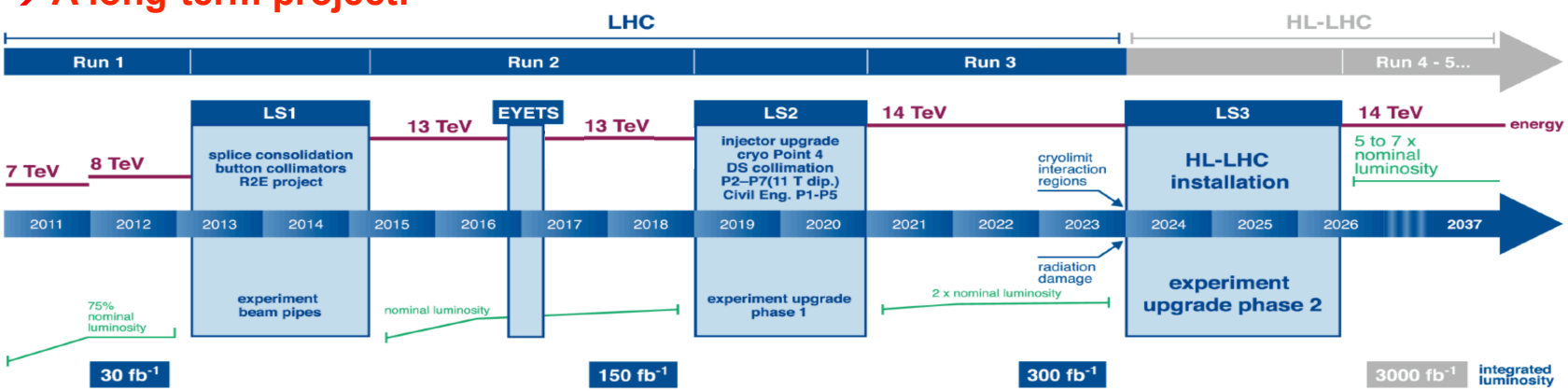
Experimental Challenges

- What do we need for this:
  - **Lots of data:** Strong physics case for Run-3 / HL-LHC
  - **Excellent detector performance:** Ultra low-p_T lepton reconstruction to maximize acceptance
  - **Advanced analysis techniques** (e.g. machine learning techniques) to get the maximum out of the data
  - **Low trigger thresholds** vs. high-luminosity high pile-up environment
    - Multi-object triggers with topological requirements (L1Topo)
    - Reconstruction of charged tracks and their vertex associations in e.g. $E_{T,miss}$ triggers (FTK and phase1/2 trigger upgrades)

ATL-PHYS-PUB-2015-032



→ **A long-term project!**



Conclusions

- Vast search program at the LHC in order to make a conclusive statement about the existence of weak-scale SUSY

- Strong effort concentrating around natural SUSY to find traces of:
  - Gluinos
  - 3rd generation squarks
  - Higgsinos

- Despite several mild deviations from the SM no convincing signs of SUSY yet at 13 TeV

- However, searches for gluinos and 3rd generation squarks remain interesting!

- Eventually only a long term Higgsino search program may be able to answer the question:

Do we live in fine-tuned or a natural supersymmetric universe?