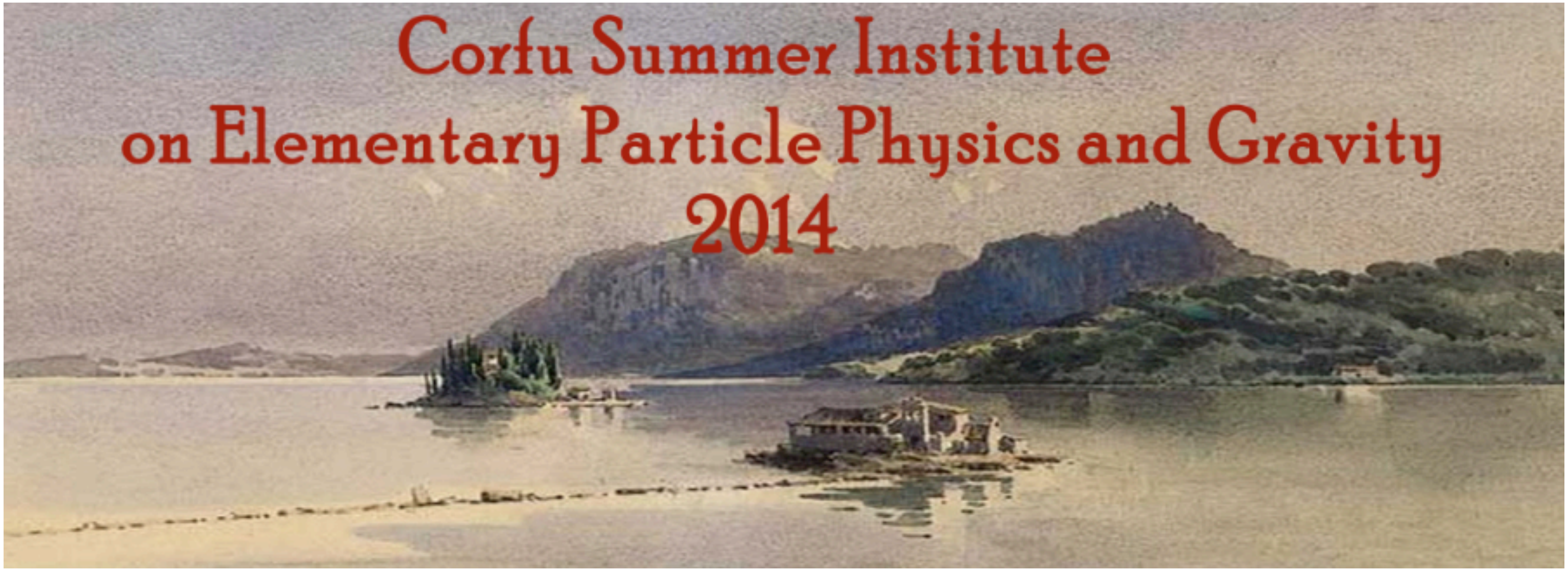
BSM searches in ATLAS



Summer School and Workshop on the Standard Model and Beyond

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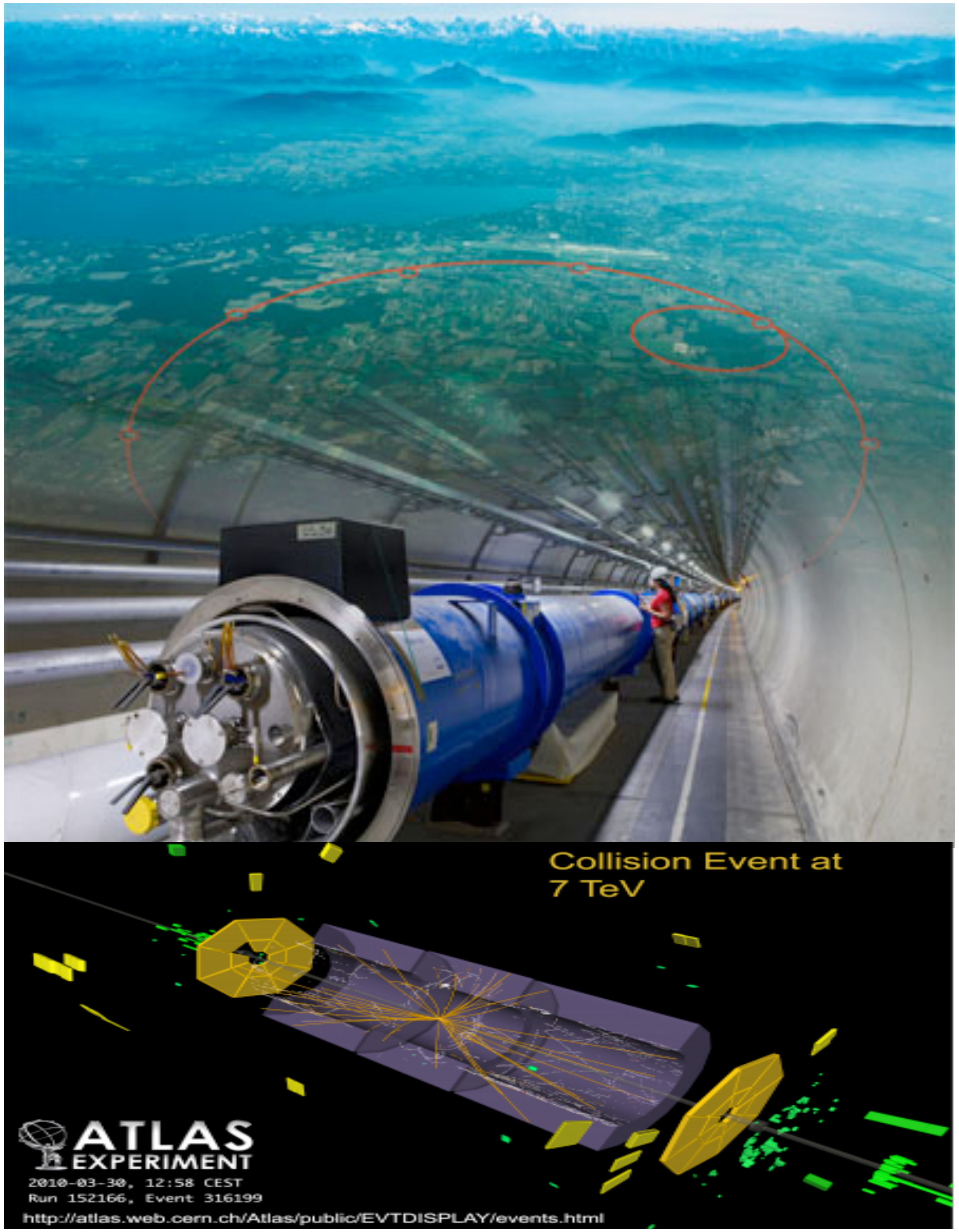
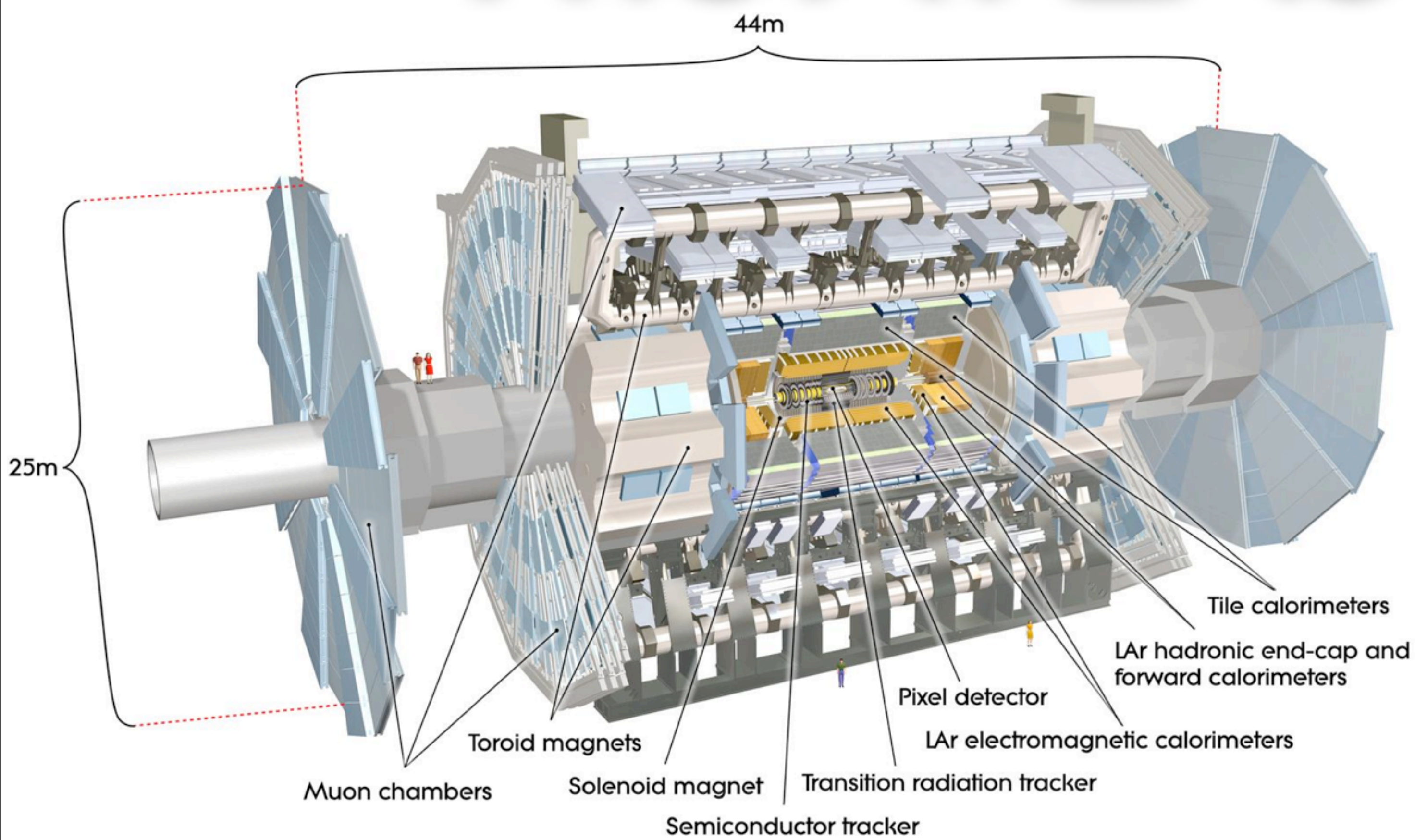
ATLAS EXPERIMENT
http://atlas.ch

Introduction



- Standard Model has survived decades of experimental tests
- But there must be something more
- The LHC offers the opportunity to search for physics beyond the Standard Model (BSM) by opening a new energy frontier
- ATLAS is a general purpose experiment designed to carry out these searches

The ATLAS detector



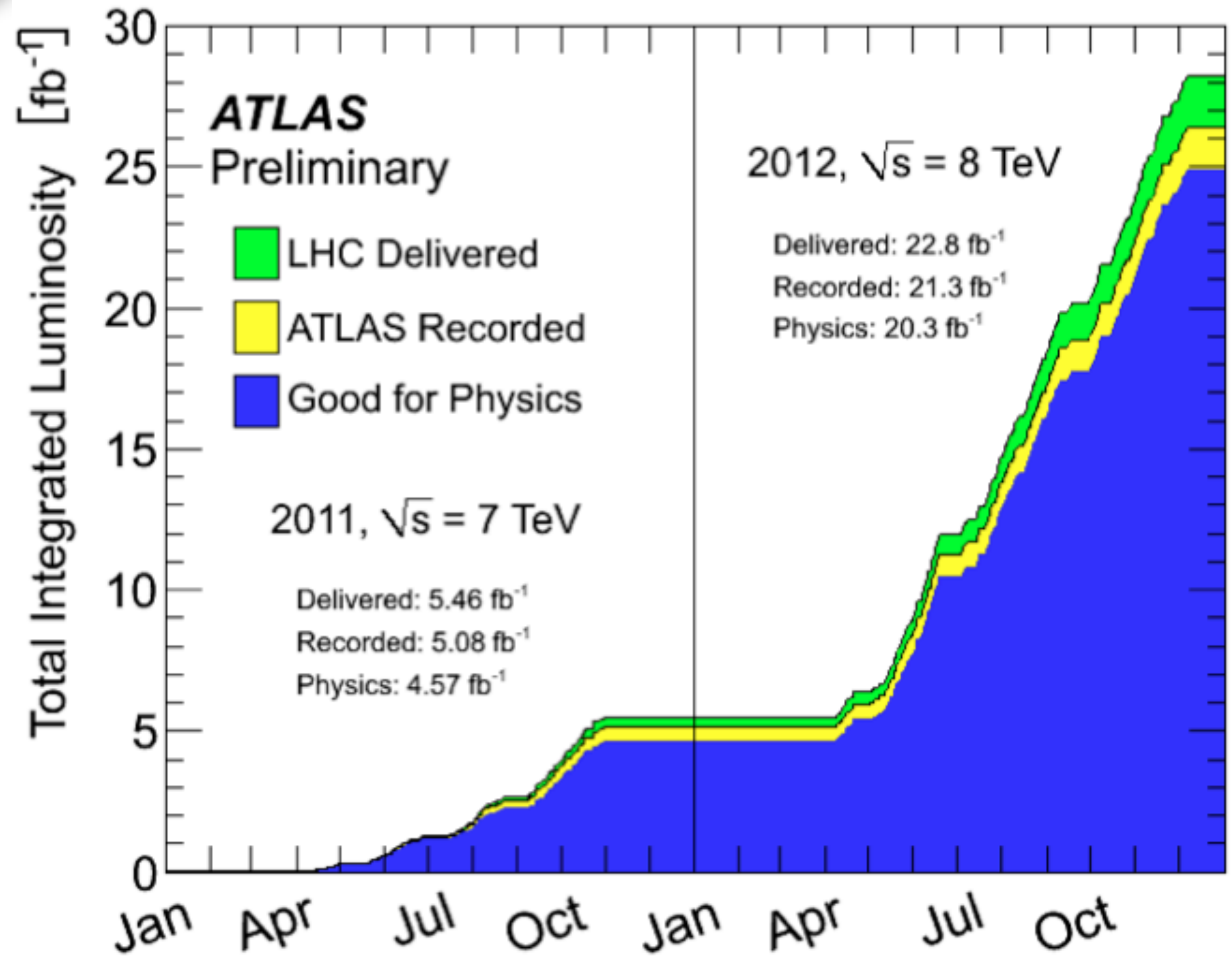
- Inner Detector (ID) tracking: semiconductors (pixel and SCT) and transition radiation tracker (TRT)
- Sampling-based calorimetry: lead+liquid argon for EM energy (ECAL), steel+scintillator for Hadronic energy (HCAL), copper/tungsten+liquid argon in the forward calorimeter (FCAL)
- 2 T magnetic field by a solenoid just enclosing the ID
- One barrel and 2 end-cap 4 T toroids in the air-core muon spectrometer provide fields to bend muon tracks in η

PERFORMANCE (E, p_T in GeV)

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	±2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	±3.2	±2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	±3.2	±3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	±2.7	±2.4

Data-taking conditions

- ATLAS results shown in this talk based on 7+8 TeV collisions recorded in 2011-2012
- collisions at $\sqrt{s}$ = 8 TeV
  - ~20 interactions per crossing
  - 20.3 fb^{-1} collected good for physics
- collisions at $\sqrt{s}$ = 7 TeV
  - ~9 interactions per crossing
  - 4.6 fb^{-1} collected good for physics



Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.

ATLAS performance close to or exceeding design specs in all compartments

Search for new physics

- **Strategy:**
  - Define selection based on signal signatures and background (bkg) kinematics
  - Compare data to Standard Model bkg (Monte Carlo (MC) + data driven) and MC signal predictions → data consistent with bkg+signal would be evidence for new physics
- **No evidence for new physics:**
  - Limits typically set on cross-section x branching fraction (σ x BR)
  - Comparisons provided for specific models, but usually possible for reader to constrain additional models
- **In this talk results are presented of some specific BSM searches**
  - focus on the most recent results
  - personal choice among tens of results carried out in the ATLAS Exotics and SUSY groups

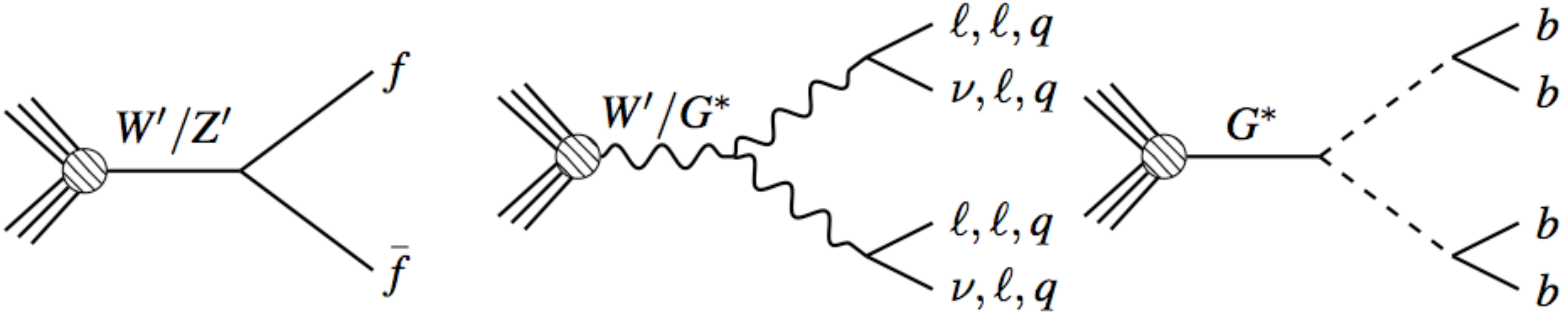
Complete list of results is summarized at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

EXOTICS searches

BSM heavy bosons

New strong dynamics and Extra Dimensions

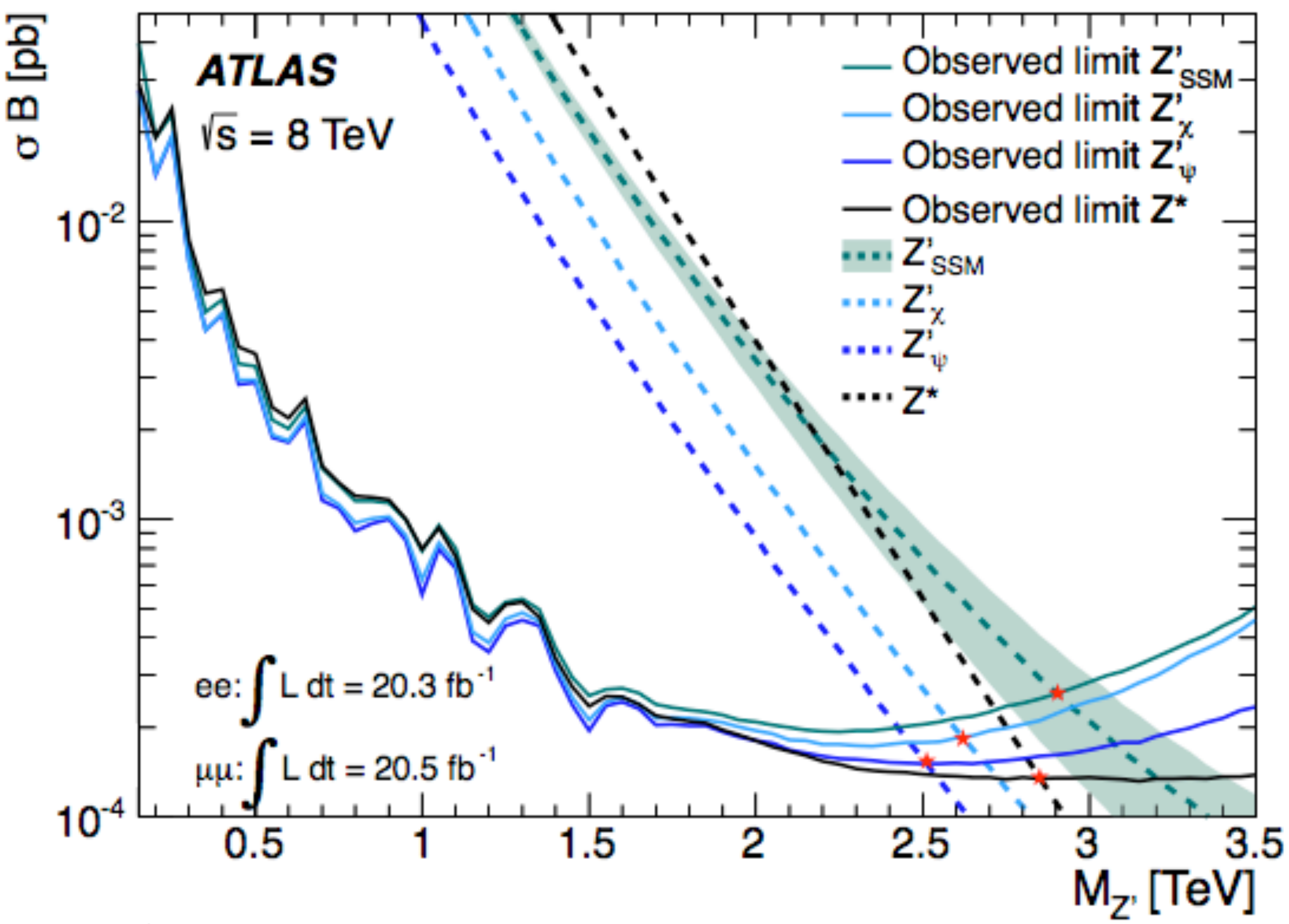
- Alternative to super-symmetric explanations of electroweak symmetry breaking
- Often accompanied by heavy new states with integer spin
  - Left-right symmetric and Extended gauge models with spin-1 states
  - Randall-Sundrum models with heavy spin-2 states
- Experimental strategy:
  - Signature-based searches benchmarked with reference models
  - Increasing emphasis on limiting model dependence



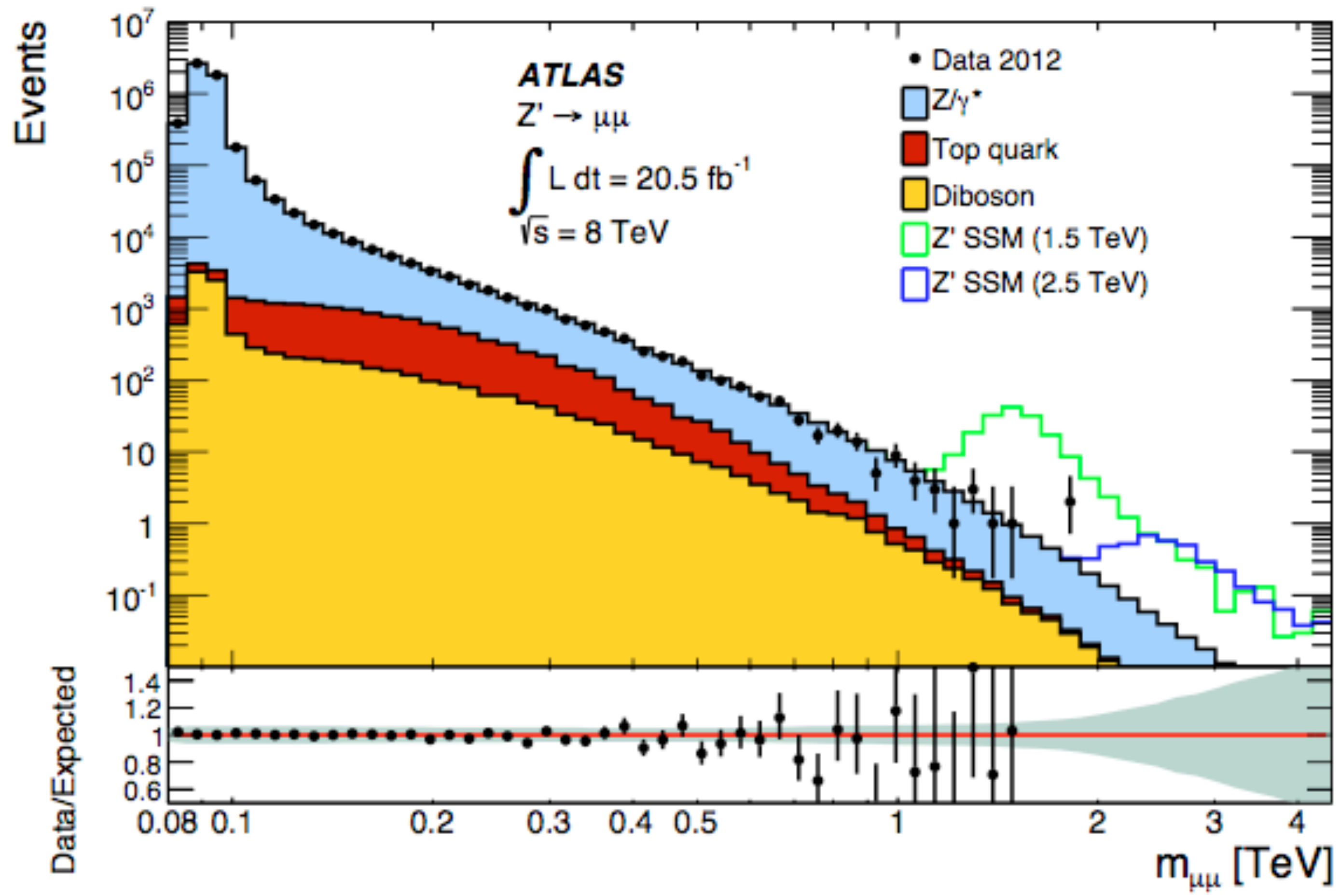
Search for high-mass dilepton resonances (8 TeV, 20.3 fb^{-1})

arXiv: 1405.4123 accepted by Phys. Rev. D

- l^+l^- shape analysis, also sensitive at low masses
  - Pairs of isolated muons or electrons are selected
  - Dominant background is $Z/\gamma^* \rightarrow ll$
  - Data-driven estimation of di-jet and W+jet backgrounds
- No excess observed
- New Interpretations for limit setting
  - SSM, E6, Z^*, Technicolor
  - Minimal models with large couplings RS-Graviton
  - Quantum Black Holes



Observed upper limits on σ x BR limits at 95% CL for Z'_{SSM}, E6-motivated Z′ and Z^* bosons using the combined dilepton channel.

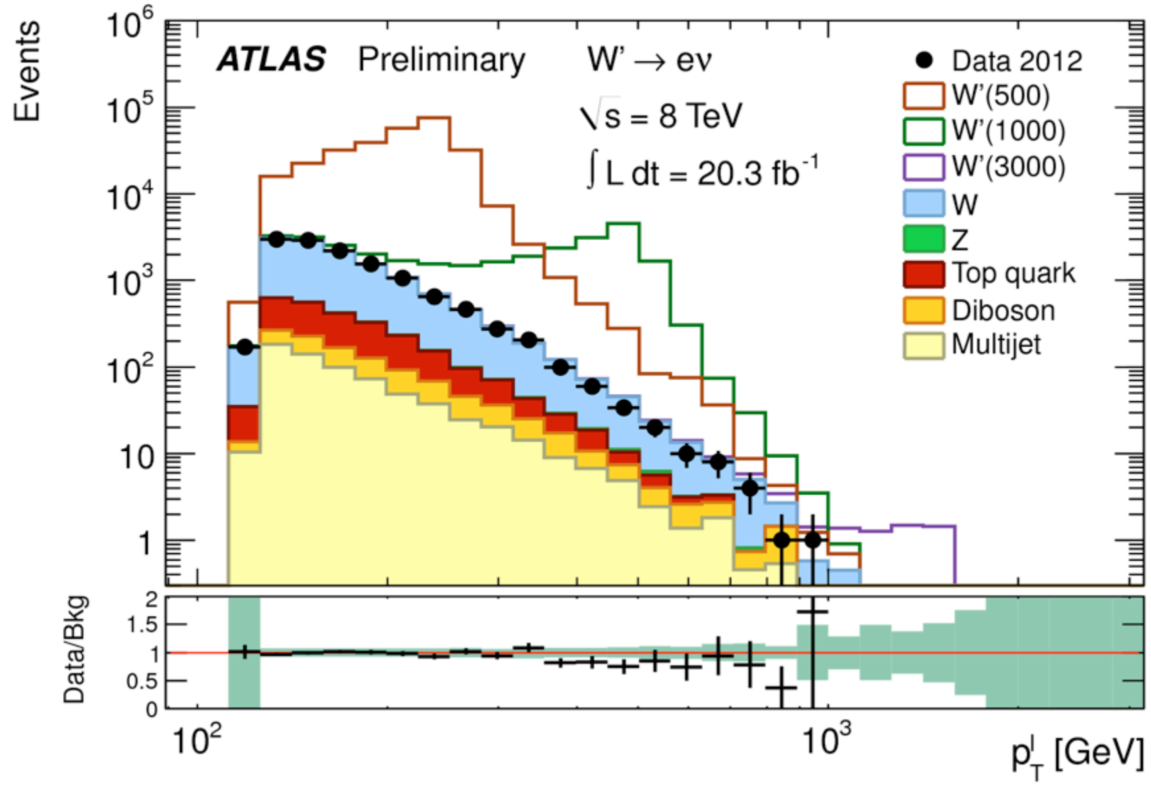


Dimuon invariant mass distribution with two selected Z'_{SSM} signals overlaid, compared to the expected backgrounds, and the ratio of data to background expectation.

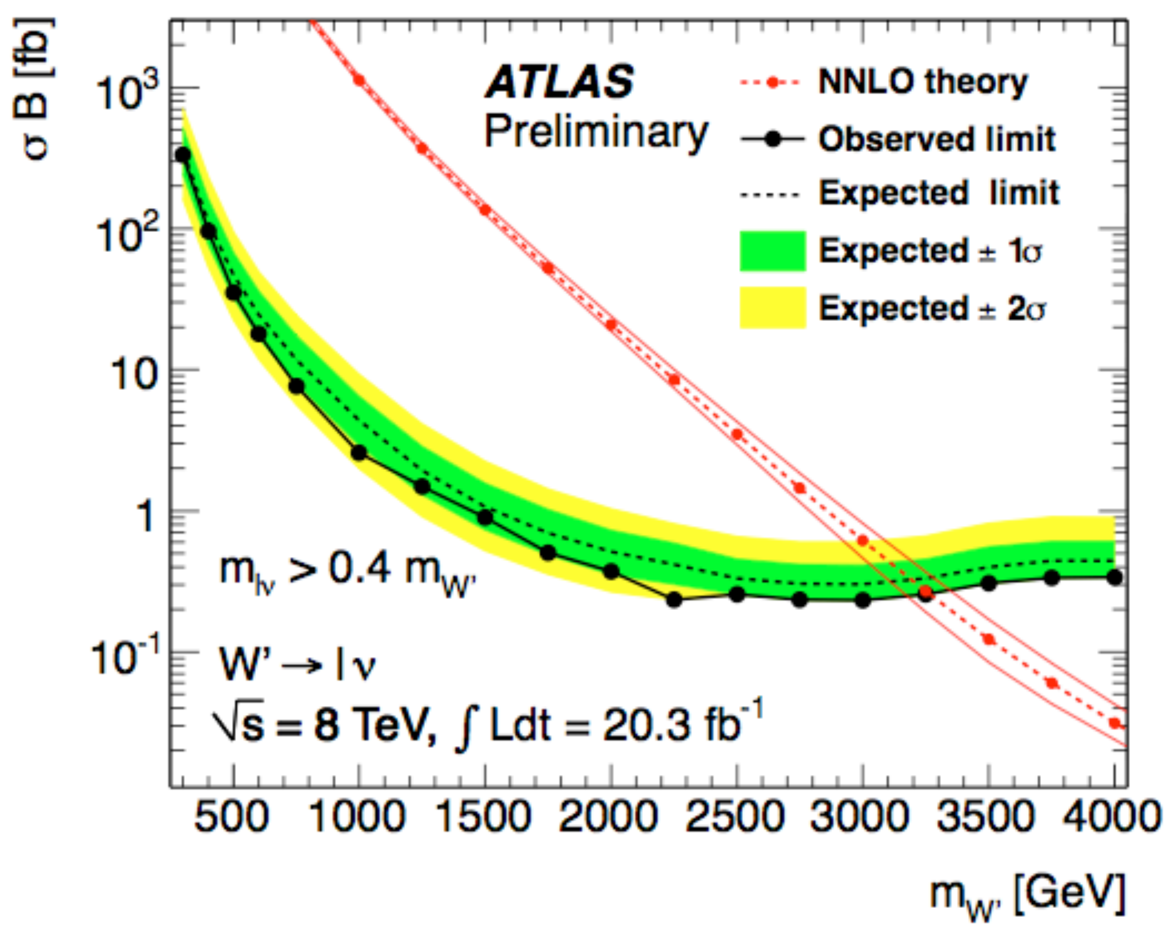
Lepton + E_T^{miss} high mass states (8 TeV, 20.3 fb^{-1})

arXiv: 1407.7494 accepted by JHEP

- Search for new high-mass states decaying to a lepton plus missing transverse energy
- Isolated electron or muon + E_T^{miss} are selected
- Main background: $W \rightarrow l\nu$
- Data-driven estimation of multijet background
- No excess observed, Bayesian tools to set limits
  - Models considered: SSM W' and W*



Spectra of lepton p_T for the electron channel after the event selection.



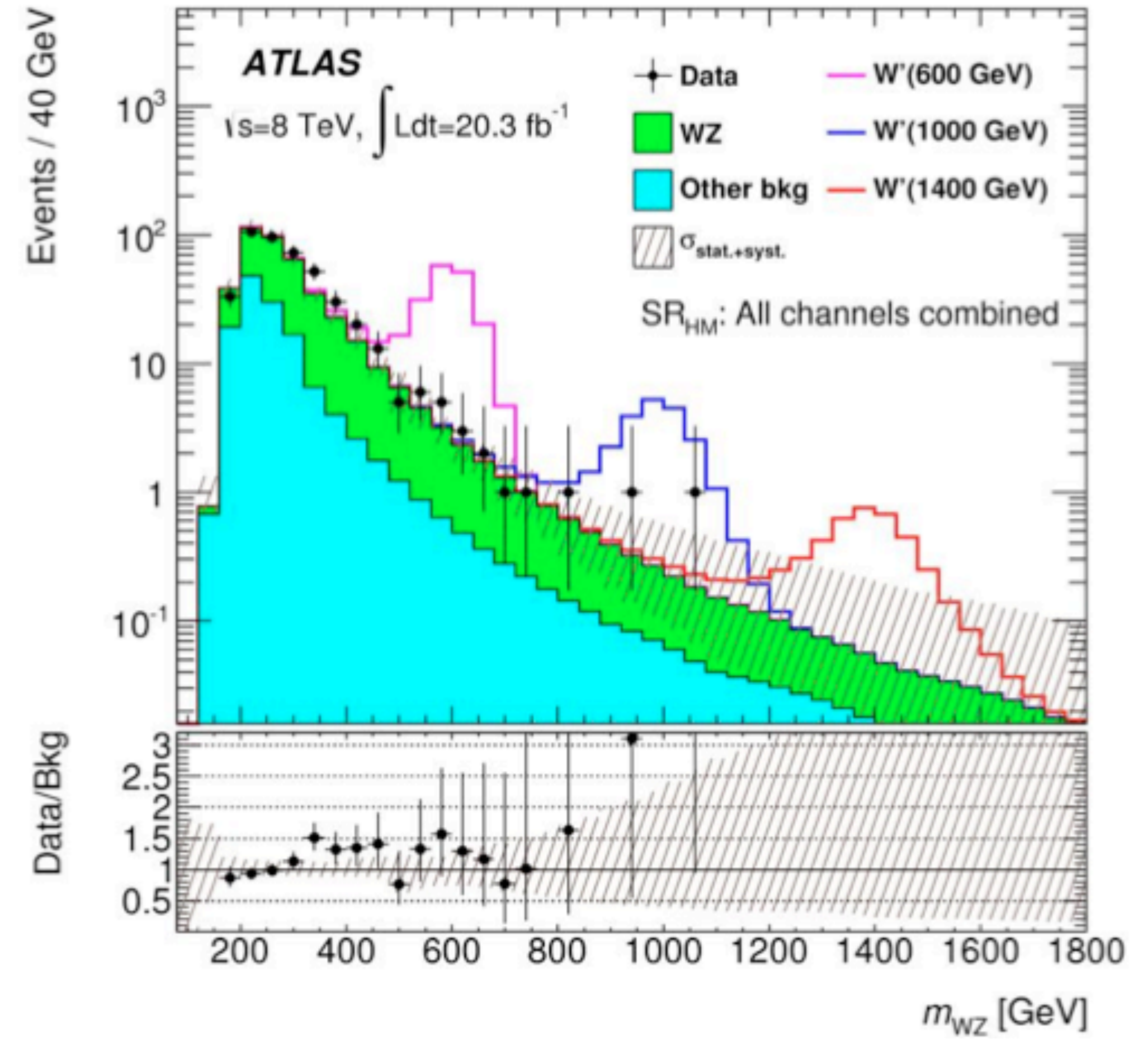
Observed and expected limits on σ x BR for W' in the combination of electron and muon channel assuming the same branching fraction for both channels.

	$m_{W'}$ [TeV]		m_{W^*} [TeV]	
decay	Exp.	Obs.	Exp.	Obs.
$e\nu$	3.15	3.15	3.04	3.04
$\mu\nu$	2.98	2.98	2.80	2.80
both	3.19	3.27	3.08	3.17

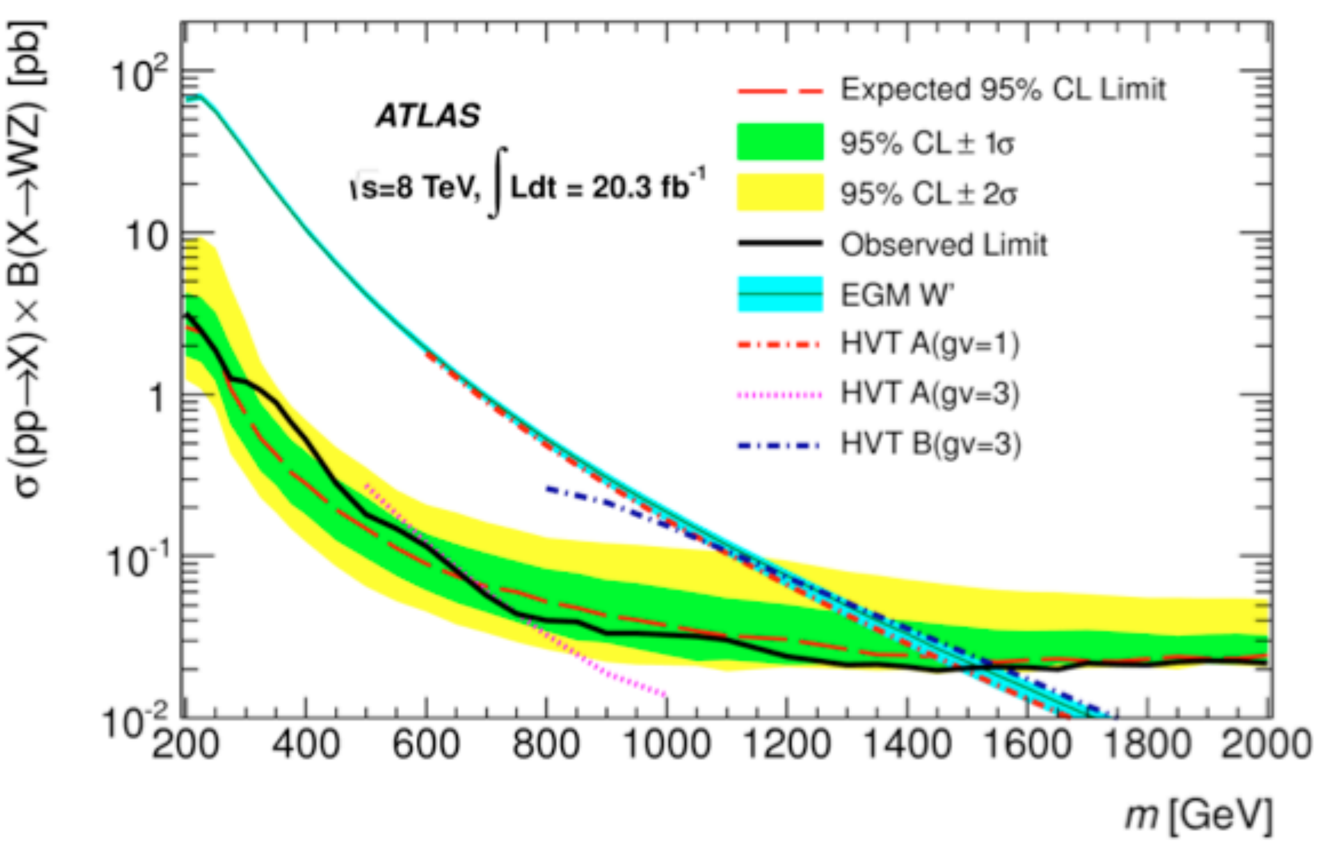
Observed and expected upper at 95% CL for W′ and W*.

WZ resonances (8 TeV, 20.3 fb^{-1})

- Extended Gauge Model W' arXiv: 1406.4456 accepted by Phys. Lett. B
  - same couplings as SM W
  - suppressed coupling to WZ by $(m_W/m_{W'})^2$
- Four decay channels are considered: eνee, μνee, eνμμ, μνμμ
- Exactly 3 charged leptons are selected
- 2 signal regions to improve sensitivity
  - Low mass ($m_{W'}$ < 250 GeV): $\Delta\varphi(l, E_T^{miss}) > 1.5$
  - High mass ($m_{W'}$ > 250 GeV): $\Delta\varphi(l, E_T^{miss}) < 1.5$
- 95% C.L. limits are set as no excess of events is observed (on W' and Heavy Vector Triples model)



Observed and predicted WZ invariant mass distribution for events in the high-mass signal region (SRHM).



The observed 95% CL upper limits on σ x BR as a function of the signal mass m, where X stands for the signal resonance.

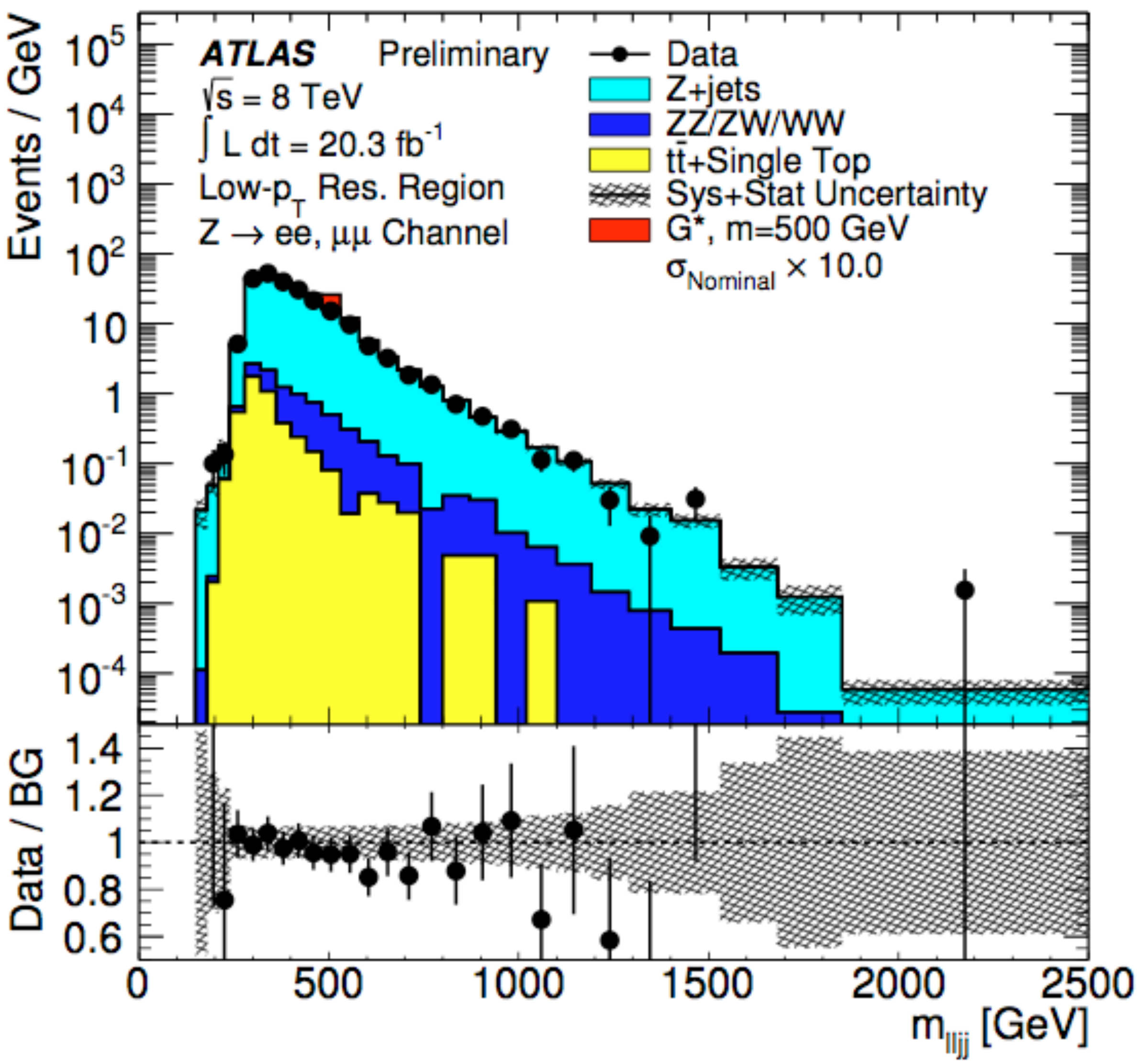
	Excluded EGM W' lower mass [TeV]				
	eνee	*μνee*	*eνμμ*	*μνμμ*	combined
Expected	1.21	1.16	1.17	1.16	1.49
Observed	1.20	1.19	1.06	1.17	1.52

Observed and expected upper at 95% CL for W′.

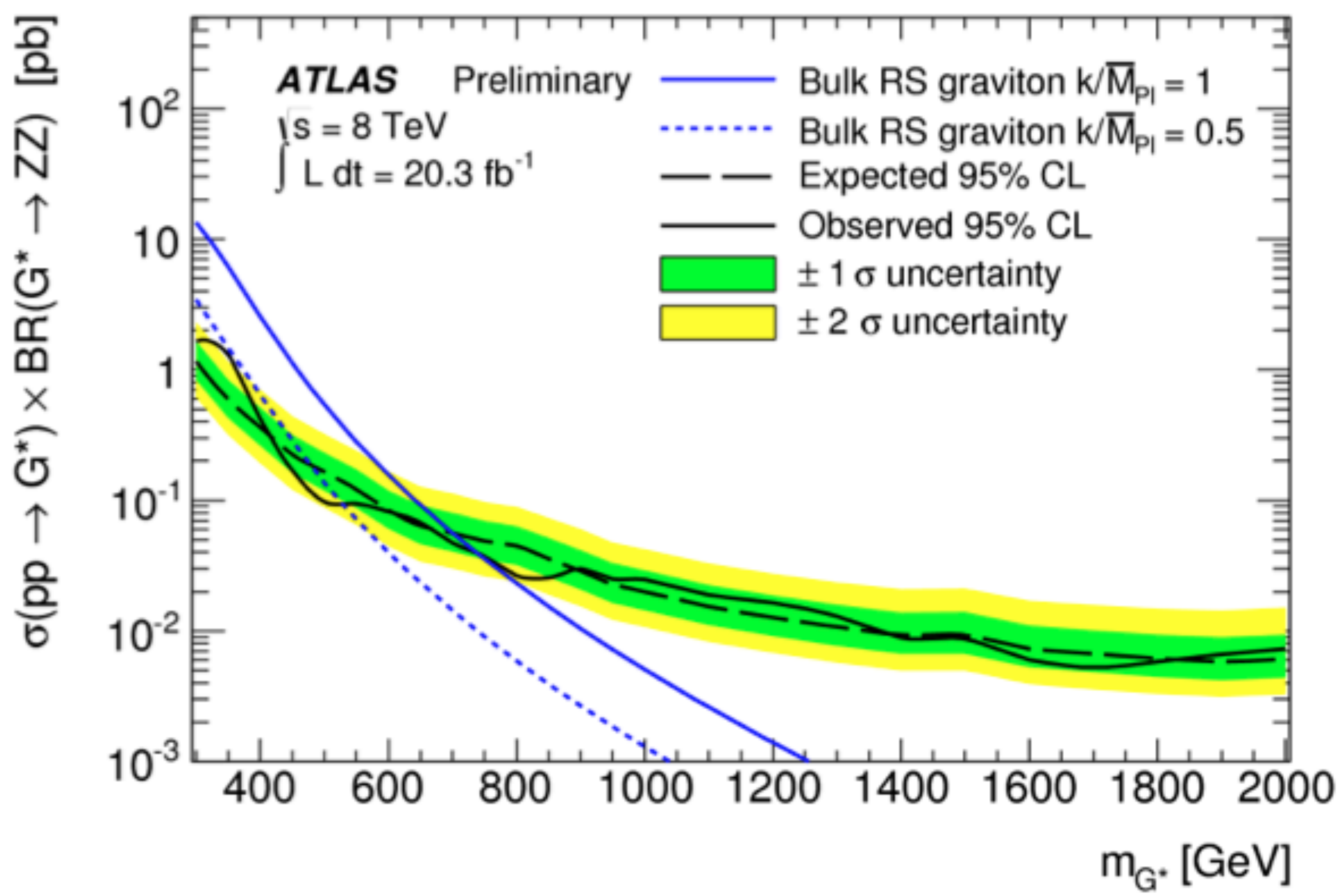
Diboson resonances to leptons and quarks (8 TeV, 20.3 fb^{-1})

ATLAS-CONF-2014-039

- ZZ or ZW → llqq
- Mass of dijet - dilepton system reconstructed in 3 regions
  - High and low P_T regions where jets are resolved and merged-jet regions
- Z+jet dominant background is corrected with data from sidebands
- No excess of events observed → upper limits set on σ x BR of Kaluza–Klein gravitons predicted by Randall–Sundrum and EGM W'



Reconstructed ℓ ℓ j j mass distributions of observed data and background predictions.

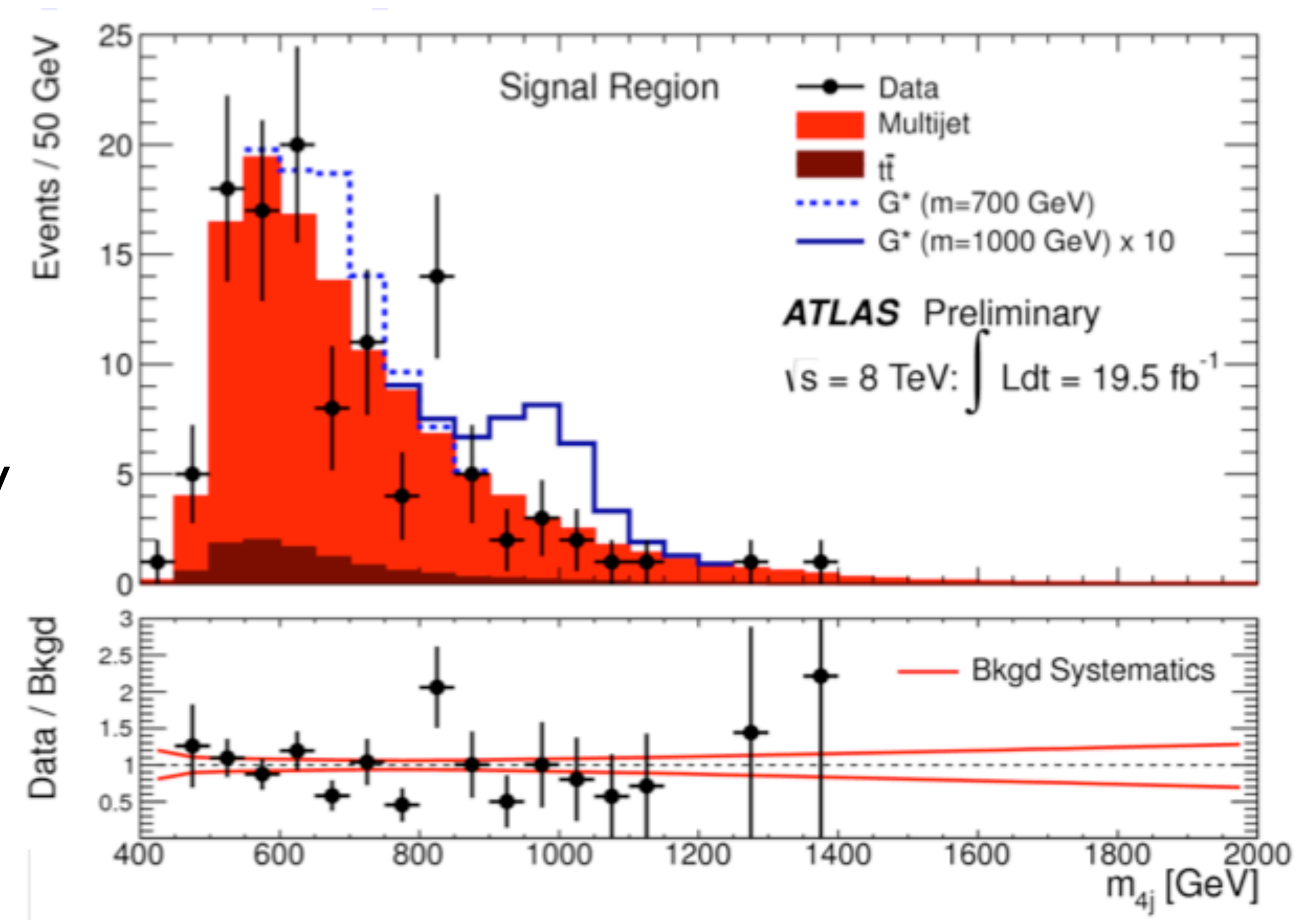


Observed and expected 95% CL upper limits on σ x BR as a function of the resonance pole mass for the G*. The LO (NNLO) theoretical cross sections for the G* production with k/M_{Pl} = 0.5 and 1.0 are also shown.

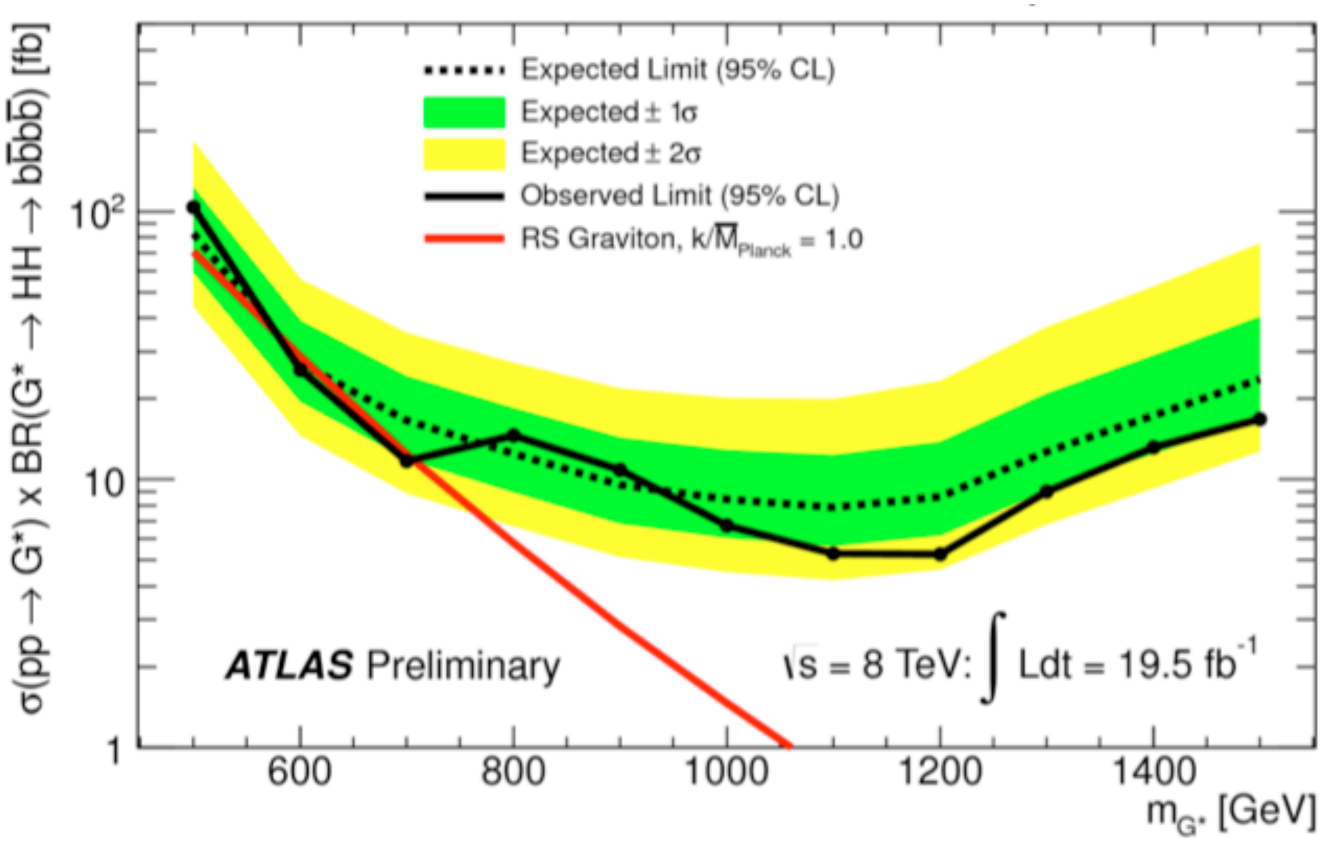
Resonant Higgs pair production (8 TeV, 19.5 fb^{-1})

ATLAS-CONF-2014-005

- First Kaluza-Klein excitation of graviton (G*) in the Randall-Sundrum model
- Branching fraction G* → HH is 7%
- Resonance narrower than m_{4j} resolution (~15%)
- At least 4 b-jets with p_T > 40 GeV
- Mass of di-jet should be consistent with m_H=125 GeV
- Observable: invariant mass of 4 b-jets, m_{4j}



m_{4j} background distribution: multijet and ttbar background contributions are shown as stacked histograms; the predicted m_{4j} distributions of two G* signal samples with m_{G^*}= 700 GeV and mG* = 1 TeV are shown.



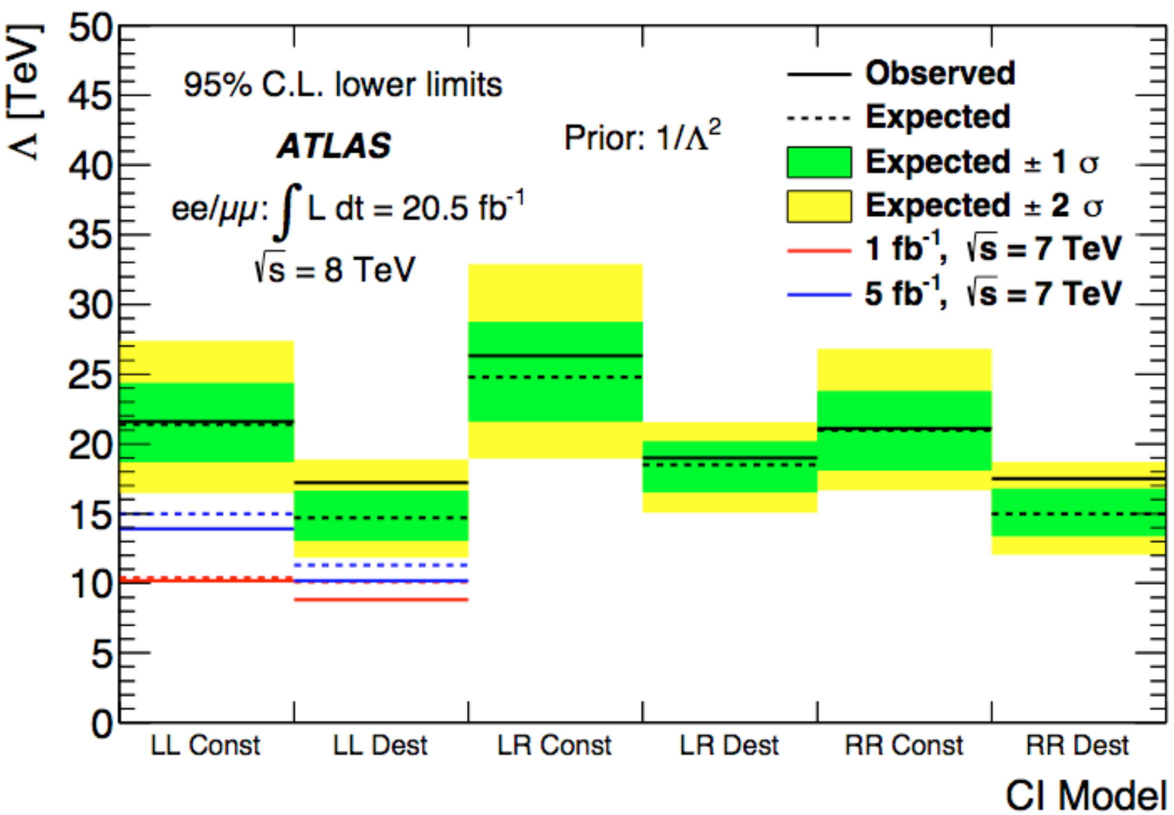
The expected and observed 95% CL upper limits on sigma(pp→G*→HH→bbbb) as a function of m_{G^*}.

- No evidence of a signal
- RS graviton (k/M_{Pl} =1.0) is excluded at 95% CL for masses between 590 and 710 GeV
- Observed upper limits on σxBR at 95% C.L. ranges from 100 fb at 500 GeV to 7 fb at 1 TeV

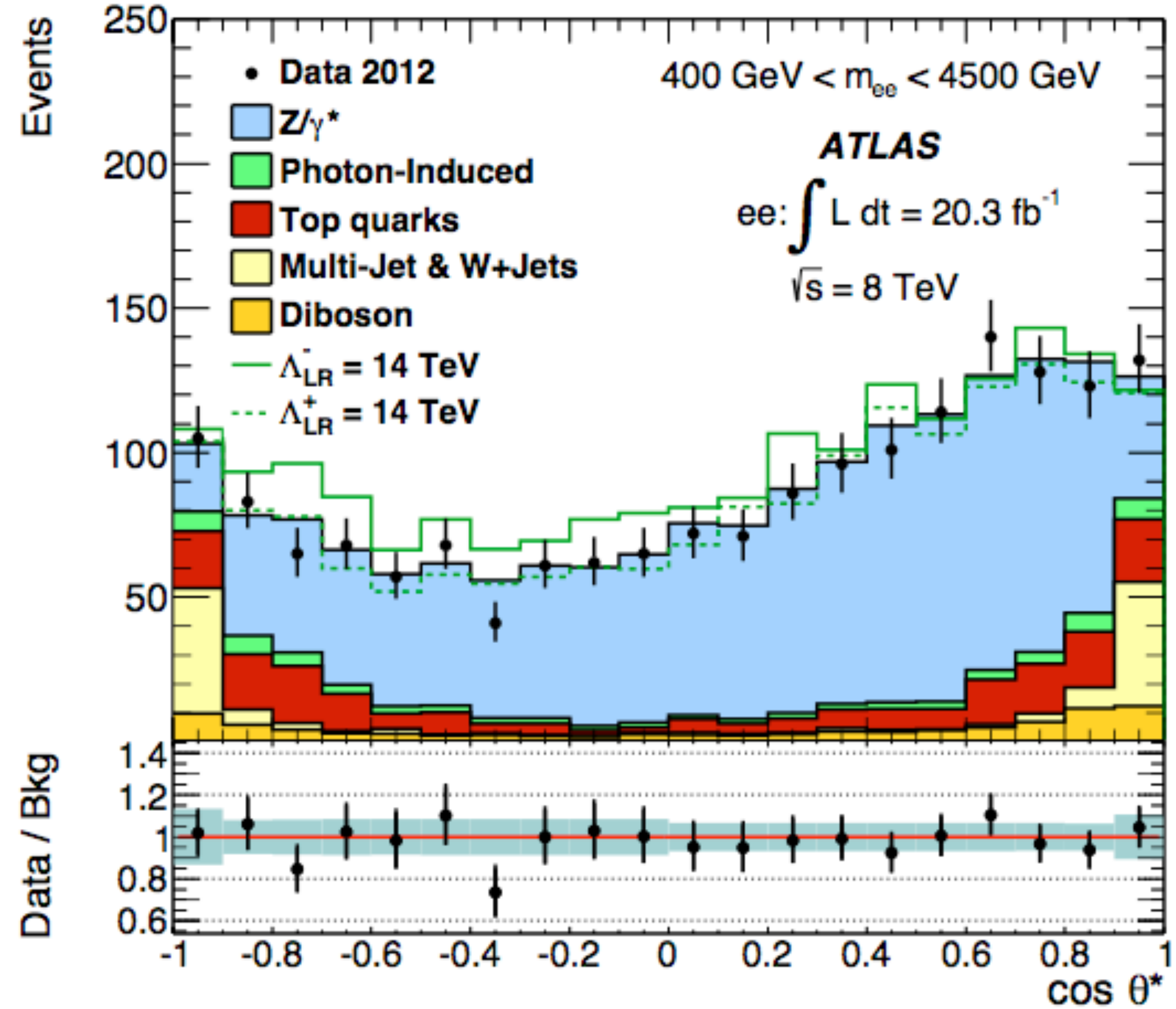
High mass dilepton: non resonant search (8 TeV, 20.3 fb^{-1})

arXiv: 1407.2410 submitted to EPJ C

- Complimentary search to dilepton resonance search
- Models: Contact interactions (CI) and Arkani-Hamed, Dimopoulos and Dvali model (ADD) with large extra dimensions
- Discriminating variable is the dilepton mass
- Additional variable for CI: dilepton decay angle θ^* in Collins-Soper frame – good discriminating variable in the left-right model



Summary of 95% C.L. lower exclusion limits on Λ for the combined dilepton contact interaction search. Previous ATLAS search results are also presented for comparison.



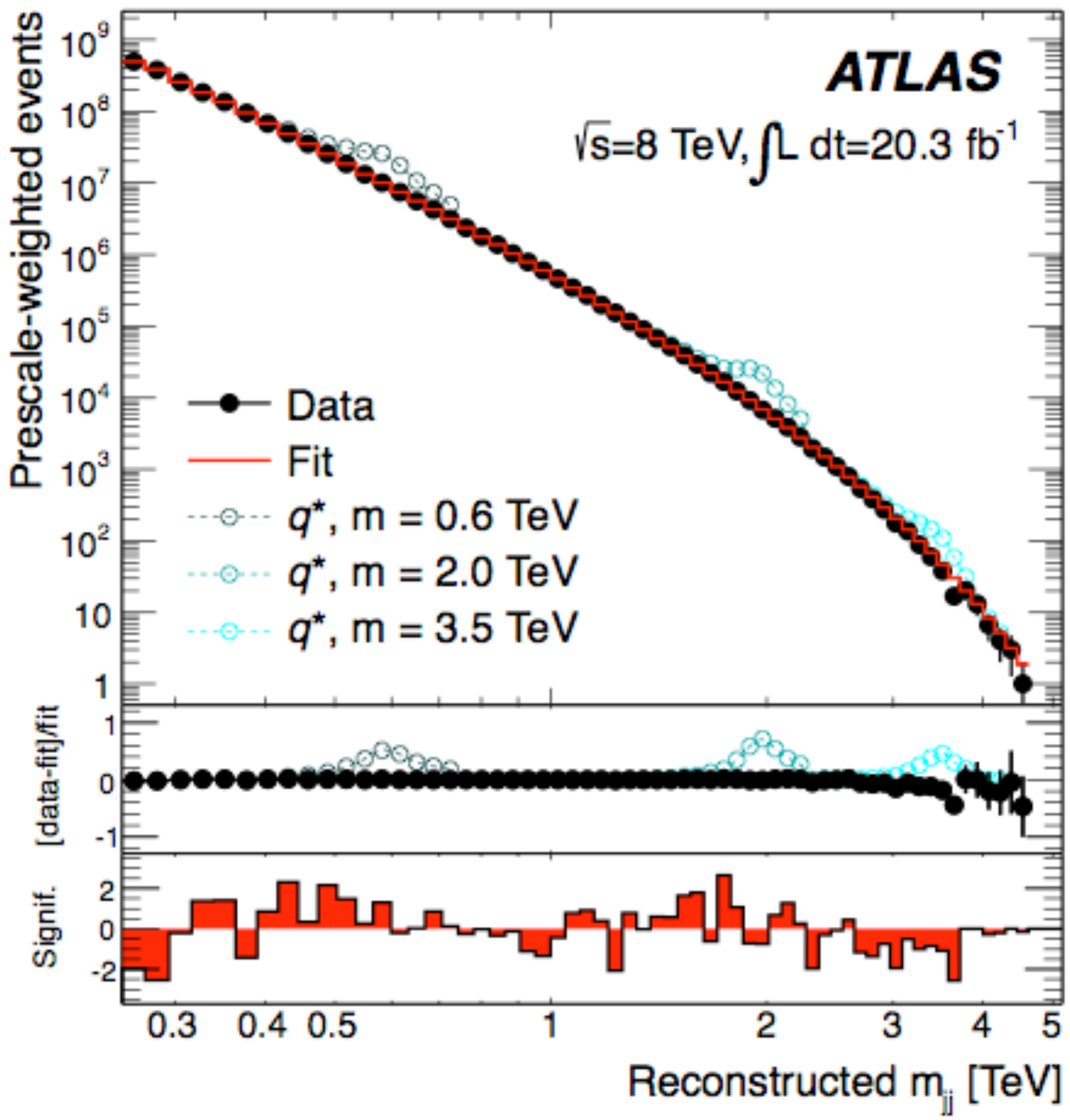
Reconstructed cosθ* distributions for data and the SM background estimate in the dielectron channel. Also shown are the predictions for a benchmark Λ value in the LR contact interaction model.

- No significant deviation from SM background
- Limits are set on the parameters of the models
  - Λ – characteristic energy scale in CI model
  - M_S – string scale used as ultraviolet cutoff in ADD model

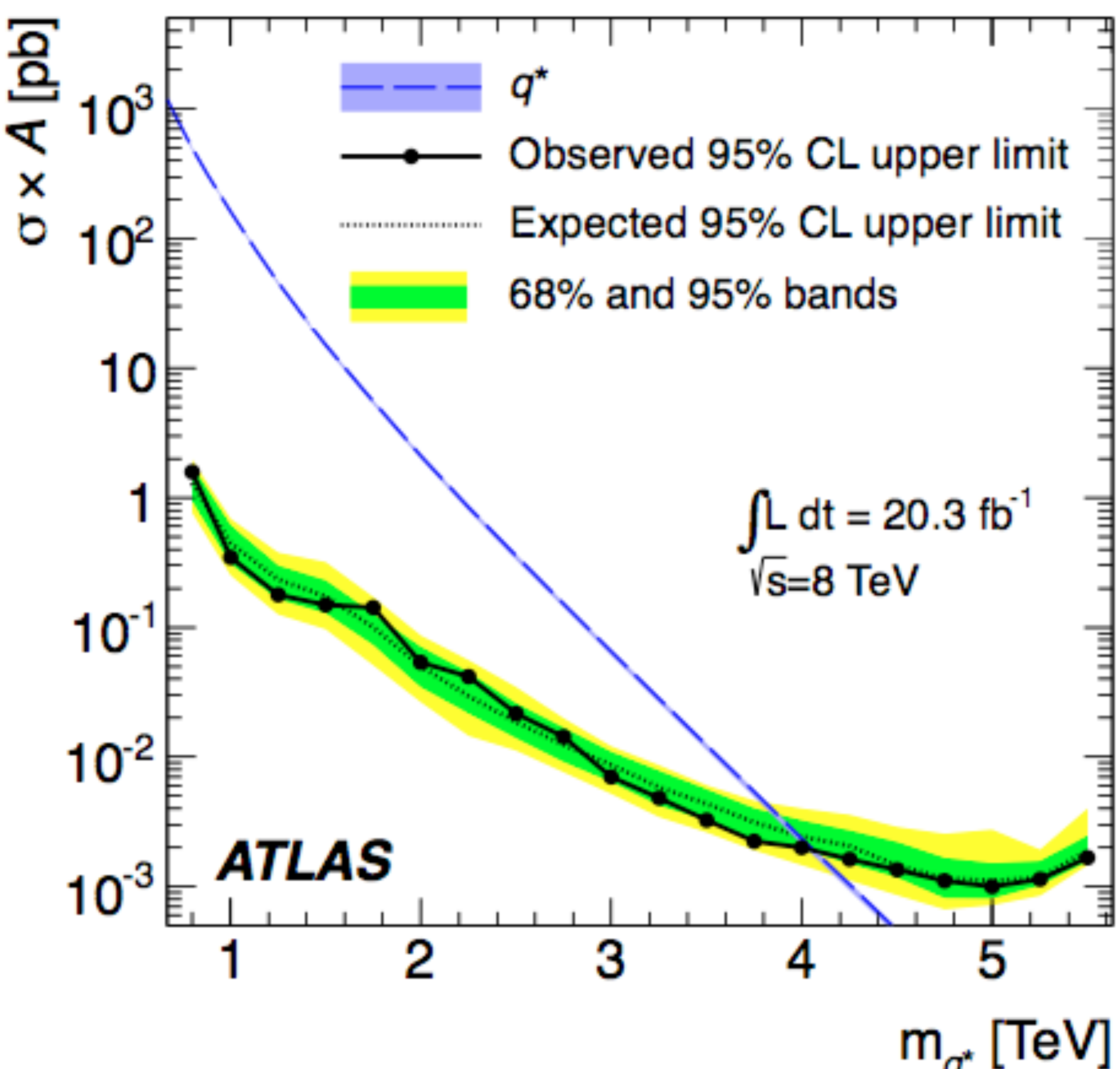
Dijet mass resonances (8 TeV, 20.3 fb^{-1})

arXiv: 1407.1376 submitted to Phys. Rev. D

- Dijet masses up to about 4.5 TeV are probed (down to 250 GeV using prescaled/delayed stream triggers)
- No resonance-like features are observed in the dijet mass spectrum
- Limits on σ × Acceptance for a simple Gaussian resonance or a Breit-Wigner narrow resonance decaying to dijets
- Specific models: excited quarks, color-octet scalars, W', W*, BH, and ED



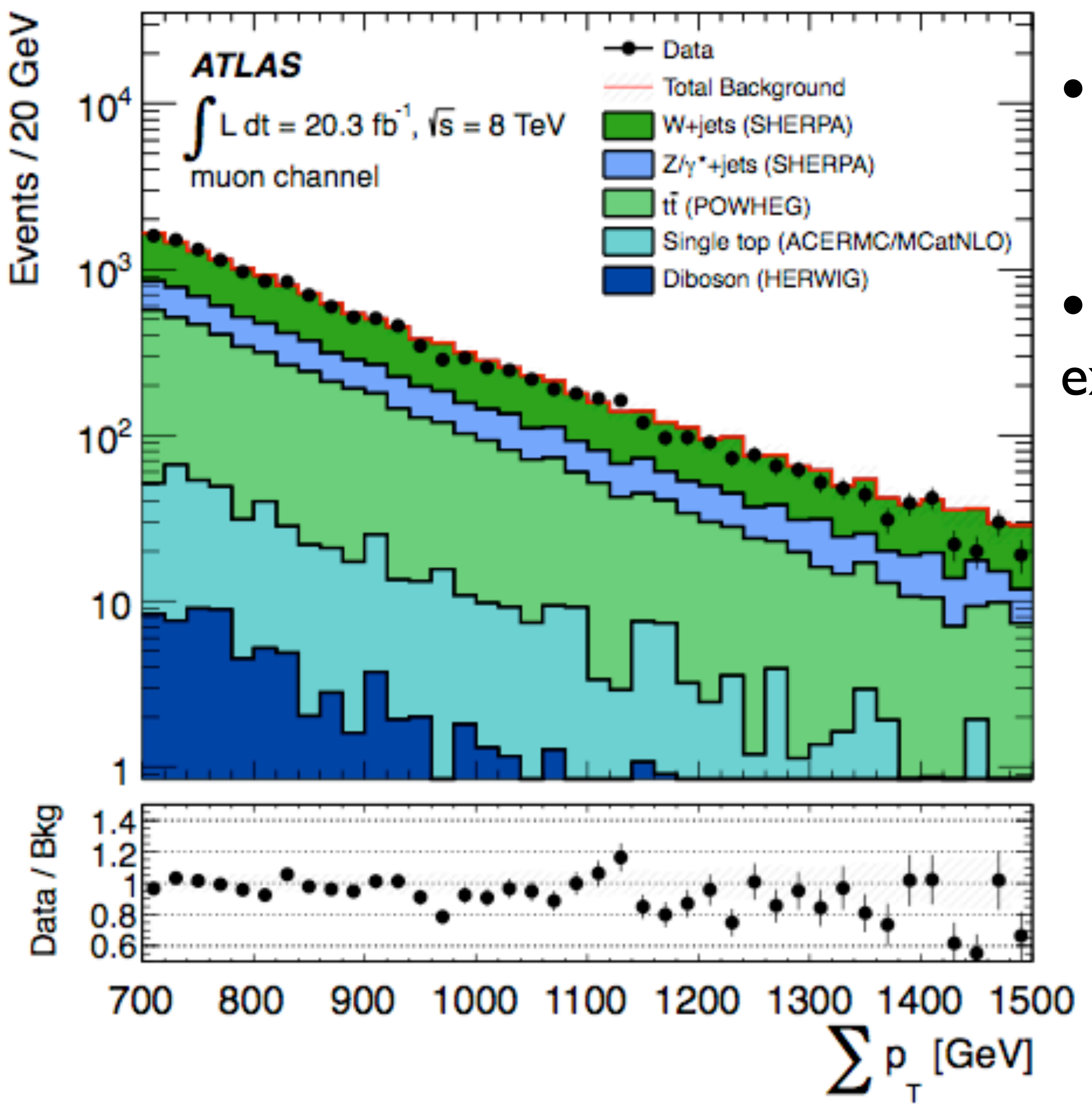
The reconstructed dijet mass distribution (filled points) fitted with a smooth functional form (solid line). Predictions for three q^* masses are shown above the background.



Observed and expected 95% CL upper limits on σ×Acceptance for excited quarks as a function of particle mass. The dashed curve is the theoretical prediction.

Microscopic black holes (8 TeV, 20.3 fb^{-1})

JHEP 08 (2014) 103



Scalar sum of the transverse momenta of the selected leptons and jets with $p_T > 60$ GeV distribution for preselected events, for the muon channels. The signal, containing multiple high-p_T leptons and jets, would manifest itself as an excess of events at higher values.

- Search for high-P_T leptons + jets
  - At least one isolated muon or electron
  - At least two additional leptons or jets
- No excess of events observed beyond the Standard Model expectations → set limits on ADD 2, 4, and 6 ED models
  - Scale in extra dimensions: $M_{D,S}$
  - Production threshold: M_{th}

Angular Mom.	Description	Excluded M_{th} value [TeV] for: $M_D = 1.5$ TeV	$M_D = 4$ TeV
Non-rotating	Black holes: High multiplicity remnant	6.2	5.7
Rotating	Black holes: High multiplicity remnant	6.0	5.4
Rotating	Black holes: Low multiplicity remnant	6.0	5.2
Rotating	Production loss model (gravitons)	5.5	4.8
		$M_S = 1.2$ TeV	$M_S = 2.5$ TeV
Non-rotating	String balls	5.7	5.1
Rotating		5.5	4.7

Limits for n = 6 for the Charybdis models

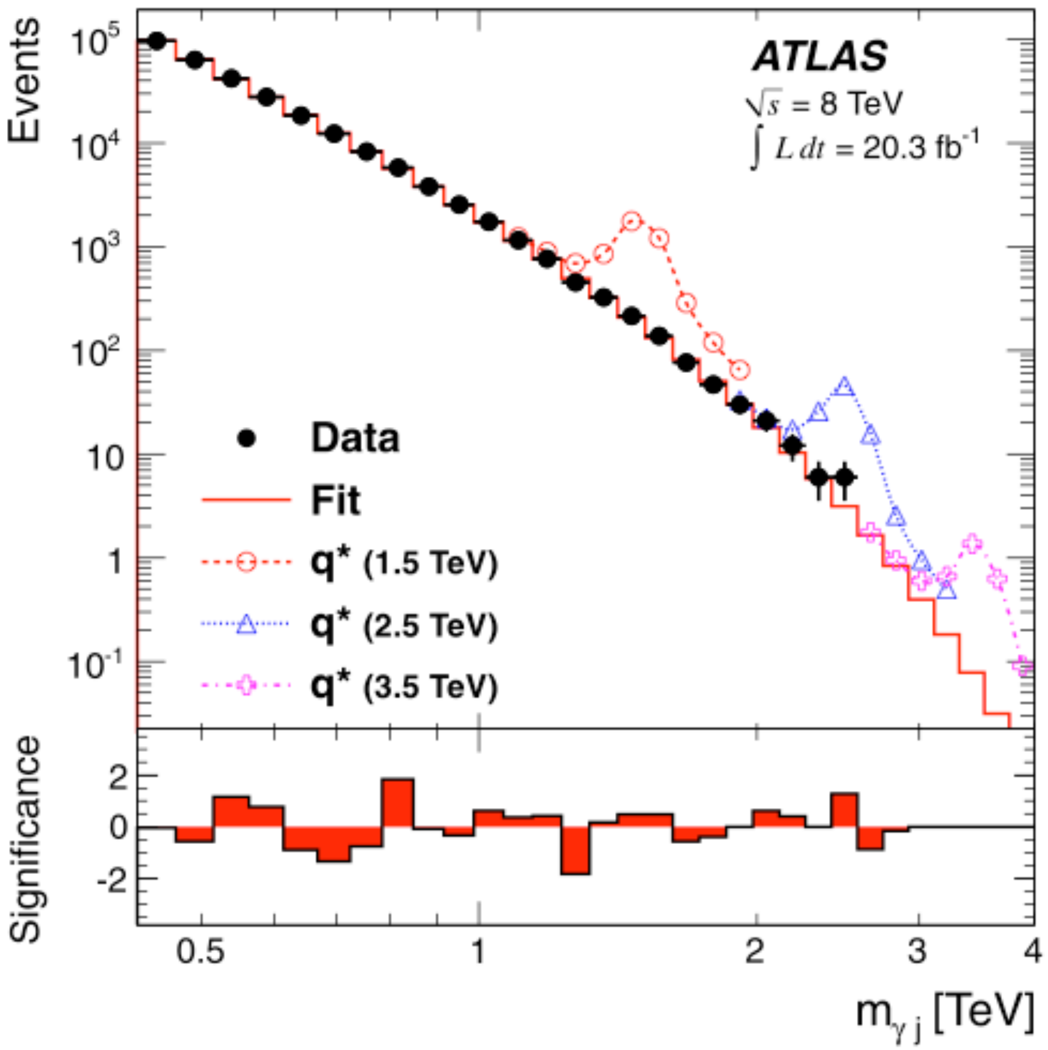
Angular Mom.	Description	Excluded M_{th} value [TeV] for: $M_D = 1.5$ TeV	$M_D = 4$ TeV
Non-rotating	Black holes: High multiplicity remnant	6.2	5.6
Rotating	Black holes: High multiplicity remnant	6.1	5.6
Non-rotating	Black holes with graviton	6.2	5.6
Rotating	10% Production loss model (photons)	6.1	5.5

Limits for n = 6 for the Blackmax models

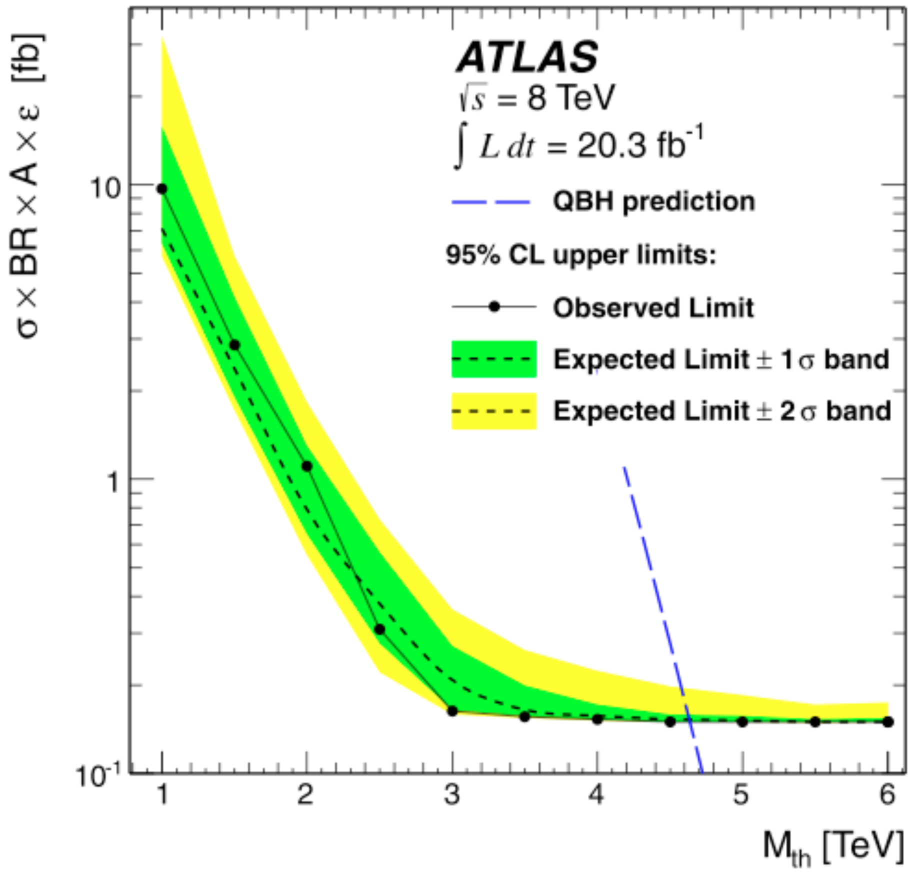
Quantum black-hole production (8 TeV, 20.3 fb^{-1})

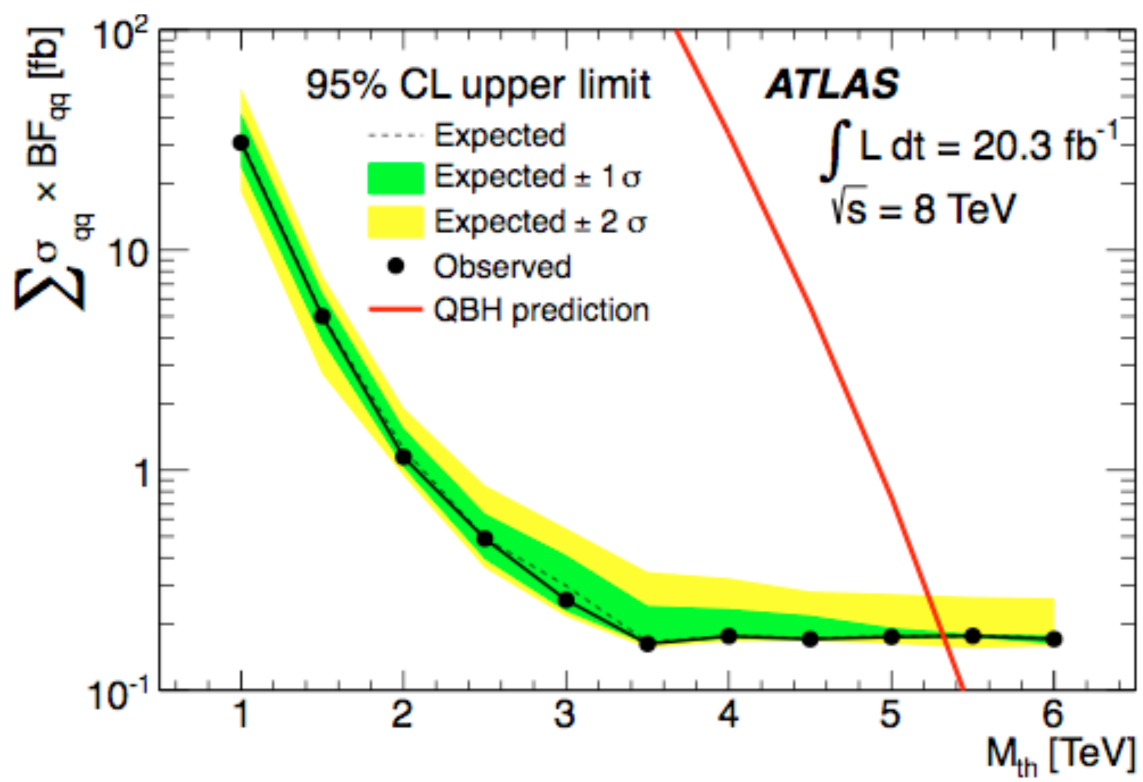
PRL 112 (2014) 091804 and Phys. Lett. B 728 (2014) 562

- Lepton+jet and photon+jet final states
- Invariant mass of trigger object (γ, e, μ) and high p_T jet
- No excess observed
  - Limits of 5.3 and 4.6 TeV QBH respectively
  - In the photon channel, limits also on exited quarks of 3.5 TeV



Invariant mass of the γ + jet pair with three examples of q* signals



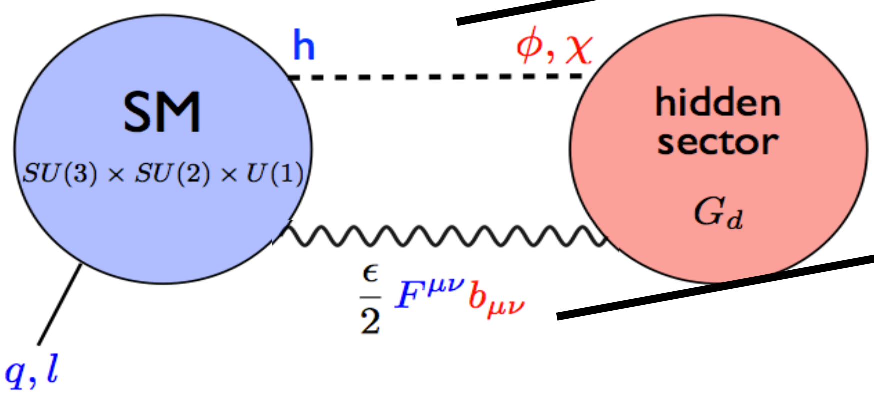


95% CL upper limits on σ×BR for QBHs decaying to a photon/ lepton and a jet, as a function of the threshold mass M_{th} assuming M_D = Mth and n=6 ED.

LeptonJets

Several BSM models predict final states containing LeptonJets

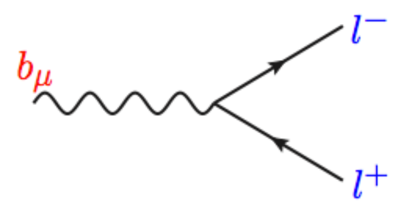
Portal to hidden sector: ex. Higgs or supersymmetric particles

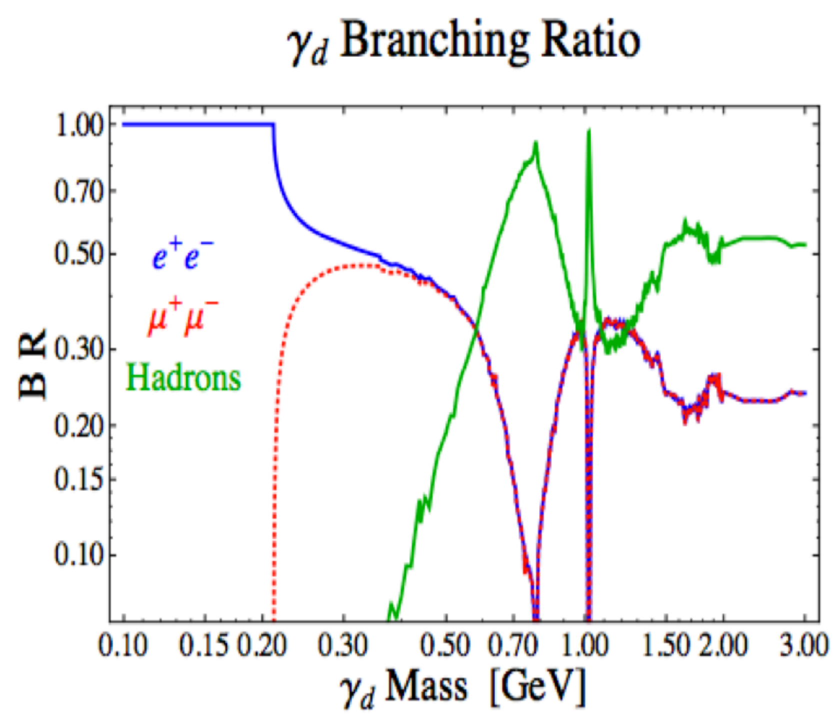


Hidden particles decay back to SM: e.g.
dark-photons (γ_d) → collimated pair of leptons (**LeptonJets**)

kinetic mixing

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} b_{\mu\nu} + m^2_{\gamma_d} b^2$$

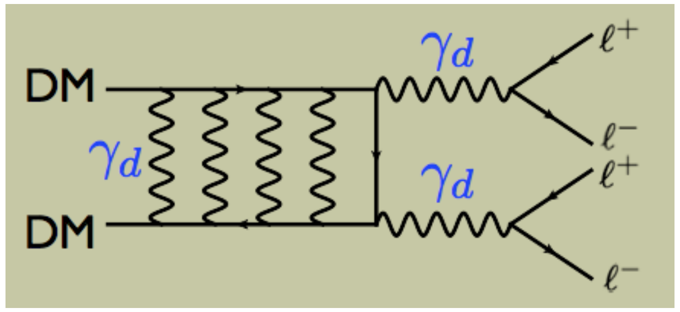


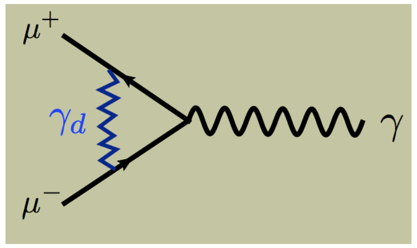


Dark photon lifetime depends on the size of kinetic mixing
ε: small ε → displaced decays

LeptonJets can be prompt or displaced

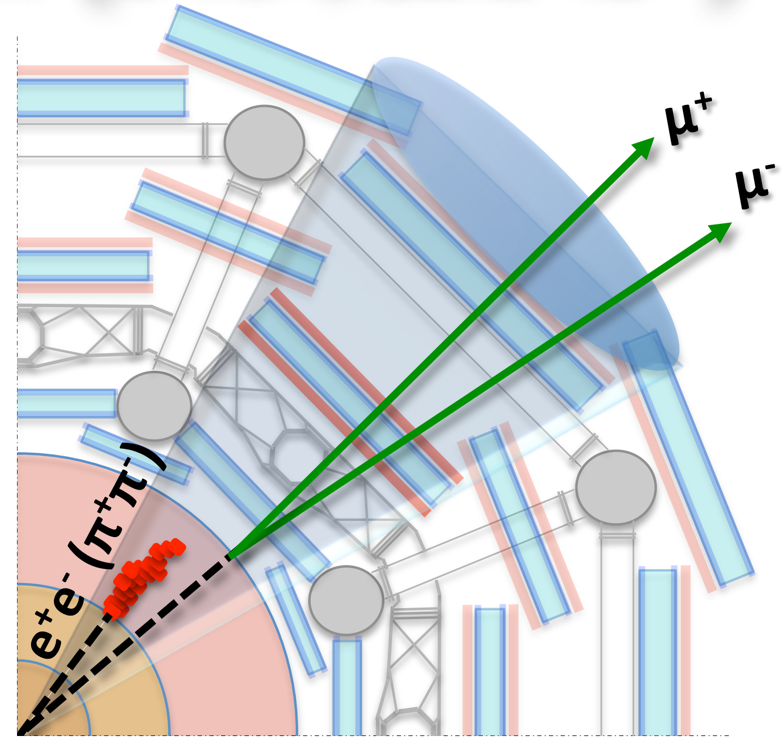
- (Some) motivations
  - Excess of positron flux in cosmic rays (not anti-proton) → if DM annihilates to a hidden sector it would produce leptons
  - $(g_s\text{-}2)_\mu$ anomaly: comparing theory to experiment there is a 3.2σ discrepancy → anomaly can be explained including corrections from an hidden photon





Non-prompt LeptonJet search (8 TeV, 20.3 fb^{-1})

arXiv: 1409.0746 submitted to JHEP



Model-independent search strategy starting from a general non-prompt LJ definition

Leptonjets: **N** long-lived neutral light objects (**dark photons γ_d**'s) in a narrow cone (ΔR) decaying to pairs of electrons/muons/pions → **lepton/hadron pairs in a narrow cone ΔR**

Non-prompt leptonjets: leptonjets with long-lived γ_d's (small ε) → **displaced decays highly isolated in ID**

LJ reconstruction

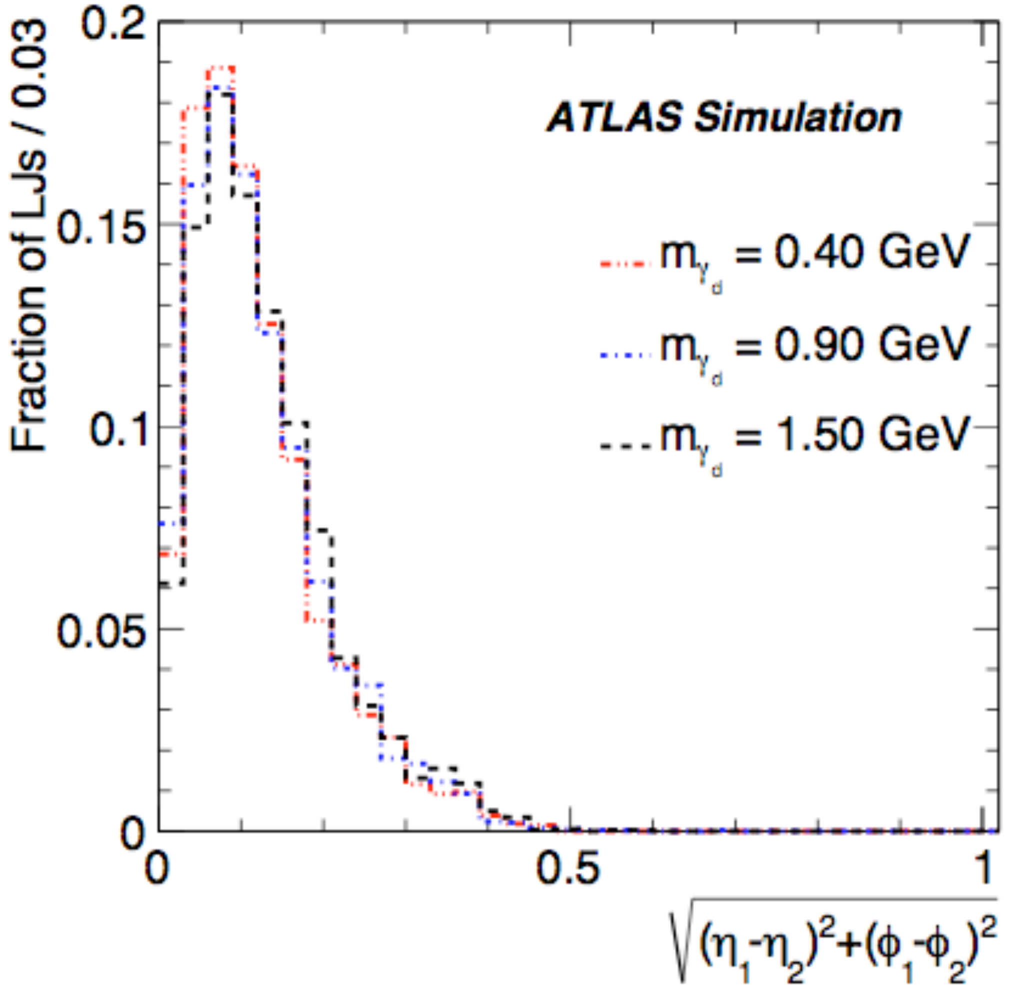
LJ with only muons: ≥2 muons clustered in a ΔR=0.5 cone and NO jets in the cone

LJ with muons and electrons/pions: ≥2 muons + jets clustered in a ΔR=0.5 cone

LJ with only electrons/pions in HCAL: jets with low EM fraction and narrow width

Event selection

- multi-muon trigger + calorimeter jet trigger
- >1LJ per event



Opening ΔR between the two muons in an LJ produced by the decay of a single γ_d.

LeptonJet gun MC generator:
- generate LeptonJets made up to two dark photons varying boost and masses in the LeptonJets parameter space
- used to optimize search criteria and to produce detection efficiency curves to constrain theory models predicting LeptonJet production.

Non-prompt LeptonJet search (8 TeV, 20.3 fb^{-1})

arXiv: 1409.0746 submitted to JHEP

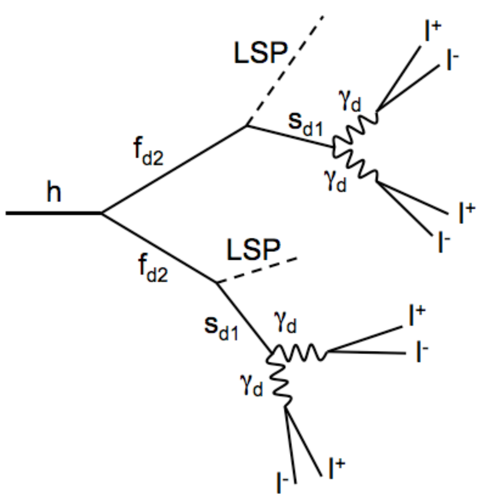
Results of LeptonJet analysis selection

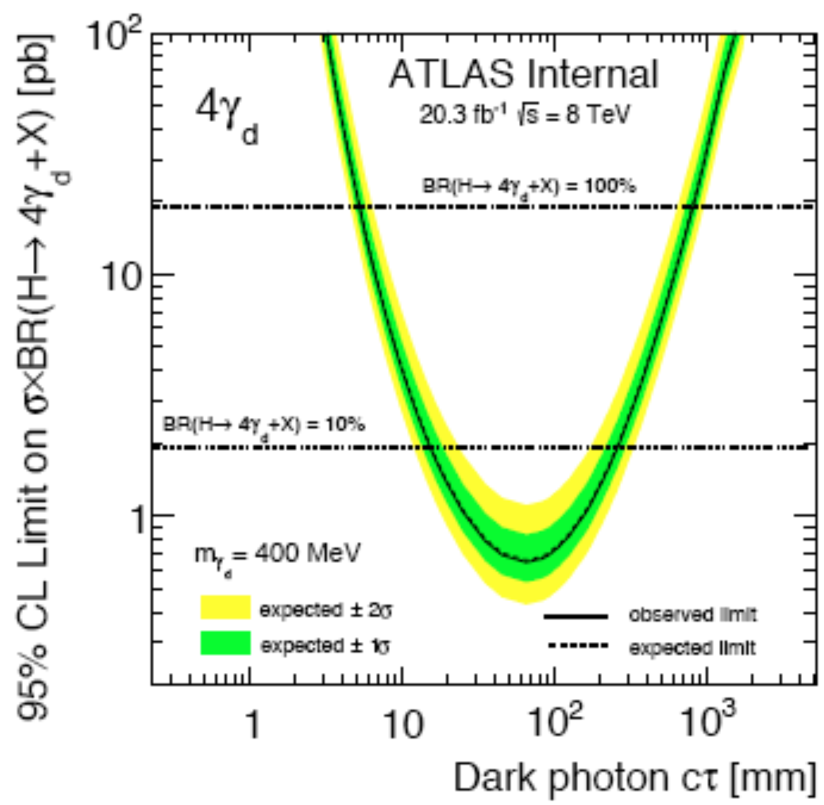
	number of events
2012 DATA	119±11 (stat)
cosmics	40±11 (stat)
QCD (data driven)	70±58 (stat)
Total background	110±59 (stat)

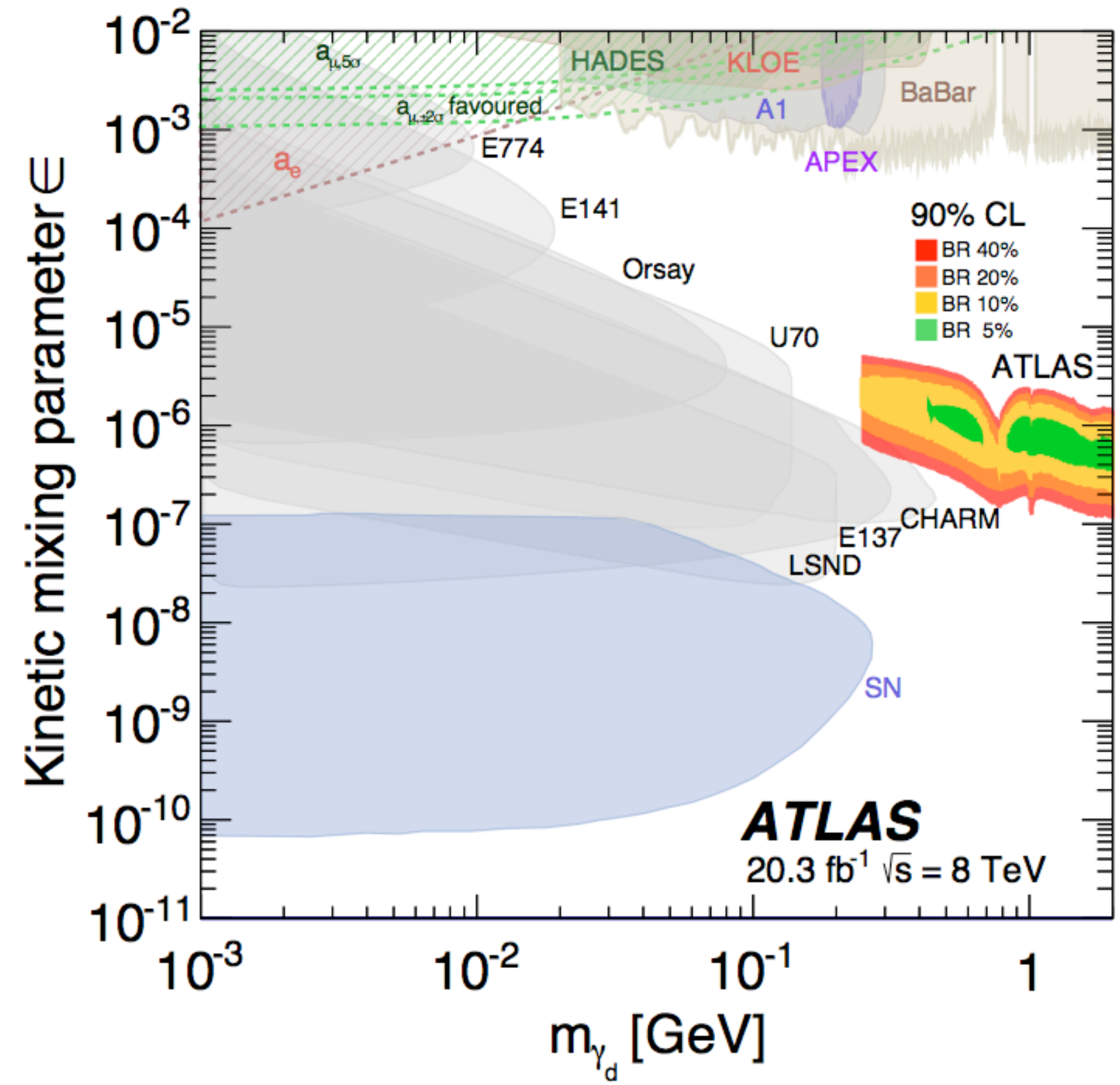
No excess of events observed over the estimated background → set limits on specific models

Falkowsky-Ruderman-Volansky-Zupan models:

Higgs boson decay to LeptonJets







ATLAS results in the (ε,m) exclusion plane as σ×BR limits

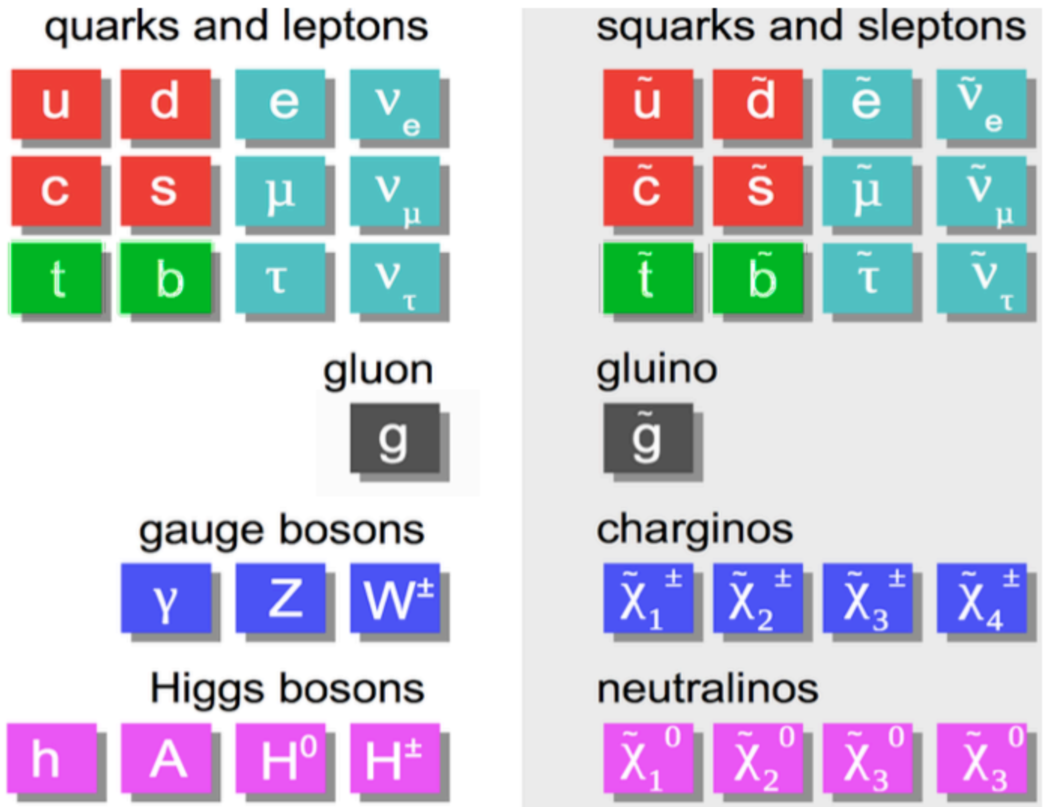
FRVZ model	excluded cτ [mm] BR(10%)	expected events at cτ 47 mm BR(10%)
Higgs → $2\gamma_d$ + X	14 ≤ cτ ≤ 140	60 ± 7 (stat)
Higgs → $4\gamma_d$ + X	15 ≤ cτ ≤ 260	104 ± 9 (stat)

Results for prompt LeptonJets with 8 TeV 20.3 fb^{-1} are on the way

SUSY searches

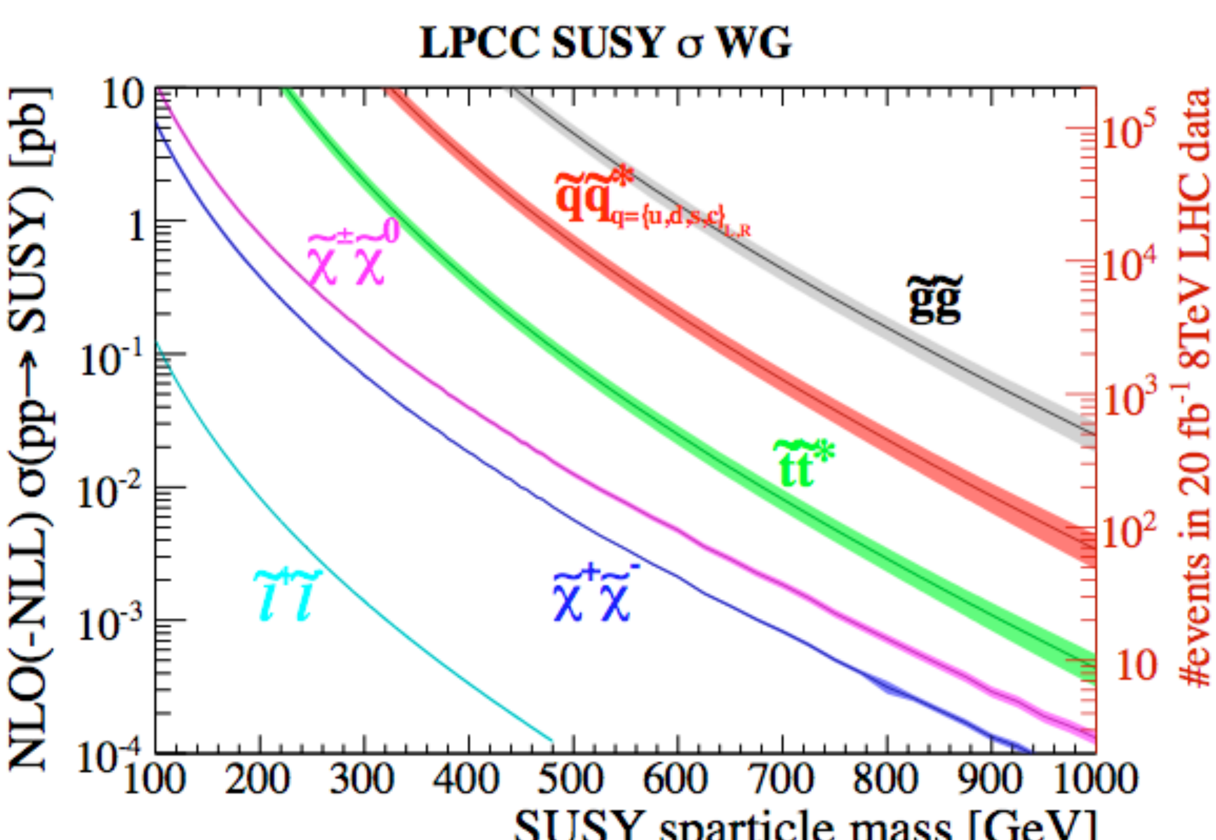
Supersymmetry

Global symmetry between fermions & bosons: all SM particles have SUSY partners with spin difference of ±1/2



Why SUSY?

- Solves the hierarchy problem (if $m_{SUSY} <\approx 1$ TeV, i.e. "natural" SUSY)
- Provides the dark matter candidate: if R-parity is conserved, lightest SUSY particle (LSP, neutralino) is stable
- Extends the Poincare group, provides unification with gravity
- Required for the string theory. Etc...



SUSY physics processes

- Strong production ($\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^*$)
- 3rd-generation squarks ($\tilde{t}\tilde{t}^*$, $\tilde{b}\tilde{b}^*$)
- Electroweak production ($\tilde{\chi}$'s, $\tilde{l}\tilde{l}$)
- R-parity violating scenarios, long-lived particles

see also A. Barr talk

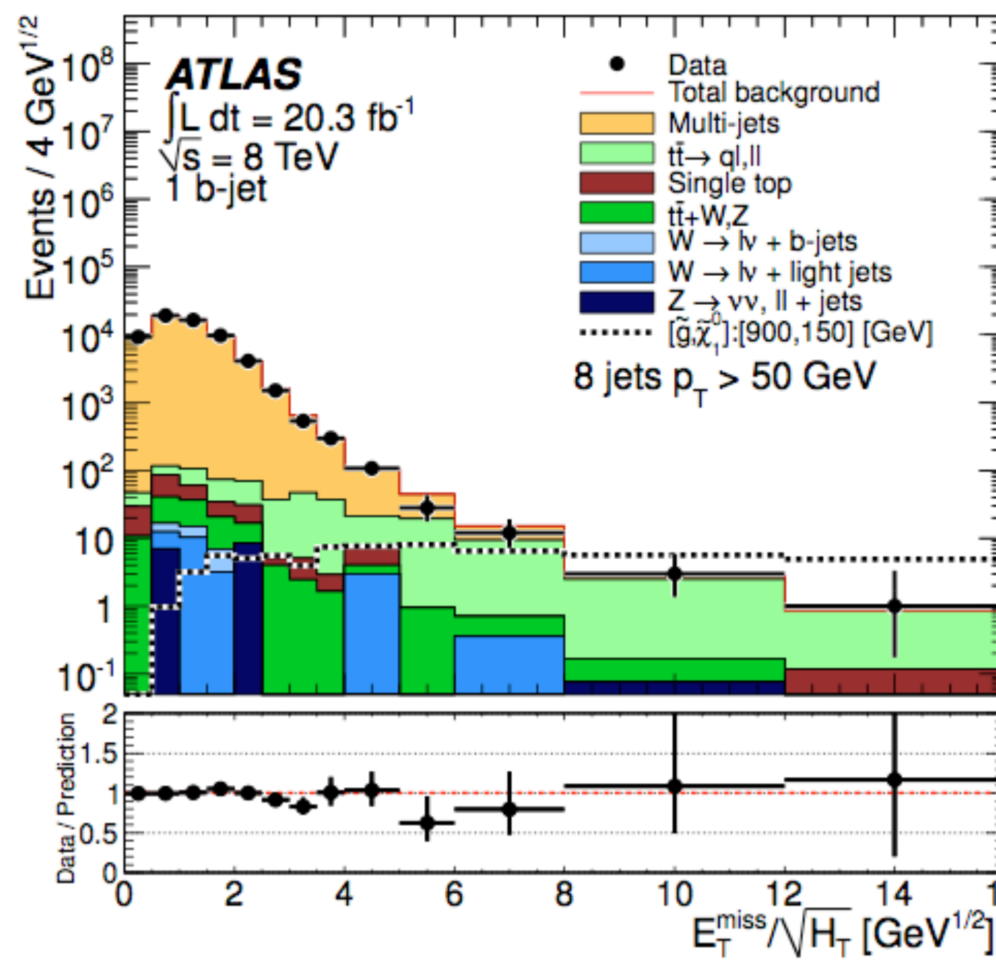
Search for Supersymmetry

Main steps of the SUSY analyses

- Define Signal Region (SR) for process of interest
- Estimate the background
  - Main background is estimated by a semi-data driven method using Control Regions (CR) which should be kinematically as close as possible to the SRs used to normalize Monte Carlo (MC) to data in CR or equivalently extrapolate to the SR using a Transfer Factor taken from MC
  - Detector background, so called „fakes" is estimated using a data-driven method: Matrix Method (MM), Jet smearing
  - Smaller background is directly taken from MC
- Check the background in Validation Regions(VR), which are closer to Signal Regions
- Unblind the SR→ look for some excess. If there is no excess, only model dependent or independent exclusion limits are set

Dominant backgrounds

- W+jets, Z+jets, t pair, single top, diboson... and QCD
- To differentiate between the signal and the backgrounds use variables with good discriminating power
  - missing transverse energy – E_T^{miss}
  - $d\varphi$ – angle between jet and E_T^{miss}
  - $H_T = \sum p_T^{jet} + \sum p_T^{lep}$
  - $m_{eff} = E_T^{miss} + H_T$
  - E_T^{miss}/m_{eff}, $E_T^{miss}/\sqrt{H_T}$

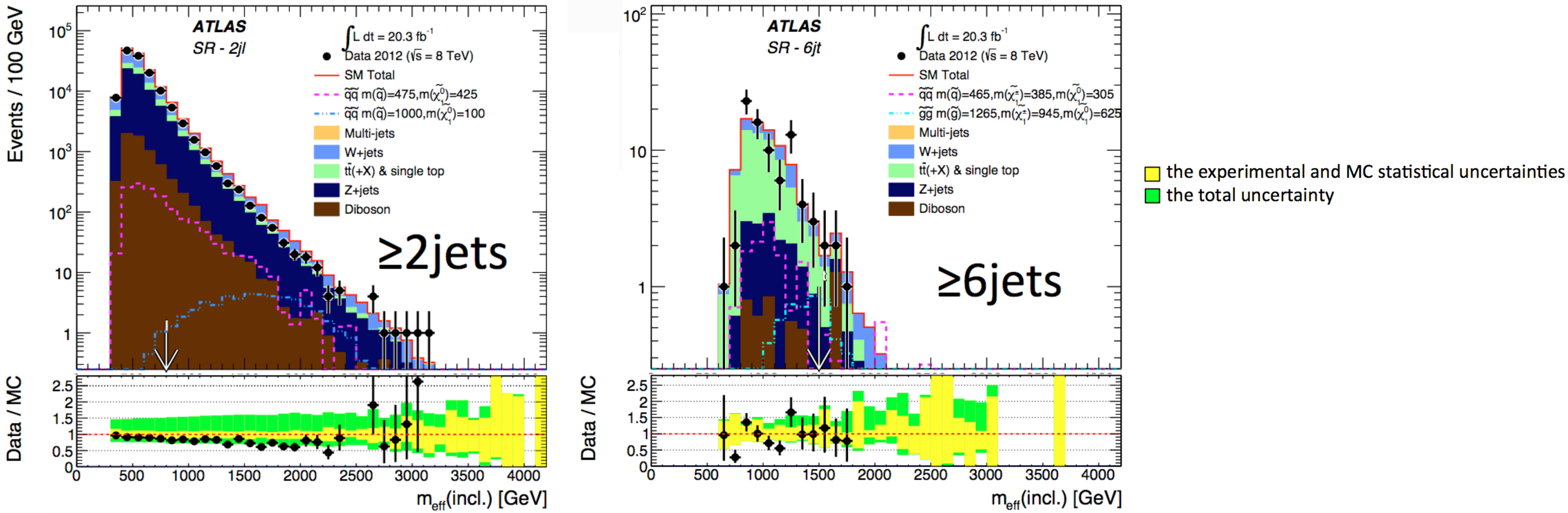


Strong production (8 TeV, 20.3 fb^{-1}) **0 lepton + ≥2−6 jets + E_T^{miss}**

arXiv: 1405.7875 submitted to JHEP

Squarks and gluinos will decay in cascades to final states with jets

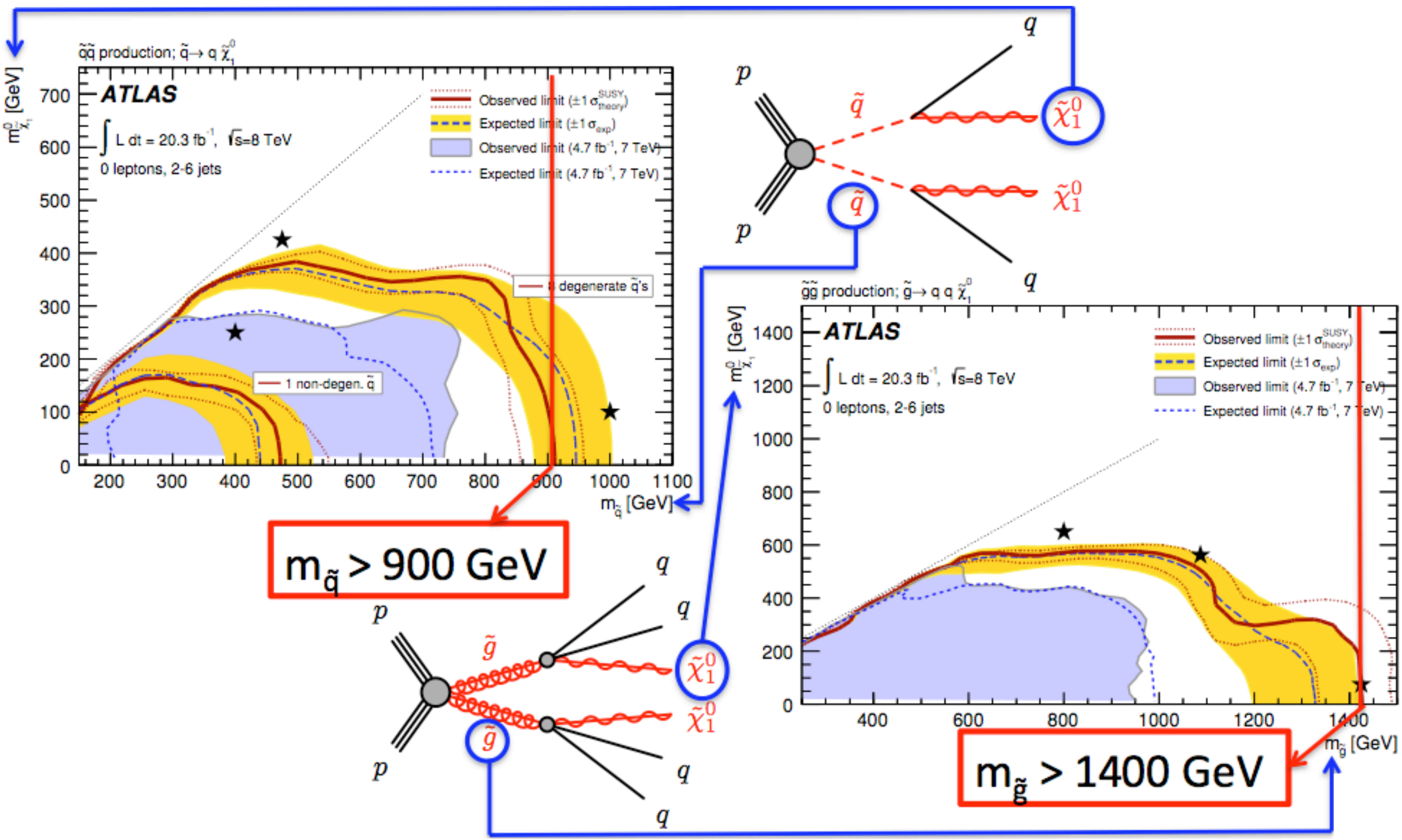
- Event selection
  - lepton (e or μ) veto
  - E_T^{miss}
  - Jet p_T > 130/60 GeV
  - dφ between jet and E_T^{miss}
  - E_T^{miss}/m_{eff}
- 15 signal regions depending on the number of jets
- Signal/background discrimination based on m_{eff} sensitive to the SUSY mass scale



Observed m_{eff} distributions for the 4-jet and 6-jet signal regions.

Strong production (8 TeV, 20.3 fb^{-1}) 0 lepton + ≥2−6 jets + E_T^{miss}

arXiv: 1405.7875 submitted to JHEP



Exclusion limits for direct production of light-flavor squark pairs and of giuino pairs. Gluinos (light-flavor squarks) are required to decay to two quarks (one quark) and a neutralino LSP.

Strong production (8 TeV, 20.3 fb^{-1}) 0/1 lepton + ≥3 bjets + E_T^{miss}

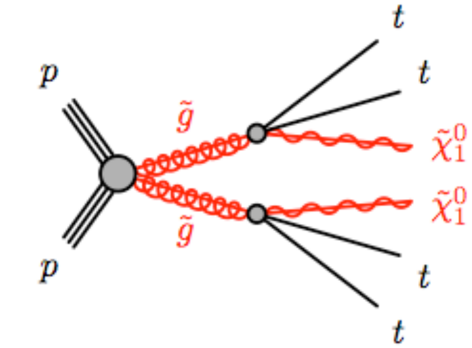
arXiv: 1407.0600 submitted to JHEP

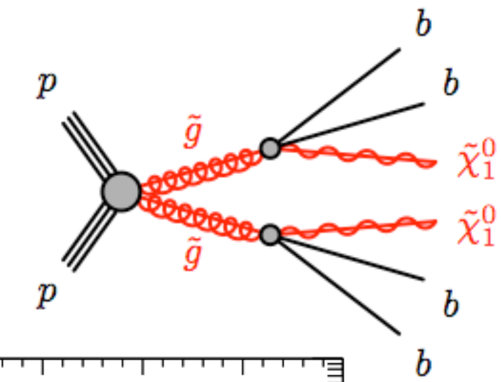
Event selection

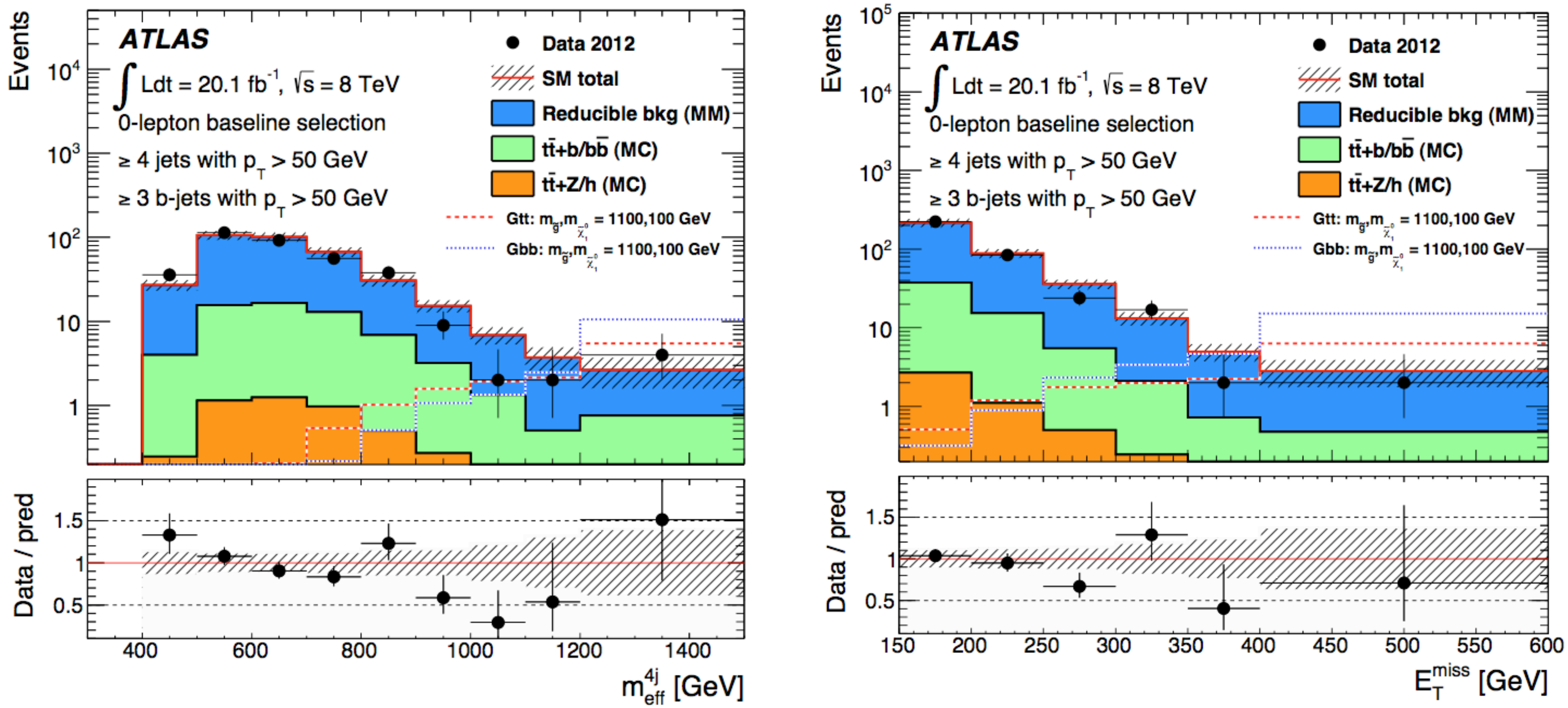
- at least 3 jets tagged as originating from b-quarks
- 0 or at least1lepton (e or μ)
- E_T^{miss} > 200 GeV

9 signal regions

- 3SRs ≥ 4 jets with E_T^{miss} > 250/350/400 GeV, veto leptons
- 3SRs ≥ 7 jets with E_T^{miss} > 200/250/350 GeV, veto leptons
- 3SRs ≥ 6 jets with E_T^{miss} > 175/225/275 GeV, ≥ 1 lepton



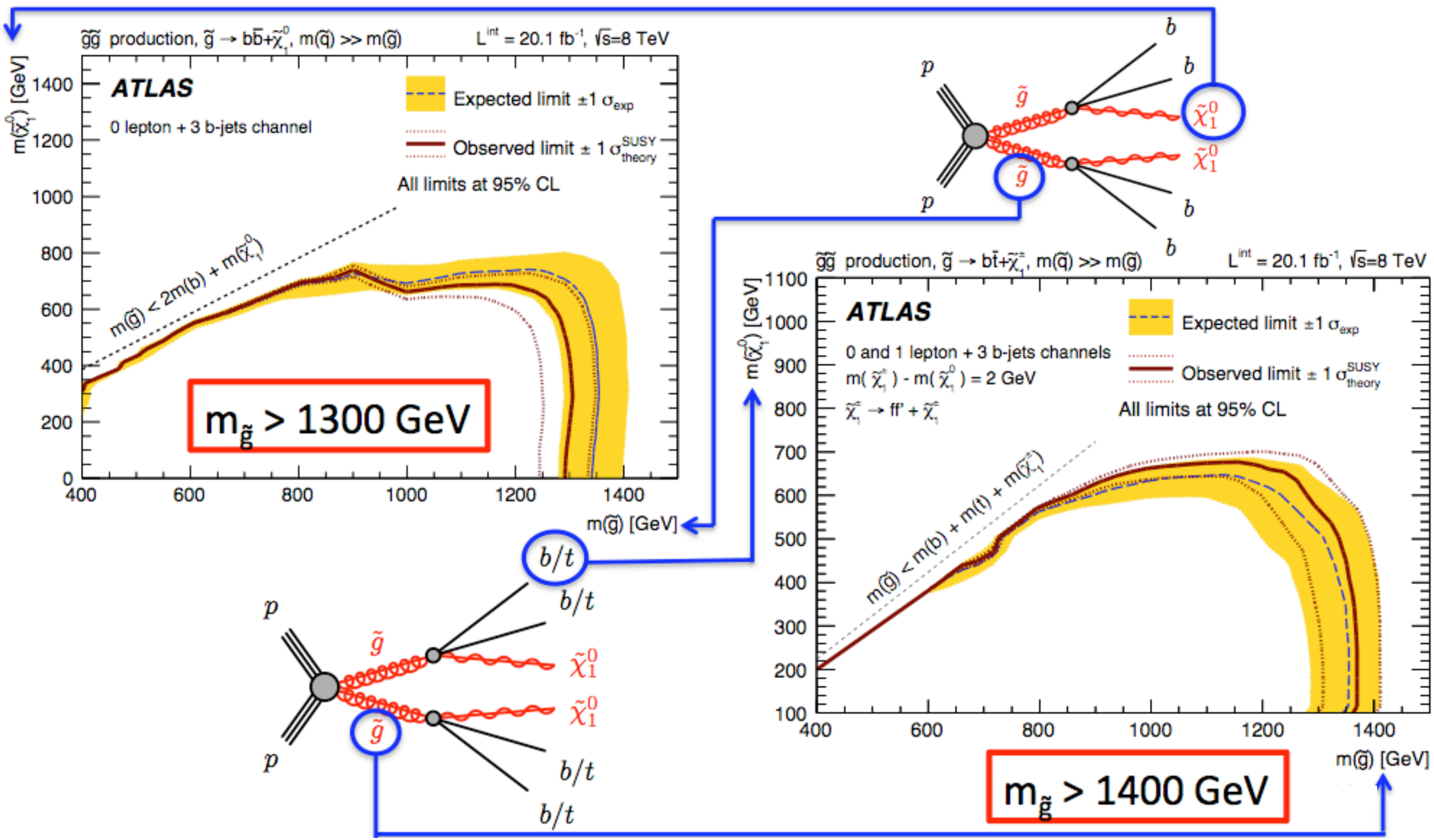




The observed distributions of m^{4j}_{eff} and E_T^{miss} after the 0-lepton baseline selection, together with the background prediction. Also displayed are the respective contributions of the backgrounds described in the legend and the ratio between the expected and observed event yields.

Strong production (8 TeV, 20.3 fb^{-1}) 0/1 lepton + ≥3 bjets + E_T^{miss}

arXiv: 1407.0600 submitted to JHEP



Exclusion limits in the ($m_{\tilde{g}}$, $m_{\tilde{\chi}^0_1}$) plane for the Gbb and Gtb models. The dashed blue and solid bold red lines show the 95% CL expected and observed limits respectively, including all uncertainties except the theoretical signal cross-section uncertainty.

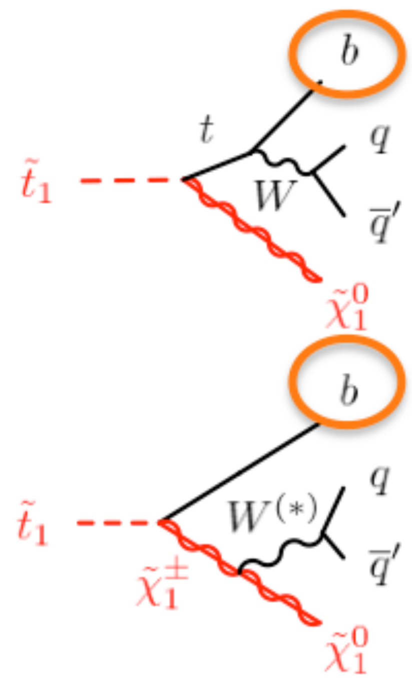
Third generation (8 TeV, 20.3 fb^{-1}) 0/1 lepton + ≥6 (2 b) jets + E_T^{miss}

arXiv: 1406.1122 accepted by JHEP

- Expect light stop from naturalness arguments

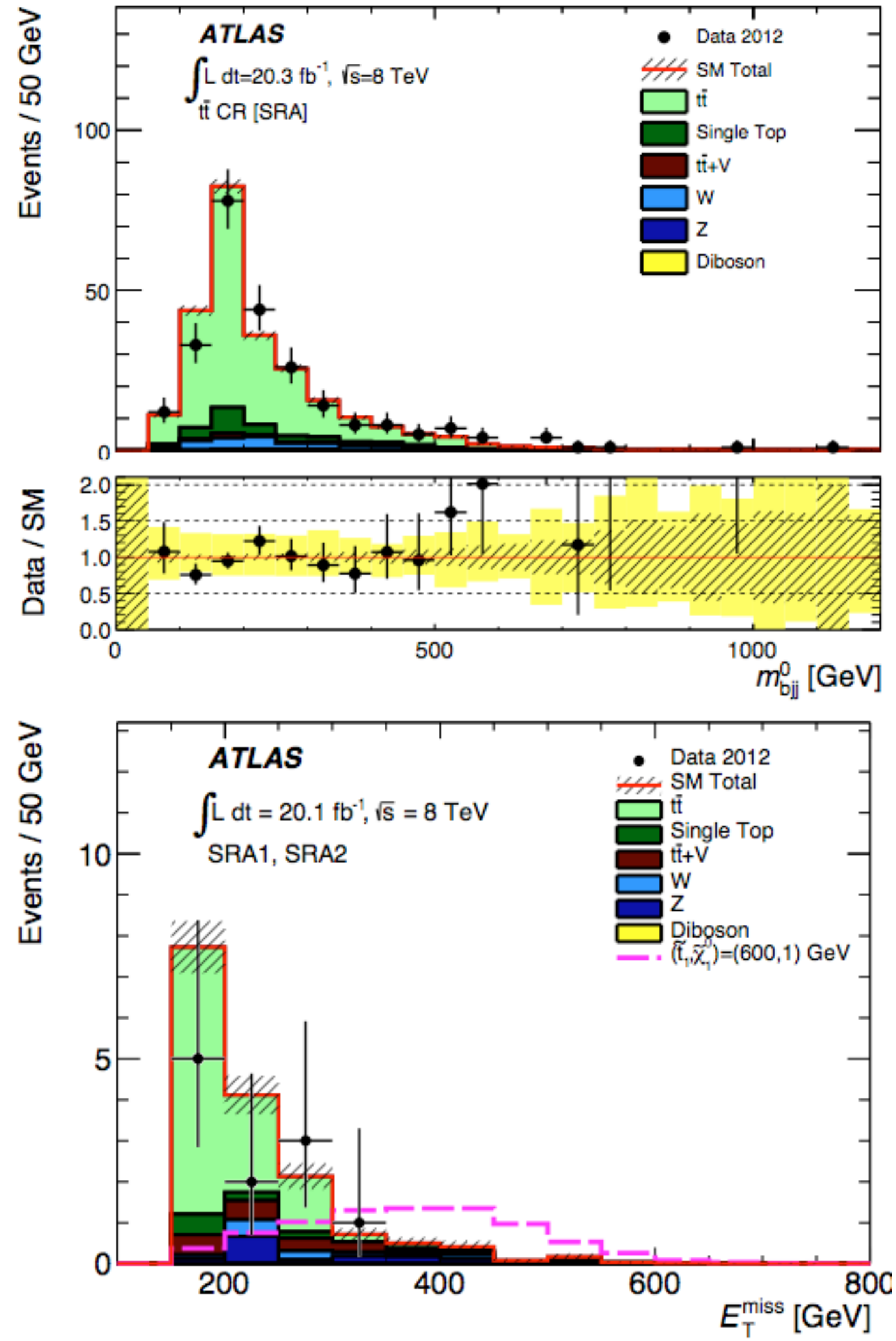
- Specific experimental signature different from 1st two generations

- Event selection
  - bjets in the final state
  - ≥ 2 b-tagged jets
  - Veto lepton
  - E_T^{miss} >150 GeV
  - dφ between jet and E_T^{miss}
  - $m_T^{b,min}$ > 175 GeV



- 8 signal regions
  - 4SRs ≥ 6 jets with E_T^{miss} > 150/250/300/350 GeV
  - 2SRs with 4 or 5 jets with E_T^{miss} > 325/400 GeV
  - 3 SRs with 5 jets with E_T^{miss} > 160/160/215 GeV

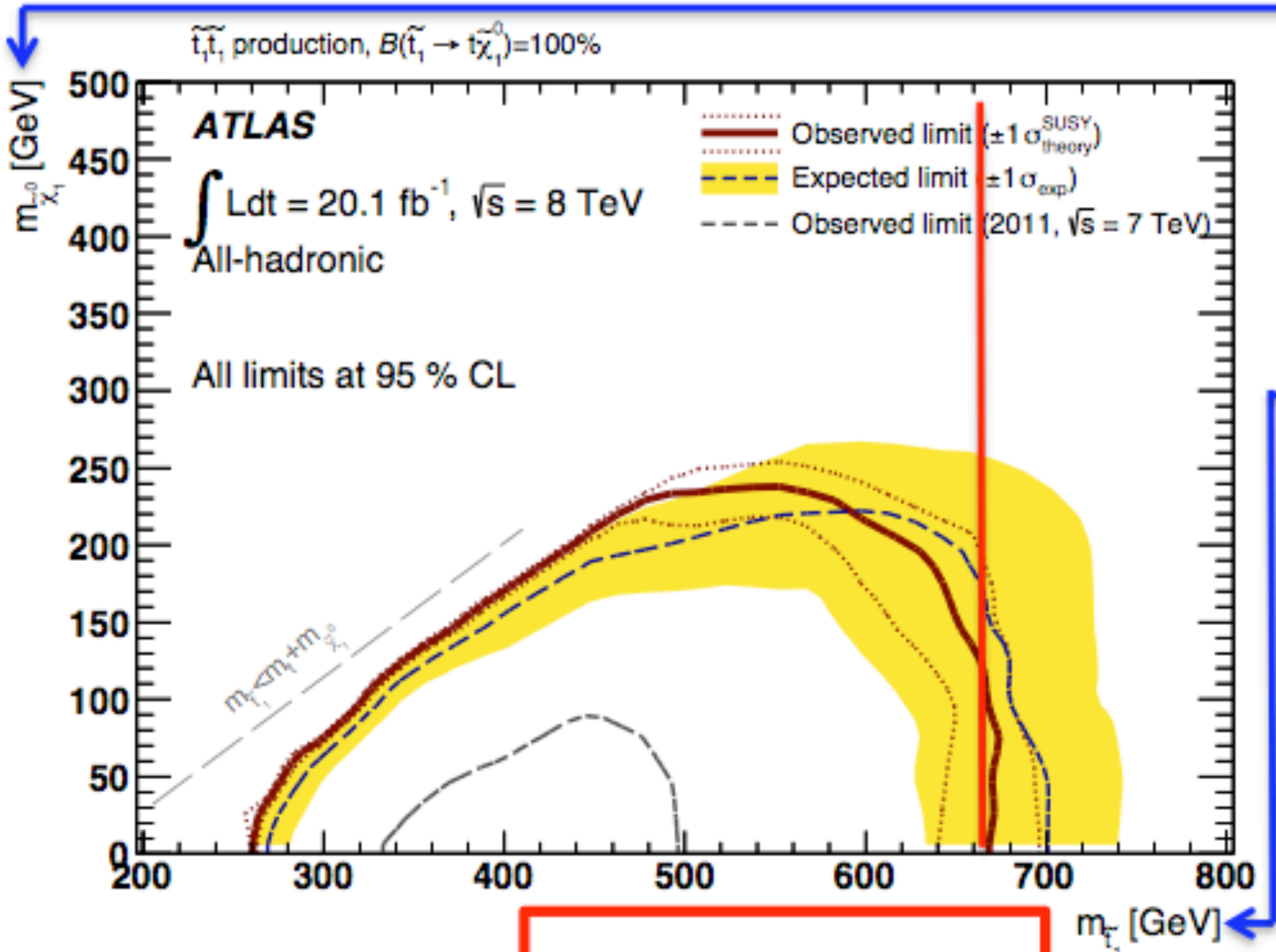
- Some of SRs with fully resolved topology or partially resolved: stop is heavy and very boosted → decay products are merged

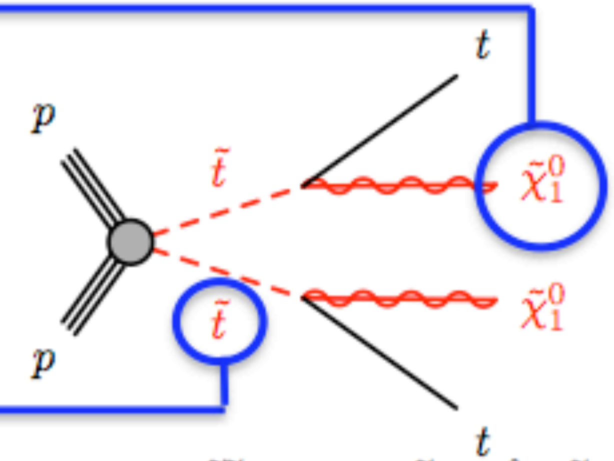


Distributions in the semileptonic $t\bar{t}$ control region of m^0_{bjj} for SRA. The E_T^{miss} distributions for SRA.

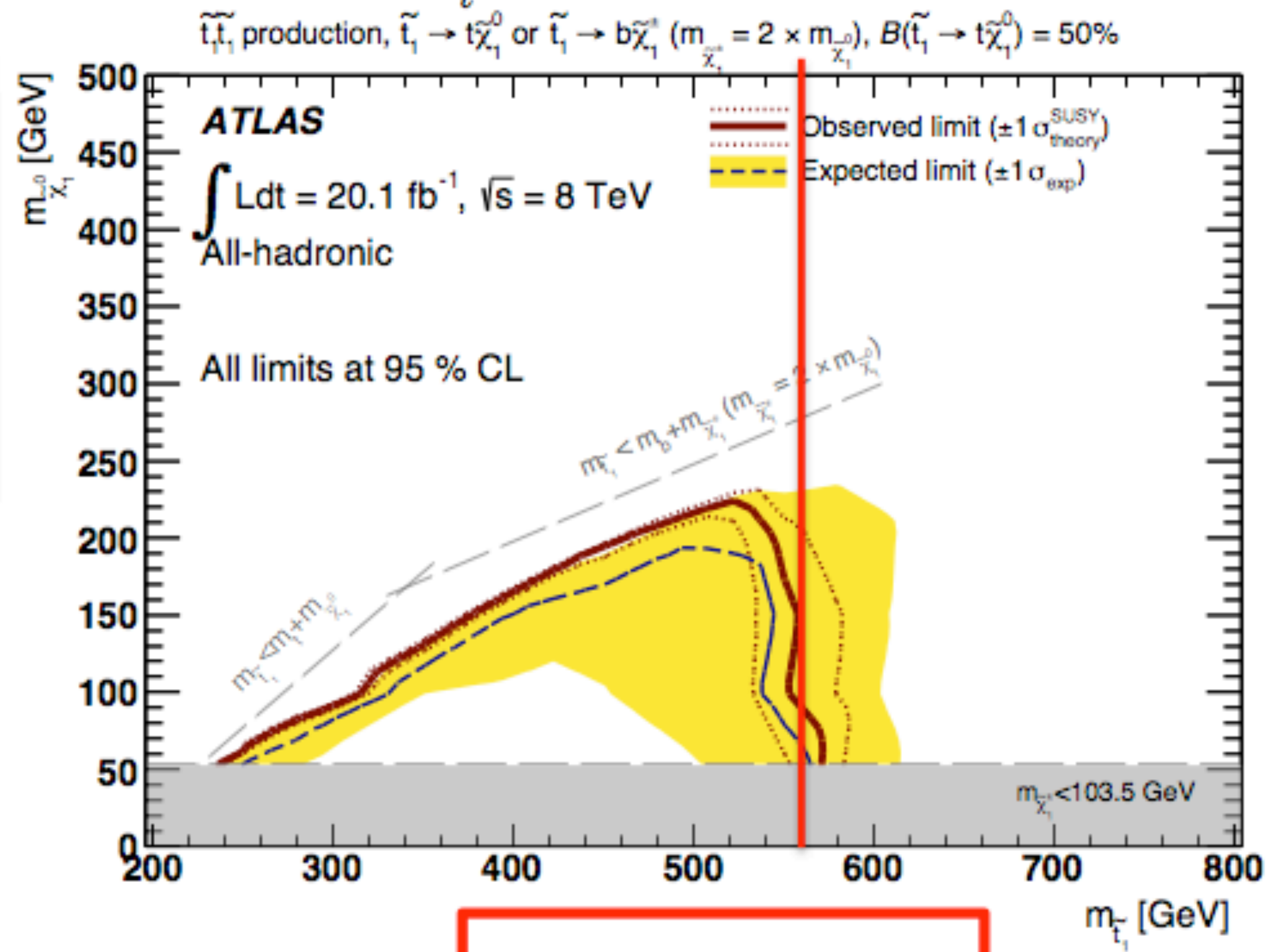
Third generation (8 TeV, 20.3 fb^{-1}) 0/1 lepton + ≥6 (2 b) jets + E_T^{miss}

arXiv: 1406.1122 accepted by JHEP

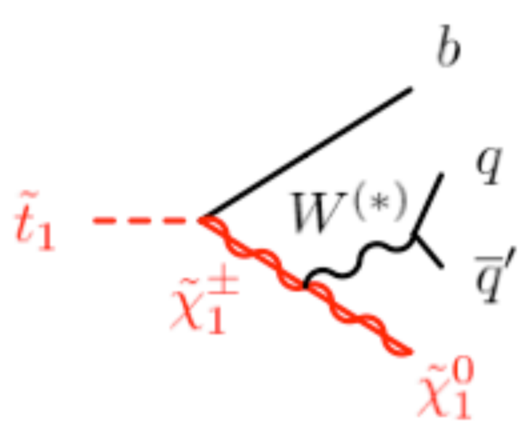


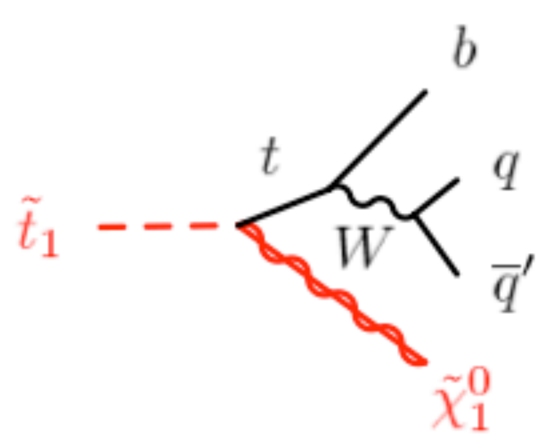


$m_{\tilde{t}}$ > 650 GeV



$m_{\tilde{t}}$ > 550 GeV



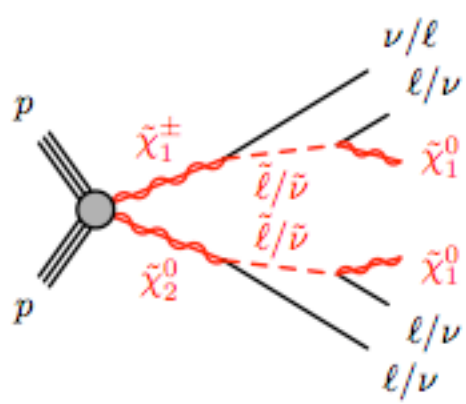


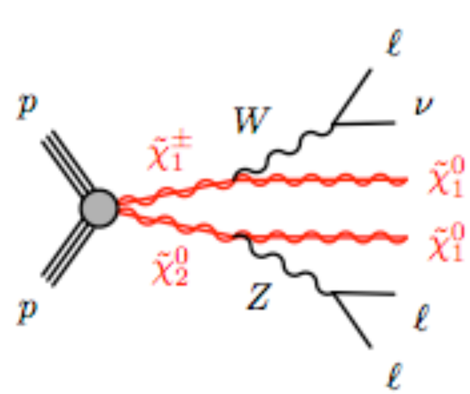
Exclusion contours at 95% CL in the scenario where both top squarks decay exclusively via t ˜→tχ ˜ and the top quark decays hadronically. Exclusion contours at 95 % CL in the scenario where the top squarks are allowed to decay via t ˜ → bχ ˜1±,χ ˜1± → W(∗)χ ˜10

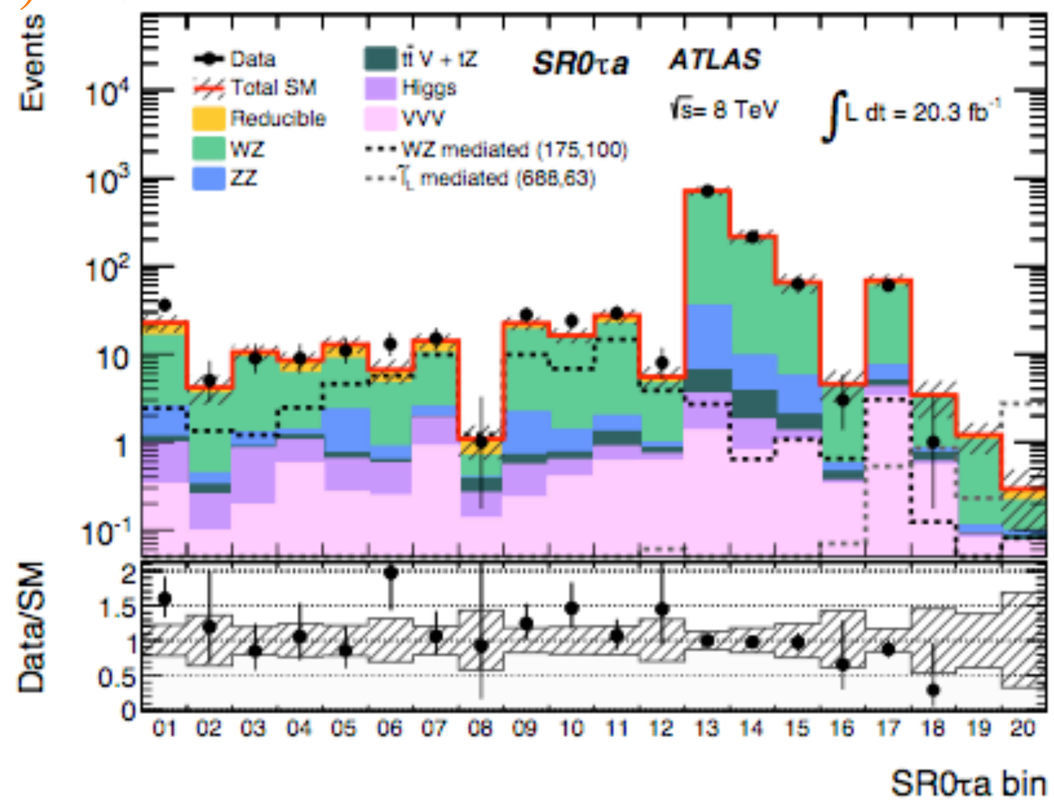
EW production (8 TeV, 20.3 fb^{-1}) 3 leptons (e, μ, τ) + E_T^{miss}

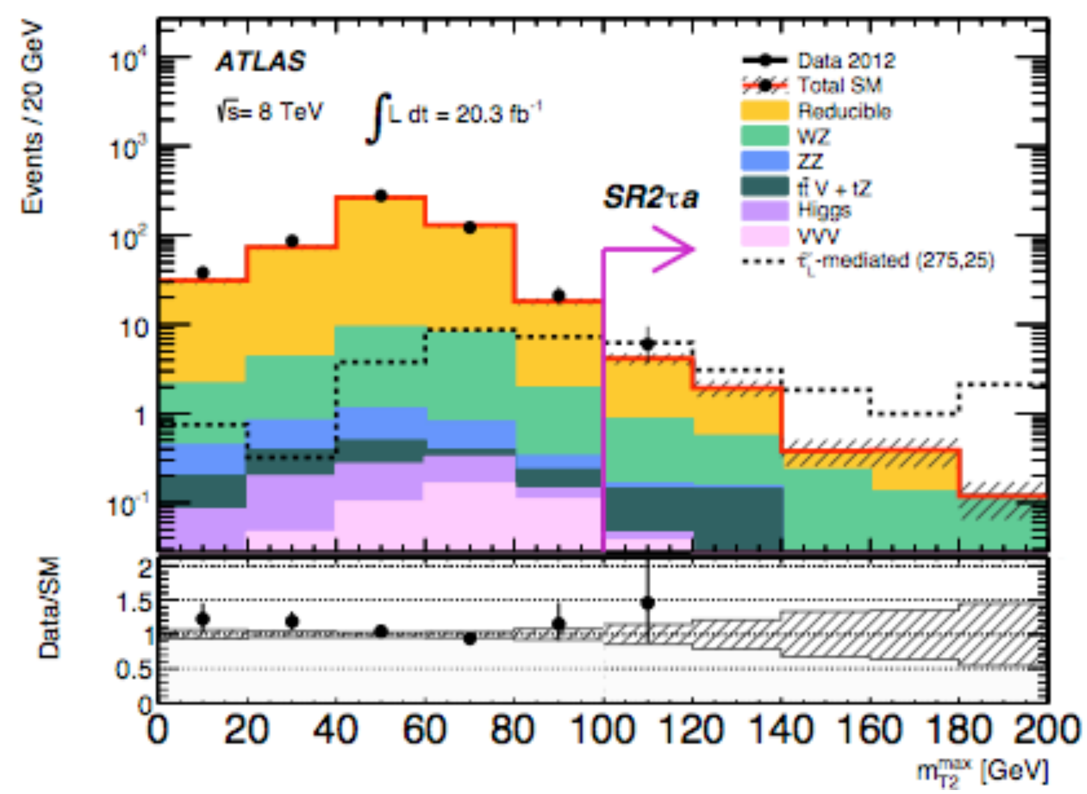
JHEP04 (2014) 169

- EW production has a low cross−section compared to strong production, but could still be the dominant SUSY production process at the LHC if there are $\tilde{q}/\tilde{g}$ heavy
    - Very challenging searches
    - Leads to multi-lepton signatures with very low SM background
- Event selection
    - 3-leptons: e, μ and up to 2τ
    - Loose cut on E_T^{miss}
    - Different signal regions based on the number of τ's









Expected distributions of SM background events and observed data distributions in the binned signal regions SR0τa. Expected distributions of SM background events and observed data distributions for m_{T2}^{max} in SR2τa region prior to the requirements on this variable.

EW production (8 TeV, 20.3 fb^{-1}) 3 leptons (e, μ, τ) + E_T^{miss}

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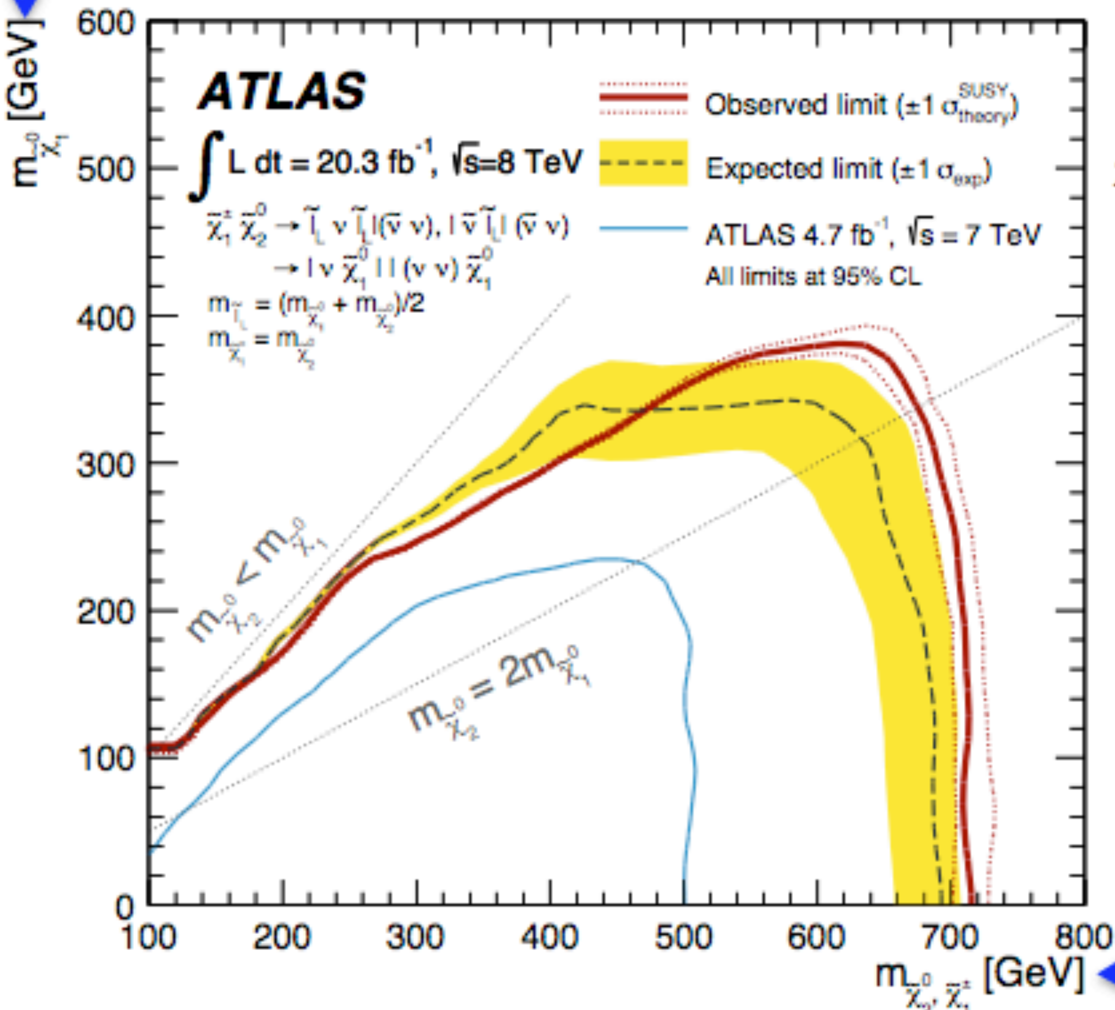
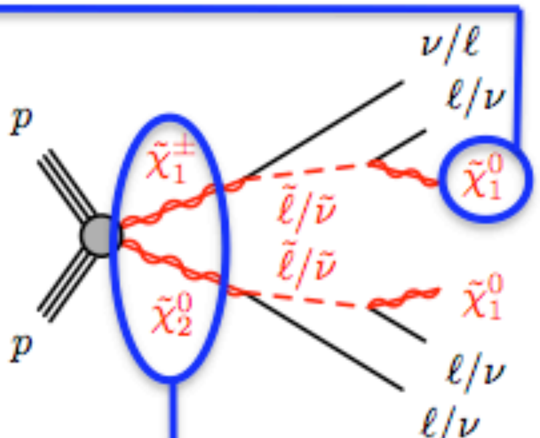
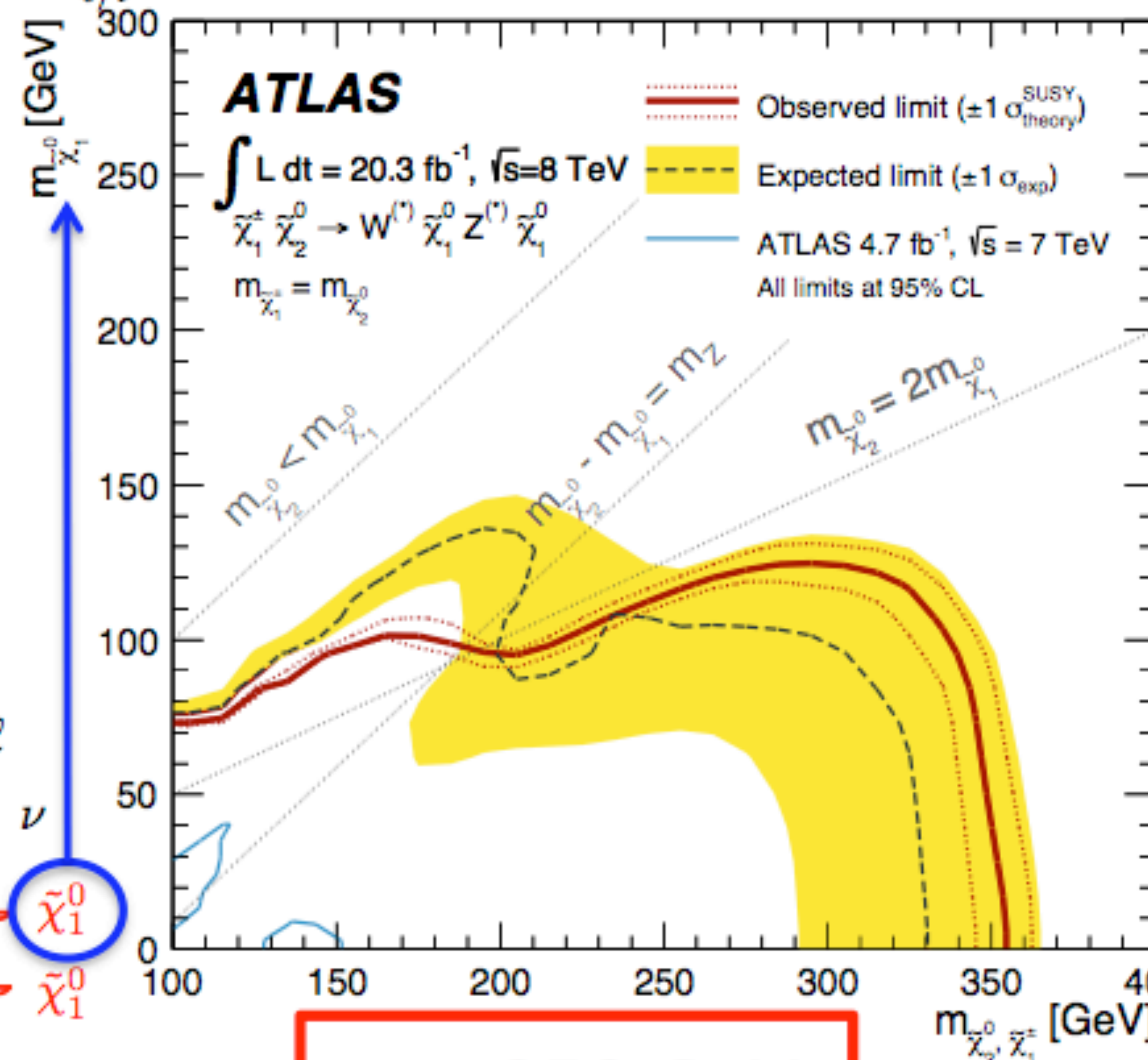
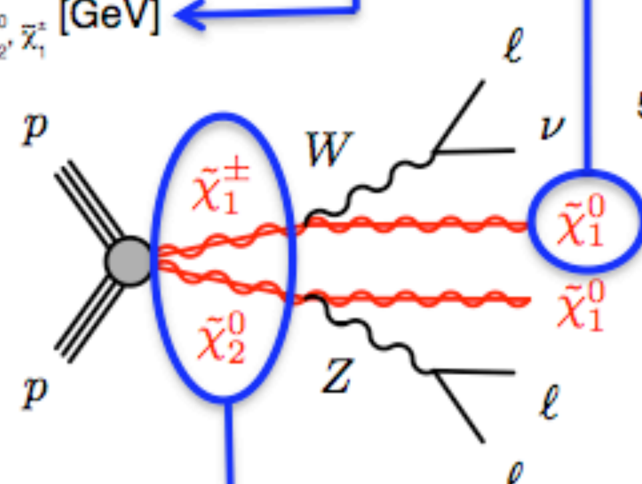








$m_{\tilde{\chi}}$ > 700 GeV

$m_{\tilde{\chi}}$ > 350 GeV

$m(\tilde{\chi}^{\pm}_1) = m(\tilde{\chi}^0_2)$

Observed and expected 95% CL exclusion contours for chargino and neutralino production in the $\tilde{\ell}_L$ mediated and WZ -mediated, simplified models. The band around the expected limit shows the 1σ variations of the expected limit, including all uncertainties except theoretical uncertainties on the signal cross-section.

R-Parity violation (RPV)

R-parity: $R = (-1)^{3(B-L)+2s}$ → $R = \begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$

R-parity conservation hinted but not required by proton stability

Rp conservation	Rp violation
Sparticles produced in pairs	Single sparticle production possible
Neutral and colorless LSP	LSP may be charged and/or carry color
Stable LSP → gives rise to high missing momentum	LSP decays → possibility for new signals • exploit LSP invariant mass • potentially long LSP lifetime • MET may or may not be high

Stable Massive Particles

- **Stable Massive Particles** (SMPs) predicted by many BSM scenarios, including several different SUSY models
- **sleptons** are massive, charged and metastable in GMSB
- **R-hadrons** are **colored** SMPs: bound states formed by **squarks and gluinos** hadronizing with a light SM quarks system, several **electric charges** (and the electric charge can change due to nuclear scattering in the detector)
- **Long-lived** for this search

	composition	notation
R-mesons	$R = \tilde{g}q\bar{q}, (\tilde{q}\bar{q})$	R^+, R^-, R^0
R-baryons	$R = \tilde{g}qqq, (\tilde{q}qq)$	R^{++}, R^+, R^-, R^0
R-gluinoballs	$R = \tilde{g}g$	R^0

arXiv:hep-ph/0611040

SMP	LSP	Scenario	Conditions
$\tilde\tau_1$	$\tilde\chi^0_1$	MSSM	$\tilde\tau_1$ mass (determined by $m^2_{\tilde\tau_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde\chi^0_1$ mass.
	$\tilde G$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde g$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde\tau_1$	MSSM	Small $m_{\tilde\tau_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde g$MSB	Generic in minimal models.
$\tilde\ell_{i1}$	$\tilde G$	GMSB	$\tilde\tau_1$ NLSP (see above). $\tilde e_1$ and $\tilde\mu_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde\tau_1$	$\tilde g$MSB	$\tilde e_1$ and $\tilde\mu_1$ co-LSP and also SMP when stau mixing small.
$\tilde\chi^+_1$	$\tilde\chi^0_1$	MSSM	$m_{\tilde\chi^+_1} - m_{\tilde\chi^0_1} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde g$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde g$	$\tilde\chi^0_1$	MSSM	Very large $m^2_{\tilde q} \gg M_3$, e.g. split SUSY.
	$\tilde G$	GMSB	SUSY GUT extensions [25–27].
	$\tilde g$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde t_1$	$\tilde\chi^0_1$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde q}$ and M_3, small $\tan\beta$, large A_t.
$\tilde b_1$			Small $m^2_{\tilde q}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

R-Hadrons (7 + 8 TeV, 24.8 fb^{-1})

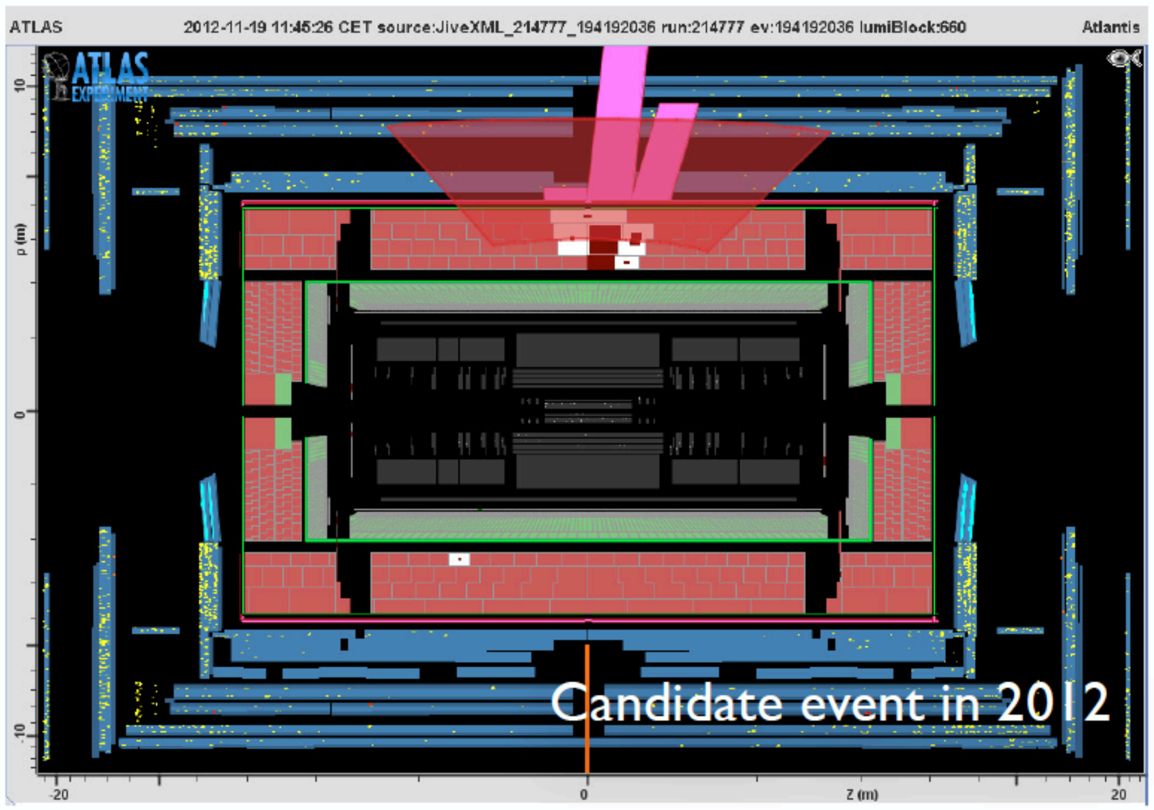
Phys Rev D 88 112003

- Signature to explore
  - R-hadrons WITH low β and "stop" in the detector; Then they decay much later
  - Look for energetic jets (from R-hadron decays) in "empty bunches"

- Selection
  - Events trigger in empty bunches, containing large calorimeter activity
  - Offline jet with E_T>100(300) GeV and |eta|<1.2
  - Muon activity veto to remove cosmic/beam-halo backgrounds

- Background
  - Mainly comes from cosmic, noise and beam halo interactions
  - Estimated using low-luminosity data (cosmic) and unpaired crossings (beam halo)

•No excess observed → A limit of > 545-784 GeV (depending on the interaction model) is set for $10^{-6}<\tau<10^{3}$ s

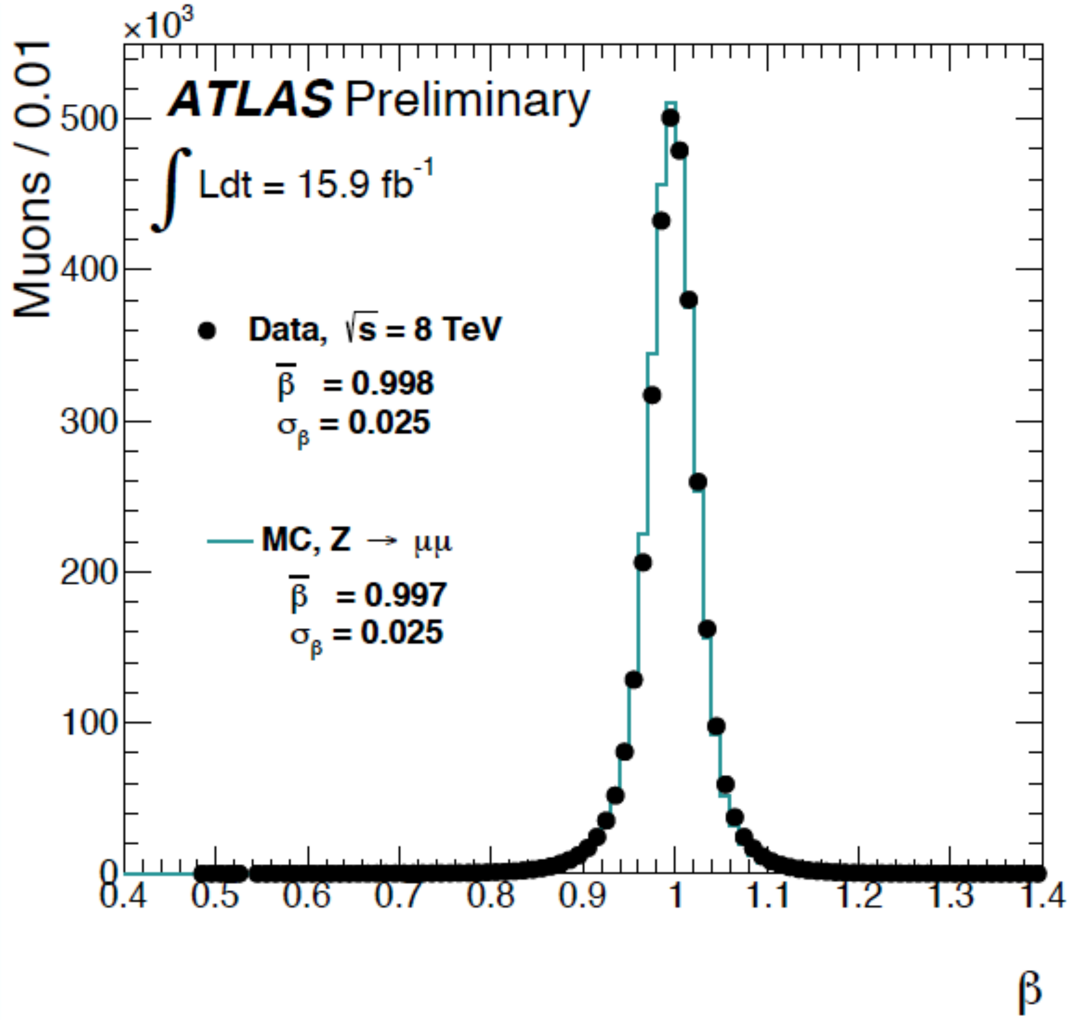


Leading jet energy (GeV)	R-hadron model	Gluino/squark decay	Neutralino mass (GeV)	Gluino/squark mass limit (GeV) Expected	Observed
100	Generic	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	$m_{\tilde{g}} - 100$	526	545
100	Generic	$\tilde{g} \to t\bar{t} + \tilde{\chi}^0$	$m_{\tilde{g}} - 380$	694	705
300	Generic	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	731	832
300	Generic	$\tilde{g} \to t\bar{t} + \tilde{\chi}^0$	100	700	784
300	Intermediate	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	615	699
300	Regge	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	664	758
100	Generic	$\tilde{t} \to t + \tilde{\chi}^0$	$m_{\tilde{t}} - 200$	389	397
100	Generic	$\tilde{t} \to t + \tilde{\chi}^0$	100	384	392
100	Regge	$\tilde{t} \to t + \tilde{\chi}^0$	100	371	379
100	Regge	$\tilde{b} \to b + \tilde{\chi}^0$	100	334	344

Slow massive charged particles (8 TeV, 15.9 fb^{-1})

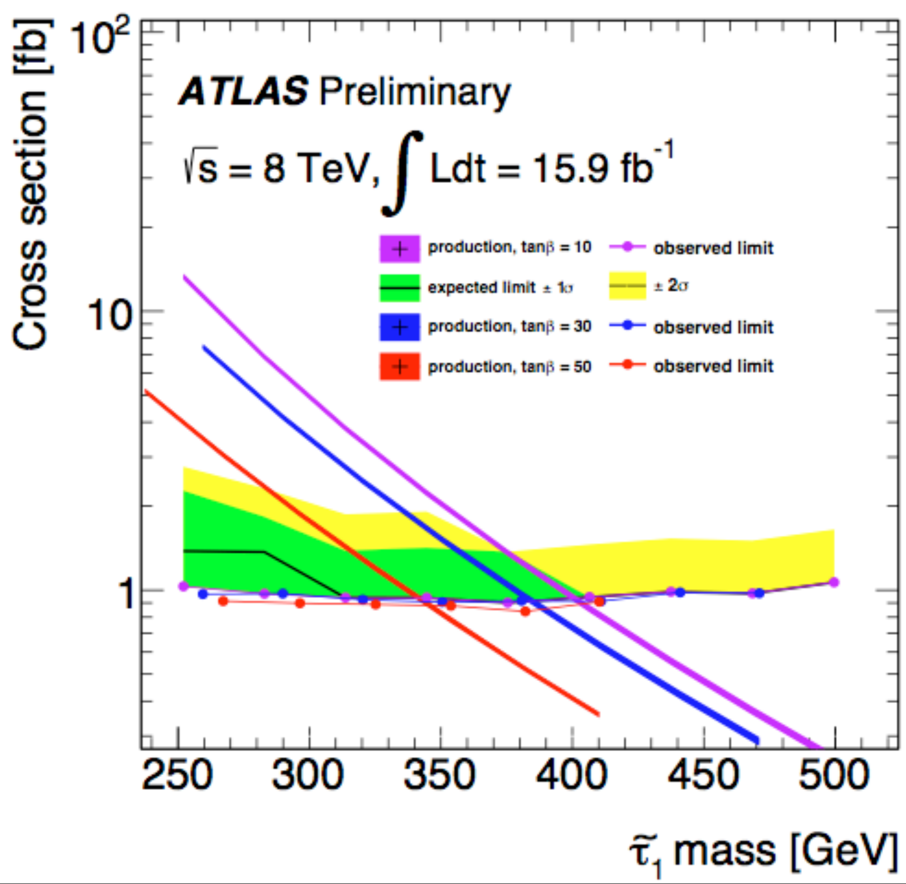
ATL-CONF-2013-058

- Nearly-stable NSLP staus in GMSB observed as "slow heavy muons"
- Select slow muon-like particles with p_T>50 GeV, β<0.95 and mass $m = p/\beta\gamma$
- Momentum p taken from track, β measured by muon detector (also required to be consistent with the calorimeter-based measurement)
- After selection, background is mainly due to high-p_T μ with mis-measured β
  - estimated by generating combination of the momentum of a candidate track with a randomly extracted β from muon-β distribution



Distribution of the combined measurement for selected muons in data and Z → μμ decays in MC simulation. The typical resolutions are 0.025.

- Significant signal-to-background ratios expected in two-track-candidates events
- No excess above SM expectation.
- Interpretations in context of GMSB:
  - stau mass >402–347 GeV (tanβ=5-50)
  - stau mass >267 GeV (assuming direct pair production)



Cross-section limits as a function of the stau mass in GMSB models

Exotics grand summary

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow WW \rightarrow \ell\nu\ell\nu$	2 e, μ	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow \ell\ell qq$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e, μ	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	2 γ	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\,\ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \rightarrow t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \rightarrow t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	0 e, μ	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \rightarrow Ht + X$	1 e, μ	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \rightarrow Zt + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \rightarrow Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \rightarrow Wt + X$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	2 e, μ	–	–	5.8	$N^\pm$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2 e, μ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \rightarrow \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1g_D$	1207.6411

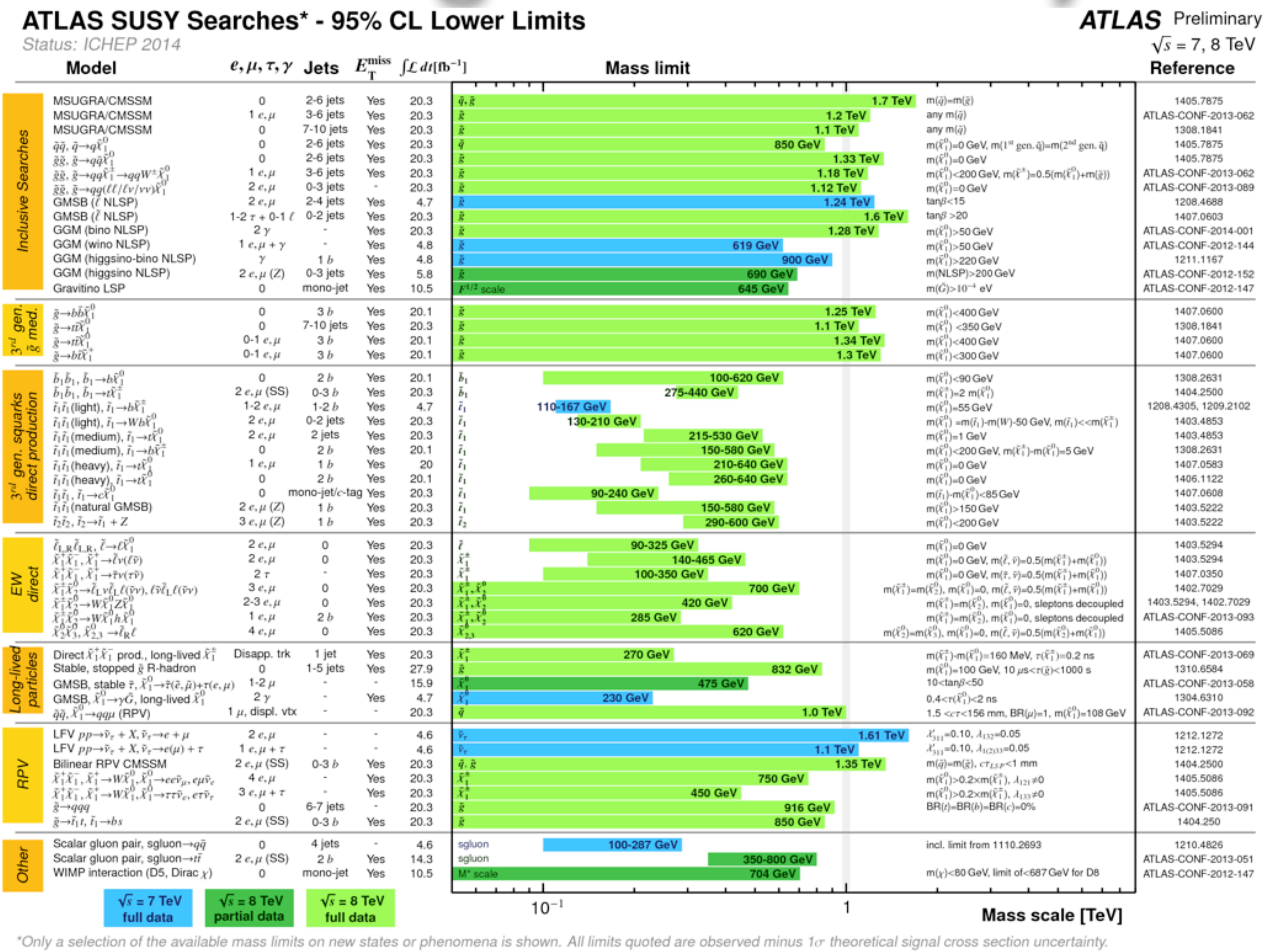
$\sqrt{s} = 7$ TeV | $\sqrt{s} = 8$ TeV

Mass scale [TeV]: 10^{-1}, 1, 10

*Only a selection of the available mass limits on new states or phenomena is shown.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

SUSY grand summary



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Summary

- Run1 at the LHC was very successful
    - more than 5+20 fb^{-1} collected by ATLAS
- Long list (but far to be exhaustive) of new physics analyses and results presented in this talk
- New or stronger limits have been established
- While we complete the Run 1 program, eagerly awaiting data at higher energy
    - Searches for high-mass objects will be more sensitive with only a few fb^{-1}
    - New challenges to meet with higher energy, luminosity:
        - Increased emphasis on boosted topologies
        - Sensitivity to rare SM processes as backgrounds
    - Expected Mass Limits [TeV] from the Collider Reach Tool [Salam, Weiler]
        - Extrapolations using parton luminosities
        - Assume sensitivity scales directly with signal yield

	8 TeV	14 TeV			
	20 fb^{-1}	3 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Vector-like quarks	0.7	0.8	1.2	1.7	2.2
$W' \to VV$	1.5	1.3	2.3	3.3	4.4
$W' \to ff$	2.0	2.1	3.2	4.2	5.4
$W' \to \ell\nu$	3.2	4.1	5.2	6.3	7.3
Excited quarks	3.2	4.1	5.2	6.3	7.3
Black Holes	5.0	8.2	8.5	9.0	10

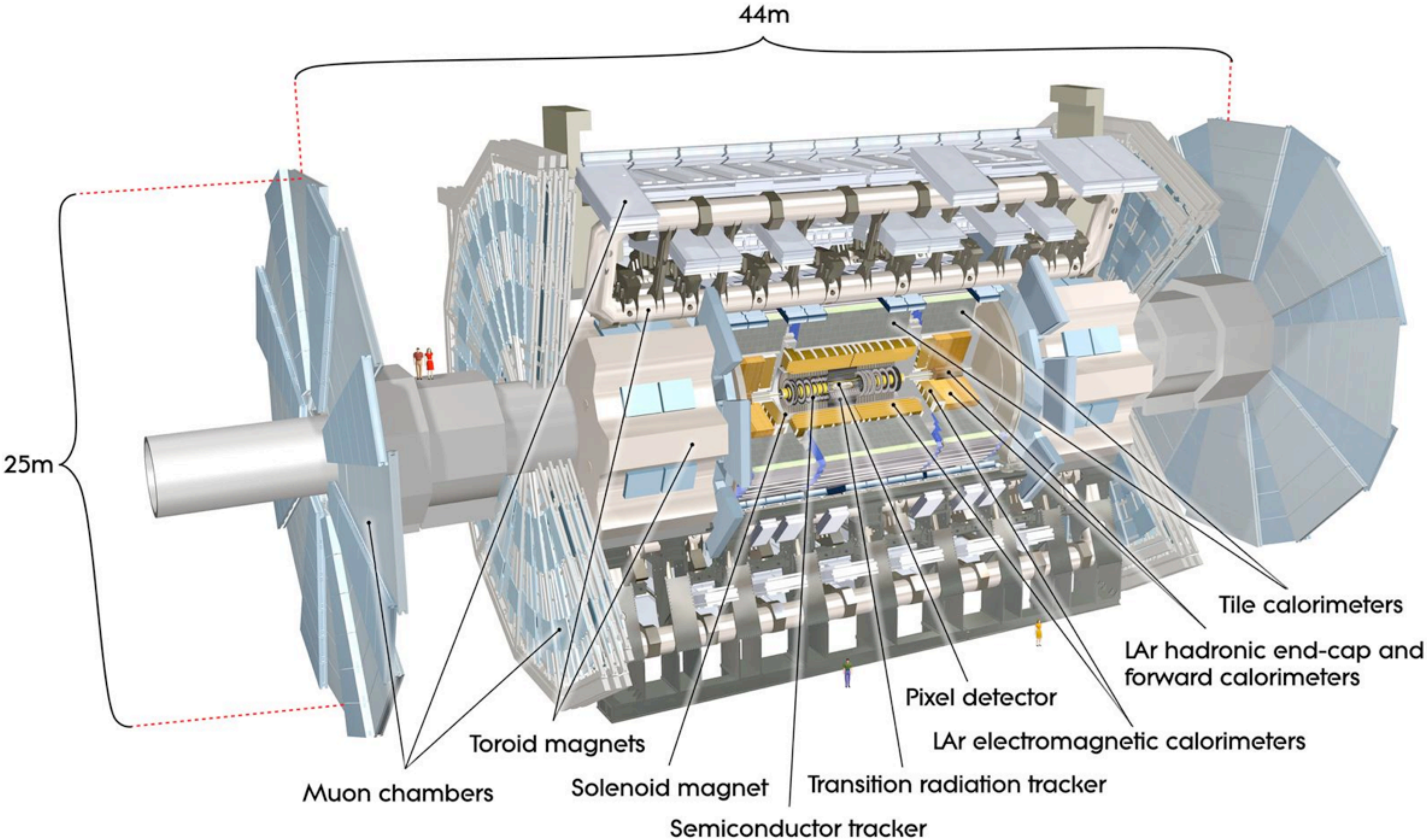
No particle left behind...

I have focused on mass reach, but of course that is not the only story: couplings can always be dialed down, either in production or decay.

New physics could be hiding in "excluded" regions.

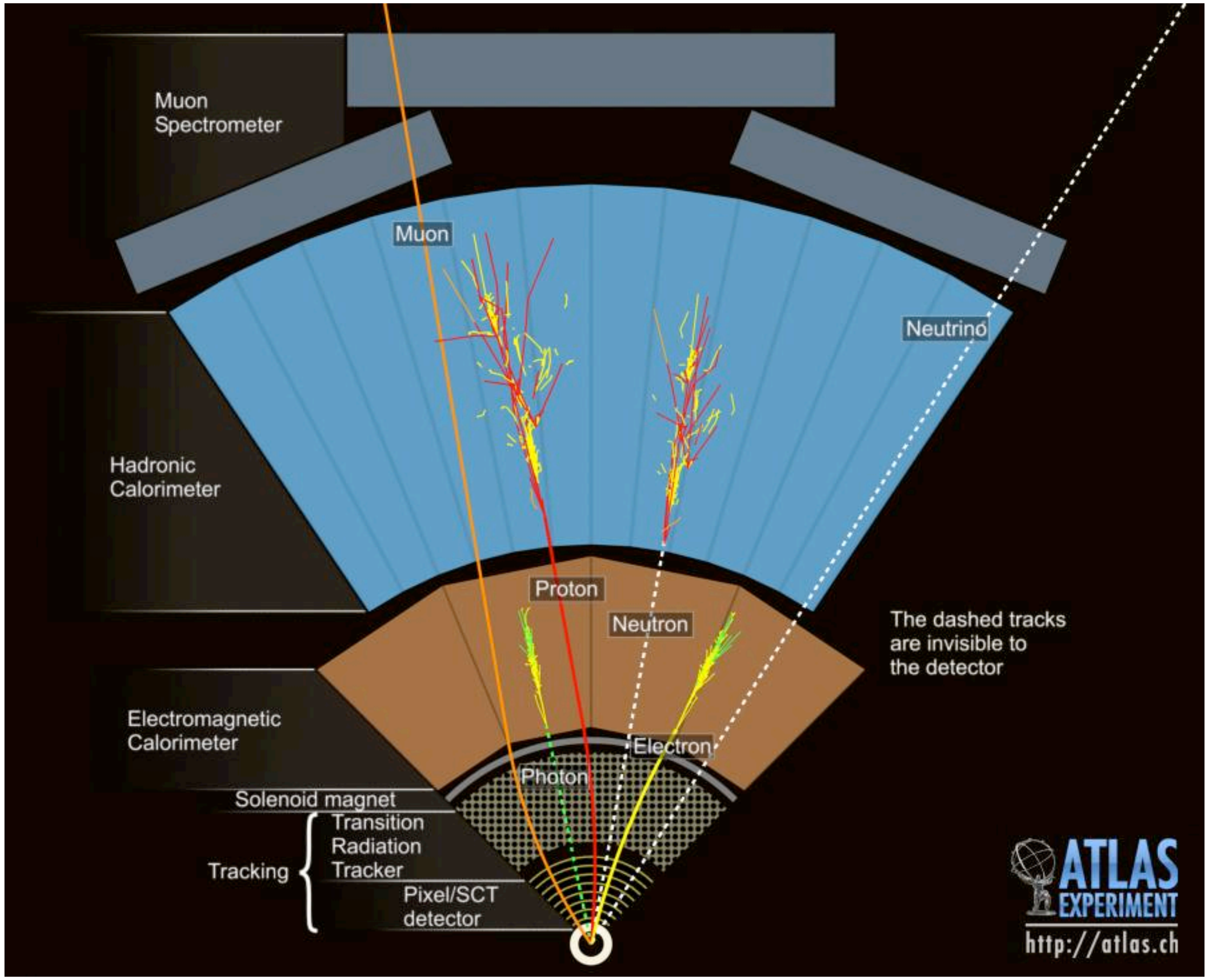
Extra

The ATLAS detector



Physics objects

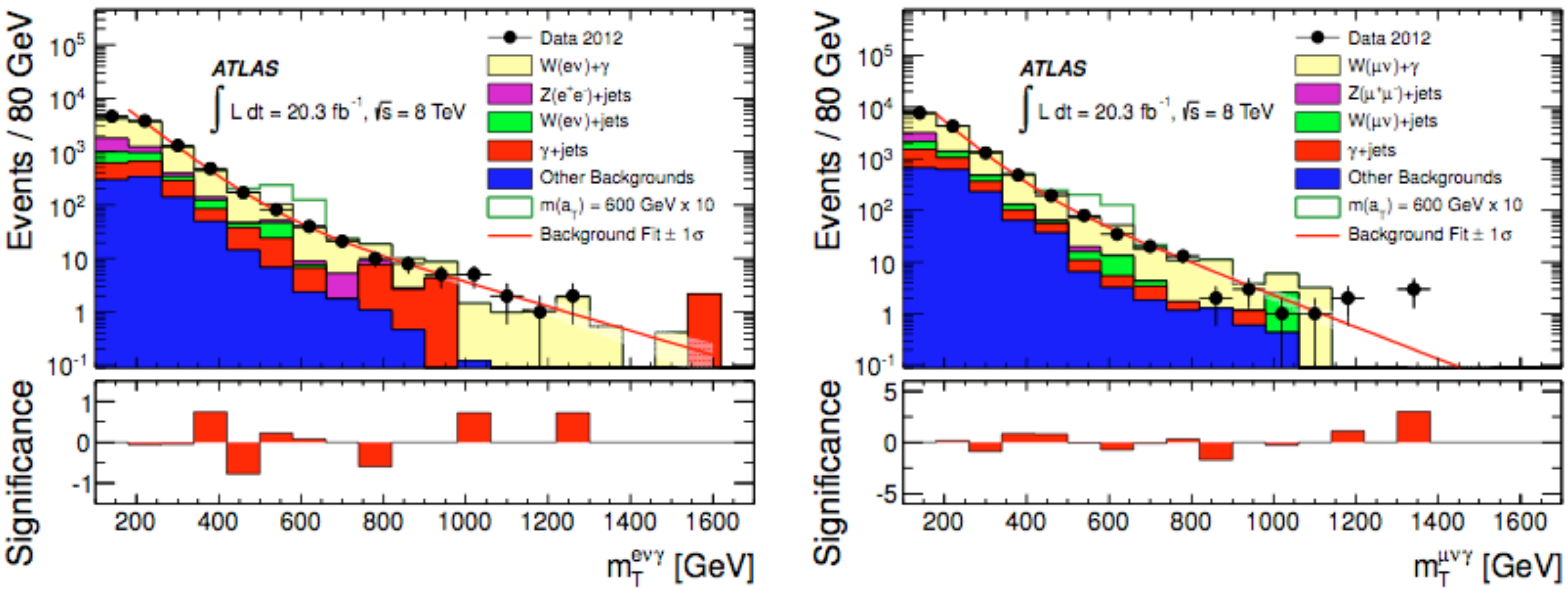
- Jet: cluster in EM and hadronic calorimeters (and Inner Detector)
- Photon: EM cluster without matching track
- Electron: EM cluster with matching track
- Muon: matching tracks in inner and muon trackers, or muon standalone extrapolated to interaction point
- Tau: Narrow jet with matching track(s)
- MET (missing E_T): p_T required to balance all of the above (and more)



Resonances in Wγ and Zγ final state (8 TeV, 20.3 fb^{-1})

arXiv: 1407:8150 submitted to Phys. Lett. B

- Low Scale Technicolor (LSTC) model is used as a benchmark model for the search for spin-1 resonances decaying to Wγ and Zγ
- The lνγ candidate events are selected by requiring exactly one lepton with p_T>25 GeV, at least one photon with E_T>40 GeV and E_T^{miss} above 35 GeV.
- The llγ candidates are selected by requiring two oppositely charged same flavor leptons with an invariant mass between 65 and 115 GeV, and at least one photon with E_T>40 GeV
- No excess of events observed → Masses of the hypothetical a_T and ω_T states of the benchmark LSTC are excluded in the ranges [275;960] GeV and [200;700]U[750;890] GeV, respectively

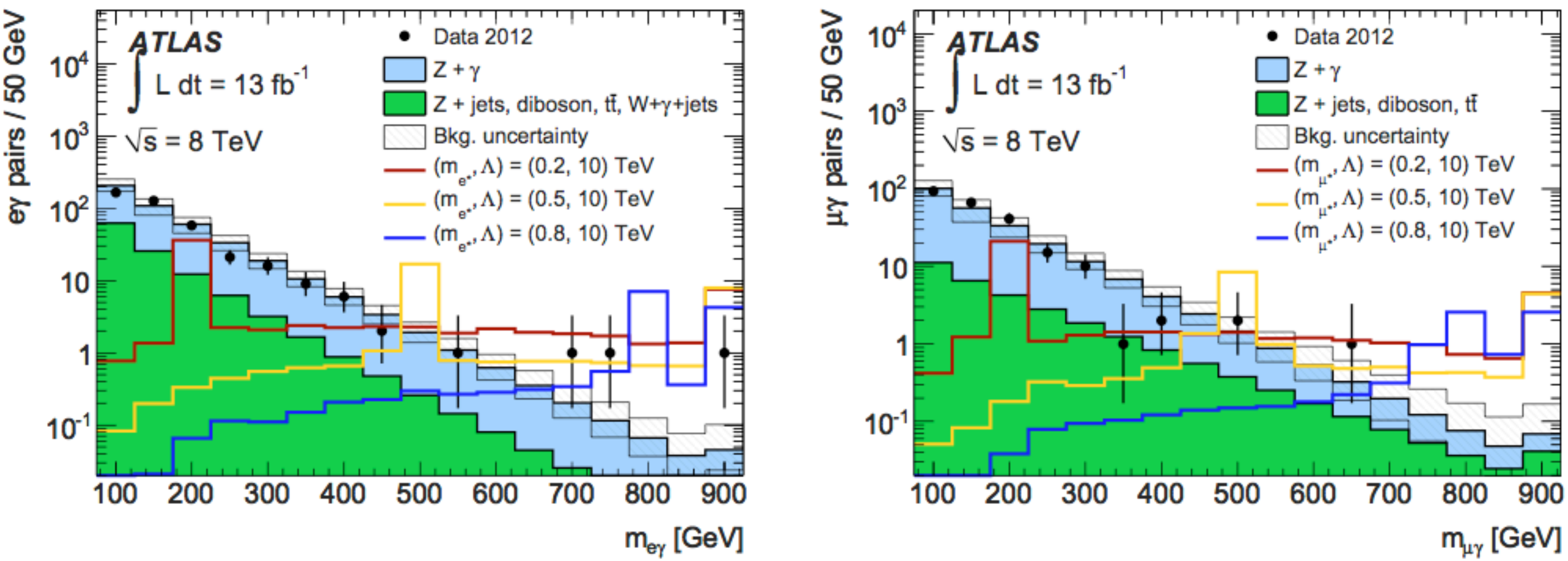


Three-body transverse mass distribution for the eνγ and μνγ final states. The expected signal for a resonance mass of 600 GeV is superimposed.

Excited leptons (8 TeV, 13 fb^{-1})

NJP 15 (2013) 093011

- $e\gamma$ resonance in $ee\gamma$ events or $\mu\gamma$ in $\mu\mu\gamma$ events: excited leptons production via four-fermion contact interaction
- Limits as a function of excited lepton mass m_{l^*} and compositeness scale Λ
- Limits for $\Lambda = m_{l^*}$: m_{l^*} > 2.2 TeV

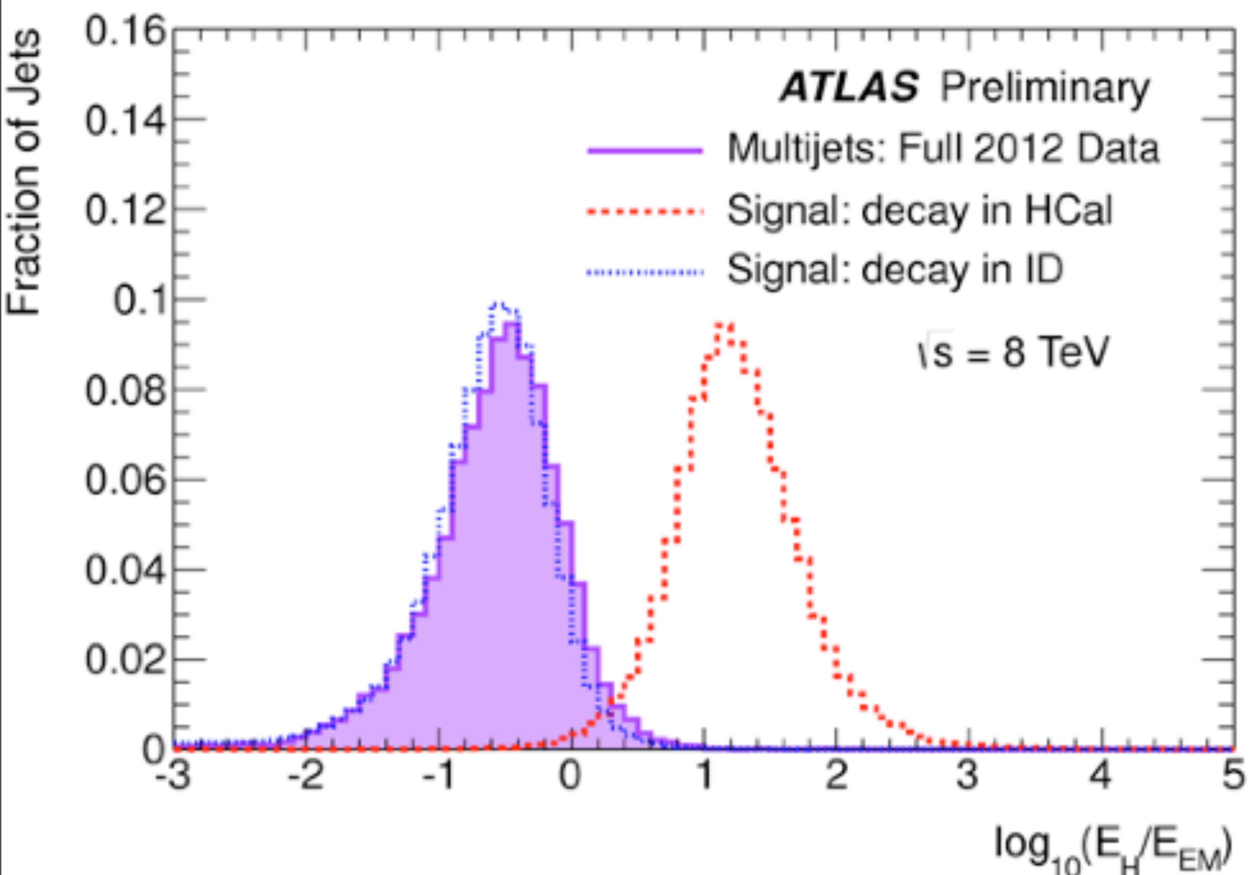


Distributions of the invariant mass for the electron and muon channels. Signal predictions for three different values of the excited-lepton mass with a compositeness scale of 10TeV are also shown.

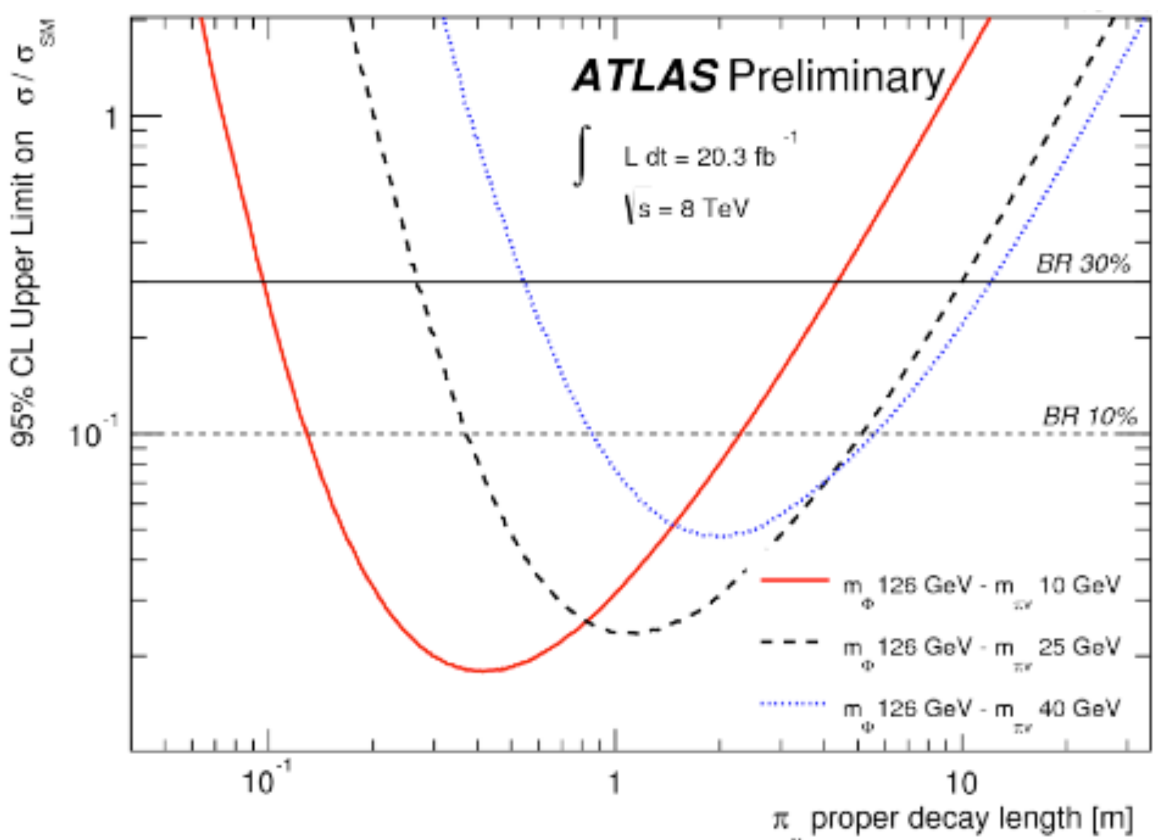
LLNP decaying to displaced heavy fermion pairs (8 TeV, 20.3 fb^{-1})

ATLAS-CONF-2014-041

- Light Higgs boson decays to two long-lived neutral particles (π_v); Then $\pi_v \rightarrow$ bb, cc or ττ
- Events selection
  - specialized calorimeter trigger: Jet with high Had/EM calorimeter energy ratio and E_T> 60GeV
  - Jets must have log10(Had/EM) > 1.2
  - No good tracks in ID with PT>1GeV
- Main background SM QCD jets estimated with data driven matrix method
- No excess of events observed → 95% CL limits as a function of the proper decay length of the π_v assuming 100% BR of $h \rightarrow \pi_v \pi_v$



Distribution of jet $\log_{10}(E_H/E_{EM})$



Observed 95% CL limits on σ×BR for a light Higgs boson with 125 GeV mass and three different π_v masses as a function of the π_v proper decay length

Disappearing track (8 TeV, 20.3 fb^{-1})

Phys Rev D 88 112006

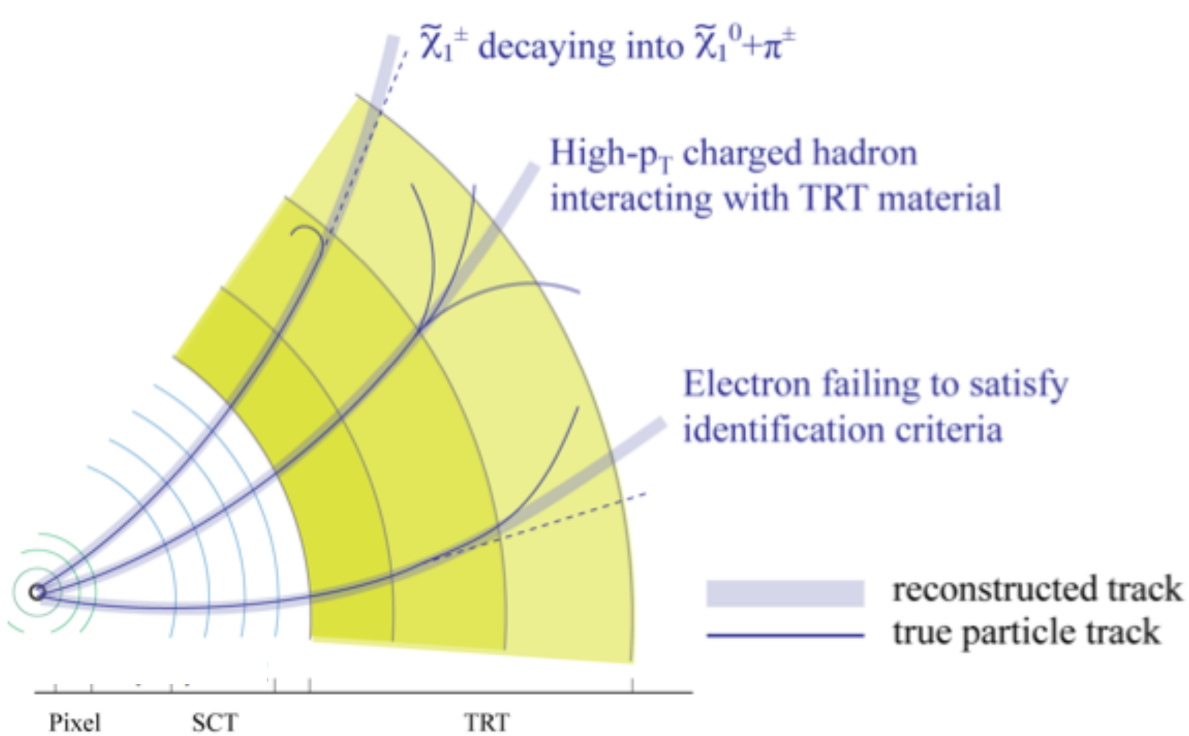
- If the lowest gauginos are approximately mass-degenerate (predicted, eg, by AMSB),
- $\tilde{\chi}_1^{\pm}$ has lifetime $\mathcal{O}$(0.1ns) and decays to $\tilde{\chi}_1^0$ and a (~100 MeV) $\pi^{\pm}$
- Look for production processes:

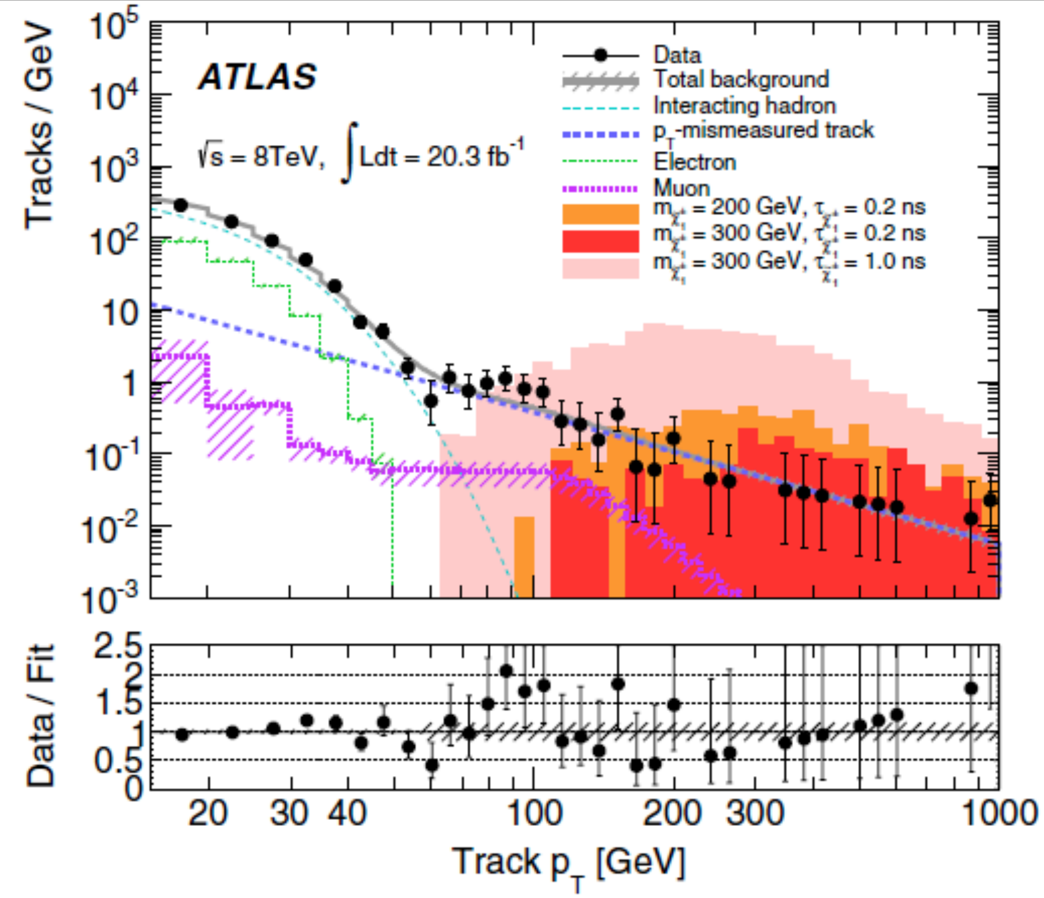
$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0} + jet \quad pp \to \tilde{\chi}_1^{+}\tilde{\chi}_1^{-} + jet$$

  - (jet from ISR, needed to trigger on event).

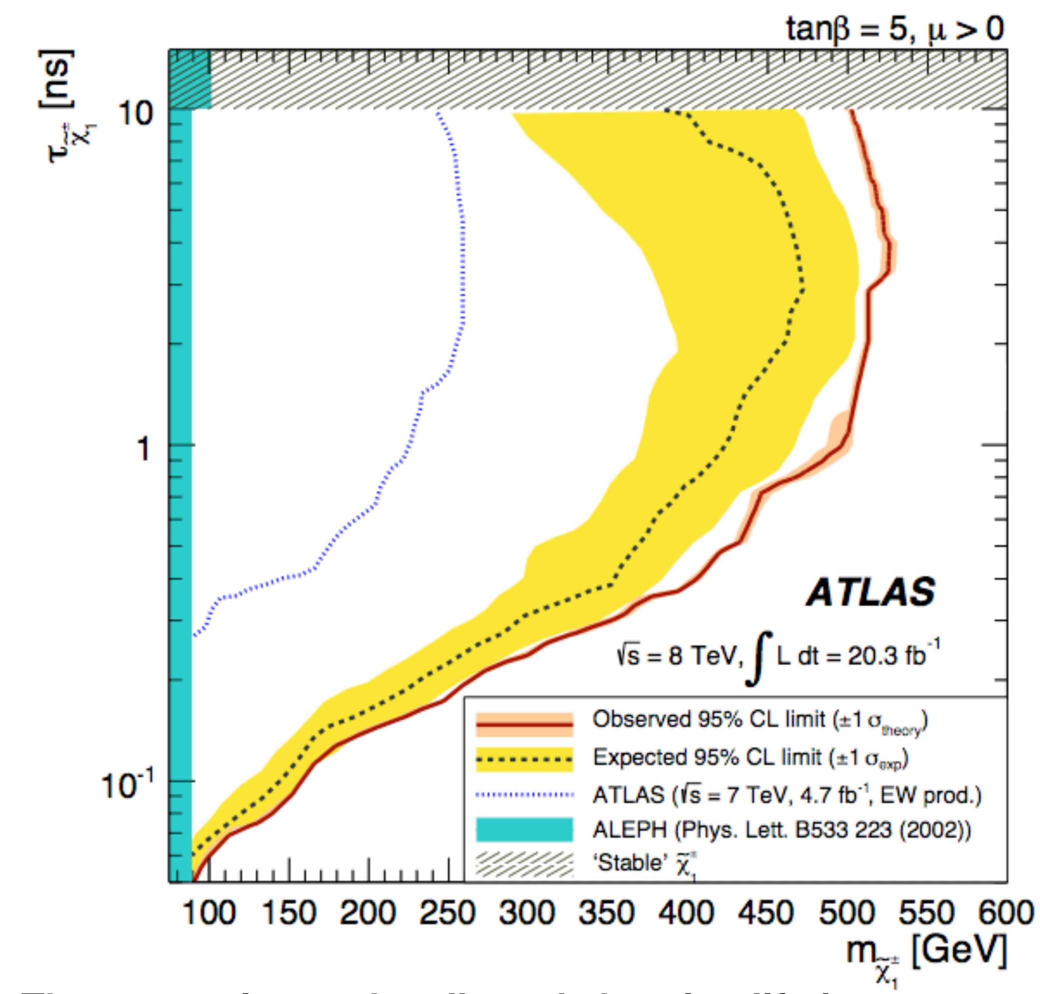
Main BG:

1. High p_T charged hadrons interacting in the TRT (80%)
2. Low p_T tracks performing large bremsstrahlung





The p_T distribution of disappearing track candidates



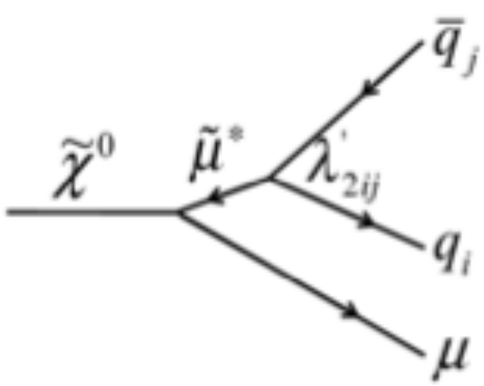
The constraint on the allowed chargino lifetime-mass space

Displaced vertices with tracks + muons SMPs (8 TeV, 20.3 fb^{-1})

ATLAS-CONF-2013-092

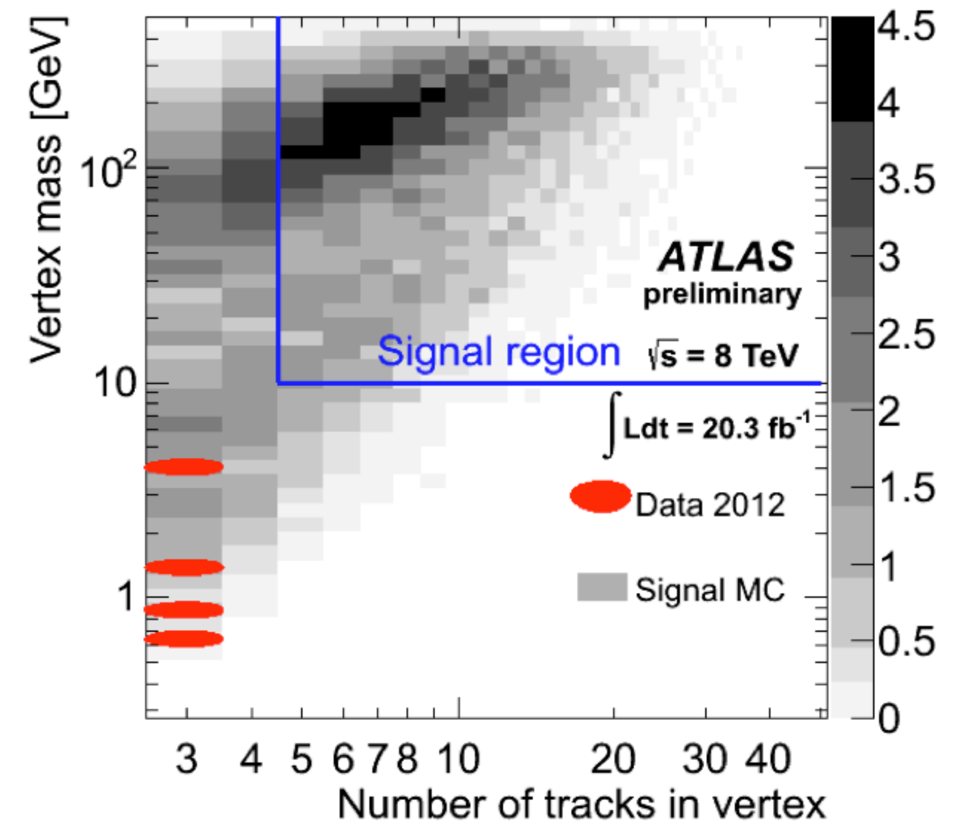
• If particle has lifetime O(few ns), it can decay inside the tracking detector, producing a vertex at a distance away from the primary vertex

• E.g. RPV SUSY with non−zero but small λ_{211}
  - Neutralino decays to muon plus jets
  - Muon is useful for triggering and background rejection
  - High track multiplicity helps vertex reconstruction
  - Dedicated vertex reconstruction

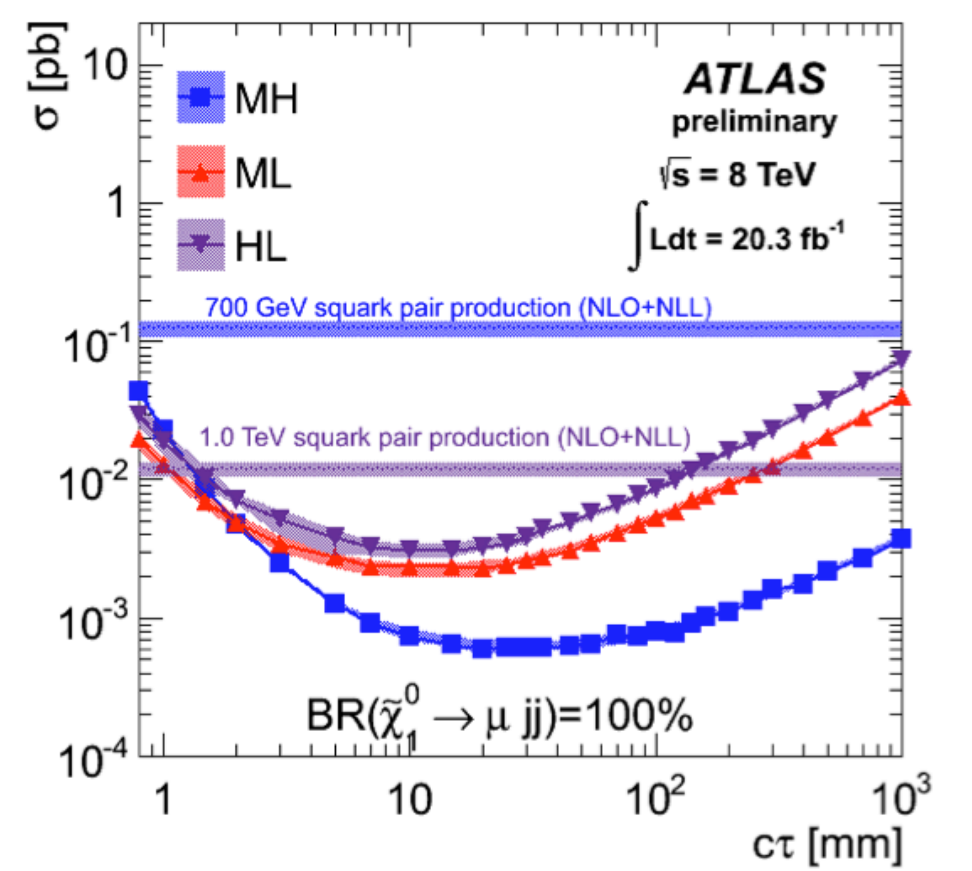


• Background is random combinations of tracks inside the beam pipe and high mass tail of distribution of real vertices from hadronic interactions with the detector material

• No events in the signal region are observed and limits are set on the production cross section for supersymmetric particles (assuming 100% branching fraction)

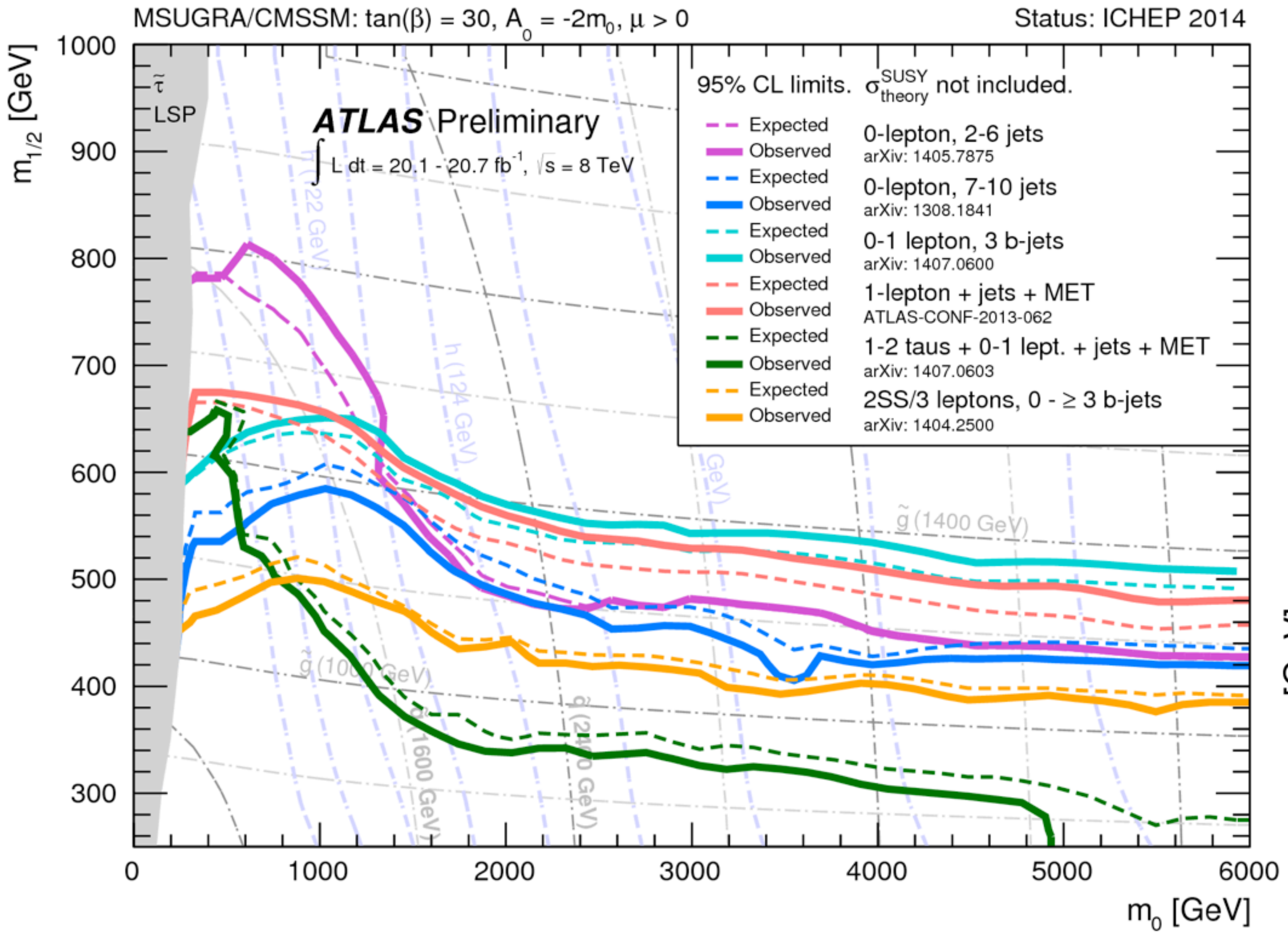


Vertex track multiplicity for reconstructed vertices

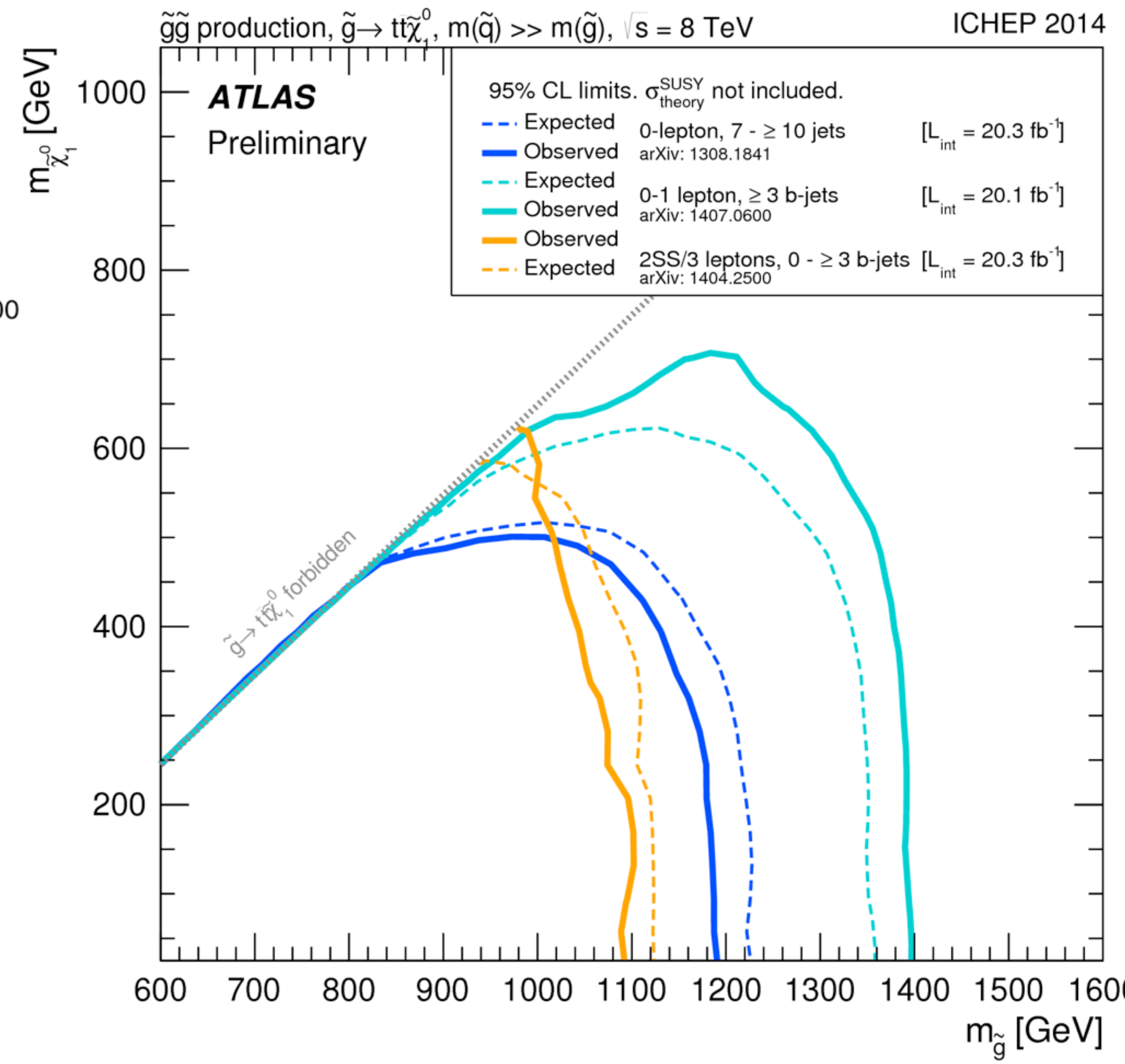


Upper limits at 95% CL on σ vs the neutralino lifetime for different combinations of squark and neutralino masses

Supersymmetry ATLAS summary plots

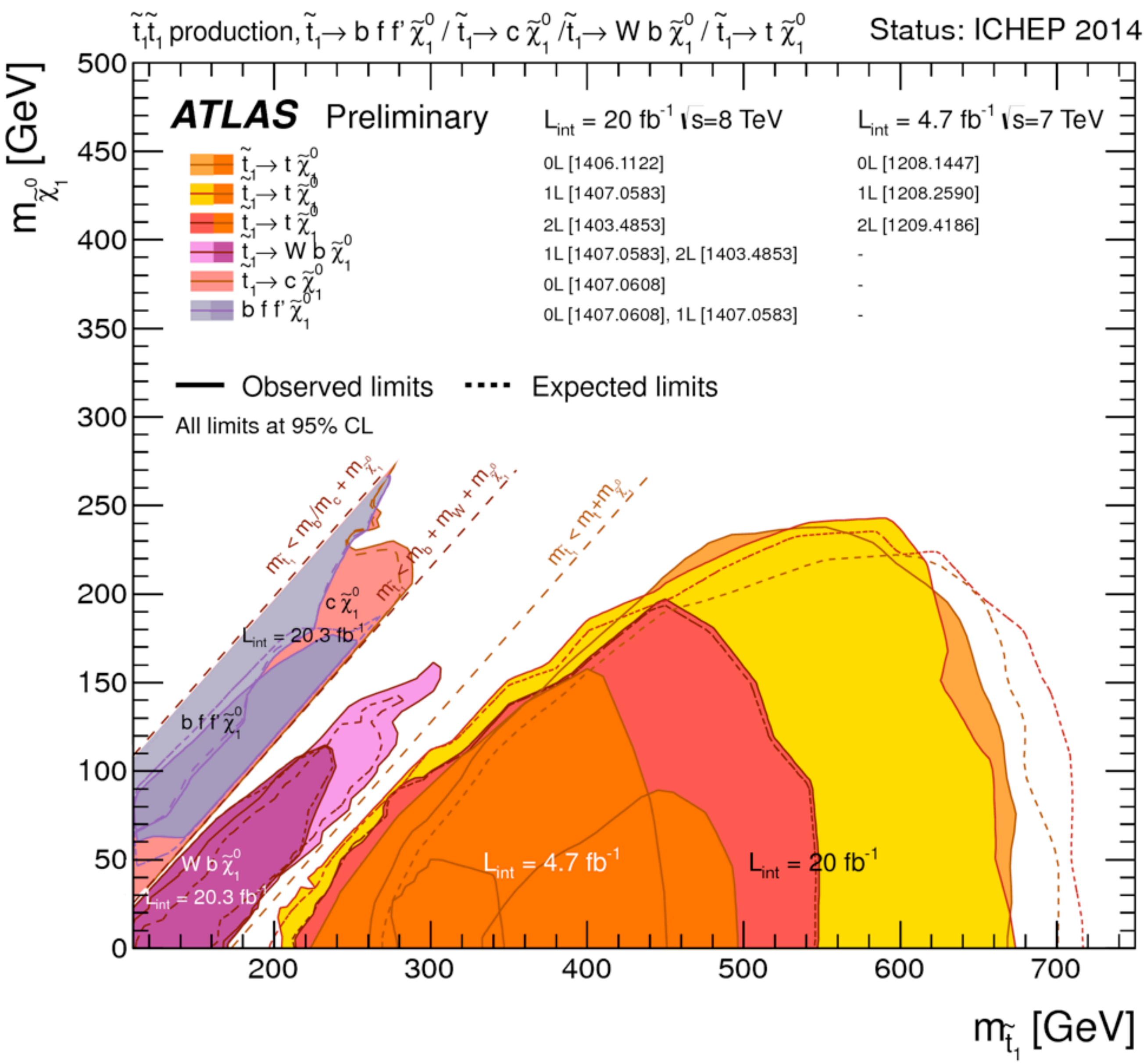


Exclusion limits at 95% CL for 8 TeV analyses in the (m_0, $m_{1/2}$) plane for the MSUGRA/CMSSM model with the remaining parameters set to tan(β) = 30, $A_0 = -2m_0$, μ > 0. Part of the model plane accommodates a lightest neutral scalar Higgs boson mass of 125 GeV

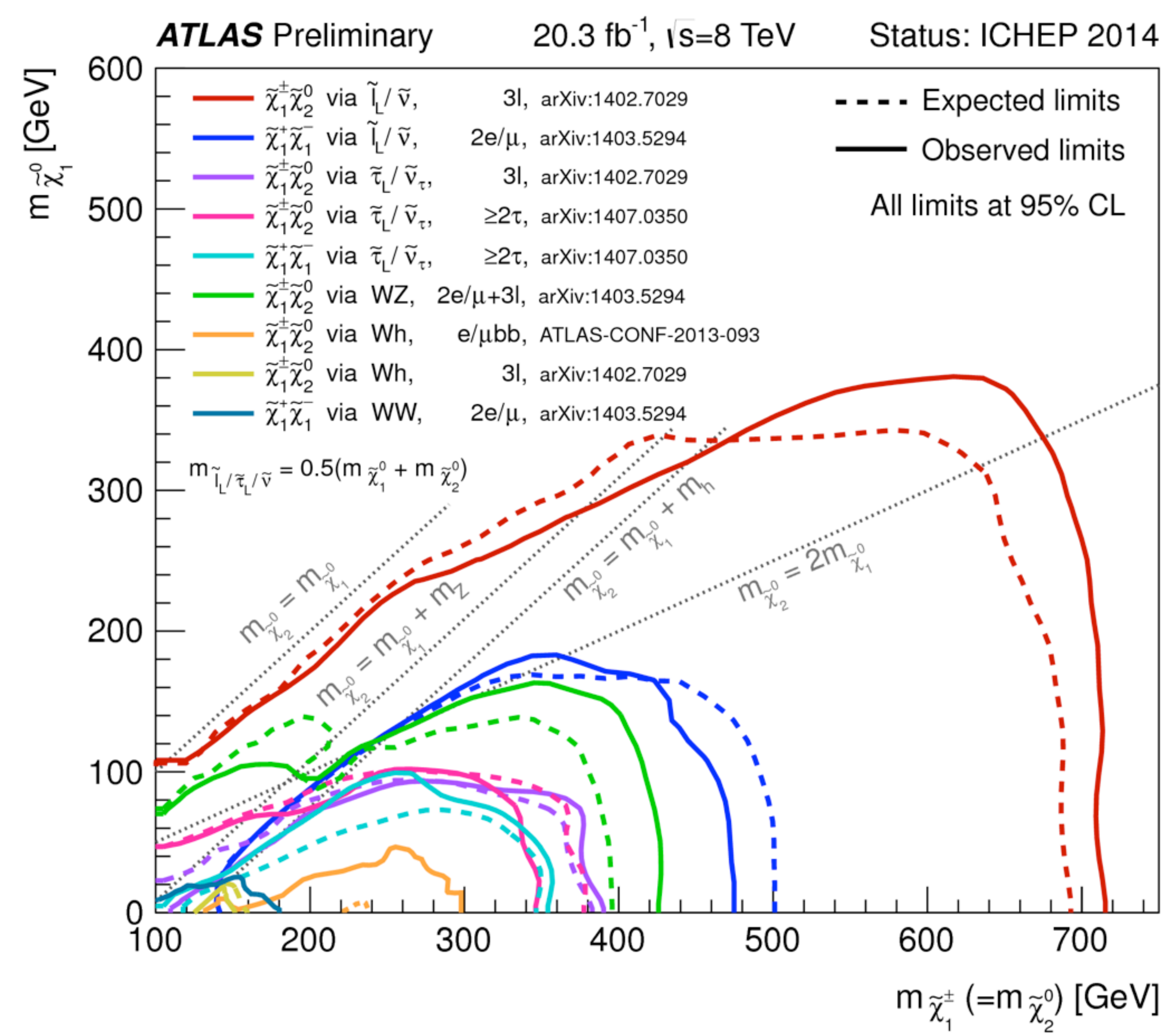


Exclusion limits at 95% CL for 8 TeV analyses in the (m(gluino), m(neutralino1)) plane for the *Gtt* simplified model where a pair of gluinos decays promptly via off-shell stop to four top quarks and two lightest neutralinos (LSP).

Supersymmetry ATLAS summary plots

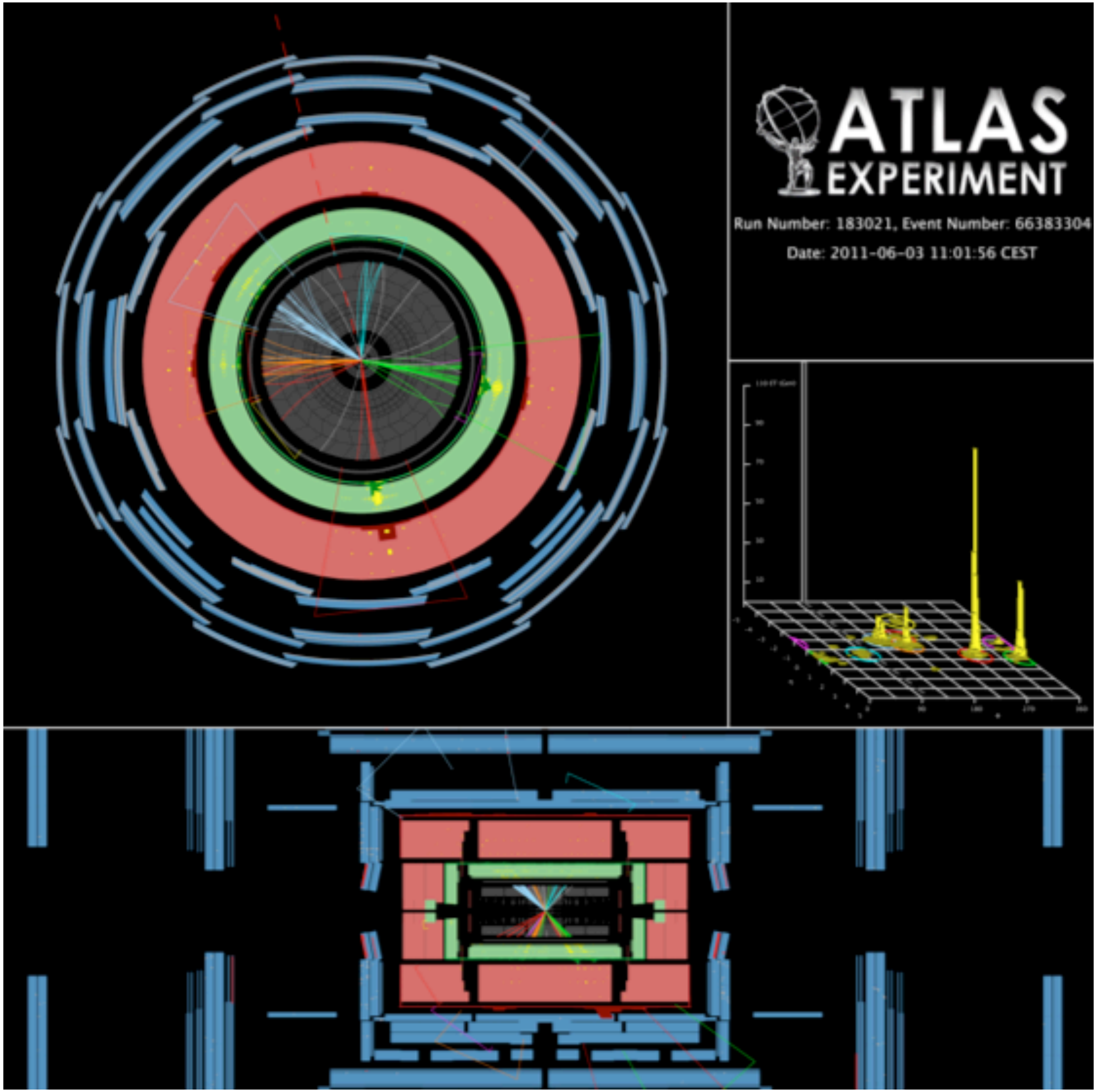


Summary of the dedicated ATLAS searches for top squark (stop) pair production based on 20 fb-1 of pp collision data taken at √s = 8 TeV, and 4.7 fb-1 of pp collision data taken at √s = 7 TeV. Exclusion limits at 95% CL are shown in the stop1-neutralino1 mass plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale)



Summary of ATLAS searches for electroweak production of charginos and neutralinos based on 20/fb of pp collision data at sqrt(s) = 8TeV. Exclusion limits at 95% confidence level are shown in the m(C1), m(N1) plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainties.

A high E_T^{miss} high m_{eff} event



- m_{eff} = 1810 GeV
- E_T^{miss} = 460 GeV
- 5 jets with p_T >40GeV
- (528, 418, 233, 171 and 42 GeV)

Quantum Black Hole

It is possible, in some theories of quantum gravity, to calculate the quantum corrections to ordinary, classical black holes. Contrarily to conventional black holes which are solutions of gravitational field equations of the general theory of relativity, quantum gravity black holes incorporate quantum gravity effects in the vicinity of the origin, where classically a curvature singularity occurs. According to the theory employed to model quantum gravity effects, there are different kinds of quantum gravity black holes, namely loop quantum black holes, non-commutative black holes, asymptotically safe black holes. In these approaches, black holes are singularity free.

Limits

What is a limit?

A limit is an upper or lower bound for a physical quantity, and we place limits when we don't have enough information to estimate the value accurately or precisely. When we say something like "The lower limit for the mass of the Higgs boson is 114GeV" what we mean is that given the data we have had access to we can be confident that the mass of the Higgs boson is at least 114GeV.

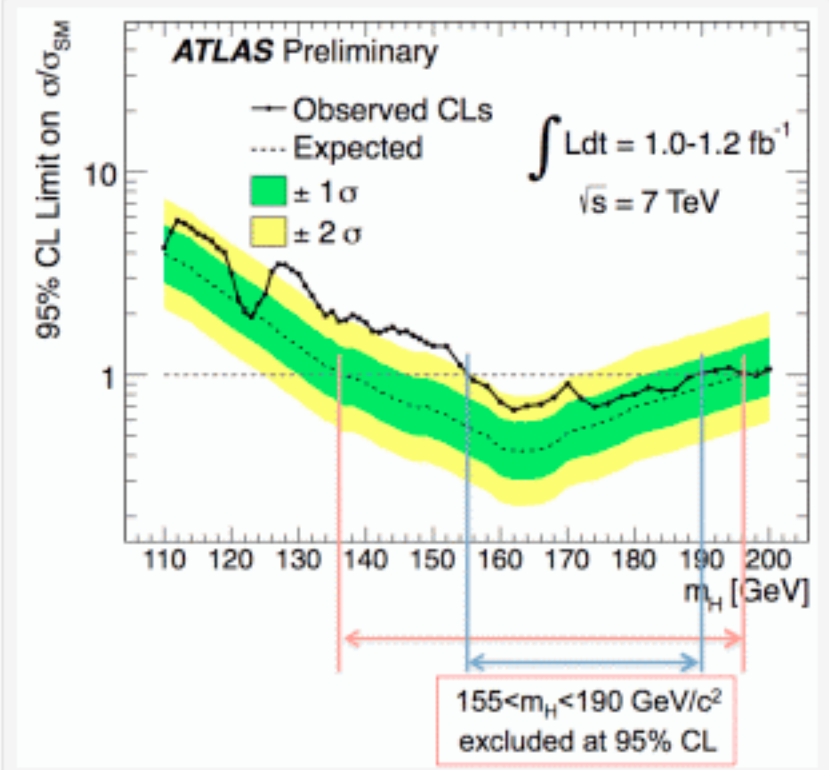
Confidence problems

Like anyone else, physicists have issues with "confidence". To a physicist, "confidence" means the extent to which they trust a measurement, so it's an important concept to get right! Our data are statistically limited, so we can never be 100% certain in any of our measurements. What we usually do is say something like "We're 95% certain that the Higgs mass is not in the region 157-174GeV". To understand what that really means you need to think backwards. We've got some data and the probability that we would get this data, given that the Higgs mass in the region 157-174GeV is 5%, or 1 in 20.

Typical limit plot

A lot of the talks contain plots like this. They look pretty, but they don't look simple. The green and yellow bands show us the expected confidence bounds for some number, and that's what we should look at first to get a feeling for what the plot is telling us. The line at the center of these bands shows us the expected limit. The "Observed" line shows us what we actually see in the experiment. If the "Observed" line stays within the bands then our expectations are about right.

The y-axis shows the production cross section of the Higgs boson, multiplied by the branching fraction to the final state, and some other factors. These numbers all vary as the mass of the Higgs boson, which is one of the reasons why the graphs look so wiggly. The exciting part is the horizontal line at 1. This is the line where we would expect to see the Higgs boson being produced. If the "Observed" line crosses the line at 1 then we can conclude that the Higgs boson probably does not exist at that mass, because our limit is already at 1 times the Standard Model. As the upper yellow band passes under the line at 1 we can be almost certain that the Higgs doesn't exist there. (Remember the definition of the confidence: "At this mass point, we're 95% sure that the Higgs production cross section is less than what the Standard Model predicts.")



ATLAS limit on Higgs mass (K. Cranmer, on behalf of ATLAS. EPS HEP 2011)

What the plots tell us

Exciting things start to happen when the limits change! As we gather more data the limits improve and we exclude more mass points. On the plot, we would see the green and yellow bands move down. If the Higgs doesn't exist in a particular mass region then the "Observed" line would move down as well. But, if we see the bands move down and the "Observed" line get left behind then that's a hint that the Higgs boson mass is in that region!

This is cause for major excitement for some physicists and skepticism for others. Remember the confidence problem of fluctuations and you can see that this kind of fluctuation would happen very often. When does a "fluctuation" turn into "evidence"? It's a topic that's not very well defined, but we've chosen to say three standard deviations (imagine a third colored band on the plot) is a good indication of evidence, and five standard deviations (a veritable rainbow of confidence!) is proof of new physics. When we see a fluctuation the answer is to add more data and see if it remains. If it stays there while the bands move down around it then there's probably a particle there.