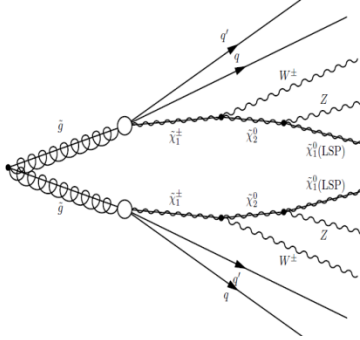
SUSY searches in ATLAS

David Côté (CERN)
for the ATLAS Collaboration
23ème Rencontres de Blois

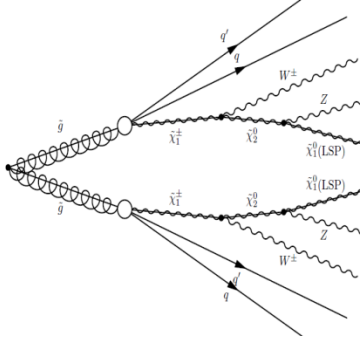
Christopher Colombus in 1492,
searching for the Indies…

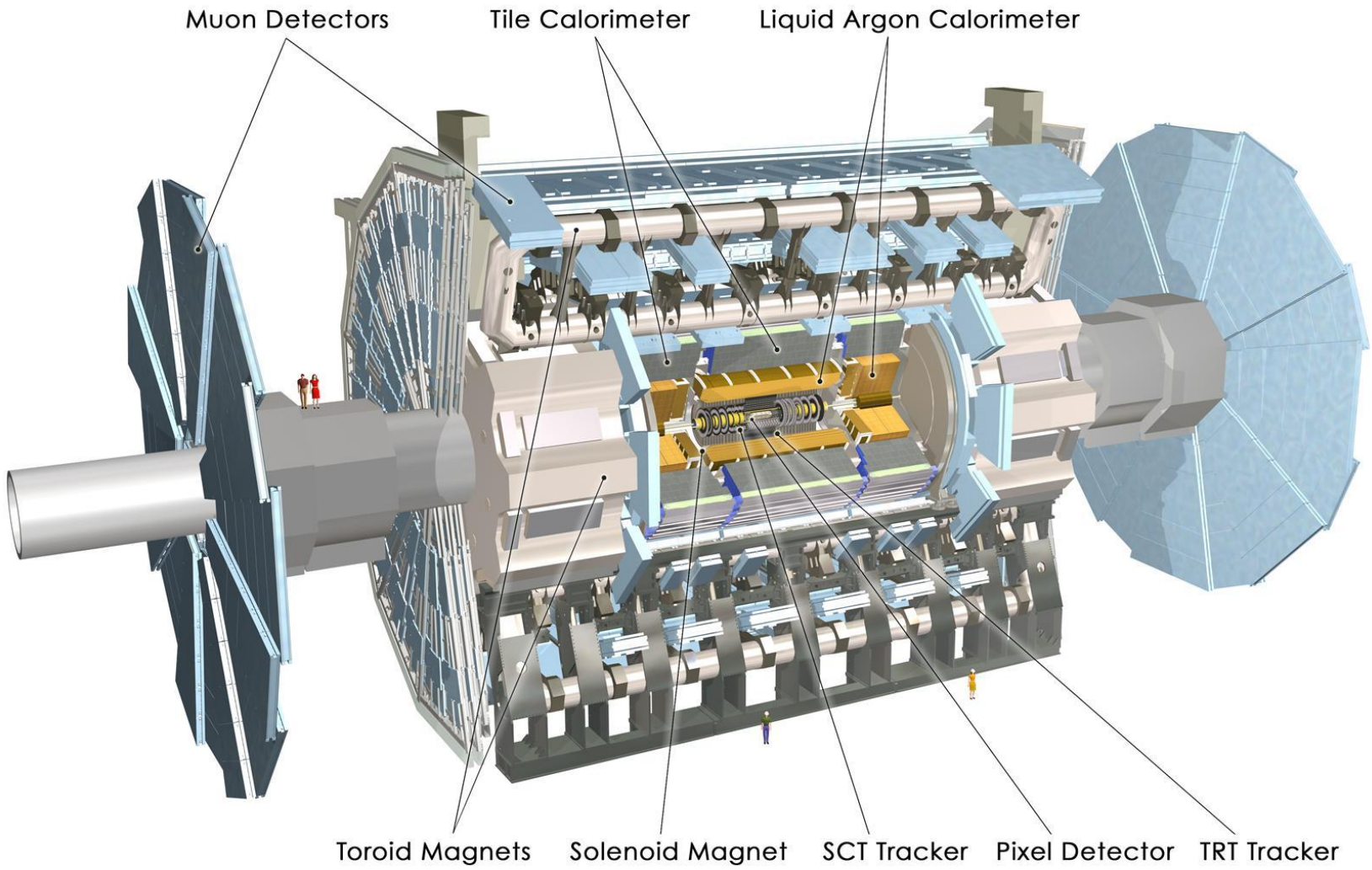
Contents



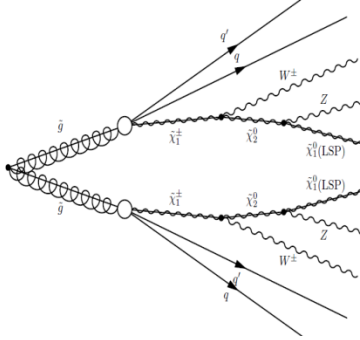
- ATLAS detector and data-taking
  - today's results based on 2010 data
- SUSY phenomenology
- Overview of all SUSY searches in ATLAS
  - emphasis on experimental results & methods
  - few words on model-dependent interpretation
- Conclusions

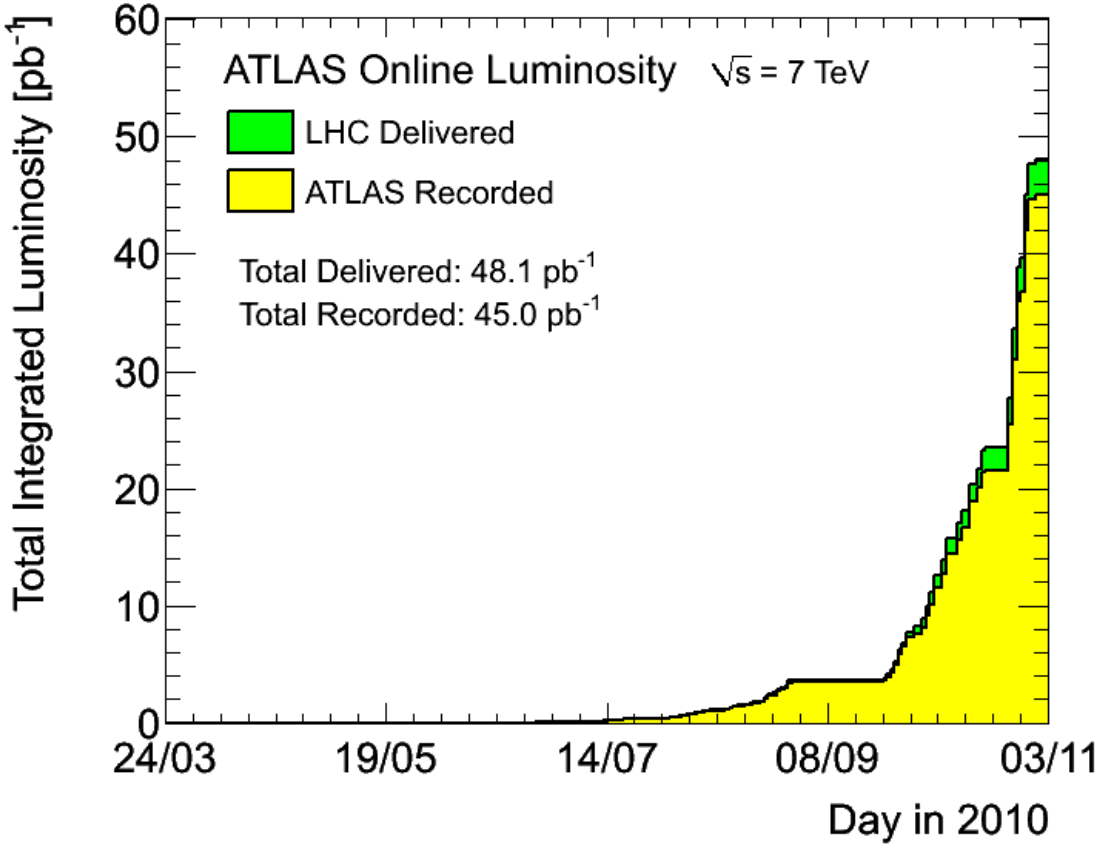
The ATLAS detector





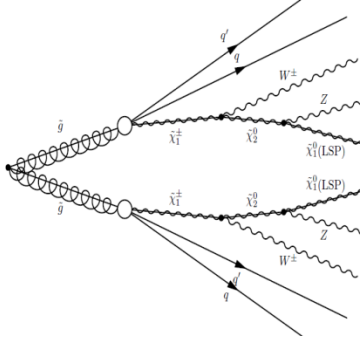
ATLAS data in 2010



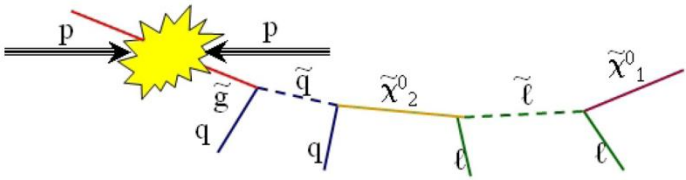


- Proton-proton collisions at **7 TeV**
- Good-quality data used for analysis: **~35 pb^{-1}**

SUSY phenomenology

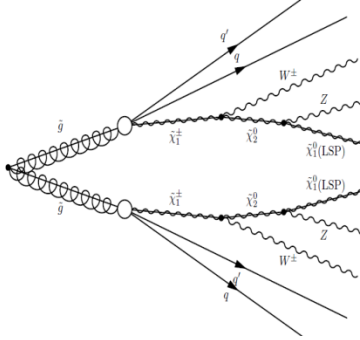


- Very rich and diverse phenomenology in general
  - if R-parity is conserved
    - Lightest Supersymmetric Particle (LSP) is stable
      - large missing transverse energy (MET)
      - dark matter candidate
  - if $\tilde{q}$ or $\tilde{g}$ masses are not very large
    - dominant production via strong force at LHC
    - decay chain to LSP (possibly long)
      - multiple jets
      - can have leptons and/or photons
        - » popular model: CMSSM/MSUGRA



  - if 3rd generation is lighter (to stabilize Higgs mass)
    - enhanced b-jet production
  - if R-parity is not conserved
    - resonance from decay of the LSP
  - if decay of NLSP to LSP is suppressed
    - meta-stable heavy particles
      - slow muon-like particles
      - slow R-hadrons

Overview of SUSY searches in ATLAS



statistically independent

- MET + jets + 0 lepton
- MET + jets + 1 lepton

combination (most sensitive search if CMSSM)

- MET + 2 leptons
- MET + ≥3 leptons
- MET + 2 photons **NEW!**
- MET + b-jet + 0/1 lepton
- e+μ resonance
- slow colored hadron
- slow muon-like particle **NEW!**

Sensitive to a wide range of hypothetical new physics, not only to SUSY.

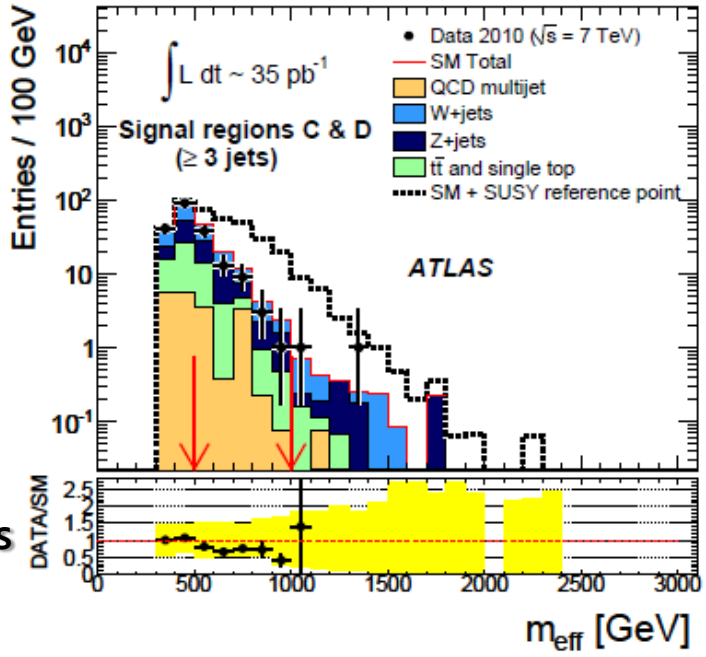
ArXiV:1102.5290
Accepted by PLB

MET + jets + 0 lepton

$$m_{Eff} \equiv \sum p_T^{jet} + E_T^{miss}$$

Event selection: (also include lepton veto)

	Four signal regions:	A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_T [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_T [GeV]	> 40	> 40	> 40	> 40
	E_T^{miss} [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\text{jet}, \vec{p}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	–	> 0.25	> 0.25
	m_{eff} [GeV]	> 500	–	> 500	> 1000
	m_{T2} [GeV]	–	> 300	–	–



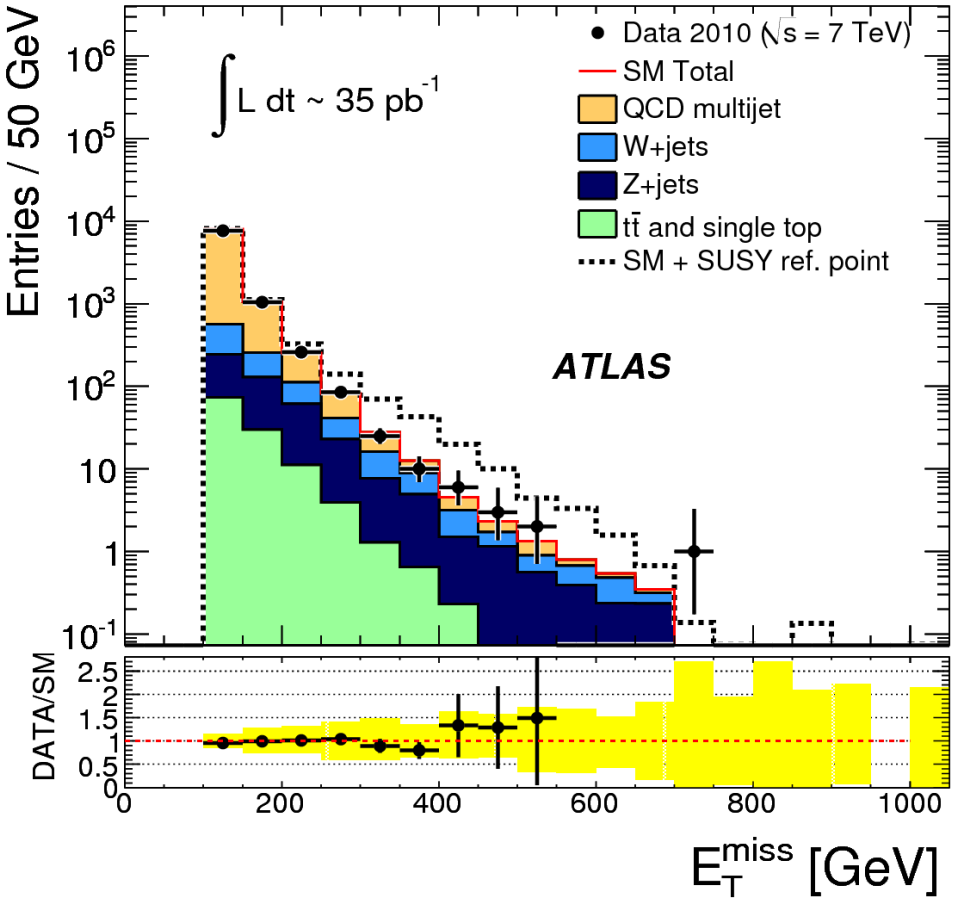
- W, Z, top bkg from mix of data-driven and MC techniques
- QCD bkg from data control sample

Results

Signal Region	A	B	C	D
observed:	87	11	66	2
expected:	118^{+42}_{-36}	$10.0^{+6.0}_{-4.8}$	88^{+33}_{-27}	$2.5^{+1.4}_{-1.1}$
W/Z+jets	102	8.5	62	1.9
top	10	0.9	17	0.3
QCD	7	0.6	9	0.2
σ·B·ε·A:	< 1.3 pb	< 0.35 pb	< 1.1 pb	< 0.11 pb

ArXiV:1102.5290
Accepted by PLB

MET + jets + 0 lepton (details)



MET distribution after the ≥2 jets pre-selections. Its excellent performance and data/MC agreement is typical for all the MET-based searches.

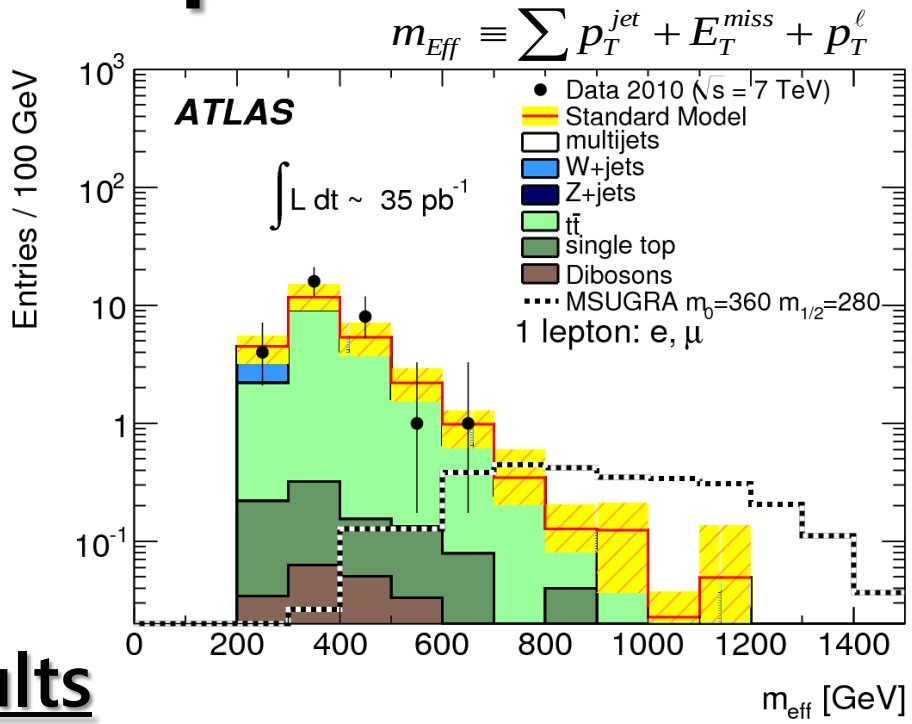
Phys. Rev. Lett. 106, 131802 (2011)
"Viewpoint" Physics 4, 27 (2011)

MET + 1 lepton

First SUSY result of ATLAS

Event selection

- exactly one lepton, p_T > 20 GeV
- ≥3 jets, p_T > 60, 30, 30 GeV
- m_T > 100 GeV
- MET > 125 GeV
- MET/M_{Eff} > 0.25
- M_{Eff} > 500 GeV

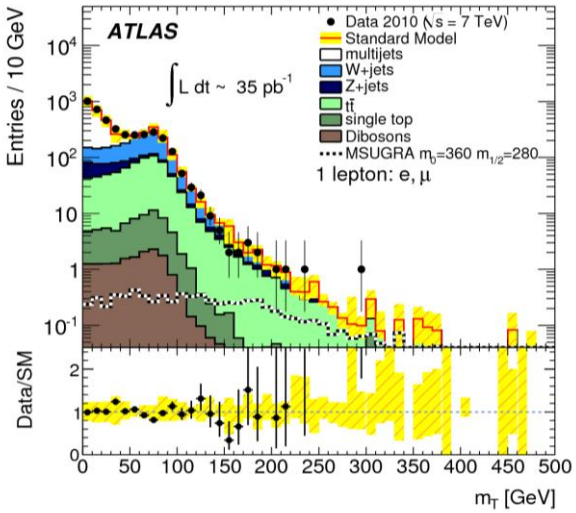


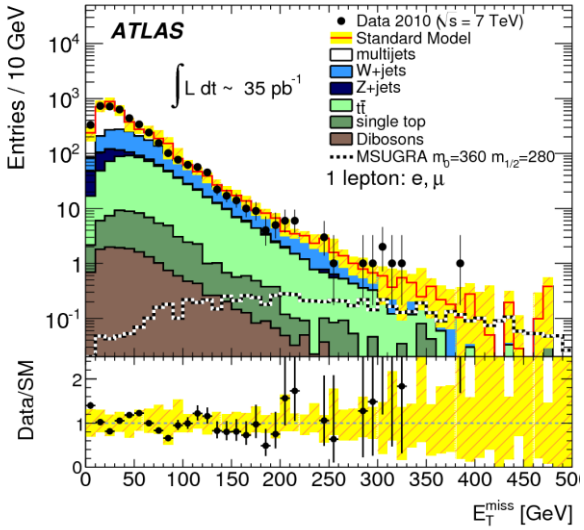
Results

Channel	electron	muon
observed:	1	1
expected:	1.81 ± 0.75	2.25 ± 0.94
top	1.34	1.76
W/Z	0.47	0.49
QCD	0	0
σ·B·ε·A:	< 0.065 pb	< 0.073 pb

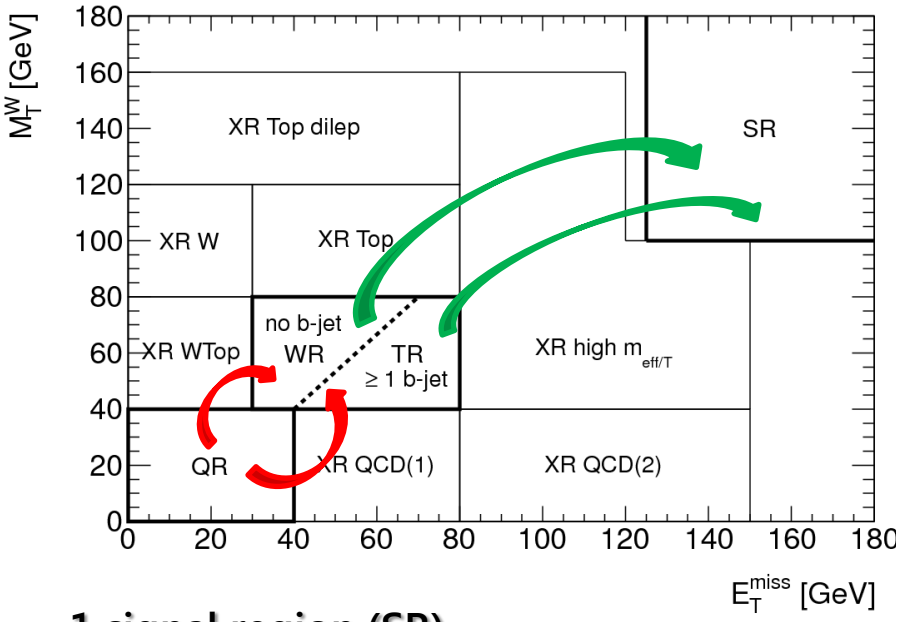
Phys. Rev. Lett. 106, 131802 (2011)
"Viewpoint" Physics 4, 27 (2011)

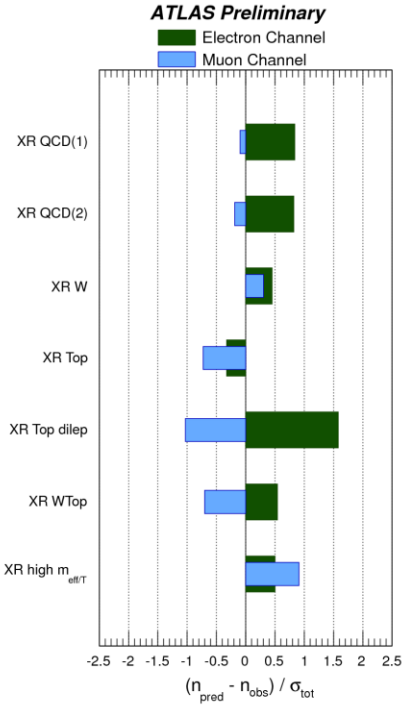
MET + 1 lepton (details)





Background estimation



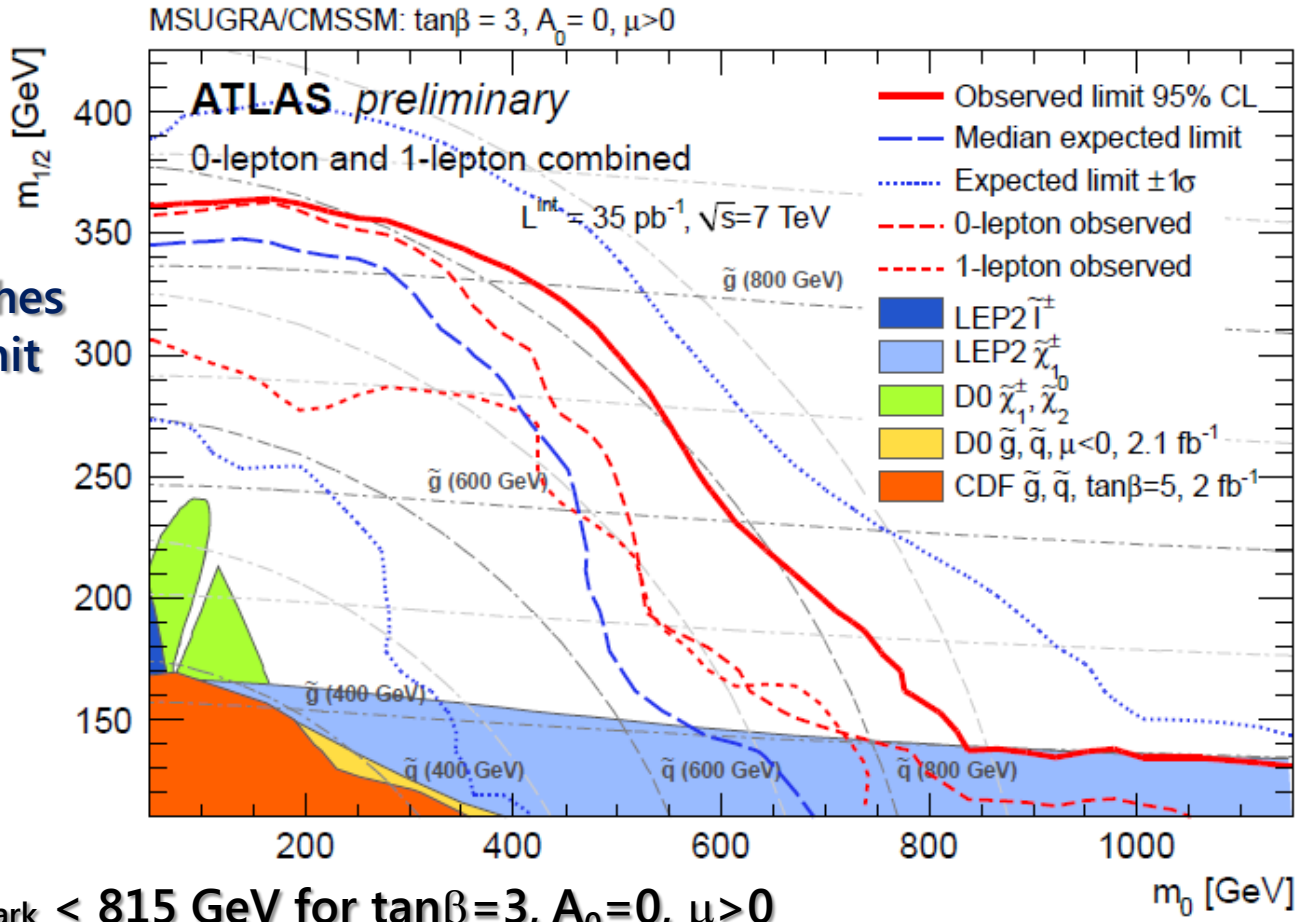


- 1 signal region (SR)
- 3 control regions (CR), for: QCD, W, Top
- extra regions (XR) to validate quality of background model

- Simultaneous fit of QCD, W, Top and signal in all CR+SR
  →normalization from data, shape from MC
- QCD in SR from data-driven loose-to-tight matrix method

0+1 lepton combination

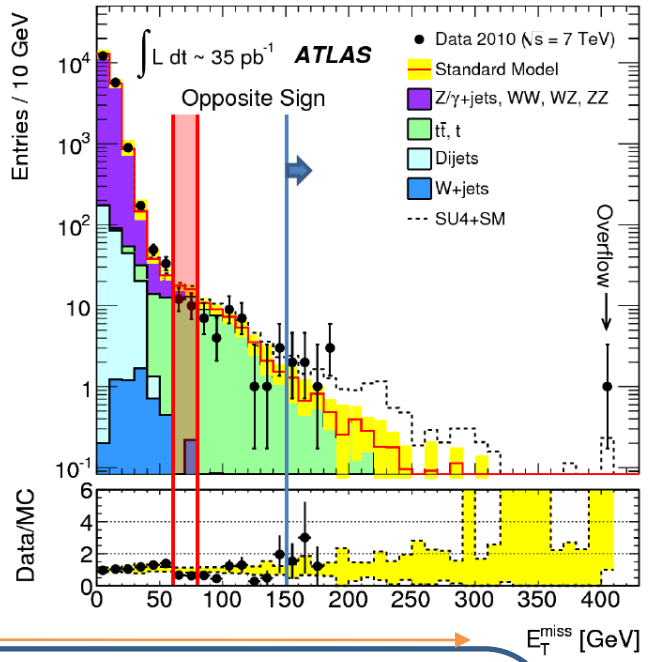
MET + 0/1 lepton searches interpreted as upper limit in CMSSM



- Exclude $M_{gluino} = M_{squark} < 815$ GeV for $\tan\beta=3$, $A_0=0$, $\mu>0$
- More stringent limits than previous ones from Tevatron and LEP
- Sensitivity is dominated by 0-lepton, except at low $m_{1/2}$
- PCL statistical method (arXiv:1105.3166)

ArXiV:1103.6208, accepted by EPJCL
ArXiV:1103.6214, submitted to EPJCL

MET + 2 leptons



Event selection

- exactly two leptons, p_T > 20 GeV
- MET > 100 (150) GeV, for same-sign (opposite-sign)

Analysis steps (published in 2 papers):

1) count same-sign (SS) and opposite-sign (OS) events
2) flavor subtraction for OS:

$$\mathcal{S} = \frac{N(e^{\pm}e^{\mp})}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^{\pm}\mu^{\mp})}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^{\pm}\mu^{\mp})}{(1-(1-\tau_\mu)^2)}$$

β: ratio of e / μ efficiencies. $\tau_{e,\mu}$: trigger efficiencies.

Results

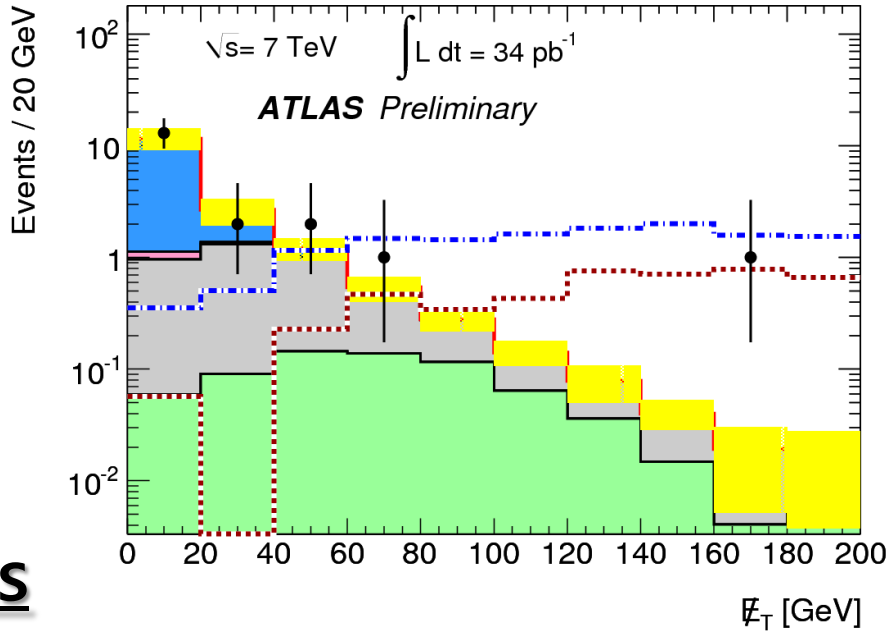
	SS			OS		
Channel	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{+}e^{-}$	$e^{\pm}\mu^{\mp}$	$\mu^{+}\mu^{-}$
observed:	0	0	0	0	4	4
expected:	0.15 ± 0.13	$0.1^{+1.2}$	0.04 ± 0.01	0.9 ± 0.4	$1.4^{+1.5}_{-0.6}$	$1.4^{+1.4}_{-0.5}$
cosmic rays	-	$0^{+1.2}$	-	-	$0^{+1.2}$	$0^{+1.3}$
instrumental	0.14	0.056	0.014	-	-	-
top	-	-	-	0.6	1.2	1.0
σ·B·ε·A:	< 0.07 pb	< 0.07 pb	< 0.07 pb	< 0.09 pb	< 0.22 pb	< 0.21 pb

Flavor subtraction result: $S_{obs} = 1.98 \pm 0.15_{\beta} \pm 0.06_{\tau}$ $(S_{exp} = 2.06 \pm 1.1)$

MET + multi-leptons

Event selection:
- ≥3 leptons, p_T > 20 (10) GeV
- ≥2 jets, p_T > 50 GeV
- MET > 50 GeV

Main background:
- top quark decays



Results

Number of events with 3 leptons (no jet nor MET cut)*

Multilep. events	All	*eee*	*eeμ*	*eμμ*	*μμμ*
$t\bar{t}$	0.68±0.16	0.032±0.016	0.24±0.07	0.31±0.08	0.096±0.030
Z backgrounds	15.6±1.3	3.8±0.8	1.60±0.34	7.9±1.0	2.4±0.4
Other backgrounds	0.28±0.13	0.02±0.14	0.03±0.06	0.21±0.09	0.01±0.11
Total SM	16.6±1.3	3.8±0.8	1.9±0.4	8.4±1.0	2.5±0.4
Data	19	2	1	10	6

*no observed events with four leptons

Number of events after all cuts

observed: 0

expected: $0.109 \pm 0.023^{+0.036}_{-0.025}$

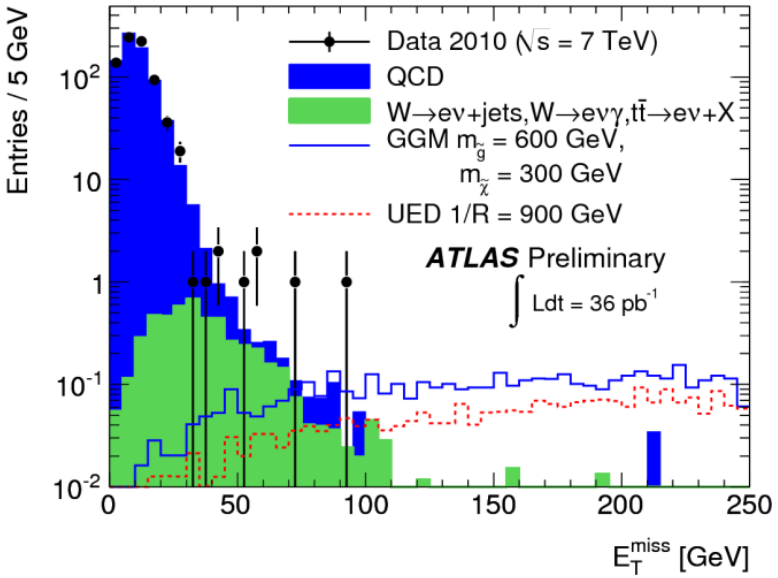
$\sigma \cdot B \cdot \varepsilon \cdot A < 0.062$ pb

NEW!

MET + di-photon

Event selection:
- ≥2 photons, E_T > 30, 20 GeV
- MET > 125 GeV

Backgrounds (data-driven):
- QCD from loose photon-ID control sample
- W and top from e-photon control sample

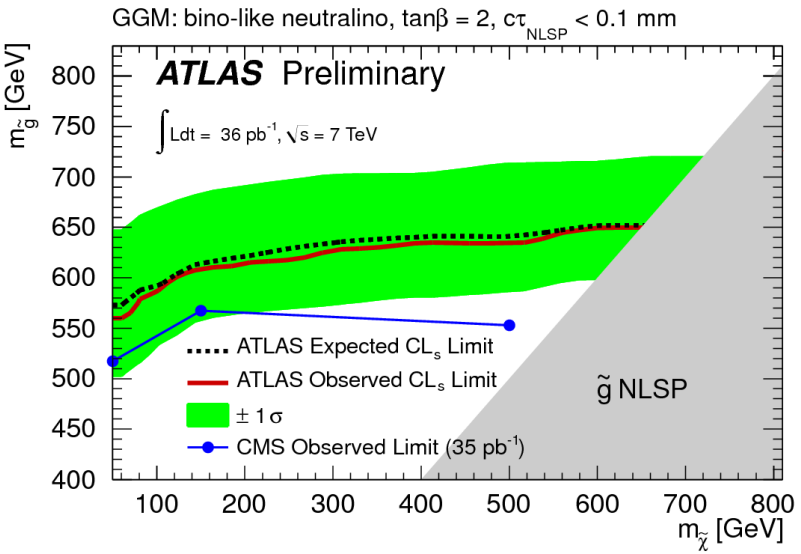


Results

observed: 0

expected: 0.13 ± 0.05

$\sigma \cdot B \cdot \varepsilon \cdot A < 0.06$ pb



ArXiV:1103.4344
Submitted to PLB

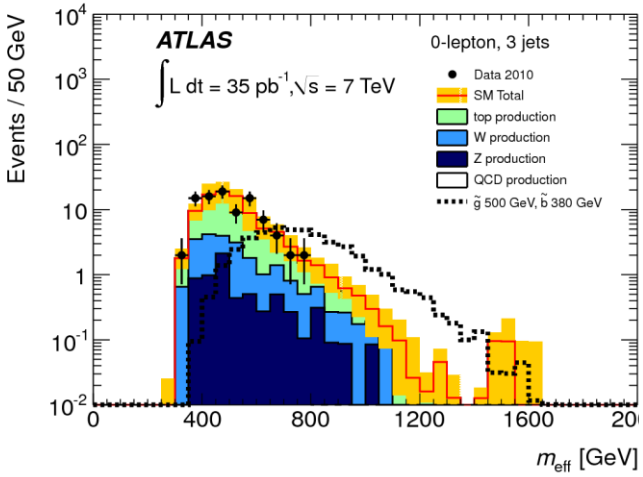
MET + b-jet + 0/1 lepton

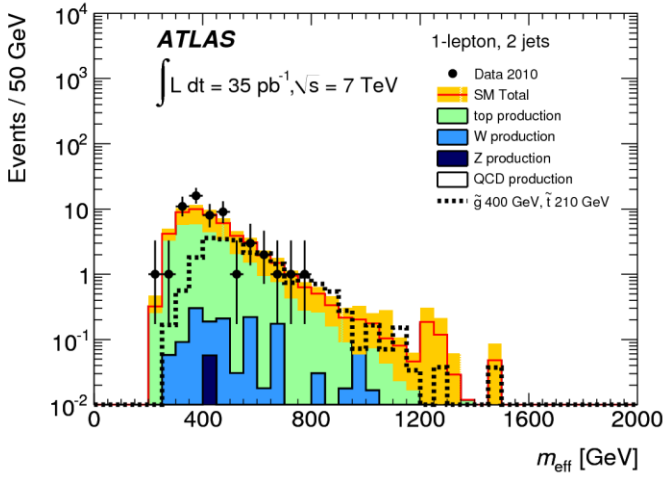
Common event selection:
- MET > 100 GeV
- ≥1 b-jet(s)

0-lepton selection:
- lepton veto
- ≥3 jets, p_T > 120, 30, 30 GeV
- M_{Eff} > 600 GeV
- MET/M_{Eff} > 0.2

1-lepton selection:
- ≥1 lepton, p_T > 20 GeV
- ≥2 jets, p_T > 60, 30 GeV
- m_T > 100 GeV
- M_{Eff} > 500 GeV

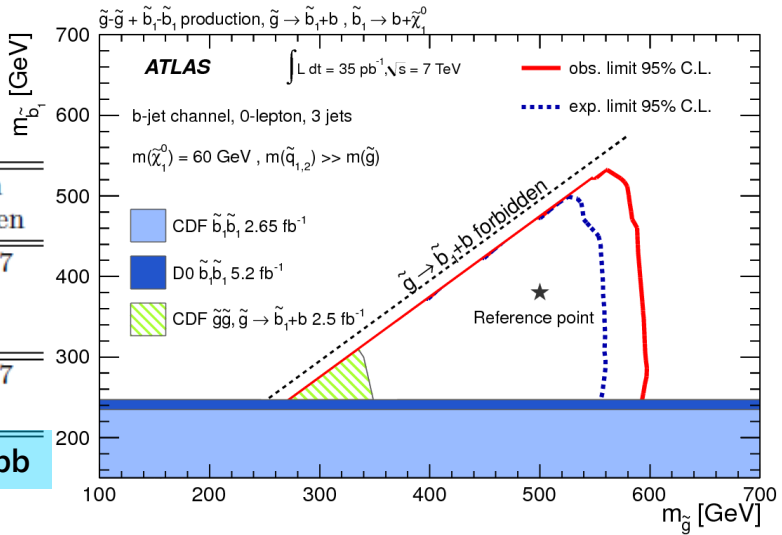
Background estimation:
- QCD from data control sample
- W, Z, Top :
  - →from simulation (0-lepton)
  - →from data-driven m_T *vs* m_{Eff} "ABCD" method (1-lepton)





Results

	0-lepton	1-lepton data-driven
$t\bar{t}$ and single top	12.2 ± 5.0	14.7 ± 3.7
W and Z	6.0 ± 2.0	-
QCD	1.4 ± 1.0	$0^{+0.4}_{-0.0}$
Total SM	19.6 ± 6.9	14.7 ± 3.7
Data	15	9
σ·B·ε·A	< 0.32 pb	< 0.13 pb



ArXiV:1103.5559
Accepted by PRL

e+mu resonance

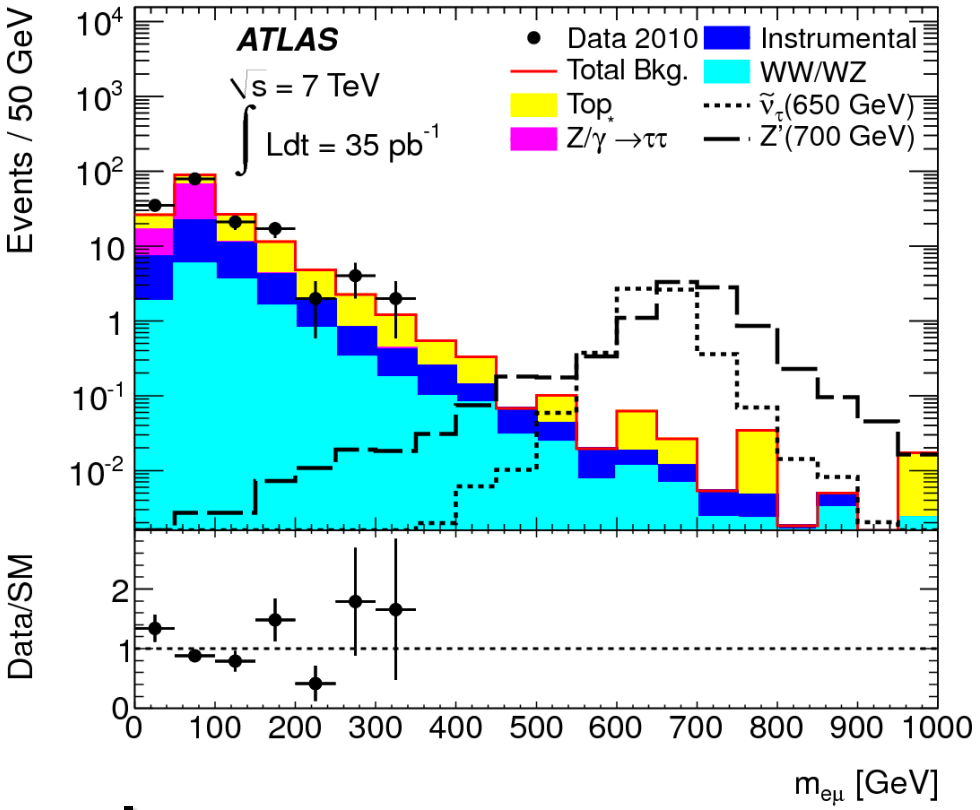
Event selection:

- exactly 1 e and 1 μ of opposite charge
- electron and muon pT > 20 GeV

Background estimate:

- instrumental bkg from data-driven loose-to-tight matrix method
- Z→ττ, top and other SM bkgs from MC

Process	Number of events
$Z/\gamma^* \to \tau\tau$	54±7
$t\bar{t}$	57±9
WW	13.4±1.7
Single top	4.6±0.9
WZ	0.79±0.11
Instrumental background	33^{+30}_{-10}
Total background	163^{+34}_{-18}
Data	160



Results

- no resonance is observed
- model-dependent exclusion of $m\tilde{\nu}_\tau$ < 0.75 GeV given RPV couplings λ'_{311} = 0.11 and λ_{312} = 0.07

(a) ArXiV:1103.1984, accepted by PLB
(b) **NEW!**

slow meta-stable particles

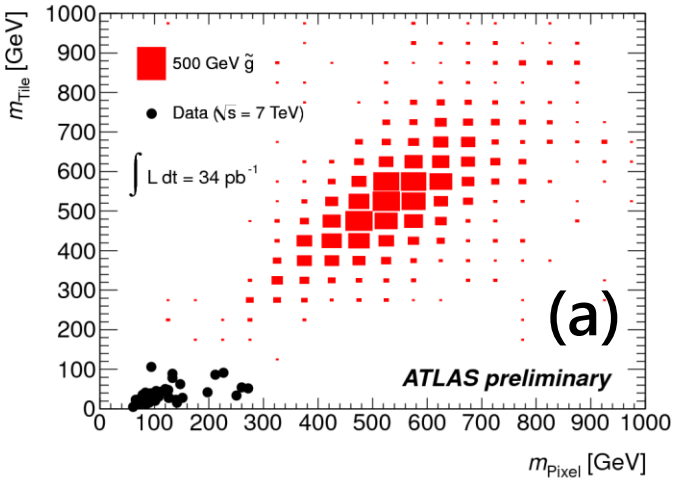
Event selection:
- large dE/dx in Pixel detector (a)
- long time-of-flight (TOF) in Tile calorimeter (a,b)
- long TOF in Muon Spectrometers (MS) (b)

Main background: instrumental

Analysis steps:
1) count events with slow particles
2) derive particle's mass

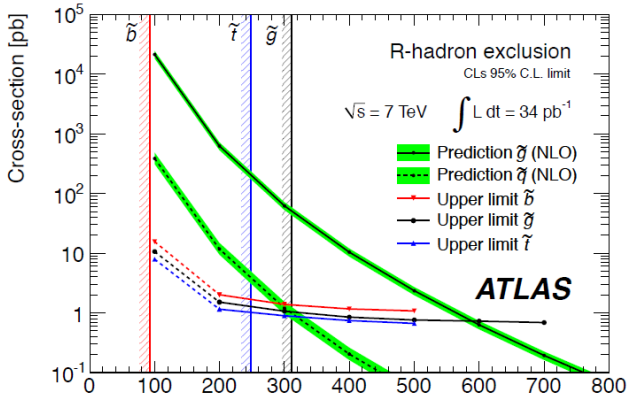
$$M_{TOF} = \frac{p}{\beta\gamma} = \frac{pc}{\gamma} \cdot \frac{TOF}{dist}$$

$$\mathcal{M}_{\frac{dE}{dx}}(\beta) = \frac{p_1}{\beta^{p_3}} \ln(1 + (p_2\beta\gamma)^{p_5}) - p_4$$



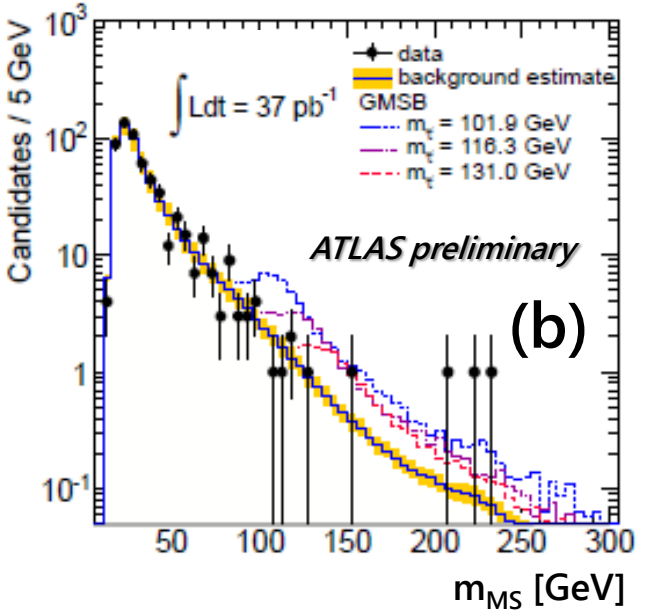
Results

Exclusions from Pixel + Tile search (a)

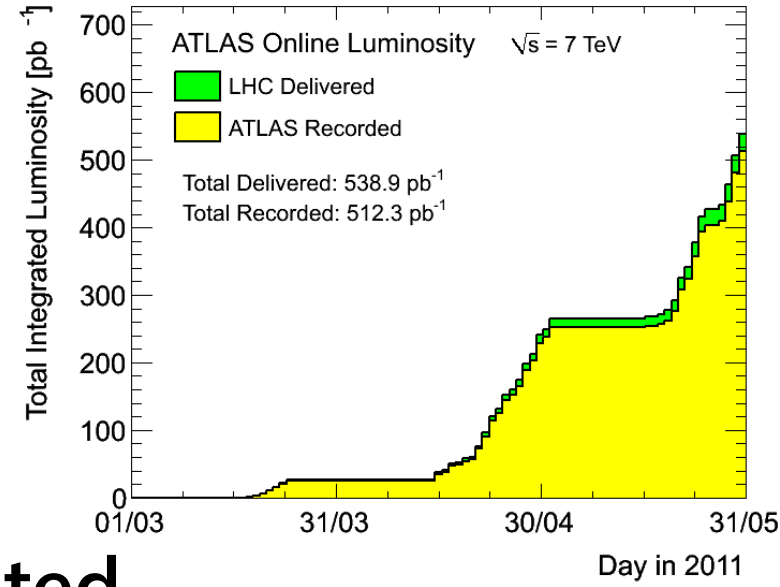


Events from MS search (b)

mass cut	$N_{expected}$	N_{obs}
90	19.2	16
110	9.8	8
130	5.4	4



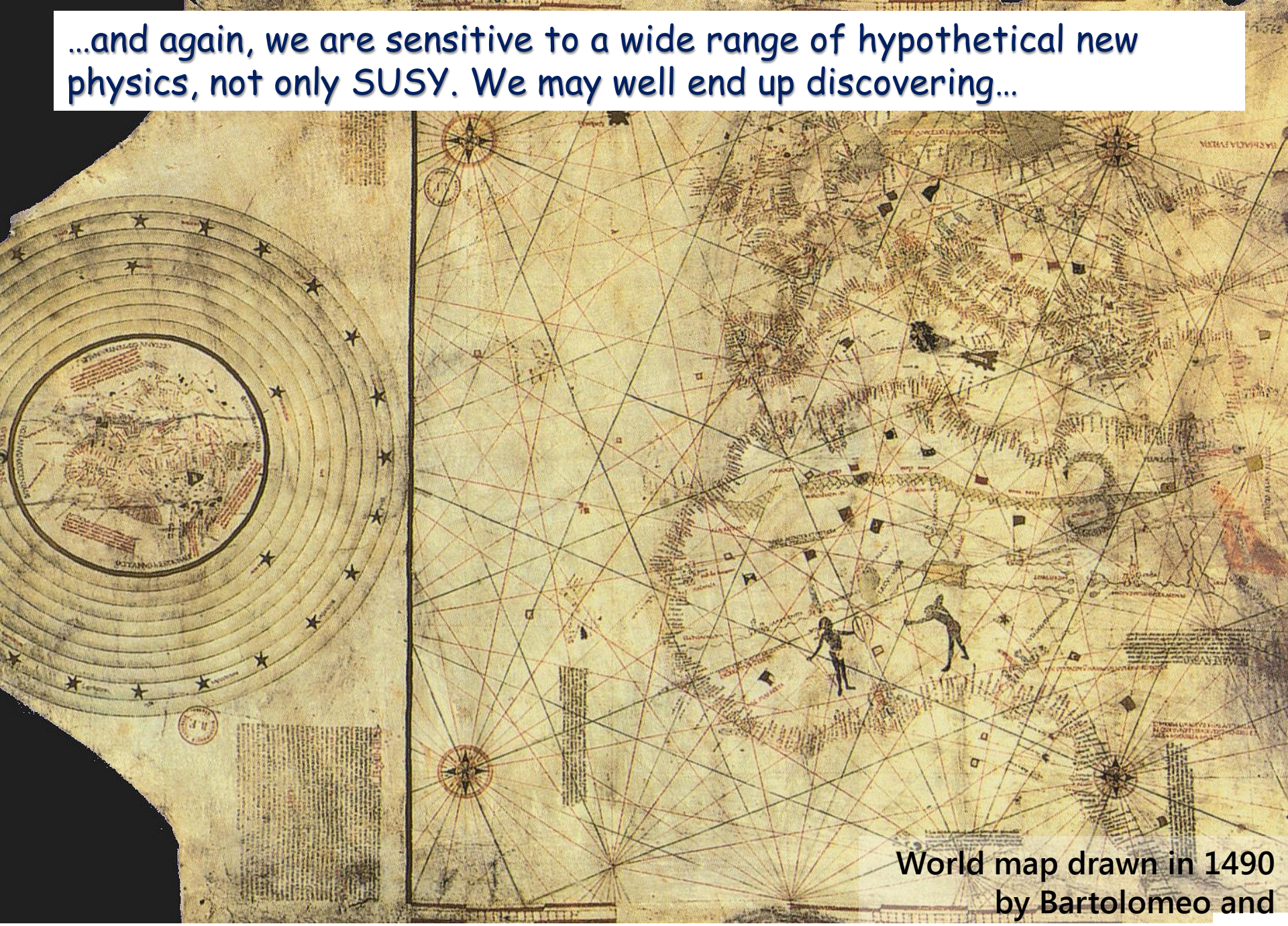
Conclusions



- 9 searches have been presented
  - all based on 2010 data
  - no signs of new physics yet
    - SUSY is still largely possible
    - surpassed Tevatron's sensitivity
- We expect ~100x more data in 2011
  - very exciting prospects for discovery!
    - stay tuned for new public results soon

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

…and again, we are sensitive to a wide range of hypothetical new physics, not only SUSY. We may well end up discovering…



World map drawn in 1490 by Bartolomeo and Christopher Columbus

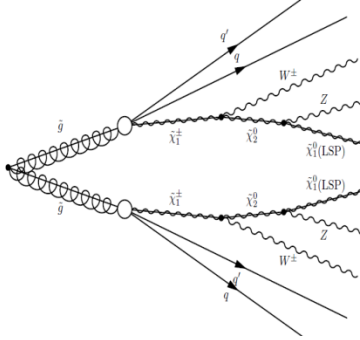
…and again, we are sensitive to a wide range of hypothetical new physics, not only SUSY. We may well end up discovering…

…THE UNEXPECTED!!!

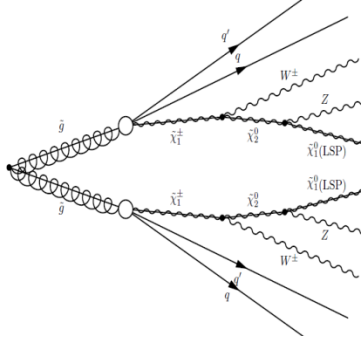
Map of the Americas drawn in 1545

World map drawn in 1490 by Bartolomeo and Christopher Columbus

backup material



Definitions



all MET searches: $m_{Eff} \equiv \sum p_T^{jet} + E_T^{miss} + \left(p_T^{\ell}\right)$

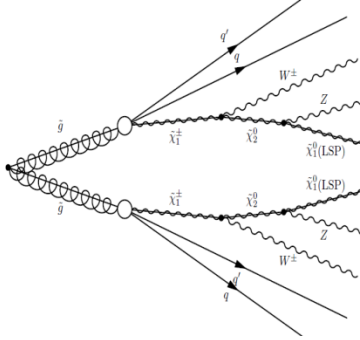
1-lepton: $m_T \equiv \sqrt{2\, p_T^{\ell} E_T^{miss} \left(1 - \cos(\Delta\phi(\ell, E_T^{miss}))\right)}$

2-lepton: $\mathcal{S} = \frac{N(e^{\pm}e^{\mp})}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^{\pm}\mu^{\mp})}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^{\pm}\mu^{\mp})}{(1-(1-\tau_\mu)^2)}$

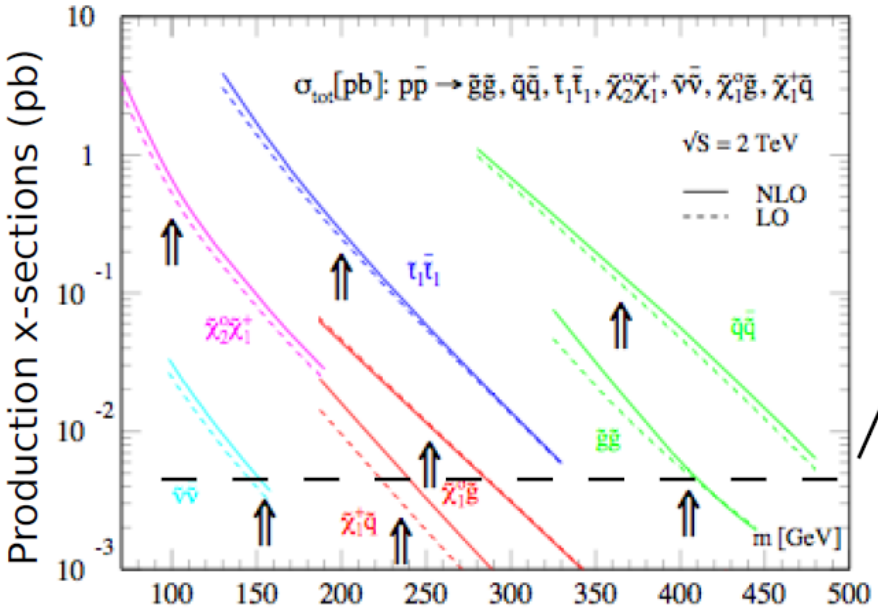
β is ratio of e, μ ID efficiencies, τ_e and τ_μ are trigger efficiencies.

0-lepton: $m_{T2}(\vec{p}_T^{(1)}, \vec{p}_T^{(2)}, \vec{p}_T) \equiv \min_{\vec{q}_T^{(1)} + \vec{q}_T^{(2)} = E_T^{miss}} \{\max(m_T(\vec{p}_T^{(1)}, \vec{q}_T^{(1)}), m_T(\vec{p}_T^{(2)}, \vec{q}_T^{(2)}))\}$

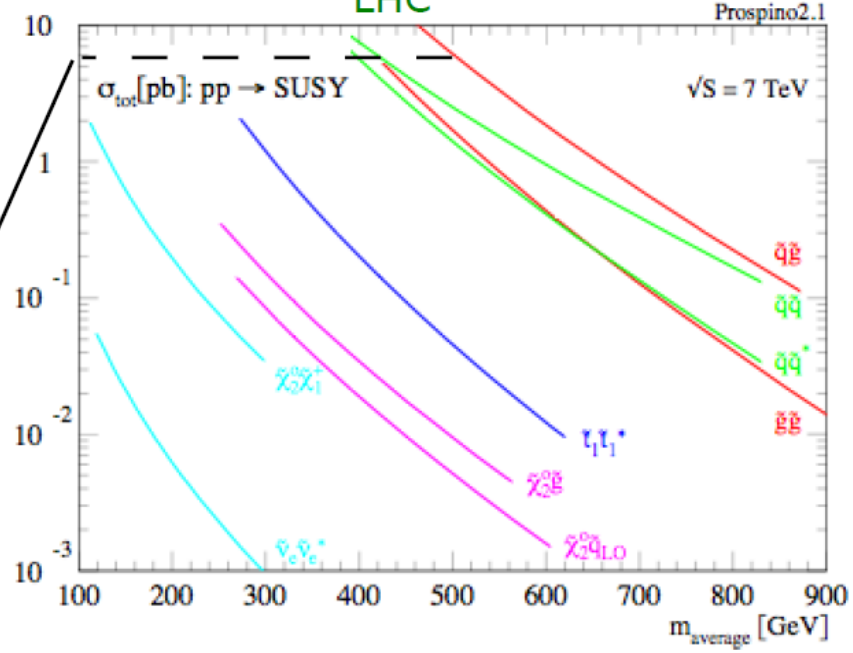
SUSY cross-sections



Tevatron



LHC

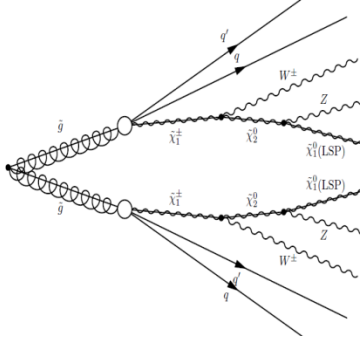


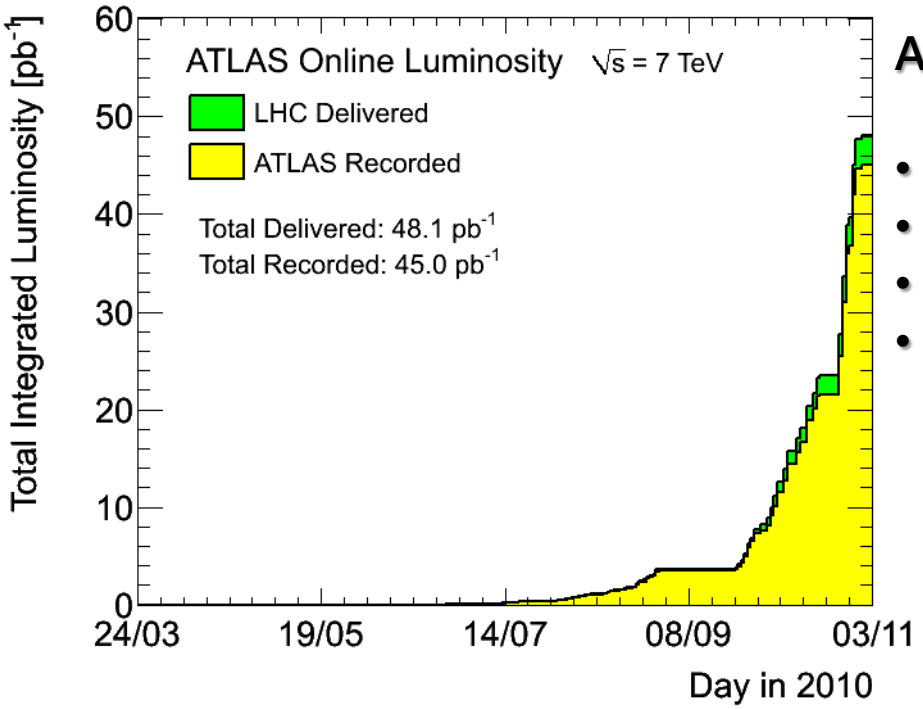
LHC x-sections for dominant SUSY processes are more than 150 times higher

Define R-parity = $(-1)^{3(B-L)+2S}$

- R = 1 for SM particles
- R = -1 for MSSM partners

ATLAS data in 2010





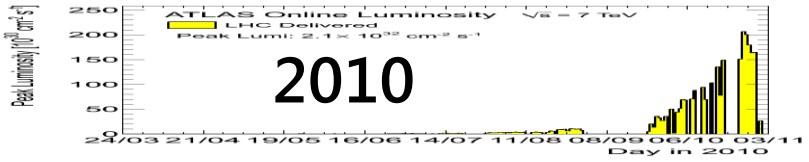
All results shown today are from 2010 data.

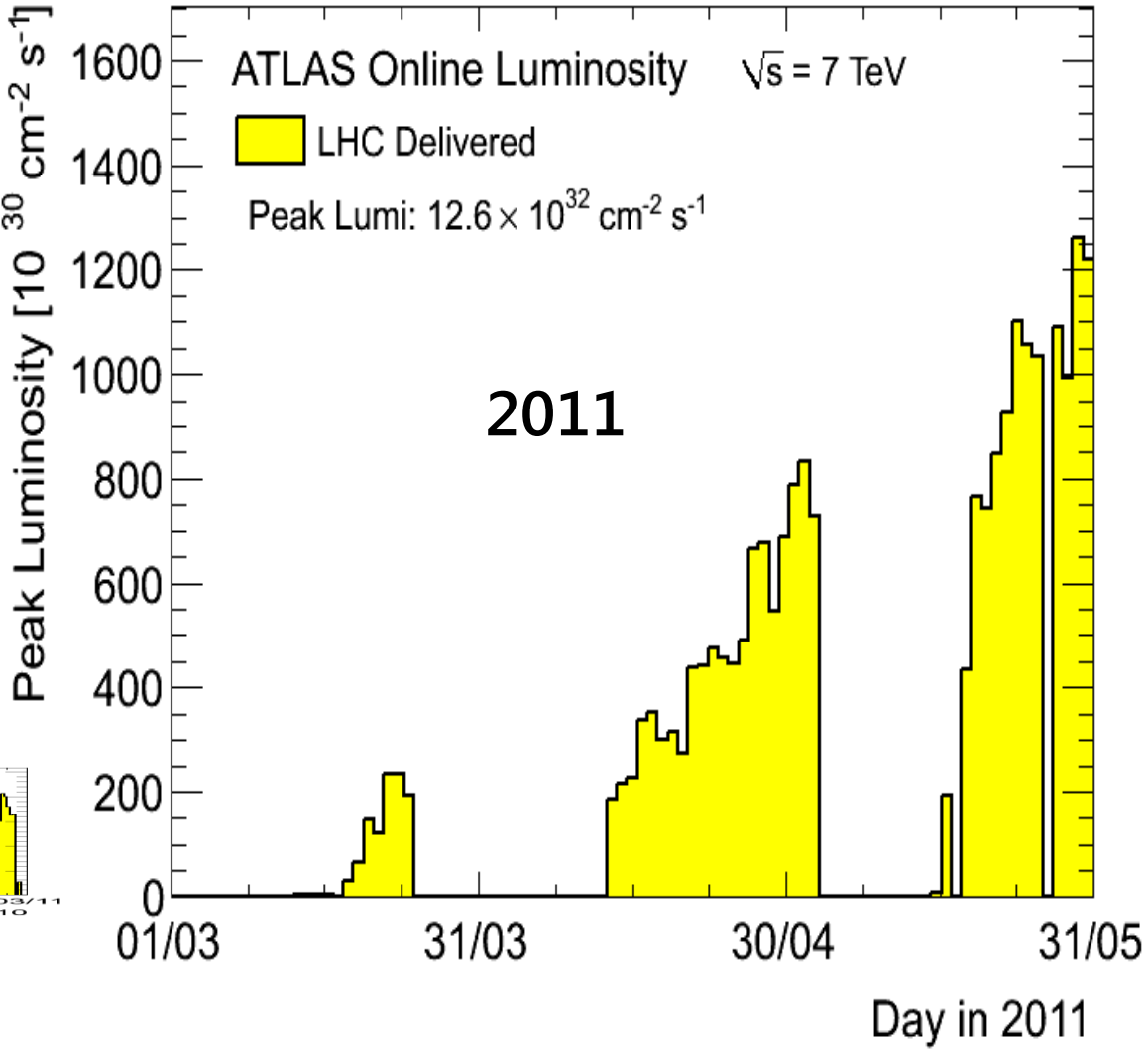
- **proton-proton collisions at 7 TeV**
- **Max instantaneous luminosity: $2 \cdot 10^{32}$ cm^{-2} s^{-1}**
- **Total recorded luminosity: 45 pb^{-1}**
- **Good data quality for analysis: ~35 pb^{-1}**

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

Fraction of good quality data (%) per subsystem

Peak luminosity per day





ArXiV:1102.5290
Submitted to PLB

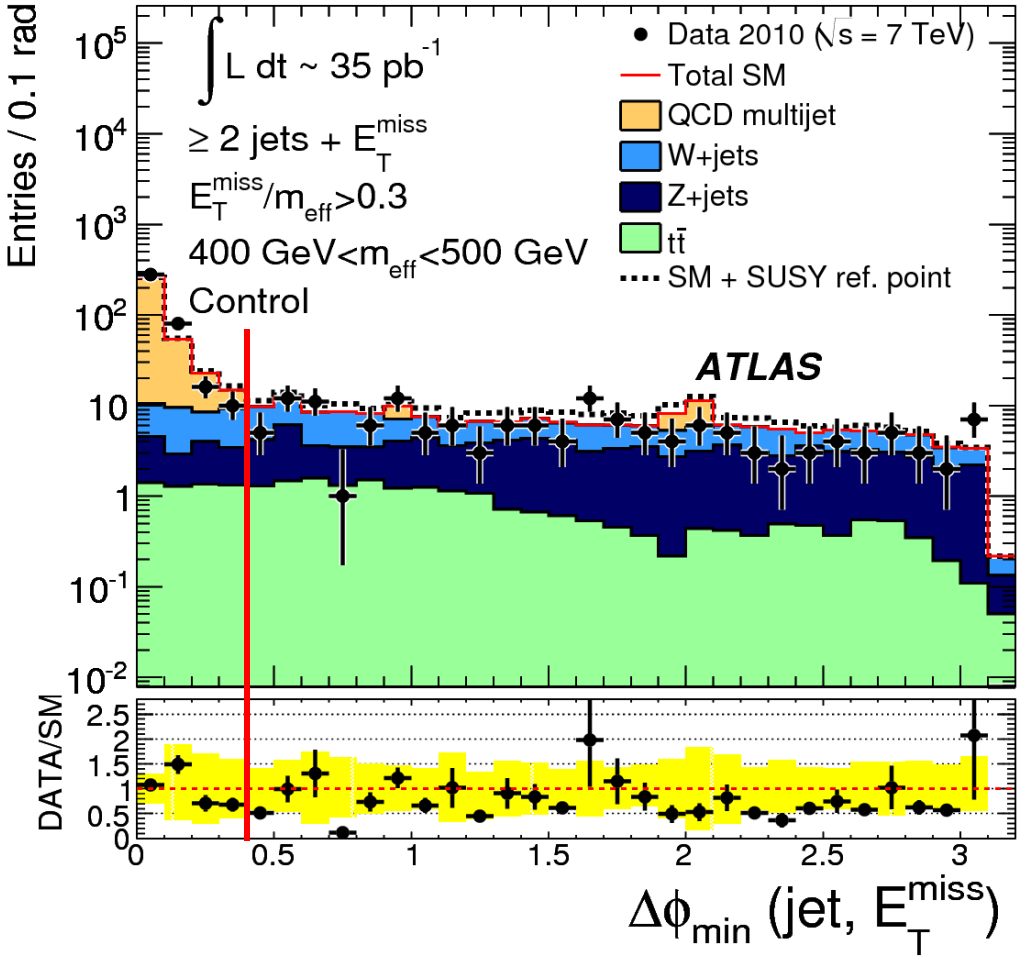
MET + jets + 0 lepton

Results

	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\ ^{+8}_{-7}$[u+j]	$0.6\ ^{+0.7}_{-0.6}$[u+j]	$9\ ^{+10}_{-9}$[u+j]	$0.2\ ^{+0.4}_{-0.2}$[u+j]
W+jets	50 ± 11[u] $^{+14}_{-10}$[j] $\pm$ 5[$\mathcal{L}$]	4.4 ± 3.2[u] $^{+1.5}_{-0.8}$[j] ± 0.5[$\mathcal{L}$]	35 ± 9[u] $^{+10}_{-8}$[j] ± 4[$\mathcal{L}$]	1.1 ± 0.7[u] $^{+0.2}_{-0.3}$[j] ± 0.1[$\mathcal{L}$]
Z+jets	52 ± 21[u] $^{+15}_{-11}$[j] $\pm$ 6[$\mathcal{L}$]	4.1 ± 2.9[u] $^{+2.1}_{-0.8}$[j] ± 0.5[$\mathcal{L}$]	27 ± 12[u] $^{+10}_{-6}$[j] ± 3[$\mathcal{L}$]	0.8 ± 0.7[u] $^{+0.6}_{-0.0}$[j] ± 0.1[$\mathcal{L}$]
$t\bar{t}$ and t	10 ± 0[u] $^{+3}_{-2}$[j] $\pm$ 1[$\mathcal{L}$]	0.9 ± 0.1[u] $^{+0.4}_{-0.3}$[j] ± 0.1[$\mathcal{L}$]	17 ± 1[u] $^{+6}_{-4}$[j] ± 2[$\mathcal{L}$]	0.3 ± 0.1[u] $^{+0.2}_{-0.1}$[j] ± 0.0[$\mathcal{L}$]
Total SM	118 ± 25[u] $^{+32}_{-23}$[j] ± 12[$\mathcal{L}$]	10.0 ± 4.3[u] $^{+4.0}_{-1.9}$[j] ± 1.0[$\mathcal{L}$]	88 ± 18[u] $^{+26}_{-18}$[j] ± 9[$\mathcal{L}$]	2.5 ± 1.0[u] $^{+1.0}_{-0.4}$[j] ± 0.2[$\mathcal{L}$]
Data	87	11	66	2
$\sigma \cdot \varepsilon \cdot A$	< 1.3 pb	< 0.35 pb	< 1.1 pb	< 0.11 pb

ArXiV:1102.5290
Submitted to PLB

MET + jets + 0 lepton

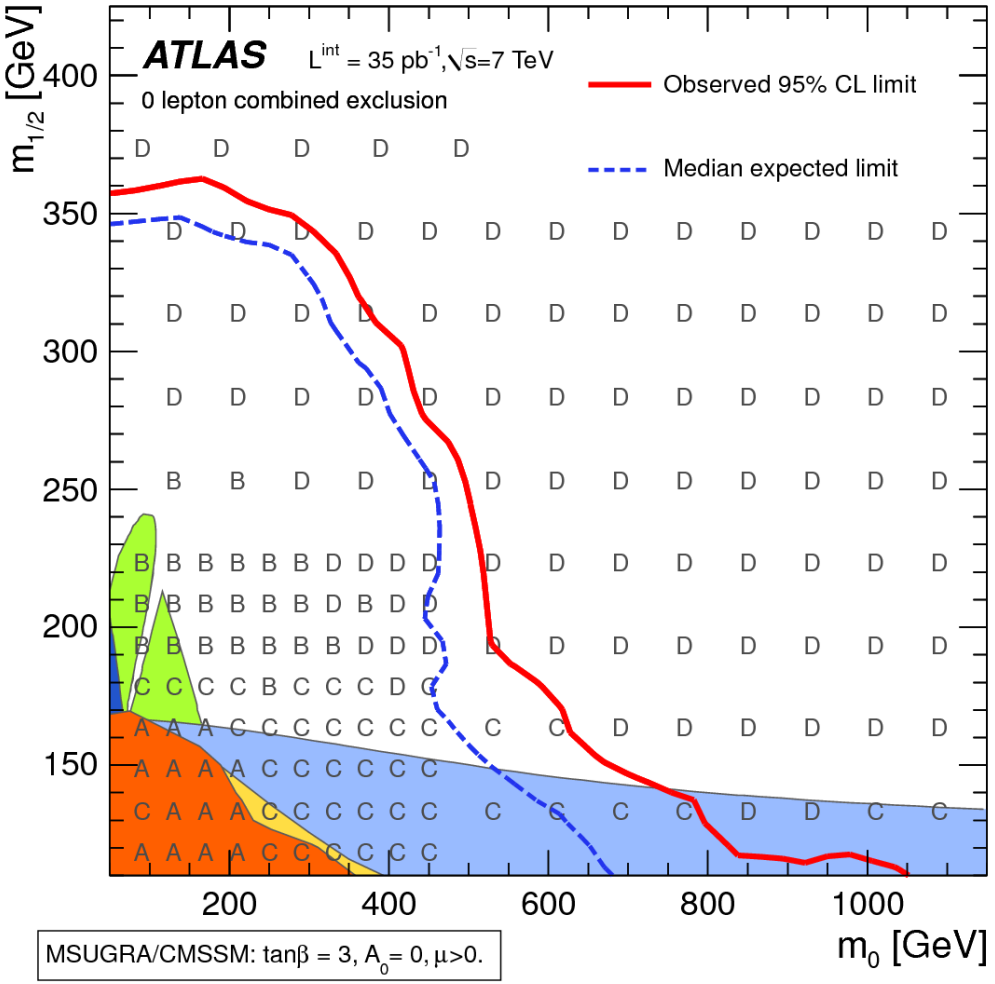


- Events with $\Delta\phi_{min}$(jet,MET) < 0.4 constitute the QCD control sample
- Events with $\Delta\phi_{min}$(jet,MET) > 0.4 are considered for the final signal selections

ArXiV:1102.5290
Submitted to PLB

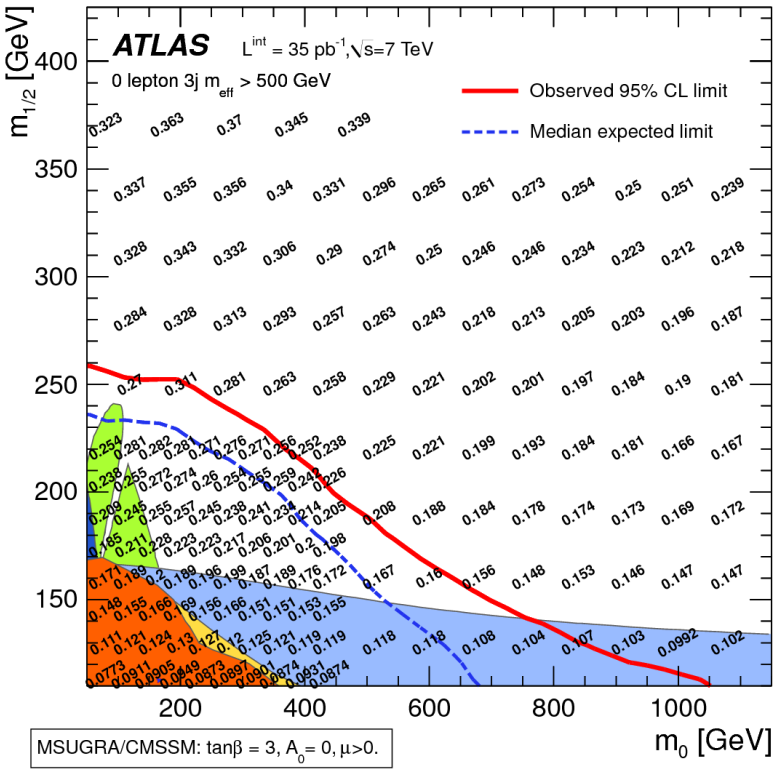
MET + jets + 0 lepton

Signal Region (SR: A, B, C or D) used for each signal Grid point to derive the exclusion curves. The decision of which SR to use was made a priori, based on MC expectations.

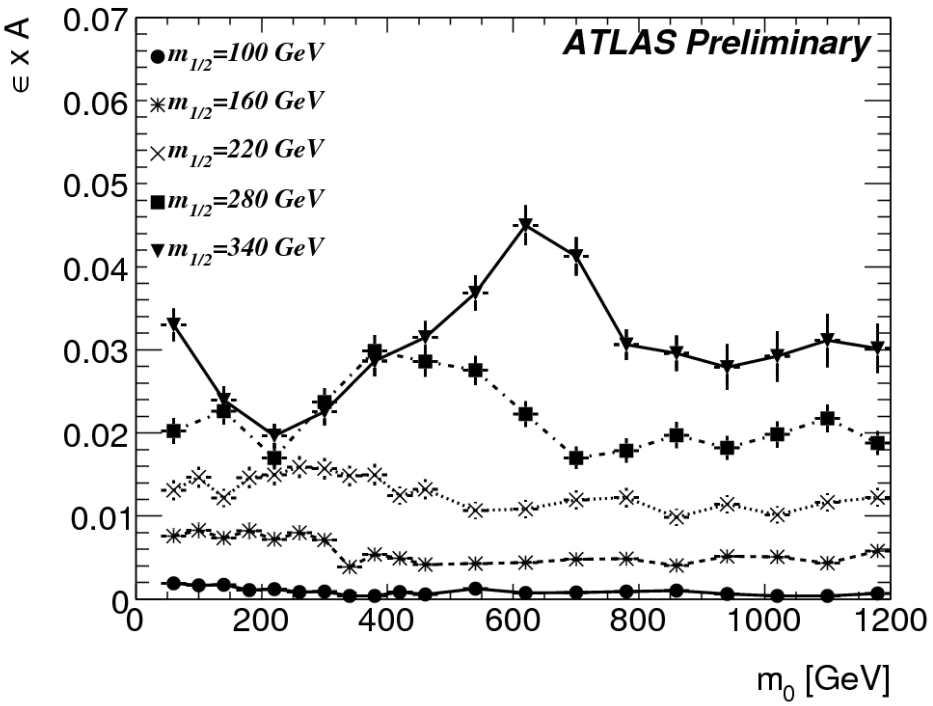


Re-interpretation of 0/1-lepton searches

Signal efficiency of 0-lepton SR C



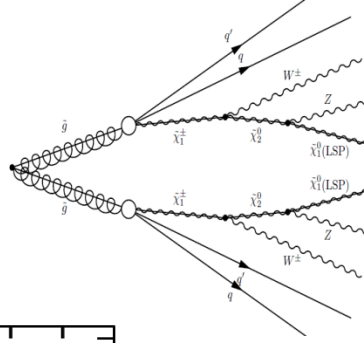
Signal efficiency of 1-lepton (channel μ)

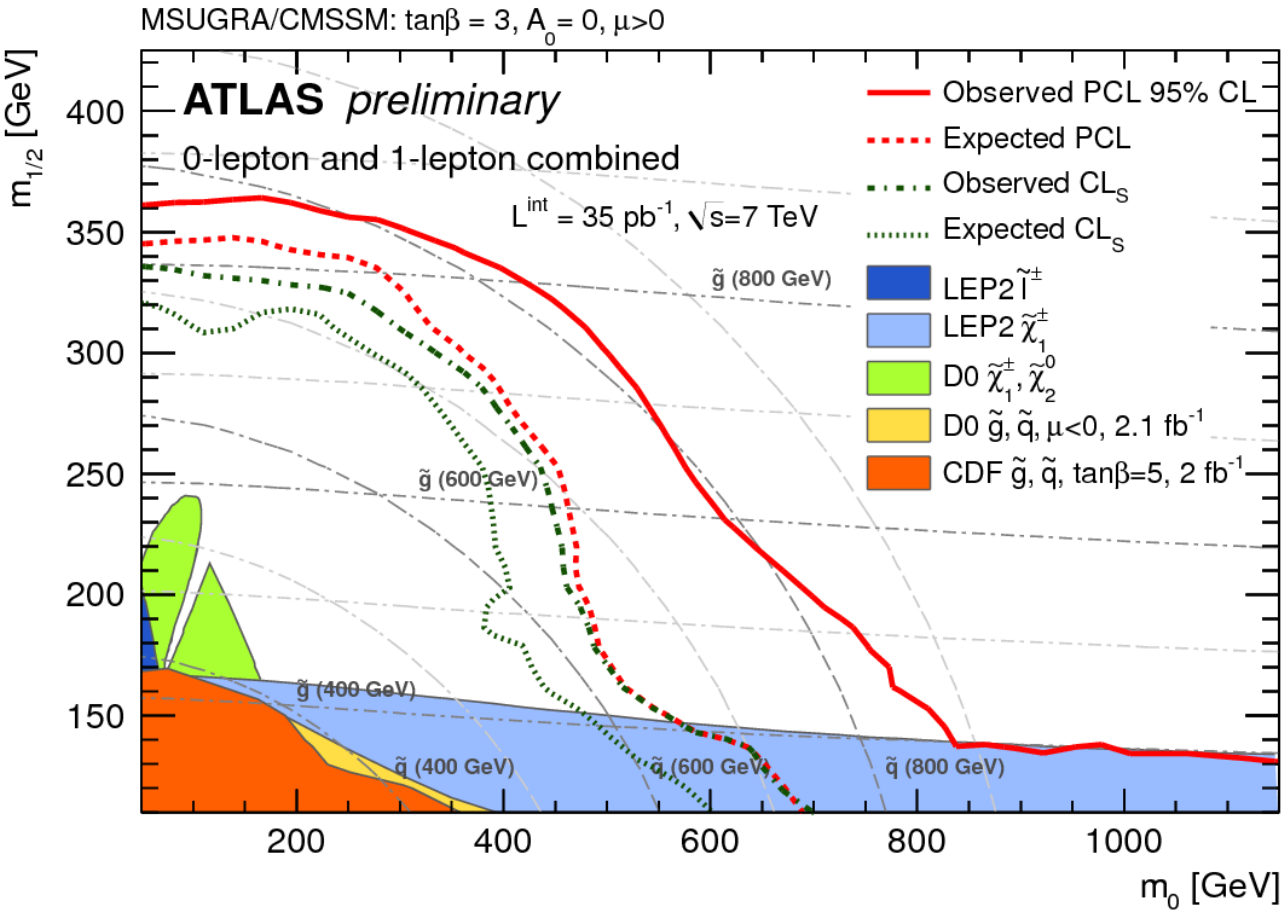


One possible way to do it:

1) reproduce the ATLAS analysis cuts with your "local" simulation of the ATLAS detector
2) validate your local setup against published ATLAS efficiencies for benchmark CMSSM points
3) use your validated setup to predict the expected signal yields for your favorite model

PCL *vs* CLs

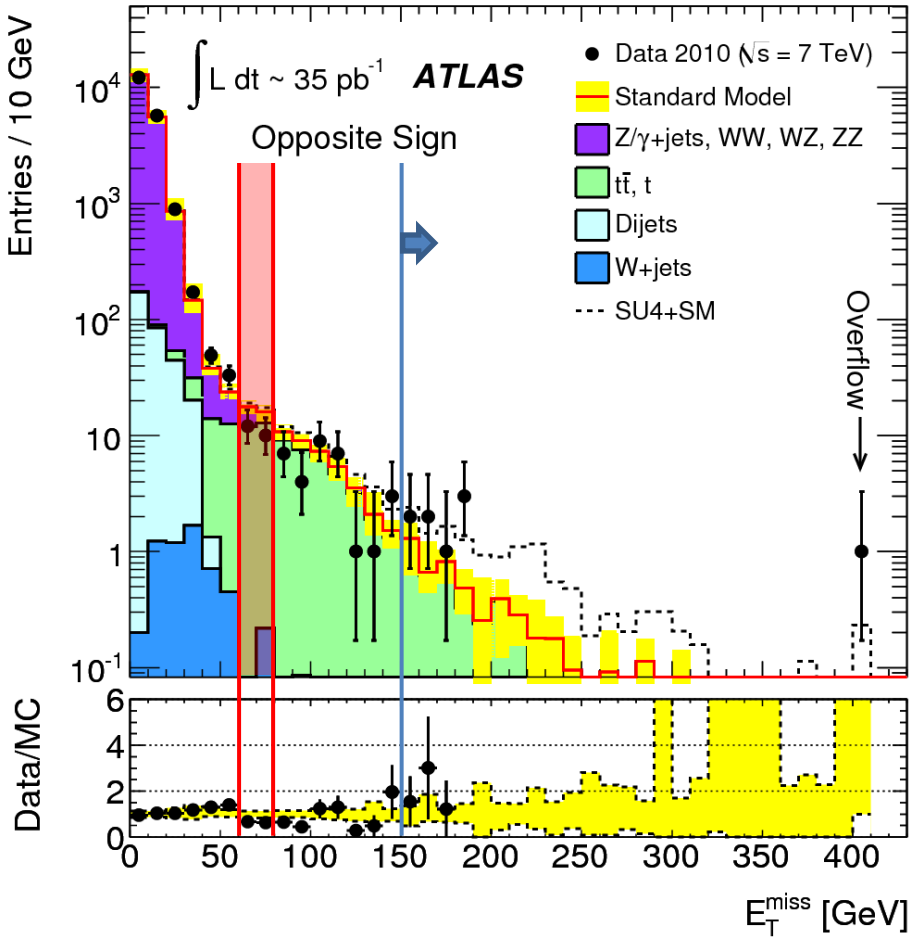




These "power-constrained" limits (PCL) address the issue that motivated the widely used CLs procedure, but do so in a way that makes more transparent the properties of the statistical test to which each value of the parameter is subjected. (arXiv:1105.3166)

ArXiV:1103.6208, accepted by EPJCL

MET + 2 leptons (details)



Flavor subtraction of opposite-sign events

- Main background: top-quark decays
  - control sample: 60<MET<80 GeV
- overflow event is likely a cosmic ray

Events used for flavor subtraction (MET > 100 GeV)

	$e^{\pm}e^{\mp}$	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\mu^{\mp}$
Data	4	13	13
Z/γ^*+jets	0.40±0.46	0.36±0.20	0.91±0.67
Dibosons	0.30±0.11	0.36±0.10	0.61±0.10
$t\bar{t}$	2.50±1.02	6.61±2.68	4.71±1.91
Single top	0.13±0.09	0.76±0.25	0.67±0.33
Fakes	0.31±0.21	-0.15±0.08	0.01±0.01
Total SM	3.64±1.24	8.08±2.78	6.91±2.20

ArXiV:1103.6208, accepted by EPJCL
ArXiV:1103.6214, submitted to EPJCL

MET + 2 leptons

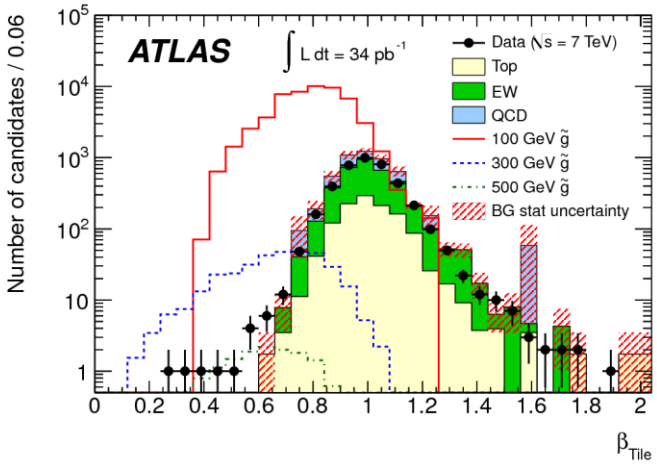
Results: $S_{obs}=1.98 \pm 0.15_{\beta} \pm 0.06_{\tau}$ ($S_{exp}=2.06 \pm 1.1$)

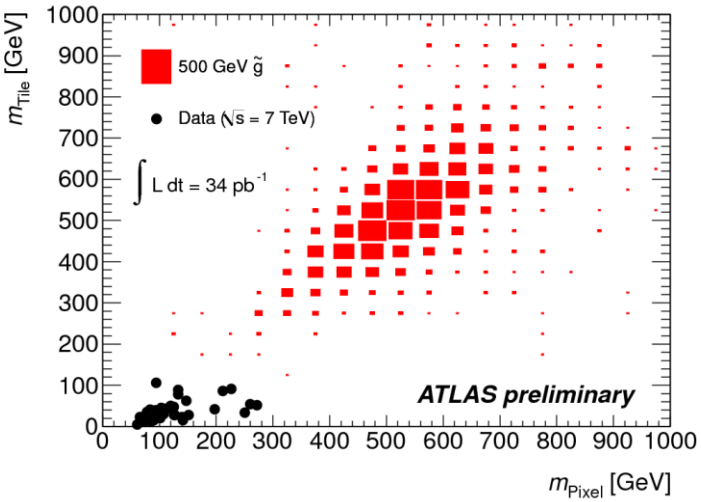
Same Sign, $E_T^{miss} > 100$ GeV	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Data	0	0	0
Fakes	0.12 ± 0.13	0.030 ± 0.026	0.014 ± 0.010
Di-bosons	0.015 ± 0.005	0.035 ± 0.012	0.021 ± 0.009
Charge-flip	0.019 ± 0.008	0.026 ± 0.011	-
Cosmics	-	$0^{+1.17}_{-0}$	-
Total	0.15 ± 0.13	$0.09^{+1.17}_{-0.03}$	0.04 ± 0.01
σ·ε·A	< 0.07 pb	< 0.07 pb	< 0.07 pb

Opposite Sign, $E_T^{miss} > 150$ GeV	$e^{+}e^{-}$	$e^{\pm}\mu^{\mp}$	$\mu^{+}\mu^{-}$
Data	1	4	4
$t\bar{t}$	$0.62^{+0.31}_{-0.28}$	$1.24^{+0.62}_{-0.56}$	$1.00^{+0.50}_{-0.45}$
Z+jets	0.19 ± 0.15	0.08 ± 0.08	0.14 ± 0.17
Fakes	$-0.02 + 0.02$	$-0.05 + 0.04$	-
Cosmics	-	-0.2 ± 1.18	-0.43 ± 1.27
Total	$0.92^{+0.42}_{-0.40}$	$1.43^{+1.45}_{-0.59}$	$1.39^{+1.41}_{-0.53}$
σ·ε·A	< 0.09 pb	< 0.22 pb	< 0.21 pb

ArXiV:1103.1984, accepted by PLB

slow meta-stable particles





Exploit lack of correlation between mass measurements