SUSY searches at the LHC with the ATLAS experiment

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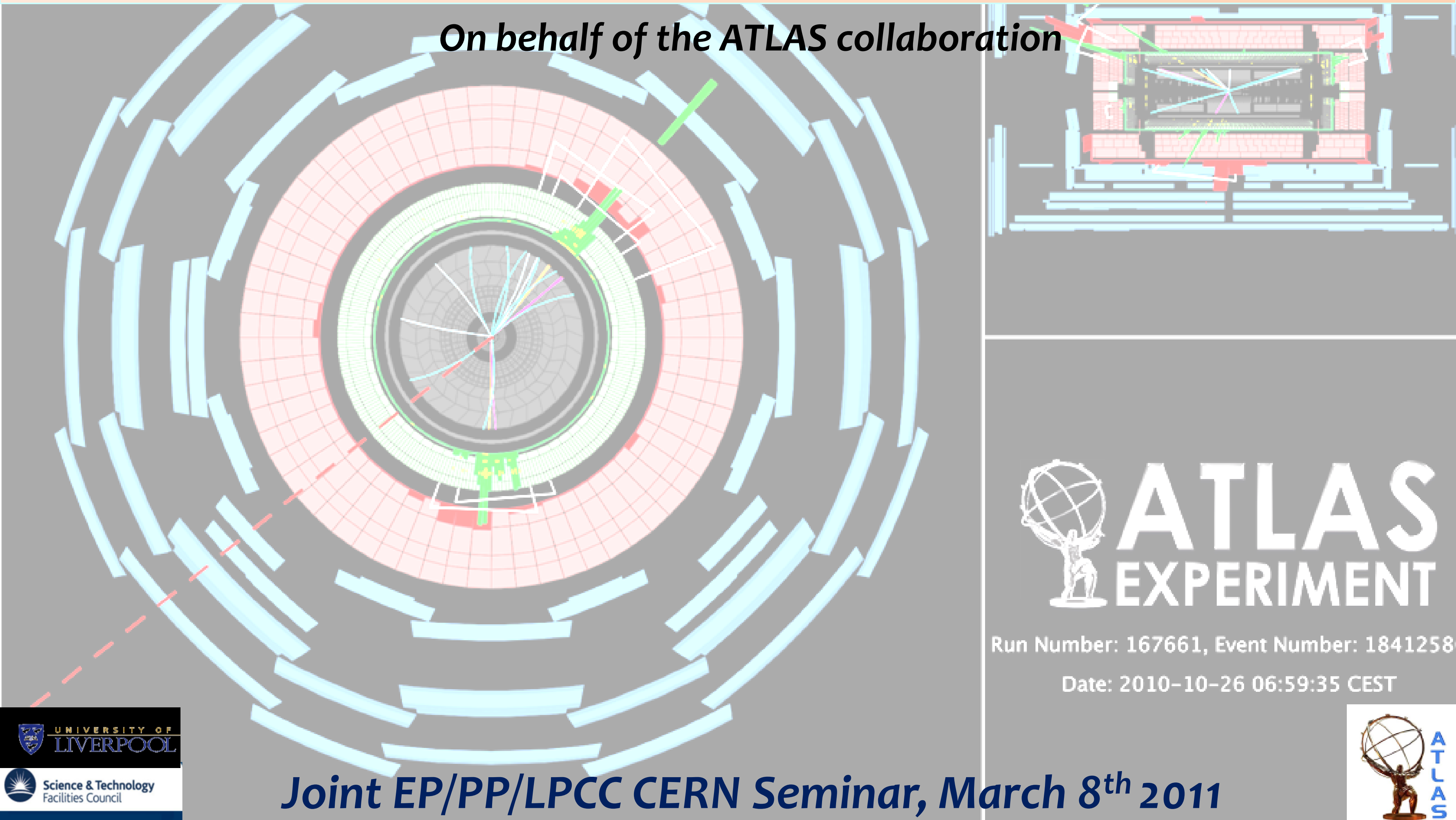
On behalf of the ATLAS collaboration



UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council

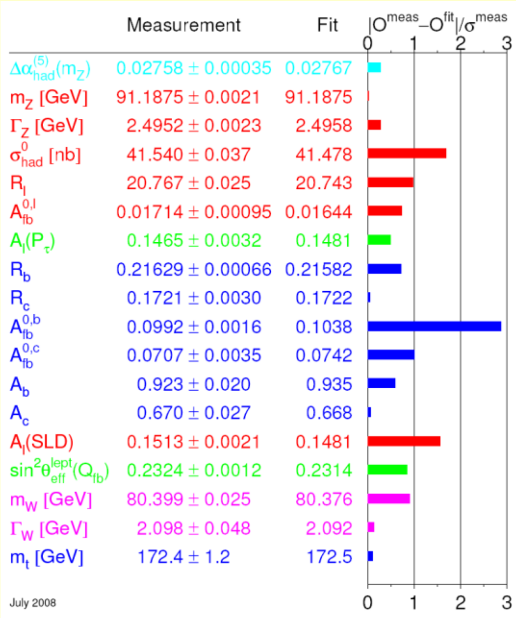
Joint EP/PP/LPCC CERN Seminar, March 8th 2011

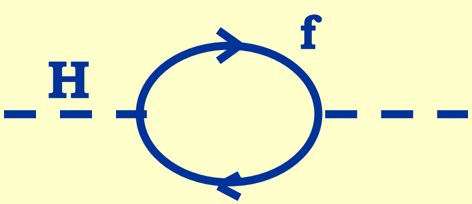
ATLAS

The Standard Model

- Matter is made out of fermions:
  - 3 generations of quarks and leptons
- Forces are carried by Bosons:
  - Electroweak: γ,W,Z, Strong: gluons
- Higgs boson:
  - Gives mass to gauge bosons via EWK symmetry breaking
    → **Not found yet**
- Remarkably successful description of known phenomena

but … ***The Standard Model is theoretically incomplete***





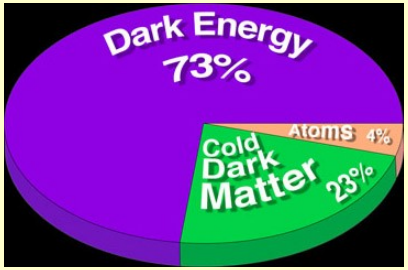
$\Delta m_H^2 \sim \Lambda^2$

$\Lambda = M_{pl}$?

- Mass hierarchy problem

→ radiative correction in Higgs sector

- Unification
- Dark Matter
- Matter-antimatter asymmetry



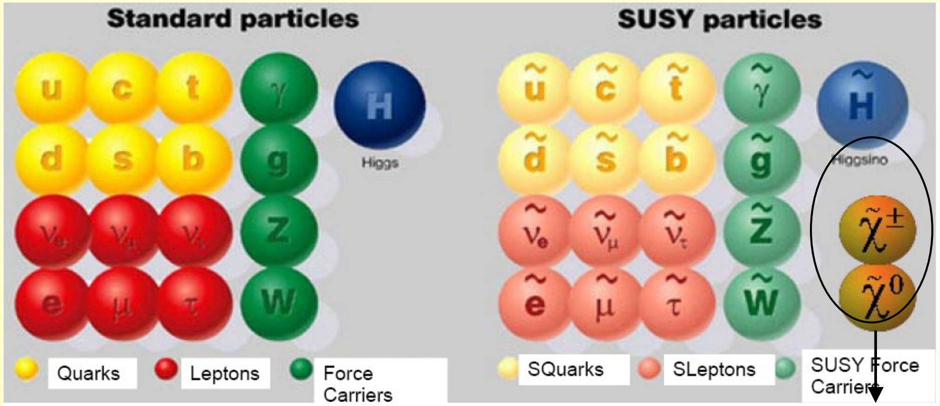
Many possible new particles and theories proposed and searched for

Supersymmetry

New spin-based symmetry relating fermions and bosons

Q|Boson> = Fermion

Q|Fermion> = Boson



gaugino/higgsino mixing

- Minimal SuperSymmetric SM (MSSM):
  - Mirror spectrum of particles
  - Enlarged Higgs sector: two doublets with 5 physical states

$$H_U, H_D \longrightarrow h, H, A, H^{\pm}$$

Naturally solve the hierarchy problem

- Unification of forces possible
- Define R-parity = $(-1)^{3(B-L)+2s}$
  - R = 1 for SM particles
  - R = -1 for MSSM partners

If conserved, provides Dark Matter Candidate

(Lightest Supersymmetric Particle)

No SUSY particles found yet!

→ SUSY must be broken

$$L = L_{SUSY} + L_{Soft}$$

SUSY phenomenology

Breaking mechanism and R-parity determines
phenomenology and the **search strategy**

Generic MSSM

MSUGRA/CMSSM

GMSB, GGM

AMSB

Split-SUSY

RPV-scenarios

….

Exploit unbalanced momentum from LSP

In R-parity conserving scenarios, $\tilde{\chi}_1^0$(or $\tilde{\nu}$) is LSP.
Signatures:
Missing E_T + jets (+ leptons)

Gravitino very light (<< MeV) → is the LSP. Neutralino can be NLSP:

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$

Signatures (R-parity cons.):
Missing E_T+2γ (+lepton/jets)

Depending on the mass spectrum
if small $\tilde{\chi}^{\pm} - \tilde{\chi}_1^0$ mass difference,
long-lived charginos expected
Signatures:
displaced vertex kinked tracks

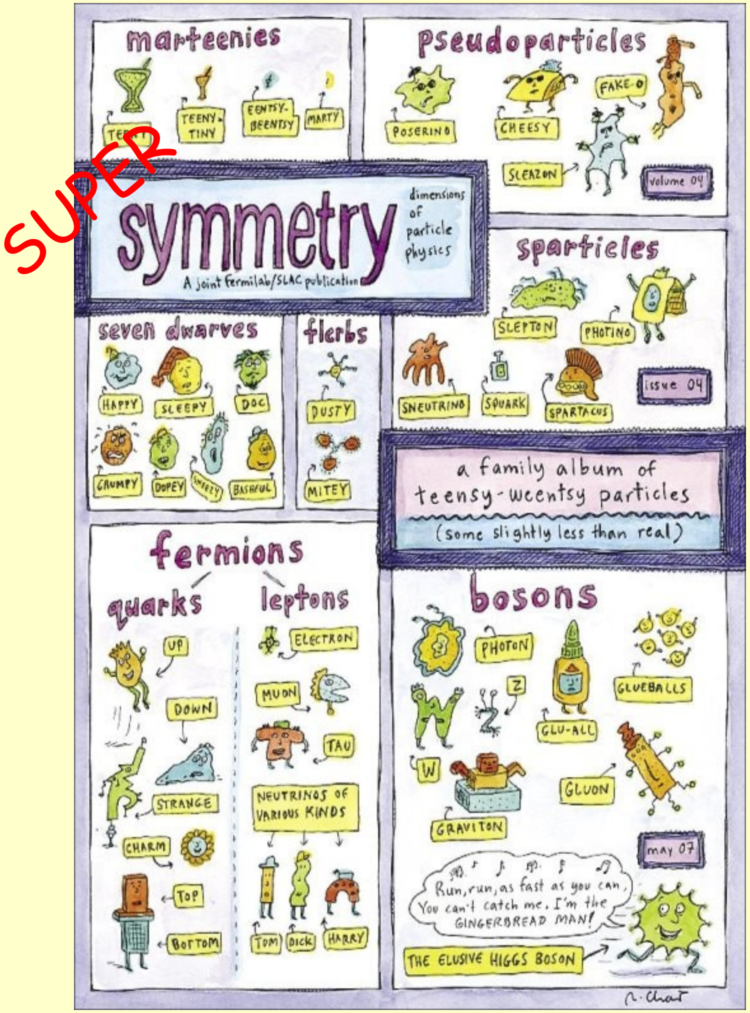
If R-parity not conserved, search for resonances

Dedicated techniques

squarks/gluinos heavy
Typical signatures:
Long-Lived / quasi stable particles (R-hadrons)

Outline

- The ATLAS detector
- Performance and SM measurements *(at a glance)*
- The search for SUSY:
  - Missing E_T-based searches
    - 0-lepton, 1-lepton
    - 2-leptons, inclusive and same-flavor
    - 0/1 lepton + bjets
  - Search for Stable Massive Particles:
    - R-hadrons
- Perspectives and Conclusions



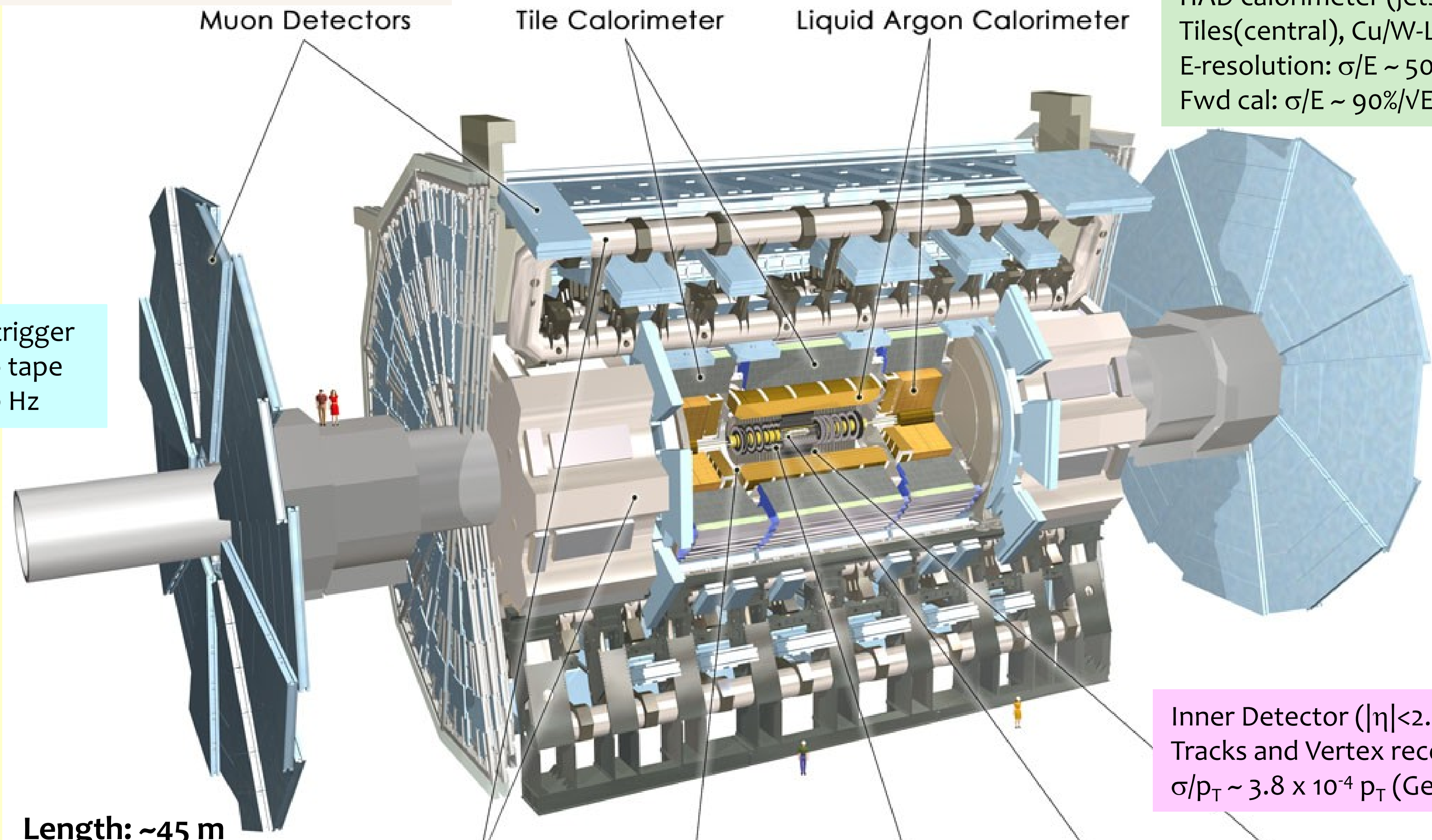
The ATLAS detector

Spectrometer coverage up to $|\eta|<2.7$
Trigger and measurement for μ with
momentum resolution < 10% up to $E_{\mu} \sim 1$ TeV

EM calorimeter, e/γ trigger, ID, measurement
Resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.007$

Coverage up to $|\eta|=4.9$

HAD calorimeter (jets, MET)
Tiles(central), Cu/W-Lar (fwd)
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$
Fwd cal: $\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$



3-level trigger
rate to tape
~200 Hz

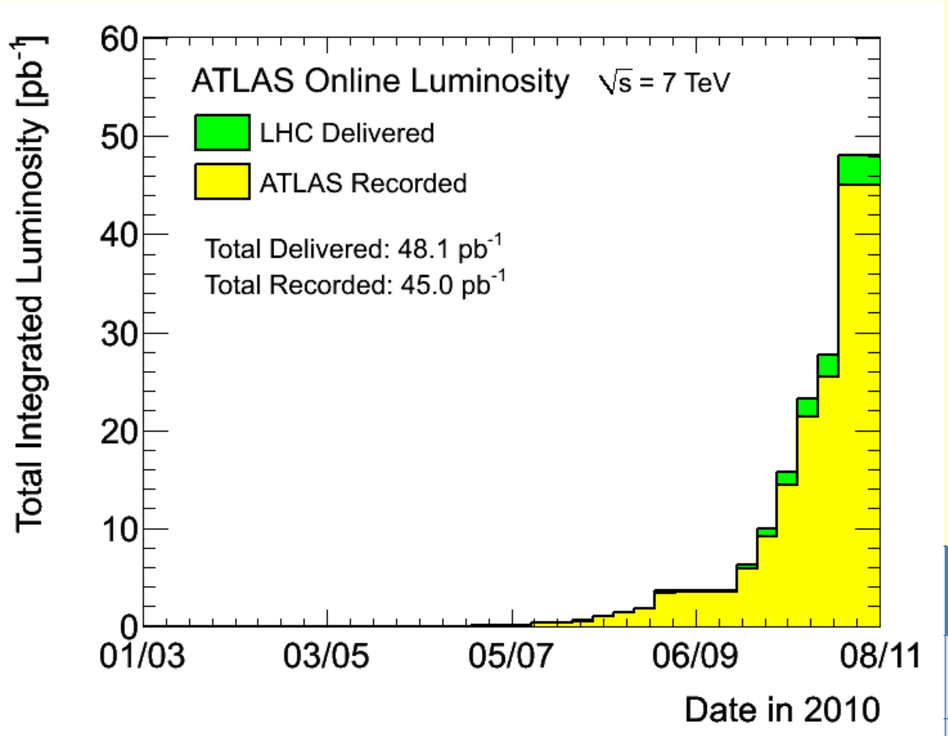
Inner Detector ($|\eta|<2.5$)
Tracks and Vertex reconstructions
$\sigma/p_T \sim 3.8 \times 10^{-4}\ p_T\ (\mathrm{GeV}) \oplus 0.015$

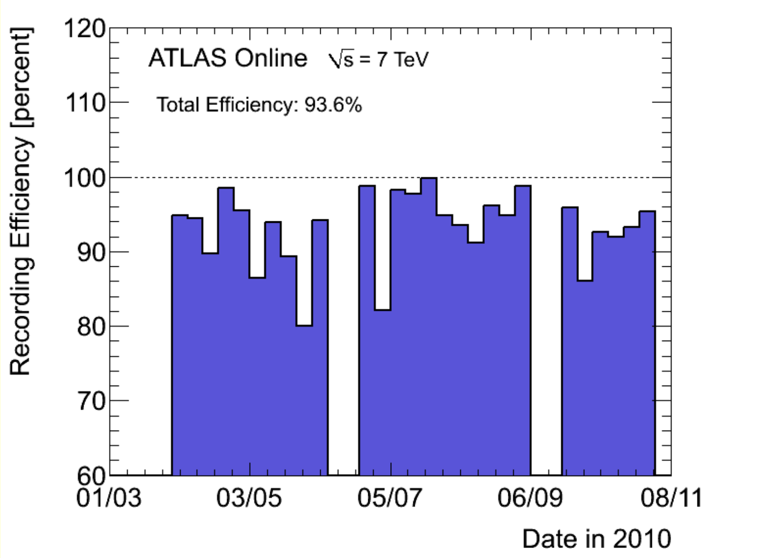
Length: ~45 m
Radius: ~12 m
Weight: ~7000 tons

2 T magnetic field

The 2010 ATLAS pp data

- Profiting at best from the excellent LHC performance:
  - Maximum values of 6 pb^{-1} luminosity per day
  - Instantaneous luminosity values up to $2 \times 10^{32}\ cm^{-2}\ s^{-1}$
- Detector efficiency above 90%



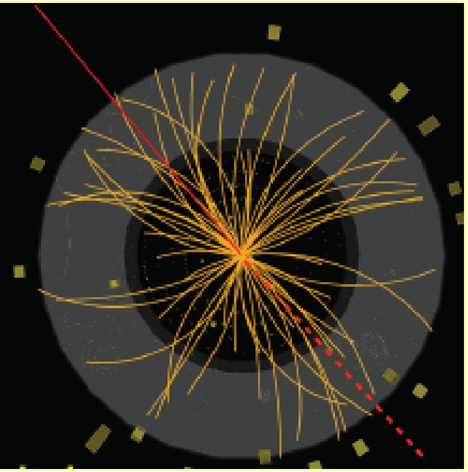


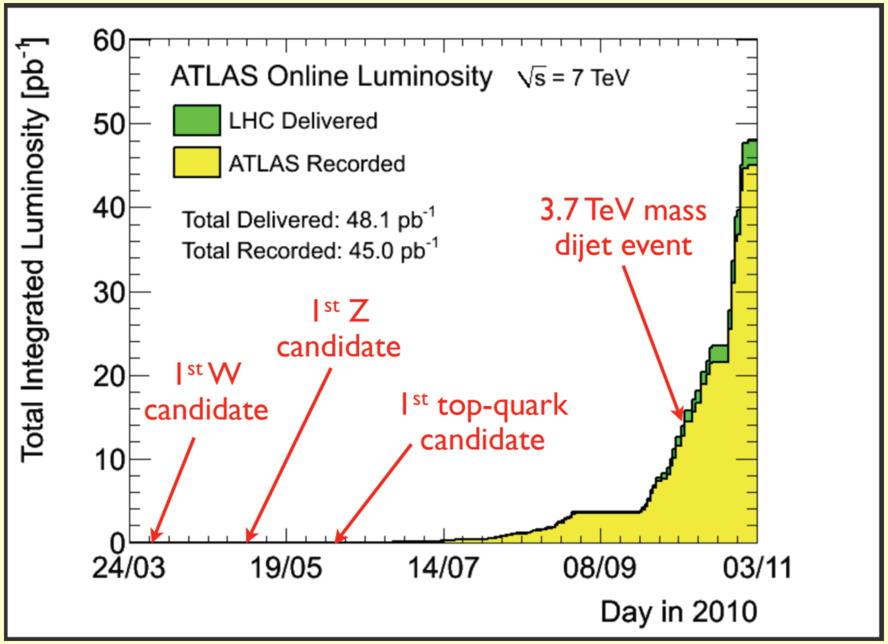
Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at √s=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.

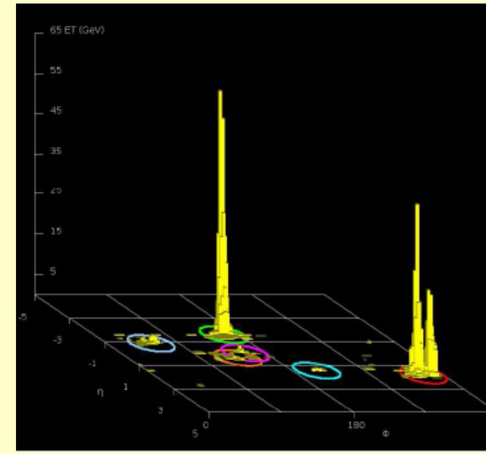
A few milestones from last year…

W → μ ν

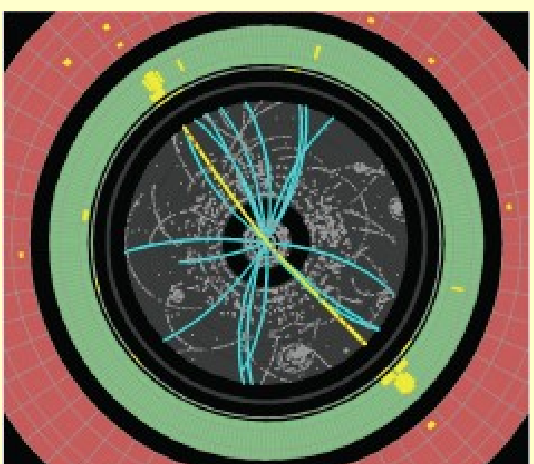




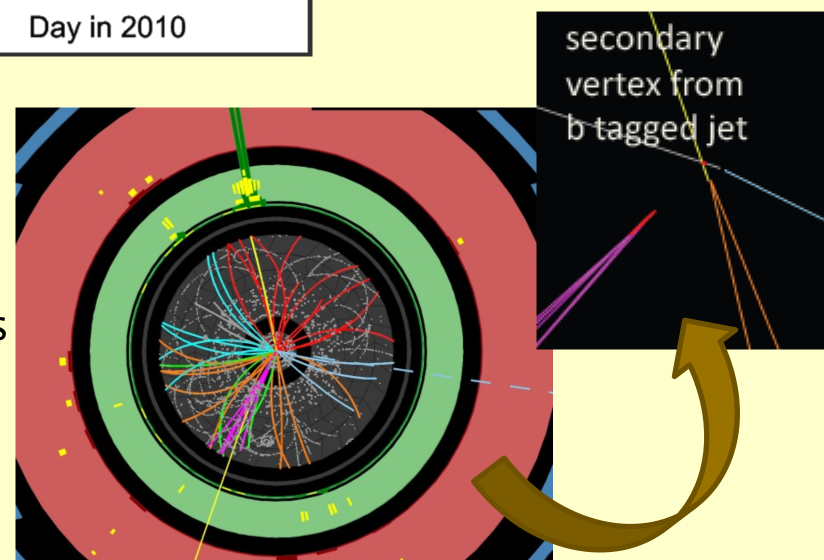
highest mass dijet event



Z → e⁺e⁻

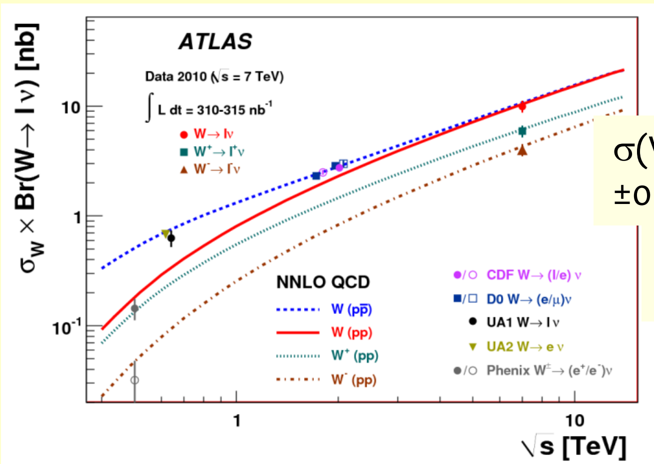


Candidate Top in e+jets



…SM measurements today!

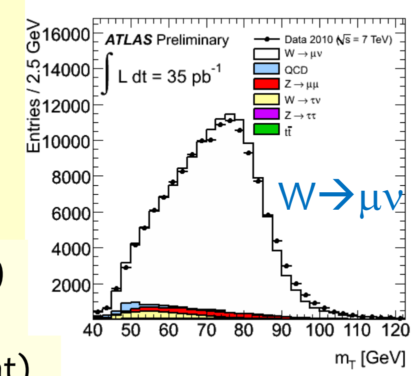
- W/Z (in e/μ) cross sections with very first data
- Excellent reconstruction and identification of e and μ

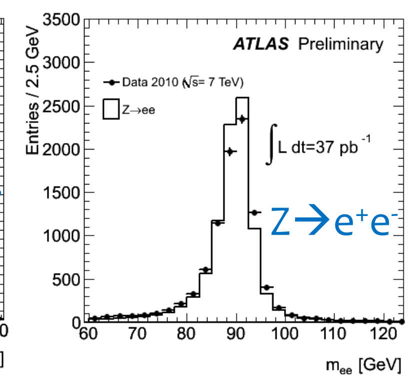


JHEP 12 (2010) 060

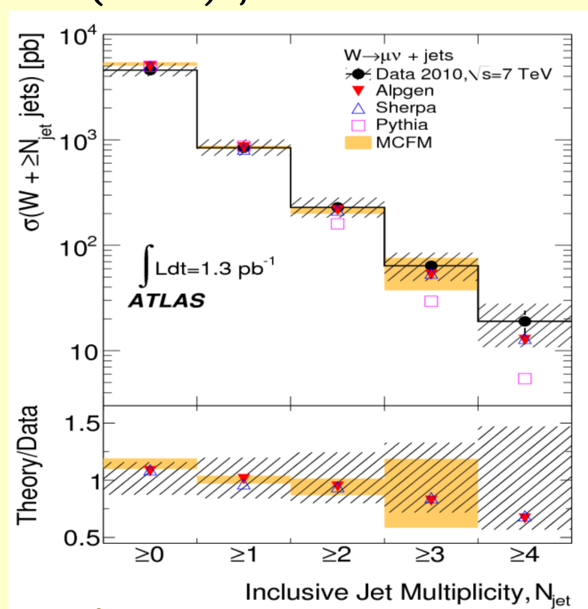
$\sigma(W \to l\nu) = 9.96 \pm 0.23(stat) \pm 0.50(syst) \pm 1.10(lumi)$ nb

$\sigma(Z \to ll) = 0.82 \pm 0.06(stat) \pm 0.05(syst) \pm 0.09(lumi)$ nb





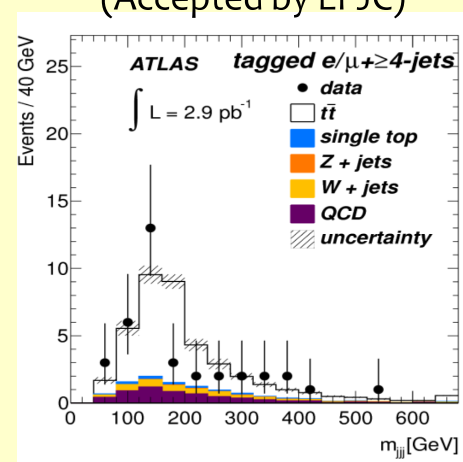
- W(and Z)+jets cross section



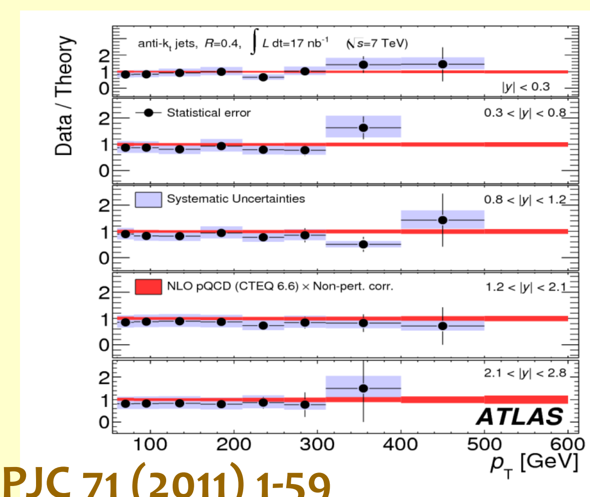
arXiv:1012.5382
(Accepted by Phys Lett. B)

- top pair cross section
(lepton+jets and dilepton)

arXiv:1012.1792
(Accepted by EPJC)

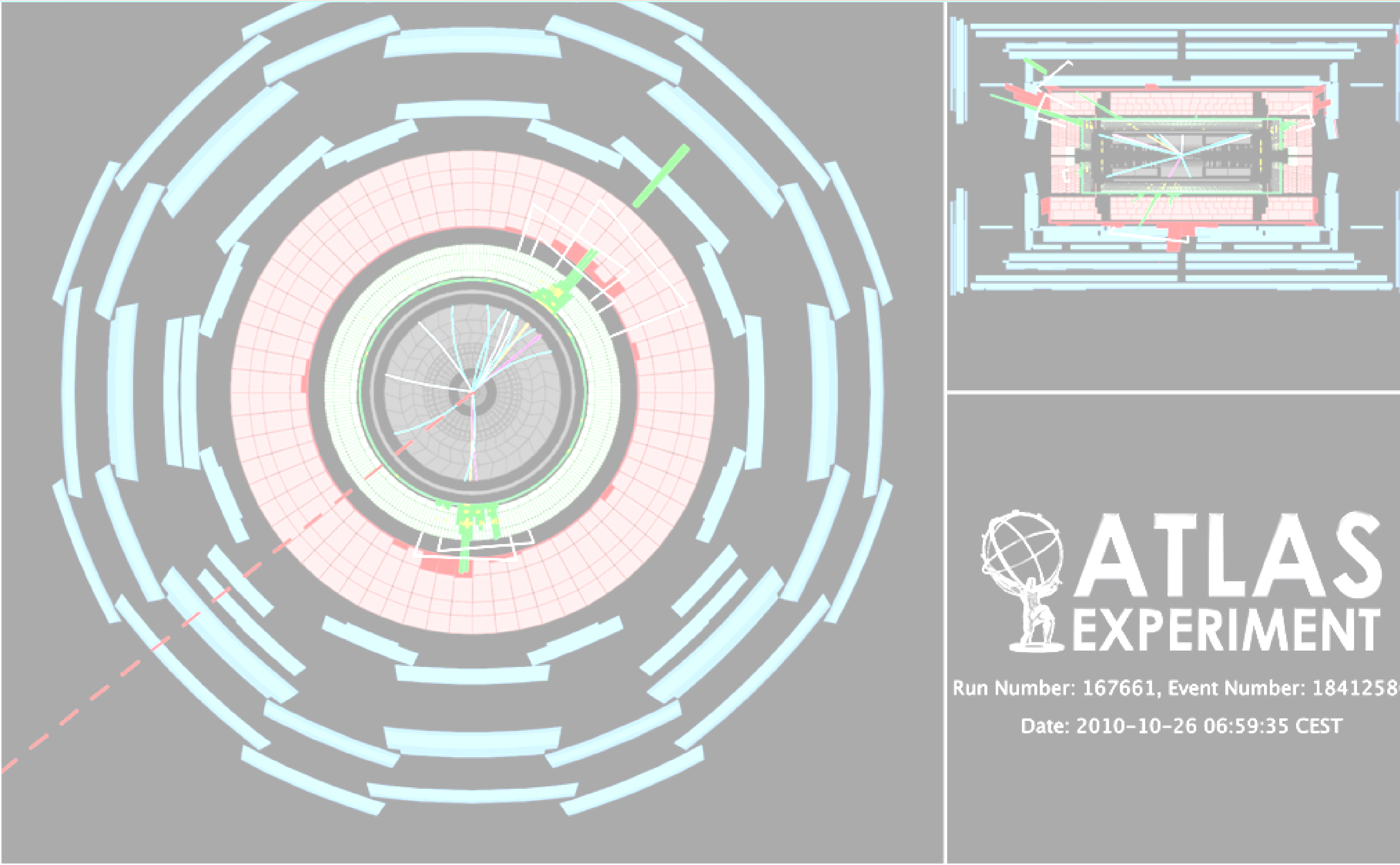


- Inclusive jet (and dijet) cross sections
  - good understanding of jets and Jet Energy Scale



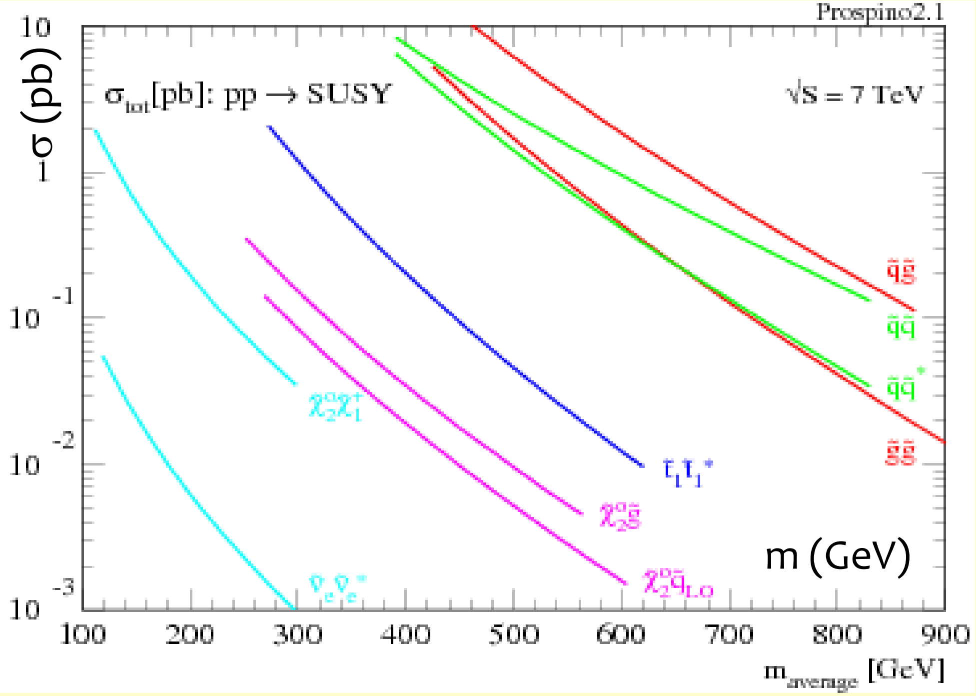
EPJC 71 (2011) 1-59

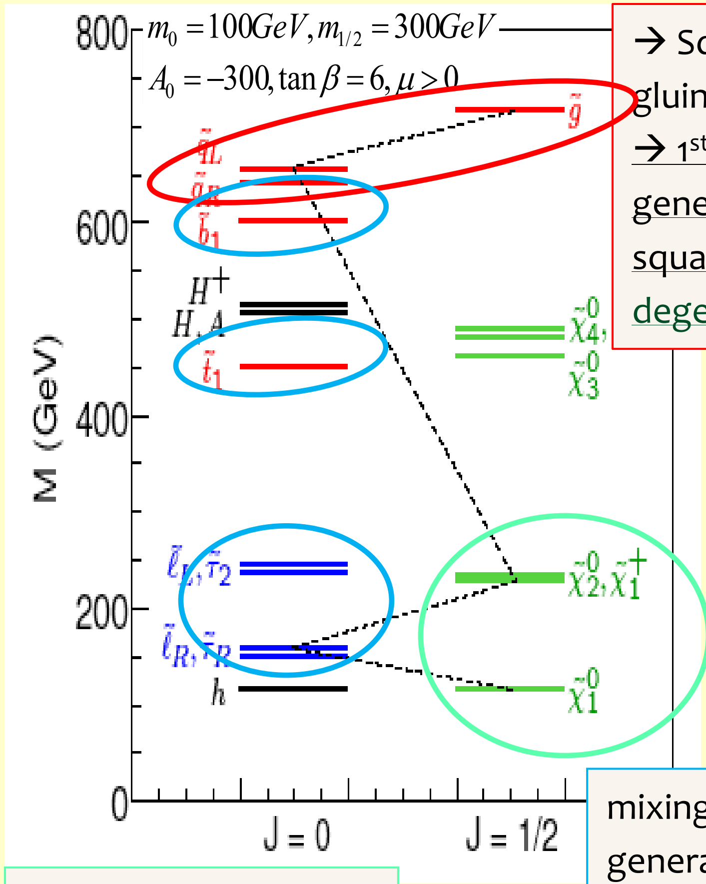
E_T^{Miss} based SUSY Searches



SUSY Topologies

- In R-parity conserving scenarios, sensitivity depends on
  - Cross section of colored sparticles
  - Mass hierarchy, i.e. dependence on $\Delta M = M(\tilde{g}/\tilde{q}) - M(LSP)$





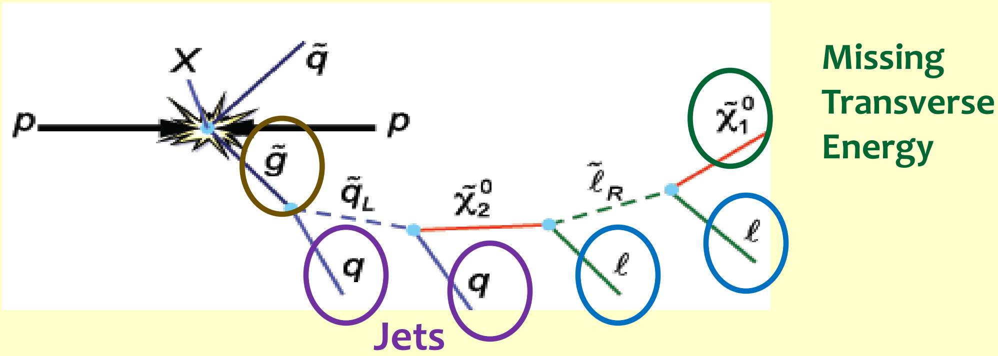
→ Squarks and gluinos heavy
→ 1st and 2nd generation squarks are mass degenerate

Light gauginos also expected

mixing of 3rd generation leads to light stop, sbottom and stau mass

Basic strategy

- Complex (and model-dependent) squark/gluino cascades



- Focus on signatures covering large classes of models while strongly rejecting SM background
  - large Missing E_T
  - High transverse momentum jets
  - Leptons
    - Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons)
  - B-jets: to enhance sensitivity to third generation squarks

Specific model assumed only for interpretation of the results and to assess experimental reach

Common pre-selections

Object identification and kinematic range, common to all MET-based analyses

Primary vertex
- At least 1 good vertex with $N_{tracks}>4$

Jets
- anti-k_T, R=0.4
- p_T > 20 GeV, $|\eta|<2.5$
- Reject events compatible with noise or cosmics

B-Jets
- Secondary vertex reconstruction algorithm (Svo), require decay length significance > 5.72 (50% b-tag eff)
- p_T > 30 GeV, $|\eta|<2.5$

Electrons
- p_T > 20 GeV, $|\eta|<2.47$
- reject events if electron candidates are in transition region ($1.37<|\eta|<1.52$)

Muons
- p_T > 20 GeV, $|\eta|<2.4$
- combined/extrapolated info from ID and Muon spectrometer
- Sum p_T of tracks <1.8 GeV in $\Delta R<0.2$

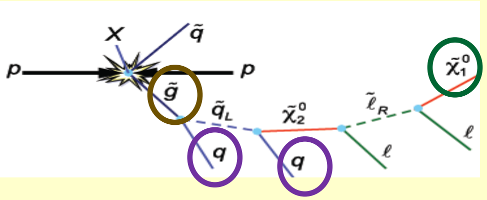
Missing E_T
- Calculated from objects and clusters

Remove overlapping objects
- If $\Delta R(jet,e)<0.2$, remove jet
- If $0.2<\Delta R(jet,e)<0.4$, veto electron
- If $\Delta R(jet,\mu)<0.4$, veto muon

arXiv:1102.5290 (Sub. PLB)

Search in no-lepton final states

- Select events with jets, missing E_T and no lepton (e/μ veto)
- Signal regions definition on the basis of jet multiplicity (n ≥2 jets or n≥3 jets), jet p_T and E_T^{Miss} thresholds, and:



Phys.Lett.B463:99-103,1999
J.Phys.G29:2343-2363,2003

Scalar sum of objects p_T
Effective mass (m_{eff})

$$m_{eff} \equiv \sum_{i-1}^{n} | p_T^{(i)} | + E_T^{miss}$$

Stransverse mass (m_{T2})

$$m_{T2}(\vec{p}_T^{(1)}, \vec{p}_T^{(2)}, \not{\vec{p}}_T) \equiv \min_{\vec{q}_T^{(1)} + \vec{q}_T^{(2)} = E_T^{miss}} \{\max(m_T(\vec{p}_T^{(1)}, \vec{q}_T^{(1)}), m_T(\vec{p}_T^{(2)}, \vec{q}_T^{(2)}))\}$$

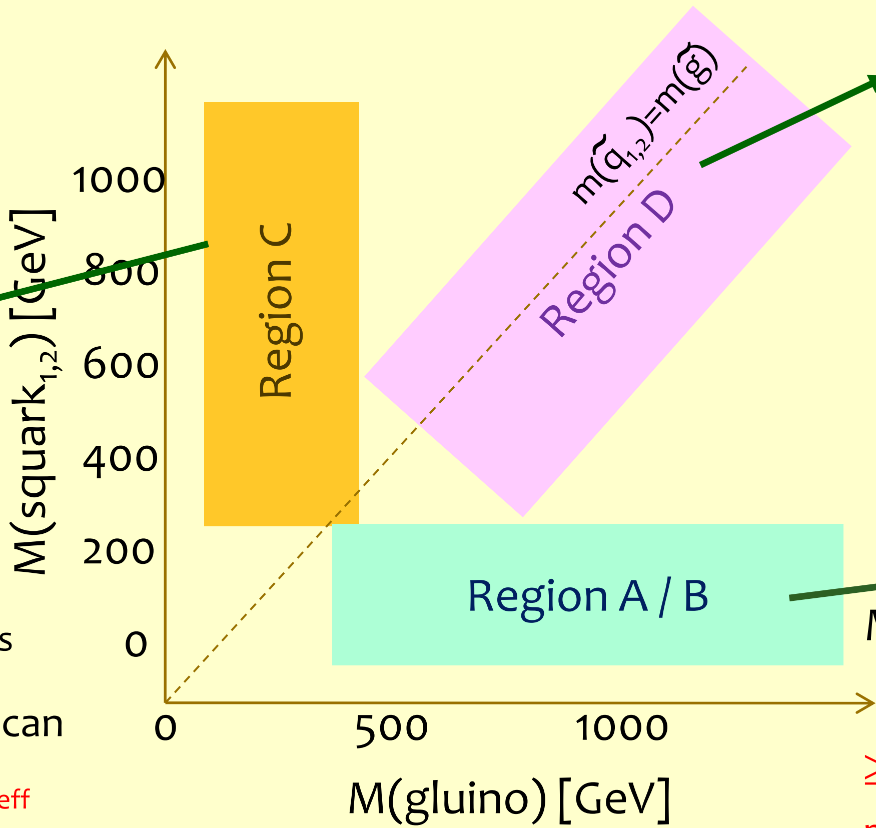
$$m_T^2(\vec{p}_T^{(i)}, \vec{q}_T^{(i)}) \equiv 2|\vec{p}_T^{(i)}||\vec{q}_T^{(i)}| - 2\vec{p}_T^{(i)} \cdot \vec{q}_T^{(i)}$$

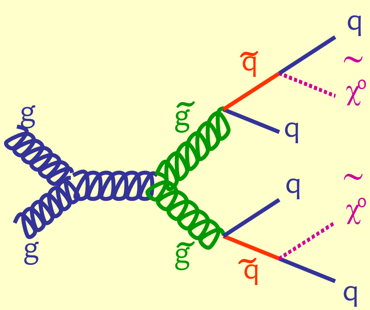
		A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_T [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_T [GeV]	> 40	> 40	> 40	> 40
	E_T^{miss} [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}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

4 signal regions

- Due to trigger requirements (pre-selection)
- QCD-multijet rejection ($\Delta\phi$, E_T^{miss}/m_{eff})
- Enhance sensitivity to SUSY (m_{eff}, m_{T2})

Signal regions sensitivity

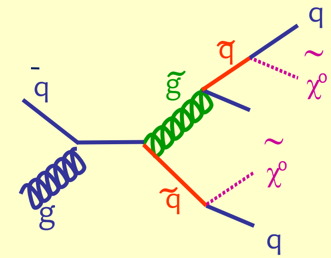




$M_{\tilde{q}} > M_{\tilde{g}}$

$\tilde{g}\tilde{g}$ production dominates

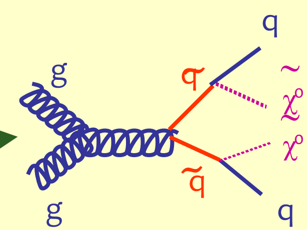
≥ 4 jets expected , 1 can be soft, selection in m_{eff}



$M_{\tilde{q}} \sim M_{\tilde{g}}$

$\tilde{q}\tilde{g}$ production dominates

≥ 3 jets expected, high m_{eff}



$M_{\tilde{q}} < M_{\tilde{g}}$

$\tilde{q}\tilde{q}$ production dominates

≥ 2 jets expected

m_{eff} or m_{T2} selection

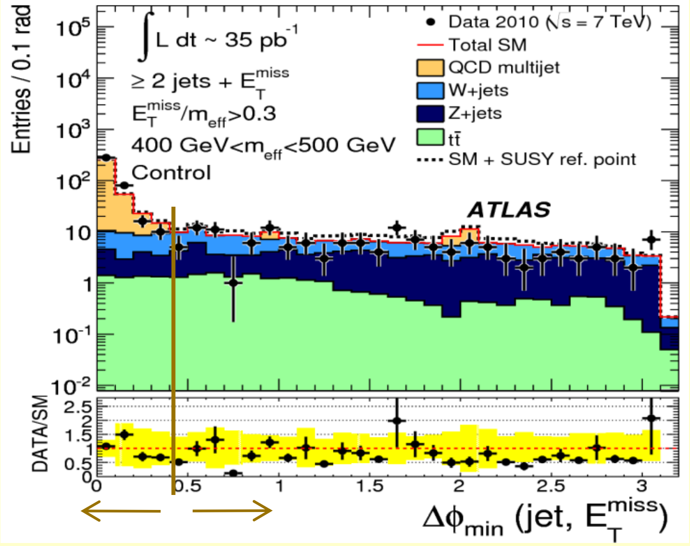
→for high(B)/low(A) masses

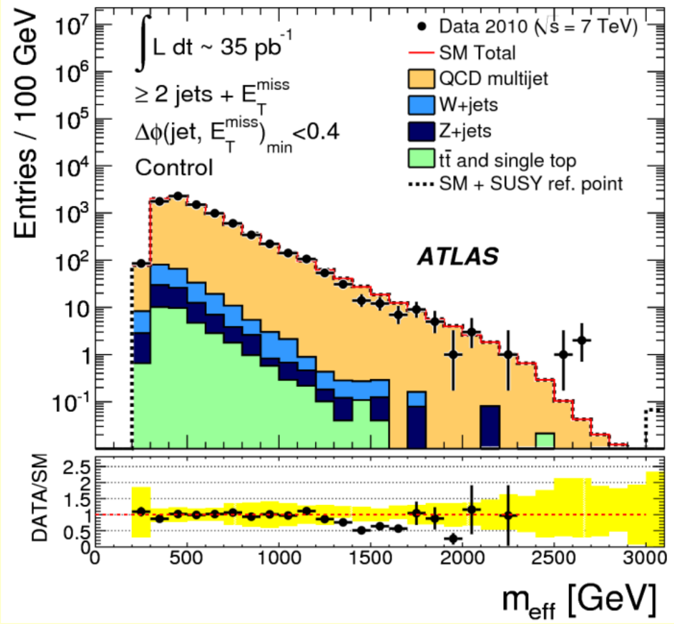
→ exploit dependence in $\Delta M(\tilde{q}_{1,2}-\tilde{\chi}_0^1)$

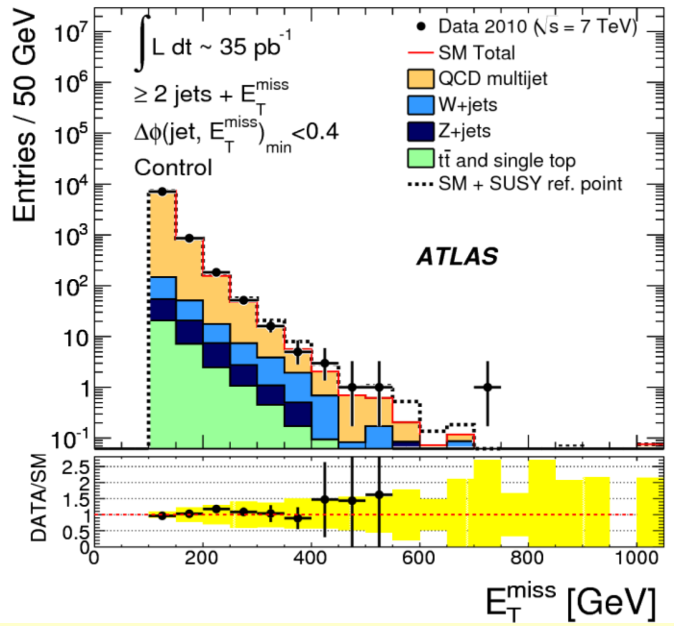
Classification of signal regions almost independent on models

QCD for 0-lepton

- QCD-multijet background due to mis-reconstructed jets and neutrinos from HF leptonic decays
  - E_T^{Miss} expected to be aligned to one of the jets
- Use partially data-driven estimate:
  - Rescale MC samples (PYTHIA and ALPGEN) in control region → **$\Delta\phi$(jet, E_T^{Miss}) < 0.4**







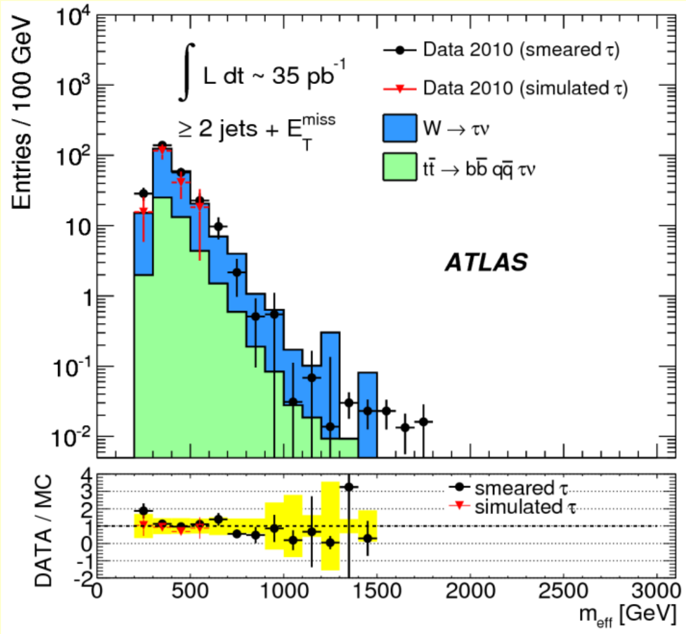
Cross-checked with
→ fully data-driven techniques (Jet smearing)
→ Use control region based on reversed E_T^{Miss}/m_{eff} for rescaling

After rejection: QCD ~5% of TOT Bkg

W/Z+jets and top

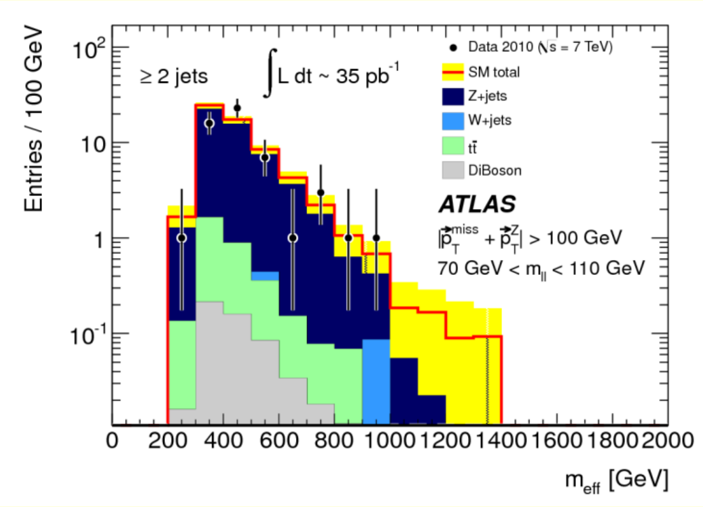
- Non-QCD bkg dominated by
  - W→τν, W→(missed)e/μ, Z→νν + jets
  - Top pair production (t → τ+jets)
- Central value derived from MC:
  - **W/Z:** ALPGEN normalized to NNLO, **Top:** MC@NLO
  - Cross checks on data:
    - Control regions with leptons removed from W/Z data
    - In-situ checks for τ background, derived from W→μν events:

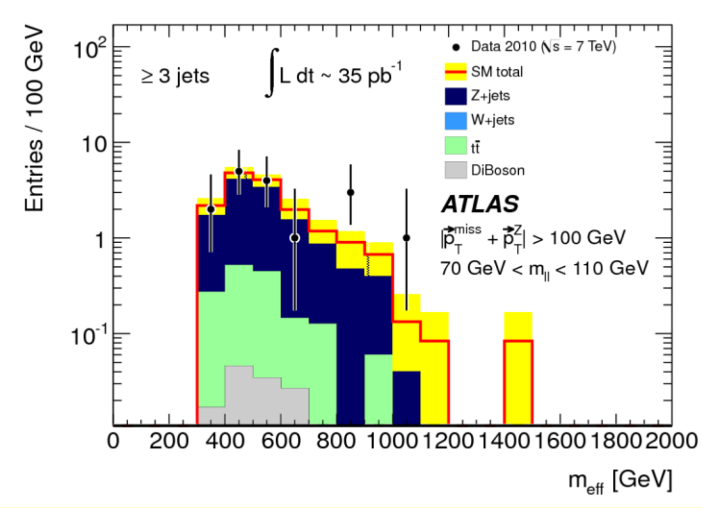
    2 'replacement' methods: smeared resolution function and full simulation
  - Theoretical uncertainties smaller than statistical uncertainty from data-driven estimates



Z+jets control sample

MET recalculated artificially removing the leptons from Z-decay



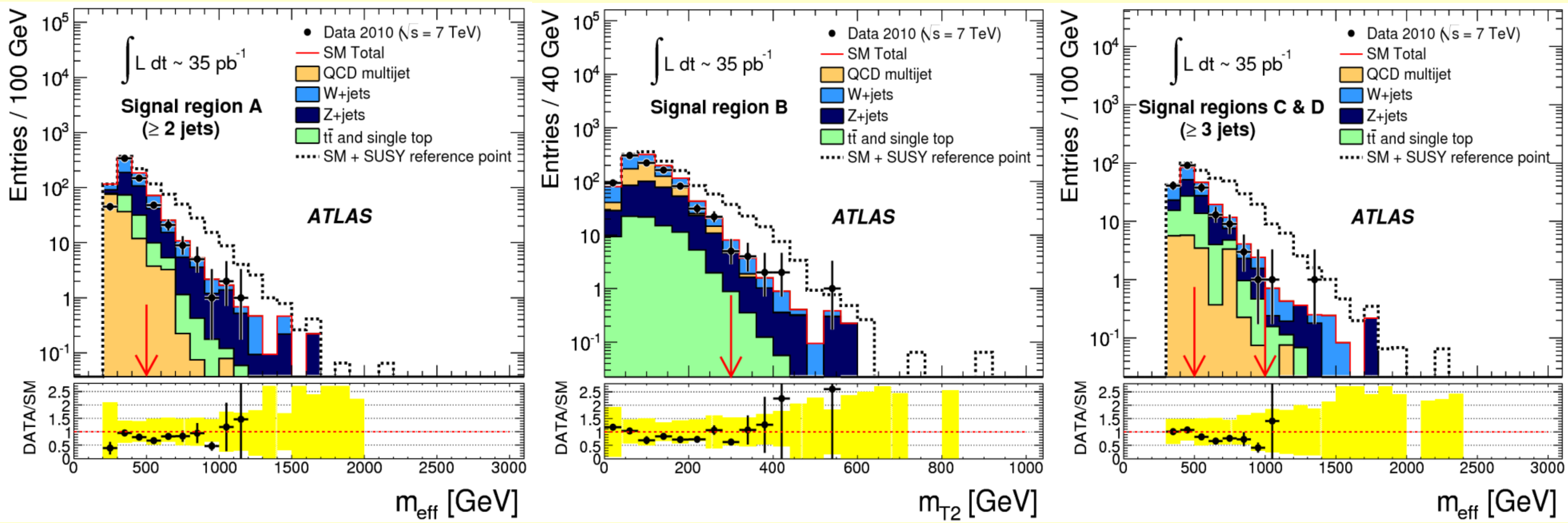


Results

	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\ ^{+8}_{-7}[\mathrm{u}]$	$0.6\ ^{+0.7}_{-0.6}[\mathrm{u}]$	$9\ ^{+10}_{-9}[\mathrm{u}]$	$0.2\ ^{+0.4}_{-0.2}[\mathrm{u}]$
W+jets	$50 \pm 11[\mathrm{u}]\ ^{+\ 9}_{-\ 8}[\mathrm{j}] \pm\ 5[\mathcal{L}]$	$4.4 \pm 3.2[\mathrm{u}]\ ^{+1.0}_{-0.7}[\mathrm{j}] \pm 0.5[\mathcal{L}]$	$35 \pm\ 9[\mathrm{u}]\ ^{+\ 7}_{-\ 7}[\mathrm{j}] \pm 4[\mathcal{L}]$	$1.1 \pm 0.7[\mathrm{u}]\ ^{+0.2}_{-0.3}[\mathrm{j}] \pm 0.1[\mathcal{L}]$
Z+jets	$52 \pm 21[\mathrm{u}]\ ^{+11}_{-\ 9}[\mathrm{j}] \pm\ 6[\mathcal{L}]$	$4.1 \pm 2.9[\mathrm{u}]\ ^{+1.7}_{-0.8}[\mathrm{j}] \pm 0.5[\mathcal{L}]$	$27 \pm 12[\mathrm{u}]\ ^{+\ 7}_{-\ 5}[\mathrm{j}] \pm 3[\mathcal{L}]$	$0.8 \pm 0.7[\mathrm{u}]\ ^{+0.3}_{-0.0}[\mathrm{j}] \pm 0.1[\mathcal{L}]$
$t\bar{t}$ and t	$10 \pm\ 0[\mathrm{u}]\ ^{+\ 2}_{-\ 2}[\mathrm{j}] \pm\ 1[\mathcal{L}]$	$0.9 \pm 0.1[\mathrm{u}]\ ^{+0.2}_{-0.2}[\mathrm{j}] \pm 0.1[\mathcal{L}]$	$17 \pm\ 1[\mathrm{u}]\ ^{+\ 4}_{-\ 3}[\mathrm{j}] \pm 2[\mathcal{L}]$	$0.3 \pm 0.1[\mathrm{u}]\ ^{+0.1}_{-0.1}[\mathrm{j}] \pm 0.0[\mathcal{L}]$
Total SM	$118 \pm 25[\mathrm{u}]\ ^{+23}_{-19}[\mathrm{j}] \pm 12[\mathcal{L}]$	$10.0 \pm 4.3[\mathrm{u}]\ ^{+2.0}_{-1.7}[\mathrm{j}] \pm 1.0[\mathcal{L}]$	$88 \pm 18[\mathrm{u}]\ ^{+18}_{-15}[\mathrm{j}] \pm 9[\mathcal{L}]$	$2.5 \pm 1.0[\mathrm{u}]\ ^{+0.6}_{-0.4}[\mathrm{j}] \pm 0.2[\mathcal{L}]$
Data	87	11	66	2

[u]=uncorrelated uncertainties (MC statistics, acceptance, jet energy resolutions..)
[j]=Jet Energy Scale (6%-10% as function of jet p_T), [$\mathcal{L}$]=luminosity (11%)

Good agreement between data and SM predictions



Interpretation of the results (I)

Use profile likelihood ratio: $\Lambda(\mu) = -2(\ln L(n \mid \mu, \hat{\hat{b}}, \hat{\hat{\theta}}) - \ln L(n \mid \hat{\mu}, \hat{b}, \hat{\theta}))$

- include correlations of uncertainties where appropriate

→ Estimate upper limits at 95% C.L. on N signal events and effective cross sections **independently** of new physics models (background-only hypothesis)

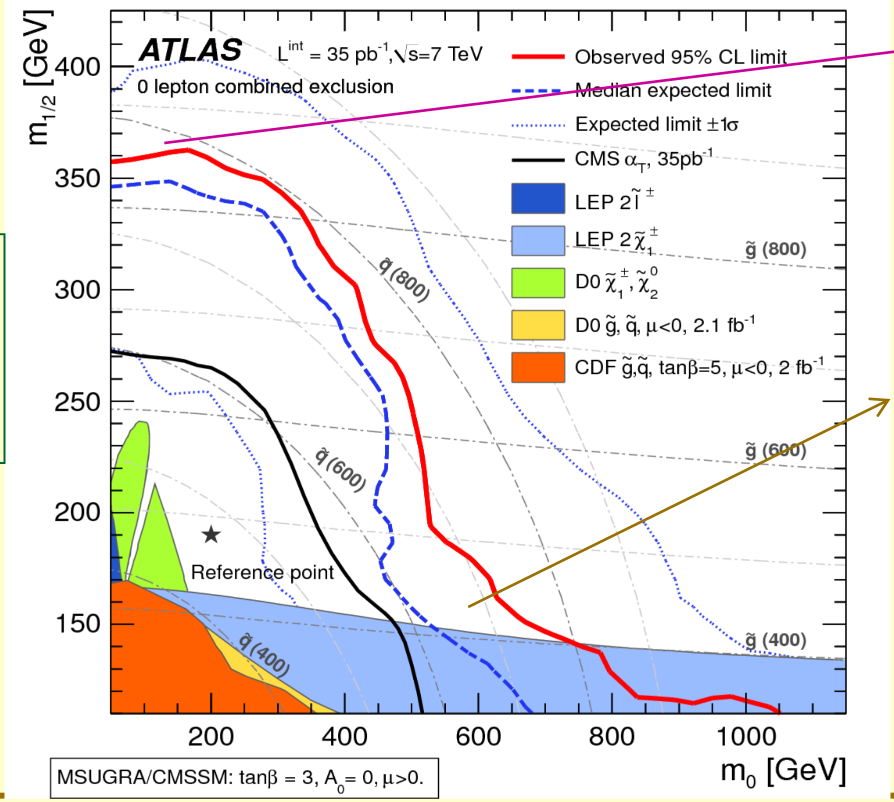
Exclude non-SM: N events 43.9(A), 11.9(B), 37.6(C), 3.5(D)
σ of 1.3(A), 0.35(B), 1.1(C), 0.11 (D) pb

Translate results in limits on **MSUGRA/CMSSM** $(m_0, m_{1/2})$-plane

parameters at GUT scale

1. Unified gaugino(scalar) mass $m_{1/2}(m_0)$
3. Ratio of H_1, H_2 vevs $\tan\beta$
4. Trilinear coupling A_0
5. Higgs mass term $\mathrm{sgn}(\mu)$

Theoretical uncertainties on SUSY NLO cross sections included in limit calculation



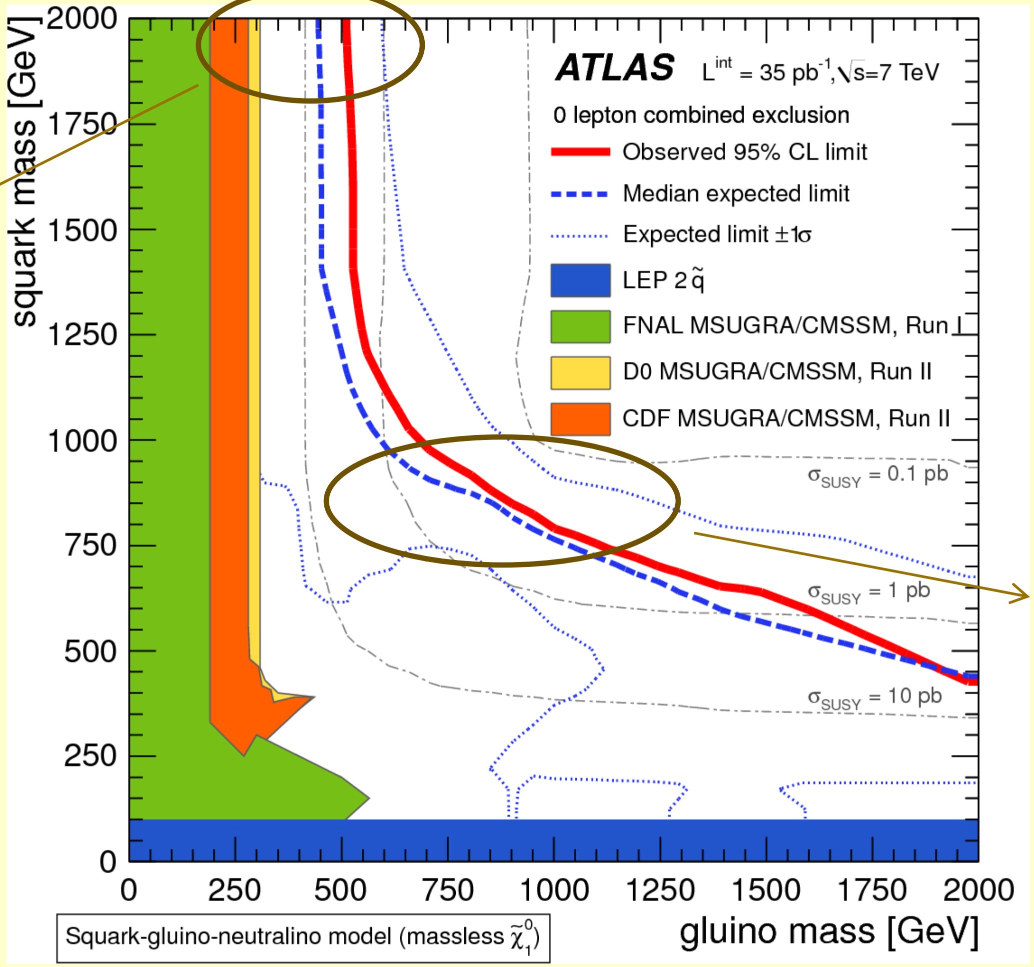
Best sensitivity
Region D
(3j, m_{eff} > 1 TeV)

Best sensitivity
Region C
(3j, m_{eff} > 500 GeV)

If m_{squark}=m_{gluino} exclude < 775 GeV

Interpretation of the results (II)

- Consider phenomenological MSSM models containing only squarks of 1st and 2nd generation, gluino and massless neutralinos

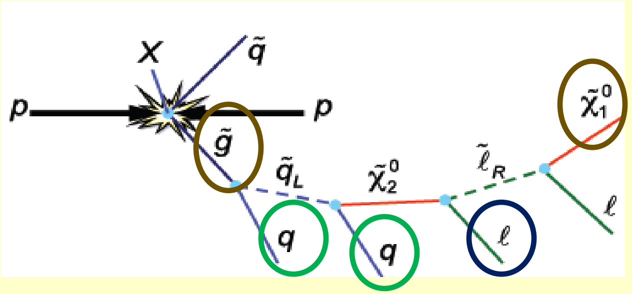


excluded gluino mass below 500 GeV

If m_{squark}=m_{gluino} exclude < 870 GeV

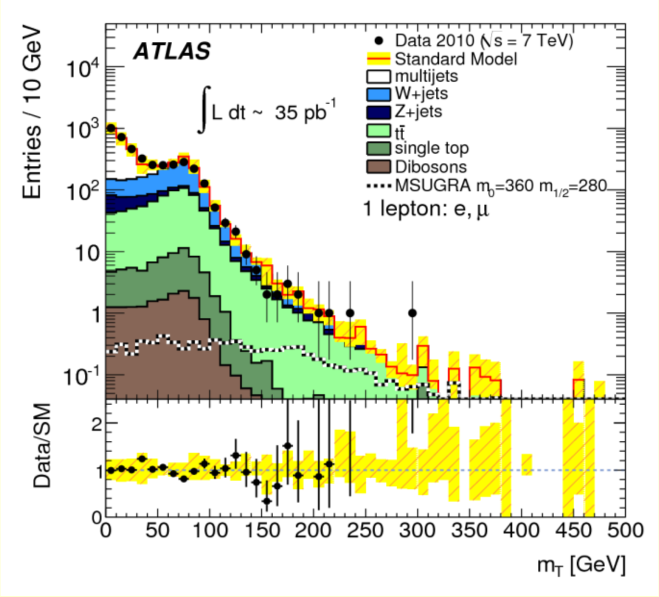
Search in 1-lepton final states

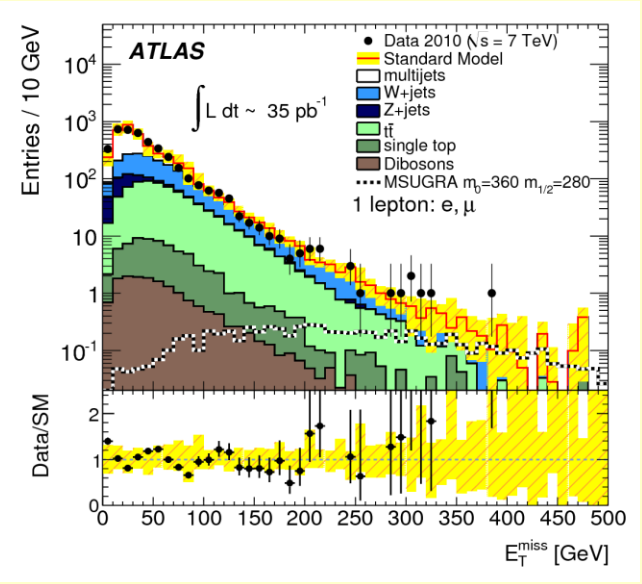
- Require exactly 1 lepton (e or μ, p_T>20 GeV) + ≥3 jets [p_T> 60,30,30 GeV]
  - Privilege signatures from gluino/squark cascade decays with intermediate steps
  - Isolated lepton suppresses QCD multijet background and facilitates triggering



- Use m_T as additional discriminating variable, Missing E_T and jets and leptons p_T

$$m_T \equiv \sqrt{2 \cdot p_T^l \cdot E_T^{Miss} \cdot (1-\cos(\Delta\varphi(l, E_T^{Miss})))}$$



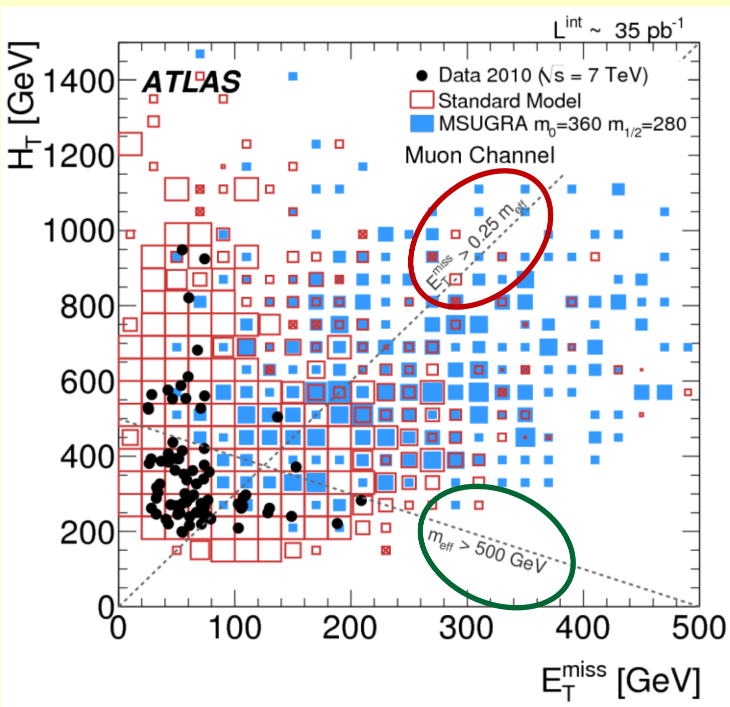


Signal region and results

- Signal region:
  - m_T>100 GeV → to suppress W+jets and top pair production
  - MET/m_{eff} > 0.25 → to suppress QCD background
  - m_{eff}>500 GeV → to enhance sensitivity to SUSY particles

+ $\Delta\phi(\text{jet}, E_T^{Miss})$ > 0.2 for QCD rejection

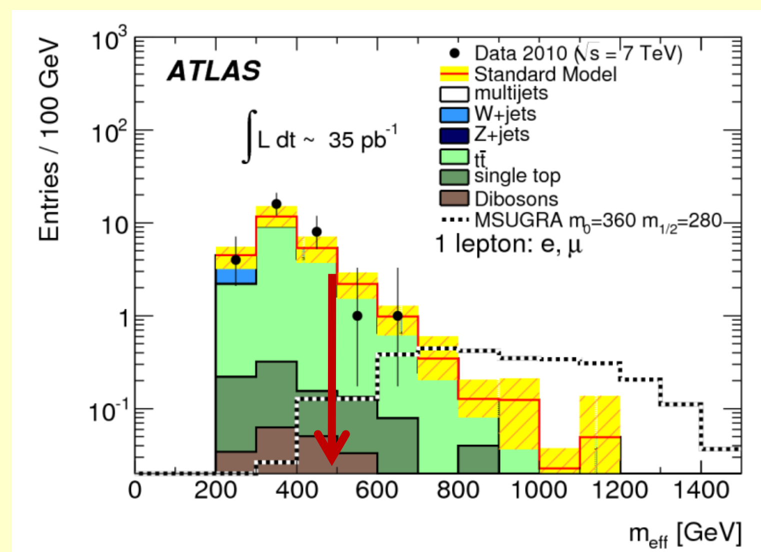
$$H_T = p_T^l + \sum_{i=1}^{3} p_T^{jet_i}$$
$$m_{eff} = H_T + E_T^{Miss}$$



(similar for the electron channel)

After all cuts:

- **One event observed in each channel**
- Main background: top ~ 70%, rest = W+jets
- Estimated with partially data-driven methods



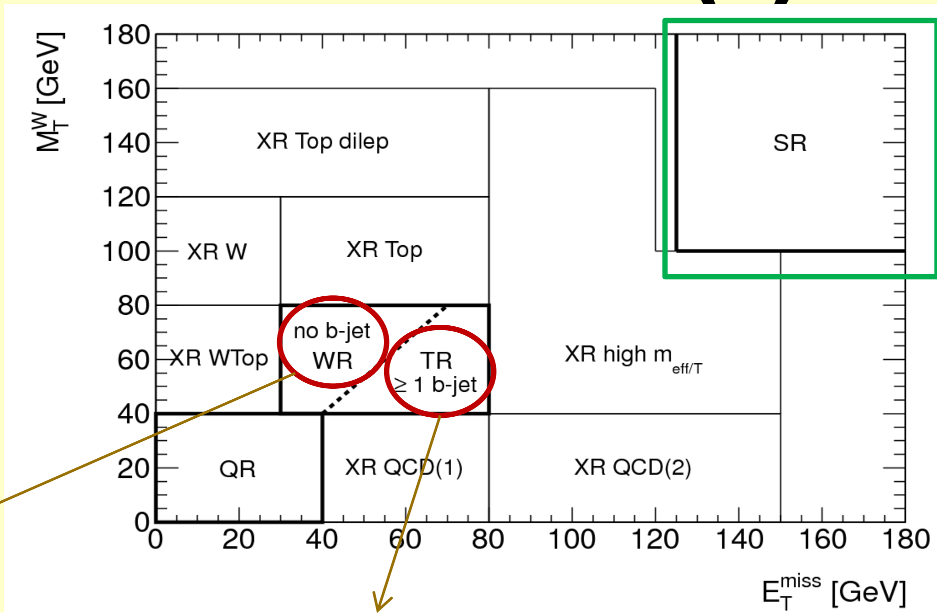
SM background estimation (I)

Exploit use of control regions:

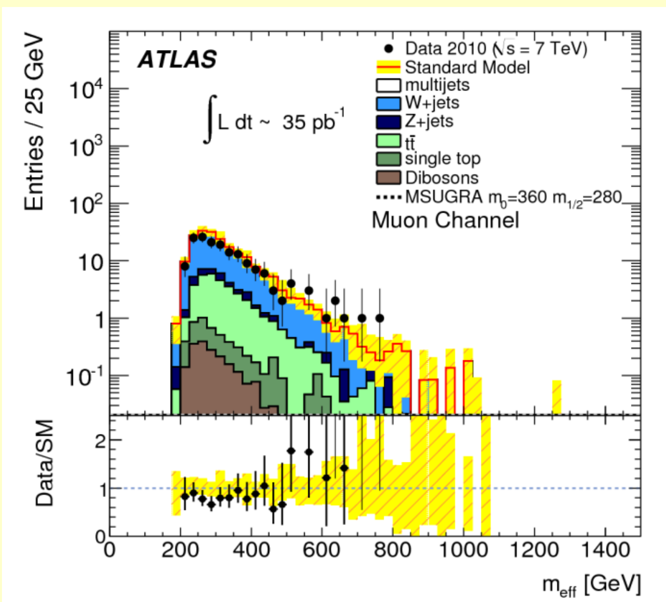
- Based on E_T^{Miss} VS M_T
- Define samples enriched in a given process
- Constrain MC predictions to data in that region *(rely on MC shapes)*
- Extrapolate to other regions (with MC). *Ex.:*

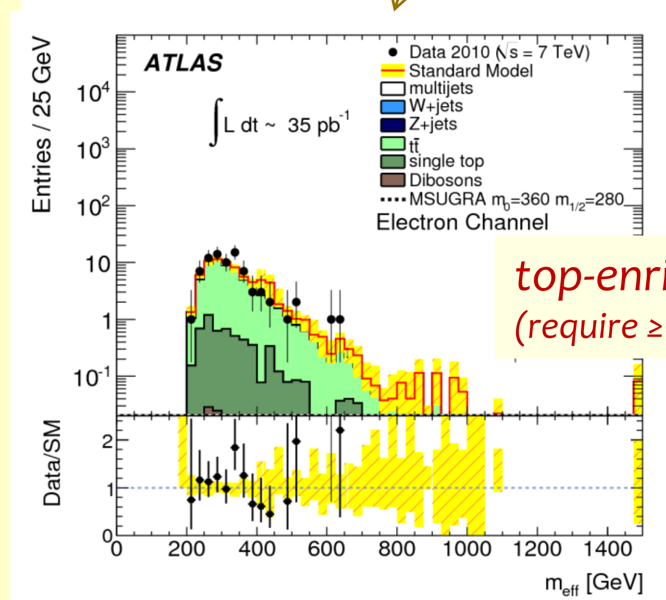
$N^{tt}_{SR}\,(pred) = (N^{data}_{CR} - N^{BkgMC}_{CR}) \times (N^{tt}_{SR,MC} / N^{tt}_{CR,MC})$

- Systematic uncertainties on extrapolation factors



W-enriched sample (require < 1 b-tagged jet)





top-enriched sample (require ≥ 1 b-tagged jet)

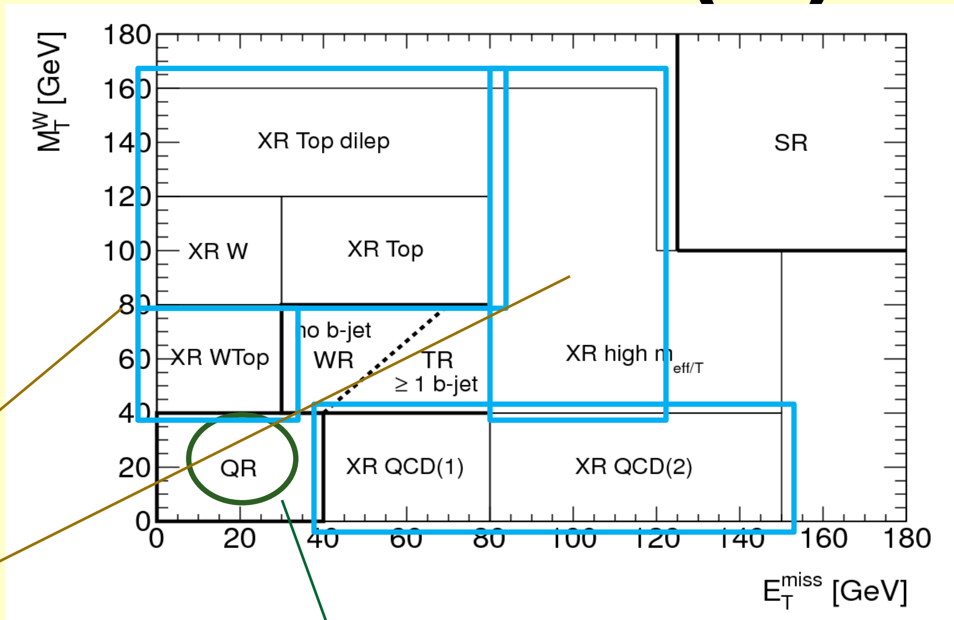
SM background estimation (II)

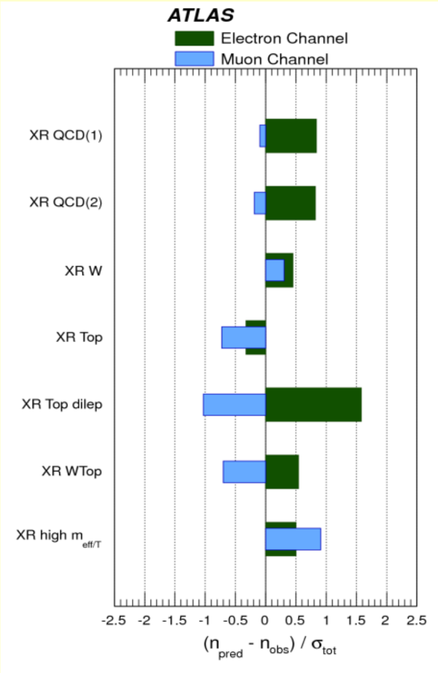
Exploit use of control regions:

– Based on E_T^{Miss} VS M_T
– Define samples enriched in a given process
– Constrain MC predictions to data in that region *(rely on MC shapes)*
– Extrapolate to other regions (with MC). *Ex.:*

$N^{tt}_{SR}(pred) = (N^{data}_{CR} - N^{BkgMC}_{CR}) \times (N^{tt}_{SR,MC} / N^{tt}_{CR,MC})$

– Systematic uncertainties on extrapolation factors





Additional control regions at low M_T or low Missing E_T used to validate the assumption on MC shape.

Pull: $\frac{N_{pred} - N_{obs}}{\sigma_{TOT}}$

Used to estimate QCD in other CR

For QCD in SR

→ from samples enriched in multijet background by relaxing e/μ requirements:

→ Use "*matrix-method*" to estimate N events with fake leptons

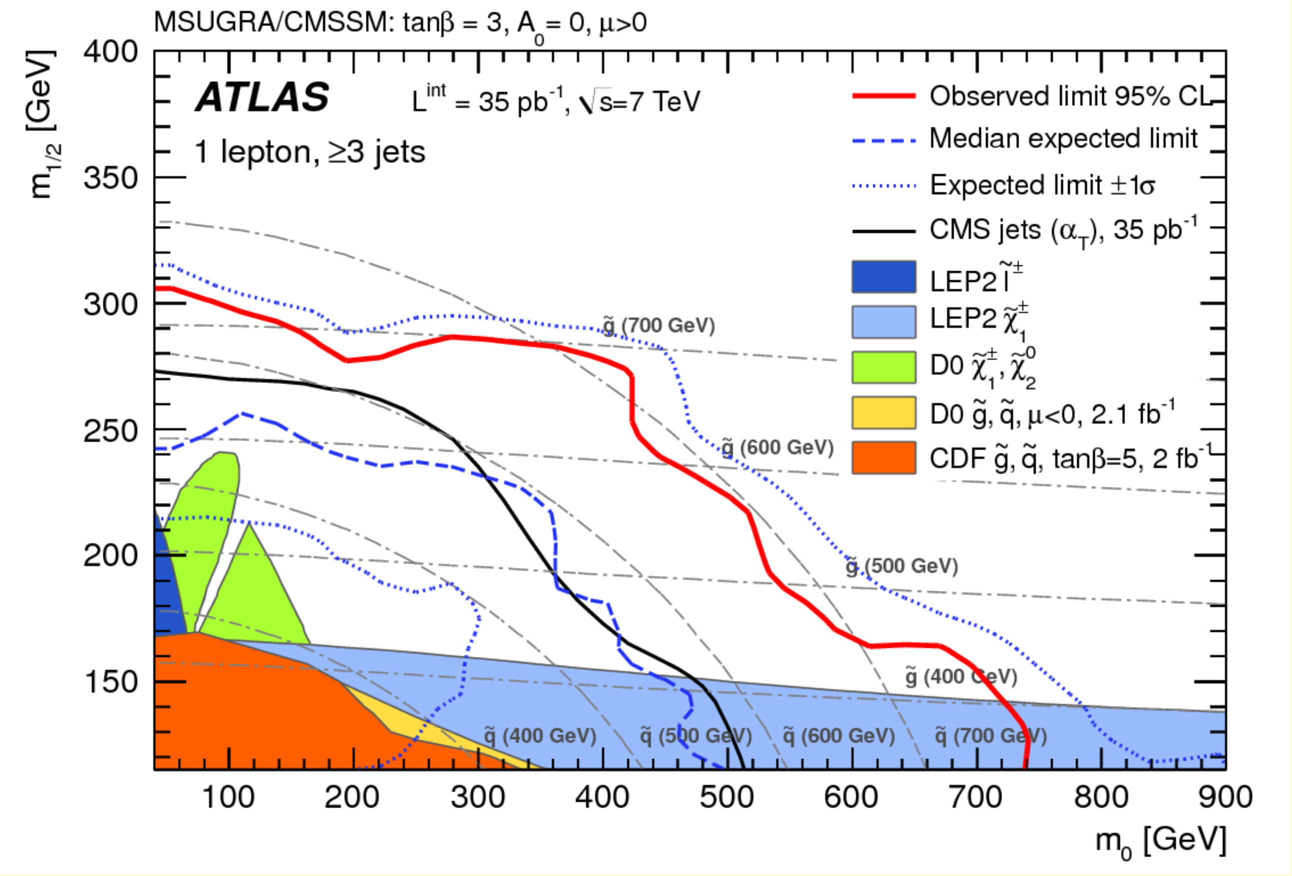
muon: $0.0^{+0.5}_{-0.0}$; electron: $0.0^{+0.3}_{-0.0}$

1-lepton results

- 1 event/channel (data), 1.81±0.75 (2.25±0.94) SM prediction (from fit) in e (μ)
- Combined fit to observed events in SR and CR:
  - 95% C.L. upper limits on N events from new physics: 2.2 (ele), 2.5 (muon) → effective cross section of 0.065 pb and 0.073 pb

Limit in mSUGRA

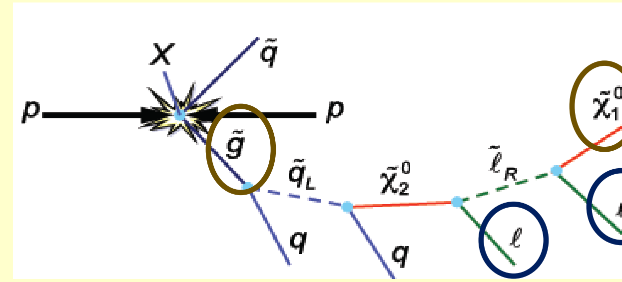
If $m_{squark}=m_{gluino}$ exclude < 700 GeV



2-leptons analysis

New

- Search for dilepton (e,μ) pairs from neutralino/chargino decays
- Two search strategies, requiring opposite-sign (OS) and same-sign (SS) dileptons events



Event selection

- exactly two leptons
- M(ll) > 5 GeV

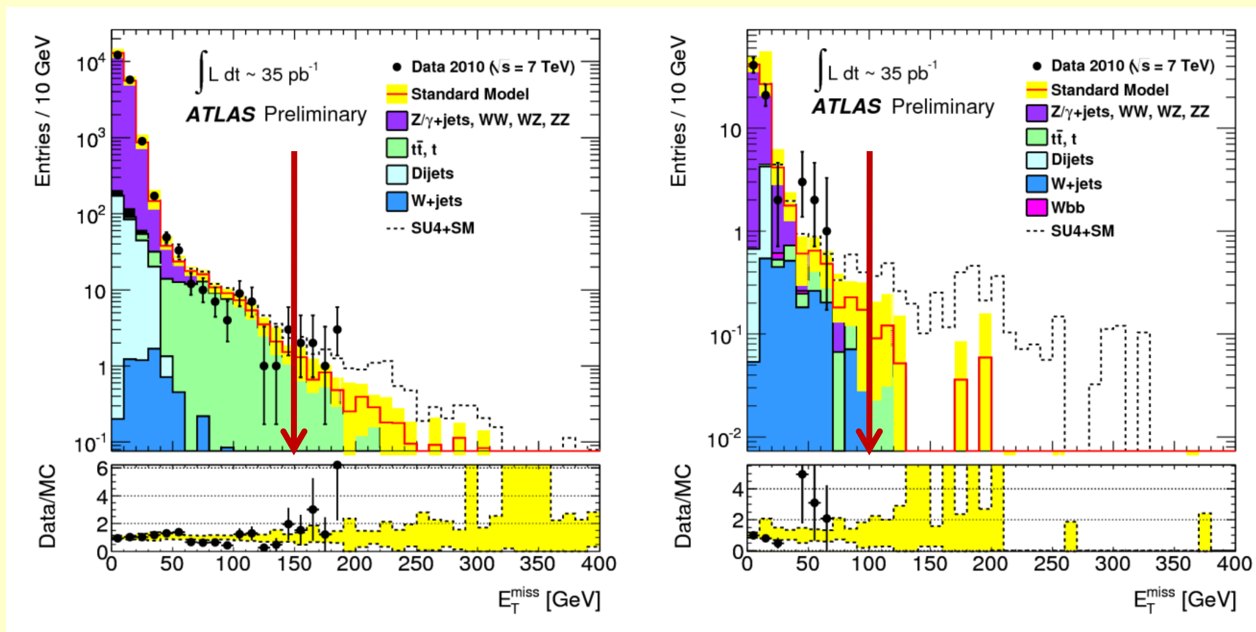
Signal regions

- OS: E_T^{Miss} > 150 GeV
- SS: E_T^{Miss} > 100 GeV

Main SM Background

- OS: **top pair** (estimate in CR)
- SS: misidentified leptons (fakes) → data-driven as in 1-lepton analysis

Opposite-Sign **Same-Sign**



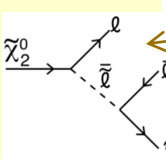
Results (I)

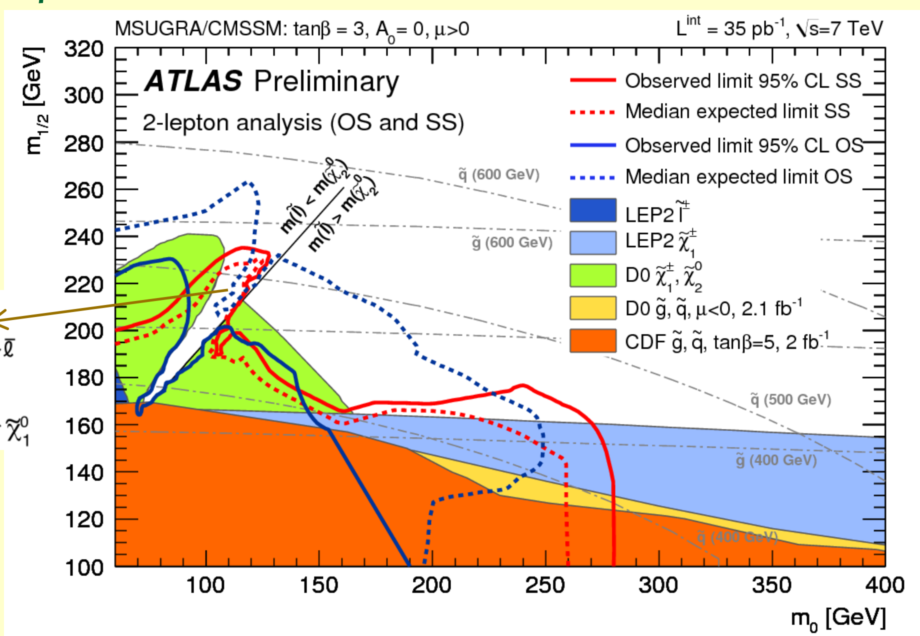
- Agreement between data and SM expectations within uncertainties:
- Use sum of ee,μμ,eμ channel for SS, combination of the three channels for OS
- 95% C.L. upper limits on effective cross section σ · A·BR from new physics:
  - SS: σ<0.07 pb
  - ee: 0.09 pb, μμ: 0.21 pb, eμ: 0.22 pb

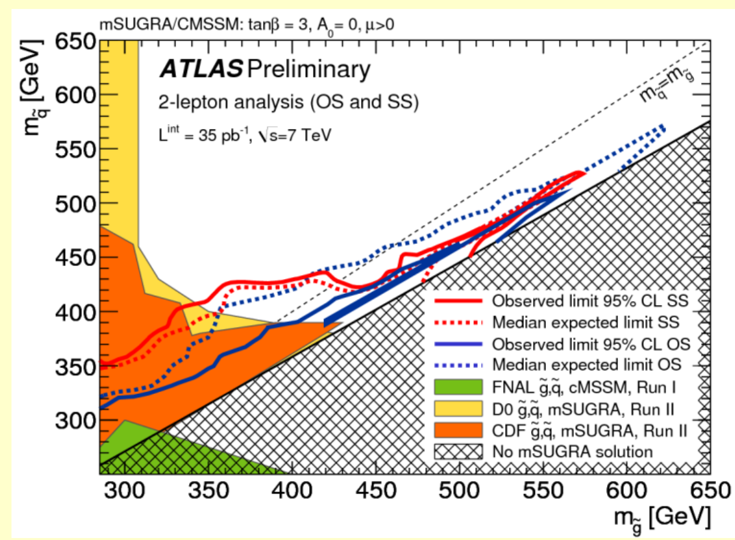
Same Sign, $E_T^{miss} > 100$ GeV	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Data	0	0	0
Fakes	0.12±0.13	0.03±0.026	0.014±0.01
Di-bosons	0.015±0.005	0.021 ±0.009	0.035 ±0.012
Charge-flip	0.019+0.008	0.026 +0.011	-
Cosmic	-	$0^{+1.32}_{-0}$	-
Total	0.14 + 0.13	$0.08^{+1.32}_{-0.03}$	0.05 +0.01

Opposite Sign, $E_T^{miss} > 150$ GeV	$e^\pm e^\mp$	$e^\pm \mu^\mp$	$\mu^\pm \mu^\mp$
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	-
Single top	$0.03^{-0.05}_{-0.03}$	$0.06^{+0.08}_{-0.06}$	0.10 ± 0.07
Di-bosons	0.09 ± 0.03	0.06 ± 0.03	0.15 ± 0.07
Cosmics	-	$0^{+1.32}_{-0}$	$0^{+1.32}_{-0}$
Total	$0.92^{+0.42}_{-0.40}$	$1.43^{+1.58}_{-0.59}$	$1.39^{+1.53}_{-0.53}$

Interpretation in mSUGRA

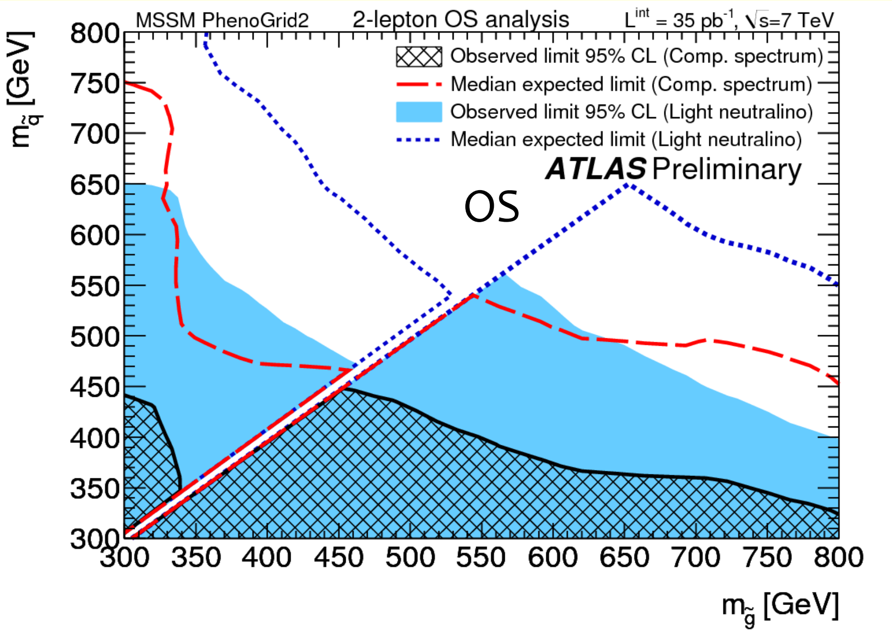


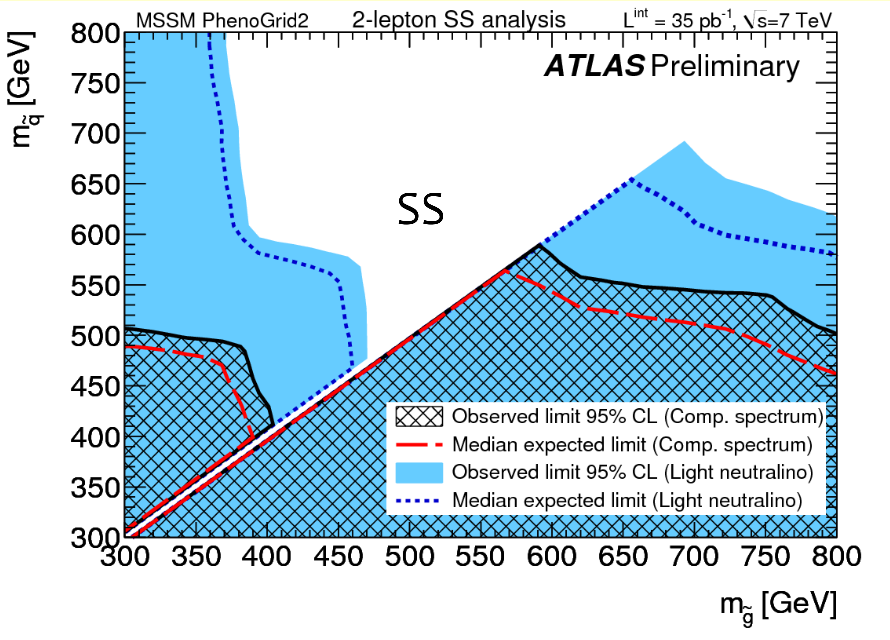




Results (II)

- Consider more general MSSM 24-parameter framework, where sleptons are in the gluino and squark decays chains :
  - m_A=1000 GeV, μ=1.5×min(m_{gl},m_q) , tanβ=4, A_t=μ/tanβ, A_b=A_l=μtanβ
  - m($\tilde{l}_R$)=m($\tilde{l}_L$), m($\tilde{q}_R$)=m($\tilde{q}_L$) , 3rd generation at high mass
- **"compressed spectrum" (CS):** m($\tilde{\chi}^0_2$) =M - 50 GeV, m($\tilde{\chi}^0_1$)=M - 150 GeV, m($\tilde{l}_L$)=M - 100 GeV, with M=min(m_{gl},m_q) → soft final state kinematics
- **"light neutralino" (LN):** m($\tilde{\chi}^0_1$)=100 GeV , m($\tilde{\chi}^0_2$) =M-100 GeV, m($\tilde{l}_L$)=M/2 GeV → hard kinematics





Limits on squark mass for m($\tilde{g}$)=m($\tilde{q}$)+10 GeV

OS: m($\tilde{q}$)>560 GeV (LN), >450 GeV (CS)
SS: m($\tilde{q}$)>690 GeV (LN), >590 GeV (CS)

2-lepton: a different approach

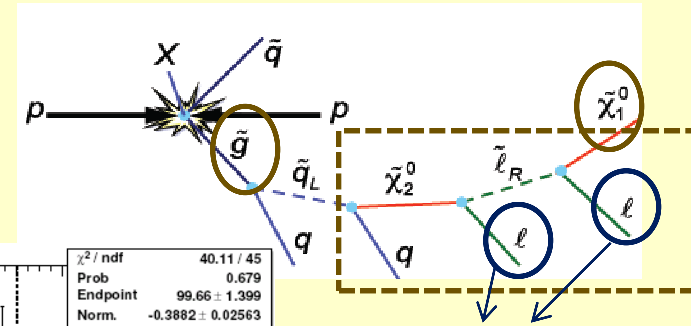
New

Search for **excess of identical flavour** opposite-sign lepton pairs:

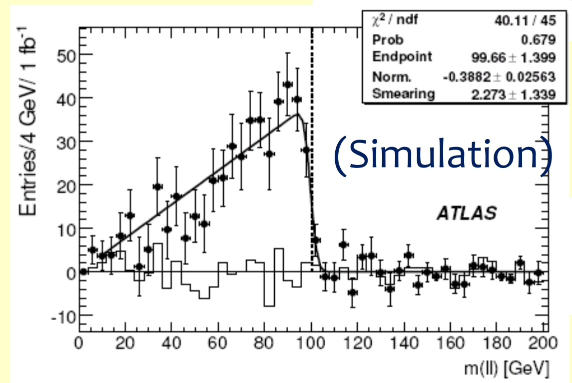
- Sensitive to SUSY particle cascade → no excess expected in SM (aside for Z/γ^* sources)
- Subtraction SF - OF allows **"cancellation" of systematic uncertainties:**

→ If no excess, set very robust limits

→ If discovery, help measuring SUSY particle masses



Same flavor for lepton flavor conservation



$$m_{\ell\ell}^{max} = \frac{1}{m_{\tilde{\ell}_R}} \sqrt{\left(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}_R}\right)\left(m^2_{\tilde{\ell}_R} - m^2_{\tilde{\chi}_1^0}\right)}$$

Event selection

- exactly two leptons (ee,μμ,eμ)
- M(ll) > 5 GeV

Signal region: E_T^{Miss} > 100 GeV

Main SM Background

- top pair, Wt-channel single top
  → self-cancelling
- residual Z/γ^*+jets → use low E_T^{Miss} CR

	$e^{\pm}e^{\mp}$	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\mu^{\mp}$
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

Same-flavor results

- From N(ee), N(eμ) and N(μμ), quantify same flavour excess: **$\mathcal{S}$ = N×Eff×Acc.**

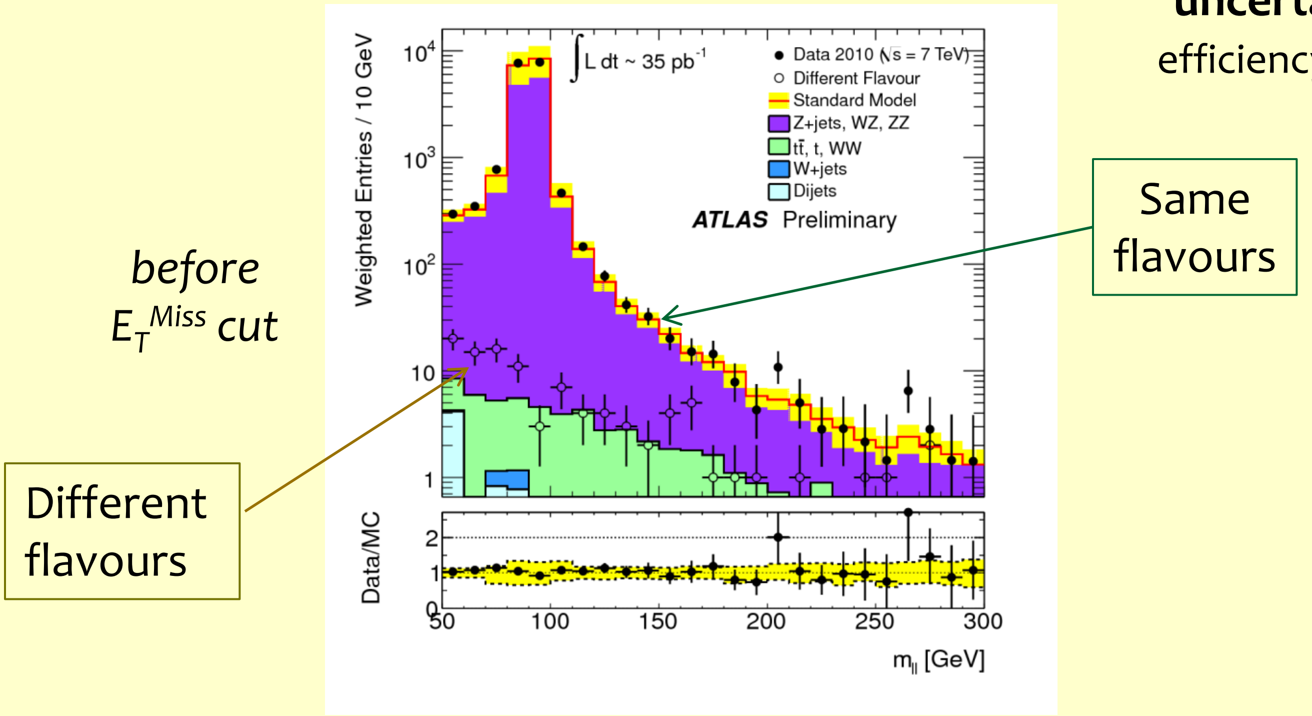
$$\mathcal{S} = \frac{N(e^{\pm}e^{\mp})}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^{\pm}\mu^{\mp})}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^{\pm}\mu^{\mp})}{(1-(1-\tau_\mu)^2)}$$

ε_e, ε_μ = ID efficiency
$\beta = \varepsilon_e/\varepsilon_\mu$
τ_e, τ_μ = trigger efficiency

$$\mathcal{S}_{obs.} = 1.98 \pm 0.15(\beta) \pm 0.02(\tau_e) \pm 0.06(\tau_\mu)$$

Low systematic uncertainties (from efficiency parameters)**!**

before E_T^{Miss} cut

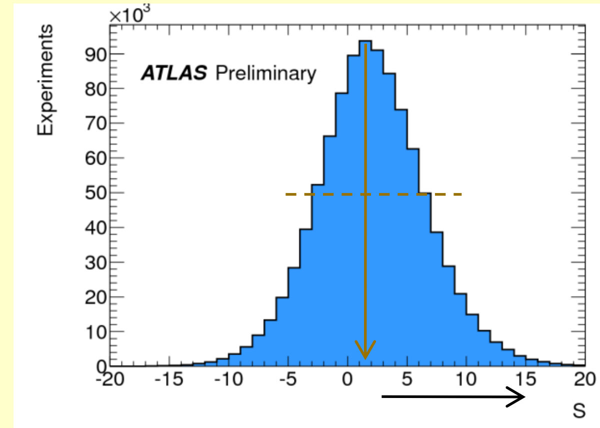


Interpretation of results

- Perform pseudo-experiments to estimate the consistency with SM expectations

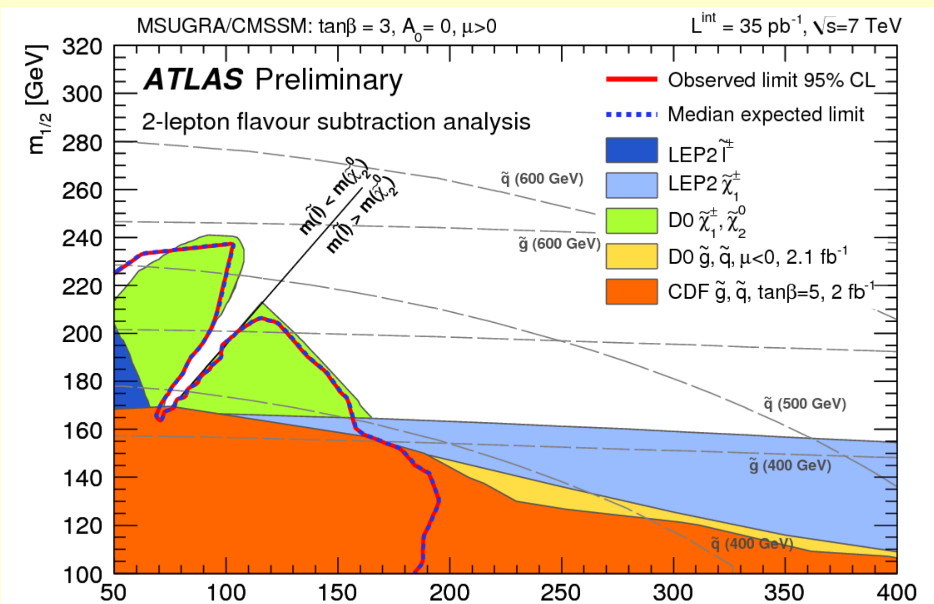
$$\bar{S}_b = 2.06 \pm 0.79(stat.) \pm 0.78(sys.)$$

→ likely observation

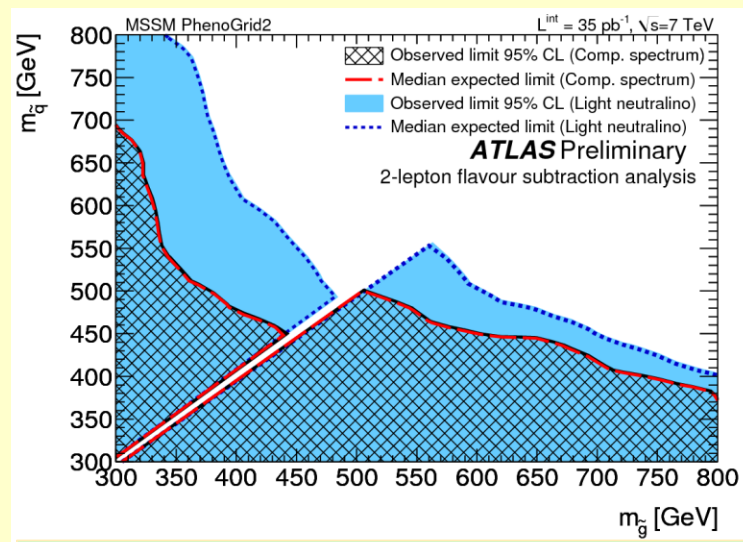


New physics would increase width and shift the distribution to the right

- To Set Limit: finding S_s for which 5% of experiments give $S<S_{obs}$



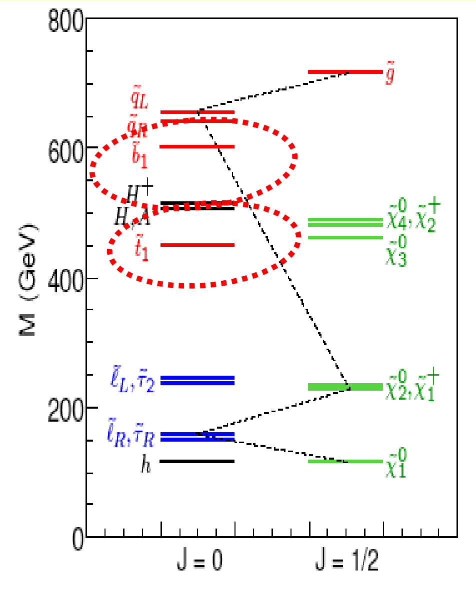
Interpretation in mSUGRA



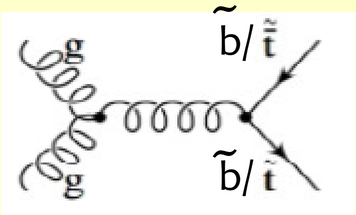
Limits for $m(\tilde{g})=m(\tilde{q})+10$ GeV
$m(\tilde{q})$>560 GeV (LN), >500 GeV (CS)

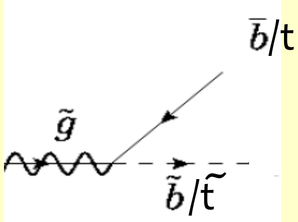
Searches in E_T^{Miss}+b-jets

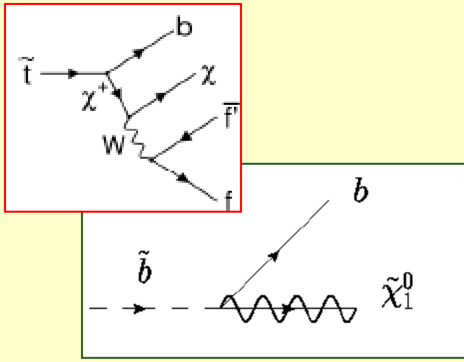
New



- Third generation squarks might be lighter than 1st, 2nd generation → possibly high cross sections:
  - direct pair or gluino-mediated production







- Final state enriched in b-jets

  → **search in events with jets (≥1 b-jet) +E_T^{Miss} (+ 0/ ≥ 1) leptons**

Event selection

0-lepton	1-lepton
no-lepton ($p_T > 20$ GeV)	≥ 1 lepton ($p_T > 20$ GeV)
jet $p_T > 120, 30, 30$ GeV, $\lvert\eta\rvert < 2.5$	jet $p_T > 60, 30$ GeV, $\lvert\eta\rvert < 2.5$
$E_T^{miss} > 100$ GeV	$E_T^{miss} > 80$ GeV
$E_T^{miss}/m_{eff} > 0.2$	–
At least 1 b-tagged jet (SV0, $L/\sigma(L) > 5.72$, $p_T > 30$GeV, $\lvert\eta\rvert < 2.5$)	
$\Delta\phi_{min} > 0.4$ rad	$m_T > 100$ GeV

Signal regions:

0-lepton: M_{eff} > 600 GeV

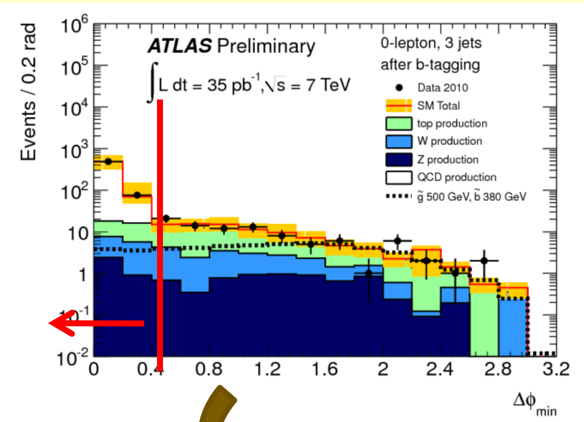
1-lepton: M_{eff} > 500 GeV

SM Background

- Top pair production dominant for both selections

0-lepton:

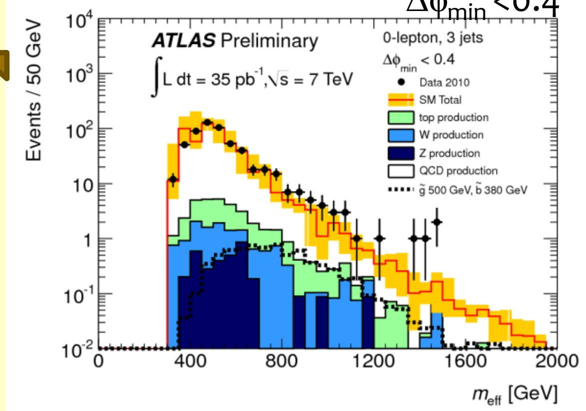
→**QCD:** Partially data-driven



Revert $\Delta\phi_{min}$<0.4

Take Meff shape from $\Delta\phi_{min}$ <0.4

$\Delta\phi_{min}$ <0.4



From MC: take fraction of QCD events passing $\Delta\phi_{min}$ >0.4

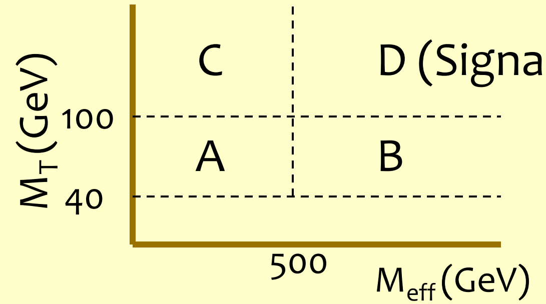
→**Top/Boson+jets:** MC estimate

1-lepton:

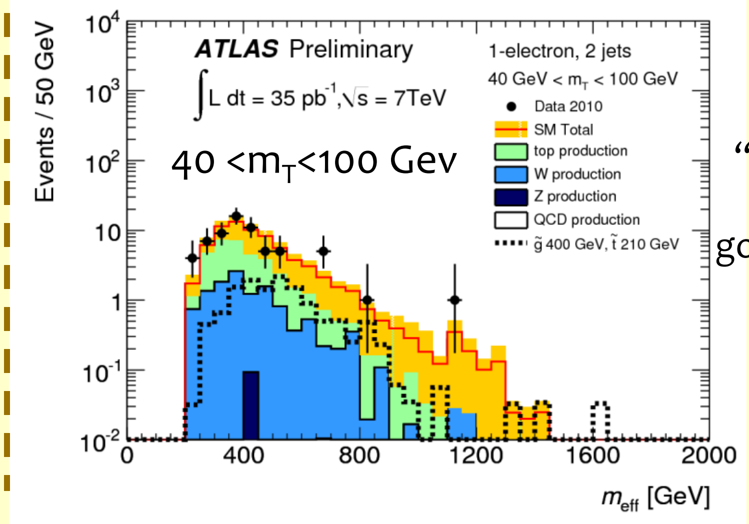
→**Data-driven techniques** for all bkg

→QCD: "matrix-method" as in previous analyses

→Top/Boson+jets: exploit low correlation between M_T and M_{eff}



$$N_D^{SM} = N_C / N_A \times N_B$$



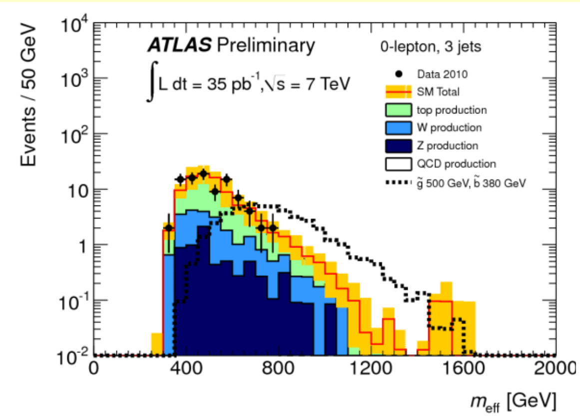
"Closure-test" with MC → good agreement with data

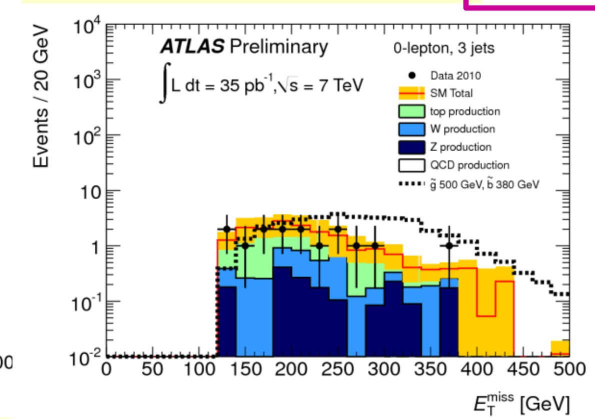
Results

Good agreement between data and SM predictions within systematic uncertainties in both channels

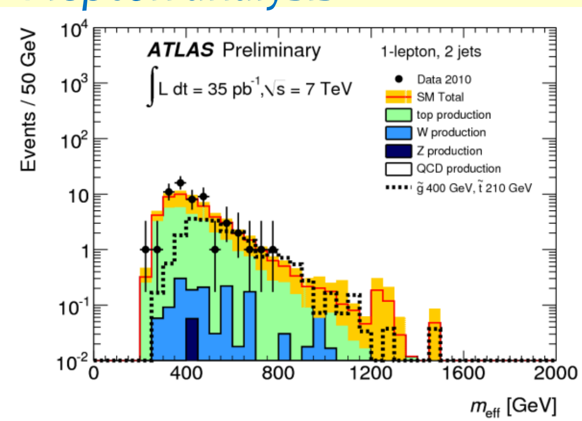
	0-lepton	1-lepton Monte Carlo	1-lepton data-driven
$t\bar{t}$ and single top	12.2 ± 5.0	12.3 ± 4.0	14.7 ± 3.7
W and Z	6.0 ± 2.0	0.8 ± 0.4	-
QCD	1.4 ± 1.0	0.4 ± 0.4	$0^{+0.4}_{-0.0}$
Total SM	19.6 ± 6.9	13.5 ± 4.1	14.7 ± 3.7
Data	15	9	9

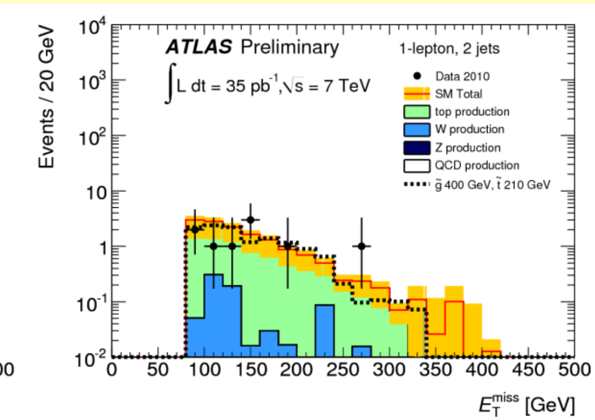
0-lepton analysis





1-lepton analysis





Interpret the results as 95%C.L. upper limits on N signal events independently of new physics models:

N(0-lepton) > 10.5
N(1-lepton)>4.7

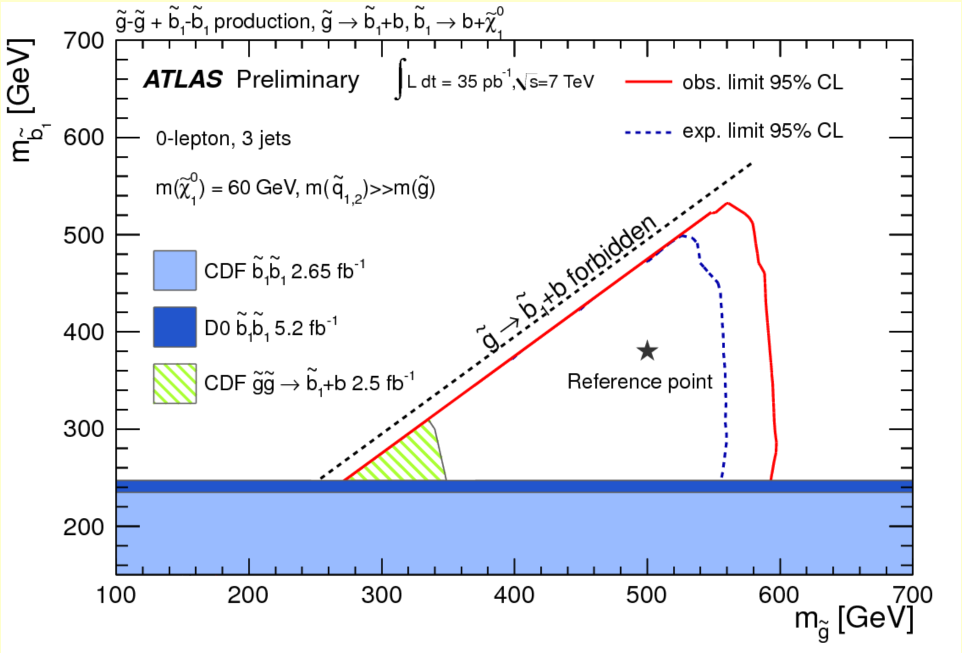
Effective cross sections:

σ (0-lepton) > 0.32 pb
σ (1-lepton) > 0.13 pb

Interpretation in pheno-MSSM

- Assume gluino decays in $\tilde{b}_1 b$ (BR=100%) and $\tilde{b}_1 \rightarrow b\tilde{\chi}^0_1$ (BR=100%)
- $m(\tilde{\chi}^0_1)$=60 GeV

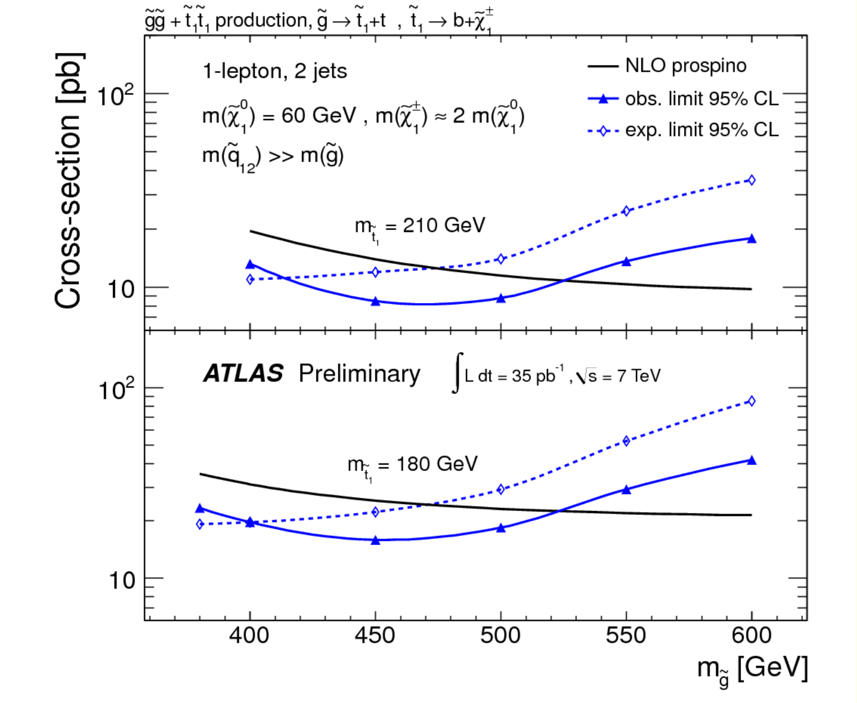
0-lepton analysis



Gluino masses below 590 GeV excluded for sbottom masses below 500 GeV

- Assume gluino decays in $\tilde{t}_1 t$ (BR=100%) and $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$ (BR=100%), $\tilde{\chi}^+_1 \rightarrow W^*\chi^0_1$
- $m(\tilde{\chi}^0_1)$=60 GeV , $m(\chi_1) \approx 2\times m(\chi^0_1)$

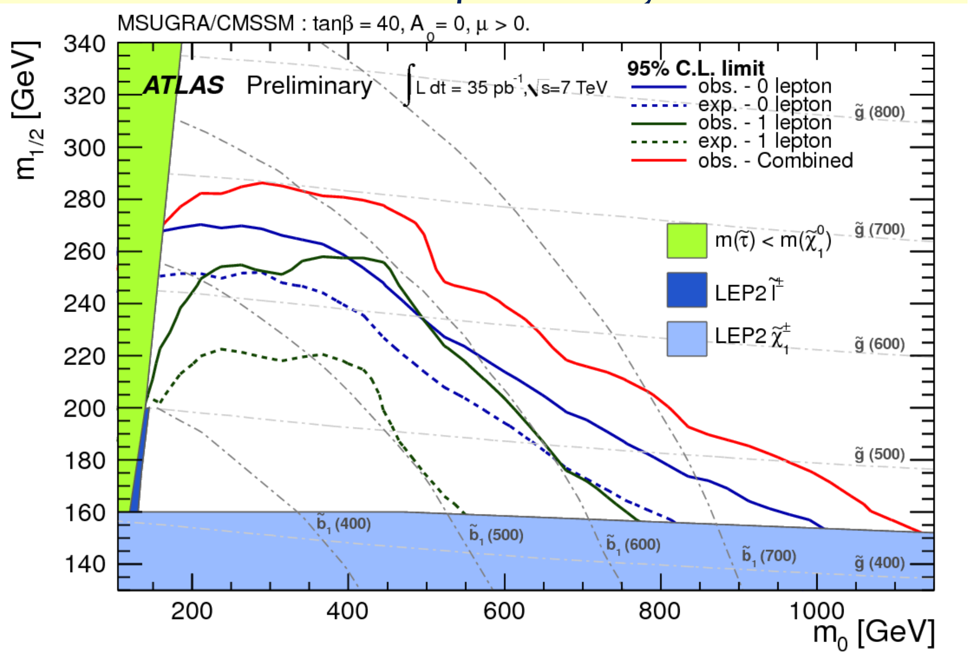
1-lepton analysis

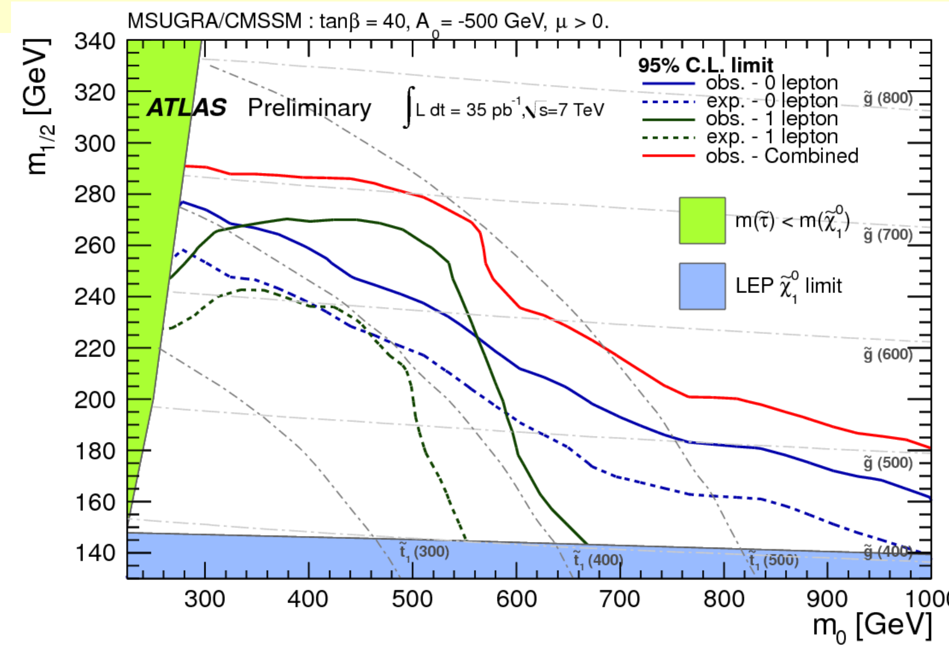


Gluino masses below 520 GeV excluded for stop masses below 300 GeV

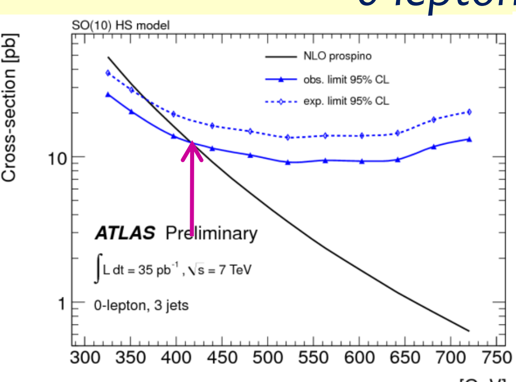
Specific SUSY models

0- and 1-lepton analyses

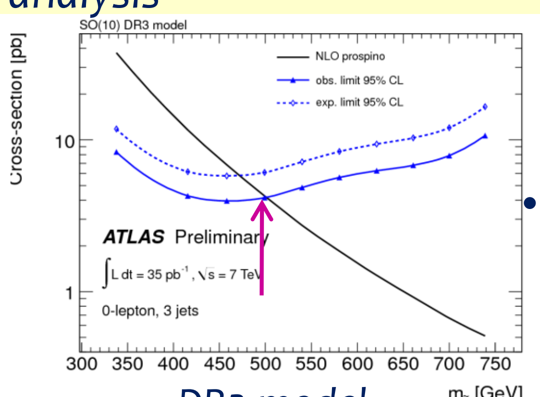




0-lepton analysis



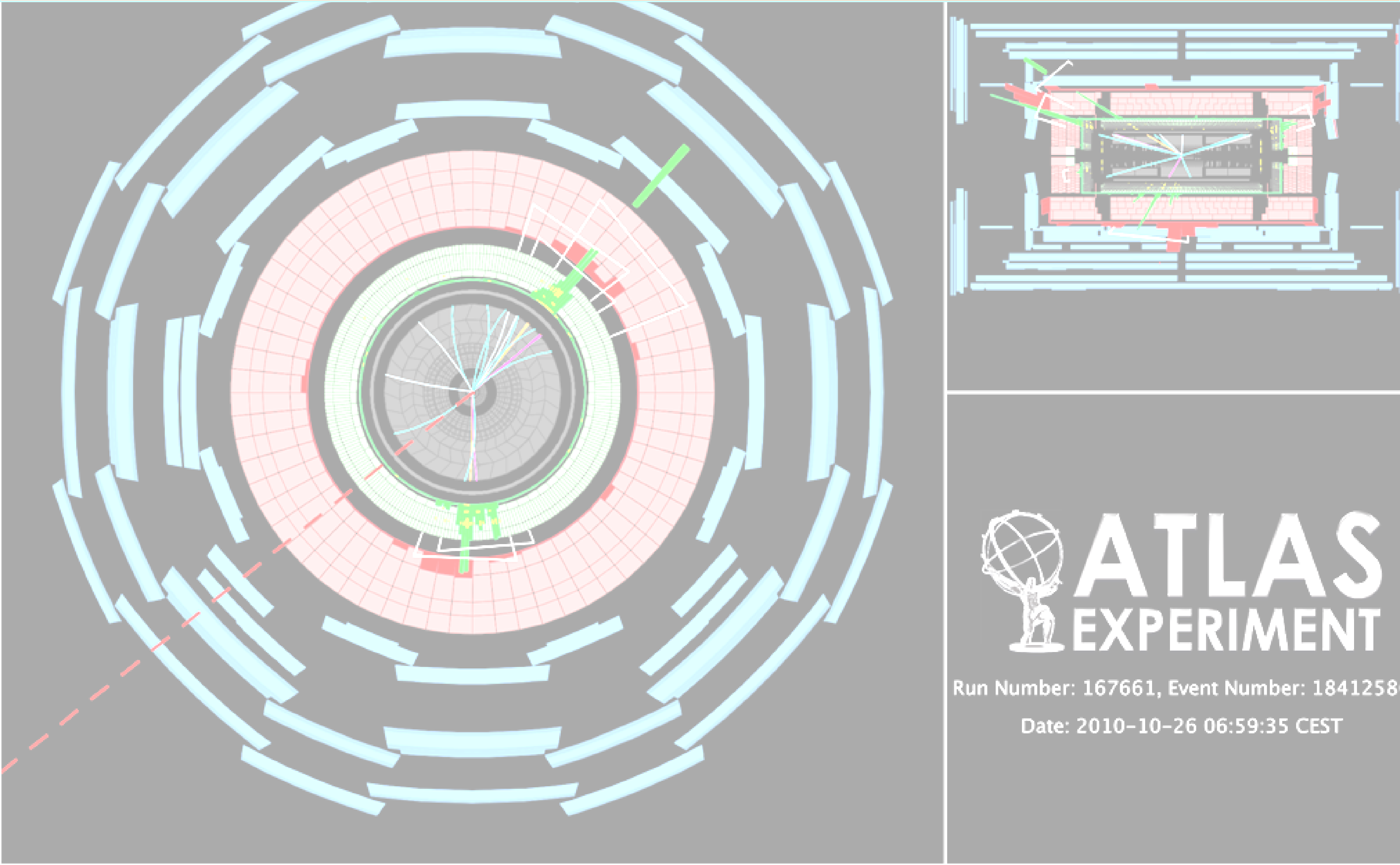
HS-model



DR3-model

- **mSUGRA:** large tan β or low A_0 values:
  - For each $(m_0, m_{1/2})$ sbottom/stop masses lower than in low tan β scenarios
  - **Exclude gluino masses up to 500 GeV for $m_0 < 1$ TeV**
- **SO(10) models:** gluino pair production one of the dominant processes:
  - Gluino → $b\bar{b}\chi^0_1$ (DR3) or $b\bar{b}\chi^0_2$ (HS)
  - **Exclude masses up to 500(420) GeV**

Non E_T^{Miss}-based SUSY Searches



Stable Massive Particles

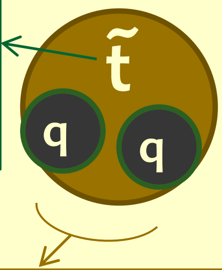
New

- SMPs predicted in several SUSY (and other BSM scenarios)
- Stable → cτ ≥ size of detector
- Produced with β<1
- *Within SUSY:*
  - $\tilde{l}$ and $\tilde{\chi}^+$
  - **$\tilde{q}/\tilde{g}$ (bound states)**

Colored sparticles can hadronise into long-lived bound hadronic states

R-hadrons

Heavy parton carrying most of the momentum

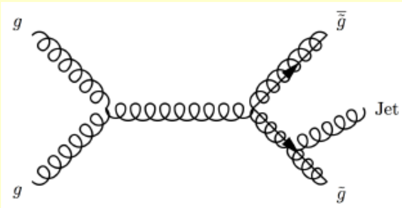


Light quark system (LQS)

SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ 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.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. 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.
$\tilde{g}$	$\tilde{\chi}_1^0$	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].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	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 $A_b \gg A_t$.

Table 1
Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario.

R-hadrons in ATLAS

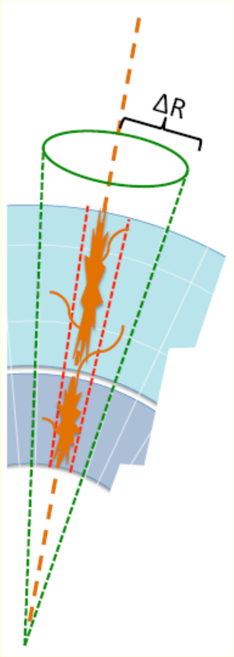


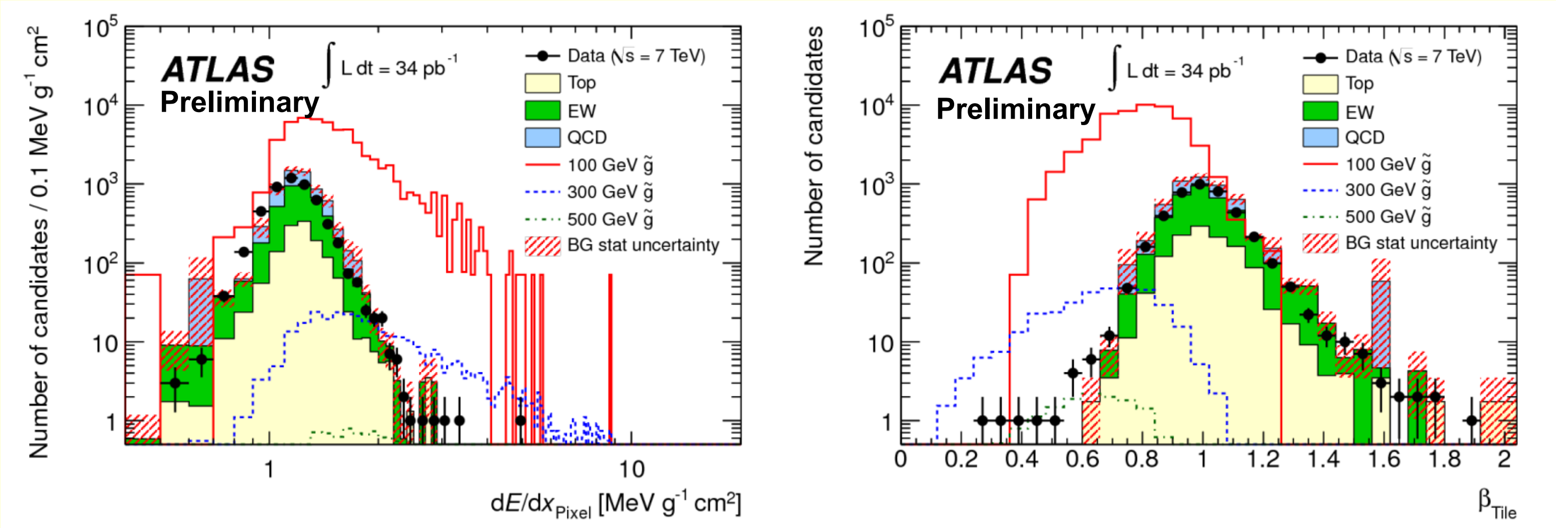
- Background mostly from instrumental effects (after selections)
- Hard to trigger! Data collected with E_T^{Miss} triggers:
  - Exploit possible additional jets from ISR/FSR
- To suppress backgrounds, combine uncorrelated discriminators:
  - **Time-of-Flight:** for SMP $\beta \neq 1$ → exploit Tile Calorimeter timing resolution
  - **dE/dx:** slow particles result in anomalous ionization E loss → from Pixel detector

Selection of SMP candidates:

ID track, $|\eta|<1.7$ and $p_T>50$ GeV, ΔR(SMPcand-jet)>0.5 ($p_T^{jets}>40$ GeV)

→ **Sensitive to neutral and charged R-hadrons at the MS**





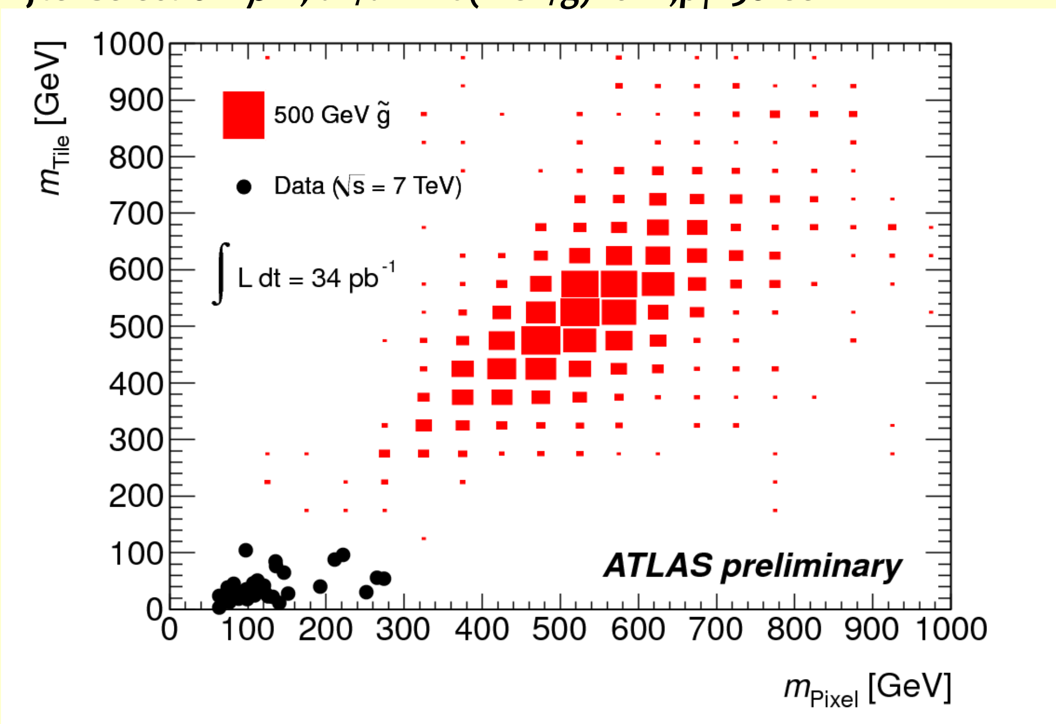
Possible signals: gluino masses of 100, 300,500 GeV

Background estimates

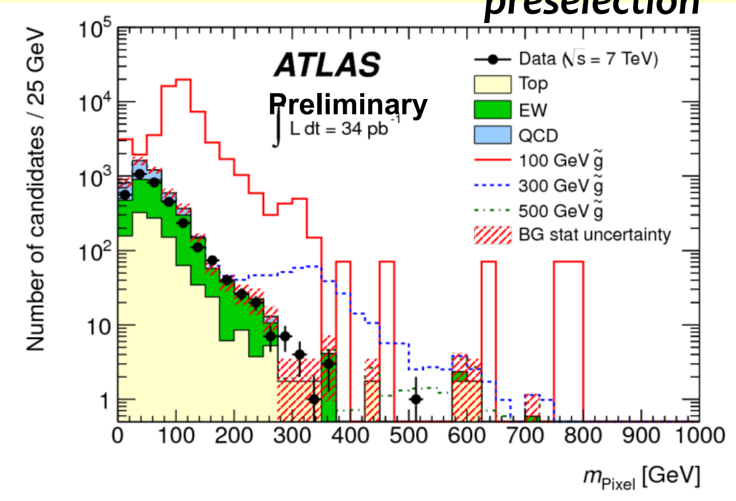
- Measurement of β combined with track *p* → mass reconstruction: ***m=p/βγ***
- MC shown for comparison: use data-driven approach to measure tails of pixel dE/dx, β_{Tile}

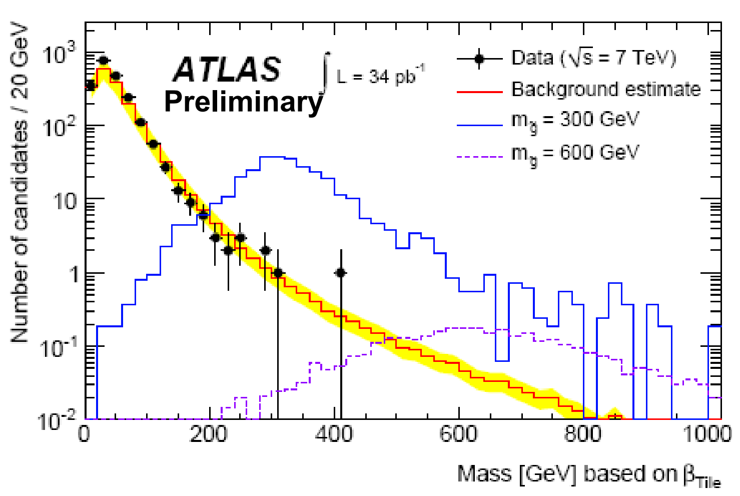
→ exploit lack of correlations between them (allow combination of random momentum values)

After selection: β<1, dE/dx>1.8(MeV/g)*cm², p_T>50 GeV



preselection





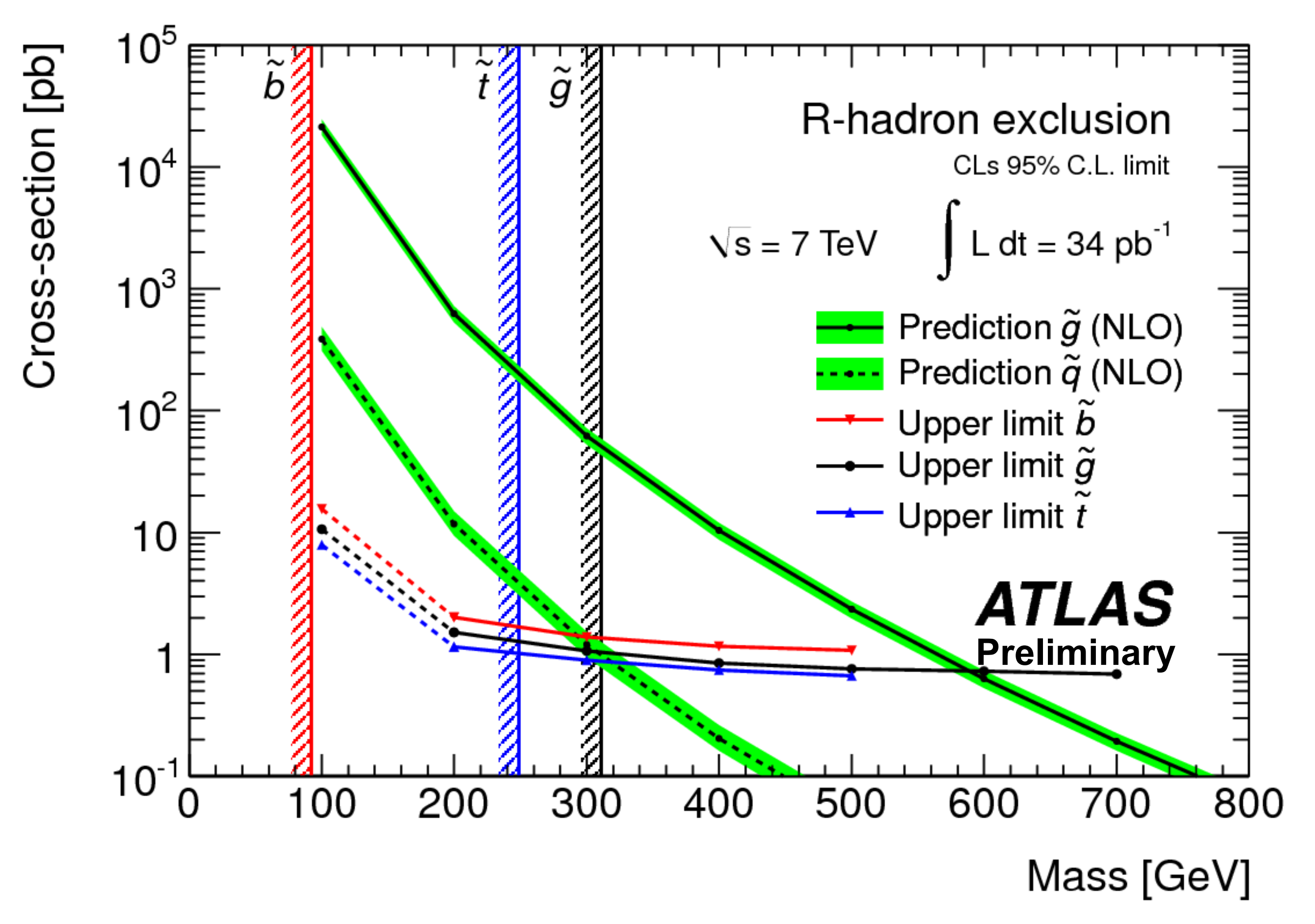
Ex: gluino mass=300 GeV

→ m_{pixel} =324±40 GeV, m_{Tile} =315±56 GeV

Combined exp. candidates: 0.22, observed: none

Results

Results interpretation and limit settings



Exclude:

M(gluino)<562-586 GeV

M(stop)<309GeV

M(sbottom)<294 GeV

→ first dedicated search for sbottom R-hadrons at hadron colliders

Previous limits:

M(gluino) MS-signature:
> 398/397 GeV (CMS/Tevatron)

M(gluino) MS-agnostic:
>311 GeV (CMS)

M(stop): 249 GeV (CDF)

M(sbottom)>92 GeV (LEP)

Conclusions

- ATLAS has a **wide and rich program** of SUSY searches:
  - One paper published, one on arXiv, five more in the pipeline
  - No SUSY found, **most stringent limits up-to-date** in several scenarios
  - More results expected for the rest of the Winter conferences 2011
    - R-parity violating searches in eμ final states
    - Trilepton searches

    ..and more in the pipeline…

Wait one more week!

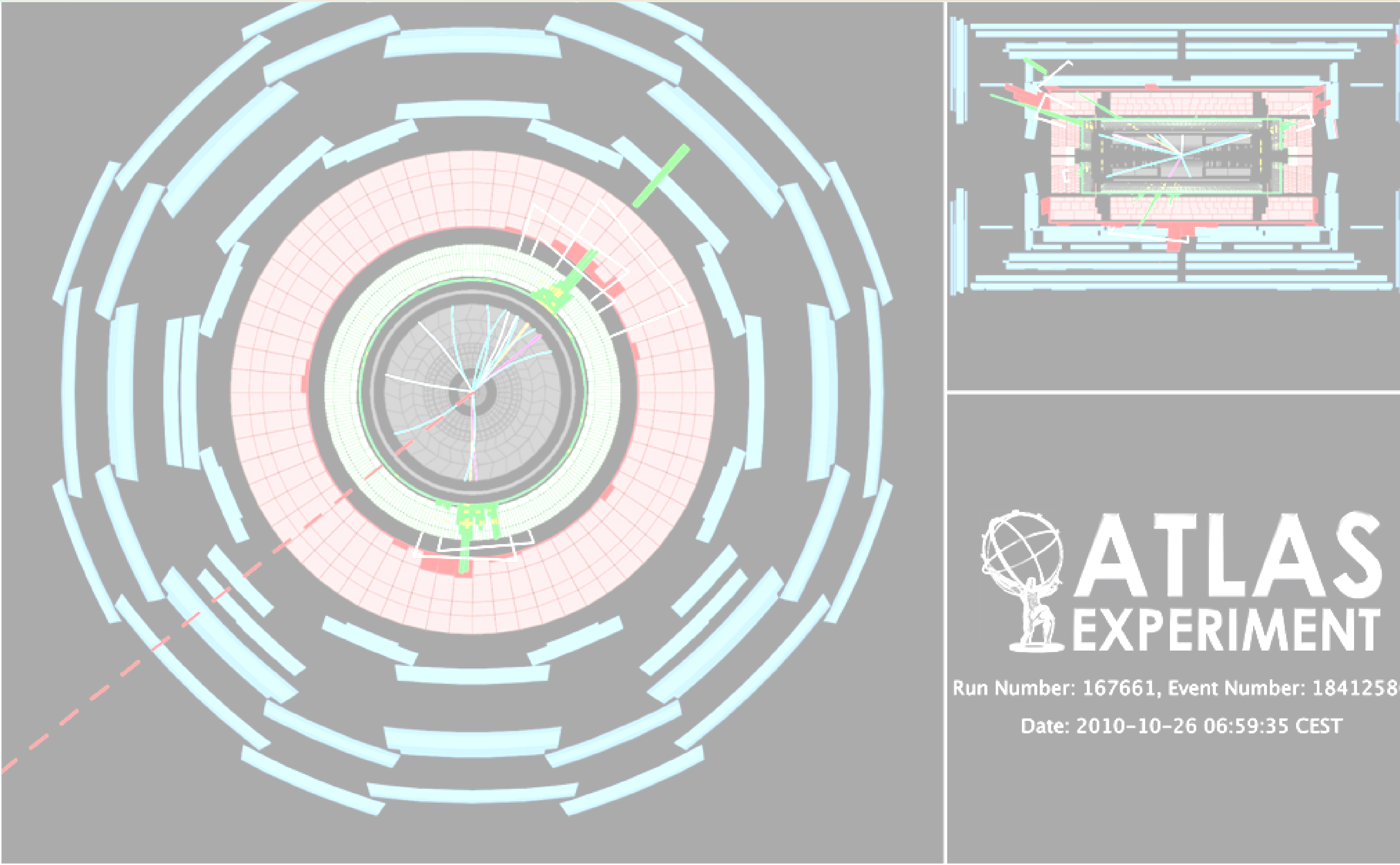
- Large variety of topologies explored:
  - Focus on important **final states for SUSY** rather than on specific breaking models

Great results achieved thanks to the effort of the **whole ATLAS** collaboration and of the **accelerator division**!

Supersymmetry is facing a crucial moment

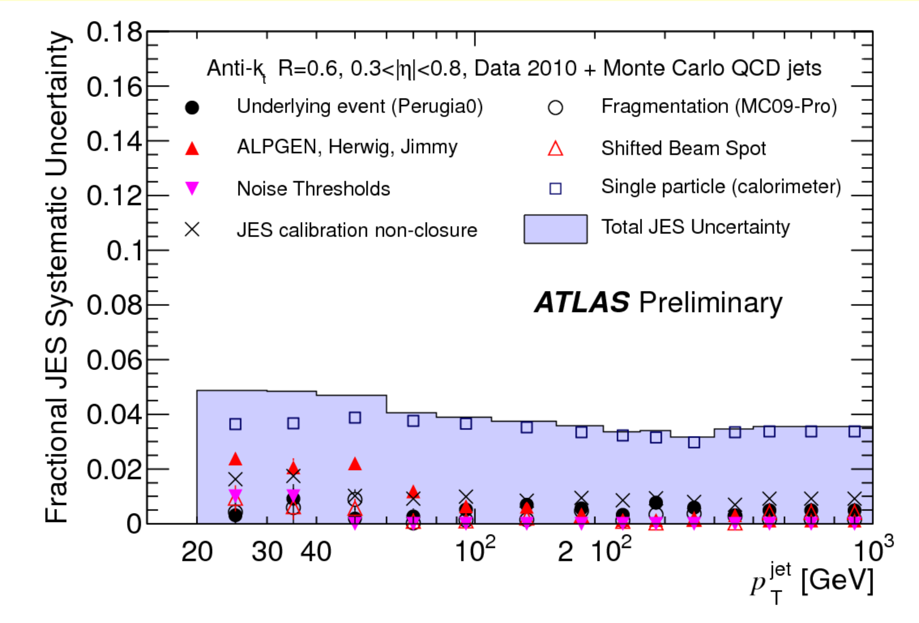
2011 is the year

Back-up

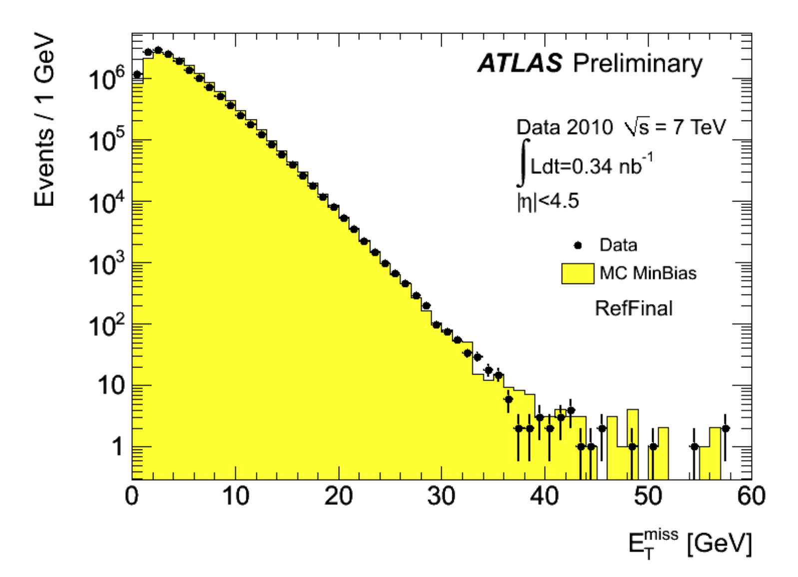

ATLAS
EXPERIMENT
Run Number: 167661, Event Number: 1841258
Date: 2010-10-26 06:59:35 CEST

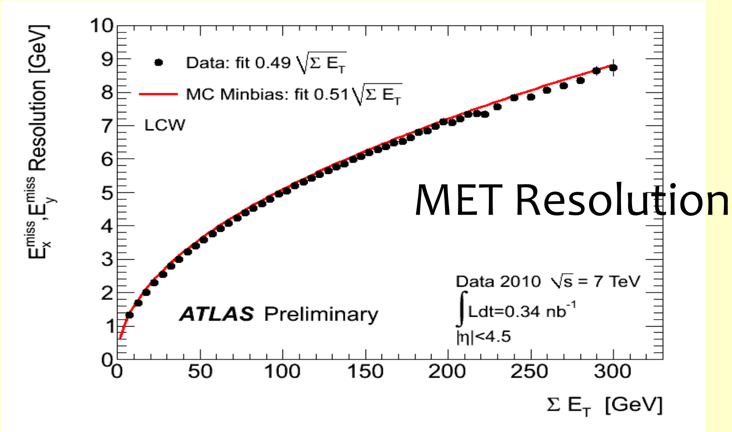
Jets and Missing E_T

- Jets corrected for non-compensation nature of the calorimeter, and dead material.
- **JES used in this analysis:**
  - 6% and 10% as a function of p_T and η
- **Current: ~ 4%**



- Unbalanced momentum (Missing E_T or MET) based on identified and calibrated objects





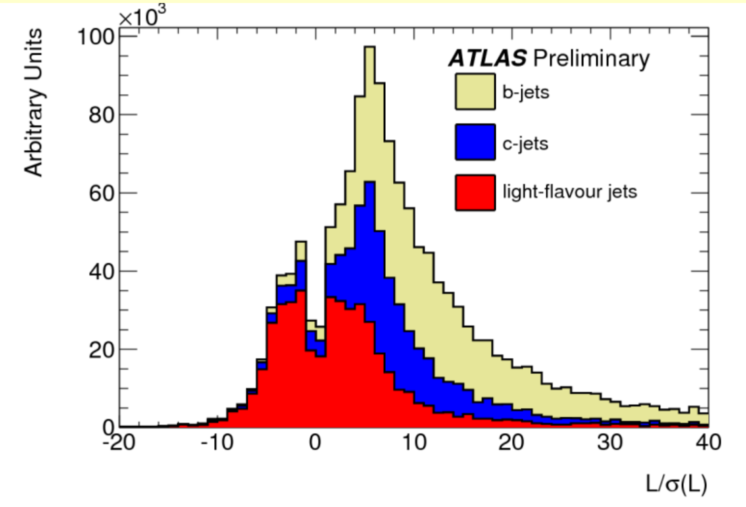
B-tagging

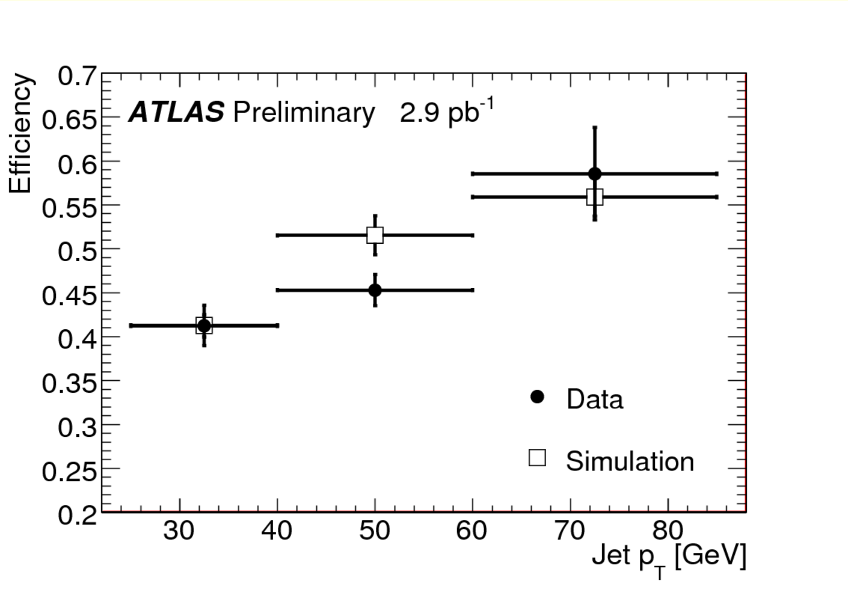
- **Use SV0 algorithm:**

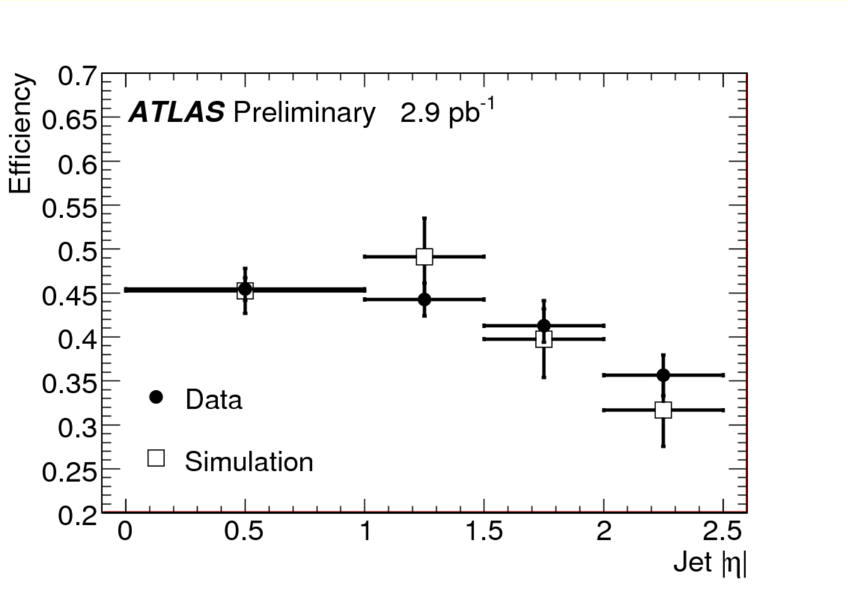
→ lifetime-based tagging algorithm which relies on the explicit reconstruction of secondary vertices within jets.

→ reconstruct a vertex from all tracks associated to the jet which are displaced from the primary vertex

→ A jet is considered as tagged if the signed decay length significance, $L/\sigma(L)$, of the reconstructed secondary vertex, computed with respect to the primary vertex, is above a certain value.

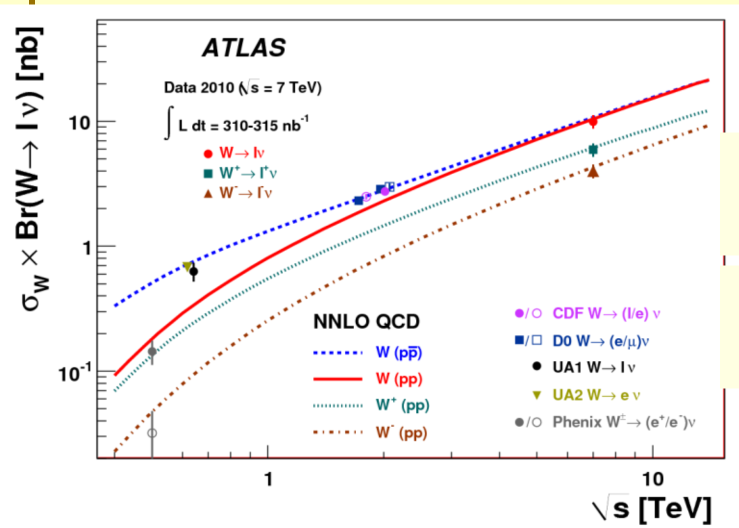






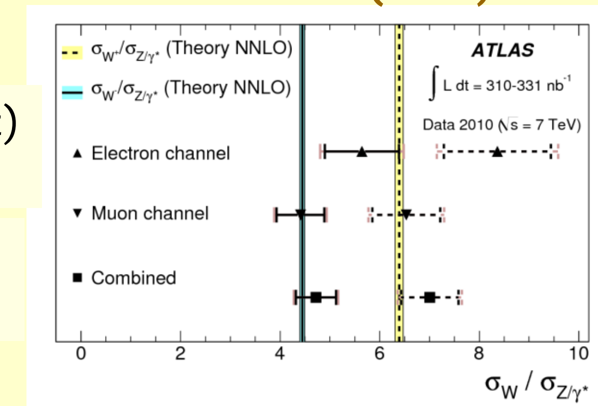
W and Z inclusive cross sections

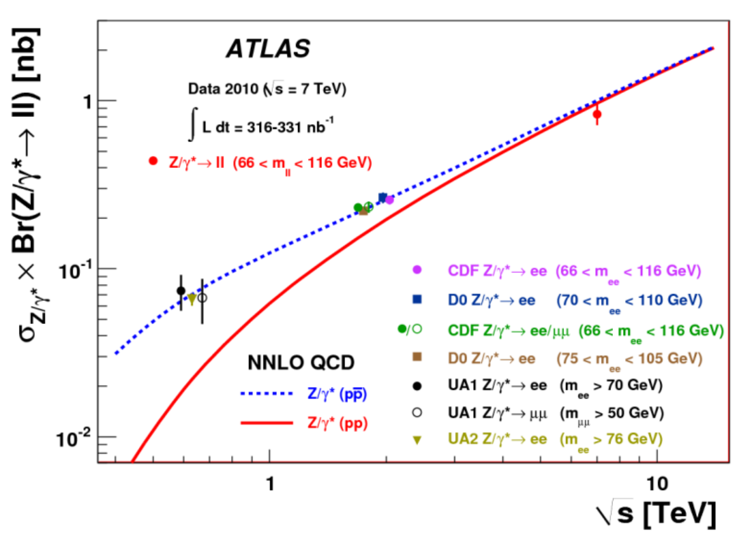
JHEP 12 (2010) 060



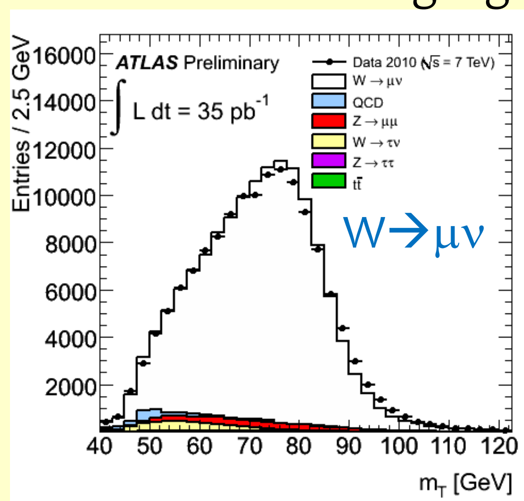
$\sigma(W \rightarrow l\nu) = 9.96 \pm 0.23(stat) \pm 0.50(syst) \pm 1.10(lumi)$ nb

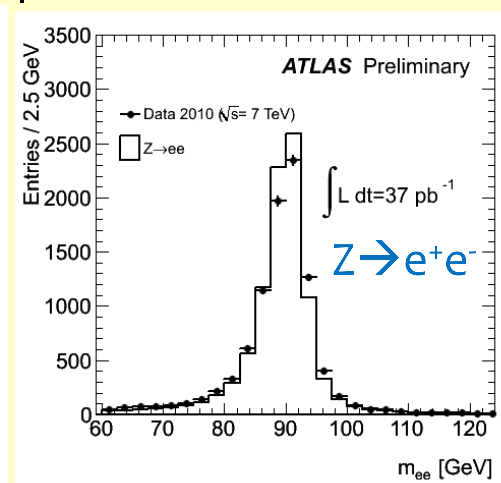
$\sigma(Z \rightarrow ll) = 0.82 \pm 0.06(stat) \pm 0.05(syst) \pm 0.09(lumi)$ nb





New results available soon
→ reaching high precision!





- W/Z (in e/μ) cross sections with very first data
- Excellent reconstruction and identification of e and μ

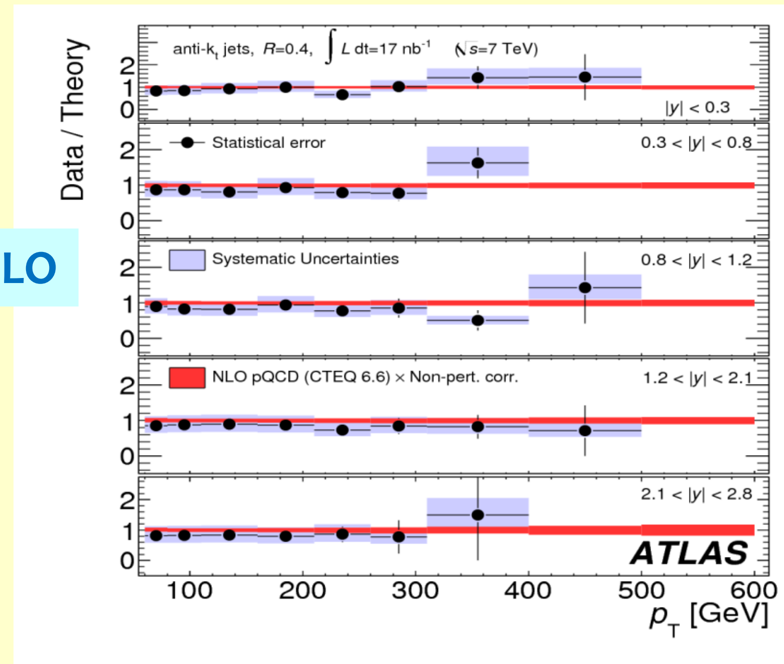
Inclusive Jet cross sections

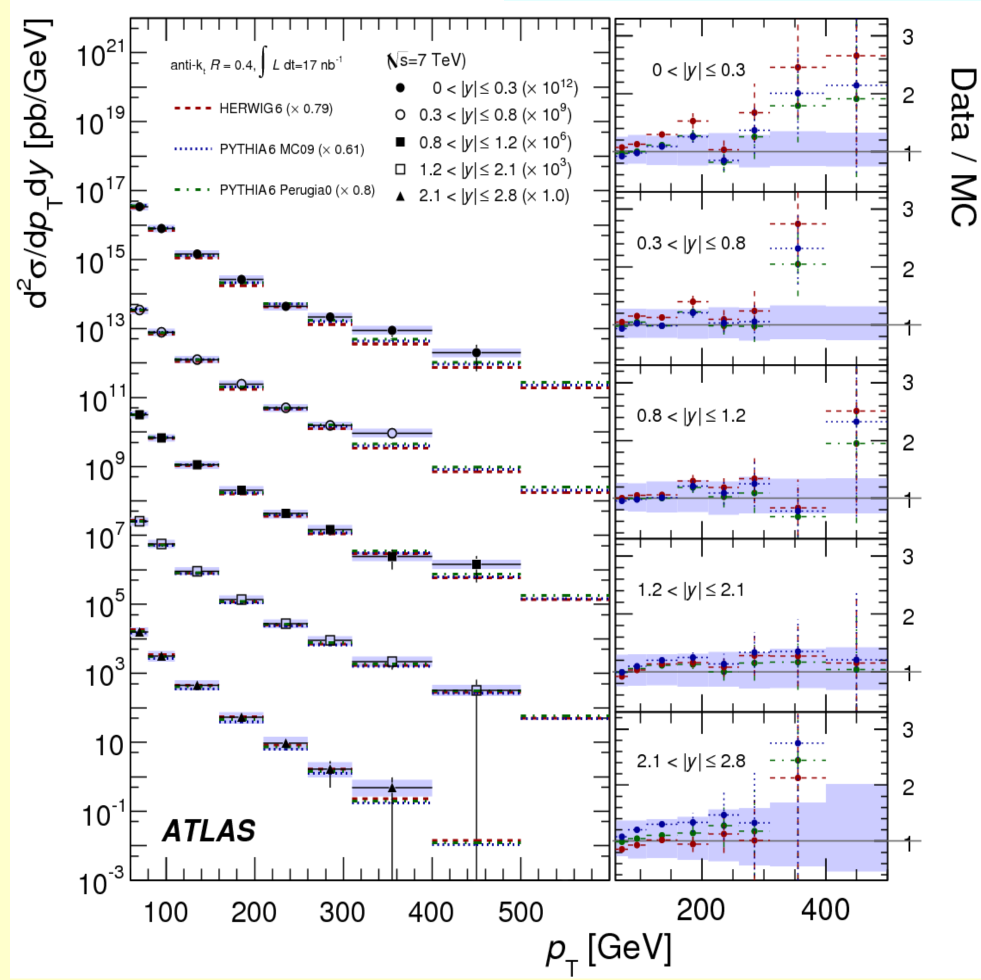
All jets with p_T>60 GeV

MC: PYTHIA, HERWIG

- Measured inclusive jet (and dijet) cross sections compared to
  - NLO QCD prediction
  - several MC tools prediction used in analyses

NLO



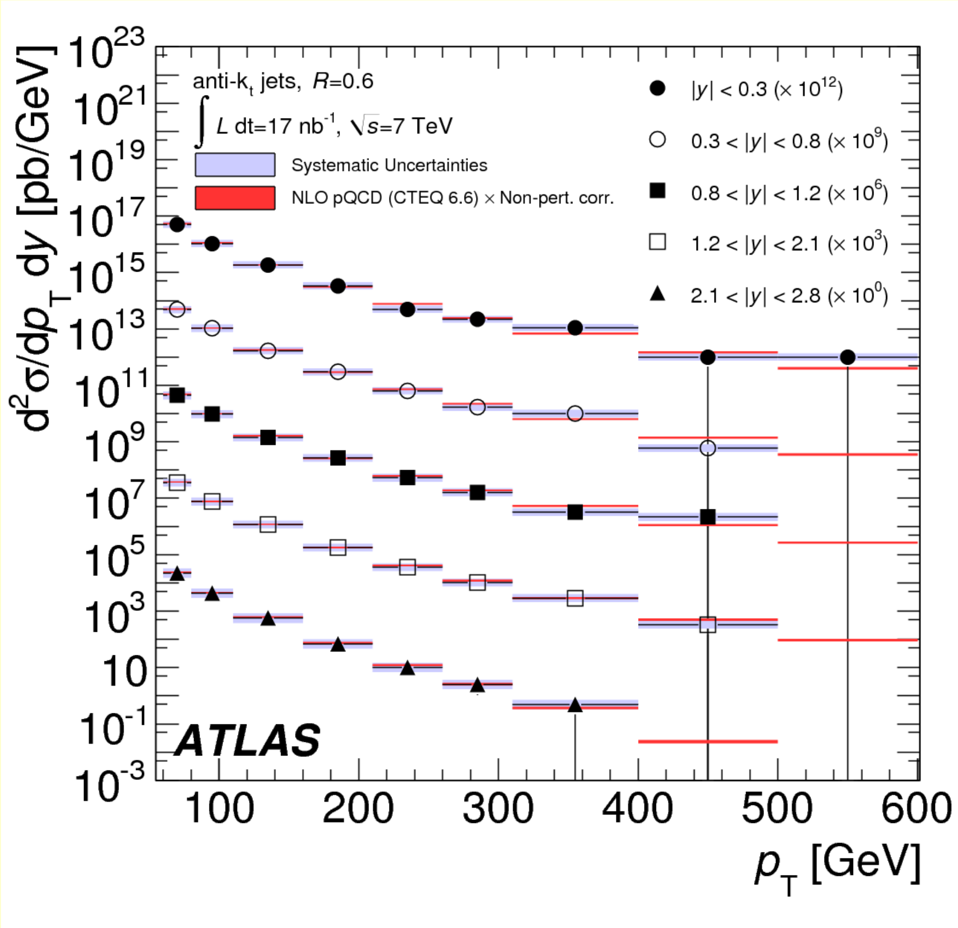


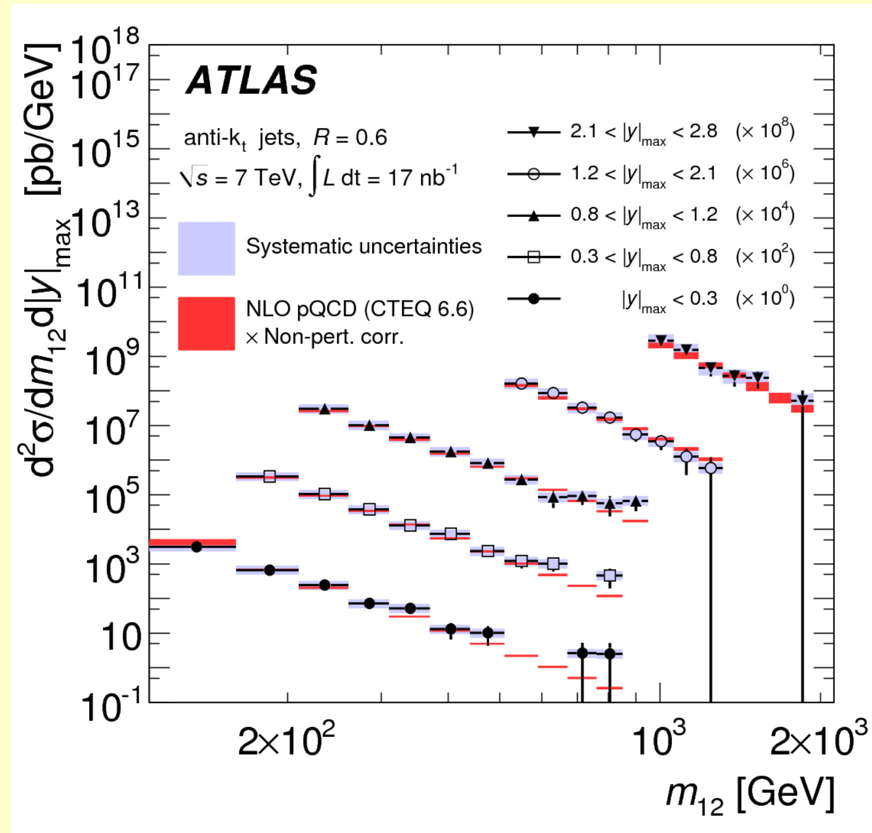
- Use anti-k_T algorithm (R=0.4 and 0.6)
- **Jet Energy Scale (JES)→** uncertainties **of** ~ 30-40% on cross section

EPJC 71 (2011) 1-59

Jet cross sections (NLO)

- Inclusive jet and dijet cross sections



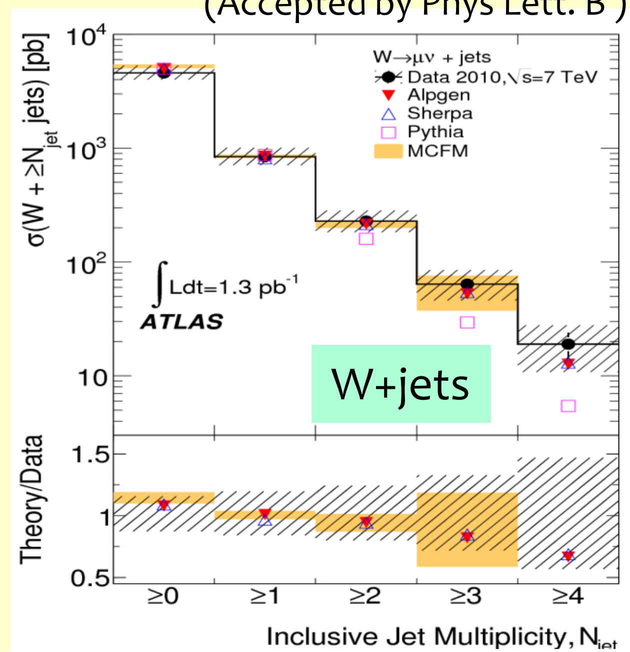


W/Z+jets and top production

arXiv:1012.5382

(Accepted by Phys Lett. B)

- Fundamental SM measurements, and background for searches for new physics
- Good agreement with NLO predictions and LO+PS MC tools

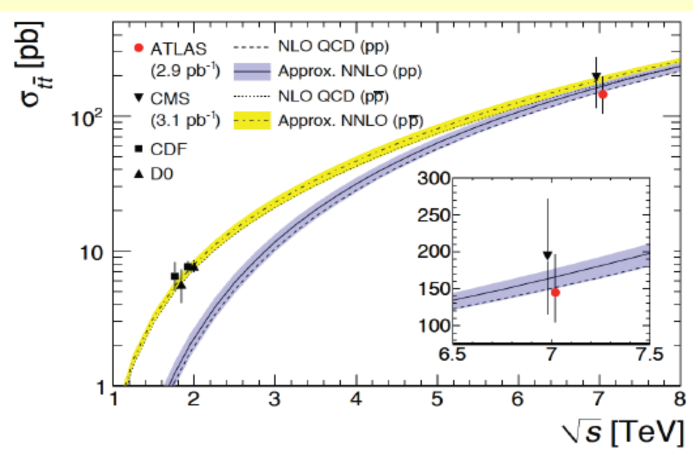


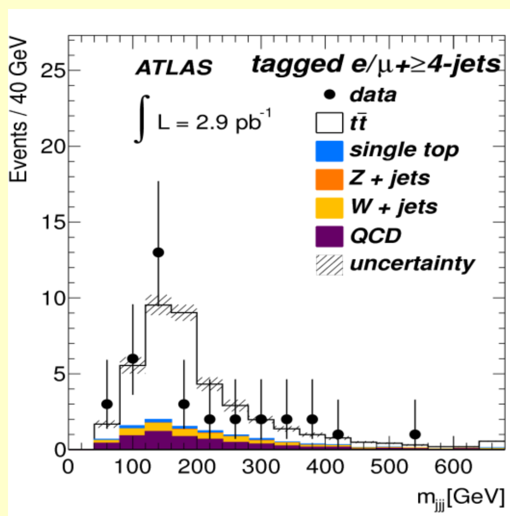
arXiv:1012.1792

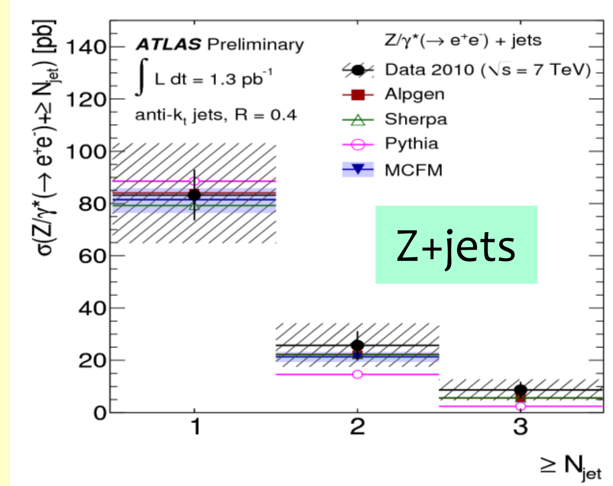
(Accepted by EPJC)

ttbar

	Cross-section [pb]	Signal significance [σ]
Single lepton channels	$142 \pm 34\ ^{+50}_{-31}$	4.0
Dilepton channels	$151\ ^{+78}_{-62}\ ^{+37}_{-24}$	2.8
All channels	$145 \pm 31\ ^{+42}_{-27}$	4.8







QCD for 0-lepton: cross checks

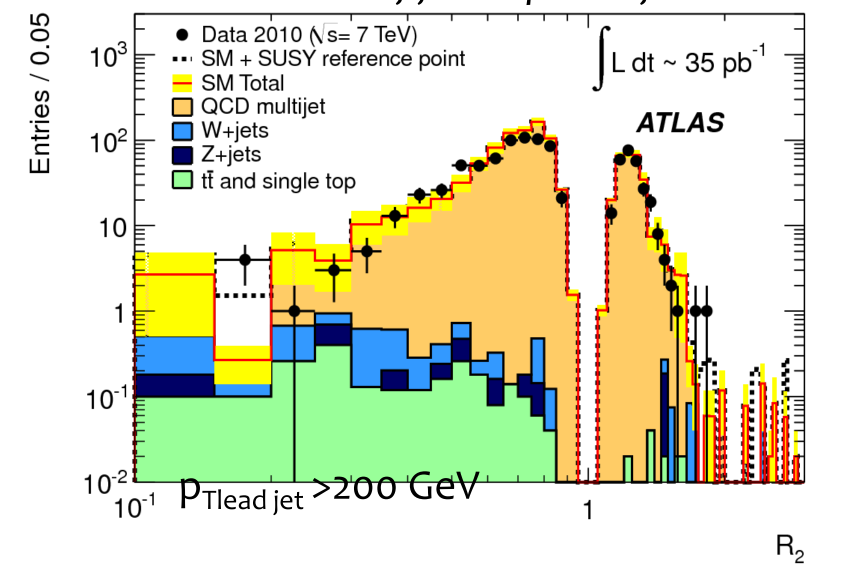
- Baseline QCD estimation consistent with fully data-driven technique:
  - High MET events 'generated' from data, smearing down low MET events on a jet-by-jet basis with measured jet energy resolution functions

(1)

$$R_2 = \frac{(\vec{p}_T \cdot (\vec{p}_T + \vec{p}_{T,Miss}))}{|\vec{p}_T + \vec{p}_{T,Miss}|}$$

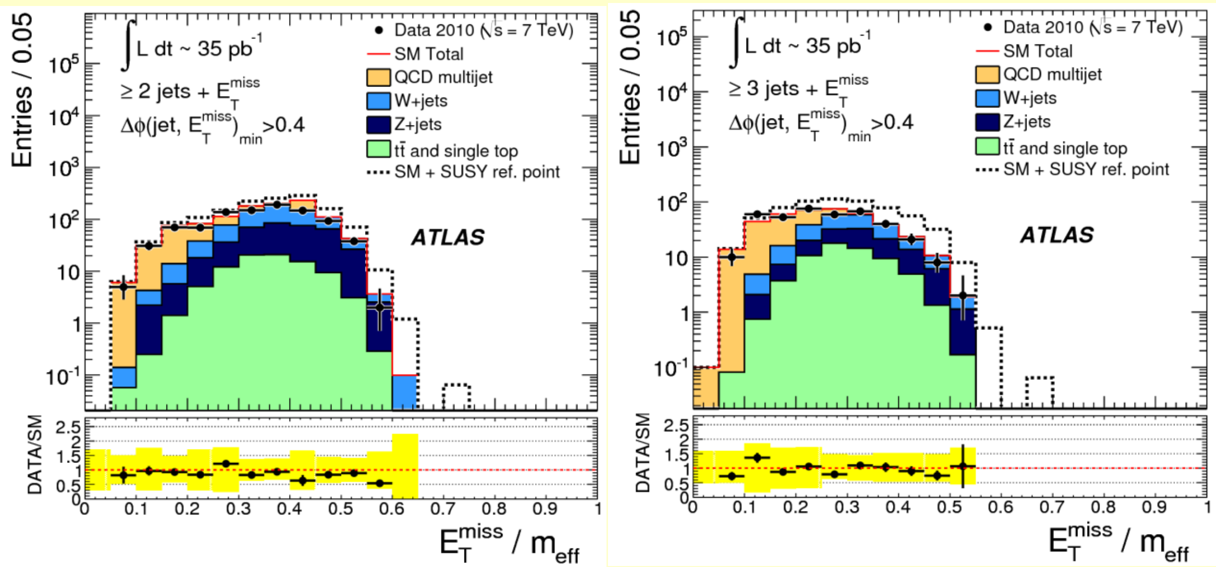
  - Assume source of E_T^{Miss} associated with jets only

Non-Gaussian tail of jet response function



(2)

-- Use additional control regions reversing E_T^{Miss}/m_{eff} requirements



Systematic uncertainties (0-lepton)

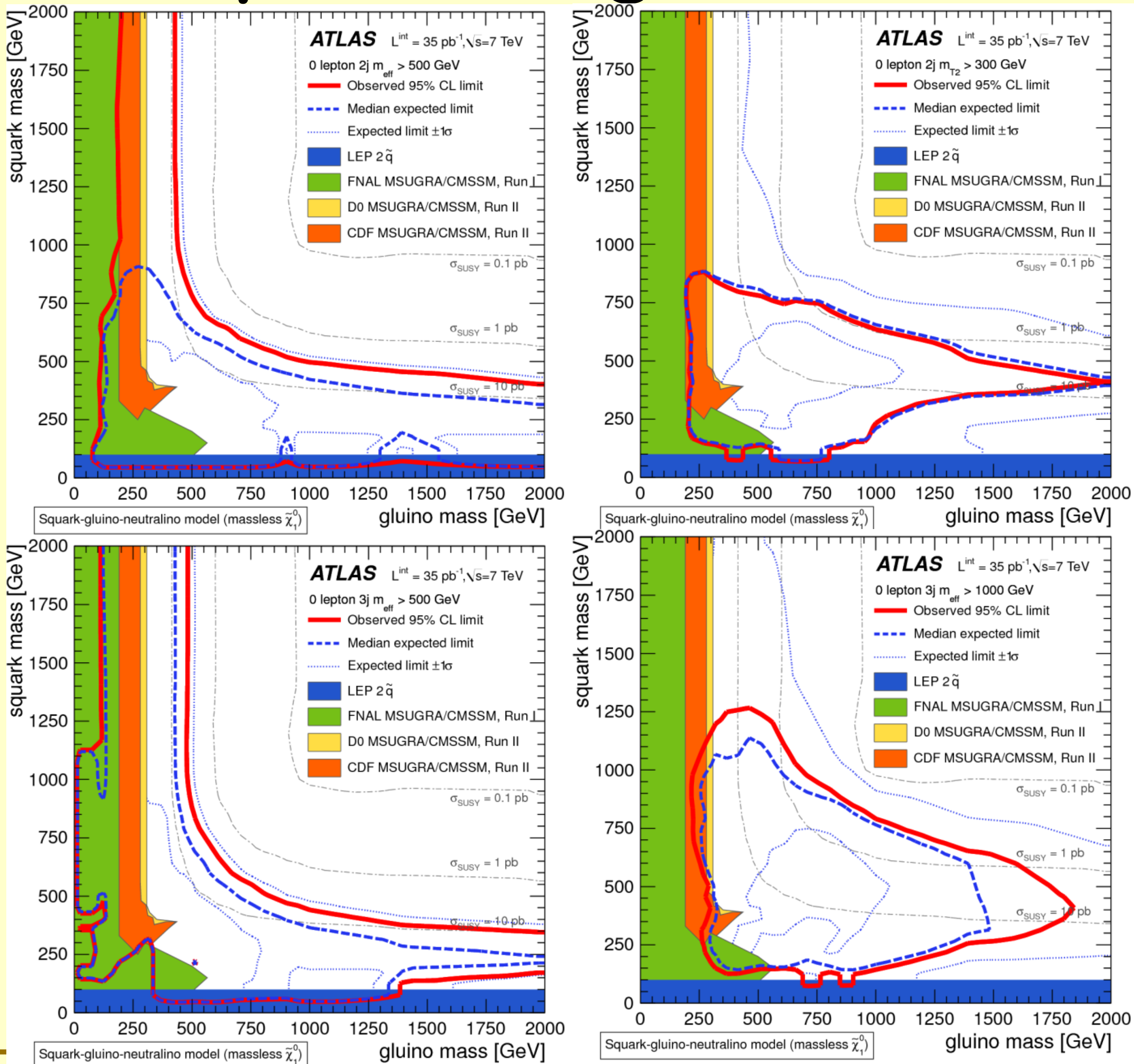
- Background estimates:
  - Jet Energy Scale → depending on jet p_T and η, between 6% and 10% → dominant
  - Jet Energy Resolution → measured in data, applied to MC simulated jets and translated on E_T^{Miss}
  - Luminosity (11%)
  - MC modeling
  - Lepton efficiencies
  - Extrapolation from control regions to signal regions (f.i.: for QCD)
  - MC finite statistics
- SUSY signal:
  - on NLO cross sections from PROSPINO v2.1
  - For each individual process
    - Renormalization/factorization scales: ½ → 2 μ, where $\mu=\mu_R=\mu_F$=average produced sparticle mass
    - PDF: CTEQ6.6M → Hessian method, uncertainties taken at 68%

In the limit calculation, correlations are taken into account when appropriate

0-lepton: 4 regions: MSSM

A

B



C

D

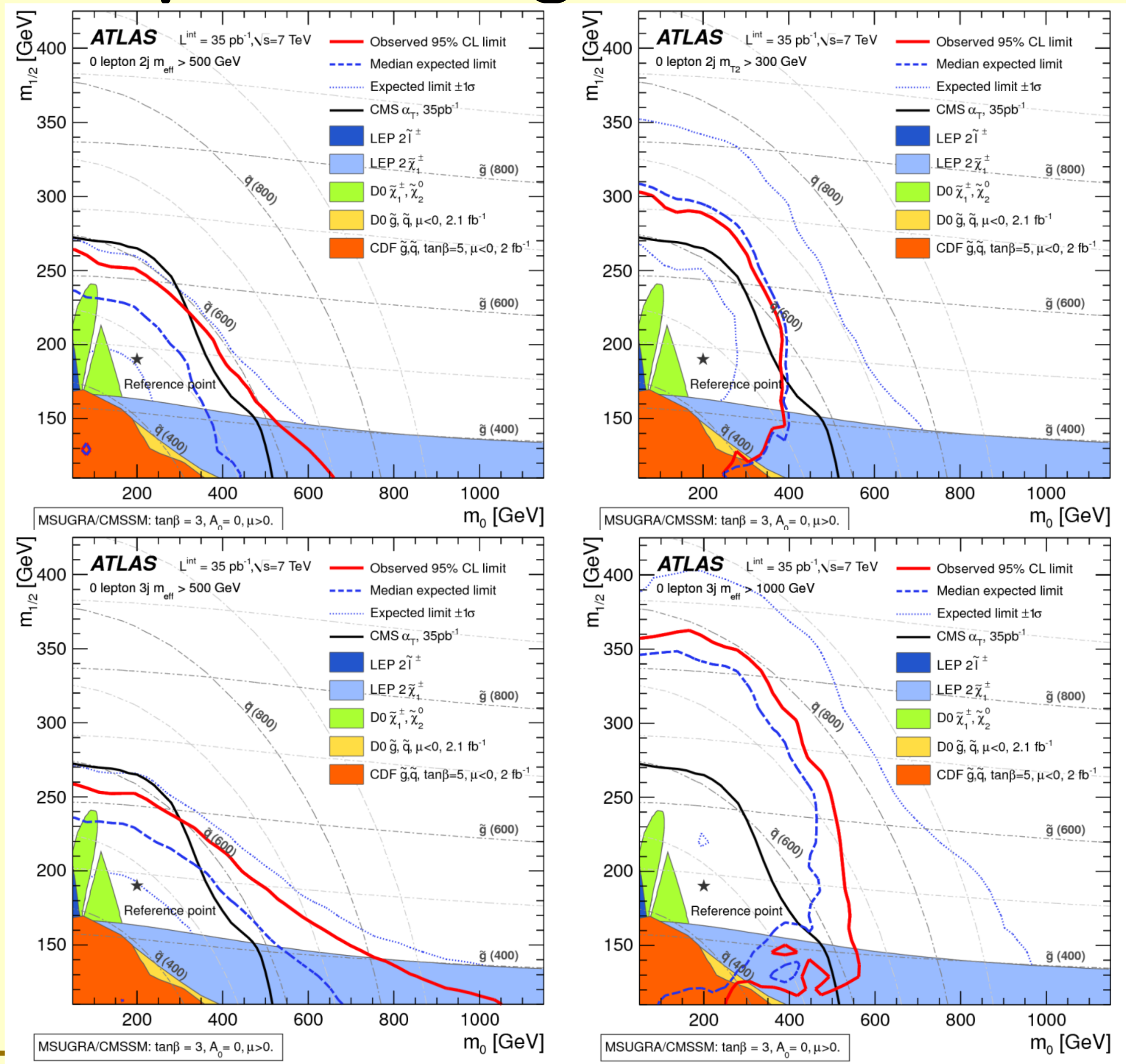
0-lepton: 4 regions: mSUGRA

A

B

C

D



Limit settings (details) (I)

- Use Likelihood approach which takes into account correlations among systematic uncertainties
  - profile LLR obtained from a likelihood defined for each specific analysis
  - Use likelihood representation provided by the ROOT framework
  - Consider Signal Regions (SR) and possibly Control Regions (CR)

$$L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu, \boldsymbol{b}, \boldsymbol{\theta}) = P_{\mathrm{SR}} \times P_{\mathrm{CR}} \times P_{\mathrm{Syst}}$$

$$= P(n_S | \lambda_S(\mu, \boldsymbol{b}, \boldsymbol{\theta})) \times \prod_{i \in \mathrm{CS}} P(n_i | \lambda_i(\mu, \boldsymbol{b}, \boldsymbol{\theta})) \times P_{\mathrm{Syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta}).$$

Poisson SR (n_S)

Poisson CR (n_i)

Probability density function for systematics: θ^0 =nominal

λ_S and λ_i → poisson expectation, function of:

- bkg normalization factors (different sources)
- nuisance parameters θ (parameterization of systematics)
- signal normalization factor μ (=0 or =1), also called signal strenght

- For setting exclusion limits → signal model hypothesis test is inverted to find the one-sided upper limit at 95% CL.

Note: similar to the procedure of the ATLAS CSC book → fully frequentist.

Limit settings (details) (II)

- The statistical treatment is based on the profile LLR

$$\Lambda(\mu) \equiv \Lambda(\mu, n, \theta^0) \equiv -2\left(\ln L(n, \theta^0 | \mu, \hat{\hat{b}}, \hat{\hat{\theta}}) - \ln L(n, \theta^0 | \hat{\mu}, \hat{b}, \hat{\theta})\right)$$

maximize likelihood for specific fixed value of μ and data n,ϑ°

Maximize likelihood function

- Consider only signal hypothesis leading to positive number of observed events → for $\hat{\mu}<0$, $\hat{\mu}=0$ is used
- If $P\chi^2$ → one-sided p-value for a give χ^2, test statistic for UL:

$$q_\mu \equiv \begin{cases} P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} \geq \mu \\ 1 - P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} < \mu. \end{cases}$$

When testing the SM hypothesis →

$$q_0 \equiv \begin{cases} P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} < 0 \\ 1 - P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} \geq 0. \end{cases}$$

- Test statistic → p-value in the *approximation* that Λ has a χ^2 distribution with 1 d.o.f. q_0= approx p-value for agreement between SM and data
- If approx is good → uniform q between 0 and 1:
  - if μ=1 and frequency ≤0.05 → model is excluded at 95% C.L.
  - If μ=0, find amount of discrepancy between data and SM expectation

Limit settings details (III)

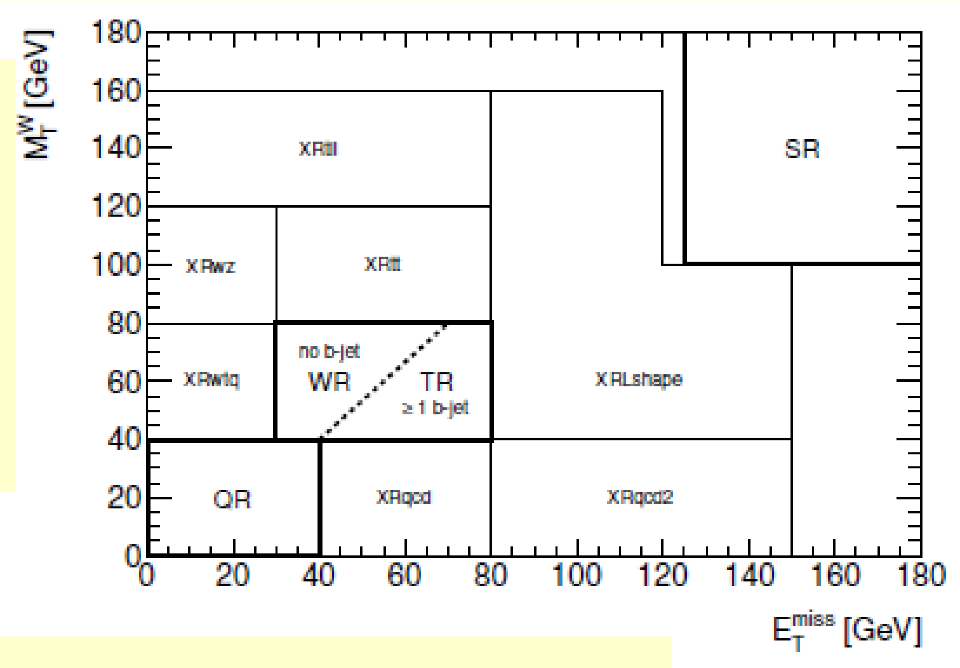
- This might be not always sufficient:
  → we **use pseudo-experiments**
- **SUSY ETMiss analysis use the most conservative amongst different LLR-based results**
- 1-lepton analysis results tested against other limit setting procedures:
  - Bayesian ($1/\sqrt{s}$ and flat in s), Bayesian Gaussian ($s>0$)
  - Corrected Cousins-Highland approach
  - Feldman-Cousins (pll), as CMS
  - Others …

→ Results as expected, CMS approach gives consistent results wrt to ours *(numbers not publicly available yet)*

W+jets and top backgrounds

Split intermediate (E_T^{miss},m_T) box with b-tagging using secondary vertex alg. SV0:

- ≥ 1 b-jet => top enriched (TR)
- < 1 b-jet => W enriched (WR)



Take Monte Carlo to extrapolate to signal region:

- Alpgen+HERWIG for Boson+jets
- MC@NLO for top production

Main uncertainties:

1. Theory: 50% W+jets (uncertainty on m_{eff} NLO shape), 25% top (comparison between generators)
2. Limited MC statistics: ~ 40% (W), ~ 10% (top)
3. B-tagging: ~ [10-25]%

Total uncertainty in signal region: Top ~ 40%, W+jets ~ 80%

Likelihood method (1-lepton)

- Fill all useful information into a likelihood => minimize to estimate bkgs

$$L(n|\mu, b, \theta) = P_{SR} \times P_{WR} \times P_{TR} \times P_{QR} \times C_{Syst}$$

- One poisson for signal region and per control region
  → simultaneous fit of all regions
- Systematic uncertainties controled by nuisance parameters
  → correlations treated properly

Electron channel	Signal region	Top region	W region	QCD region
Observed events	1	80	202	1464
Fitted top events	1.34 ± 0.52 (1.29)	65.0 ± 12.3 (62.9)	31.8 ± 15.8 (31.0)	40.1 ± 11.3
Fitted W/Z events	0.47 ± 0.40 (0.46)	11.2 ± 4.6 (10.2)	161 ± 27 (146)	170 ± 34
Fitted QCD events	$0.0^{+0.3}_{-0.0}$	3.7 ± 7.6	9.4 ± 19.6	1254 ± 51
Fitted sum of background events	1.81 ± 0.75	80 ± 9	202 ± 14	1464 ± 38

Muon channel	Signal region	Top region	W region	QCD region
Observed events	1	93	165	346
Fitted top events	1.76 ± 0.67 (1.39)	85.0 ± 10.5 (67.1)	41.8 ± 18.6 (33.0)	49.7 ± 10.2
Fitted W/Z events	0.49 ± 0.36 (0.71)	7.7 ± 3.3 (11.6)	120 ± 26 (166)	71.4 ± 16.4
Fitted QCD events	$0.0^{+0.5}_{-0.0}$	0.3 ± 1.2	3.4 ± 12.1	225 ± 22
Fitted sum of background events	2.25 ± 0.94	93 ± 10	165 ± 13	346 ± 19

Fitted predictions in agreement with observation

Other backgrounds for 2-lepton

- **Electron charge-flip:**
  - Relevant for Same-Sign dilepton final states
  - Background from dilepton top events:
    - Hard bremsstrahlumng process

$$e^{\mp}_{\rm hard} \rightarrow \gamma_{\rm hard}\, e^{\mp}_{\rm soft} \rightarrow e^{\mp}_{\rm soft}\, e^{\mp}_{\rm soft}\, e^{\pm}_{\rm hard}$$

    - Charge mis-identified rate taken from Zee MC samples as a function of $|\eta|$
    - Validated in Z→ee data
- **Z+jets:**
  - Z→eμ from MC (low statistics in data)
  - Semi-data driven estimation for Z→ee,μμ
  - Control region:
    - 81<m(ll)<101 GeV
    - E_T^{Miss} < 20 GeV
  - Corrected for predicted number of W and top in control region

$$N^{\rm est,SR}_{Z/\gamma^*} = \beta \cdot N^{\rm data,CR}_{Z/\gamma^*} \qquad \beta = \frac{N^{\rm MC,SR}_{Z/\gamma^*}}{N^{\rm MC,CR}_{Z/\gamma^*}}$$

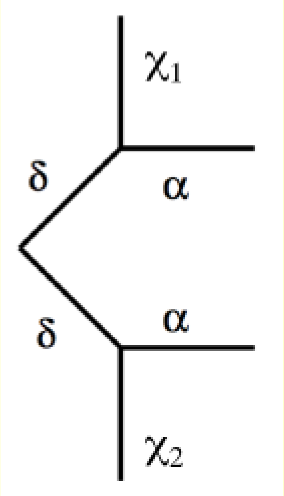
- **Cosmics:**
  - 2 methods considered →
    - matrix method based on impact parameter
    - Trigger Lifetime
  - Both consistent to zero
  - Define an upper bound: Ncos < 1.32 at 68% CL, Ncos < 3.45 at 95% CL

Top-tagger: m_{CT}

Tovey, JHEP 0804 (2008) 034
Polesello, Tovey, JHEP 1003 (2010) 030

- In the decay of a two pair-produced heavy states which decay via $\delta \rightarrow \alpha\chi_i$

$$m_{CT}^2(\chi_1,\chi_2) = [E_T(\chi_1) + E_T(\chi_2)]^2 - [\mathbf{p_T}(\chi_1) - \mathbf{p_T}(\chi_2)]^2$$



- m_{CT} distributions have endpoints defined by m(δ), m(α) and the vector sum of transverse momenta of the visible particles upstream of the system for which the contransverse mass is calculated (p_b)
- For the top-pair system m_{CT} (ll), m_{CT} (jj), m_{CT} (j l, jl) can be constructed

Contransverse mass tagger

1. Event with least 2 jets with $p_T > 20$ GeV
2. Consider all 2 jet permutations j_1, j_2, such that the two jets have $p_T > 20$ GeV and $p_T(j_1) + p_T(j_2) + p_T(\ell_1) + p_T(\ell_2) > 100$ GeV
3. $m_{CT}(\ell_1, \ell_2)$ in the allowed area of the $(m_{CT}(\ell_1, \ell_2), p_b(\ell\ell))$ plane
4. Build all pairs $((j_i\ell_1)(j_j\ell)_2)$ such that $m(j_i\ell_1) < 155$ GeV and $m(j_j\ell_2) < 155$ GeV
5. One combination with $m_{CT}(jj)$ in the allowed area of the $m_{CT}(jj)$, $p_b(jj)$ plane
6. $m_{CT}(j\ell, j\ell)$ should be compatible with $t\bar{t}$

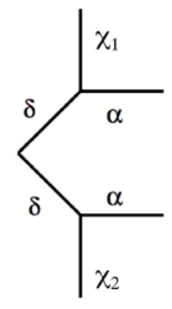
- Efficiency m_{CT} tagger = 85%
- control region for ttbar:
  - m_{CT}-tagged events
  - $60 < E_T^{Miss} < 80$ GeV

Top background for OS

Dileptonic top decays $tt \rightarrow l^{+} \nu b\, l^{-} \nu b$

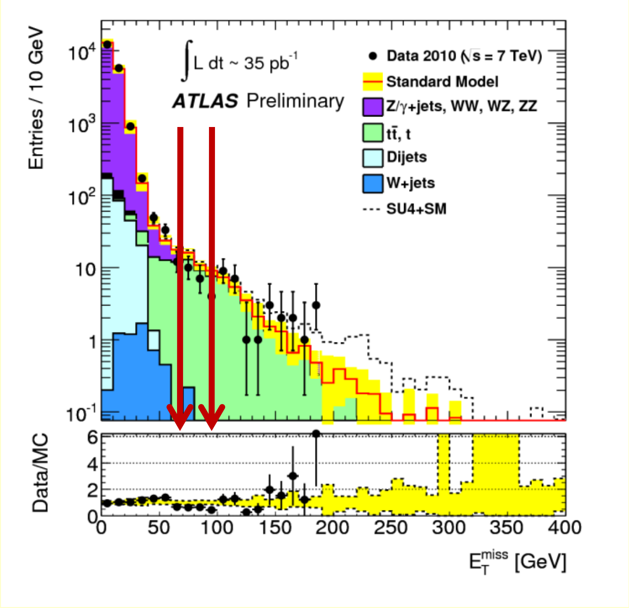
- **"Top tagging" algorithm** based on contransverse mass (m_{CT})

$$m_{CT}^2(\chi_1,\chi_2) = [E_T(\chi_1) + E_T(\chi_2)]^2 - [\mathbf{p}_T(\chi_1) - \mathbf{p}_T(\chi_2)]^2$$



Control Sample

- E_T^{Miss} [60,80] GeV, ≥2 jets with p_T>20 GeV
- Calculate m_{CT} from 4-vectors of leptons and jets → must be consistent with $t\bar{t}$ bounds
- m(jet,l1) and m(jet,l2) consistent with top decays



Data CR: 15 top-tagged events
MC CR: 21.3±3.8 (18.8 from ttbar)

Estimation in Signal Region →

$$(N_{tt})_{SRch} = \left((N_{data}^{tag})_{CR} - (N_{non-tt,MC}^{tag})_{CR} \right) f_{MC}^{CR \rightarrow SR}$$

$$f_{MC}^{CR \rightarrow SR} = (N_{top,MC})_{SRch} / (N_{top,MC}^{tag})_{CR}$$

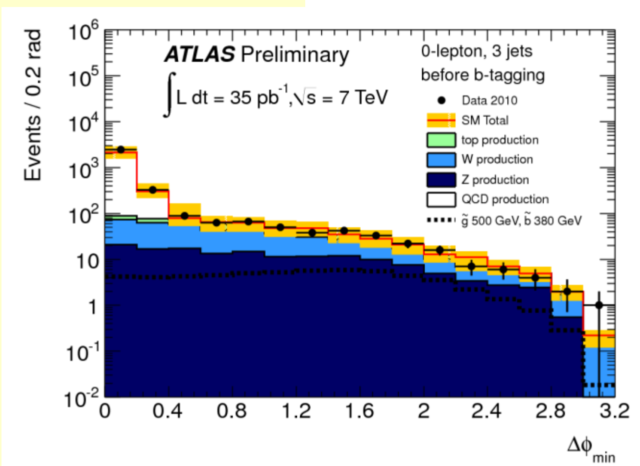
2.8+1.4-1.3

0-lepton bkg details (b-jets)

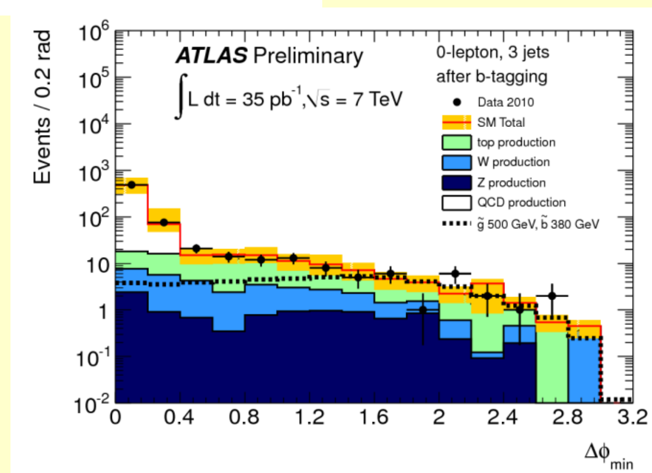
- Breakdown of non-QCD SM-background contributions for 0-lepton analysis at each stage of the selection (per pb^{-1})

Cut	$t\bar{t}$	W+ jets	Wbb	Z + jets	Zbb	single top
$E_T^{miss} > 100$ GeV	3.55 ± 0.02	9.29 ± 0.15	0.1 ± 0.01	4.66 ± 0.14	0.054 ± 0.002	0.30 ± 0.02
$E_T^{miss}/m_{eff} > 0.2$	3.05 ± 0.02	8.36 ± 0.14	0.09 ± 0.01	4.28 ± 0.14	0.047 ± 0.001	0.26 ± 0.02
1 b-tagged jet	2.15 ± 0.02	0.69 ± 0.04	0.06 ± 0.01	0.28 ± 0.03	0.022 ± 0.001	0.16 ± 0.01
$\Delta\phi_{min} > 0.4$	1.60 ± 0.02	0.42 ± 0.03	0.05 ± 0.01	0.19 ± 0.03	0.016 ± 0.001	0.11 ± 0.01
$m_{eff} > 600$ GeV	0.33 ± 0.01	0.11 ± 0.02	0.006 ± 0.002	0.05 ± 0.01	0.0031 ± 0.0003	0.02 ± 0.01

Selection	Expected events	Observed Events
$E_T^{miss} > 100$ GeV	4800 ± 1600	5834
$E_T^{miss}/m_{eff} > 0.2$	2800 ± 900	3221
b-tag	620 ± 200	656
$\Delta\phi_{min} > 0.4$	90 ± 30	91
$m_{eff} > 600$ GeV	20 ± 7	15



b-tagging



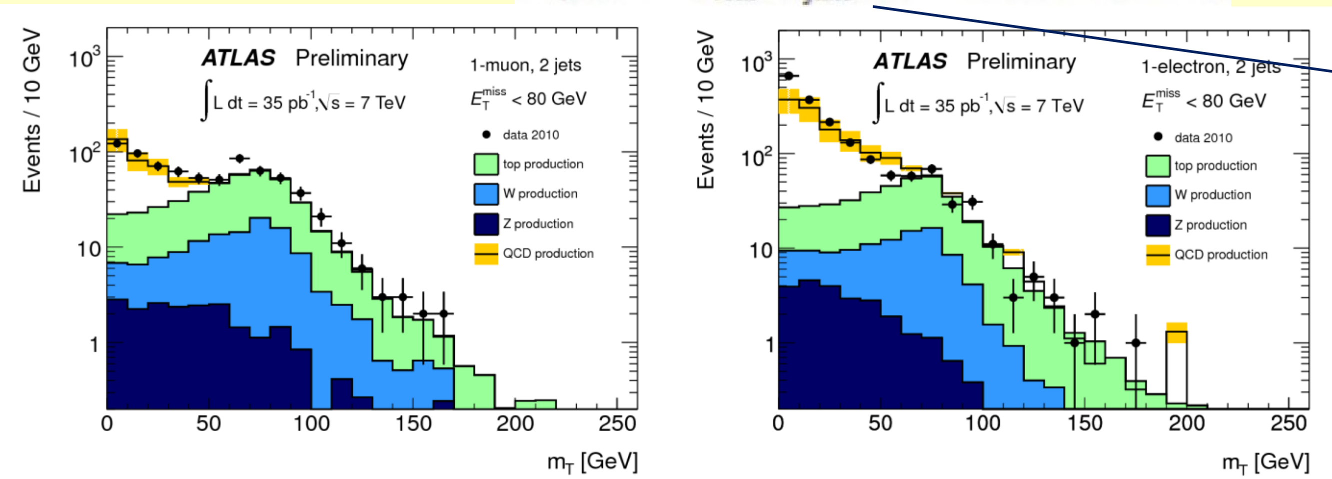
1 lepton bkg details (b-jets)

- QCD estimation from a Matrix method relying on 2 data sets differing only in the lepton ID criteria: tight (standard) and loose (relaxed):

$$N^{tight}_{fake} = \frac{\varepsilon_{fake}}{\varepsilon_{real}-\varepsilon_{fake}}\left(N^{loose}\varepsilon_{real} - N^{tight}\right)$$

ε_{real}=measured in Z-samples

ε_{fake}=measured QCD-enriched sample



QCD yield consistent with 0 in the signal region

- Breakdown of non-QCD SM-background contributions for 1-lepton analysis at each stage of the selection

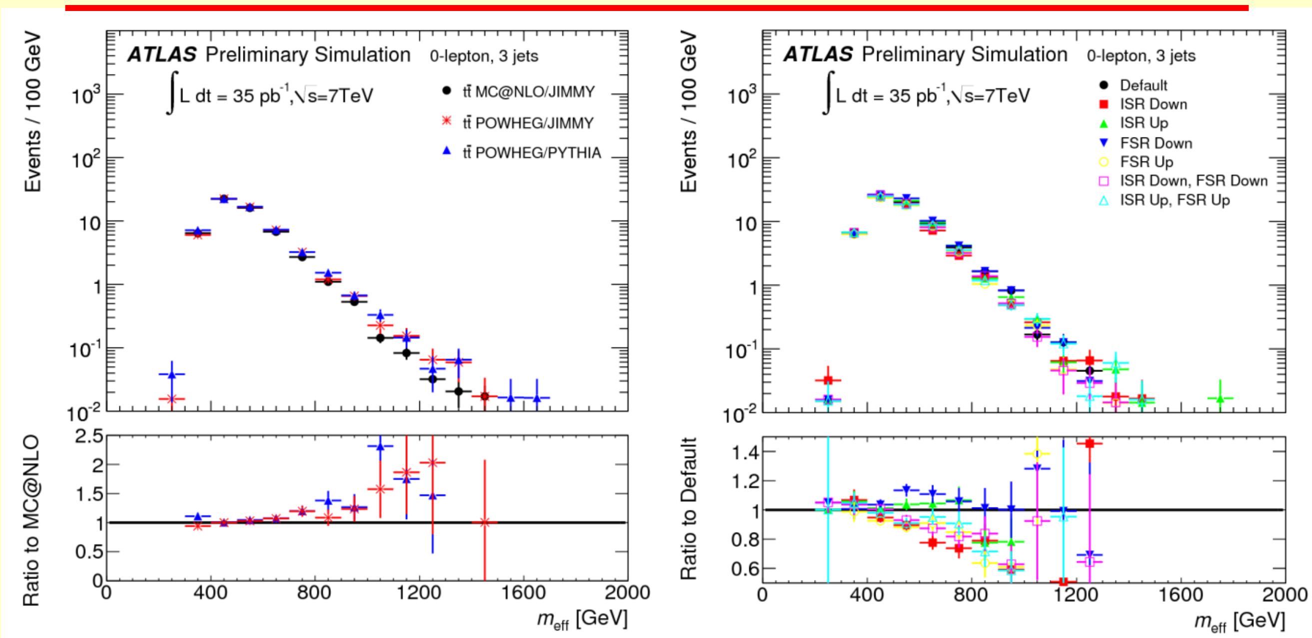
Cut	Top	W	Z	QCD	Di–boson production
1 electron with $p_T > 20$ GeV	24.4	3760	631.4	16865	6.2
2 jets ($p_T > 60, 30$ GeV)	17.2	59.6	21.2	590	1.0
$E_T^{miss} > 80$ GeV	4.6	10.4	0.3	6.6	0.2
$m_T > 100$ GeV	1.0	0.38	0.025	0.08	0.0021
1 b-tag	0.70	0.016	3×10^{-4}	0.06	0.0013
$m_{eff} > 500$ GeV	0.18	0.011	–	–	–

Cut	Top	W	Z	QCD	Di–boson production
1 muon with $p_T > 20$ GeV	24.4	4700	770	4880	6.8
2 jets ($p_T > 60, 30$ GeV)	17.3	70	15.5	65	1.0
$E_T^{miss} > 80$ GeV	4.7	12	0.63	0.02	0.21
$m_T > 100$ GeV	1.0	0.57	0.037	1×10^{-4}	0.02
1 b-tag	0.67	0.03	0.002	–	0.002
$m_{eff} > 500$ GeV	0.17	0.013	–	–	–

Systematic uncertainties (b-jets) (I)

- 0-lepton analysis:

Process	MC stat	JES	b-tagging	Lum.	Theor.	Pileup	other (lepton, trigger)	Total
W	$\pm 15\%$	$\pm 24\%$	$\pm 24\%$	$\pm 11\%$	$\pm 27\%$	$\pm 5\%$	$\pm 3.5\%$	$\pm 43\%$
Z	$\pm 27\%$	$\pm 20\%$	$\pm 25\%$	$\pm 11\%$	$\pm 27\%$	$\pm 5\%$	$\pm 3.5\%$	$\pm 45\%$
Top	$\pm 2.5\%$	$^{+30\%}_{-23\%}$	$^{+12\%}_{-15\%}$	$\pm 11\%$	$^{+20\%}_{-27\%}$	$\pm 5\%$	$\pm 3.5\%$	$\pm 40\%$

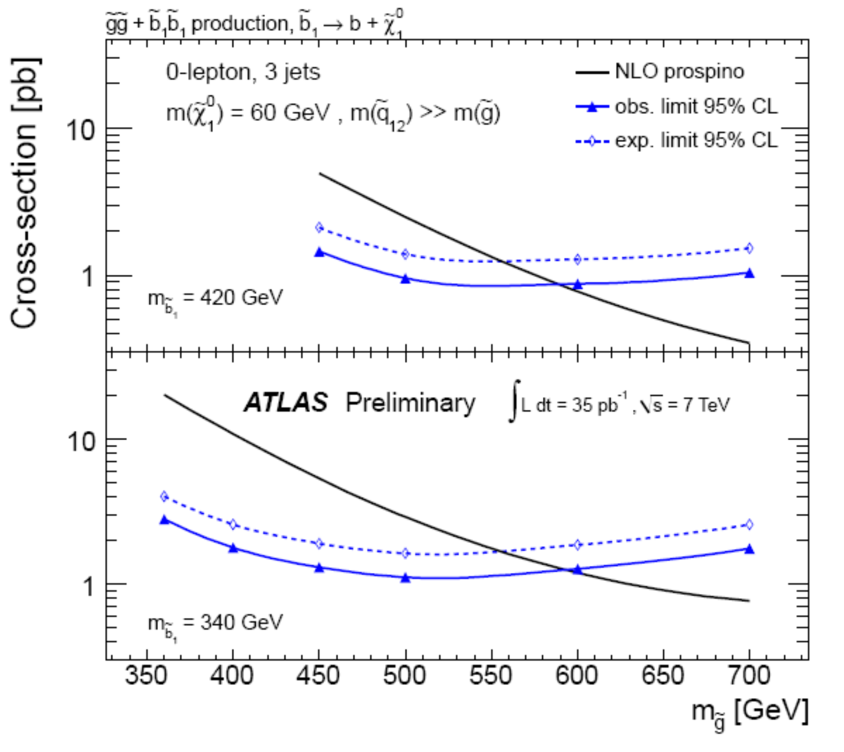


Gluino-sbottom/stop limits

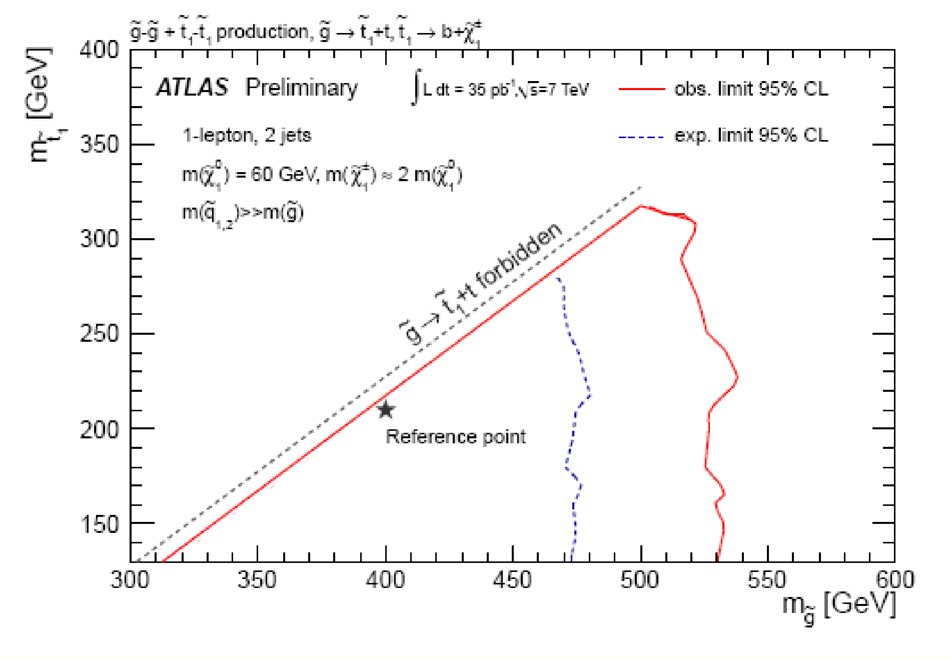
- Assume gluino decays in $b_1 b$ (BR=100%) and $\tilde{b}_1 \rightarrow b \tilde{\chi}^0_1$ (BR=100%)
- $m(\tilde{\chi}^0_1)$=60 GeV

- Assume gluino decays in $\tilde{t}_1 t$ (BR=100%) and $\tilde{t}_1 \rightarrow b \tilde{\chi}^+_1$ (BR=100%), $\tilde{\chi}^+_1 \rightarrow W^* \chi^0_1$
- $m(\tilde{\chi}^0_1)$=60 GeV , $m(\chi_1) \approx 2 \times m(\chi^0_1)$

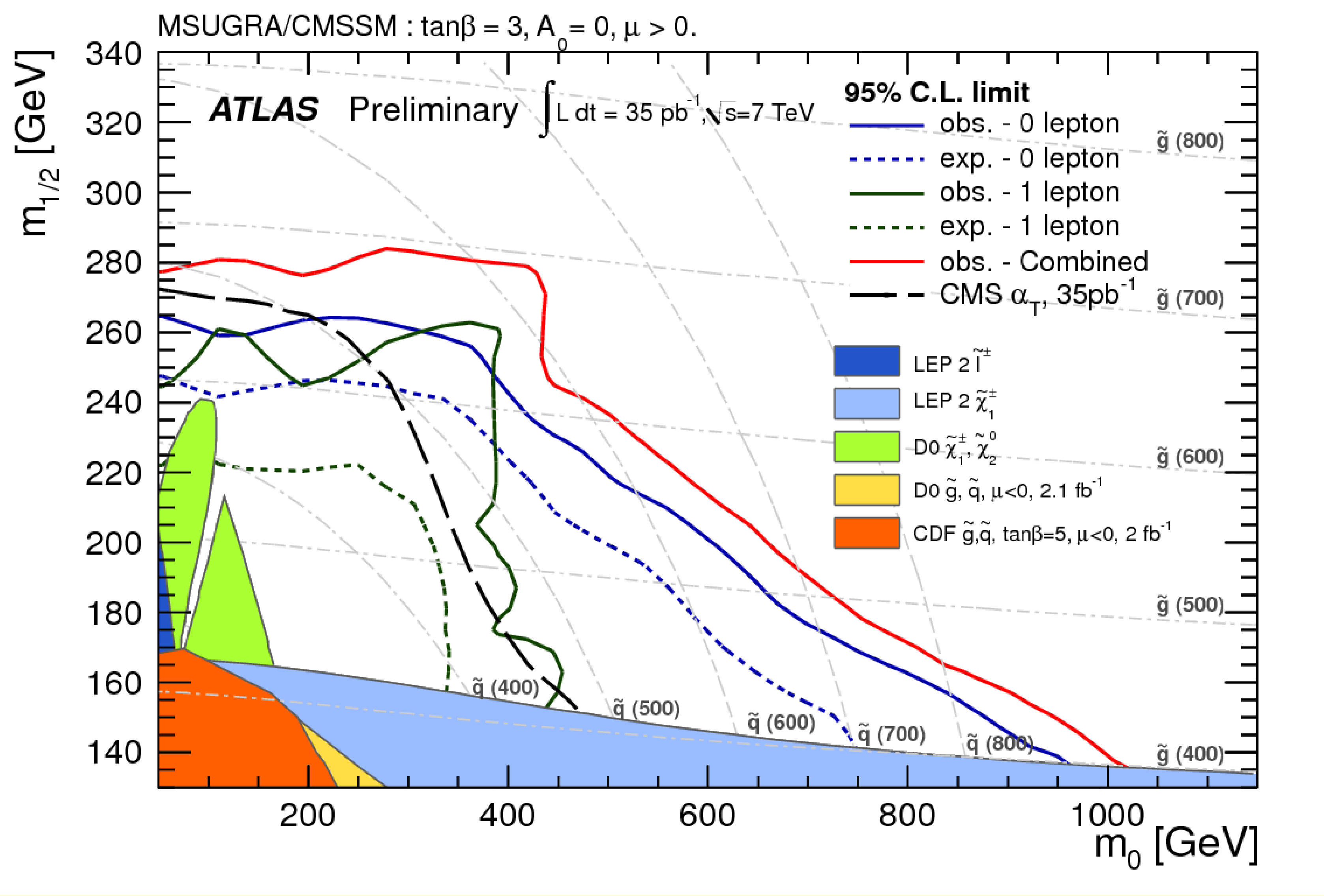
0-lepton analysis



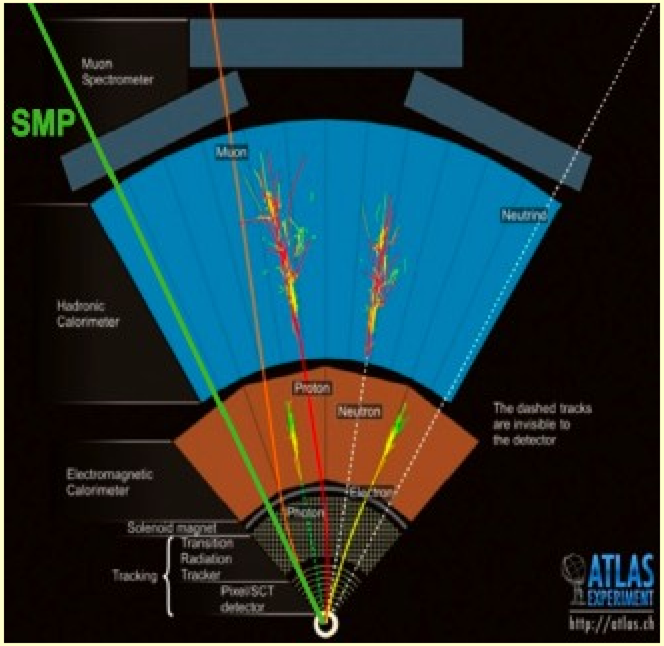
1-lepton analysis

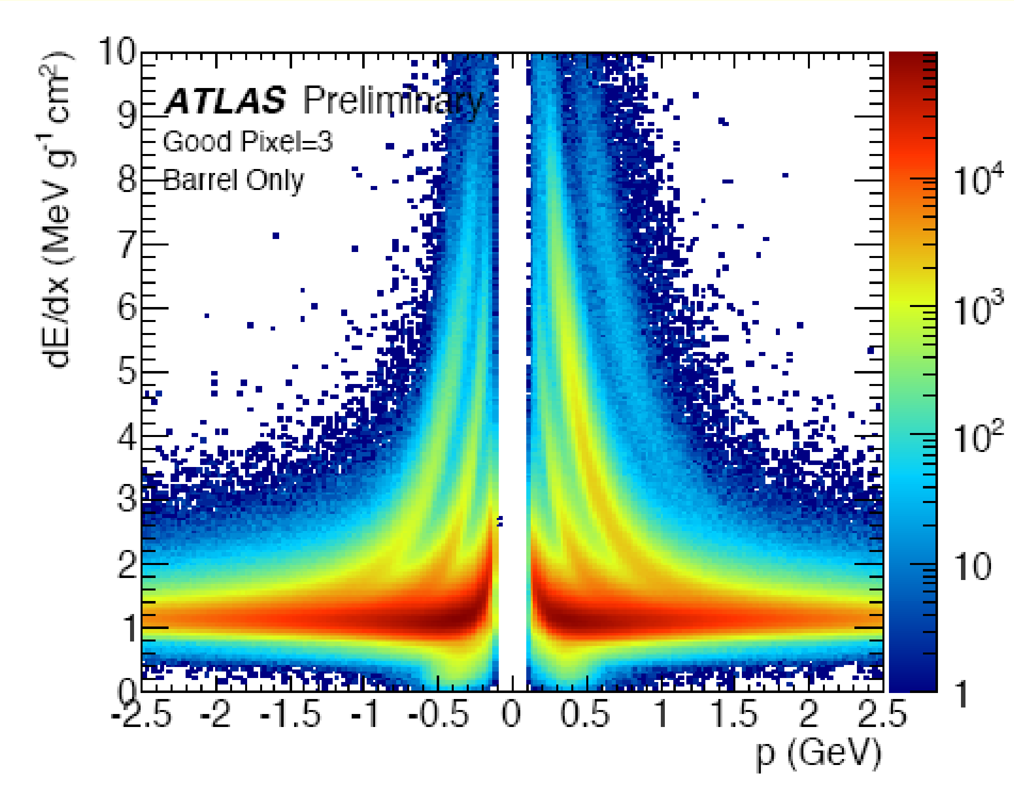


mSUGRA tanβ=3 (b-jets)



SMP observables





- dE/dx from pixel:
  - Can separate deuteron, p, k, π
  - Only rely on βγ
  - Mass available when dE/dx is outside MIP band