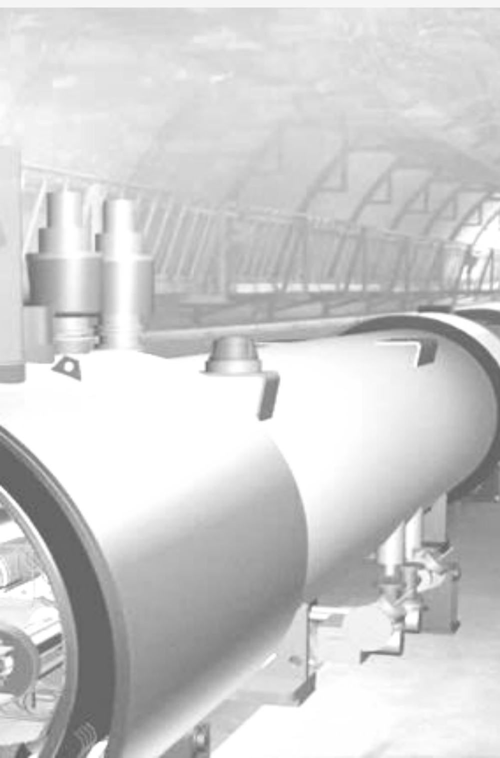
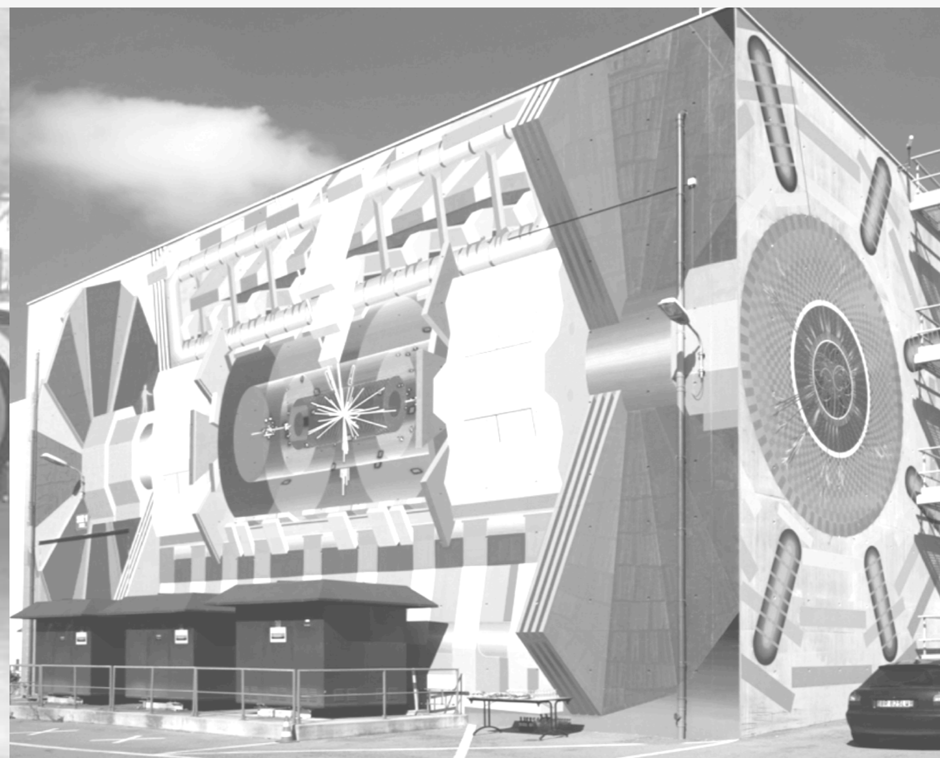
SUSY searches with ATLAS
— approaches and challenges—

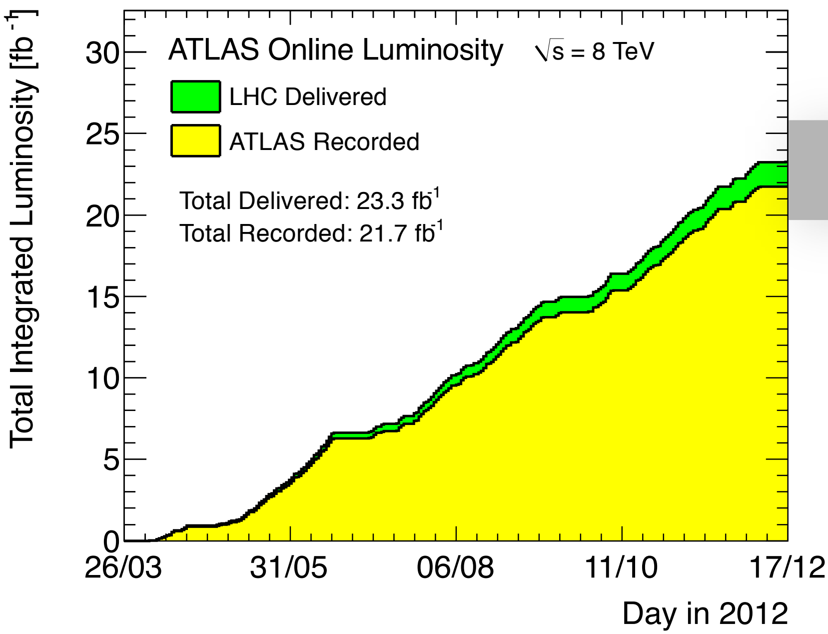
Andreas Hoecker (CERN)

National SUSY workshop, DESY, May 68, 2013

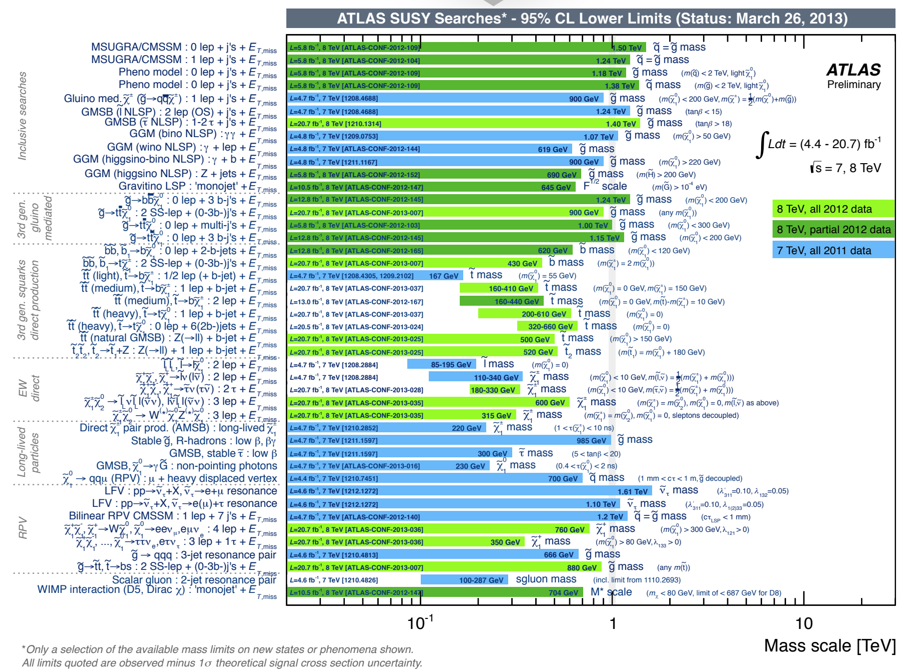




Great luminosity recorded at 8 TeV in 2012

and also at 7 TeV in 2011 …



… allowed us to deeply mine SUSY signatures & models



But no hint for a signal so far…

What is our task ?

Prove the Standard Model wrong, and thereby collect hints for SUSY

But how can that work for a theory of >100 new parameters

Many more if we account for RPV and/or an extended Higgs sector
(and what about N > 1 SUSY?)

Constraints from precision & "intensity" physics and from previous searches are guides, but still large allowed parameter space

We started by building inclusive searches along generic signatures (and models), covering large parameter space with few, powerful analyses

But: nature may have chosen *any* point in this space, so we must try to cover all points, however rare and exotic the signature may appear

Generic searches not enough: must also develop dedicated searches along (simplified) models designed around the features to be studied

But also need "realistic" MSSM models (eg, pMSSM) to avoid overtuning these dedicated searches

Slide inspired by Giacomo Polesello, ATLAS-SUSY workshop, Apr 2013

How do we search for SUSY at the LHC ?

SUSY duplicates spectrum of particles wrt. Standard Model (sparticles)

Complex sparticle decays in (*b*/*c*-)jets, leptons, taus, photons, MET, …

R-parity conserving (RPC) signatures:

- Sparticles produced in pairs, each decay to (WIMP) LSP, mostly N1 or gravitino
- One invisible LSP per decay chain → MET

R-parity violating (RPV) signatures:

- Resonances or multijets / multileptons: single sparticle production or LSP decay
- Displaced vertices from late LSP decay

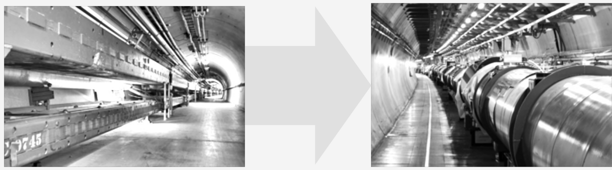
Long-lived particles from:

- Weak couplings (eg, gravitino, RPV)
- High virtuality from heavy mediator sparticles (eq, heavy squarks in split SUSY)
- Mass degeneracy (eg, *m*(chargino) ~ *m*(LSP) in AMSB)

Slide taken from Giacomo Polesello, ATLAS-SUSY workshop, Apr 2013

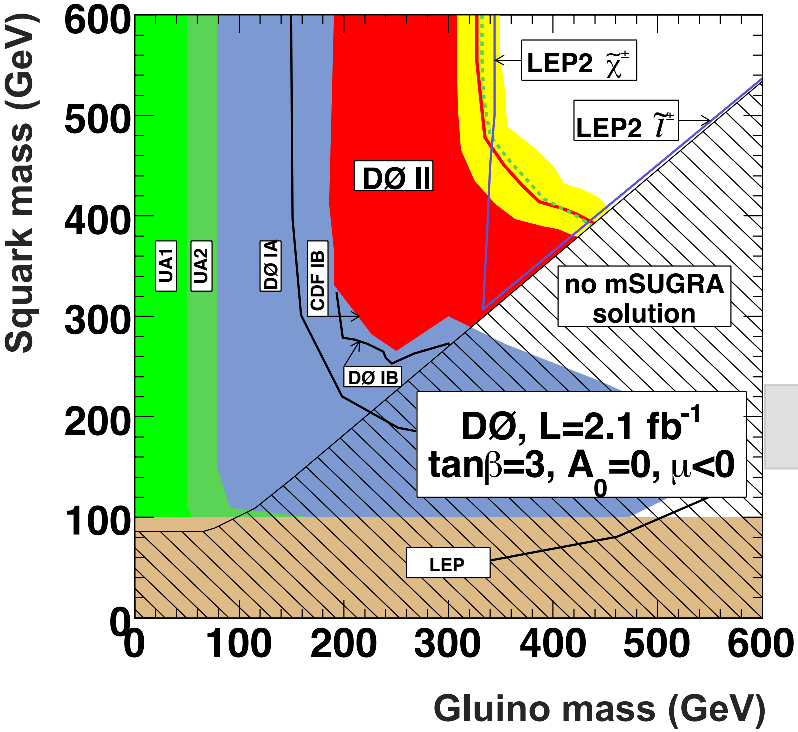
We went a long way

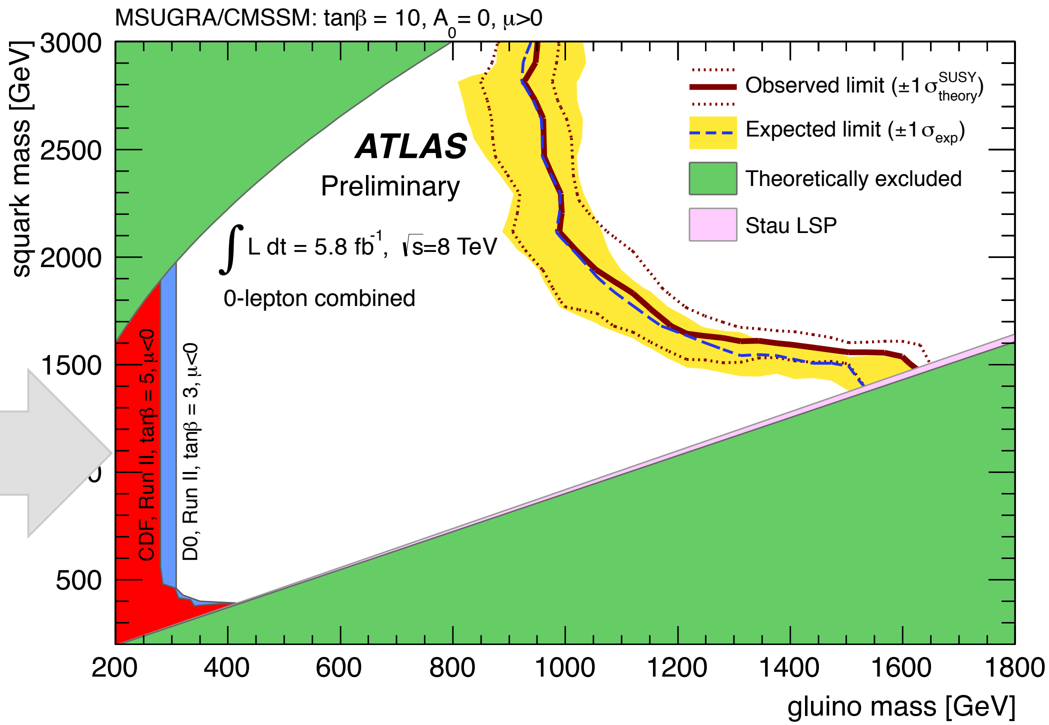
…since the Tevatron searches



D0 0712.3805, ATLAS-CONF-2012-109

Jets + MET searches for squarks and gluinos at D0 and ATLAS





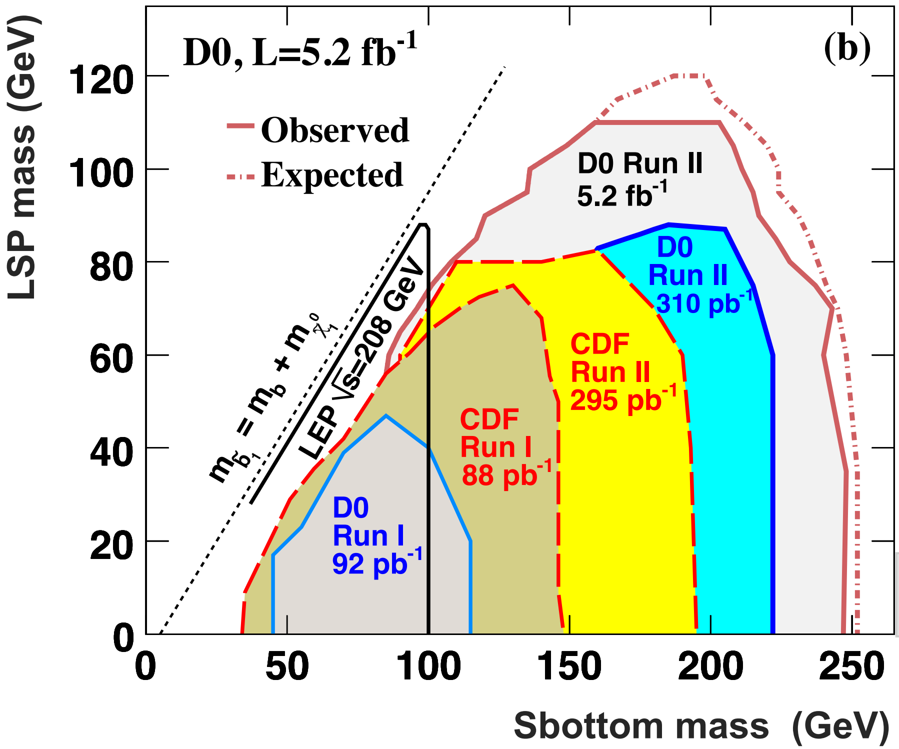
Slide inspired by Giacomo Polesello, ATLAS-SUSY workshop, Apr 2013

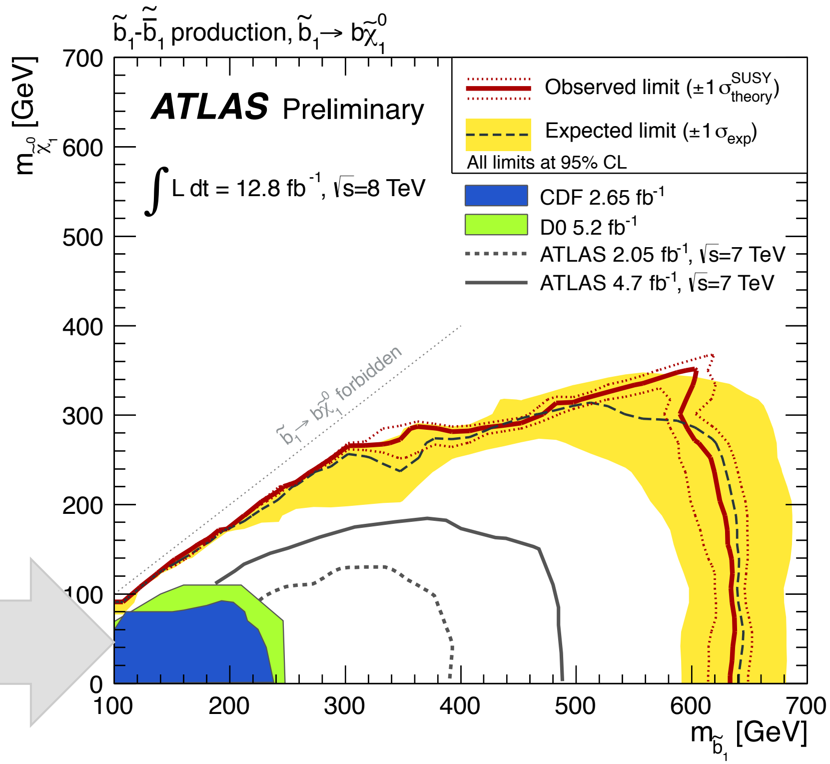
We went a long way

...since the Tevatron searches

D0 1005.2222, ATLAS-CONF-2012-109

b-jets + MET searches for sbottom pair production at D0 and ATLAS





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We went a long way

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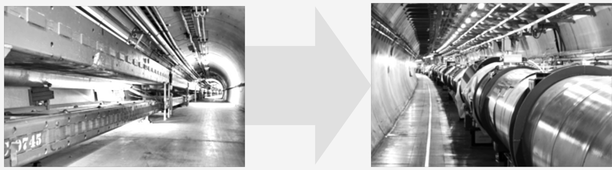
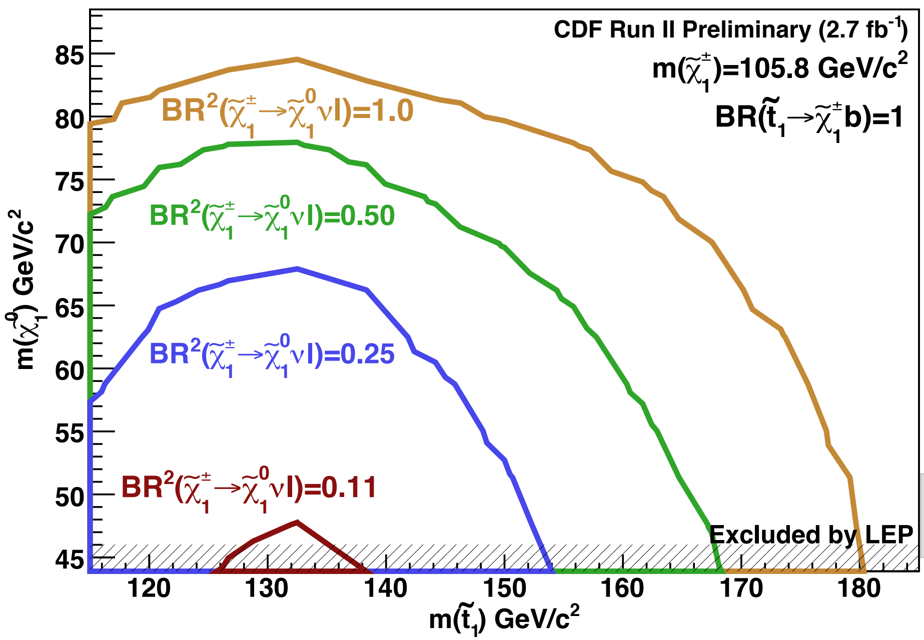


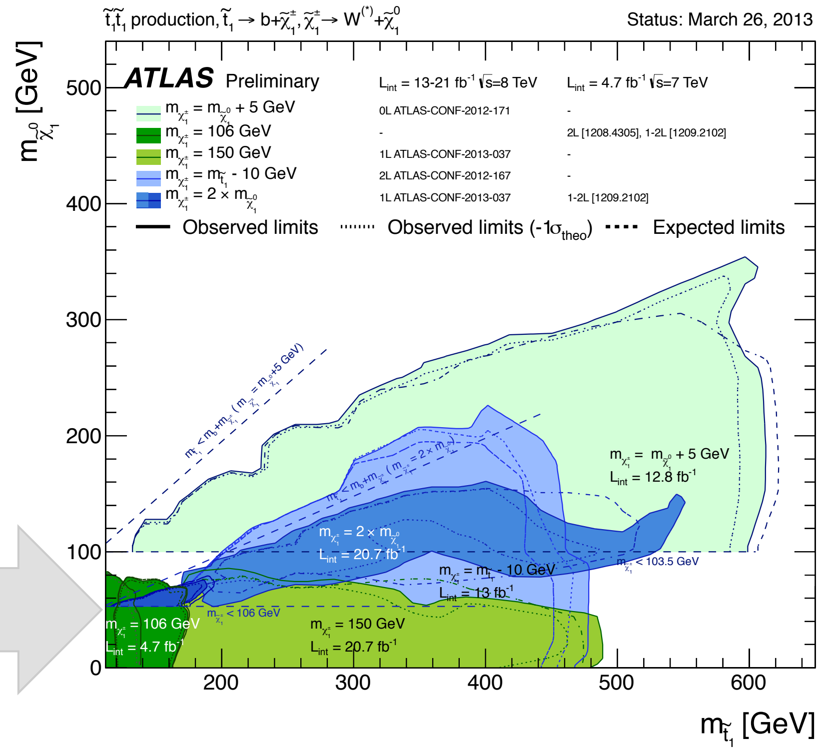
CDF note-9439, ATLAS preliminary

Searches for pair production of light stops to *b* + C1 at CDF and ATLAS

(Stop decay to top+LSP not accessible at Tevatron)

Observed 95% CL limits





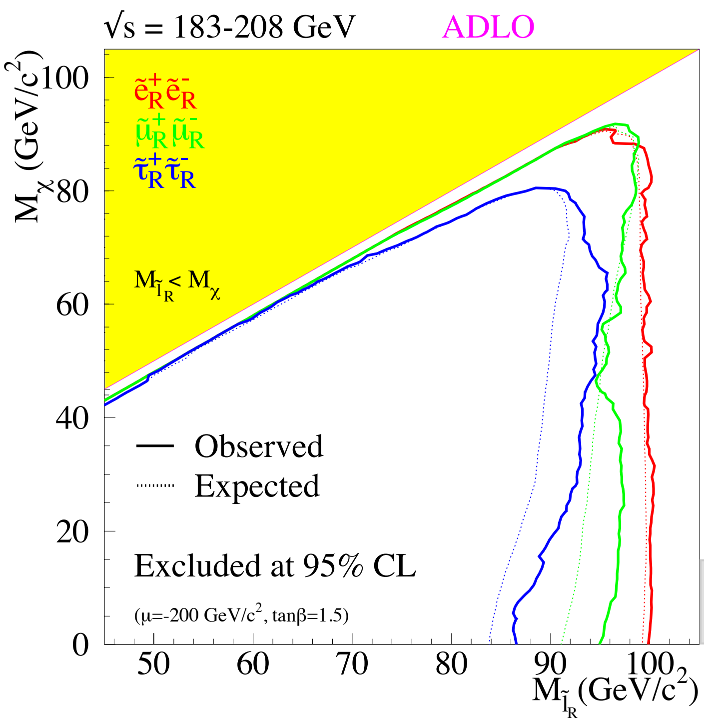
Slide inspired by Giacomo Polesello, ATLAS-SUSY workshop, Apr 2013

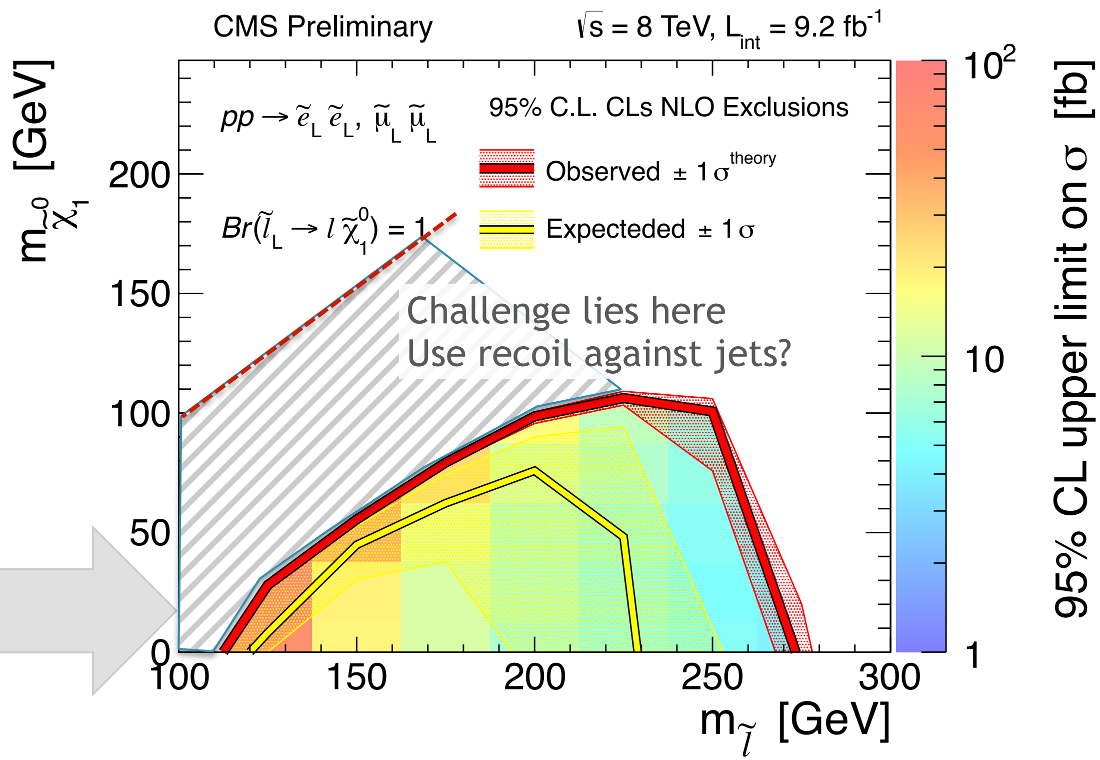
We went a long way

…since the LEP searches

LEP-SUSY WG, CMS-PAS-SUS-12-022

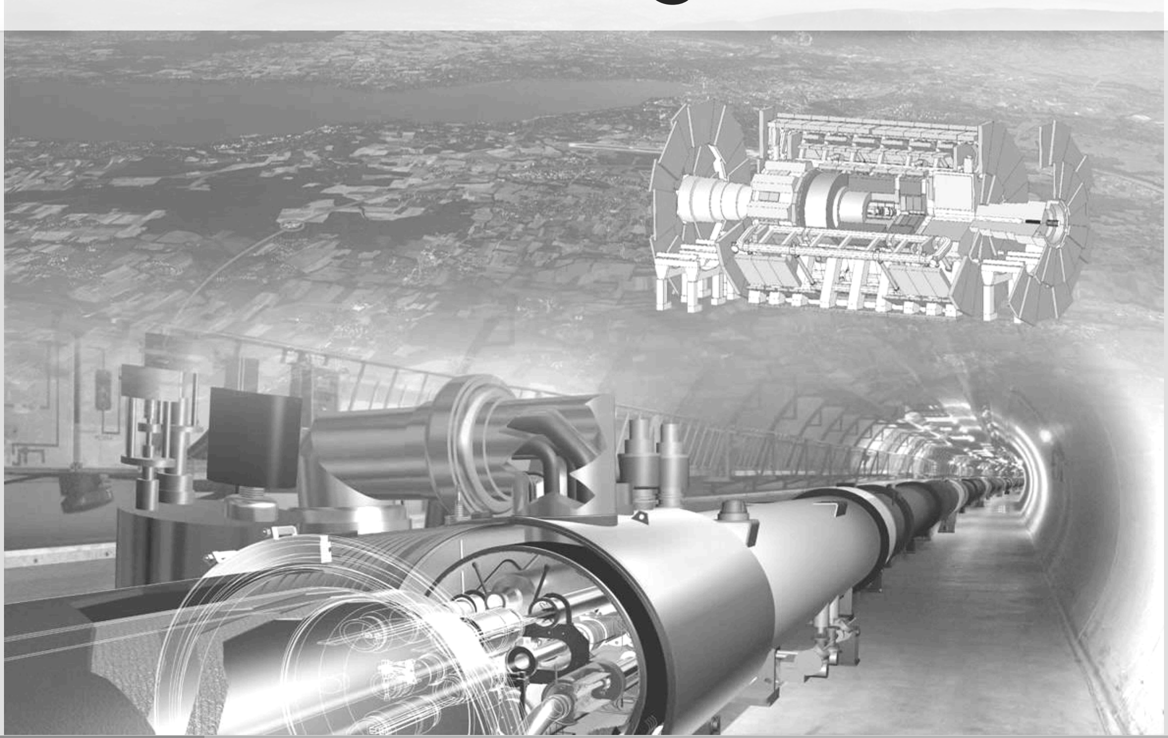
Slepton limits at LEP and CMS.
Beating LEP is hard, but expanded reach!





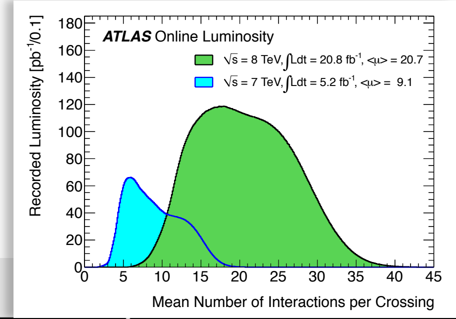
Slide inspired by Giacomo Polesello, ATLAS-SUSY workshop, Apr 2013

Mastering the LHC environment & understanding the data



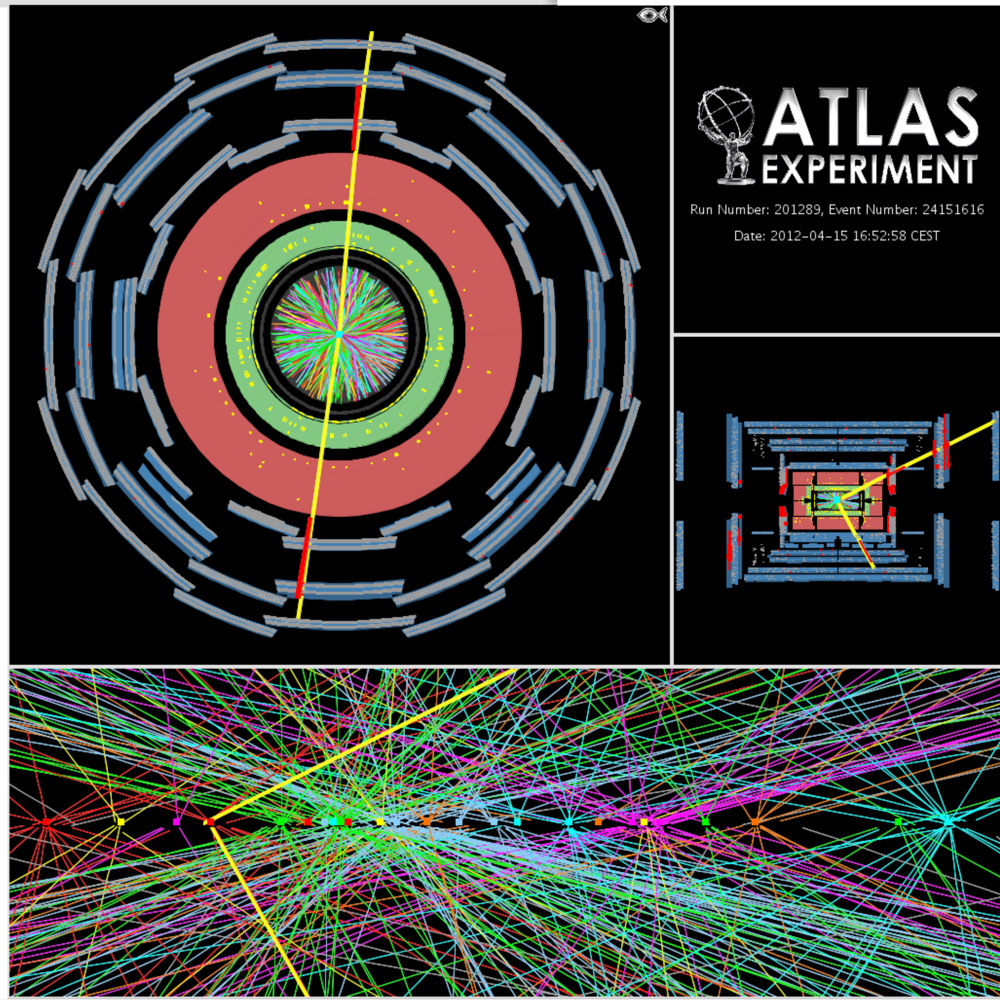
Pileup in 2012

<Average> of 21 (2012), 9 (2011)



In general, do not expect a significant impact on tracking, nor muons, nor even electrons and photons

However, sizable impact on jets, E_T^{miss} and tau reconstruction as well as on trigger rates and computing



$Z \rightarrow \mu\mu$ event in ATLAS with 25 reconstructed vertices
Display with track p_T threshold of 0.4 GeV and all tracks are required to have at least 3 Pixel and 6 SCT hits

Data taking efficiency

Continued excellent performance of detector, trigger and reconstruction

Average data taking efficiency: ~93%

- Deadtime is dominant inefficiency source (~4%)

Stable detector performance

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

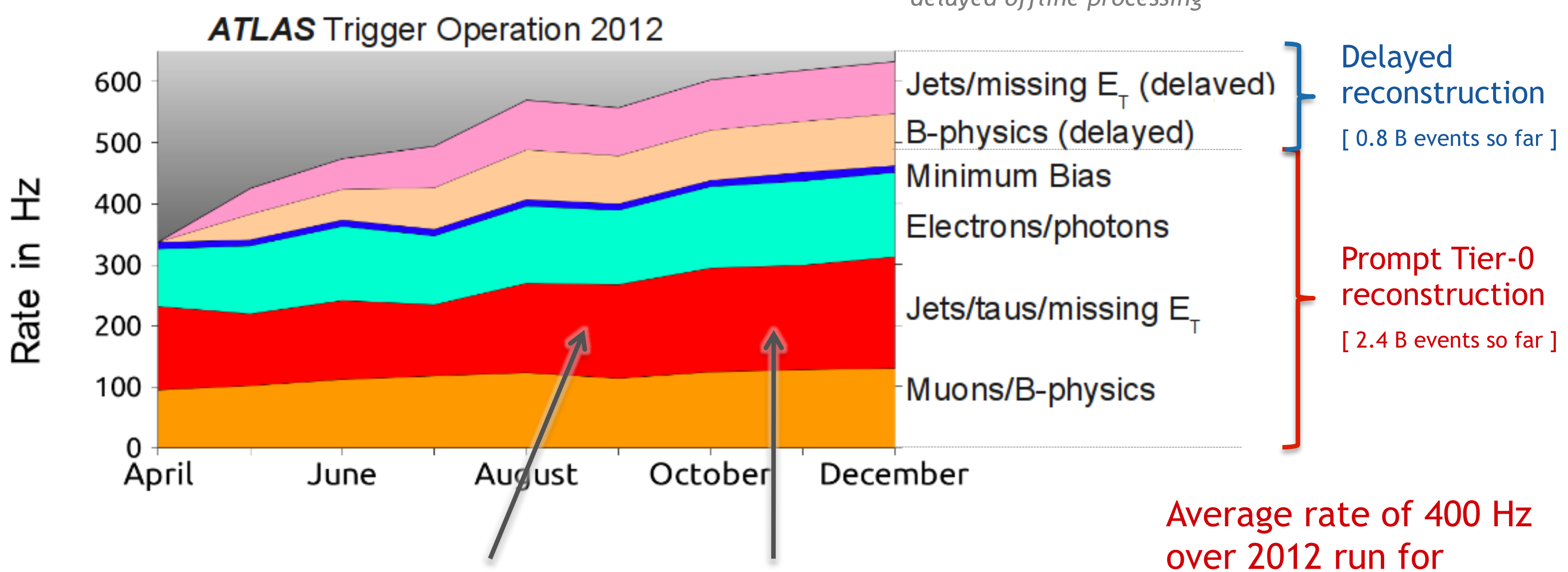
Total efficiency (delivered → physics analysis): ~89%

2012 Trigger

Baseline menu designed for $L = 8 \times 10^{33}$ cm^{-2}s^{-1} and mostly unchanged during 2012 run

Average trigger rate during stable beam:

Spare DAQ capacity used for lower priority triggers with delayed offline processing



Additional / looser E_T^{miss} & tau as well as VBF triggers added to increase sensitivity for 125 GeV Higgs in *bb* and $\tau\tau$ modes

Average rate of 400 Hz over 2012 run for prompt trigger streams

(~1700 stable beam hours)

Primary triggers in 2012

★ *Looser selection available later in 2012 data in either prompt or delayed streams*

Signature	Offline selection	Trigger selection L1	Trigger selection EF		L1 Peak (kHz) $L_{peak} = 7\times10^{33}$	EF Ave (Hz) $L_{ave} = 5\times10^{33}$
Single leptons	Single muon $p_T > 25$ GeV	15 GeV	24 GeV		**8**	**45**
	Single electron $p_T > 25$ GeV	18 GeV	24 GeV		**17**	**70**
Two leptons	2 muons $p_T > 6$ GeV	$2 \times 6(4_{EOF})$ GeV (also 2mu4 barrel only)	2×6 GeV		**3**	**2**
	2 muons $p_T > 15$ GeV 2 muons $p_T > 20,10$ GeV	2×10 GeV 15 GeV	2×13 GeV 18,8 GeV		**1** **8**	**5** **8**
	2 electrons, each $p_T > 15$ GeV	2×10 GeV	2×12 GeV		**6**	**8**
	2 taus $p_T > 45, 30$ GeV	15,11 GeV	29,20 GeV	★	**12**	**12**
Two photons	2 photons, each $p_T > 25$ GeV 2 loose photons, $p_T > 40,30$ GeV	2×10 GeV 12,16 GeV	2×20 GeV 35, 25 GeV		**6** **6**	**10** **7**
Single jet	Jet $p_T > 360$ GeV	75 GeV	360 GeV	★	**2**	**5**
E_T^{miss}	$E_T^{miss} > 120$ GeV	40 GeV	80 GeV	★	**2**	**17**
Multi-jets	5 jets, each $p_T > 60$ GeV 6 jets, each $p_T > 50$ GeV	4×15 GeV	5×55 GeV 6×45 GeV	★	**1**	**8**
b-jets	*b* + 3 other jets $p_T > 45$ GeV	4×15 GeV	4×45 GeV + *b*-tag		**1**	**4**
TOTAL					**< 75**	**~ 400 (ave)**

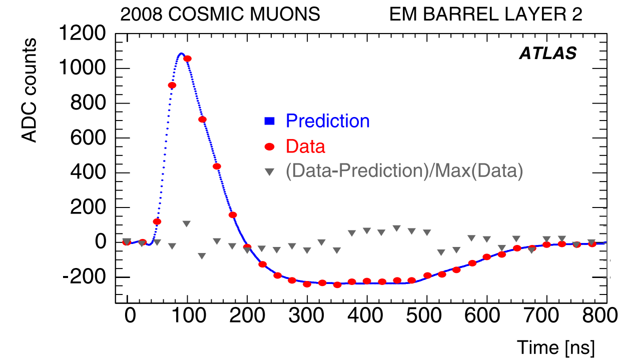
Stability of electron energy response versus pileup

With bipolar LAr pulse shape bunch-integrated pileup contribution cancels*

**Designed for 25 ns bunches and uniform bunch luminosity*

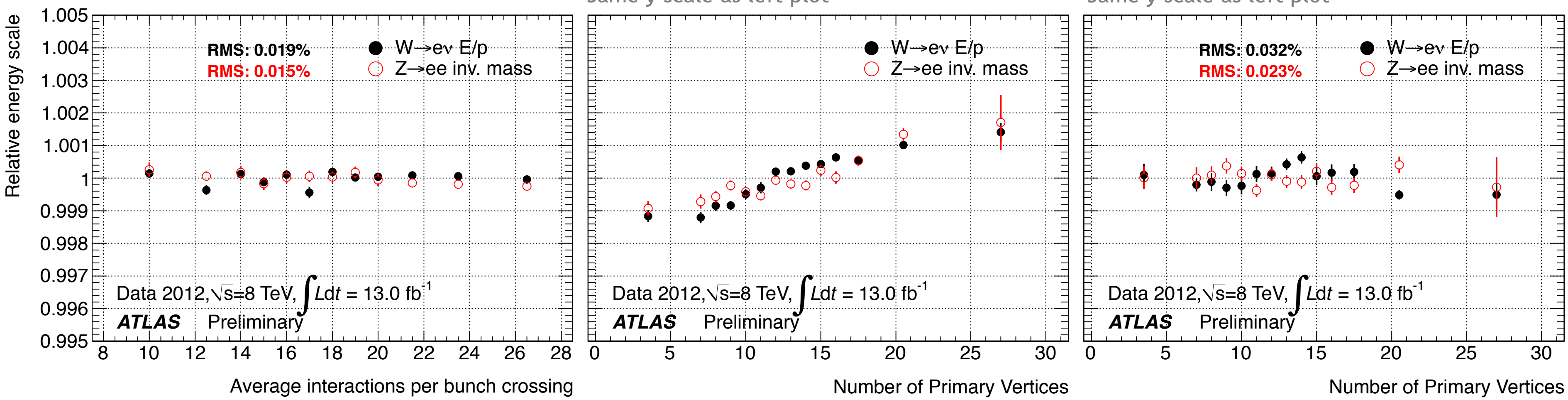
Reconstructed e energy in $Z \to ee$ and $W \to e\nu$ (E/p)

- Left plot: relative stability versus <μ> better than 0.1%
- Center: however, energy rise versus *number of vertices* seen: expected from in-time versus out-of time selection bias
- Right: data / MC ratio: effect well reproduced by simulation



Same y scale as left plot

Same y scale as left plot



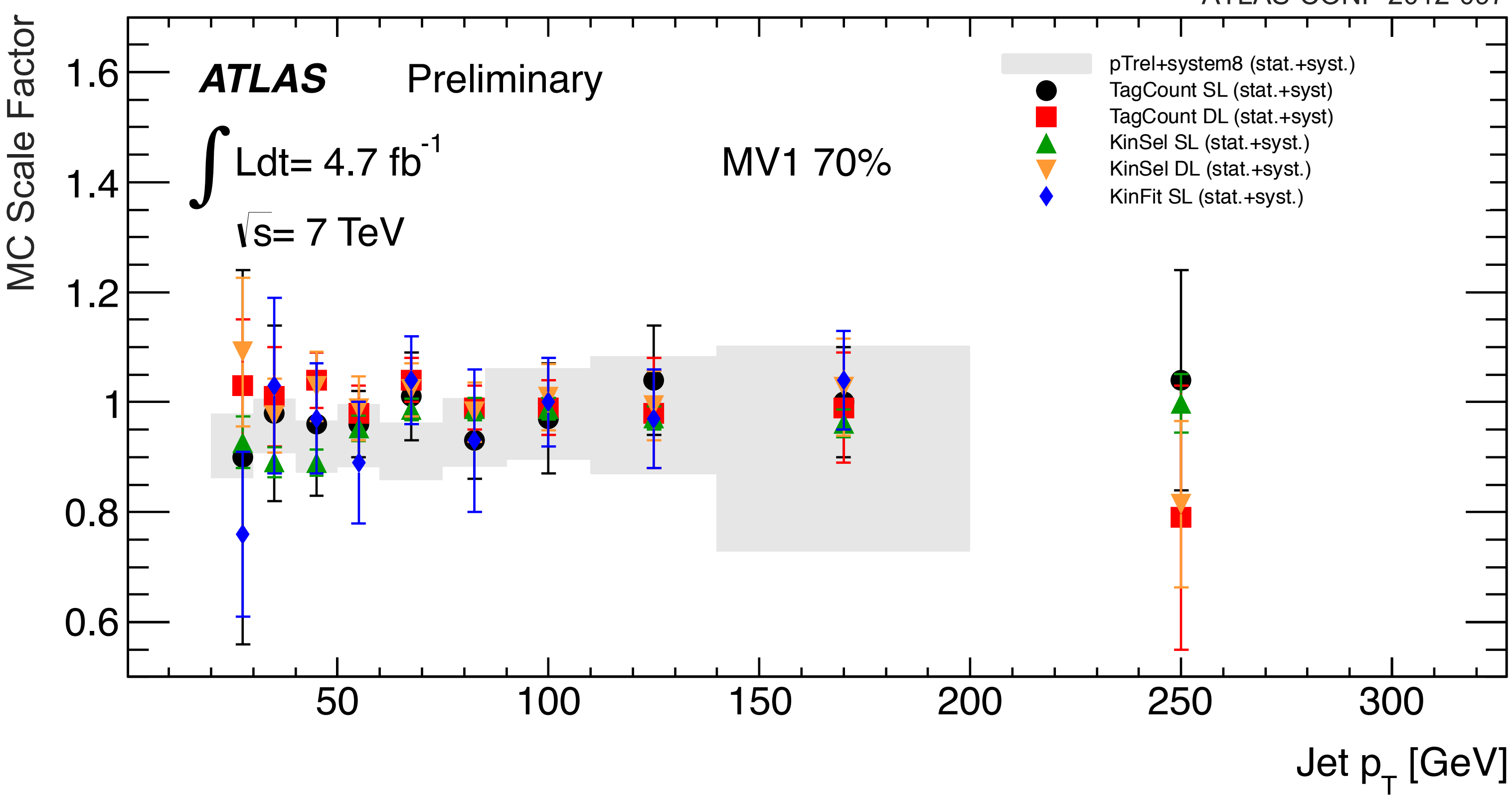
Flavour tagging

Understanding of *b*-tagging efficiencies crucial for many analyses (SM, $H \to bb$, *searches*)

Default tagger: 'MV1' neural network using other taggers as input

Several methods available to determine *b*-tagging efficiency versus *b*-jet p_T. Compatible results found among all of them, including those using *tt* and dijet events

ATLAS-CONF-2012-097



Comparison of all *tt*-based scale factors with the combined scale factors from the *System8* and *pTrel* calibration methods [see: ATLAS-CONF-2011-089]

Scale factors close to unity, systematic uncertainties between 5% and 15% versus p_T

Jet energy scale, resolution and pileup

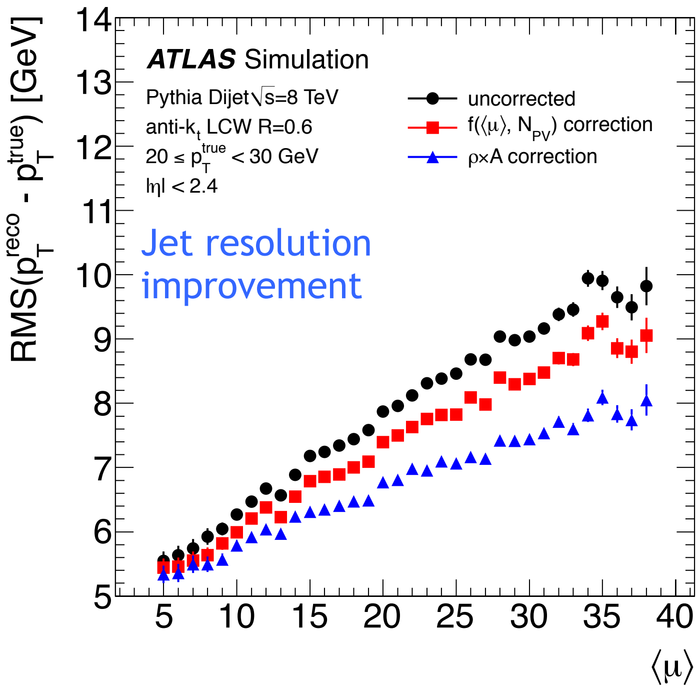
Pileup dependence from soft activity in calorimeter

Cacciari-Salam, 0707.1378

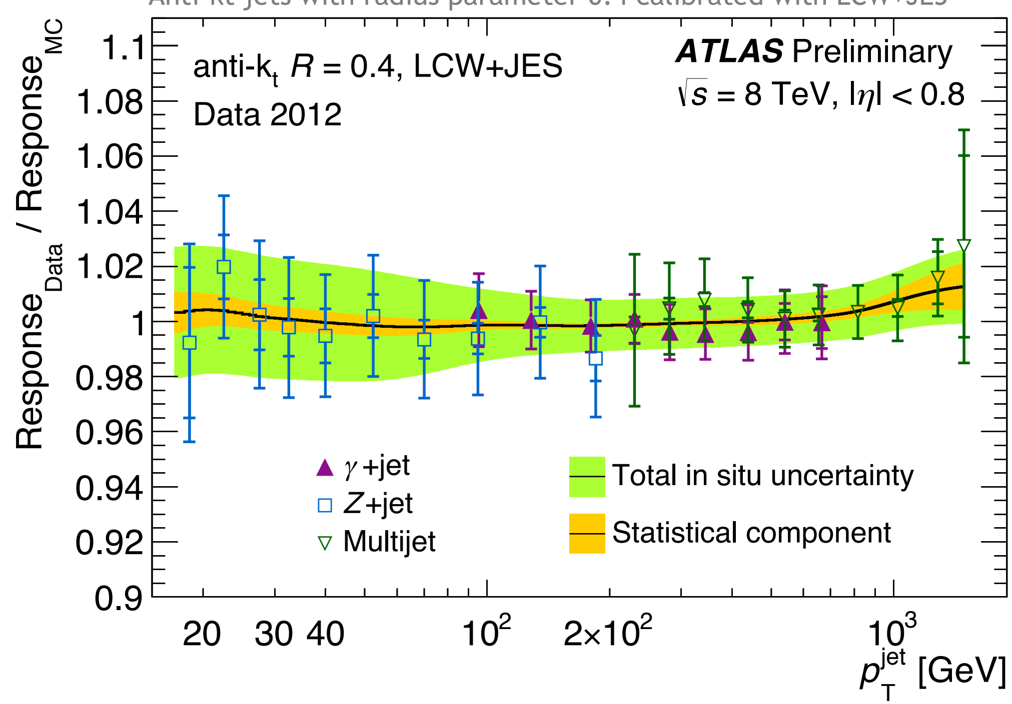
Subtract pileup contribution based on jet area, event-by-event: $p_T^{\text{jet,corr}} = p_T^{\text{jet}} - \rho \cdot A_T^{\text{jet}}$

Residual correction to compensate for noise suppression, occupancy and out-of-time pileup

- Reduces event-by-event pileup fluctuations → *improved jet energy resolution*
- Reduced reliance on MC for pileup corrections → *Smaller systematic uncertainty*



Anti-kt jets with radius parameter 0.4 calibrated with LCW+JES

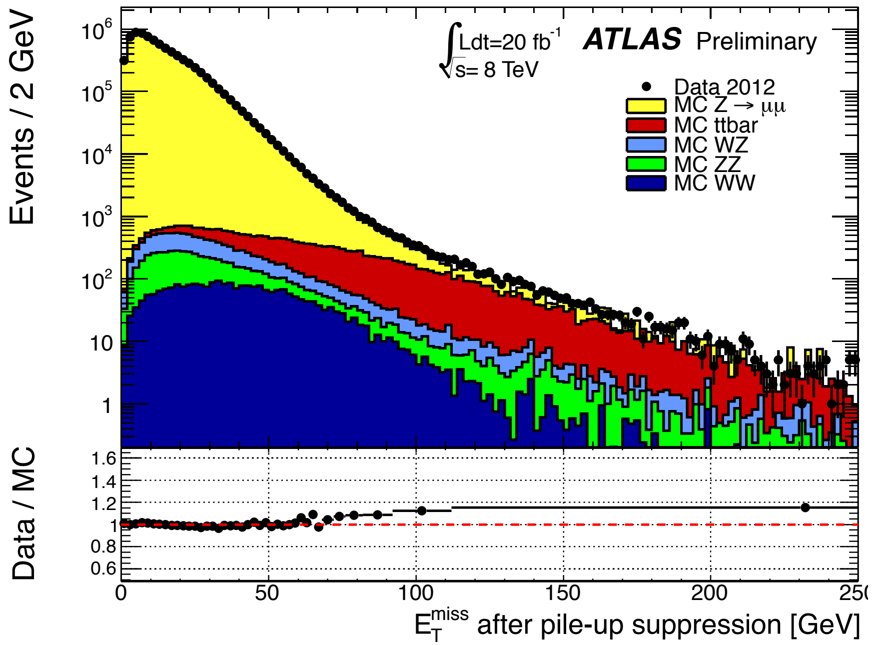


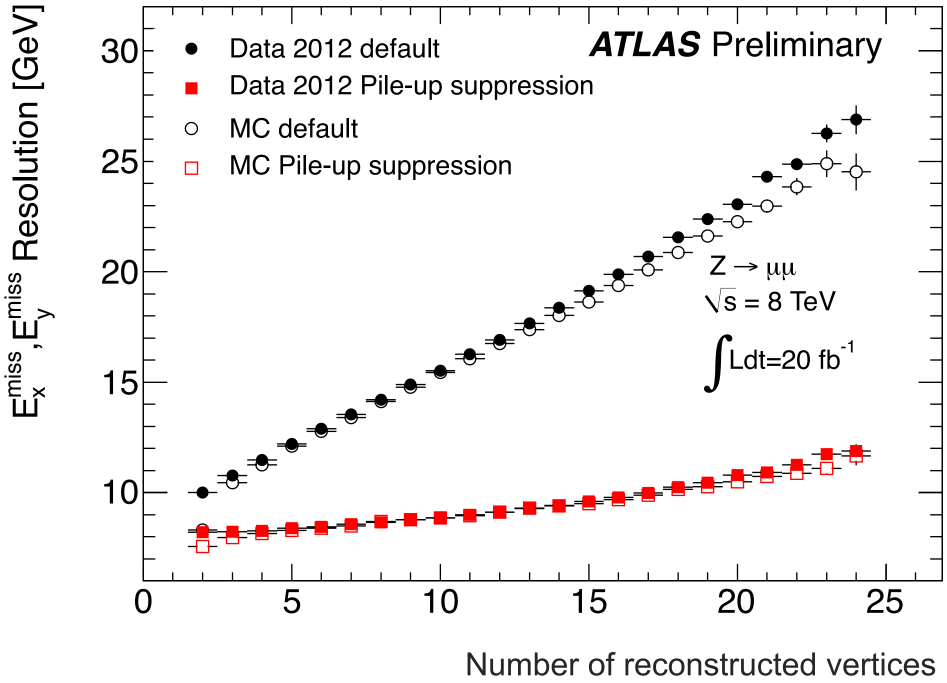
E_T^{miss} reconstruction versus pileup

Pileup dependence from soft activity in calorimeter

E_T^{miss} in Z → μμ events after pileup suppression with STVF+JVF

Jet objects have $p_T > 20$ GeV & |JVF|>0, corrected with jet area and calibrated. Soft contribution from LCW topoclusters and tracks, scaled with STVF (ratio of sum p_T of tracks associated to primary vertex and all tracks outside reconstructed objects).





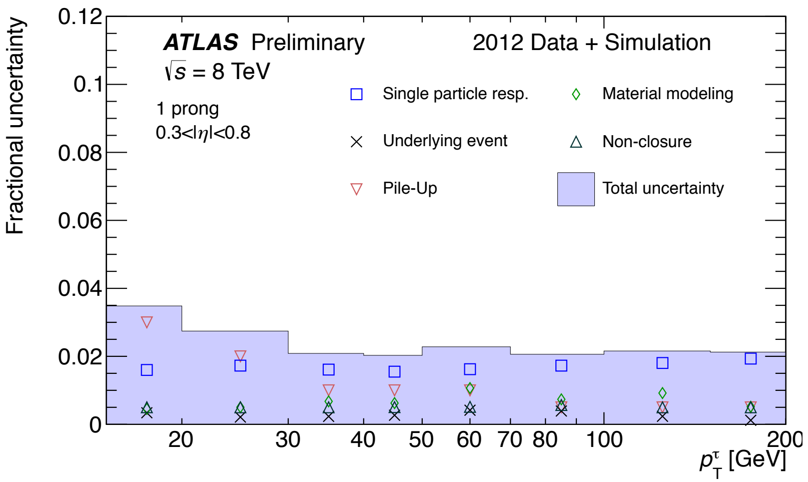
Tau reconstruction

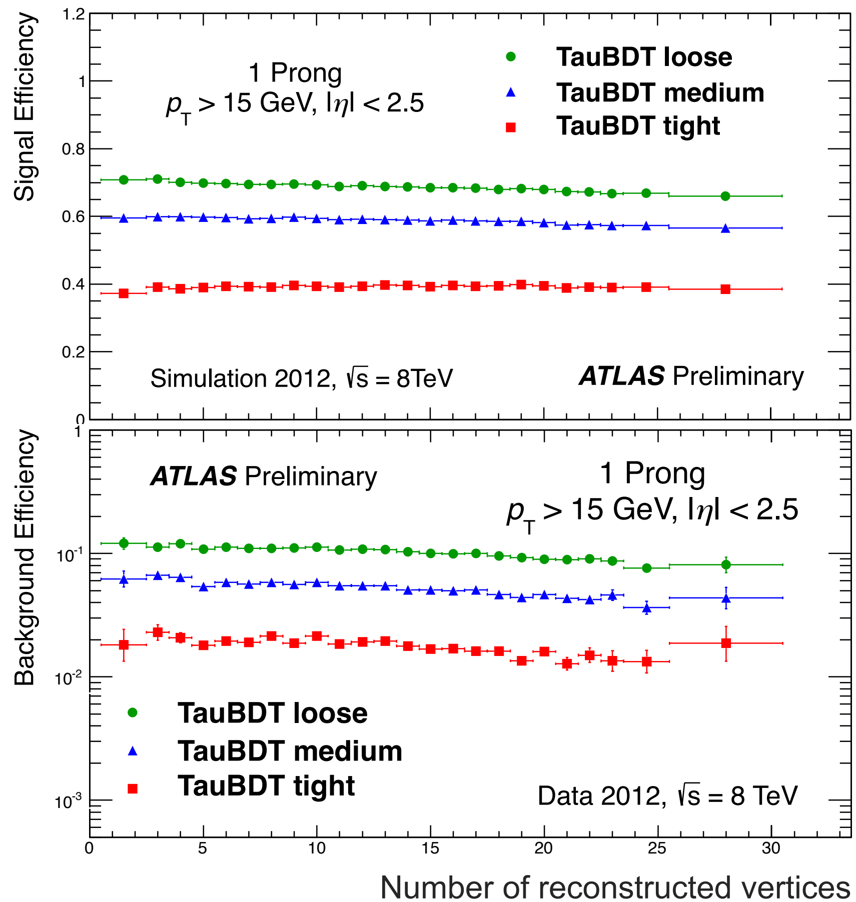
Tau reconstruction uses BDT combining tracking and calorimeter information

Tau reconstruction efficiency versus pileup (right) and tau energy scale uncertainty (bottom)

Tau energy scale (TES) uncertainty

For $p_T(\tau)$ > 20 GeV, δ(TES) ≤ 3% for 1-prong, ≤ 4% for multi-prong, verified with $Z \rightarrow \tau\tau$





Efficiencies predicted by PYTHIA8 MC

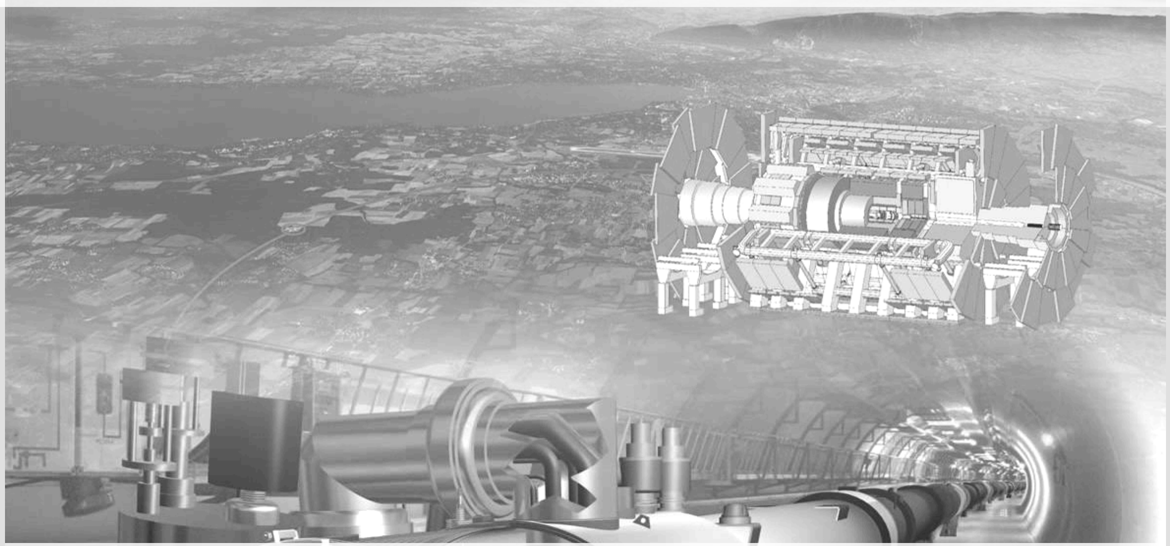
Tested in data with $Z \rightarrow \tau\tau$ tag-and-probe analysis

Background efficiencies measured in dijet data samples

Small extract of results particularly relevant for SUSY searches shown

ATLAS Physics

Standard Model Measurements

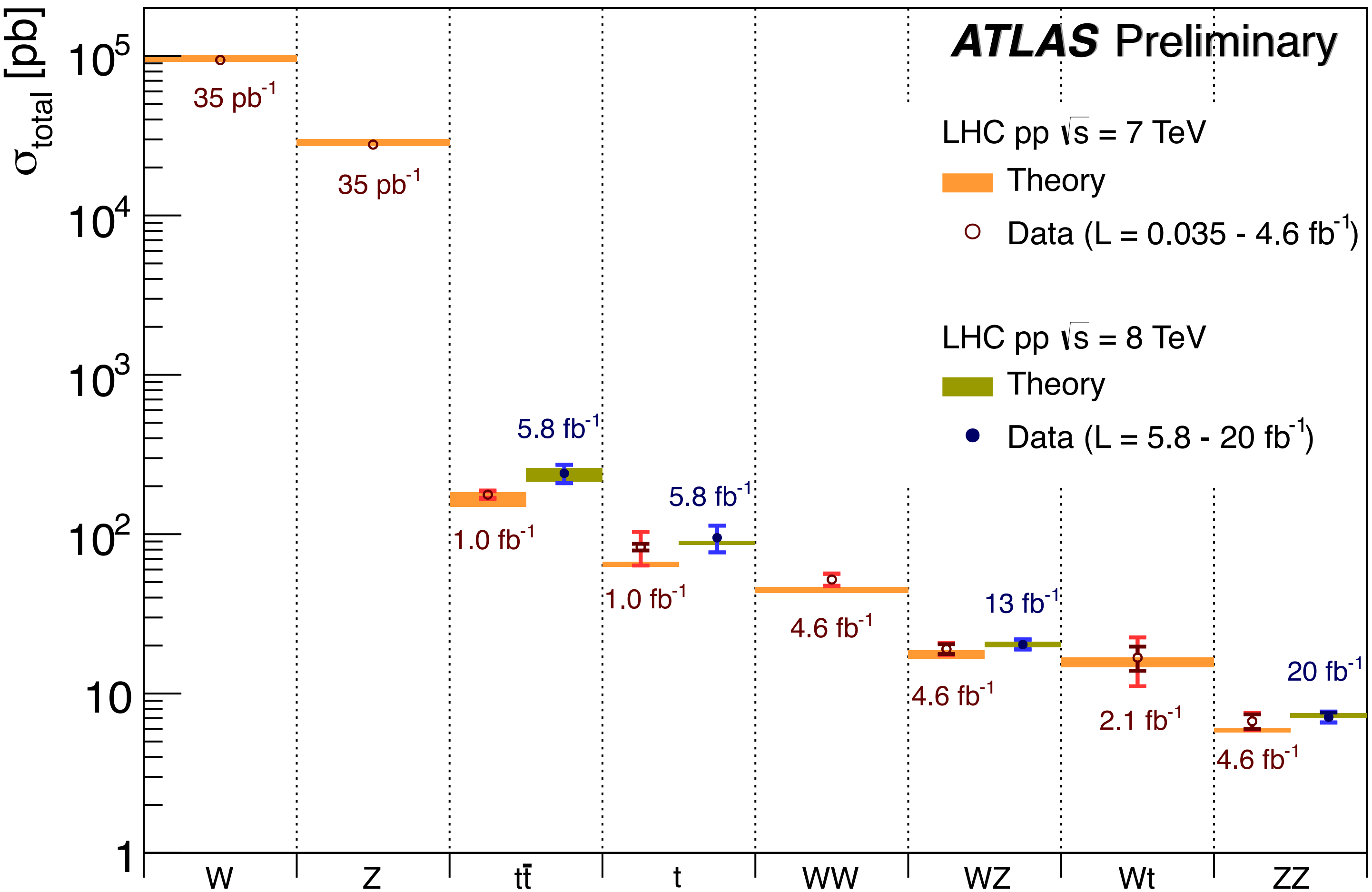


Available statistics allows to perform powerful fiducial and differential and cross-section measurements even in rare channels as dibosons

W, *Z* and top production — big picture

SM processes well understood over many orders of magnitude production rate

ATLAS 1304.7098



No hints for new physics

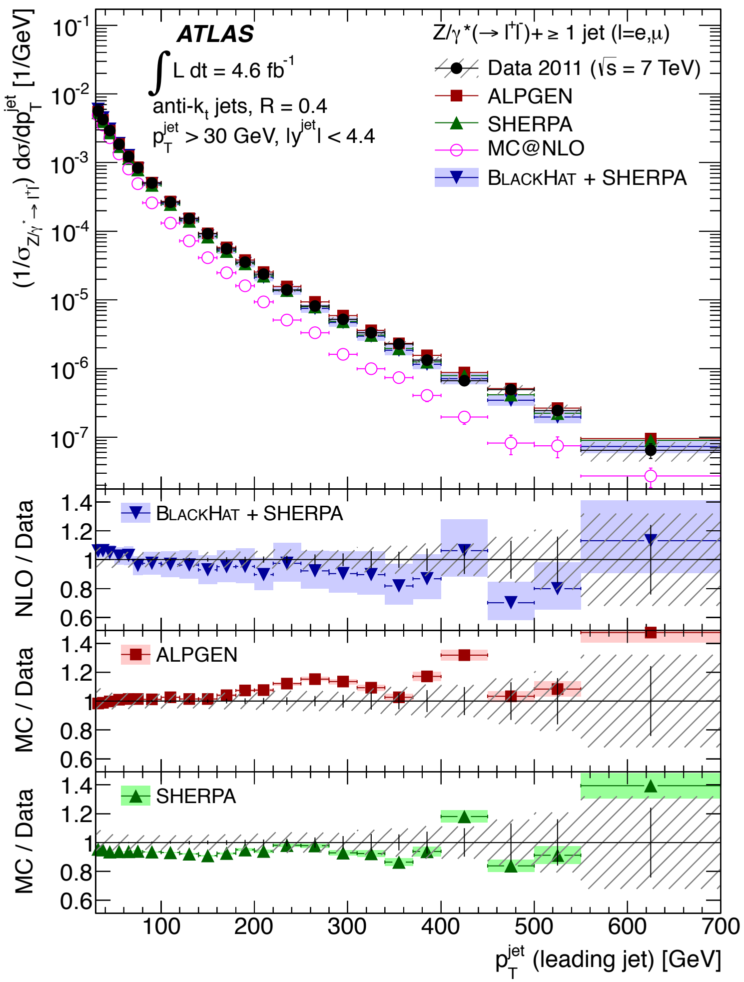
Slight overshoot in *WW* cross section, but not significant

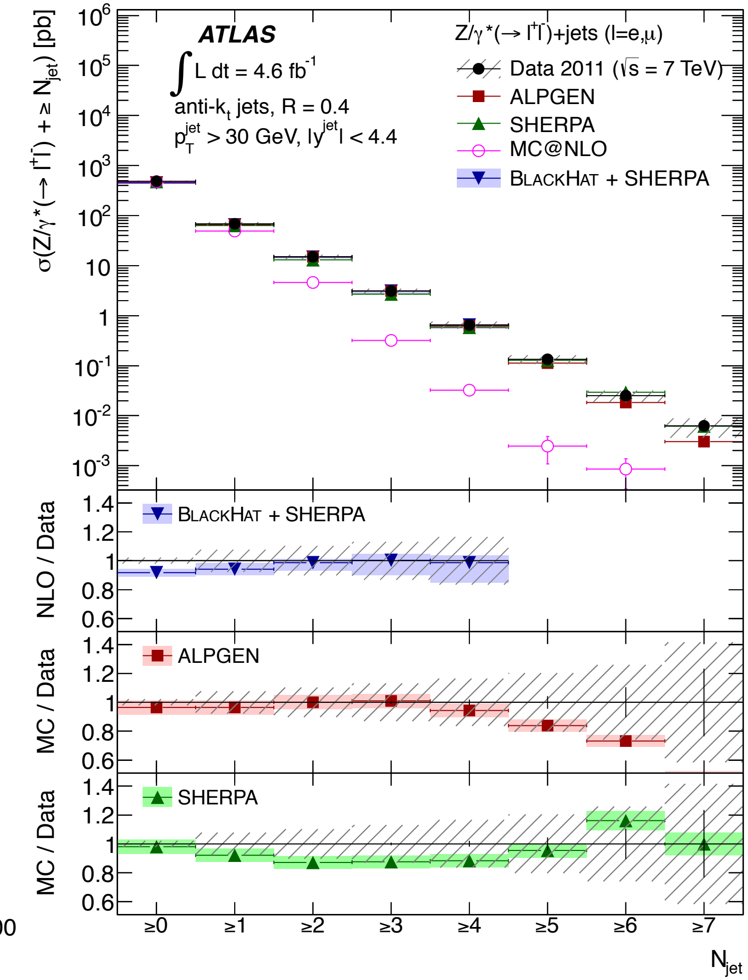
W and *Z* physics — differential measurements

Large statistics allows precise tests of generators/theory, PDFs and bkg to searches

ATLAS 1304.7098

Measurement of *Z* + jets production





Satisfying agreement for multileg generators.

Improved for MEnloPS.

Insufficient jet emission for MC@NLO + PS (Herwig)

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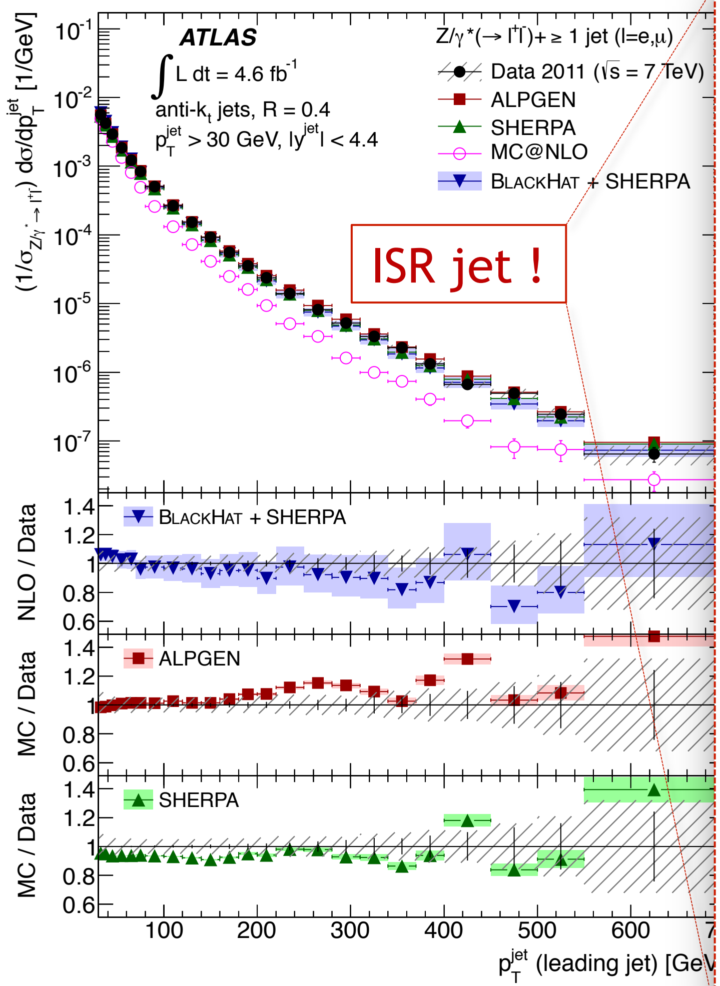
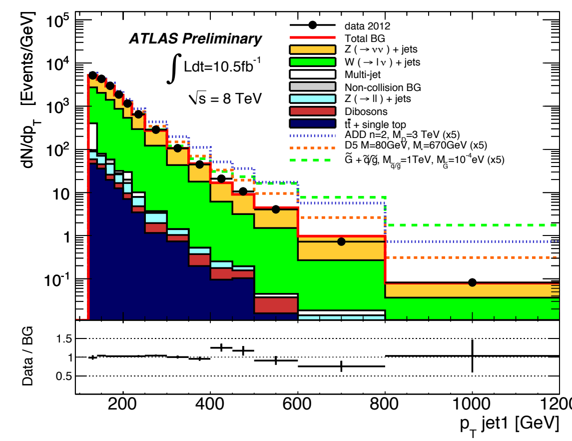


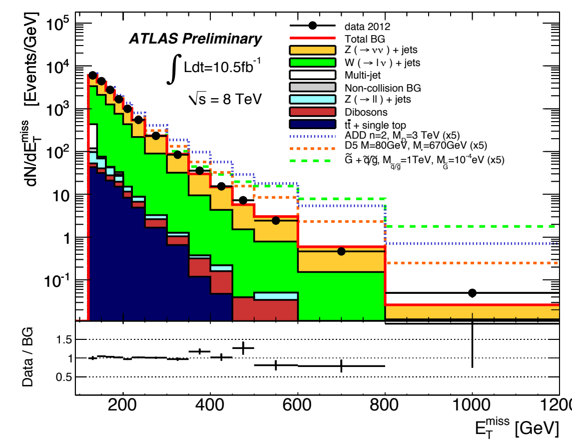
Satisfying agreement for multileg generators.

Improved for MEnloPS.

Insufficient jet emission for MC@NLO + PS (Herwig)

Satisfying understanding of leading ISR jets also reproduced in monojet analysis



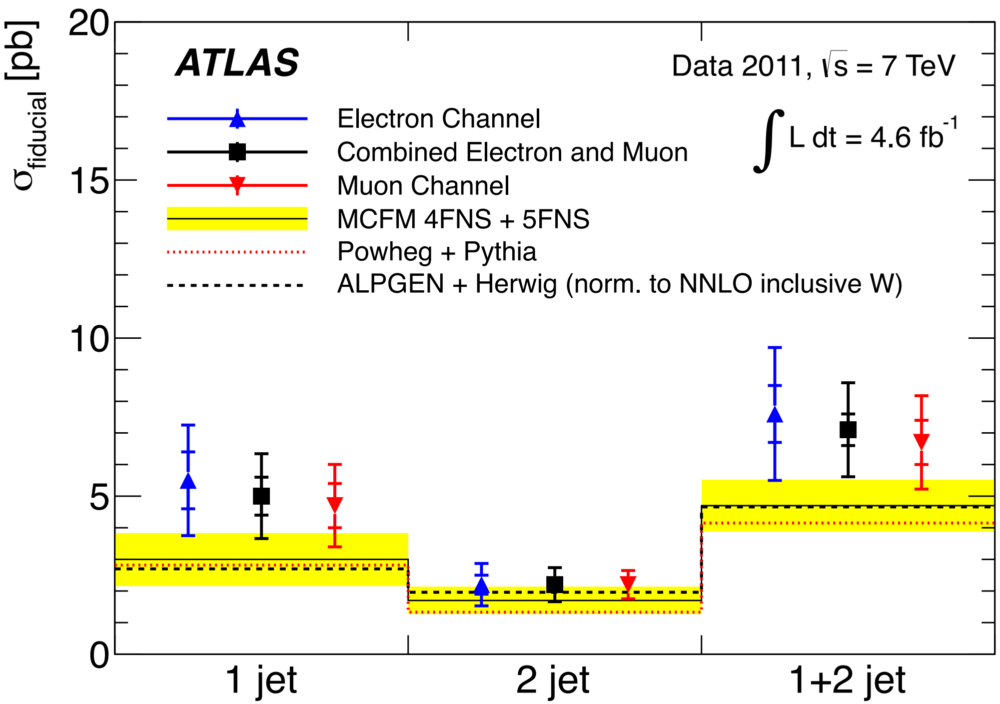


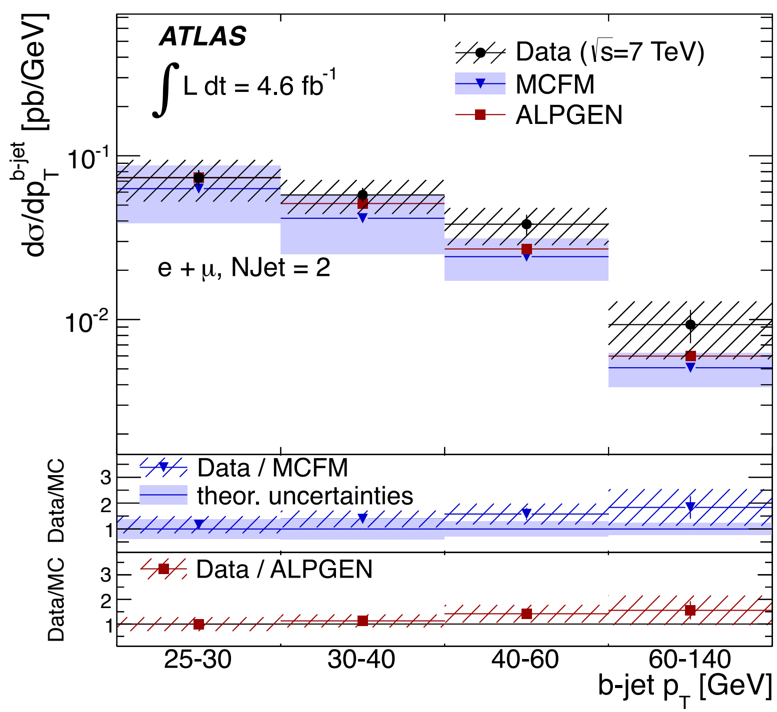
W and *Z* physics — differential measurements

Large statistics allows precise tests of generators/theory, PDFs and bkg to searches

ATLAS 1302.2929

Measurement of *W* + *b*-jets fiducial (p_T > 25 GeV, $|\eta|$ < 2.1) & differential cross section





Fiducial cross section within 1.5σ of theory prediction

p_T spectrum harder in data, but compatible within uncertainties with generators

Diboson physics: *WW*, *WZ*, *ZZ*, *Wγ*, *Zγ*, *γγ*

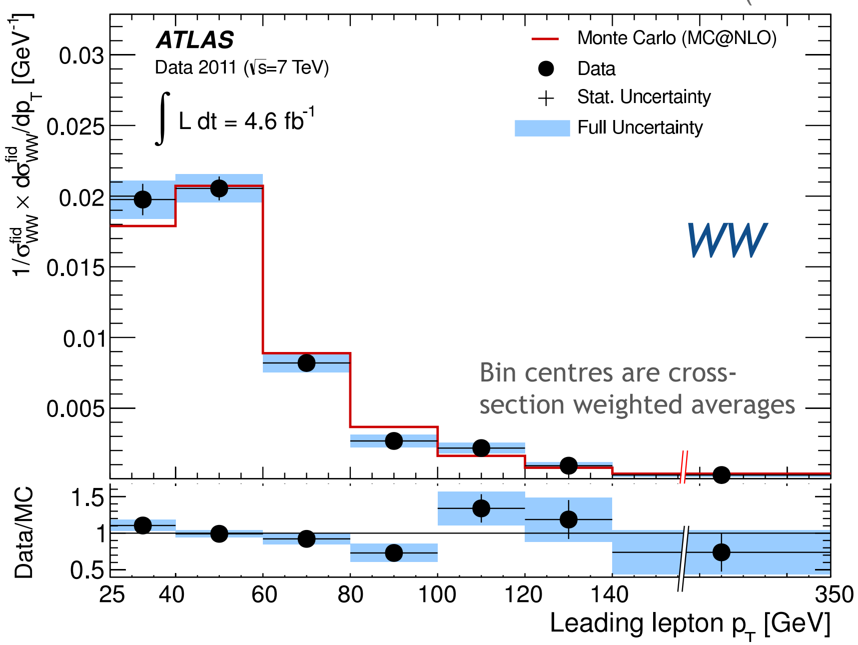
ATLAS performed total, fiducial & differential diboson cross-sections measurements

Measured 11 diboson fiducial cross-sections: most are slightly above theory expectation (but syst. and theo. errors correlated)

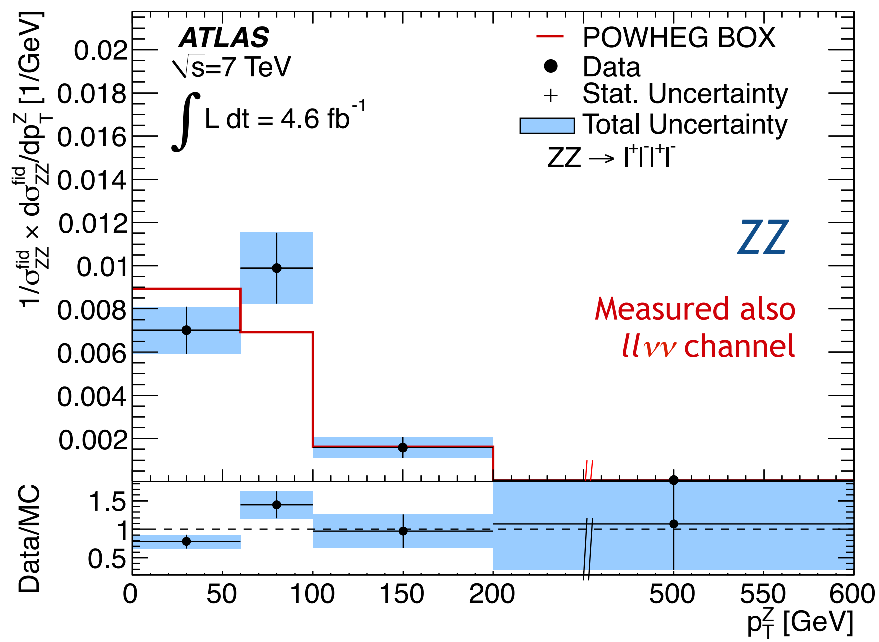
ATLAS 1210.2979, 1208.1390, 1211.6096

Examples for differential cross section measurements: *WW*, *ZZ* (7 TeV, 4.6 fb^{-1})

Normalised fiducial differential cross-section (→ unfolded)



Normalised fiducial differential cross-section



- So far, satisfying agreement with NLO generators, also for mass spectra. Same for *WZ*
- Also searched for diboson resonance production (*ZZ* [8 TeV, ATLAS-CONF-2012-150], *Wγ*, *Zγ*)

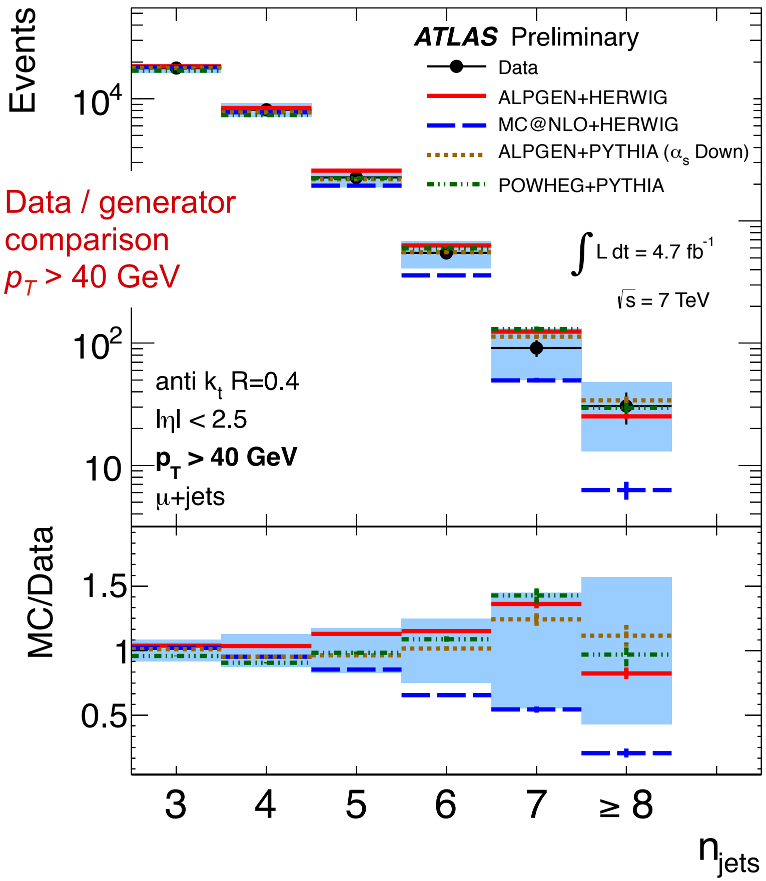
Top physics – differential measurements

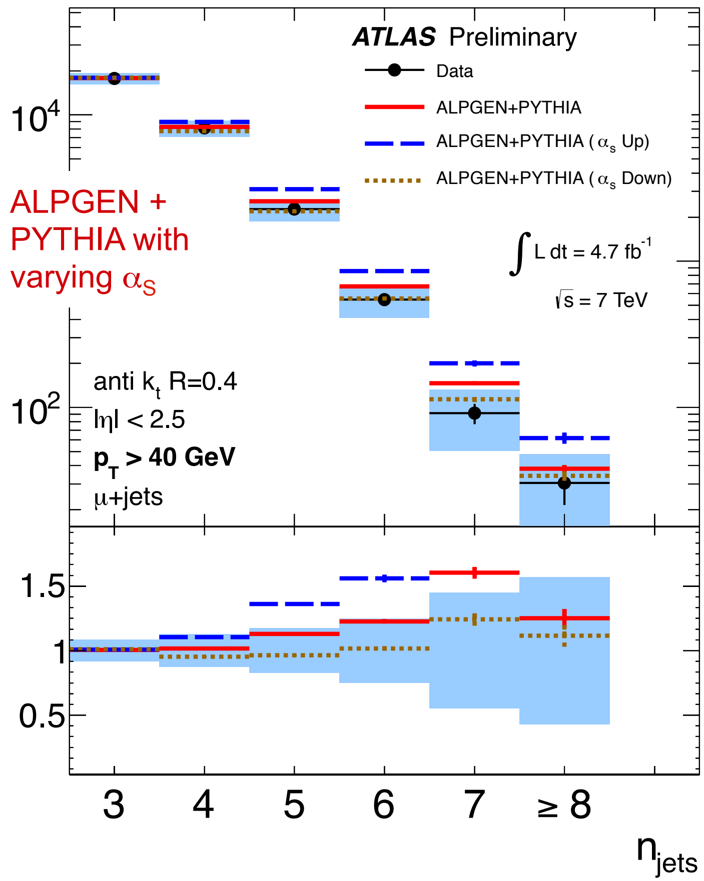
Top pairs in association with jets are dominant background for most SUSY searches

ATLAS-CONF-2012-155, see also: 1203.5015

Measurement of fiducial jet multiplicity in $t\bar{t}$ production (lepton+jets) at 7 TeV (4.7 fb^{-1})

MC scaled to approx. NNLO inclusive prediction (as always)





Rapidity gap fraction(*) measurements vs. $|y|$ help to assess uncertainties related to ISR/FSR

Variation of α_S and PS parameters describes ISR/FSR uncertainties

Q_0 is the fraction of events with no additional jet radiated within a considered rapidity interval

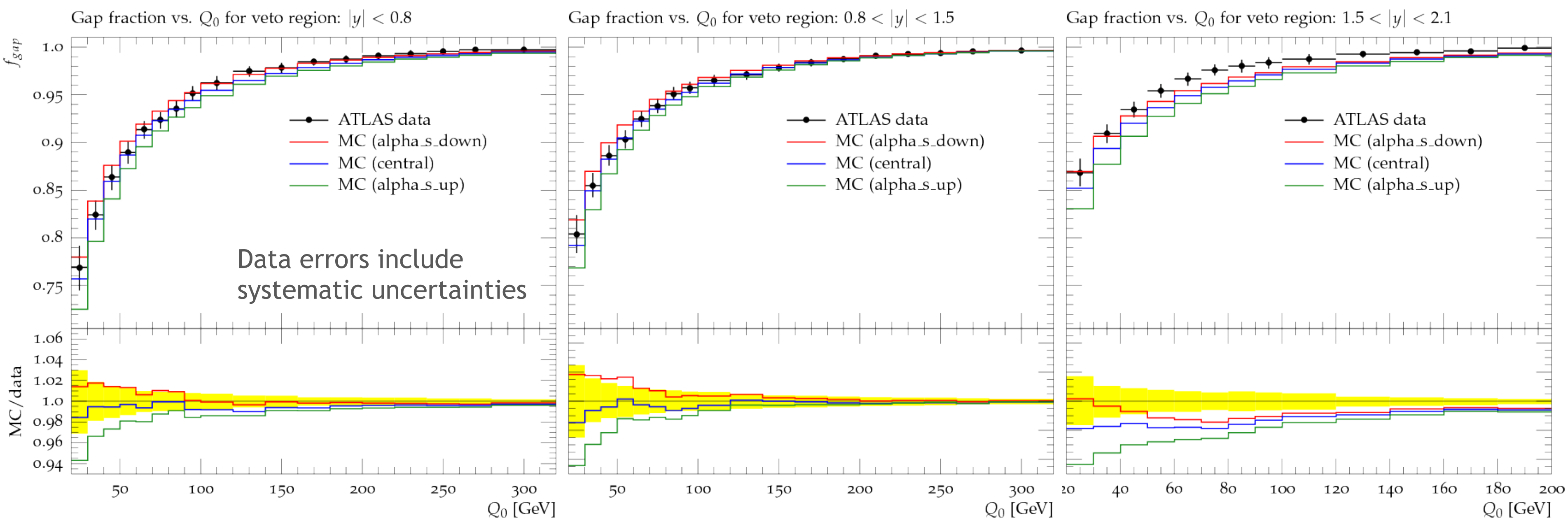
Top physics — differential measurements

Top pairs in association with jets probe ISR/FSR activity

ATLAS-CONF-2012-155, see also: 1203.5015

Rapidity gap fraction(*) measurements vs. |y| help to assess uncertainties related to ISR/FSR

ALPGEN+PYTHIA α_S up/down variations used in *tt* differential cross section measurement



Satisfying description for |*y*| < 1.5, but for large |*y*| too much jet activity predicted

* f_{gap} is the fraction of events with no additional jet radiated within a considered rapidity interval
Events are vetoed if they contain an additional jet with $p_T > Q_0$ in considered rapidity interval

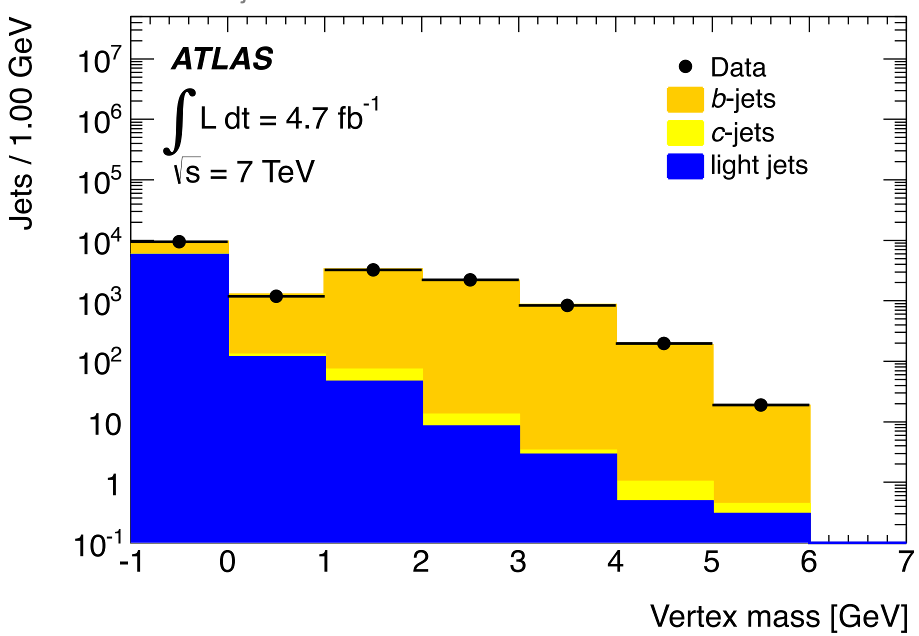
Top physics — differential measurements

Top pairs + *b*-jets are important background for gluino-med. stop/sbottom searches

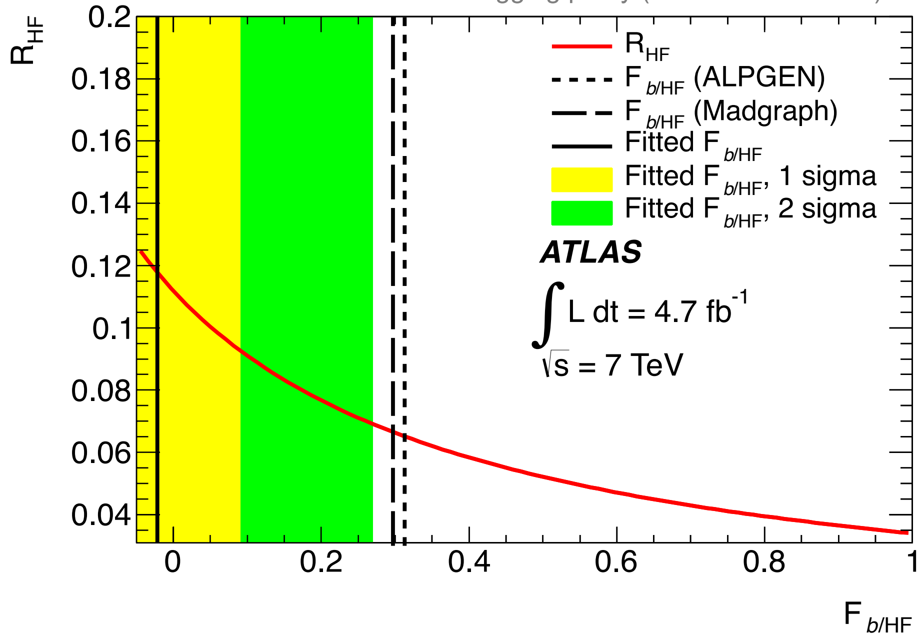
ATLAS-CONF-2012-155, see also: 1203.5015

Study of $t\bar{t}$ + *b*/*c*-jet ($t\bar{t}$ + HF) production at 7 TeV (4.7 fb^{-1})

A 2D template vertex mass vs. jet pT is used to discriminate between jet flavours



HF fraction in tt+jet sample determined from fit to 3 bins in vertex mass and 3 bins in b-tagging purity (total of 9 fitted bins)

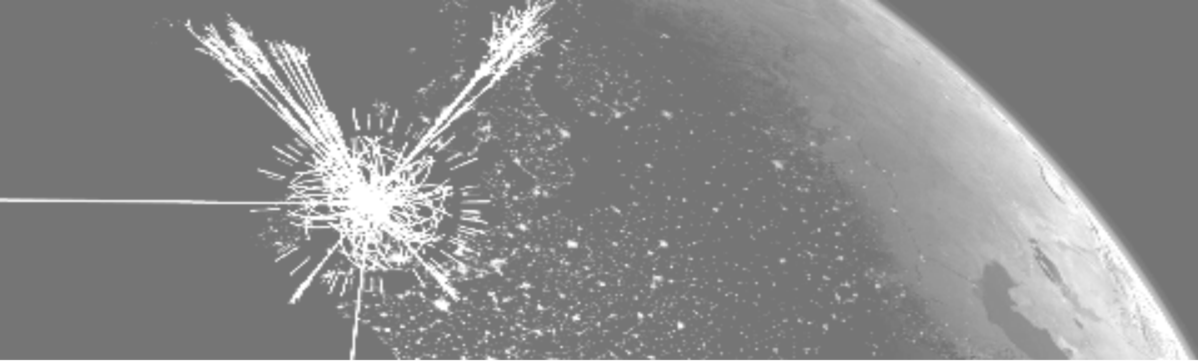


R_{HF}: Fiducial HF fraction in *tt* sample + jet with p_T > 25 GeV and |η| < 2.5

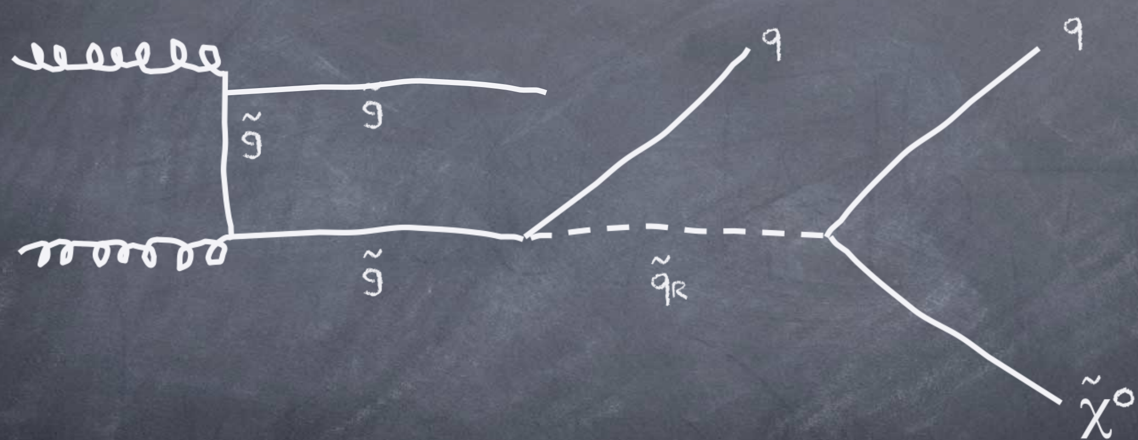
R_{HF} [$F_{b/HF}^{Alpgen}$] = 7.1 ± 1.3 (stat) + 5.3/−2.0 (syst) %

R_{HF} [SM, LO] = 3.4 ± 1.1 % (Alpgen+Herwig)

R_{HF} [SM, NLO*] = 5.2 ± 1.7 % (Powheg+Herwig)



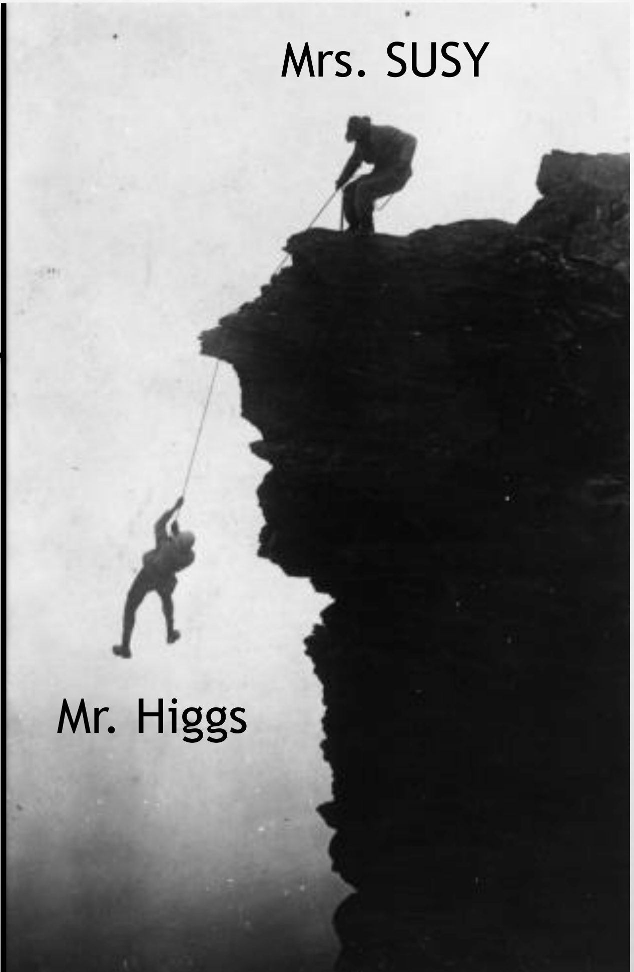
Searching for Supersymmetry



Not only that ! Very rich phenomenology

Broad and deep SUSY research programme in ATLAS

The scalar precipice



EW scale^{-1}

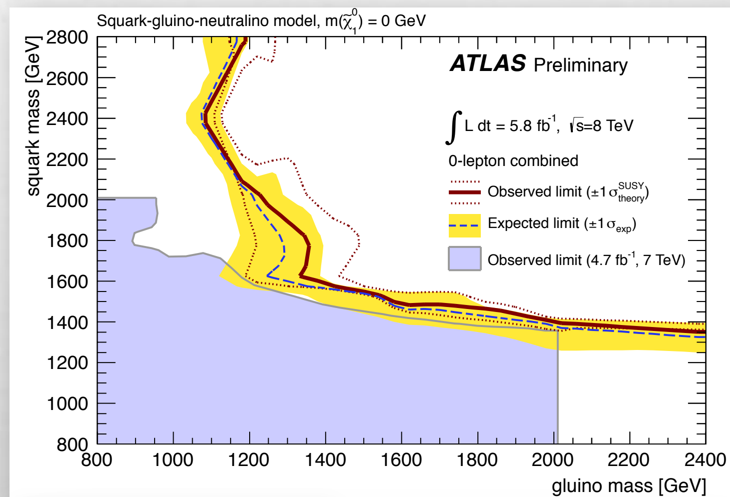
GUT scale^{-1}

Fundamental scalar length scale

After …

- 25 papers at 7 TeV with full 2011 statistics
- 22 preliminary 8 TeV results (8 with complete 2012 data)

No discovery yet …



ATLAS-CONF-2012-109

Limits from this model:

$$m(\tilde{q}) \approx m(\tilde{g}) < 1.5 \text{ TeV}$$

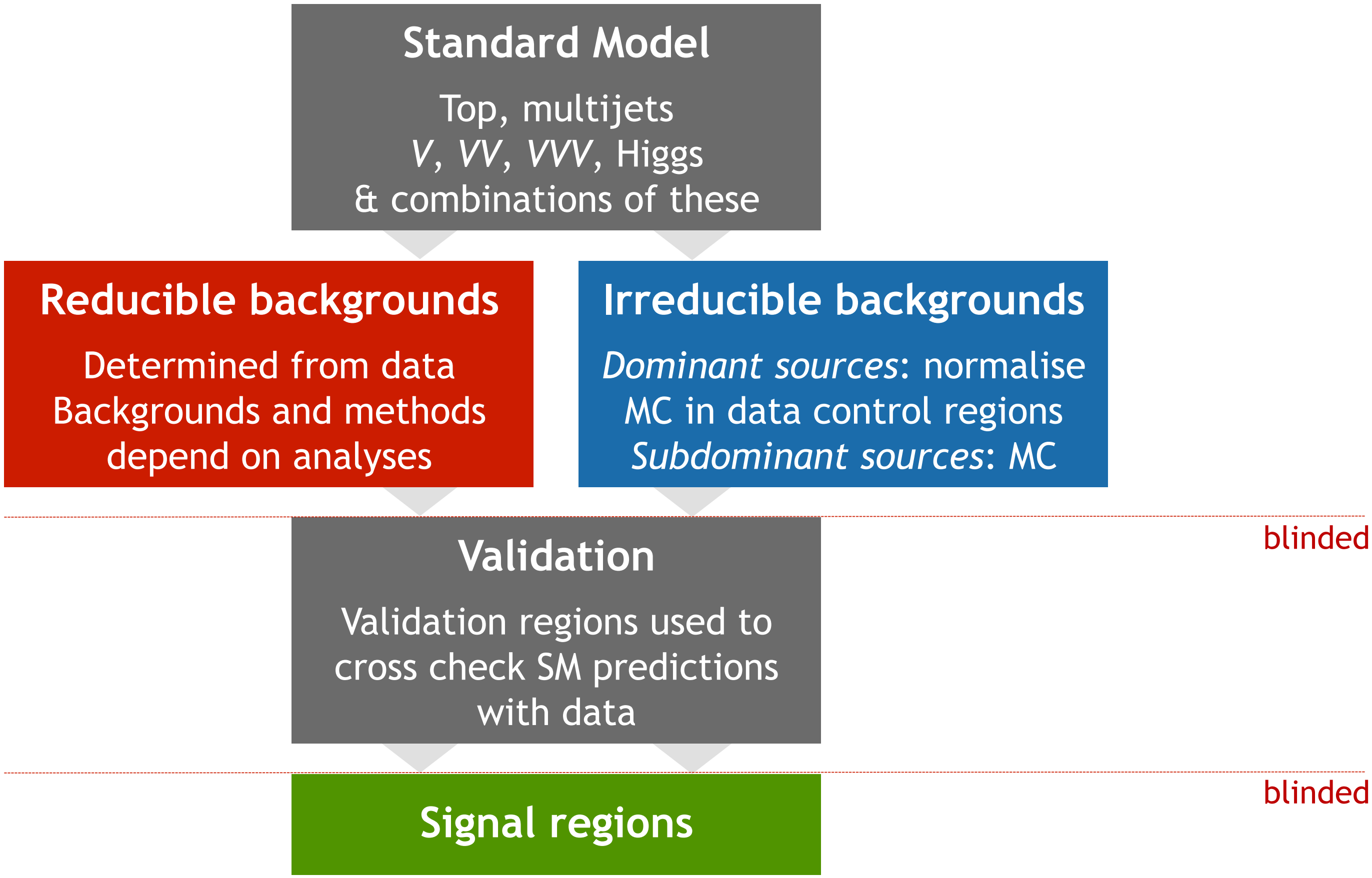
$$m(\tilde{q}) < 1.4 \text{ TeV } (\forall\ m(\tilde{g}) < 2 \text{ TeV})$$

$$m(\tilde{g}) < 1 \text{ TeV } (\forall\ m(\tilde{q}) < 2 \text{ TeV})$$

How do we search for SUSY ?

A brief primer …

SUSY searches rely primarily on the understanding of the SM backgrounds



How do we search for SUSY ?

A brief primer …

SUSY searches rely primarily on the understanding of the SM backgrounds

Standard M

Top, multij
V, *VV*, *VVV*,
& combinations

Reducible backgrounds

Determined from data
Backgrounds and methods
depend on analyses

- Fake MET from multijet background predicted using MC sampling from response function measured in dijet (core) and trijet events (tail)
- Fake leptons or heavy-flavour jets determined with "matrix method" in different-purity samples using "real" and "fake" probabilities measured in data.
- Charge flip rate measured in *Z* events
- Also use "ABCD method" (not always applicable)

Validatio

Validation region
cross check SM pr
with data

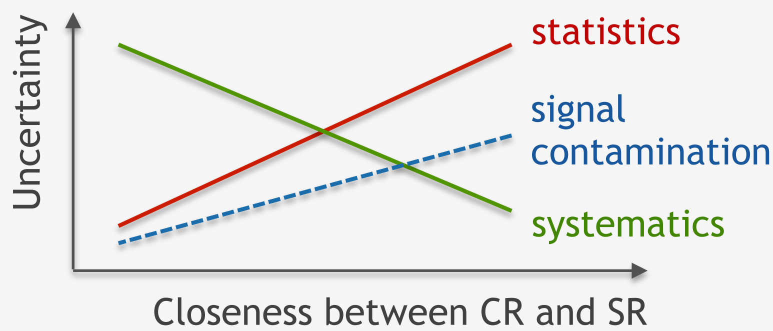
Signal regions

How do we search for SUSY ?

A brief primer …

SUSY searches rely primarily on the understanding of the SM backgrounds

- Normalise MC prediction in SRs using dedicated CRs → transfer factor: ***T***
- Robustness of method depends on CR



- Uncertainty in ***T*** includes:
  - All experimental effects (JES, *b*-tag, PU, ….)
  - Theory effects (generator: μ_F, μ_R, ME/PS matching, α_S scale choice, … (when possible otherwise compare generators), PS, PDF)

dard Model

, multijets
, *VVV*, Higgs
nations of these

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

lidation

regions used to
ck SM predictions
with data

al regions

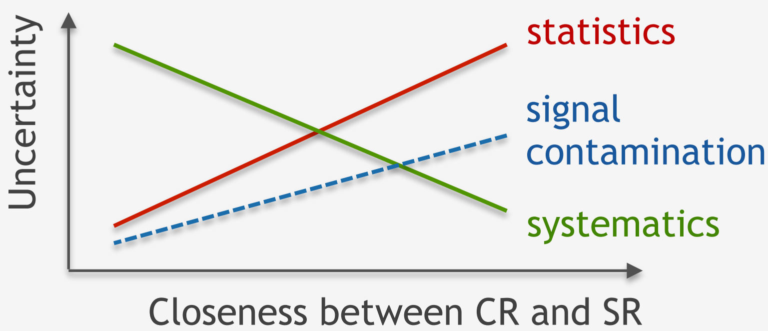
How do we search for SUSY ?

A brief primer …

Other difficult areas are diboson backgrounds, with sometimes large differences between generator predictions in SUSY phase space

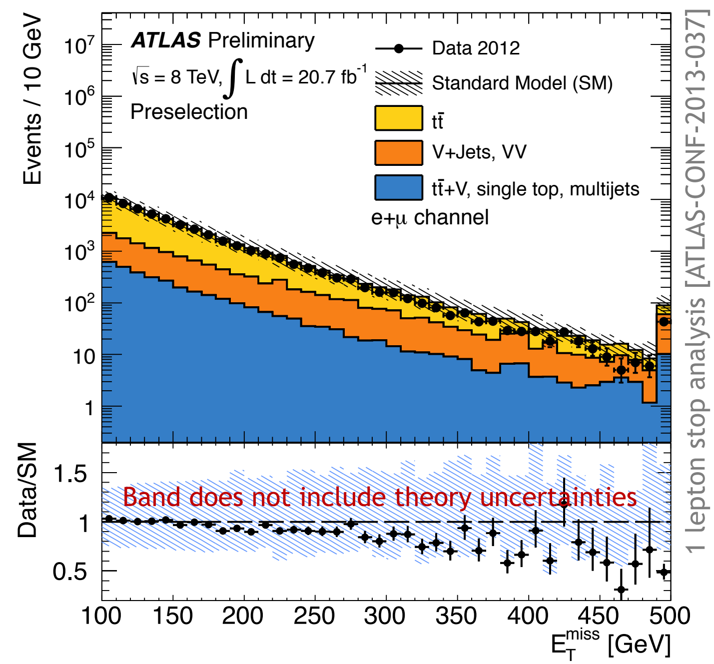
SUSY searches rely primarily on the understanding of the SM backgrounds

- Normalise MC prediction in SRs using dedicated CRs → transfer factor: ***T***
- Robustness of method depends on CR



- Uncertainty in ***T*** includes:
  - All experimental effects (JES, *b*-tag, PU, ….)
  - Theory effects (generator: μ_F, μ_R, ME/PS matching, α_s scale choice, … (when possible otherwise compare generators), PS, PDF)

CR technique relies on well-understood shape of selection variables, but there exist difficulties. Example:



How do we search for SUSY ?

A brief primer …

SUSY searches rely primarily on the understanding of the SM backgrounds

Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

Validation

Validation regions used to cross check SM predictions with data

Signal regions

- Combined binned profile likelihood fit using CL_s prescription for limits
- Systematic uncertainties treated as nuisance parameters in fit, correlated among regions
- Perform 3 types of fits:
  1) Background-only (CR)
  2) Discovery (CR+SR|S=0)
  3) Limit setting (CR+SR|S_{model})
- Signal contamination in CRs taken into account in 3)

How do we search for SUSY ?

A brief primer …

SUSY searches rely primarily on the understanding of the SM backgrounds

Brief digression on SUSY likelihood fits

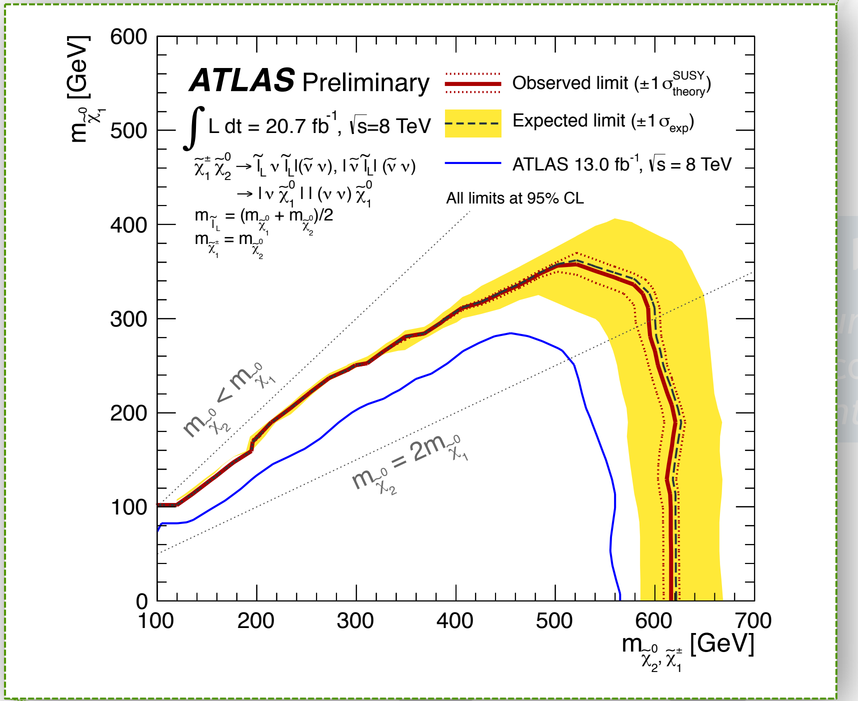
- SRs can be defined exclusively or inclusively (former case requires combined fit, not possible in latter case)
- Some analyses employ (binned!) shape fits
- These tricks usually do **not** increase discovery potential (our main interest), but strengthen exclusion limits (also important)
- Exclusive (shape) fits bear danger of unwanted profiling of correlated nuisance parameters with reduction of systematic uncertainties
- Profiling can be true or fake (**true**: correlation of nuisance parameter among fitted samples fully understood; achieving this often increases number of parameters — and thereby reduces profiling)

- Combined binned profile likelihood fit using CL_s prescription for limits
- Systematic uncertainties treated as nuisance parameters in fit, correlated among regions
- Perform 3 types of fits:
  1) Background-only (CR)
  2) Discovery (CR+SR|S=0)
  3) Limit setting (CR+SR|S_{model})
- Signal contamination in CRs taken into account in 3)

How do we search for SUSY ?

A brief primer …

Results of searches presented in form of raw numbers and (so far only) limits



Signal regions

- Raw results presented as number of observed and expected events and uncertainty for each signal region
- *P*-value for background-only hypothesis
- Results translated into 95% CL limit on "visible" (not fiducial !) cross section:

  $\sigma_{vis} = \sigma_{prod} \times$ efficiency $\times$ acceptance

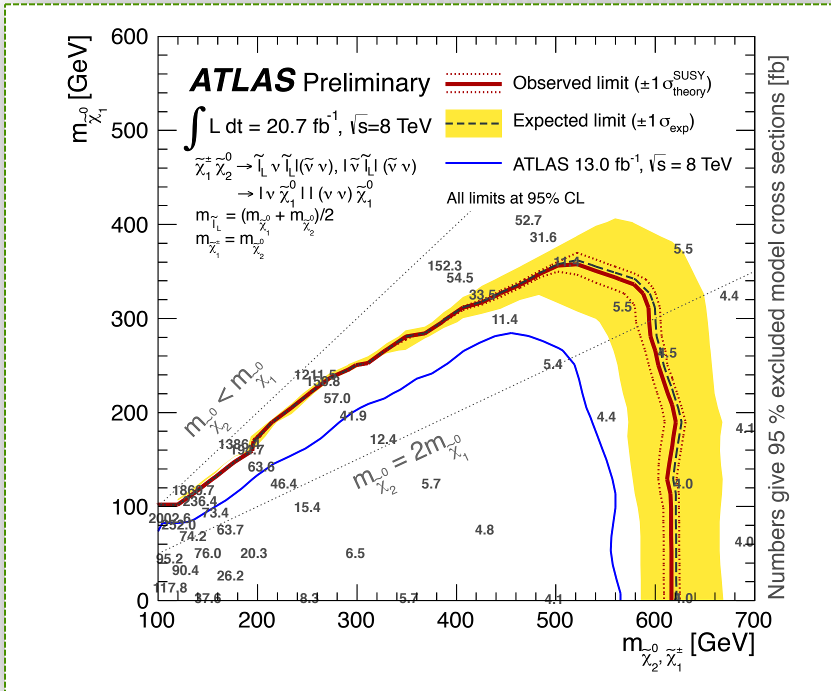
  Assumes no signal contamination in control regions
- Model-dependent 95% CL limits:
  - Observed and expected limits
  - All uncertainties included in limits, except theoretical signal cross section uncertainty
  - Effect of included uncertainties indicated by yellow band around expected limit
  - Theoretical signal cross section uncertainties indicated by dotted lines around obs. limit

How do we search for SUSY ?

A brief primer …

To allow external reinterpretation of analysis, results stored in **HepData**

http://hepdata.cedar.ac.uk



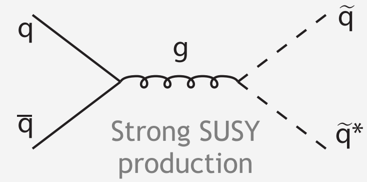
Signal regions

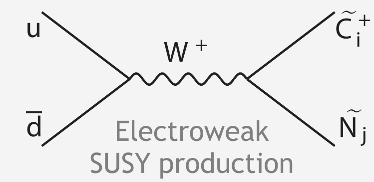
Information provided

- Detailed description of analysis cuts and signal model parameters used
- Cut-flow table for MC signal examples for each signal region
- Plots for each grid indicating which signal region is used for given signal model and corresponding cross section limits
- *For papers only*: numerised values for acceptance, efficiency, experimental uncertainty, MC statistics, signal cross sections and uncertainties, and expected and observed upper limits per model
- *For papers only*: SLHA file for signal example (one per grid)

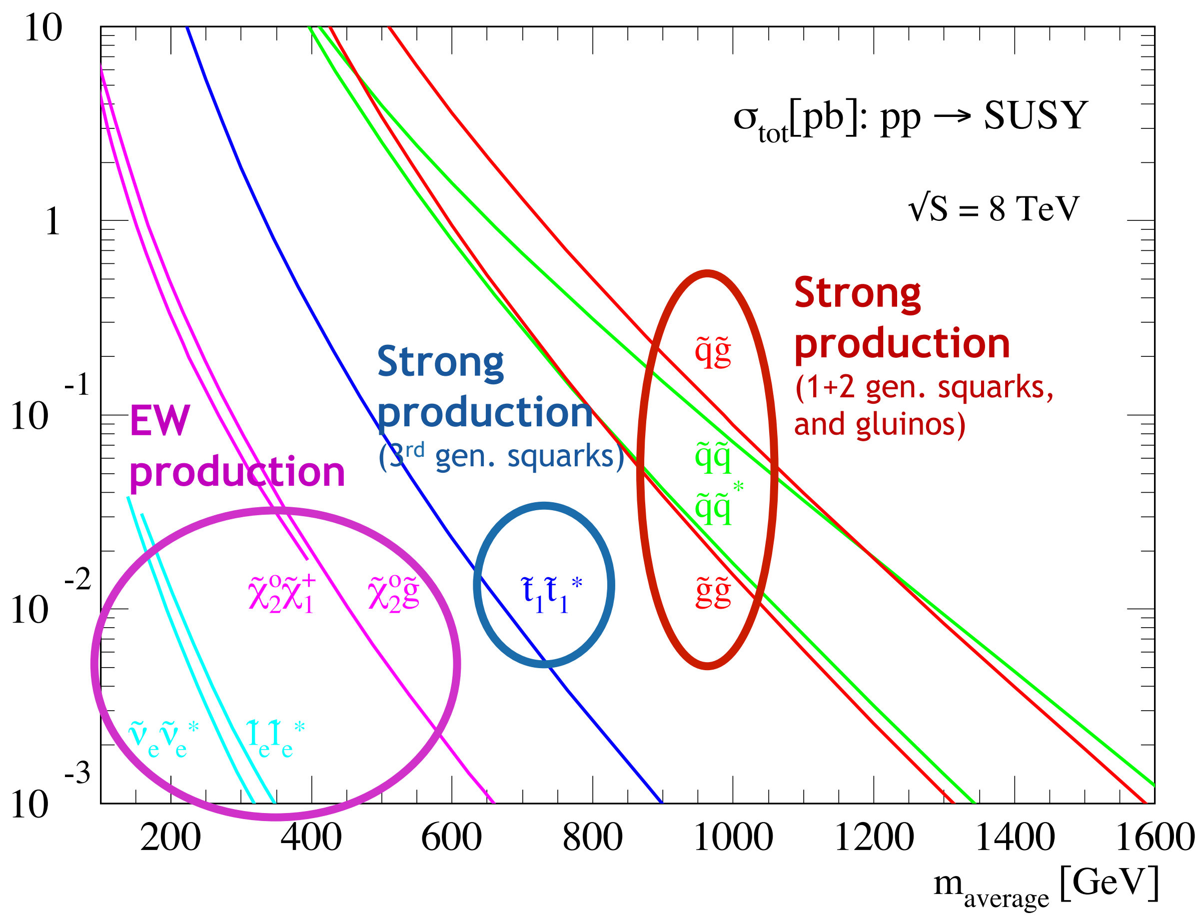
How do we search for SUSY ?

A brief primer …





SUSY searches strategy driven by cross section and luminosity



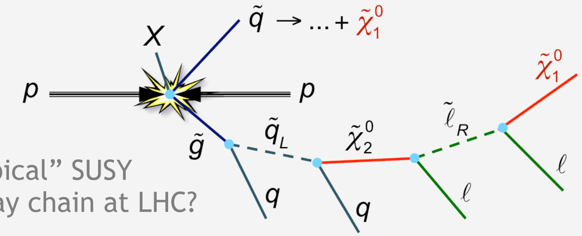
Early analyses dominated by broad and inclusive searches for gluino and squark production,
but right from the start also attacked experimentally challenging searches such as for long-lived particles and RPV

Increasing luminosity gave access to rarer production channels. Additional motivation from *Natural SUSY* paradigm

It was quickly realised that dedicated searches had to be developed to adequately cover the rich decay spectrum

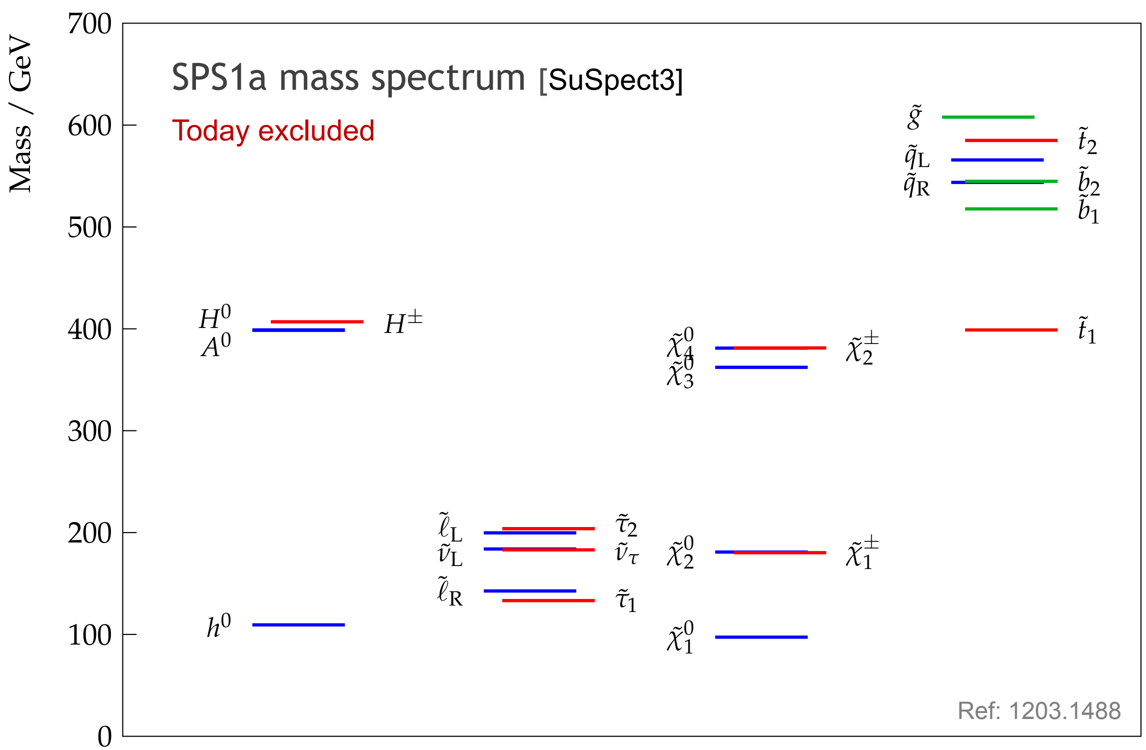
How do we search for SUSY ?

A brief primer …



"Typical" SUSY decay chain at LHC?

Top-down SUSY models: mSUGRA/cMSSM or GMSB as a guiding principle



Over many years, the SUSY community worked with spectra like this SPS1a:

> Sub-TeV squarks, large BRs of squark to C1 and N2 with production of leptons and jets

It was not supposed to represent the truth, but it was a *guiding principle* on how SUSY was expected to appear

Today, many scenarios excluded, new ones considered not general enough. Still useful, however, to compare experiments and test inclusive searches

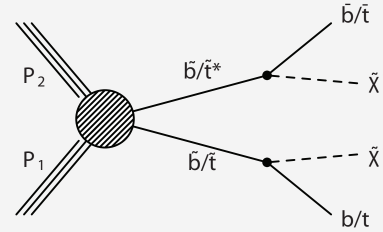
→ *More interesting*: **pMSSM**, allows to relax correlations between sparticle masses

Slide taken from Giacomo Polesello, ATLAS-SUSY workshop, Apr 2013

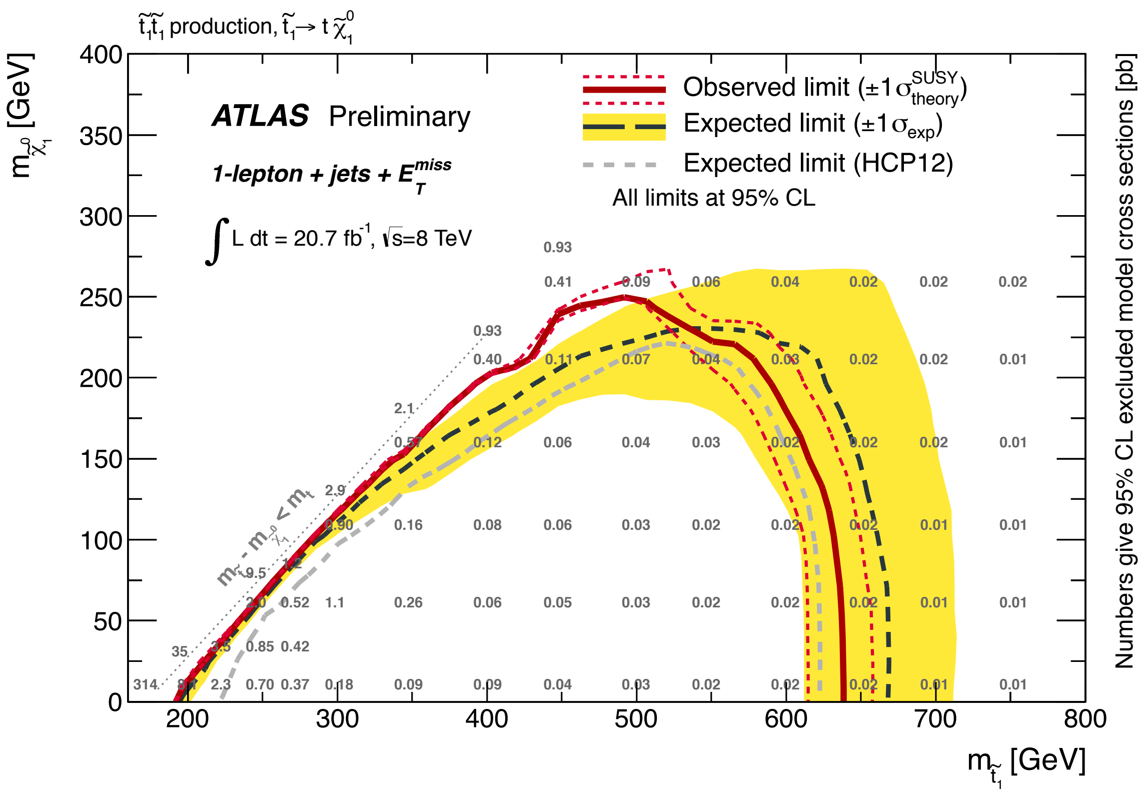
How do we search for SUSY ?

A brief primer ...

Simplified model



Bottom-up: simplified models as a tool for analysis optimisation and display



- Generate events with given decay chain on both legs
- Assume 100% BR in both legs and SUSY NLO(+NLL) production cross section
- Express reach as a function of the involved masses → grid
- No statement on theory but clean representation of potential
- Main results are **not** 95% CL limit curves, but cross section limits

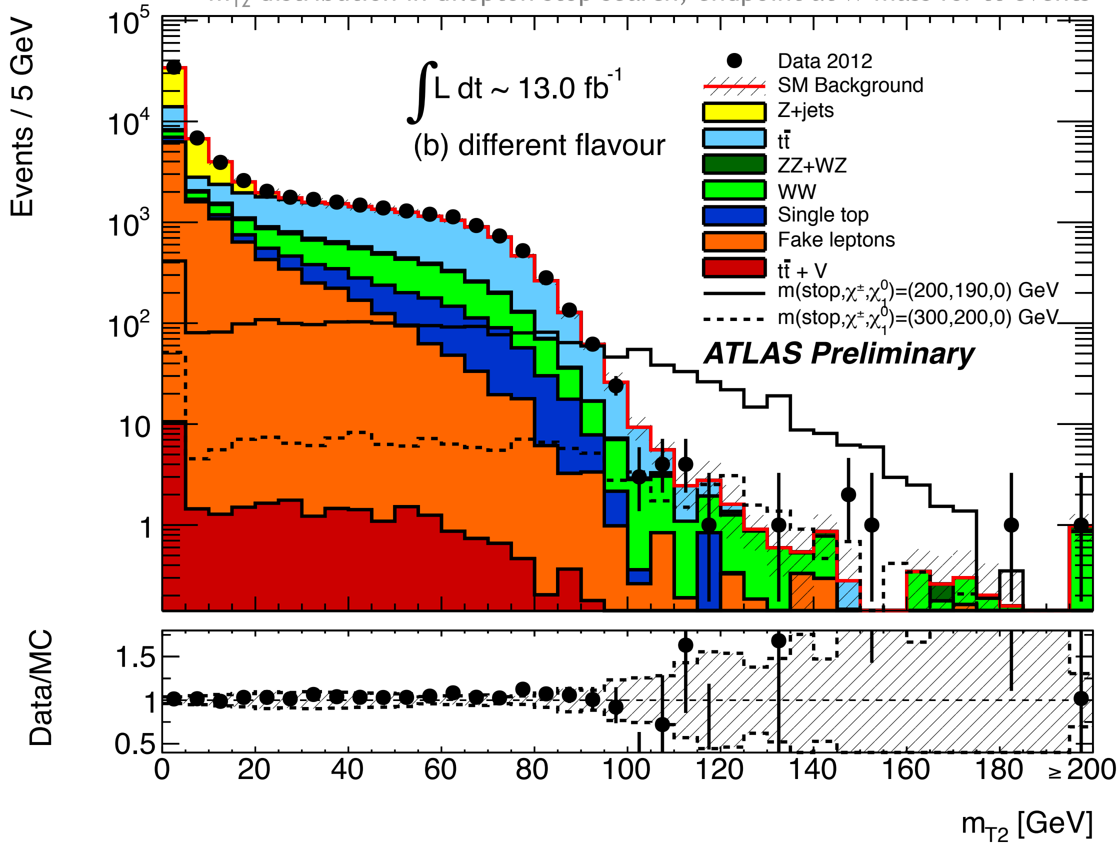
Slide taken from Giacomo Polesello, ATLAS-SUSY workshop, Apr 2013

How do we search for SUSY ?

A brief primer …

Kinematic and topological variables in SUSY searches

m_{T2} distribution in dilepton stop search; endpoint at W mass for tt events



Numerous kinematic variables developed since many years to exploit kinematic information in events with two massive invisible particles for SUSY spectroscopy in case of discovery

Turned out to be also useful for SUSY vs. SM discrimination

Long list: p_T(jets/leptons), N_{jets}, $\Delta\phi$, E_T^{miss}, H_T, m_{eff}, m_T, m_{T2}, m_{CT}, M_R, R, MVA, …

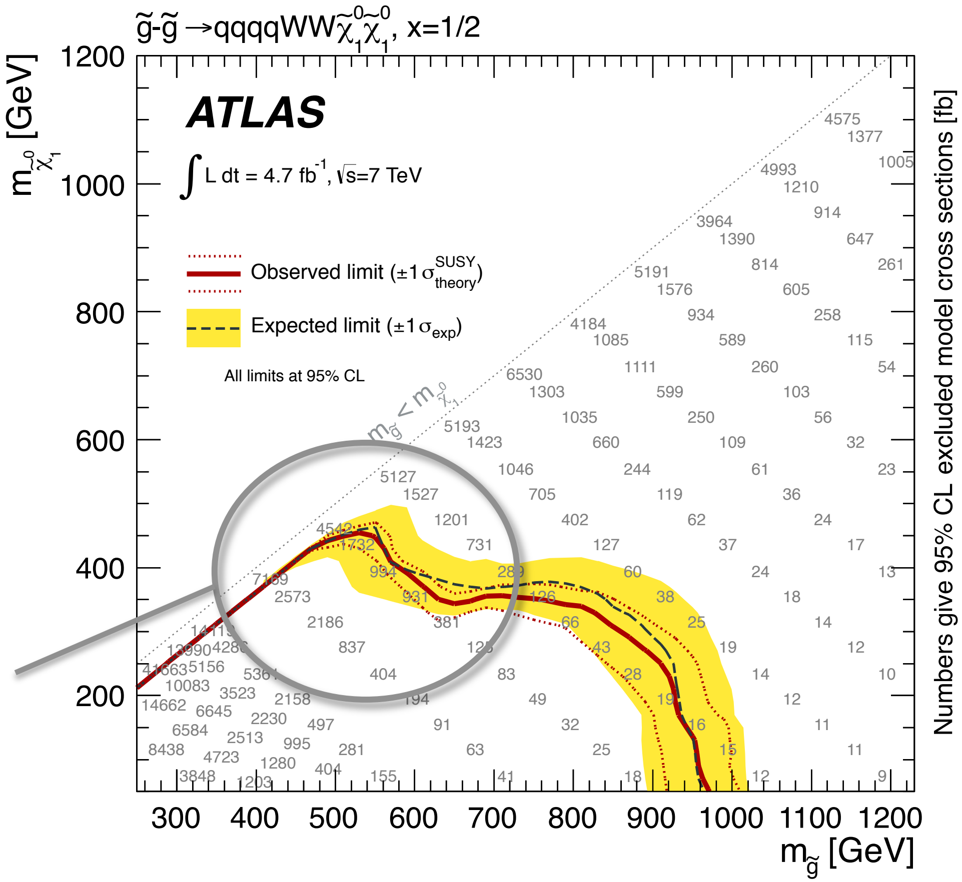
Optimal working point can be achieved in many and often fairly equivalent ways

How do we search for SUSY ?

A brief primer …

"Compressed" SUSY

Addressing the difficult corners of parameter (and phase) space



Dedicated soft lepton analysis to target small ΔM models

[1208.4688]

Compressed SUSY mass spectrum leads to softer kinematics

Analyses targeting bulk spectra have too small acceptance for these scenarios

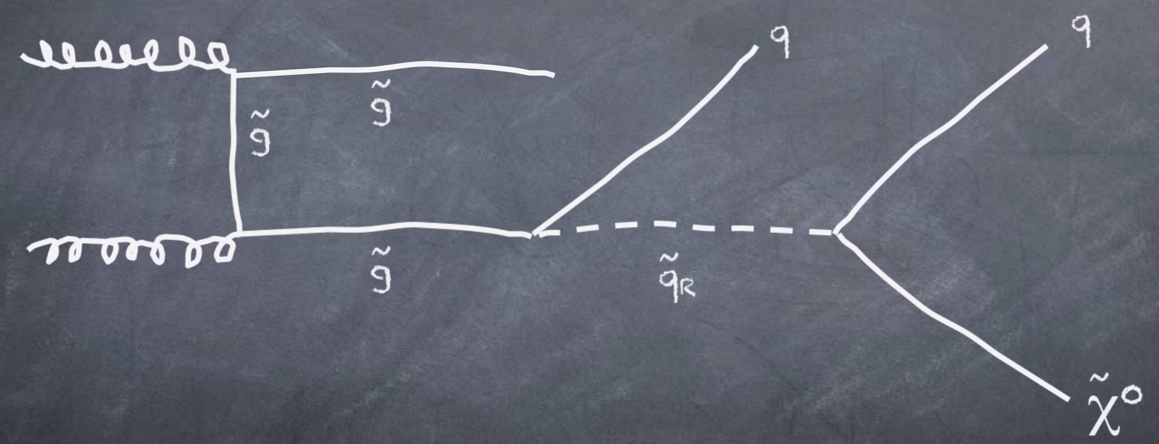
Remedies:

- Softer cuts
  Challenge: increased backgrounds
- Boost system using ISR jets
  Challenge: reduced σ & ISR modelling

QCD ISR found to be well modelled. Powerful tool that can be deployed for all compressed configurations (strong and EW production)

SUSY — state-of-the-art in ATLAS

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



Will not discuss individual analyses here as there will be many ATLAS talks providing all the details during this workshop

Inclusive searches for squark and gluino production

Extensive "jets + X + E_T^{miss} " programme

Most recent references: ATLAS-CONF-2012-109, ATLAS-CONF-2012-103, ATLAS-CONF-2012-104, 1208.4688, ATLAS-CONF-2013-007

Specific analyses (neutralino LSP):

- Traditional 2–6 jets + MET analysis
- Extension to 6–10 jets, using different trigger and background technique
- Traditional 1 lepton + jets + MET analysis
- Extension to 2 leptons (OS) and soft leptons
- Same-sign dilepton (e/μ) + jets + MET

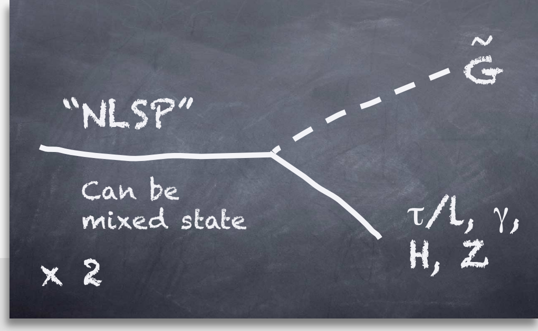
Most recent references: 1208.4688, ATLAS-CONF-2012-152, ATLAS-CONF-2013-026, 1211.1167, ATLAS-CONF-2012-144, 1209.0753

Specific analyses (gravitino LSP):

- 2 leptons (OS w/, w/o *Z*) + jets + MET
- 1-2 taus + 0–1 leptons + jets + MET
- γ + *b*-jet + jets + MET
- γ + lepton + MET
- 2γ (+ H_T) + MET

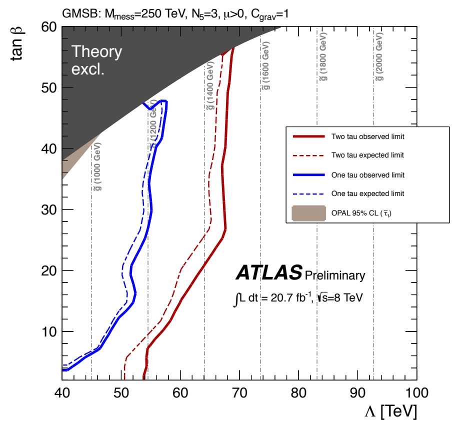
Inclusive squark and gluino searches

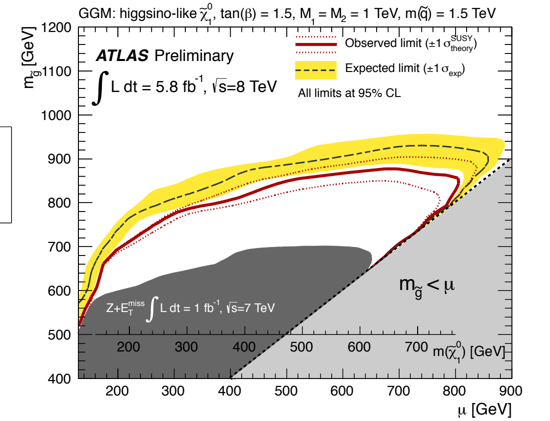
Complete “jets + X + E_T^{miss} ” programme, for example: GM

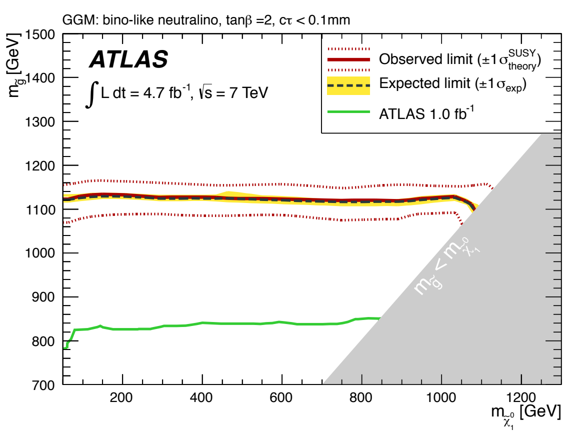


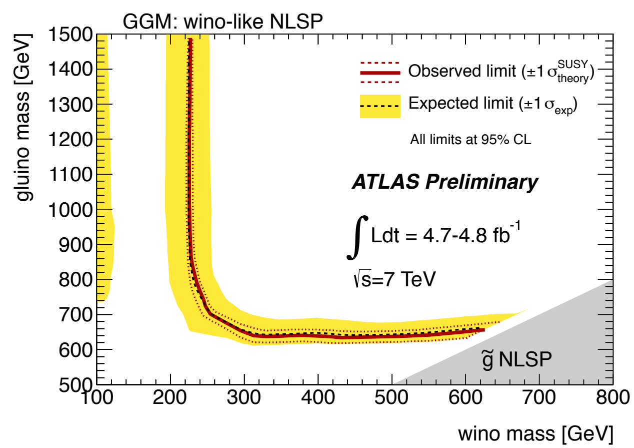
Gauge-mediated SUSY breaking scenarios feature very light gravitino. Phenomenology determined by nature of next-to-LSP

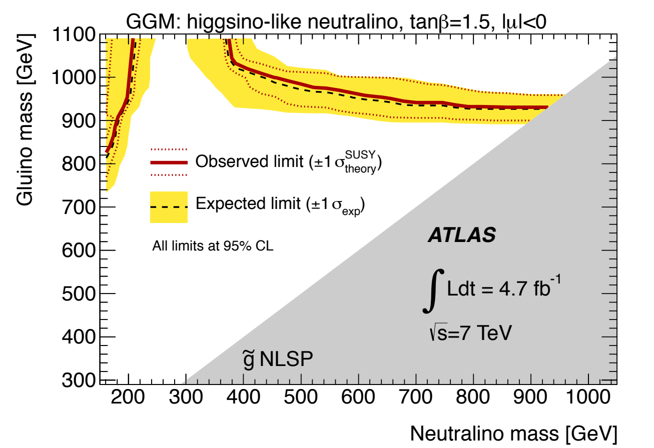
Dedicated search programme including final states with E_T^{miss} + taus, dilepton (Z & non-Z), diphotons, photon + lepton, photon + b











Top-left to bottom-right: ATLAS-CONF-2013-007/, ATLAS-CONF-2012-152, 1209.0753, ATLAS-CONF-2012-144, 1211.1167

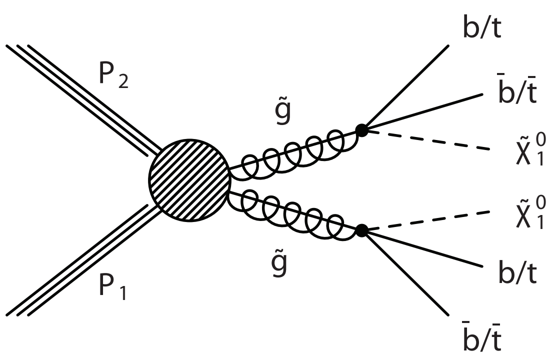
Searches for “Natural” SUSY scenarios

Lightest squarks are stop/sbottom, gluinos possibly too heavy, gauginos accessible ?

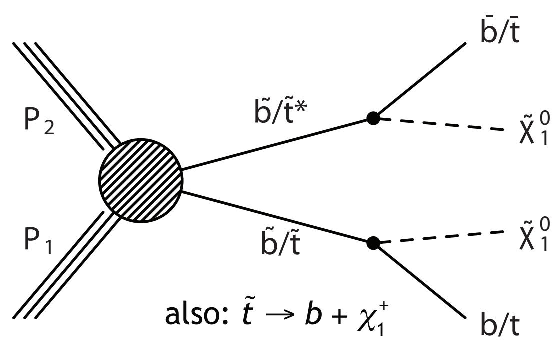
See recent CERN seminar by Iacopo Vivarelli: https://indico.cern.ch/getFile.py/access?resId=0&materialId=slides&confId=240895

Comprehensive & strategic approach by ATLAS

In particular direct stop and chargino/neutralino production requires dedicated analyses covering all possible decay modes

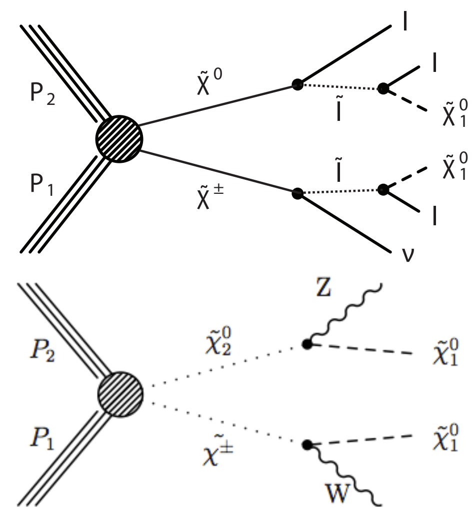


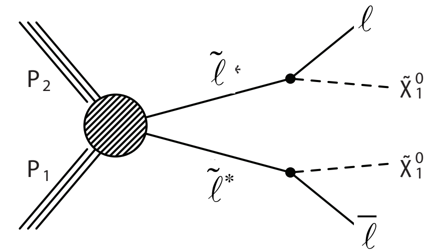
Gluino-mediated $\tilde{b}/\tilde{t}$ production



Direct $\tilde{b}/\tilde{t}$ pair production

Associated gaugino production





Direct slepton-pair production

Searches for "Natural" SUSY scenarios

Gluino-mediated stop / sbottom production

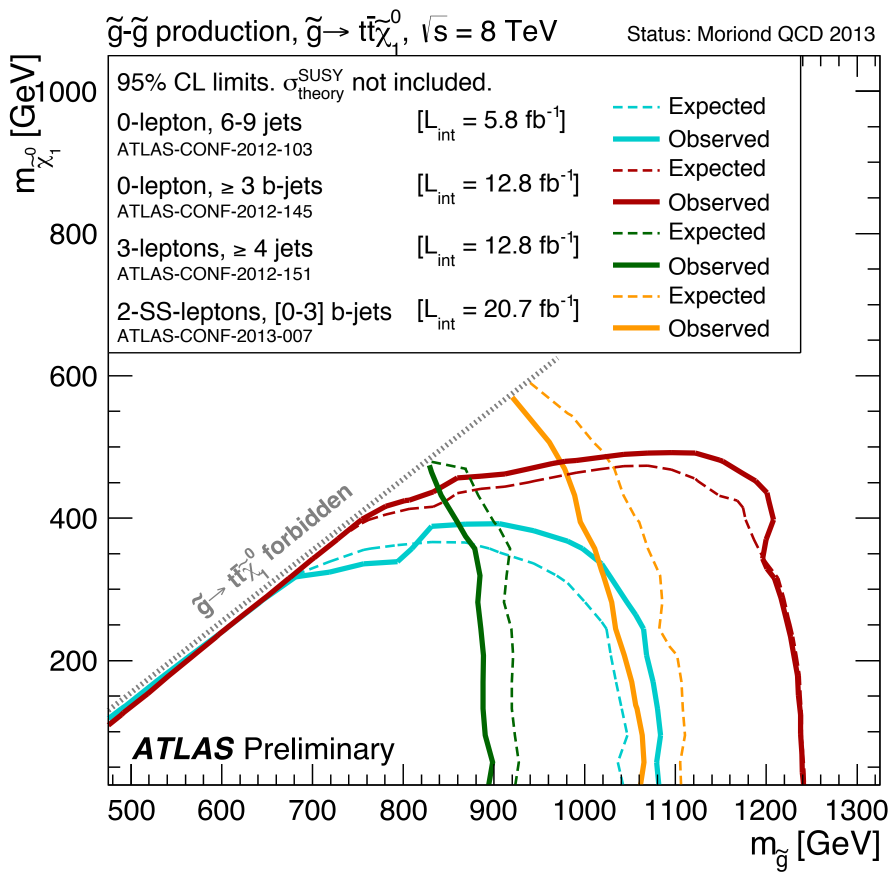
Most recent references: ATLAS-CONF-2012-103, ATLAS-CONF-2012-145, ATLAS-CONF-2012-151, ATLAS-CONF-2013-007

Characteristic signatures:

Gluino-mediated stop/sbottom produces
4 *b*-quarks and/or multileptons
additional jets and E_T^{miss} in finals state

Specific analyses:

- 6–9 jets + MET analysis
- 3 *b*-jets + 1[sbottom]–3[stop] jets + MET
  Challenging due to large top+fakes and top+HF bkgs
- 3 leptons + jets + MET
- Same-sign dilepton + (0–3 *b*) jets (+ MET)
  Clean channel, 3*b* signal region w/o MET requirement



Searches for "Natural" SUSY scenarios

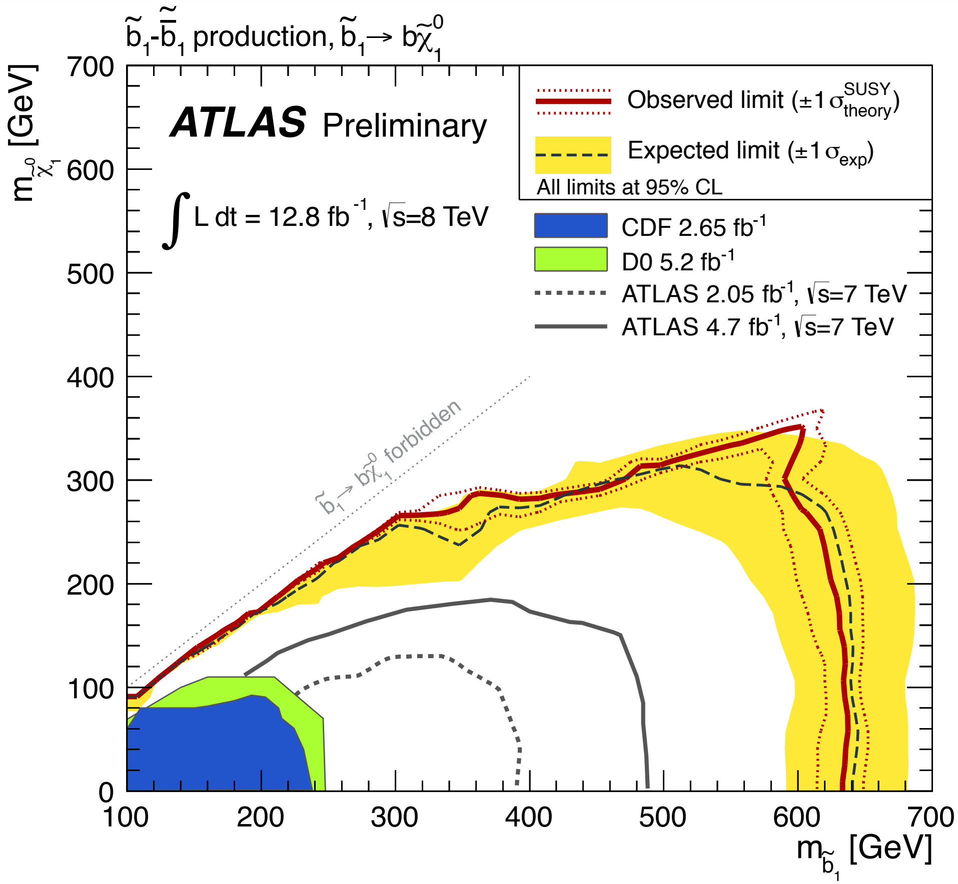
Direct sbottom pair production

Most recent references: ATLAS-CONF-2012-165, ATLAS-CONF-2012-151, ATLAS-CONF-2013-007

Direct sbottom production can lead to $2b + E_T^{miss}$ (shown here) or also to multilepton + jets + E_T^{miss} final states

Specific analyses:

- 2 *b*-jets + MET
  Includes "compressed" signal reg. using ISR selection
- 3 leptons + jets + MET
- Same-sign dilepton + (0-3 *b*) jets + MET



Searches for “Natural” SUSY scenarios

Direct stop pair production

5 papers on 7 TeV: 1208.4305, 1209.2102, 1209.4186, 1208.2590, 1208.1447

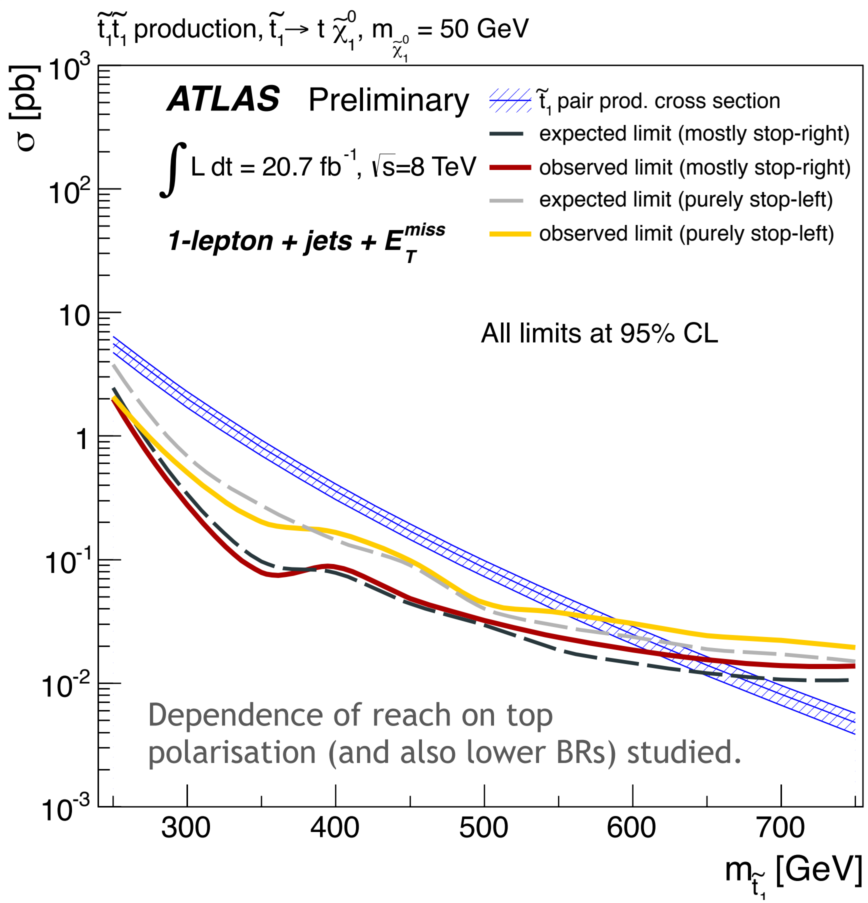
Most recent references: ATLAS-CONF-2013-024, ATLAS-CONF-2013-037, ATLAS-CONF-2012-167, ATLAS-CONF-2013-025

Large spectrum of possible stop decays:
t+Ni, *b*+Ci, *Wb*Ni, *Wb*lν, *c*+Ni, & gravitino LSP

Effort so far concentrated on simplified models with 100% BRs to *t*+N1 or *b*+C1, and stop-right

Specific analyses:

- 0 lepton + 2 *b*-jets + 4 jets + MET
- 0 lepton + 2 *b*-jets + MET
- 1 lepton + 1 *b*-jet + 3 jets + MET
- 2 leptons + MET
- *Z* (+ lepton) + 1 *b*-jet + 2–4 jets + MET
  Includes search for heavy stop2 production



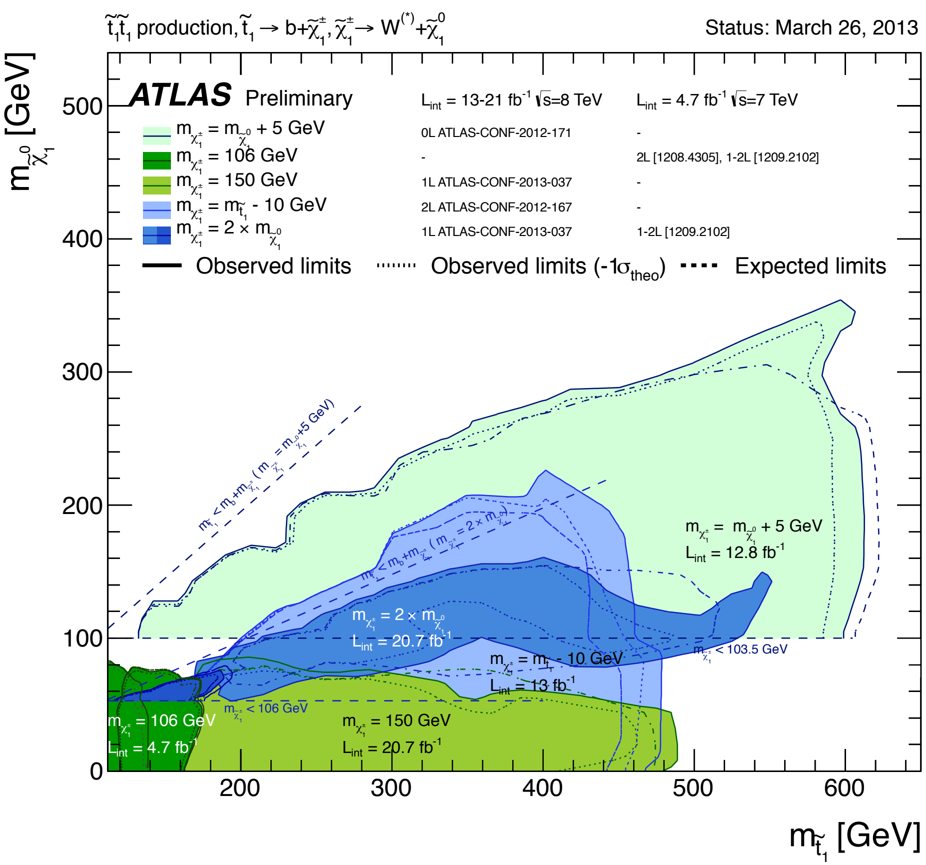
Dependence of reach on top polarisation (and also lower BRs) studied.

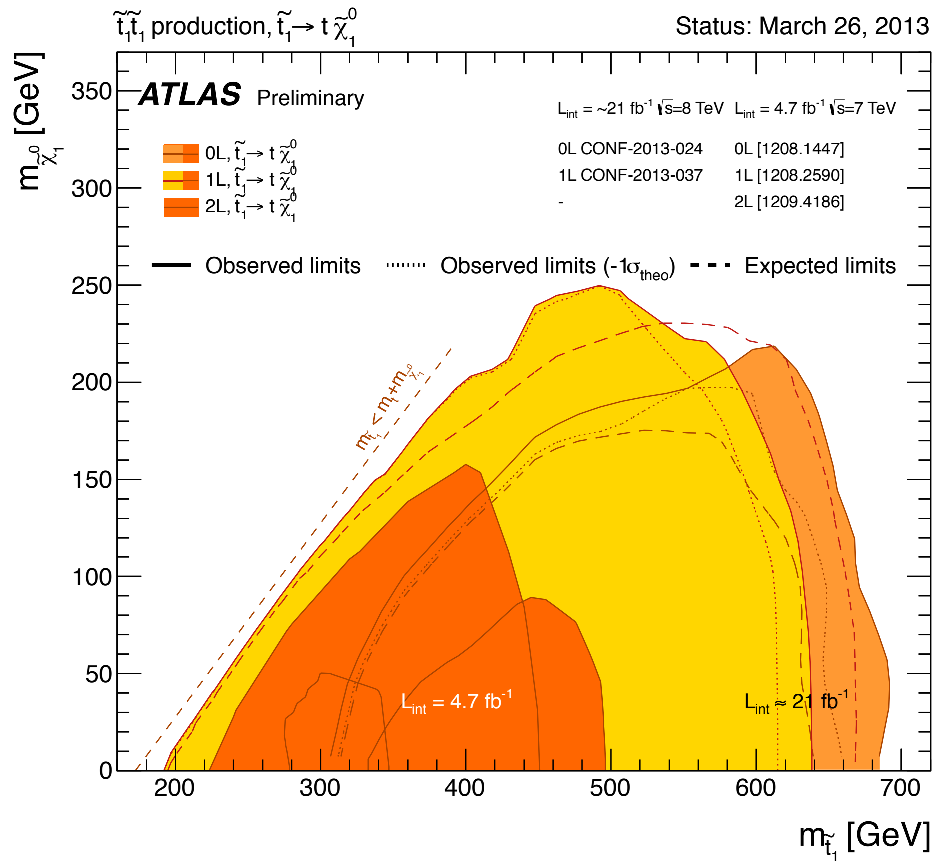
Searches for “Natural” SUSY scenarios

Direct stop pair production

5 papers on 7 TeV: 1208.4305, 1209.2102, 1209.4186, 1208.2590, 1208.1447

Most recent references: ATLAS-CONF-2013-024, ATLAS-CONF-2013-037, ATLAS-CONF-2012-167, ATLAS-CONF-2013-025





Searches for "Natural" SUSY scenarios

Electroweak neutralino, chargino and slepton pair production

Most recent references: ATLAS-CONF-2013-024, ATLAS-CONF-2013-037, ATLAS-CONF-2012-167, ATLAS-CONF-2013-025

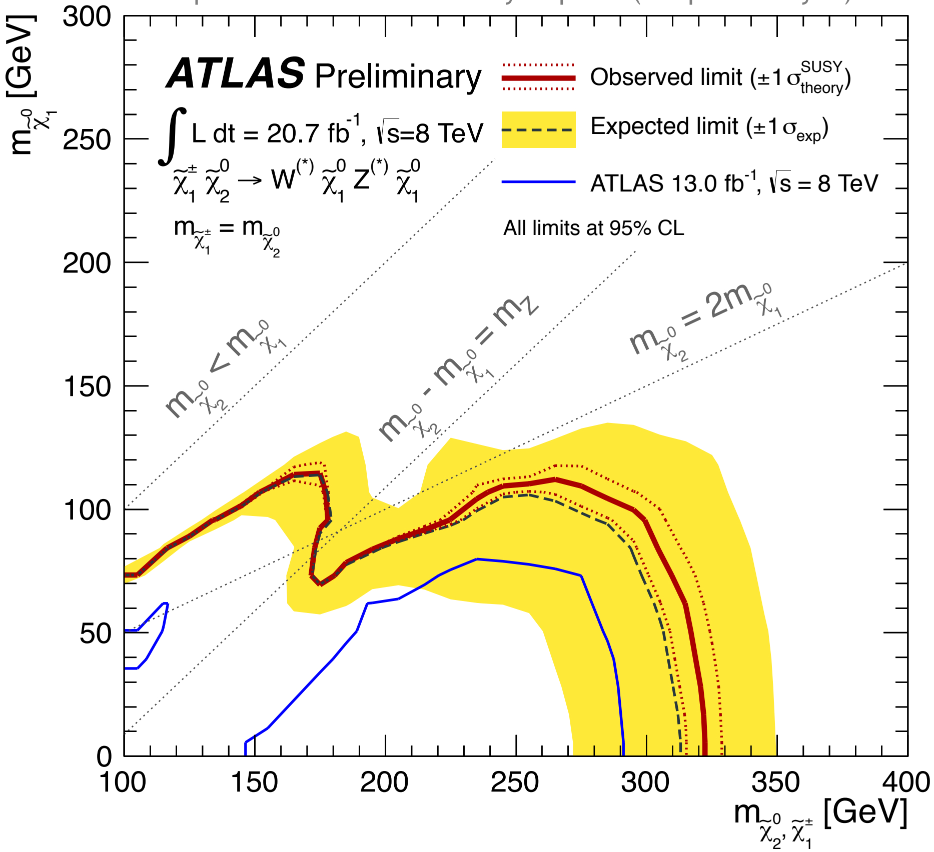
Production & decay depends on sparticle nature; sleptons increase acceptance

Interpretation with simplified models and "realistic" pMSSM scans (versus μ, M_2, M_1)

Specific analyses:

- 2 leptons + MET
  Not yet updated with 8 TeV
- 2 taus + MET
  First time targeting C1C1 pair production with staus
- 3 leptons + MET
  Optimised for heavy and light slepton cases
- 4 leptons + MET
  Targets N2+N3 (light sleptons) and RPV

C1N2 production limits for heavy sleptons (3-lepton analysis)



SUSY searches for long-lived particles

Generated by weak coupling, high virtuality or mass alignment

Most recent references: 1211.1597, 1210.7451, 1210.2852, 1304.6310

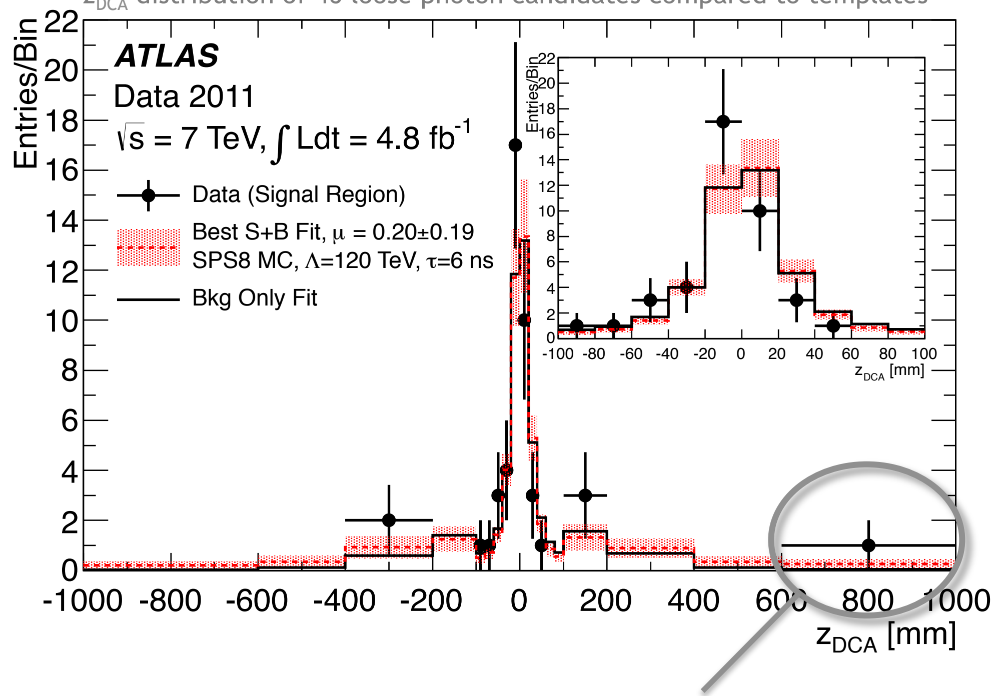
Challenging analyses developed beyond mainstream by small dedicated teams

Need for special calibration and/or reconstruction algorithms no 8 TeV update yet

Specific analyses:

- Stable *R*-hadron and slepton search
  β **and** $\beta\gamma$ from ID, calorimeters and muon system
- Long-lived N1 RPV decay to μ + jets
  Search for heavy, track-rich **displaced vertex**
- Long-lived charginos (AMSB)
  Search for **disappearing tracks** in TR tracker
- Long-lived neutralinos (GMSB)
  Search for **non-pointing photons** using calorimeter

z_{DCA} distribution of 46 loose photon candidates compared to templates



Outlier event with arrival time consistent with prompt production, and strip distribution that may indicate π^0 background

SUSY searches for *R*-parity violation (RPV)

Add 45 trilinear λ_{ijk} couplings plus bilinear couplings plus “normal” SUSY channels

Most recent references: ATLAS-CONF-2013-036, 1212.1272, 1210.7451, 1210.4813, ATLAS-CONF-2012-153, 1109.6606

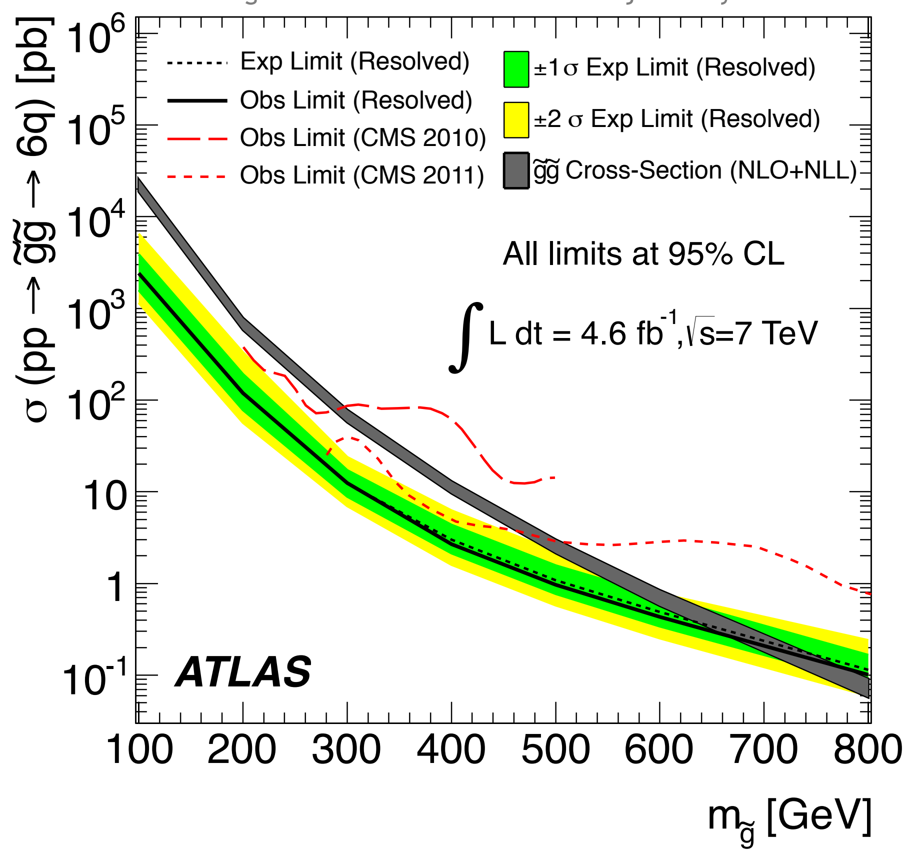
Dedicated analyses and reinterpretation

Most analyses consider RPV in decay only
(sparticle pair production, exact λ_{ijk} value unimportant)

Specific analyses:

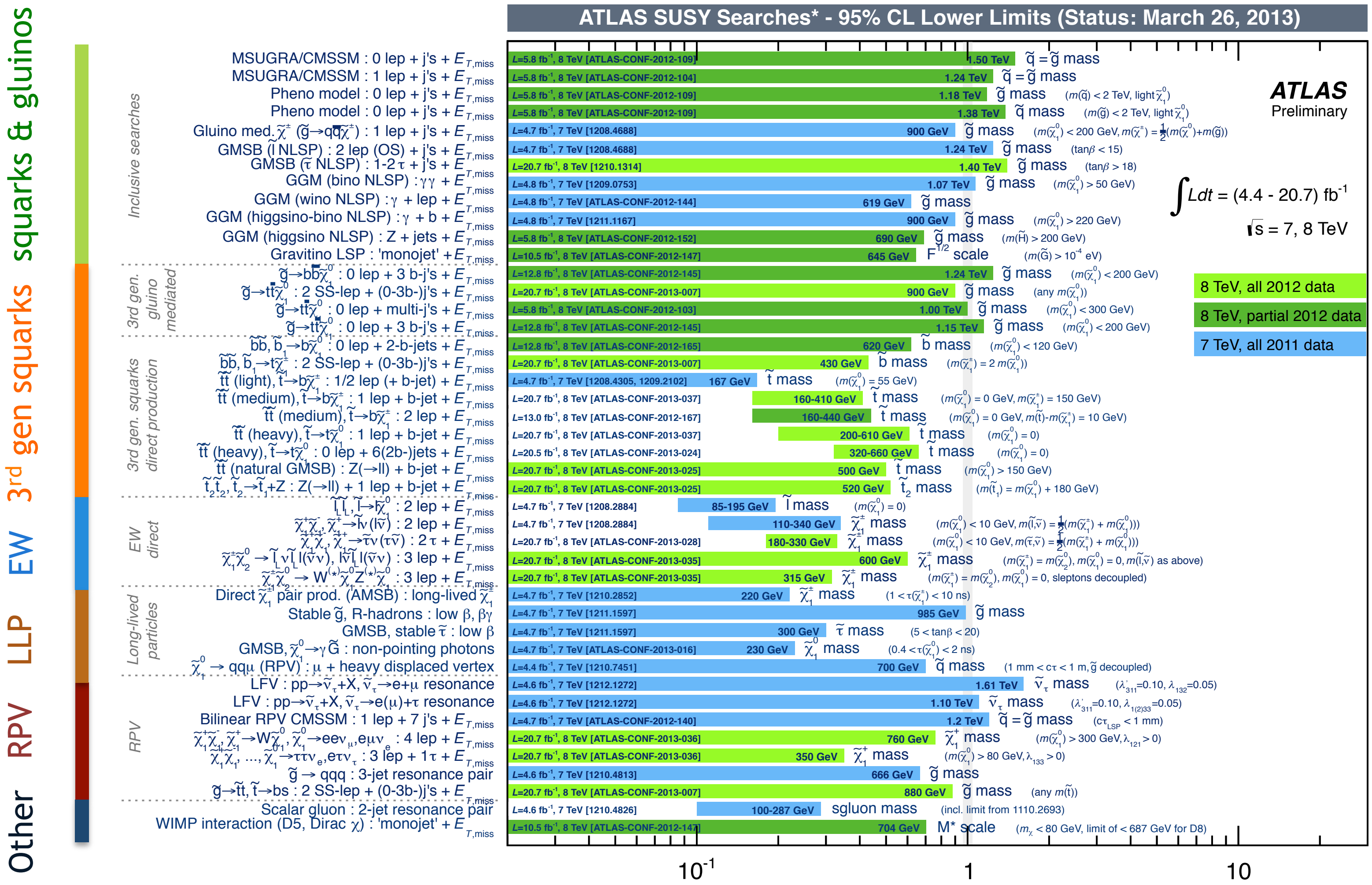
- 4-leptons + MET
  RPV in 2-lepton+ν decay of LSP (N1)
- $e\mu$, $e\tau$, $\mu\tau$ narrow resonance search
- Long-lived N1 RPV decay to μ + jets
- Pair of 3-jet resonance search
- Same-sign dilepton + 3 b-jets
  Gluino-mediated stop with stop → bs (λ''_{323} > 0)
- Bilinear RPV in 1-leptom + jets + MET

Limit on gluino mass from resolved multijet analysis



ATLAS deeply mines SUSY signatures & models

But no hint for a signal so far



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

What's left

We've come a long way and spent a huge amount of work to search for SUSY in large areas of parameter space

We have to finish the job for the 2012 8 TeV data

R & D time during LS1 allows us to:

- Complete the searches for Natural SUSY in all possible decays
- Move closer to the "diagonals" in most analyses by further exploiting ISR and soft-object techniques
- Solidify our understanding of SM backgrounds by improving Monte Carlo generator predictions in collaboration with the generator authors, and by further measuring rare background channels

We need to prepare our searches for the harsher conditions of the 13-14 TeV run in 2015: more pileup, larger expected generator and PDF uncertainties

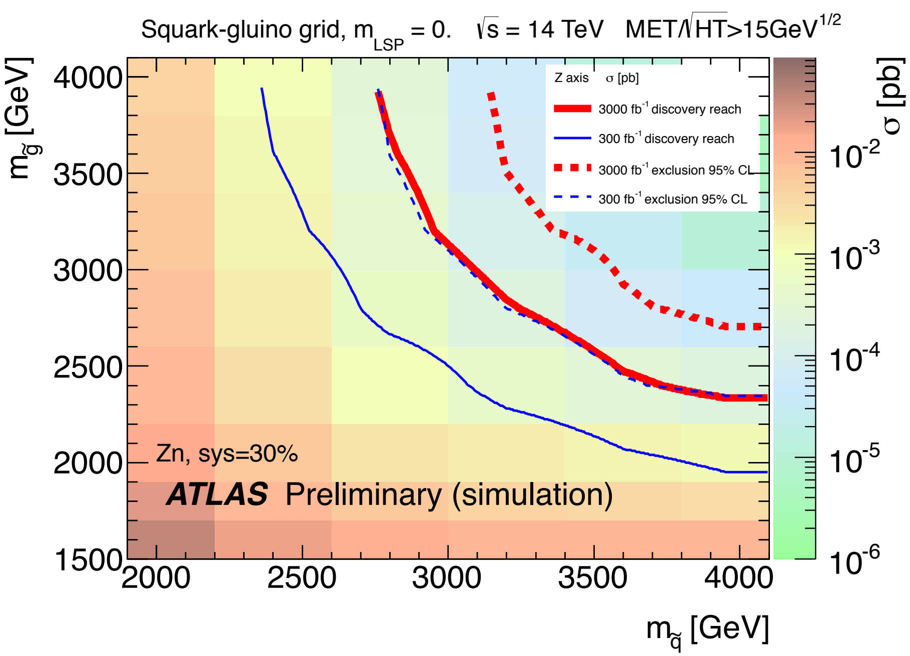
Extra slides…

Future SUSY studies for European Strategy Document

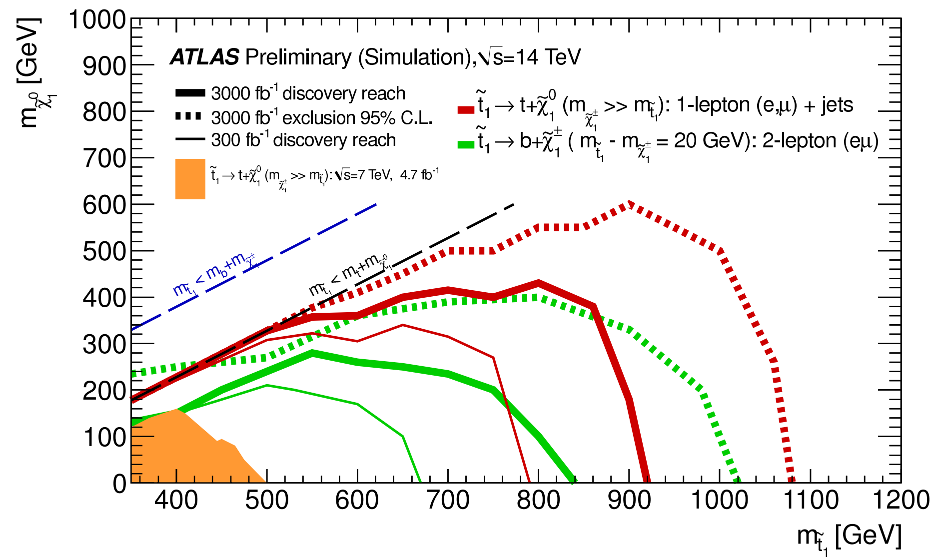
Approximate results only, no full detector simulation, estimates of conditions

ATL-PHYS-PUB-2012-001

95% CL limits (solid lines) and 5σ discovery reach (dashed lines) in a simplified squark-gluino model with massless N1 with 300 fb^{-1} (blue lines) and 3000 fb^{-1} (red lines)



95% CL limits for 3000 fb^{-1} (dashed) and 5σ discovery reach (solid) for 300 fb^{-1} and 3000 fb^{-1} in the stop-N1 mass plane assuming 100% stop → top +N1 (red) or stop → b+C1 (green) decay modes



ATLAS thoroughly studies signatures for new physics…

Huge variety of models probed, but also model-independent results

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

Exotics Models:

- Extra dimensions:
  - RS KK Graviton (dibosons, dileptons, diphotons)
  - RS KK gluons (top antitop)
  - ADD (monojets, monophotons, dileptons, diphotons)
  - KK Z/gamma boosns (dileptons)
- Grand Unification symmetries
  - (dielectons, dimuons, ditaus)
  - Leptophobic topcolor Z' boson (dilepton ttbar, l+j, all had)
- S8- color octet scalars (dijets)
- String resonance (dijets,)
- Benchmark Sequential SM Z', W'
- W' (lepton+MET, dijets, tb)
- W* (lepton+MET, dijets)
- Quantum Black Holes (dijet)
- Black Holes (l+jets, same sign leptons)
- Technihadrons (dileptons, dibosons)
- Dark Matter
  - WIMPs (Monojet, monophotons)
- Excited fermions
  - q*, Excited quarks (dijets, photon+jet)
  - l*, excited leptons (dileptons+photon)
- Leptoquarks (1st, 2nd, 3rd generations)
- Higgs -> hidden sector (displaced vertices, lepton jets)
- Contact Interaction
  - llqq CI
  - 4q CI (dijets)
- Doubly charged Higgs (
  - multi leptons, same sign leptons)
- 4th generation
  - t'->Wb, t'->ht, b'-Zb, b'->Wt (dileptons, same sign leptons, l+J)
- VLQ-Vector Like quarks
- Magnetic Monopoles (and HIP)
- Heavy Majorana neutrino and RH W

What about Dark Matter ?

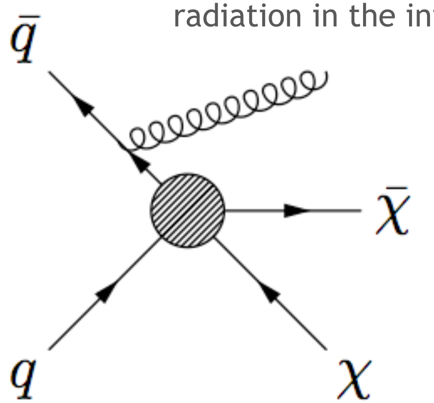
Detection of invisible particle production

1210.4491, ATLAS-CONF-2012-147

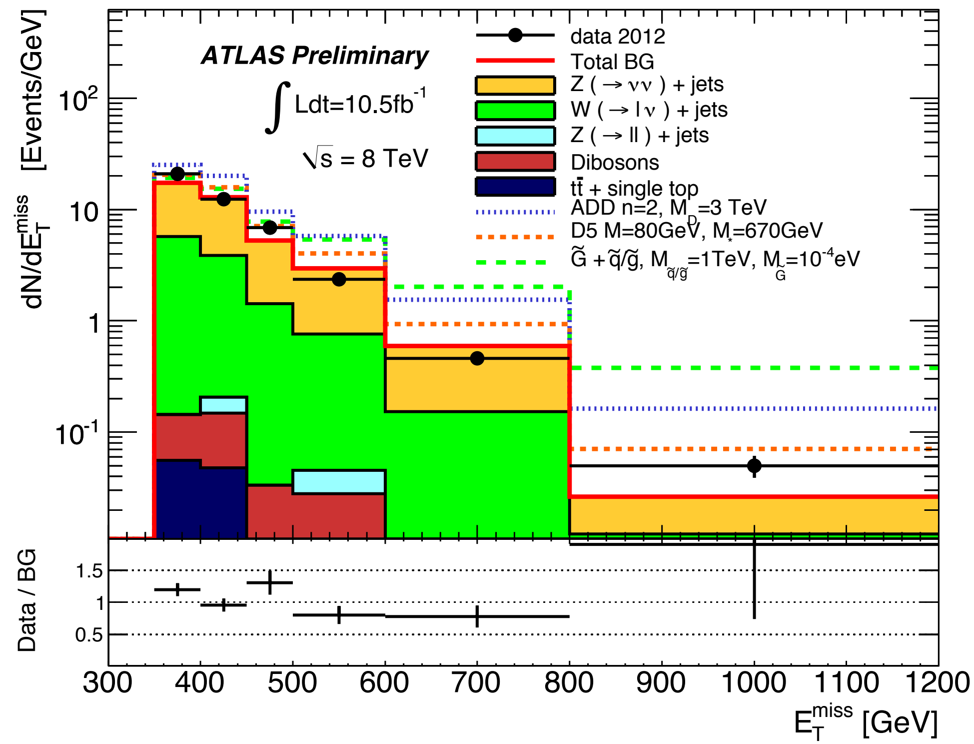
Should we give up on natural SUSY and directly search for WIMP (dark matter) production in proton−proton collisions ?

Exploit “ISR technique” (huge potential!)

Energetic gluon/photon radiation in the initial sate



→ Search for mono-jets events



Interpretation in variety of models: extra dimensions, WIMP, gravitinos

What about Dark Matter ?

Limits on WIMP production assuming high-scale contact interaction

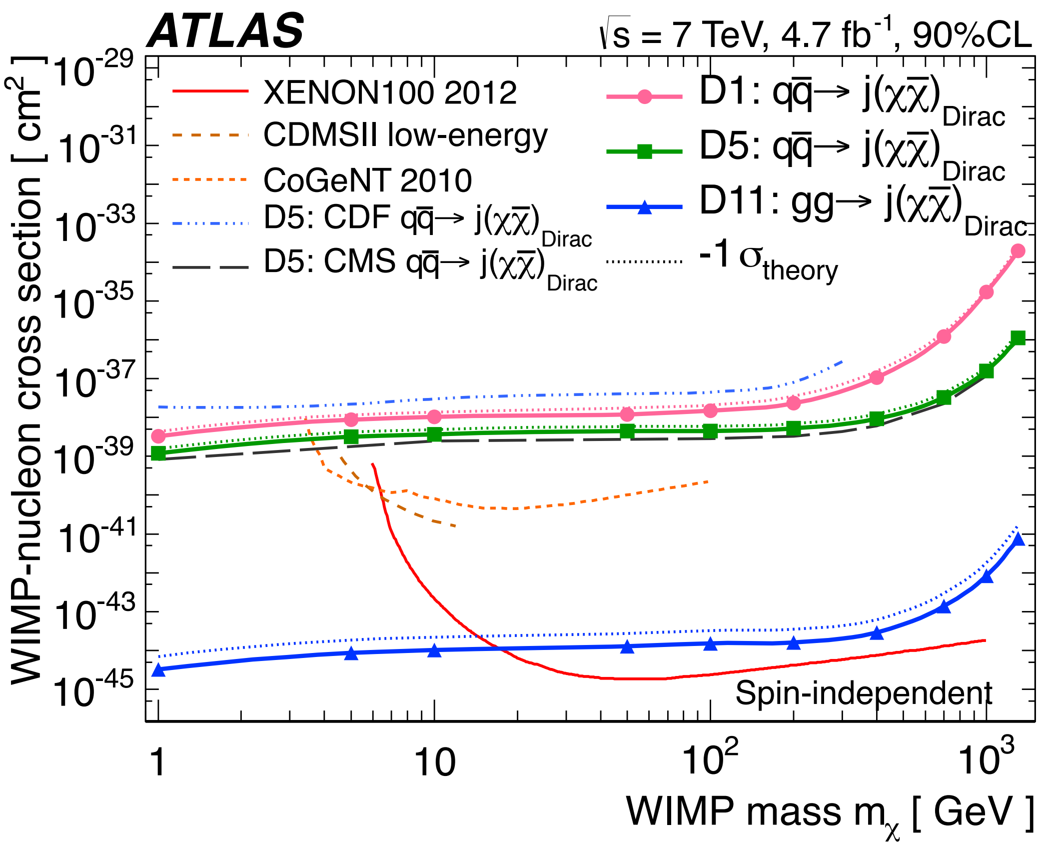
1210.4491, ATLAS-CONF-2012-147

Limit on WIMP pair production cross-section can be transformed into limit on effective WIMP-hadronic contact interaction:

Vector (SI): $(\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q)\cdot\Lambda^{-2}$

Axial-v. (SD): $(\bar{\chi}\gamma_{\mu}\gamma^{5}\chi)(\bar{q}\gamma^{\mu}\gamma^{5}q)\cdot\Lambda^{-2}$

WIMP-nucleon scattering cross-section: $\sigma \propto \frac{1}{\Lambda^4}$

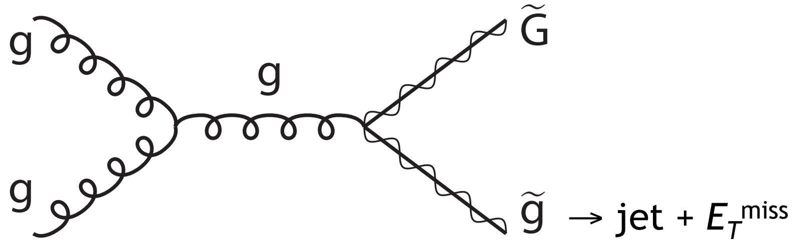


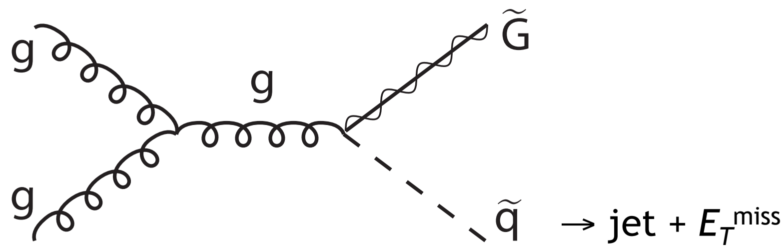
Monojet analysis as search for gravitino production

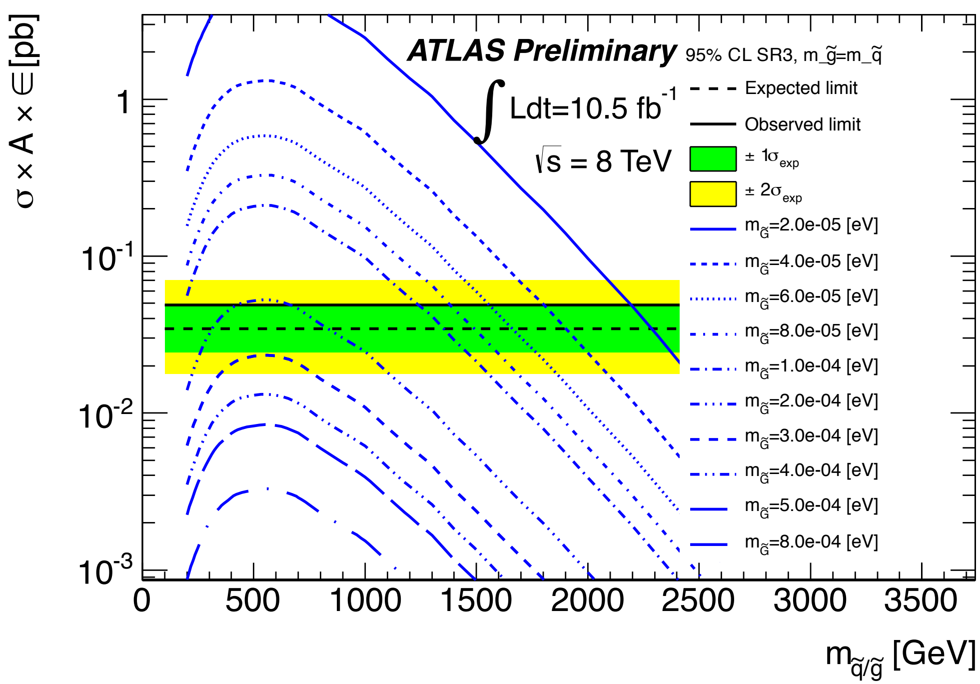
Same signature as WIMP production, but not ISR search (similar to ADD)

ATLAS-CONF-2012-147

In GM SUSY, gravitino LSP with mass related to SUSY breaking scale
At LHC with low-scale SUSY breaking, direct $\tilde{G}+\tilde{q}$ or $\tilde{G}+\tilde{g}$ production can dominate. Cross-section ~ $1/m^2(\tilde{G})$







Lower limits on gravitino mass as function of squark/gluino masses

Improves existing limits by *O*(magnitude)

Beam induced backgrounds (BIB)

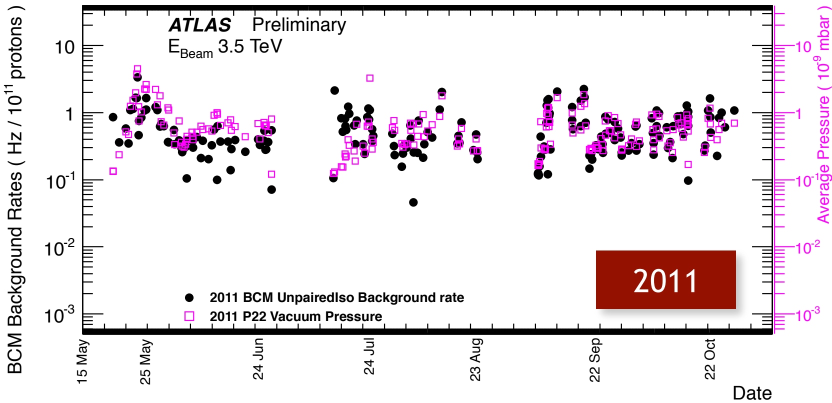
Measured with various subdetectors, monitored throughout the year

BIB rates low in 2012 as in 2011

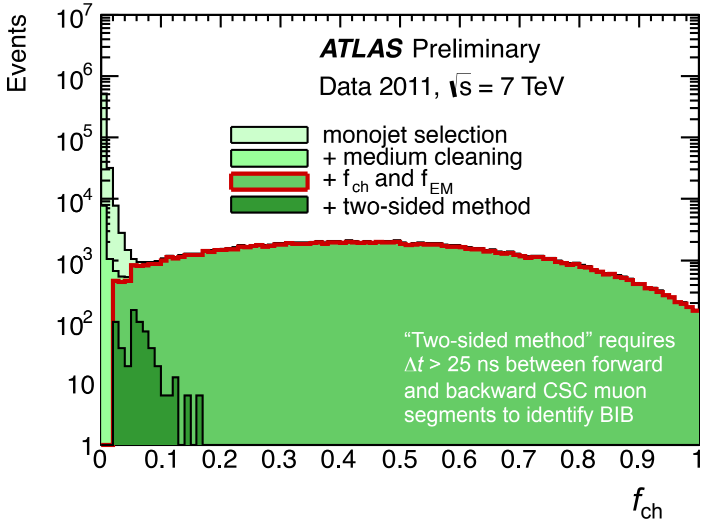
- No significant change between years

BIB can nevertheless be harmful in searches

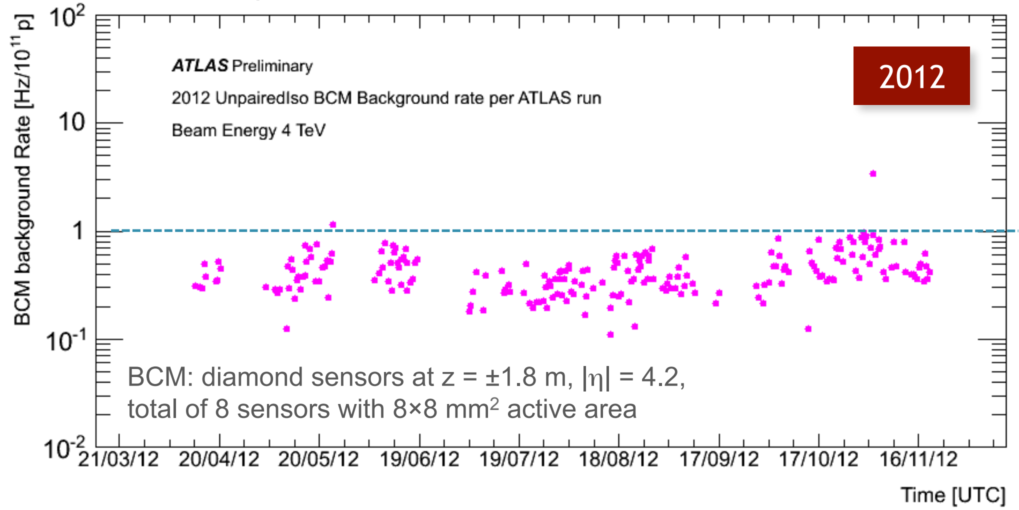
- Relatively loose cleaning applied everywhere
- Tighter cleaning in, eg, monojet analysis: require minimum charge and EM fractions for jets



Events selected for the monojet analysis



BCM background rates in unpaired bunched



Diboson physics: *WW*, *WZ*, *ZZ*, *Wγ*, *Zγ*, *γγ*

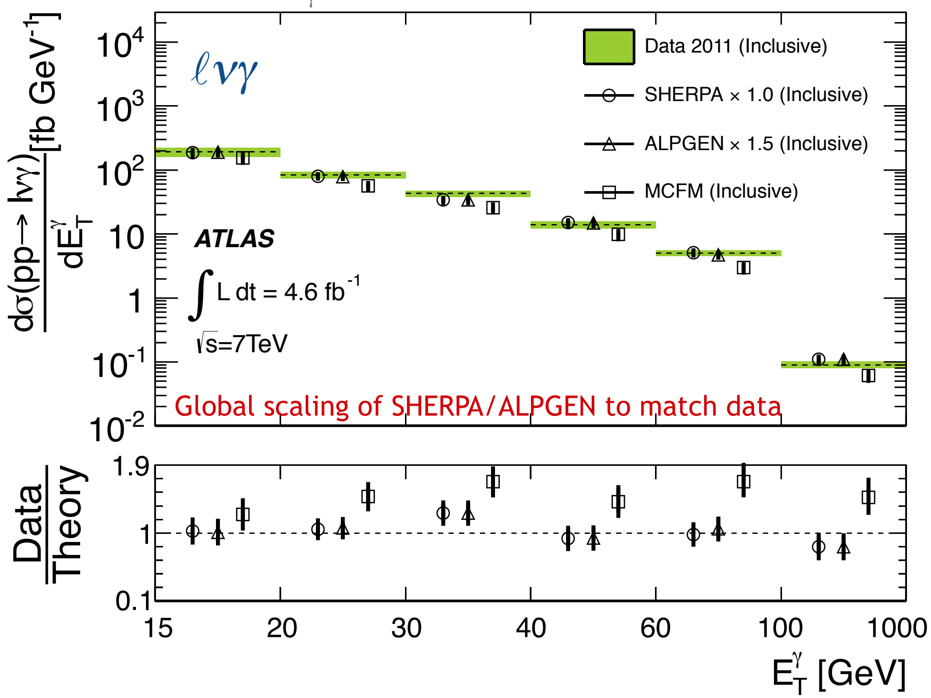
ATLAS performed total, fiducial & differential diboson cross-sections measurements

Measured 11 diboson fiducial cross-sections: most are slightly above theory expectation (but syst. and theo. errors correlated)

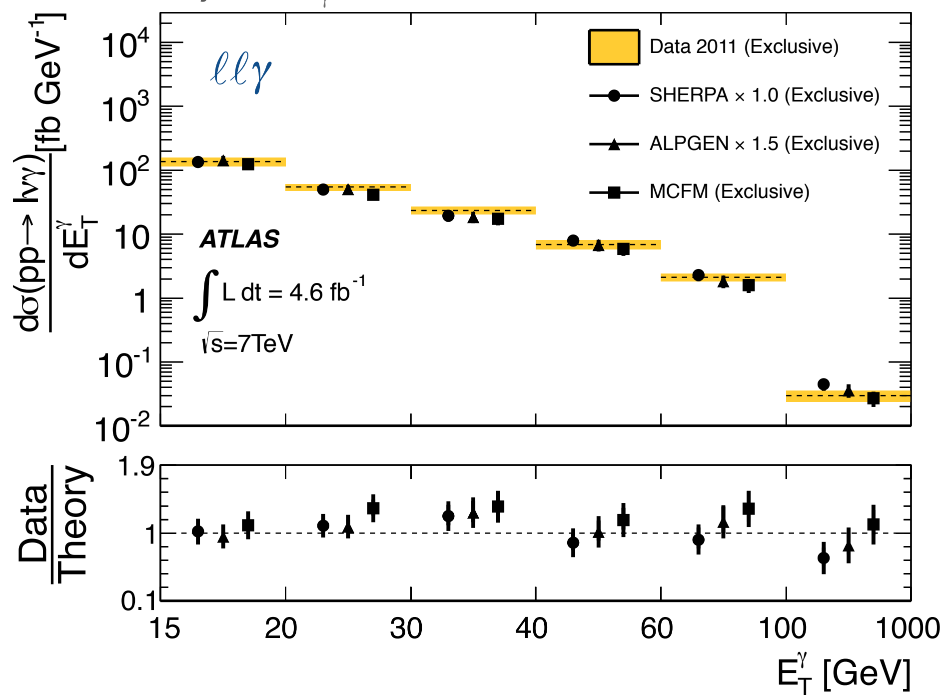
ATLAS 1302.1283

Examples for differential cross section measurements: *Wγ*, *Zγ* (7 TeV, 4.6 fb^{-1})

Inclusive E_γ fiducial differential cross-section



N-jet = 0 E_γ fiducial differential cross-section



Too low incl. cross-section by MCFM (NLO, parton-level). Scaled ALPGEN/SHERPA (LO) with multiple quark/gluon emission in ME more accurate → Similar for *γγ* [1211.1913]

W and *Z* physics — differential measurements

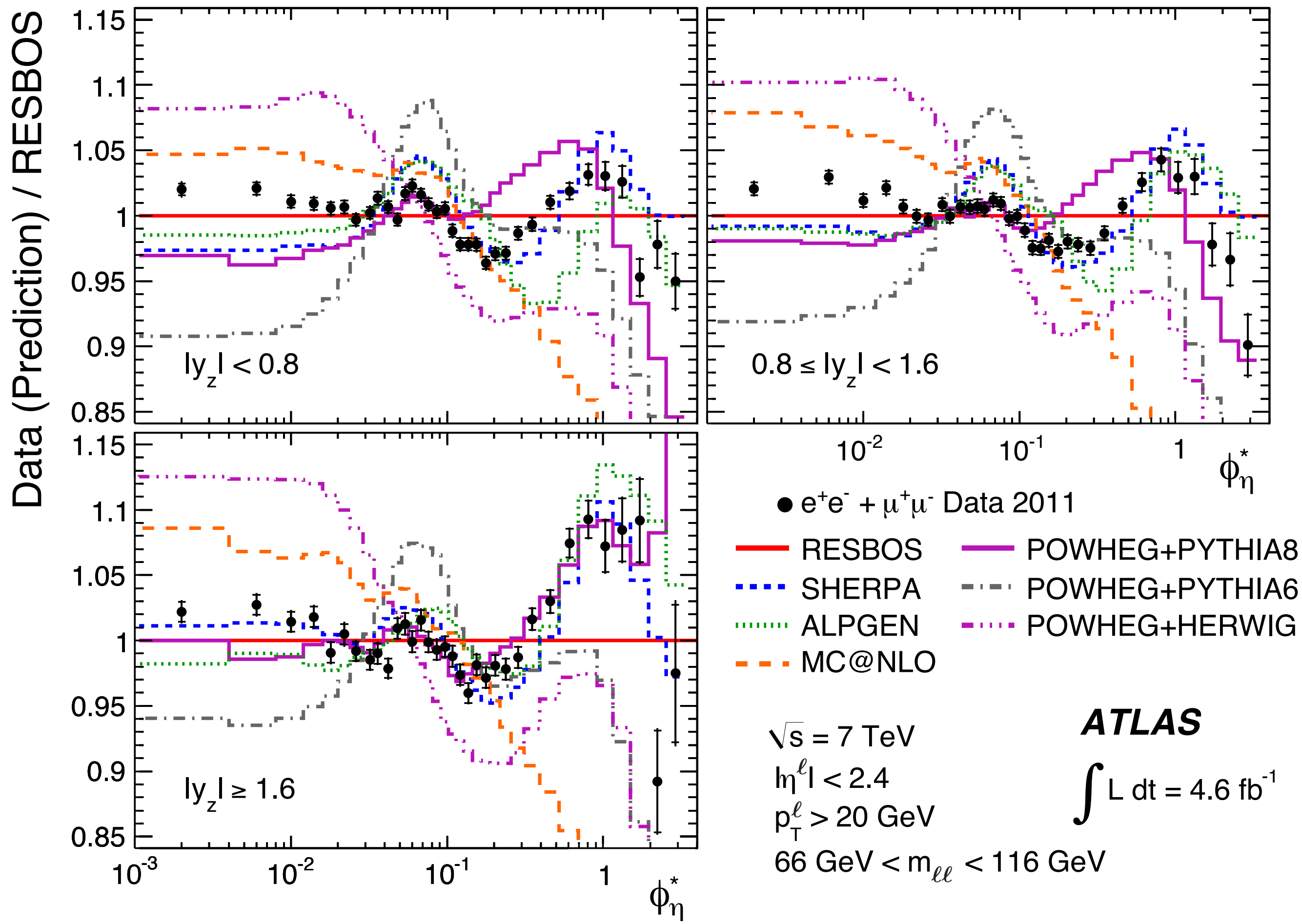
Large statistics allows precise tests of generators/theory, PDFs and bkg to searches

1211.6899

Measurement of Z/γ ϕ_η^* distribution

- ϕ_η^* is measure of scattering angle of leptons wrt. z in Z/γ rest frame
- Depends on lepton angles only, more precisely measured than momenta
- ϕ_η^* correlated to $p_{T,Z}/m_{ll}$ → probes same physics

ResBos provides best description (within 4%), large deviations for POWHEG / MC@NLO



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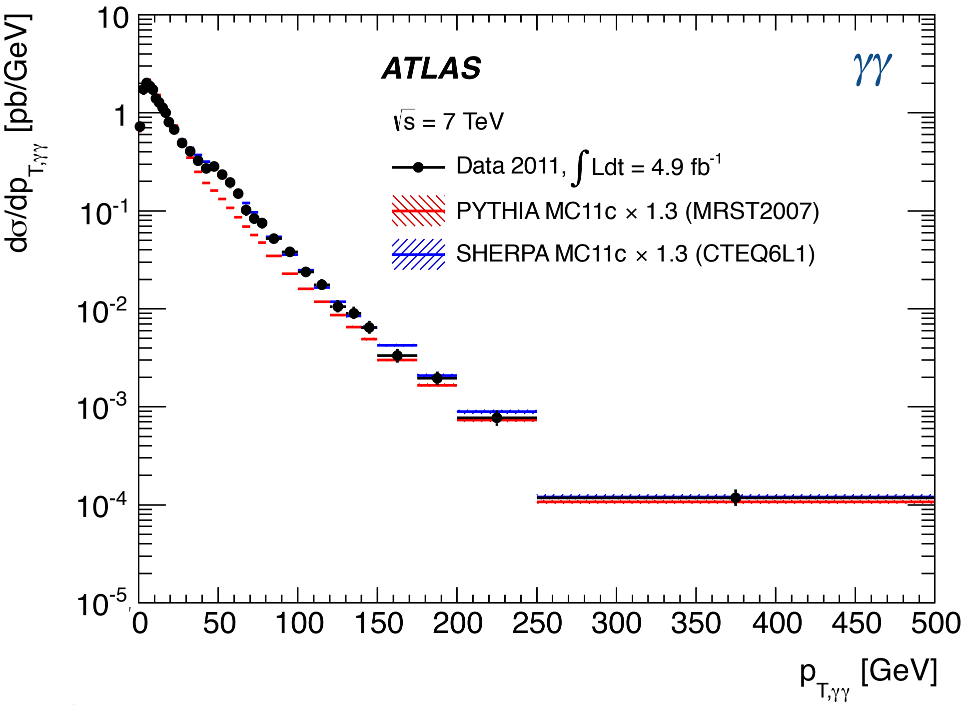
See last week's ATLAS diboson seminar by Shih-Chieh Hsu: http://indico.cern.ch/conferenceDisplay.py?confId=218398

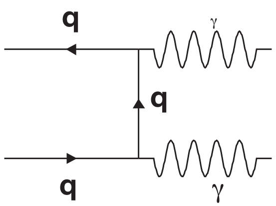
1211.1913

Examples for differential cross section measurements: $\gamma\gamma$ (7 TeV, 4.9 fb^{-1})

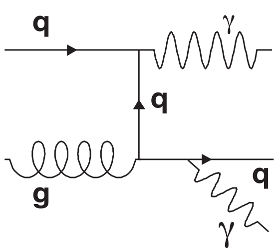


Rescaled LO PS generators describe spectra better than HO FO generators (DIPHOX, 2γNNLO) w/o soft gluon resummation

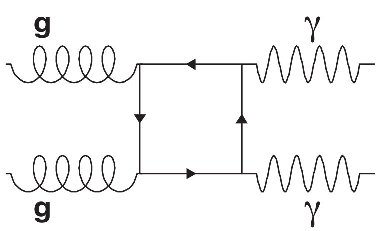
Powerful test of perturbative QCD and quark fragmentation



"Direct" quark annihilation (dominant: O(α^2))



Collinear fragmentation, $O(\alpha^2\alpha_S)$, but non-isolated γ



Box diagram, $O(\alpha^2\alpha_S^2)$, but due to *gg* luminosity comparable to LO terms

Diboson physics: *WW*, *WZ*, *ZZ*, *Wγ*, *Zγ*, *γγ*

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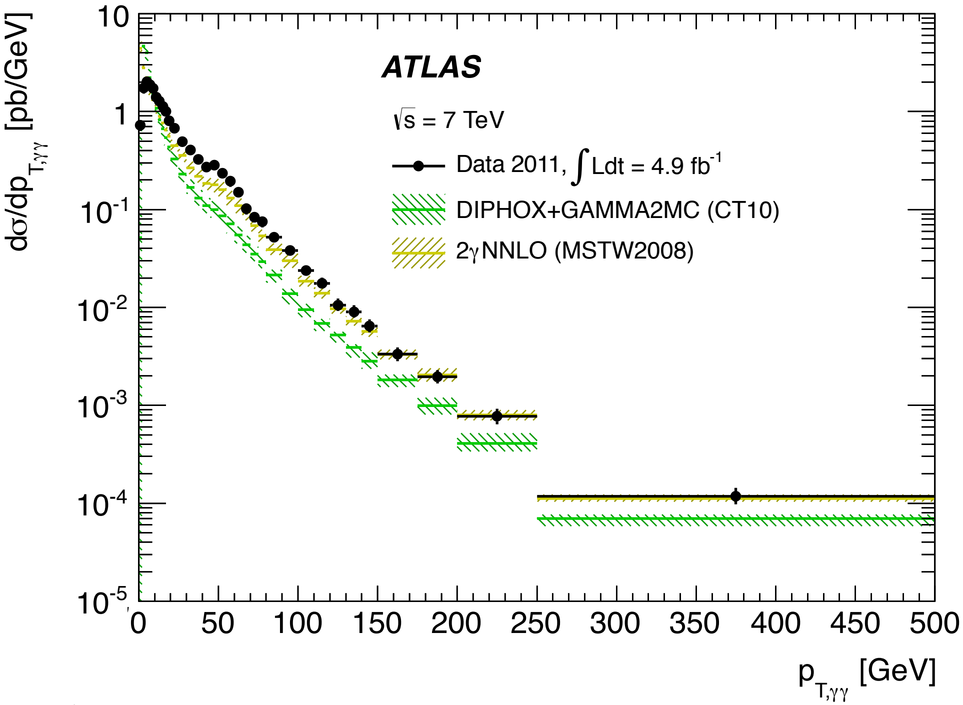
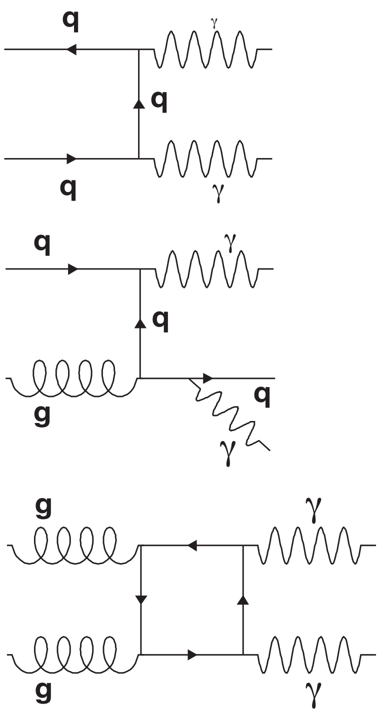


Fixed-order generators lack soft gluon resummation (IR divergence)

Powerful test of perturbative QCD and quark fragmentation



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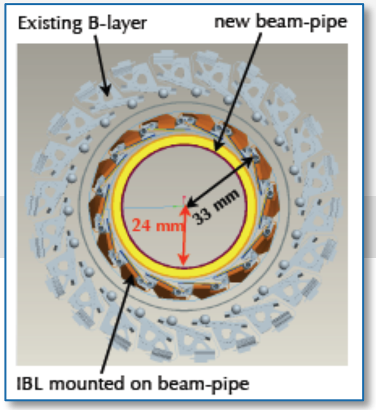
Box diagram, $O(\alpha^2\alpha_S{}^2)$, but due to *gg* luminosity comparable to LO terms

LS1 and more



LS1 consolidation and upgrade work

- New Insertable Pixel *B*-layer (IBL)
  [installation either on surface (preferred) or in situ / decision end of Jan 2013]
- New Pixel service quarter panels (nSQP) [***if IBL installed on surface***]
- New ID evaporative cooling plant
- New Al forward beam pipe
- New calorimeter LVPS
- Consolidation of other detectors and infrastructure
- Complete muon spectrometer (EE, RPC, feet)
- Add specific muon shielding
- Upgrade magnet cryogenics
- Detector readout for Level-1 100 kHz rate

Towards the Phase-1 upgrade

- LoI submitted Marc 2012 / received strong support from LHCC
- Work for TDRs in full swift: four (new μ SW, FTK, LAr+Tiles, TDAQ) expected to be completed in 2013, AFP in 2014

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 LS1: prepare LHC for design *E* & lumi

Collect ~30 fb^{-1} per year at 13/14 TeV

2018 Phase-1 upgrade for ultimate lumi

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

~2022 Phase-2 upgrade to HL-LHC

~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

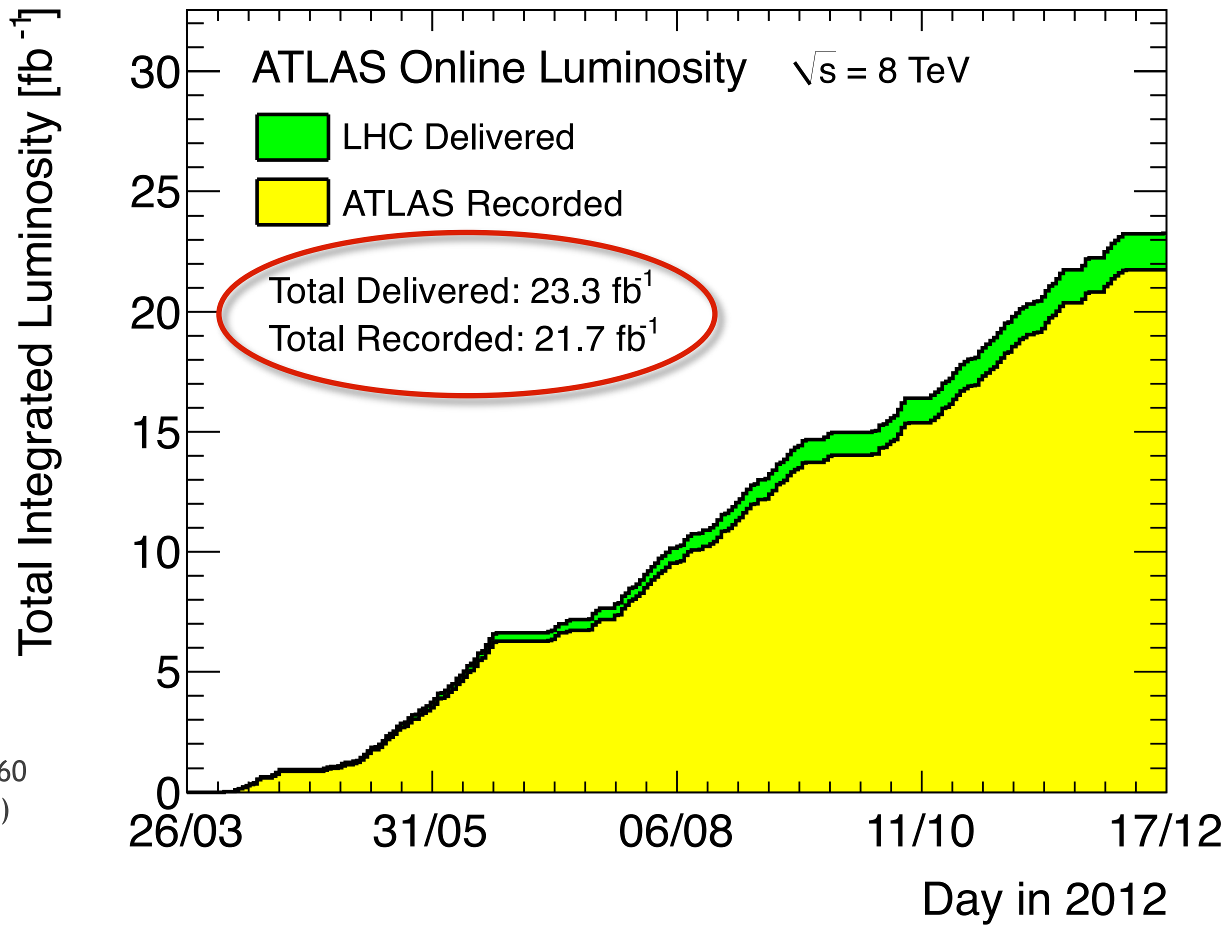
~2030

Good luminosity recorded in 2012 (and already in 2011) …

Measured with forward detectors, calibrated with beam separation scans (±2.8%)

ATLAS integrated luminosity in 2012

- Peak $L = 7.7\times10^{33}$ $s^{-1}cm^{-2}$ (Aug)
- Max L/fill: 237 pb^{-1} (June)
- Weekly record: 1350 pb^{-1} (June)
- Longest stable beams: 22.8 h (July)
- Fastest turn-around between stable beams: 2.1 h (April)
- Best weekly data-taking efficiency: 92 h (55%) (July)



At $L = 7\times10^{33}$ $s^{-1}cm^{-2}$ and 8 TeV pp collisions, 560 Higgs bosons of mass 125 GeV ($\sigma_{pp\to H}$ = 22.3 pb) are produced in ATLAS and CMS per hour

Or: every 45 min. 1 $H \to \gamma\gamma$, need ~2 typical 160 pb^{-1} fills to produced one $H \to 4l$ ($l=e/\mu$)