Background estimation in ATLAS SUSY searches

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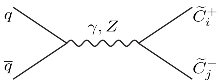
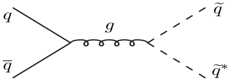
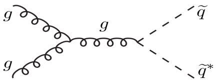
Overview of SUSY searches



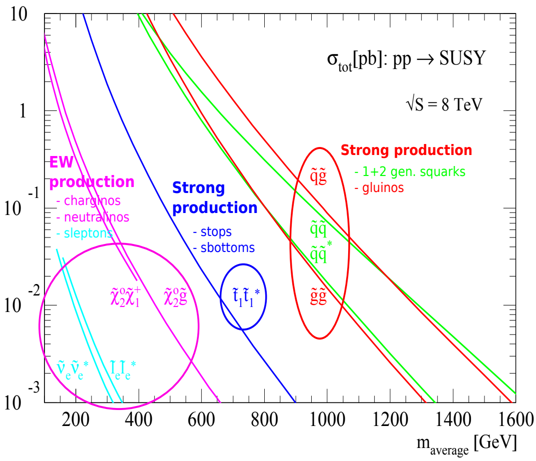
chargino pair production



squarks pair production



gluino pair production



- **Inclusive searches for $\tilde{q}$ and $\tilde{g}$**
  - Large cross-section
  - Rich final states in case of $\tilde{g}$-$\tilde{g}$ production

- **Searches for $\tilde{t}_1$ and $\tilde{b}_1$**
  - final state very similar to the $t\bar{t}$ bkg :
    - $\sigma(\tilde{t}_1\tilde{t}_1)$ for $m_{\tilde{t}_1} = 500$ GeV ~ 0.1 pb
    - $\sigma(t\bar{t}) = 253$ pb

$\Longrightarrow$ need dedicated searches to extract the signal from the $t\bar{t}$ background

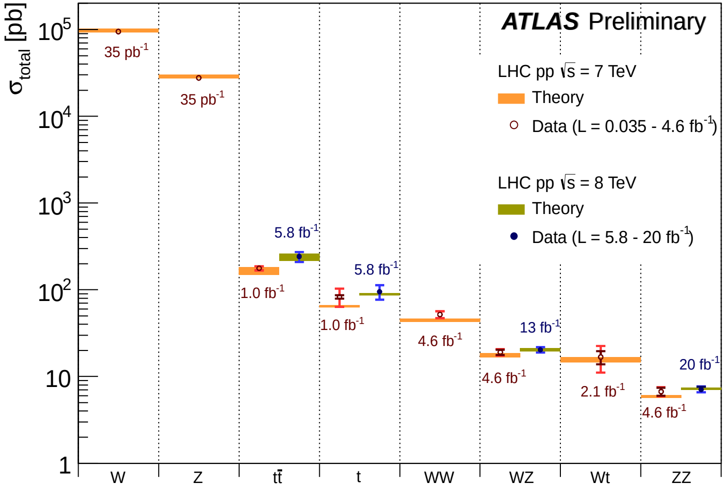
- **Searches for $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^{\pm}$**
  - low cross-section
  - multi-leptons final states with low SM bkg (mainly diboson WW, WZ and ZZ)

+ dedicated searches for long-lived particles and RPV SUSY

Overview of the Standard Model backgrounds

- Large statistics allow precise tests of higher order perturbative QCD calculations and MC generators with different scales, parton showers, PDFs for SM processes

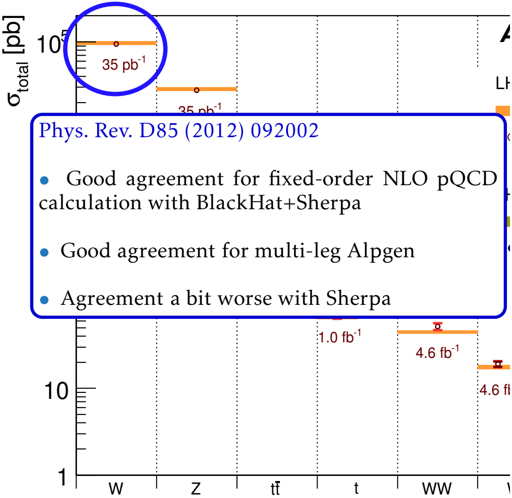
- Very good agreement between SM prediction and measurement for all SM processes over many order of magnitude production rate, except a small excess in data for *WW*



Overview of the Standard Model backg

- Large statistics allow precise tests of higher orde generators with different scales, parton showers, PDFs

- Very good agreement between SM prediction and m order of magnitude production rate, except a small exc

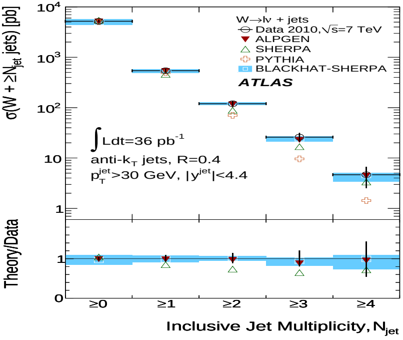


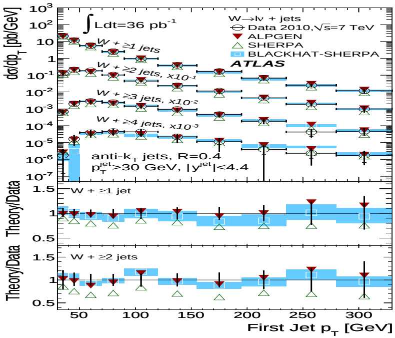
Phys. Rev. D85 (2012) 092002

- Good agreement for fixed-order NLO pQCD calculation with BlackHat+Sherpa

- Good agreement for multi-leg Alpgen

- Agreement a bit worse with Sherpa





Overview of the Standard Model backg

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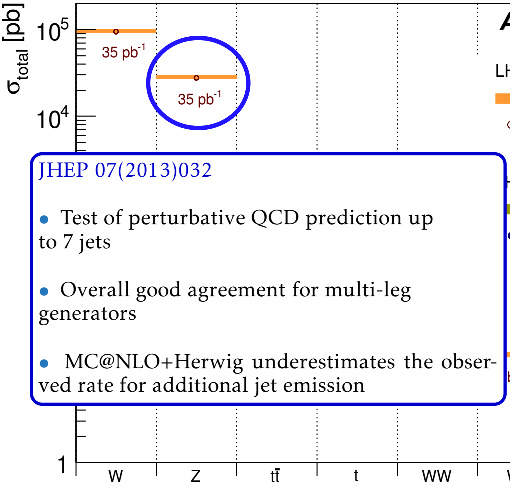
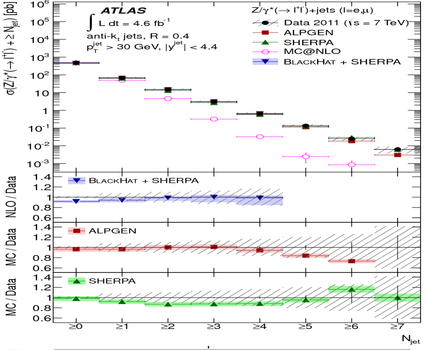
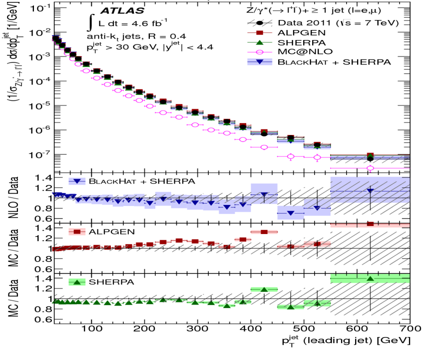


JHEP 07(2013)032

- Test of perturbative QCD prediction up to 7 jets
- Overall good agreement for multi-leg generators
- MC@NLO+Herwig underestimates the observed rate for additional jet emission



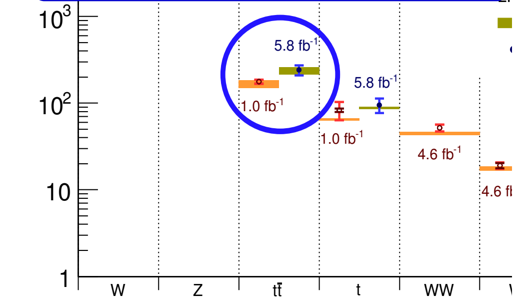


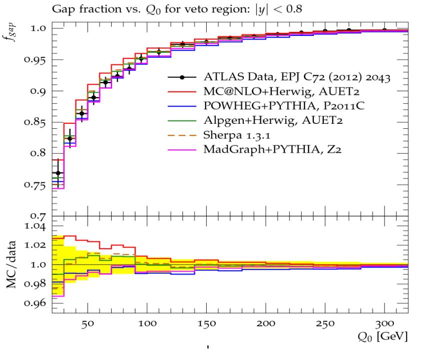
Overview of the Standard Model backg

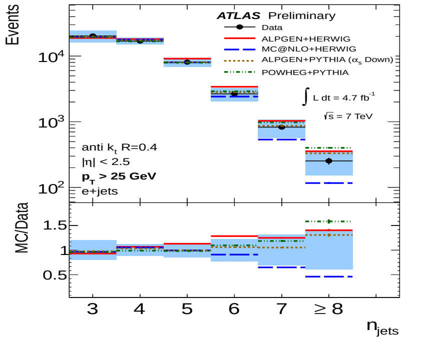
- Large statistics allow precise tests of higher orde generators with different scales, parton showers, PDFs
- V orde

ATL-PHYS-PUB-2013-005

- Jet p_T spectrum predicted by MC@NLO is too soft
- Good agreement with the other NLO generator Powheg+Pythia
- Good agreement too with multi-leg generators Alpgen and Sherpa



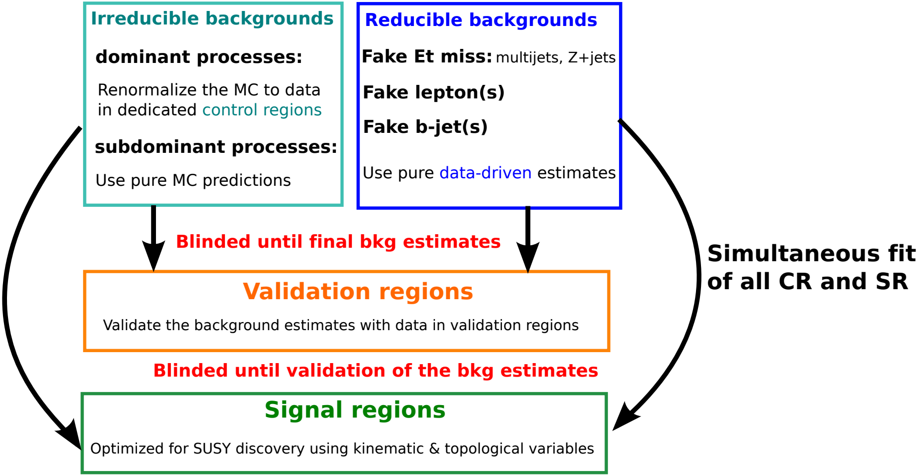




Standard Model processes

Top, QCD multijets,V, VV, VVV, Higgs,
& combinations of processes

can mimic the SUSY signal in the signal regions



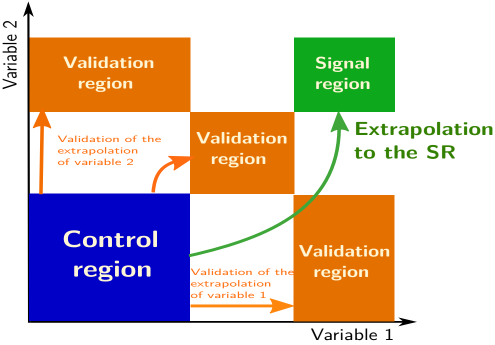
Irreducible backgrounds : semi data-driven technique

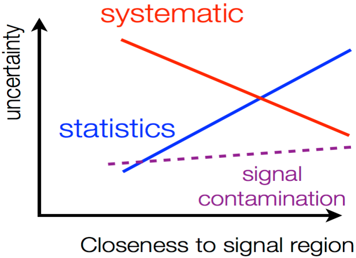
- Principle : renormalize the MC prediction in control regions kinematically close to the signal region :

$$N_{\mathrm{SR}}^{bkg,est} = \frac{N_{\mathrm{SR}}^{\mathrm{bkg,MC}}}{N_{\mathrm{CR}}^{\mathrm{bkg,MC}}} \cdot \left[N_{\mathrm{CR}}^{\mathrm{data}} - N_{\mathrm{CR}}^{\mathrm{other,MC}} \right] = T_f(CR \to SR) \cdot \left[N_{\mathrm{CR}}^{\mathrm{data}} - N_{\mathrm{CR}}^{\mathrm{other,MC}} \right]$$

► Systematic uncertainties which are correlated between CR and SR (experimental : JES, JER, b-tagging... and theoretical : MC generator modelling, Parton Shower, μ_F, μ_R, PDFs...) largely cancel out in the transfer factor.

- CR can be defined by reverting some cuts, or by requiring 1-2 lepton(s) and treating the lepton as a jet or a ν to reproduce hadronic taus from $W \to \tau\nu$ or neutrinos from $Z \to \nu\nu$
- The extrapolation from the CR is validated in intermediate validation regions
- Cross-contamination of other bkg and signal in each CR taken into account in the simultaneous fit of all CR and SR, the systematic uncertainties being treated as nuisance parameters



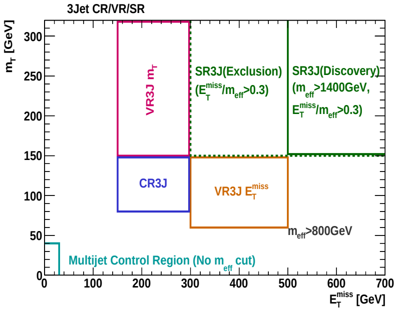


Example from the inclusive 1-lepton analysis ATLAS-CONF-2013-062

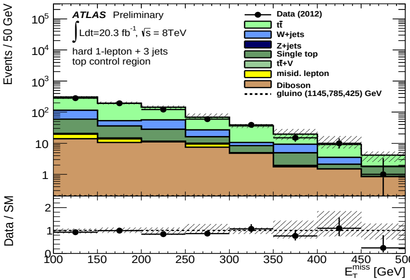
- SR defined with cuts on $m_T, \not{E}_T, \not{E}_T/m_{eff}$ and m_{eff} (binned fit of m_{eff} for exclusion limits)

- 2 CR defined be reverting the m_T and $\not{E}_T$ cuts, and dropping the $\not{E}_T/m_{eff}$ cut to gain statistics :
  - $t\bar{t}$ control region : $\geqslant 1$ b-jet
  - W+jets control region : $= 0$ b-jet

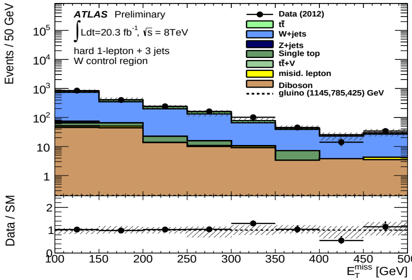
- 2 validation regions are used to cross-check the extrapolation in m_T and $\not{E}_T$



$t\bar{t}$ CR : $\geqslant 1$ b-jet



W+jets CR : b-jet veto



Estimation of the irreducible $Z \to \nu\nu$+jets background

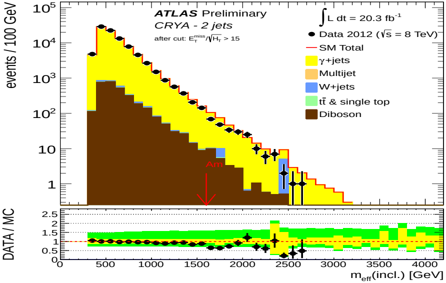
- $Z \to \nu\nu$+jets is often an important background for 0-lepton analyses due to presence of real $E\!\!\!/_T$
  - 2 semi-data driven methods to estimate its contribution

γ+jets method

- Use to estimate Z+jets in the 0-ℓ inclusive search : 0-ℓ + 2-6 jets + $E\!\!\!/_T$: ATLAS-CONF-2013-047

- CR defintion :
  - 1 photon with $p_T > 130$ GeV
  - $\vec{p_T}(\gamma)$ added to $\vec{p_T}^{miss}$ to mimic the ν
  - all SR selection applied

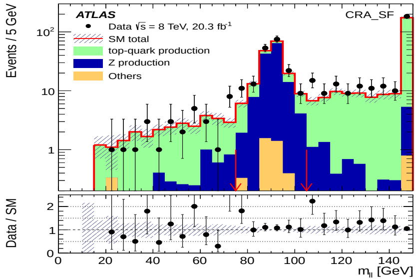
$$N^{Z\to\nu\nu} = N^{\gamma}\left[\frac{1-f^{\gamma})}{\varepsilon^{\gamma}\cdot\mathcal{A}^{\gamma}}\right]\cdot R^{MC}_{Z/\gamma}\cdot Br[Z\to\nu\nu]$$



$Z \to \ell\ell$+jets method

- Use to estimate $Z + b\bar{b}$ in the sbottom search : 0-ℓ + 2b-jets + $E\!\!\!/_T$: arXiv:1308.2631

- CR defintion :
  - e^+e^- + $\mu^+\mu^-$
  - $\vec{p_T}(\ell)$ added to $\vec{p_T}^{miss}$ to mimic the ν
  - $75 < m(\ell\ell) < 105$ GeV
  - 2 b-jets (+ SR cuts)



Estimation of the reducible fake $\not{E}_T$ bkg : the jet smearing method

■ QCD multi-jets events can mimic signal events with high $\not{E}_T$ because of jet energy mismeasurement

- ▸ very low probability for each event to pass the tight selection cuts
- ▸ very large cross-section could lead to significant contamination in the signal regions

A pure MC estimate would require huge MC samples are required and a detailed understanding of the calorimeter performance to model jet energy mismeasurement

$\Longrightarrow$ **Use the data-driven Jet Smearing Method :** (Phys.Rev. D87 (2013) 012008)

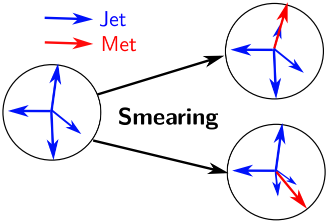
■ Principle of the method :

I Build the jet response function R=p_T^{reco}/p_T^{true} which quantifies the probability of fluctuation of the jet p_T

II Select a data set of well-measured multi-jets events with $\not{E}_T$ significance $\not{E}_T/\sqrt{H_T} < 0.6\ \mathrm{GeV}^{\frac{1}{2}}$

III Smear each jet p_T of this sample with a random number drawn from R to generate QCD pseudo-data events

IV Normalise the shape in a multijets enhanced region with $\Delta\phi_{min}(\not{E}_T, jet) < 0.4$



The jet smearing method : jet response functions

- The jet response function R takes into account the response of the calorimeters and the contributions from neutrinos and muons in jets from heavy-flavor decays.

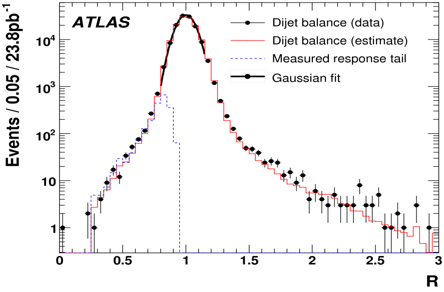
- It is first estimated from MC and then constrained to data using dijet balance (Gaussian core) and Mercedes events (tails)

Gaussian response

- Use p_T asymetry in di-jet events :

$$A(p_{T,1}, p_{T,2}) = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- a fit of A for QCD pseudo-data events and for data is used to adjust R

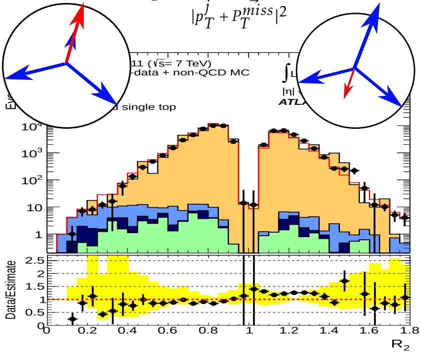


Full jet response

- Use mercedes events where $\not{E}_T$ can be unambiguously associated to 1 jet

- Fit the response R_2 of this jet in (p_T, η) bins :

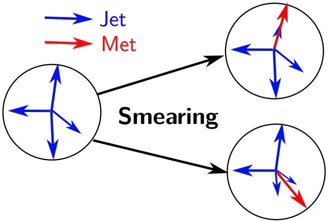
$$R_2 \equiv \frac{\vec{p_T^j} \cdot (\vec{p_T^j} + \vec{P_T^{miss}})}{|\vec{p_T^j} + \vec{P_T^{miss}}|^2}$$



The jet smearing method : final estimate

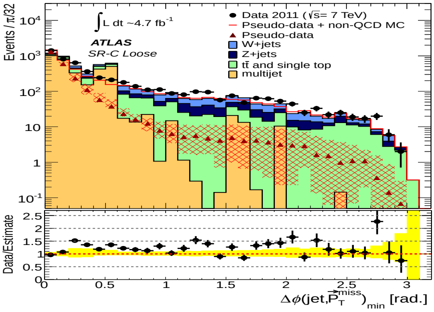
- This response function is then used to randomly smear each jet p_T of the seed sample to generate QCD pseudo-data events.

Each sample is smeared several times to reduce the statistical uncertainty

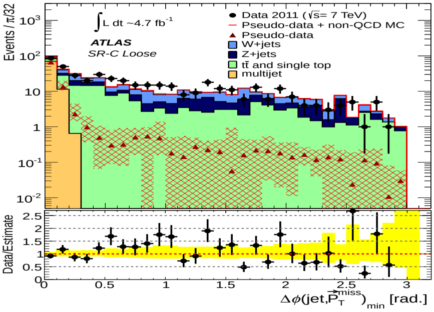


- Finally, the QCD pseudo-sample is normalized to data in a multijets enhanced region with $\Delta\phi_{min}(\not{E}_T, jet) < 0.4$

Before selection



After selection

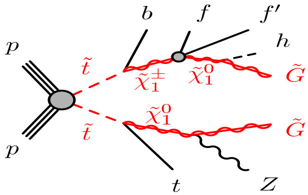


The jet smearing method for the Z+jets background

- Some analyses target signal with Z-bosons in the decay chain selecting events with 2-leptons SFOS consistent with M_Z

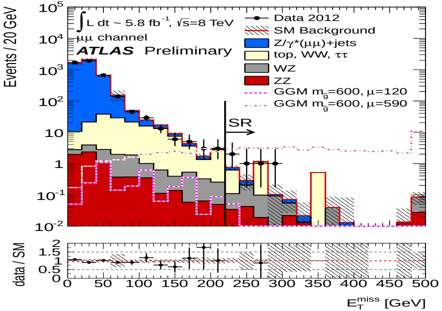
$\Longrightarrow$ **Use a data-driven Jet Smearing Method**

- The jet response function tuned to data using the balanced photon in γ+jet events

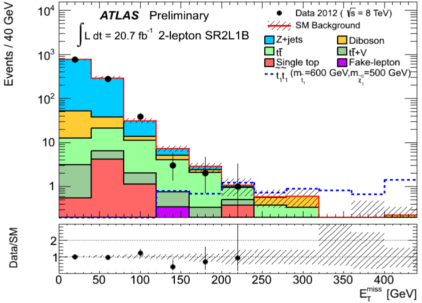


- the QCD pseudo-sample is normalized to data in a multijets enhanced region with low $\not{E}_T$

ATLAS-CONF-2012-152



ATLAS-CONF-2013-025



Alternative method : the template method   ATLAS-CONF-2013-025

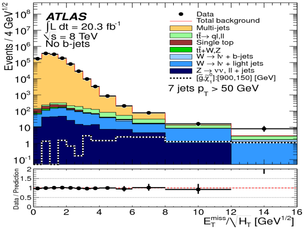
- Method based on the observation that the jet p_T resolution is $\propto \sqrt{p_T}$
  - ▶ In events dominated by jet activity, $\not{E}_T/\sqrt{H_T}$ is $\sim$ invariant under changes in jet multiplicity
- The multijet background can be estimated using control regions with lower $\not{E}_T/\sqrt{H_T}$ and/or jet multiplicity than the signal region (ABCD method) :

$$N^{pred}_{\not{E}_T/\sqrt{H_T}>4.0,N_j\geqslant 9} = N^{obs}_{\not{E}_T/\sqrt{H_T}<1.5,N_j\geqslant 9} \frac{N^{obs}_{\not{E}_T/\sqrt{H_T}>4.0,N_j=6}}{N^{obs}_{\not{E}_T/\sqrt{H_T}<1.5,N_j=6}}$$

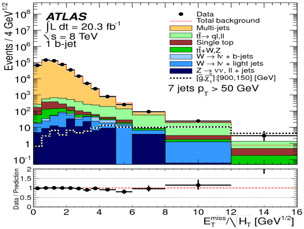
where N^{obs} have the non-QCD background subtracted from MC

- Semi-leptonic heavy flavours decays are taken into account using consistent b-jets requirement used in the control and signal region

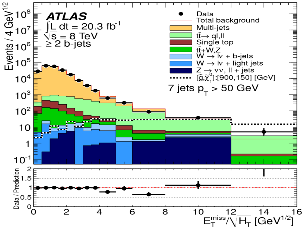
0 b-jets



1 b-jets



$\geqslant$ 2 b-jets



Estimation of the fake lepton background : The matrix method

■ Several sources of non-prompt leptons :

- fake electrons : γ conversion, misindentified jets, HF decay
- fake muons : π, K decay, punch-through, HF decay

$\Longrightarrow$ **Use the data-driven Matrix Method :**

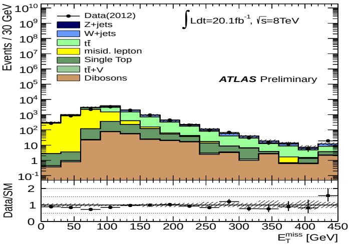
I Define 2 data samples with ≠ lepton criteria selection : tight (signal) and loose (relaxed)

II Measure in data the “loose → tight” ε for real/fake leptons

$$\varepsilon_{real} = N_{real}^{tight} / N_{real}^{loose} \quad \text{and} \quad \varepsilon_{fake} = N_{fake}^{tight} / N_{fake}^{loose}$$

- ▸ ϵ_{real} : can be estimated from MC using $Z \to \ell^+\ell^-$ or from data with the tag and probe method.
- ▸ ε_{fake} : can be estimated from data using control regions enriched in each source of fake leptons.

1-lepton analysis (ATLAS-CONF-2013-062)



III Solve the system of 2 equations to get $N_{fake}^{data}(SR)$:

$$N_{data}^{loose} = N_{real}^{loose} + N_{fake}^{loose}$$

$$N_{data}^{tight} = \varepsilon_{real} N_{real}^{loose} + \varepsilon_{fake} N_{fake}^{loose}$$

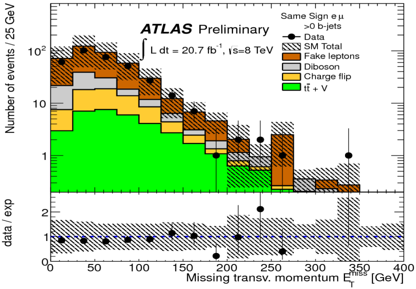
Extension of the matrix method for multilepton analyses

- In dilepton analyses, we can use a 4×4 matrix to take into account all possible combinations of tight (T) and loose (L) lepton :

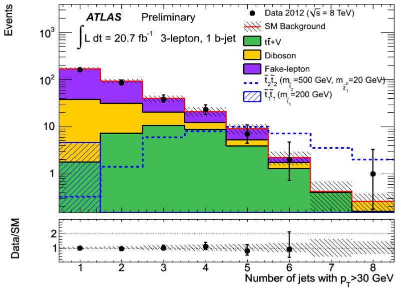
$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} \varepsilon_r\varepsilon_r & \varepsilon_r\varepsilon_f & \varepsilon_f\varepsilon_r & \varepsilon_f\varepsilon_f \\ \varepsilon_r(1-\varepsilon_r) & \varepsilon_r(1-\varepsilon_f) & \varepsilon_f(1-\varepsilon_r) & \varepsilon_f(1-\varepsilon_f) \\ (1-\varepsilon_r)\varepsilon_r & (1-\varepsilon_r)\varepsilon_f & (1-\varepsilon_f)\varepsilon_r & (1-\varepsilon_f)\varepsilon_f \\ (1-\varepsilon_r)(1-\varepsilon_r) & (1-\varepsilon_r)(1-\varepsilon_f) & (1-\varepsilon_f)(1-\varepsilon_r) & (1-\varepsilon_f)(1-\varepsilon_f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

- In analyses with 3-leptons, it has been observed that the leading lepton is almost always real. Therefore the same 4×4 matrix method can be applied to the 2^{nd} and 3^{rd} leptons

2-leptons analysis (ATLAS-CONF-2013-007)



3-leptons analysis (ATLAS-CONF-2013-025)



Extension of the matrix method for the fake b-jets background

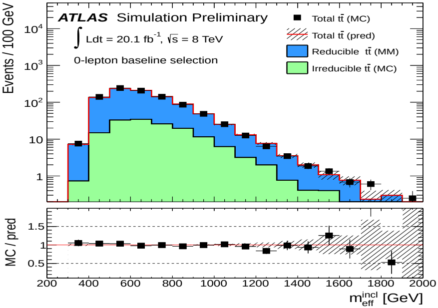
- Analyses with $\geqslant 3$ b-jets are dominated by reducible backgrounds with at least 1 fake b-jet arising from charm, tau or light jet (ATLAS-CONF-2013-061)

► this fake b-jets background can be estimated using an extension of the matrix method

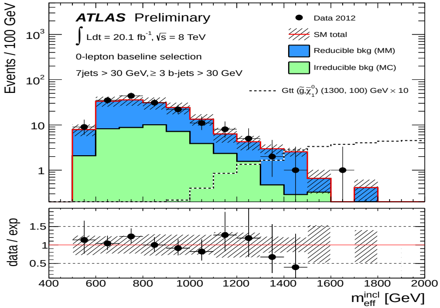
- As for the lepton matrix method, it is based on 2 data samples with ≠ jet tagging criteria : tight (with) and loose (without) b-tagging requirement

- To take into account all possible combinations of real and fake b-jets amongst the N_j jets of the event, we solve a system of 2^{N_j} equations based on the b-tagging efficiencies and fake rates of these jets

Closure test in MC



Results in data



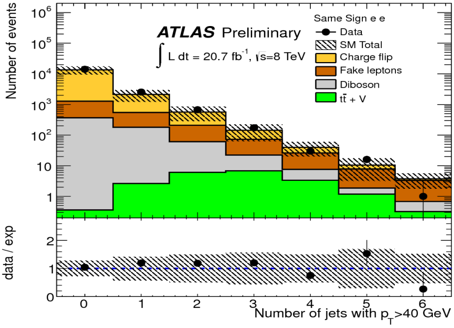
Lepton charge mis-identification

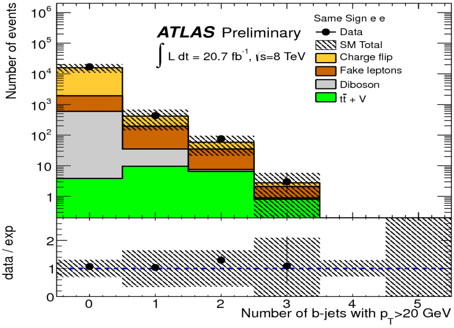
ATLAS-CONF-2013-007

- Reducible background for 2-leptons same-sign analysis due to OS ee events (mainly dilepton $t\bar{t}$) with conversion of a hard photon bremsstrahlung $e^{\pm} \rightarrow e^{\pm}\gamma \rightarrow e^{\pm}e^{\pm}e^{\mp}$
- Contribution from charge mis-ID for muons is negligible
- charge flip probability is measured as a function of the electron (p_{T},η) in 2-e events with $|m(ee) - m(Z| < 15$ GeV :

$$\varepsilon_{flip}(p_{\mathrm{T}},\eta) = \frac{N_{SS}}{(N_{SS}+N_{OS})} \qquad (\varepsilon_{flip} \quad \text{from} \quad 10^{-4} \quad \text{to} \quad 0.02)$$

- ε_{flip} is then applied in CR with all SR cuts applied, but with OS leptons





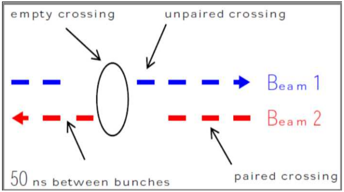
Example of background estimate in RPV SUSY searches

- Search for long-lived gluinos producing hadronic activity in out of time collisions : arXiv:1310.6584

  $\Longrightarrow$ look events with 1 high p_T jet and muon segment veto in empty bunch crossings

- Beam-halo bkg from muons produced in the interaction of the beam with the residual gas in the beampipe (or the beampipe itself) which travel parallel to the beamline up to the ATLAS detector

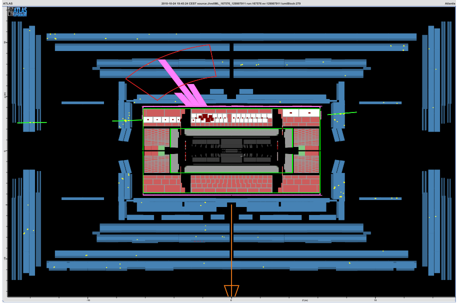
  ▶ Measure the ratio of beam-halo events which pass/fail the muon segment veto in SR in orthogonal data sample with unpaired bunches



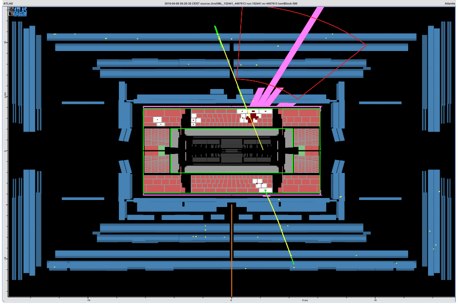
- Cosmic muon bkg :

  ▶ scaled from early 2011 data periods with low integrated luminosity

beam-halo candidate in unpaired data



cosmic muon bkg before muon segment veto



Summary and prospects

■ Well established strategy to estimate the backgrounds in SUSY searches

→ Irreducible background : semi data-diven estimates based on the renormalization of the MC to data in control region

→ Reducible background : fully data-driven estimates

■ No hint of SUSY so far, but SUSY discovery potential strongly increased at 13/14 TeV :

- $\sigma(t\bar{t})\times \sim 4$
- $\sigma(\widetilde{t_1} = 0.6TeV)\times \sim 10$
- $\sigma(\tilde{g} = 2TeV)\times \sim 200$

but we will also have to cope with more pileup and larger expected MC uncertainties

▶ Important to have robust bkg predictions :

- improve the MC generator predictions
- Reduce systematic uncertainties
- measuring more rare SM process cross-sections
- develop new data driven method etc..

Result for ECFA meeting - showing HL-LHC reach for direct stop search (ATL-PHYS-PUB-2013-011)