SUperSYmmetry searches at LHC: Part I

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"I am sure we all agree that a giraffe is truly beautiful, but she doesn't seem to serve any purpose".
J. Weiss (1974)

"Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it."
A. Einstein (1933)

"Theories are like fishing : only he who casts can catch"
Novalis (1772-1801)

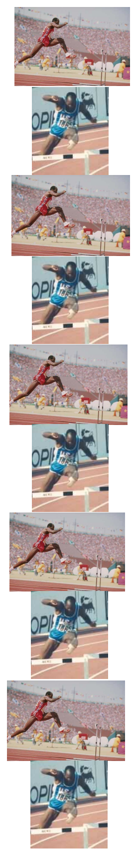
Mandate: "Cover the broad scope of the many various SUSY searches by both CMS and ATLAS at the LHC and their possible future prospects"

Lecture Overview

❑ Part I : Ingredients needed for a SUSY search at LHC

400 m hurdles
➔ 400m to run
➔ 10 hurdles to clear

First (but last) sections of the SUSY papers



1. Motivation
2. Detector description
3. Monte Carlo Simulation
4. Object Reconstruction
5. Trigger & Event Selection
6. Background Estimation
7. Systematic uncertainties on background estimation
8. Results
9. Result Interpretation
10. Conclusion

TODAY !

❑ Part II : Status of SUSY searches at LHC & Prospects

Edwin Moses, , 400 m hurdles (47s75")
Los Angeles Olympic Games 1984

Result (last) section of SUSY papers

1. R-Parity Conserving [RPC] inclusive searches
2. Natural RPC: stop, sbottom, EWK-inos
3. Long Lived particles
4. R-Parity Violating [RPV] signatures
5. Monojets ←→ Dark Matter production **See Dan Hooper**
6. MSSM Higgs Searches **See Vivek Sharma**
7. Future prospects

TOMORROW !

Lecture Overview

❑ Part I : Ingredients needed for a SUSY search at LHC

→ "What drives the sensitivity to SUSY at LHC ?"

400 m hurdles
➔ 400m to run
➔ 10 hurdles to clear

First (but last) sections of the SUSY papers

1. Motivation
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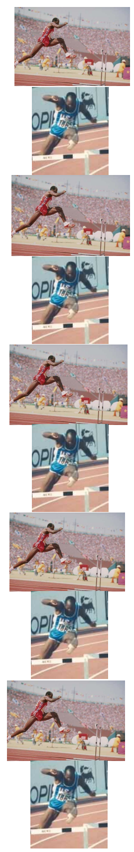

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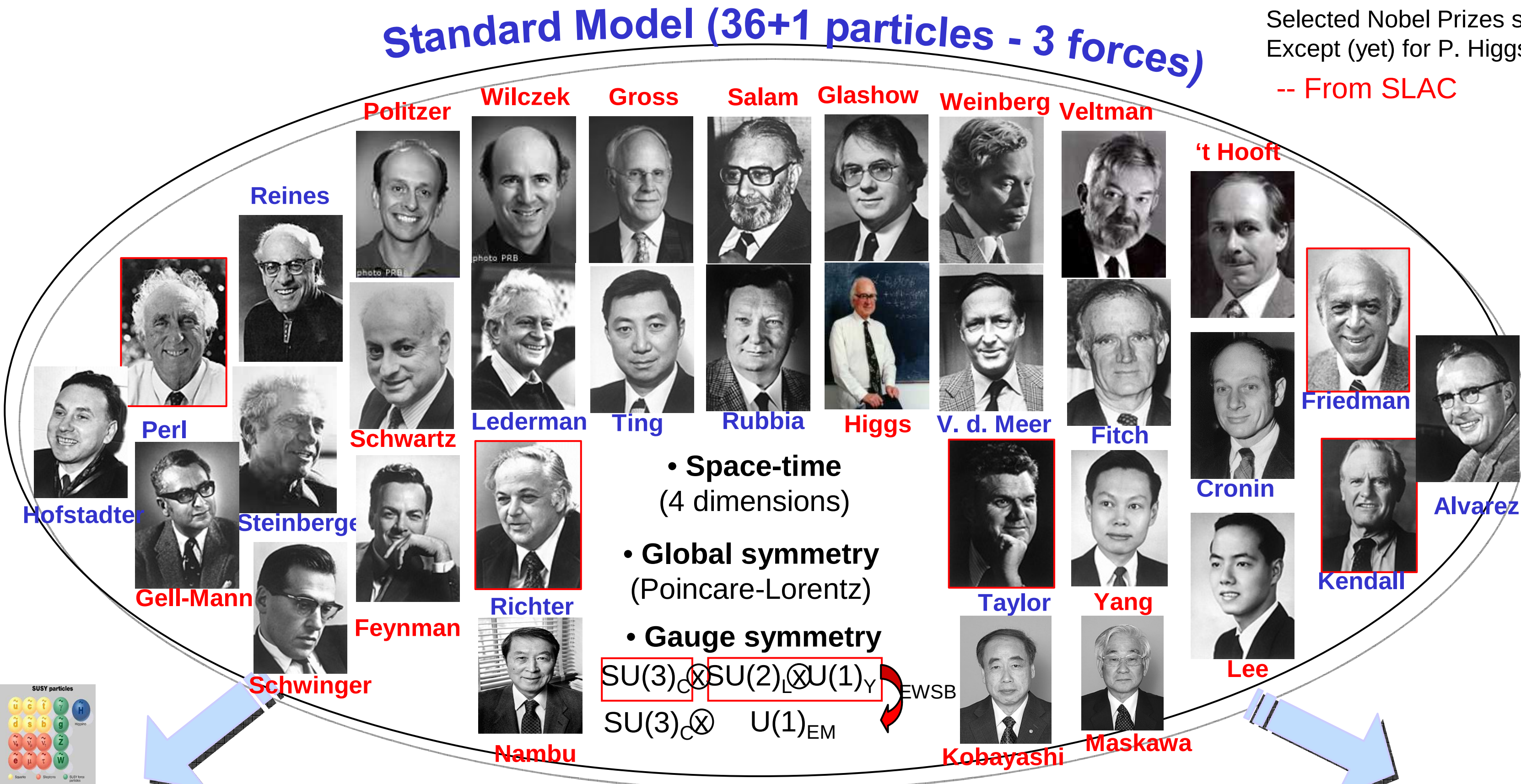
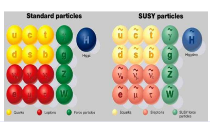
Motivation

Selected Nobel Prizes since 1957
Except (yet) for P. Higgs
-- From SLAC





AdS/CFT

Supersymmetry (SUSY)

- New symmetry between boson & fermions (broken) following generalisation of space-time symmetries
- Higgs (H) mass stabilized

➔New particles at ≈ TeV scale (2xSM) weakly coupled to H

+ *Force unified at 2 10^{16} GeV, Dark Matter candidate, gravitation*

Extra Dimensions/Technicolor

- New dimensions/interactions/substructure
- Higgs (H) mass stabilized

➔New particles at ≈ TeV scale, strongly coupled to H

SUSY at LHC (1)

❑ Theoretical framework used for SUSY searches at LHC

- Concentrate on SUSY models that give new particles in 100 GeV- 1TeV range !
  - ➔ By default here SUSY = weak scale SUSY = Minimal SuperSymmetric Model (MSSM)
- A wide spectrum of SUSY models on the market

MSSM with R-Parity Violation
Lepton/Baryon Number Violation, lepton/jet Resonance

NMSSM
Additional light scalars (Higgs, scalar gluon), Resonances

MSSM-105 (N=1) with R-Parity Conservation
Simplified MSSM (MSSM-24, pMSSM-19)
MSSM-5: GMSB(GGM) AMSB CMSSM/mSUGRA
TeV range new particles: Long decay chain, Dark Matter candidate (LSP), mass degeneracies

See J-A Hewett

Split SUSY
Long Lived particle

Simplified Model
Mimic SUSY topologies

Stealth SUSY
Compressed spectra

➔ LHC SUSY Analyses are interpreted in those models

SUSY at LHC (2)

❑ General (weak-scale) SUSY features

- **105** model parameters in the **MSSM**
- Not swamped by SUSY particle: SUSY is **broken**, but how ? (several models xxSB)
- R-parity (P_R or R_P)= -1 SUSY, +1 SM

MSSM: 29 sparticles + 5 Higgs undiscovered

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde u_L\ \tilde u_R\ \tilde d_L\ \tilde d_R$	(same)
			$\tilde s_L\ \tilde s_R\ \tilde c_L\ \tilde c_R$	(same)
			$\tilde t_L\ \tilde t_R\ \tilde b_L\ \tilde b_R$	$\tilde t_1\ \tilde t_2\ \tilde b_1\ \tilde b_2$
sleptons	0	−1	$\tilde e_L\ \tilde e_R\ \tilde \nu_e$	(same)
			$\tilde \mu_L\ \tilde \mu_R\ \tilde \nu_\mu$	(same)
			$\tilde \tau_L\ \tilde \tau_R\ \tilde \nu_\tau$	$\tilde \tau_1\ \tilde \tau_2\ \tilde \nu_\tau$
neutralinos	1/2	−1	$\tilde B^0$ (Bino) $\tilde W^0$ (Wino) $\tilde H_u^0\ \tilde H_d^0$ (Higgsino)	$\tilde N_1\ \tilde N_2\ \tilde N_3\ \tilde N_4$
charginos	1/2	−1	$\tilde W^\pm$ (Wino) $\tilde H_u^+\ \tilde H_d^-$ (Higgsino)	$\tilde C_1^\pm\ \tilde C_2^\pm$
gluino	1/2	−1	$\tilde g$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde G$	(same)

Some key parameters of MSSM

- **μ** = SUSY version of the SM Higgs mass
- **tanβ** = Ratio of vacuum expectation values of H_u/H_d
- $\mathbf{m_h}$ = Mass of h^0 $\quad m_h^2 \le M_Z^2 + \Delta m_{rad}^2 (A_t, \tan\beta, \mu, m_{\tilde t_{1,2}}, m_t, v^{**})$
- $\mathbf{m_A}$ = Mass of A^0
- $\mathbf{m_{H^+}}$ = Mass of $H^{+/-}$ $\quad \frac{1}{2}M_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$
- $\mathbf{m_{H_u}^2, m_{H_d}^2}$ from SUSY breaking
- $\mathbf{M_Q^2}$= Squark 3x3 mass term
- $\mathbf{M_L^2}$= Slepton 3x3 mass term

  } $= m_0^2$ at GUT scale*

- $\mathbf{M_1}$= Bino mass term
- $\mathbf{M_2}$= Wino mass term
- $\mathbf{M_3}$= gluino mass term

  } $= m_{1/2}$ at GUT scale*

- $\mathbf{A_{u,d,e}}$~Yukawa-like 3x3 matrix $\quad = A_o$ at GUT scale*

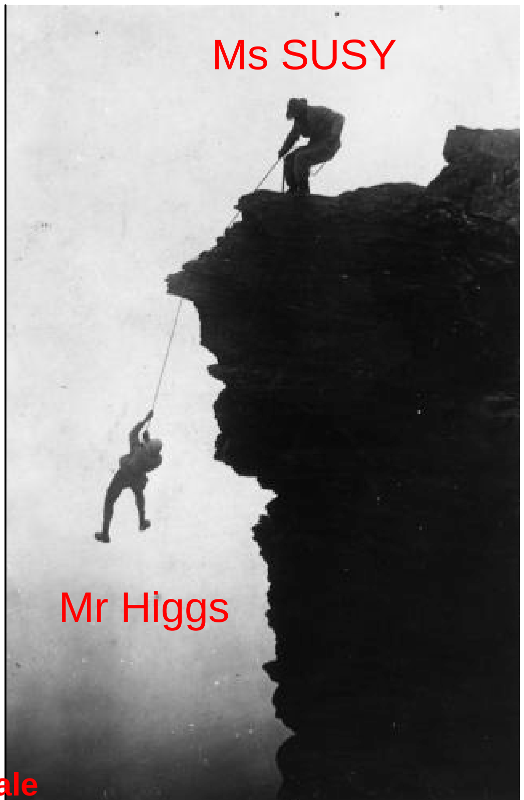
➔ A new world to explore (if it exists). Will take decades !

* In Planck scale-mediated SUSY breaking models like mSUGRA, ** $v=\sqrt{(v_u^2+v_d^2)}$

Parenthesis on the Higgs

❑ **Higgs and (weak-scale) SUSY in close relation** See M. Papucci

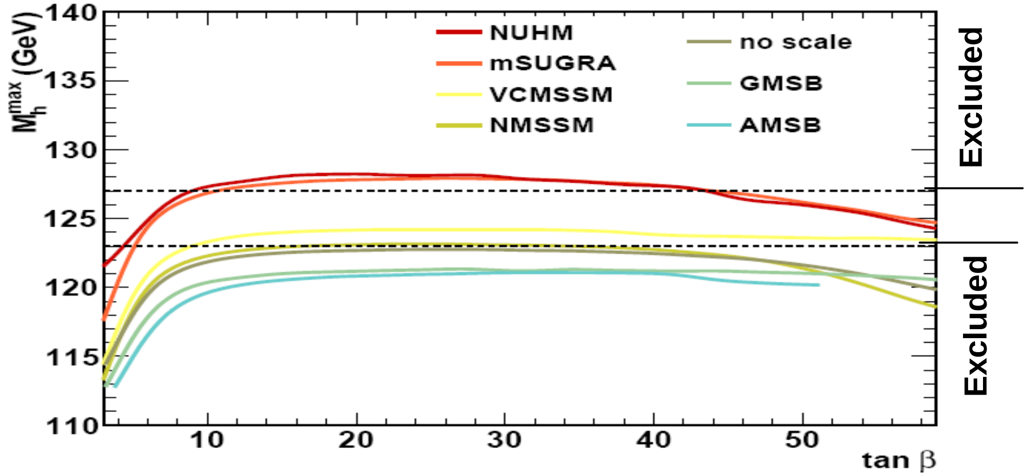
EW scale



GUT scale

Planck scale

These lectures !



➔ Already huge constraints on simpliest SUSY models

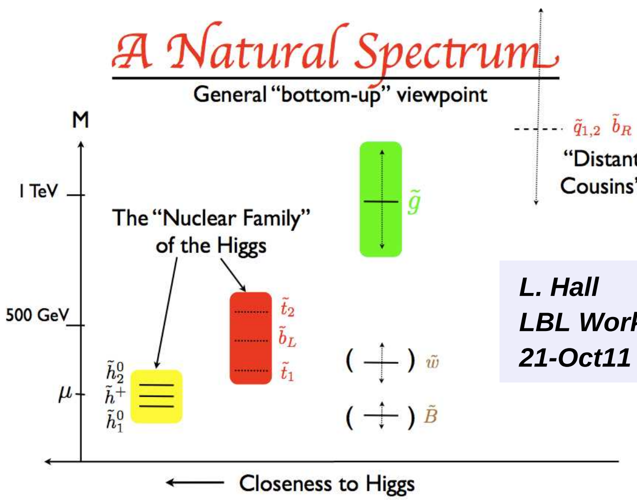
See V. Sharma

➔ 1) Direct SUSY search and 2) Higgs are equally powerfull tools to discover SUSY

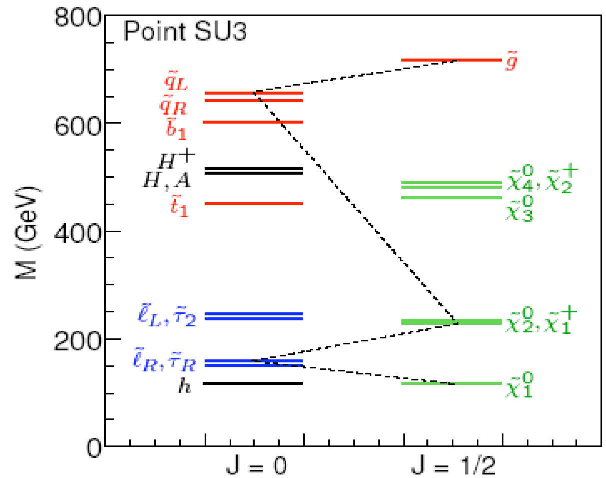
SUSY at LHC (3)

❑ Some guiding principles for the mass spectrum

- At least one **low mass Higgs** ~ Higgs of Standard Model
- 1^{rst}/2nd generation **squarks, sleptons heavy and degenerate** to avoid Large CP violation/FCNC
- 3rd generation and gauginos = Higgs Bodyguards**: M($\tilde{t}$, $\tilde{b}$, $\tilde{\chi}^{+/-/0}$) < 1 TeV**, **M($\tilde{g}$) > M($\tilde{\chi}^{+/-/0}$)**
  to naturally cancel the Higgs mass divergence via top, W, Z loops
- Nature of **Lightest Supersymmetric Particle (LSP):** $\tilde{\chi}_1^0$, $\tilde{G}$, $\tilde{\tau}$
- Mass Spectrum can also be quite **compressed** i.e. harder to discover at LHC



L. Hall
LBL Workshop
21-Oct11



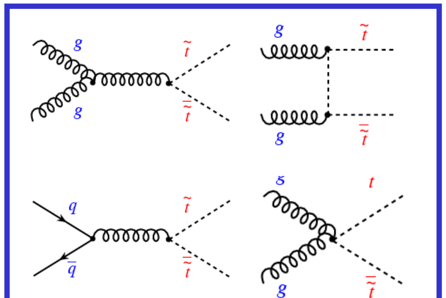
A typical point in mSUGRA:
m_0=100 GeV,
$m_{1/2}$=300 GeV,
A_0= -300,
tanβ=6,
sgn(μ) = +

➔ Experimental inputs are vital to make progress !

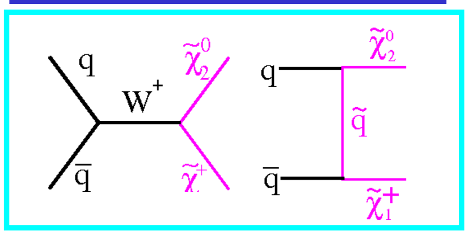
SUSY at LHC (4)

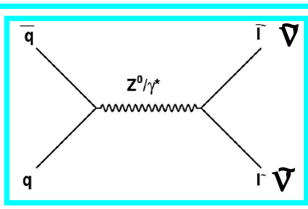
❑ **R-Parity conserved ➔ sparticles are paired produced at LHC**

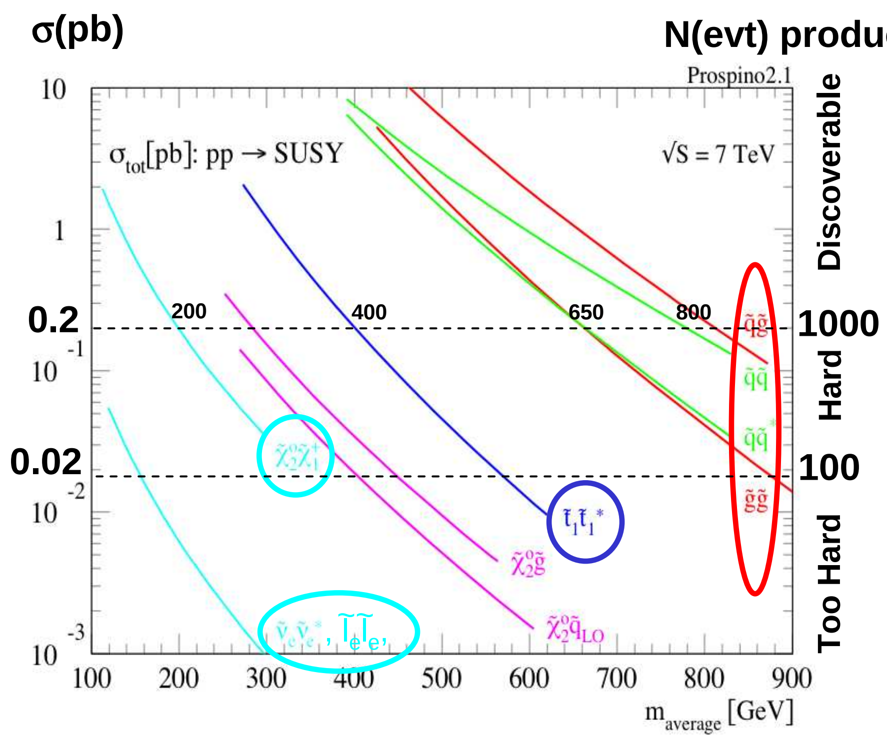
"Dedicated" searches



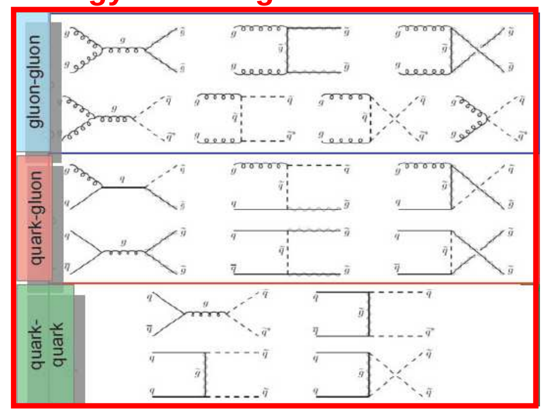
Note: no t channel, σ lower







"Energy frontier/generic" searches



Spin structure of SUSY spectrum (lots of scalars) : lower σ than other BSM models

➔ Searching for SUSY often means building dedicated/refined analyses

SUSY at LHC (5)

- **Once mass spectrum known, theoretically computable decay rate**
  - Mix of on-shell (2 body decay) and off-shell (3-body decay)

MSSM: 29 sparticles + 5 Higgs undiscovered

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$ (Bino) (Wino) (Higgsino)	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$ (Wino) (Higgsino)	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

Main decay channels in MSSM

$h \to bb, WW, \tau\tau$; $H^0 \to hh, WW, tt, bb$; $A^0 \to tt, bb$; $H^{+/-} \to \tau\nu, tb$

$\tilde{q} \to q\tilde{g}, q\tilde{\chi}_1^0, q'\tilde{\chi}_1^{+/-}, q'W^{(*)}\tilde{\chi}_1^0$
$\tilde{g} \to q\tilde{q}, q\tilde{q}\tilde{\chi}_1^0, q\tilde{q}'\tilde{\chi}_1^{+/-}$

$\tilde{q}_L \to q\tilde{\chi}_{1(2)}^0, q'\tilde{\chi}_1^{+/-}$ ($\tilde{\chi}_2^0$ wino
$\tilde{q}_R \to q\tilde{\chi}_1^0$ ($\tilde{\chi}_1^0$ bino)

STRONG

$\tilde{l} \to l\tilde{\chi}_{1(2)}^0, \nu\tilde{\chi}_1^{+/-}$
$\tilde{\nu} \to \nu\tilde{\chi}_{1(2)}^0, l\tilde{\chi}_1^{+/-}$

$\tilde{l}_L \to l\tilde{\chi}_{1(2)}^0, \nu_l\tilde{\chi}_1^{+/-}$ ($\tilde{\chi}_2^0$ wino)
$\tilde{l}_R \to l\tilde{\chi}_1^0$ ($\tilde{\chi}_1^0$ bino)

$\tilde{\chi}_{1(2)}^0 \to W^{(*)}\tilde{\chi}_1^{+/-}, Z^{(*)}\tilde{\chi}_1^0, \tilde{l}l, \tilde{\nu}\nu, \tilde{q}q$
$\tilde{\chi}_{1(2)}^{+/-} \to W^{(*)}\tilde{\chi}_1^0, Z^{(*)}\tilde{\chi}_1^{+/-}, l\tilde{\nu}, \nu\tilde{l}, \tilde{q}q'$

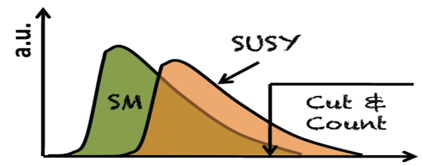
Electro-Weak

➔ Predictable but huge combinatorics: (Possible decays) x (mass spectrum) !

SUSY at LHC (6)

❑ R-Parity conserved ➔ cascade of particles + Missing Energy

- SUSY appears as excess in tails



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			$\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$	(same)
			$\tilde{t}_L$ $\tilde{t}_R$ $\tilde{b}_L$ $\tilde{b}_R$	$\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$	(same)
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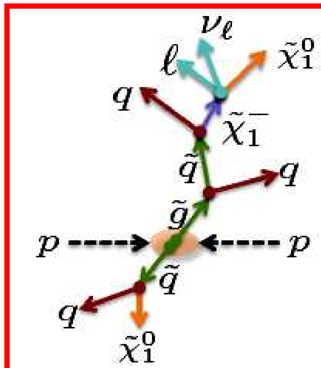
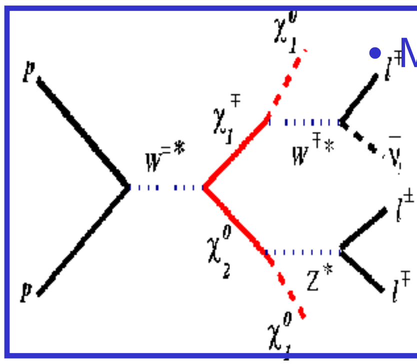
@ LHC



- Missing Energy=MET ($\tilde{\chi}_1^0$)
- "Jetty" (some from b)
- Eventually leptons
- Eventually γ

STRONG



- Missing Energy=MET ($\tilde{\chi}_1^0$)
- Jet veto
- 2 or 3 leptons

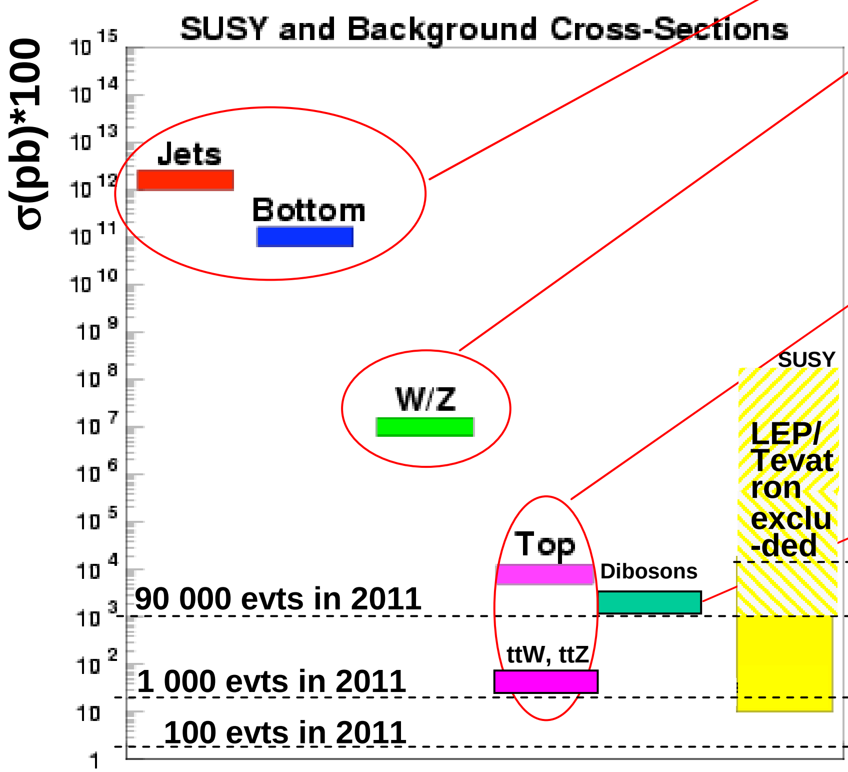
Electro-Weak (EWK)

➔ Generally signal acceptance quite low (~1% **strong**, ~10% **EWK**)

SUSY at LHC (7)

❑ Background to SUSY searches

*MET=Missing transverse Energy



- ✓Later called «QCD»: **fake MET** (**low MET** for bb**)**
- ✓W→lv+jets (ISR/FSR): l=**e**,**μ**, l=**τ**→**jet**, v→**MET***
- ✓Z→vv+jets (ISR/FSR): **MET+jets** irreducible
- ✓tt→bWbW→bqqbqq: **jet**s and low **MET** (b-decay)
- ✓tt→bWbW→bqqblv: l=**e**,**μ**, l=**τ**→**jet**, v→**MET**
- ✓tt→bWbW→blvblv: l=**e**,**μ**, l=**τ**→**jet**, v→**MET**
- ✓**tt+jets (ISR,FSR)**
- ✓tt+X with X=bb,Z,W,H, γ : Predicted but not yet discovered!
- ✓Single top: Wt, tb, tbqq
- ✓WW→lvlv, ZZ→llvv, WZ→lvqq: **lept.**, **jet**s, **MET**

Excluded by LHC 2010
m(g,q)~ **500** GeV, m(t_1)~ **200** GeV, m($\chi_{1,2}$)~ **60** GeV

Discoverable
m(g,q)~ **850** GeV, m(t_1)~ **400** GeV, m($\chi_{1,2}$)~ **200** GeV

Hard
m(g,q)~**1300** GeV, m(t_1)~ **600** GeV, m($\chi_{1,2}$)~ **350** GeV

Too Hard

➔ Need to suppress QCD / WZ / top by ~ 10^{10} / 10^5 / 10^2 and estimate small remaining quantities

SUSY at LHC (8)

❑ R-parity violating search at LHC

$$W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Number Violation (LFV)}} + \kappa_i L_i H_u + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violation (BNV)}}$$

- Proton decays only forbids simultaneous violation of lepton and baryon number

From H. Dreiner

	Signature	Model
1)	4 charged leptons: $e^+e^+\mu^-\mu^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LL\bar{E}$
2)	2 leptons, 2 taus: $e^+e^+\tau^-\tau^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LQ\bar{D}$
3)	6 jets or 2 w/ substructure	χ_1^0–LSP, $\bar{U}\bar{D}\bar{D}$
4)	like-sign dileptons + jets	χ_1^0–LSP, $LQ\bar{D}$
5)	dilepton resonance	$LL\bar{E} \otimes LQ\bar{D}$
6)	mono lepton	$LL\bar{E} \otimes LQ\bar{D}$
7)	dijet resonance	pure $LQ\bar{D}$
8)	like sign ditau's $\tau^-\tau^-$ + 6jets	$\tilde{\tau}$–LSP, $LQ\bar{D}$

Multilepton production (including taus)

Resonances (2jets, 2x2 jets, 2x3 jets, eμ, eτ, mτ)

Note: Absence of Z and Importance of taus

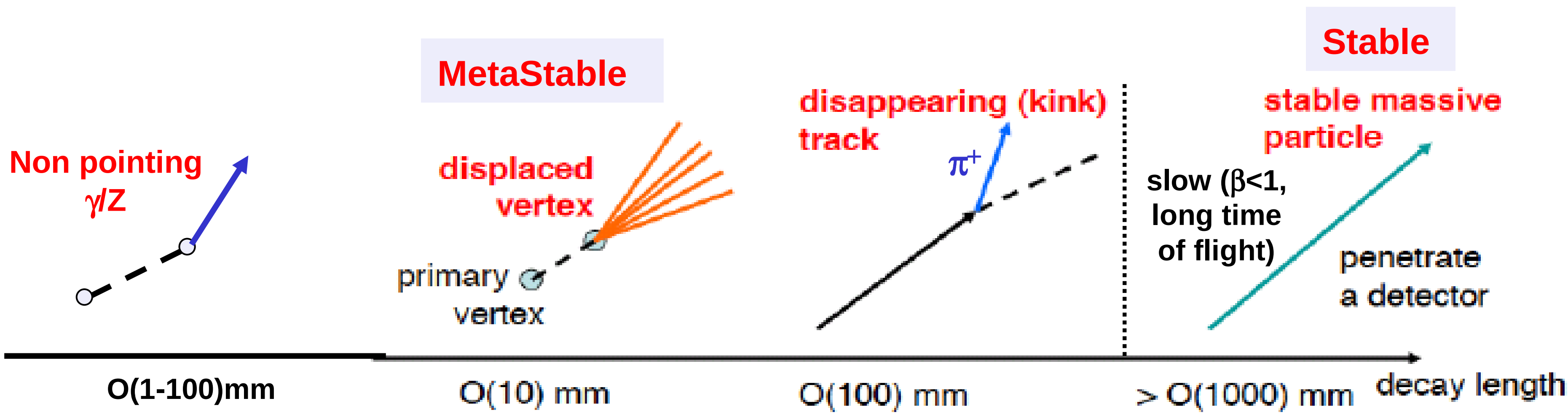
➔ Generally: lower background (no LFV nor BNV in SM) and MET than RPC

SUSY at LHC (9)

❑ Long-lived Particles (examples)

- Very weak coupling with $\tilde{G}$=LSP [GMSB] : ➔ Non pointing γ or Z
- Lifetime proportionnal to $\lambda^2, \lambda'^2, \lambda''^2$ [R-Parity violation] ➔ Displaced vertex if $\lambda, \lambda', \lambda'' < 10^{-7}$
- Low mass difference $\Delta M(\chi_1^+ - \chi_1^0) \sim 100$ MeV [AMSB] ➔ Low π emitted, kinked track
- Stable Massive Particle ➔ R-hadron ($\tilde{g}$ or $\tilde{q}$) or sleptons

Note: R-hadrons can stopped in the detector and decay later (stopped gluinos) or change sign

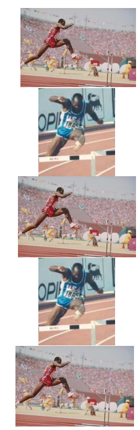


➔ Very detailed understanding of the detector/LHC beams to remove the background

Experimental challenges

- How to find direct evidence of (weak-scale) SUSY at LHC ?
  - SUSY cross-section is weak (pb-fb) and SM background is huge
  - SUSY mass spectrum is unknown, but some guidelines exists
  - SUSY signatures can be numerous and striking

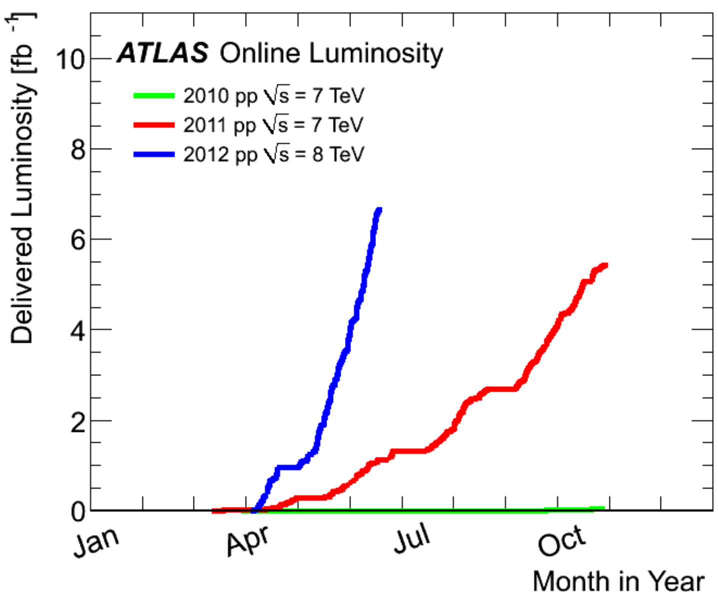
- Experimental challenges = systematics = search sensitivity
  - Changing LHC conditions (especially pile-up)
  - Trigger can kill the signal …
  - Object reconstruction in hadronic environment
  - Detector understanding (timing, …) crucial for non standard SUSY
  - (+) Data/Monte-Carlo agreement in hadronic environment

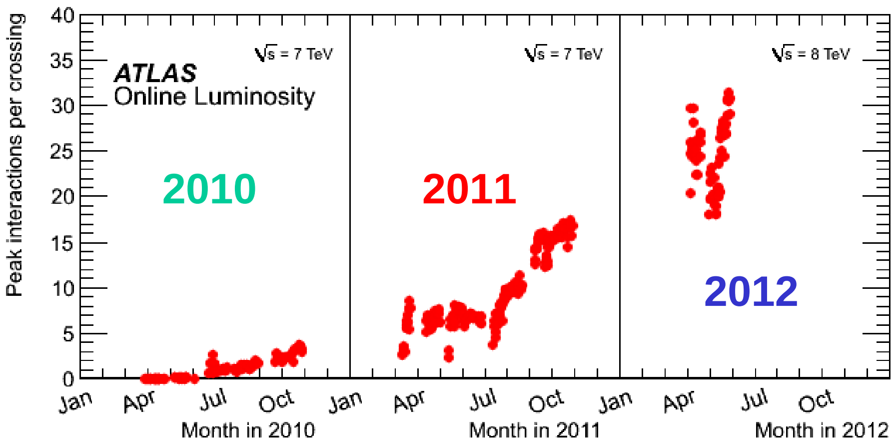


LHC

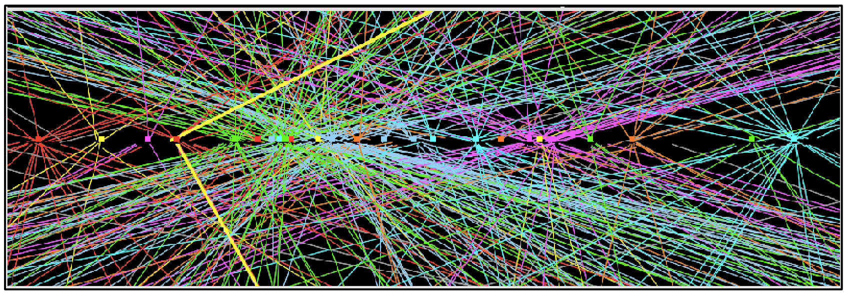
❑High luminosity, center of mass energy and Pile-up events !

- Impact on track reconstruction, object definition (jets , MET, τ/b-tagging, electron)





Z→ μμ event from 2012 data with 25 reconstructed vertices



Non collision + cosmic muon

- **LHC Beam Halo, single bunch, …** (esp. early 2010 and monojet-type searches)
  - All prompt RPC analysis ask for a reconstructed primary vertex
  - Reject very badly reconstructed jets or EM-like jet $f_{em} = p_T^{jet(EM)} / p_T^{jet} > 0.1$
  - Use jet charge fraction $f_{ch} = \sum p_T^{track,jet} / p_T^{jet} > 0.02$

- **Cosmic muons**
  - Despite underground, ATLAS/CMS reconstruct lots of cosmic muons (few Hz pseudo-projective)
    - ✓ Best measurement of R= μ^+/μ^- (CMS) while waiting for data [PLB 692 (2010) 83] R=1.2766 ± 0.0032 (stat.) ± 0.0032 (syst.)
  - Stringent cuts (~0.1-1 mm) on d_0 and z_0 wrt to Primary Vertex remove all of them

➔Well under control. Negligible in all SUSY searches (except stopped R-hadrons)

Trigger

❑ Often drive the main analysis cuts

- Work on the trigger plateau (>95% efficient, low systematics)
- Most analyses use combined trigger to reduce the p_T threshold [Ex: ATLAS RPC 2011]

Object	Unprescaled thres.
j	p_T^{jet} > 350 GeV
MET	MET>170 GeV
e	p_T > 25 GeV
μ	p_T > 20 GeV
γ	p_T > 85 GeV

→

j + MET

p_T^{jet}>130 GeV + MET>150 GeV

- 0lepton + MET + ≥2-6jets
- 0lepton + MET + 1-3bjets + jets (incl. direct stop)
- 1-2Taus + MET + jets

e OR μ OR

e μ OR e e OR μ μ

p_T^e>17 GeV + p_T^μ>12 GeV

- 2leptons + MET + jet veto
- 3leptons + MET
- 4leptons + MET

j j j j (j)

5 jets p_T>80 GeV + 6 jets p_T>55 GeV

- 0lepton + MET/$\sqrt{H_T}$ + 6-9jets

γ γ

2 photons p_T^γ>25 GeV

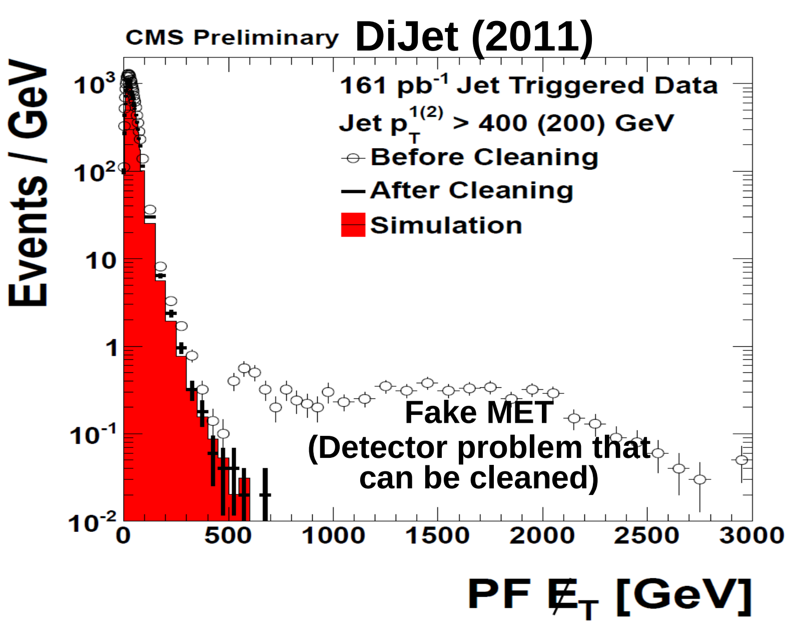
- 2photons + MET

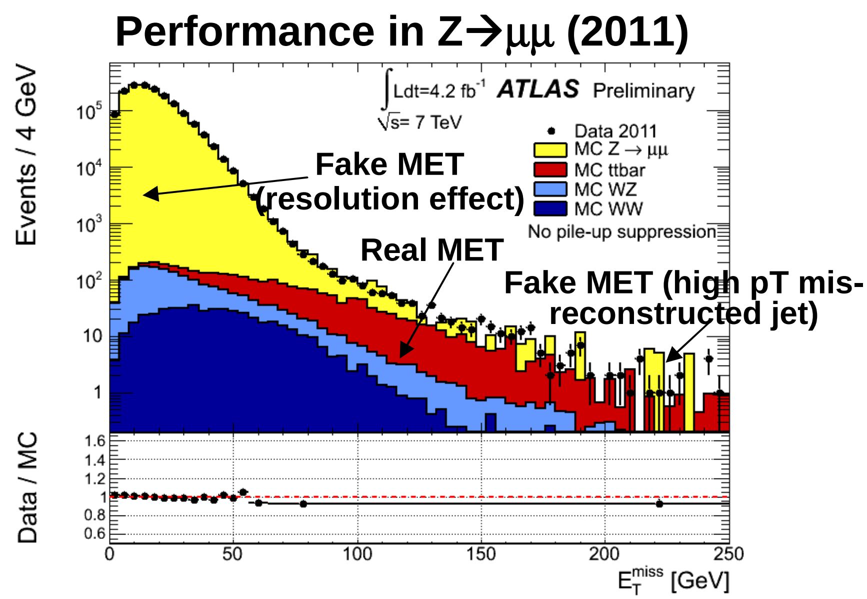
- Dedicated SUSY triggers for low beta particles, stopped gluinos (out of collision),

➔ Triggering is really challenging and may limit what we can do : soft MET, soft jet, …

MET reconstruction (1)

- **An object crucial for all SUSY searches**
  - Energy conservation (transverse plane) **:** $\overrightarrow{\mathbf{MET}} = \vec{\mathbf{E}}_{\mathbf{T}}^{\mathbf{non\text{-}int}} = -\Sigma\, \vec{E}_T$ (calo) - $\Sigma\, \vec{E}_T$ (muon)
  - Real MET: Presence of a neutral weakly interacting particle in the event (i.e. ν)
  - Fake MET : Mismeasurement + detector malfunctions, poorly instrumented regions



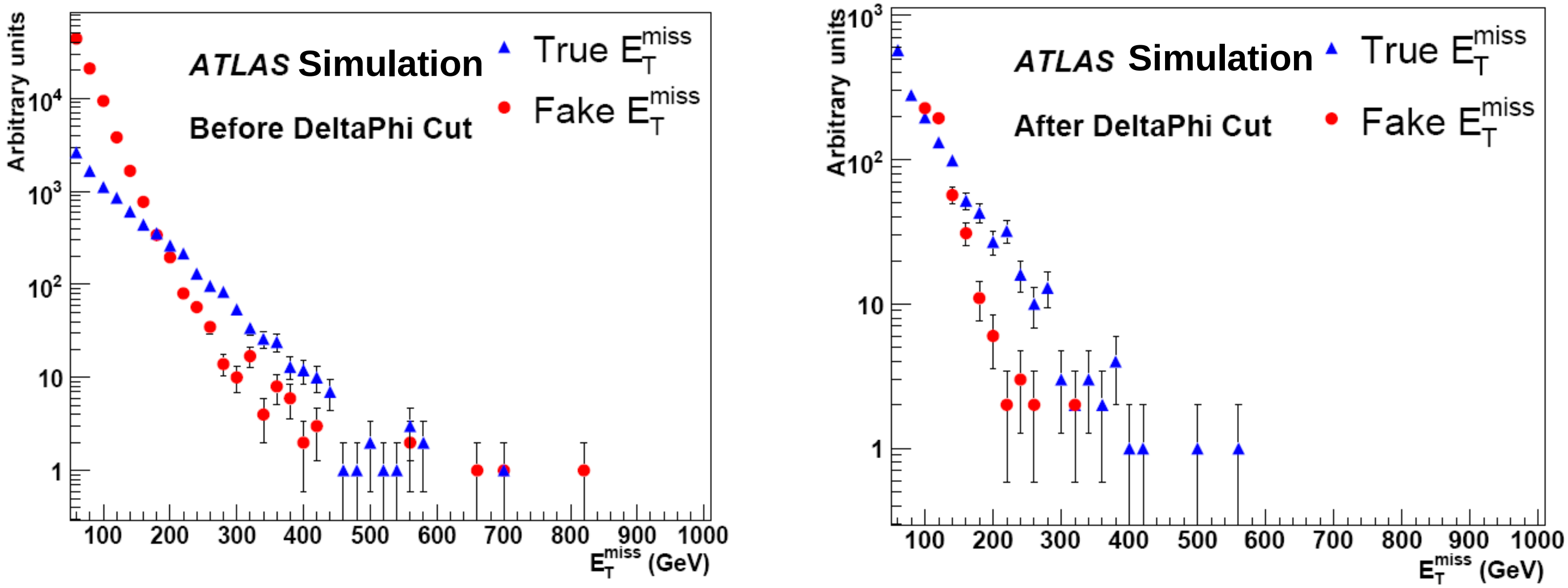


➔ Generally fair agreement data – Monte Carlo

MET reconstruction (2)

- **SUSY ~ high MET : Need to remove efficiently high pT 'fake' jets**
  - Simpliest is to cut on $\Delta\phi(\text{jet,MET})_{min}$: $\Delta\phi(\text{jet, MET})_{min}>0.2\text{-}0.4$
  - Reverting this cut provide a very nice QCD enriched sample

QCD sample (0.5<pT<1.1 TeV)



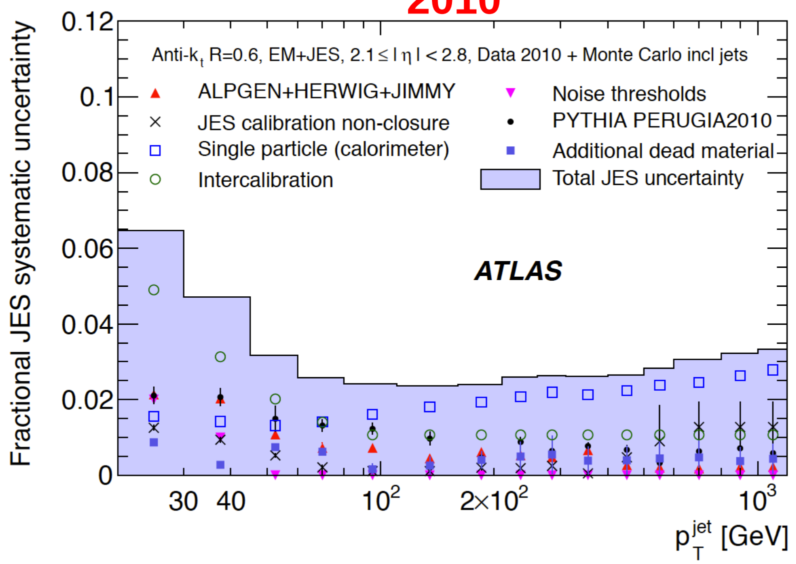
➔ Can also consider Track jet based MET, …

Jet Reconstruction

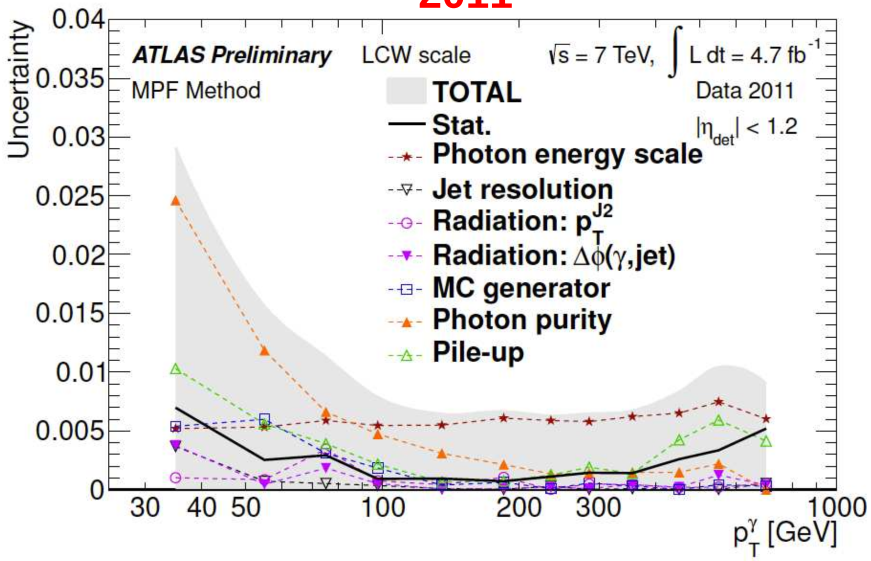
❑ Central for SUSY searches

- Anti-kt Jet with Radius R=0.4/0.5 (ATLAS/CMS)
- Uncertainties on Jet Energy Scale (JES) and Resolution are generally the dominant exp. syst.
- Several technics to remove pile-up dependence

2010



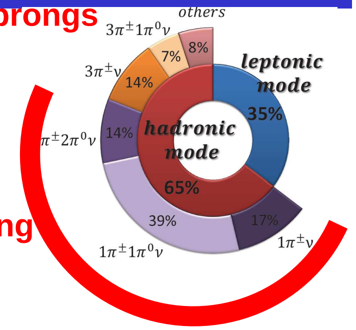
2011

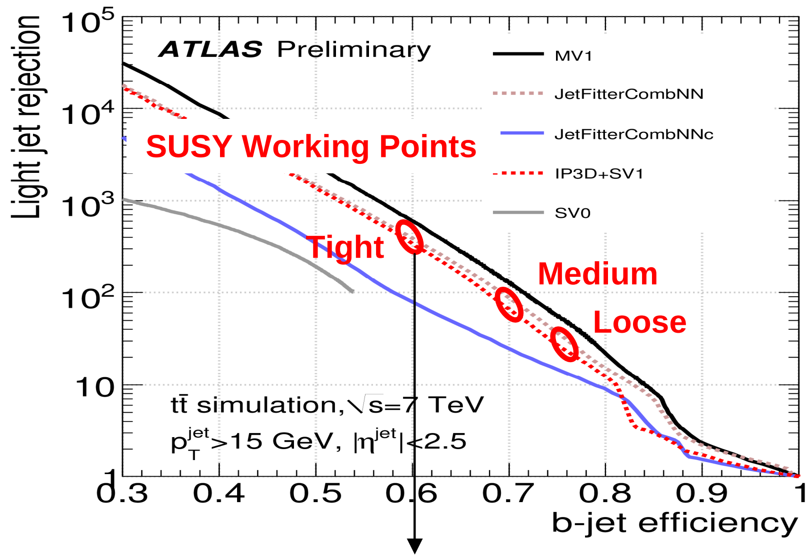


➔ATLAS and CMS now reach the 1% level for JES Uncert. (even with high pile-up) !

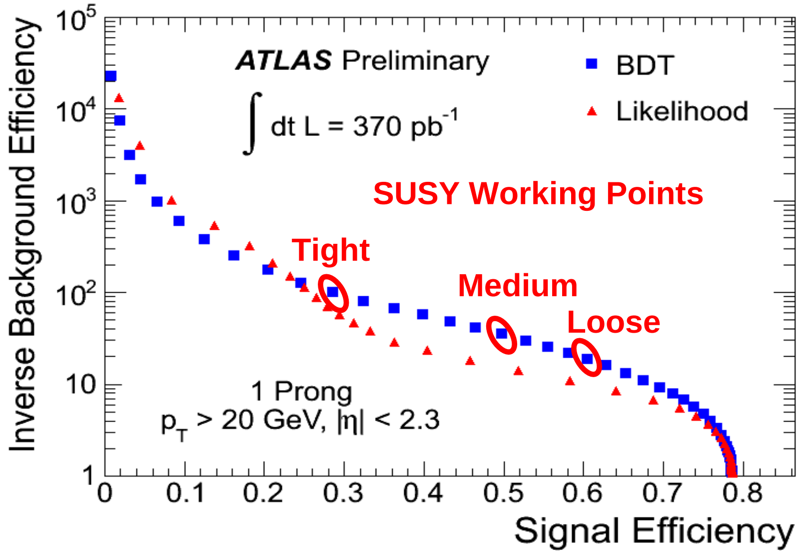
B and τ tagging

- **Crucial for 3rd generation studies !**
  - Combined many inputs in a likelihood/BDT to increase light jet rejection
    - ✓ b : Impact parameter, secondary vertex information
    - ✓ τ (hadronic): seeded from jet, 11 shower shape + tracker variables





Rejection c-jet/light-jet/τ = 10/380/30



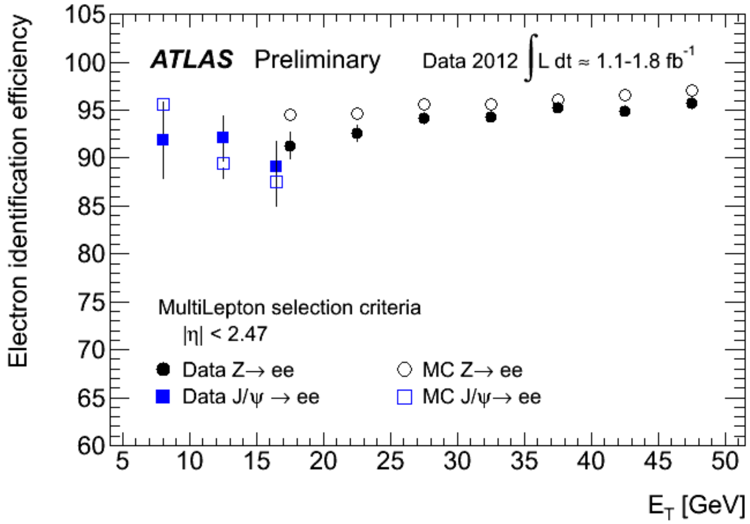
➔ Compete with Jet Energy scale systematics in b/τ enriched analyses

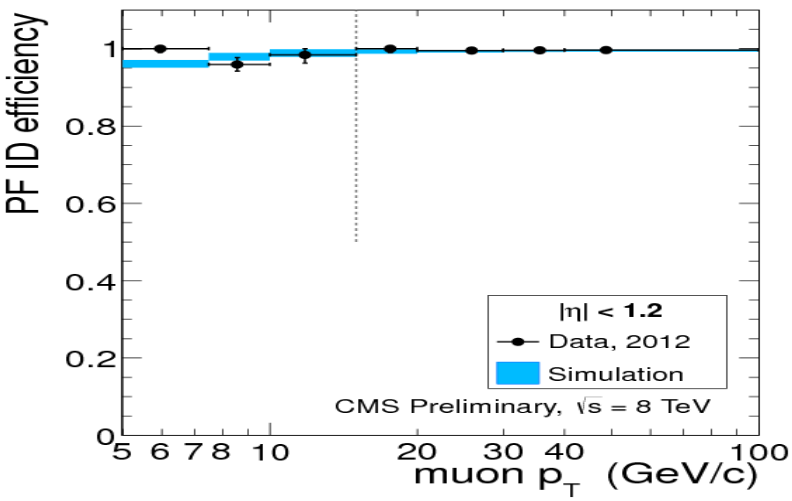
➔ Final states with had. τ (eg, tt→τ+X) are often the main SM background

Leptons (e, mu)

❑ Identification & Reconstruction down to very low pT (5-7 GeV)

- Generally ask for isolated leptons (can be tuned per analysis)
- RPC: Very helpful for compressed spectra and direct Gaugino searches
- RPV: Mandatory for high signal efficiency in Multilepton searches





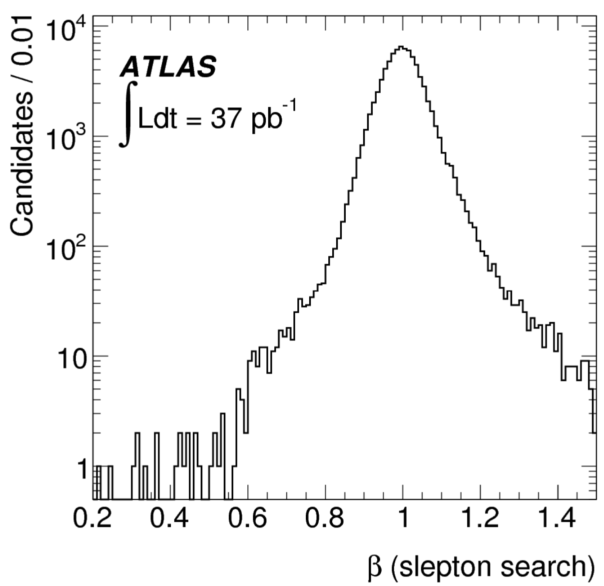
➔ Systematics from Lepton energy scale and resolution small in SUSY

Speed measurement of muons

❑ Crucial for long-lived particles

- Test on a (pure) Z→μμ samples
- Combine Muon Spectrometer + Calorimeter

2010 : σ_β~4.8% + tails

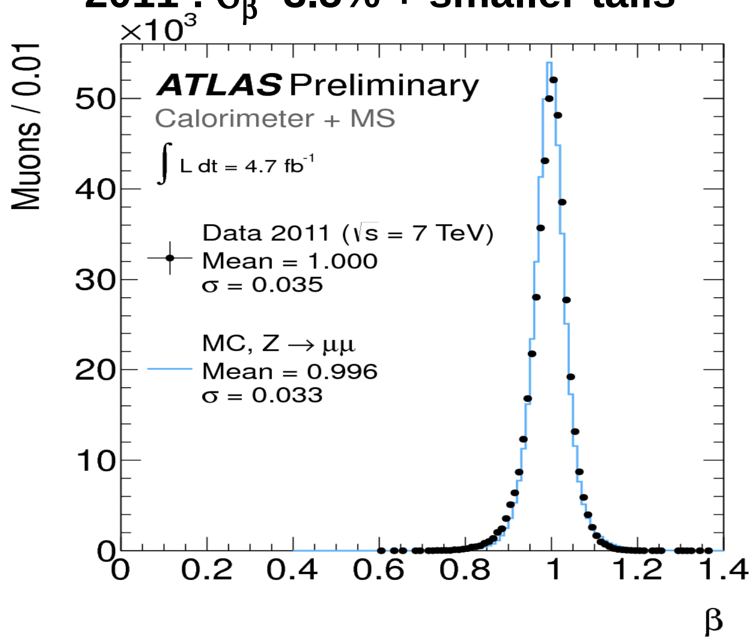


- Improve RPC and calo combination
- Include all calorimeters

→

- Check consistency between detector measurement

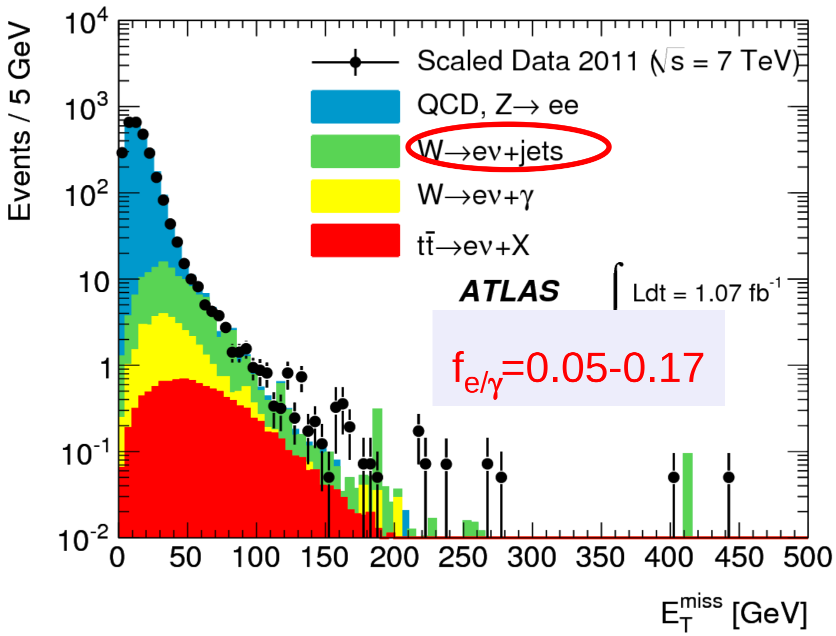
2011 : σ_β~3.5% + smaller tails

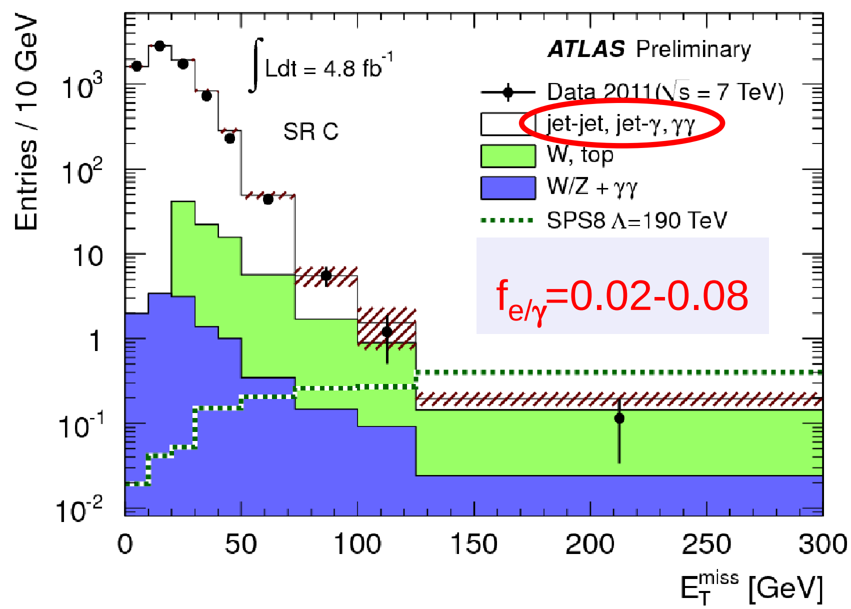


➔Also good description by Monte-Carlo. A great achievement !

Photon

- **Fake rate electron-photon ($f_{e/\gamma}$) can amper SUSY sensitivity**
  - Ex: ATLAS $\gamma\gamma$ + MET 1fb-1 →5 fb-1
  - Improve $f_{e/\gamma}$ by introducing categorisation (conv. vs unconv., barrel vs endcap)

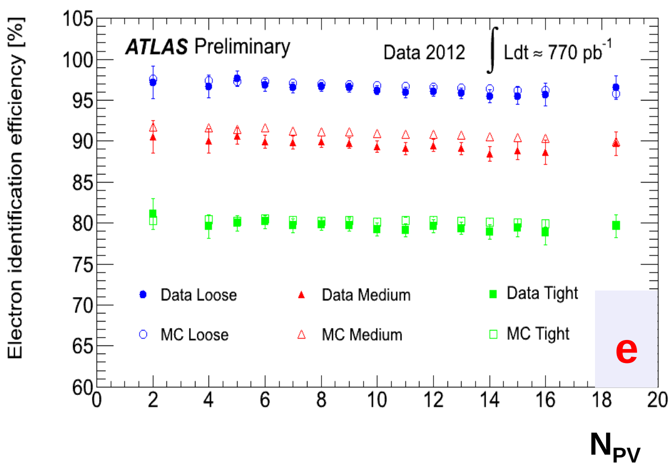


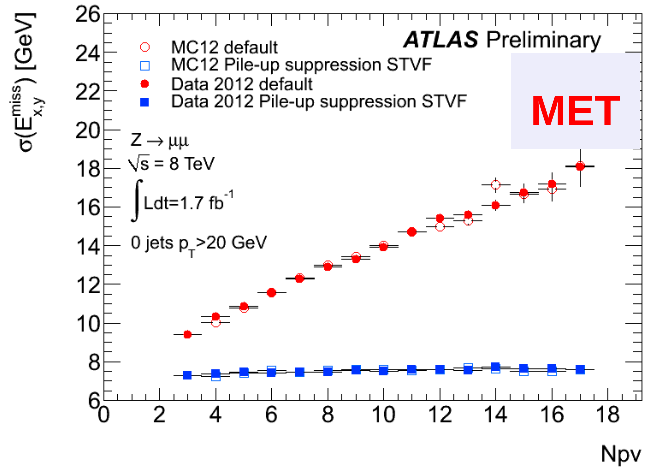


➔ A nice example of object performance implication on SUSY Sensitivity

Pileup

❑ Object Id./Reconstruction robust against pile-up (check with data)

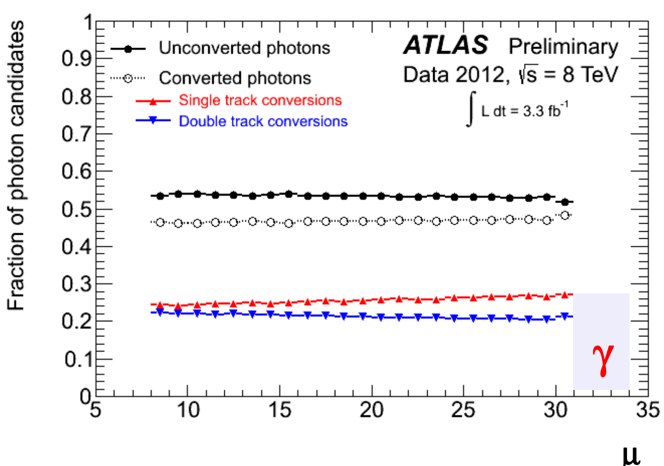


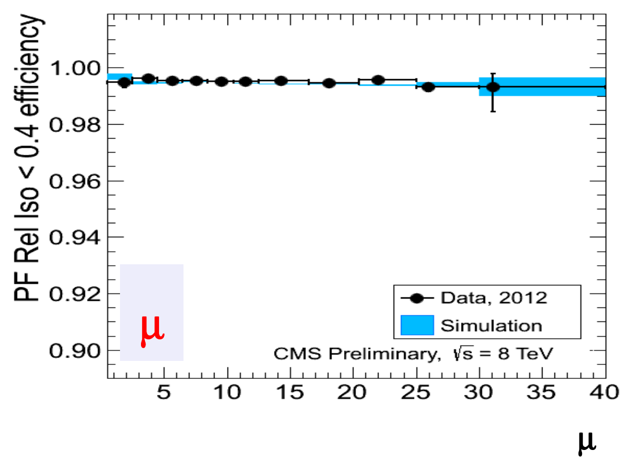


Average interactions per bunch crossing

$\mu \sim 1.4 * N_{PV}^{rec}$

Number of reconstructed primary vertex





➔Also good description by Monte-Carlo. A great achievement !

Monte Carlo (1)

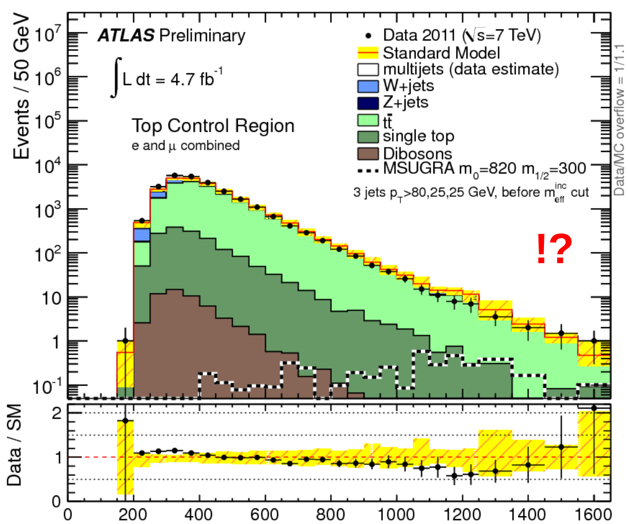
❑ Challenging to model SM processes with high jet mulitplicities

- Parton Shower (PS) : PYTHIA, HERWIG
- Matrix Element (ME) + PS : MADGRAPH, ALPGEN

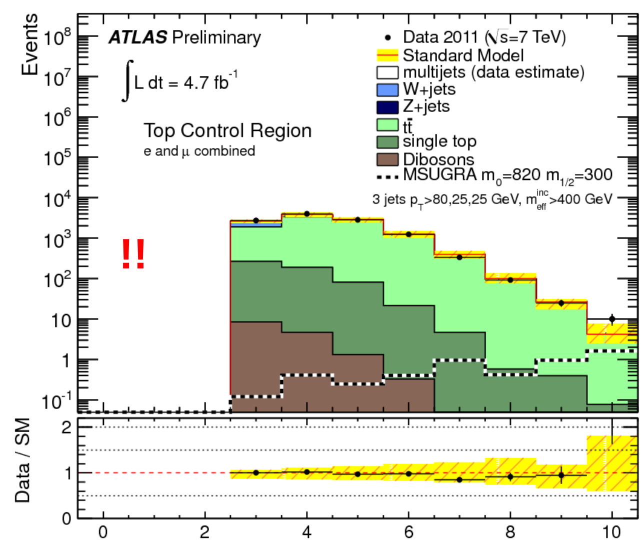
Note: SHERPA, HERWIG++, NLO+PS (MC@NLO, POWHEG) also used as cross-check or for systematics

➔'Best' to describe large-angle emissions beyond the hardest jet (jets well separated)

SUSY -1lepton Top Control Region



Meff=MET+Σp_T^{jets} (GeV)



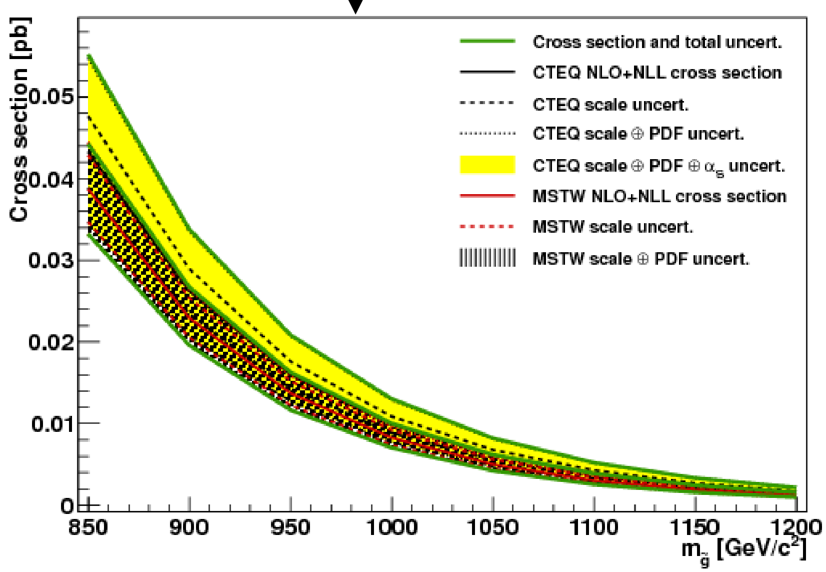
N(jets) with p_T^{jets} >25 GeV

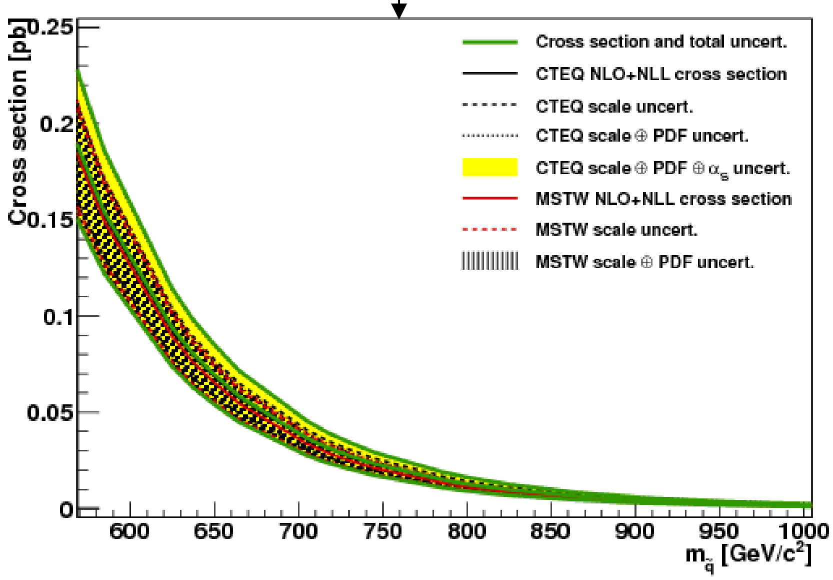
➔ Yellow band = kT scale variation barely cover data-MC discrepancy in Meff

Monte Carlo (2)

❑ SUSY Signal: standard for ATLAS/CMS for 5 fb^{-1} results (1206.2892)

- Cross-section from Prospino: NLO (EWK), NLO+NNLL (Strong)
- Systematics: PDF4LHC and Factorisation/renormalisation scale variation
- Example: **$\tilde{g}\tilde{g}$ with $\tilde{q}$ decoupled** **$\tilde{q}\tilde{q}^*$ with $\tilde{g}$ decoupled**





➔ Typical systematics (scale + PDF) = 20-30 % for $m_{\tilde{g},\tilde{q}}$<1 TeV

➔ Initial/Final State Radiation for compressed spectra (up to 30%)

Systematic Summary

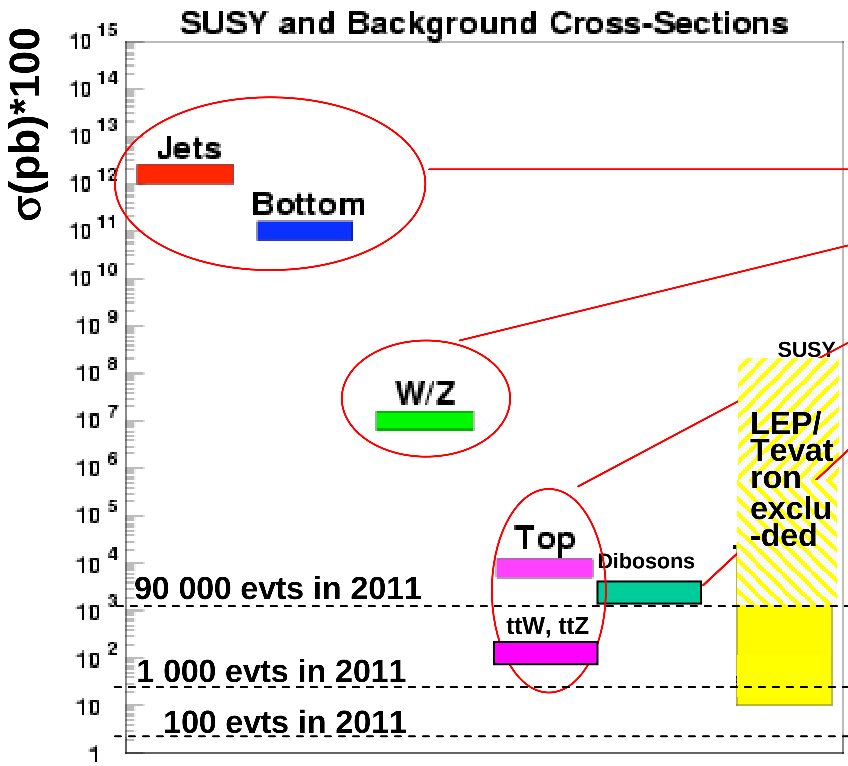
- **Need to fill the following table per analysis**

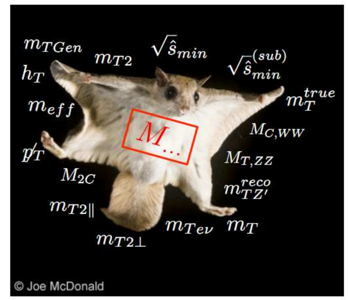
	Systematics	SM background estimate	SUSY Signal <1 TeV	Comments
Experimental	Pile-up			Negligible or Small
	Trigger			Small
	Jet Energy scale (JES)	.		Generally dominates exp
	Jet Energy resolution (JER)	Less than JES (apart Z+jets)	Less than JES	
	b/τ-tagging			Take over for ≥ 2 b/τ
	Lepton/γ energy scale			Small (even for multilep.) except τ
	Lepton/γ energy resolution			negligible
Theory	Scale, PDF uncertainties	Not for data-driven methods	~20% for NLO+NLL	Depend on many parameters
	Generators+Showering	Poor man's method	N.A.	
	ISR/FSR	Generally important for ttbar	Up to 30% for Compressed spectra	
	MC stat			Depend on grid computing !
	Total (indicative)	**~20-100%**	**~20-50%**	

(Jet Energy scale through Lepton/γ energy resolution:) Fully **correlated** between signal & backgrd

➔ Will give some concrete examples tomorrow !

Signal Region Definition





Excluded by LHC 2010

m(g,q)~ **500** GeV, m(t_1)~ **200** GeV, m($\chi_{1,2}$)~ **60** GeV

Discoverable

m(g,q)~ **850** GeV, m(t_1)~ **400** GeV, m($\chi_{1,2}$)~ **200** GeV

Hard

m(g,q)~**1300** GeV, m(t_1)~ **600** GeV, m($\chi_{1,2}$)~ **350** GeV

Too Hard

1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^5 / 10^2

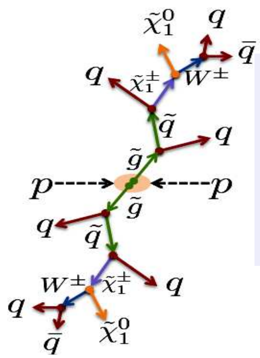
2) Estimate small remaining quantities

3) Interpret the results if no excess

Signal Region Definition (1)

❑ First need hard kinematic cuts

- To reduce “difficult” background (Fake MET/ lepton, pile-up): Ex leptonic RPC



SM Background

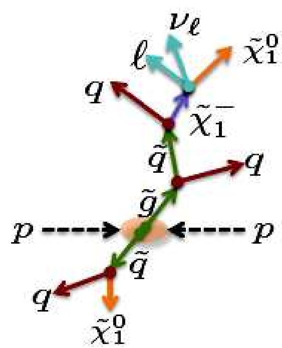
1.Z(→νν)+jets

2.ttbar/W+jets

3.QCD

0lepton+jets+MET:

- Jet+MET trigger
- Ask several high pT jets
- High MET cuts needed to kill QCD



SM Background

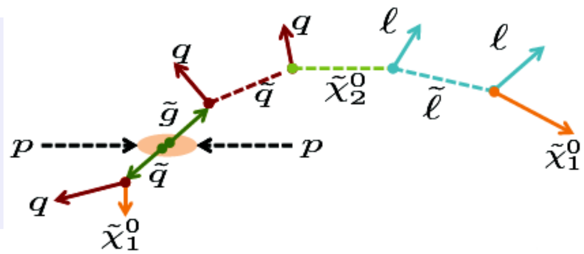
1.ttbar

2.W+jets

(3.Fake lepton)

1lepton+jets+MET:

- Lepton trigger
- Ask several high pT jets
- Lower MET cuts than 0lep
- $m_T(W) > m(W)$



≥2lepton+jets+MET:

- Dilepton trigger
- MET and/or high pT jets
- 2l Opp. sign: Z or non Z
- 2l Same sign
- 3, 4leptons

❑ Then add powerful discriminating variables

✓ Define ‘Signal’ populated regions (SR)

✓ Choose the best ones to discover a certain SUSY topology [best **S/√(B+ΔB)** from MC]

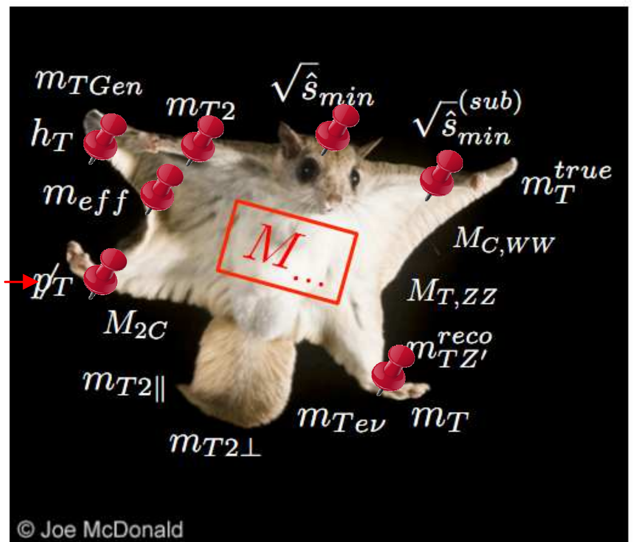
Signal Region Definition (2)

❑ Discriminating variables commonly used in SUSY analyses

- LHC: unknown momentum along the beams
- SUSY: Sparticles pair produced + Presence of invisible (massive) particles

Assume knowledge of SUSY decay chain
➔ Transverse mass-like variables

MET



PRD 84 (2011) 095031 =used in SUSY analyses

Other approaches w/o this assumption:

- Reconstruction of 2megajets: Razor, α_T

- QCD killers: $\Delta\phi$(jets, MET)

- QCD+EWK killers: b-jets

- ttbar killers: 2lepton Same sign, 3 bjets, 3leptons

➔ Optimal choice of variable(s)/method(s) is analysis dependent

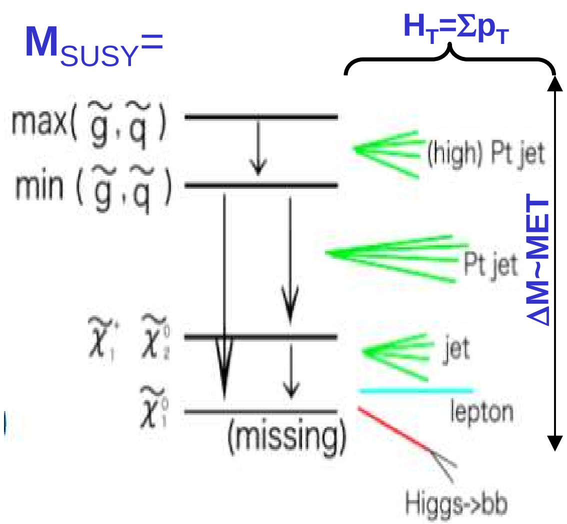
Signal Region Definition (5)

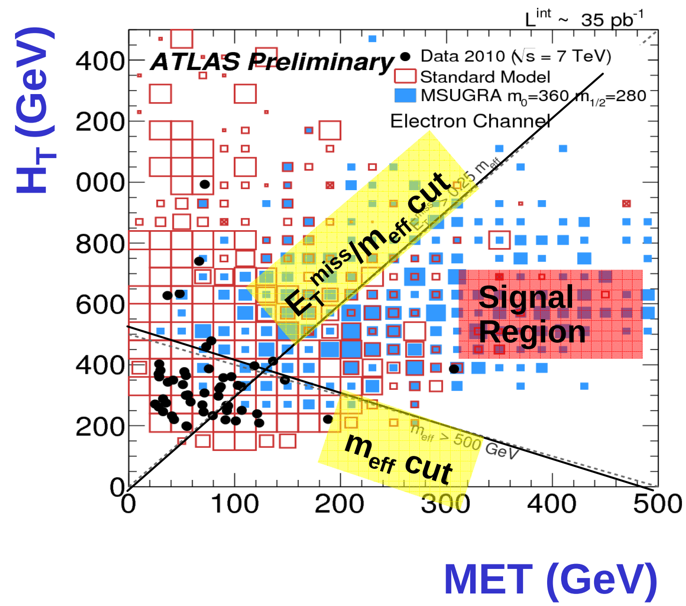
1. Effective mass (M_{Eff}) : *inclusive* "transverse mass", used w or w/o leptons in final states

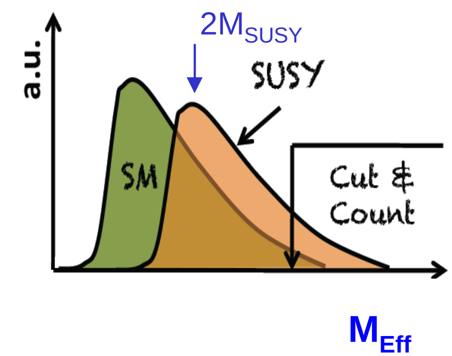
- Profit from the correlation between H_T and MET in SUSY absent in SM

$$M_{Eff} = H_T + MET$$

Typical SUSY chain







➔ Hard M_{Eff} and MET cuts: signal efficiency ~0.1-10 %, high purity for signal

Signal Region Definition (6)

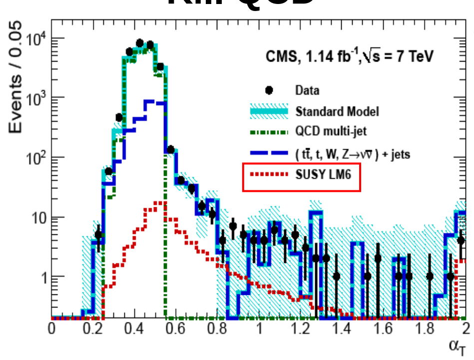
2. α_T : used w/o lepton in final states

$$M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2} \qquad \alpha_T = \frac{E_T^{j_2}}{M_T}$$

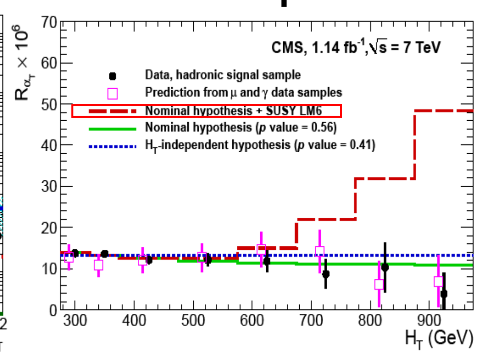
(j_2 less energetic jet)

- Group part. in 2 hemispheres (2 megajets)
  - ➔ α_T=0.5 if perfect megajet balance
  - ➔ α_T<0.5 if 2 megajets imbalanced
  - ➔ α_T>0.5 if 2 megajets not back-to-back+real MET
- More discrimin. w R_{α_T}=N(α_T>0.5)/N(α_T<0.5)

Kill QCD



Kill Top/W/Z



PRL 101 (2008) 221803

3. Razor : used w or w/o leptons in final states

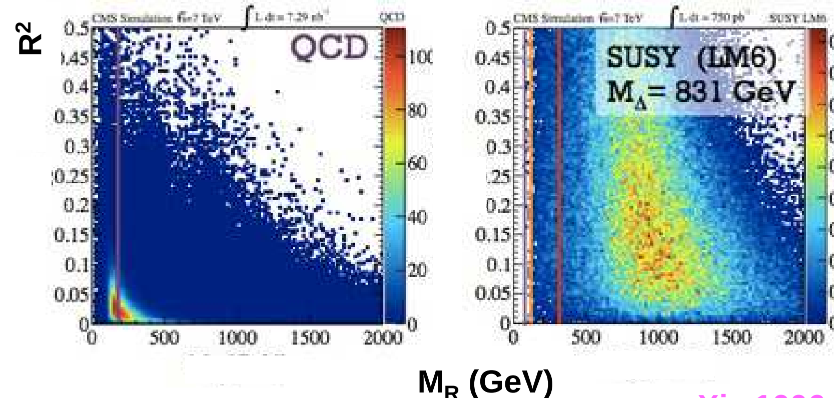
$$M_R = 2|\vec{p}^{\,R}_{j1}| = 2|\vec{p}^{\,R}_{j2}| \sqrt{\frac{(E^{j1}p_z^{j2} - E^{j2}p_z^{j1})^2}{(p_z^{j1} - p_z^{j2})^2 - (E^{j1} - E^{j2})^2}}$$

M_R peaks at mass scale M_D

$$R \equiv \frac{M_T^R}{M_R}$$

Razor (R) has a kinematic edge of 1 **(M_T^R kinematic edge at M_D)**

- Similar + use longitudinal information
- Boost in "R Frame" where p(J_1)=p(J_2)
  - ➔ If no ISR: R Frame=Center of Mass Frame
  - ➔ If M_Δ high: signal peaks at M_R ~ M_Δ
- Increase discrimination with R^2

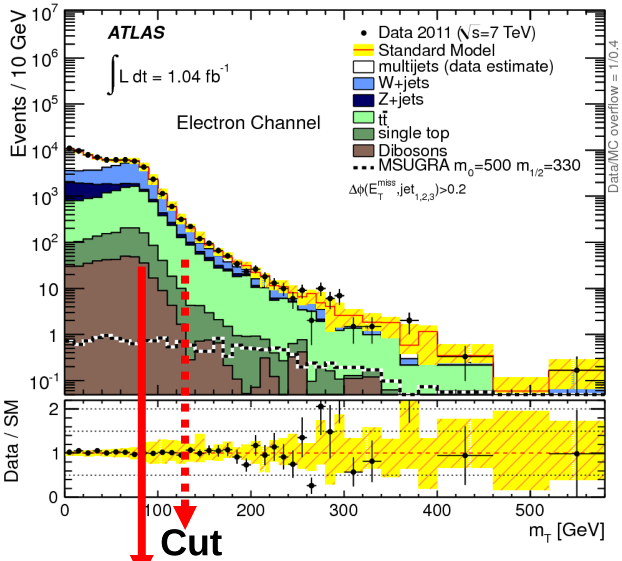


arXiv.1006.2727

Signal Region Definition (3)

4. $m_T(W)$: 1 lepton

$$M_T^2(e,\nu) = 2\, p_T^e\, MET(1-\cos\Delta\phi_{e\nu}),\ m_e \sim m_\nu \sim 0$$



W Mass end-point (smeared by resolution)

➔ Remove W+jets but cut also signal !

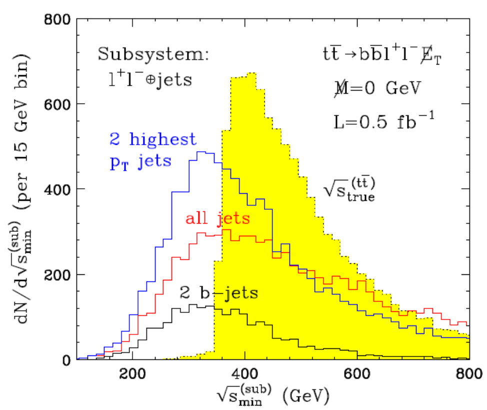
5. Root-smin : direct stop 1, 2 lepton + bjets

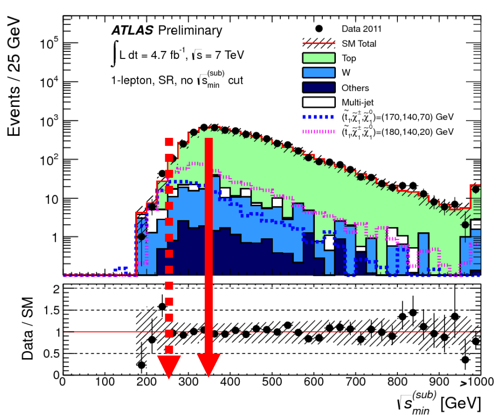
$$\sqrt{s}_{\min}^{(\mathrm{sub})} = \left\{ \left(\sqrt{m^2_{(\mathrm{sub})} + p^2_{\mathrm{T(sub)}}} + \sqrt{(m^{\mathrm{miss}})^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2} \right)^2 - \left(\mathbf{p}_{\mathrm{T(sub)}} + \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} \right)^2 \right\}^{\frac{1}{2}}$$

Visible hard process | Invisible from hard process | Boost correction caused by ISR

For ttbar, starting point ~2m(t), no ISR+m(ν)~0

For $\tilde{t}\tilde{t}$, $\tilde{t}\rightarrow t\tilde{\chi}$, $m(\tilde{t})-m(\tilde{\chi})<m(t)$ starting point <2m(t)





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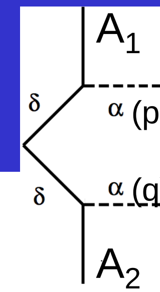
Signal Region Definition (4)



6. M_{T2}, m_{CT}: *exclusive* “transverse mass”, 2 leptons/bjets + MET + Jet veto

- Generate end-point at different position than SM because of massive LSP*

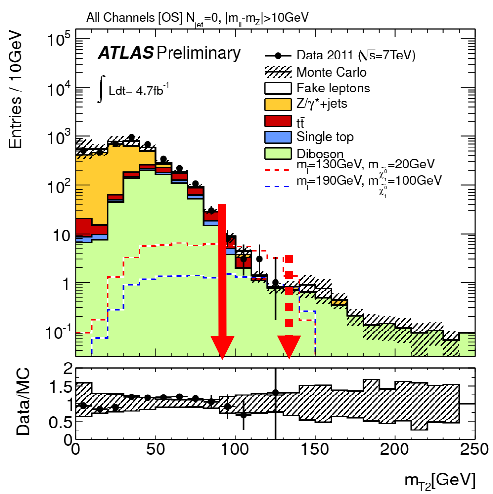
$$M_{T2}^2 = \min_{\vec{p}_T+\vec{q}_T=MET} [\max\{M_T^2(A_1,p), M_T^2(A_2,q)\}]$$

- Min.: most ‘consistent’ missing momentum sharing between invisibles
- Max.: Better of the 2 lower bounds

$$M_{CT}^2 = [E_T(A_1) + E_T(A_2)]^2 - [\vec{p}_T(A_1) - \vec{p}_T(A_2)]^2$$

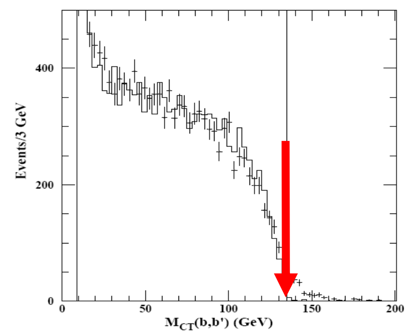
For ttbar, endpoint $[M(t)^2 - M(W)^2] / M(t)$ ~ 135 GeV, m(b,ν)~0

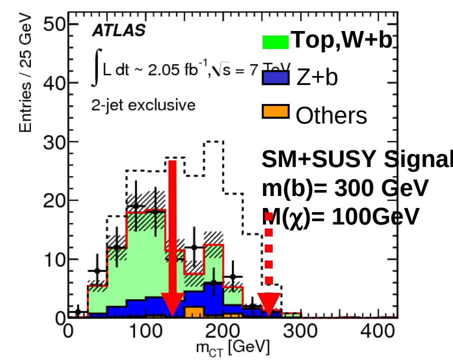
For $\tilde{b} \rightarrow b\chi$ endpoint $[M(\tilde{b}) - M(\chi)]^2 / M(\tilde{b})$ ~260 GeV, m(b)~0



For $\tilde{l} \rightarrow l\chi$ endpoint $[M(\tilde{l})^2 - M(\chi)^2] / M(\tilde{l})$ ~130 GeV for m(A)~0

JP G29 (2003) 2343



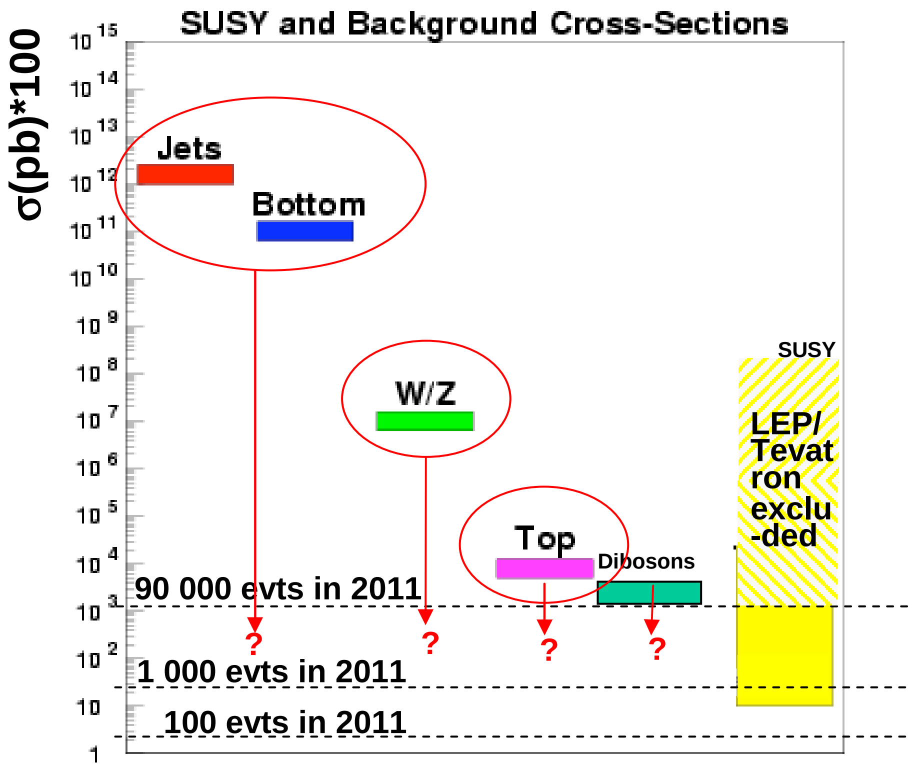


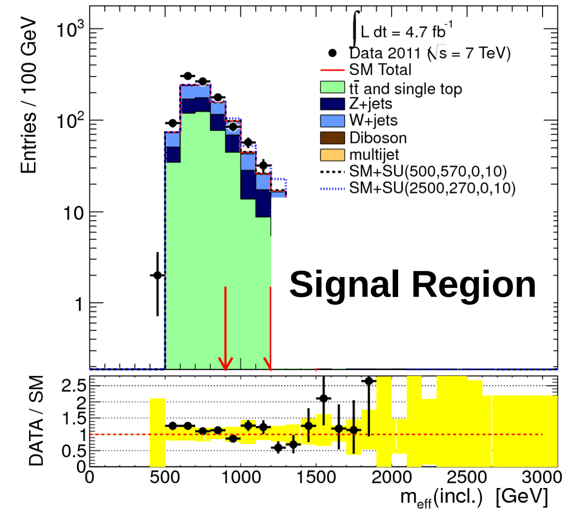
JHEP 0804 (2008) 034, JHEP 1003 (2010) 030

➔ Powerfull to reject SM background but need to assume value of endpoint to cut !

***Originally designed to measure SUSY masses**

Background estimate





Excluded by LHC 2010

$m(g,q)\sim$ **500** GeV, $m(t_1)\sim$ **200** GeV, $m(\chi_{1,2})\sim$ **60** GeV

Discoverable

$m(g,q)\sim$ **850** GeV, $m(t_1)\sim$ **400** GeV, $m(\chi_{1,2})\sim$ **200** GeV

Hard

$m(g,q)\sim$**1300** GeV, $m(t_1)\sim$ **600** GeV, $m(\chi_{1,2})\sim$ **350** GeV

Too Hard

1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^{5} / 10^{2}

2) Estimate small remaining quantities

3) Interpret the results if no excess

Background estimate (1)

❑ Different strategies for different background

- Note: out of the box Data-Monte Carlo agreement is generally very good at LHC

Fully data-driven

Methods : a lot !

Pros: i) Don't rely on potential failures in simulation, ii) Suited for large σ

Cons: Rely strongly on simplifying assumptions ➔ systematics

Targets: Fake MET (QCD, Z+jets), fake leptons, long-lived particle (high pT muons with mis-measured β)

Semi data-driven

Methods : i) isolate a pure background sample, ii) normalise MC iii) assume MC shape to transfer it to Signal Region

Pros: Main systematics cancel in the transfer factor

Cons: full study of possible theory systematics

Targets: Main irreducible background (top, W/Z+jets)

Pure MC

Methods : none !

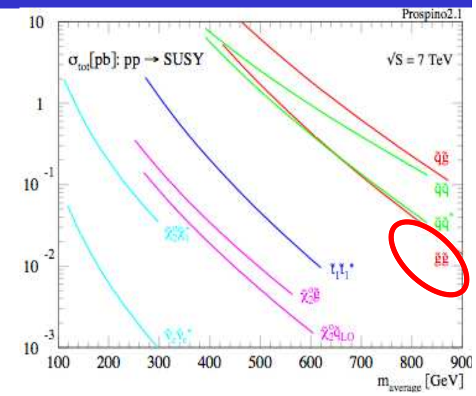
Pros: Easy, helpful to start and design Signal Regions

Cons: Suffer from large syst and/or statistical errors

Targets: Well suited for small backgrounds

➔ Precision in background determination drives the SUSY sensitivity

Background estimate (2)



❑ Take the example of 0lepton + ≥4jets + MET channel

- Production : m(gluinos, squarks) <~1 TeV➔ $\tilde{g}\tilde{g}$
- Decay (1) : $\tilde{g}$→$\tilde{q}$q$\tilde{\chi}$ and $\tilde{q}$→q$\tilde{\chi}$ dominates ➔ **0lepton + ≥4 jets + MET**
- Discriminant variable : **M_{Eff} >1200 GeV**

ATLAS-CONF-2012-033

Signal Region (SR) Definition: Lepton veto pT (e/μ)>20/10 GeV

Requirement	Channel C 4j	
E_T^{miss}[GeV] >	160	**Trigger**-driven
$p_T(j_1)$ [GeV] >	130	
$p_T(j_2)$ [GeV] >	60	**Pile-up** driven
$p_T(j_3)$ [GeV] >	60	
$p_T(j_4)$ [GeV] >	60	
$p_T(j_5)$ [GeV] >	–	
$p_T(j_6)$ [GeV] >	–	
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ >	0.4 ($i = \{1, 2,$	**QCD rejection** -driven
$E_T^{miss}/m_{eff}(Nj)$ >	0.25 (4j)	
m_{eff}(incl.) [GeV] >	1200	**Discriminating variable**

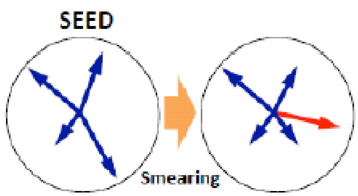
➔ 3 main backgrounds: QCD, semileptonic ttbar/Leptonc W, Z→νν +jets,

Background estimate (3)

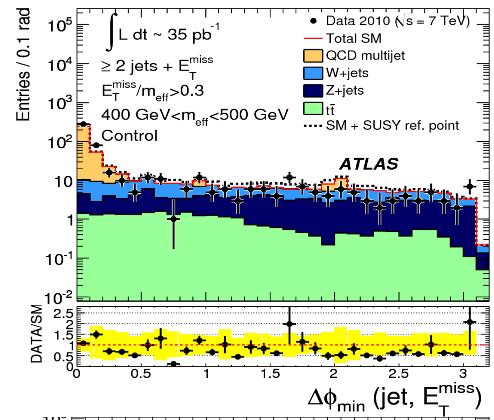
❑ QCD/Multijets background (Data driven)

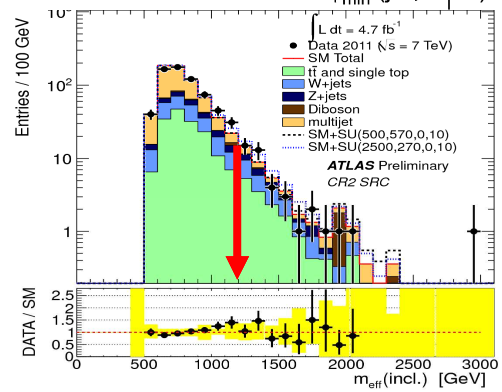
- Enter SR because of fake MET or ν inside jet
- Can not trust MC + limited by MC stat ➔ Compute Jet response R=pT(jet reco)/pT(jet true) and generate pseudo data to populate SR

1. Determine the jet response function R from dijet balance and 3-jets mercedes events
2. Take a control sample of multijets events with small MET.
3. Smear each jet by its response R ➔ Pseudo-data



4. Normalize the shape obtained in a QCD enhanced region with low $\Delta\phi(\text{jet}, E_T^{miss}) < 0.4$
5. Propagate to signal region





Background estimate (4)

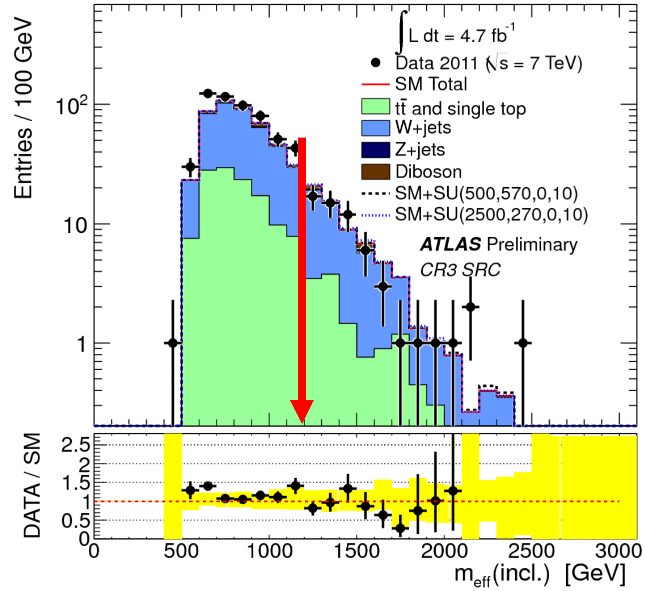
❑ W→lν +jets and ttbar→blνbqq (Semi Data-driven)

- Enter SR because lepton is reconstructed as a jet, is τ, out of acceptance
- Have ν (real MET): can trust MC
  - ✓ Define enriched background "control" region (CR) by **reverting a cut** (Ex: ask 1lepton for 0lepton channel)
  - ✓ Force the lepton as a jet (acceptable approximation)
- Look in the Control Region:
  - ✓ Monte Carlo should reproduce the data
  - ✓ High P**urity** (N_{MC}^{oth}~small), small Signal contamination
- Estimate N_{SR}^{bkg} **Transfer factor** (**c**) relying on MC shape:

$$N_{SR}^{Bkg} = \frac{N_{SR}^{MC}}{N_{CR}^{MC}}\left(N_{CR}^{data} - N_{CR}^{MC,others}\right) = N_{SR}^{MC}\frac{\left(N_{CR}^{data} - N_{CR}^{MC,others}\right)}{N_{CR}^{MC}}$$

$c_{CR \rightarrow SR}$ Scale factor (k~1)

W+4jets CR
1 lepton, 0 bjet, 30<mT(lν)<100 GeV



➔ Systematics partially cancel in the ratio, but need small extrapolation (c~0.1-1)

Background estimate (5)

❑ Z→νν +jets (Data Driven)

- Enter SR because it is exactly signal like: Irreducible background !

1. Use a close-by SM process: γ+jets

   ✓Similar kinematic at pT~400 GeV>>mZ

   ➔Obtain a very pure sample

   ✓Force the photon as a jet

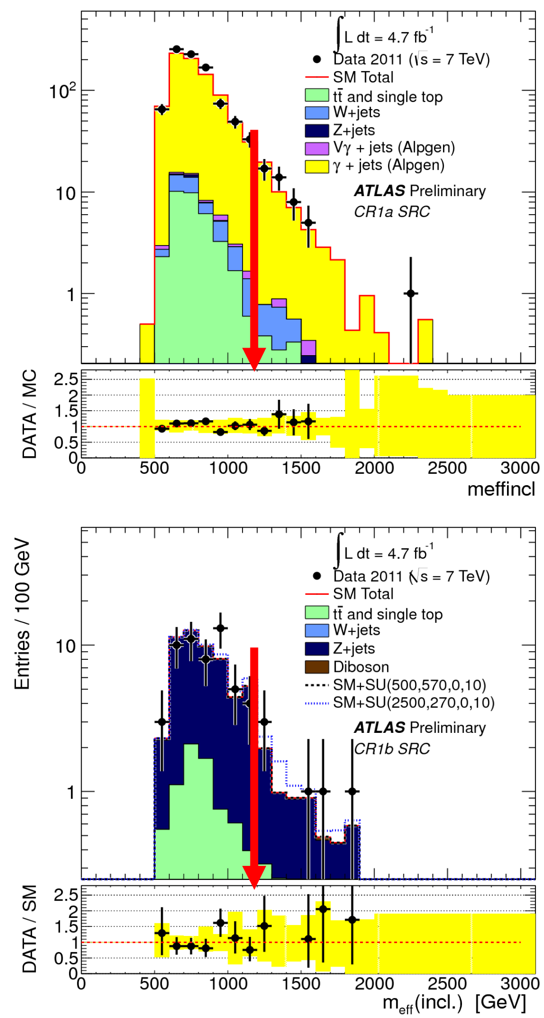
   ✓Gain a factor **~3** in stat: R=σ(Z+jets)/σ(γ+jets)~0.3

2. Use a close-by SM process: Z→ll+jets

   ✓More statistically limited (~10 times less than γ+jets)

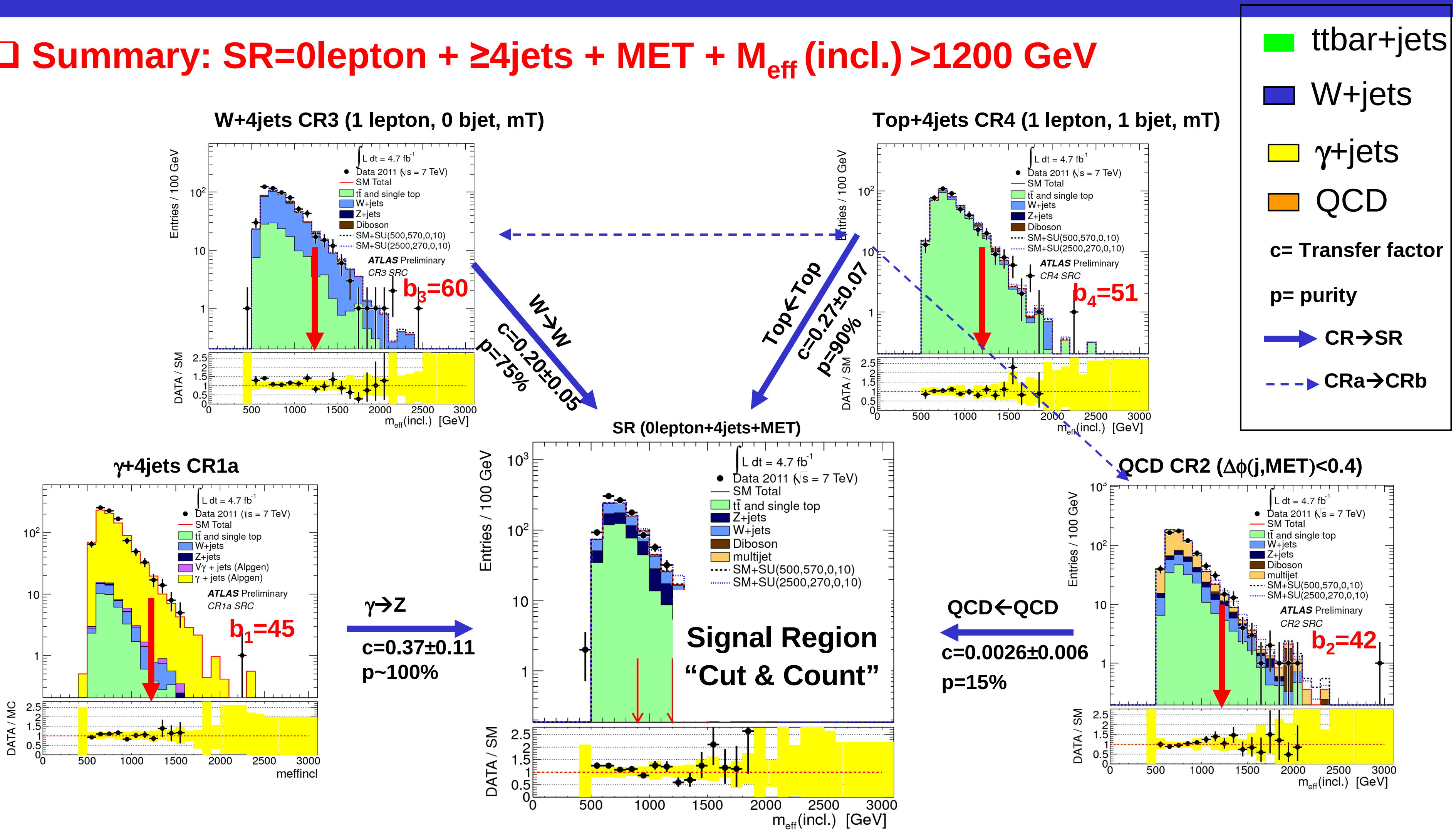
   ✓Will not consider it in the following

γ+4jets Control Region



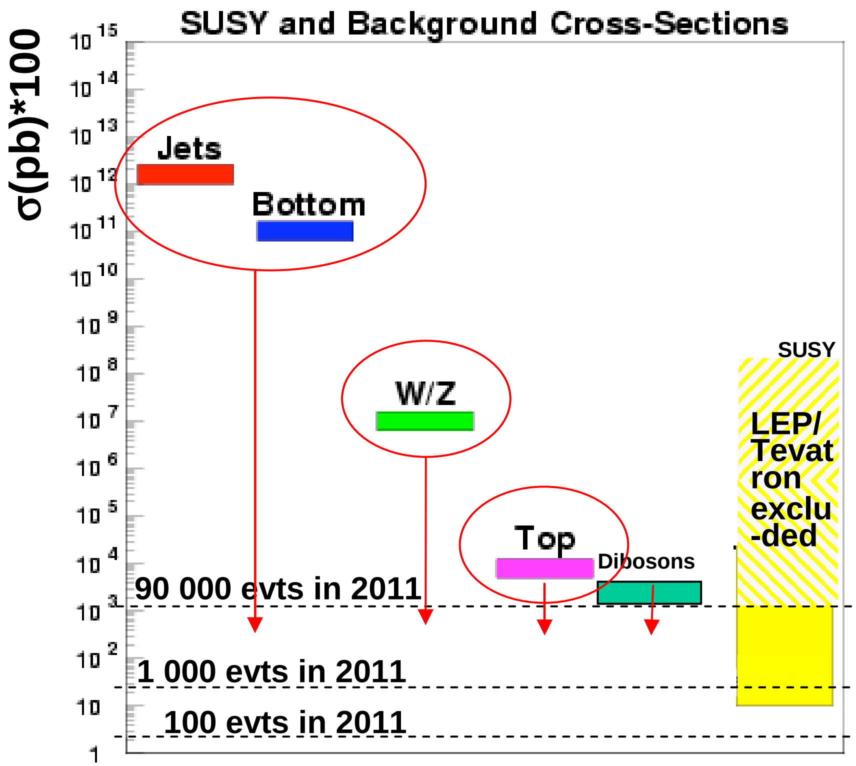
Background estimate (6)

- **Summary: SR=0lepton + ≥4jets + MET + M_{eff} (incl.) >1200 GeV**



➔ Errors contains exp. (Jet Energy scale, btagging) and theo. (PDF, scale) syst.

Fit Result & Interpretation



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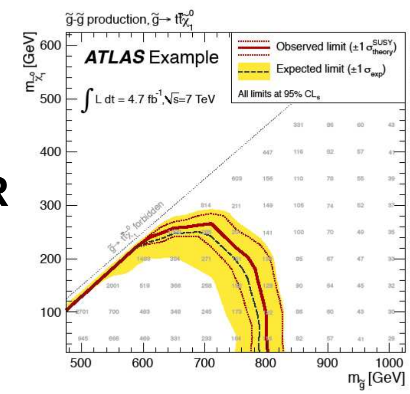

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Too Hard

1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^{5} / 10^{2}
2) Estimate small remaining quantities
3) Excess or another SUSY limit ?

Fit Results (1)

Building the likelihood

*pdf=probability density function

- **Likelihood function** : products of Poisson pdf* for SR and CR (as mutually exclusive) & syst.

$$L(n \mid \mu, b, \theta) = P_{SR} \times P_Z \times P_W \times P_{Top} \times P_{QCD} \times C_{syst}$$

b=background
θ= systematics treated as nuisance parameters with Gaussian
n=Number of observed events in data
μ= SUSY signal strength to be tested

- **Inputs**: Transfer factors (c), #evts for data in SR (s) and CR_j (b_j)

$$P_{SR} = P(n \mid \lambda_S(\mu, b, \theta)) = \mu \bullet c_{sR->SR}(\theta) \bullet s + \sum_j c_{jR->SR}(\theta) \bullet \mathrm{b}_j$$

$$P_i = P(n \mid \lambda_i(\mu, b, \theta)) = \mu \bullet c_{sR->iR}(\theta) \bullet s + \sum_j c_{jR->iR}(\theta) \bullet \mathrm{b}_j$$

λ (μ, **b**, θ) = expected number of events

$c_{CR,SR \rightarrow SR}$

Region	Main CR/Process			
	CR1a / Z/γ+jets	CR2 / QCD jets	CR4 / $t\bar{t}$+ Single Top	CR3 / W+jets
CR1a	1	0	0	0
CR2	0.1	1	0.39	0.2
CR4	0.0034	0	1	0.093
CR3	0.0078	0	0.32	1
SR	0.37	0.0026	0.27	0.2

➔ Can correctly take the systematic correlation and cross-contamination into account

Fit Results (2)

❑ Background-only fit (μ=0)

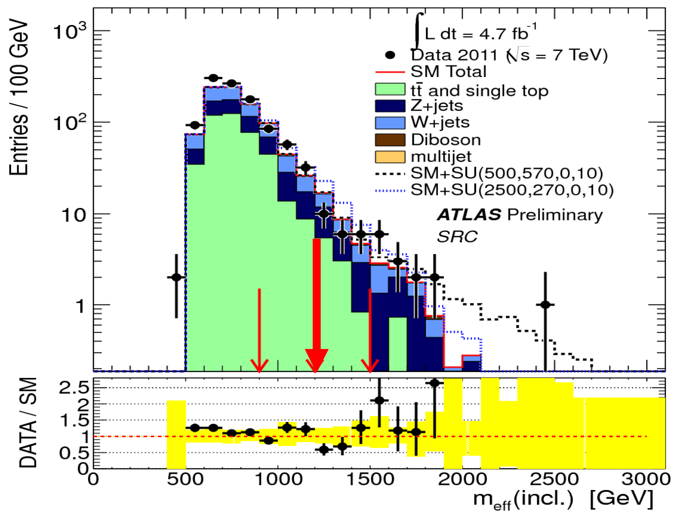
[all examples from SR: 0lepton+≥4jets+MET, Meff>1200 GeV]

- Predict the background in the Signal Region by maximizing the likelihood
- SR not in the fit + no signal contamination in CR (can be reproduced by theorists)

	Background in SR $c_{jR\to SR}(\ )\bullet b_j$				Others	Total Background in SR
	Zvv+jets	QCD	W+jets	Top	Dibosons	SR
MC	16	0.01	11	10	1.7	39
Fit Output	17±6	0.02±0.03	8±3	12±5	1.7±0.9	**39±9 [±5(stat)±7(syst)]**

➔ **25% error** (mainly from γ/Z acceptance, CR stat)

➔ Observed **36** evts in Data. No Excess !



Fit Results (3)

❑ Quantify the agreement between data and SM prediction

- **Test**: compatibility of data with background only hypothesis in the signal region
- **Test statistic:** based on one-sided profile log likelihood ratio (a la Higgs)

$$\Lambda(\mu) = -2 \times [L(n \mid \mu, \hat{\hat{b}}, \hat{\hat{\theta}}) - L(n \mid \hat{\mu}, \hat{b}, \hat{\theta})] \sim \chi^2 \text{ dist with Ndof } = 1^* \; (\mu \geq 0)$$

Maximise L for a choice of μ   *Maximise L*

See Eilam Gross lectures

***In practice this approximation works well for sufficient stat (n>5). If not the case, use toys**

- Use CLs prescription (a la Higgs)
- In 0lepton+≥4jets+MET + M_{eff} (incl.) >1200 GeV:

Predict 39+/-9 and observe 36

CLs **p-value**=0.6 (-0.2 σ). Compatible !

Fit Results (4)

❑ Derive a model independent limit

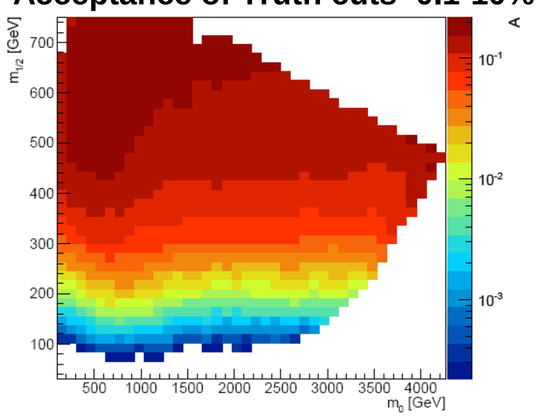
- Limit on visible cross-section on non-SM: $\sigma_{vis} = \sigma \times A \times \varepsilon$
- In 0lepton+≥4jets+MET + M_{eff} (incl.) >1200 GeV:

Predict 39+/-9, observe 36 ➡

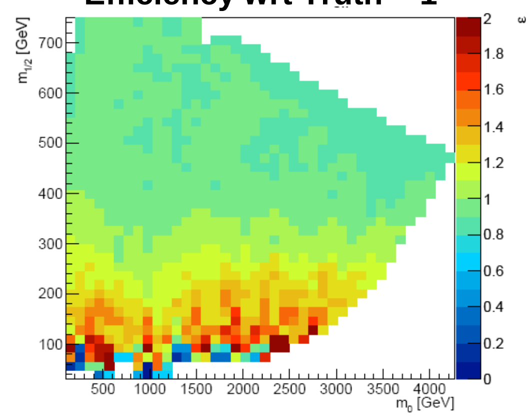
> ➔ **Exclude at 95%CL N(BSM)≥ 18 and N/L = σ_{vis} > 3.7 fb**
>
> ➔ *Expected to exclude N(BSM)>= 19 and N/L=σ_{vis} > 4.1 fb*

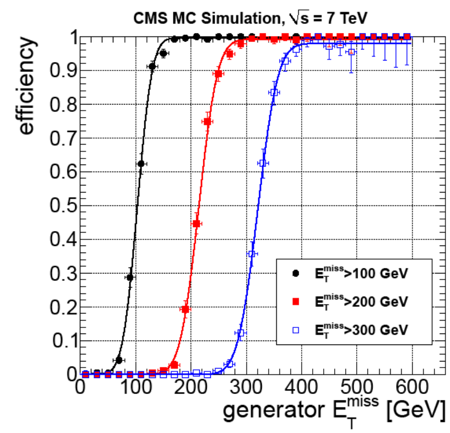
- A and ε given for a well-defined SUSY model : Examples below

Acceptance of Truth cuts~0.1-10%



Efficiency wrt Truth ~ 1





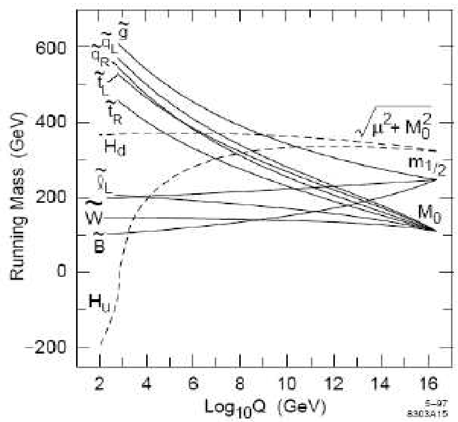
➔ Result can be recasted in other models than the one considered

Interpretation: exp. view (1)

❑ Derive a limit in a very constrained SUSY model (or parametrize or ignorance !)

- Reduce number of SUSY parameters from 105 (MSSM) to 5 or 6

- Model of SUSY breaking: gravity mediated, gauge mediated…
- Assume GUT scale parameters (few)
- Predict phenomenology at the EWK scale



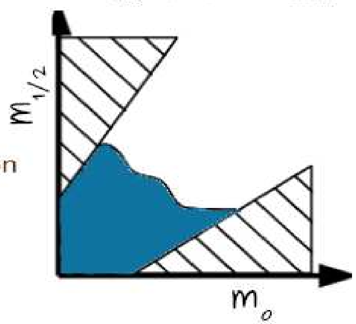
MSSM-105 (N=1) with R-Parity Conservation
Simplified MSSM (MSSM-24, pMSSM-19)

MSSM-5: GMSB(GGM)	**AMSB**	**CMSSM/mSUGRA**

***TeV range new particles: Long decay chain, Dark Matter candidate (LSP)*, mass degeneracies**

E.g. mSUGRA/CMSSM:

m_0: common scalar mass (GUT)
$m_{1/2}$: common gaugino mass (GUT)
tanβ: Ratio of Higgs vaccum expectation values
A_0: Trilinear coupling
Sign(μ): Higgs mass term



Note: 5 fb-1 ATLAS/CMS papers use a common mSUGRA framework described in Matchev et al, 1202.6580 :
m_0, $m_{1/2}$, tanβ =10, A_0 =0, μ>0

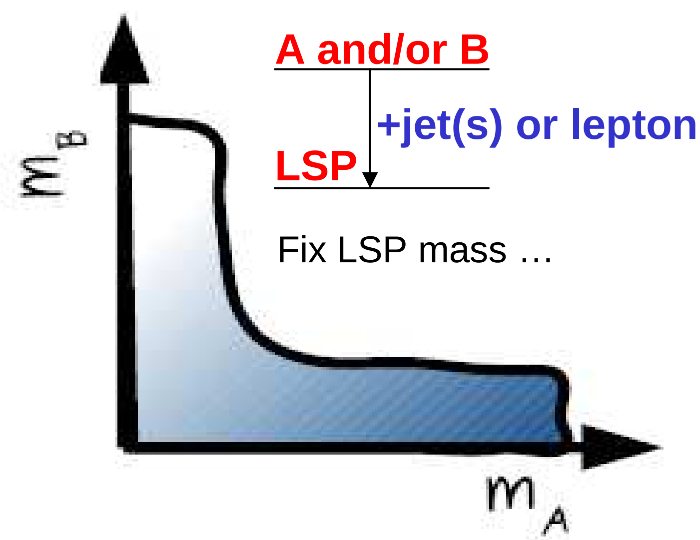
➔ Useful to calibrate our exclusion and compare with other results

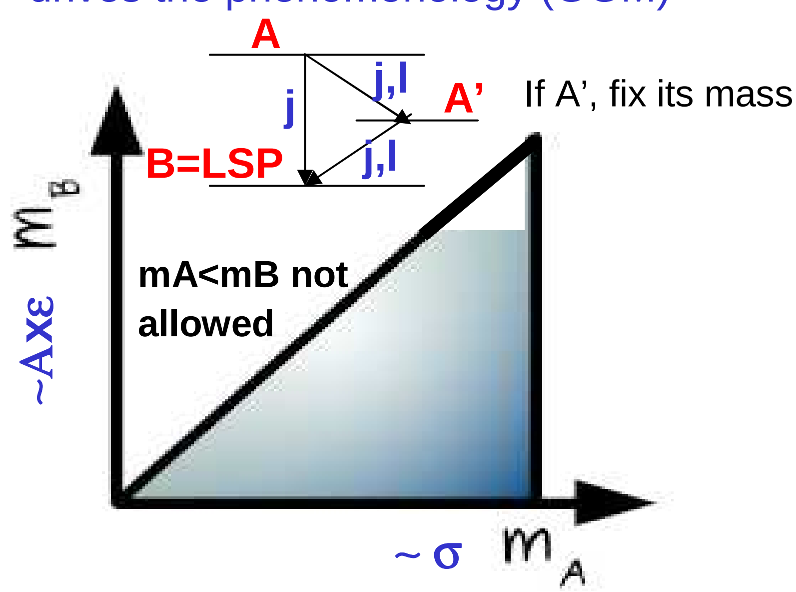
Interpretation: exp. view (2)

Simplified Model
Mimic SUSY topologies

❑ Derive a limit in a simplified decay chain Model (SMS)

- Well suited for **natural SUSY** and **direct production** (not a SUSY model !):
  - ✓ 29 sparticles → 2 or 3, **decoupled** all other particles, force a specific decay mode
- Assumptions on the chirality and nature of particle involved “arbitrary”
- Perfect for GMSB where gravitino=LSP. NLSP drives the phenomenology (GGM)





➔ Very helpful also to design analyses. Possible to recast SMS in mSUGRA (1202.2662)

Interpretation: exp. view (3)

❑ Derive a limit in a simplified MSSM

- Reduce number of SUSY parameters from 105 (MSSM) to 19, i.e. "manageable":
  - ✓ Well justified assumptions
  - ✓ "Standard" exp. constraints
- Recover the SUSY complexity ➔ can track missing features of SMS in "simple" cases

MSSM-105 (N=1) with R-Parity Conservation

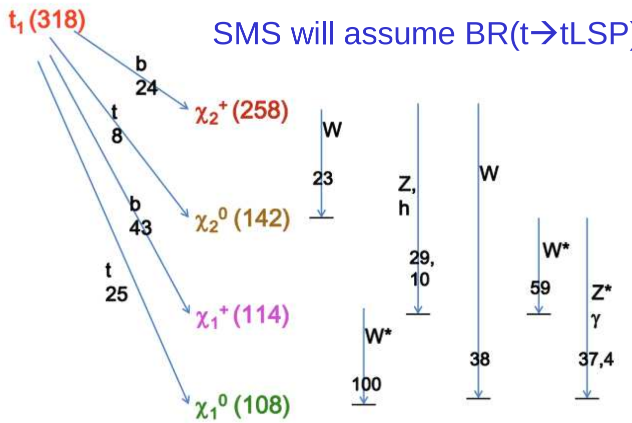
Simplified MSSM (MSSM-24, pMSSM-19)

MSSM-5: GMSB(GGM) AMSB CMSSM/mSUGRA

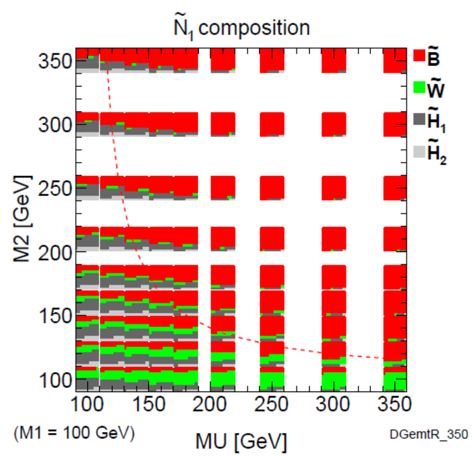
***TeV range new particles: Long decay chain, Dark Matter candidate (LSP)*, mass degeneracies**

Direct Stop production

SMS will assume BR(t→tLSP)=100%



Direct Gaugino production



SMS will assume χ bino or higgsino-like

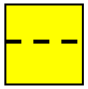
➔ Should definitely be checked when designing our signal regions

Interpretation: exp. view (4)

❑ Exclusion limits : a new standard ATLAS/CMS procedure (>June 2012)

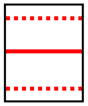
- Ease the life of theorist by separating the signal theoritical and experimental systematics

Expected limit:

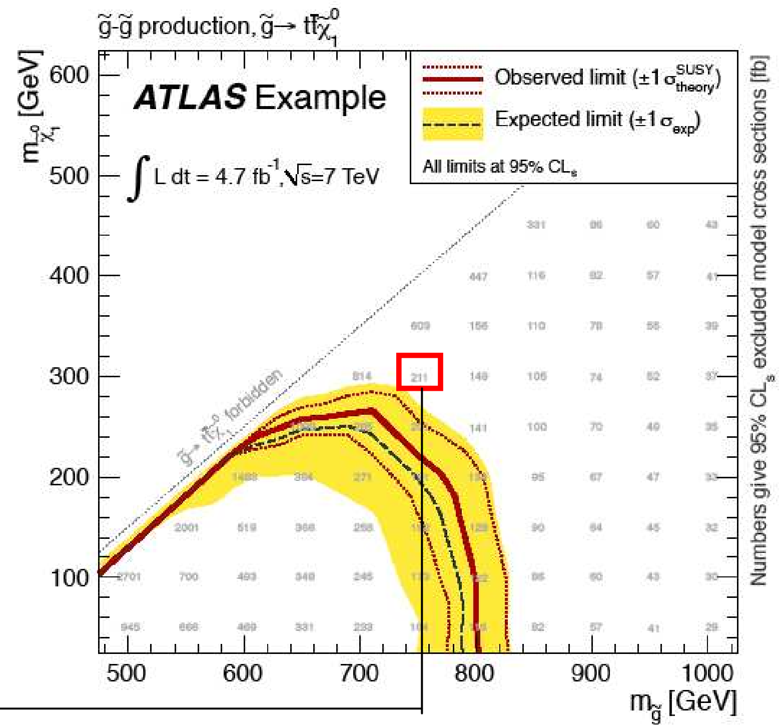


- **Central value:** all uncertainties included in the fit as nuisance parameters, except theoretical signal uncertainties (PDF,scales)
- **±1σ band :** ±1σ results of the fit

Observed limit:



- **Central value**: Idem as for expected limit
- **±1σ band** : re-run and increase/decrease the signal cross section by the theoretical signal uncertainties (PDF, scales)

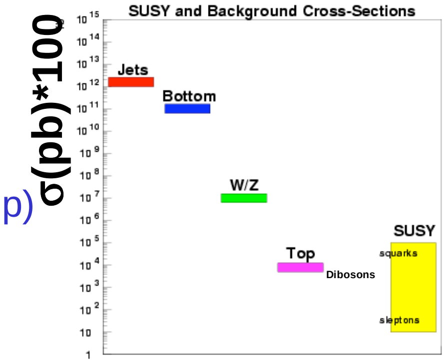


Excluded Model Cross section (SMS)

➔ Number quoted in paper correspond to observed -1 σ observed (conservative)

Summary of First Lecture

❑ Ingredients needed for a SUSY search



1. **Signal Region definition ("cut and count" approach)**
   - Trigger (Jet+MET or leptonic)
   - Hard kinematic cuts to reduce "difficult" background (Fake MET/lepton, pile-up)
   - Enhance S/B by cutting on a discrimant variable (M_{Eff}, M_{CT}…)

2. **Background estimate in signal region**
   - 4 possibilities: MC, closed by process, CR→SR, fully data driven
   - Experimental syst: Jet Energy scale, b-tagging, ...
   - Theory syst: Renormalization/factorisation scale, PDF, …

3. **Quantify the SM - data agreement in Signal Region**
   - Any significant excess (p-value) ?

4. **If not interpret the results:**
   - Model independent
   - Simplified models, Constrained SUSY models

➔ Remember: this drives the sensitivity to SUSY at LHC !

Appetizers for tomorrow

- Weak-scale SUSY searches **before** first LHC SUSY results

MSSM: 29 sparticles + 5 Higgs undiscovered

Mass Limits from PDG2010 (95% CL)
$\tilde{\chi}_1^0$=LSP, RPC, degenerate squarks (except $\tilde{b}$,$\tilde{t}$), $\tilde{l}=\tilde{l}_R$, Gaugino mass unification at GUT scale

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates	Mass Limits
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$	**114.4 , 92.8 , 93.4 , 79.3 GeV** (m_h^{max} benchmark scenarios)
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)	**379 GeV**
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)	
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$	**95.7 , 89 GeV**
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)	**107 GeV**
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)	**94 GeV**
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$	**81.9 GeV**
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$	**46 , 62.4, 99.9 , 116 GeV**
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$	**94 GeV**
gluino	1/2	−1	$\tilde{g}$	(same)	**308 GeV**
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)	

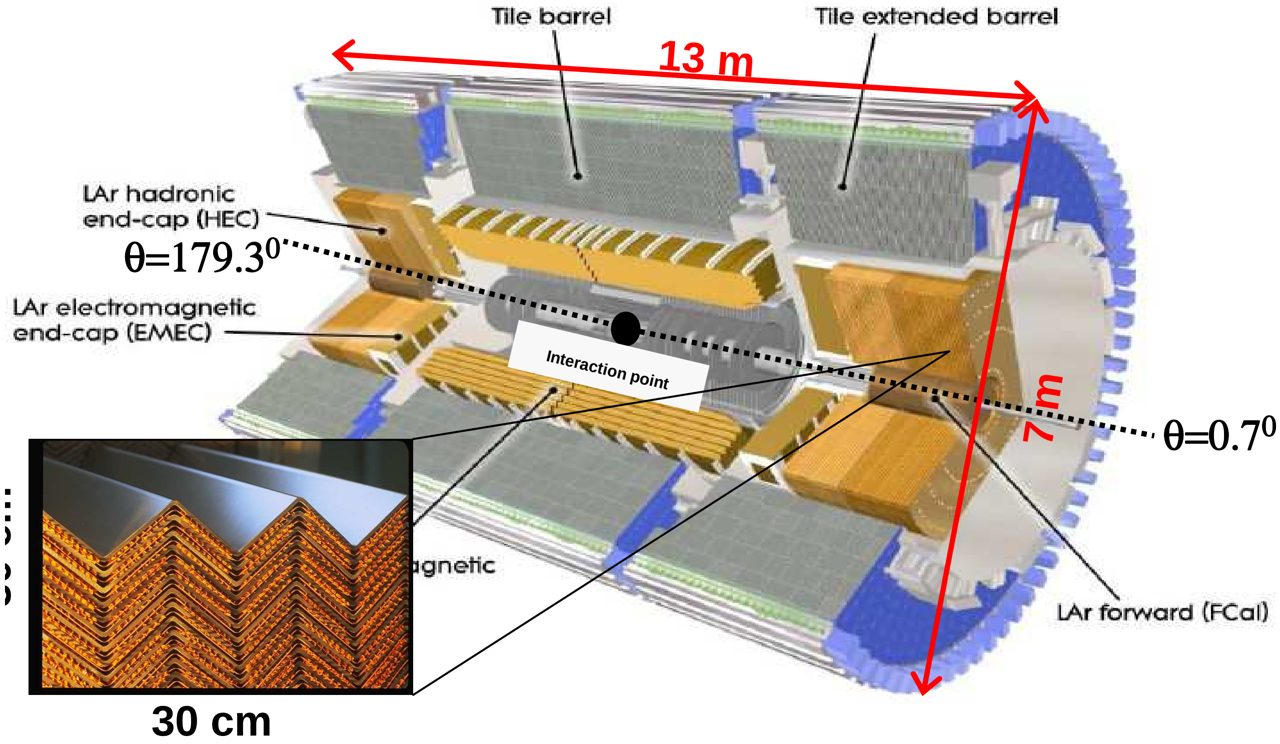
Note: These limits are also model dependent

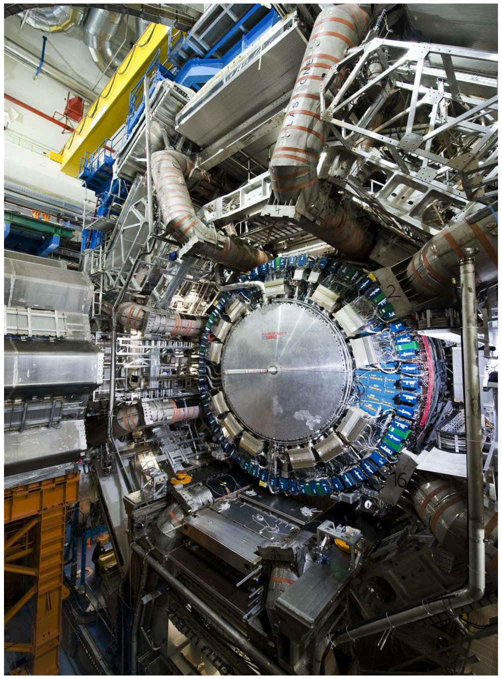
Covers most of SUSY production and decays ... But most in the 0-100 GeV range limited by √s

➔ Come back tomorrow to explore the 0.1-1 TeV range !

SPARE

ATLAS Calorimetry





- **Very granular :** EM (173 500), HAD (14000 = 5 000 Tile + 5500 HEC + 3500 FCal)
- **Hermetic :** EM (22-35 X_0), EM+HAD (11-15 λ), $0.7^o < \theta < 179.3^o$

➔ Measure electrons/photons/jets, missing transverse momentum (MET)

MET reconstruction

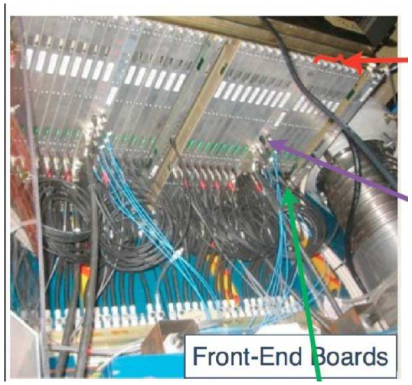
❑ **To identify weakly interacting particle, avoid «holes» in the detector !**

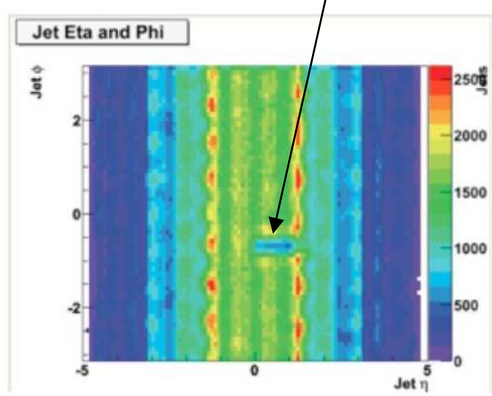
- Extracted from an ATLAS SUSY papers

During a fraction of the data-taking period (about 20% of the total integrated luminosity), a localised electronics failure in the LAr barrel calorimeter created a dead region in the second and third calorimeter layers ($\Delta\eta \times \Delta\phi \simeq 1.4 \times 0.2$) in which on average 30% of the incident jet energy is not measured. Negligible impact is found on the reconstruction efficiency for jets with $p_T > 20$ GeV. For events selected during this data period, if any jet with $p_T > 50$ GeV falls in the aforementioned region, the event is rejected. The loss in signal acceptance is smaller than 10% in the affected period for the models considered.

- Reminder: 187500 cells in ~3000 Front-End boards on the ATLAS EM calorimeter cryostat
- 1rst may 2011: 6 boards lost their 25 ns clock (power glitch)

  ➔ Dip in the number of reconstructed jets, E_T^{miss} tail





Take out **Plug in**

- Successful repair «acrobatique/téléguidé» during the shutdown early July 2011

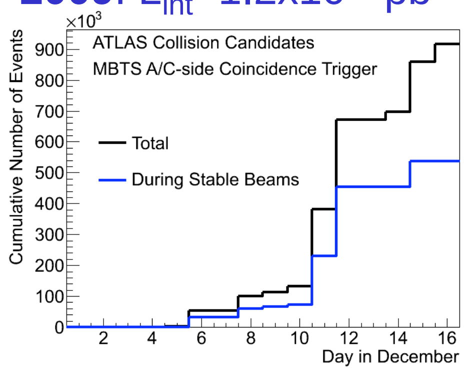
➔ Affected ~1fb-1 of 2011 data (an offline fix was applied)

LHC Luminosity

- **Start 23 November 2009 !**

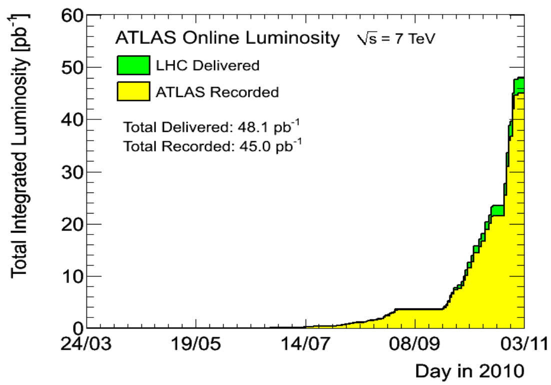
$$L \approx \frac{N^2 f B \gamma}{4\pi\varepsilon_n \beta^*}$$

2009: L_{int}=1.2x10^{-5} pb^{-1}



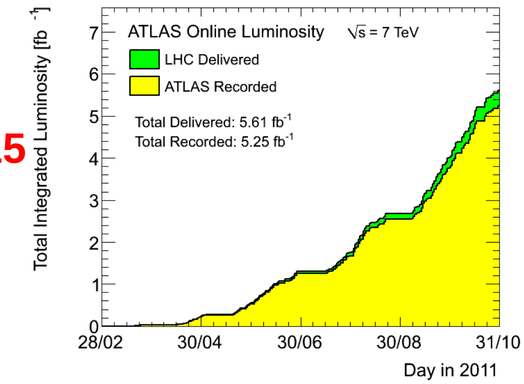
x3.10^6

2010: L_{int}=45 pb^{-1}



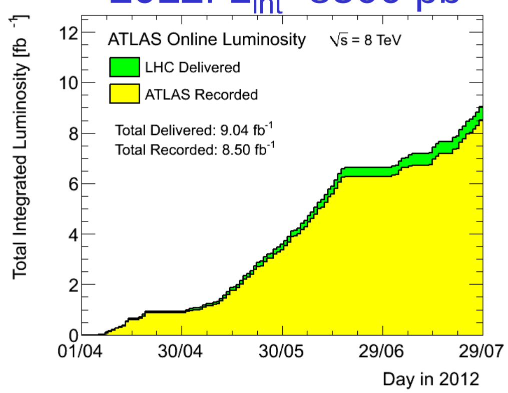
x115

2011: L_{int}=5250 pb^{-1}



2012: L_{int}>8500 pb^{-1}

X >1.6



Calorimeter : Jet

❑ **Application : Measure the energy of non interacting particle ($E^{non\text{-}int}$)**

longitudinal energy leakage

detector signal inefficiencies (dead channels, HV…)

pile-up noise from (off-time) bunch crossings

calo signal definition (clustering, noise suppression ,…)

electronic noise

dead material losses (front, cracks, transitions…)

detector response characteristics (e/h ≠ 1)

jet reconstruction algorithm efficiency

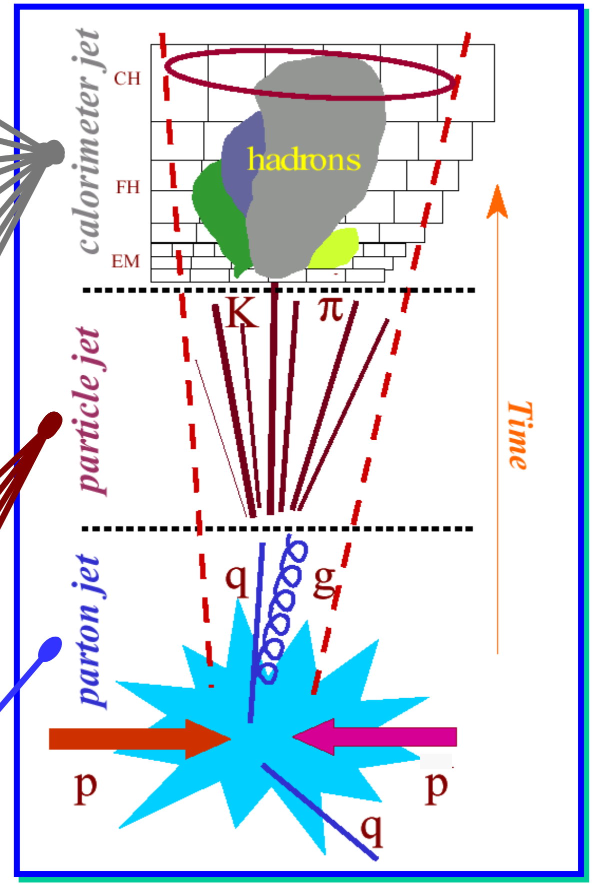
jet reconstruction algorithm efficiency

added tracks from in-time (same trigger) pile-up event

added tracks from underlying event

lost soft tracks due to magnetic field

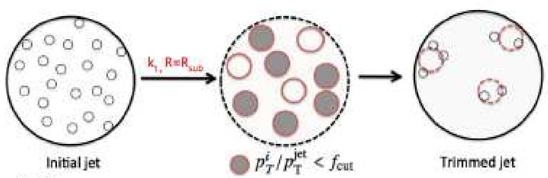
physics reaction of interest (parton level)



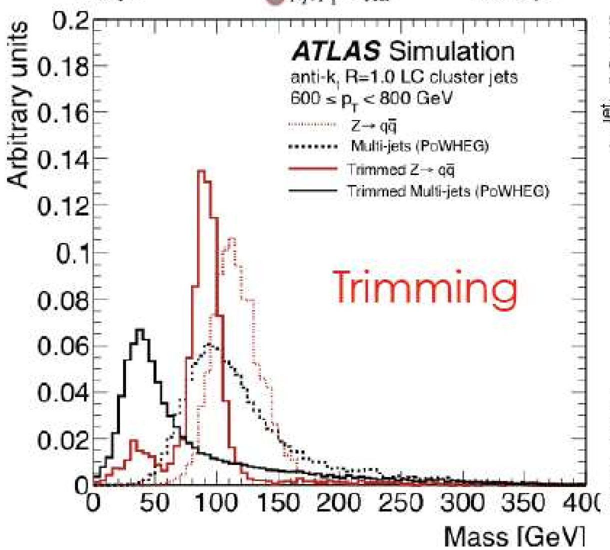
➔ **Not so easy to reconstruct jet … Need lots of LHC data to check**

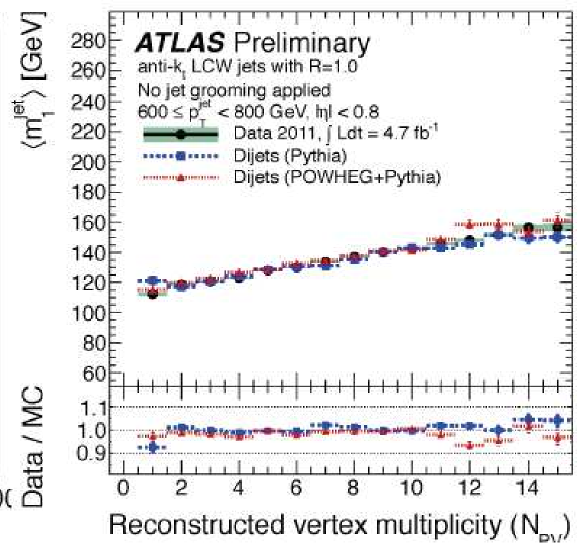
Jet Grooming

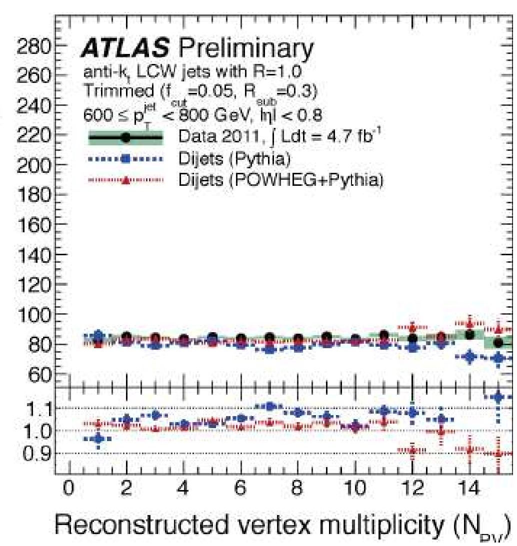
- **Distinguish jets from the decay of massive objects from massive QCD jets by removing soft wide angle radiation:**
  - Improve large-R jet mass resolution
  - Increase S/B
  - Remove pile-up effects on jet mass (reduced area)



- ATLAS has commissioned three grooming algorithms: **trimming, pruning, filtering**

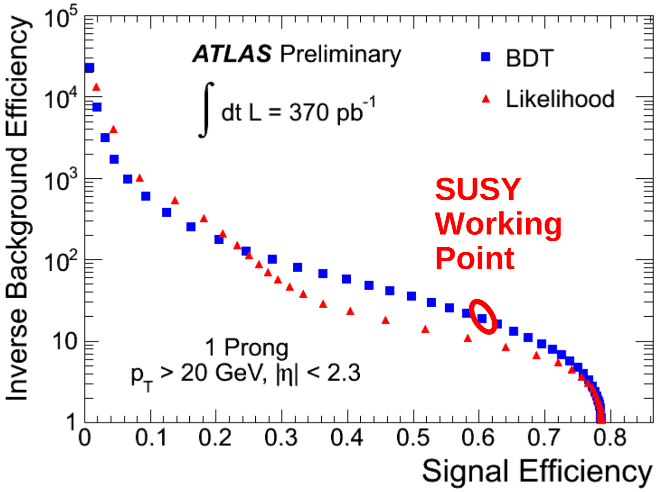


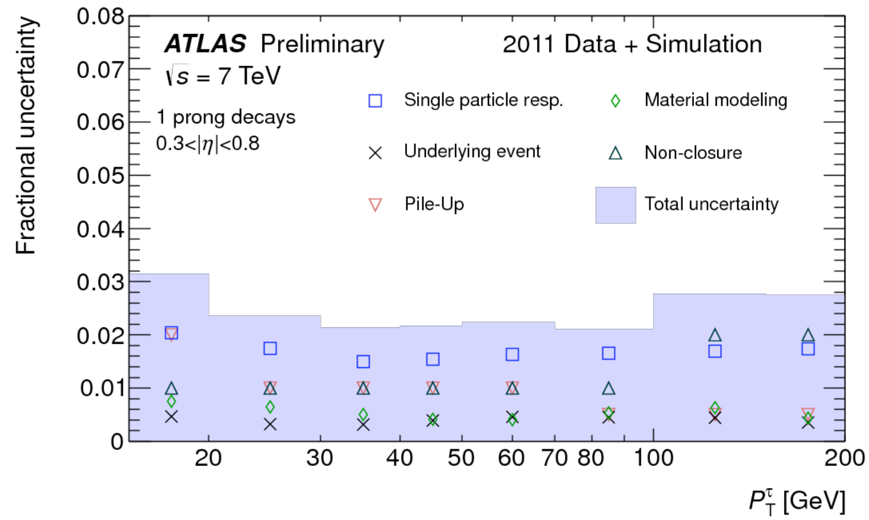




taus

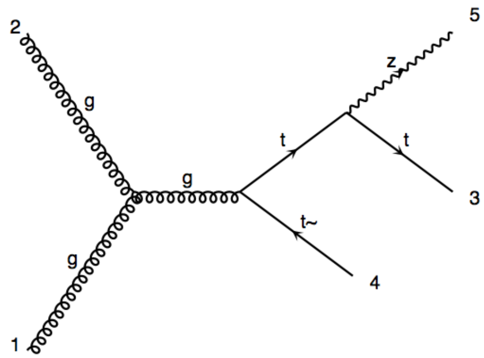
- **Often lightest slepton=stau, i.e. tau in final states**
  - Seeded by anti-kt R=0.4 jet
  - Keep often separated from other leptons (e,μ)

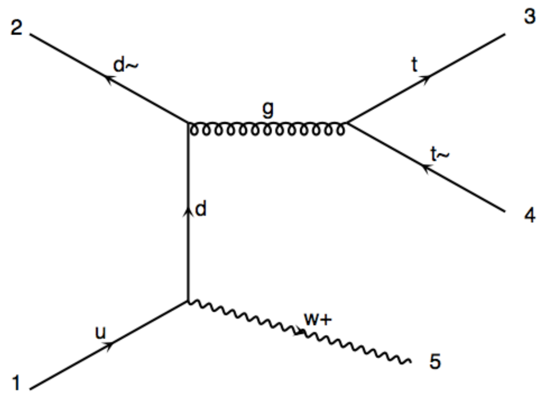


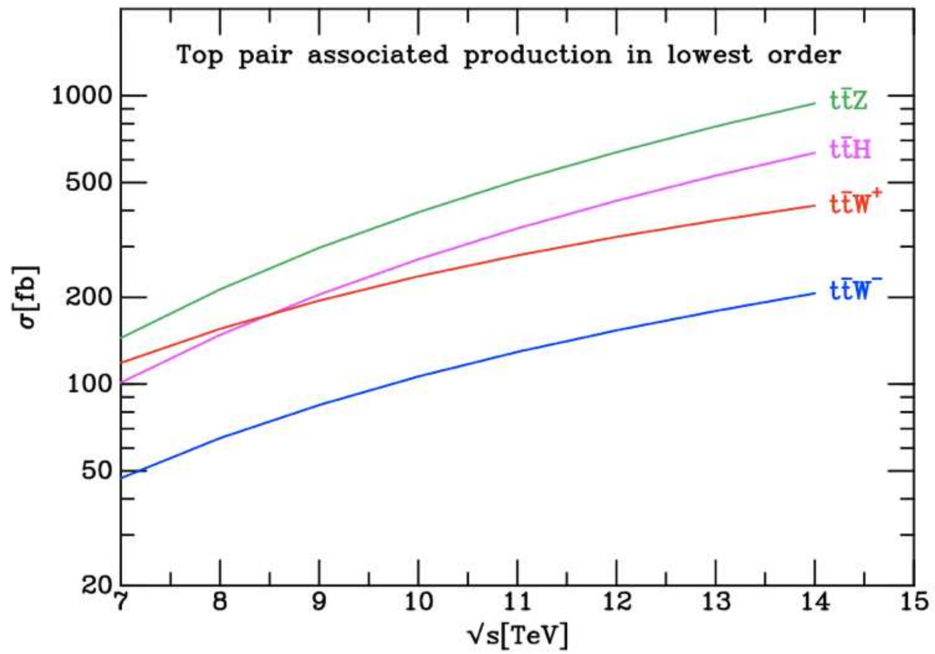


→Note: final states with had. taus (eg, tt→τ+X) are often the main SM background

Ttbar+X

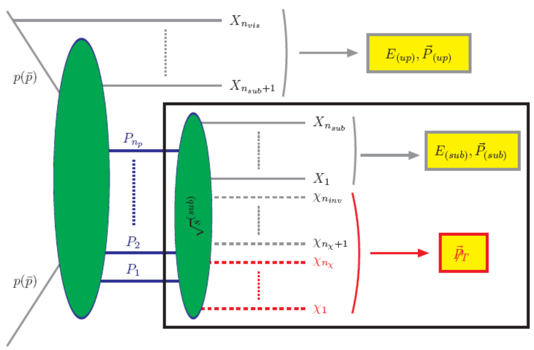


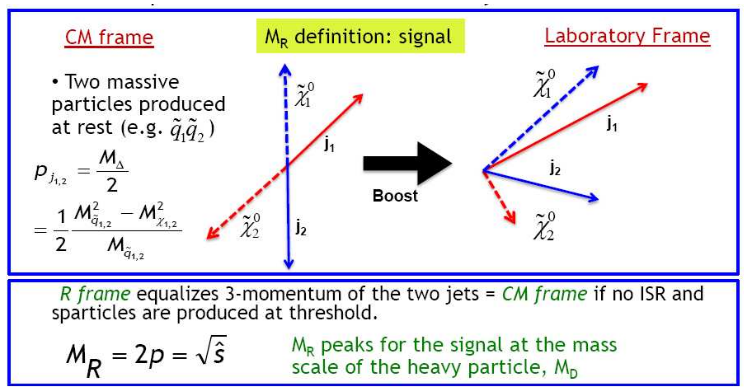




σ (ttbb) ~ 1 pb

Miscellaneous





Item	Lowest unprescaled EF threshold (GeV)	Rate (Hz) @ 5x10^{33}
Incl. e	24	60
Incl. μ	24	45
ee	12	8
μμ	13	5
ττ	29,20	12
γγ	20	10
E_T^{miss}	80	17
5j	55	8