SUSY or not, what is the evidence? Status and perspectives of collider searches – Part IB

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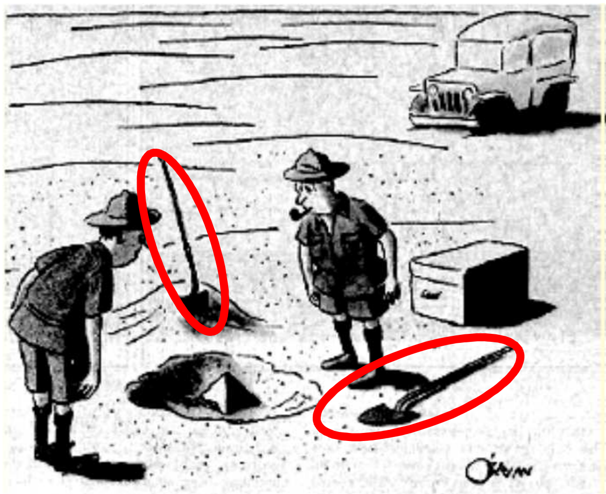
Lectures at Niels Bohr Institute



"This could be the discovery of the century. Depending, of course, on how far down it goes"

Part I (2 lectures)
The tools to dig

W 30-Oct	Th 31-Oct	Fr 01-Nov
--	Lecture IIA **Exercise 1**	Lecture IIC **Exercise 2**
Lecture IA Lecture IB	**Exercise 1** Lecture IIB	**Exercise 2** Lecture III

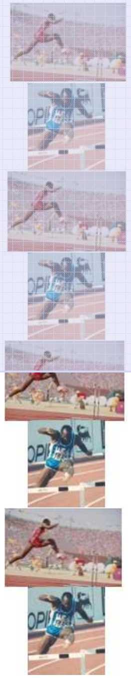
Lectures Part I

❑ **Part I : Ingredients needed for a SUSY search at LHC** → "What drives the sensitivity to SUSY at LHC ?"

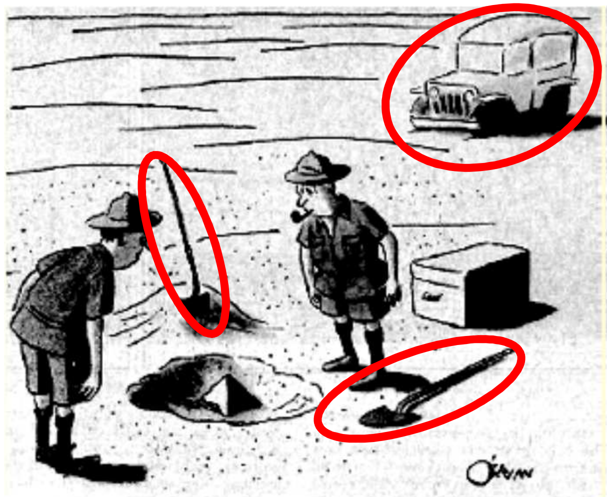
400 m hurdles
➔ 10 hurdles to clear

A
1. Scale and New Physics
2. Guide to find New physics
3. Detector description
4. Object Reconstruction
5. Monte Carlo Simulation

B
6. Discriminant variables
7. Background Estimation
8. Fit Results
9. Result Interpretation
10. Signal Region Definition



"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)



Part I (2 lectures)
Motivation + the tools to dig

W 30-Oct	Th 31-Oct	Fr 01-Nov
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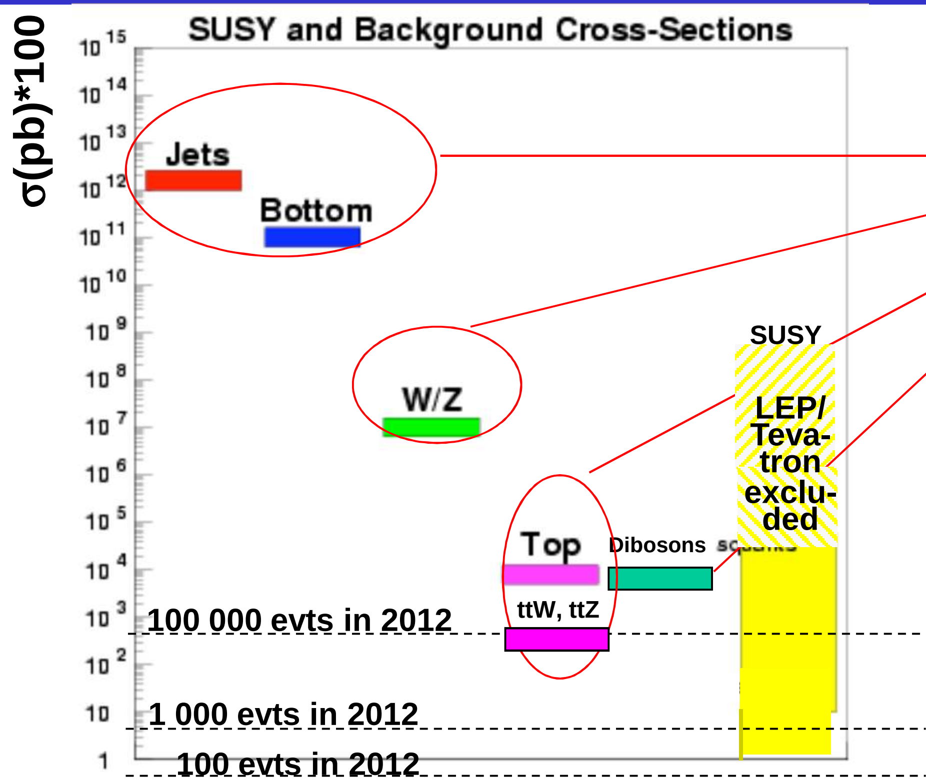
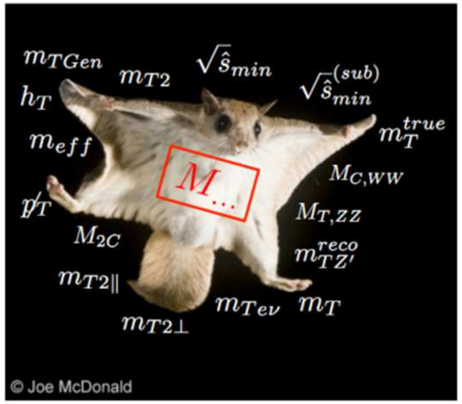
Discriminant variables





m(g,q)~ **500** GeV, m(t_1)~ **200** GeV, m($\chi_{1,2}$)~ **100** GeV

Discoverable

m(g,q)~**1000** GeV, m(t_1)~ **600** GeV, m($\chi_{1,2}$)~ **400** GeV

Hard

m(g,q)~**1200** GeV, m(t_1)~ **800** GeV, m($\chi_{1,2}$)~ **600** GeV

Too Hard

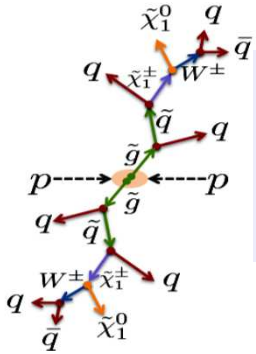
1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^5 / 10^2

2) Estimate small remaining quantities
3) Fit results
4) Interpret the results if no excess
5) How to design a signal region?

Discriminant variables (1)

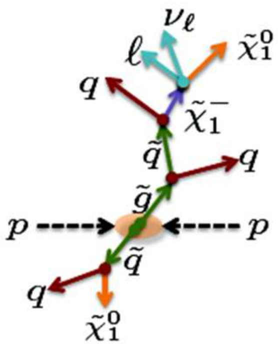
❑ First need hard kinematic cuts

- To reduce "difficult" background (Fake MET/ lepton, pile-up)



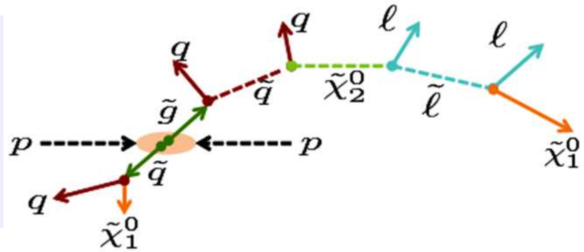
SM Background
1.Z(→νν)+jets
2.ttbar/W+jets
3.QCD

<u>**0lepton**+jets+MET</u>:
- ✓ Jet+MET trigger
- ✓ Ask several high pT jets
- ✓ High MET cuts to kill QCD



SM Background
1.ttbar
2.W+jets
(3.Fake lepton)

<u>**1lepton**+jets+MET:</u>
- ✓ Lepton trigger
- ✓ Ask several high pT jets
- ✓ Lower MET cuts than 0lep
- ✓ m_T(W) >m(W)



<u>**≥2lepton**+jets+MET:</u>
- ✓ 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

- Choose the best variables to <u>discover</u> a certain SUSY topology [best Z=**S/√(B+ΔB²)** from MC]
- Define 'Signal' populated regions (SR)

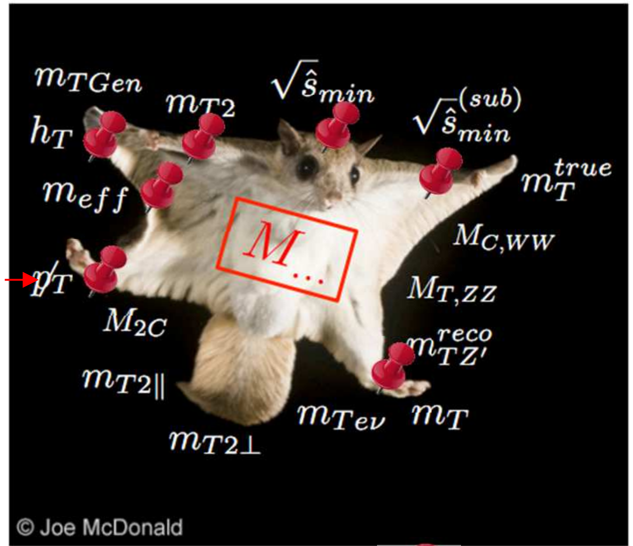
Discriminant variables (2)

❑ 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 2 megajets: Razor, α_T
- QCD killers: $\Delta\phi$(jets, MET)
- QCD+EWK killers: b-jets
- ttbar killers : 2lepton Same sign, 3 bjets, 3leptons, >6 jets
- Z veto

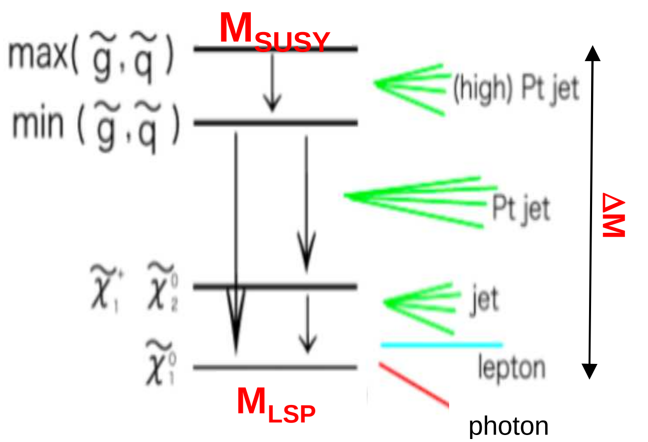
➔ Optimal choice of variable(s)/method(s) is analysis dependent

Discriminant variables (3)

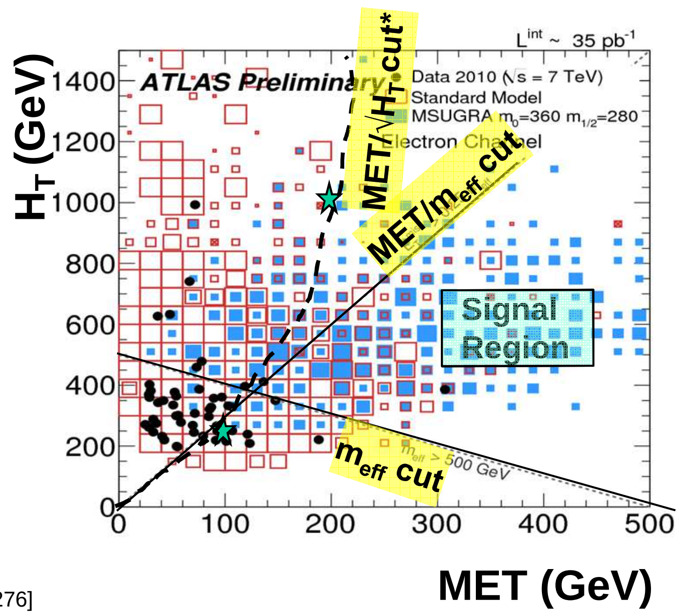
1. Effective mass (M_{Eff})

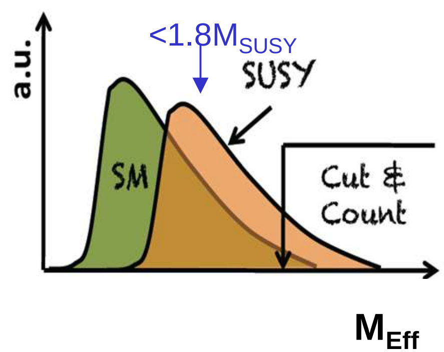
used w or w/o leptons in final states

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



- **Module of Vectorial Sum: MET ~ ΔM**
- **Scalar Sum: $H_T = \Sigma\, p_T$ (jet) [+ p_T (l,γ)] ~ ΔM**
- **M_{Eff}=MET+H_T~1.8(M_{SUSY}^2-M_{LSP}^2)/M_{SUSY}** [hep-ph/0006276]





arXiv:hep-ph/9610554

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

* Useful for lower MET SUSY signal (here cut~6 GeV$^{1/2}$)

Discriminant variables (4)

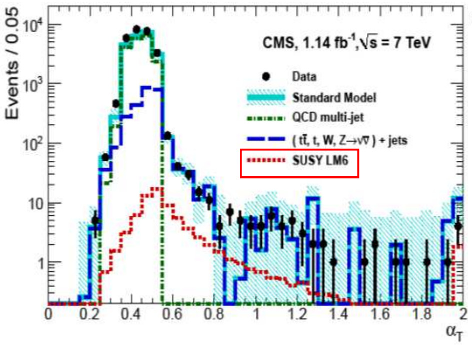
2. α_T *used w/o lepton in final states*

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

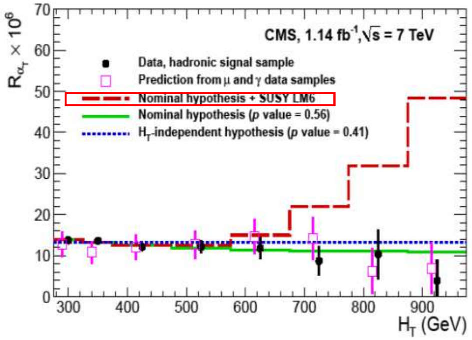
(j_2 less energetic jet)

- 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*

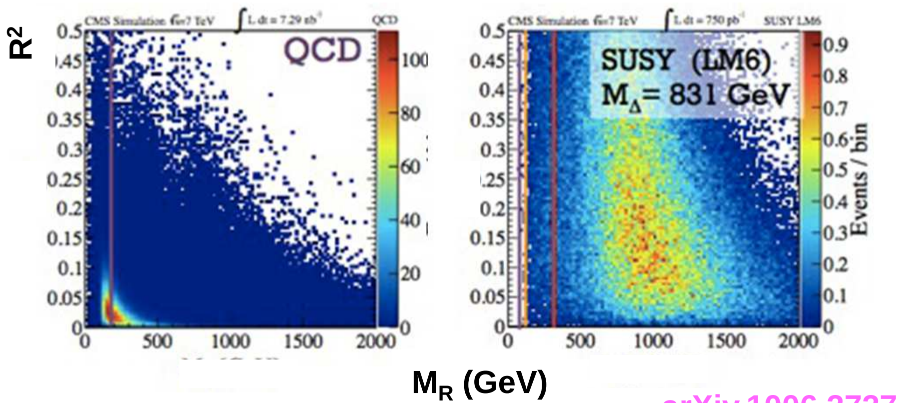
$$M_R = 2|\vec{p}^{\,R}_{j1}| = 2|\vec{p}^{\,R}_{j2}| \sqrt{\frac{(E^{j1}p_z^{j2} - E^{j2}p_z^{j1})^2}{(p_z^{j1} - p_z^{j2})^2 - (E^{j1} - E^{j2})^2}}$$

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_D high: signal peaks at M_R ~ M_D
- Increase discrimination with R^2

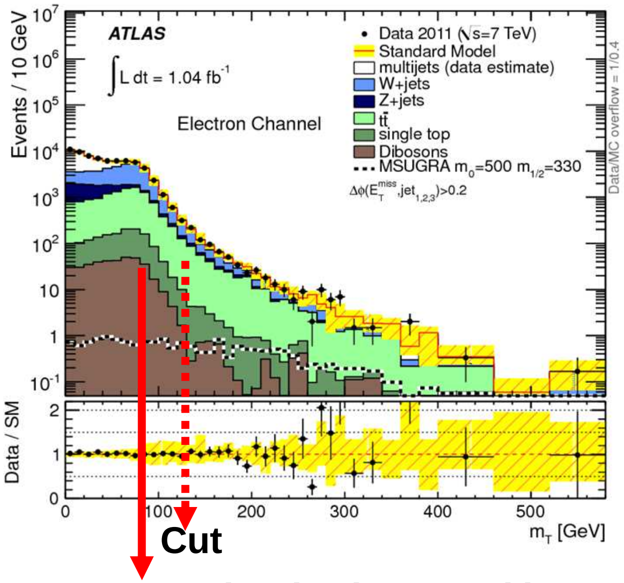


arXiv.1006.2727

Discriminant variables (5)

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 !

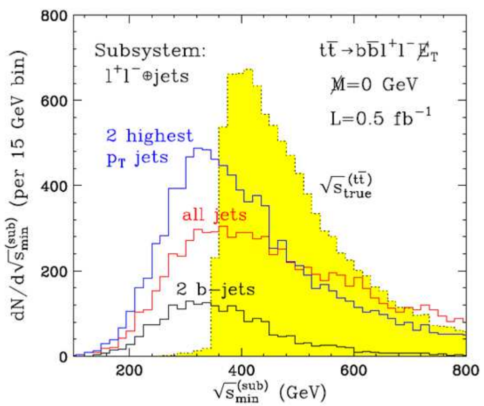
5. Root-smin : direct stop 1, 2 lepton + bjets

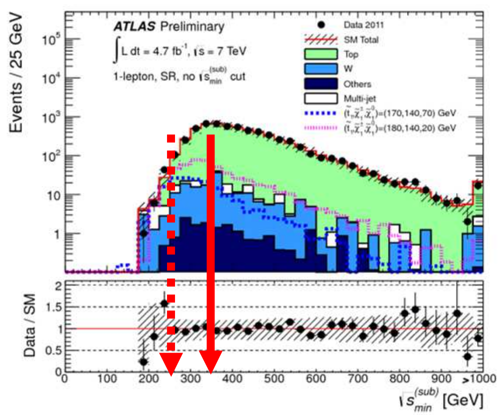
$$\sqrt{s}_{min}^{(sub)} = \left\{\left(\sqrt{m_{(sub)}^2 + p_{T(sub)}^2} + \sqrt{(m^{miss})^2 + (E_T^{miss})^2}\right)^2 - \left(\mathbf{p}_{T(sub)} + \mathbf{p}_T^{miss}\right)^2\right\}^{\frac{1}{2}}$$

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

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

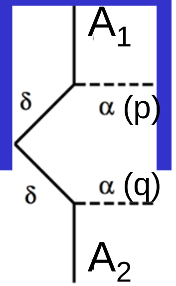
For $\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}$, $m(\tilde{t})-m(\tilde{\chi})<m(t)$ starting point <2m(t)





JHEP 1106 (2011) 041

Discriminant variables (6)

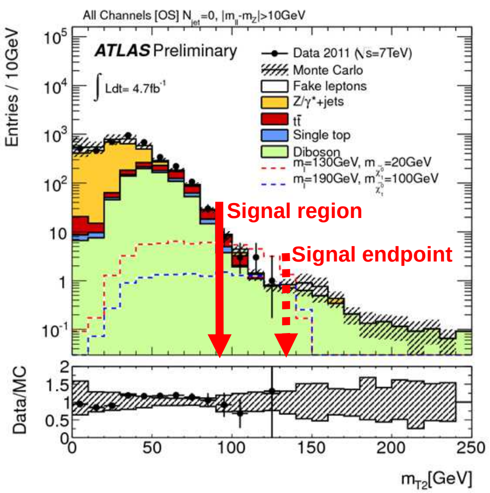


6. M_{T2}, m_{CT}

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

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

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



For $\tilde{l} \to l\chi$ endpoint

$[M(\tilde{l})^2 - M(\tilde{\chi})^2] / M(\tilde{l})$

~130 GeV for m(l)~0

JP G29 (2003) 2343

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

For ttbar, endpoint

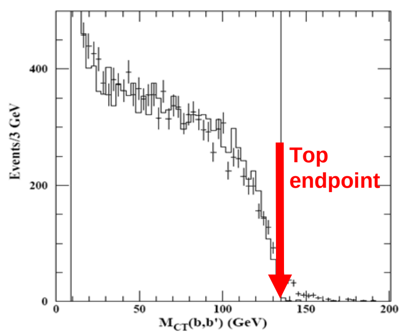
$[M(t)^2 - M(W)^2] / M(t)$

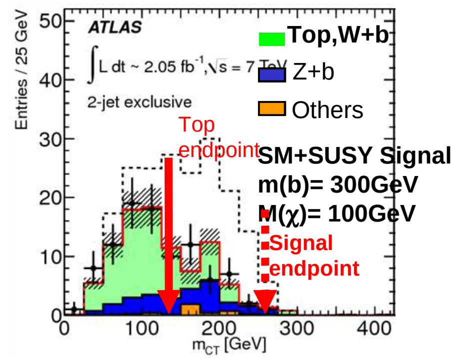
~ 135 GeV, m(b,ν)~0

For $\tilde{b} \to b\tilde{\chi}$ endpoint

$[M(\tilde{b})^2 - M(\tilde{\chi})^2] / M(\tilde{b})$

~260 GeV, m(b)~0



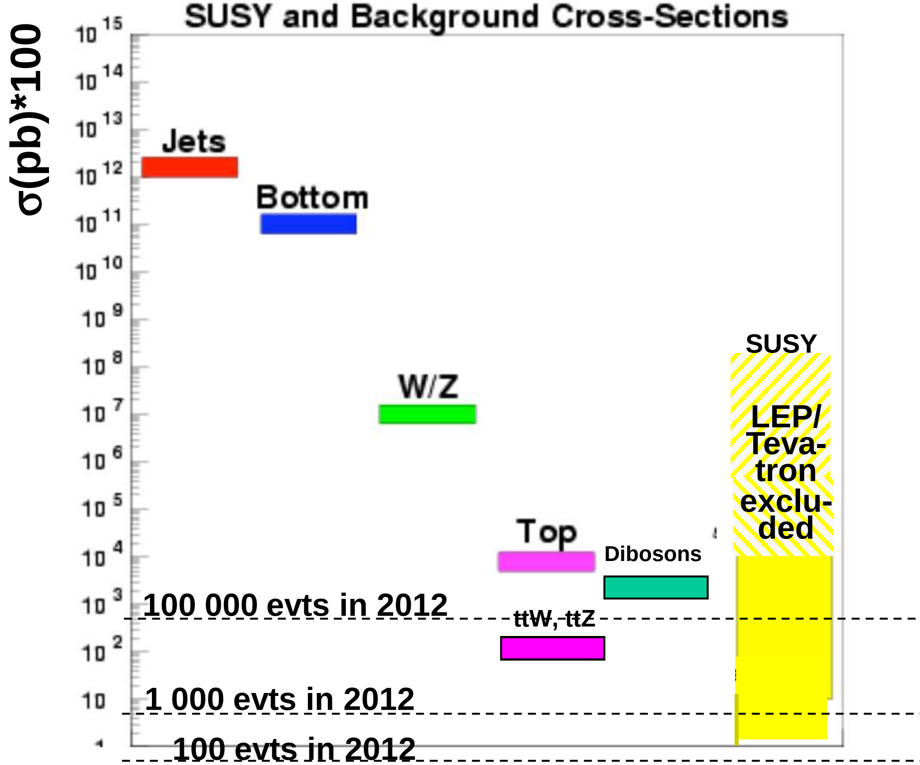


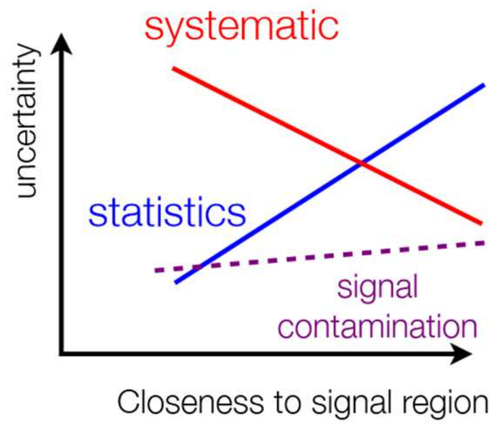
JHEP 0804 (2008) 034, JHEP 1003 (2010) 030

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

*Originally designed to measure SUSY masses

Background estimation





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

2) Estimate small remaining quantities

3) Fit results

4) Interpret the results if no excess

5) How to design a signal region?

Background estimation (1)

❑ Different strategies for different background

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

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

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)

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)

➔ Precision in background determination drives the SUSY sensitivity

Background estimation (2)

ATLAS-CONF-2012-033

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

- Production : $\tilde{g}\tilde{g}$
- Decay : $\tilde{g} \to \tilde{q}q$ with $\tilde{q} \to q\tilde{\chi}$ dominates ➔ **0lepton + ≥4 jets + MET**
- Discriminant variable : **M_{Eff} >1200 GeV**

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	Pile-up driven
$p_T(j_2)$ [GeV] >	60	
$p_T(j_3)$ [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, 3	QCD rejection -driven
$E_T^{miss}/m_{eff}(Nj)$ >	0.25 (4j)	
m_{eff}(incl.) [GeV] >	1200	Discriminating variable

➔ 3 main backgrounds: QCD, Z→νν +jets, [ttbar→bWbW→blνbjj&W→lν]

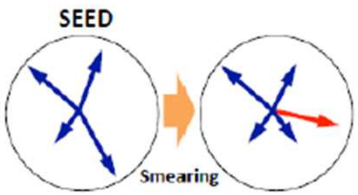
Background estimation (3)

ATLAS-CONF-2012-033

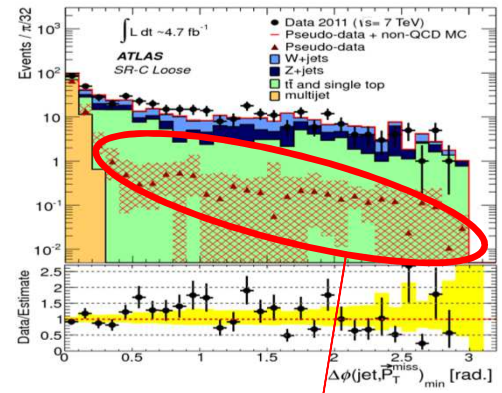
❑ QCD/Multijets background (Data driven)

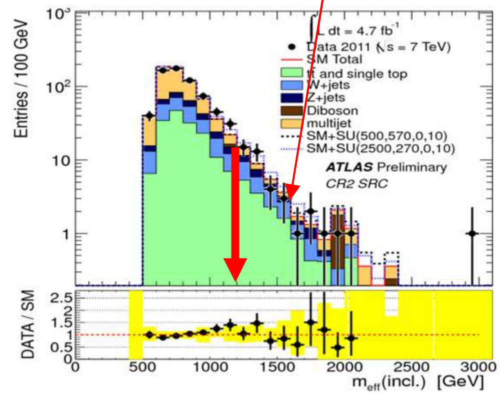
- Enter Signal Region because of fake MET or ν inside jet
- Can not trust MC + limited by MC stat
  - ✓ Compute jet response R=pT(jet reco)/pT(jet true) and generate pseudo data to populate SR

1. Determine the jet response function R from dijet balance and 3-jets mercedes events **(1jet aligned with MET)**
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 estimation (5)

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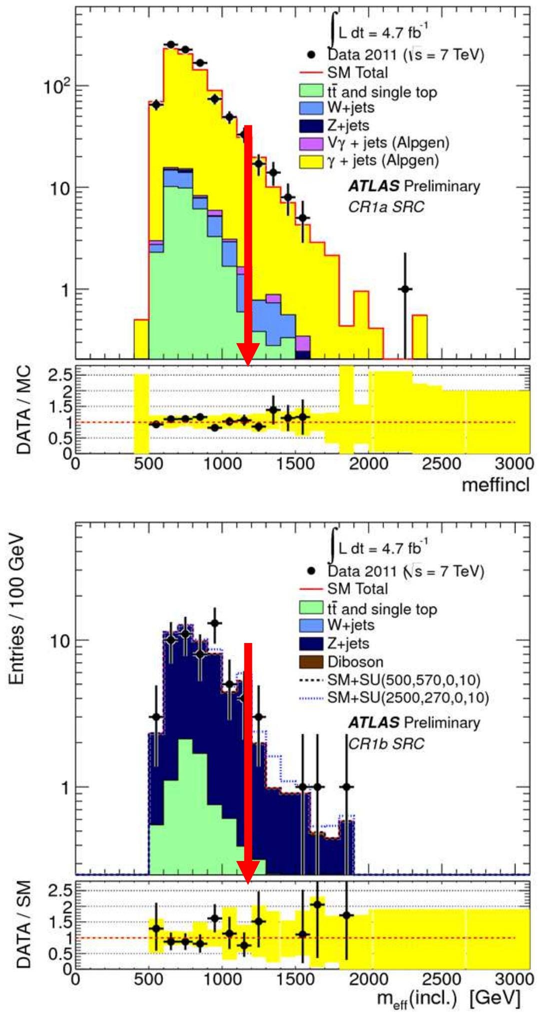
❑ Z→νν +jets (Data Driven)

- 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>>m_Z
   - ➔Obtain a very pure sample
   - ✓Force the photon as MET
   - ✓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 estimation (4)

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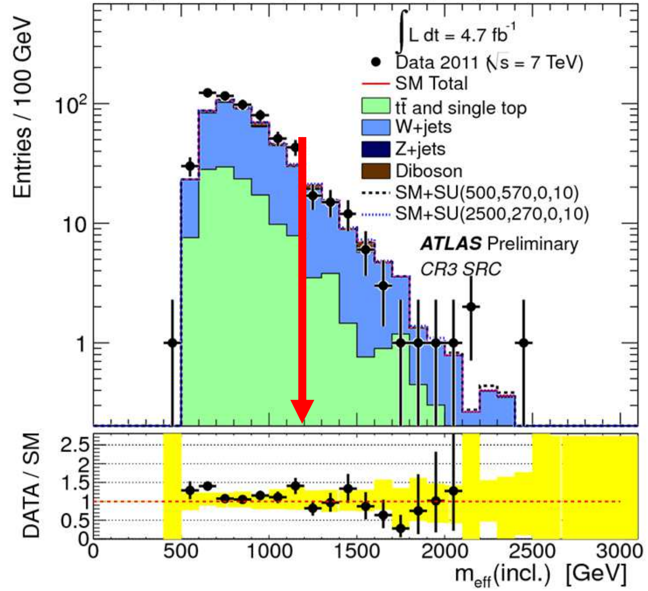
❑ W→lν +jets and ttbar→blνbqq (Semi Data-driven)

- Enter Signal Region 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 ch.)
  - ✓ Force the lepton as a jet (acceptable approximation)
- Look in the Control Region:
  - ✓ Monte Carlo should reproduce the data
  - ✓ High **Purity** (N_{MC}^{oth}~small), small Signal contamination
- Estimate N_{SR}^{bkg} **Transfer factor** (**c**) relying on MC shape:

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

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

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



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

Background estimation (6)

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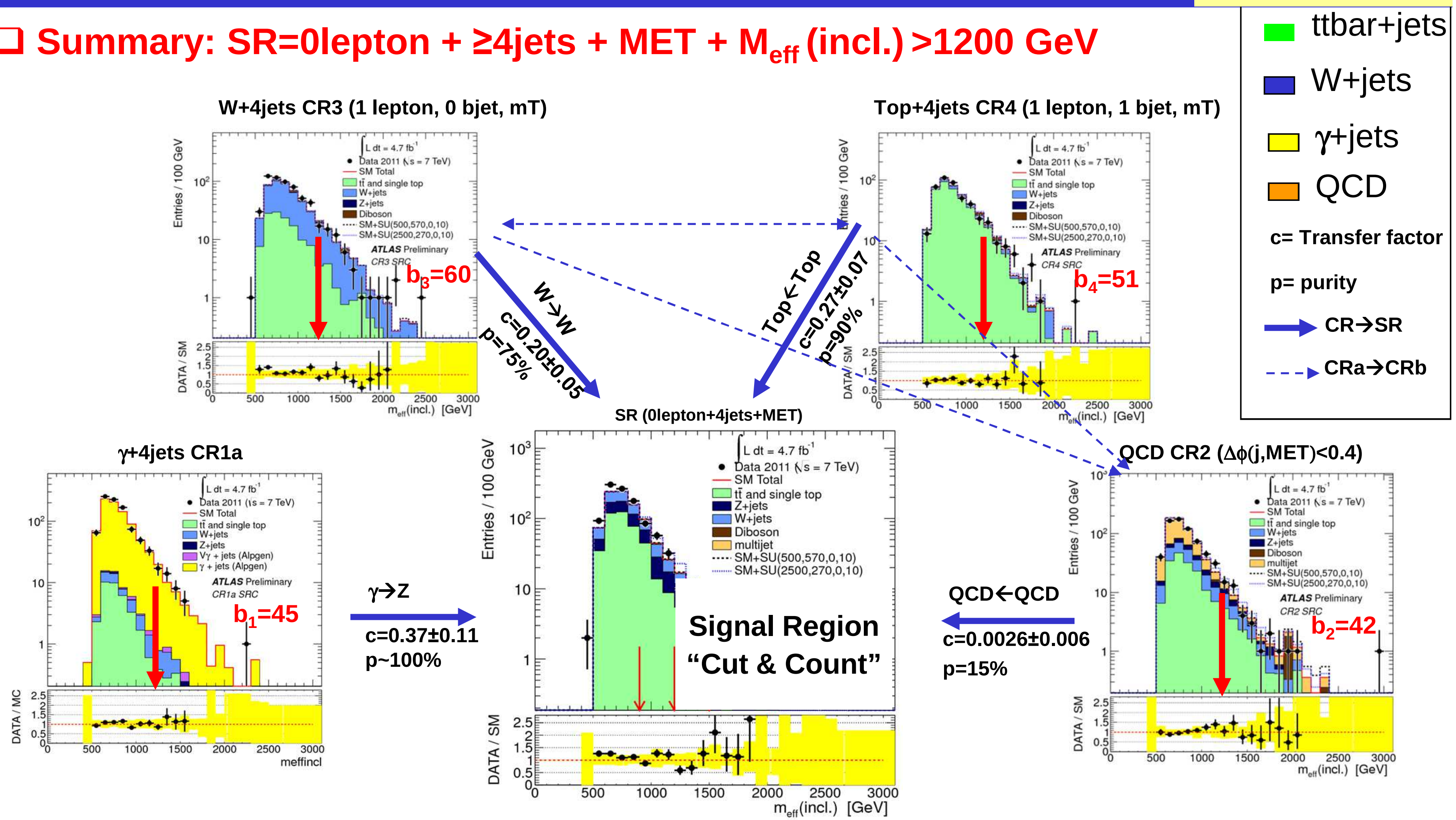
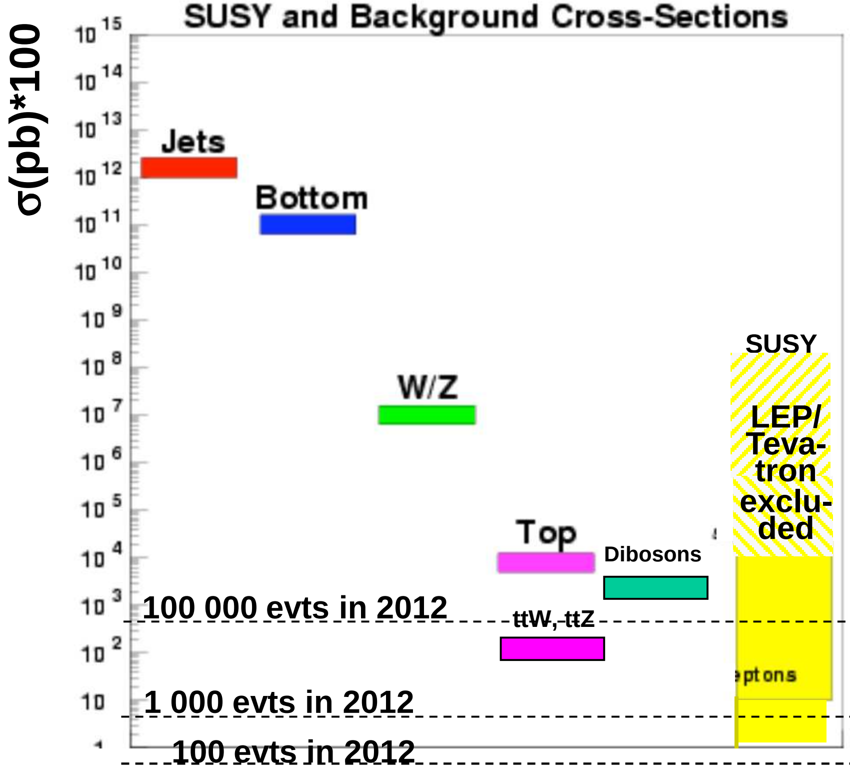
- **Summary: SR=0lepton + ≥4jets + MET + M_{eff} (incl.) >1200 GeV**



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

Fit Results



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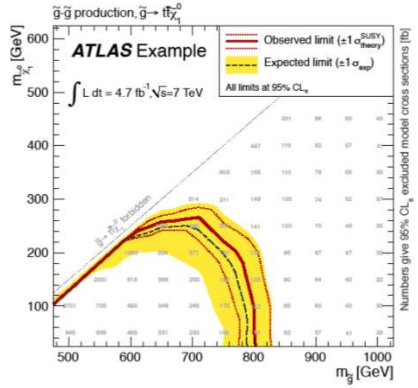

m(g,q)~ **500** GeV, $m(t_1)$~ **200** GeV, $m(\chi_{1,2})$~ **100** GeV

Discoverable

m(g,q)~**1000** GeV, $m(t_1)$~ **600** GeV, $m(\chi_{1,2})$~ **400** GeV

Hard

m(g,q)~**1200** GeV, $m(t_1)$~ **800** GeV, $m(\chi_{1,2})$~ **600** GeV

Too Hard

1) Need to suppress QCD / W,Z / top by 10^{10} / 10^5 / 10^2
2) Estimate small remaining quantities

3) Fit results

4) Interpret the results if no excess
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Fit Results (1)

ATLAS-CONF-2012-033

❑ Building the likelihood

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

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

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

- **Inputs**: Transfer factors (**c**), data events in SR (**s**) and CR_j ($\mathbf{b_j}$)

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

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

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

$\mathbf{c_{CR,SR \rightarrow SR}}$

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 by doing a simultaneous fit of all regions

*pdf=probability density function

Fit Results (2)

ATLAS-CONF-2012-033

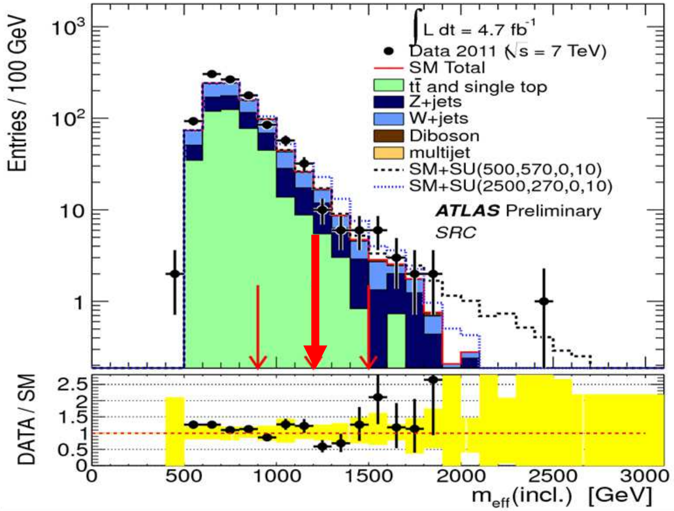
❑ Background-only fit (μ=0)

- Predict the background in the Signal Region (SR) by maximizing the likelihood
  - ✓ Cross-checks of the extrapolation are done in ``validation'' region, close to SR
- SR not in the fit + no signal contamination in CR (can be reproduced by theorists)

	Background in SR $c_{jR->SR}(\boldsymbol{\theta}) \bullet b_j$				Others	Total Background in SR
	Zνν+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)

ATLAS-CONF-2012-033

❑ 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)

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

Maximise L for a choice of μ   *Maximise L*

***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)

ATLAS-CONF-2012-033

❑ Derive a model independent limit

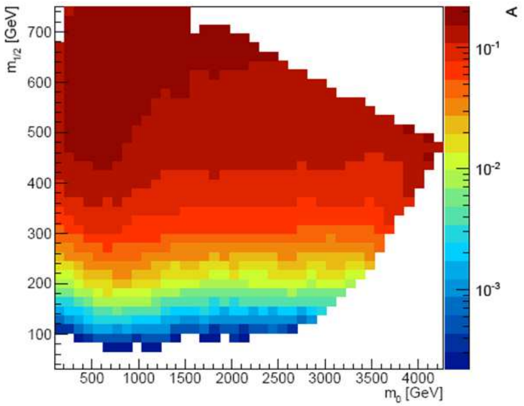
- Limit on visible cross-section of non-SM process: $\sigma_{vis} = \sigma \times A \times \varepsilon$
- In 0lepton+≥4jets+MET + M_{eff} (incl.) >1200 GeV:

Predict 39+/-9, observe 36 →

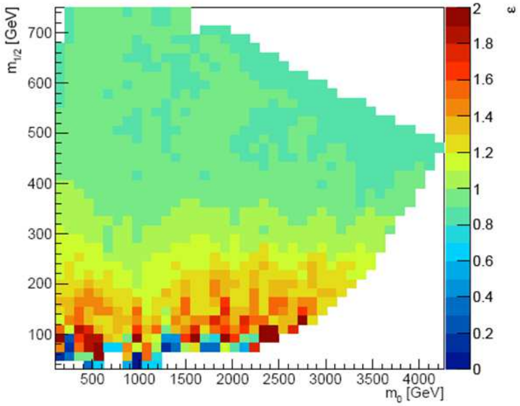
> ➔ **Exclude at 95%CL N(BSM)≥ 18 and N/L = σ_{vis} > 3.7 fb**
>
> ➔ *Expected to exclude N(BSM)≥ 19 and N/L=σ_{vis} > 4.1 fb*

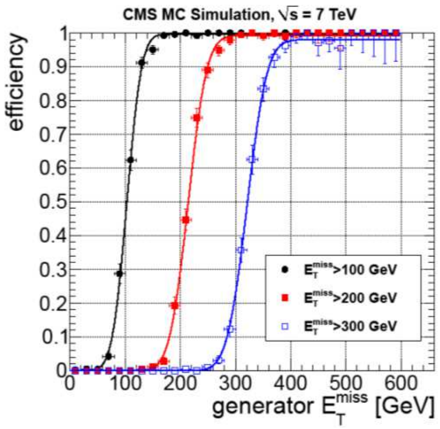
- A and ε given for a well-defined SUSY model : Examples below

Acceptance of Truth cuts~0.1-10%



Efficiency wrt Truth ~ 1





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

Fit Results (5)

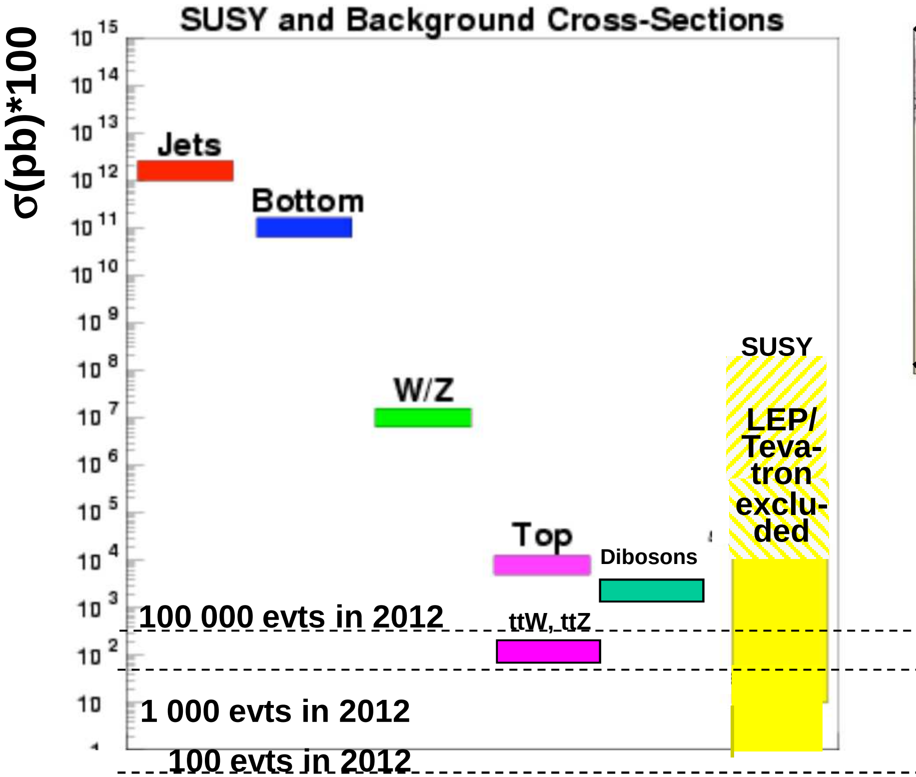
❑ Side Note : A simpler estimation of the signal sensitivity

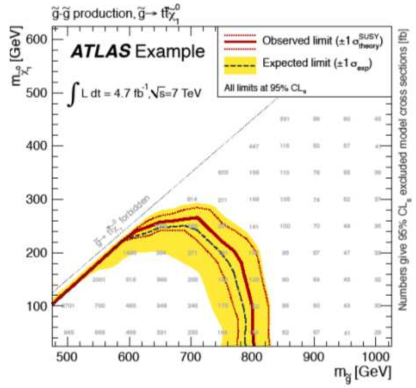
- Compute Zn ≈ $S/\sqrt{(B+(x.B)^2)}$, where x = error on background determination (stat +/- syst)
  - ✓ More correct formula RooStats::NumberCountingUtils::BinomialExpZ(S,B,x)
  - ✓ Rule of a thumb: Zn=2 exclude the signal, =5 can discover it !
- Works well for low number of signal events <100 and 1-2 dominating background

  Predict 39+/-9 ➡ *Expected to exclude N(BSM)≥ 27 (correct number is 19) ~ Right ballpark !*
- If several channels (like e and mu) can add Zn in quadrature.
- Ideal for the optimisation of new signal regions
  - ✓ Lots of unknowns → x, complicated background, …
  - ✓ Can assess the relevance (or not) of this search

➔ For this reason Zn will be used in the exercise session

Interpretation





m(g,q)~ **500** GeV, m(t_1)~ **200** GeV, m($\chi_{1,2}$)~ **100** GeV

Discoverable

m(g,q)~**1000** GeV, m(t_1)~ **600** GeV, m($\chi_{1,2}$)~ **400** GeV

Hard

m(g,q)~**1200** GeV, m(t_1)~ **800** GeV, m($\chi_{1,2}$)~ **600** GeV

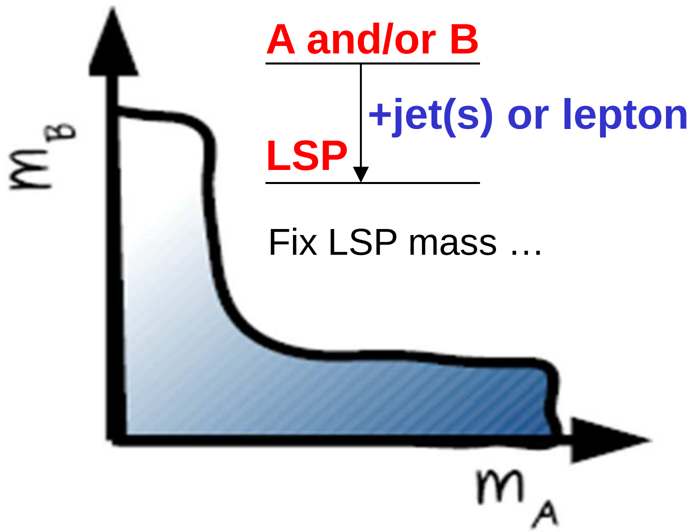
Too Hard

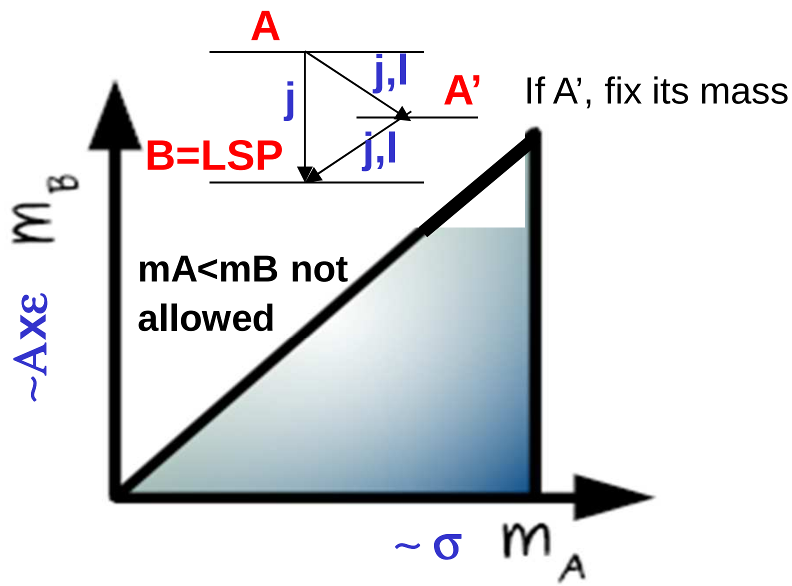
1) Estimate small remaining quantities
2) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^5 / 10^2
3) Fit results
4) **Interpret the results if no excess**
5) How to design a signal region?

Interpretation (1)

❑ 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 "arbitrary"



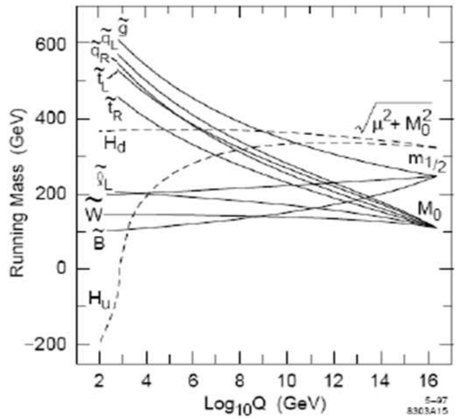


➔ Very helpful also to design analyses. Possible to recast in mSUGRA (1202.2662)

Interpretation (2)

- **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

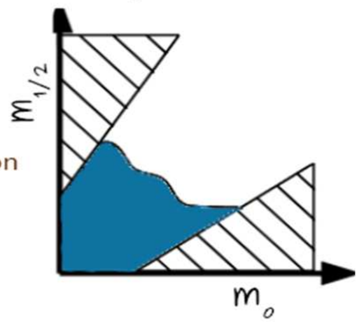


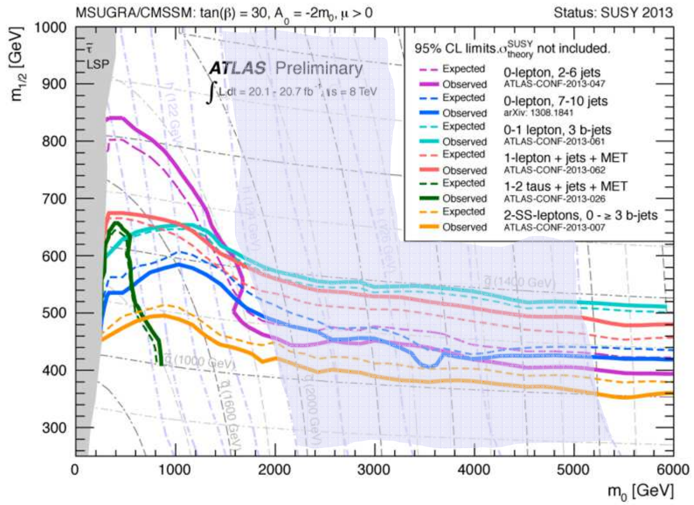
Note: 5 fb-1 ATLAS/CMS papers use a common mSUGRA framework described in Matchev et al, 1202.6580 :

m_0, $m_{1/2}$, $\tan\beta$ =10, A_0 =0, μ>0
m_0, $m_{1/2}$, $\tan\beta$ =30, A_0 =0, μ>0 [Higgs aware]

E.g. mSUGRA/CMSSM:

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





➔ Useful to calibrate our exclusion and compare with other results

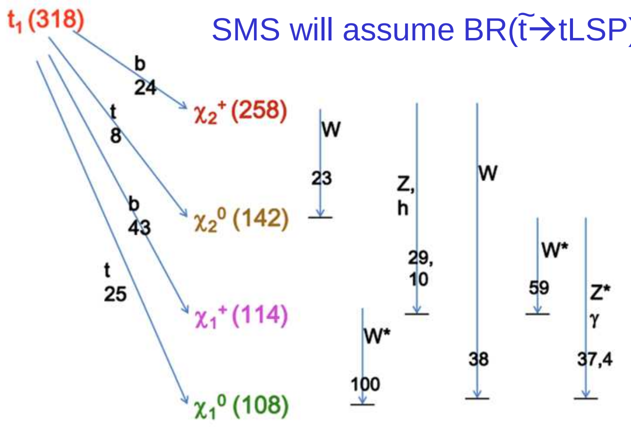
Interpretation (3)

❑ Derive a limit in a simplified MSSM

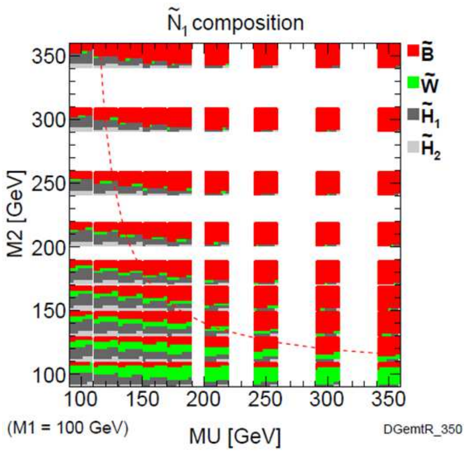
- Reduce number of SUSY parameters from 105 (MSSM) to 19, i.e. "manageable":
  - ✓ Well justified assumptions
  - ✓ "Standard" exp. constraints
- Recover the SUSY complexity ➔ can track missing features of SMS in "simple" cases

Direct Stop production

SMS will assume BR($\tilde{t}$→tLSP)=100%



Direct Gaugino production



SMS will assume χ bino or higgsino-like

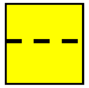
➔ Could be a way to exclude natural SUSY

Interpretation (4)

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

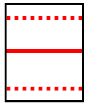
- Ease the life of theorist by separating the signal theoritical and experimental systematics

Expected limit:

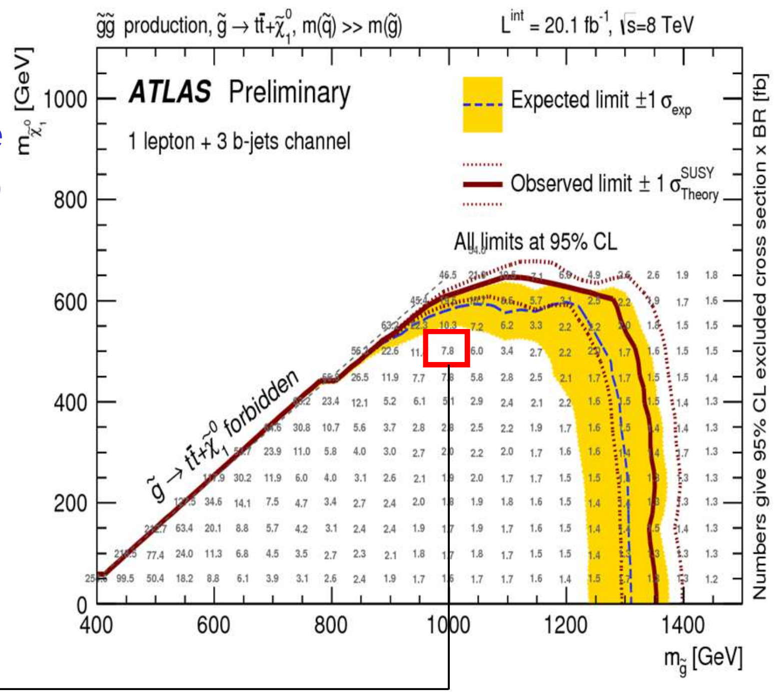


- **Central value:** all uncertainties included in the fit as nuisance parameters, except theoretical signal uncertainties (PDF,scales)
- **±1σ band** : ±1σ results of the fit

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)

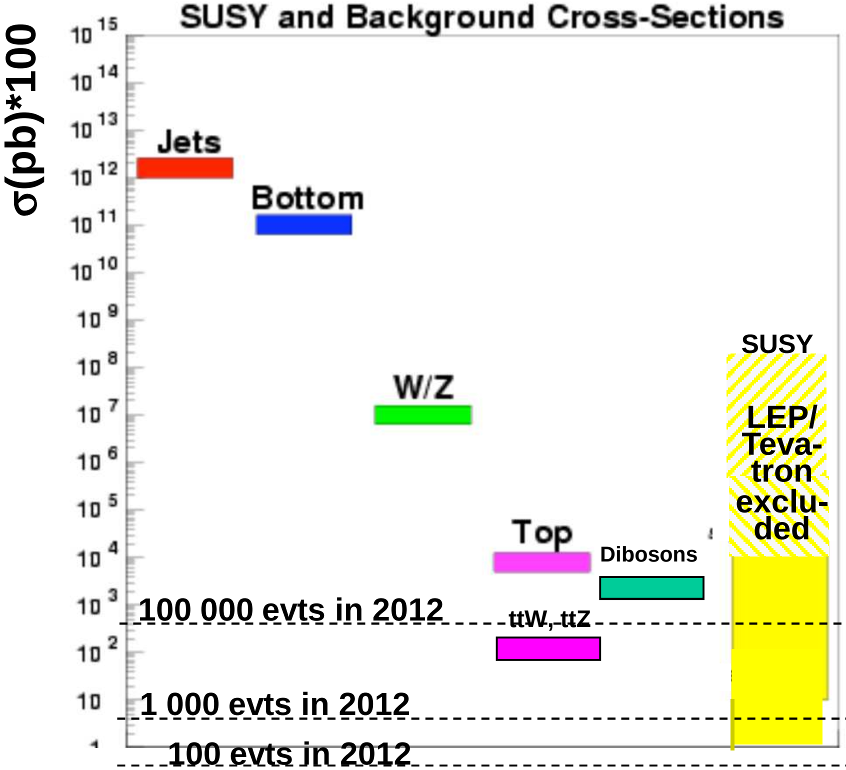


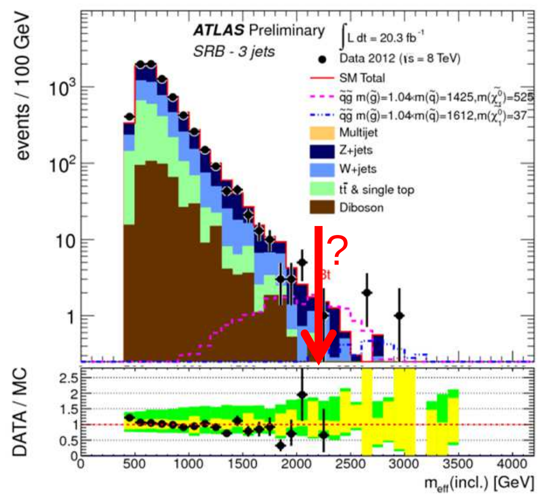
Excluded Model Production Cross section (σ_{excl})

e.g M($\tilde{g}$)=1 TeV $\sigma(\tilde{g}\tilde{g})$~30 fb If $\sigma_{excl} < \sigma(\tilde{g}\tilde{g})$

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

Signal Region Definition





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Discoverable

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Hard

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Too Hard

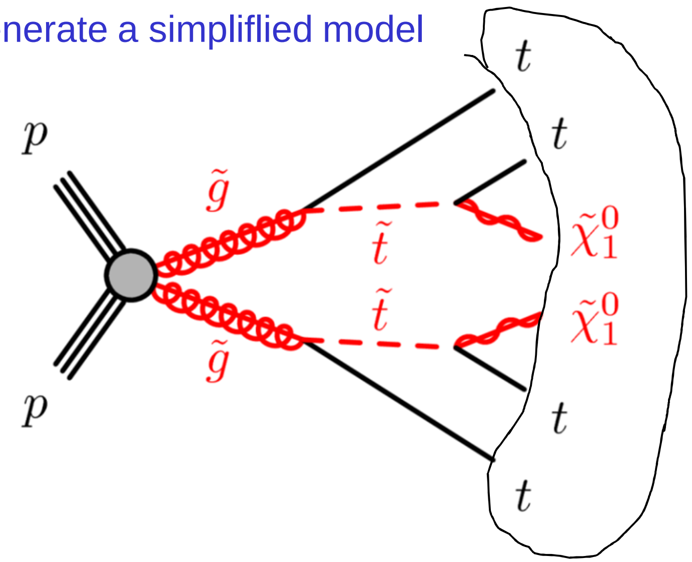
1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^{5} / 10^{2}
2) Estimate small remaining quantities
3) Fit results
4) Interpret the results if no excess

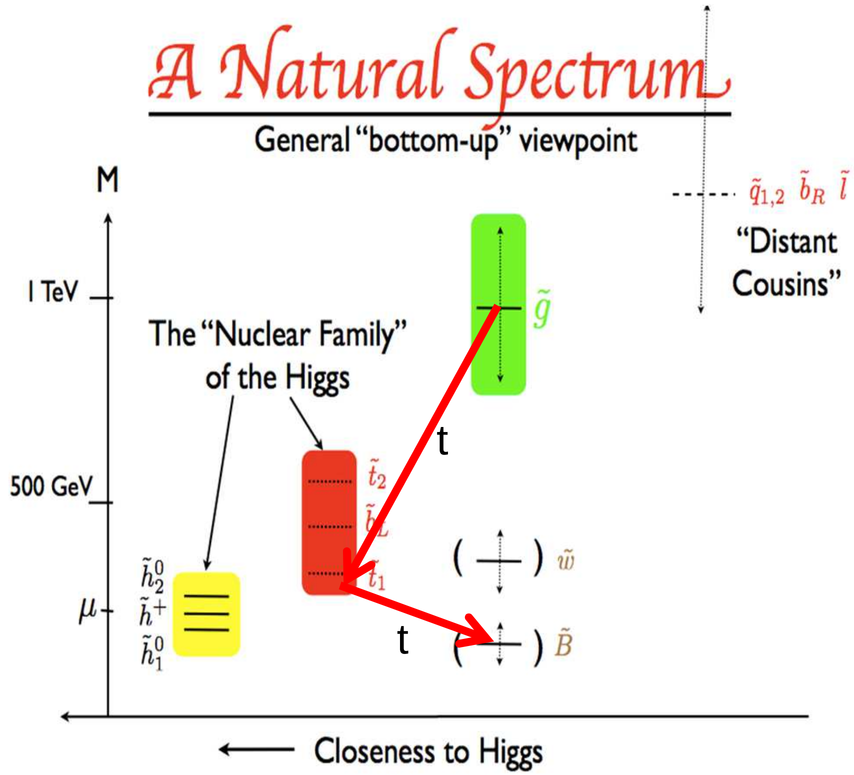
5) How to design a Signal Region?

Signal Region Definition (1)

❑The steps to follow

1. Choose a process to target
   - ✓ Current limits ?
   - ✓ Cross-section ?
   - ✓ Generate a simplified model





Final state : 4 tops + 2 χ_1^0 → 4 W(lv, jj) + 4 b + 2 χ_1^0 → 4 l + 0 j + 4 b + MET   Let's consider this one
(at tree level)
→ 3 l + 2 j + 4 b + MET
→ 2 l + 4 j + 4 b + MET
→ 1 l + 6 j + 4 b + MET
→ 0 l + 8 j + 4 b + MET

Signal Region Definition (2)

❑The steps to follow

1. Choose a process to target   4 l + 0 j + 4 b + MET
2. Choose a trigger (Jet+MET, leptonic, photonic, …) or define a new one !

   Dileptonic trigger seems best, MET or Jet+MET possible
3. Choose object functionning point

   Lepton: medium, tight

   Bjet: medium, loose
4. Use kinematic cuts to reduce “difficult” background (Fake MET/lepton, pile-up)

   Lepton, Bjet: pT ?
5. Select the dominant background (B) and generate/use MC samples

   ttbar
6. Define signal region: select relevant discriminant variables (M_{Eff}, M_{CT}, …) and optimise cuts to obtain higher discovery significance with **Zn = $S/\sqrt{(B+\Delta B^2)}$**

   >=3b or 2lepton Same sign or 3 leptons
7. Perform a detail background estimation + systematics
8. **Open the signal box !!**

➔ This will be our guidelines for Exercise 1 tomorrow

Summary of Part IA

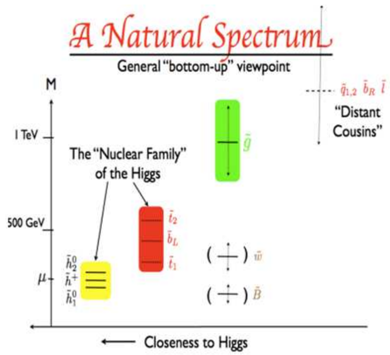
❑ Historical period for SUSY searches

- Naturalness predicts new EW-scale particles (Nx, Cx, stop, sbottom_L, gluino)
- 2012 @ LHC: N(SUSY) = 1000 for mC1=mN2 ~ 0.4, m(stop) ~ 0.6, m(gluino) ~ 1 TeV
- General Decay (spart → SM part + N1) and final states (Jets, MET, leptons/photon)

→ LHC is an ideal place to discover Natural Weak scale SUSY !

❑ Theory unknowns → Drive experimental SUSY searches [Part II]

- R-Parity (RPC, RPV) ?
- SUSY Breaking (SUGRA, GMSB, AMSB) ?
- Open/compressed spectra ?



MSSM: 29 sparticles + 4 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	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

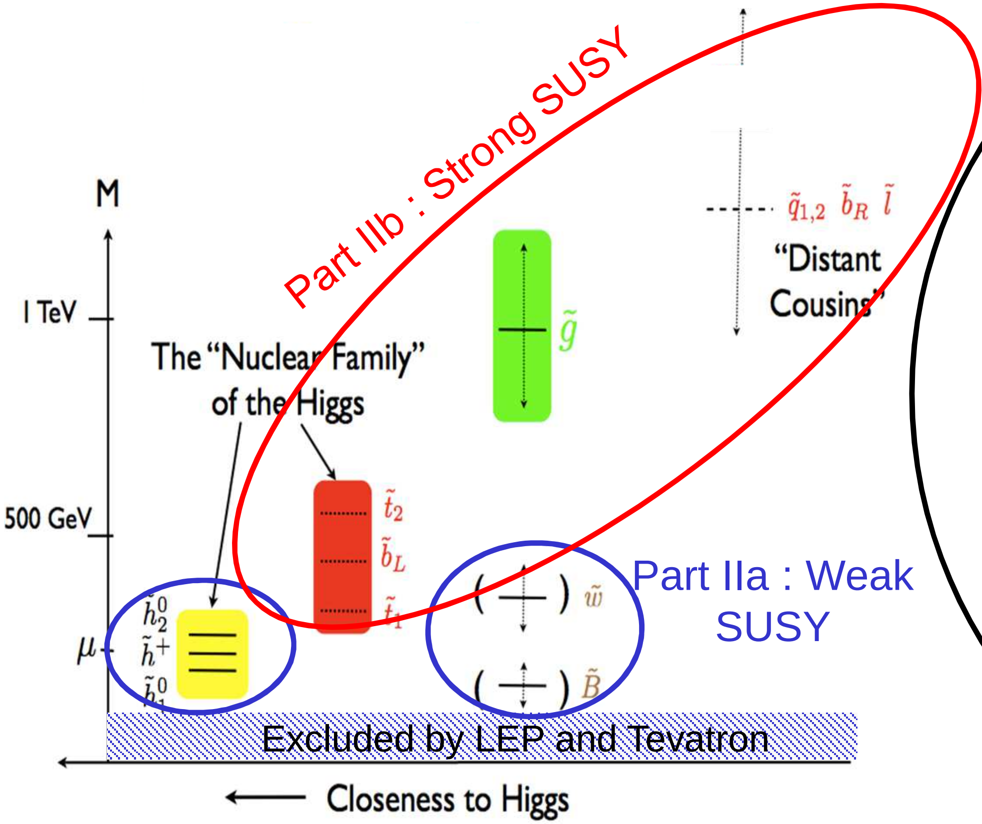
Summary of Part IB

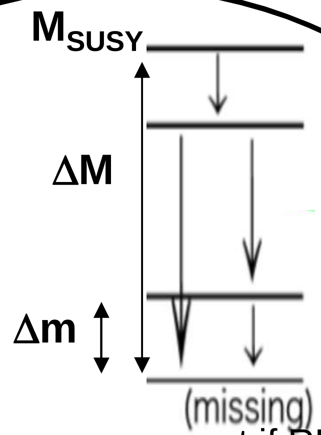
- **How to find SUSY at LHC and what drive the sensitivity ?**
  - Well understood reconstructed objects
  - Well defined signal regions
    - ✓ Based on powerfull discriminant variables MET, HT and Transverse mass
  - Background estimation technics adapted to each background type:
    - ✓ Background with fake MET → data-driven
    - ✓ Background ttbar, W, Z → Semi data-driven (with Control Region)
  - Handy stat tools
  - If no discovery, interpret our results :
    - ✓ In Simplified Model (SMS), i.e. topological models.
    - ✓ In reduced MSSM (5 or 19 parameters)

Tomorrow we put in practice : go fishing in uncharted sea (see next two slides) !!

Lecture Part II (1)

Part IIc: R-Parity Violated, Long-Lived Particles, beyond MSSM





or not if RPV

1. Low **Δm**, tiny RPV, weak coupling to $\tilde{G}$
   Long Lived or meta-stable sparticles
2. 'Sizeable' RPV
   Multileptons, No Z, jet resonances, LFV
3. MSSM Extensions?
   Scalar Gluon
4. Un-natural SUSY ?

Lecture Part II (2)

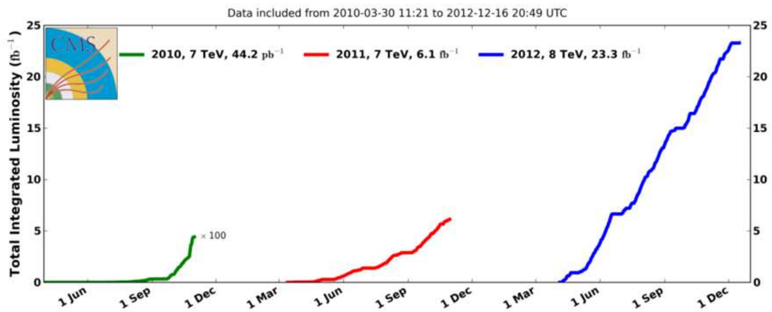
SUSY Related papers in ATLAS/CMS*

- 2010 data (7 TeV, 0.03 fb^{-1}) : 12 / 10+2
- 2011 data (7 TeV, 1-5 fb^{-1}) : 40 / 19+7
- 2012 data (8 TeV, 10-20 fb^{-1}) : 3 / 5+2

SUSY Related CONF notes in ATLAS/CMS*

- 2010 data (7 TeV, 0.03 fb^{-1}) : 3 / 1+0
- 2011 data (7 TeV, 5 fb^{-1}) : 6 / 7+0
- 2012 data (8 TeV, 20 fb^{-1}) : 21 / 10+1

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



~ 150 public analyses in 2 years ! → 15-20% of the ATLAS/CMS results

➔ Show most powerful 8 TeV, 20fb^{-1} searches
➔ Give general status of each topical search

All information on ATLAS/CMS Public pages:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

* CMS= SUSY + RPV LongLived in EXOTIC

SPARE

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 !