mSUGRA search with muons

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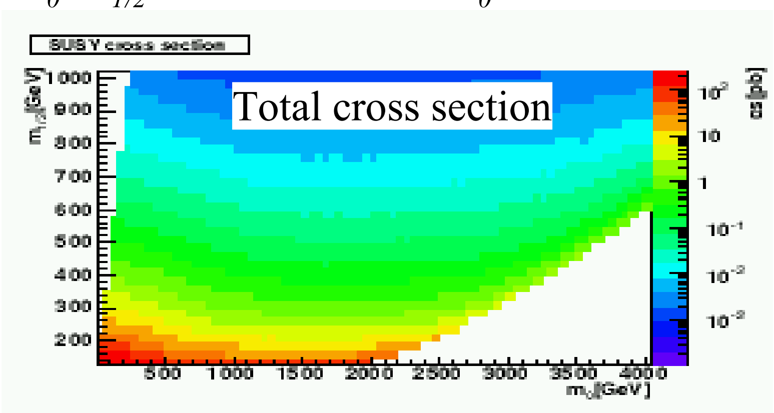
SUSY muonic signatures

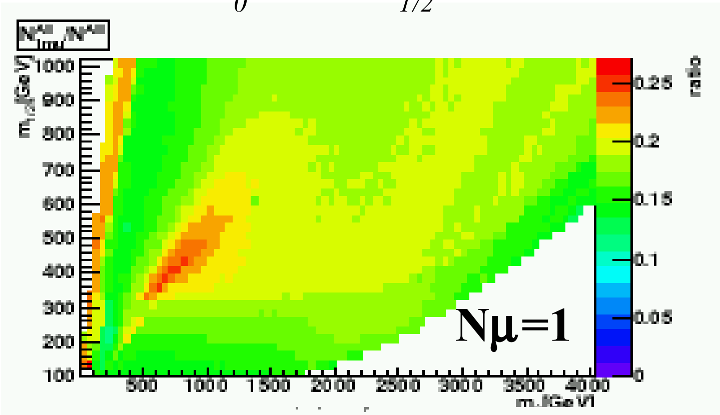
- **Muons from gauginos $\chi^{\pm}$, χ^{o} decays**
- **Gauginos are produced directly or in cascade decays with jets.**

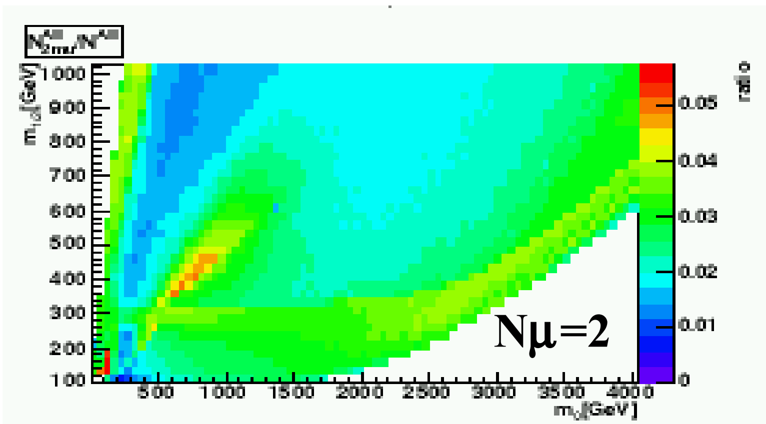
1μ	$\chi^{\pm}_1 \to W^*\chi_1^0 \to \mu\nu\chi_1^0$
$2\mu(OS)$	$\chi_2^0 \to Z^*\chi_1^0 \to \mu^+\mu^-\chi_1^0$ $\chi_1^+ \to \mu^+\nu\chi_1^0; \chi^- \to \mu^-\nu\chi_1^0$
$2\mu(SS)$	$\chi_1^+ \to \mu^+\nu\chi_1^0;\ \ \chi_1^+ \to \mu^+\nu\chi_1^0$
$3\mu(OS+1)$	$\chi_2^0 \to \mu^+\mu^-\chi_1^0;\ \ \chi_1^{\pm} \to \mu^{\pm}\nu\chi_1^0$

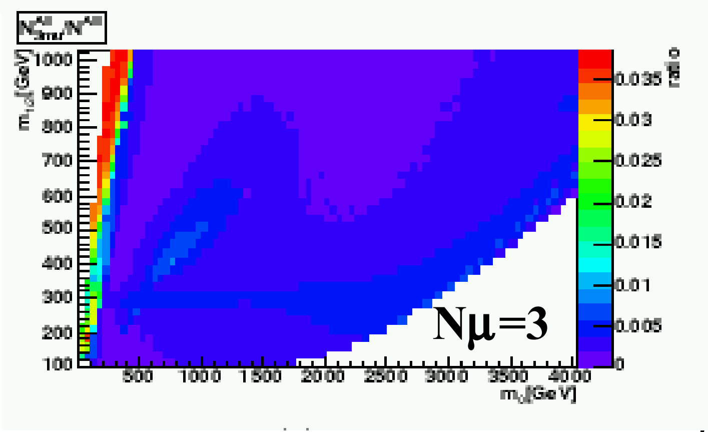
Total cross section mSUGRA and fractions of 1,2,3 exclusive muons in m_0-$m_{1/2}$ plane (tb=10 A_0=0, μ>0)

Use reference mSUGRA model LM0: m_0=200 $m_{1/2}$=180 tb=10 A=-400





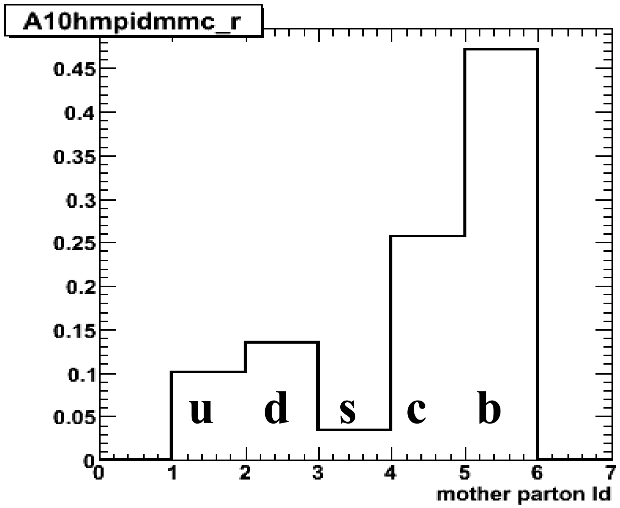




SM backgrounds

Best SUSY parameters: MET from LSP and hard Jets from decays of ~g, ~q
but also most prone to systematics: instrumental(JES), theory (QCD)
Start with the most reliable objects -> muons

Fake muons origins from QCD
μ isolated by isoPT<5 GeV



Can split SM muons onto:

- **prompt muons from Z,W**
- **fake muons:**
  1. heavy flavors b, c ->μ+X
  2. light jets π,K -> μ+..
  3. others: punchtrough, beamhalo, cosmics..

N muons	Prompt	Heavy flavor	Light jets	Others
1	tttbar(W), Wjets, (missed muon in Z , ZW)	ttbar, bbj,ccj	ttbaj, qcd	Cosmics, halo
2SS	(sign wrong Zjets, ttbar(WW))	ttbar(W), Wj,bbj	ttbar, qcd	-
2OS	ttbar, Zj,ets (missed mu in ZW , ZZ)	bb, cc	ttbar, qcd	-
3	ZW , (missed in ZZ)	ttbar(WW), Zj, Wj	ttbar, qcd	-
	Kinematic selections	Isoaltion and Id	Isolation	Event cleaning
	Topology sensitive	Large uncertainties		Small contributio

Fake rate mostly depends on the heavy flavor content of the selected events.

- **optimize muons selection for fakes suppression**
- **control the residual fakes contribution using data driven methods**

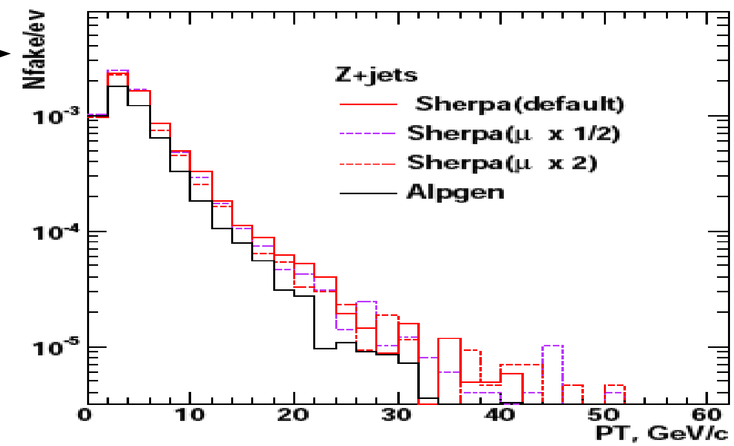
Muons selection

Uncertainties in fakes:

1) theoretical: heavy flavor production in state radiation (g->bb,cc) up to 40%

2) instrumental: ES, alignment, tracks efficiency, vertex reconstruction and caloisolation uncertainties up to 10%

Zjets fake rate/event for different generators muon isolated with isoPT<5 GeV



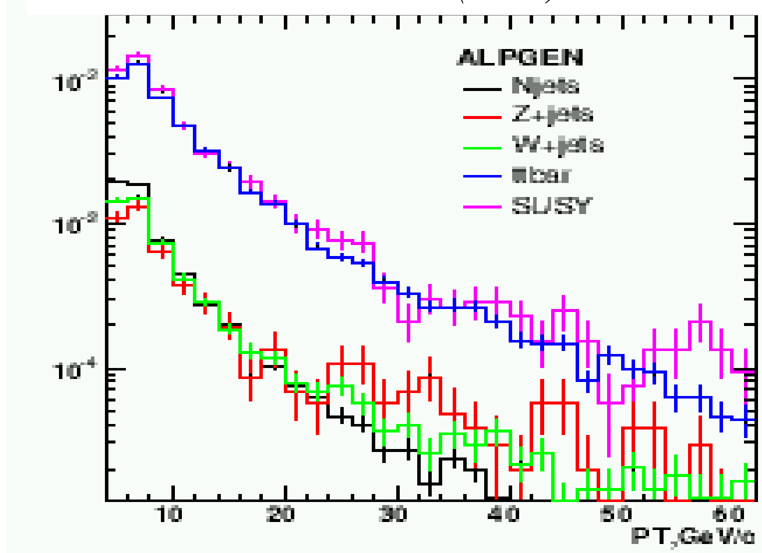
Optimization:

fake muons from jets are similar for all SM channels

➨ use reference samples enriched with fakes and prompt muons for optimization.

The prompts muons from Z,W are well known and can be suppressed by kinematics

Muon fake rate for different SM channels and SUSY (LM0)



Validation:

➨ fakes rate in reference sample can be used to validate the simulation model

➨ data driven methods to estimate the residual fake background in the selected sample

Reference Samples

Fake muons enriched sample: QCD dijets (also the bbjets can be used with the loose btag)

Observables	selection
HLT Trigger	DiJet70
N_j	=2
$\phi(j1,j2)$	160^o-180^o
$\alpha 2$	<0.42
N_μ	>0
$M(MET,\mu)$	<40GeV
MET_{rec}	<100GeV

Sample	HLT[%]	Nev 100 pb^{-1}
QCD100to250	78	9430000
QCD250to500	100	362000
QCD500to1000	100	15900
QCD1000toInf	100	386
$t\bar{t}$	99	112
W+jets	25	905
Z+jets	38	338
VV+jets	60	1.4

Reference sample with fakes from QCD:
10^8 ev at 100pb^{-1}
purity ~10^{-4}

*) *Selection cuts optimized with the Genetic Algorithm(GA)*

**)*Uncertainties (jet energy scale , resolution, etc) change selection by ~20% only.*

Kinematics difference (pt-η) of muons from Z and SUSY can be corrected by reweighting samples using MC factors.

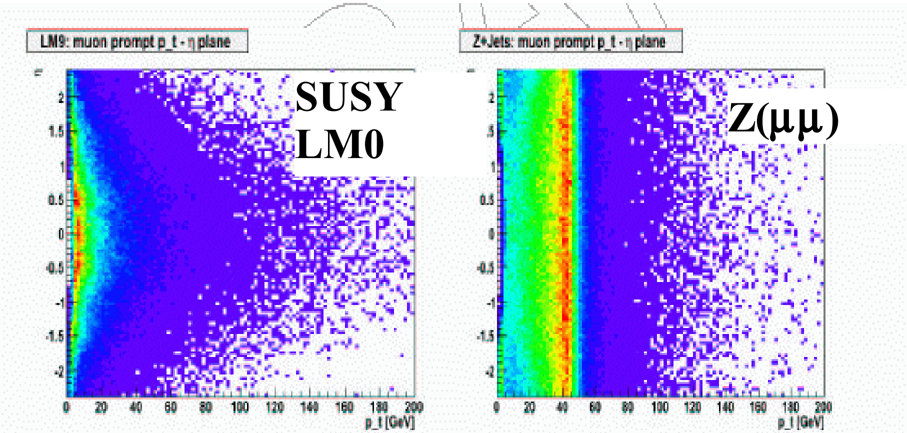
Prompt muons enriched sample: Z(μμ) +jet

Observables	selection
HLT Trigger	DoubleMu3
N_μ	=2
$M_{\mu^+\mu^-}$	70-180 GeV
N_j	<2
MET_{rec}	<100GeV
ET_{eff}	<120GeV

Sample	HLT[%]	Nev 100 pb^{-1}
Z+jets	35	42560
VV+jets	52	140
QCD100to250	5	0
QCD250to500	10	0
QCD500to1000	17	0
QCD1000toInf	29	0
$t\bar{t}$	48	1
W+jets	26	2.7

Prompt muon sample selected from Zjets :
4 10^5 ev at 100 pb^{-1}
purity ~10^{-5}

PT-η distribution for SUSY and Zjets muons



Muon selection parameters

Best muons observables for fakes suppression, selected after ranking:

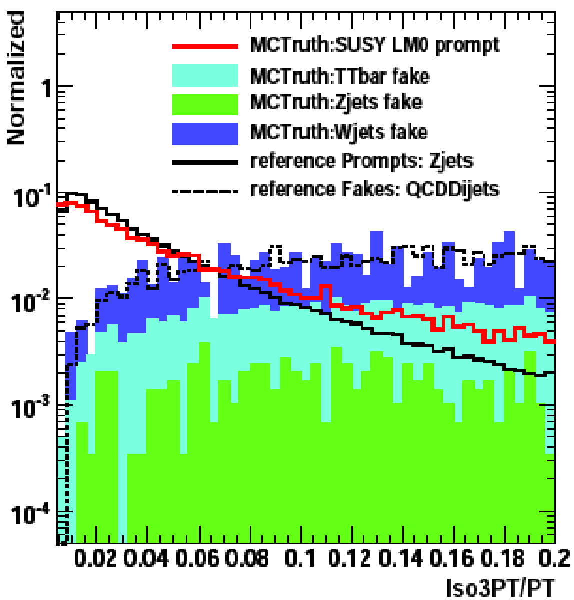
1) relative isolation in dR <0.3 by sum of tracks PT (isoPT/PT) , i.e low PT better isolated

2) relative isolation by calo (isoCal/PT)

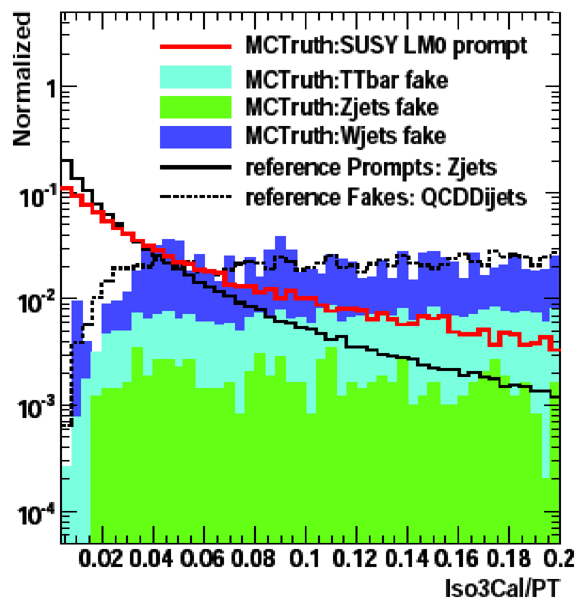
3) significance of impact parameter, calculated relative to the vertex Sdxy=dxy/σ_{dxy} less sensitive to the misalignment

Compare distributions of isolation and Sdxy for the reference samples, SUSY and SM bkg.

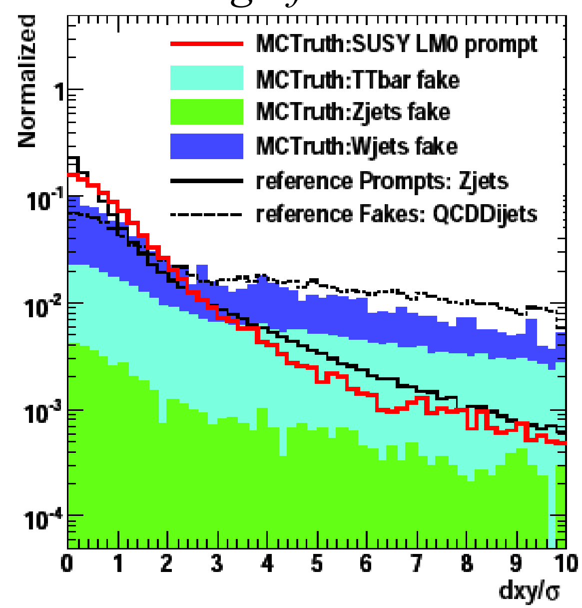
Rel. tracker isolation



Rel. calo isolation



Impact parameter significance

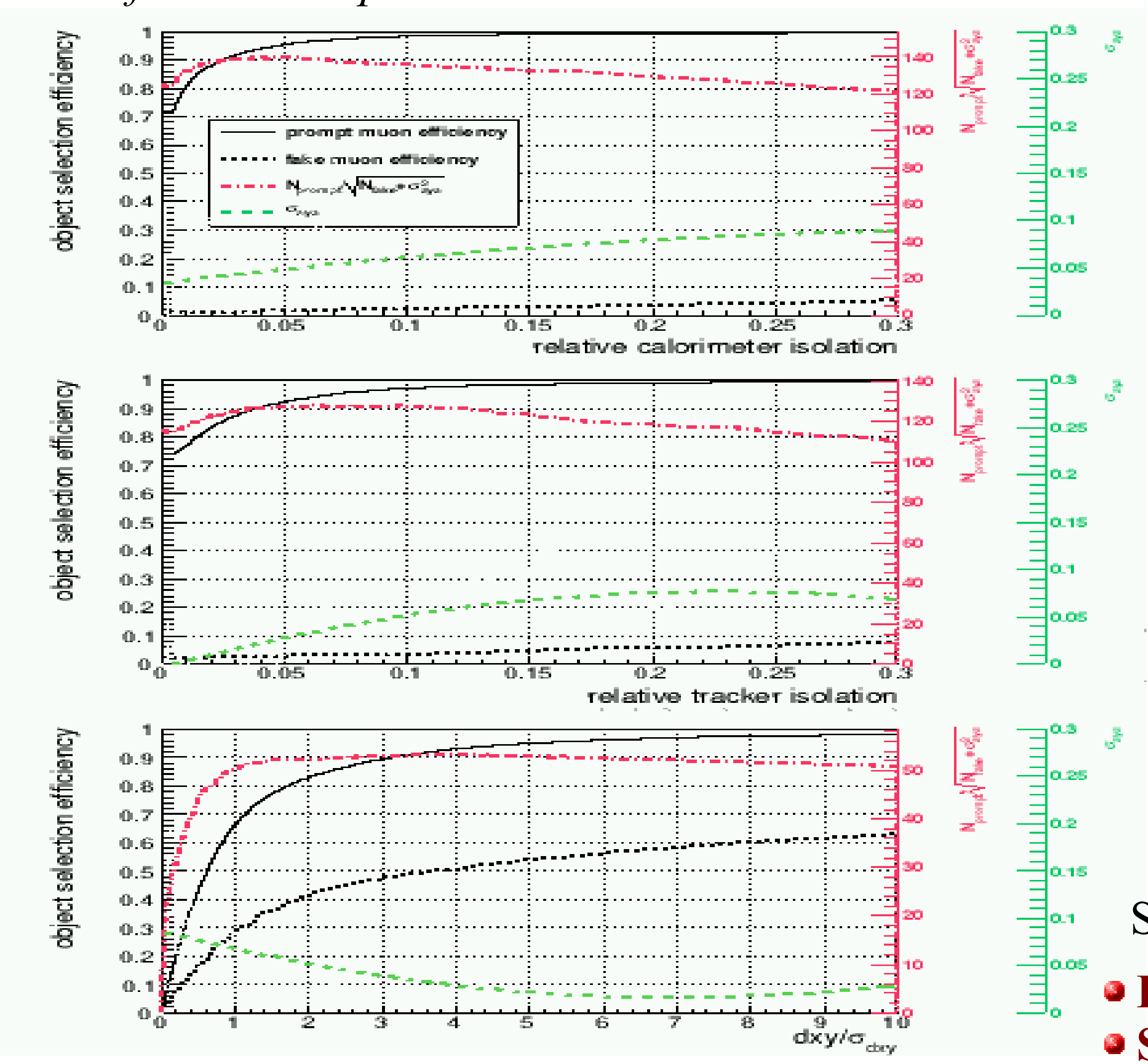


Use distributions from refernce samples for the template fit with the selected data

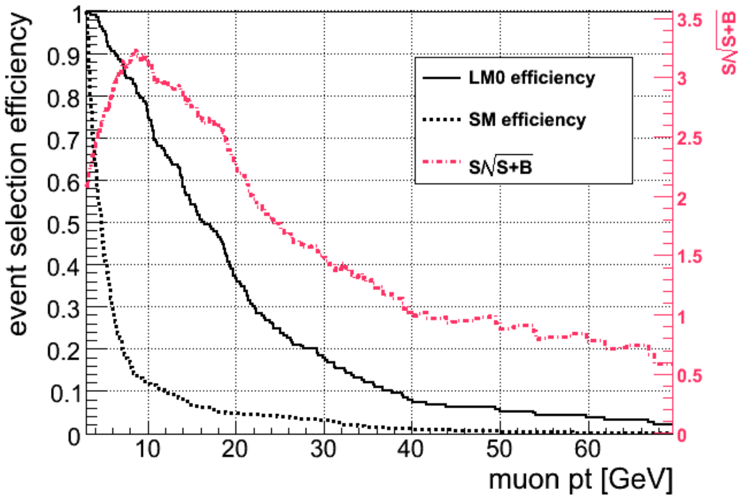
Optimizing muon selection

Check stability of selection.

Efficiency of the prompt and fake muons selection, Significance and sensitivity to 5% changes for reference samples



Efficiency, Significance vs pt cut for SUSY (LM0) and SM bkg



Final selection: tight muons

PT>8 GeV/c $|\eta|<2.1$
track $\chi^2<10$, $N_{hits}>11$
isoPT/PT<0.08
isoCal/PT<0.08
Sdxy < 4

Example numbers obtained with MC samples.

Same selection for all muons(1,2,3)

- **Large plateau for all parameters**
- **Similar behavior for SUSY-SMbkgs**

SUSY event selection

Trigger: **single muon (PT>9 GeV/c) and double muon (PT>3 GeV/c)**
efficiency >98% for the selected samples st LM0

Muons: select MC samples with 1, 2 and 3 tight muons exclusively

Add more observables: jets, MET (see full list in backup slides)

Optimization of selection:

use genetic algorithm to rank observables, select best and optimize selection cuts for S/σ_{bkg} with all SM bkg channels(weighted with cs) and LM0 reference SUSY.

Observables	1muon	2 muons OS	3 muons OS+1
Trigger	SingleMu	DoubleMu	DoubleMu
N tight muons	1 (PT>10GeV/c)	2 OS (>8GeV/c)	3 OS+1 (>8)
N iso electrons	0	0	0
HT=Σ ETjets	>450 GeV	>400 GeV	>100(ETj >50)
METrecoil	>120 GeV	>100 GeV	>50 GeV
Njets (ETj1, Etj2,..)	>3(100,60,30,..)	>2(60,30,30,..)	>0 (50,50..)
Minv OS muons	-	<60 GeV	20-85 GeV

- **no systematics in optimization, needs iteration to optimize list of observables**
- **optimization depends on reference model**

Event selection summary (100 pb^{-1})

	cs(LO) pb	Nev 100pb-1	1 muon 1μ	1 muon All	2 muons 2μ OS	2 muons All	3 muons 3μ OS+1	3 muons All
SUSY LM0	110	11000	1288	134	112	20.5	8.6	4.4
Ttbar (incl.)	317	3.2E+5	4289	20.6	164	1.6	0.22	0.09
W jets	40000	4.0E+6	6.0E+5	9.8	26	0	0	0
Z(ll) jets	3700	3.7E+5	58114	0.8	2.6E+4	0	1.9	0
AV jets	150	15000	2185	0.15	246	0	0	0
VV jets	118	1180	343	0.11	52.5	0.01	2.3	0.21
QCD(100-250)	1.5E+7	1.5E+9	0	0	474	0	0	0
QCD(250-500)	4.0E+5	4.0E+7	265	0	0	0	0	0
QCD(500-1000)	14000	1.4E+7	22	0	0	0	0	0
QCD(1000-inf)	370	3.7E+4	1.2	0	0	0	0	0
SM bkgtot				31.5		1.6		0.3
Significance LM0 (no systematics)				16.7		8.6	3.3	3.6

Selection steps:
N μ - trigger+N tight muons
All - rest of selection cuts

SM bkg: Madgraph+Pythia(MLM)
V=Z, W leptonic decays
QCD in HT ranges
SUSY: SoftSUSY+SusyHit+Pythia

CMSSW : Full CMS simulations

↑ *Can be seen with only 3 muons selections*

Systematics

Consider 'anticipated' sources of systematics

	Systematics +- %
Instrumental ;	
Resolution dPT	2
Muon IsoPT	2
Vertex impact	σ(dxy)
ET jets	10
MET	10
Muon isoCalo	10
Muon efficiency	2
Theory *	
Cross section	5
Kine. JetMET	5
PDF	2
Fakes	10
Luminosity	5

*) *from different generators, mu scale variations, LHPDF,etc*

Vary parameter and check variation δn=dN/N in N_{sel}

Instrumental uncertainties in different searches

	1 muon		2 muons		3 muons	
	Nev 100 pb-1	dN/N, %	Nev	dN/N,%	Nev	dN/N,%
SUSY LM0	134	20	20.5	22	4.4	10
Ttbar	20.6	23	1.6	34	0.09	~0
W8In) jets	9.8	53	0	0	0	0
Z(II) jets	0.8	~0	0	0	0	0
AV jets	0.15	101	0	0	0	0
VV jets	0.11	12	0.01	~0	0.21	45
QCD(100-250)	-	0 *	0	0	0	0
QCD(250-500)	0	0	0	0	0	0
QCD(500-1000)	0	0	0	0	0	0
QCD(1000-inf)	0	0	0	0	0	0
SM bkgtot	31.5 ev	**32%**	1.6 ev	**34%**	0.4 ev	**45%**

*) *Neglect bkg with Nb=0*

Main uncertainties are from energy scale (10%) ->30%
muons contributes only 10% (if fakes are controlled)

Correlations (simplified)**:**

- all instrumental uncertainties are correlated for all bkg, but sources of uncertainties are uncorrelated in each search
- theoretical uncertainties are uncorrelated for different bkg in single search but correlated for each bkg in different searches

Stat model for SUSY searches

Use RooFit for the modeling

- **Counting like experiments, single channel:**

see details eg.
R.Cousins et al 2007
N.Reid 1995,
K.Cranmer 2005,,,

δ_o -nuisance for correlated instrumental uncertainties

f_i -weighting factor for instrumental systematics due to correlations $f_i = \delta n_i / \sigma_0$

δ_i - nuisance for the bkg(m=Nbkg) related uncertainties i=0,m

$L = \mathrm{Poiss}(n_{obs}|\mu)\ \mathrm{Gauss}(\delta_o, \sigma_0)\ \Pi_i^m \mathrm{Gauss}(\delta_i, \sigma_i)$

L_b: $\mu_b = \Sigma_i^m\ n_b^i\ (1+\delta_o * f_i)(1+\delta_i)$

L_{b+s}: $\mu_{b+s} = n_s(1 + \delta_o * f_s) + \mu_b$

In total m+1 nuisance parameters in case of correlations

- **Combining channels** (1μ,2μ,3μ) **k=3:** $L = \Pi_\kappa^3\ P(n_{obs}^k|\mu^k)\ G(\delta_o, \sigma_0)\ \Pi_i^m G(\delta_i, \sigma_i)$
  where $\mu^k = \nu * s^k + \mu_b^k$

Calculate: 'discovery', 'exclusion' and confidence interval for a test model

Use simplified approach: Lhood ratio $Q=L_{s+b}/L_b$ where -2logQ -> χ^2 in asymptotic (Wilks , 1938)

Generally this is not true, better to consider the direct integration using 'toy' experiments or Markov chain MC (under work..)

maximize Lhoods in respect to all δ to get rid of systematics n_{obs}=b+s

$Q = \max L(n_{obs} | \delta) / \max L(b | \delta)$ **->** p-value -> Significance

use profile Lhood to calculate confidence interval for $n_s = \nu * s$, ν **-strength of signal**

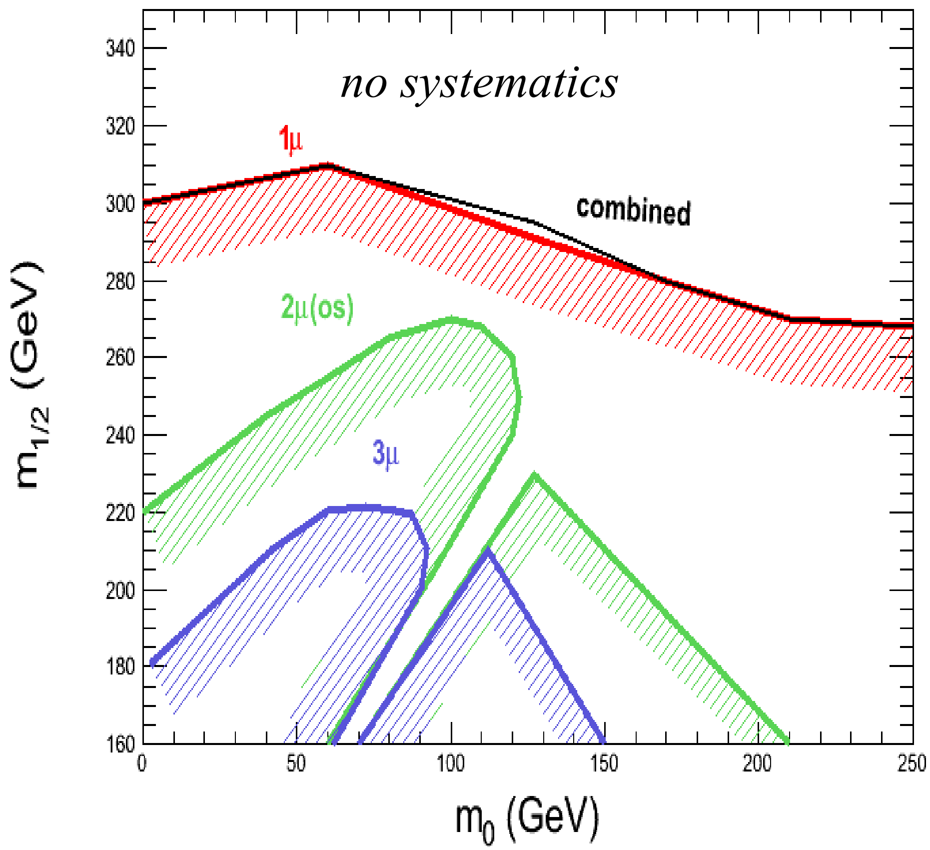
$Q(\boldsymbol{\nu}) = \max L(\boldsymbol{\nu}| \delta) / \max L(\nu, \delta)$ -> 95%CL for the model ν=1, and exclusion limit at ν=0

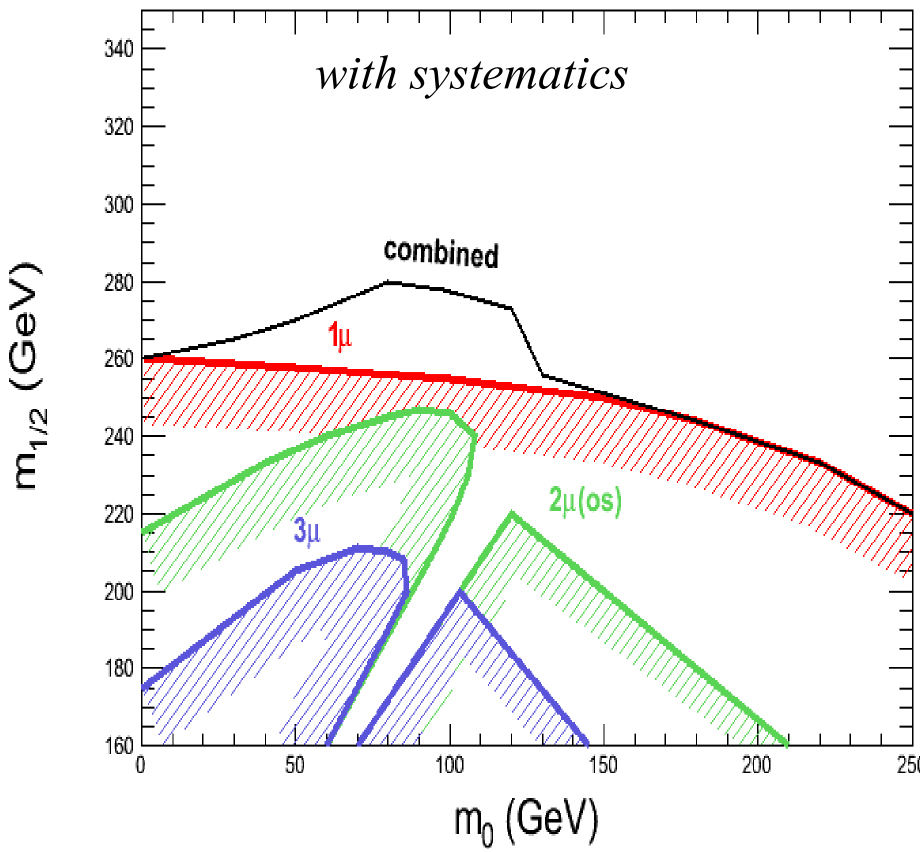
Discovery reaches at 100 pb^{-1}

Find mSUGRA models(ns) which give 5 sigma deviations from the bkg. hypothesis n_{obs}=nb+ns

10 TeV L=100 pb^{-1}

MSUGRA m_0-$m_{1/2}$ plane (tb=3) 5 sigma discovery with/wo systematics





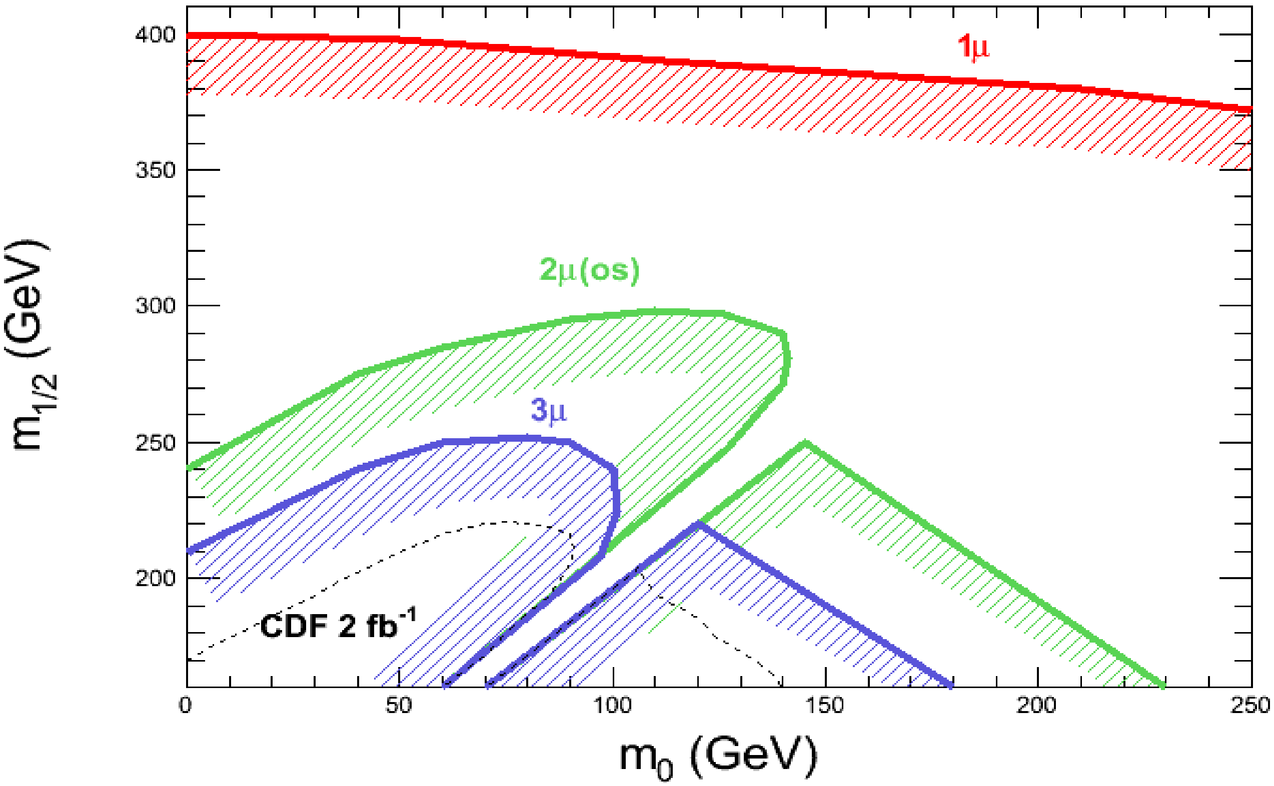
CMSSW FastSim mSUGRA scan

Exclusion limits

Exclude with 95% CL the signal hypothesis in case of n_{obs}=<n_b>, i.e ν=0

95% CL exclusion limit for different searches, with systematics

L=100 pb^{-1} 10 TeV

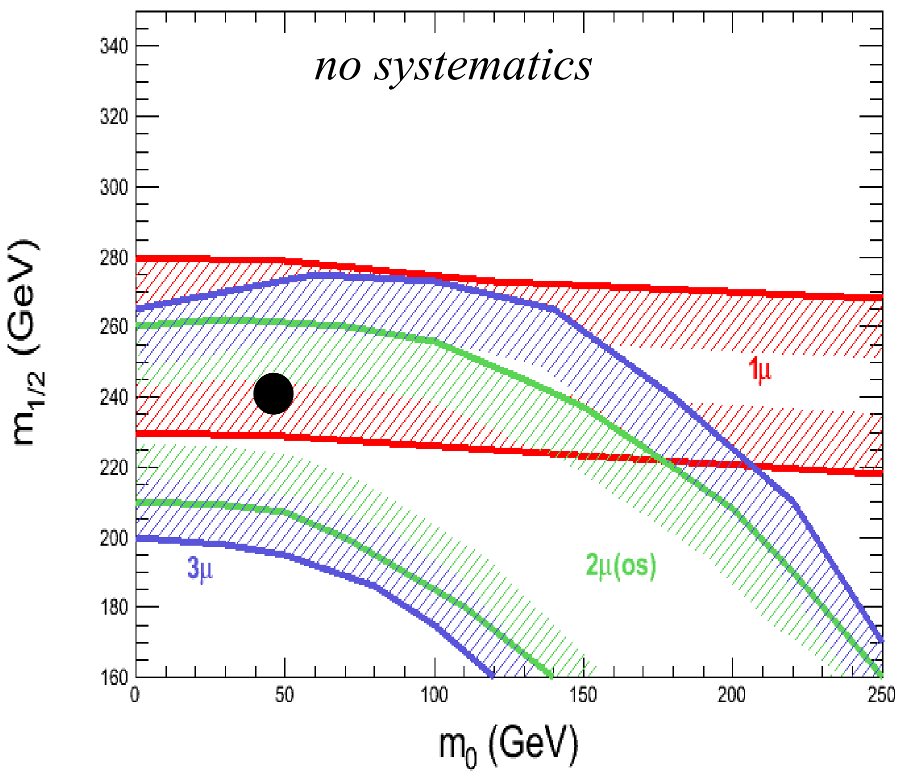


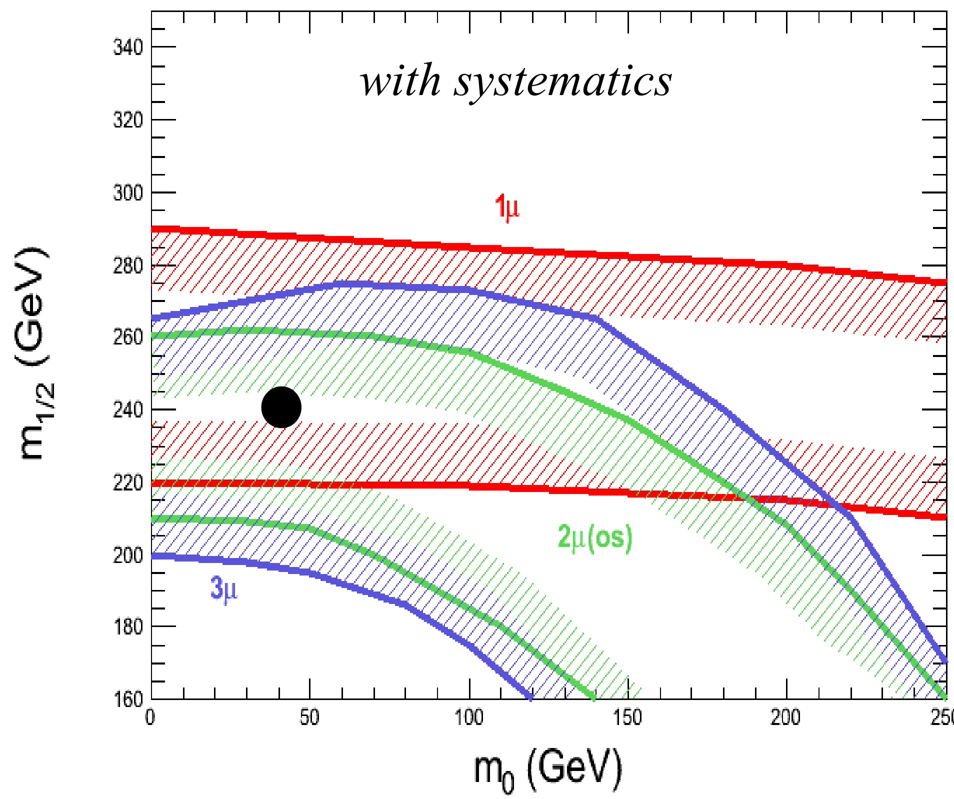
Exclusion dominates by single muon search with largest statistics

Confidence intervals

Consider 95% CL for the test model ***(m_0=50 $m_{1/2}$=240 tb=3 Ao=0)***
in mSUGRA m_0-$m_{1/2}$ mass plane.

L=100pb^{-1} 10 TeV





Complementarity of different searches can be used to constrain the model:
min $\chi^2=\Sigma\,(n^i_{obs}-n^i_m)^2/\sigma^2$, **n_m – model predicted, n_{obs} -observed in i-search (1,2,3 muons)**

SM bkg: data driven

- **validate MC model in control regions, spot unexpected systematics**
- **reduce systematics, replace by calibration measurement**
- **extrapolate bkg. directly from the control to the signal region:**
  - **use MC defined templates for extrapolations**
  - **use 'ABCD' like method: at least two uncorrelated observables $N_A = N_D * N_B / N_C$**

	Systematics +- %
Muon efficiency	2
ET jets	10
MET	10
Fakes	10
Kine. JetMET	5

.....

Examples:

Tag&probe Z /J($\mu\mu$)

Z($\mu\mu$)+jet balancing

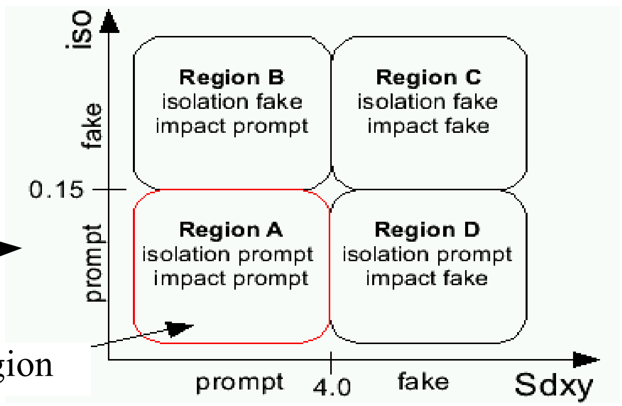
QCD MET templates

ABCD iso-Sdxy for fakes

ABCD (χ^2_{tt} ,MET/HT, M3) ,

etc

Signal region



Many possibilities, which DD method will work really?

Check if systematics in DD methods is smaller than the expected one

- **Include control measurements into Stat model, with all related uncertainties and correlations:**

$L_b \to L_b * L_c$, L_c control measurement $c = \tau b$: $L_c = P(n_c \mid \tau\ n_b)\ G(\delta_\tau, \sigma_\tau) G(\delta_c, \sigma_c)$

two sources of systematics on MC correction factor δ_τ and control measurement δ_c

$\tau\ n_b \to \tau\ n_b (1+\delta_\tau)\quad (1+\delta_c)$ **How to define $\delta\tau$ for the 'not calibrated' Sim model?**

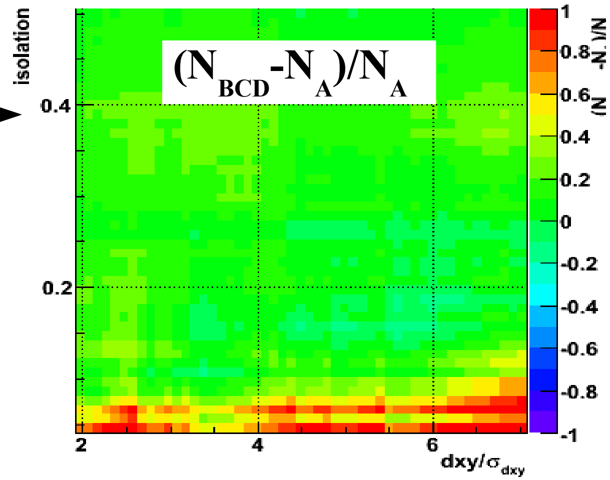
Ex: data driven bkg in 3 muons

Consider 3 tight muons without jetMet selection

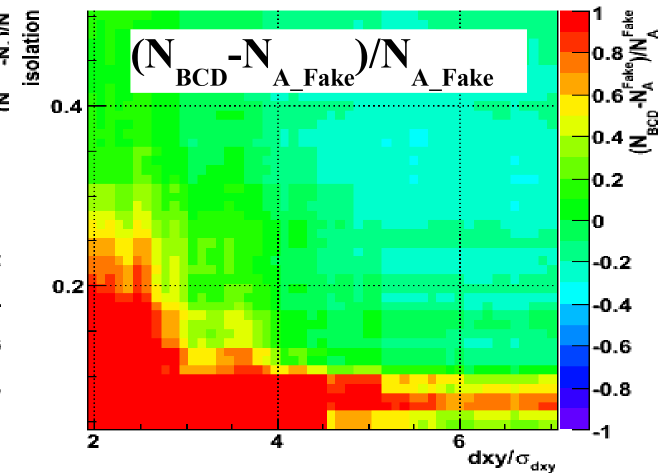
Two DD methods for bkg estimation:
1) ABCD(esio-Sdxy) select 2 tight, consider loose third as a fake candidate

N_{BCD} = 6.8 ± 2.6 [SUSY+SM]
N_{BCD} = 5.8 ± 2.4 [only SM]
N_{A_Fake} = 6.5 ± 1.4 [MC Truth]

Check $(N_{BCD}-N_{A\ Fake})/N_{A\ Fake}$ for different region boundaries



QCD reference samples



SM bkg +SUSY(LM0)

2) Zcandle for prompt from ZW, ZZ

R_{MC} = 1.72 ± 0.14(stat) ± 0.03(sys)

N_{sig} = 4.0 ± 2.7 [SUSY+SM]
N_{sig} = 3.8 ± 2.6 [only SM]
N_{truth} = 2.8 ± 0.3 [MC truth]

ABCD works for the QCD reference sample but contamination from SM prompts, SUSY and uncertainties in bkg composition spoils the methods introducing large uncertainties in τ

Significance LM0 L= 200pb^{-1} with different uncertainties in τ

MC truth:		DD:	
No systematics	4.01	ABCD δτ=10% , Zcandle 8%	3.81
8.1 % MC systematics	3.86	ABCD δτ=30% , Zcandle 8%	2.24

Summary

Muons+X signatures are the most promising at LHC for SUSY search. The low mass region m_0, $m_{1/2}$<200 GeV can be covered already at L~100 pb^{-1} , competitive with Tevatron

For the discovery or exclusion limits the SUSY search topologies and control measurement has to be combined taking into account all possible systematics and correlations.

The data driven methods have to be selected according to the final benefit in the hypothesis testing.

Back Up

Observables

<u>Jets definition:</u>
ET>30 GeV
eta<2.1
Hadronic fraction >0.1

<u>Electrons:</u>
PT>20 GeV/c
eta<2.5
isoPT/PT <0.1
RobustTight

<u>Muons:</u>
PT>8 GeV7c
eta<2.1
chi2<10, Nhits>10
isoPT/PT <0.08
isoCal/PT<0.08

METrec	**recoil MET of all jets,leptons**
Etj1,,3	**ET of 1...3 leading jets**
HT	**scalar sum of jets ET**
MHT	**recoil MET from jets only**
aj1met	**asimuth. Agngle jet1 and METrec**
aj1j2	**angle between jets**
ammet	**asim. Angle muon and METrec**
MT	**transverse mass muons, METrec**
χ^2 tt	

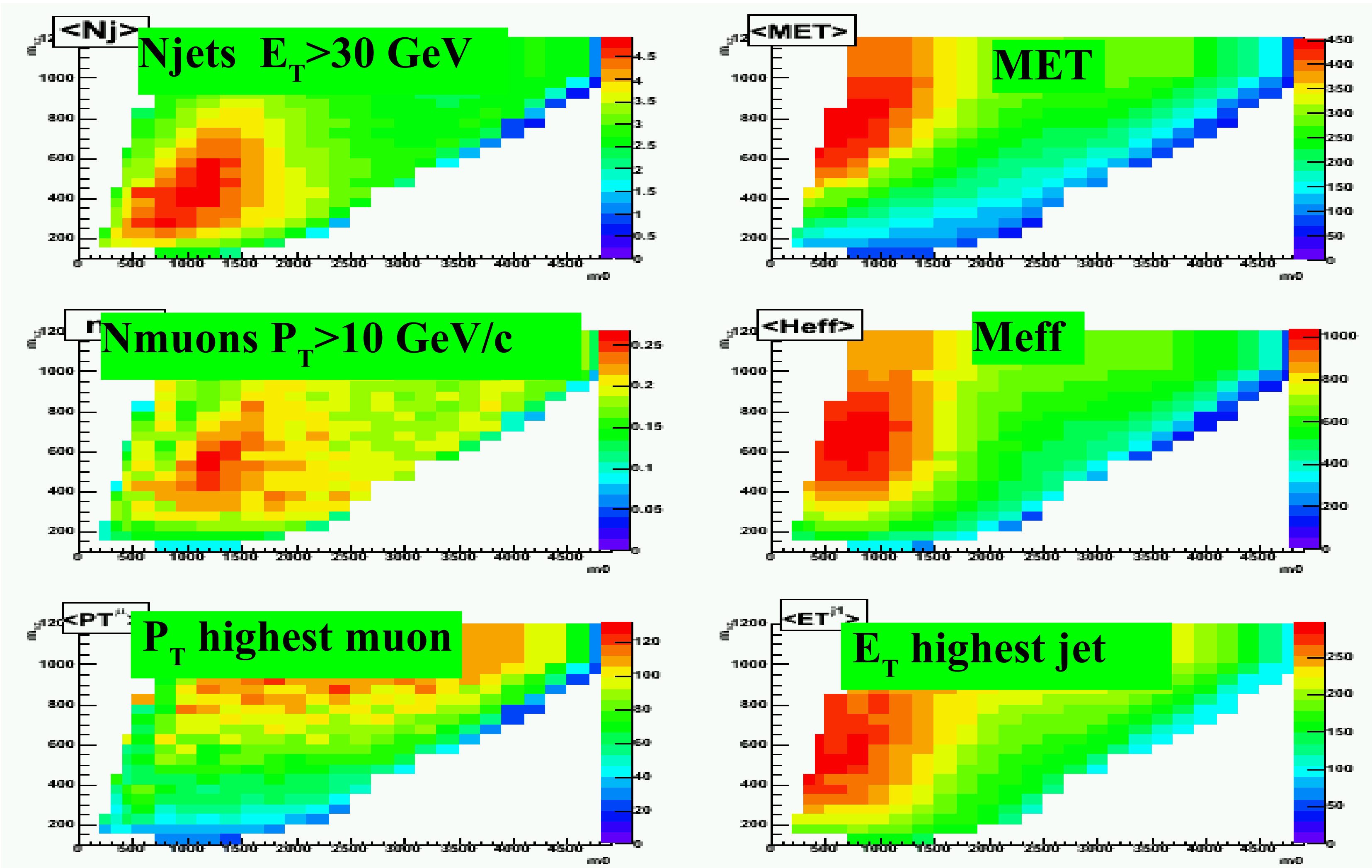
$$\chi^2 = \frac{(m_{j_1j_2} - m_W)^2}{\sigma^2_{jj}} + \frac{(m_{j_1j_2j_3} - m_{t-had})^2}{\sigma^2_{jjj}} + \frac{(m_{\mu\nu j_4} - m_{t-lep})^2}{\sigma^2_{\mu\nu j}}.$$

alphaT

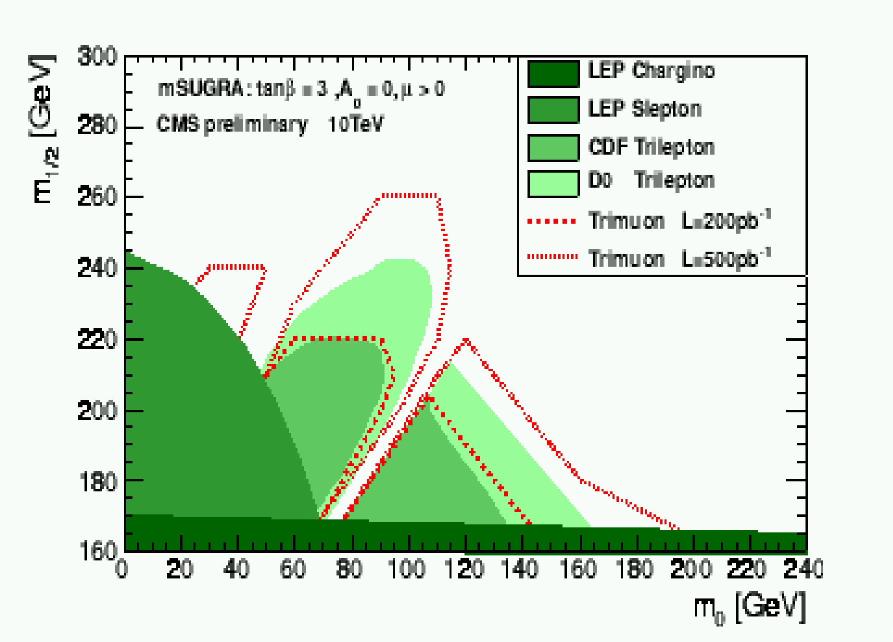
$$\alpha_T = \frac{\frac{1}{2}\left(H_T - \Delta H_{T(n)}\right)}{\sqrt{H_T^2 - |\not{H}_T|^2}}$$

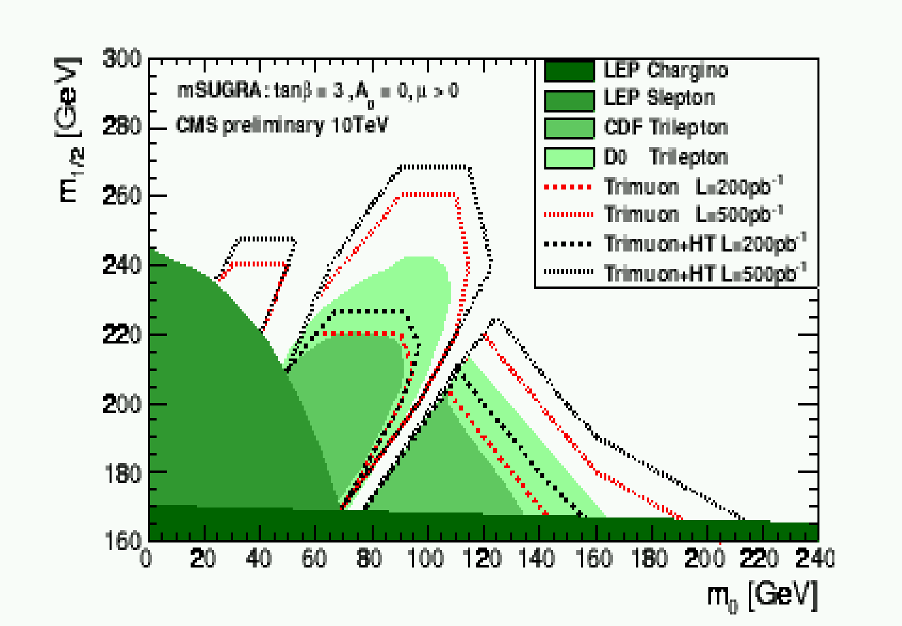
invm	**mass of OS muons**
aplan	**acoplanarity of all jets and leptons**
spher	**sphericity**
M3	**max (Σ Pj) of three jets**

Average observables in mSUGRA m0-mhf plane tb=50



Discovery reaches with only trimuons selection and trimuons+HT
Comparison with Tevatron trileptons exclusion CL.





Theoretical systematics in SM bkg

Cross sections with different generators

processes	Alpgen(Pythia)	SHERPA	SHERPA (x1/2)	SHERPA (x2)
Z+0j	930	900	830	968
Z+1j	208	234	235	229
Z+2j	78	88.4	95.1	81
Z+3j	20	36	42	29
Σ_{Total}	1236	1258.4	1202.1	1307
W+0j	10730	10339	9480	
W+1j	2264	2400	2377	
W+2j	690	1048	963	
W+3j	200	433	390	
Σ_{Total}	13384	14420	13212	

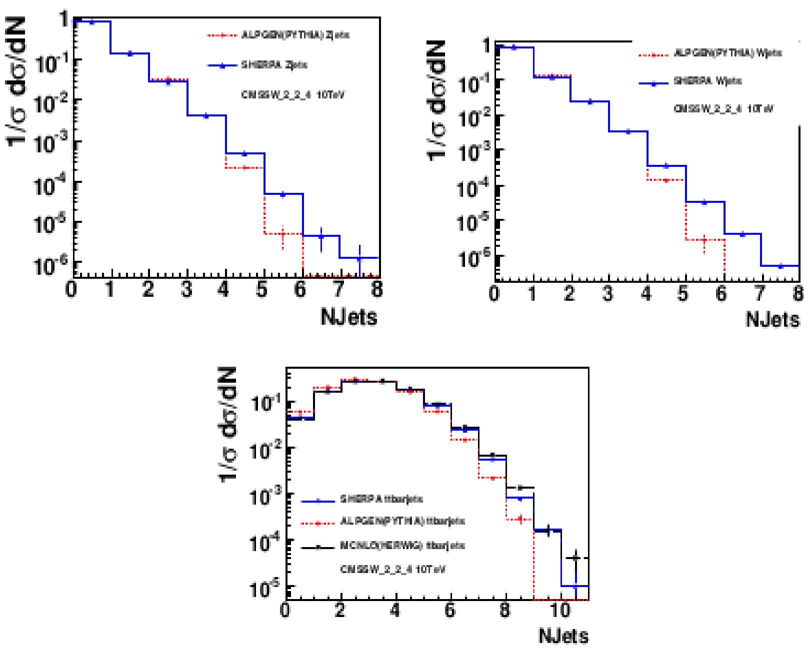
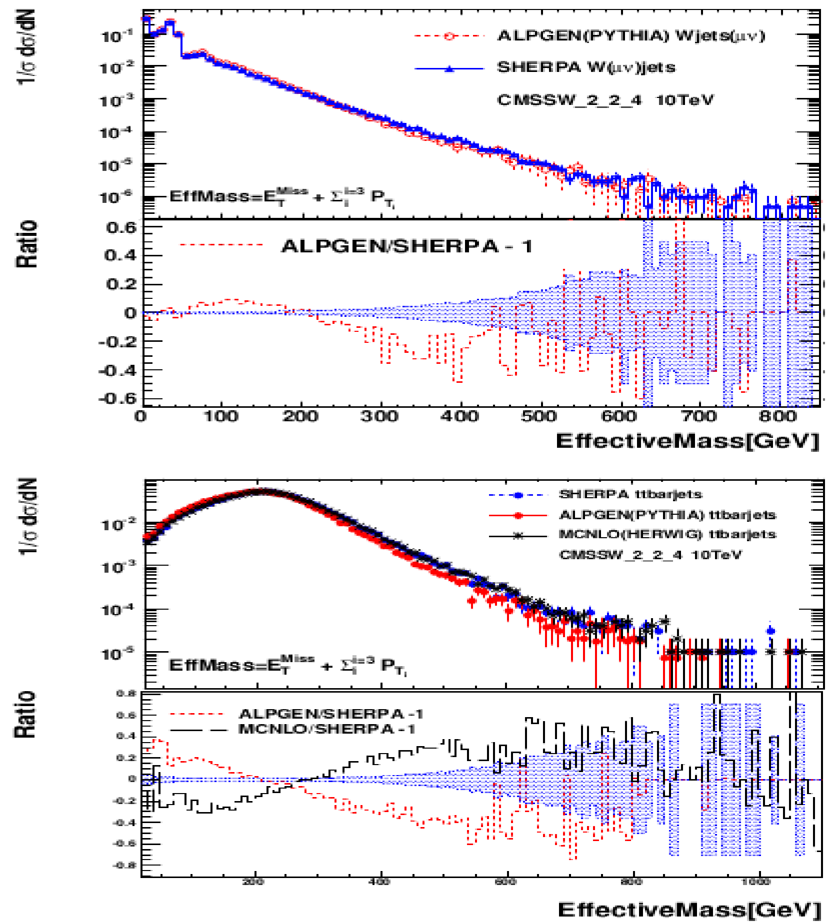


Figure 13: Number of jet multiplicity(RT>30 GeV) for Zj(0-3), Wj(0-3) and ttbar(0-1) in different generators



Effective mass distributions for W($\mu\nu$)+jets (upper plot) and ttbar (lower plot) calculated with Alp-
. Sherpa and MC@NLO(Herwig). The shaded area is shown the uncertainty ($1/\sqrt{2 * N_{events}}$) for the
ı distributions. In this case , missing transverse energy for Wjets, ttbarjets shows deviation on lower
on, pt of leading jets effect on tail which is important for the new physics searches.