BEYOND THE STANDARD MODEL' 06

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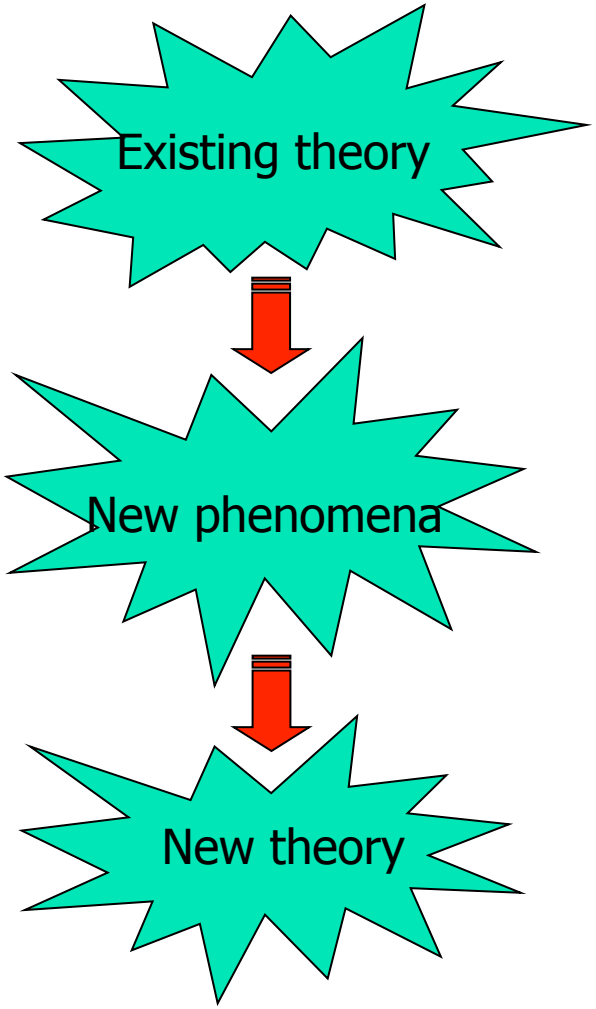
ICHEP'06, Moscow, August 1, 2006

The Standard Model of Fundamental Interactions

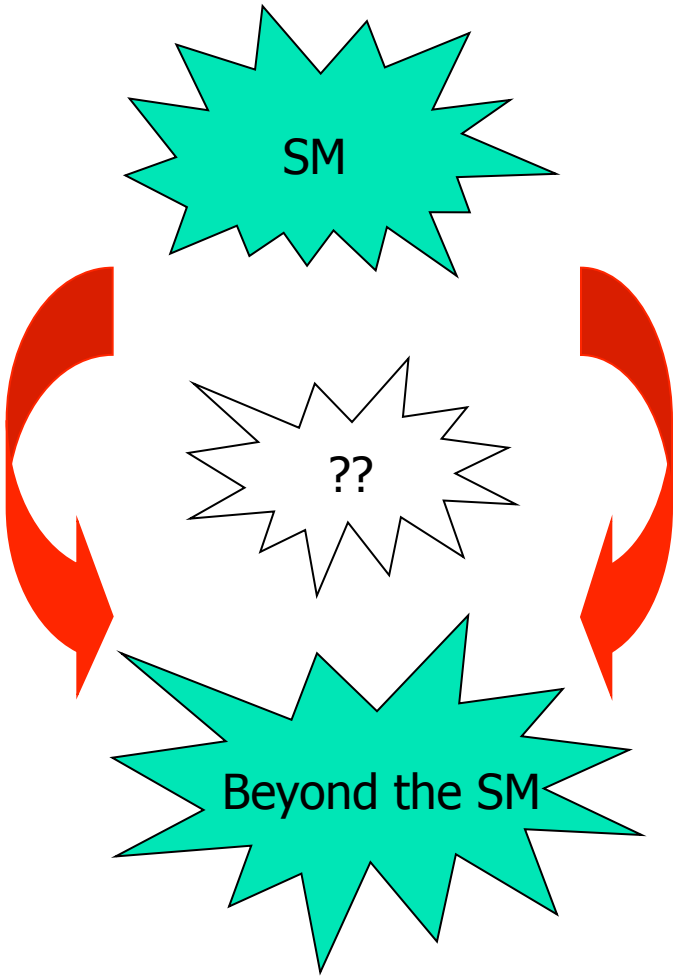
Something one may be proud of

HEP Paradox

The usual way

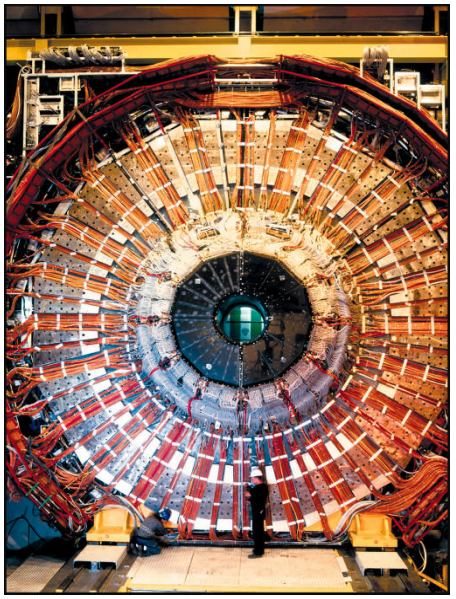


Modern HEP



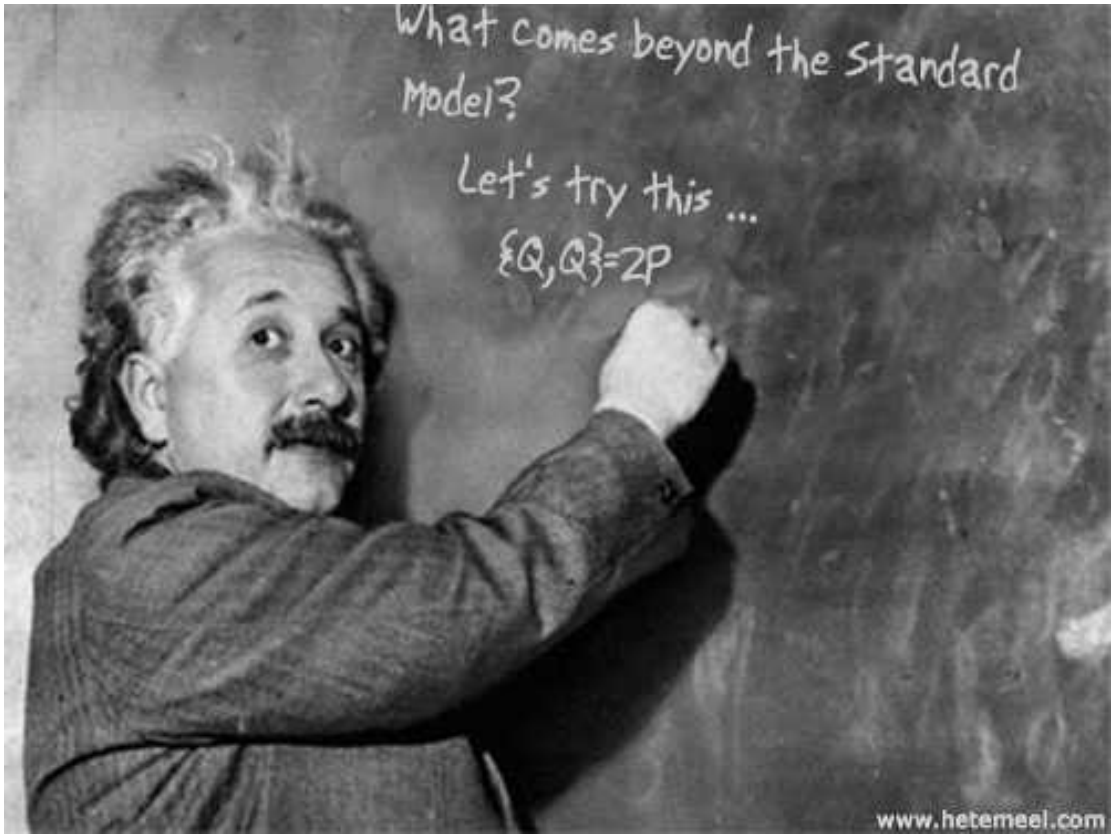
Physics beyond the SM

- Low Energy Supersymmetry
- Extra gauge bosons
- Axions
- Extra dimensions
- Deviation from Unitarity triangle
- Modification of Newton law
- Free quarks
- New forces / particles
- Violation of Baryon number
- Violation of Lepton number
- Monopoles
- Violation of Lorentz invariance
- Compositeness

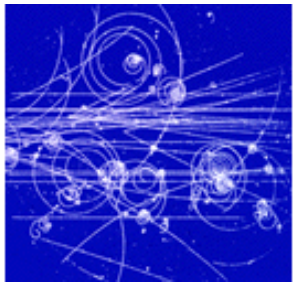


Not found so far …

Physics beyond the SM



Problem # 1

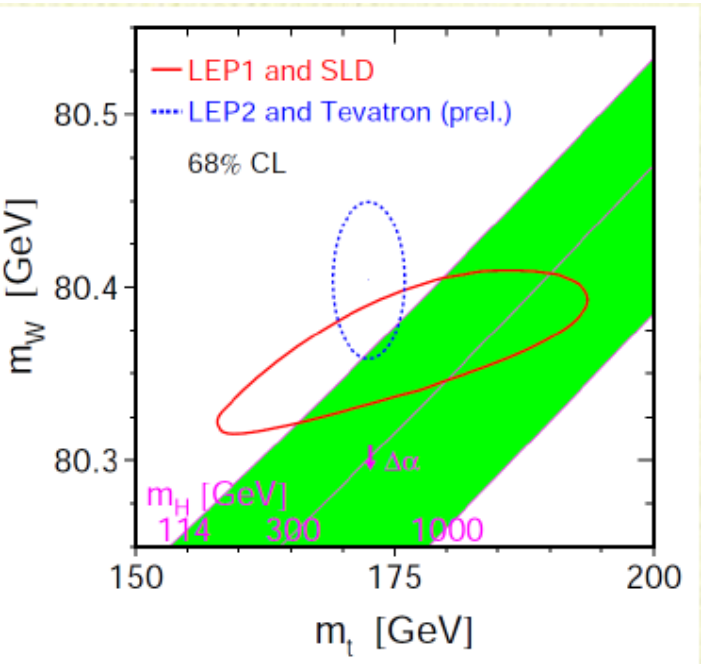


Mechanism of Electroweak Symmetry Breaking:

- The Higgs mechanism
- Alternatives

The SM Higgs Boson

- Indirect limit from radiative corrections
- Direct limit from Higgs non observation at LEP II (CERN)

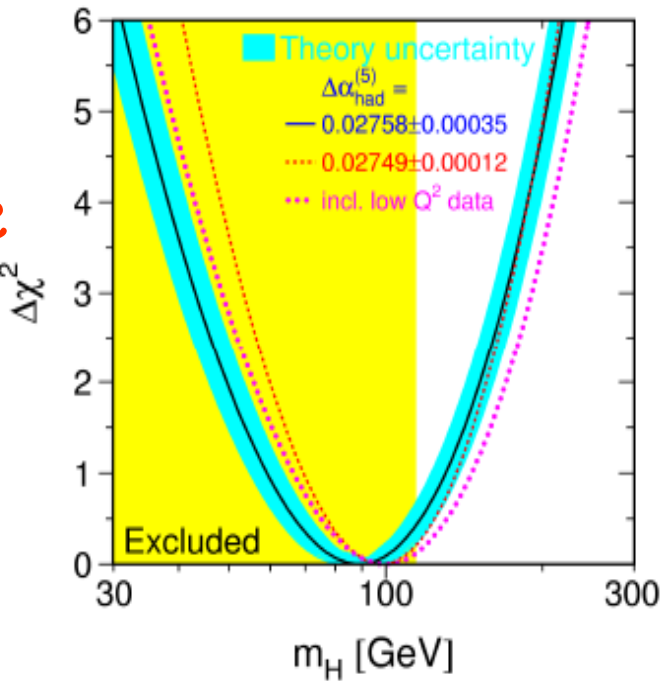


If it is there we may see it soon

χ^2 versus M_H for SM Fit

- M_H=89 +42-30 @68%CL
- M_H < 175 GeV @95%CL

for m_{top}=172.5 GeV



Alternatives to SM Higgs

- Two-Higgs Doublet Models
- Inert Higgs Model
- Little Higgs Models
- Twin Higgs Model
- Gauge-Higgs Unification Models
- Higgsless Models

Alternatives to SM Higgs

- Two-Higgs Doublet Model

Hundreds of papers ..

- More Higgses -> more freedom in parameters
- Multiphase case -> new source of CP violation
- Making the lightest Higgs almost sterile
  (very weak coupling to Z ~ sin(α-β)) allows Higgs boson mass below 100 GeV

- Inert Higgs Model

R.Barbieri, L.Hall,V.Rychkov

- Inert Higgs doublet that has neither a vev nor couplings to quarks and leptons,
- It is the lightest particle and may compose the Dark Matter
- The usual Higgs boson is heavy (> 400 GeV)
- Does not contradict the precision EW tests

Alternatives to HM

Little Higgs Model

Arkani-Hamed, Cohen and Georgi

- Higgs bosons as pseudo-goldstones -> quadratically divergent one-loop contribution to the Higgs mass is not generated -> Log hierarchy
- Needs larger gauge group and "collective" symmetry breaking
- New heavy states with masses around 1 TeV
- LHC signatures are similar to SUSY albeit different angular dependence due to spin structure

Perelstein
Birkedal, Noble, Spray
Martin

- T-parity (similar to R-parity) -> stable particle-> DM

Twin Higgs Model

Chacko, Goh, Hornik, Su

- Similar to Little Higgs, Higgses are pseudo-goldstones
- Has discrete symmetry – twin symmetry (mirror or L-R)
- SUSY generalization

Chang, hall, Weiner;
Fialkowski, Pokorski, Schmaltz

Alternatives to HM

Gauge-Higgs Unification Models

Manton; Fairlie;
Candelas, Horowitz, Stromonger, Witten;
Hosotani; Csaki, Grojean, Murayama, …

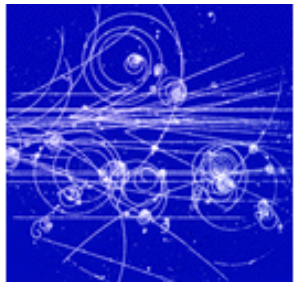
- Higgs is a gauge scalar of XD
- Discrete symmetry protects Higgs mass
- Orbifold compactification to get chiral matter and fundamental rep Higgs
- Leads to KK excitations of W and Z at 500 GeV – 1 TeV and extra scalars

Higgsless Models

Csaki, Grojean, Murayama;
Cacciapaglia, Lillie, Terning, Hubisz, Meade,
Shirman, Barbieri, Pomarol, Rattazzi,
Hebecker, March-Russell, …

- Extra dimensions/Non-flat geometry (warped)
- EWSB from boundary conditions -> W & Z are KK states -> unitarity is preserved
- No scalars at low energies
- Fermions in a bulk , mass at IR vector-like brane
- New (KK) spin1 states, slightly different couplings to SM gauge bosons
- Not to contradict precision EW tests needs heavy scale
- All these theories are effective (non-renormalizable)

Problem # 2



New physics at the TeV scale:

- Supersymmetry
- Extra Dimensions
- Unknown ?

TeV Scale SUSY

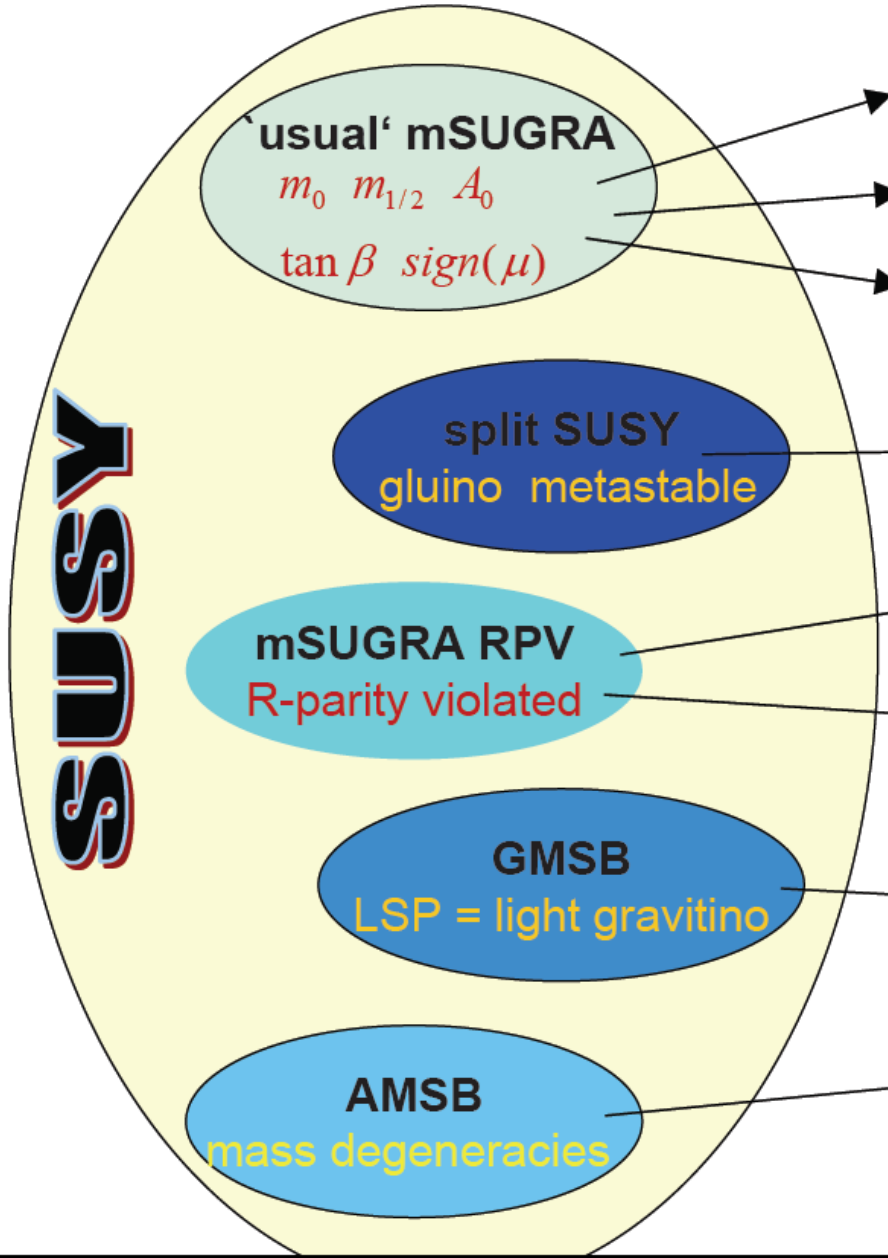
SUSY'06 Review talks

ICHEP'06

- MSSM (gravity mediation)
- MSSM (gauge mediation) — M.Nojiri — T.Hebbeker K.Klein
- MSSM (anomaly med, etc)
- MSSM (non-universality) — H.Baer — T.Krupovnickas
- NMSSM (Singlet extensions) — V.Barger — R.Godbole
- R-parity violation — A.Dedes — T.Hebbeker

SUSY Models and Signatures

T.Hebbeker



generic squarks and gluinos

sbottom and stop might be light

gauginos → leptons

stopping gluinos

gluinos $\tilde{g}$ long lived

form `R hadrons'

lepton-lepton couplings

lepton-quark couplings

photons + missing energy

$$NLSP = \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$$

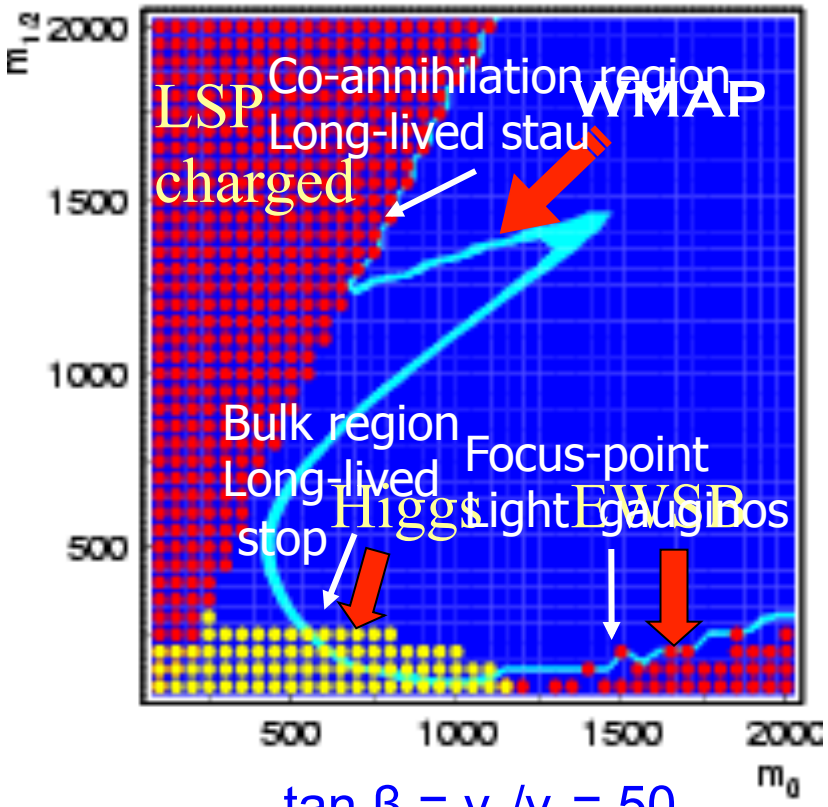
long lived heavy charged particles

decay inside detector

Mirage unification

Allowed regions after WMAP (mSUGRA)

m_0 common spin 0 mass
$m_{1/2}$ common spin ½ mass



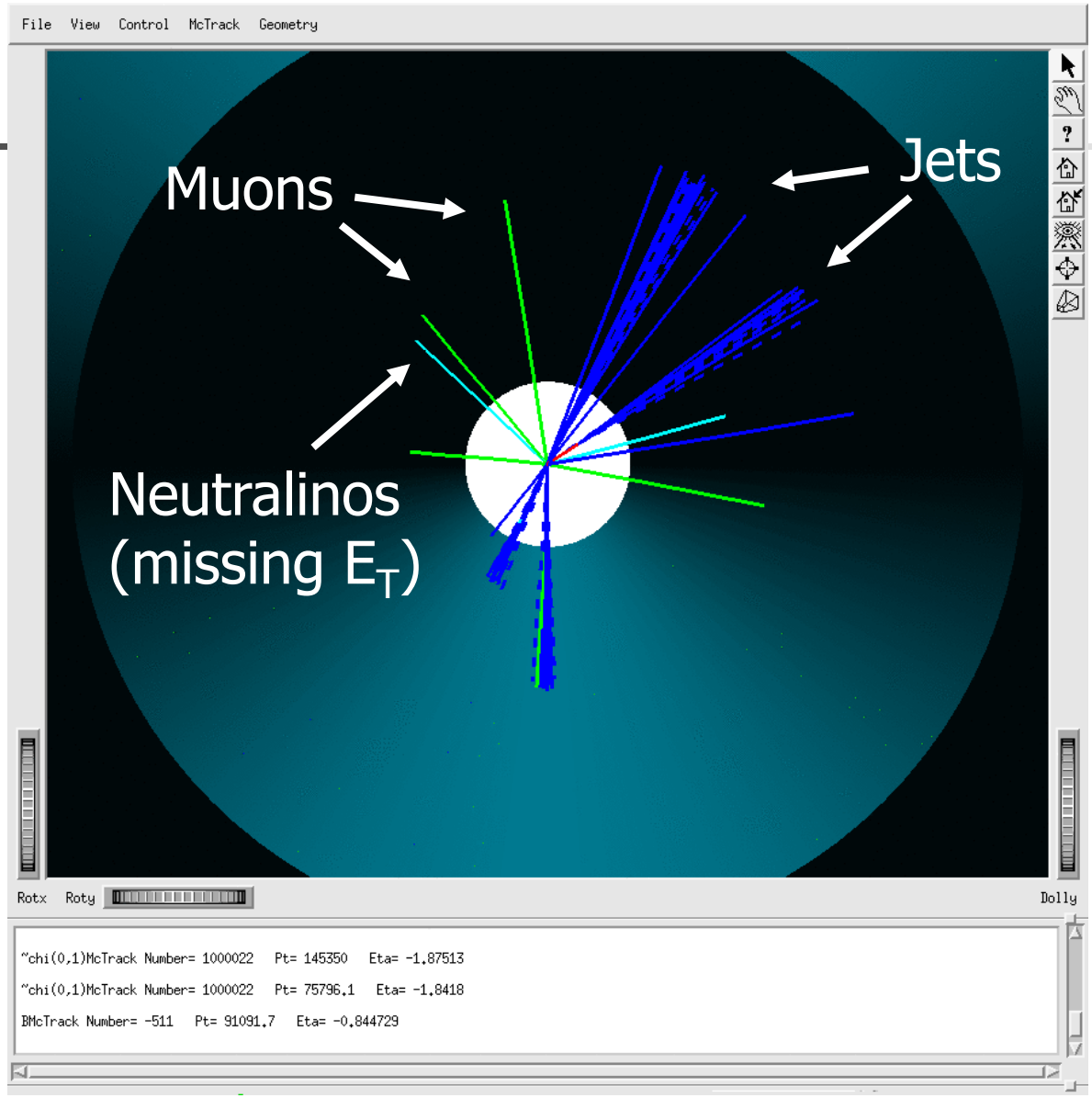
$\tan\beta = v_2/v_1 = 50$

In allowed region one fulfills all the constraints simultaneously and has the suitable amount of the dark matter

Narrow allowed region enables one to predict the particle spectra and the main decay patterns

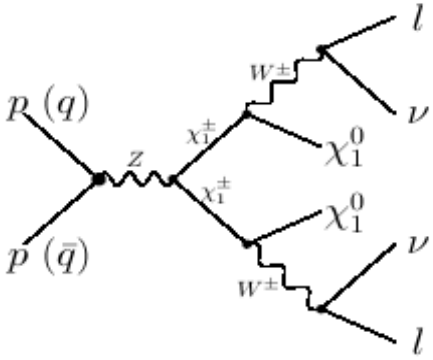
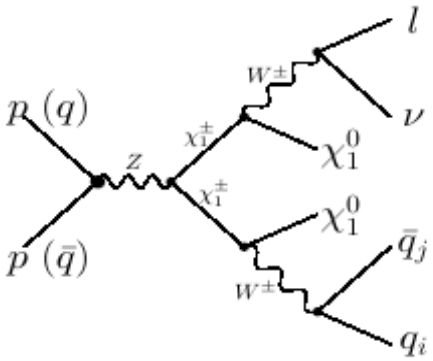
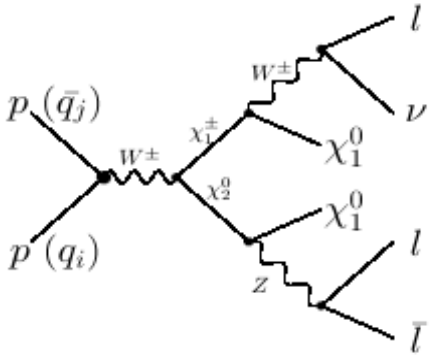
Phenomenology essentially depends on the region of parameter space and has direct influence on the strategy of SUSY searches

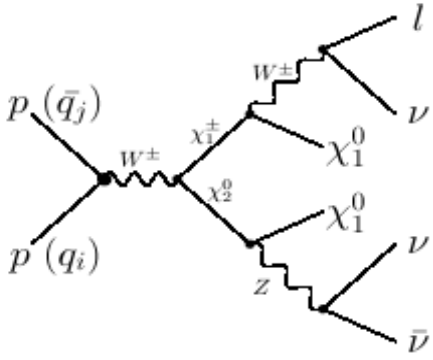
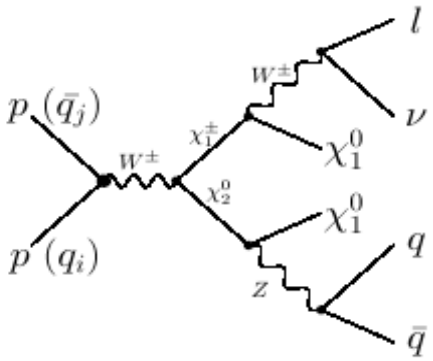
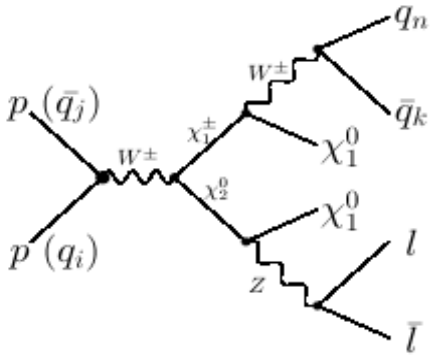
SUSY Production at LHC



Cascade Processes

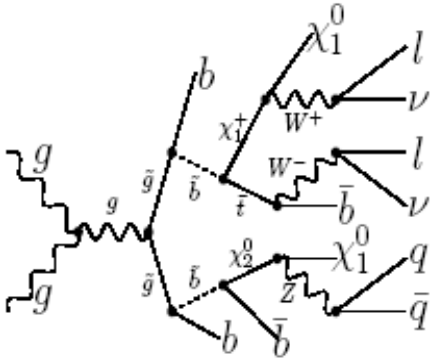
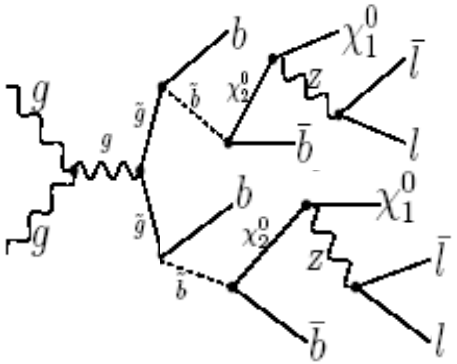
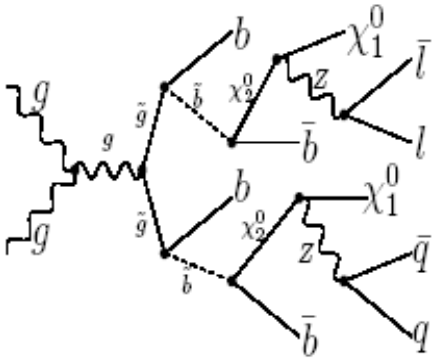
weak ints

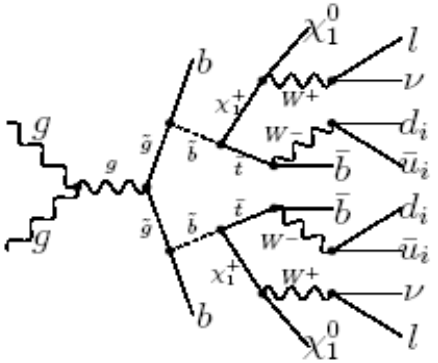
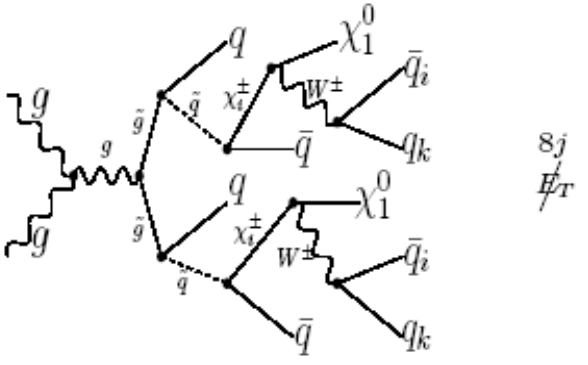
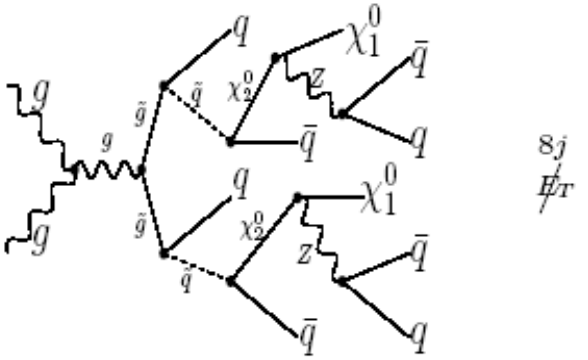
process	final states
	2ℓ 2ν $\not{E}_T$
	1ℓ $2j$ ν $\not{E}_T$
	3ℓ ν $\not{E}_T$

process	final states
	ℓ 3ν $\not{E}_T$
	ℓ ν $2j$ $\not{E}_T$
	2ℓ $2j$ $\not{E}_T$

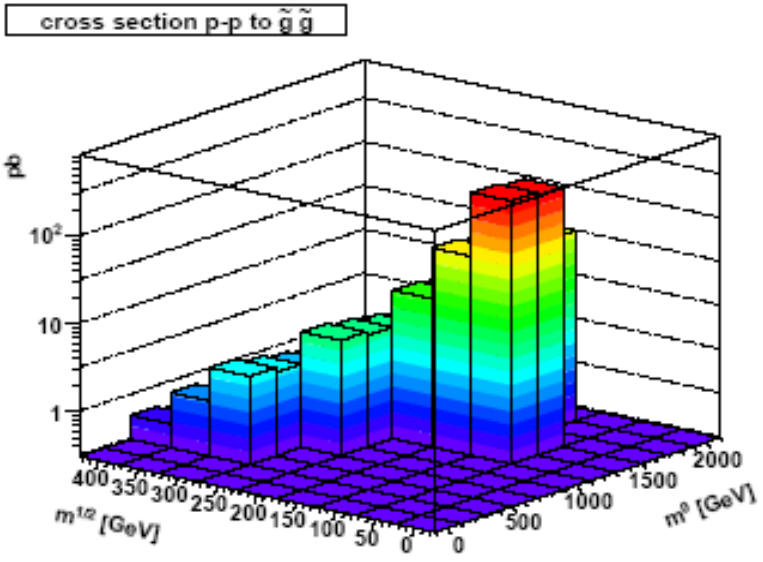
Cascade Processes

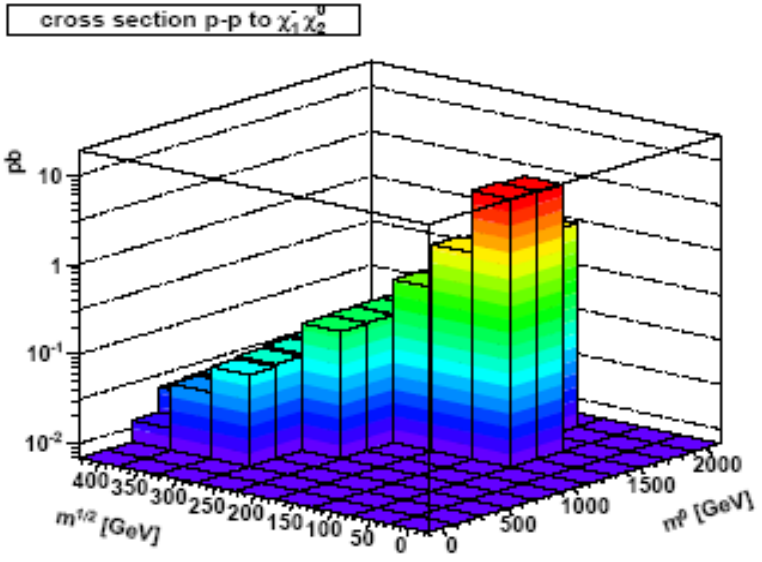
Strong int's

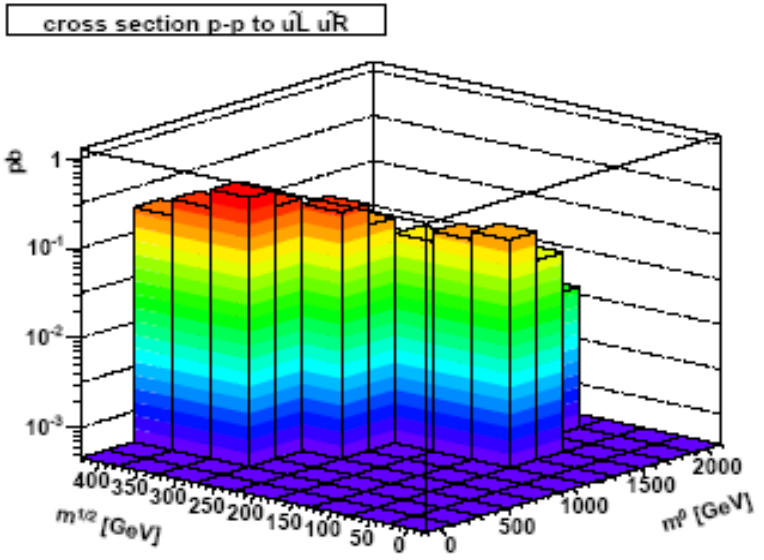
process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	$4l$ $4j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$

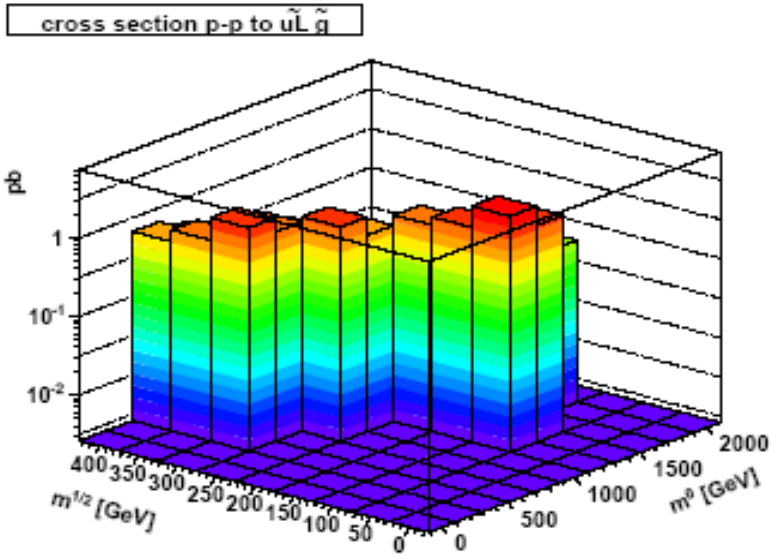
process	final states
	2ℓ 2ν $8j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	$8j$ $\not{E}_T$

Cross-Sections at LHC

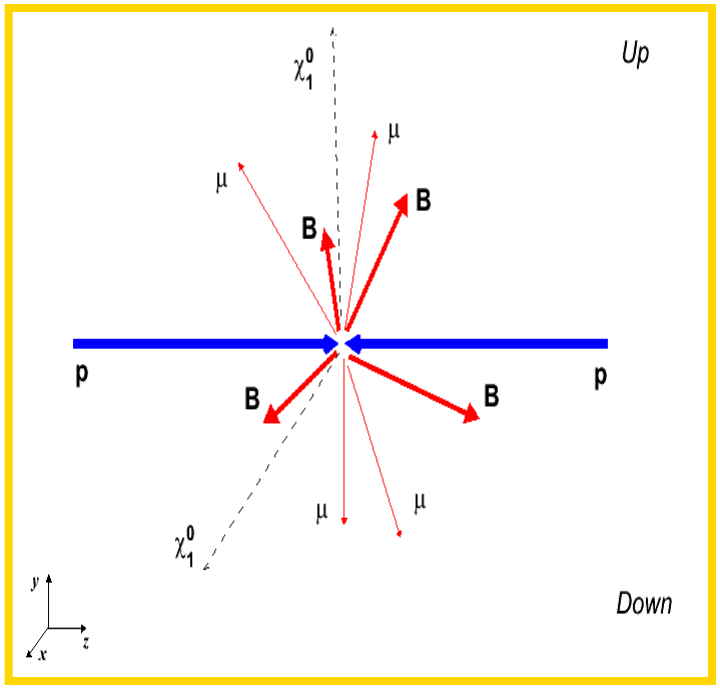


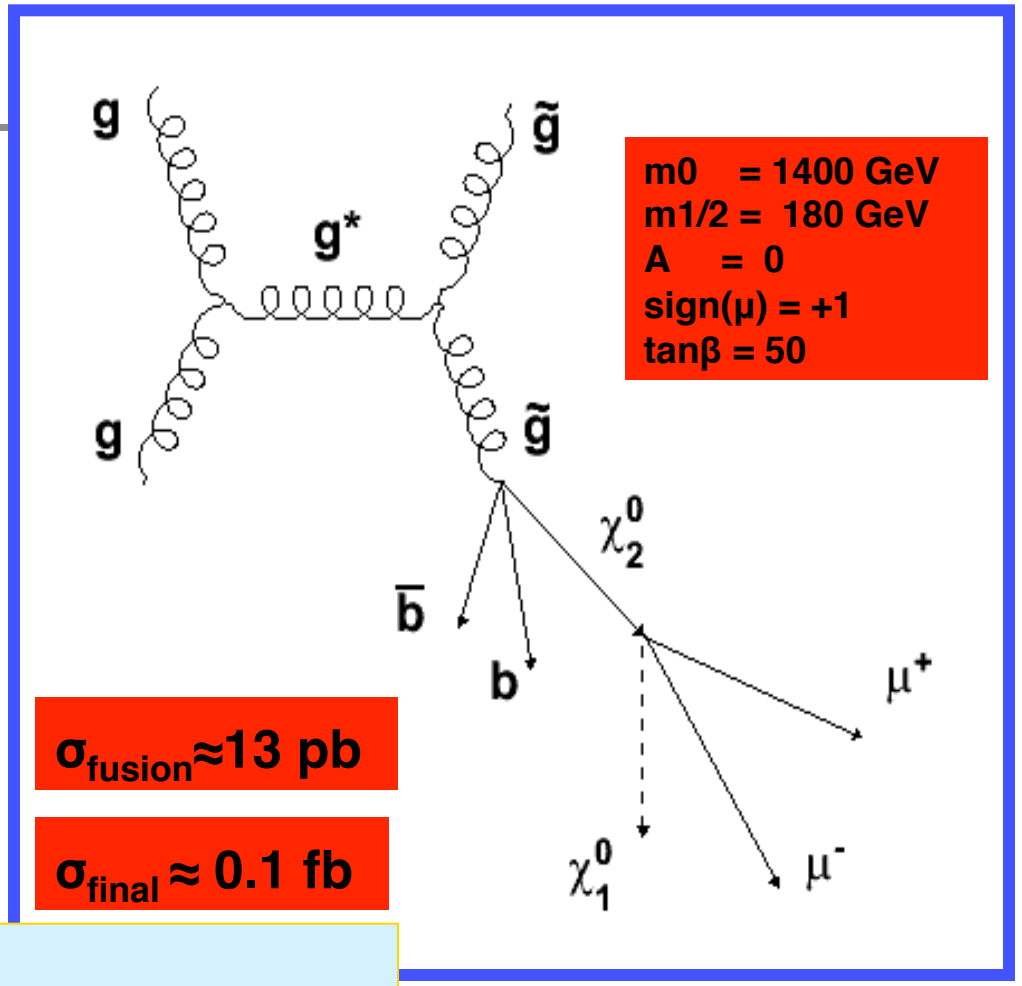






SUSY Production AT LHC





SIGNATURE:
4 b-jets + 4 muons + E_T^{miss}

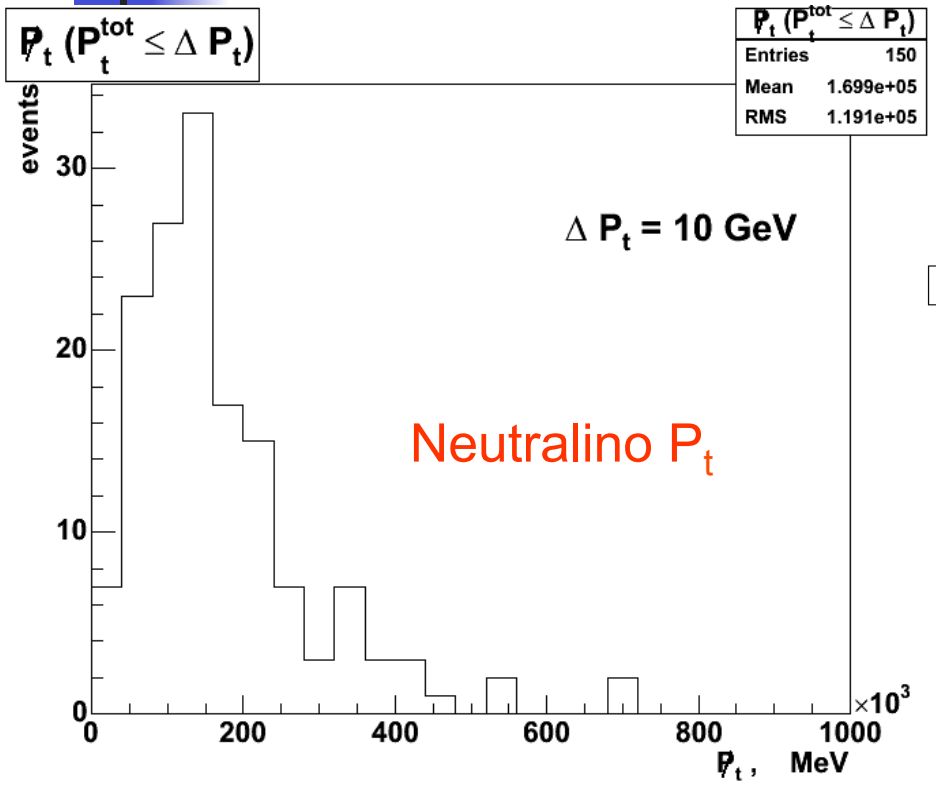
LARGE!

SUSY Event in ATLAS

$gg \to \tilde{g}\tilde{g}$

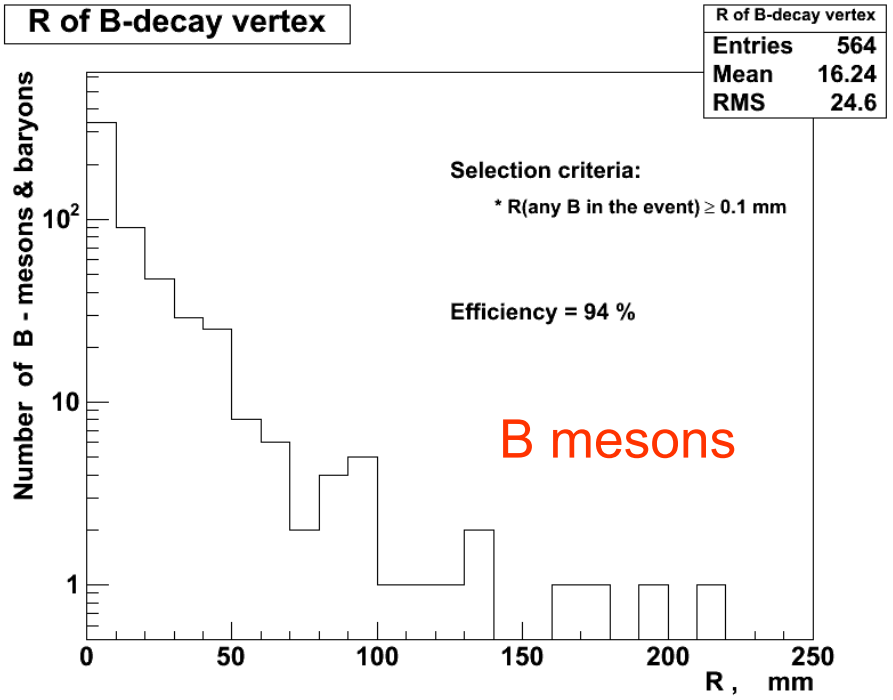
JINR(Dubna) ATLAS Group

V. Bednyakov, Y.Budagov, G. Khoriauli, J.Khubua



Pythia within ATHENA,

B-vertex taging

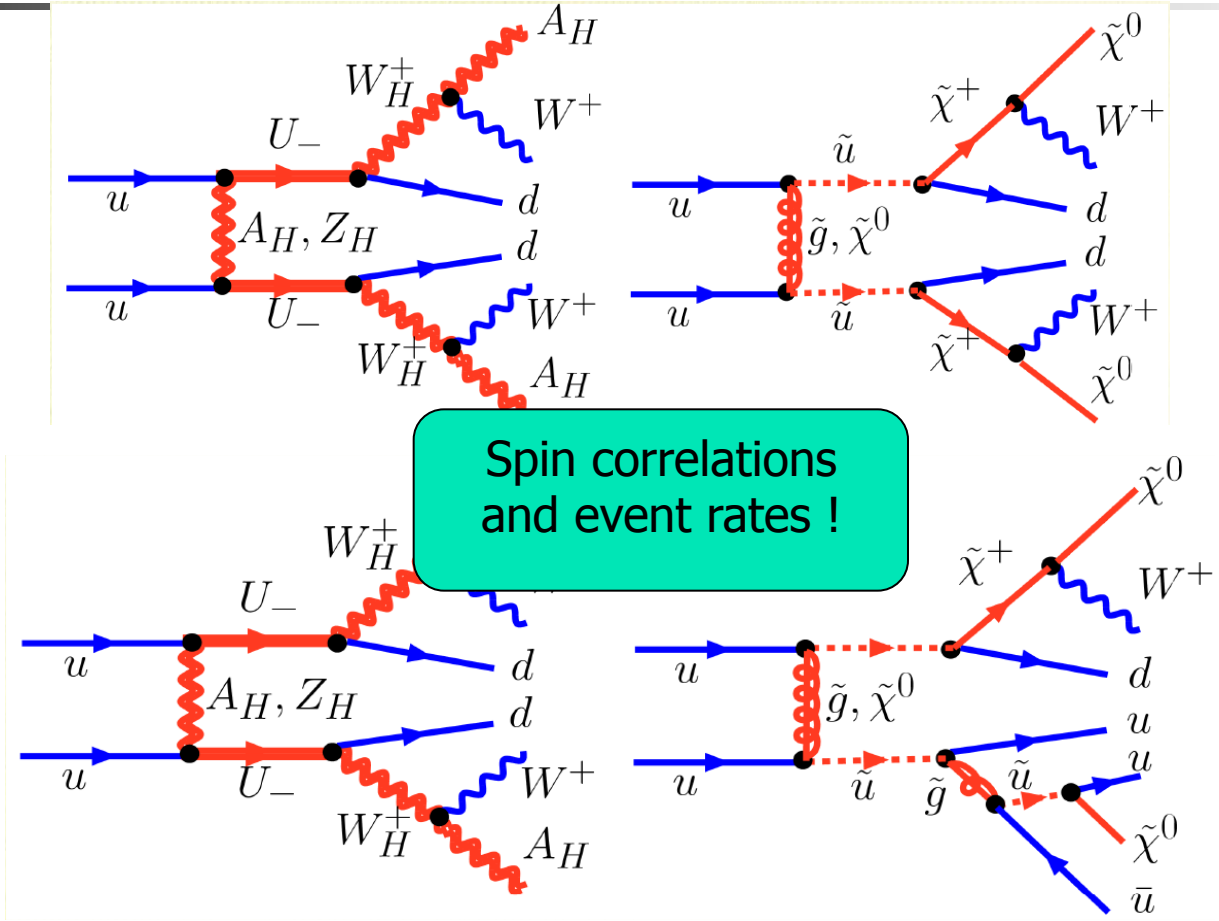


$$\Sigma P_t^{B,B,\mu,\mu}(\text{down}) - \Sigma P_t^{B,B,\mu,\mu}(\text{up}) = \not{P}_t \equiv \not{E}_t$$

SUSY Versus Little Higgs

A.Belyaev

Little Higgs

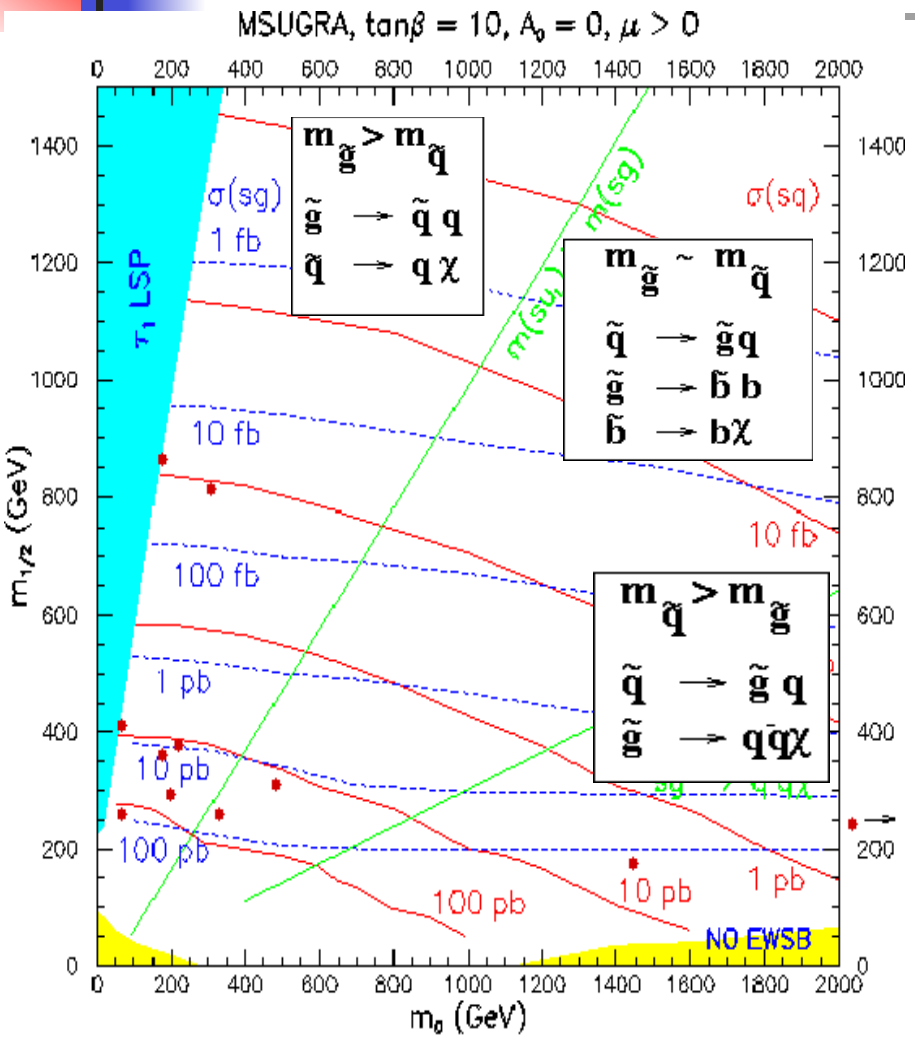


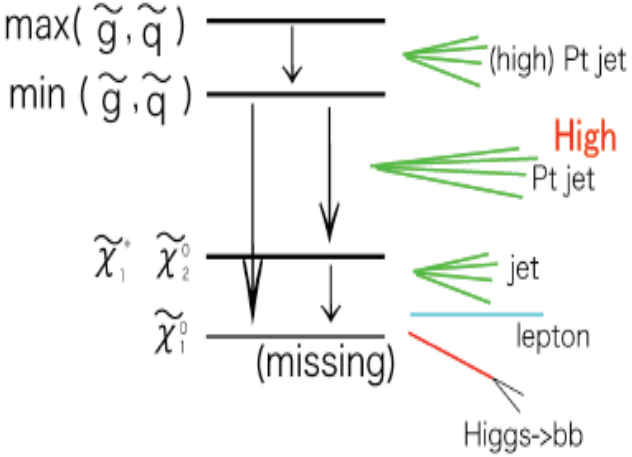
SUSY

Study of spin correlations is quite a challenge for LHC

SUSY Searches at LHC

V.Zhukov

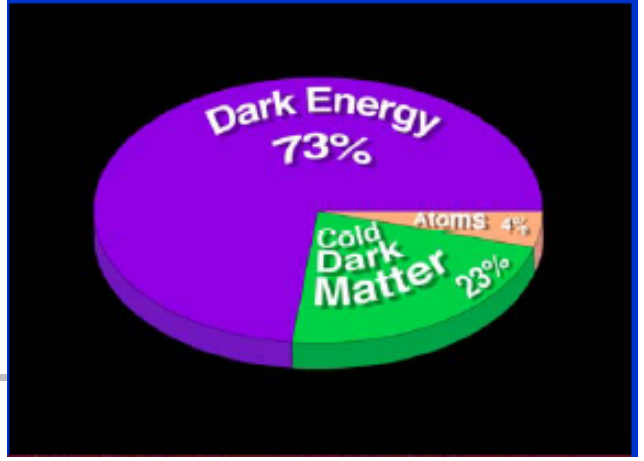




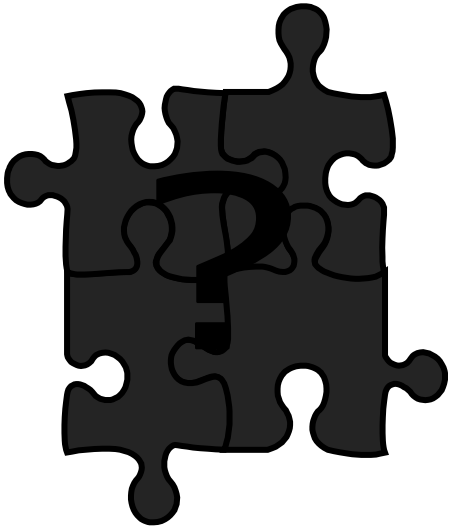
Main final state in the cascade decays:

MET+Jets+Leptons

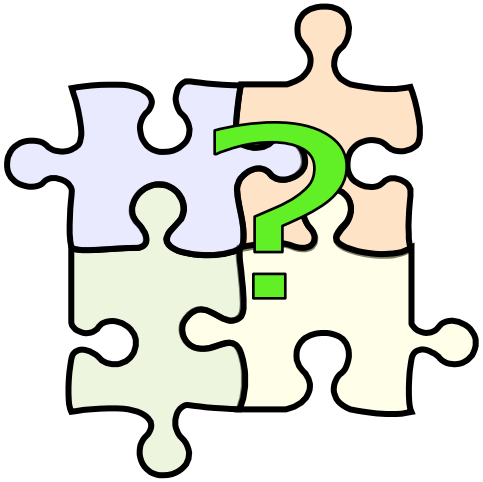
Problem # 3



What is Dark Matter ?



DARK



TRANSPARENT

?

INVISIBLE

What is it made of ?

The Origin of Dark Matter

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – axion (axino)

Belram, Garcia-Bellido, Lesgourges;Kaplan, Zurek
Chun, KimJedamzik, Lemoike, Moultaka
Steffen;Panotopoulos

Non from the SM

- neutralino
- sneutrino

mSUGRA

- right neutrino

Asaka, Blanchet, Shapohsnikov

- gravitino

Gauge Mediation

- heavy photon

Little Higgs Models

- heavy pseudo-goldstone
- light sterile higgs

Inert Higgs Model

DM Detection

Direct detection

DAMA, Zeplin,
CDMS, Edelweiss

No convincing evidence so far
Hope for new results soon

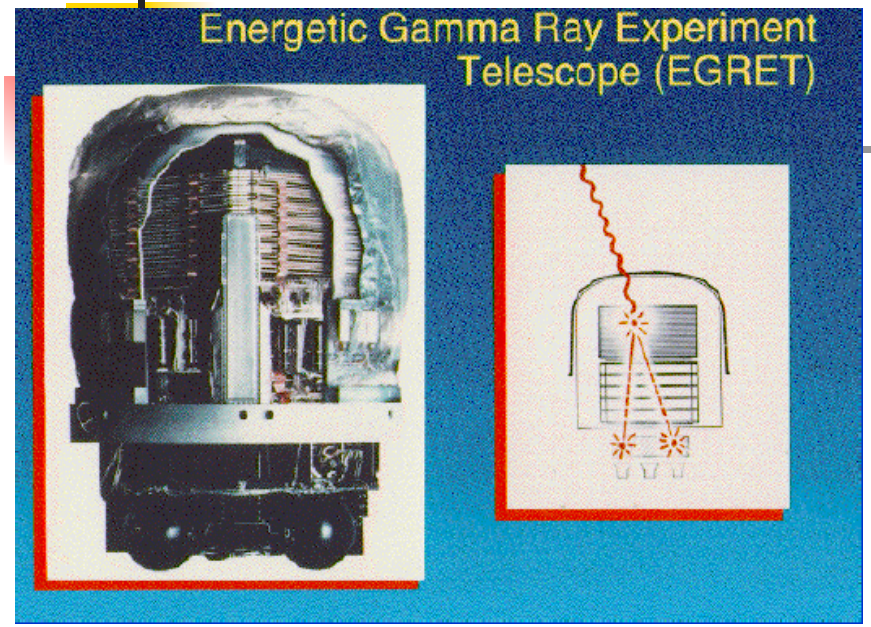
Indirect detection

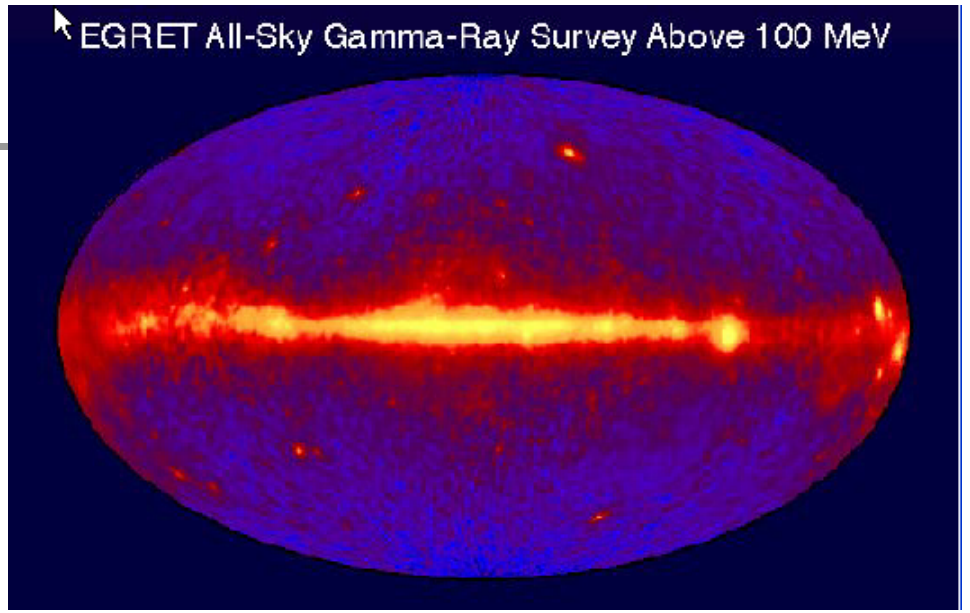
- EGRET -> GLAST
  Diffuse Gamma Rays
- HEAT, AMS01 -> PAMELA
  Positrons in Cosmic Rays
- BESS -> AMS02
  Antiprotons in Cosmic Rays

E.Bloom
A.Morselli
P.Picozza
C.Goy

First Evidence of DM annihilation!

Diffuse Gamma Rays from the Sky





Instrumental parameters:

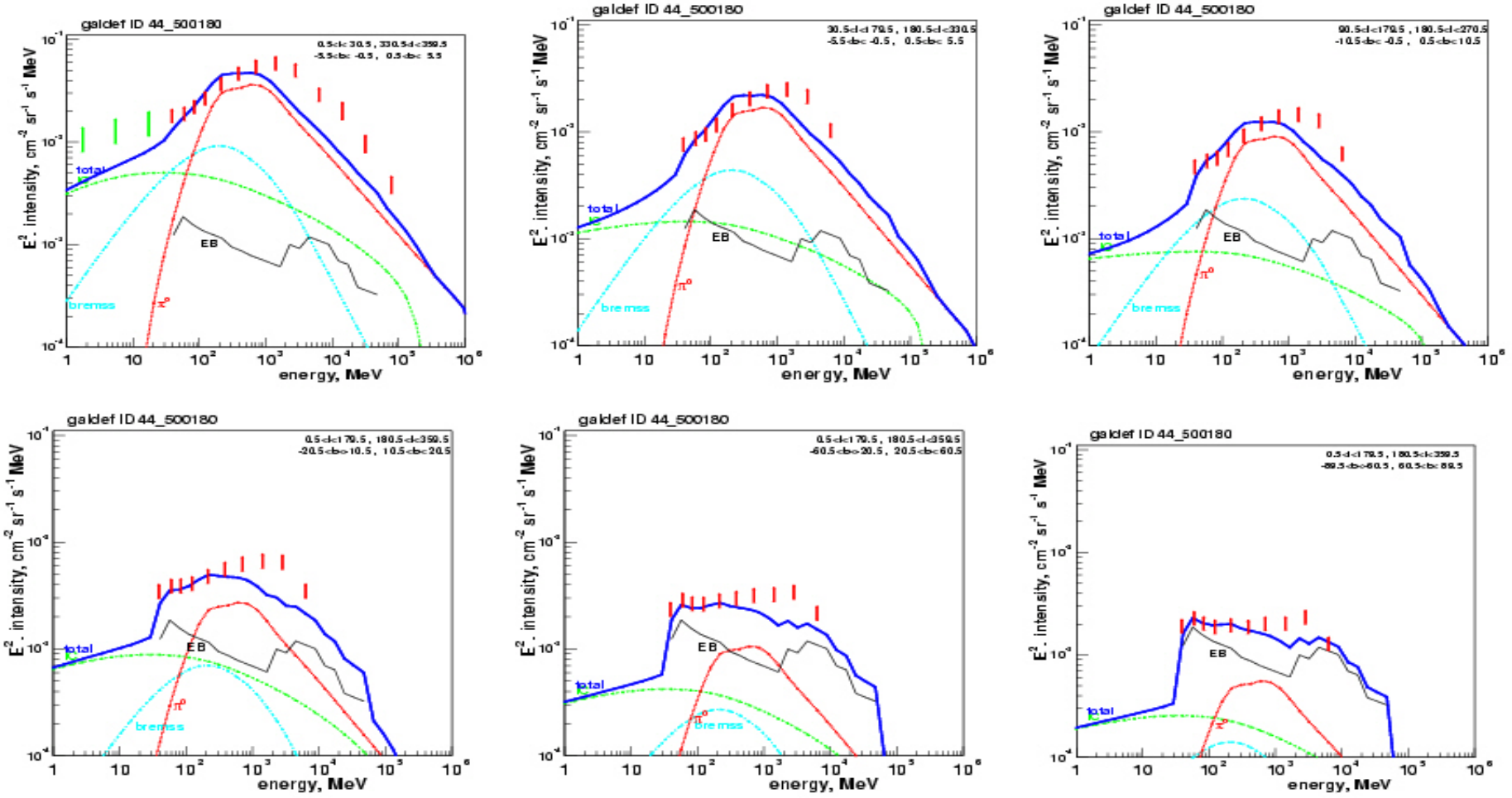
Energy range: 0.02-30 GeV
Energy resolution: ~ 20%
Effective area: 1500 cm^2
Angular resol.: <0.5°

Data taking: 1991-2000

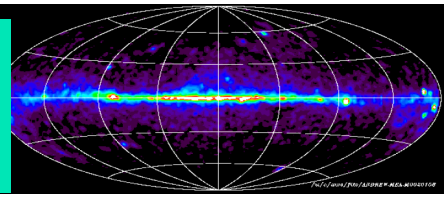
Main EGRET results:
Catalogue of point sources
Excess in diffuse gamma rays

First indirect evidence for DM annihilation

EXCESS OF DIFFUSE GAMMAY RAYS ABOVE 1 GEV

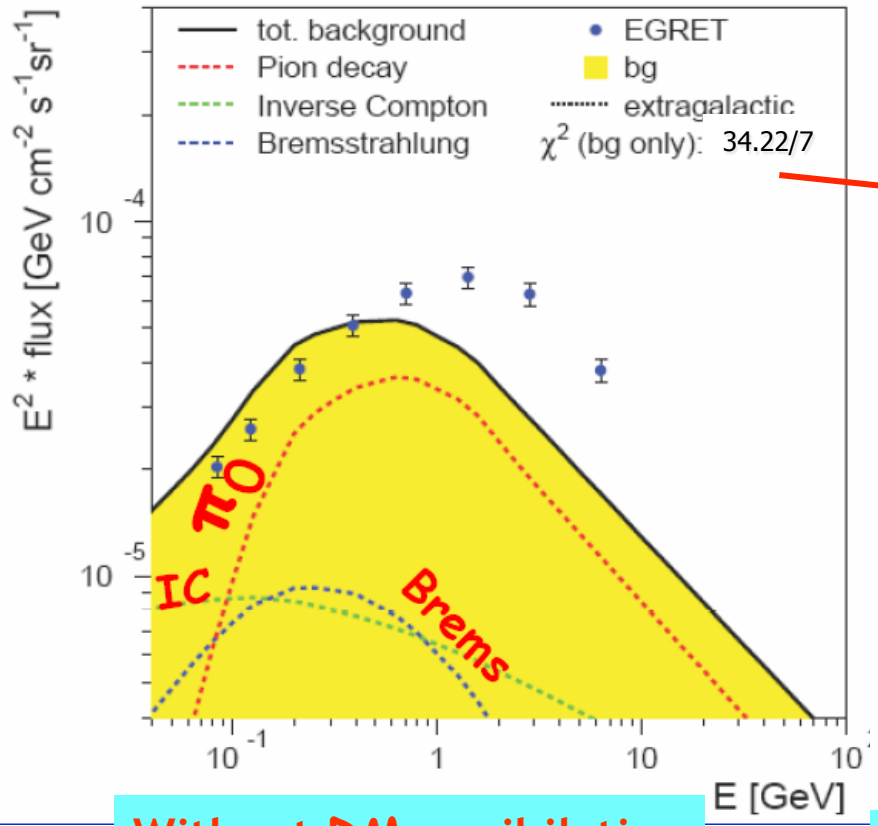


A: inner Galaxy (l=±30°, |b|<5°)
B: Galactic plane avoiding A
C: Outer Galaxy
D: low latitude (10-20°)
E: intermediate lat. (20-60°)
F: Galactic poles (60-90°)

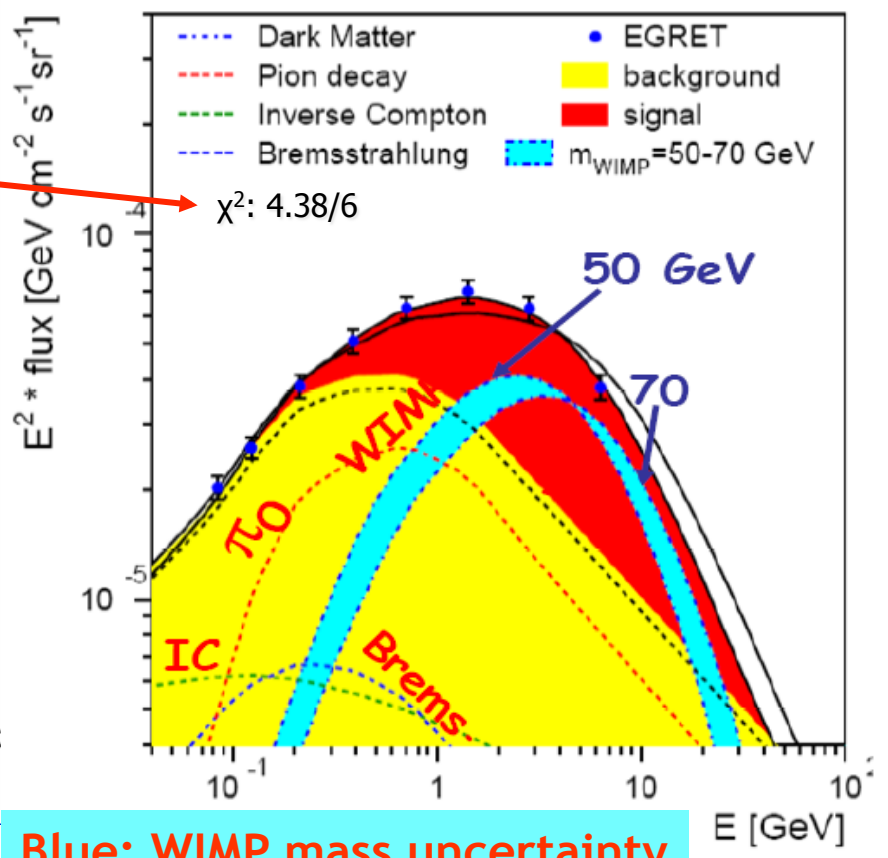


Excess of Diffuse Gamma Rays with and without DM Annihilation

W.De Boer, C.Sanders, V.Zhukov, A.Gladyshev and D.Kazakov



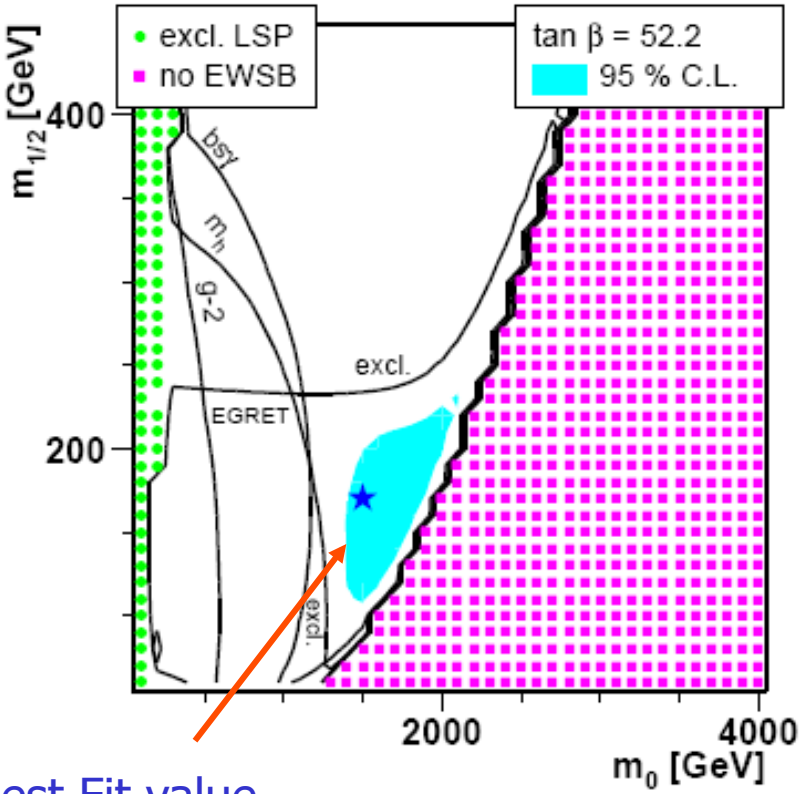
Without DM annihilation



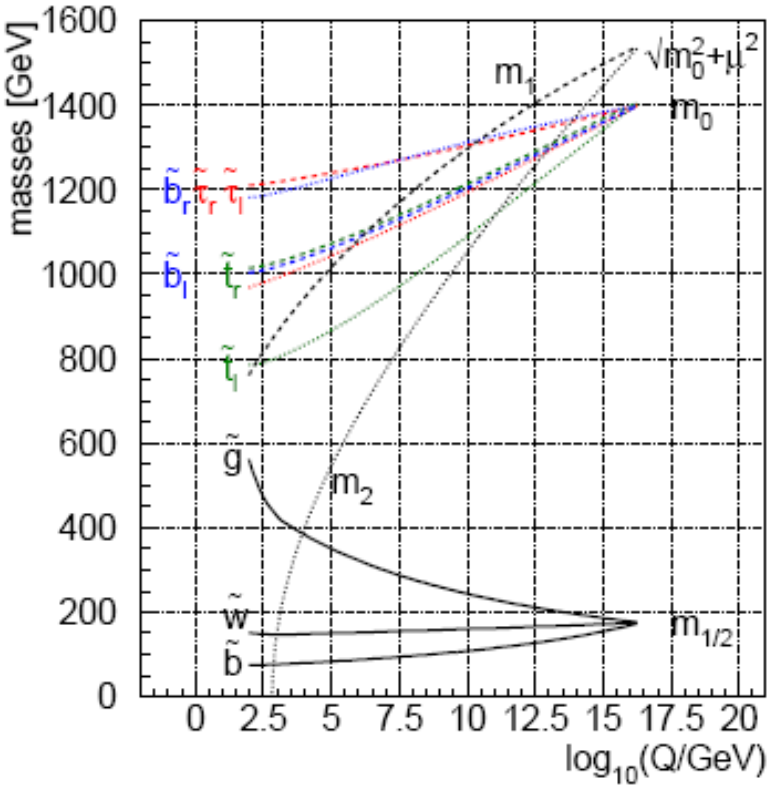
Blue: WIMP mass uncertainty

Fit to the shape of spectrum + intensity from rotation curve of Milky Way

EGRET Point and Mass Spectrum



Best Fit value



Split SUSY: light gauginos & heavy matter

WIMP = LSP (Neutralino) – superpartner of CMB

SUSY MASS SPECTRUM

Fitted SUSY Parameters

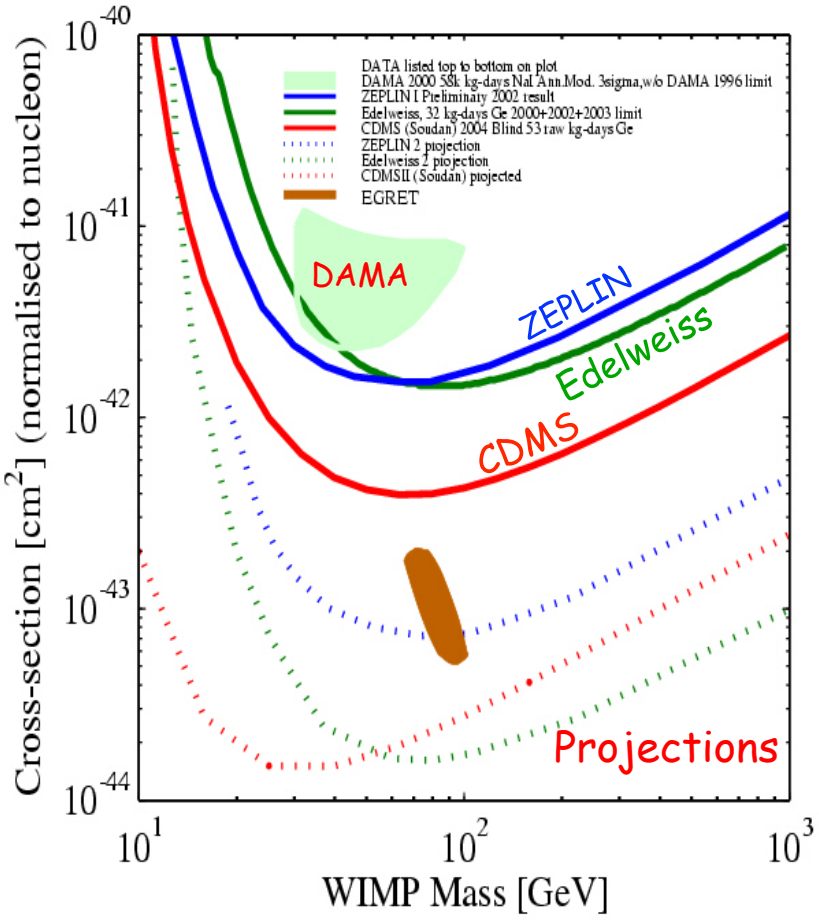
Parameter	Value
Tan β	52.2
m_0	1500
$m_{1/2}$	170
Sign μ	+
A(0)	0
$\alpha_s(M_Z)$	0.122
$\alpha_{em}(M_Z)$	0.0078153697
$Sin^2\theta_W\|_{\overline{MS}}$	0.2314
m_t	175 GeV
m_b	4.214 GeV

SUSY Masses in GeV

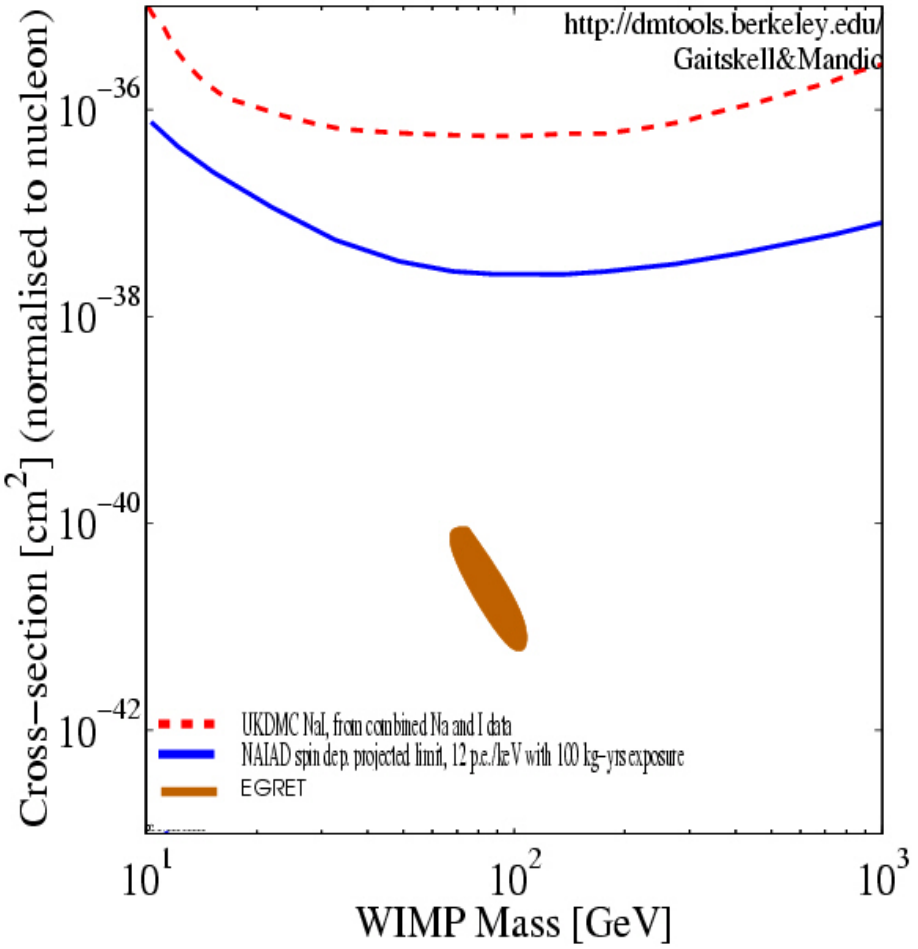
Particle	Mass
$\tilde{\chi}^0_{1,2,3,4}$ →	64, 113, 194, 229
$\tilde{\chi}^{\pm}_{1,2}$, $\tilde{g}$ →	110, 130, 516
$\tilde{u}_{1,2} = \tilde{c}_{1,2}$	1519, 1523
$\tilde{d}_{1,2} = \tilde{s}_{1,2}$	1522, 1524
$\tilde{t}_{1,2}$	906, 1046
$\tilde{b}_{1,2}$	1309, 1152
$\tilde{e}_{1,2} = \tilde{\mu}_{1,2}$	1497, 1499
$\tilde{\tau}_{1,2}$	1305, 1288
$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	1495, 1495, 1286
h, H, A, $H^{\pm}$ →	115, 372, 372, 383

Direct DM Searches

Spin-independent



Spin-dependent



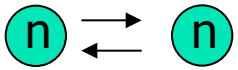
Predictions from EGRET data assuming Supersymmetry

Further Major Problems

- Baryon Asymmetry → Baryo and leptogenesis

- Violation of B-L (required for baryogenesis)

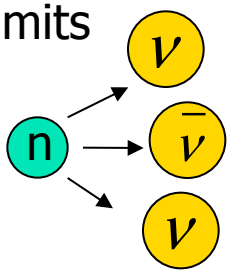
  Neutron-antineutron oscillations ΔB=2

  Kuzmin, Rubakov, Shaposhnikov
  B. Dutta, K. Babu et al.
  A. Dolgov et al., C. Bambi

  Nucleon decays, τ→nucleon decays with Δ|B-L|=2

  New n→ννν and n→inv limits

  Yu.Kamyshkov
  KamLAND

- Dark Energy

Physics beyond the SM

What the future may bring?

Instead of Conclusion

"Blessed are those who believe and yet have not seen"

St. John, XX, 29

"Блаженны не видевшие и уверовавшие"

Св. Иоанн, XX, 29