Supersymmetry (SUSY)

for particle physicists

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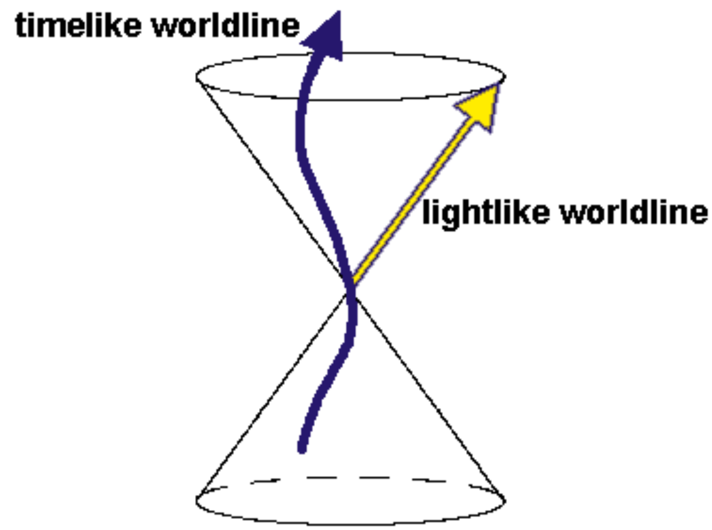
WHAT DO WE KNOW??
a particle physicist view - STANDARD MODEL

- SPACE R^3 (continuous, flat)
- TIME R^{1*} (continuous with an arrow of time!!)
- MATTER leptons+quarks
- INTERACTIONS strong
  electromagnetic
  weak
  gravity

WHAT DO WE KNOW??
Minkowski "WORLD" or spacetime



Physics laws are invariant under Poincare group of transformations:

space translations

space rotations

time translations

Lorentz boosts = rotations in 4-dim "world" or spacetime
mixing time and space coordinates

symmetries <=> conservation laws

- Emmy Noether discovered the connection between symmetries and conservation laws while working with David Hilbert and Felix Klein in Gottingen
- In 1918 she proved two theorems, for finite continuous groups and infinite continuous groups which are the foundations of the modern (XXth century) physics. The theorems are collectively known as "Noether's theorem"
- Informally, Noether's theorem says:

differentiable symmetry generated by local actions <=> conserved current

or

there is one-to-one correspondence between symmetries and conservation laws

symmetry <=> conservation law

symmetries <=> conservation laws

- examples:
  - energy is conserved if and only if (iff) the physical laws are invariant under time translations (if the form of physics laws do not depend on time)
  - linear momentum is conserved only iff the physical laws are invariant under space translations (if the form of physics laws do not depend on the position)
  - angular momentum is conserved iff the physical laws are invariant under rotations (if the physics laws do not depend on orientation; if only true about a particular direction <=> only the component of angular momentum in that direction is conserved)

symmetries <=> conservation laws

- Symmetries observed in physics:

  – Symmetries of discrete space-time transformations: parity, time-reversal, charge conjugation

  – Symmetries of continuous space-time transformations: translational and rotational invariance and Lorentz (space-time rotations) invariance

  – Symmetries of permutations: lead to two kind of particles: bosons, which obey Bose-Einstein statistics, and fermions, which obey Fermi-Dirac statistics

  – Gauge symmetries: internal symmetries inherent from the nature of the field associated with a given particle carrying such attributes as electric charge - U(1), color - SU(3) et cetera (conservation of electric charge <=> invariance under the global phase transformation in the internal space; electromagnetic field <=> invariance under the local phase transformation; et cetera….you'll learn all this in the first 2 years in graduate school)

symmetries <=> conservation laws

- Modern particle physics (XXth-century) is based entirely on the idea of underlying internal symmetries:
  - The electro-weak sector is based upon the (internal) symmetries which the electromagnetic and weak interactions obey - U(1) and SU(2)
  - The strong sector of the Standard Model (SM), quantum chromodynamics (QCD) is based on the (internal) SU(3) symmetries observed in hadron spectroscopy
  - Spontaneous symmetry breaking has been proposed to explain massive weak bosons (Z, W) and the massless photon. The prediction of the W and Z bosons came from symmetry arguments and the discovery of these particles at CERN was one of the greatest successes of modern particle physics

STANDARD MODEL

- Current understanding of elementary particles and their strong and electro-weak interactions is given by Standard Model, a gauge theory based on the following internal symmetries:

$$SU(3)_c \times SU(2)_I \times U(1)_Y$$

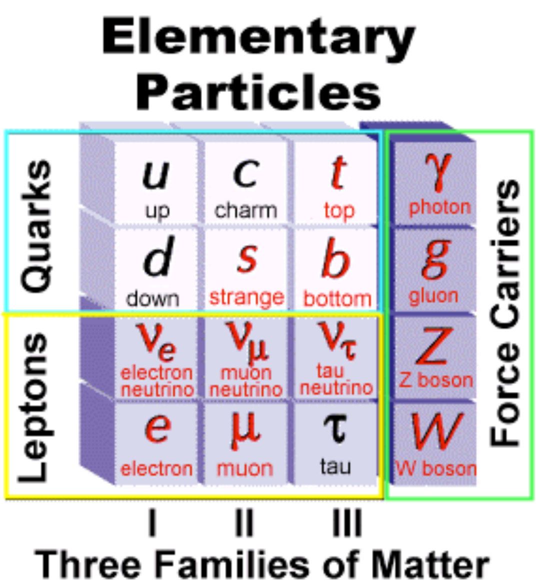
- The SU(3) is an unbroken symmetry, it gives QCD, a quantum theory of strong interactions, whose carriers (gluons) are massless

- $SU(2) \times U(1)$ (quantum theory of electroweak interactions) is spontaneously broken by the Higgs mechanism; which gives mass to electroweak bosons (W^+, W^-, Z^o and a massless photon)

- In the Minimal Standard Model, the Higgs sector is the simplest possible: contains two complex Higgs fields, which after giving masses to W,Z give leaves a neutral scalar Higgs particle which should be observed - the ONLY particle not yet discovered in MSM

STANDARD MODEL

- Matter is build of fermions - quarks and leptons, three families of each, with corresponding antiparticles; quarks come in three colors
- Bosons are carriers of interactions: 8 massless gluons, 3 heavy weak bosons ($W^{\pm}$,Z^0) and 1 massless photon
- A massive scalar Higgs field permeates the Universe and is (in some way) responsible for masses of other particles



~28 parameters NOT predicted by SM:

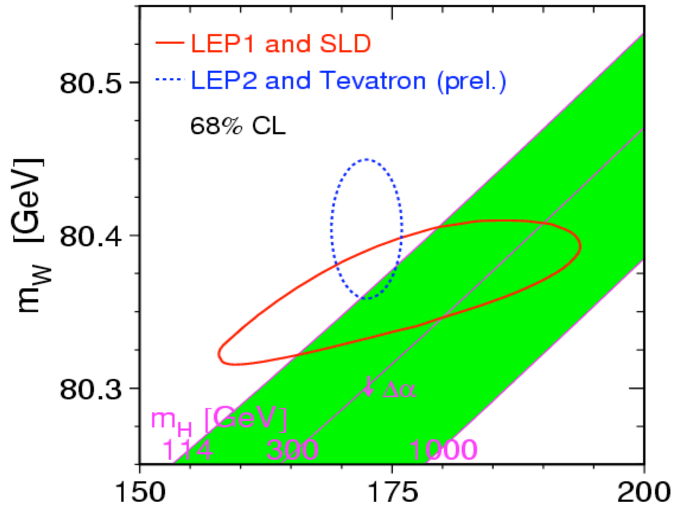
- masses of 6 quarks
- masses of 6 leptons
- coupling constants of SU(3), SU(2) and U(1)
- Higgs mass and vacuum expectation value
- Cabibbo-Kobayashi-Maskawa matrix angles and complex phase
- Maki-Nakagawa-Sakata matrix angles and complex phase
- QCD phase θ

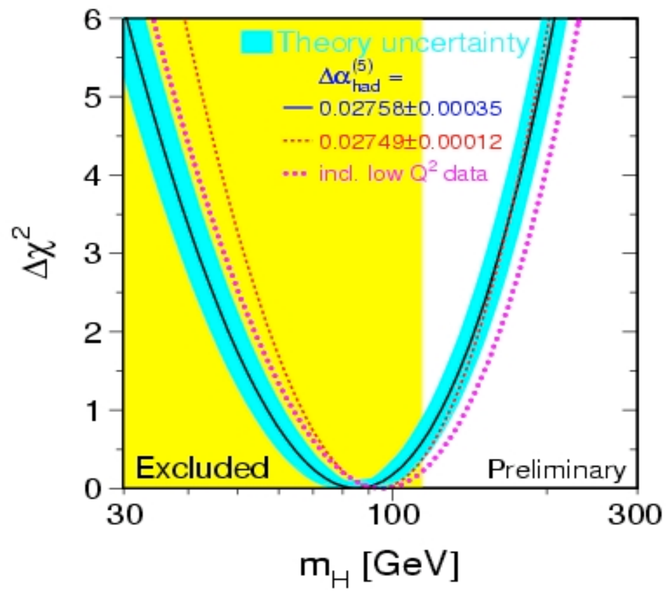
ALL MUST BE MEASURED !!!

STANDARD MODEL

- Masses of quarks and leptons, as well as those of carriers of interactions and Higgs scalar particle are fundamental parameters of SM - to be determined by measurement
- mixing angles in quark and lepton sector, and the phases are also parameters to be measured
- It is possible to verify the internal consistency of SM through precise measurements: together with other already very precise EW measurements, precise measurements of W and top mass constrain Higgs mass. Fundamental consistency tests of Standard Model; sensitivity through radiative corrections (quadratic in m_t, logarithmic in m_H)

COMPARE WITH DIRECT LIMITS ON HIGGS MASS



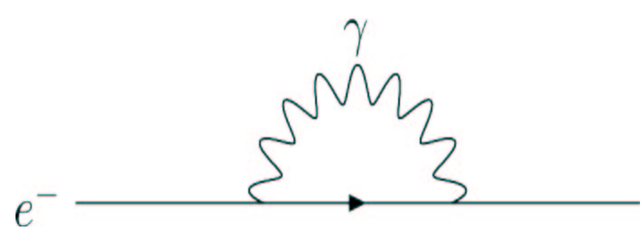


spontaneous breaking of the electroweak symmetry by Higgs mechanism

• This part of SM is the only remaining untested part of SM. Higgs has not been observed as of yet; remember, the EW symmetry could be broken in a different way, not necessarily like in MSM

• Difficulties with the elementary Higgs sector: suppose that SM is just an effective theory and that NEW physics is at some scale Λ.

the quantum corrections to fermion masses would depend only logarithmically on scale Λ ("mass is protected"):



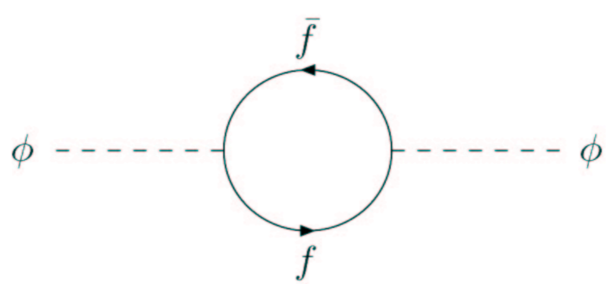
$\delta m_f \sim m_f \ln\Lambda$

spontaneous breaking of the electroweak symmetry by Higgs mechanism

• Difficulties with the elementary Higgs sector: the analogous quantum corrections to scalar particle (Higgs) would exhibit a quadratic dependence on scale Λ. This means that Higgs mass is VERY sensitive to the scale of the NEW physics => FINE TUNING PROBLEM (for m_o) as m_H=O(100) GeV in SM !!

$$m_H^2 = - m_0^2 + g^2\Lambda^2$$

SM cannot be valid for very large momenta, the scale Λ serves as a cutoff above which physics not contained in SM becomes important. At least one such scale, Planck scale at which gravity becomes relevant, Λ=O(10^{19}) GeV, must be present in any theory. The only other scale known above EW scale is Λ=O(10^{16}) GeV, the unification scale.



$$\delta m_H^2 \sim \Lambda^2$$

spontaneous breaking of the electroweak symmetry by Higgs mechanism

• This fine tuning has to be performed for each order of perturbation theory; this is a very unpleasant feature of SM

• This sensitivity is called also the GAUGE HIERARCHY PROBLEM, as the Higgs mass is related to the weak boson masses in the spontaneously broken gauge theory. One may say that the original problem of how to give masses to weak gauge bosons in a gauge invariant way was only partially solved by Higgs mechanism, and the problem was transferred to a new level, where the new puzzle is how to keep Higgs mass stable against large quantum corrections from the higher energy scales

• A method of controlling Higgs mass divergence other than fine tuning of parameters would be very welcomed

supersymmetry - the most elegant solution?

• the interesting thing about the scalar mass divergencies from virtual particle loops (quantum corrections) is that *virtual fermions and virtual bosons contribute with opposite signs and would cancel each other exactly if for every boson there was a fermion of the same mass and charge - divergencies would cancel without any fine tuning and in all orders of perturbation theory !!*

• supersymmetry is such a symmetry: it connects bosons to fermions, it introduces a fermionic partner to every boson and vice-versa, identical in all quantum numbers; such boson <=> fermion connection is unique to supersymmetry; all the symmetries listed before provide no such connection

supersymmetry - the most elegant solution?

• at the quantum mechanical level, this Fermi-Bose symmetry would require some quantum operator, Q, whose action would be to transform bosons into fermions and vice-versa

$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$
$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$

• and since this is is a symmetry, this operator must commute with the Hamiltonian

$$[Q,H] = 0$$

supersymmetry - the most elegant solution?

• Such a theory is called a *supersymmetric theory* and the *operator Q* is called the *supercharge*. Since the operator Q changes a particle with spin 1/2 to a particle with spin 1 or 0, the Q itself must be a spinor that carries spin 1/2 of its own

• Bosons are particles with integer spins, they obey Bose-Einstein statistics, any number of them may occupy the same quantum state at a time. Fermions carry half-integer spin (or odd multiples of 1/2), they obey Fermi statistics and only one fermion can occupy any given quantum state at a time. The classical limit of quantum mechanics is approached when the occupation numbers of available states are very high. The quantum photon field behaves like the classical EM field described by Maxwell's equations. However, there is NO classical limit for fermions, fermion fields are quantum phenomena.

• A symmetry that interchanges fermions and bosons is a symmetry that exchanges physics that has a classical limit with physics with NO classical limit - POTENTIALLY EXTREMELY POWERFUL and interesting

supersymmetry - the most elegant solution?

• Obviously, if supersymmetry is part of our world, it must be somehow broken as we have not yet observed superparticles. One needs to allow such breaking of supersymmetry while still keeping the ability of such a theory to solve the gauge hierarchy problem. Not easy, depends on the scale at which SUSY is broken, and on how it is broken. To some extent it remains still an open question

• Another reason for SUSY theories being attractive is that in string theories the most viable versions are supersymmetric

• Local supersymmetry could also be a viable theory of gravity, supergravity. Local gauge invariance of SUSY requires existence of spin-3/2 and spin-2 particles and this naturally introduces the spin-2 graviton, assumed to mediate the gravitational force

supersymmetry - the most elegant solution?

- space-time symmetries in relativistic QM are contained in the Poincare group; it includes symmetries under spatial rotations, translations in space and time and space-time boosts (space-time rotations), or, co-ordinate transformations in special relativity
- a symmetry group is described by the algebra of the group which is defined by a set of commutation relations. For the Poincare group:

$$[P^\mu, P^\nu] = 0$$

$$[J^{\mu\nu}, P^\kappa] = P^\mu \eta^{\nu\kappa} - P^\nu \eta^{\mu\kappa}$$

$$[J^{\mu\nu}, J^{\kappa\lambda}] = J^{\mu\lambda}\eta^{\nu\kappa} - J^{\nu\lambda}\eta^{\mu\kappa} - J^{\mu\kappa}\eta^{\nu\lambda} + J^{\nu\kappa}\eta^{\mu\lambda}$$

P^μ is the momentum generator which generates space and time translations, the Lorentz matrices $J^{\nu\kappa}$ generate rotations in space and Lorentz boosts (rotations) in space-time, and $\eta^{\mu\kappa}$ is the metric tensor.

These are all bosonic symmetries, which should be true as energy, momentum and angular momentum conservation and Lorentz invariance are present in classical physics

supersymmetry - the most elegant solution?

• our world is decribed by:

Poincare (space-time) symmetry: with generators P^{μ}, $J^{\nu\kappa}$

internal symmetries (U(1)xSU(2)xSU(3) of SM): with generators T_a

• However, the Poincare group also has representations that describe fermions. This should be expected as spin 1/2 particles appear as solutions to a relativistically invariant equation - the Dirac equation. If there exist spin 1/2 particles could there be spin 1/2 symmetry generators in a space-time symmetry algebra?

• This would be an extension of Poincare group of symmetries valid for relativistic QFT in D=4

supersymmetry - the most elegant solution?

- in 1971 Golfand and Likhtman (whose work was forgotten for years..):

$$[P^\mu,P^\nu] = 0$$
$$[P^\mu,Q_a] = [P^\mu,\bar{Q}_a] = 0$$
$$\{Q_a,Q_b\} = \{\bar{Q}_a,\bar{Q}_b\} = 0$$
$$\{Q_a,\bar{Q}_b\} = 2\gamma^\mu{}_{ab}P_\mu$$

Note $E = H = P^0$ => $[Q_a,H]=0$ => Q is a conserved charge.

Q_a is fermionic generator (spinor) with $\bar{Q}_b$ its complex conjugate. What are these new symmetry generators Q? These are the *supercharges* mentioned before (note anticommutators {,} instead of commutators [,] for those fermionic generators)

- If there is just one fermionic generator (supercharge) Q we call such a theory N=1 SUSY; if there are two, we have N=2 SUSY, et cetera…
- in 1974 Wess and Zumino wrote a Lagrangian with the same symmetries

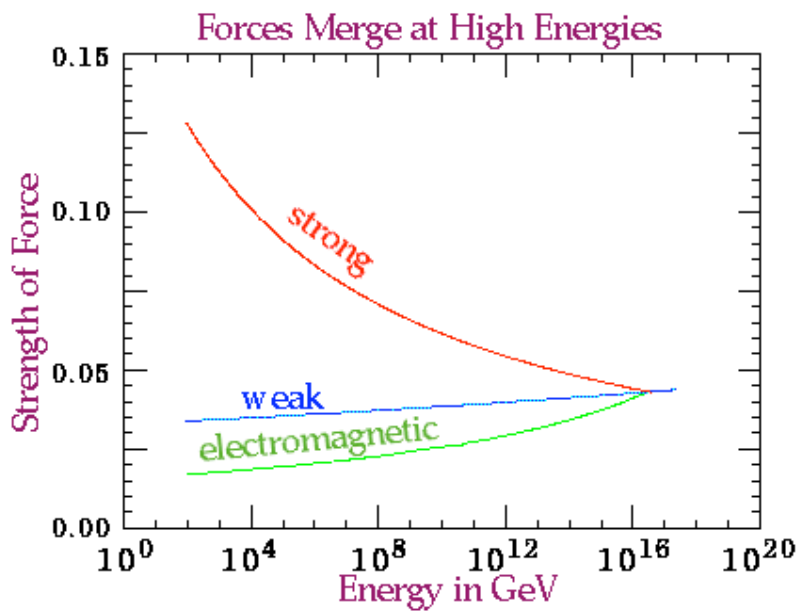
supersymmetry - the most elegant solution?

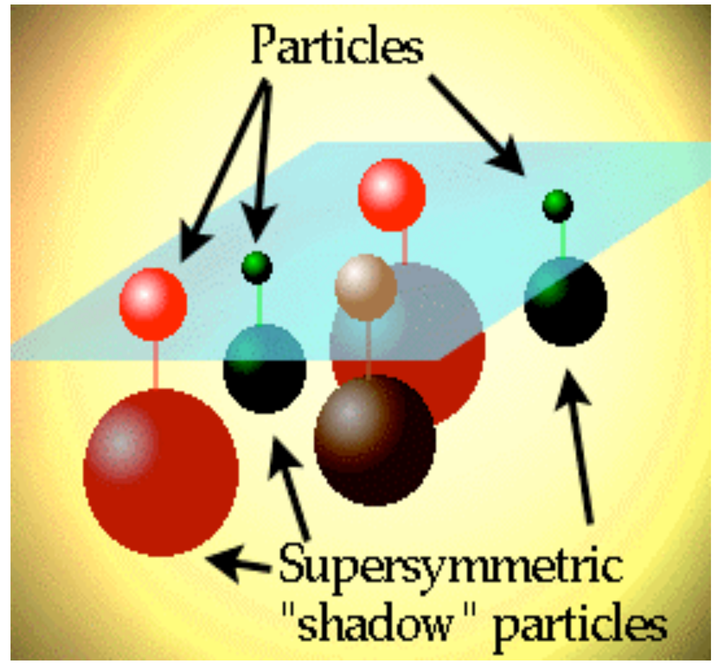
• Independently of Golfand and Likhtman, Akulov and Volkov in 1972 tried to explain the neutrino (and its small mass) as a massless fermion (Goldstino) - appearing due to *spontaneous supersymmetry breaking* - (in analogy with massless Goldstone bosons which appear due to spontaneous symmetry breaking).

• In 1972-73, Volkov and Soroka developed a gauge theory of the super-Poincare group, which led to elements of *supergravity*. They suggested that a spin 3/2 graviton's superpartner obtain mass by ”absorbing” the Goldstino that Akulov and Volkov had discussed earlier.

• This established existence of the "super-*Higgs mechanism*" in supergravity, later rediscovered in the West.

SUPERSYMMETRY



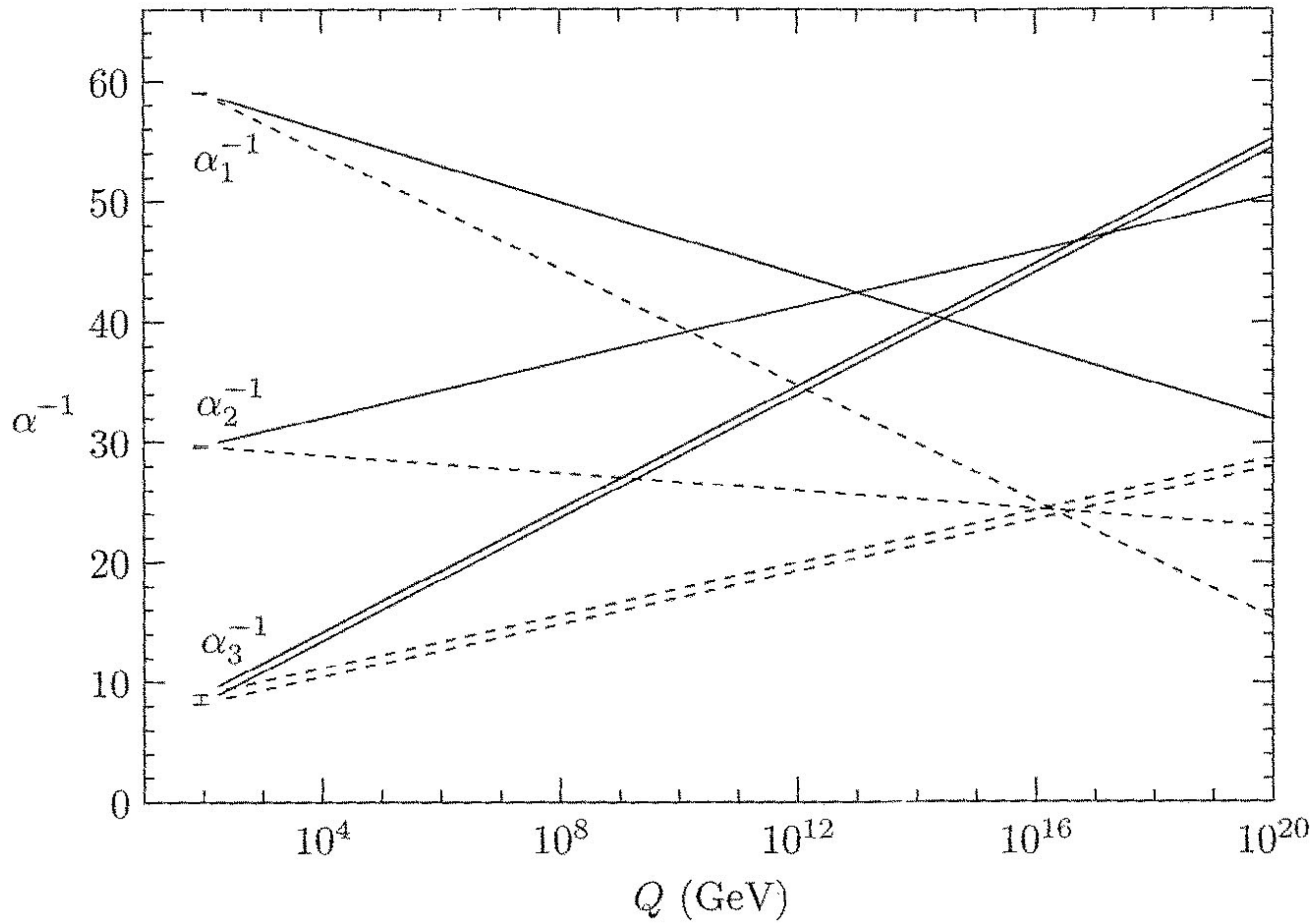


SUPERSYMMETRY (a space-time symmetry) - postulates existence of bosonic matter particles, and fermionic carriers of interactions, not exact, since supersymmetric partners must be heavy as they have not been observed; for every known particle there should be a supersymmetric partner

running coupling constants in SM and MSSM models

Solid lines - SM

Dotted lines - MSSM



SM and MSSM particle spectrum

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q) (spin-$\frac{1}{2}$)	$\binom{u}{d}_L$, u_R, d_R $\binom{c}{s}_L$, c_R, s_R $\binom{t}{b}_L$, t_R, b_R	squarks ($\tilde{q}$) (spin-0)	$\begin{pmatrix}\tilde{u}\\\tilde{d}\end{pmatrix}_L$, $\tilde{u}_R$, $\tilde{d}_R$ $\begin{pmatrix}\tilde{c}\\\tilde{s}\end{pmatrix}_L$, $\tilde{c}_R$, $\tilde{s}_R$ $\begin{pmatrix}\tilde{t}\\\tilde{b}\end{pmatrix}_L$, $\tilde{t}_R$, $\tilde{b}_R$	$\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$
leptons (l) (spin-$\frac{1}{2}$)	$\begin{pmatrix}e\\\nu_e\end{pmatrix}_L$, e_R $\begin{pmatrix}\mu\\\nu_\mu\end{pmatrix}_L$, μ_R $\begin{pmatrix}\tau\\\nu_\tau\end{pmatrix}_L$, τ_R	sleptons ($\tilde{l}$) (spin-0)	$\begin{pmatrix}\tilde{e}\\\tilde{\nu}_e\end{pmatrix}_L$, $\tilde{e}_R$ $\begin{pmatrix}\tilde{\mu}\\\tilde{\nu}_\mu\end{pmatrix}_L$, $\tilde{\mu}_R$ $\begin{pmatrix}\tilde{\tau}\\\tilde{\nu}_\tau\end{pmatrix}_L$, $\tilde{\tau}_R$	$\tilde{\tau}_{1,2}$
gauge/Higgs bosons (spin-1, spin-0)	g, Z, γ, h, H, A $W^\pm$, $H^\pm$	gauginos/Higgsinos (spin-$\frac{1}{2}$)	$\tilde{g}$, $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}_1^0$ $\tilde{W}^\pm$, $\tilde{H}^\pm$	$\tilde{\chi}^0_{1,2,3,4}$ $\tilde{\chi}^\pm_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde{G}$	

supersymmetry - classification of models

• in the past 30 years extended studies of low-energy SUSY and a number of experimental searches => no evidence for SUSY. However, if SUSY is broken on a scale of ~1 TeV, LHC will have a great chance to discover superparticles

• the minimal supersymmetric standard model (MSSM), two Higgs doublets. Has one less parameter than SM if SUSY is unbroken. Obviously this is not true; supersymmetry must be broken *without* destroying the cancellations which solve the fine-tuning problem => soft SUSY breaking, however no particular way that it is done is assumed. In MSSM R parity is conserved (R=+1 for SM particles, R=-1 for superparticles) which means SUSY particles must be produced in pairs and that the lighest SUSY particle (LSP) is stable (a candidate for "dark matter")

$$R=(-1)^{3B+2S+L}$$

Difficult to use MSSM for experimental studies because of large number of parameters (~105 free parameters !)

supersymmetry - classification of models

• Different models of SUSY breaking are used to reduce the number of parameters. They all have a common feature: SUSY is broken in some hidden sector and then transmitted to the MSSM fields. The models differ in how this is done:

• SUGRA: in supergravity models all scalar masses (M_0), the gaugino mass ($M_{1/2}$), and the A and B parameters are assumed to be unified at at GUT scale ($\sim 10^{15}$ GeV). Five parameters: M_0, $M_{1/2}$, A, sgn(μ) and tanβ completely determine the mass spectrum and decay patterns of particles (tanβ=ratio of vacuum expectation values of the two Higgs doublets, A-trilinear coupling and sgn(μ)-sign of supersymmetric Higgs parameter. Mediating interaction is gravitational

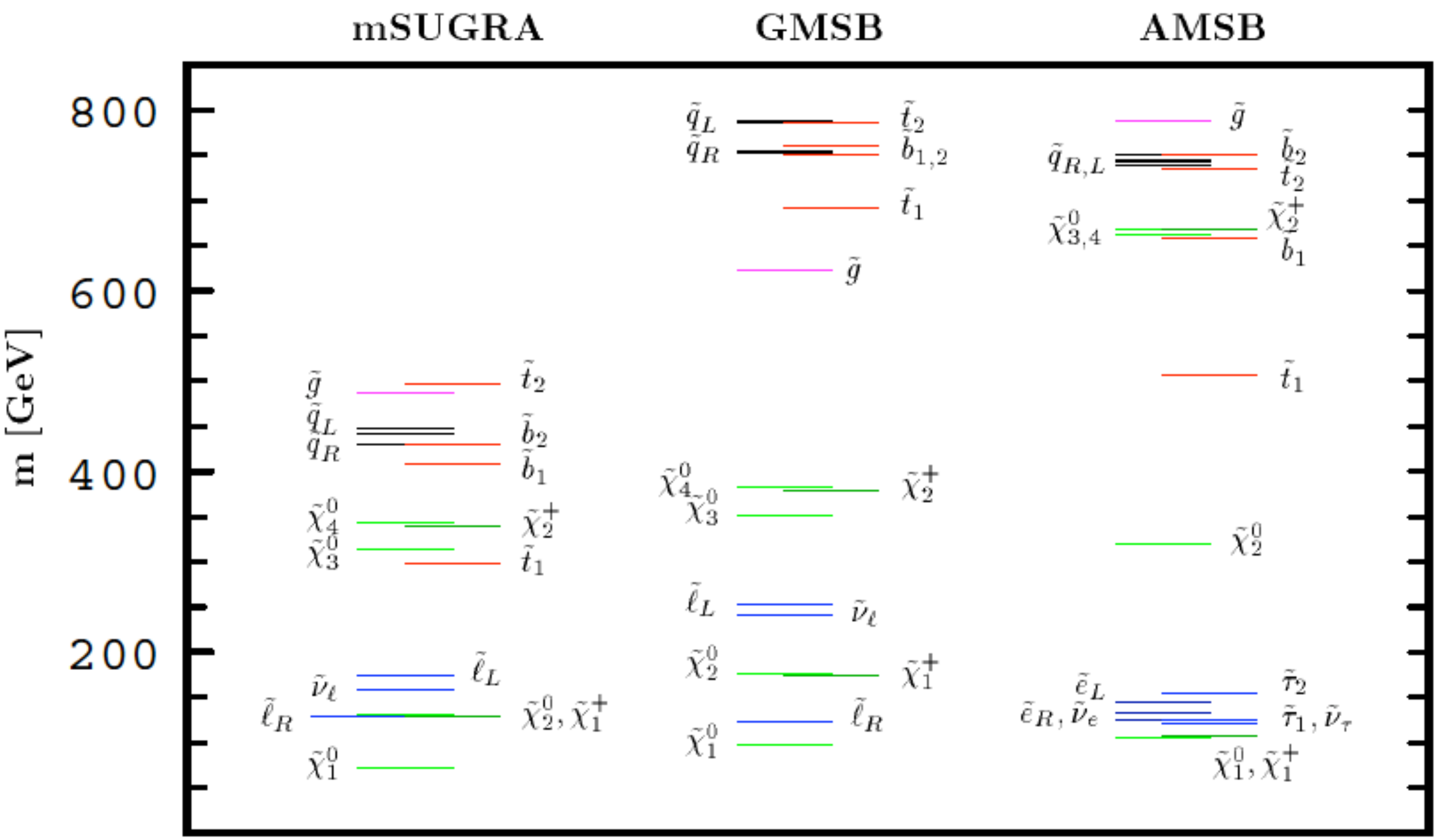
supersymmetry - classification of models

• GMSB: (gauge mediated symmetry breaking) rather than using gravity to transmit the SUSY breaking, gauge interactions are used. The messenger sector consists of some particles, X, which have SM interactions and are aware of SUSY breaking. The LSP is almost massless gravitino. The model has 6 parameters….

• AMSB: (anomaly mediated symmetry breaking); the mAMSB model has 4(5) parameters, very similar to mSUGRA

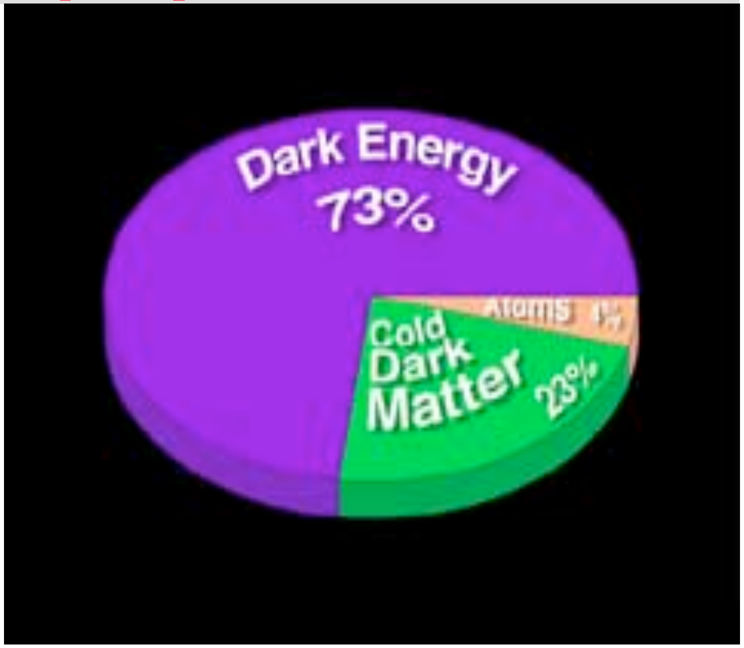
• as you can imagine, many others……

spectrum of particle masses in SUSY models

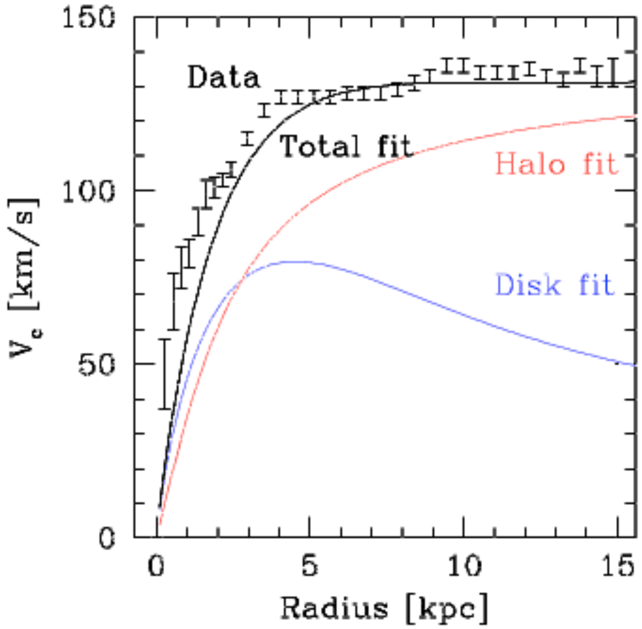


Results from astrophysics

- Expansion rate $H_o = 71 \pm 4$ km/s/Mpc
- Dark energy $\Omega_\Lambda = 73 \pm 4\%$
- Dark matter $\Omega_m = 23 \pm 4\%$
- Ordinary matter $\Omega_b = 4 \pm 0.4\%$ (about 1/10 visible)
- Space is flat $\Omega_{tot} = 1.02 \pm 0.02$
- Age 13.7±0.2 billion years
- Universe will expand forever and its expansion rate is accelerating



SUSY (LSP) GREAT CANDIDATES FOR DARK MATTER !!!



HOW TO SEARCH FOR SUSY (or any New Physics?)

• ACCELERATOR EXPERIMENTS - collide particles (protons, antiprotons, electrons, positrons) at as high energies as possible, study particles that emerge from collisions; deviations from SM maybe "new physics"

• Precision (usually low energy) experiments - compare results with precise calculations where tiny deviations from predictions based on SM may point to "new physics"

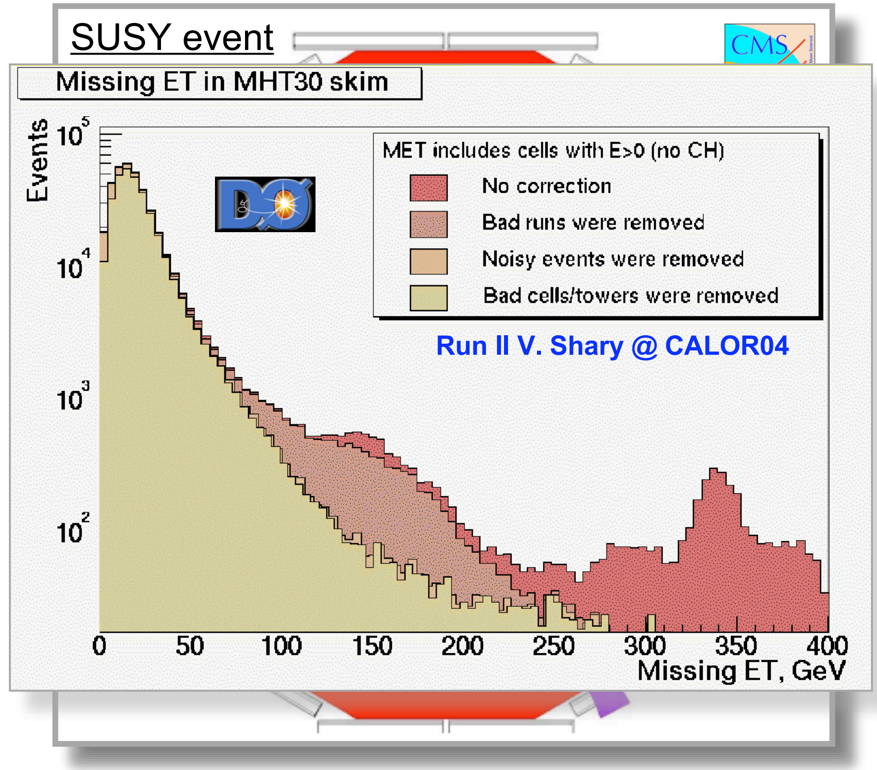
• astrophysics + cosmology: look at the Universe, the farther out one looks, the more back in time one sees, one can extrapolate from very early Universe to present assuming known physics laws, and compare the predicted sky with reality = ASSUMES VALIDITY OF KNOWN PHYSICS LAWS AT ALL TIMES, also violates the scientific principle = ONE CANNOT REPEAT THE EXPERIMENT !! (our Universe is the only one we know!)

Inclusive SUSY Searches

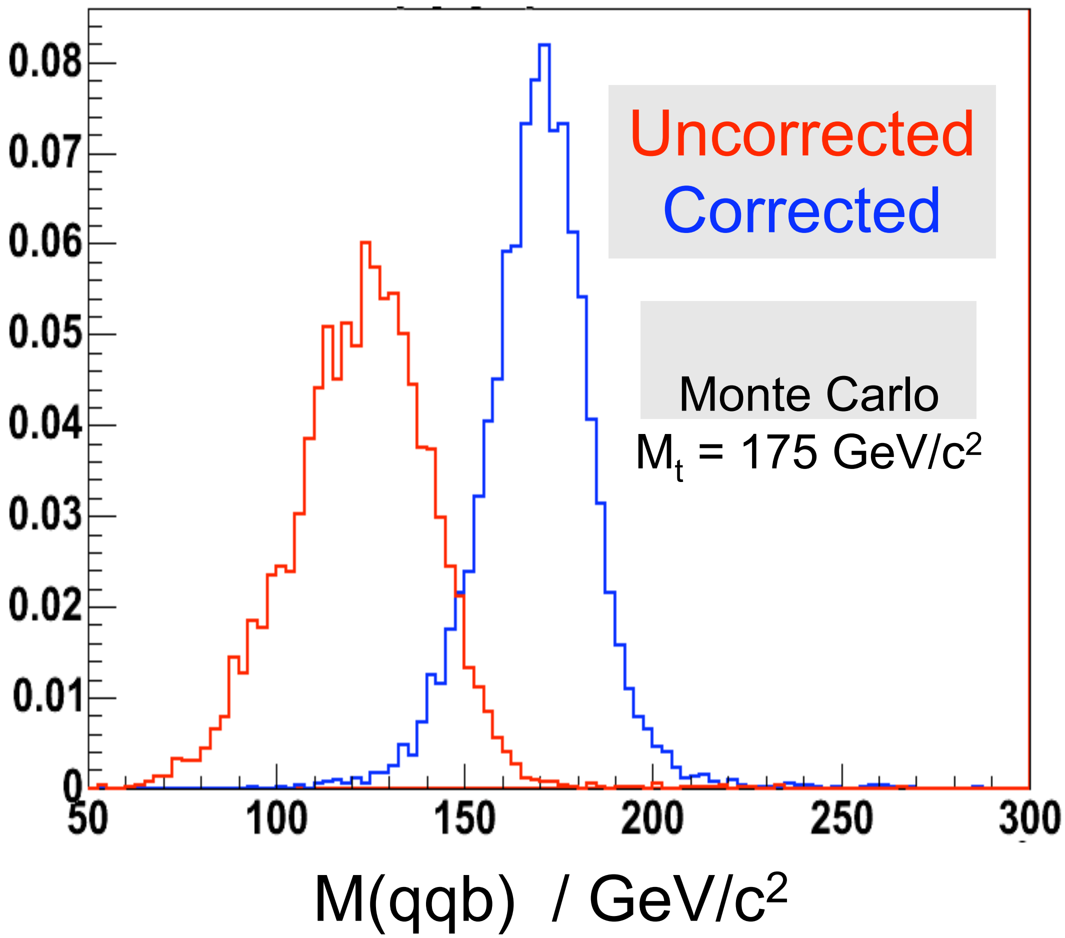
(from A. Höcker "Discovery Physics at the LHC", 5th Particle Physics Workshop, November 2006, Islamabad, Pakistan)

- The precise signatures of the SUSY "cascades" are driven by the masses of the SUSY particles
- To good generality we can expect:
  - High-p_T jets from squark & gluino decays
  - Leptons from gaugino & slepton decays
  - Missing energy from LSPs
- This lays out an **inclusive** search strategy
- Detector requirements:
  - Excellent jet-energy measurement
  - Excellent lepton identification
  - Hermeticity of the detector (good acceptance)

Measuring missing energy is a tough task !

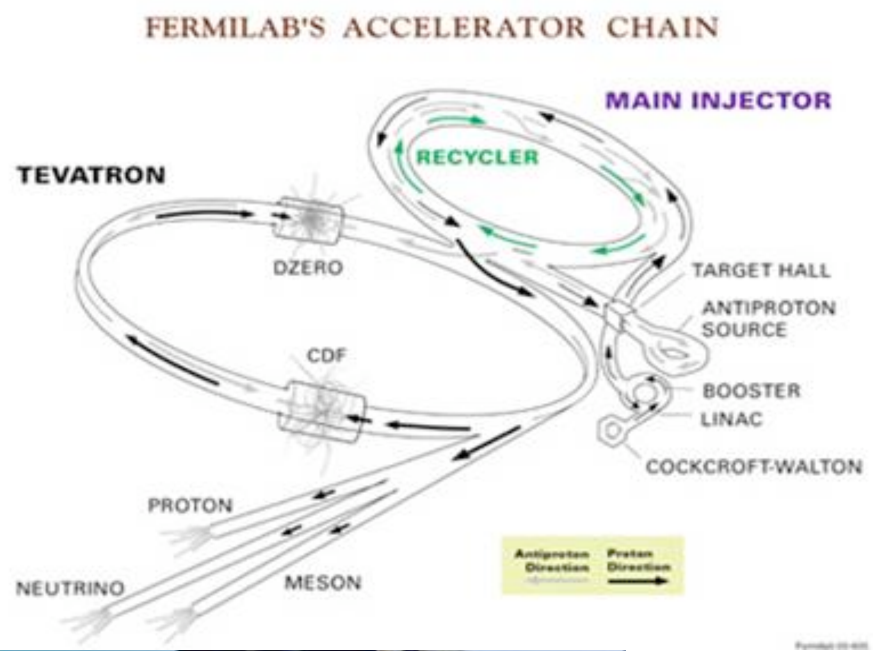


Jet energy scale <=> mass scale : NOT EASY



- hadronization, non-linearities, pile-up, multiple-interactions, underlying event
- From Data and MC
- known to ~3% for M_t jet energies (CDF)
- Leading Run I and Run II systematic error (CDF)

RUN-II AT TEVATRON



Fermi National Accelerator Laboratory

RUN-II AT TEVATRON
2001-?

New Main Injector ⇒ CM energy ($\sqrt{s}$) increased from 1800 GeV to 1960 GeV (tt cross section increases by ~35%)

Different beam crossing time (396 ns and 132 ns later (?), instead of 3.5 μs in Run-I) - fewer multiple interactions

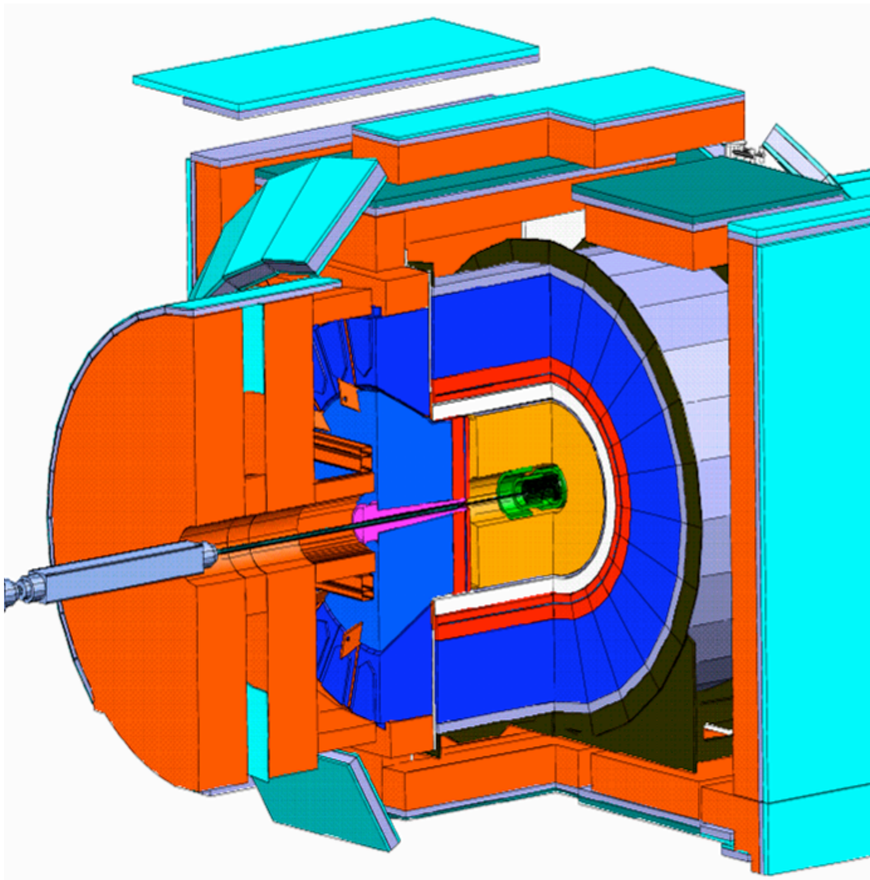
Significant upgrades to both detectors:

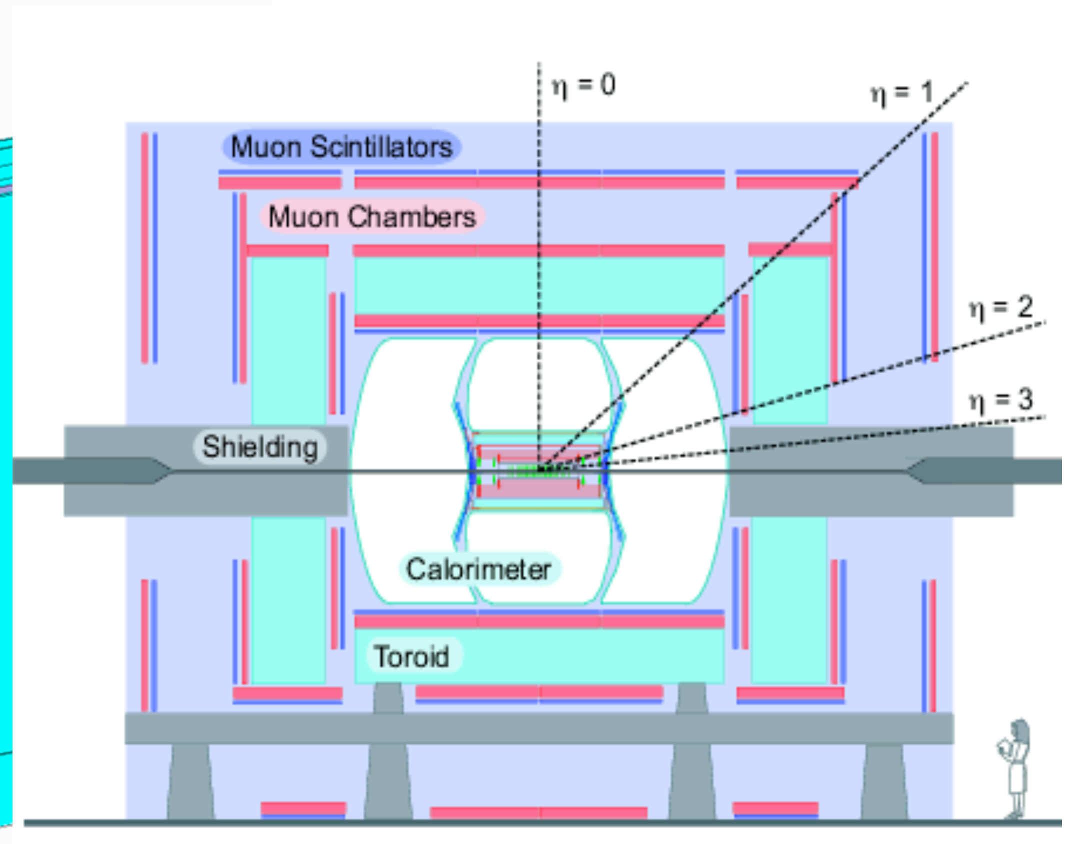
D0 : addition of SVX to allow better b-tagging
addition of a solenoid to allow track momentum reconstruction

CDF : new calorimeter for 1.1< $|\eta|$<3.5 (much better energy resolution)
new (longer) SVX with double the Run-I tagging efficiency

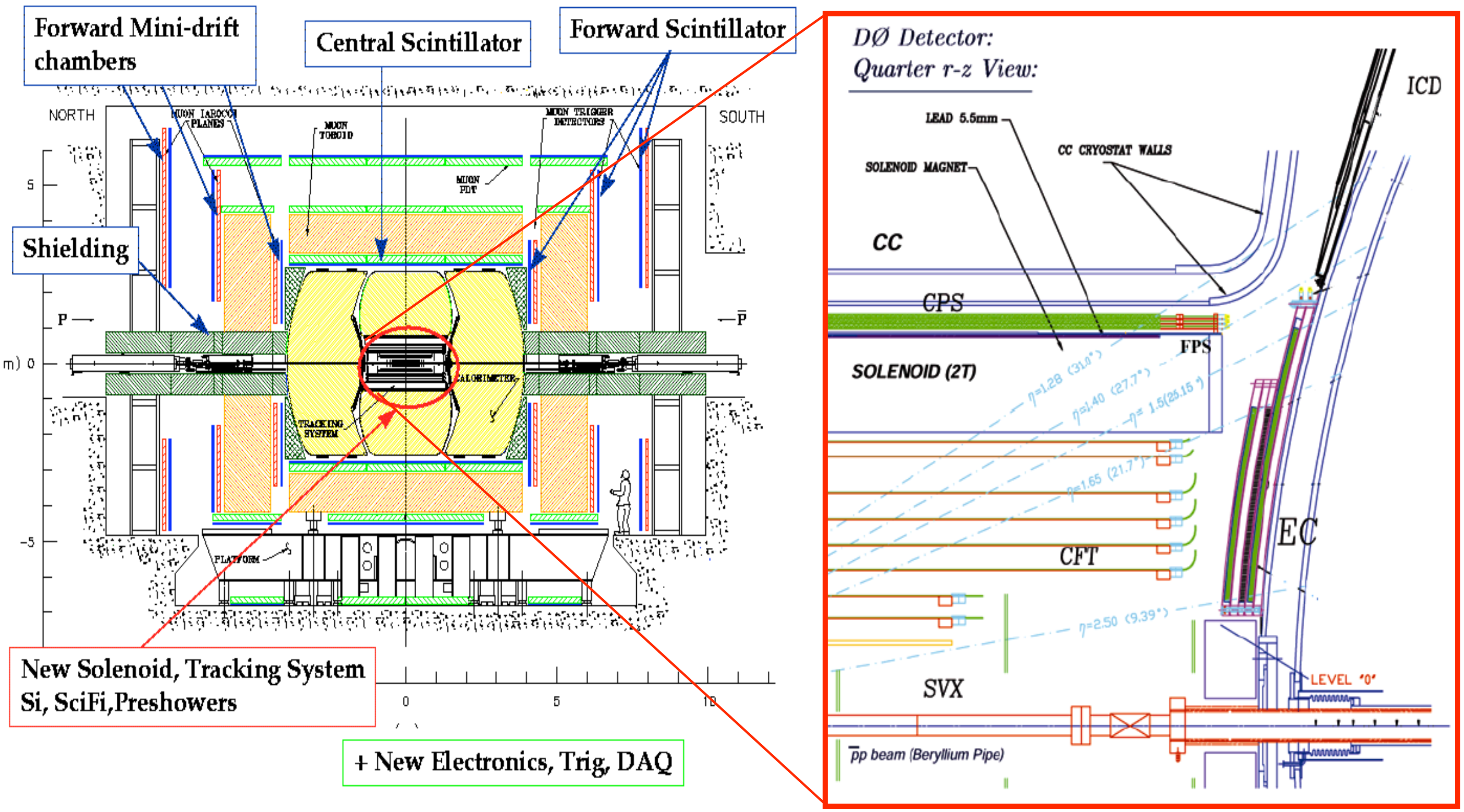
RUN-II AT TEVATRON 2001-?

- CDF and D0: well-understood, mature detectors with excellent particle identification, coverage, tracking and triggering



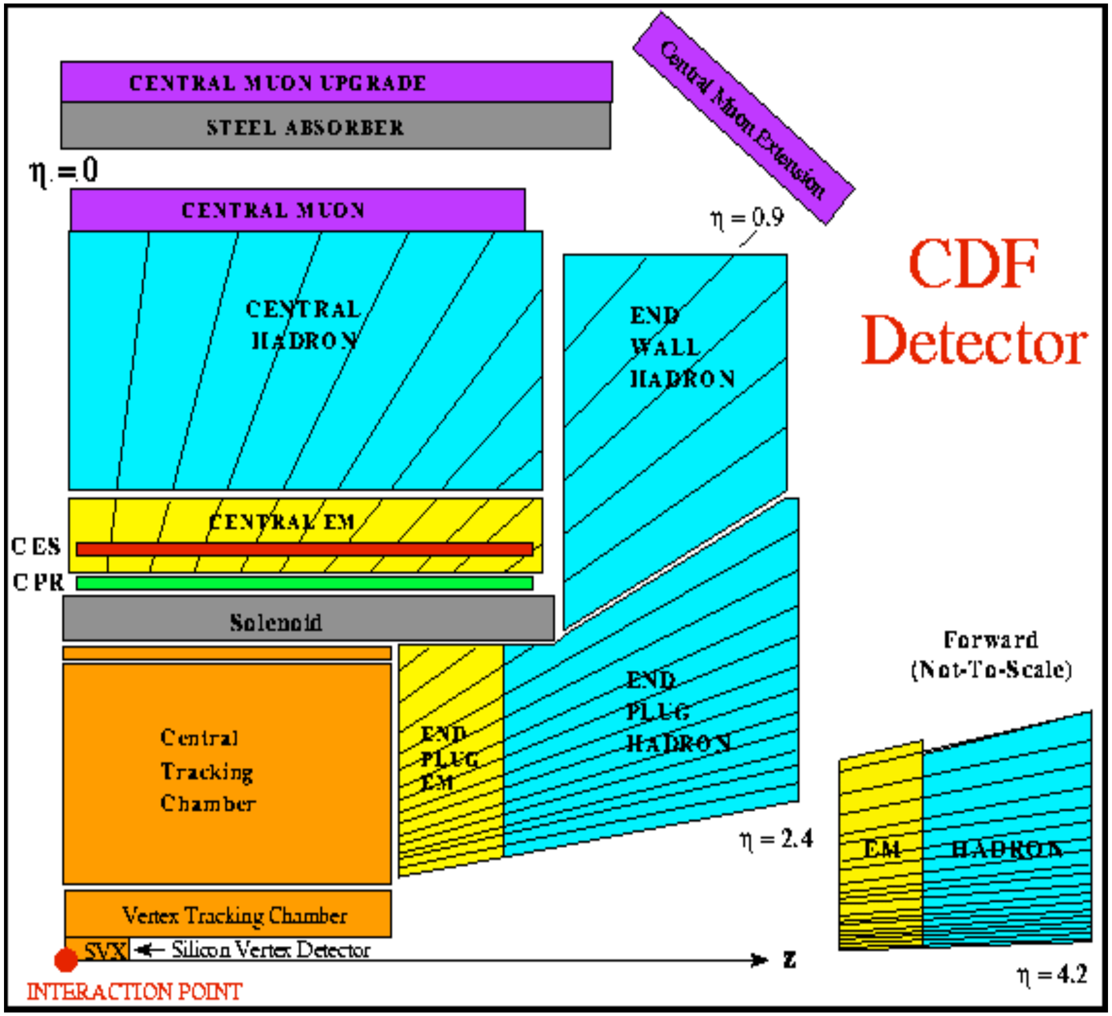


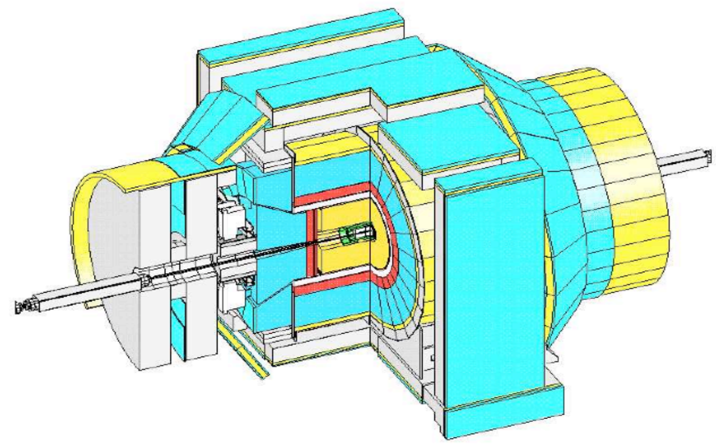
RUN-II AT TEVATRON 2001 - ?



D0 detector in its current configuration

RUN-II AT TEVATRON 2001 - ?

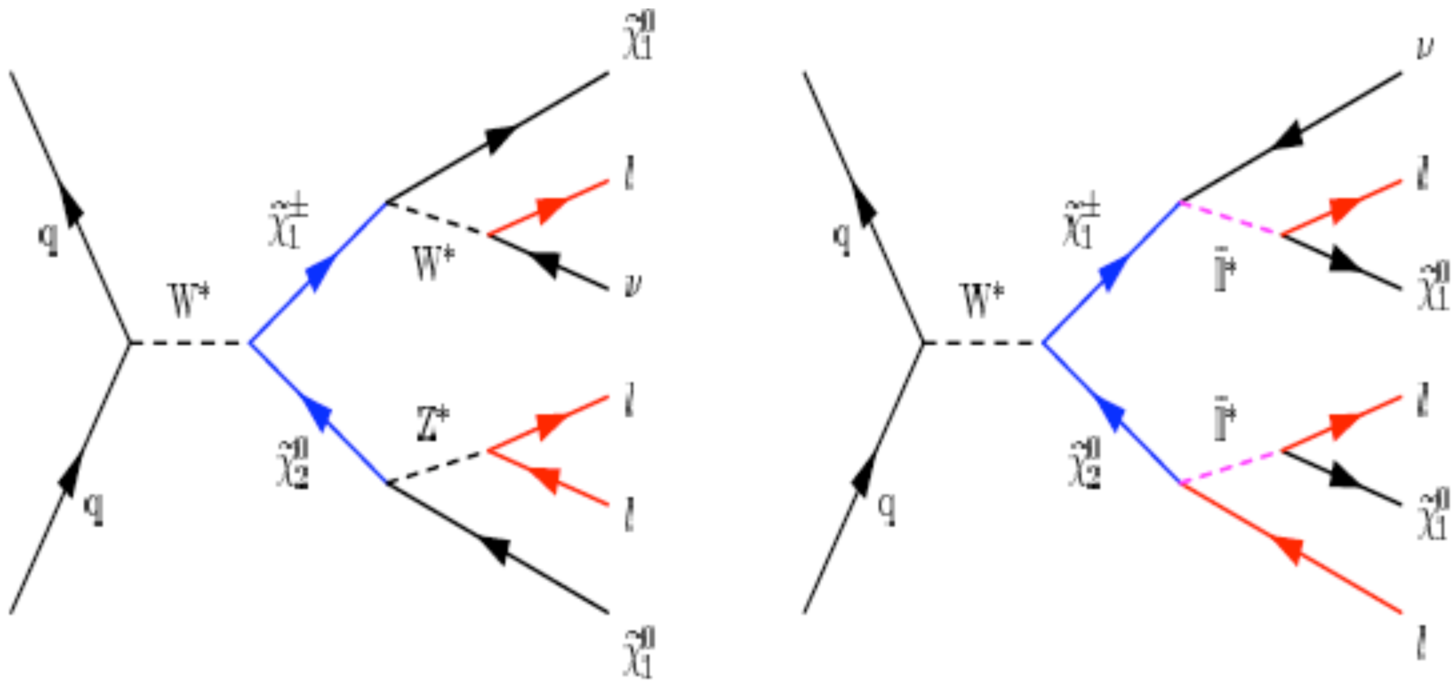




CDF detector in its current configuration

chargino-neutralino searches

$$\boxed{\widetilde{\chi}_2^0 \widetilde{\chi}_1^\pm \rightarrow l^\pm l^\mp l^\pm \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 X}$$



chargino-neutralino searches

$$\boxed{\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow l^\pm l^\mp l^\pm \tilde{\chi}_1^0 \tilde{\chi}_1^0 X}$$

- at Tevatron: look for lightest chargino, 2nd neutralino
- final state with many leptons, large E_T^{Miss} from LSP
- one of the SUSY "golden modes"
  - small SM backgrounds but small (EW) cross sections
  - striking signature

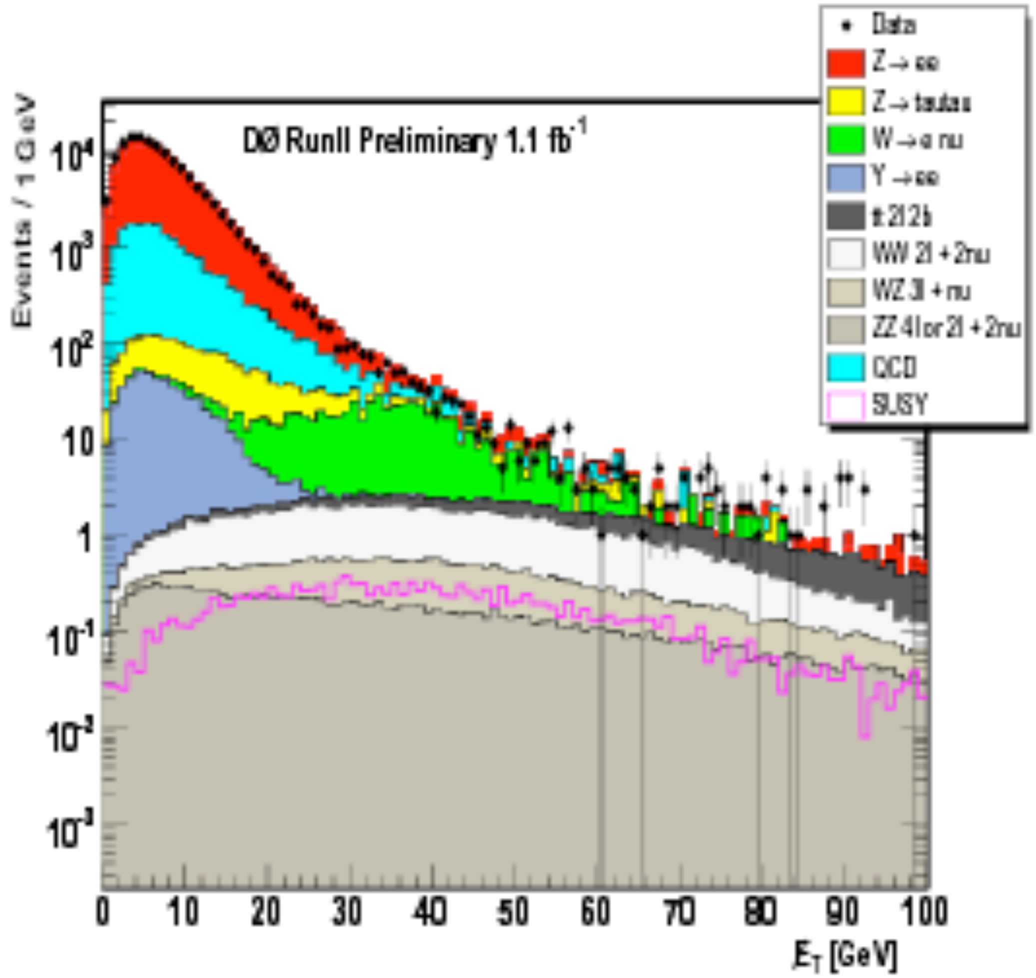
chargino-neutralino searches (D0)

In models with R_p:

3 leptons+E_T^{Miss}

- σxBR˜ 0.2 pb
- Very clean signature
- SM background very small

Selection	Bkgnd expected	data
ee+l (1.2)	0.82±0.66	0
eμ+l (0.3)	0.31±0.13	0
μμ+l (0.3)	1.75±0.57	2
μ±μ± (0.9)	1.1±0.4	1
eτ+l (0.3)	0.58±0.14	0
μτ+l (0.3)	0.36±0.13	1
SUM	5±1	4



chargino-neutralino searches (D0)

"3l-max"

-

Limits :

➡ $M(\chi^{\pm}{}_1) > 140\ GeV/c^2$

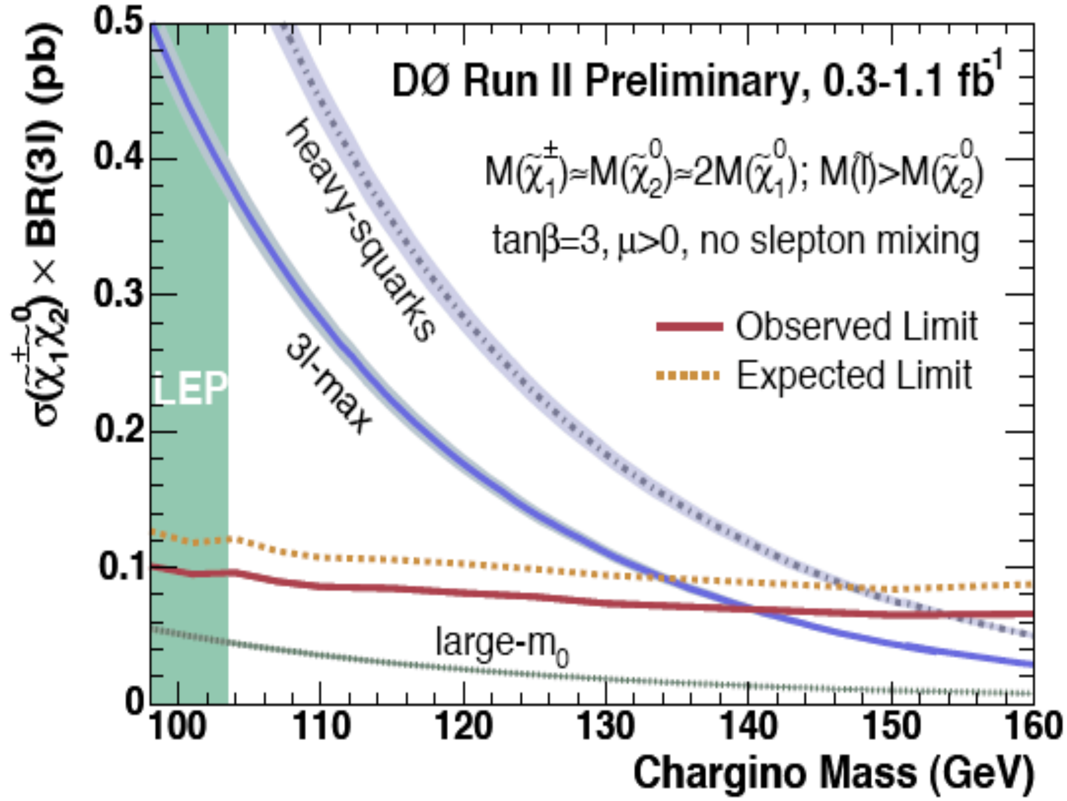
"Heavy Squarks"

-

➡ $M(\chi^{\pm}{}_1) > 155\ GeV/c^2$

"Large m_0"

- $M(\sim l) >> M(\chi^0{}_2, \chi^{\pm})$
  - No sensitivity due to smaller leptonic BR's

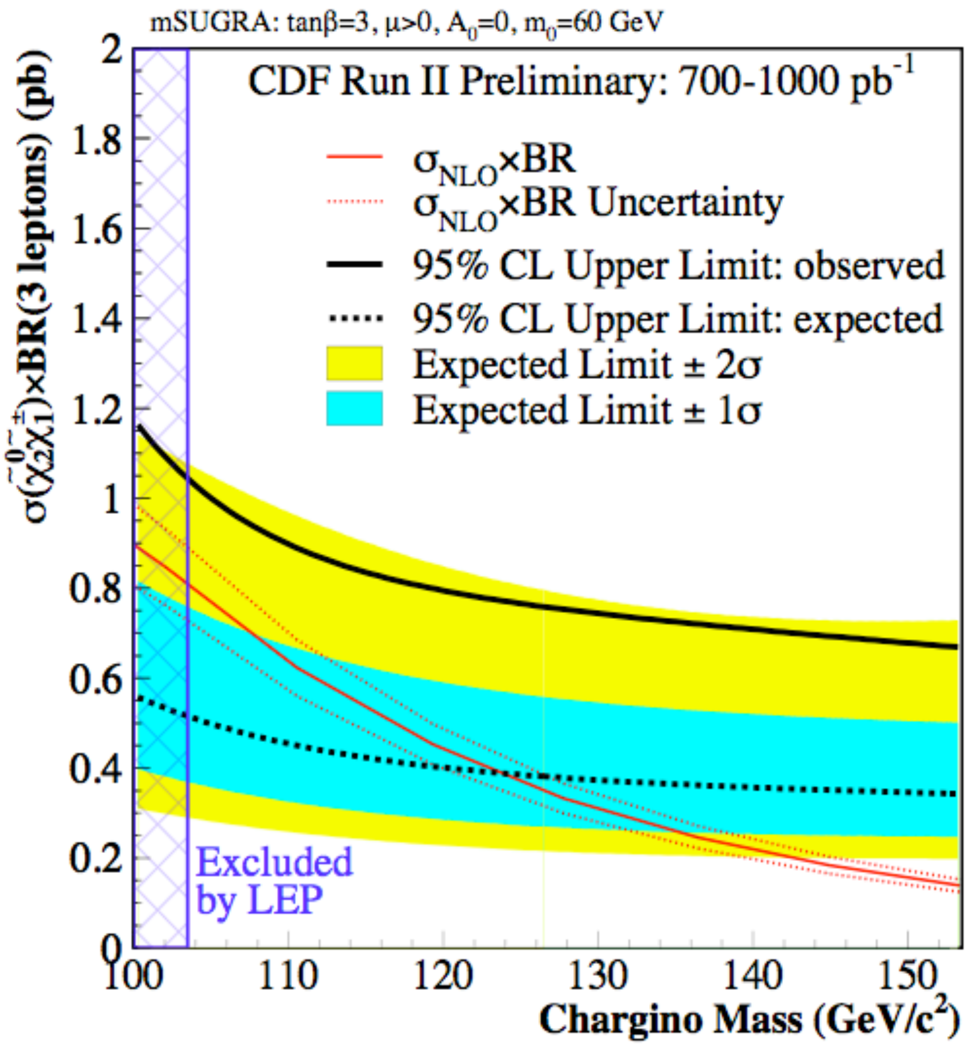


chargino-neutralino searches (CDF)

In models with R_p:

3 leptons+E_T^{Miss}

Selection	Bkgnd expected	data
2 lep (.71)	6.8±1.0	9
μμ+e/μ low pt(0.3)	0.13±0.03	0
μμ+e/μ (0.75)	0.64±0.18	1
ee+e/μ (0.4)	0.17±0.05	0
ee+tr (0.6)	0.48±0.07	1
eμ +e/μ (0.75)	0.78±0.15	0



chargino-neutralino searches (CDF)

SELECTION:

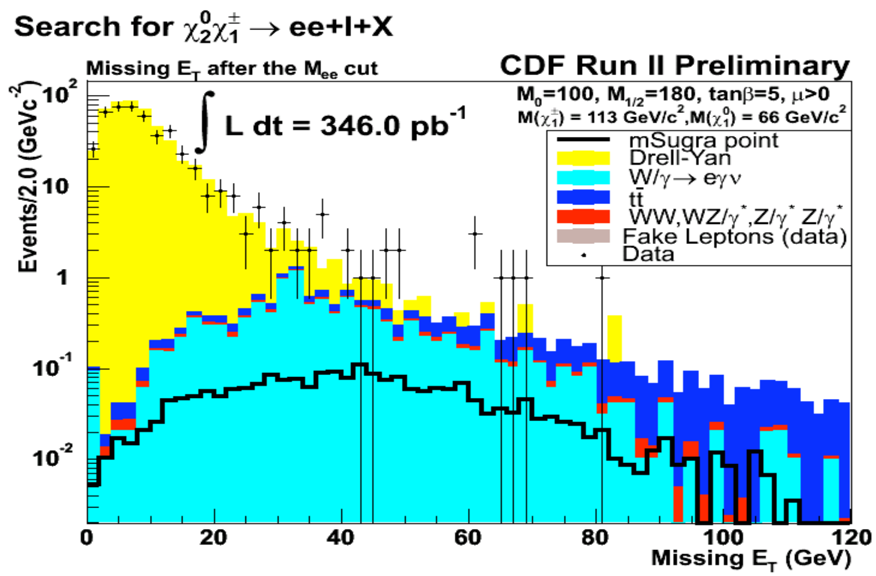
2 <u>electrons</u>+ $\ell(\ell$=e,μ) $|\eta|<1$

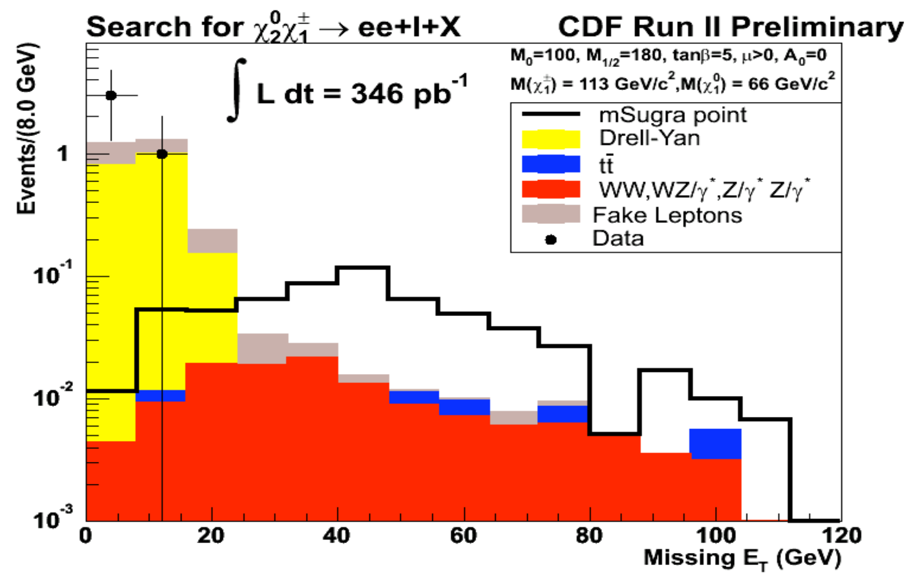
large $E_T^{Miss}>15$ GeV/c²

$15<M_{ll}<76, >106$ GeV/c²
$|\Delta\phi|<160$

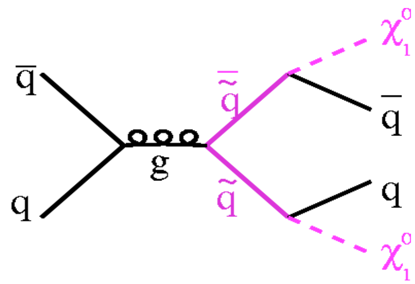
Njets(20 GeV) <2

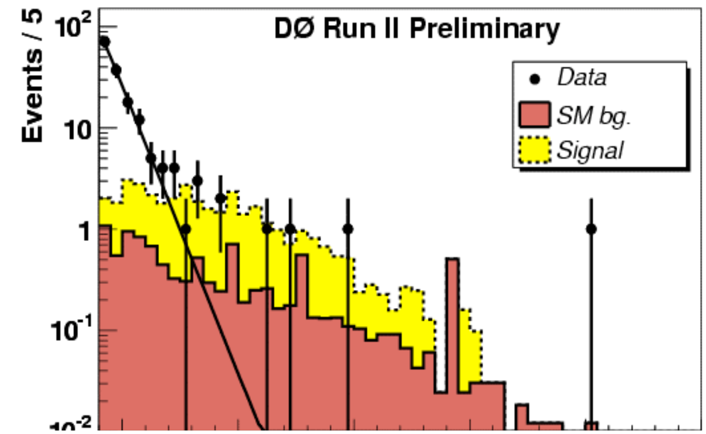
Process	
mSugra eeℓ	0.5
Bkgnd Expected	0.16±0.07
OBSERVED	0



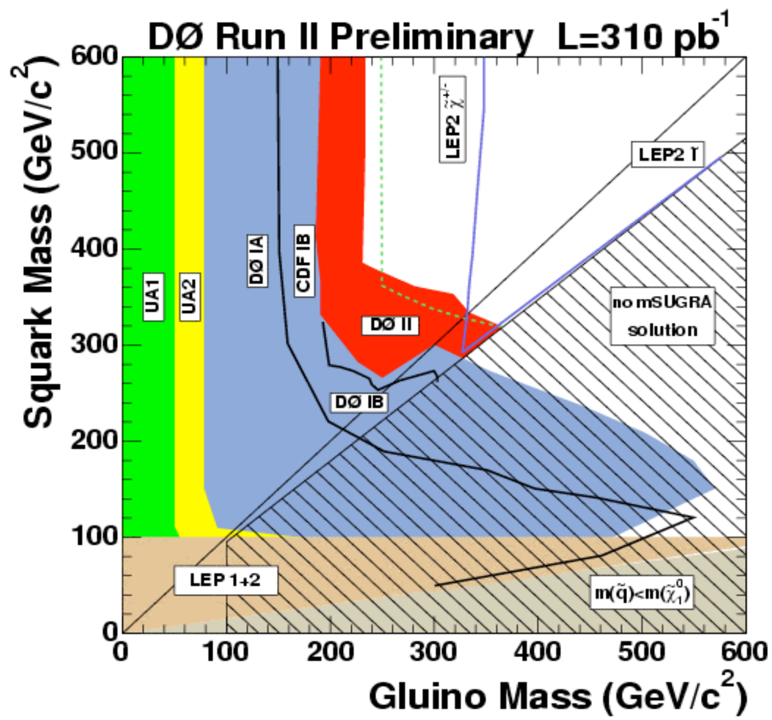


chargino-neutralino searches (D0)





#jets(P_T (GeV))	$\sum P_t^{jet}$	E_T^{Miss}	Bkgd Expected	data
2 jets(60,50)	250 GeV	175 GeV	12.8±5.4	12
3 jets(60,40,25)	325 GeV	100 GeV	6.1±3.1	5
4 jets(60,40,30,25)	175 GeV	75 GeV	9.3±0.5	10



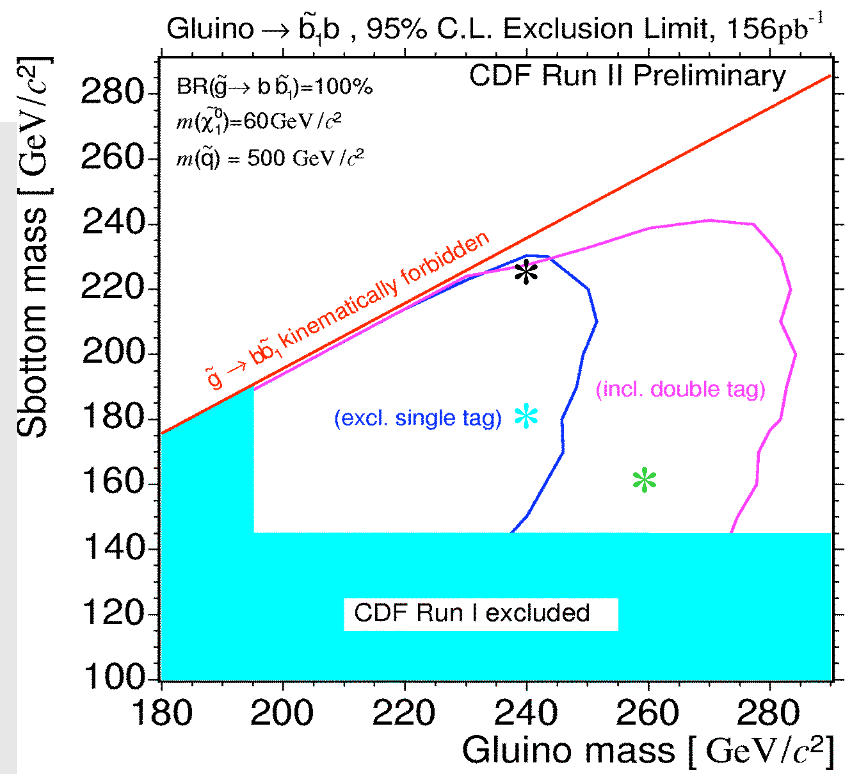
Limits ($\tan\beta=3$, $A_0=0$, $\mu<0$, $\tilde{q}=\tilde{u},\tilde{d},\tilde{c},\tilde{s},\tilde{b}$):

- 2j : $M_0=25$ GeV → $M(\tilde{q}) > 318$ GeV/c^2
- 3j : $M(\tilde{g})=M(\tilde{q})$ → $M(\tilde{q}) > 333$ GeV/c^2
- 4j : $M_0=500$ GeV→ $M(\tilde{g}) > 233$ GeV/c^2

gluino-sbottom searches (CDF)

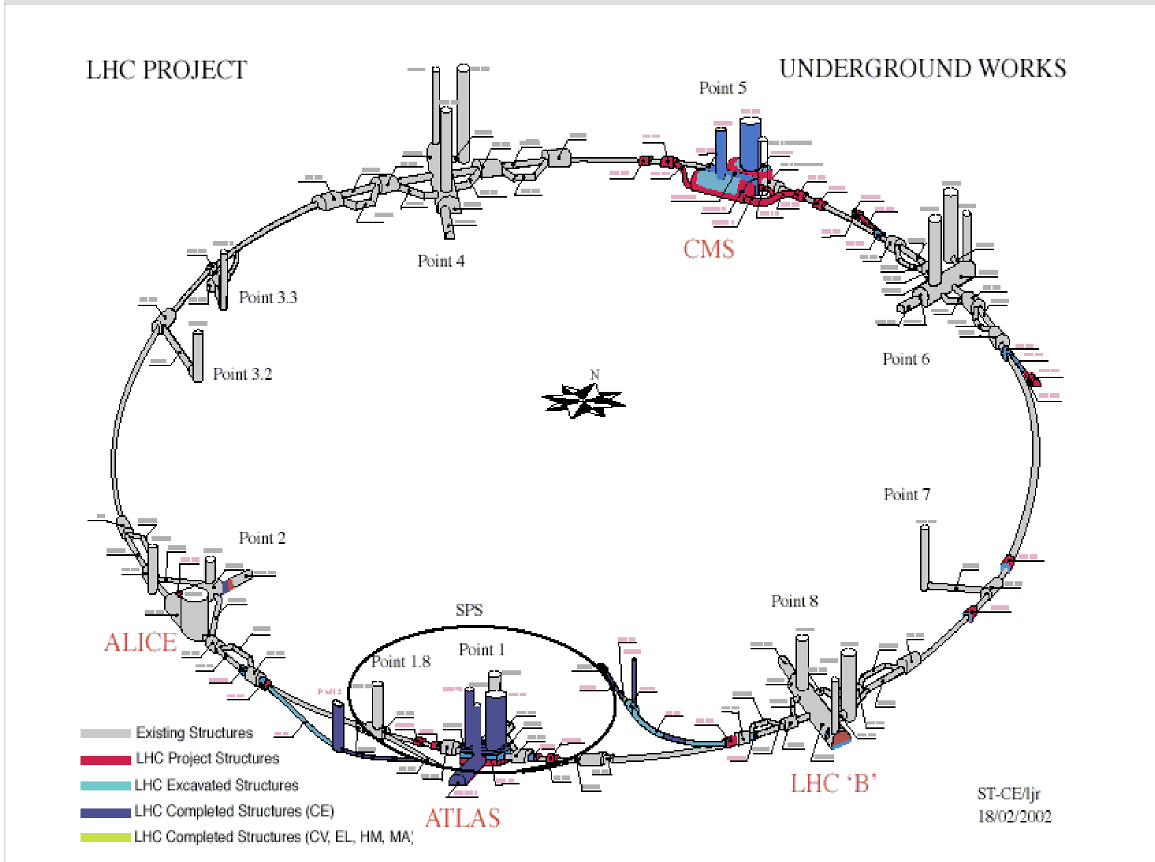
$$\tilde{g}\tilde{g} \rightarrow \tilde{b}_1 \bar{\tilde{b}}_1 b\bar{b} \rightarrow b\bar{b}b\bar{b}\,\tilde{\chi}_1^0 \tilde{\chi}_1^0$$

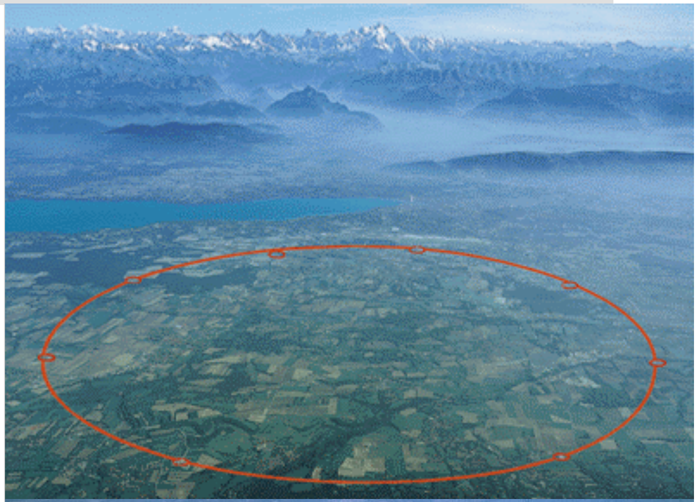
- striking signature: four b's in final state + large E_T^{Miss}.
- identify b quark jets to reduce dijet backgrounds
  - use displaced tracks to tag
- efficiency of b-taggging depends on
  - m(gluino) – m(sbottom)
- set limits as function of m_{gluino}, $m_{sbottom}$



n_{tag}	background	observed
=1	16.4 ± 3.7	21
>=2	2.6 ± 0.7	4

LHC at CERN: SUSY particles factory?



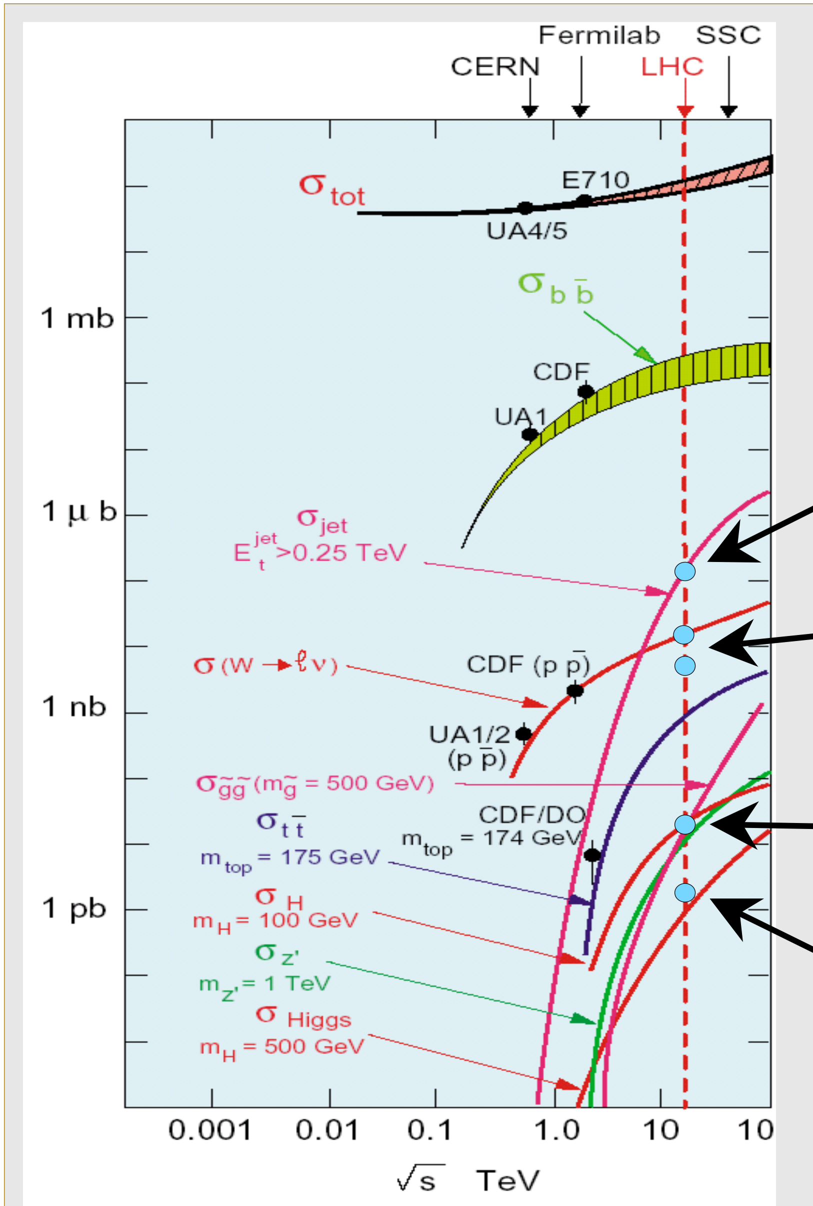


	$\sqrt{s}$ [TeV]	Luminosity [cm^{-2}s^{-1}]	$\int Ldt$ [fb^{-1}/y]
Tevatron	**2**	**$<10^{32}$**	**0.3**
LHC (low lum)	**14**	**10^{33}**	**10**
LHC (high lum)	**14**	**10^{34}**	**100**

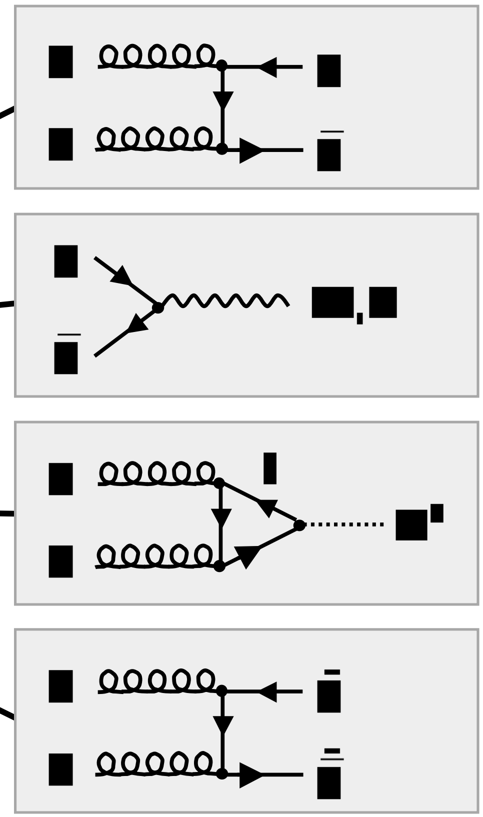
Data in 2008?

LHC at CERN: SUSY particles factory?

SUSY Production at LHC



At LHC, the total event rate is dominated by huge QCD cross section



High-p_T QCD jets

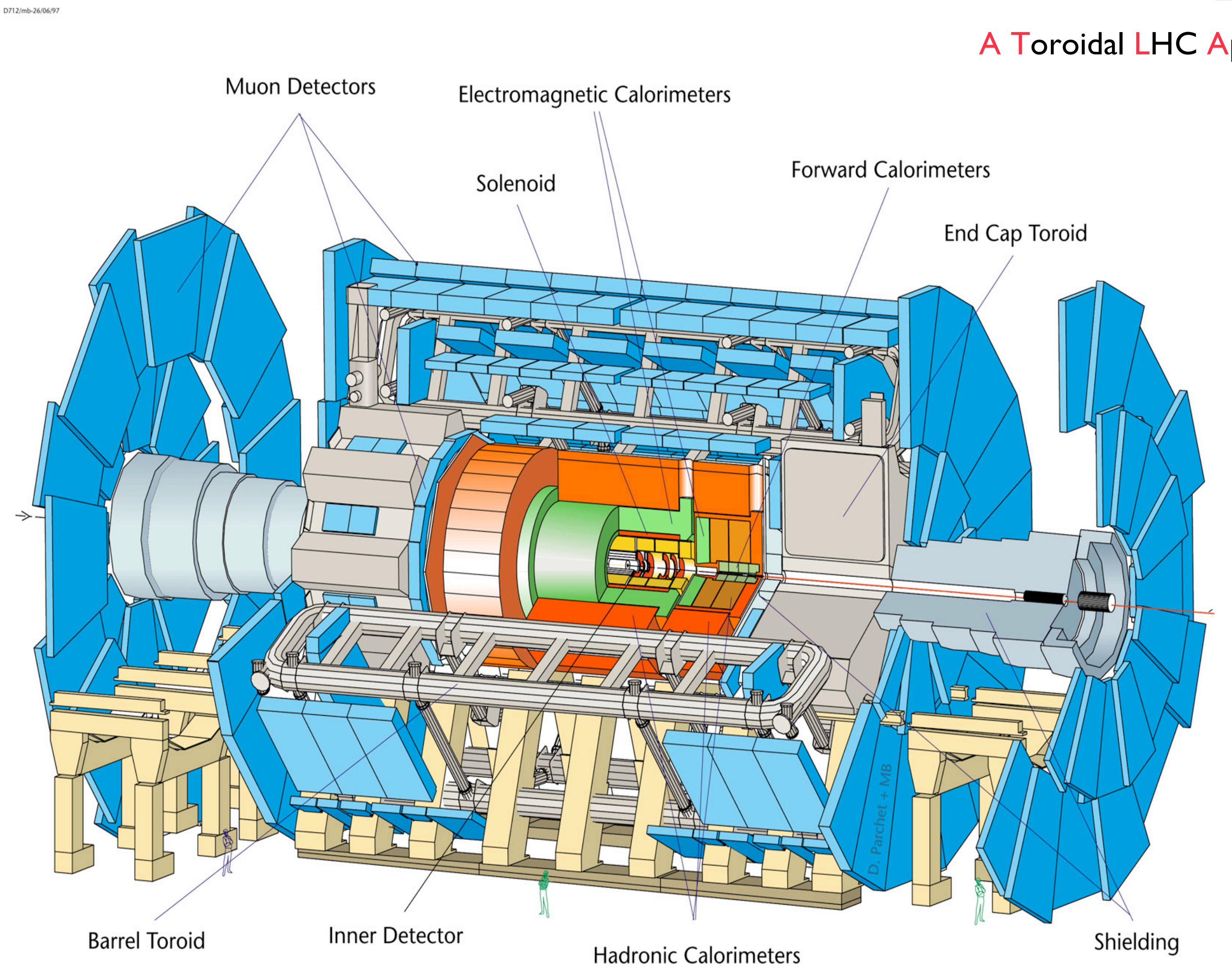
W, *Z* production

gluon-to-Higgs fusion

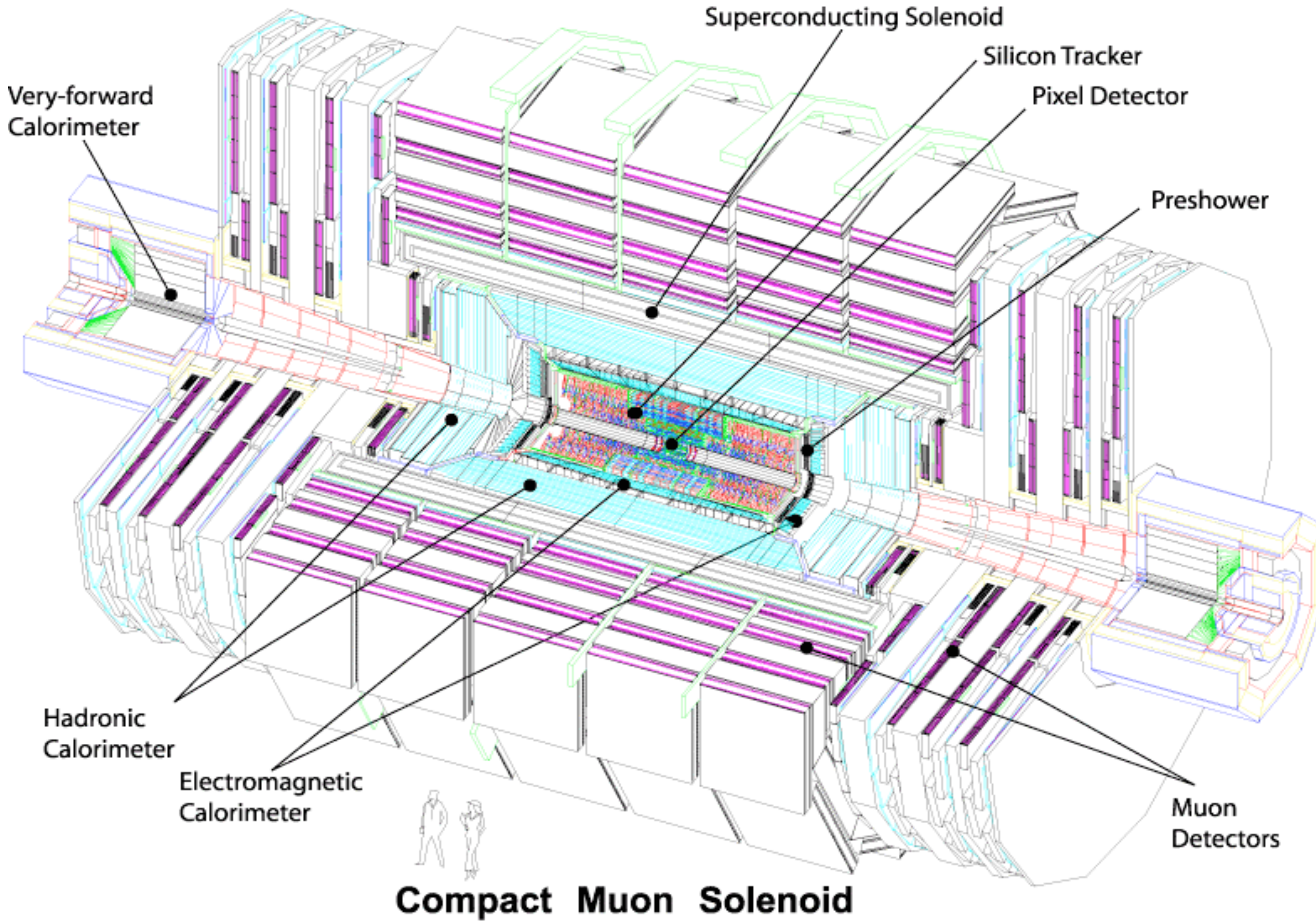
squarks, gluinos
(m ~ 1 TeV)

Future: SUSY at LHC

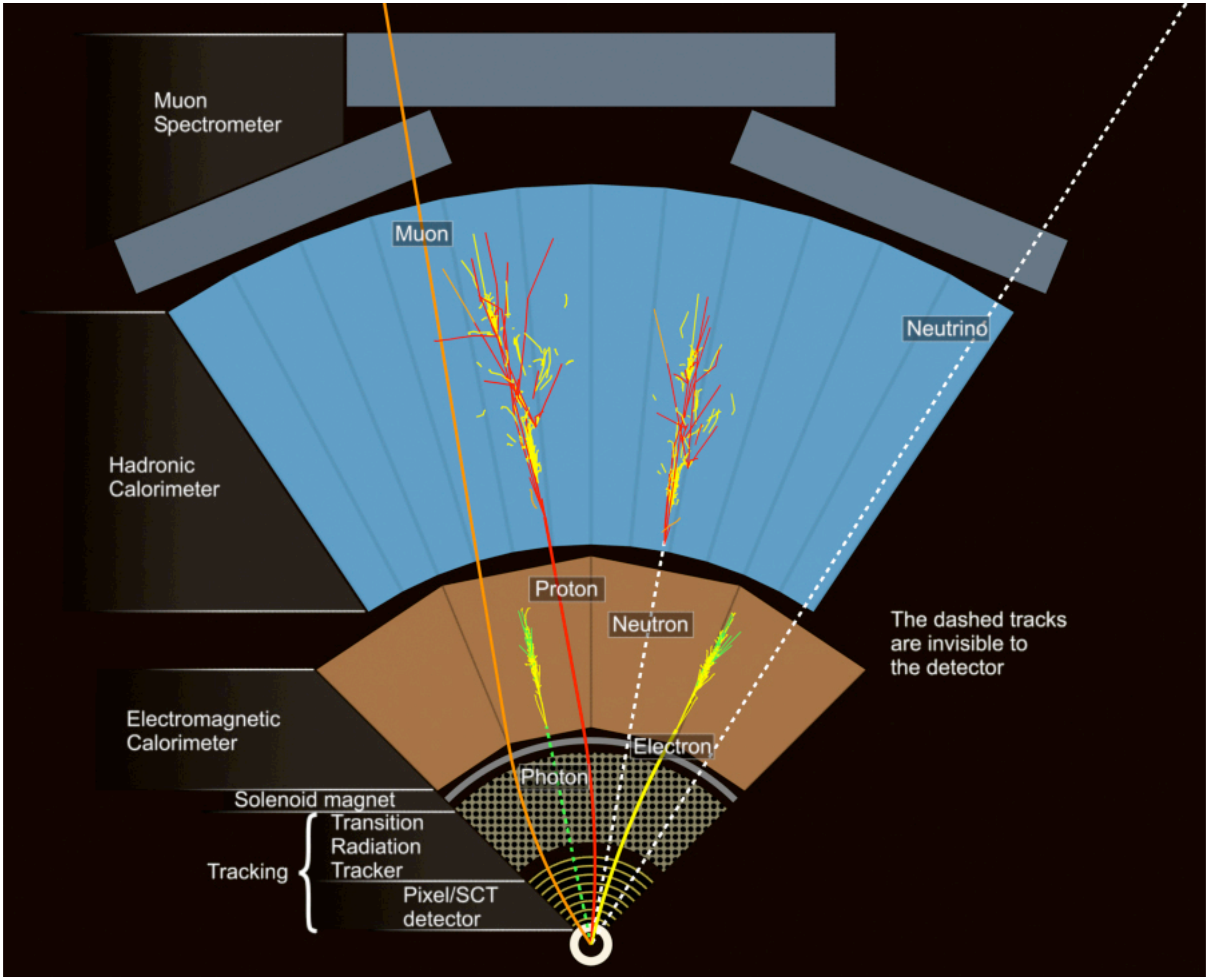
A Toroidal LHC ApparatuS



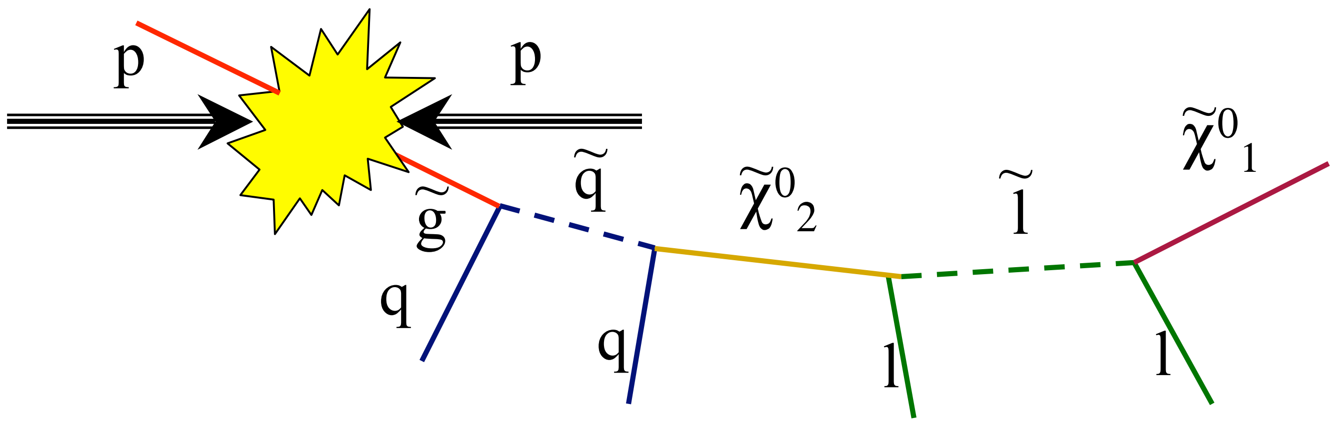
Future: SUSY at LHC



Particle Identification (example: ATLAS)



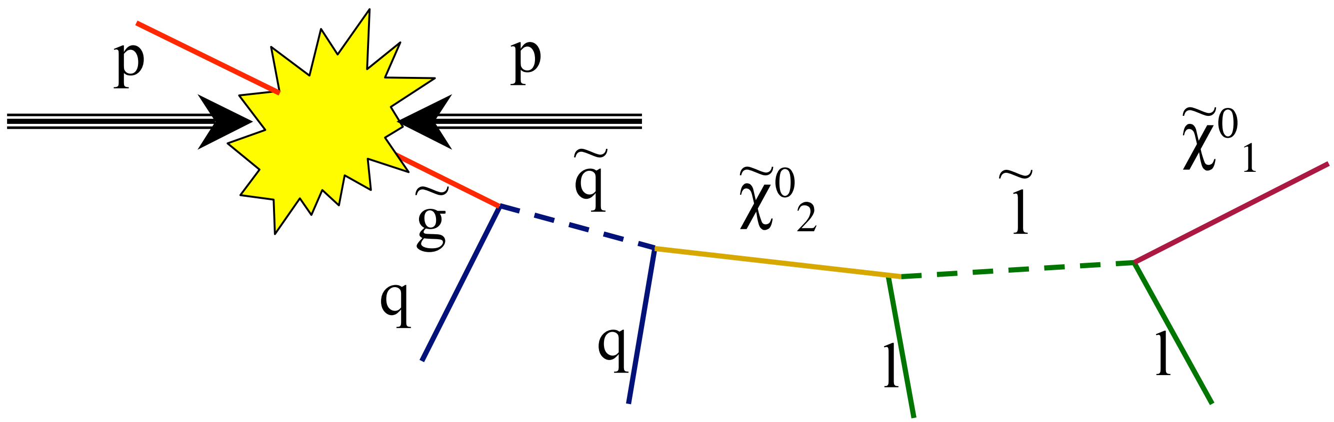
SUSY signatures at LHC



- Heavy gluinos and squarks (strongly interacting particles) produced in initial interaction
- Long decay chains and large mass differences between SUSY states; many high P_T objects are observed (lepton, jets, b-jets)

- If the model is mSUGRA R-Parity is conserved, lighest SUSY particle (LSP) is a stable neutralino, cascade decays lead to stable undetected LSP => large E_T^{miss} signatures (also DARK MATTER candidate)

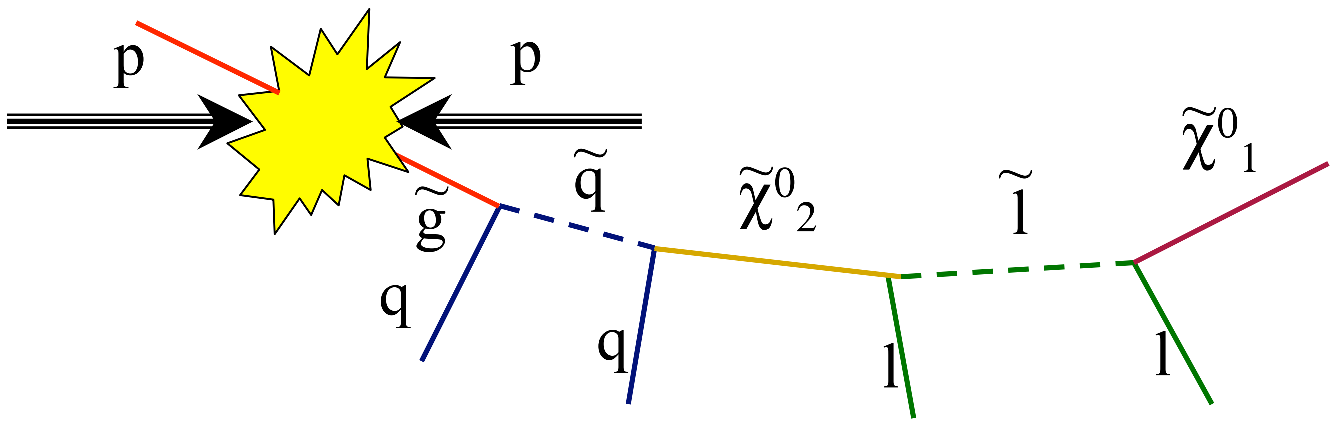
SUSY signatures at LHC



- Heavy gluinos and squarks (strongly interacting particles) produced in initial interaction
- Long decay chains and large mass differences between SUSY states; many high P_T objects are observed (lepton, jets, b-jets)

- If the model is GMSB, LSP is gravitino. Additional signatures from NLSP (next-to-lightest SUSY particle) decays; for example photons (neutralino decays into photon and gravitino) and leptons from slepton decays (from neutralino decaying into lepton and gravitino)

SUSY signatures at LHC

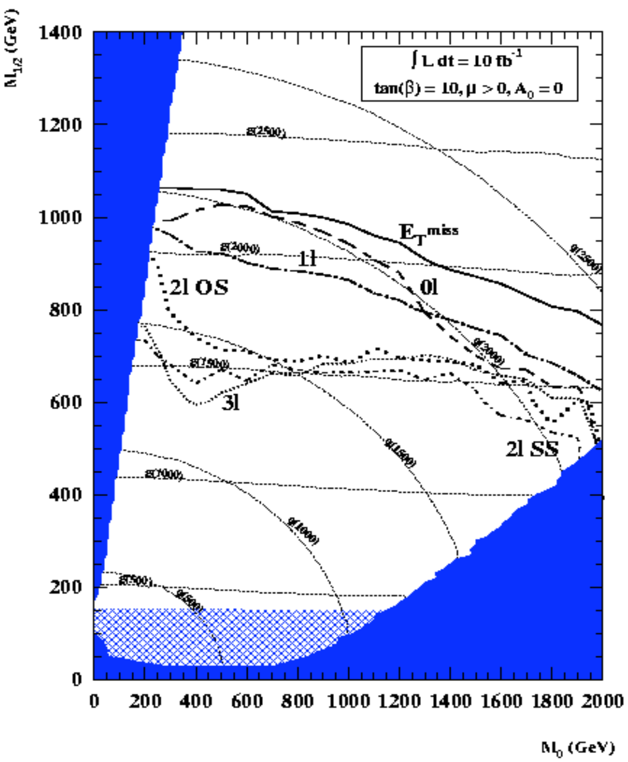


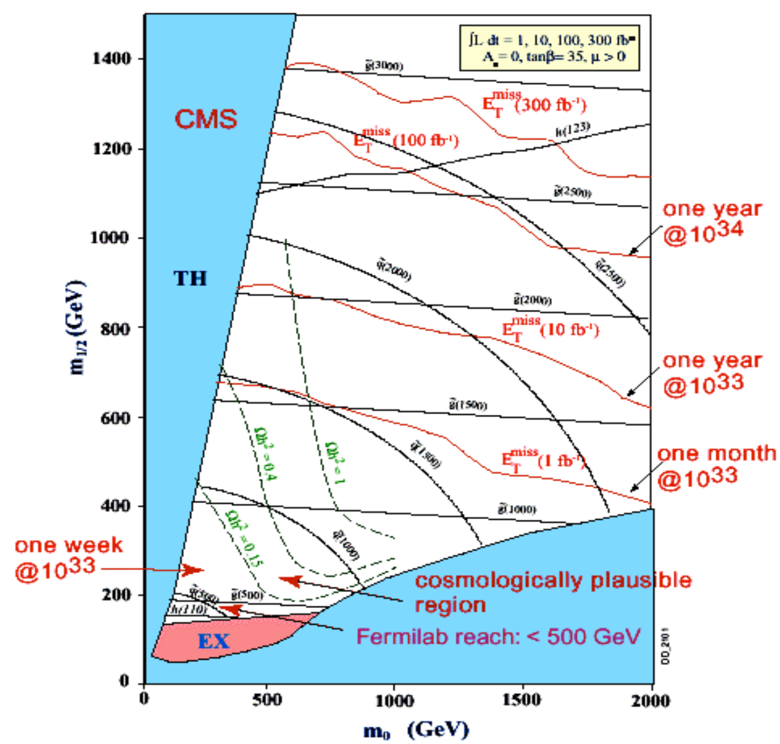
- Heavy gluinos and squarks (strongly interacting particles) produced in initial interaction
- Long decay chains and large mass differences between SUSY states; many high P_T objects are observed (lepton, jets, b-jets)

- If R-parity is not conserved LSP decays to 3-leptons, 2leptons+1jet, 3 jets; E_T^{miss} signature is lost

mSUGRA

- mSUGRA framework: five free parameters: m_0, $m_{1/2}$, A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$
- sensitivity only weakly dependent on A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$
- multiple signatures on most of parameter space: E_T^{miss} (dominant signature), E_T^{miss} with lepton veto, one lepton, two leptons same sign (SS), two leptons opposite sign (OS)





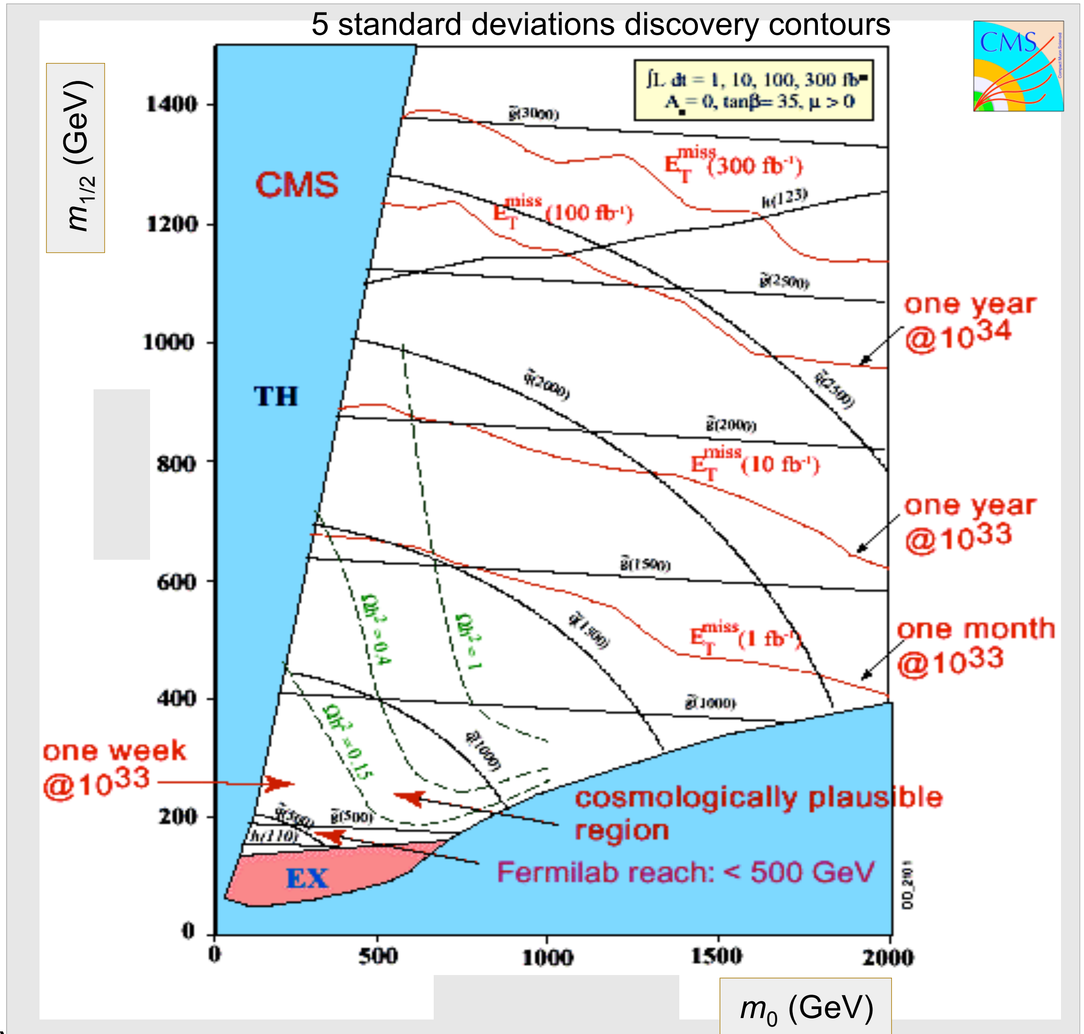
Squarks and Gluinos: Reach of the LHC

- Current limit on squark and gluino masses from the **TEVATRON** experiments (example: D0)

- Experiments evaluate their SUSY discovery potential using some “standard” mSUGRA setup

5σ discovery reach for SUSY:

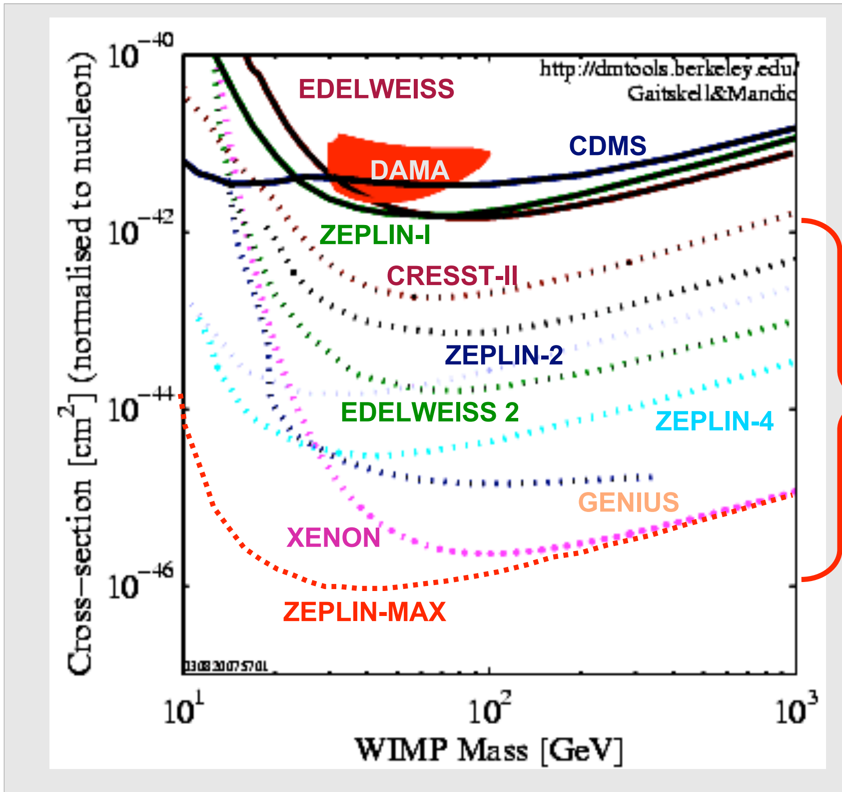
Time period	Luminosity [$cm^{-2}s^{-1}$]	squark/gluino masses
1 month	10^{33}	~1.3 TeV
1 year	10^{33}	~1.8 TeV
1 year	10^{34}	~2.5 TeV
Ultimate	$\int$ = 300 fb^{-1}	~2.5–3 TeV
D0 & CDF	$\int$ = 0.3 fb^{-1}	$>_{(2\sigma)}$ 0.35 TeV



Comparison with Direct Dark Matter Searches

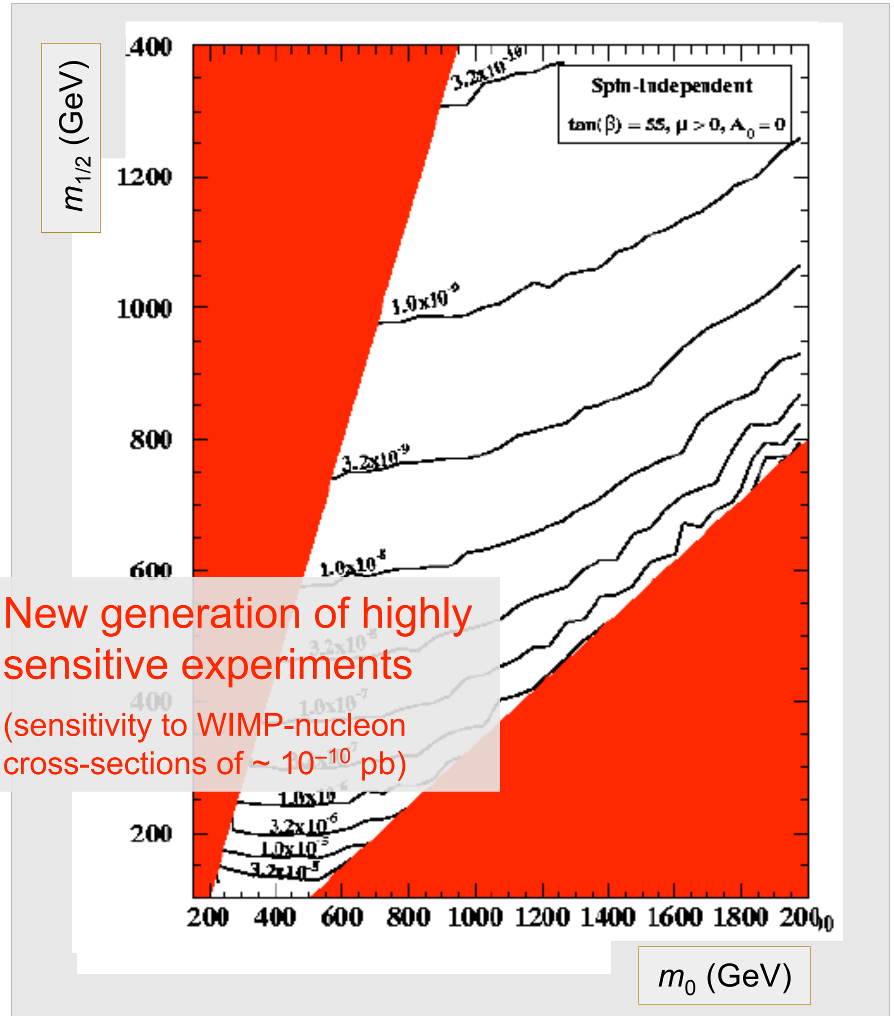
- Not mentioned so far: there exist direct searches for WIMP's through elastic scattering between cosmic WIMP (*e.g.*, a neutralino) and nucleus, generating a recoil of the nucleus

- Complementary sensitivity to mSUGRA masses, in particular for large tanβ values



New generation of highly sensitive experiments

(sensitivity to WIMP-nucleon cross-sections of ~ 10^{-10} pb)



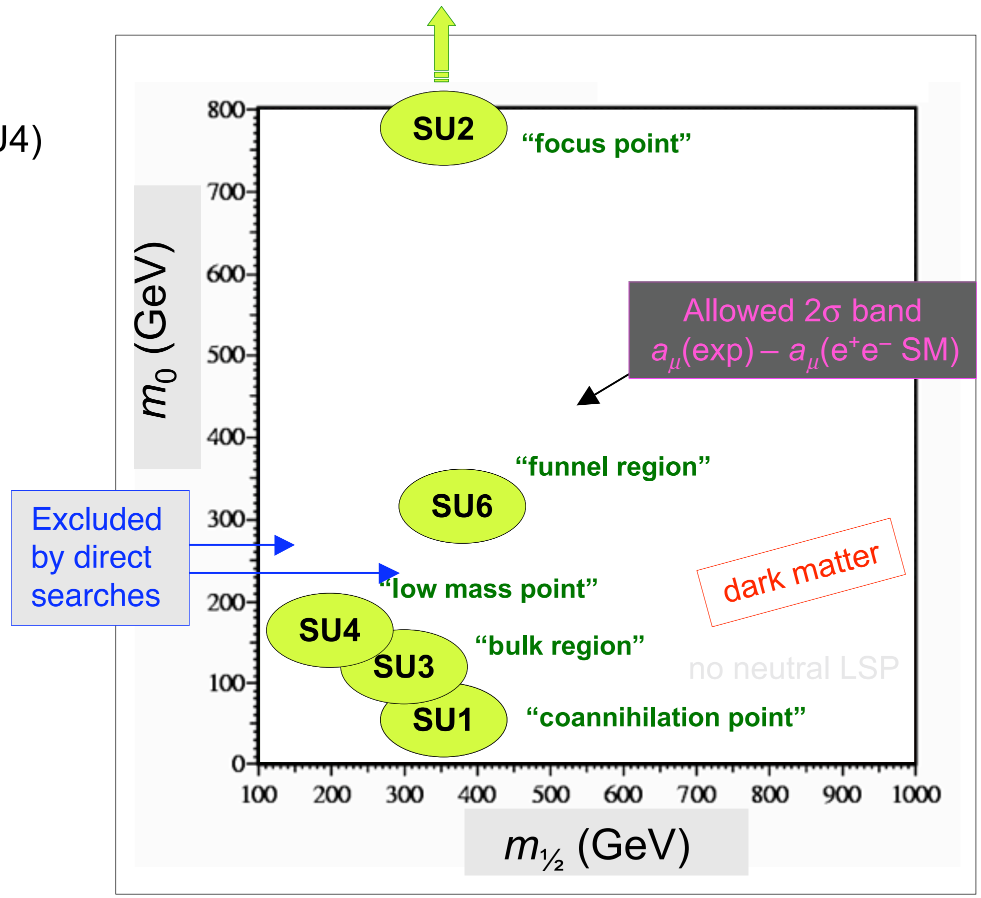
Inclusive SUSY Searches

(from A. Höcker "Discovery Physics at the LHC", 5th Particle Physics Workshop, November 2006, Islamabad, Pakistan)

- SUSY searches are prepared by studying simulated data ("Monte Carlo"): since SUSY parameters are unknown, simplify the task by choosing "minimal SUGRA" scenarios

- Choose a few "characteristic" points
  - At the limit of experimental exclusion (SU4)
  - "Typical" point (SU3)
  - Special-feature points (SU1, SU2, SU6)

- Since mSUGRA has only 5 parameters, it is highly constraining …and can quite well be constrained from data already !
  - From direct accelerator searches
  - From indirect accelerator searches
  - From cosmology



mSUGRA: selected points

- DC1 bulk region point (new underlying event in generation)
  - m_0 =100 GeV, $m_{1/2}$ = 300 GeV, A_0 = -300 GeV, tanβ = 6, sgn(μ) = +
  - LSP is mostly bino, light l_R enhance annihilation. 'Bread and butter' region for the LHC experiments
  - llq distributions, tau-tau measurements, third generation squarks (both tau identification and B tagging improved)
- Coannihilation point
  - m_0 =70 GeV, $m_{1/2}$ = 350 GeV, A_0 = 0 GeV, tanβ = 10, sgn(μ) = +
  - LSP is pure bino. LSP/sparticle coannihilation. Small slepton-LSP mass difference gives soft leptons in the final state
- Focus point
  - m_0 = 3350 GeV, $m_{1/2}$ = 300 GeV, A_0 = 0 GeV, tanβ = 10, sgn(μ) = +
  - LSP is Higgsino, near μ^2=0 bound. Heavy sfermions; all squarks and sleptons have mass >2 TeV, negligible FCNC, CP, g_μ-2, etc. Complex events with lots of heavy flavor
- Funnel region point
  - m_0 = 320 GeV, $m_{1/2}$ = 375 GeV, A_0 = 0 GeV, tanβ = 50, sgn(μ) = +
  - wide H, A for tanβ >> 1 enhance annihilation. Heavy Higgs resonance (funnel); main annihilation chain into bb pairs
  - dominant tau decays
- Low mass point at limit of Tevatron RunII reach
  - m_0 = 200 GeV, $m_{1/2}$ = 160 GeV, A_0 = -400 GeV, tanβ = 10, sgn(μ) = +
  - big cross section, but events rather similar to top
  - measure SM processes in presence of SUSY background to show detector is understood

mSUGRA points

The following points in the mSUGRA space have been selected for analysis with the full ATLAS detector simulation (GEANT4).

	M_0 (GeV)	$M_{1/2}$(GeV)	A_0	tanβ	sgn(μ)	m_{top} (GeV)
Coannihilation	70	350	0	10	+	175
Focus point	3550	300	0	10	+	175
Funnel region	320	375	0	50	+	175
Bulk (ATL-PHYS-2004-011)	100	300	-300	6	+	175
Scan	130-6000	600,1000	0	10	+	175
low mass point	200	160	-400	10	+	175

Events generated with HERWIG 6.505 (+JIMMY).
SUSY spectra obtained with ISAJET7.71

All results shown in this talk are obtained from new full simulation data!

SPS1a Point

- **mSUGRA fundamental parameters :**

$m_0 = 100$ GeV, $m_{1/2} = 250$ GeV,

$\tan\beta = 10,\ A = -100$ GeV, $\mu > 0$

- **Main branching ratios :**

BR($\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau$)=87%

BR($\tilde{\chi}_2^0 \to \tilde{\ell}_R\ell$)=12.6%

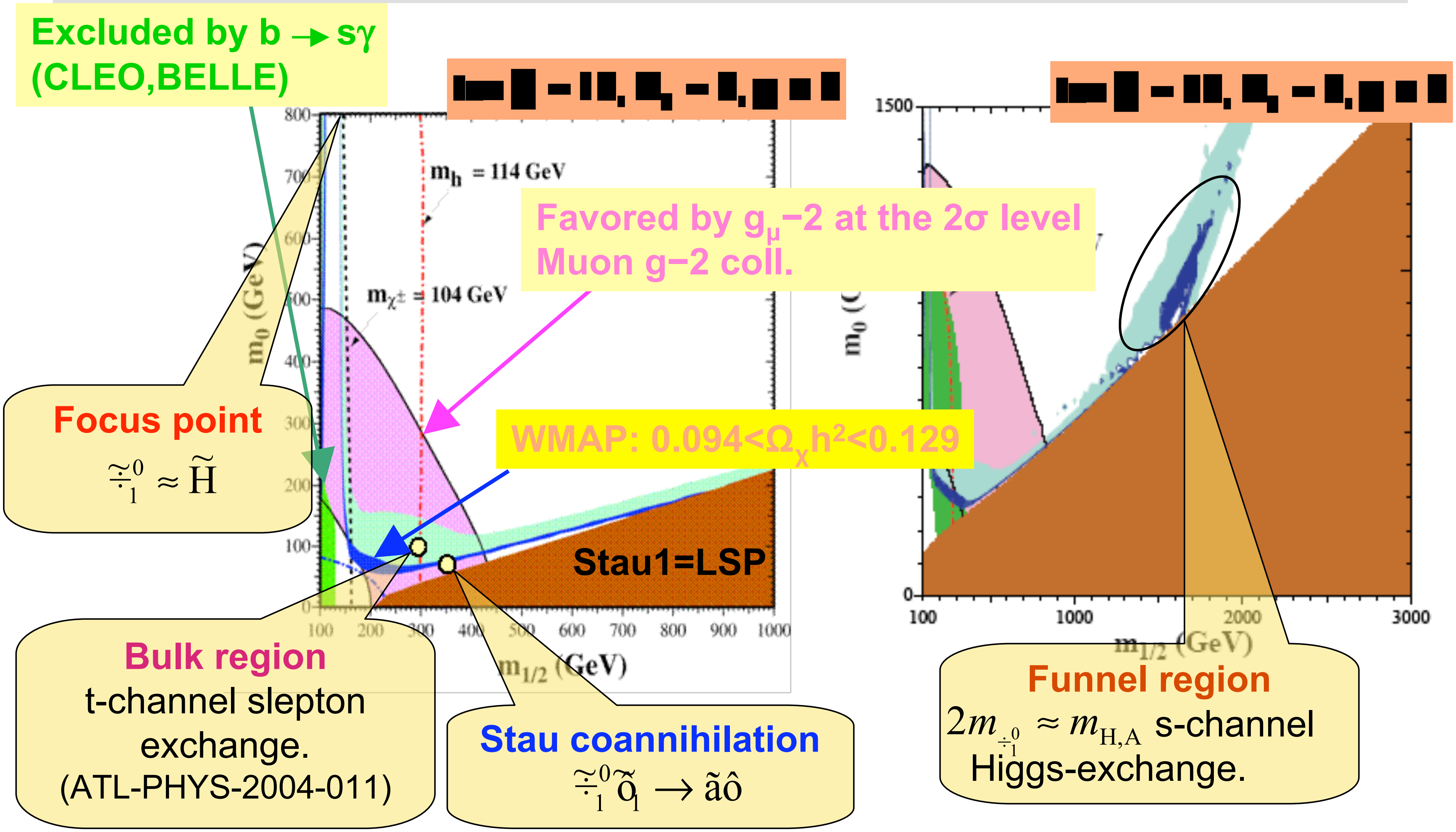
BR($\tilde{\chi}_1^\pm \to \tilde{\tau}_1\nu_\tau$)~ 100%

(note: $m(\tilde{\chi}_2) < m(\tilde{l}_L)$ thus $\tilde{\chi}_2 \not\to \tilde{l}_L\, l$ **)**

- **Mass spectrum :**

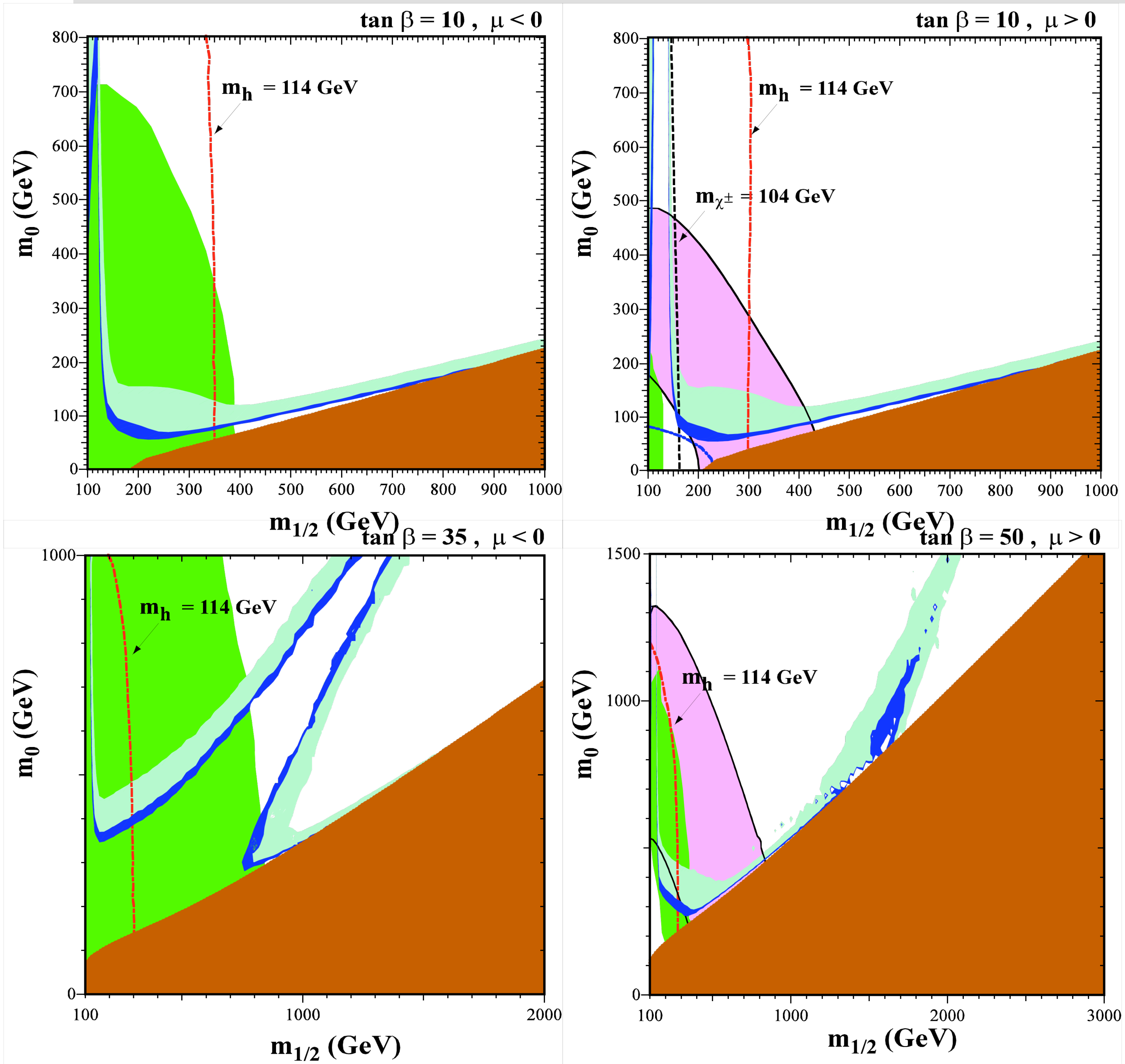
Particle	Mass (GeV)	Particle	Mass (GeV)
$\tilde{g}$	595.5	$\tilde{u}_R$	520.5
$\tilde{u}_L$	537.25	$\tilde{d}_L$	543.04
$\tilde{b}_1$	491.92	$\tilde{t}_1$	379.14
$\tilde{e}_L$	202.12	$\tilde{e}_R$	143.00
$\tilde{\tau}_1$	133.39	$\tilde{\tau}_2$	206.02
$\tilde{\chi}_1^0$	96.05	$\tilde{\chi}_1^\pm$	176.37
$\tilde{\chi}_2^0$	176.80	$\tilde{\chi}_4^0$	377.83
h	113.98	A	394.37

The $(m_0, m_{1/2})$ - mSUGRA plane



(Ellis et al., Phys. B565 (2003) 176)

mSUGRA (Ellis et al., Phys. B565 (2003) 176)



- brown has a charged LSP.
- pink favoured by g-2.
- green excluded by b to sγ
- cyan favoured by older cosmological constraints.
- blue by the WMAP results.

(RPC) SUSY Models

(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

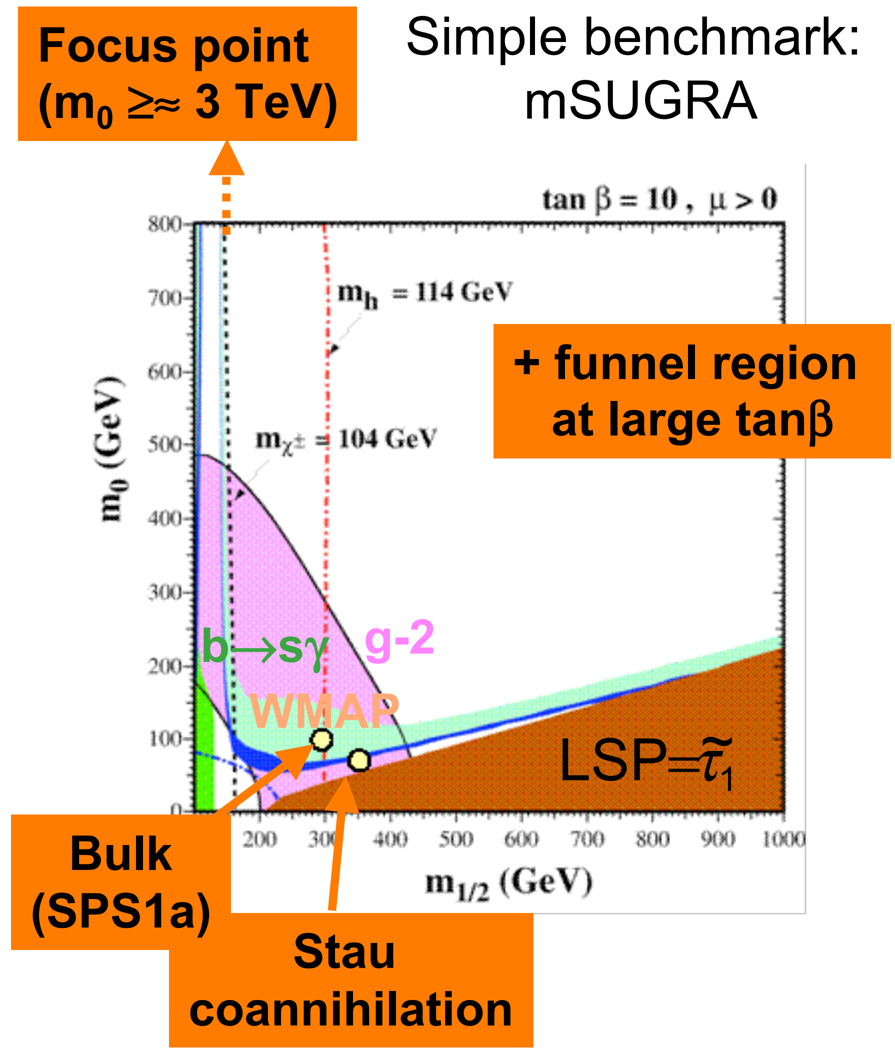
SUSY Parameters (SM ≈ 28):

- **M.S.S.M.** 105
  (note: if RPV + 48)

Constrained models:

- **mSUGRA**
  - m_0, $m_{1/2}$, A_0, tan β, sgn μ 5
- **G.M.S.B.**
  - λ, M_{mes}, N_5, tan β, sgn μ, C_{grav} 6
- **A.M.S.B.**
  - m_0, $m_{3/2}$, tan β, sgn μ 4

Simple benchmark: mSUGRA



Ellis et al., Phys. B565 (2003) 176

(RPC) SUSY Models

(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

SUSY Parameters (SM = 19):

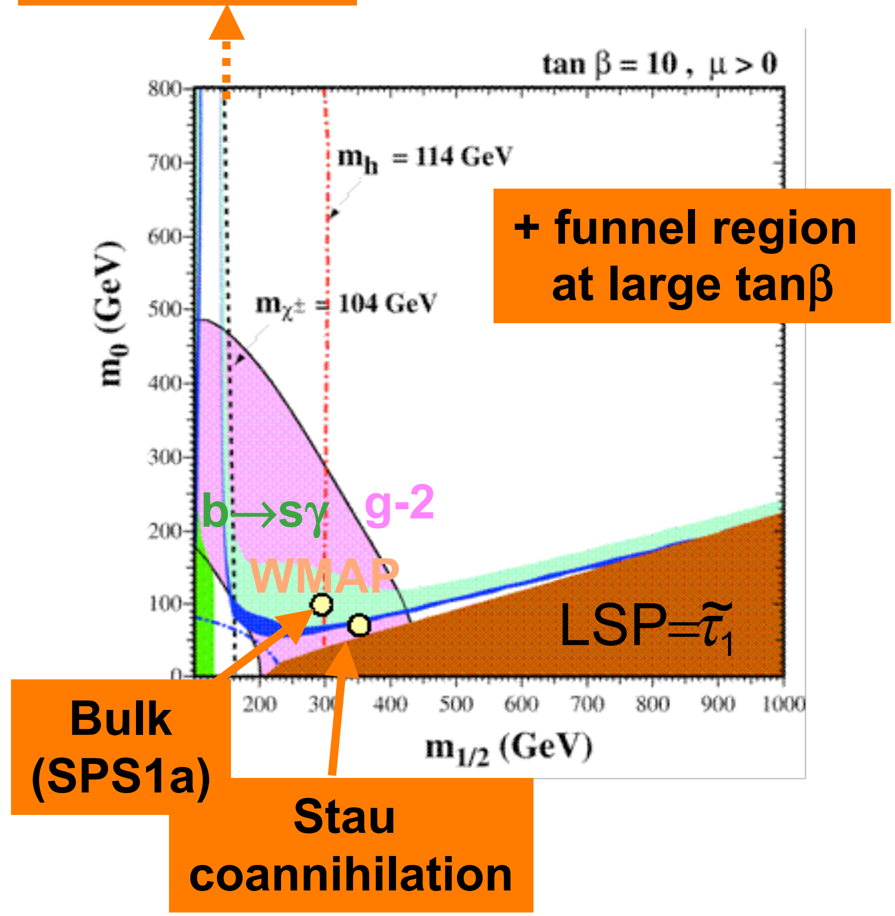
- **M.S.S.M.** 105
  - (note: if RPV + 48)

Constrained models:

- **mSUGRA**
  - – m_0, $m_{1/2}$, A_0, tan β, sgn μ 5
- **G.M.S.B.**
  - – λ, M_{mes}, N_5, tan β, sgn μ, C_{grav} 6
- **A.M.S.B.**
  - – m_0, $m_{3/2}$, tan β, sgn μ 4

Focus point ($m_0 \gtrsim$ 3 TeV)

Simple benchmark: mSUGRA



Ellis et al., Phys. B565 (2003) 176

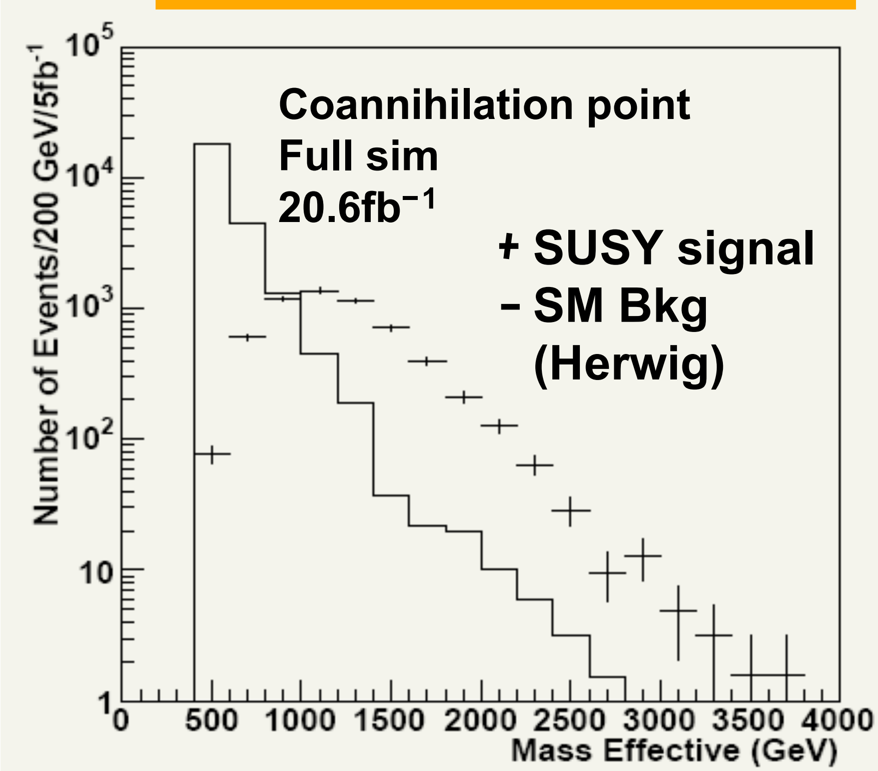
Discovering SUSY and measuring M_{SUSY}

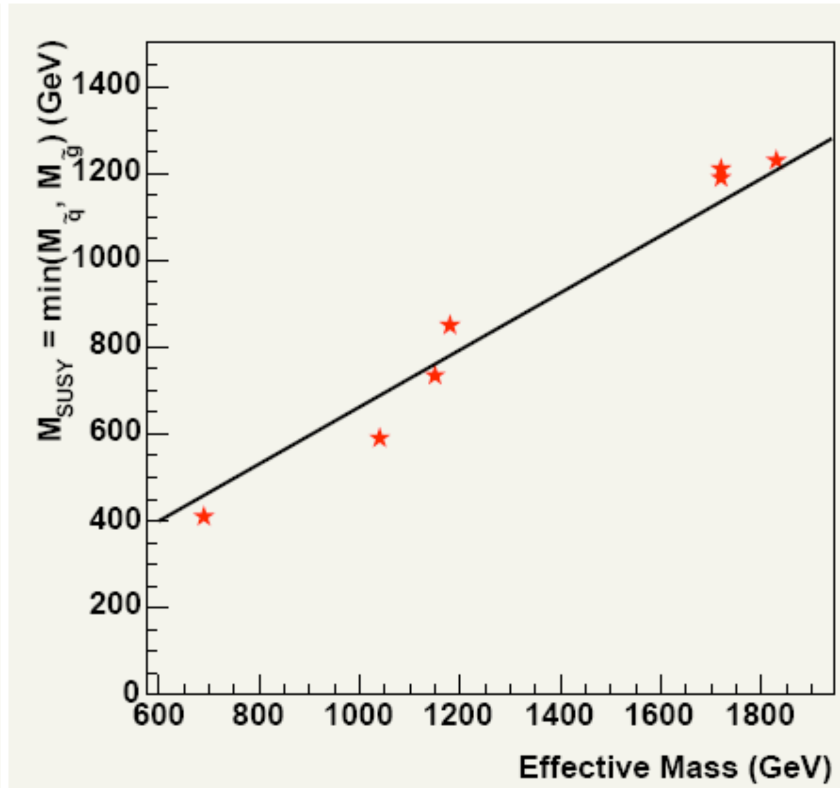
(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

RPC models signature: MET + several high-pT jets

$\rightarrow$ Build discriminating variable M_{eff}:

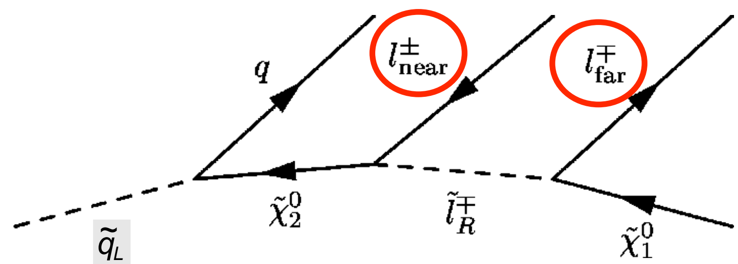
$$M_{eff} = \sum_{i}^{4} \left| p_T^i \right| + E_T^{miss} \propto M_{SUSY}$$ where $$M_{SUSY} = \min(m_{\tilde{g}}, m_{\tilde{q}})$$



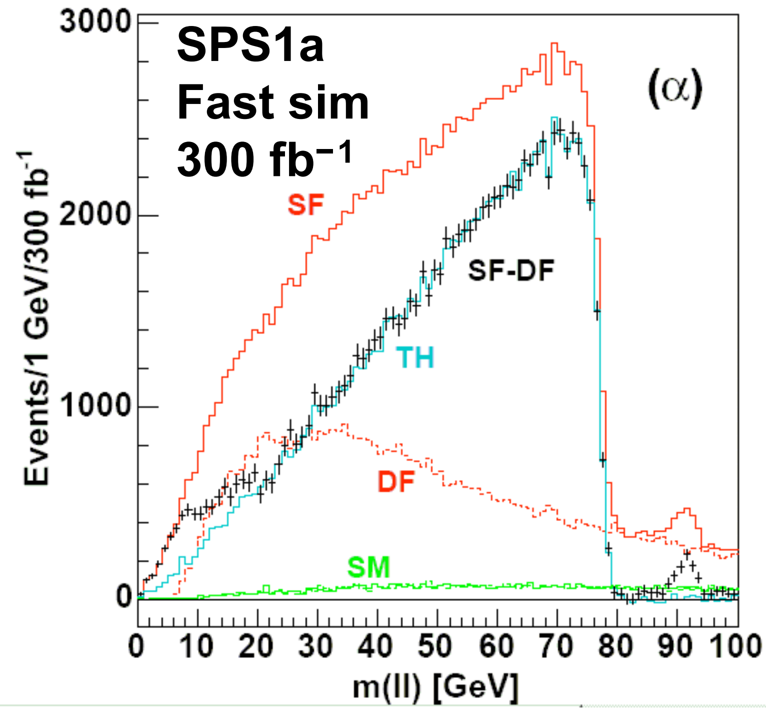


$\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{l}_R, \tilde{q}_L$ mass Measurement: endpoint Method

- **Example:** dilepton endpoint
  m_{ll} has a kinematic endpoint that depends on the masses of the sparticles in the chain



- **Does not need a-priori knowledge of any sparticle mass**
- **Backgrounds:**
  - SM & uncorrelated (not Z) SUSY: use Same Flavour (SF) – Different Flavour (DF)



- **Edge fit:** stat. error = 0.05%, syst. error dominated by lepton energy scale (0.1%)

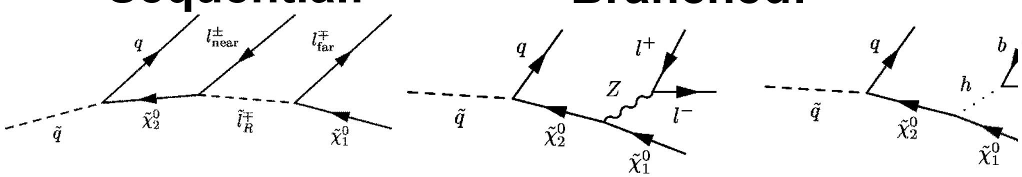
$$m(e^\pm e^\mp)+m(\mu^\pm \mu^\mp)-m(e^\pm \mu^\mp)$$

B.K. Gjelsten et al, J. High Energy Phys. JHEP12(2004)003

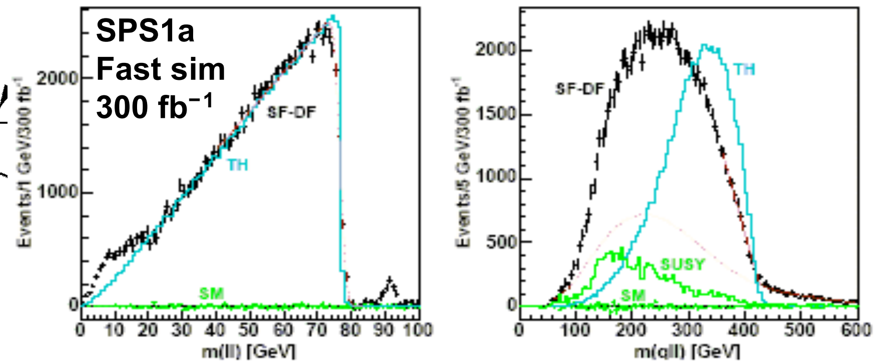
A Variety of Endpoint Measurements

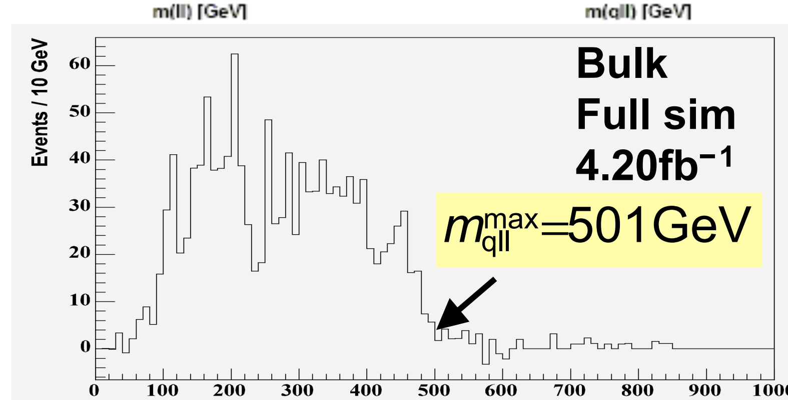
(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

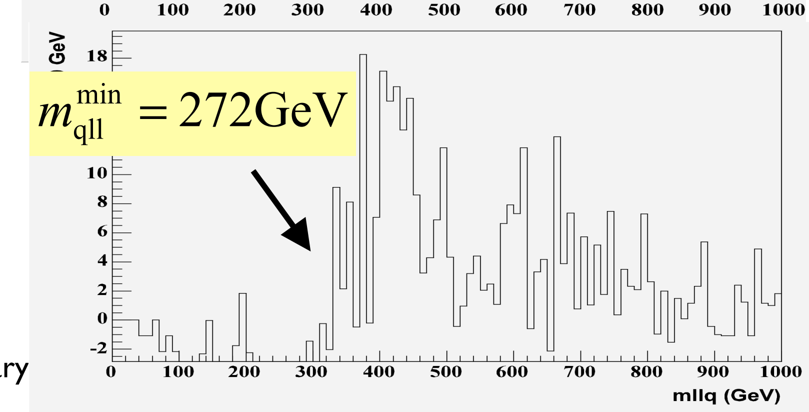
Sequential: **Branched:**



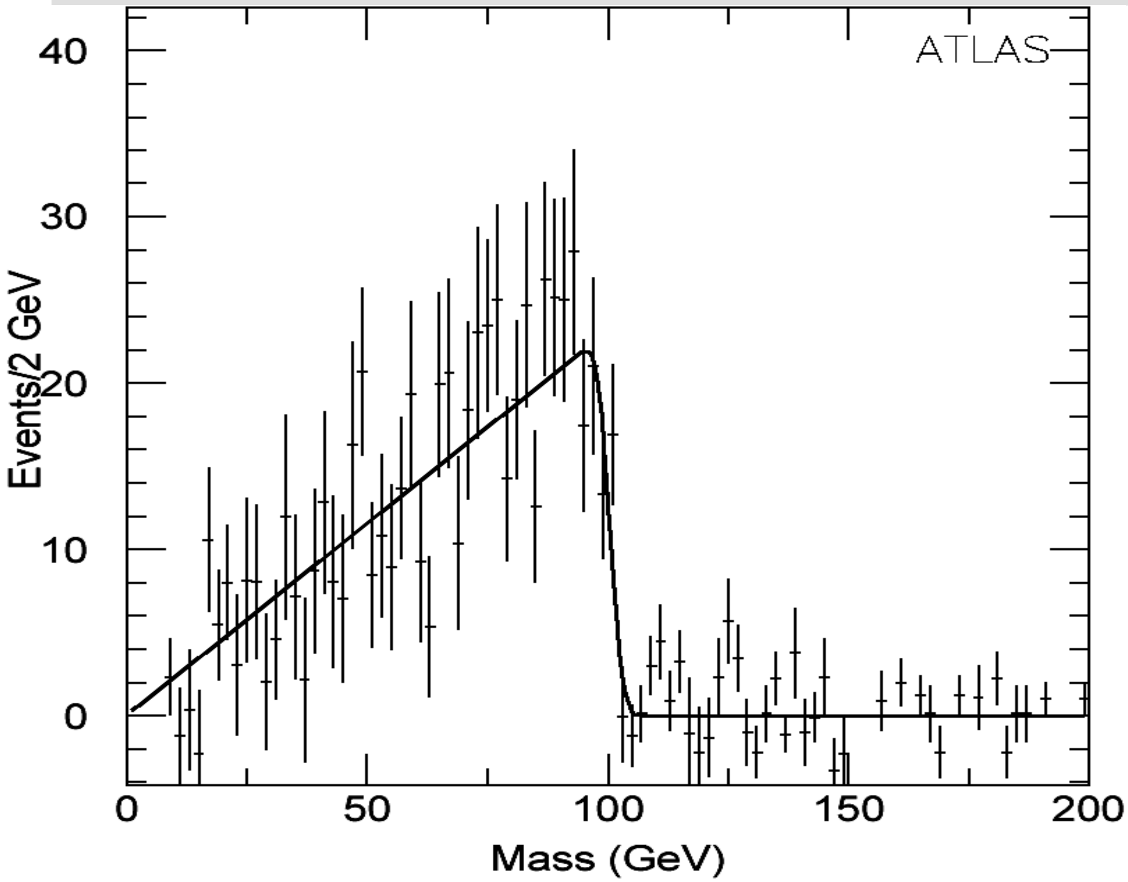
Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{\max})^2 = (\tilde\xi-\tilde l)(\tilde l-\tilde\chi)/\tilde l$
l^+l^-q edge	$(m_{llq}^{\max})^2 = \begin{cases}\max\left[\frac{(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi)}{\tilde\xi}, \frac{(\tilde q-\tilde l)(\tilde l-\tilde\chi)}{\tilde l}, \frac{(\tilde q\tilde l-\tilde\xi\tilde\chi)(\tilde\xi-\tilde l)}{\tilde\xi\tilde l}\right] \\ \text{except for the special case in which } \tilde l^2<\tilde q\tilde\chi<\tilde\xi^2 \text{ and} \\ \tilde\xi^2\tilde\chi<\tilde q\tilde l^2 \text{ where one must use } (m_{\tilde q}-m_{\tilde\chi_1^0})^2.\end{cases}$
Xq edge	$(m_{Xq}^{\max})^2 = X + (\tilde q-\tilde\xi)\left[\tilde\xi+X-\tilde\chi+\sqrt{(\tilde\xi-X-\tilde\chi)^2-4X\tilde\chi}\right]/(2\tilde\xi)$
l^+l^-q threshold	$(m_{llq}^{\min})^2 = \begin{cases}[\ 2\tilde l(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi)+(\tilde q+\tilde\xi)(\tilde\xi-\tilde l)(\tilde l-\tilde\chi) \\ -(\tilde q-\tilde\xi)\sqrt{(\tilde\xi+\tilde l)^2(\tilde l+\tilde\chi)^2-16\tilde\xi\tilde l^2\tilde\chi}\ \ ]/(4\tilde l\tilde\xi)\end{cases}$
$l^\pm_{\rm near}q$ edge	$(m_{l_{\rm near}q}^{\max})^2 = (\tilde q-\tilde\xi)(\tilde\xi-\tilde l)/\tilde\xi$
$l^\pm_{\rm far}q$ edge	$(m_{l_{\rm far}q}^{\max})^2 = (\tilde q-\tilde\xi)(\tilde l-\tilde\chi)/\tilde l$
$l^\pm q$ high-edge	$(m_{lq({\rm high})}^{\max})^2 = \max\left[(m_{l_{\rm near}q}^{\max})^2, (m_{l_{\rm far}q}^{\max})^2\right]$
$l^\pm q$ low-edge	$(m_{lq({\rm low})}^{\max})^2 = \min\left[(m_{l_{\rm near}q}^{\max})^2, (\tilde q-\tilde\xi)(\tilde l-\tilde\chi)/(2\tilde l-\tilde\chi)\right]$
M_{T2} edge	$\Delta M = m_{\tilde l}-m_{\tilde\chi_1^0}$







DC1: dilepton endpoint



• in mSUGRA R-parity is conserved, all SUSY events contain two neutralinos which escape the detector

• neutralinos are not detected, but one can measure kinematic end-points in dilepton invariant mass distributions rather than mass peaks

$$\tilde{\chi}_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp} \rightarrow \tilde{\chi}_1^0 l^{\pm} l^{\mp}$$

$$M_{ll}^{\max} = \sqrt{\frac{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}}^2)(M_{\tilde{l}}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{l}}^2}} = 100.31\ GeV$$

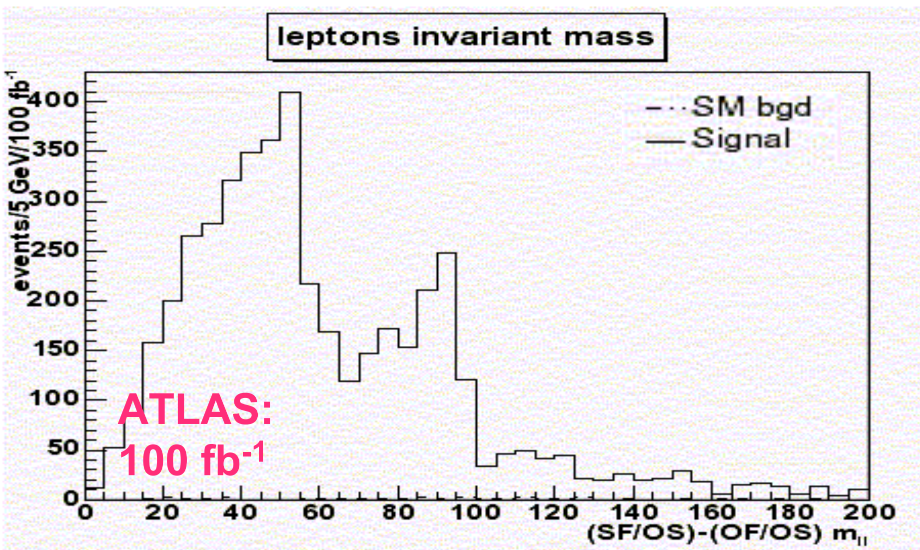
coannihilation point:

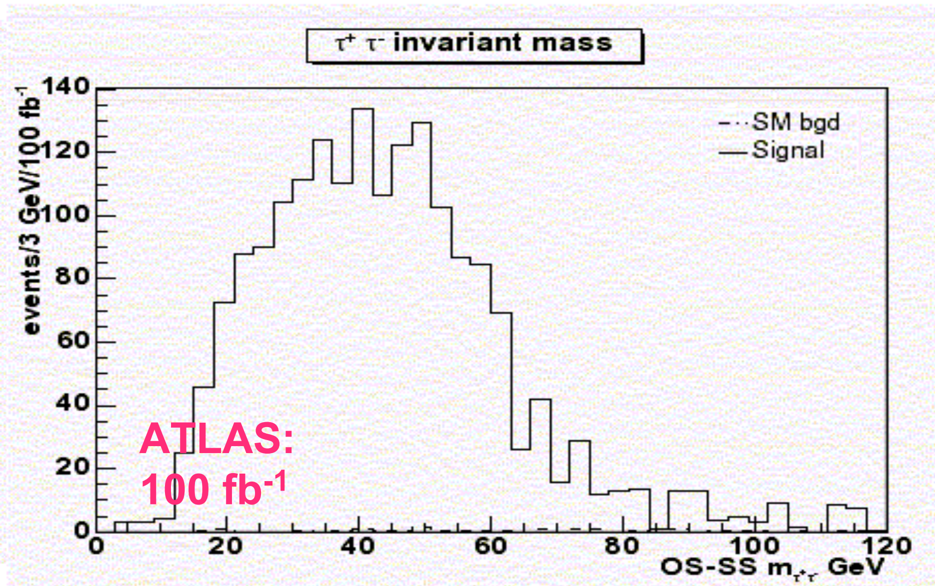
- Chosen point: m_0=70 GeV; $m_{1/2}$=350 GeV; A_0=0; tanβ=10 ; μ>0;

- Small slepton-neutralino mass difference gives soft leptons

- Decays of χ^0_2 to both l_L and l_R kinematically allowed; double dilepton invariant mass edge structure, edges expected at 58 / 98 GeV

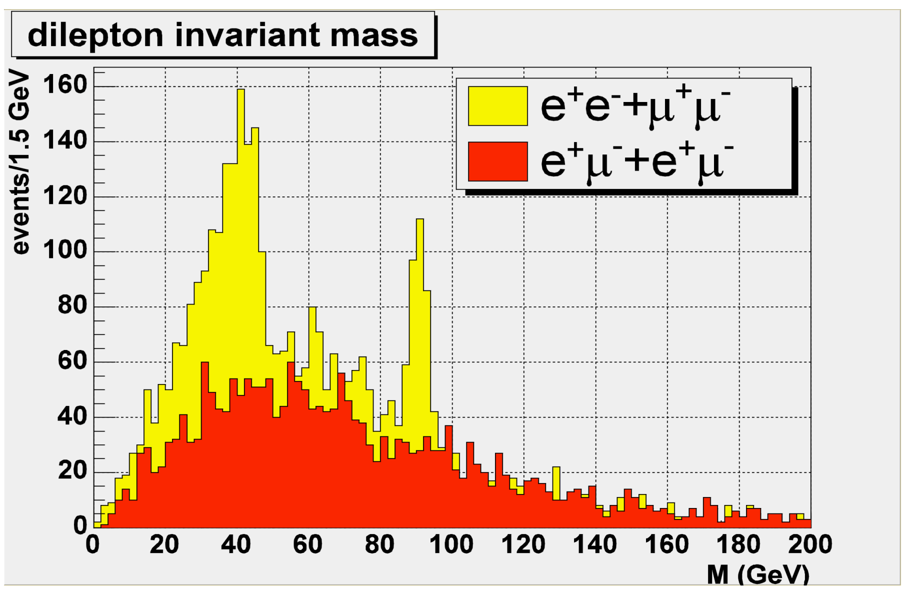
- Stau channels enhanced (tanβ); soft tau signatures, edge expected at 79 GeV. Less clear due to poor tau visible energy resolution

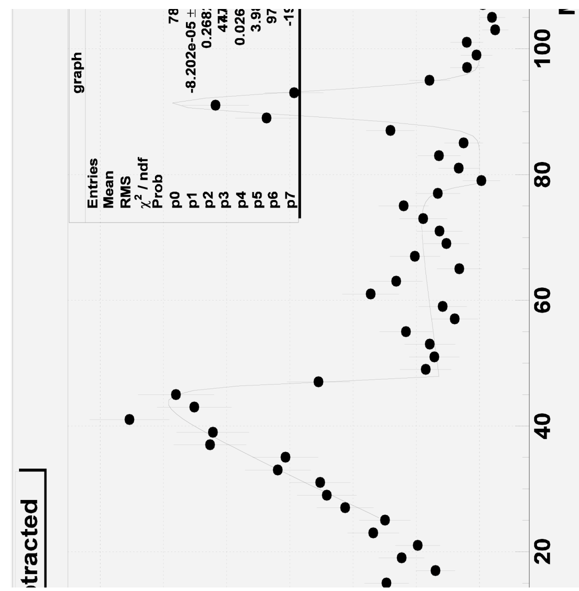




focus point

- chosen point: m_0=3000 GeV; $m_{1/2}$=215 GeV; A_0=0; tanβ=10 ; μ>0
- large m_0 → sfermions are heavy
- most useful signatures from heavy neutralino decay
- direct three-body decays $\chi^0_n \rightarrow \chi^0_1 ll$
- fit results give:
- $M(\chi^0_2)-M(\chi^0_1)$= 57.45 ± 0.28 GeV
- $M(\chi^0_3)-M(\chi^0_1)$= 73.27 ± 0.47 GeV



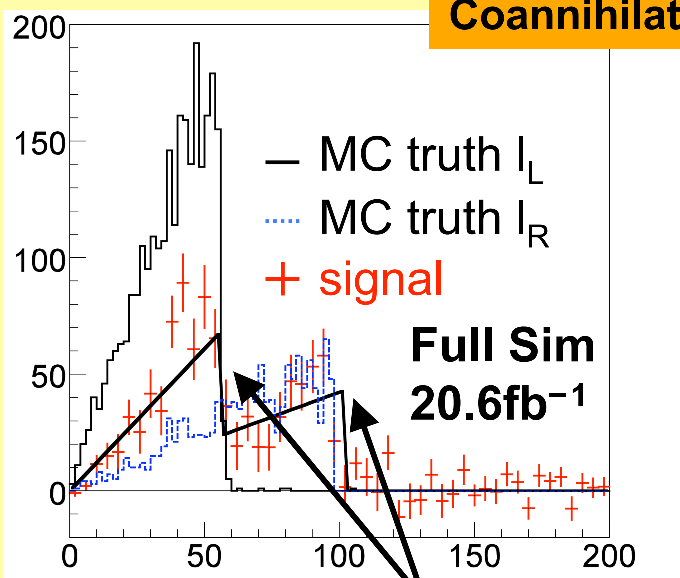


Di-lepton endpoint in various mSUGRA points

(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

Depending on point: different shape, number of edges, 2-body vs 3-body decay, …

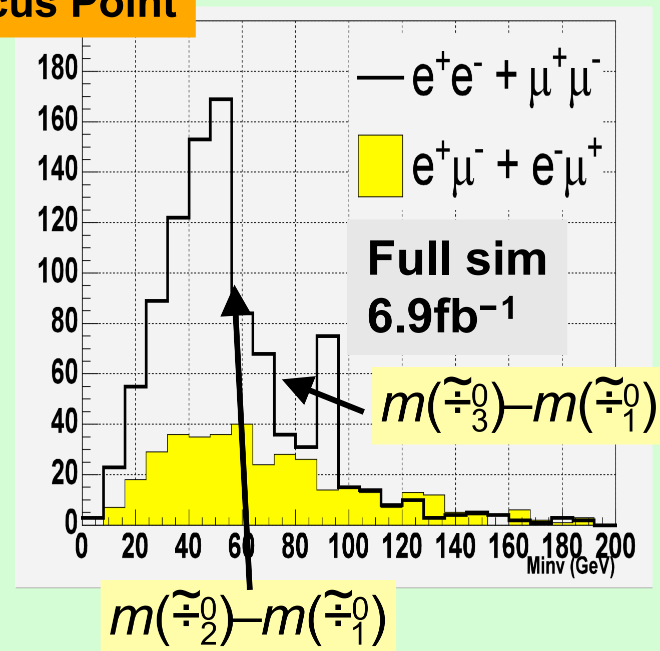
Coannihilation



[redacted] → **2 edges for left and right slepton**

- **small BR**
- **at least 1 lepton with small p_T**

Focus Point



- **m_0 large, heavy scalars → no sleptons in χ decays**
- **direct 3-body decay:**

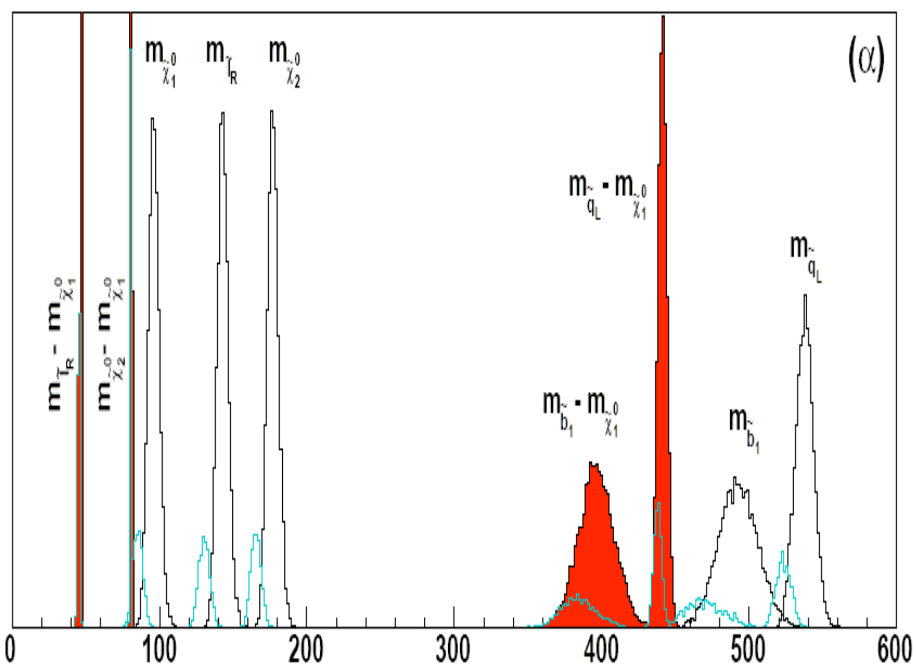
[redacted]

Extraction of sparticle masses from endpoints

(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

100 fb^{-1}

MC toy of 10000 ATLAS experiments, use inversion formulae to get masses from edges:



SPS1a	Nom	$\langle m \rangle$	σ
$m_{\tilde{\chi}_1^0}$	96.1	96.3	3.8
$m_{\tilde{l}_R}$	143.0	143.2	3.8
$m_{\tilde{\chi}_2^0}$	176.8	177.0	3.7
$m_{\tilde{q}_L}$	537.2	537.5	6.1
$m_{\tilde{b}_1}$	491.9	492.4	13.4
$m_{\tilde{l}_R} - m_{\tilde{\chi}_1^0}$	46.92	46.93	0.28
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	80.77	80.77	0.18
$m_{\tilde{q}_L} - m_{\tilde{\chi}_1^0}$	441.2	441.3	3.1
$m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$	395.9	396.2	12.0

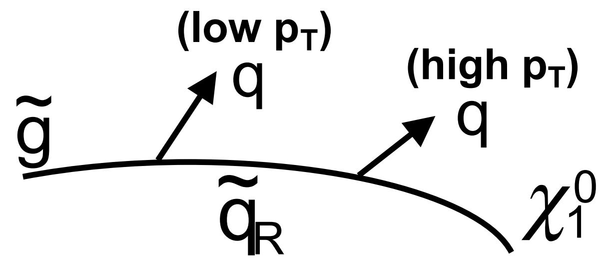
All masses are strongly correlated with $m(\tilde{\chi}_1^0)$

B.K. Gjelsten *et al, J. High Energy Phys.* JHEP12(2004)003

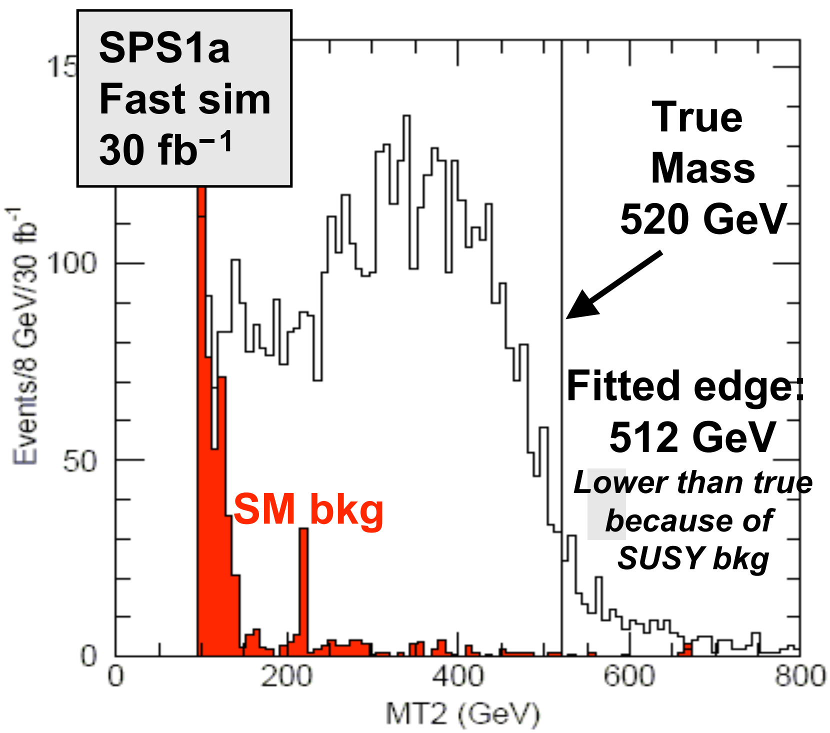
right-handed squark mass

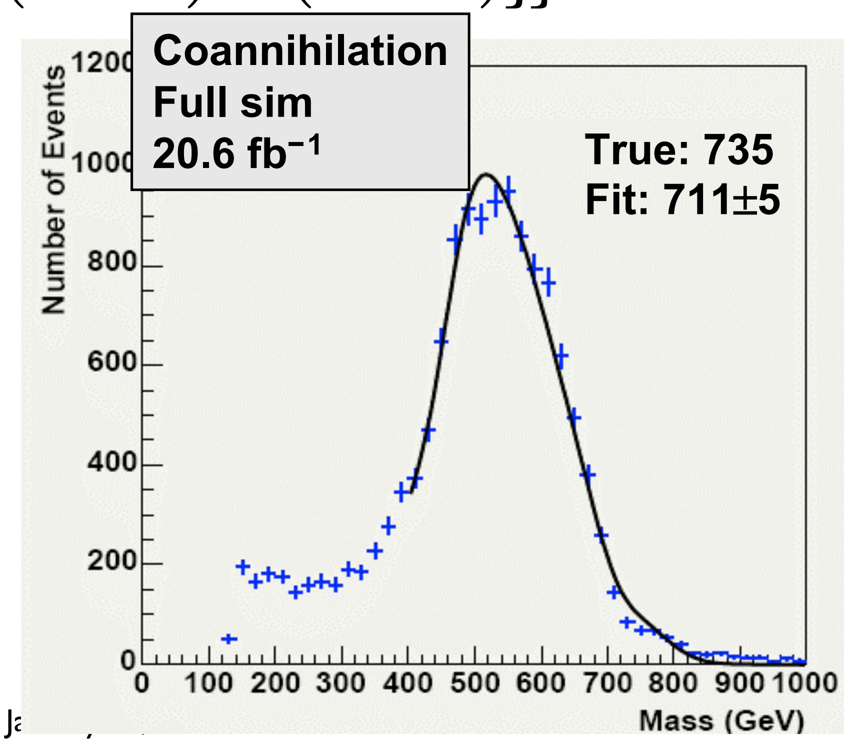
(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

- **mSUGRA: χ_1 essentially a bino: Br($\tilde{q}_R \rightarrow q\chi_1^0$) ≈ 100%**
  If both gluino decay to right-handed squarks:
  $\rightarrow$ require 2 high-p_T jets, MET
- **Discriminant: Cambridge variable M_{T2} endpoint gives the right squark mass:**



$$M_{T2} = \min_{E^{T}_{miss} = E^{T1}_{miss} + E^{T2}_{miss}} \left\{ \max \left\{ m_T^2\left(p^T_{j1}, E^{T1}_{miss}\right), m_T^2\left(p^T_{j2}, E^{T2}_{miss}\right) \right\} \right\}$$

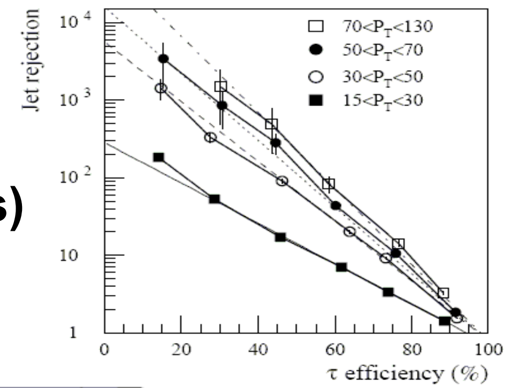




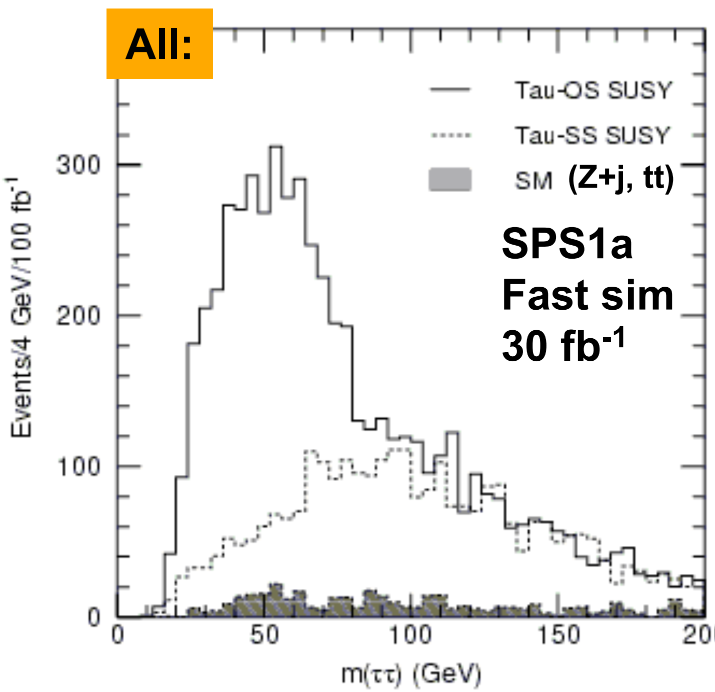
staus signatures

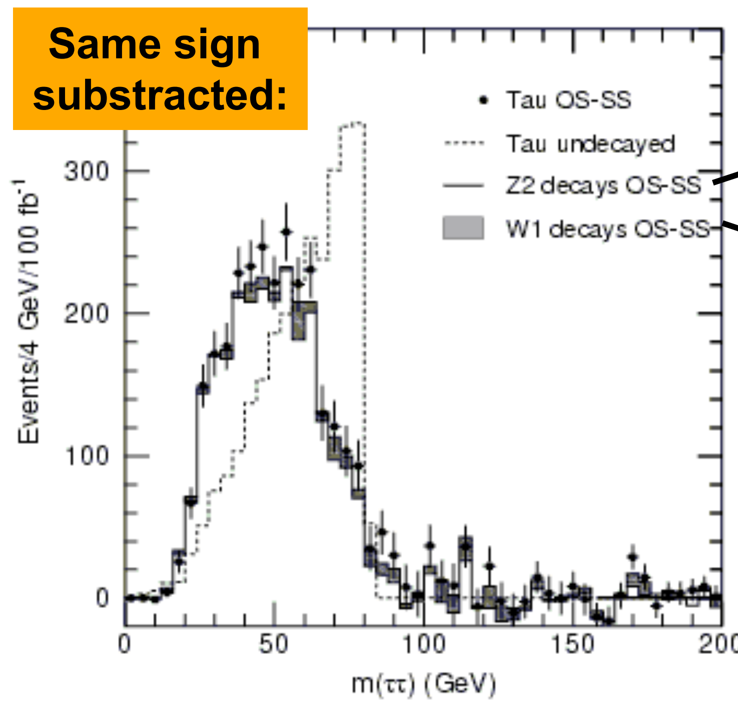
(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

- **SPS1a: dominant $\tilde{\chi}_2^0$ decay is $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \rightarrow \tau^+ \tau^- \tilde{\chi}_1^0$ (because of relatively high tanβ value)**



- **Look at hadronic τ decays (dedicated algorithms for τ-jets) Background (QCD jets misidentified as τ) evaluated from same signs events:**





$\chi_2^0 \rightarrow \tilde{\tau}_1 \tau$ **(signal)**

$\chi_1^{\pm}$ decays **(background)**

B.K. Gjelsten *et al, ATL-PHYS-2004-007*

di-lepton endpoint invarious mSUGRA points

(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

Depending on point: different shape, number of edges, 2-body vs 3-body decay, …

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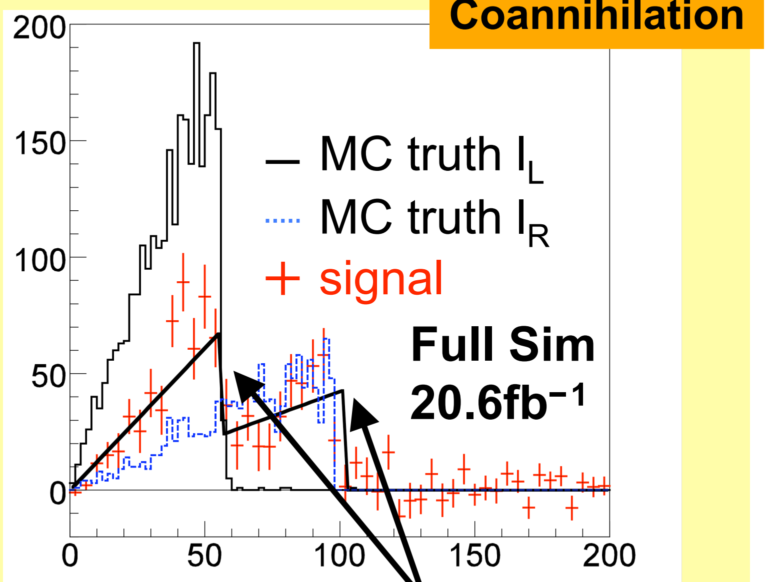

→ 2 edges for left and right slepton

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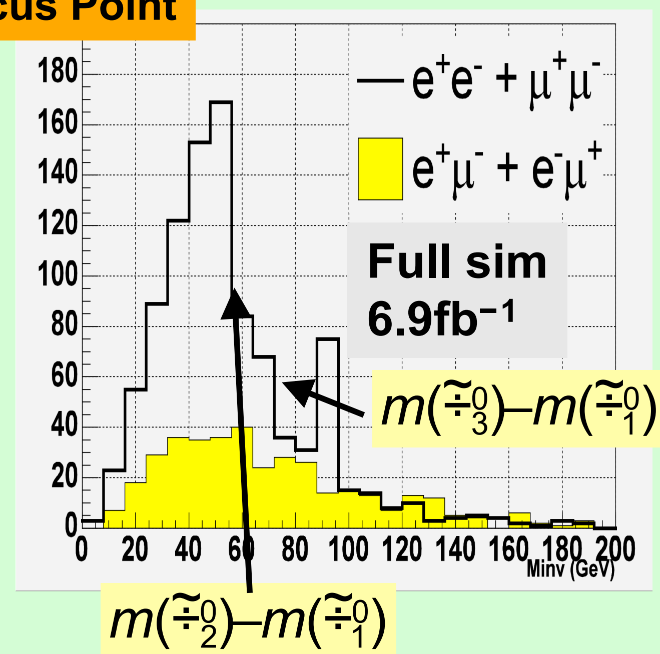
Focus Point



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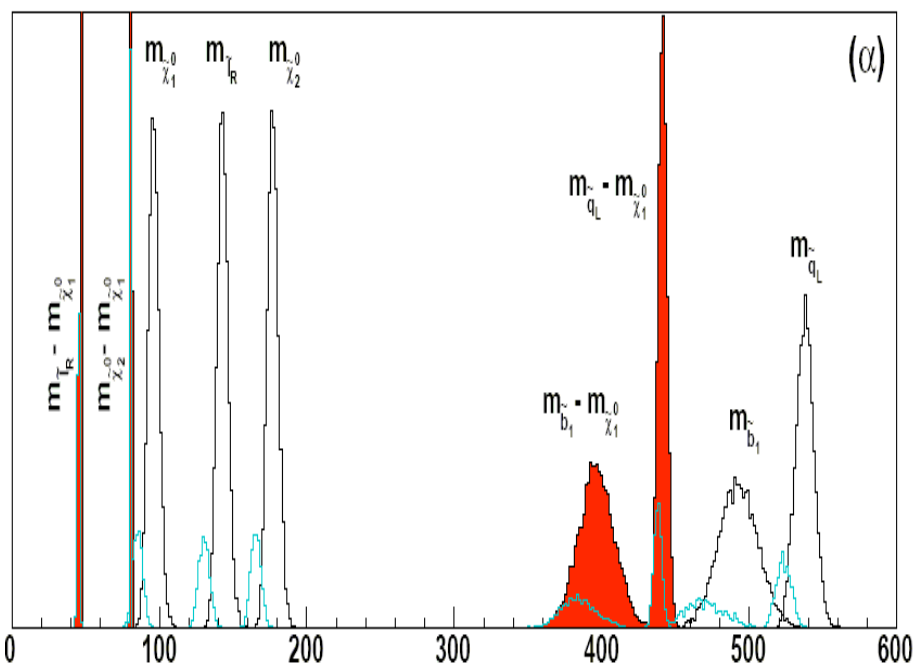

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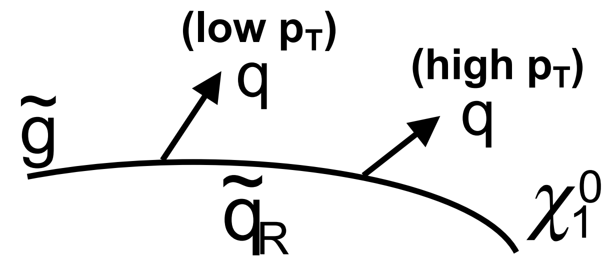
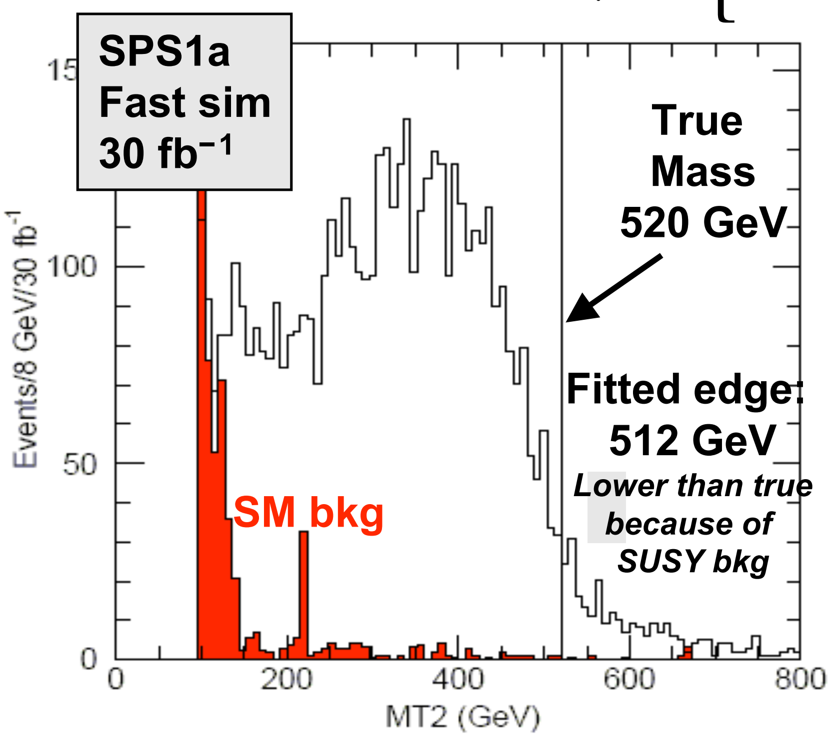
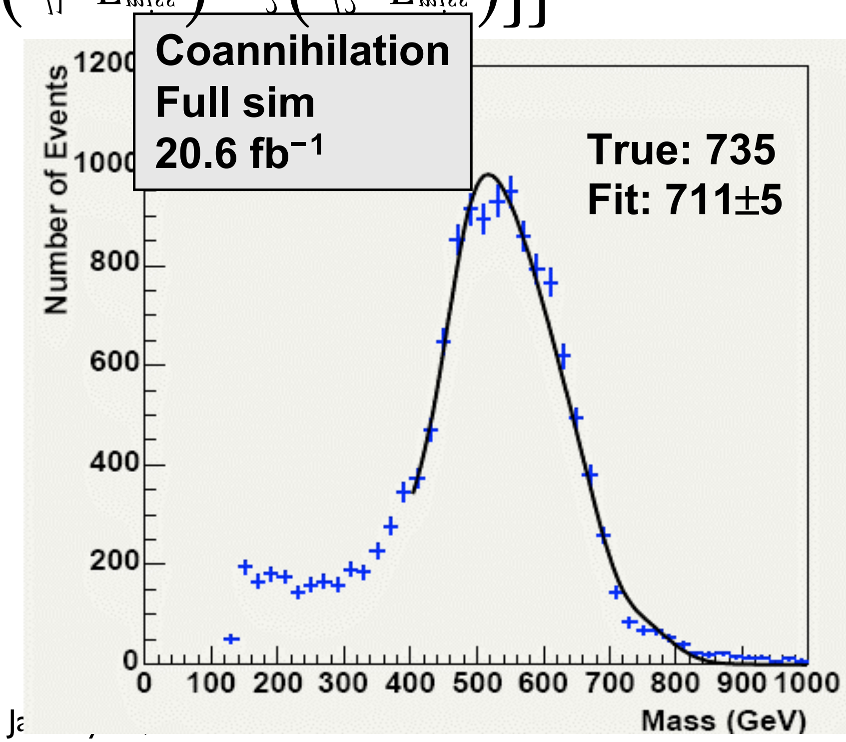


$$M_{T2} = \min_{E_T^{miss} = E_T^{miss,1} + E_T^{miss,2}} \left\{ \max \left\{ m_T^2\left(p_{T1}, E_T^{miss,1}\right), m_T^2\left(p_{T2}, E_T^{miss,2}\right) \right\} \right\}$$



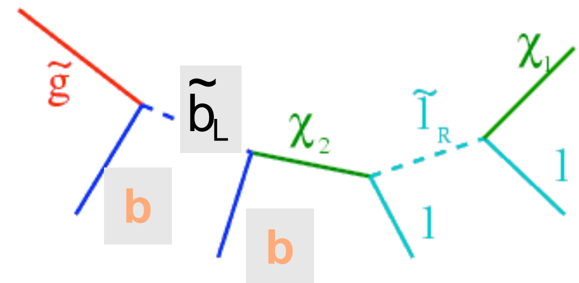


Sbottom and Gluino masses: near l^+l^- endpoint

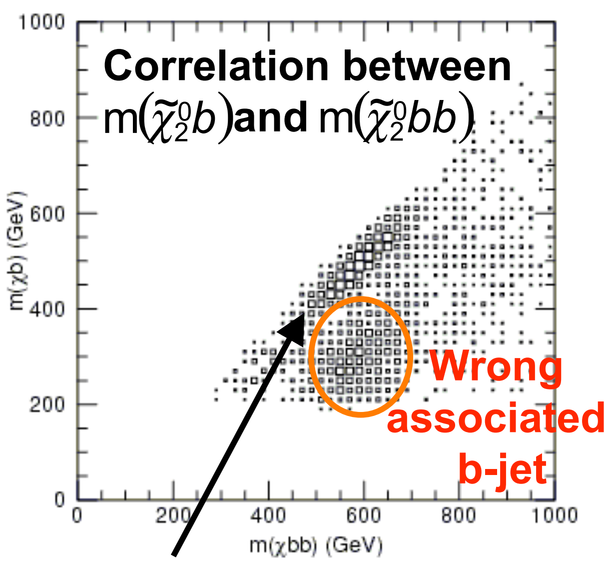
- **Near l^+l^- endpoint: LSP and l^+l^- are at rest in $\tilde{\chi}_2^0$ frame, thus can evaluate $\tilde{\chi}_2^0$ momentum (approximation):**

$$\vec{p}(\tilde{\chi}_2^0) \approx \left(1 + \frac{m_{\tilde{\chi}_1^0}}{m_{l^+l^-}}\right) \vec{p}(l^+l^-)$$

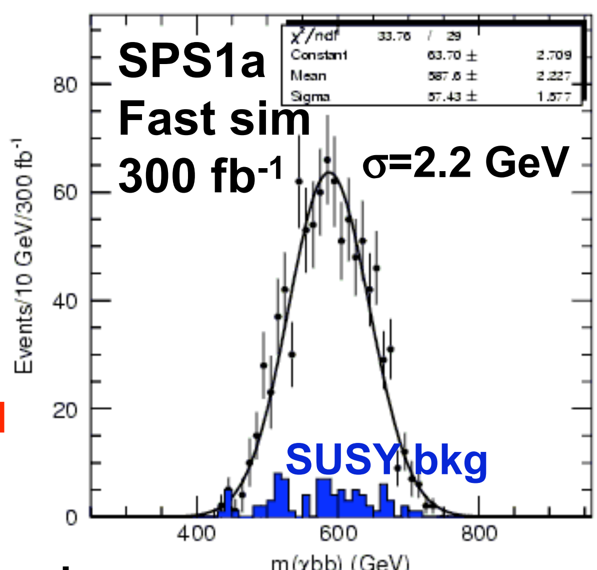
where $m(\tilde{\chi}_1^0)$ and $m(\tilde{\chi}_2^0)$ are known from endpoints



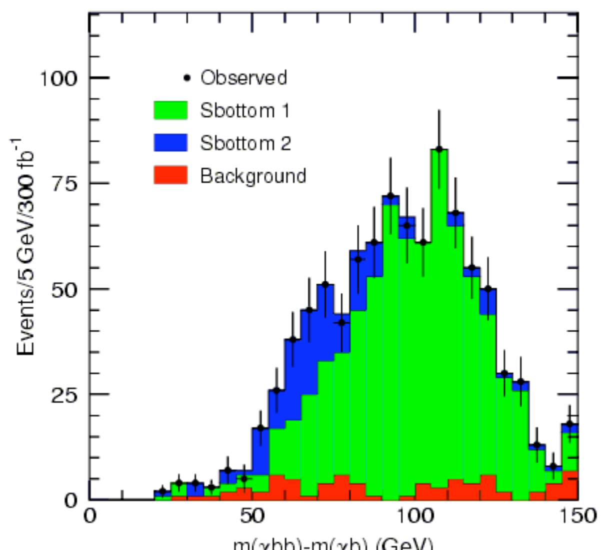
- **Add 1 or 2 b-jet to get sbottom and gluino masses: $m(\tilde{\chi}_2^0 b)$ and $m(\tilde{\chi}_2^0 bb)$**



Spread from p(χ$_2$) approximation is common to both masses



Gluino mass



Gluino – sbottom masses

B.K. Gjelsten *et al, ATL-PHYS-2004-007*

Sbottom and Gluino Masses:
Mass Relation Method

Alternative method to previous one using ALL data set (not only near endpoint)

$$\begin{aligned}
\boxed{\begin{aligned} m^2_{\tilde\chi^0_1} \\ m^2_{\tilde\ell} \\ m^2_{\tilde\chi^0_2} \\ m^2_{\tilde b} \\ m^2_{\tilde g} \end{aligned}}
\end{aligned}
\begin{aligned}
&= p^2_{\tilde\chi^0_1}, \\
&= (p_{\tilde\chi^0_1} + p_{\ell_1})^2, \\
&= (p_{\tilde\chi^0_1} + p_{\ell_1} + p_{\ell_2})^2, \\
&= (p_{\tilde\chi^0_1} + p_{\ell_1} + p_{\ell_2} + p_{b_1})^2, \\
&= (\boxed{p_{\tilde\chi^0_1}} + p_{\ell_1} + p_{\ell_2} + p_{b_1} + p_{b_2})^2.
\end{aligned}$$

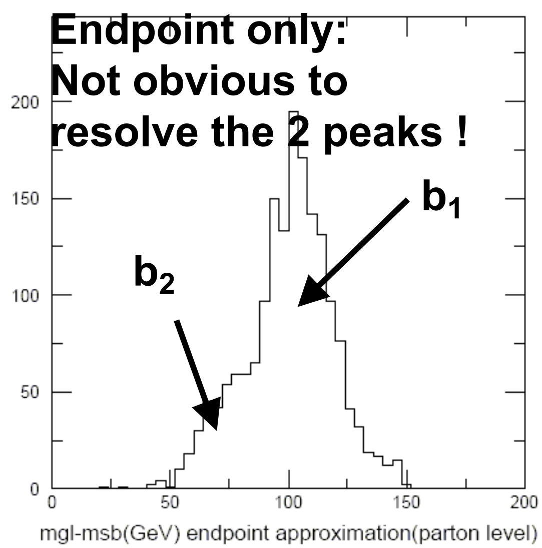
5 parameters **4 unknowns (4-momentum)**

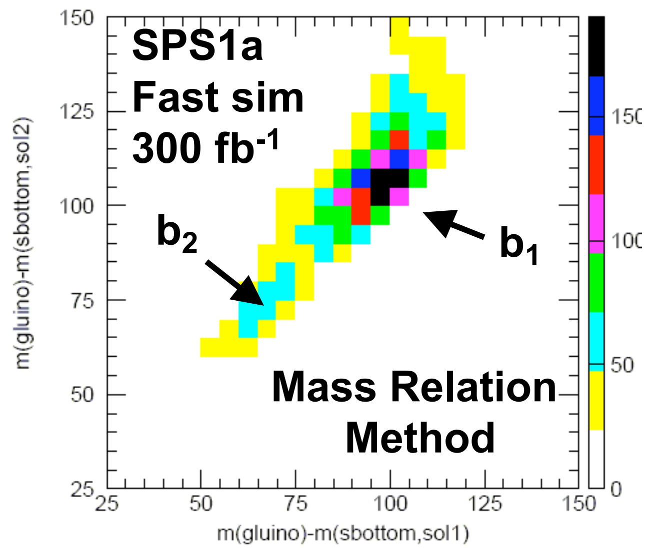
- **Each event = 4D surface in 5D space**
- **In principle: 5 events to determine the 4 unknowns !**
- **In practice: know** $(m_{\chi_1}, m_{\tilde\ell_R}, m_{\chi_2})$ **so have following constraint:**

$$a m^4_{\tilde g} + b m^2_{\tilde g} m^2_{\tilde b} + c m^4_{\tilde b} + d m^2_{\tilde g} + e m^2_{\tilde b} + f = 0$$

$\downarrow$

Two possible solutions (2 lepton assignments)





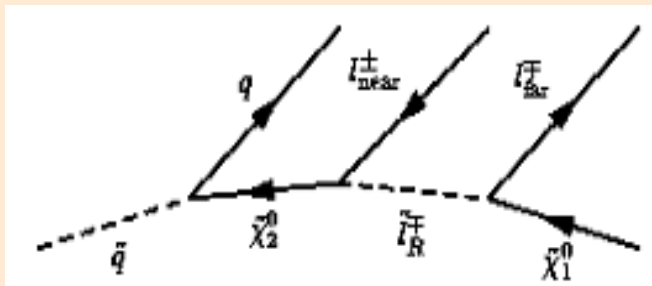
→ The two b-peaks are well resolved

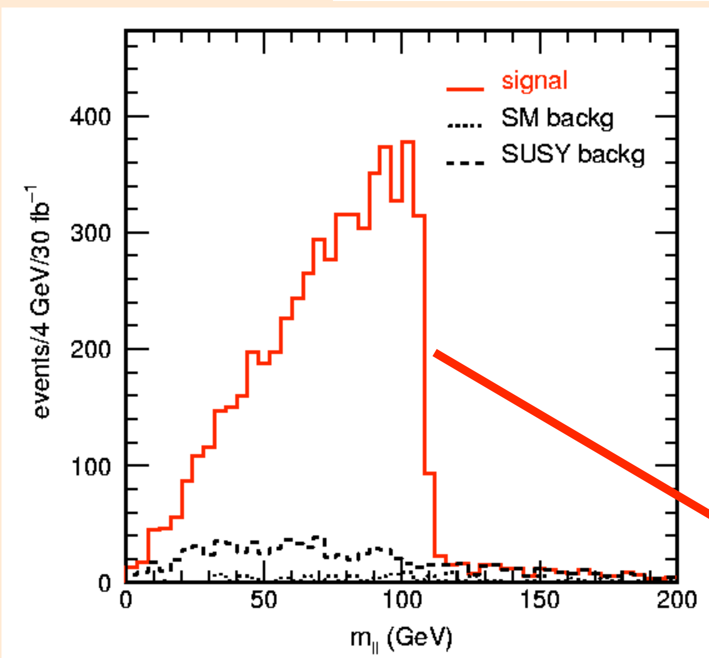
Kawagoe et al, hep-ph/0410160

Obtaining the Fundamental Model Parameters

LHC Measurements

Ex: endpoints





SUSY Model

Ex: mSUGRA

m_0, $m_{1/2}$, A_0, $\tan\beta$, sgn(μ)

Spectrum Generator (Ex: SUSPECT, SoftSUSY, …)

$m_{\chi^0_2}, m_{\tilde{l}^{\pm}_R}, m_{\chi^0_1}$

$(m^2_{ll})^{edge}_{Pred.}$

Fit: χ^2

$$(m^2_{ll})^{edge}_{\text{Mes.}} = \frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}}$$

Note: better to exploit edges than masses (correlations)

An Example

List of measurements (300 fb^{-1})

Variable	Value (GeV)	Errors Stat. (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

SFITTER program:

mSUGRA Parameter determination

	SPS1a	ΔLHC edges
m_0	100	**1.2**
$m_{1/2}$	250	**1.0**
$\tan\beta$	10	**0.9**
A0	-100	**20**

Sign(μ) fixed

Note: m(ll) most powerful input (m_0 driven by 1st and 2nd generation slepton sector)

R. Lafaye, T. Plehn, D. Zerwas, hep-ph/0512028

Conclusion

(from Sandrine Laplace's talk at Physics at LHC, Krakow, Poland, June 2006)

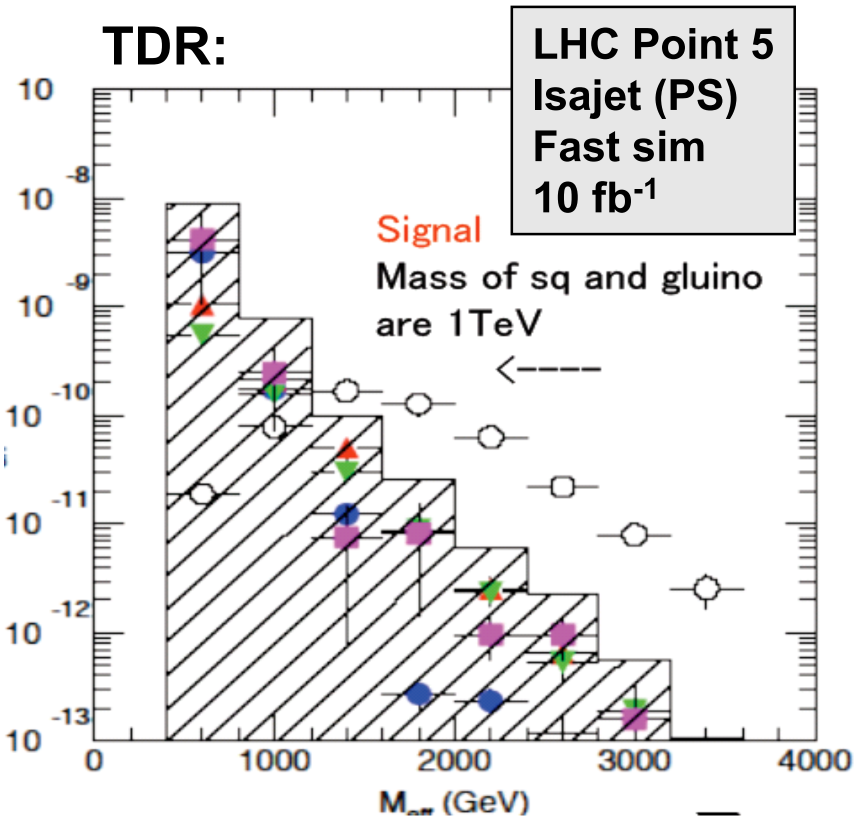
New era for SUSY studies in ATLAS is currently starting:

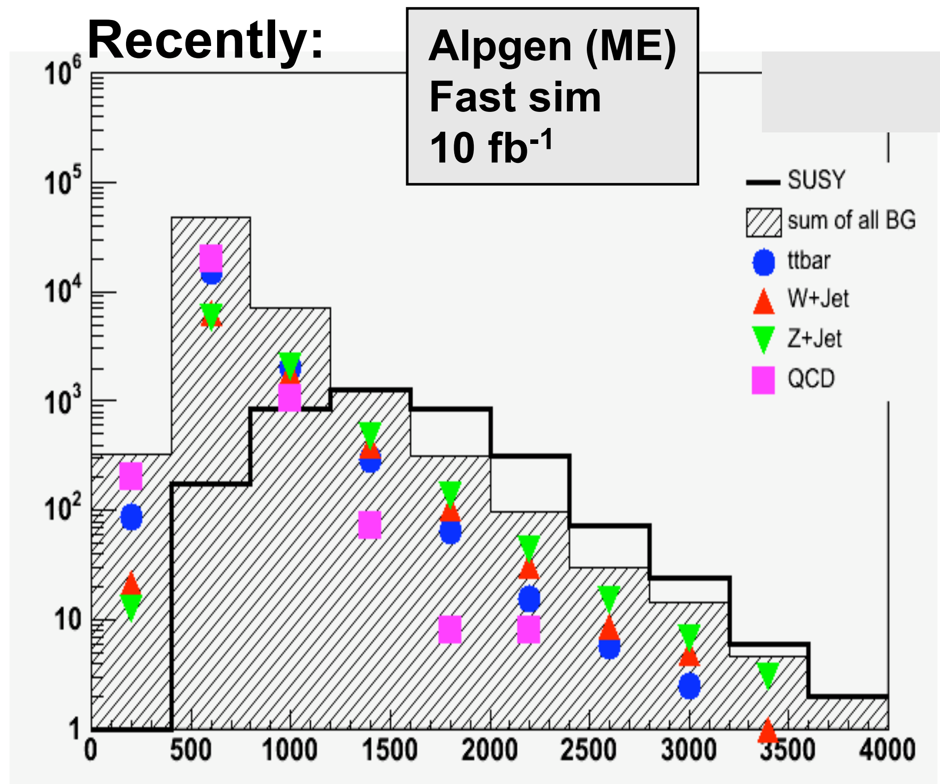
- large scale productions to prepare for real data analysis
- study detector systematics
- SM background: latest MC and plans to measure it from data
- new models studied
- new techniques developed

Discovery potential: in most models, a few fb^{-1} are sufficient to:

- observe squarks and gluons below 1-2 TeV and sleptons below 300 GeV
- accurately measure squark, slepton and neutralino masses using cascades

M_{eff}: Parton Shower vs Matrix Element for background simulation





Parton Shower (only good in collinear region)

Matrix Element (more correct)

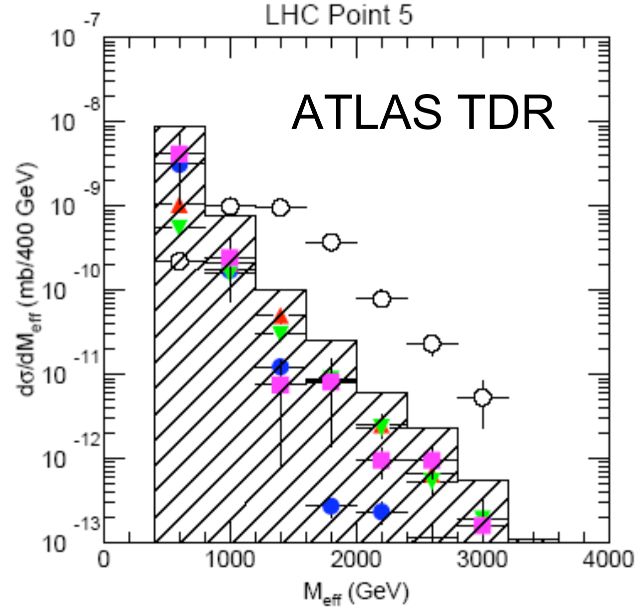
→ Background increases by factor 2 to 5 !

SM background

Dominant SM background processes:

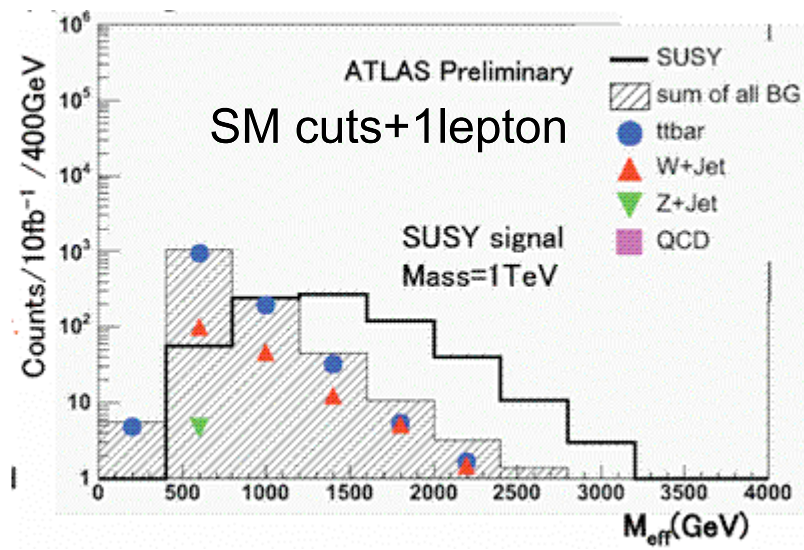
- Z+N jets
- W+N jets
- tt+N jets
- multijets (QCD)
- sum of all BG

Previous studies are based on Parton shower.



New SM BG estimation using ME generator (ALPGEN 1.33)

- W/Z + N jets, tt + N jets are generated and processed with the fast ATLAS simulation
- Collinear and soft kinematic regions are assessed with PS (PYTHIA). MLM method used for ME-PS matching.



SUSY: the "default new physics ??"

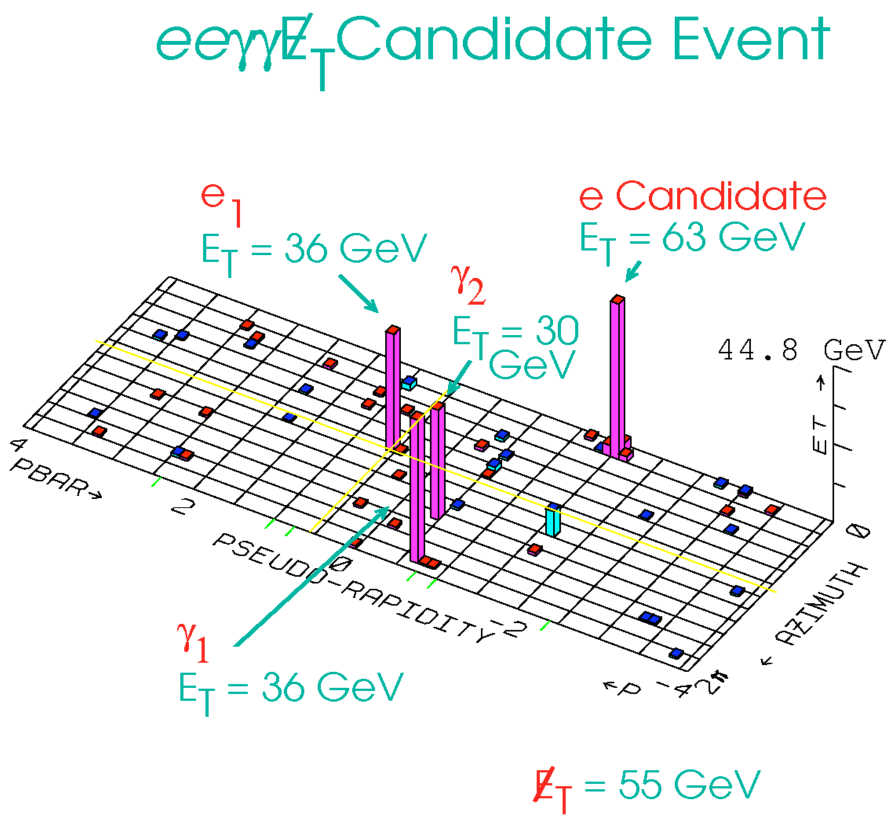
- SUSY is perhaps the most explored of "beyond the SM" physics scenarios
- As such, it will perhaps be "blamed" for any deviations from SM physics if observed at Tevatron or at LHC
- The problem will be to prove that, even if a statistically significant deviation from SM predictions is found, the observed events are really due to the supersymmetric particles and NOT to anything else. This will NOT be easy. As you should realize by now, there is an almost continuous spectrum of different SUSY models with different parameters
- Several times in the past (monojets at UA1- see Gary Taubes's "Nobel Dreams", CDF- the famous $ee\gamma\gamma$ event) the excitement ran quite wild about what later proved to be just very rare, but still normal SM, events ….

supersymmetry - the most elegant solution?

- Other SUSY models exist, for example the SPLIT Supersymmetry
- From the observation that the M_{EWK}-M_{Planck} hierarchy problem is not the only one (e.g: why is the cosmological constant so small $\Lambda \sim (0.002 \text{ eV})^4$ compared to M_{EWK}), one might chose to neglect the necessity to cure the EW hierarchy problem with SUSY.
- Consequences:
- Lightest Higgs and gaugino sector light (keeps dark matter candidate and GUT)
- Very heavy sfermions ~ 10^{10} GeV
- Cures problem that no indirect SUSY hints have been observed
- Very different phenomenology and experimental signature

SUSY: the "golden" candidate for "new physics"

- CDF- the famous eeγγMET event: recorded April 28, 1995 in Run-I. Its "a posteriori" probability according to SM ~10^{-6}



SUSY: the “golden” candidate for “new physics”

- LEARN SM WELL, KNOW WHAT TO IS TO BE EXPECTED, EVEN IF IT IS RARE
- Top was basically “defined” at Tevatron as what shows up in the data as physics beyond SM with 5 quarks (u,d,c,s,b)
- Top will have to be very well understood by the time LHC turns on as at ATLAS any “new physics” will show up in the data as physics beyond SM with 6 quarks (including top)
- DON’T GET TOO EXCITED, MAINTAIN CLARITY OF THOUGHT AT ALL TIMES, IF POSSIBLE

SUSY: the “golden” candidate for “new physics”

- THE NEXT 5 YEARS COULD BE VERY INTERESTING, TEVATRON AND CERTAINLY LHC WILL PROVIDE A CLOSER LOOK AT THE COMPLETELY UNEXPLORED REGION OF PHASE-SPACE

- REMEMBER THAT THE ATTRACTIVENESS OF SUSY IS REALLY PURELY ESTHETIC, AS IT SOLVES (OR AT LEAST POSTPONES) THE FINE-TUNING PROBLEM AND PROVIDES THE LINK BETWEEN FERMIONS AND BOSONS

- DISCOVERING ANY NEW PHYSICS BEYOND SM WOULD BE A BREAKTROUGH, WE DON’T KNOW WHAT IT WILL BE, IT DOES NOT HAVE TO BE SUSY