Physics at the LHC

Lecture 9: Searches for Supersymmetry at the LHC

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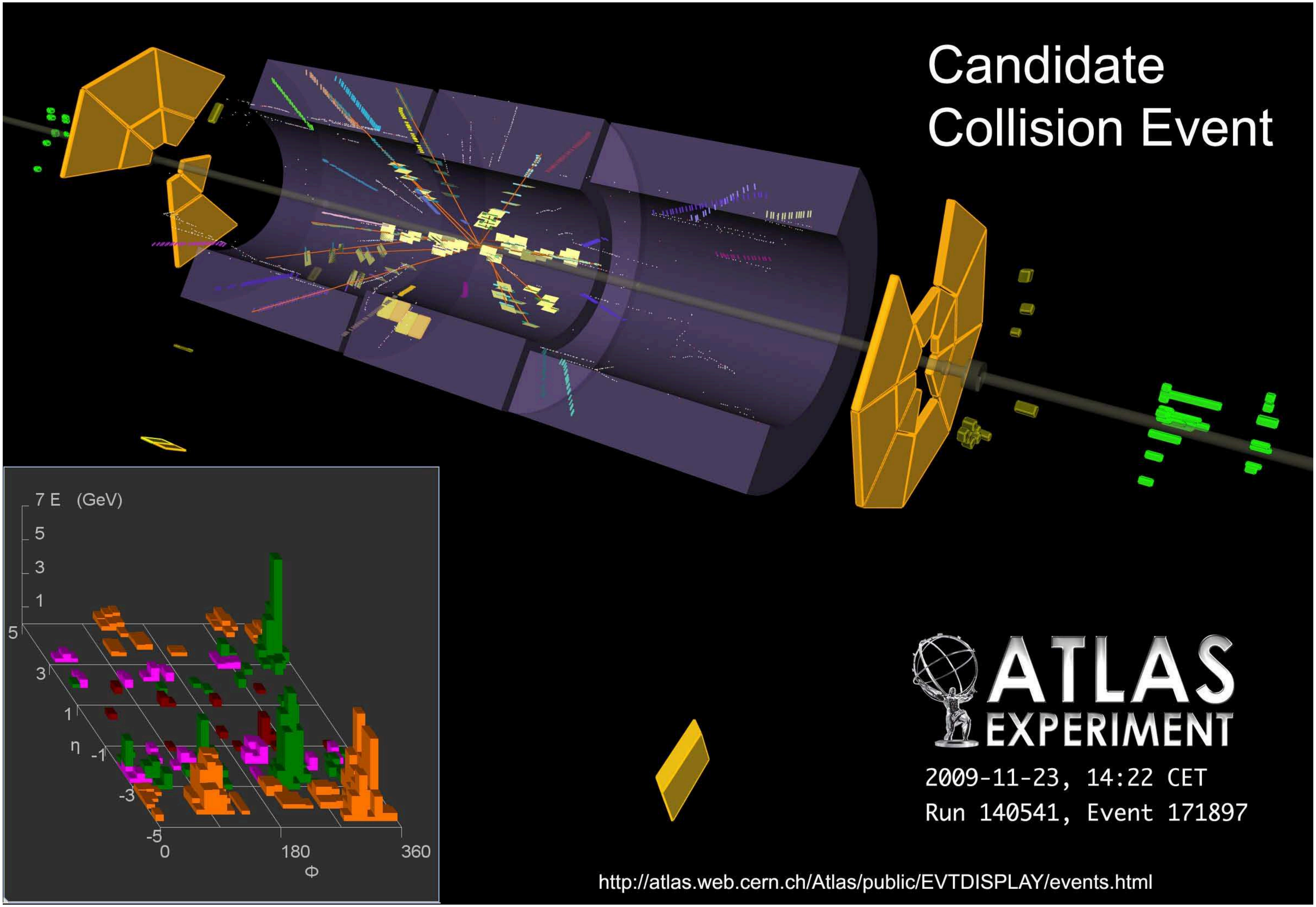
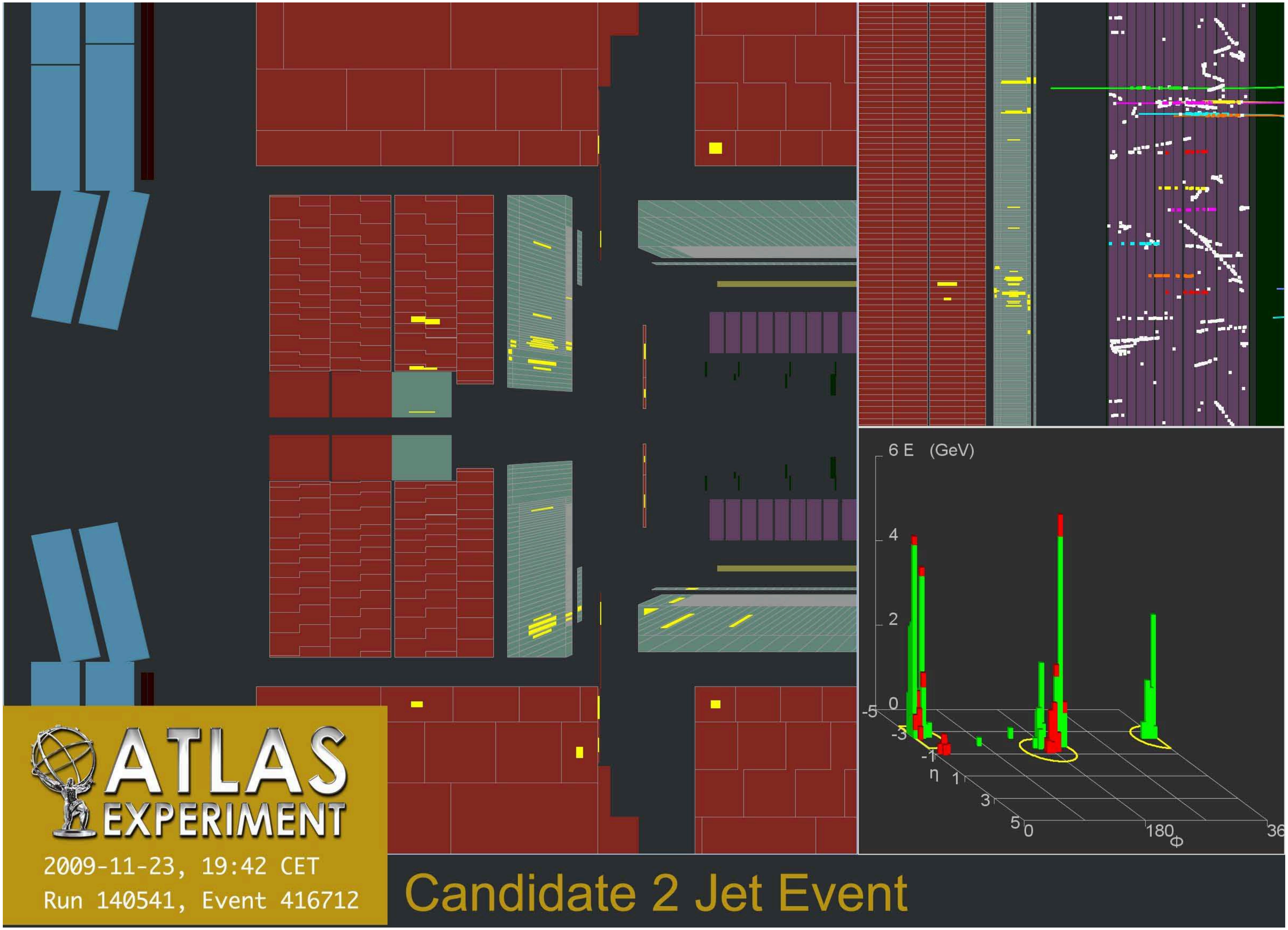
LHC status

- LHC started beam operation on November 20
- November 23: collisions in all 4 experiemnts at $\sqrt{s} = 900\,\mathrm{GeV}$, magnets off
  - first events by all experiments
  - only partial detector on to protect sensitive components
- November 29: World record for beam acceleration, both beams at 1180 GeV
- December 1: beam with solenoids on in ALICE, ATLAS, CMS
- December 6,7: Collisions at 900 GeV with four bunches, solenoids on; $\sim 20\,000$ minimum bias events per experiment
- December 9: Very short fill with collisions at $\sqrt{s} = 2.36\,\mathrm{TeV}$

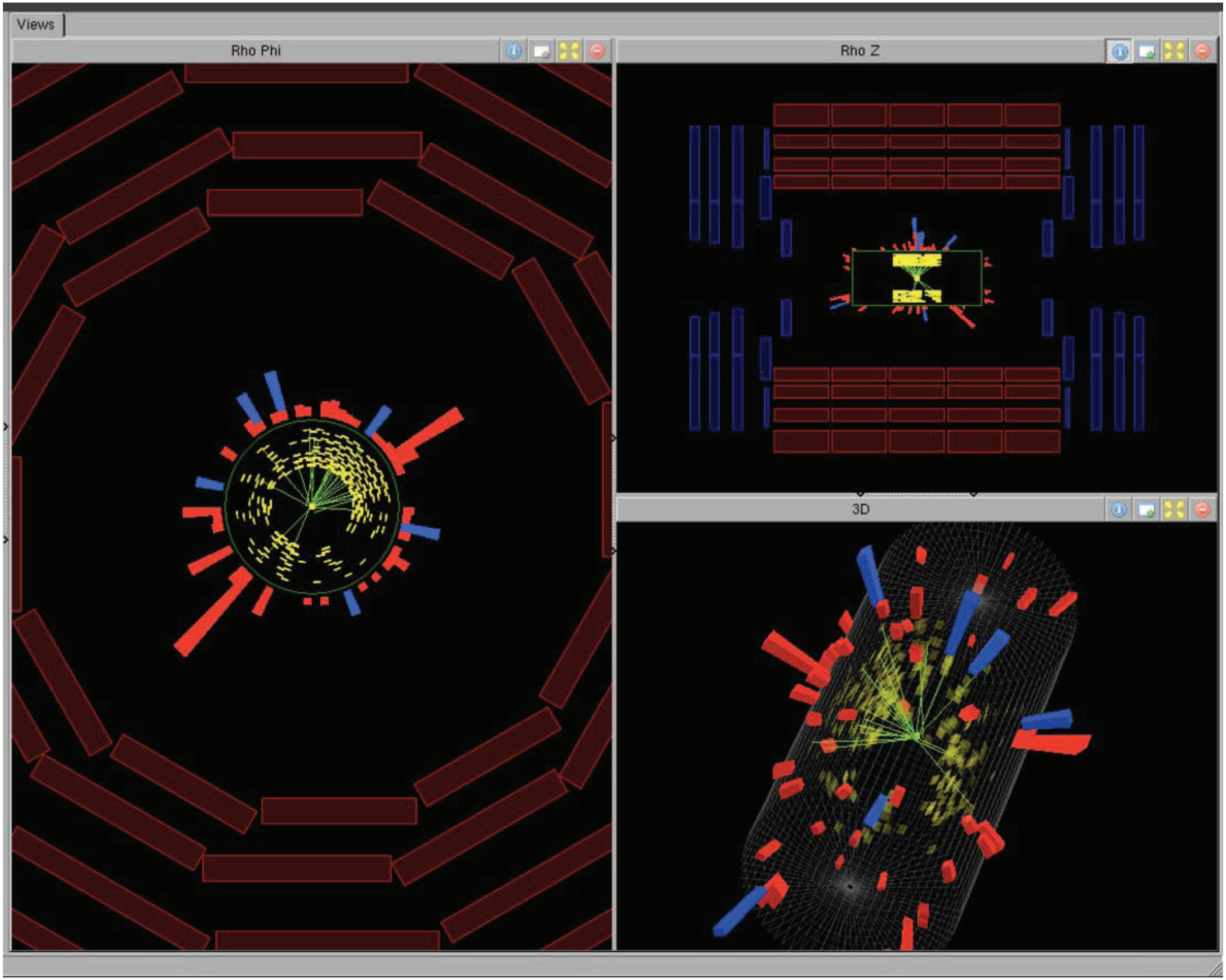
ATLAS minimum bias event



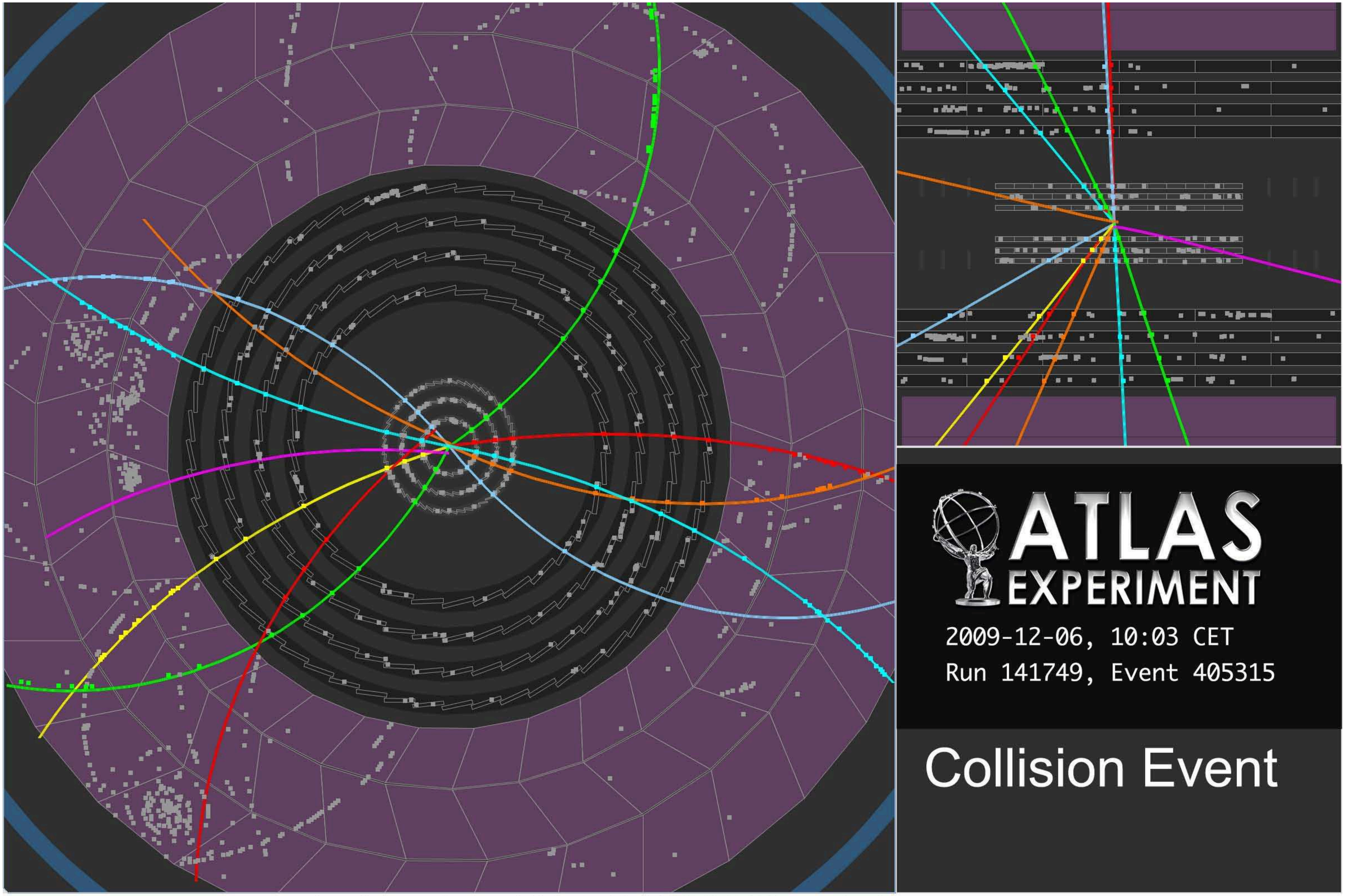
ATLAS jet event



CMS minimum bias event

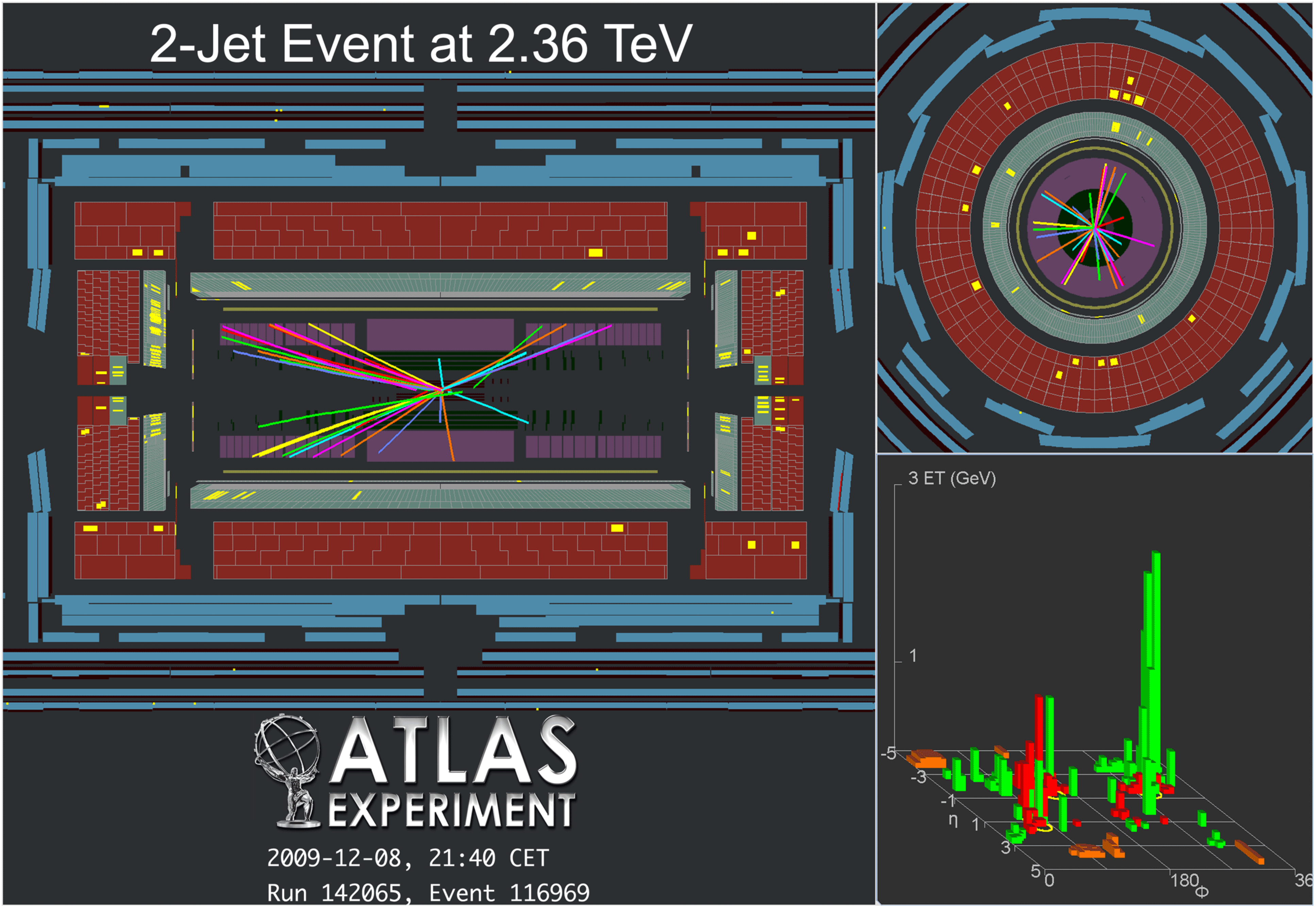


ATLAS minimum bias event with B field on

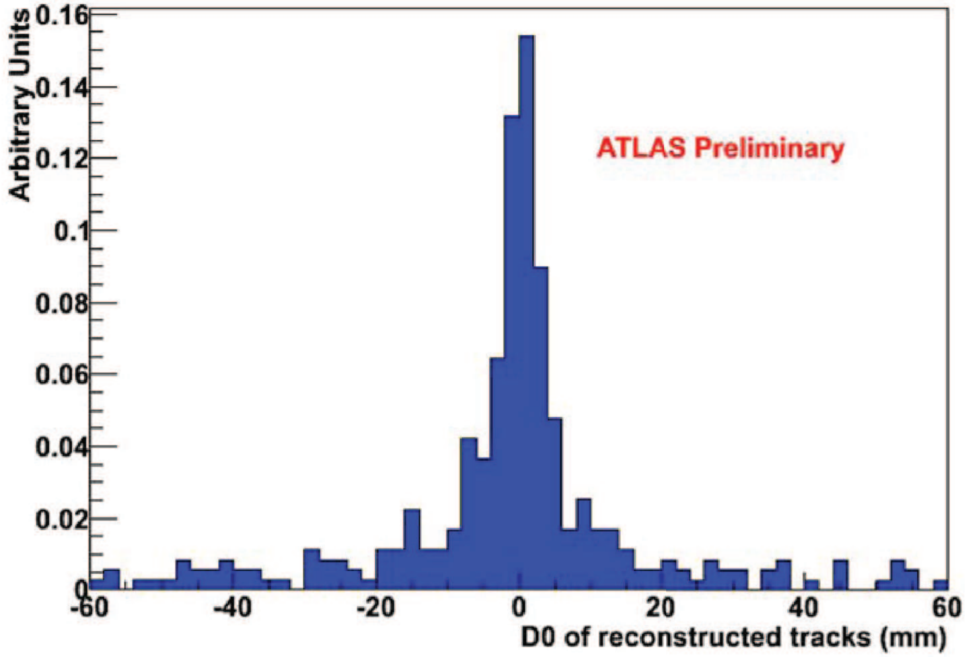


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

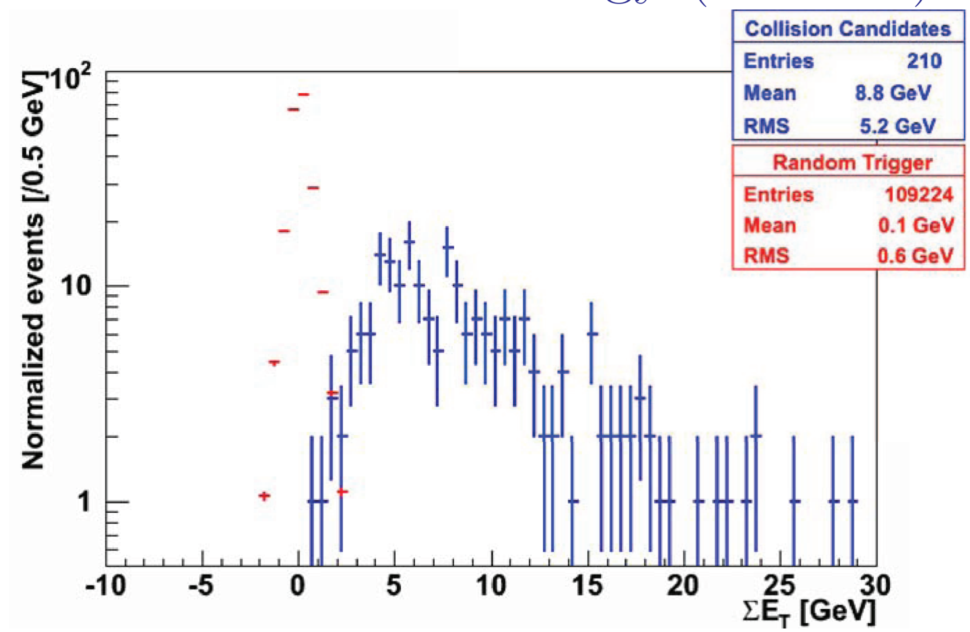
ATLAS jet event at $\sqrt{s} = 2.36$ TeV



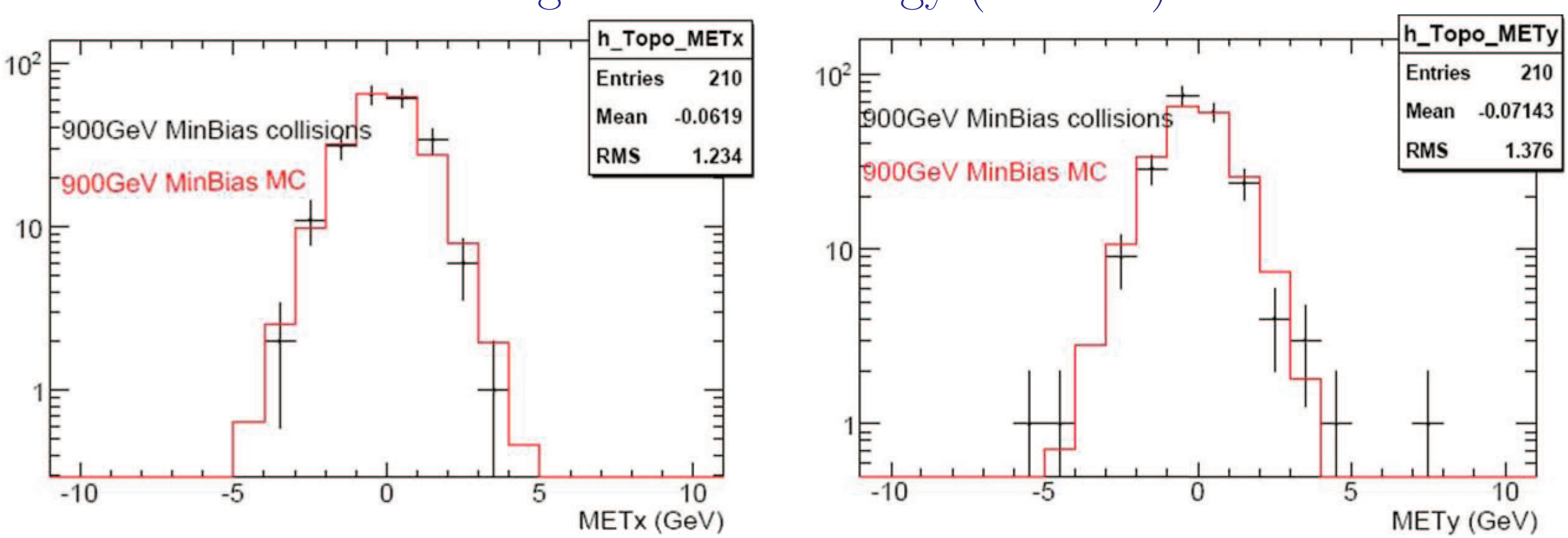
Track-impact parameter distribution



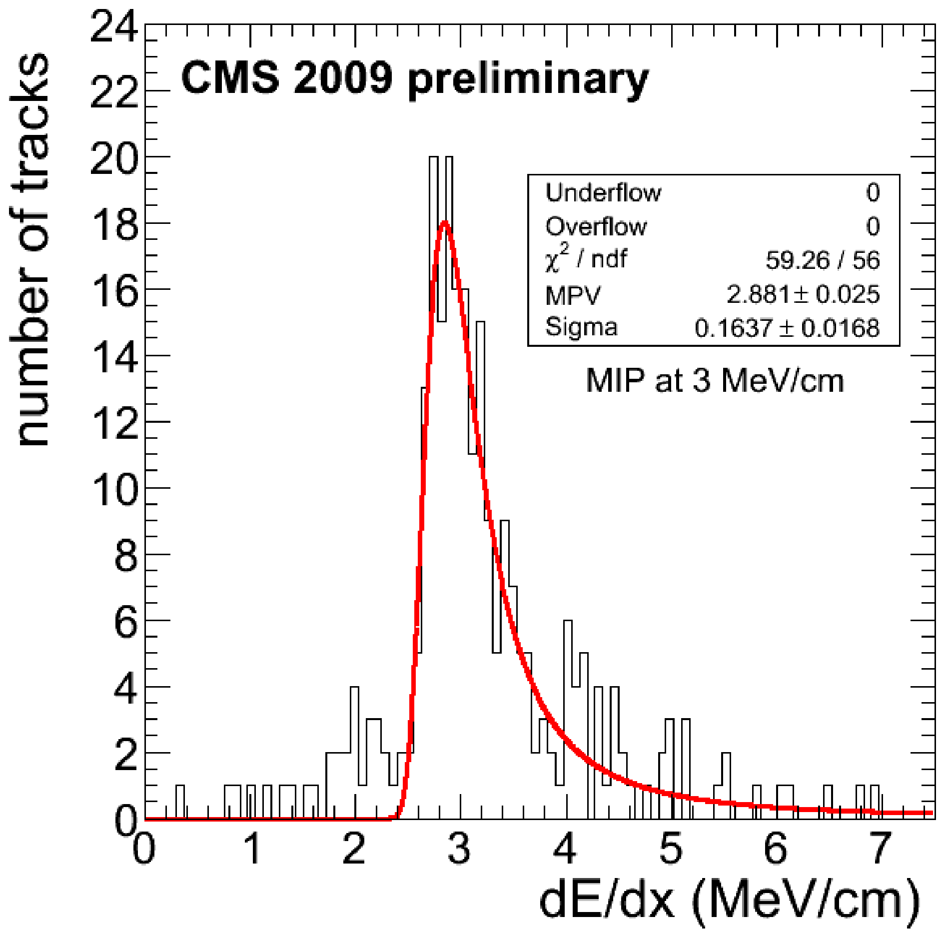
Total transverse energy (ATLAS)



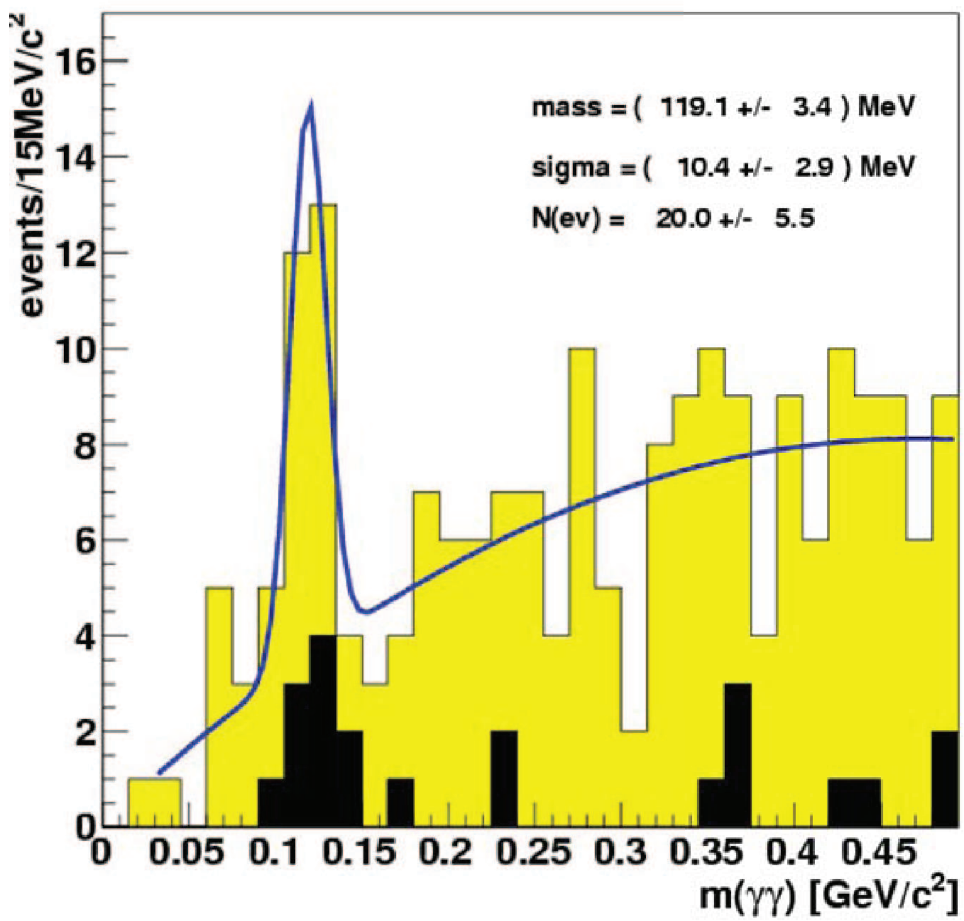
Missing transverse energy (ATLAS)



dE/dx in Silicon tracker



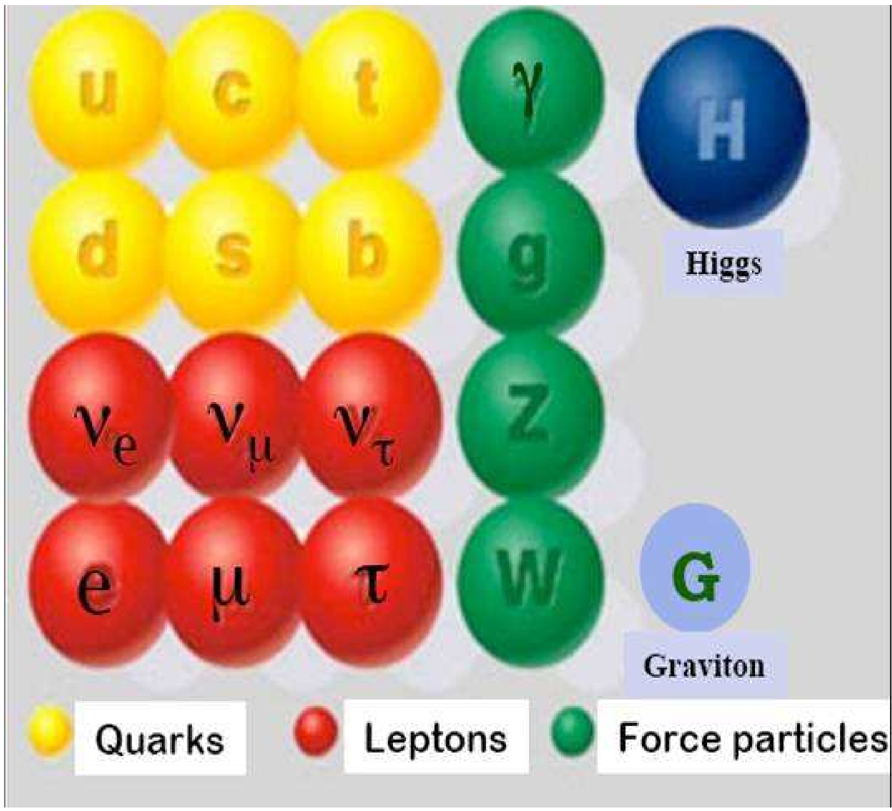
$\gamma\gamma$ invariant mass (CMS)

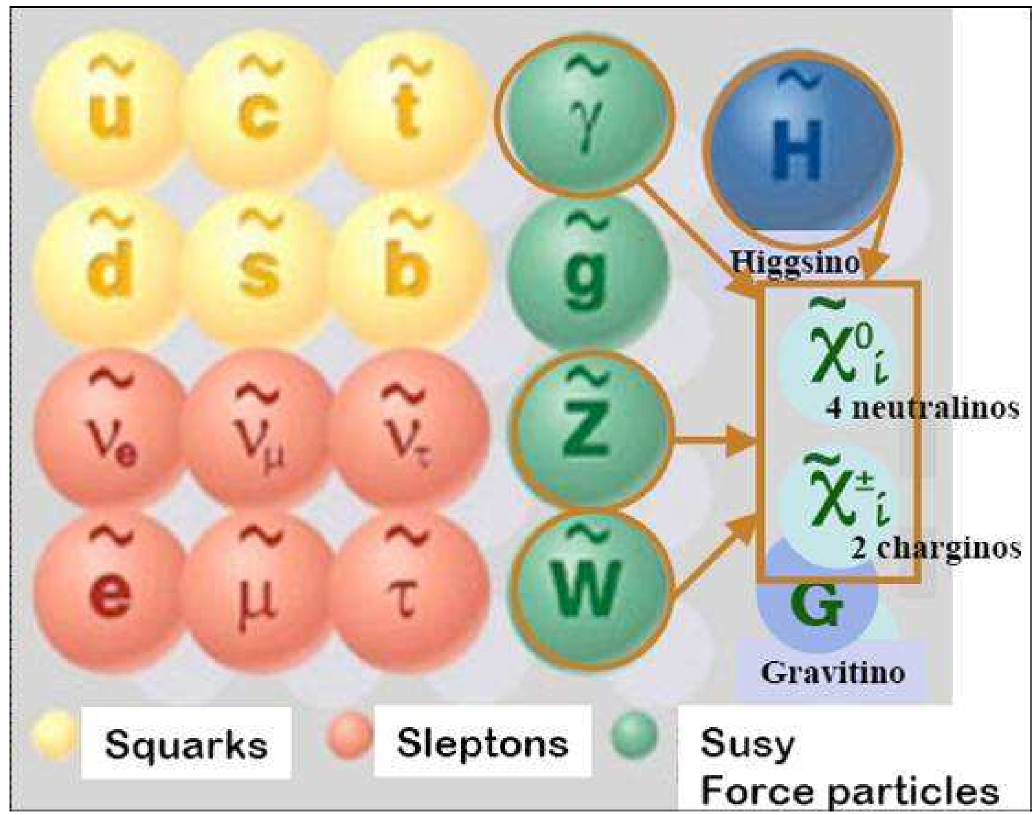


Introduction

Supersymmetry is a symmetry coupling fermions and bosons

Particle content:





Particle content:

- All known particles
- SUSY needs two Higgs doublets to give masses to up- and down-type particle
  $\Rightarrow$ 5 Higgs particles $\rightarrow$ last lecture
- Each fermion has a scalar partner (where left- and right-handed fermions have to be counted separately)
- Each boson has a fermionic partner:
  - Two charginos $\chi^{\pm}_{1,2}$ ($m_{\chi^{\pm}_1} < m_{\chi^{\pm}_2}$), partner of $W^{\pm}, H^{\pm}$, mixed
  - Four neutralinos $\chi^0_{1,2,3,4}$ ($m_{\chi^0_1} < ... < m_{\chi^0_4}$), partner of γ, Z, h, H, mixed
  - gluinos ($\tilde{g}$), gravitino ($\tilde{G}$)

However $m_{\text{Particle}} \neq m_{\text{Partner}}$ $\Rightarrow$ SUSY is broken

Need $m_{\text{SUSY}} < 1\text{TeV}$ to solve hierarchy-problem

In general > 100 new free parameters $\Rightarrow$ have to make some assumptions how they are correlated

SUSY-breaking parameters in the minimal model (MSSM):

- $U(1), SU(2), SU(3)$ Gaugino-masses $M_{1,2,3}$
- Higgsino mass-parameter μ
- Scalar-masses m_i (or universal m_0)
- Sfermion-Higgs couplings A_i, B_i

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

($R = 1$ for SM particles, $R = -1$ for superpartners)

R-parity conservation

- Protects proton decay
- SUSY-particles only in pairs
- Lightest SUSY particle (LSP) is stable

➠ Excellent dark matter candidate (which means LSP must be neutral and weakly interacting)

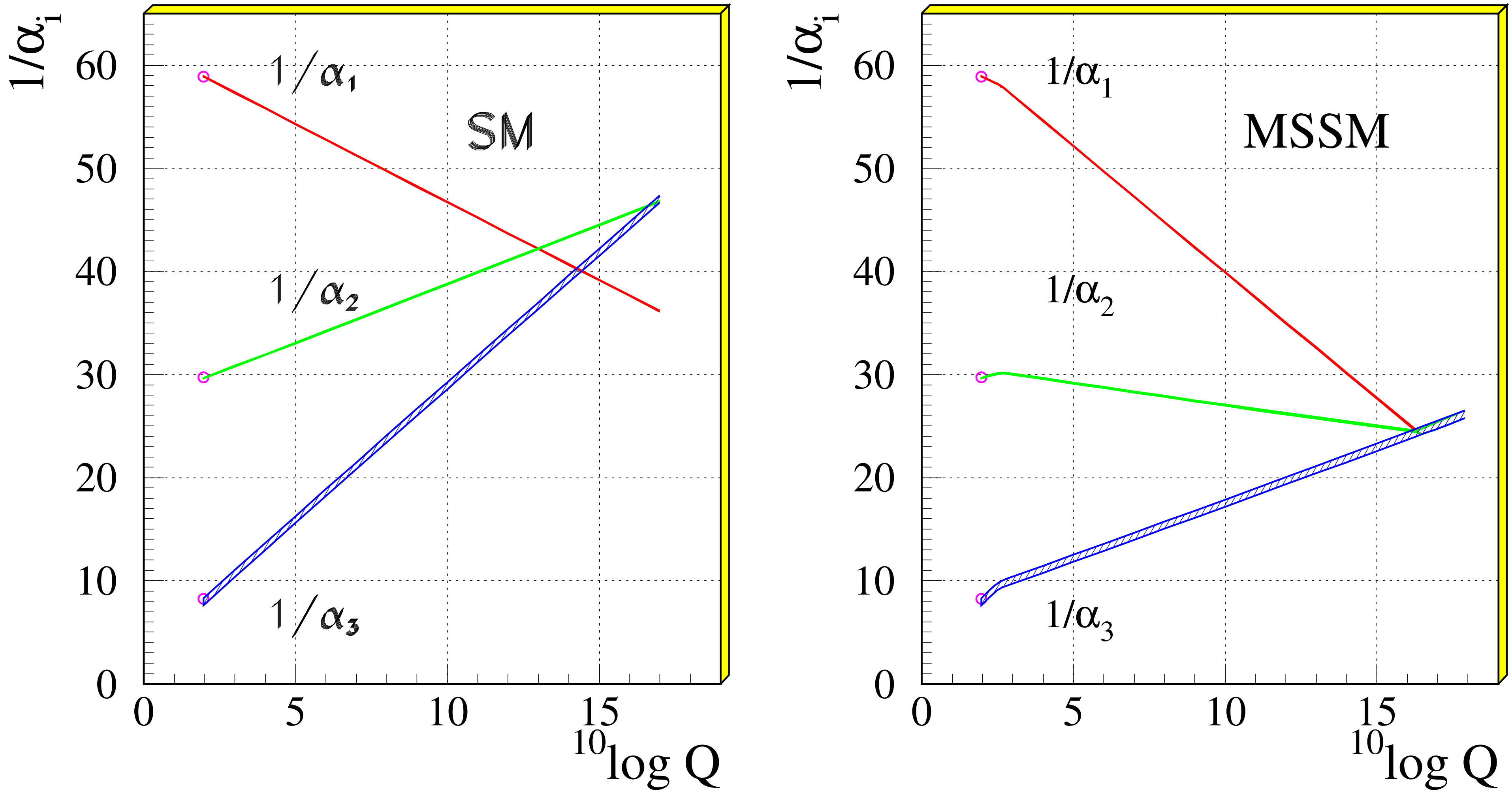
R-parity can also be broken

- Very rich phenomenology
- However special care has to be taken to avoid proton decay

Why SUSY in a nutshell

- Hierarchy problem:
  - SM particles give huge loop-contribution to Higgs mass ($\mathcal{O}(10^{19}\,\mathrm{GeV})$)
    ➠ unnatural
  - SUSY partners exactly cancel the contributions from SM particles (if SUSY exact)
- SUSY gives a good dark matter candidate
- SUSY can be a new source of CP-violation
  ➠ may explain the matter/anti-matter asymmetry in the universe
- String theories are the only known way to connect gravity with quantum mechanics
  ➠ all string theories are supersymmetric
- SUSY enables unification of forces at a high scale

Running of coupling constants with and without SUSY



SUSY breaking schemes

Gravity mediated SUSY breaking

- SUSY is broken at a high scale by gravitational interaction to a hidden sector
- Gauge coupling unification at the GUT scale ($m_{\rm GUT} \sim 10^{16}\,$GeV) possible

➨ Common gaugino mass $m_{1/2}$ at $m_{\rm GUT}$
$\Rightarrow \frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}$ at the weak scale

- Often also universal scalar mass m_0 assumed
- Slepton masses:

$$\begin{aligned} M^2_{\tilde{\nu}} &= m_0^2 + 0.77 M_2^2 + 0.5 m_{\rm Z}^2 \cos 2\beta \\ M^2_{\tilde{\ell}_L} &= m_0^2 + 0.77 M_2^2 - 0.27 m_{\rm Z}^2 \cos 2\beta \\ M^2_{\tilde{\ell}_R} &= m_0^2 + 0.22 M_2^2 - 0.27 m_{\rm Z}^2 \cos 2\beta \end{aligned}$$

- Squark masses similar with M_3^2 term
- L-R sfermion mixing $\propto m_f(A_f - \mu \tan\beta)$ only relevant for 3rd generation

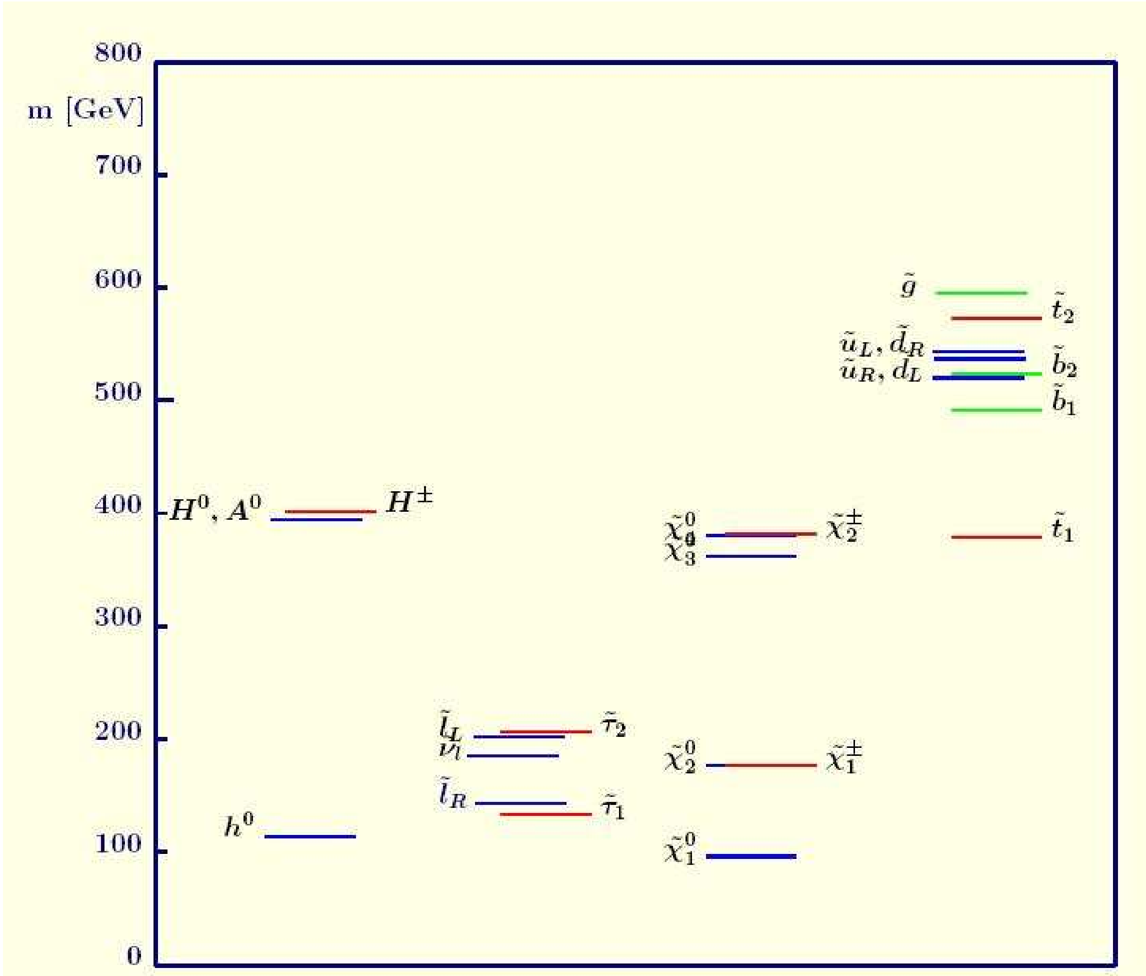
- Chargino mass matrix

$$\mathcal{M}_\chi = \begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

  detailed properties of $\chi^\pm_{1,2}$ (gaugino-,Higgsino-like) depend on values of parameters
- Neutralinos similar

"Typical" mass spectrum
($m_0 = 100\,\mathrm{GeV}, m_{1/2} = 200\,\mathrm{GeV}$)

$$\begin{aligned} m_{\chi^0_1} &\sim 100\,\mathrm{GeV} \\ m_{\chi^\pm_1,\chi^0_2} &\sim 160\,\mathrm{GeV} \\ m_{\chi^\pm_2,\chi^0_{3,4}} &\sim 350\,\mathrm{GeV} \\ m_{\tilde{\ell}} &\sim 150\,\mathrm{GeV} \\ m_{\tilde{q}} &\sim 500\,\mathrm{GeV} \end{aligned}$$



- Of course all moves with m_0, $m_{1/2}$
- $m_{\tilde{t}_1}$ can be moved arbitrarily by changing A

mSUGRA

The minimal model which is mostly studied is given by:

- Gravity mediated SUSY breaking
- Minimal Higgs sector (2 doublets)
- Unification of masses at the GUT scale
- Free parameters
  - m_0: universal scalar mass at GUT scale
  - $m_{1/2}$: universal fermion mass at GUT scale
  - $\tan\beta$: ratio of Higgs vacuum expectation value
  - A_0: universal trilinear coupling at GUT scale
  - $\mathrm{sign}(\mu)$: the absolute value of μ is given by electroweak symmetry breaking

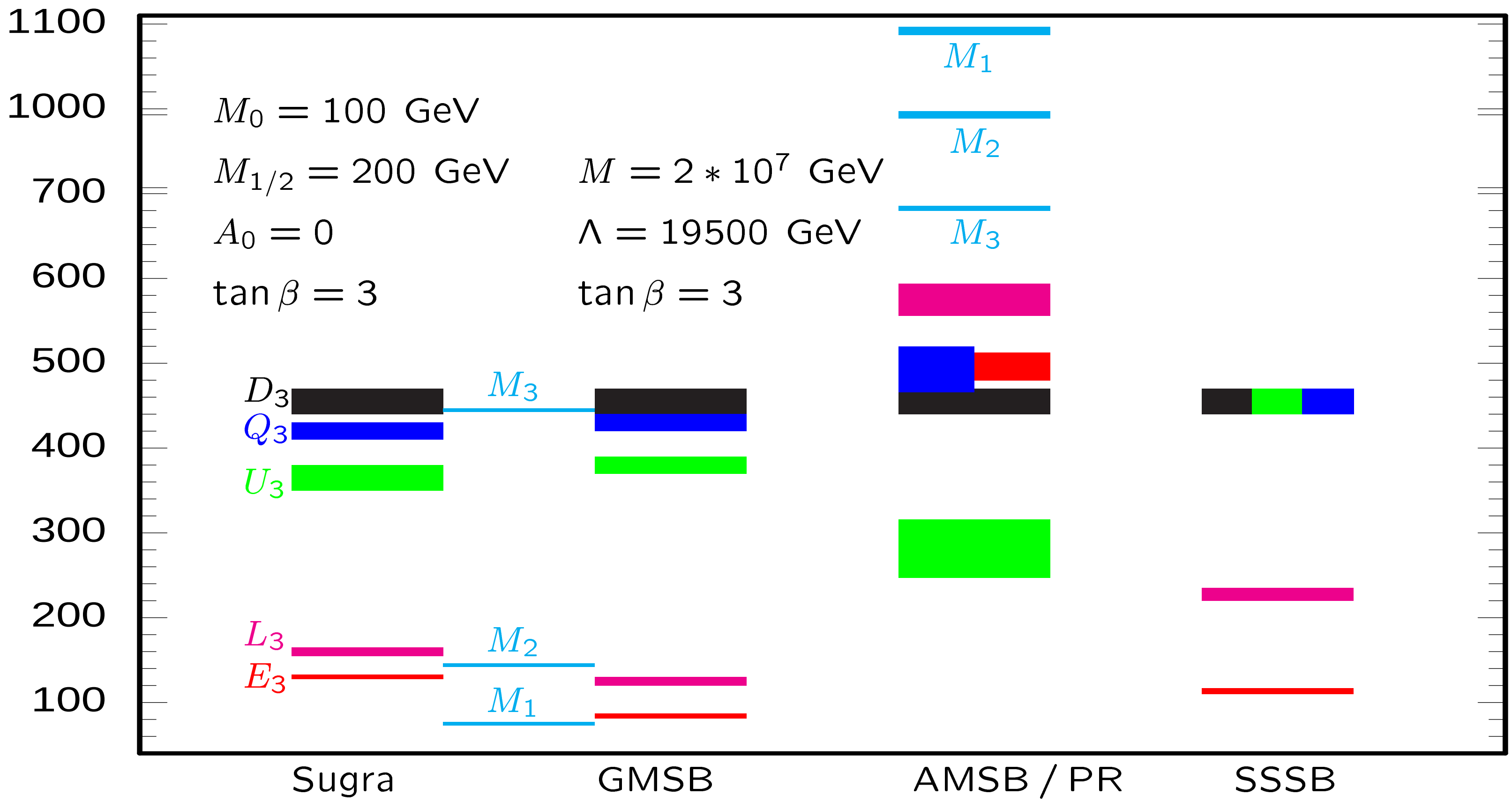
Gauge mediated SUSY breaking

- SUSY is broken at intermediate scales ($10^3 - 10^8$ GeV) by gauge interactions involving messengers between the visible and the hidden sector
- Main free parameters:

M_{mess}	messenger mass scale
N_{mess}	number of messenger generations
Λ	universal soft braking scale
$\tan\beta$	
$\mathrm{sign}(\mu)$	

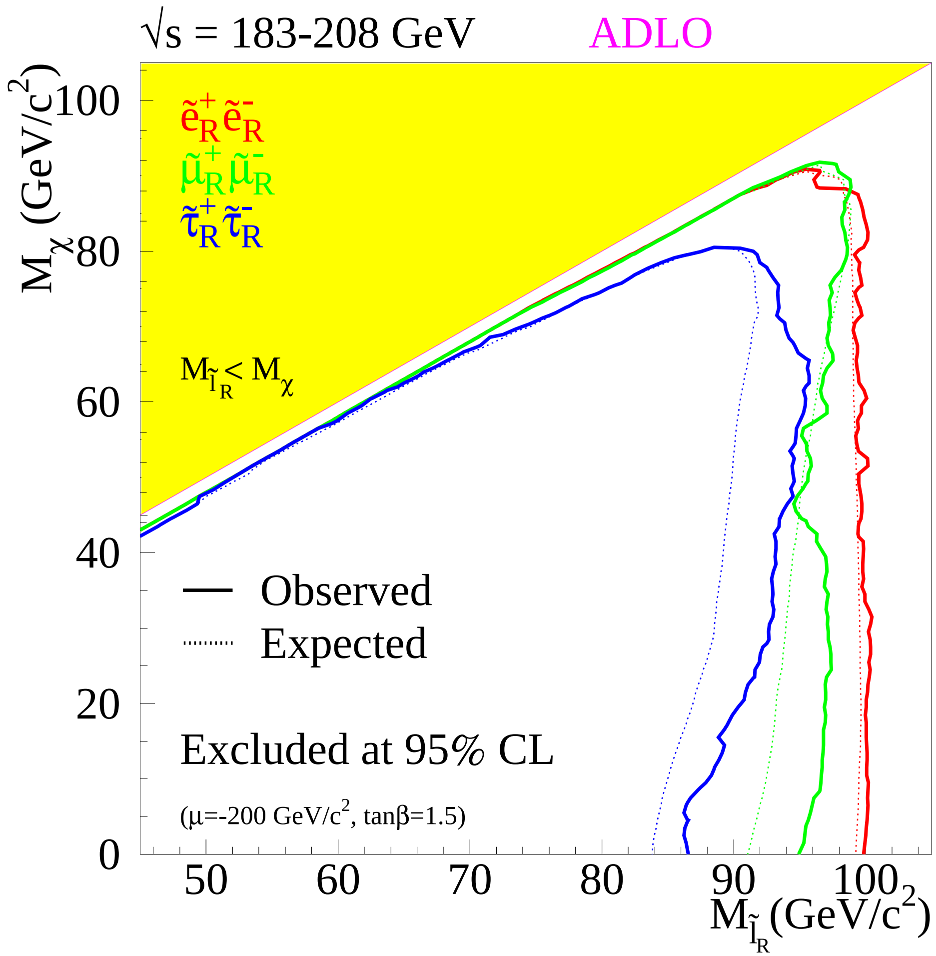
- Main differences to SUGRA
  - very light gravitino $\sim$ eV
  - NLSP either χ_1^0 with $\chi_1^0 \to \tilde{G}\gamma$ or $\tilde{\ell}$ with $\tilde{\ell} \to \tilde{G}\ell$ (if mixing is large in 2nd case, $\tilde{\tau}_1$ is NLSP)
    in both cases NLSP lifetime can be significant
  - sfermion masses $\propto \alpha_i$, $i =$QED,QCD
    $\Rightarrow$ larger mass splitting between sleptons and squarks

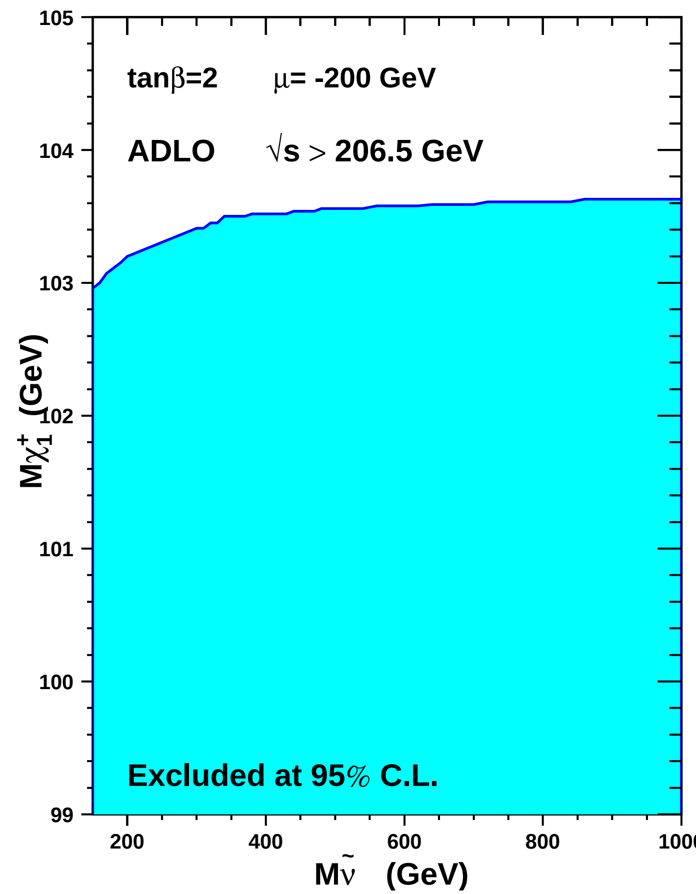
Gaugino and Sfermion Mass Parameters



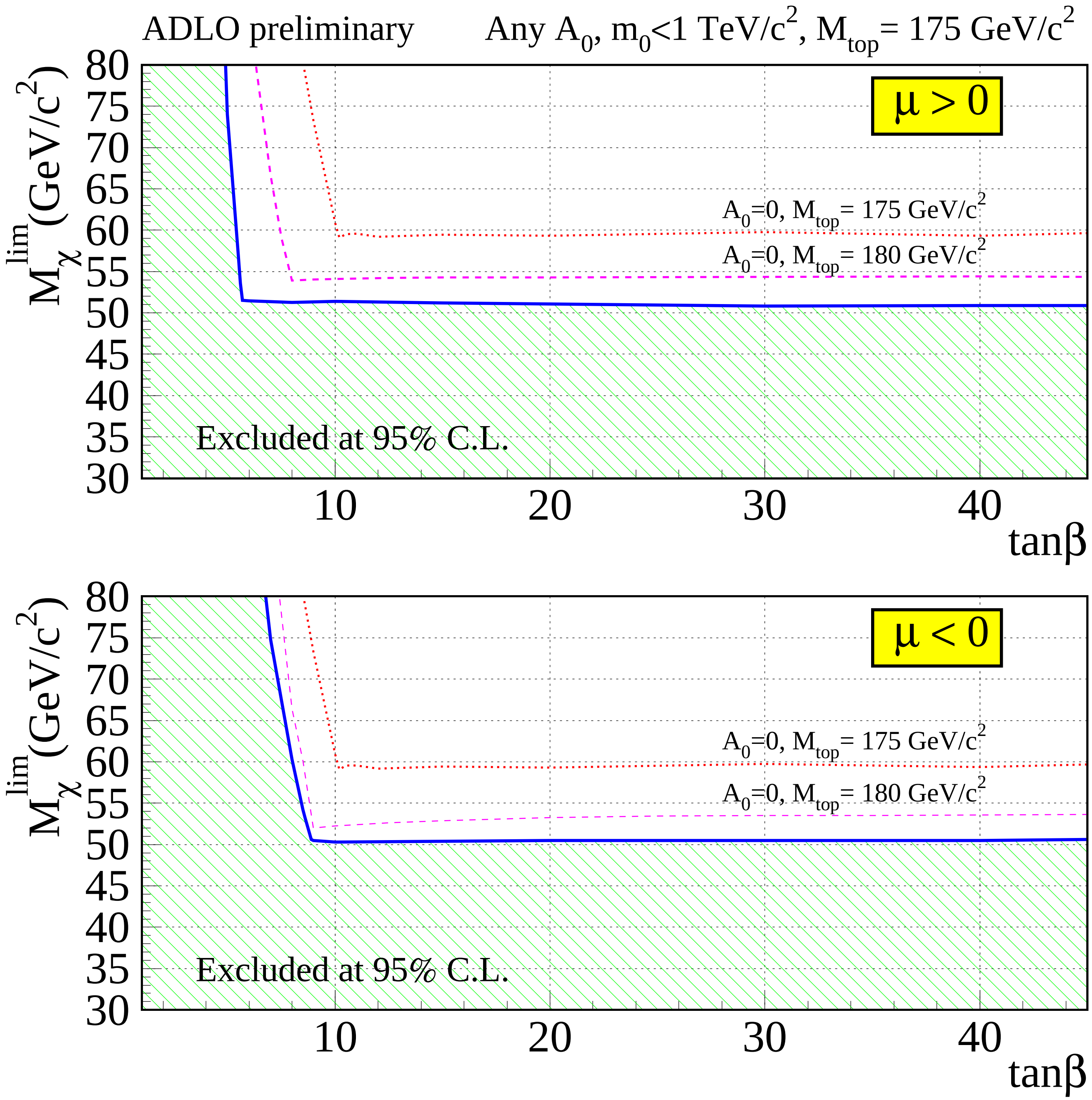
SUSY limits

- Searches for SUSY at all past accelerators
- Most stringent model independent limits from LEP
  $m_{\tilde{s}} \gtrsim 100\,\mathrm{GeV}$ for $\tilde{s} \neq$LSP



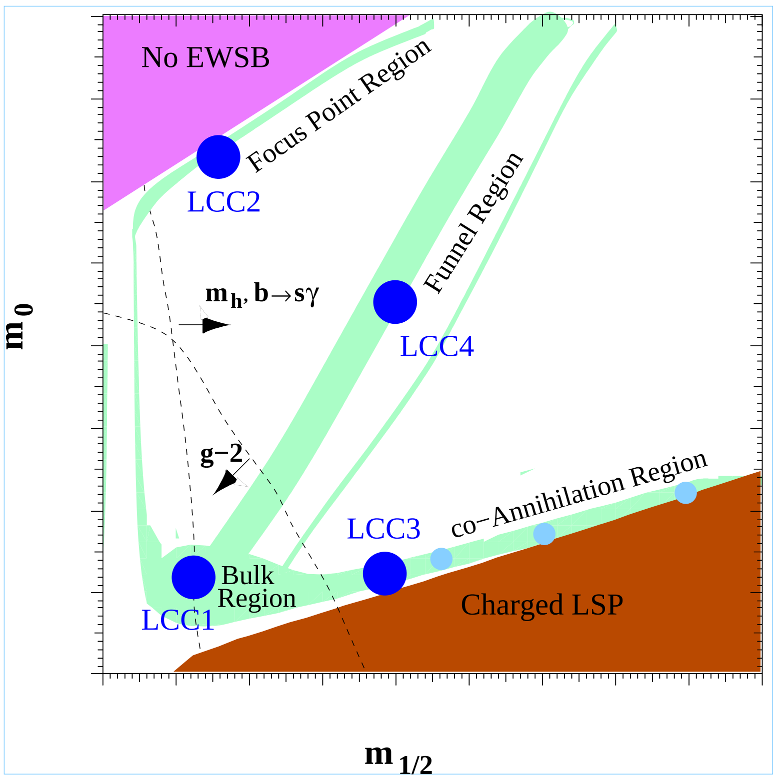


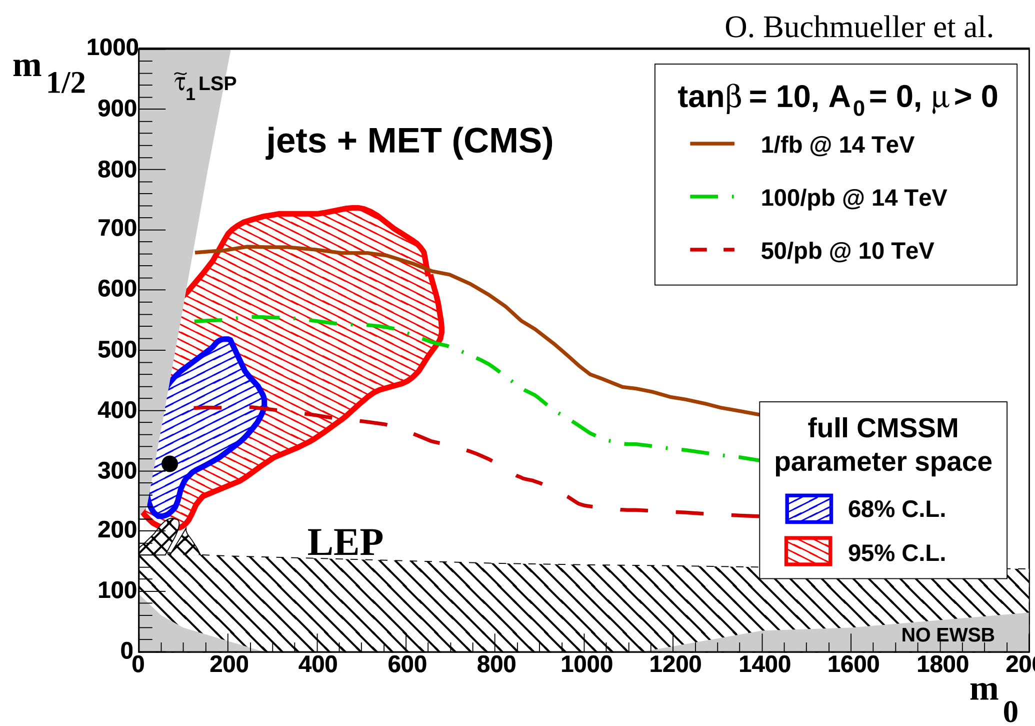
For the LSP a limit is possible assuming minimal SUGRA



Where do we expect SUSY

- Hierarchy problem suggests that SUSY is below 1 TeV
- $(g-2)_\mu$ can be best explained by SUSY just above the LEP limit (however not all corrections fully understood)
- Cosmology also prefers light SUSY with some bands extending to high masses

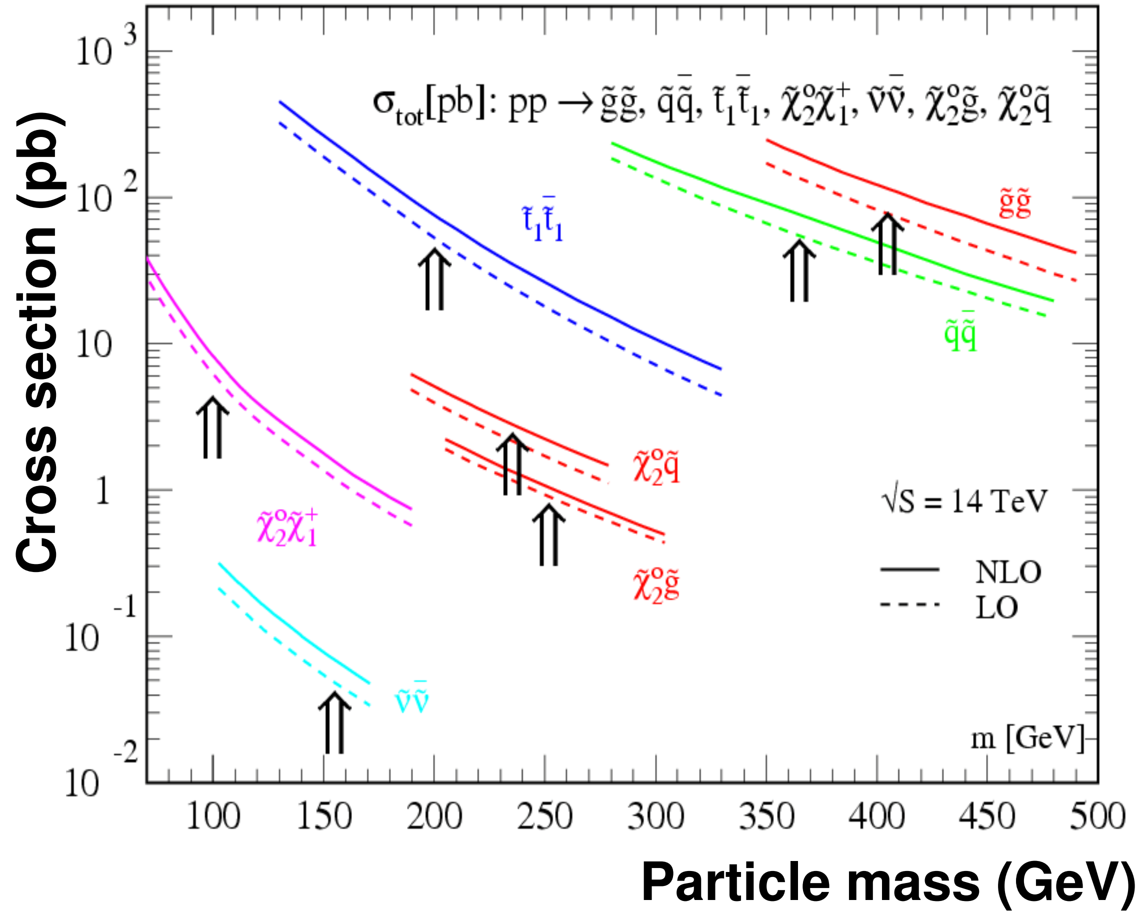




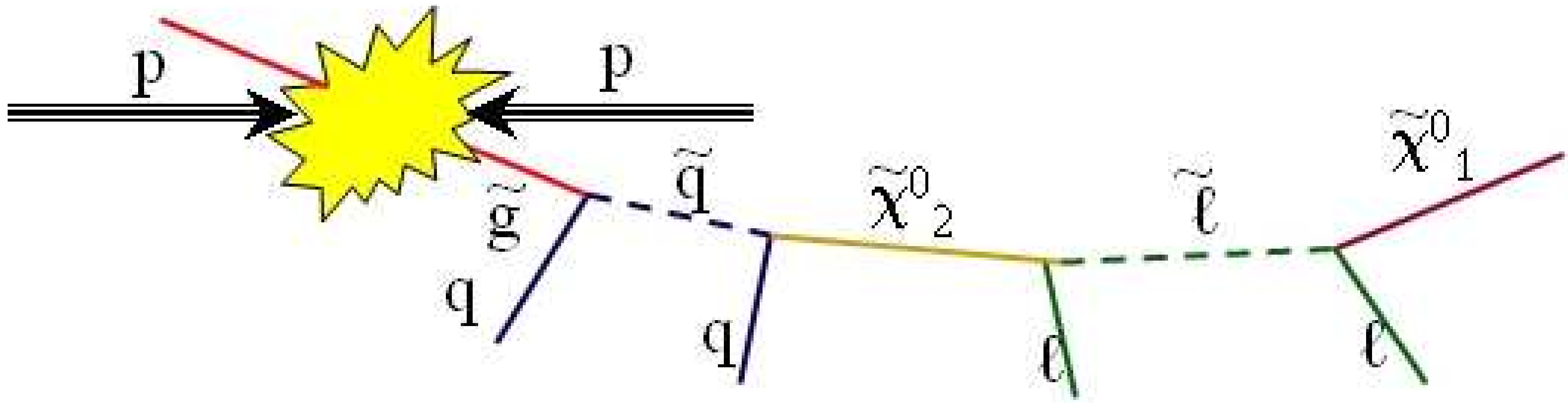
SUSY at the LHC

- Most studies are within mSUGRA with R-parity conservation
- R-parity conservation results in stable, invisible LSP ➠ missing E_T

- Squarks and gluinos are strongly interacting ➠ Large cross sections even at high masses



- Squarks and gluinos decay in long chains
  ➠ also access to charginos, neutralinos, sleptons

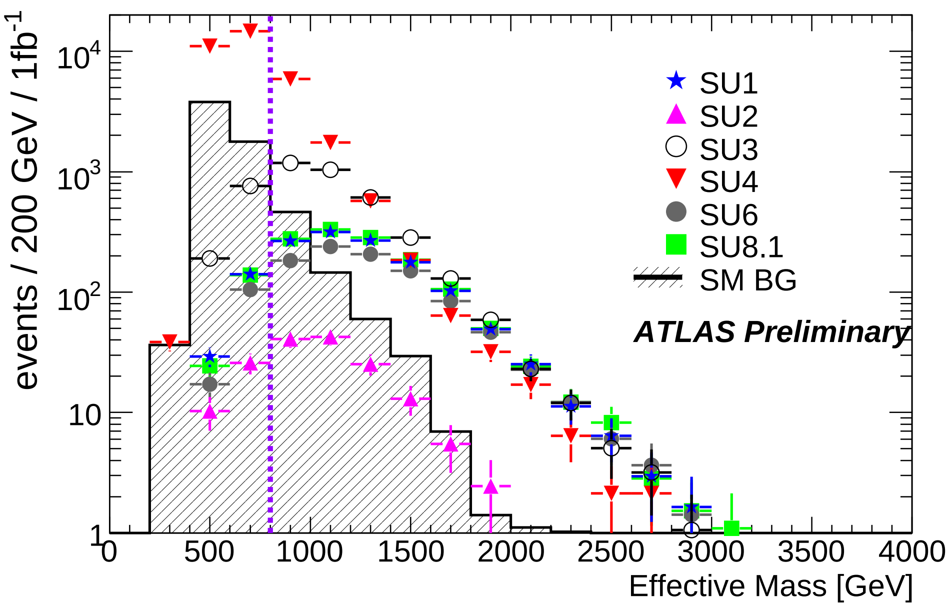


- Cascades produce also leptons ➠ easier background rejection

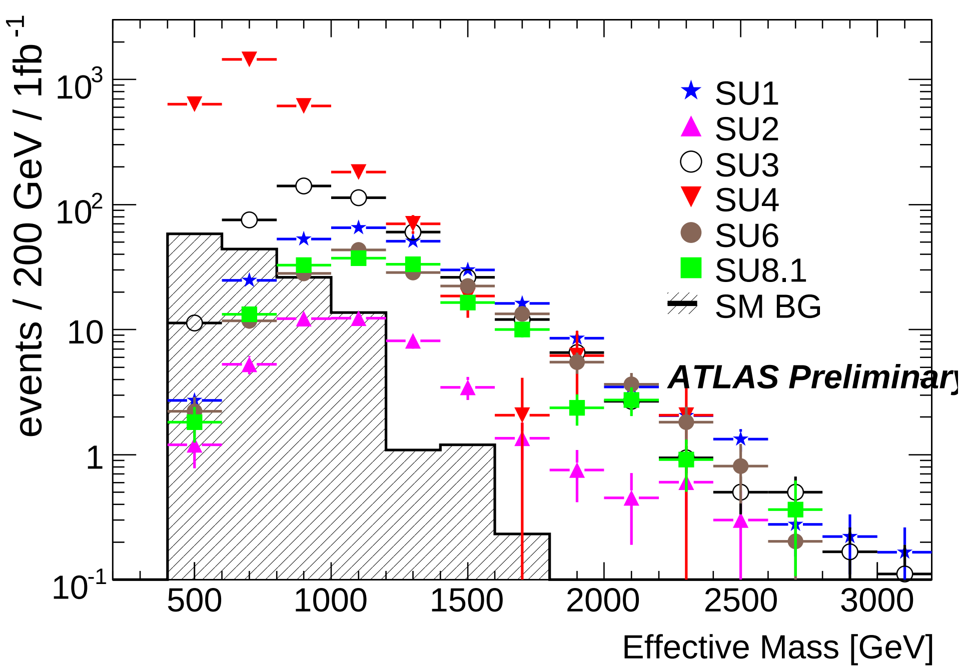
SUSY discovery modes

- 2 missing LSPs per event don't allow to reconstruct mass-peaks
- However they result in large missing E_T
- Leptons can help to reduce background
- Typical preselection: ≥ 4 jets, $E_T^{\text{miss}} > 100\,\text{GeV}$
- Separating variable: $M_{\text{eff}} = E_T^{\text{miss}} + \sum p_T^i$

0-lepton mode



1-lepton mode



Even cleaner: 2 leptons

- Most events start with $\tilde{g}\tilde{g}$ ➠ charge symmetric

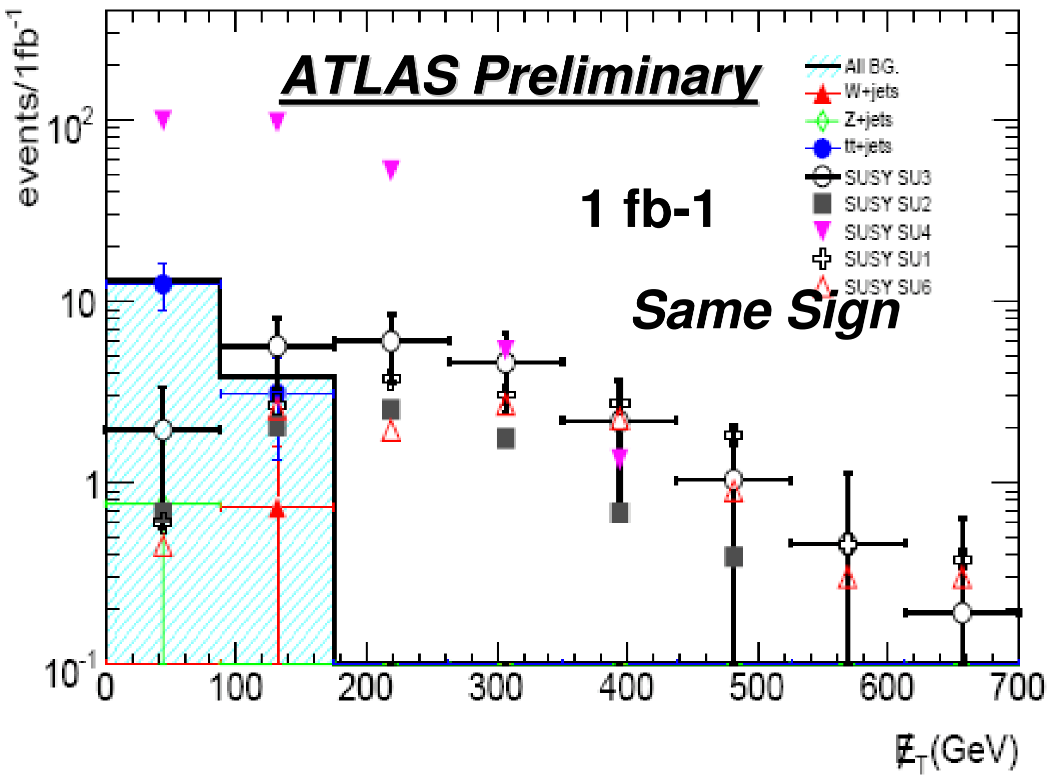
➠ There is no charge correlation of leptons from different $\tilde{g}$

➠ The probability for same-charge and opposite-charge lepton pairs is equal

- On the contrary SM events with two leptons like , Z-production, W^+W^- production produce opposite-charge pairs

➠ Very clean sample

- However less events

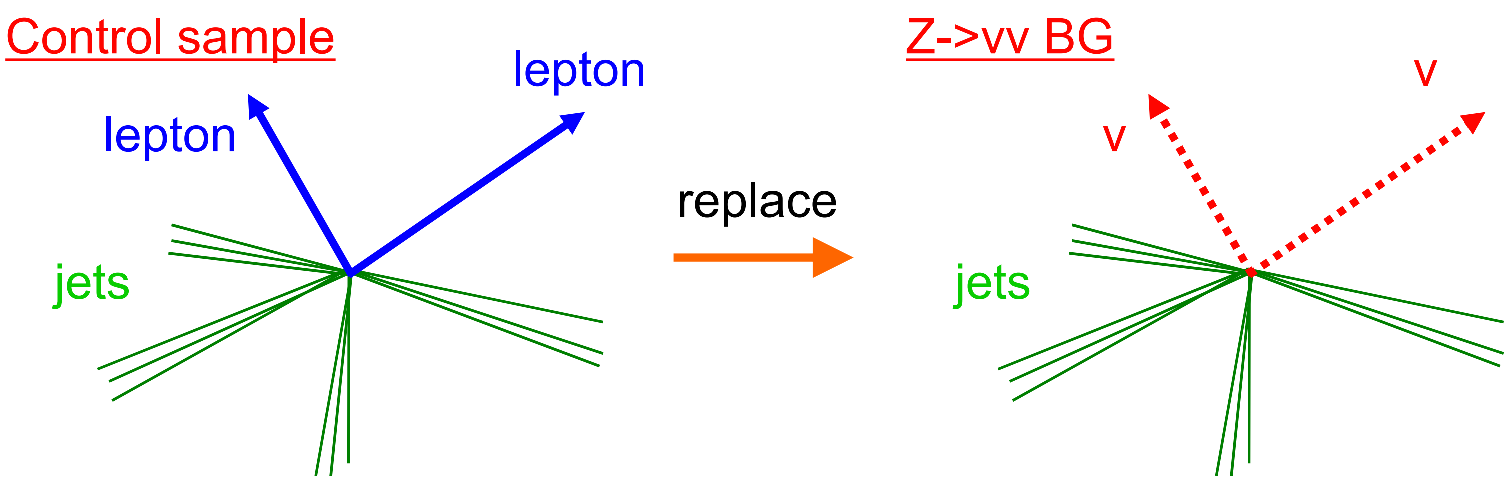


How to understand the background

QCD multijet background is difficult to predict

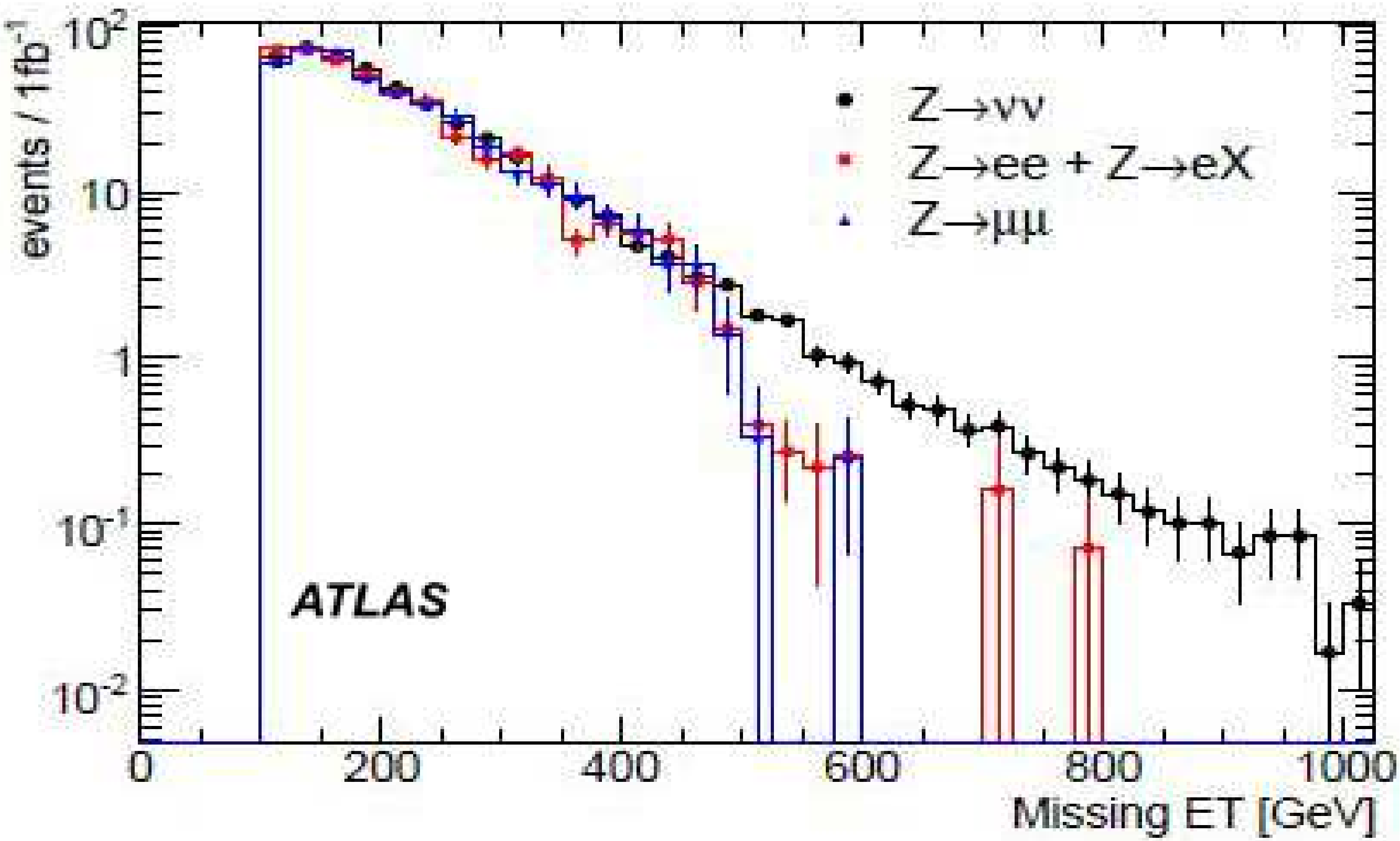
➠ better to estimate with data

Example: Z+jets events:



- Select Z+jet events with $Z \longrightarrow \ell^+\ell^-$
- Calculate E_T^{miss} removing leptons
- Use MC to verify procedure (and get small corrections)

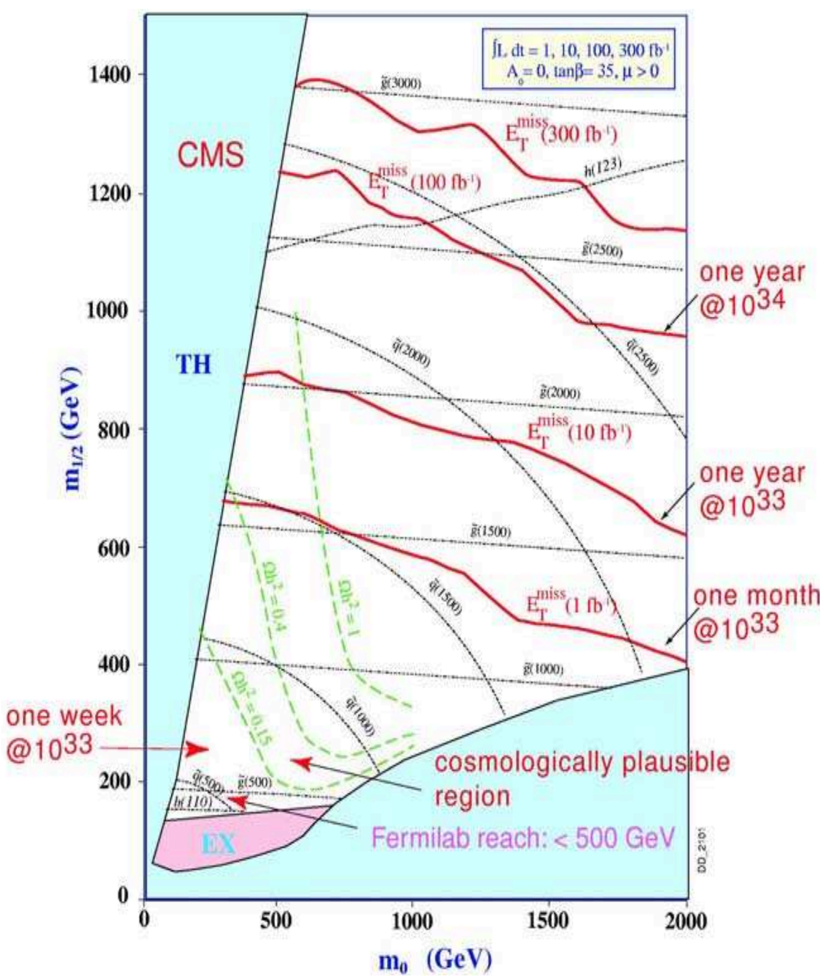
Procedure works well



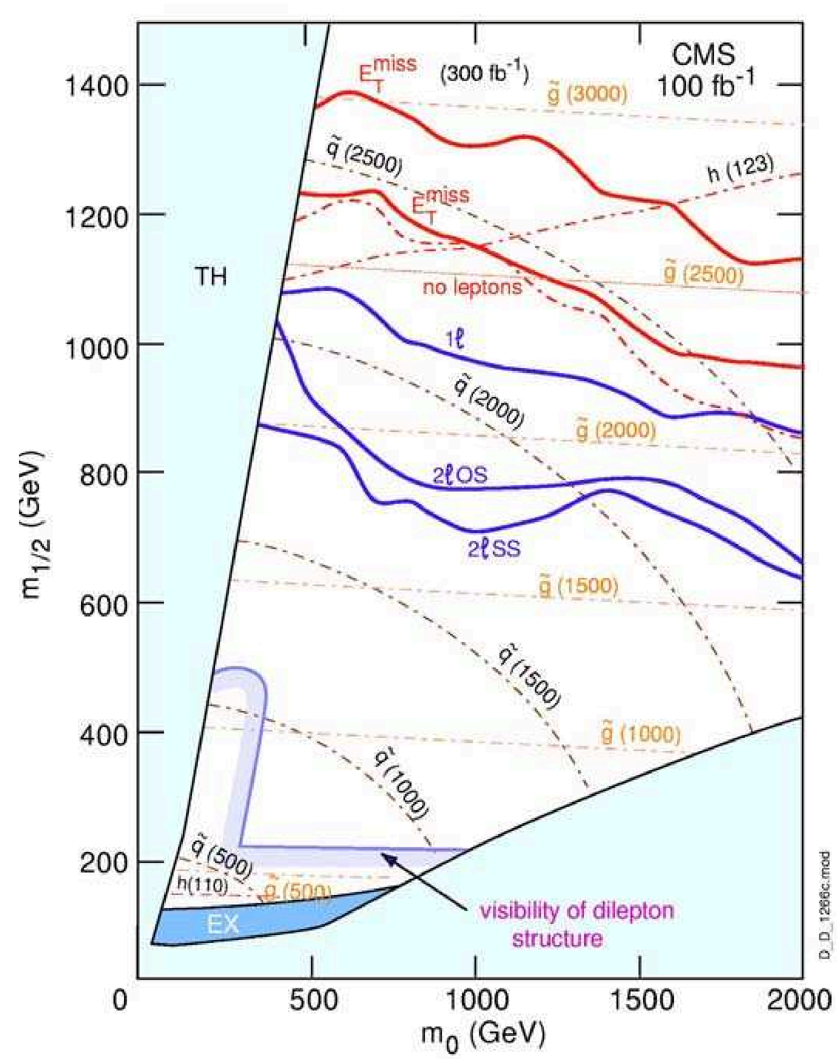
However $BR(Z \to \nu\nu)/BR(Z \to \ell\ell) \approx 6 \Rightarrow$ statistical errors increase

LHC reach for discovering SUSY

- The 1 TeV region can be excluded already after a very short time
- With 300 fb^{-1} masses of $\sim 3\,$TeV can be excluded



- In most of the region several signatures are visible



How to measure SUSY properties?

- Two missing LSPs with unknown mass
  ➠ no mass peaks can be reconstructed
- Simplest case 3-body decays, e.g.: $\chi_2^0 \to Z^* \chi_1^0 \to \ell\ell\chi_1^0$:

$$m(\ell\ell) < m(\chi_2^0) - m(\chi_1^0)$$

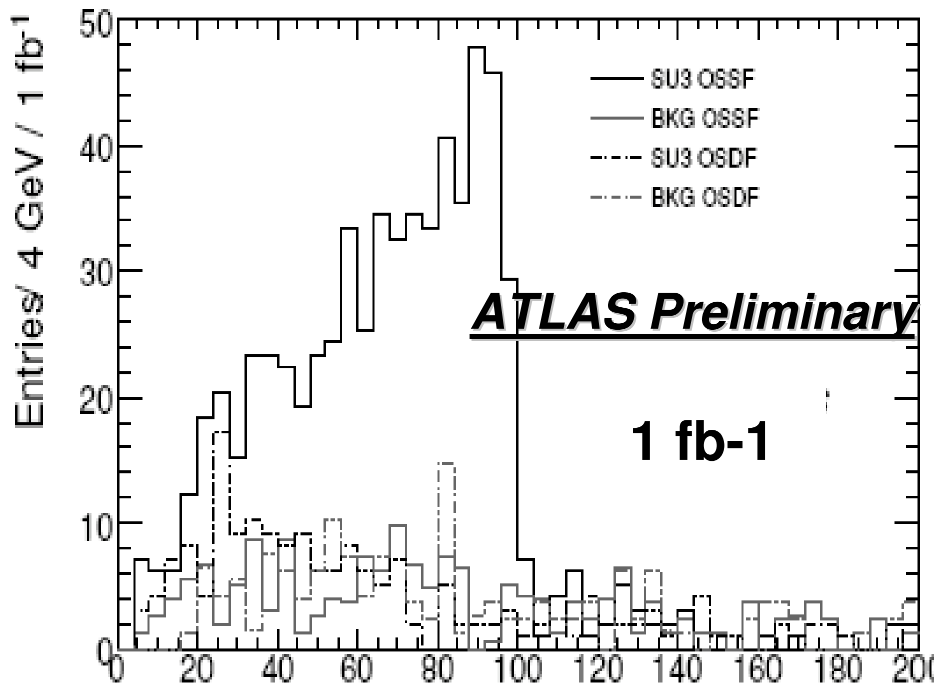
- More complicated case sequential 2-body decays: $\chi_2^0 \to \tilde{\ell}\ell \to \ell\ell\chi_1^0$:

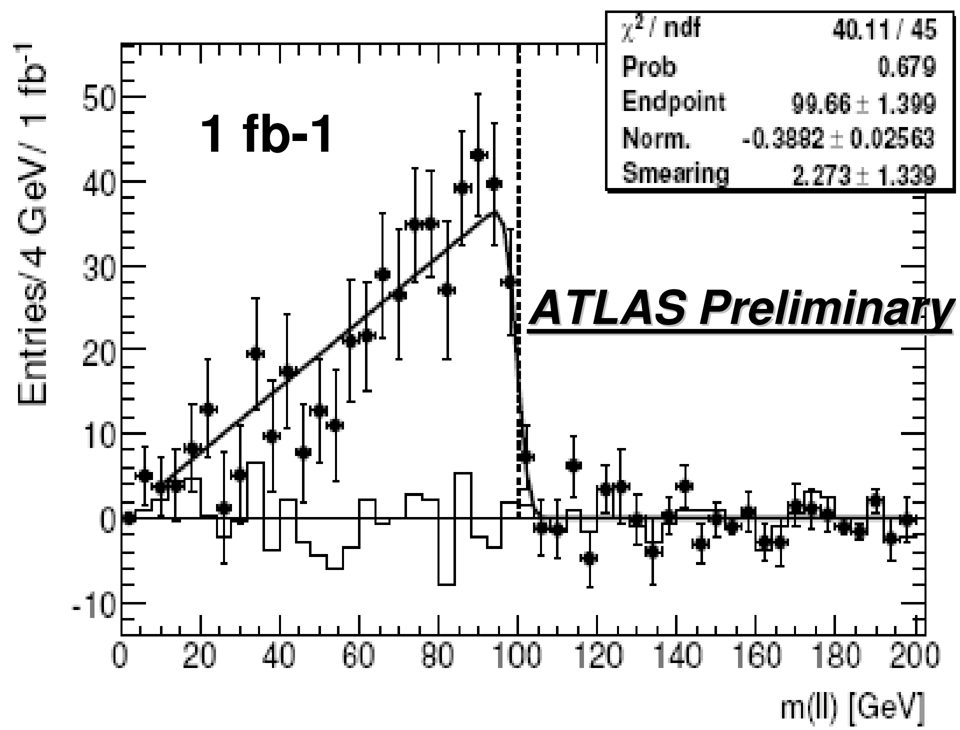
$$m(\ell\ell) < m(\chi_2^0)\sqrt{1-\left(\frac{m(\tilde{\ell})}{m(\chi_2^0)}\right)^2}\sqrt{1-\left(\frac{m(\chi_1^0)}{m(\tilde{\ell})}\right)^2}$$

- Mainly sensitive to mass differences
- Absolute masses can be measured with over-constrained system

- After SUSY selection background is already small
- However also background from wrong pairing in SUSY events
- Good pairing are leptons of same flavour
- SM background (WW+X) and wrong SUSY pairing are symmetric in lepton flavour

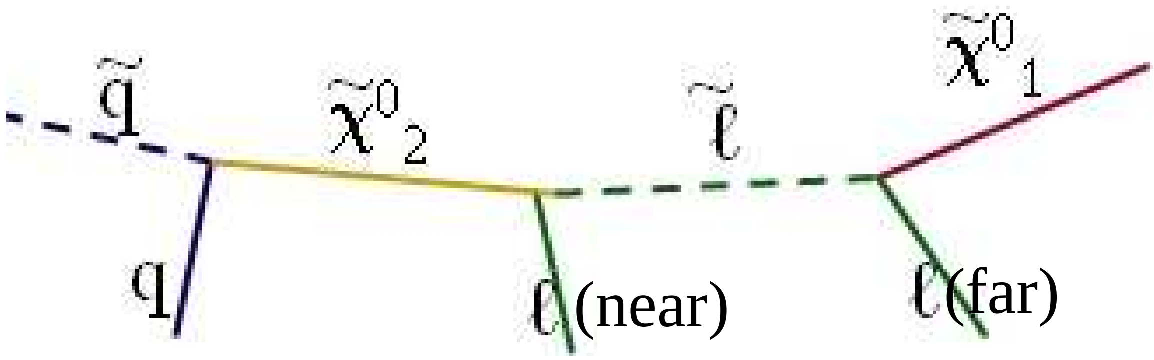
➠ can subtract background from data





Good precision on mass-edge possible!

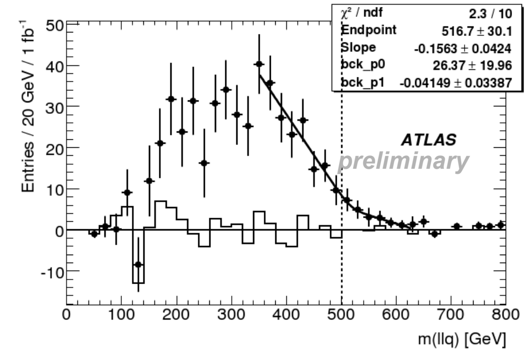
Look at



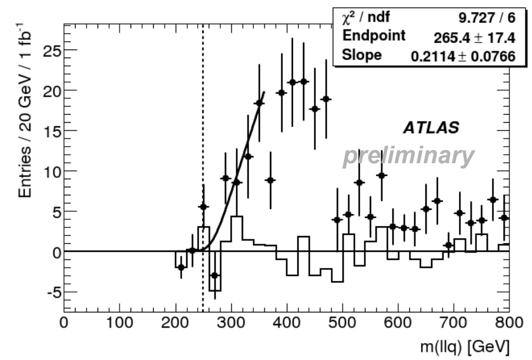
Several mass edges can be reconstructed:

- $m(\ell\ell q, \max)$
- $m(\ell\ell q, \min)$
- $m(\ell_{\text{near}} q, \max)$
- $m(\ell_{\text{far}} q, \max)$

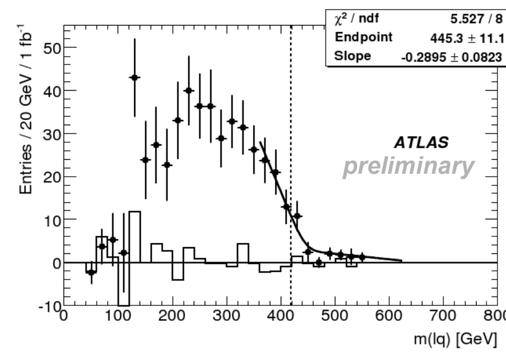
SUSY masses can then be obtained from a fit to all edges



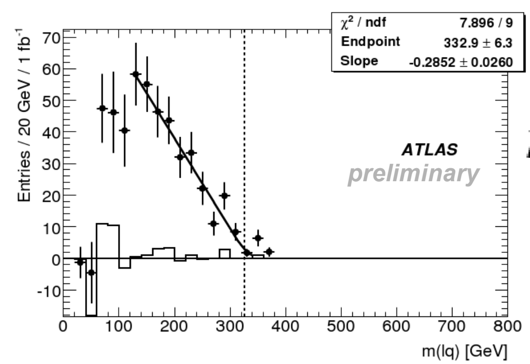
$m_{\ell\ell q}^{\max}$



$m_{\ell\ell q}^{\min}$



$m_{lq(\text{high})}^{\max}$



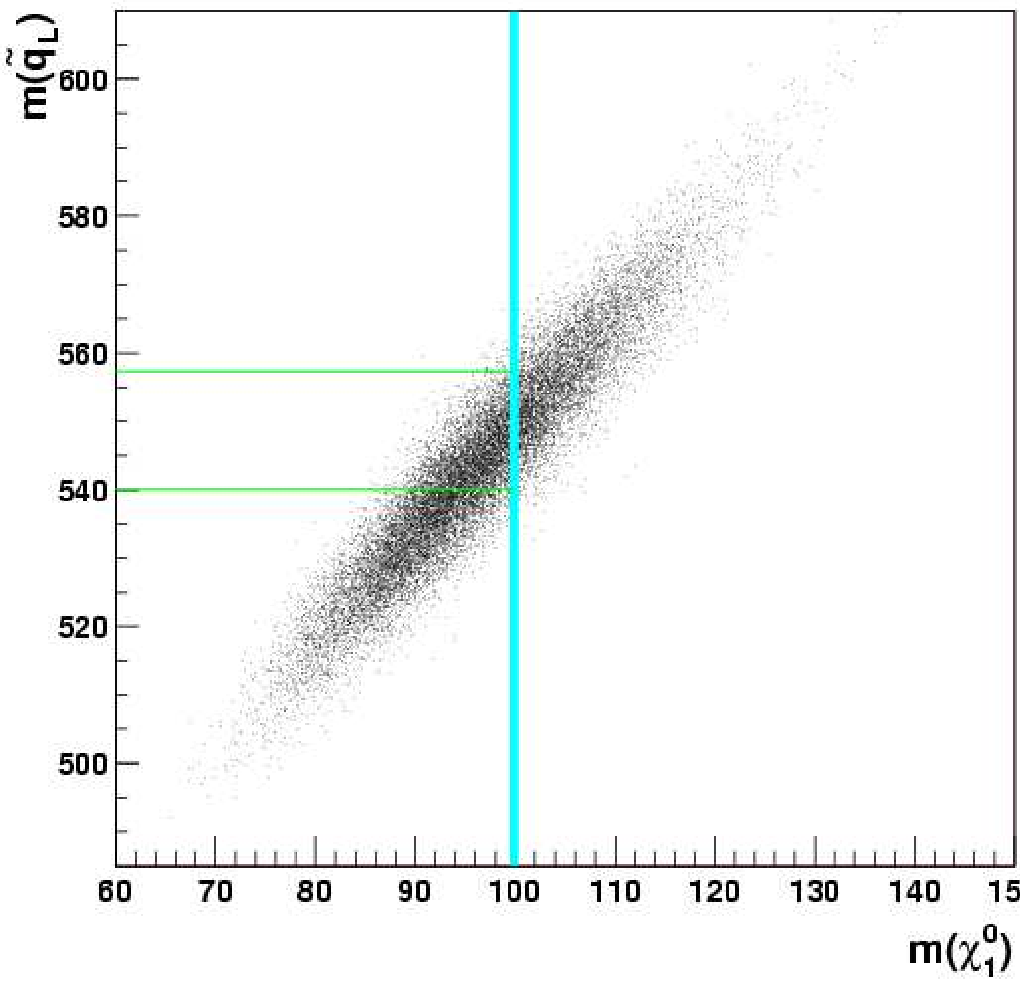
$m_{lq(\text{low})}^{\max}$

Masses can be determined by a global fit

Precision on masses: 20-50%

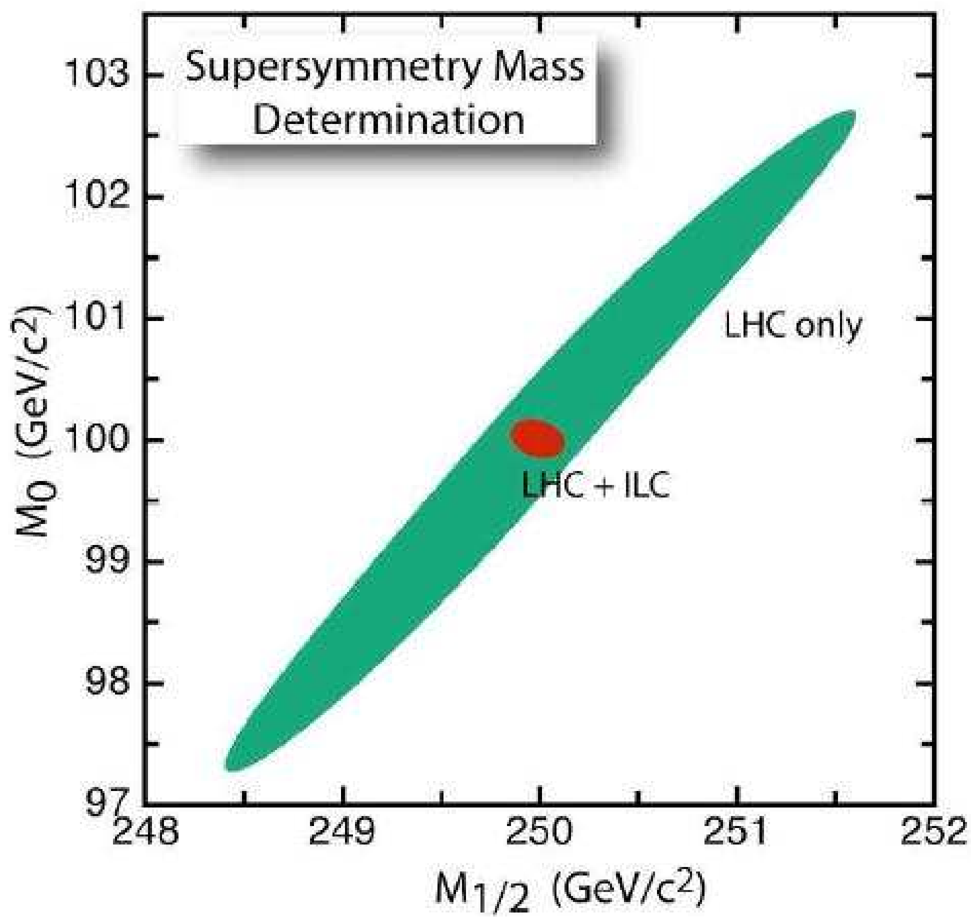
However precision on mass differences: 1-5%

LHC (+ILC) precision on $m(\chi_1^0)$ and $m(\tilde{q})$



If mSUGRA is assumed, m_0 and $m_{1/2}$ can be determined with 5-10% precision

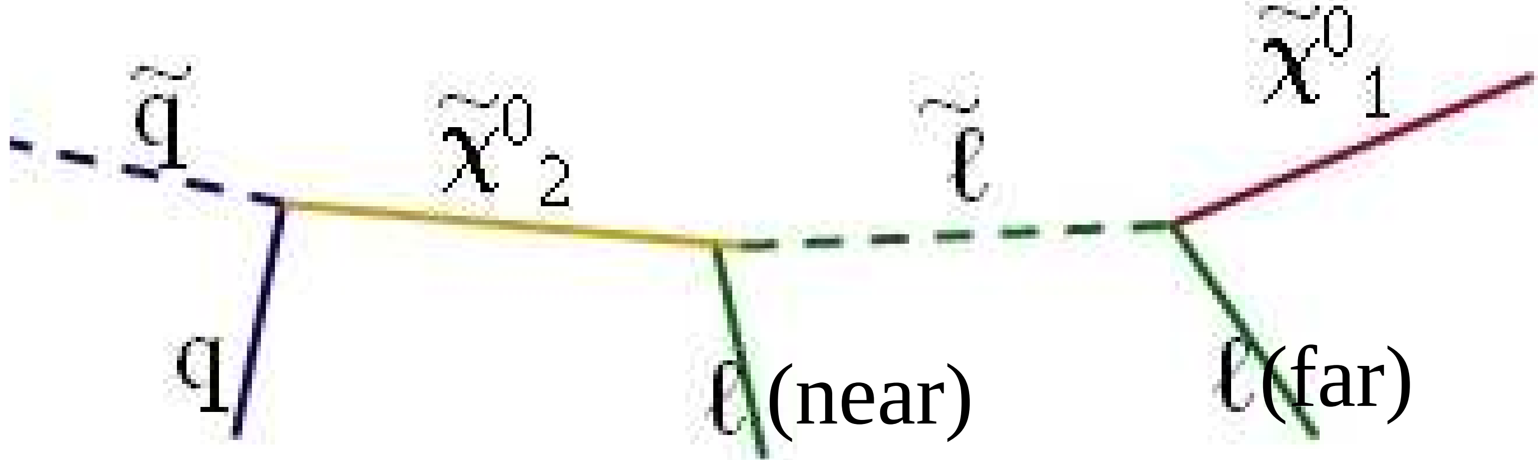
However also here a strong correlation remains



For reasonable precision on $\tan\beta$, A need measurements of heavy Higgses and $\tilde{t}$ masses.

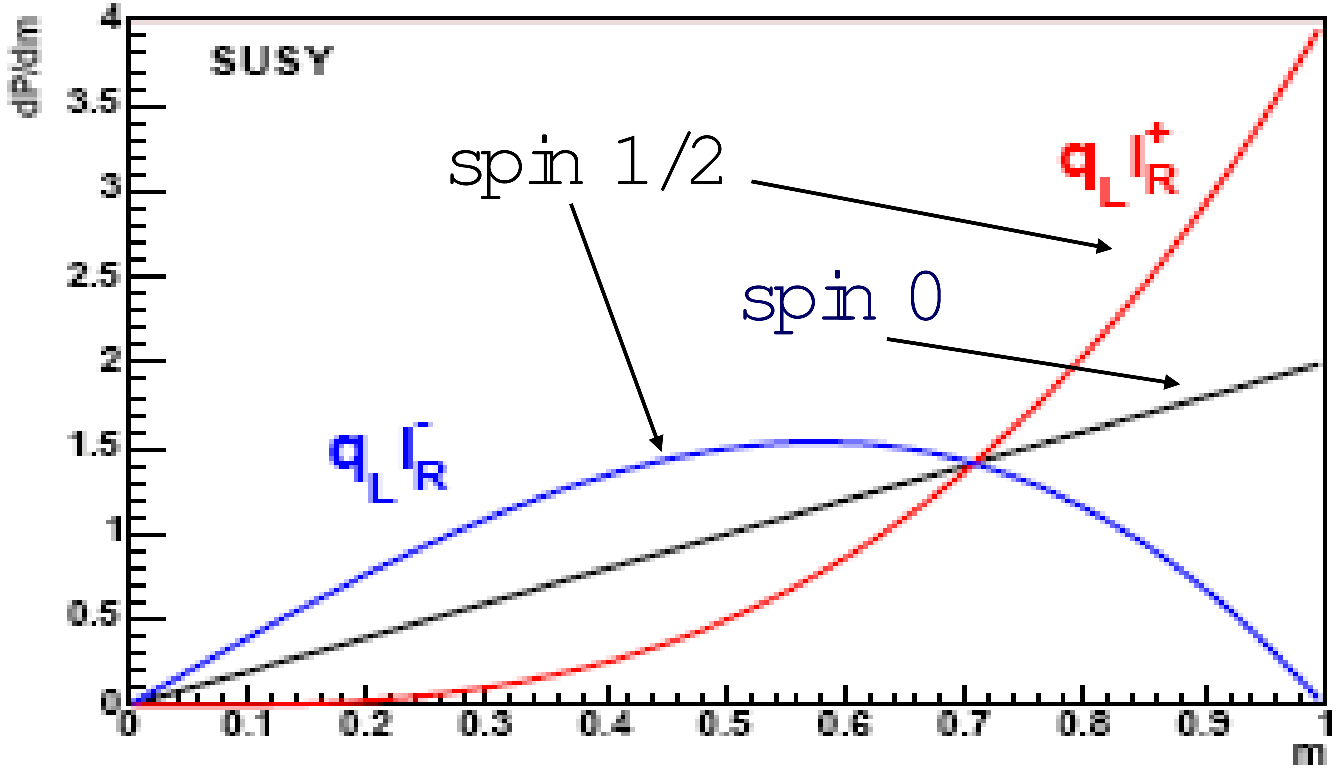
Can the LHC prove that it discovered SUSY?

- Suppose LHC has discovered new particles that seem to be partners of SM particles
- However e.g. in extra dimension models there can be partners of same spin
- Spin measurement is one necessity to prove SUSY
- Ideally would also like to measure couplings



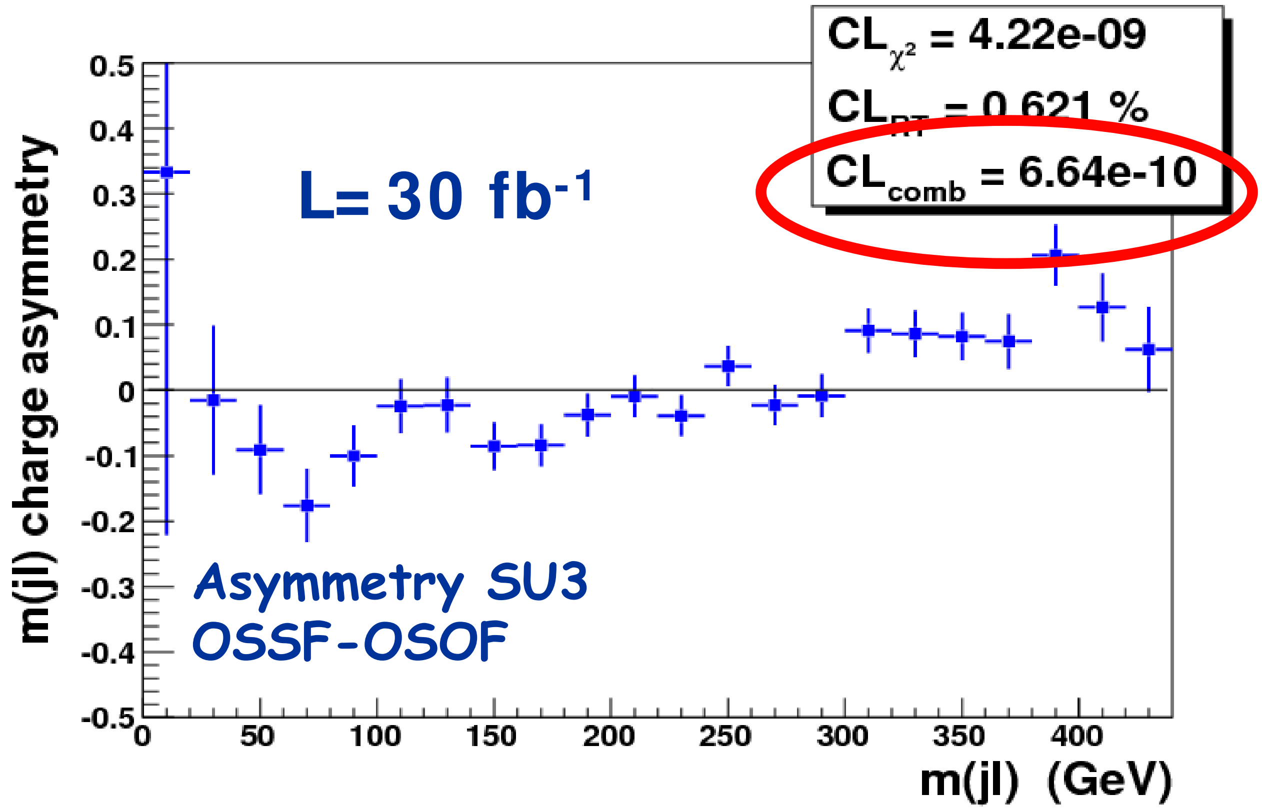
ℓ(near) can be positive or negative

For χ_2^0 with spin 1/2 there is a charge asymmetry in the ℓq mass, for spin 0 it is symmetric



Dilution factors:

- ℓ(near) and ℓ(far) cannot be distinguished ➟ add them
- anti-$\tilde{q}$ gives opposite asymmetry as $\tilde{q}$
  ➟ pp collider produces more $\tilde{q}$ than anti-$\tilde{q}$



Some asymmetry remains ⇒ excludes scalar

However be careful: $\tilde{q}$ spin is assumed

Complication at large $\tan\beta$ $\tilde{\tau}$s

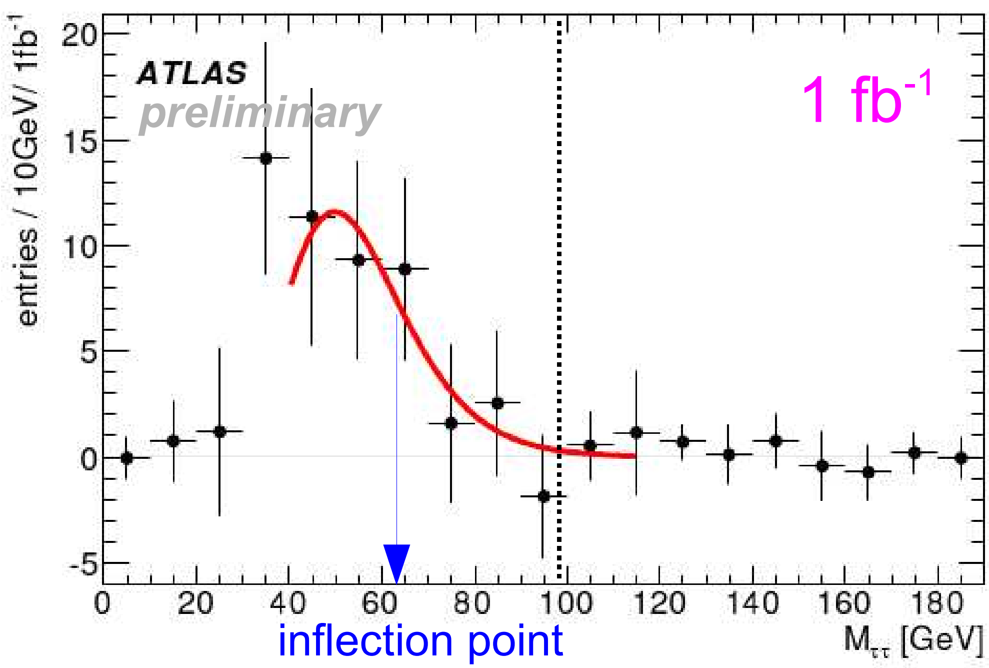
If $\tan\beta$ large:

- Significant mixing in $\tilde{\tau}$ sector ($\propto m_f(A_f - \mu\tan\beta)$) $\Rightarrow$
  - $\tilde{\tau}$ lighter than $\tilde{\ell}$
  - left handed component in $\tilde{\tau}$ favoured in Wino decay
- Larger Higgsino component in lighter neutralino, chargino $\Rightarrow$
  - Stronger coupling to heavier sfermions

All this favours $\tilde{\tau}$ over $\tilde{e}$, $\tilde{\mu}$

Need to analyse SUSY with τ leptons

$\tau\tau$ mass measurement worse resolution but possible



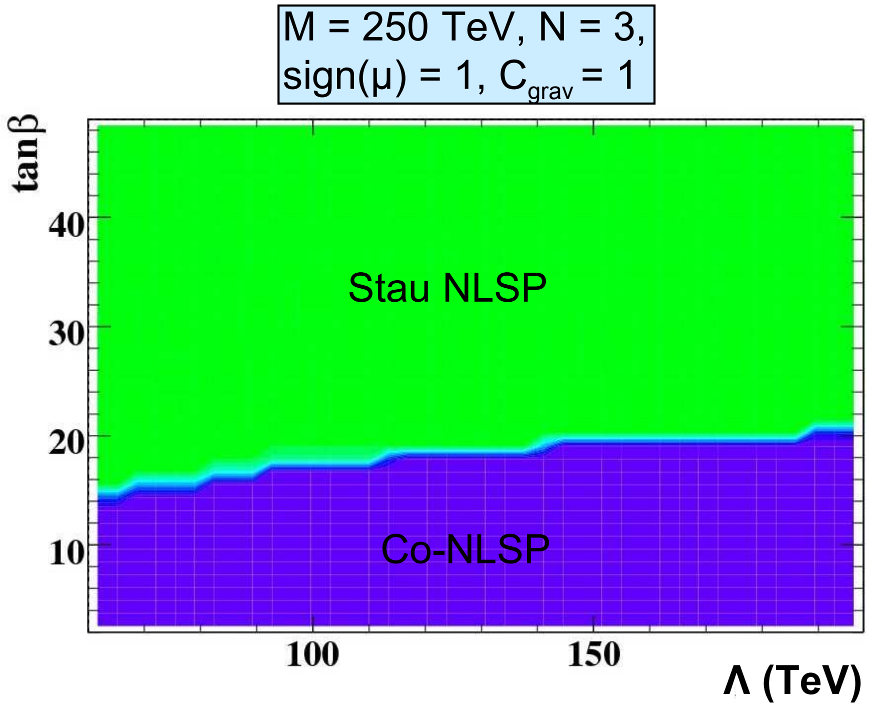
Some comments on models

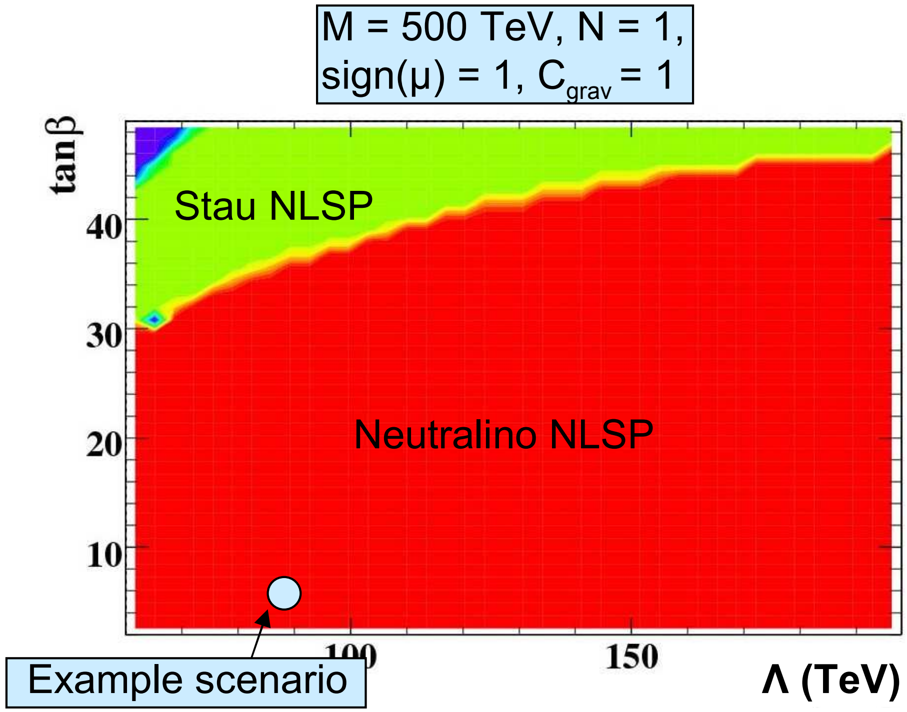
- mSUGRA with universal masses gives very few parameters
  ➠ easy for simulation studies
- However in nature (if SUSY should be found)
  - don't know if gravity mediation is true at all
  - don't know if masses are universal (for sfermion masses relatively straight forward to measure, for gauginos complicated
  - don't know if Higgs sector is minimal (more complicated Higgs sector would actually solve some theoretical problems)
- Discovery of "new physics with invisible particles" is relatively robust
- Prove that this is SUSY will be difficult, although some evidence will be obtained
- Reconstruction of the underlying model will be even more difficult
- A discussion is only possible when the data are there

Gauge mediated SUSY breaking

Main phenomenological difference: Gravitino is very light (eV) ➟

- The NLSP can be charged (typically $\tilde{\tau}$ or degenerate sleptons) or neutral (typically χ_1^0)
- The NLSP lifetime can be from short (prompt decays at the main vertex) to long (stable inside the detector)

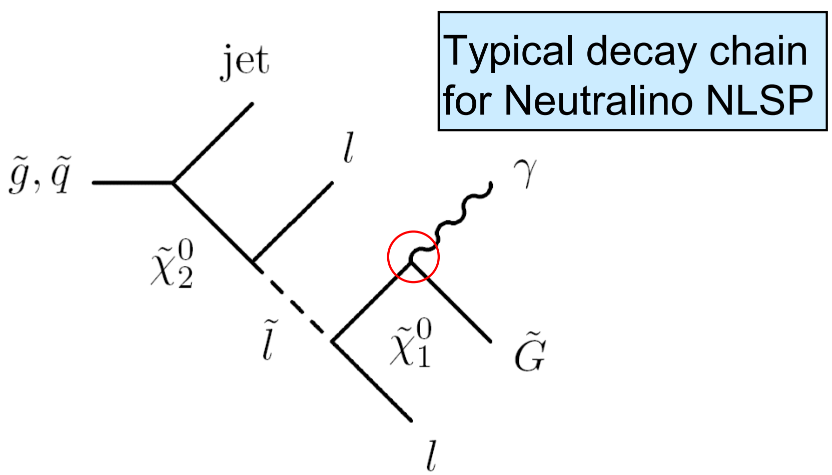


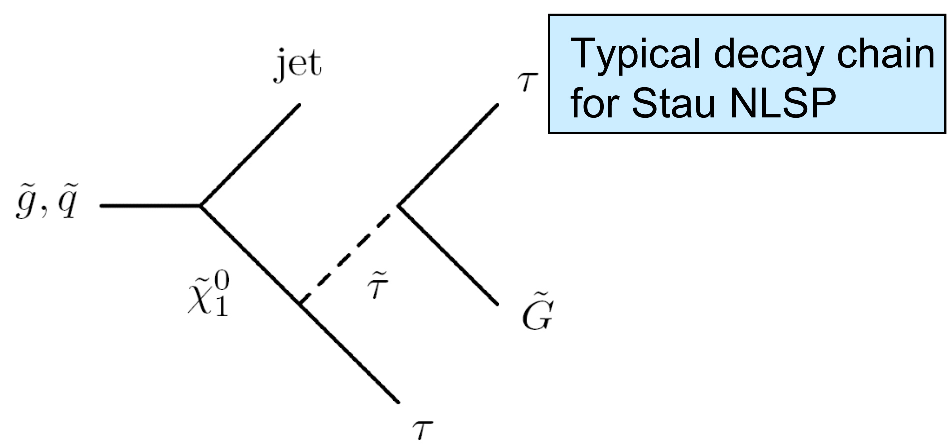


Typical signatures:

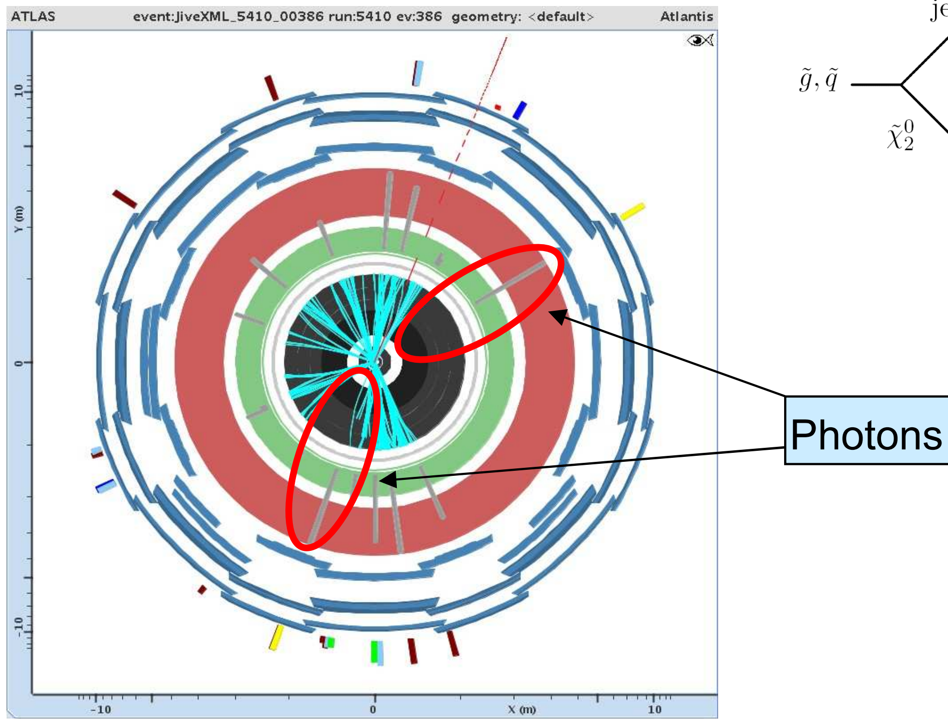
- Neutralino NLSP
  - Prompt decay: di-photon signature
  - Intermediate lifetime: non pointing photons
  - Long lifetime: like mSUGRA (mass pattern!)
- Stau NLSP
  - Prompt decay: di-lepton final state (lower missing E_T)
  - Long lifetime: stable heavy leptons

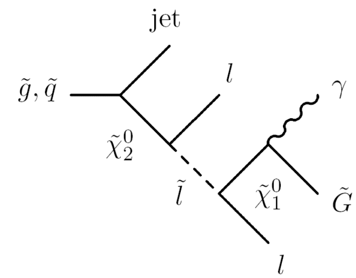
Decay chains in GMSB



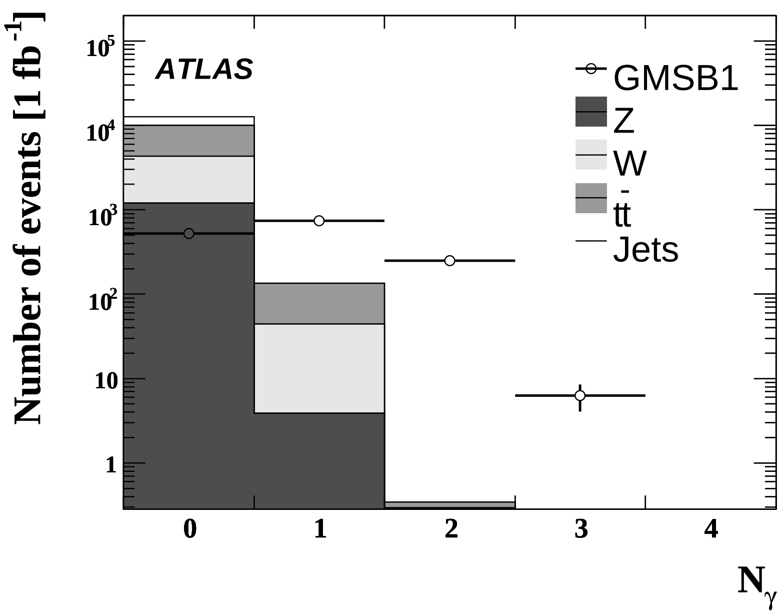


Prompt photon scenario



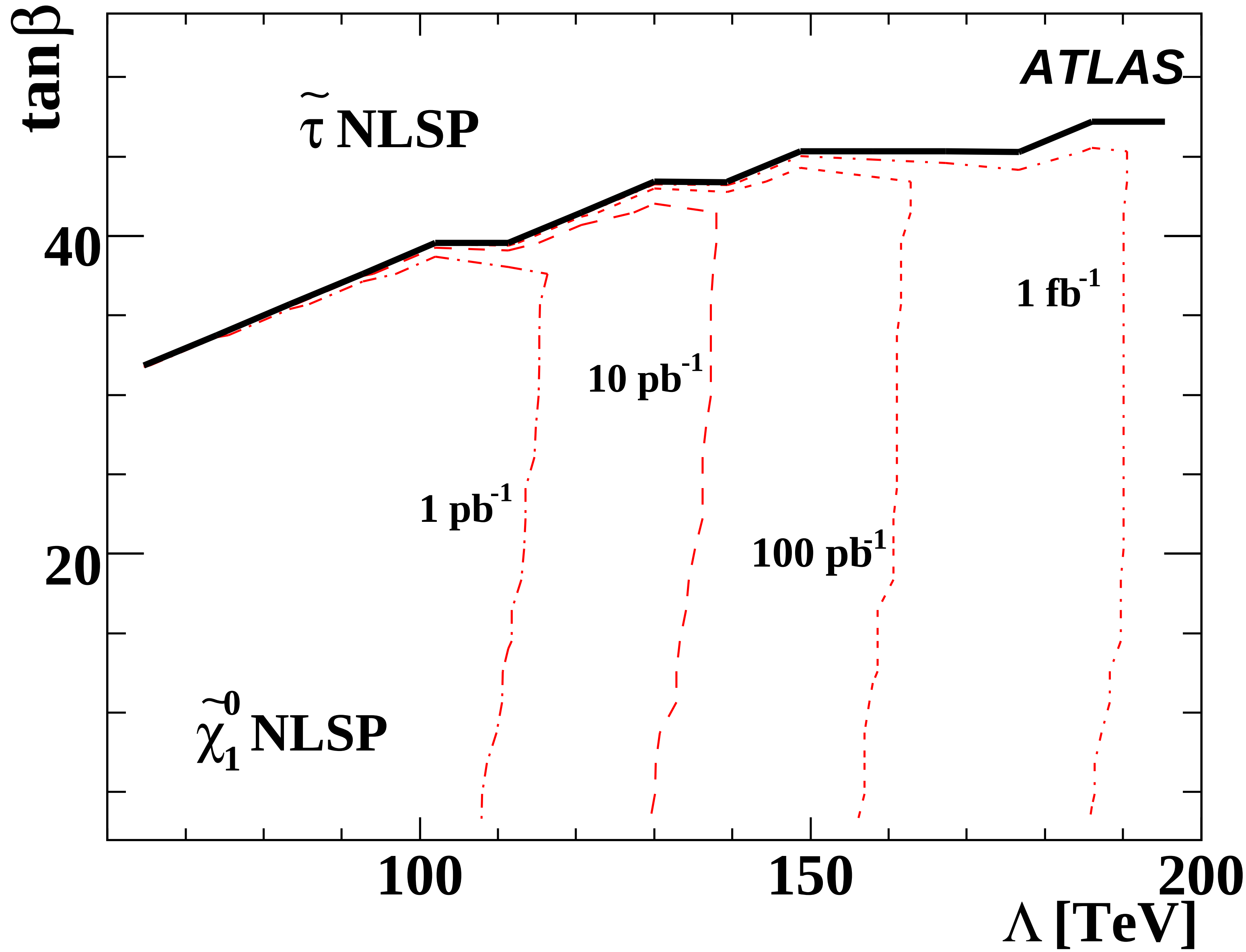


Start with "standard" SUSY cuts on $E_T^{\rm miss}$, $N_{\rm jets} p_T(\rm jets)$



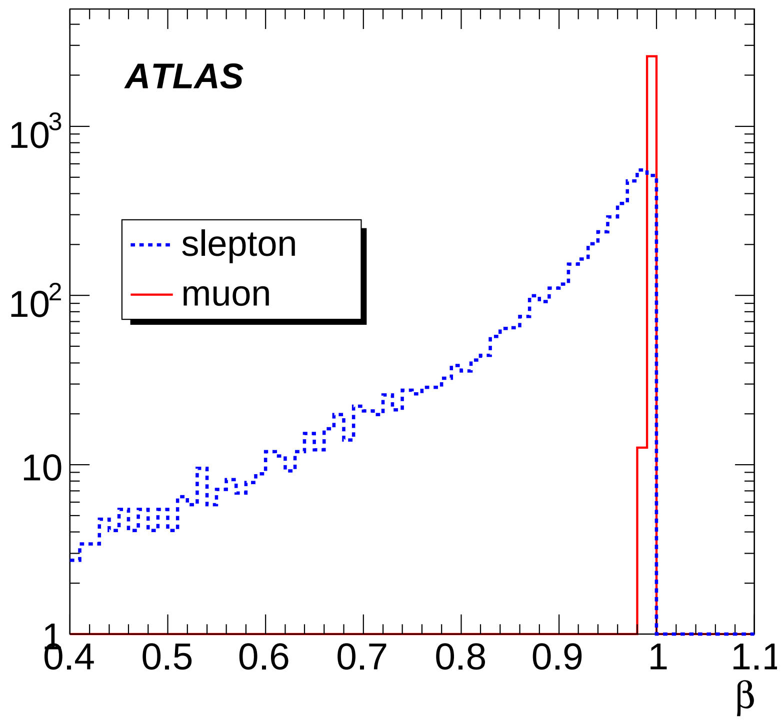
After additional cut on $N_\gamma \geq 2$ clean signal with no background

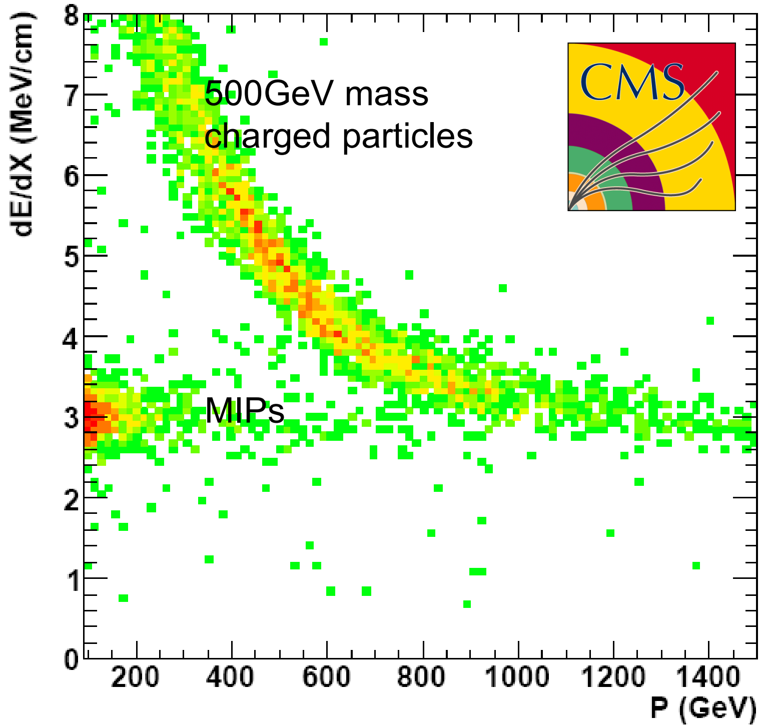
Accessible region can be discovered with low luminosity



Quasi stable lepton scenario

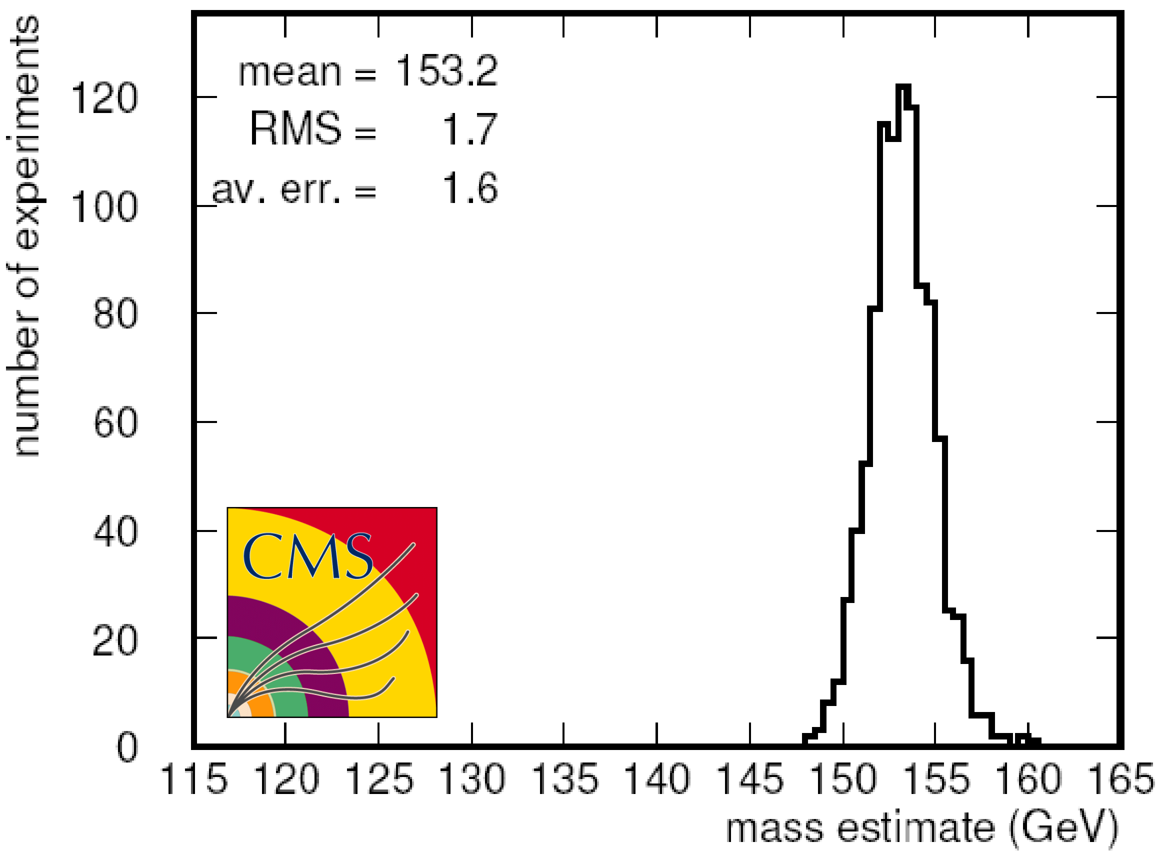
- NLSP lifetime can be so large that it decays outside of the detector
- If charged slepton is NLSP there are two signatures:
  - the lower velocity β can be measured with the drift chambers
  - the high specific ionisation can be measured with detectors that have pulse-height readout





This would allow absolute mass measurements!

$$\left(m = p\sqrt{\frac{1}{\beta^2} - 1} \right)$$



Conclusions on Supersymmetry

- The most probable part of the supersymmetric parameter space will be visible at the LHC already with low luminosity
- Inside a given model parameter fits are no problem
- However it will be difficult to prove that it is really SUSY and to fix the model unless striking signatures are present