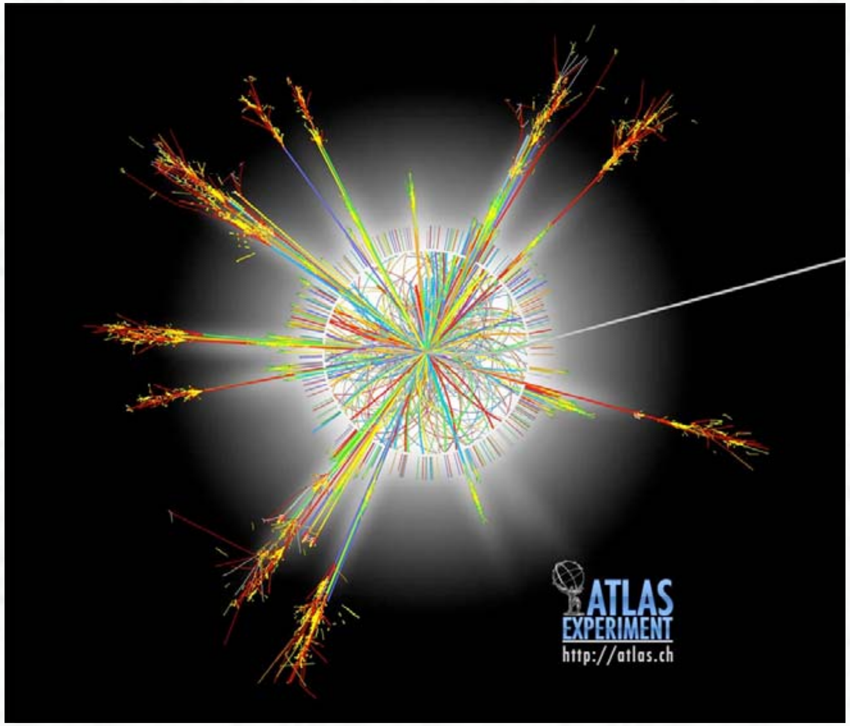
Physics at the LHC

Part 4

Search for Physics

Beyond the Standard Model



Why ?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accomodated

3. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) $\rightarrow$ m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

All this calls for a ***more fundamental theory*** of which
the Standard Model is a low energy approximation $\rightarrow$ **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

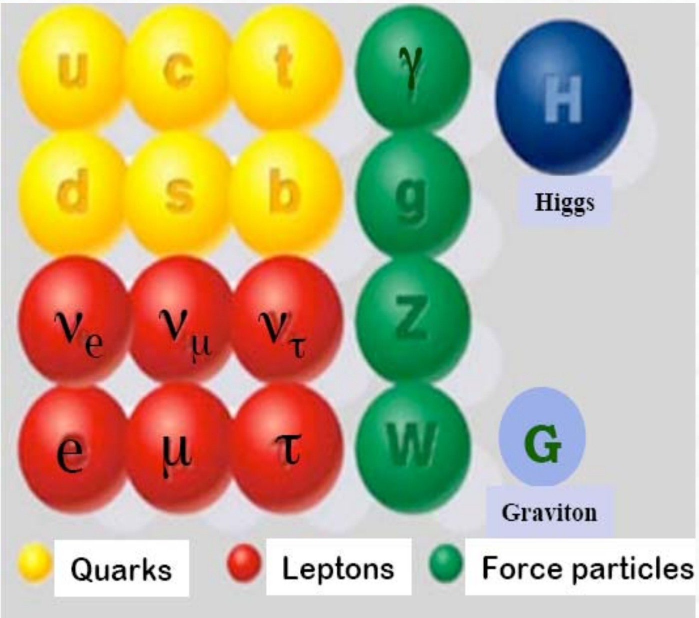
Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV

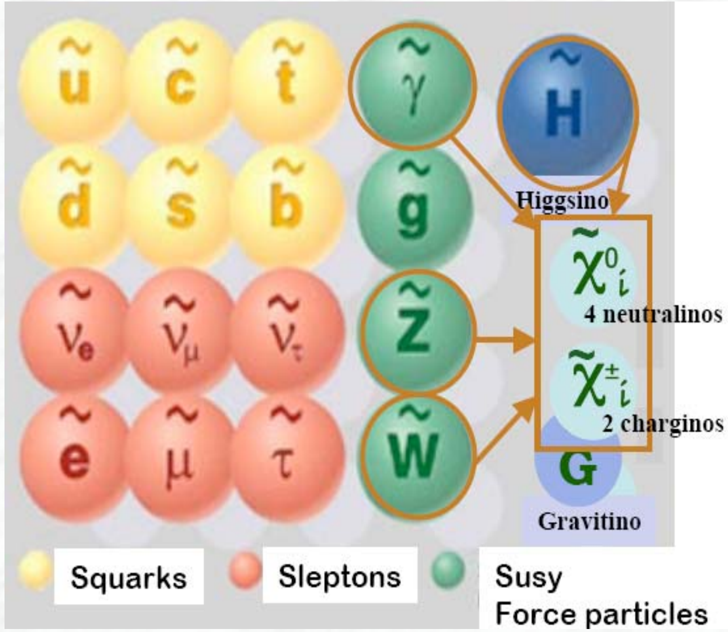
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

Experimental consequences of R-parity conservation:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.

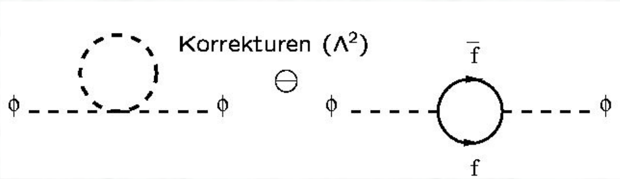
LSP is only weakly interacting:
LSP ≡ χ^0_1 (lightest neutralino, in many models)

→ LSP behaves like a ν → it escapes detection

→ E_T^{miss} (typical SUSY signature)

Why do we like SUSY so much?

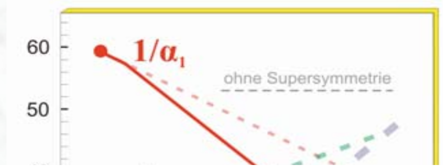
1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided



$$\Delta m_H = f(m_B^2 - m_f^2)$$

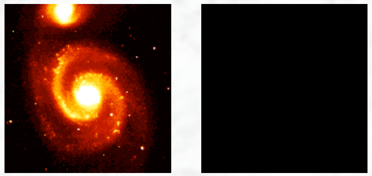
→ m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)



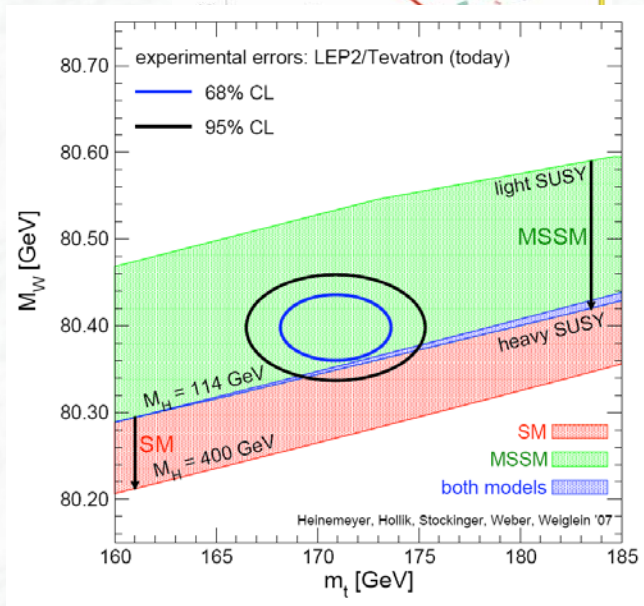
2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter



The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data



Link to the Dark Matter in the Universe ?

Parameters of the SUSY model ⇒ predictions for the relic density of dark matter

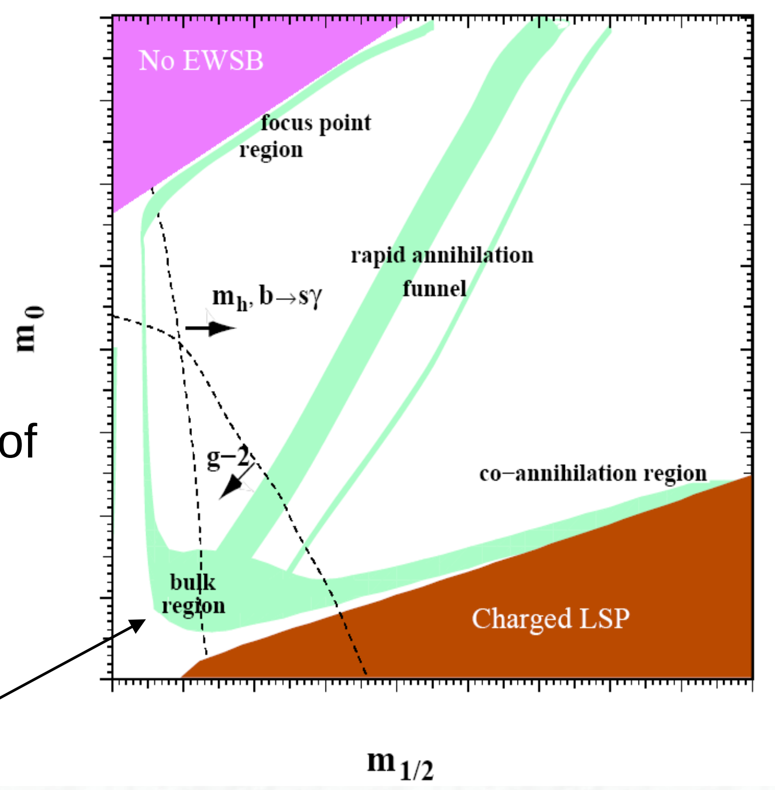
$$\rho_\chi \sim m_\chi n_\chi , \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \rightarrow \ldots)}$$

Interpretation in a simplified model

cMSSM
(constrained Minimal Supersymmetric
Standard Model)

Five parameters:

m_0, $m_{1/2}$	particle masses at the GUT scale
A_0	common coupling term
tan β	ratio of vacuum expectation value of the two Higgs doublets
μ (sign μ)	Higgs mass term

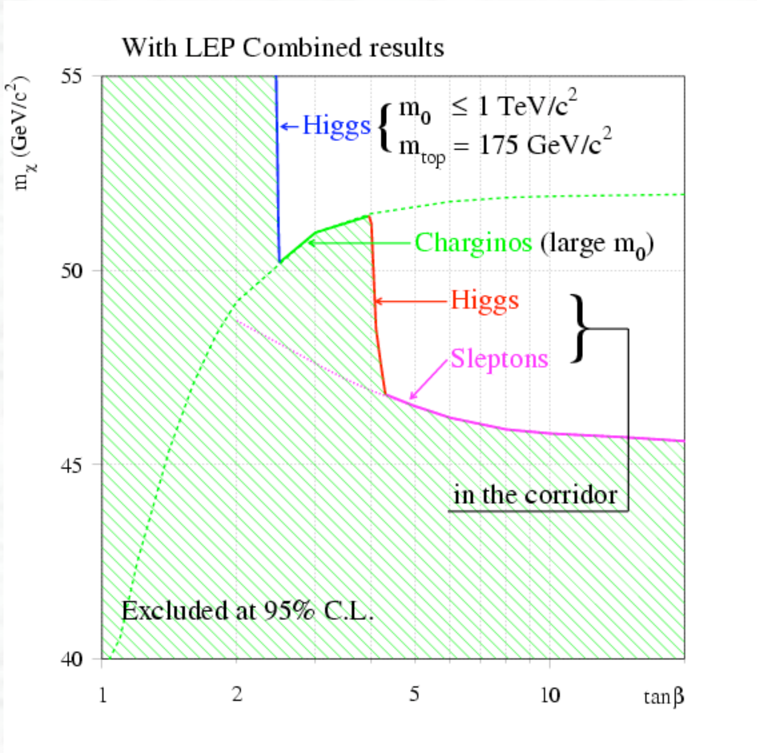


regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

The **masses of the SUSY particles** are not predicted;
Theory has many additional new parameters (on which the masses depend)

However, charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

Mass limits before LHC :	m (sleptons, charginos)	>	90-103 GeV	LEP II
	m (squarks, gluinos)	>	~ 350 GeV	Tevatron
	m (LSP, lightest neutralino)	>	~ 45 GeV	LEP II



LEP-II limit on the mass of the
Lightest SUSY particle

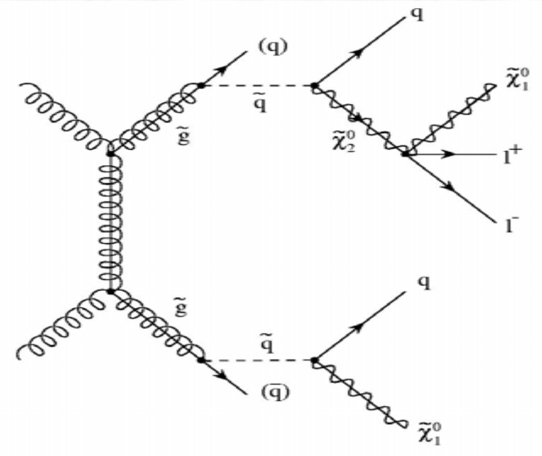
assumption:
lightest neutralino = LSP

Search for Supersymmetry at the LHC

- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



$\Rightarrow$ combination of
Jets, Leptons, E_T^{miss}

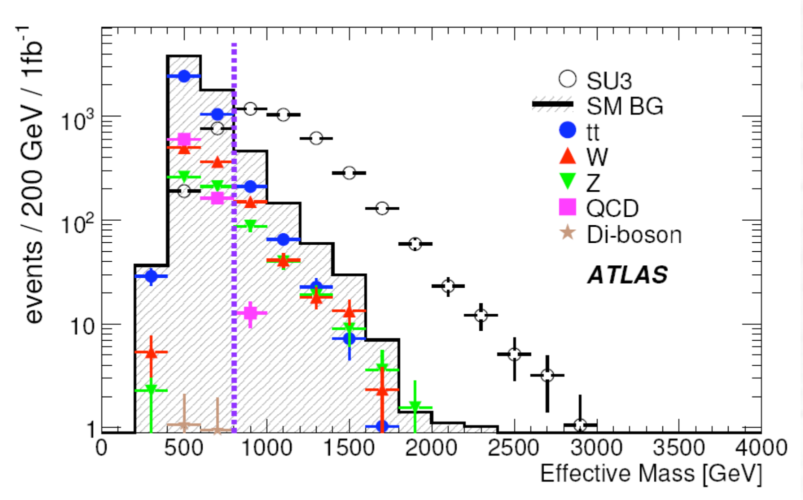
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

Squarks and Gluinos

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}
- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV
- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)



example: mSUGRA, point SU3 (bulk region)
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
$\tan\beta$ = 6, A_0 = -300 GeV, $\mu > 0$

Expectations from simulations:

LHC reach for squark- and gluino masses:

0.1 fb^{-1}	⇒	M ~ 750 GeV
1 fb^{-1}	⇒	M ~ 1350 GeV
10 fb^{-1}	⇒	M ~ 1800 GeV

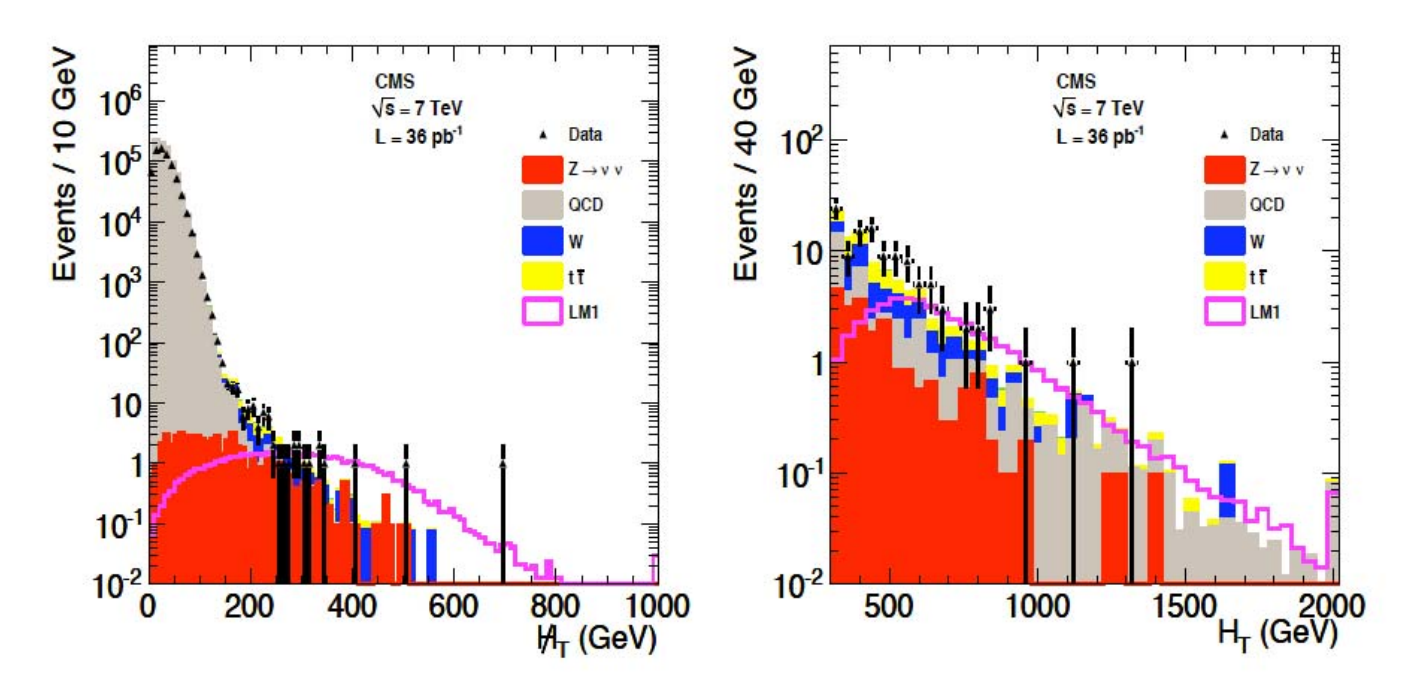
Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

What do the LHC data say ?

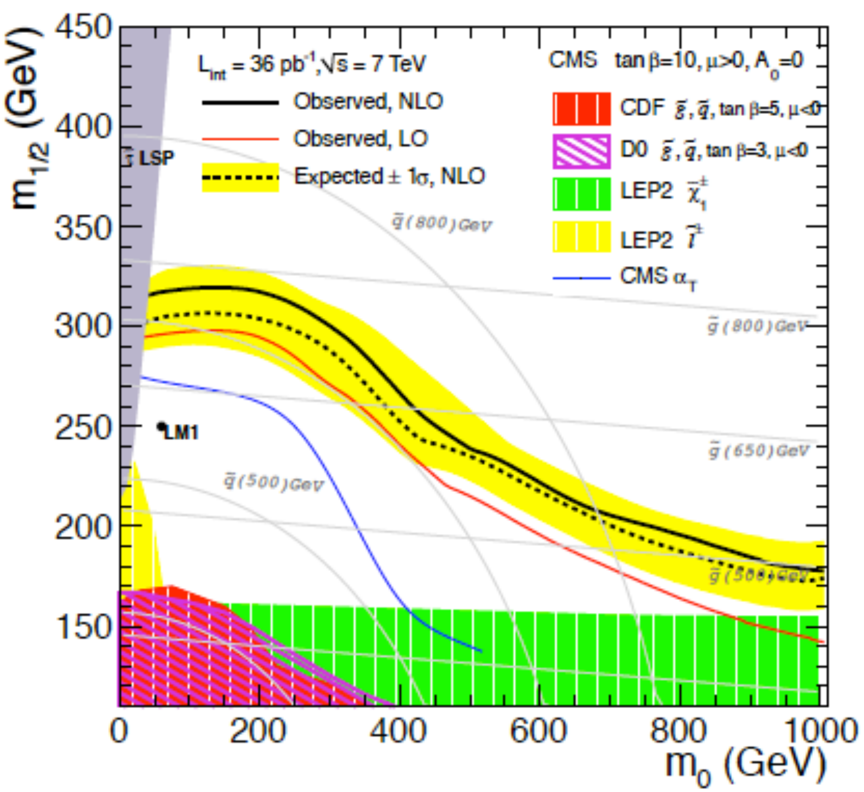
First results on the search for Etmiss + jets, no leptons (2010 data)

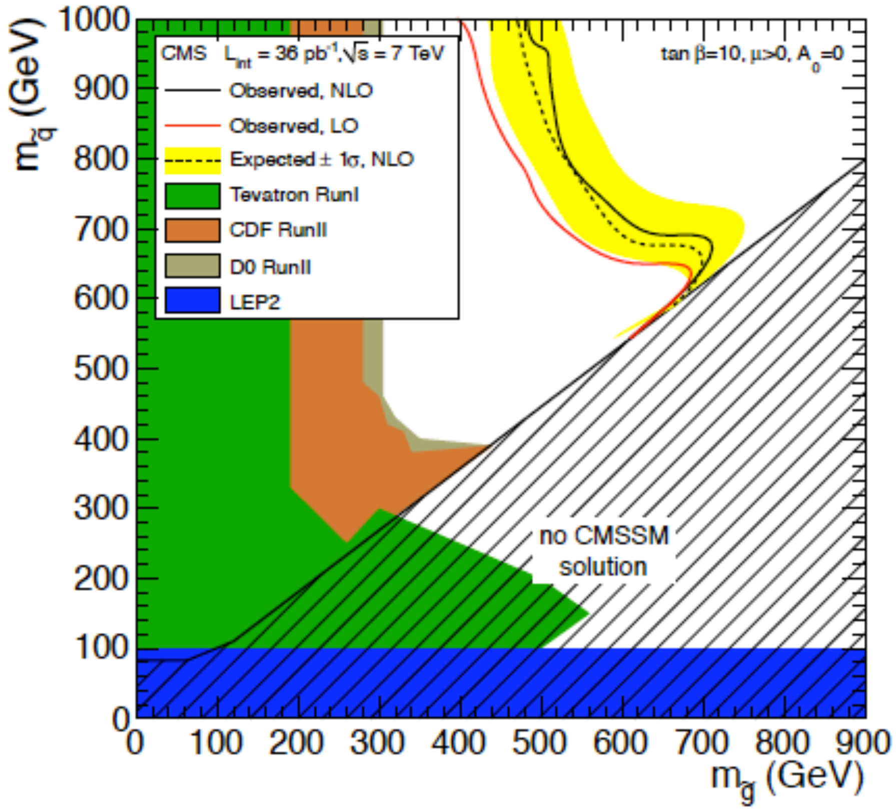
Simple selection:

- 3 jets with $p_T > 50$ GeV , $\eta < 2.5$
- $H_T > 300$ GeV (scalar sum of jets with $p_T > 50$ and $\eta < 2.5$)
- $H_T^{miss} > 150$ GeV (modulus of vector sum of jets with $p_T > 30$ GeV and $\eta < 5$)



- Good agreement between data and expectations from Standard Model processes
- No evidence for an excess → limits in SUSY parameter space





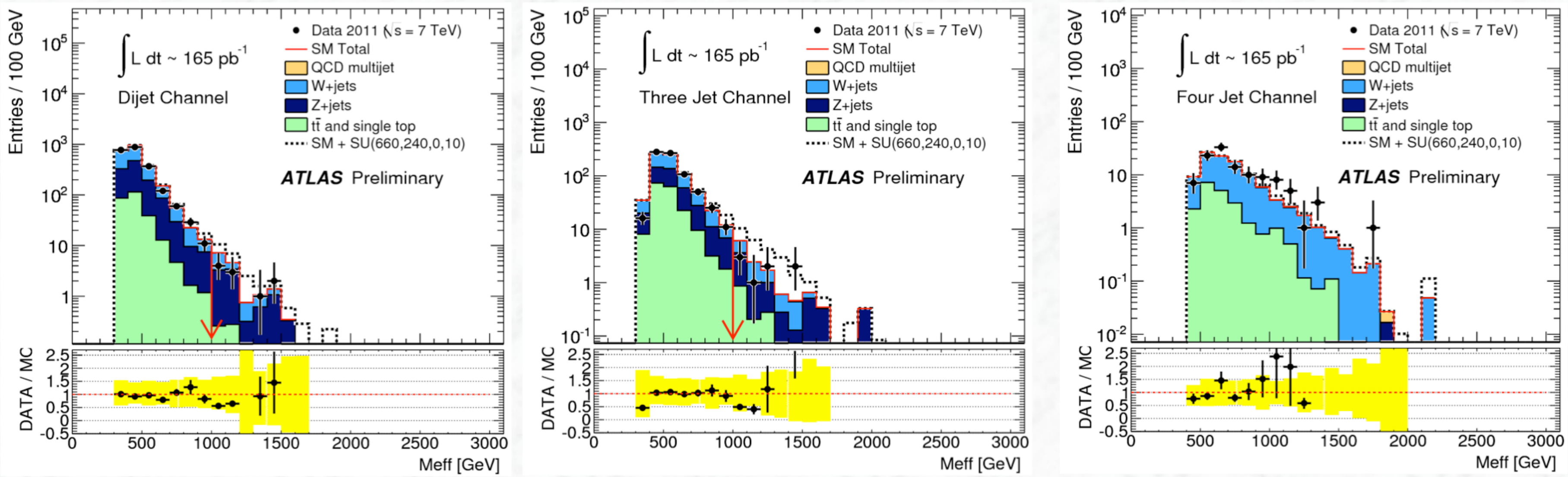
- Significant extension of exclusion contours in the squark-gluino mass plane
- Gluinos below 500 GeV are excluded for m(squarks) < 1000 GeV

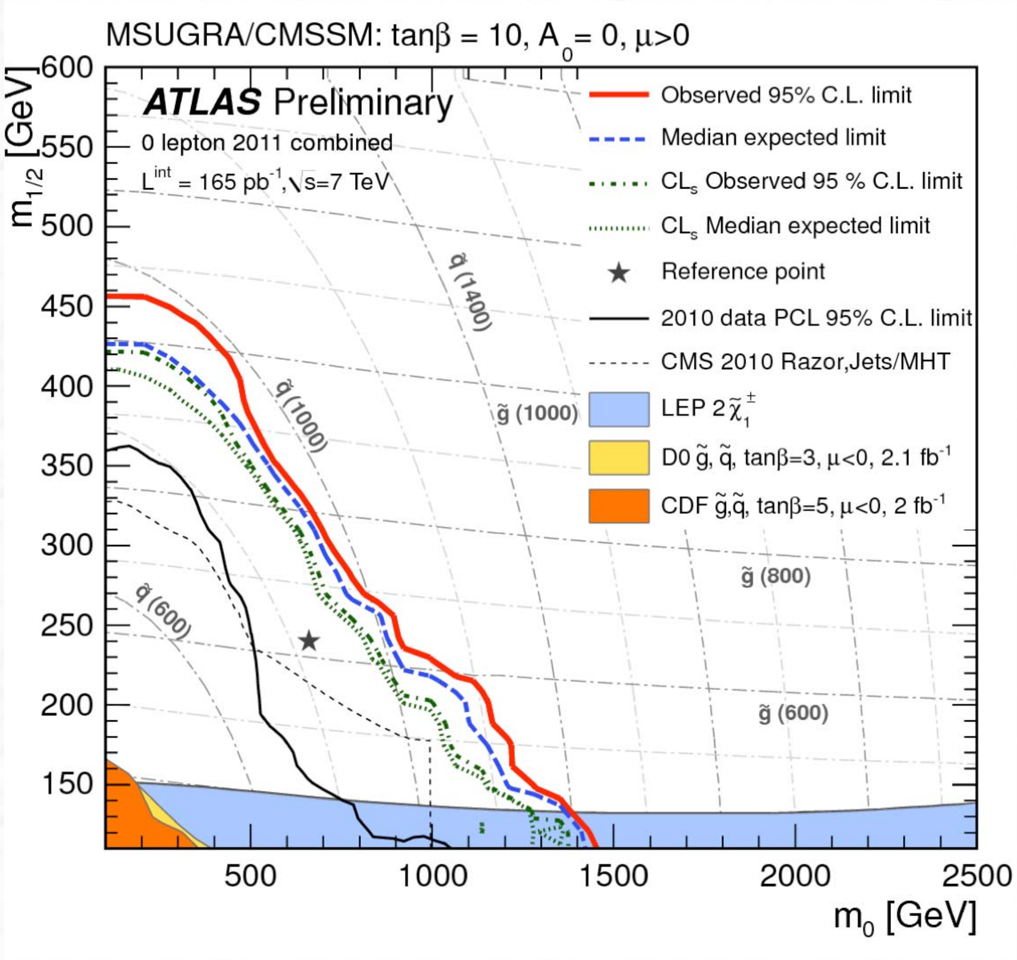
First results on the search for E_T^{miss} + jets (165 pb^{-1})

(part of 2011 data already included)

Selection of events with E_T^{miss} + jets

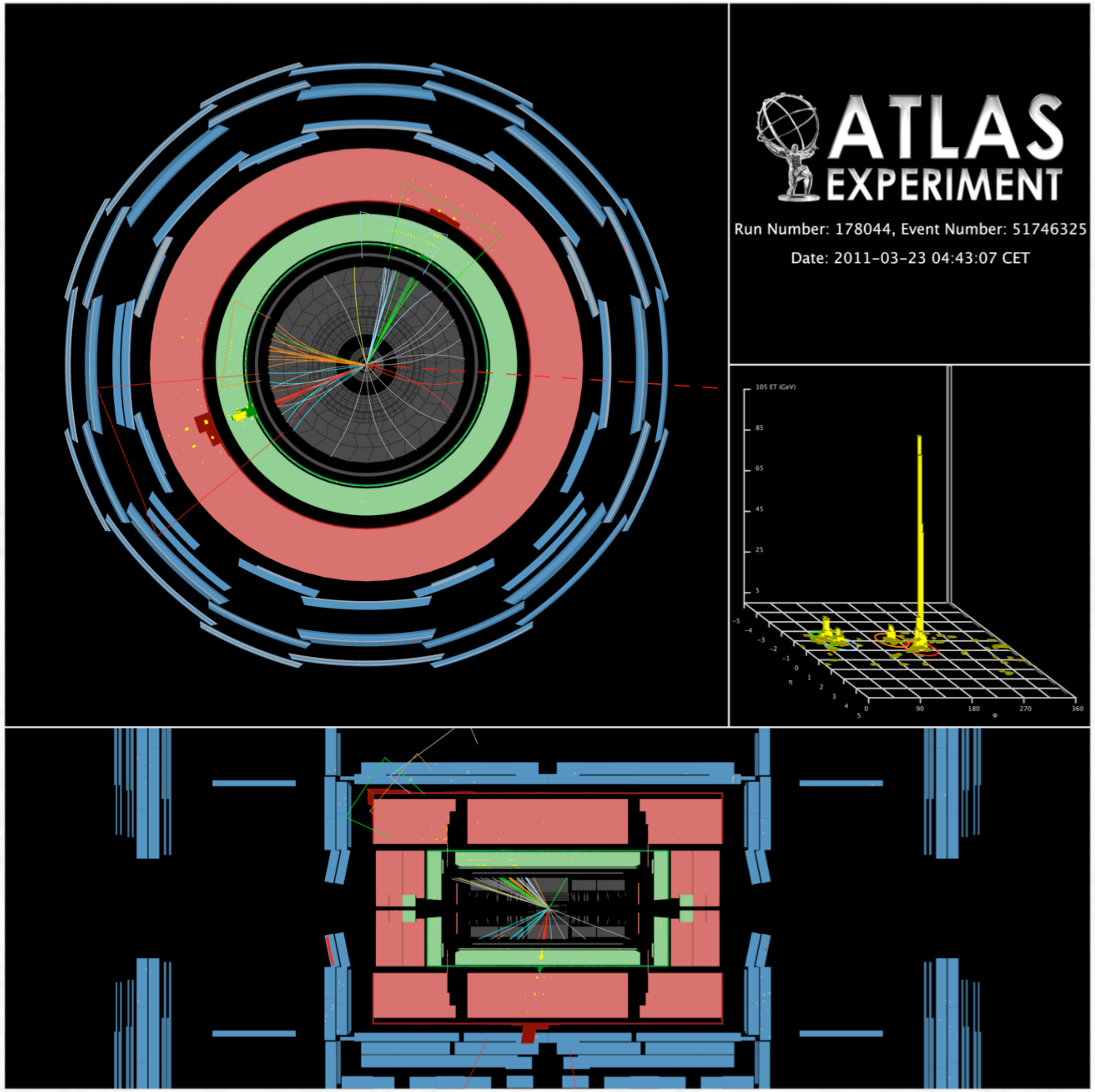
Split the analysis according to jet multiplicities: 2,3 and 4 jets
(different sensitivity for different squark/gluino mass combinations, i.e. in different regions of SUSY parameter space)





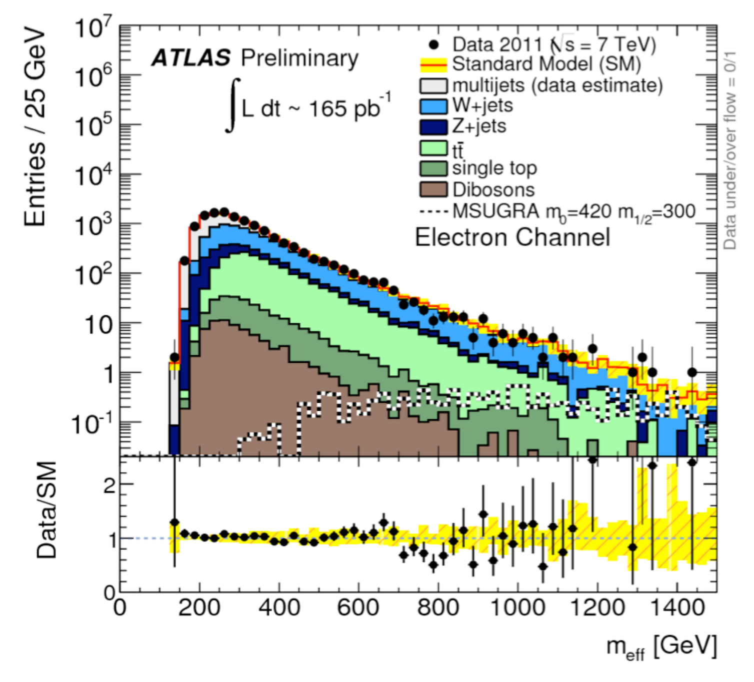
MSSM/cMSSM interpretation (for equal squark and gluino masses):

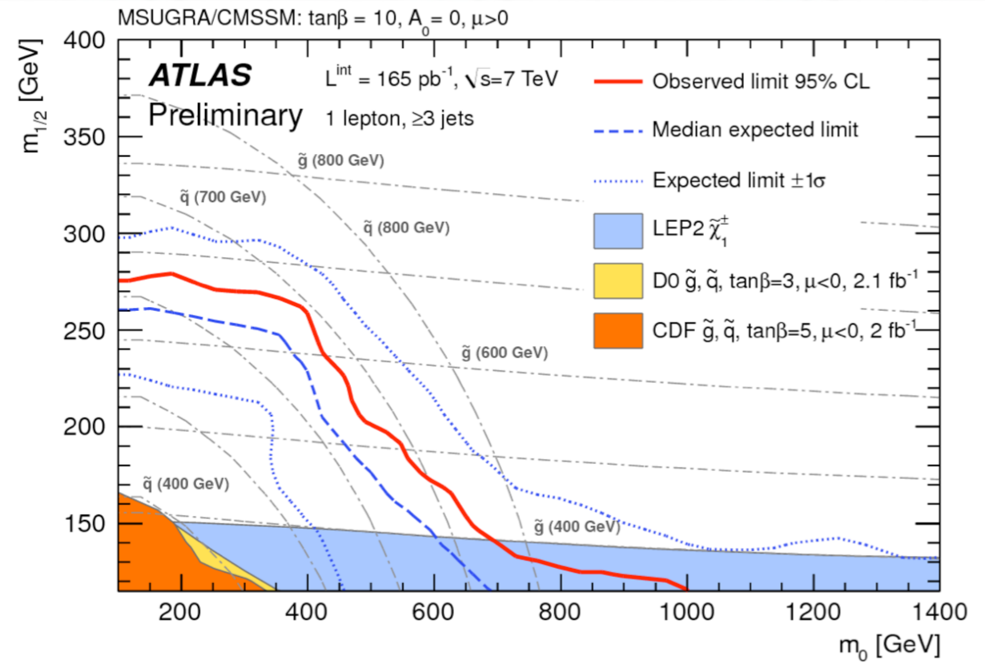
$L = 165\ pb^{-1}$: m(squark), m(gluino) > 950 GeV



A display of the reconstructed event with the highest m_{eff} (1548 GeV) found in the ATLAS data sample. This event possesses four jets with p_T > 40 GeV (p_T = 636, 189, 96 and 81 GeV respectively) and E_T^{miss} = 547 GeV.

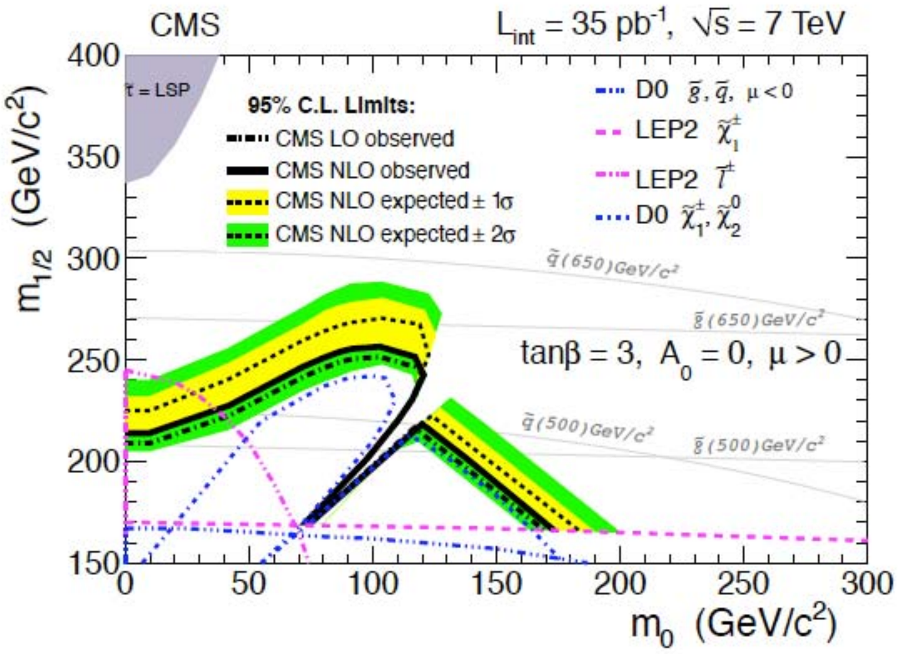
…additional potential: inclusive searches with leptons
i.e. E_T^{miss}, jets + leptons

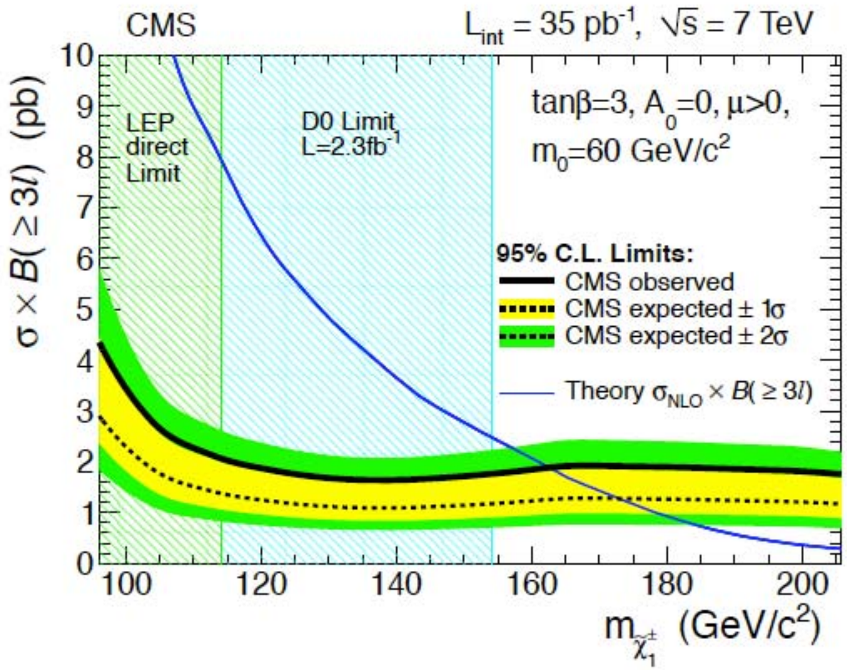




- Smaller signal rates, but different background composition
- Again: data are well described by contributions from Standard Model processes
- Similar exclusions in the MSSM models

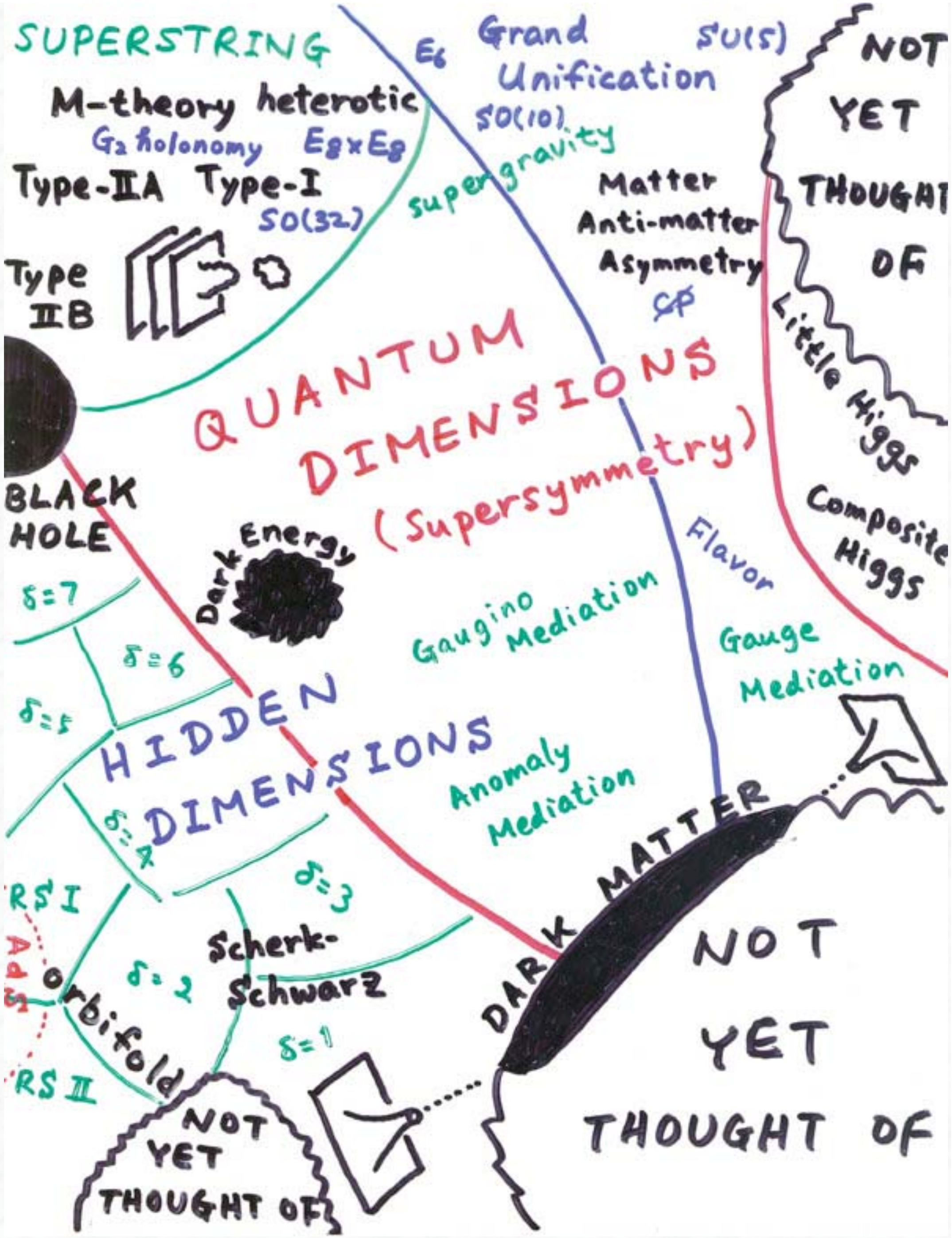
Multi-lepton search in CMS





- Multi-leptons are produced via associated production of charginos and neutralinos
- Limits extracted are already beyond the Tevatron

More Ideas ?



SUPERSTRING
M-theory
heterotic
G2 holonomy
E8×E8
Type-IIA
Type-I
SO(32)
Type IIB
E6
Grand Unification
SU(5)
SO(10)
supergravity
Matter Anti-matter Asymmetry
CP
NOT YET THOUGHT OF
Little Higgs
Composite Higgs
BLACK HOLE
QUANTUM DIMENSIONS
(Supersymmetry)
Dark Energy
Flavor
Gaugino Mediation
Gauge Mediation
δ=7
δ=6
δ=5
δ=4
δ=3
δ=2
δ=1
HIDDEN DIMENSIONS
Anomaly Mediation
DARK MATTER
RS I
AdS
orbifold
RS II
Scherk-Schwarz
NOT YET THOUGHT OF
NOT YET THOUGHT OF

Two examples with leptons in the final state

1. New resonances decaying into lepton pairs

examples: W ´ and Z´ or Graviton resonances (extra dimensions)

use again leptonic decay mode to search for them: $W' \rightarrow \ell \nu$
$Z' \rightarrow \ell \ell$

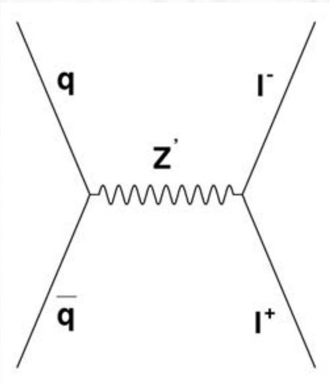
2. Leptoquarks ?

Particles that decay into leptons and quarks
(violate lepton and baryon number; appear in Grand Unified theories)

here: search for low mass Leptoquarks (TeV scale)

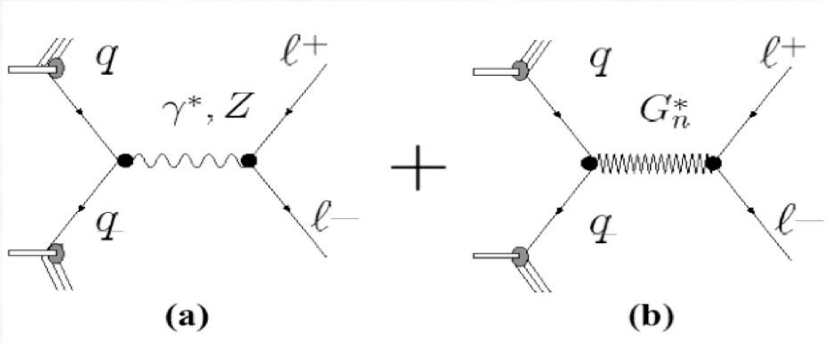
Search for new, high-mass di-lepton resonances

- **Additional neutral Gauge Boson Z´**



- **Randall-Sundrum narrow Graviton resonances decaying to di-lepton**

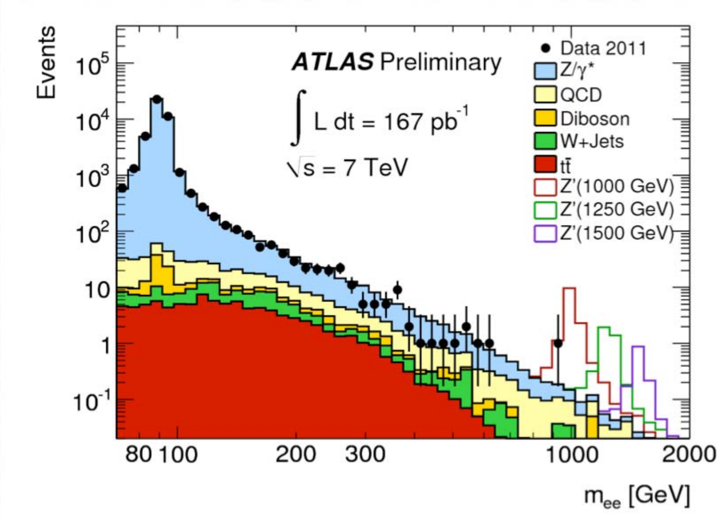
appear in Extra Dim. Scenarios



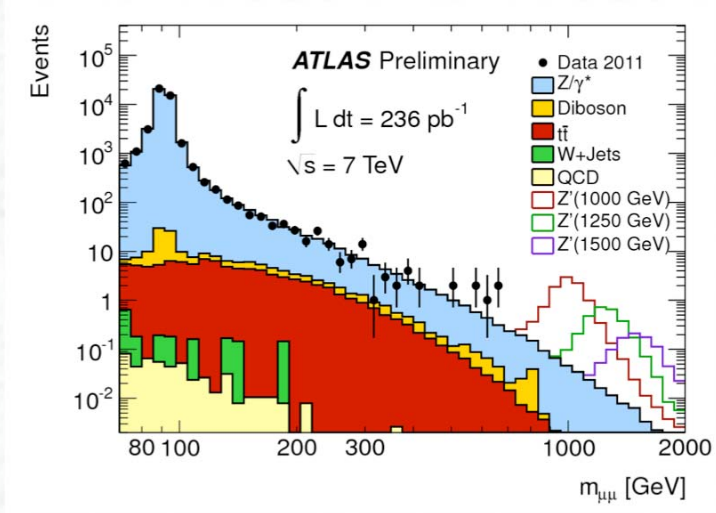
Main background process: Drell-Yan production of lepton pairs

Search for New Resonances in High Mass Di-leptons

Di-electron invariant mass

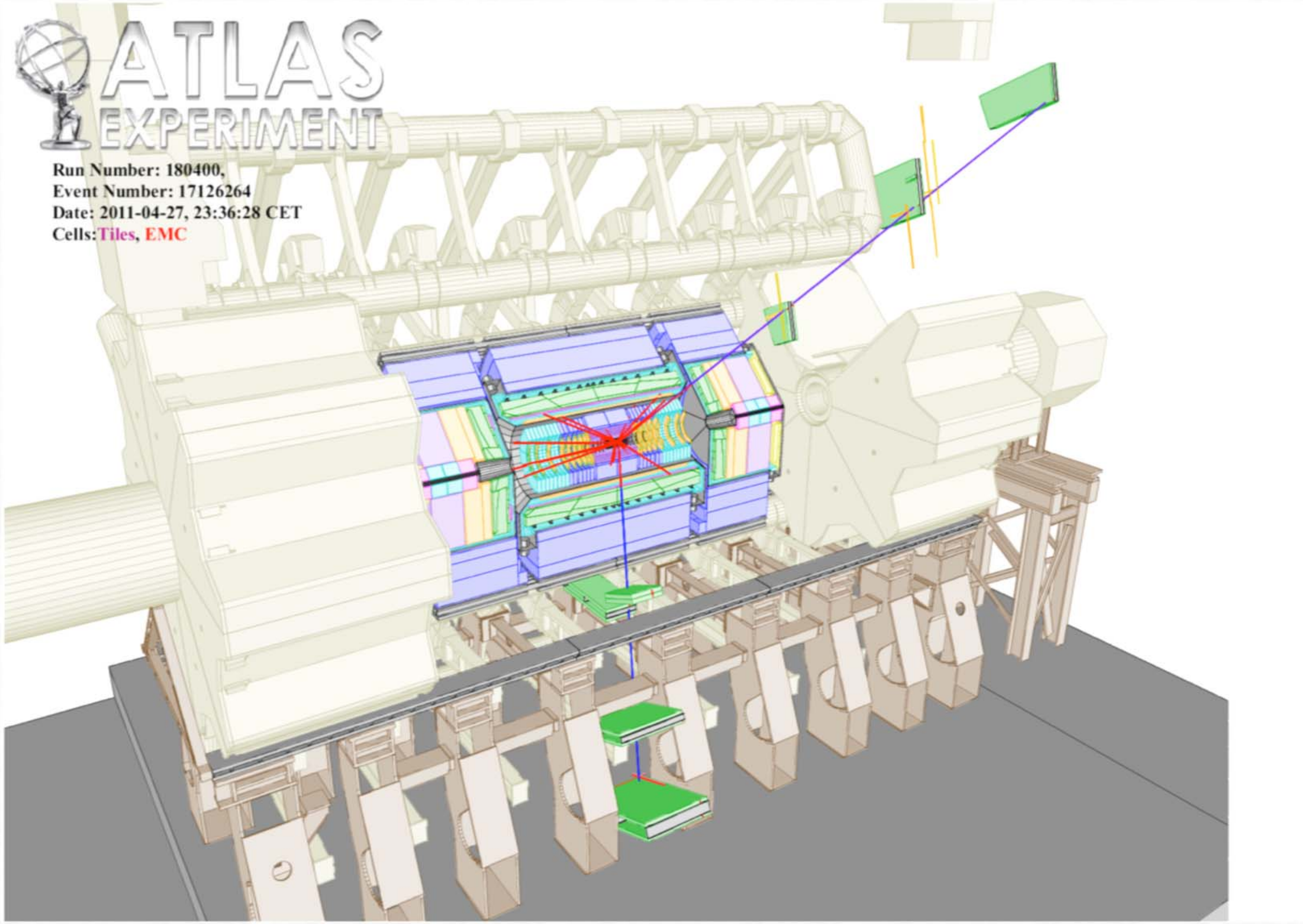


Di-muon invariant mass



Data are consistent with background from SM processes. No excess observed.

95% C.L. limits (SM couplings)	ee	μμ	ll combined
CDF / D0 5.3 fb^{-1}			1.07 TeV
ATLAS 36 pb^{-1}	0.96 TeV	0.83 TeV	1.05 TeV
ATLAS 167 / 236 pb^{-1}	1.28 TeV	1.22 TeV	1.41 TeV
CMS 35 / 40 pb^{-1}			1.14 TeV



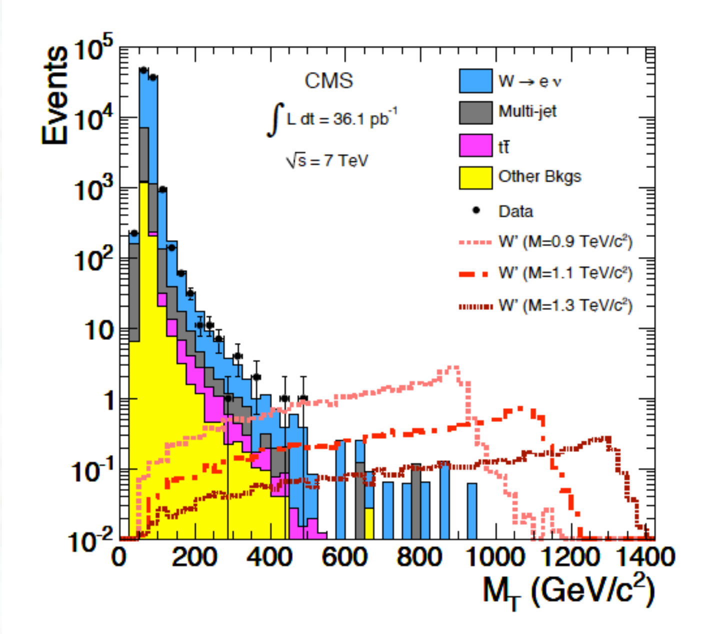
The highest invariant mass di-muon event in the ATLAS data. The highest momentum muon has a p_T of 270 GeV and an (eta, phi) of (1.56, 1.30). The subleading muon has a p_T of 232 GeV and an (eta, phi) of (-0.09, -1.82). The invariant mass of the pair is 680 GeV.

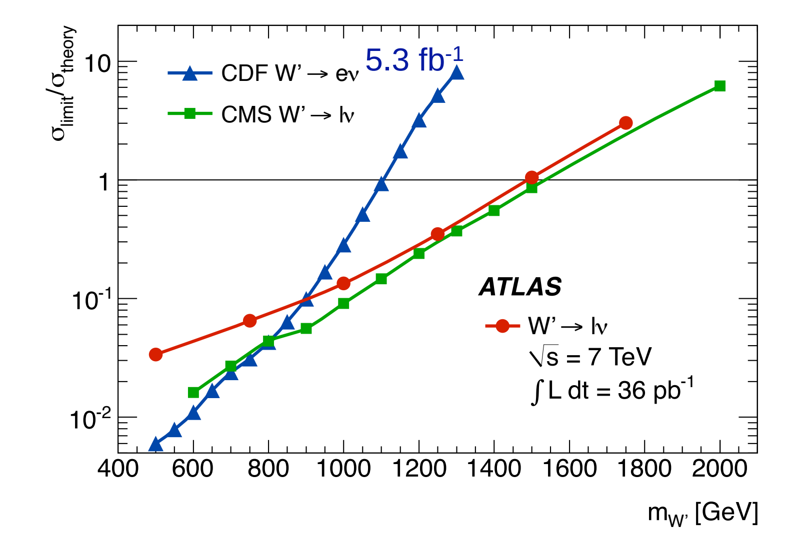
Search for W' → lν

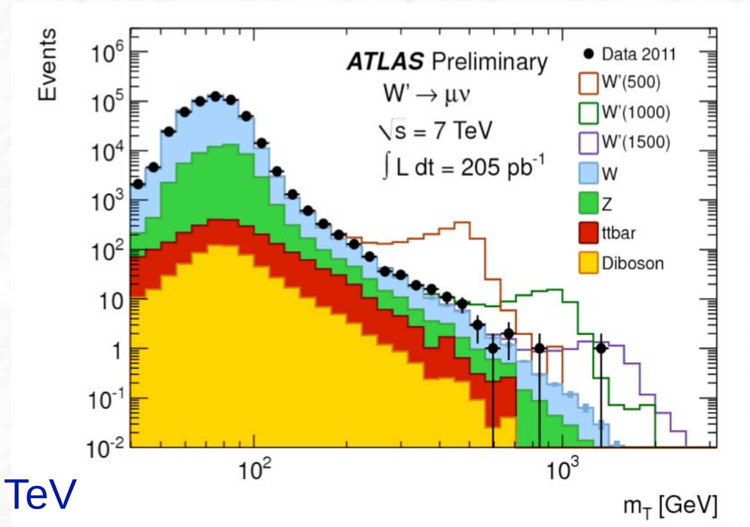
- W': additional charged heavy vector boson
- Appears in theories based on the extension of the gauge group

  e.g. Left-right symmetric models: $SU(2)_R$ W_R
- Assume ν from W' decay to be light and stable, and W' to have the same couplings as in the SM (*"Sequential Standard Model, SSM")*

Signature: high p_T electron + high E_T^{miss}
→ peak in transverse mass distribution

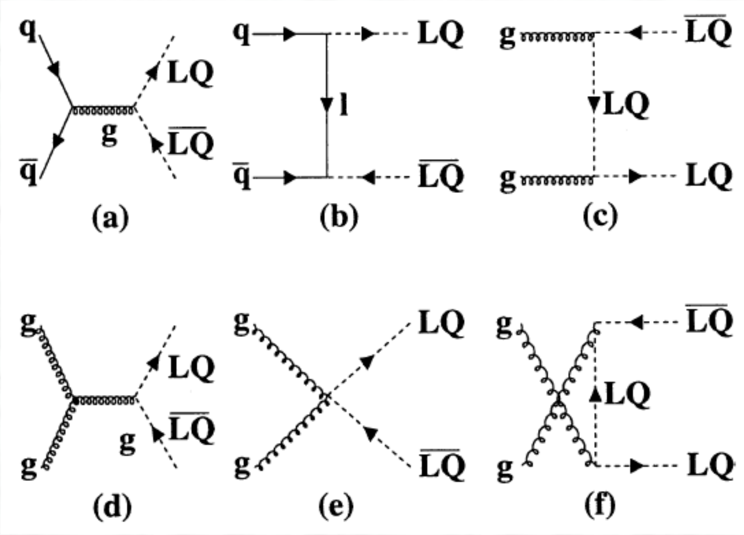






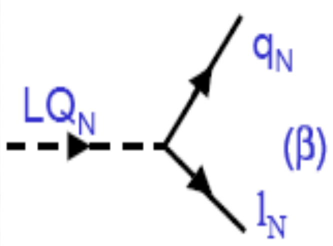
Comparable limits (ATLAS, CMS, 36 pb^{-1}): ~1.49 / 1.58 TeV
New ATLAS limit (W → μν, 205 pb^{-1}): ~1.70 TeV

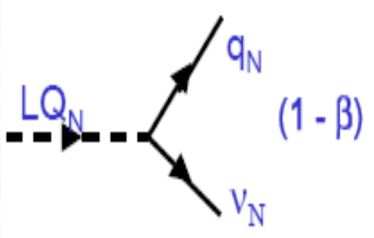
Search for Scalar Leptoquarks (LQ)



- <u>Production:</u>
  pair production via QCD processes
  (qq and gg fusion)

- <u>Decay:</u> into a lepton and a quark



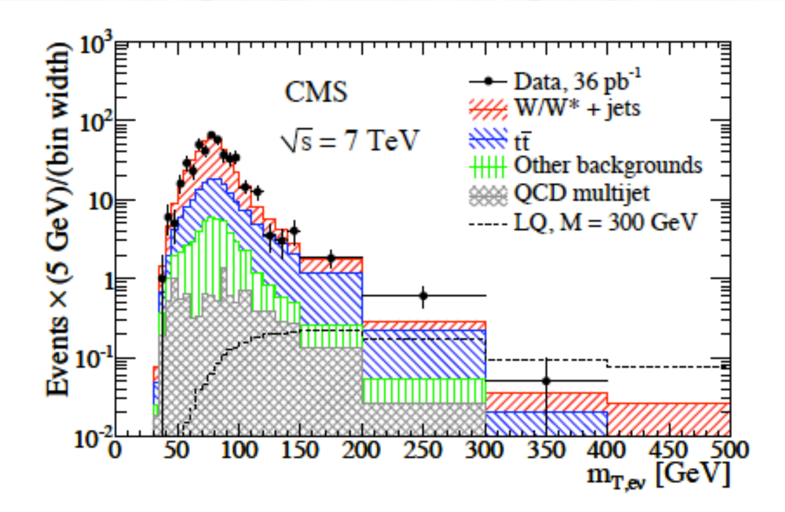


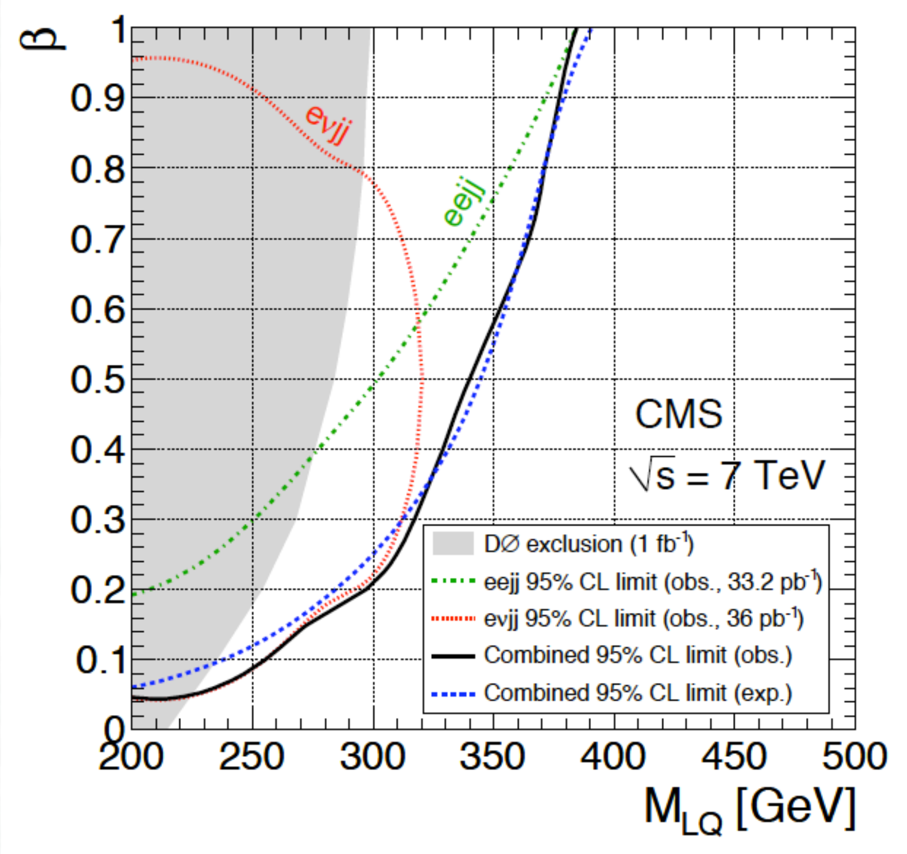
β= LQ branching fraction to charged lepton and quark
N = generation index
Leptoquarks of 1., 2., and 3. generation

<u>Experimental Signatures:</u>

- two high p_T isolated leptons + jets .OR.
- one isolated lepton + E_T^{miss}+ jets .OR.
- E_T^{miss} + jets

1st, 2nd and 3rd generation Leptoquarks





95% C.L. Mass Limits	1. Generation LQ	2. Generation LQ	3. Generation LQ
CDF (Run II)	235 GeV/c^2	224 GeV/c^2	129 GeV/c^2
D0 (Run I + II)	282 GeV/c^2	200 GeV/c^2	
ATLAS	319 GeV/c^2	362 GeV/c^2	
CMS	340 GeV/c^2	290 GeV/c^2	

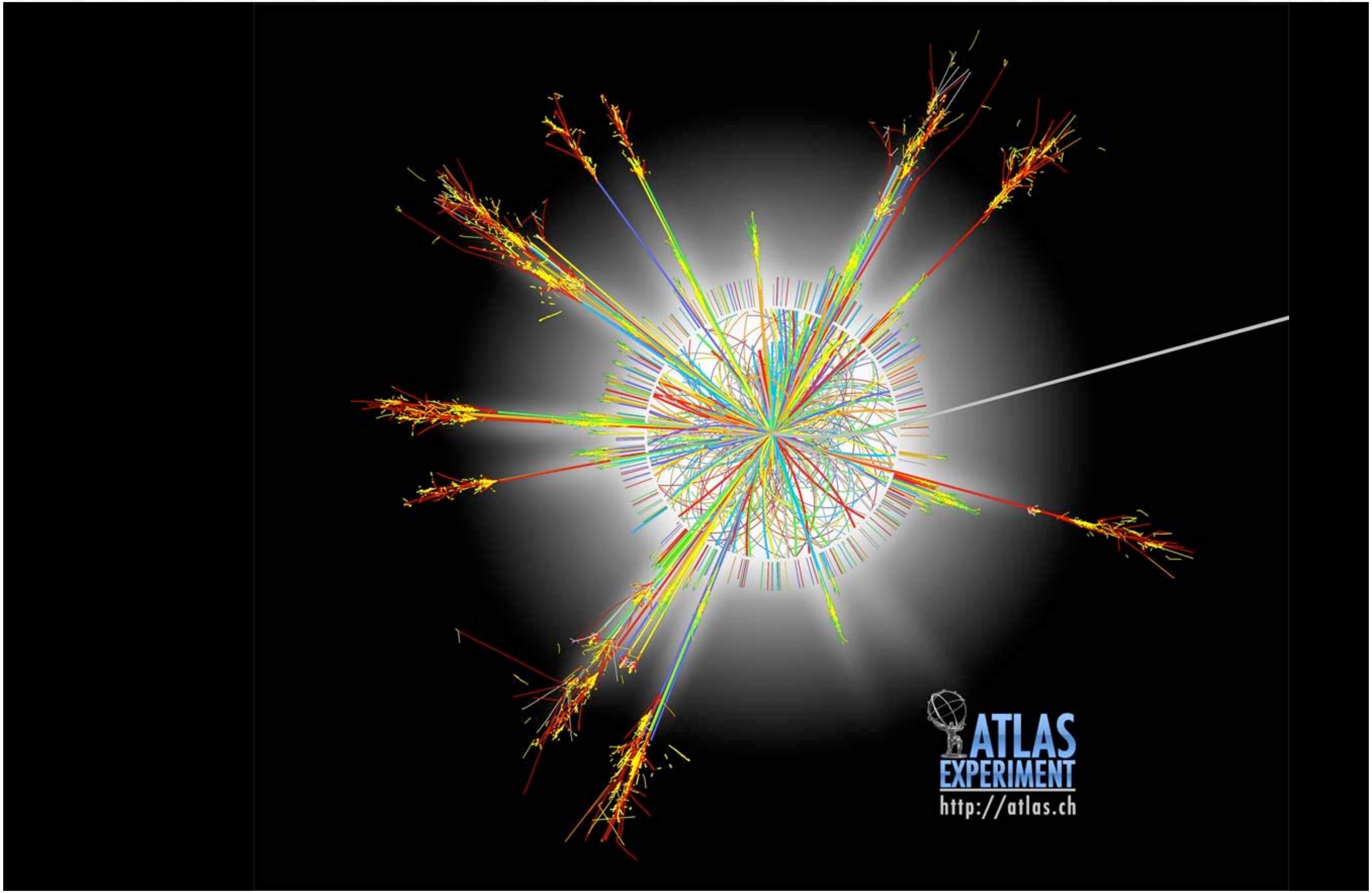
$\beta = 0.5$

LHC reach for other BSM Physics

(expected discovery sensitivity for 30 and 100 fb^{-1})

	30 fb^{-1}	**100 fb^{-1}**
Excited Quarks $Q^* \rightarrow q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
$Z' \rightarrow \ell\ell$, jj $W' \rightarrow \ell\,\nu$	M (Z') ~ 3 TeV M (W') ~ 4 TeV	M (Z') ~ 5 TeV M (W') ~ 6 TeV
Compositeness (from Di-jet)	Λ ~ 25 TeV	Λ ~ 40 TeV

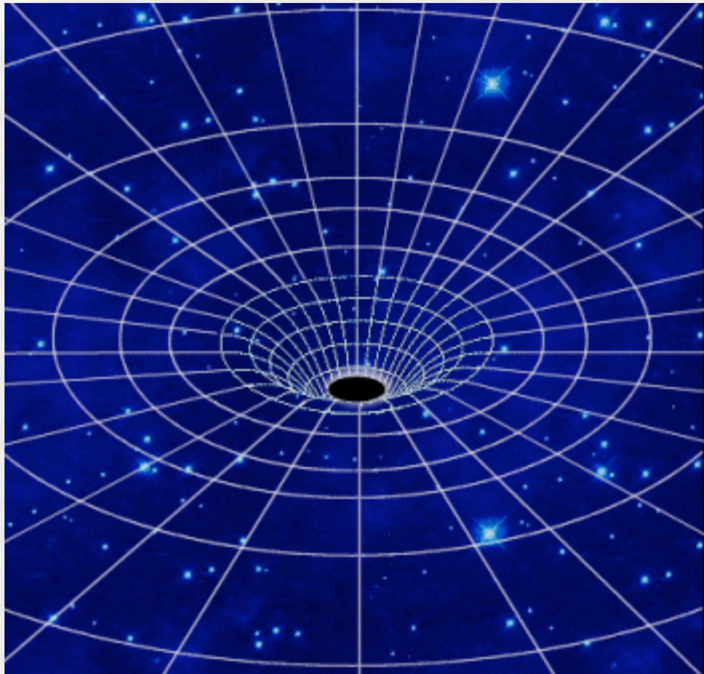
Microscopic-Black Hole Events at the LHC ?



Microscopic-Black Holes ?

According to some theoretical models, tiny black holes could be produced in collisions at the LHC.

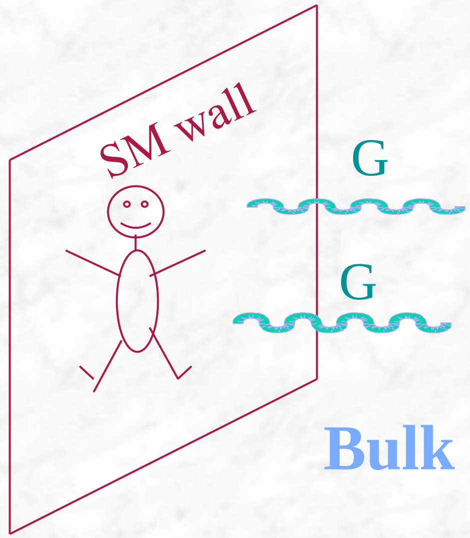
They would then very quickly decay and be detected by experiments (the tinier the black hole, the faster it evaporates).



Can LHC probe extra dimensions ?

- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity, or the hierarchy problem, by extra dimensions)

- New physics, scale of gravity M_D, can appear at the TeV-mass scale, i.e. accessible at the LHC

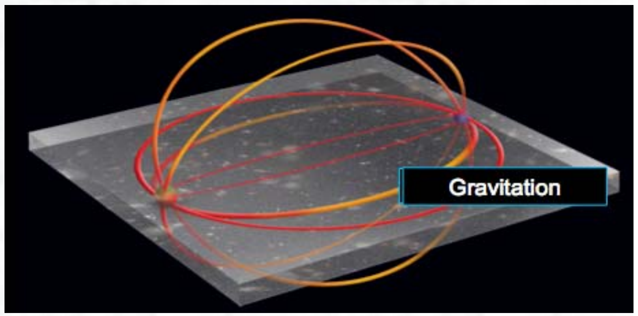


- Extra dimensions are compactified on a torus or sphere with radius r

  relation between Planck mass in 4 and (4+n) dimensions: $$M_{\rm Pl}^2 = 8\pi M_D^{n+2} r^n$$

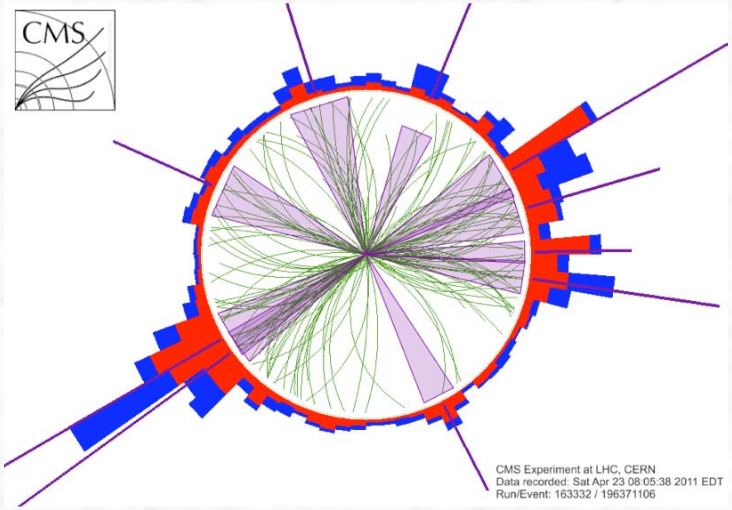
- Black hole formation at energies greater than M_D

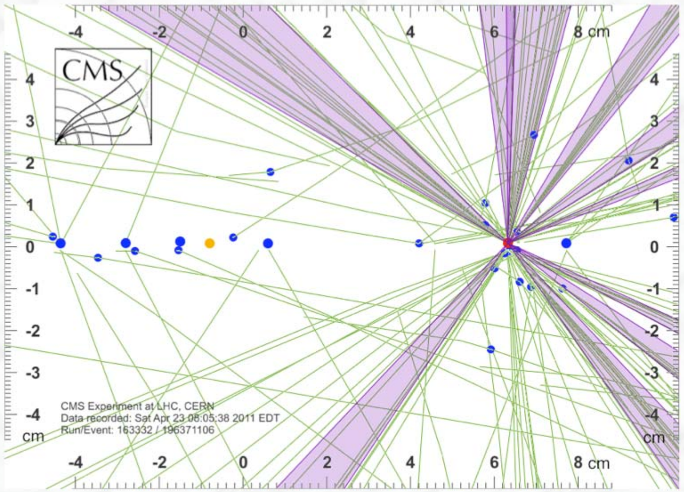
  Production cross section can be in the order of 100 pb for M_D ~1 TeV (large model dependence)



- Once produced, the black hole is expected to decay via Hawking radiation, democratically to all Standard Model particles (quarks and gluons dominant,75%)
  → multijet events with large mass and total transverse energy

CMS search for events with high jet multiplicity and large transverse energy



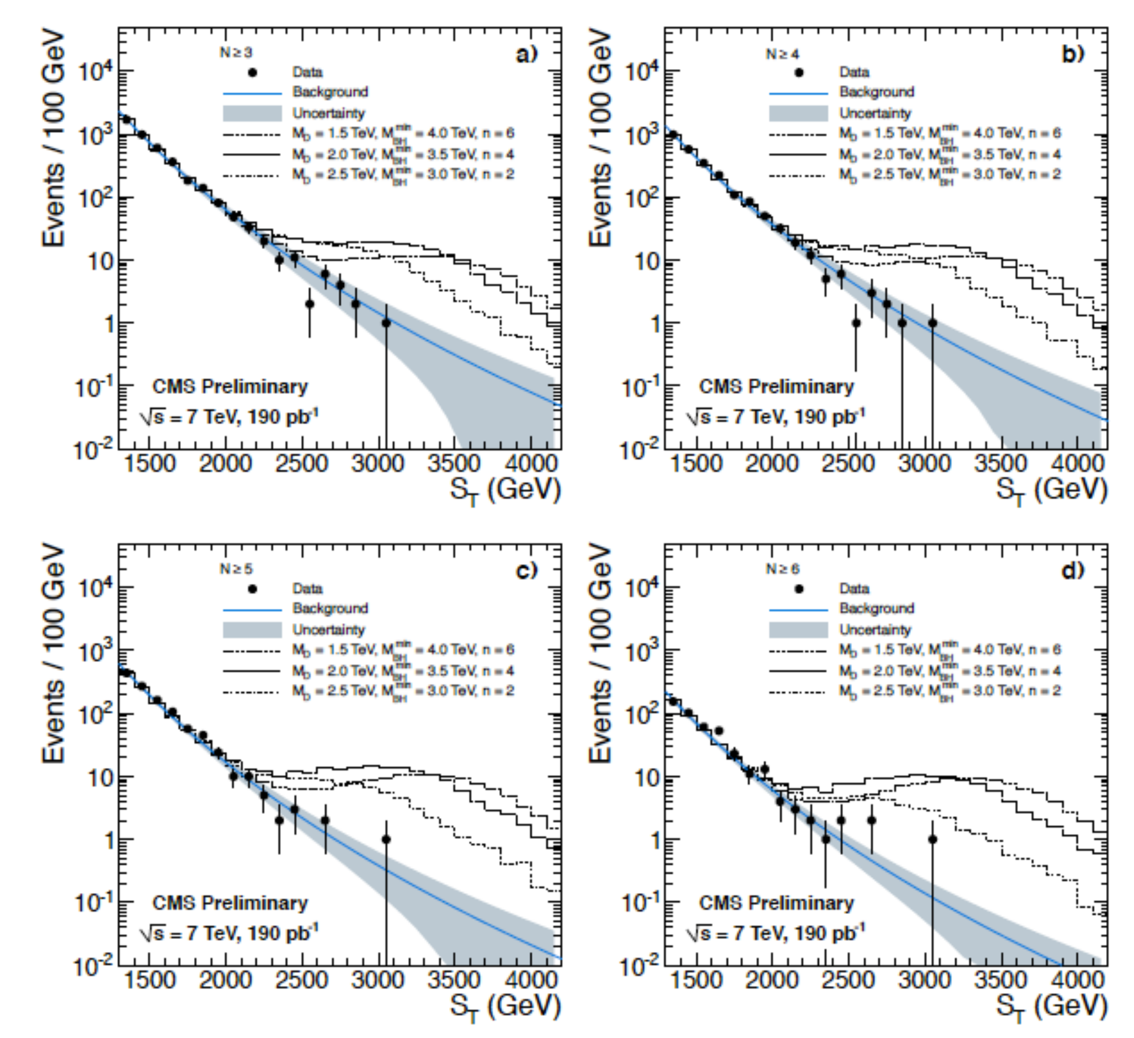


Candidate events exist….

event with high multiplicity of jets, high mass….

all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?



Total transverse energy S_T for events with N>3, 4, 5, 6 objects

No evidence for excess above the QCD expectations

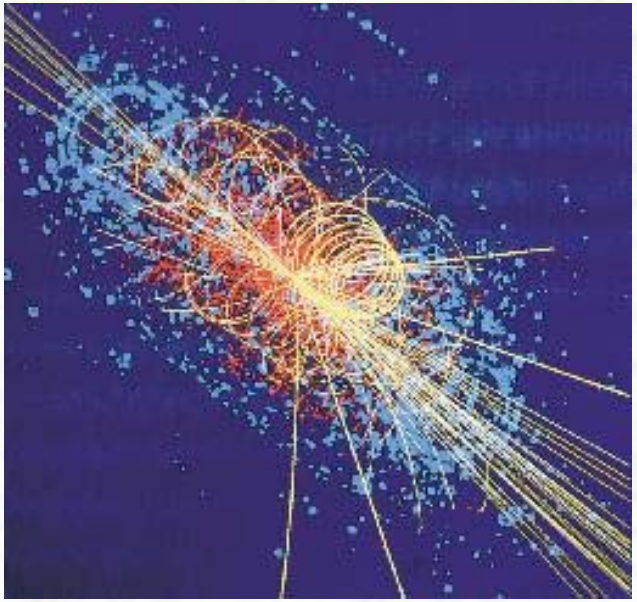
→ No evidence for the formation of micro Black Holes

Conclusions

- With the operation of the LHC at high energies, particle physics has entered a new era
- Detectors and accelerator work extremely well;
  The 1 fb^{-1} threshold has been passed
- Many Standard Model measurements have already been performed in 2010, (important for searches for new physics, precision will increase with more data)

  The Standard Model is still alive
- LHC has reached the threshold for new discoveries; higher sensitivity than the Tevatron in searches
- 2011/12 are exciting years, LHC reaches sensitivity in the search for the Higgs boson and largely extends the range for new particle searches.

End of lectures



• In case you have any questions:
please do not hesitate to contact me: karl.jakobs@uni-freiburg.de

• Transparencies will be made available as .pdf files on the web
(school pages)