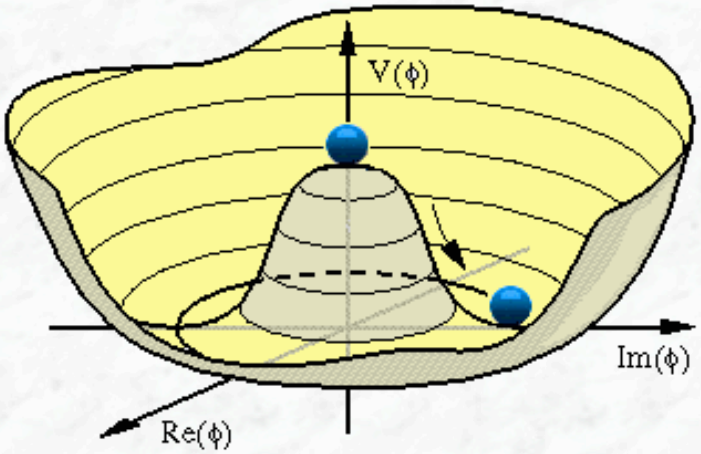
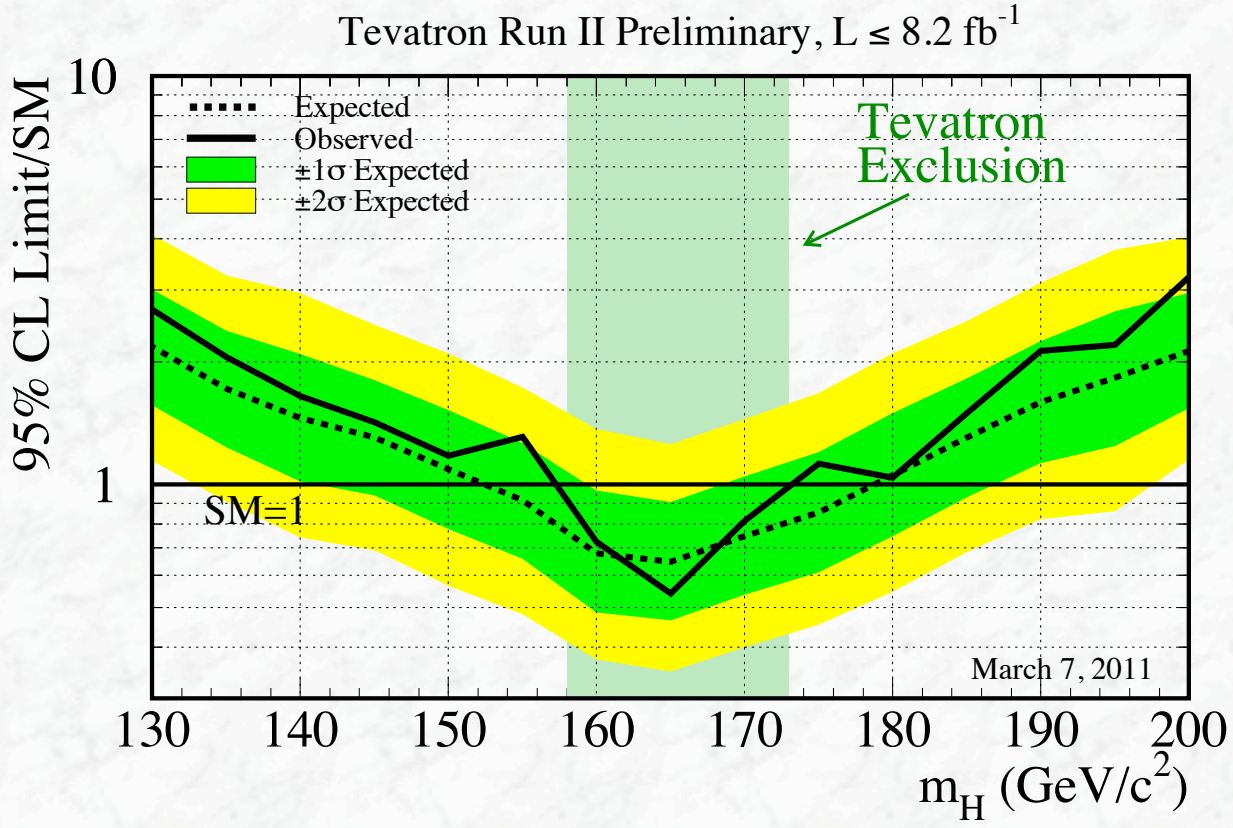
Part 3: Search for the Higgs Boson



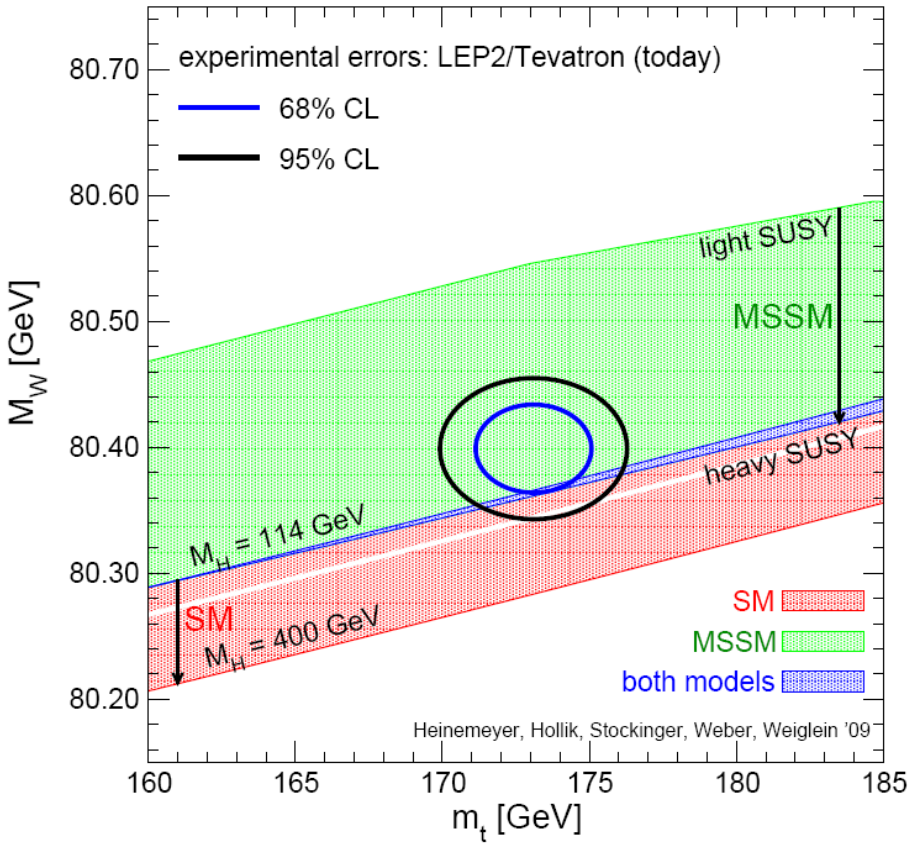
What was known about the Higgs Boson before the LHC?

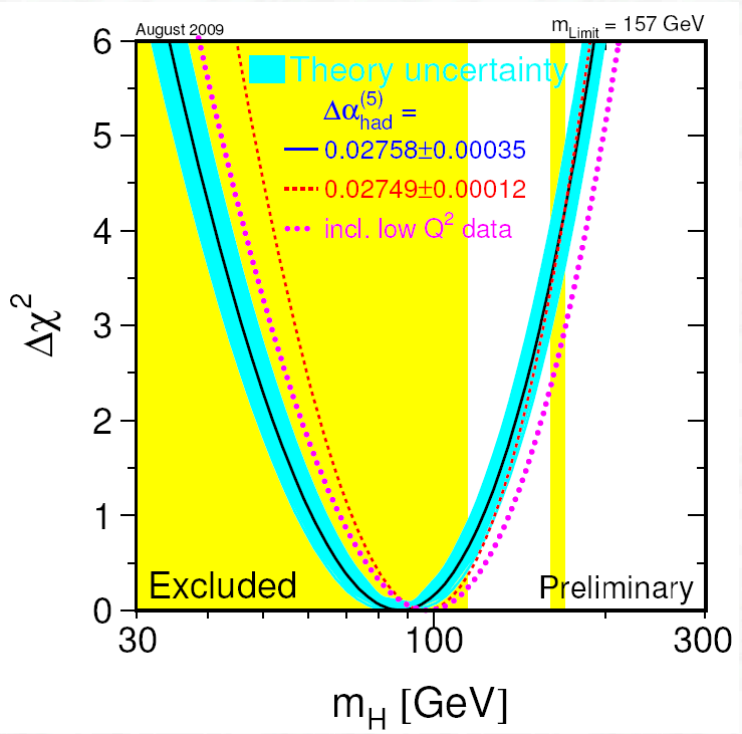
- Mass not predicted by theory, except that m_H < ~1 TeV (unitarity)
- m_H > 114.4 GeV from direct searches at LEP
  m_H < 158 GeV .or. m_H > 173 GeV from direct searches at the Tevatron



What was known about the Higgs Boson before LHC? (cont.)

- Indirect limits from electroweak precision measurements (LEP, Tevatron and other experiments….)

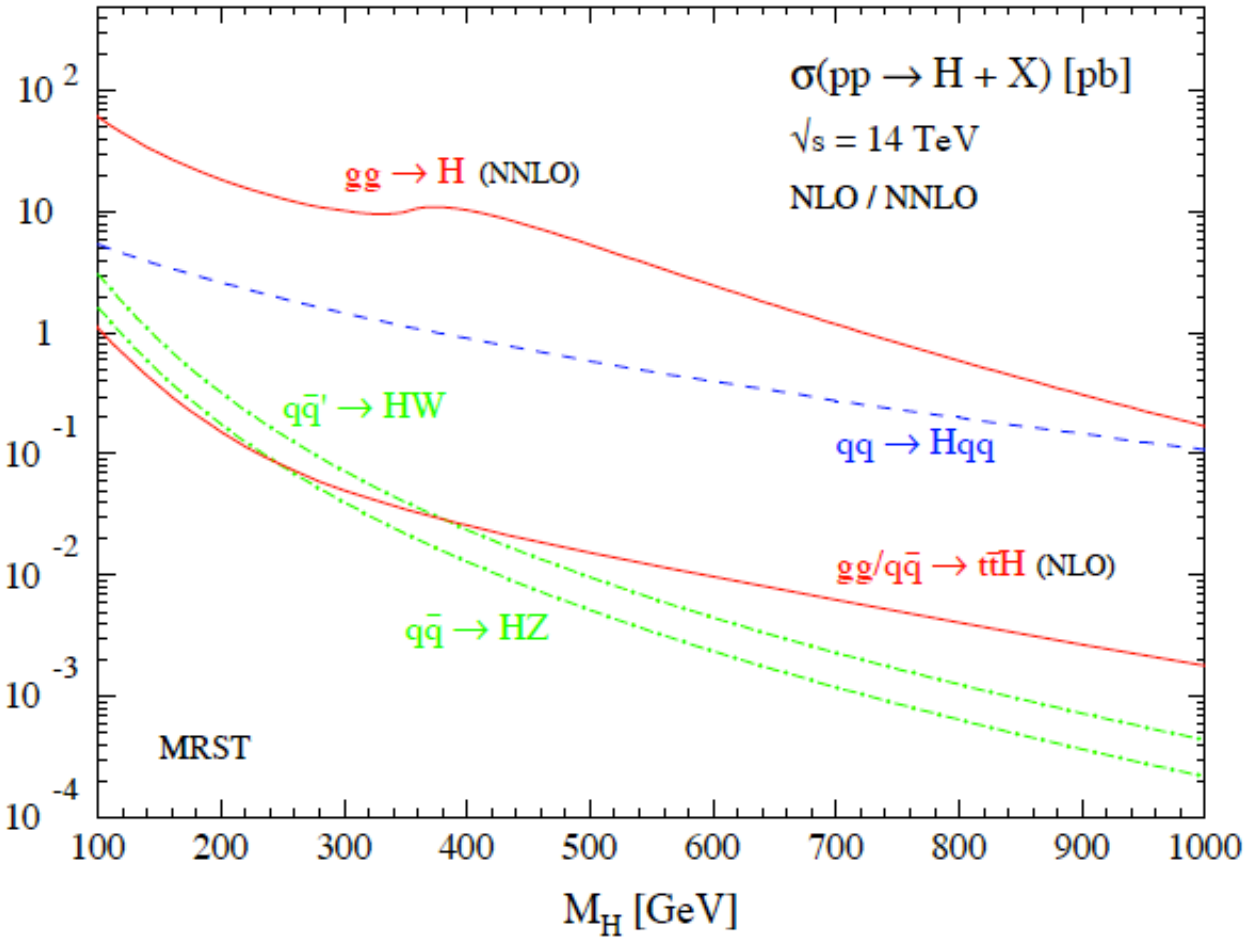


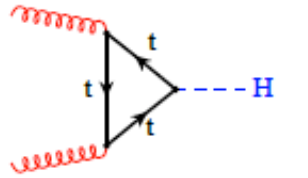


m_H = 89 (+35) (-26) GeV/c^2
m_H < 158 GeV/c^2 (95 % CL)

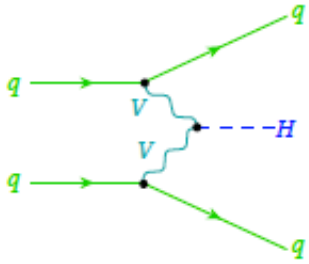
→ Higgs boson could be around the corner !

Higgs boson production at the LHC

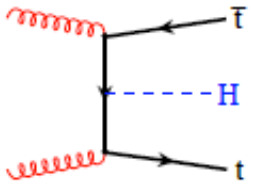




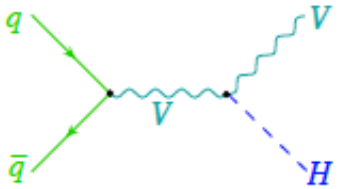
Gluon Fusion



Vector boson fusion

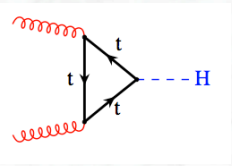


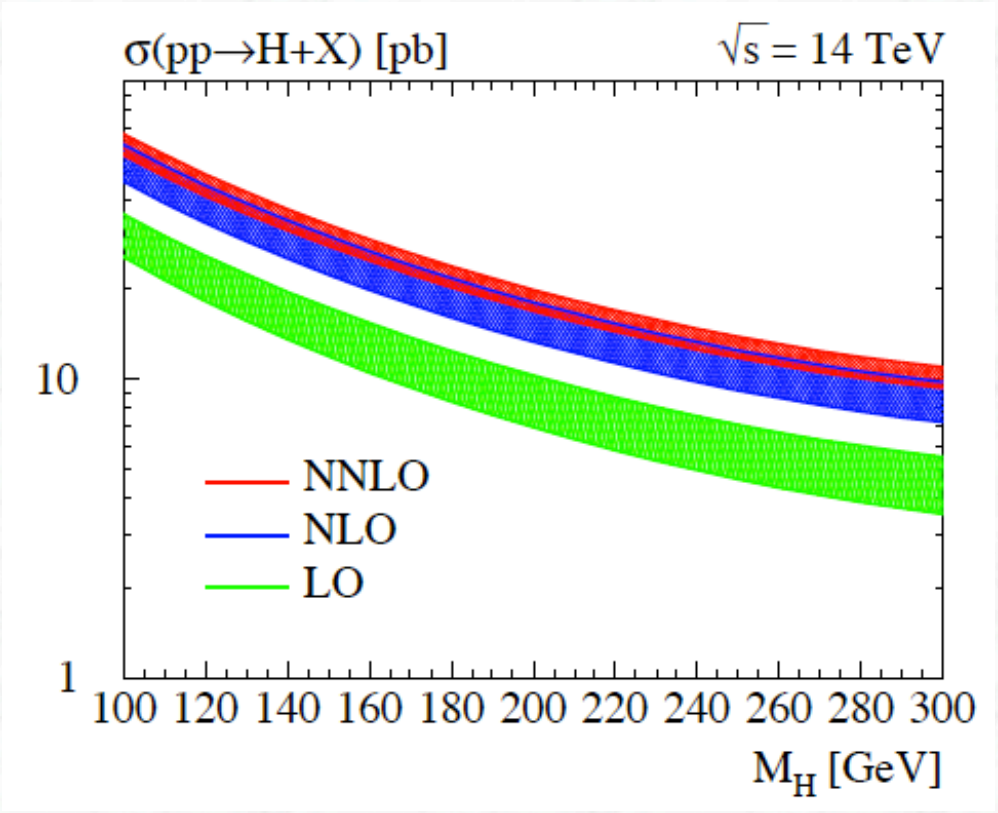
tt associated production



WH/ZH associated production

Higher order corrections:



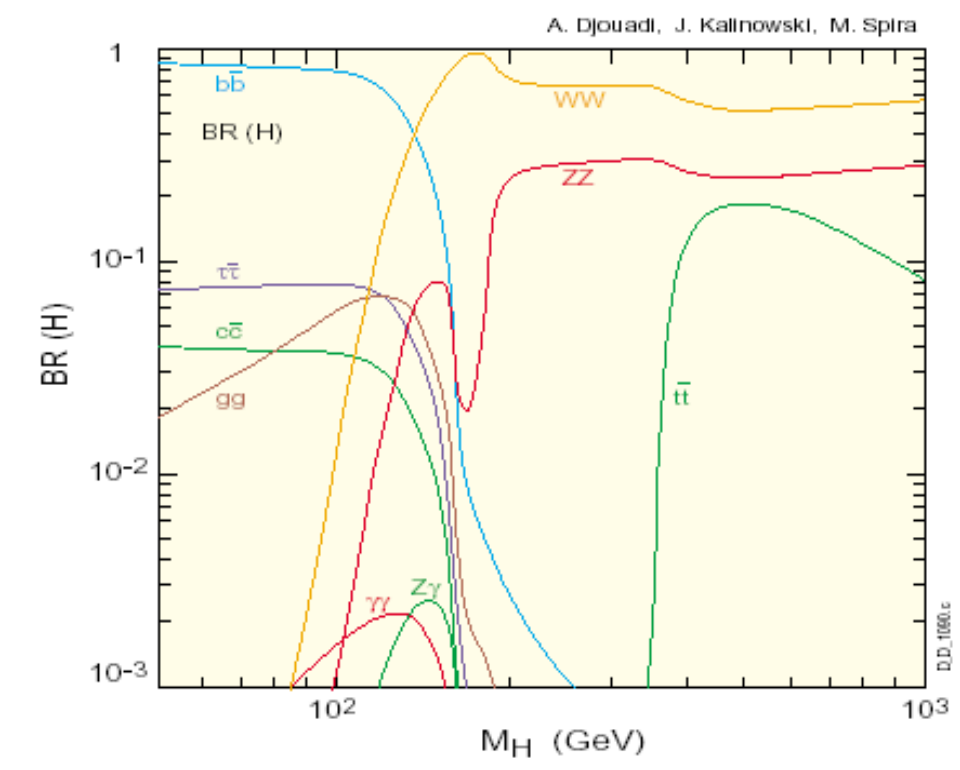


- Spira, Djouadi, Graudenz, Zerwas (1991)
- Dawson (1991)

- Harlander, Kilgore (2002)
- Anastasiou, Melnikov (2002)
- Ravindran, Smith, van Neerven (2003)

Independent variation of renormalization and factorization scales
(with $0.5\ m_H < \mu_F, \mu_R < 2\ m_H$)

Useful Higgs Boson Decays at Hadron Colliders



at high mass:
Lepton final states
(via H → WW , ZZ)

at low mass:
Lepton and Photon final states
(via H → WW*, ZZ*)

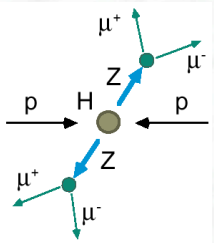
Tau final states

The dominant **bb decay mode** is only useable in the associated production mode (ttH, W/Z H)

(due to the huge QCD jet background, leptons from W/Z or tt decays)

$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

Signal: σ BR = 5.7 fb (m_H = 100 GeV)



$P_T(1,2) > 20$ GeV
$P_T(3,4) > 7$ GeV
$|\eta| < 2.5$
Isolated leptons

$M(\ell\ell) \sim M_Z$
$M(\ell'\ell') \sim < M_Z$

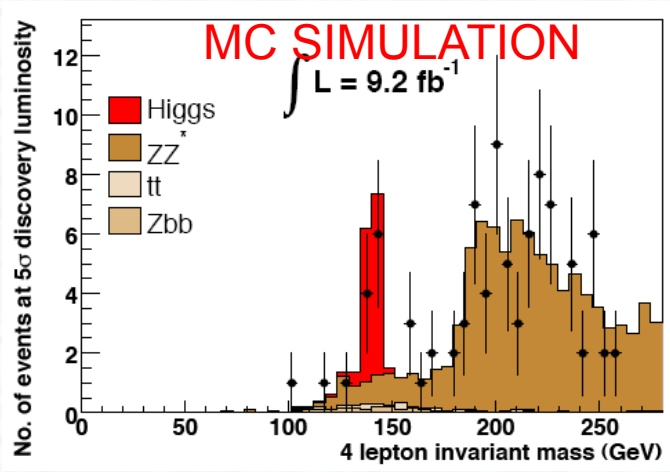
Background: Top production

$t\bar{t} \rightarrow Wb\ Wb \rightarrow \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$

σ BR ≈ 1300 fb

Associated production Z bb

$Z\ b\bar{b} \rightarrow \ell\ell\ c\ell\nu\ c\ell\nu$



Background rejection:

Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

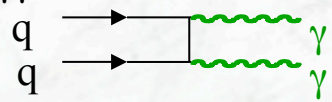
Dominant background after isolation cuts: ZZ continuum

Discovery potential in mass range from ~130 to ~600 GeV/c^2

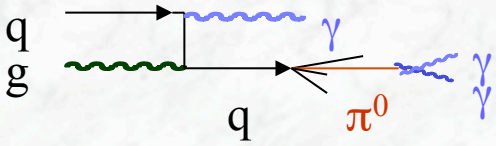
Decay modes at low mass: $H \rightarrow \gamma\gamma$

Main backgrounds:

$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)

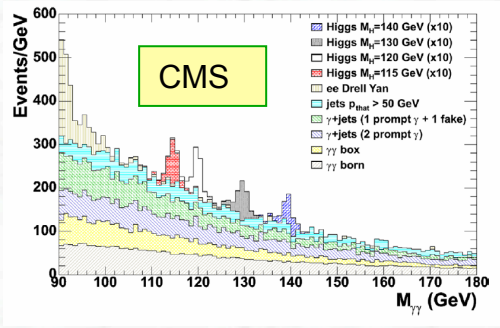


$\sigma_{\gamma j+jj} \sim 10^6 \, \sigma_{\gamma\gamma}$ with large uncertainties

$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

MC SIMULATION



- Main exp. tools for background suppression:
  - photon identification
  - γ / jet separation (calorimeter + tracker)

Signal expectation for 10 fb^{-1}

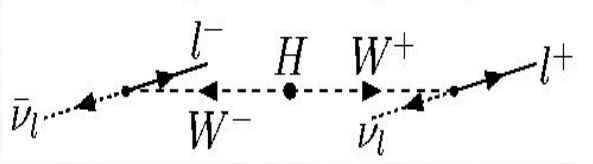
Sensitivity in the low mass region, however, higher integrated luminosities required

$H \rightarrow WW \rightarrow \ell\nu\,\ell\nu$

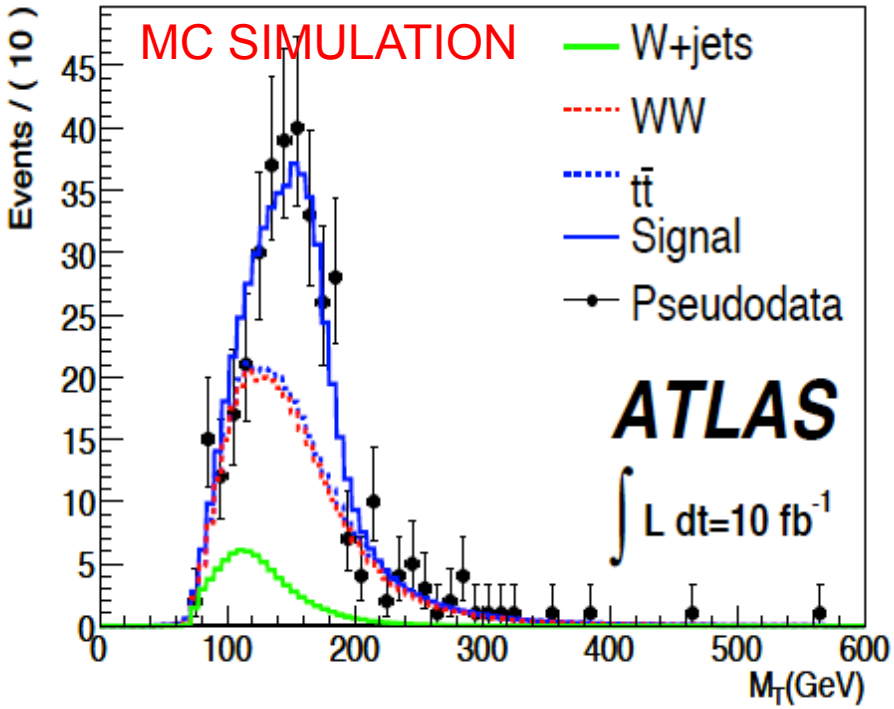
- Large $H \rightarrow WW$ BR for $m_H \sim 160$ GeV/c^2
- Neutrinos → no mass peak,
  → use transverse mass
- Large backgrounds: WW, Wt, tt

- Two main discriminants:

(i) Lepton angular correlation



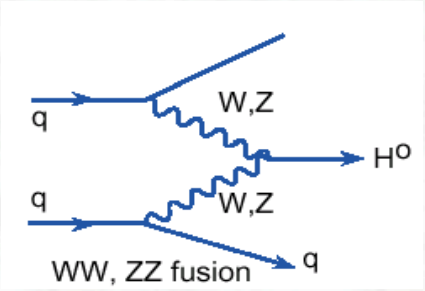
(ii) Jet veto: no jet activity
in central detector region



Channel with highest sensitivity !
Sensitive to a Standard Model Higgs boson already now, with 1 fb^{-1} !

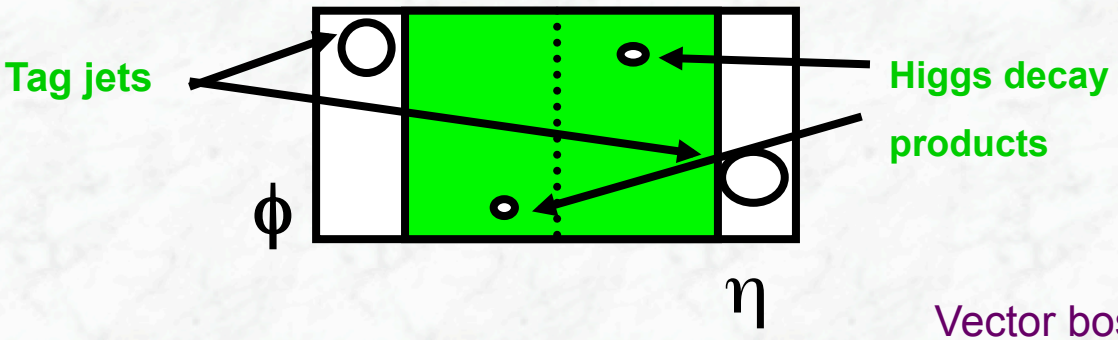
Vector Boson Fusion qq H

Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

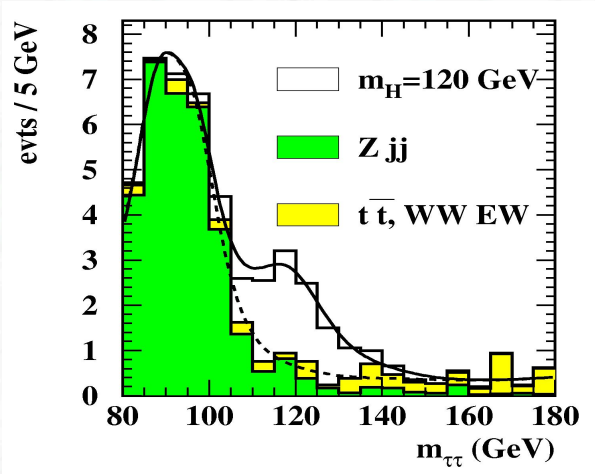


Distinctive Signature of:

- two high p_T forward jets (tag jets)
- little jet activity in the central region (no colour flow)
  ⇒ central jet Veto

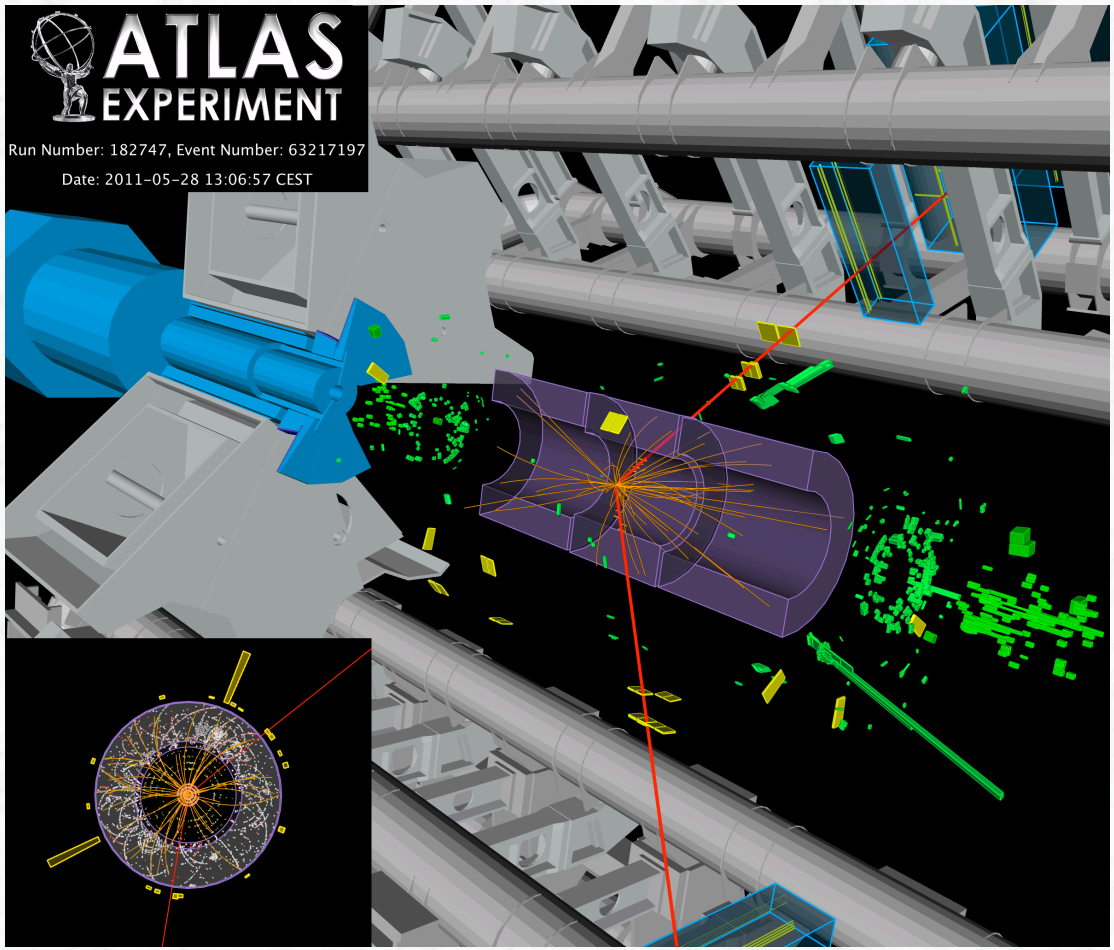


MC SIMULATION



Vector boson fusion mode provides access to H → ττ decay modes (e-τ_{had}, μ–τ_{had}, e-μ);
In addition: strong on WW decay mode

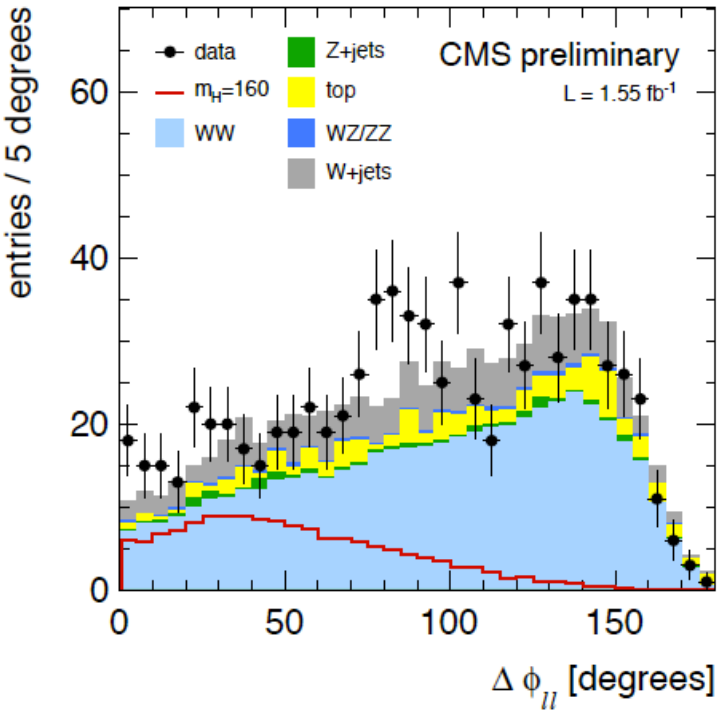
What do the data say ?



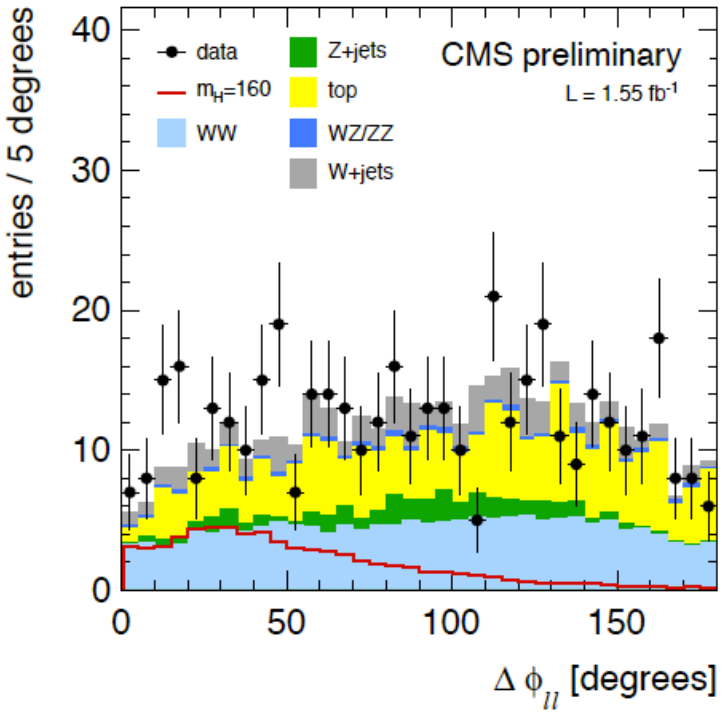
Event with 2 identified electrons and 2 muons
(m_{4l} = 210 GeV)

Results from CMS on the H → WW → ℓν ℓν search:

L = 1.55 fb^{-1} (large fraction of 2011 data)



ll + E_T^{miss} + 0 jets

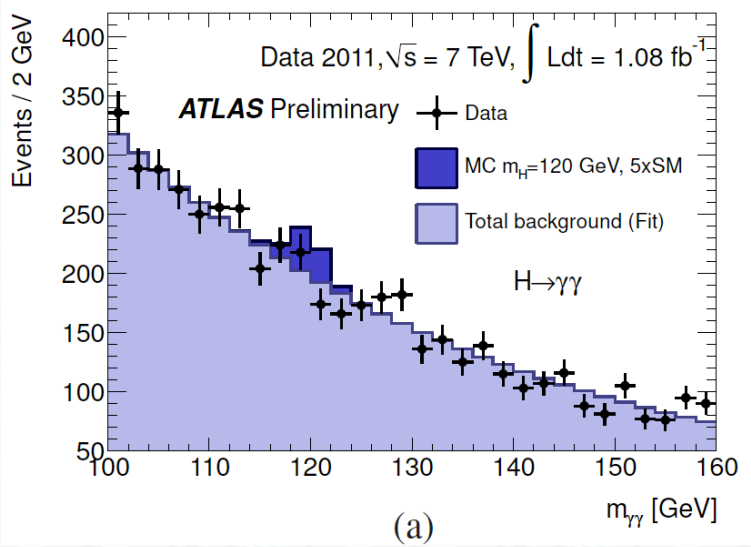


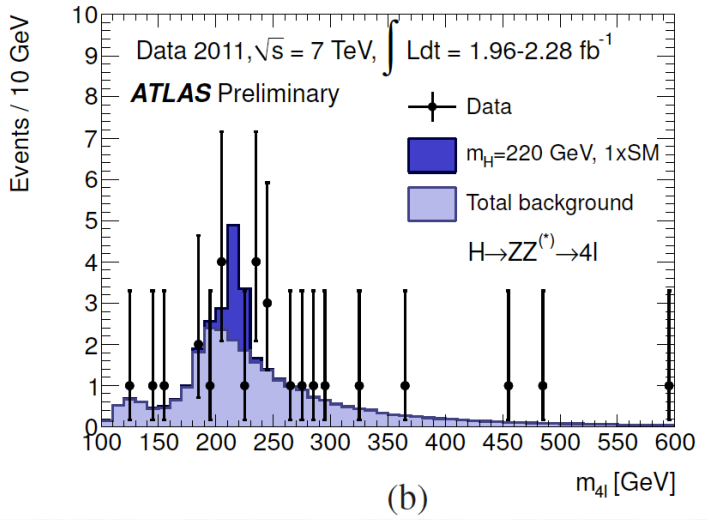
ll + E_T^{miss} + 1 jet

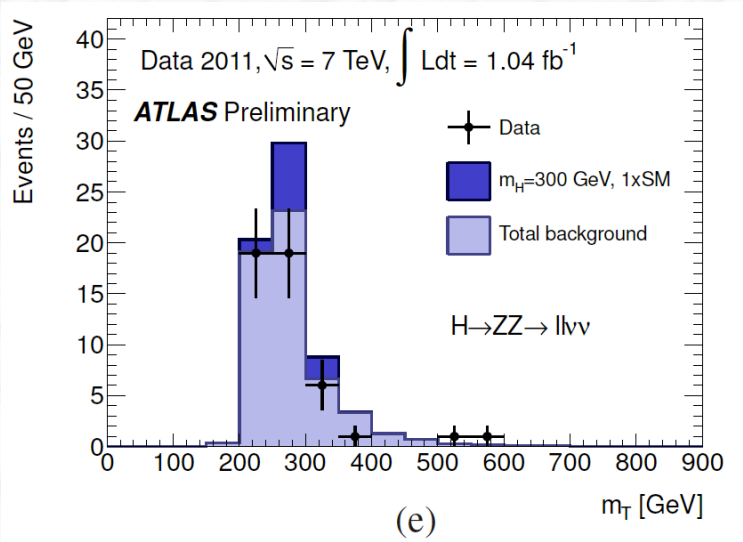
- Data are in “reasonable” agreement ” with expectations from Standard Model processes; some small excess at small Δϕ visible;
- Important background normalized using control regions in data

Results from ATLAS on various other search channels:

L = 1.08 – 2.28 fb^{-1} (up to data taken shortly before Lepton-photon conference)



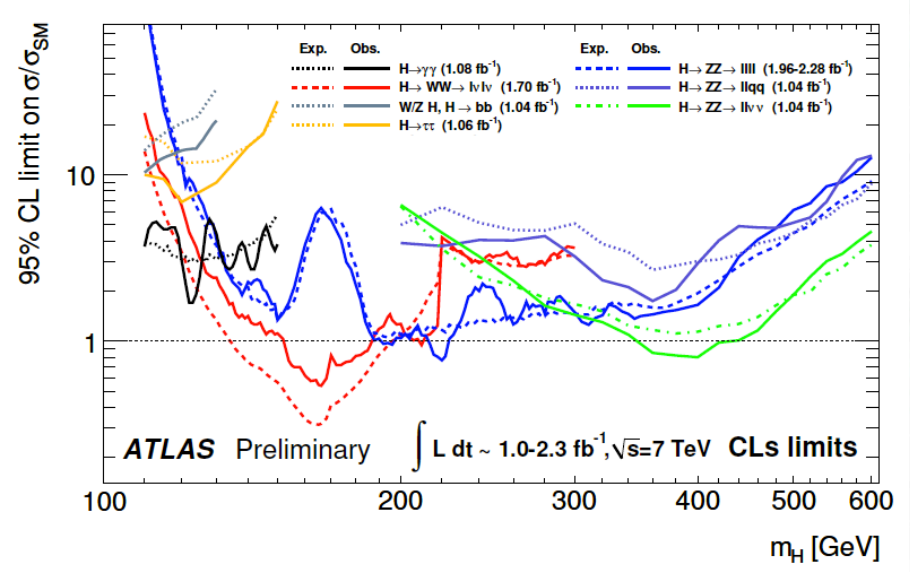


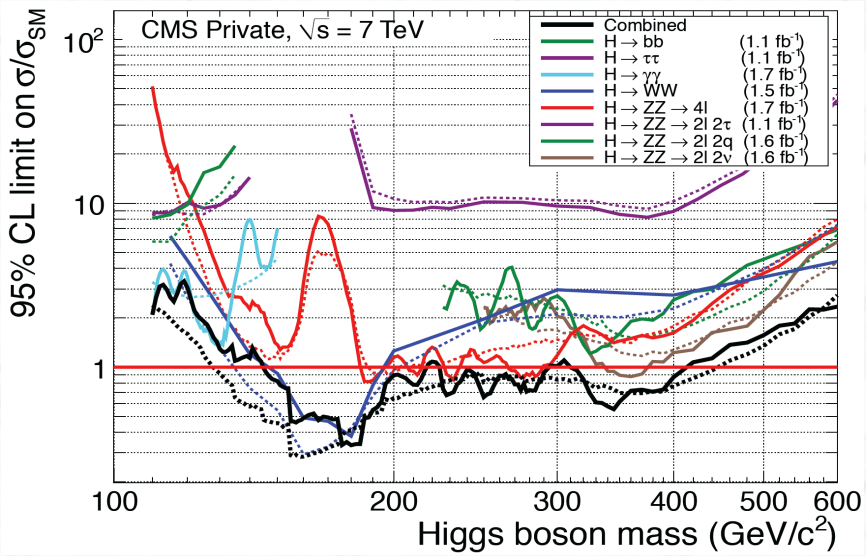


Also in these channels: data are consistent with expectations from Standard Model background processes

→ work out significances / statistics

Current status of the Higgs boson search at the LHC
-ATLAS and CMS-



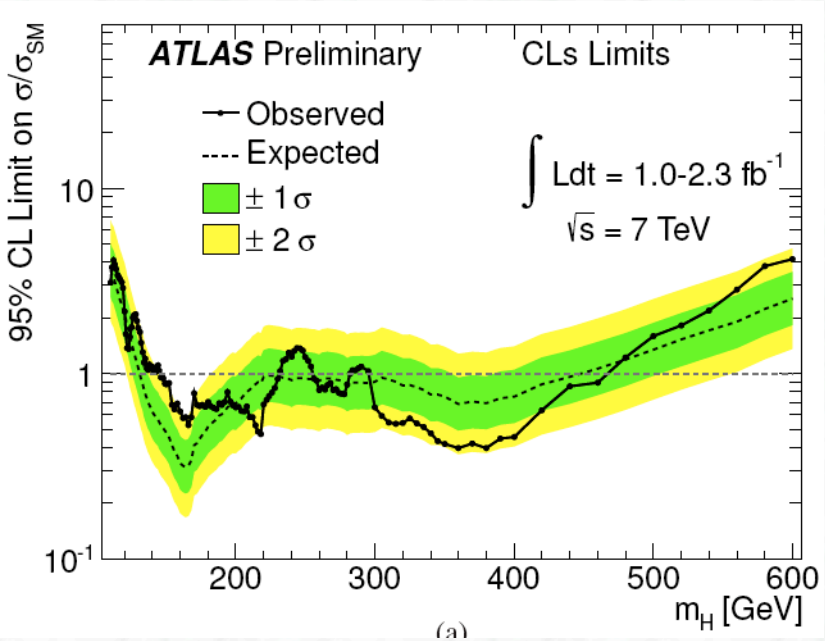


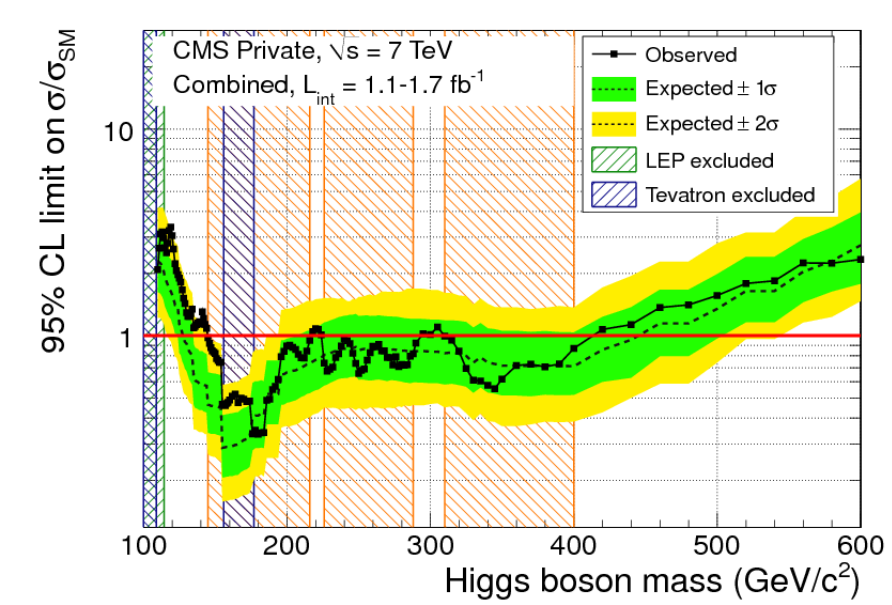
- The two collaborations show similar performance

  - in terms of analysis power in the collaboration (many channels)
  - in terms of sensitivity
  - in terms of conclusions on the existence of the Higgs boson

- → The grand combination (lecture by Kyle Cranmer on the details on statistics)

Current status of the Higgs boson search at the LHC
-ATLAS and CMS combinations-





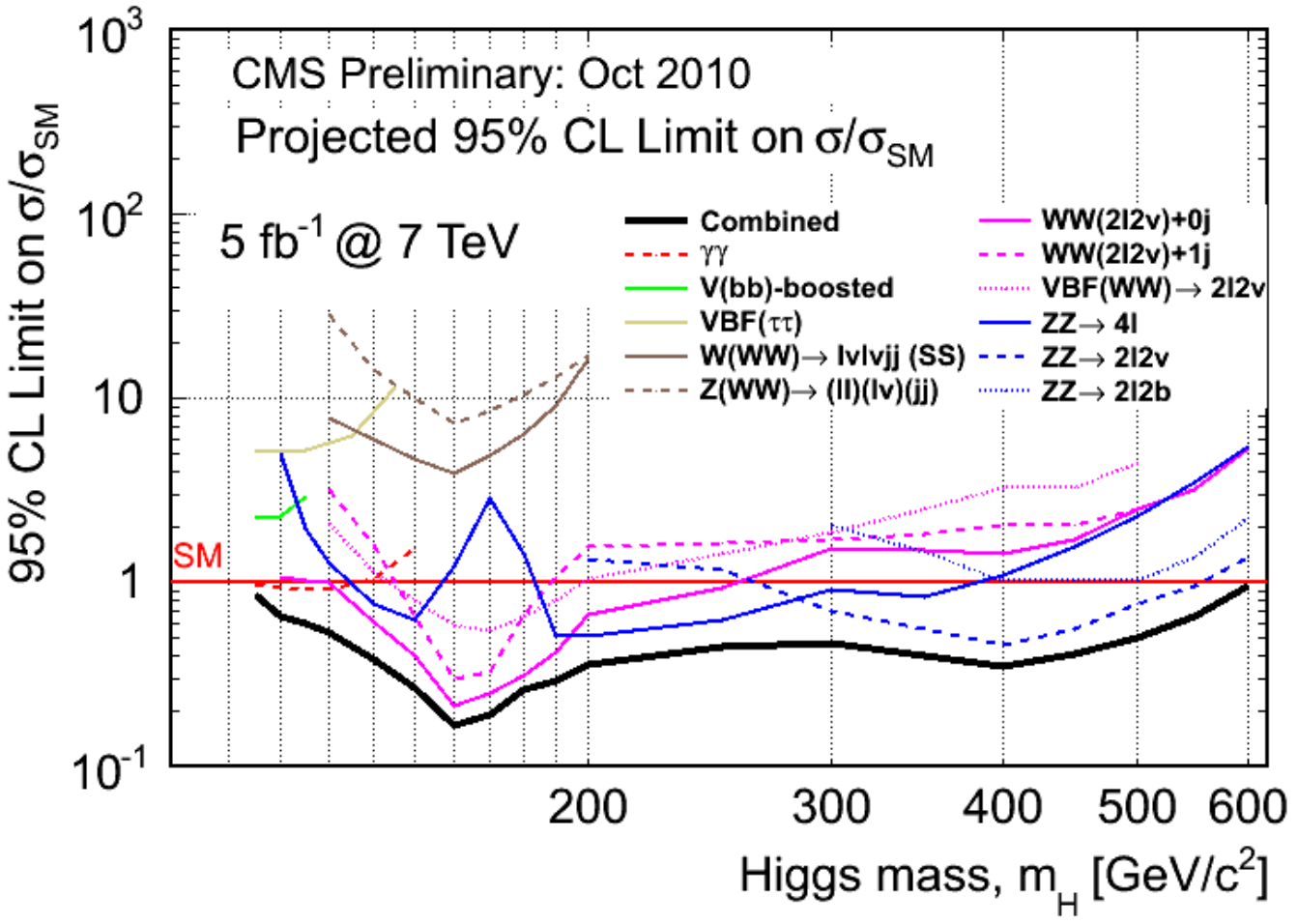
Excluded mass regions (95% C.L.):

$146 < m_H < 232$ GeV
$256 < m_H < 282$ GeV
$296 < m_H < 466$ GeV

Excluded mass regions (95% C.L.):

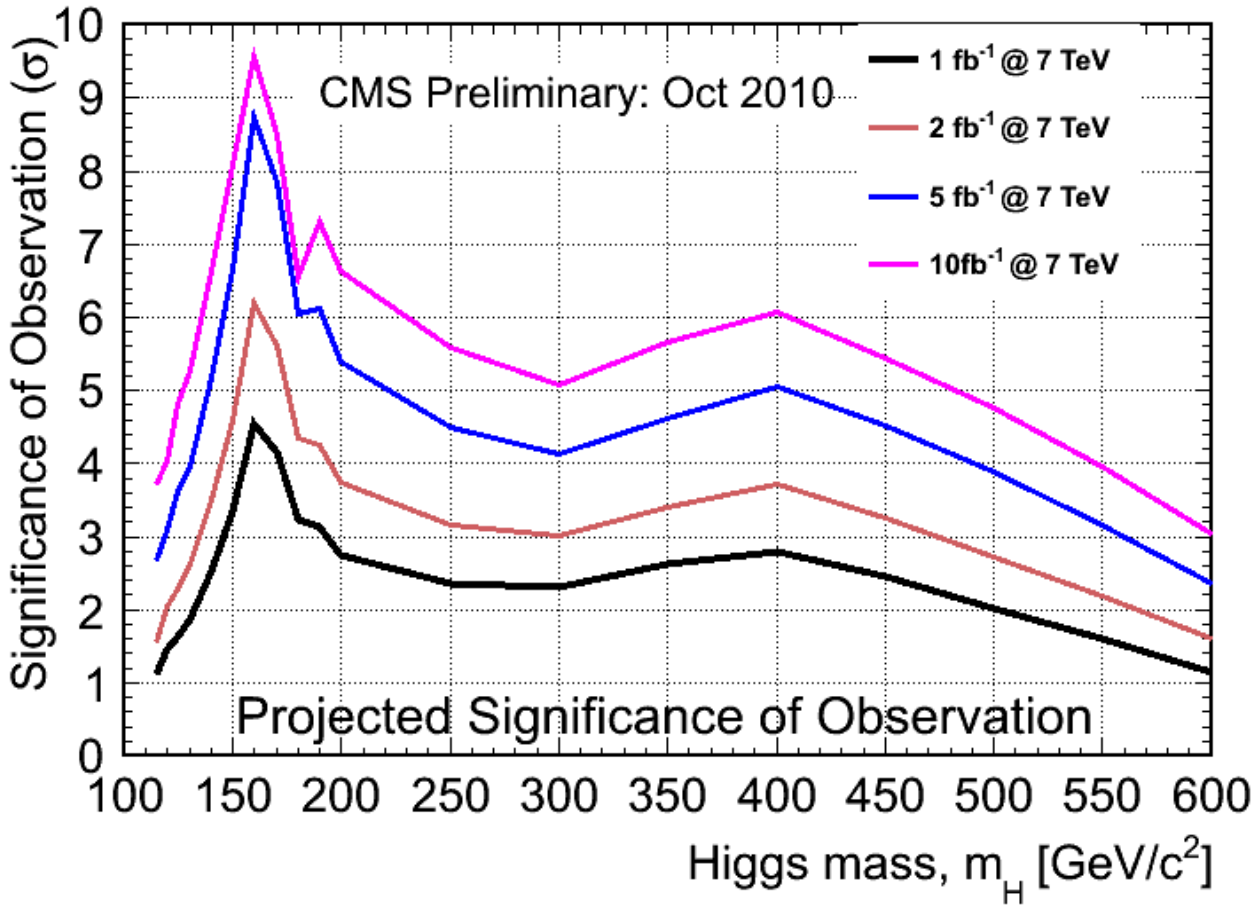
$145 < m_H < 216$ GeV
$226 < m_H < 288$ GeV
$310 < m_H < 400$ GeV

Expectations for higher integrated luminosities
-95% C.L. exclusion limits-



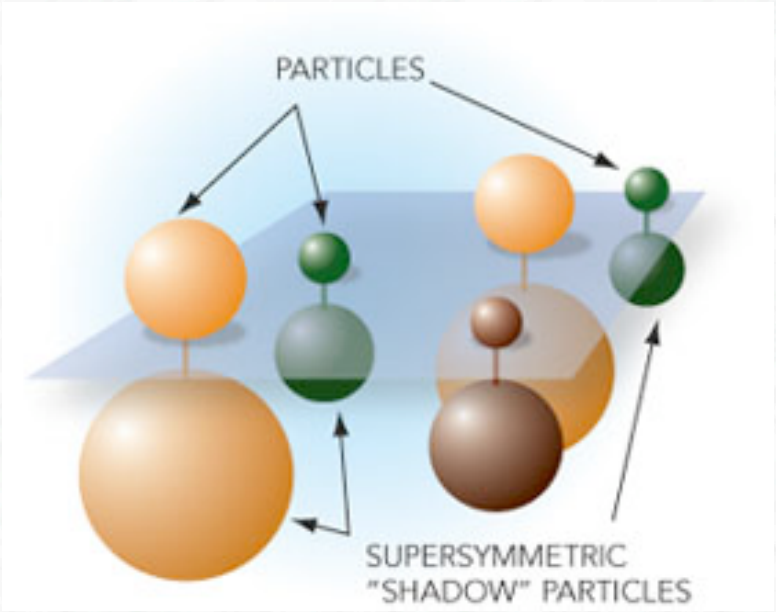
CMS, V. Sharma, Lepton-Photon 2011

Expectations for higher integrated luminosities -discovery significances-



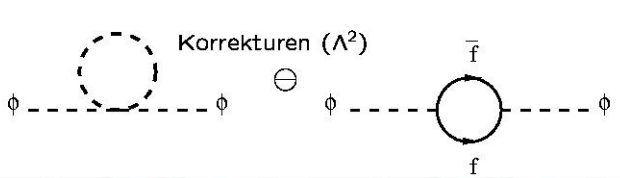
CMS, V. Sharma, Lepton-Photon 2011

Part 4: Search for Supersymmetry



Why do we like SUSY so much?

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

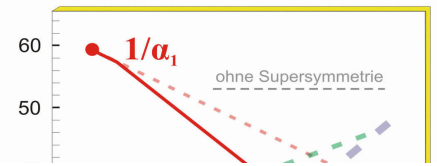


$$\Delta m_H = f(m_B^2 - m_f^2)$$

→ m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)

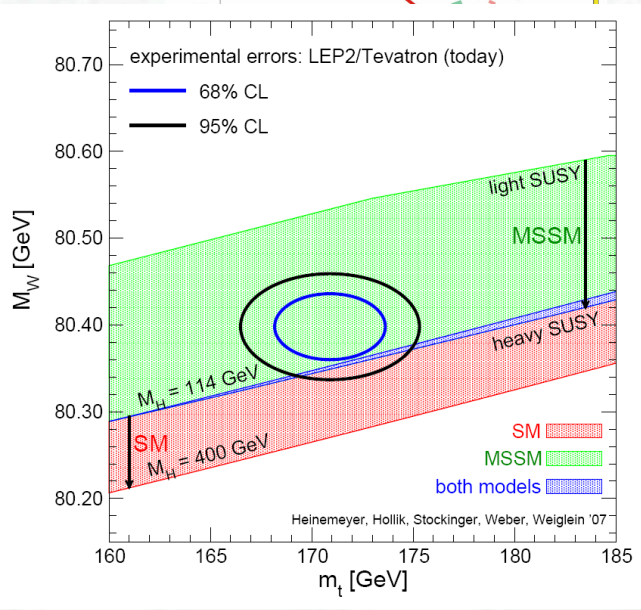
2. Unification of coupling constants of the three interactions seems possible



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

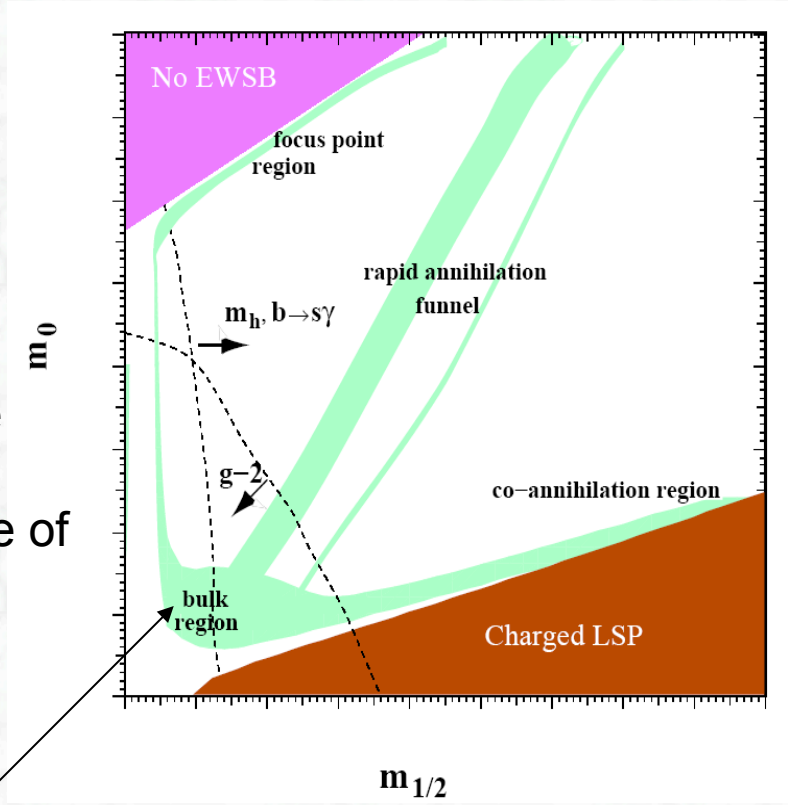


Interpretation in a simplified model

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

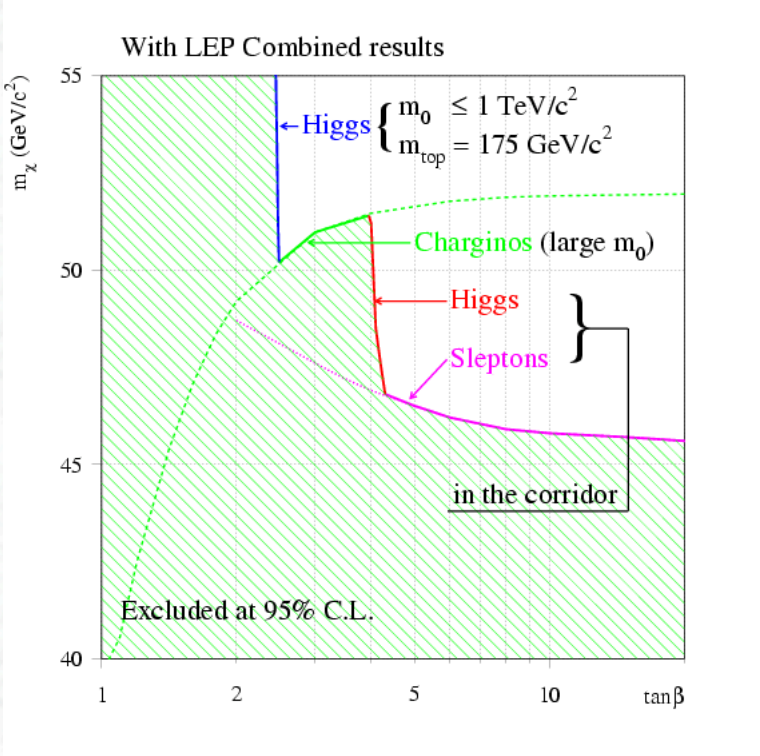


regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

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



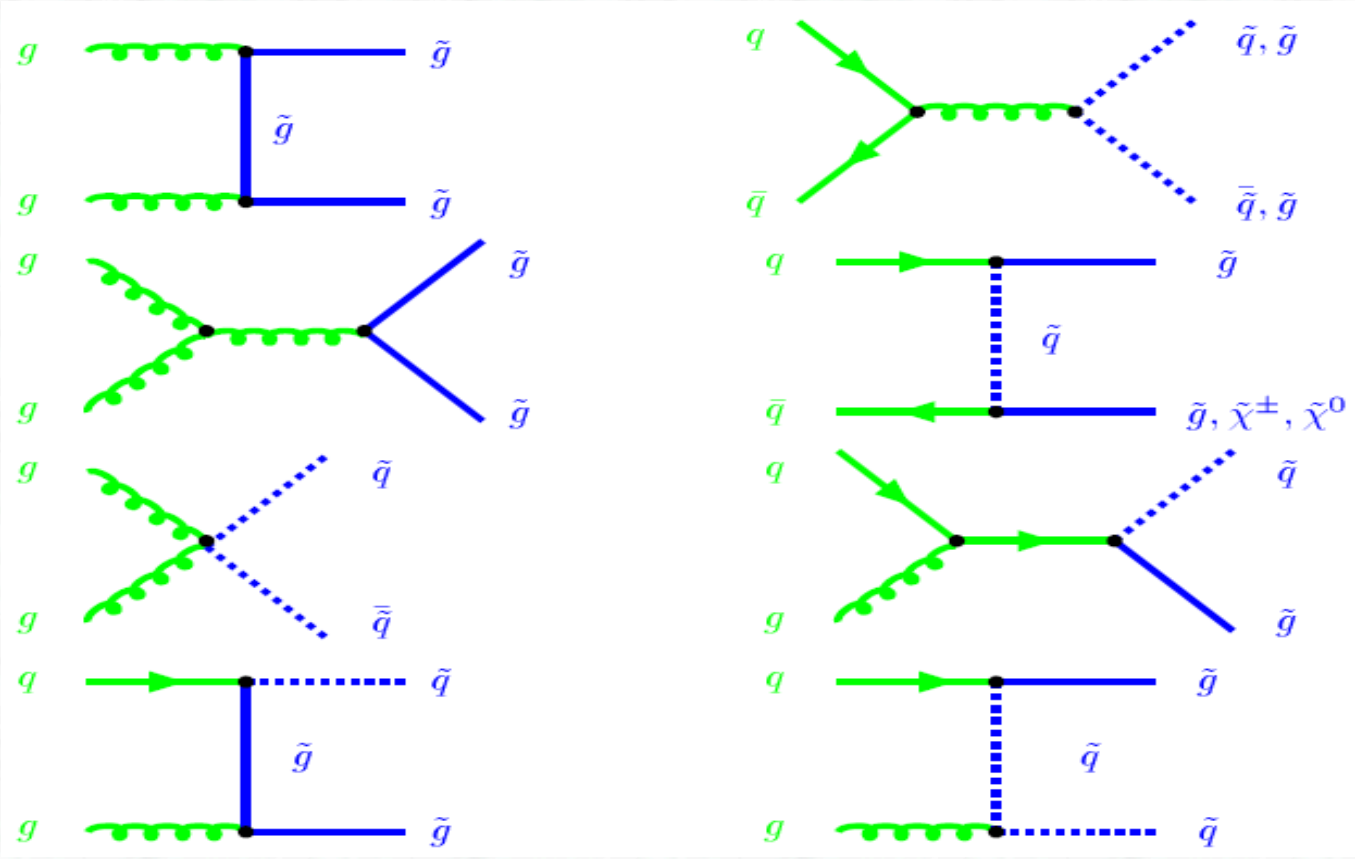
LEP-II limit on the mass of the
Lightest SUSY particle

assumption:
lightest neutralino = LSP

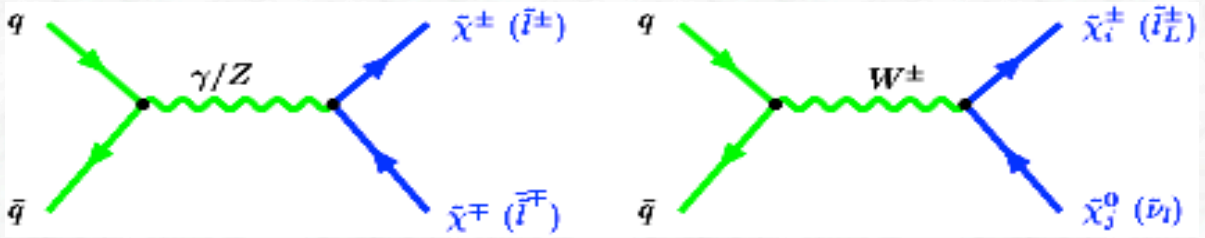
Sparticle production at the LHC

qq, qg and gg
in the initial state

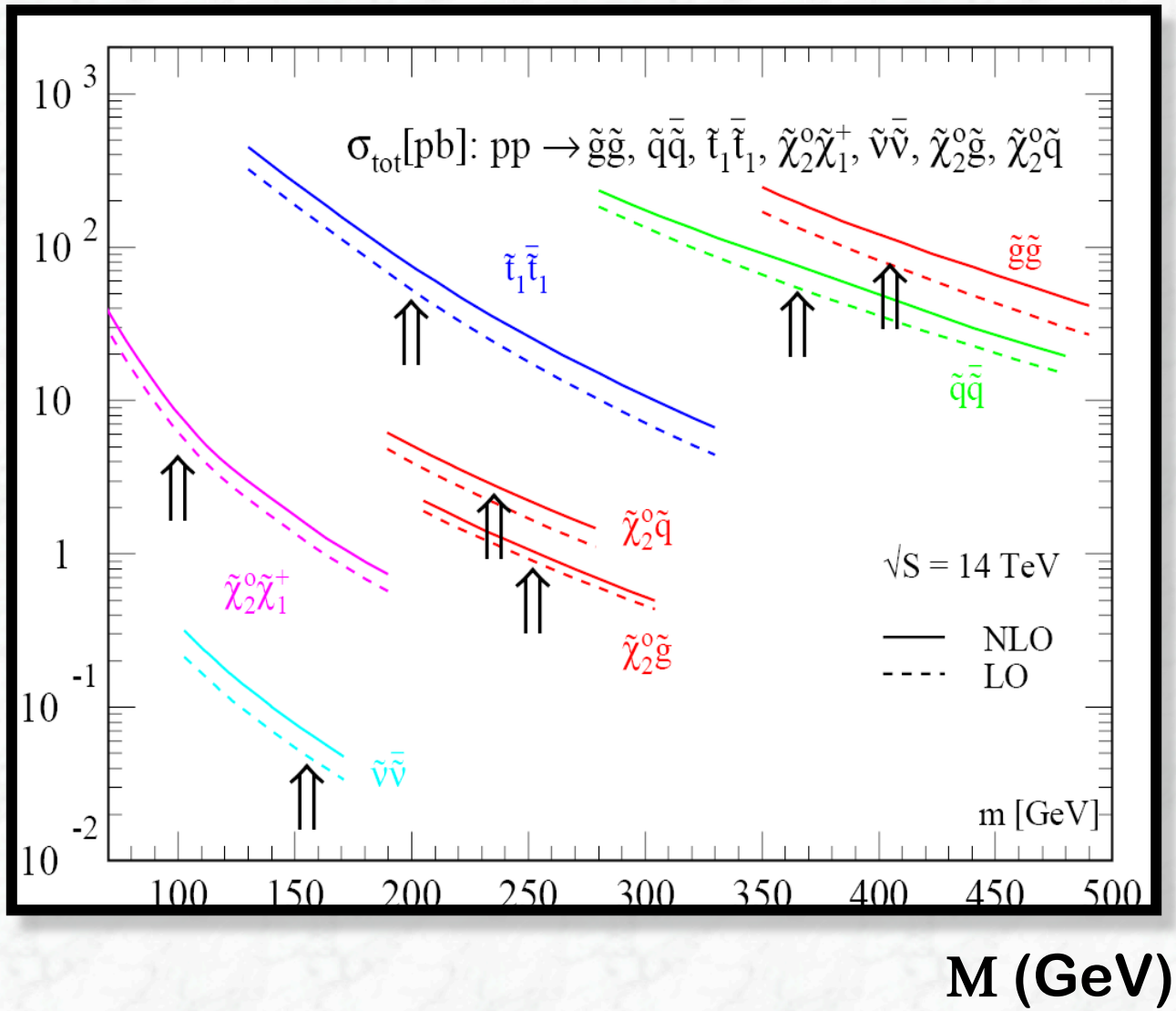
→ production
of coloured SUSY
particles dominant,
via strong interaction
(α_s)



Drell-Yan production
of sleptons, charginos
and neutralinos
(lower cross sections)

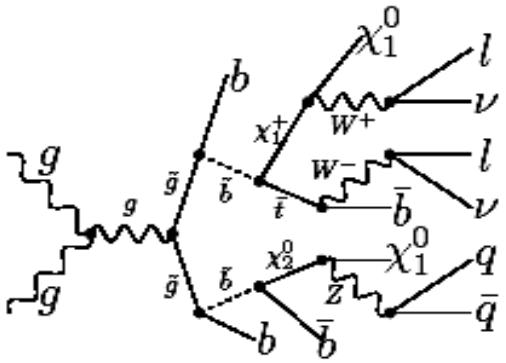
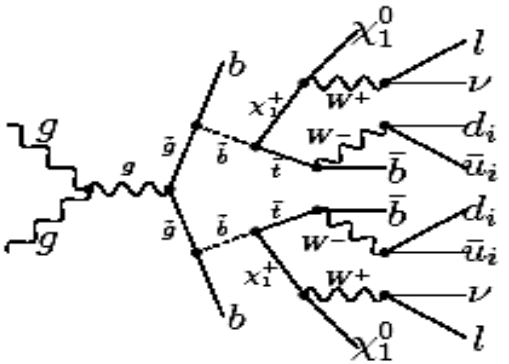
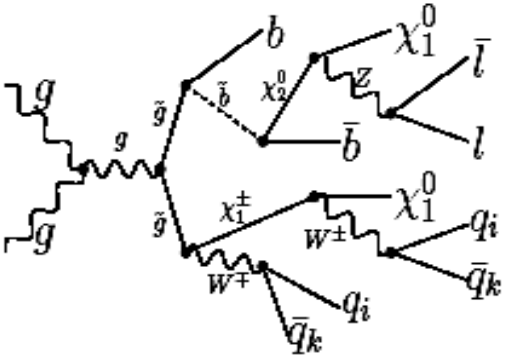
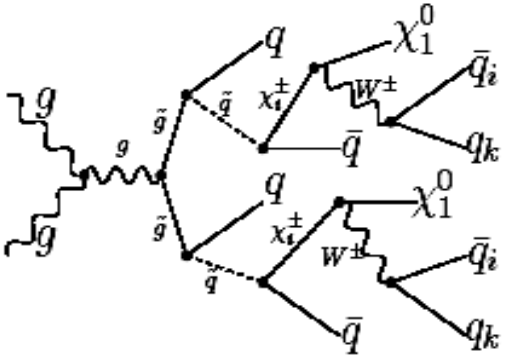
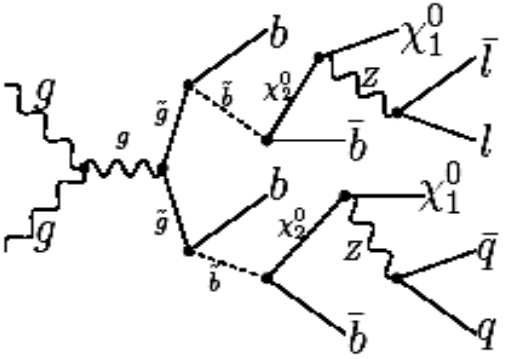
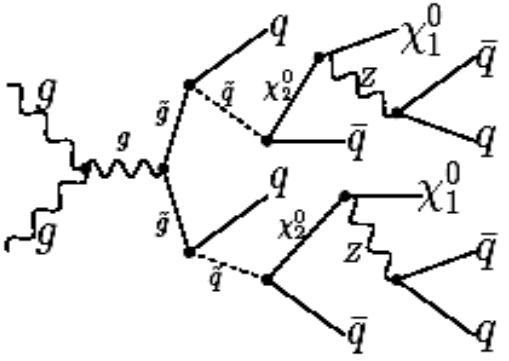


Cross sections for SUSY production processes

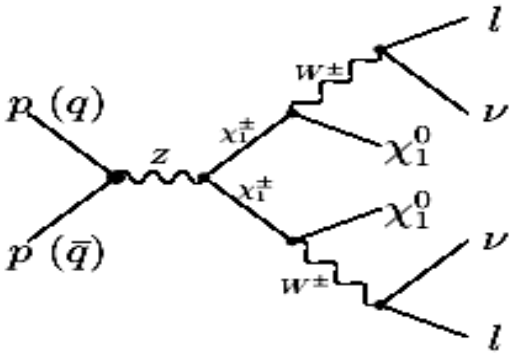
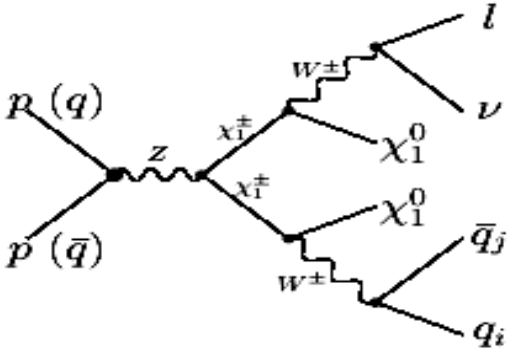
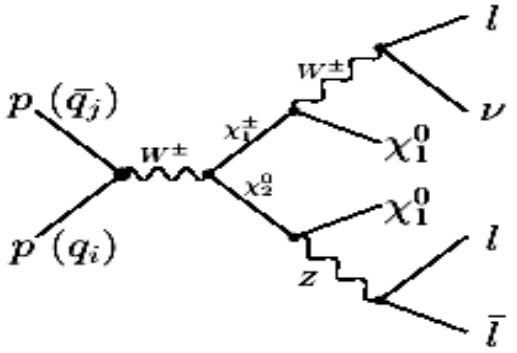


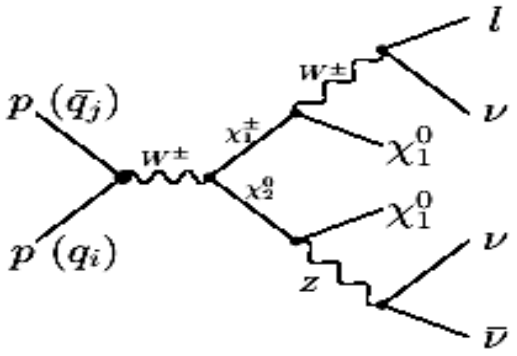
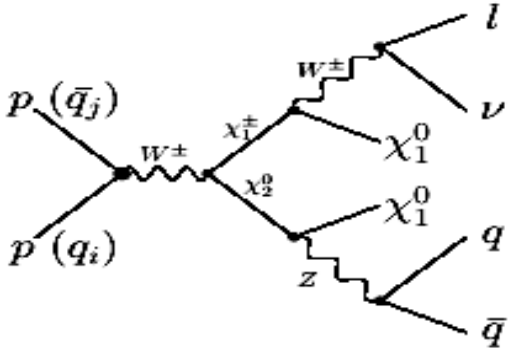
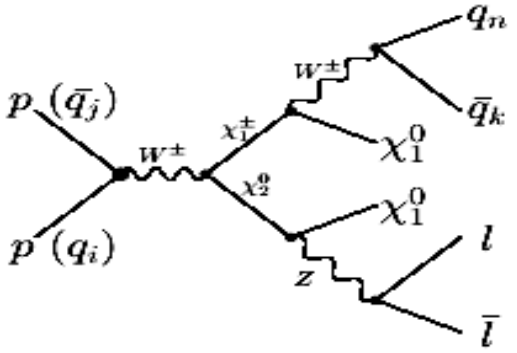
NLO corrections in QCD perturbation theory are known

Decays of heavy SUSY particles → long and complex decay chains
Invariants in R-parity conserving SUSY: jets, E_T^{miss} (2 LSPs)

process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	2ℓ 2ν $8j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$
	$8j$ $\not{E}_T$

shorter decay chains for direct chargino / neutralino production

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

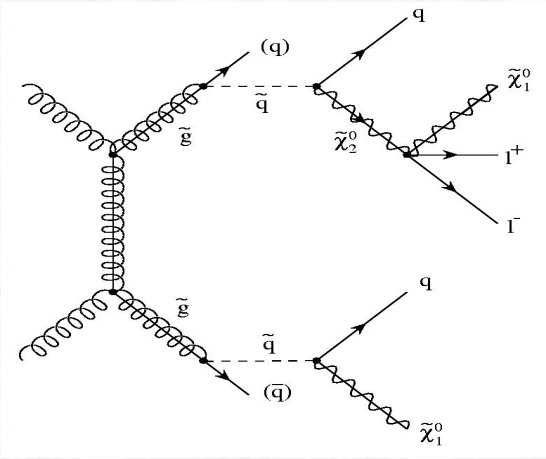
process	final states
	ℓ 3ν $\not{E}_T$
	ℓ ν $2j$ $\not{E}_T$
	2ℓ $2j$ $\not{E}_T$

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

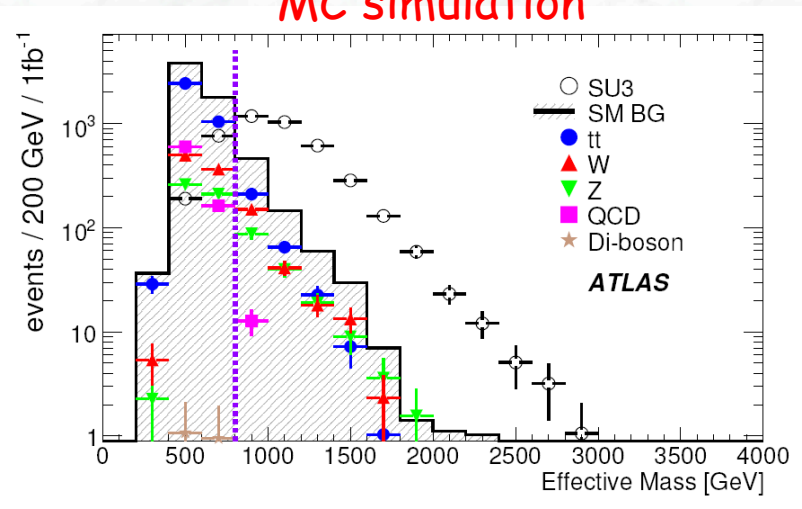
2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

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

A typical search for squark and gluino production

- 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)

MC simulation



example: mSUGRA, point SU3 (bulk region)
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan β = 6, A_0 = -300 GeV, μ > 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 !

Strategy in SUSY Searches at the LHC:

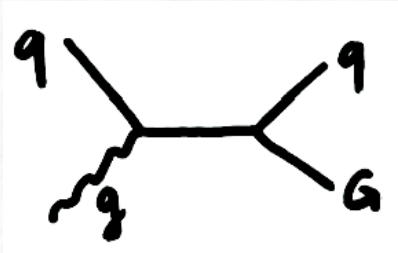
- Search for multijet + E_T^{miss} excess
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^{\pm}$, $\ell^+ \ell^-$, $\ell^{\pm} \ell^{\pm}$, b-jets, τ's
- End point analyses, global fit $\rightarrow$ SUSY model parameters

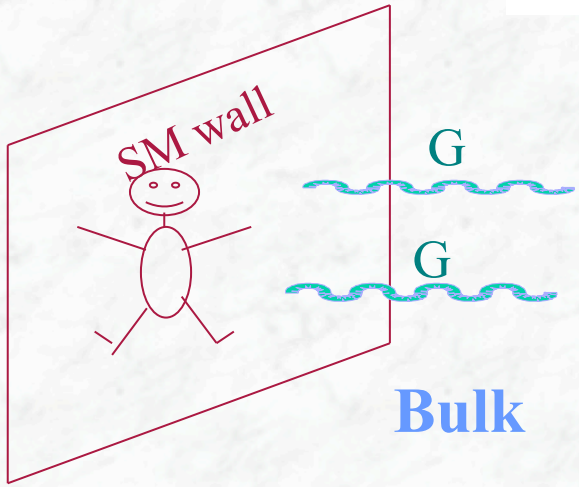
How can the parameter of the SUSY model be constrained ?

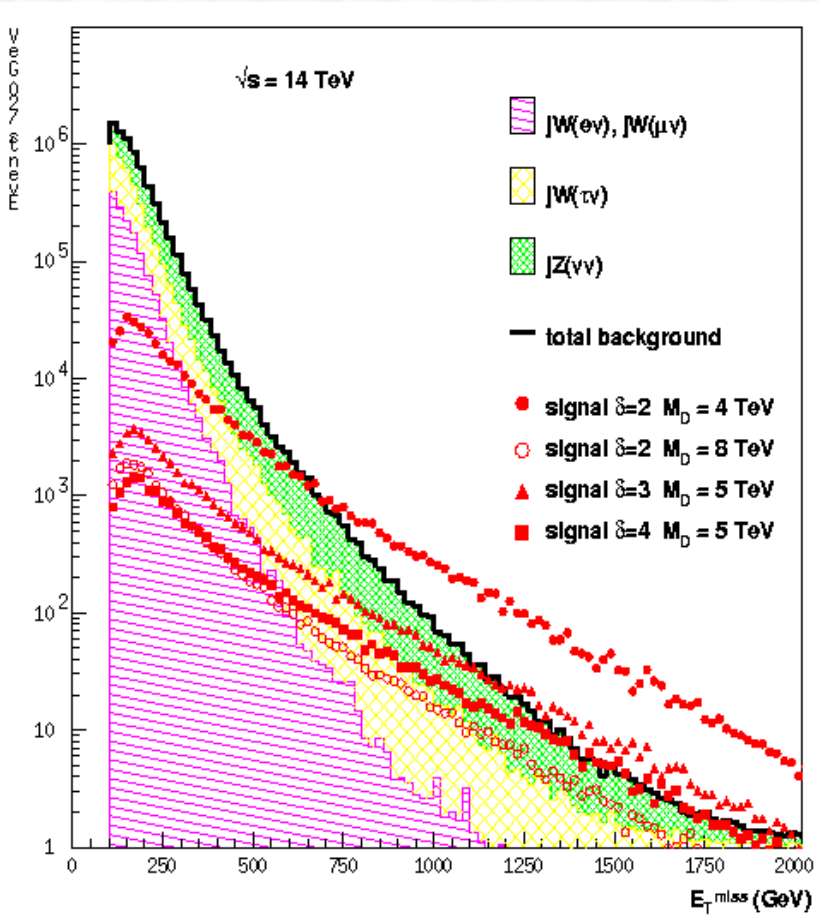
- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

$gg \rightarrow gG, qg \rightarrow qG, q\bar{q} \rightarrow Gg$

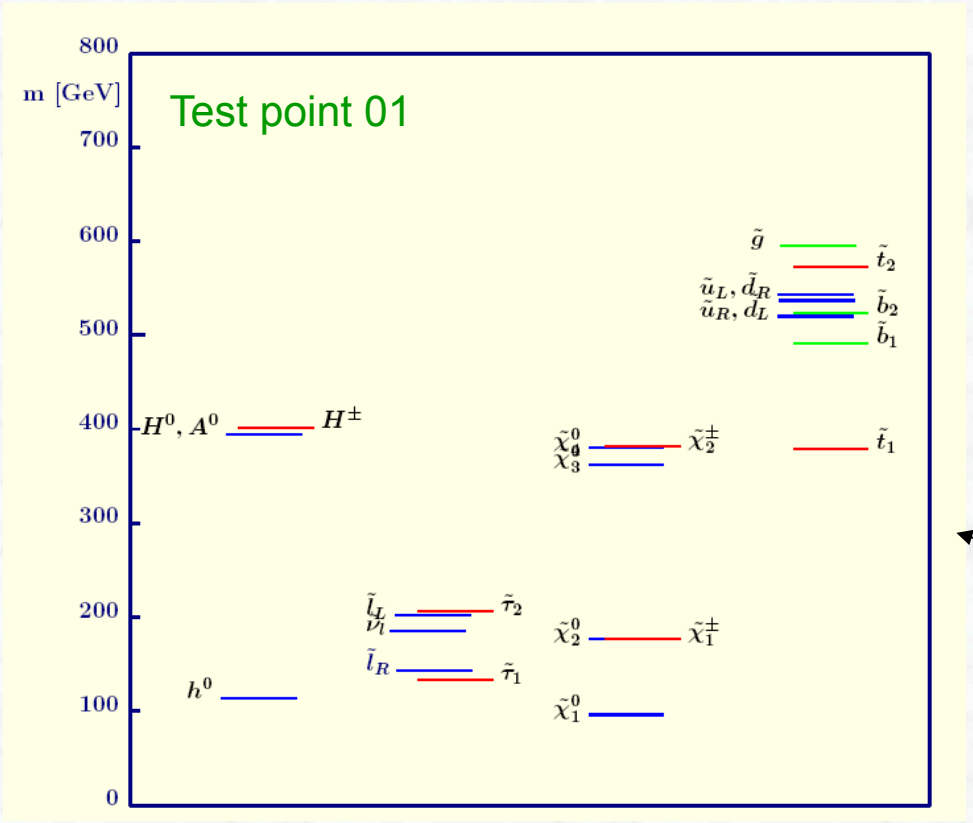
$q\bar{q} \rightarrow G\gamma$

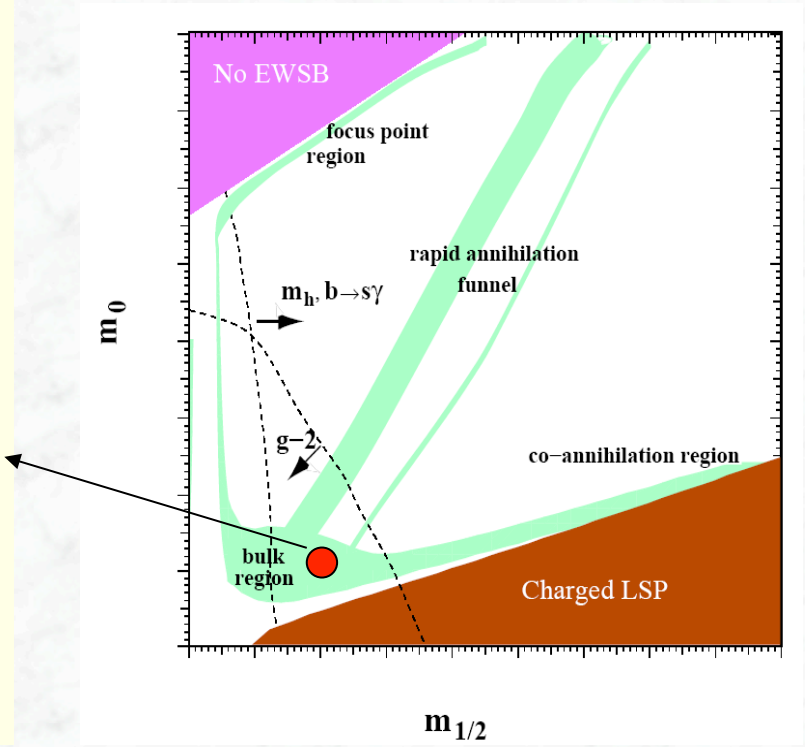






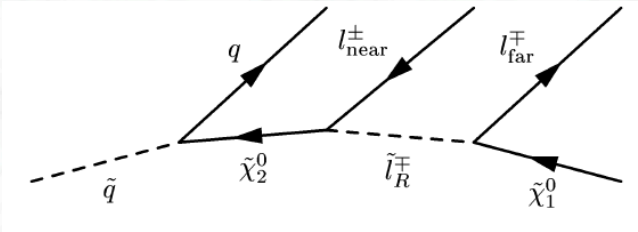
Measurement of the SUSY spectrum → Parameter of the theory





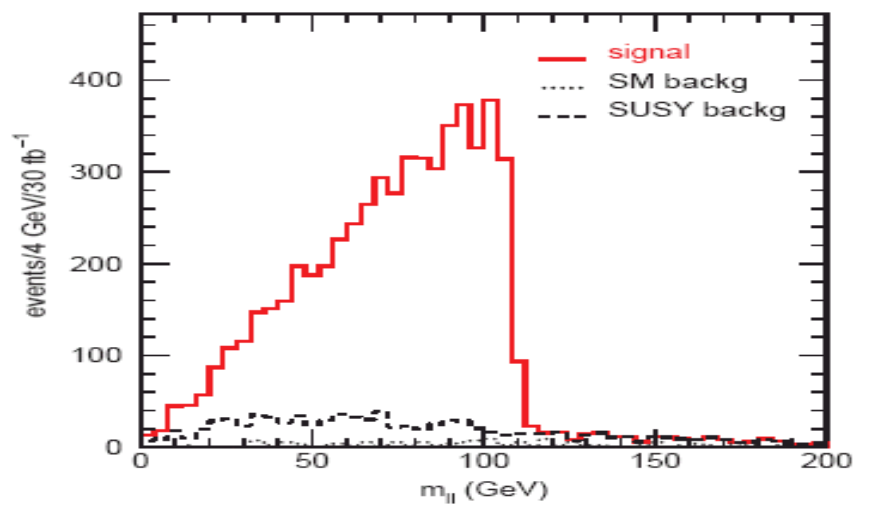
LHC Strategy: End point spectra of cascade decays

Example: $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^{\pm}\ell^{\mp} \to q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$



$$M^{\max}_{\ell^+\ell^-} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\chi_1^0})}}{m_{\tilde{\ell}}}$$

$$M^{\max}_{\ell_1 q} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{q}} - m^2_{\chi_2^0})}}{m_{\chi_2^0}}$$



→ look for structures in kinematic distributions, e.g. di-lepton mass spectrum

What do the LHC data say ?

Search channels (R parity violation):

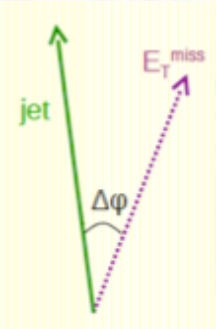
- E_T^{miss} + multijets + 0 lepton
- E_T^{miss} + multijets + 1 lepton
- E_T^{miss} + b-jets + 0/1 lepton
- E_T^{miss} + leptons
- E_T^{miss} + photons
- …….

Some useful variable for SUSY searches at the LHC

- E_T^{miss} : missing transverse energy,
  (measured from the energy depositions in the calorimeters and from muons)
- M_{eff} : effective mass,
  scalar sum of transverse energies of selected high p_T objects, including leptons and E_T^{miss}
- H_T : scalar sum of total transverse energy in selected jets (hadronic activity)
- H_T^{miss} : modulus of vector sum of selected jets
- m_T : transverse mass (in general: m_T (lepton, E_T^{miss}))

$$m_T = \sqrt{2 p_T^e E_T^{miss} (1 - \cos \Delta\phi(e, p_T^{miss})}$$

- $\Delta\phi$ (jet, E_T^{miss}): angle between the missing transverse energy vector and a jet in the transverse plane
  important to reject “fake” background from QCD jet production



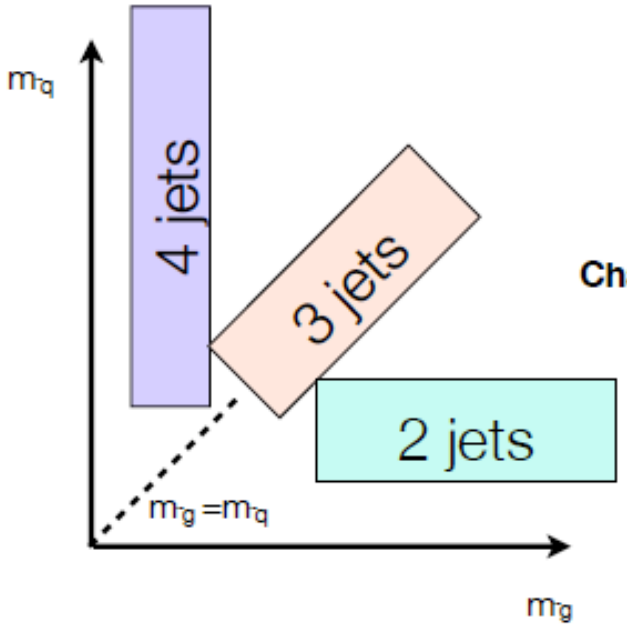
First results on the search for E_T^{miss} + jets (1.04 fb^{-1})

(large 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)

Definition of signal regions:



	Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

- Three different analyses, depending on squark / gluinos mass relations:

  (i) dijet analysis
  small m_0, m(squark) < m(gluino)

  $$\tilde{q}\bar{\tilde{q}} \rightarrow q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$$

  (ii) 3-jet analysis
  intermediate m_0 m(squark) ≈ m(gluino)

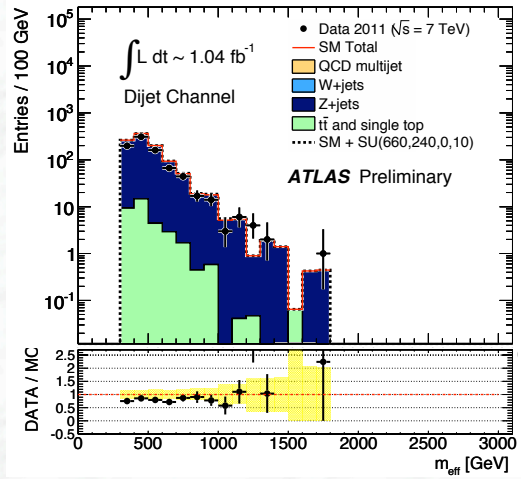
  $$\tilde{q}\tilde{g} \rightarrow q\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$$

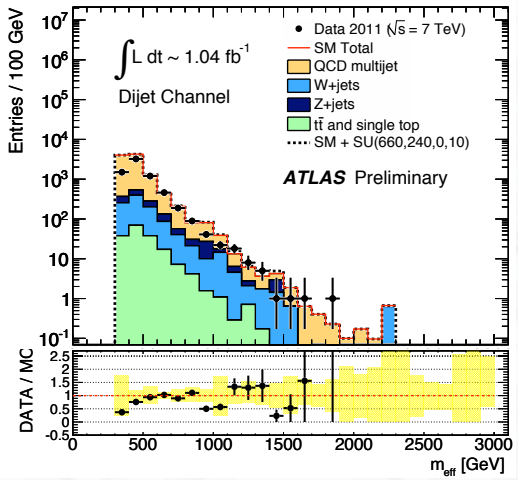
  (iii) Gluino analysis
  large m_0, m(squark) > m(gluino)

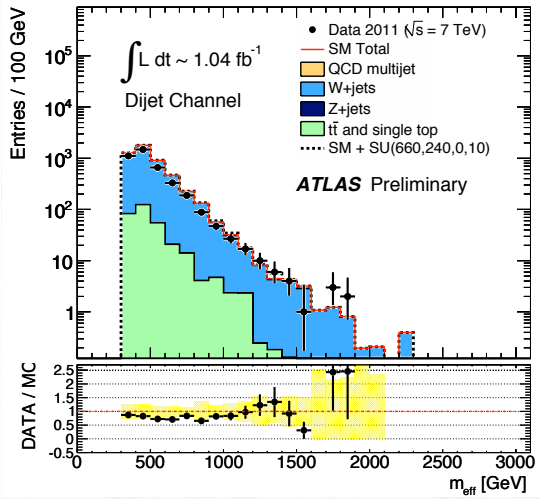
  $$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$$

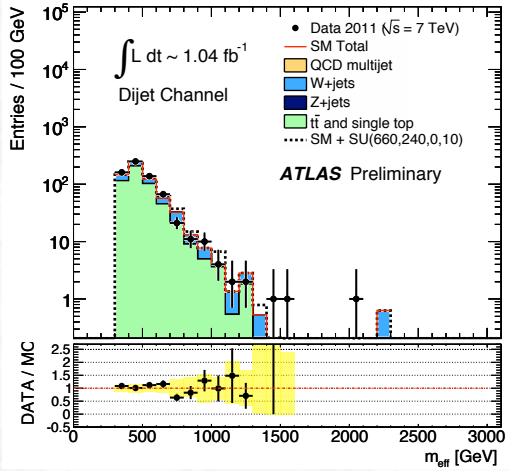
Summary on control of backgrounds using data

(control regions, very important !!)









A: Z + jet events, Z → ee
(to estimate Z → νν background,
likewise γ + jet events were used)

B: QCD multijet background
(reverse cut on $\Delta\phi$ (jet, E_T^{miss})

C: W → lν + jet control region
(select events with one lepton,
$30 < M_T(l,E_T^{miss}) < 100$ GeV,
no b-jet to suppress top contribution)

D: top quark control region
(same selection as for W events,
but require b-tag)

First results on the search for E_T^{miss} + jets (1.04 fb^{-1})

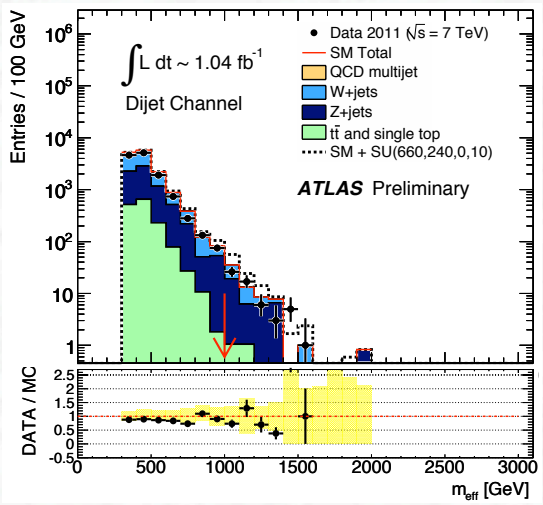
(large part of 2011 data already included)

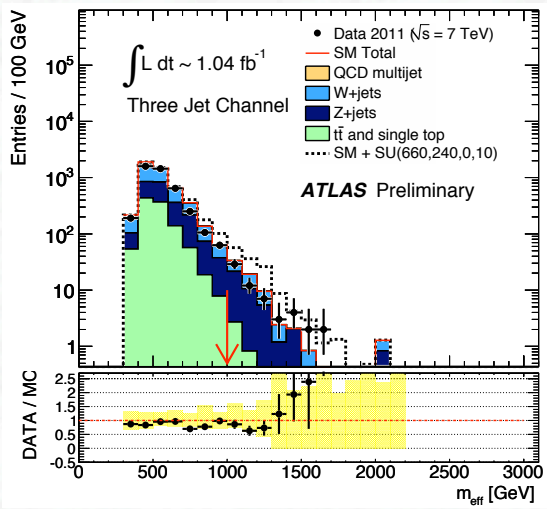
Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, m_{eff} > 500 GeV	≥ 4-jet, m_{eff} > 1000 GeV	High mass
Z/γ+jets	32.5 ± 2.6 ± 6.8	25.8 ± 2.6 ± 4.9	208 ± 9 ± 37	16.2 ± 2.1 ± 3.6	3.3 ± 1.0 ± 1.3
W+jets	26.2 ± 3.9 ± 6.7	22.7 ± 3.5 ± 5.8	367 ± 30 ± 126	12.7 ± 2.1 ± 4.7	2.2 ± 0.9 ± 1.2
$t\bar{t}$+ Single Top	3.4 ± 1.5 ± 1.6	5.6 ± 2.0 ± 2.2	375 ± 37 ± 74	3.7 ± 1.2 ± 2.0	5.6 ± 1.7 ± 2.1
QCD jets	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.74 ± 0.14 ± 0.51	2.10 ± 0.37 ± 0.83
Total	62.3 ± 4.3 ± 9.2	55 ± 3.8 ± 7.3	984 ± 39 ± 145	33.4 ± 2.9 ± 6.3	13.2 ± 1.9 ± 2.6
Data	58	59	1118	40	18

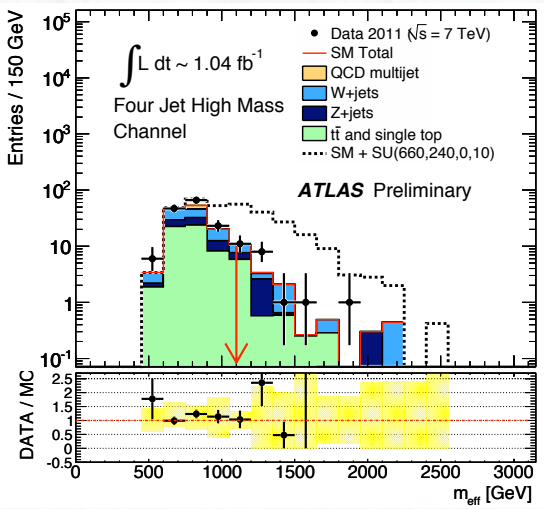
Observed and expected event numbers (from Standard Model processes)

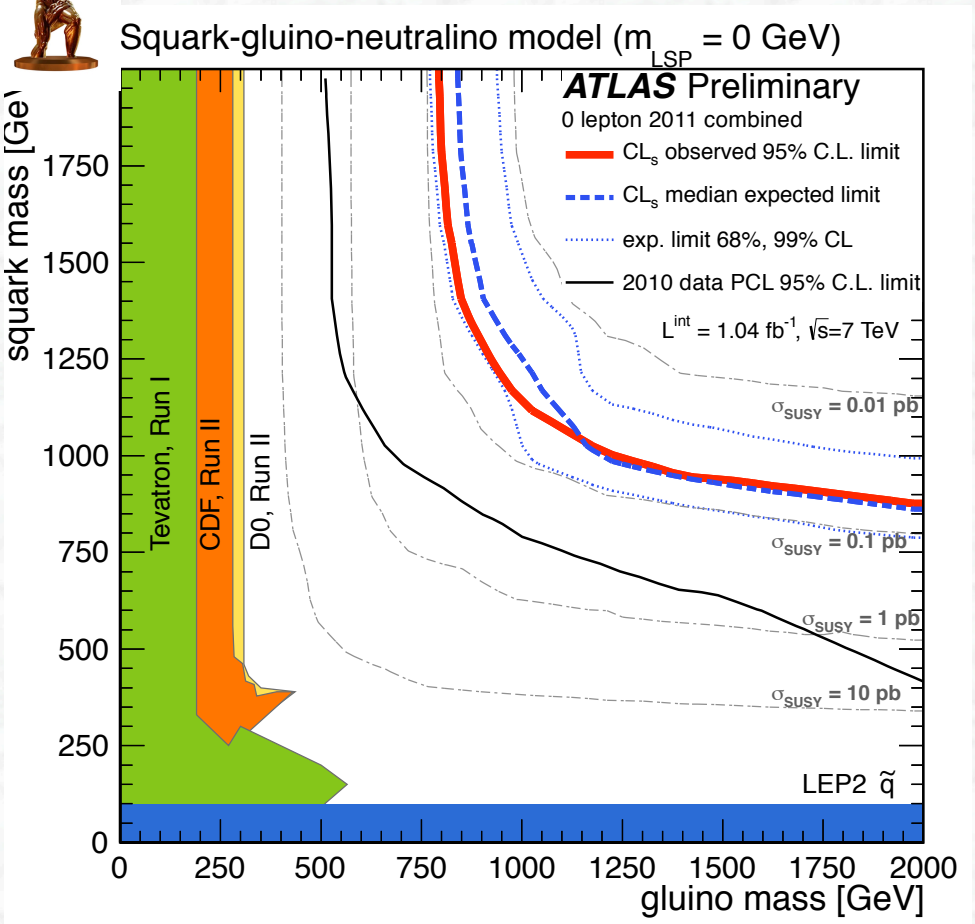
dominant backgrounds:
- W/Z + jets
- tt production

Normalized in control regions ! (as explained on the previous slide)







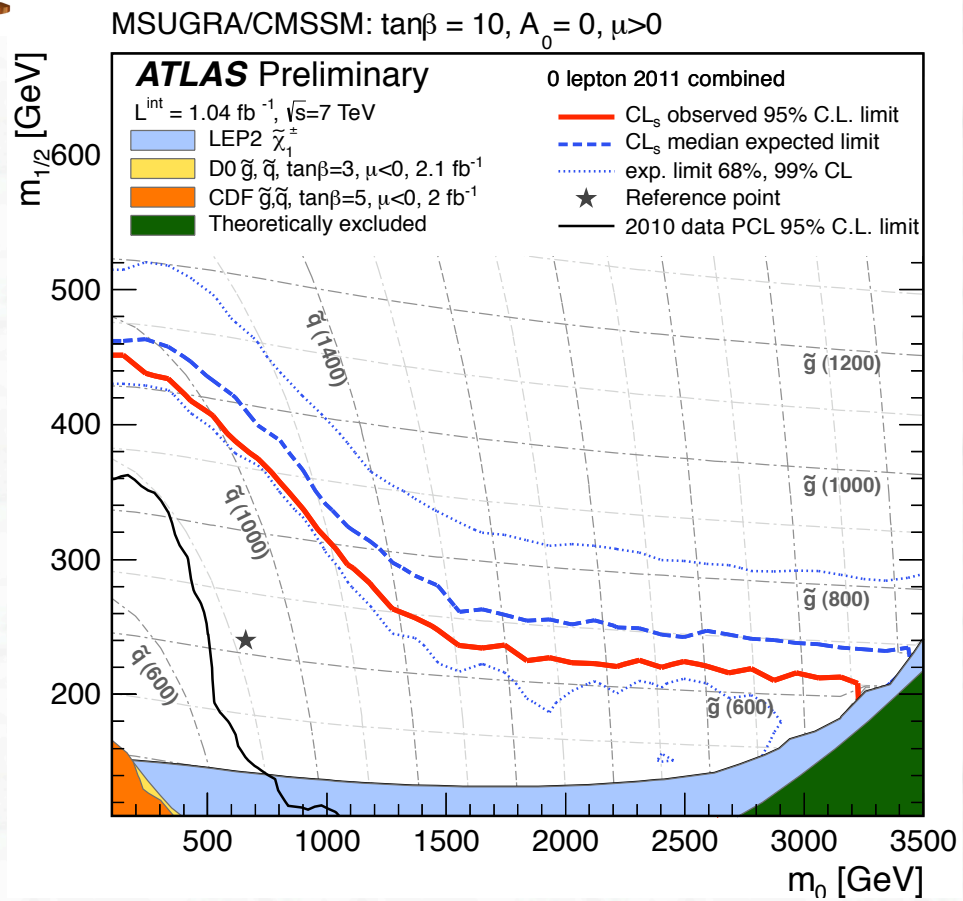


Interpretation of the results in the (m_{gluino}, m_{squark})-plane as 95% C.L. exclusion limits in a simplified SUSY model:

- $m_{\chi} = 0$
- masses of gluinos and of 1st and 2nd generation squarks as given on plot
- all other SUSY masses are assumed to be decoupled, with masses of 5 TeV

Large area of mass combinations excluded, significant improvement compared to Tevatron results and to 2010 results (black curve)

mSUGRA interpretation



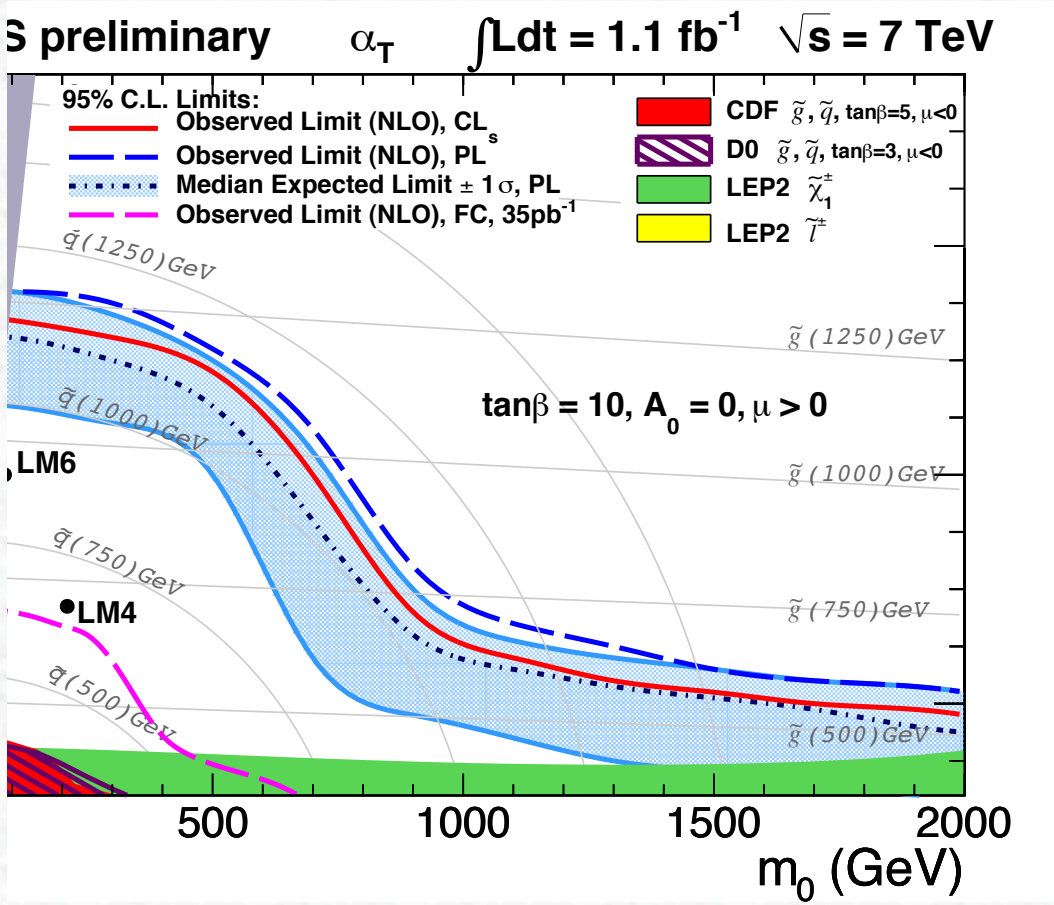
$\tan\beta = 10,\ A_0 = 0,\ \mu > 0$

The channel (2, 3, 4, jets) with the best expected limit is taken at each point in parameter space

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

$L = 1.04\ fb^{-1}$: m(squark), m(gluino) > 980 GeV

CMS exclusion limits in the cMSSM model

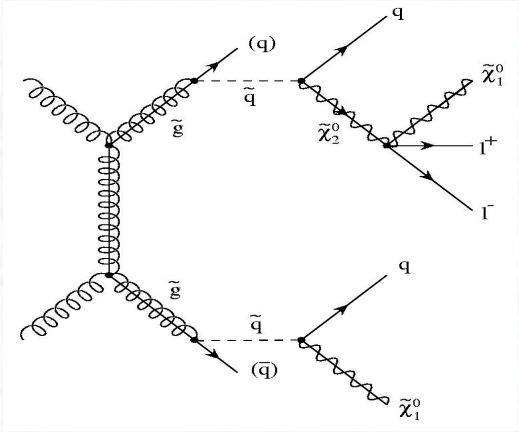


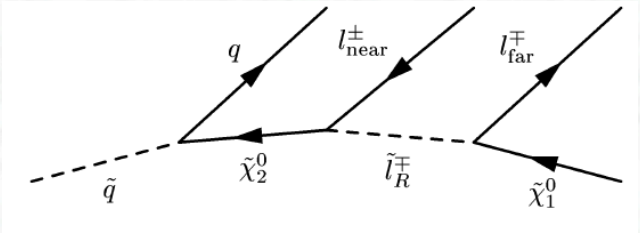
- Similar exclusion as from the ATLAS experiment:

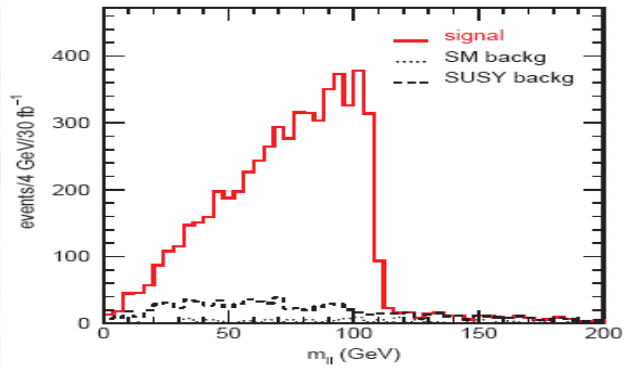
Squarks and gluinos with masses of 1.1 TeV can be excluded for m_0 < 500 GeV

E_T^{miss} + 2 leptons

(same sign or opposite sign)







- Leptons might appear from resonance decays
- more interesting: sensitive to cascade decays producing flavour correlated lepton pairs

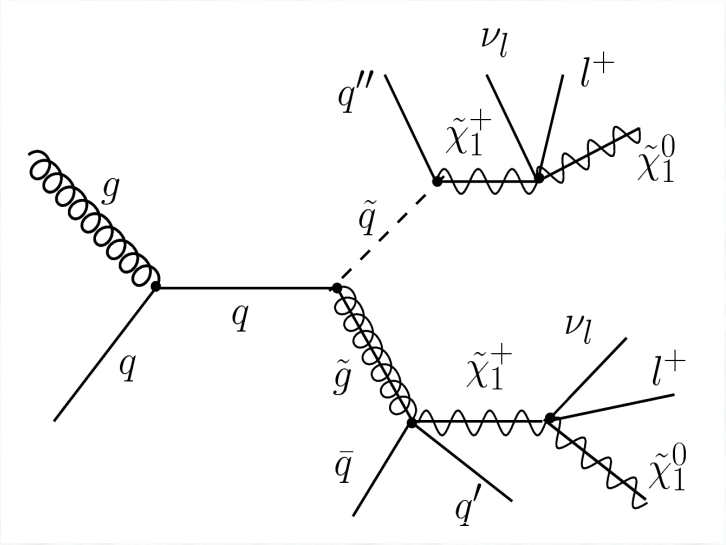
→ endpoint spectra contain information on mass differences of SUSY particles

→ important for SUSY parameter determination (as explained)

- Standard Model physics background expected to be small, in particular for like-sign lepton pairs

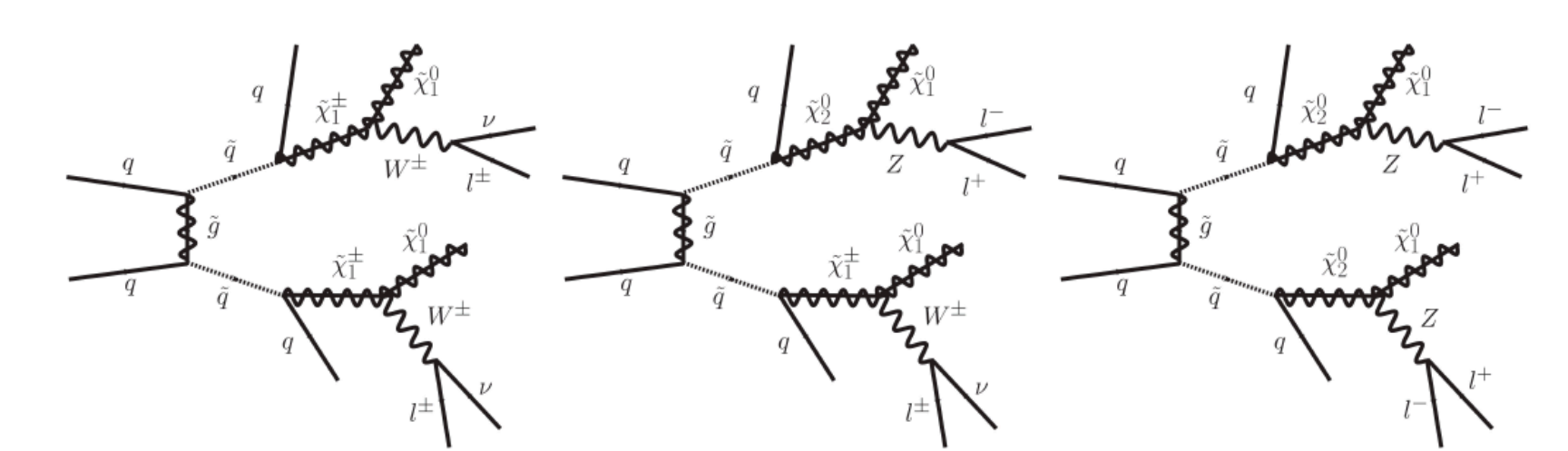
Like-sign di-leptons appear in many models of Physics Beyond the Standard Model:

- Supersymmetry
- Universal extra dimensions
- Heavy Majorana neutrinos
- Same sign top pair resonances



Backgrounds from Standard Model processes are in general small, contributions arise from:

- di-boson production (WZ)
- tt production, where a second lepton comes from semileptonic b-decays
- in general: non isolated leptons from heavy flavour decays
- fake leptons from misidentified jets

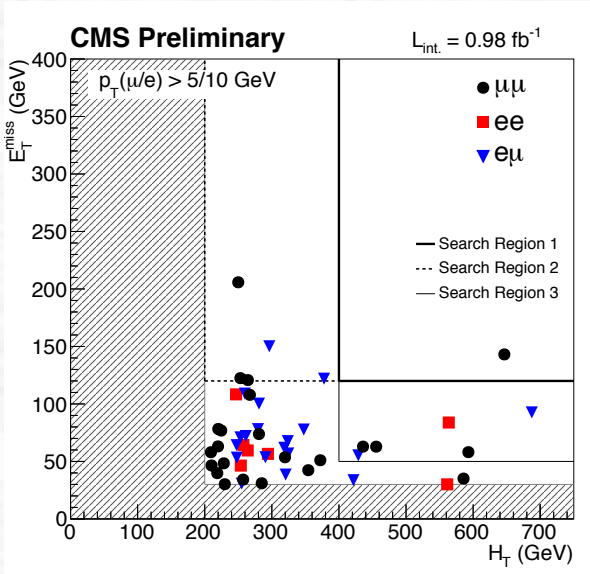


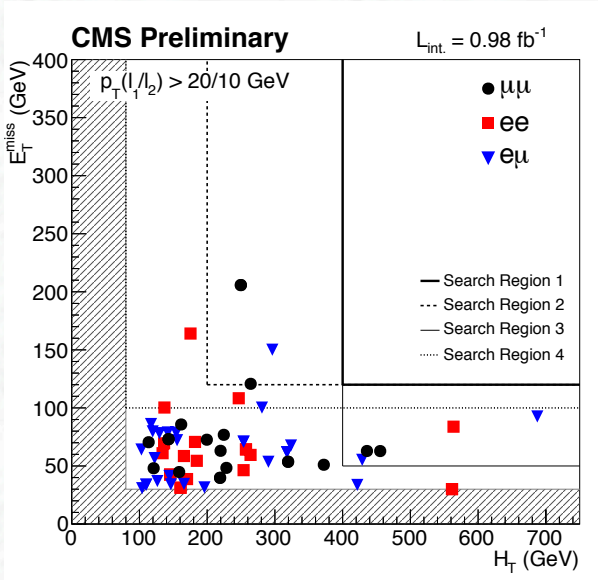
- Lepton p_T values in SUSY cascades might be low, depends on the mass differences of the SUSY particles involved → search for as low p_T leptons as possible

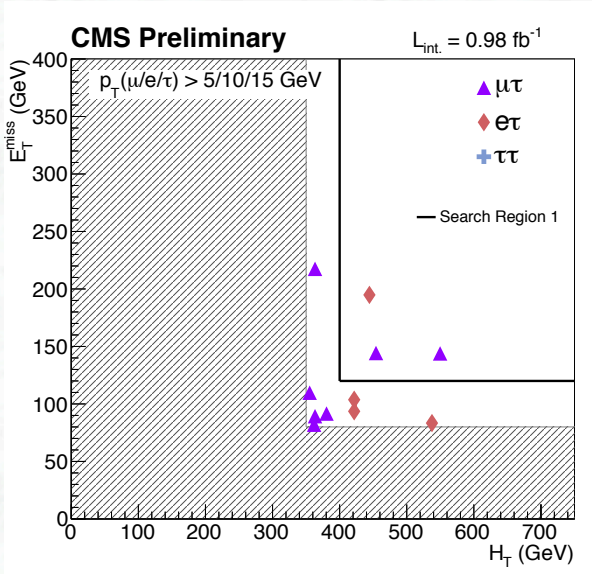
- Taus (3rd generation) may play a larger role, stau could be the lightest slepton → include leptons (hadronic decays in the search)

Di-lepton search in CMS

- Analysis based on data from 2011, L_{int} = 0.98 fb^{-1}
- Search for same-sign di-leptons (ee, eμ, μμ, eτ, μτ, ττ) ($\tau = \tau_{had}$) accompanied by E_T^{miss} and jets in three different regions of phase space to increase sensitivity







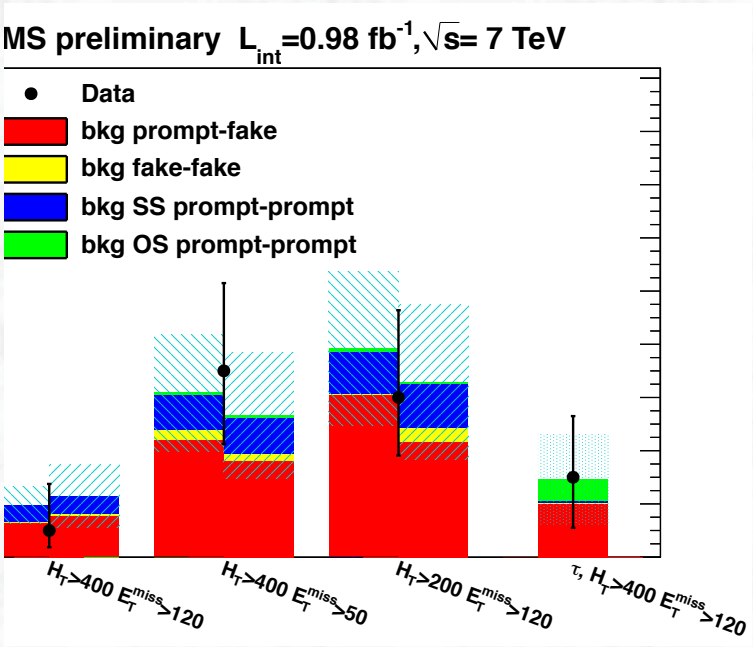
Inclusive di-leptons

high p_T di-leptons

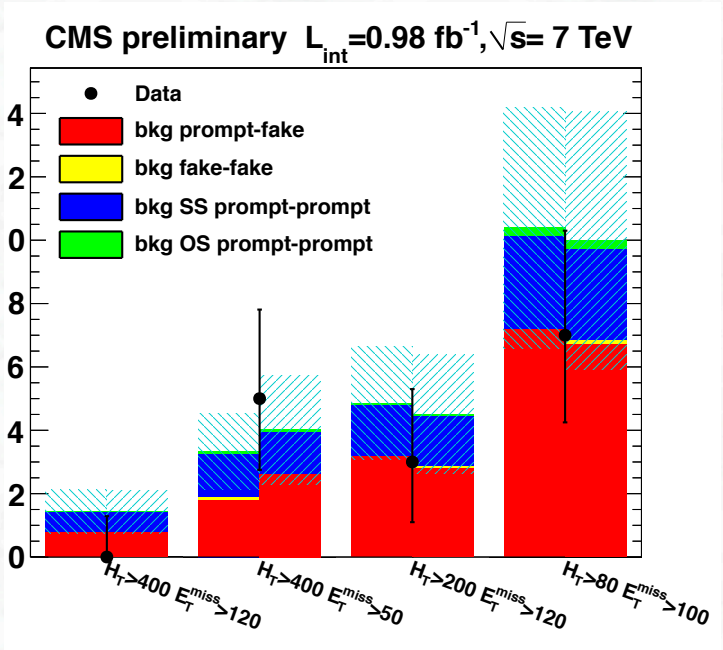
τ−di-leptons

- Discriminating variables to define signal regions: H_T and E_T^{miss}
- Low p_T lepton cuts compensated by higher cute on the hadronic activity (H_T)
- Three signal regions defined (see figure)

Comparison between data and expectations:



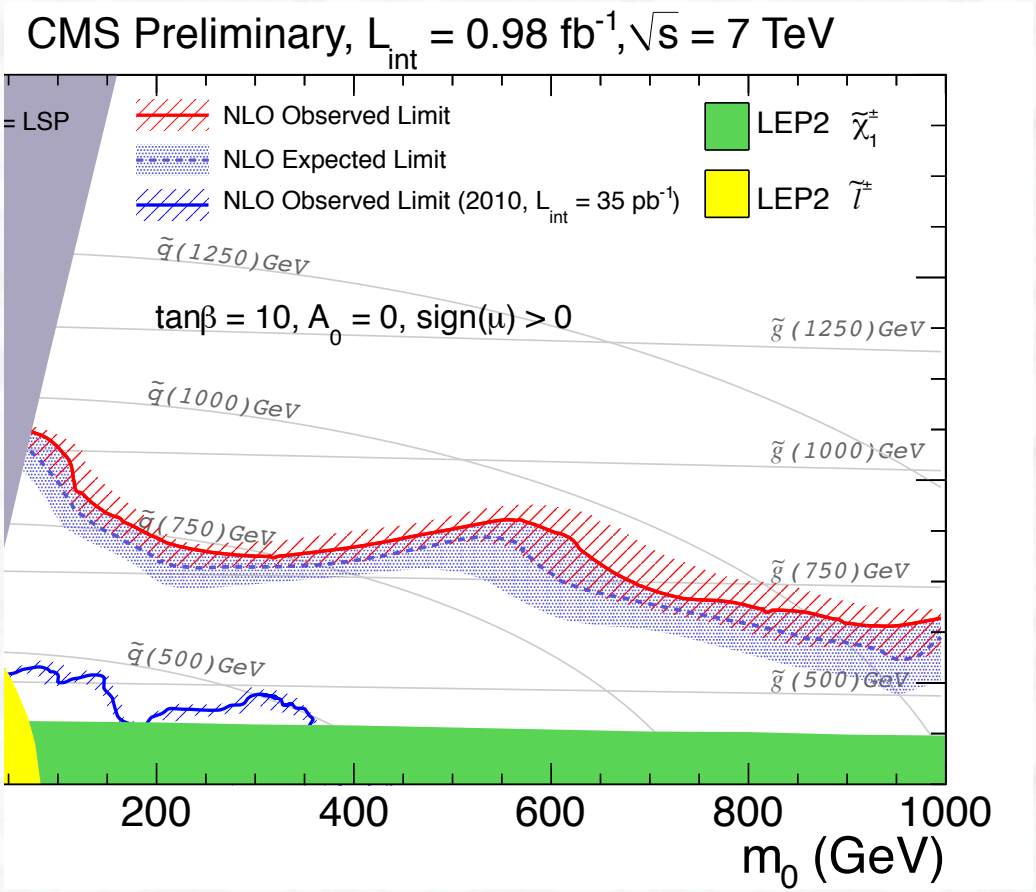
Inclusive and tau selection



high p_T di-lepton selection

- Good agreement beween data and expectations; no evidence for an excess
- Backgrounds are dominated by “fake” leptons;
  in addition, there is a component from charge mis-identification
- Estimates have large uncertainties (results from two methods shown)

Di-lepton based exclusion in the cMSSM model



uncertainties on the cross sections (renormalization, factorization scale, pdfs) are indicated by the bands

- Exclusion extends to gluino masses of 825 GeV in the region $m_{squark} = m_{gluino}$
- For higher squark masses, gluinos with masses below 675 GeV are excluded

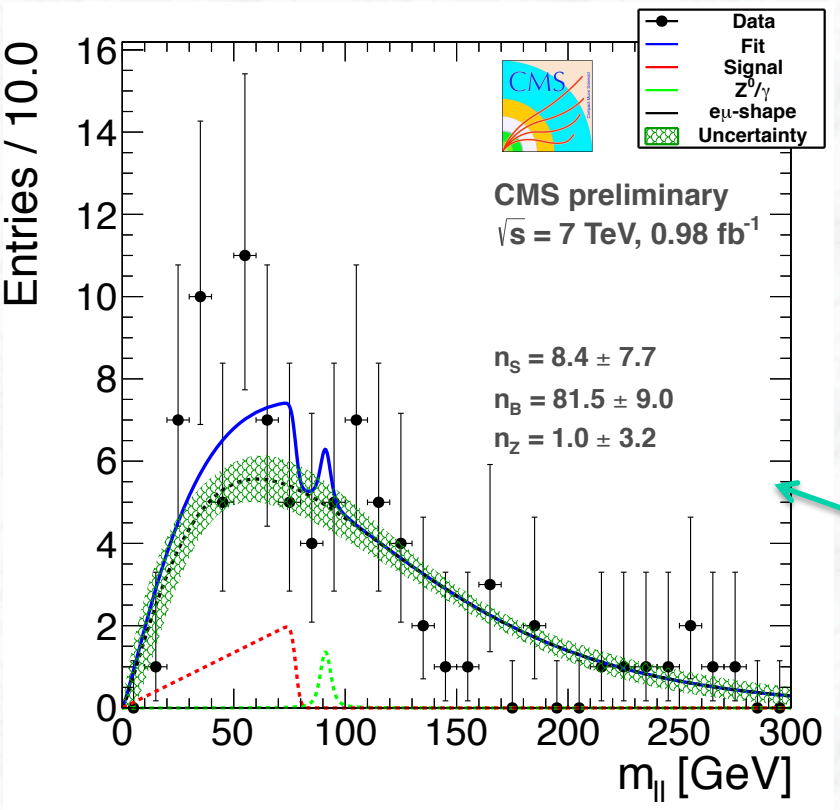
A first example to search for a characteristic edge in the opposite sign di-lepton mass spectra:

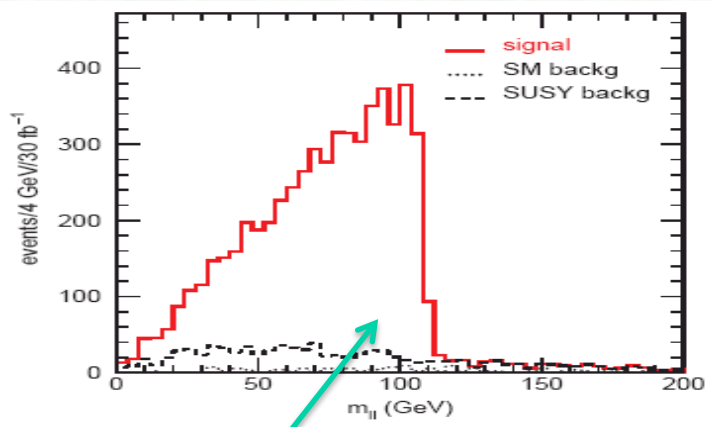
$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$$

$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\chi_1^0}^2)}}{m_{\tilde{\ell}}}$$

- Remove Z veto cut

- Tighter E_T^{miss} cut: $E_T^{miss} > 100$ GeV
- Signal region: $H_T > 300$ GeV
- Control region: $100 < H_T < 300$ GeV



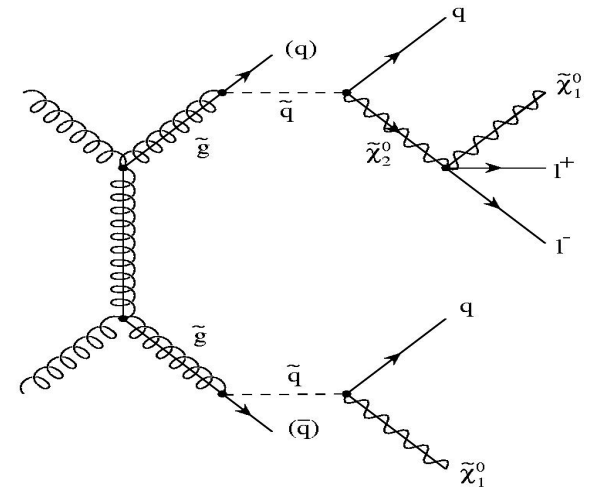


MC simulation

CMS Data 2011

No evidence for a characteristic di-lepton edge in the data

E_T^{miss} + 0/1 leptons + b jets



- There might be large mixing effects, between scalar partners of left- and right-handed quarks

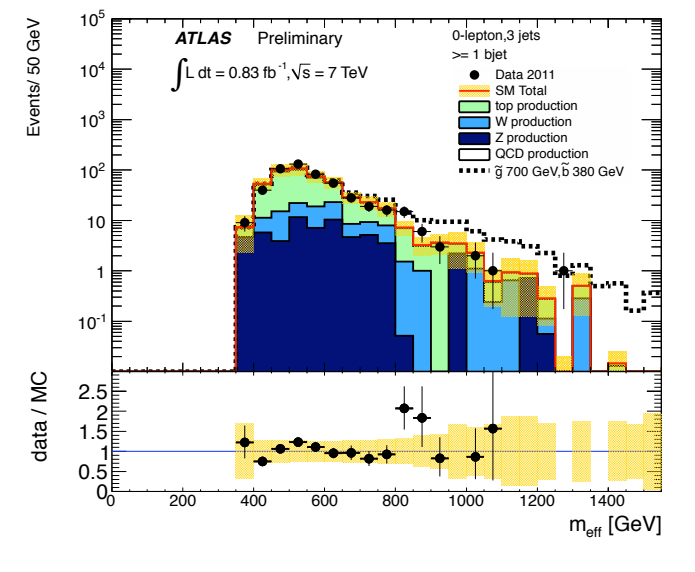
- proportional to the corresponding SM fermion masses, therefore important in the third generation
  sbottom and stop might be the lightest squarks

  → b quarks appear in their decays

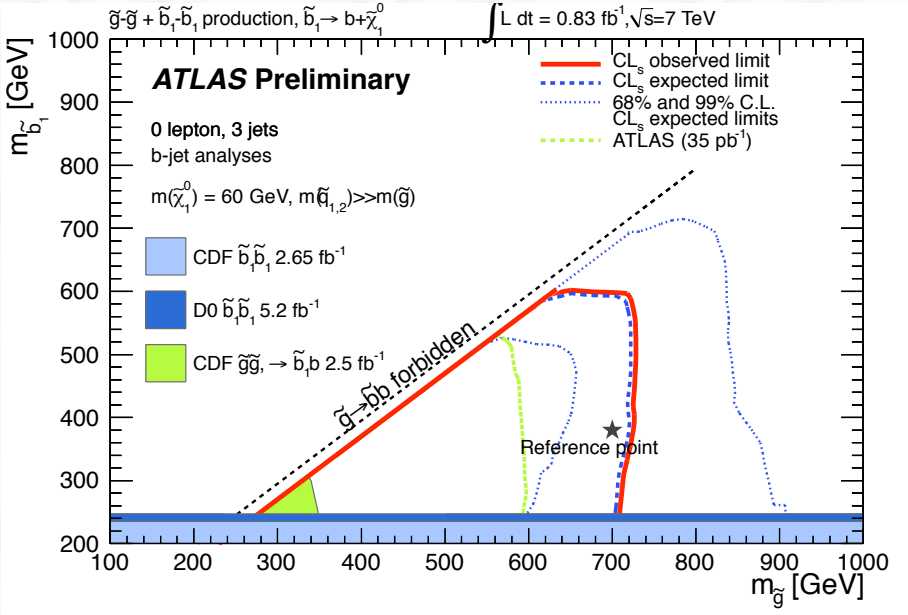
  production e.g. via gluino-pair production with subsequent decays:

$$\tilde{g} \rightarrow \tilde{\bar{b}}_1 b \text{ or } \tilde{g} \rightarrow \tilde{t}_1 t$$

Exclusion limits in the ($m_{sbottom}$-m_{gluino})-plane, for the hypothesis that the lightest squark (sbottom1) is produced via gluino-mediated production or direct pair production and decays 100% via $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$

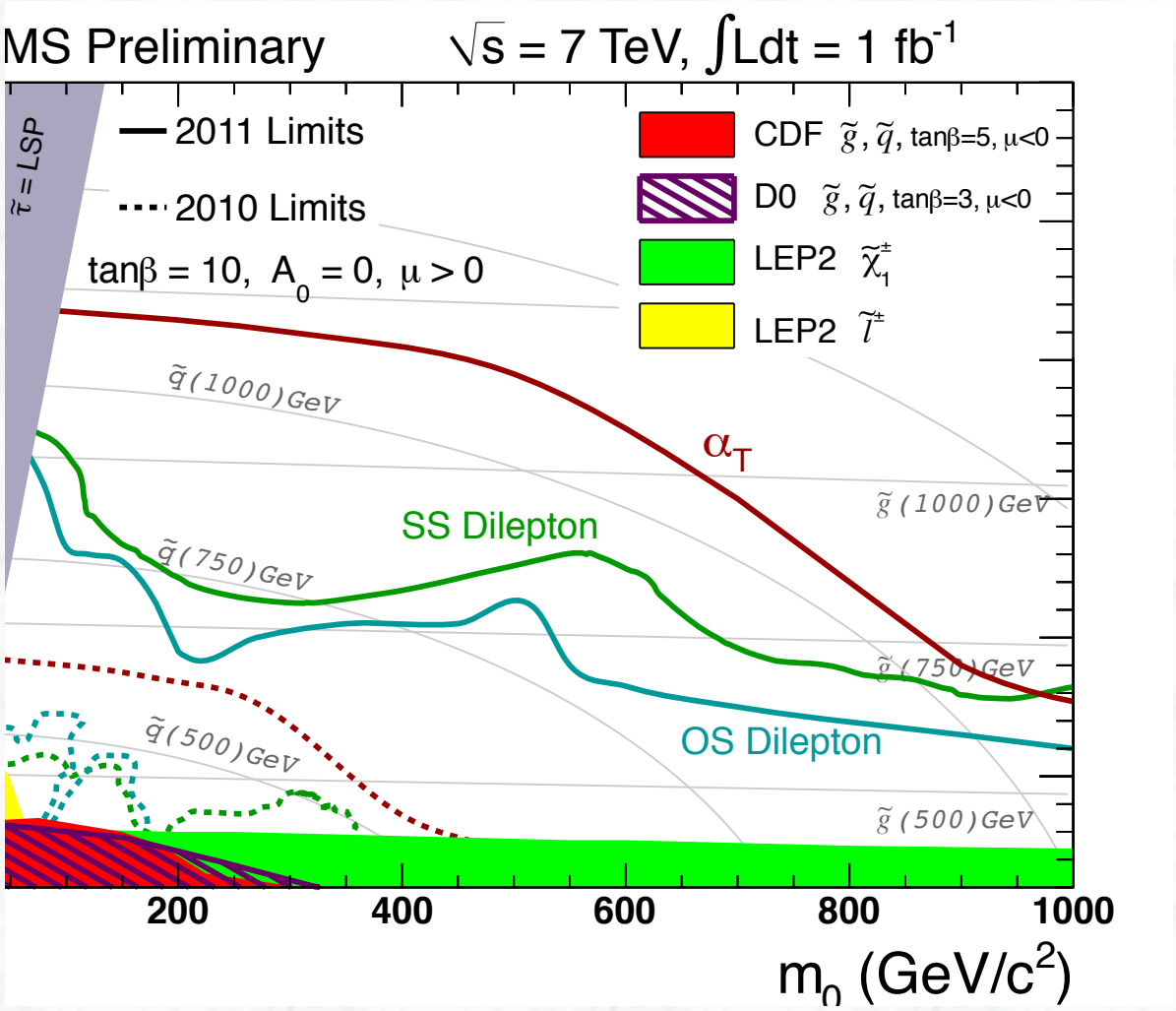


events with 1 b-tagged jet



- Gluino masses below 720 GeV for sbottom masses of ~600 GeV

Summary of R-parity conserving SUSY searches in CMS



Intermediate Summary:

- ATLAS and CMS experiments have very efficiently analyzed their data;
- Results already available for data corresponding to an integrated luminosity of ~1 fb^{-1}
- So far: search for R-parity conserving SUSY scenarios not successful:

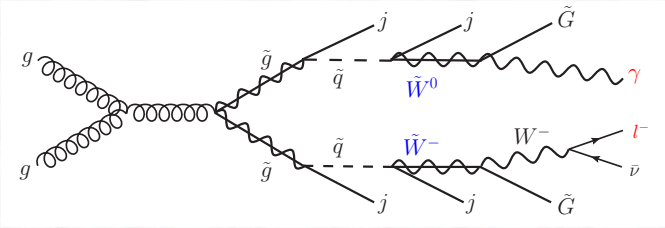
  - Many final states and topologies were explored;
  - Data are consistent with expectations from Standard Model processes

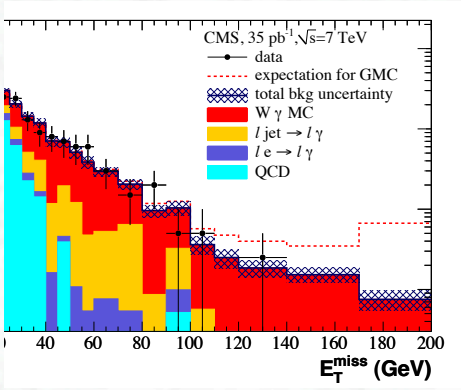
→ What about other SUSY scenarios ?

(i) Change SUSY breaking scenario

e.g. GMSB
- search for photons
- search for long-lived particles

CMS search for lepton (e,μ) + photon + E_T^{miss}:



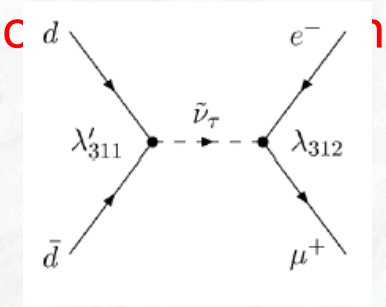


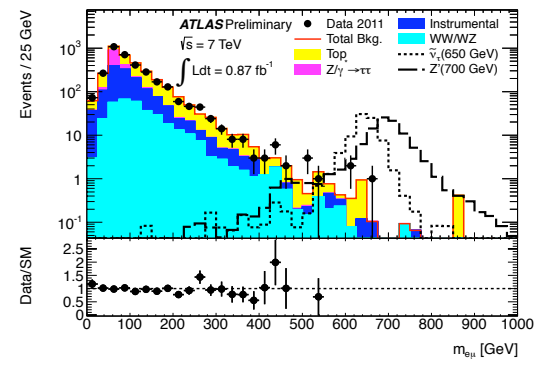
no evidence for new physics found so far

(ii) Give up R-parity conservation

- Abandon pair production and the E_T^{miss} signature

first analyses dc ı for e-μ resonances





again: no evidence for new physics found so far

Search for Gauge Mediated SUSY breaking scenarios (GMSB)

- In Gauge mediated SUSY breaking (GMSB) models, SUSY breaking occurs at energy scales much smaller than the Planck scale, breaking linked to gauge interactions

- The gravitino is the LSP, escapes detection → E_T^{miss} signature is kept

- Phenomenology is determined by the NLSP (next-to-lightest SUSY particle);

  In many scenarios the NLSP are the superpartners of the $SU(2)_L$ gauge fields, with small mass splittings between the charged and neutral winos

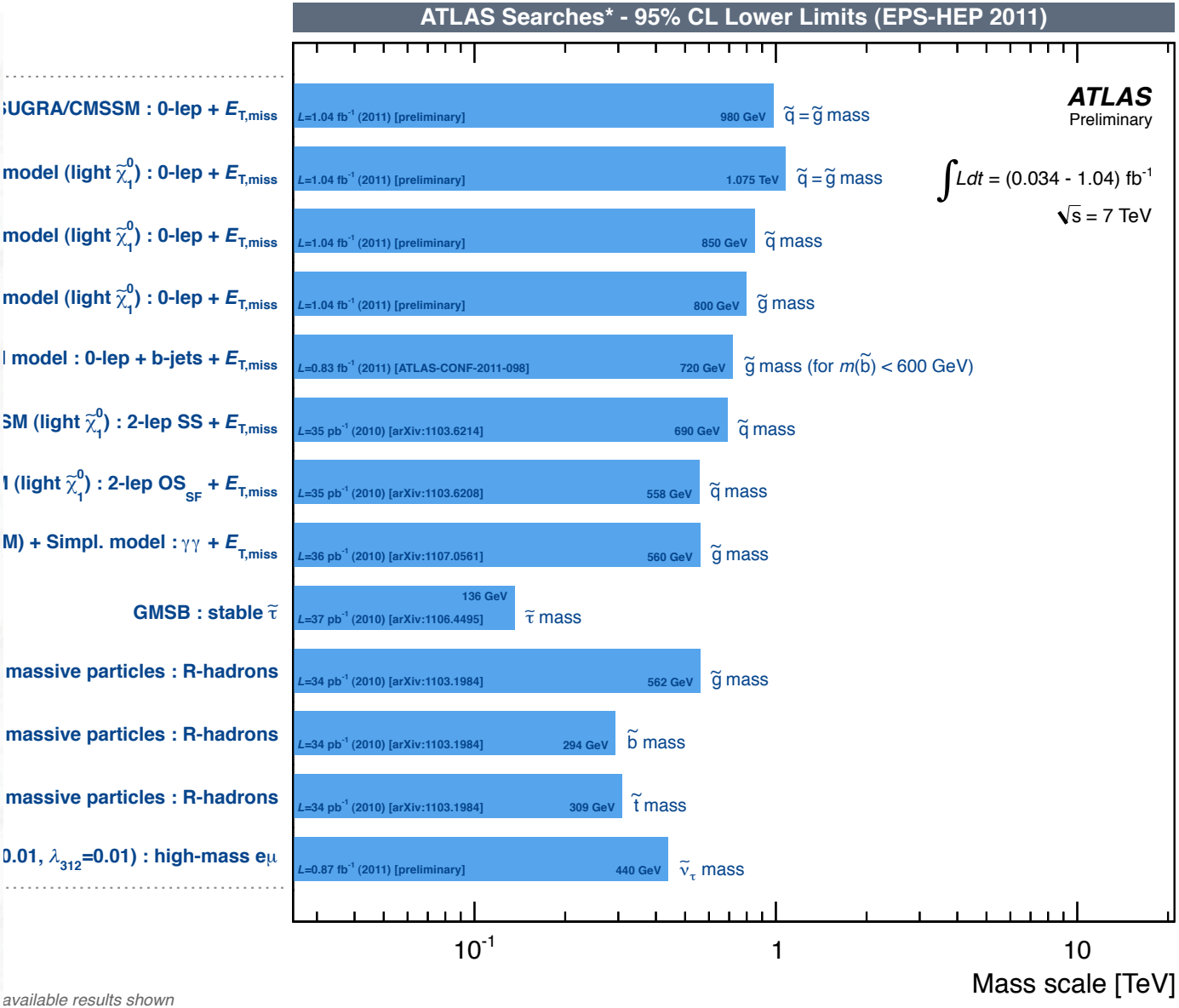
  - Decays scenarios: $\tilde{W} \rightarrow \gamma \tilde{G}$ $\tilde{W}^+ \rightarrow W^+ \tilde{G}$

  - Also χ_1^0 can be the NLSP with decays: $\chi_1^0 \rightarrow \gamma \tilde{G}$

  → expect / search for events with Photons, Leptons and E_T^{miss}

- In GMSB models sleptons, squarks and gluinos might have long lifetimes

Summary of R-parity conserving SUSY searches in ATLAS



*available results shown

Changing Prospects for Higgs and SUSY ?

1985: No – Lose theorem
LHC will discover a Higgs boson and/or a Supersymmetric World

1995: Maybe SUSY will not be realized in its minimal version ….
(maybe there is NMSSM, …..)

…. but we believe in SUSY (see e.g. J. Ellis, hep-ph 9503426)

> negligible in this range. Similar sensitivity is to be expected in the CMS experiment [14]. Thus essentially all the parameter space of the MSSM allowed by naturalness arguments will be covered. If the LHC does not discover supersymmetry, we theorists will have to eat our collective hat.

2006: No discoveries at LEP-II and Tevatron (so far), Standard Model still rules !
Maybe SUSY is not realized as a *Low Energy SUSY* …..

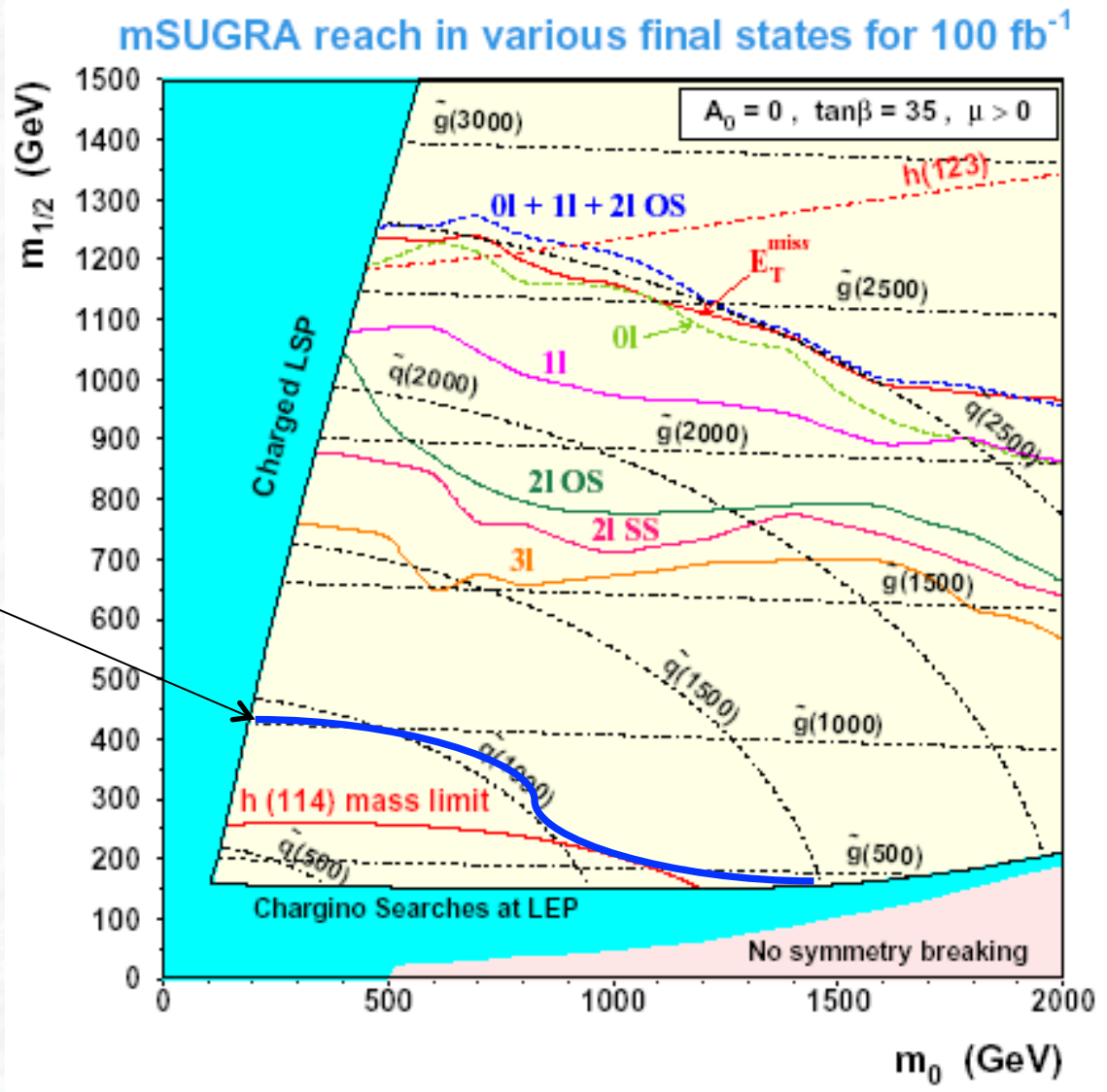
"The SUSY-train is already a bit late….." (G. Altarelli)

New models: extra space time dimensions, …… including dark Higgs scenarios !
(e.g. J.van der Bij et al., Higgs boson coupled to a higher dimensional singlet scalar, hep-ph/0605008)

> in the range $s^{1/2} > 100\,\mathrm{GeV}$. The data show a slight preference for a five-dimensional over a six-dimensional field. This Higgs boson cannot be seen at the LHC, but can be studied at the ILC.

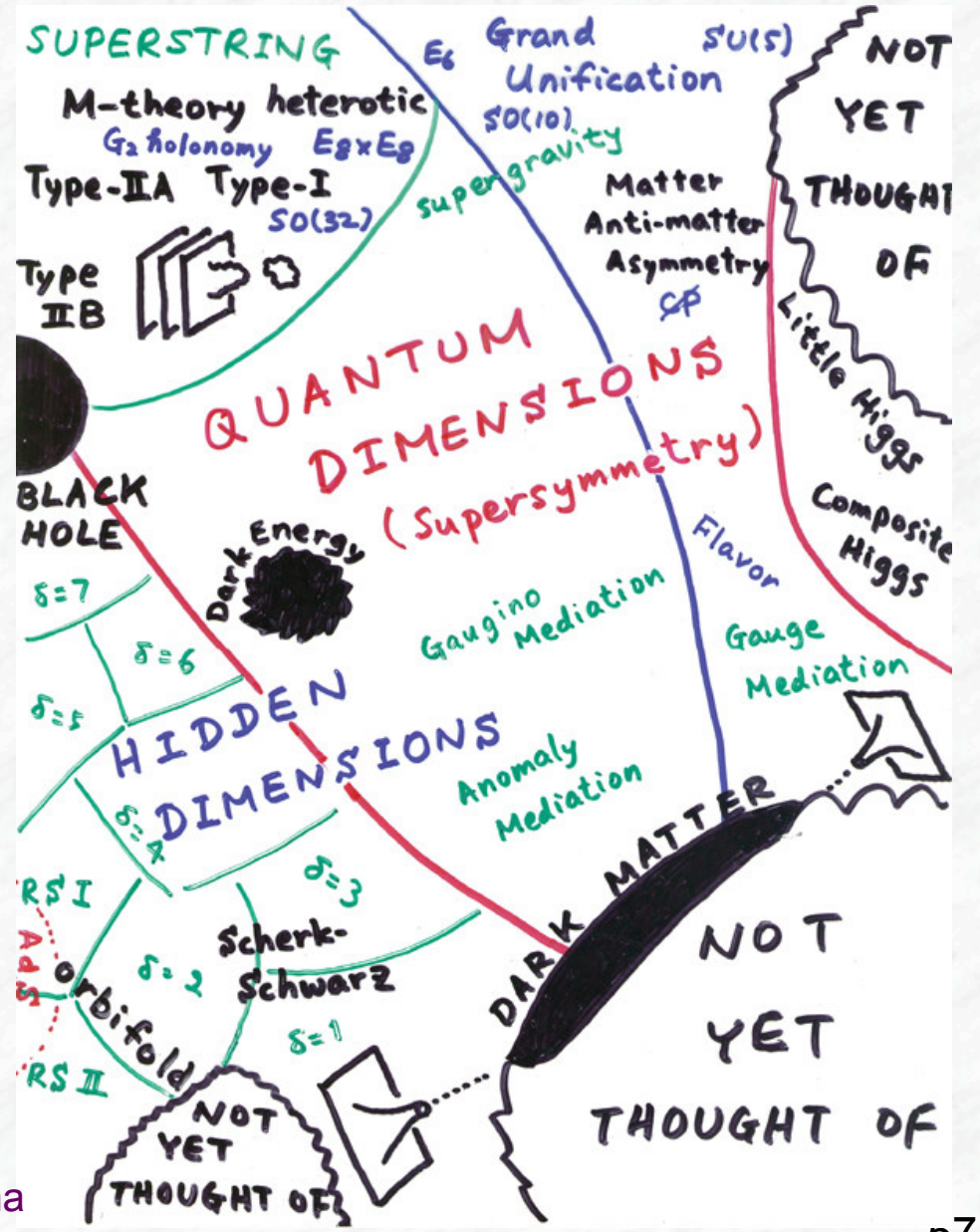
LHC reach: or where can we go with √s = 14 TeV

present ATLAS and CMS limits



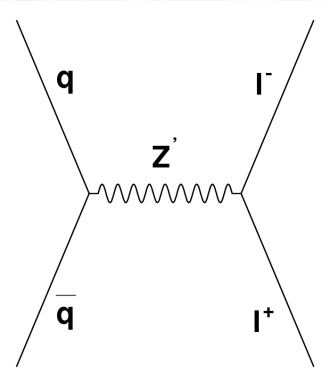
Part 5: Other Extensions of the Standard Model

- Additional Gauge bosons, Z' and W' searches
- Search for compositeness
- Excited quarks
- Search for signals from Extra Dimensions



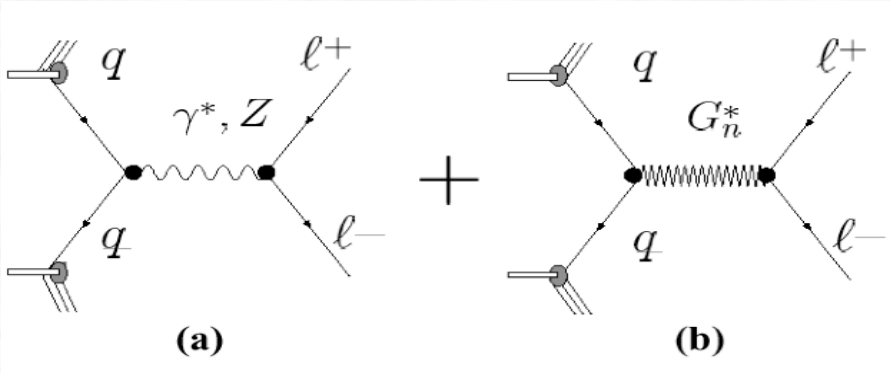
5.1 Search for new, high-mass di-lepton resonances

- Additional neutral Gauge Boson Z´



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

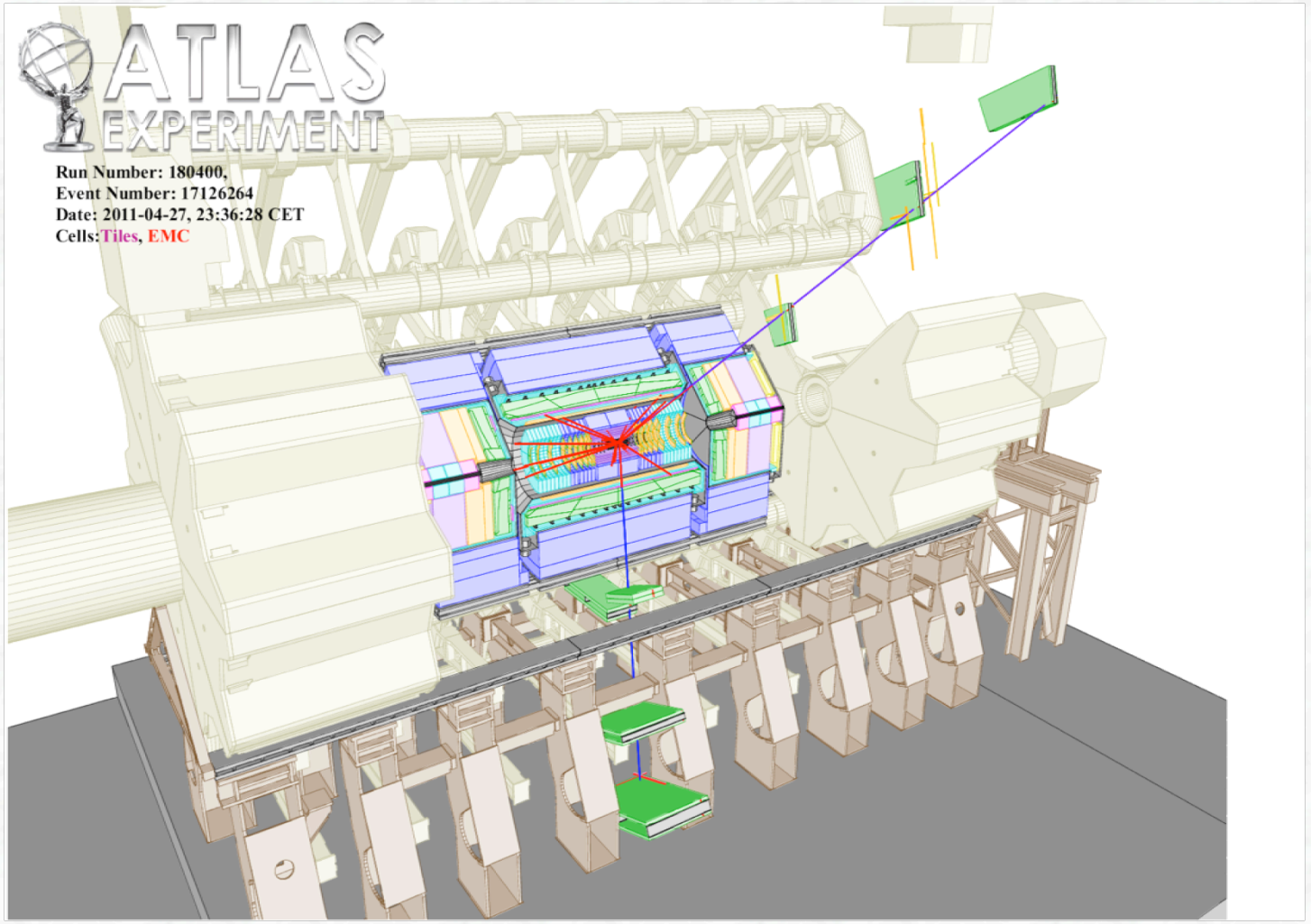
appear in Extra Dim. Scenarios



Standard Model background process

Signal

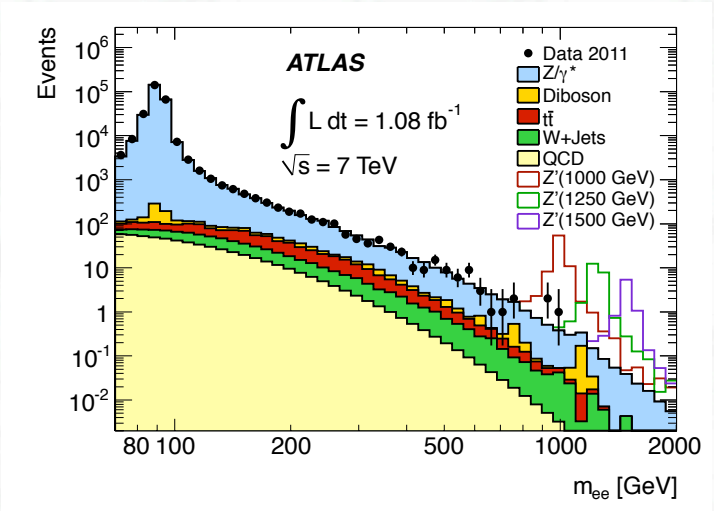
- Identical final state (two leptons), same analysis, interpretation for different theoretical models
- Main background process: Drell-Yan production of lepton pairs



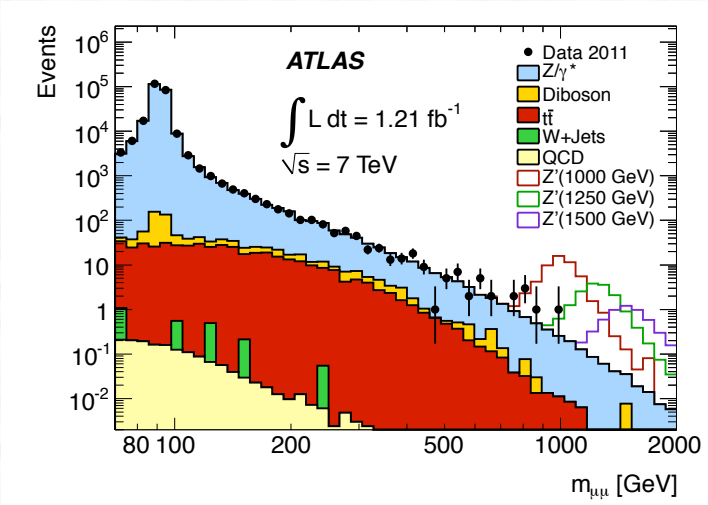
A high invariant mass di-muon event in the ATLAS data. The highest momentum muon has a p_T of 270 GeV and an (eta, phi) of (1.56, 1.30). The subleading muon has a p_T of 232 GeV and an (eta, phi) of (-0.09, -1.82). The invariant mass of the pair is 680 GeV.

Search for 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.

Detailed numbers on signal and background for the ee channel:

$m_{e^+e^-}$ [GeV]	70-110	110-200	200-400	400-800	800-3000
DY	258482 ± 410	5449 ± 180	613 ± 26	53.8 ± 3.1	2.8 ± 0.1
$t\bar{t}$	218 ± 36	253 ± 10	82 ± 3	5.4 ± 0.3	0.1 ± 0.0
Diboson	368 ± 19	85 ± 5	29 ± 2	3.1 ± 0.5	0.3 ± 0.1
W+jets	150 ± 100	150 ± 26	43 ± 10	4.6 ± 1.8	0.2 ± 0.4
QCD	332 ± 59	191 ± 75	36 ± 29	1.8 ± 1.4	< 0.05
Total	259550 ± 510	6128 ± 200	803 ± 40	68.8 ± 3.9	3.4 ± 0.4
Data	259550	6117	808	65	3

Drell-Yan background can be normalized in the Z peak region, 70-110 GeV

Z' models used in the interpretation

(i) Sequential Standard Model Z'

- Z' has the same couplings to fermions as the Standard Model Z, width of the Z' increases proportional to its mass

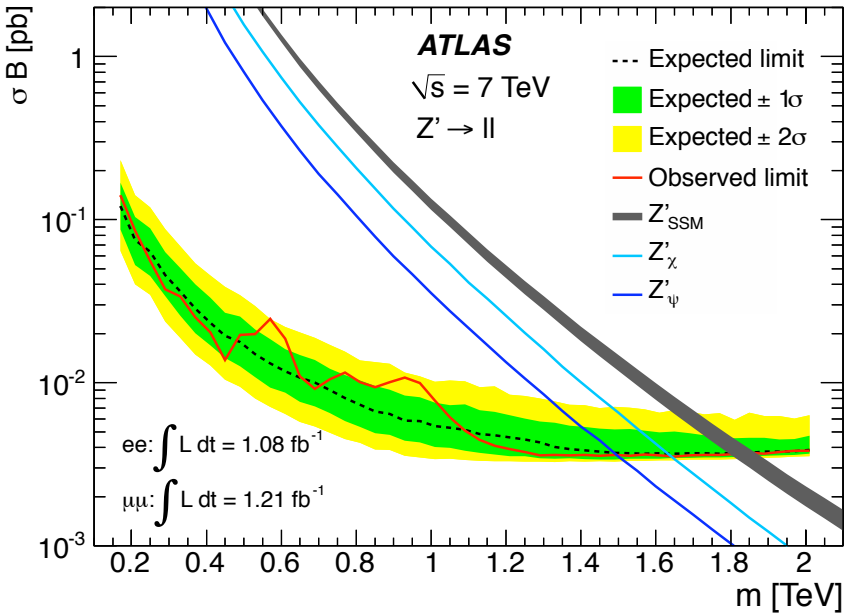
(ii) Models based on the E_6 grand unified symmetry group

- Broken into SU(5) and two additional U(1) groups, leading to two new neutral gauge fields, denoted Ψ and χ.
  The particles associated with the additional fields can mix to form the Z' candidates

$$Z' = Z'_{\psi} \cos\theta_{E6} + Z'_{\chi} \sin\theta_{E6}$$

- The pattern of symmetry breaking and the value of θ_{E6} determine the Z' couplings to fermions
  (several choices are considered)

Interpretation in the SSM and E6 models:

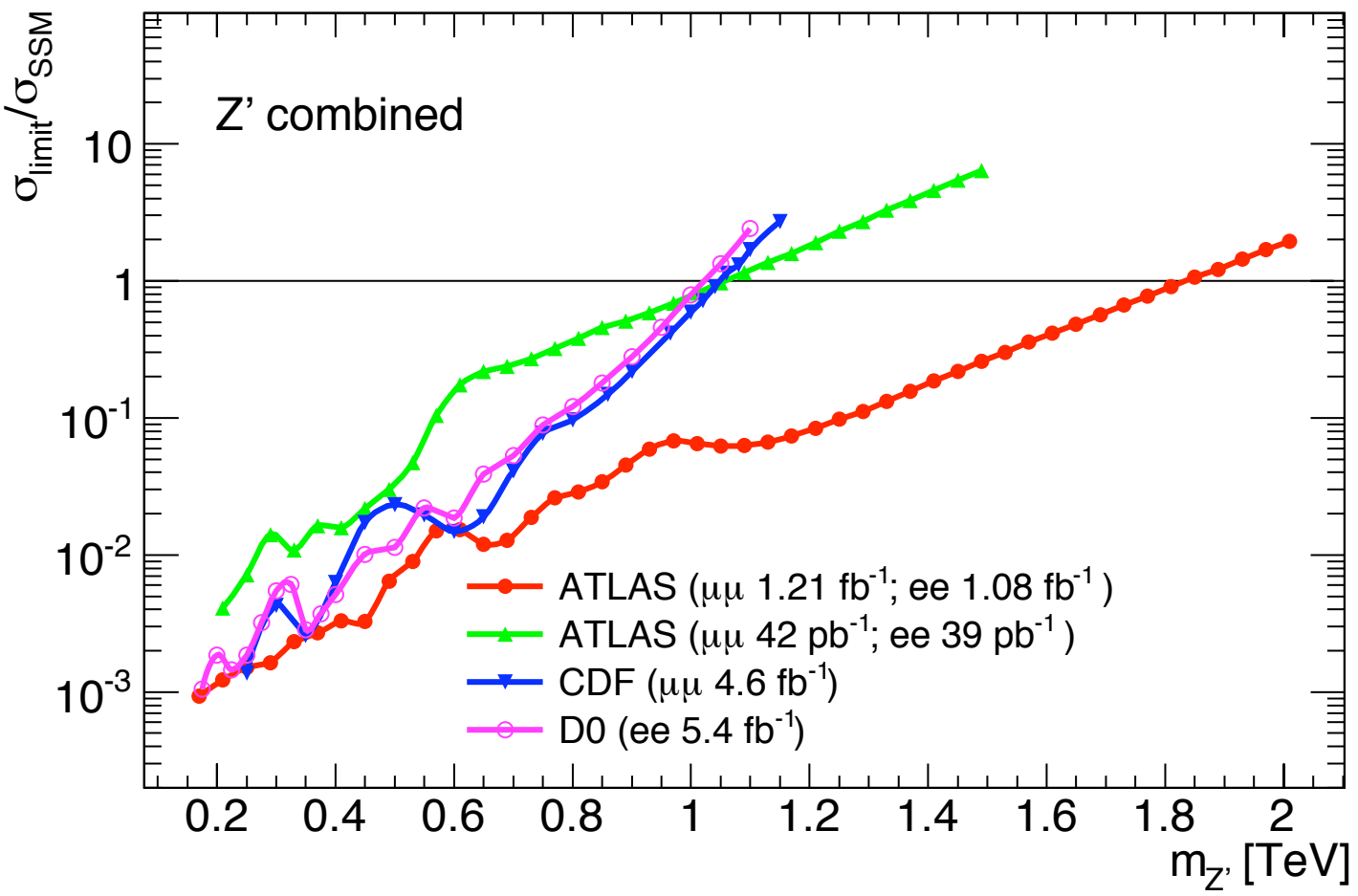


Resulting mass limits: ee + μμ
95% C.L.

Sequential SM: $m_{Z'} > 1.83$ TeV
E_6 models: $m_{Z'} > 1.49 – 1.63$ TeV

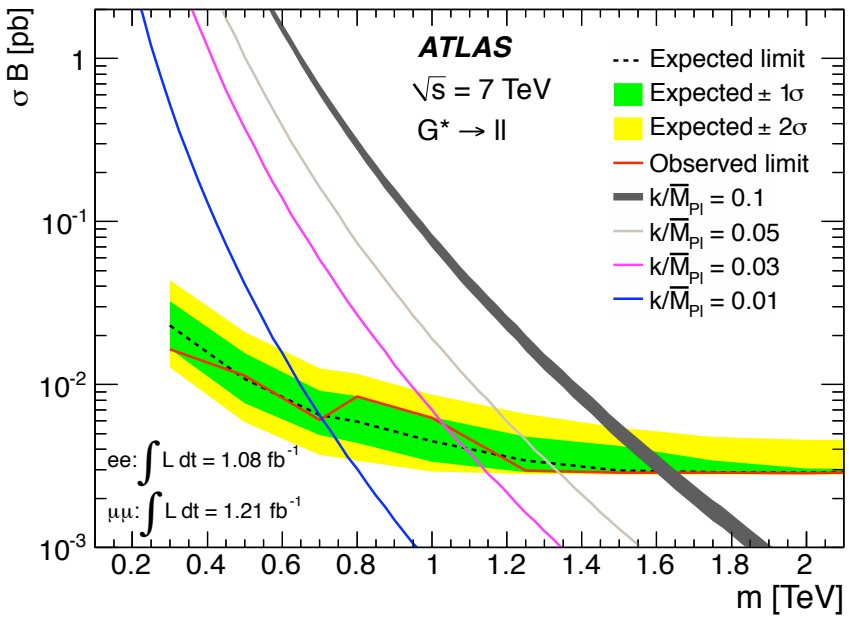
Summary of 95% C.L. SSM exclusion limits from various experiments:

95% C.L. limits (SM couplings)		ee	μμ	ll combined
CDF / D0	5.3 fb^{-1}			1.07 TeV
ATLAS	0.036 fb^{-1}	0.96 TeV	0.83 TeV	1.05 TeV
ATLAS	1.1 / 1.2 fb^{-1}	1.70 TeV	1.61 TeV	1.83 TeV
CMS	1.1 fb^{-1}			1.94 TeV



Ratio of observed combined limit for the Z' search using both channels divided by the SSM Z' cross section time branching ratio.

Interpretation in the Randall-Sundrum models: Graviton resonances: G → ll
(Kaluza-Klein modes)

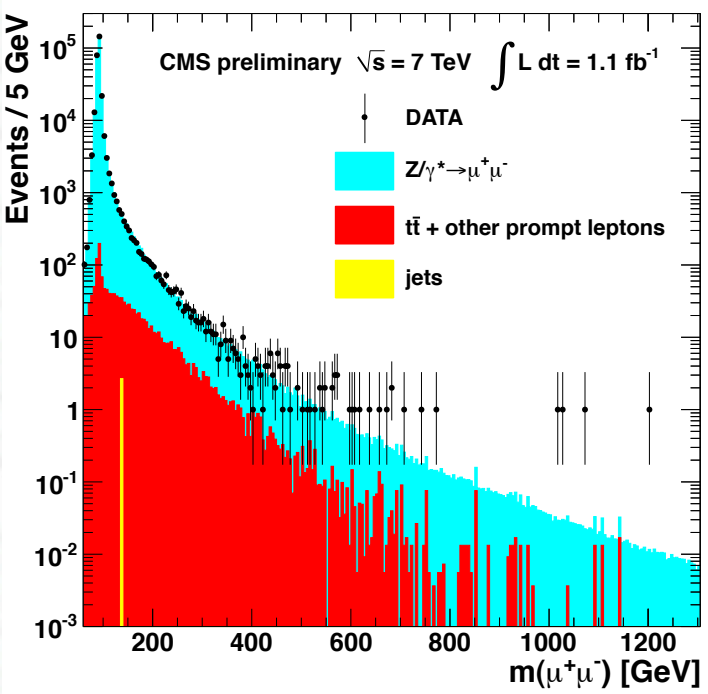


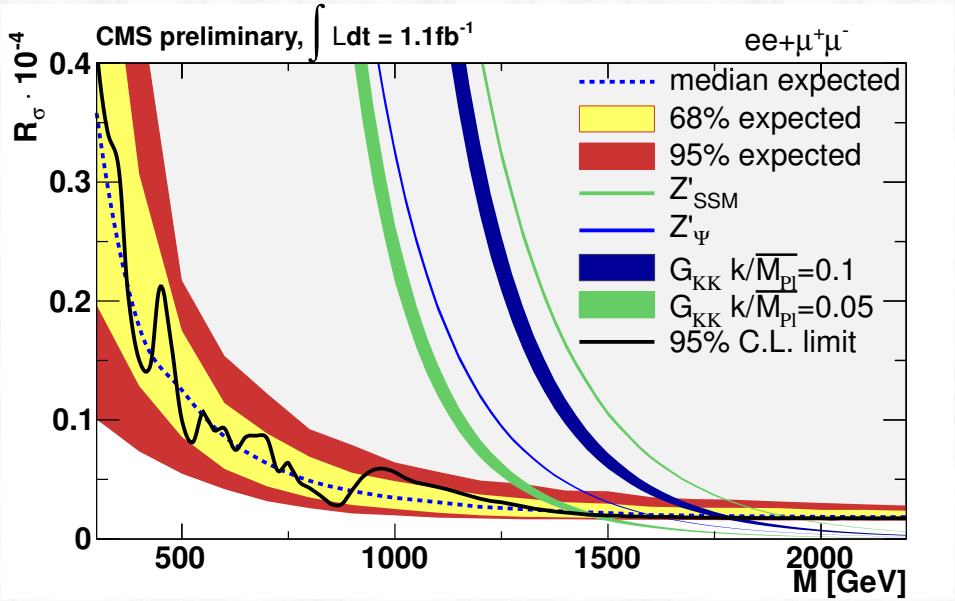
Resulting mass limits: ee + μμ
95% C.L.

$k/M'_{Pl} = 0.01$: $m_{Z'} > 0.71$ TeV
$k/M'_{Pl} = 0.03$: $m_{Z'} > 1.03$ TeV
$k/M'_{Pl} = 0.05$: $m_{Z'} > 1.33$ TeV
$k/M'_{Pl} = 0.10$: $m_{Z'} > 1.63$ TeV

Limits as a function of the coupling strength k/M'_{Pl}

k : = space-time curvature in the extra dimension
$M'_{Pl} = M_{Pl} / \sqrt{8\pi}$ (reduced Planck scale)





Resulting mass limits: ee + μμ
95% C.L. from the CMS analyses

Sequential SM: $m_{Z'} > 1.94$ TeV
E_6 models: $m_{Z'\psi} > 1.62$ TeV

Kaluza-Klein Gravitons:
$k/M'_{Pl} = 0.05$: $m_{Z'} > 1.45$ TeV
$k/M'_{Pl} = 0.10$: $m_{Z'} > 1.78$ TeV

Search for W' → lν

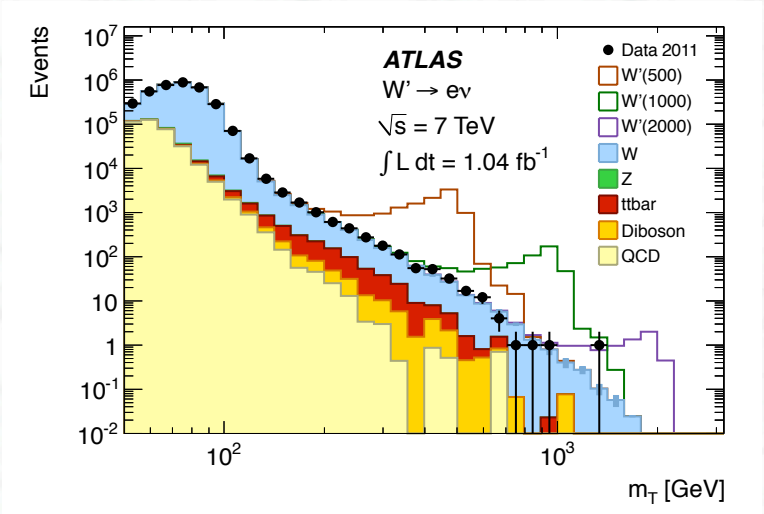
- W': additional charged heavy vector boson
- Appears in theories based on the extension of the gauge group
  e.g. Left-right symmetric models: $SU(2)_R$ W_R
- Assume ν from W' decay to be light and stable, and W' to have the same couplings as in the SM (*"Sequential Standard Model, SSM"*)

Signature: high p_T electron + high E_t^{miss}

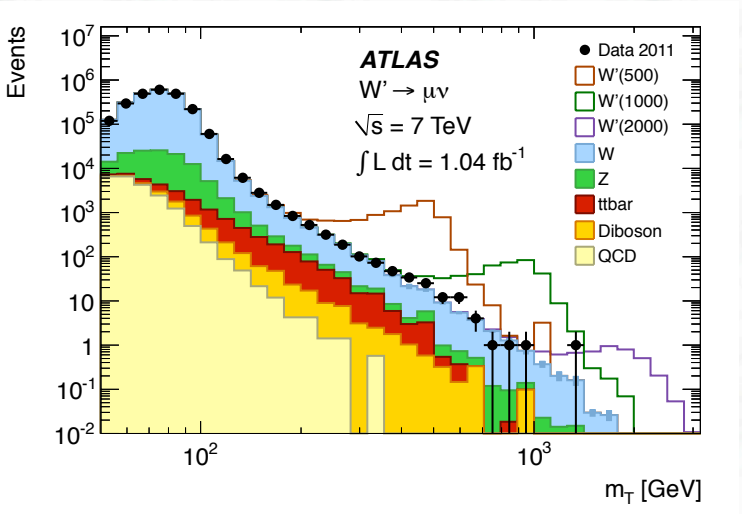
→ peak in transverse mass distribution

Search for New Resonances in High Mass lν events

Transverse mass (e, E_T^{miss})



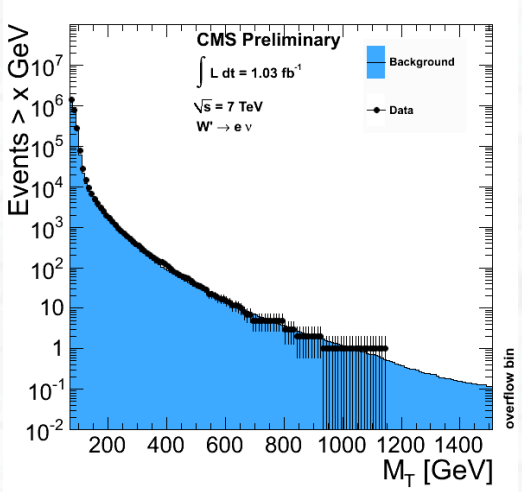
Transverse mass (μ, E_T^{miss})

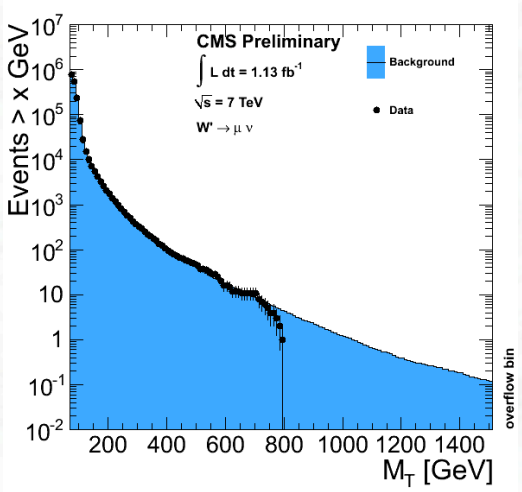


Data are consistent with background from SM processes. No excess observed.

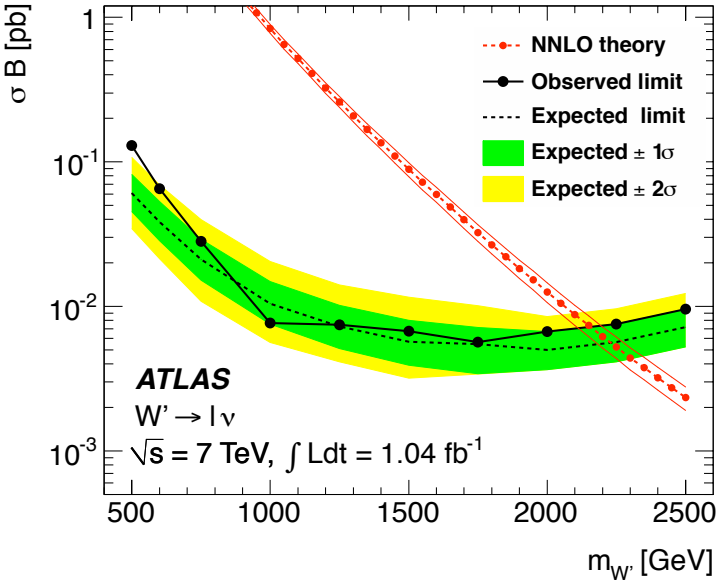
Above: Differential transverse mass distributions from ATLAS in the eν and μν channels

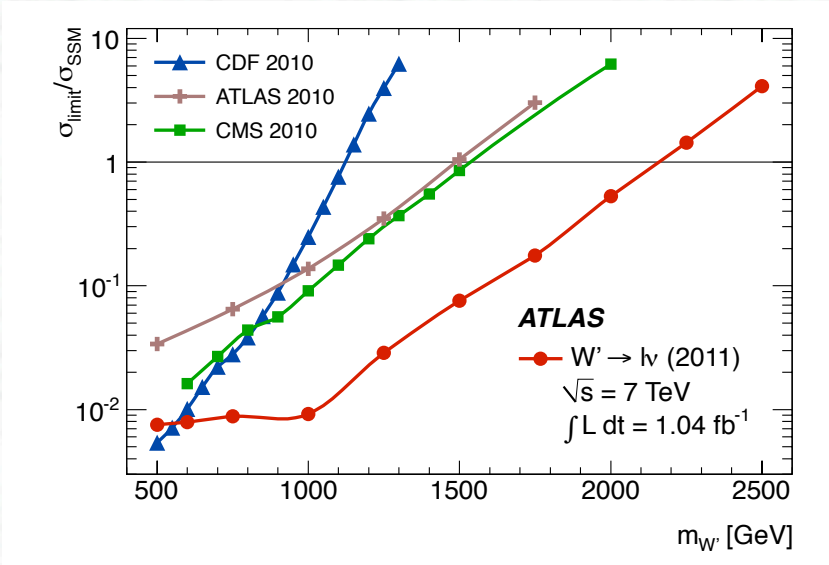
Below: Cumulative transverse mass distributions from CMS in the eν and μν channels

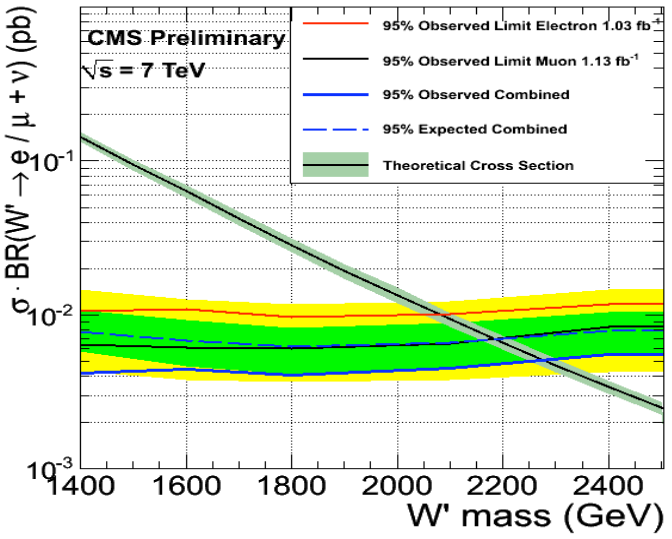




Interpretation in the Sequential SM







Summary of 95% C.L. SSM exclusion limits from ATLAS and CMS:

95% C.L. limits (SM couplings)		ll combined
ATLAS	1.1 fb^{-1}	2.23 TeV
CMS	1.1 fb^{-1}	2.27 TeV

5.2 Search for substructure /

compositeness of quarks

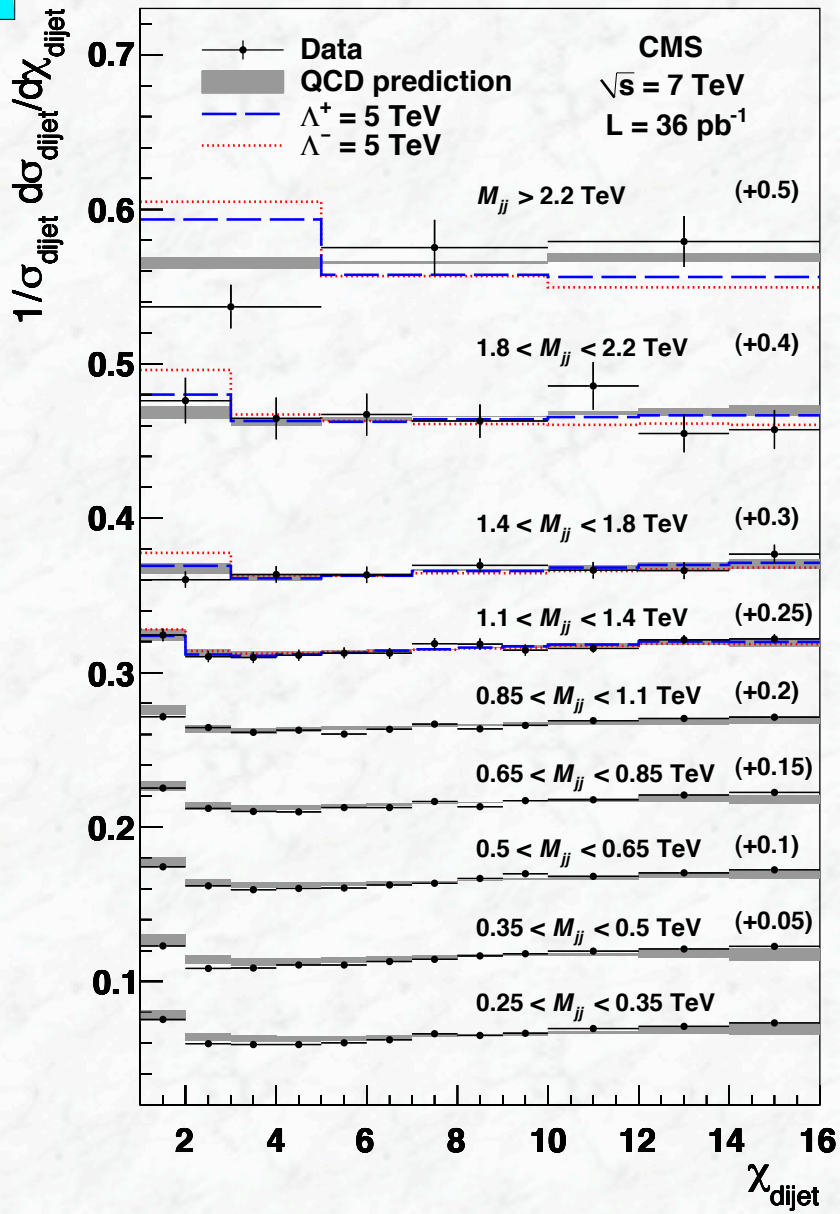
- Substructure of quarks would lead to contact interactions at high energy scales between the constituents

- Such interactions would lead to deviations from the expected QCD scattering behaviour, which would be most visible in:
  - the inclusive jet cross section at high p_T
  - the di-jet invariant mass distribution
    (traditional variables, but very sensitive to uncertainties on the jet energy measurement, i.e. jet energy scale)
  - the di-jet angular distributions of jets in the parton-parton centre-of-mass system

- Parametrize effects by using an effective Lagrangian, in addition to the QCD terms

$$L_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda^2}\,\psi_q^L \gamma^\mu \psi_q^L \;\; \psi_q^L \gamma^\mu \psi_q^L \qquad \text{where} \qquad \frac{g^2}{4\pi} = 1$$

corresponds to a 4-fermion interaction (analogue to Fermi theory) ;
$\xi = \pm 1$, interference parameter, relative phase between QCD terms and contact terms
Λ = scale parameter of new interaction, to be determined in experiment



In QCD: gluon exchange diagrams dominate, have the same angular dependence as Rutherford scattering; essentially flat in the variable

$$\chi = e^{|y_1 - y_2|}$$

y_1, y_2 = rapidities of the two jets

Results on χ measurement from the CMS experiment

based on full 2010 dataset, 36 pb^{-1}

95% C.L. Limits on scale Λ :

ATLAS 3.1 pb^{-1} Λ > 3.4 TeV

CMS: 36 pb^{-1} Λ^+ > 5.6 TeV
Λ^- > 6.7 TeV

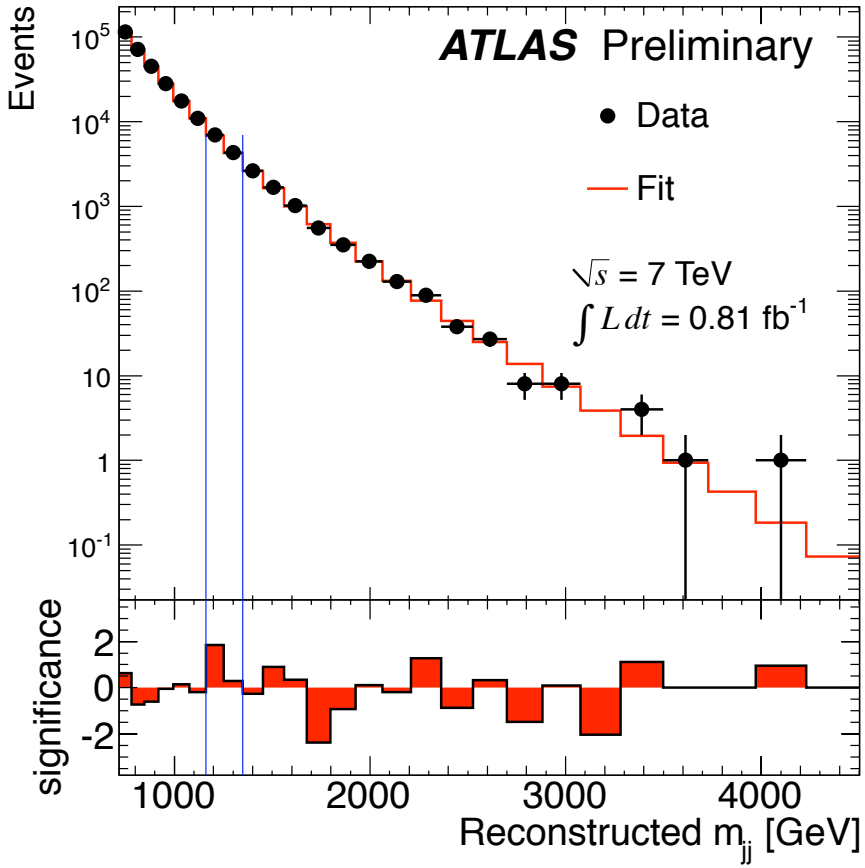
5.3 Search for Resonances in the di-jet mass distribution

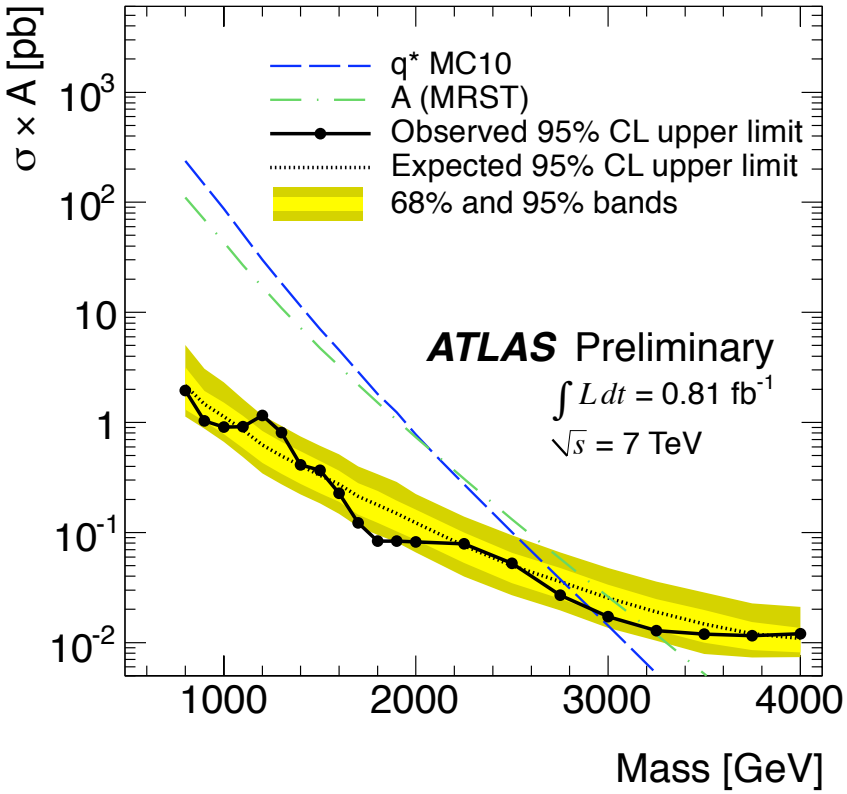
Many extensions of the Standard Model predict the existence of new massive objects that couple to quarks (q) and gluons (g) and result in resonances in the di-jet mass spectrum:

Some examples searched for by ATLAS and CMS:

- Excited quarks q*, which decay to qg, predicted if quarks are composited objects
- Axial-vector particles called axigluons (A), which decay to qq, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $SU(3)_L \times SU(3)_R$
- New gauge bosons (W' and Z'), which decay into qq, predicted by models that include new gauge symmetries; the W' and Z' are assumed to have Standard Model couplings
- Randall-Sundrum (RS) gravitons (G), which decay to qq and gg, predicted in the RS model of extra dimensions; the value of the dimensionless coupling k/M'_{Pl} is chosen to be 0.1.
- .....

ATLAS search in data corresponding to L_{int} = 0.81 fb^{-1}

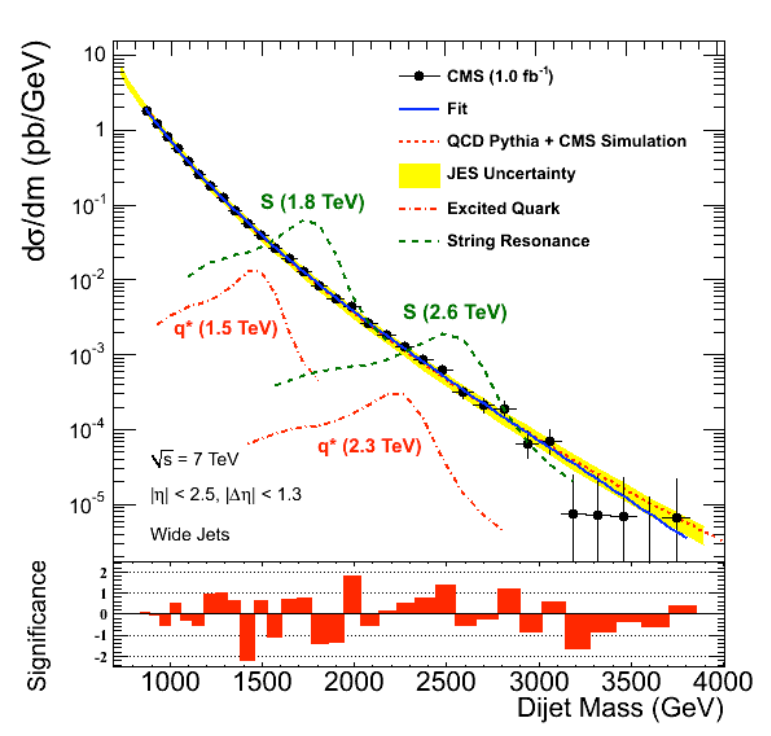


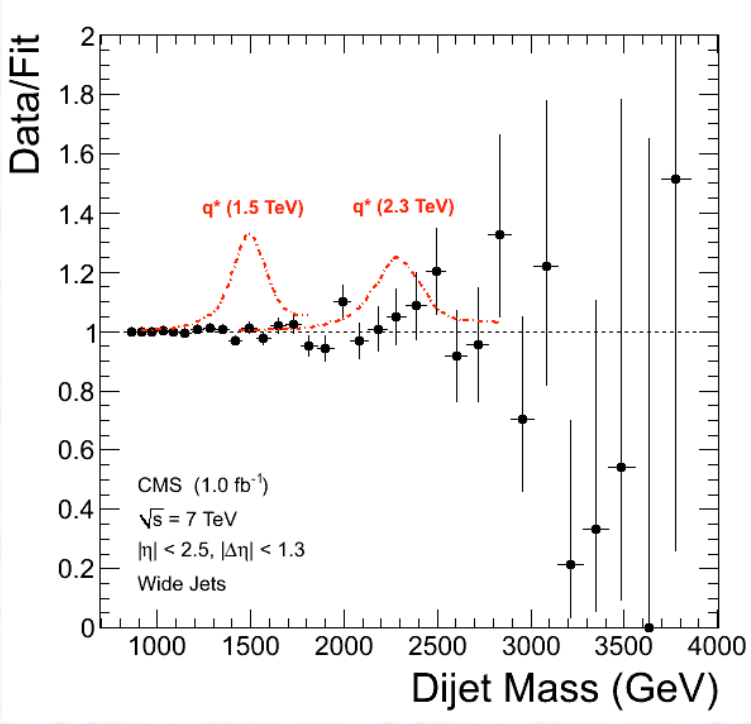


- Search for resonance / bump in the invariant dijet mass spectrum
- Assume smooth functional form of the QCD mass spectrum
- No evidence for a resonance → exclusion limits

Model	95% CL Limits (TeV)	
	Expected	Observed
Excited Quark q^*	2.77	2.91
Axigluon	3.02	3.21

CMS search in data corresponding to L_{int} = 0.81 fb^{-1}





- Search for resonance / bump in the invariant dijet mass spectrum
- Compare to PYTHIA QCD model
- No evidence for a resonance → exclusion limits

Model	Excluded Mass (TeV)	
	Observed	Expected
String Resonances	4.00	3.90
E_6 Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
W′ Bosons	1.51	1.40

No exclusion limits set yet on RS gravitons and Z' → qq decays

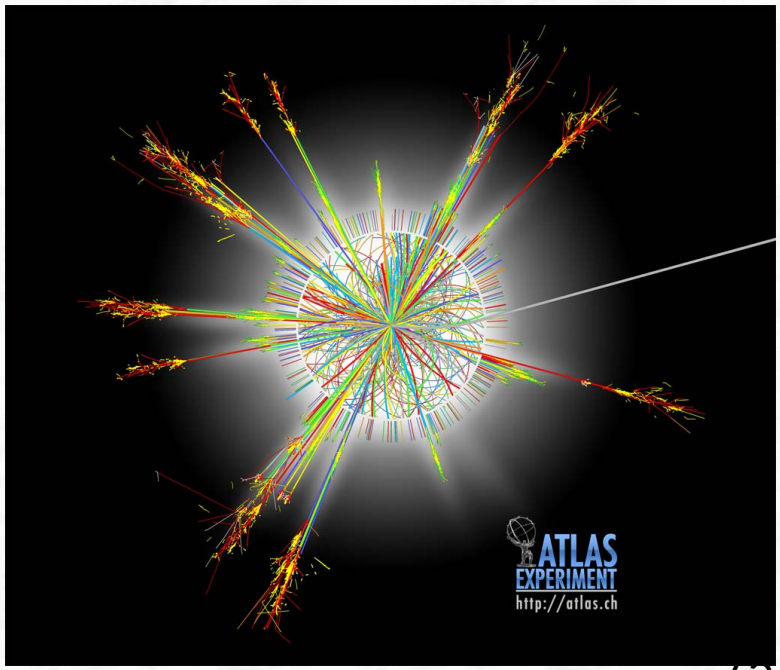
LHC reach for other BSM Physics

(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

5.4 Search for signals from extra dimensions

- Search for escaping gravitons at the LHC
- Search for Black Hole Production



Microscopic-Black Hole events at the LHC ?

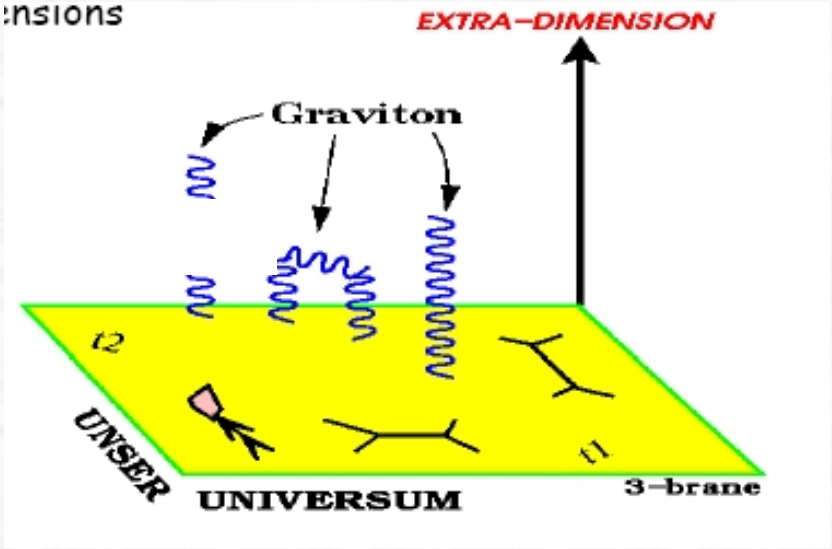
Large Extra Dimensions & the ADD Model

- Assume that there are n compactified extra space dimensions, with size r
- Only gravity can propagate in the extra dimensions;

Relation between Planck mass M_{Pl} in 4 and (4+n) dimensions M_D:

$$M_{\mathrm{Pl}}^2 = 8\pi M_D^{n+2} r^n$$

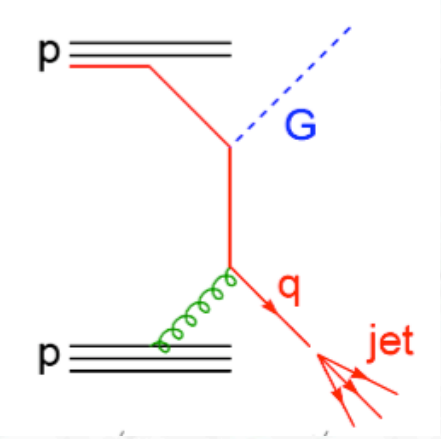
- The Standard Model interactions and all matter particles are confined to our 3-dimensional world



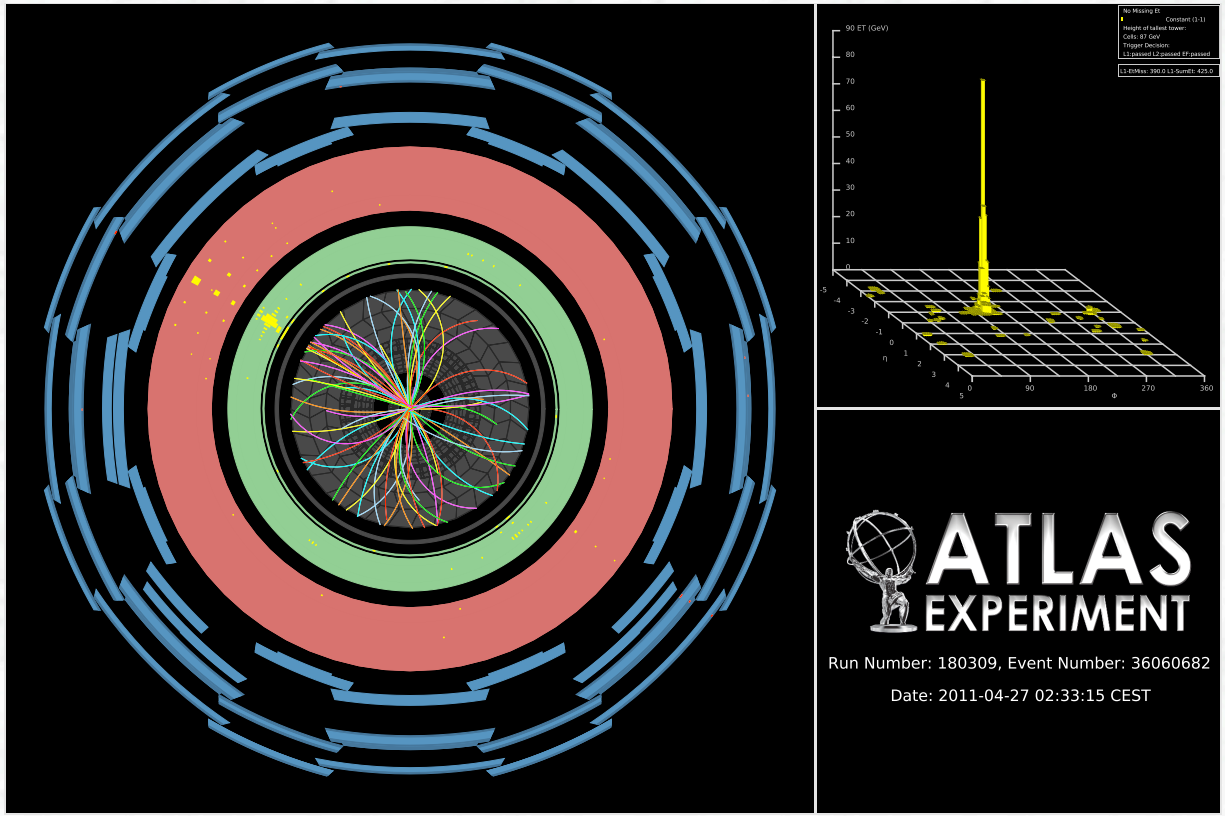
Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315, 9804398, 9807344

Experimental Signature: Mono-jets from graviton production

Signal: single jet, E_T^{miss}

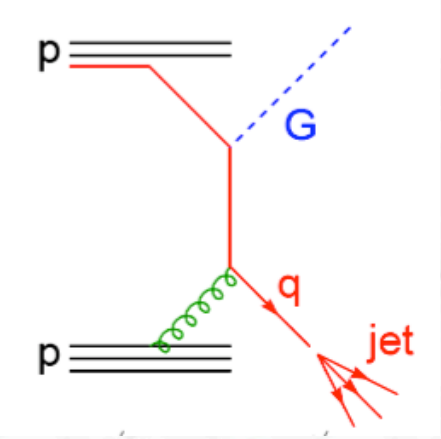


A nice candidate event: 1 jet with p_T = 602 GeV
E_T^{miss} = 523 GeV



Experimental Signature: Monojets

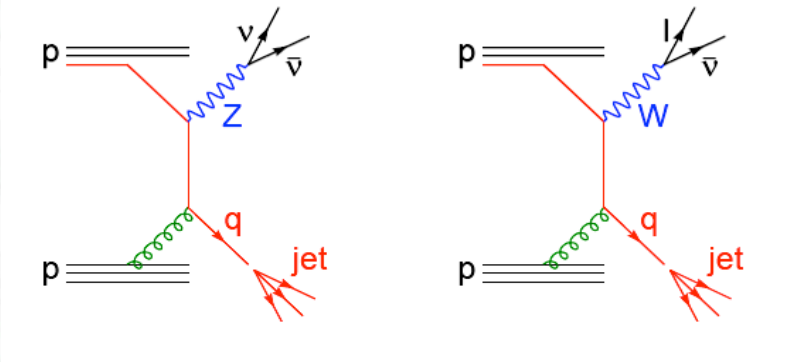
Signal: single jet, E_T^{miss}



Physics background:

- Z + jet, Z → νν (irreducible)

- W+ jet, W → lν, l not detected
- QCD jet background, jet mis-measured



In addition, there could be a sizeable "instrumental / non-physics" background:

- Calorimeter noise, coherent noise in one region of the calorimeter
- Beam induced background
- Background from cosmic rays
  (e.g. high energy muon showers)

Typical selection: ATLAS, 2011 data, $L_{int} = 1.0\ fb^{-1}$

- require strict vertex cuts (five tracks associated to a primary vertex)
  suppresses beam-related background and cosmic ray backgrounds

- apply tight cuts on the shape of the calorimeter energy depositions,
  i.e. fraction of el.magn. energy, timing cuts, …
  (to suppress jets from "correlated noise in the calorimeter")

- Require 1 jet with $p_T > 120$ GeV (low p_T), 250 GeV (high p_T), 350 GeV (very high)
  in the central detector region, $|\eta| < 2.0$

  No further jets in the event with $p_T > 30$ GeV within $|\eta| < 4.5$

- $E_T^{miss} > 120$ GeV (low), 220 GeV (high) and 300 GeV (very high)
  and $\Delta\phi$ (jet, E_T^{miss}) > 0.5

- Lepton veto: reject all events with an identified lepton,
  electrons with $p_T > 20$ or muons with $p_T > 10$ GeV

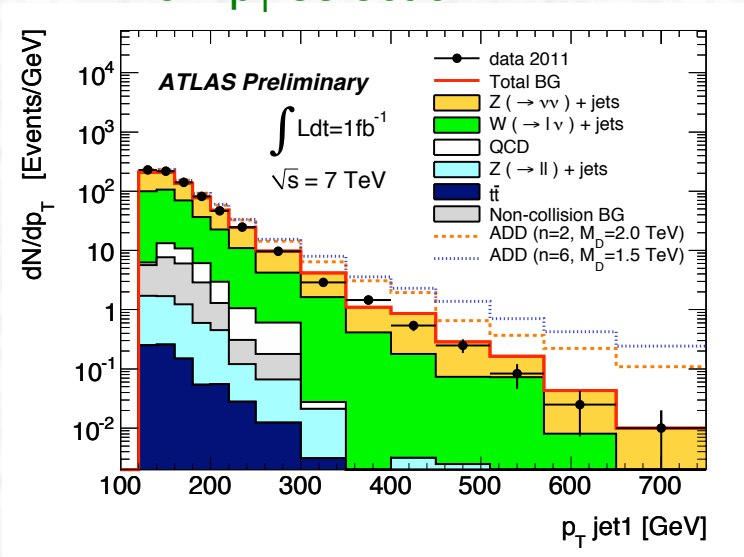
➔ 15750, 965 and 167 events observed in ATLAS data for the low, high and very high selections, respectively

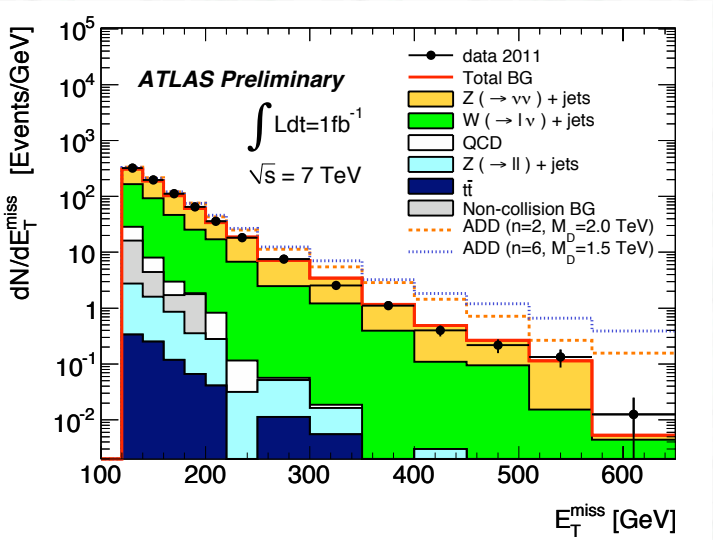
Numbers of observed events in data in comparison to expectations from Standard Model background:

	Background Predictions ± (stat.) ± (syst.)		
	LowPt Selection	HighPt Selection	veryHighPt selection
$Z(\to \nu\bar{\nu})$+jets	$7700 \pm 90 \pm 400$	$610 \pm 27 \pm 47$	$124 \pm 12 \pm 15$
$W(\to \tau\nu)$+jets	$3300 \pm 90 \pm 220$	$180 \pm 16 \pm 22$	$36 \pm 7 \pm 8$
$W(\to e\nu)$+jets	$1370 \pm 60 \pm 90$	$68 \pm 10 \pm 8$	$8 \pm 1 \pm 2$
$W(\to \mu\nu)$+jets	$1890 \pm 70 \pm 100$	$113 \pm 14 \pm 9$	$18 \pm 4 \pm 2$
Multi-jets	$360 \pm 20 \pm 290$	$30 \pm 6 \pm 11$	$3 \pm 2 \pm 2$
$Z/\gamma^*(\to \tau^+\tau^-)$+jets	$59 \pm 3 \pm 4$	$2.0 \pm 0.6 \pm 0.2$	-
$Z/\gamma^*(\to \mu^+\mu^-)$+jets	$45 \pm 3 \pm 2$	$2.0 \pm 0.6 \pm 0.1$	-
$t\bar{t}$	$17 \pm 1 \pm 3$	$1.7 \pm 0.3 \pm 0.3$	-
γ+jet	-	-	-
$Z/\gamma^*(\to e^+e^-)$+jets	-	-	-
Non-collision Background	$370 \pm 40 \pm 170$	$8.0 \pm 3.3 \pm 4.1$	$4.0 \pm 3.2 \pm 2.1$
Total Background	$15100 \pm 170 \pm 680$	$1010 \pm 37 \pm 65$	$193 \pm 15 \pm 20$
Events in Data (1.00 fb^{-1})	15740	965	167

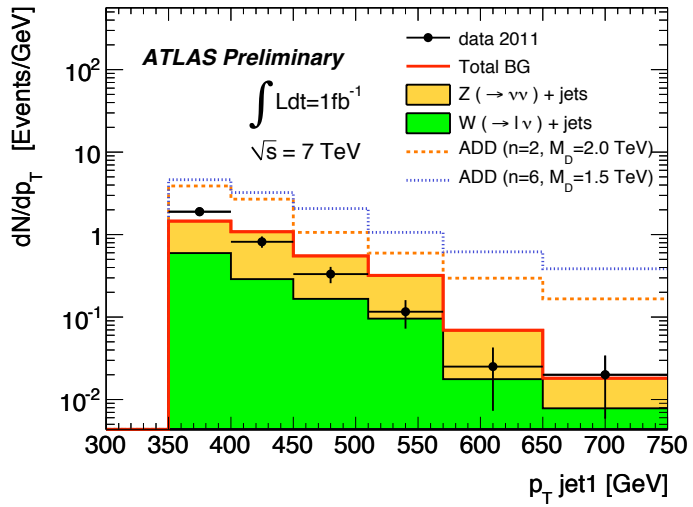
Agreement between data and expectations for the p_T(jet) and E_T^{miss} spectra:

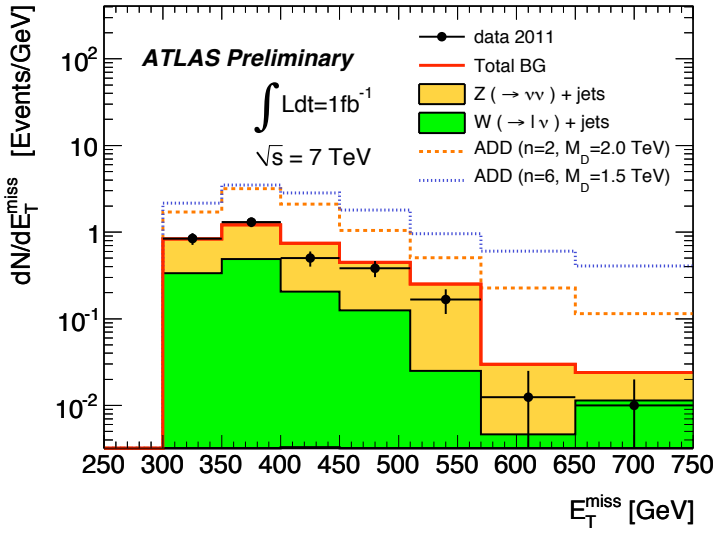
Low p_T selection:



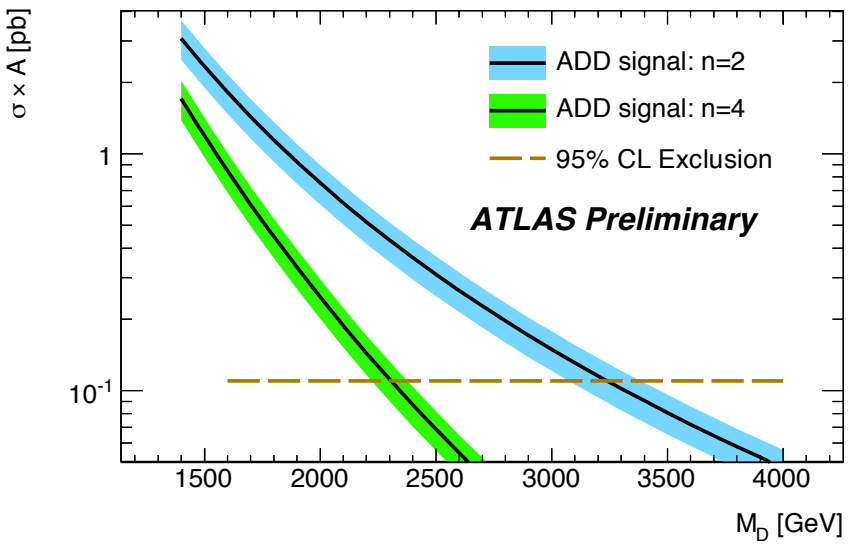


Very high p_T selection:

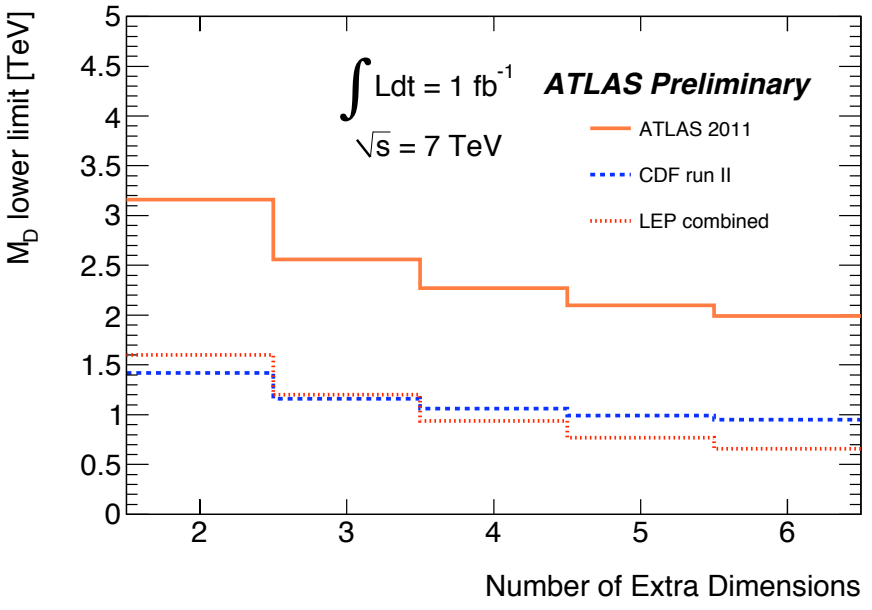




Constraints on the ADD model parameters:



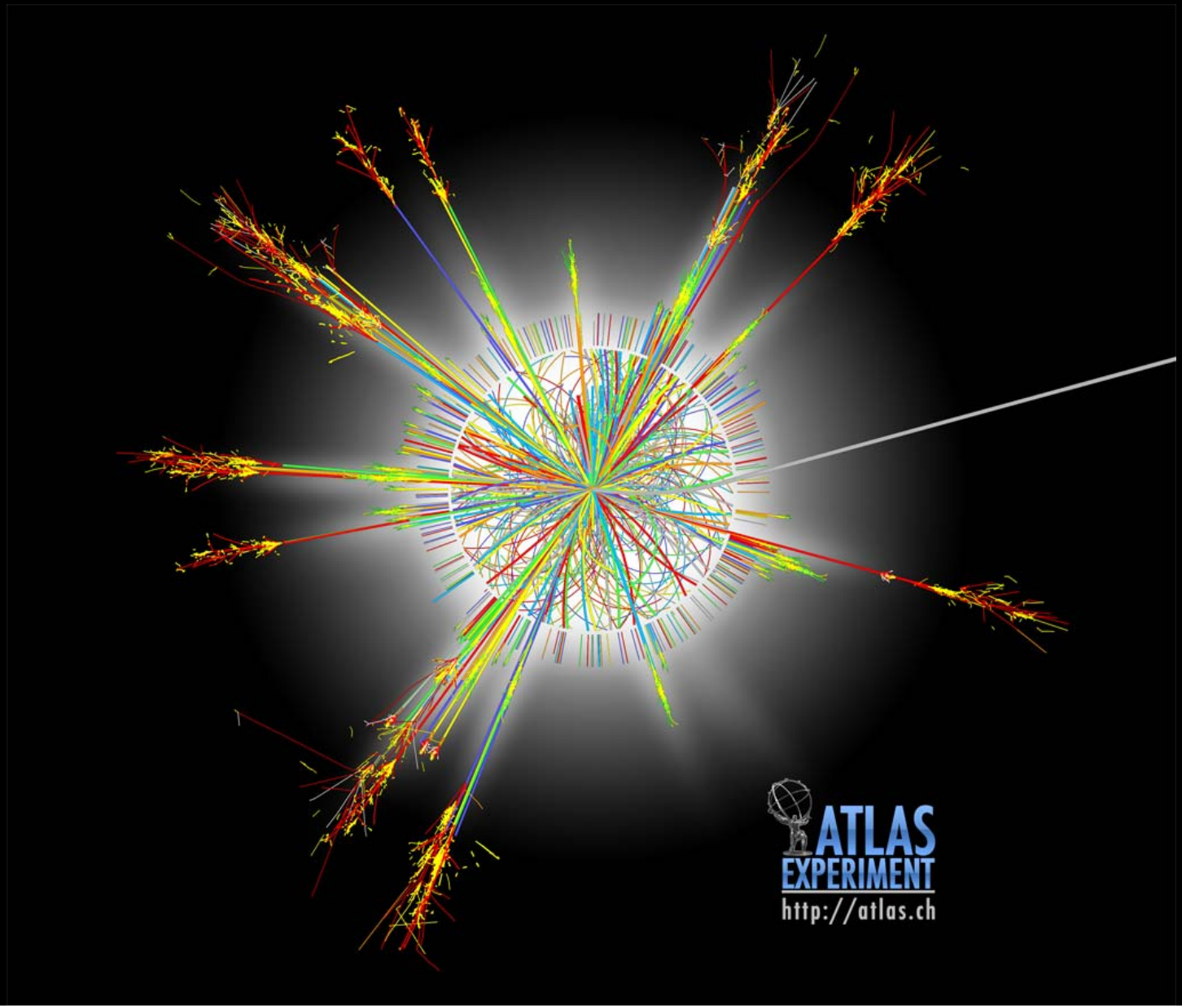
Cross sections as a function of M_D for n=2 and n=4 extra dimensions (cutoff for $s^{\wedge} < M^2_D$)



Excluded M_D values (95% C.L.):

95% CL limits on M_D for the ADD model ($\hat{s} < M_D^2$)			
	LowPt selection	HighPt selection	veryHighPt selection
n	observed [TeV]	observed [TeV]	observed [TeV]
2	2.20	3.16	3.39
3	1.76	2.50	2.55
4	1.54	2.15	2.26
5	1.37	1.89	1.90
6	1.24	1.68	1.58

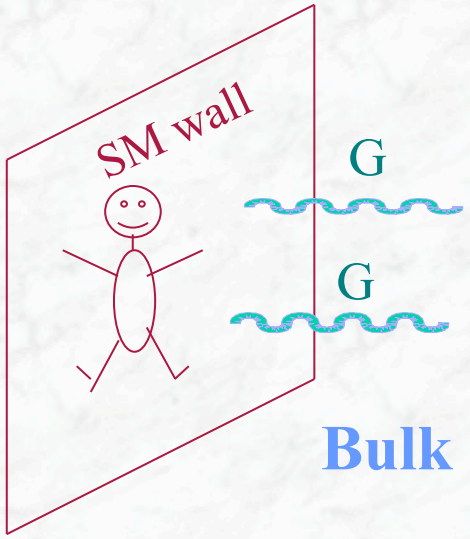
Microscopic Black Holes at the LHC ?



- 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:

$$M_{\mathrm{Pl}}^2 = 8\pi M_D^{n+2} r^n$$

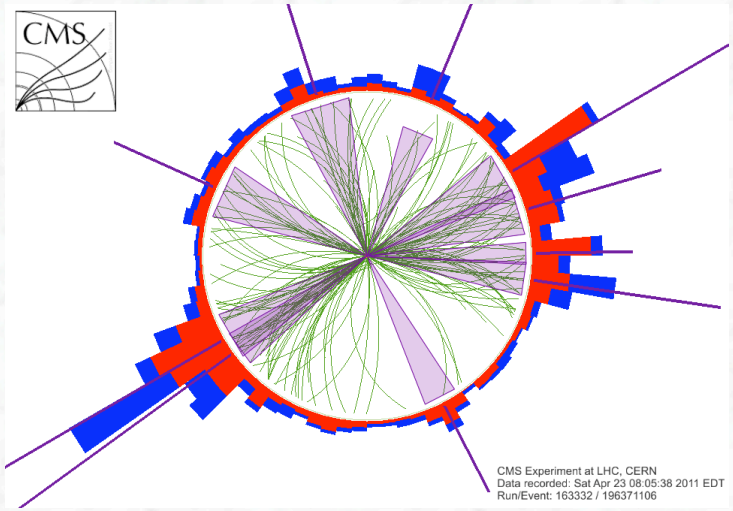


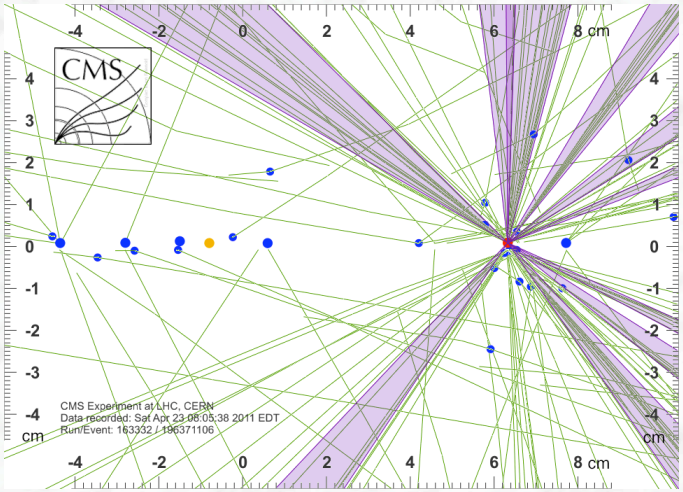
- Black hole formation at energies greater than M_D, (above a threshold mass, M_{th})

  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….

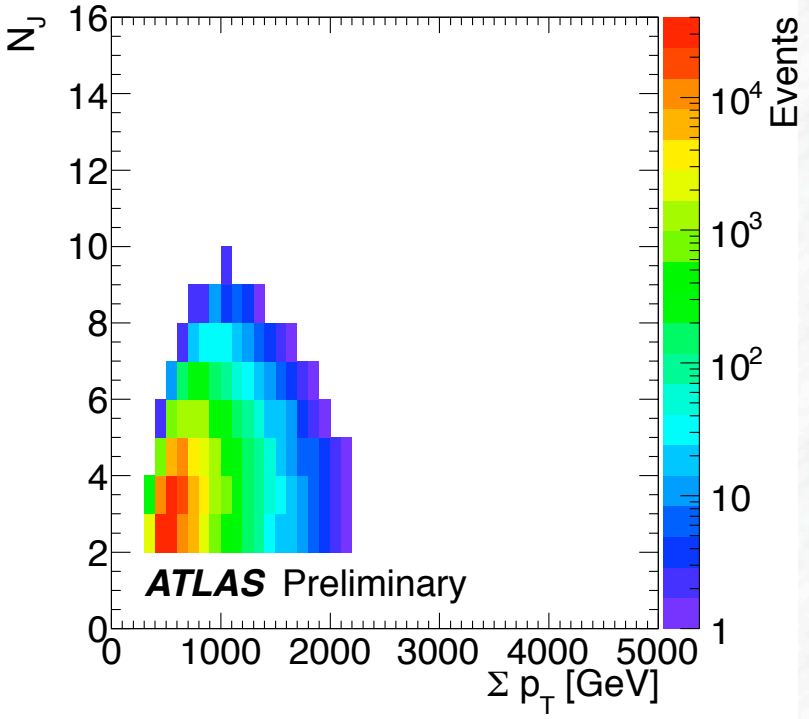
all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?

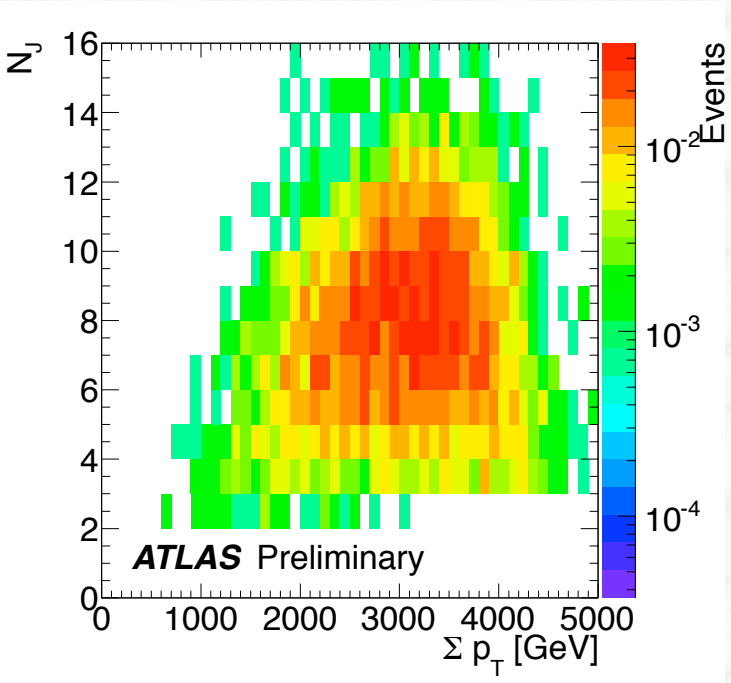
Discriminating variables between QCD background and black hole signals:

- jet multiplicity N_J
- total transverse momentum/energy (scalar sum) in the event, Σp_T =: S_T

Results of an ATLAS Monte Carlo simulation:

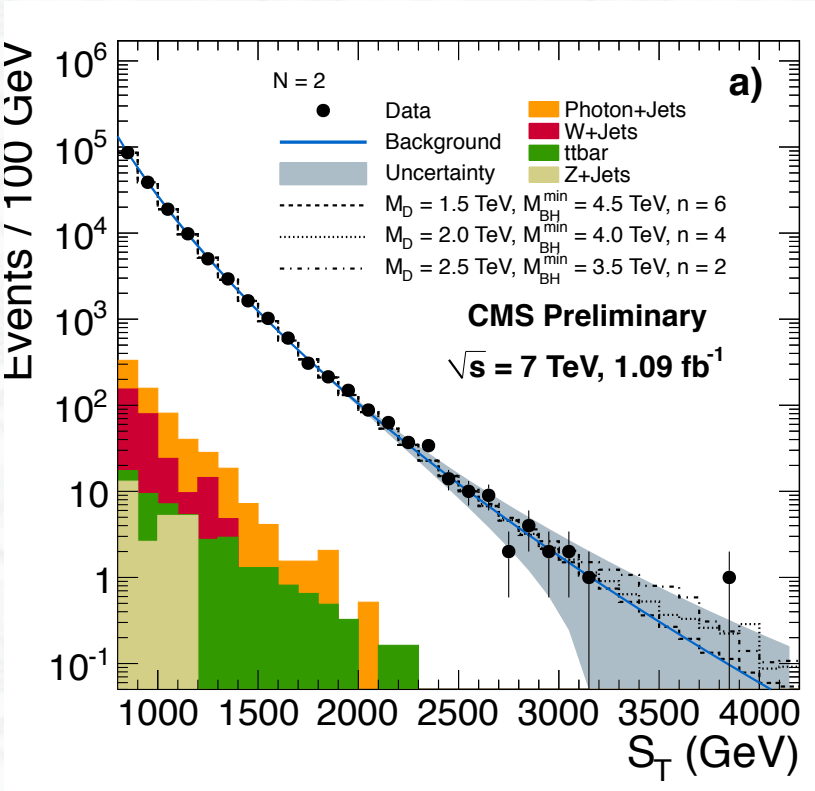


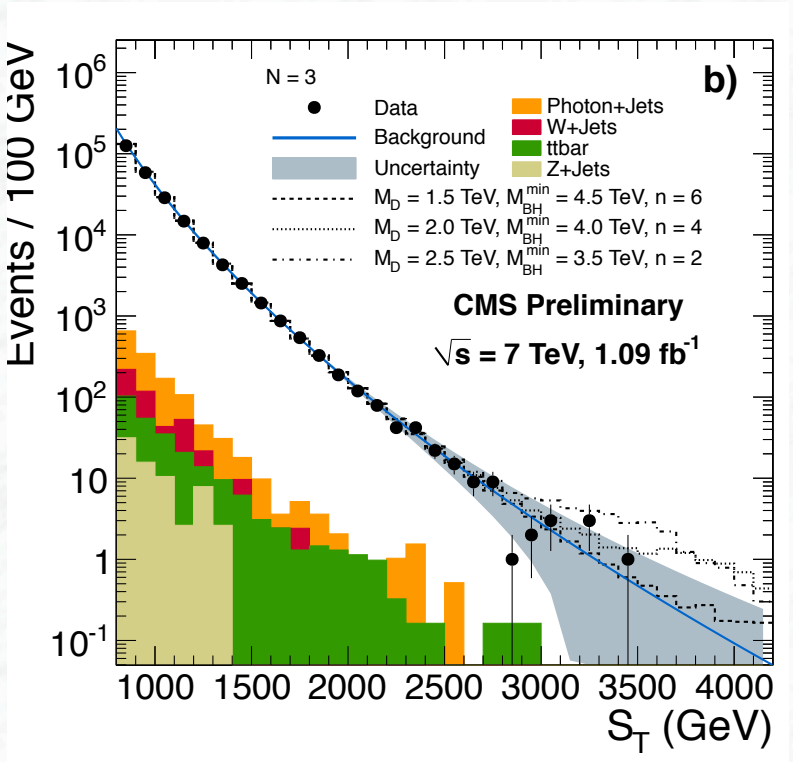
QCD multijet “background”



Black hole signal events with Planck scale M_D = 1 TeV and n = 2, threshold production mass 4.3 TeV

Background model / “calibration” of QCD multijet background



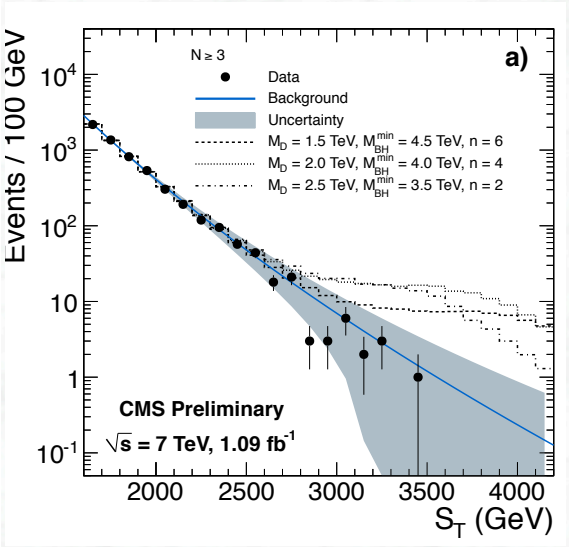


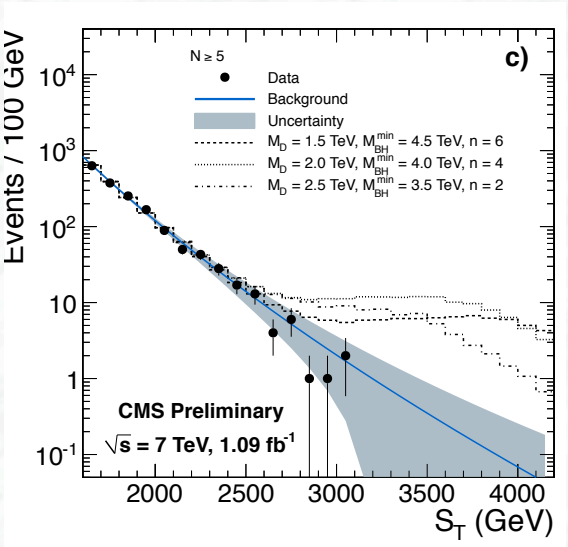
Shape of ST distribution cannot be reliably calculated in Monte Carlo simulation

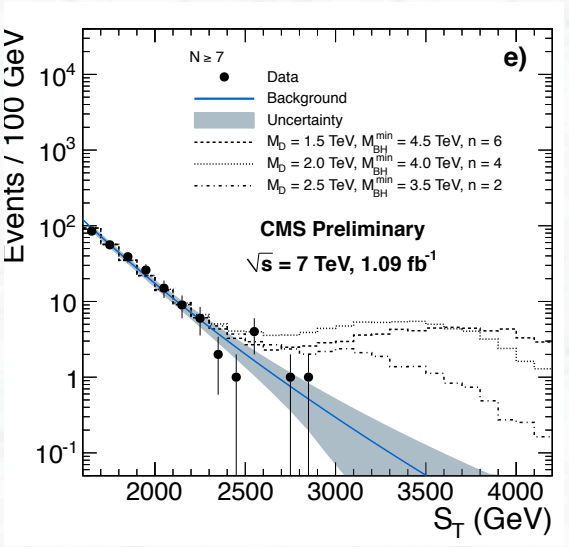
problem: high jet multiplicities

→ Fit a smooth QCD model to data in low ST region, determine parametrization (functional form) at low multiplicities (n=2)

CMS analysis, use large part of the 2011 data, L_{int} = 1.09 fb^{-1}



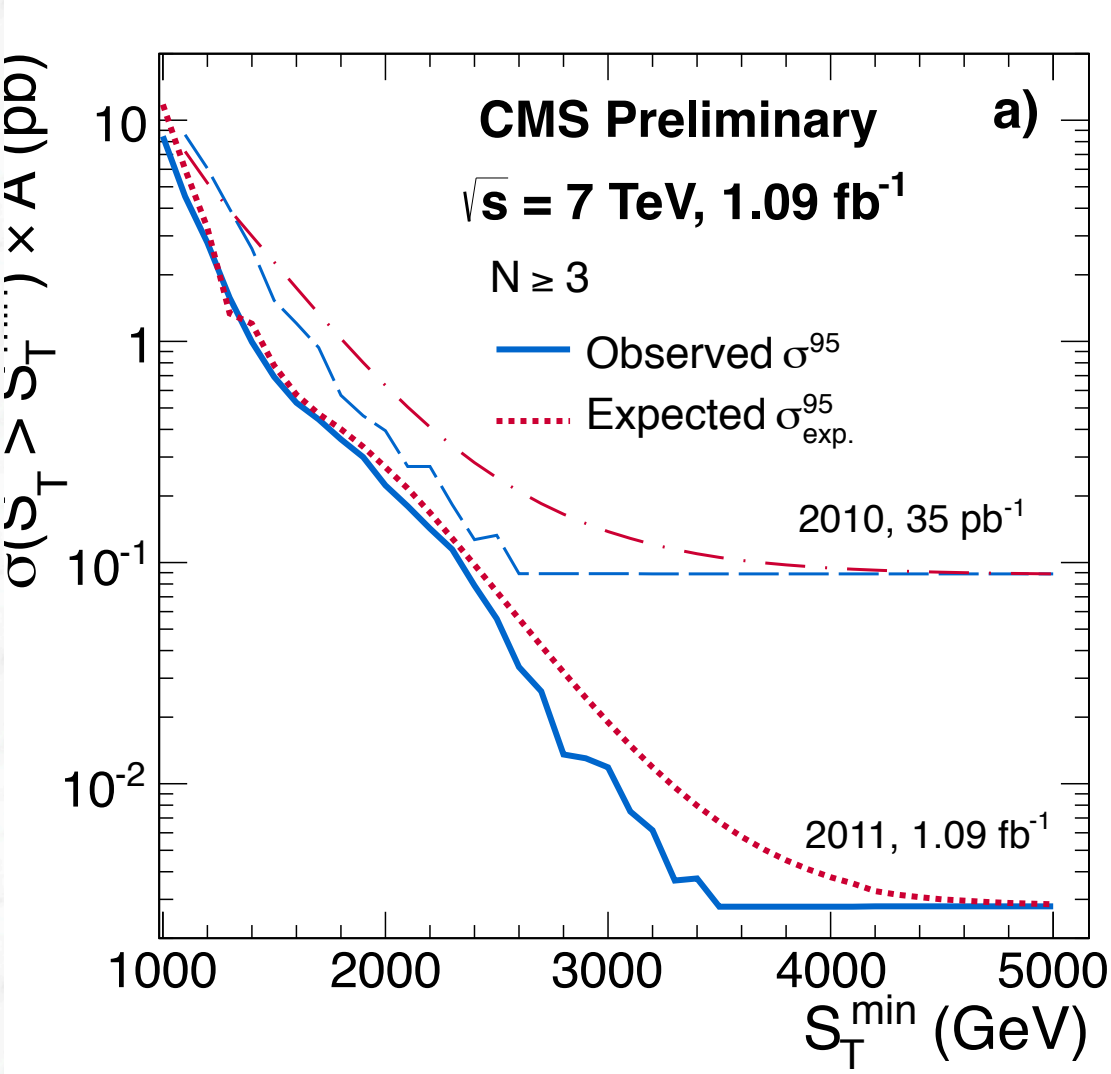
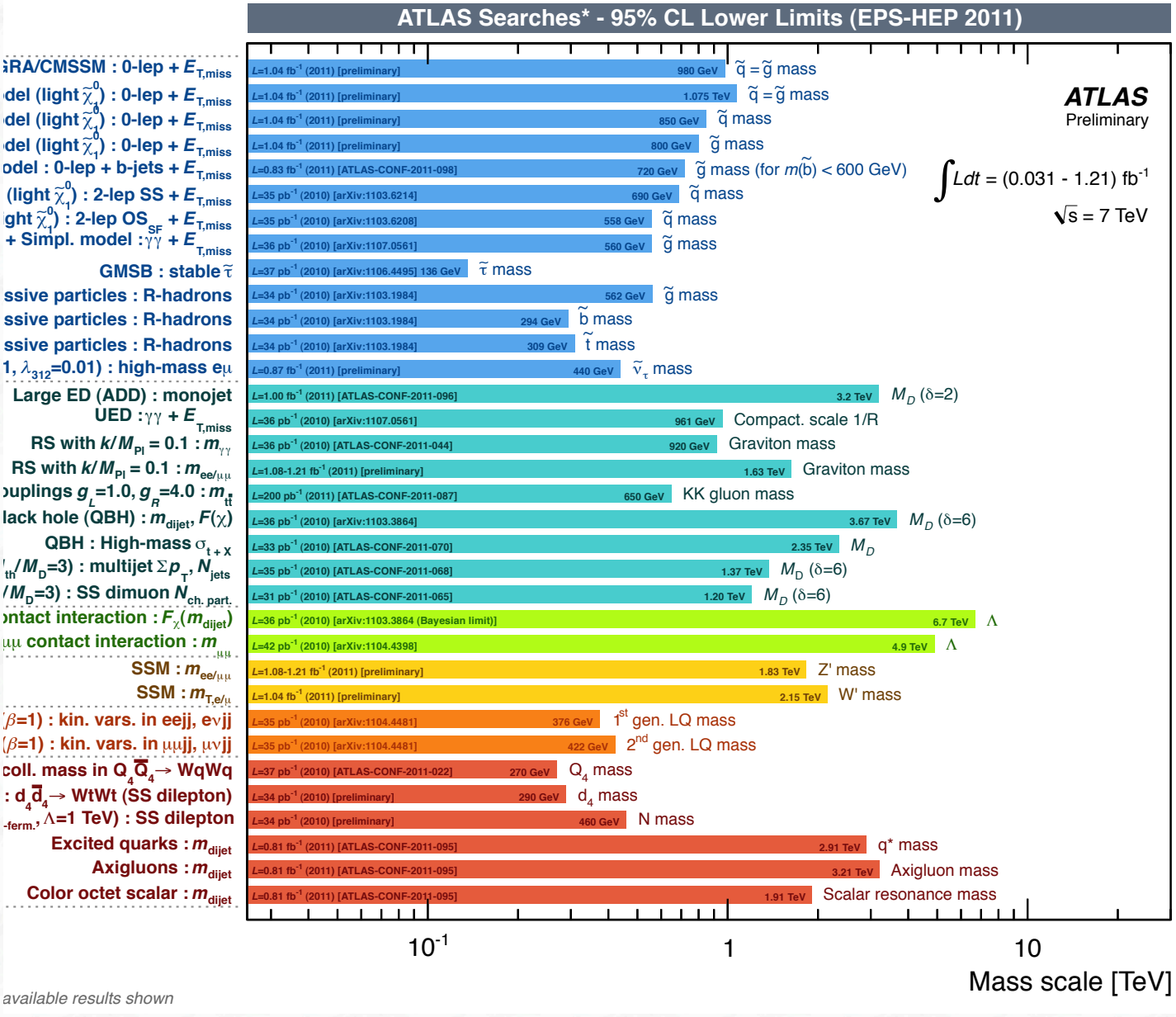




Total transverse energy S_T for events with N > 3, 5, 7 objects

No evidence for excess above the QCD expectations
→ No evidence for the formation of micro Black Holes

Extracted limits (at 95% C.L.) on the excluded cross section times acceptance for $S_T > S_T^{min}$



Summary of results on searches for Physics Beyond the Standard Model in ATLAS in ATLAS