LHC and Tevatron Results (3)

J. Alcaraz (CIEMAT – Madrid)

6th CERN - Latin-American School of High-Energy Physics, Natal 2011

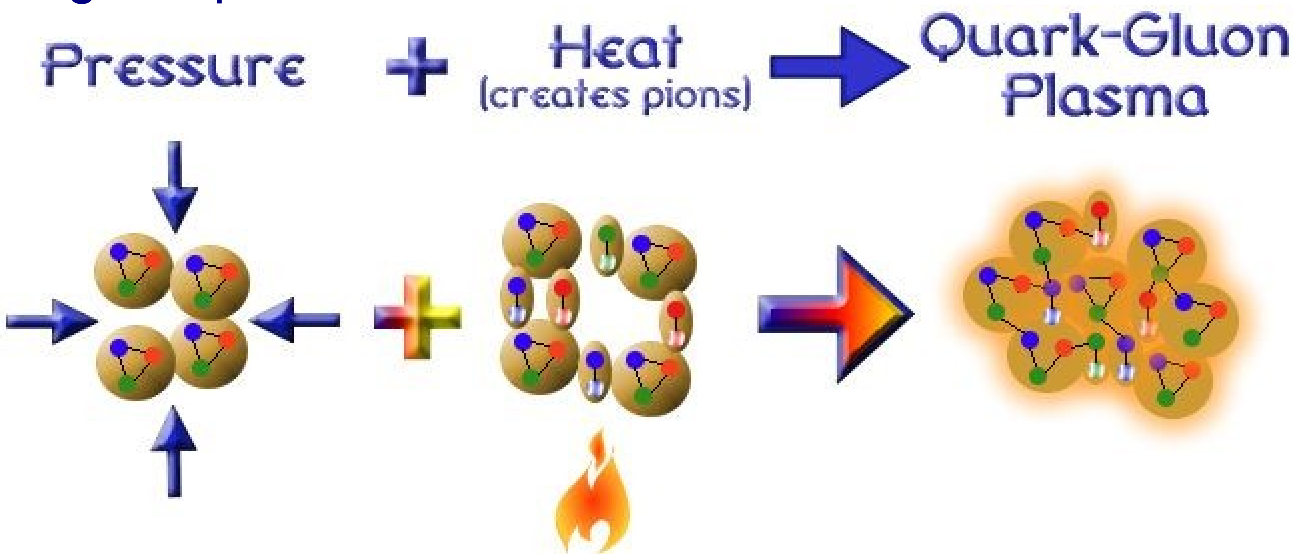
Outline

- Searches at the LHC ans more ...
  - A couple of results from heavy ion collisions
  - Exotica searches
  - SUSY searches
  - Higgs searches
  - The future (2011-2012)

A couple of results from heavy-ion Collisions

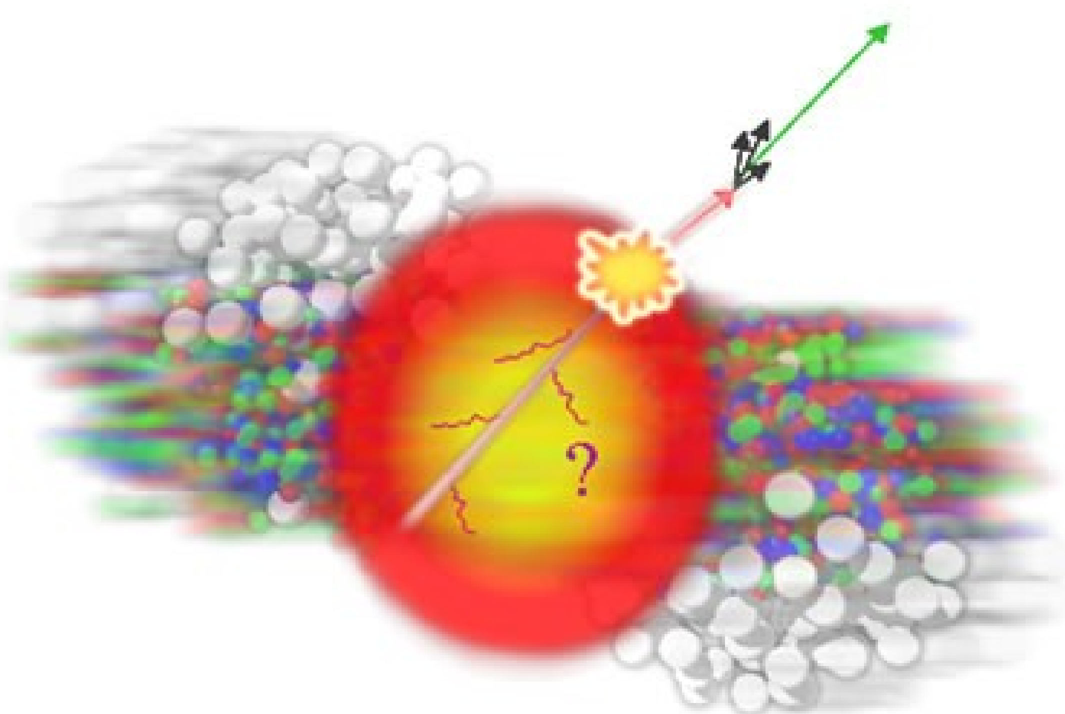
Why Heavy Ion Collisions

- At very high energy densities, heavy ion interactions are not expected to show the products of elementary quark or gluon interactions, but collective effects, probably derived from the production and evolution of a quark-gluon plasma state



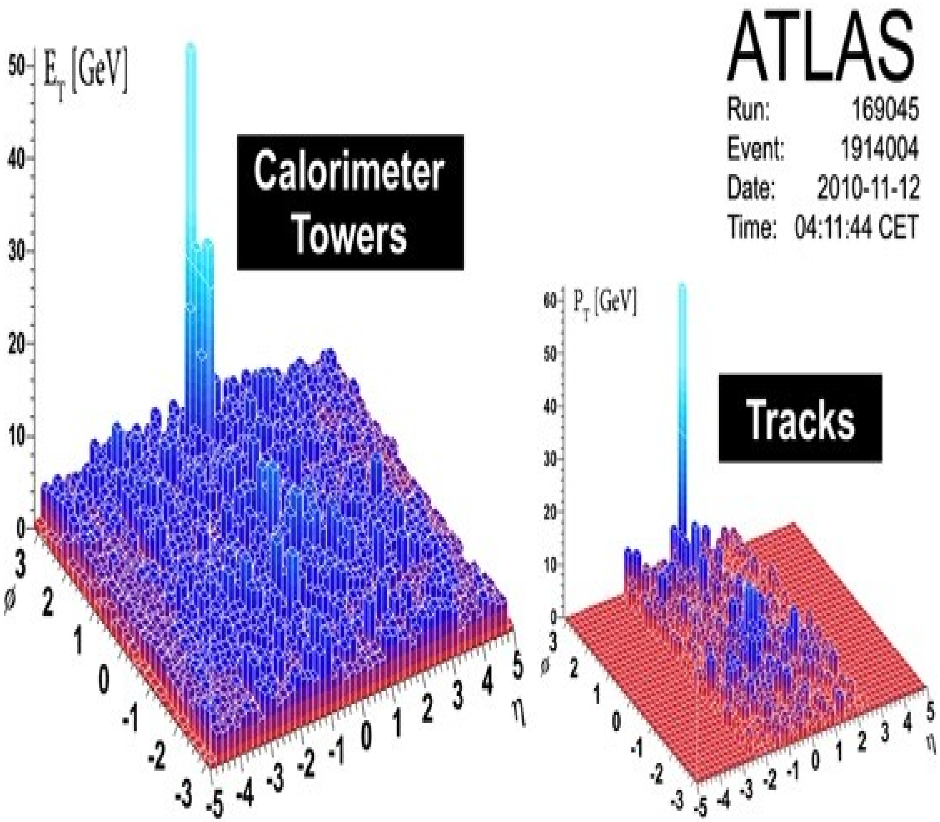
- Due to lack of time, I would only flash a couple of results from ATLAS and CMS:
  - Jet quenching
  - Observation of Z decays in heavy ion collisions

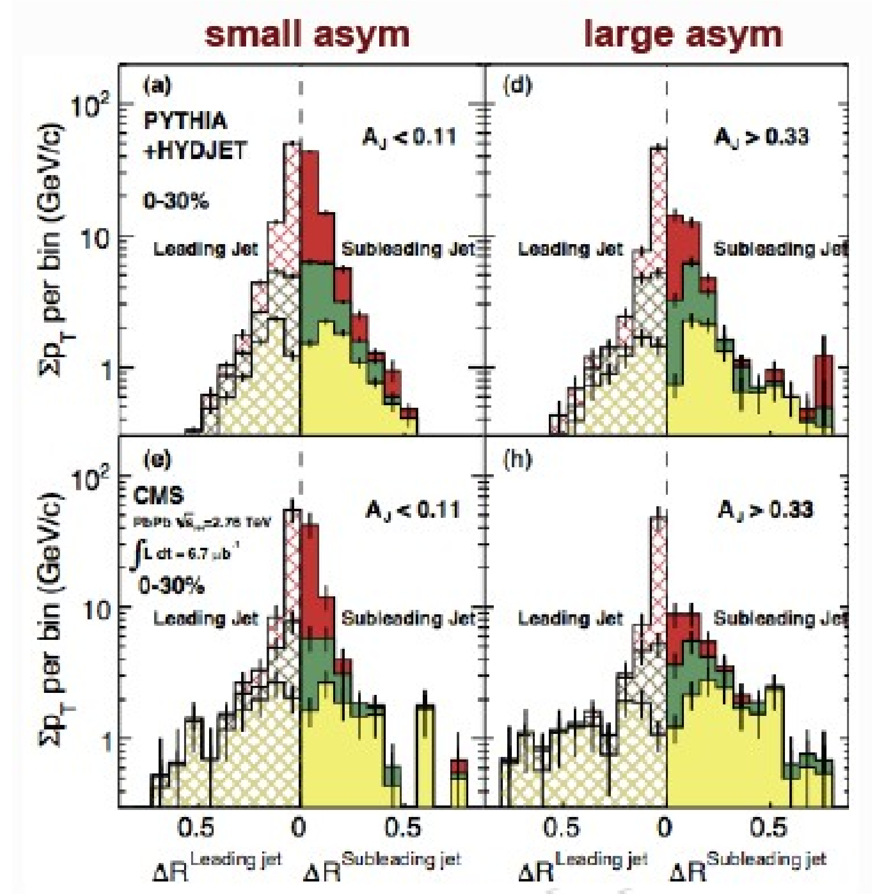
Heavy Ions: jet quenching



- The idea is simple: if there is a sizable QCD plasma, jets produced in hard collisions may suffer QCD “bremssttrahlung”, losing energy
  - It should frequent to see di-jet events in which one of the jets has given a significant part of its energy to the medium

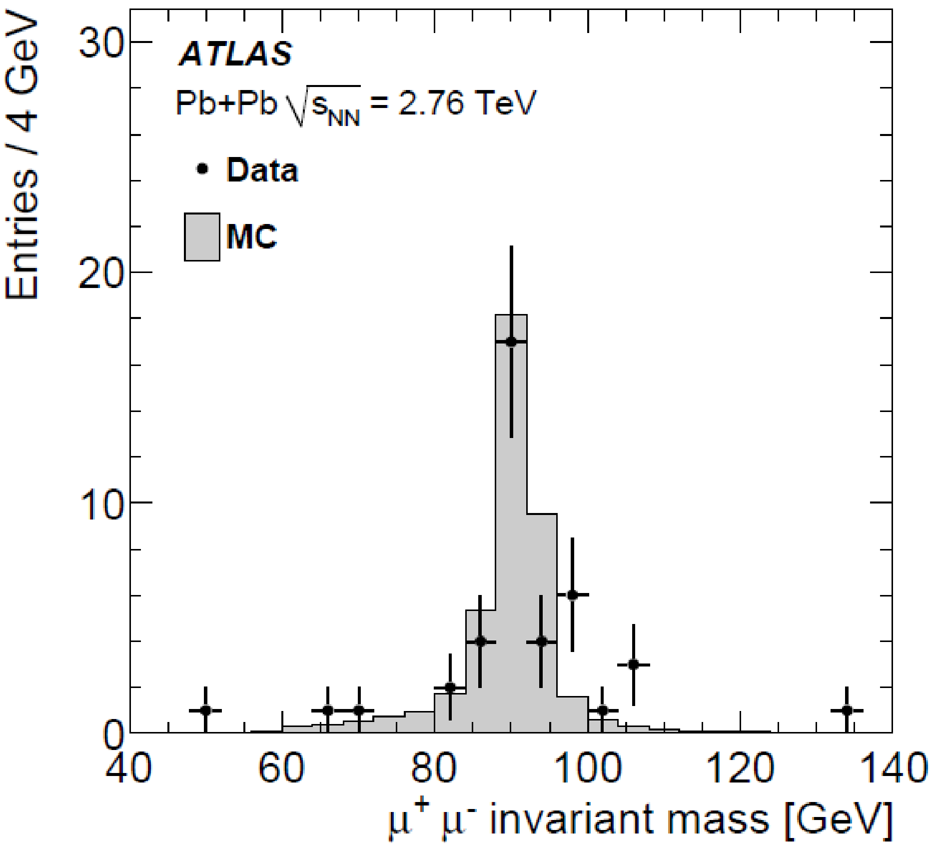
Heavy Ions: jet quenching

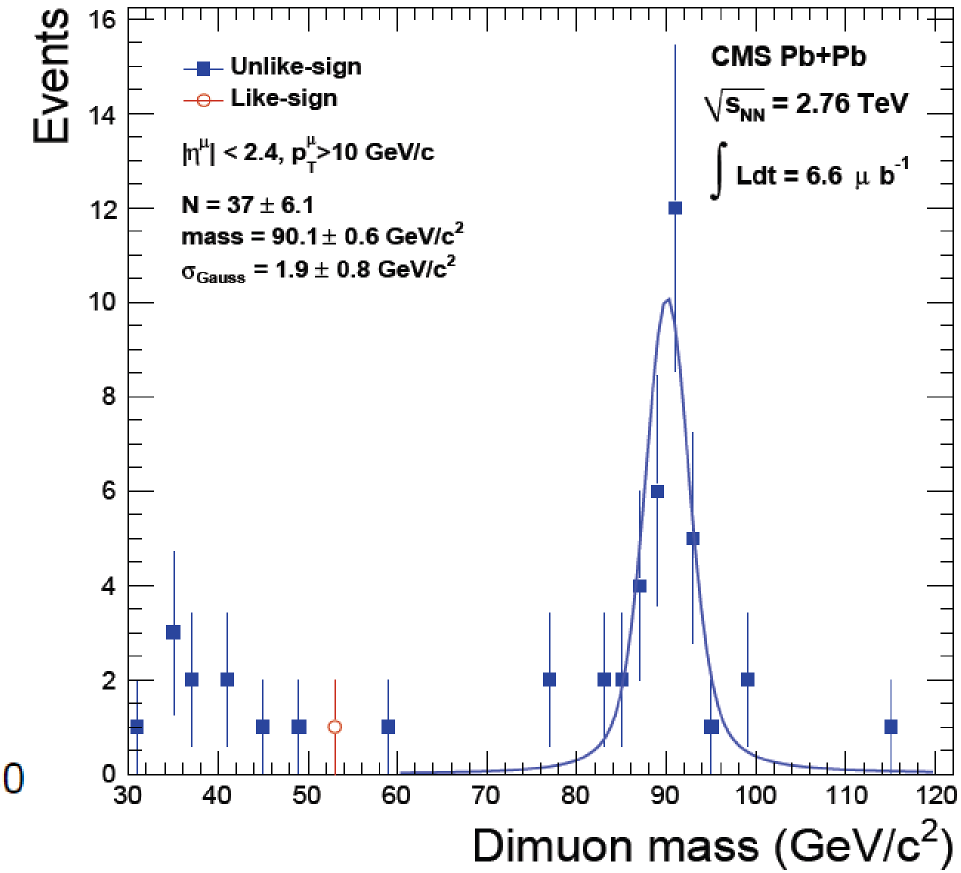




- The effect increases with the centrality of the collision (more head-on collision → more QCD medium to interact with)
- We have also confirmed that the energy of the quenched jet is not lost!

Heavy Ions: Z production





- $Z \rightarrow \mu\mu$ observed for the first time in heavy ion collisions
- This is an important channel, because the Z does not interact with the QCD medium → it could be used for normalization purposes

Exotica

Theory choices and experiment

- The difficulty of choice is really only solved by accumulation of evidence. That means experiment, and there is no substitute for that.
- One might think there could be a substitute if one just follows the theoretical superheroes who eventually led us to the truth.
- By definition, superheroes are so talented that they tend to make major contributions to most of the 'irrelevant' ideas as well.
- So that method doesn't work either. There is no substitute for facts and evidence.

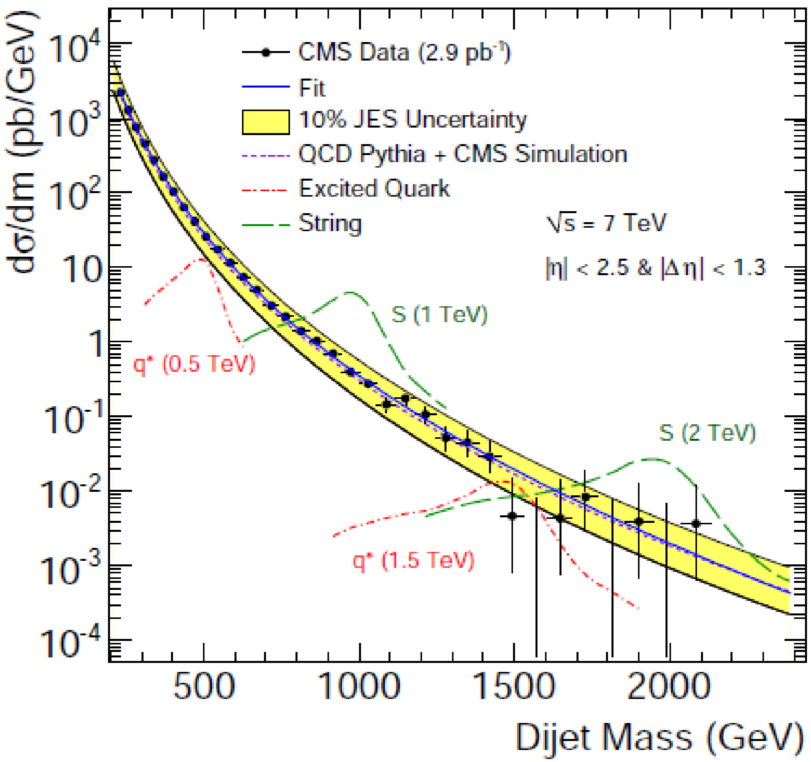
Theory choices and experiment

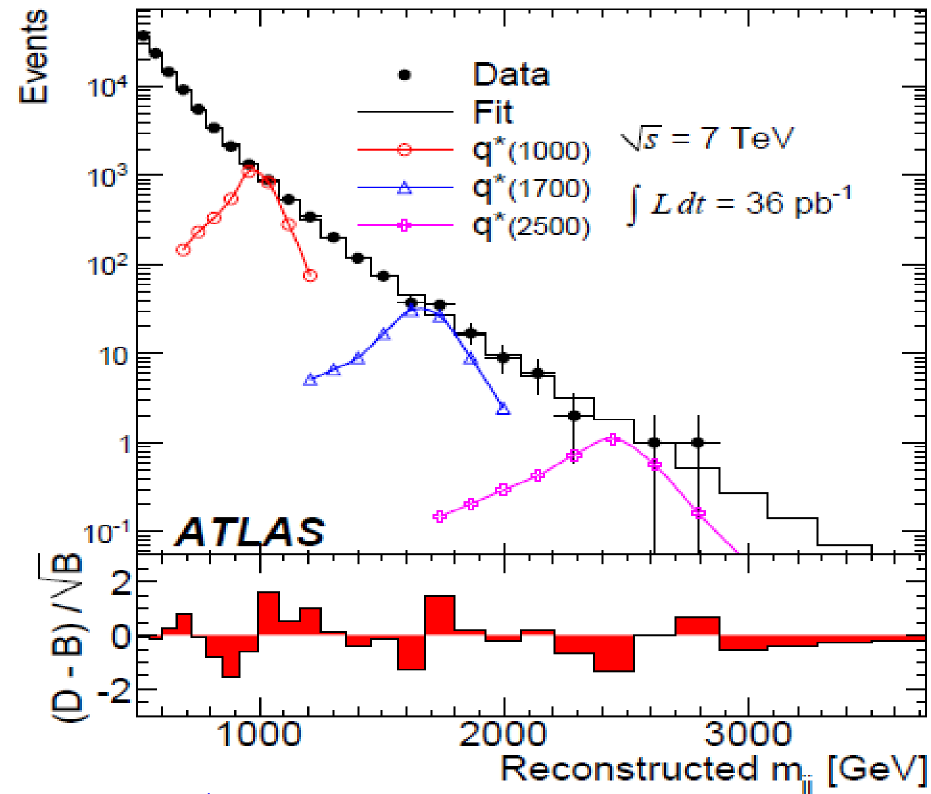
*The difficulty of choice **WAS** really only solved by accumulation of evidence. That means experiment, and there is no substitute for that. One might think there could be a substitute if one just **FOLLOWED** the theoretical superheroes who eventually led us to the truth.[...] By definition, superheroes are so talented that they tend to make major contributions to most of the 'irrelevant' ideas as well. So that method doesn't work either. There is no substitute for facts and evidence.*

J.D. Bjorken, "The November Revolution" (referring to the discovery of the J/Psi particle in Nov. 1974)

LHC physics results: searches

- Jet searches: two ways to observe a convincing signal of new physics in di-jet events:
  - a) Search for unexpected resonant production in di-jet systems



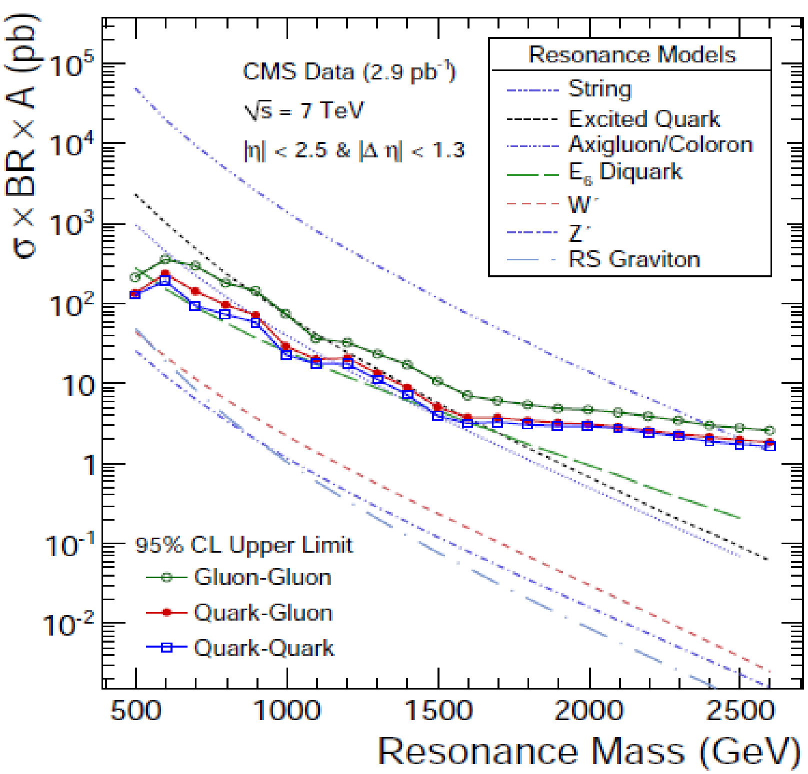


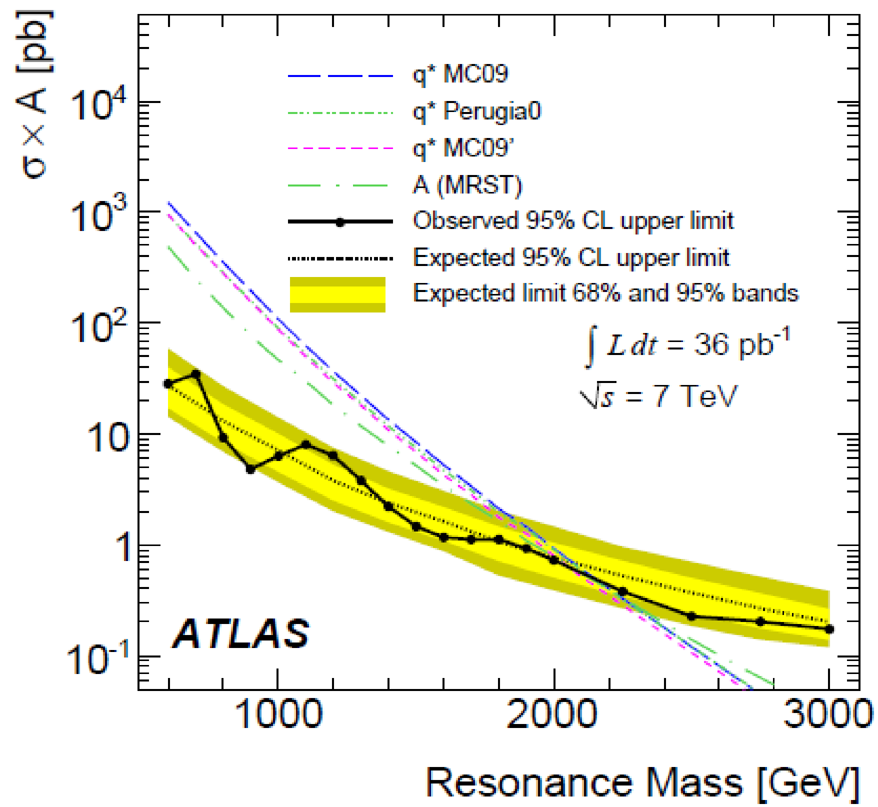
- Here we can see the power of increasing √s. Tevatron limits already superseded by LHC

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CMS physics results: searches

- a) Search for unexpected resonant production in di-jet systems
  - Here the energy reach counts more than the integrated luminosity. A factor of 10 more luminosity (see below) improves excited quark and axigluon limits from 1.5 TeV to 2 TeV (already beyond the Tevatron reach)



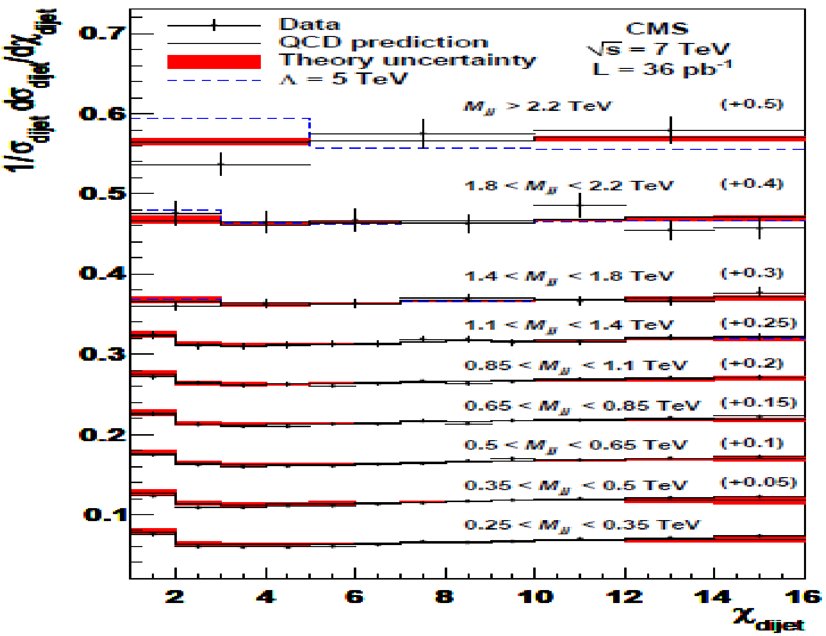


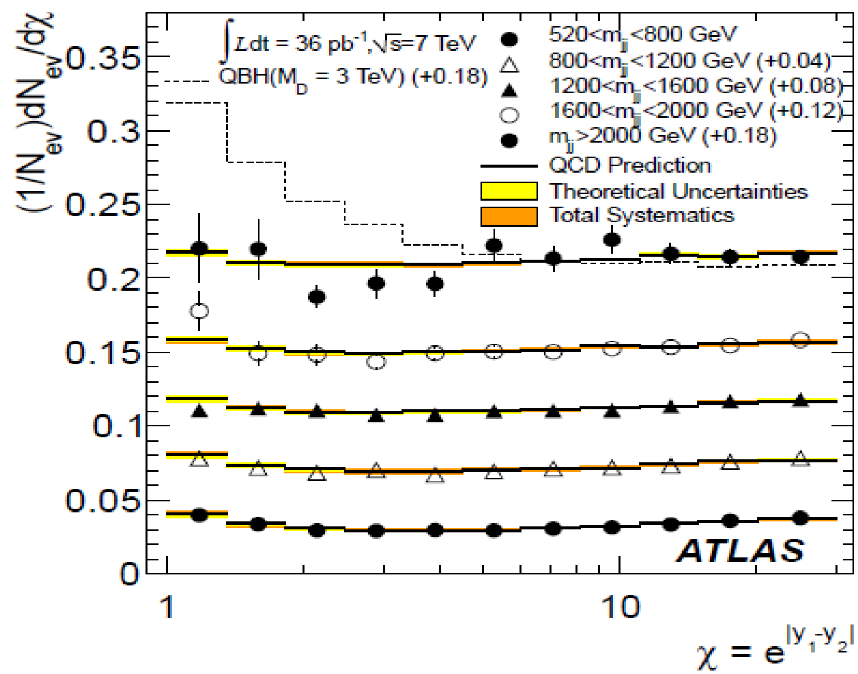
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

LHC dijet searches

- b) Search for an excess of jet production in the central region with respect to non-central region. Build with the two jets the variable χ:

$$\chi = \exp(2y^{*}) \equiv \exp(|y_1 - y_2|); \qquad y_i = \frac{1}{2} \log \frac{E_i + p_{zi}}{E_i - p_{zi}}$$





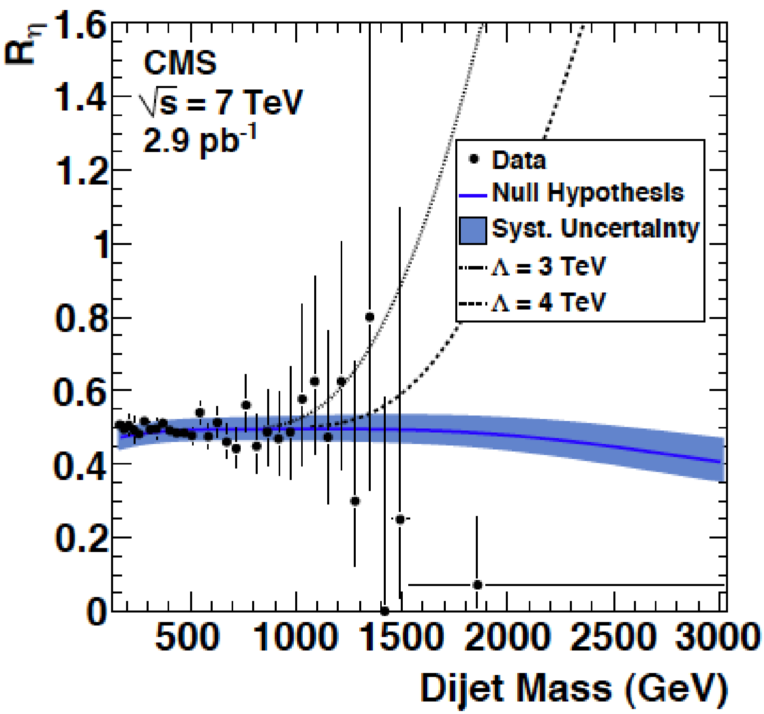
- QCD cross section should be flat as a function of χ (t-channel dominance)
- New physics should manifest at low values of χ (central production)

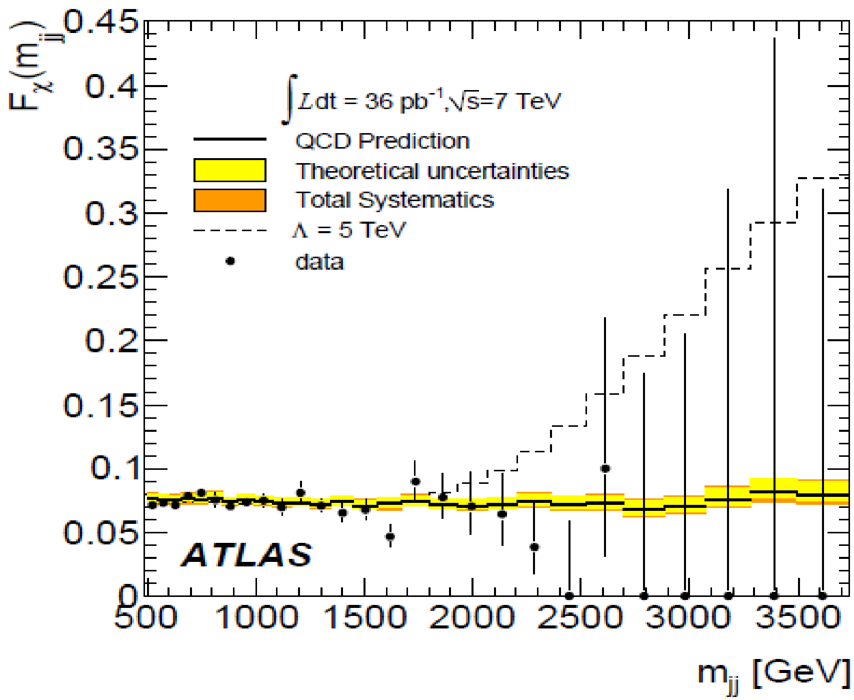
LHC dijet searches

- b) Search for an excess of jet product in the central region with respect to non-central region:

$$R_\eta = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)}$$

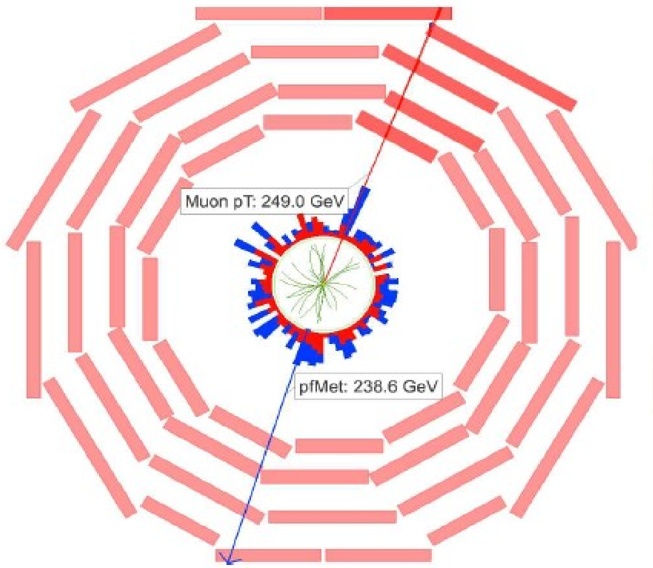
$$F_\chi = \frac{N(|y^*| < 0.6)}{N(|y^*| < 1.7)}$$

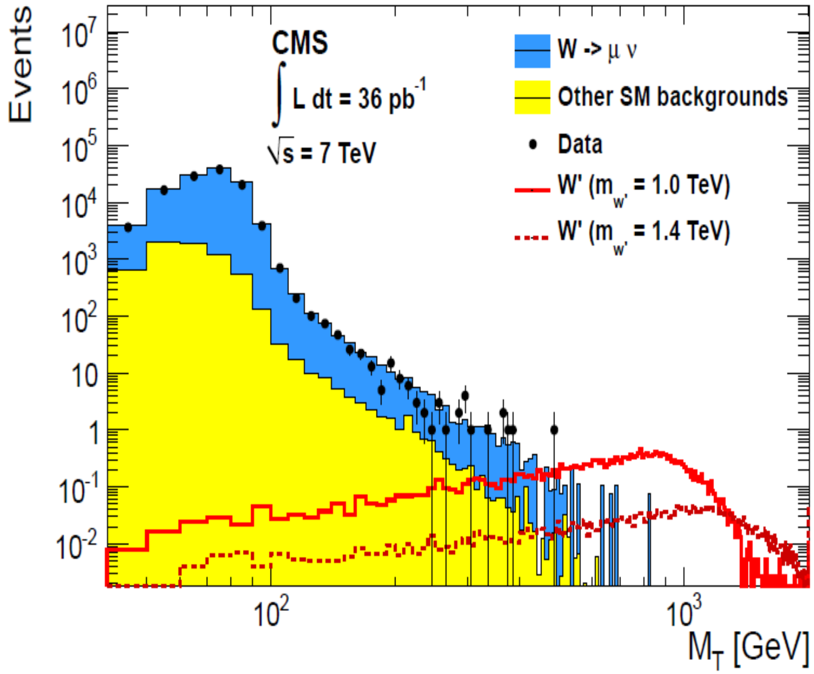




W' searches at LHC

- For the moment, only in leptonic channels: W' → $l\bar{\nu}$:

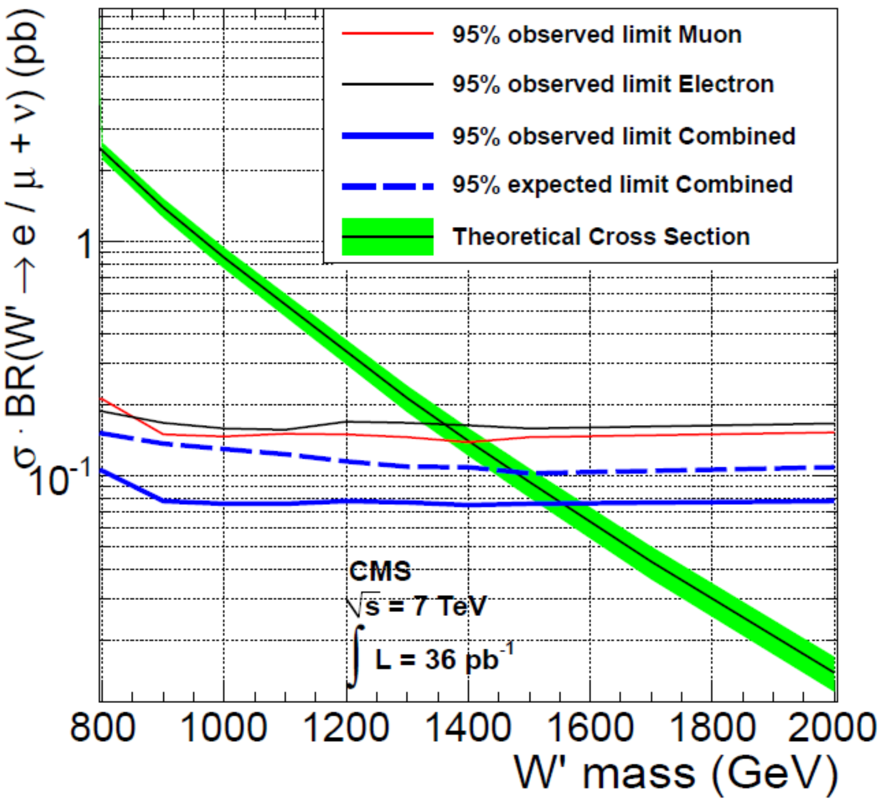


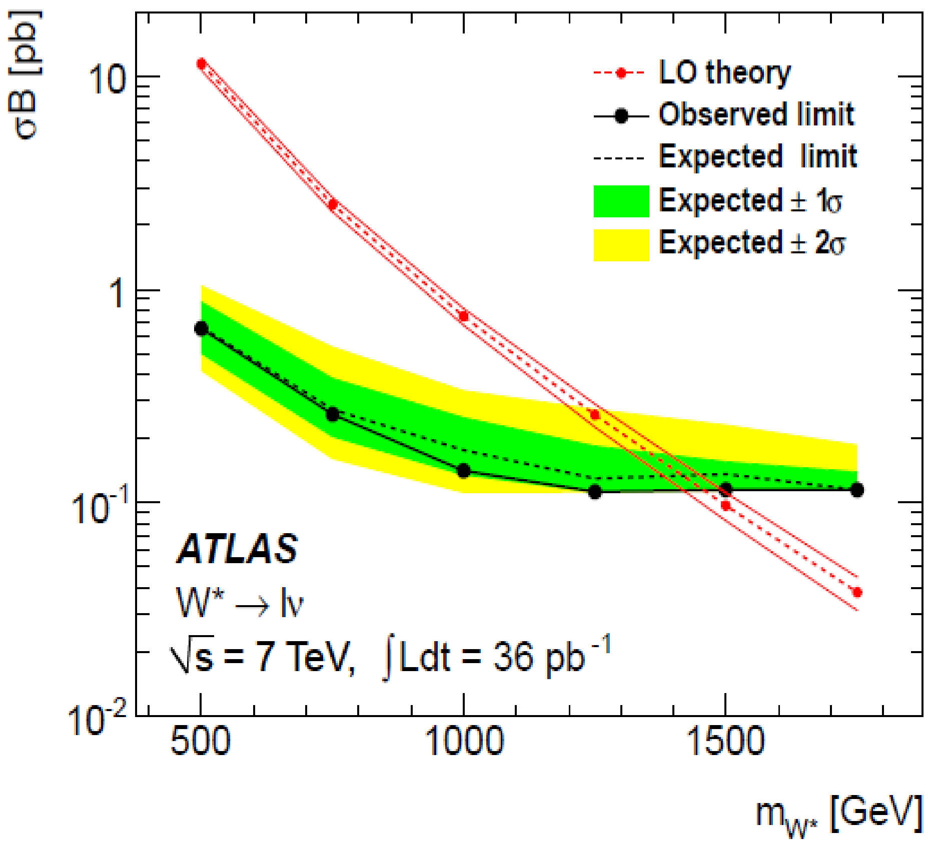


- Basic strategy:
  - Isolated lepton of very high p_T, with high missing E_T opposite to muon (direction+magnitude)
  - Look for 'bumps' in the tail of the missing transverse mass distribution (M_T)
- Key points: good lepton momentum resolution at high p_T, good missing E_T resolution
- Main background: SM W → lν (W highly off-shell)

W' searches at LHC

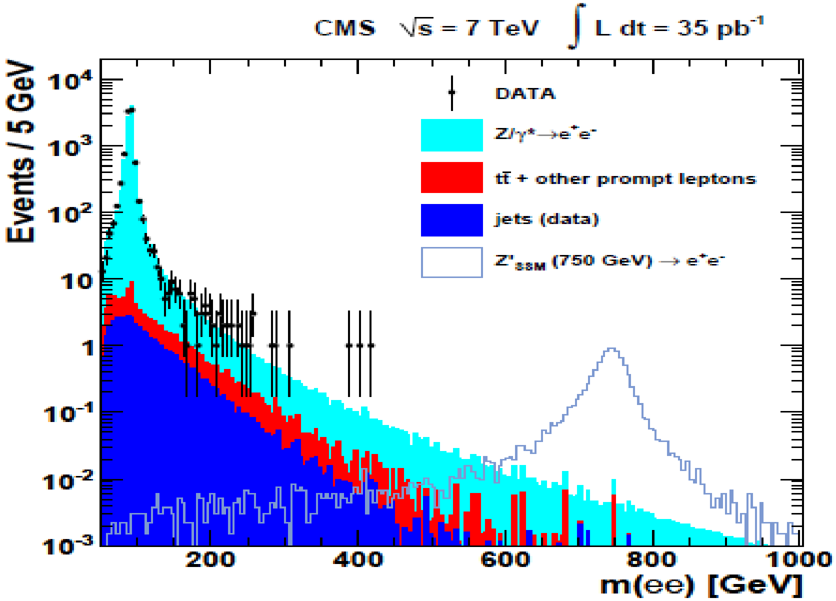
- No W' signal found:
  - m(W') > 1.58 TeV (CMS, best world limit for SM-like W')
  - m(W*) > 1.47 TeV (ATLAS, best world limit for a W' with anomalous magnetic-moment-like couplings to leptons)

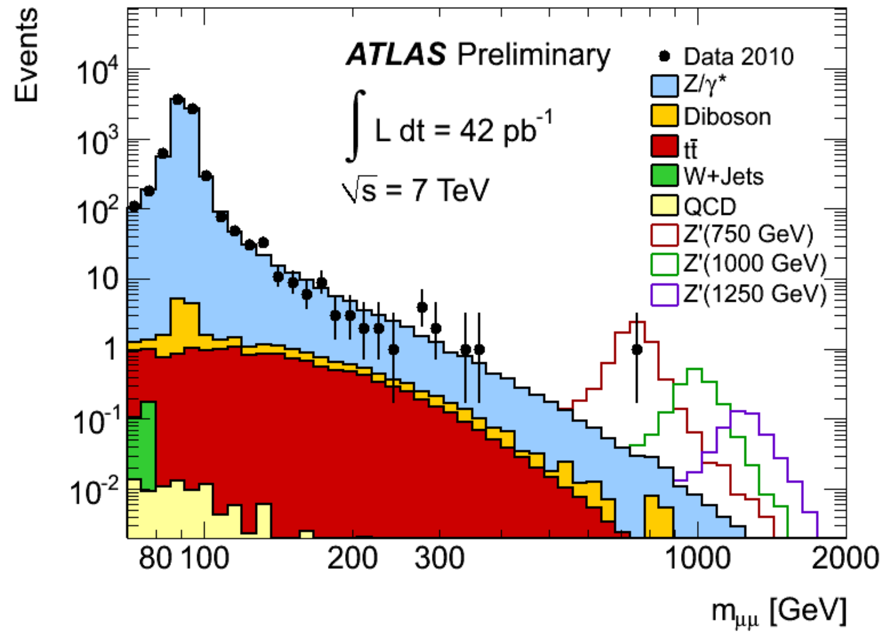




Z' searches at LHC

- Leptonic decay channels, $Z' \rightarrow l\bar{l}$, are excellent due to the good lepton resolution:

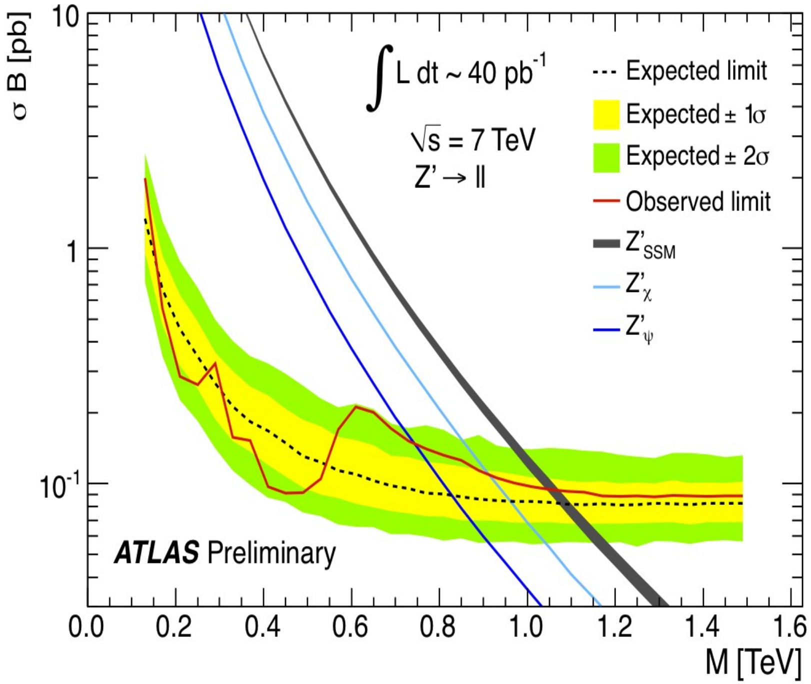


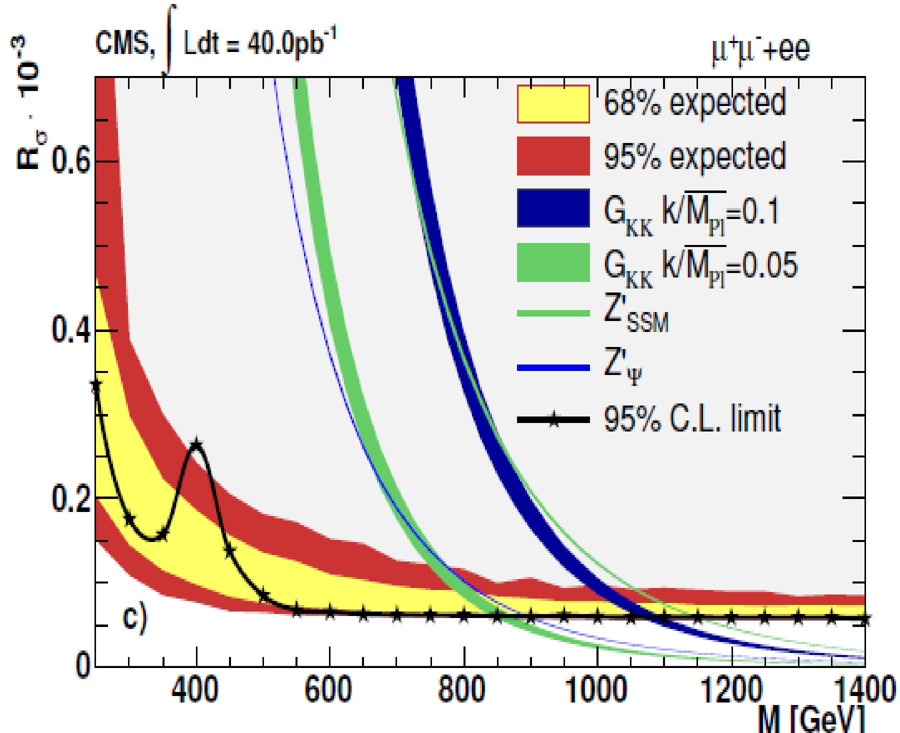


- Basic strategy:
  - Isolated di-leptons of very high p_T
  - Look for 'peaks' in the di-lepton invariant mass
- Key (critical) point: good lepton momentum resolution at high p_T
- Main background: SM $Z \rightarrow l\bar{l}$ (Z off-shell)

Z' searches at LHC

- Again, best world limits on Z's, but a plethora of possible theoretical scenarios with different “left” and “right” lepton couplings to the Z'
- All lower limits in the range 0.8-1.1 TeV, depending on the specific model



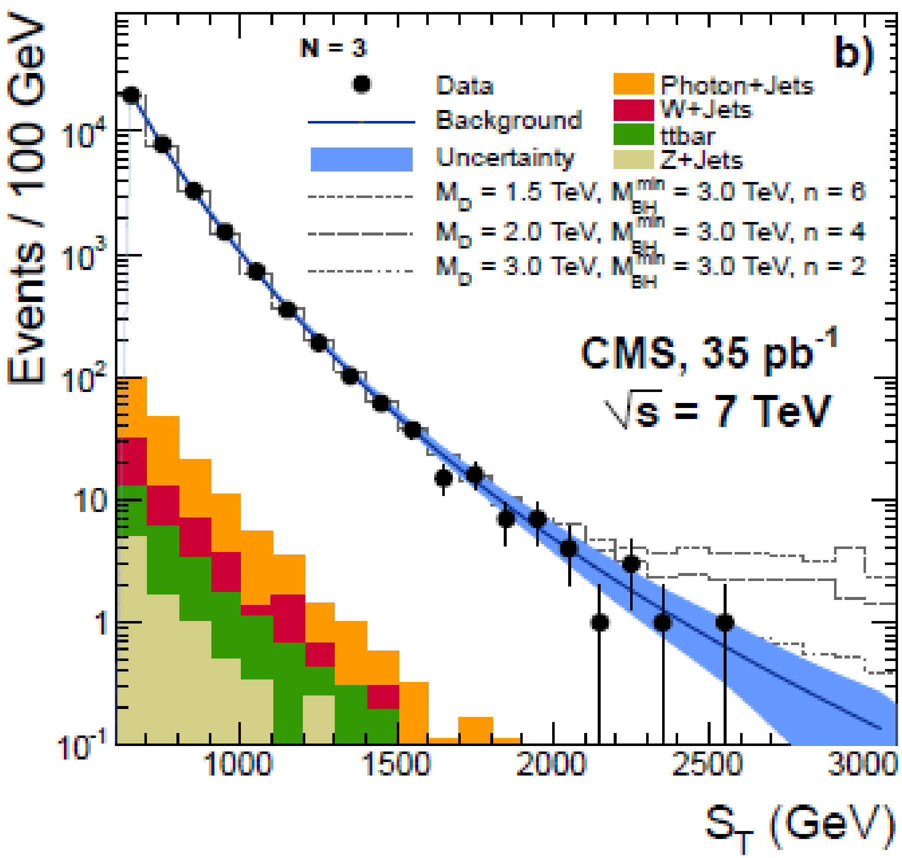


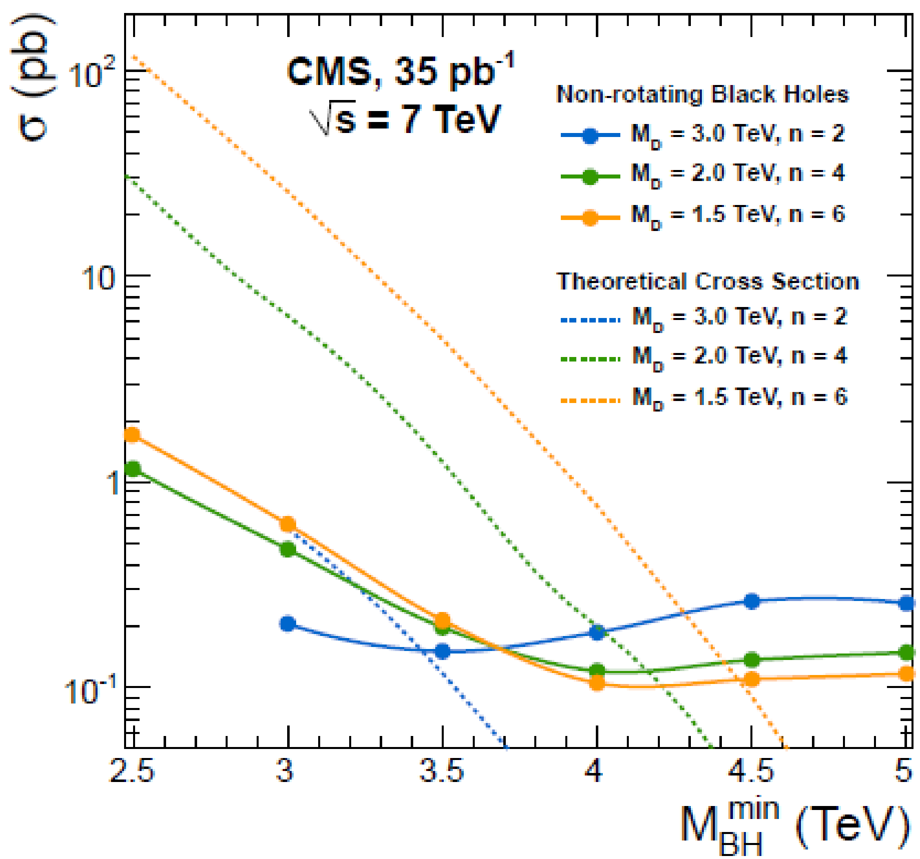
- G_{KK} → Kaluza-Klein graviton excitations
- Z'_{SSM} → Sequential Standard Model (same couplins as SM)
- Z'_{Ψ} , Z'_{χ} → Z' predicted by grand unified theories

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Microscopic black holes at the LHC

- Main signature: huge multiplicity and released energy (mostly balanced)



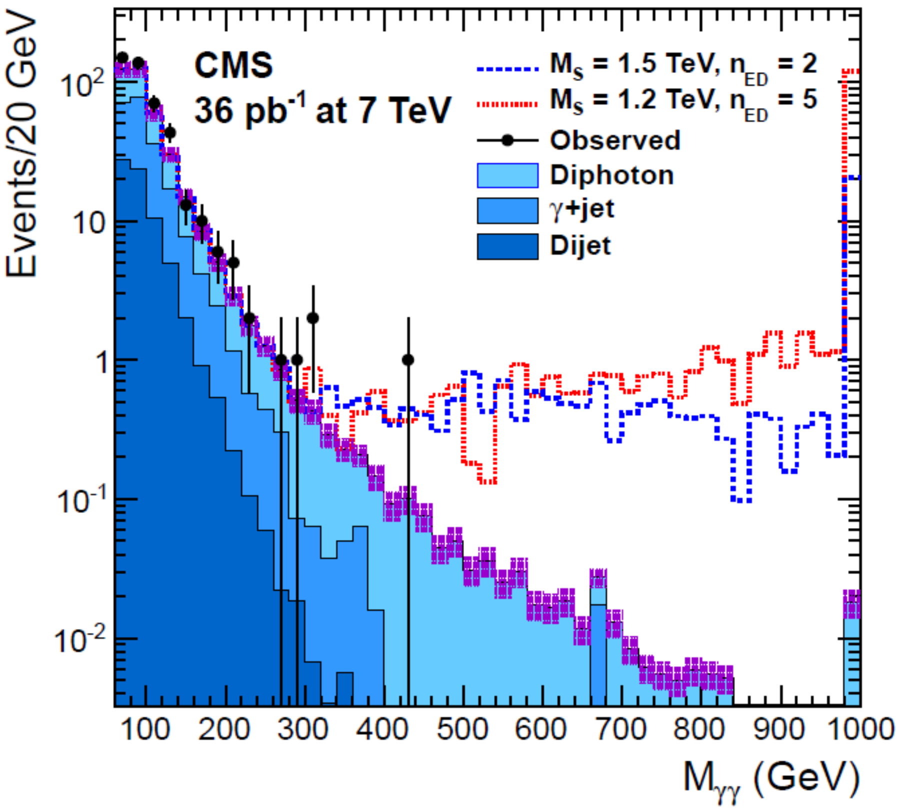


No black holes from gravity at the TeV scale

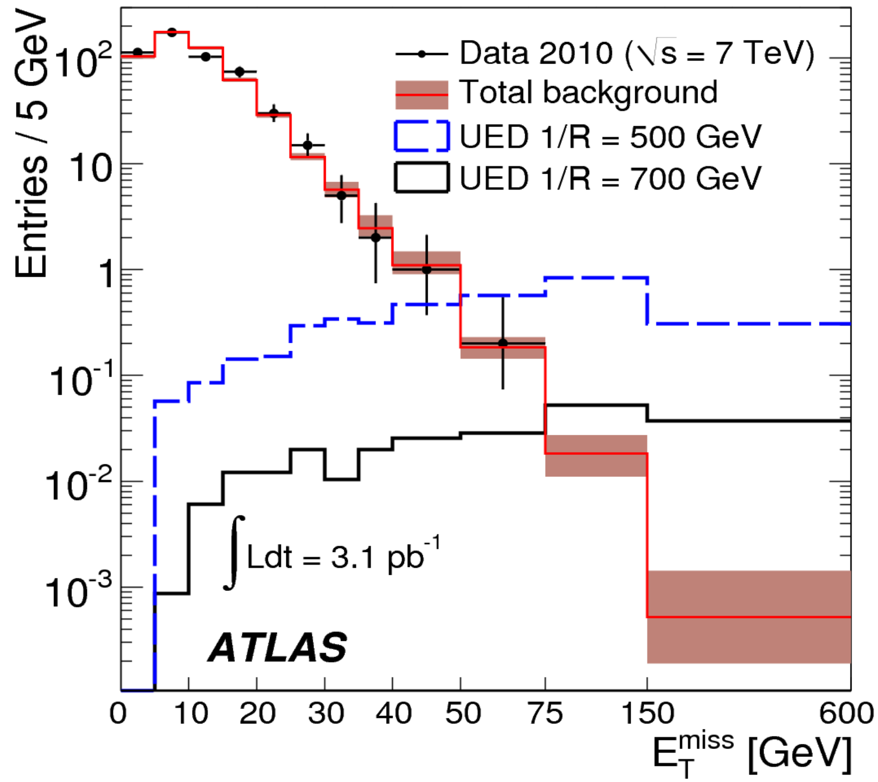
(lower limits on mass in the 3.5-4.5 TeV range)

More searches at LHC

- Now with photons for extra-dimensions ...



Di-photon mass...



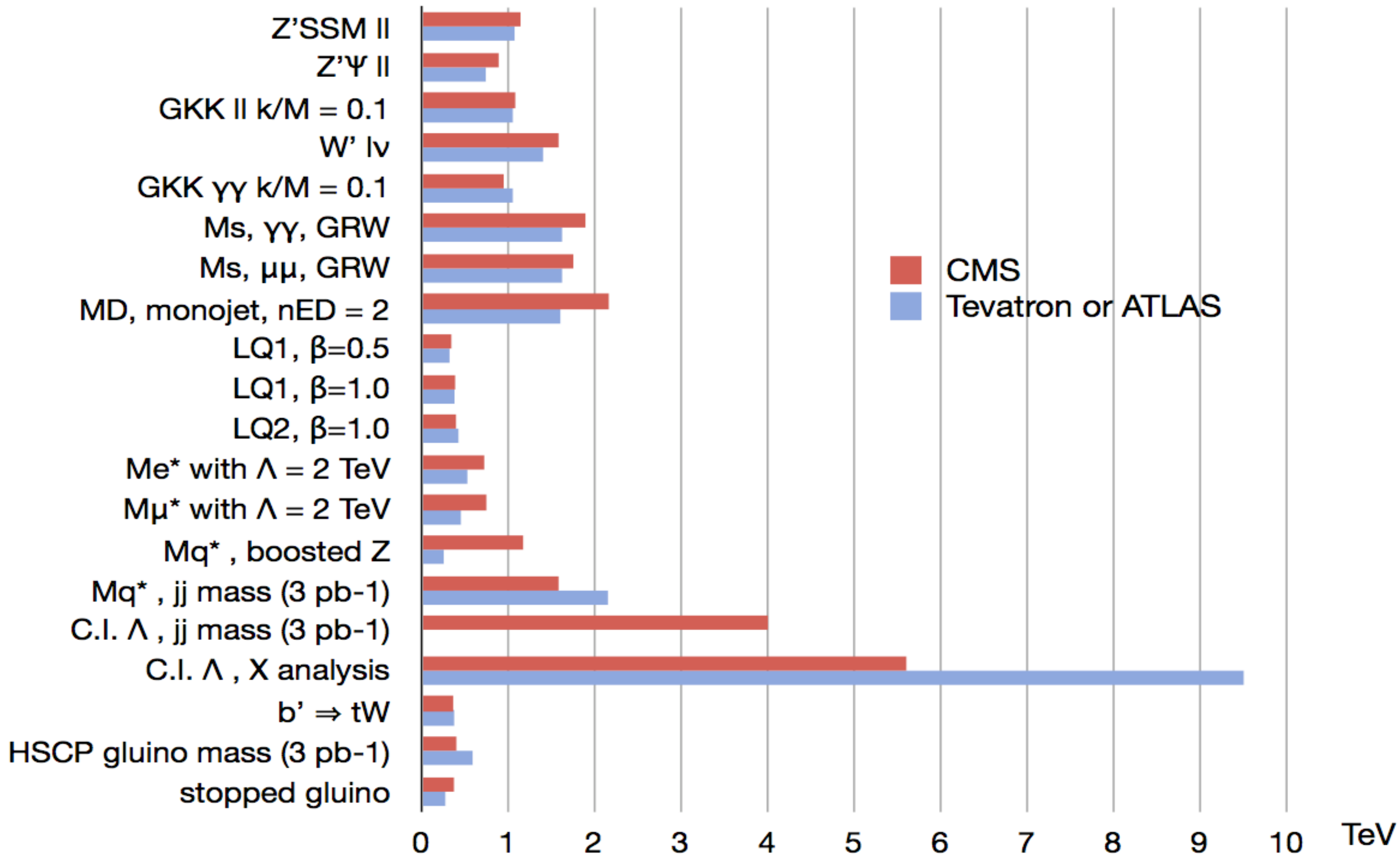
di-photons and missing E_T

Excellent electromagnetic resolution and missing E_T resolution required

Always extending Tevatron limits with present luminosities...

More searches at LHC

- The list of possible searches beyond the SM is almost infinite ...



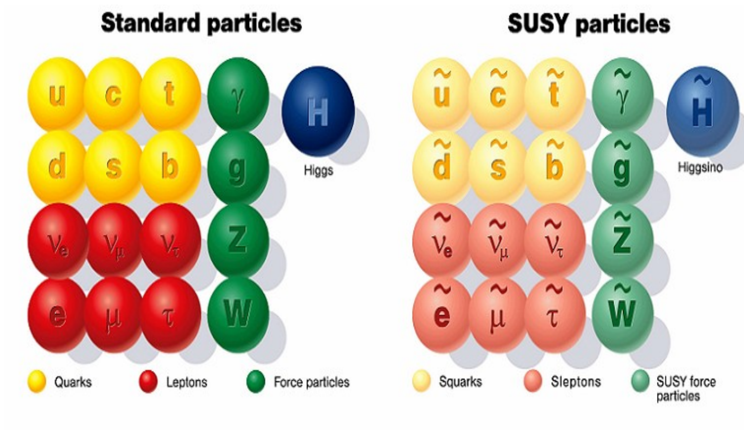
The main message is that we have not found new exotic signals … YET!

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

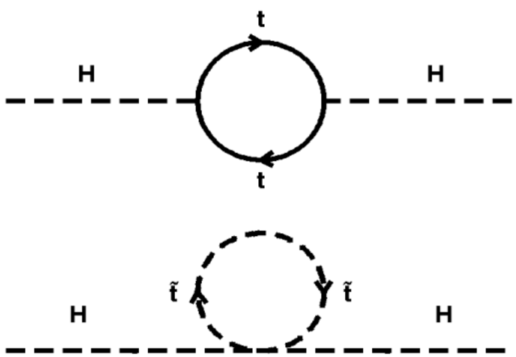
SUSY

SUperSYmmetry

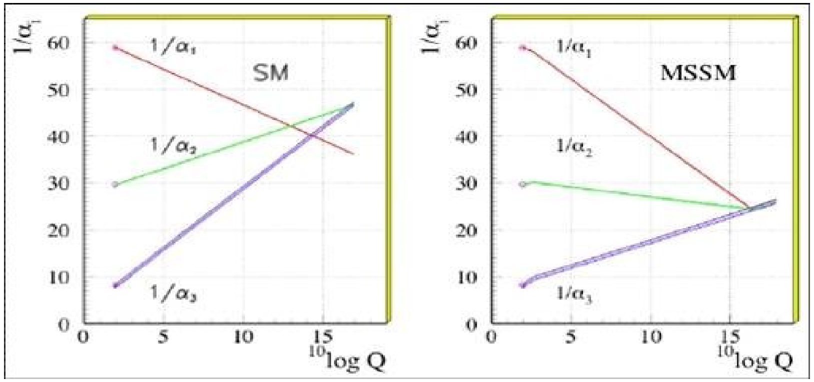
- Super-symmetry is a new symmetry relating bosons and fermions. For each known particle, we expect a super-symmetric partner, of spin differing by 1/2



- Why SUSY at the TeV scale? According to theorists:



Hierarchy problem solved



Natural unification of forces

Dark matter candidate

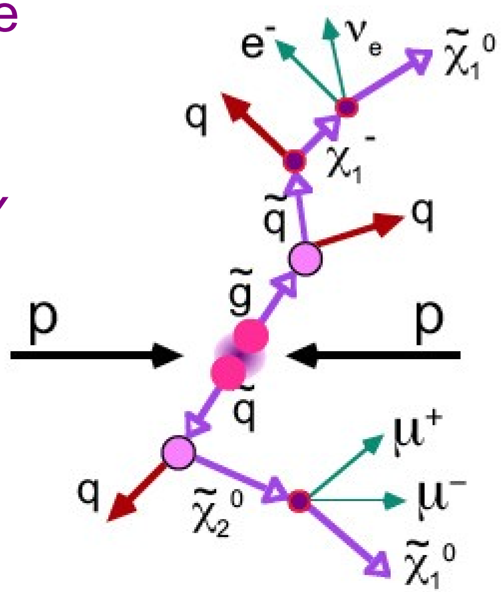
- If found at the LHC: many new particles, couplings and properties to be studied at the TeV scale...

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

SUperSYmmetry

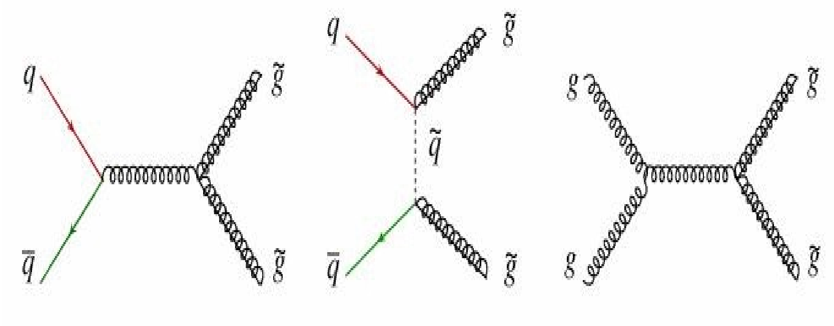
- How does it manifest at the LHC? We have not seen SUSY particles yet, so this new symmetry must be broken and SUSY particles must have masses above the current scale (but not much, to solve the hierarchy problem)

- In most cases (but not all) it will be assumed that at the LHC:
  - We will produce heavy squarks and gluinos via strong couplings. They will decay into lighter SUSY particles (+other SM particles)
  - The lightest SUSY particle is stable (R-parity conservation) and interacts very weakly with matter (dark matter candidate, undetectable)



- From the detector point of view:
  - Long cascade decays with jets and eventually Z, W, leptons, γ
  - Substantial missing E_T

Strategy to search for SUSY at LHC



- SUSY has many parameters (>100):
  - We know the gluino and squark cross sections, given their mass
  - But the subsequent cascade depends too heavily on those parameters and mass differences
- We want to find SUSY if existing. So, to be more independent on parameter choices, we focus on generic signatures:

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

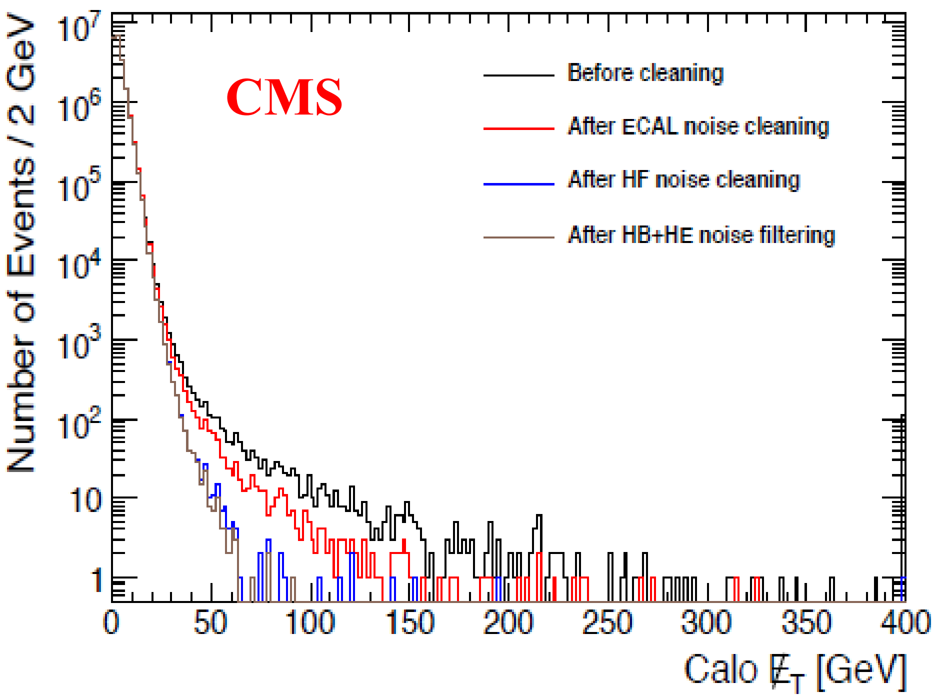
Large SM backgrounds Low

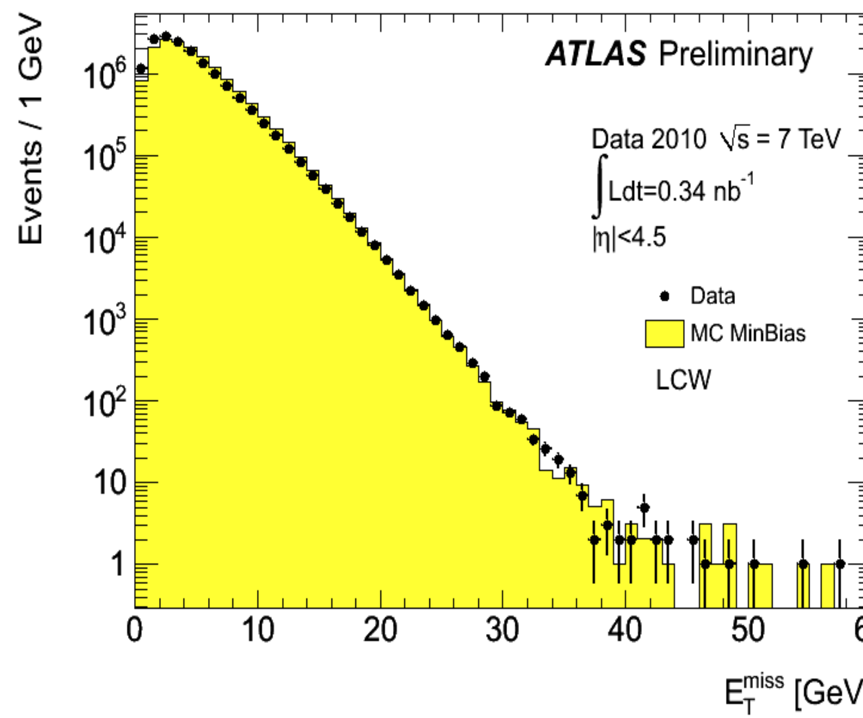
sensitivity to strongly produced SUSY

sensitivity to gauge-mediated SUSY

SUSY at LHC: jets and missing E_T

- An excellent jet resolution and an excellent missing E_T resolution are a MUST for SUSY searches. Both ATLAS and CMS have them, but this required some extra effort:

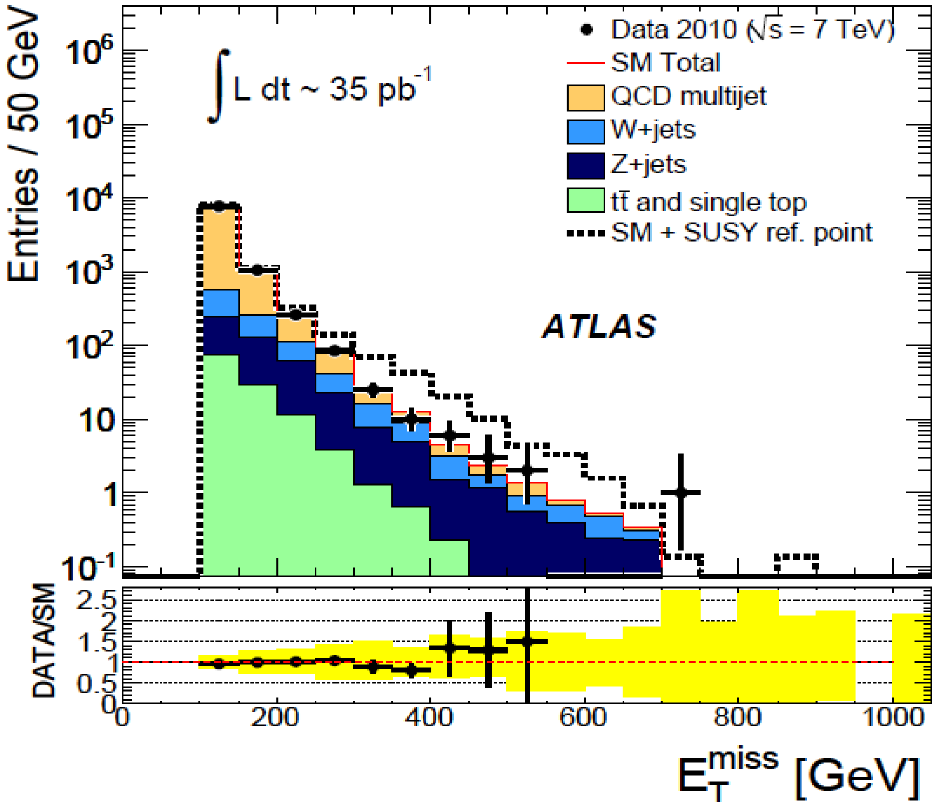


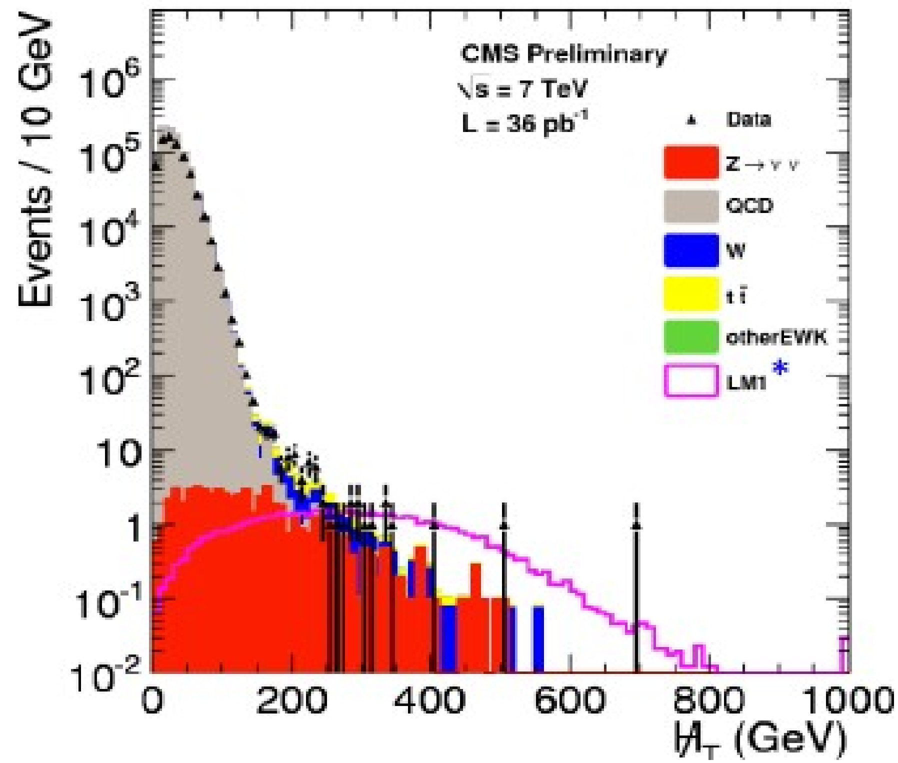


- This is more challenging that what it seems. Having a well calibrated missing ET from (almost) the start was a very optimistic scenario !!

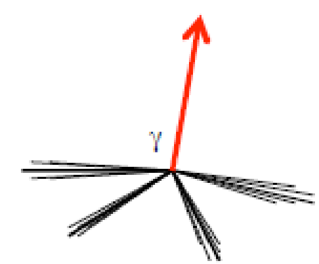
SUSY results: hadronic + missing E_T

- Here we concentrate on final states with just jets and substantial missing E_T



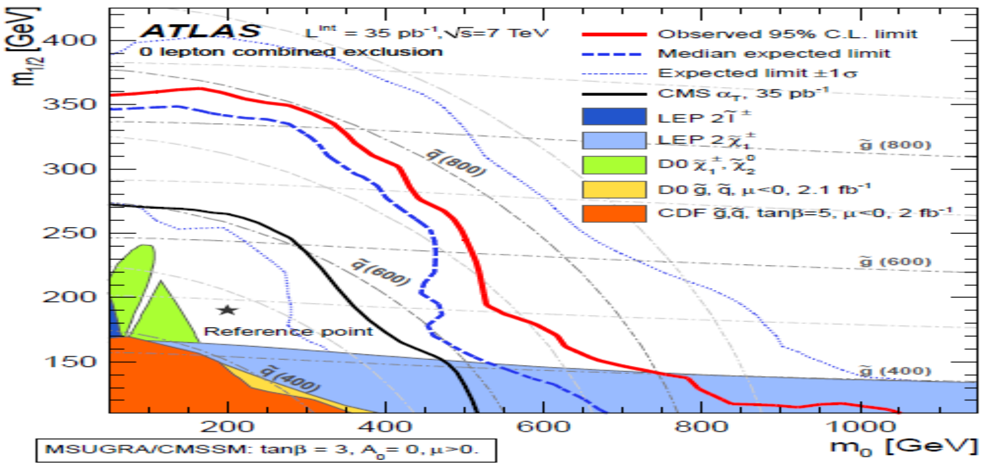


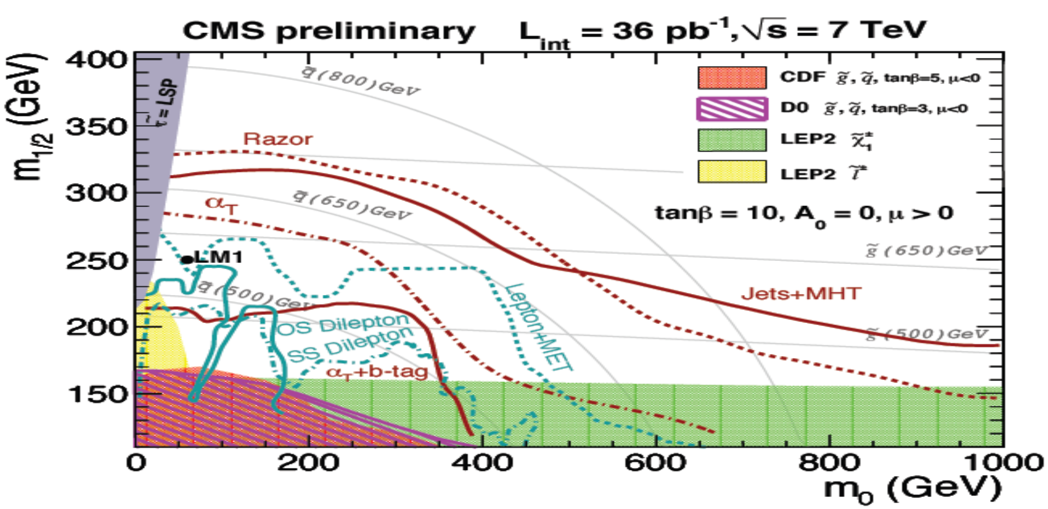
- The detector resolution is so good that the key backgrounds are backgrounds that have intrinsic missing E_T (W+jets, $\nu\nu$+jets, top).
  - They are determined from control samples in data



SUSY results: hadronic + missing E_T

- We do not see any significant excess yet. We therefore set limits in some benchmark SUSY scenarios:





- Sensitivity already much beyond Tevatron reach !!

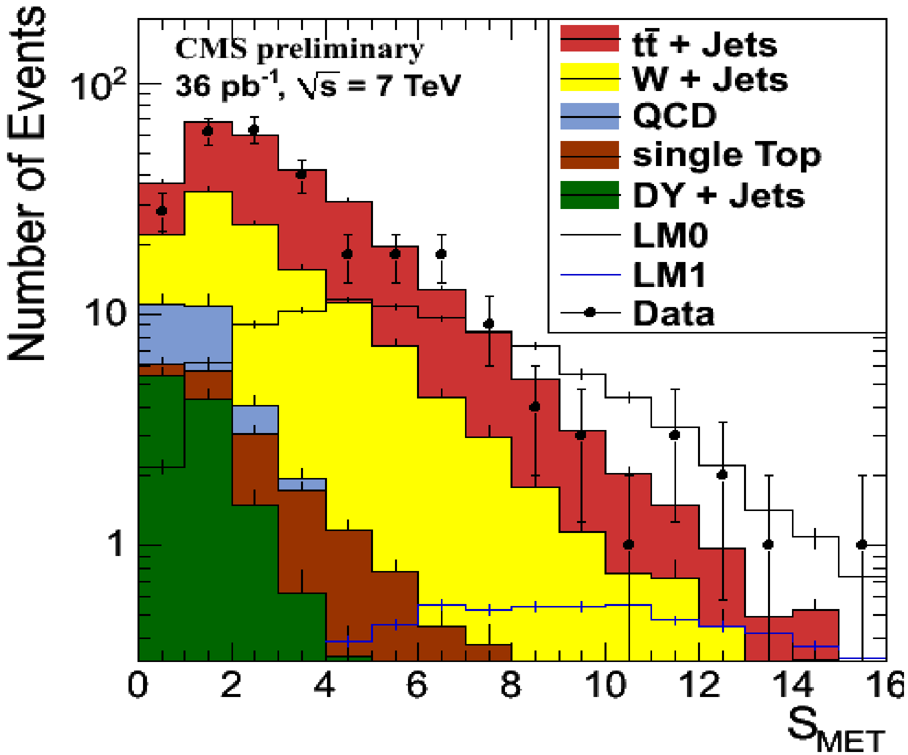
- In this benchmark model, squark masses below ≈ 700 GeV are excluded

A few details on the model:

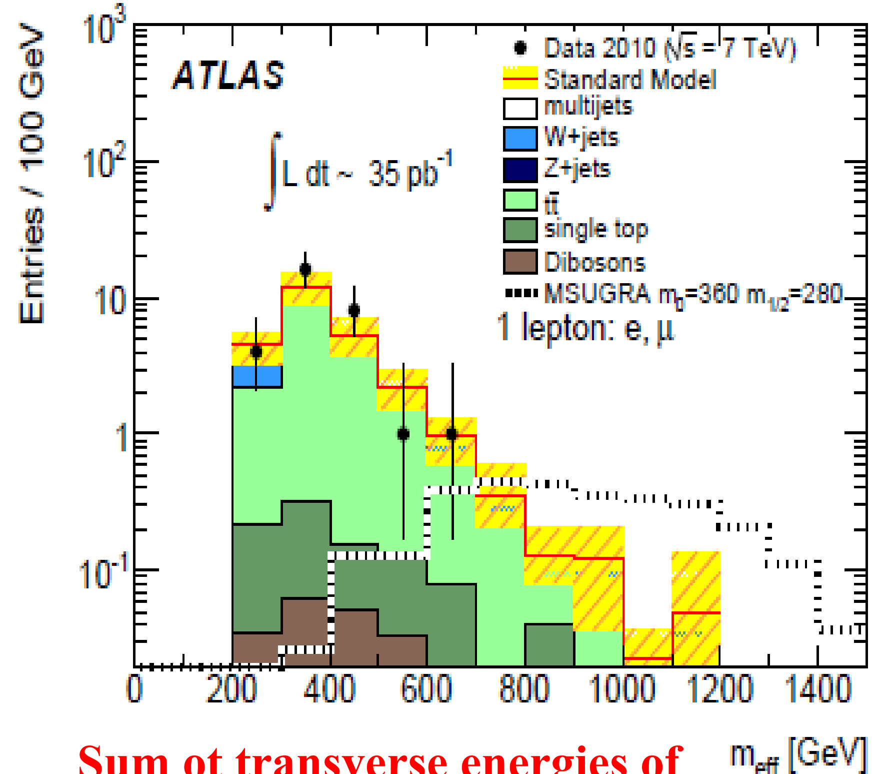
- Gravity mediated SUSY breaking
- m_0: mass of SUSY scalar sector
- $m_{1/2}$: mass of SUSY fermion sector
- tanβ: ratio of vacuum expectation values of the two Higgs fields
- A_0: trilinear couplings
- μ: Higgs bilinear coupling

SUSY results: had. + lepton + missing E_T

- This channel is cleaner, but the background composition is different



MET significancce



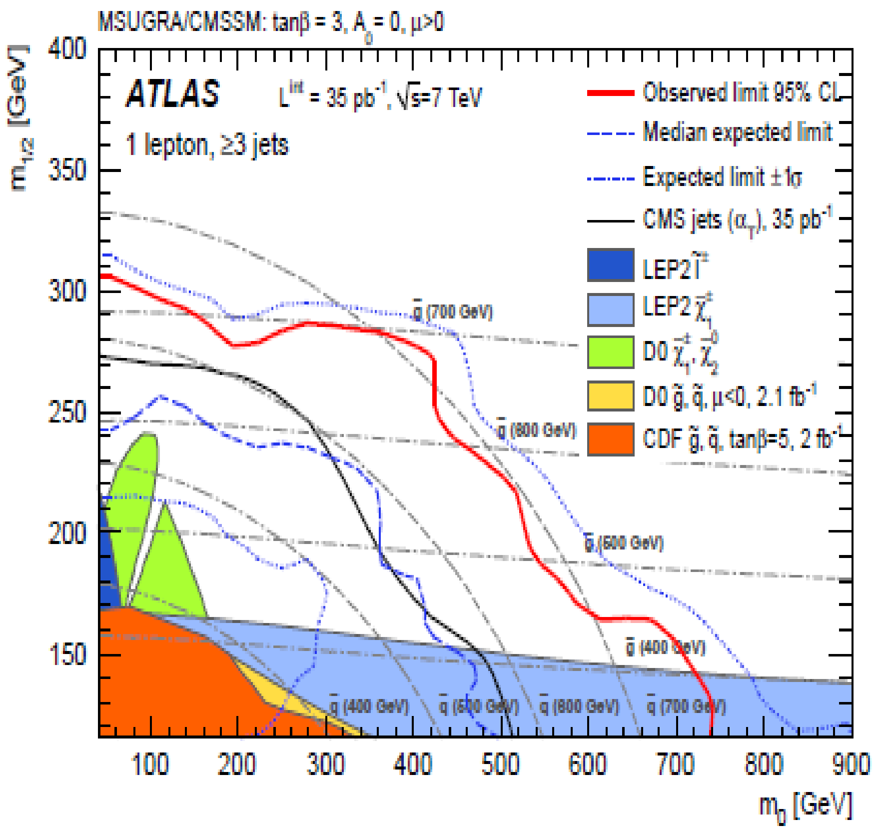
Sum ot transverse energies of jets+lepton+MET

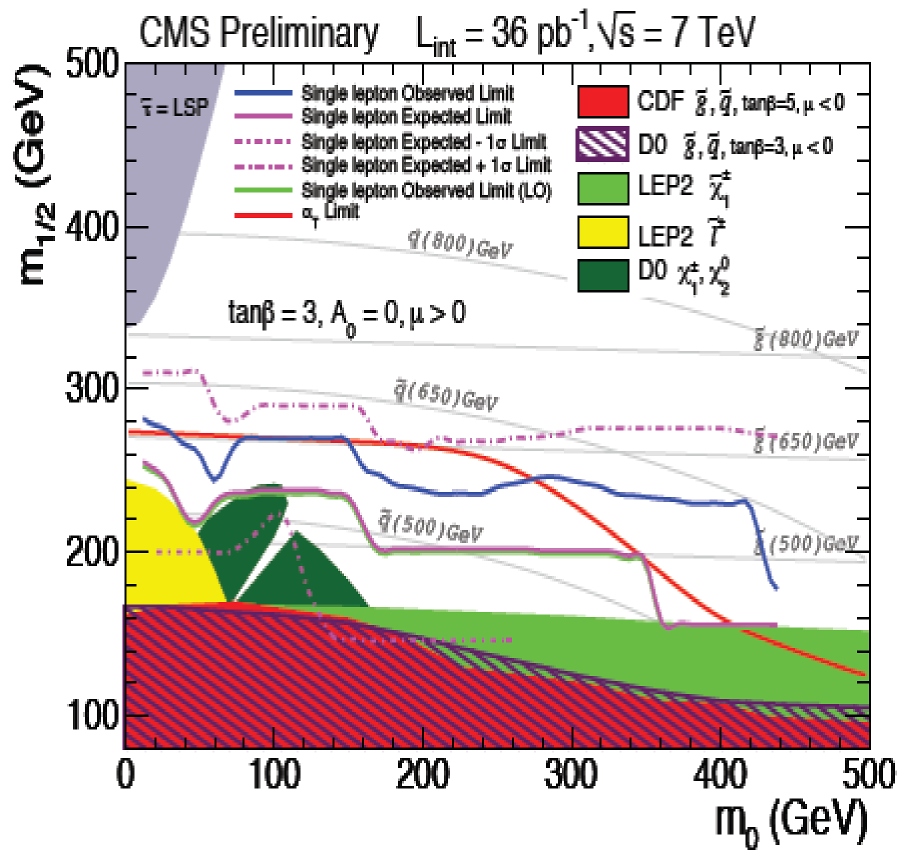
- W+ jets and top are the key backgrounds (as expected, since we are looking for high-p_T leptons, jets and missing E_T)
  - Again, control regions in data are used to understand these backgrounds

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

SUSY results: had. + lepton + missing E_T

- We do not see any significant excess yet. We therefore set limits in some benchmark SUSY scenarios:



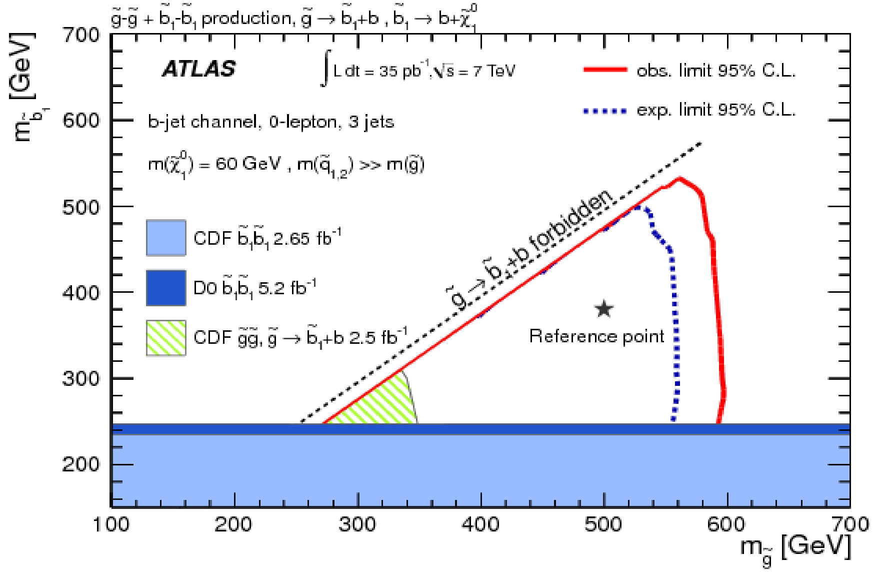


- Again, sensitivity well beyond Tevatron limits

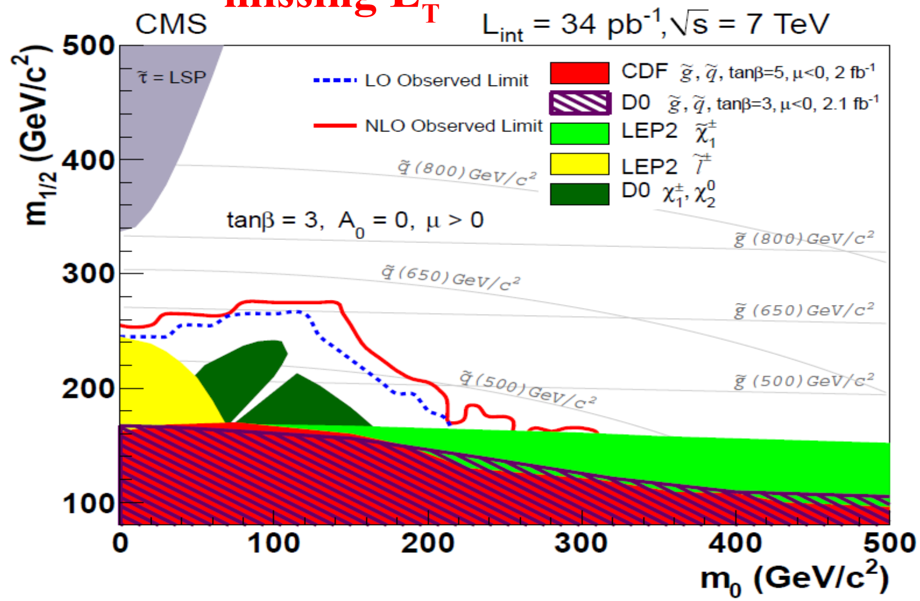
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

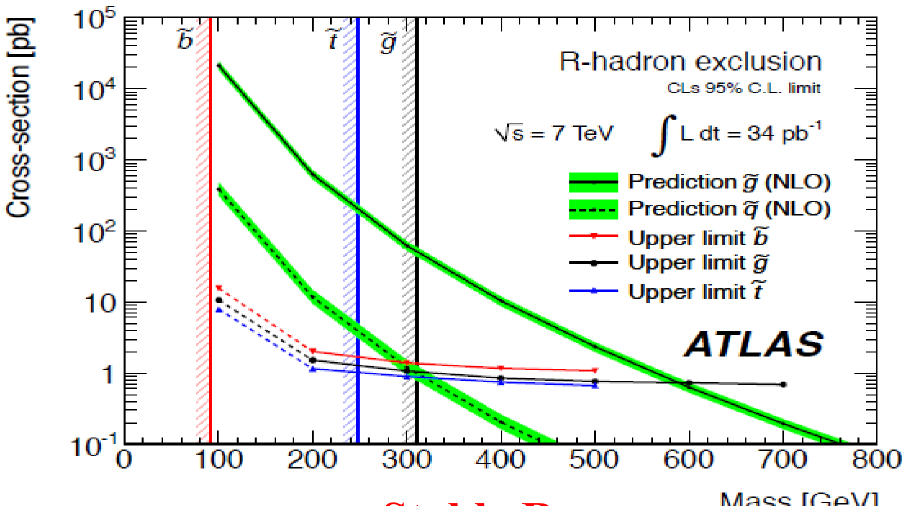
Many other world-best SUSY results at LHC...

B-jet + missing E_T

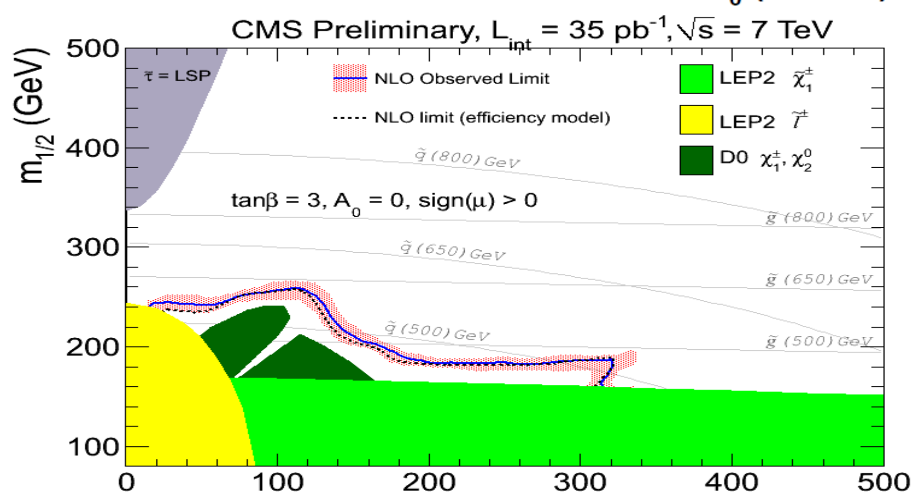


Opposite-sign leptons + missing E_T





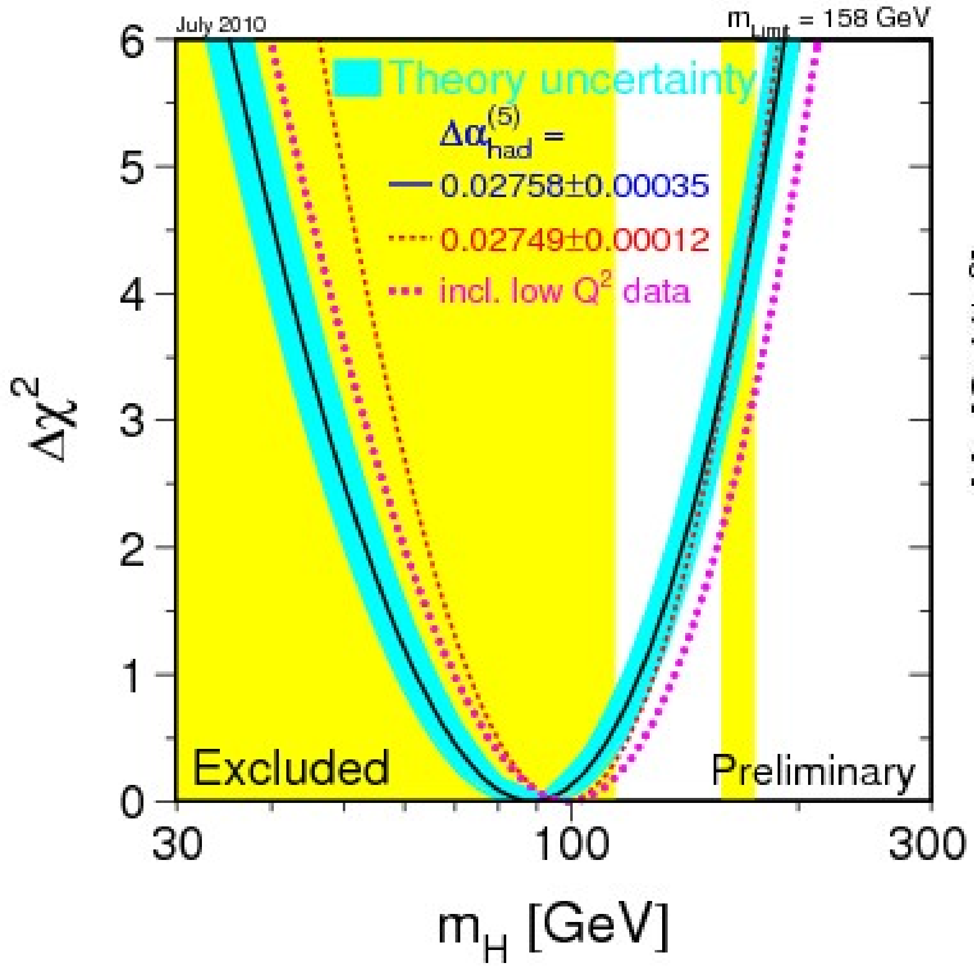
Stable R-hadrons

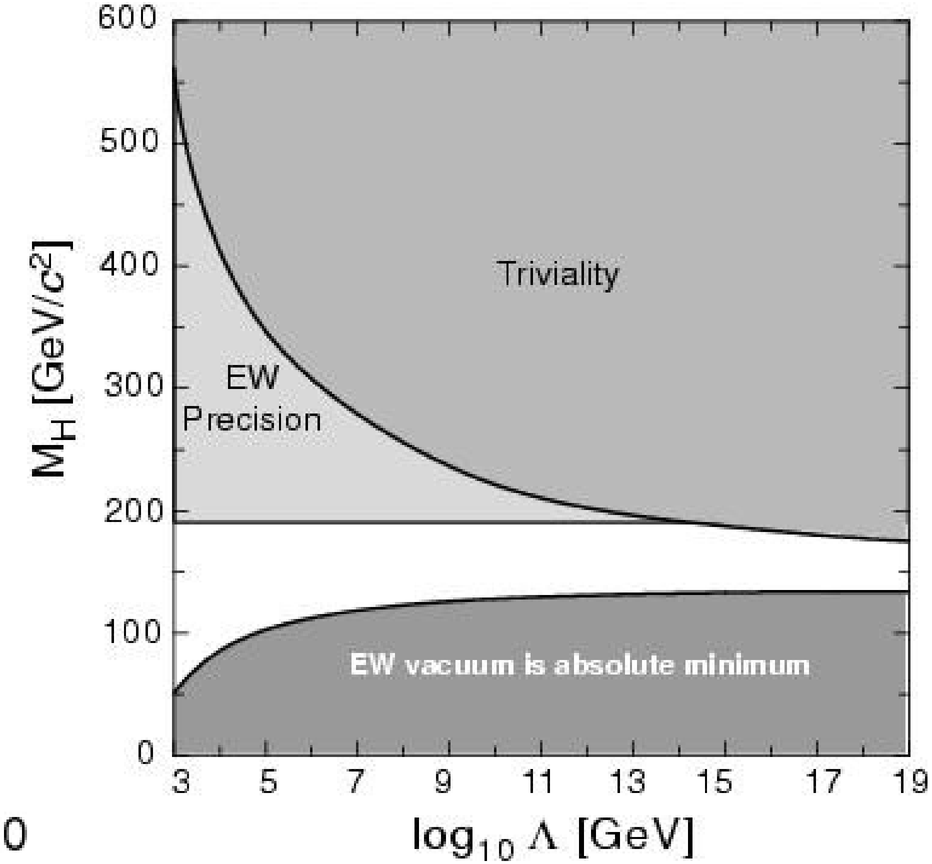


Same-sign leptons + missing E_T

Higgs

What we know about the *SM* Higgs





- **114 < M_H < 158 GeV at 95% CL**

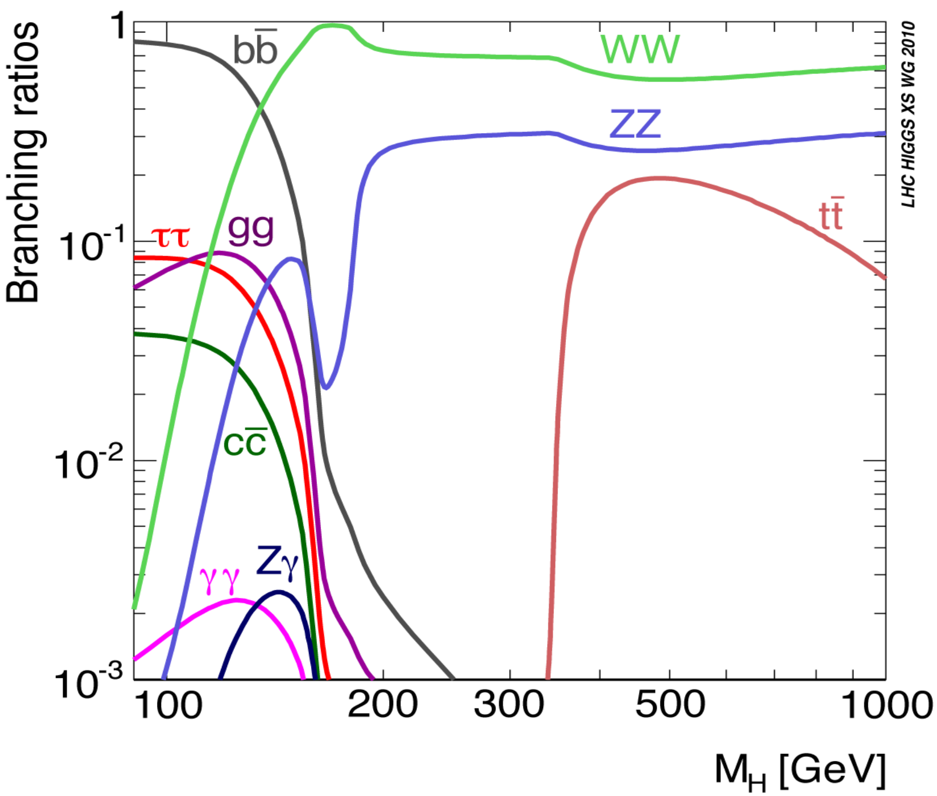
- **Only a narrow band allowed if the SM is strictly valid up to $\Lambda=10^{15\text{-}19}$ GeV**

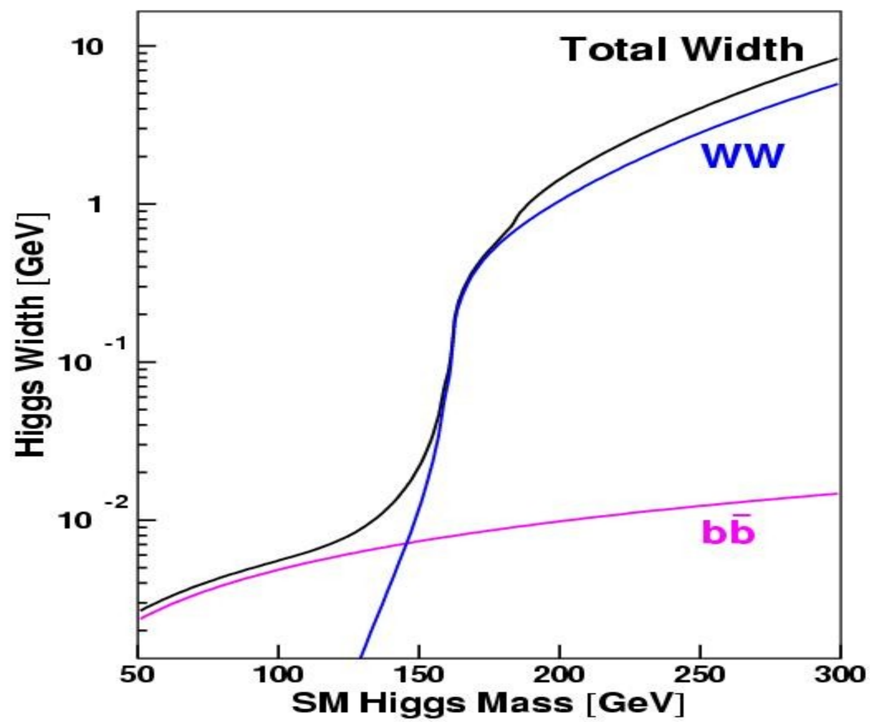
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

SM Higgs properties

1) It couples to particles proportionally to their mass. This determines most of the Higgs production properties

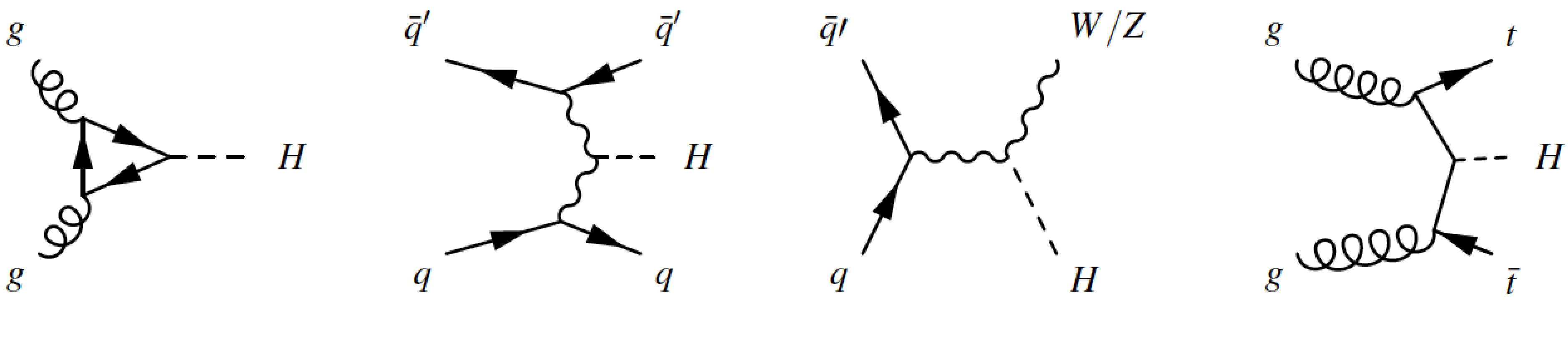
2) The value of the Higgs mass determines which decays are accessible (→ width and BRs)





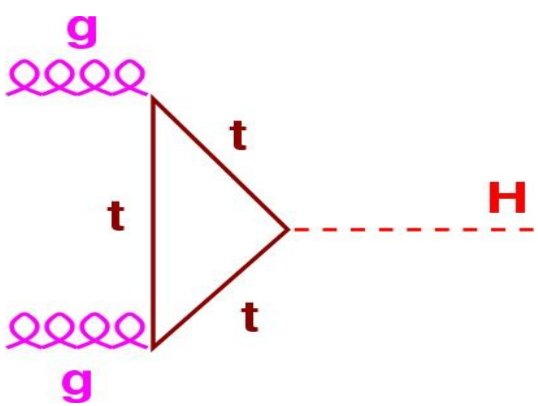
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

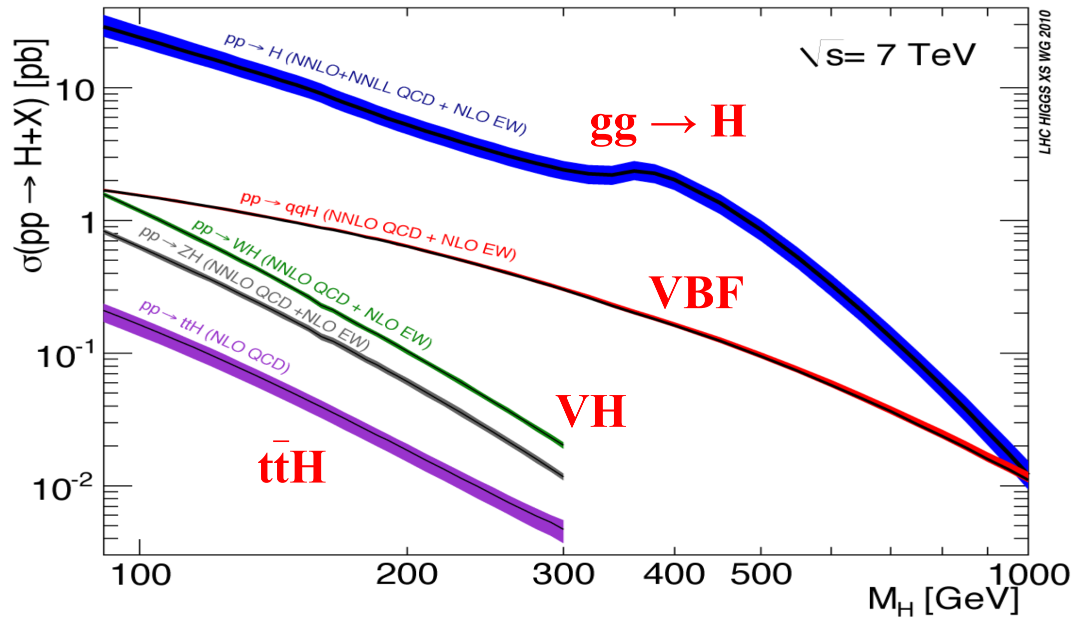
SM Higgs production in hadron colliders



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

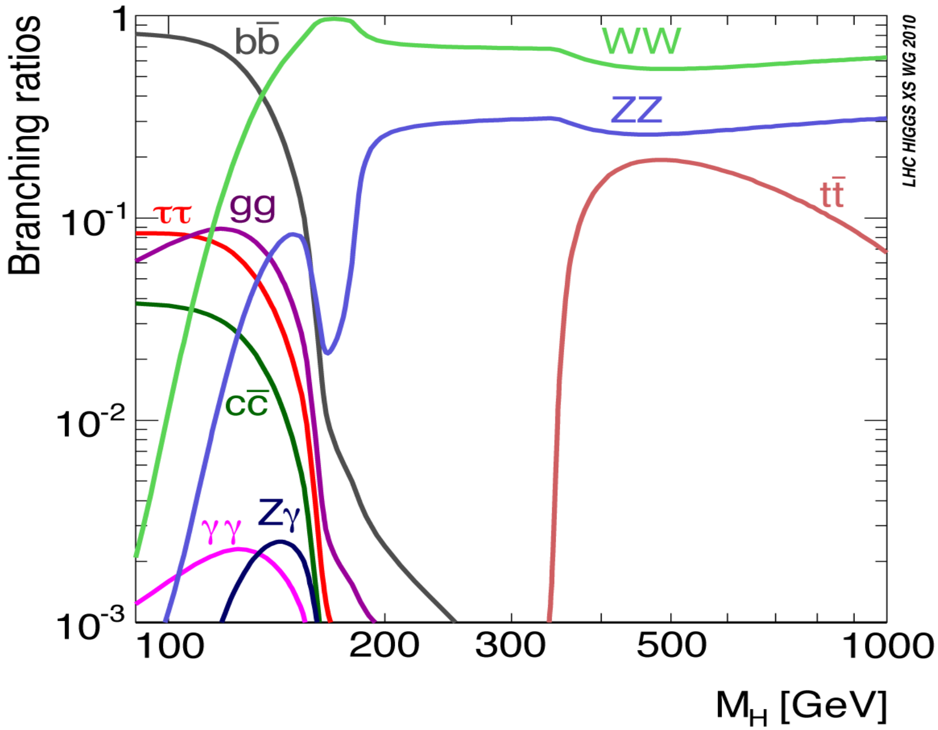
- **gg → H is the dominant production mechanism at the LHC**



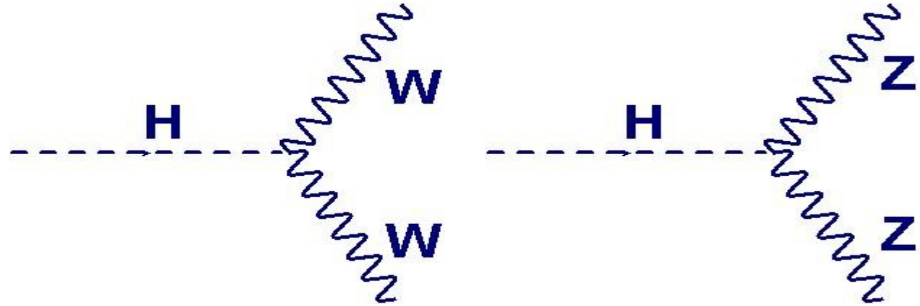


Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

SM Higgs decay in hadron colliders



- For Higgs masses above 140 (180) GeV or so, the WW (ZZ) decay channel opens up

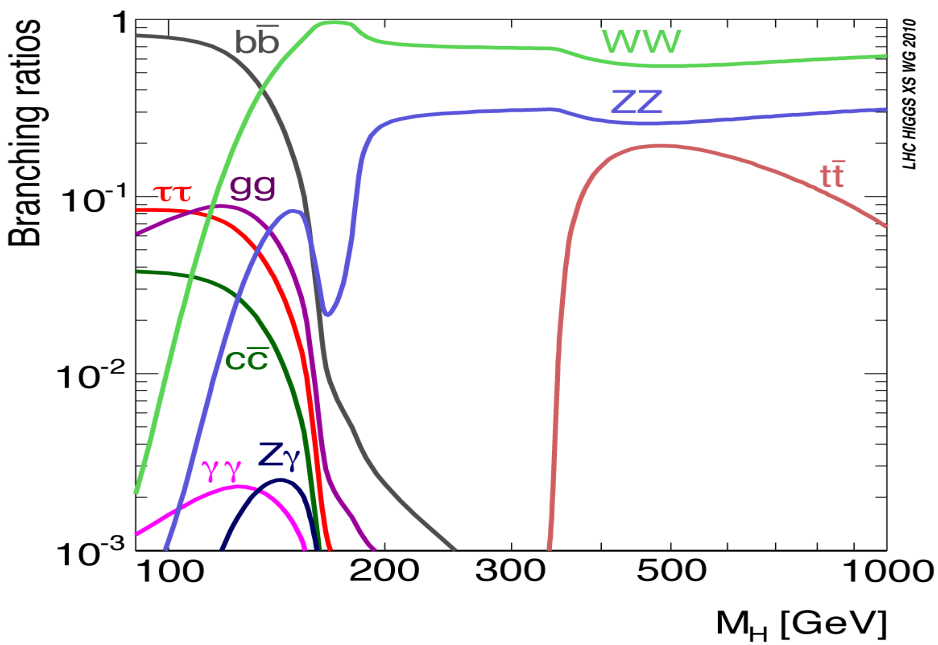


- In clean final states (electrons, muons), the dominant backgrounds are 'standard' $q\bar{q}\rightarrow WW$ and $q\bar{q}\rightarrow ZZ$ events

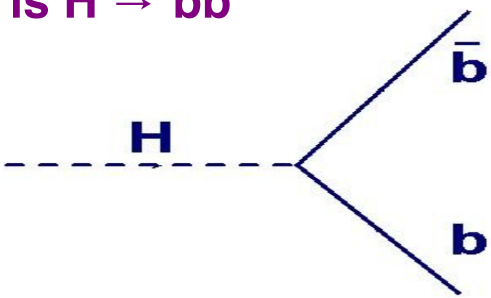
- **We preferentially exploit electron and muon decays of W and Z, but not exclusively:**
  - gg → H → ZZ → ll $q\bar{q}$, ll$\nu\bar{\nu}$ are also convenient at high Higgs masses

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

SM Higgs decay in hadron colliders



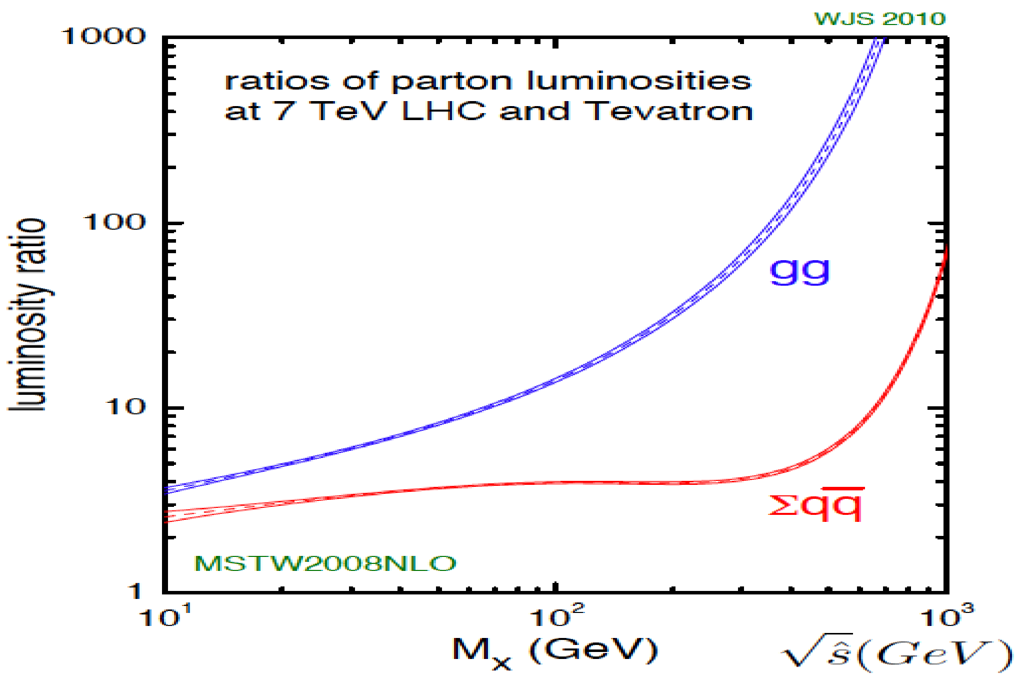
- For Higgs masses below 140 GeV or so, the most probable decay is $H \rightarrow b\bar{b}$



- Unfortunately, $b\bar{b}$ backgrounds from pure QCD processes are huge, and $gg \rightarrow H \rightarrow b\bar{b}$ is not a good channel for Higgs search

- **We exploit other decay channels and production mechanims:**
  - $gg \rightarrow H \rightarrow \gamma\gamma$ (very low BR, but clean peak in $\gamma\gamma$ mass)
  - $q\bar{q} \rightarrow VH \rightarrow Vb\bar{b}$ (but still difficult, due to V+$b\bar{b}$ and top backgrounds)
  - $q\bar{q} \rightarrow q'\bar{q}' H \rightarrow q'\bar{q}' \tau\bar{\tau}$ (VBF, good tau identification needed)

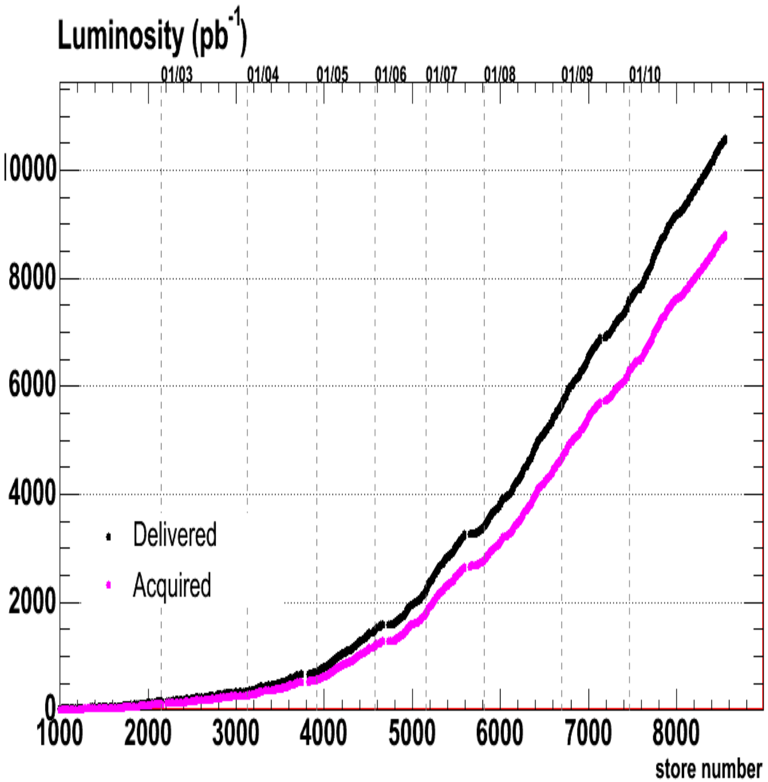
How do LHC and Tevatron compare?

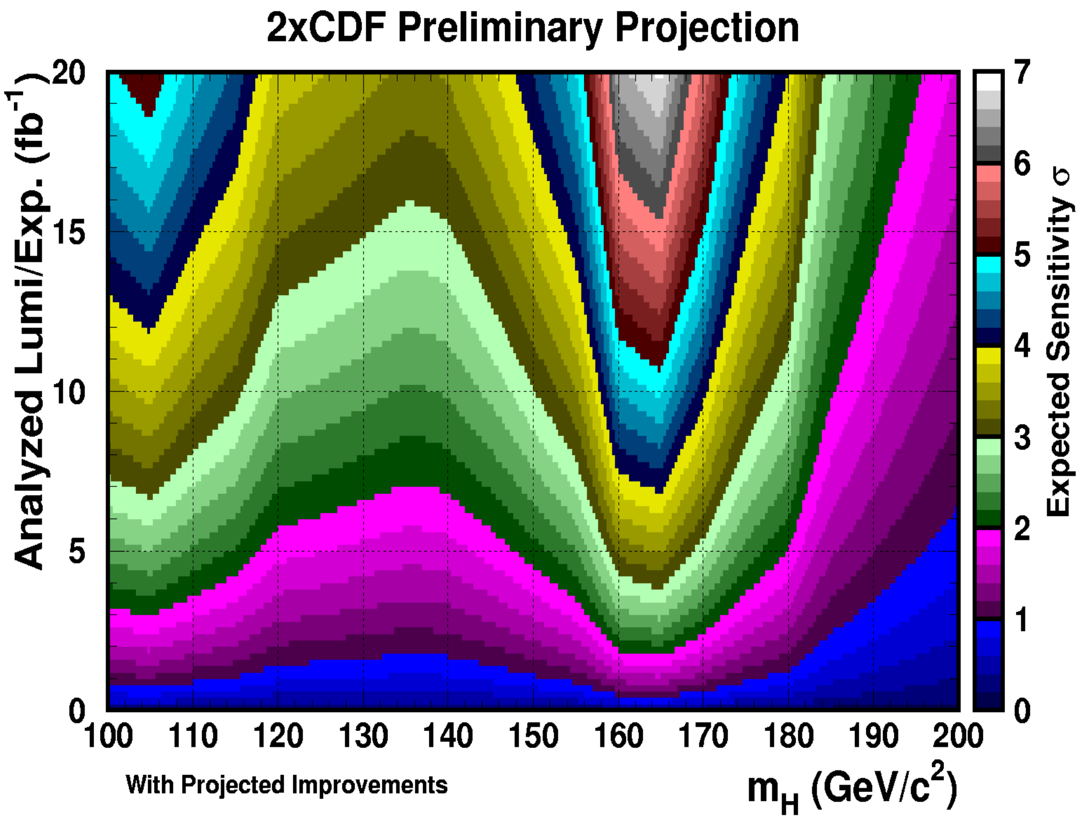


- For Higgs masses above 100 GeV, there is one order of magnitude more gg → H, $t\bar{t}H$ production
  - Higgs searches are extremely advantageous at the LHC for m_H> 140 GeV

- For Higgs masses above 100 GeV, there is ~ 3 times more qq→VH and $q\bar{q}$ → $q'\bar{q}'$ H (VBF) production:
  - But life is still complicated at the LHC for m_H<140 GeV, where these production mechanisms are important

How do LHC and Tevatron compare?

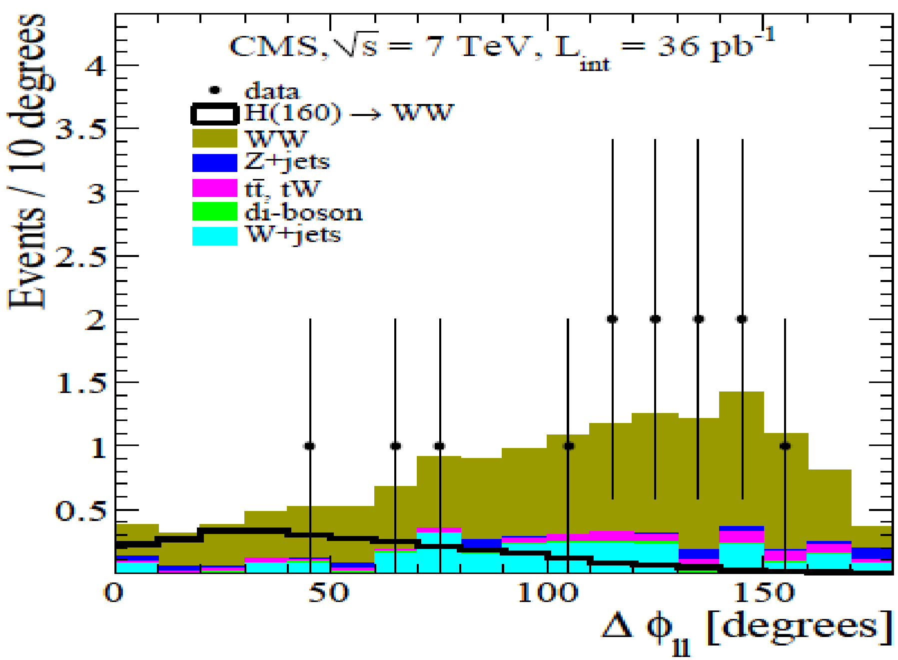


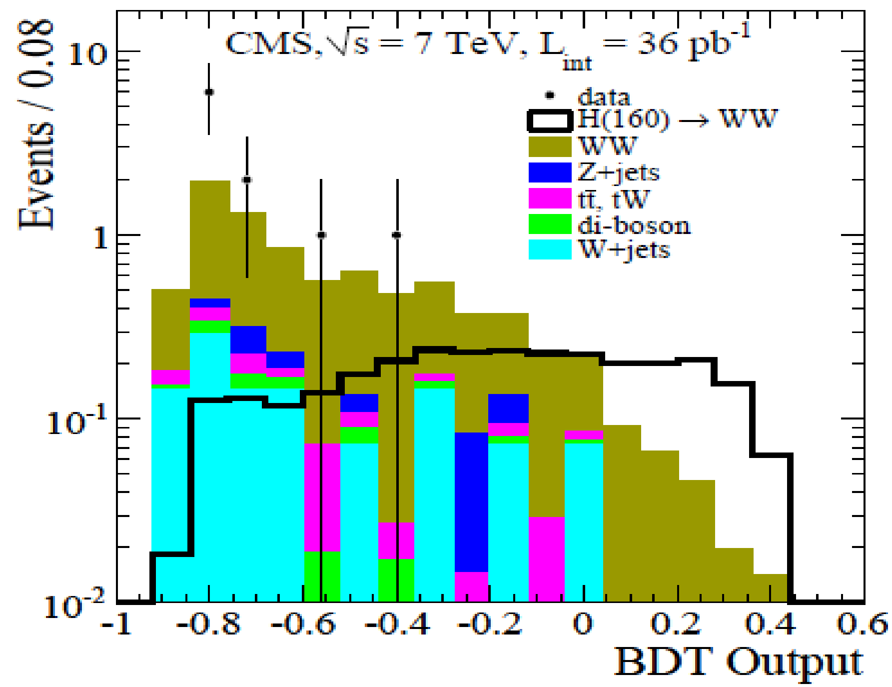


- ~10 fb^{-1} delivered at Tevatron, total of 12 fb^{-1} expected by the end of the program (September 2011)
- Still, with 'projected improvements' in the performance of the Tevatron analyses, a 3σ signal significance at 115 GeV is expected!

H→WW search at the LHC

- **In the meantime, the LHC experiments are already providing new (and competitive) Higgs results with just 40 pb^{-1} !!**

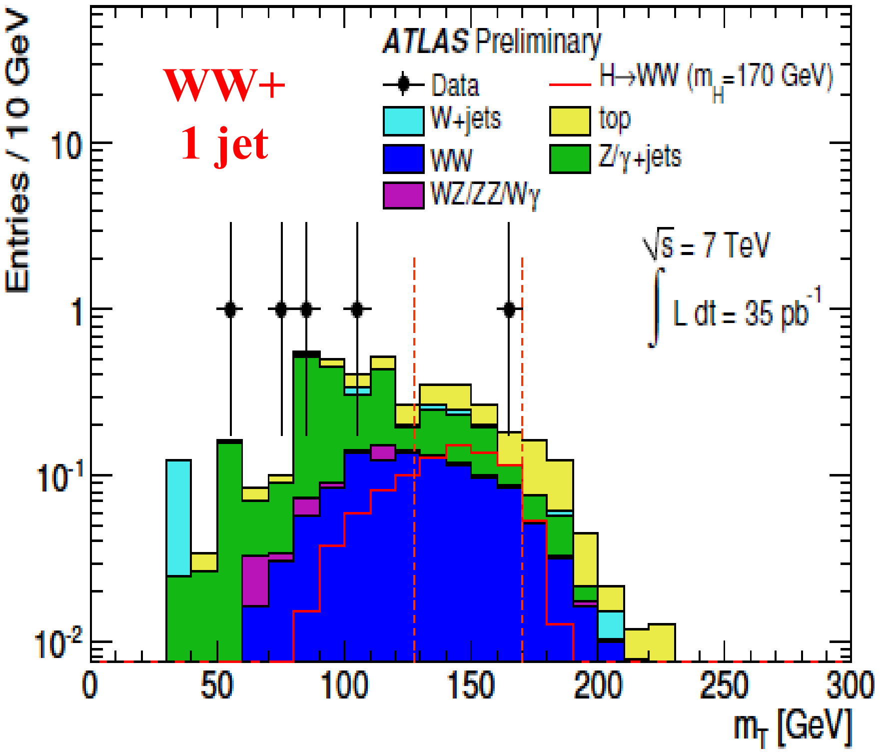


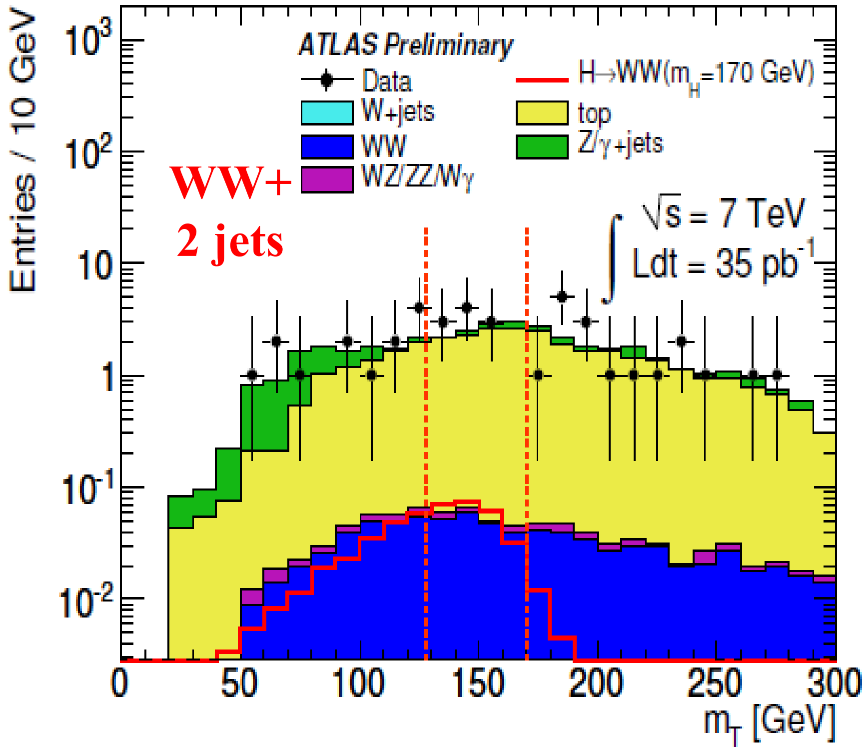


- **Extension of the WW Standard Model analysis at ATLAS and CMS. Now, the SM WW signal becomes 'background'. Two methods in CMS:**
  - **Cut-based, using momenta, dilepton mass and angle between leptons (there are different spin correlations in H production)**
  - **Boosted decision tree (BDT) decision with similar inputs**

H→WW search at the LHC

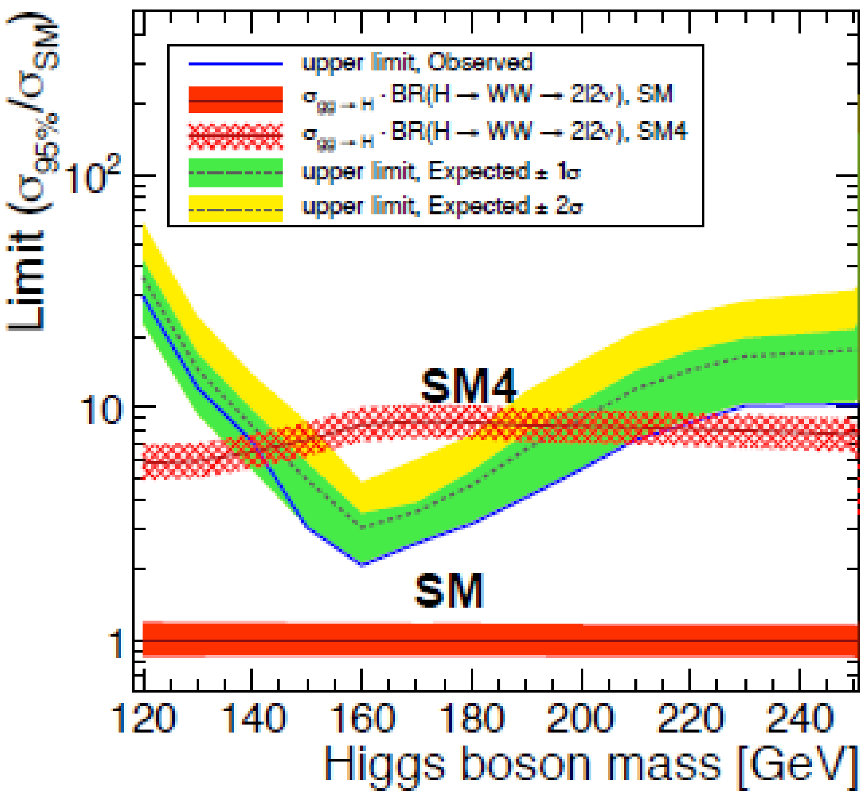
• In ATLAS, the WW + 1-jet and WW + 2-jet final states are not vetoed, but also analyzed separately to slightly increase the significance

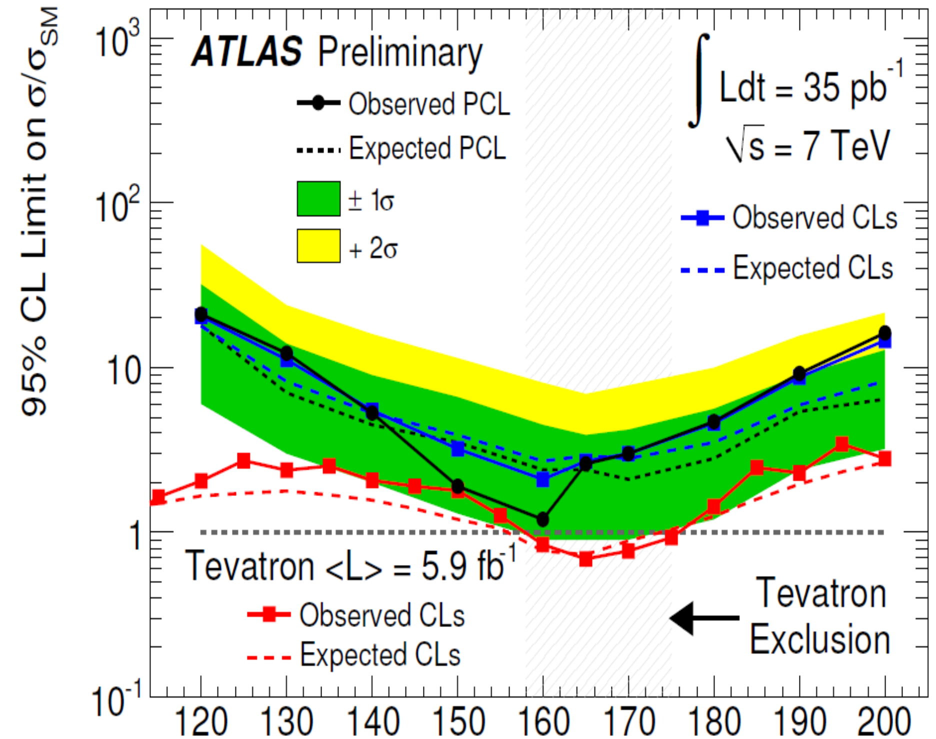




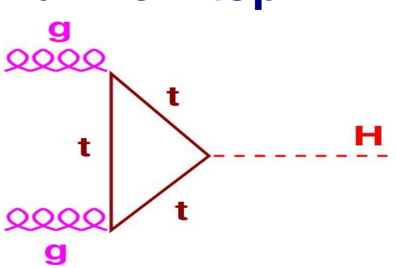
• Several kinematic cuts are employed to reduce the backgrounds, which are important (in particular top backgrounds for WW + 2 jets in the final state)

H→WW search at the LHC



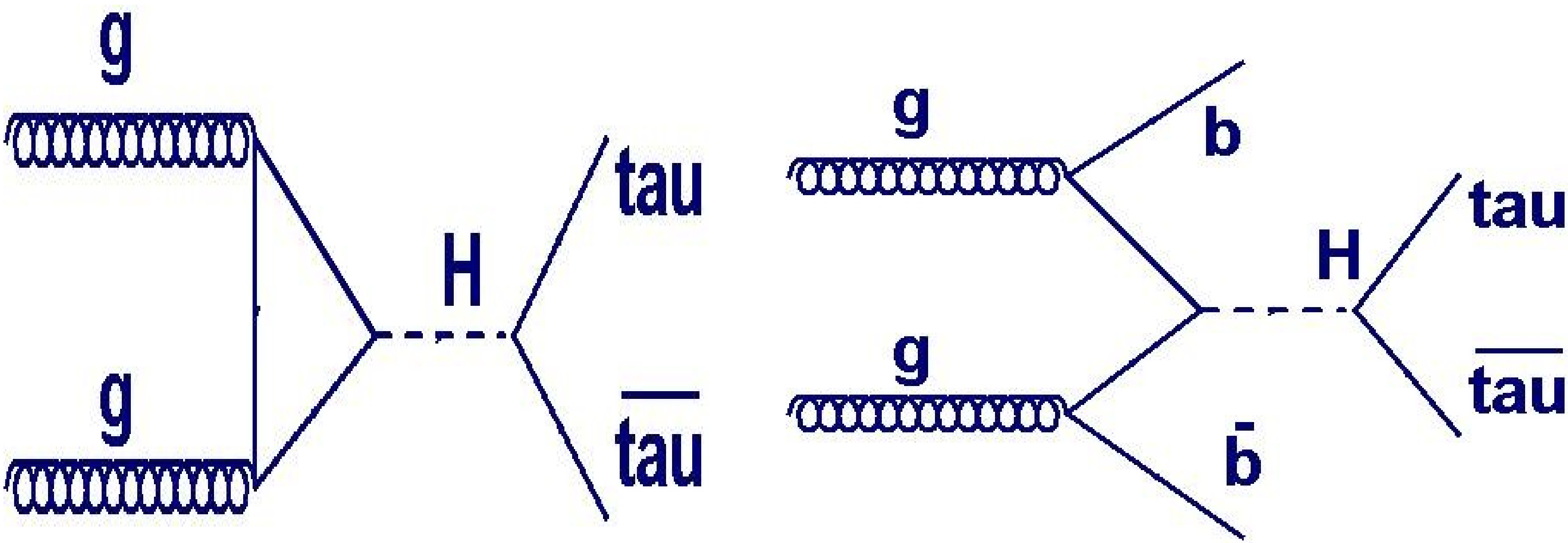


- Already excluding a region around $m_H \approx 160$ GeV for a scenario with 4 generations (cross section expected to be larger because of a "new top" quark contributing to gg → H)
- Higgs reach in the SM not too far from Tevatron reach !!



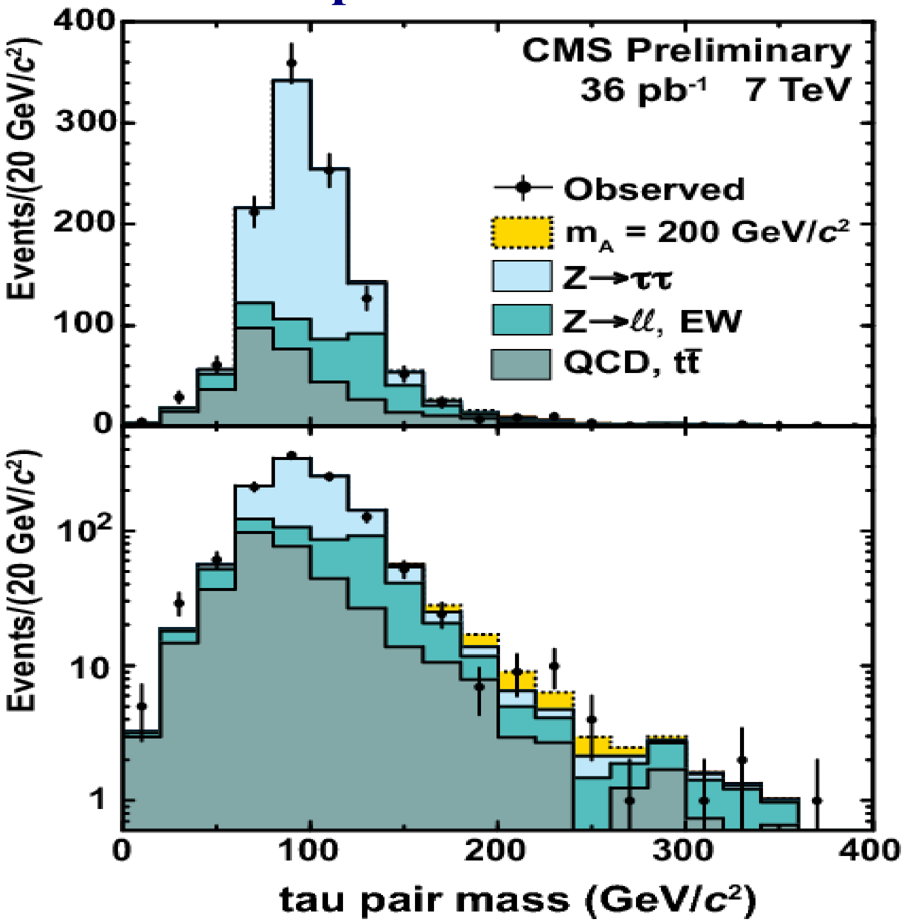
$\Phi \rightarrow \tau\bar{\tau}$ searches at the LHC

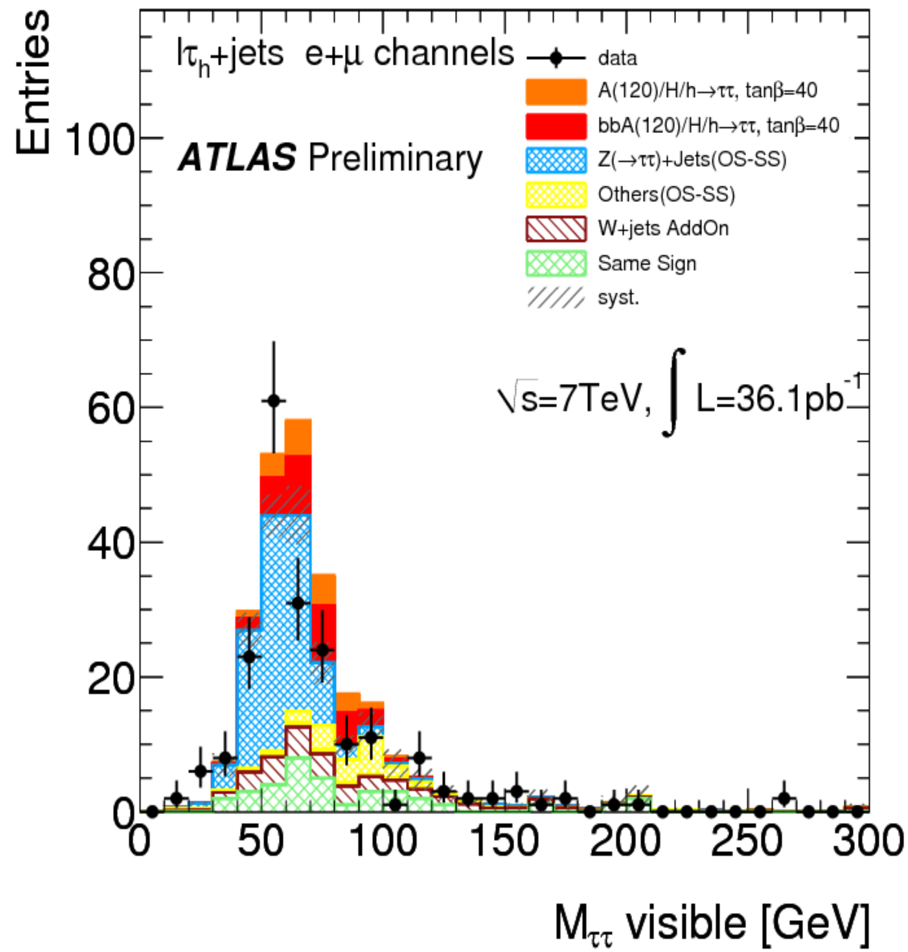
- We profit from our $Z \rightarrow \tau\bar{\tau}$ analyses to set limits on $H \rightarrow \tau\bar{\tau}$. This rate is expected to be particularly abundant in supersymmetric models, where the coupling of the Higgs to $b\bar{b}$ states can be significantly enhanced (large tanβ) with respect to the SM.



$\Phi \to \tau\bar{\tau}$ searches at the LHC

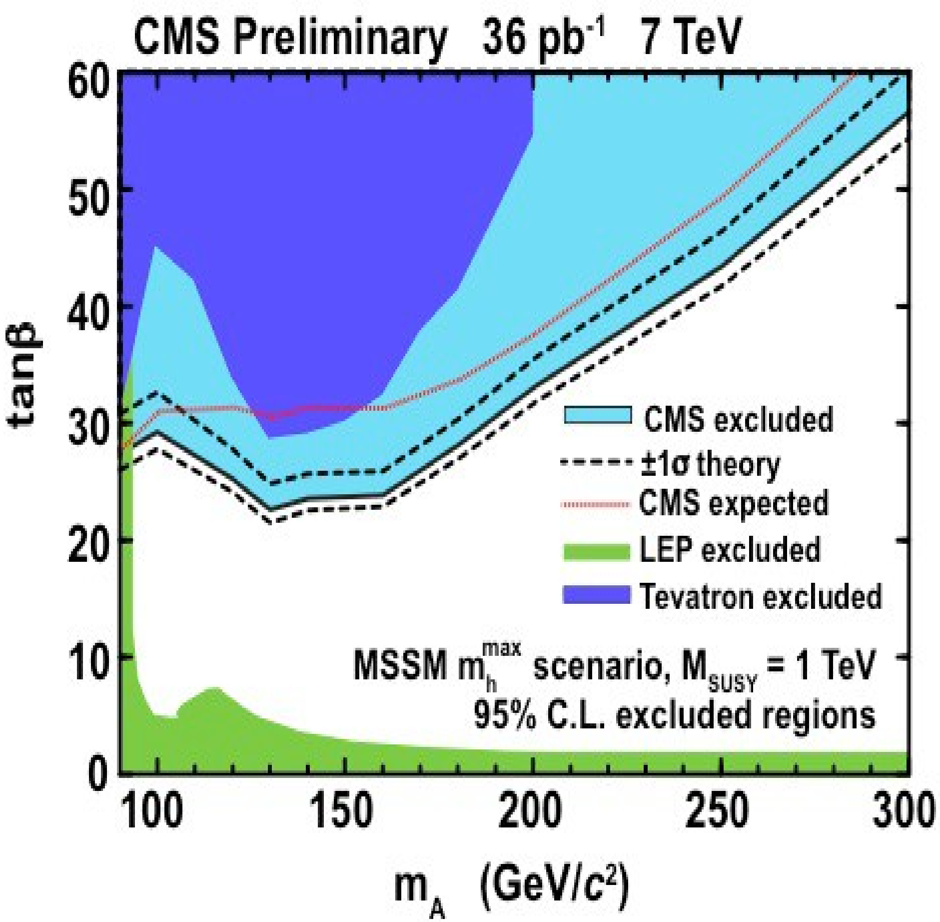
• Just looking for tau-tau final states, no additional requirements for accompanying b-jets. In CMS, an additional kinematic fit using particle ID is done to improve the tau-tau mass resolution

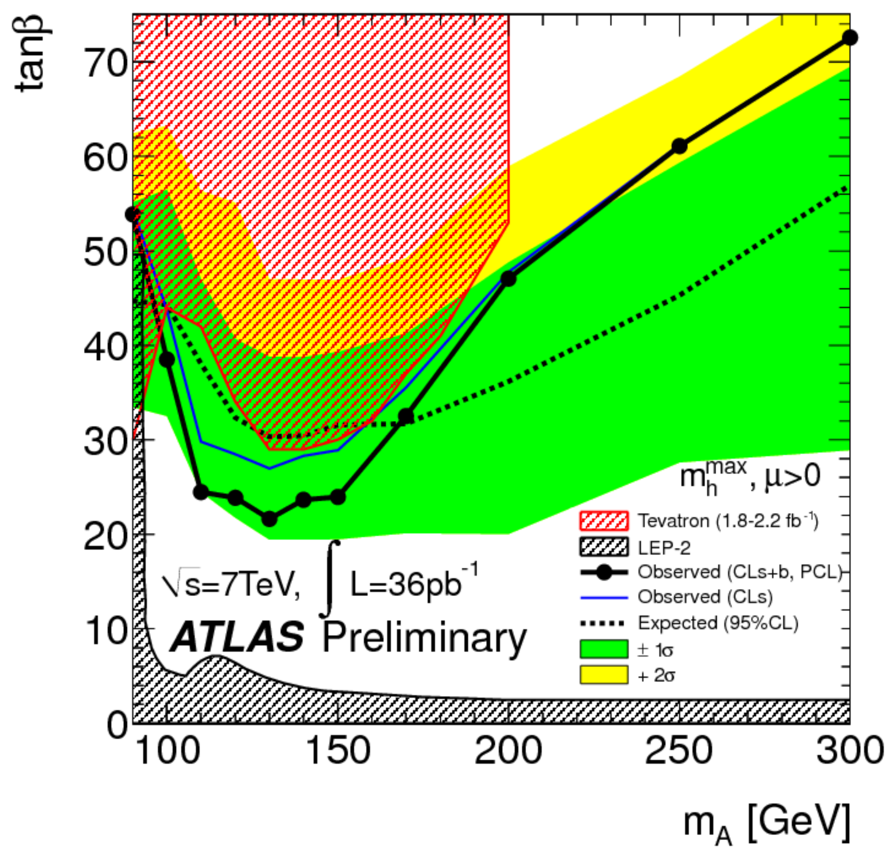




$\Phi \to \tau\bar{\tau}$ searches at the LHC

- **Already beyond Tevatron sensitivity!**
- **These results are very encouraging for the future!**

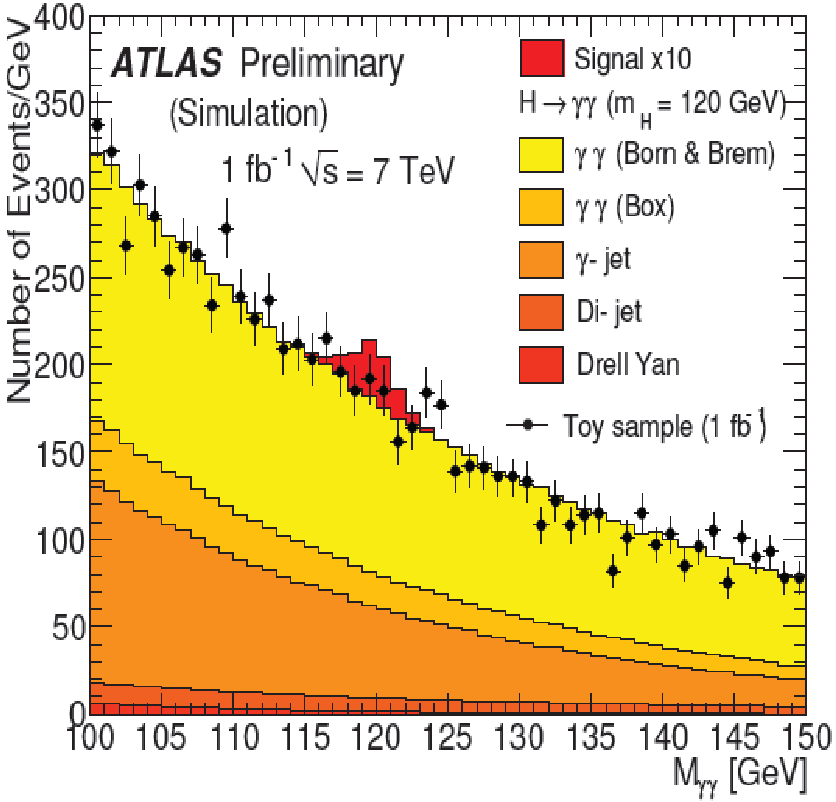


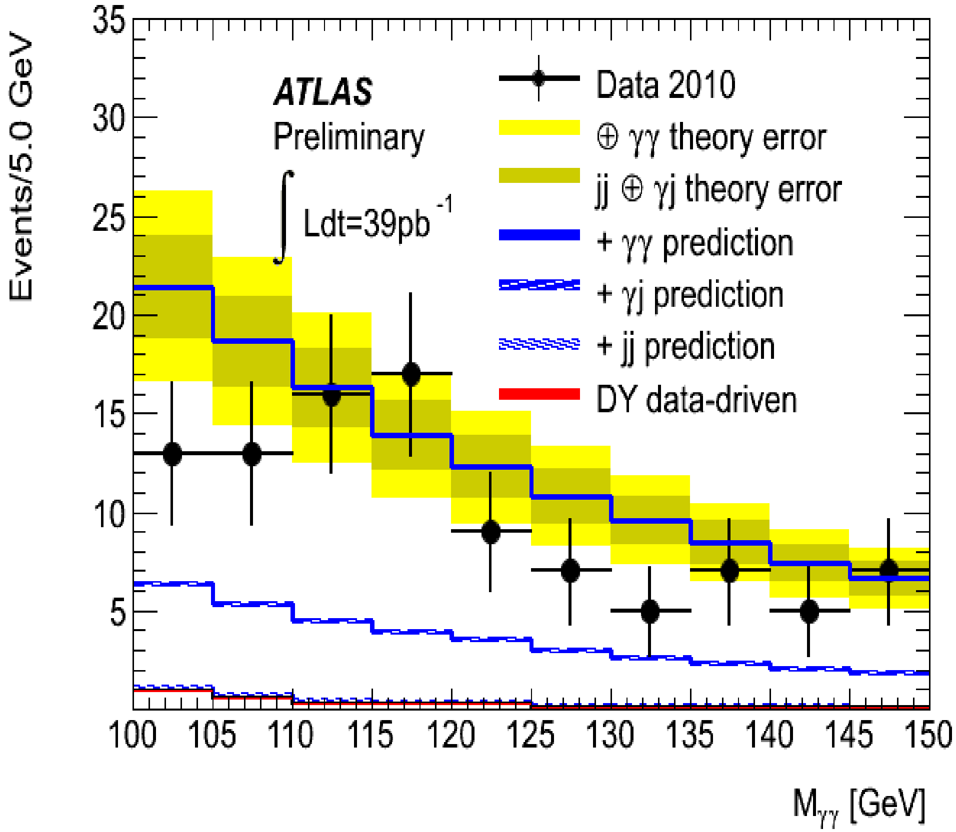


Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

H→ γγ searches at the LHC

- **Despite the low integrated luminosity, this analysis has been already tried by ATLAS**



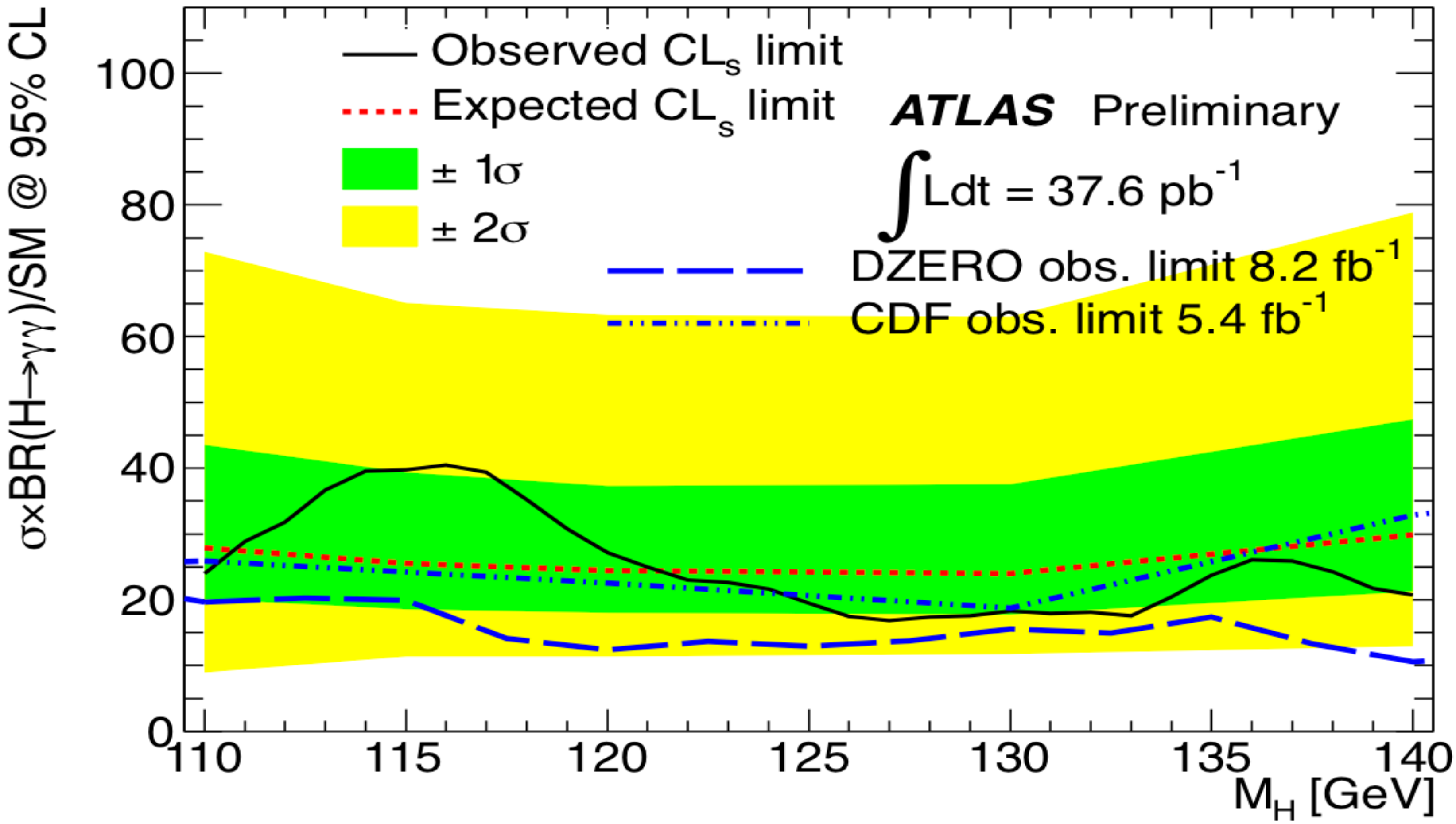


Expectations for 1 fb^{-1}

What is seen with 39 pb^{-1}

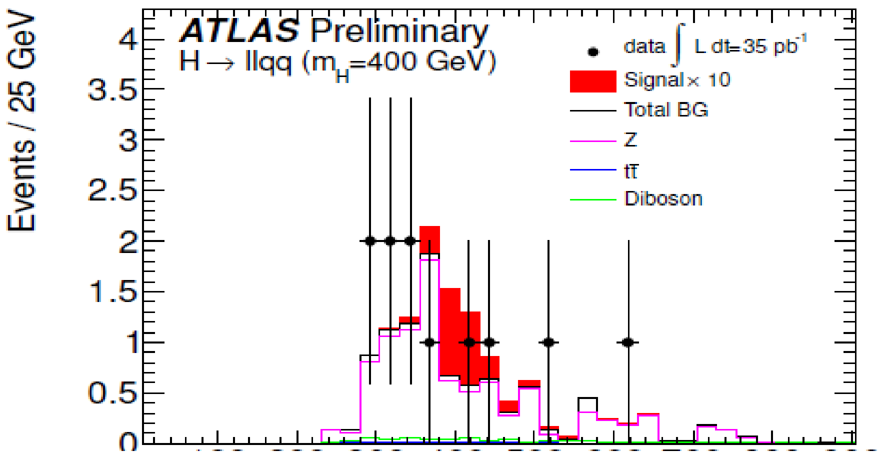
H→ γγ searches at the LHC

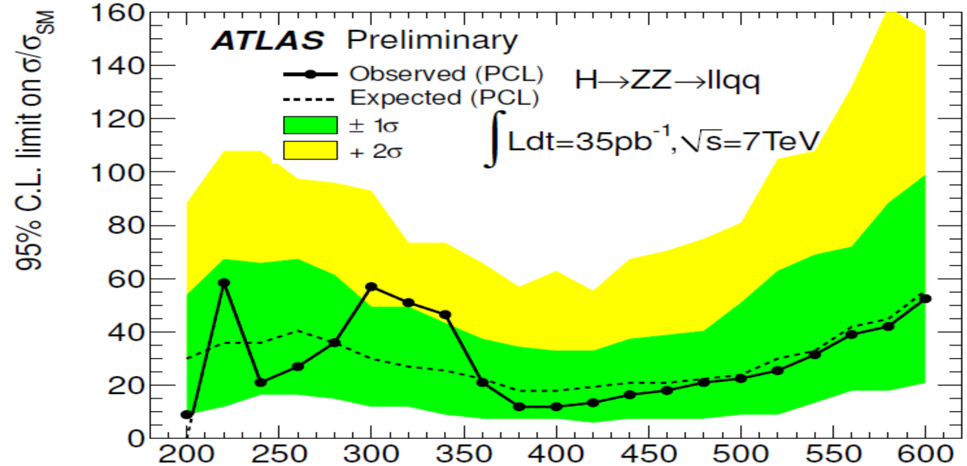
- **They are poor limits, right, but already competitive with those of Tevatron !!**

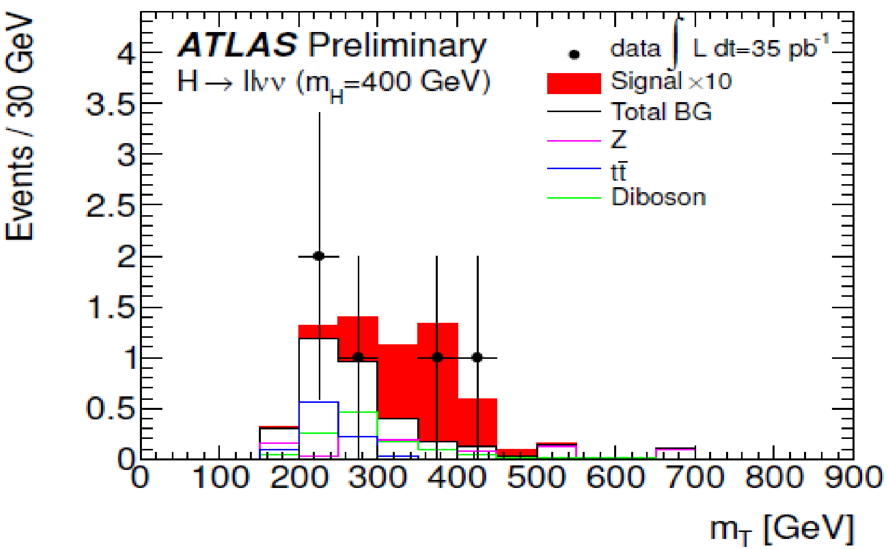


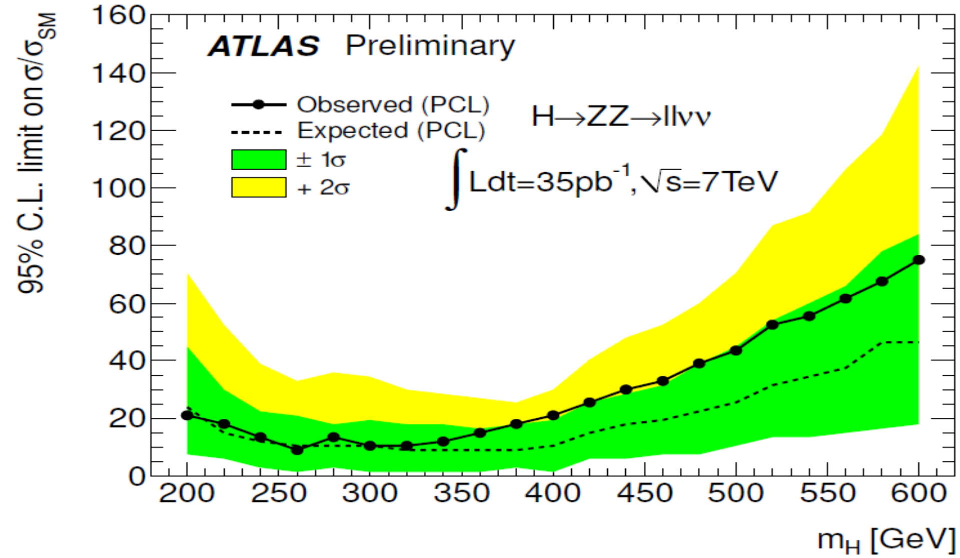
H→ZZ→$l\bar{l}q\bar{q}$, $l\bar{l}\nu\bar{\nu}$ at the LHC

- **ATLAS also set limits in the ZZ channel for high Higgs masses**





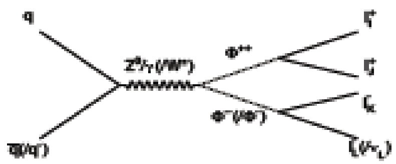




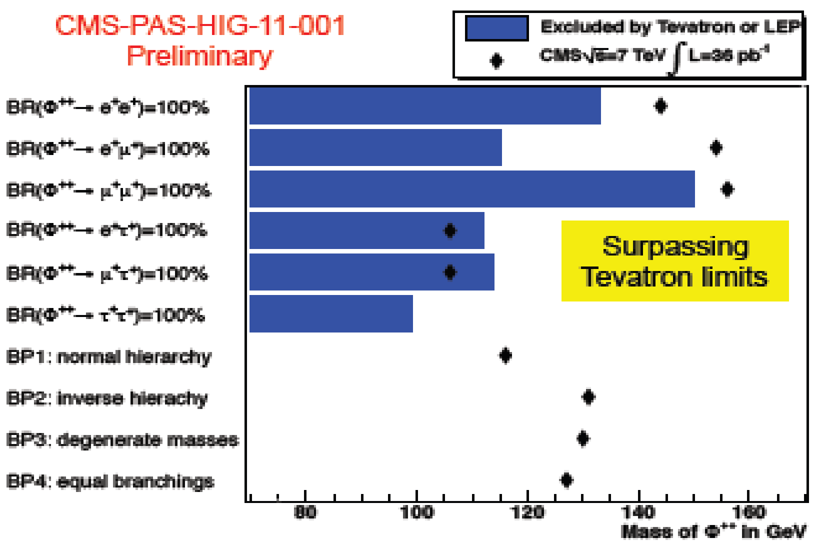
Charged Higgs searches at the LHC

$\Phi^{++} \rightarrow l^+ l^+$

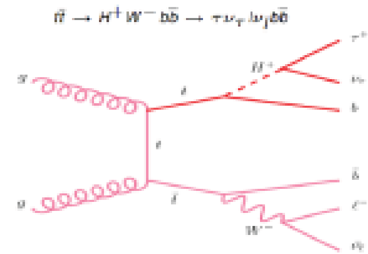
- Arises in models with extra Higgs triplets
  - Φ^{++}, Φ^{+}, Φ^{0}
- Triplet responsible for small neutrino mass
- Unknown neutrino mass matrix
  → unknown branching ratios → broad search
- Below M ≈2M_W, only leptonic decays



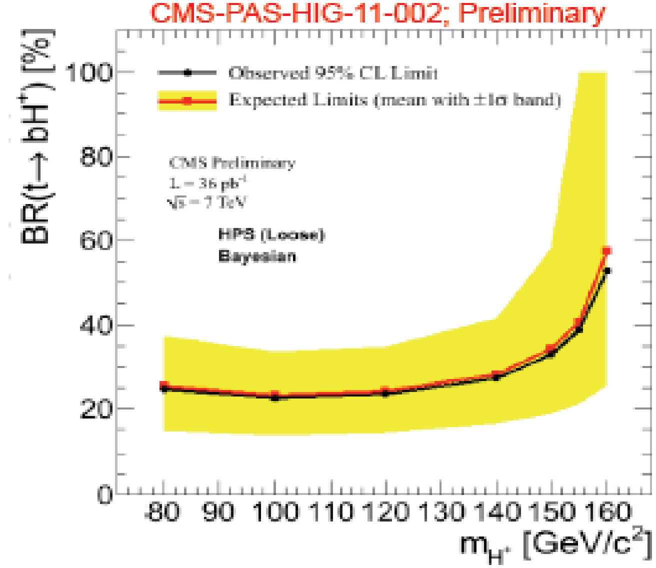
CMS-PAS-HIG-11-001
Preliminary



$H^+ \rightarrow \tau^+ \upsilon$
in ttbar decays



CMS-PAS-HIG-11-002; Preliminary



Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

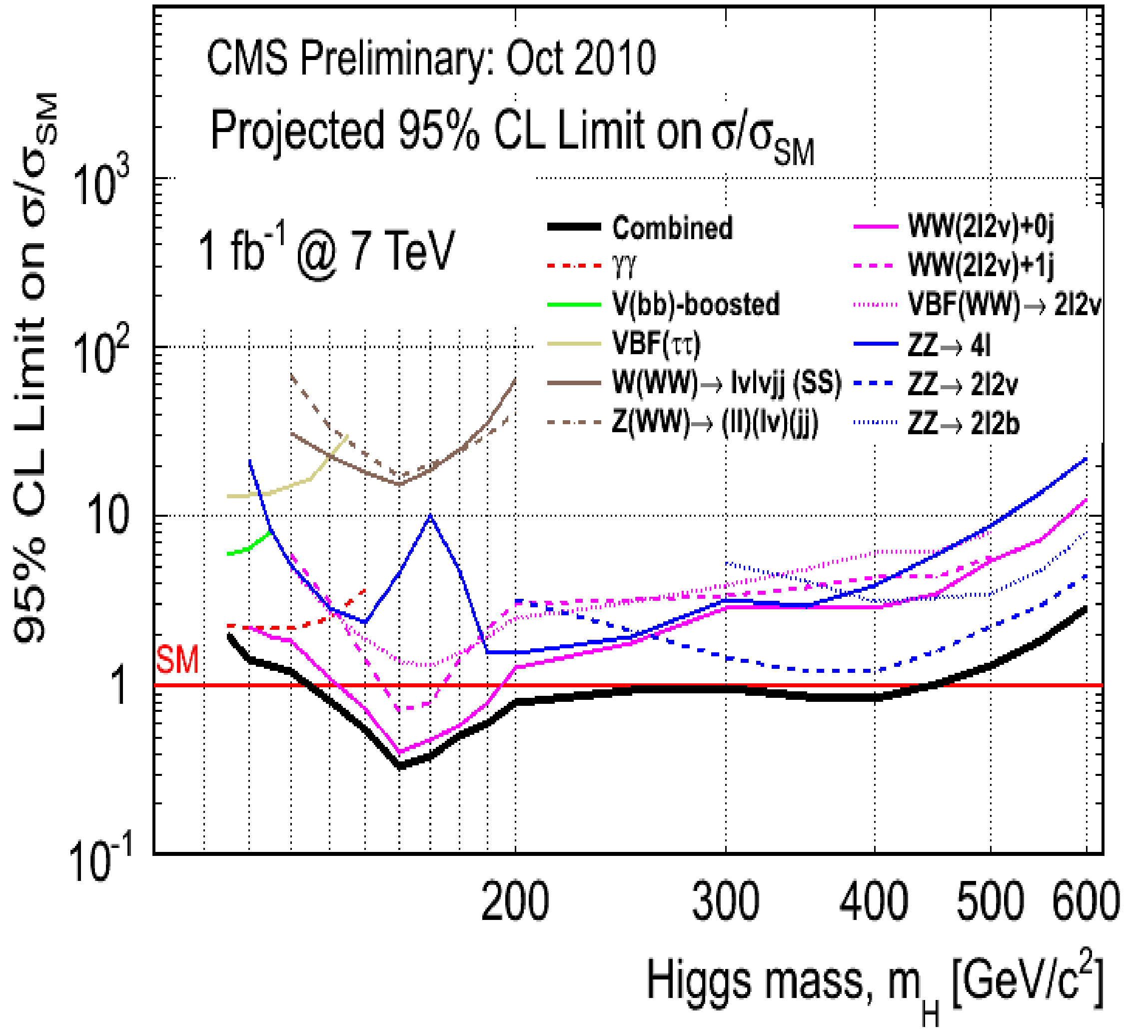
Higgs projections for 2011-2012

LHC projections for 2011-2012

Channels included	≈ Mass range (GeV)
$H \rightarrow \gamma\gamma$	115-150
VBF $H \rightarrow \tau\tau$	115-145
VH, $H \rightarrow bb$ (highly boosted)	115-125
VH, $H \rightarrow WW \rightarrow l\nu jj$	130-200
$H \rightarrow WW \rightarrow 2l2\nu$ + 0/1 jets	120-600
VBF $H \rightarrow WW \rightarrow 2l2\nu$	130-500
$H \rightarrow ZZ \rightarrow 4l$	120-600
$H \rightarrow ZZ \rightarrow 2l2\nu$	200-600
$H \rightarrow ZZ \rightarrow 2l2b$	300-600

With 1 fb^{-1} per experiment: CMS

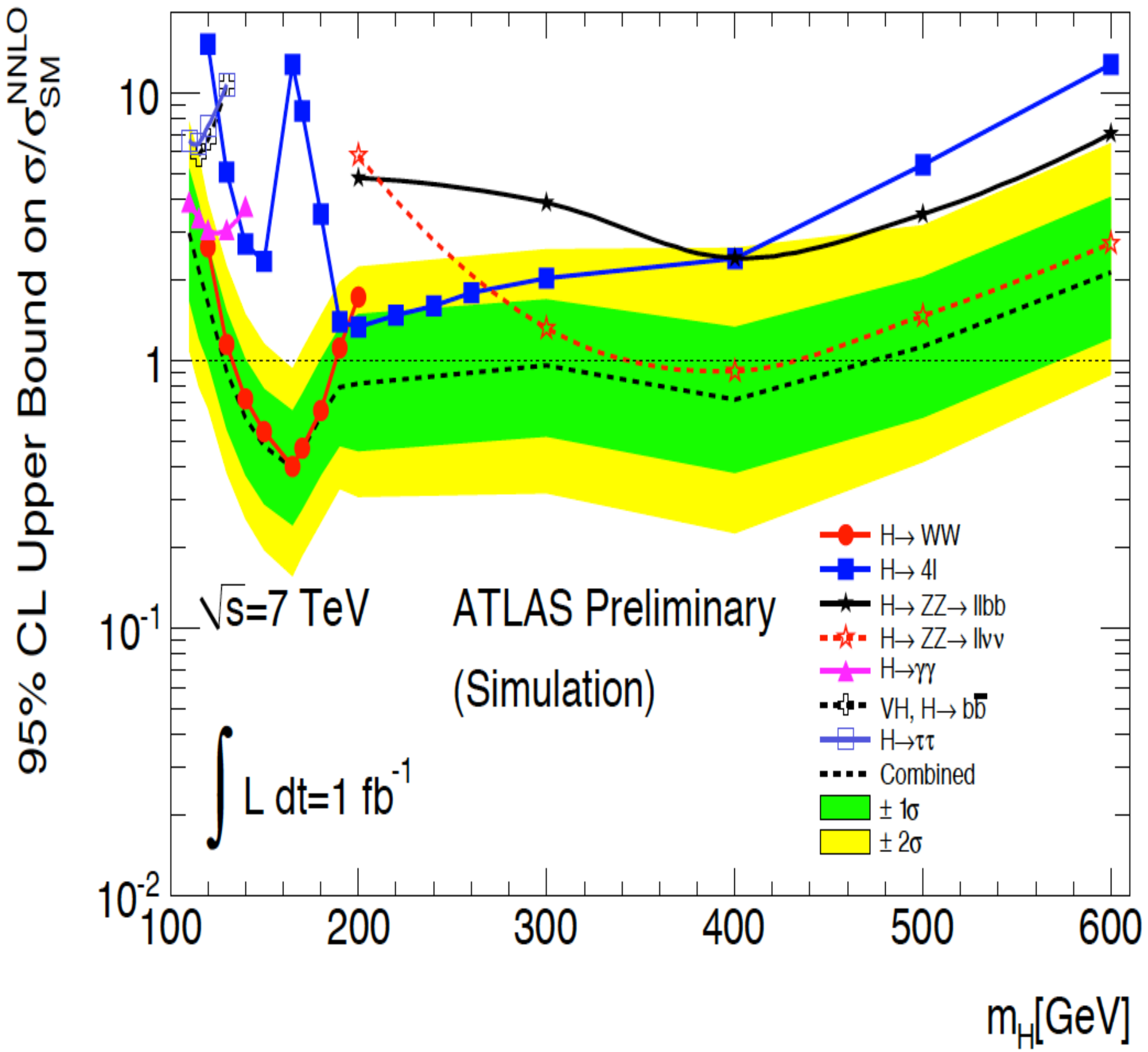
- This is approximately the luminosity expected in 2011, so 2011 should be a year for exclusions in a wide range of masses and hopefully for a hint of Higgs signal for masses down to 130 GeV



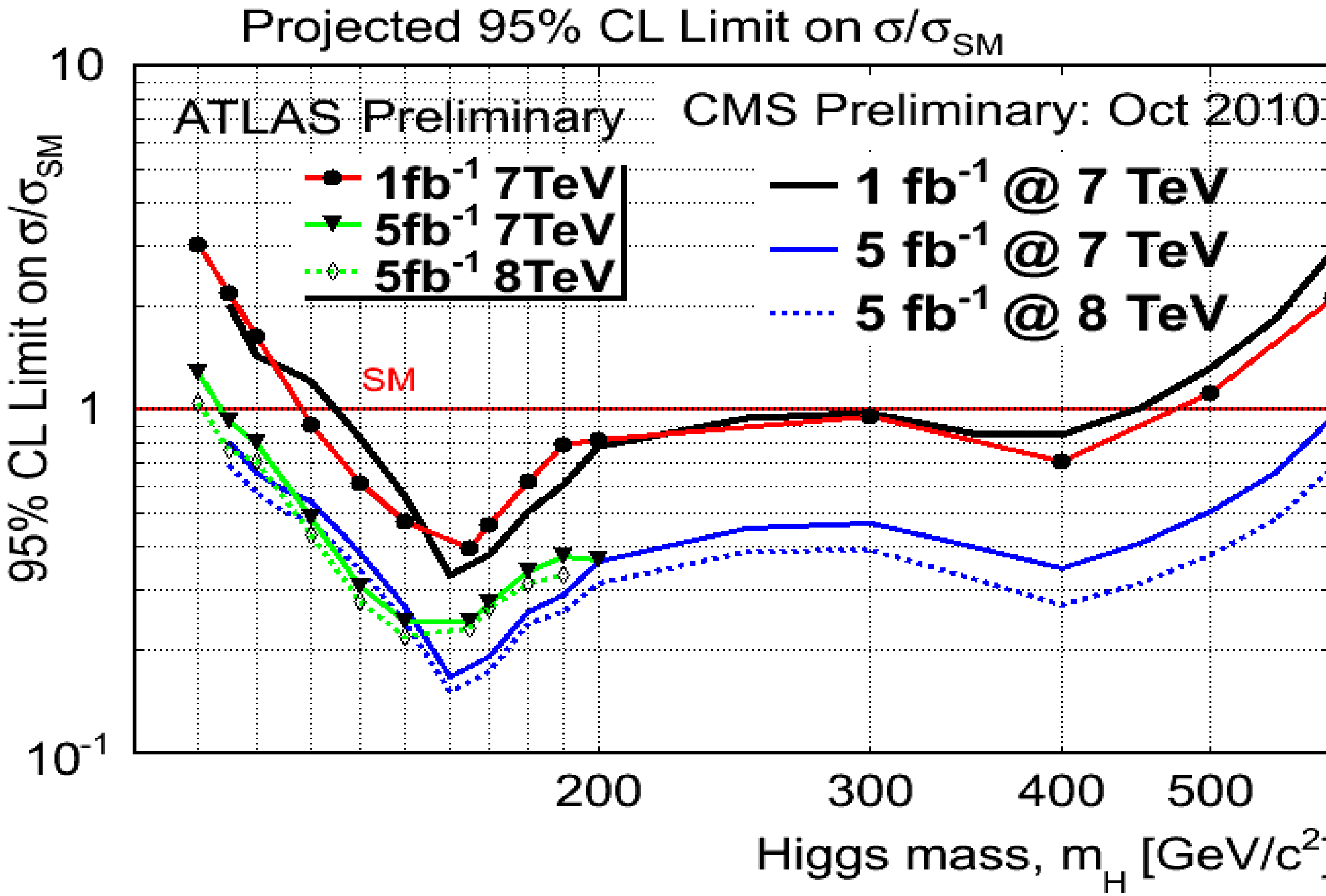
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

With 1 fb^{-1} per experiment: ATLAS

- This is approximately the luminosity expected in 2011, so 2011 should be a year for exclusions in a wide range of masses and hopefully for a hint of Higgs signal for masses down to 130 GeV



With 5 fb^{-1} per experiment



Good agreement between the projections of each experiment

5 fb^{-1} of integrated luminosity should be enough to go down to a 115 GeV Higgs mass !

The summary of Higgs projections

ATLAS + CMS $\approx$ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

With the data collected in 2011-2012 we should be able to cover the whole mass range 114-600 GeV for the SM Higgs boson, and find it if it is there !!!

Outlook

- We are living exciting times in Particle Physics:
  - The LHC accelerator and the associated detectors are working beautifully and providing first class results, already with an integrated luminosity of 40 pb^{-1}
  - 2011 and 2012 are going to be critical years for the LHC physics programme. We should be able to
    - a) find or exclude the SM Higgs in the mass range 114-600 GeV
    - b) get the first hints of new physics beyond the SM in many of the possible theoretical scenarios that are being considering

- Stay tuned !!