RESULTS FROM THE LHC: ATLAS


Dark Matter Beach Ascona ?


Higgs beach Florida

Dark Attack,
July 2012

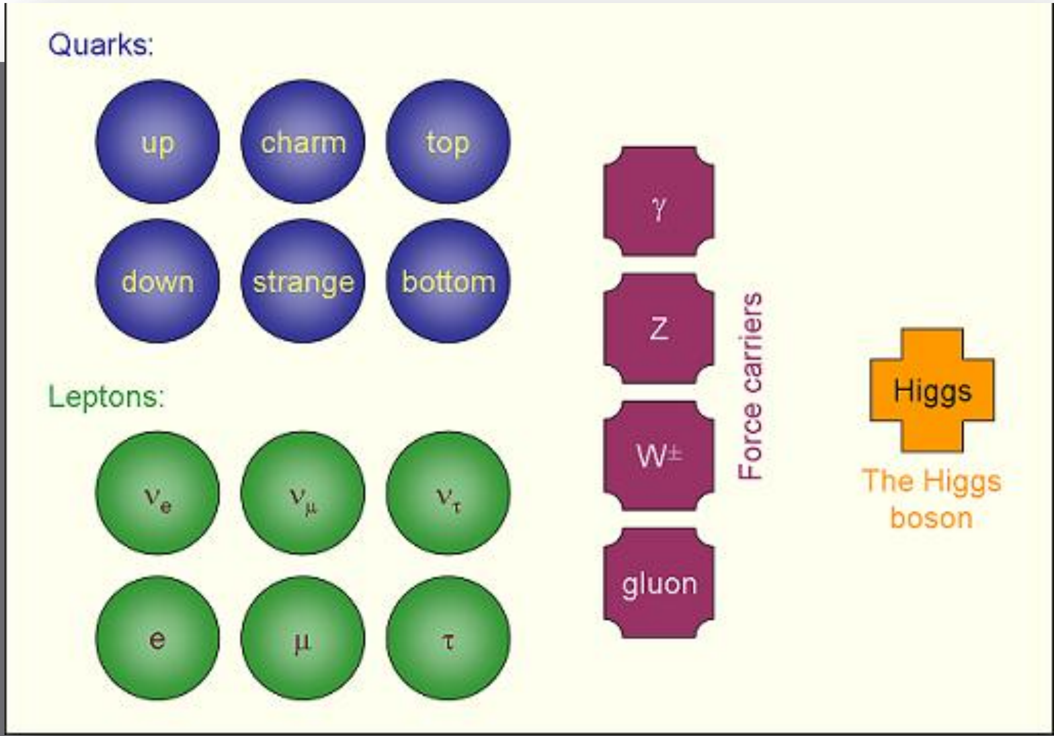
Sascha Caron (Radboud University Nijmegen and NIKHEF)

Outline of the talk

- Motivation of ATLAS physics
- Machine & detector status and prospects
- SM physics at LHC: Is the SM correct ?
- **What did we learn in 2012 about the Higgs mechanism ? ➔ Mini-review Higgs**
- **What did we learn in 2012 about Dark Matter candidate searches ? Mini-review SUSY et al.**

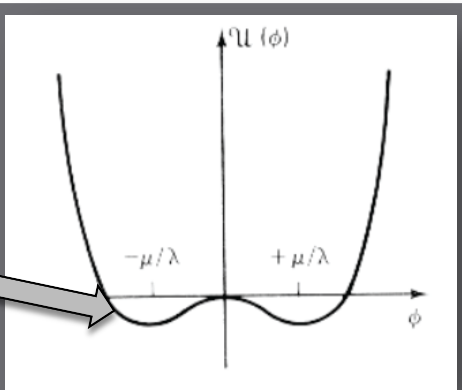
Standard Model reminder

QFT is invariant under a <u>local</u> change of gauge
➔Massless force carriers (spin 1 bosons) for the *electroweak and the strong force*
But the W and Z bosons are massive!



Problem is solved by Higgs mechanism:
➔*Mass of W and Z only generated after transformation into a ground state of the system* (electroweak symmetry breaking)

Or Englert-Brout-Higgs-Guralnik-Hagen-Kibble



<u>**Predicts observable Higgs boson with spin 0**</u>

The Standard Model: Is this it ?

Dark Matter / Dark Energy is not explained by the Standard Model

(but WIMP miracle hinting to DM at LHC energies)

Higgs mass suffers from unnatural fine-tuning due to quadratic quantum corrections

(hierarchy or fine-tuning problem)

Major LHC goals:

Clarify EW symmetry breaking → Higgs mechanism and Higgs particle(s)

Physics Beyond the Standard Model → Supersymmetry, something else ?

LHC luminosity 2012

4 TeV beam energy

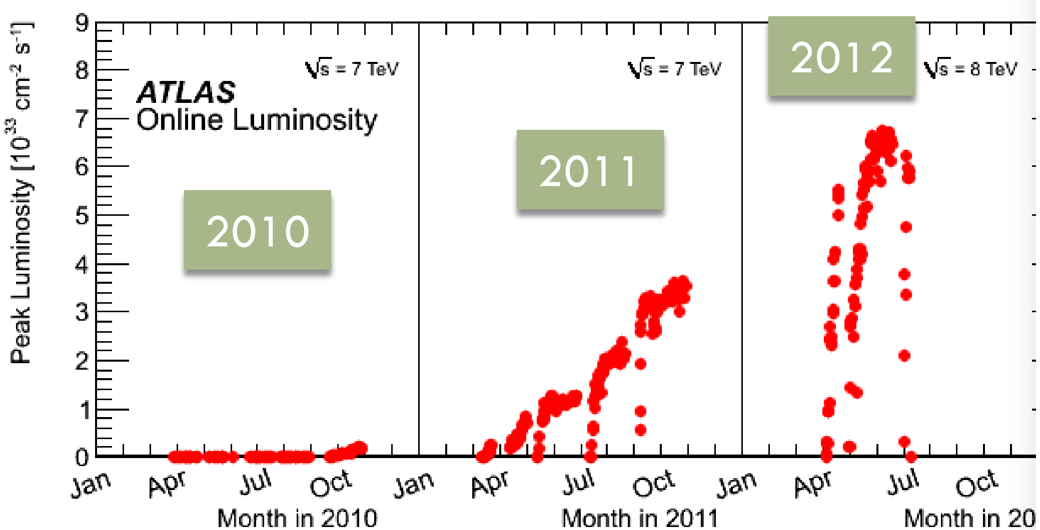
2012 compared to 2011 :
Luminosity increased from **3×10^{33} to 7×10^{33}**$\mathrm{cm^{-2}s^{-1}}$ (nominal 10^{34})

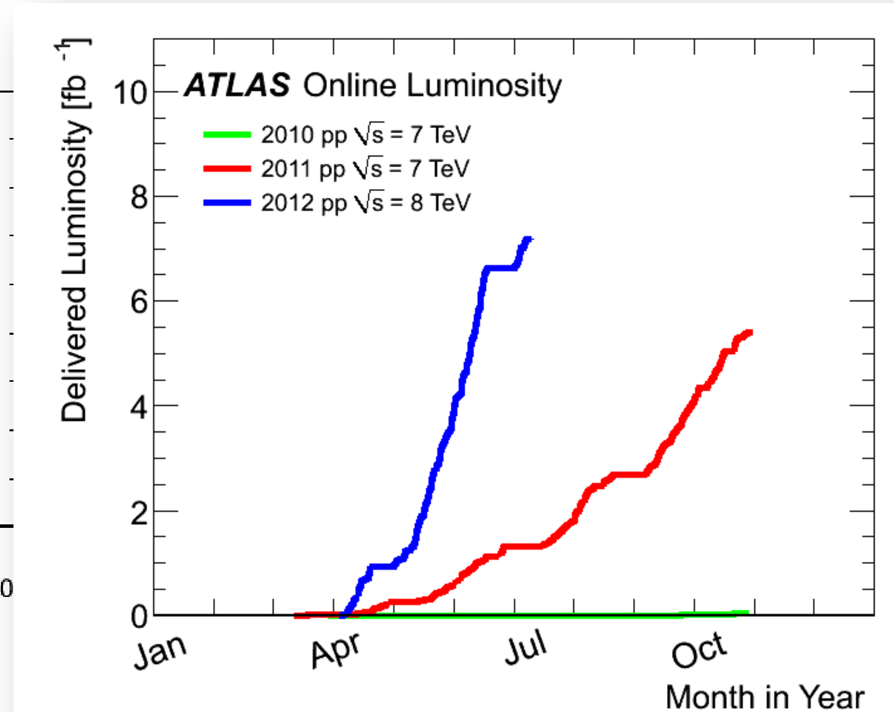
Improvements in last 2 years due to:

-Better beam understanding of aperture (smaller beam size σ)

-Number of bunches increased from 368 to up to 1380 (nominal 2808)

➔ Bunch spacing reduced from 150 to 50 (nominal 25 ns)





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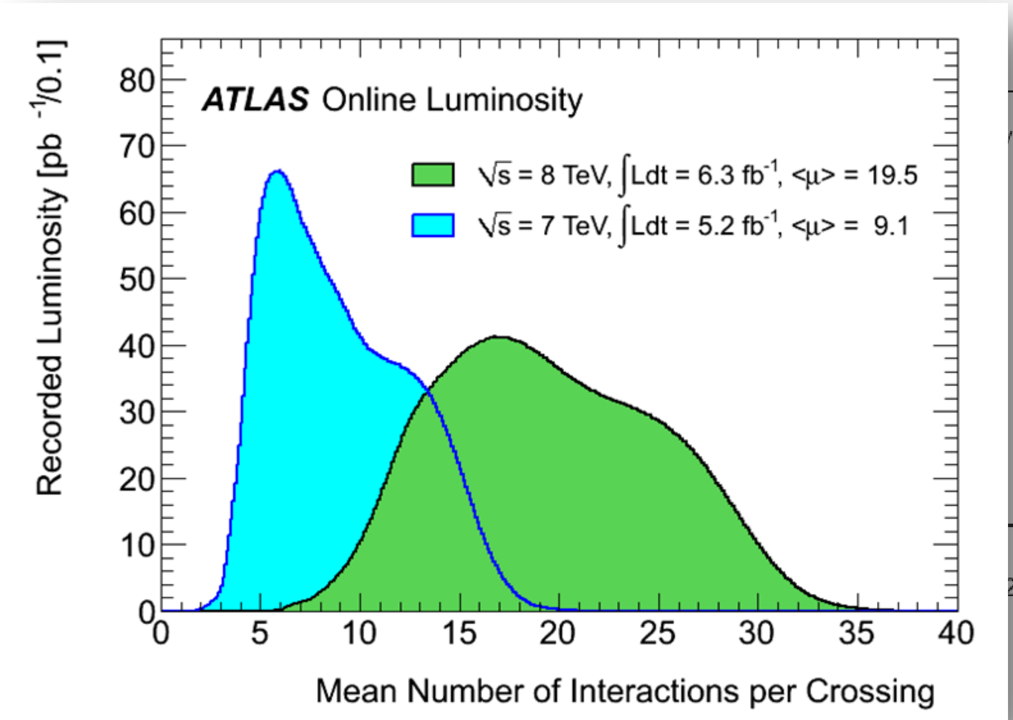
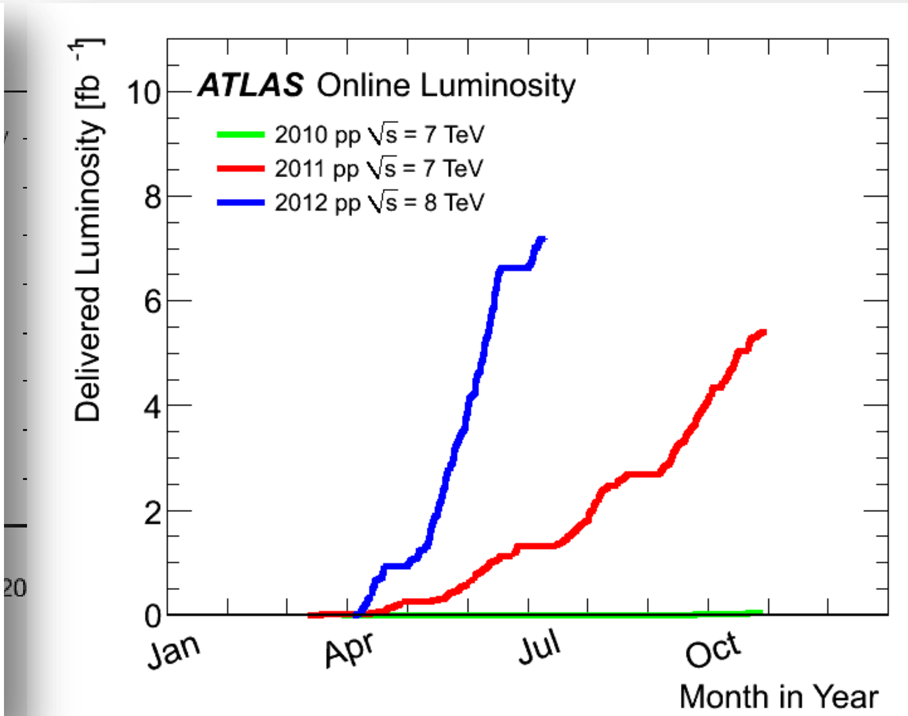
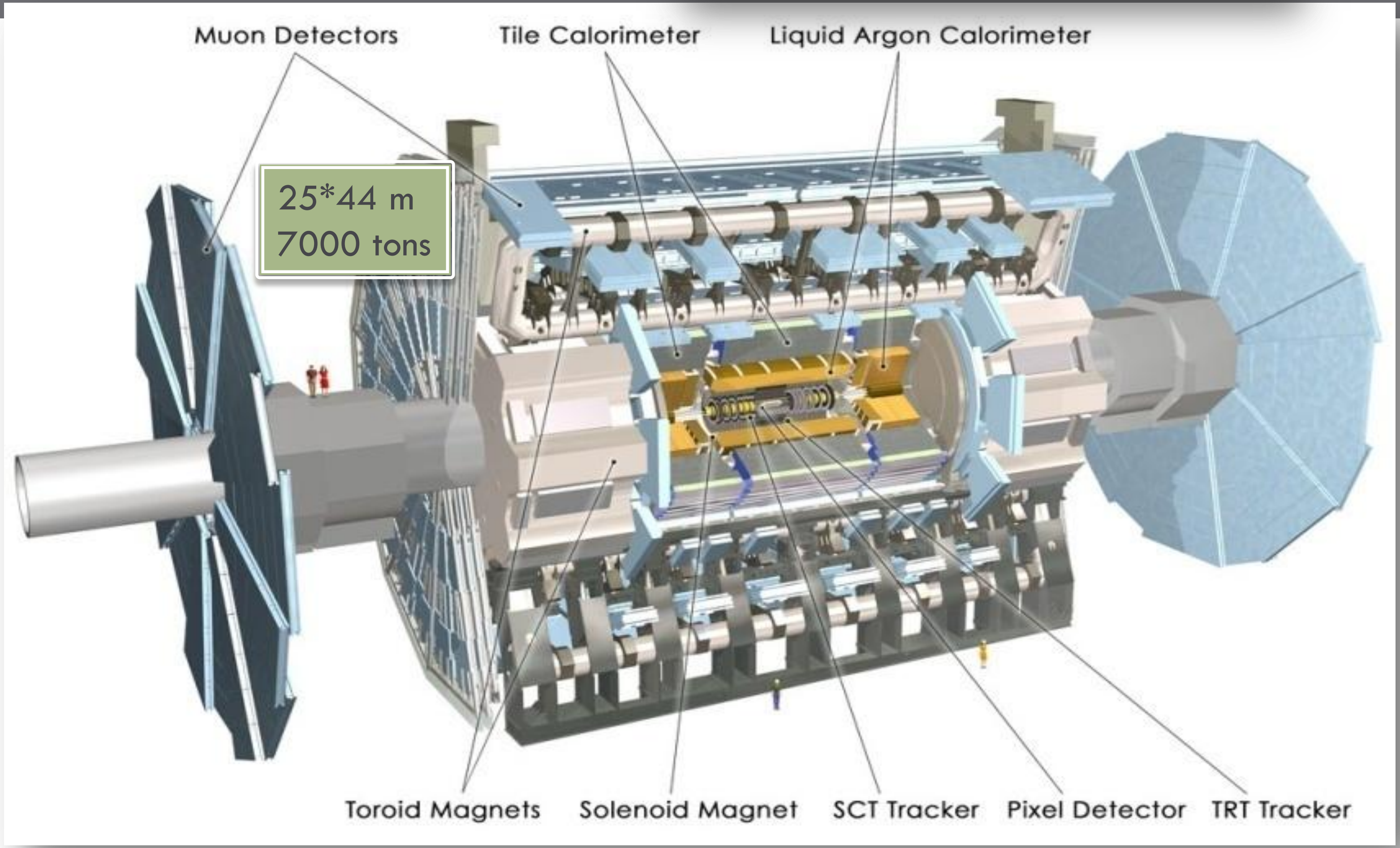


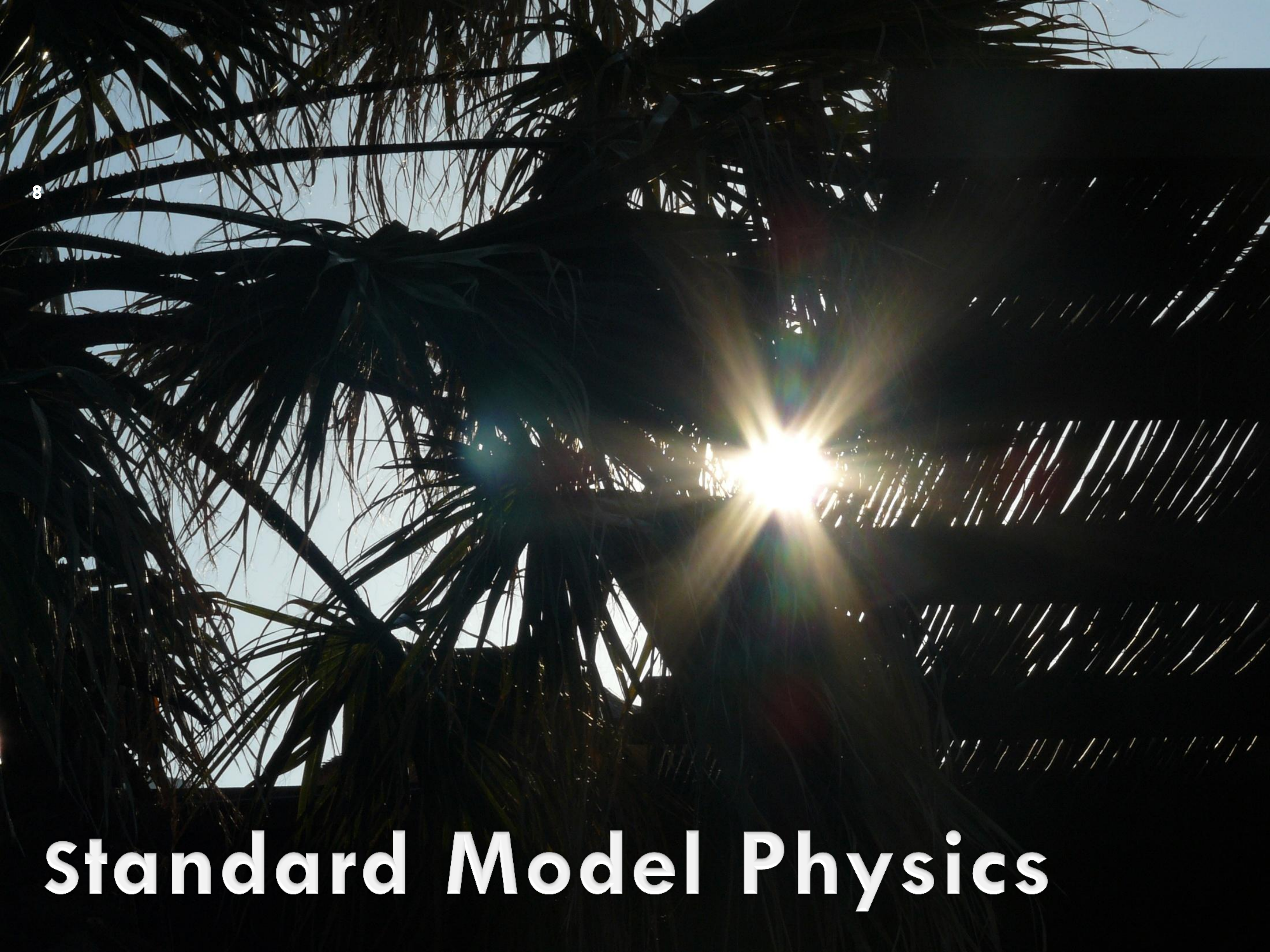


The ATLAS detector

The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.



Good operational status: ~ 99% of channels working!
Overall data taking efficiency ~ 95%
~90% of data taken with all sub-detectors fully operational

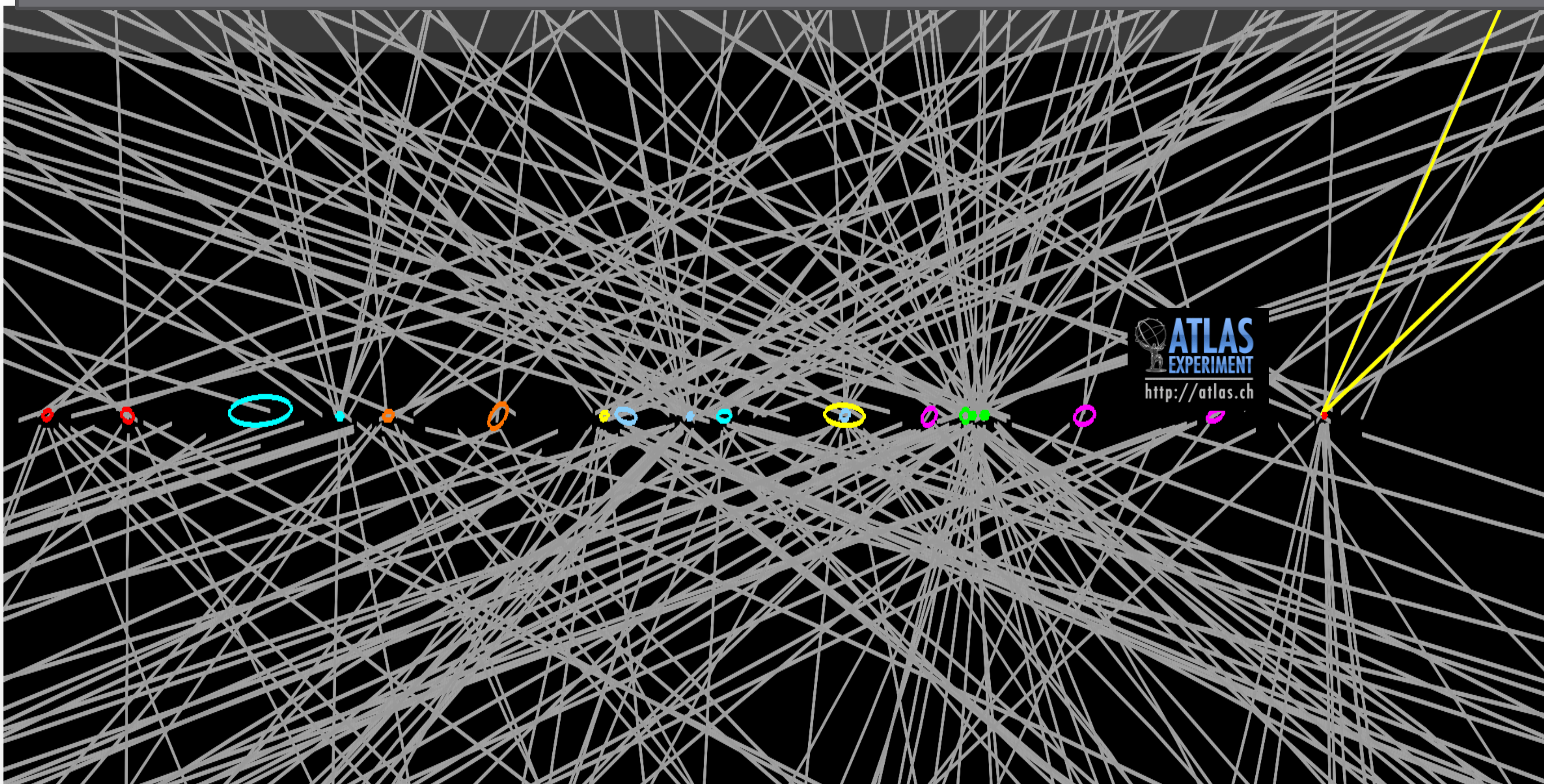


Standard Model Physics

Multiple interactions

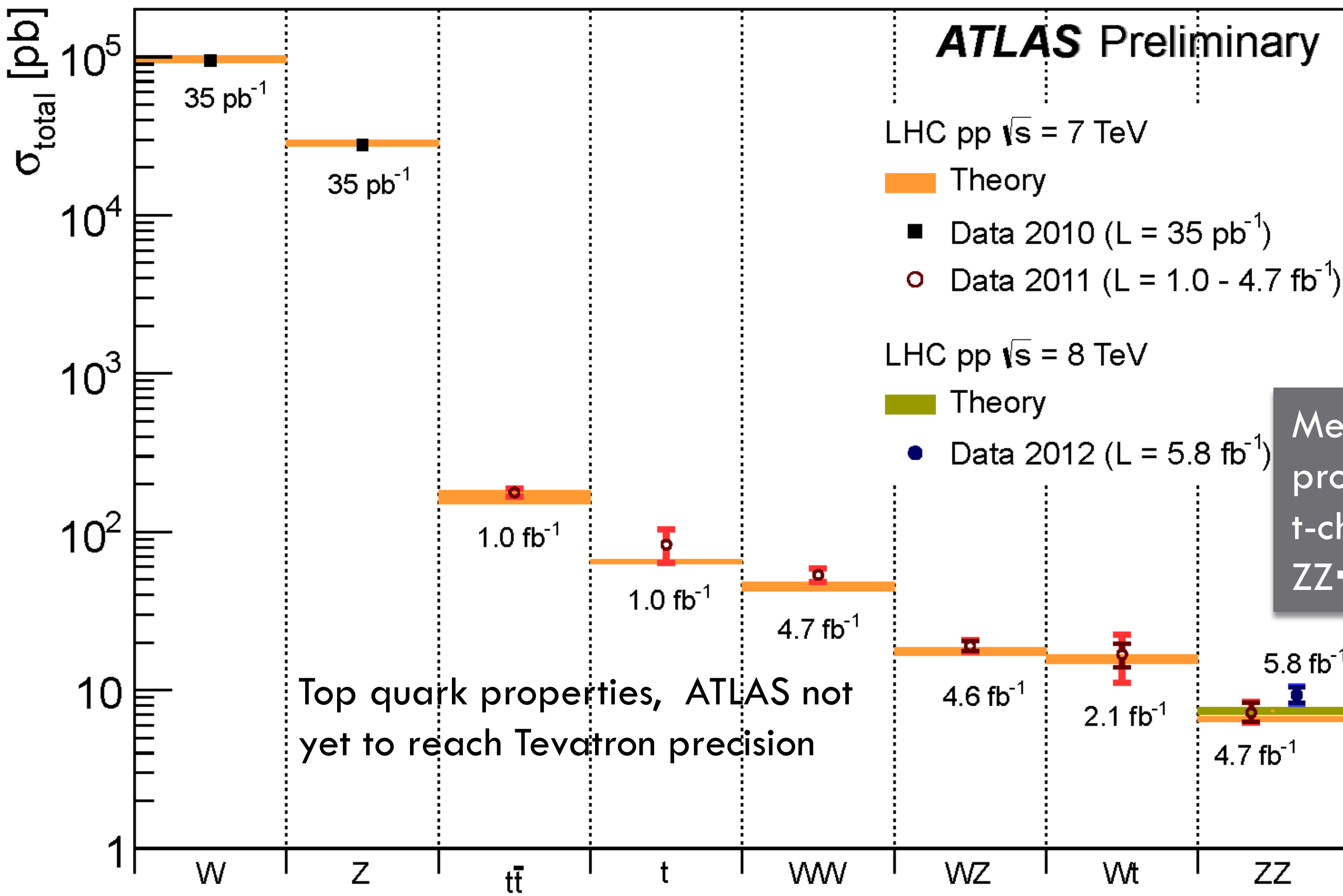
Challenge for 2012 data taking:

High rate of multiple interactions due to decreased beam size → Effects modeled in Monte Carlo simulations, challenge for particle IDs



Example of $Z \rightarrow \mu\mu$ decay with 20 reconstructed vertices (shown ± 15 cm, p_T (track) > 0.4 GeV

SM processes : Summary from ATLAS



Top quark properties, ATLAS not yet to reach Tevatron precision

Measurements of rare processes,
t-channel single top,
ZZ→ 4 leptons

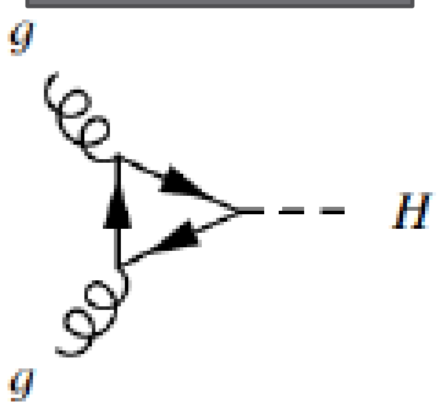
Conclusion SM@ATLAS

- Remarkable agreement with theoretical models in all published channels
- Let’s have a look at the searches

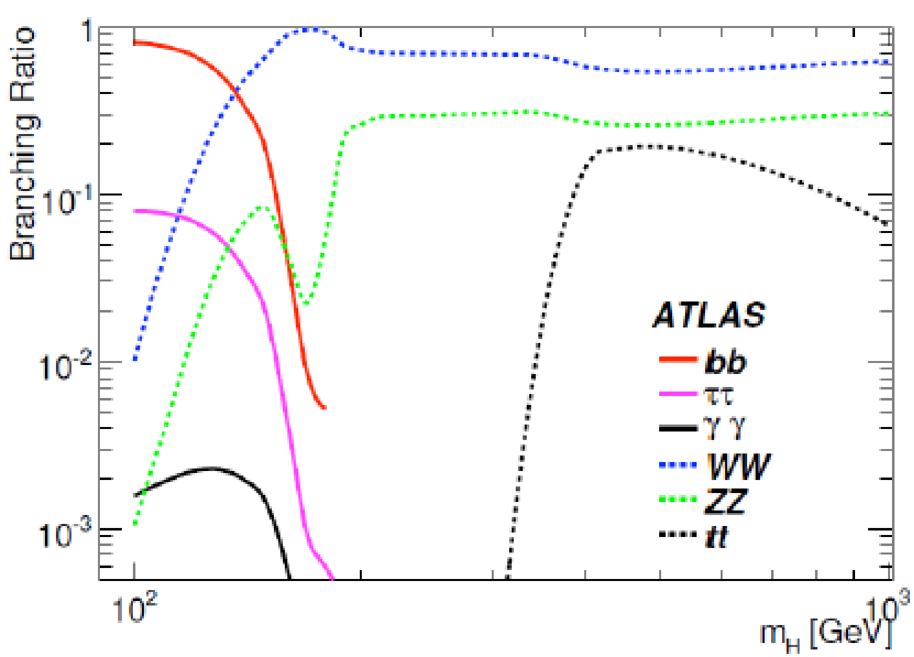
Standard Model Physics
The search for the SM Higgs boson

Higgs channels and their importance

Main production diagram



(a) $gg \to H$



High mass Higgs: WW, ZZ, tt

Low mass Higgs: Tautau, WW, ZZ, gammagamma, bbar

Analyse 2012 data : A few weeks time only

→ Concentrate on cleanest channels with best signal/background ratio

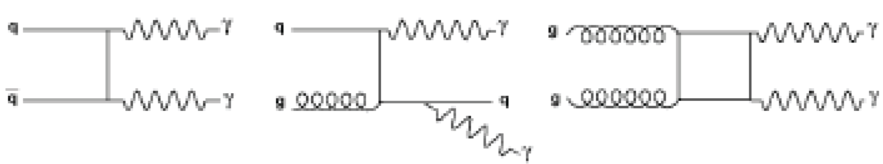
→ ZZ and gamma gamma

Low Mass Higgs Search : H→ γγ

-Small branching ratio (0.002) σ x BR ~ 50 fb mH ~ 126 GeV
-Higgs decays via top and W loops
Advantage: **Nice 2 photon mass peak!**
-Main background from pi0's
-Need large jet rejection factors to reduce background and to see possible signal
→Photon identification is crucial ! (shower shapes, no track)
- Fit background with "assumed" function (**no peak in bkgr.**)

Reducible background: pp→γj , jj+ X

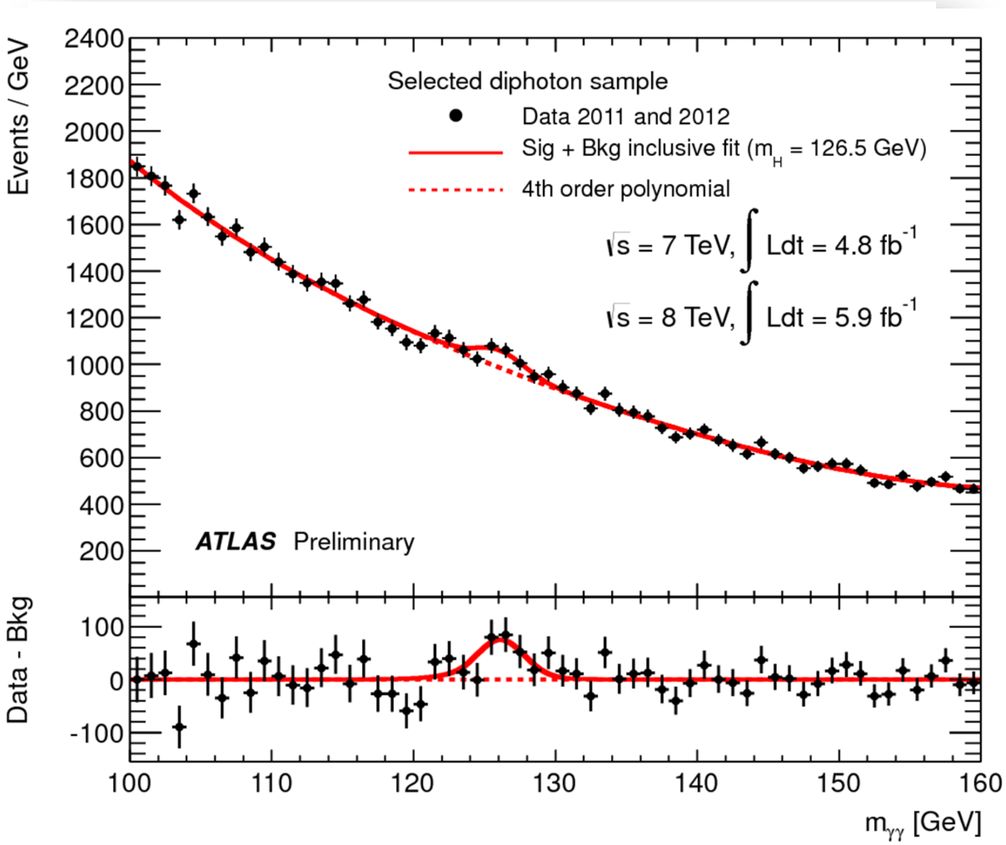
Irreducible background: pp→γγ + X

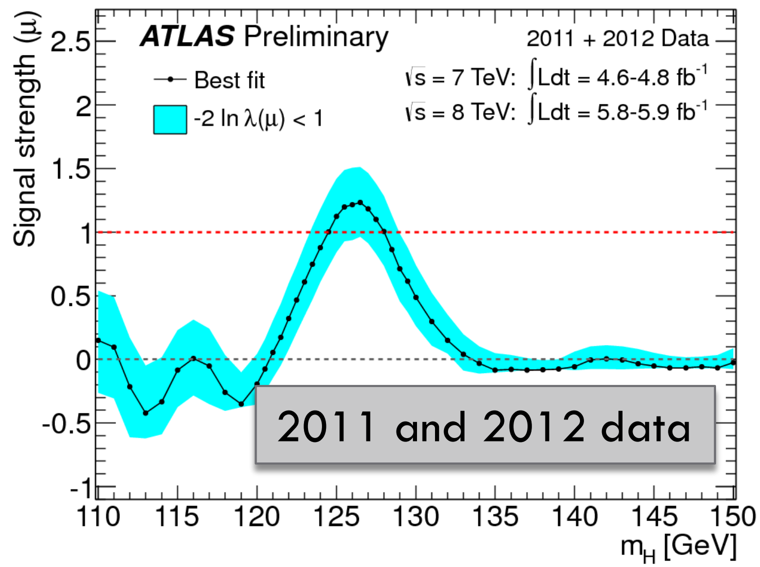


ATLAS

-Photon ID efficiency 85+-5 %
-Energy scale at Z mass known to 0.5 % (mass resolution 1.6 GeV at 125 GeV)
-Contribution to mass resolution from angular terms in negligible

Low Mass Higgs Search : H→ γγ



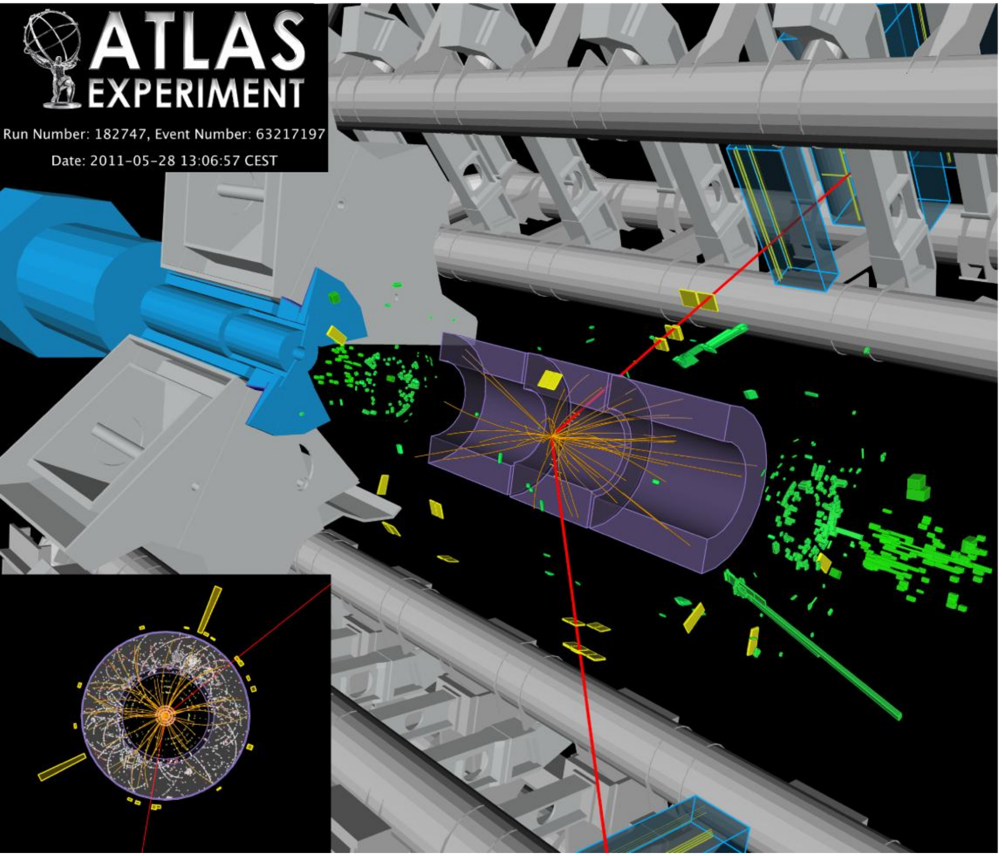


Events subdivided in categories to increase sensitivity !

2011+2012 conclusion:
Excluded (95% CL):
112-122.5 GeV, 132-143 GeV
Expected: 110-139.5 GeV

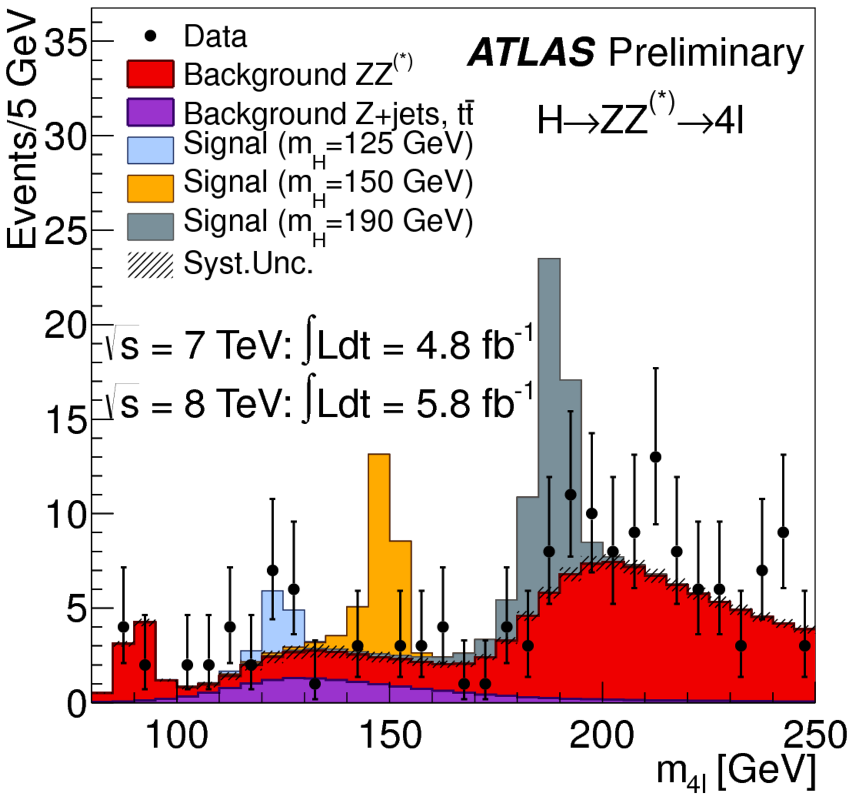
Local significance: **4.5 σ**

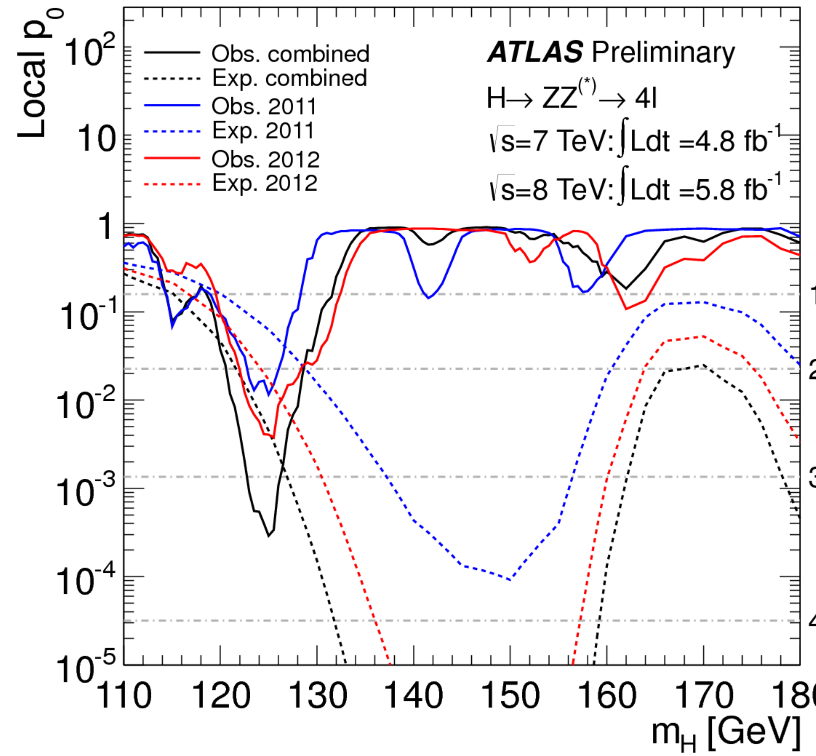
H → ZZ → 4e, 4μ, 2e 2μ : The Golden Channels



- Signal: 4 isolated lepton from common vertex
- Fully reconstructed, Mass resolution~ - 1.8 GeV at 130 GeV
- Reducible Backgrounds:
  - ttbar → 2l2v2b ; Z+bb
  - Removed by Isolation & Impact parameter requirements
- <u>Irreducible background: pp → ZZ Continuum</u>
- Event Selection: Same Flavor, opposite charge

H➔ ZZ golden channel





Background estimates:

-ZZ background estimated from MC (uncertainties 10-15%)

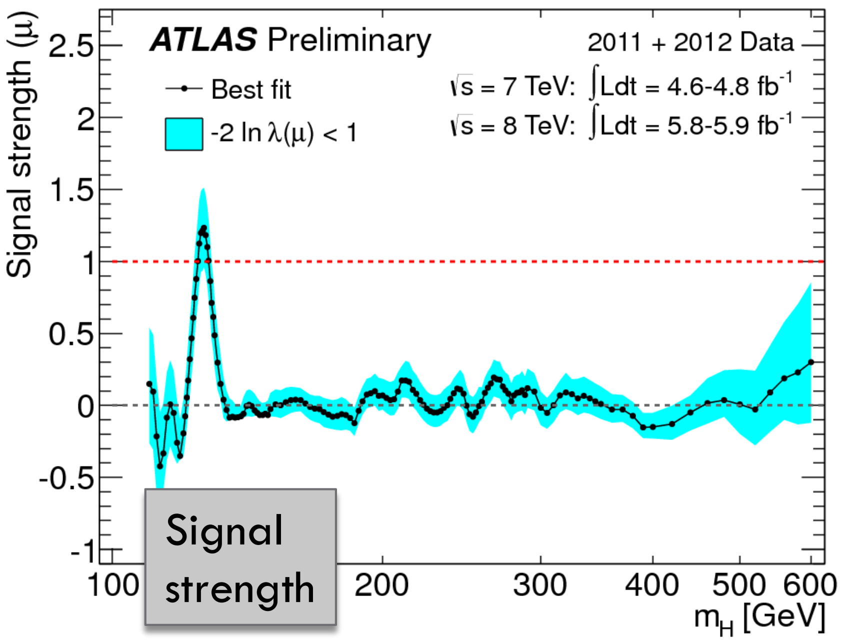
-Z+jets and top bkg. estimated from control region

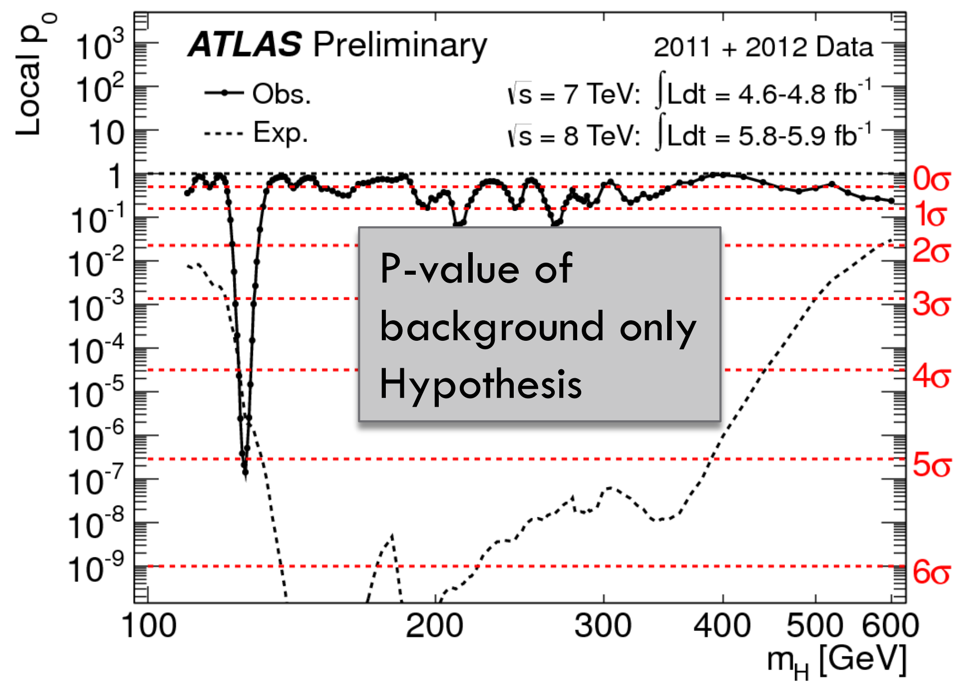
Combinations of channels

Best sensitivity by performing one combined statistical test of the SM Higgs hypothesis
➔ Build combined likelihood with all channels

2012 gamma gamma and ZZ
+ all 2011 channels

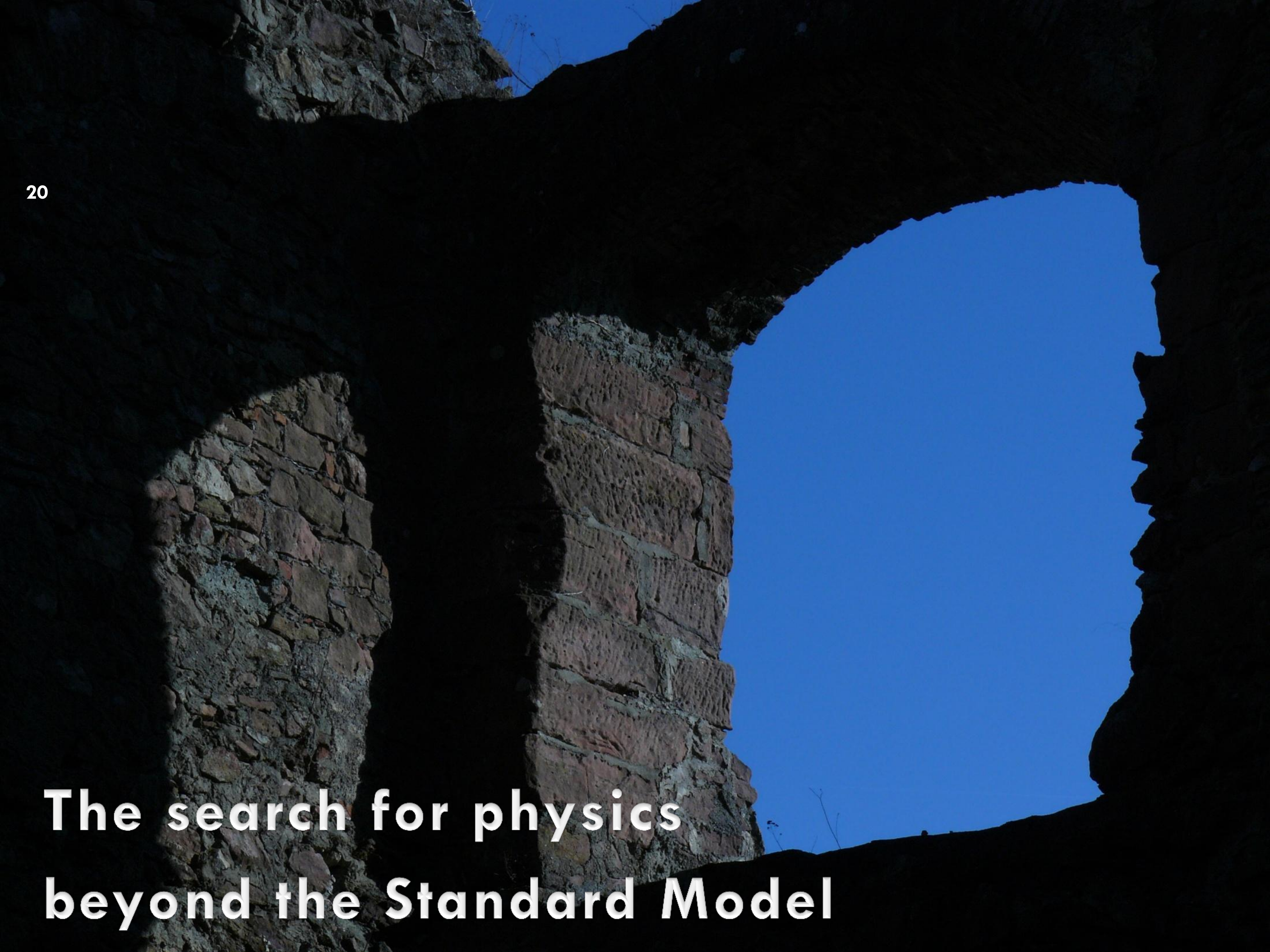
Combined ATLAS Higgs results





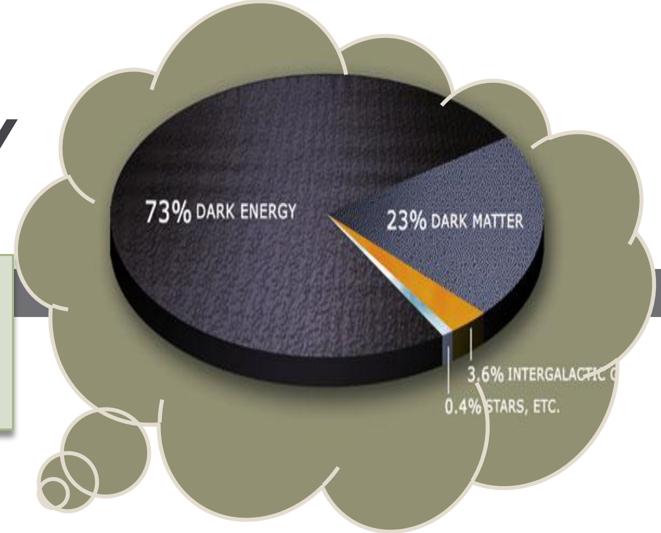
Due to look-elsewhere effect, systematics, etc.
we demand a 5-sigma deviation in both experiments
Combined signal strenght consistent with SM Higgs hypothesis

local significance of this excess is 5.0 σ



The search for physics beyond the Standard Model

Candidate Nr. 1 : SUSY



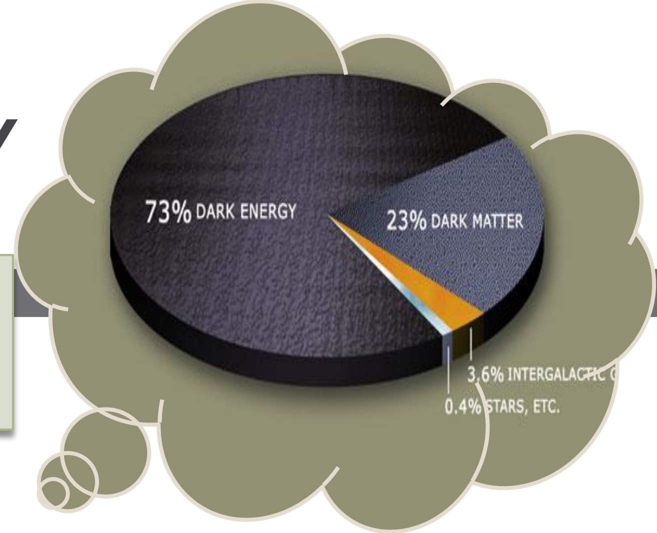
Most studied new physics theory for several reasons :

- "Easier QFT": Fermion and Boson loops protect the Higgs mass at large energies (reduces "fine tuning") if SUSY mass scale <u>is not too large</u> **(LHC)!**

- SUSY is a broken symmetry and thus offers (with R-parity conservation) weakly interacting massive particles for Dark Matter with a mass of O(100) GeV

- unification of 3 coupling constants at high energy in one point (GUT scale at 10^{16} GeV?), SUSY breaking connected to electroweak symmetry breaking ?

Candidate Nr. 1 : SUSY



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- "Easier QFT": Fermion and Boson loops protect the Higgs mass at large energie … not too large **(LHC)!**

- SUSY is a b …
  R-parity cons … s for Dark Matter with a …

- unification o … oint
  (GUT scale at 10 GeV?), SUSY breaking connected to electroweak symmetry breaking ?

Important drawback:

SUSY has not been found yet

➔ *some (small) fine tuning needed already in the model !*

Is SUSY still candidate Nr. 1 ?

… more on SUSY Higgs

- Mass of the lightest MSSM Higgs boson h0 must fulfill:
  $M(h^0) < \cos(2\beta)\, M_Z$

  Weakend to $M(h^0) <$ 135 GeV if radiative corrections are included

  "Aha, SUSY predicts a low mass higgs."

Higgs of 126 GeV consistent with
a) Degenerate stops
b) Quite heavy stops

Scenario might be

- 1st and 2nd gen. heavy
- Light stop caused by naturalness
- Somehow light gluino

Most sensitive at early LHC:

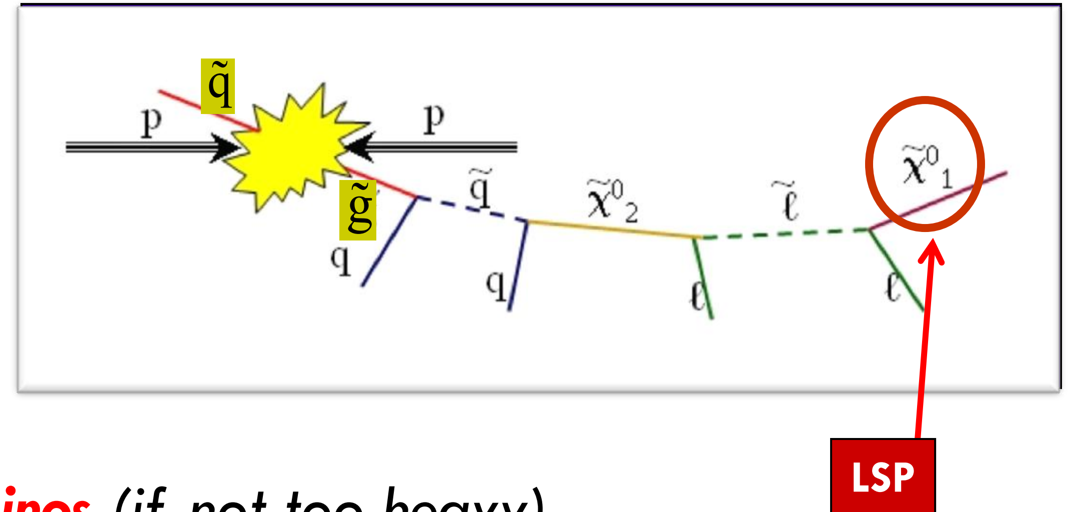
- SUSY search for squarks and gluinos

Maybe most sensitive if 1st and 2nd generation squarks are heavy due to 126 GeV Higgs :

- stop searches
- gluino searches

SUSY and the LHC : Signal

If R-Parity is conserved then SUSY particles are pair produced



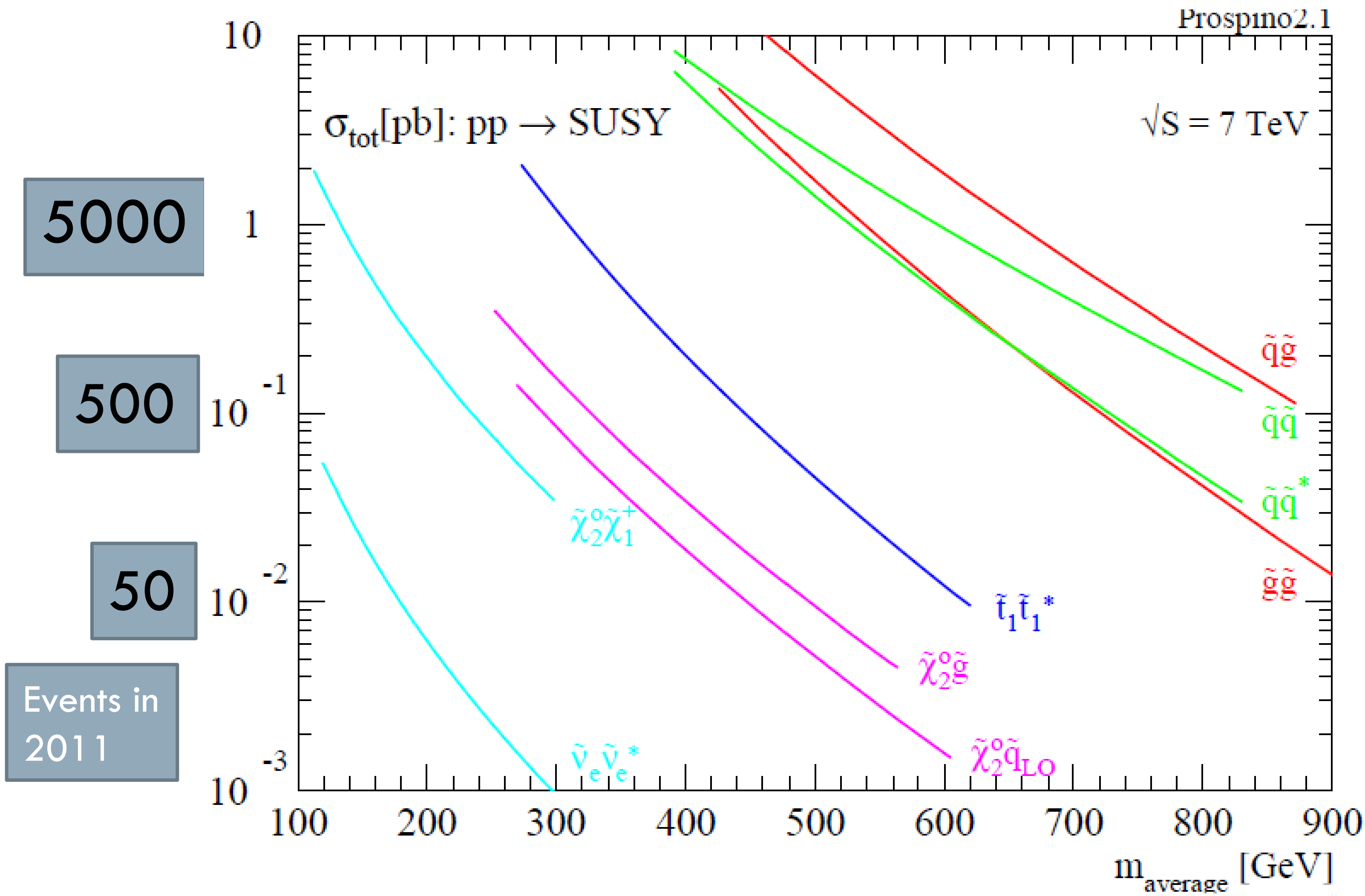
LHC:

Due to strong force dominant production of ***squarks*** *and* ***gluinos*** *(if not too heavy)*
Cascade decay to lighter SUSY particles and finally the lightest SUSY particle (LSP)

Similar conclusions /channels For many other models (Universal Extra Dimension, ADD, Little Higgs, ….)

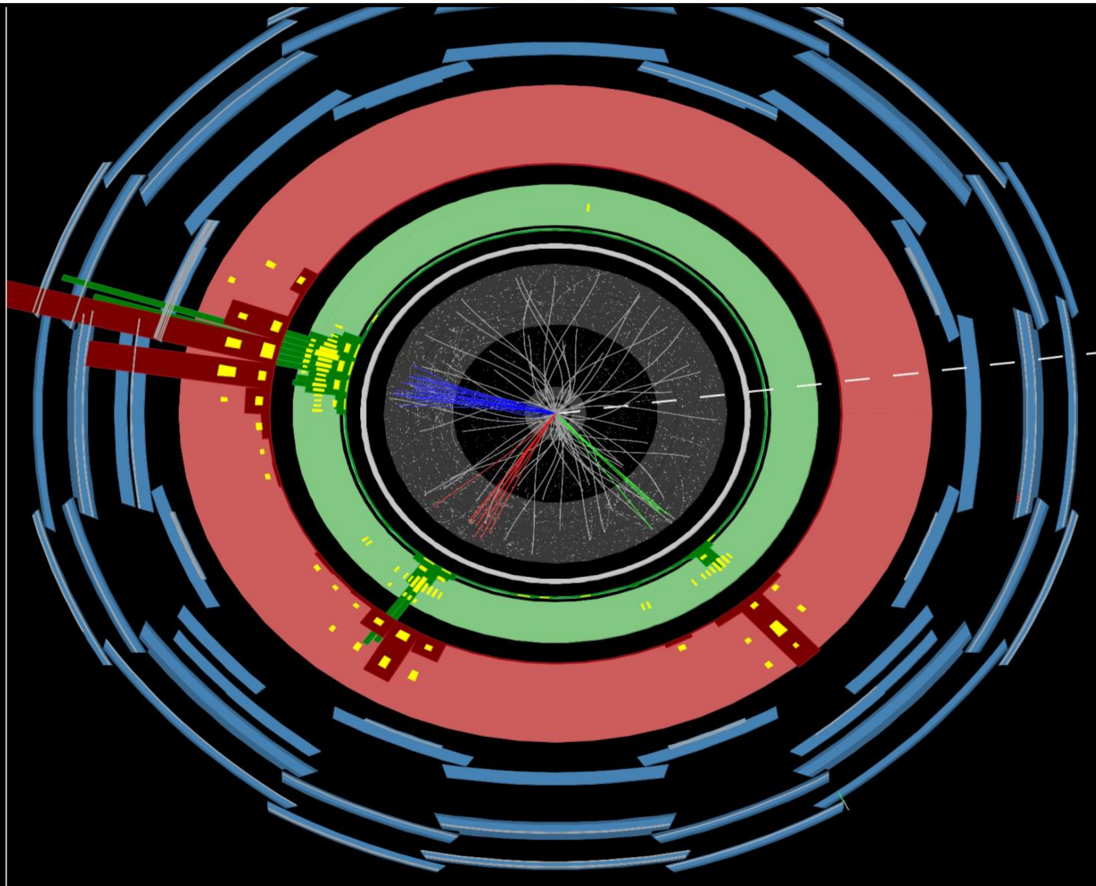
Mass pattern in general SUSY unknown ! Searches need to be quite general and model-parameter-independent

Production rate



3 jets with p_T of approximately 400 GeV, 120 GeV, 60 GeV and E_t^{miss} of approximately 420 GeV

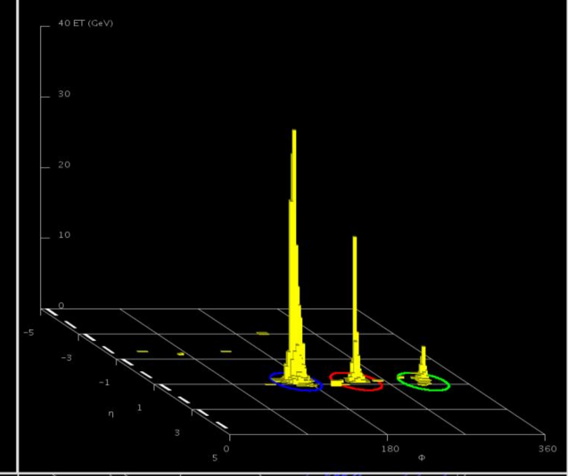
Event found in signal region of jet+ E_t^{miss} Analysis in 2010 data

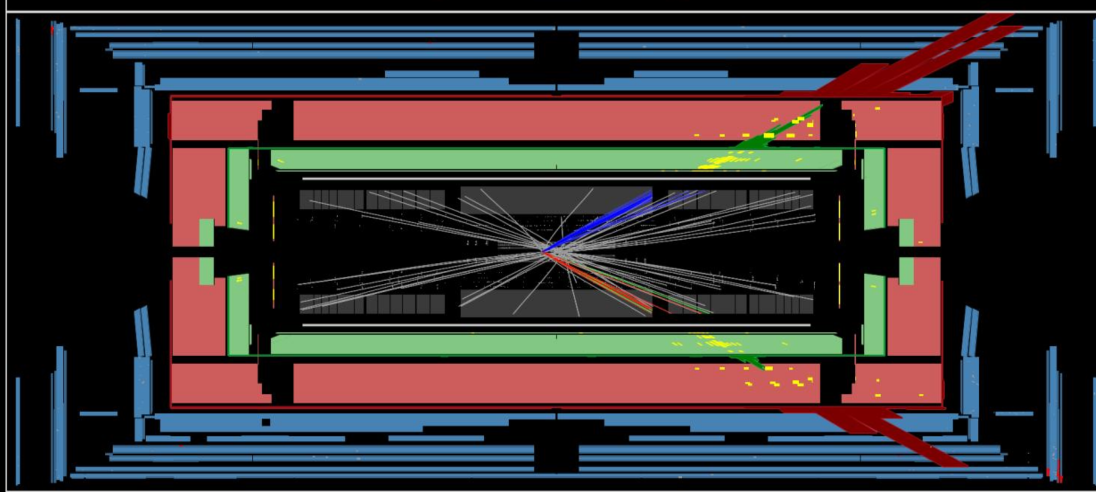


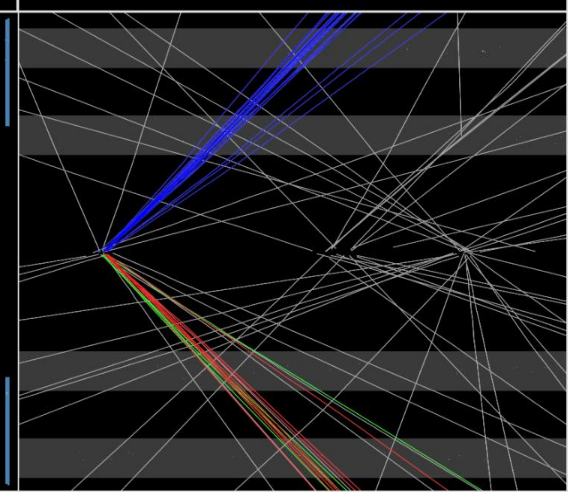
ATLAS EXPERIMENT

Run Number: 167607, Event Number: 104148673

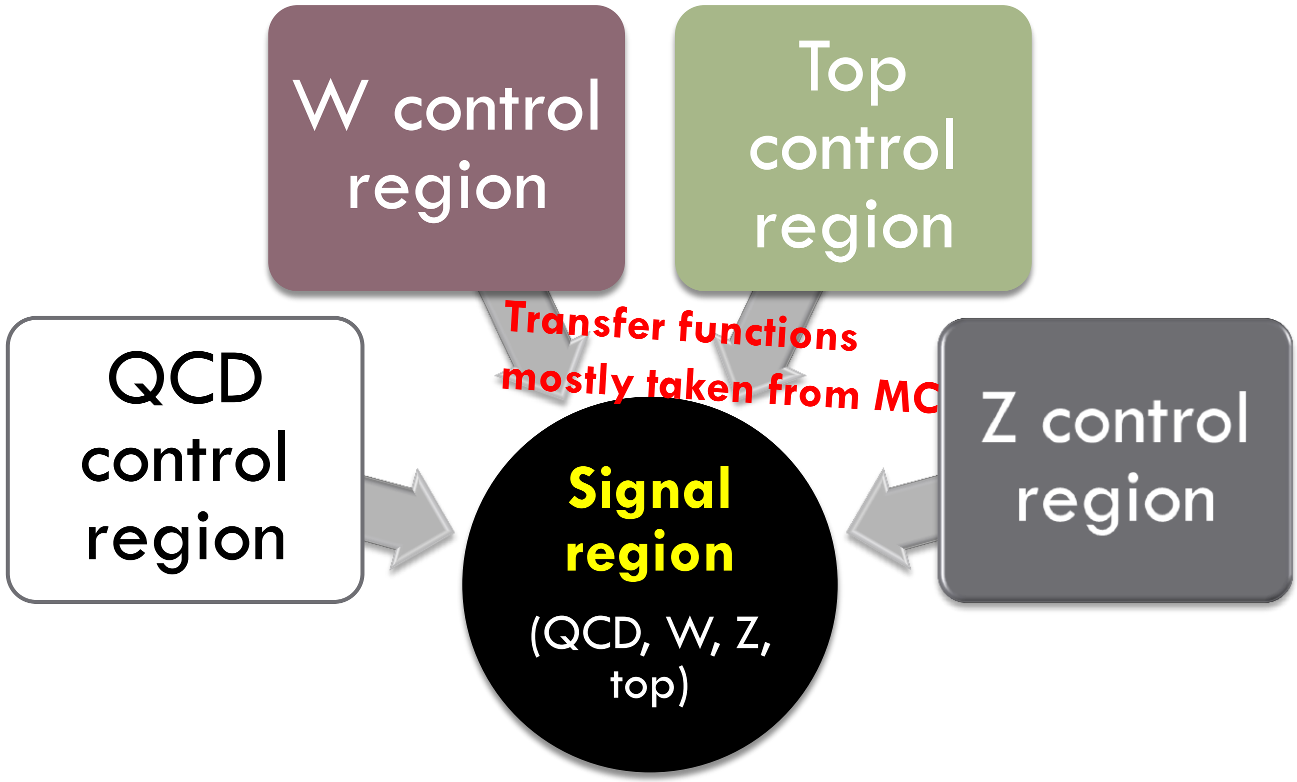
Date: 2010-10-25 11:44:55 CEST







Analysis model - control regions



- Measure number of events in control selections
- Predict number of events in signal region via a fit to control regions
- Important : Test model and transfer functions
  (e.g. by alternative control regions or methods)

SUSY searches overview

Short Title of the CONF note	Date	√s (TeV)	L (fb^{-1})	Document	Plots
Monophoton [ADD, WIMP] NEW	07/2012	7	4.7	ATLAS-CONF-2012-085	Link
Monojet [ADD, WIMP] NEW	07/2012	7	4.7	ATLAS-CONF-2012-084	Link
3 leptons + Etmiss [Direct Gauginos] NEW	07/2012	7	4.7	ATLAS-CONF-2012-077	Link
2 leptons + Etmiss [Direct Gauginos/sleptons] NEW	07/2012	7	4.7	ATLAS-CONF-2012-076	Link
Long-Lived Particles [R-hadron, slepton] NEW	07/2012	7	4.7	ATLAS-CONF-2012-075	Link
0 lepton + jets + Etmiss [Heavy Stop] NEW	07/2012	7	4.7	ATLAS-CONF-2012-074	Link
1 lepton + jets + Etmiss [Heavy Stop] NEW	07/2012	7	4.7	ATLAS-CONF-2012-073	Link
2 photons + Etmiss [GGM] NEW	07/2012	7	4.8	ATLAS-CONF-2012-072	Link
2 leptons + jets + Etmiss [Medium stop] NEW	07/2012	7	4.7	ATLAS-CONF-2012-071	Link
1-2 bjets + 1-2 leptons + jets + Etmiss [Light Stop] NEW					
2 leptons + jets + Etmiss [Very Light stop]					
3 bjets + 0lepton + jets + Etmiss [Gluino med. stop/sbo					
1 lepton + 3-4 jets + Etmiss					
Disappearing track + jets + Etmiss [AMSB]					
0 lepton + >=(2-6) jets + Etmiss					
Add. >=4 leptons + Etmiss Interpretation [RPV]					
Long lived Particle (Pixel-like)					
>=4 leptons + Etmiss	01/2012	7	2.05	ATLAS-CONF-2012-001	Link (inc. HEPData)
Z->ll + jets + Etmiss [GGM]	04/2012	7			
Add. 2 leptons + jets + Etmiss interpretation [GMSB]	11/2011	7			

ATLAS hunts now with a twofold strategy:

- Broad inclusive searches with many signal regions
- Highly optimized dedicated searches for exclusive SUSY signals

Also various searches on R-Parity violation

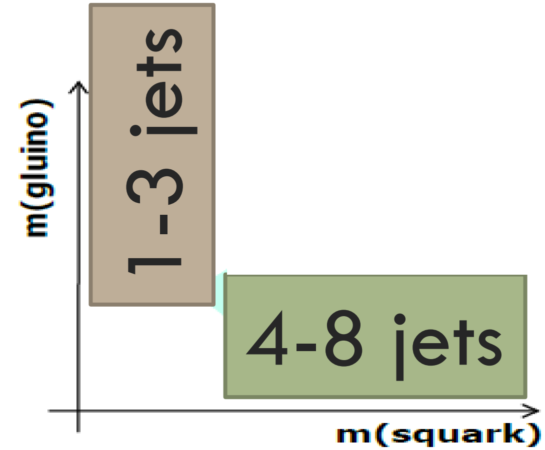
Example: Jets + E_t^{miss}

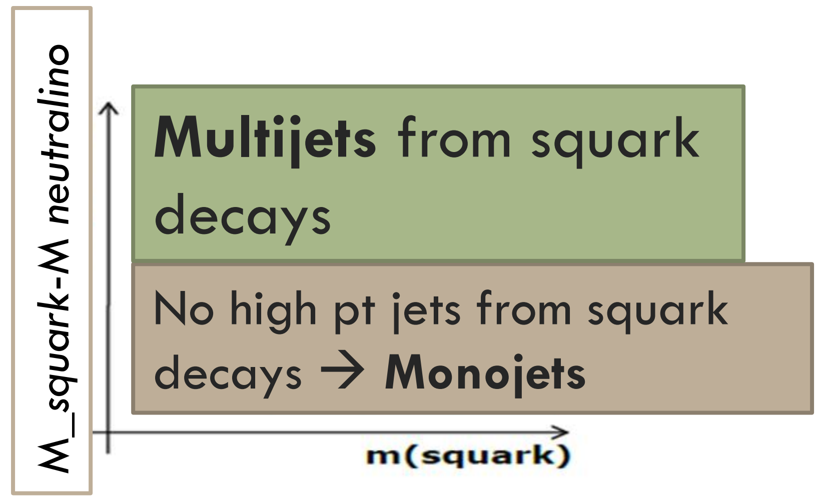
Studies are about 15 signal regions

From monojets to >8 jet events
(jets from squark/gluino decay
or if mass difference to LSP to low
No jets from squark/gluino decay)

From low E_t^{miss} to high E_t^{miss}
(best cut depends on ratio of produced
particle mass to neutralino mass)

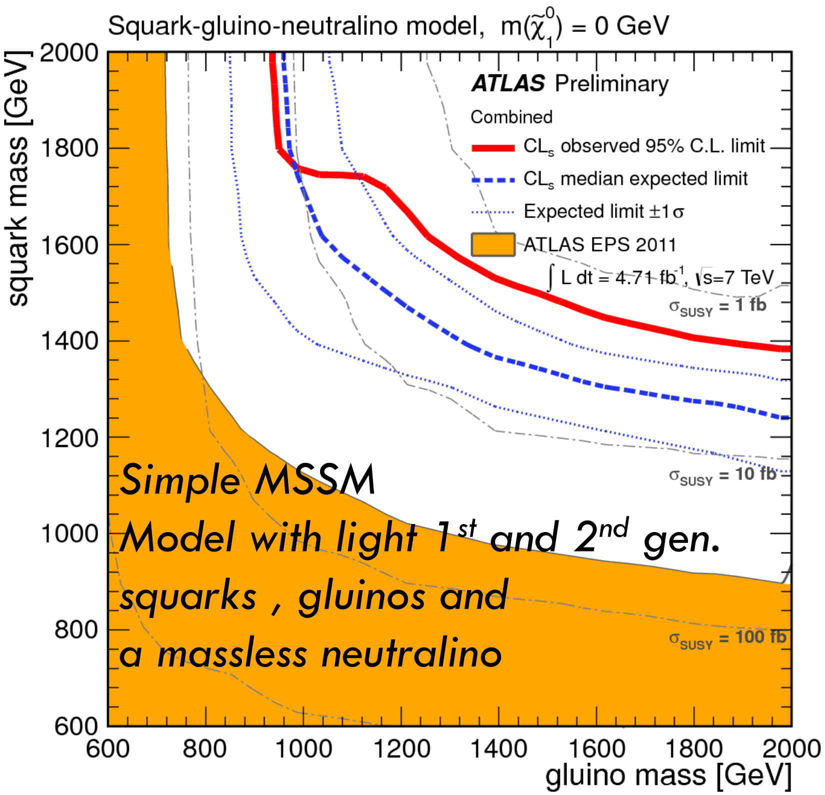
From high mass to low mass



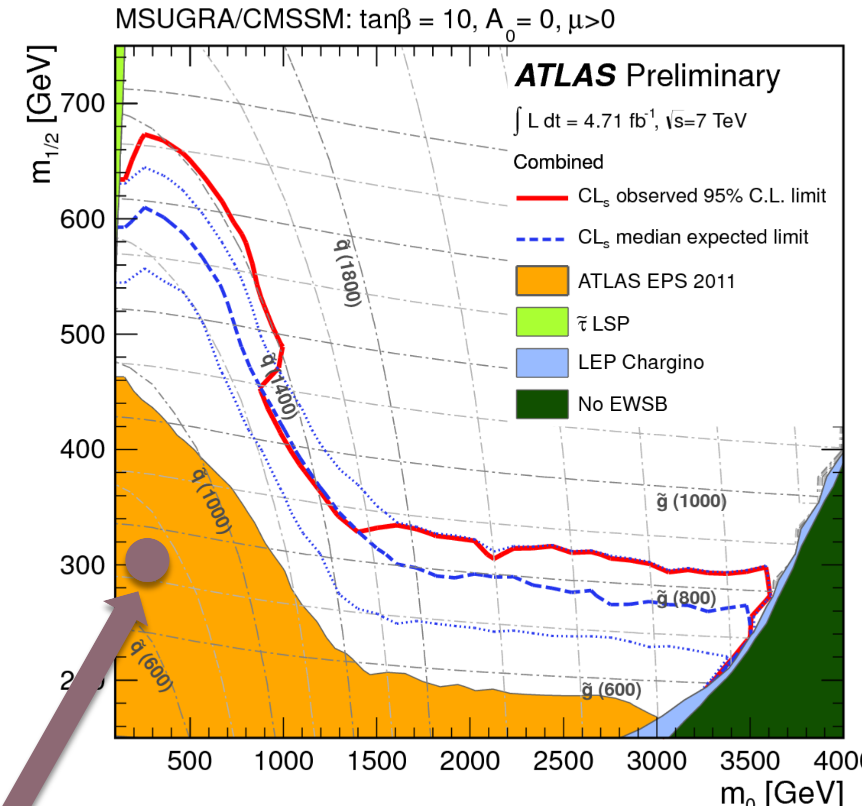


Jets + E_t^{miss} : Results on 2011 data

Constrained MSSM Model with common Fermion and Boson Masses at the GUT scale



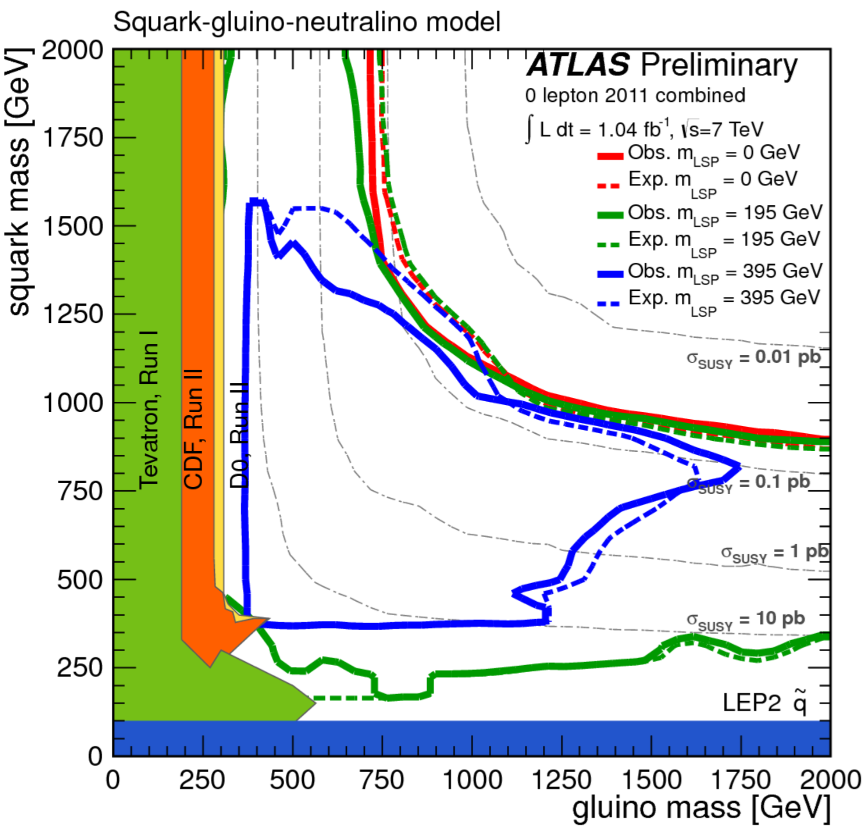
Simple MSSM
Model with light 1st and 2nd gen.
squarks , gluinos and
a massless neutralino



2009 "Best fit" cMSSM fit pre-LHC

Exclusion reach not strongly sensitive to sign(mu), tan beta and A_0

Jets + E_t^{miss} : LSP mass dependence



Not full dataset

SUSY parameter space very large !

Here e.g. dependence of limits on neutralino (LSP) mass (old data)

Investigated now with projections on “relevant” parameters (simplified models)

You can make your own limit for any model with a fast det. sim..
We are providing model independent limits on sigma * BR * efficiency
efficiencies etc. *at hepdata*

Stop search

- **Stop decays**

  Stop → top neutralino *(if kinematically allowed, and no chargino..)*

  Stop → b chargino *(if chargino is light enough and likes to couple)*

  Stop → charm neutralino *(if stop is heavier than chargino +LSP)*

  (also other options)

- **Possible stop production**

  - **direct production**

    → Does not depend on other parameters (light gluino)

  - **produce gluinos which decay to stops**

    → Potentially large cross section

    → Easier to detect

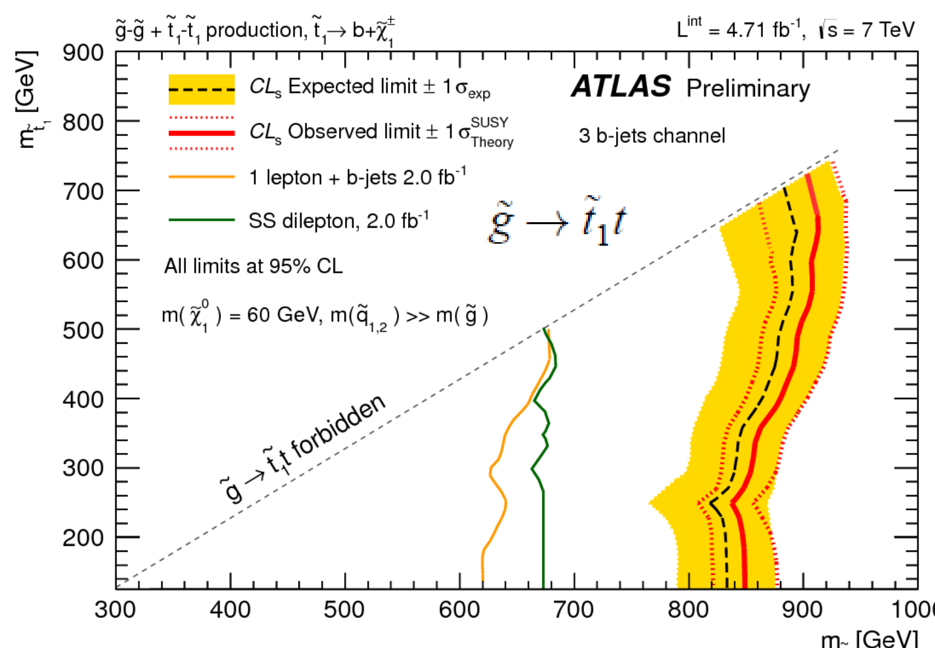
3rd generation example analysis

SR	$t\bar{t}$+jets (MC)	others	SM	data
SR4-L	33.3 ± 7.9 (32.6 ± 15.4)	11.1 ± 4.9	44.4 ± 10.0	45
SR4-M	16.4 ± 4.1 (16.1 ± 8.4)	6.6 ± 2.9	23.0 ± 5.4	14
SR4-T	9.7 ± 2.1 (11.4 ± 5.4)	3.8 ± 1.6	13.3 ± 2.6	10
SR6-L	10.3 ± 3.3 (10.0 ± 6.2)	2.4 ± 1.4	12.7 ± 3.6	12
SR6-T	8.3 ± 2.4 (7.9 ± 5.3)	1.6 ± 1.1	9.9 ± 2.6	8

- Searching in events with 4-6 jets **where 3 jets are tagged as b-jets** and large missing transverse momentum

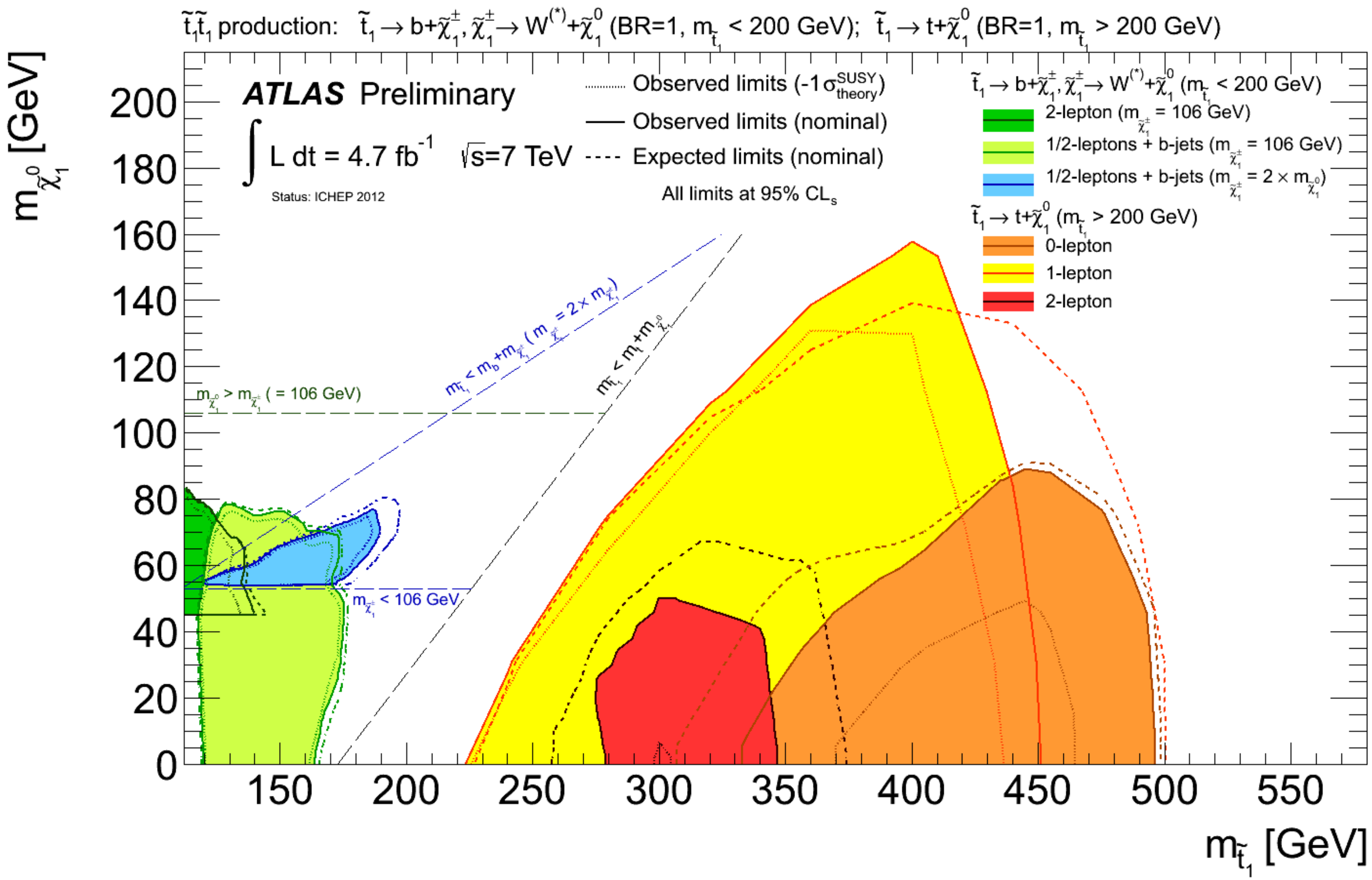
Consider, among others, models where gluino decays 100% to stop and top and stop decays to

$$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$$



Gluino masses up to 1 TeV are excluded

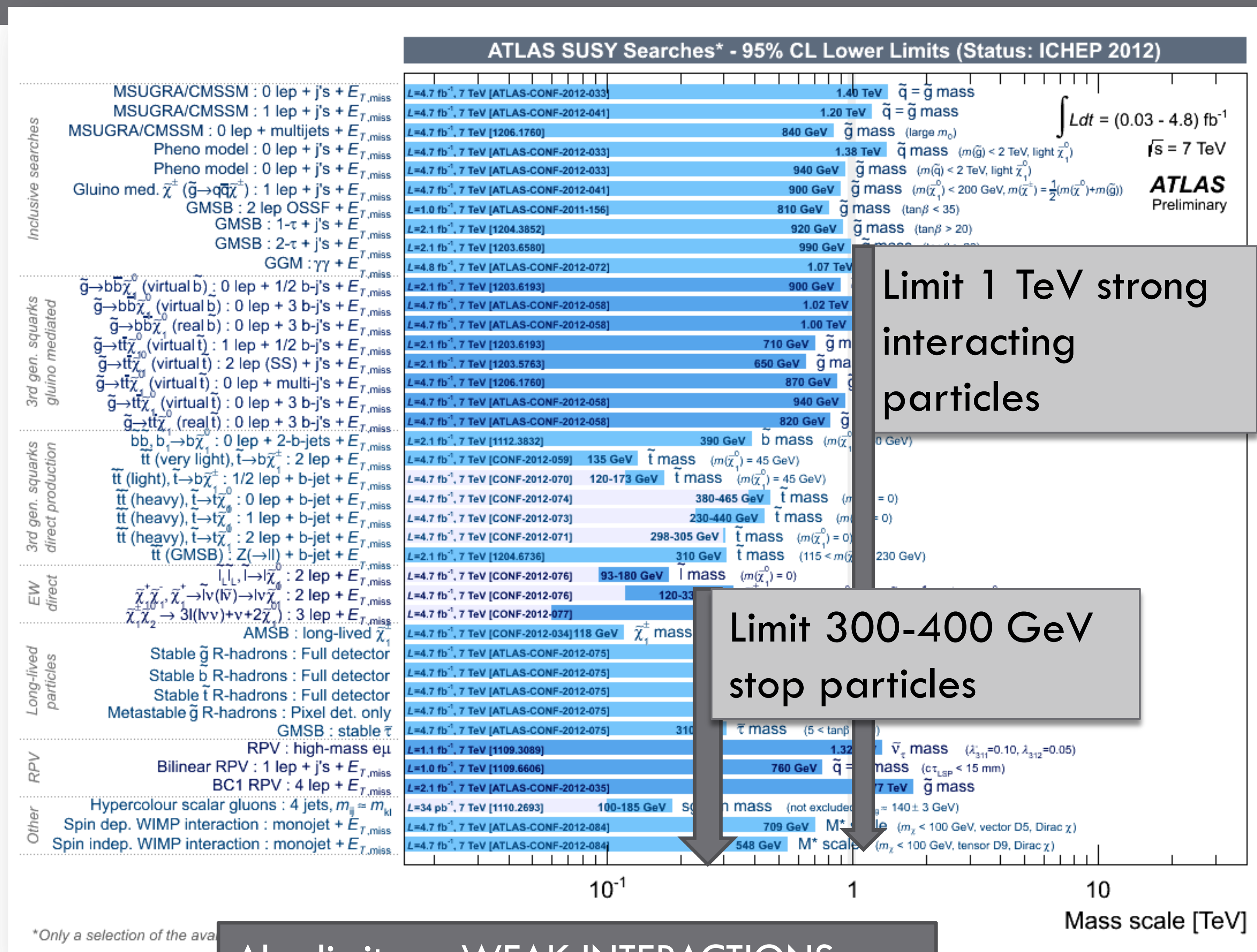
Summary direct stop production



DM production in SUSY decays

Summary of current limits, mostly on the production of Squarks and Gluinos

→Strong constrains on SUSY models



Limit 1 TeV strong interacting particles

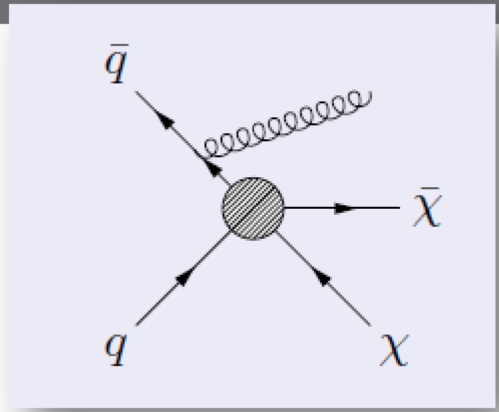
Limit 300-400 GeV stop particles

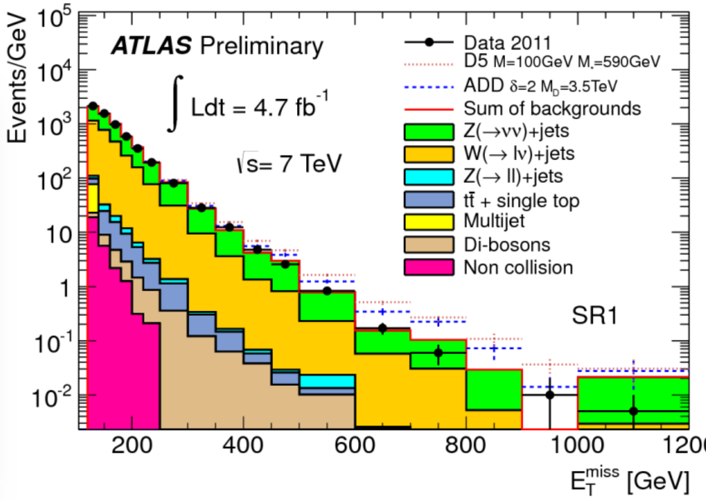
Also limits on WEAK INTERACTIONS now

Monojets/Monophotons

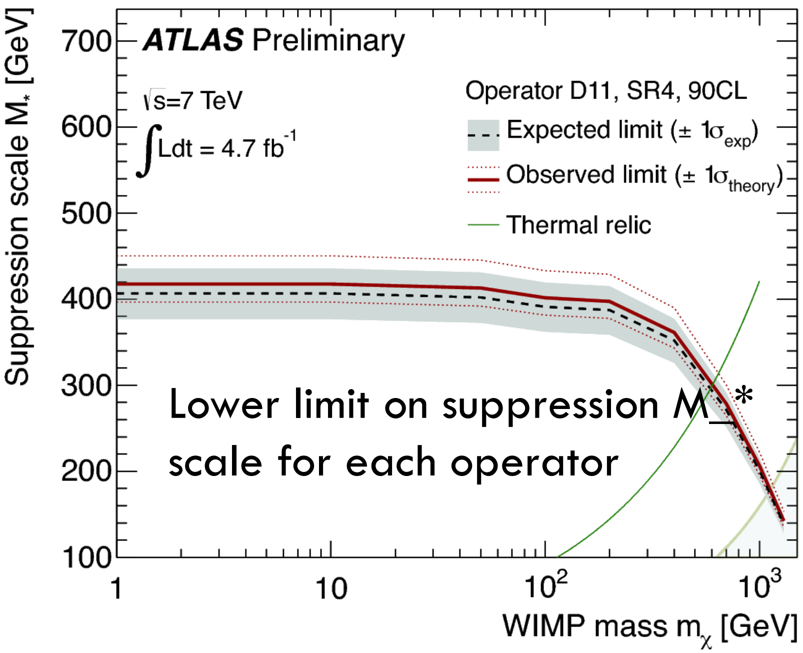
Looking for a jet from initial state Radiation to search for WIMP WIMP Events

- Signal is a Monojet/monophoton event !
- Missing momentum distribution





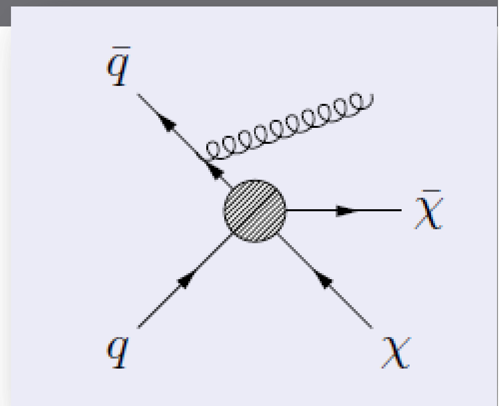
Assuming coupling ATLAS monojet searches can give bounds on WIMP-nucleon spin dependent cross section **(assuming heavy mediator with free coupling)** *Collider limit competitive if WIMP couple only via D11 (gg) coupling and for very low WIMP masses*



Monojets/Monophotons

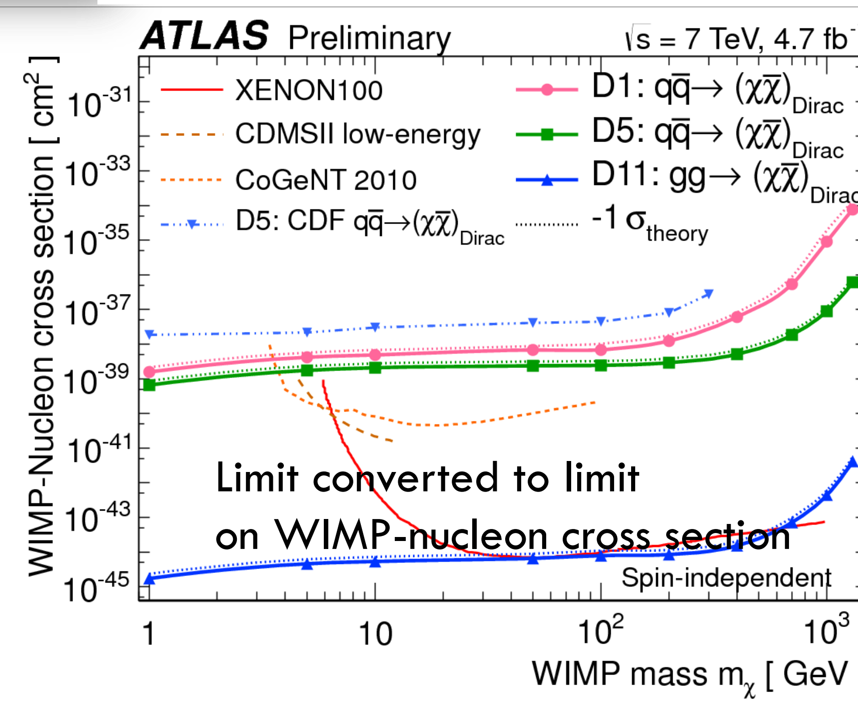
Looking for a jet from initial state Radiation to search for WIMP WIMP Events

- Signal is a Monojet/monophoton event !
- Missing momentum distribution



Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Assuming coupling ATLAS monojet searches can give bounds on WIMP-nucleon spin dependent cross section **(assuming heavy mediator with free coupling)** *Collider limit competitive if WIMP couple only via D11 (gg) coupling and for very low WIMP masses*



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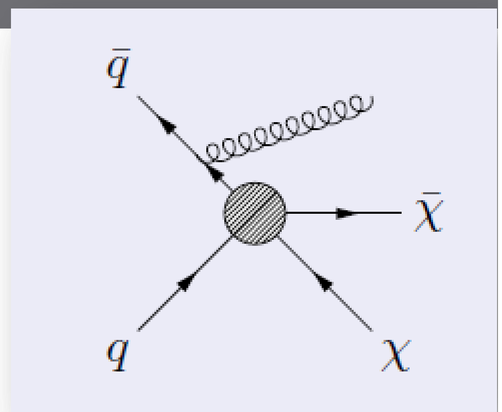

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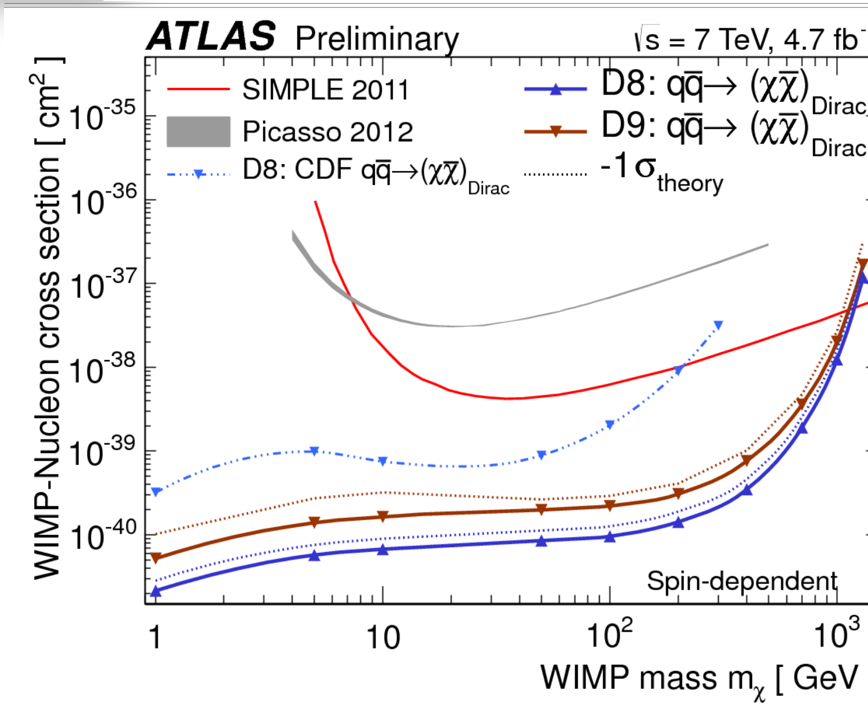

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No SUSY ? → Are there ways out …

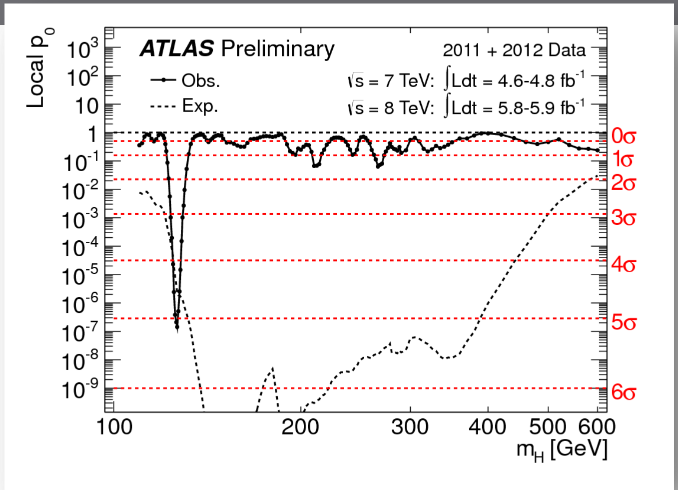
- Maybe SUSY is hidden ?
- → Close the gaps, e.g. low mass splittings, long decay chains
- → Search for a initial state radiation + NOTHING → Monojets
- Or SUSY is a bit heavier ?

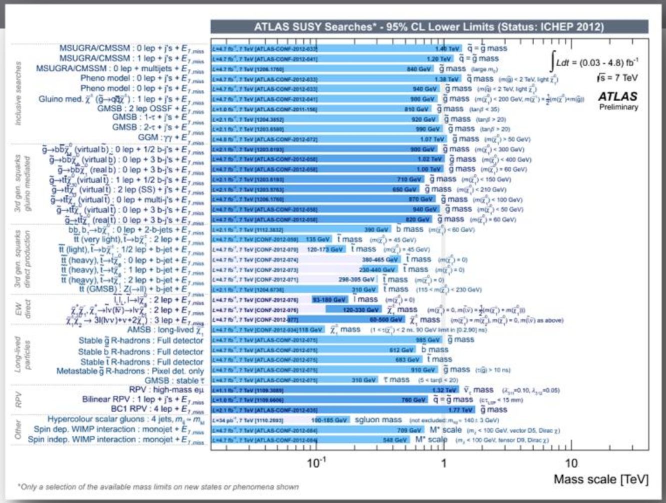
  - For electroweak symmetry breaking not all SUSY particles have to be close to the 1 TeV scale, light stop and heavy 1st and 2nd gen. fermions

  - If the Higgs is around 125 GeV, usually stop heavier, also other **SUSY particles expected to be >1 TeV ?**
- **Or SUSY looks a bit different ?**

  - Extend searches to non-standard SUSY scenarios

Summary



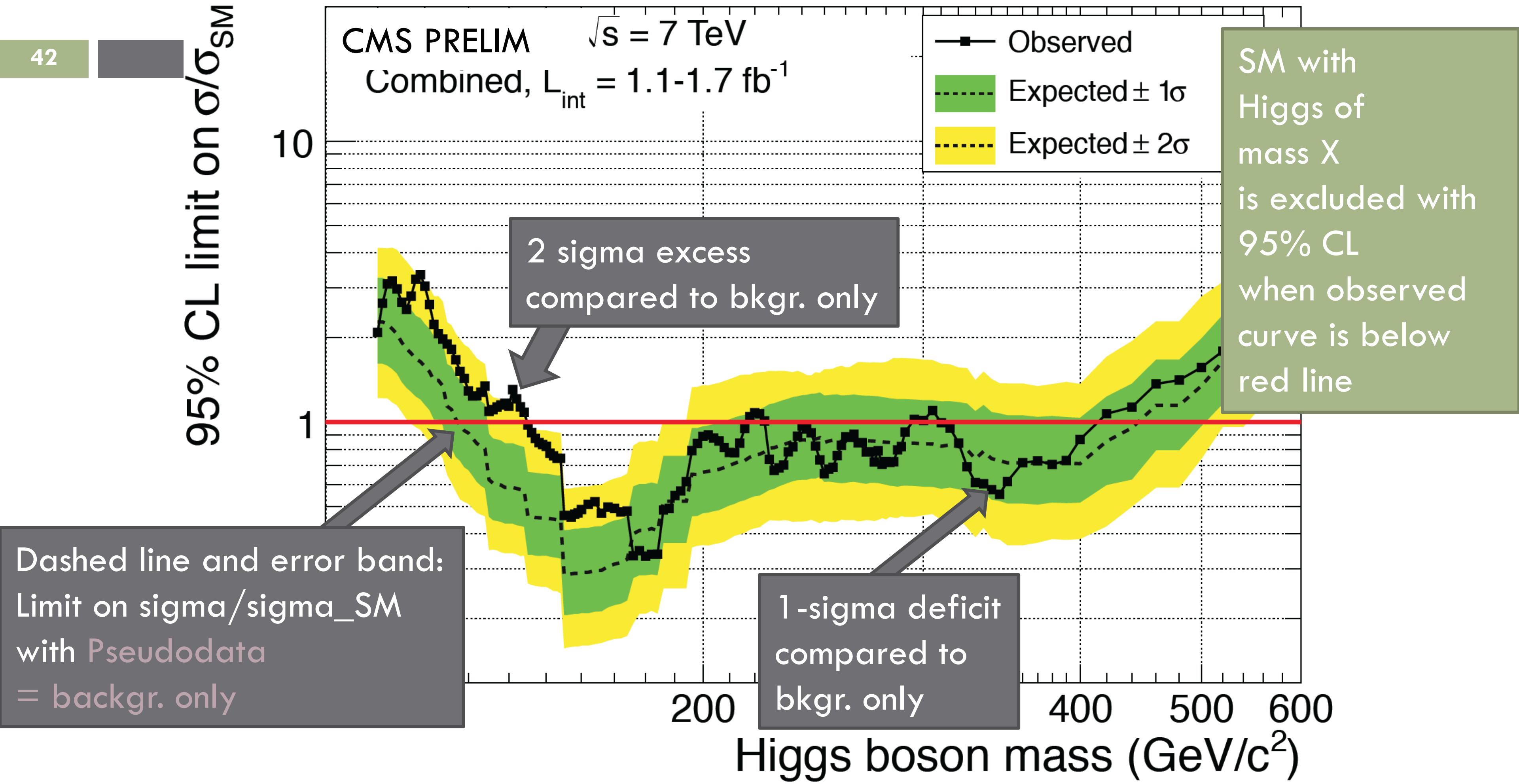


- Opened the door to real understanding of EW symmetry breaking:

  Is this signal the SM Higgs? Or a BSM Higgs ?
- Where is SUSY hidden ?

  Are we closing all “gaps” ?
- Is new physics hidden in an unexpected place ?

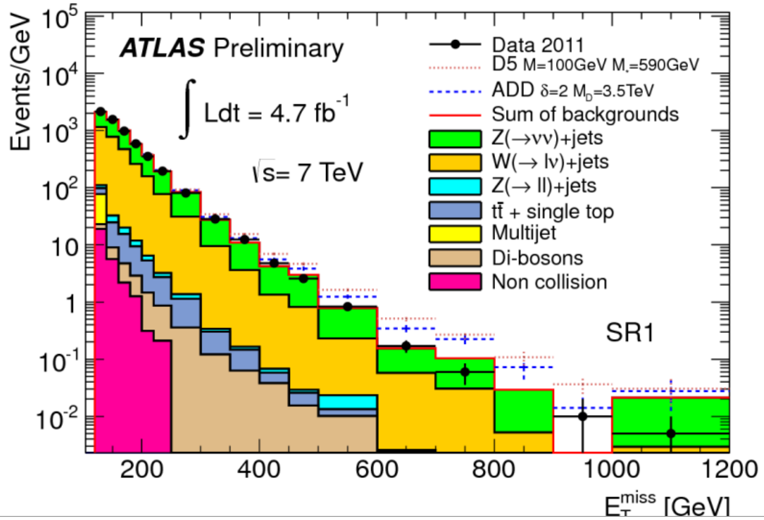
INTERMEZZO: Higgs limit plots…

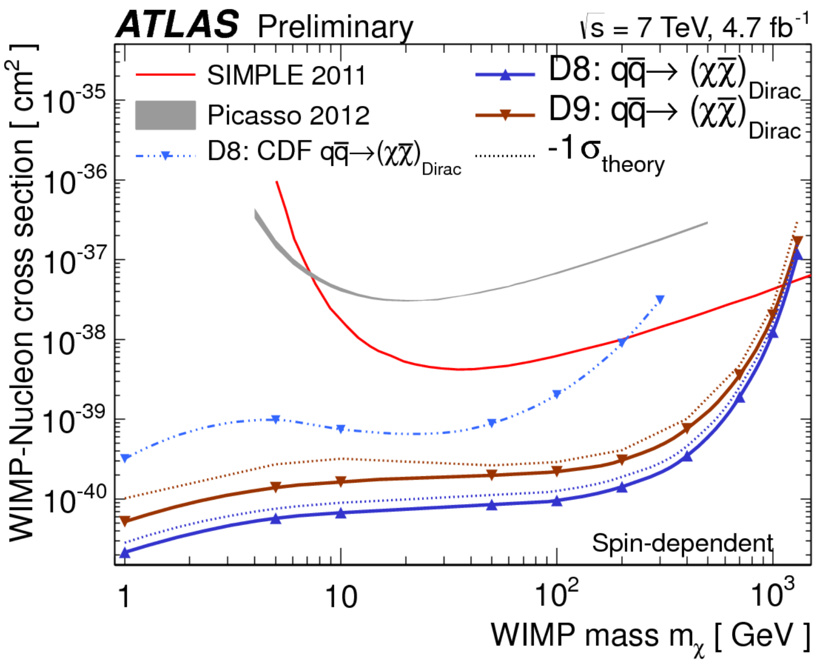


Previous 95 % CL limits from LEP (<114 GeV) and Tevatron (156-177 GeV)

Monojets/Monophotons

Looking for a jet
from initial state radiation
to search for WIMP WIMP
events!
- Signal is a Monojet event !
- Missing momentum
distribution as measured by
ATLAS





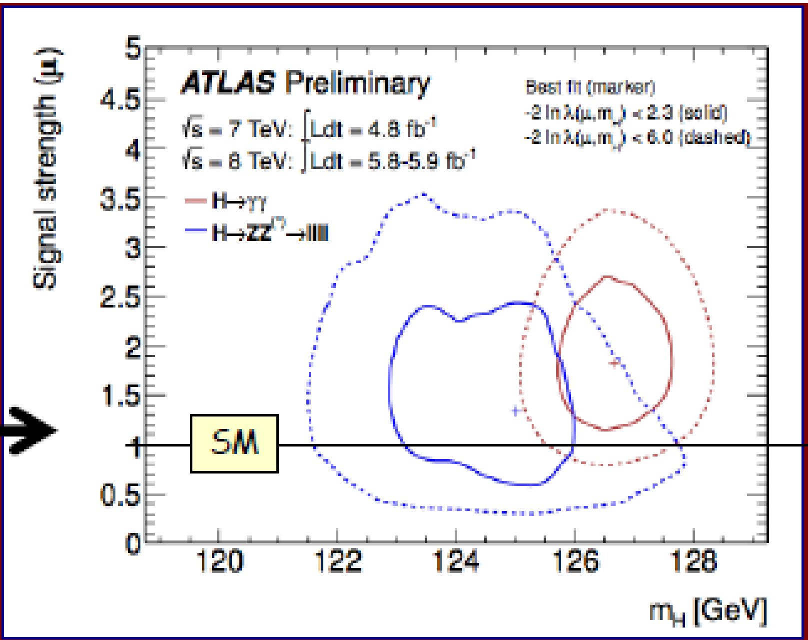
Assuming coupling ATLAS monojet searches can give bounds on WIMP-nucleon spin averaged cross section

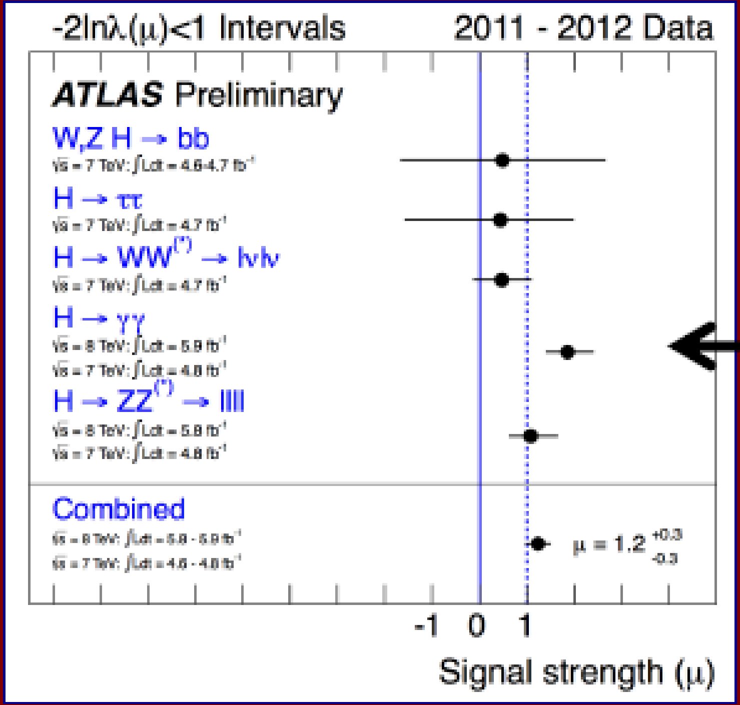
(assuming Z' mediator with free coupling)

Combined results: consistency of the global picture

Are the 4l and γγ observations consistent ?

From 2-dim likelihood fit to signal mass and strength →curves show approximate 68% (full) and 95% (dashed) CL contours





Best-fit signal strengths, normalized to the SM expectations, for all studied channels, at m_H = 126.5 GeV,

Intermediate mass: Higgs → WW → llνν

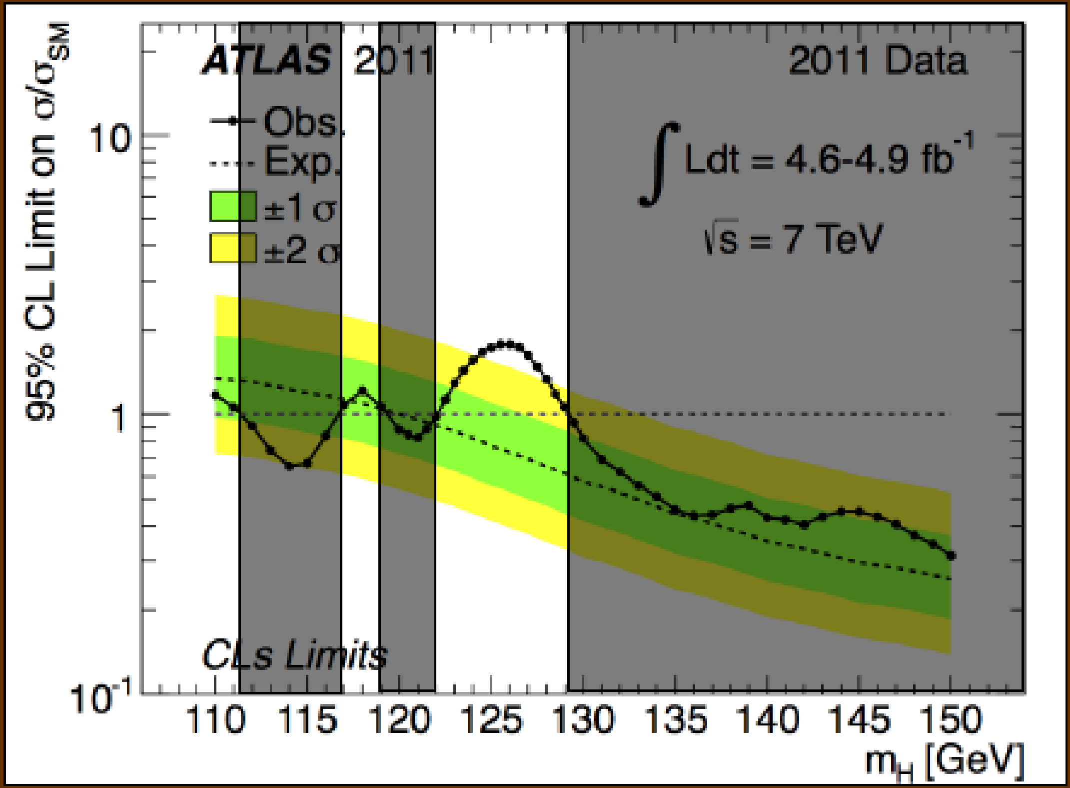
- H→WW→lνlν most sensitive 130 < m_H < 200 GeV

  (H→WW → jjlν less sensitive, but also taken into account into combination)
- … but challenging : complete reconstruction of the invariant mass not possible
- Largest background is irreducible WW SM production
- But also Drell-Yan and top process when looking to final states associated to one jet channel
- Select events with two high-pT opposite sign leptons and large transverse missing energy
- Subdivide into 0,1 and 2 jet channel

→ Channel not ready yet

Status of ATLAS searches … until this morning

Results on the full 7 TeV dataset submitted for publication



Combination of 12 channels:

- $H \to \gamma\gamma$
- $W/ZH \to W/Z\ bb$ (3 final states)
- $H \to \tau\tau$ (3 final states)
- $H \to ZZ(^*) \to 4l$
- $H \to WW(^*) \to l\nu l\nu$
- $H \to ZZ \to llqq$
- $H \to ZZ \to ll\nu\nu$
- $H \to WW \to l\nu qq$

Excluded at 95% CL	$111.4 < m_H < 122.1$ GeV (except 116.6-119.4) $129.2 < m_H < 541$ GeV	Expected if no signal: 120-560 GeV
Excluded at 99% CL	$130.7 < m_H < 506$ GeV	