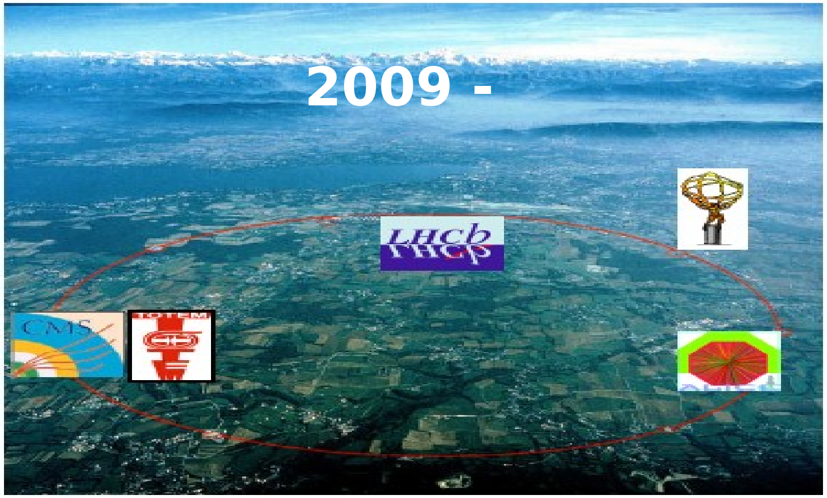
Hadron Collider Physics

Lecture 4:

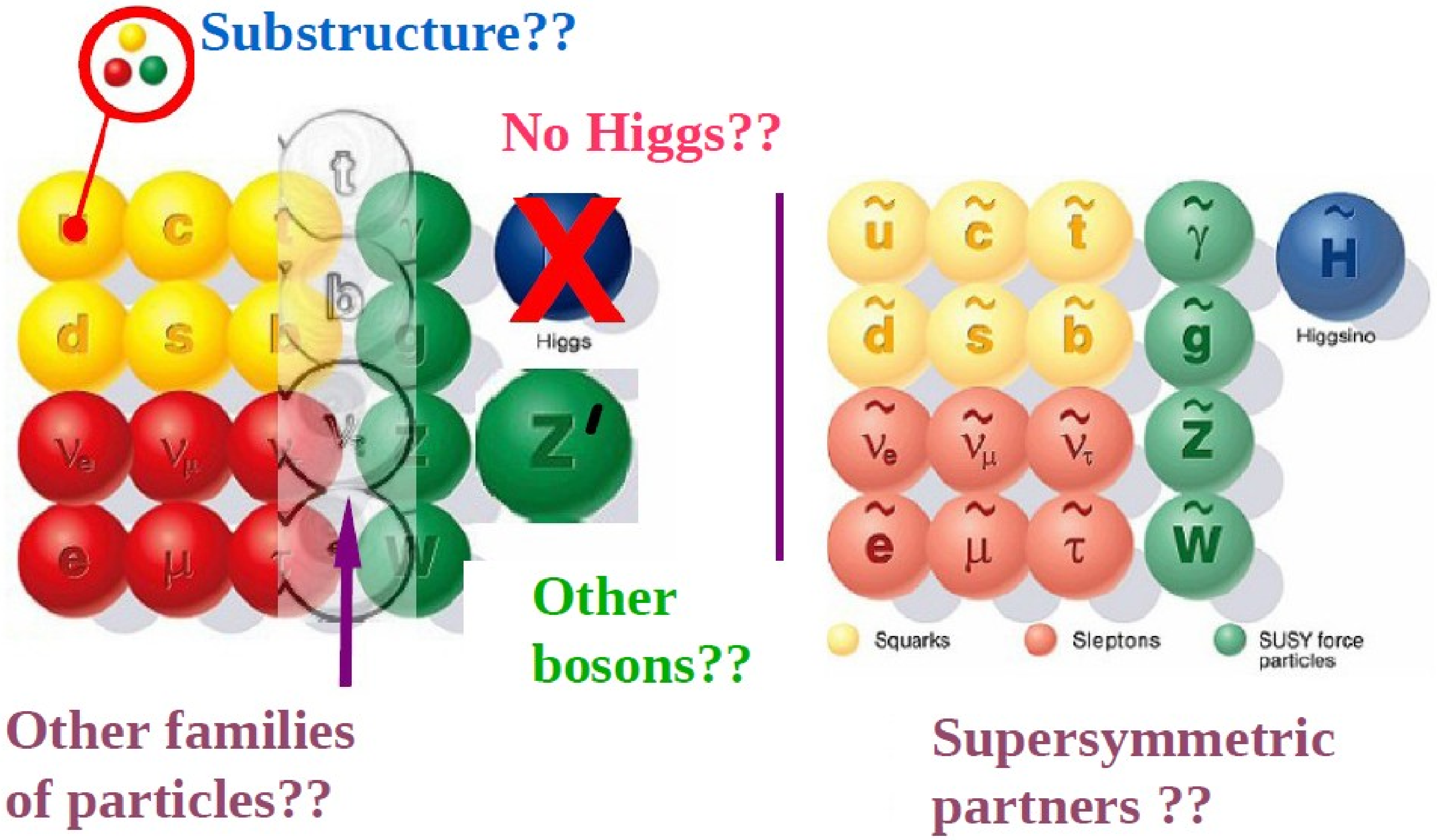
- SM and MSSM Higgs boson
- SUSY and exotic scenarios



Disclaimer:

- Shown results based on 2010-2011 data for LHC
- The 2012 news left to topical lectures of the next week

Beyond Standard Model



Substructure??

No Higgs??

Other bosons??

Other families of particles??

Supersymmetric partners ??

The Standard Model cross-sections measurements in 2011

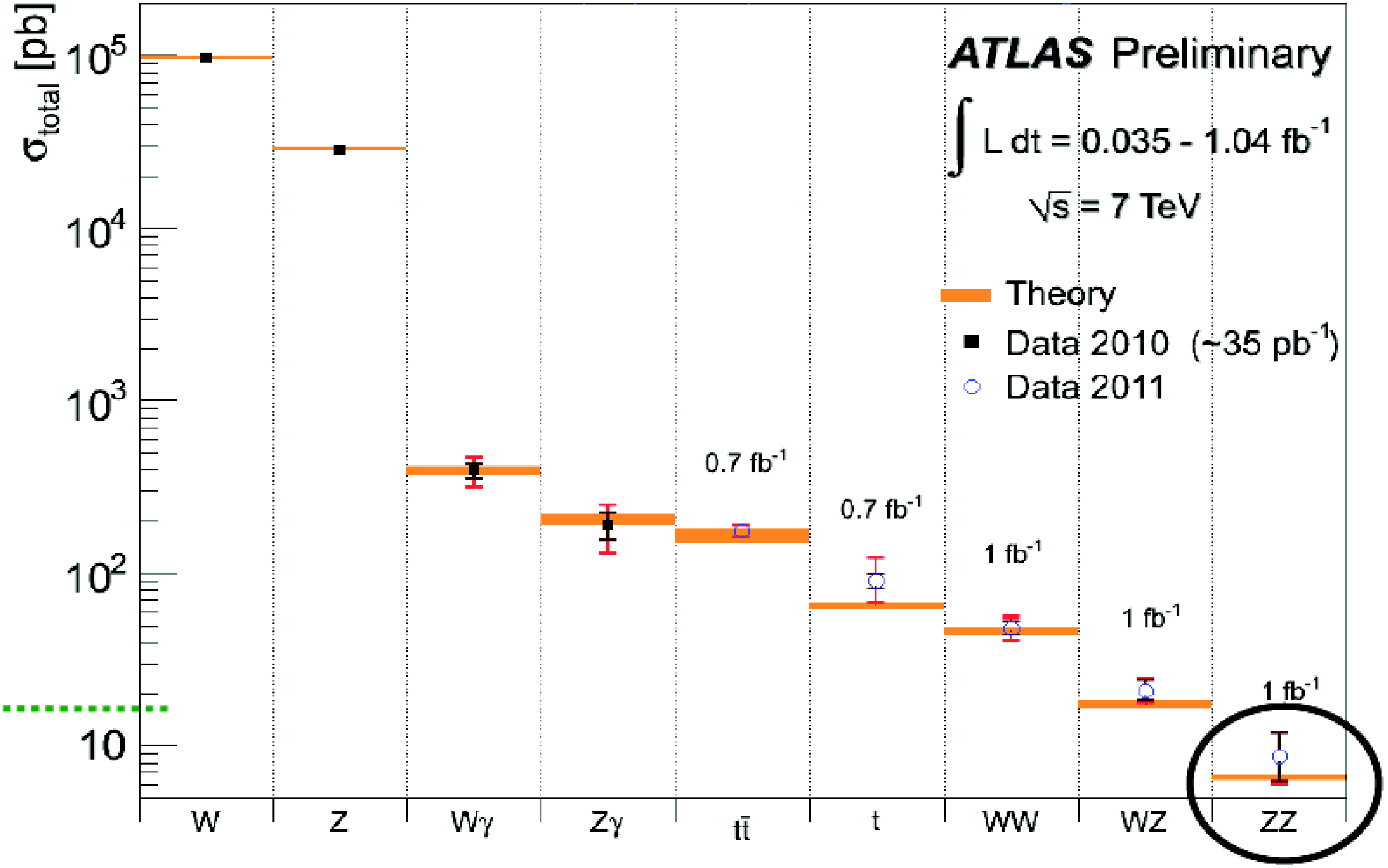
Events after selection cuts

~30M $W \to \mu\nu, e\nu$

~3M $Z \to \mu\mu, ee$

~60k top-pairs

σ (pp → H)
m_H=130 GeV



- The amount of data allowed measurements of “rare” physics processes:
  - In ~70 trillion pp collisions, ~40 ZZ → 4l events are produced
- Good agreement with the Standard Model expectations

SM Higgs mass constraints (2008)

Experiment

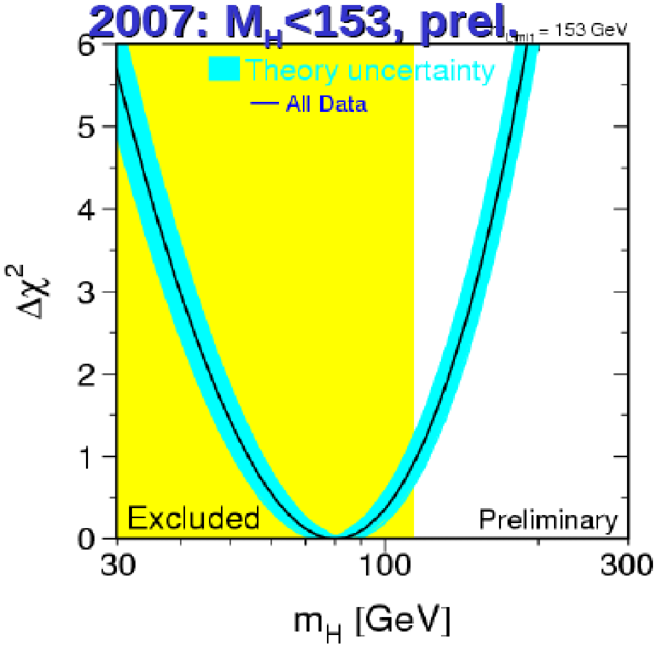
Indirect constraints from precision EW data :

M_H < 260 GeV at 95 %CL (2004)

M_H < 186 GeV with Run-I/II prelim. (2005)

M_H < 166 GeV (2006, ICHEP06)

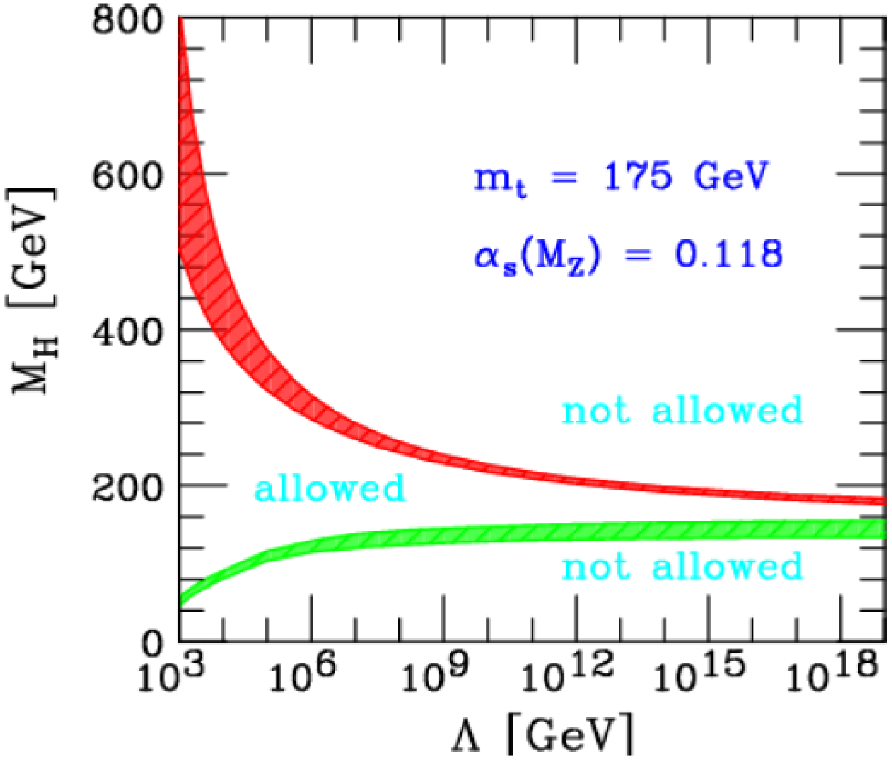
2007: M_H<153, prel.



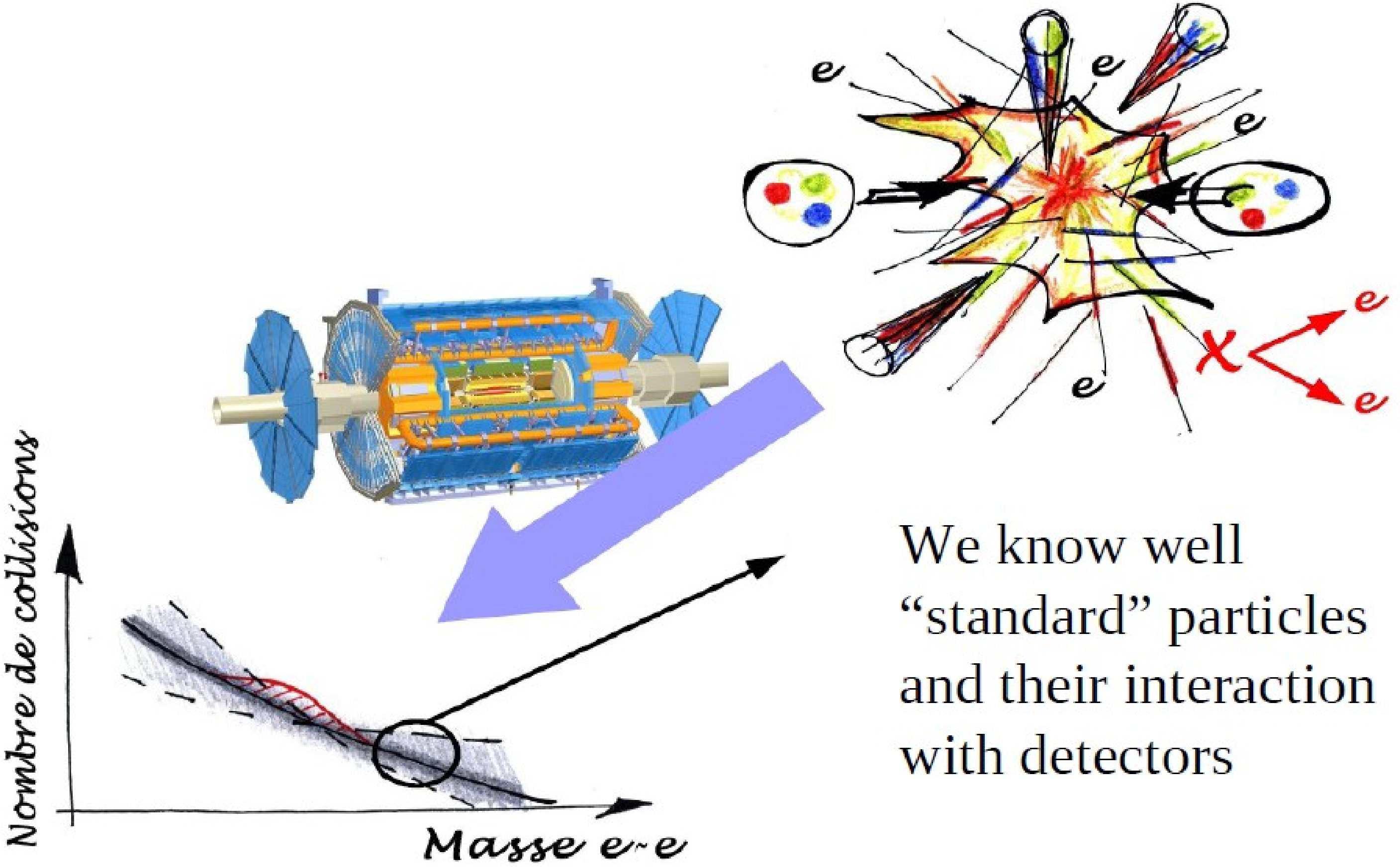
Direct limit from LEP: M_H > 114.4 GeV

SM theory

The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale Λ

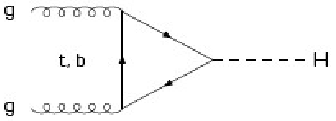


How we look for new particle?

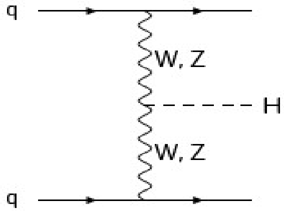


We know well
“standard” particles
and their interaction
with detectors

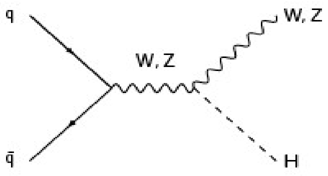
Higgs cross-section



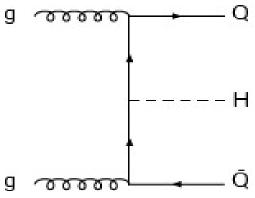
gg fusion



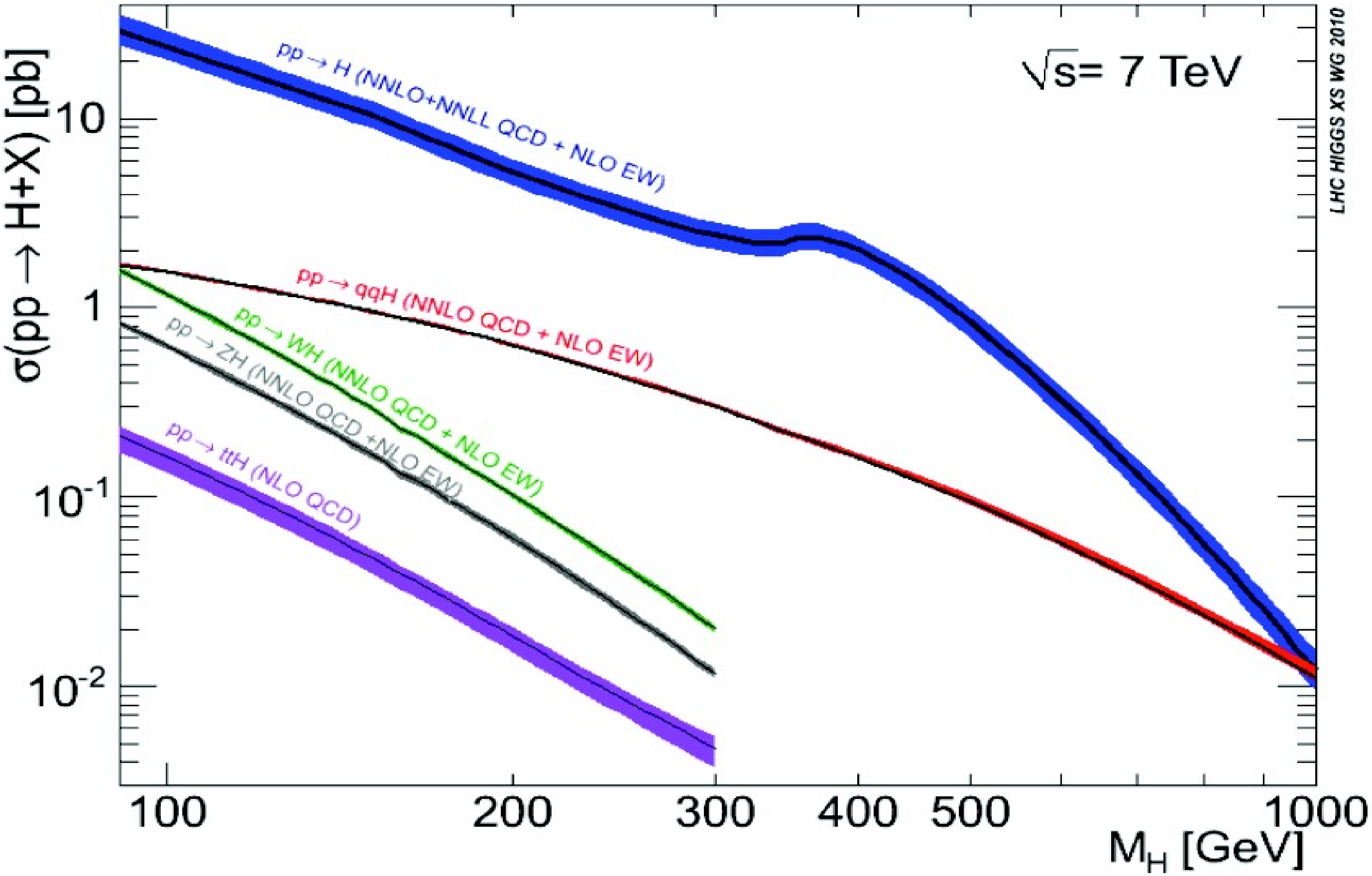
vector boson fusion



associated production with W, Z



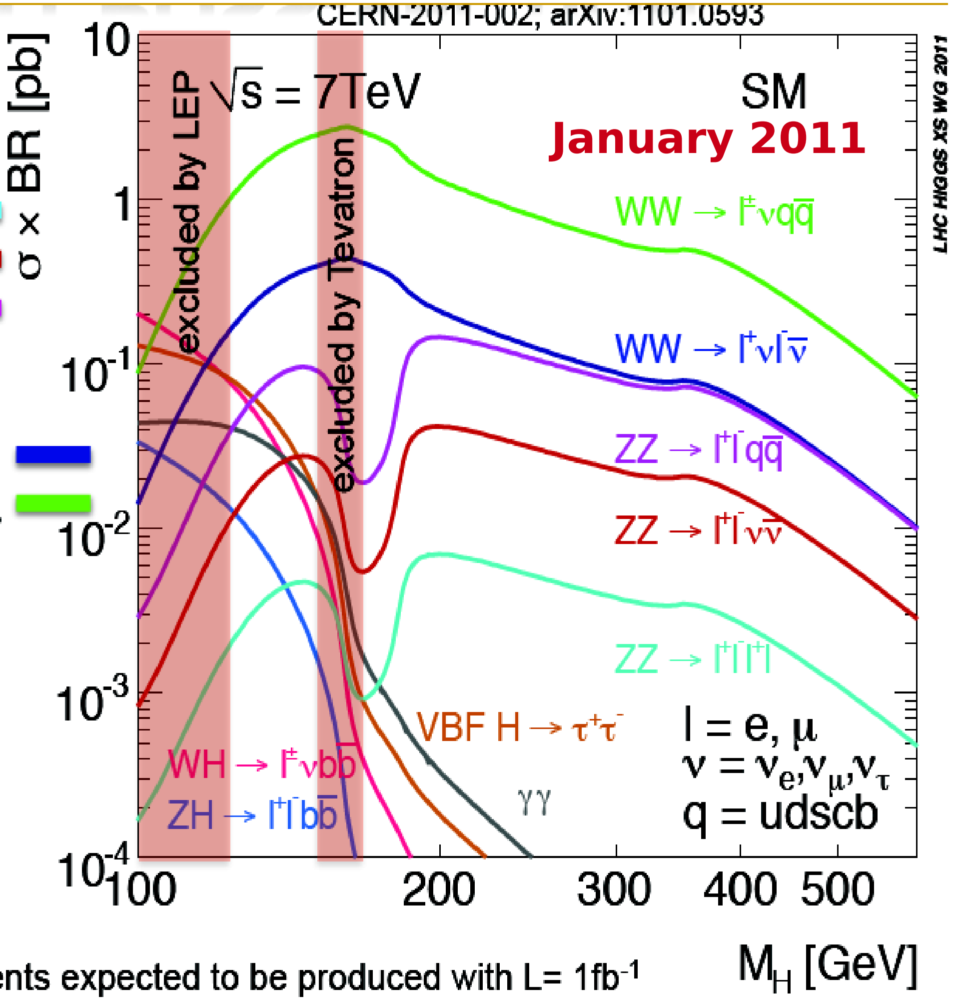
associated production with QQ



Large gluon luminosity → gg fusion is the dominant production channel over the whole range of m_H

Most important channels :

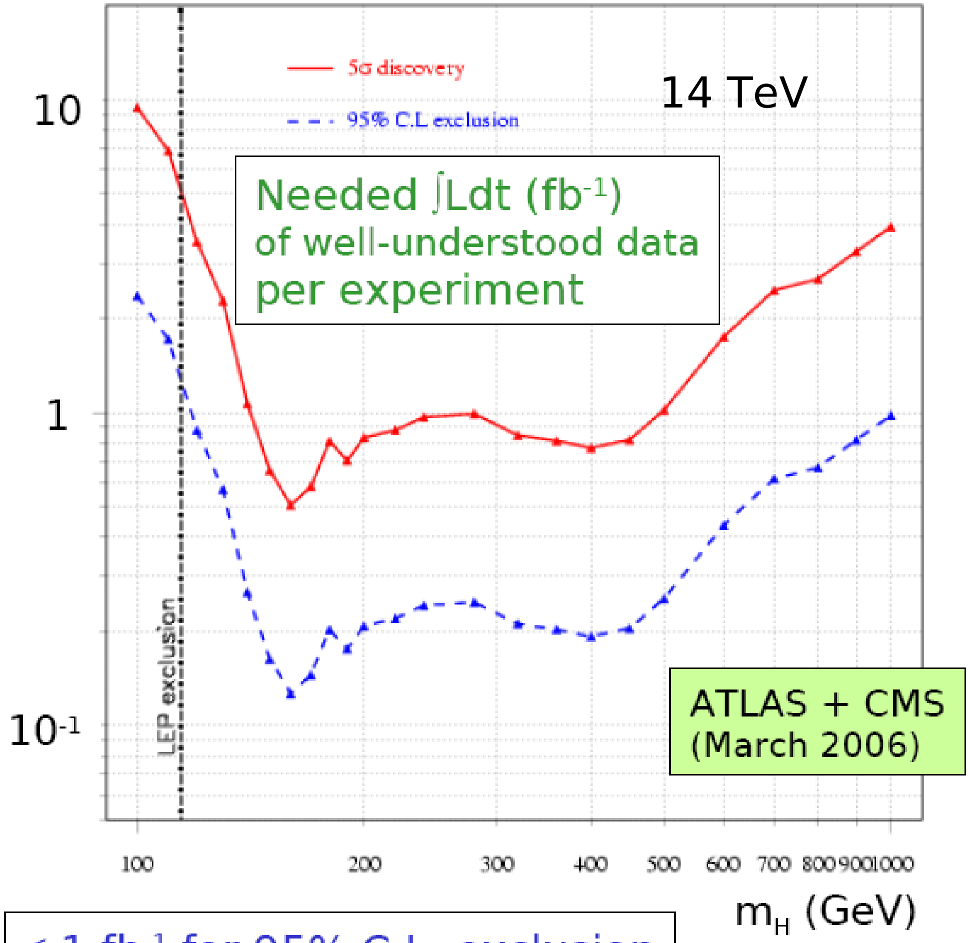
- $H \rightarrow ZZ^{(*)}$:
  - $ZZ \rightarrow llll$: "golden" mode 🟦
  - $ZZ \rightarrow ll\nu\nu$: good for high mass 🟥
  - $ZZ \rightarrow llqq$: good at high mass 🟪
- $H \rightarrow WW^{(*)}$:
  - $WW \rightarrow l\nu l\nu$: most sensitive 🟦
  - $WW \rightarrow l\nu qq$: important at high mass 🟩
- $H \rightarrow \gamma\gamma$: ⬜
  - rare channel
  - best for low mass
- $H \rightarrow \tau\tau$: 🟧
  - good s/b
  - low mass
  - rare
- $H \rightarrow bb$: 🟦 🟥
  - with associated production
  - useful but difficult



Events expected to be produced with L= $1fb^{-1}$

m_H, GeV	$WW \rightarrow l\nu l\nu$	$ZZ \rightarrow 4l$	$\gamma\gamma$
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

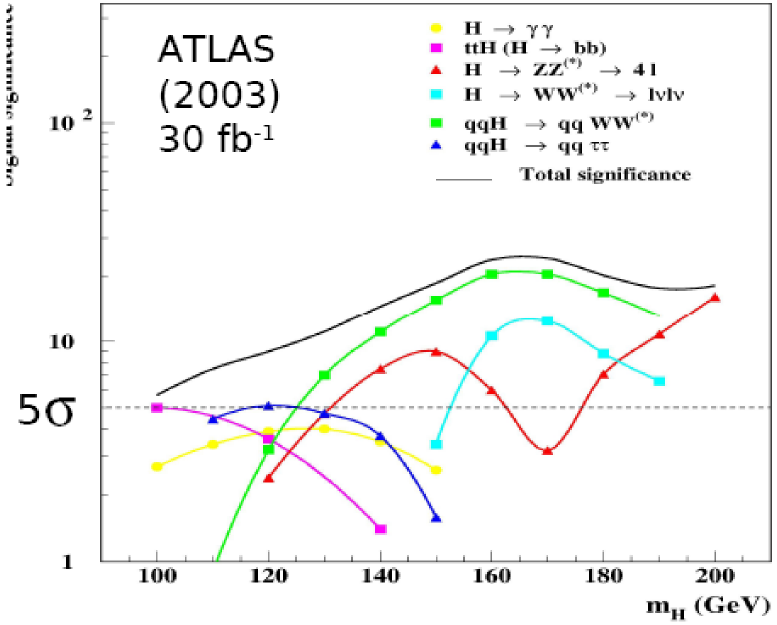
Discovery potential in a complete mass range



14 TeV

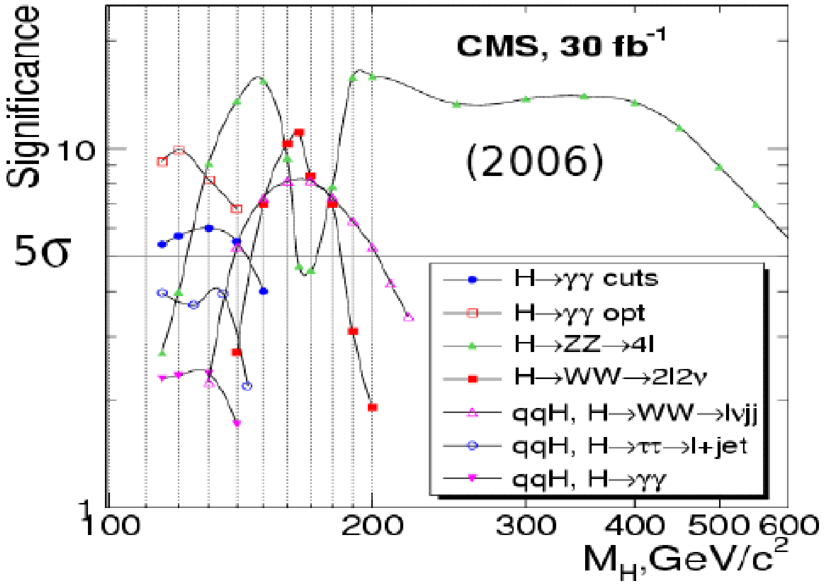
Needed ∫Ldt (fb^{-1}) of well-understood data per experiment

ATLAS + CMS (March 2006)



ATLAS (2003) 30 fb^{-1}

5σ



(2006)

5σ

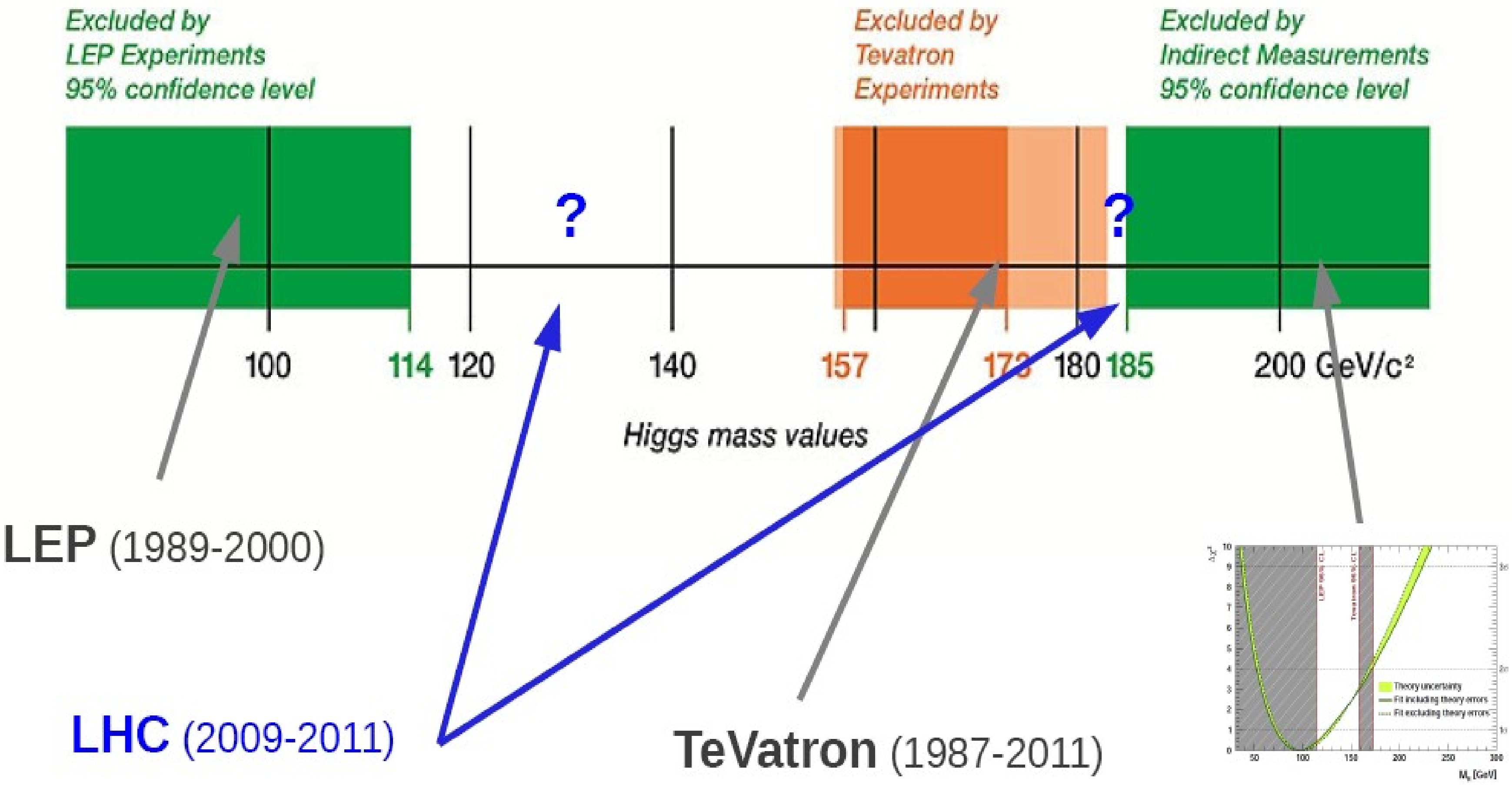
≤ 1 fb^{-1} for 95% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range
Final word about Higgs mechanism by 2010 ?

Search for the Higgs Particle

Status as of March 2011

90% confidence level

95% confidence level



LEP (1989-2000)

LHC (2009-2011)

TeVatron (1987-2011)

Understanding of the Yellow and Green bands :

- Upper limit on the Standard Model (SM) Higgs Boson production cross section divided by the Standard Model expectation as a function of m_{Higgs}

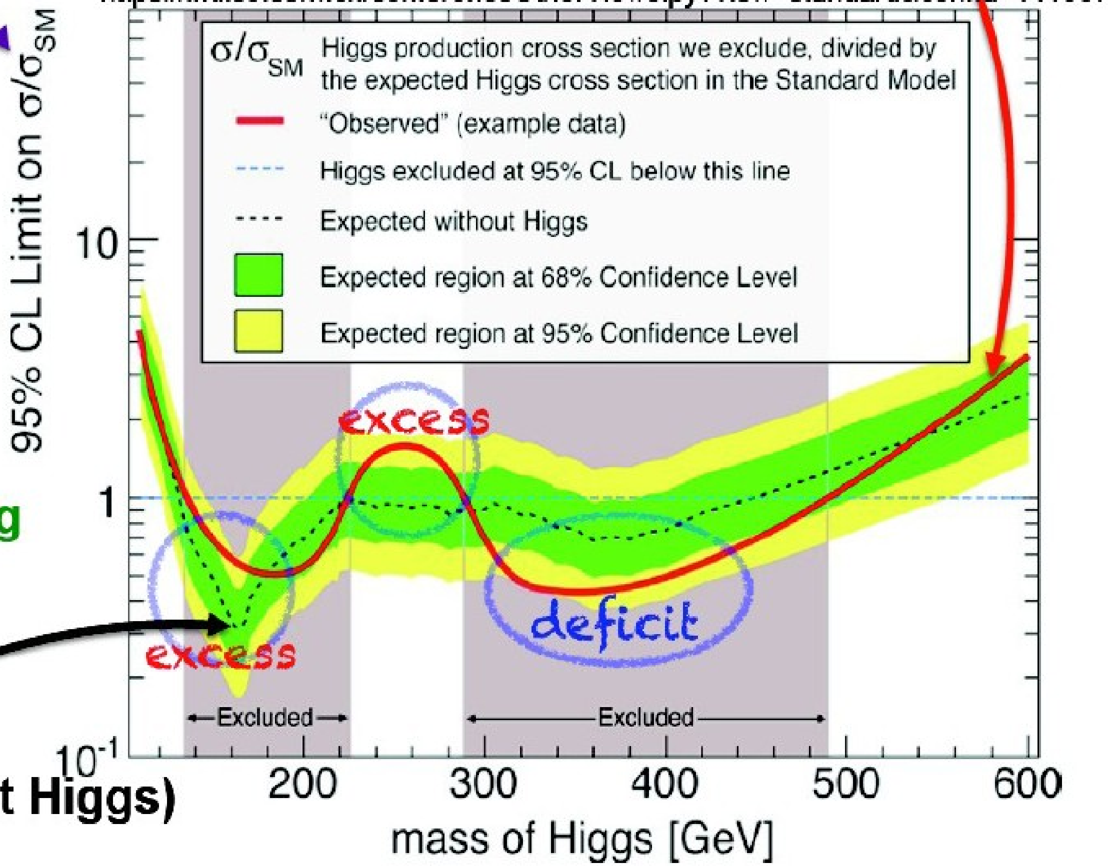
observed limit (data)

$\mu=\sigma/\sigma^{SM}$

this is a 95% limit using the CLs method

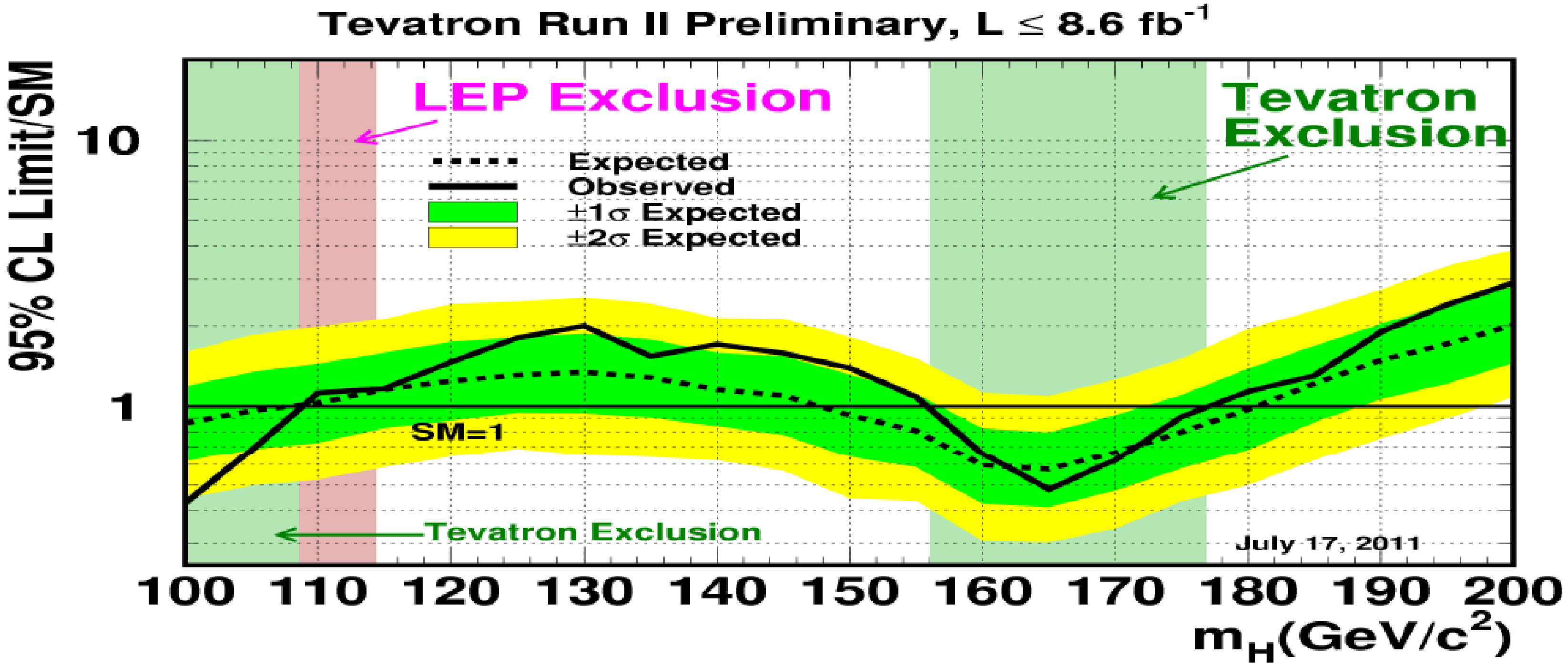
expected limit (without Higgs)

Eilam Gross
https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=14198



Tevatron combination (2011)

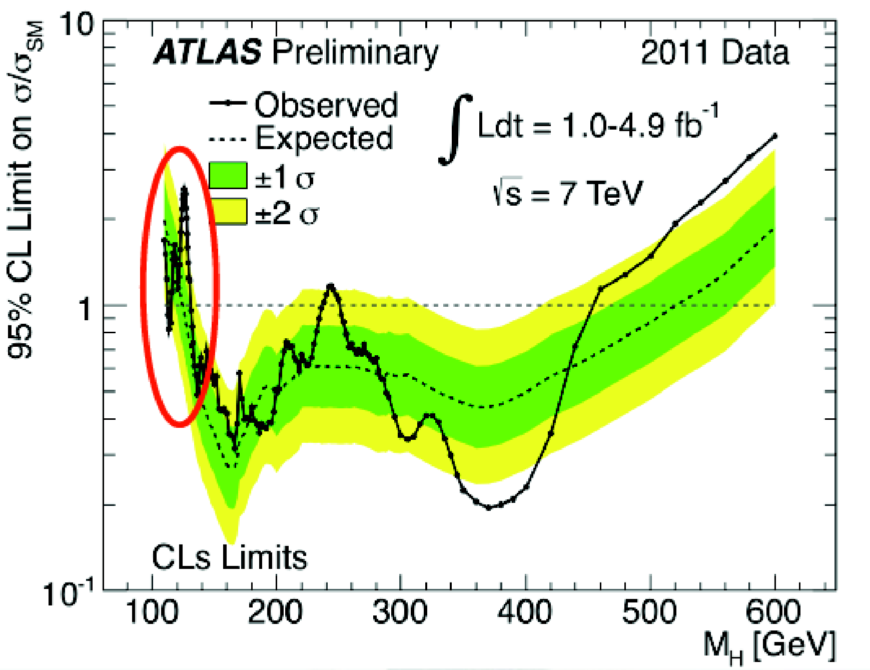
- **Observed Exclusion:** $100<M_H<109$ & $156<M_H<177$ GeV/c^2 @95%CL.
- **Expected Exclusion:** $100<M_H<108$ & $148<M_H<181$ GeV/c^2@95%CL.



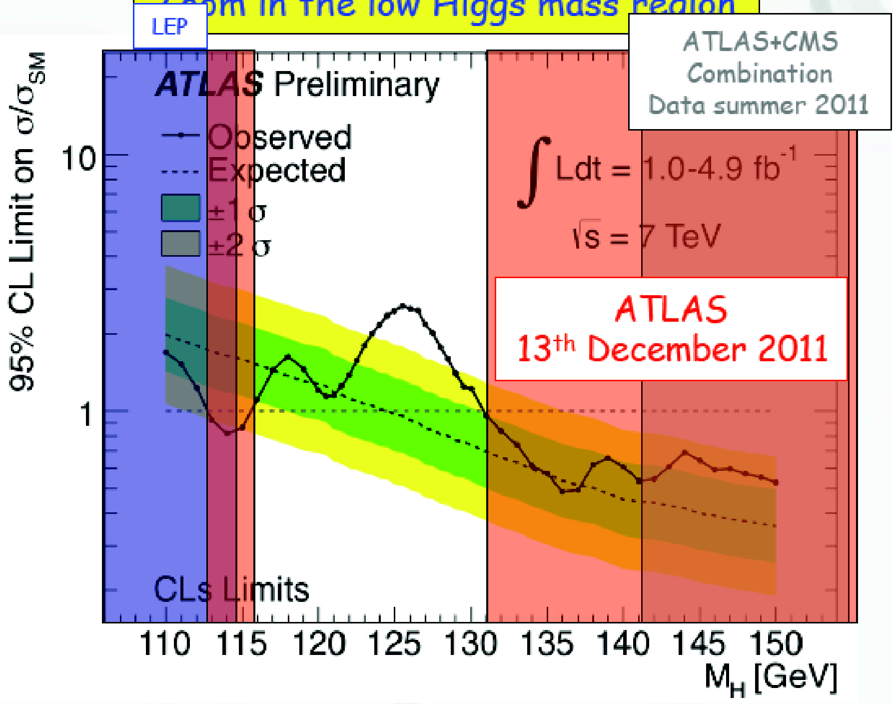
ATLAS exclusion of Higgs masses (2011)

$H \to \gamma\gamma$, $H \to \tau\tau$
$H \to WW^{(*)} \to l\nu l\nu$
$H \to ZZ^{(*)} \to 4l$, $H \to ZZ \to ll\nu\nu$
$H \to ZZ \to llqq$, $H \to WW \to l\nu qq$

Higgs masses with $\sigma / \sigma_{SM} < 1$ excluded at 95%CL



Zoom in the low Higgs mass region



Excluded at 95% CL

$114.4 < m_H < 115.5$ GeV
$131 < m_H < 453$ GeV, except 237-251 GeV

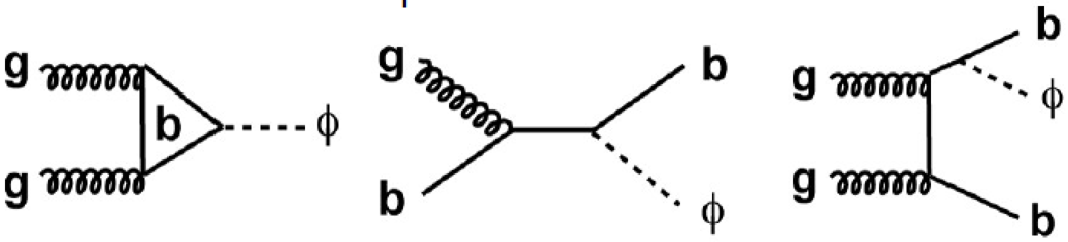
Most likely Higgs mass region at 95% CL: 115.5 – 131 GeV

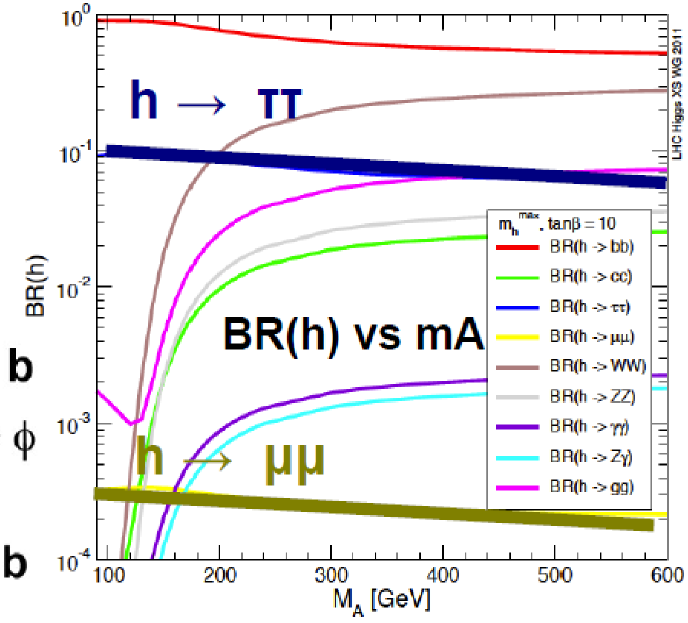
MSSM Higgs sector

- MSSM: a popular and well-studied extension of the SM
  - 5 Higgs bosons: CP-even (h,H), CP-odd (A), charged ($H^\pm$)
  - Mass of h < 135 GeV; Higgs sector depends only on 2 parameters at tree level (e.g. m_A , tanβ)

For large parts of the parameter space $H \to \tau\tau$ and $H^\pm \to \tau^\pm \nu$ decays are dominant, WW/WZ decays suppressed

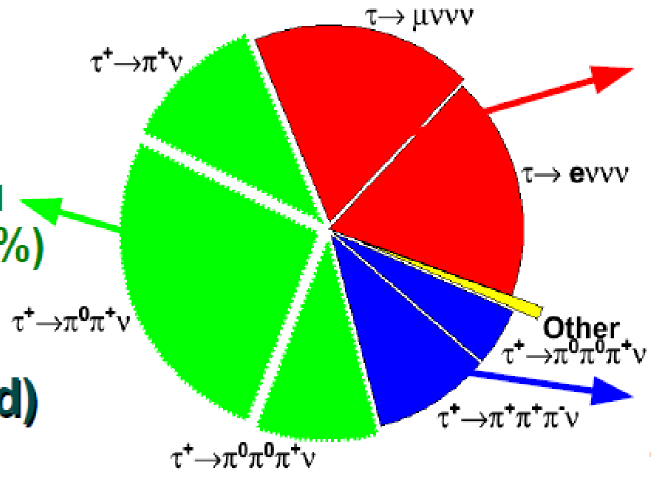
Neutral Higgs produced by gluon fusion or in association with b-quarks





Taus in ATLAS

- The main search channels for MSSM Higgs involve tau-leptons in the final state: $H \rightarrow \tau\tau$, $H^{\pm} \rightarrow \tau^{\pm}\nu$
- Taus: the only leptons that can decay hadronically



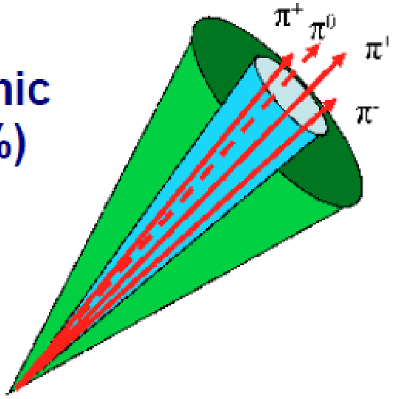
Leptonic tau decays (~35%)
τ(lep)

"1-prong" hadronic tau decays (~50%)

τ(had)

"3-prong" hadronic tau decays (~15%)

Studies with taus are involved:
- neutrinos in the final state: challenging to reconstruct di-tau invariant mass without degrading resolution a lot
- pions in τ(had): difficult to separate them from QCD jets



Special techniques used

- Di-tau invariant mass has poor resolution due to the presence of neutrinos in the final state
  - Simplest option: **visible mass** (mass of visible objects)
  - More advanced techniques like **Missing Mass Calculator** (MMC)

MMC concept:

constrain the neutrino momenta using tau decay kinematics to improve resolution

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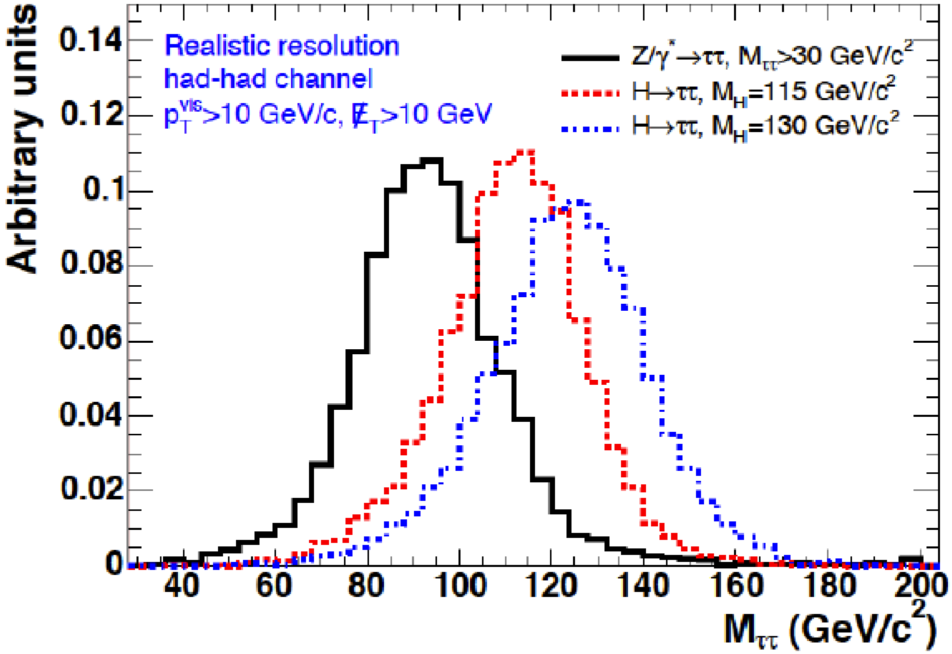
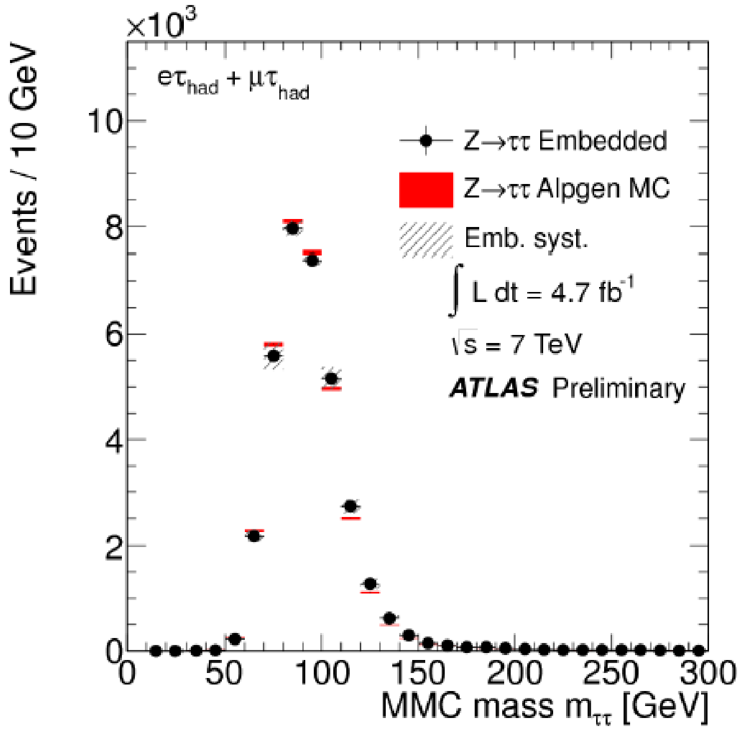


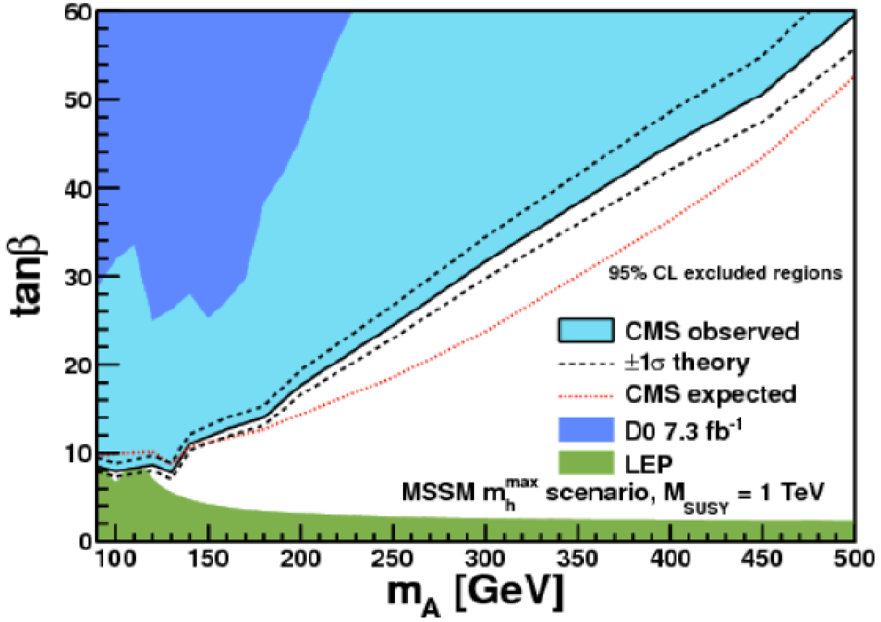
Special techniques used

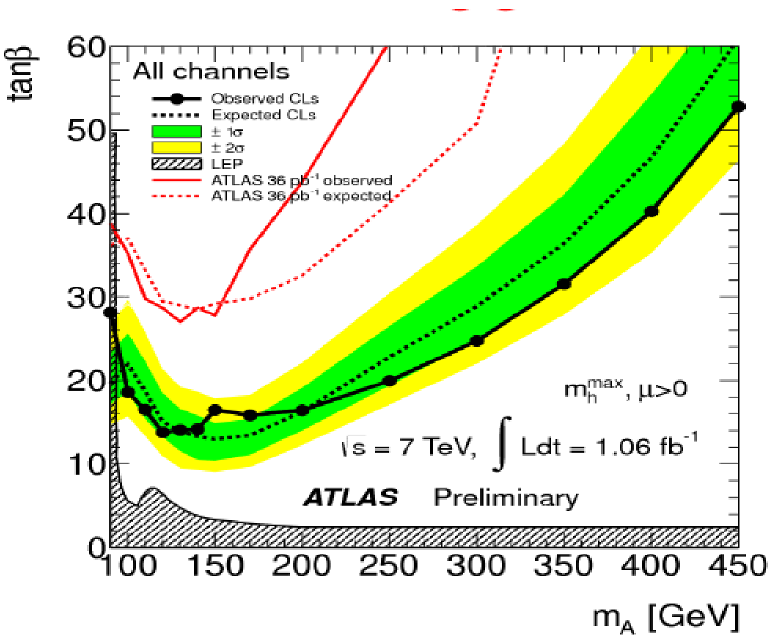
- $Z\rightarrow\tau\tau$ is the most important background source for di-tau final states
  - "τ-embedded" $Z \rightarrow \mu\mu$ data events:
    - semi-data-driven method: select an adequately pure $Z\rightarrow\mu\mu$ event sample from data and then replacing the muons with simulated taus
    - Pile-up, underlying event, kinematics etc directly from data



Embedding techniques can also be used with W or ttbar events

Neutral MSSM Higgs(es)





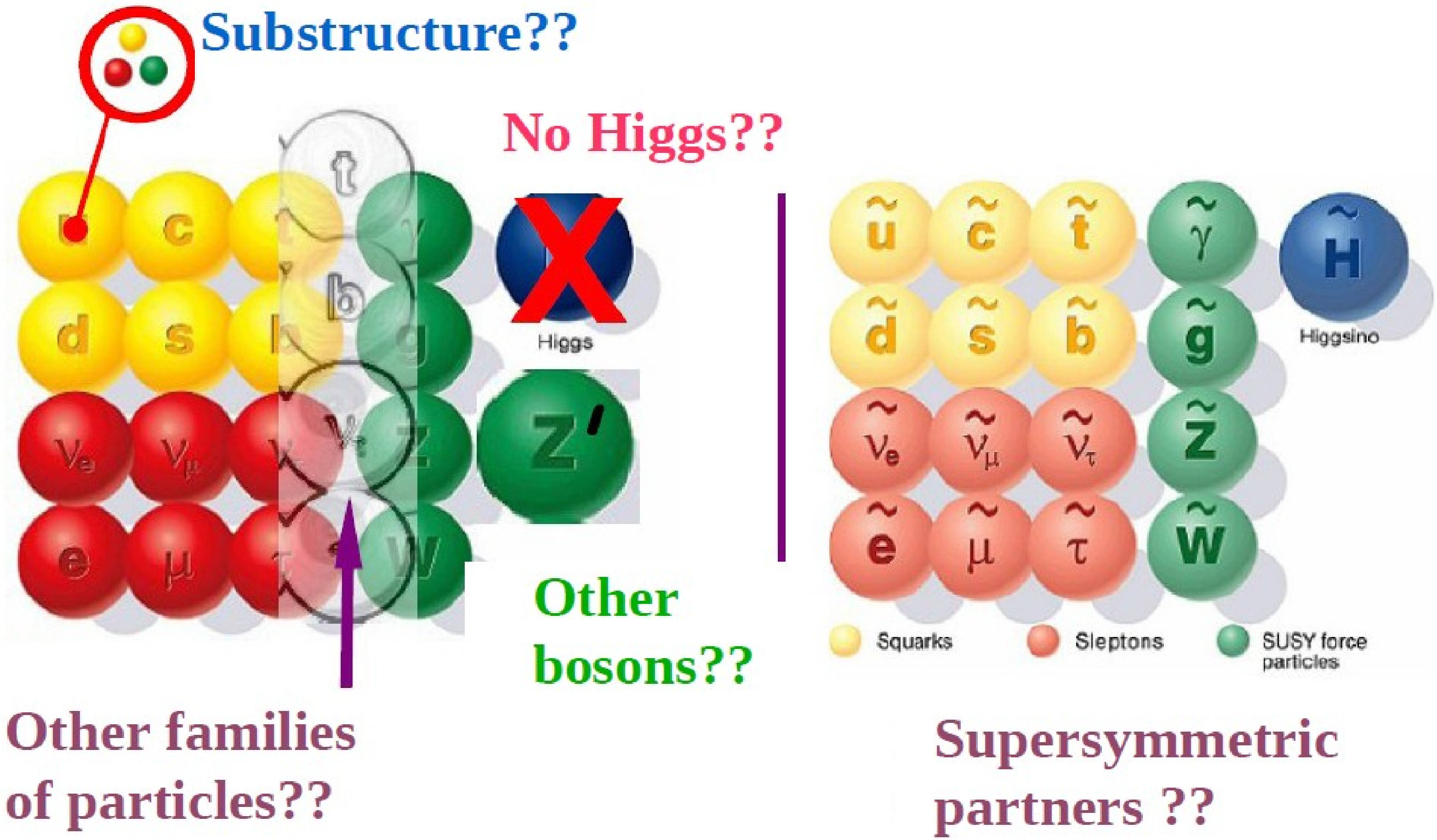
Direct searches sparticle searches have low sensitivity to tanβ and m(A) parameters of MSSM

Higgs searches provide highest sensitivity on these parameters

Already significant coverage from A→ττ

As we become sensitive to light higgs below 135-140 GeV more and more of the plane will be covered

Beyond Standard Model



Substructure??

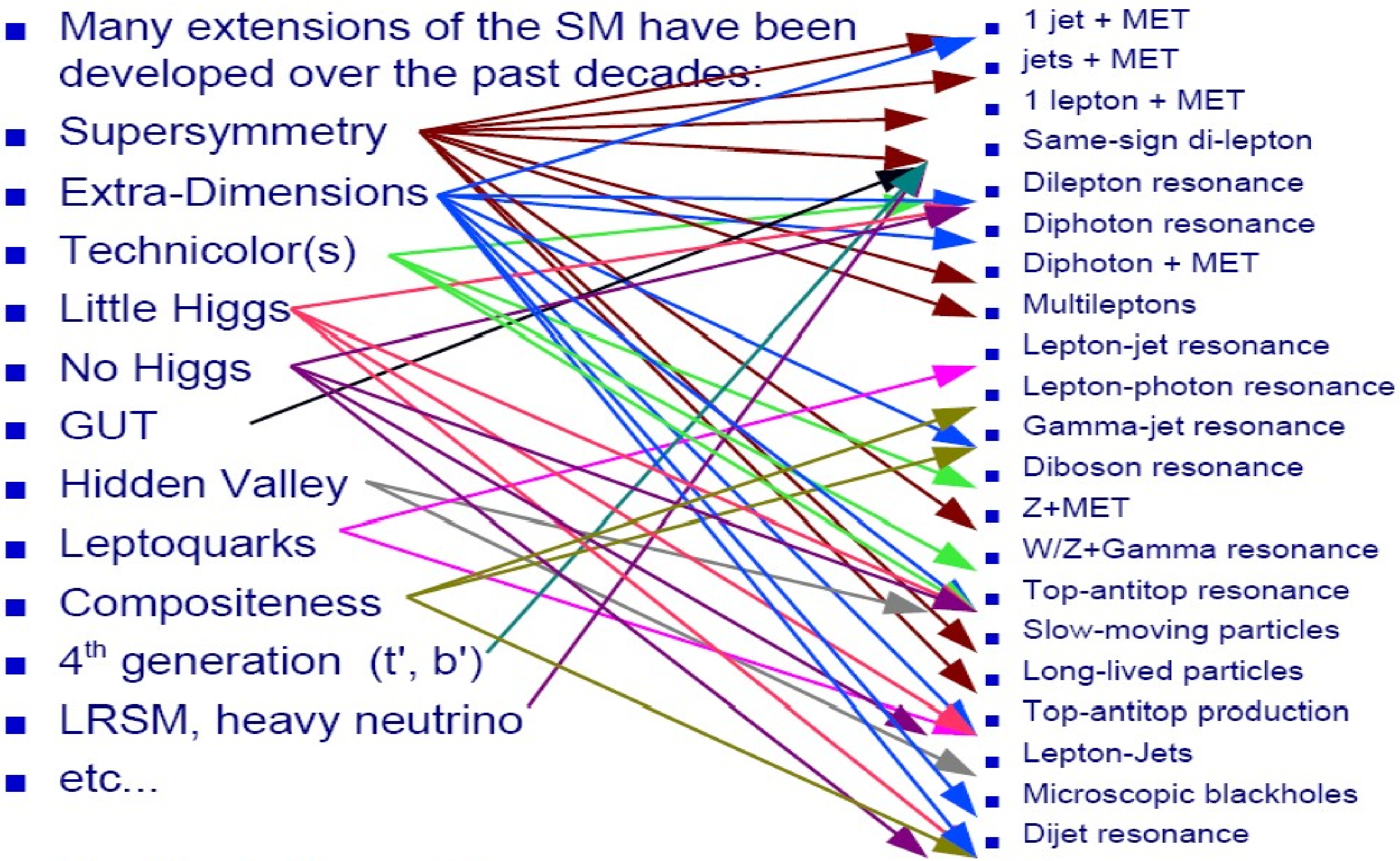
No Higgs??

Other bosons??

Other families of particles??

Supersymmetric partners ??

Long list of models and signatures

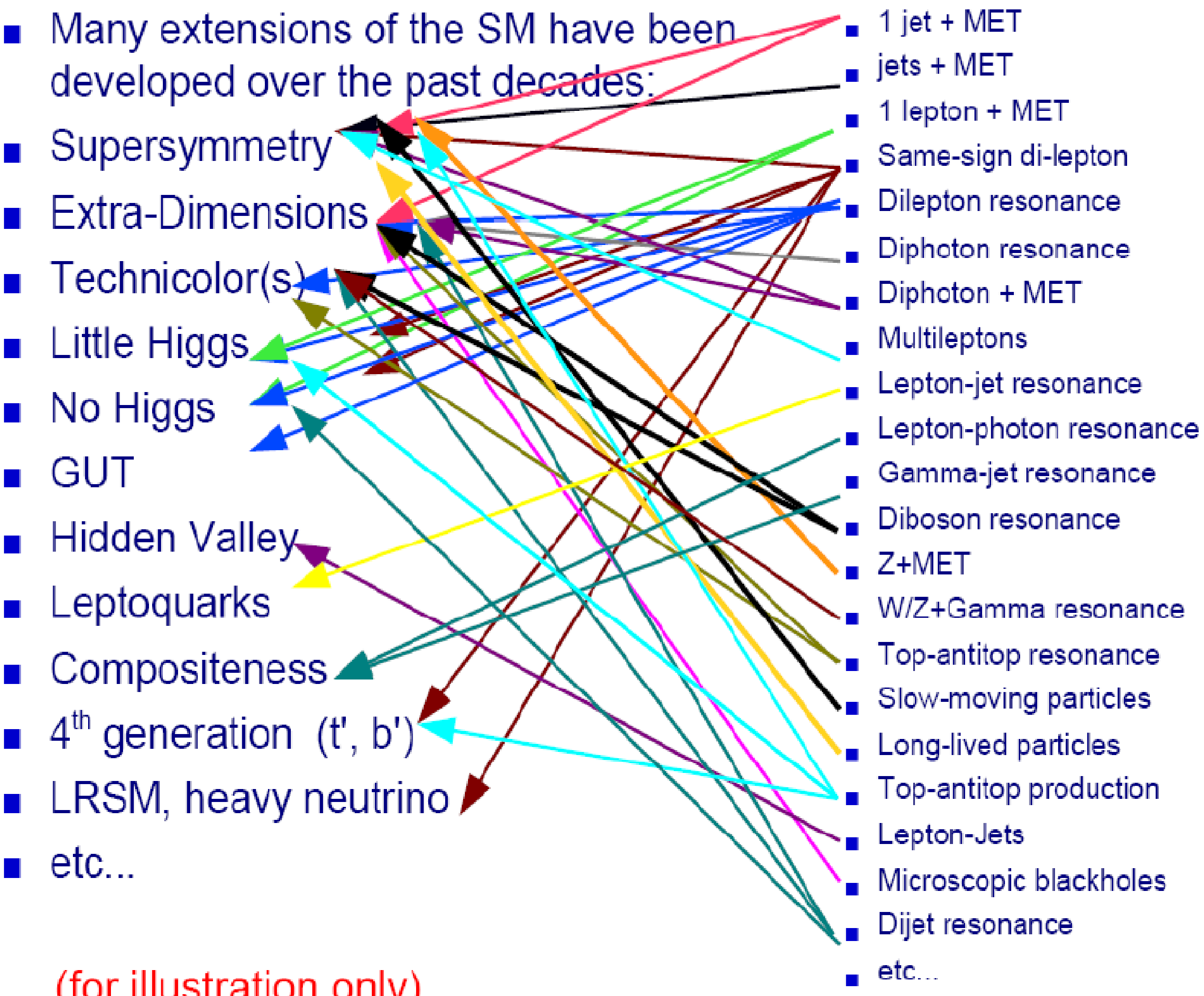


- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4^{th} generation (t', b')
- LRSM, heavy neutrino
- etc...

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

(for illustration only)

Long list of models and signatures



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A complex 2D problem

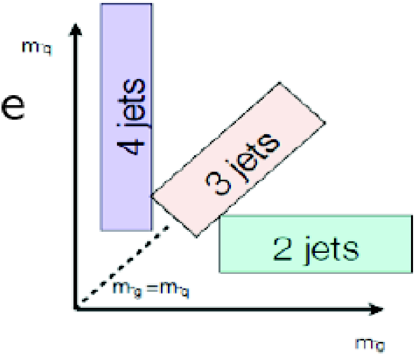
Experimentally, a **signature standpoint** makes a lot of sense:

→ Practical

→ Less model-dependent

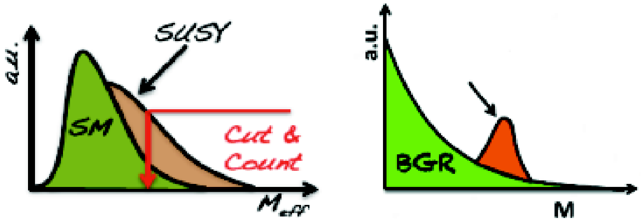
→ Important to cover every possible signature

General search strategy



- Definition of **Signal Regions** (SRs) that maximise sensitivity to different models
  - → based on **discriminating variables**

- Identification and estimation of **SM backgrounds**
  - → different techniques (preferably data-driven)



- Search for **non-SM excess**
  - → cut & count
  - → resonances

- If no excess, **model independent limits** set
  - → different stat. methods
  - → different interpretations

$$\sigma_{\mathrm{BSM}} \times \varepsilon \times A$$

Supersymmetry

Cascade ending with LSP
→ large MET

1 Jets+MET: Gluino and Squark prod. dominate

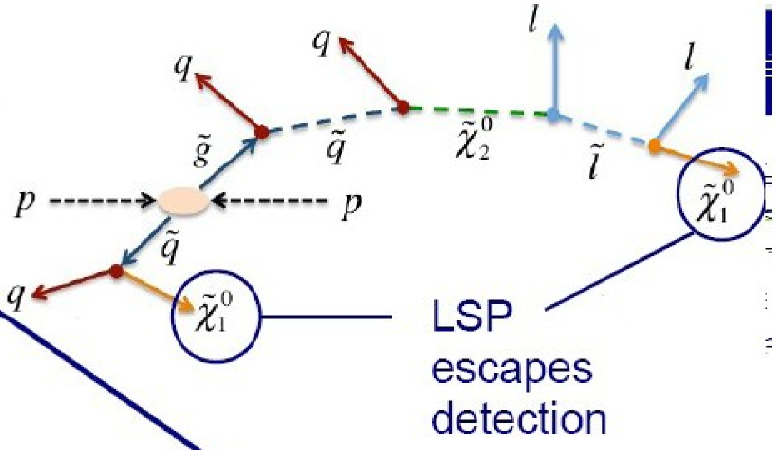
2 Leptons(+jets)+MET: lower branching ratio/cross-section but complementary

3 3rd generation (b or t)+MET:

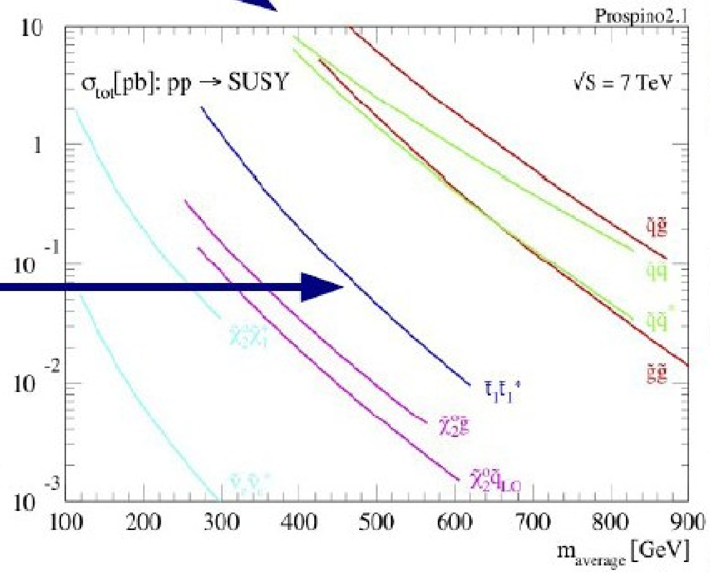
- → in cascade
- → direct production requires > 1 fb^{-1}
  → coming soon

4 Photon(s)+MET: GMSB models

5 “Exotic” SUSY: long-lived, no MET

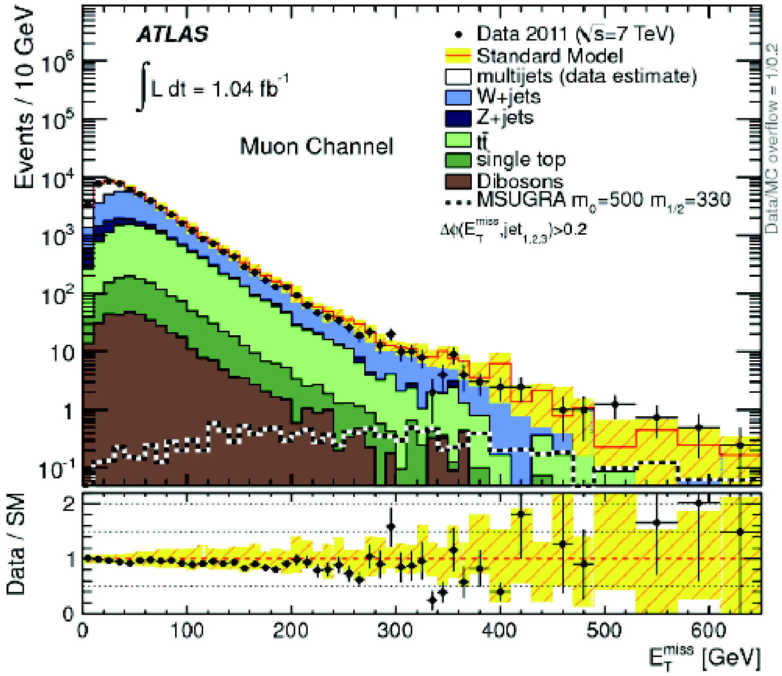


LSP escapes detection

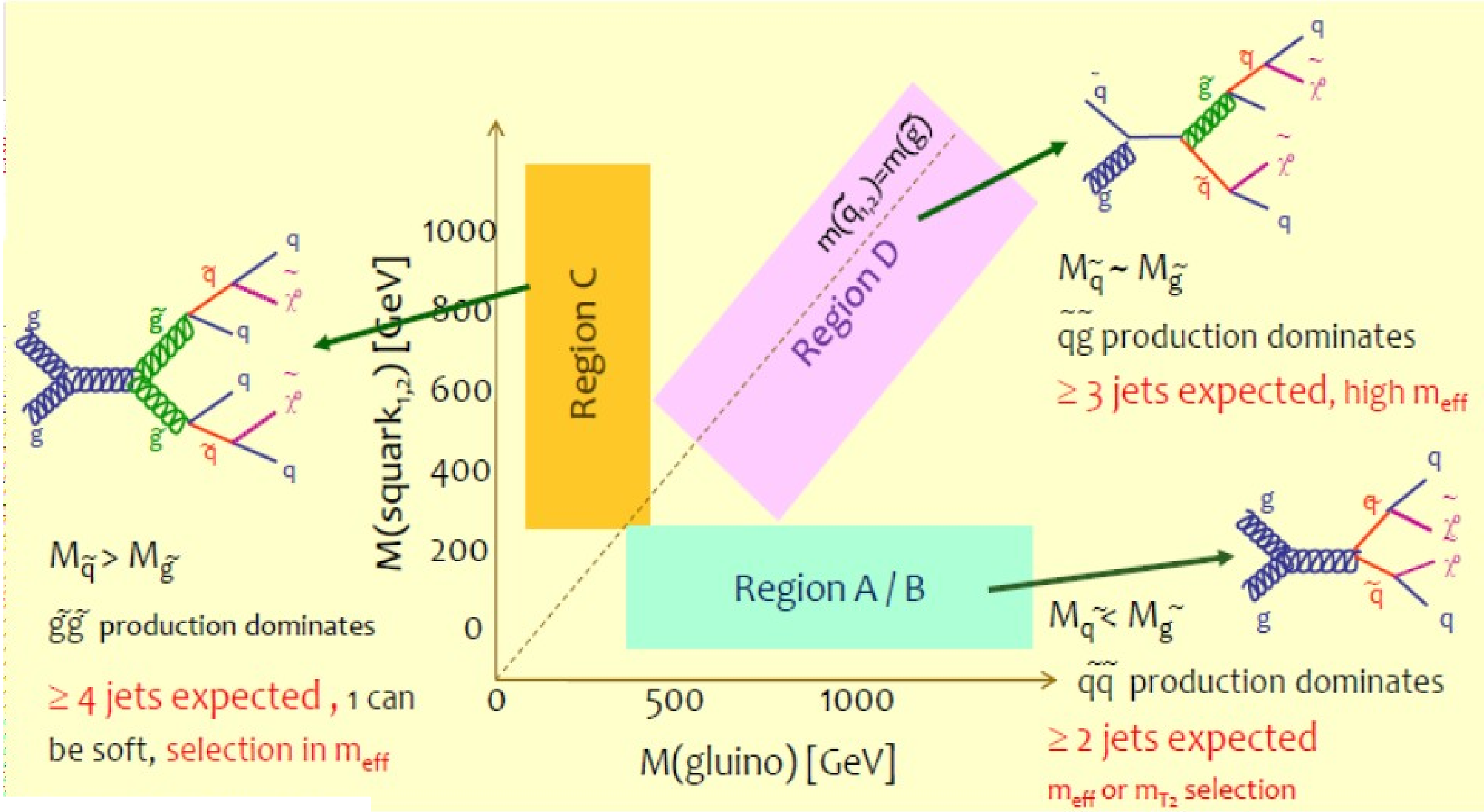


SUSY search results

- Searching for SUSY:
    - Sum all energy in the detector
    - Compute the energy balance in the plane transverse to the beam axis (E_T^{miss})
- E_T^{miss} distribution well described within 5 orders of magnitude:
    - Very good understanding of the detector!



0-lepton + Jets + E_T^{miss}



$M_{\tilde{q}} > M_{\tilde{g}}$

$\tilde{g}\tilde{g}$ production dominates

≥ 4 jets expected , 1 can be soft, selection in m_{eff}

$M_{\tilde{q}} \sim M_{\tilde{g}}$

$\tilde{q}\tilde{g}$ production dominates

≥ 3 jets expected, high m_{eff}

$M_{\tilde{q}} < M_{\tilde{g}}$

$\tilde{q}\tilde{q}$ production dominates

≥ 2 jets expected

m_{eff} or m_{T_2} selection

0-lepton signature

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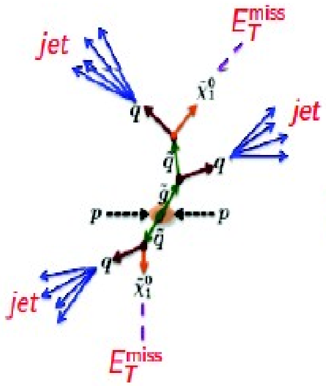
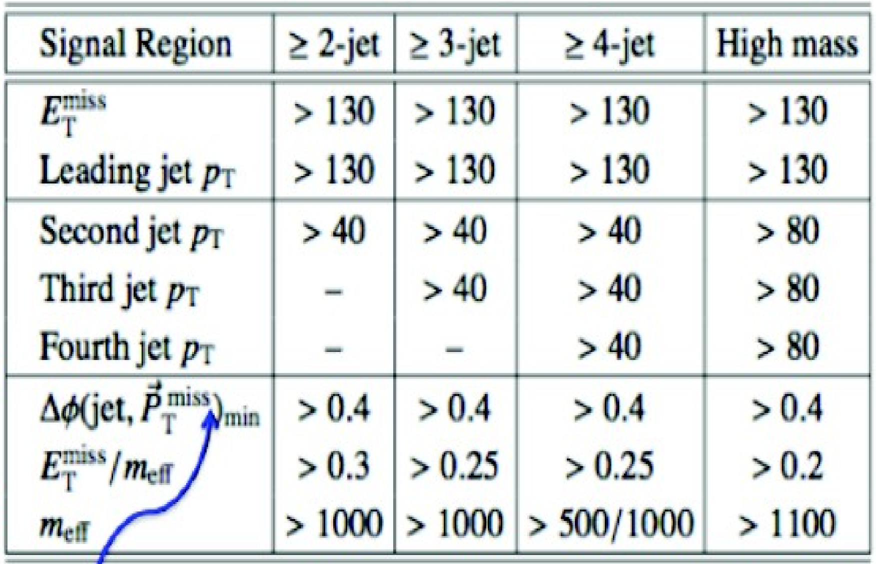
$1.04\ \mathrm{fb}^{-1}$



R-parity conservation assumed

$\tilde{q}\tilde{q}$ (≥ 2-jet), $\tilde{q}\tilde{g}$ (≥ 3-jet), $\tilde{g}\tilde{g}$ (≥ 4-jet, High mass)



	Signal Region	≥ 2-jet	≥ 3-jet	≥ 4-jet	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
QCD rejection	$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 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}	> 1000	> 1000	> 500/1000	> 1100

$\Delta\phi$ cut up to 3rd leading jet

$$m_{eff} = E_T^{miss} + \sum_{\text{SR jets}} p_T$$

$$m_{eff}^{incl} = E_T^{miss} + \sum_{\text{jets } p_T > 40} p_T$$

0-lepton signature

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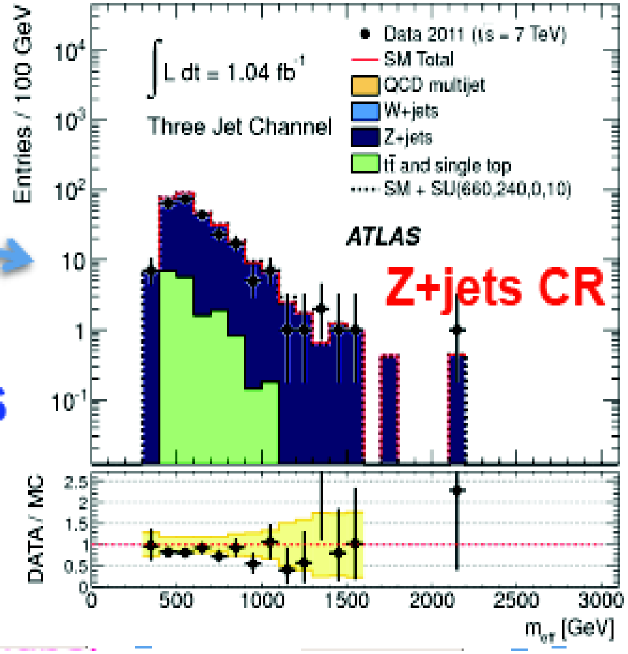
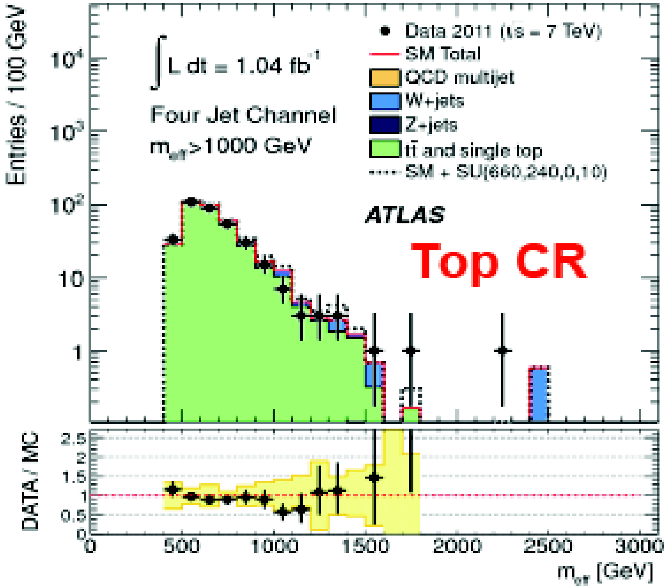
Backgrounds: ttbar, Z+jets, W+jets multijet

control regions

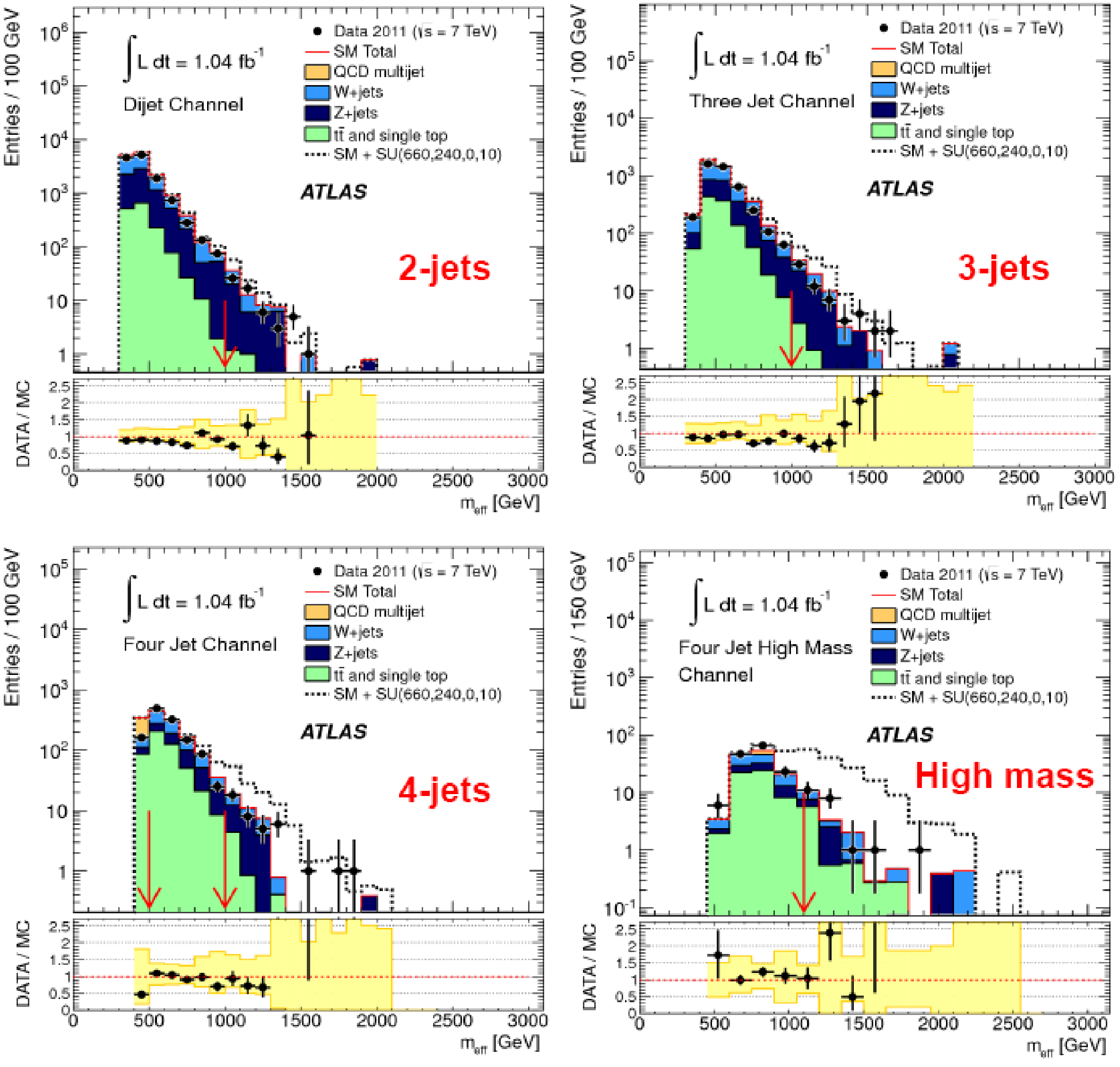
reverse $\Delta\Phi(\text{jet}, p_T^{miss})$ cut



Z+jets CR



Top CR



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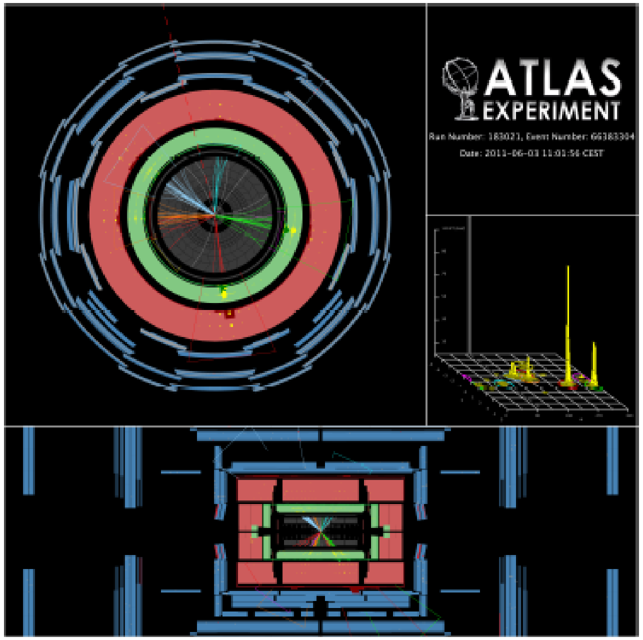
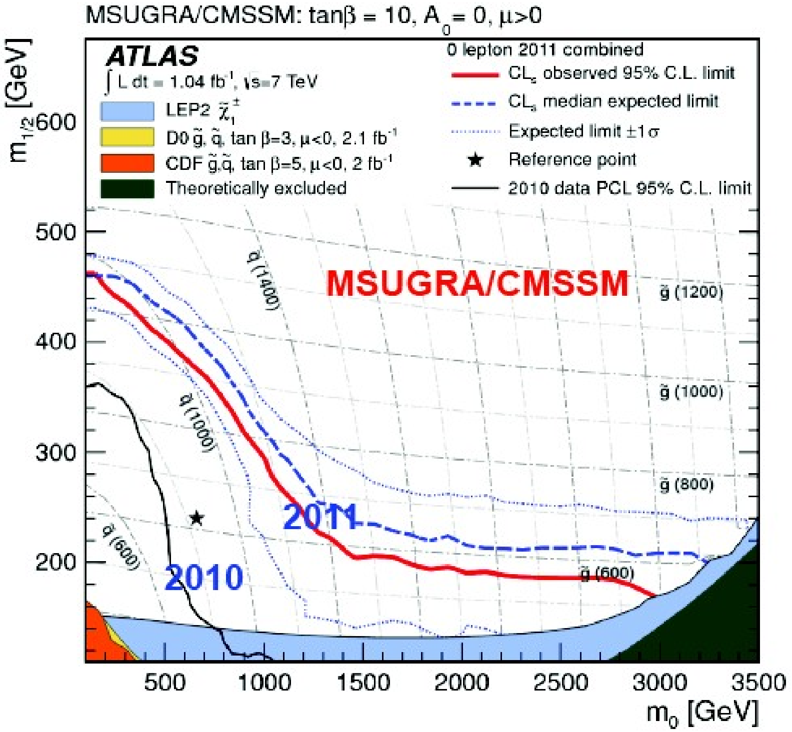


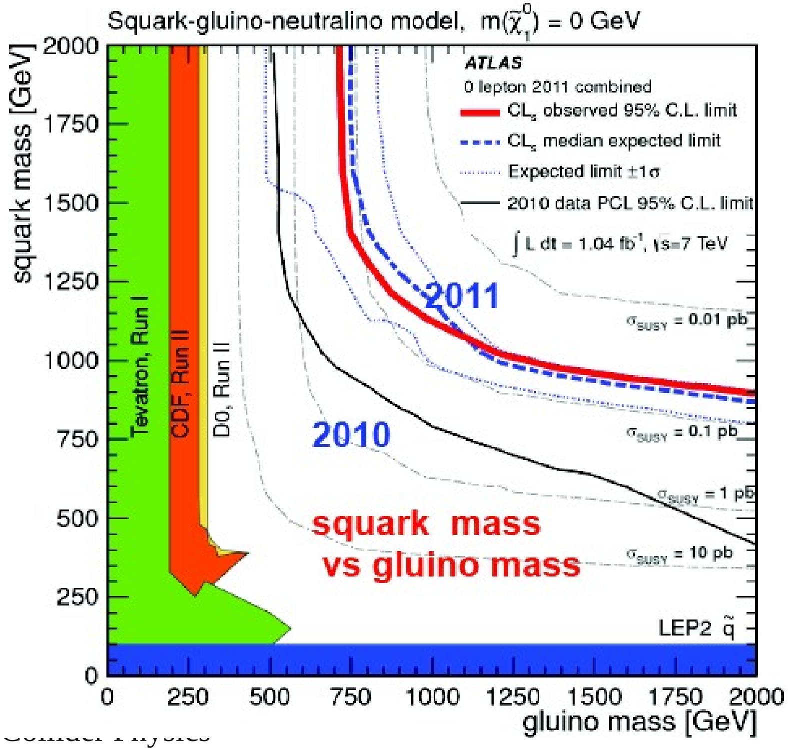
Highest m_{eff} event
m_{eff} = 1.81 TeV
E_T^{miss} = 460 GeV

Effective mass (m_{eff}) distributions in signal regions.

No excess observed: limits set (CL_s method, profile likelihood technique))

Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, $m_{\mathrm{eff}} > 500$ GeV	≥ 4-jet, $m_{\mathrm{eff}} > 1000$ GeV	High mass
Z/γ+jets	32.3 ± 2.6 ± 6.9	25.5 ± 2.6 ± 4.9	209 ± 9 ± 38	16.2 ± 2.2 ± 3.7	3.3 ± 1.0 ± 1.3
W+jets	26.4 ± 4.0 ± 6.7	22.6 ± 3.5 ± 5.6	349 ± 30 ± 122	13.0 ± 2.2 ± 4.7	2.1 ± 0.8 ± 1.1
$t\bar{t}$+ single top	3.4 ± 1.6 ± 1.6	5.9 ± 2.0 ± 2.2	425 ± 39 ± 84	4.0 ± 1.3 ± 2.0	5.7 ± 1.8 ± 1.9
QCD multi-jet	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.73 ± 0.14 ± 0.50	2.10 ± 0.37 ± 0.82
Total	62.4 ± 4.4 ± 9.3	54.9 ± 3.9 ± 7.1	1015 ± 41 ± 144	33.9 ± 2.9 ± 6.2	13.1 ± 1.9 ± 2.5
Data	58	59	1118	40	18
εσA limit (fb):	22	25	429	27	17





1 lepton+Jets+E_T^{miss}

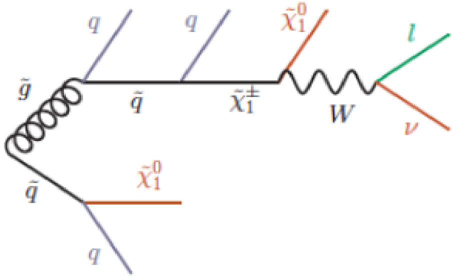
Cornell University Library

arXiv.org 1109.6606

1.04 fb^{-1}

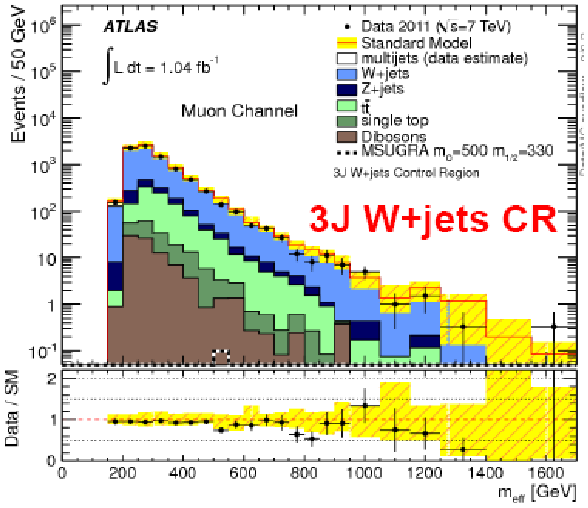
Selection	Signal Regions 3JL	 3JT	 4JL	 4JT	Control Regions 3J	 4J
Number of Leptons	= 1					
Lepton p_T (GeV)	> 25(20) for electrons (muons)					
Veto lepton p_T (GeV)	> 20(10) for electrons (muons)					
Number of jets	≥ 3		≥ 4		≥ 3	≥ 4
Leading jet p_T (GeV)	60	80	60	60	60	60
Subsequent jets p_T (GeV)	25	25	25	40	25	25
$\Delta\phi(\vec{\text{jet}}_i, \vec{E}_T^{\text{miss}})$	$[> 0.2\ (\text{mod.}\pi)]$ for all 3 (4) jets					
m_T (GeV)	> 100				$40 < m_T < 80$	
E_T^{miss} (GeV)	> 125	> 240	> 140	> 200	$30 < E_T^{\text{miss}} < 80$	
$E_T^{\text{miss}}/m_{\text{eff}}$	> 0.25	> 0.15	> 0.30	> 0.15	–	–
m_{eff} (GeV)	> 500	> 600	> 300	> 500	> 500	> 300

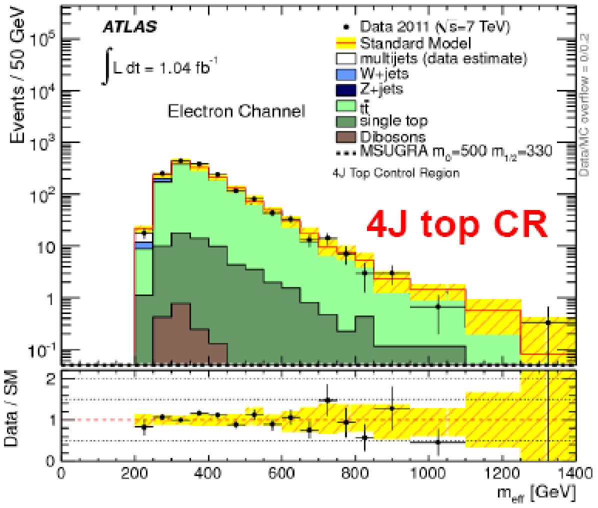
Example 1-lepton signature



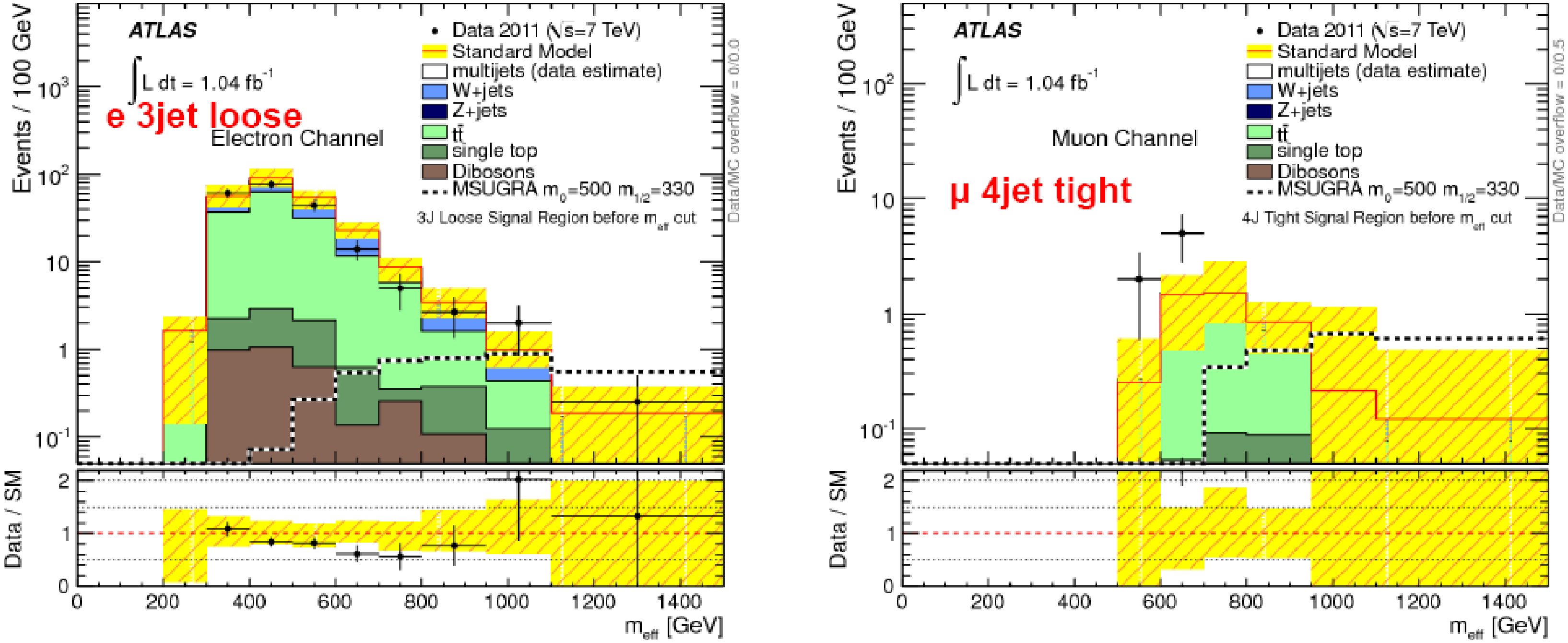
Backgrounds: W+jets, ttbar
(multijet negligible)

BG estimation using
control regions

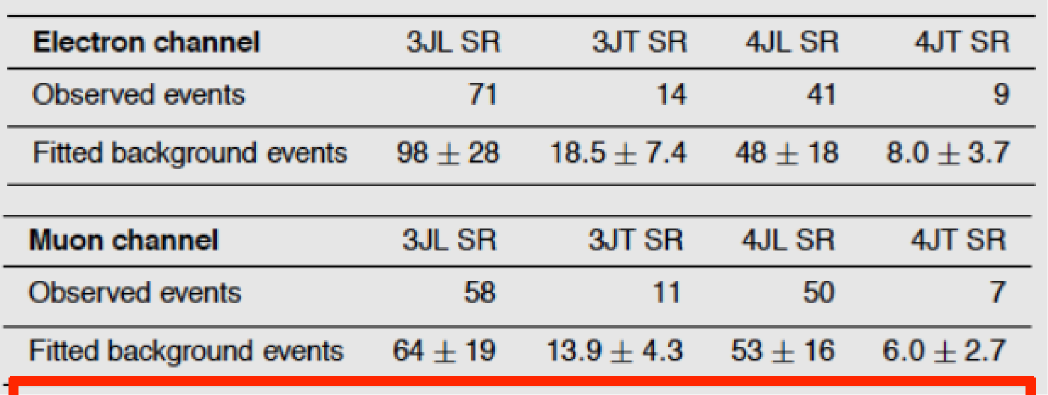




E,



m_{eff} in signal regions: no excess

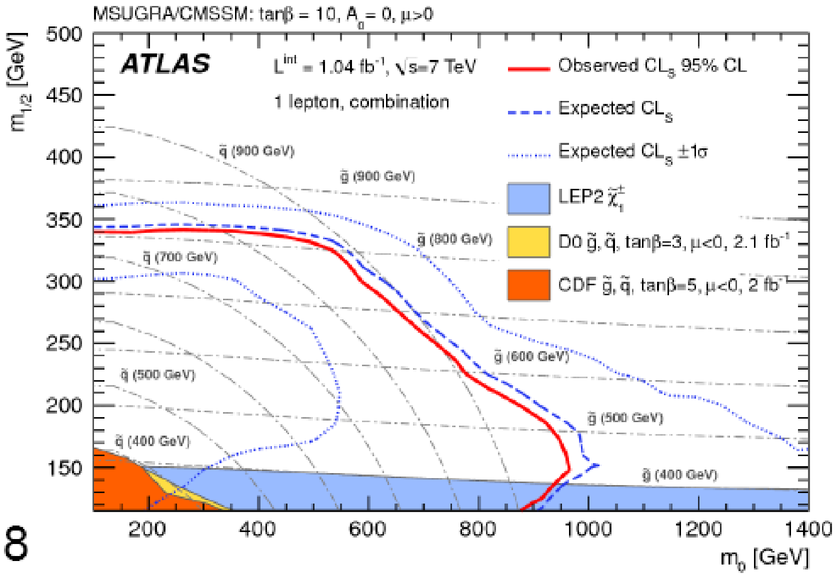


Electron channel	3JL SR	3JT SR	4JL SR	4JT SR
Observed events	71	14	41	9
Fitted background events	98 ± 28	18.5 ± 7.4	48 ± 18	8.0 ± 3.7

Muon channel	3JL SR	3JT SR	4JL SR	4JT SR
Observed events	58	11	50	7
Fitted background events	64 ± 19	13.9 ± 4.3	53 ± 16	6.0 ± 2.7

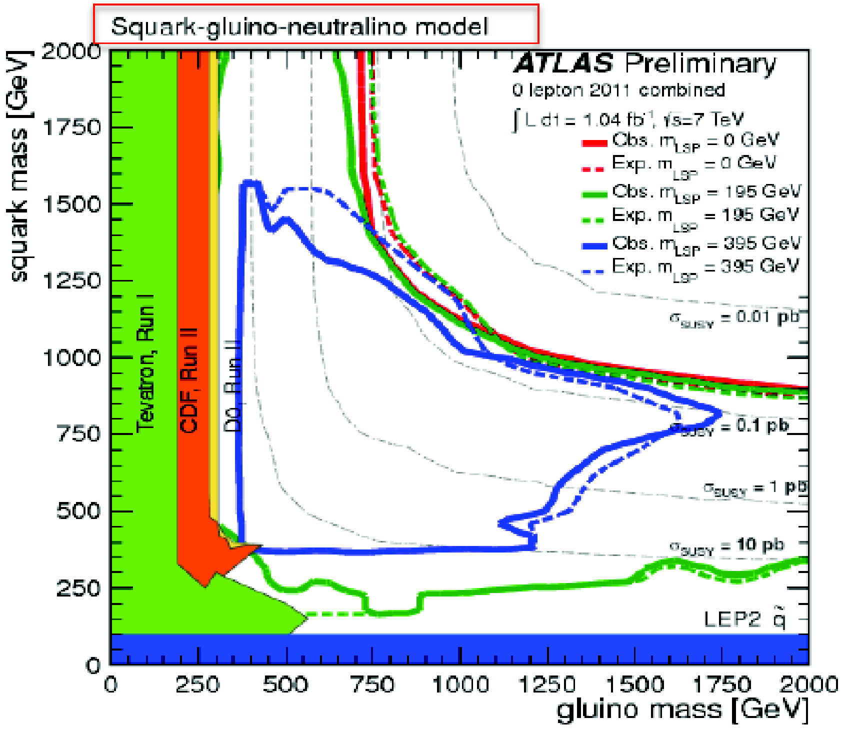
εσA limits (fb) e:	**50**	**14**	**33**	**10**
μ:	**36**	**10**	**31**	**9**

MSUGRA/CMSSM



SUSY : simplified models

MSSM-inspired models of well-defined production and decay modes
Explore dependence of free parameters
Introduce complexity progressively



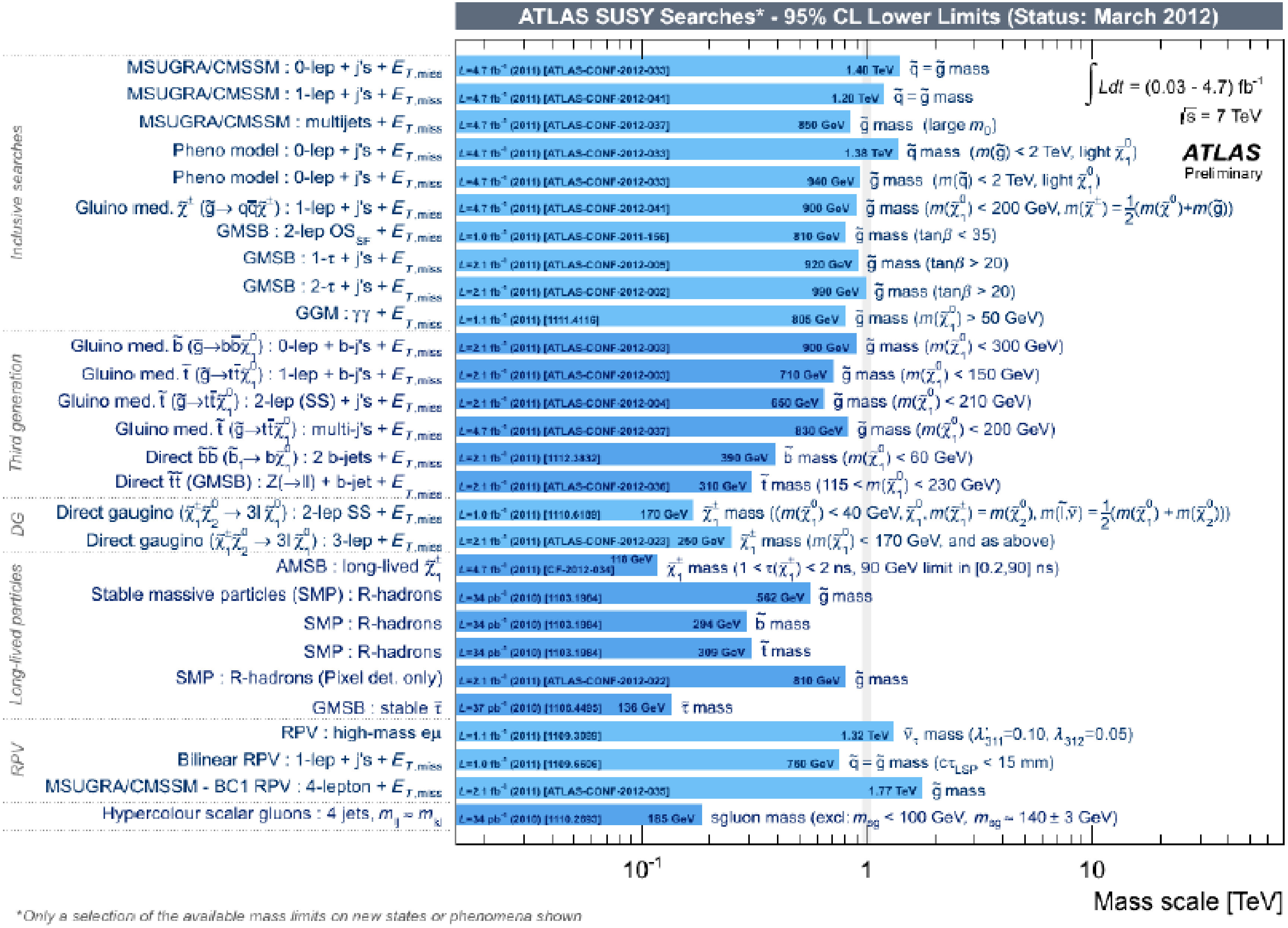
- Simplified models for 0-lepton channels

red: massless LSP
green: LSP 195 GeV
blue: LSP 395 GeV

ATLAS-CONF-2011-155

2011:Null searches so ...

- Null searches also for any other BSM signal
- **What next...**
  - Generalize away from (over) constrained scenarios
  - Gaugino sector and sleptons: multi-leptons, photons
  - Stop (and sbottom and stau) sectors (major motivation for SUSY at low energies)
  - Non- “canonical” scenarios:
    - semi-stable SUSY particles, R-parity violation


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 2012)
$\int L dt = (0.03 - 4.7)$ fb^{-1}
$\sqrt{s}$ = 7 TeV
ATLAS
Preliminary
Inclusive searches
MSUGRA/CMSSM : 0-lep + j's + $E_{T,miss}$ | L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-033] | 1.40 TeV | $\tilde{q} = \tilde{g}$ mass
MSUGRA/CMSSM : 1-lep + j's + $E_{T,miss}$ | L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-041] | 1.20 TeV | $\tilde{q} = \tilde{g}$ mass
MSUGRA/CMSSM : multijets + $E_{T,miss}$ | L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-037] | 850 GeV | $\tilde{g}$ mass (large m_0)
Pheno model : 0-lep + j's + $E_{T,miss}$ | L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-033] | 1.38 TeV | $\tilde{q}$ mass ($m(\tilde{g})$ < 2 TeV, light $\tilde{\chi}^0_1$)
Pheno model : 0-lep + j's + $E_{T,miss}$ | L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-033] | 940 GeV | $\tilde{g}$ mass ($m(\tilde{q})$ < 2 TeV, light $\tilde{\chi}^0_1$)
Gluino med. $\tilde{\chi}^{\pm}$ ($\tilde{g} \to q\bar{q}\tilde{\chi}^{\pm}$) : 1-lep + j's + $E_{T,miss}$ | L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-041] | 900 GeV | $\tilde{g}$ mass ($m(\tilde{\chi}^0_1)$ < 200 GeV, $m(\tilde{\chi}^{\pm}) = \frac{1}{2}(m(\tilde{\chi}^0)+m(\tilde{g}))$
GMSB : 2-lep OS$_{SF}$ + $E_{T,miss}$ | L=1.0 fb^{-1} (2011) [ATLAS-CONF-2011-156] | 810 GeV | $\tilde{g}$ mass (tanβ < 35)
GMSB : 1-τ + j's + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-005] | 920 GeV | $\tilde{g}$ mass (tanβ > 20)
GMSB : 2-τ + j's + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-002] | 990 GeV | $\tilde{g}$ mass (tanβ > 20)
GGM : $\gamma\gamma$ + $E_{T,miss}$ | L=1.1 fb^{-1} (2011) [1111.4116] | 805 GeV | $\tilde{g}$ mass ($m(\tilde{\chi}^0_1)$ > 50 GeV)
Third generation
Gluino med. $\tilde{b}$ ($\tilde{g} \to b\bar{b}\tilde{\chi}^0_1$) : 0-lep + b-j's + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-003] | 900 GeV | $\tilde{g}$ mass ($m(\tilde{\chi}^0_1)$ < 300 GeV)
Gluino med. $\tilde{t}$ ($\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$) : 1-lep + b-j's + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-003] | 710 GeV | $\tilde{g}$ mass ($m(\tilde{\chi}^0_1)$ < 150 GeV)
Gluino med. $\tilde{t}$ ($\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$) : 2-lep (SS) + j's + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-004] | 650 GeV | $\tilde{g}$ mass ($m(\tilde{\chi}^0_1)$ < 210 GeV)
Gluino med. $\tilde{t}$ ($\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$) : multi-j's + $E_{T,miss}$ | L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-037] | 830 GeV | $\tilde{g}$ mass ($m(\tilde{\chi}^0_1)$ < 200 GeV)
Direct $\tilde{b}\tilde{b}$ ($\tilde{b}_1 \to b\tilde{\chi}^0_1$) : 2 b-jets + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [1112.3832] | 390 GeV | $\tilde{b}$ mass ($m(\tilde{\chi}^0_1)$ < 60 GeV)
Direct $\tilde{t}\tilde{t}$ (GMSB) : $Z(\to ll)$ + b-jet + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-036] | 310 GeV | $\tilde{t}$ mass (115 < $m(\tilde{\chi}^0_1)$ < 230 GeV)
DG
Direct gaugino ($\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2 \to 3l\,\tilde{\chi}^0_1$) : 2-lep SS + $E_{T,miss}$ | L=1.0 fb^{-1} (2011) [1110.6189] | 170 GeV | $\tilde{\chi}^{\pm}_1$ mass (($m(\tilde{\chi}^0_1)$ < 40 GeV, $\tilde{\chi}^0_1$, $m(\tilde{\chi}^{\pm}_1) = m(\tilde{\chi}^0_2)$, $m(\tilde{l},\tilde{\nu}) = \frac{1}{2}(m(\tilde{\chi}^0_1) + m(\tilde{\chi}^0_2))$)
Direct gaugino ($\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2 \to 3l\,\tilde{\chi}^0_1$) : 3-lep + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-023] | 250 GeV | $\tilde{\chi}^{\pm}_1$ mass ($m(\tilde{\chi}^0_1)$ < 170 GeV, and as above)
Long-lived particles
AMSB : long-lived $\tilde{\chi}^{\pm}_1$ | L=4.7 fb^{-1} (2011) [CF-2012-034] | 118 GeV | $\tilde{\chi}^{\pm}_1$ mass (1 < $\tau(\tilde{\chi}^{\pm}_1)$ < 2 ns, 90 GeV limit in [0.2,90] ns)
Stable massive particles (SMP) : R-hadrons | L=34 pb^{-1} (2010) [1103.1984] | 562 GeV | $\tilde{g}$ mass
SMP : R-hadrons | L=34 pb^{-1} (2010) [1103.1984] | 294 GeV | $\tilde{b}$ mass
SMP : R-hadrons | L=34 pb^{-1} (2010) [1103.1984] | 309 GeV | $\tilde{t}$ mass
SMP : R-hadrons (Pixel det. only) | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-022] | 810 GeV | $\tilde{g}$ mass
GMSB : stable $\tilde{\tau}$ | L=37 pb^{-1} (2010) [1106.4495] | 136 GeV | $\tilde{\tau}$ mass
RPV
RPV : high-mass eμ | L=1.1 fb^{-1} (2011) [1109.3089] | 1.32 TeV | $\tilde{\nu}_\tau$ mass (λ'_{311}=0.10, λ_{312}=0.05)
Bilinear RPV : 1-lep + j's + $E_{T,miss}$ | L=1.0 fb^{-1} (2011) [1109.6606] | 760 GeV | $\tilde{q} = \tilde{g}$ mass (cτ_{LSP} < 15 mm)
MSUGRA/CMSSM - BC1 RPV : 4-lepton + $E_{T,miss}$ | L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-035] | 1.77 TeV | $\tilde{g}$ mass
Hypercolour scalar gluons : 4 jets, $m_{ij} \approx m_{kl}$ | L=34 pb^{-1} (2010) [1110.2693] | 185 GeV | sgluon mass (excl: m_{sg} < 100 GeV, $m_{sg} \approx$ 140 ± 3 GeV)
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

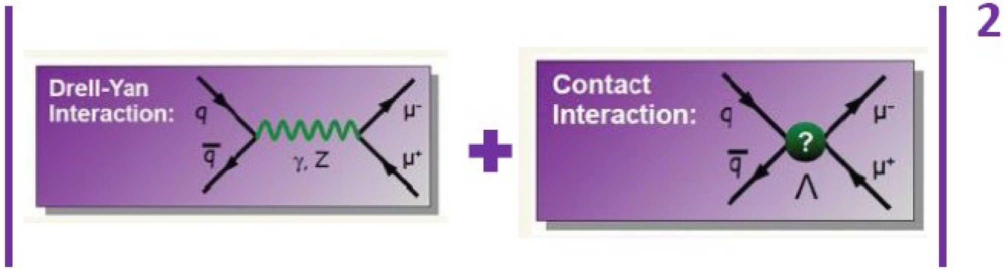
Search for contact interactions

Motivations: 4-fermion contact interaction (CI) can be a low-energy description of:

- Large Extra Dimension ADD model
- Quark-lepton compositeness

Analysis strategy:

Look for excess over Drell-Yan production selecting high-quality leptons



Context of left-left isoscalar model:

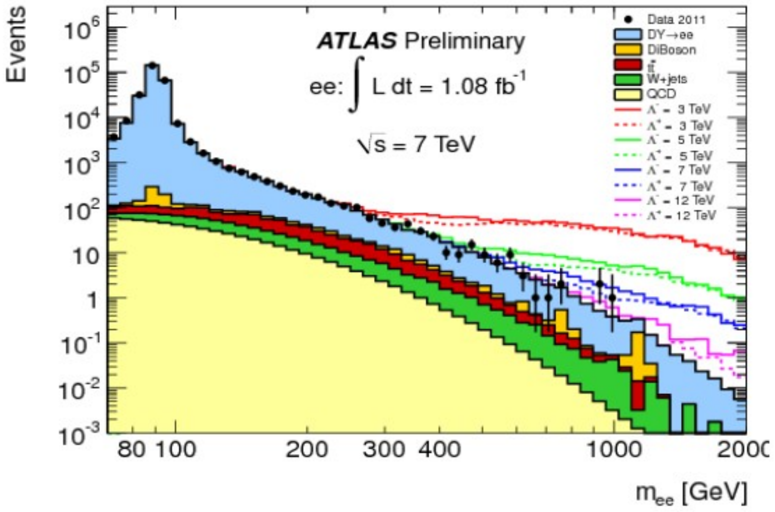
$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta_{LL}\frac{F_I(m_{\ell\ell})}{\Lambda^2} + \frac{F_C(m_{\ell\ell})}{\Lambda^4}$$

- F_I: interference interaction
- η_{LL}±1
- F_C: pure contact interaction

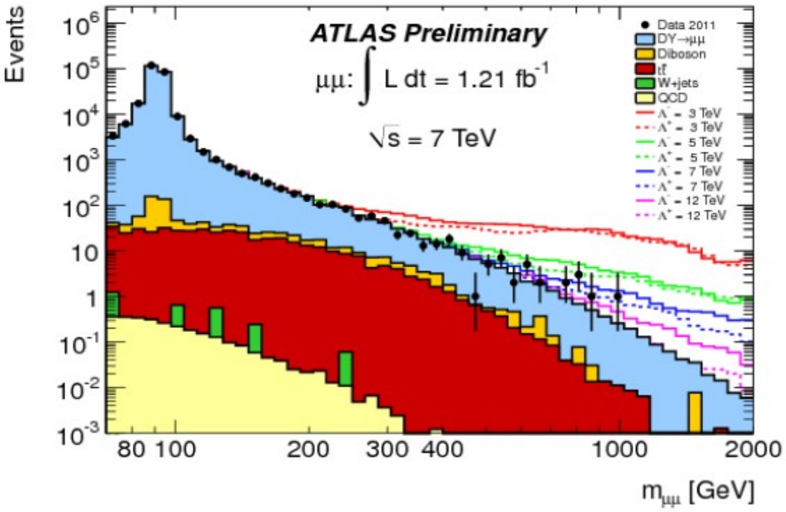
- Λ: Energy scale below which fermion constituents are bound

Search for contact interactions

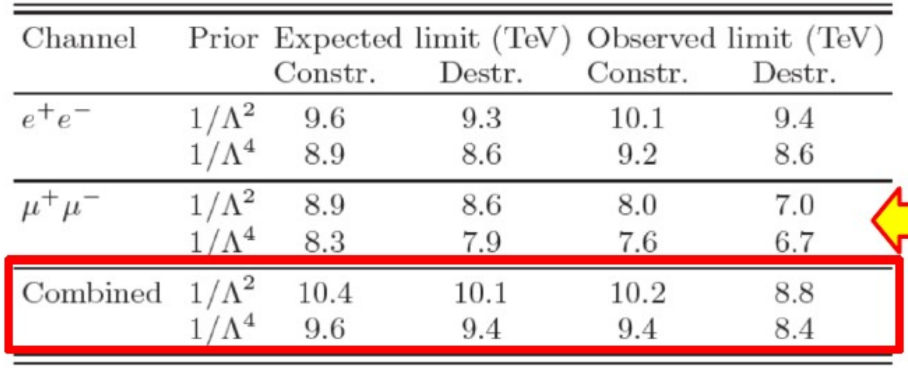
Results: Electron channel



Muon channel



Lower limits on scale Λ at 95% of Credibility Level:



Channel	Prior	Expected limit (TeV)		Observed limit (TeV)	
		Constr.	Destr.	Constr.	Destr.
e^+e^-	$1/\Lambda^2$	9.6	9.3	10.1	9.4
	$1/\Lambda^4$	8.9	8.6	9.2	8.6
$\mu^+\mu^-$	$1/\Lambda^2$	8.9	8.6	8.0	7.0
	$1/\Lambda^4$	8.3	7.9	7.6	6.7
Combined	$1/\Lambda^2$	10.4	10.1	10.2	8.8
	$1/\Lambda^4$	9.6	9.4	9.4	8.4

Most stringent limits to date

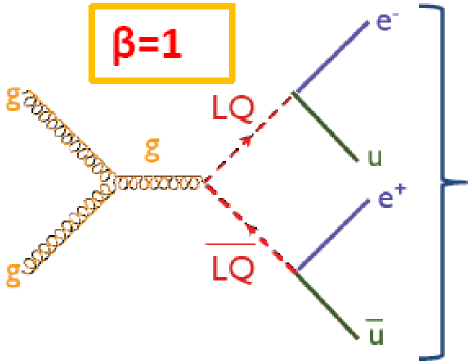
Leptoquarks

Motivations: **Leptoquarks (LQ) are color-triplet bosons that carry both lepton and baryon numbers, and fractional electric charge**

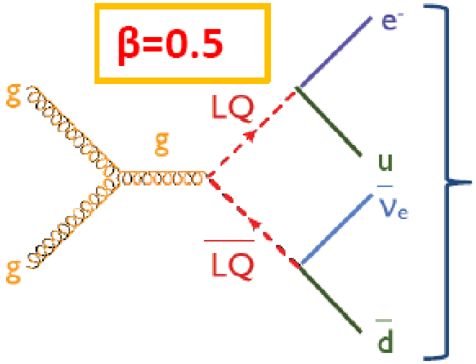
- Introduced by various extension of the SM (technicolor, GUTs, etc)
- Could explain **similarities between the 3 generations of leptons and quarks in the SM**, and lead to some **symmetry at high energy scale**

Analysis strategy: **Search for pair-produced LQs assumed to couple only to quarks and leptons of the same SM generation**

→ Focus here on 1st generation for 2 scenarii: β=BR(LQ→eq)

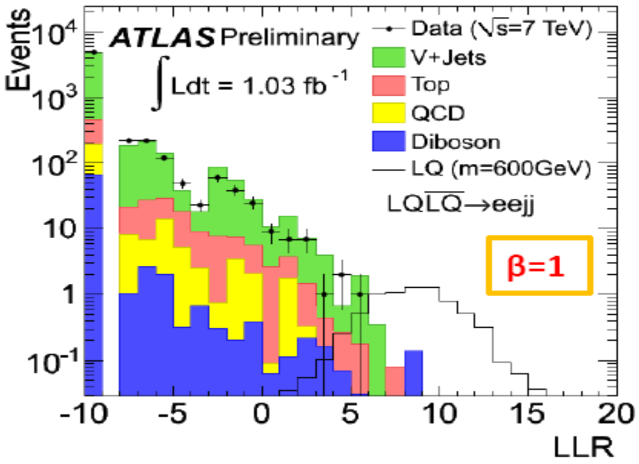


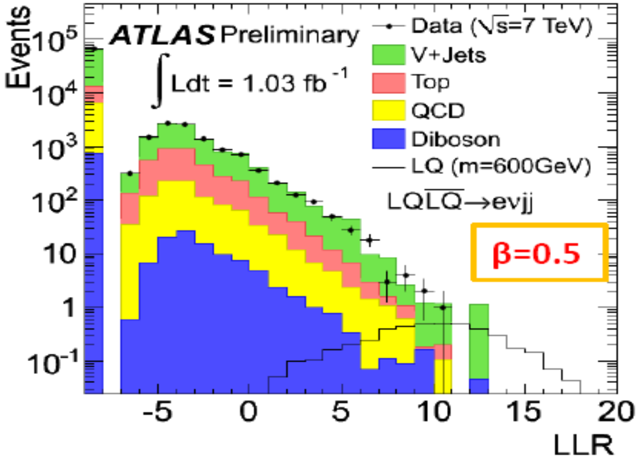
Select:
- •2 electrons
- •2 jets



Select:
- •1 electron
- •2 jets
- •Missing energy

Search for first generation of scalar leptoquarks

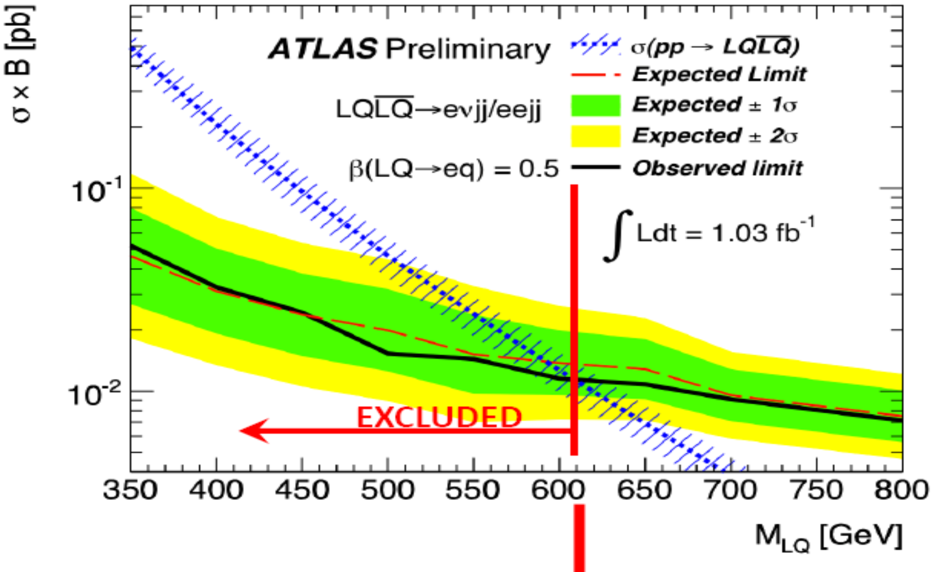




Analysis strategy cont'd:

Use of Likelihood ratio method to discriminate signal from SM backgrounds

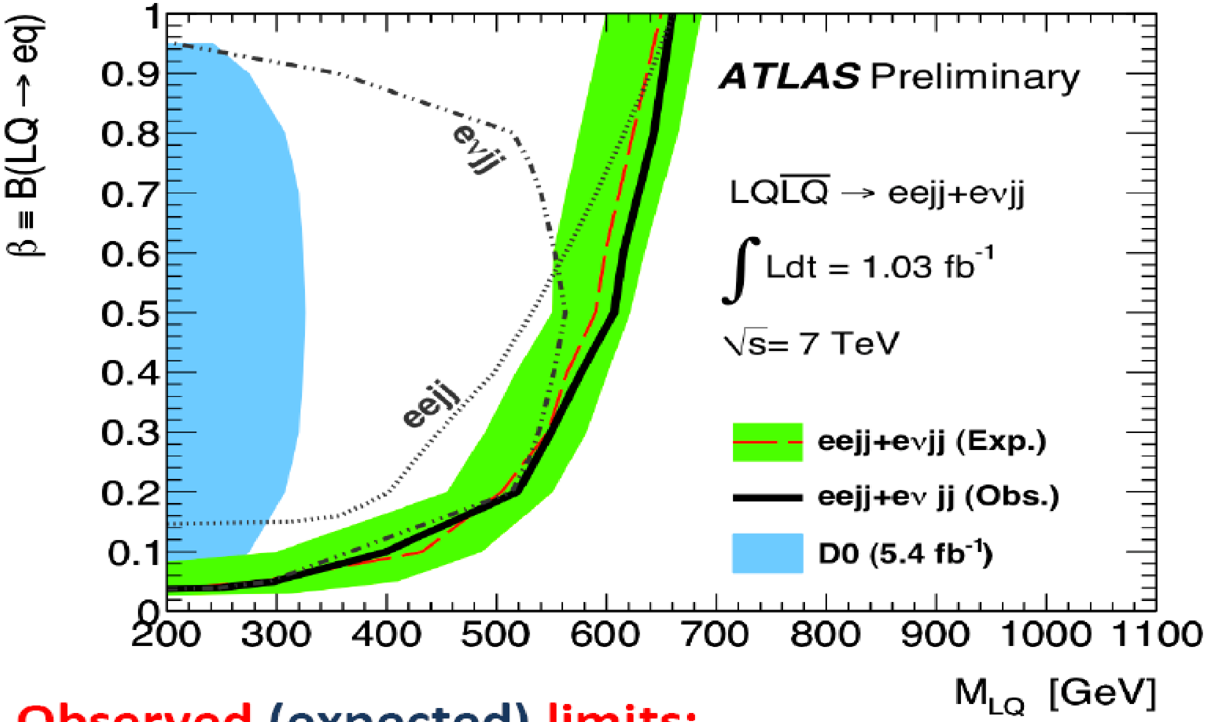
… then put 95% CLs upper limits on σxBR:



m_{LQ} > 607 GeV

Search for first generation of scalar leptoquarks

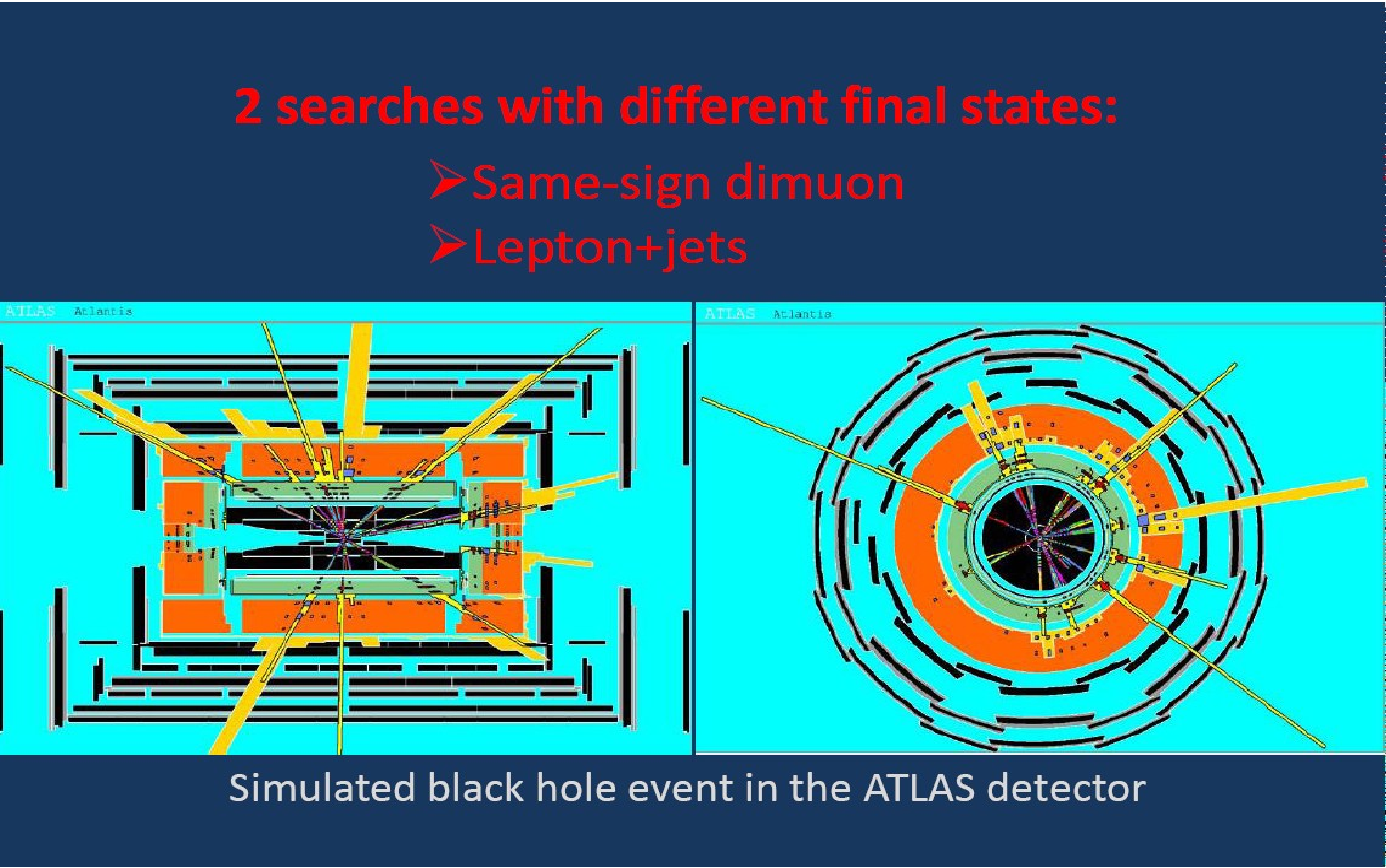
Results: **95% CL exclusion regions**



Observed (expected) limits:

- **β=1: m_{LQ} > 660(650) GeV**
- **β=0.5: m_{LQ} > 607(587) GeV**

Black holes



2 searches with different final states:

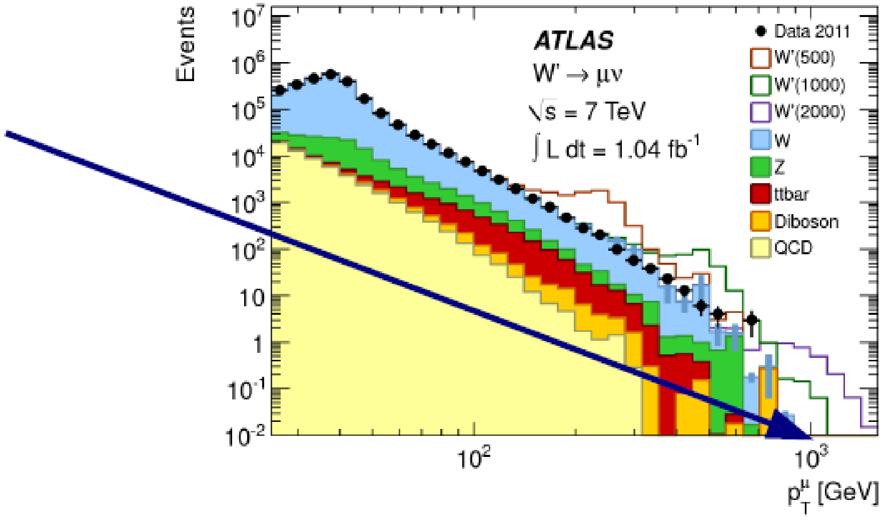
- Same-sign dimuon
- Lepton+jets

Simulated black hole event in the ATLAS detector

Search for heavy resonances

- Predicted by numerous extensions of the Standard Model:
  - → GUT-inspired theories, Little Higgs → heavy gauge boson(s) Z' (W')
  - → Technicolor → narrow technihadrons
  - → Randall-Sundrum ED → Kaluza-Klein graviton
- Experimental challenge: understand detector performance (resolution, efficiency) for a signal with (almost) no control sample at very high momentum → confidence in alignment, simulation, etc…
- Electrons and muons:

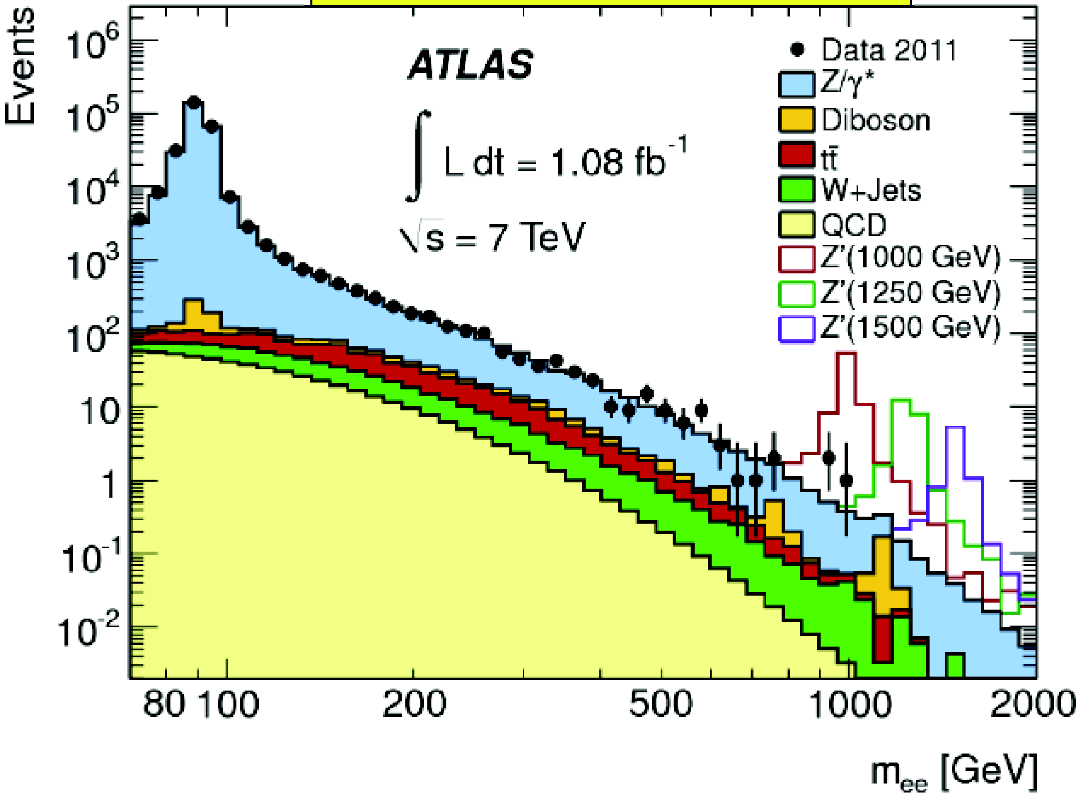
  Rapidly approaching 1 TeV!



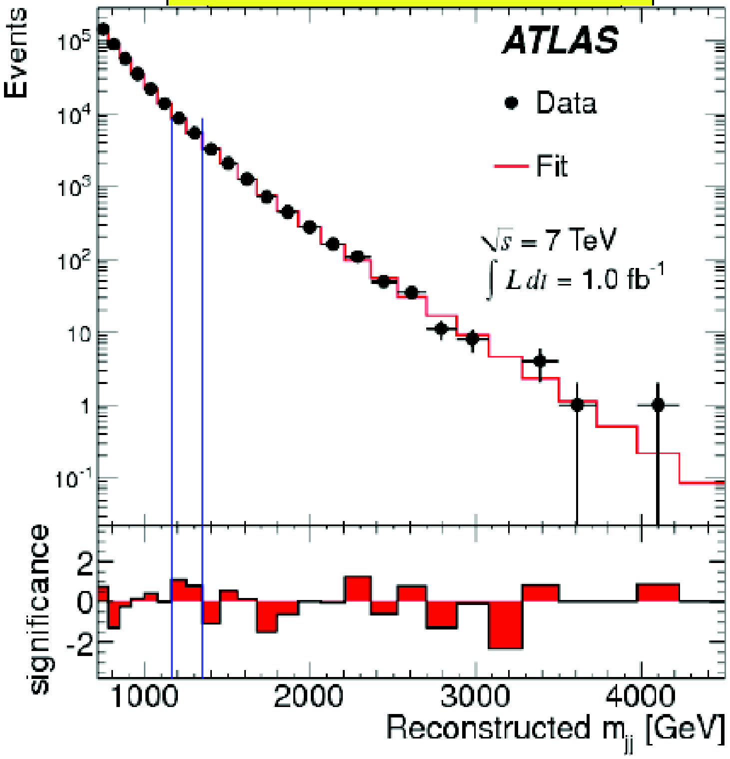
Search for heavy particles-resonances

- Search for peaks in different spectra
  - Reached very high masses: ~4TeV (m_{jj}) and 1 TeV (m_{ee})

2 electrons invariant mass



2 jets invariant mass



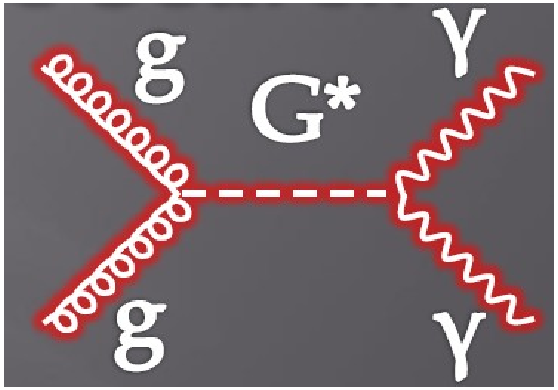
This allows to put more stringent lower mass limits to heavy new particles

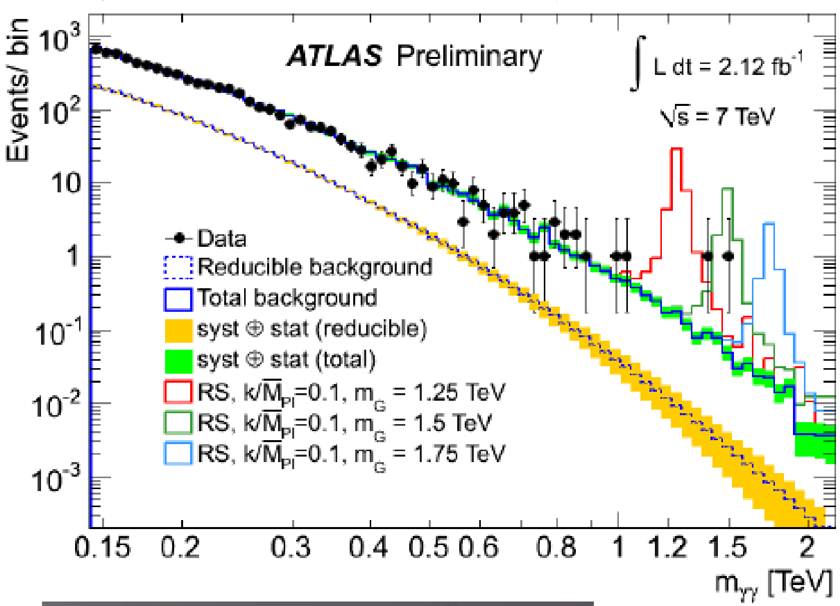
Diphoton resonances search

- No excess in the $m_{\gamma\gamma}$ spectrum

2.12 fb^{-1}

arXiv:1112.2194v1

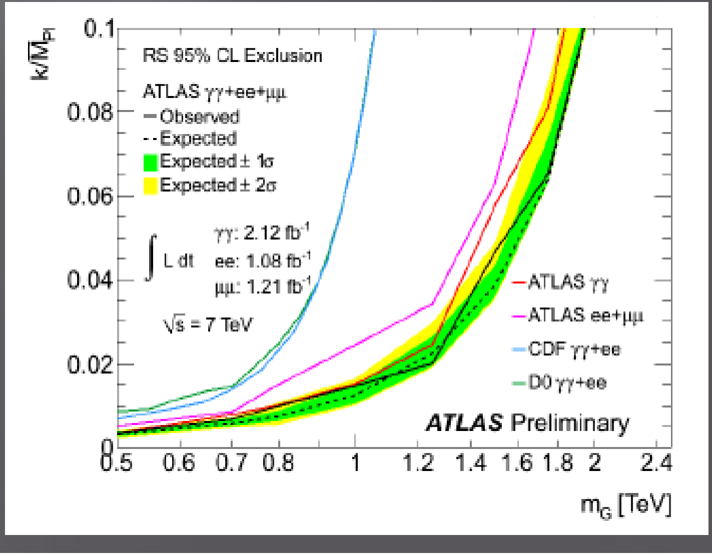


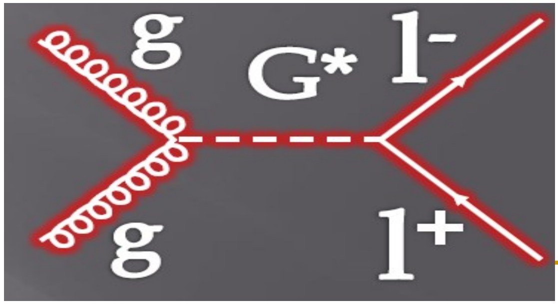


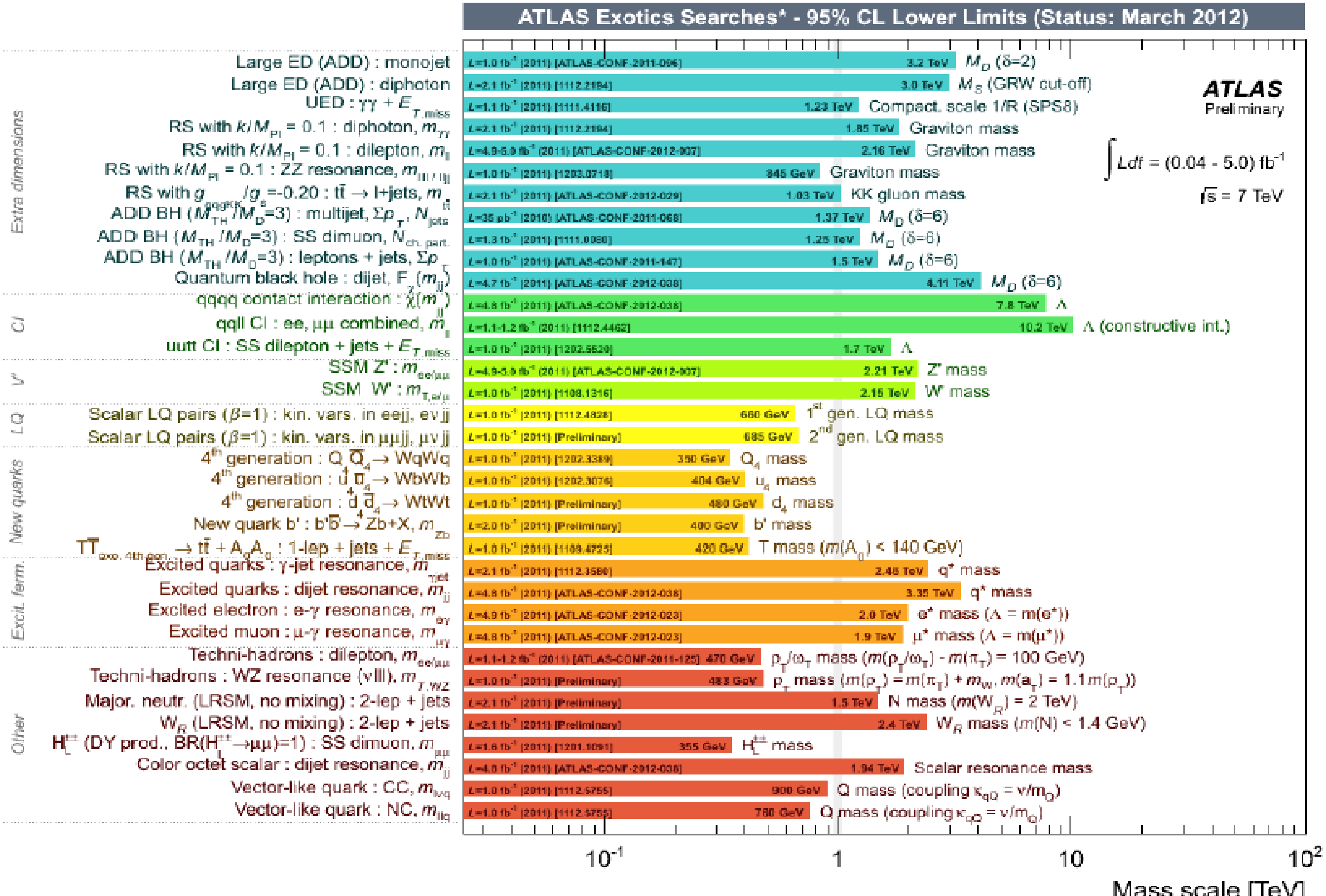
Bayesian approach using templates

RS G* limits ($\gamma\gamma$+ll):

- m_{G^*}>1.95 TeV ($k/\bar{M}_{PL}$=0.1)
- m_{G^*}>0.8 TeV ($k/\bar{M}_{PL}$=0.01)







*Only a selection of the available mass limits on new states or phenomena shown

LHC running in 2012: 8 TeV

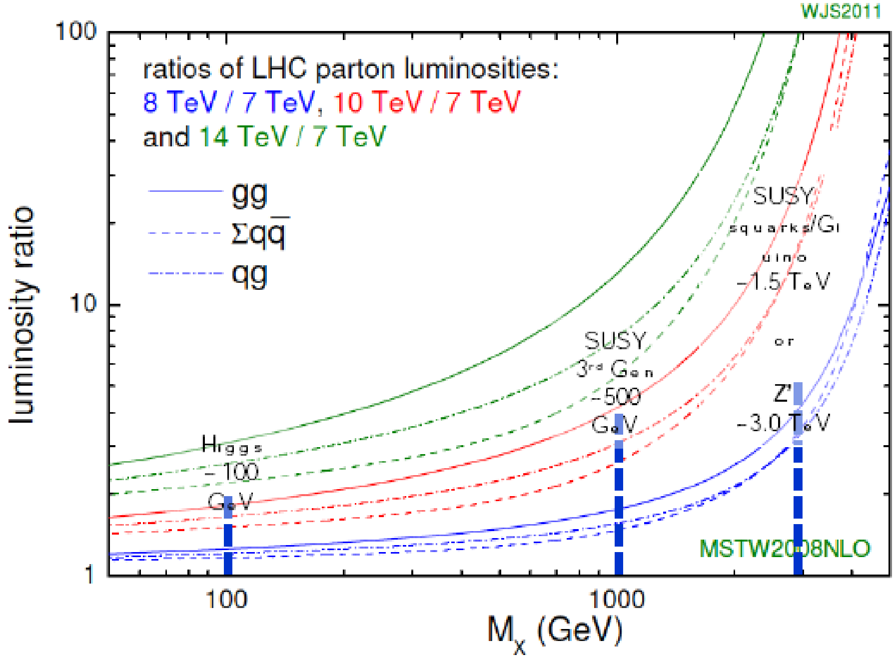
- **Enhances physics reach in two ways:**
  - Higher cross-sections for new physics in full mass range

Higgs: **pp → H, H→ WW, ZZ & γγ**
mainly gg: Factor ~1.2

SUSY: 3rd Gen Mass ~ 0.5 TeV
qq and gg: Factor ~1.5

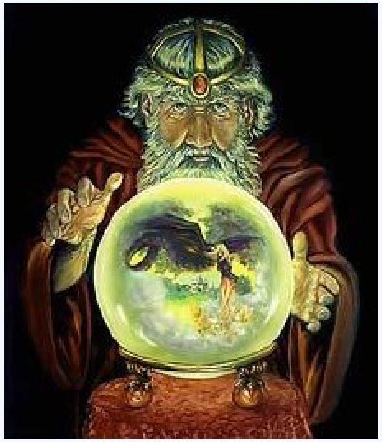
SUSY: Squarks/Gluino M~1.5TeV
qq,gg,qg: Factor ~4.0

Z' : Mass ~ 3.0 TeV
qq: Factor ~3.5



- More integrated luminosity
  - **@ 8 TeV: 16 – 25fb^{-1} expected (50 ns bunch crossing)**

The predictable future: LHC Time-line



2009

Start of LHC

Run 1: 7 TeV centre of mass energy, luminosity ramping up to few 10^{33} cm^{-2} s^{-1}, few fb^{-1} delivered

2013/14

LHC shut-down to prepare machine for design energy and luminosity

Run 2: Ramp up luminosity to design (10^{34} cm^{-2} s^{-1}), ~50 to 100 fb^{-1}

2017 or 18

Injector and LHC Phase-I upgrades to go to ultimate luminosity

Run 3: Ramp up luminosity to 2.2 x design, reaching ~100 fb^{-1} / year accumulate few hundred fb^{-1}

~2021/22

Phase-II: High-luminosity LHC. New focussing magnets and CRAB cavities for very high luminosity with luminosity levelling

Kick-Off meeting for HL-LHC: Nov 2011

Run 4: Collect data until > 3000 fb^{-1}

2030

Summary and Outlook

- **LHC and experiments' run truly impressive**
  - By now detectors are fully functioning scientific instruments;
- **With ~40pb^{-1} the LHC observed all particles of the Standard Model**
  - Solid base for understanding the “background” to searches at higher mass and transverse energy scales
- **With 5 fb^{-1} (at 7 TeV) we entered a true discovery era**
- **With 15-25 fb^{-1} (at 8 TeV)**
  - SM Higgs sector and SUSY explorable over very large area; possible new resonances; very large reach for other new physics;
- **The journey has just started.**