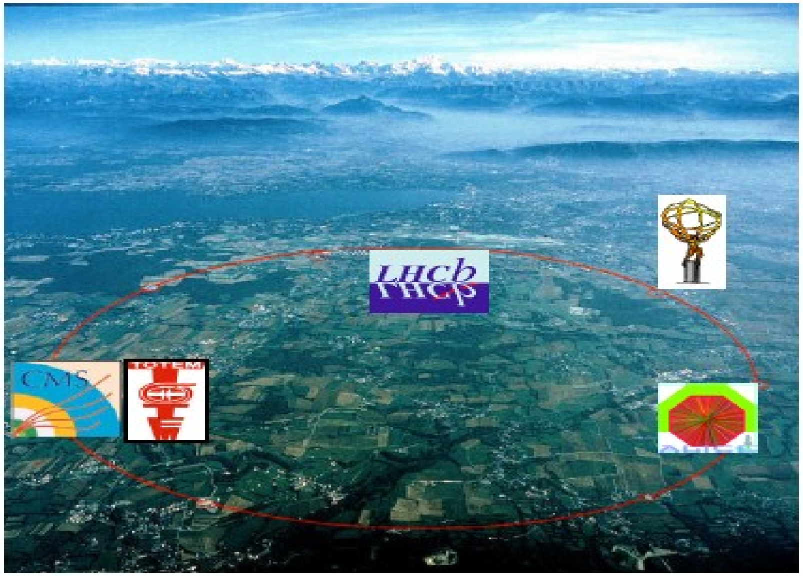
Lecture 11

Physics Program
of the experiments at
Large **H**adron **C**ollider

SM Higgs boson: properties

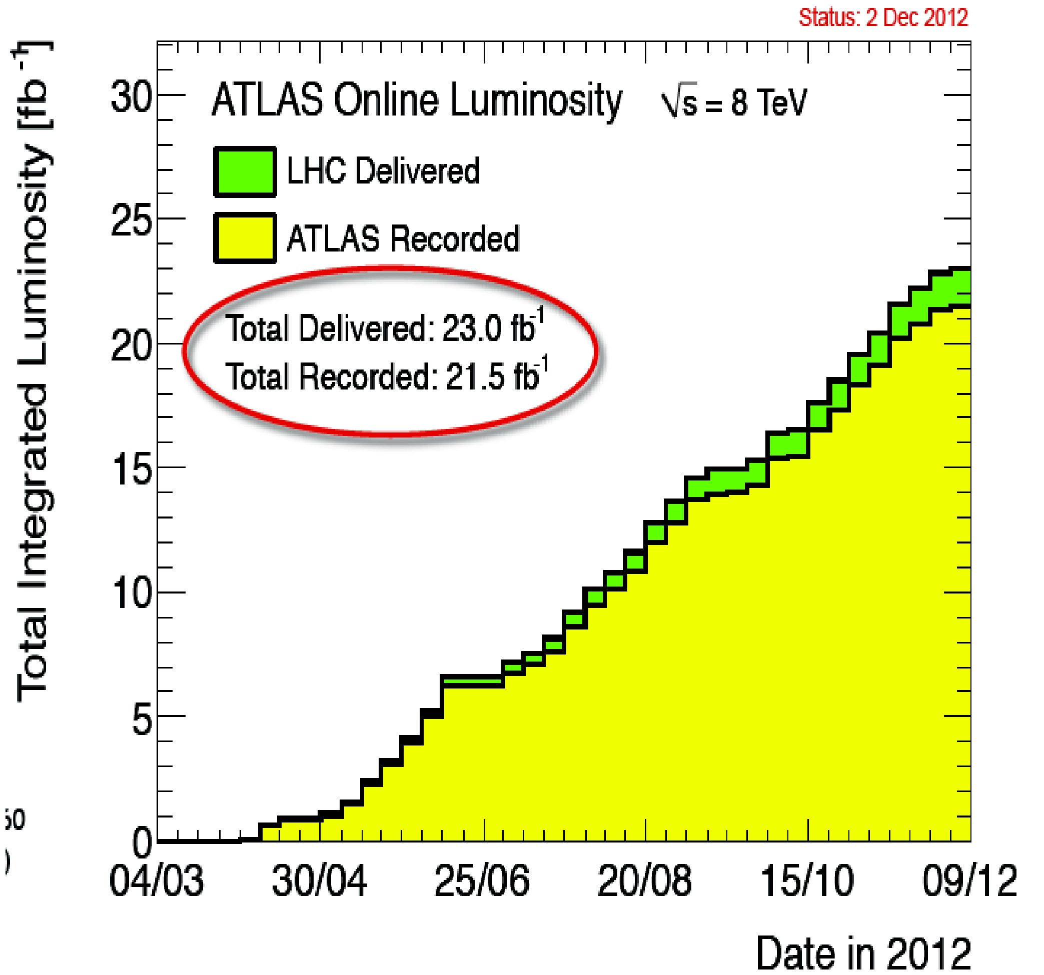
Supersymmetry



Recorded luminosity in 2012

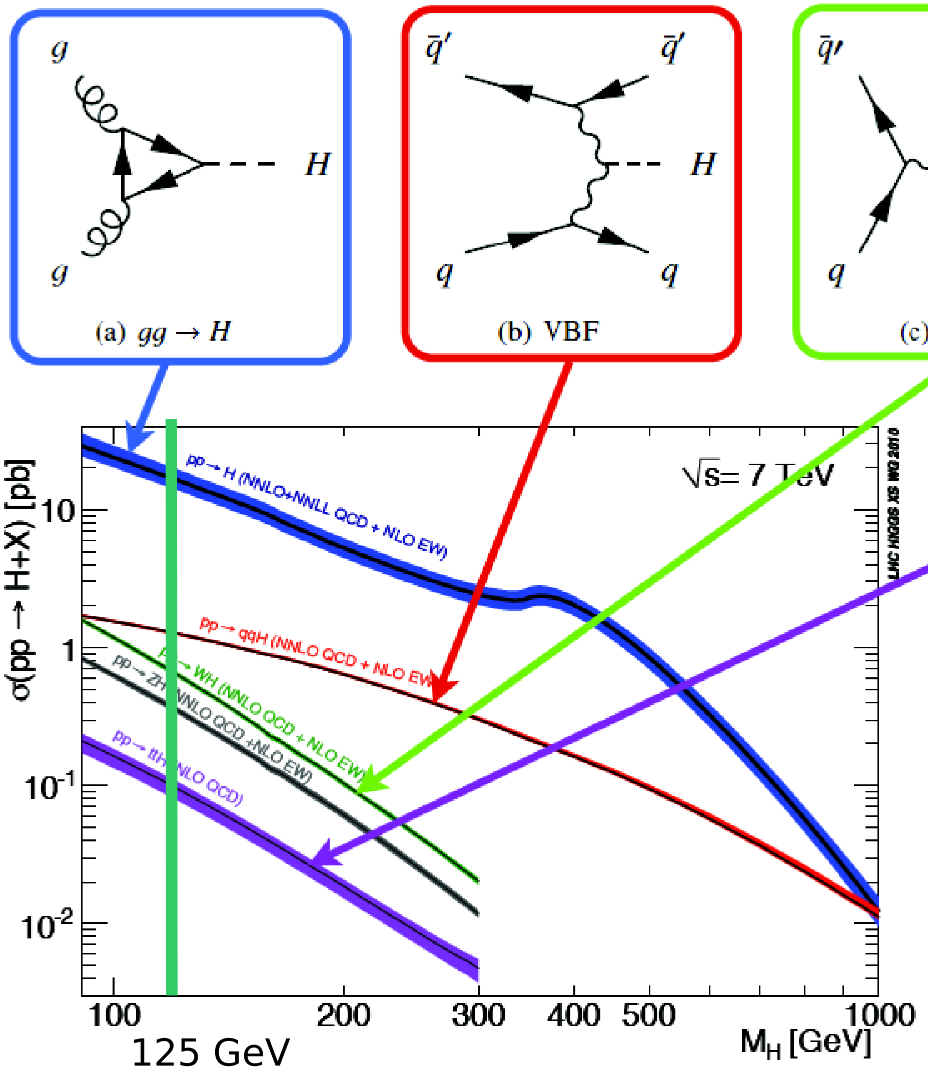
ATLAS integrated luminosity in 2012

- Peak $L = 7.7\times10^{33}\ s^{-1}cm^{-2}$ (Aug)
- Max L/fill: 237 pb^{-1} (June)
- Weekly record: 1350 pb^{-1} (June)
- Longest stable beams: 22.8 h (July)
- Fastest turn-around between stable beams: 2.1 h (April)
- Best weekly data-taking efficiency: 92 h (55%) (July)



Measured with forward detectors, calibrated with beam separation scans

SM Higgs production at the LHC



At $L = 7\times10^{33}\ s^{-1}cm^{-2}$ and 8 TeV *pp* collisions, 560 Higgs bosons of mass 125 GeV ($\sigma_{pp\to H}$ = 22.3 pb) are produced in ATLAS and CMS per hour

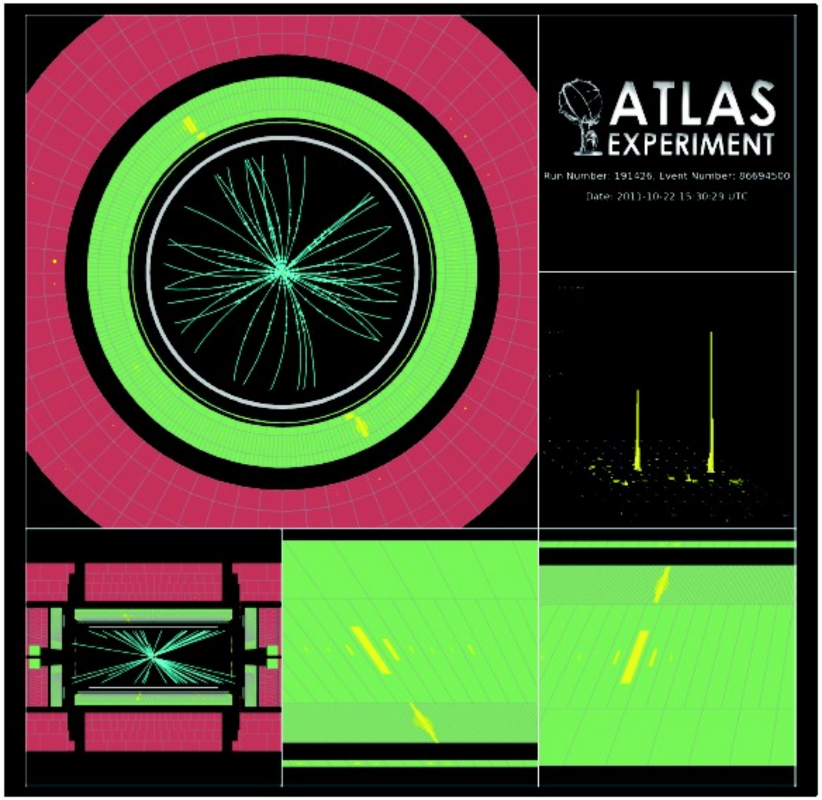
Or: every 45 min. 1 $H \to \gamma\gamma$, need ~2 typical 160 pb^{-1} fills to produced one $H \to 4l$ ($l=e/\mu$)

December 13-th update (CERN)

$H \rightarrow \gamma\gamma$ Update

Since "Discovery Paper" PLB 716

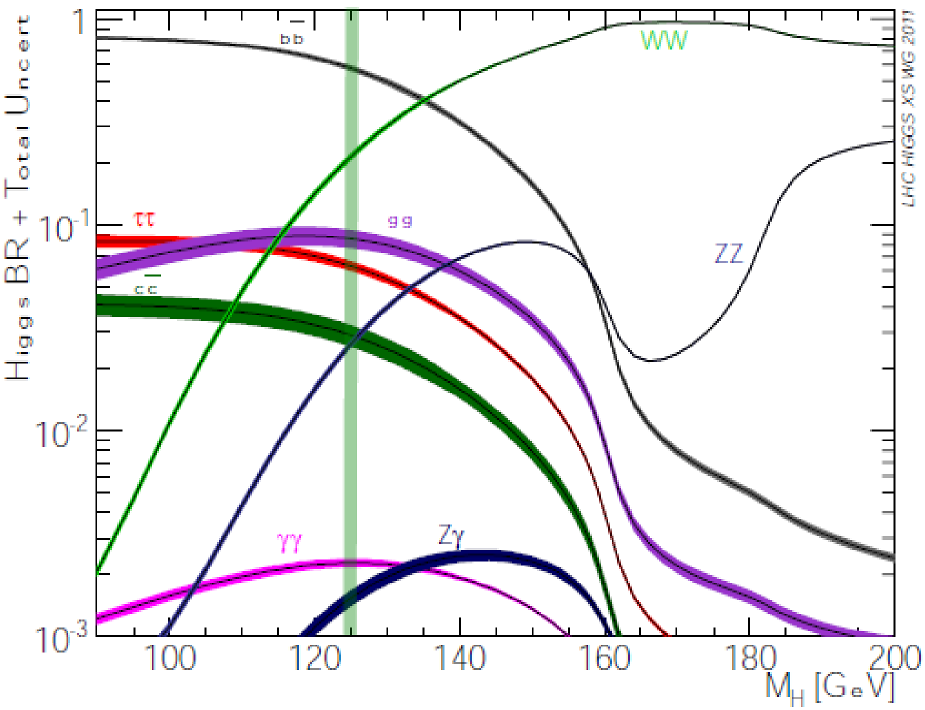
ATLAS-CONF-2012-168



$\gamma\gamma$ channel basic facts sheet :

Signal ($SM_{126\ GeV}$)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L\,dt$
~330	2% - 20%	$\gamma\gamma$,γj and jj	Hgg, VBF, VH	4.9 & 13 fb^{-1} 22

Higgs boson decay



M_H=125 GeV

Process	Branching ratio	Uncertainty	
$H \to bb$	5.77 x 10^{-1}	+3.2%	-3.3%
$H \to \tau\tau$	6.32 x 10^{-2}	+5.7%	-5.7%
$H \to \mu\mu$	2.20 x 10^{-4}	+6.0%	-5.9%
$H \to cc$	2.91 x 10^{-2}	+12.2%	-12.2%
$H \to gg$	8.57 x 10^{-2}	+10.2%	-10.0%
$H \to \gamma\gamma$	2.28 x 10^{-3}	+5.0%	-4.9%
$H \to Z\gamma$	1.54 x 10^{-3}	+9.0%	-8.8%
$H \to WW$	2.15 x 10^{-1}	+4.3%	-4.2%
$H \to ZZ$	2.64 x 10^{-2}	+4.3%	-4.2%
Γ_H [GeV]	4.07 x 10^{-3}	+4.0%	-3.9%

- Experimentally accessible:
  - bb, ττ, WW, ZZ, γγ, Zγ, (μμ)
- Γ_H 4MeV NOT direct measure at LHC

Mass dependency:

- δBR(bb)/0.5 GeV → 1%
- δBR(γγ)/0.5 GeV → <1%
- δBR(WW)/0.5 GeV → 4%
- δBR(ZZ)/0.5 GeV → 4%

H->γγ update

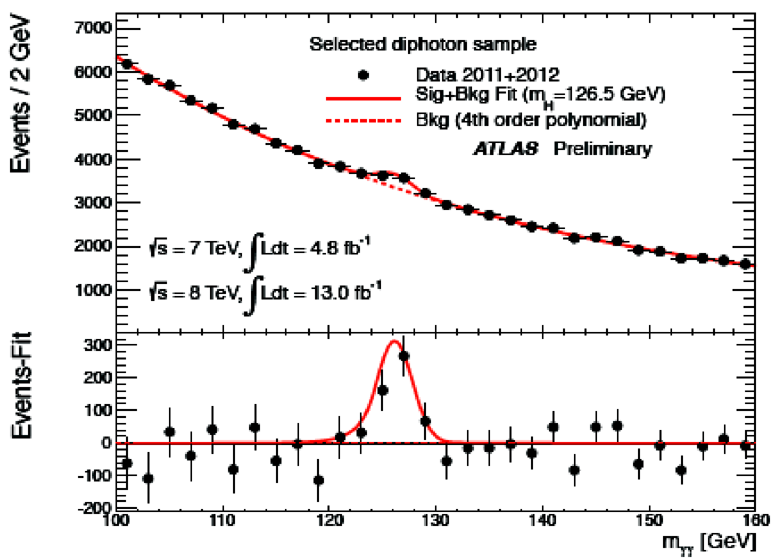
Simple topology: two high-p_T isolated photons E_T (g_1, g_2) > 40, 30 GeV

To increase sensitivity, overall and to specific production processes 12 exclusive categories:

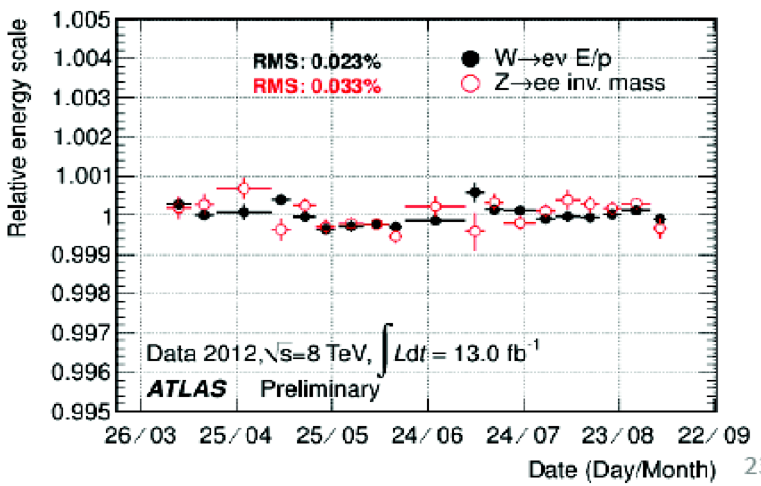
- γ rapidity, converted/unconverted γ, p_{Tt}($p_T^{\gamma\gamma}$ perpendicular to γγ "thrust" axis)
- presence of 2 high-mass (m_{jj} 400 GeV) forward jets target VBF process

- 1 lepton → target W/Z/ttH
- Low-mass di-jet (60 <m_{jj}<100 GeV) jets → target W/ZH

NEW since PLB716

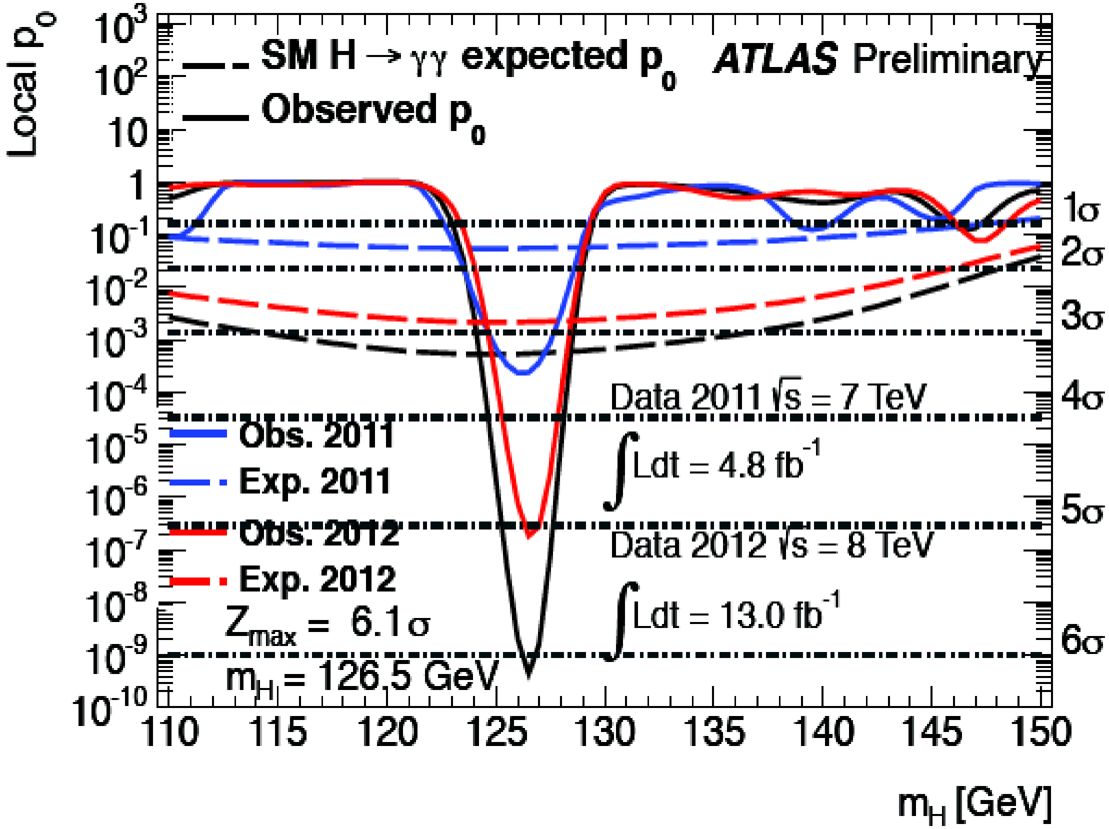


Stability of EM calorimeter response vs time (and pile-up) <0.1%



23

H->γγ update: single channel discovery!



Observed local significance:

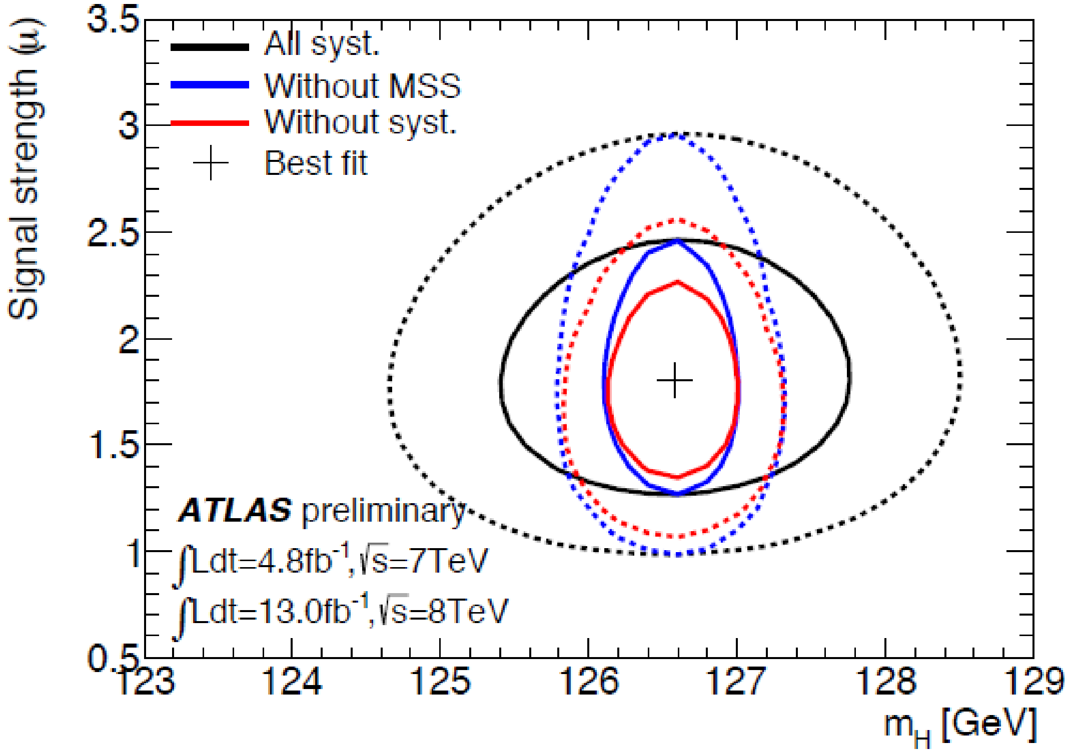
6.1σ

Expected local significance:

3.3σ

2011	126.0 GeV	3.5σ	(exp. 1.6σ)
2012	127.0 GeV	5.1σ	(exp. 2.9σ)

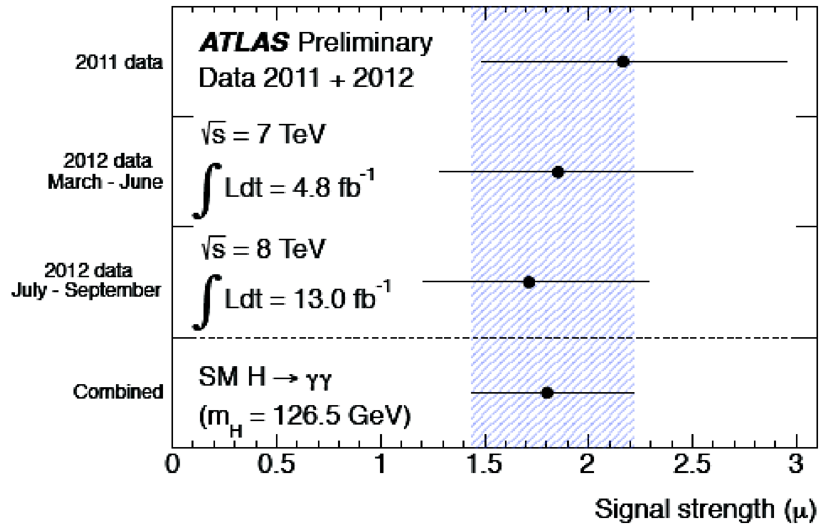
H->γγ update: mass measurement



Measurement of narrow resonance mass :

$$m_H = 126.6 \pm 0.3\ (stat) \pm 0.7\ (syst)\ \text{GeV}$$

H->γγ update: signal strength



Measurement of signal strength :

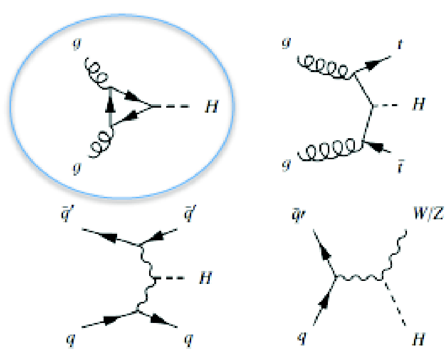
(at best fit mass 126.5 GeV)

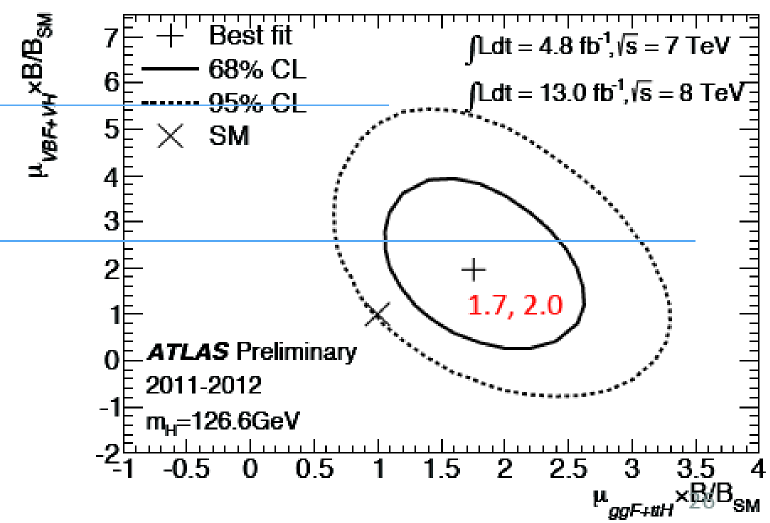
$$\hat{\mu} = 1.8 \pm 0.3\ (stat)^{+0.29}_{-0.21}\ (syst)$$

Signal strength for different production modes :

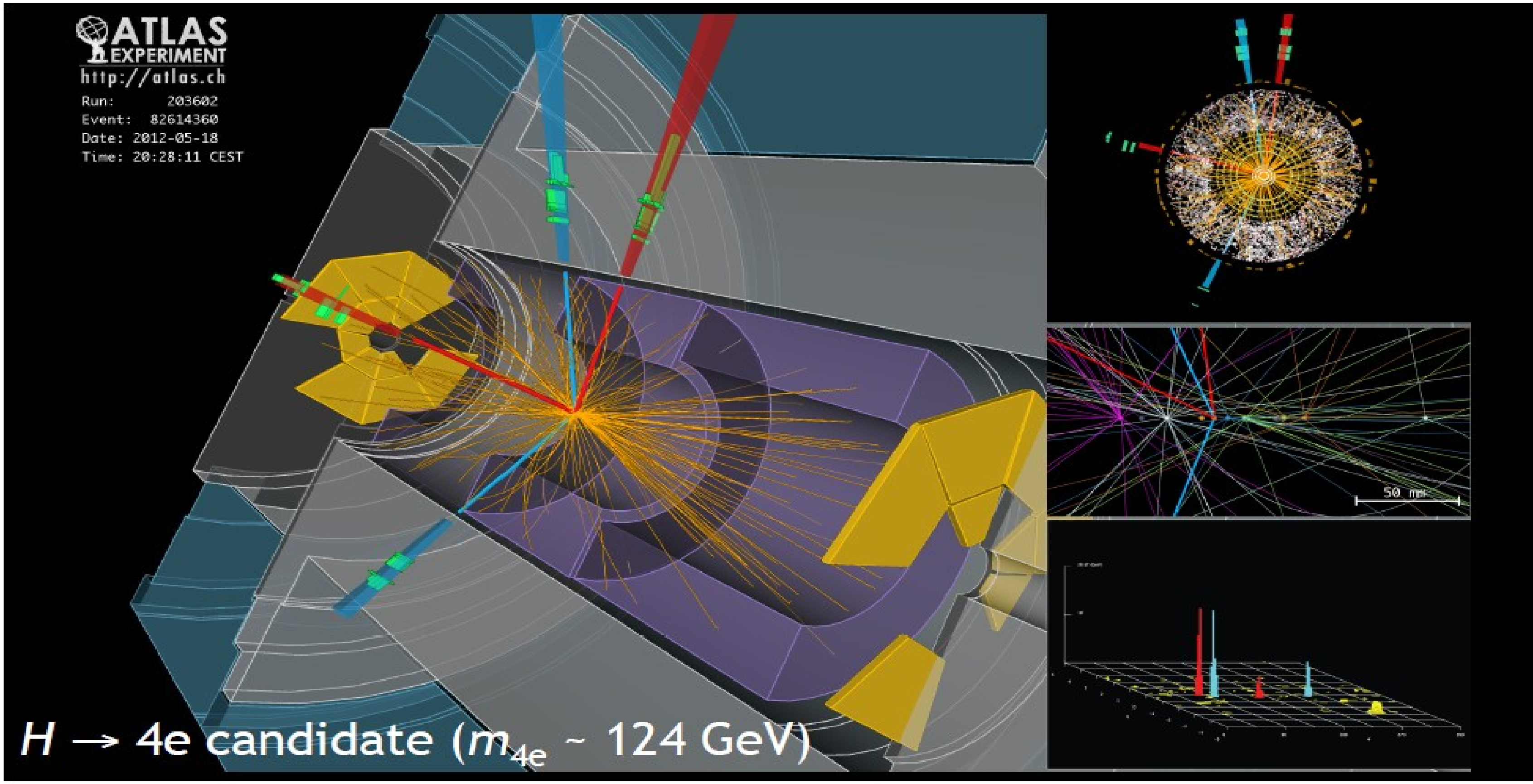
Fermion couplings dominated modes
ggH+ttH

Vector boson dominated modes
VBF+VH





December 13-th update (CERN)



4l channel basic facts sheet :

Signal	Signal Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L\,dt$
~10	~1	ZZ, Z+jets, top	All inclusive	4.9 & 13 fb^{-1}

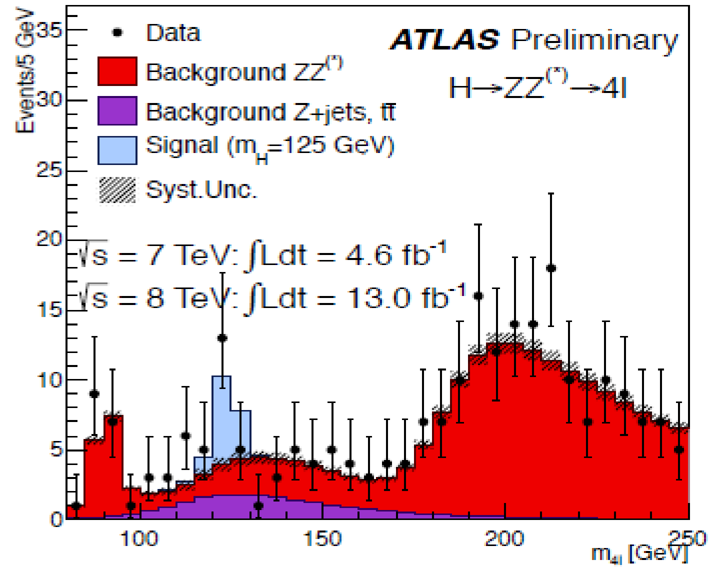
H->4l update: signal confirmation

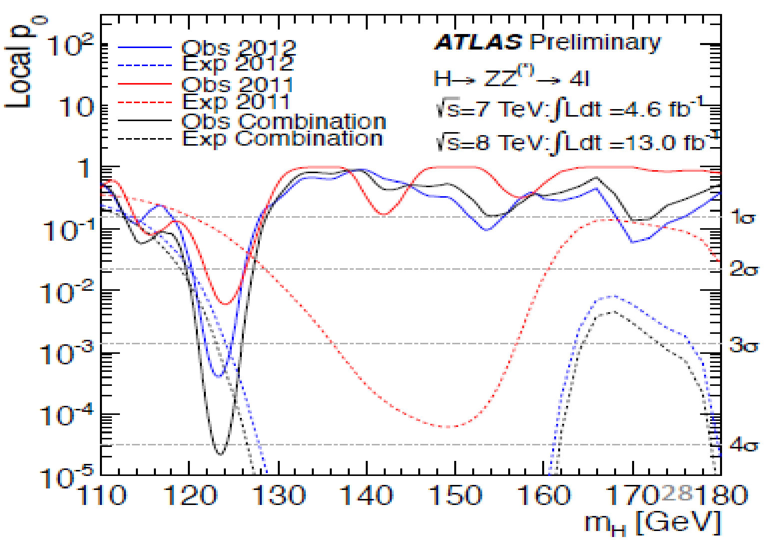
Simple selection :

- 4 leptons: $p_T^{1,2,3,4} > 20,15,10,7\text{-}6$ (e-μ) GeV
- $50 < m_{12} < 106$ GeV
- $m_{34} > 17.5$ GeV

In the signal region 125 ± 5 GeV

Observed	18 events
Expected from bkg only	8.3 ± 0.3
Expected from SM Higgs	9.9 ± 1.3



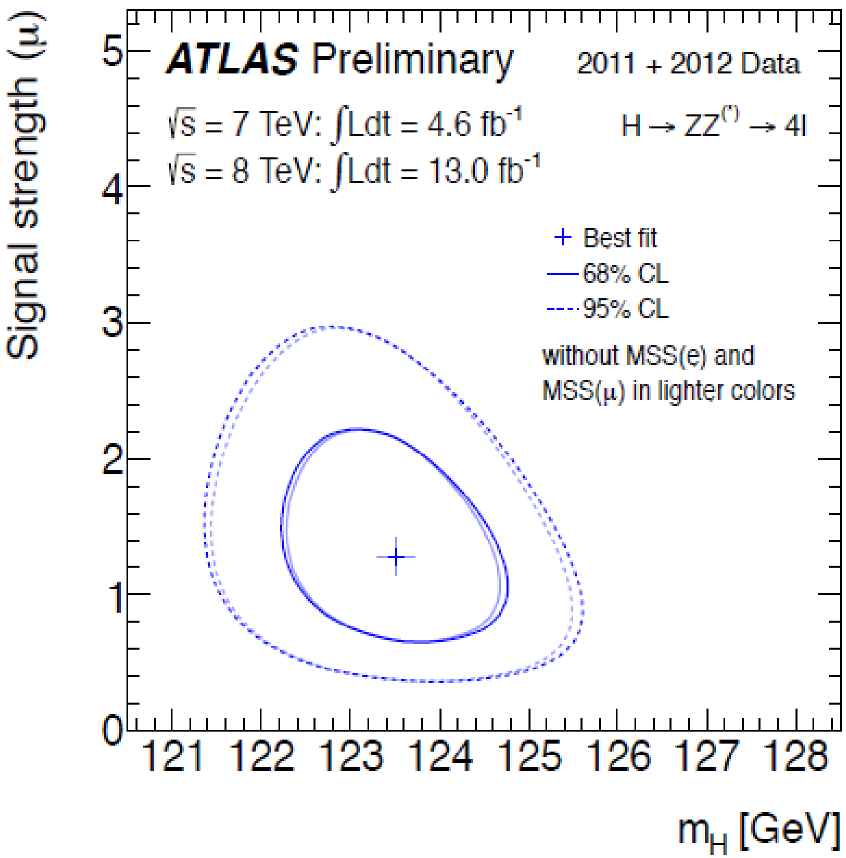


Observed local significance: 4.1σ

Expected local significance: 3.1σ

2011	124.1 GeV	2.5σ	(exp. 1.4σ)
2012	123.3 GeV	3.4σ	(exp. 2.8σ)

H->4l update: signal strength



Measurement of signal strength

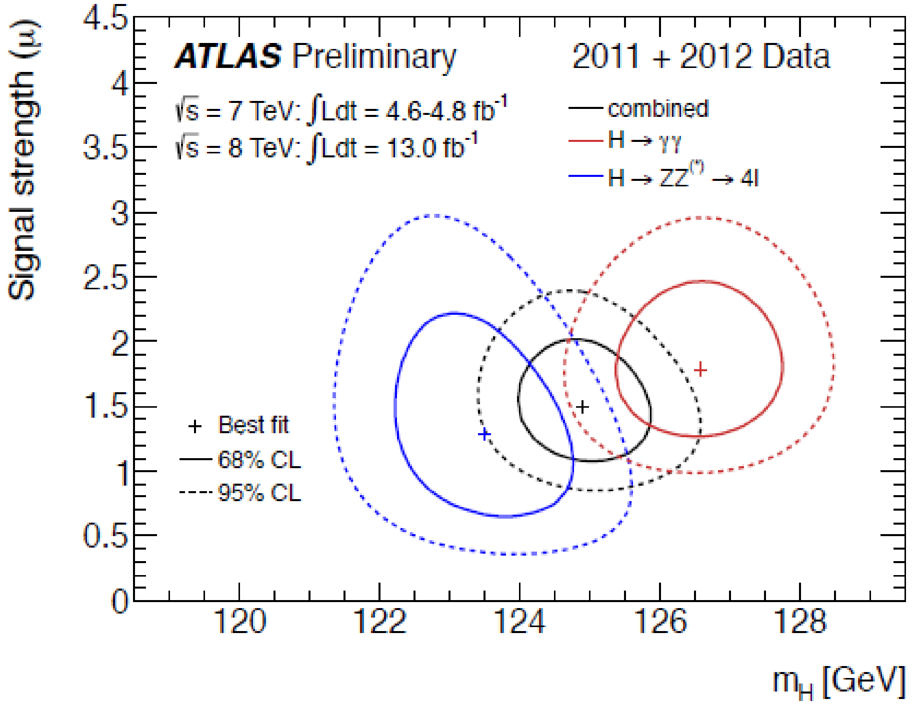
$$\hat{\mu} = 1.3 \pm 0.4$$

Measurement of narrow resonance mass

$$m_H = 123.5 \pm 0.9\ (stat)\ ^{+0.4}_{-0.2}\ (syst)\ \mathrm{GeV}$$

H->γγ and H->4l combination

Best fit signal strength $\hat{\mu} = 1.5^{+0.33}_{-0.29}$



Combined Mass Measurement :

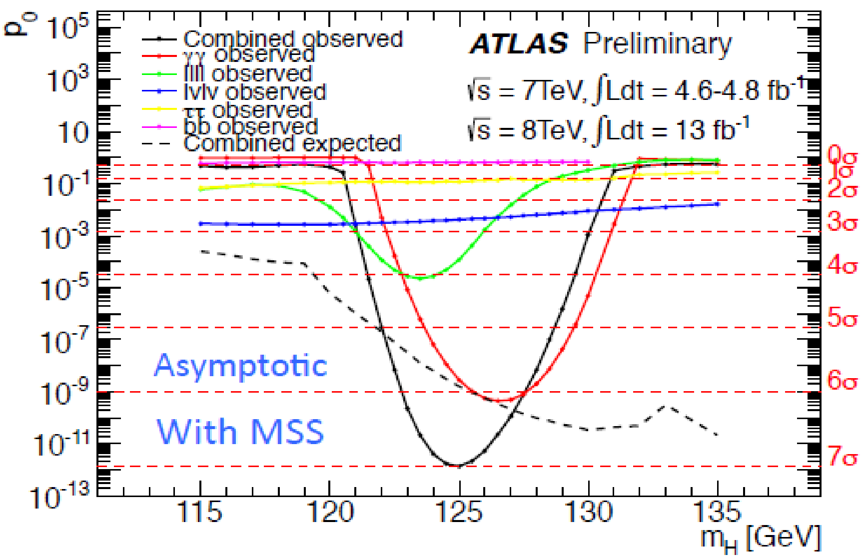
$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \mathrm{GeV}$$

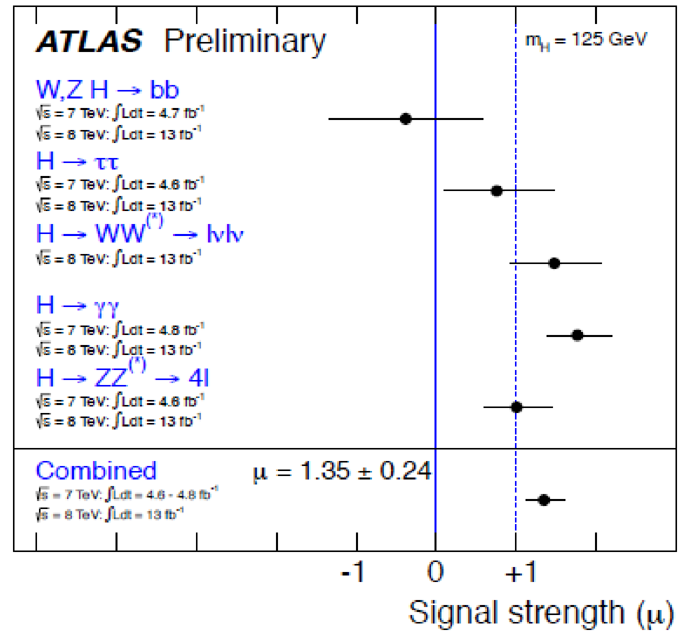
Taking all mass scale systematic uncertainties and their correlations into account the compatibility of the two measurements is estimated to be at the 2.7σ level

All channels combination

Updated with 13 fb^{-1} of 2012 8 TeV data

Summary of the signal strength in all SM Higgs search channels





Observed local significance (w/ MSS): 7.0σ

Without MSS: 6.6σ

Expected local significance: 5.9σ

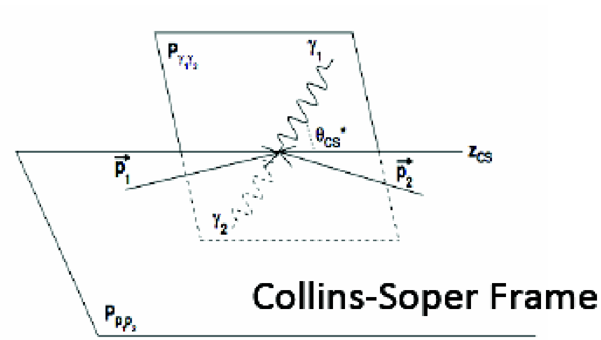
$$\hat{\mu} = 1.35 \pm 0.19\ (stat) \pm 0.15\ (syst)$$

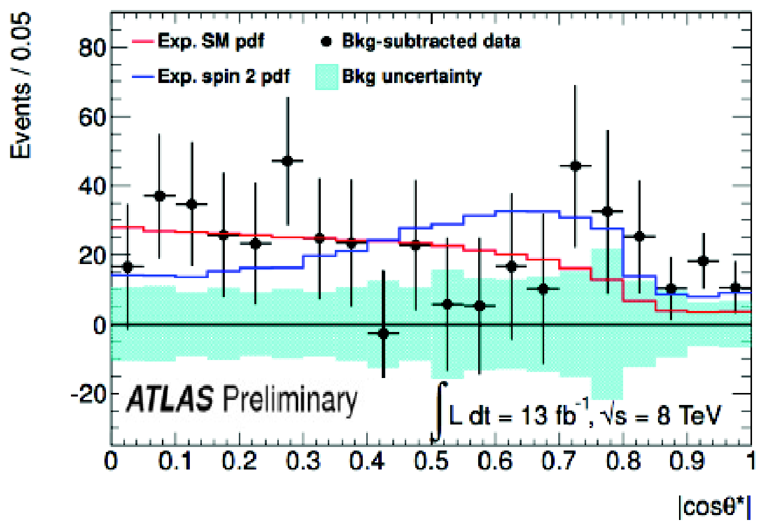
Overall agreement with the SM Higgs boson hypothesis 31

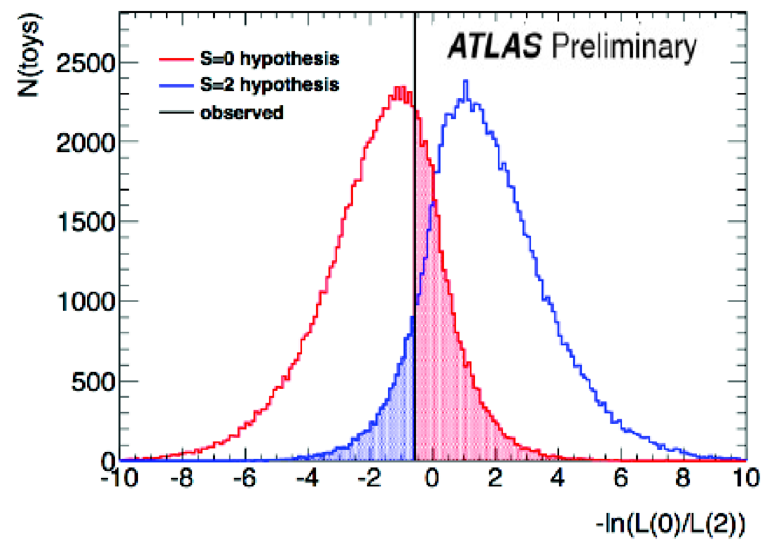
First analysis of spin in H->$\gamma\gamma$ channel

Using the inclusive analysis

- Sensitive variable is dihoton cos θ^* distribution
- Use events within 1.5σ of the peak (m_H=126.5 GeV)





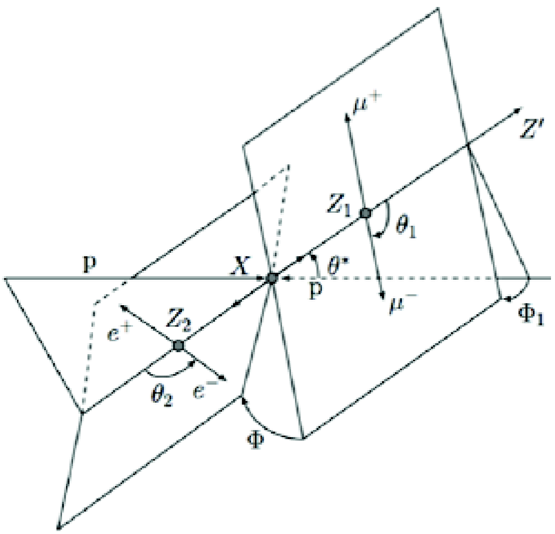


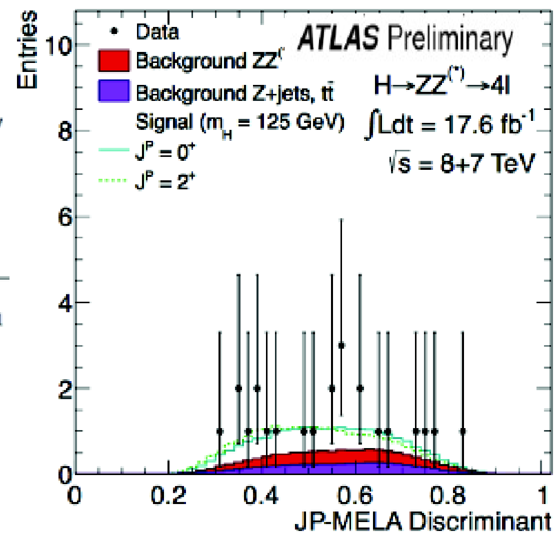
- Expected sensitivity: exclusion of the spin 2^+ hypothesis at the 97% CL
- Observed exclusion of spin 2^+ hypothesis at the 91% CL

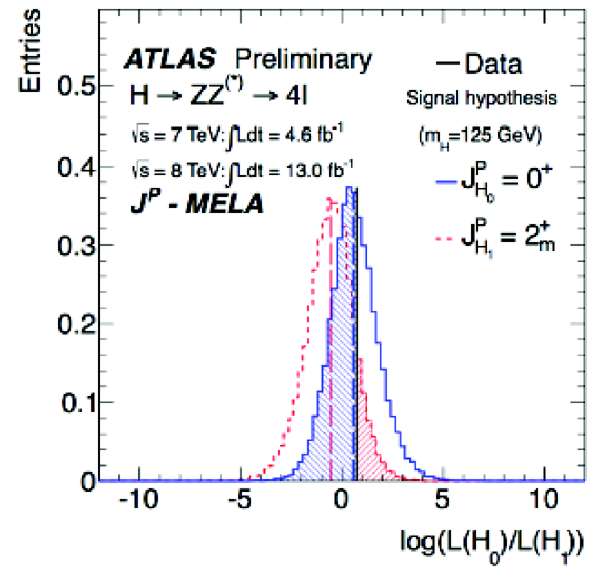
  Observation compatible with spin 0 (within 0.5σ)

Analysis of spin in H->4l channel

Using the distributions of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants





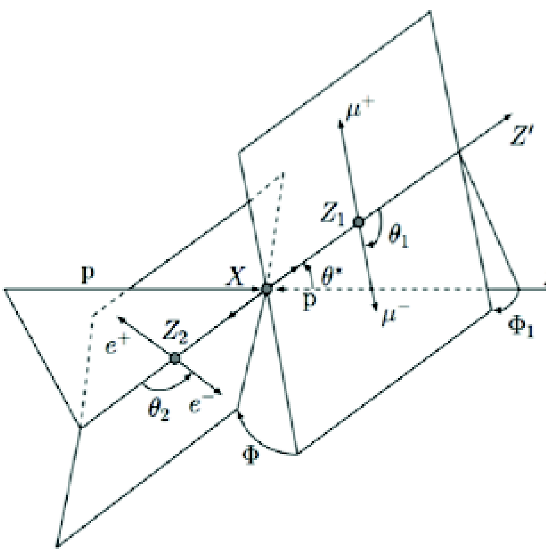


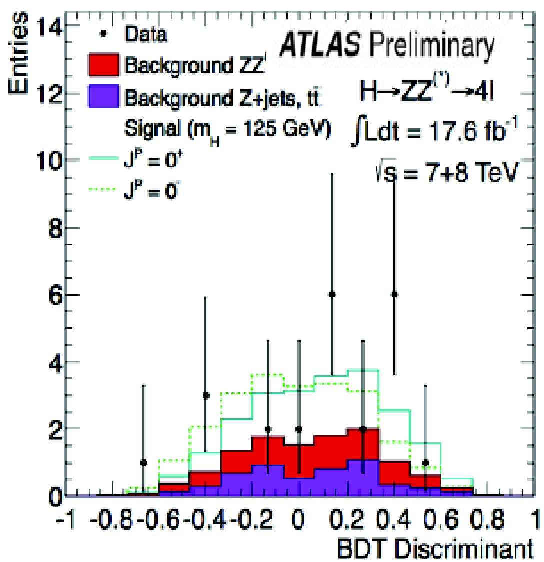
- 0^+ vs 2^+ : (Low) Expected Exclusion of 2^+ at the 80% CL
- Observed exclusion of spin 2^+ at the 85% CL

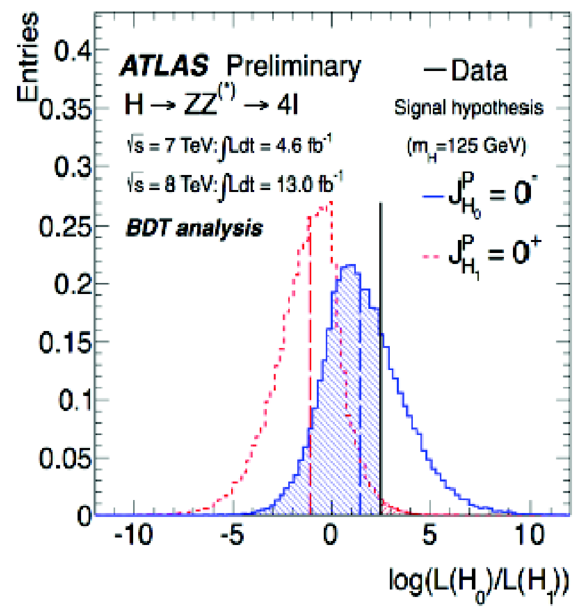
Observation fully compatible with spin 0^+ (within 0.18 σ)

Analysis of parity in H->4l channel

Using the distributions of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants







- 0^+ vs 0^- : Expected Exclusion of 0^- at the 96% CL
- Observed exclusion of 0^- at the 99% CL

Observation fully compatible with spin 0^-(within 0.5 σ)

Couplings (presented at HCP)

SM Higgs ($G_F \rightarrow$ v= 246 GeV) all Γ predicted once M_H measured: proportional to (measured) fermion/boson masses

- Γ_{ff} ~ $(m_f / v)^2$
- Γ_{WW} ~ $(2 M_W^2/v)^2$
- Γ_{ZZ} ~ $(M_Z^2 / v)^2$
- Γ_{HH} ~ $(M_H^2/v)^2$
- $\Gamma_{\gamma\gamma}$ ~ $(1.6\ \Gamma_{WW} + 0.07\ \Gamma_{tt} - 0.7\ \Gamma_{Wt})$ $\rightarrow$ Wt interference
- Γ_{gg} ~ $(1.1\ \Gamma_{tt} + 0.01\ \Gamma_{bb} - 0.12\ \Gamma_{bt})$ $\rightarrow$ bt interference
- $\Gamma_{Z\gamma}$ ~ $(1.12\ \Gamma_{WW} + 0.003\ \Gamma_{tt} - 0.12\ \Gamma_{Wt})$ $\rightarrow$ Wt interference

Γ_{tot} (126 GeV) = 4.2 MeV (dominated by bb ~57%, ferm.>70%)

Couplings

Assume SM Lagrangian CP=0$^+$ + NW approximation to parameterize coupling dependency of measured Yield → Test agreement between SM and observed yields

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \quad (3)$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H) \quad (4)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2 \quad (5)$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2 \quad (6)$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2 \quad (7)$$

LHC-XS wg

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$\Gamma\gamma\gamma / \Gamma\gamma\gamma^{SM} = (1.6\ \kappa^2_W + 0.07\ \kappa_t^2 - 0.67\ \kappa_W\kappa_t)$

Global k fit

Several Fits performed with 2011(~4.8 fb-1) +2012(~5.9 fb-1) results.

Fit global scale factor κ:

Based on July results

Common scale factor Free parameter: $\kappa (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z)$.					
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH					
$t\bar{t}H$					
VBF			κ^2		
WH					
ZH					

$$\kappa = 1.19 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.06\,(\text{theory})$$

As expected just ~square root of $\mu = 1.4 \pm 0.3$

Theory error not dominant yet … but already sizable

k_F vs k_V fit

- Couplings to Fermion and Vector boson sectors:
  κF vs κV

Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_W = \kappa_Z)$, $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

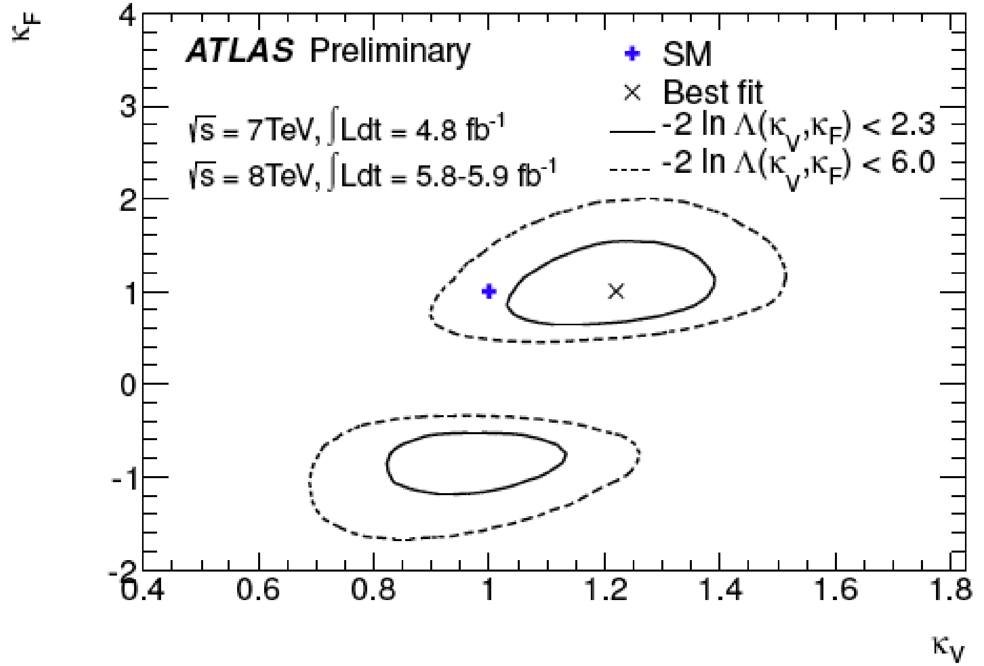
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

Assumption only SM particles in $\Gamma_H \sim \kappa_H^2(\kappa_F, \kappa_V)$

- All Fermion couplings scale with the same factor κ_F
- All Boson couplings scale with the same factor κ_V

k_F vs k_V fit

Based on July results



- Good compatibility with SM
- $\kappa_F = 0$ (Fermiophobic Higgs) Excluded at $>2\sigma$
  - Thanks to channels that distinguish ggH from VBF production

Custodial Symmetry $\lambda_{WZ} = k_W/k_Z$

Testing Custodial Symmetry W vs Z couplings

Move to fit of RATIO's (can relax assumption on total width)

- $\lambda_{wz} = \kappa_w/\kappa_z$

Two additional parameters λ_{FZ} κ_{ZZ} in the fit but with small correlation with λ_{WZ} dominated by relative WW and ZZ yields and by BR$\gamma\gamma$ that scales mainly as $\kappa_W{}^2$

Probing custodial symmetry without assumptions on the total width

Free parameters: $\kappa_{ZZ}(=\kappa_Z\cdot\kappa_Z/\kappa_H)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{FZ}(=\kappa_f/\kappa_Z)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$	
VBF	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{FZ}^2$	
WH	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{FZ}^2$	
ZH	$\kappa_{ZZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	κ_{ZZ}^2	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\cdot\lambda_{FZ}^2$	

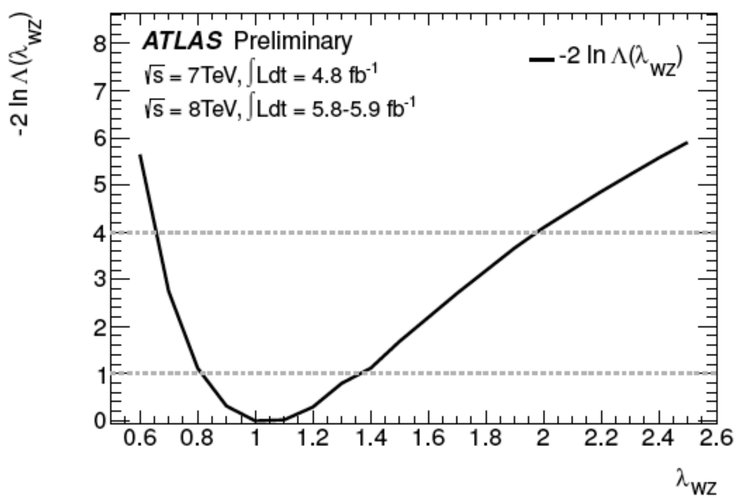
Custodial Symmetry $\lambda_{WZ} = k_W/k_Z$

Testing Custodial Symmetry W vs Z couplings

Move to fit of RATIO's (can relax assumption on total width)

- $\lambda_{wz} = \kappa_w/\kappa_z$

Two additional parameters λ_{FZ} κ_{ZZ} in the fit but with small correlation with λ_{WZ} dominated by relative WW and ZZ yields and by BR$\gamma\gamma$ that scales mainly as $\kappa_W{}^2$



$$\lambda_{WZ} = 1.07^{+0.35}_{-0.27}$$

Based on July results

*In this plot λ_{FZ} >0

Loop contributions k_g vs k_γ

Assumptions:

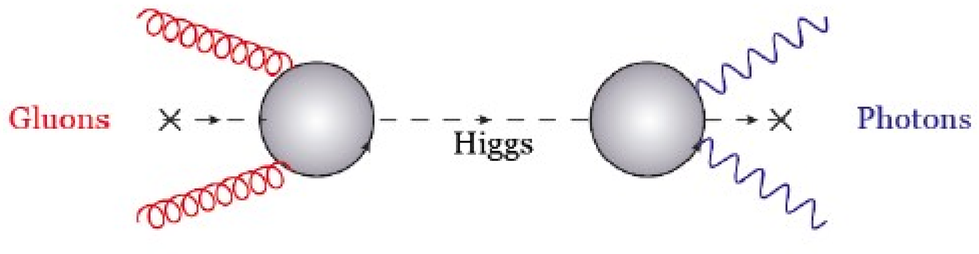
- Direct Coupling to known SM particles assumed to be as in SM:
- $\kappa_b = \kappa_W = \kappa_Z = \kappa_\tau = ... = 1$
- $\kappa_H \sim 0.9 + 0.1\,\kappa_g$
- No extra contributions to total width (only known SM and gg)
- Fitted parameters κ_g vs κ_γ

Probing loop structure assuming no invisible or undetectable widths

Free parameters: κ_g, κ_γ.

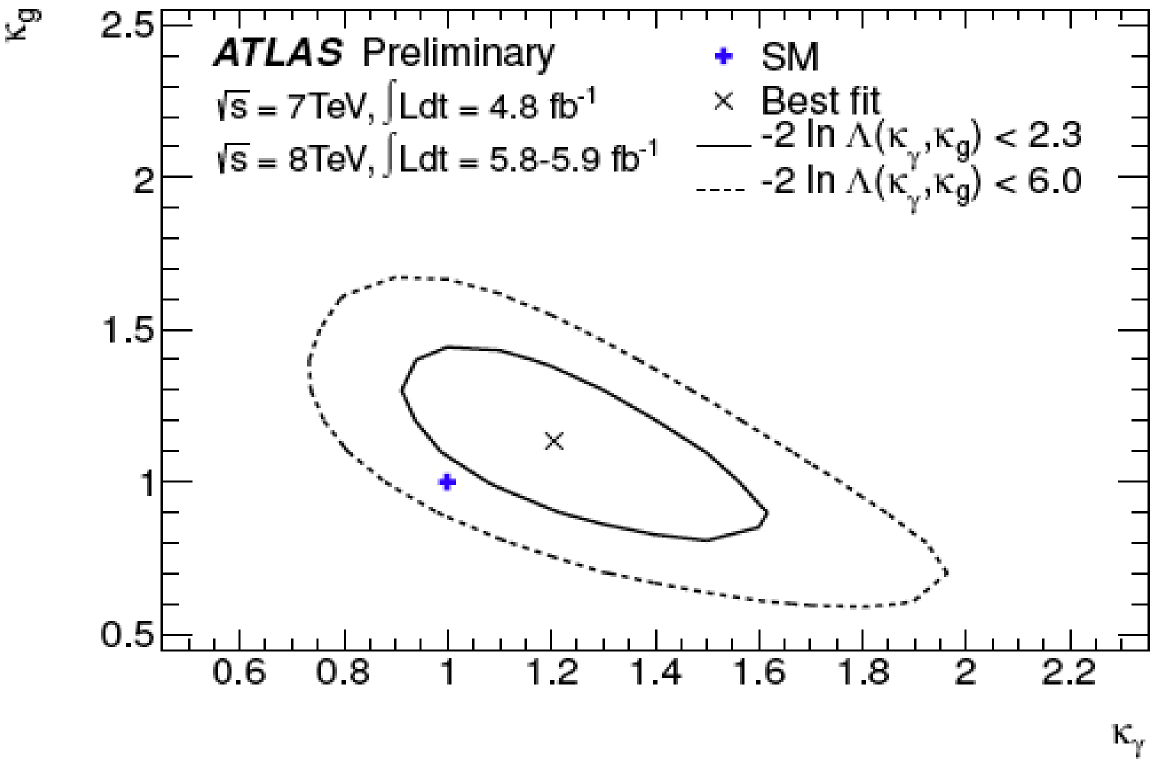
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{1}{\kappa_H^2(\kappa_i)}$			

Loop contributions k_g vs k_γ



- Couplings to gg and $\gamma\gamma$ expected to proceed via loop: very sensitive to BSM physics
- Hierarchy problem related to top loop that are the same that contributes to gg Higgs coupling
- Treat gg and $\gamma\gamma$ loops as free parameters (no relationship with SM content assumed)

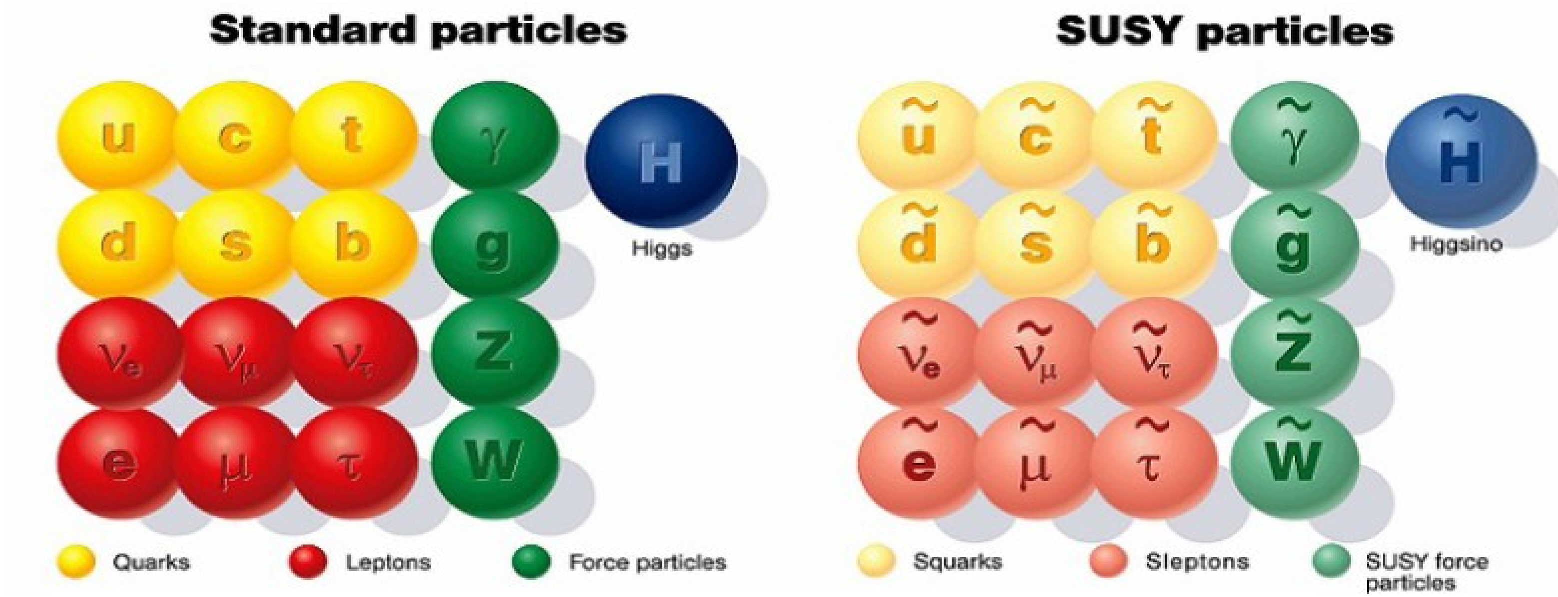
Loop contributions k_g vs k_γ



Still dominated by statistical uncertainty

Without theorerical error ~20% smaller error

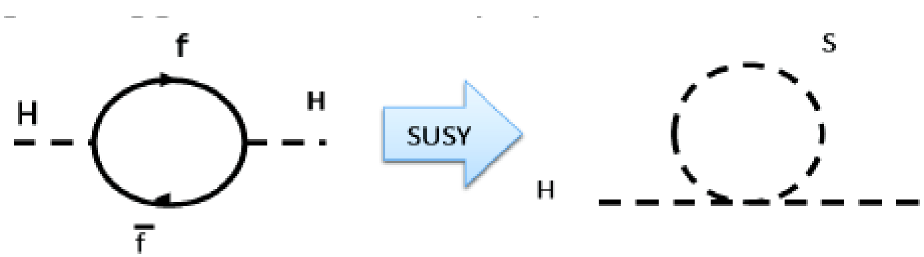
SUSY



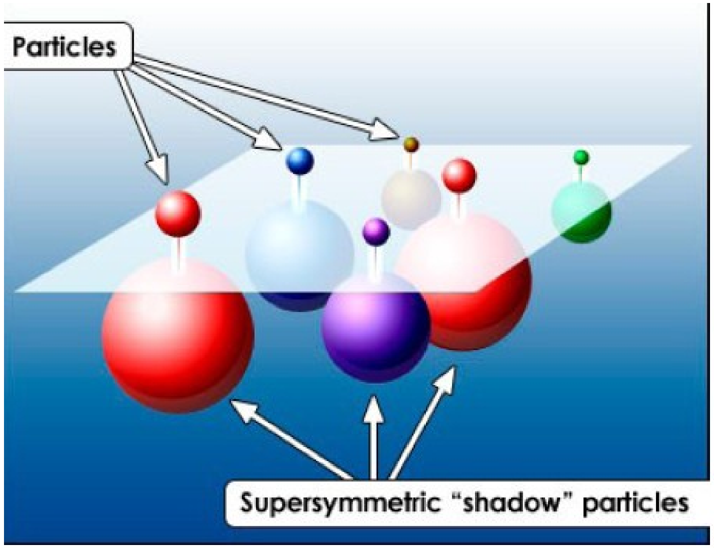
Supersymmetry common in many SM extensions

Strong motivation for TeV-scale SUSY:

- Stabilize a light Higgs mass
- Dark-matter candidate
- Gauge coupling unification



SUSY



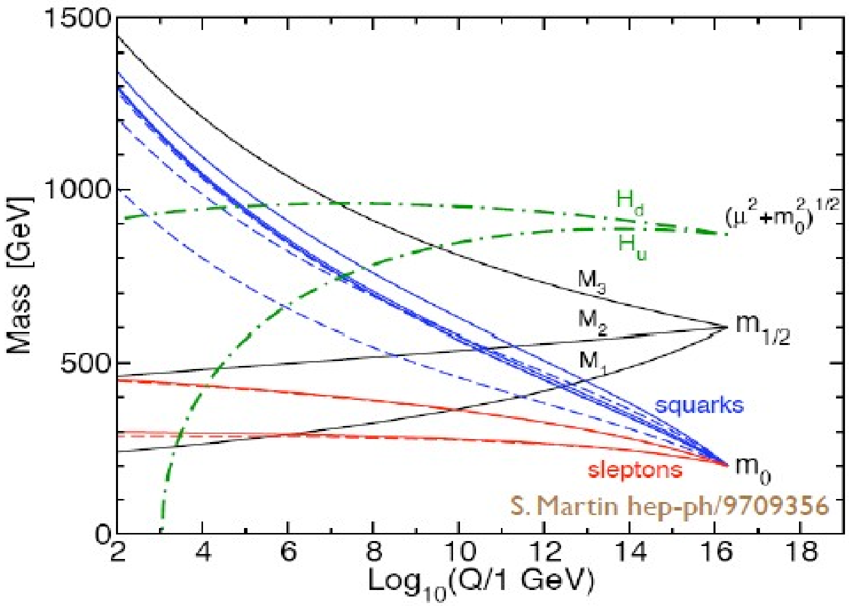
- Heavier superpartners with spin-½ compared to the SM
- MSSM: 105 parameters to be determined!

- Introducing R-parity (aka matter parity)
  - SM particles (+1), SUSY particles (-1)
  - Phenomenology centered around the Lightest Supersymmetric Particle (LSP)
  - Can be violated

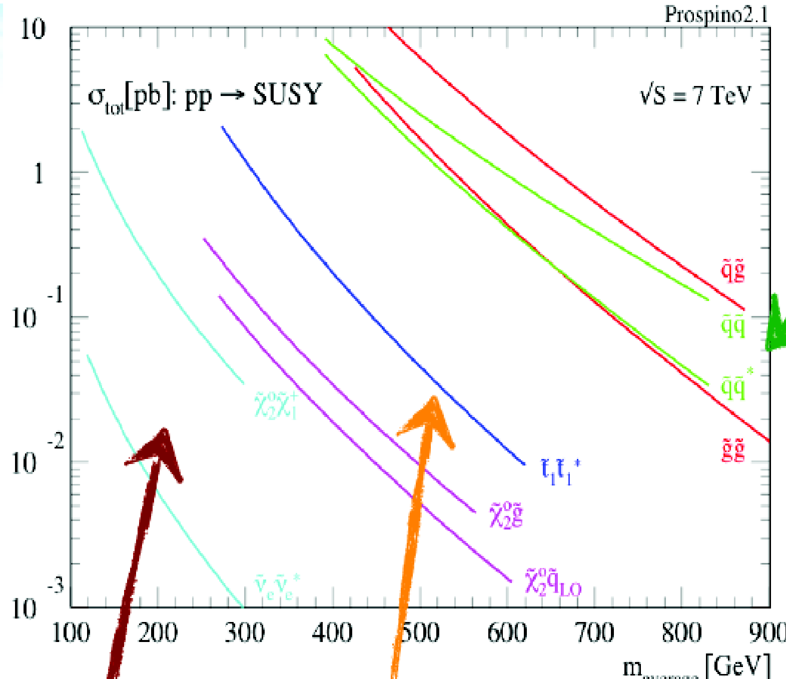
Minimal SUGRA

High-scale boundary condition: $m_0, M_{1/2}, A, B, \mu$

Radiative EWSB



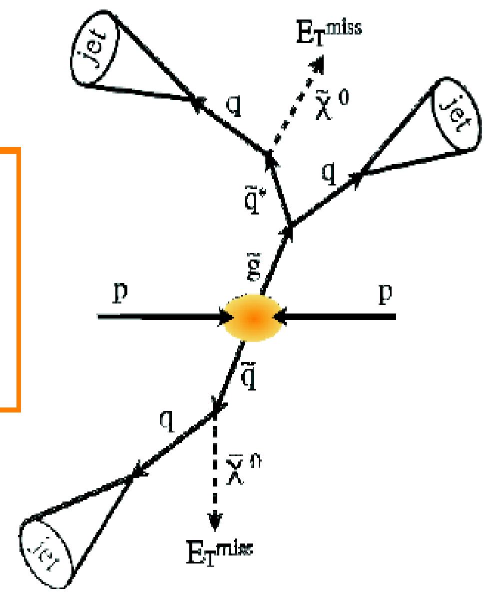
Inclusive searches



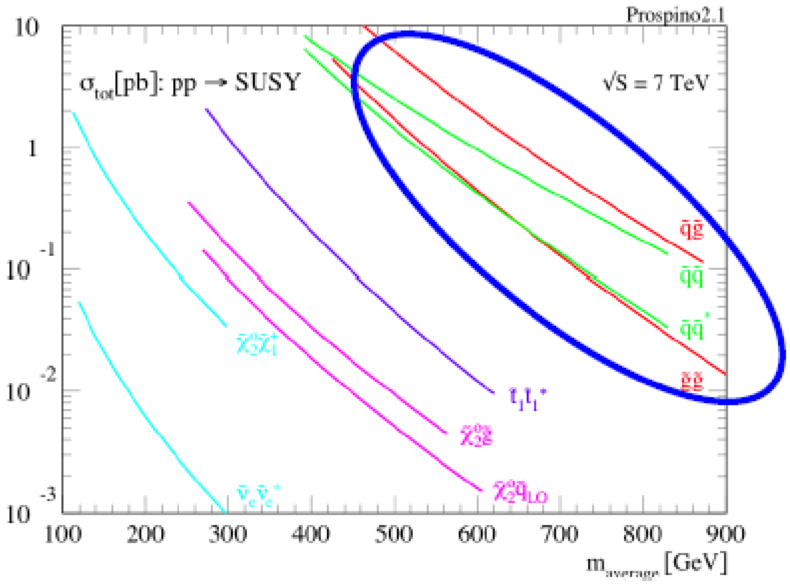
- LHC is first sensitive to strong production of squark and gluinos
- Typical signature: jets + leptons + photons (+ assuming R-parity conservation E_T^{miss})

- At lower cross section 3rd generation squark production becomes relevant
- Dedicated 3rd generation searches (see M. Hodgkinson talk for dettais)

- Gaugino production has a very low cross section
- dedicated searches in leptonic final states

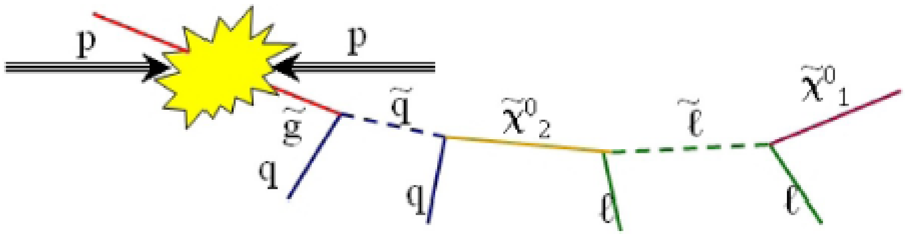


Inclusive searches



Most generic searches: strongly produced squarks/gluons

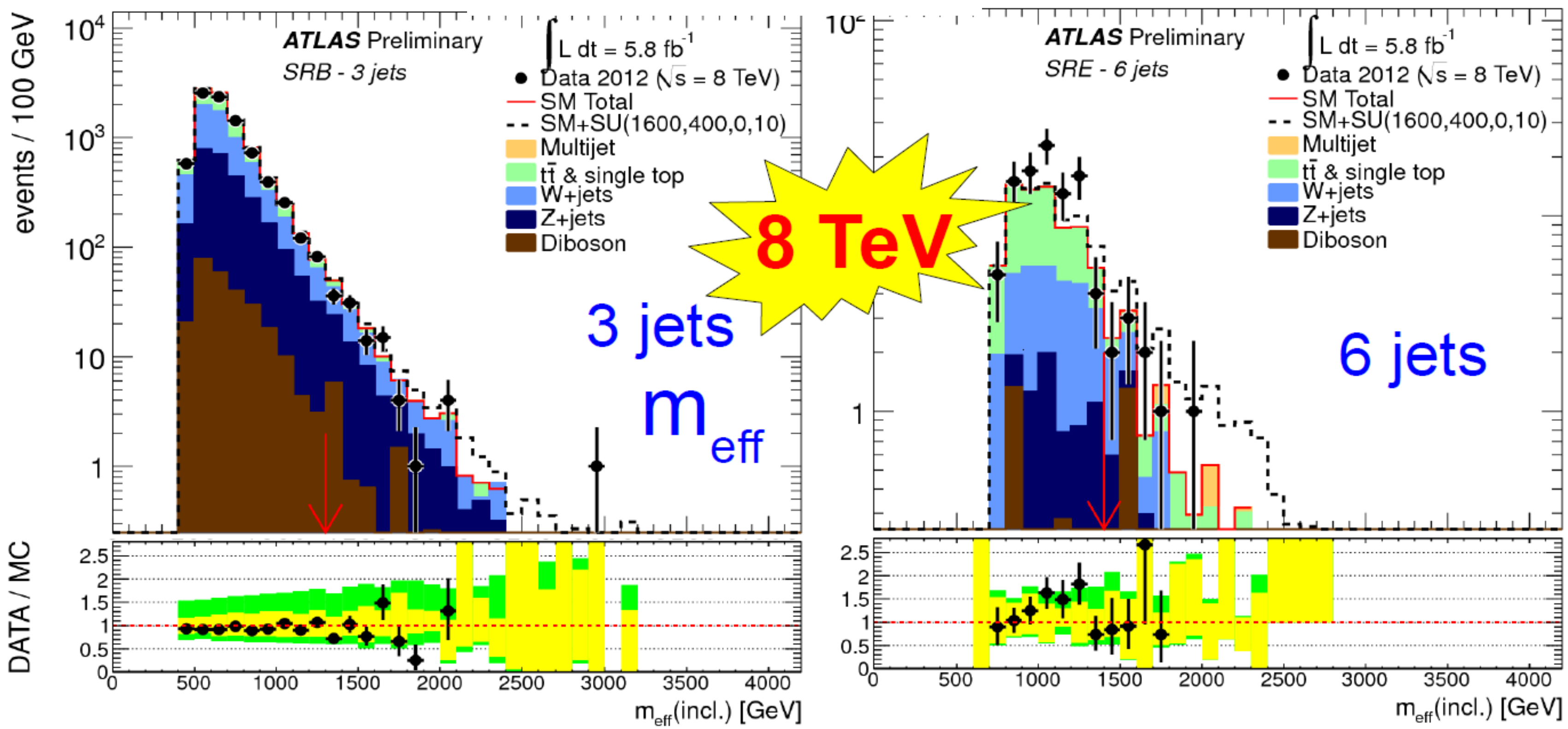
- High production cross-section
- Select on jets+$\not{E}_T$ signature
- Can reduce backgrounds by requiring additional leptons/photons/(b)-jets) from intermediate sparticles in cascade decay



Inclusive searches

ATLAS example: jets+$\not{E}_T$

- 5 signal regions (2-6 jets) each with 1-3 m_{eff} selections to probe multiple SUSY masses
- 4 control regions per SR to estimate backgrounds

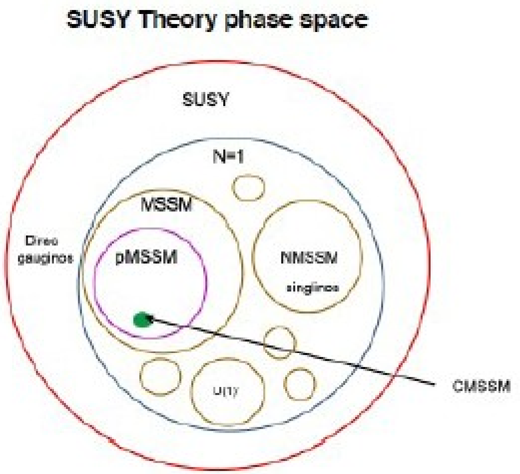


SUSY

SUSY is not just one model

Many possible variations

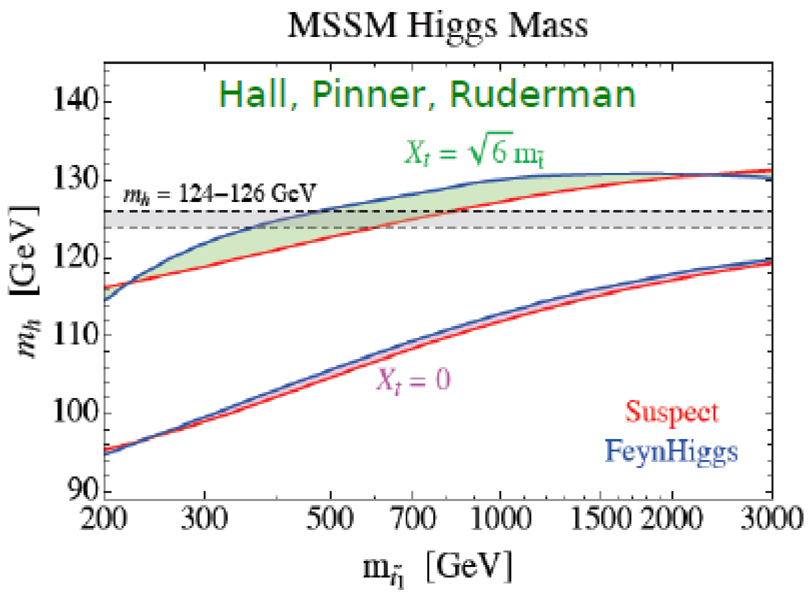
- SUSY breaking mechanism
  gravity-, gauge-, anomaly-mediated, …
- Beyond MSSM
- R-parity = $(-1)^{2S}(-1)^{3B+L}$ conserved?
  If not, lifetime of lightest sparticle



No signs of SUSY yet

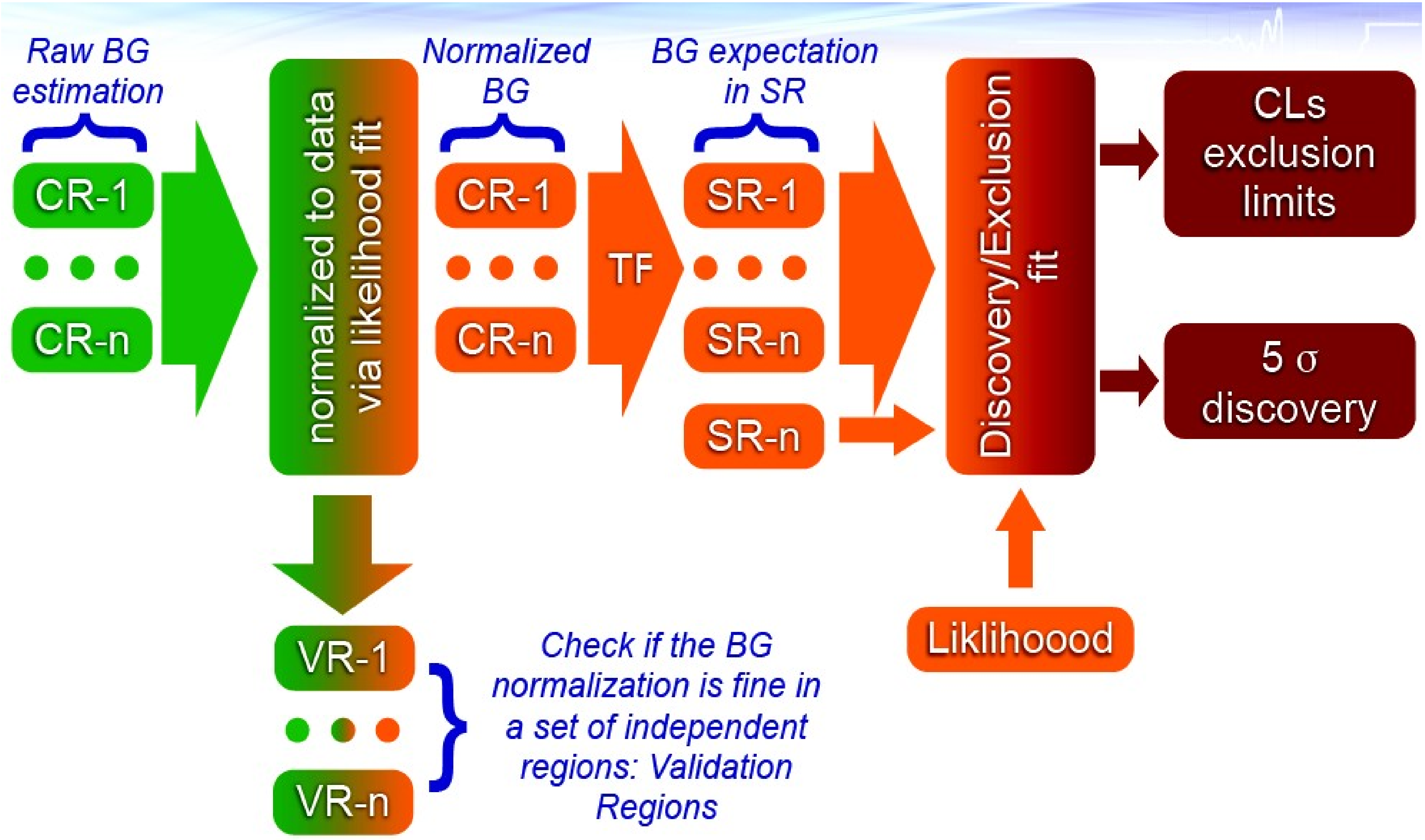
Allowed phase space is getting squeezed

- Flavor physics remains in good agreement with SM
- Light Higgs-like boson discovered,
  but at high end of (MSSM) preference



- Either large stop mixing
- Very heavy squarks
- Or beyond MSSM

Analysis setup

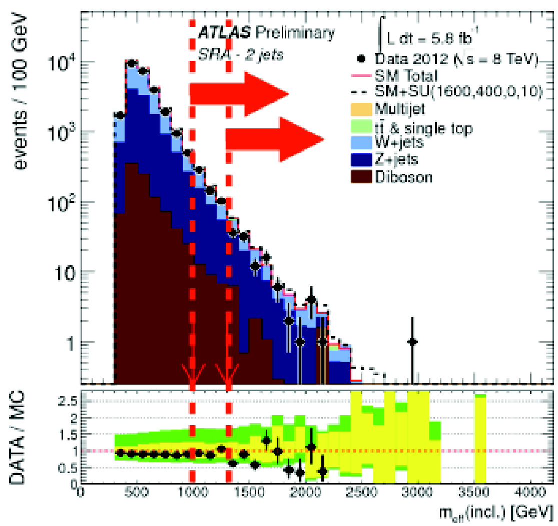


0 lepton+ jets + E_T^{miss}

Inclusive search for sqark and gluino strong production:

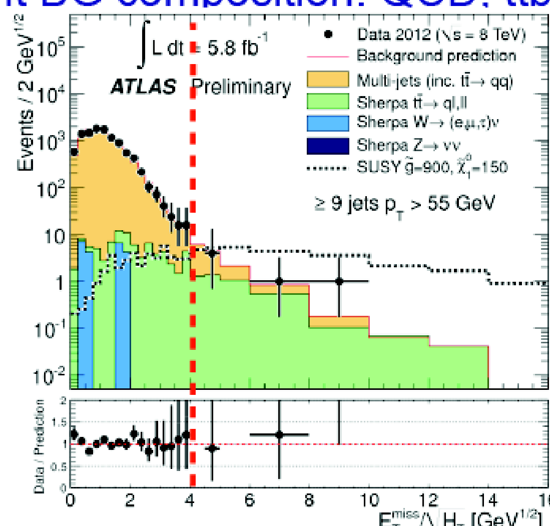
0 lepton analysis:
ATLAS-CONF-2012-109

- lepton veto + 2-6 jets
- $m_{eff} = \sum_i p_T^{jet,i} + E_T^{miss}$
- Simultaneous background fit in 4 control region for each signal region
- Main background $Z\nu\nu$ + jets



0 lepton multi-jet analysis:
ATLAS-CONF-2012-103

- Specific for long decay chains form gluino decay
- 6 Signal region with 6-9 jets
- E_T^{miss} significance: $E_T^{miss}/\sqrt{H_T}$, with $H_T = \sum_i p_T^{jet,i}$
- different BG composition: QCD, ttbar(hadronic)

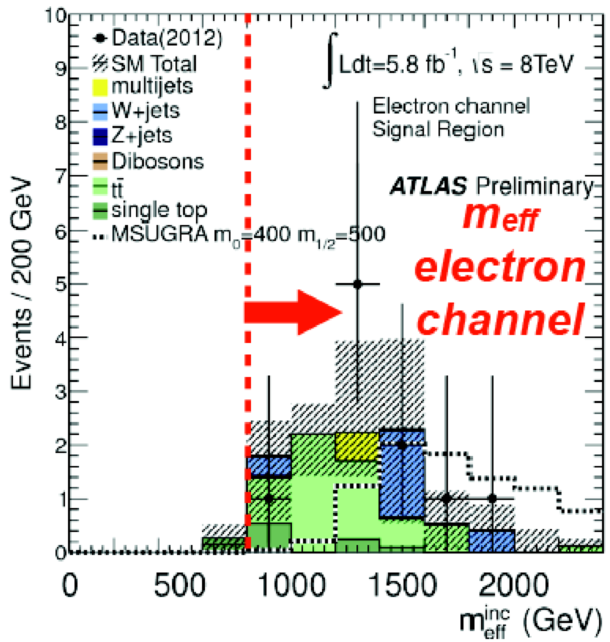


1 lepton+ jets + E_T^{miss}

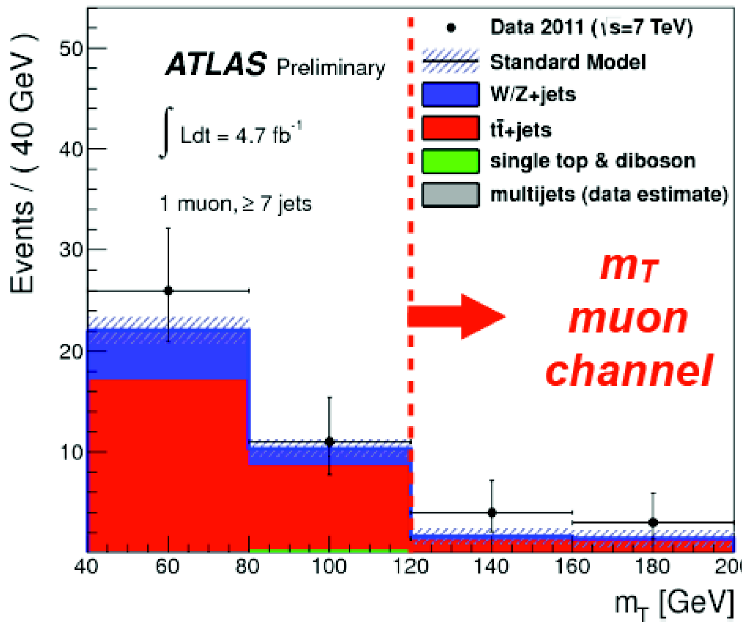
Focused on final states with leptonic chargino decay or sleptons

- 1 signal region with exactly 1 isolated lepton (e, μ)
- $m_{eff} = p_T^{\ell} + \sum_i p_T^{jet,i} + E_T^{miss}$
- $m_T = \sqrt{2\, p_T^{\ell} E_T^{miss} (1 - \cos(\Delta\Phi(\ell, p_T^{miss})))}$

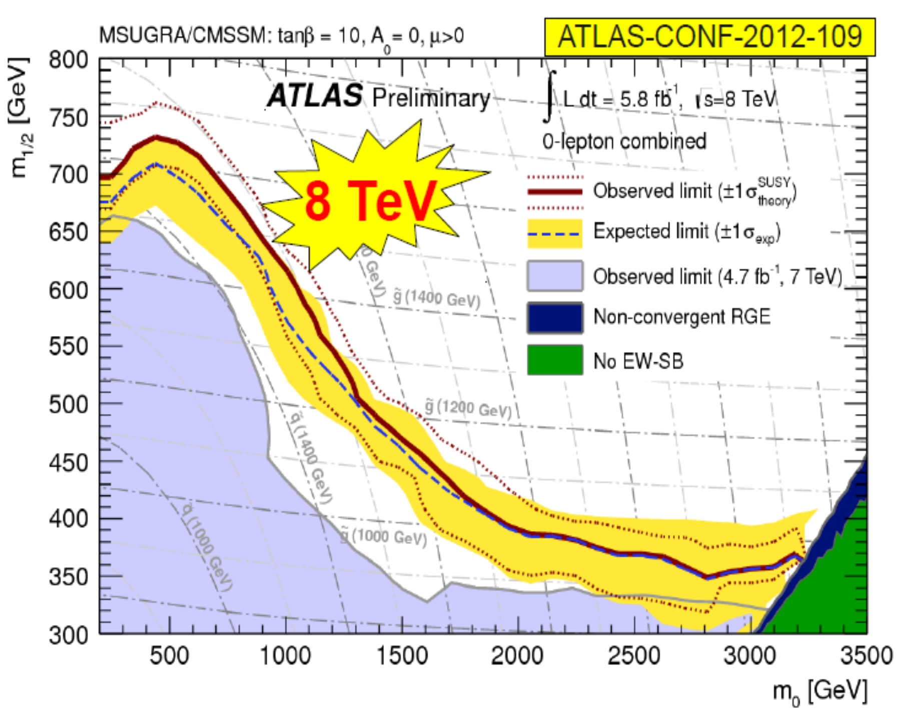
1 lepton analysis + ≥ 4 jets @ 8 TeV
ATLAS-CONF-2012-104

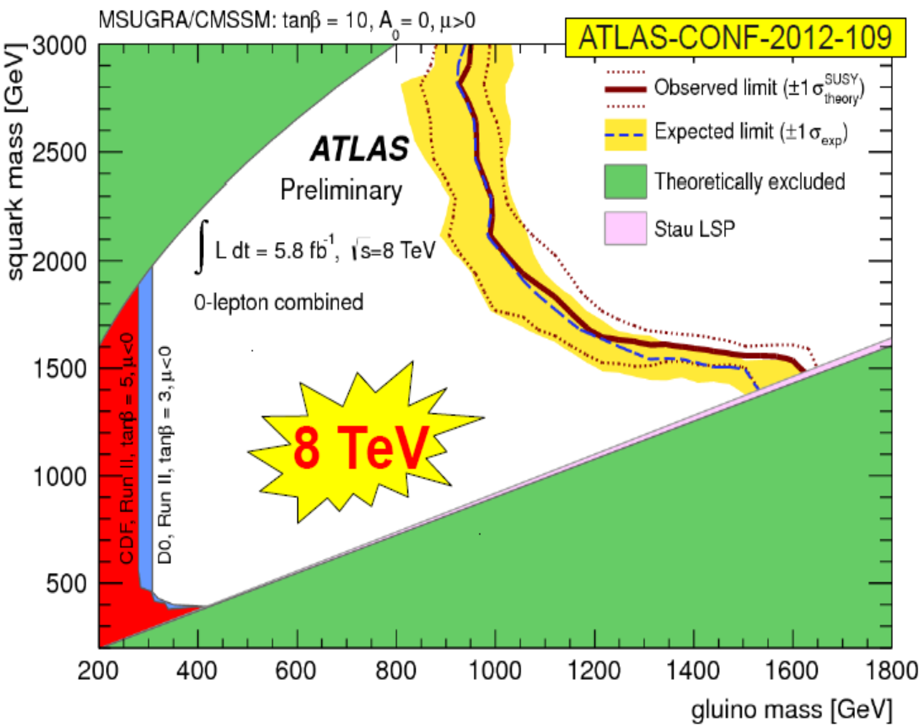


***new**: 1 lepton analysis + ≥ 7 jets @ 7 TeV*
ATLAS-CONF-2012-140



SUSY

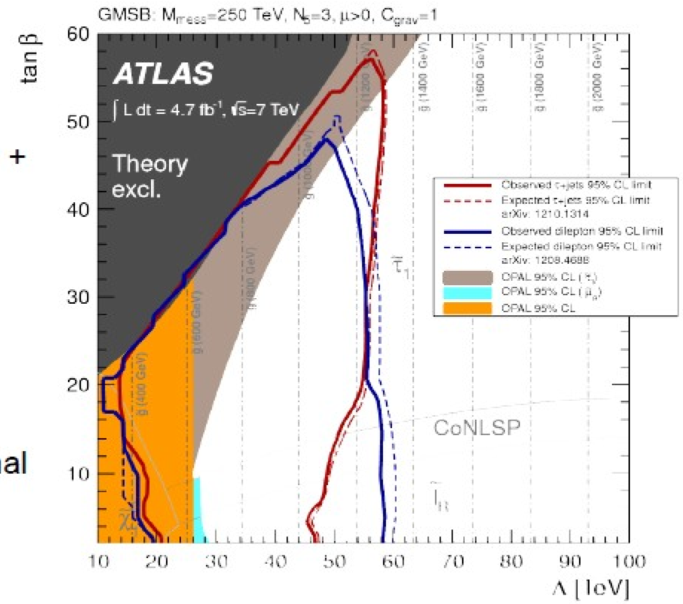

MSUGRA/CMSSM: tanβ = 10, A0 = 0, μ>0
ATLAS-CONF-2012-109
ATLAS Preliminary
∫ L dt = 5.8 fb-1, √s=8 TeV
0-lepton combined
8 TeV
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
Observed limit (4.7 fb-1, 7 TeV)
Non-convergent RGE
No EW-SB
m1/2 [GeV]
m0 [GeV]
800
750
700
650
600
550
500
450
400
350
300
500
1000
1500
2000
2500
3000
3500


MSUGRA/CMSSM: tanβ = 10, A0 = 0, μ>0
ATLAS-CONF-2012-109
ATLAS
Preliminary
∫ L dt = 5.8 fb-1, √s=8 TeV
0-lepton combined
8 TeV
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
Theoretically excluded
Stau LSP
CDF, Run II, tanβ = 5, μ<0
D0, Run II, tanβ = 3, μ<0
squark mass [GeV]
gluino mass [GeV]
3000
2500
2000
1500
1000
500
200
400
600
800
1000
1200
1400
1600
1800

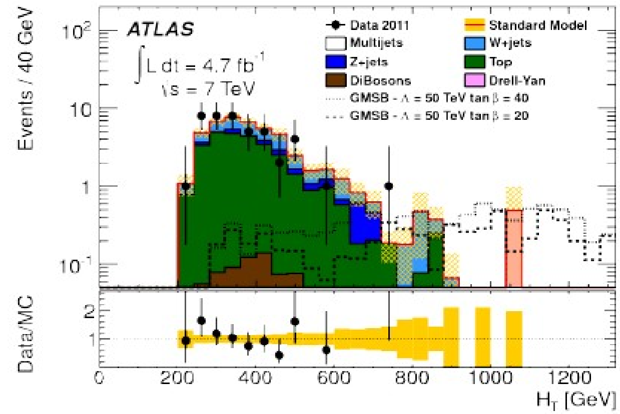
Supersymmetry: search results

MET + jets + Tau

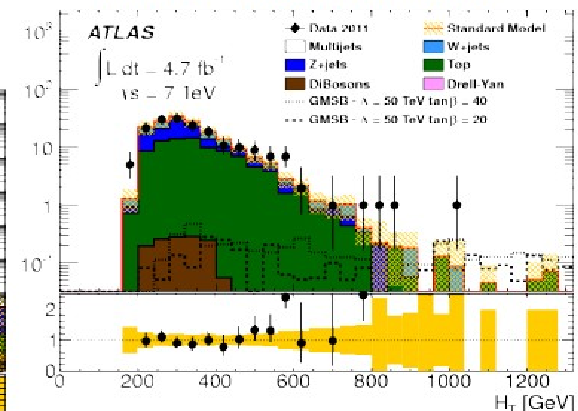
- This analysis assumes NLSP is a stau
  - Decays to gravitino + tau
- Look for events with a tau + leptons
- 4 signal regions
  - 1 tau
  - 2 taus
  - tau+muon
  - tau + electron
- Use MET, HT, and mT to discriminate between signal and background
  - Tune cuts for each signal region separately



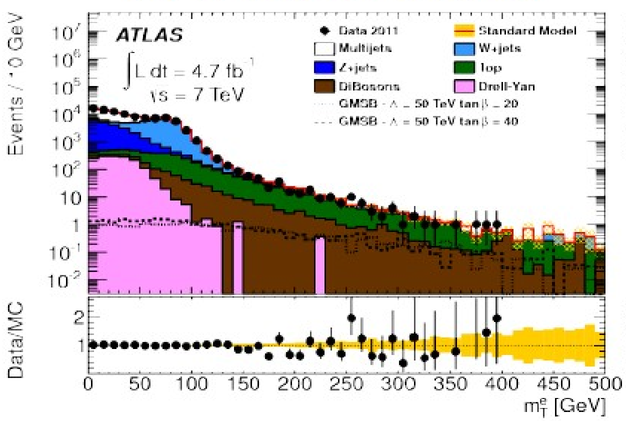
HT for 2 tau final state



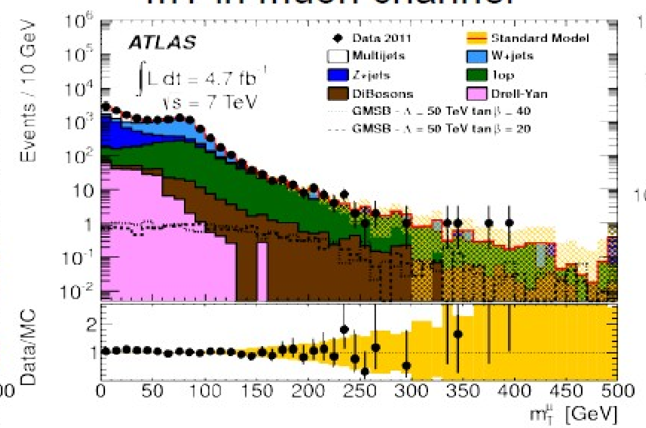
HT for 1 tau final state



mT in electron channel

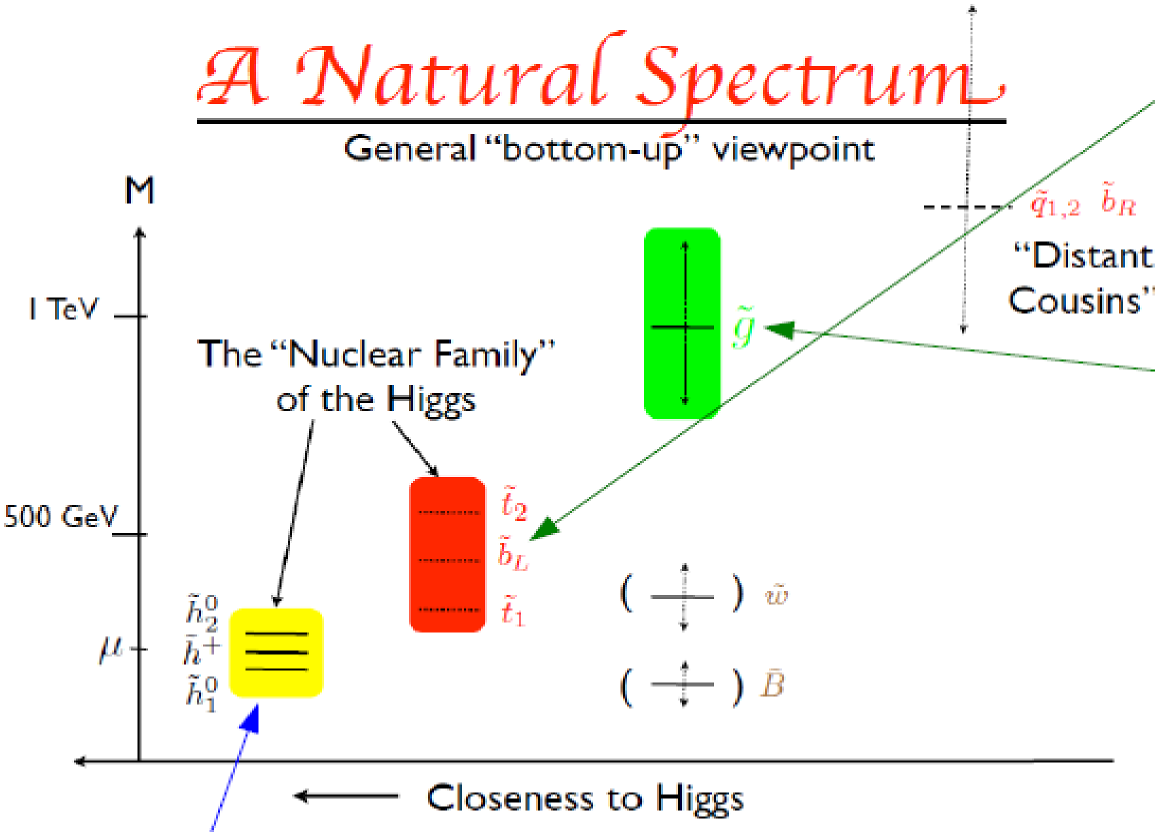


mT in muon channel



Natural SUSY

Inclusive searches constrain 1st/2nd generation squarks and gluinos to be $\gtrsim$ TeV, unless χ^0_1 is heavy



Only light stop needed to regularize light Higgs boson

The gluino should not be too heavy either

Light as $\mu \sim m_Z$ at tree level

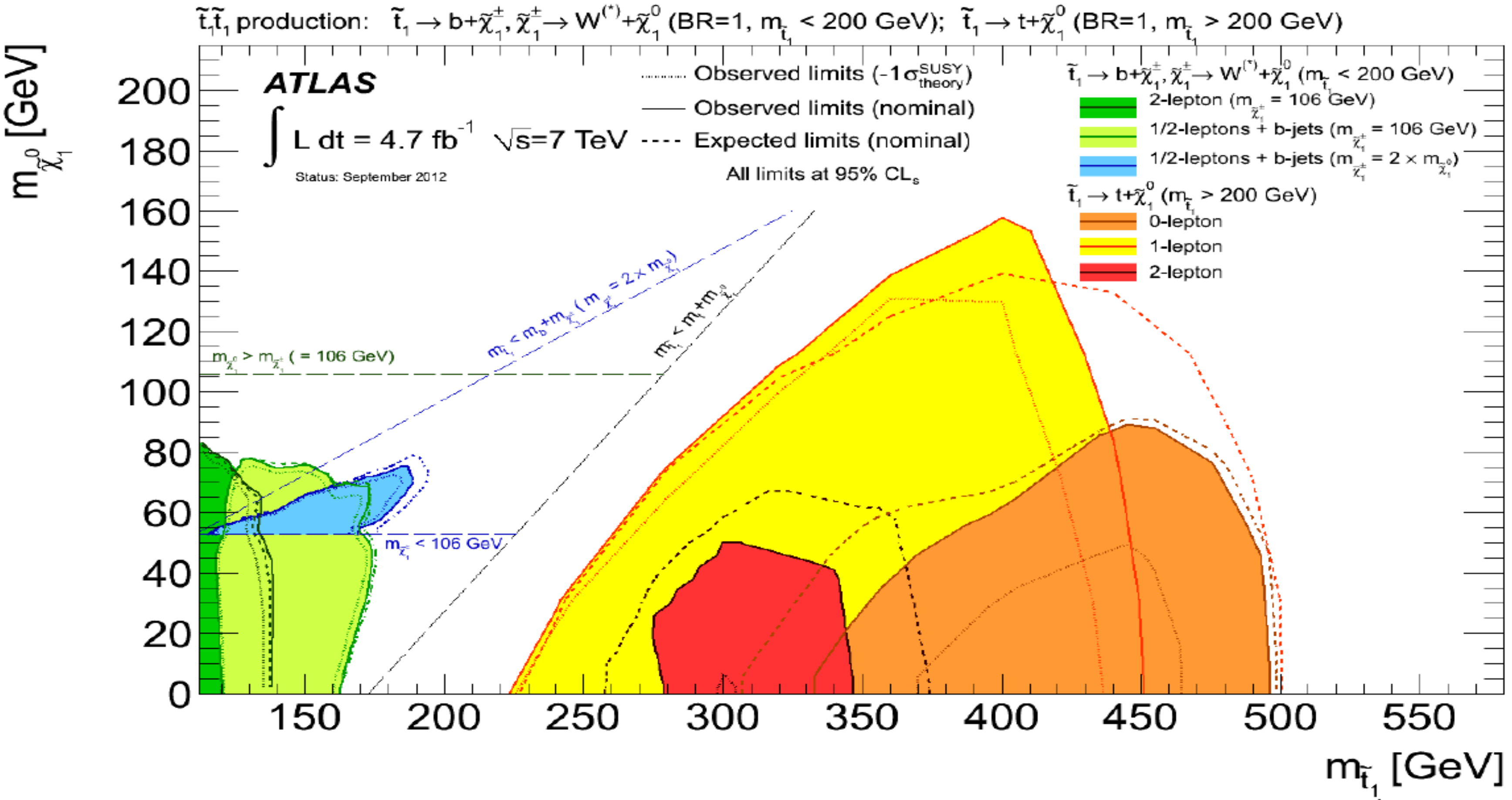
New search frontier

- Search for stop and sbottom
- Direct production or through gluino pairs

SUSY

Multiple dedicated searches
Target different stop mass & decay

- High stop mass, $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1$
- $m(\tilde{t}_1) \sim m(t)$
- Light stop, $\tilde{t}_1 \rightarrow b\tilde{\chi}^{\pm}_1$



RPV supersymmetry

- Many SUSY models assume R-Parity conservation, i.e. Lightest Supersymmetric Particle (LSP) is stable.
  - Typical missing transverse energy SUSY signature
  - Could be a candidate for Dark Matter
- BUT no reason to assume this *a priori*..
  - If we introduce R-Parity Violating terms into superpotential, LSP can decay to SM particles.

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_2 + \lambda''_{ijk} \bar{D}_i \bar{D}_j \bar{D}_k$$

Lepton Violating — Baryon Violating

  - Stability of photon forbids simultaneous lepton and baryon number violation
    - We look at both multi-leptonic and multijet final states

Long life-time particle

RPV:

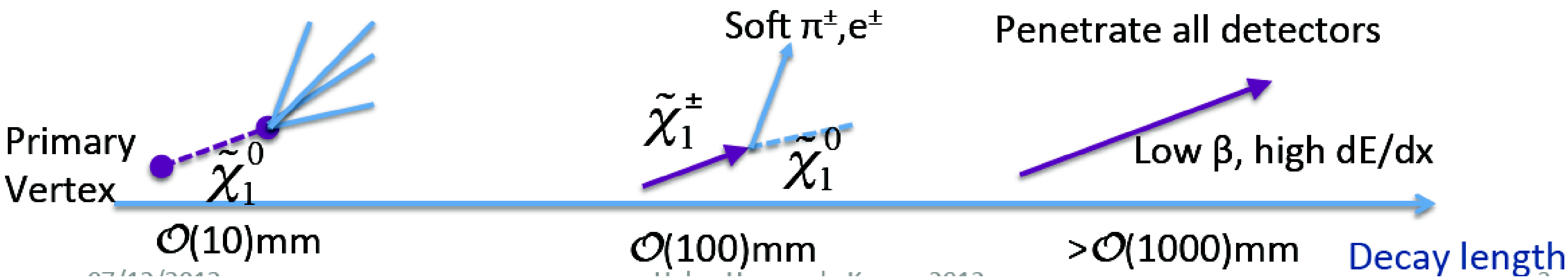
$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_2 + \lambda''_{ijk} \bar{D}_i \bar{D}_j \bar{D}_k$$

If $\lambda, \lambda', \lambda''$ are small, LSP can have a long lifetime.

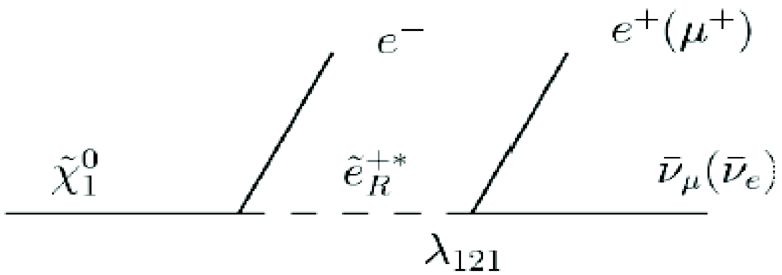
(lifetime proportional to $\lambda^{-2}, \lambda'^{-2}, \lambda''^{-2}$)

RPC:

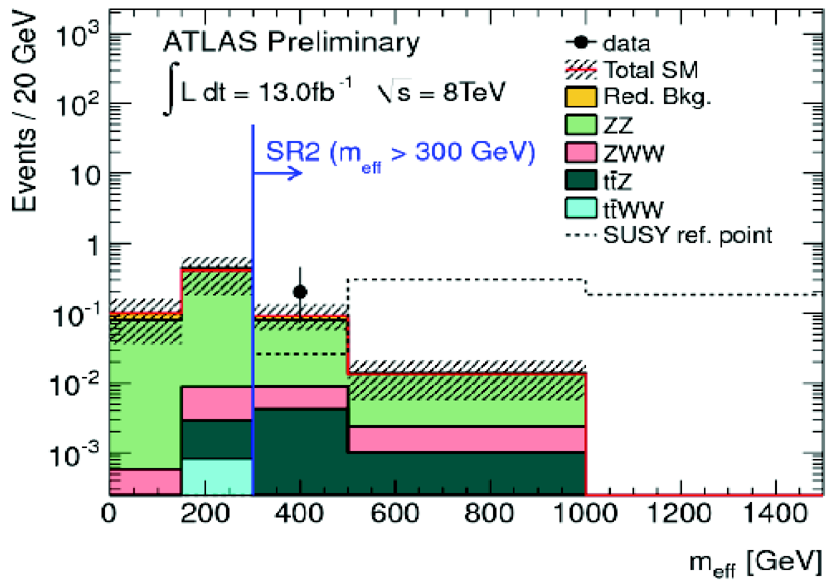
- $\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ ~ 100 MeV, e.g. AMSB: disappearing track
- Long-lived gluino due to squarks mediating its decay : Rhadrons
- Weak coupling NLSP-gravitino in GMSB : slepton

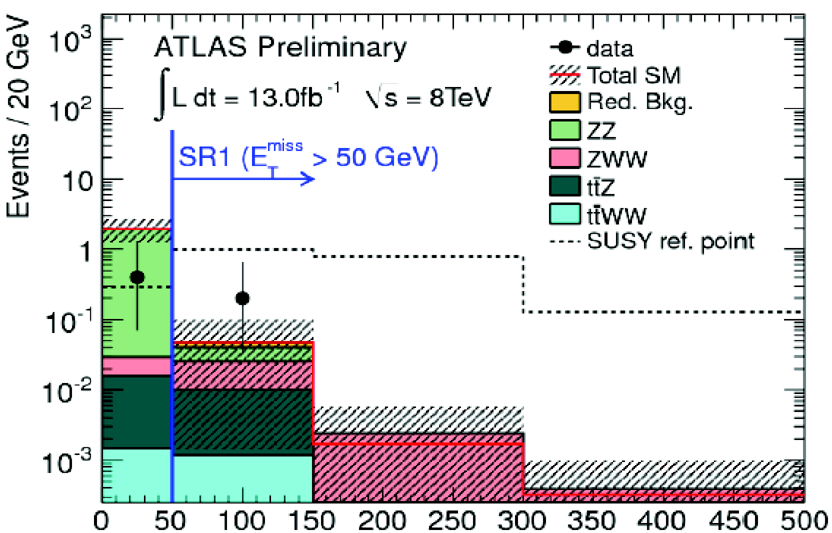


RPV SUSY in events with ≥ 4 leptons



- RPV models which allow lepton number violating can have multiple leptons
- Low SM BG (mainly WZ and ZZ)





- Event Selection:
  - 4 or more leptons
  - Z-candidate veto
  - E_T^{miss}> 50 GeV, or m_{eff}> 300 GeV

$$m_{eff} = E_T^{miss} + \sum_{\mu} p_T^{\mu} + \sum_{e} p_T^{e} + \sum_{jet} p_T^{jet}$$

RPV SUSY in events with ≥ 4 leptons

- Irreducible = 4 leptons
- Reducible BG has one or more fake lepton

Selection	E_T^{miss}> 50 GeV,	m_{eff}> 300 GeV
Irreducible Bkg.	$0.22^{+0.27}_{-0.21}$	$1.1^{+0.5}_{-0.4}$
Reducible Bkg.	$0.028^{+0.107}_{-0.028}$	$0.10^{+0.14}_{-0.10}$
Total Bkg.	$0.25^{+0.29}_{-0.25}$	$1.2^{+0.5}_{-0.4}$
Data	1	2

95% CL limits on the NLSP mass

Wino : 710 GeV

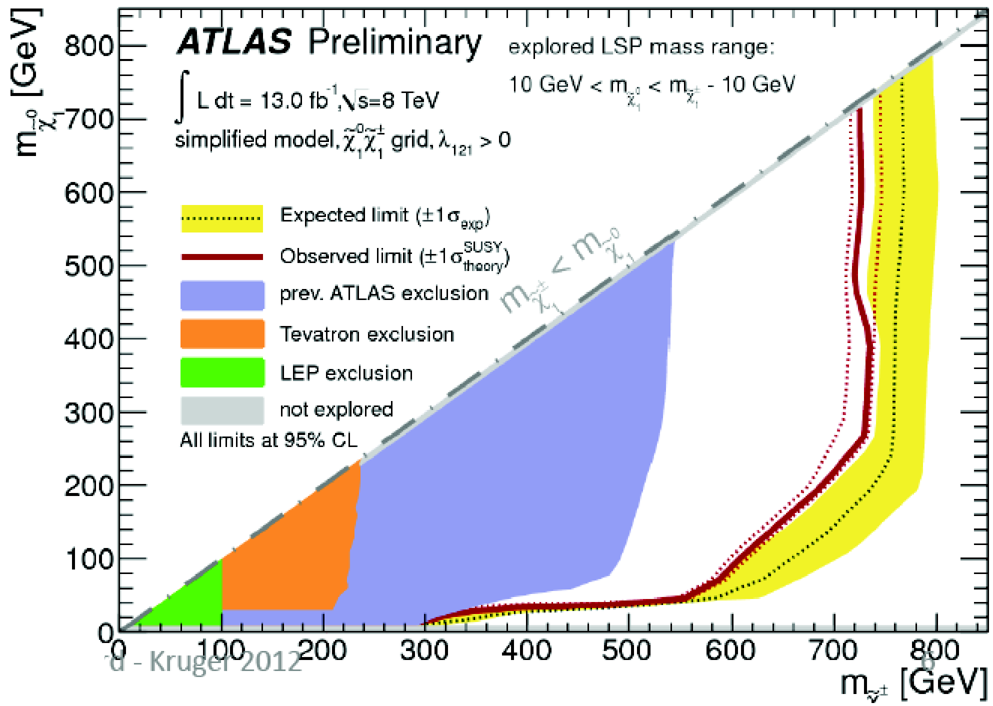
left handed slepton : 450 GeV

sneutrino : 410 GeV

gluino : 1300 GeV

- No excess over SM background is observed.
- The results are interpreted in simplified SUSY models which include ≥ 1 NLSP.
  - LSP: Bino-like neutralino
  - NLSP: Wino charginos, lem-sleptons, sneutrinos, gluino

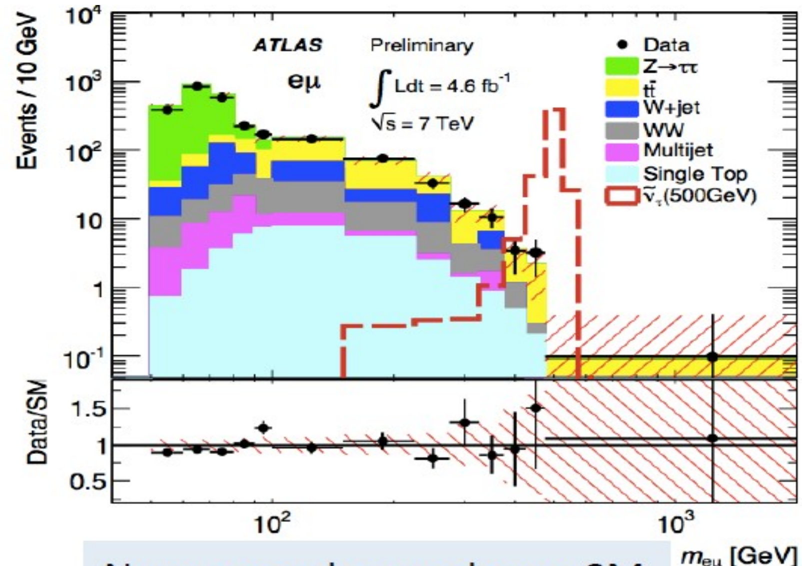
RPV Wino simplified model: λ_{121}>0



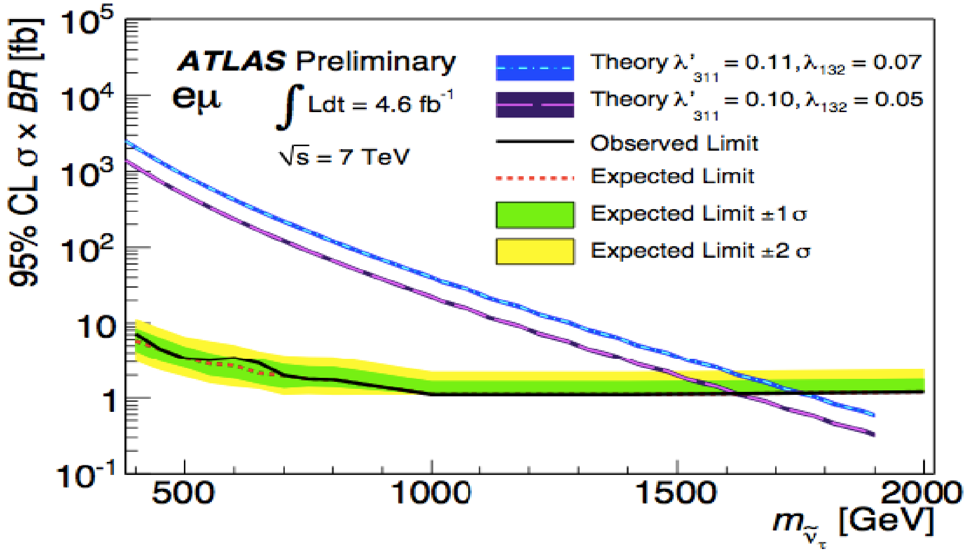
Different flavour leptons resonances

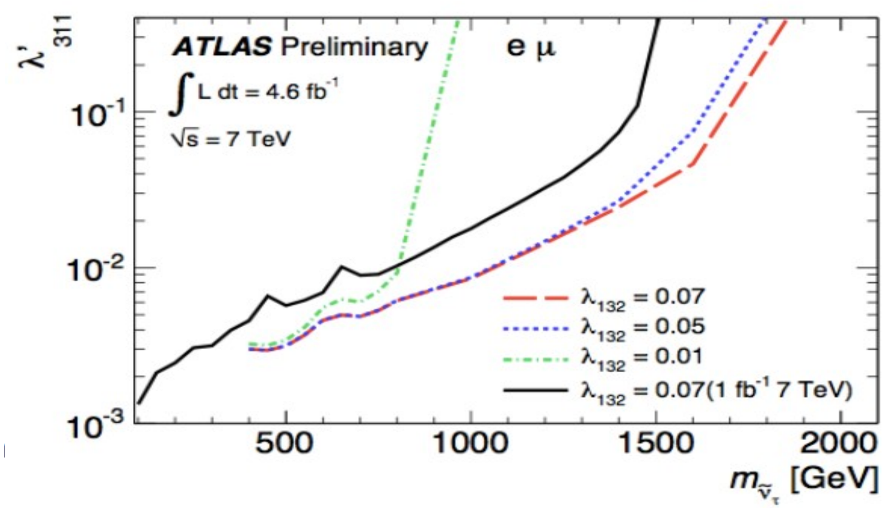
- Search for heavy particle decaying to $e^{\pm}\mu^{\mp}, e^{\pm}\tau^{\mp}, \mu^{\pm}\tau^{\mp}$
- p_T>25 (20 for τ) GeV
- Single lepton trigger
- 2 leptons that are:
  - Opposite sign
  - Opposite flavour
  - Back-to-back: ΔΦ(l,l')>2.7

Main backgrounds: $WW, t\bar{t}$
estimated MC
Fake leptons – data driven estiation



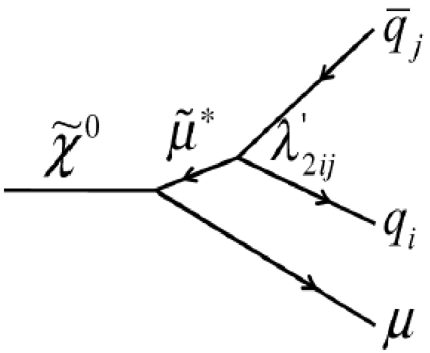
No excess observed over SM

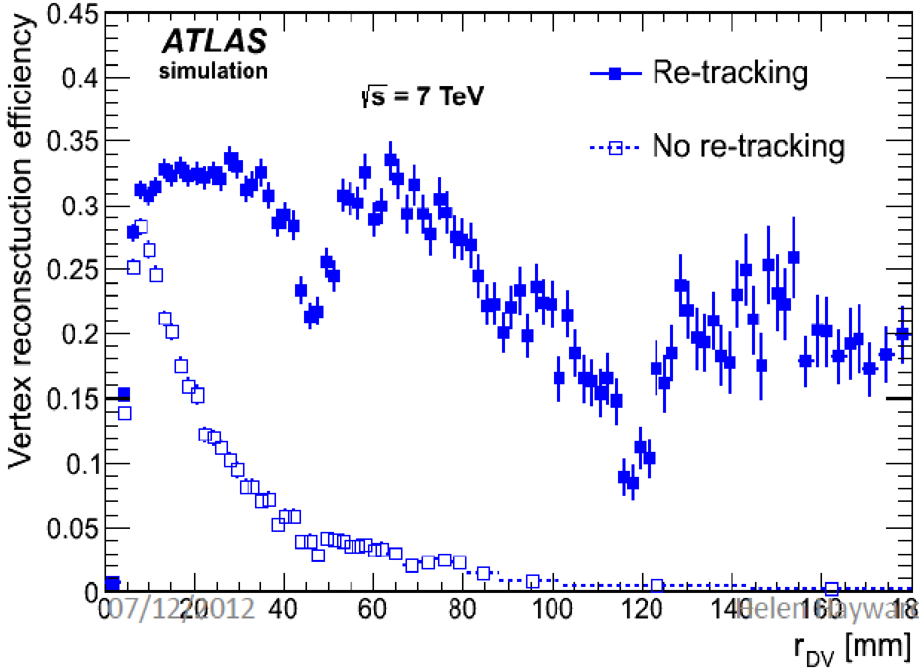




Events with displaced vertices

- If particle has lifetime $\mathcal{O}$(few ns), it can decay inside the tracking detector, producing a vertex at a distance away from the primary vertex.
- E.g. RPV susy with non-zero but small λ_{211}:
  - Neutralino decays to muon plus jets.
  - Muon is useful for triggering and background rejection.
  - High track multiplicity helps vertex reconstruction.
- Develop a dedicated tracking algorithm to increase signal efficiency.

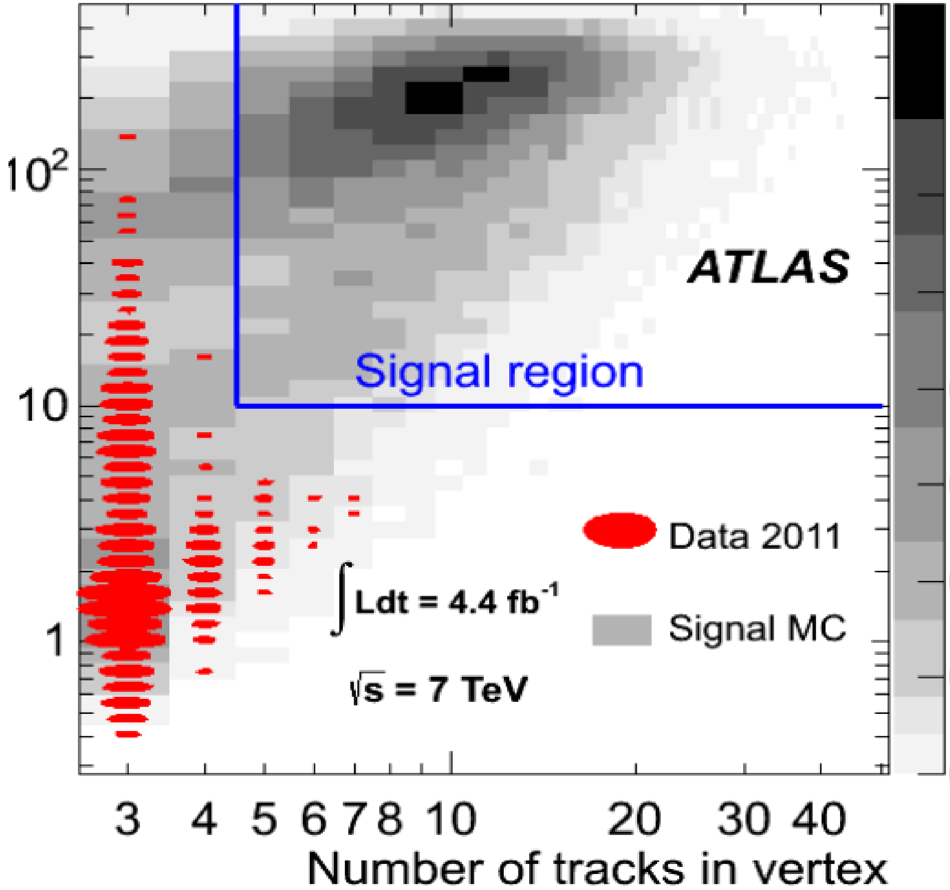




07/12/2012 Helen Hayward - Kruger 2012 12

- Standard ATLAS tracking is highly optimized for tracks coming from the primary interaction point (IP).
- To increase efficiency for secondary tracks, we re-run Silicon-seeded tracking algorithm, with looser cuts on transverse impact parameter, using “left-over” hits from Standard tracking.

Events with displaced vertices



Background is :

- random combinations of tracks inside the beampipe (where vacuum is good, but track density is high).
- High-mass tail of distribution of real vertices from hadronic interactions with gas molecules.

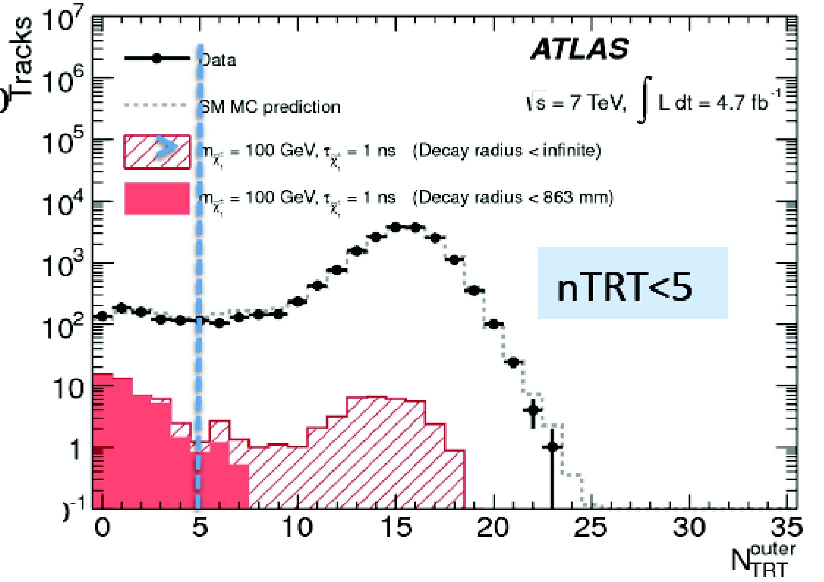
Total BG estimate in signal region is
$(4 \pm 60)*10^{-3}$. 0 events found in data

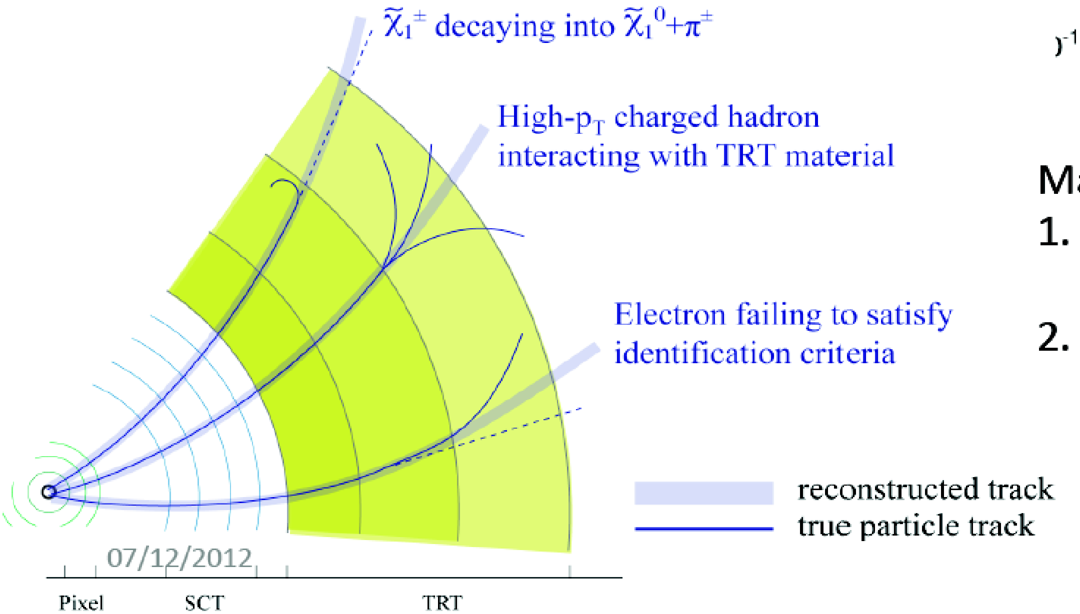
Disapering tracks

- If the lowest gauginos are approximately mass-degenerate (predicted, eg, by AMSB),
- $\tilde{\chi}_1^{\pm}$ has lifetime $\mathcal{O}$(0.1ns) and decays to $\tilde{\chi}_1^0$ and a (~100 MeV) $\pi^{\pm}$
- Look for production processes:

$$pp \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0} + jet \quad pp \rightarrow \tilde{\chi}_1^{+}\tilde{\chi}_1^{-} + jet$$

  - (jet from ISR, needed to trigger on event).



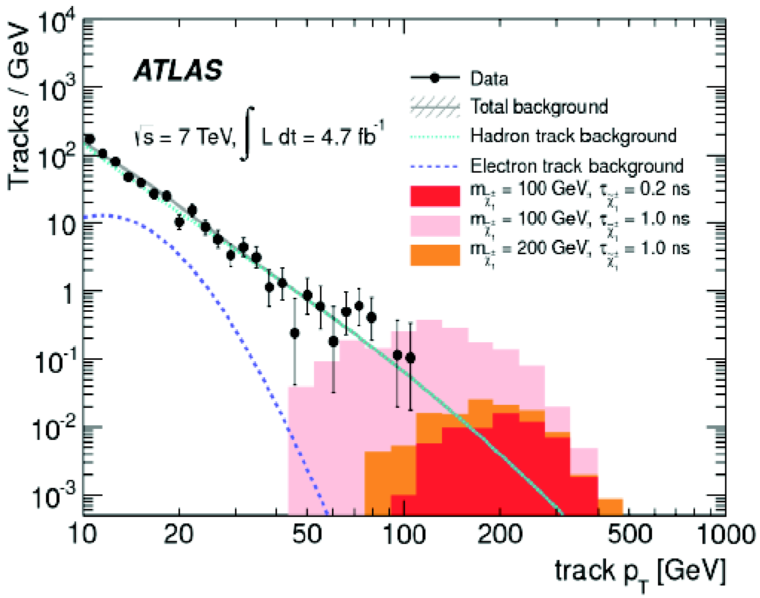


Main BG:

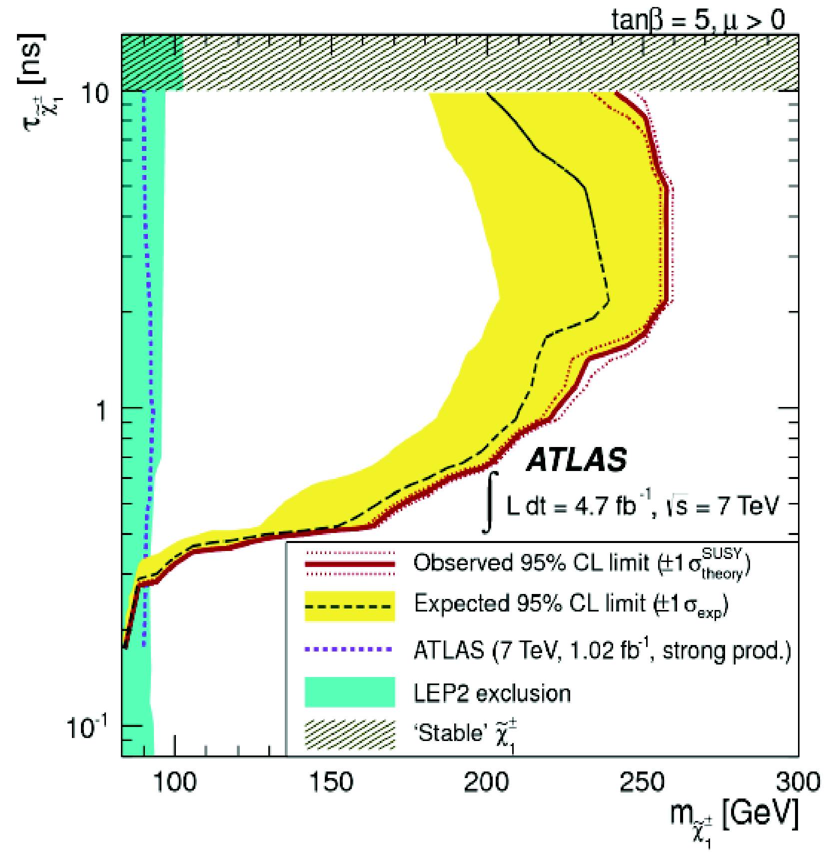
1. High p_T charged hadrons interacting in the TRT (80%)
2. Low p_T tracks performing large bremsstrahlung

Disapering tracks

No excess over SM background is observed.



For Δm ~ 160 (170) MeV (most probable in AMSB), m(chargino) up to 103 (85) GeV is excluded



Resulting final state will include:

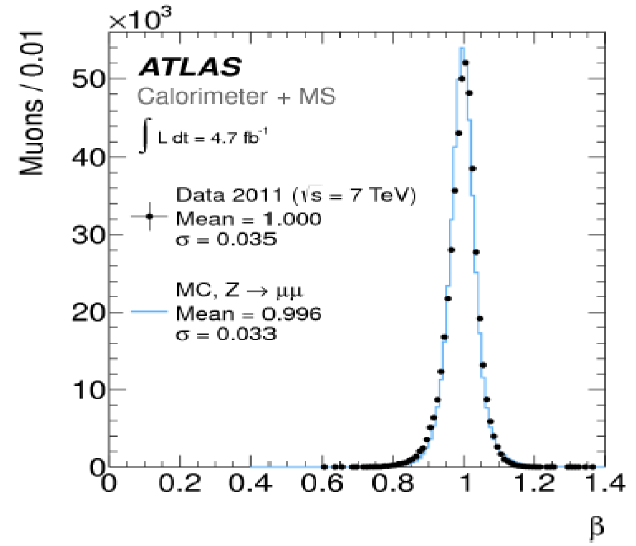
- High p_T jet
- Large missing transverse momentum.
- A kinked track or a high p_T track due to poor reconstruction efficiency for soft pion.

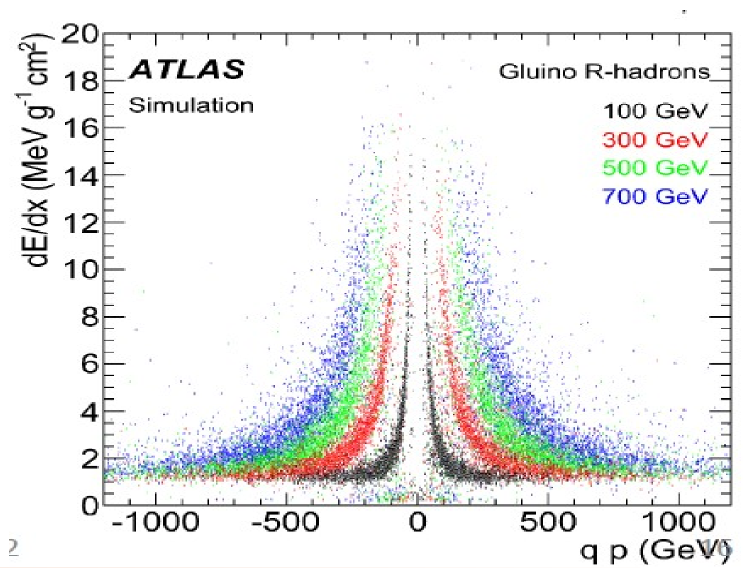
Stable massive particles

- Several candidate particles, including:
  - Long-lived sleptons in GMSB models.
  - R-hadrons.
- Common feature: if they are massive, they will be produced with low velocities: $\beta < 1$.

$$m_\beta = \frac{p}{\gamma\beta}$$

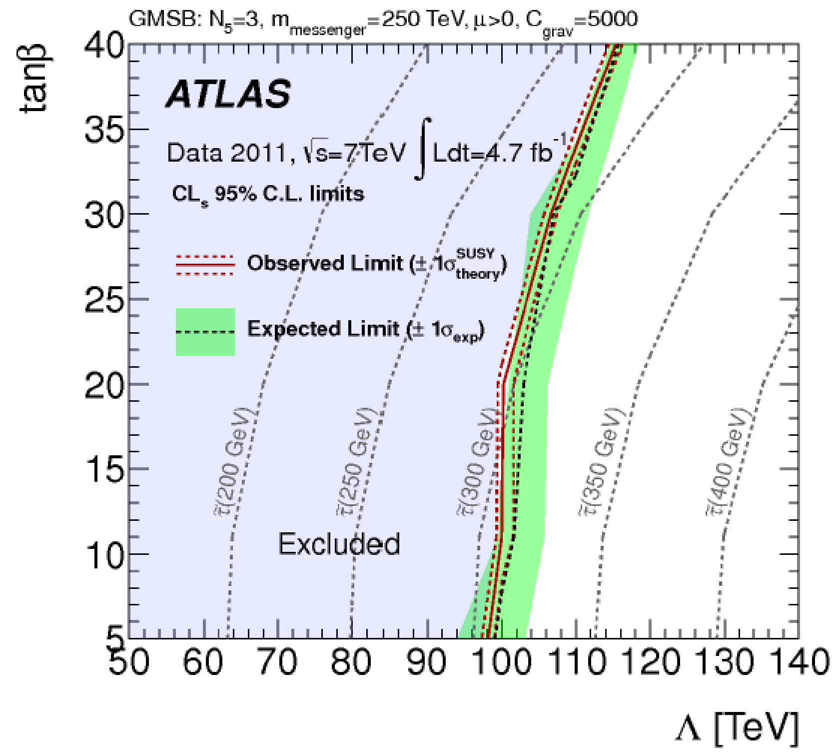
- Search for heavy muon-like particles
  - low β using muon chambers and Calorimeters
  - high dE/dx measured from pixel detector (related to $\gamma\beta$)
- Main background for both slepton and R-hadron searches is high-p_T muons with mis-measured β.

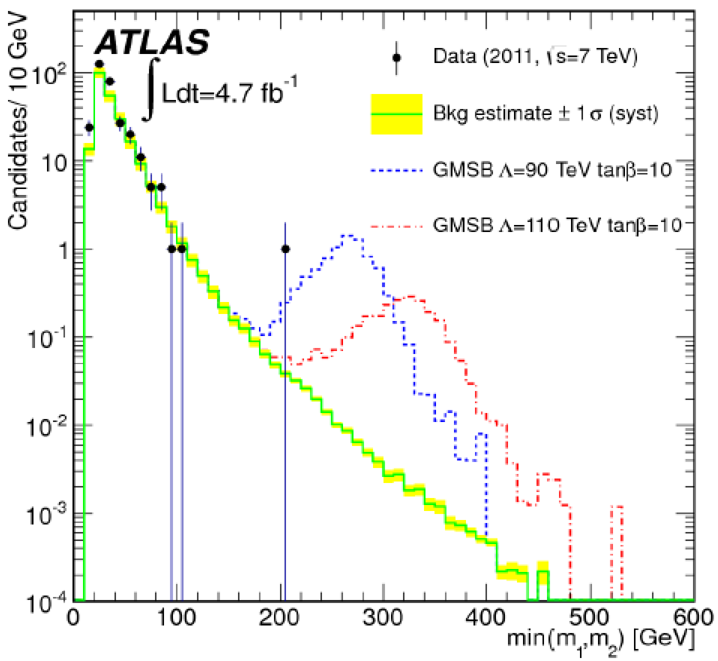




Stable massive particles

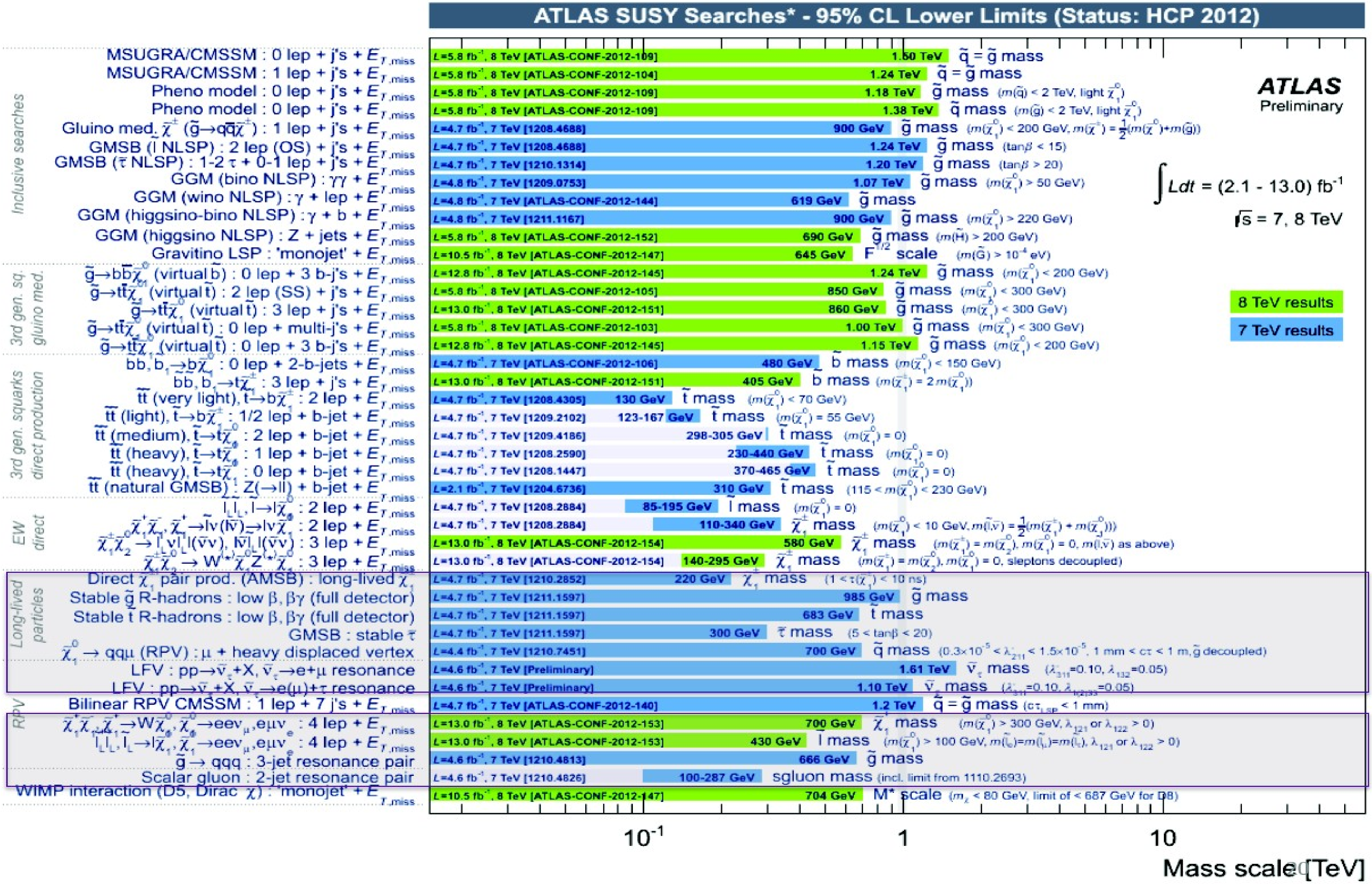
- Use single muon trigger
- Select 2 muon candidates
- Background (for both slepton and rhadron) is estimated by :
  - Randomly sampling β or βγ values from control sample distributions and combining with measured p for each candidate



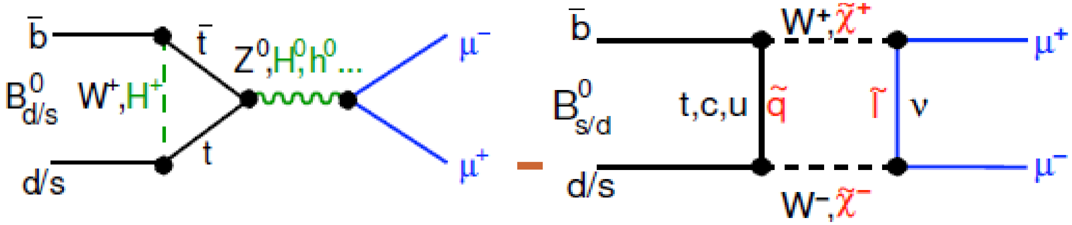


No excess over SM background is observed.
Long-lived staus (GMSB) excluded upto 300 GeV for 5<tanβ < 20
Directly produced sleptons excluded up to a mass of 278 GeV

Supersymmetry: search results



Rare decays



First observation of $B_s^0 \to \mu^+\mu^-$ LHCb-PAPER-2012-043

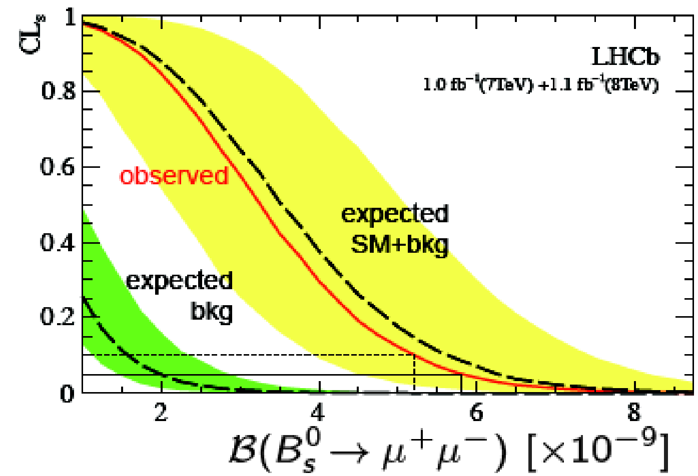
- In $1\,\text{fb}^{-1}$ ($\sqrt{s} = 7\,\text{TeV}$) + $1.1\,\text{fb}^{-1}$ ($\sqrt{s} = 8\,\text{TeV}$) of data, LHCb observes a signal for $B_s^0 \to \mu^+\mu^-$ that is **incompatible with the background only hypothesis at 3.5 σ.** With:

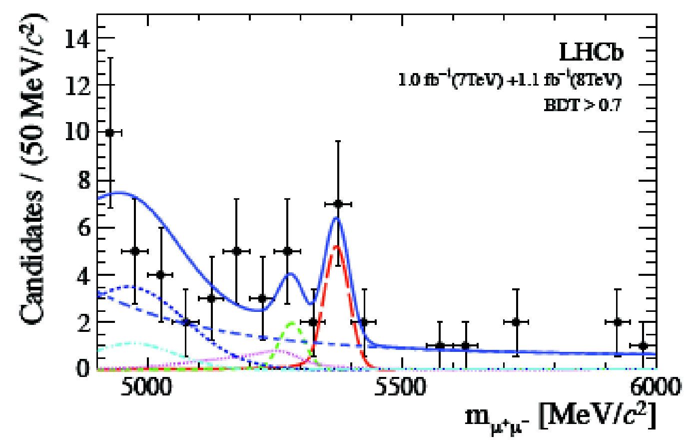
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.2\,^{+1.5}_{-1.2} \times 10^{-9}$$

c.f. a time integrated SM expectation of:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$$

[arXiv:1208.0934], [arXiv:1204.1735]





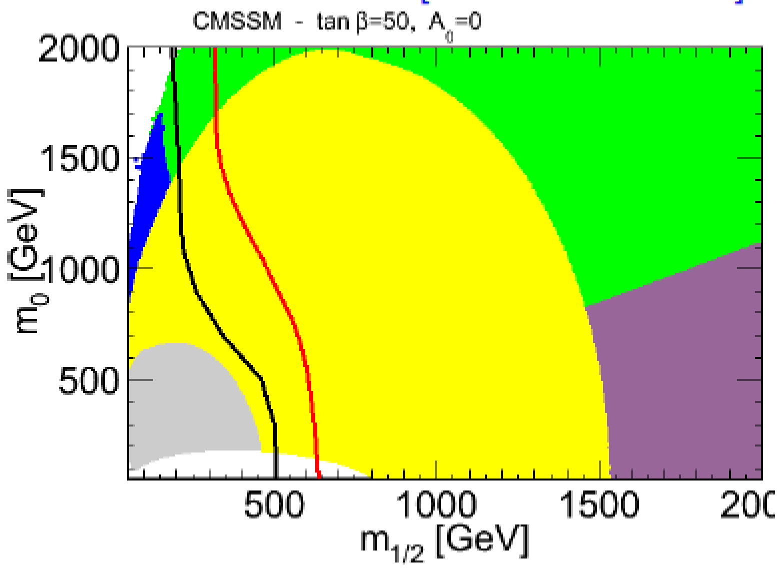
Constraints in CMSSM model

In general a SM-like $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ rules out CMSSM points with large $\tan\beta$.

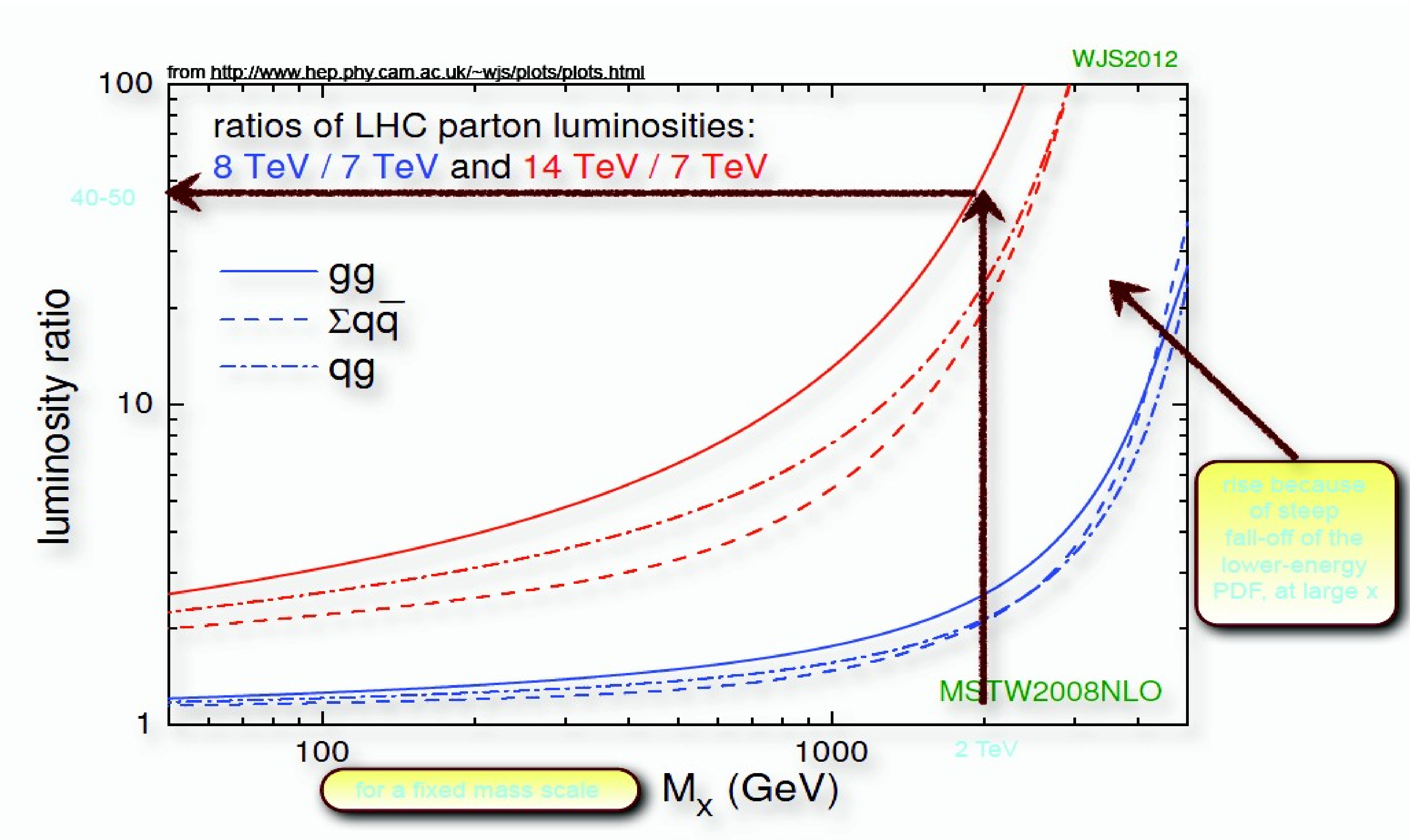
Direct search results (CMS $5\,\mathrm{fb}^{-1}$), Charged LSP, $B \to \tau\nu$, $B_s^0 \to \mu^+\mu^-$, Allowed region.

At lower tanβ the relative importance of direct searches increases.

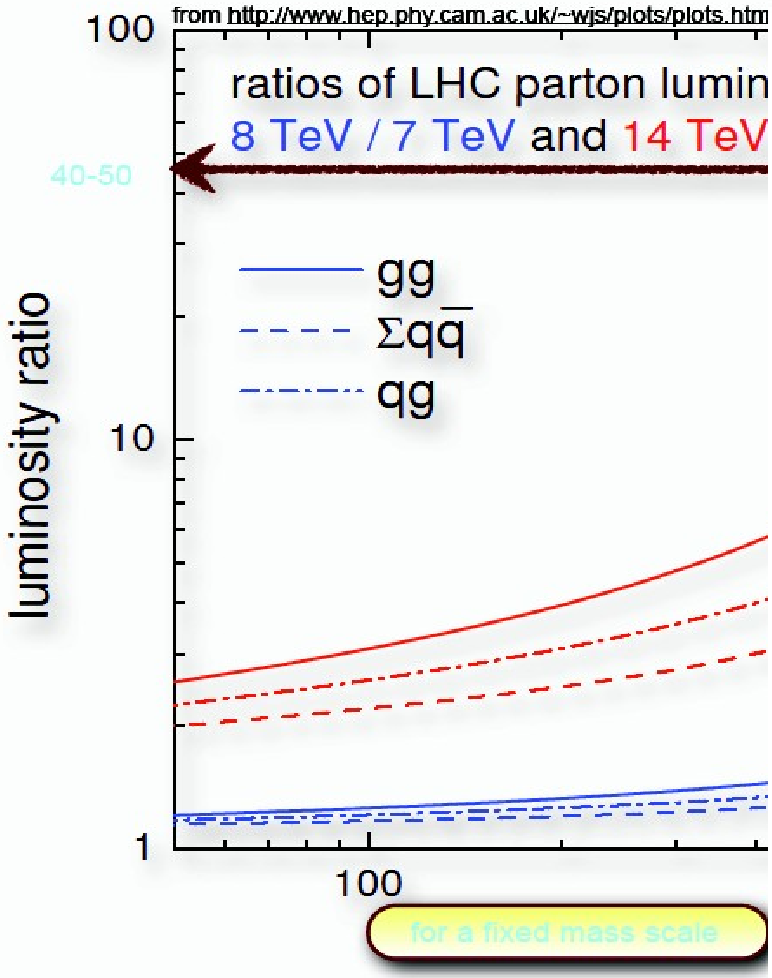
F. Mahmoudi et. al. [arXiv:1205.1845]

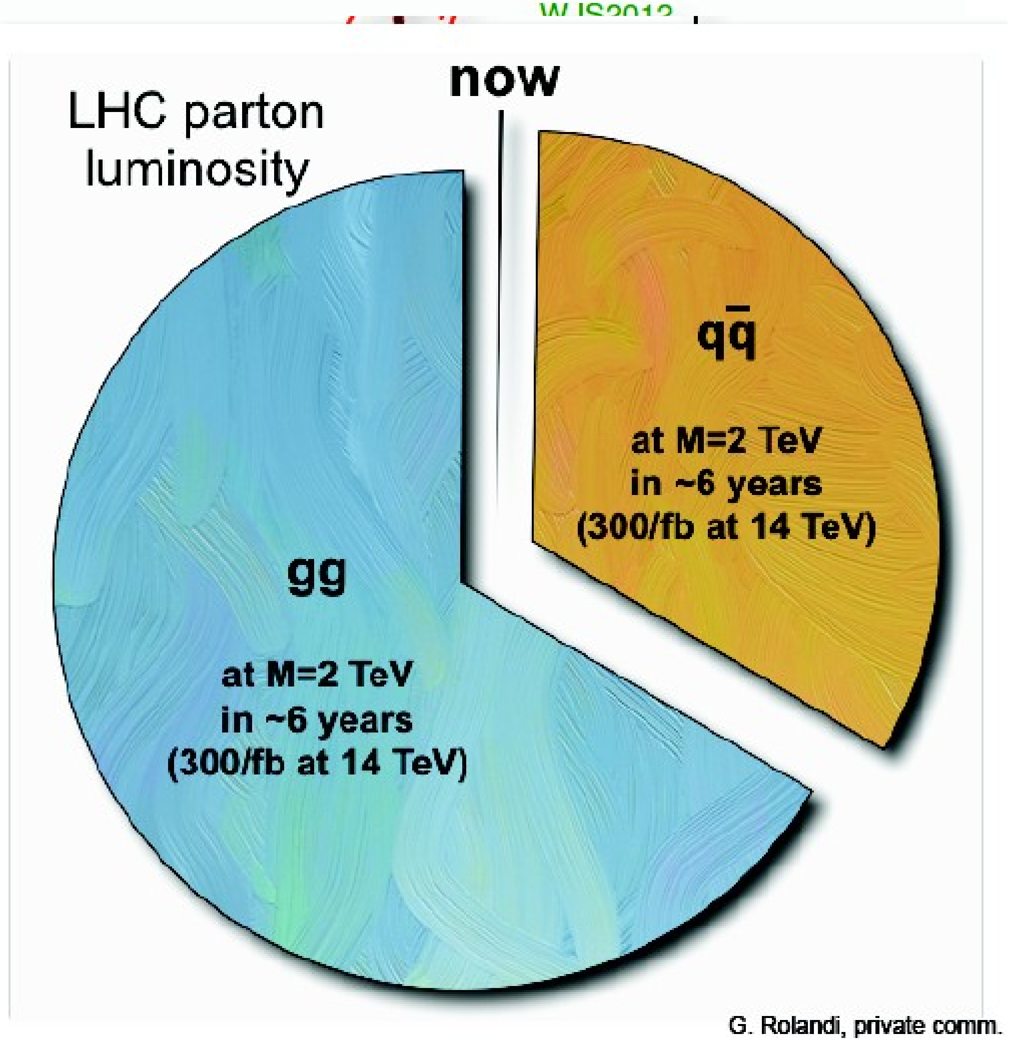


Parton luminosity



Parton luminosity





Next topics

- 9.1 – other searches for New Physics
- 16.1 - B-physics programme
- 23.1 – heavy ion programme

Living in incredibly exciting time for fundamental partcile physics!