Higgs boson searches with ATLAS

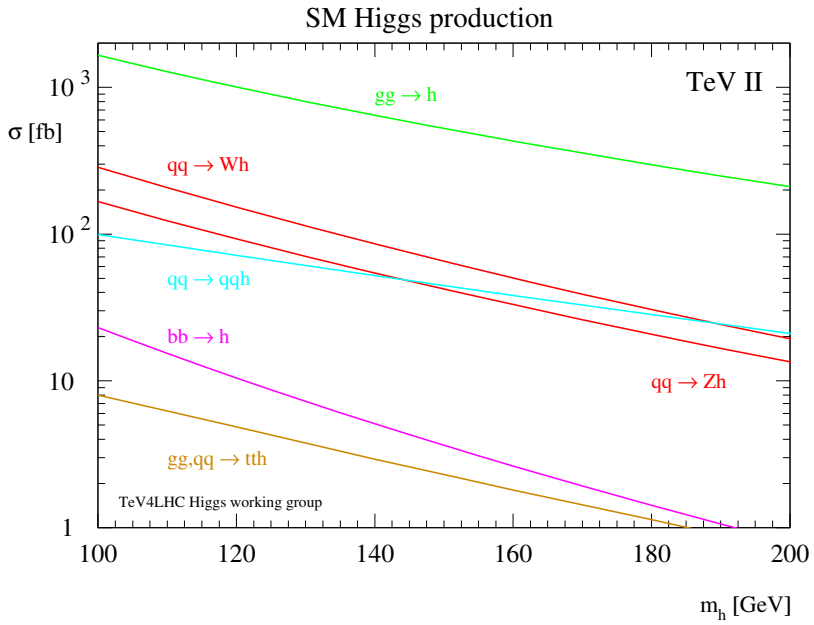
Nicolas Möser[1]
on behalf of the ATLAS Collaboration

[1]University of Bonn

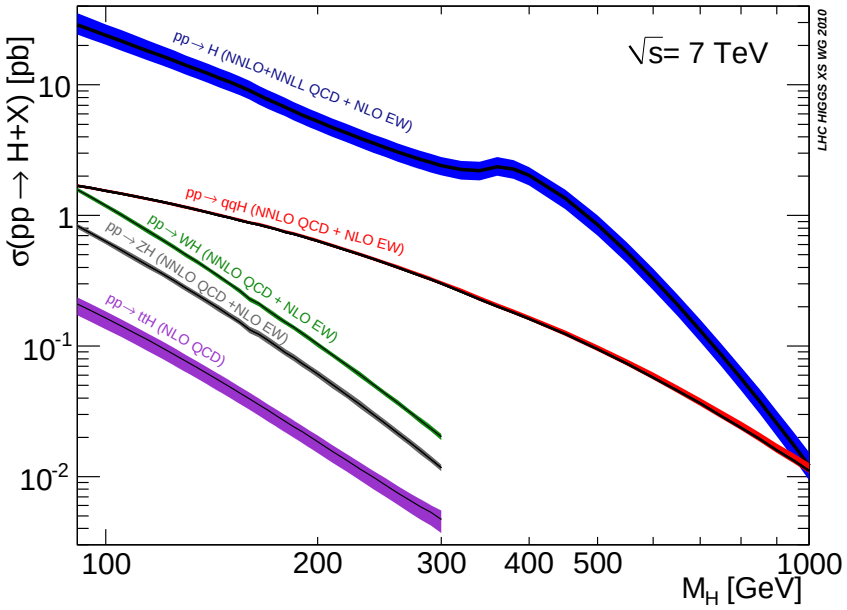
XIX International Workshop on Deep-Inelastic Scattering and Related Subjects

Higgs @ LHC

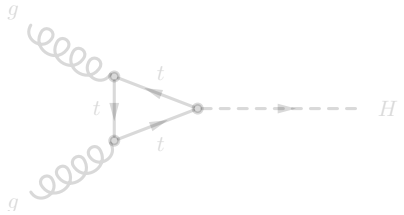
- **Tevatron**



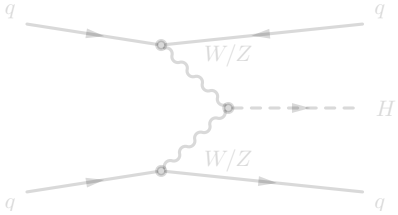
- **LHC**



- dominant production processes at LHC



gluon fusion (ggF)



vector boson fusion (VBF)

- cross sections (ggF, VBF) $\sim$ 15 times higher (@ $m_H = 100\,\mathrm{GeV}$)

- **combined effort** by ATLAS, CMS and theorists:

  "Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables."

  arXiv:1101.0593 [hep-ph]

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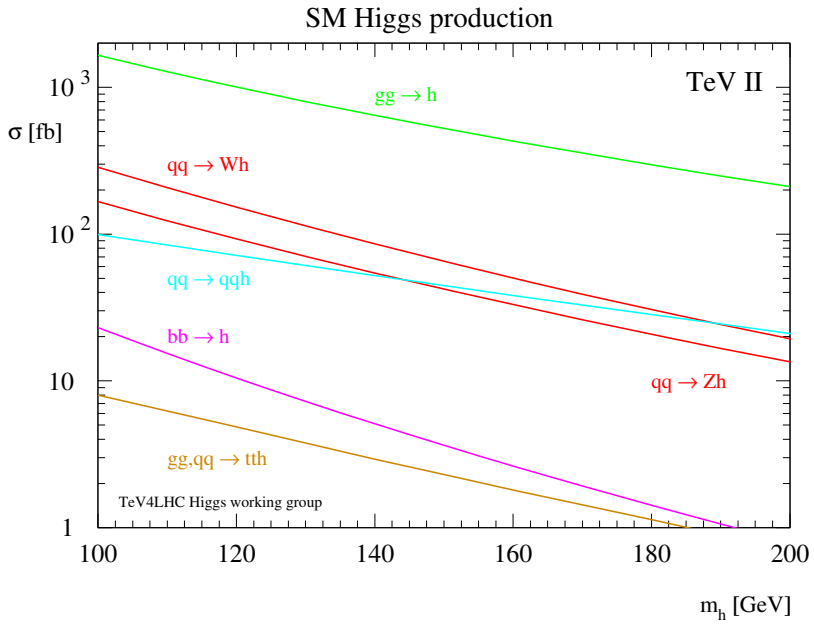

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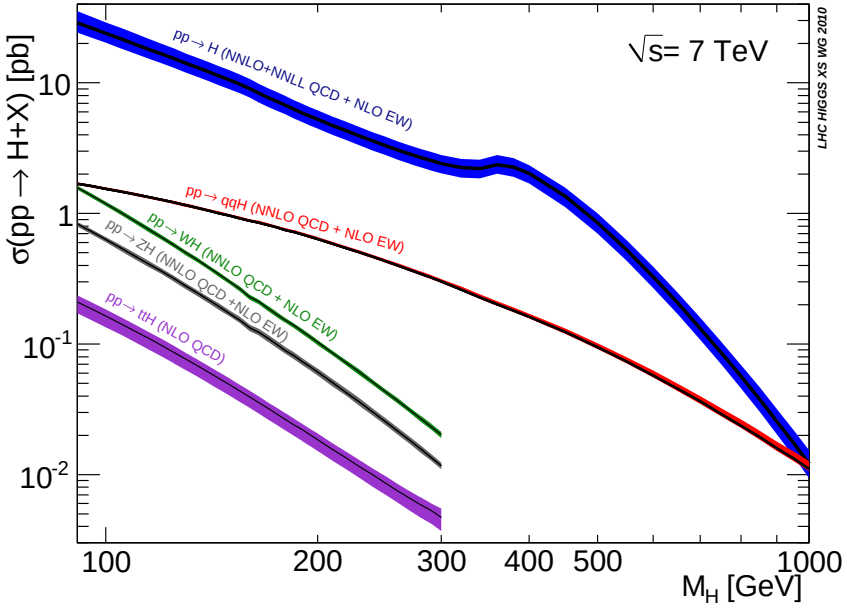

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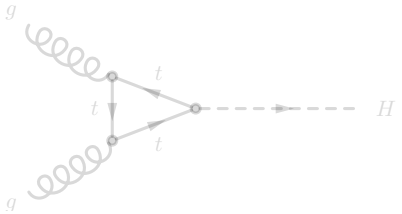

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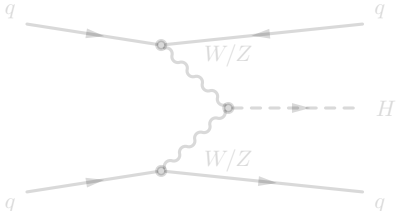

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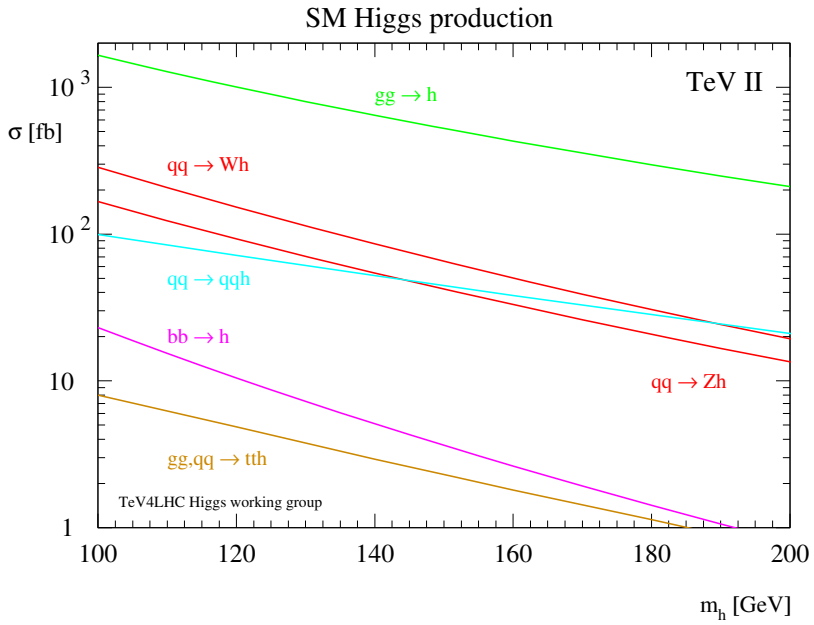

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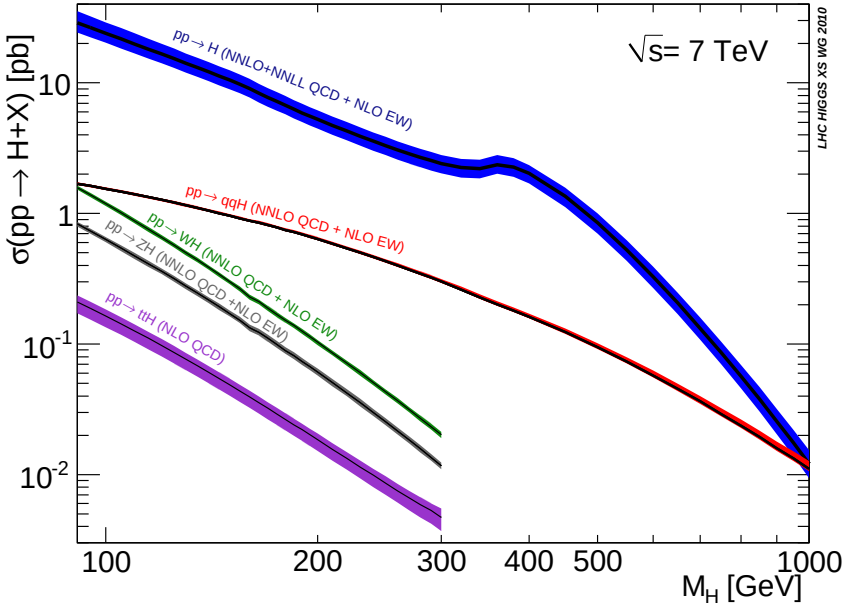

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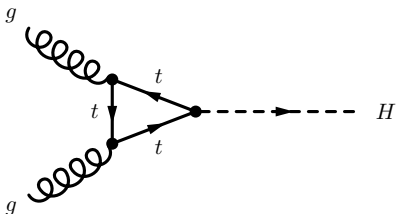

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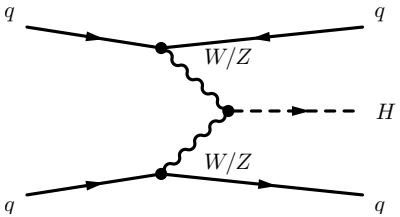

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In this Talk:

SM:

- $H \to \gamma\gamma$
- $H \to ZZ$
  - $\to 4\ell$
  - $\to \ell\ell qq$
  - $\to \ell\ell\nu\nu$
- $H \to WW \to \ell\nu\ell\nu$
  - $+$ 0 / 1 / 2 jets

MSSM:

- $h/H/A \to \tau\tau \to \ell\tau_{\text{had}}\, 3\nu$

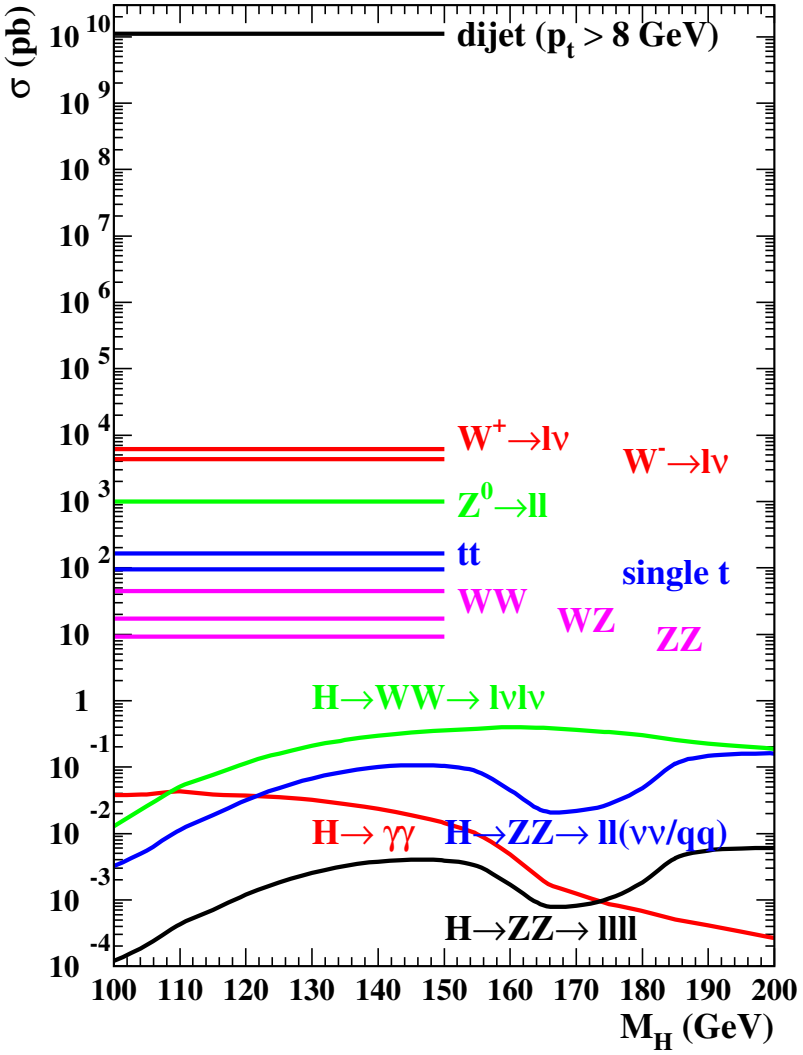
NMSSM:

- $a_1 \to \mu\mu$

- **limit derivation**:

  profile likelihood method (nuisance parameters for systematic uncertainties)

  power constrained limit (PCL):
  $\sigma_{\text{obs}} < \text{exp. median} - 1\sigma \Rightarrow$
  $\sigma_{\text{obs}} = \text{exp. median} - 1\sigma$



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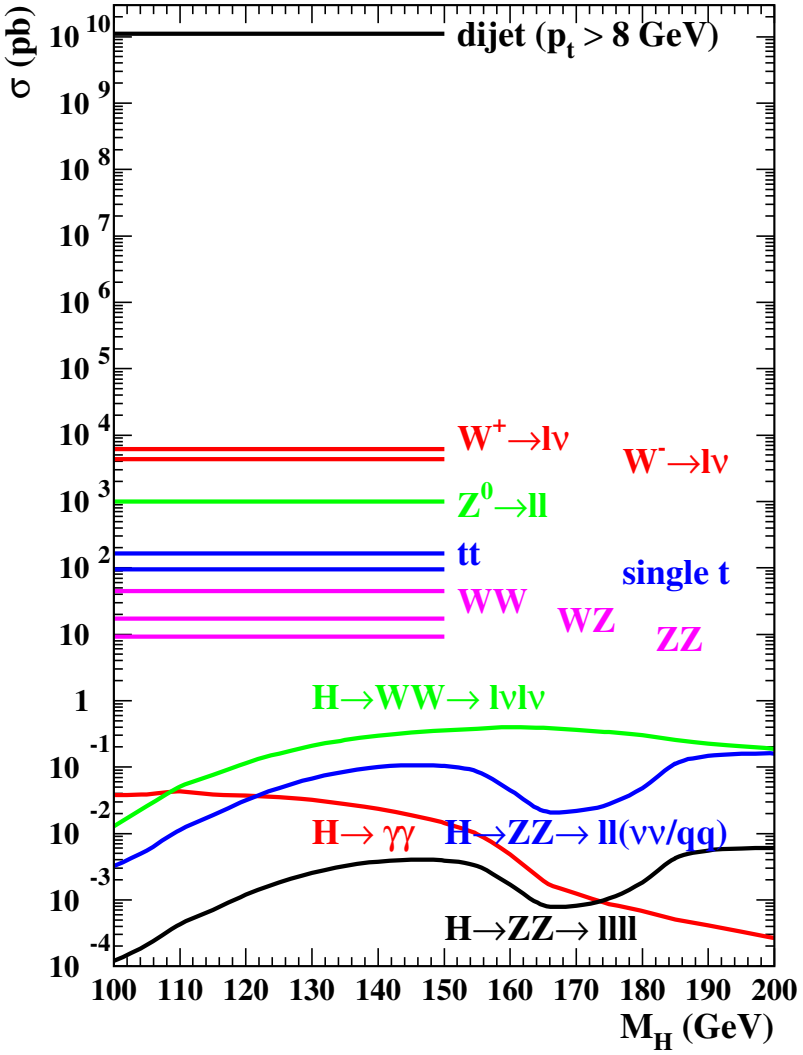

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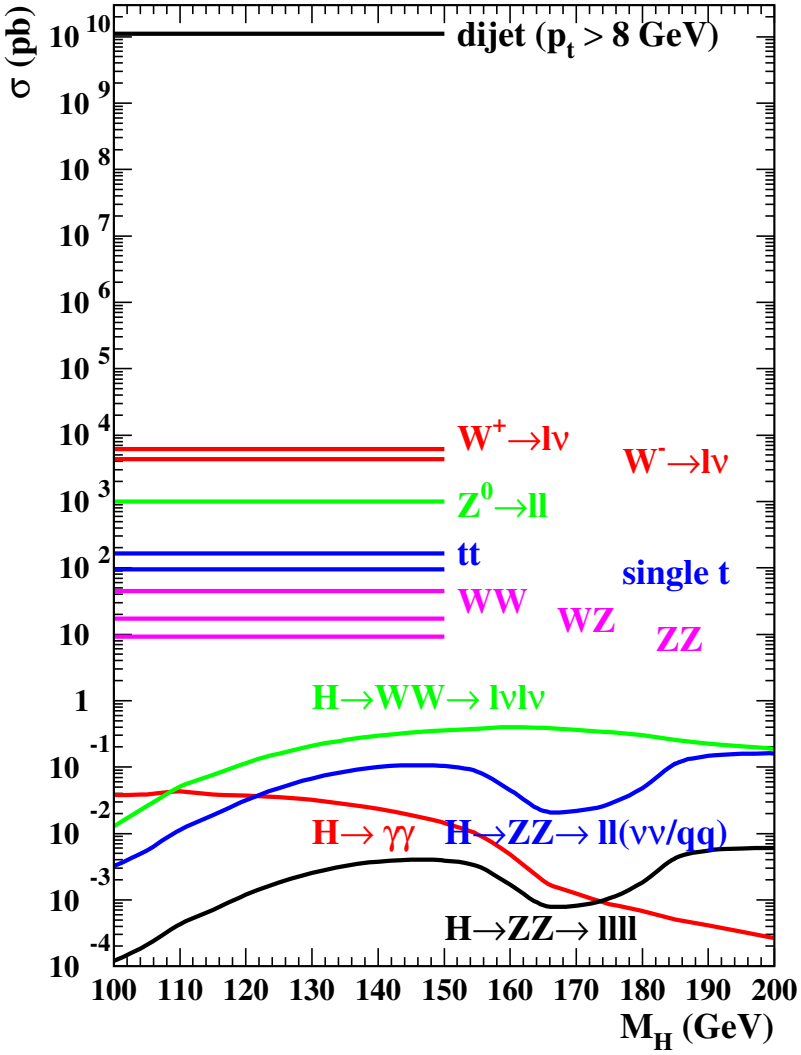

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$H \rightarrow \gamma\gamma$

- **signal**: small branching ratio

  but excellent $M_{\gamma\gamma}$ resolution expected ($4.4\,\mathrm{GeV}$ @ $m_H = 120\,\mathrm{GeV}$)

Selection

2 isolated photons

- **background**
  - γ-γ (irreducible) $\longrightarrow$ mass resolution
  - γ-jet, jet-jet; jet: fake γ or from π^0

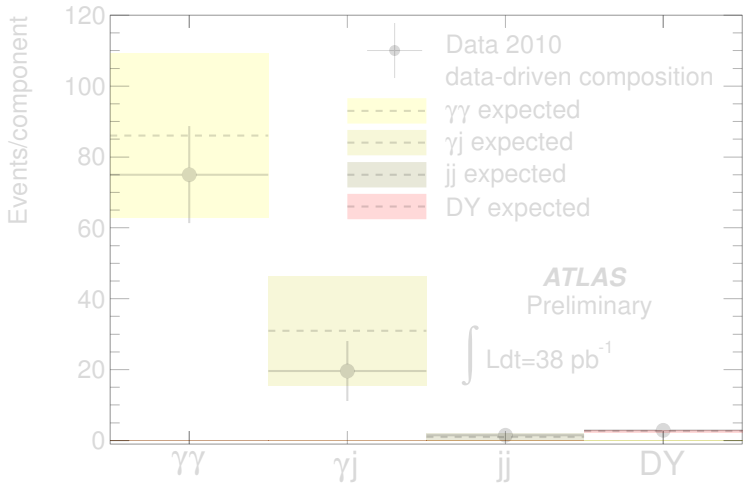
    $\longrightarrow$ photon ID and calorimeter isolation

  - Drell-Yan

- **estimate background**
  - "signal" region $A = C \cdot B/D$, sample admixture from system of equations

    consecutively for harder and softer photon
  - Drell-Yan from dedicated study

E_T^{isol}	$< 3\,\mathrm{GeV}$	$> 3\,\mathrm{GeV}$	tight ID
	C	D	✗
	A	B	✓



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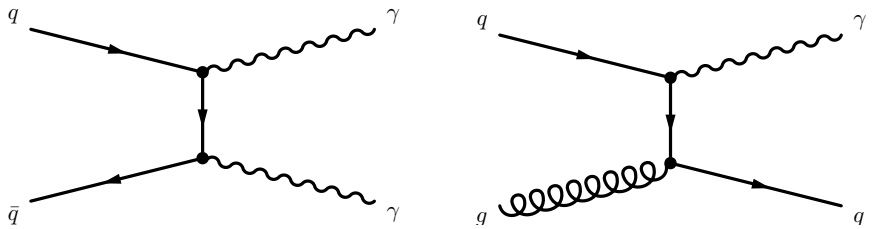

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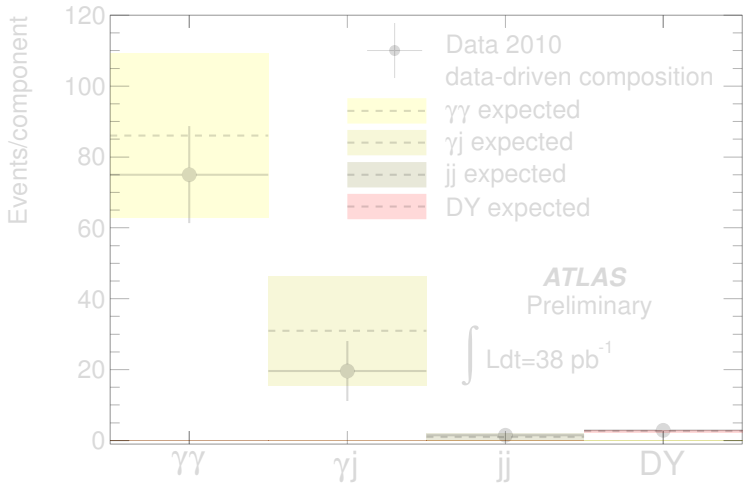

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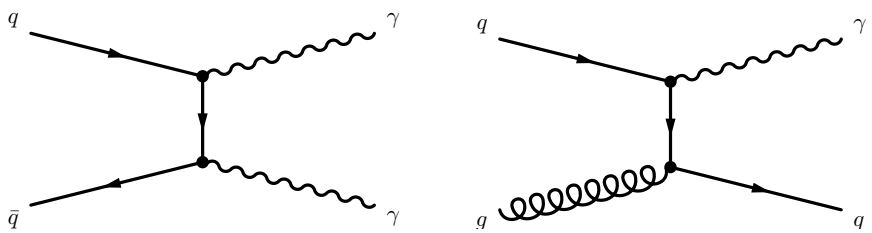

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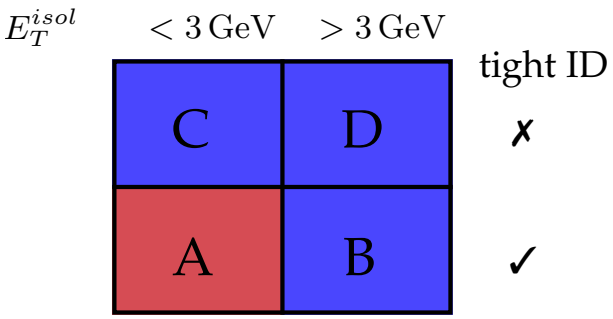
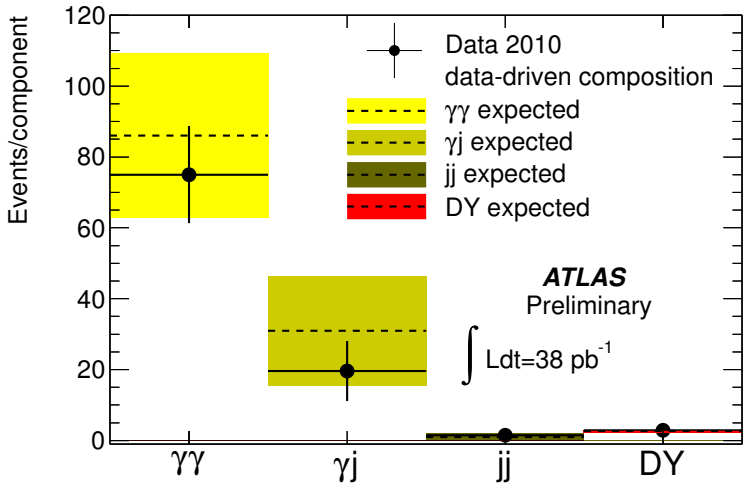




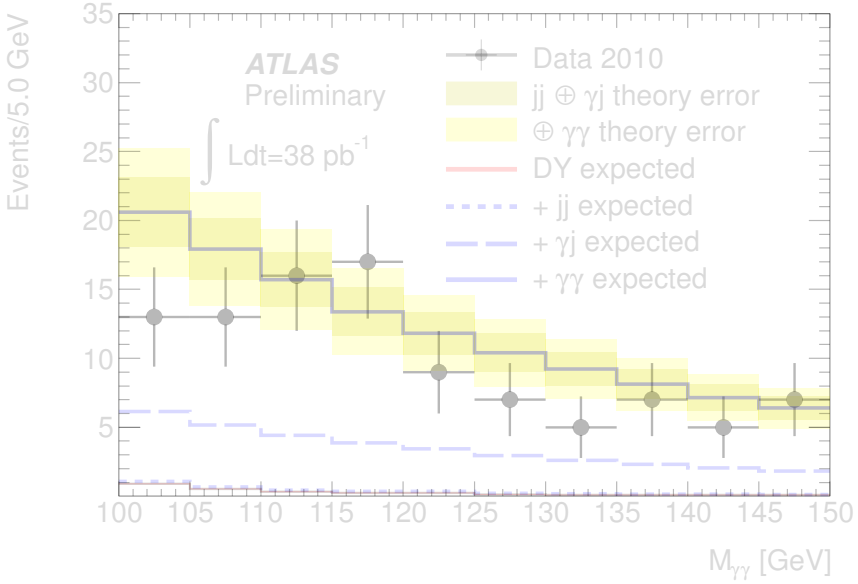
$H \rightarrow \gamma\gamma$

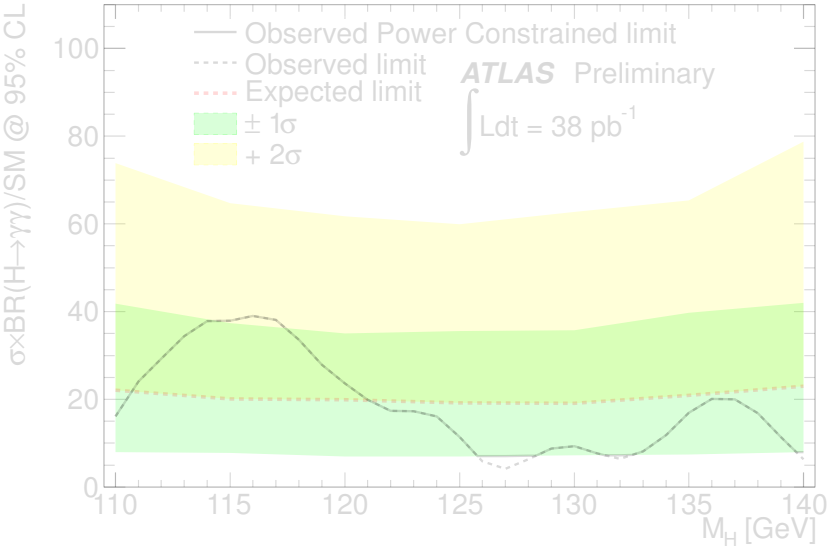
Event Yields

	Data	Exp. Bkg.
$N_{\gamma\gamma}$	$75.0 \pm 13.3^{+2.7}_{-3.6}$	86 ± 23
$N_{\gamma j} + N_{j\gamma}$	$19.6 \pm 7.5 \pm 3.9$	31 ± 15
N_{jj}	$1.5 \pm 0.7^{+1.8}_{-0.5}$	1 ± 1
N_{DY}	$2.9 \pm 0.1 \pm 0.6$	2.7 ± 0.2

Source	Uncertainty [%]
luminosity	± 3.4
cross section	$+20/-15$
photon ID	± 11
photon isolation	± 10
trigger	$+1.1/-3.7$
resolution	$\pm 13/\sigma_{M_{\gamma\gamma}}$

- discriminating observable: $M_{\gamma\gamma}$





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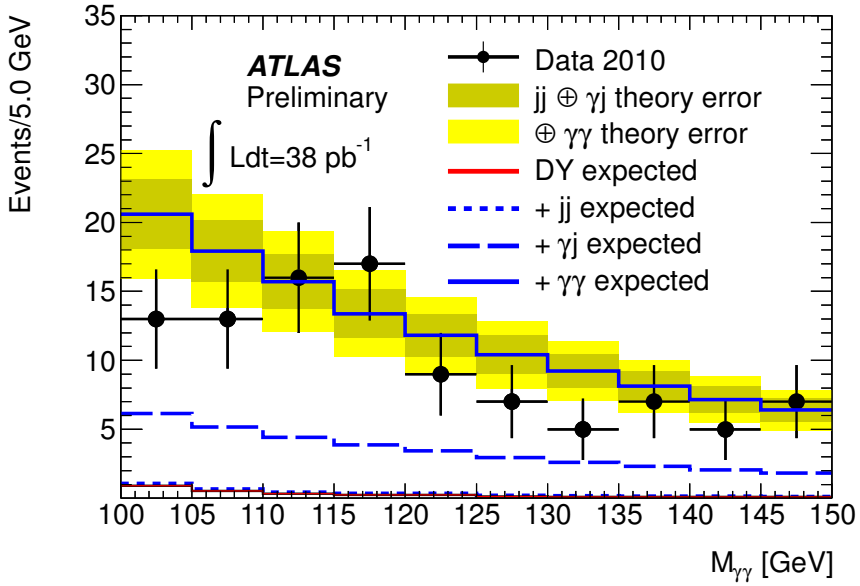
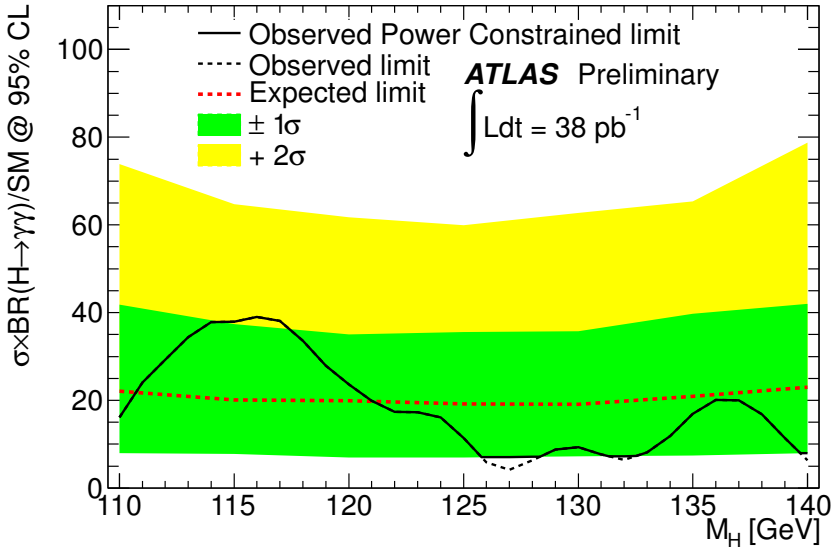


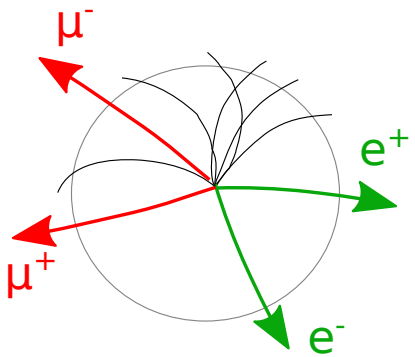


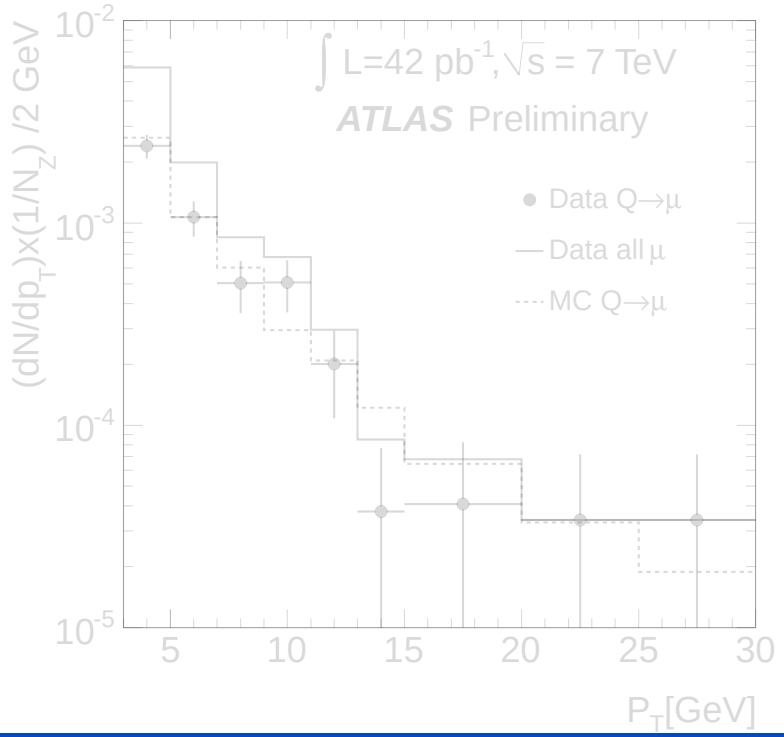
$H \longrightarrow ZZ \longrightarrow 4\ell$

Selection

- 4 isolated leptons
- $\mu^+\mu^-$ or e^+e^- pairs
- leading pair: $m_{\ell\ell}$ closest to m_Z
- 2nd pair: $m_{\ell\ell} > f(M_{4\ell})$

- very **clean signature**





- **background**
- $ZZ^{(*)}$

  from MC, normalisation **corrected with** $\mathbf{Z \longrightarrow \mu\mu}$ to reduce sys. uncertainties:
- ZQQ, $Q = c$ or b

  normalisation ($QQ \longrightarrow 2\ell$ fraction) from control regions
- for details see ATLAS-CONF-2011-048

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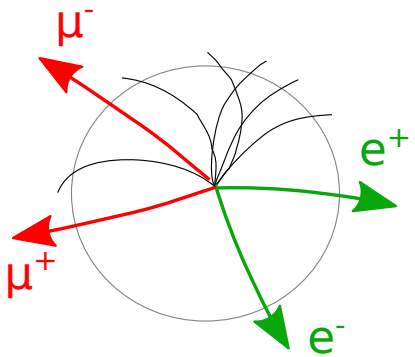

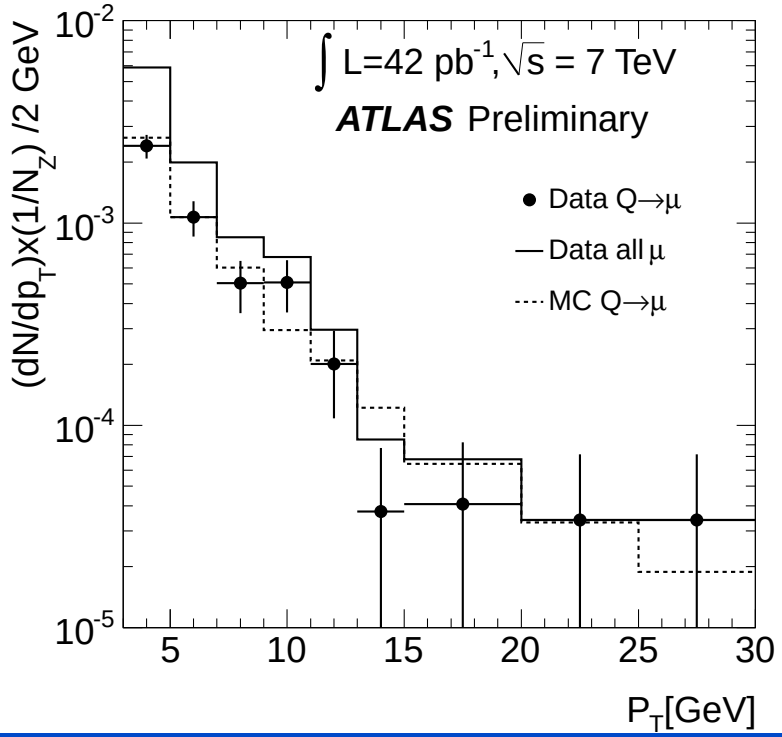

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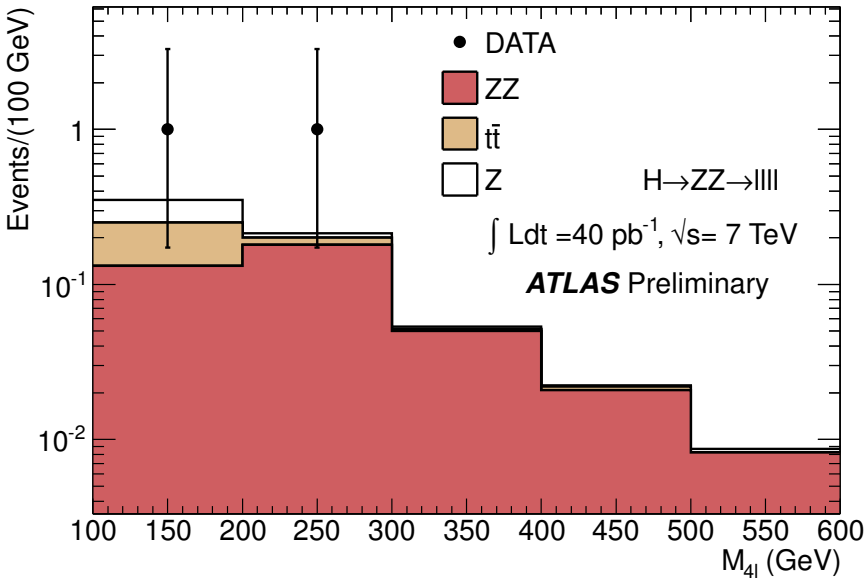
- **discriminating observable**: $M_{4\ell}$
- 0 events expected, 0 observed

Event Yields

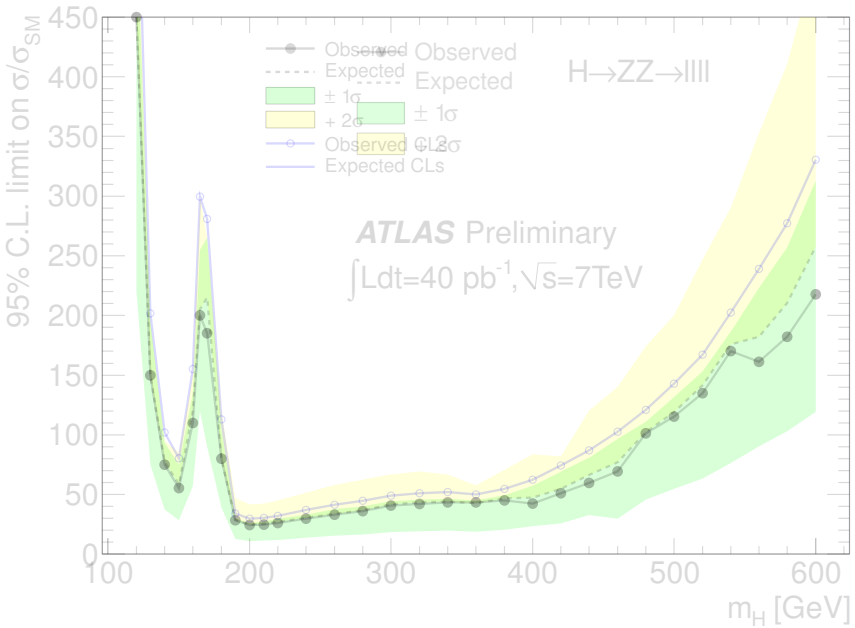
Exp. Signal[a]	Exp. Bkg.	Data
0.095 ± 0.017	0.41	0

[a] $m_H = 200\,\mathrm{GeV}$

- $M_{4\ell}$ after subset of cuts:



- best limit at $m_H = 200\,\mathrm{GeV}$ ($\sim 25 \times \sigma_{SM}$)



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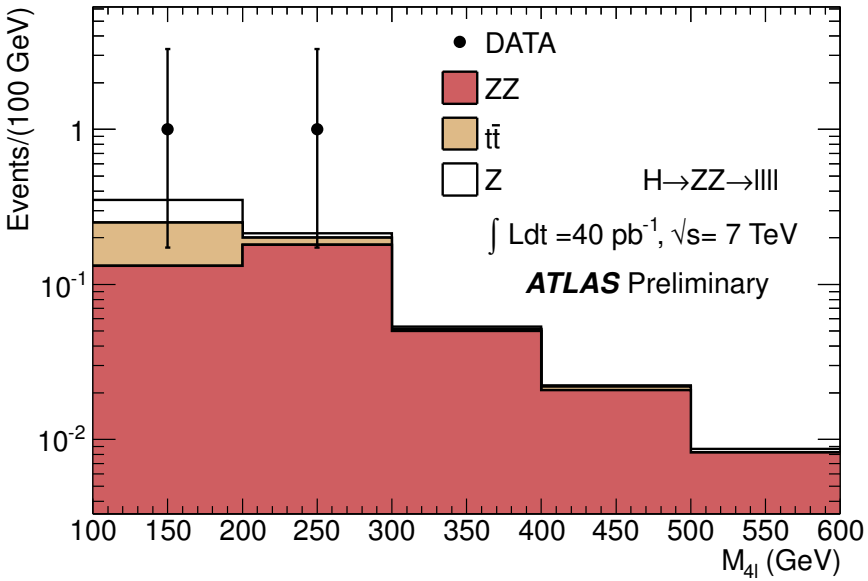

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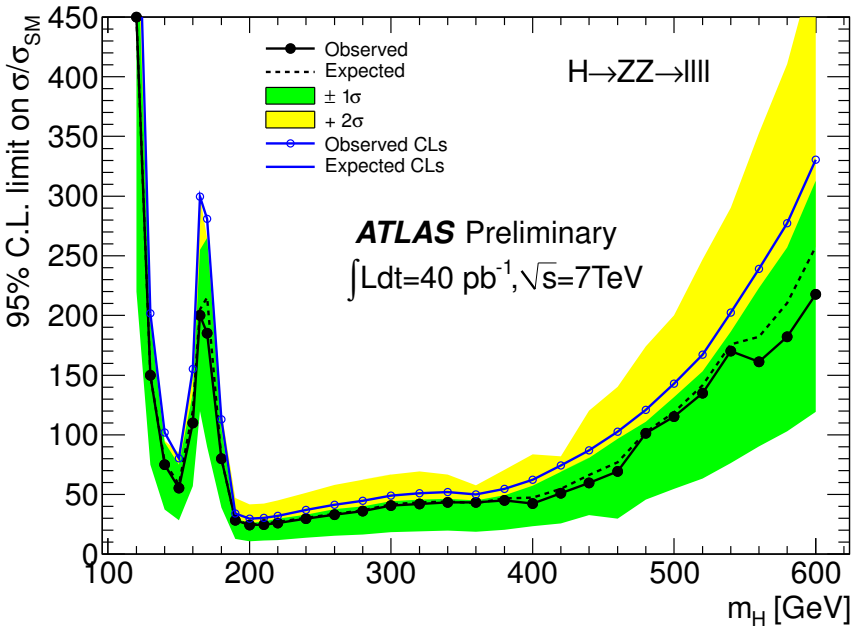

$H \rightarrow ZZ \rightarrow \ell^+\ell^-(q\bar{q}/\nu\bar{\nu})$

- **signal**: less clean than 4ℓ channel

  but factor of ~ 27 higher BR (12%/0.45%)

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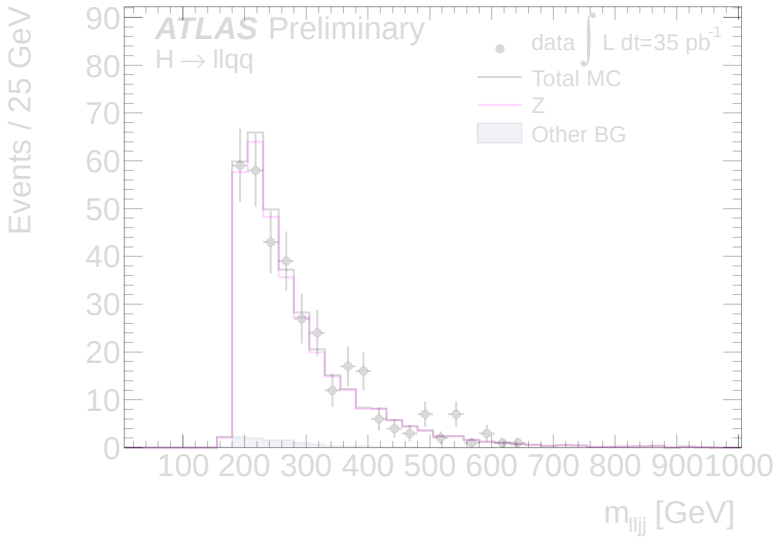
- **common**:
  - 2 isolated leptons, e^+e^- or $\mu^+\mu^-$
  - $m_{\ell\ell}$ close to m_Z
- $\ell\ell q\bar{q}$:
  - low E_T^{miss}
  - m_{jj} close to m_Z
  - small opening angle of leptons and jets in ϕ
- $\ell\ell\nu\bar{\nu}$:
  - large E_T^{miss}
  - b-jet veto

- **background**
  - ZZ, WZ from MC
  - **Z + jets** checked in jet-jet sidebands: m_{jj} above or below $Z - peak$
  - $t\bar{t}$: checked in $\ell\ell$ sidebands: $m_{\ell\ell}$ above or below $Z - peak$
  - QCD, control samples, ee: inverted electron ID, $\mu\mu$: same-sign; normalisation from fit to data

- Z+jets control sample



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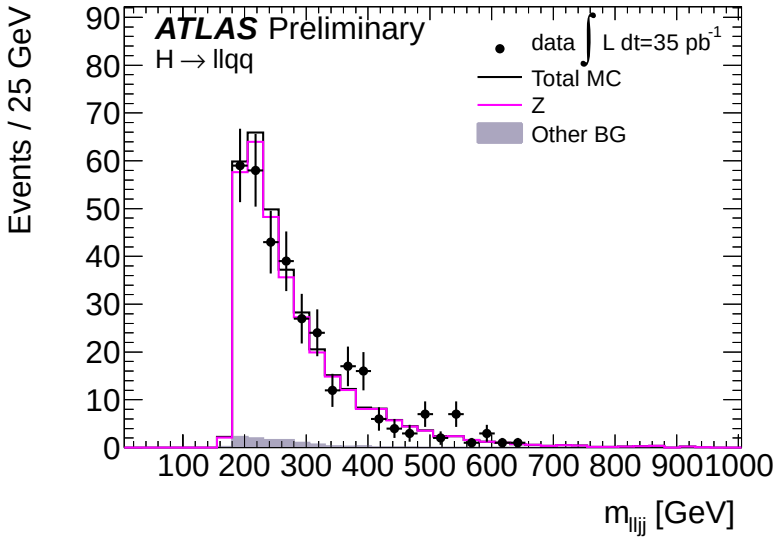
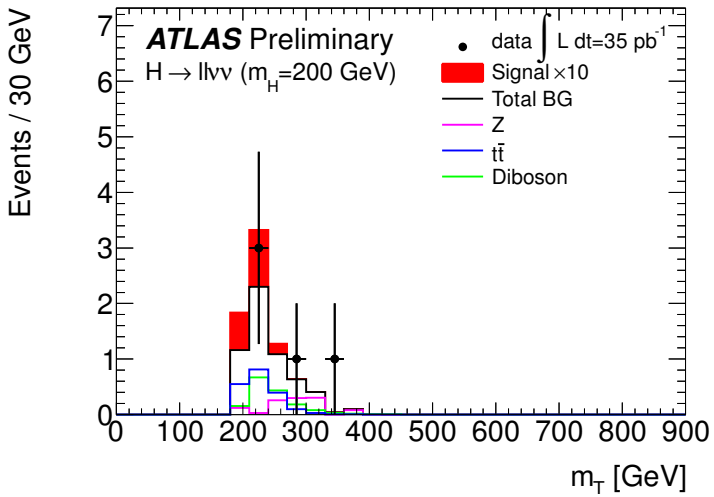


$H \to ZZ \to \ell^+\ell^-(q\bar{q}/\nu\bar{\nu})$

- discriminating observable $\ell\ell\nu\nu$: M_T [a]



[a] $M_T = \left[\sqrt{m_Z^2 + |\vec{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\text{miss}}|^2}\right]^2 - \left[\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}}\right]^2$

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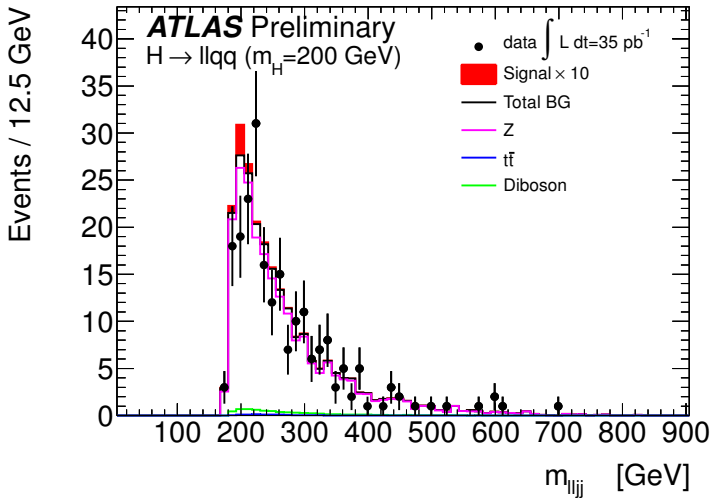

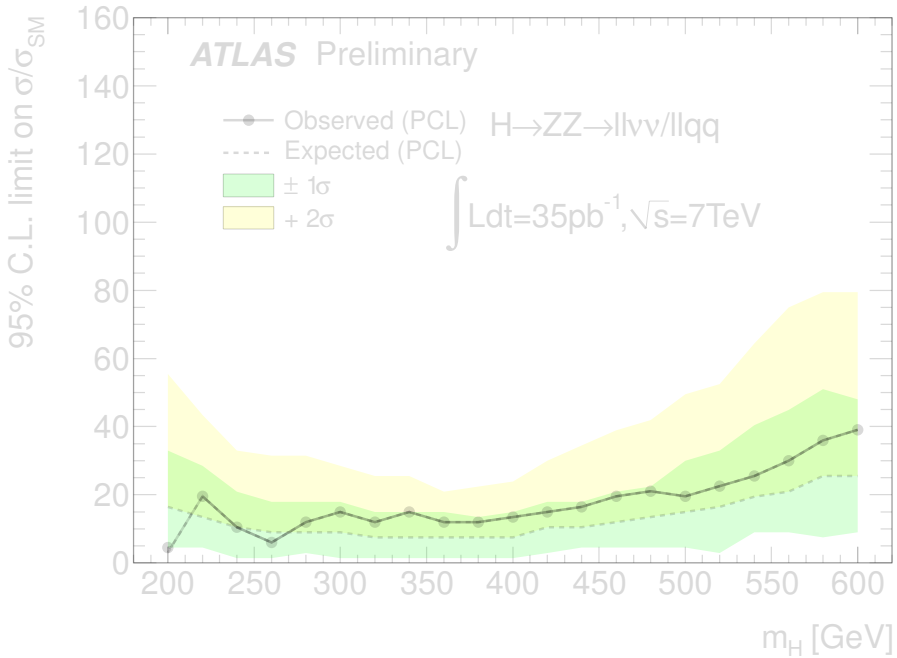

- most sensitive channel for large m_H

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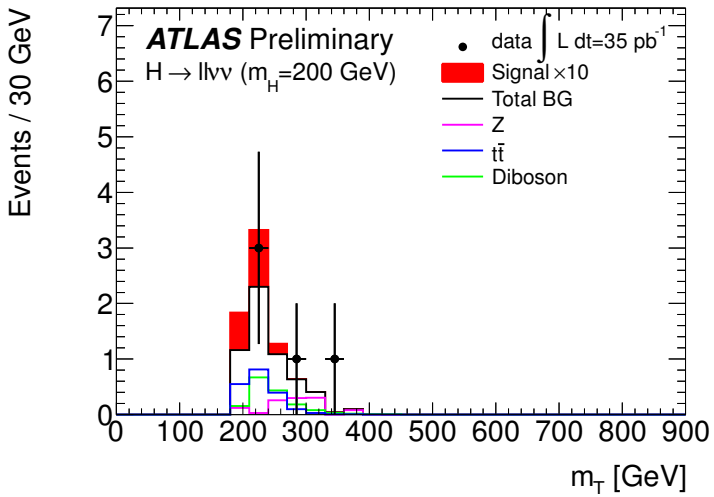

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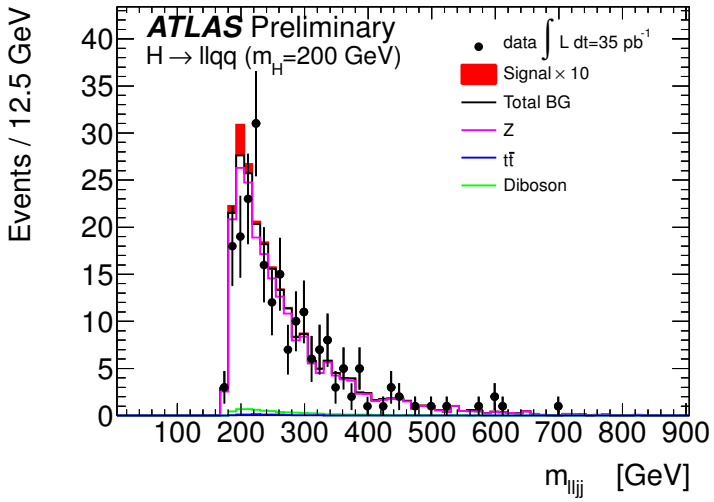

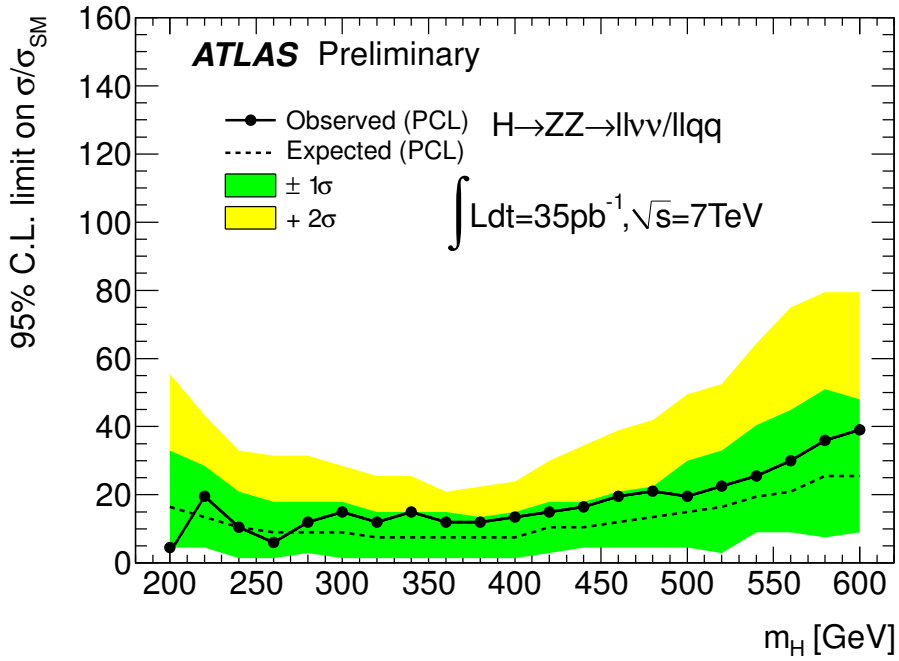

- most sensitive channel for large m_H

$H \to WW \to \ell\nu\ell\nu$

- $H \to WW$: **highest branching ratio** above $\sim 135\,\mathrm{GeV}$
- analysis optimised in **0-, 1- and 2-jet bins** (jet: $p_T > 25\,\mathrm{GeV}$, $|\eta| < 4.5$)
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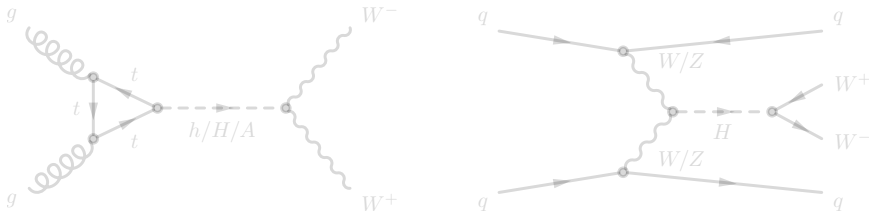

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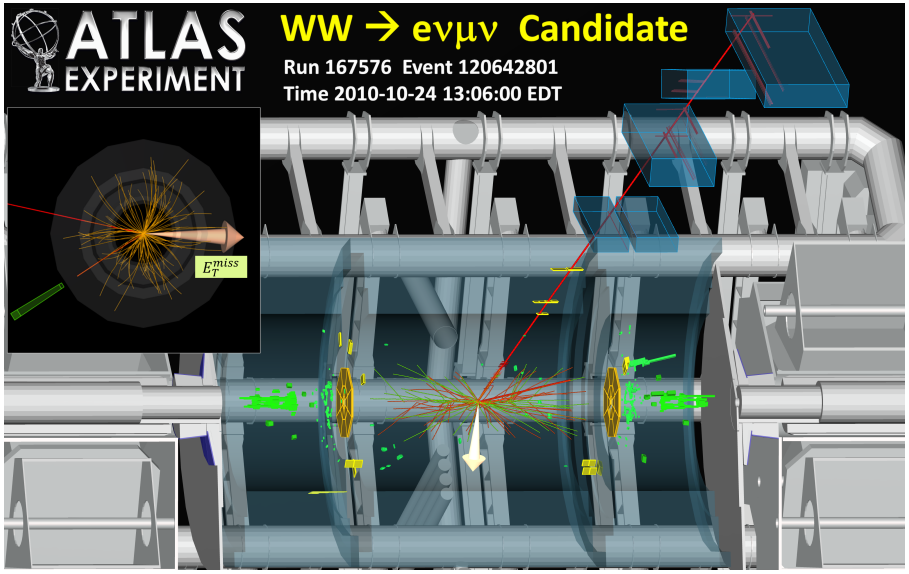
  - $WZ/ZZ/W\gamma$



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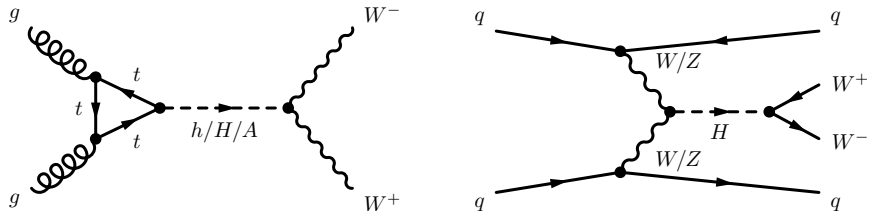

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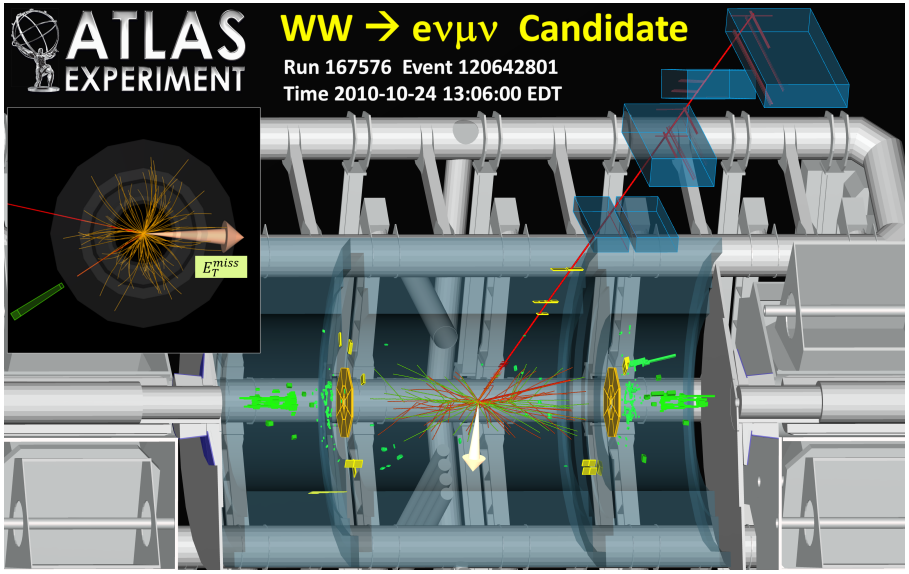

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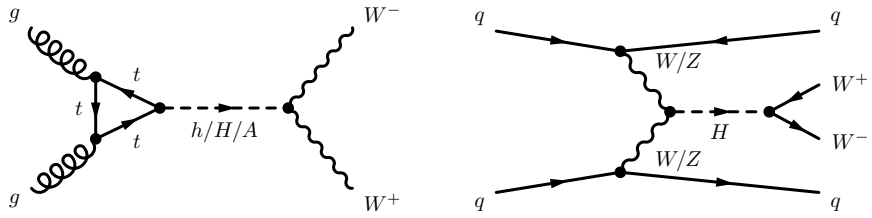

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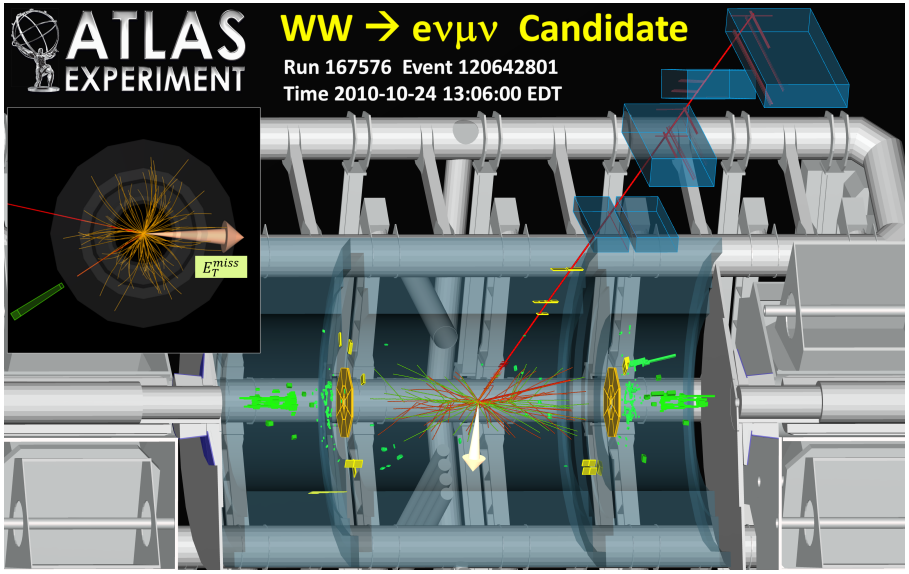

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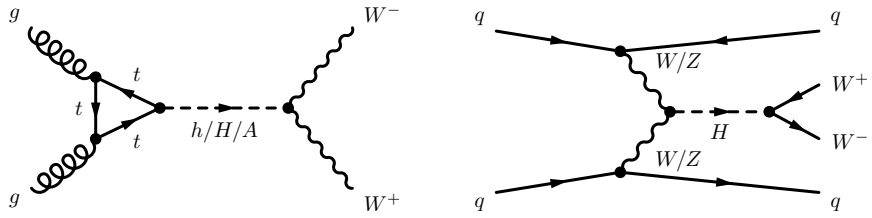

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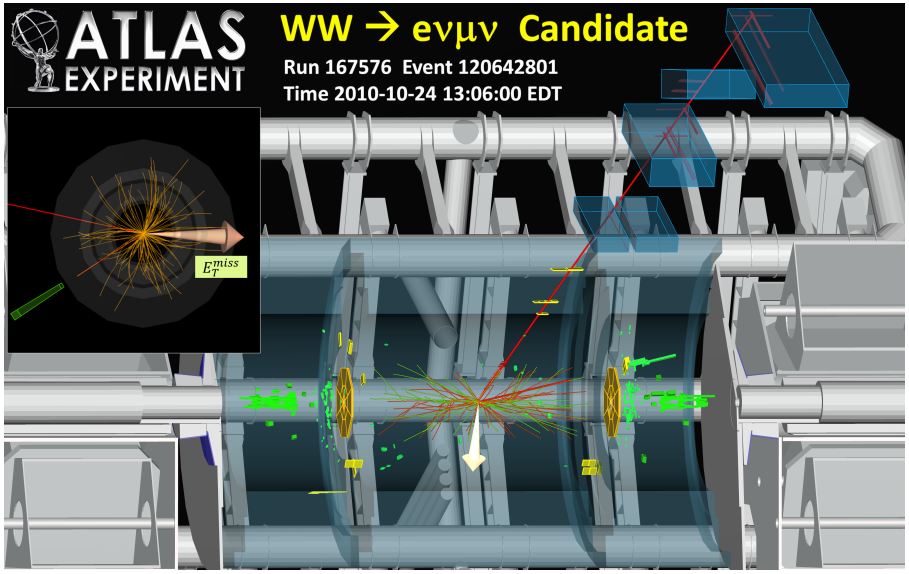

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- check all major backgrounds with **data**

- **estimation**
  - **WW**: shape from control sample with $m_{\ell\ell} > 80\,\mathrm{GeV}$
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    $$A_{MC}^{corr} = A_{MC} \frac{B_{data}}{D_{data}} \frac{D_{MC}}{B_{MC}}$$
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    lepton *fake prob.* from **jet-trigger** sample with small transverse mass

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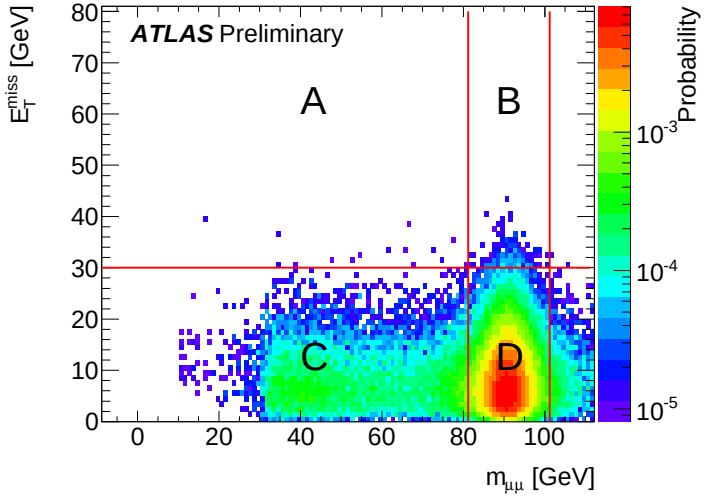

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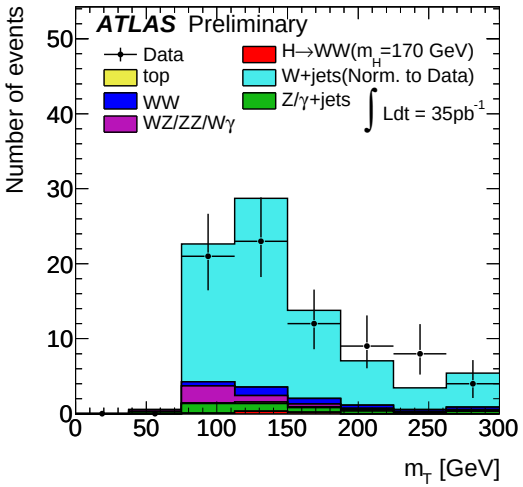

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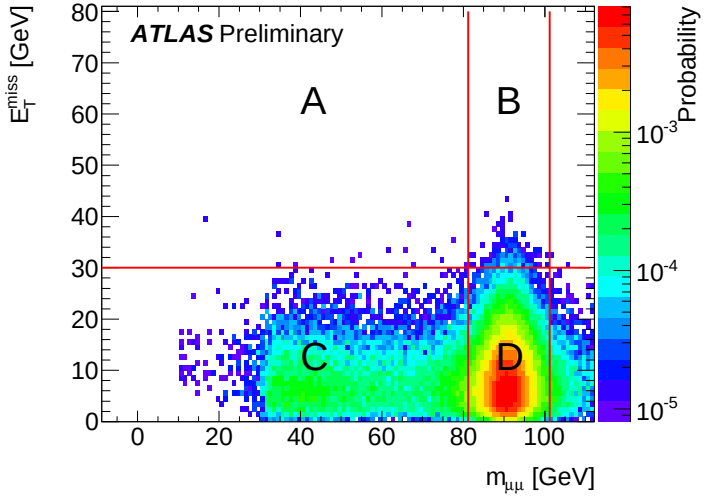

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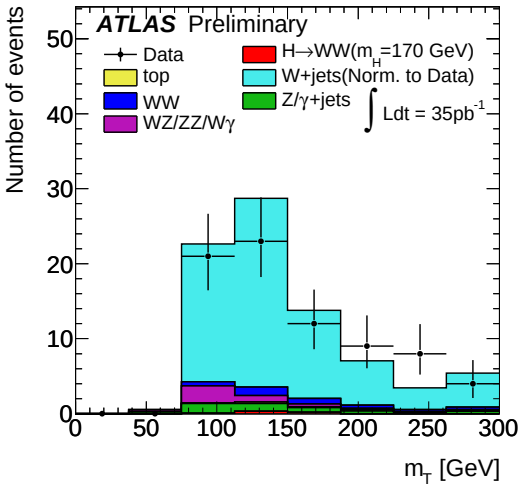

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- data compatible with bkg. exp.

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	exp. signal	exp. bkg.	data
0 jets	1.3 ± 0.4	1.7 ± 0.3	3
1 jet	0.6 ± 0.2	1.3 ± 0.5	1
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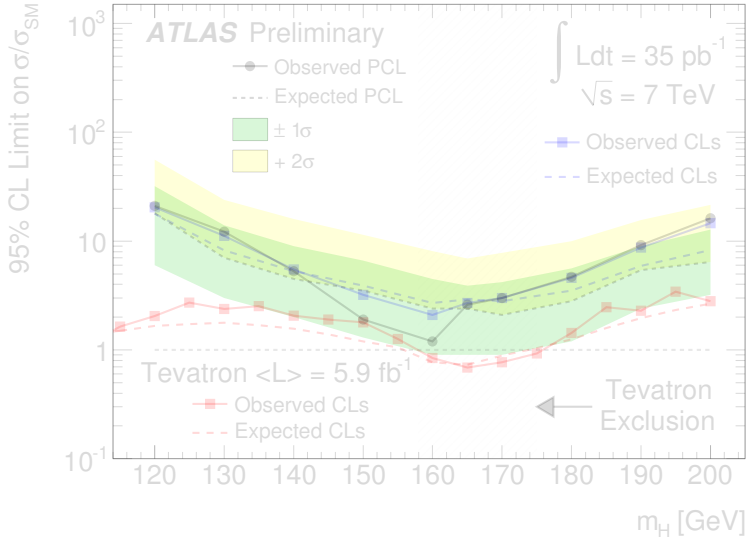
- excl. $2.1\sigma_{\text{SM}}$ @ $m_H = 170\,\text{GeV}$ (exp.)



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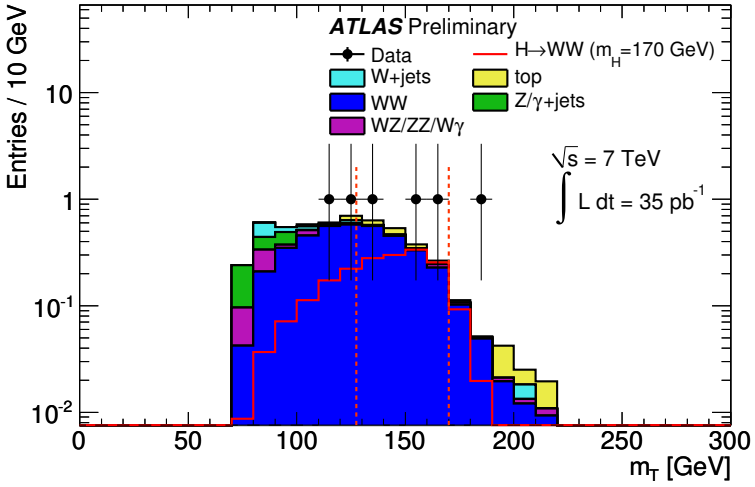

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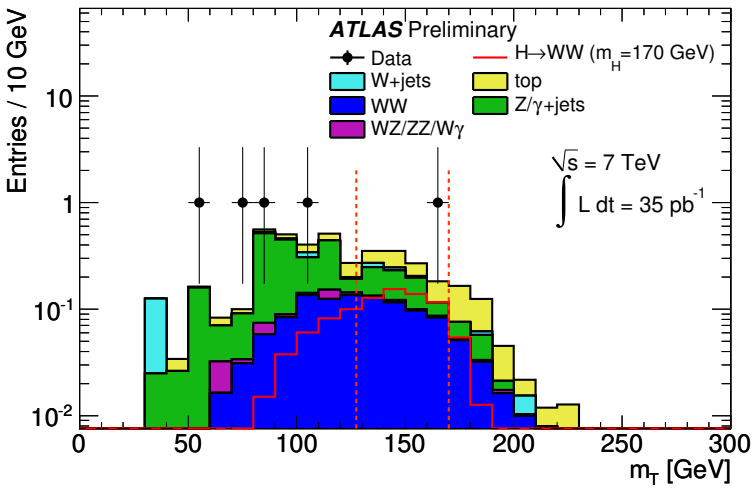

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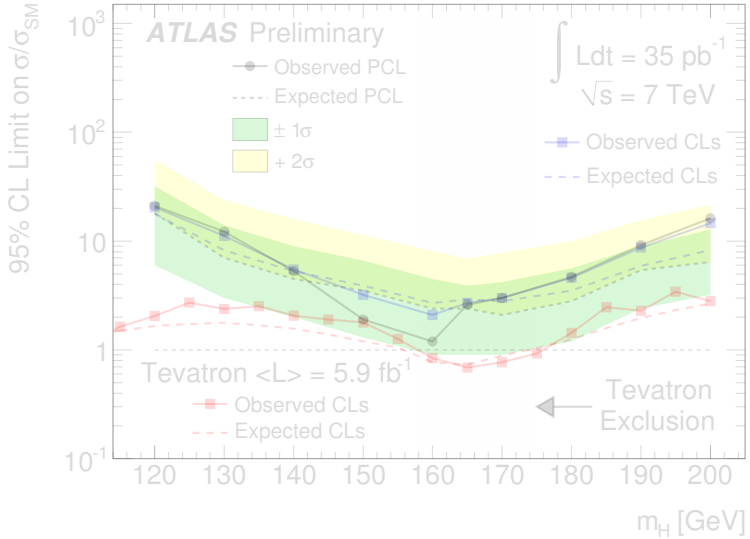

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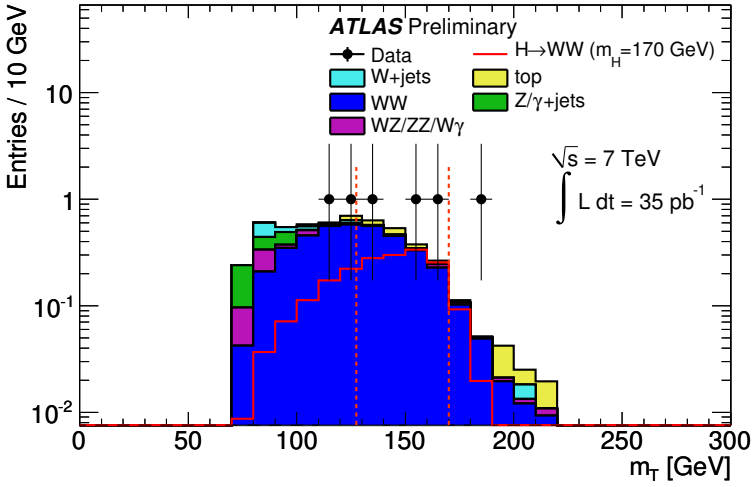

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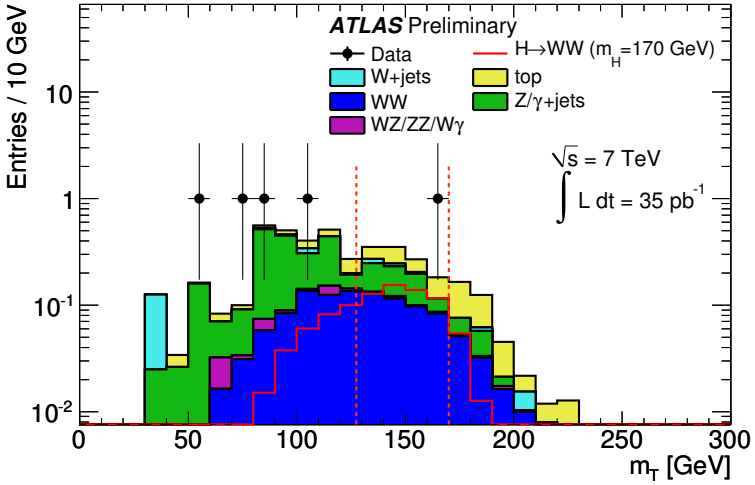

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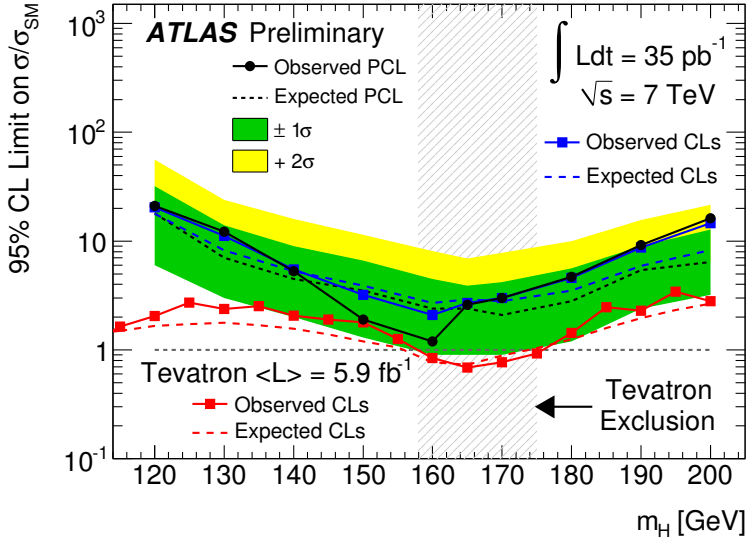

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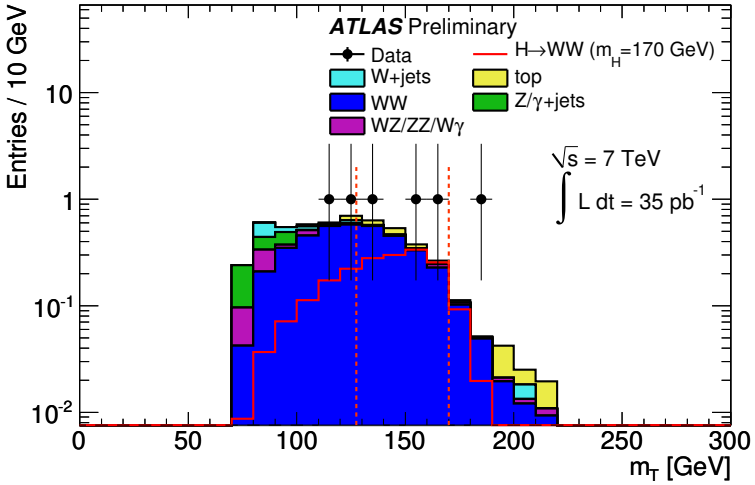

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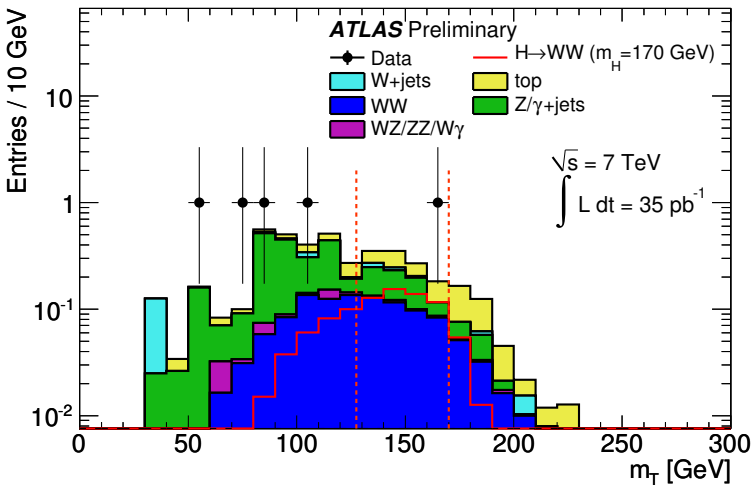

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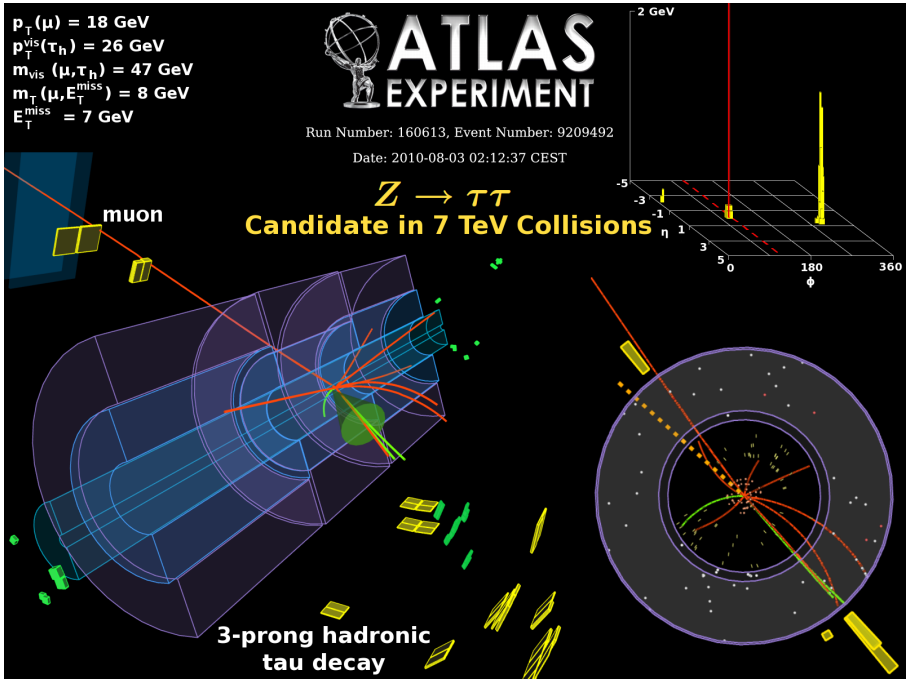

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- **Higgs sector in MSSM**

  3 neutral: h, H, A; 2 charged: $H^{\pm}$

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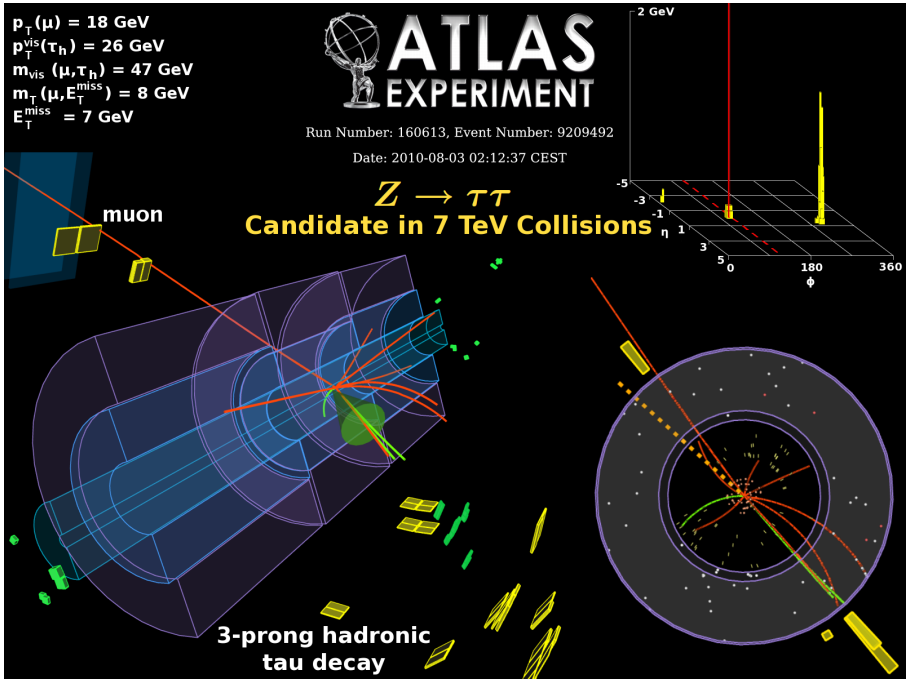

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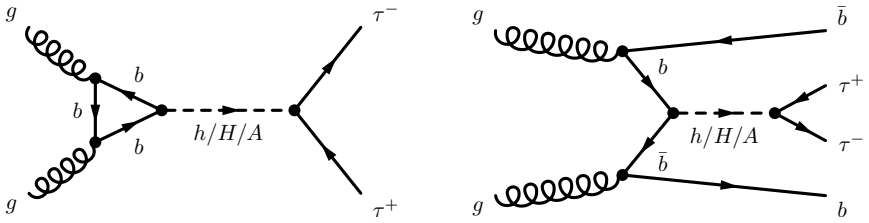

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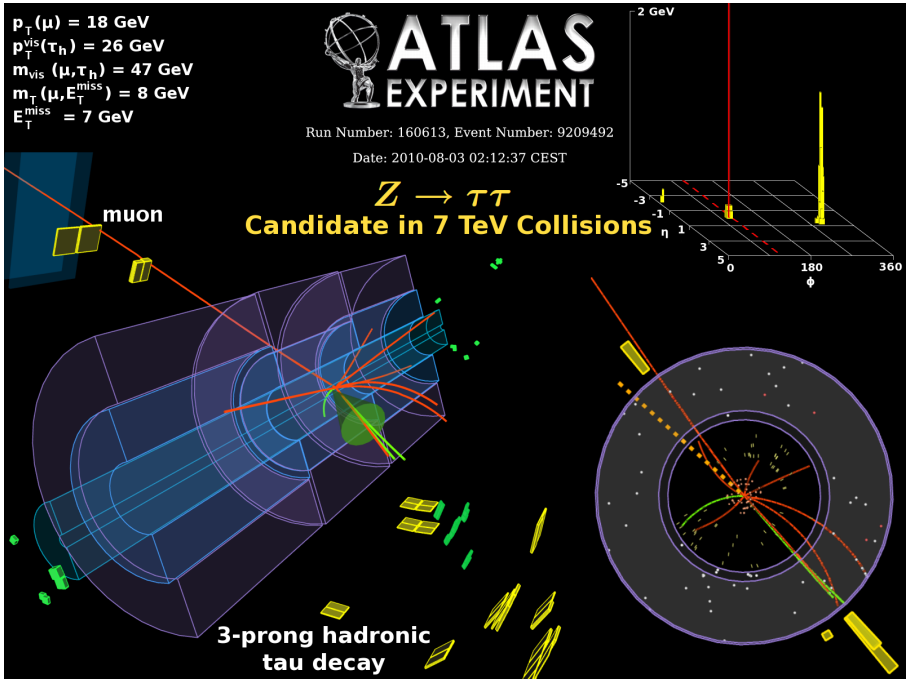

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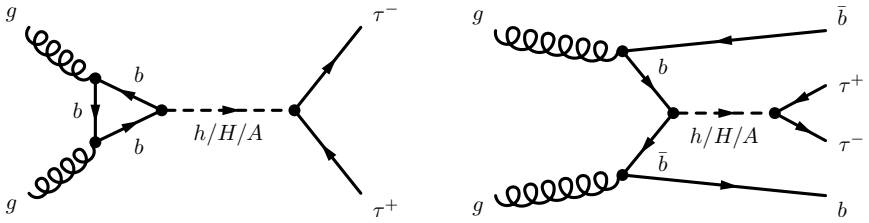

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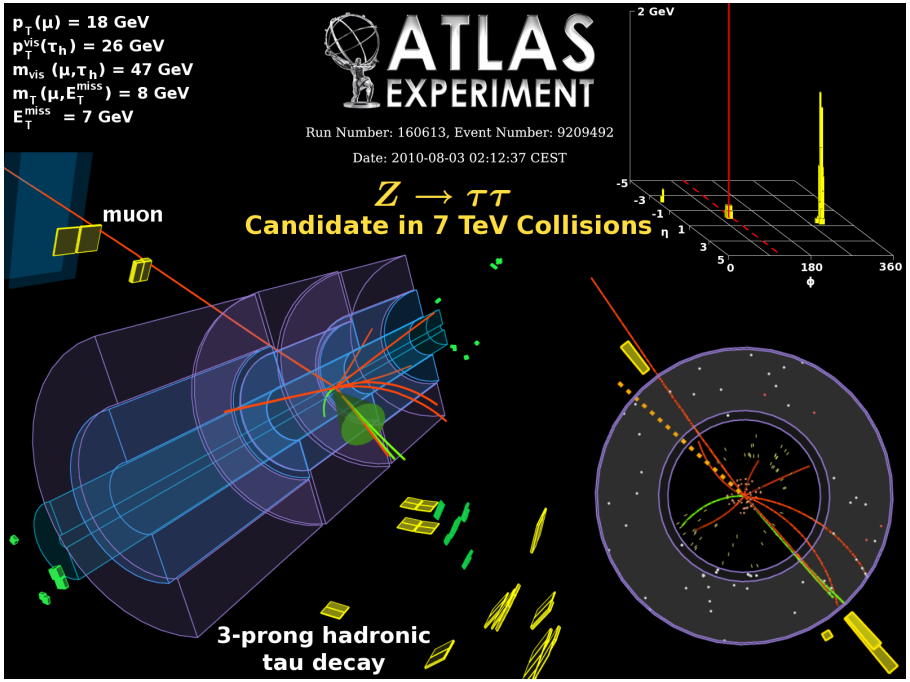

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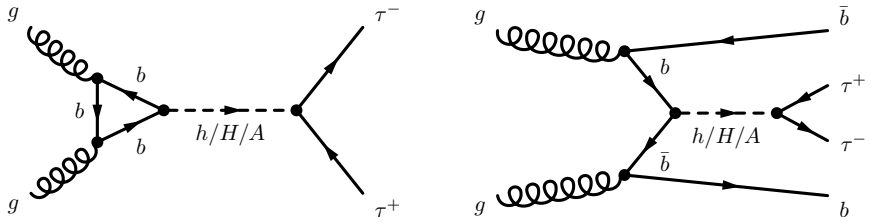

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$h/H/A \to \tau^+\tau^- \to \ell\tau_{had}3\nu$

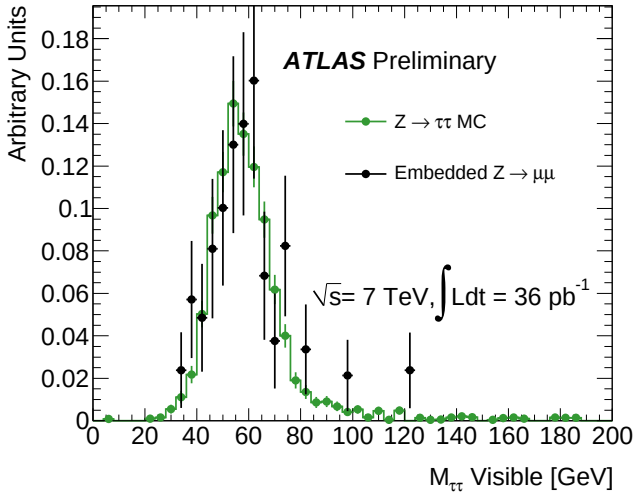
- mass shape ($M_{\tau\tau}^{vis}$) from data-driven methods
  - $Z \to \tau\tau$ checked with **embedding technique**: select $Z \to \mu\mu$ data and replace μs with simulated τs

    normalisation from theory
  - **W+jets and QCD**

    $M_{\tau\tau}^{vis}$ determined from same-sign (ss) events

    normalisation, N_{os}/N_{ss} from control-regions

- $M_{\tau\tau}^{vis}$ from embedded sample



- **systematic uncertainties**

	signal[a]	$Z \to \tau\tau$
jet/τ_{had} E scale	$+17\%/-14\%$	$+32\%/-21\%$
cross section	$10-20\%$	4%
total efficiency	24%	-

[a] $m_A = 120\,\mathrm{GeV}$

Event Yields

	exp. signal[a]	bkg. (MC)	data
e-channel	17.9 ± 0.5	70 ± 3	74
μ-channel	35.4 ± 0.8	137 ± 4	132

[a] $m_A = 120\,\mathrm{GeV}$, $\tan\beta = 40$

$h/H/A \to \tau^+\tau^- \to \ell\tau_{had}3\nu$

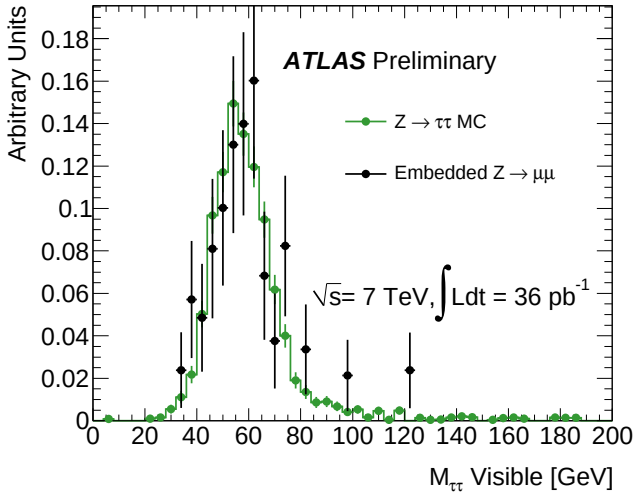
- mass shape ($M_{\tau\tau}^{vis}$) from data-driven methods
  - $Z \to \tau\tau$ checked with **embedding technique**: select $Z \to \mu\mu$ data and replace μs with simulated τs

    normalisation from theory
  - **W+jets and QCD**

    $M_{\tau\tau}^{vis}$ determined from same-sign (ss) events

    normalisation, N_{os}/N_{ss} from control-regions

- $M_{\tau\tau}^{vis}$ from embedded sample



- **systematic uncertainties**

	signal[a]	$Z \to \tau\tau$
jet/τ_{had} E scale	$+17\%/-14\%$	$+32\%/-21\%$
cross section	$10-20\%$	4%
total efficiency	24%	-

[a] $m_A = 120\,\mathrm{GeV}$

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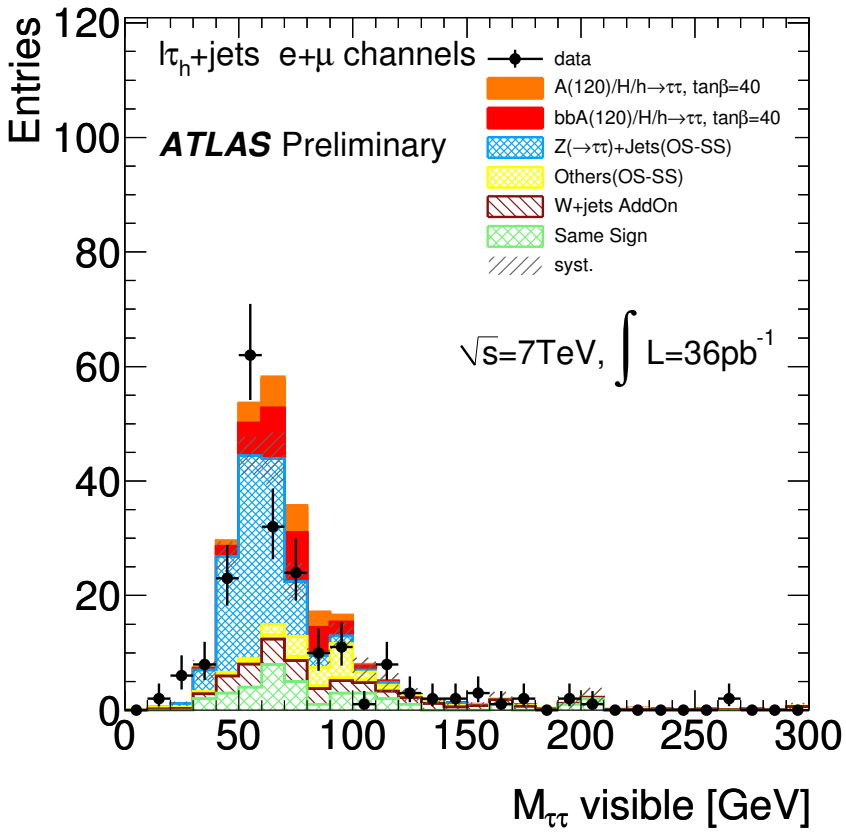
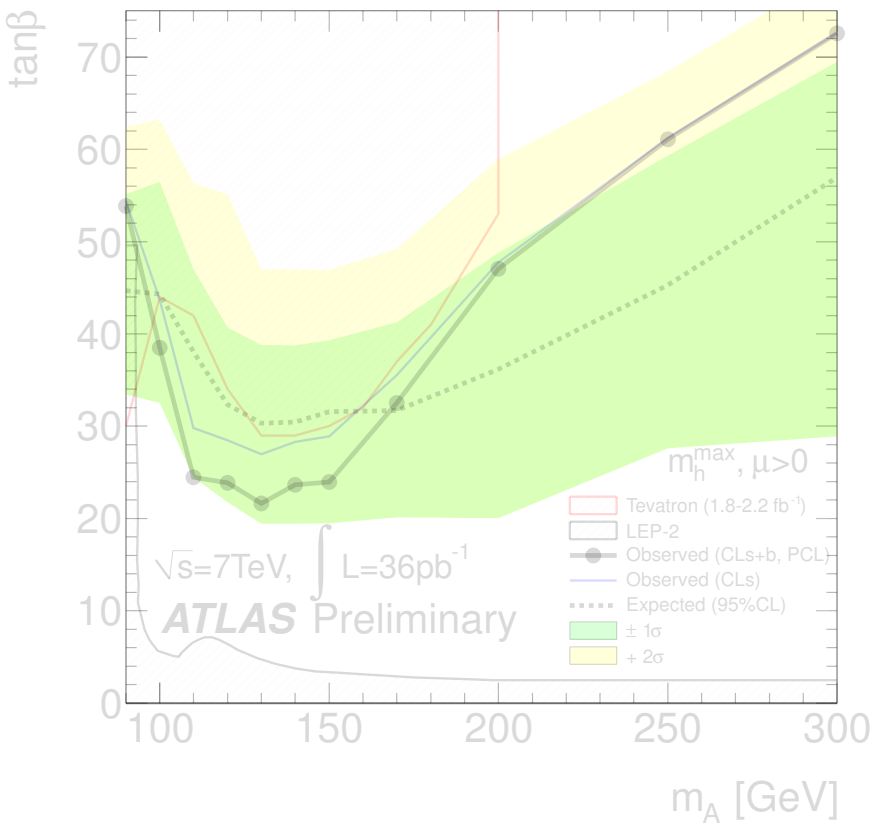
- **discriminating obs.**: $M_{\ell\tau_{had}}$ $(= M^{vis}_{\tau\tau})$



- **expands** Tevatron exclusion area



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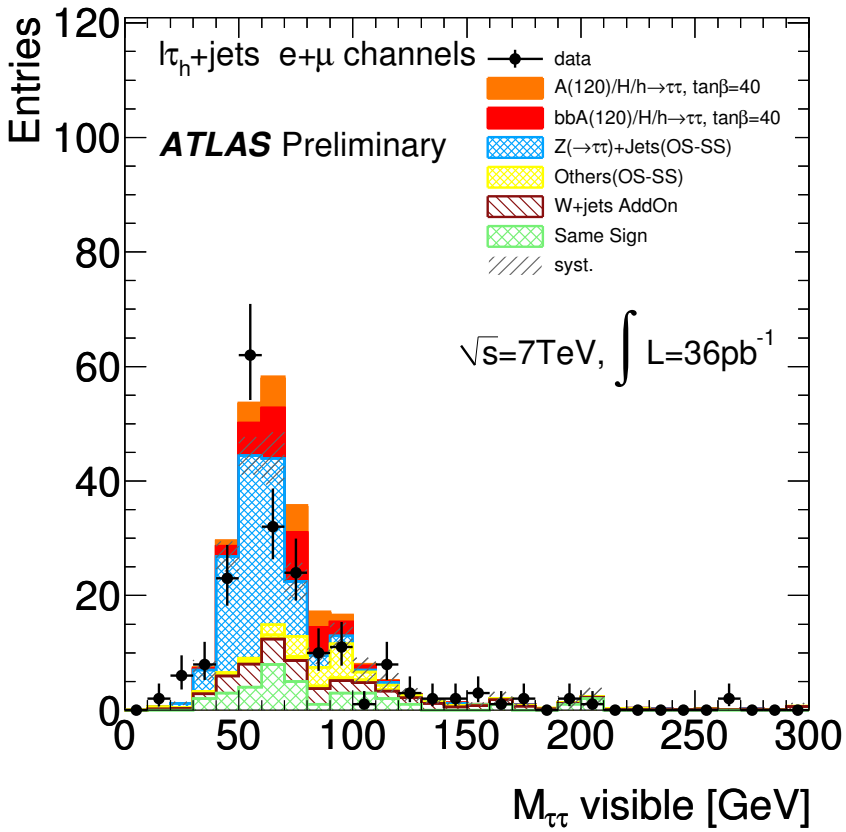

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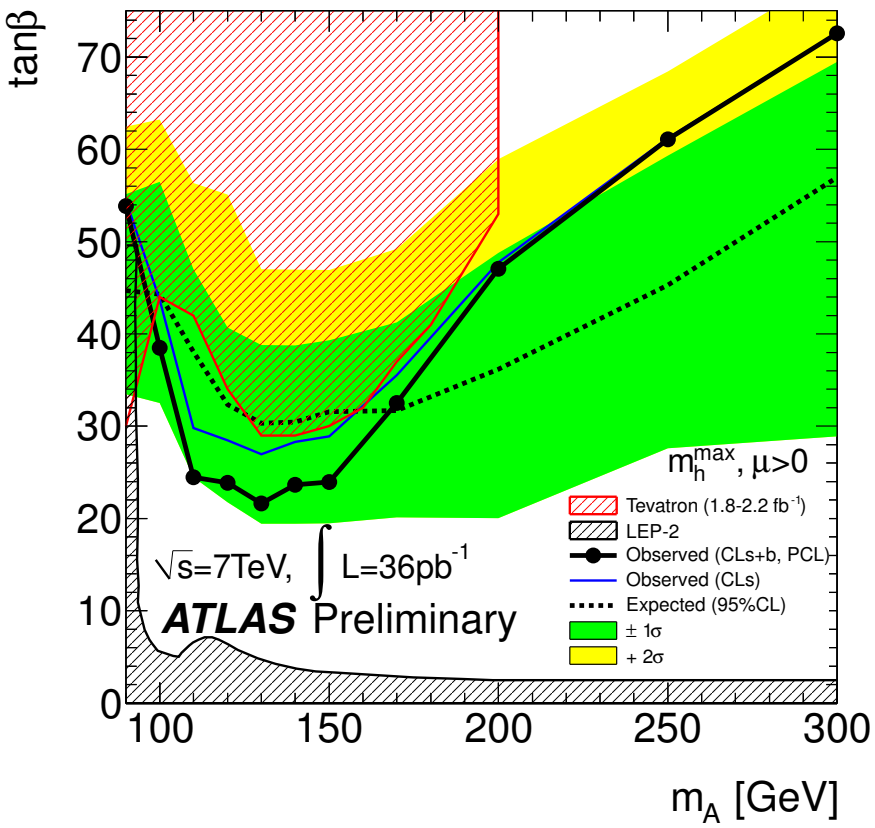


$a_1 \longrightarrow \mu\mu$

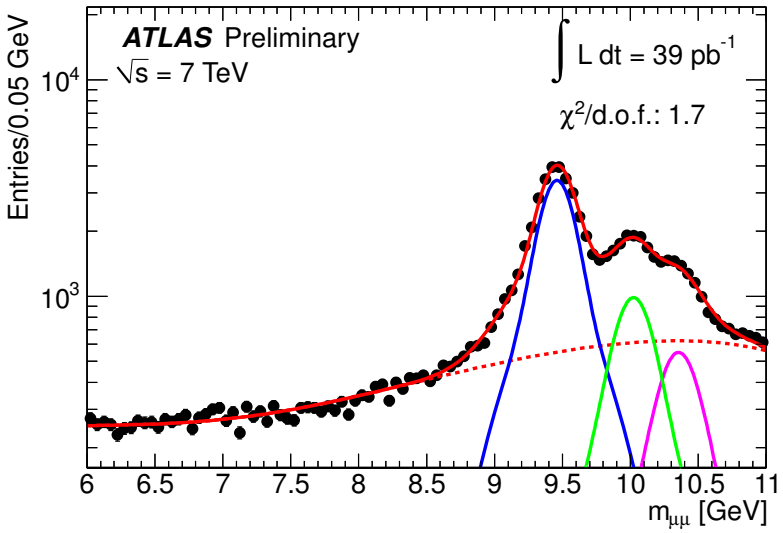
- inspired by **NMSSM**:
  search for a **low-mass scalar** a_1
- look for **resonance in** $M_{\mu\mu} = [6, 9]\,\mathrm{GeV}$ and $[11, 12]\,\mathrm{GeV}$

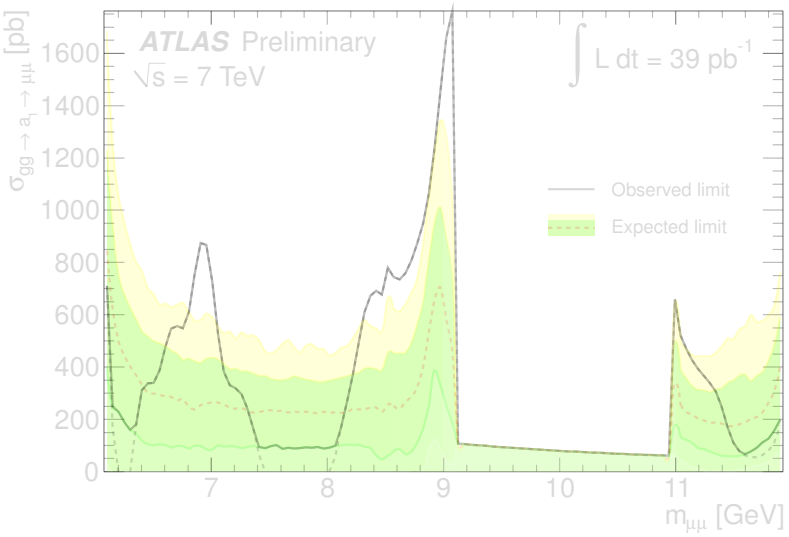
Selection

- 2 μ, opp. charge, $p_T > 4\,\mathrm{GeV}$
- likelihood ratio selection
  vertex χ^2/N_{dof}, $E_T^{\Delta R<0.2}(\mu)$

- likelihood PDFs directly from data

- $9 < M_{\mu\mu} < 11\,\mathrm{GeV}$:
  not considered in analysis due to **uncertainty** in Υ rate





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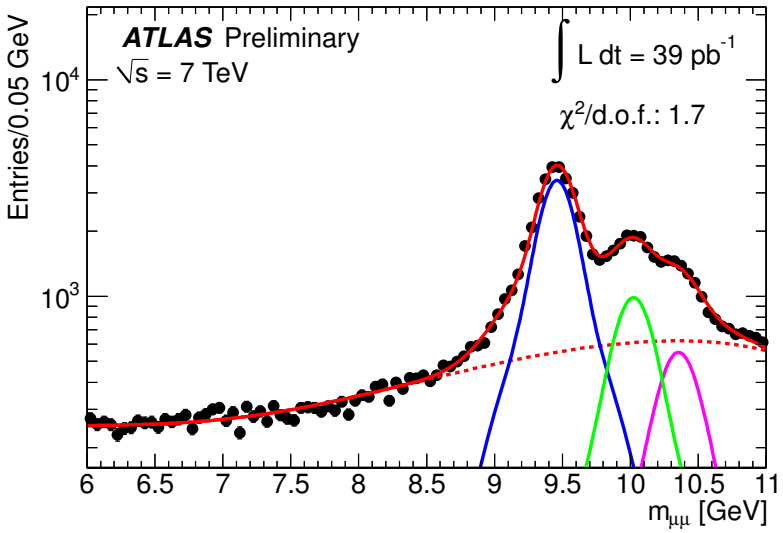

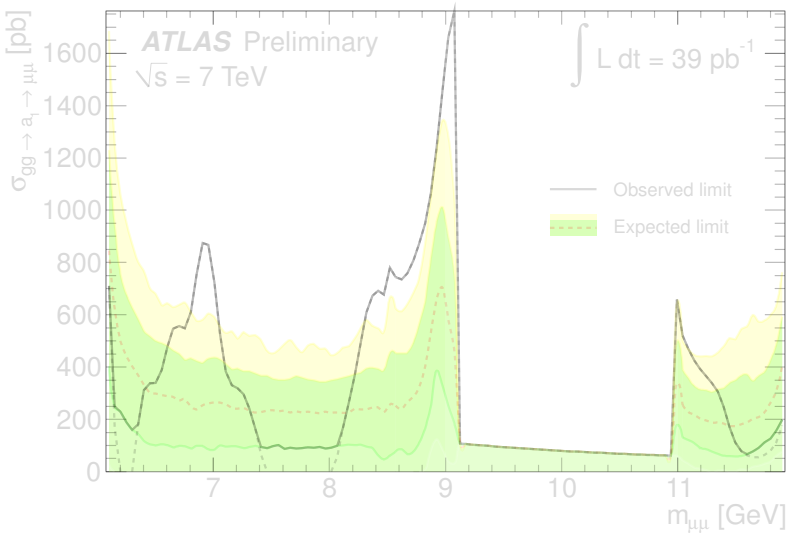

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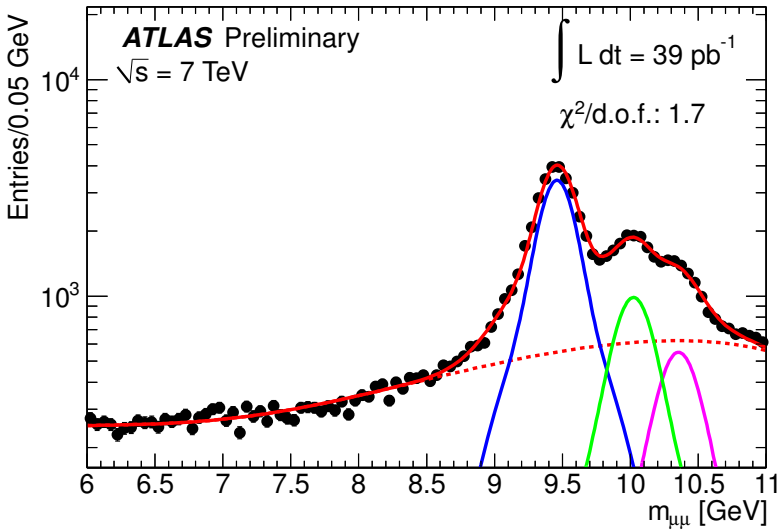
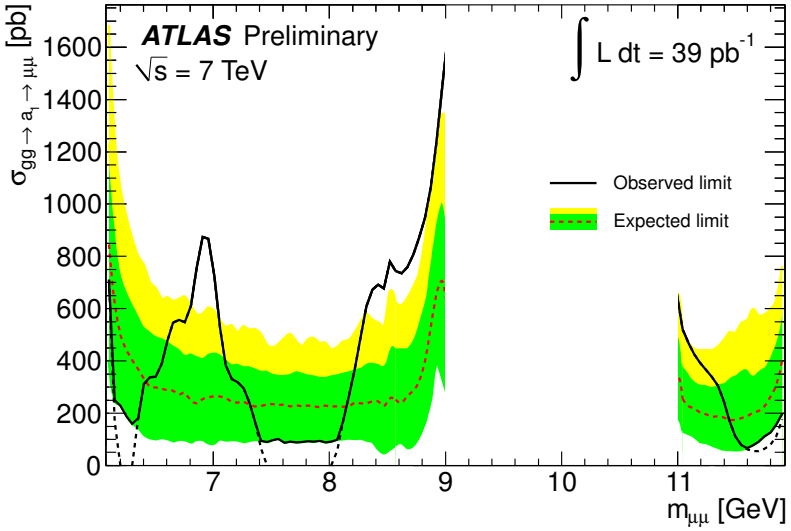
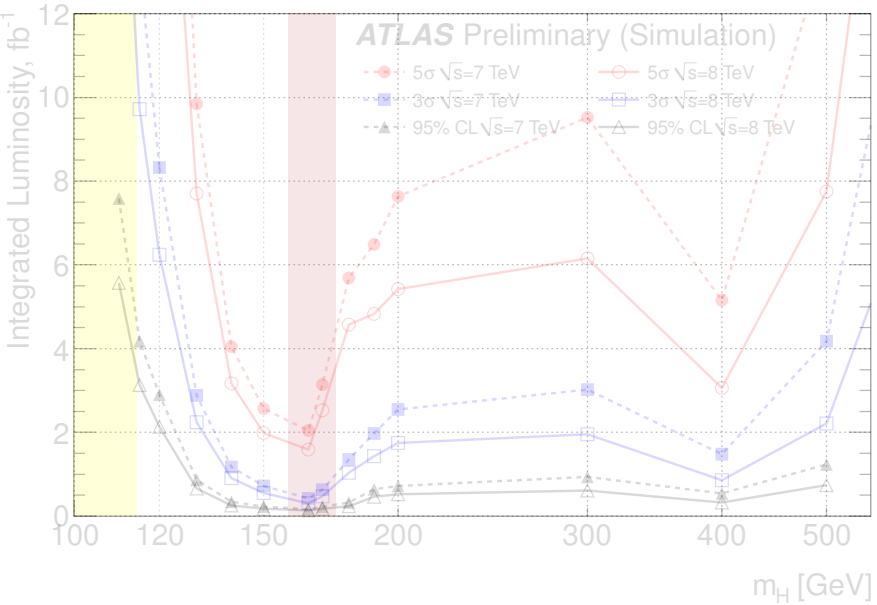




Summary

- analyses inclusive; **simple cut selections**
- estimate major **background from data**
- with first $\sim 45\,\mathrm{pb}^{-1}$:
  - $H \to WW$: **close to SM** cross section, $2.1\,\sigma_{\mathrm{SM}}$ (exp.)
  - $h/H/A \to \tau\tau$: **expanding excluded area** in m_A-$\tan\beta$ plane
- not covered here: search for $H^{\pm} \to \tau\nu$ in $t\bar{t}$ events
- 2011: recorded 60% of data in 2010!
- projection: exclude Higgs masses down to LEP limit with $\lesssim 4\,\mathrm{fb}^{-1}$ ...



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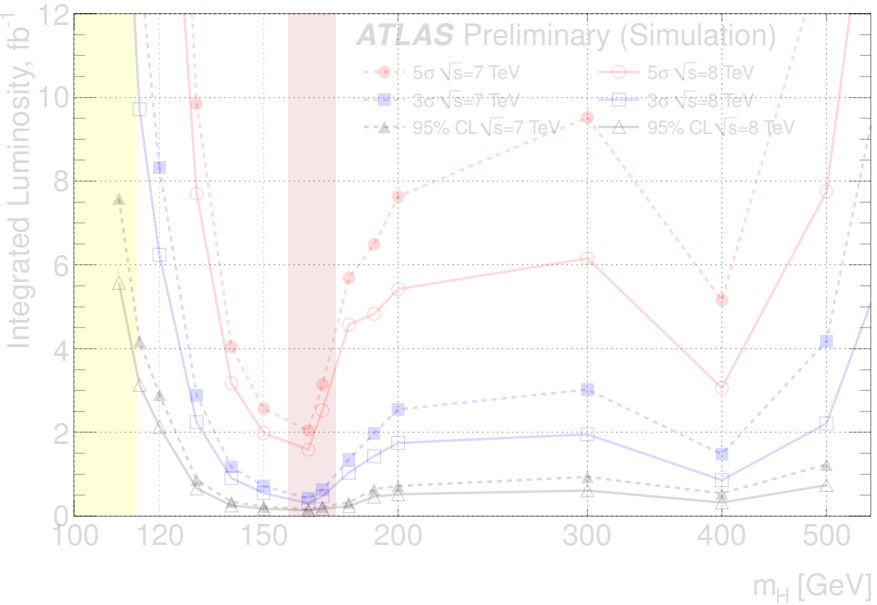

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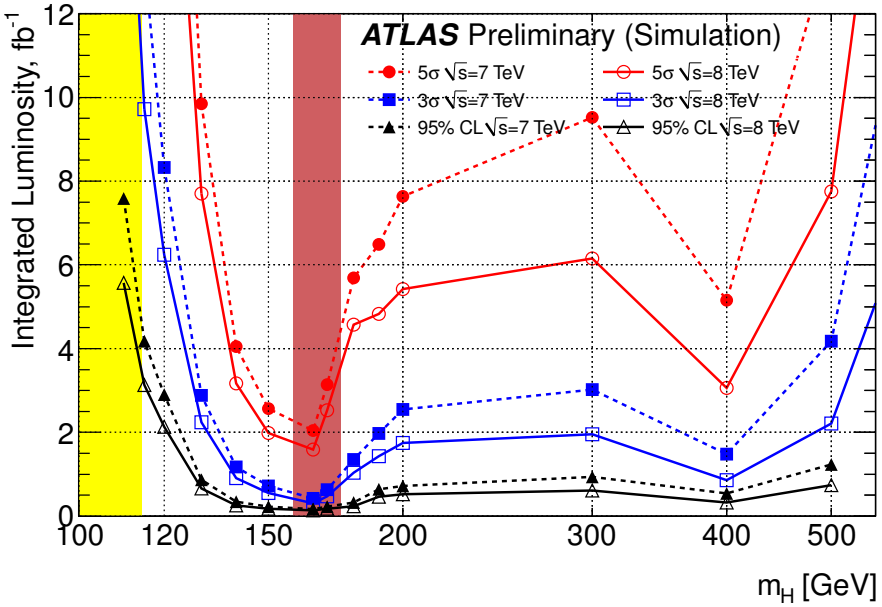

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Documentation

- **Standard Model**

$H \to \gamma\gamma$	ATLAS-CONF-2011-025
$H \to WW \to \ell\ell\nu\nu$	ATLAS-CONF-2011-005
$H \to ZZ \to \ell\ell(\nu\nu/qq)$	ATLAS-CONF-2011-026
$H \to ZZ \to 4\ell$	ATLAS-CONF-2011-048

- **MSSM**

$h/H/A \to \tau\tau \to \ell\tau_{\text{had}}3\nu$	ATLAS-CONF-2011-024
$H^{\pm} \to \tau\nu$ in $t\bar{t}$	ATLAS-CONF-2011-018
	ATLAS-CONF-2011-051

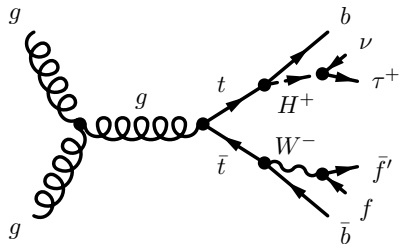
- **NMSSM**

$a_1 \to \mu\mu$	ATLAS-CONF-2011-020

BACKUP

$H^{\pm} \rightarrow \tau\nu$ in $t\bar{t}$ (to be included if enough time)

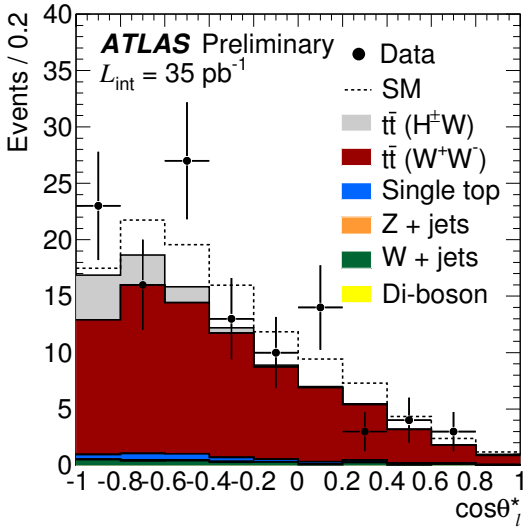
- **MSSM**: 2 charged Higgs bosons, $H^{\pm}$
- can appear in top decays ($t \rightarrow H^{+}b$) if $\mathbf{m_{H^+} < m_t}$

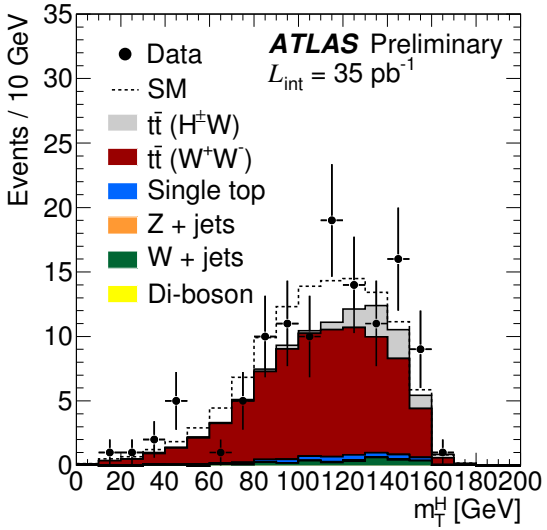


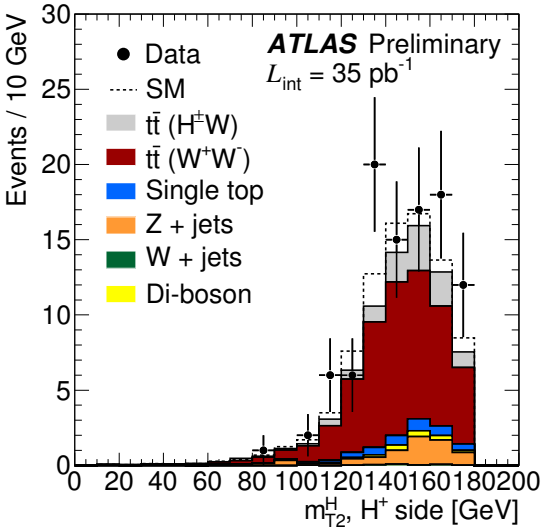
Discriminating Variables

- $\cos\theta^*_\ell = 4p^b \cdot p^\ell/(m_t^2 - m_W^2) - 1$
- $(m_T^H)^2 = \left(\sqrt{m_t^2 + (\vec{p}_T^{\,\ell} + \vec{p}_T^{\,b} + \vec{p}_T^{\,\text{miss}})^2} - p_T^b\right)^2 - \left(\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\text{miss}}\right)^2$
- $m_{T2}^H = \max_{\{\text{constraints}\}}[m_T^H(\vec{p}_T^{\,H^+})]$

- discr. observables **validated** with data







$H^{\pm} \longrightarrow \tau\nu$ in $t\bar{t}$ (to be included if enough time)

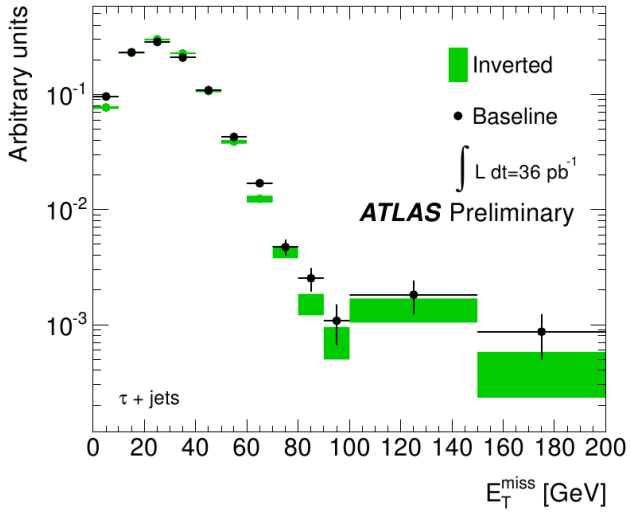
- **background** from data: (hadronic τ decays)
  - true τ_{had}s
    embedding method (cf. $h/H/A \longrightarrow \tau\tau$)
  - $\ell \longrightarrow \tau_{\text{had}}$ fakes
    tag-and-probe with in $Z \longrightarrow \ell\ell$
  - jet $\longrightarrow \tau_{\text{had}}$ fakes (quark dominated)
    tag-and-probe with in $\gamma +$ jet events
  - QCD jets (gluon dominated)
    select τ_{had} candidates failing tight ID; fit E_T^{miss} shape to data

Event Yield

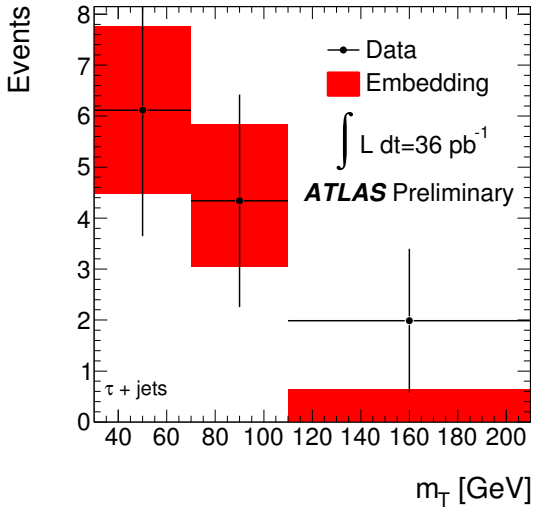
	τ+jets channel	τ+lepton channel
true τ_{had}	$4.7 \pm 1.3^{+1.4}_{-1.1}$	$6.9 \pm 0.3 \pm 1.4$
jet $\longrightarrow \tau_{\text{had}}$ fakes	$1.2 \pm 0.2 \pm 0.2$	$7.9 \pm 1.1 \pm 1.6$
$e \longrightarrow \tau_{\text{had}}$ fakes	$0.7 \pm 0.0 \pm 0.3$	$0.65 \pm 0.01 \pm 0.04$
QCD	$11.3 \pm 3.7 \pm 1.7$	-
$\sum$	$18 \pm 5 \pm 4$	$15.5 \pm 1.4 \pm 3.0$
data	17	11

- data in agreement with estimated background

- E_T^{miss} shape from QCD control sample



- M_T from embedding technique

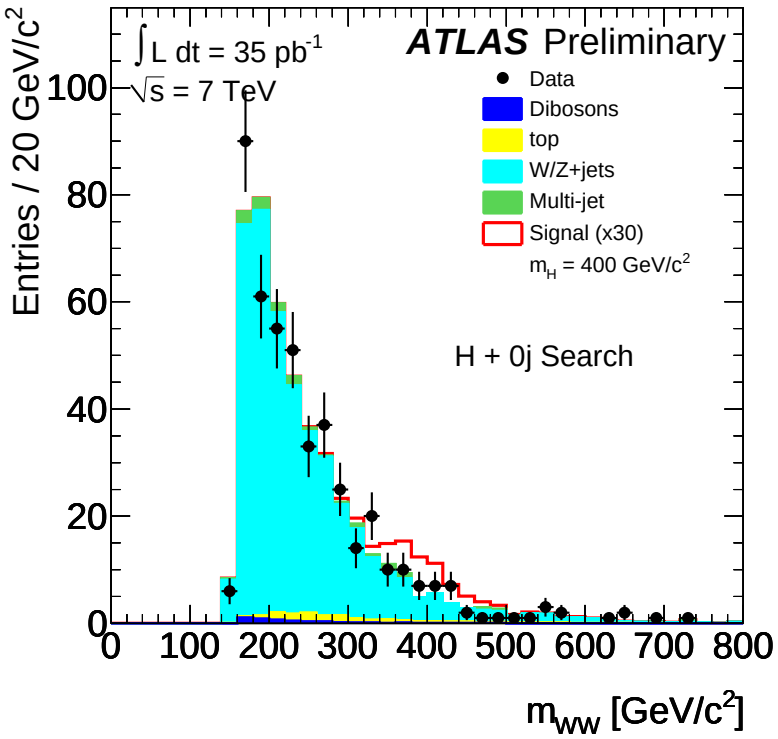


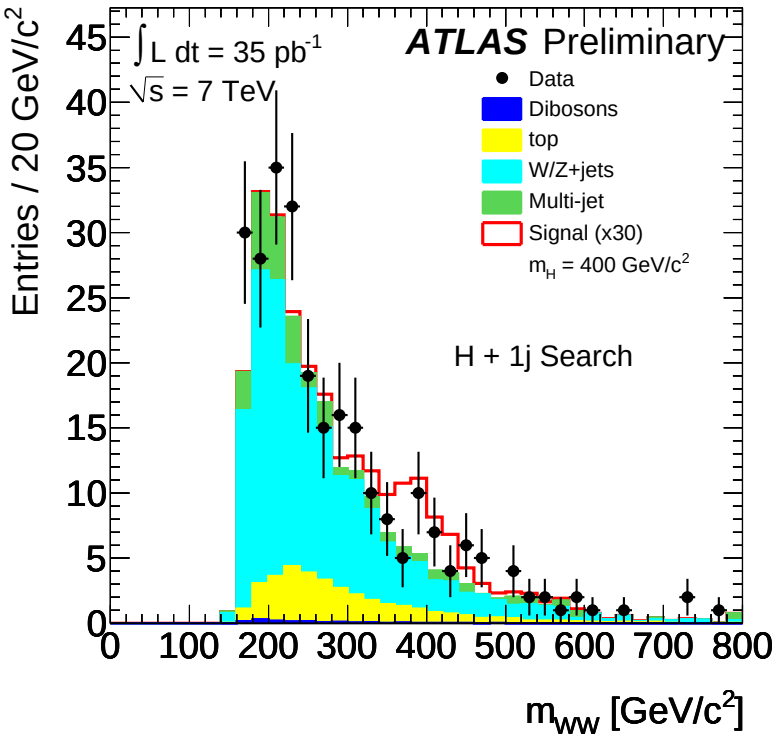
$H \rightarrow WW \rightarrow \ell\nu qq$

- **discriminating observable**: $M_{\ell\nu qq}$
- can be reconstructed with $M_{\ell\nu} = M_W$
- **background**:
  dominant: W/Z+jets
  multi-jet, top, diboson

Selection

- 1 isolated lepton
- 2(3) jets, 2 with m_{jj} close to m_W
- E_T^{miss}
- b-jet veto





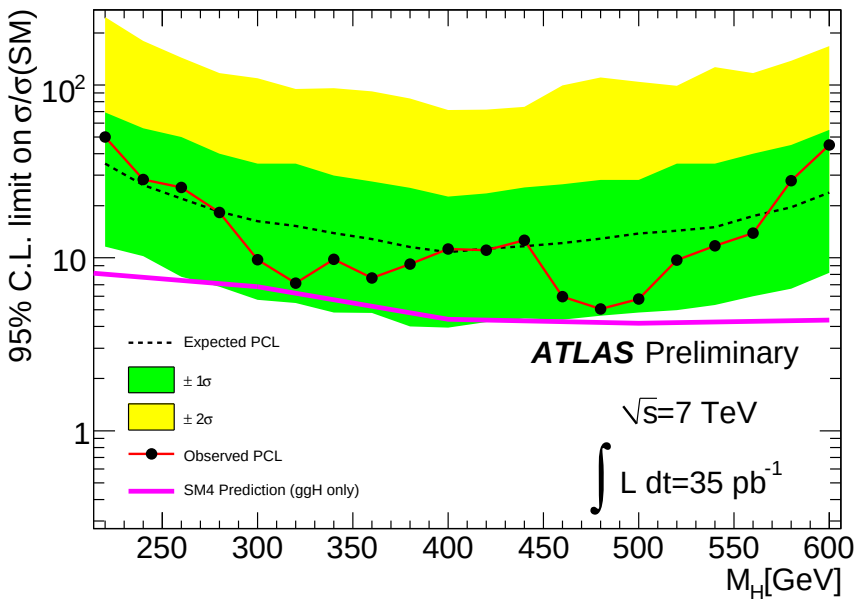
$H \rightarrow WW \rightarrow \ell\nu qq$

Event Yields (combined)	
exp. signal[a]	2.1 ± 0.7
exp. bkg.	674 ± 45.7
data	713

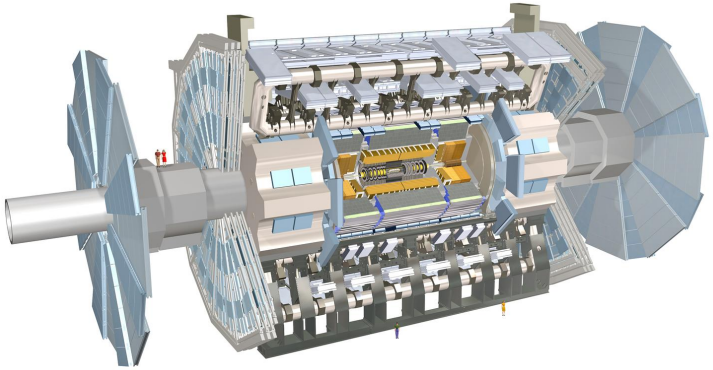
[a] $m_H = 400\,\mathrm{GeV}$

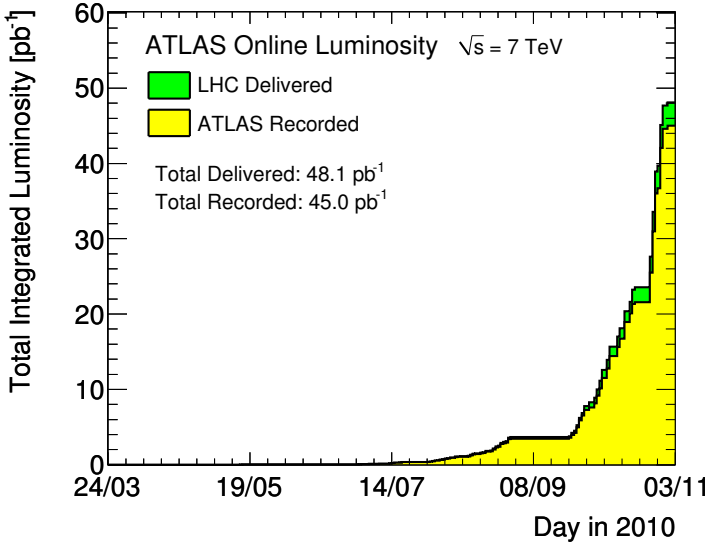
- sys. uncertainties on signal:

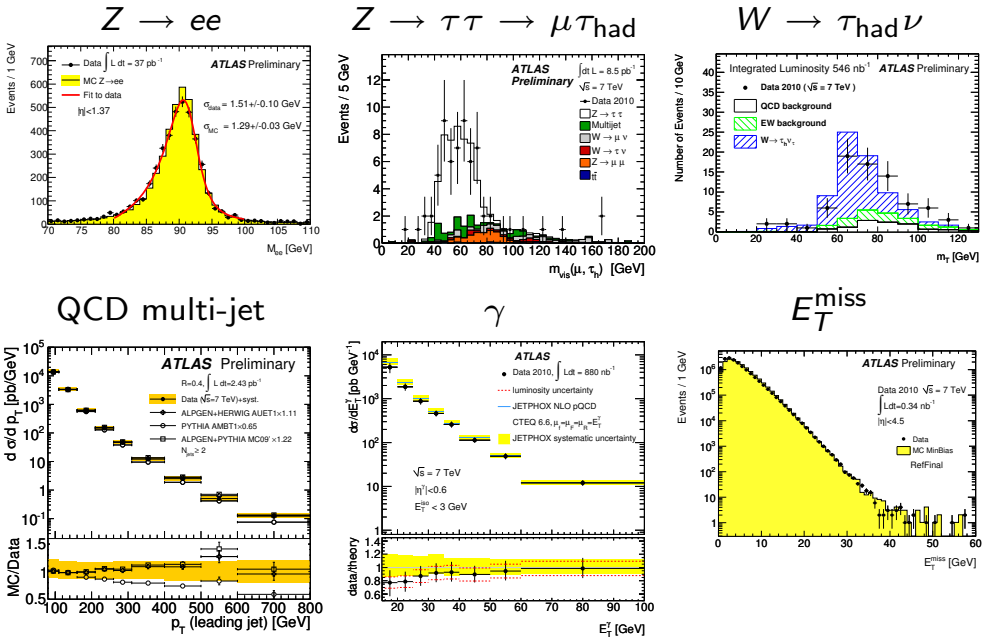
source	uncertainty [%]
electron eff.	± 5
muon eff.	± 2
jet energy scale	± 26
luminosity	± 11
cross section	± 19



The ATLAS Detector







- ATLAS recorded **45 pb^{-1}** of data in **2010**
- understanding the performance of the detector is crucial for Higgs searches

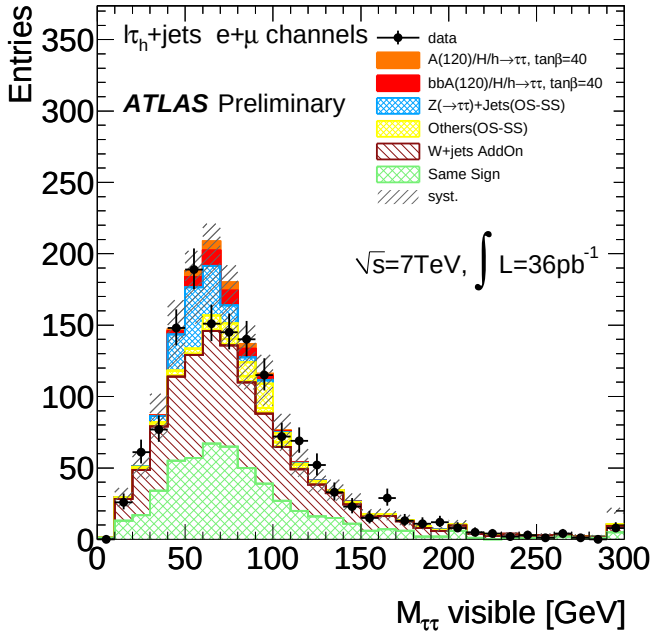
→ measured plenty of processes, but still some work to be done

- conditions still varying
- luminosity (→ pile-up), trigger menus, etc...

⇒ Higgs searches based on **"simple" selections**, data-driven methods to estimate background

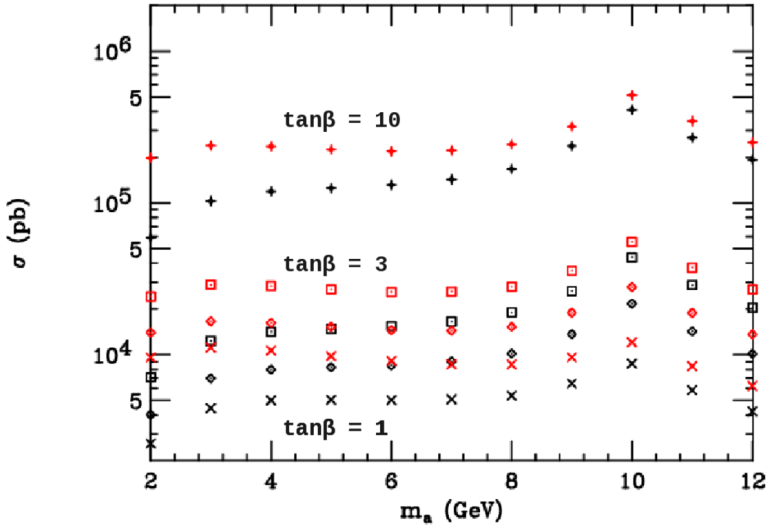
$h/H/A \to \tau^+\tau^- \to \ell\tau_{had}3\nu$

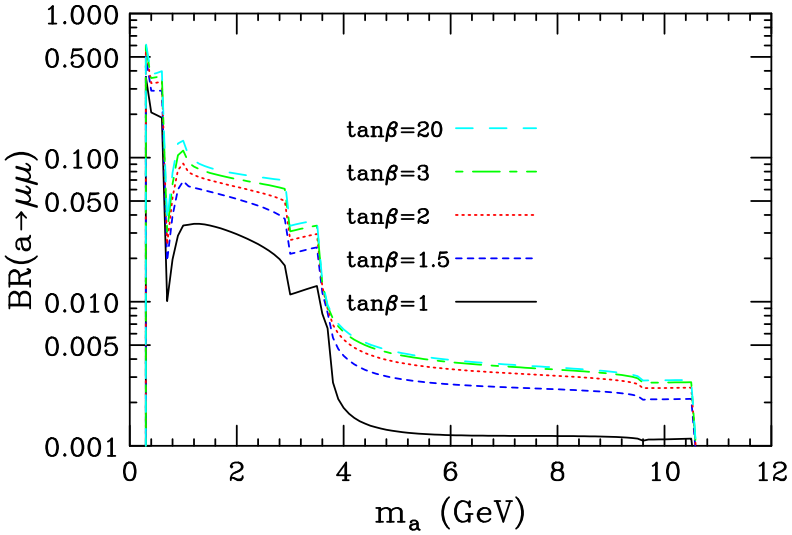
- sample composition with loose selection



$a_1 \longrightarrow \mu\mu$

- cross section of a_1 in Ideal Higgs scenario





- signal uncertainty dominated by theory:
  $m_A = 6(11.5)\,\mathrm{GeV}$

source	uncert.[%]
PYTHIA vs MC@NLO	67(20)
muon efficiency	14(15)
trigger	13(12)
luminosity	3.4
likelihood method	3

Limits

- limits on $\mu = \sigma/\sigma_{\mathrm{SM}}$ calculated with **Profile Likelihood Technique**
- purely frequentist approach
- by construction: downward fluctuation of 2σ leads to $\mu = 0$ if there is only background

$\longrightarrow$ allows to exclude signals with very low cross sections, such that the experiment is not sensitive to

- protect angainst this:

- **$\mathbf{CL_s}$**: reports conservative limit

or

Power Constrained Limit (PCL)

- reports **raw** Profile Likelihood limit **if power of test $> 16\%$**
- else: report **smallest μ** with **power $> 16\%$**.
- equivalent to cutting off limit at -1σ band.