Search for $H \to \tau_\ell \tau_{\text{had}}$ in pp collisions collected by the ATLAS experiment

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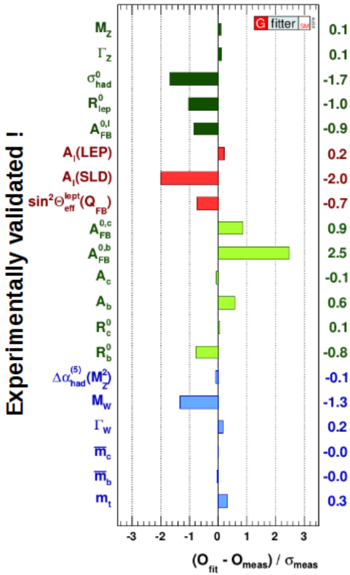
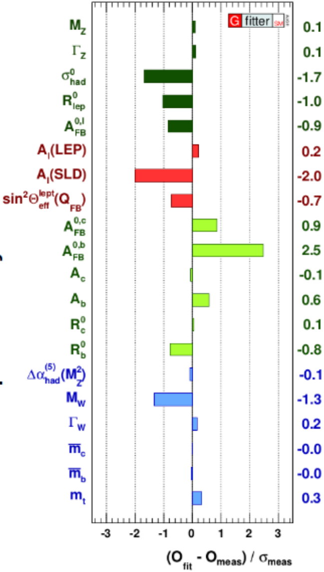


Unified theory of interactions

$$SU(2)_L \times U(1)_Y \times SU(3)_c$$
+ Higgs mechanism

Is the Higgs mechanism realized in Nature?

Experimentally validated !



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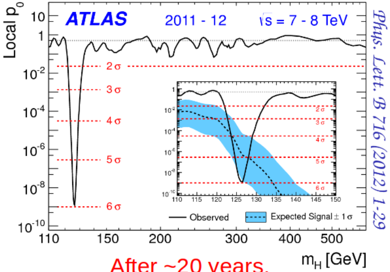
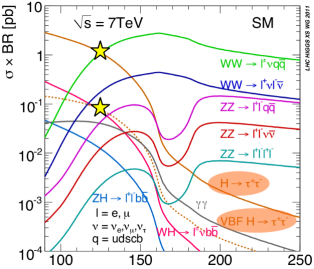


After ~20 years,
close to an **experimental answer !**

Role of τ-leptons in this discovery context

Understand EWSB with τ :

- Observation of $H \to \tau\tau$ process ? (CMS result)
- Unique test of $g_{Hff} \propto m_f$ in the fermionic sector (together with $H \to b\bar{b}$ measurement)
- particularly sensitive to VBF
- Polarization studies : access to $\mathcal{J}^{\mathrm{CP}}$



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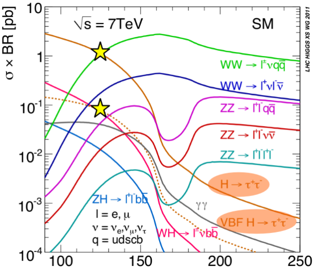

New physics with τ : To be pursued in parallel of the new resonance identification

- SUSY, Larger gauge group (doubly charged Higgs),
- new interaction (Z' search), lepton flavor violation in Z (H ?) decay, ...

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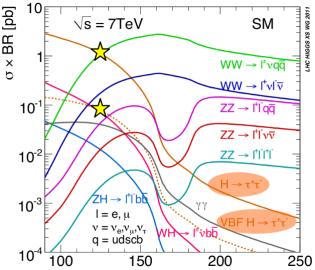

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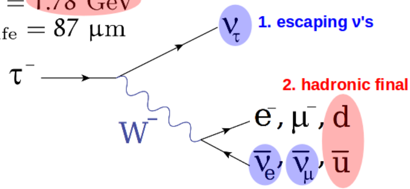
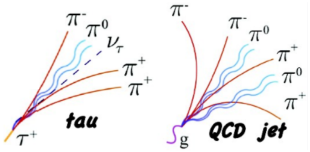
τ lepton final states have a key role in undersdanding the SM and beyond !

But experimentally challenging ! Jets contamination very frequent in hadrons collider !

$m_\tau = 1.78$ GeV
$c\tau_{\mathrm{life}} = 87\ \mu\mathrm{m}$





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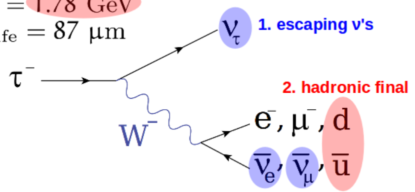

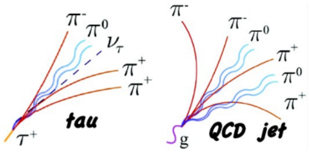

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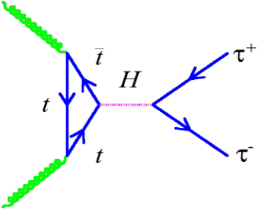
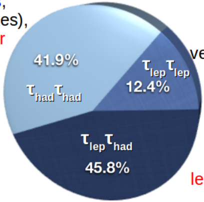
General strategy of $H \to \tau\tau$ search :



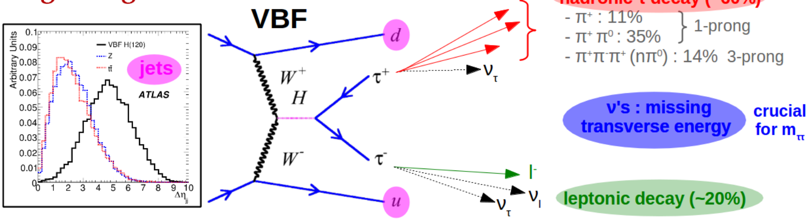
$\bigotimes$



- Each final state has specific backgrounds : dedicated analysis.
- In this seminar, I will mostly focus on $\tau_\ell \tau_{\mathrm{had}}$ final state.

$\tau_\ell \tau_{\mathrm{had}}$ final state : signal and background

Signal signature



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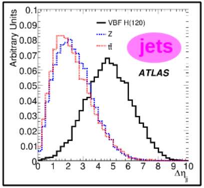
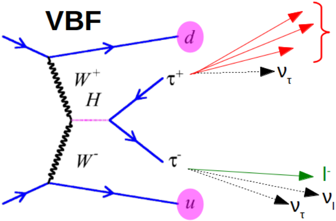


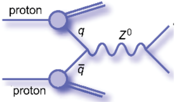


hadronic τ decay (~60%)
- π^+ : 11% } 1-prong
- $\pi^+ \pi^0$: 35% } 1-prong
- $\pi^+\pi^-\pi^+$ ($n\pi^0$) : 14% 3-prong

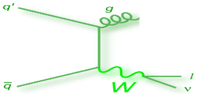
ν's : missing transverse energy — crucial for $m_{\tau\tau}$

leptonic decay (~20%)

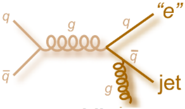
Other processes with this signature : background



Z → ττ
irreducible background
$m_{\tau\tau}$ peak, but $m_Z < m_H$



W (→ lν) + jets
jet wrongly identified as τ
reduced with m_T(l,mET), τID

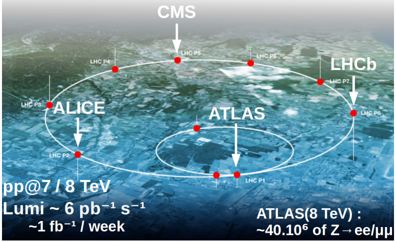


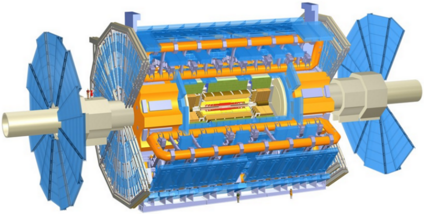
Multijets
jet wrongly identified as τ & l
reduced with kinematic, τID

Overview

1. **Object reconstruction : τ lepton and $\not{E}_T$**
2. **$m_{\tau\tau}$ reconstruction**
3. **Analysis description**
4. **Towards X(125) properties in $\tau\tau$ final state**
5. **Summary and outlooks**

The LHC and the ATLAS experiment





Comments :

- $qq' \to qq'H$: second dominant Higgs production (instead of VH for TeV)
- Better σ_H/σ_Z than TeV, "LHC$\approx gg$ collider", $\langle\mu\rangle \sim 20$,
- $\Delta p_T/p_T$ at 50 GeV : $\sim 2.7\%$ (tracker) and $\sim 2.0\%$ (calo).
- Typical calorimeter segmentation : $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$

Overview

Reconstruction of τ lepton in ATLAS

τ_{had} candidate is built from the calorimeter ($\pi^{\pm}$ and π^{0}) and the tracking system ($\pi^{\pm}$)

1. Calorimeter object :

1. calorimeter cells $\rightarrow$ 3D clusters (topological cluster)
2. τ_{calo} is defined as a jet of topo-clusters (anti-k_T algorithm with $\Delta R = 0.4$)

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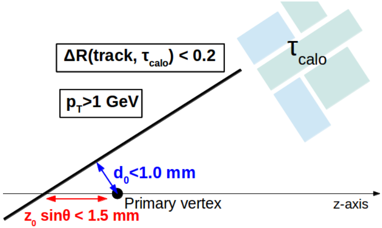

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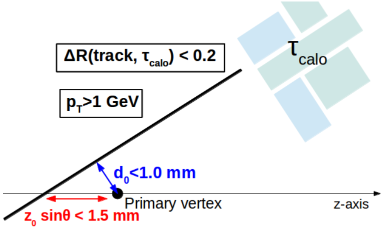
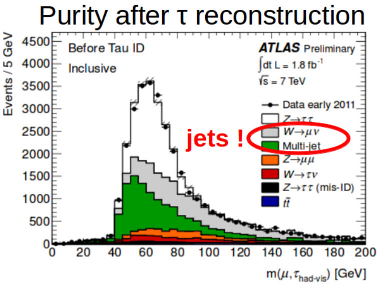
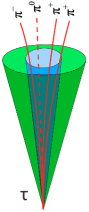
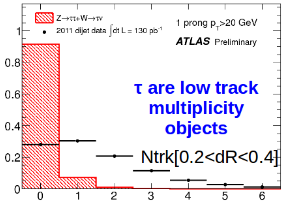
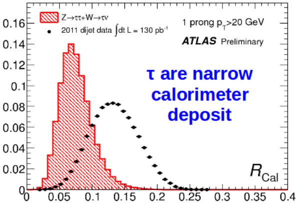


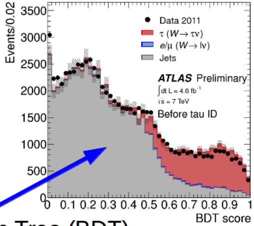


Identification of τ lepton in ATLAS









+ 6 **others observables** combined in a Boosted Decision Tree (BDT)

$\varepsilon_{sig} \sim 65\%$ – $\varepsilon_{bkg} \sim 2\%$

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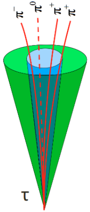

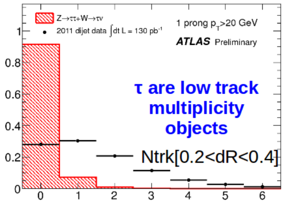

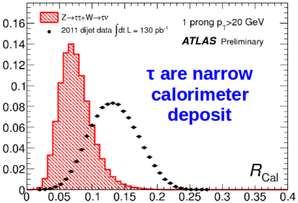

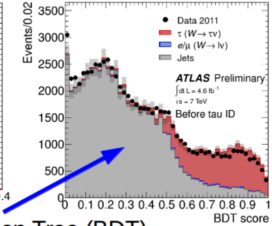

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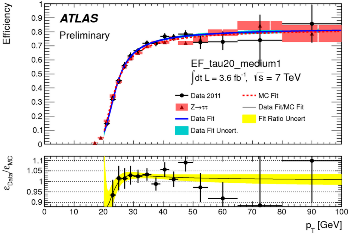
$\tau_{\rm had}$-based triggers : $\ell + \tau_{\rm had}$ triggers allow to lower p_T^ℓ threshold wrt ℓ triggers

- **Level 1** : based on isolated calorimeter deposits
- **Level 2** : consider isolated tracks matching the L1 objects
- **Event Filter** : exploit shower shapes with similar algorithms to offline ID



Energy calibration of τ lepton

Why and how ?

- $m_{\tau\tau} \propto E_\tau$: a wrong scale will lead to shifted mass peak.
- Use the simulation to measure the energy response
- Use data (and MC) to estimate the uncertainty - and a potential bias

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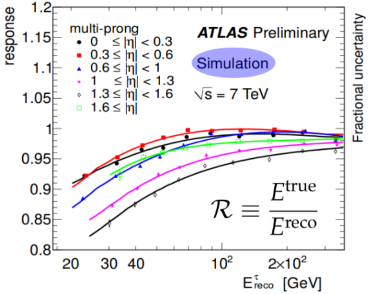
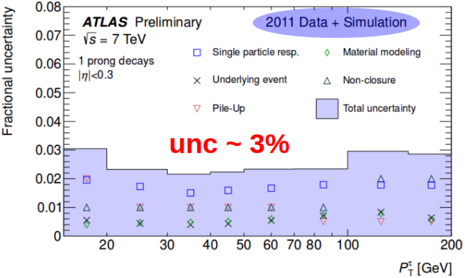


Uncertainty



Neutrinos momentum : $\not{E}_T$ reconstruction

Neutrinos don't interact with the detector : they are measured using the unbalance of the total transverse momentum.

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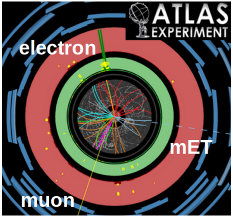

Calorimeter based :

- Raw : $\vec{\not{E}}_{\mathrm{T}} \equiv -\sum_{\text{cell } i} \vec{E}^{i}_{T}$,
- Corrected for muons (only MIP),
- Corrected for energy scale of each type of object

Keep in mind : $\vec{\not{E}}_{\mathrm{T}} \overset{\text{reco}}{=} \left(\sum_i \vec{p}_{\nu_i}\right)_T$

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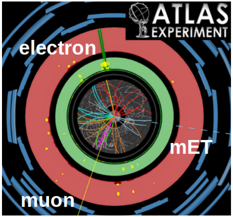

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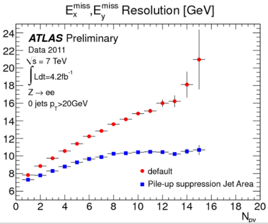
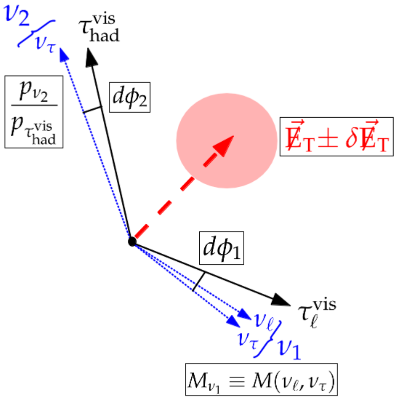
Comments : sensitive to all the activity in the event (pile up, detector noise, soft radiations, ...).

Some technics are elaborated to reduce pile-up effect on the $\not{E}_T$ resolution.



Overview

$m_{\tau\tau}$ reconstruction : Missing Mass Calculator



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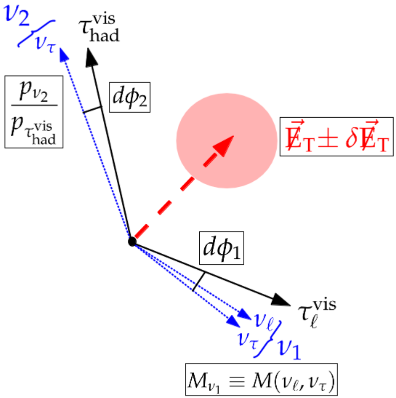

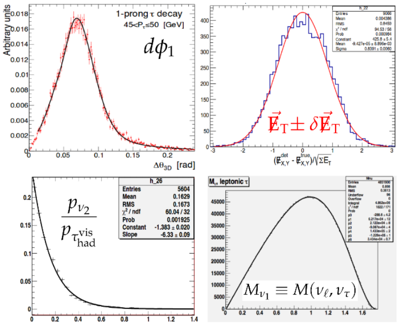

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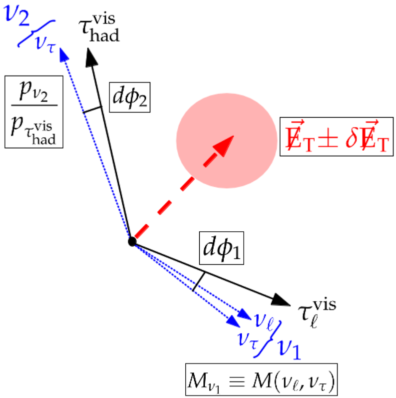

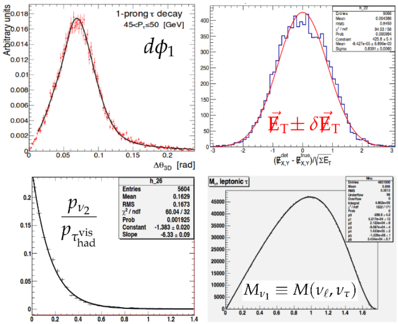

☐ = unknown value

(1) **Perform a scan** over the unknowns, ie choose a config : q = ($d\Phi_1$, $d\Phi_2$, $M_{\nu 1}$, mET, p_ν/p_τ)

(2) For each configuration q_i : compute the **full invariant mass** m_i

(3) Fill an histogram of m_i **weighted by w_i=PDF(q_i)** , as a product each above PDF

(4) Final reconstruced mass, **MMC**, is given by the **max of this histogram**

Overview

$H \to \tau_\ell \tau_{\mathrm{had}}$ overview

Background estimation :

- MJ & W+jets[SS] : SS **data**
- W+jets add-on : (corrected) MC
- Z : either **data** or (corrected) MC

Categorization : 7 categories based on

- jet multiplicity and lepton flavor
- $p_T(\ell, \tau_{\mathrm{had}}, \not{E}_{\mathrm{T}})$ and VBF topology
- The **VBF** category is **the priority**

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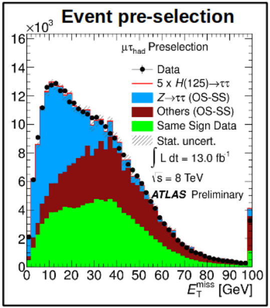
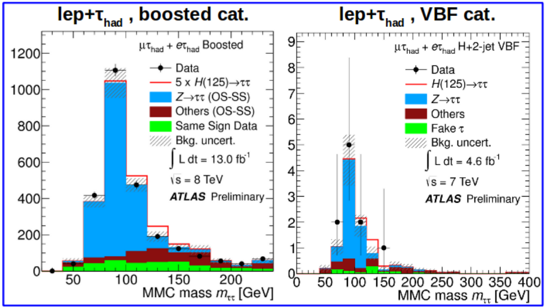


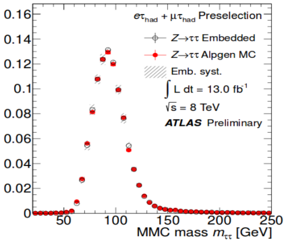


before signal extraction → Two most sensitive categories

- **mT<30 GeV** supress W+jets
- **mET>20 GeV** supress QCD
- more (complicated) cuts to reduce fake and top
- cut specific to each category

Background modeling : $Z \to \tau\tau$ and W+jets

$Z \to \tau\tau$ modeling :



Data driven : τ "embedding" in $Z \to \mu\mu$ data events

- remove μ deposits and replace by a simulated τ.
- It's data (jets, pile-up, calo noise, soft radiations)
- limited by data statistics

Corrected (filtered) MC :

- goal : more stat in VBF category,
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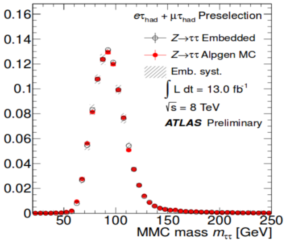

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W+jets : corrected MC

- Norm corr factor (k_W) derived for $m_T > 70$ GeV
- Derived for OS and SS separatly :
  $k_W^{OS} \sim 0.6$ and $k_W^{SS} \sim 0.8$

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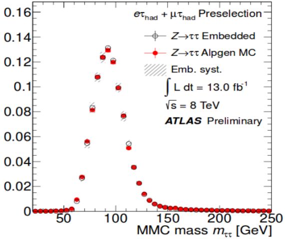


Data driven : τ "embedding" in $Z \to \mu\mu$ data events

- remove μ deposits and replace by a simulated τ.
- It's data (jets, pile-up, calo noise, soft radiations)
- limited by data statistics

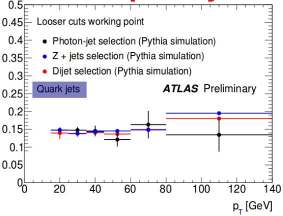
Corrected (filtered) MC :

- goal : more stat in VBF category,
- correct jet topology based on $Z \to \ell\ell$[data].

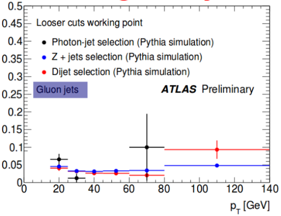
W+jets : corrected MC

- Norm corr factor (k_W) derived for $m_T > 70$ GeV
- Derived for OS and SS separately :
  $k_W^{\rm OS} \sim 0.6$ and $k_W^{\rm SS} \sim 0.8$

fake : quark jets



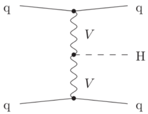
fake : gluon jets



Signal modeling : EW corrections of $qq' \to qq'H$

Motivations and goal :

- VBF@LO is EW : $\delta_{\text{EW}} \sim \delta_{\text{QCD}}$ (unlike $gg \to H$)
- σ_{tot} is already QCD+EW NLO : but shape effects of δ_{EW} ?



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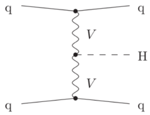

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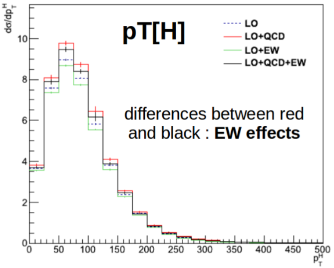
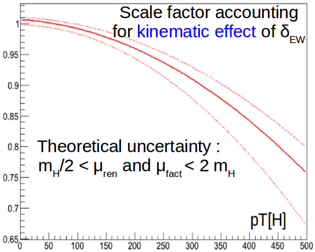
At generated level : most affected distribution is p_T^H - HAWK





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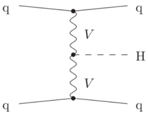

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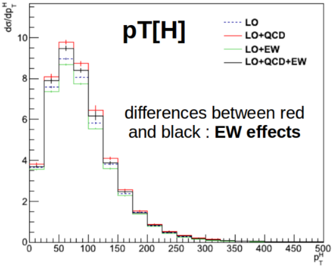
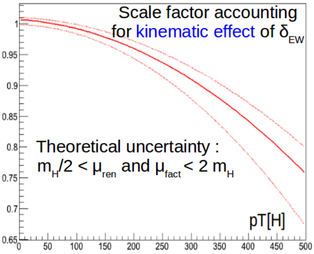


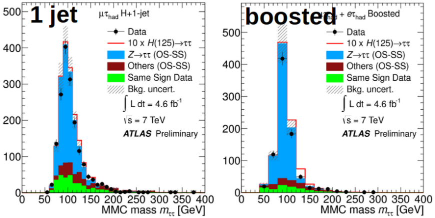


At reconstructed level :

- negligeable impact, wrt to other exisiting systematics,
- This spectrum distortions should be kept in mind for the future.

Re-optimization of 2011 analysis

The boosted topology : defined by $p_T^H \stackrel{\text{reco}}{=} p_T(\ell, \tau_{\text{had}}, \not{E}_T) > 100$ GeV



- better resolution on $m_{\tau\tau}$ for boosted system
- significantly reduce fake τs
- theo uncert. well under control for p_T^H, unlike n_{jets}
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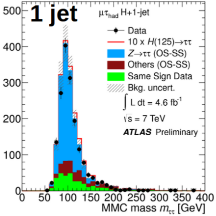

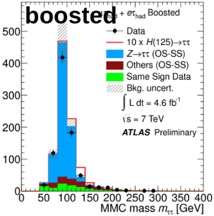

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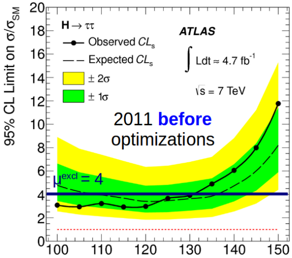

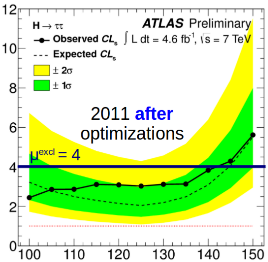

With other improvements :
expected sensitivity almost divided by 2 !

Uncertainty	$H \to \tau_{lep}\tau_{lep}$	$H \to \tau_{lep}\tau_{had}$	$H \to \tau_{had}\tau_{had}$
		$Z \to \tau^+\tau^-$	
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	9–10%
		Signal	
Jet Energy Scale	1–5% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	8–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

Most important systematic :
τ energy scale

→ direct impact on final observable ($m_{\tau\tau}$)

Uncertainty	$H \to \tau_{\rm lep}\tau_{\rm lep}$	$H \to \tau_{\rm lep}\tau_{\rm had}$	$H \to \tau_{\rm had}\tau_{\rm had}$
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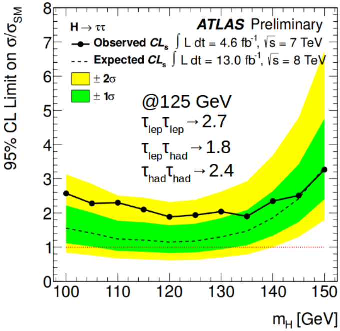

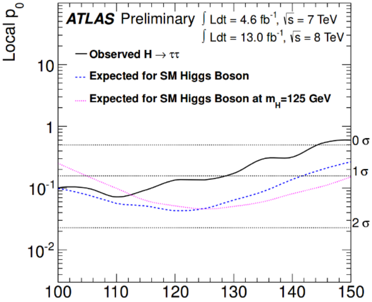

Overview

3 type of property

1. other SM particles couplings constant : **observed event rate**
2. spin : **polarization, angular distributions**
3. CP : **angular correlation/distributions**

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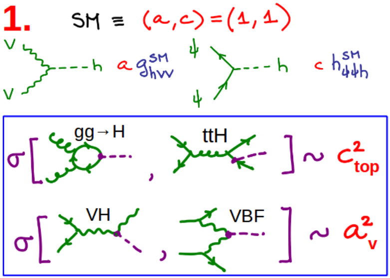

arXiv :1209.0040, ATLAS-CONF-2012-127

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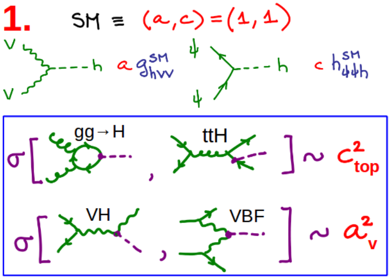

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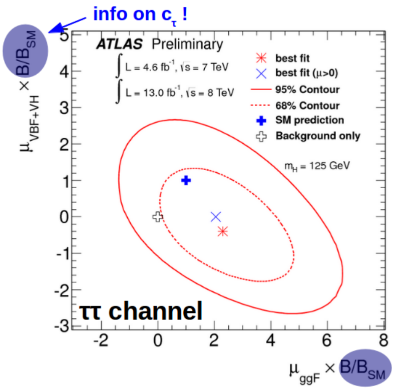
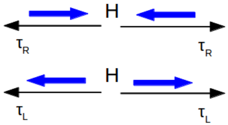


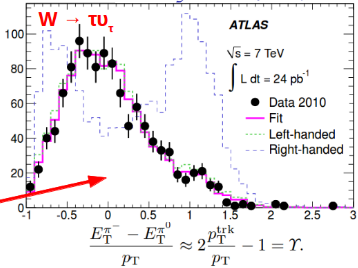
2.

Probe τ spin **correlations** :



Be able to measure τ polarization ? **YES**

Eur.Phys.J. C72 (2012) 2062



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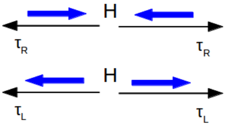

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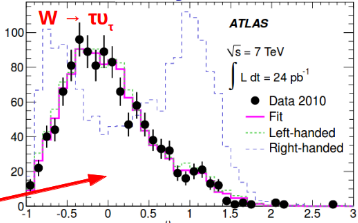
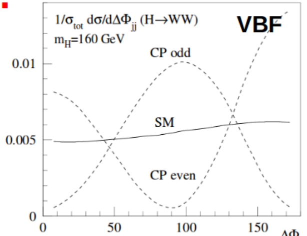


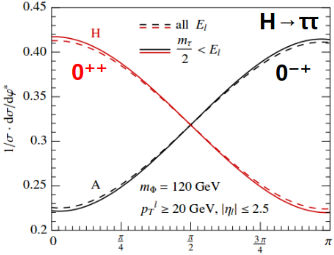
$$\frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T} \approx 2\frac{p_T^{\text{trk}}}{p_T} - 1 = \Upsilon.$$

3. *Phys. Rev. Lett. 88 (2002) 051801*



tagging jets related angles

arXiv :1108.0670



φ^* (related τ angles)

Overview

Summary and outlooks

The τ-lepton final states provide key informations to understand the EWSB mechanism at hadrons colliders

Experimental challenges :

- Hadronic τ highly contaminated by QCD jets,
- Need sophisticated algorithms (for analysis AND trigger),
- Importance of $\not{E}_{\mathrm{T}}$ for τ final state.

Search for $H \to \tau\tau$:

- Essential to test $g_{Hff} \propto m_f$, unique probe of Higgs-lepton couplings,
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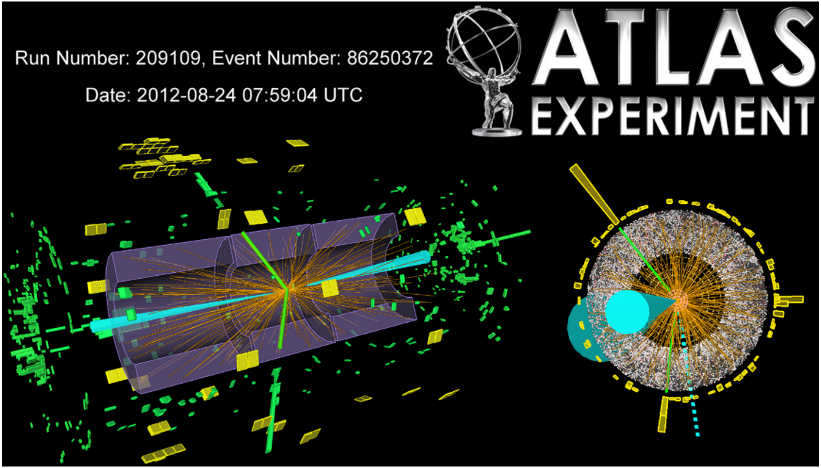
An update of $H \to \tau\tau$ search with the full dataset and several improvements is to come : stay tuned !


Run Number: 209109, Event Number: 86250372
Date: 2012-08-24 07:59:04 UTC
ATLAS
EXPERIMENT

Backup slides

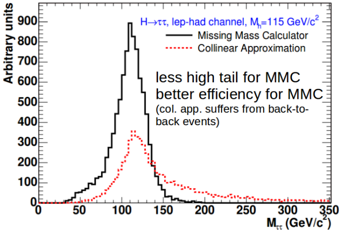
7 TeV		8 TeV	
VBF Category	**Boosted Category**	**VBF Category**	**Boosted Category**
▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV	–	▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV	▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV	▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV
▹ $p_T{}^{j1}, p_T{}^{j2} > 40$ GeV	▹ $0 < x_1 < 1$	▹ $p_T{}^{j1} > 40$, $p_T{}^{j2}$ >30 GeV	▹ $0 < x_1 < 1$
▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$	▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$
▹ $m_{jj} > 500$ GeV	▹ Fails VBF	▹ $m_{jj} > 500$ GeV	▹ Fails VBF
▹ centrality req.	–	▹ centrality req.	–
▹ $\eta_{j1} \times \eta_{j2} < 0$	–	▹ $\eta_{j1} \times \eta_{j2} < 0$	–
▹ $p_T{}^{\text{Total}} < 40$ GeV	–	▹ $p_T{}^{\text{Total}} < 30$ GeV	–
–	–	▹ $p_T{}^{\ell}$ >26 GeV	–
• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV
• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 1.6$	• $\sum \Delta\phi < 2.8$	–
–	–	• b-tagged jet veto	• b-tagged jet veto
1 Jet Category	**0 Jet Category**	**1 Jet Category**	**0 Jet Category**
▹ ≥ 1 jet, p_T >25 GeV	▹ 0 jets p_T >25 GeV	▹ ≥ 1 jet, p_T >30 GeV	▹ 0 jets p_T >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ Fails VBF, Boosted	▹ Fails Boosted	▹ Fails VBF, Boosted	▹ Fails Boosted
• m_T <50 GeV	• m_T <30 GeV	• m_T <50 GeV	• m_T <30 GeV
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^\ell - p_T^\tau < 0$	–	• $p_T^\ell - p_T^\tau < 0$

$m_{\tau\tau}$ reconstruction and boosted topology

Missing Mass Calculator (MMC) :

- single ν kinematic unknown
- scan the 4-vector of each ν
- scan $\vec{E}\!\!\!/_{\rm T}$, given its resolution
- compute the most likely mass, according the τ decay ME

(more in backup ...)



Selected parts of possible improvements (1/2)

Problem : τ_{had} ID relies on shower shape variable. If the simulation poorly models them, ϵ_{ID} from simulation might be wrong.

Solution : measure ϵ_{ID} in $Z \to \tau\tau$ events selected in data (“tag & probe”).

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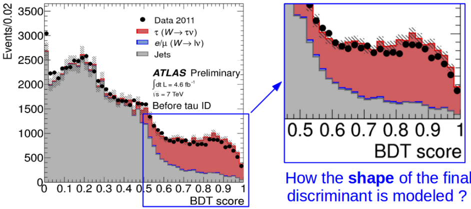
Solution : measure ϵ_{ID} in $Z \to \tau\tau$ events selected in data ("tag & probe").

But how to go further ? undersdand the variable shape

- major impact on physics analysis via MVA signal extraction,
- undersdand correlations between input variables,
- look at different detector regions (fwd VS central).

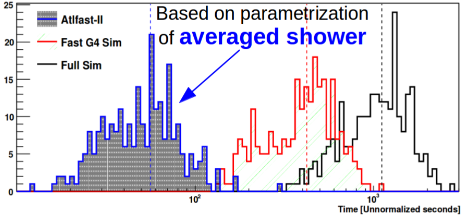


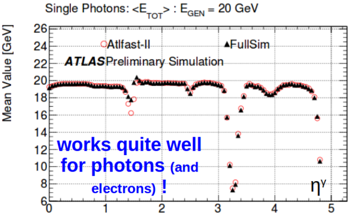
How the **shape** of the final discriminant is modeled ?

Cons : not clear if this will lead to a concluding result on the short term.
Pros : work at a deeper level for a better understanding of τ_{had}.

Selected parts of possible improvements (2/2)

Fast simulation of the calorimeter : to increase the MC statistics





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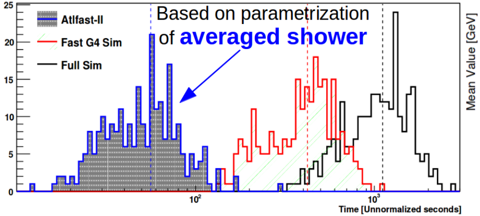

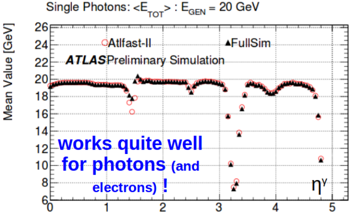

Connexion with τ leptons :

- hadrons : important shower fluctuations
- usually averaged in jets (high number of hadrons)
- τ_{had} : low hadrons multiplicity object $\rightarrow$ fluctuations become important

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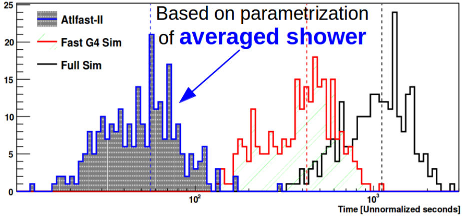

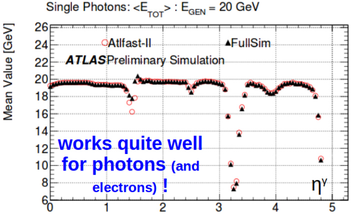

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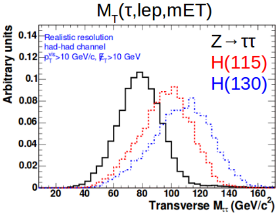
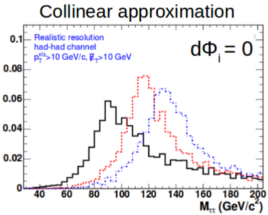
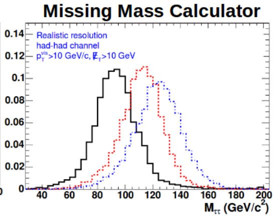
On going work on this :

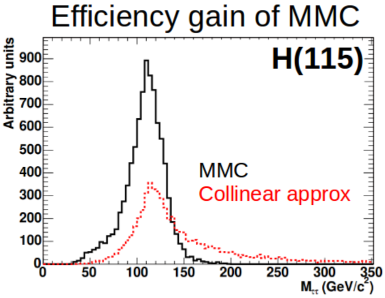
- particle gun experiment with π : shower at the cells and clusters level
- capure microscopic effects which lead to sizable effects at the reco level
- look at $Z \to \tau\tau$ events in the same perspective (calo noise, pile-up, ...)

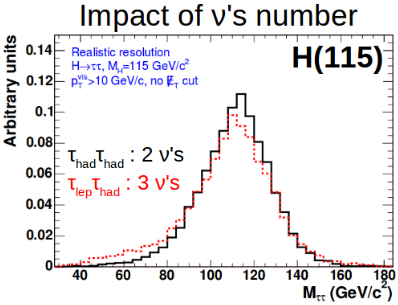
MMC : results and features











ATLAS verus CMS