How to probe electroweak physics and beyond with τ leptons at hadron colliders ?

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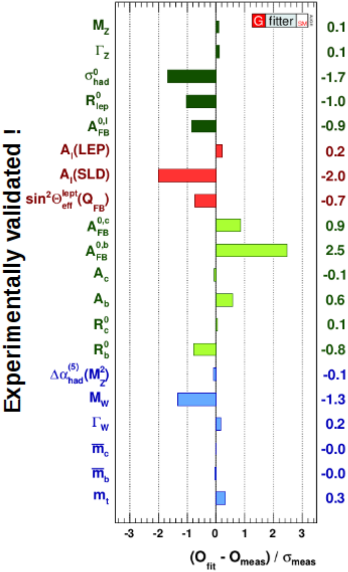
Albert-Ludwigs-Universität, Freiburg – Germany

Laboratoire de Physique Corpusculaire

The 24th of January 2014 – Clermont-Ferrand, France

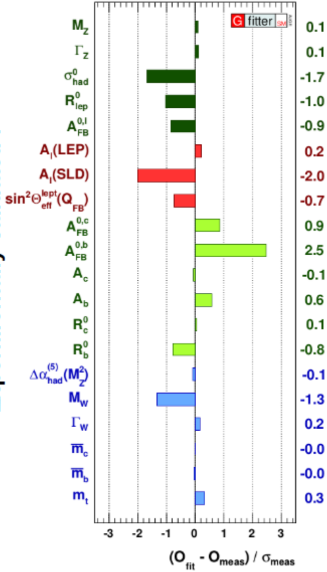


Unified theory of interactions

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

Is the Higgs mechanism realized in Nature?

Experimentally validated !



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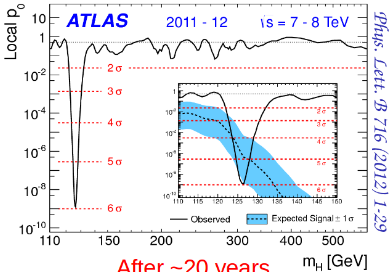

After ~20 years, reaching an **experimental answer !**

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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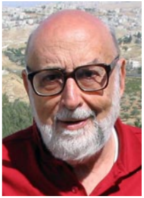


Photo: Pnicolet via Wikimedia Commons
François Englert

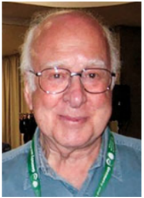
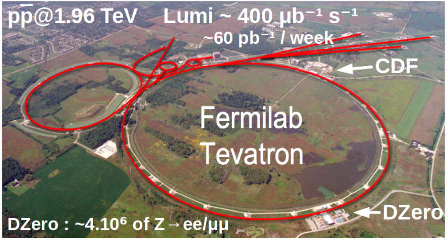
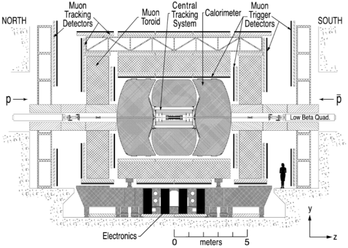


Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

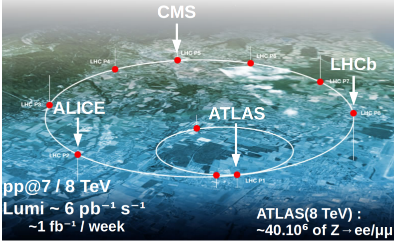
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

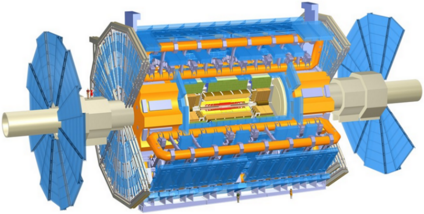
The Tevatron and DØ :





The LHC and ATLAS :





Role of τ leptons in this discovery context

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Keep testing SM at the TeV scale ($V - A$ vertex, lepton universality, ...).

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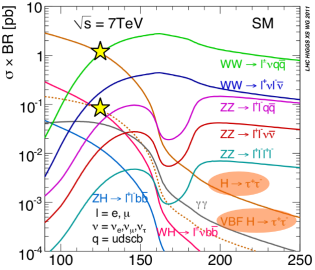
- Unique test of $g_{Hff} \propto m_f$ in the fermionic sector (together with $H \to b\bar{b}$ measurement)
- particularly sensitive to VBF
- Polarization studies : access to $\mathcal{J}^{CP}$



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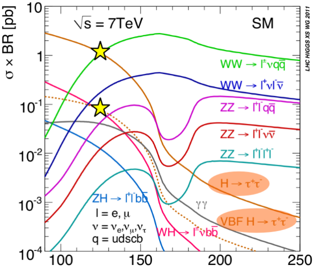

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- SUSY, Larger gauge group (doubly charged Higgs),
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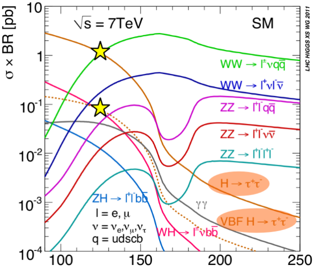

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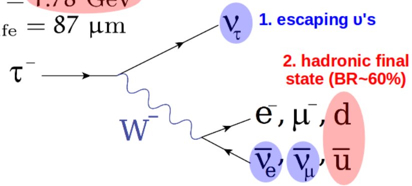
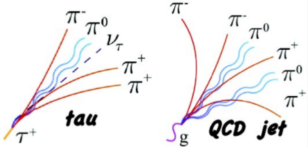
τ lepton final states have a key role in undersdanding the SM and beyond !

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

$m_\tau = 1.78$ GeV

$c\tau_{\text{life}} = 87$ μm





$\tau_{\text{had}} \approx$ narrower jet with lower track multiplicities

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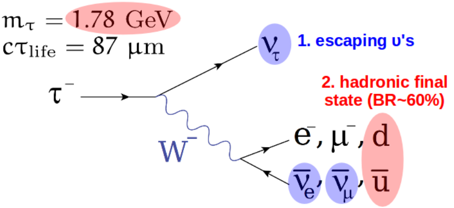

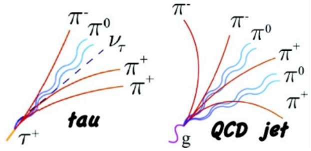

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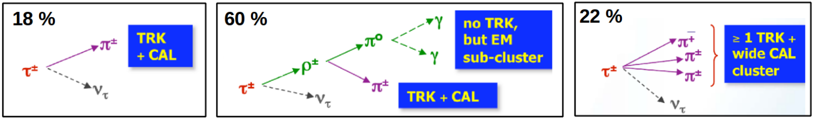
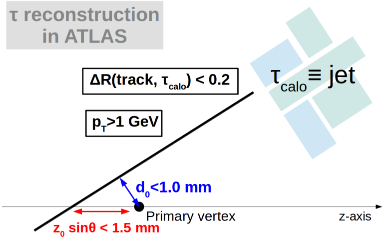
Typical signature of hadronic τ decay :



- 1 or 3 isolated tracks, with possible secondary vertex reconstruction.
- Collimated calorimeter energy deposit.
- Large leading track fraction momentum.

A τ_{had} candidate is built from :

1. the calorimeter ($\pi^{\pm}$ and π^{0})
2. the tracking system ($\pi^{\pm}$)



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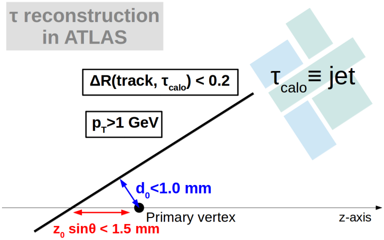
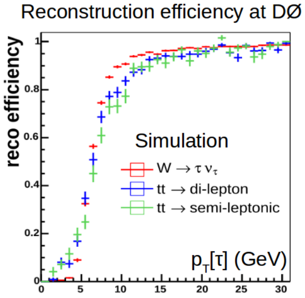
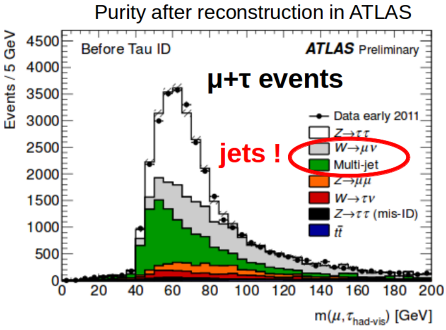
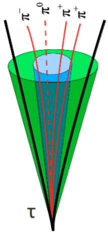
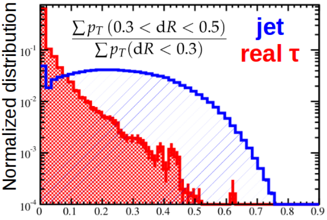








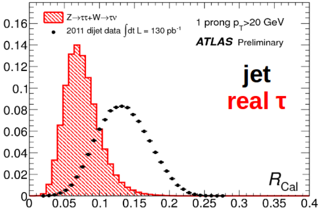
Track isolation at DØ



use NN to combine ~10 observables

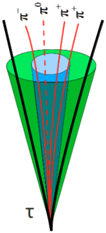
ε_{sig} ~ 65% ; ε_{bkg} ~ 1%

Calorimeter shower extension in ATLAS



use BDT to combine ~8 observables

ε_{sig} ~ 60% ; ε_{bkg} ~ 2%



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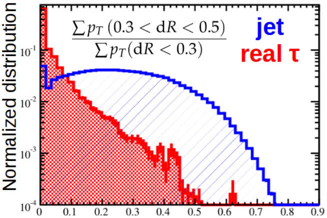

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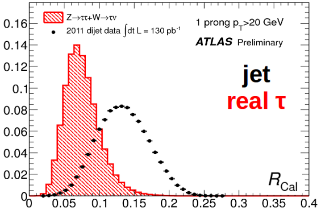

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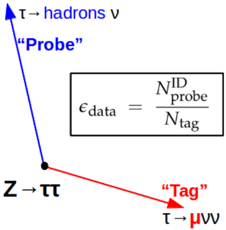
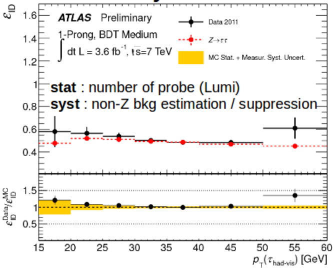
"Tag and probe" method



Efficiency measurement



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
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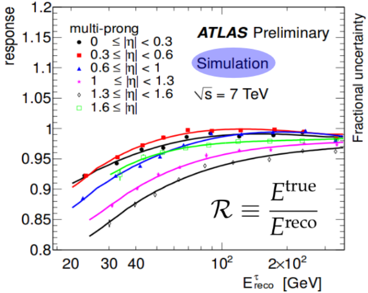
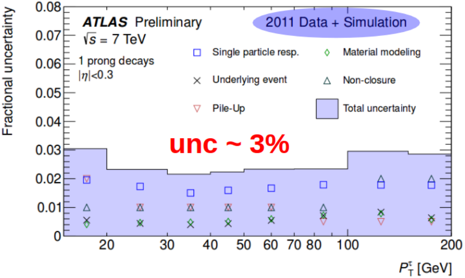
Calibration



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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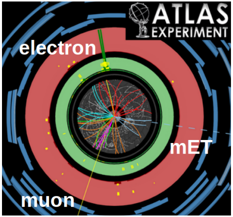

Calorimeter based :

- Raw : $\vec{\not{E}}_{\mathrm{T}} \equiv -\sum_{\text{cell } i} \vec{E}_T^i$,
- 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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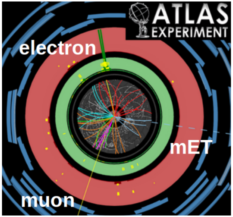

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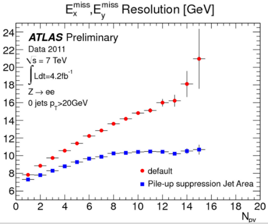
Comments : sensitive to all the activity in the event (pile up, detector noise, soft radiations, ...).

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



Overview

Standard Model physics (1/2)

Main SM properties accessible through τ :

1. $\sigma_{Z,W}$ measurement for 2 initial states / center-of-mass energy,
2. $V - A$ structure of weak current at $Q^2 \sim M_W^2$: $\mathcal{L} \sim W_\mu \, \bar{\nu} \, \gamma^\mu \frac{(1-\gamma^5)}{2} \, \ell$.

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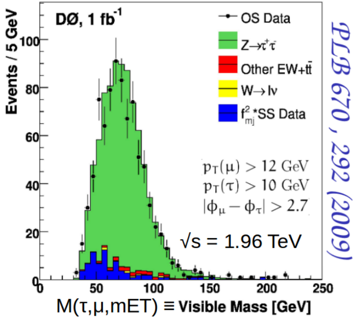
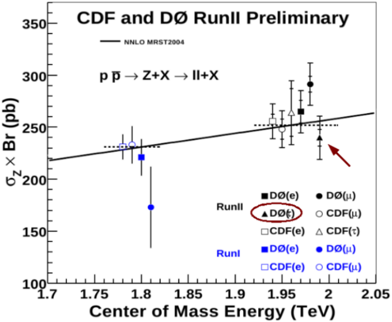
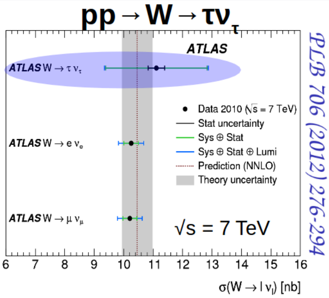
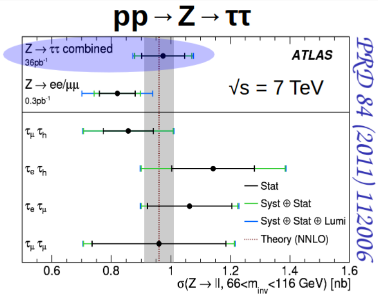
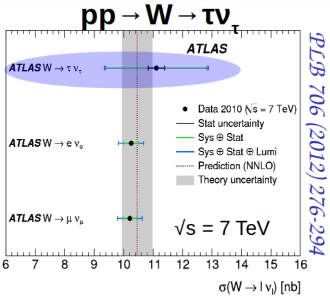
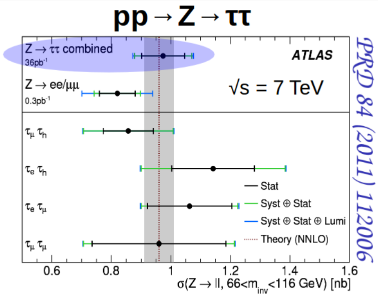





pp → W → τν_τ
ATLAS
ATLAS W → τ ν_τ
ATLAS W → e ν_e
ATLAS W → μ ν_μ
Data 2010 (√s = 7 TeV)
Stat uncertainty
Sys ⊕ Stat
Sys ⊕ Stat ⊕ Lumi
Prediction (NNLO)
Theory uncertainty
√s = 7 TeV
6 7 8 9 10 11 12 13 14 15 16
σ(W → l ν_l) [nb]
PLB 706 (2012) 276-294

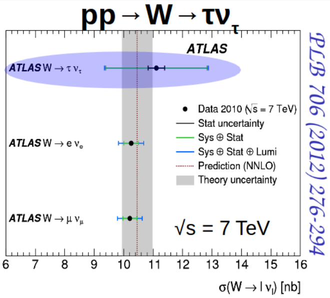

pp → Z → ττ
Z → ττ combined
36pb⁻¹
Z → ee/μμ
0.3pb⁻¹
ATLAS
√s = 7 TeV
τ_μ τ_h
τ_e τ_h
τ_e τ_μ
τ_μ τ_μ
Stat
Syst ⊕ Stat
Syst ⊕ Stat ⊕ Lumi
Theory (NNLO)
0.6 0.8 1 1.2 1.4 1.6
σ(Z → ll, 66<m_inv<116 GeV) [nb]
PRD 84 (2011) 112006

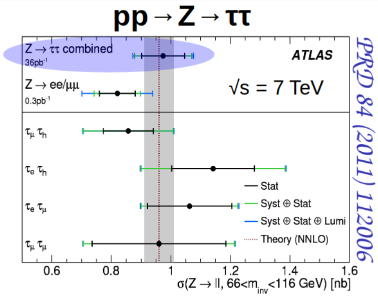




τ - Production $W^- \to (\tau^-)_{Left}\,(\bar{\nu}_\tau)_{Right}$

$$P_{\tau^-} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \overset{SM}{\equiv} -1$$





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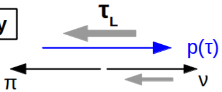
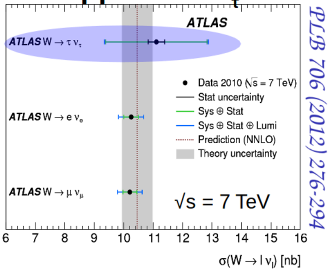


$$\tau_L \ : \ \langle p_\pi^{\text{lab}} \rangle < \langle p_\nu^{\text{lab}} \rangle$$

$pp \to W \to \tau\nu_\tau$



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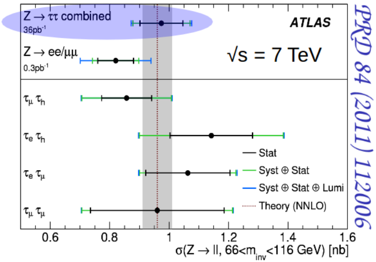

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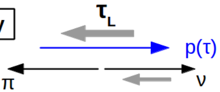

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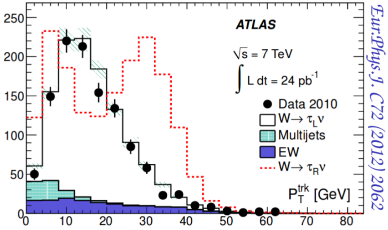
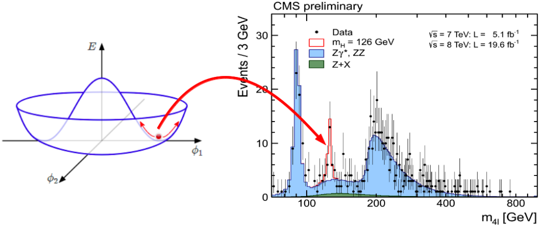


$$P_\tau = -1.06 \pm 0.04\,(stat)\,{}^{+0.05}_{-0.07}\,(syst).$$

Higgs boson search in τ final states

1. Overview of one Tevatron analysis
2. $H \to \tau\tau$ search in ATLAS
3. Prospect for properties measurement



Analysis overview

Motivations (out-of-date) **and strategy :**

- $H \to WW \to \tau\mu$ process allow to complete other $H \to WW$ channels
- Select events with one τ and one isolated μ (based on trigger mixture),
- Look for an excess of events at high $M(\mu, \tau_{\text{had}}, \not{E}_{\text{T}})$,
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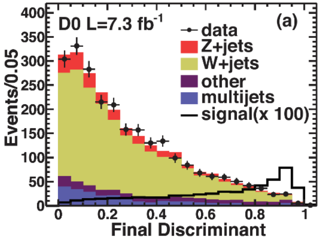
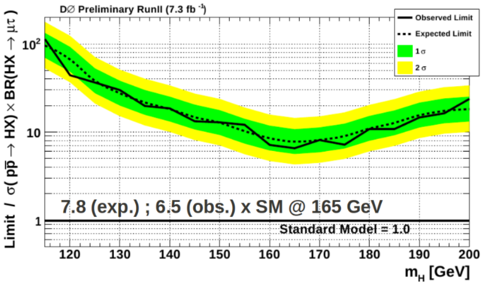
Phys. Lett. B 714, 237 (2012)





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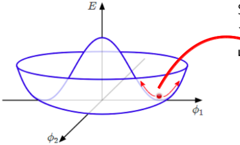
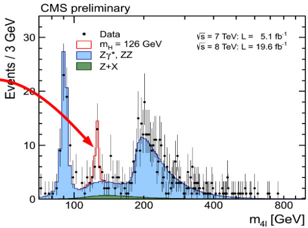
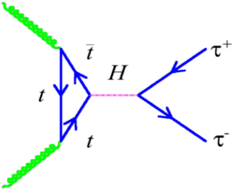
2. $H \to \tau\tau$ search in ATLAS
3. Prospect for properties measurement



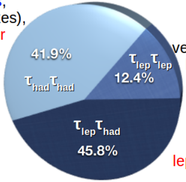


General strategy of $H \to \tau\tau$ search :



$\otimes$

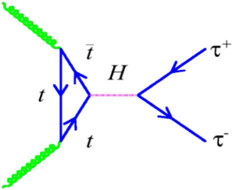
high BR, 2 ν's,
high MJ bkg (fakes),
τ-based trigger



low BR, 4 ν's,
very clean signature,
lep-based trigger

high BR, 3 ν's,
~clean signature
(W+jets as bkg),
lep & τ-based trigger

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



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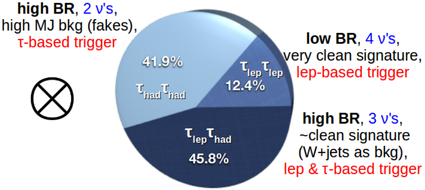
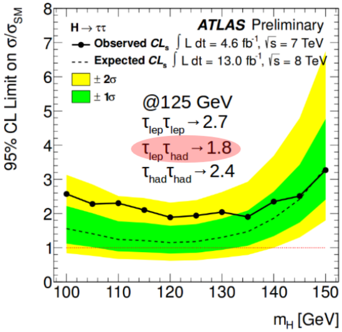
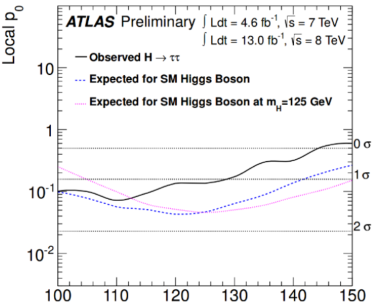
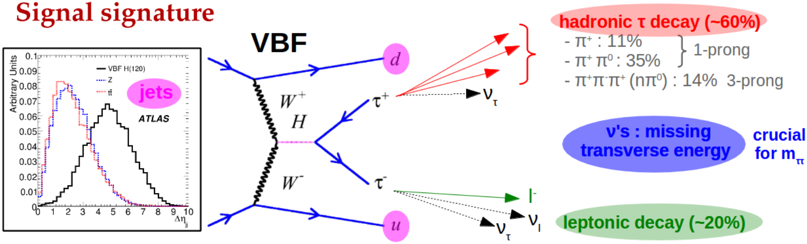






$\tau_\ell \tau_{had}$ final state : signal and background

Signal signature



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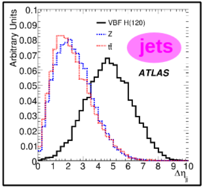
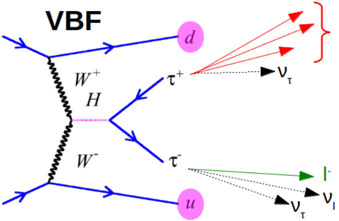




hadronic τ decay (~60%)

- π^+ : 11%
- $\pi^+ \pi^0$: 35%

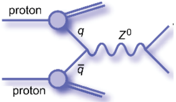
} 1-prong

- $\pi^+\pi^-\pi^+$ ($n\pi^0$) : 14% 3-prong

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

leptonic decay (~20%)

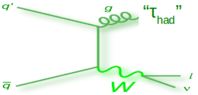
Other processes with this signature : background



Z → ττ

irreducible background

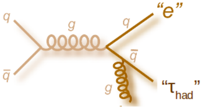
$m_{\tau\tau}$ peak, but m_Z<m_H



W (→lν) + jets

jet wrongly identified as τ

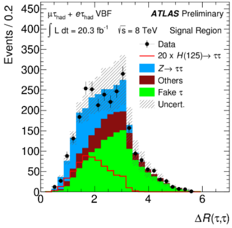
reduced with m_T(l,mET), τID

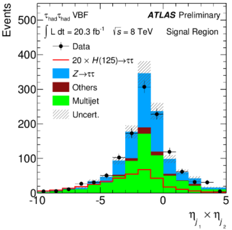


Multijets

jet wrongly identified as τ & l

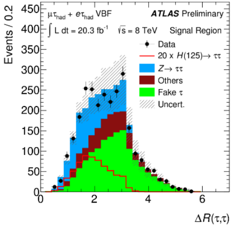
reduced with kinematic, τID

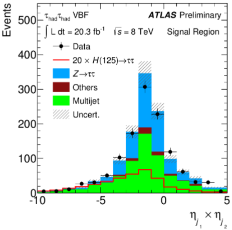




Multi Variate Analysis (MVA)
- 7-9 variables
- Boosted Decision Tree (BDT)

Input variables based on
- ττ resonance (mass, angle, ...)
- mET (neutrino direction)
- VBF topology (forward jets)





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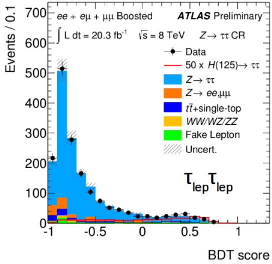
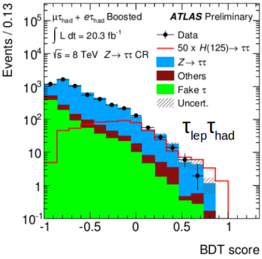
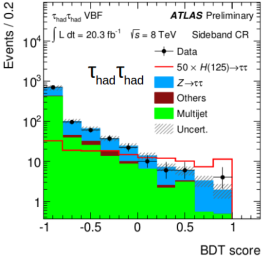
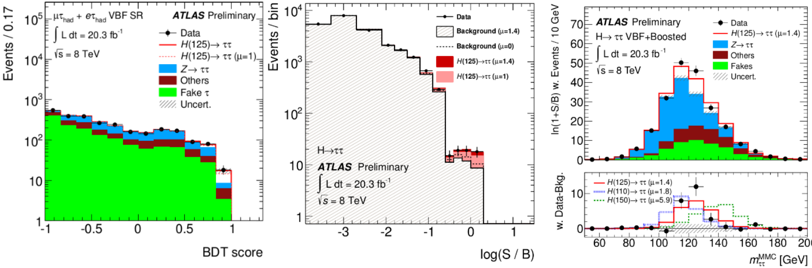
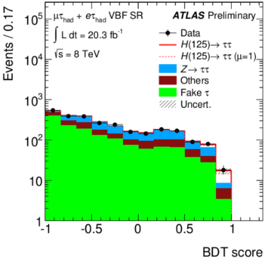
Validation of Z → ττ modeling in **control regions**

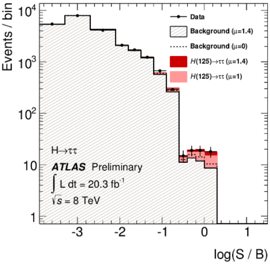


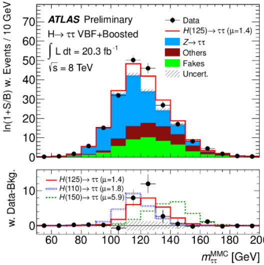





Events / 0.17
μτhad + eτhad VBF SR
ATLAS Preliminary
∫ L dt = 20.3 fb-1
√s = 8 TeV
Data
H(125)→ ττ
H(125)→ ττ (μ=1)
Z→ ττ
Others
Fake τ
Uncert.
BDT score
Events / bin
Data
Background (μ=1.4)
Background (μ=0)
H(125)→ττ (μ=1.4)
H(125)→ττ (μ=1)
H→ττ
ATLAS Preliminary
∫ L dt = 20.3 fb-1
√s = 8 TeV
log(S / B)
ln(1+S/B) w. Events / 10 GeV
ATLAS Preliminary
H→ ττ VBF+Boosted
∫ L dt = 20.3 fb-1
√s = 8 TeV
Data
H(125)→ ττ (μ=1.4)
Z→ ττ
Others
Fakes
Uncert.
w. Data-Bkg.
H(125)→ ττ (μ=1.4)
H(110)→ ττ (μ=1.8)
H(150)→ ττ (μ=5.9)
m_ττ^MMC [GeV]







$$q_{\mu=0} = -2\ln(\mathcal{L}(0,\hat{\hat{\vec{\theta}}})/\mathcal{L}(\hat{\mu},\hat{\vec{\theta}}))$$

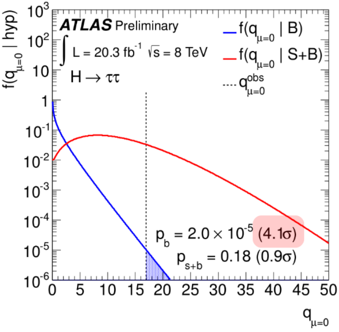
$$\mu \equiv \frac{\sigma_H^{obs}}{\sigma_H^{SM}}$$

fit assuming no signal

Best fitted signal

$$\mu = 1.43^{+0.31}_{-0.29}(\text{stat.})^{+0.41}_{-0.30}(\text{syst.})$$

Excess of 4.1σ (3.2σ expected)



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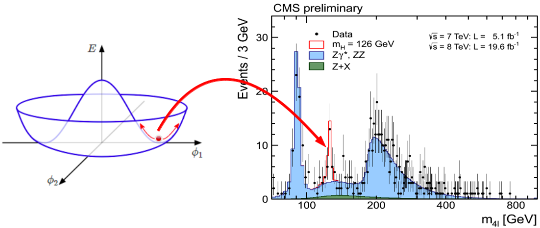

3 types of property

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

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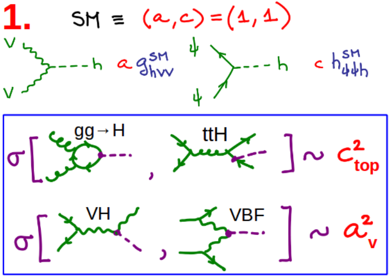

arXiv :1209.0040, ATLAS-CONF-2012-127

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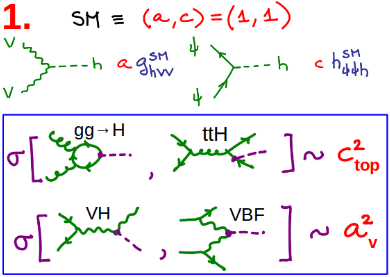

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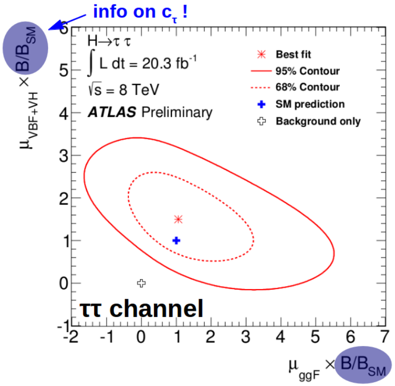
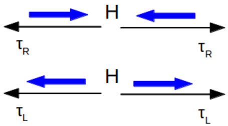


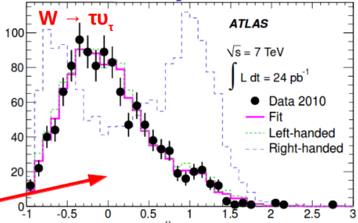
2.

Probe τ spin **correlations** :



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

Eur.Phys.J. C72 (2012) 2062



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

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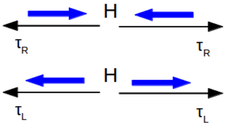

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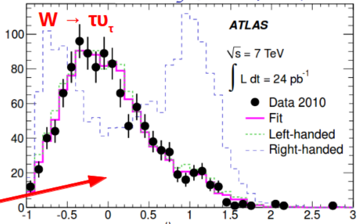

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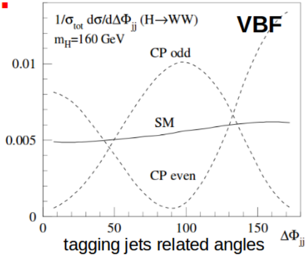
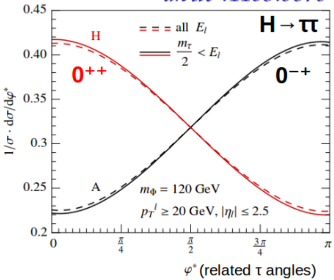
Phys. Rev. Lett. 88 (2002) 051801



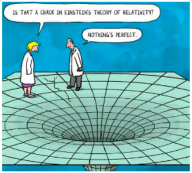
tagging jets related angles

arXiv :1108.0670

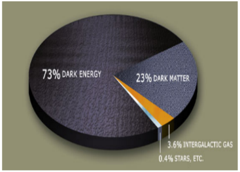


φ* (related τ angles)

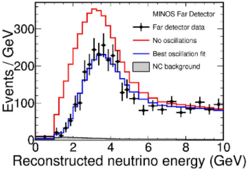
Quantum gravity



Dark matter / energy



Neutrinos oscillations



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How to go beyond the Standard Model ?

1. Higgs sector of supersymmetry (MSSM)
2. New group of gauge symmetry ? (heavy resonance)

MSSM Higgs sector : overview

MSSM Higgs sector : 2 doublets $\hat{H}_u, \hat{H}_d$ coupling to *up* and *down* quarks

- After EWSB, 5 Higgs bosons : $\boldsymbol{\phi} = (h^0, H^0, A^0)$ and $\boldsymbol{H^{\pm}}$
- Tree level predictions depend on $(m_A, \tan\beta)$ $\tan\beta \equiv \langle H_d \rangle / \langle H_u \rangle$
- Decay :
  - $\phi \to b\bar{b} \sim 90\%$
  - $\phi \to \tau\tau \sim 10\%$ cleaner

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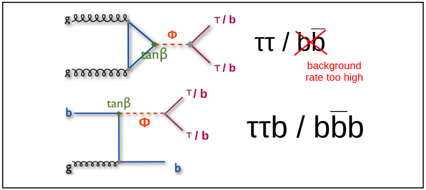

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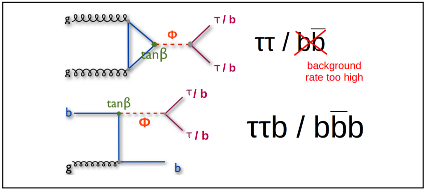
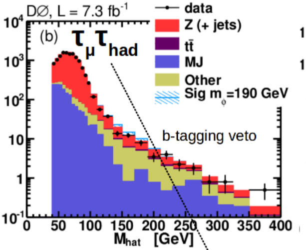
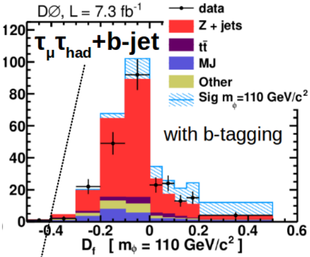


I will focus on **neutral Higgs boson(s)** searches in τ (and b) final states.

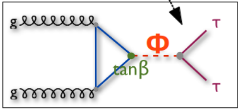
For a wide review of BSM Higgs searches on Tevatron, see the 3^{rd} Higgs Hunting presentation

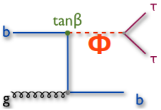




M_{hat} ≡ ~minimal center-of-mass energy of the event

D_f ≡ final discriminant (combination of kinematic and b-tag)

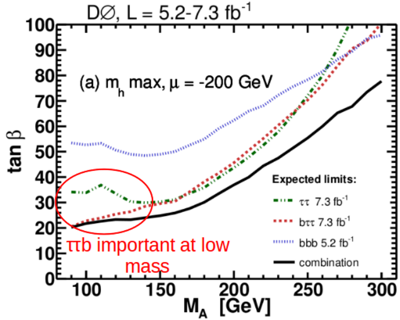




$$\frac{\sigma^{\text{incl}}(Z)}{\sigma(Z+b_{\text{tag}})} < 0.005$$

$$\frac{\sigma^{\text{incl}}(\phi)}{\sigma(\phi+b_{\text{tag}})} \sim 0.16$$

S/B gain at low M_Φ !

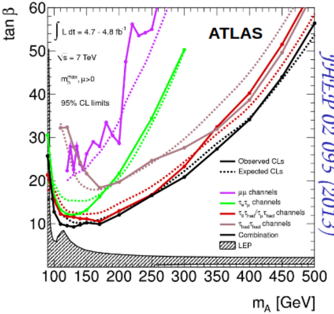


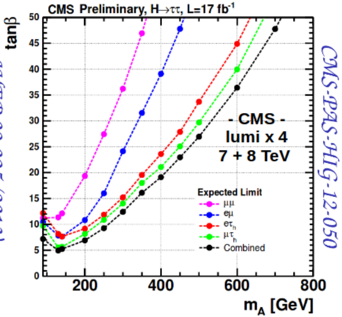
Phys. Lett. B 710, 569 (2012)

Neutral MSSM Higgs search at LHC

Same strategy for ATLAS :

- exploit 2 production modes (with and without *b*-jet),
- use larger $\sqrt{s}$: reach higher masses,
- $(\sigma_H/\sigma_Z)_{\mathrm{LHC}} > (\sigma_H/\sigma_Z)_{\mathrm{TeV}}$, due to the specific initial state.

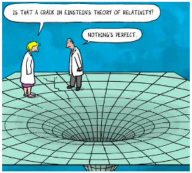




In both cases, dominated by $\tau_\mu\tau_{had}$ channel

Still a lot of open questions, from theoretical level to clear observations ...

Quantum gravity



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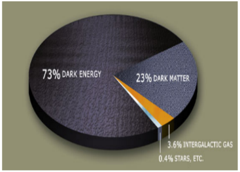

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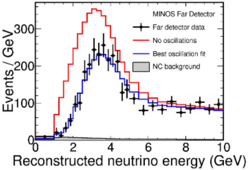

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Z' searches in ATLAS

Motivations :

- New gauge symmetry,
- Kaluza-Klein excitation,
- Relatively generic search.

Challenges :

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- τ_{had} of very high p_T : control of ϵ_{ID} and energy scale.

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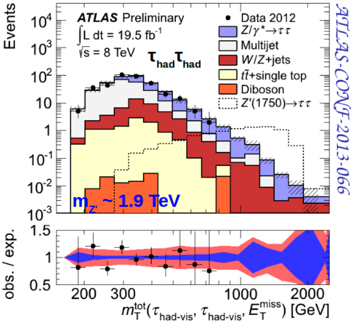
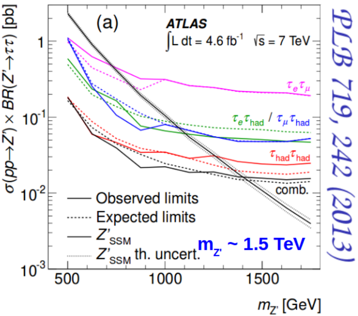
- τ_{had} of very high p_T : control of ϵ_{ID} and energy scale.





SSM ≡ Sequential Standard Model (same coupling to fermions as Z^0)

Overview

The $\boldsymbol{\tau}$ **lepton** final states provide **key informations** to understand the **Standard Model and beyond** at hadrons colliders.

Need sophisticated algorithms and a deep understanding of the experiment !

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- Test of the $V - A$ vertex at $Q \sim m_W$ - **first time at hadron colliders**.

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- Sensible to VBF, test consistency of the Higgs sector structure,
- **Evidence** at 4.1σ ! Possible perspectives for spin/CP.

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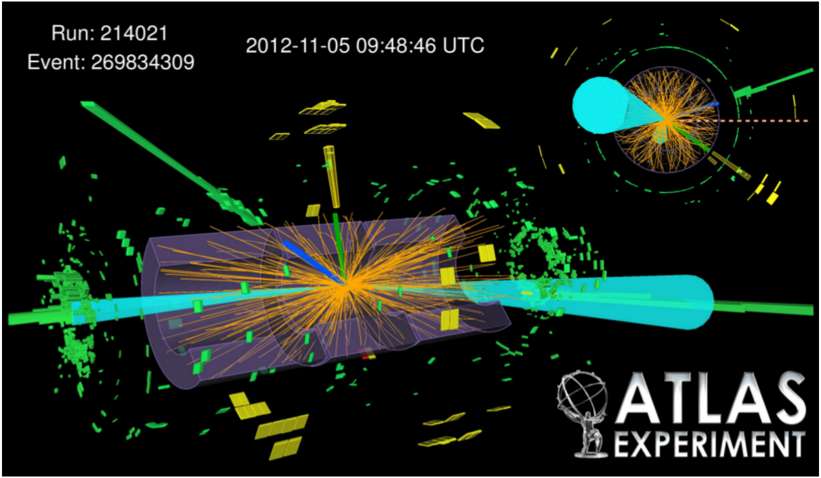
Search for new phenomena :

- Push limits of supersymmetric extensions of the SM,
- Search for bigger/new gauge symmetry,
- And many other covered areas not described here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2012-11-05 09:48:46 UTC
ATLAS
EXPERIMENT

BACKUP SLIDES

Reconstruction at DØ (1/2)

Calorimeter cluster :
found by `Simple Cone Algorithm` in a $\Delta R \leq 0.5$ cone.

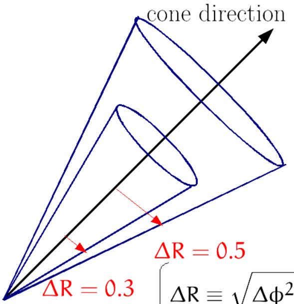
CAL clu

Electromagnetic subcluster :
found by `Nearest Neighbour Algorithm` with seed in the 3rd EM layer (finer segmentation). $E_{\text{EMsubclu}} \geq 800$ MeV.

EM sub clu

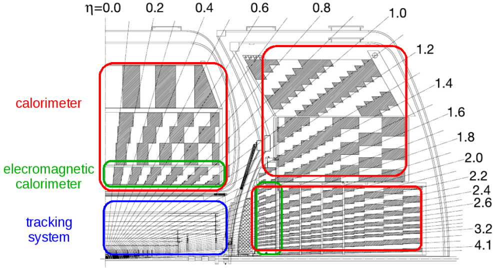
Tracks :
All tracks in a $\Delta R \leq 0.3$ cone around the cal cluster compatible with τ decay (inv. mass cut).
Highest track $p_T \geq 1.5$ GeV.

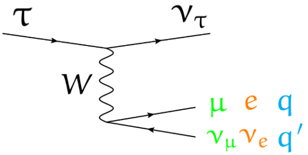
trk(s)

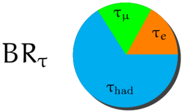


$$\begin{cases} \Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} \\ \eta \equiv -\frac{1}{2}\ln(\tan(\theta/2)) \end{cases}$$

Reconstruction at DØ (2/2)







We will focus on **hadronic decay of** τ : τ_{had}

Reconstruction and DØ τ type definition for <u>hadronic</u> decay :

- DØ type 1 $\equiv$ 1 trk , CAL clu $\sim \tau^{\pm} \to \pi^{\pm}\nu_{\tau}$
- DØ type 2 $\equiv$ 1 trk , CAL clu, EM sub clu $\sim \tau^{\pm} \to \rho^{\pm}(\to \pi^{0}\pi^{\pm})\nu_{\tau}$
- DØ type 3 $\equiv \geq$ 2 trks, CAL clu $\sim \tau^{\pm} \to a_1^{\pm}(\to 3\pi^{\pm})\nu_{\tau}$

Improvement of τ lepton identification

General point of view : Neural Network output $\eta^{\mathrm{NN}}(\vec{X})$ **converges** to

$$\eta^{\mathrm{true}}(\vec{X}) \equiv \frac{\mathcal{S}(\vec{X})}{\mathcal{S}(\vec{X}) + \mathcal{B}(\vec{X})}$$

best discriminating function, related to Prob$(S|X)$

where $\vec{X} \equiv (x_1, x_2, ..., x_n)$ describes the discriminating variables space.

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In the τ identification context :
A lot of ideas were tested to optimize the identification of τ leptons :

- Include preshower detector measurement ✗
- Exploit the long τ life time (like for b-jets) ✓

} improve $\eta^{\text{true}}(\vec{X})$

- Tune NN parameters (epoch, nodes, statistics) ✓
- Dedicated training for τ of high p_T ✓
- Dedicated training for high luminosity events ✗

} minimize $|\eta^{\text{NN}} - \eta^{\text{true}}|$

✗ $\equiv$ no improvement ; ✓ $\equiv$ improvement

Final improvement on τ identification

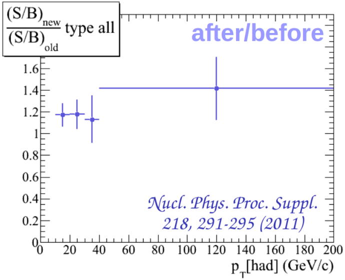
Final result :

comparaison of $S/B(p_T^{\tau_{\text{cand}}})$ before and after optimisations.

15 – 30% improvement

Tool used by the collaboration in τ related papers (arXiv :1211.6993, PRD)

Résultats présentés à TAU2010



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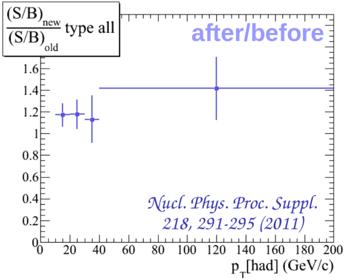
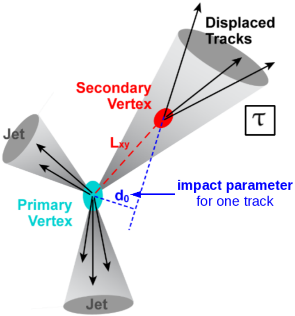
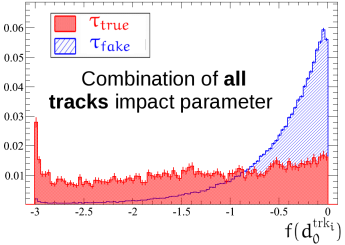


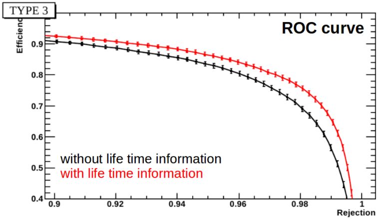
Experimental skills developped during this work on τ lepton identification

- Quite deep experience in multivariate classification,
- Reconstruction of EM energy deposit with scintillating strips detector, in an hadronic environnement (more in backup).
- Get familiar with couple of b-tagging algorithms.

τ is a long lived particle







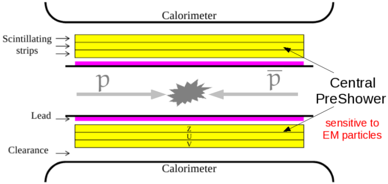
Use impact parameter to remove jets faking τ more efficiently. (large $c\tau_{\text{life}} \Rightarrow$ large d_0)

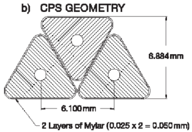
$\sim$ 10% more signal for the same bkg

Le détecteur de pieds de gerbe (CPS)

Idée physique : exploiter les résonances spécifiques de la désintégration des τ (type 2) : $\tau^\pm \to \rho^\pm \nu \to \pi^\pm \pi^0 \nu$. Utiliser la segmentation de ce détecteur, plus fine que celle du calorimètre : $\Delta\phi_{\text{CPS}} \simeq 0.1 \times \Delta\phi_{\text{calo}}$

CPS sensible aux e, γ donc permet de reconstruire un dépôt dû au $\pi^0 \to \gamma\gamma$





3 bandes scintillantes

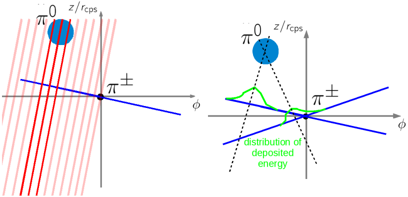
Radiateur (Pb) et 3 couches z, u, v d'environ 2600 bandes scintillantes chacunes :

- couche z (ou axiale) : les bandes sont dirigées suivant l'axe du faisceau,
- couche u : les bandes font un angle de $+23$ avec la couche z,
- couche v : les bandes font un angle de -23 avec la couche z.

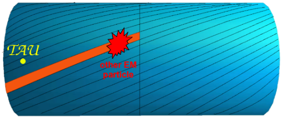
Reconstruction officielle de DØ : un dépôt CPS est reconstruit pour 85% des candidats τ et pas d'accès à l'extension transverse du dépôt. Développement d'une reconstruction dédiée à l'identification des τ.

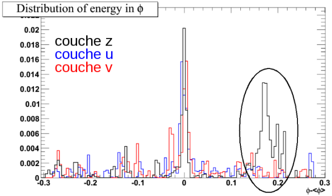
Détecteur de pieds de gerbe : reconstruction

1. Pour chaque couche, on cherche un dépôt d'énergie au voisinage de la trace du candidat ($\approx \pi^{\pm}$).



2. Corrélations entre les couches : élimination des dépôts parasites

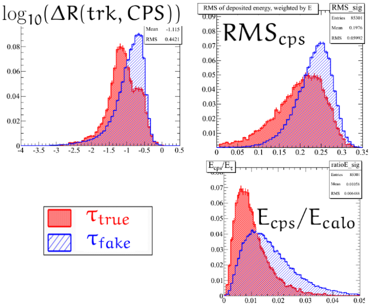




3. Les informations des 3 couches z, u, v sont combinées entre elles.

Résultat : un dépôt d'énergie $\equiv (\eta, \phi, E, \text{RMS})$ est reconstruit pour 95% des candidats

Détecteur de pieds de gerbe : résultats



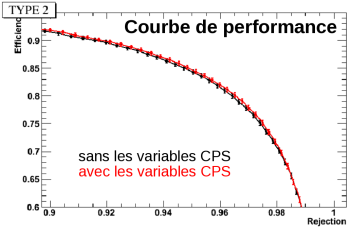
$$CPS_{\mathrm{cluster}} \approx \gamma\gamma\left[\pi^0\right], \mathrm{trk} \approx \pi^{\pm}$$

Observables :

- angle(dépôt CPS,trace)
- taille du dépôt CPS
- rapport de l'énergie calo et CPS

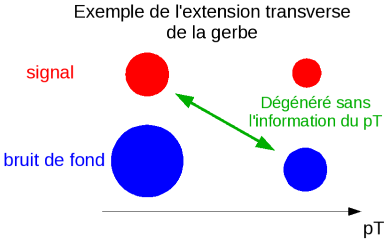
Après ajout de ces observables dans le NN, aucune amélioration significative n'a été observée.

Raison : ces informations sont fortement corrélées à celles du calorimètre.

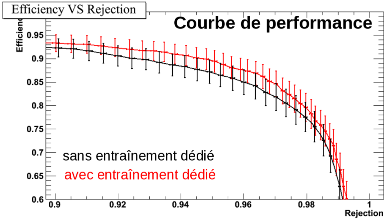


Prise en compte de la cinématique

Objectif : lever la dégénérescence entre des jets de haut p_T et des vrais τ de bas p_T



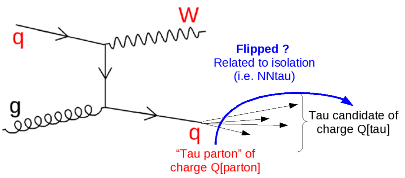
Méthode : Inclure l'information du p_T des candidats à travers un NN dédié à la région de haut p_T (45 GeV)



événements testés : $p_T(\tau) > 45$ GeV

W+jets modelling (2/3)

Strategy : Understand the origin of the NN-dep. of OS/SS

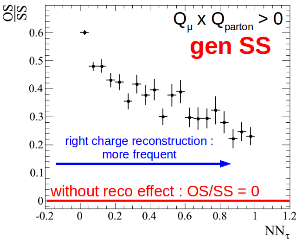


1. Some elementary processes exhibe correlation between Q_{parton} and $Q_W (= Q_\mu)$
2. Charge correlation between the parton and the reconstructed τ depends on NN_τ

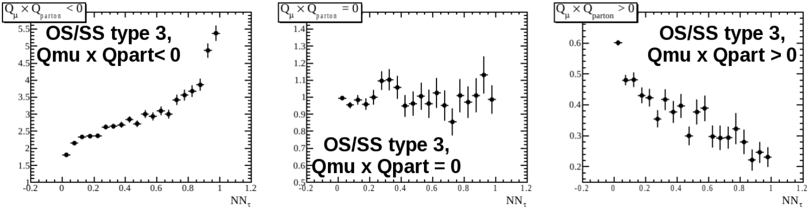
Convolution of these two effects give specific OS/SS dependence with NN_τ :

3 possibilities at the generated level :

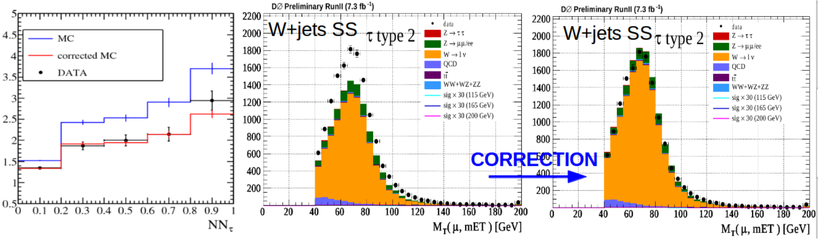
1. $Q_\mu \times Q_{\text{parton}} < 0$ (gen OS)
2. $Q_{\text{parton}} = 0$ (gluons)
3. $Q_\mu \times Q_{\text{parton}} > 0$ (gen SS)



W+jets modelling (3/3)



Model : final prediction will be a "linear combination" of 3 above plots.
Roughly : fit the relative contributions - related to q/g fraction in W+jets.

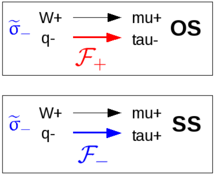


W+jets modelling

1. $W(\to \mu)$+jets$(\to \tau)$ composition assumed to have 3 componants :
   - $\widetilde{\sigma}_+$: μ and parton of same sign ;
   - $\widetilde{\sigma}_-$: μ and parton of op. sign ;
   - $\widetilde{\sigma}_0$: neutral parton (gluon).needs each

   where $\widetilde{\sigma} \equiv \epsilon_{\text{type}}\, \sigma\, \mathcal{L}$ (the τ reco. efficency ϵ can be type dependant)

2. The charge correlation have NN dependance (see previous plots). Lets consider 3 fake rates according to their charge correlation :
   - $\mathcal{F}_+(\text{NN})$: parton reconstructed as a same sign τ ;
   - $\mathcal{F}_-(\text{NN})$: parton reconstructed as an opposite sign τ ;
   - $\mathcal{F}_0(\text{NN})$: gluon reconstructed as a τ.



$$N_{OS} = \mathcal{F}_+\,\widetilde{\sigma}_- + \mathcal{F}_0\,\widetilde{\sigma}_0 + \mathcal{F}_-\,\widetilde{\sigma}_+$$
$$N_{SS} = \mathcal{F}_-\,\widetilde{\sigma}_- + \mathcal{F}_0\,\widetilde{\sigma}_0 + \mathcal{F}_+\,\widetilde{\sigma}_+$$

W+jets modelling (3/3)

Strategy : factorize the NN dependances of N_{OS} and N_{SS}. By rewritting previous equations, we have :

$$N_{OS} = F\ (1 + \rho_0 R_0 + \rho_- R_+) \quad (1)$$
$$N_{SS} = F\ (\rho_- + \rho_0 R_0 + R_+) \quad (2)$$

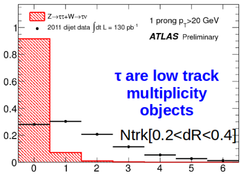
where

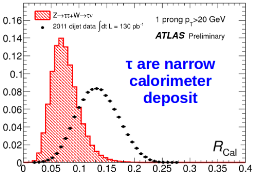
- $F = \mathcal{F}_+ \tilde{\sigma}_-$ **fake(NN-dependant) + norm.** common for OS & SS ;
- $\rho_0 = \frac{\mathcal{F}_0}{\mathcal{F}_+}$, $\rho_- = \frac{\mathcal{F}_-}{\mathcal{F}_+}$ **explain the OS/SS(NN)** (NN-dependant) ;
- $R_+ = \frac{\tilde{\sigma}_+}{\tilde{\sigma}_-}$, $R_0 = \frac{\tilde{\sigma}_0}{\tilde{\sigma}_-}$ fixed by physics and reco. (not NN-dependant).

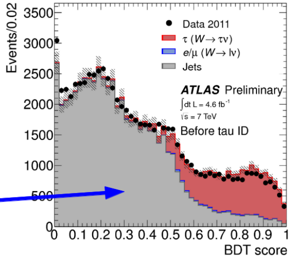
Method to measure W+jets in DATA

- assumtion : trust ρ_0(NN) and ρ_-(NN) in the MC (**ratio** of fake)
- find $(F_{NN}, R_0, R_+)_{MC}$ in MC by fitting distributions ;
- find $(F_{NN}, R_0, R_+)_{DATA}$ in DATA by fitting distributions ;
- **Correct the MC set of parameters by the data one**

Identification of τ lepton in ATLAS



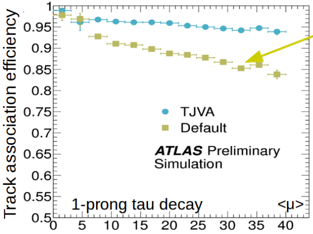




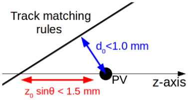
+ 6 **others observables** combined
in a Boosted Decision Tree (BDT)

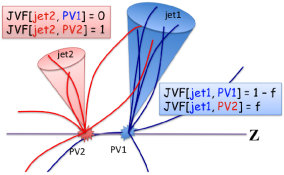
$\varepsilon_{sig} \sim 65\%$ – $\varepsilon_{bkg} \sim 2\%$

Pile-up robustness : Tau Jet Vertex Association (TJVA)



When **pile-up increases**, the PV might be wrongly selected : track-candidate matching will fail. Need to associate the right PV to the tau !





For each candidate : take the PV having the highest JVF

Trigger based on τ_{had} signature

Very challenging : reduce the rate from $\sim$ 1 GHz to few 100 Hz based on τ_{had} signature

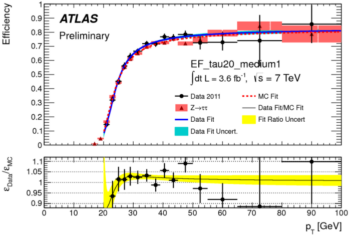
Motivations :

- Allow to exploit $\tau_{\text{had}}\tau_{\text{had}}$ final state,
- For some $\tau_\ell\tau_{\text{had}}$ final state : allow to lower p_T^ℓ threshold (wrt ℓ triggers).

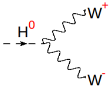
  In 2012, $p_T^\ell > 25$ GeV (at trigger level) but for $H(125) \rightarrow \tau_\mu\tau_{\text{had}}$ process, $\langle p^\ell \rangle \sim 20$ GeV : efficiency loss !

τ_{had}-based triggers :

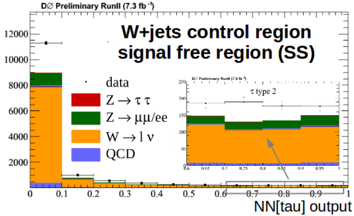
- **Level 1** : based on isolated calorimeter deposits
- **Level 2** : consider isolated tracks matching the L1 objects
- **Event Filter** : exploit shower shapes with similar algorithms to offline ID



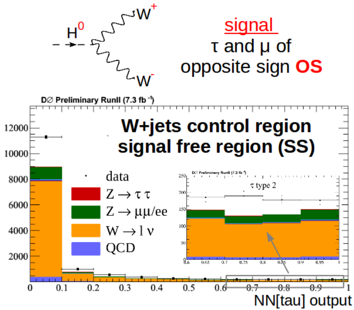
W+jets modeling (1/2)



signal
τ and μ of
opposite sign **OS**

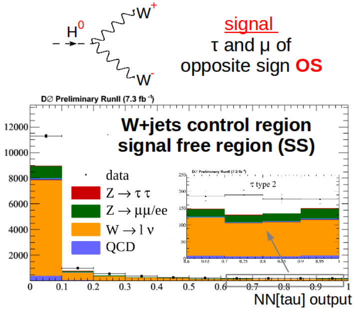


W+jets modeling (1/2)



- scale W+jets in a control region (*ie.* signal free), selected in data (SS or OS low NN_{τ})

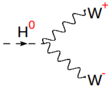
W+jets modeling (1/2)



- scale W+jets in a control region (*ie.* signal free), selected in data (SS or OS low NN_τ)
- **But** extrapolation in the signal region needs :

$$\left.\frac{\mathrm{OS}}{\mathrm{SS}}\right|_{\mathrm{MC}}(\mathrm{NN}_\tau) \rightarrow \text{well modeled ?}$$

W+jets modeling (1/2)



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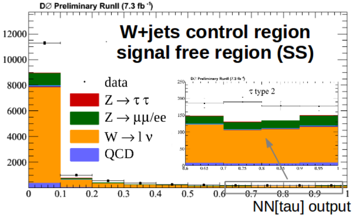
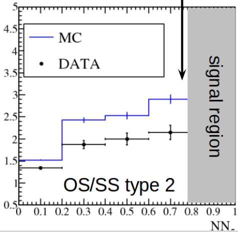


- scale W+jets in a control region (*ie.* signal free), selected in data (SS or OS low NN_τ)
- **But** extrapolation in the signal region needs :

$$\left.\frac{\text{OS}}{\text{SS}}\right|_{\text{MC}} (\text{NN}_\tau) \;\rightarrow\; \text{well modeled ?}$$

NO !

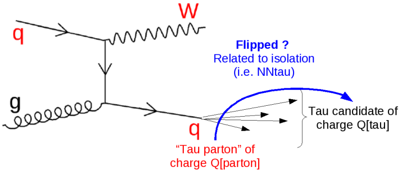


A new approach is needed :

1. understand the NN_τ variation of OS/SS,
2. build a model based on 3 parameters,
3. fit the model on data.

W+jets modeling (2/2)

Strategy : Understand the origin of the NN-dep. of OS/SS



1. Some elementary processes have correlation between Q_{parton} and $Q_W (= Q_\mu)$ - related to ***q*/*g* fraction**
2. Charge correlation between the parton and the reconstructed τ depends on NN_τ

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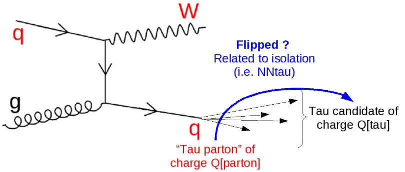
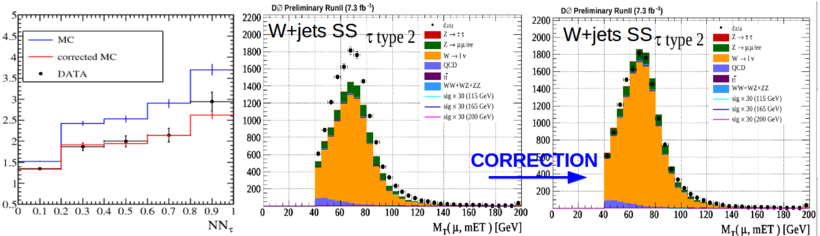


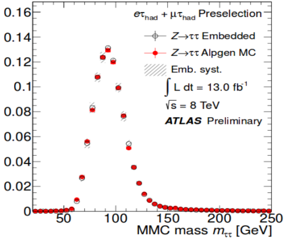
1. Some elementary processes have correlation between Q_{parton} and $Q_W (= Q_\mu)$ - related to ***q*/*g* fraction**
2. Charge correlation between the parton and the reconstructed τ depends on NN_τ

Model : final prediction will be a convolution of these 2 effects, which can be parametrized and fit in data W+jets control regions.



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

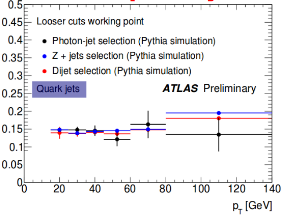
Corrected (filtered) MC :

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

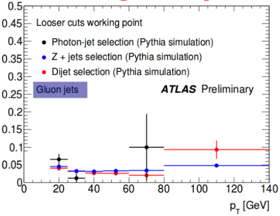
W+jets : corrected MC

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

fake : quark jets



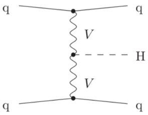
fake : gluon jets



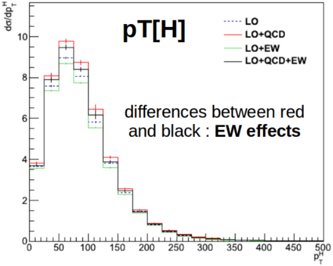
Signal modeling : EW corrections of $qq' \to qq'H$

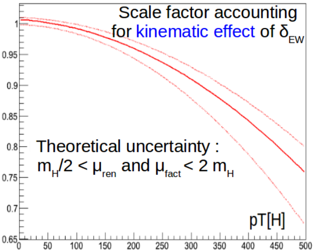
Motivations and goal :

- 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} ?



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

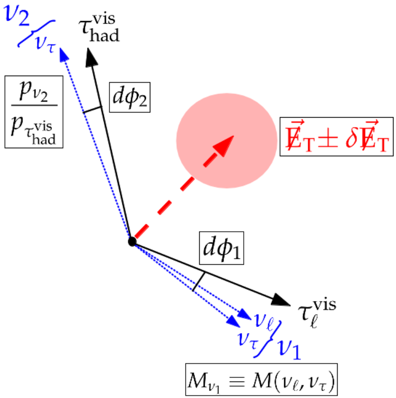


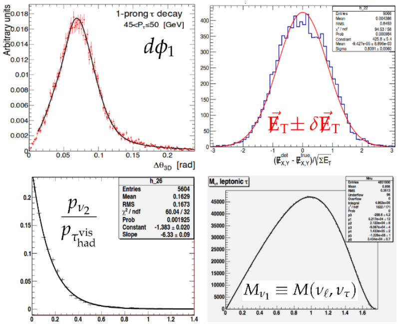


At reconstructed level :

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

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





= unknown value

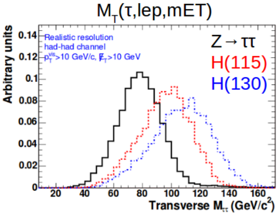
(1) **Perform a scan** over the unknowns, ie choose a config : q = ($d\Phi_1$, $d\Phi_2$, $M_{\nu 1}$, mET, p_ν/p_τ)

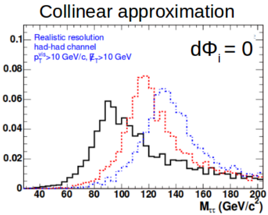
(2) For each configuration q_i : compute the **full invariant mass** m_i

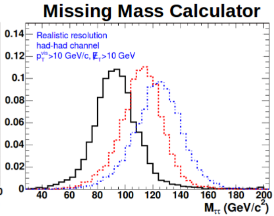
(3) Fill an histogram of m_i **weighted by w_i=PDF(q_i)** , as a product each above PDF

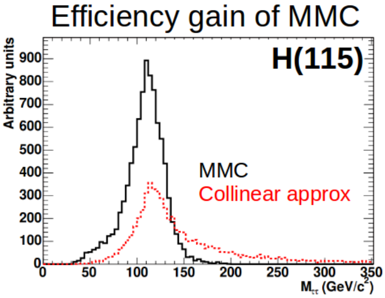
(4) Final reconstruced mass, **MMC**, is given by the **max of this histogram**

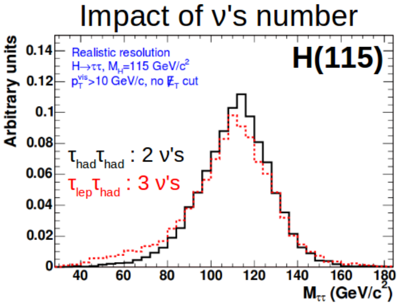
MMC : results and features







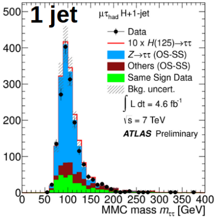


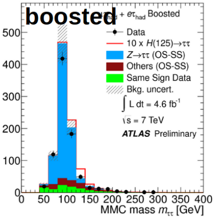


7 TeV		8 TeV	
VBF Category	Boosted Category	VBF Category	Boosted Category
▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV	–	▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV	▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ ≥ 2 jets	▹ $p_T^H > 100$ 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
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^\ell - p_T^\tau < 0$	–	• $p_T^\ell - p_T^\tau < 0$

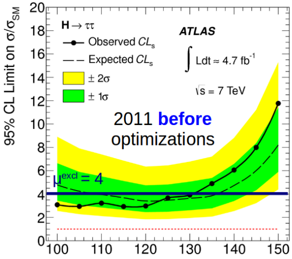
Re-optimization of 2011 analysis

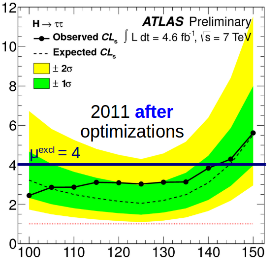
The boosted topology : defined by $p_T^H \overset{\text{reco}}{=} p_T(\ell, \tau_{\text{had}}, \not{E}_T) > 100$ GeV





- 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}
- $\sim$ sensitive as VBF category



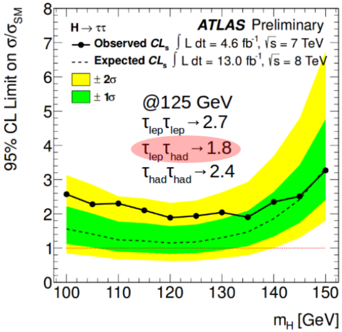


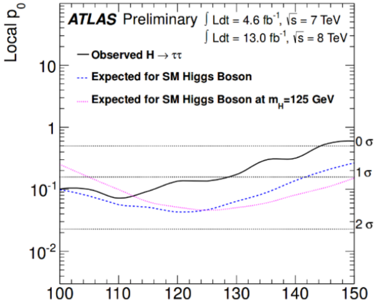
With other improvements :
expected sensitivity almost divided by 2 !

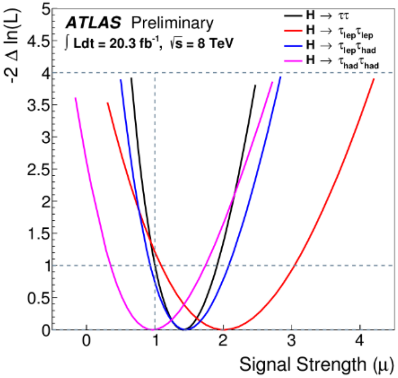
Uncertainty	$H \to \tau_{lep}\tau_{lep}$	$H \to \tau_{lep}\tau_{had}$	$H \to \tau_{had}\tau_{had}$
		$Z \to \tau^+\tau^-$	
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	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

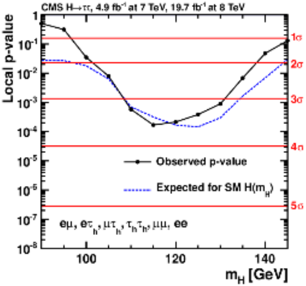
→ direct impact on final observable ($m_{\tau\tau}$)

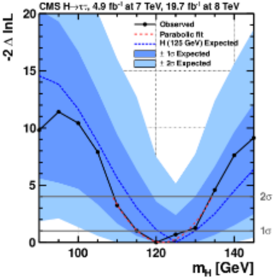


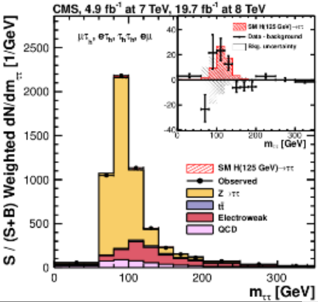


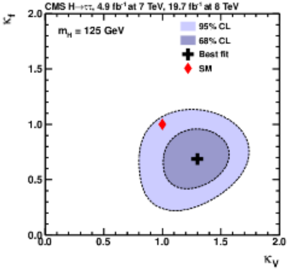


Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \to \ell\ell$ normalization ($\tau_{\rm lep}\tau_{\rm had}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{\rm lep}\tau_{\rm had}$ VBF)	0.12
Top normalization ($\tau_{\rm lep}\tau_{\rm had}$ boosted)	0.12
$Z \to \ell\ell$ normalization ($\tau_{\rm lep}\tau_{\rm had}$ VBF)	0.12
QCD scale	0.07
di-$\tau_{\rm had}$ trigger efficiency	0.07
Fake backgrounds ($\tau_{\rm lep}\tau_{\rm lep}$)	0.07
$\tau_{\rm had}$ identification efficiency	0.06
$Z \to \tau^+\tau^-$ normalization ($\tau_{\rm lep}\tau_{\rm had}$)	0.06
$\tau_{\rm had}$ energy scale	0.06


CMS H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
Local p-value
1σ
2σ
3σ
4σ
5σ
Observed p-value
Expected for SM H(mH)
eμ, eτh, μτh, τhτh, μμ, ee
100
120
140
mH [GeV]


CMS H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
-2 Δ lnL
Observed
Parabolic fit
H (125 GeV) Expected
± 1σ Expected
± 2σ Expected
2σ
1σ
100
120
140
mH [GeV]


CMS, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
S / (S+B) Weighted dN/dmττ [1/GeV]
μτh, eτh, τhτh, eμ
SM H(125 GeV)→ττ
Observed
Z→ττ
tt
Electroweak
QCD
mττ [GeV]


CMS H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
κf
mH = 125 GeV
95% CL
68% CL
Best fit
SM
κV

Uncertainty	Affected processes	Change in acceptance
Tau energy scale	signal & sim. backgrounds	1–29%
Tau ID (& trigger)	signal & sim. backgrounds	6–19%
e misidentified as τ_h	$Z \to ee$	20–74%
μ misidentified as τ_h	$Z \to \mu\mu$	30%
Jet misidentified as τ_h	Z + jets	20–80%
Electron ID & trigger	signal & sim. backgrounds	2–6%
Muon ID & trigger	signal & sim. backgrounds	2–4%
Electron energy scale	signal & sim. backgrounds	up to 13%
Jet energy scale	signal & sim. backgrounds	up to 20%
E_T^{miss} scale	signal & sim. backgrounds	1–12%
$\varepsilon_{b\text{-tag}}$ b jets	signal & sim. backgrounds	up to 8%
$\varepsilon_{b\text{-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Norm. Z production	Z	3%
$Z \to \tau\tau$ category	$Z \to \tau\tau$	2–14%
Norm. W + jets	W + jets	10–100%
Norm. $t\bar{t}$	$t\bar{t}$	8–35%
Norm. diboson	diboson	6–45%
Norm. QCD multijet	QCD multijet	6–70%
Shape QCD multijet	QCD multijet	shape only
Norm. reducible background	Reducible bkg.	15–30%
Shape reducible background	Reducible bkg.	shape only
Luminosity 7 TeV (8 TeV)	signal & sim. backgrounds	2.2% (2.6%)
PDF (qq)	signal & sim. backgrounds	4–5%
PDF (gg)	signal & sim. backgrounds	10%
Norm. ZZ/WZ	ZZ/WZ	4–8%
Norm. $t\bar{t}$ + Z	$t\bar{t}$ + Z	50%
Scale variation	signal	3–41%

Search for H^{++} (DØ)

PRL 108, 021801 (2012)

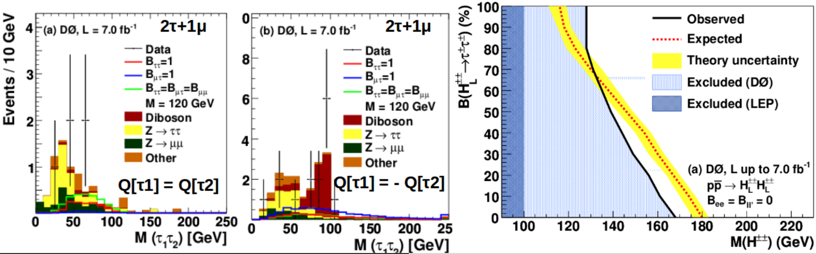
Motivations : doubly charged Higgs are predicted by :

- models with **larger gauge symmetry**, like $SU(3)_c \otimes SU(3)_L \otimes U(1)_Y$.
- **Seesaw mechanism** giving mass to neutrinos (with Higgs triplets).

Data sample : $7.3\ \mathrm{fb}^{-1}$ of analyzed data with at least 1 muon and at least 2 τ

Analysis overview :

- Production of doubly charged Higgs : $q\bar{q} \to Z/\gamma^* \to H^{++}H^{--}$
- Decay : $H^{++} \to \tau\tau, \mu\tau, \mu\mu$ ($\mathcal{BR}$ dependent on m_ν hierarchy)
- Splitting events according N_τ and N_μ, and electric charge of τs



Lepton Flavor Violation (LFV)

Motivations :

- LFV is **actually observed** in neutrino oscillations.
- SM extension should contain LFV at some level !
- Constraints from low energy physics ($\tau \to \mu\mu\mu$, $\tau \to \mu\gamma$, ...)

Study of 2 sectors at LHC : Higgs and Z decay, $X \to \mu\tau/e\tau/e\mu$

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Study of 2 sectors at LHC : Higgs and Z decay, $X \to \mu\tau / e\tau / e\mu$

LFV phenomenology : (for Z decay only)

$$g_Z m_Z^2 [\bar{\mu}\gamma_\alpha (A_{L\mu\tau} P_L + A_{R\mu\tau} P_R) Z^\alpha \tau + h.c.]$$
$$+ 2 g_Z [\bar{\mu}\gamma_\alpha (C_{L\mu\tau} P_L + C_{R\mu\tau} P_R) \partial^\beta \tau + h.c.] Z^{\beta\alpha}$$
$$+ i g_Z m_\tau [\bar{\mu}\sigma_{\alpha\beta} (D^Z_{L\mu\tau} P_L + D^Z_{R\mu\tau} P_R) \tau - h.c.] Z^{\alpha\beta}$$

A and D terms constrained by low energy measurements

$$\mathcal{BR}(Z \to \mu\tau) \sim 1.7 \times 10^{-5} \left(\frac{m_Z}{\Lambda_{NP}} \right)^4$$

Λ_{NP} : scale involved in loops generating C coefficients (Effective Operator, valid for $m_Z < \Lambda_{NP}$)

Existing constraints (a) OPAL (b) DELPHI

process	exp. limit
$BR(Z \to e^\pm \mu^\mp)$ (a)	1.7×10^{-6}
$BR(Z \to e^\pm \tau^\mp)$ (a)	9.8×10^{-6}
$BR(Z \to \mu^\pm \tau^\mp)$ (b)	1.2×10^{-5}

Interesting constraints : BR < 10^{-5}

Analysis strategy for LFV in Z decay :

- Focus on $e\mu$ final state : $Z \to e\mu$, $Z \to \tau(\to e2\nu)\mu$ and $Z \to e\tau(\to \mu2\nu)$.
- Main background : $Z \to \tau\tau \to e\mu4\nu$, reducible with kinematic.

Analysis strategy for LFV in Z decay :

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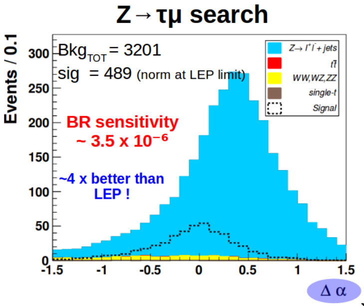
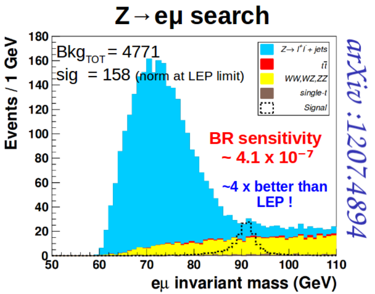
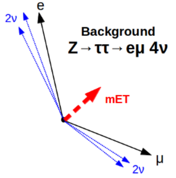
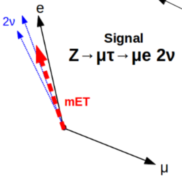


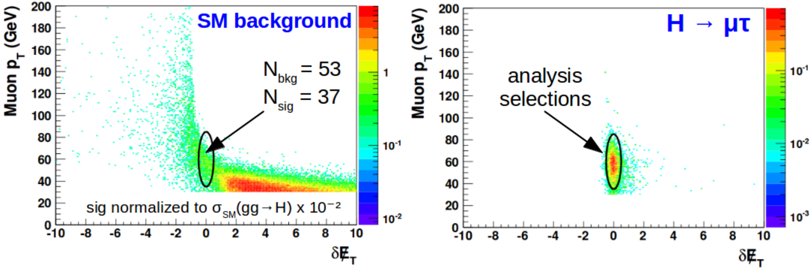






Δα : exploits **different number/direction of ν** in ττ and μτ final state

Lepton Flavor Violation in *H* decay



$$\frac{\sigma(pp(gg) \to h)}{\sigma_{SM}(pp(gg) \to h)} BR(h \to \tau^{\pm}\mu^{\pm}) < 4.5 \times 10^{-3}$$

arXiv:1211.1248

Interesting sensitivity
because probing **natural flavor violation scale** for BSM flavor model (Cheng-Sher) →

$$y_{\tau\mu} \sim \sqrt{\frac{m_\tau m_\mu}{v^2}}$$