Identification of τ leptons and Standard Model Higgs boson search in $\mu + \tau$ events at The DØ Experiment

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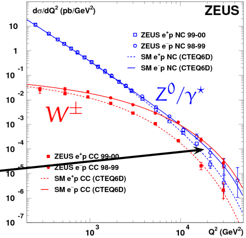
GENERAL CONTEXT

Fundamental interactions

Theory of fundamental interactions

- Gauge invariance known in EM interactions
- Generalised and etablished as a first principle
  - full dynamics of the 3 **interactions**
  - unify EM and weak interaction



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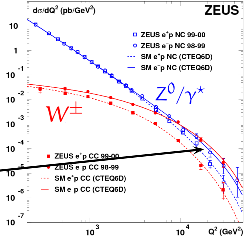
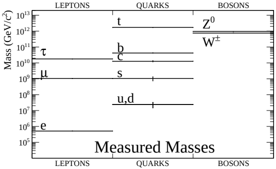


Constraints from EW gauge symmetry

- Gauge invariance not compatible with massive gauge boson : no mass term for bosons
- left-handed and right-handed fermions interacts differently : no mass term for fermions



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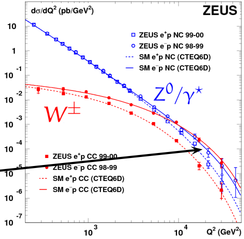

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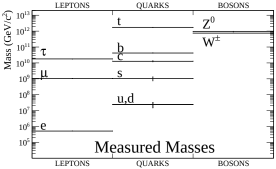


To keep benefit from gauge invariance and be compatible with experiments, one needs to dynamically generate masses of particles

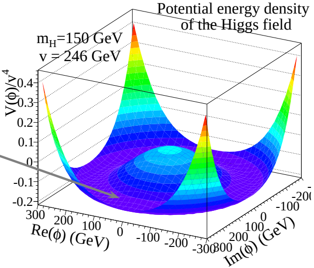
Dynamical generation of masses

Higgs-Englert-Brout mechanism

A doublet of complex scalar field Φ is introduced to spontanesously break the EW gauge symmetry :

$$\mathcal{L} = \underbrace{|D_\mu \Phi|^2}_{m_W,\, m_Z} - \underbrace{\left(\mu^2|\Phi|^2 + \lambda|\Phi|^4\right)}_{vev \neq 0}$$

$$+ \underbrace{\lambda_\ell (\bar{\nu}_\ell, \bar{\ell})_L \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \ell_R + \ldots}_{\text{fermion's mass}}$$



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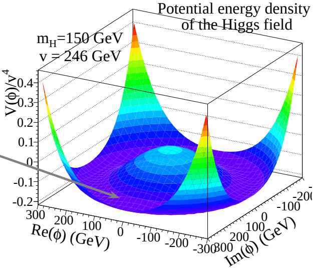


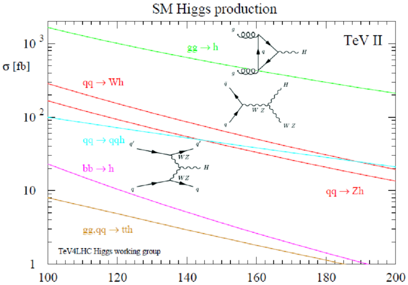
After EWSB

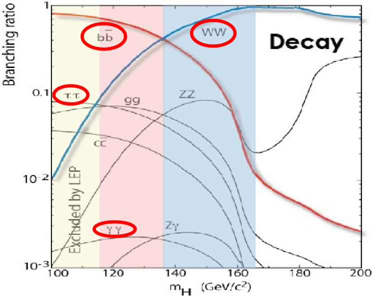
One remnante scalar excitation H, the Higgs boson, of unknown mass m_H

$\Longrightarrow$ Potential signature in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in Tevatron

$\Longrightarrow$ Experimental search strategy ?

Search strategy at Tevatron





High mass Higgs boson : $m_H \gtrsim 135$ GeV

- benefits from $gg \to H$ (at low mass H decays mainly in $b\bar{b}$, final state dominated by QCD production of $b\bar{b}$) ;
- $m_H \approx 165$ GeV : $\mathcal{BR}(H \to WW) \sim 1$.

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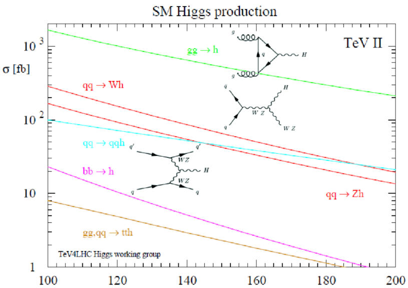

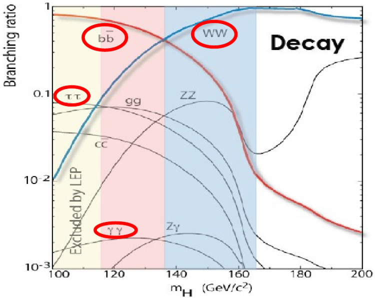

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According to *W* decays : relevent final states are $\underbrace{e\mu,\ ee,\ \mu\mu}_{\text{gloden signatures}}$, $\overbrace{\mu\tau}^{\text{additional sensitivity}}$, $e\tau$, $\tau\tau$.

Why τ leptons ?

Potential acceptance gain for leptonic final states :
$(e, \mu) \Rightarrow (e, \mu, \tau)$: single lepton $\times 1.5$, dilepton $\times 2.0$, trilepton $\times 3.0$

- **Higgs searches :** Many decay chains initiated by Higgs boson (Electroweak Symmetry breaking origin) involve τ leptons and allow to increase the sensitivity.

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- **Electroweak physics :** Test of lepton universality with $Z \to \tau\tau$ and $W \to \tau\nu_\tau$ cross section measurement.
- **Top quark physics :** top quark property measurements in τ final state are sensitive to new physics and test the Standard Model (SM) consistency.
- **New physics :** Supersymmetric extensions of SM predict new particles that can preferentially decay in τ leptons. τ final state acts as a probe of new physics.

... But experimentally challenging !

Impact of neutrino(s) involved in τ decay :

1. Invisible energy : ν escapes the detector without interaction.
2. Visible decay products are soft : more sensitive to backgrounds from multijets processes.

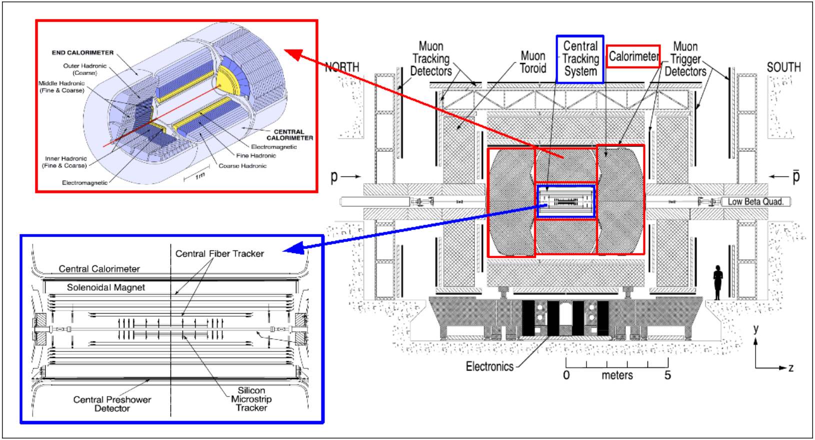
Impact of various τ decay modes :

1. **leptonic decays** ($\sim 35\%$) :
   already included in usual leptonic channels by construction.
2. **hadronic decays** ($\sim 65\%$) :
   1. different signatures depending on the hadronic final state.
   2. large bkg from multijets processes in hadronic collisions.
3. Need to combine several channels.

Hadronically decaying τ leptons require sophisticated algorithms to deal with all these difficulties.

The DØ detector

Multi purpose detector :
electrons, muons, taus, photons ID, (b-)jets, mET

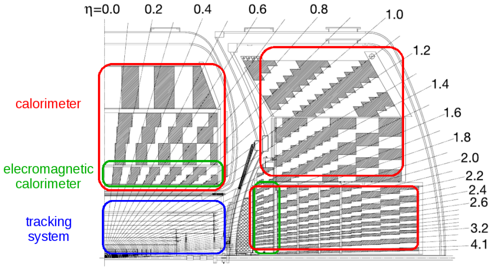


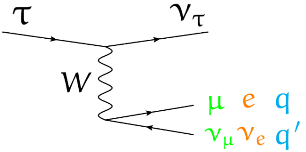
Overview

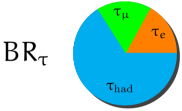
1. **General context**
2. **The τ lepton at DØ**
3. **Improvement of τ/jet discrimination**
   - Preshower information
   - Long life time of τ lepton
   - Final result
4. **Search for Higgs boson in $\mu + \tau$ events**
   - Samples and basic selections
   - Background modelling
   - Signal search and limits
   - Fourth fermion generation scenario
5. **Summary**

Reconstruction of τ lepton

Physical properties : $m_\tau = 1.78$ GeV, $c\tau_{\text{life}} = 87$ µm





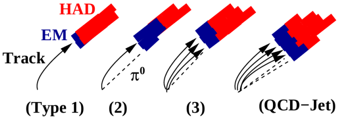


We will focus on **hadronic decay of** τ : τ_{had}

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

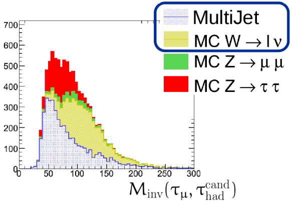
- DØ type 1 $\equiv$ 1 trk , CAL clu $\sim \tau^\pm \to \pi^\pm \nu_\tau$
- DØ type 2 $\equiv$ 1 trk , CAL clu, EM sub clu $\sim \tau^\pm \to \rho^\pm (\to \pi^0 \pi^\pm)\nu_\tau$
- DØ type 3 $\equiv \geq 2$ trks, CAL clu $\sim \tau^\pm \to a_1^\pm (\to 3\pi^\pm)\nu_\tau$

Identification of τ lepton



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

Jets could have the same experimental signatures as hadronic τ and need to be removed.



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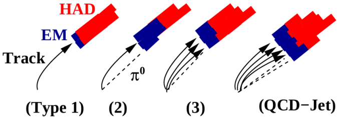

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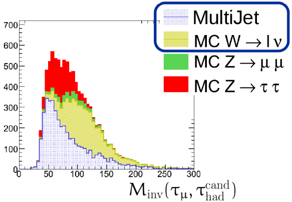
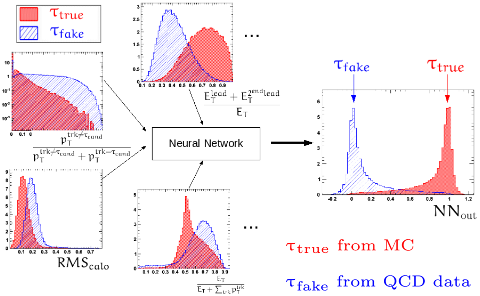


~ 12 discriminating observables

- track isolation,
- calo isolation,
- shower shape,
- trk-cal correlations.

67% eff. for 1% fake rate



τ_{true} from MC

τ_{fake} from QCD data

Overview

Optimization strategy

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

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

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

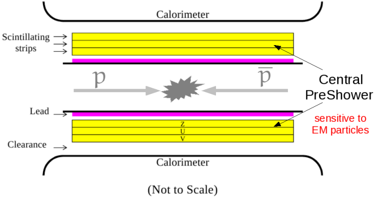
- Tune NN parameters (epoch, nodes, statistics) ✓
- Dedicated training for τ of high p_T ✓
- Dedicated training for high luminosity events ✗

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

Central PreShower (CPS) for type 2

Physical idea. Exploit specific resonance of τ **type** 2 decay : $\tau^{\pm} \to \rho^{\pm}\nu \to \pi^{\pm}\pi^{0}\nu$. Use Central PreShower detector with fine segmentation : $\Delta\phi_{\mathrm{CPS}} \simeq 0.1 \times \Delta\phi_{\mathrm{calo}}$

$$\boxed{\mathrm{CPS}_{\mathrm{cluster}} \approx \pi^{0} \ , \ \mathrm{trk} \approx \pi^{\pm}}$$



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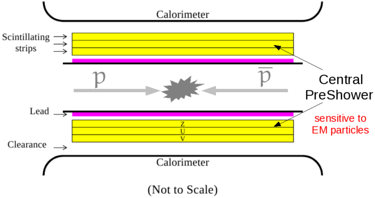

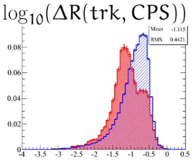

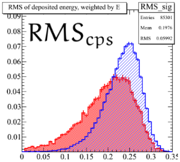

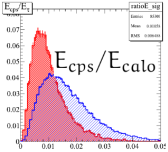

τ_{true}
τ_{fake}

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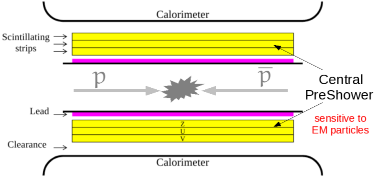
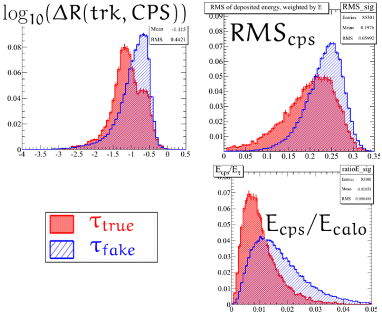


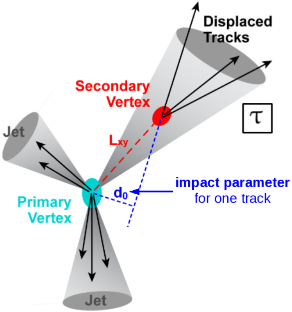
(Not to Scale)



After adding these variables in the NN **No significant improvement** was observed.

Reason : these informations were already included via calorimeter measurement.

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)

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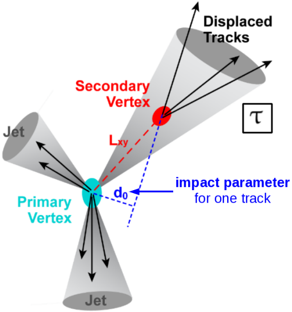

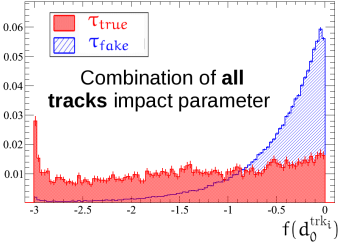

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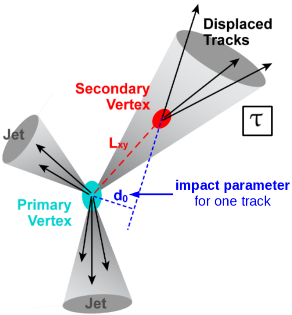

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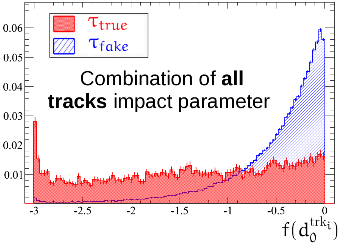

After adding these variables in the NN **clear improvement** was observed :
$\sim 10\%$ more signal for the same bkg

Impact of optimizations

Consequences of optimizations : comparison of $S/B(p_T^{\tau_{cand}})$ after a cut

1. on NN[whitout opt.] (old NN)
2. on NN[with opt.] (new NN)
3. ratio of new/old

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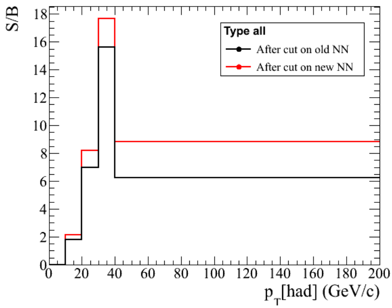
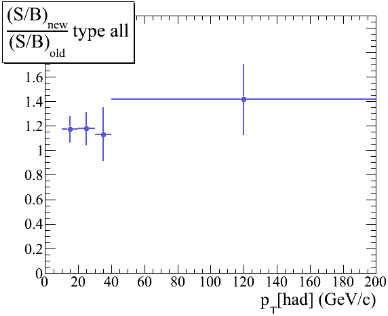
TAU2010 conf. *arXiv:1012.5400*





Optimizations bring ~ 15% improvement on $N(\tau_{true})/N(\tau_{fake})$ ratio

Overview

Data and simulated events

Data : 7.3 fb^{-1} (2002-2010), event recording based on an inclusive trigger strategy (+30% acceptance compared with muon only based trigger).

Standard Model background : generated by ALPGEN+PYTHIA

- $Z/\gamma^*(\to \ell\ell)$+jets : main background at preselections
- $W(\to \ell\nu)$+jets ($\Rightarrow \tau_{\text{cand}}$) : main background at final selections
- $t\bar{t}$, WW, WZ, ZZ (only PYTHIA for diboson processes)
- multijet from data driven method.

Signal : generated by PYTHIA for $115 \le m_H/\text{GeV} \le 200$ by 5 GeV step

- gluon fusion,
- associated productions with W and Z,
- Vector boson fusion.

Main sensitivity : $H \to WW \to \tau\nu\mu\nu$

Analyzed events :
one isolated muon and one "good" τ candidate (i.e. $NN_\tau \approx 1$)

Data understanding

Orthogonality with others searches

- $n_{jets} \leq 1$ for the $\tau\tau jj$ final state
- electron veto for the $H \to WW \to e\mu$ analysis (electons fakes τ type 2)

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$$M_T^{\min} \equiv \mathrm{Min}[M_T(\tau, \not{E}_T)\, M_T(\mu, \not{E}_T)]$$
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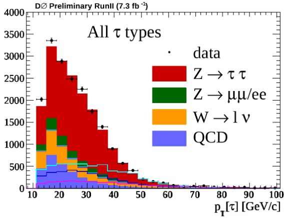
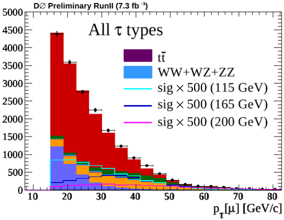
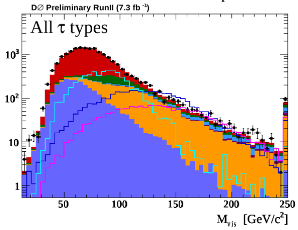
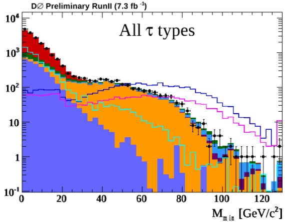




data	18956
exp. bkg	18491
exp. sig	6.6
$\frac{\text{data}}{\text{exp.bkg}}$	1.02





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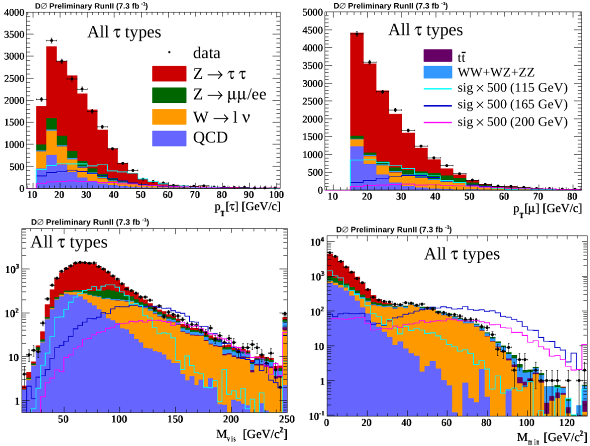

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eff of $M_{min} > 25$ GeV

Z+jets	1%
sig	80%

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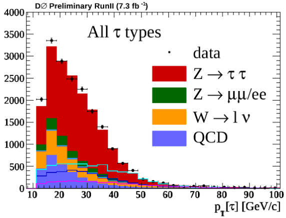
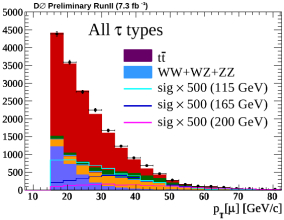
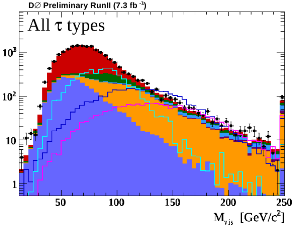
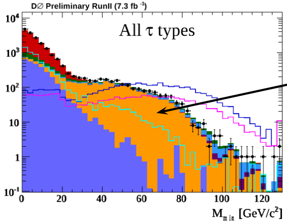
- electron veto for the $H \to WW \to e\mu$ analysis (electons fakes τ type 2)





data	18956
exp. bkg	18491
exp. sig	6.6
$\frac{\text{data}}{\text{exp.bkg}}$	1.02





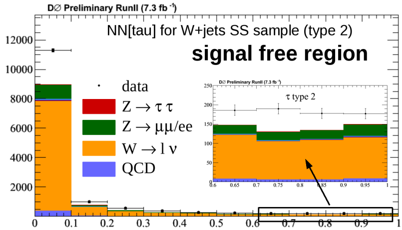
eff of $M_{min} > 25$ GeV	
Z+jets	1%
sig	80%

signal region dominated by *W*+jets. Do we have a good modelisation of it ?

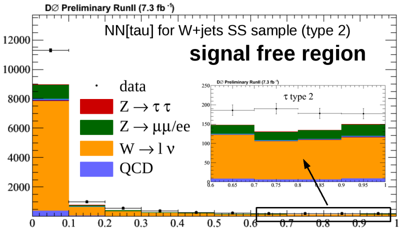
Overview

1. **General context**
2. **The τ lepton at DØ**
3. **Improvement of τ/jet discrimination**
   - Preshower information
   - Long life time of τ lepton
   - Final result
4. **Search for Higgs boson in $\mu + \tau$ events**
   - Samples and basic selections
   - Background modelling
   - Signal search and limits
   - Fourth fermion generation scenario
5. **Summary**

W+jets modelling (1/2)

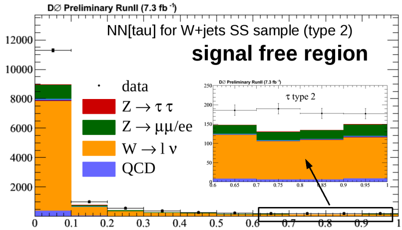


W+jets modelling (1/2)



- τ fake rate not well modelled by simulation ;
- need to be measured in SS data (signal free region) ;
- need to trust the OS/SS ratio in MC but not well modelled **already** in a signal free region.

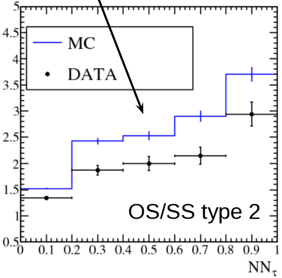
W+jets modelling (1/2)



- τ fake rate not well modelled by simulation ;
- need to be measured in SS data (signal free region) ;
- need to trust the OS/SS ratio in MC but not well modelled **already** in a signal free region.

New approach :

1. understand the origins of OS/SS NN-dep ;
2. build a model based on 3 parameters ;
3. fit the model in data.

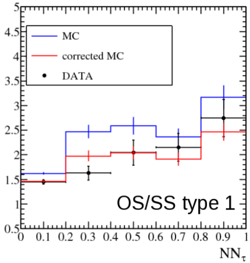


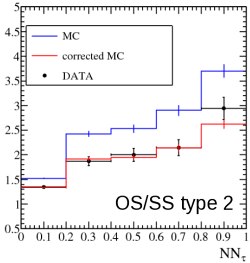
Result :

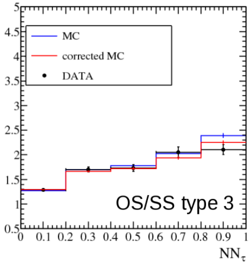
τ fake rate in the signal region is constrained from all the signal free W+jets samples

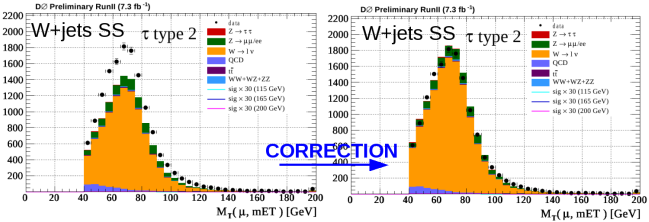
W+jets modelling (2/2)

Corrections : model parameters are obtained by a fit in data and used to correct the MC.



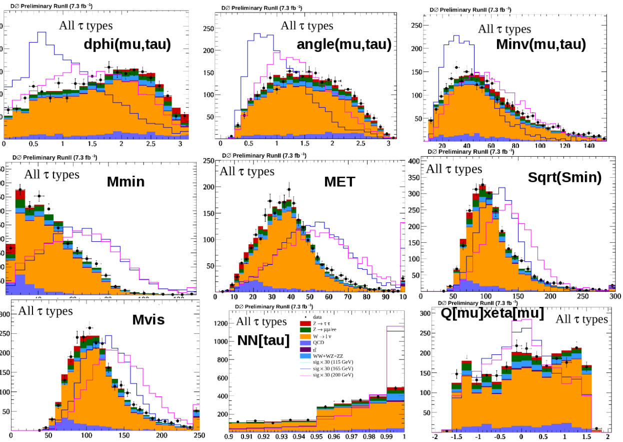






Overview

sig norm = N_{bkg}



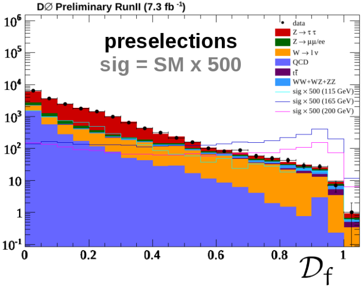
data	2473
exp. bkg	2428
exp. sig	5.3
$\frac{\text{data}}{\text{exp.bkg}}$	0.98

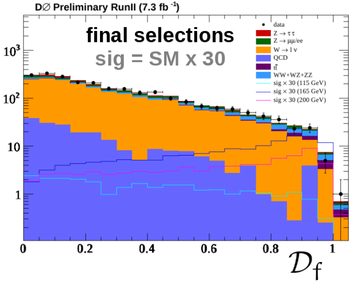
Input observables of the final discriminant $\mathcal{D}_f$.

- $M_T^{min} \equiv \mathrm{Min}[M_T(\tau, \not{E}_T)\ M_T(\mu, \not{E}_T)]$
- $M_{vis} = M_{inv}(\mu, \tau, \not{E}_T)$
- $\hat{s}_{min} = \left(\sqrt{E^2(\mu,\tau) - p_z^2(\mu,\tau)} + \not{E}_T\right)^2 - p_T^2(\mu, \tau, \not{E}_T)$

$\mathcal{D}_f$ is used to search a potential signal.

Distribution of the final variable $\mathcal{D}_f$





Main uncertainties summary (%)

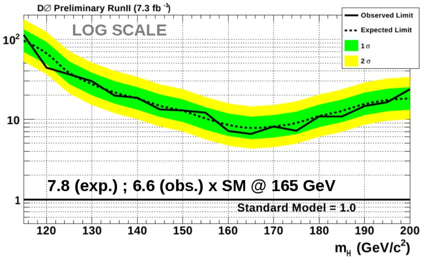
source	diboson	Z+jets	W+jets	top	QCD	H(165)
lumi+trigger	8	8	-	8	-	8
cross section	7	4	-	10	-	10
Modelling	1	-	**10**	-	-	3
QCD	–	-	-	-	20-50	-
Lepton ID	5	5	-	5	-	5
EM veto	5	-	-	5	-	5

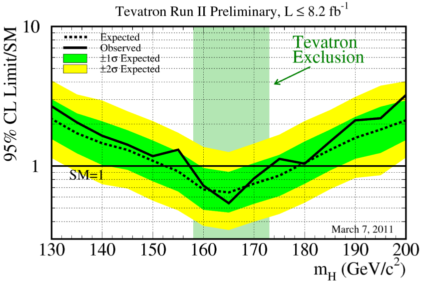
Limit on $\sigma \times \mathcal{BR} / [\sigma \times \mathcal{BR}]_{SM}$

$H \to WW \to \tau\nu\mu\nu$ *6179-Conf* included for the **first time** in

- DØ combination *6183-Conf*
- TeV combination *6184-Conf*

presented at Moriond EW 2011





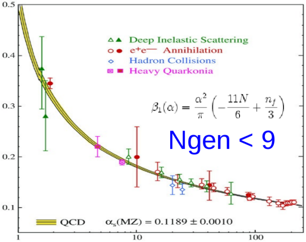
Preliminary Tevatron limits on SM Higgs boson. Exclusion at 95% CL :

$158 < m_H < 173$ GeV/c^2

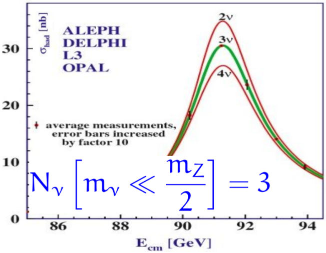
Overview

Glimpse of fourth generation constraints

QCD asymp. freedom



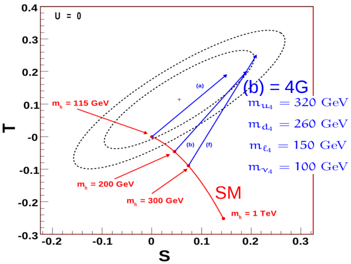
Z into hadrons



+ CKM matrix
+ theo. motiv.
+ theo. pb.
+ ...

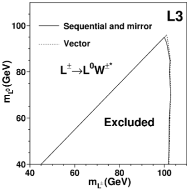
more on *arXiv:0904.4698v2*

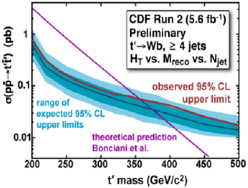
EW global fit



Direct searches (LEP & TEV)

$m_{\nu_4}, m_{\ell_4} \gtrsim 100$ GeV $\quad$ $m_{u_4} \gtrsim 360$ GeV

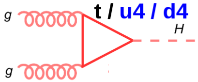




Impact on Higgs sector and result in 4G$^{\text{th}}$

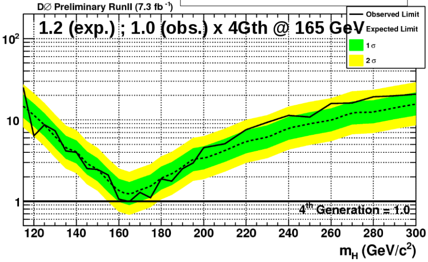
$$\mathcal{M}_{4G^{th}}(gg \to H) \overset{m_{q_4} \gg m_H}{\approx} 3\,\mathcal{M}_{SM}(gg \to H)$$

$$\boxed{\sigma_{4G^{th}}(gg \to H) \approx 9\sigma_{SM}(gg \to H)}$$



$$115\text{ GeV} \leq m_H \leq 300\text{ GeV}$$

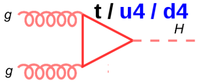
EW global fit with 4Gth



Impact on Higgs sector and result in $4G^{th}$

$$\mathcal{M}_{4G^{th}}(gg \to H) \overset{m_{q_4} \gg m_H}{\approx} 3\,\mathcal{M}_{SM}(gg \to H)$$

$$\sigma_{4G^{th}}(gg \to H) \approx 9\,\sigma_{SM}(gg \to H)$$



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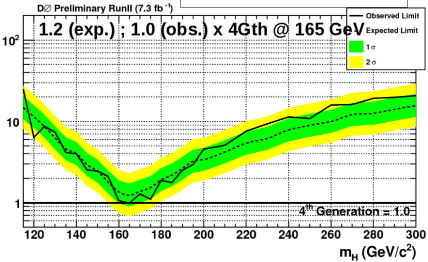

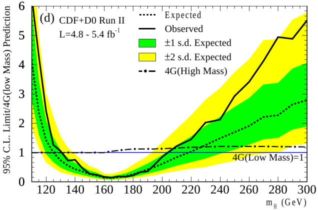

Current Tevatron limit on $4G^{th}$ Higgs boson.

$\mu + \tau$ analysis **not yet included**

arXiv:1005.3216v2

Overview

Summary

PhD started in October 2008

Work on τ leptons

- Reconstruction and identification of τ lepton involved in
  Electroweak physics, physics beyond SM, Top physics, Higgs searches
- Important impact of an improvement of jet/τ discrimination. 15% relative gain achieved during the first half of my PhD.

Summary

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Work on τ leptons

- Reconstruction and identification of τ lepton involved in
  Electroweak physics, physics beyond SM, Top physics, Higgs searches
- Important impact of an improvement of jet/τ discrimination. 15% relative gain achieved during the first half of my PhD.

Work on Higgs boson search in $\mu + \tau$ events

- $\mu + \tau$ channel add sensitivity, included for the first time in TeV comb ;
- Background modelisation is tricky, but fairly under control thanks to a dedicated study ;
- Interpretation in the SM and in the case of a fourth fermion generation.

Defence planned for September 2011

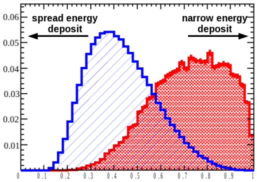
BACKUP SLIDES

Discriminating observables for τ idenfication

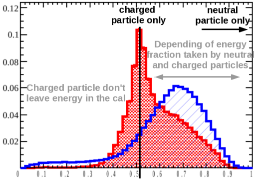
Which observables ?

- Isolation in the tracking system
- Isolation in the calorimeter
- Shower shape variables
- Correlations between tracks and calorimeter objects

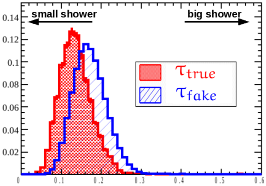
Example of input variables and their physical meaning :



$$\frac{E_T^{\text{lead Tower}} + E_T^{\text{second lead Tower}}}{E_T}$$



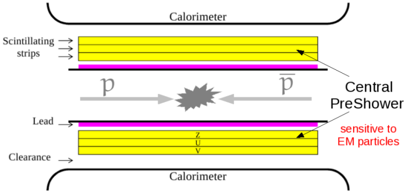
$$\frac{E_T}{E_T + \sum_{\text{trk}} p_T^{\text{trk}}}$$

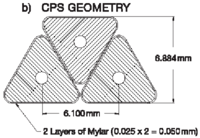


$$\sqrt{\sum_{\text{cell}_i} \frac{E_T^i}{E_T} (\Delta\phi_i^2 + \Delta\eta_i^2)}$$

Central preshower (CPS)

Physical idea. Exploit specific resonance of τ **type** 2 decay : $\tau^{\pm} \to \rho^{\pm}\nu \to \pi^{\pm}\pi^{0}\nu$. Use Central PreShower detector with fine segmentation : $\Delta\phi_{\text{CPS}} \simeq 0.1 \times \Delta\phi_{\text{calo}}$





3 layers

3 layers z, u, v of about 2600 scintillating strips each :

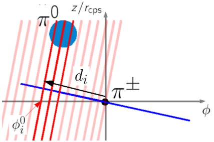
- layer z (or axial) : strips are along the beam axis ;
- layer u : strips have an angle of $+23°$ with the beam axis ;
- layer v : strips have an angle of $-23°$ with the beam axis ;

Official DØ reconstruction doesn't allow to access to the cluster size. A dedicated reconstruction for τ lepton idenfication was elaborated.

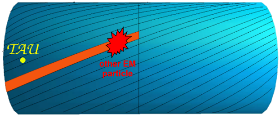
Central preshower : reconstruction

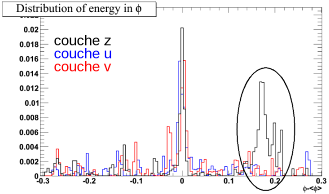
Schematical view of the elaborated reconstruction :

1. For each layer j, $\langle\phi_j\rangle, \langle\eta_j\rangle, E_j, \mathrm{RMS}_j$ are computed using strips arround the τ track $\Delta R(\mathrm{layer}, \tau_{\mathrm{track}}) \leq 0.3$;



2. Consider correlations between layers (contamination from the event) ;



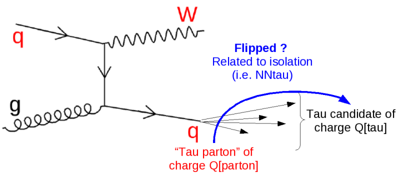


3. Combination of the information from the 3 layers z, u, v.

Result : a cluster $\equiv (\eta, \phi, E, \mathrm{RMS})$ is reconstructed with a resolution comparable to the one of the official reconstruction (algo tested in electrons)

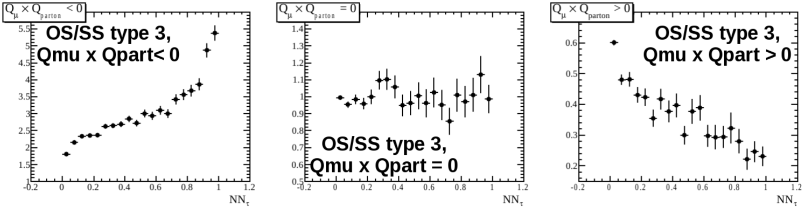
W+jets modelling (1/3)

New strategy Understand the origin of the NN-dep. of OS/SS, build a model and perform a global fit in data in a signal free region $NN_\tau < 0.9$.



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 :

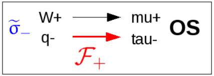


W+jets modelling (2/3)

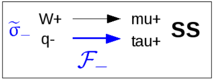
1. $W(\to \mu)$+jets$(\to \tau)$ composition assumed to have 3 componants :
   - $\tilde{\sigma}_+$: μ and parton of same sign ;
   - $\tilde{\sigma}_-$: μ and parton of op. sign ;
   - $\tilde{\sigma}_0$: neutral parton (gluon).

   where $\tilde{\sigma} \equiv \epsilon_{\text{type}}\, \sigma\, \mathcal{L}$ (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.



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



W+jets modelling (3/3)

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

$$N_{OS} = F\,(\,1 + \rho_0 R_0 + \rho_- R_+\,) \tag{1}$$

$$N_{SS} = F\,(\,\rho_- + \rho_0 R_0 + R_+\,) \tag{2}$$

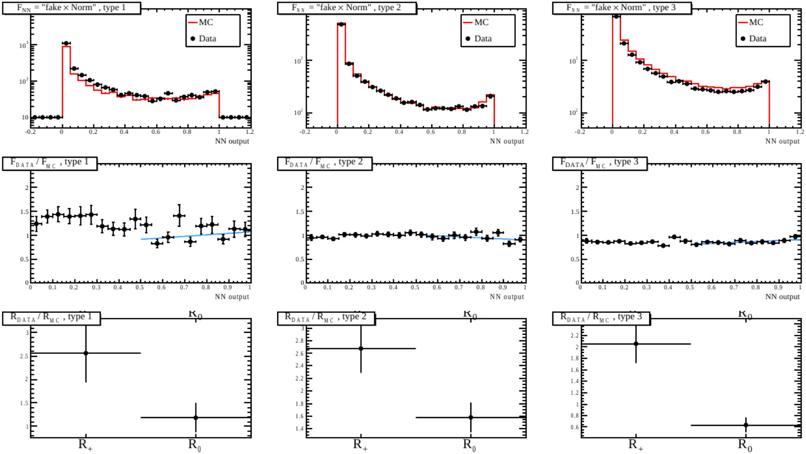
where

- $F = \mathcal{F}_+ \tilde{\sigma}_-$ **fake(NN-dependant) + norm.** <u>common for OS & SS</u>;
- $\rho_0 = \frac{\mathcal{F}_0}{\mathcal{F}_+}$, $\rho_- = \frac{\mathcal{F}_-}{\mathcal{F}_+}$ **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).

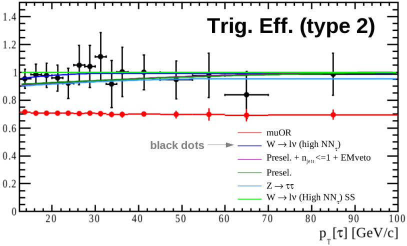
Method to measure W+jets in DATA

- 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**

W+jets correction factors



Inclusive trigger approach



p_T^τ-dependent eff. are measured wrt MuOR eff. such as :

$$\epsilon_{\mathrm{All}} = \frac{N_{\mathrm{All}}^{\mathrm{data}}}{N_{\mathrm{muOR}}^{\mathrm{data}}} \times \epsilon_{\mathrm{muOR}}$$