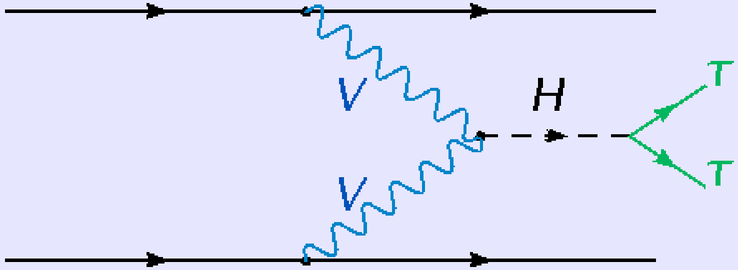
2^{nd} ARTEMIS Annual Meeting

July 3-4, 2008

“ VBF Higgs → τ(h) τ(h) ”



Z. Zenonos ☺
F. Sarri

V. Cavasinni
I. Vivarelli

Universitá & INFN di Pisa

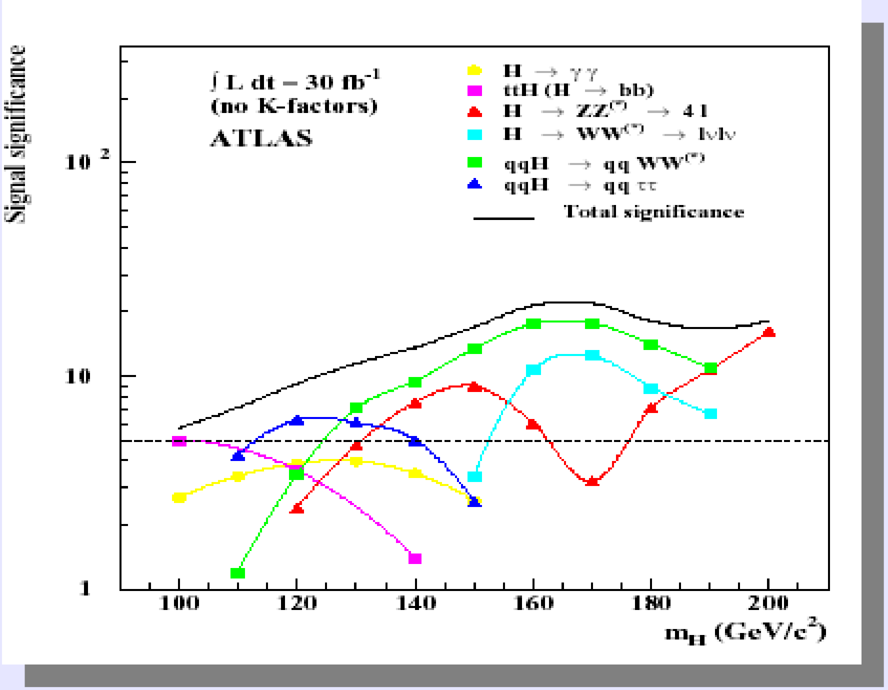
VBF Higgs :: Outline

Vector Boson Fusion Higgs @ hadronic taus

- Discovery significance at LHC environment with ATLAS
- Topology and kinematics
- Events selection analysis
- Triggering
- How we could the first data?

VBF Higgs :: Overview

- VBF Higgs → τ τ: important for the Higgs potential discovery at ATLAS in the low-mass region: $110 < m_H < 155\,GeV : \sigma_{NLO} = 4.96 - 3.52\,pb\,,\ BR(\tau\tau) = 7.5 - 1.1\%$.
- Up to recently, analysis has been performed by using only the *ll* & *lh* final states of taus.
- The *hh* channel could also contribute significantly.



- τ τ BR :

ll = 12.25% (fully leptonic) lh = 45.50% (semi-leptonic) hh = 42.25% (fully hadronic)

- VBF Higgs →τ τ production cross section: $\sigma_{LO}^{theo}(120\text{GeV}) \times BR(\tau\tau) \times BR(hh) = 124.4\,fb$
- Major backgrounds:

SoB	Z QCD	Z EW	ttbar	W→τνNj	QCD 2j
σ_S / σ_B	$4.2\text{x}10^{-4}$	0.2	$3.7\text{x}10^{-4}$	$3.4\text{x}10^{-5}$	$1.6\text{x}10^{-11}$

VBF Higgs :: Forward Jets

Topology:

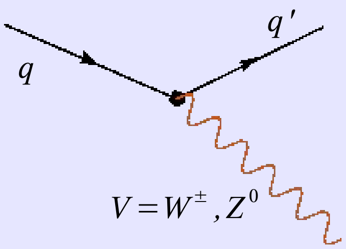
- Two forward 'tagging' high P_T jets

$$P_T(j_1) \ge P_T^{min}(j_1) \wedge P_T(j_2) \ge P_T^{min}(j_2)$$

- Forward jets occupy the opposite hemispheres

$$\eta(j_1) \times \eta(j_2) < 0$$

$$D_V \propto \frac{1}{p_V^2 - M_V^2 + i\epsilon}$$



$$p_V^2 = (p_q - p_q')^2 \approx E^2 \theta^2$$

A *t-channel* process;

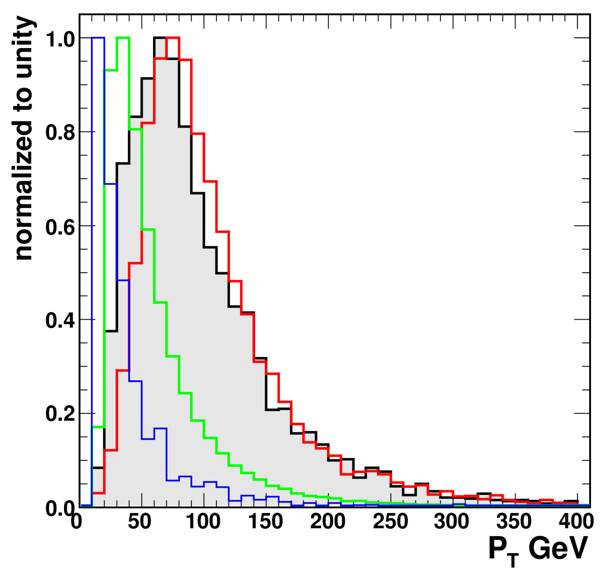
the propagator suppresses the amplitude least when p_V^2 is small:

→ small polar scattering angles θ

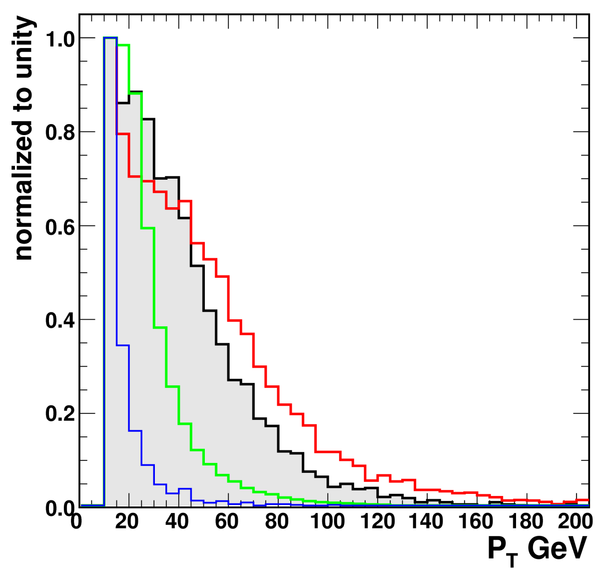
→ large pseudo-rapidity $\eta = -\log(\tan(\frac{\theta}{2}))$

- Large **Δη** separation in the pseudorapidity projection

$$\Delta\eta = |\eta(j_1) - \eta(j_2)| \ge \Delta\eta_{min}$$

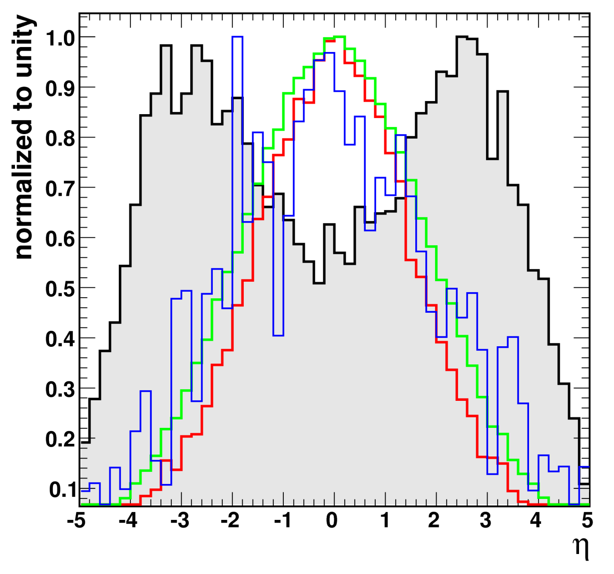


Transverse momentum of first leading forward jet.

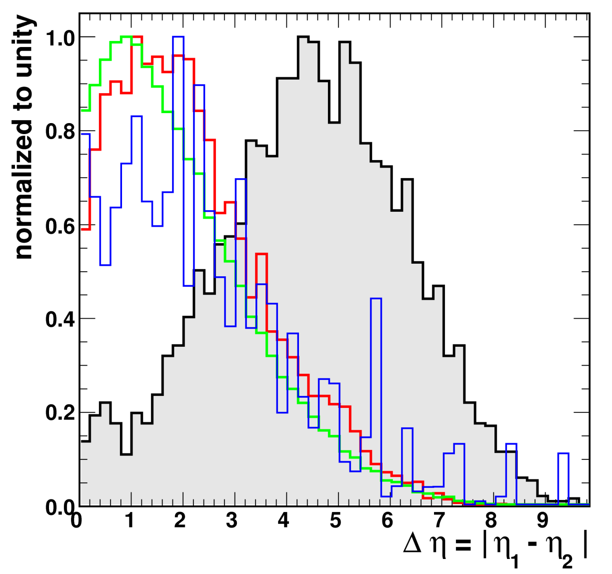


Transverse momentum of second leading forward jet.

— VBF Higgs — $t\bar{t}$ — $Z^0 \to \tau\tau$ 2j — $W \to \tau\nu$ Nj



Pseudo-rapidity distribution of the tagging jets.



Pseudo-rapidity separation of the forward jet pair.

VBF Higgs :: Forward Jets

Topology:

- Large di-jet invariant mass

$m_{j_1 j_2} \geq m_{j_1 j_2}^{min}$

- Azimuthal tagging jets separation:

VBF produces a nearly **flat** distribution $\Delta\phi_{jj}$.

☆ a new cut in the analysis

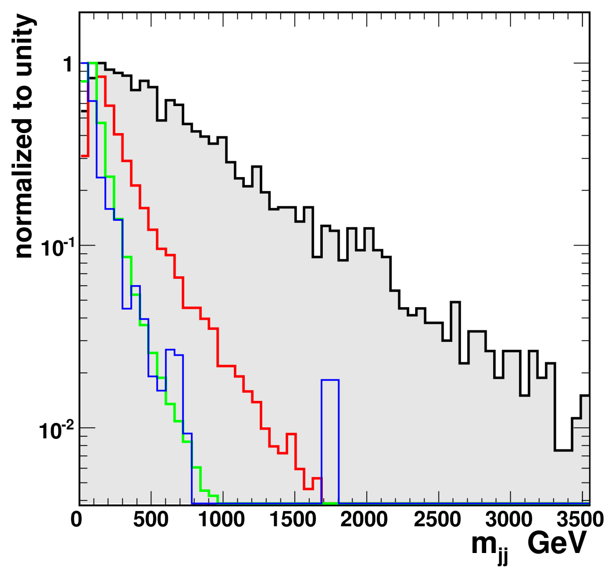
- Low central QCD jet activity – soft forward radiation (bremsstrahlung of color charge at *small* θ in the t-channel).

→ Central Jet Veto; large background reduction (QCD Z^0+multi-jets & $t\bar{t}$): two options

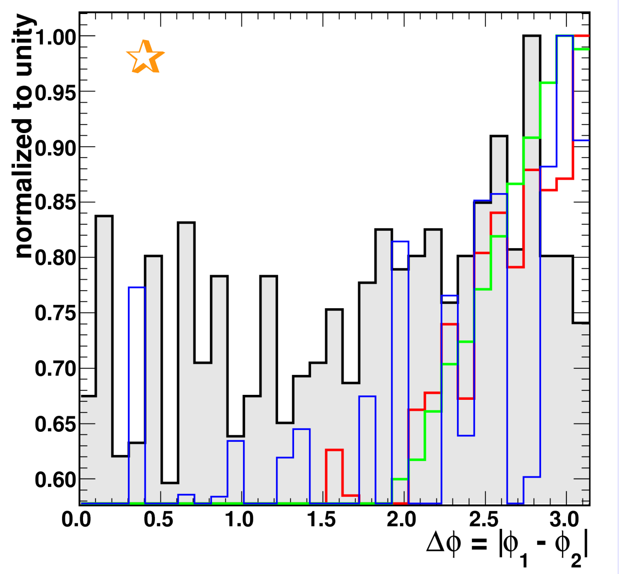
a) no jet with $P_T(j) \geq P_T^{min}(j) \wedge \eta_j^{min} \leq \eta_j \leq \eta_j^{max}$

✓ b) no jet with $P_T(j) \geq P_T^{min}(j) \wedge |\eta_j| \leq \eta_{max}^{central}$

ATLAS central region: $|\eta| \leq 3.2$

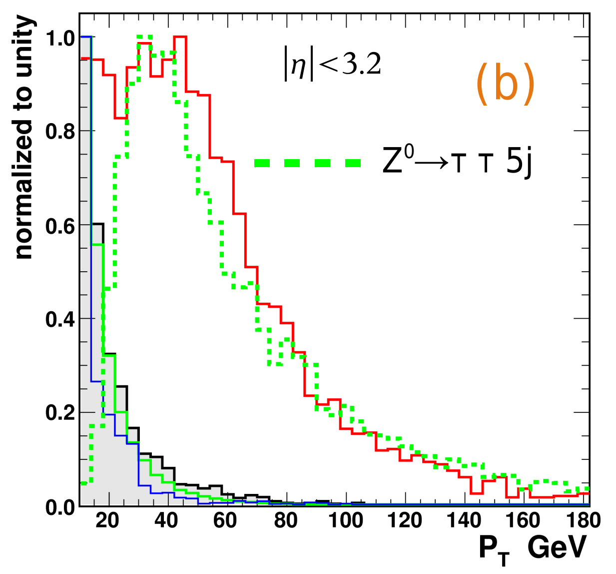


Reconstructed invariant mass of the high P_T tagging jet pair

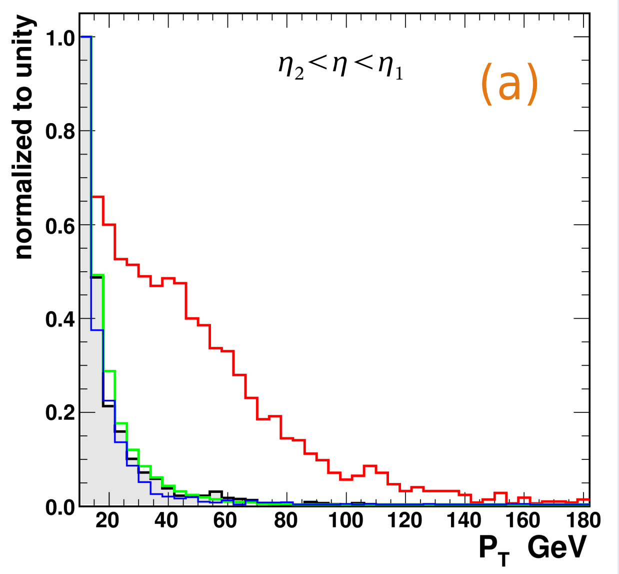


Azimuthal angular distribution.

▬ VBF Higgs ▬ $t\bar{t}$ ▬ $Z^0 \to \tau\tau$ 2j ▬ $W \to \tau\nu$ Nj



P_T of jets in the central region of the detector.



P_T of jets in the central region spanned by the tagging jets.

VBF Higgs :: Tau Jets

Topology:

- Two boosted and narrow tau jets (AtlfastTauJet candidates).

$$P_T(\tau_1) \geq P_T^{min}(\tau_1) \wedge P_T(\tau_2) \geq P_T^{min}(\tau_2)$$

- Missing transverse energy (fundamental cut to reject QCD events)

$$E_T^{miss} \geq E_{T\ \ min}^{miss}$$

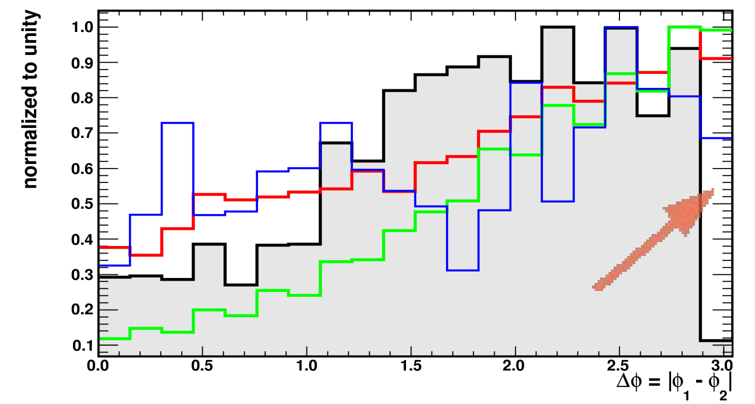
- Narrow transverse mass distribution.

$$m_T = \sqrt{2\left|\boldsymbol{P}_T(\tau_1\tau_2)\right|\left|\boldsymbol{P}_T^{miss}\right|(1-\cos\Delta\phi)} \leq m_T^{max}$$

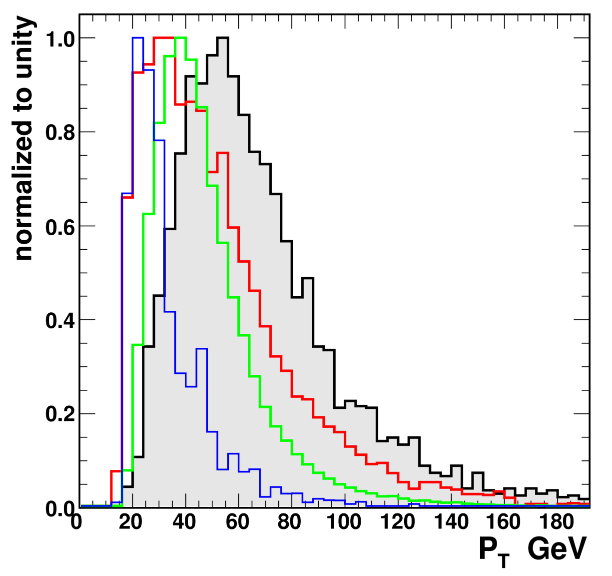
$$\Delta\phi = |\phi(\tau_1\tau_2) - \phi(P_T^{miss})|$$

- No back-to-back tau pairs

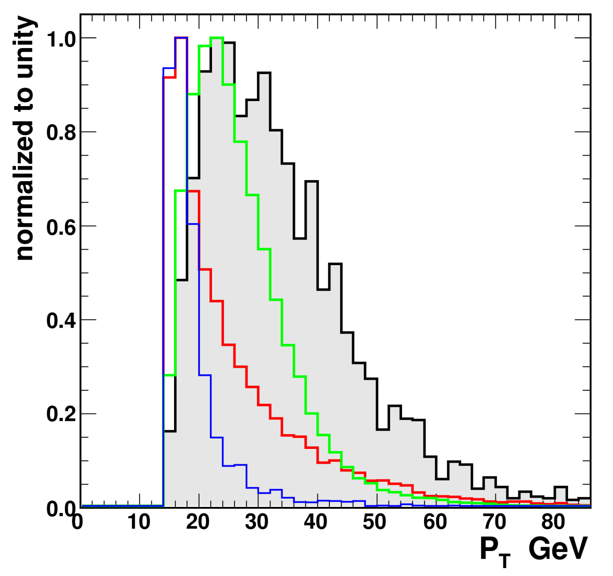
$$\Delta\phi_{\tau\tau} < \pi - \delta\phi$$



Azimuthal angular distribution of taus.

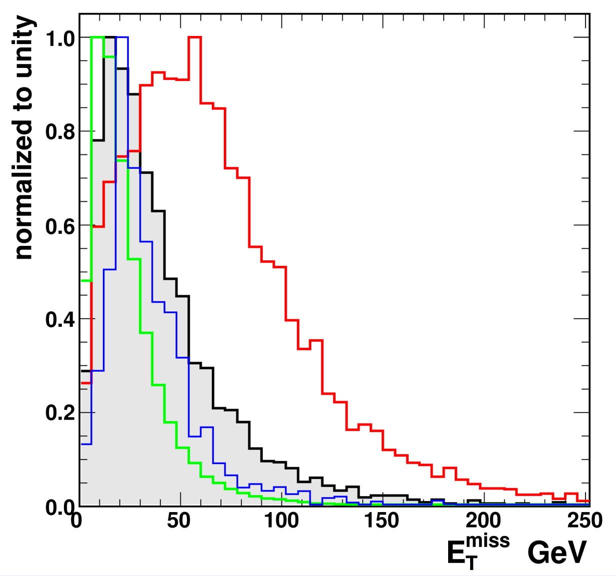


Transverse momentum of first tau jet (TauRec).

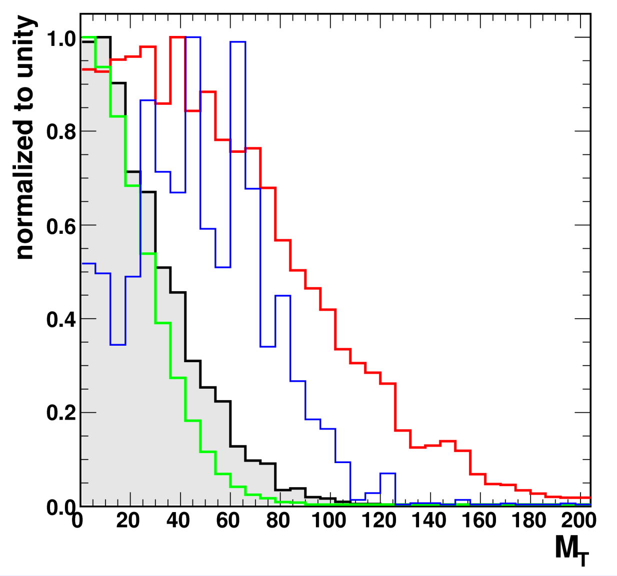


Transverse momentum of second tau jet (TauRec).

VBF Higgs — $t\,\bar{t}$ — $Z^0 \to \tau\,\tau$ 2j — $W \to \tau\,\nu$ Nj



Missing transverse energy E_T^{miss}.



Transverse mass M_T.

VBF Higgs :: Fwd jets – di-tau

Topology:

- Transverse momentum balance.

$$P_T = \boxed{P_T(j_1)+P_T(j_2)} + \boxed{P_T(\tau_1)+P_T(\tau_2)+P_T^{miss}} \le P_T^{max}$$

- Taus centrality.

Tau candidates are expected to lie centrally; two options:

✓ (a) both taus be within the eta window spanned by the forward jets:

$$\eta_j^{min} \le \eta(\tau_1) \le \eta_j^{max} \wedge \eta_j^{min} \le \eta(\tau_2) \le \eta_j^{max}$$

(b) di-tau system be within the eta gap of the 2 tag jets:

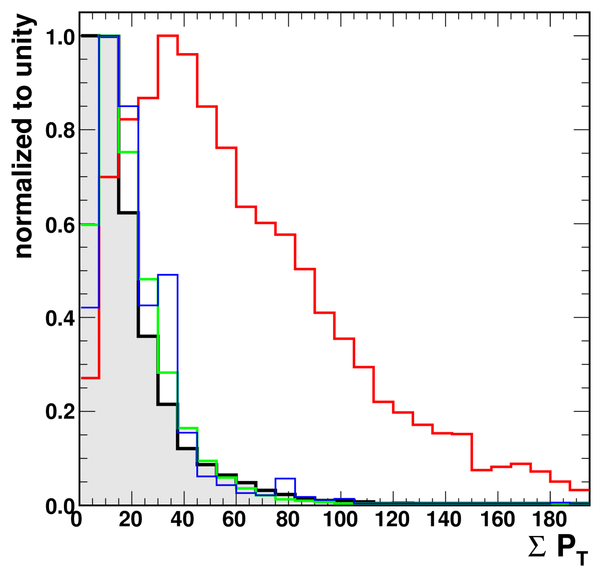
$$\eta_j^{min} \le \eta(\tau_1 \tau_2) \le \eta_j^{max}$$

- Taus polar angle distribution;

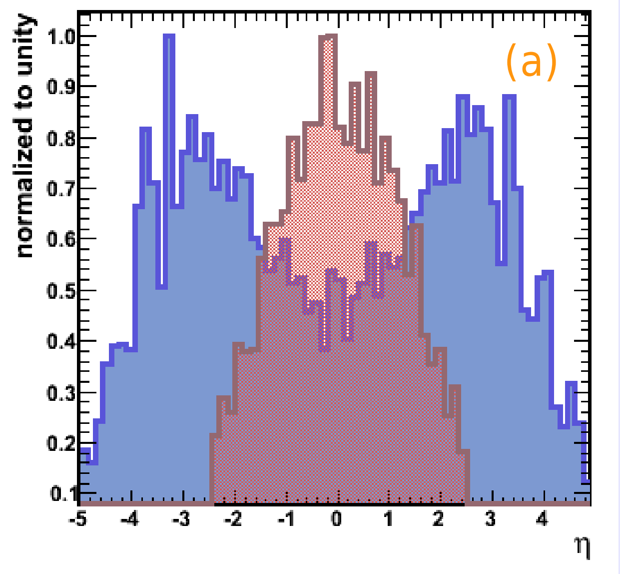
→ uncorrelated to Higgs (scalar, spin=0)

→ correlated to Z-boson (vector, spin=1)

☆ a new cut in the analysis (under study)



Momentum balance among the reconstructed taus, jets and MET.



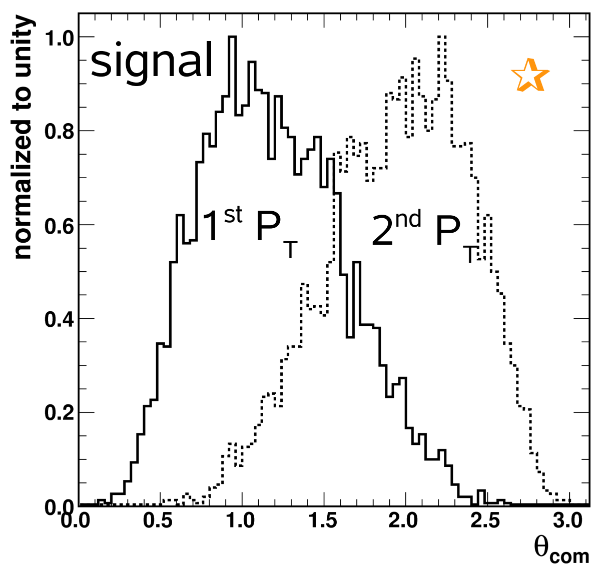
η distribution of tagging jets and tau jets.

VBF Higgs

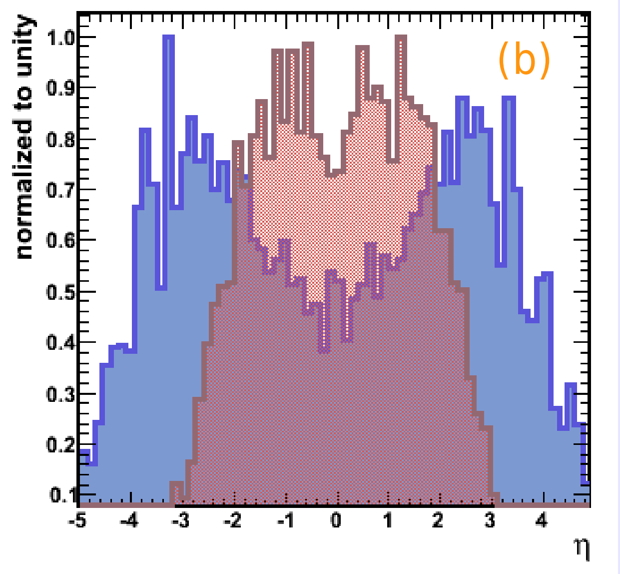
$t\bar{t}$

EW $Z^0 \to \tau\,\tau$ 2j

$W \to \tau\,\nu$ Nj

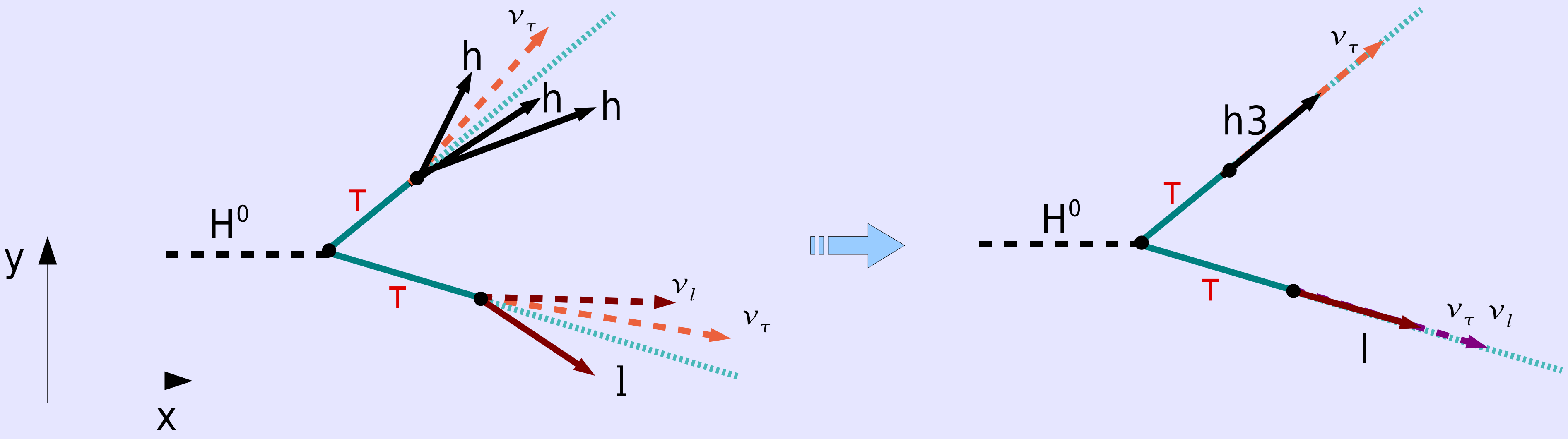


Angle between tau and reconstructed ditau measured in the COM.



η distribution of tagging jets and the di-tau system.

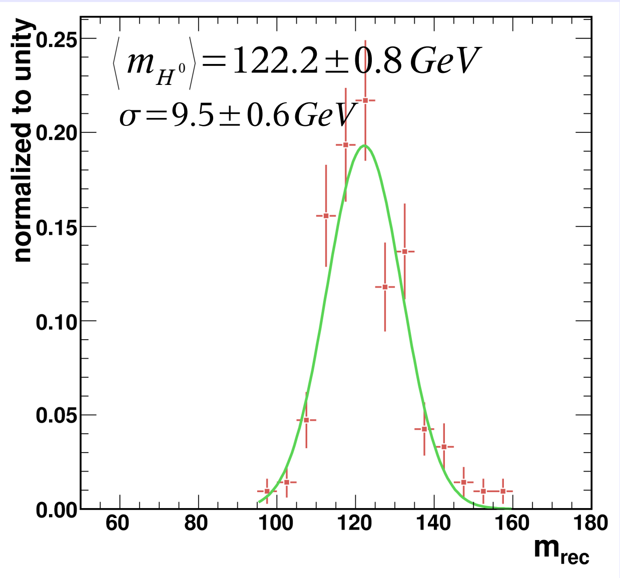
VBF Higgs :: Mass Reconstruction



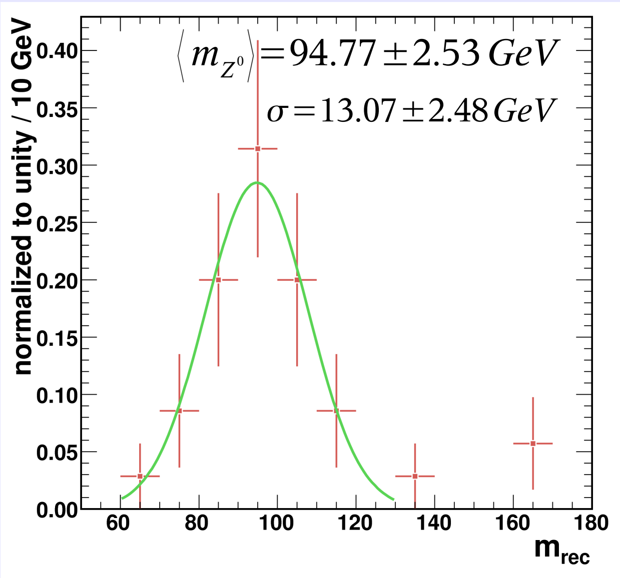
- Collinear Approximation: decay products of the boosted tau are almost collimated .
- Principle: the initial momenta are equal to the final ones in the transverse plane $\vec{P}_T^{\tau_\alpha}+\vec{P}_T^{\tau_\beta}=\vec{P}_T^{\alpha}+\vec{P}_T^{\beta}+\vec{P}_T^{miss}$.
- *The only unknowns in the collinear approximation are the 2 fractions x of parent tau energy*

  $$x_{\tau_{\alpha,\beta}}=\frac{P_T^{\vec{\alpha},\beta}}{\vec{P}_T(\tau_{\alpha,\beta})}$$

  carried by each observable decay particle .
- *α, β are the visible measured quantities.*



Reconstructed Higgs mass (input mass = 120 GeV).



Reconstructed Z^0 mass (input mass = 91 GeV).

VBF Higgs :: Collinear Approximation

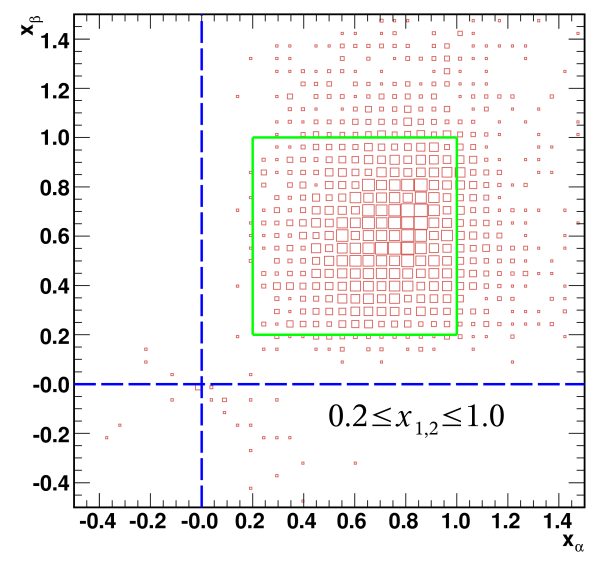
- Azimuthal angle requirement for mass reconstruction

$$\Delta\phi = |\phi(\tau_1) - \phi(\tau_1)| \leq \Delta\phi_{max} \wedge x_{1,} x_2$$

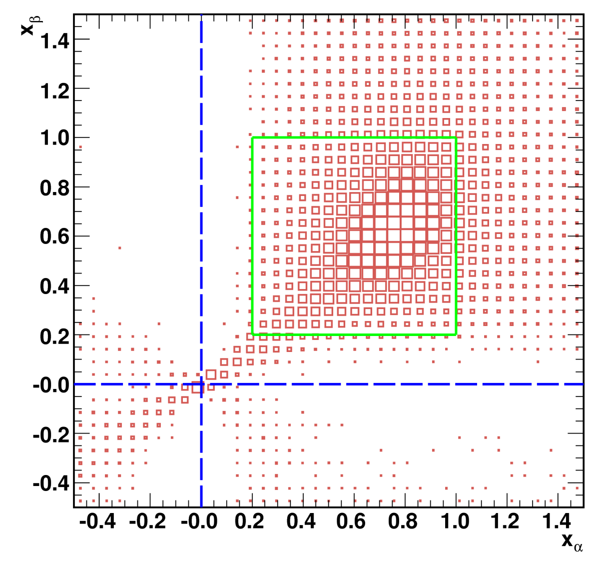
- x-momentum fractions condition: two options

✓ (a) square $x_{min} \leq x_1 \leq 1.0 \wedge x_{min} \leq x_2 \leq 1.0$

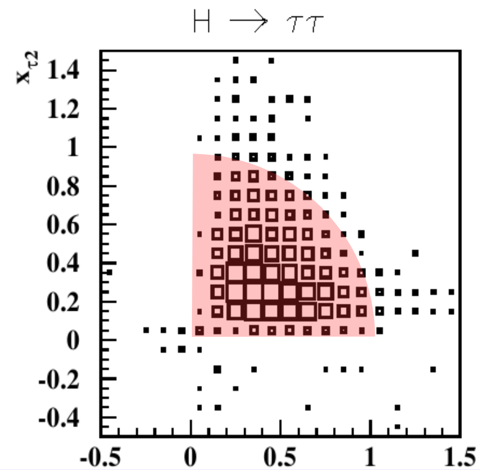
(b) quadrant $x_1^2 + x_2^2 \leq 1 \wedge x_1, x_2 \geq 0$



VBF H(120GeV) → τ^+(had) τ^-(had)

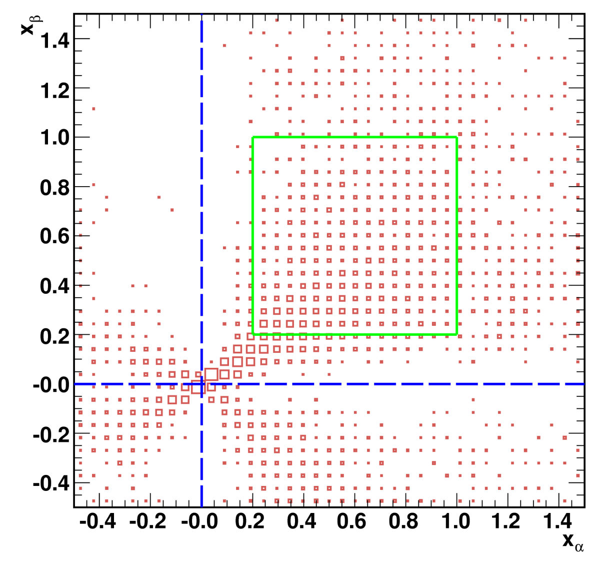


$Z^0 \rightarrow \tau^+ \tau^-$ 2 j

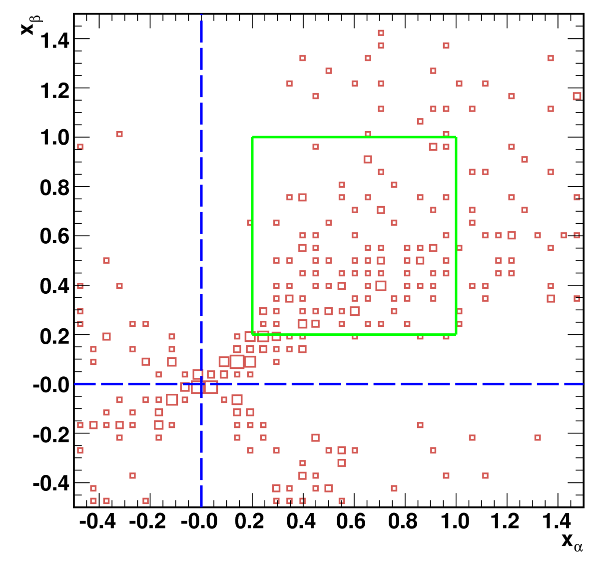


Quadrantal selection in the ll channel.

arXiv:hep-ph/0402254v1



Inclusive $t\bar{t}$.



$W^\pm \rightarrow \tau^\pm$ ν Nj

VBF Higgs :: Background Estimation

A Cut Factorization Method (CFM)

- A Monte Carlo–based prediction is limited by insufficient statistics.

- The global efficiency of the full cut selection cannot be estimated directly.

- Utilize an approximative technique to estimate the QCD background rate.

- Cut factorization procedure :
  - → ignore cuts not related to jet kinematics (tau & MET related cuts),
  - → normalize efficiency at the transverse mass M_T point of the complete cut flow.

QCD multi-jets background prediction

- Strategy:
  - → Sample of 80M AtlFast QCD di-jet events in the P_T window [17, 280] GeV.
  - → Selected events with 2 central jets above tau P_T thresholds are weighted with *TauId* parametrization from full simulation.

- Uncertainties:
  - ▸ factor 2~3 ◊ ← the parton shower (Pythia) underestimates the forward tagging jet requirement
  - ▸ factor ~5 ← the final additional safety factor to multiply the prediction of CFM

◊ SN-ATLAS-2003-024, arXiv:hep-ph/0402254

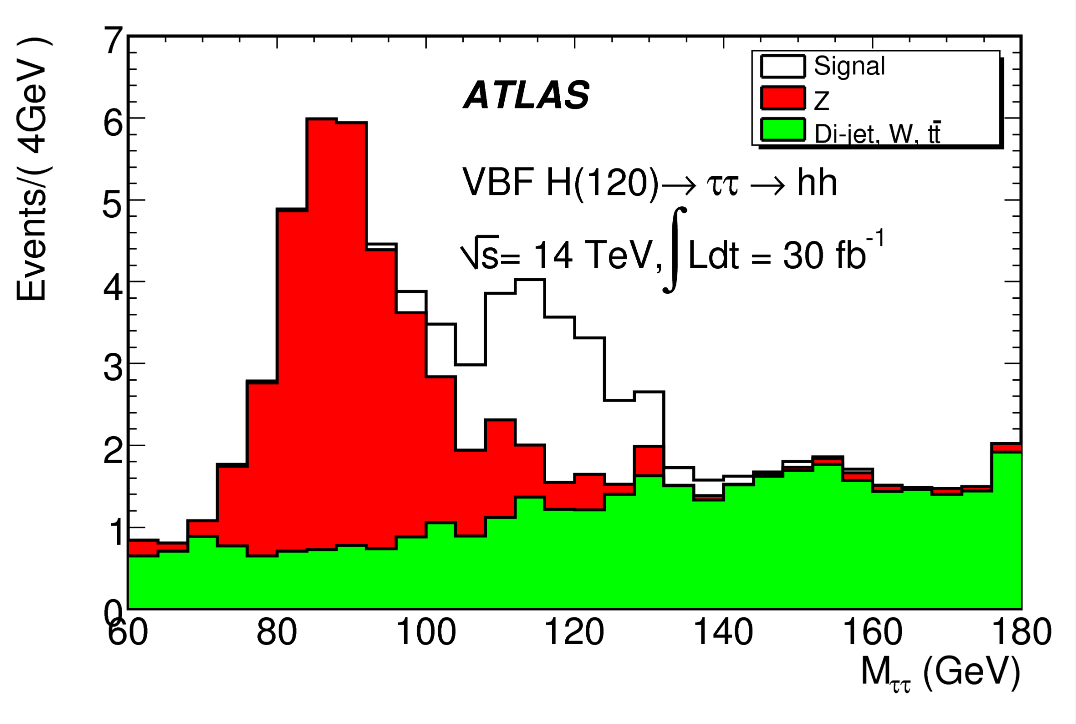
Francesca Sarri
francesca.sarri@pi.infn.it

VBF Higgs :: Analysis Summary

	VBF H(120 GeV)	Z^0 QCD	Z^0 EW	ttbar	W→τν +Nj (|η|>1)	QCD 2j X f=5
Cross Section (fb)	309.1	740E+03	1693	833E+03	9087E+03	1.91E+013
EF	73.3	40330	1693	498900	922E+03	1.91E+013
tau35i+MET40	11.4	1756	126	78177	39.6E+03	
2 hadronic taus	1.83	161	4.9	384	317	2.76E+006
MET > 40 GeV	1.43	108	3.7	352	243	970
Collinear Approx.	1.03	72	2.3	50	20	170
M_T	1.03	72	2.3	44	18	160
N jets > 2	0.86	46	2.1	39	8	86
ΣP_T	0.83	40	1.9	28	8	75
Forward jets	0.72	17	1.1	11	3	23
Jet kinematics	0.45	1.4	0.43	0.7	0.5	8
CJV	0.39	0.7	0.36	0.3	0.3	4
Mass window	0.34	0.08	0.03	0.06	0.1	1

- VBF H – hh channel,
- Red: Estimated by CFM,
- QCD multi-jets: an additional safety factor (5) is adopted.

Analysis included in the ATLAS CSC note 2008.



Potential Discovery Significance

- → $\int dt\, L = 30\ fb^{-1}$
- → Higgs input mass = 120 GeV
- → Fully simulated events
- → QCD jets background estimated by AtlFast
- → Mass window [105, 140] GeV

Including the safety factor x5

$$S=\frac{N_S}{\sqrt{N_B}}=1.65(\sigma) \qquad S=\frac{N_S}{\sqrt{N_S+N_B}}=1.47(\sigma)$$

Without the safety factor x5

$$S=\frac{N_S}{\sqrt{N_B}}=2.72(\sigma) \qquad S=\frac{N_S}{\sqrt{N_S+N_B}}=2.07(\sigma)$$

VBF Higgs :: Triggering

For the several tau final states ATLAS trigger system provides the following possibilities:

ll & lh channels

- clean signature – prompt lepton
- events are selected by **e25i** or **mu20i**
- combined triggers **tau+e**, **tau+mu**, **forward tagging jets** are under study

hh channel

- unlike the signature of the lepton trigger, a single tau trigger is expected to be exposed to the huge QCD jets background
- a combined tau trigger **tau35i+MET40**
- disadvantage of **MET40**: relatively low efficiency on signal (applied at first level of trigger)
- tau trigger performance have been improved and double tau triggers (e.g. **2tau35i**) are under study.

τ τ Final State	**Trigger Menu**	**Efficiency x Acceptance (%) (VBF Higgs 120 GeV)**
ll, lh	e25i	9.08 ± 0.03
ll, lh	mu20i	9.88 ± 0.04
hh	tau35i+MET40	3.67 ± 0.02

Mario Campanelli, UCL
mario.campanelli@cern.ch

VBF Higgs :: Triggering

Forward Jets Trigger

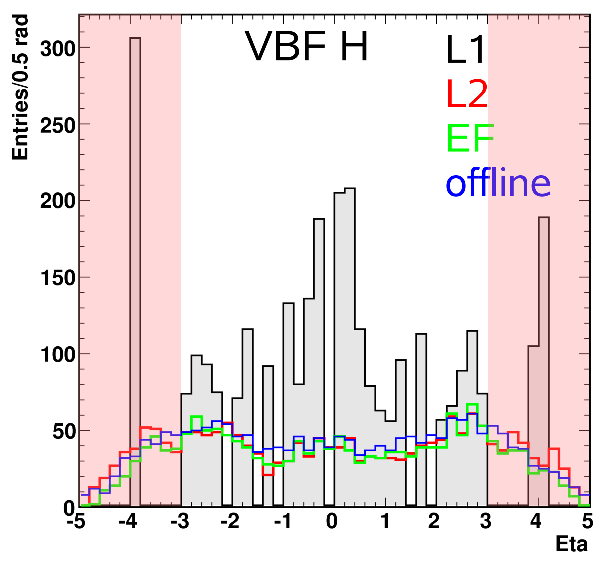
- Until a few weeks ago, FCAL data have not been unpacked at **L2** and **EF** level, so no triggering was possible for jets with |*η*| > *3.2*.
- Now, that unpacked code is present; we can access jets at trigger level in the forward region and create more complex trigger paths to apply.
- For the moment, only single-jet (e.g. **fj18**) and di-jet (**2fj18**) paths are implemented but implications for VBF physics are obvious and important.
- Plan: start this year with diffractive topologies, like jet-gap-jet and adopt a VBF trigger next year.

→ **η** distribution obtained with an *OR* of central and forward jets at trigger level:

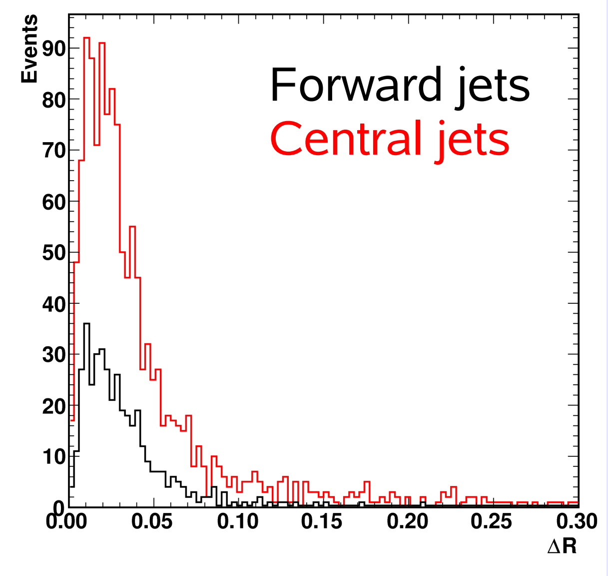
- **j18** = |*η*| <*3.2* & P_T >18 GeV
- **fj18** = 3.2 < *η* <*4.9* & P_T >18 GeV
- there are jets at |*η*| > *3.2*
- no discontinuity in ***ε*** around that area

→ **ΔR** distribution:

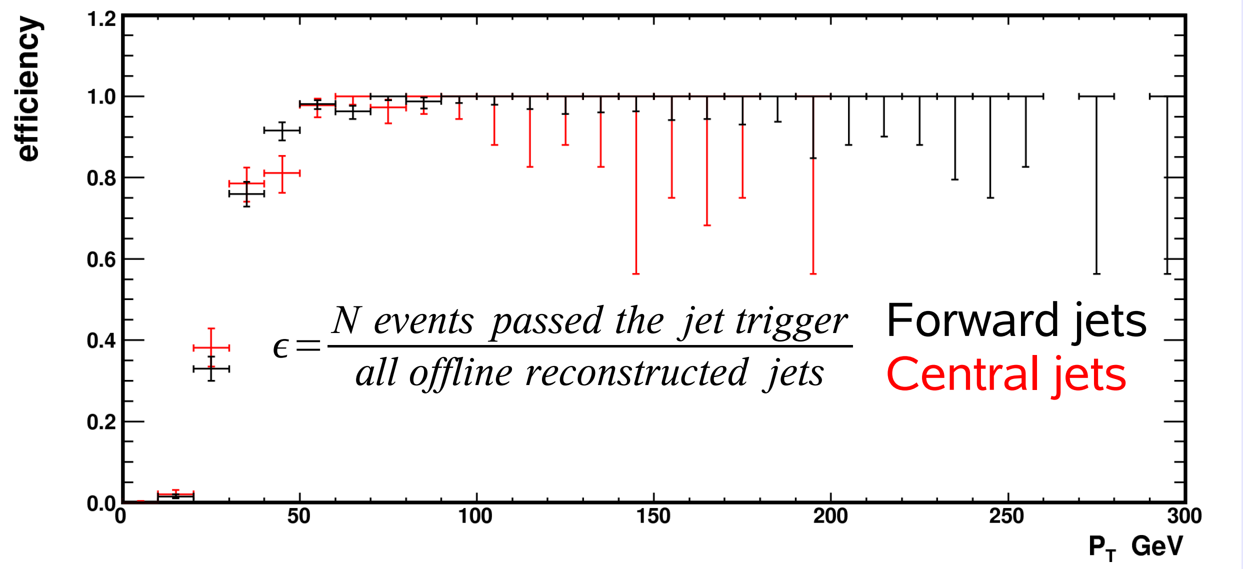
- the position resolution for forward jets is not much worse than the central ones



η *distribution obtained with an OR of central and forward jets (for |η| > 3.2 granularity has integer values).*



ΔR *between the triggered jet and the off-line reconstructed one.*



Trigger jet efficiency: is almost the same for central and forward jets.

Francesca Sarri
francesca.sarri@pi.infn.it

VBF Higgs :: Multi-Jet bkgd – First data

With the triggers **2j42_xe30** and **j70_xe30** for $L=10^{31}$, in 10 pb^{-1} of data we could have few **thousands** events (*) characterized by:

- E_T^{miss} > 40 GeV
- 4 jets :
  - two central with
    - → P_T above 35 and 30 GeV,
  - two forward with
    - → $\eta_1 . \eta_2 < 0$, $\Delta\eta > 4$,
    - → P_T > 40 and 20 GeV,
    - → M_{jj} > 700 GeV.

(*) estimated by using atlfast multijet events

This allows to study the *shape* and the *normalization* of the multi-jet background for our channel.

VBF Higgs :: Synopsis

- For first time ATLAS has investigated the potential of the VBF $H \rightarrow \tau\tau$ *hh*-channel.
- The reconstruction of the signal maintains an efficiency and $M_{\tau\tau}$ resolution comparable to the *ll*- and *lh*-channels.
- Significant improvements could be done:
  - → trigger efficiency and performance
  - → implement new analysis cuts and likelihood techniques
- Understand the tau jet efficiency power on signal and background.
- The open question for this channel is estimating the size of the QCD background; a question that can only be answered with data.

Backup Material

VBF Higgs :: Analysis Skeleton

Fast Simulation:

Jet multiplicity minimum requirement: 4 jets	✓
Tau multiplicity minimum requirement: 2 taus	✓
Event jet topology – 4 pJets +2 τJets (initial acceptance)	✓
Two tau tagged jets (TauRec)	✓
First tau candidate minimum P_T (GeV)	35.0
Second tau candidate minimum P_T (GeV)	30.0
Two forward 'tag' jets (no overlap with taucands), $\Delta R > 0.2$	✓
First forward jet minimum P_T (GeV)	40.0
Second forward jet minimum P_T (GeV)	20.0
Minimum E_T^{miss} (GeV)	40.0
Forward jets in opposite hemispheres: $\eta_1 \times \eta_2 < 0$	✓
Minimum $\Delta\eta$-gap of the forward jets	4.0
Minimum invariant mass of the forward jet pair (GeV)	700.0
Central Jet Veto: no jets in the η-range defined by the forward jets of PT >20 GeV	✓
Central Jet Veto: no jets in the central pseudorapidity region of the detector, PT >20 GeV	✘
Maximum azimuthal separation $\Delta\varphi$ between the tagging jets	2.9
Maximum $\Delta\varphi$ between the taus (to ensure the collinear approximation functionality)	2.9
Momentum fraction carried by tau: $x_{min} < x_i, x_j < x_{max}$	✓
Momentum fraction carried by tau: $x_a^2 + x_b^2 < 1$	✘
Minimum x_a-fraction in collinear approximation / tau reconstruction	0.2
Maximum x_b-fraction in collinear approximation / tau reconstruction	1.0
Maximum reconstructed transverse mass M_T (GeV)	80.0
Taus centrality: both taus be within the η-window spanned by the forward jets	✓
Taus centrality: taus as system be within the η-gap of the 2 tagging jets	✘
Maximum amplitude of the total vector P_T (ΣP_T balance) (GeV)	60.0
Taus angular correlation to spin	✘
Left offset of the reconstructed Higgs mass window (GeV)	15.0
Right offset of the reconstructed Higgs mass window (GeV)	20.0
Higgs recontructed mass center point (GeV)	120.0

VBF Higgs :: Analysis Skeleton

Full Simulation: **... +**

trigger tau35i + L1 MET40	✓
Two tau tagged jets of PT	> 30, 35 GeV
Good tau candidate (TauRec):	✓
$\Sigma\|Q\|$	1.0
Σ Ntracks = 1 or 3	1 or 3
Likelihood discriminant > 4	30.0
Opposite sign cut	✓
Electron veto:	✓
if $\|\eta(\tau)\| < 1.7$ → TRT_HT_Hits / TRT_Hits	<0.2
EHAD/EEM > 0.002 in full pseudorapidity range in AOD within $\Delta R(\eta, \varphi)<0.1$ (Electron author =1,3)	✓

VBF Higgs :: AtlFast MultiJet Estimation

	3jets (Id.6916)	Cross (pb)	Lumi (pb^{-1})	Trigger
Total	1255000	17000000	0.073	
$E_T^{miss} > 40GeV$	820			
4jets	385			
2 central	131			3 w. 2jets > 42GeV & E_T^{miss} > 30GeV
2 forward	3			2 w. 1 jet > 70GeV & E_T^{miss} >30GeV

	4jets (Id.6917)	Cross (pb)	Lumi (pb^{-1})	Trigger
Total	2295000	2630000	0.87	
$E_T^{miss} > 40GeV$	2626			
4jets	2145			
2 central	1275			19 w 2jets > 42GeV & E_T^{miss} > 30GeV
2 forward	23			18 w 1jet > 70GeV & E_T^{miss} >30GeV

	5jets (Id.6918)	Cross (pb)	Lumi (pb^{-1})	Trigger
Total	2000000	521000	3.84	
$E_T^{miss} > 40GeV$	5053			
4jets	4999			
2 central	4081			147 w 2jets > 42GeV & E_T^{miss} > 30
2 forward	164			133 w 1jet > 70GeV and E_T^{miss} >30

VBF Higgs :: Collinear Approximation

Collinear Approximation; A method to reconstruct tau pairs

Principle of the collinear approximation:conservation of momenta in the *x-y* plane

$$\boxed{\vec{P}_T^{\tau_\alpha} + \vec{P}_T^{\tau_\beta} = \vec{P}_T^{\alpha} + \vec{P}_T^{\beta} + \vec{P}_T^{miss}}$$

$$x_{\tau_\beta} = \frac{\vec{P}_T^{\beta}}{\vec{P}_T^{\tau_\beta}} \rightarrow \vec{P}_T^{\tau_\beta} = \frac{\vec{P}_T^{\beta}}{x_{\tau_\beta}} \qquad \frac{P_x^\alpha}{x_{\tau_\alpha}} + \frac{P_x^\beta}{x_{\tau_\beta}} = P_x^\alpha + P_x^\beta + P_x^{miss} \qquad x_{\tau_\alpha} = \frac{\vec{P}_T^{\alpha}}{\vec{P}_T^{\tau_\alpha}} \rightarrow \vec{P}_T^{\tau_\alpha} = \frac{\vec{P}_T^{\alpha}}{x_{\tau_\alpha}} \qquad \frac{P_y^\alpha}{x_{\tau_\alpha}} + \frac{P_y^\beta}{x_{\tau_\beta}} = P_y^\alpha + P_y^\beta + P_y^{miss}$$

$$x_{\tau_\beta} = \frac{P_y^\alpha P_x^\beta - P_x^\alpha P_y^\beta}{P_y^\alpha P_x^\beta - P_x^\alpha P_y^\beta + P_y^\alpha P_x^{miss} - P_x^\alpha P_y^{miss}} \quad (1)$$

$$x_{\tau_\alpha} = \frac{P_y^\alpha P_x^\beta - P_x^\alpha P_y^\beta}{P_y^\alpha P_x^\beta - P_x^\alpha P_y^\beta + P_x^\beta P_y^{miss} - P_y^\beta P_x^{miss}} \quad (2)$$

$$m_{\tau\tau}^2 = (p_{\tau_\alpha} + p_{\tau_\beta})^2 = (p_{\tau_\alpha})^2 + (p_{\tau_\beta})^2 + 2(p_{\tau_\alpha}).(p_{\tau_\beta})$$

$$E_\tau = \sqrt{(p_\tau^2 + m_\tau^2)} \simeq p_\tau ,\; p_\tau \gg m_\tau \qquad p_{\tau_\alpha,\mu}\, p_{\tau_\beta}^{\mu} = E_{\tau_\alpha} E_{\tau_\beta} - \vec{p}_{\tau_\alpha} \vec{p}_{\tau_\beta} \approx p_{\tau_\alpha} p_{\tau_\beta} (1 - \cos\theta_{\tau_\alpha \tau_\beta})$$

$$\vec{P}_{\tau_\alpha} = \frac{\vec{P}_\alpha}{x_{\tau_\alpha}} = \frac{1}{x_{\tau_\alpha}} (P_x , P_y , P_z)_\alpha \rightarrow |\vec{P}_{\tau_\alpha}| = \frac{1}{x_{\tau_\alpha}} |\vec{P}_\alpha| \qquad \rightarrow \cos\theta_{\tau_\alpha \tau_\beta} = \frac{\vec{P}_{\tau_\alpha} . \vec{P}_{\tau_\beta}}{|\vec{P}_{\tau_\alpha}| . |\vec{P}_{\tau_\beta}|} = \frac{\vec{P}_\alpha . \vec{P}_\beta}{|\vec{P}_\alpha| . |\vec{P}_\beta|} = \cos\theta_{\alpha\beta}$$

$$\boxed{m_{\tau\tau}^2 \approx 2 \left(m_\tau^2 + 2 \frac{p_\alpha}{x_\alpha} \frac{p_\beta}{x_\beta} \sin^2 \frac{\theta_{\alpha\beta}}{2} \right)}$$