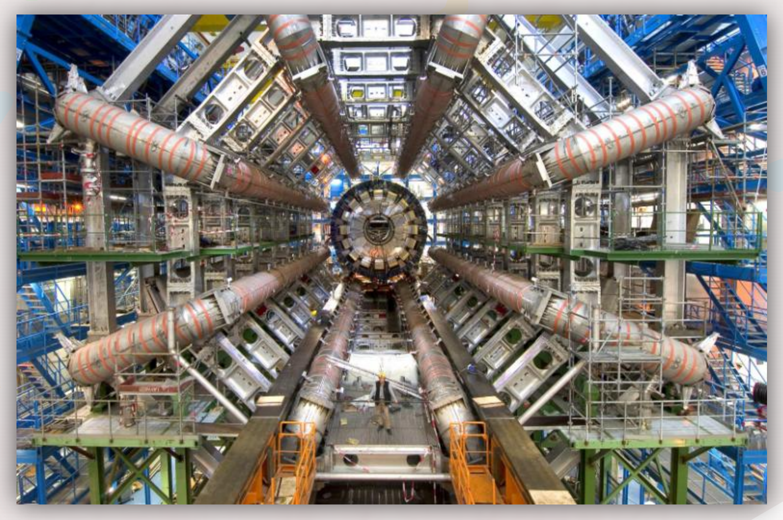
Higgs Boson Search in the VBF Channel of NMSSM with the ATLAS detector

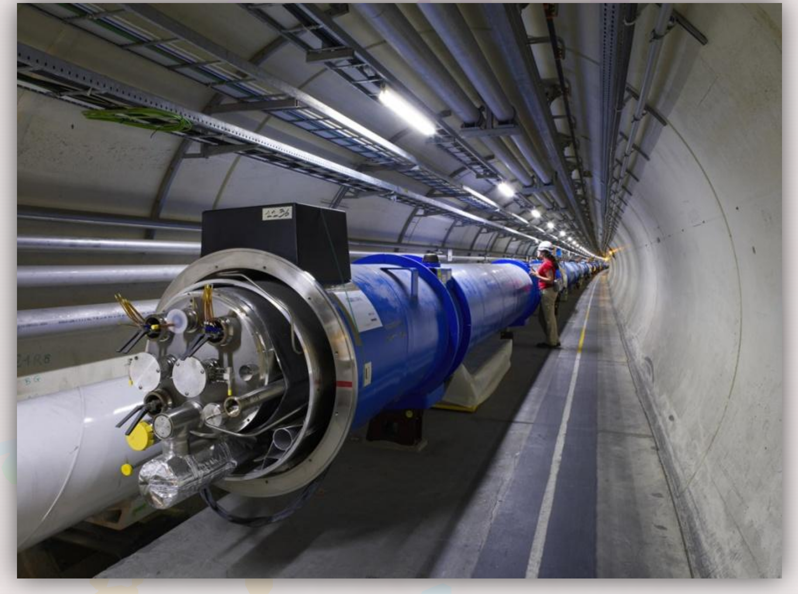
Khaw Kim Siang
University of Tokyo
16th February 2010

Outline

- Introduction (LHC and ATLAS)
- Physics Motivation of NMSSM Higgs
- Event Topology
- Analysis Algorithms
- Result
- Conclusion
- Future Plan

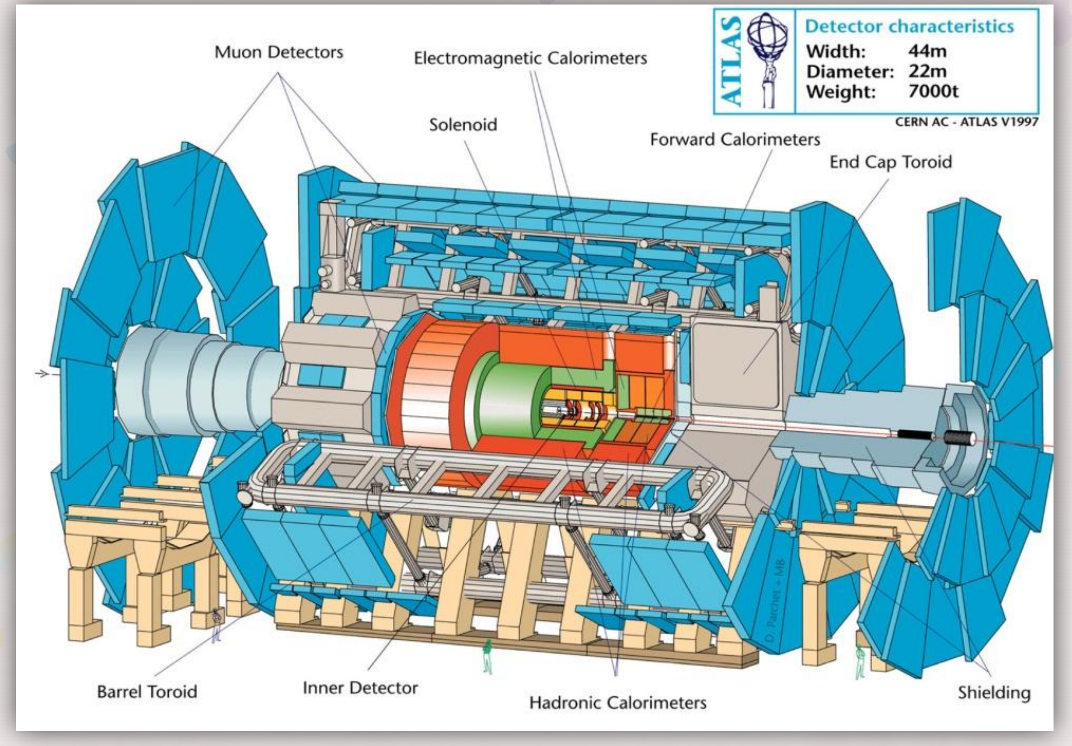


LHC and ATLAS (1)



Large Hadron Collider (LHC)
Circumference ~ 27 km
Superconductor Magnet = 8.33T @ T=1.9K
10^{11} protons per bunch, 40MHz
World Highest Energy (ECM=14 TeV)
Designed Luminosity of $L = 10^{34} cm^{-2} s^{-1}$

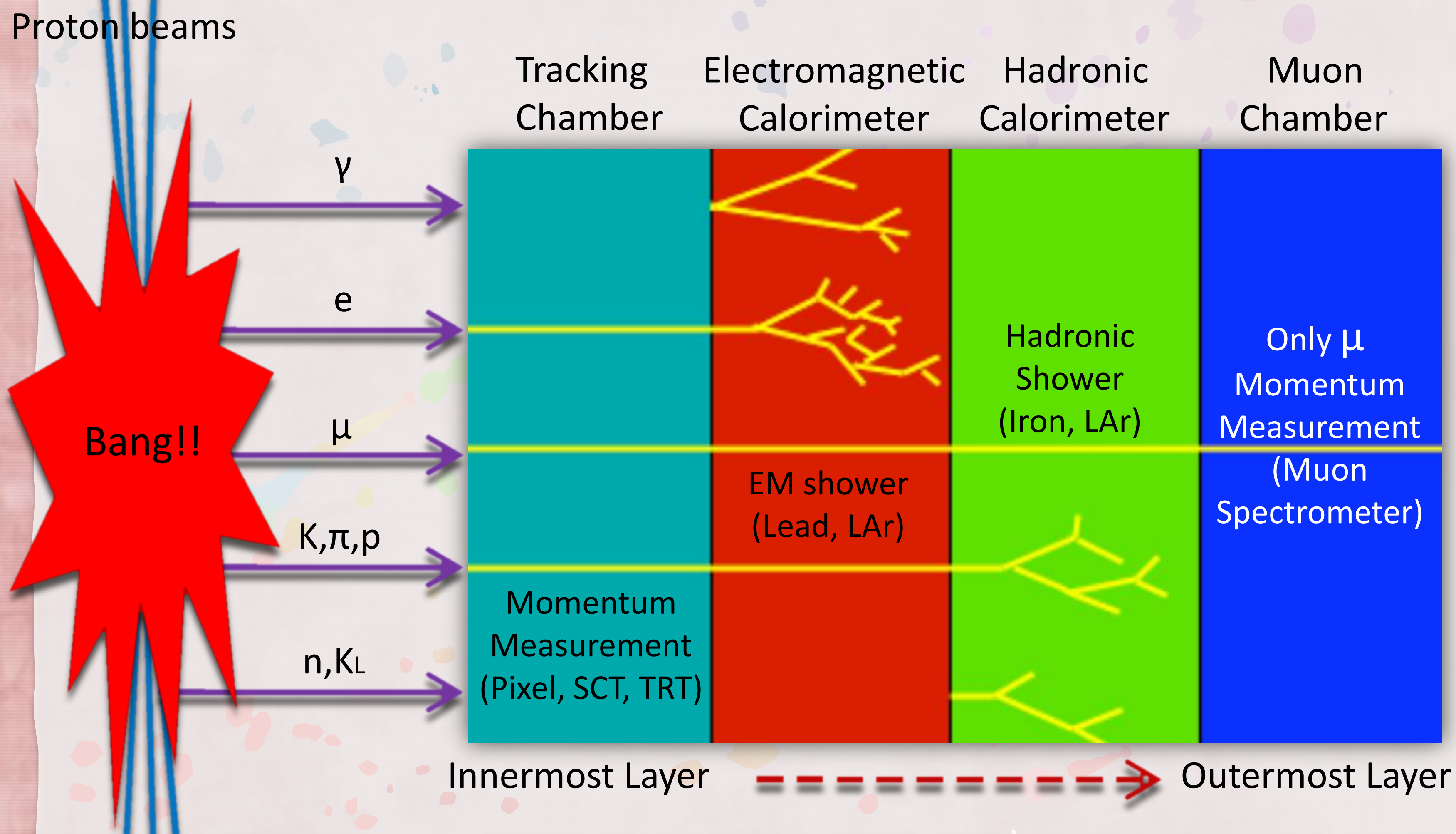
LHC and ATLAS (2)



A Toroidal LHC ApparatuS (ATLAS)
Multipurpose Detector
Superconducting Solenoid=2T
Width 44m, Height 22m, 7000t

Physics at ATLAS
Aiming at the discovery of Higgs, SUSY, Extra Dimension, BlackHole, ….???

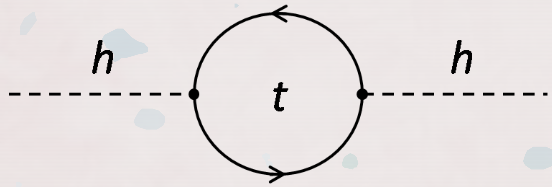
ATLAS Particle Detector

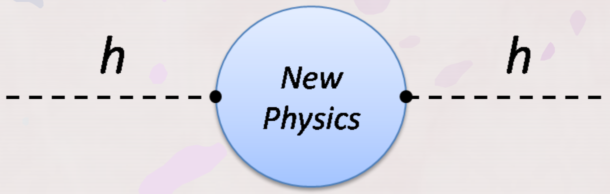


My work is "NMSSM Higgs Search" using this detector.

What is NMSSM?

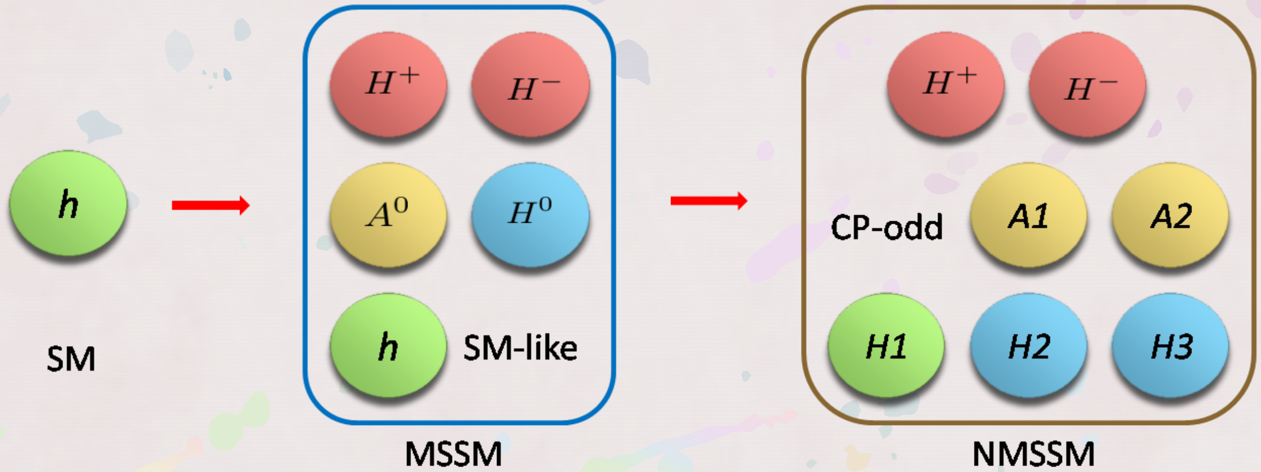
- Next-to-the-Minimal Super Symmetry Standard Model



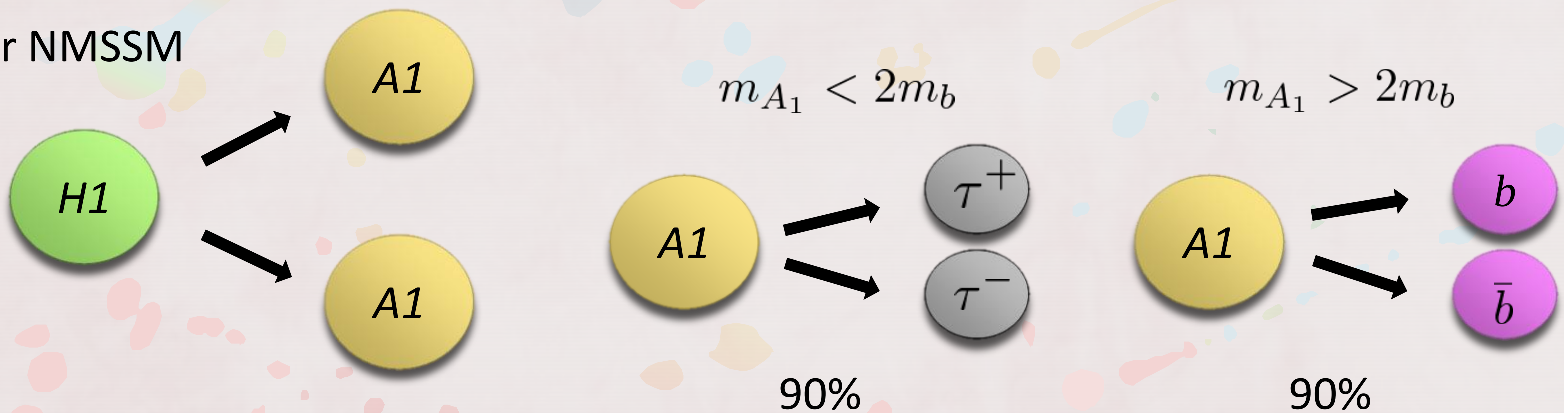


- Large Fine Tuning is needed in Standard Model. (Large Radiative Correction on SM Higgs mass, Naturalness Problem)
- By introducing Super symmetry Partner (fermion⇔boson),
  → logarithm divergence → Naturalness Problem solved
- Minimal SUSY → MSSM, but with μ-problem (origin of mass term in Lagrangian, $\mu H_u H_d$)
  (μ ~ ElectroWeak Scale (Phenomenological))
- By adding a SM singlet superfield , S →NMSSM
  → μ=λ<S>, μ as function of <S> → μ-problem solved

Higgs in SM, MSSM and NMSSM

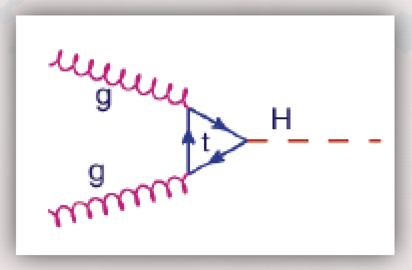


For NMSSM

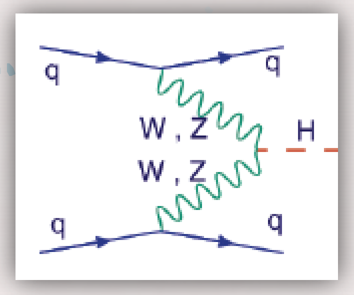


Light A1 scenario =100%
Typically = 90%

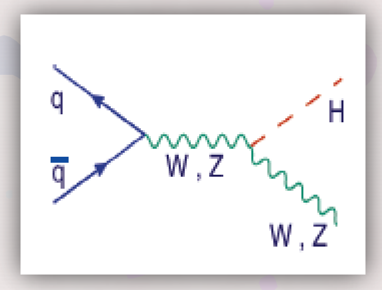
Higgs production



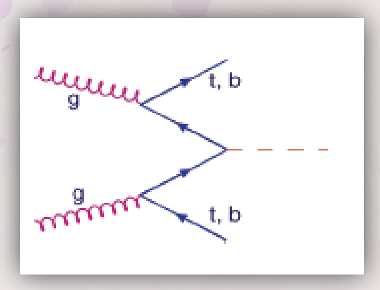
Gluon Fusion



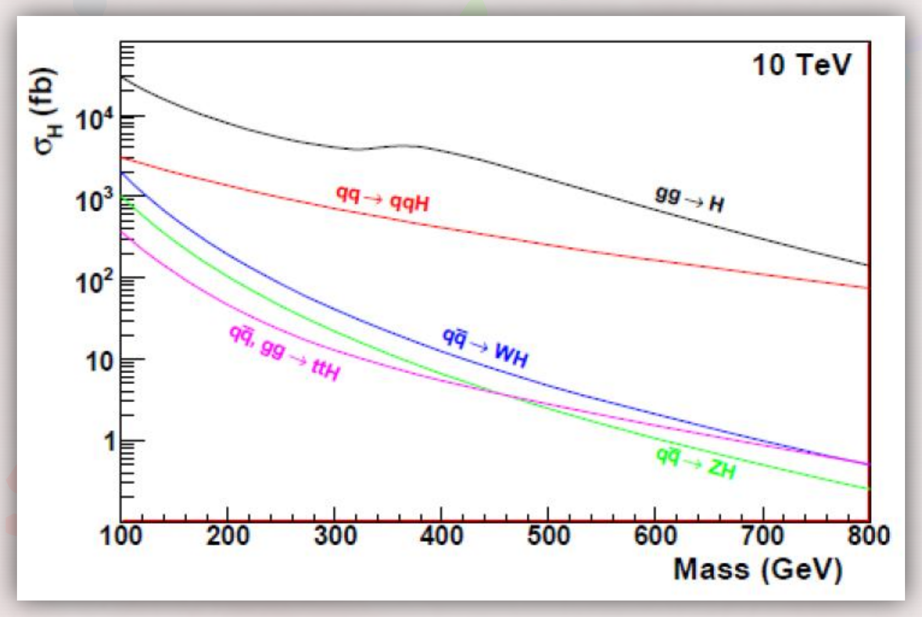
Vector Boson Fusion



Associative Production with W, Z



Associative Production with top, bottom

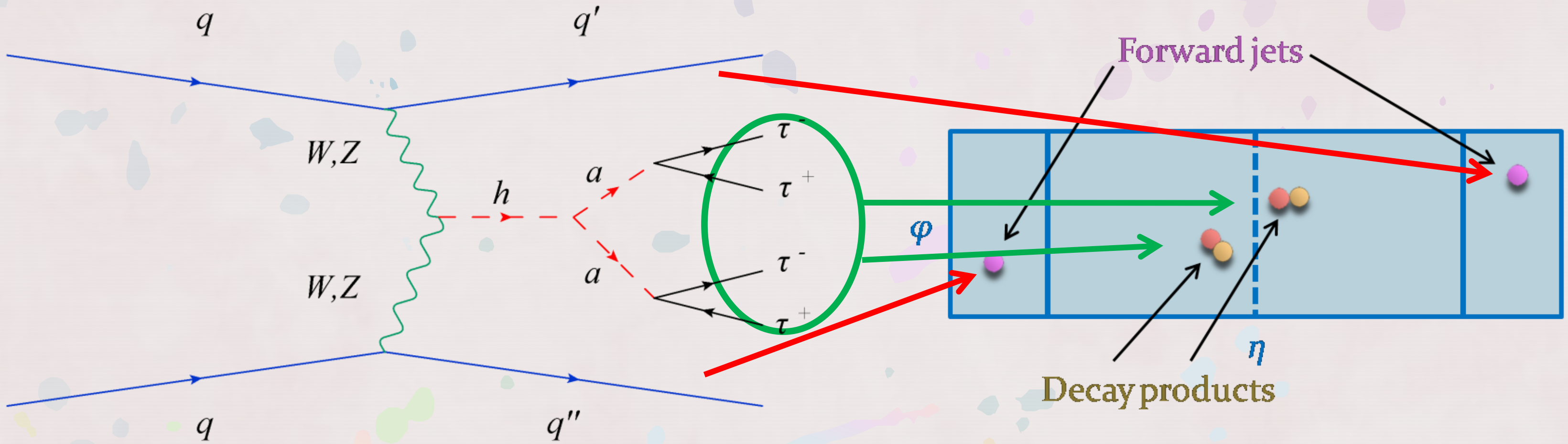


Higgs Production Cross Section (SM)

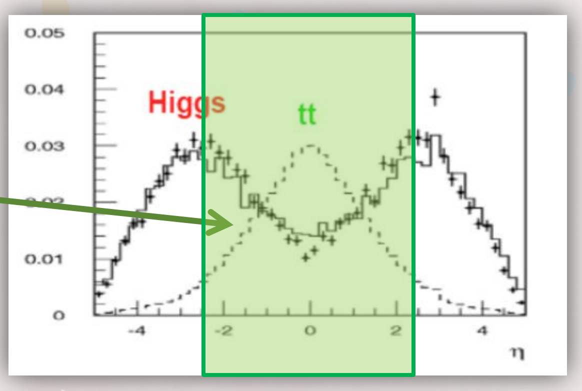
Typical cross section (SM) is about 3 picobarn (pb) for Vector Boson Fusion (VBF)

For NMSSM, some corrections are needed. → σ=2.9pb @ 10TeV (~SM)

Event Topology



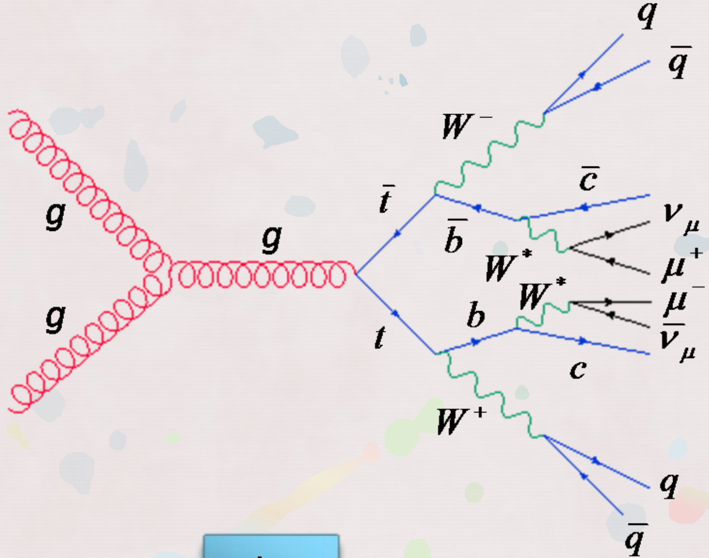
- 2 high pt forward jets (*O*(W,Z mass)) → apply high Jet Pt cut
- No activity in the central region,
  only Higgs decay products are detected.
  → QCD BG suppressed
- By focusing on 4τ→hμhμ, we find signals
  where taujet-μ are very near to each other.



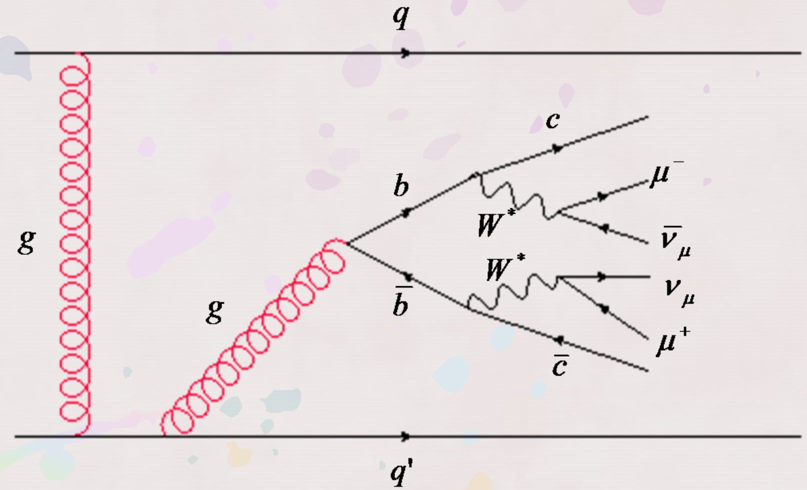
➤ Br(τ→h)   ~ 65% : hadronic decay of tau

➤ Br(τ→μνν) ~ 17% : leptonic decay of tau

Background

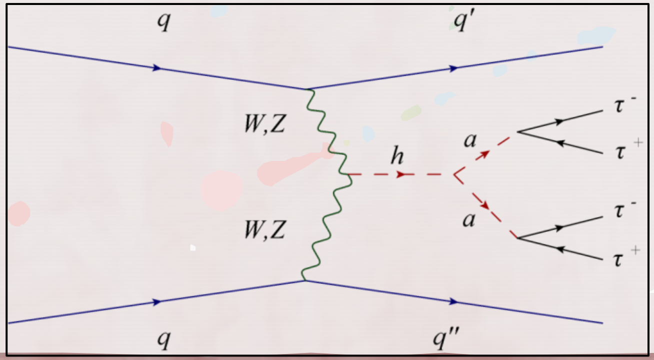


ttbar



bbar

Examples of background from QCD. When the c-jets are mis-ID as Taujets, they look like VBF topology. However, they are reducible backgrounds.



Introduction of my analysis

- In NMSSM model, the SM-like Higgs, h will decay dominantly in the channel h→aa when $m_a < 2m_b$.
- At the same time, the CP-odd singlet, a will decay mainly into 2taus. Br(a → τ τ) = 90%.
- In this analysis, we focus on the h→aa→4τ channel, where h is produced through vector boson fusion process.
- Since τ→eνν mode is quite complicated and requires special reconstruction algorithm, only h→aa→4τ→2μ2h is discussed here.

σ*Br(NMSSM VBF h→2a→4τ→2h2μ) = 437 fb

- My analysis is based on data of $30\ fb^{-1}$ (<1 year with designed luminosity.)

Samples

Signal and backgrounds are studied using full simulation data
→ GEANT4 Simulation with Detector Response at ATLAS (10 TeV)

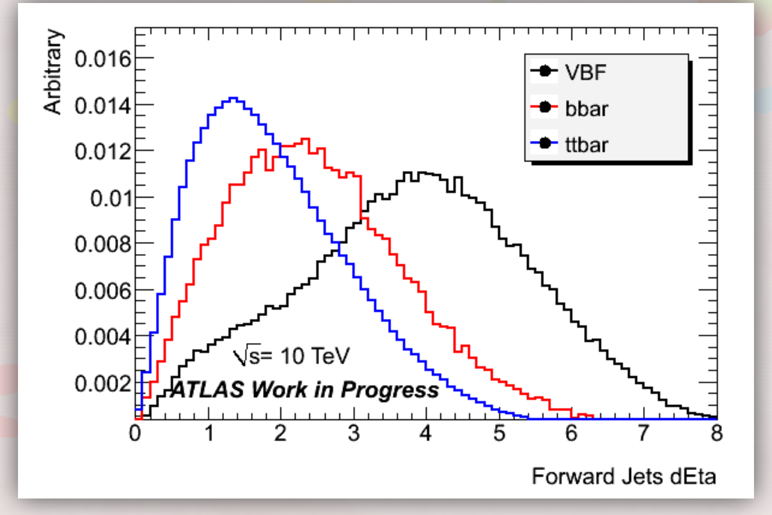
Signal	Event Generator	Cross section (pb)	Size
NMSSM VBF Higgs	PythiaMadgraph	0.437	235k
Background	**Event Generator**	**Cross section (pb)**	**Size**
ttbar	McAtNloJimmy	205.5	1960k
bbar	AlpgenJimmy	5630	377k

Singal with Higgs mass = 100 GeV, CP-odd singlet mass = 5 GeV is used.

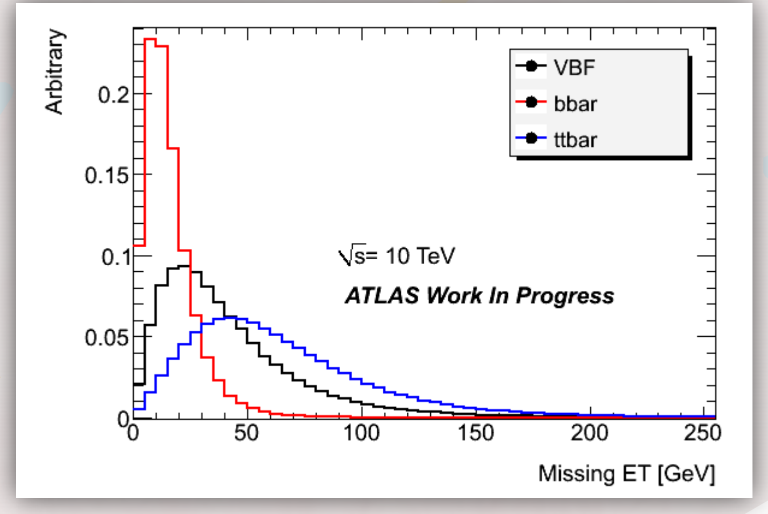
Cut Based Event Selection

Basically, to select good events, sequential cuts are applied as to separate the signal from the backgrounds.

- Njet=>2, all with pT > 20 GeV
- j1_eta*j2_eta<0
- **dEta of 1st Jet-2nd Jet**
- **Missing ET**
- Bjet Veto
- Mjj > 500GeV
- Central Jet Veto
- 2 mu 2 tau



Apply |dEta|>3.6



Apply MET > 25 GeV

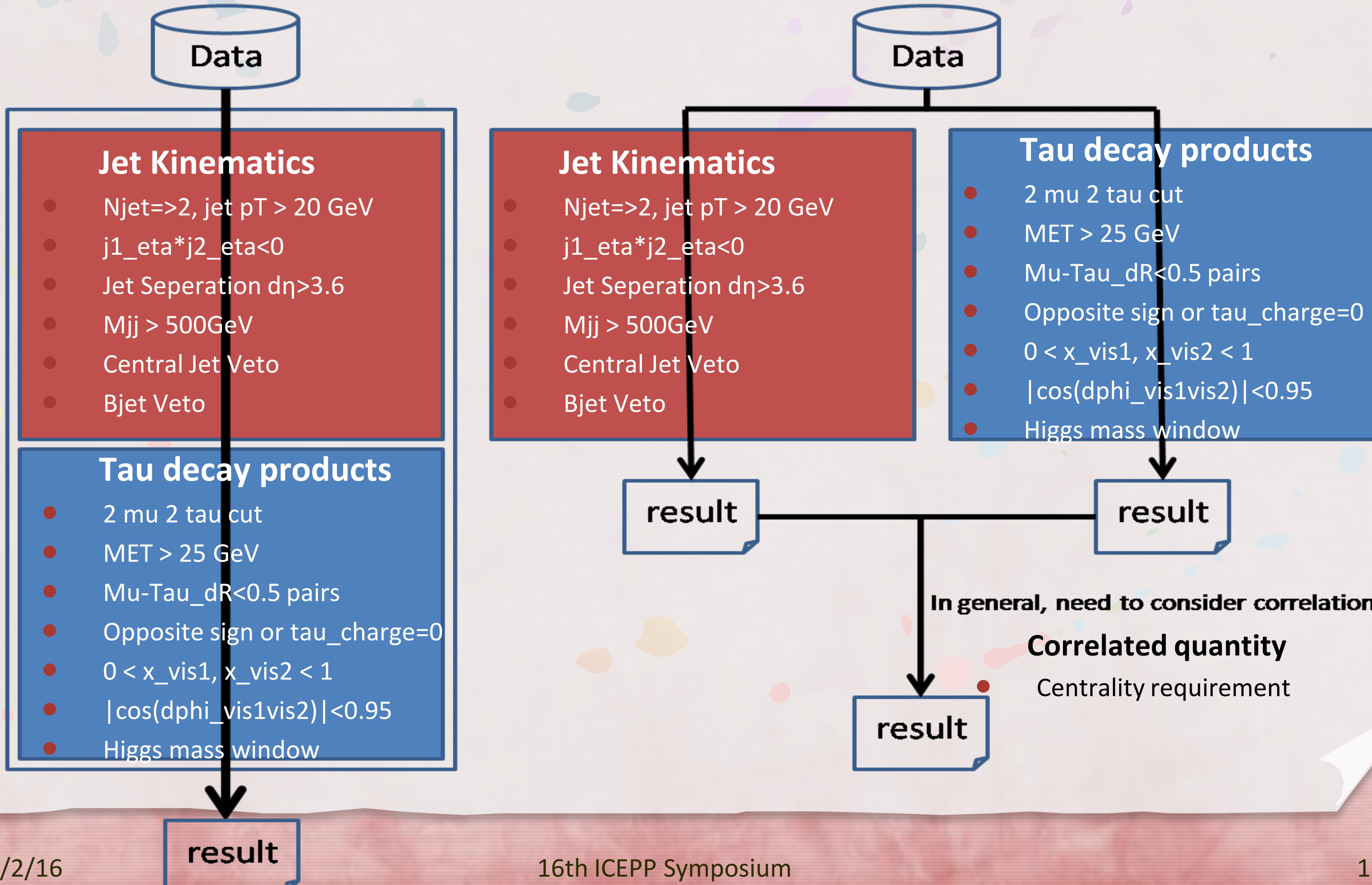
Event Selection

Event Selection	vbf	bbar	ttbar
Cross Section (pb)	0.437	9582	205.5
Start : Total Event	1.3E+04	2.8E+08	6.0E+06
Luminosity(fb-1)	30.0	30.0	30.0
Njet=>2, all with pT > 20 GeV	1.2E+04	1.5E+08	6.0E+06
j1_eta*j2_eta<0	6.0E+03	5.6E+07	2.2E+06
Jet Seperation dη>3.6	3.1E+03	7.7E+06	2.0E+05
Bjet Veto	3.1E+03	3.7E+06	6.0E+04
Mjj > 500GeV	2.2E+03	9.4E+05	4.1E+04
Central Jet Veto	920	4.2E+05	3.9E+03
2 mu 2 tau	19.7	6.2E+03	12.0
MET > 25 GeV	17.6	660	9.4
Mu-Tau_dR<0.5 pairs	17.0	660	0(9.4)
Opposite sign or Qtau=0	15.5	92	0(<9.4)
0 < x_vis1, x_vis2 < 1	12.8	0(92)	0(<9.4)
|cos(dphi)|<0.95	11.5	0(<92)	0(<9.4)
80 GeV < Higgs mass < 120 GeV	11.0	0(<92)	0(<9.4)

It seems good but the statistical uncertainty is too huge.
(xsec: QCD>>Higgs)

Factorization Method

- Due to the lack of statistics for BG, factorization method is applied where the event selection is divided into mainly 2 categories:



Factorization Method

Event Selection	VBF	bbar	ttbar
Start : Total Event	1.3E+04	2.8E+08	6.0E+06
Luminosity(fb-1)	30.0	30.0	30.0
Njet=>2, all with pT > 20 GeV	1.2E+04	1.5E+08	6.0E+06
j1_eta*j2_eta<0	6.0E+03	5.6E+07	2.2E+06
Jet Seperation dη>3.6	3.1E+03	7.7E+06	2.0E+05
Bjet Veto	3.1E+03	3.7E+06	6.0E+04
Mjj > 500GeV	2.2E+03	9.4E+05	4.1E+04
Central Jet Veto	920	4.2E+05	3.9E+03

Event Selection	VBF	bbar	ttbar
Start : Total Event	1.3E+04	2.8E+08	6.0E+06
Luminosity(fb-1)	30.0	30.0	30.0
2 mu 2 tau	1.9E+02	1.6E+06	2.5E+03
MET > 25 GeV	1.6E+02	7.3E+04	9.0E+02
Mu-Tau_dR<0.5 pairs	1.5E+02	6.4E+04	7.7E+02
Opposite sign or Qtau=0	1.0E+02	1.4E+04	2.4E+02
0 < x_vis1, x_vis2 < 1	9.4E+01	7.7E+03	1.2E+02
|cos(dphi)|<0.95	8.6E+01	6.0E+03	9.9E+01
80 GeV < Higgs mass < 120 GeV	8.1E+01	7.3E+02	3.1E+01

Background estimation

Event Selection .	VBF (normal)	VBF	bbar	ttbar
Start : Total Event	1.3E+04	1.3E+04	2.8E+08	6.0E+06
Luminosity(fb-1)	30.0	30.0	30.0	30.0
Njet=>2, all with pT > 20 GeV	1.2E+04	1.2E+04	1.5E+08	6.0E+06
j1_eta*j2_eta<0	6.0E+03	6.0E+03	5.6E+07	2.2E+06
Jet Seperation dη>3.6	3.1E+03	3.1E+03	7.7E+06	2.0E+05
Bjet Veto	3.1E+03	3.1E+03	3.7E+06	6.0E+04
Mjj > 500GeV	2.2E+03	2.2E+03	9.4E+05	4.1E+04
Central Jet Veto	920	920	4.2E+05	3.9E+03
2 mu 2 tau	19.7	13.4	2.4E+03	1.6
MET > 25 GeV	17.6	11.3	110	0.6
Mu-Tau_dR<0.5 pairs	17.0	10.6	96.0	0.5
Opposite sign or Qtau=0	15.5	7.1	21.0	0.2
0 < x_vis1, x_vis2 < 1	12.8	6.7	11.6	0.08
|cos(dphi)|<0.95	11.5	6.1	9.0	0.06
80 GeV < Higgs mass < 120 GeV	11.0	5.7	1.1	0.02

Discovery Potential

$$Significance = \frac{Signal}{\sqrt{Background}}$$

- Signal=11

  Background=1.12

  Hence, $Significance = \frac{11}{\sqrt{1.12}} = 10.4$

Discovery @ATLAS
Signal > 10
Significance > 5

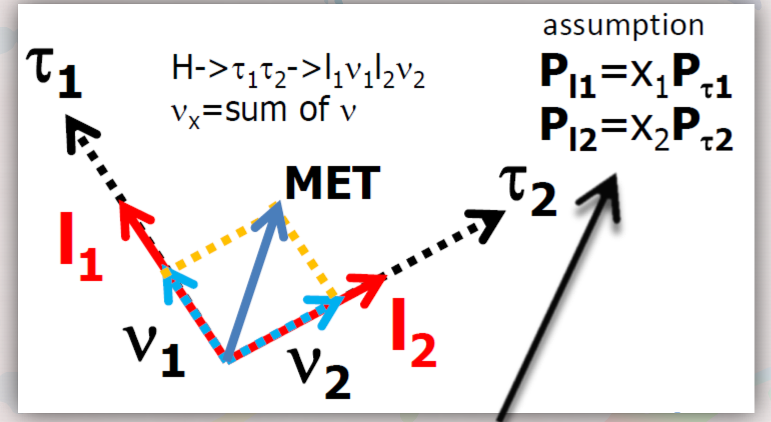
- But the problem is, is this method reliable?

  (from VBF, the actual number is 11, but from F.M., it is about 2 times fewer → BG might be underestimated by a factor of 2)

  → Take into account of this error gives us Sig. > 7.3 Discovery !

- Factorization method is not working well. Solutions are:
  - Increase the statistics
  - Detailed study of Factorization Method

Reconstruction of Higgs masses
- Collinear Method -



Assume that decay products of Tau and Tau are travelling in the same direction.

This is true when the Tau is highly boosted

$$
\begin{aligned}
MET &= \mathbf{P}_{\nu 1}+\mathbf{P}_{\nu 2} \\
&= (1-x_1)\mathbf{P}_{\tau 1}+(1-x_2)\mathbf{P}_{\tau 2} \\
&= (1-x_1)/x_1\ \mathbf{P}_{l1}+(1-x_2)/x_2\ \mathbf{P}_{l2}
\end{aligned}
$$

$$
\begin{aligned}
m_{\tau\tau}{}^2 &= (\mathbf{P}_{\tau 1}+\mathbf{P}_{\tau 2})^2 \\
&= (\mathbf{P}_{l1}/x_1+\mathbf{P}_{l2}/x_2)^2 \\
&\sim 2\mathbf{P}_{l1}\mathbf{P}_{l2}/(x_1 x_2)
\end{aligned}
$$

$(l_1, l_2 \rightarrow$ massless$)$

$$
\begin{aligned}
m_{l1l2}{}^2 &= (\mathbf{P}_{l1}+\mathbf{P}_{l2})^2 \\
&\sim 2\mathbf{P}_{l1}\mathbf{P}_{l2}
\end{aligned}
$$

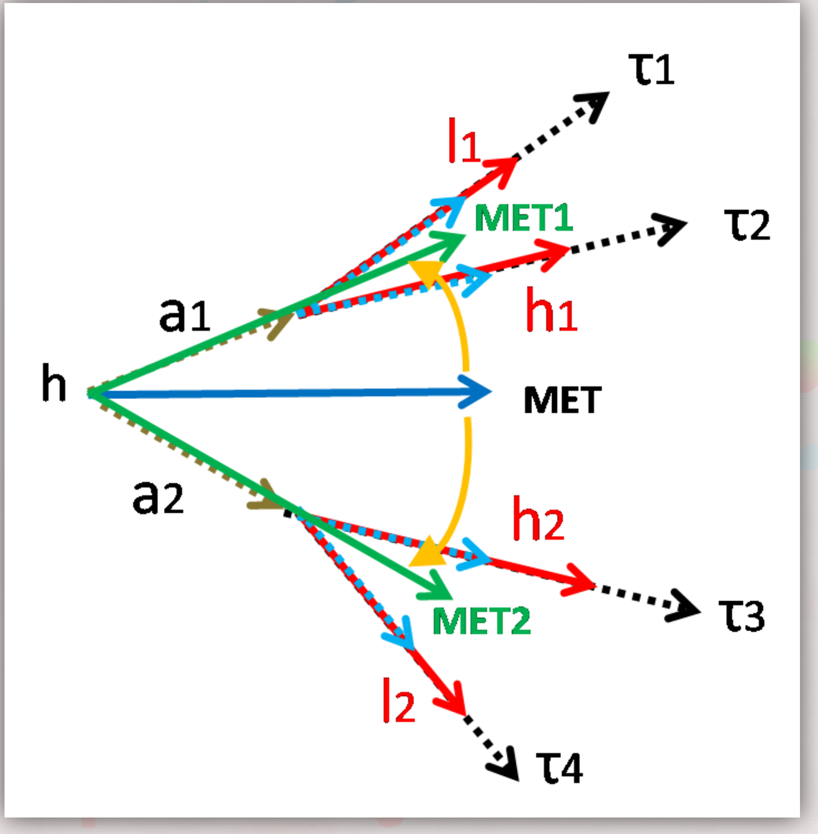
$(l_1, l_2 \rightarrow$ massless$)$

$m_{\tau\tau} \sim m_{l1l2}/\sqrt{x_1 x_2}$
$(l_1, l_2 \rightarrow$ massless$)$

Since MET, $P_{\nu 1}$ and $P_{\nu 2}$ can be measured, we can calculate x_1 and x_2 in order to reconstruct the mass of Higgs particle.

This can be applied to the $h \rightarrow aa \rightarrow 4\tau$ as well.

Reconstruction of Higgs masses
- Collinear Method -



$$P_{vis1} = P_{l1} + P_{h1} = x_{vis1} P_{a_1}$$

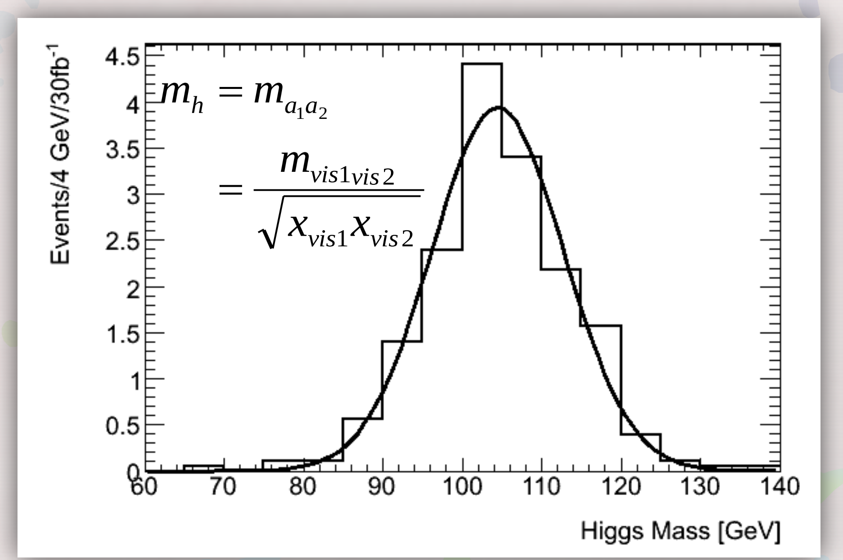
$$P_{vis2} = P_{l2} + P_{h2} = x_{vis2} P_{a_2}$$

$$\begin{aligned} MET &= MET_1 + MET_2 \\ &= (1 - x_{vis1}) P_{a_1} + (1 - x_{vis2}) P_{a_2} \\ &= \left(\frac{1 - x_{vis1}}{x_{vis1}} \right) P_{vis1} + \left(\frac{1 - x_{vis2}}{x_{vis2}} \right) P_{vis2} \end{aligned}$$

Sum of l1 and h1

Sum of l2 and h2

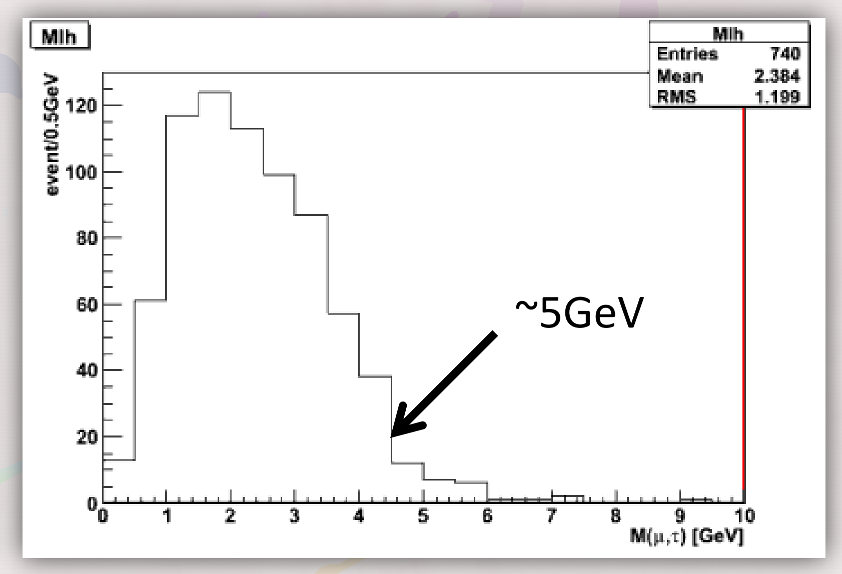
Results



Reconstructed Higgs mass m_h

Collinear Method works well here as the a1-a2 are far away.

Truth = 100 GeV
Mean = 104.6 GeV
Sigma= 8.42 GeV



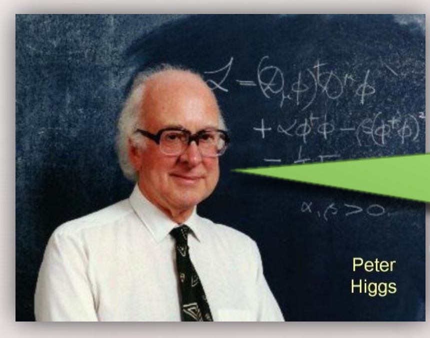
Distribution of M(μ,τ)

By looking at the cutoff, we can briefly estimate the mass of higgs a.

Truth = 5 GeV
Cutoff ~ 6 GeV?

Conclusion

- NMSSM is as important as MSSM and it should be studied in detail.
- By using ATLAS detector, it is possible to discover Higgs(100 GeV) in NMSSM.
- The resolution is about 10% and we can estimate the mass of CP-odd Higgs.



Are you sure you will hunt me down?

Future Plan

- Optimization of Statistics → earlier discovery?
- Higgs mass scanning through the parameter space

  → Establish mass-independent analysis algorithm and discovery potential plot
- Study of Trigger for low Pt Muon and Taujet

  → Key of discovery
- Study of Forward Jet

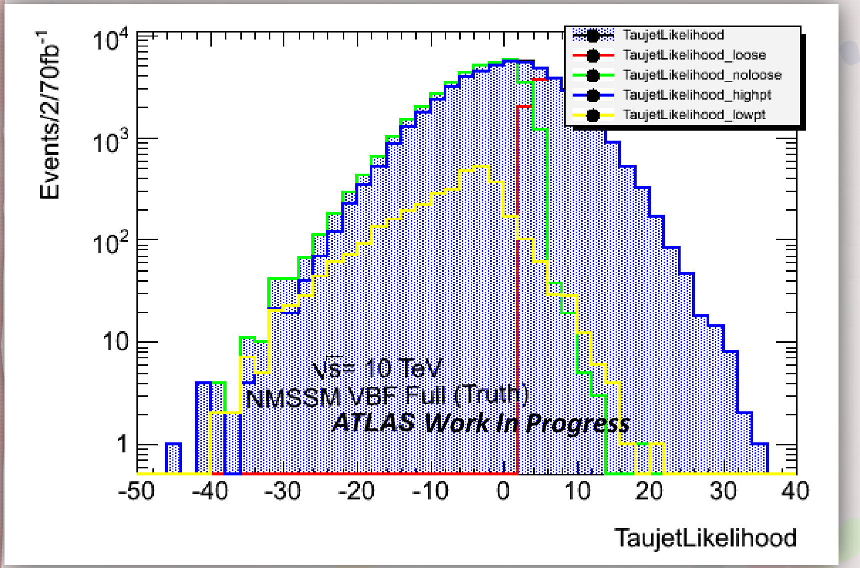
  → Event Topology Identification
- And more……

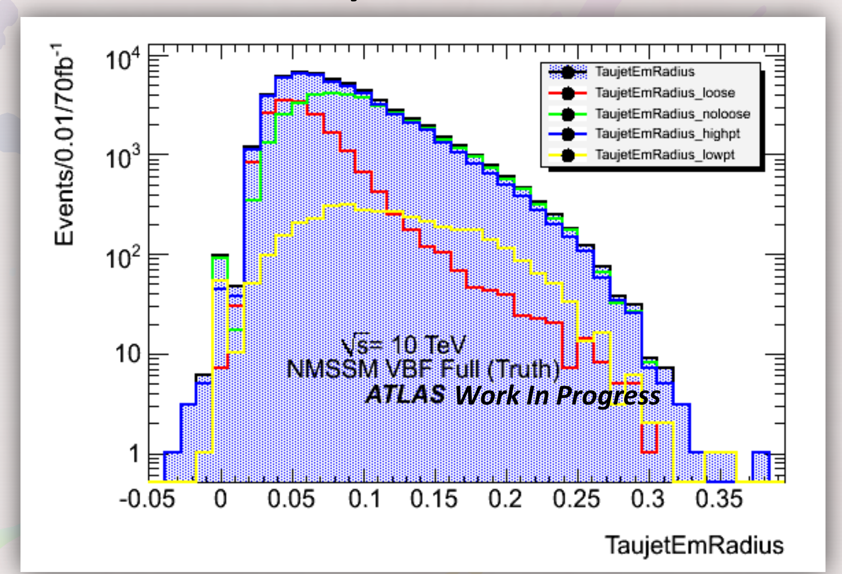
Thanks for Listening

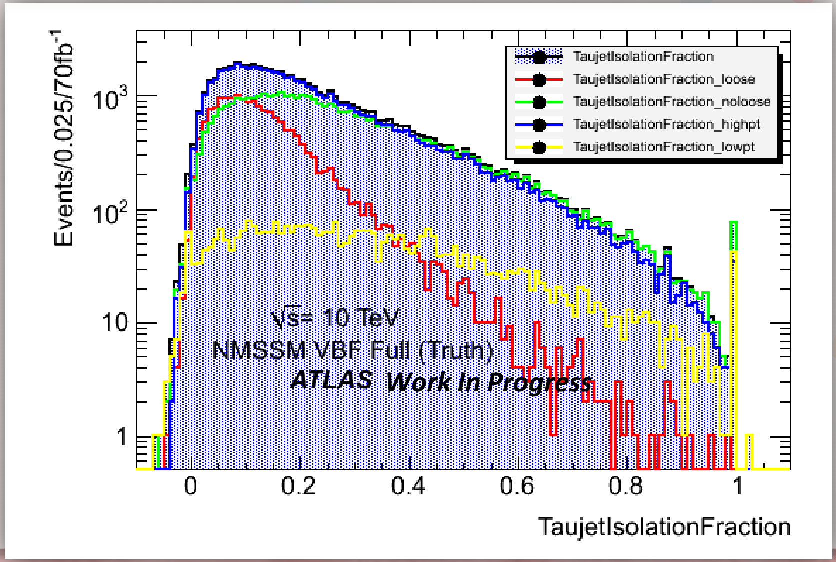
and don’t stop searching for me!

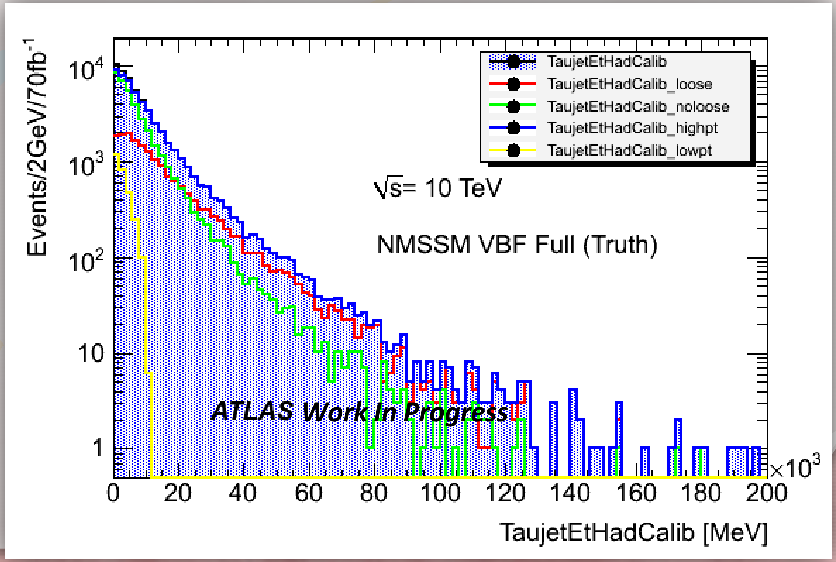
Back up

Variables used for TauID study

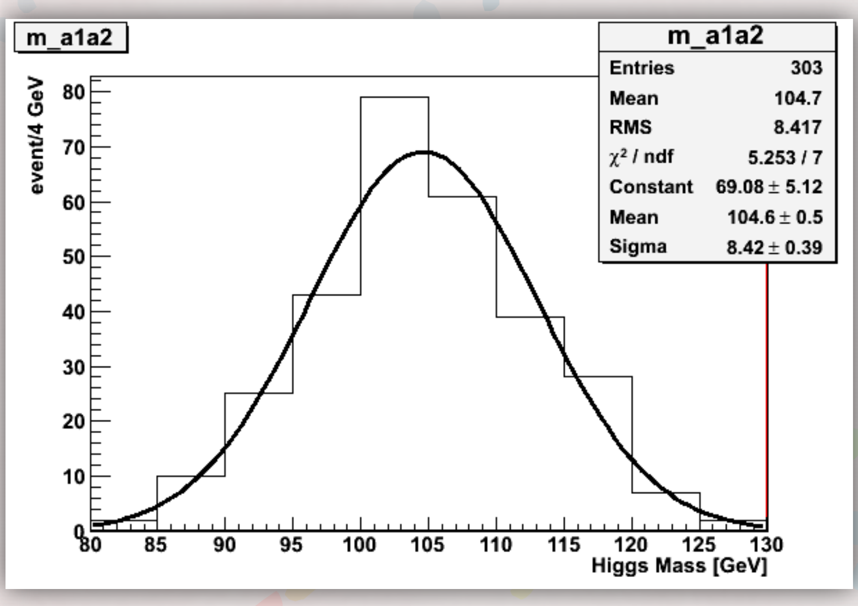


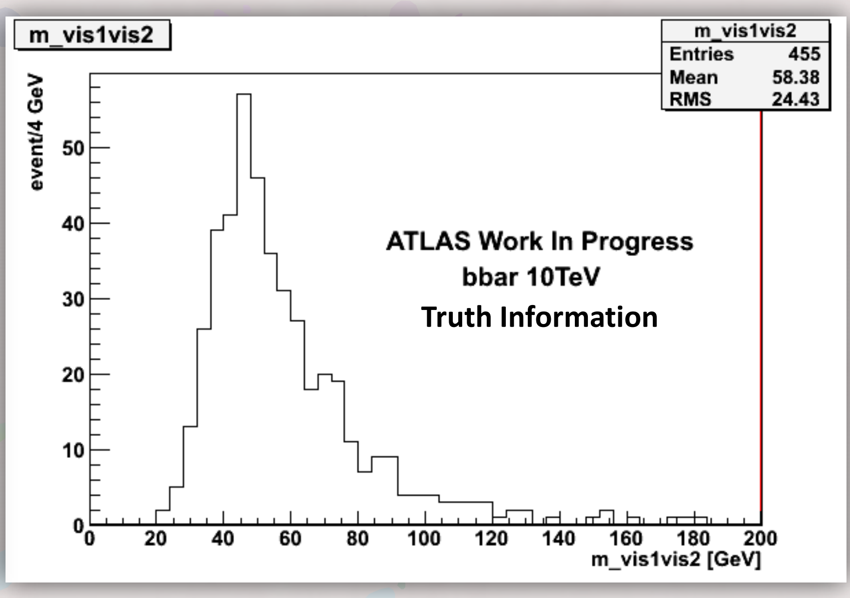






Reconstructed mass of bbar





Reconstructed Higgs mass m_h

Reconstructed mass from bbar

As we can see from the left plot, bbar BG can be reduced by applying high m_h cut.

Analysis (Object Selection)

Electron:
pt>8 GeV
|eta|<2.7
author=1 or 3
ElectronMediumNoIso

ε~80%
fake~0.01-0.1%

Muon:
pt>8GeV
|eta|<2.7
StacoIsCombinedMuon
StacoBestMatch
StacoMatchChi2<100
StacoFitChi2<500

ε~90%
fake~0.01%

Analysis

Taujet:
pt>10GeV
|eta|<2.7
ntrk=1, 2, 3 or 4
Q=-1, 0, 1
TauLikelihood>-5

ε~40%
fake~1%

Jet:
Cone4H1TopoJets
pt>20GeV
|eta|<4.8

ε~100%

MissingET:
RefFinal

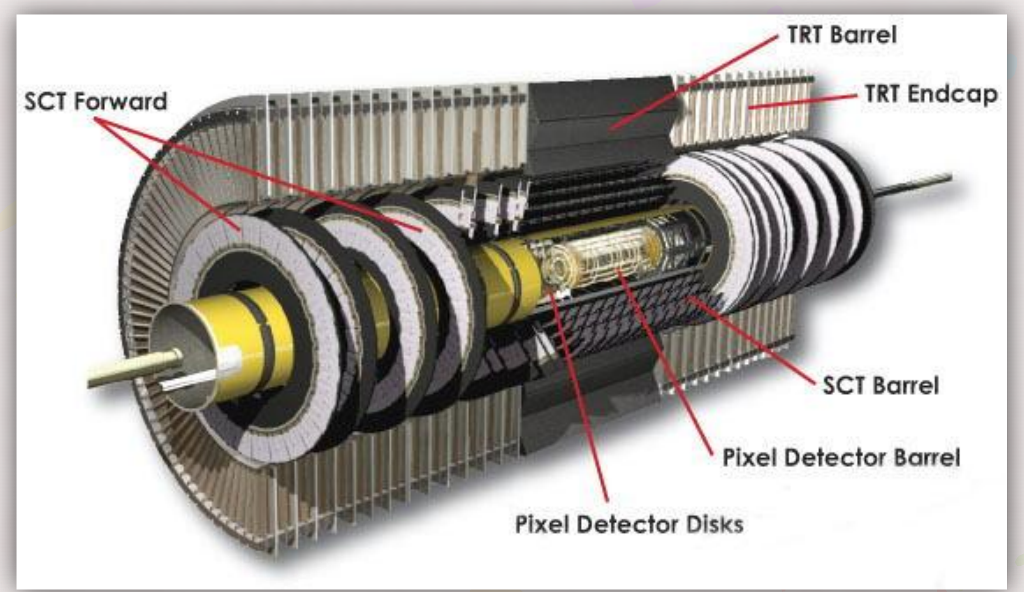
Inner Tracker ($|\eta|<2.5$)

SemiconductorTracker (SCT)

- Silicon strip detector
- Barrel : 4 cylindrical layers
- End-cap : 9 disks per side

Pixel Detector

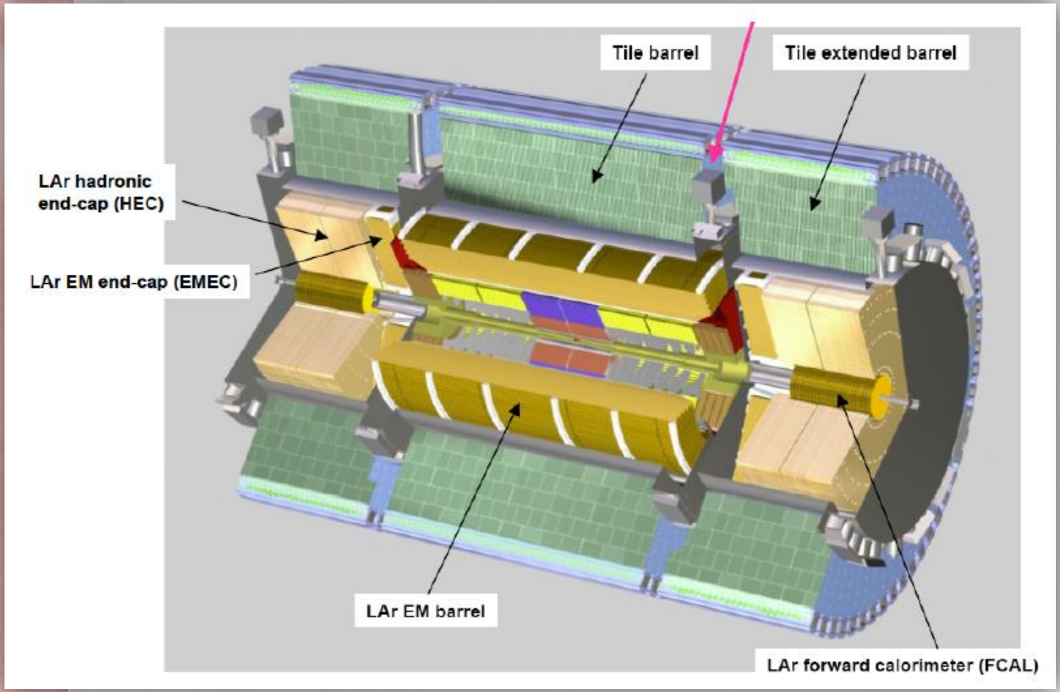
- Hybrid silicon pixel detector
- Barrel : innermost cylindrical layer and 2 outer cylindrical layers
- End-cap : 3 disks per side

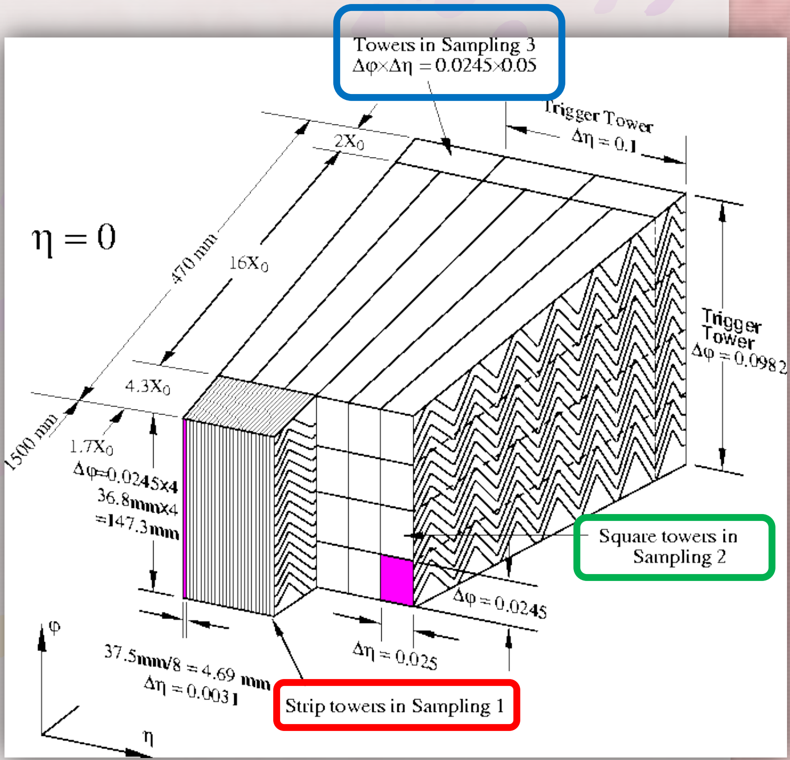


Transition Radiation Tracker (TRT)

- Straw-tube tracking chamber w/ transition radiation capability.
- Straws run in axial direction in barrel and radial direction in end-caps.

EM Calorimeter

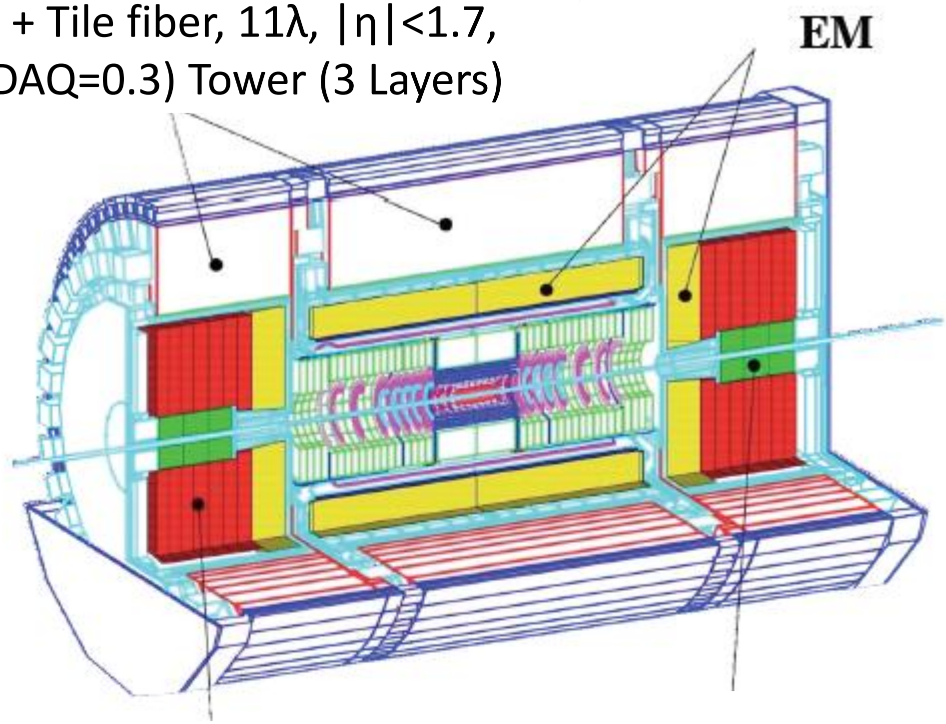




- ***Pb/Lar sampling calorimeter*** with accordion-shaped electrodes
- ***Three longitudinal segmentation***
- ***Cell size in Δη ×Δφ***
  - 1st (strip) : 0.003 × 0.1, 2nd (middel) : 0.025 × 0.025, 3rd (back) : 0.05 × 0.025
- ***Pre-sampling in front*** of calorimeter in |η| < 1.8 : Δη × Δϕ~0.025 × 0.1

Hadronic Calorimeter

Barrel Fe + Tile fiber, 11λ, |η|<1.7,
0.1x0.1 (DAQ=0.3) Tower (3 Layers)



Endcap Cu+LAr, 14λ, |η|=1.5-3.2,
0.1x0.1 for |η|=1.5-2.5,
0.2x0.2 for |η|=2.5-3.2, 4 Layers

Forward Cu+W+W 3 Layers
LAr 0.5mm gap 10λ
|η|=3.1-4.9 0.2x0.2

Performance of ATLAS Detectors

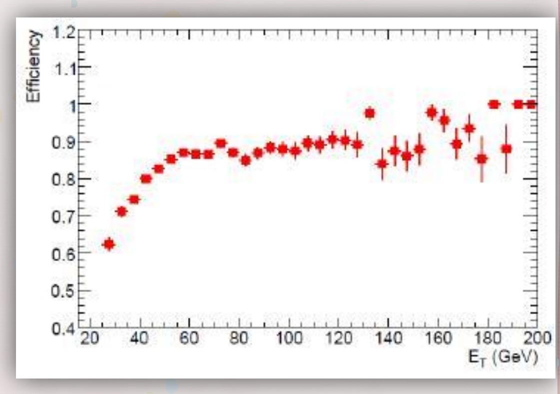
	ATLAS
Magnetic field	2 T solenoid + toroid (0.5 T barrel; 1 T end-cap)
Tracker	Si pixels and strips + TRT $\sigma/p_T \approx 5 \times 10^{-4} p_T + 0.01$
EM calorimeter	LAr + Pb $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.007$
Hadronic calorimeter	Scint. + Fe / LAr + Cu (10 λ) $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$ GeV
Muon spectrometer	$\sigma/p_T \approx 2\%$ @ 50 GeV – 10% @ 1 TeV (ID + MS)

- G. Aad et al (ATLAS Collaboration). J. Instrum. 3. s08003 (2008)
- S.Chatrchysn (CMS Collaboration), J. Instrum. 3. s08004 (2008)

Electron/γ Reconstruction

- ***Leakage into Hadronic calorimeter***
- ***Calorimeter shower shapes in 2nd sampling***
- Shower shape in η and ϕ
- Energy-weighted lateral width
- ***Calorimeter shower shapes in 1st sampling***
- Details of energy deposition structure in cells
- Shower width
- ***Track quality***
- Number of hits in pixel, SCT, TRT
- Transverse impact parameter
- ***Track-cluster matching***
- $\Delta\eta \times \Delta\phi$ position matching at calorimeter, E/p

Fake rate < 0.1%

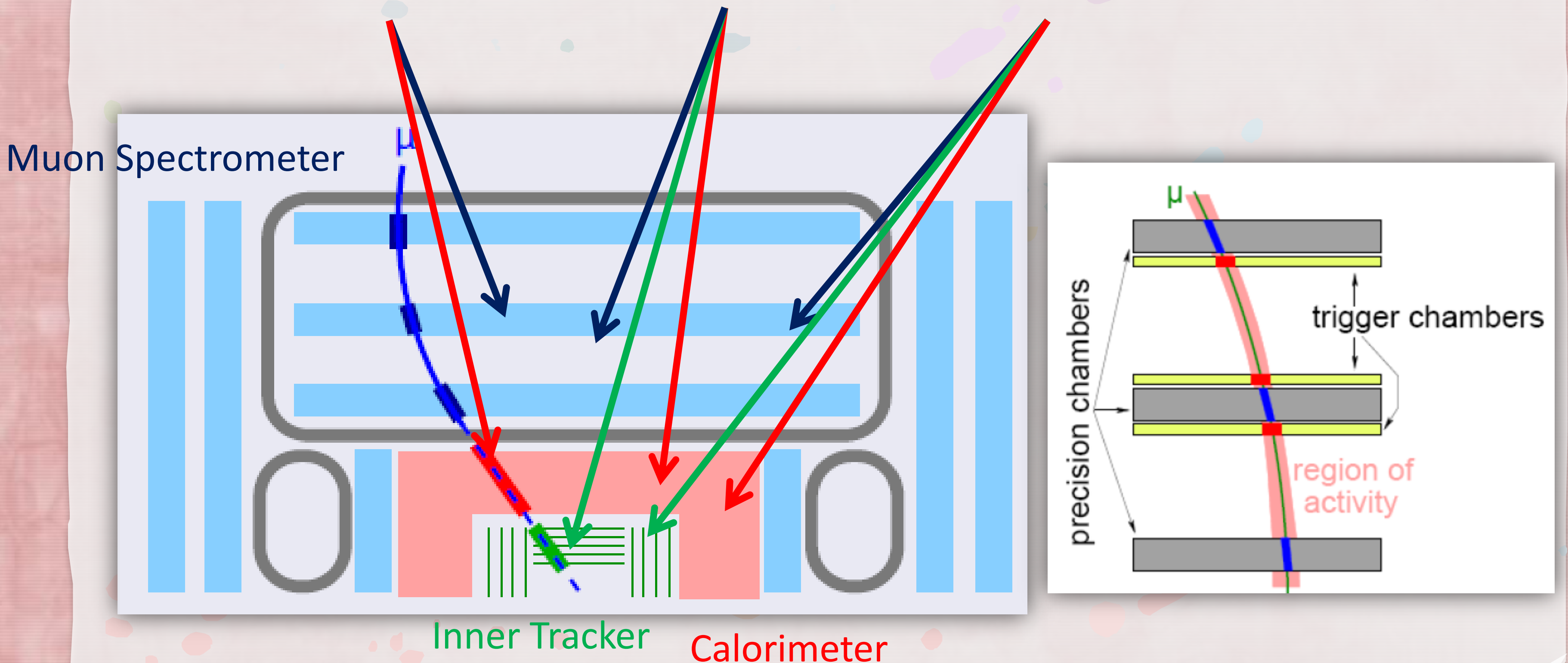


Red : Calorimeter-related
Blue : ID-related
Green : track-cluster

Muon Reconstruction

Keywords: Hits, Track, E_{loss}, Inner, Tag

Standalone, Combined, Tagged Muon



Efficiency~90% (Pt>10GeV), fake rate~0.01%, Pt resolution~2%-4%

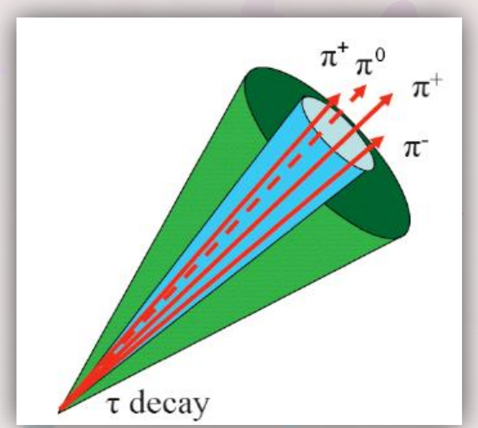
Hadronic Tau Reconstruction

- Main decay modes of Tau Lepton

$\tau^- \rightarrow l^- \nu_\tau \bar{\nu}_l$ ~35%

$\tau^- \rightarrow \nu_\tau \pi^- + N\pi^0$ ~45% 1 prong

$\tau^- \rightarrow \nu_\tau \pi^- \pi^+ \pi^- + N\pi^0$ ~10% 3 prong



3 prong decay

- Characteristic of TauJet

1. One or Three Charged Tracks
2. Pions are boosted → narrow signal cone

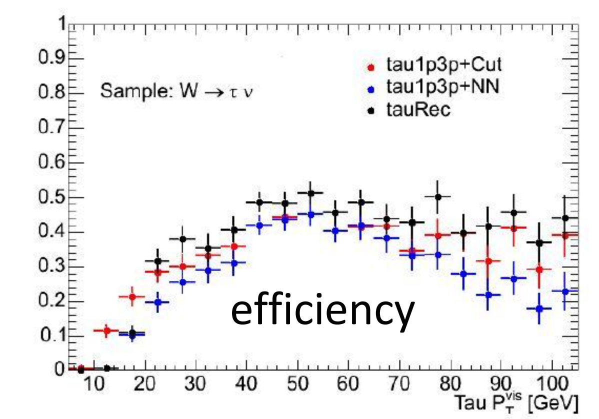
- Hadronic taus are Identified using the facts above. There are 2 ways:

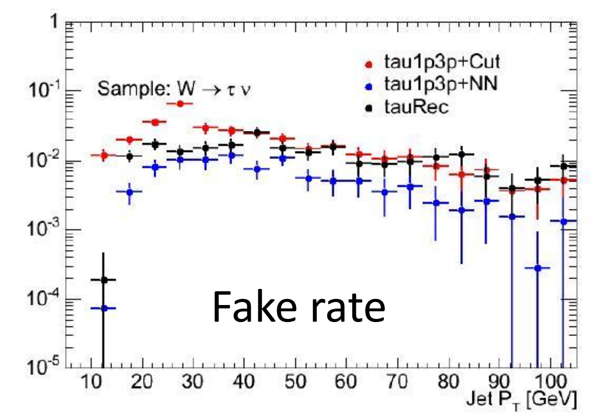
A) Track-base

B) Calo-base

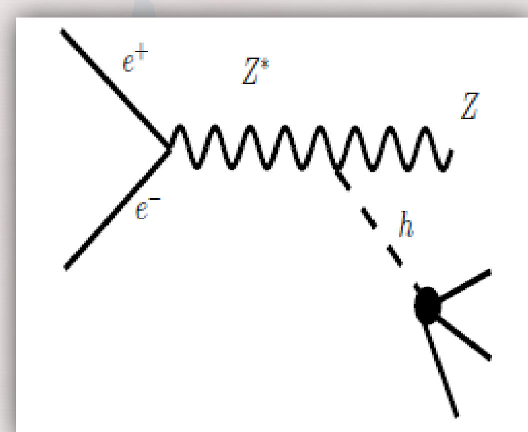
Eff~40%, Fake~1%

for my analysis





LEP limits on Higgs



$$\begin{pmatrix} \text{SM higgs :} & m_h \geq 114.4\text{GeV} \\ \text{Invis. higgs :} & m_h \geq 114\text{GeV} \\ \text{Model indep. :} & m_h \geq 81\text{GeV} \\ \text{4b :} & m_h \geq 110\text{GeV} \\ 4\tau \text{ :} & m_h \geq 86\text{GeV} \end{pmatrix}$$

@95% Confidence level