Top and Tau Measurements

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Examples of early LHC discoveries from M. Peskin, Rethinking the LHC-ILC Connection:

3. A Z-prime at 1 - 1.5 TeV

For example, for $e^-_L e^+_R \to f_L \overline{f}_R$, the Z' adds an amplitude

$$\frac{g_{eL} \cdot g_{fL}}{s - m_Z^2 + i m_Z \Gamma_Z}(1 + \cos\theta)$$

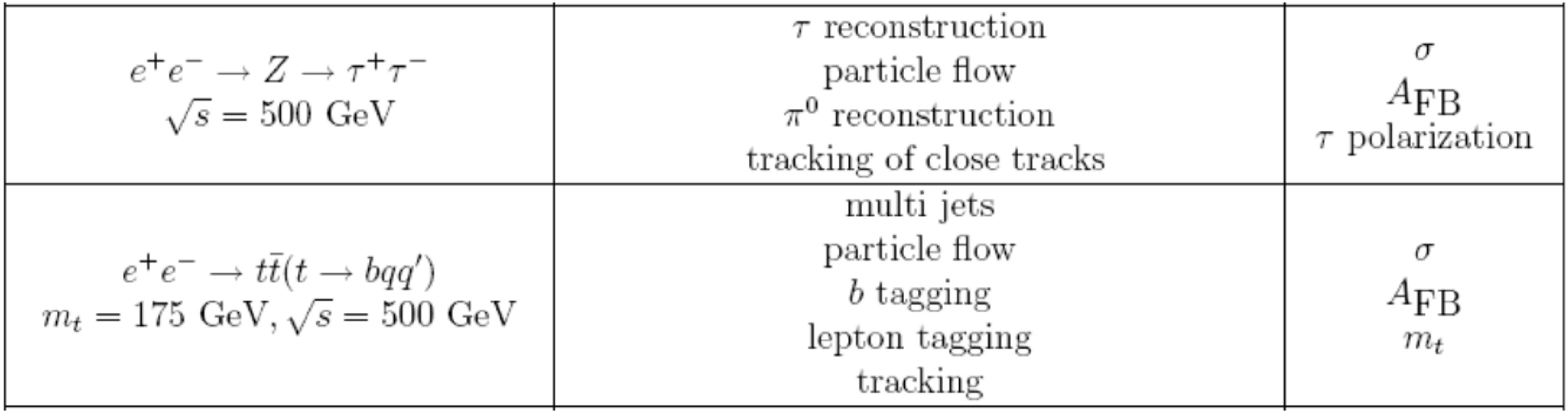
which interferes with the Standard Model pair-production amplitude. Using the mass from the LHC, we can use the polarized forward and backward cross sections to obtain all of the Z' couplings.

4. A top-antitop quark resonance at 1 - 1.5 TeV.

For the QCD strong interactions, we understood the composite structure of meson and baryons by measuring their coupling to pointlike currents.

For the top quark, the composite structure would be manifest in the form factors of vector and axial vector currents:

$$e A_\mu \, \bar{t}\gamma^\mu [F_{LA}(Q^2) P_L + F_{RA}(Q^2) P_R] t$$
$$+ \frac{e}{c_w s_w} Z_\mu \, \bar{t}\gamma^\mu [F_{LZ}(Q^2) P_L + F_{RZ}(Q^2) P_R] t$$



$e^+e^- \to Z \to \tau^+\tau^-$ $\sqrt{s} = 500$ GeV	τ reconstruction particle flow π^0 reconstruction tracking of close tracks	σ A_{FB} τ polarization
$e^+e^- \to t\bar{t}(t \to bqq')$ $m_t = 175$ GeV, $\sqrt{s} = 500$ GeV	multi jets particle flow b tagging lepton tagging tracking	σ A_{FB} m_t

The top and tau analyses of ILD and SiD are very similar. For each topic I will discuss the analysis of just one detector concept in detail while noting differences. At the end of the talk I will present the results from all concepts.

- σ
-
- σ
-

Top Mass & σ Measurement

Analysis framework

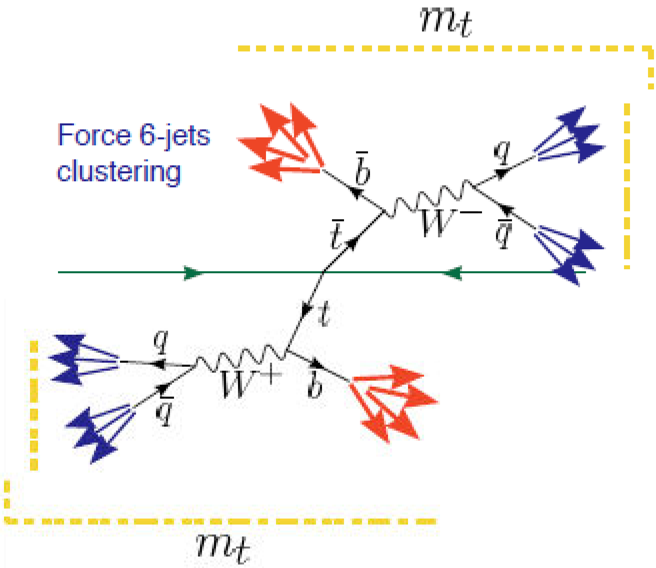
- All standard model MC samples (included signal processes): produced as common inputs (StdHep format) by SLAC team (WHIZARD + PYTHIA)
- Detector exact-hits: Geant4-based detector simulator (Mokka) => Smeared tracker hits and calorimeter hits (MarlinReco)
- Pattern recognition of track segments in the TPC and silicon detector separately / link the found track segments together / track-fit using a Kalman filter (MarlinReco)
- Reconstructed individual particles (Particle flow objects): Sophisticated particle flow algorithm (PandoraPFA)
- 6-jets clustering for signal & all BG events (Durham force 6-jets clustering)
- Heavy flavour tagging: Search for secondary vertices inside jets and determine mass, momentum and decay length of the vertex. In addition, the impact parameter joint probability and the two highest impact parameter significances are used as an input into NN with jets having 0, 1 and more than 1 secondary vertices / Each reconstructed jet is assigned with the NN outputs, referred to as b- and c-tags (LCFIVertex)

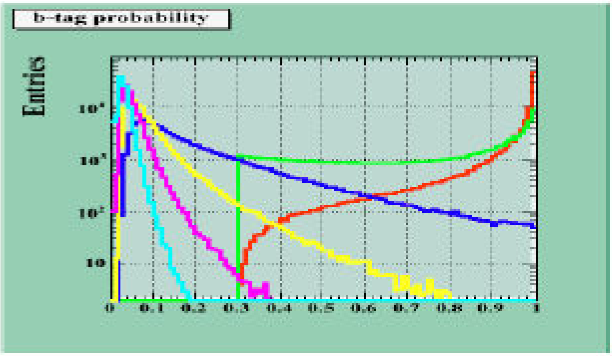
ttbar -> 6-jets reconstruction

- 2 different top-antitop combinatorics schemes and BG rejection (multi-variate or cut-bases) methods: 2 independent analyses (MPI-Munich and KEK)

★ 6-jets combinatorics scheme (1)

1. Using flavour tagging information, the jets with the 2 highest b-tag values are taken. => They are regarded as b-jets, resulting directly from the top quark decays.
2. The 4 remaining jets are considered as decay products of the 2 W bosons. => There are 3 possible ways to combine 4-jets into 2 di-jets. For each possible combination the quantity $\Delta m_W = |m_{ij} - m_W| + |m_{kl} - m_W|$ is calculated. (with m_{ij} and m_{kl} di-jet masses for a given jet pairing) => The combination yielding the smallest value of Δm_W is chosen to form the 2 W bosons.
3. The 2 top candidates having the same mass is expected. Choose the 2 "di-jet / b-jet pairs" which yields minimal tri-jet mass difference.


Force 6-jets clustering



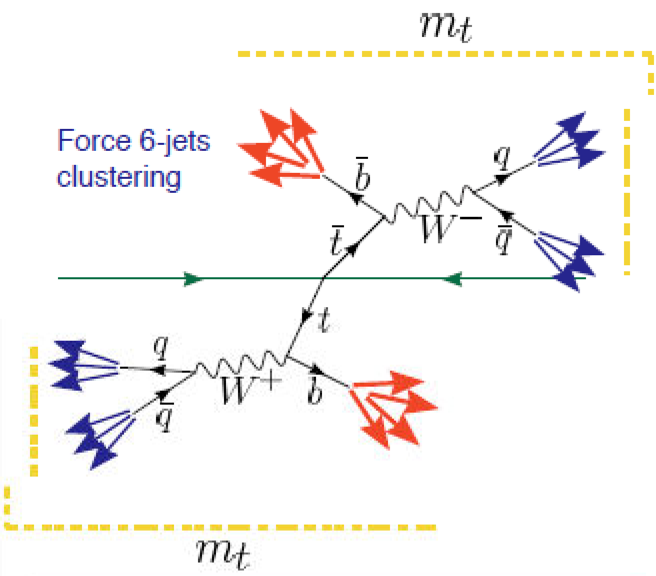
ttbar -> 6-jets reconstruction

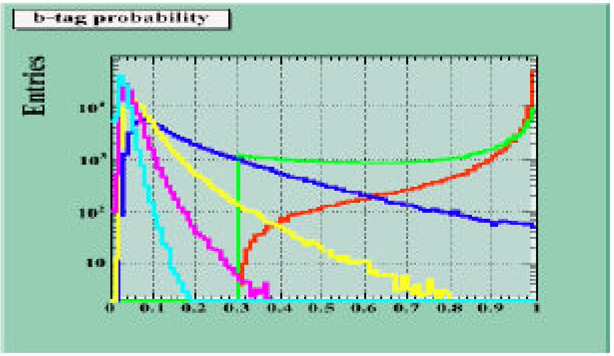
- 2 different top-antitop combinatorics schemes and BG rejection (multi-variate or cut-bases) methods: 2 independent analyses (MPI-Munich and KEK)

★ 6-jets combinatorics scheme (2)

1. Choose all the 15-possible pairs out of 6-jets => W_1 candidate
2. Choose all the 6-possible paris out of remaining 4-jets => W_2 candidate
3. When the remaining 2-jets are b-jets, there are 2 possibilities to attach a b-jet to the W_1 and the W_2 candidates => 2 b-W (t_1 and t_2) candidates
4. Store all solutions w/ $\chi^2 = (m_{w1} - m_w)^2/\sigma^2_{2j} + (m_{w2} - m_w)^2/\sigma^2_{2j} + (m_{t1} - m_t)^2/\sigma^2_{3j} + (m_{t2} - m_t)^2/\sigma^2_{3j}$

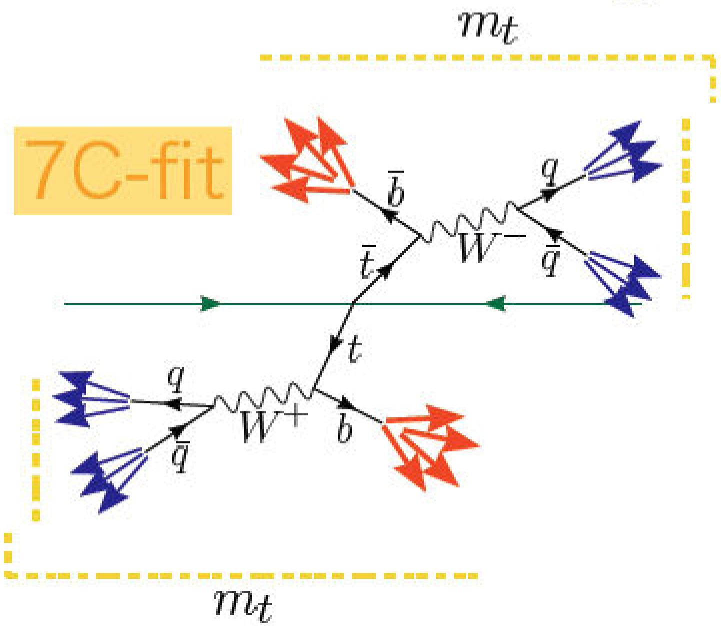
I) Sort solutions according to χ^2 => choose the best solution





- Consistency check => ILD-LOI result

Kinematic fitting for ttbar -> 6-jets

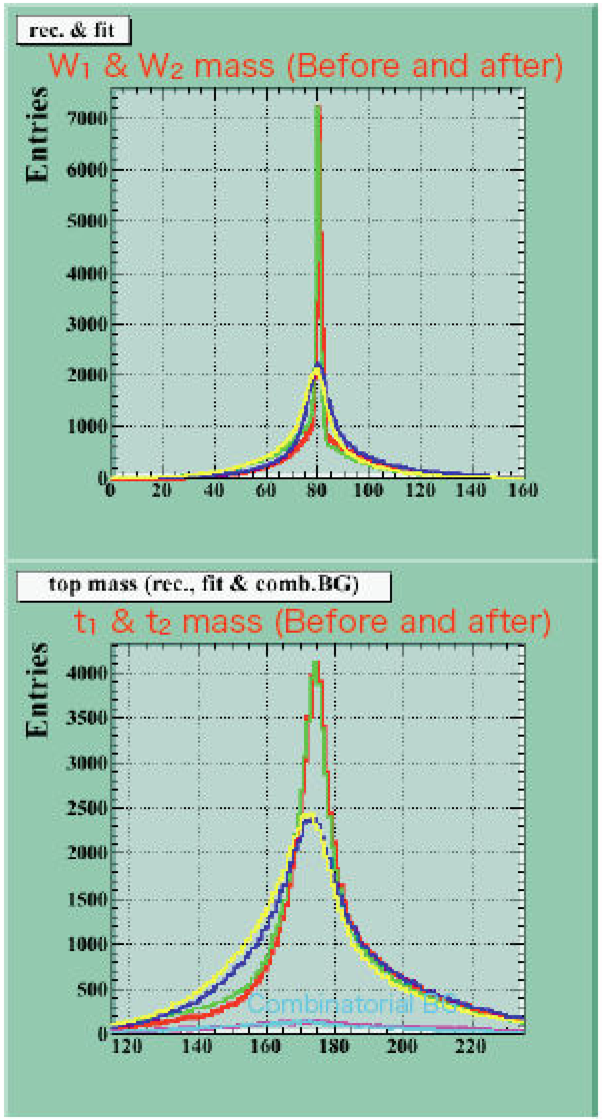


$\sum_{i=1}^{6} \vec{p}_i = 0$ *momentum conservation*

$\sum_{i=1}^{6} E_i = \sqrt{s}$ *energy conservation*

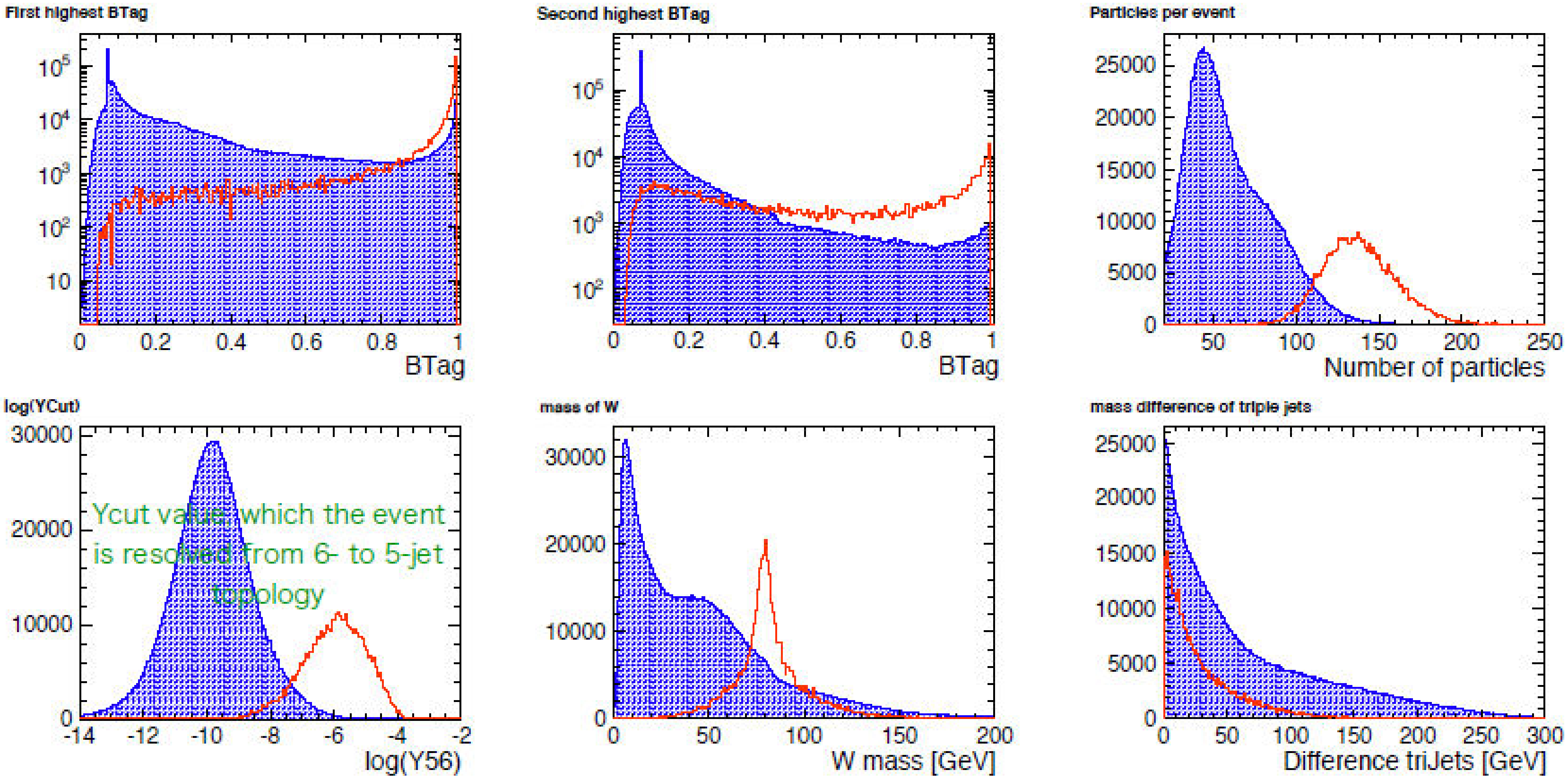
$|m_{ij} - m_W| = 0$
$|m_{kl} - m_W| = 0$ *mass difference W di-jet and nominal W mass*

$\Delta m_3 = 0$ *same mass t and $\bar{t}$*



BG rejection - discriminating variables

- Discriminating variables are combined into 1-discriminant (using binned likelihood technique) to reject BGs efficiently

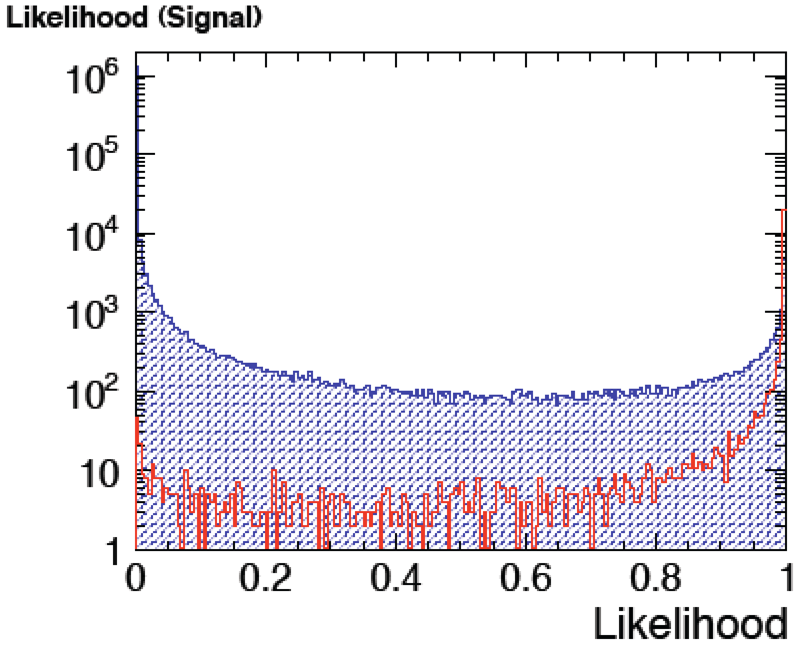


red: signal / blue: BG

Signal distributions are multiplied by a factor 20

BG rejection - likelihood / BG classes

- BG rejection: signal likelihood > 0.9 => S/B = 21210/10530
- Kinematic fitting χ^2 cut: improve S/B (also combinatorial BGs)

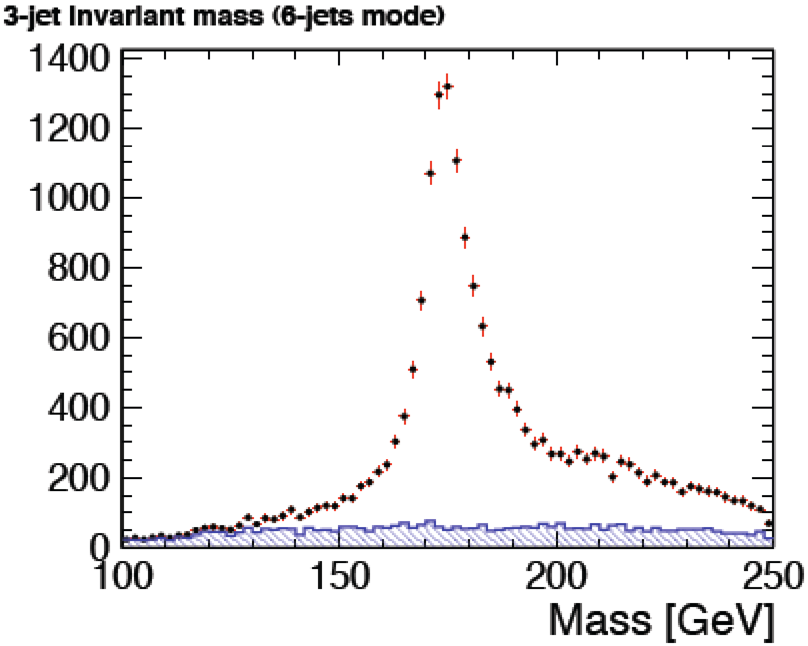


red: signal / blue: BG

BG event classes	Distinction	Contribution to BGs
ttbar semi-leptonic decay	Isolated lepton veto (2806/15946 ~ 17.6%) => kinematic fitting χ^2 cut	Negligible
6-fermion (incl. 2b)	Small cross section	Small contribution
6-fermion (the others)	Double b-tagging	Negligible
4-fermion (4q mainly from W^+W^-)	Large cross section	Main BG source
4-fermion (2q + 2l)	Double b-tagging Ycut$_{56}$	Negligible
2-fermion (bb)	Huge cross section	Main BG source
2-fermion (cc)	Huge cross section Double b-tagging	Small contribution
2-fermion (qq)	Double b-tagging	Negligible

3-jets mass dist. w/ signal + BGs

- Overall selection efficiency: 72%
- Final S/B ~ 4.1 (= 15744/3811 @100fb^{-1})
- σ (e^+e^- -> ttbar) = 0.4 % @500fb^{-1}



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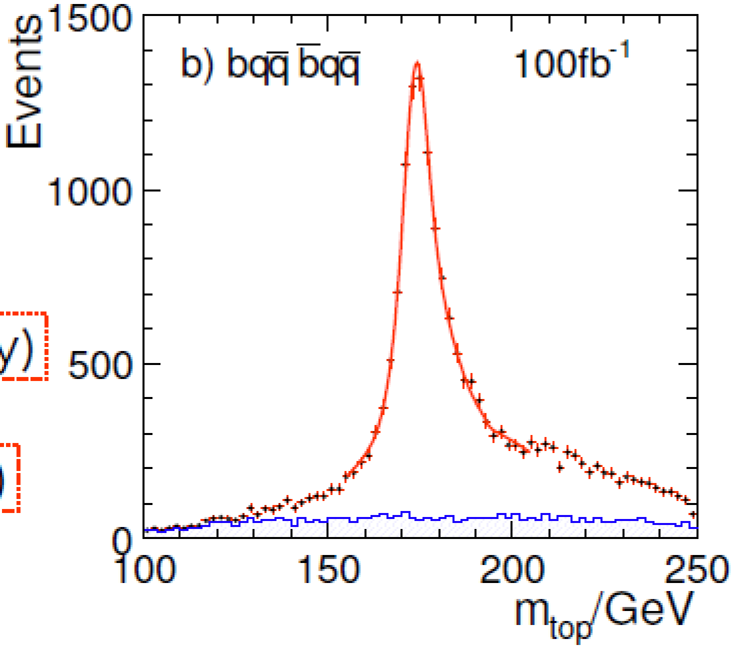
Define line-shape, then fit M_{3j}

- Line-shape function: convoluted Breit-Wigner w/ detector resolution function + 2nd order polynomial
  - Assume detector resolution function as asymmetric double Gaussian (double Gaussian w/ a mean shift and a weight = 4 parameters)
  - Decide resolution functions using hight statistics samples w/ fixed top mass (174 GeV) and top width (1.34 GeV) which were obtained from input SLAC StdHep gen-info.
- M_{3j} fit w/ the line-shape
  - Free 3 parameters (m_t, Γ_t, N_{event})
  - Un-polarized beams

$m_t = 174.0 \pm 0.09$ (stat. only)

$\Gamma_t = 1.44 \pm 0.06$ (stat. only)

(100 fb^{-1})



ILD M_t & σ_{tt} Summary

- Precise methods to reconstruct top-quark pair production events using fully-hadronic decay mode are worked out with the ILD detector model and sophisticated software chains.

- For an integrated luminosity of 500 fb^{-1}, σ (e^+e^- -> ttbar) can be determined with a statistical uncertainty of 0.4 % using the fully-hadronic decays only.

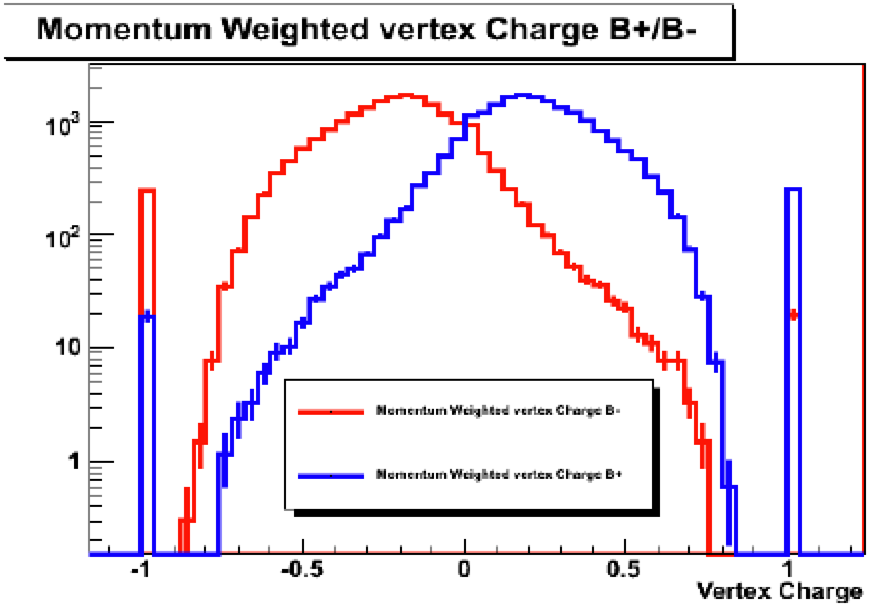
- The invariant mass spectra are fitted with the convolution of a Breit-Wigner function and an asymmetric double Gaussian, the latter representing the detector resolution. The combinatoric background and the background from other process is described by a 2nd order polynomial.

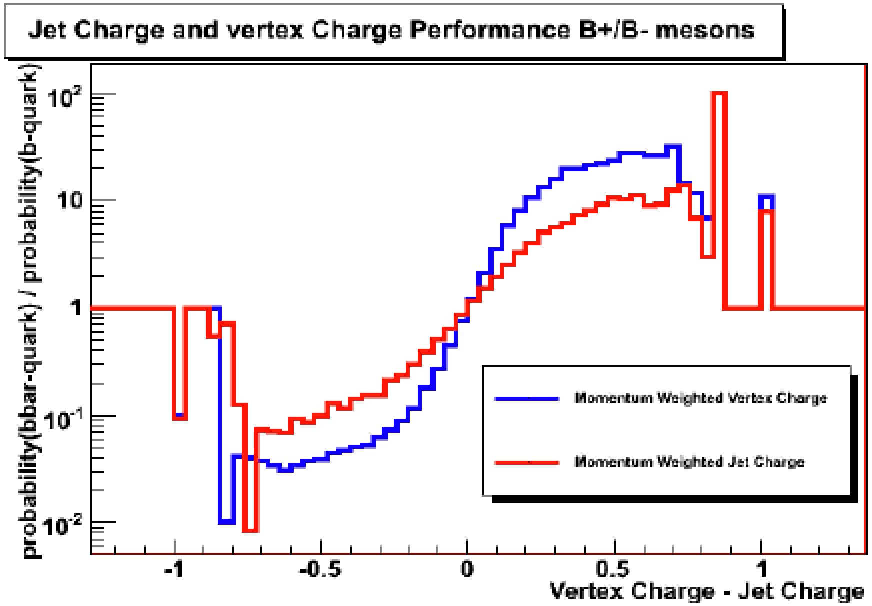
- The fully-hadronic analysis branch results in statistical uncertainties of 90 MeV and 60 MeV for m_t and Γ_t respectively. Scaling the combined results to an integrated luminosity of 500 fb^{-1} leads to uncertainties of 40 MeV on m_t and 27 MeV on Γ_t.

Top A_{FB} Measurement

Reconstructing Parton Charge

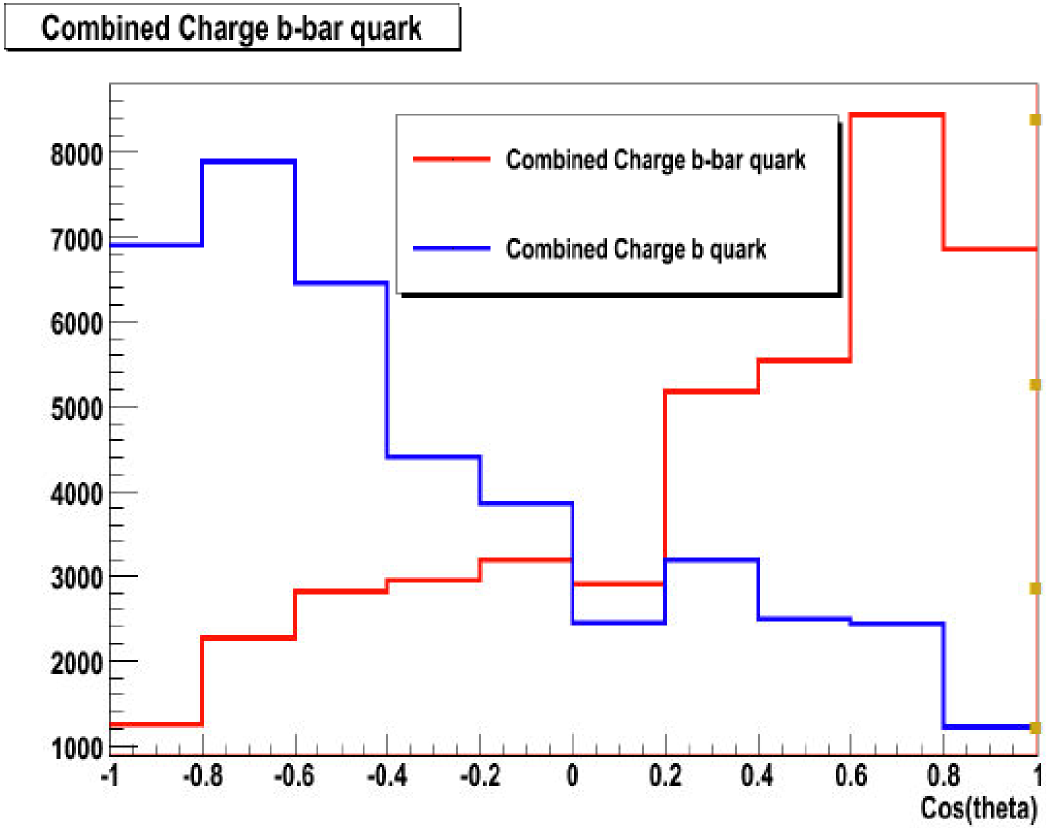
- Develop series of discriminating variables, then recombining them
  - Similar to what it is done in the flavour tagging.
- Momentum weighted secondary vertex charge
  - This is the weighted sum of the charge of all tracks in a vertex
  - Good for B+/B- if secondary found
- Momentum weighted Jet charge
  - This is the weighted sum of the charge of all tracks in a jet
  - Good for B0s and if no secondary.


Momentum Weighted vertex Charge B+/B-


Jet Charge and vertex Charge Performance B+/B- mesons

Combining charge variables

To calculate Combined Charge variable:



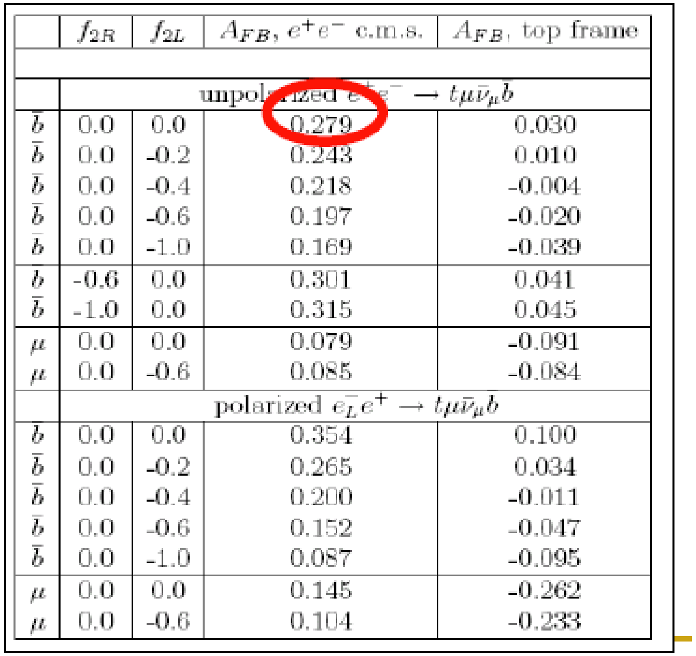
- Use "template sample" to determine ratio of signal to backgrounds in each bin for each variable.
- Use this ratio as a discriminating power of each variable in any specific "data" event
- Multiplies the ratios of each variable considered.
- Apply transformation to get a result between -1 and 1.

Method describe in:
arXiv:hep-ex/0609034v1

b quark A_{fb}

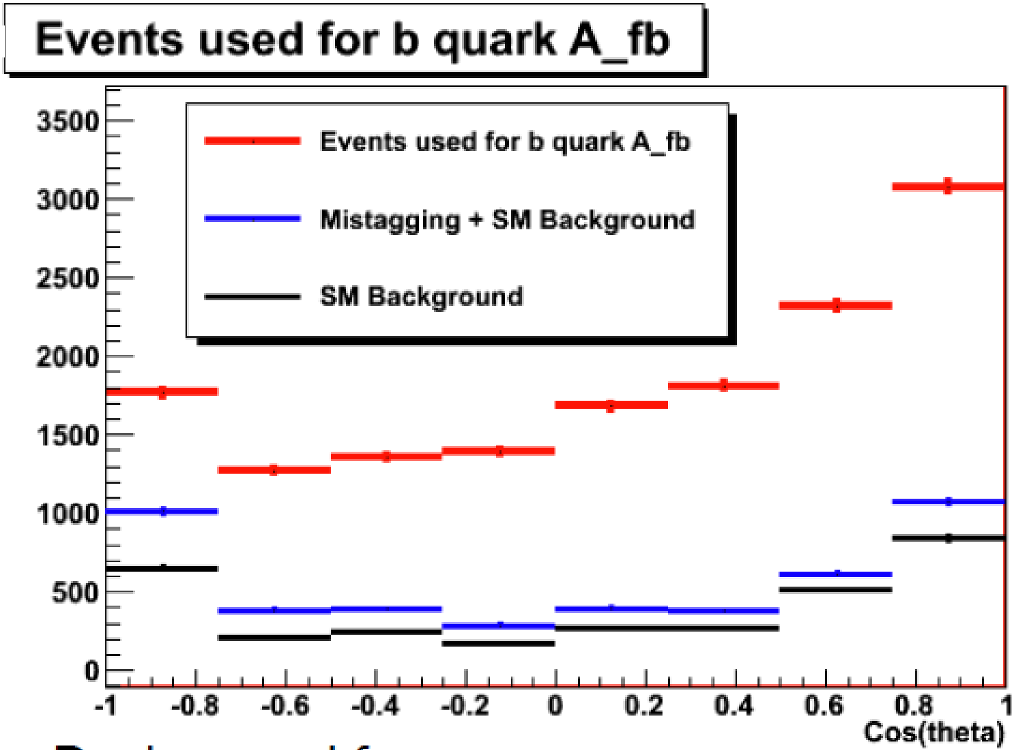
- Cut on combined charge
  - $\text{Charge}_{\text{Jet1}} \times \text{Charge}_{\text{Jet2}} < -0.3$
- Efficiency low: 7.1%
  - Events without secondary
  - B0/B0bar

Theoretical Prediction



	f_{2R}	f_{2L}	A_{FB}, e^+e^- c.m.s.	A_{FB}, top frame
	unpolarized $e^+e^- \to t\mu\bar{\nu}_\mu\bar{b}$			
$\bar{b}$	0.0	0.0	0.279	0.030
$\bar{b}$	0.0	-0.2	0.243	0.010
$\bar{b}$	0.0	-0.4	0.218	-0.004
$\bar{b}$	0.0	-0.6	0.197	-0.020
$\bar{b}$	0.0	-1.0	0.169	-0.039
$\bar{b}$	-0.6	0.0	0.301	0.041
$\bar{b}$	-1.0	0.0	0.315	0.045
μ	0.0	0.0	0.079	-0.091
μ	0.0	-0.6	0.085	-0.084
	polarized $e_L^-e^+ \to t\mu\bar{\nu}_\mu\bar{b}$			
$\bar{b}$	0.0	0.0	0.354	0.100
$\bar{b}$	0.0	-0.2	0.265	0.034
$\bar{b}$	0.0	-0.4	0.200	-0.011
$\bar{b}$	0.0	-0.6	0.152	-0.047
$\bar{b}$	0.0	-1.0	0.087	-0.095
μ	0.0	0.0	0.145	-0.262
μ	0.0	-0.6	0.104	-0.233

E. Boos et al. arXiv:hep-ph/0001048v2



- Background from:
  - Standard model
  - b quark and charge mistagging

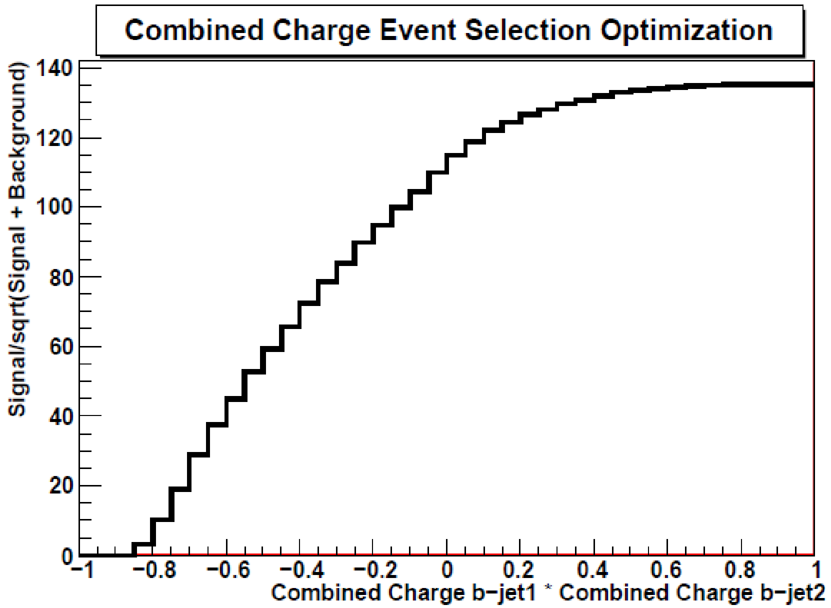
$$A_{FB} = \frac{\sigma(\theta < 90^\circ) - \sigma(\theta > 90^\circ)}{\sigma(\theta < 90^\circ) + \sigma(\theta > 90^\circ)}$$

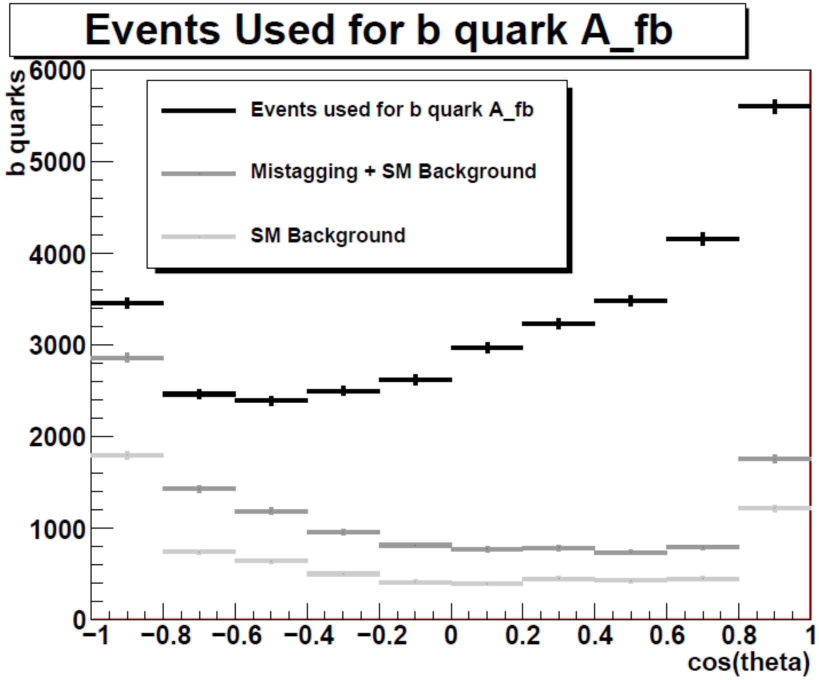
- Calculate A_{fb}: 0.272 ± 0.015 (stat)

b quark A_{fb} post LOI update

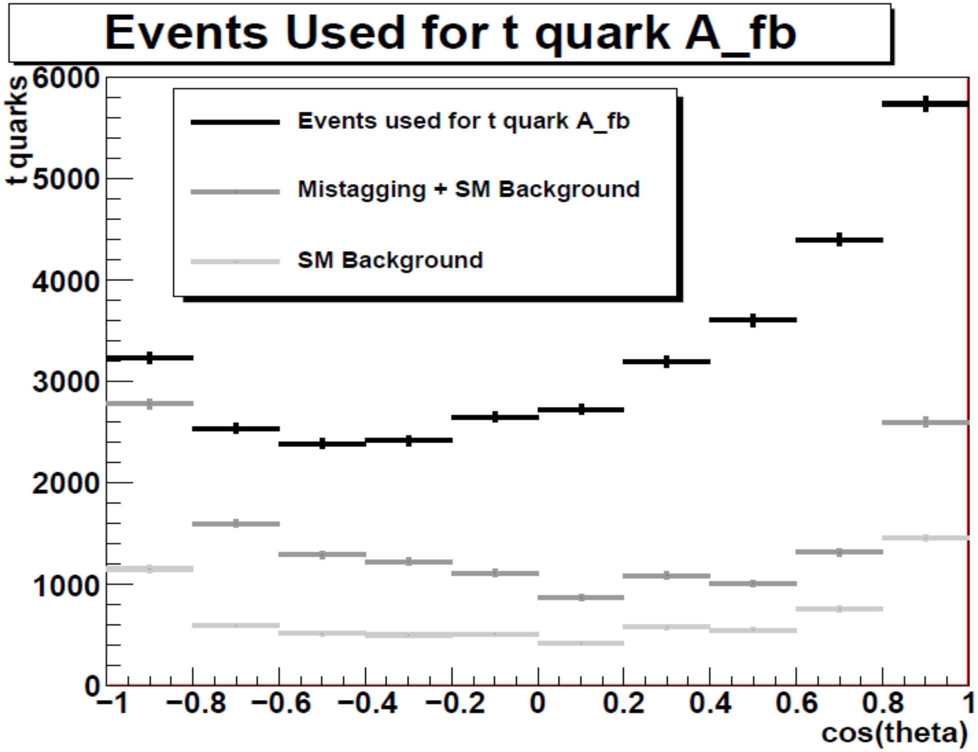
- No cut on combined charged:
  - $\text{Charge}_{\text{Jet1}} \times \text{Charge}_{\text{Jet2}} < 1$
- Efficiency = 22.7%
- Purity=58.1%
- Impurity composition:
  - SM bkgd 45.9%
  - ttbar with wrong b-jet charge 45%
  - ttbar with wrong b-jet id 9.1%

$A_{fb}(b)=0.293\pm0.008$





t quark A_{fb}



- Same events as for b quark
- Complication associate b quark with the correct W jets.
- Use kinematic fitter for correct jet pairing

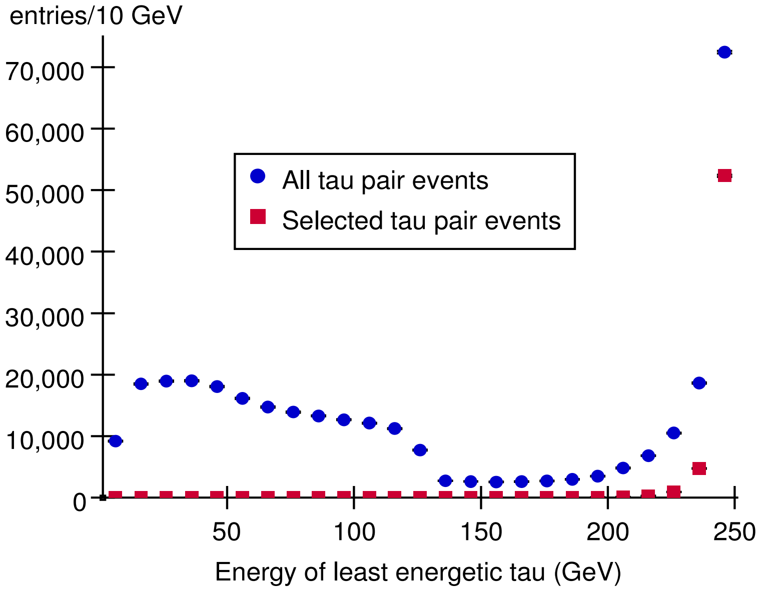
- Calculate A_{fb}: 0.356±0.008 (stat)
- Compare with data at MC pre-reconstruction level: 0.351

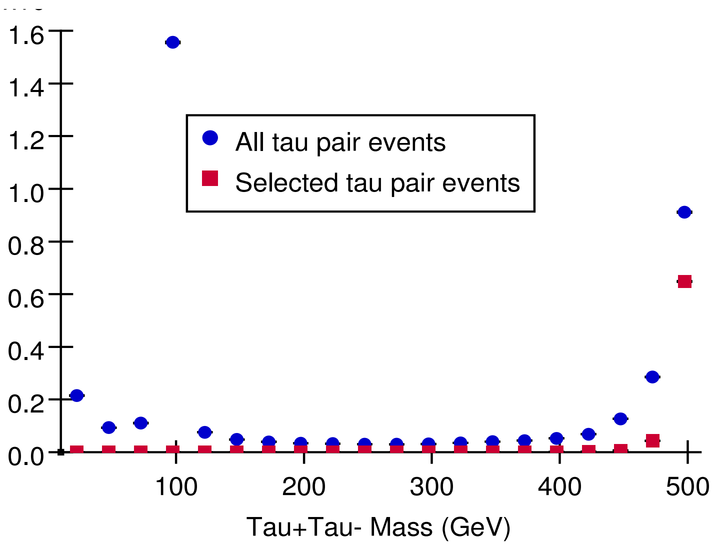
Tau σ_{tot}, A_{FB} and Decay Mode ID

Tau selection and background

- ~~Event cuts: 2-6 tracks, 40<Evis<450 GeV~~
- Event cuts: 2-6 tracks, 100<Evis<450 GeV
- Tau jet clustering, 2 jets, each cosθ < .95
- Opening angle > 178 degrees
- Eliminate events with both mu or both e
- Selects 17.4% of all tau pairs, 72% of minE > 240
- Background from other SM 2.4%

Post-LOI: Increase min E_{vis} cut
to remove $\gamma\gamma \rightarrow \tau^+\tau^-$ events
which had low stats & high weight
in fully simulated SM bgnd sample.
Gives 3% loss in signal efficiency.


+80e- -30e+ -> tau+tau-


-80e- +30e+ -> tau+ tau-

Tau pair cross section and A_{FB}

The selected sample of mostly full energy taus is used to measure the tau pair cross section and A_{FB} at $\sqrt{s} = 500$ GeV.

The total cross section precision is 0.28%.

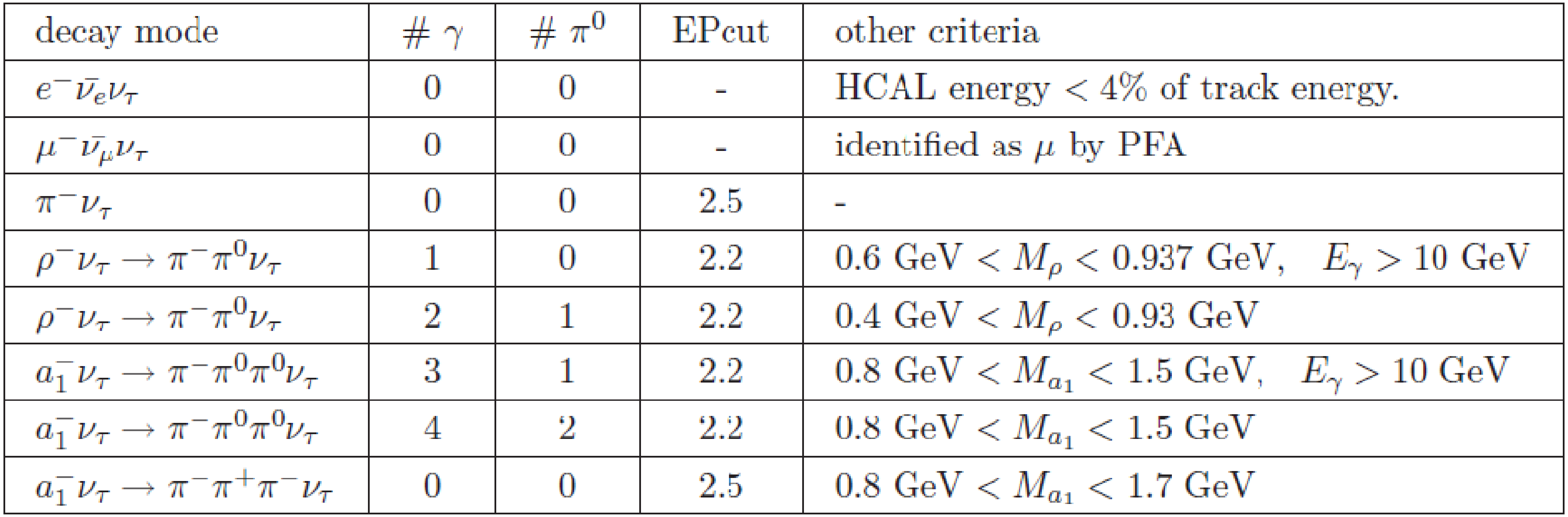
A_{FB} was measured by fitting the tau $\cos\theta$ distribution to

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3} A_{FB} \cos\theta$$

$A_{FB} = 0.5038 \pm 0.0021$ for 250 fb^{-1} with $e^-(80\%L)\ e^+(30\%R)$

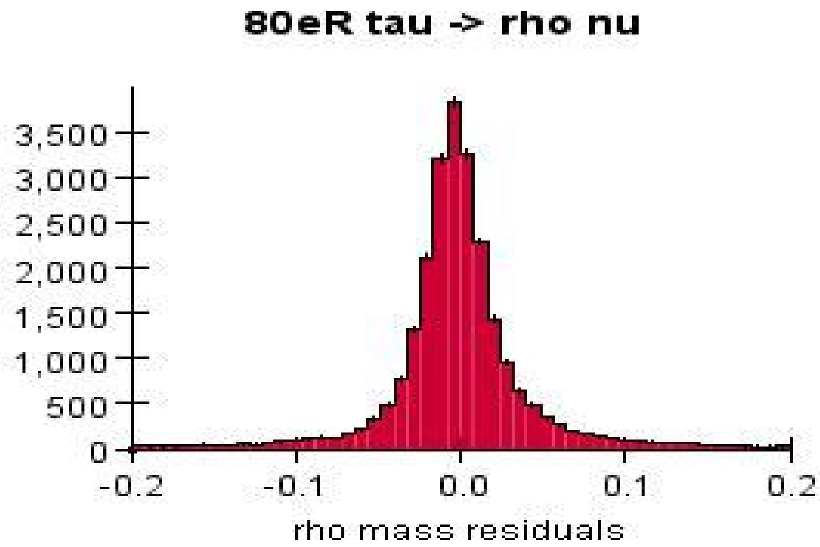
$A_{FB} = 0.4704 \pm 0.0024$ for 250 fb^{-1} with $e^-(80\%R)\ e^+(30\%L)$

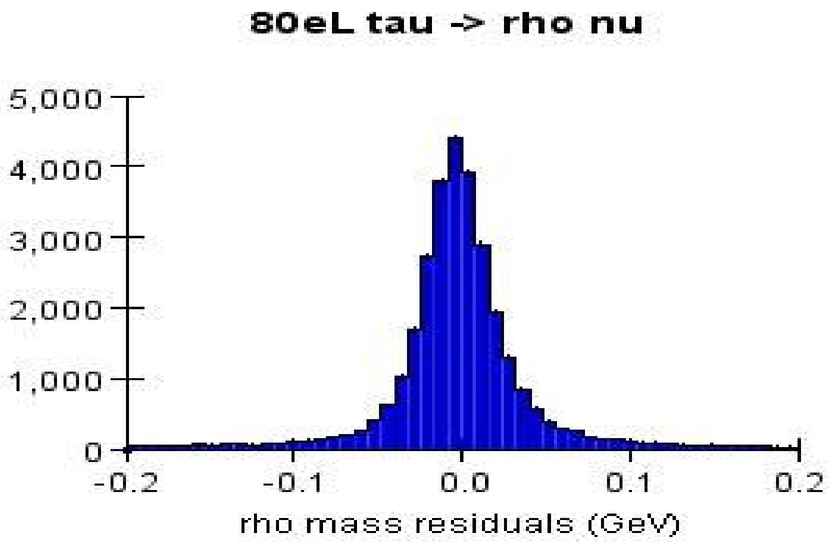
Decay mode selection using modification of SiD pfa

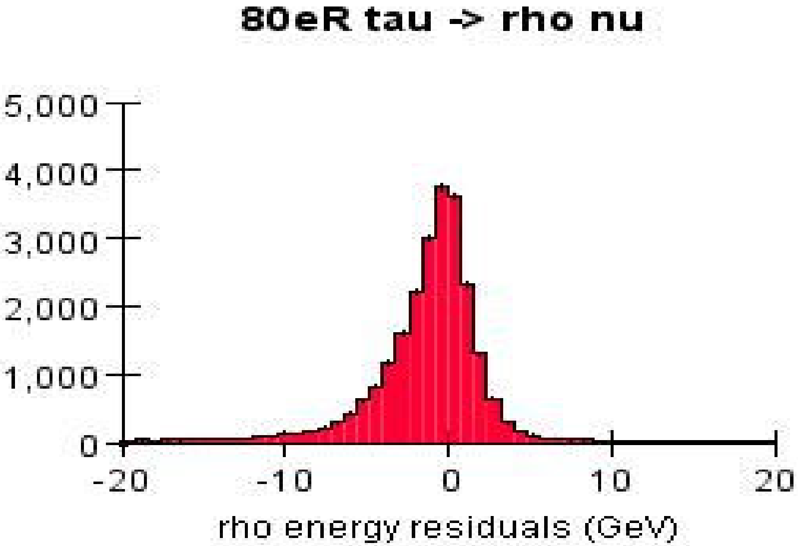


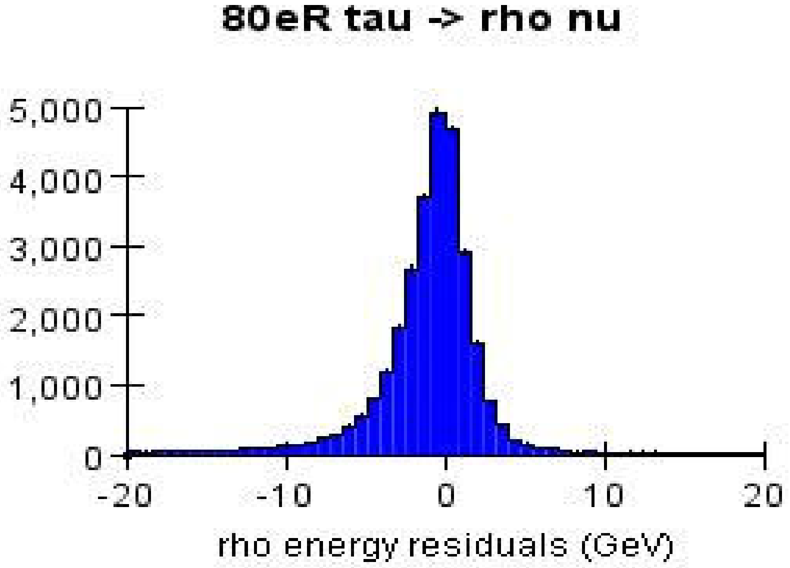
decay mode	# γ	# π^0	EPcut	other criteria
$e^- \bar{\nu}_e \nu_\tau$	0	0	-	HCAL energy $<$ 4% of track energy.
$\mu^- \bar{\nu}_\mu \nu_\tau$	0	0	-	identified as μ by PFA
$\pi^- \nu_\tau$	0	0	2.5	-
$\rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$	1	0	2.2	$0.6 \text{ GeV} < M_\rho < 0.937 \text{ GeV}, \quad E_\gamma > 10 \text{ GeV}$
$\rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$	2	1	2.2	$0.4 \text{ GeV} < M_\rho < 0.93 \text{ GeV}$
$a_1^- \nu_\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$	3	1	2.2	$0.8 \text{ GeV} < M_{a_1} < 1.5 \text{ GeV}, \quad E_\gamma > 10 \text{ GeV}$
$a_1^- \nu_\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$	4	2	2.2	$0.8 \text{ GeV} < M_{a_1} < 1.5 \text{ GeV}$
$a_1^- \nu_\tau \to \pi^- \pi^+ \pi^- \nu_\tau$	0	0	2.5	$0.8 \text{ GeV} < M_{a_1} < 1.7 \text{ GeV}$

Rho reconstruction

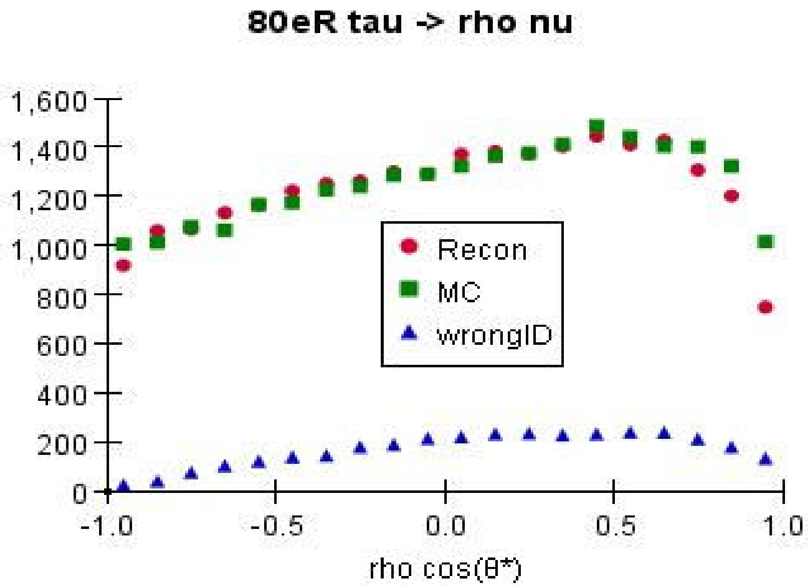


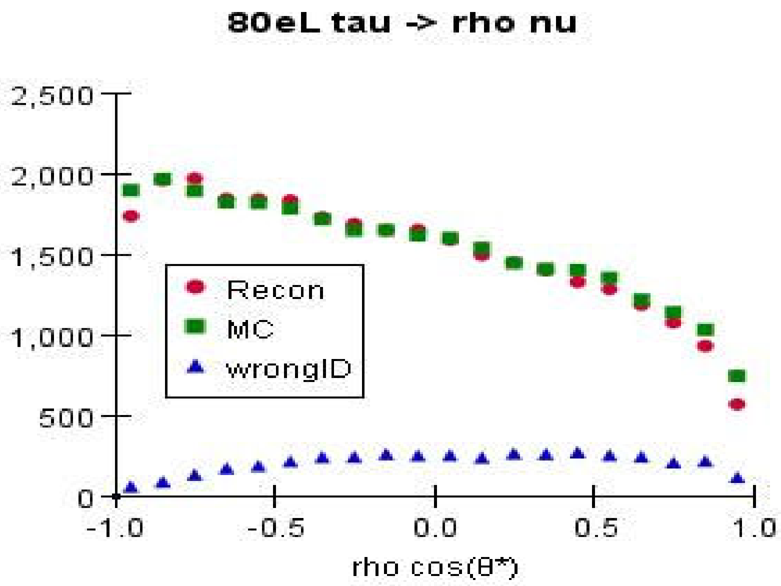


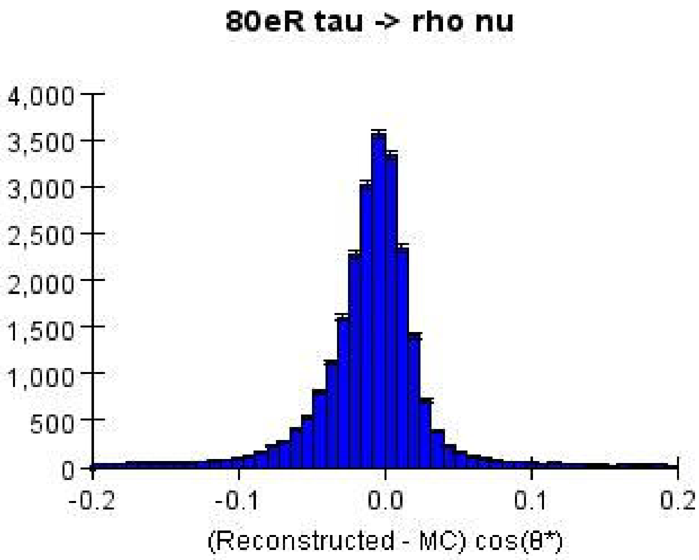


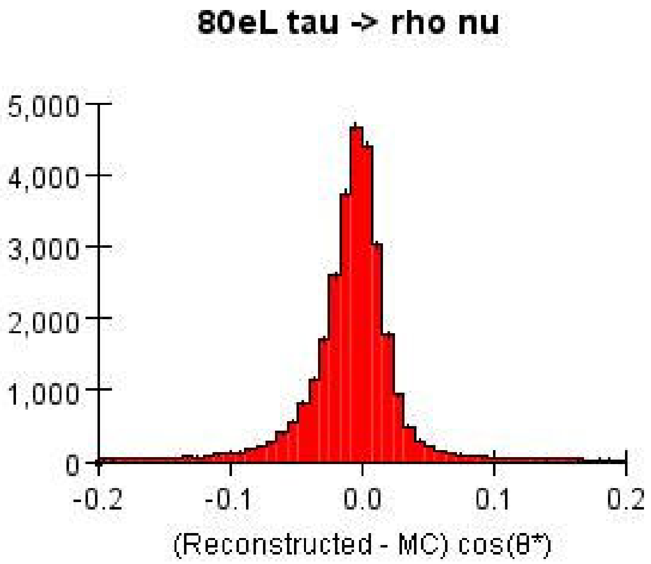


Θ* = angle between rho and tau in tau rest frame



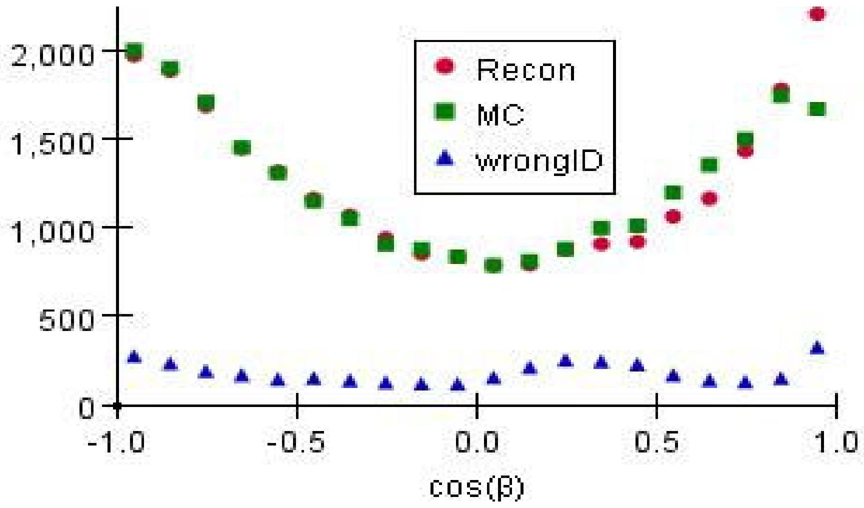




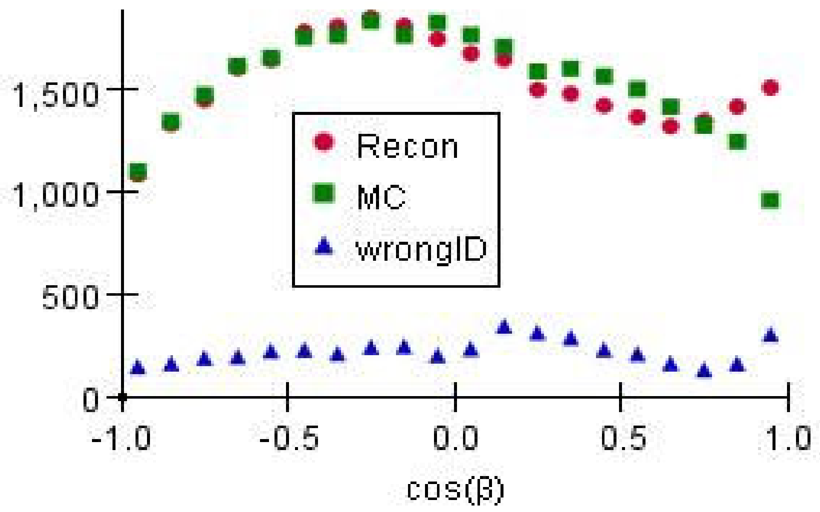


β = angle between pi+- in rho rest frame

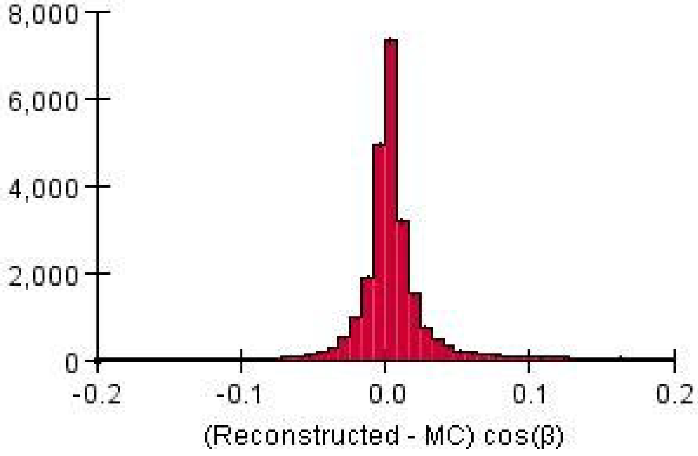
80eR tau -> rho nu



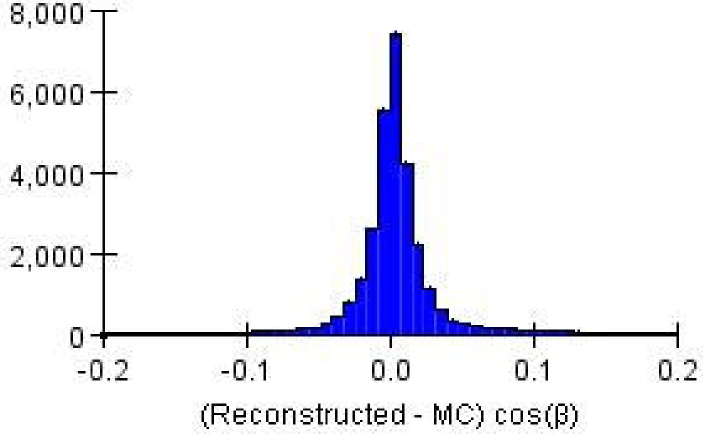
80eL tau -> rho nu



80eR tau -> rho nu



80eR tau -> rho nu



Tau decay mode purity and efficiency

decay mode	Correct ID	Wrong ID	ID eff	ID purity	SM bgnd
$e^-\bar{\nu}_e\nu_\tau$	39602	920	0.991	0.977	1703
$\mu^-\bar{\nu}_\mu\nu_\tau$	39561	439	0.993	0.989	1436
$\pi^-\nu_\tau$	28876	2612	0.933	0.917	516
$\rho^-\nu_\tau \rightarrow \pi^-\pi^0\nu_\tau$	55931	8094	0.790	0.874	1054
$a_1^-\nu_\tau \rightarrow \pi^-\pi^0\pi^0\nu_\tau$	18259	11140	0.732	0.621	847
$a_1^-\nu_\tau \rightarrow \pi^-\pi^+\pi^-\nu_\tau$	21579	2275	0.914	0.905	141

Tau Polarization Measurement

Decay modes in A_{pol} analysis

4 decay modes:

- $\tau^+ \rightarrow e^+\overline{\nu_e}\nu_\tau \ (17.9\%), \ \tau^+ \rightarrow \mu^+\overline{\nu_\mu}\nu_\tau \ (17.4\%)$
  - Separated by lepton-ID (high eff.)
  - Polarization information is lost by two missing neutrinos
- $\tau^+ \rightarrow \pi^+\nu_\tau \ (10.9\%)$
  - 1 charged π, moderate BR, good for pol. derivation
- $\tau^+ \rightarrow \rho^+\nu_\tau \rightarrow \pi^+\pi^0\nu_\tau \ (25.2\%)$ ρ (770 MeV mass, 150 MeV width)
  - 1 charged π+2 γ photon separation (detector)

Minimize stat. error by combining decay modes

Optimal observable

- Polarization calculation varies by decay modes.
  - Energies and angles of/between daughters
  - Better if single criterion can be used in all decay modes.

→ optimal observable ω

- expression of ω differs by decay modes, but ω can be summed up through all decay modes. (multi-dimensional fit in each decay mode is not needed)
- Developed in LEP.

Optimal observable

1. Pure-leptonic decay:

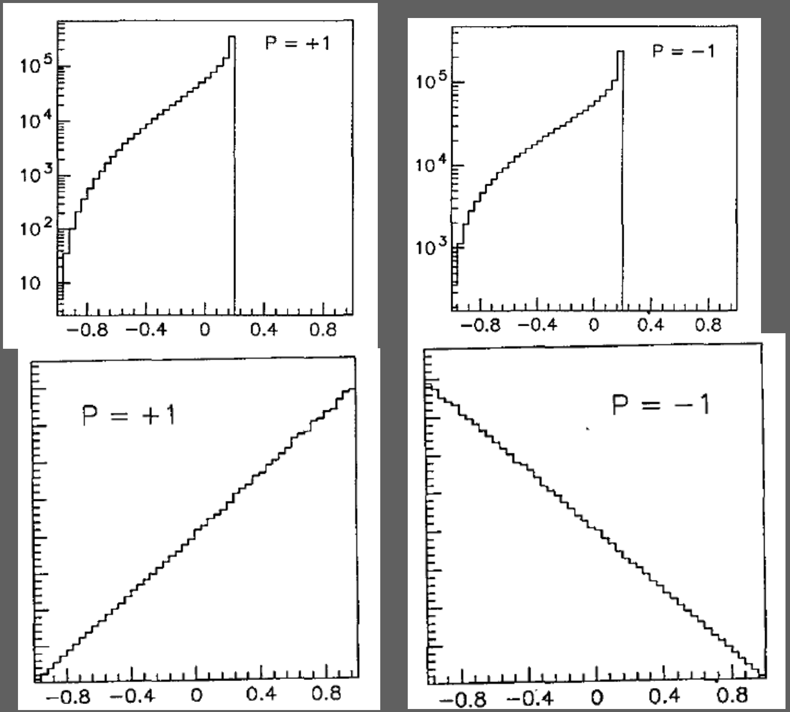
ILD:

$$\omega_\ell = \frac{1 + x - 8x^2}{5 + 5x - 4x^2}$$

SiD:

$$\omega_l = 2x - 1$$

(x: lepton energy / tau energy)

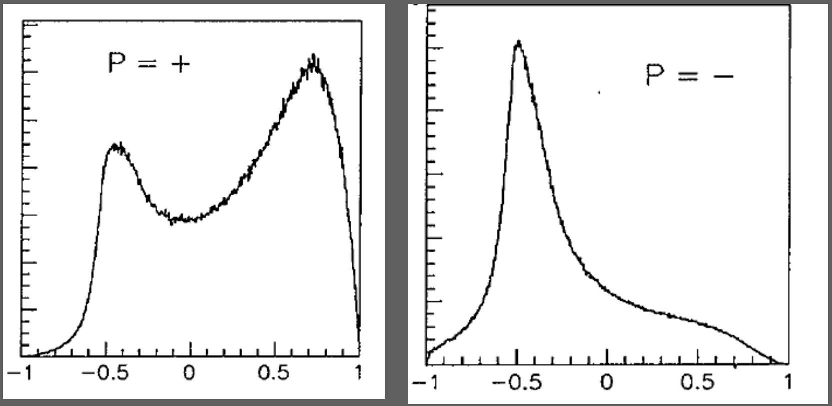


2. $\pi^+\nu_\tau$ decay:

$$\omega_\pi = 2x - 1$$

3. $\rho^+\nu_\tau$ decay: (2 energies and 3 angles, 5 parameters)

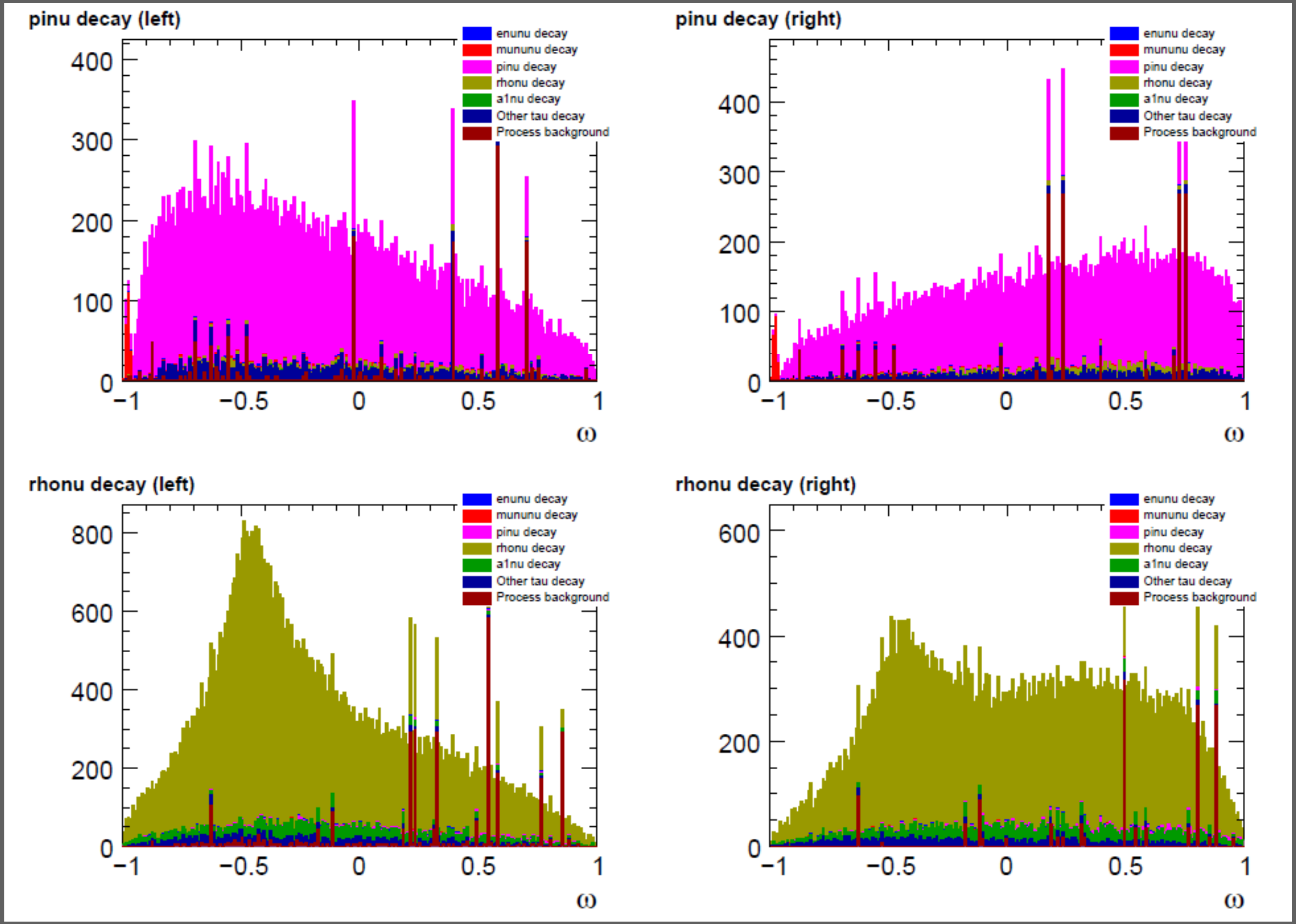
$$\begin{aligned}
\omega_\rho &= \frac{\left(-1+\frac{m_\tau^2}{Q^2}+2\left(1+\frac{m_\tau^2}{Q^2}\right)\frac{3\cos^2\psi-1}{2}\,\frac{3\cos^2\beta-1}{2}\right)\cos\theta+3\sqrt{\frac{m_\tau^2}{Q^2}}\,\frac{3\cos^2\beta-1}{2}\sin 2\psi\sin\theta}{2+\frac{m_\tau^2}{Q^2}-2\left(1-\frac{m_\tau^2}{Q^2}\right)\frac{3\cos^2\psi-1}{2}\,\frac{3\cos^2\beta-1}{2}} \\
\cos\psi &= \frac{x(m_\tau^2+Q^2)-2Q^2}{(m_\tau^2-Q^2)\sqrt{x^2-4Q^2/s}} \\
x &= 2\frac{E_h}{\sqrt{s}}
\end{aligned}$$



(4. a_1 : almost ready…)

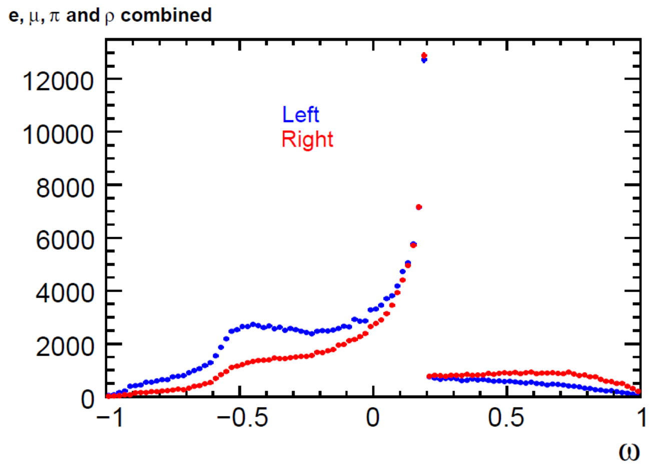
Optimal observable distribution

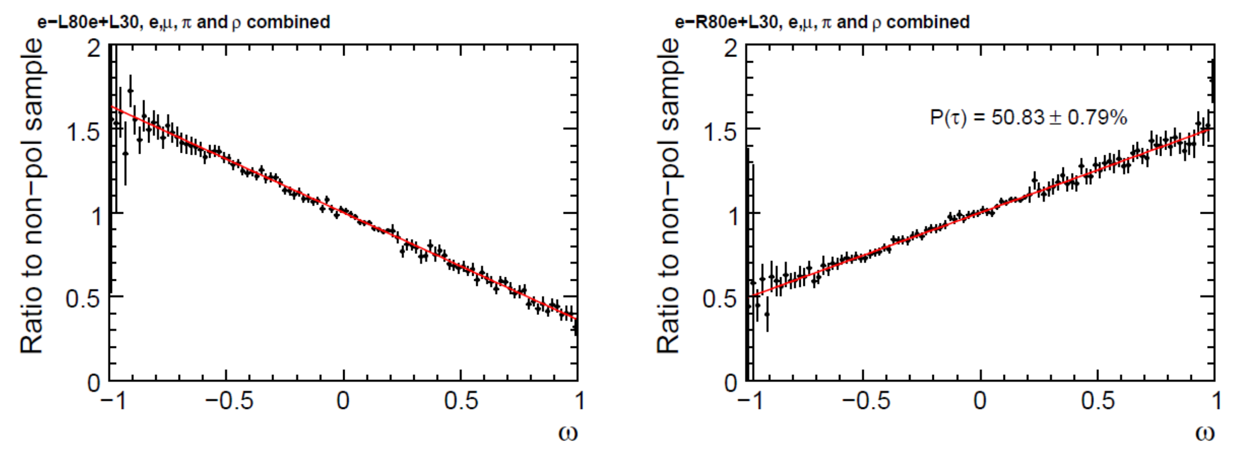
- Apply ω formula on sample of initial polarization $P(e^+, e^-) = (30\%, 80\%)$



Polarization of tau

- Summed up 4 ω distributions
  - Process background is excluded (short statistics)
- Obtain $P(\tau)$
- Obtain $P(\tau)$ stat. error with 500 fb^{-1}



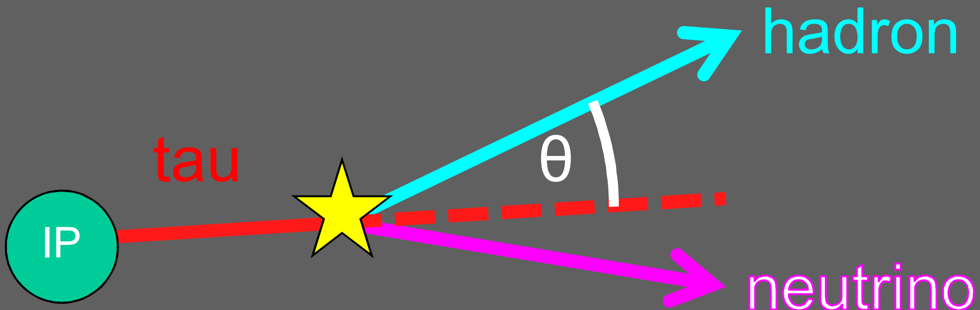


$P(\tau) = -63.82 \pm 0.66\% \ (e^-_L e^+_R)$
$P(\tau) = +50.83 \pm 0.79\% \ (e^-_L e^+_R)$

Tau flight direction

- should help with polarization measurement
  - 3 degrees of freedom of tau four-vector
  - 3 constraints:
    1. $E_\tau = \sqrt{s}/2$
    2. tau/hadron angle from two-body decay kinematics
    3. tau track must meet the hadron track at a point (1-prong) or the vertex (3-prong)
  - can be solved for tau direction analytically

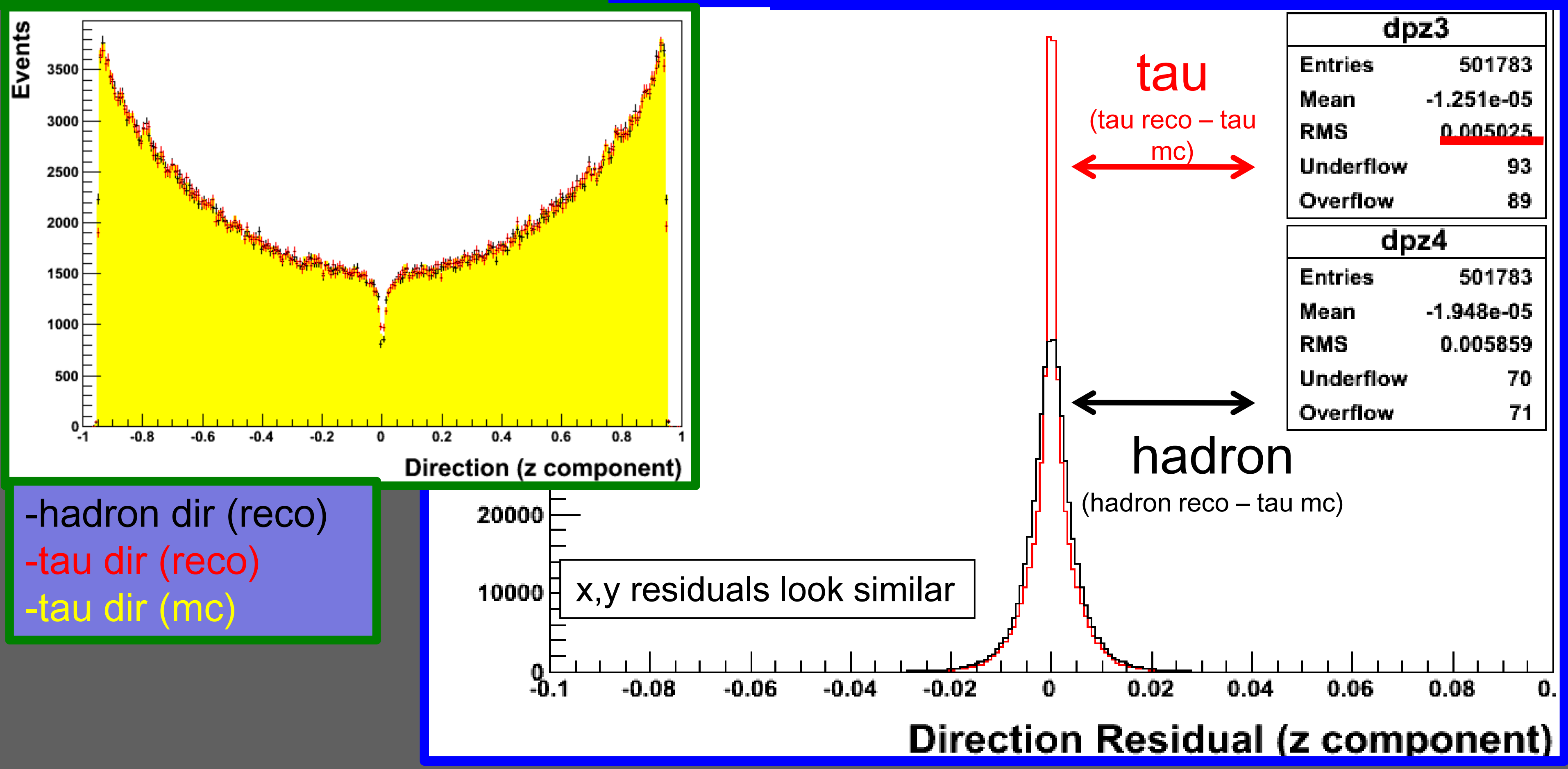
a sneak preview of this concept will be shown for 1-prong events
using first-order approximation for tracks (using line segment instead of helix)



Tau flight direction (1-prong events)

tau direction in lab frame

tau direction residual (reco – mc)



-hadron dir (reco)
-tau dir (reco)
-tau dir (mc)

x,y residuals look similar

dpz3	
Entries	501783
Mean	-1.251e-05
RMS	0.005025
Underflow	93
Overflow	89

dpz4	
Entries	501783
Mean	-1.948e-05
RMS	0.005859
Underflow	70
Overflow	71

tau direction successfully reconstructed (3-prong work next)
better than assuming tau dir = hadron dir (rms: 0.0059 > 0.0050)

Summary of Results from the Detector Concept Groups

Top Measurements in fully hadronic mode for $\sqrt{s} = 500$ GeV and 500 fb^{-1} luminosity

	$\Delta M_t\,(MeV)$	$\Delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}}$	$\Delta A_{FB}(t\bar{t})$
4th	59	–	–
ILD	40	0.0040	0.008
SiD	45	0.0045	0.008

Tau Decay Mode Efficiencies and Purities at $\sqrt{s} = 500$ GeV

		ILD			SiD	
Mode		Eff	Purity		Eff	Purity
$e\nu\nu$		0.989	0.989		0.991	0.977
$\mu\nu\nu$		0.988	0.993		0.993	0.989
$\pi\nu$		0.960	0.895		0.933	0.917
$\rho\nu$		0.916	0.886		0.790	0.874
$a_1\nu$ 1-prong		0.675	0.734		0.732	0.621
$a_1\nu$ 3-prong		0.911	0.889		0.914	0.905

Tau Cross Section, A_{FB} and P_τ for $\sqrt{s} = 500$ GeV and 500 fb^{-1} luminosity

			$P(e^+, e^-) = (+30\%, -80\%)$			$P(e^+, e^-) = (-30\%, +80\%)$	
	$\Delta\sigma_{\tau\tau} / \sigma_{\tau\tau}$		$\Delta A_{FB}(\tau^+\tau^-)$	ΔP_τ		$\Delta A_{FB}(\tau^+\tau^-)$	ΔP_τ
ILD	0.0029		0.0025	0.0066		–	0.0079
SiD	0.0028		0.0015	0.0065		0.0017	0.0072

Conclusion

ILD (SiD) have demonstrated that they can measure the mass of the top quark in the fully hadronic channel at Ecm=500 GeV with 40 (45) MeV statistical precision. They have also shown that the vector and axial-vector couplings of the top quark can be measured through the forward-backward asymmetry in the challenging fully hadronic mode with a precision of 0.008

ILD and SiD can identify the decay modes of 250 GeV tau leptons with purities and efficiencies in the 90% range. They both measure the tau polarization with an accuracy of 0.7%.

ILD and SiD are well positioned to take the next steps in studies of top and tau couplings:

Future studies of top quark coupling measurements would involve top polarization studies with optimal observables.

Future studies of tau coupling measurements are already underway in ILD with the addition of the a_1 decay mode and the incorporation of vertex detector information to further constrain the tau direction.