Tau-pair analysis in the ILD detector

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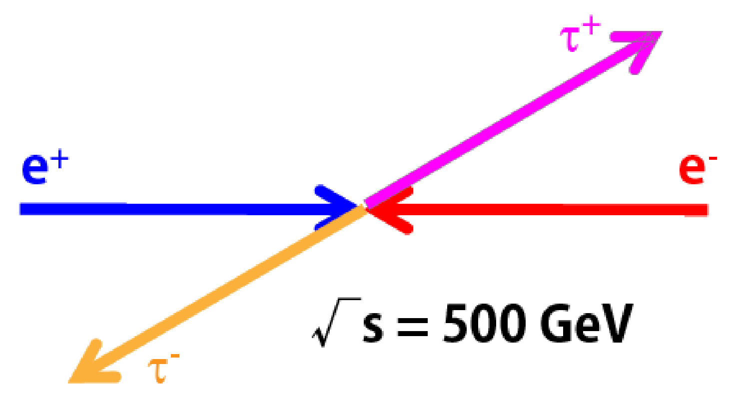
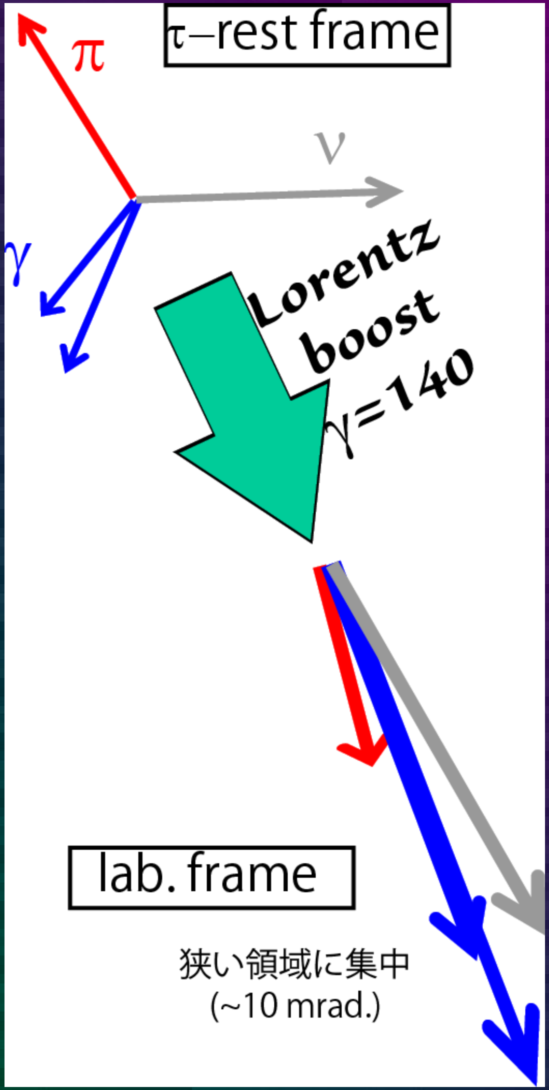
Tau-pair process



Difficulty on decay analysis



σ=2600 fb^{-1} ($e^-_L e^+_R$) σ=2000 fb^{-1} ($e^-_R e^+_L$)

radiative events: ~70%

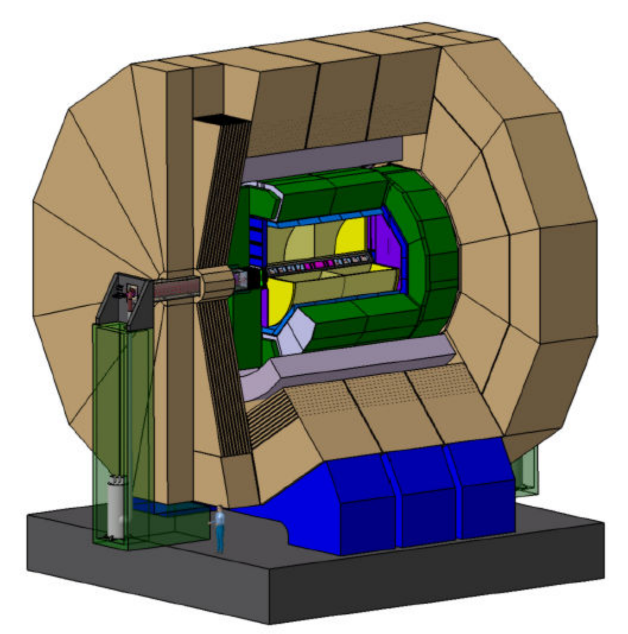
[Observables]

P(e^-)=80%, P(e^+)=30%, 500 fb^{-1}

- σ, A_{FB} (bg suppression)
- Polarization P(τ)

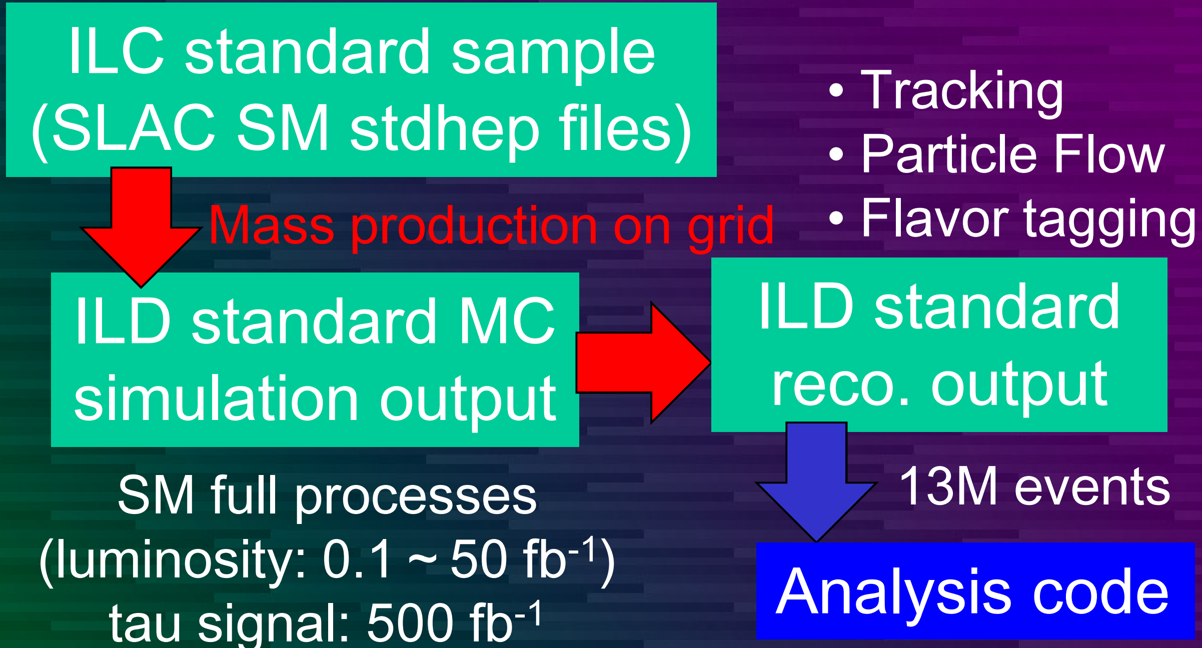
  ↑Decay angle determination

ILD Analysis framework



ILD detector

- Vertex: Si pixel (3x2 layers)
- Silicon Tracker: 4 layers
- TPC(main tracker)
- ECAL/HCAL (<1cm^2/9cm^2 pixel)
- Solenoid (3.5Tesla)
- Muon detector



ILC standard sample (SLAC SM stdhep files)

Mass production on grid

ILD standard MC simulation output

SM full processes (luminosity: 0.1 ~ 50 fb^{-1}) tau signal: 500 fb^{-1}

- Tracking
- Particle Flow
- Flavor tagging

ILD standard reco. output

13M events

Analysis code

- Centered production result can be accessible as DST LCIO files on grid.
- Original Marlin processor to collect information for analysis to ROOT trees.
- Analysis by ROOT macros.

σ and A_{FB} analysis

- Key task: background separation
  - – Apply cuts through all standard model background.
  - – Add more bhabha & $\gamma\gamma$ -> $\tau\tau$ events with preselection.
    - 1 fb^{-1} for bhabha, 5-10 fb^{-1} for $\gamma\gamma$ -> $\tau\tau$
- Main backgrounds and efficient cuts
  - – Bhabha: e/μ/π separation
    - Drop electron-electron events: 3% loss on signal
    - Drop events with E_{vis}~500GeV
  - – $\gamma\gamma$ -> $\tau\tau$: same final state, huge cross section in low E_{vis} region
    - Drop by opening angle and E_{vis} cuts
  - – WW -> lνlν : same final state if l=τ
    - Drop by opening angle (some fractions remain)

Selections

BG suppression cuts

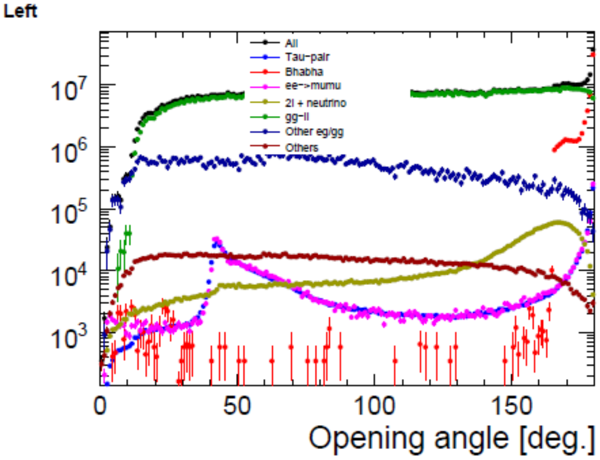
- # Track <=6
- 1(+)+1(-) clusters
- Opening angle >178 deg
- $|\cos\theta|_\tau < 0.95$
- < 2 electrons, < 2 muons
- $70 < E_{vis} < 450$ GeV

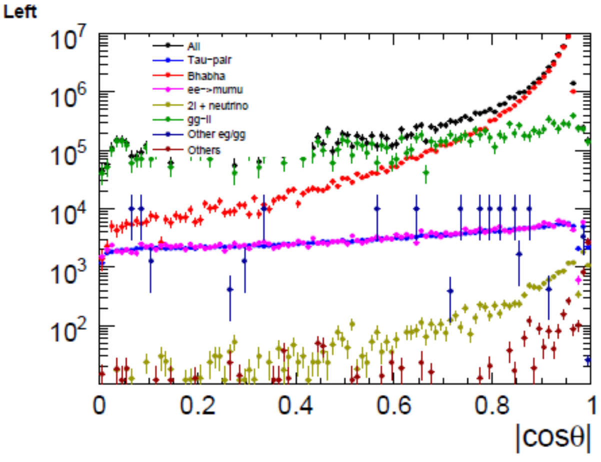
Purity ~ 90% (almost bg free)

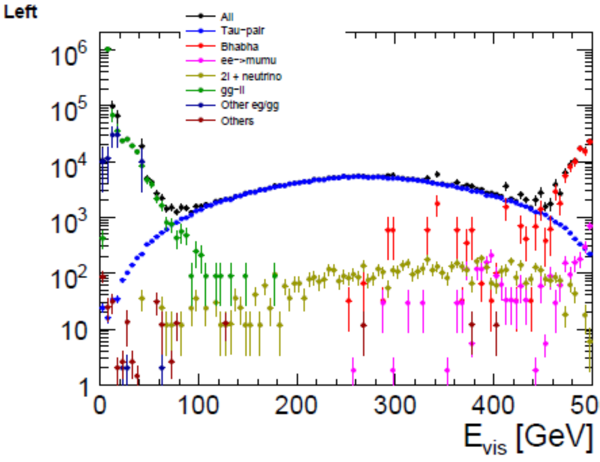
Cuts modified since TILC09 to obtain compatibility to SiD.

Cuts	Tau-pair	Bhabha	$\mu\mu$	$n\ell + n\nu$	$\gamma\gamma \to \ell\ell$	other $\gamma\gamma$, $e\gamma$	other
# tracks, # clusters	573180	2.88e+07	590770	1.15e+06	5.58e+08	4.07e+06	1.21e+06
Opening angle > 178 deg.	152865	1.89e+07	157430	7938	6.93e+06	59454	2633
$\|\cos\theta\| < 0.95$	142371	1.39e+07	147571	5020	6.25e+06	57746	610
ee, $\mu\mu$ veto	130383	96482	1606	3225	616265	45645	141
$70 < E_{vis} < 450$ GeV	125400	5071	635	2953	1641	0	32

e_L^- (80%) e_R^+ (30%)



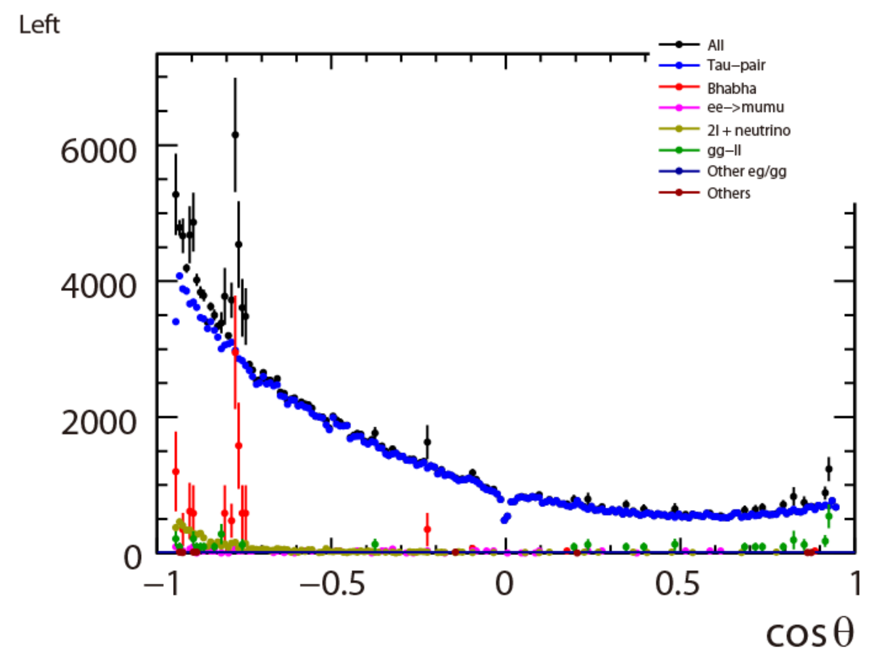


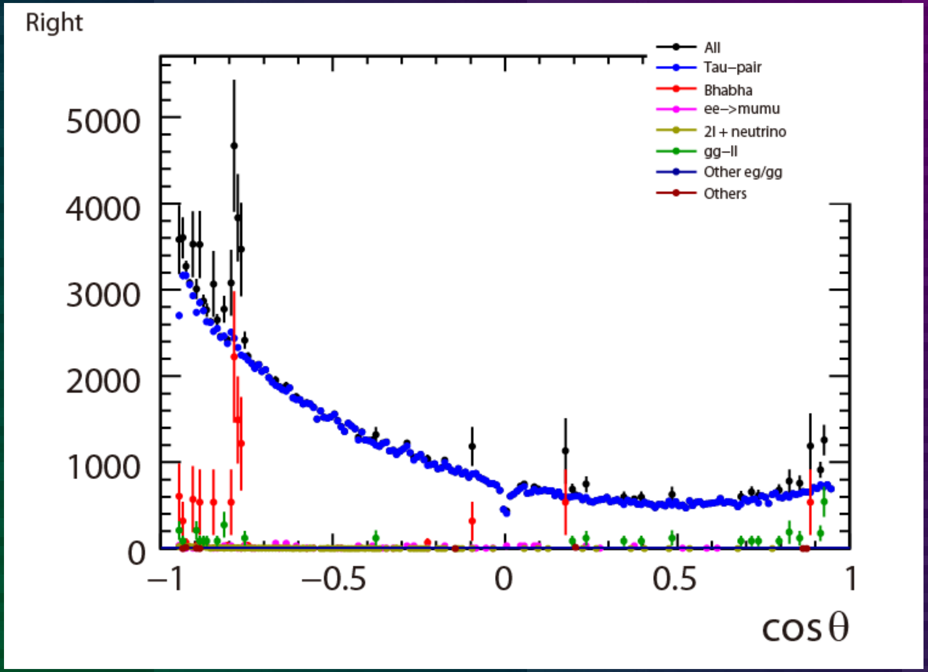


σ, A_{FB}

σ: 0.29% ($e^-_L e^+_R$), 0.32% ($e^-_R e^+_L$) stat. error (count based)

A_{FB}: 52.36 ± 0.25% ($e^-_L e^+_R$), 44.19 ± 0.28% ($e^-_R e^+_L$)





Sufficient statistics obtained.

Tau polarization

- “polarimeter vector” can be reconstructed from decay kinematics to obtain polarization.
  - Various dependence by decay modes
    opposite behavior on leptonic and hadronic mode.
- ~90% of taus decay to 5 decay modes
  no dominant decay mode
  - Decay mode identification is important
    high granular ECAL is effective for photon separation

→ Mode selection and polarization reconstruction were studied in the events passing A_{FB} cuts.

Decay modes in A_{pol} analysis

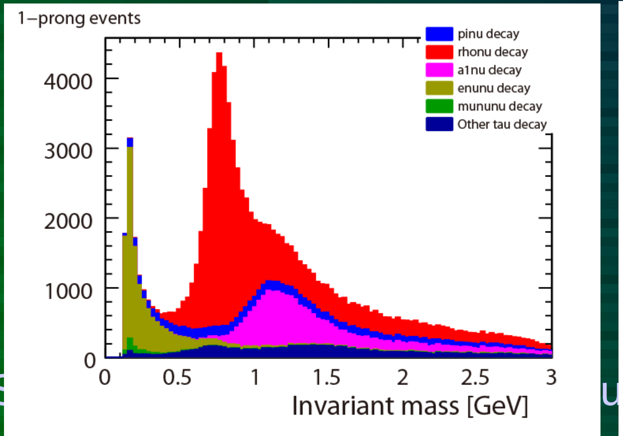
5 main decay modes

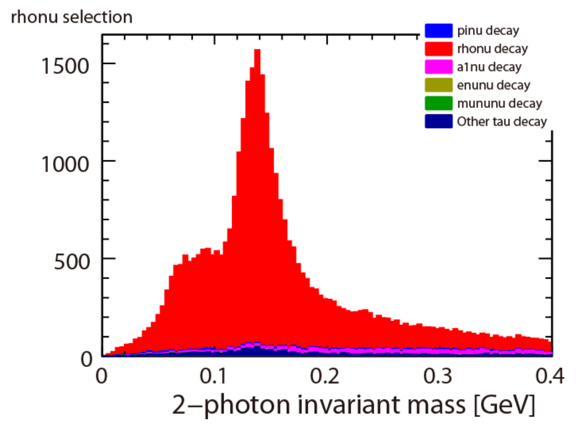
- $\tau^+ \rightarrow e^+\overline{\nu_e}\nu_\tau$ (17.9%), $\tau^+ \rightarrow \mu^+\overline{\nu_\mu}\nu_\tau$ (17.4%)
  - Separated by lepton-ID (high eff.)
  - Polarization information is lost by two missing neutrinos
- $\tau^+ \rightarrow \pi^+\nu_\tau$ (10.9%)
  - 「1 charged π」, moderate BR, good 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)
- $\tau^+ \rightarrow a_1^+\nu_\tau \rightarrow \pi\pi\pi\nu_\tau$ (9.3% (1-prong) and 9.0% (3-prong))
  - 「1 chargedπ+4γ」 or 「3 charged π」 a_1 (1260 MeV mass, 250-600 MeV width)
  - Track separation (3-prong, detector)

Minimize stat. error by combining decay modes

Mode selection

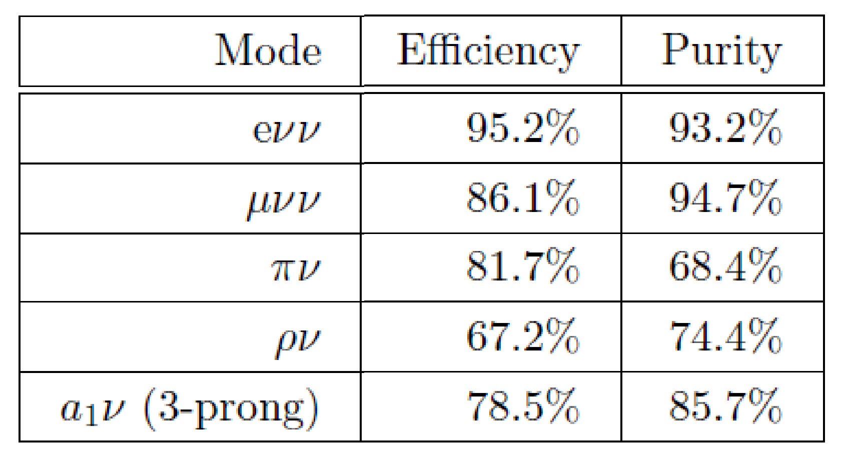
- Parameters for mode selection
  - Lepton-ID (e, μ) simple id by following observables (optimum lepton-ID in Marlin cannot be used due to a technical problem in the mass production DSTs)
    - Energy deposit of ECAL vs. HCAL (electron ID)
    - Momentum by track vs. energy deposit in CAL (muon ID)
  - Energy and number of neutral particles
    - Exclude neutral particle tagged as hadrons
  - Invariant masses (all visible, photons)
    - ρ, π_0 ID
- Compare cut-based and neural-net.





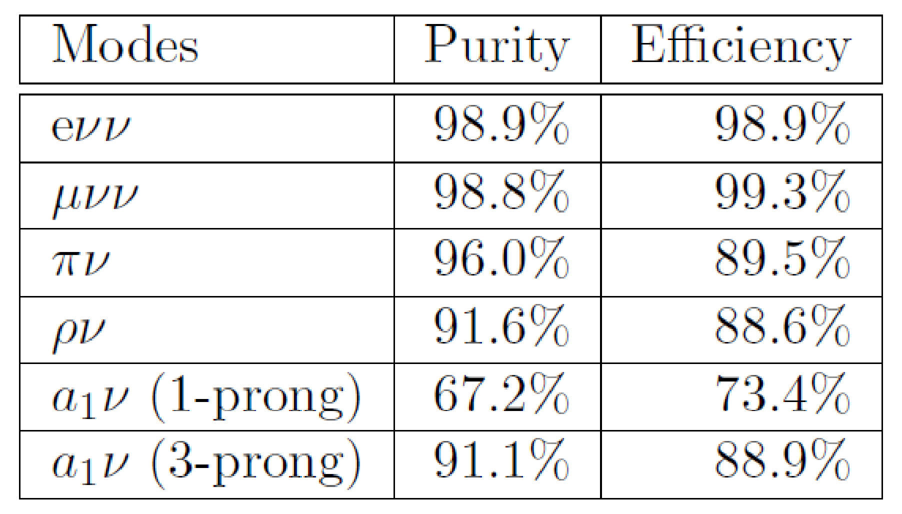
Mode selection result

Cut-based



Mode	Efficiency	Purity
$e\nu\nu$	95.2%	93.2%
$\mu\nu\nu$	86.1%	94.7%
$\pi\nu$	81.7%	68.4%
$\rho\nu$	67.2%	74.4%
$a_1\nu$ (3-prong)	78.5%	85.7%

Neural net



Modes	Purity	Efficiency
$e\nu\nu$	98.9%	98.9%
$\mu\nu\nu$	98.8%	99.3%
$\pi\nu$	96.0%	89.5%
$\rho\nu$	91.6%	88.6%
$a_1\nu$ (1-prong)	67.2%	73.4%
$a_1\nu$ (3-prong)	91.1%	88.9%

(Cut might not be fully optimized, but anyway)
neural net gives better result.

near 90% efficiency and purity in ρ mode →
high photon separation performance in ILD?

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

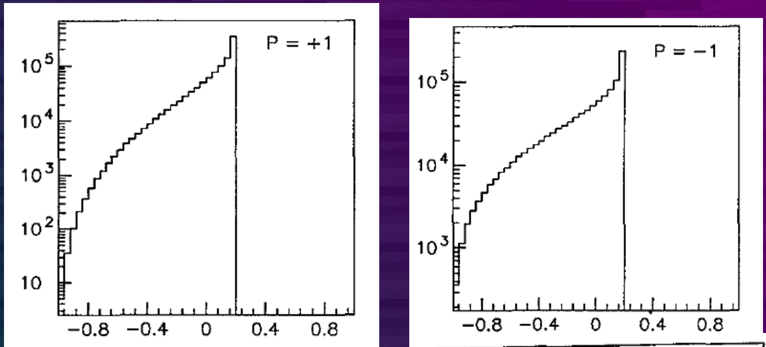
- $\omega = (P(\tau_R) - P(\tau_L))$ $(-1 < \omega < 1)$, one ω/tau candidate
- $\omega = 1$: 100% τ_R, $\omega = -1$: 100% τ_L, $\omega = 0$: no tendency
- expression of ω differs by decay modes, but ω can be summed up through all decay modes. (multi-dimensional fit in each decay mode is not needed)
- Developed in LEP.

Optimal observable

1. Pure-leptonic decay:

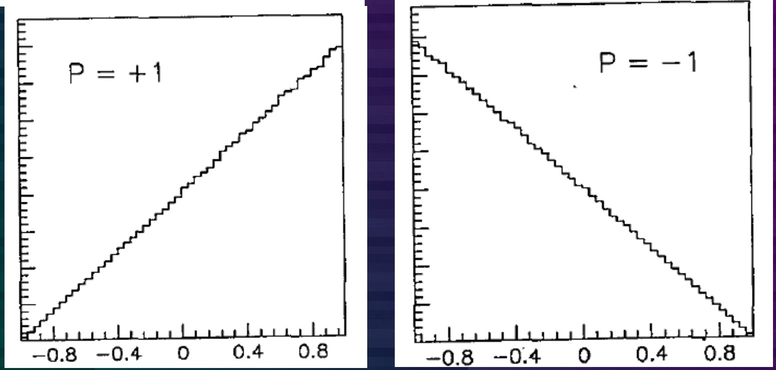
$$\omega_\ell = \frac{1 + x - 8x^2}{5 + 5x - 4x^2}$$

(x: lepton energy / tau energy)



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

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

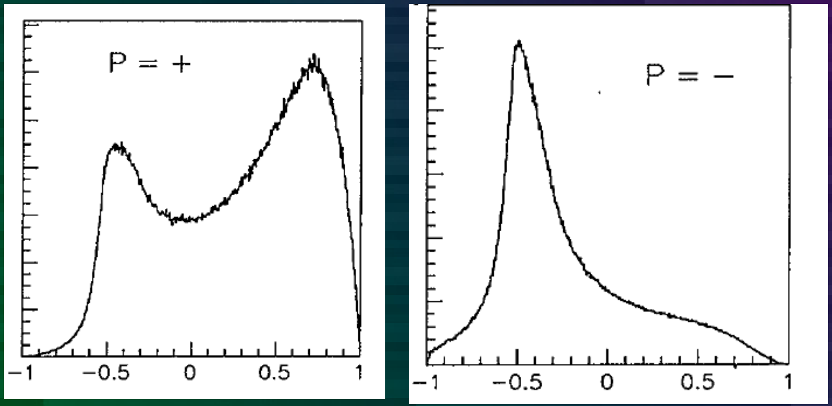


3. $\rho^+\nu_\tau$ decay: (2 energies and 3 angles, 5 parameters)

$$\omega_\rho = \frac{\left(-1+\frac{m_\tau^2}{Q^2}+2\left(1+\frac{m_\tau^2}{Q^2}\right)\frac{3\cos^2\psi-1}{2}\frac{3\cos^2\beta-1}{2}\right)\cos\theta+3\sqrt{\frac{m_\tau^2}{Q^2}}\frac{3\cos^2\beta-1}{2}\sin 2\psi\sin\theta}{2+\frac{m_\tau^2}{Q^2}-2\left(1-\frac{m_\tau^2}{Q^2}\right)\frac{3\cos^2\psi-1}{2}\frac{3\cos^2\beta-1}{2}}$$

$$\cos\psi = \frac{x(m_\tau^2+Q^2)-2Q^2}{(m_\tau^2-Q^2)\sqrt{x^2-4Q^2/s}}$$

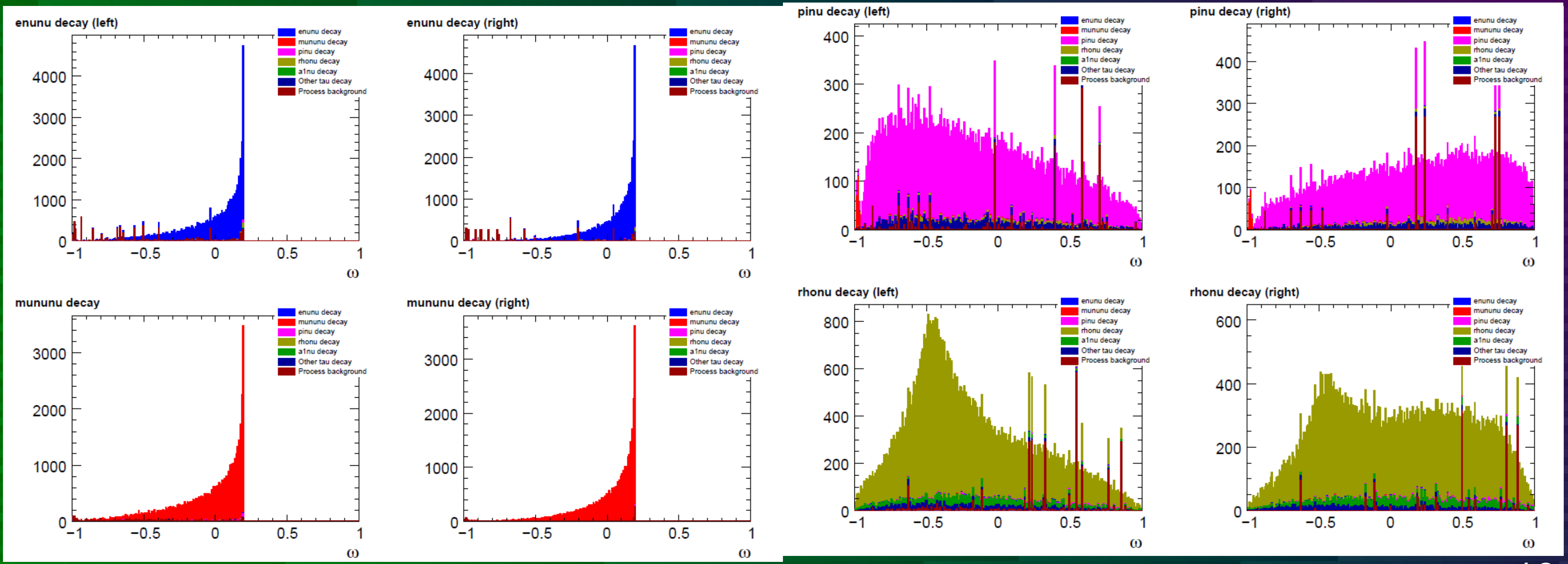
$$x = 2\frac{E_h}{\sqrt{s}}$$



(4. a_1 : now working…)

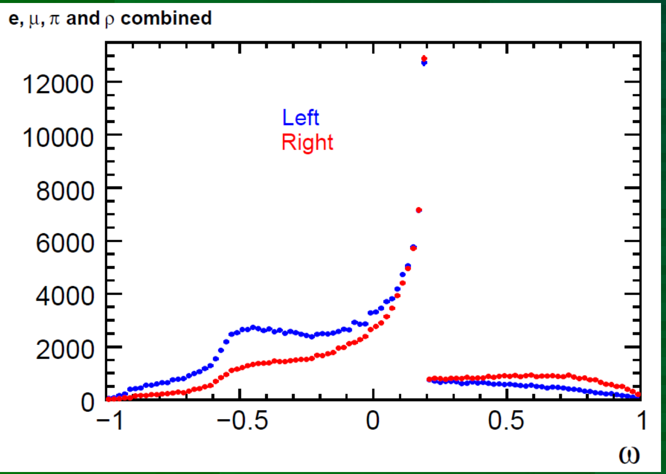
Optimal observable distribution

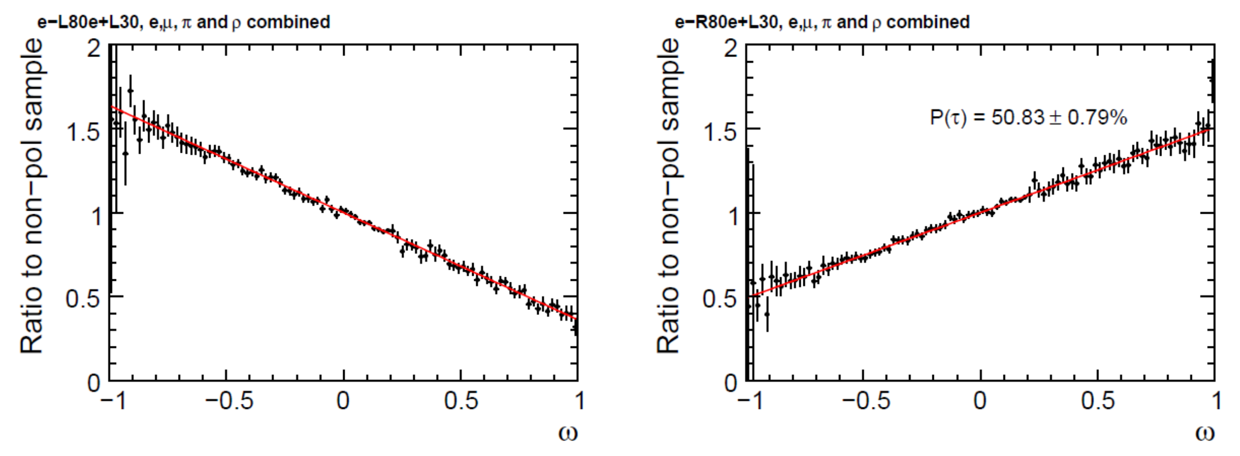
- Apply ω formula on sample of initial polarization P(e^+, e^-) = (30%, 80%)
  - SM separation cut applied
  - Neural net is used for mode selection



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}



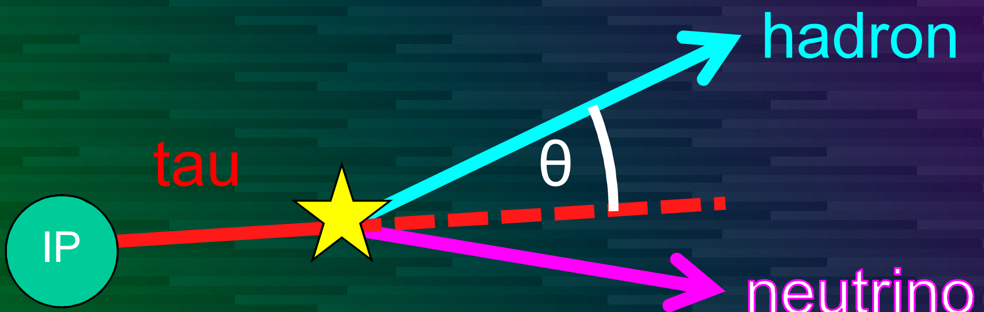


$P(\tau)$ = -63.82 ± 0.66% ($e^-_L e^+_R$)
$P(\tau)$ = +50.83 ± 0.79% ($e^-_L e^+_R$)

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

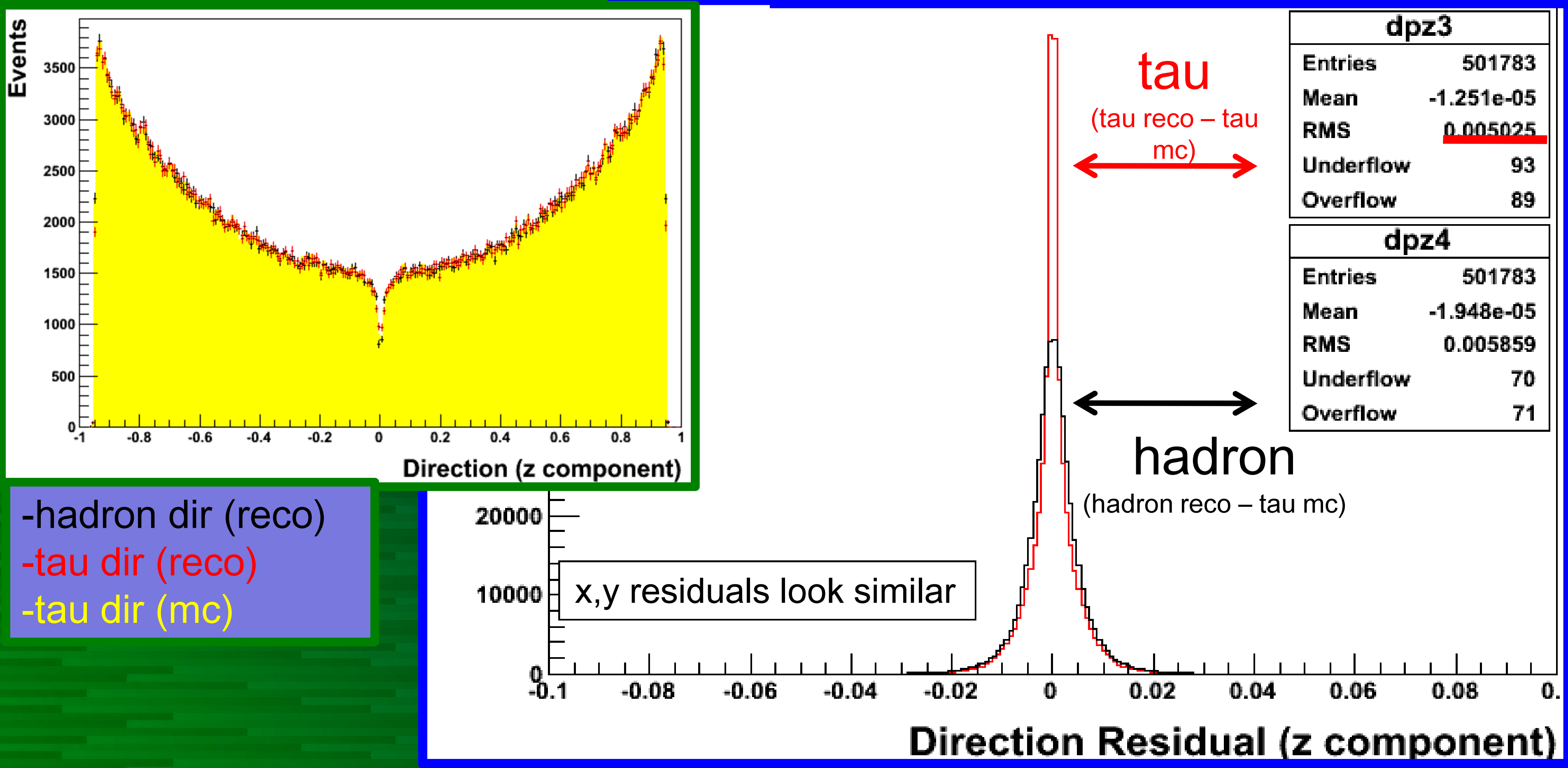
a sneak preview of this concept will be shown for 1-prong events
using first-order approximation for tracks (using line segment instead of helix)



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

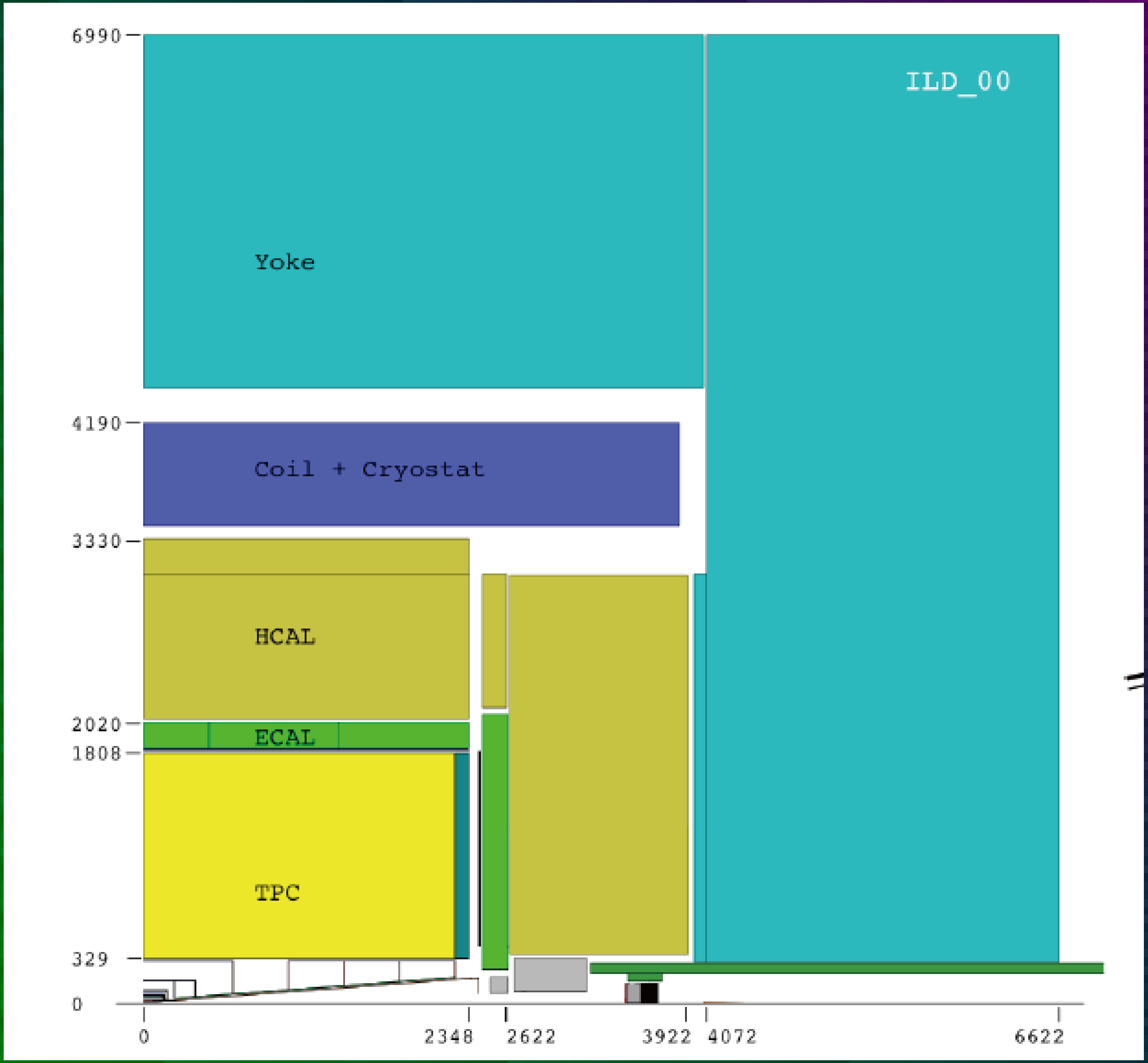
tau direction successfully reconstructed (3-prong work next)
better than assuming tau dir = hadron dir (rms: 0.0059 > 0.0050)

Summary

- Cross section, angular distribution and polarization analysis is performed in the ILD detector model with full simulation.
- >90% purity is obtained by scanning all SM events. Sufficient statistics is obtained for cross section and angular distribution.
- ~90% purity and efficiency are obtained in mode separation for polarization analysis.
- 0.7-0.8% stat. error of polarization for 500 fb^{-1} data with optimal observable method.

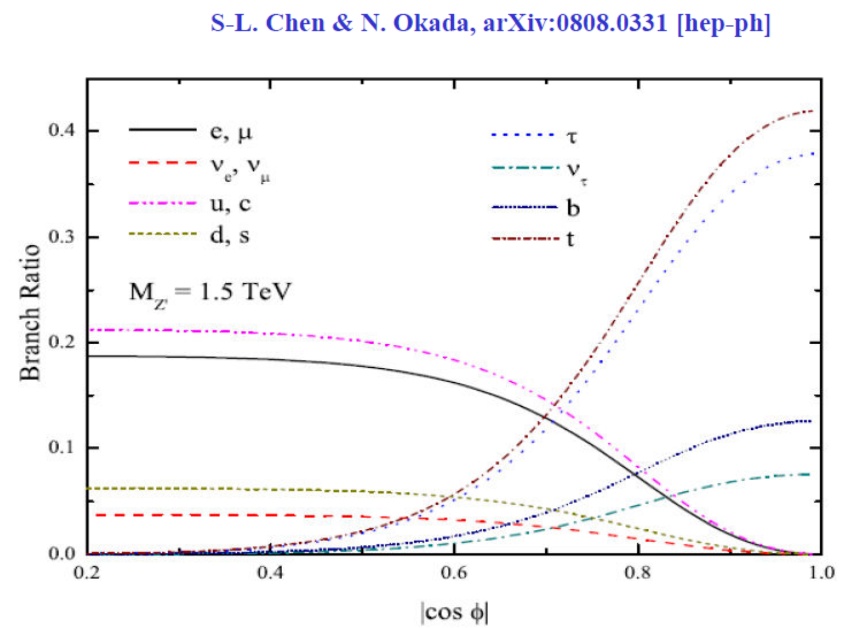
backup

ILD_00 detector for full simulation



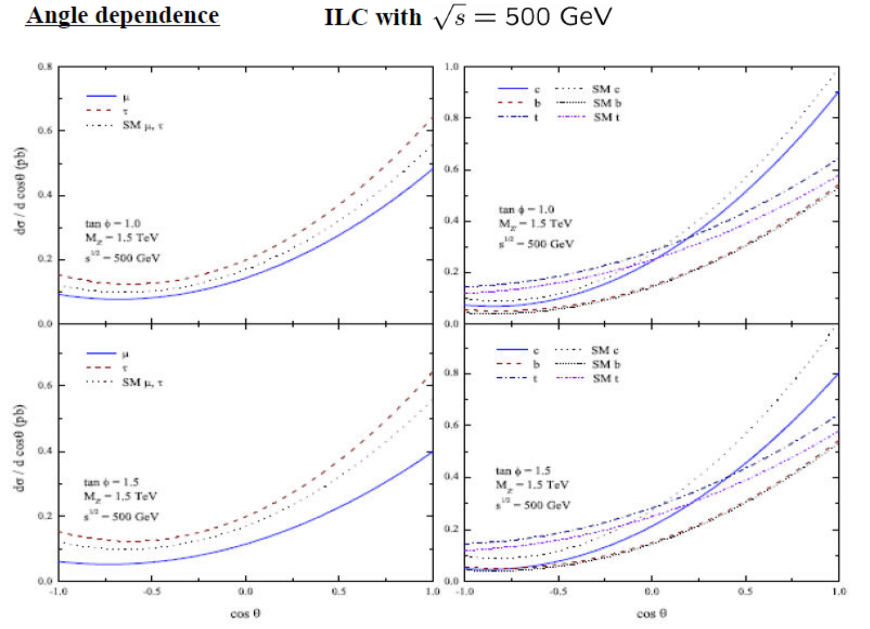
Flavor dependent Z’ model

- Additional Z’ boson can make tau-pair production cross section and angular distribution deviated from SM.
- If the coupling to Z’ (-> Z’ decay branching ratio) is flavor dependent, measuring tau-pair production can be the main process to measure Z’ properties.



S-L. Chen & N. Okada, arXiv:0808.0331 [hep-ph]

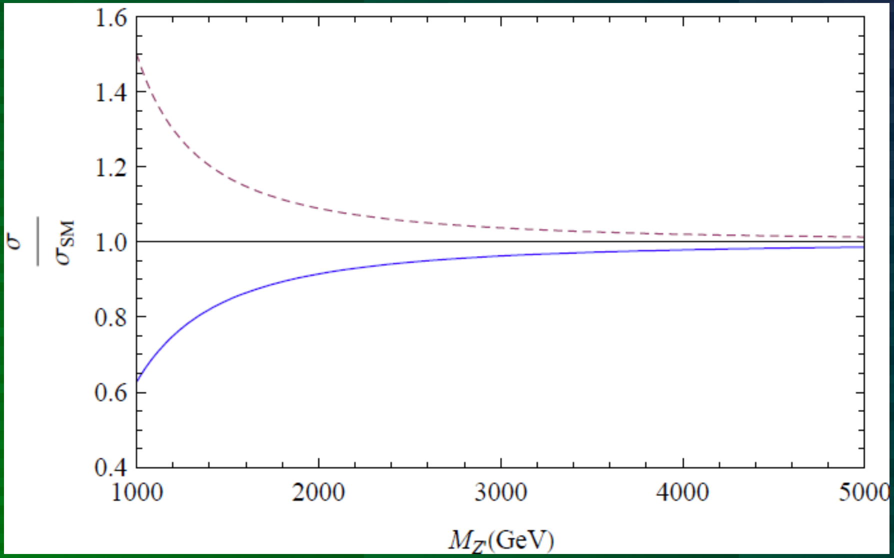
Branching ratio of Z’
with a model parameter ϕ

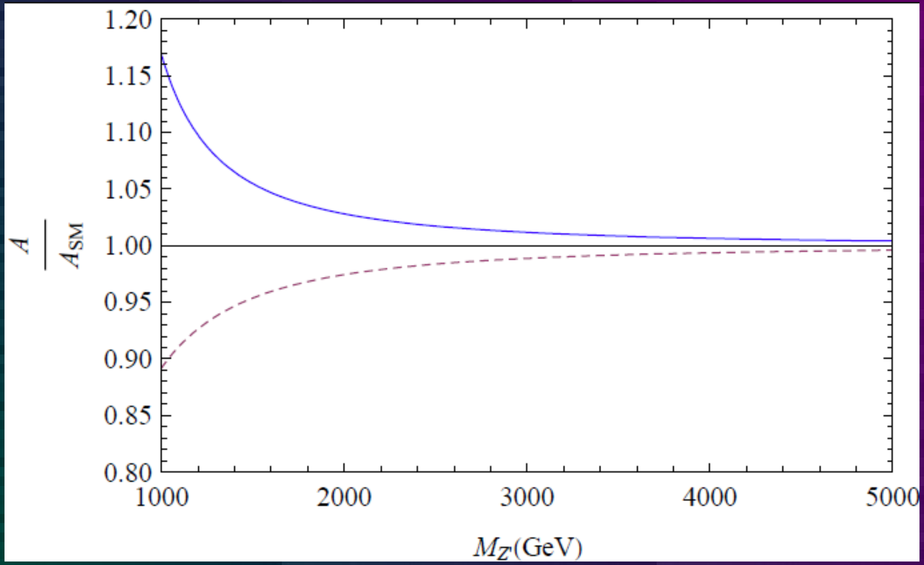


Angle dependence ILC with $\sqrt{s} = 500$ GeV

Deviation of angular dependence by Z’

Required precision for σ and A_{FB}

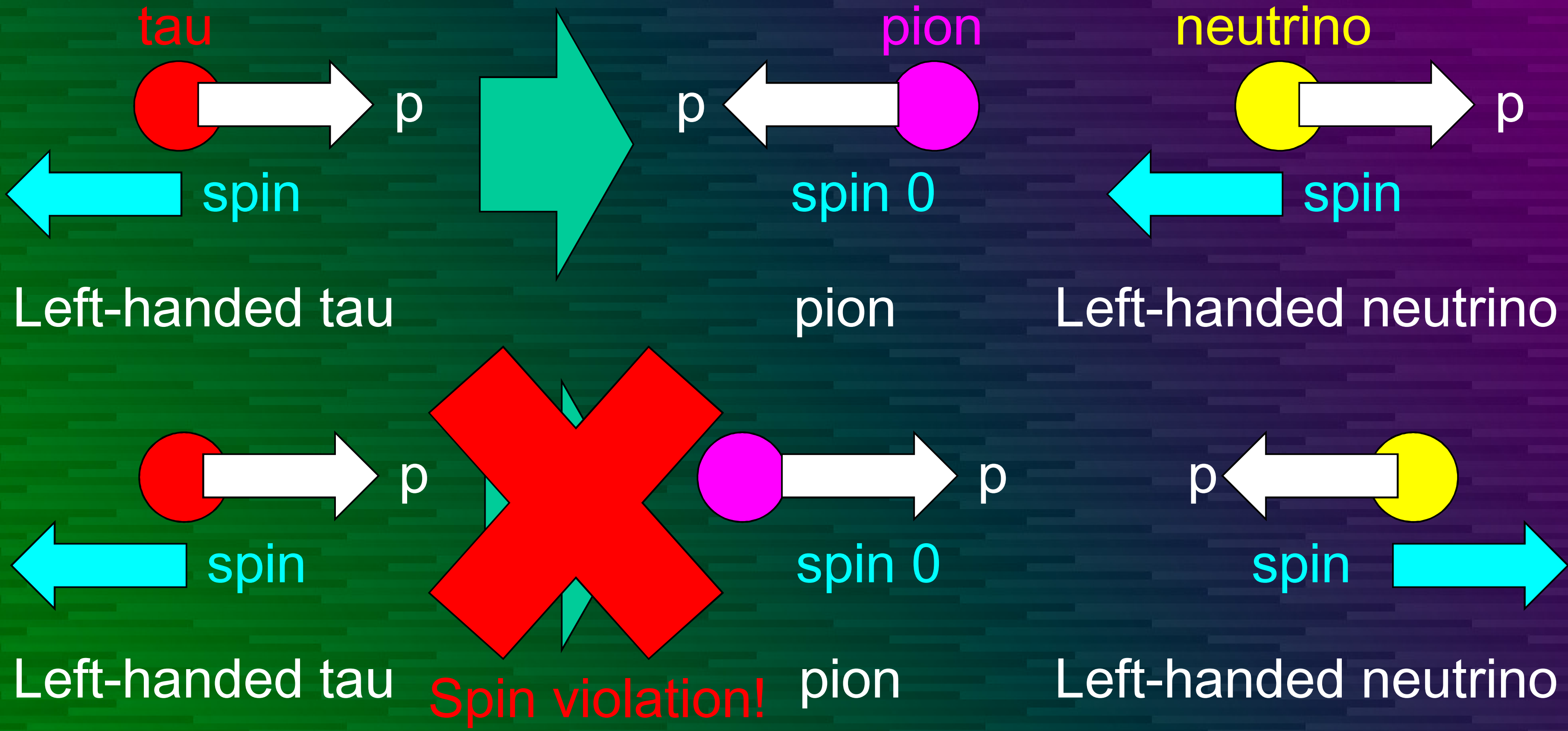




- 1% precision for cross section and A_{FB} can detect ~5 TeV Z’

A sample of tau polarization effect

- $\tau^{+} \rightarrow \pi^{+}\nu_{\tau}$



tau p p pion neutrino p

spin spin 0 spin

Left-handed tau pion Left-handed neutrino

p p p

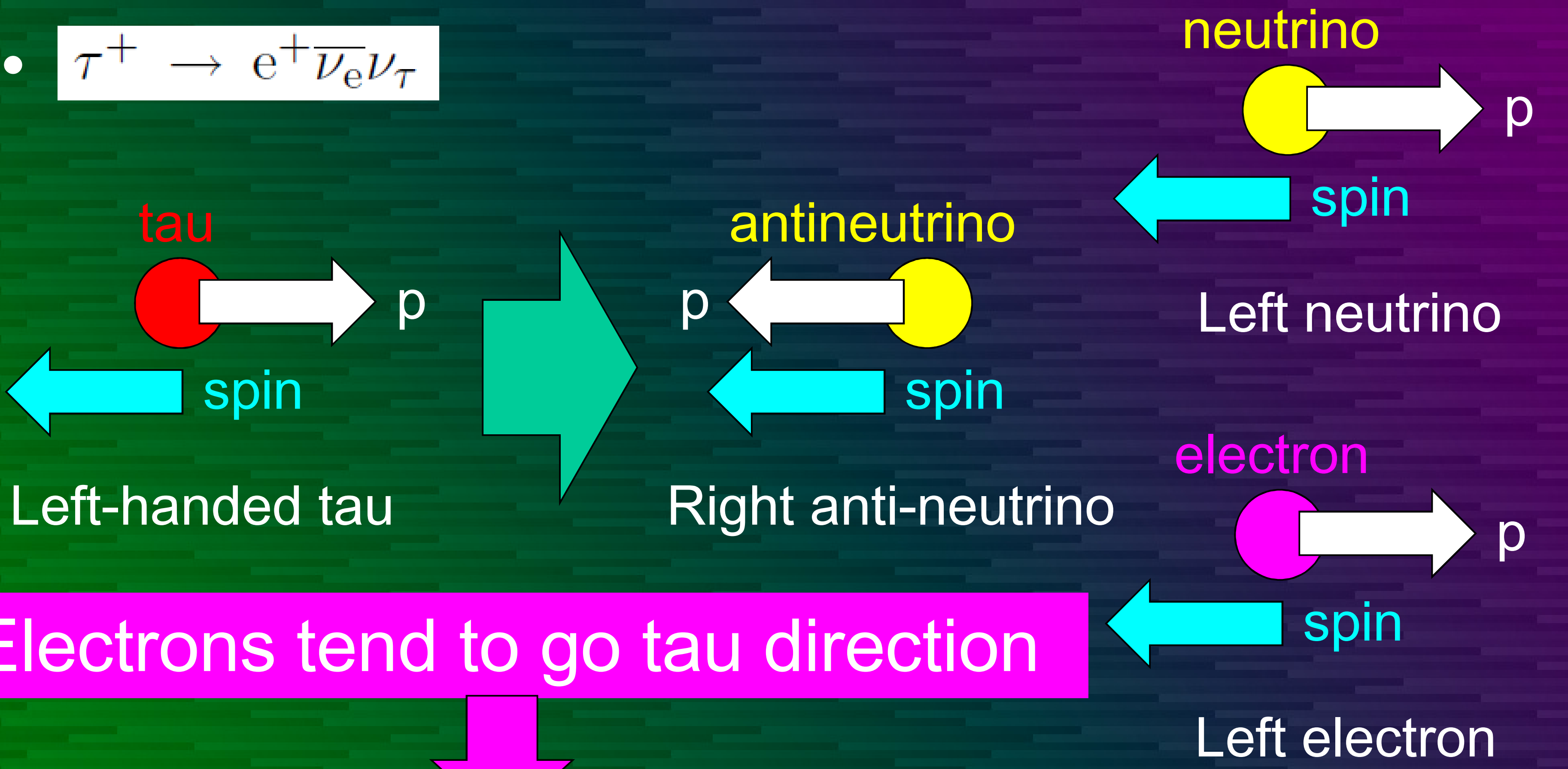
spin spin 0 spin

Left-handed tau Spin violation! pion Left-handed neutrino

Pions tend to go opposite direction to tau

A sample of tau polarization effect

- $\tau^+ \rightarrow e^+ \overline{\nu_e} \nu_\tau$



tau

p

spin

Left-handed tau

antineutrino

p

spin

Right anti-neutrino

neutrino

p

spin

Left neutrino

electron

p

spin

Left electron

Electrons tend to go tau direction

Opposite correlation to pions
→ decay identification purity is important!

Tau flight direction backup

- three algebraic equations (normalized):
  1. $\hat{p}_\tau \cdot (\hat{r}_{\mathrm{had}} \times \hat{p}_{\mathrm{had}}) = 0$
  2. $\hat{p}_\tau \cdot \hat{p}_{\mathrm{had}} = \cos\theta_{\tau-\mathrm{had}}$
  3. $\hat{p}_\tau \cdot \hat{p}_\tau = 1$
- Eq. 3 introduces 2-fold ambiguity
  - we choose the solution which is consistent with connecting the IP and the tau->had+nu vertex