Full simulation study of Higgs CP mixing via tau pair decays at the ILC

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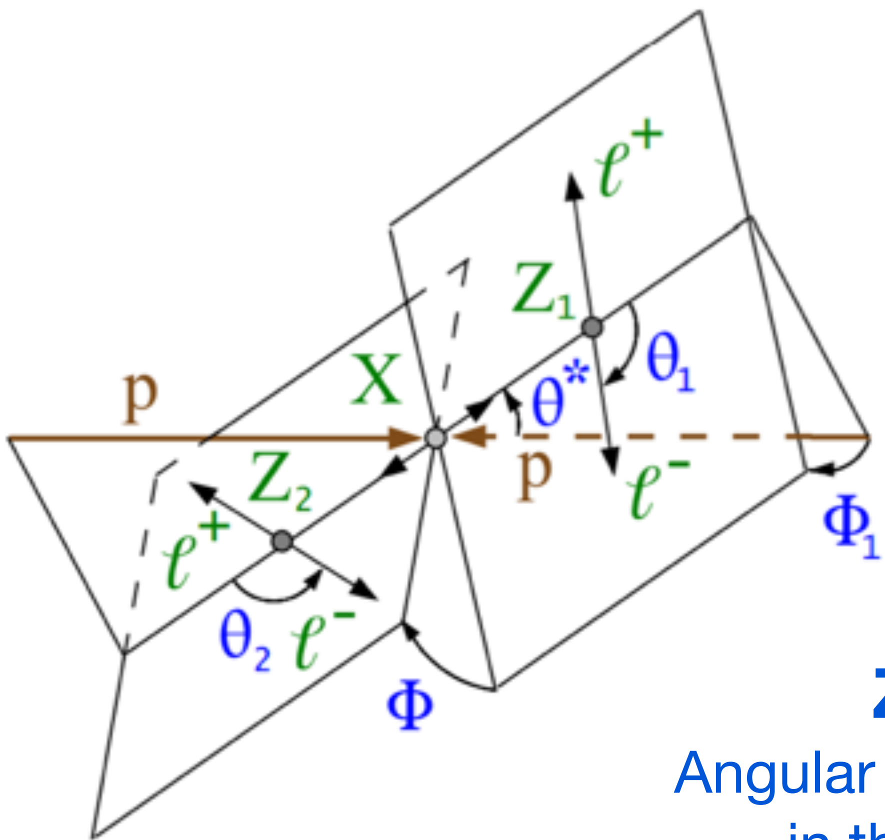
Introduction

- “Higgs boson” discovery at LHC -> Must determine its nature, e.g. **CP**
- BSM models (e.g. MSSM, 2HDMs) predict multiple Higgs fields, which cause CP violation in the Higgs sector. Determination of the **CP mixing angle** leads to **search for new physics.**
- At the **LHC,** Higgs CP is studied with the **$H \to ZZ$** mode. However, for the HVV coupling, the CP-odd component can only appear in loops. Its sensitivity to the CP mixing angle is limited.
- Fermions can couple to CP-odd Higgs at the tree-level. **$H \to \tau\tau$** is potentially much more sensitive to the CP mixing angle. **Study $H \to \tau\tau$ at the ILC**.
- In this talk, focus on the separation between CP-even and CP-odd **pure states.** The next step in the study is to determine the sensitivity to the CP mixing angle.

Higgs CP measurement at LHC

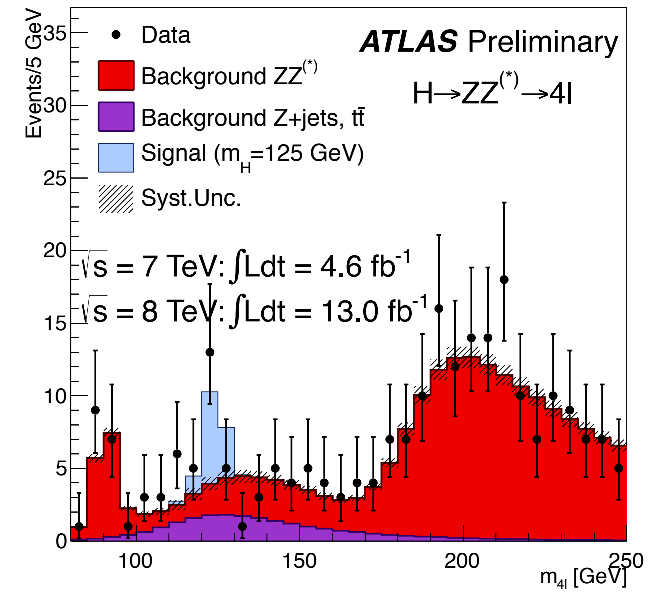
125 GeV Higgs being a **pure CP-odd** state is **excluded.**

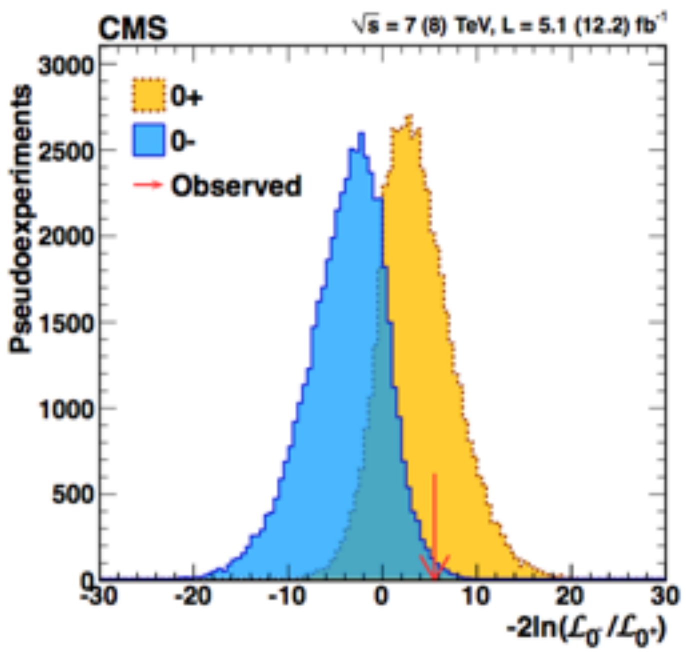
p-value : 0.72% (spin 0, CP-odd) and 0.7 (spin 0, CP-odd) ,
CMS 5.1 fb-1 @ 7 TeV, 12.2 fb-1 @ 8TeV



arXiv:1212.6639v2

Z → ee or μμ
Angular correlation of Z decays
in the Higgs rest frame





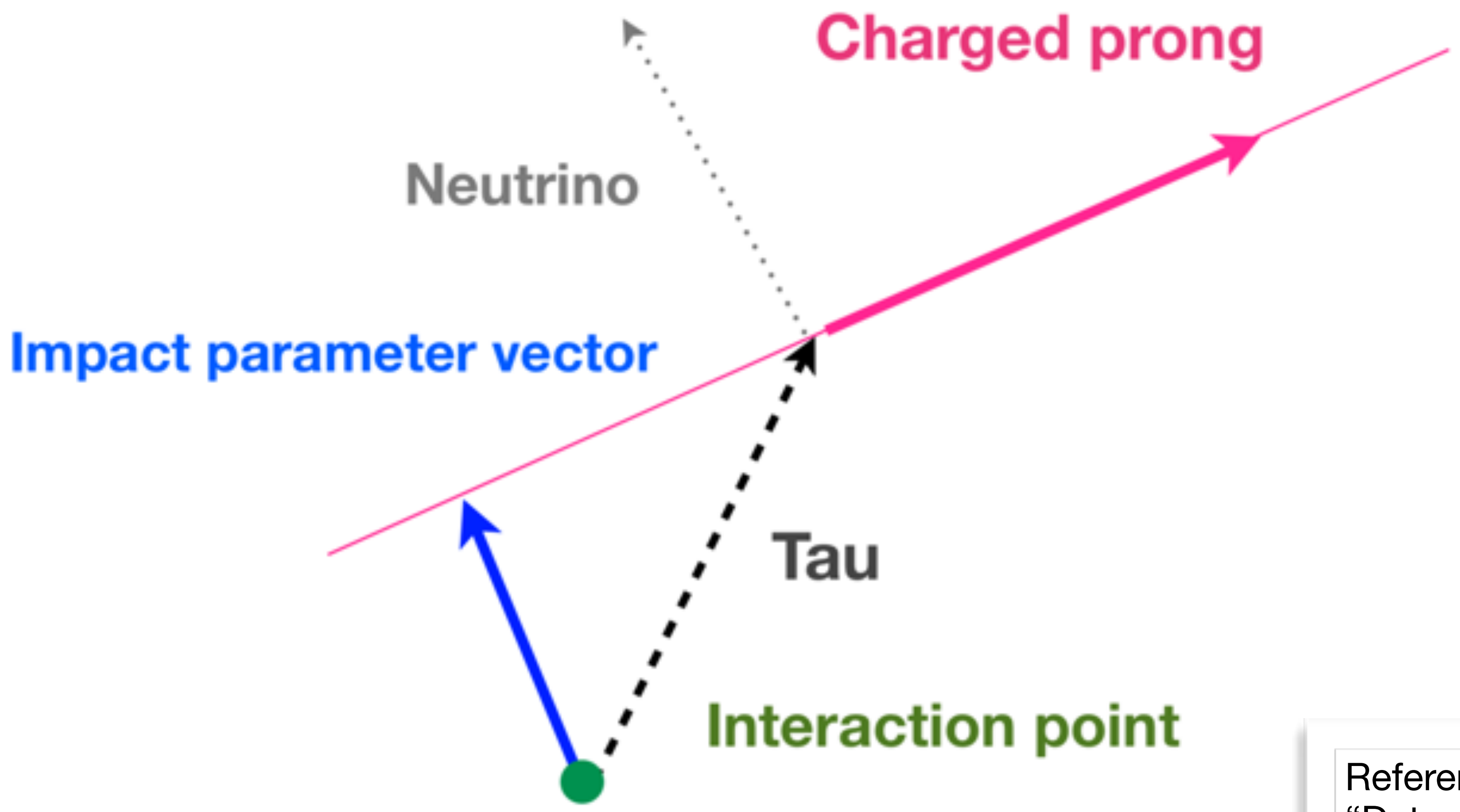
H→ZZ channel is **less sensitive to CP admixture**
because the CP-odd coupling is suppressed by a loop.

CP measurement from tau pair decays

Because of the neutrino(s) in the decay, the **tau momentum cannot be fully reconstructed.**

↓

Use **impact parameter vector** to form a observable sensitive to the CP.



Reference
"Determination of the CP parity of Higgs bosons in their τ decay channels at the ILC"
arXiv:1208.1507

Events for CP measurement

Higgs production at **$\sqrt{s}$ = 250 GeV**: **ZH Associated production**

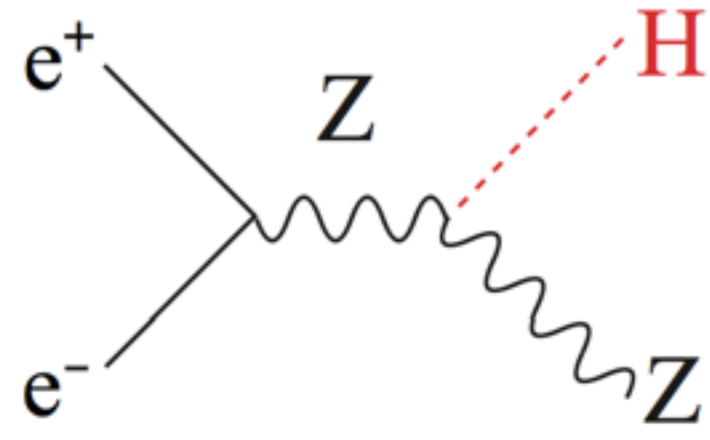
Precision of **BR(H→ττ)** at the ILC is studied with full simulation (S. Kawada)

We use the same event selection for our Higgs CP study.

L = 250fb^{-1}	# Signal Events	# Background Events	Statistical Significance
Z→ee	86.8	76	6.8
Z→μμ	103.1	91.2	7.4
Z→qq	808.5	554.4	21.9
Combined			24.1

arXiv:1305.5489

ZH associated production



xsec ~ 300fb (P(e-, e+)=(-0.8, 0.3))

Main background: ZZ(→ττ)

Observable sensitive to CP:
Acoplanarity angle

Definition of CP mixing angle

No assumption on specific model.
Effective lagrangian of **Higgs-tau Yukawa** descibing CP admixture.

$$\tau(\cos\alpha + i\sin\alpha\,\gamma^5)\bar{\tau}\,\phi$$

$\alpha = 0$: CP-even
$\alpha = \pi/2$: CP-odd

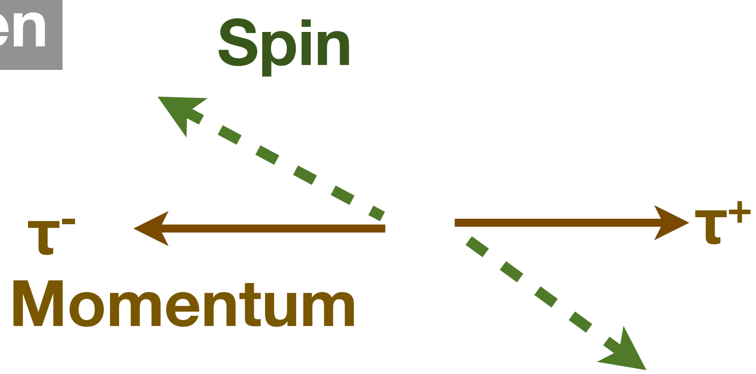
This is CP-mixing angle !

CP-mixing angle affects kinematics of tau lepton decay.
This is implemented by **TAUOLA.**

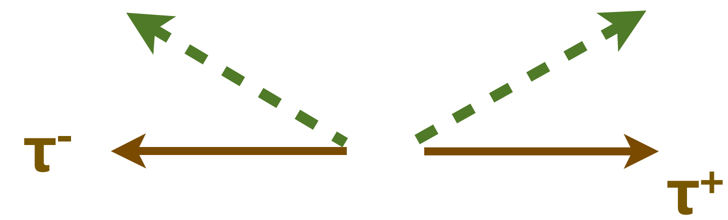
Spin correlation and CP mixing angle

Correlation in the **transverse spin** relative to the tau flight direction

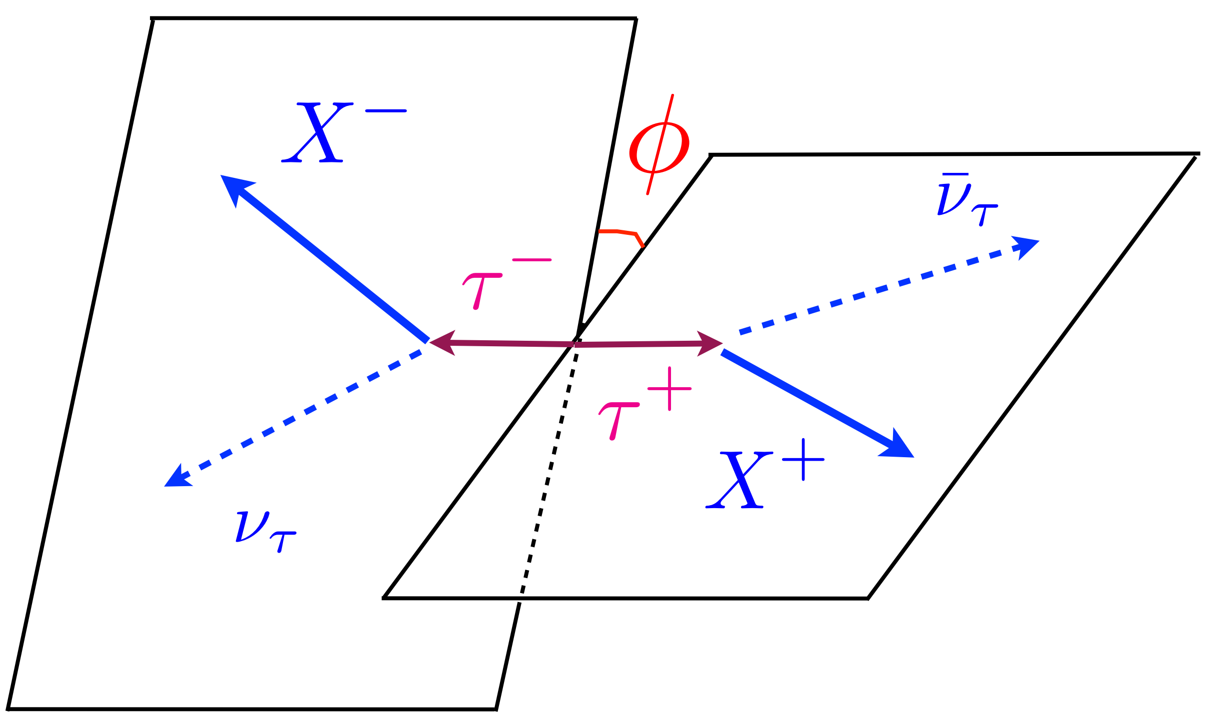
CP even



CP odd

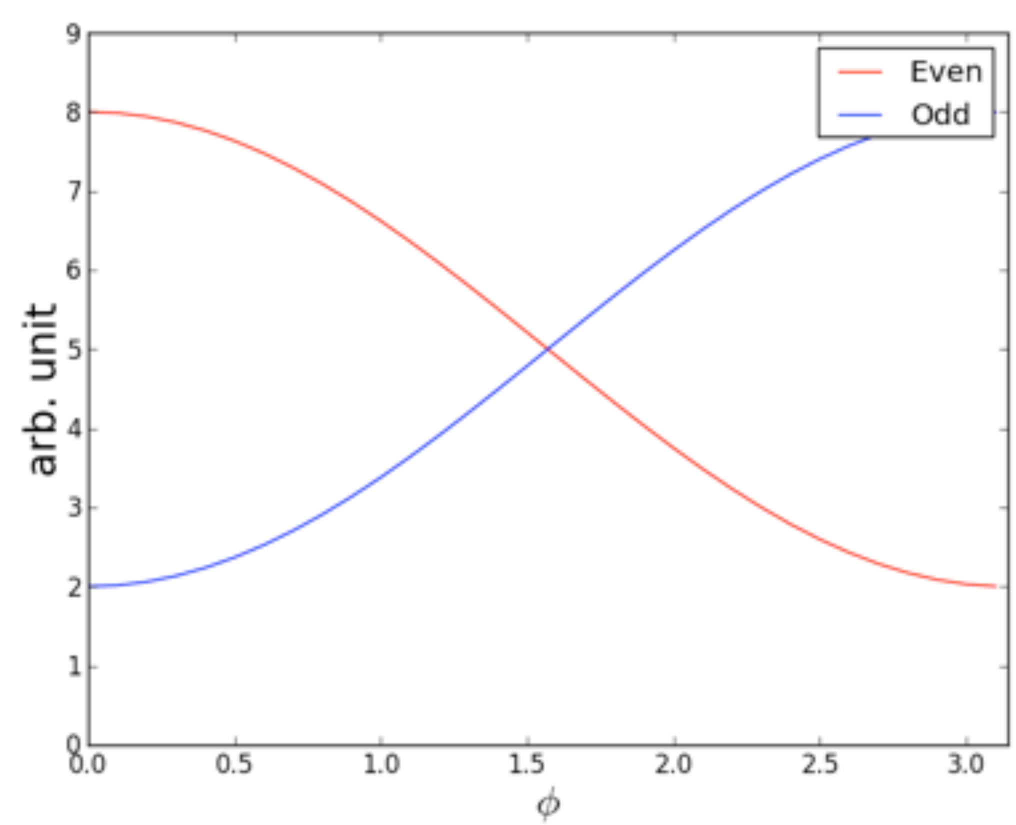


Transverse spin correlation -> **angle Φ between the two decay planes**



$$X^{\pm} = \pi^{\pm}, e^{\pm}, \mu^{\pm}, \rho^{\pm}, a_1^{\pm}, \ldots$$

Angle distribution in **Higgs rest frame** for τ->πν decays



Definition of acoplanarity angle

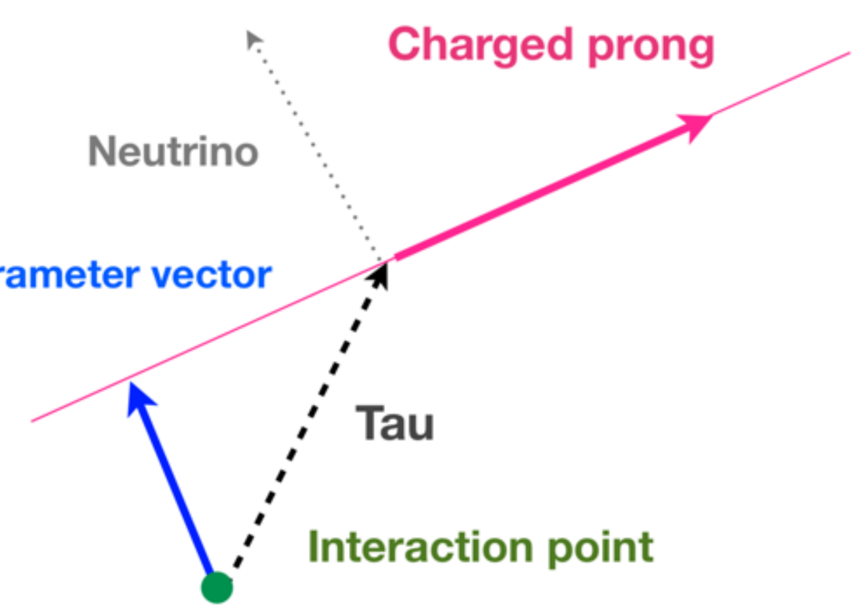
Impact parameter vector of charged track in lab frame

Rest frame of visible tautau decay products ($\pi^\pm$, $e^\pm$, $\mu^\pm$, ...)

$$\mathbf{v}^{\pm}_{\mathrm{lab}} \dashrightarrow \mathbf{v}^{\pm} \dashrightarrow \hat{\mathbf{v}}^{\pm}_{\perp}$$

Boost

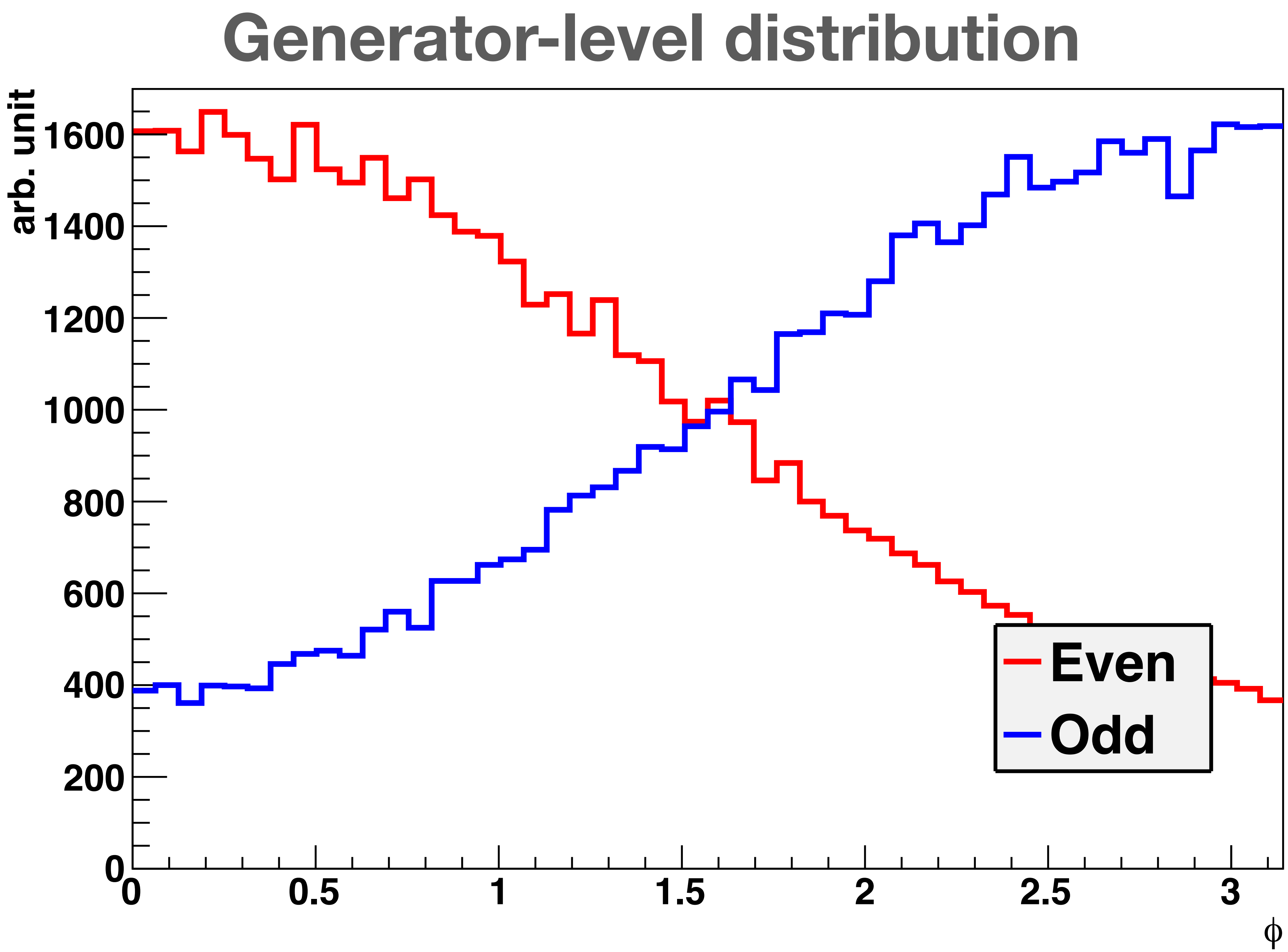
Normalized transverse component w.r.t. charged track momentum



Acoplanarity angle

$$\phi = \arccos(\hat{\mathbf{v}}^{+}_{\perp} \cdot \hat{\mathbf{v}}^{-}_{\perp})$$

Acoplanarity angle distribution ($\tau^- \to \pi^- \nu$, $\tau^+ \to \pi^+ \nu$)

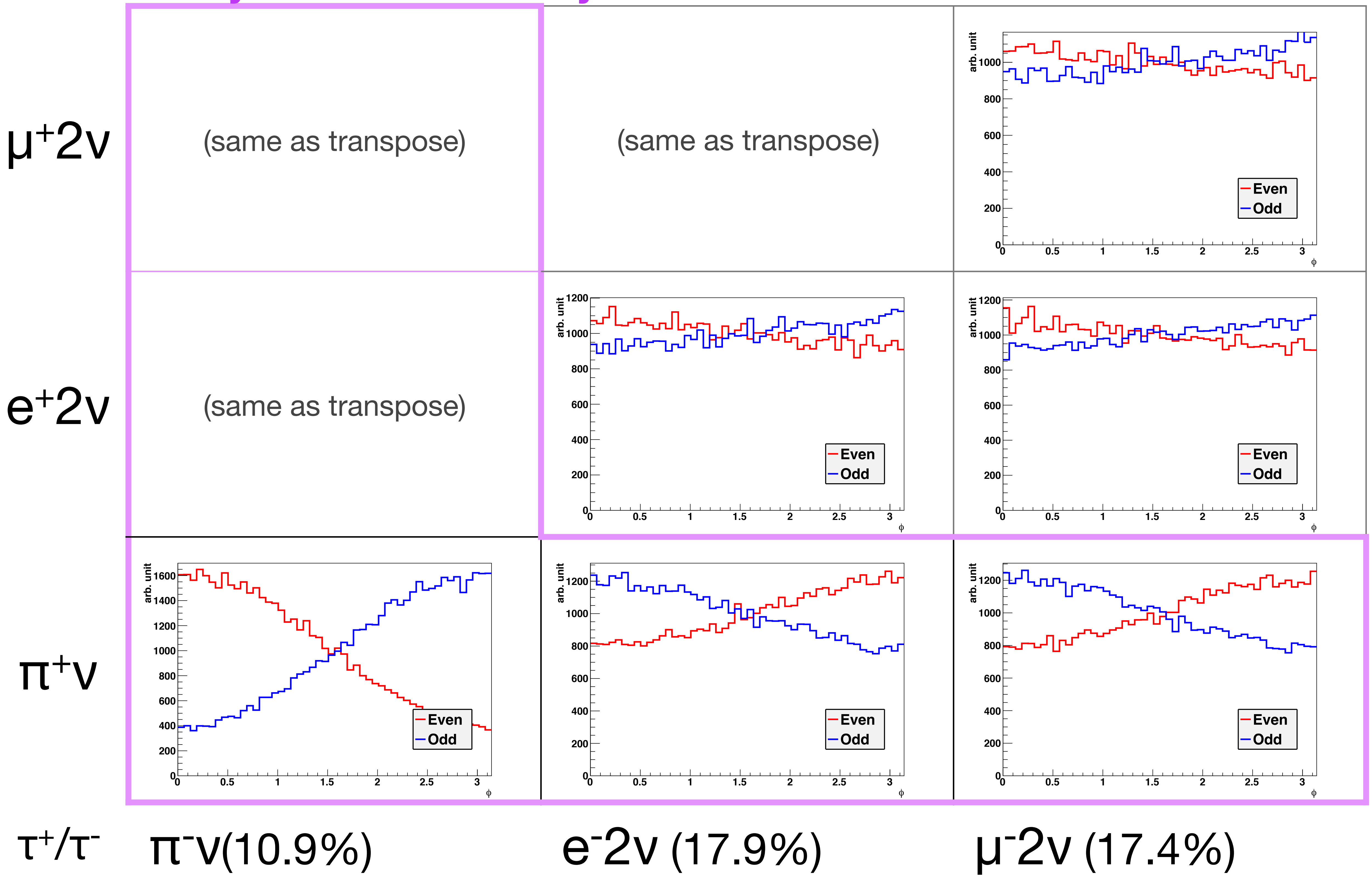


This tau decay mode has the best separation.

Unfortunately the rate is small: **1.2%** of all $H \to \tau\tau$ events.

Acoplanarity angle for different tau decays

Decays used in this study = 8.8% of all $H \to \tau\tau$ events.



Decays involving more particles have less sensitivity.

Full Simulation study with ILD Detector

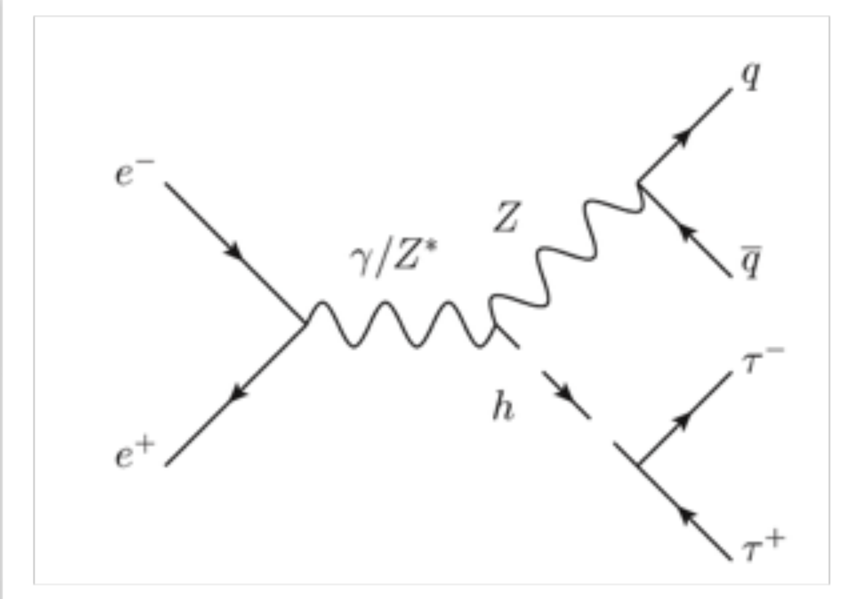
Analysis Overview

- Analysis condition
  $\sqrt{s}$ = **250 GeV**, L = **250 fb^{-1}**, beam pol. P(e^+,e^-)=(+0.3, -0.8),
  Assume same cross section for both CP states
  Z→qq (Better precision on primary vertex, large rate)

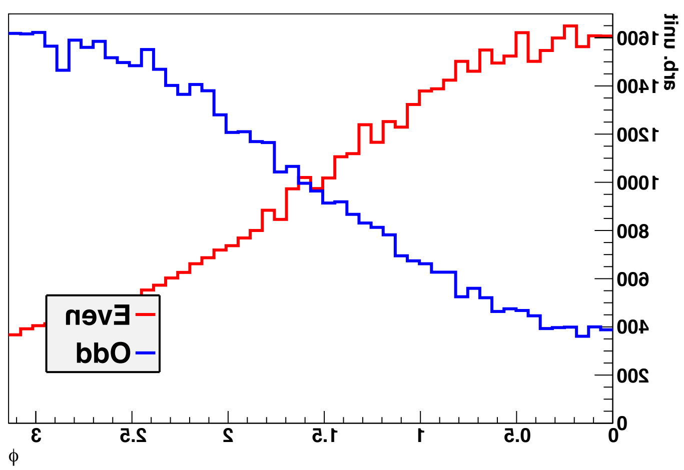
- Event generation
  Parton generation: **GRACE**; Tau decays: **TAUOLA**

- Analysis flow
  Tau jet reconstruction (select tau decays from the event)
  Rest of event = Z decay
  Signal event selection
  Categorization of tau decay mode
  Computation of acoplanarity angle

ZH associated production



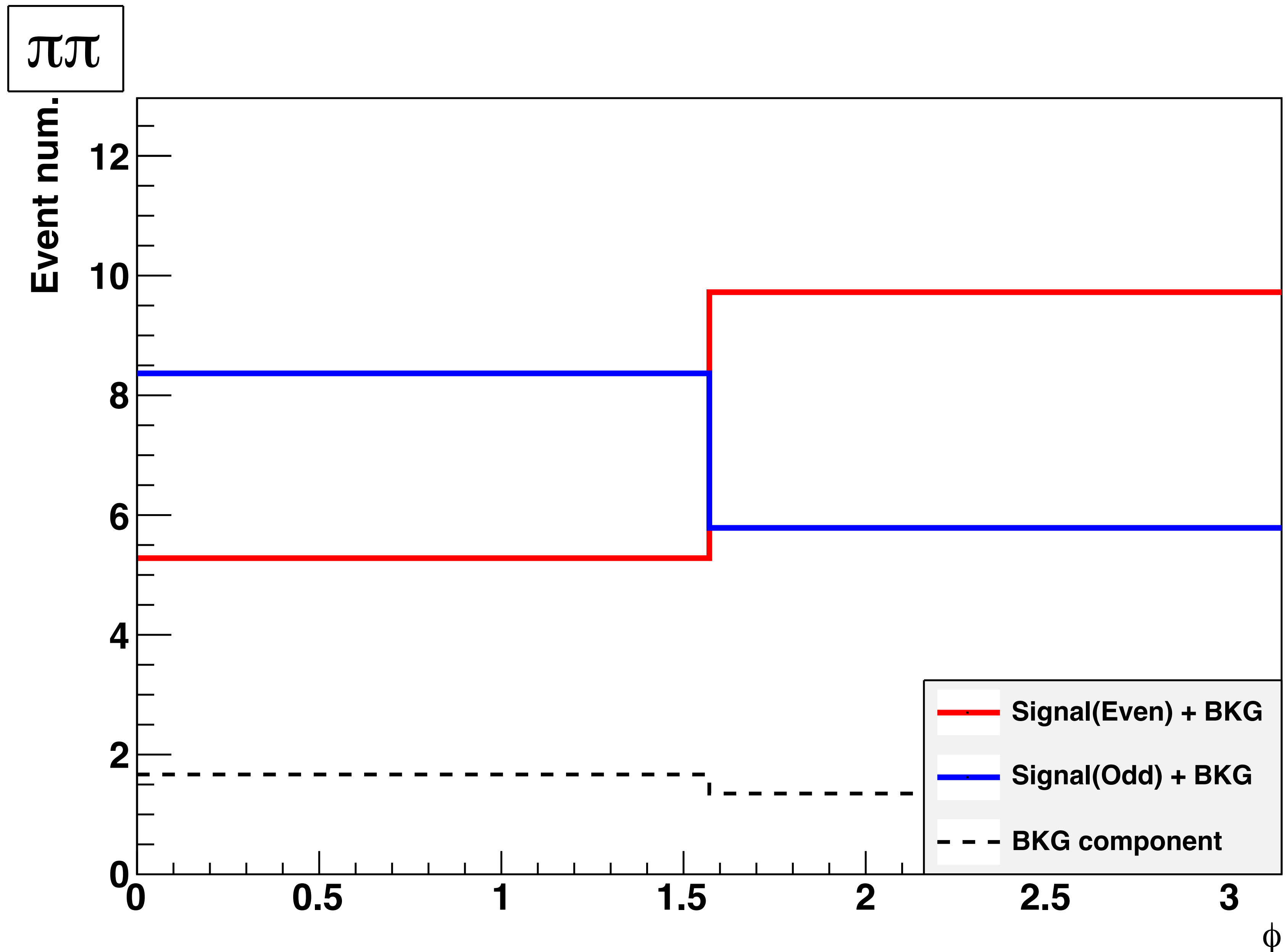
Full simulation results



Generator-level

Full simulation

Acoplanarity angle in **2 bins**



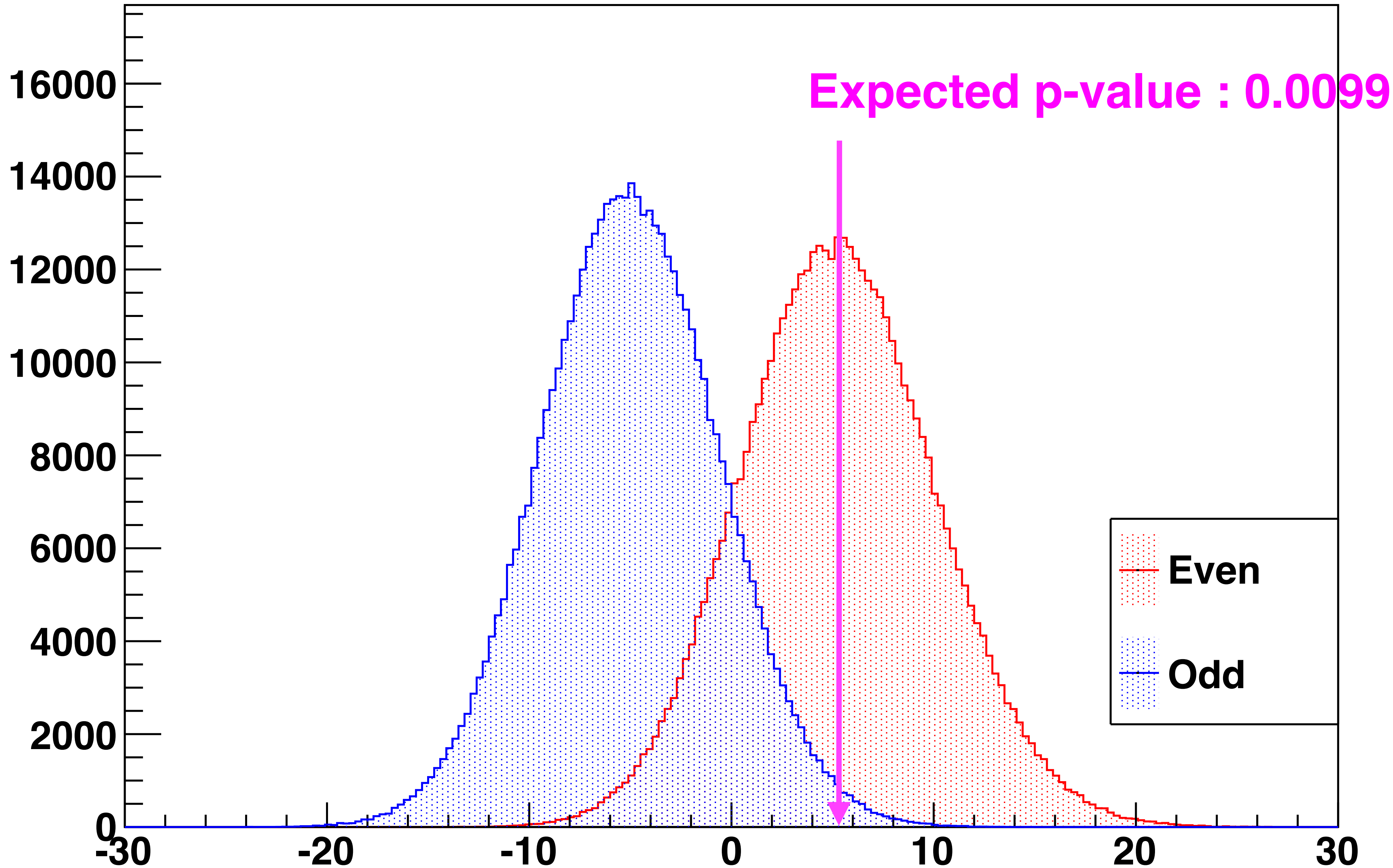
Three categories total: “ππ”,“πμ”,“πe” -> 6 statistically independent bins

Perform pseudo-experiments to estimate the sensitivity

Pseudo-experiments

Log-likelihood ratio for CP-even and CP-odd hypotheses

$$t = -2\ln(L(\text{pseudo exp} \; ; \; \text{Odd})/L(\text{pseudo exp} \; ; \; \text{Even}))$$



Summary

- **Developed event generator** using GRACE & TAUOLA for the study of Higgs CP mixing.
- **Observable sensitive to the CP mixing angle** (Acoplanarity angle) has been implemented and verified using generator-level information
- Performed analysis with **full simulation** using the ILD detector model
- CP-odd hypothesis can be excluded with C.L. >98% for pure CP-even state.

Prospects

- Estimate the sensitivity to the **CP mixing angle**
- Optimization of the tau decay categorization
- Utilization of other tau decay modes (e.g. rho meson, 3-prong)

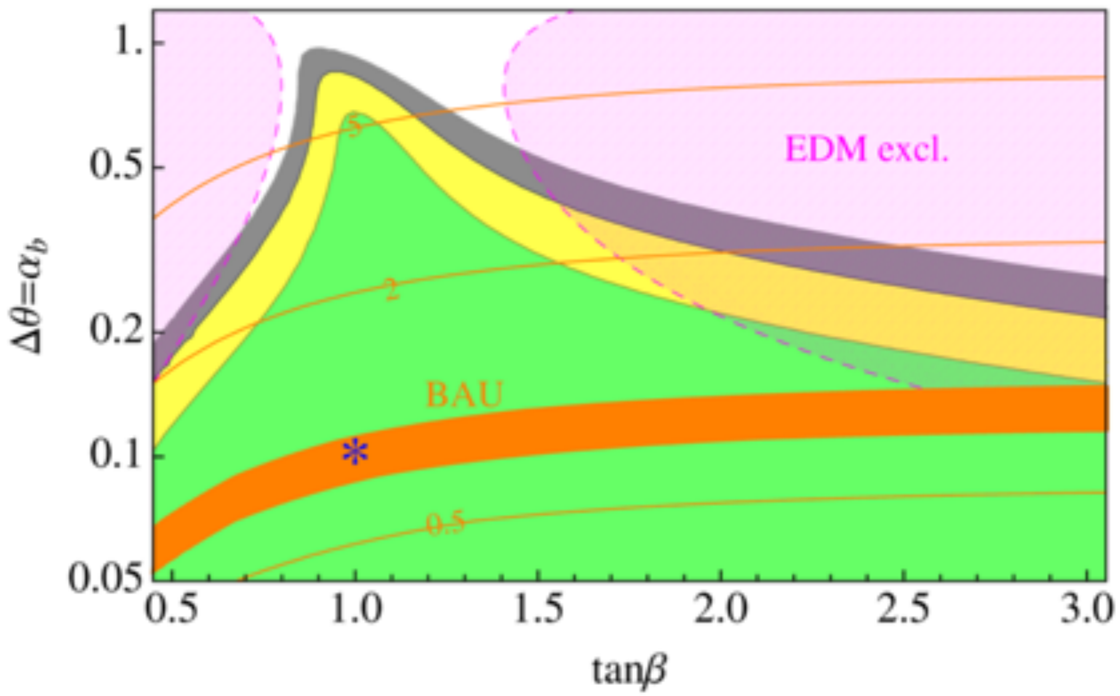
Additional Slides

CP mixing and effect on benchmark models

$$\mathcal{L}_{\mathrm{Y}} = \bar{\psi}(\cos\alpha + i\sin\alpha\gamma_5)\psi\phi$$

•As origin of EW Baryogenesis
•Constraints from EDM
↓
CP mixing: **10%**
↓

PRL 111, 091801 (2013)



BAU : Baryon asymmetry of universe

$$\cos\alpha : \sin\alpha = 9 : 1$$

$$\text{mixing angle} : \alpha = 0.11 \text{ rad} = 6.3 \text{ deg.}$$

分布に対する寄与はこの2乗で影響する。

$$N = (\cos^2\alpha)N_{\mathrm{even}} + (\sin^2\alpha)N_{\mathrm{odd}}$$

Sensitivity to Higgs CP

"target (theory)" is given assuming 10% CP-odd component

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	126	126	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$4 \cdot 10^{-5}$	$8 \cdot 10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

Snowmass Energy Frontier Higgs Subgroup Report (Sept. 27 draft)
http://www.snowmass2013.org/tiki-download_file.php?fileId=329

Higgs CP mixing angle: TAUOLA implementation

Define **CP mixing angle α** based on the general Yukawa interaction:

$$\tau(\cos\alpha + i\sin\alpha\,\gamma^5)\bar{\tau}\,\phi$$

$$\alpha = 0 : \mathrm{CP\ even},\ \ \alpha = \pi/2 : \mathrm{CP\ odd}$$

In TAUOLA, the tau polarization vector (x,y,z) is generated according to the **density matrix** consistent with the parent particle

$$\mathrm{weight} = \sum_{i,j}^{0,1,2,3} R_{ij}\, h_i^+\, h_j^-$$

Pol. Vector

Density Matrix

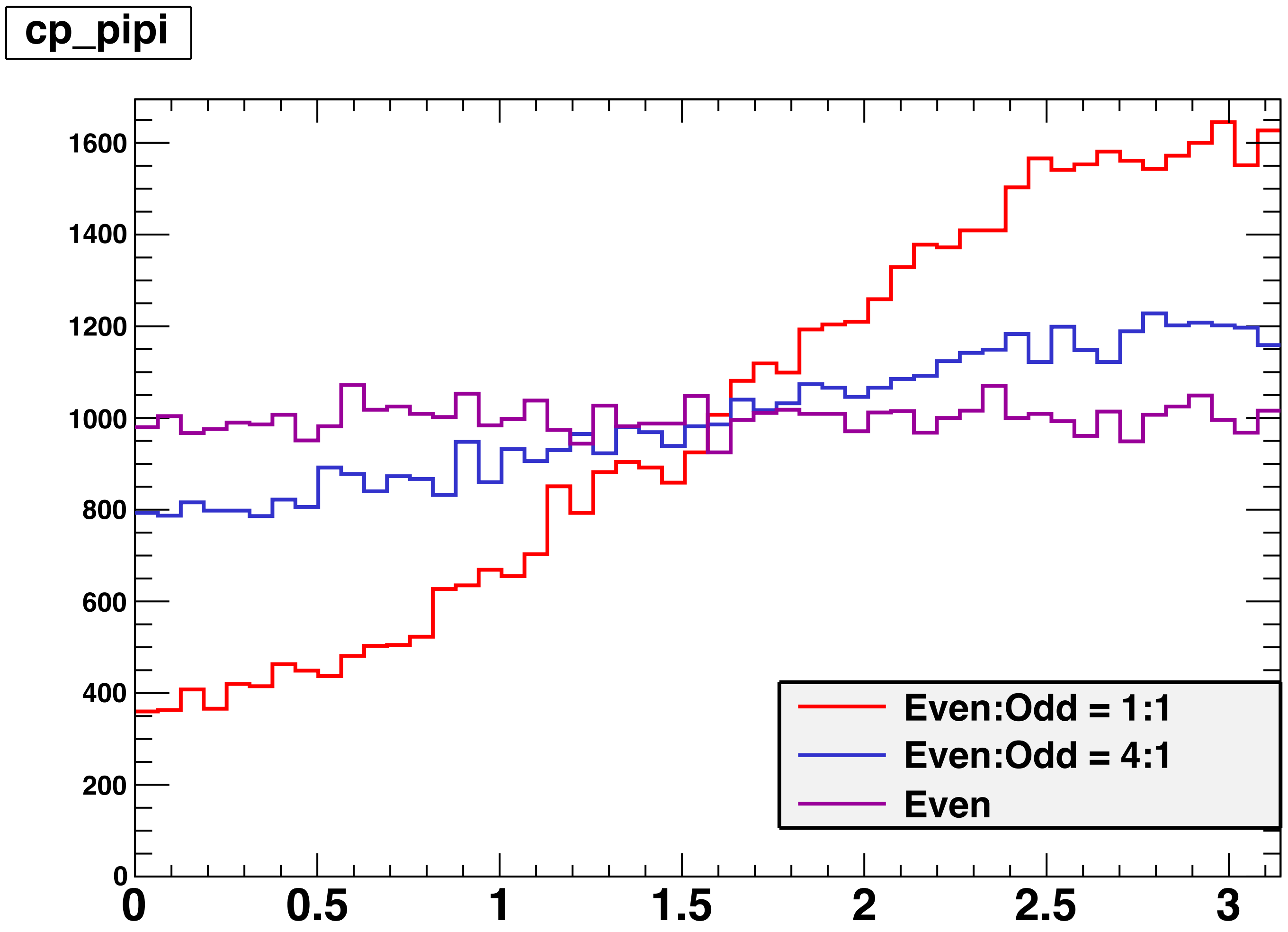
Density Matrix
$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{(\beta cos\phi)^2 - sin\phi^2}{(\beta cos\phi)^2 + sin\phi^2} & -\frac{2\beta cos\phi sin\phi}{(\beta cos\phi)^2 + sin\phi^2} & 0 \\ 0 & \frac{2\beta cos\phi sin\phi}{(\beta cos\phi)^2 + sin\phi^2} & \frac{(\beta cos\phi)^2 - sin\phi^2}{(\beta cos\phi)^2 + sin\phi^2} & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Observable for CP mixing angle

Triple odd correlation

$$\psi = \arccos(\hat{\mathbf{p}} \cdot (\hat{\mathbf{v}}_{\perp}^{+} \times \hat{\mathbf{v}}_{\perp}^{-}))$$

For $\pi^- \nu$ and $\pi^+ \nu$ decays



Tau decay branching ratios

Table 1: Basis modes and fit values(%) for the 2012 fit to τ branching fraction data.

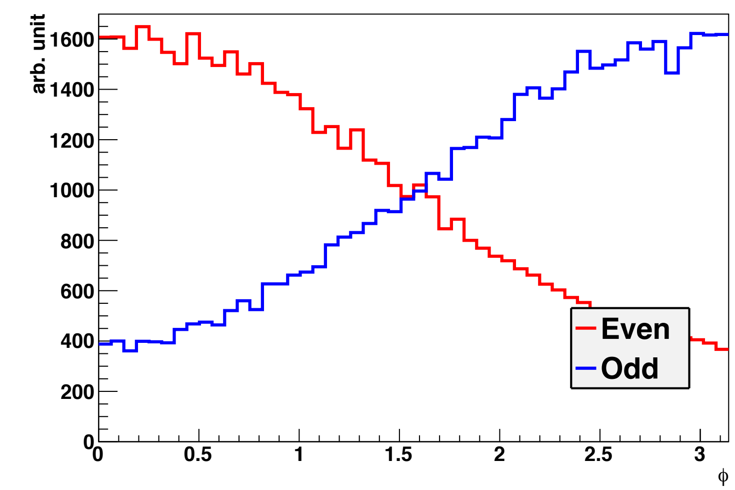
$e^-\overline{\nu}_e\nu_\tau$	17.83 ± 0.04
$\mu^-\overline{\nu}_\mu\nu_\tau$	17.41 ± 0.04
$\pi^-\nu_\tau$	10.83 ± 0.06
$\pi^-\pi^0\nu_\tau$	25.52 ± 0.09
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.30 ± 0.11
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.05 ± 0.07
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	0.11 ± 0.04
$K^-\nu_\tau$	0.700 ± 0.010
$K^-\pi^0\nu_\tau$	0.429 ± 0.015
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.065 ± 0.023
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.048 ± 0.022
$\pi^-\overline{K}^0\nu_\tau$	0.84 ± 0.04
$\pi^-\overline{K}^0\pi^0\nu_\tau$	0.40 ± 0.04
$\pi^-K^0_SK^0_S\nu_\tau$	0.024 ± 0.005
$\pi^-K^0_SK^0_L\nu_\tau$	0.12 ± 0.04
$K^-K^0\nu_\tau$	0.159 ± 0.016
$K^-K^0\pi^0\nu_\tau$	0.159 ± 0.020
$\pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0, ω)	8.99 ± 0.06
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0, ω)	2.70 ± 0.08

From PDG

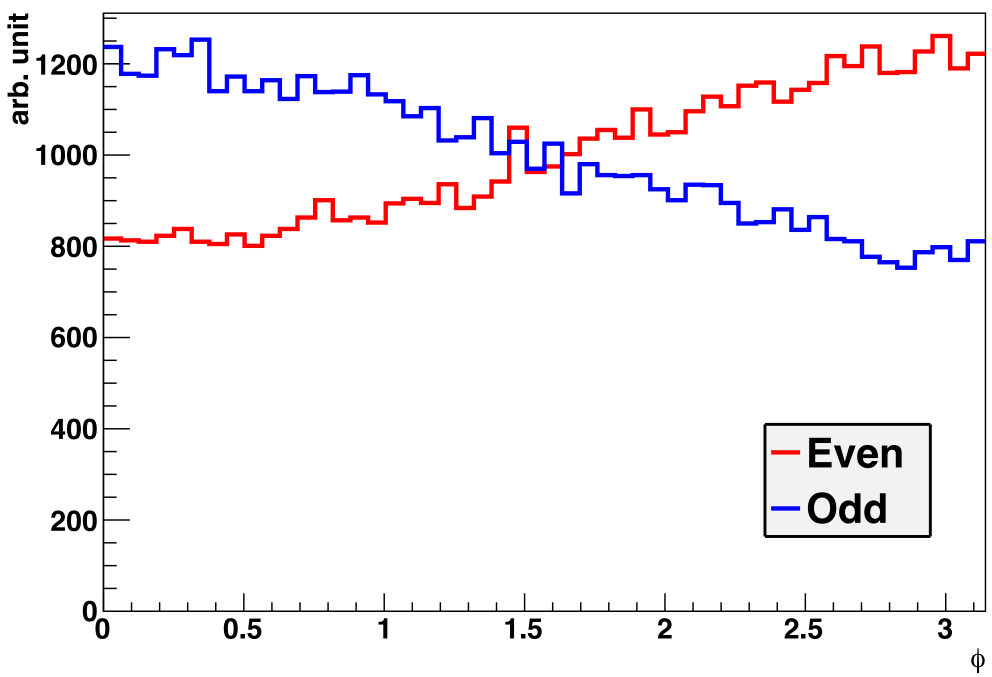
$\tau^- \to \pi^- \nu$, $\tau^+ \to \mu^+ (e^+) \nu\nu$

- Two neutrinos: spin correlation diluted
- The distribution is flipped for every lepton

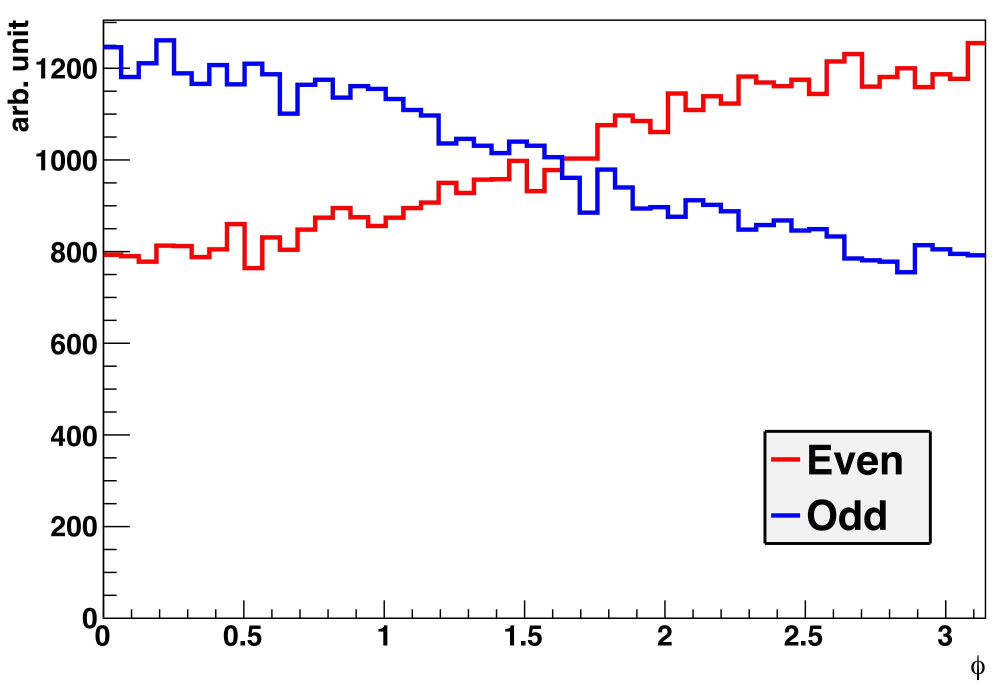
$\tau^- \to \pi^- \nu$, $\tau^+ \to \pi^+ \nu$



$\pi\nu, e\nu\nu$



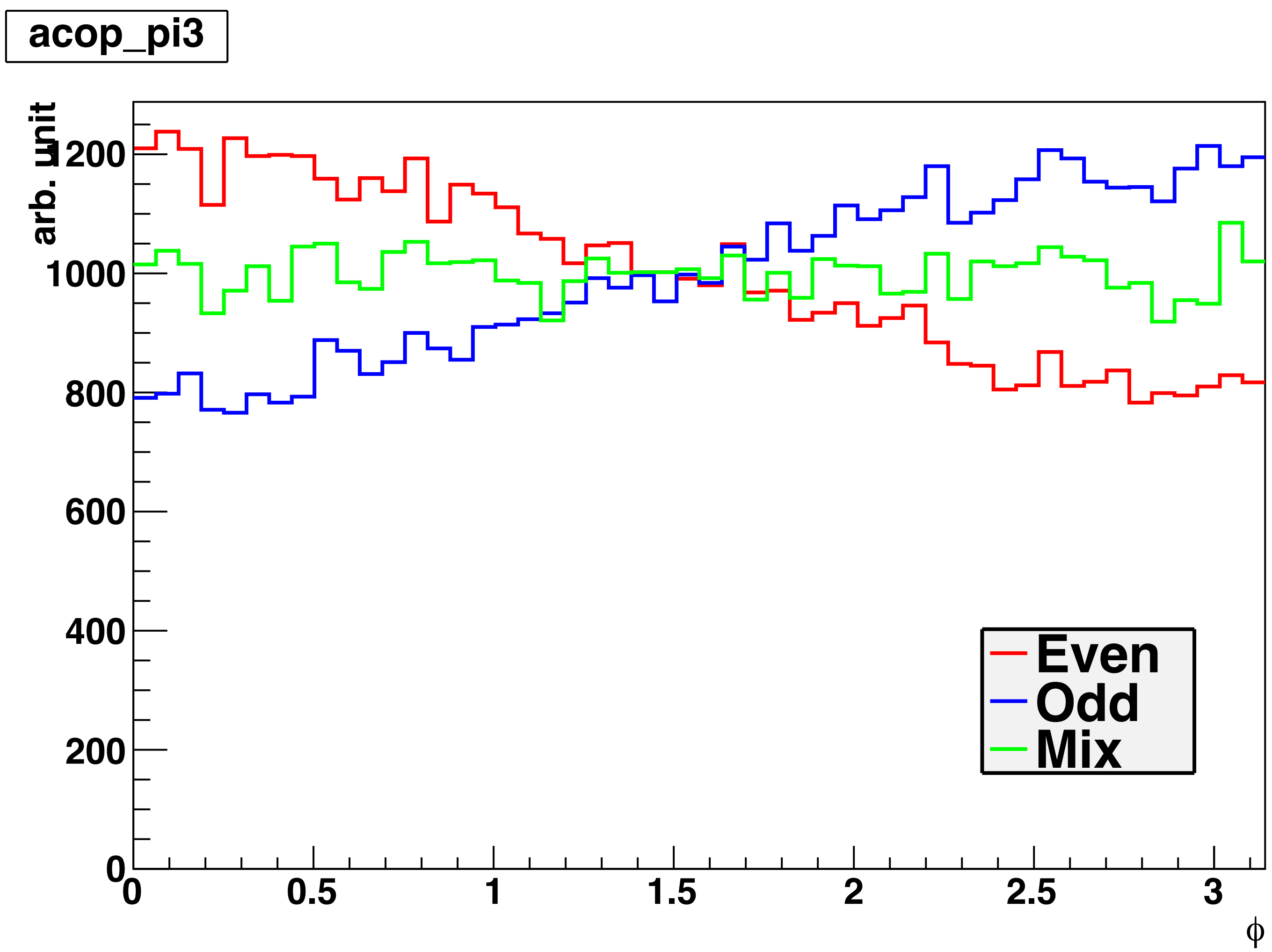
$\pi\nu, \mu\nu\nu$



1.2% of all H->tautau events

$\pi^- \nu$と $\pi^+ \pi^+ \pi^- \nu\nu$ (3 prong)

Reconstruction the 3-prong decay vertex should be investigated.
Question: How does it compare with the impact parameter method?

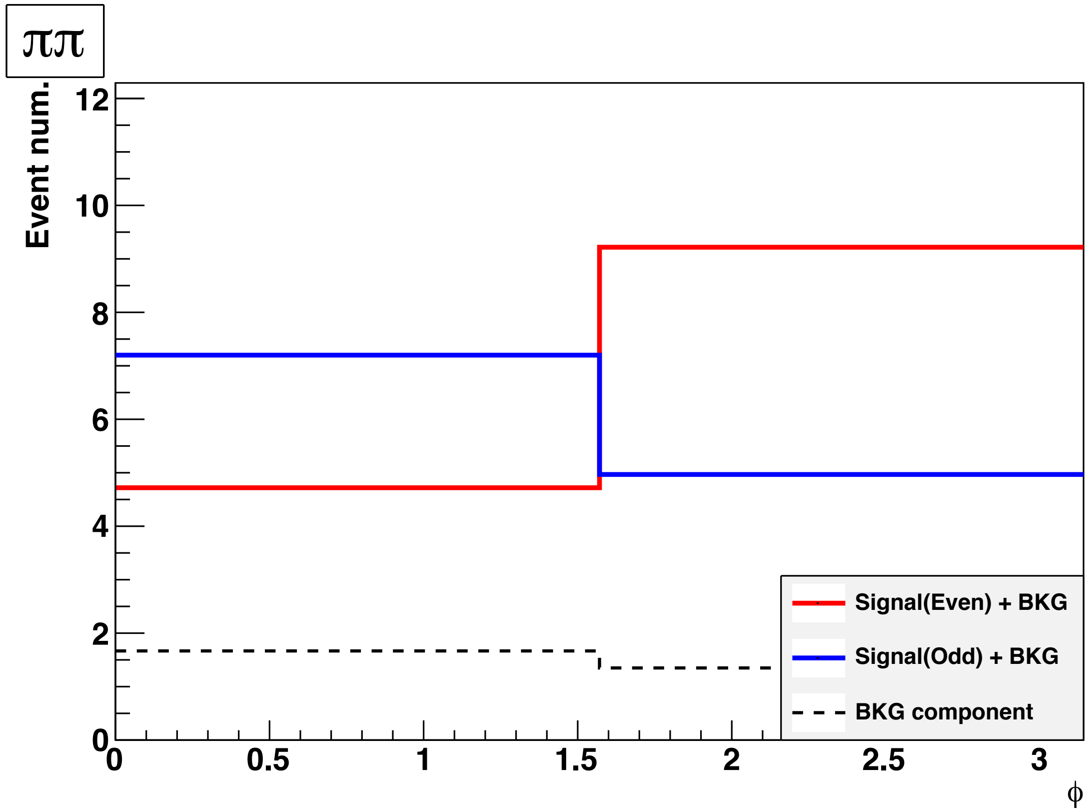


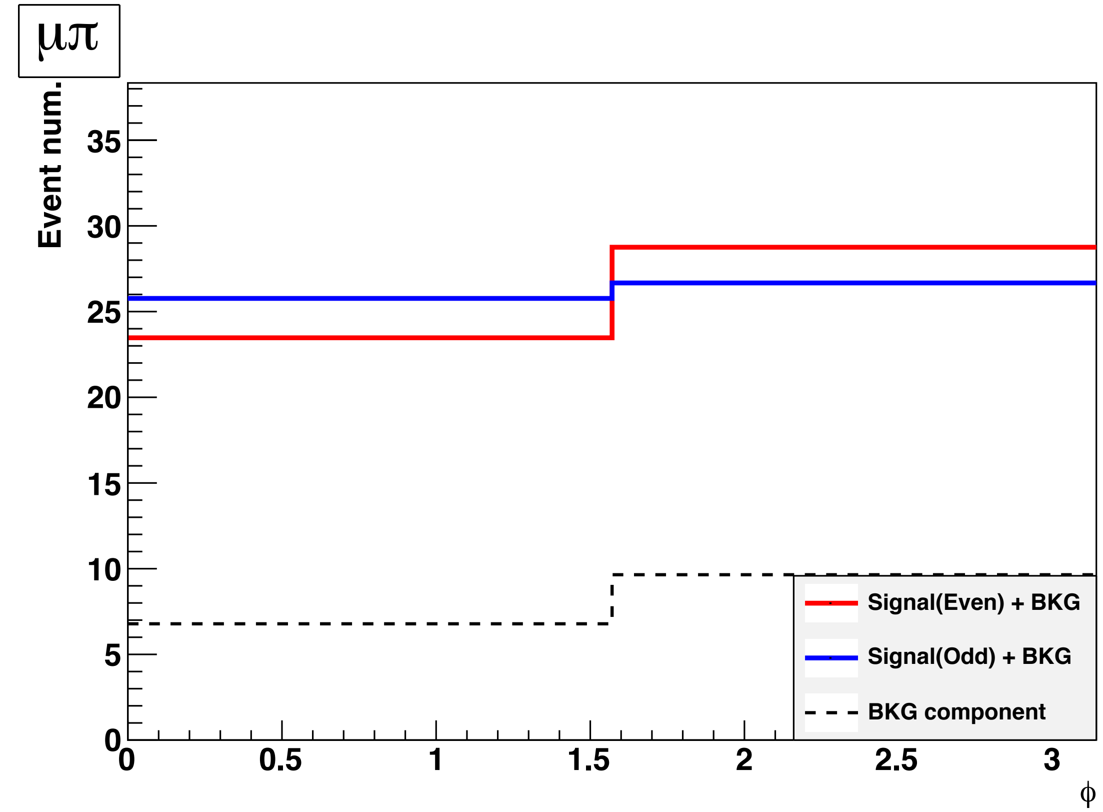
1.9%
of all H->tautau events

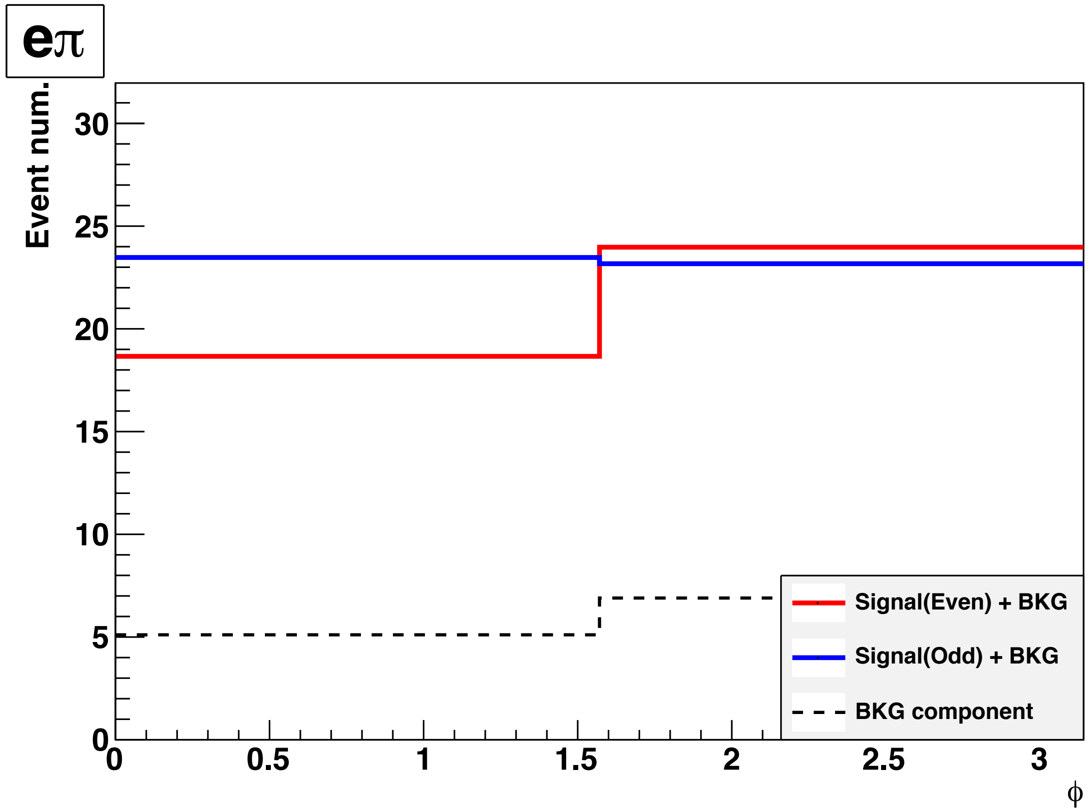
Tau decay mode categorization

category	# of PFOs	ECAL/(ECAL+HCAL)	Track P/(ECAL+HCAL)
ππ	< 2	< 0.9	> 0.7
πe	< 3	> 0.9	
πμ	< 3	< 0.9	< 0.7

Acoplanarity angle: three categories



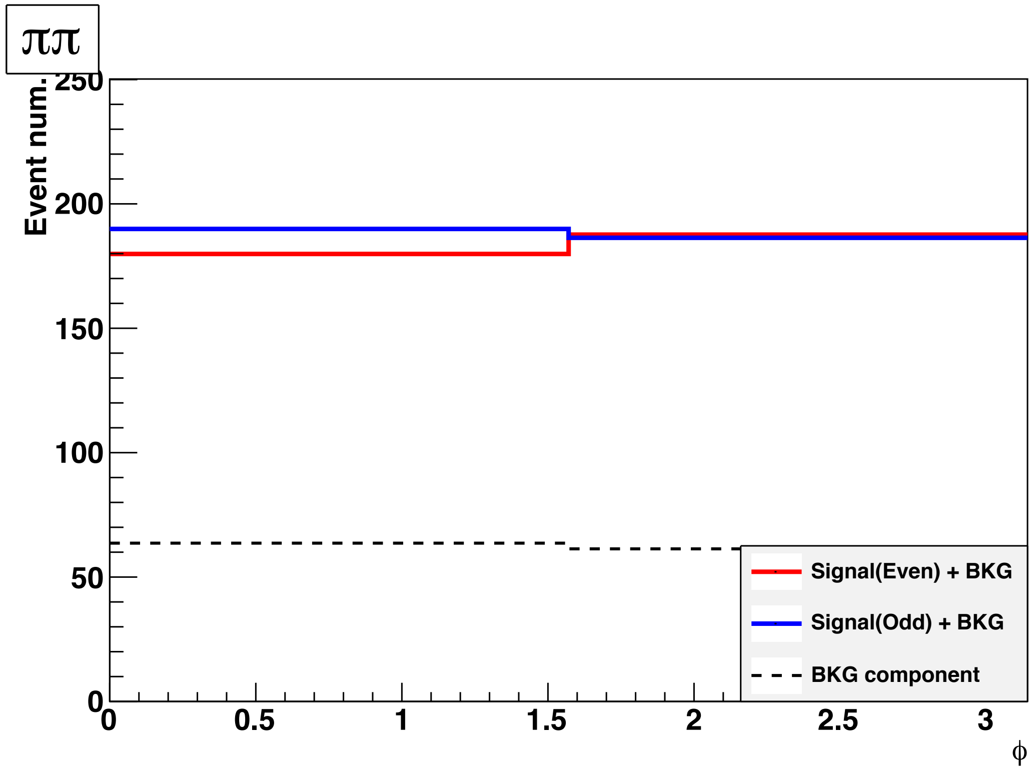


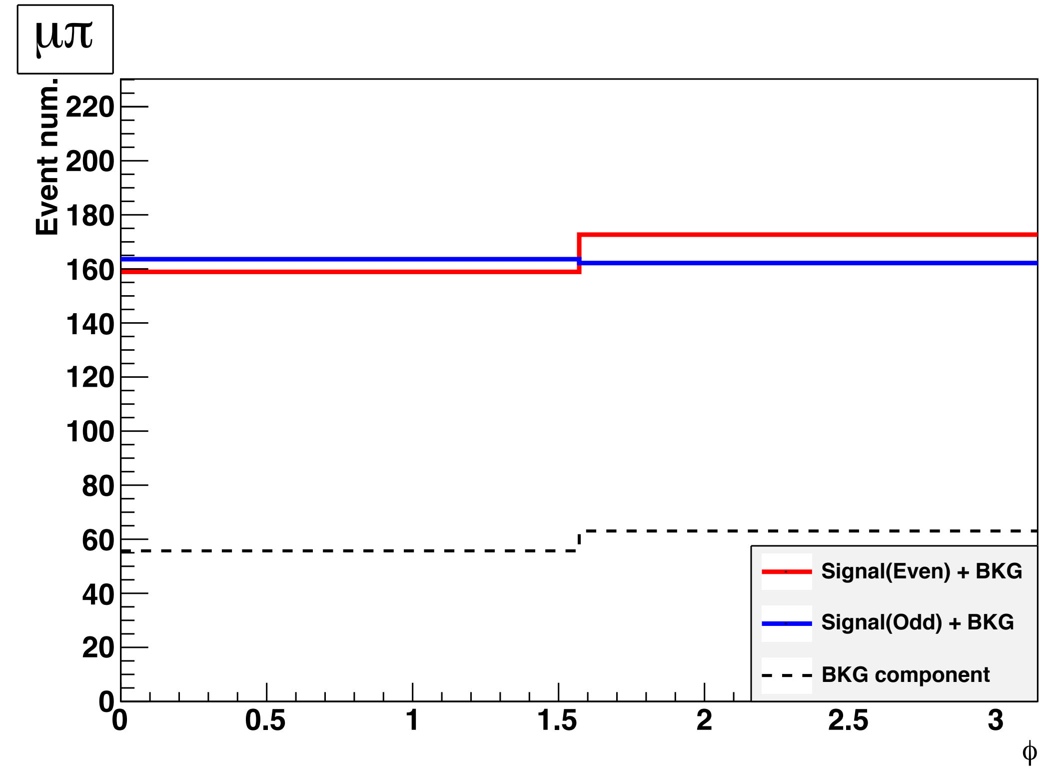


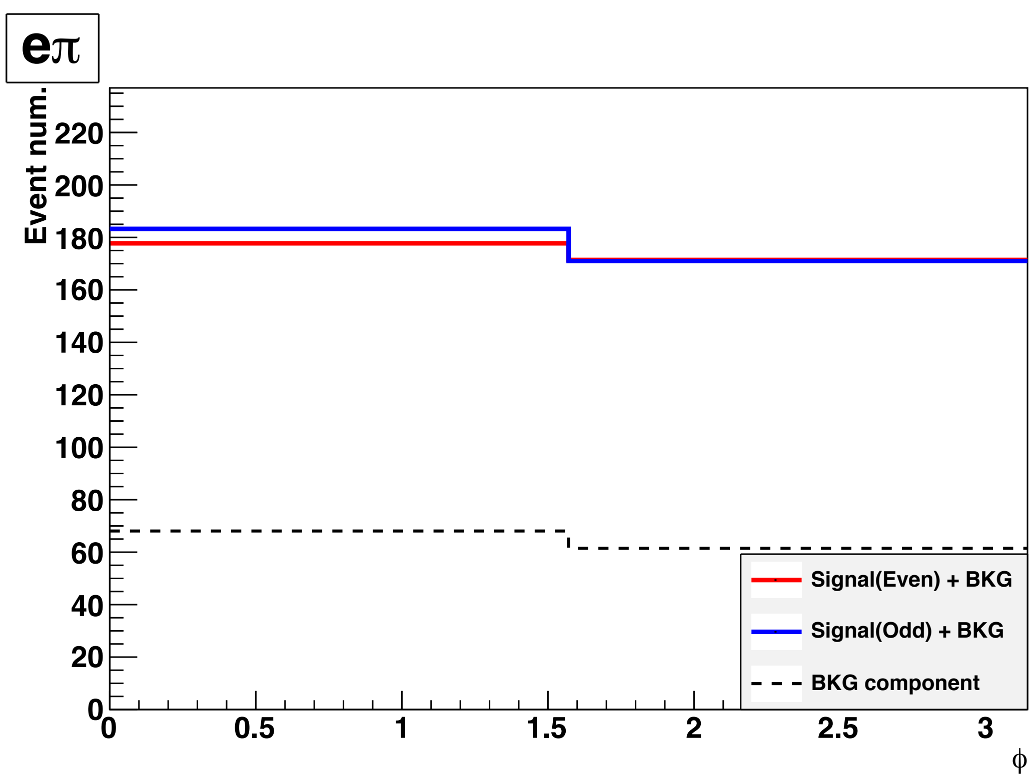
* Distribution is flipped for ππ category

Acoplanarity angle: three categories

In case of removing cut about the number of PFOs,







Test statistics

i : bin number.
$\nu_i(H)$: Expected number in bin i assuming hypothesis H.
n_i : Number of event in bin i , randomly generated in pseudo-experiment.

Likelihood is ,

$$L(\{n_i\};H) = \prod_i \frac{\nu_i(H)}{n_i!} e^{-\nu_i}$$

$$\ln L(\{n_i\};H) = \sum_i \{n_i \ln \nu_i(H) - \nu_i - \ln(n_i!)\}$$

Likelihood-ratio is,

$$\begin{aligned} t &= -2\ln\left(\frac{L(\{n_i\};\mathrm{Odd})}{L(\{n_i\};\mathrm{Even})}\right) \\ &= -2\sum_i \left(n_i \ln \frac{\nu_i(\mathrm{Odd})}{\nu_i(\mathrm{Even})} - (\nu_i(\mathrm{Odd}) - \nu_i(\mathrm{Even}))\right) \end{aligned}$$