# Measurement of $A_{LR}$ in the $e^+e^-$ -> $Z\gamma$ at the 250 GeV ILC

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# Outline

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  - SiD
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- Simulation
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  - Event Selection
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- Conclusion and Future Plan

# Motivation
# - Previous studies -

## Why Z boson?

Z boson can be produced 'on resonance' in very large numbers giving low statistical errors and with a sensitive energy dependence

-> That makes it much easier to fit its parameters with very high precision

-> It is possible to predict other physical parameters

Z boson parameters have served as good references

## SLC

- longitudinal polarization electron beam was established
- the first e+e− linear collider
- 600 thousand Z decays collected by the SLD experiment

- Current Value -

$A^0_{LR} = 0.1514 \pm 0.0022$

## LEP

- an electron-positron circular collider with a circumference of approximately 27 km
- 17 million Z decays accumulated by the ALEPH, DELPHI, L3 and OPAL experiments

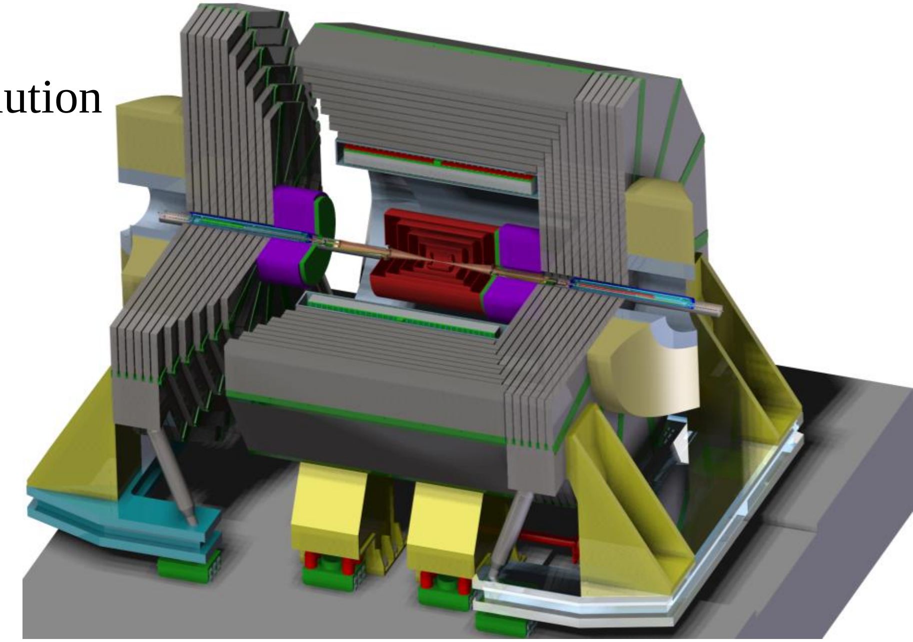
# Motivation
# - SiD overview-

<u>SiD</u>

provides excellent momentum and energy resolution over the broad range of particles energies expected at the ILC

due to
- 5T solenoidal magnetic field,
- a vertex detector with silicon pixels
- a main tracker with silicon strips

et al.



The ILC baseline design includes 80% polarized electron and 30% polarized positron

Especially for quantities where beam polarization is needed, exactly $A_{LR}$, huge progress compared to the present precision can be expected

# Motivation
# - Higgs Effective Field Theory -

General SU(2) × U(1) gauge invariant Lagrangian with dimension-6 operators in addition to the SM

$$\Delta L = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+ \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^a_{\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}_{\rho}W^{c\rho\mu}$$
$$+ i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\bar{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\bar{L}\gamma_\mu t^a L)$$
$$+ i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\bar{e}\gamma_\mu e) + c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)\bar{L}_3\cdot\Phi_{\tau R} + h.c.$$

$$s_*^2 = s_0^2 + \frac{s_0^2}{c_0^2 - s_0^2}(c'_{HL} + 8c_{WB} - c_0^2 c_T) - \frac{1}{2}c_{HE} - s_0^2(c_{HL} - c_{HE})$$

If the incoming beams can be polarized,

$A_{LR}$ is the most sensitive variable to the effective weak mixing angle

# Set up

- **Simulation setup**

Event Generation : WHIZARD 1.95

- Samples : Mixed DBD sample

  - Signal Process : $e^+e^-$ => $\gamma^*/Z^*$ => a fermion-pair
  - Background Processes :

    $e^+e^-$ => $W^+W^-$, ZZ, single W, single Z, $\gamma\gamma$, $\gamma e$ -> X
  - ISR & Beamstrahlung ON
  - $E_{CM}$ = 250 GeV
  - Integral luminosity

    250 $fb^{-1}$ for 80L30R / 80R30L

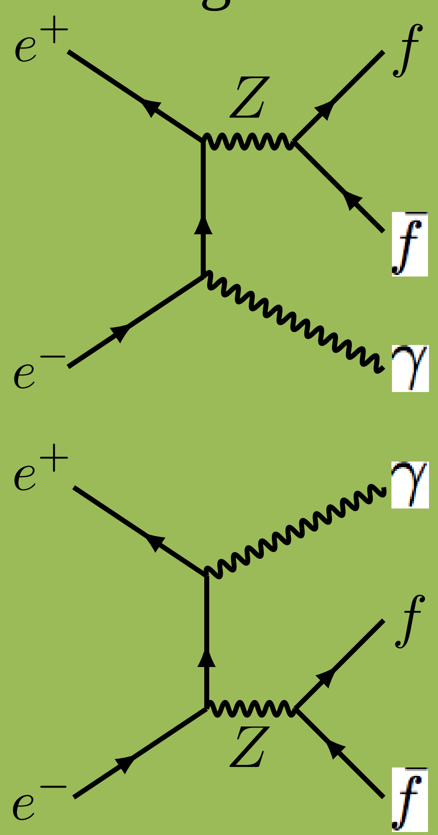
    25 $fb^{-1}$ for 80L30L / 80R30R

Detector Simulation : DSiD (a fast simulation Delphes detector)

# Signal Process Definition

$$Signal : e^+e^- \rightarrow f\bar{f} + 86GeV < M_{f\bar{f}}(truth) < 96GeV$$

**Signal**

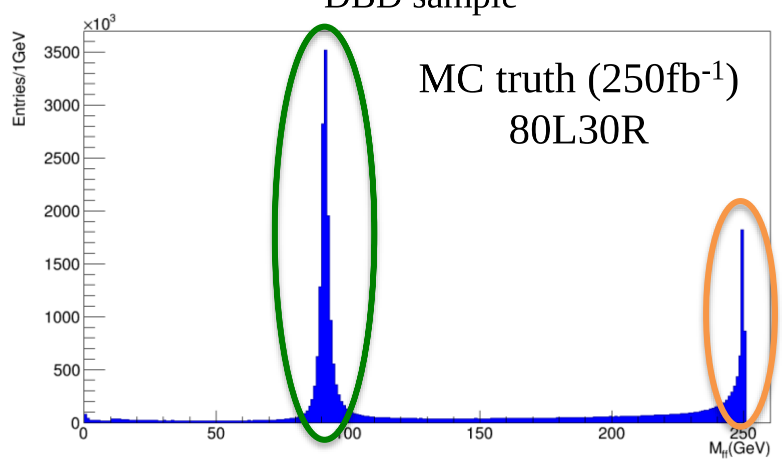



# Cross section

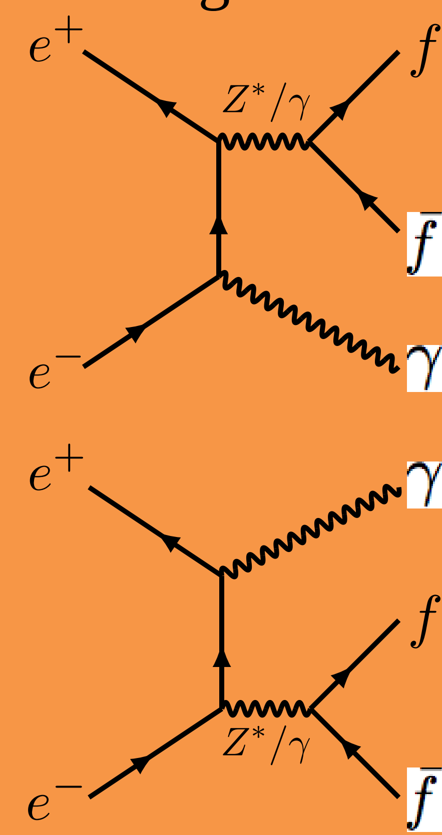
$\sigma_{80L30R}$ = 50.67 pb

$\sigma_{80R30L}$ = 34.40 pb

$M_{ff}$ distribution
DBD sample




**Background**



# Method

## Precise measurement of the beam energy at LEP

Motivation

The direct measurement of the W mass with an accuracy of 30-50 MeV at LEP2
-> It requires a precise determination of the $E_{COM}$ (below 30 MeV)

Signal

$e^+e^-$ => $Z\gamma$ => hadrons events (2jets)

$\theta_1$, $\theta_2$ : the angles of the 2 jets with respect to the direction of Z boson's velocity

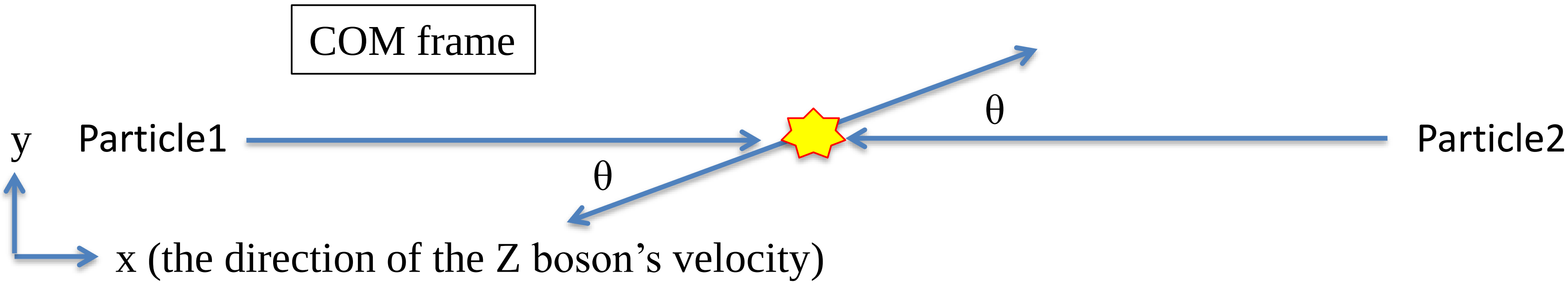
$$|\beta| = \frac{|sin(\theta_1 + \theta_2)|}{sin\theta_1 + sin\theta_2} \cdots (1) \qquad x = \frac{2|\beta|}{1 + |\beta|} \cdots (2)$$

**$\theta_1$, $\theta_2$ ⇔ Effective Center-of-Mass Energy**

arxiv.org/abs/hep-ex/9810047

This method was actually applied for the data collected with the ALEPH detector

# Method




**COM frame**

<u>Particle1</u>

$E_1 = E$

$P_{1x} = P\cos\theta$

$P_{1y} = P\sin\theta$

<u>Particle2</u>

$E_2 = E$

$P_{2x} = P\cos\theta$

$P_{2y} = P\sin\theta$

Lorentz transformation →

**Rest frame of Z boson**

<u>Particle1</u>

$E_1' = \gamma E + \eta P\cos\theta$

$P_{1x}' = \eta E + \gamma P\cos\theta$

$P_{1y}' = P\sin\theta$

<u>Particle2</u>

$E_1' = \gamma E - \eta P\cos\theta$

$P_{1x}' = \eta E - \gamma P\cos\theta$

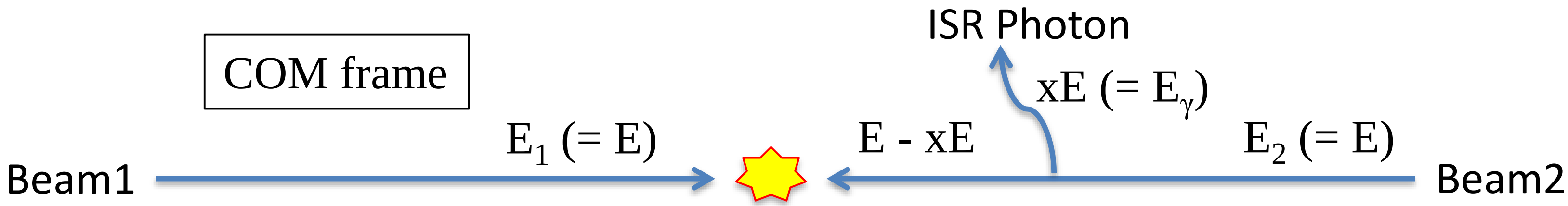
$P_{1y}' = -P\sin\theta$

$$sin\theta_1 = \frac{|P'_{1y}|}{E'_1} \qquad sin\theta_2 = \frac{|P'_{2y}|}{E'_2}$$

$$cos\theta_1 = \frac{P'_{1x}}{E'_1} \qquad cos\theta_2 = \frac{P'_{2x}}{E'_2}$$

$$\frac{|sin(\theta_1 + \theta_2)|}{sin\theta_1 + sin\theta_2} = \frac{\eta}{\gamma} = |\beta| \cdots (1)$$

# Method



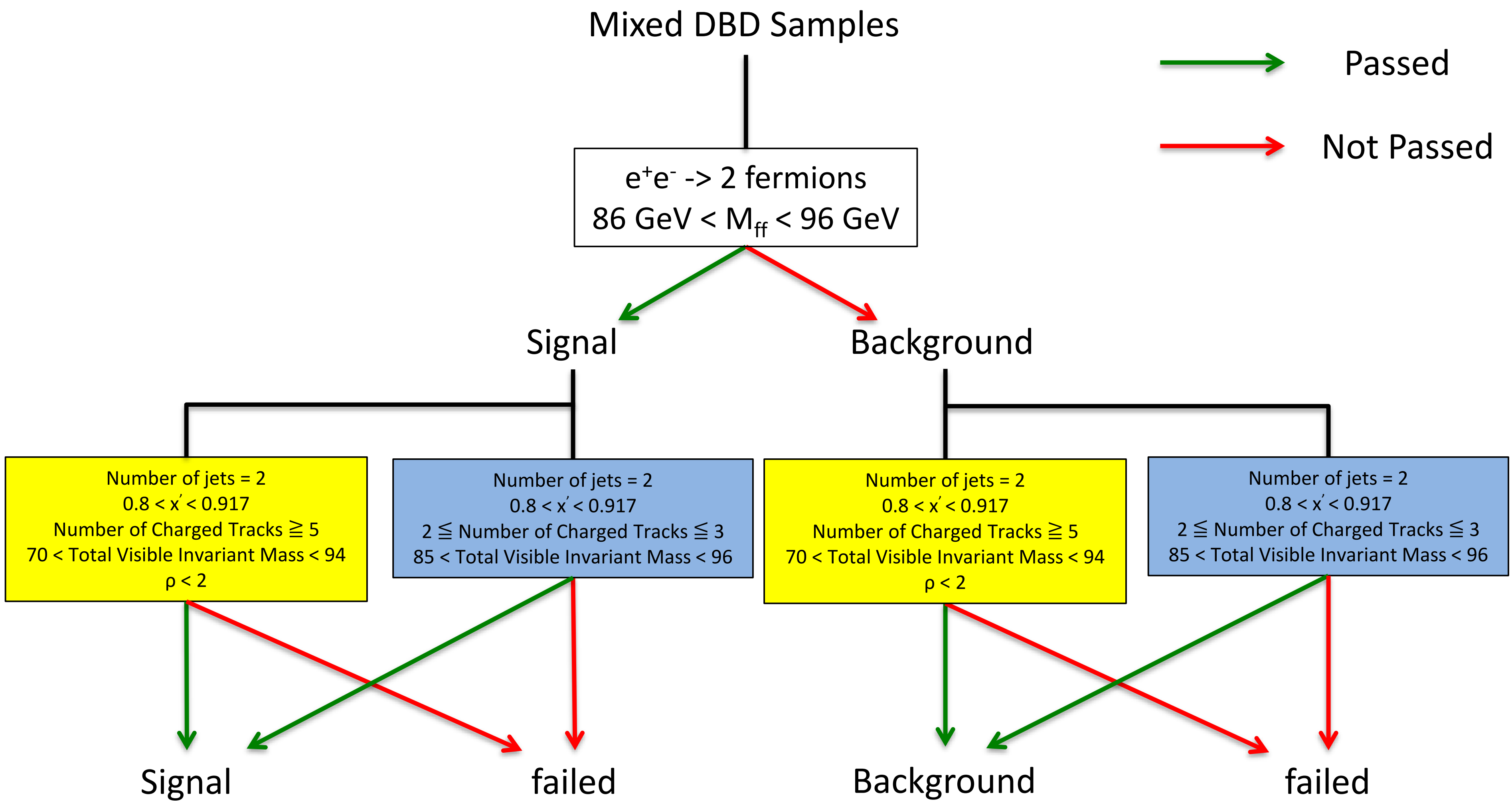

$$|\beta| = \frac{P_{tot}}{E_{tot}} = \frac{E_\gamma}{E_1 + E_2} = \frac{xE}{E + E(1-x)} = \frac{x}{2-x}$$

$$x = \frac{2|\beta|}{1+|\beta|} \cdots (2)$$

No ISR case $\sqrt{s} = \sqrt{4E_1E_2} = \sqrt{4E^2}$

ISR case $\sqrt{s'} = \sqrt{4E_1E_2} = \sqrt{4E(E - xE)} = \sqrt{4E^2(1-x)} = \sqrt{s(1-x)}$

# Event Selection



# Efficiency and Significance -for 250fb$^{-1}$ 80L30R -

| GenJet | | Before Event Selection | After Event Selection |
|---|---|---|---|
| Signal | Z -> charged leptons | 1435325.0 (100%) | 491475.0 (34.2%) |
| | Z -> hadrons | 11231604.0 (100%) | 4476526.2 (39.9%) |
| Background | | 710042679.9 (100%) | 1252105.9 (0.176%) |
| Significance | | 471.2 | 1992.0 |

| FastJet | | Before Event Selection | After Event Selection |
|---|---|---|---|
| Signal | Z -> charged leptons | 1435325.0 (100%) | 511737.5 (35.7%) |
| | Z -> hadrons | 11231604.0 (100%) | 4313152.1 (38.4%) |
| Background | | 710042679.9 (100%) | 1258844.1 (0.177%) |
| Significance | | 471.2 | 1956.2 |

| VLCJet | | Before Event Selection | After Event Selection |
|---|---|---|---|
| Signal | Z -> charged leptons | 1435325.0 (100%) | 433637.5 (30.2%) |
| | Z -> hadrons | 11231604.0 (100%) | 3916783.4 (34.9%) |
| Background | | 710042679.9 (100%) | 1466618.1 (0.207%) |
| Significance | | 471.2 | 1803.8 |

# $A_{LR}$ Table

| FastJet | $N_{LR}$ (250fb$^{-1}$) | $N_{RL}$ (250fb$^{-1}$) | $N_{LR}-N_{RL}/N_{LR}+N_{RL}$ | $A_{LR}$ |
|---|---|---|---|---|
| All Events | 6083733.7 | 3813950.0 | 0.2293 | 0.2585 |
| All Signal | 4824889.6 | 3270475.0 | 0.1920 | 0.2165 |
| Z -> charged leptons (Signal) | 511737.5 | 360337.5 | 0.1736 | 0.1957 |
| Z -> hadrons (Signal) | 4313152.1 | 2910137.5 | 0.1942 | 0.2189 |
| All Background | 1258844.1 | 543475.0 | 0.3969 | 0.4474 |
| Background (ZZ, WW, single Z, single W) | 518950.0 | 71262.5 | 0.7585 | 0.8551 |
| γγ, γe -> X | 159375.0 | 109125.0 | 0.1872 | 0.2109 |
| Background (ee -> ff outside 86 < $M_{ff}$ < 96) | 580519.1 | 363087.5 | 0.2304 | 0.2598 |

$$DBD \;\; sample : sin^2\theta_{eff} = 0.22225 \;\; -> A_{LR}(DBD) = 0.2193$$

For equal luminosity, $$A_{LR} = \frac{N_{LR} - N_{RL}}{N_{LR} + N_{RL}} \frac{1 + P^+P^-}{P^+ + P^-}$$

# The Statistical Error of $A_{LR}$

$$A_{LR} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}} \frac{1 + P^+P^-}{P^+ + P^-} = \frac{N_{LR} - N_{RL} \cdot r_L}{N_{LR} + N_{RL} \cdot r_L} \frac{1 + P^+P^-}{P^+ + P^-}$$

$$r_L = \frac{luminosity\ for\ 80R\,30L}{luminosity\ for\ 80L\,30R}$$

The propagation of the errors

$$\Delta A_{LR} \approx \sqrt{(\frac{\partial A_{LR}}{\partial N_{LR}})^2 (\Delta N_{LR})^2 + (\frac{\partial A_{LR}}{\partial N_{RL}})^2 (\Delta N_{RL})^2} = \frac{2 N_{LR} N_{RL} \cdot r_L}{(N_{LR} + N_{RL})^2} (\frac{1}{\sqrt{N_{LR}}} + \frac{1}{\sqrt{N_{RL}}}) \frac{1 + P^+P^-}{P^+ + P^-}$$

The statistical error of $A_{LR}$ for all signal

$$N_{LR}(250 fb^{-1}) = 4824889.6$$
$$N_{RL}(250 fb^{-1}) = 3270475.0$$
$$r_L = 1$$

$$\Delta A_{LR}(500 fb^{-1}) = 0.00055$$

For the full-running at 250GeV,

$$\Delta A_{LR}(2ab^{-1}) = \frac{1}{2} \Delta A_{LR}(500 fb^{-1}) = 0.00028$$

# $A_{LR}$ correction

$$A_{LR} = \frac{1+P^+P^-}{P^+ + P^-} \cdot A_m + \frac{1+P^+P^-}{P^+ + P^-}\left[f_{bkg}(A_m - A_{bkg}) - A_L + A_m^2 A_P - E_{cm}\frac{\sigma'(E_{cm})}{\sigma(E_{cm})}A_E - A_{eff}\right]$$
$$= \frac{1+P^+P^-}{P^+ + P^-}[A_m(1+f_{bkg}) - f_{bkg}A_{bkg} + \ldots] \approx \frac{1+P^+P^-}{P^+ + P^-}[A_m(1+f_{bkg}) - f_{bkg}A_{bkg}]$$

| | |
|---|---|
| $A_m$ | Measured left-right asymmetry |
| $f_{bkg}$ | Fraction of background |
| $A_{bkg}$ | Background asymmetry |
| $A_L$ | Luminosity asymmetry |
| $A_P$ | Polarization asymmetry |
| $A_E$ | Center-of –mass energy asymmetry |
| $A_{eff}$ | Efficiency asymmetry |

| FastJet | $A_m$ | $A_{bkg}$ | $f_{bkg}$ | $A_{LR}$ |
|---|---|---|---|---|
| All Events | 0.2293 | 0.3969 | 0.2226 | 0.2164 |
| All Z -> leptons | 0.1646 | 0.1161 | 0.1776 | 0.1953 |
| All Z -> hadrons | 0.2367 | 0.4230 | 0.2285 | 0.2188 |

$$A_m = \frac{N_L(total) - N_R(total)}{N_L(total) + N_R(total)} \qquad A_{bkg} = \frac{N_L(bkg) - N_R(bkg)}{N_L(bkg) + N_R(bkg)} \qquad f_{bkg} = \frac{N_L(bkg) + N_R(bkg)}{N_L(signal) + N_R(signal)}$$

# Introduction
# - The Blondel Scheme -

The cross-section e+e- -> Z -> a fermion-pair for polarized beams can be written as

$$\sigma = \sigma_u \left[1 - P^+P^- + A_{LR}(P^+ - P^-)\right]$$

$\sigma_u$ : the unpolarized cross section
$P^+$ : the longitudinal polarizations of the positrons measured in the direction of the particle's velocity
$P^-$ : the longitudinal polarizations of the electrons measured in the direction of the particle's velocity

$$\begin{aligned}
\sigma_{++} &= \sigma_u \left[1 - P^+P^- + A_{LR}(\ \ P^+ - P^-)\right] \\
\sigma_{-+} &= \sigma_u \left[1 + P^+P^- + A_{LR}(-P^+ - P^-)\right] \\
\sigma_{+-} &= \sigma_u \left[1 + P^+P^- + A_{LR}(\ \ P^+ + P^-)\right] \\
\sigma_{--} &= \sigma_u \left[1 - P^+P^- + A_{LR}(-P^+ + P^-)\right]
\end{aligned}$$

$\sigma_{\pm\pm}$ the first sign denotes the positron- and the second one the electron polarization

$$A_{LR} = \sqrt{\frac{(\sigma_{++} + \sigma_{-+} - \sigma_{+-} - \sigma_{--})(-\sigma_{++} + \sigma_{-+} - \sigma_{+-} + \sigma_{--})}{(\sigma_{++} + \sigma_{-+} + \sigma_{+-} + \sigma_{--})(-\sigma_{++} + \sigma_{-+} + \sigma_{+-} - \sigma_{--})}}$$

# $A_{LR}$ Table
# - The Blondel Scheme -

| FastJet | $N_{LR}$ (250fb$^{-1}$) | $N_{RL}$ (250fb$^{-1}$) | $N_{LL}$ (25fb$^{-1}$) | $N_{RR}$ (25fb$^{-1}$) | $A_{LR}$ |
|---|---|---|---|---|---|
| All Events | 6083733.7 | 3813950.0 | 361667.6 | 258947.6 | 0.2625 |
| All Signal | 4824889.6 | 3270475.0 | 284825.1 | 214270.1 | 0.2173 |
| Z -> leptons (Signal) | 511737.5 | 360337.5 | 31511.3 | 24648.8 | 0.2023 |
| Z -> hadrons (Signal) | 4313152.1 | 2910137.5 | 253313.8 | 189621.3 | 0.2193 |
| All Background | 1258844.1 | 543475.0 | 76842.5 | 44677.5 | 0.4801 |
| Background (ZZ, WW, single Z, single W) | 518950.0 | 71262.5 | 28595.0 | 8165.0 | 0.8627 |
| γγ,γe -> X | 159375.0 | 109125.0 | 13950.0 | 12087.5 | 0.7120 |
| Background (ee -> ff, outside 86 < $M_{ff}$ < 96) | 580519.1 | 363087.5 | 34297.5 | 24425.0 | 0.2623 |

$$A_{LR} = \sqrt{\frac{(\sigma_{++} + \sigma_{-+} - \sigma_{+-} - \sigma_{--})(-\sigma_{++} + \sigma_{-+} - \sigma_{+-} + \sigma_{--})}{(\sigma_{++} + \sigma_{-+} + \sigma_{+-} + \sigma_{--})(-\sigma_{++} + \sigma_{-+} + \sigma_{+-} - \sigma_{--})}}$$

# The Statistical Error of $A_{LR}$
# - The Blondel Scheme -

$$A_{LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$$

The propagation of the errors

$$\Delta A_{LR} = \sqrt{(\frac{\partial A_{LR}}{\partial \sigma_{++}})^2(\Delta\sigma_{++})^2 + (\frac{\partial A_{LR}}{\partial \sigma_{+-}})^2(\Delta\sigma_{+-})^2 + (\frac{\partial A_{LR}}{\partial \sigma_{-+}})^2(\Delta\sigma_{-+})^2 + (\frac{\partial A_{LR}}{\partial \sigma_{--}})^2(\Delta\sigma_{--})^2}$$

$$\Delta\sigma = \Delta\frac{N}{L} \approx \sqrt{(\frac{\partial \frac{N}{L}}{\partial N})^2(\Delta N)^2} = \frac{\sqrt{N}}{L}$$

The statistical error of $A_{LR}$ for all signal

$$N_{RR}(\ 25fb^{-1}) = 214270.1$$
$$N_{LR}(250fb^{-1}) = 4824889.6$$
$$N_{RL}(250fb^{-1}) = 3270475.0$$
$$N_{LL}(\ 25fb^{-1}) = 284825.1$$

$$\Delta A_{LR} = 0.00074$$

For the full-running at 250GeV,

$$\Delta A_{LR}(2ab^{-1}) = 0.00039$$

# Future Plan

- Do full detector simulation
- Add the photon to the subprocess final state in Whizard in order to obtain the correct photon angular distribution
- Estimate the systematic error requirement on
  $r_L$, $P^+$, $P^-$
  $A_{bkg}$, $f_{bkg}$, $A_L$, $A_{eff}$, $A_p$, $A_E$

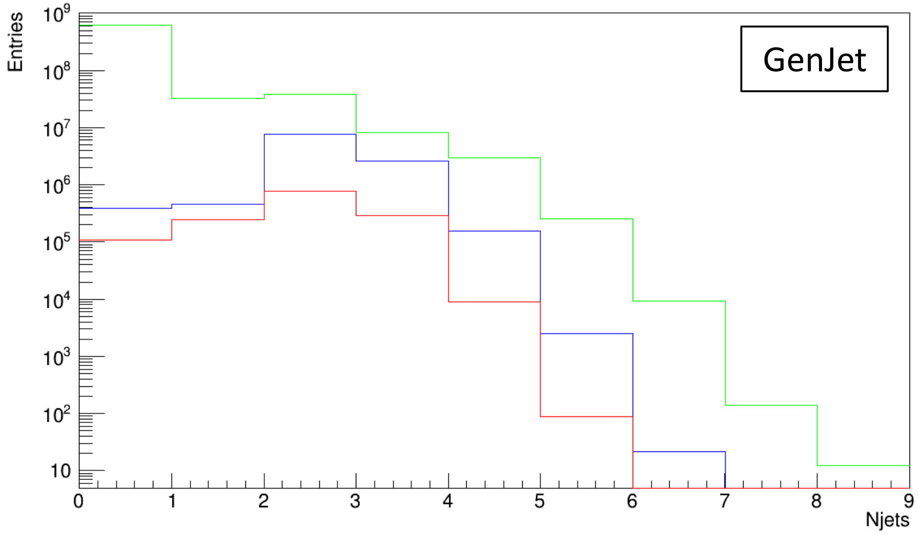
# Conclusion

- With the SiD at ILC, the relative statistical error of $A_{LR}$ can be reduced to about 0.1% with the full-running at 250 GeV

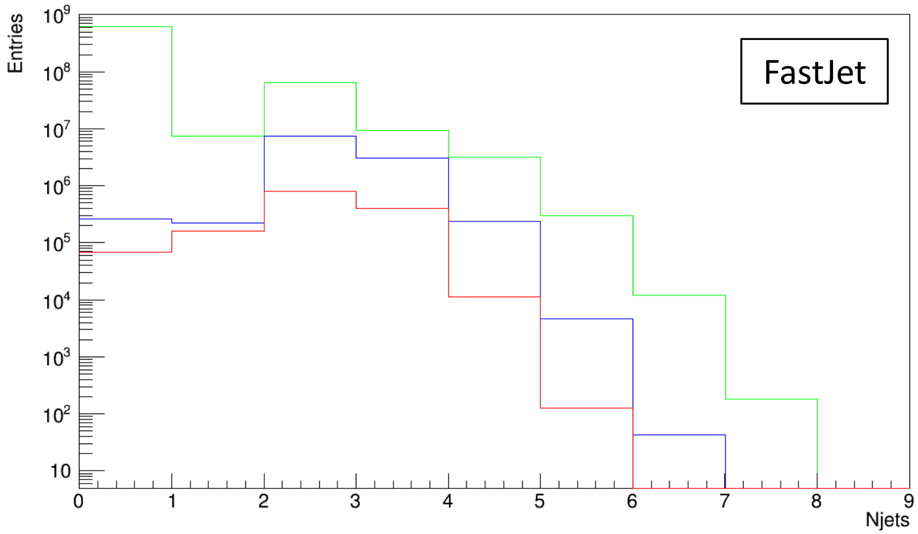
⇒ Assuming the systematic error can be controlled, this should help improve the Higgs coupling errors in the EFT framework

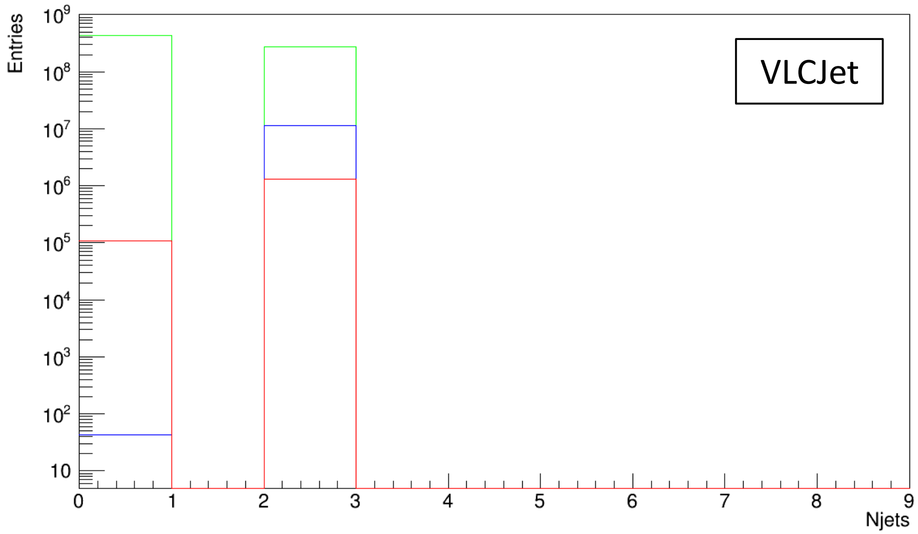
# Backup

# Number of Jets

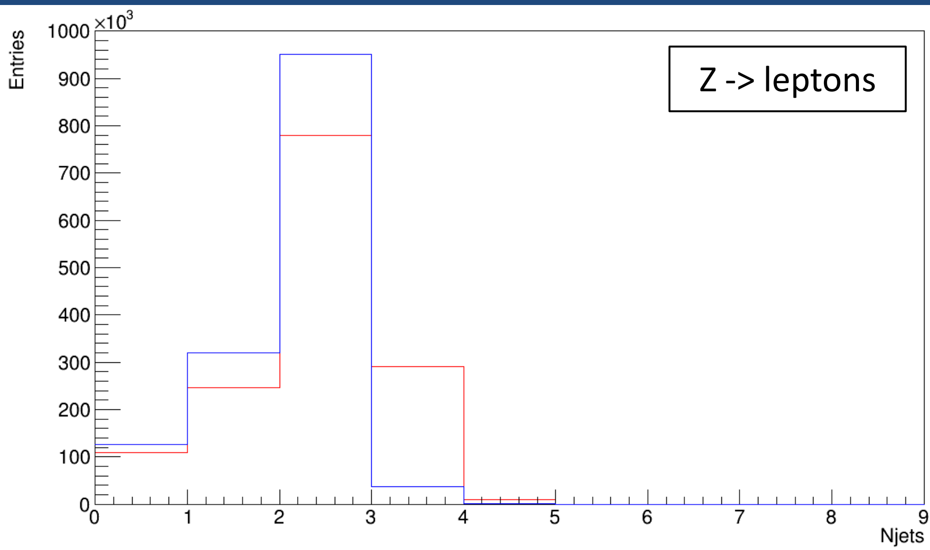



Z -> leptons (Signal)
Z -> hadrons (Signal)
Background



# Number of Jets



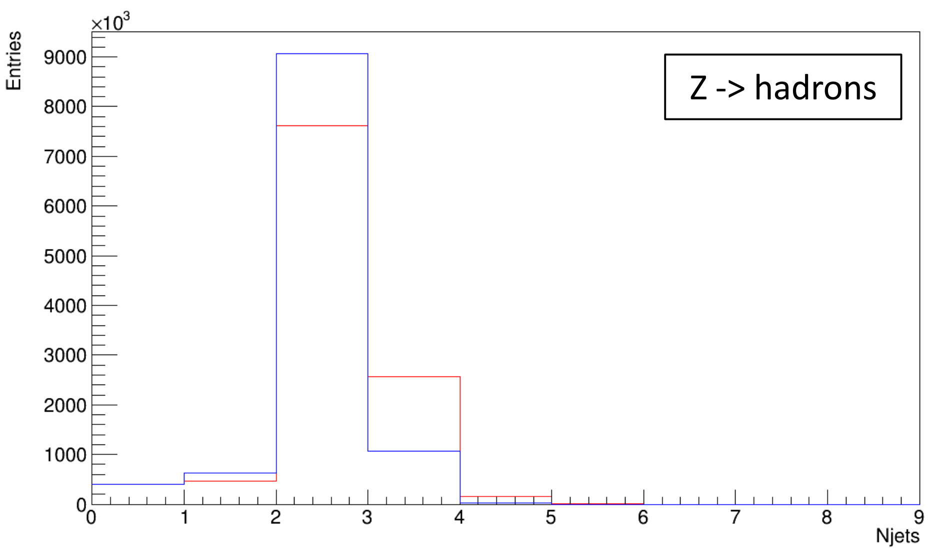

Before

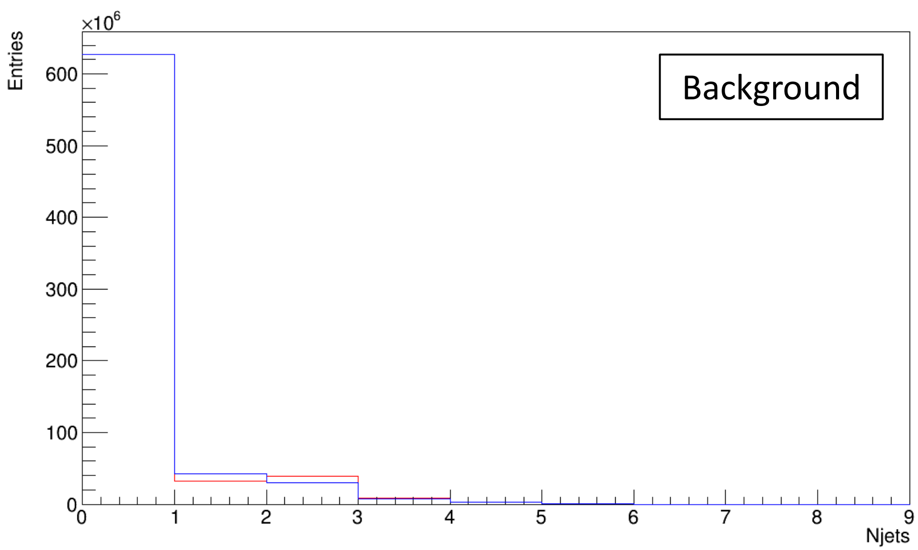
After

Jet : FastJet

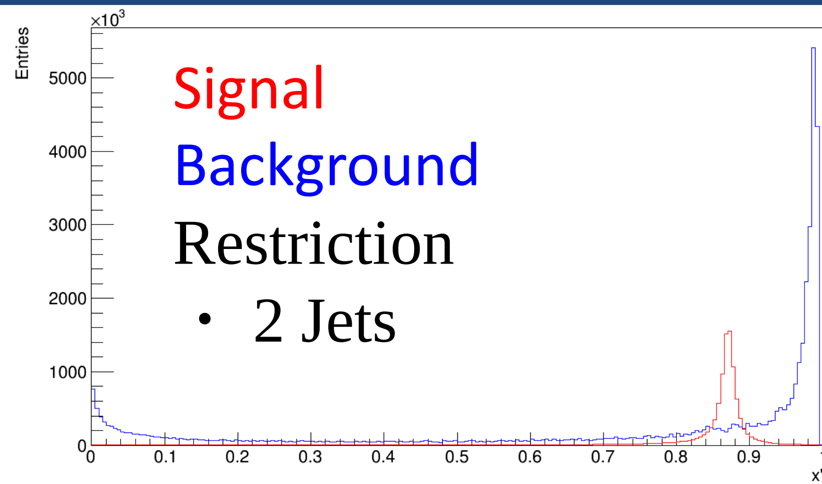
If a jet pass all the following restrictions
it is not counted. (Hard photon candidate)

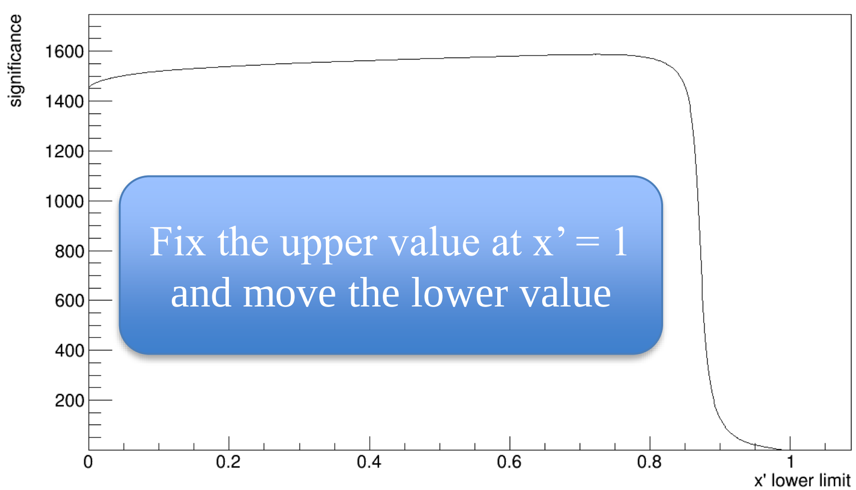
- Jet mass = 0
- Jet charge = 0
- Jet Energy > 70GeV

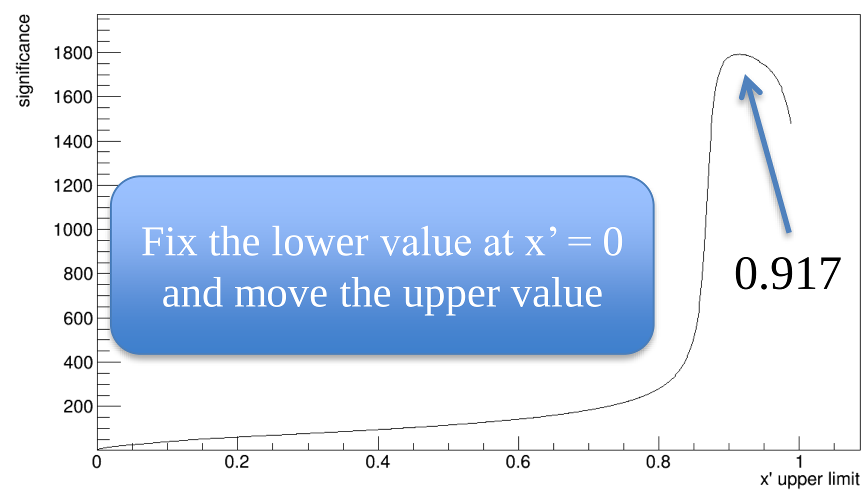


# x’

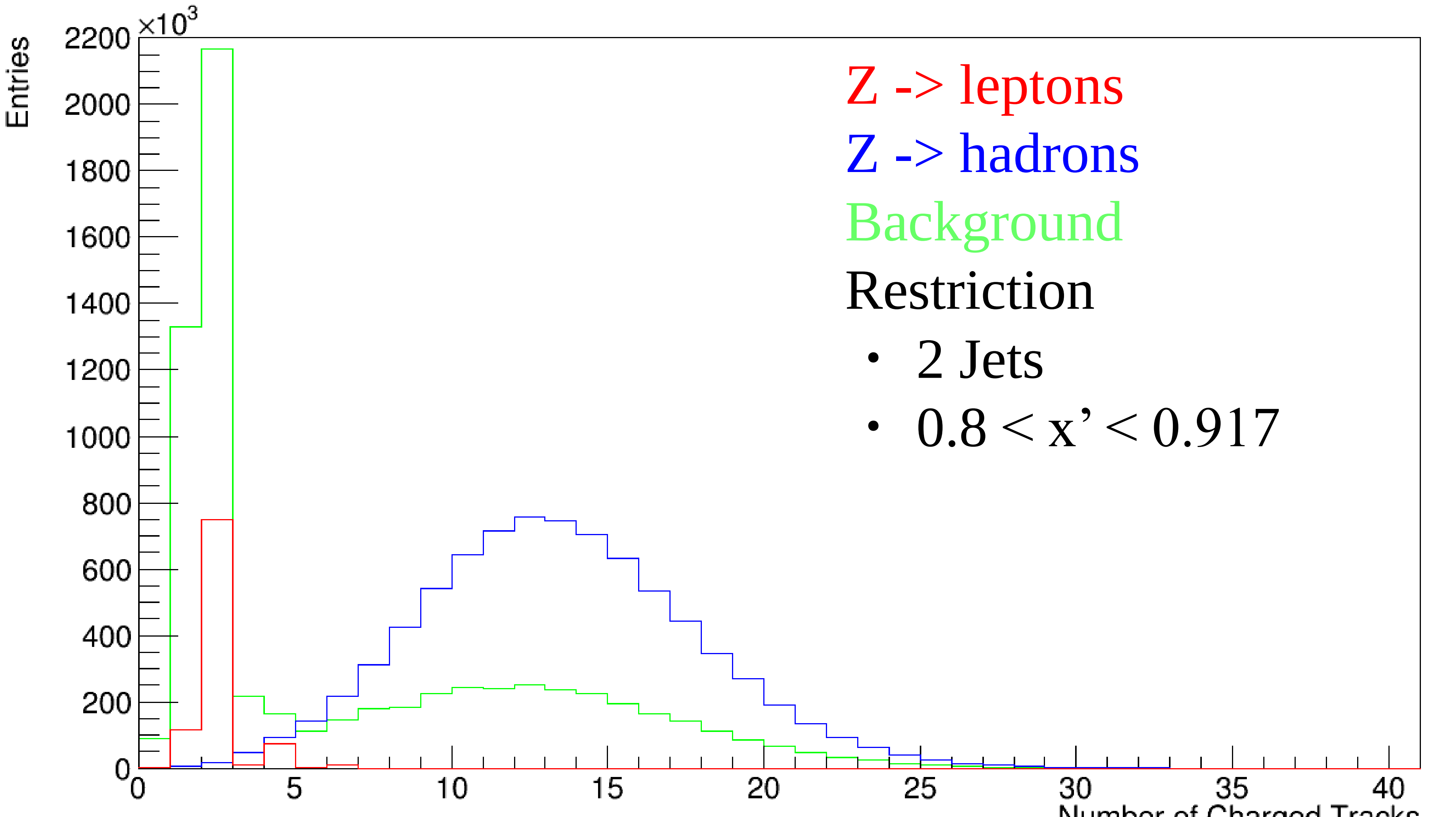

Signal
Background
Restriction
• 2 Jets
Entries
×10³
x'


significance
x' lower limit
Fix the upper value at x’ = 1
and move the lower value

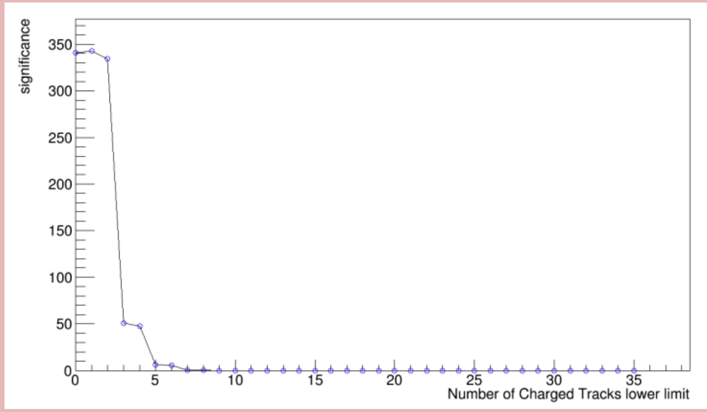

significance
x' upper limit
Fix the lower value at x’ = 0
and move the upper value
0.917

$0.8 < x' < 0.917$

# Number of Charged Tracks



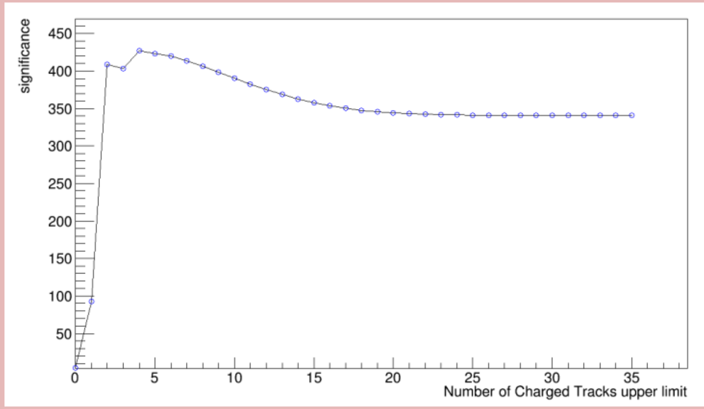
# Number of Charged Tracks
# - Significance -



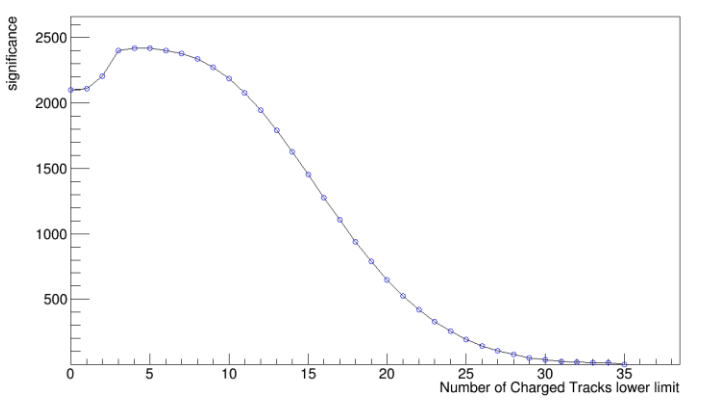

Z -> leptons

Restriction

- 2 Jets
- 0.8 < x' < 0.917



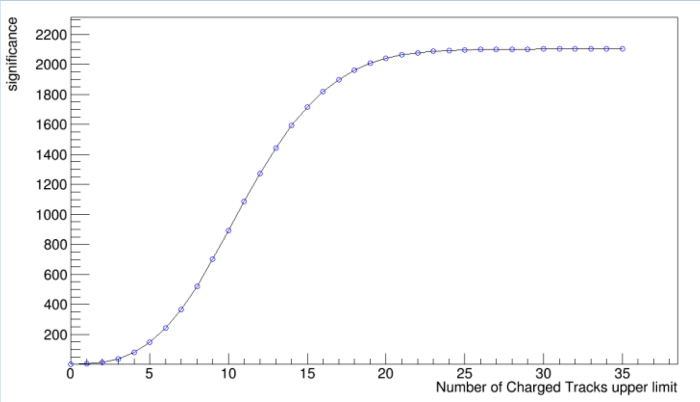

2 ≦ Number of Charged Tracks ≦ 3




Z -> hadrons

Restriction

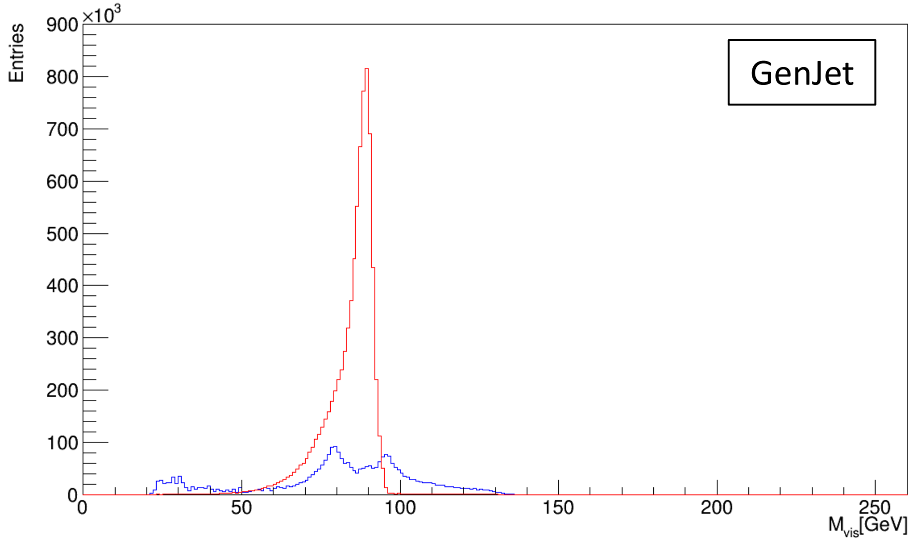
- 2 Jets
- 0.8 < x' < 0.917






5 ≦ Number of Charged Tracks

# Total Visible Invariant Mass
# - Event Selection For Z -> hadrons -



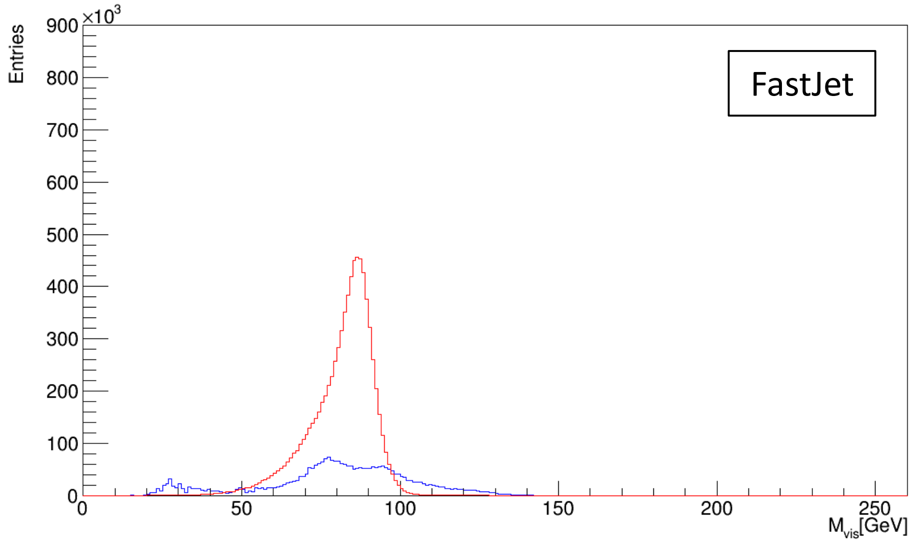

Red : Z -> hadrons (Signal)

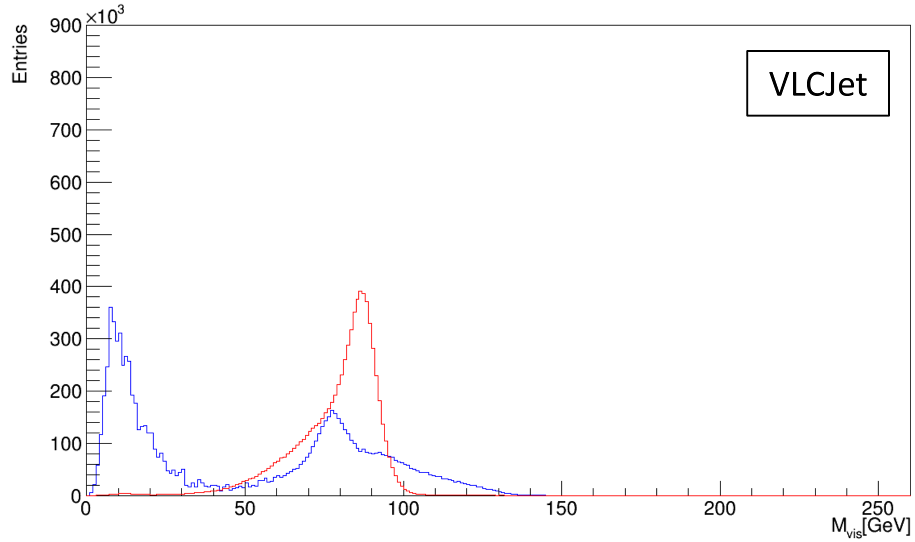
Blue : Background

Restriction

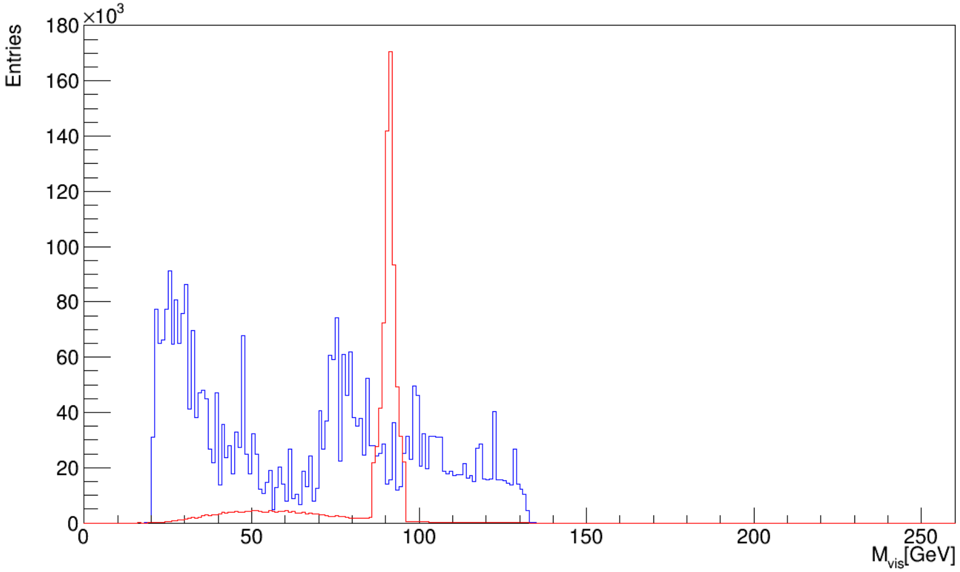
- 2 Jets
- $0.8 < x' < 0.917$
- 5 ≦ Number of Charged Tracks

70GeV < Total Visible Invariant Mass < 94GeV



# Total Visible Invariant Mass
# - Event Selection For Z -> leptons -



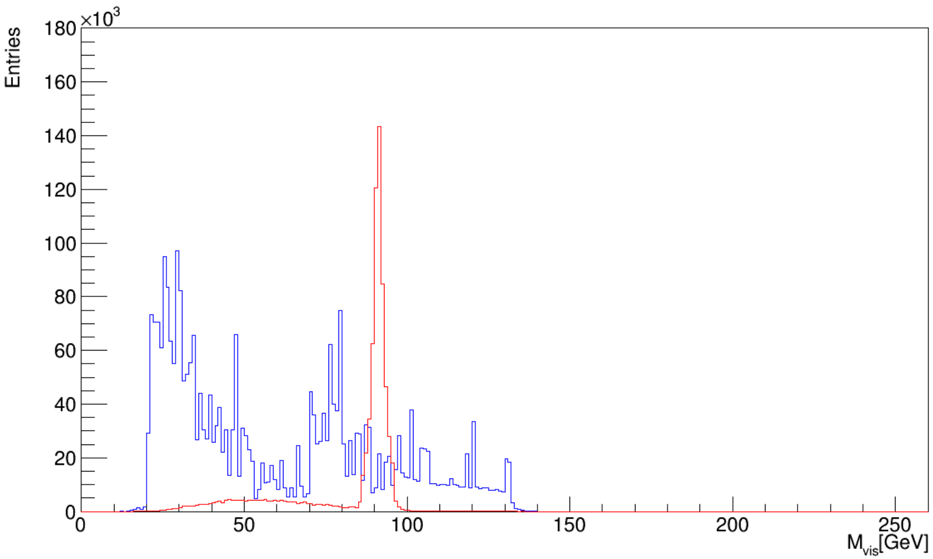

Z -> leptons (Signal)

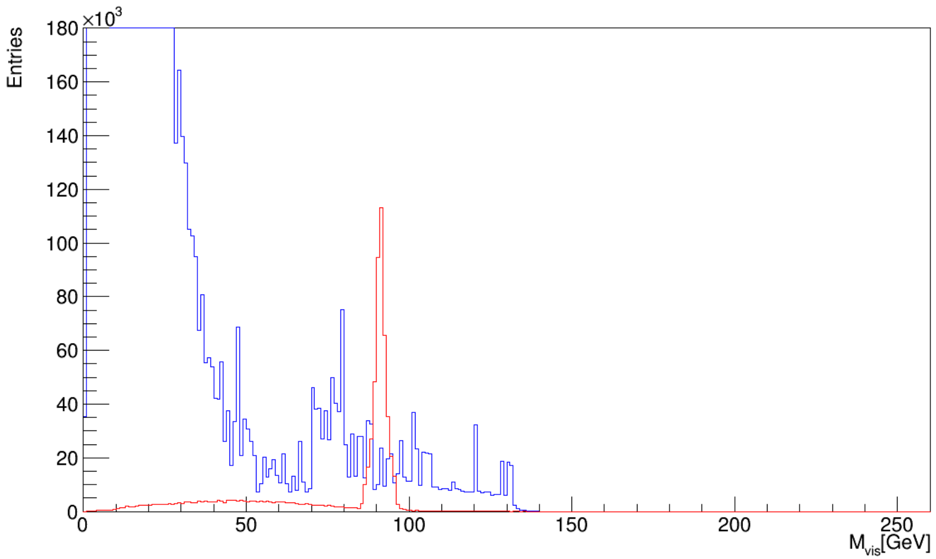
Background

Restriction

- 2 jets
- 0.8 < x’ < 0.917
- 2 ≦ Number of Charged Tracks ≦ 3

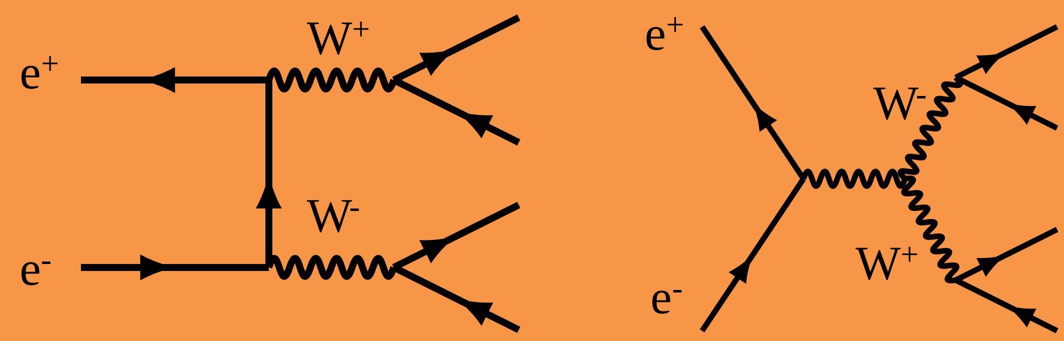
85GeV < Total Visible Invariant Mass < 96GeV

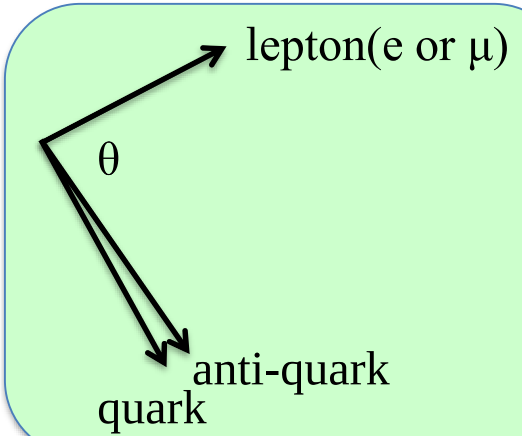


# Background Study

$e^+e^-$ => $W^+W^-$ => semi-leptonic decay



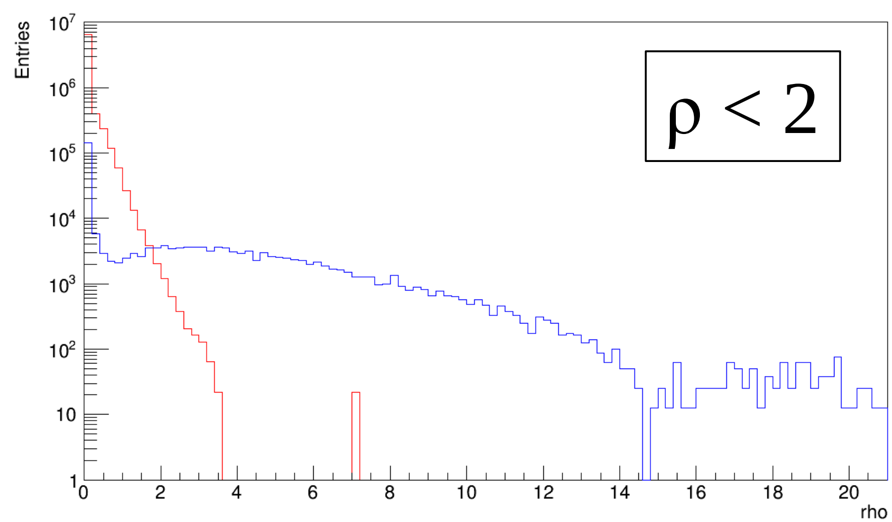

$$\rho = \sqrt{2E_l(1 - cos\theta)}$$

Z -> hadrons (Signal)

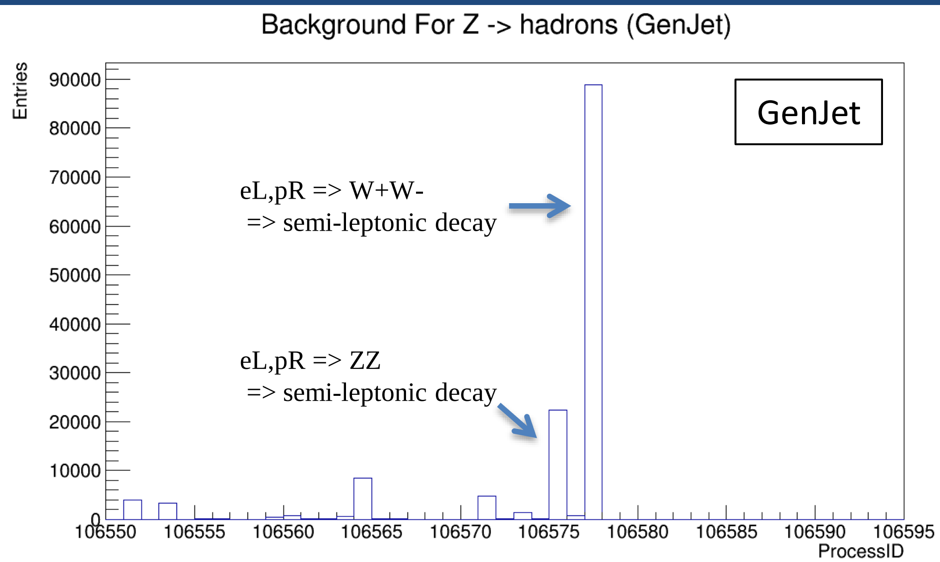
$W^+W^-$ => semi-leptonic decay

Restriction

- 2 jets (GenJet)
- $0.8 < x' < 0.917$
- $5 \leqq$ Number of Charged Tracks
- 70 < Total Visible Invariant Mass < 94

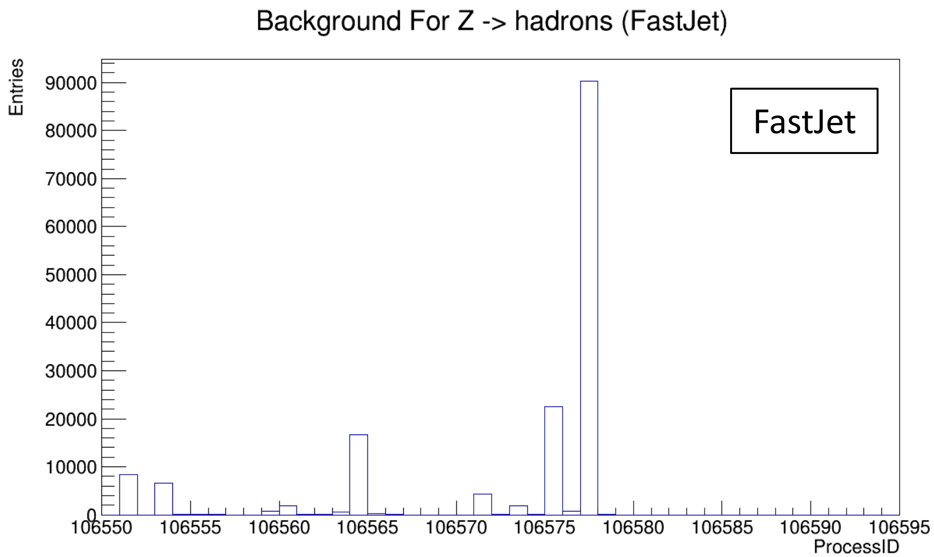


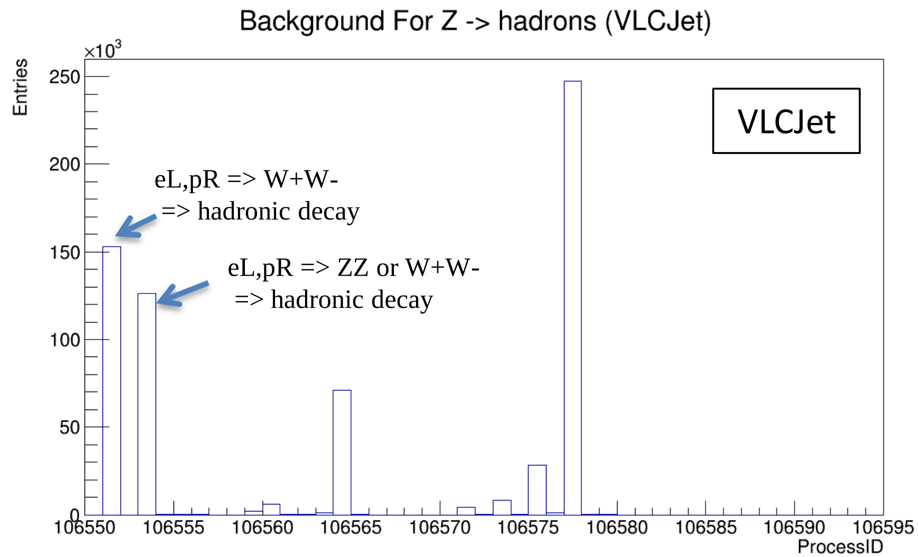
# Background Study For Z -> hadrons



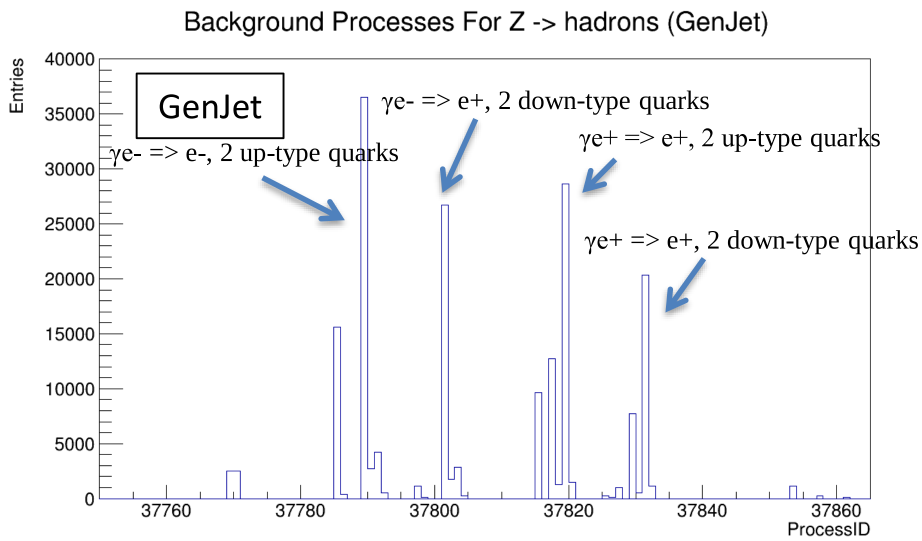

Background Processes

- Restriction -
2 jets
0.8 < x' < 0.917
5 ≦ Number of Charged Tracks
70GeV < Total Visible Invariant Mass < 94GeV



# Background Study
# for Z -> hadrons
# (Beam Background)




Background Processes

- Restriction -
2 Jets
0.8 < x' < 0.917
5 ≦ Number of Charged Tracks
70GeV < Total Visible Invariant Mass < 94GeV