# *NLO correction of ChPT for K-π* structure in $K_L \to \pi^{\pm} e^{\mp} \nu e^{+} e^{-}$

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# Contents

- Branching fraction of *Ke3ee*
- $t$ /$M_\pi^2$
- Summary

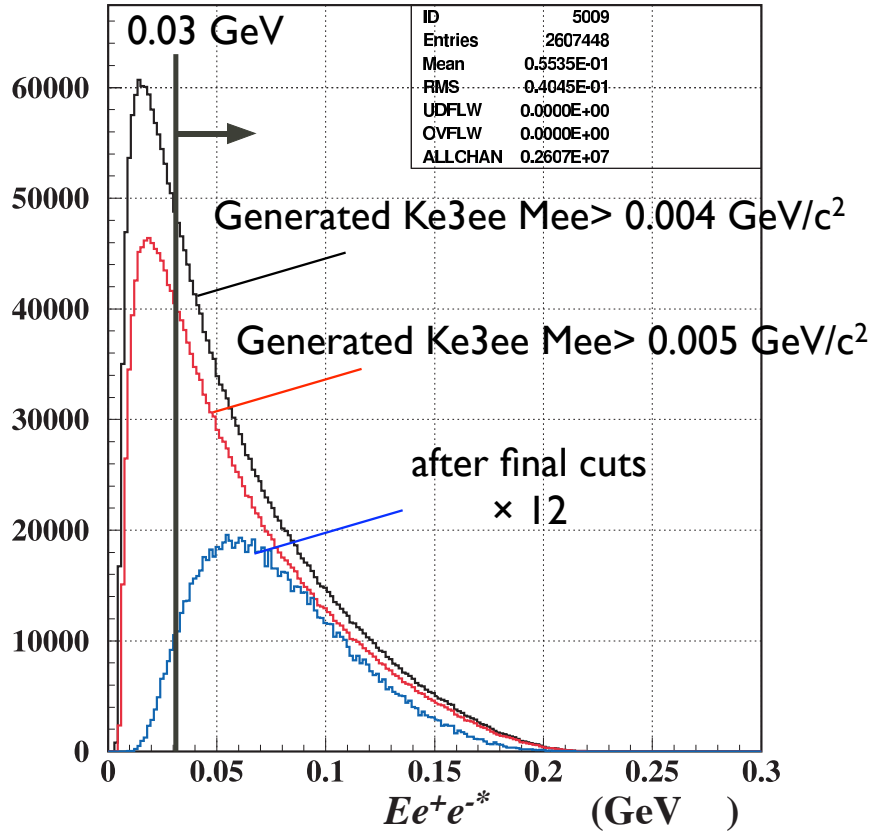
# *BR*(Ke3ee)

$=[1.281\pm0.010(\text{stat})\pm0.040(\text{syst})]\times10^{-5}$

Cutoff
: Mee > 0.005 GeV/$c^2$
: Eee(CM) > 0.03 GeV

$$R=\frac{\Gamma(ke3ee;\ \text{Mee}>0.005\ \text{GeV}/c^2)}{\Gamma(ke3)}$$

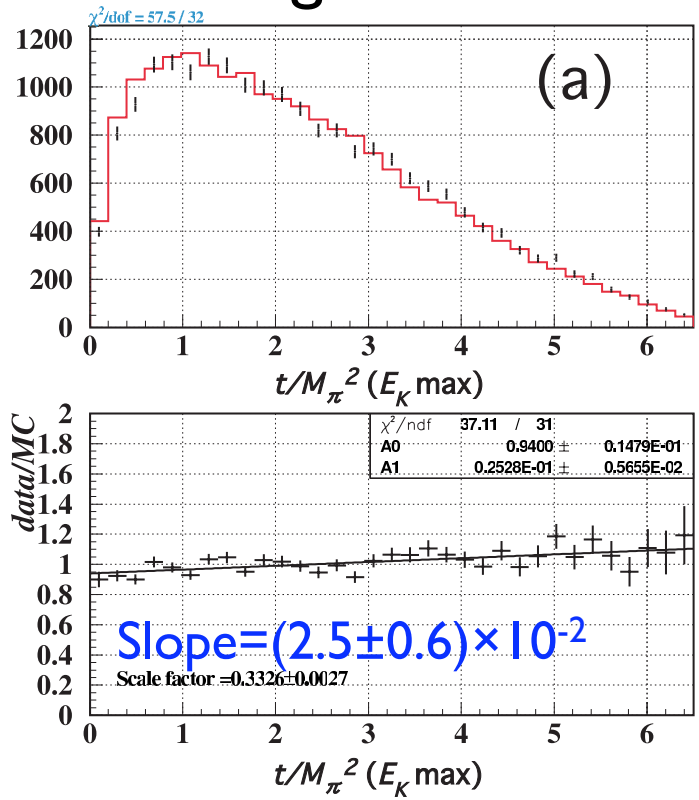
| | |
|---|---|
| NLO($p^4$) by Tsuji : | $4.29\times10^{-5}$ |
| LO by our MC : | $4.06\times10^{-5}$ |
| Our Result : | $(4.54\pm0.15)\times10^{-5}$ |
| 1.7 σ from NLO prediction | |
| 3.2 σ from LO prediction | |



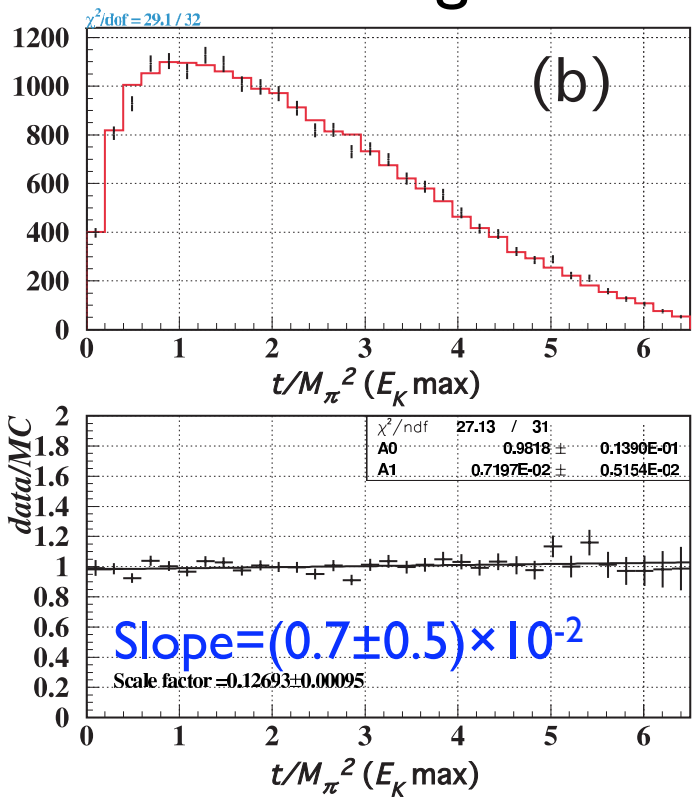
# $t$ /$M_\pi^2$ for max. soln. of $E_K$

$t = (P_K - P_\pi)^2$

Leading Order Cal.



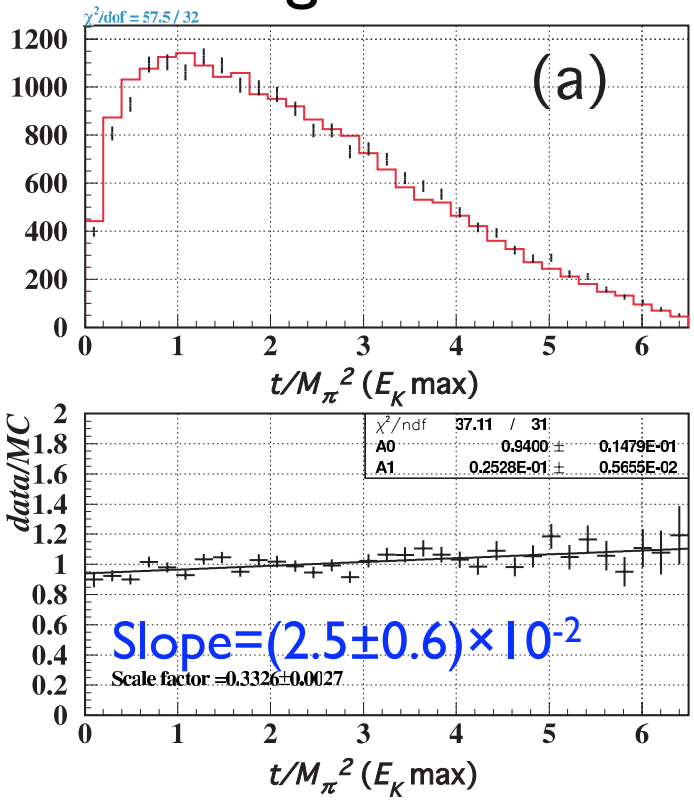

Next to Leading Order Cor.



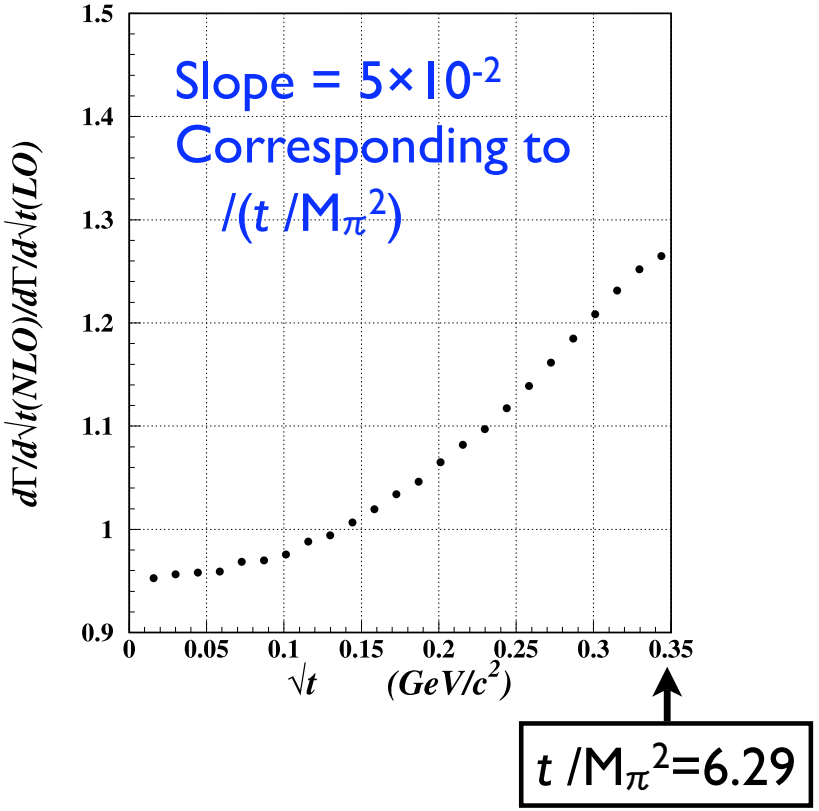
# Comparing with Theoretical calculation

$t = (P_K - P_\pi)^2$

## Leading Order Cal.



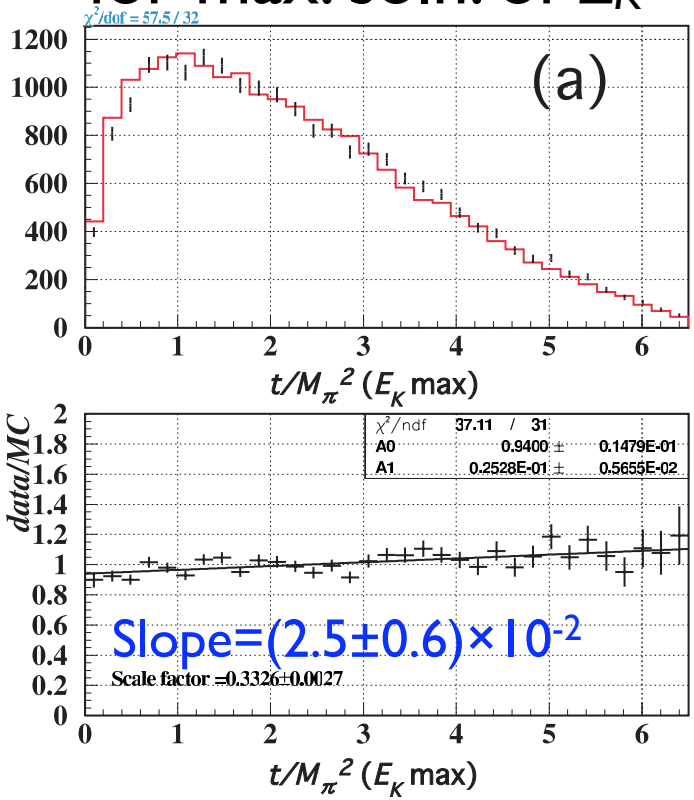

## Theoretical Cal.



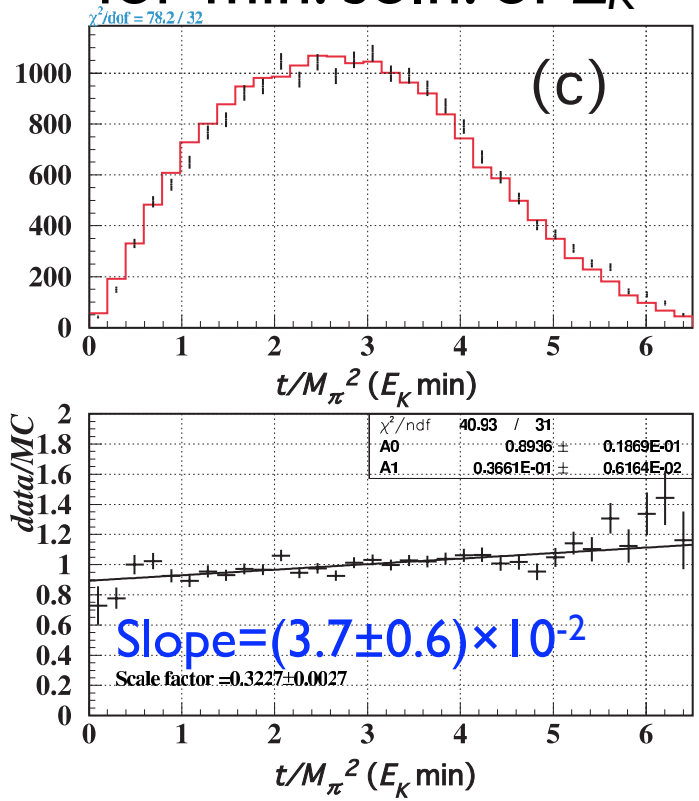
# min. vs. max. soln. of $E_K$

$t/M_\pi^2=(P_K - P_\pi)^2$

for max. soln. of $E_K$




for min. soln. of $E_K$



# Problems

- Why is the 'slope' of data/LO so small comparing with the theoretical prediction for NLO/LO?

- Why is there large difference of shapes of $t$ /$M_\pi^2$ between for $E_K$ max and $E_K$ min?

# Effect of incorrect soln.

MC NLO/LO slope without any cut but boosted

Theoretical cal: $5\times10^{-2}$

| | for $E_K$ max | for $E_K$ min |
|---|---|---|
| correct | 4.61±0.07 (48%) | 4.61±0.07 (52%) |
| incorrect | 1.87±0.06 (52%) | 1.58±0.06 (48%) |
| whole | 3.01±0.05 | 3.05±0.05 |
| data/LO | 2.5±0.6 | 3.7±0.6 |

( $\times10^{-2}$)

# Effects of analysis cuts

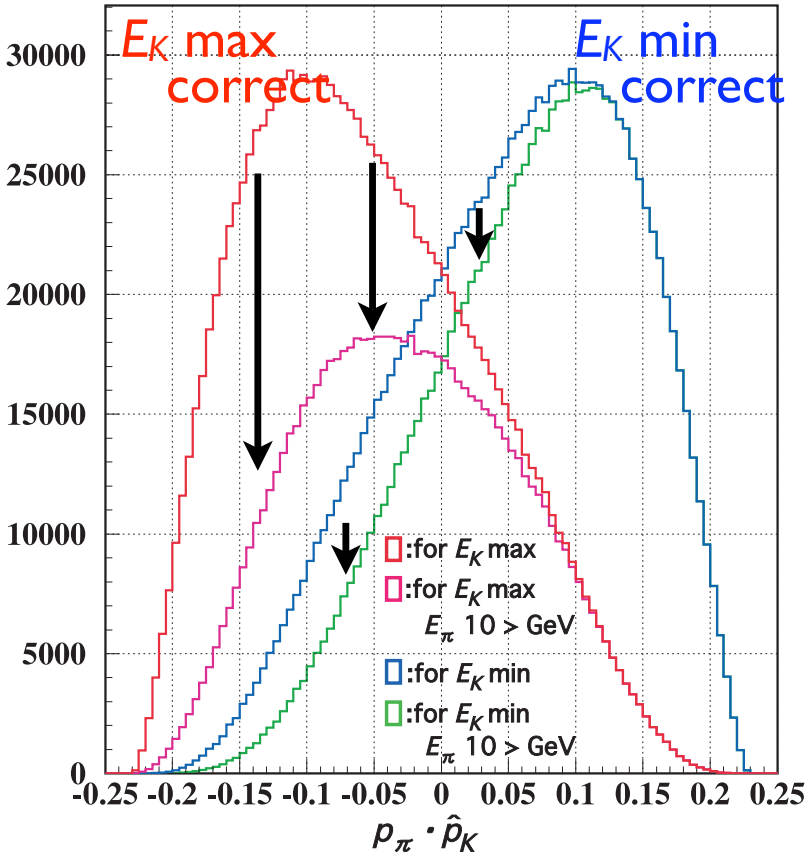
MC NLO/LO slope (correct + incorrect)

| | for $E_K$ max | for $E_K$ min |
|---|---|---|
| Z-vertex > 95 m | 3.01±0.05 | 3.04±0.05 |
| Z-vertex <150 m | 3.05±0.05 | 3.08±0.05 |
| $E_K$ max < 200 GeV | 3.09±0.05 | 3.01±0.05 |
| $E\pi$ > 10 GeV | 2.75±0.06 | 3.58±0.06 |
| $Ee_{Ke3}$ > 10 GeV | 3.48±0.09 | 3.43±0.08 |
| $Ee^+, Ee^-$ > 3 GeV | 2.39±0.14 | 3.12±0.14 |
| whole | 2.5±0.6 | 3.7±0.6 |

( $\times 10^{-2}$)

# $E\pi$ > 10 GeV→$2.8\times10^{-2}$, $3.8\times10^{-2}$

$E_K$ max $E_K$ min




$E_K$ max : $E_K$ min

50 : 50 (%)

$E\pi$ > 10 GeV

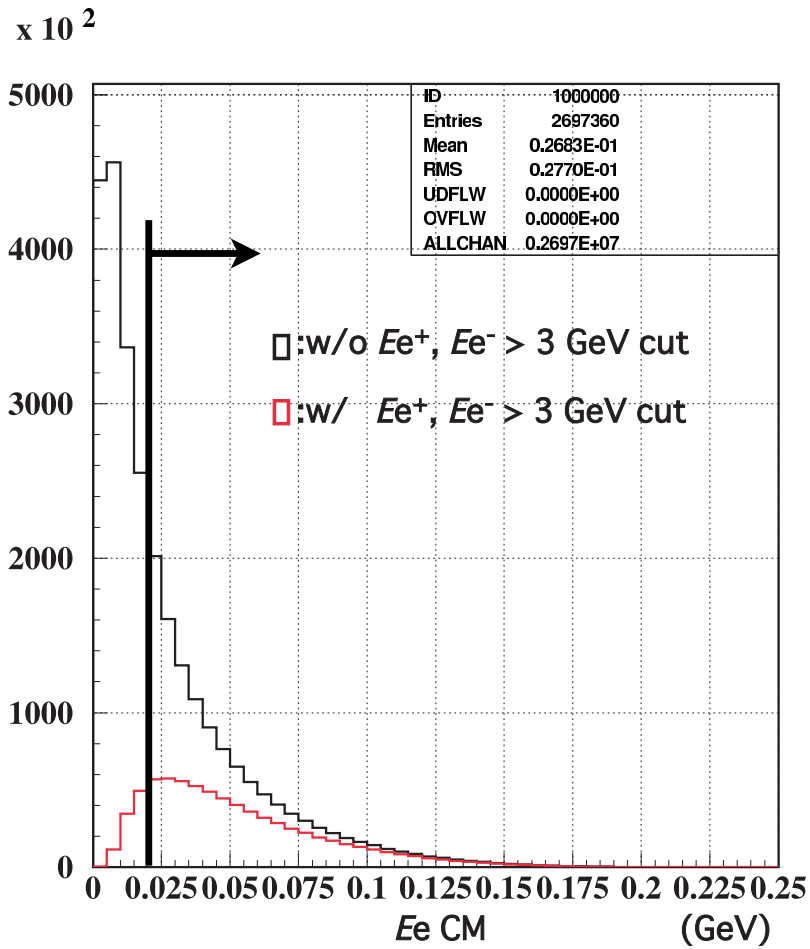
42 : 58 (%)

3.0 : 3.1 ( $\times10^{-2}$)

2.8 : 3.3 ( $\times10^{-2}$)

# $Ee^+, Ee^- > 3$ GeV → $2.4\times10^{-2}$, $3.1\times10^{-2}$

$E_K$ max $E_K$ min

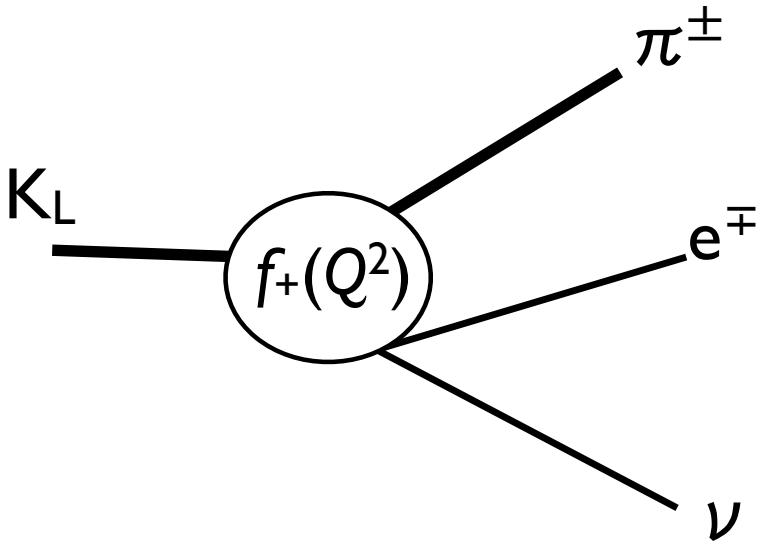



$Ee^+_{CM}, Ee^-_{CM} > 0.02$ GeV

$2.3\times10^{-2}$ for $E_K$ max
$2.5\times10^{-2}$ for $E_K$ min

Way large $Ee$ → Small slope?

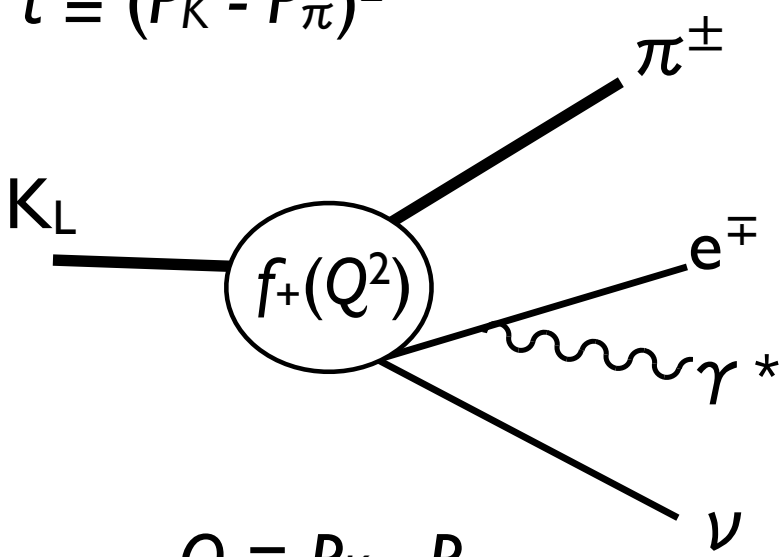
# In the case of $K_{e3}$, the form factor depends on the transition momentum




Transition momentum $Q = P_K - P_\pi$ for $K_{e3}$

# For Ke3ee, we have to cace

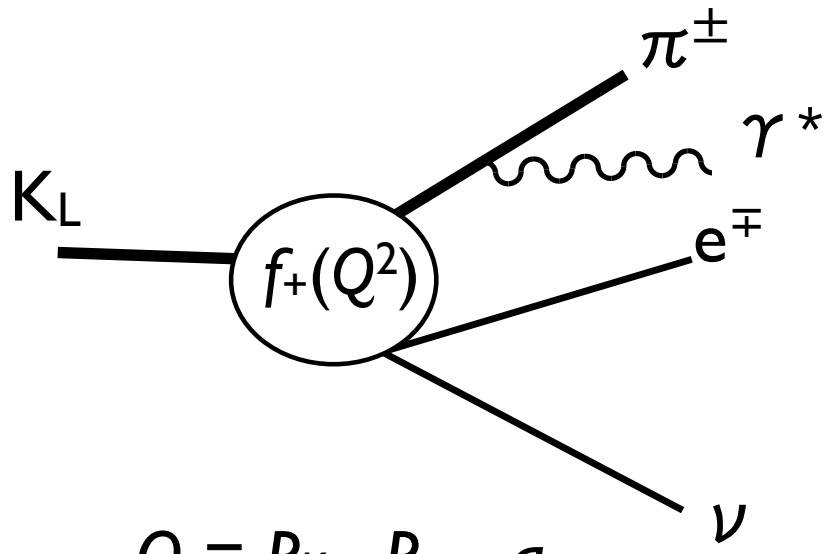
$t \equiv (P_K - P_\pi)^2$




$Q = P_K - P_\pi$

$t = (P_K - P_\pi)^2 = Q^2$

$t' = (P_K - P_\pi - q)^2 \neq Q^2$




$Q = P_K - P_\pi - q$

$t = (P_K - P_\pi)^2 \neq Q^2$

$t' = (P_K - P_\pi - q)^2 = Q^2$

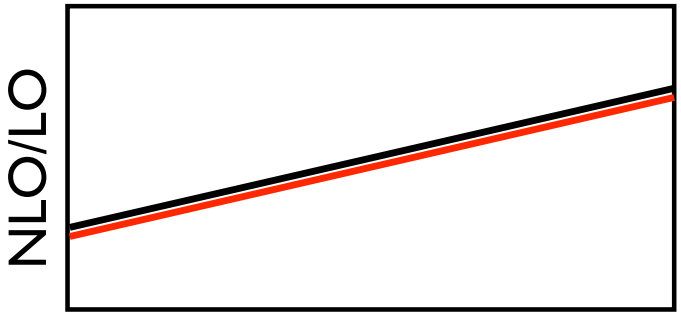
$q \rightarrow 0$, then $t = Q^2$

# Schematical view of two case

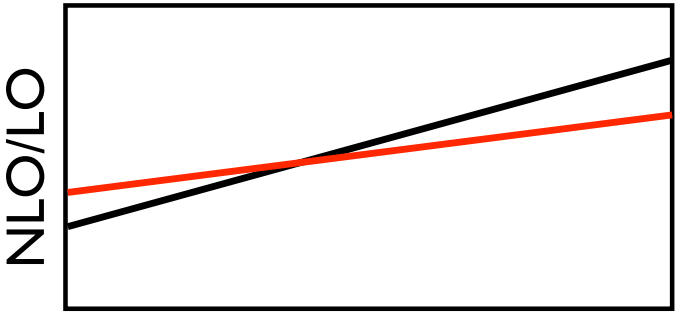
Inner Brem. from $e^{\pm}$

Inner Brem. from $\pi^{\mp}$

Our Definition

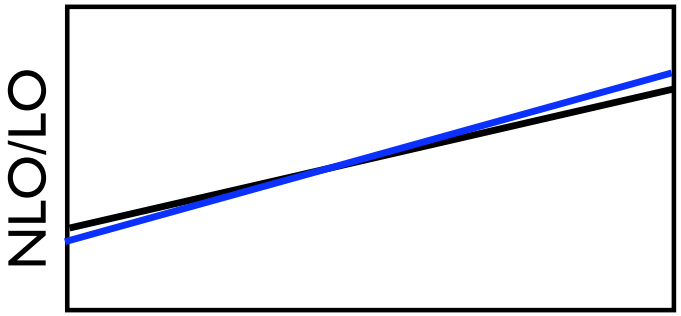



$t = (P_K - P_\pi)^2 = Q^2$

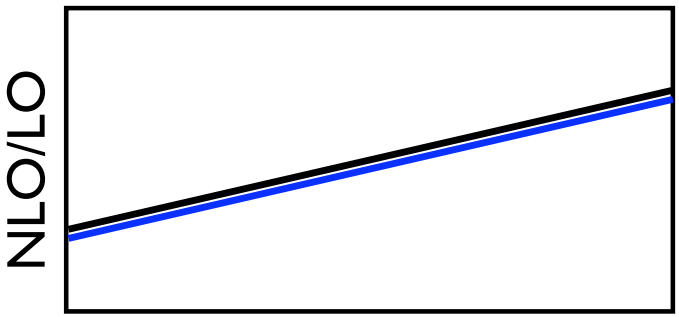



$t = (Q + q)^2 \neq Q^2$

The other Definition

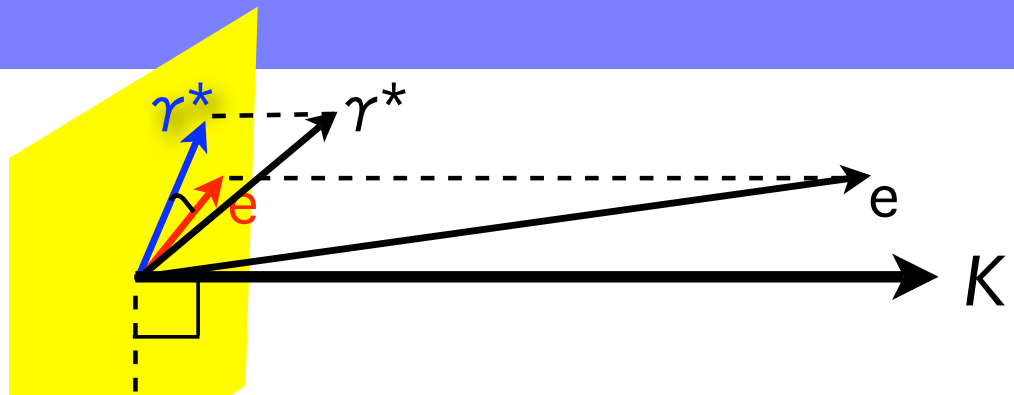


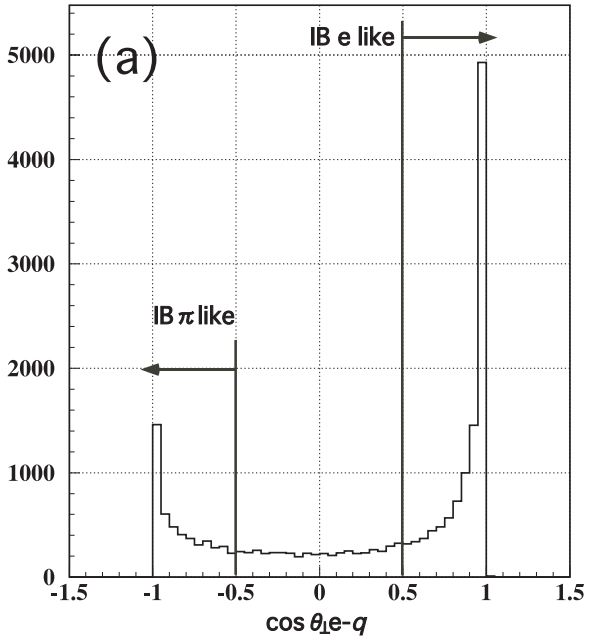

$t' = (Q - q)^2 \neq Q^2$



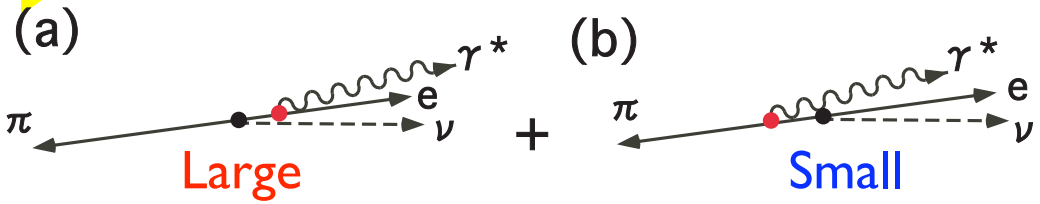

$t' = (P_K - P_\pi - q)^2 = Q^2$

# How to separate IBe and IBπ

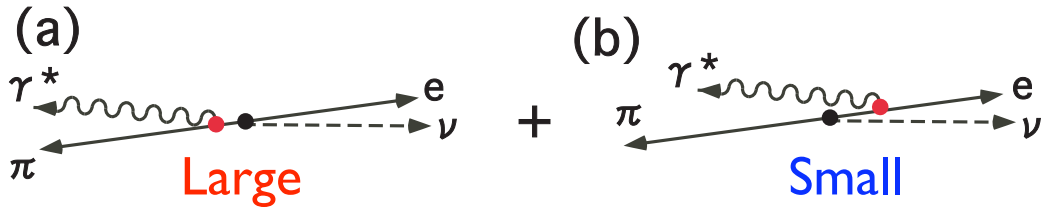



$\cos\theta_{\perp e\text{-}q} \sim 1$ ($IB_e$ like)




$\cos\theta_{\perp e\text{-}q} \sim -1$ ($IB_\pi$ like)




Propagator has

$$(2\,P_{e,\pi}\,q+q^2)^{-1}$$

$$E_{e,\pi}E_q-|P_{e,\pi}||q|\cos\theta_{e,\pi\text{-}q}$$

# Effect of Ee cut on IBe and IB$\pi$

Using only correct $E_K$ soln.

| | Whole | IB e like | IB $\pi$ like |
|---|---|---|---|
| *w/o* $Ee^+$, $Ee^-$>3 GeV | 4.65±0.05 | 5.69±0.08 | 3.11±0.12 |
| *w/* $Ee^+$, $Ee^-$>3 GeV | 3.79±014 | 5.40±0.21 | 2.31±0.33 |
| variance | - 18±3% | - 5±4% | - 26±11% |

( $\times 10^{-2}$)

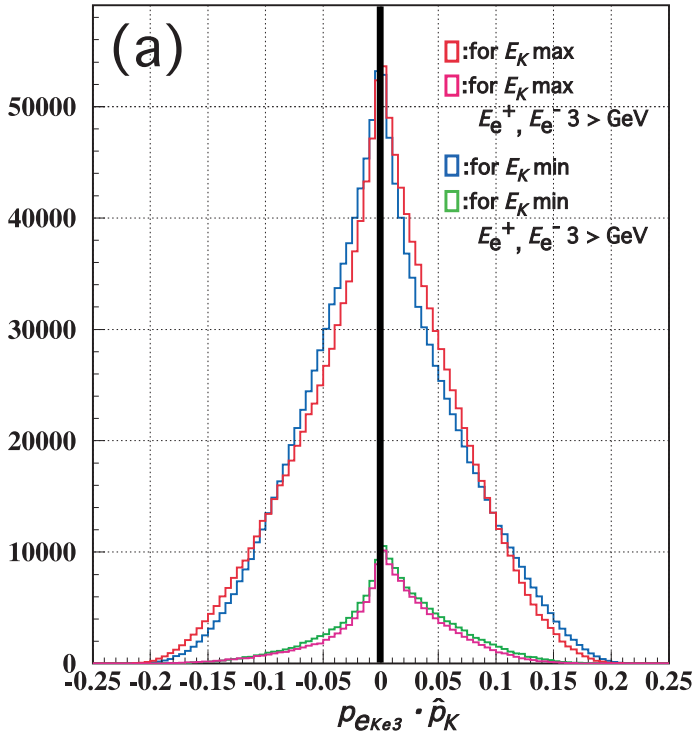
# Different slopes for IBe and IB$\pi$

data/MC with final analysis cut for Ke3ee

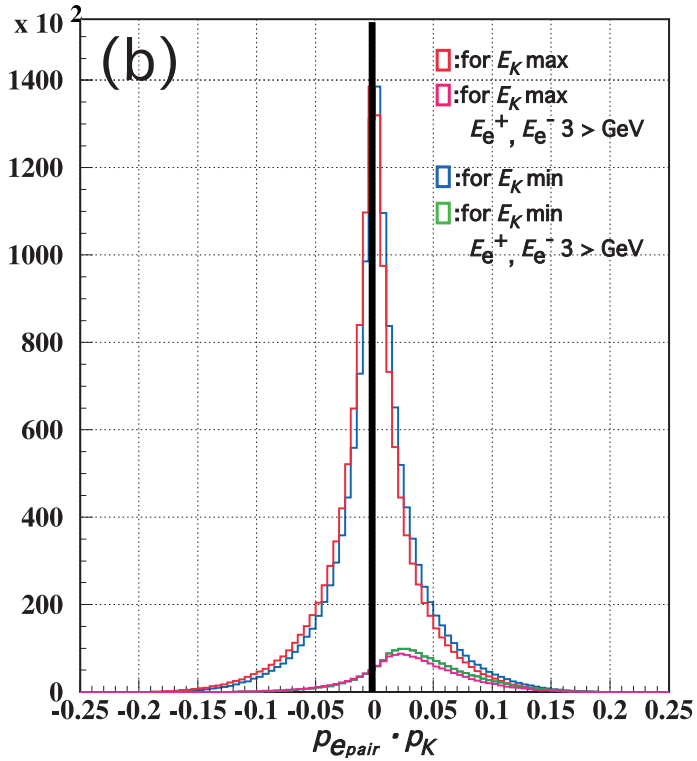
| | for $E_K$ max | for $E_K$ min |
|---|---|---|
| Whole | 2.5±0.6 | 3.7±0.7 |
| IB e like | 4.9±0.9 | 5.5±0.9 |
| IB $\pi$ like | 1.3±1.2 | 4.4±1.5 |

( $\times 10^{-2}$)

# Why is Slope of IB$\pi$ events for $E_K$ min not small

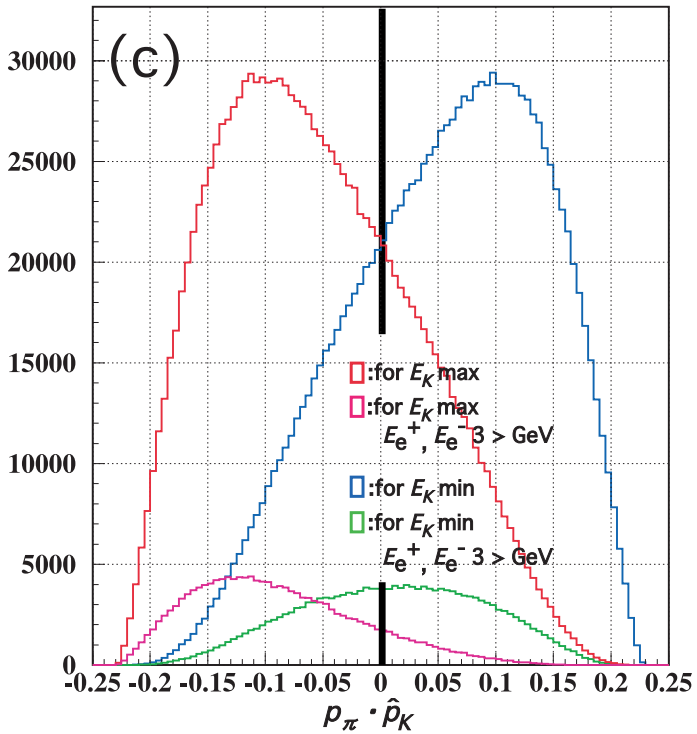



Longitudinal $Pe_{Ke3}$




Longitudinal $Pe_{pair}$

# Why is Slope of IB$\pi$ events for $E_K$ min not small




Longitudinal $P\pi$

Consequently,

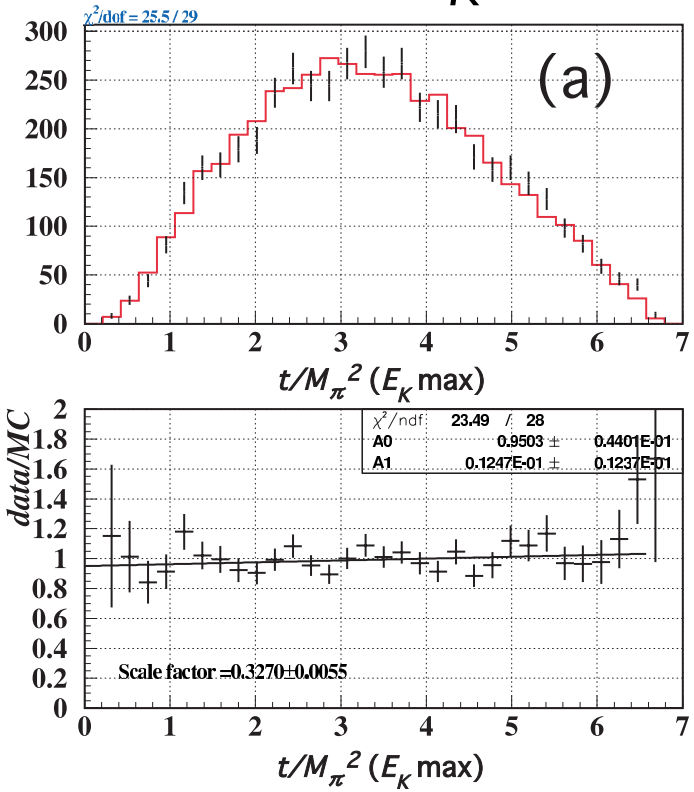
$P\pi$ for EK minimum soln becomes smaller.

$Q^2$ becomes larger

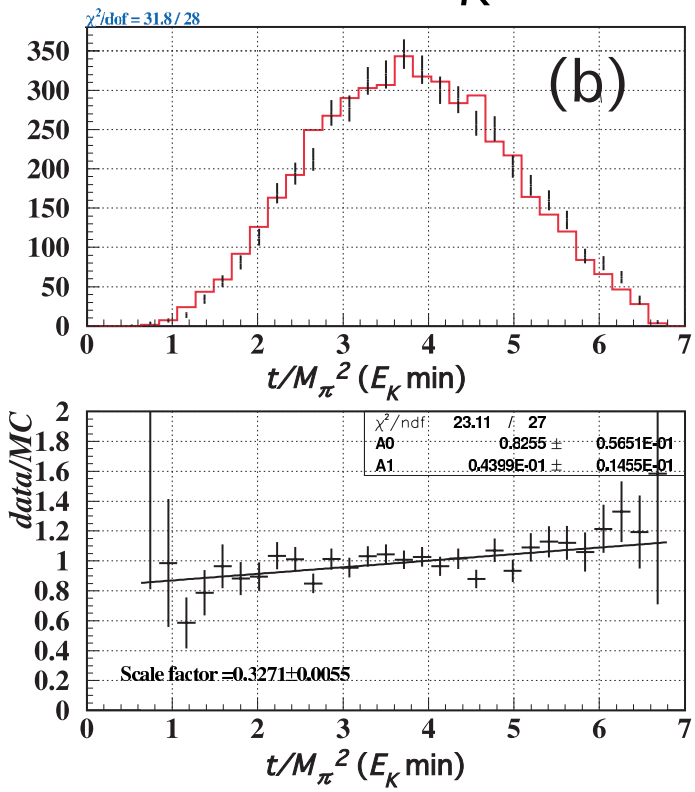
$q$ / $Q$ becomes smaller

# Why is Slope of IB$\pi$ events for $E_K$ min not small

$E_K$ max

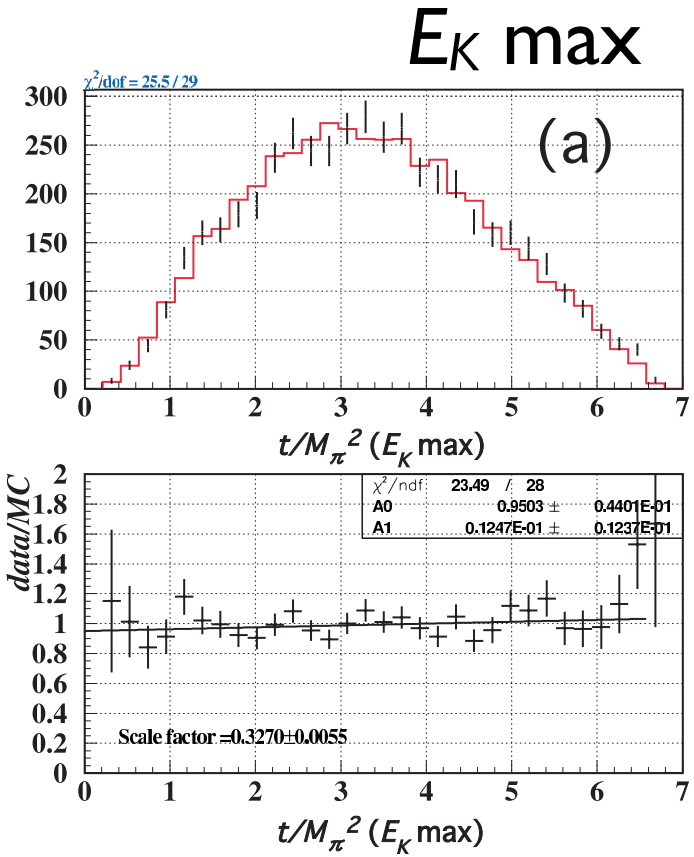


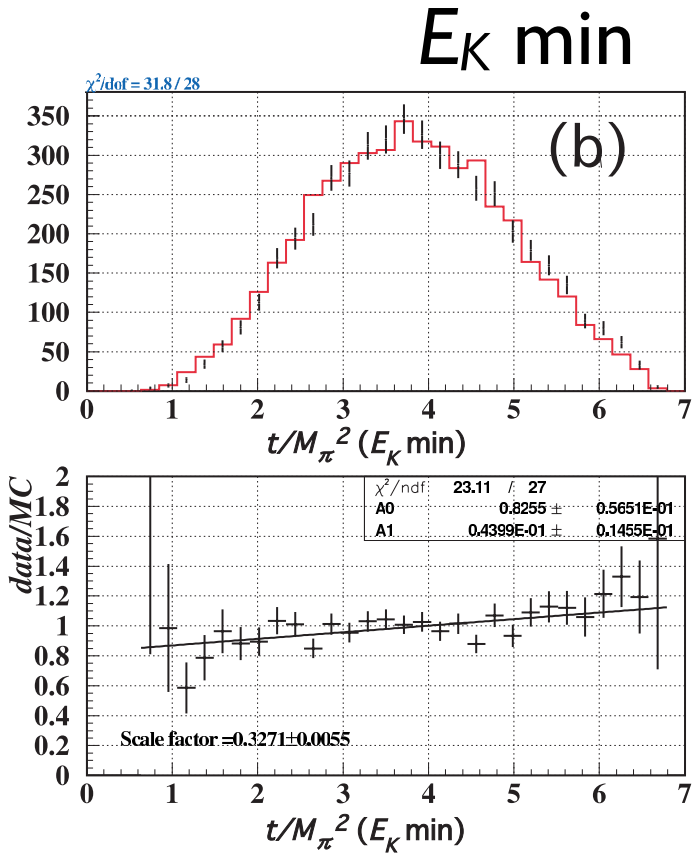

$E_K$ min



# Summry

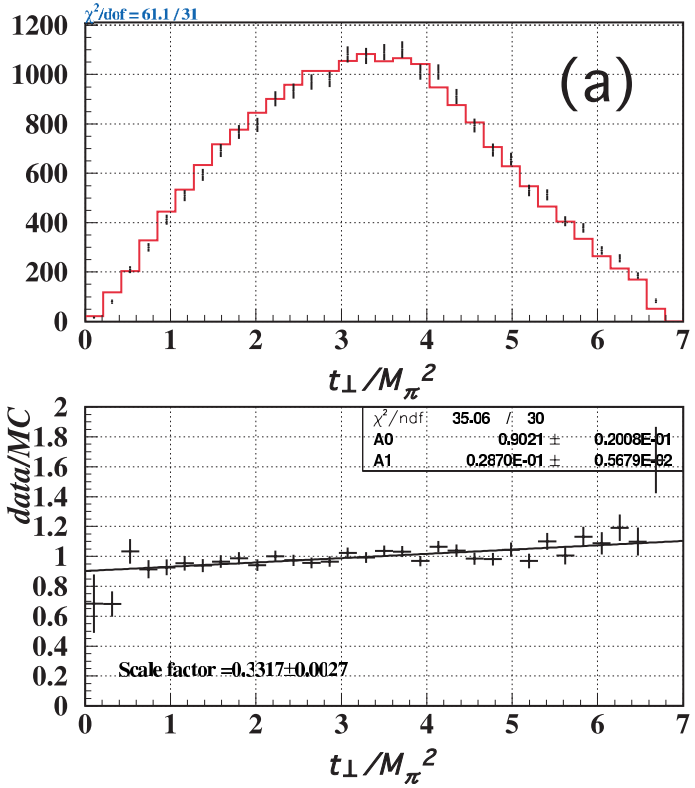
# Back up


$E_K$ max
$\chi^2$/dof = 25.5 / 29
(a)
$t/M_\pi^2$ ($E_K$ max)
data/MC
$\chi^2$/ndf 23.49 / 28
A0 0.9503 ± 0.4401E-01
A1 0.1247E-01 ± 0.1237E-01
Scale factor =0.3270±0.0055
$t/M_\pi^2$ ($E_K$ max)

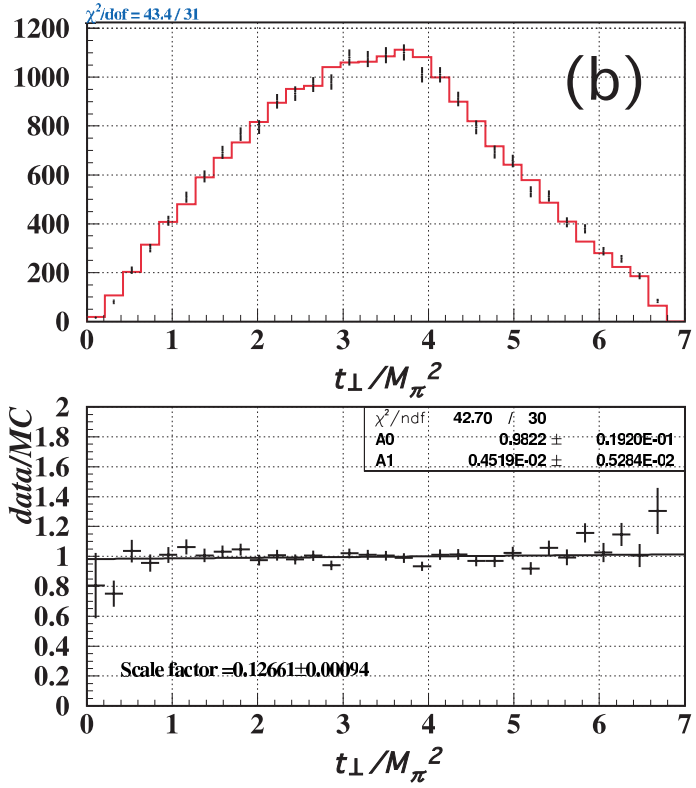

$E_K$ min
$\chi^2$/dof = 31.8 / 28
(b)
$t/M_\pi^2$ ($E_K$ min)
data/MC
$\chi^2$/ndf 23.11 / 27
A0 0.8255 ± 0.5651E-01
A1 0.4399E-01 ± 0.1455E-01
Scale factor =0.3271±0.0055
$t/M_\pi^2$ ($E_K$ min)

# Perpendicular component of $t\ /M_\pi^2$

data/LO




data/NLO



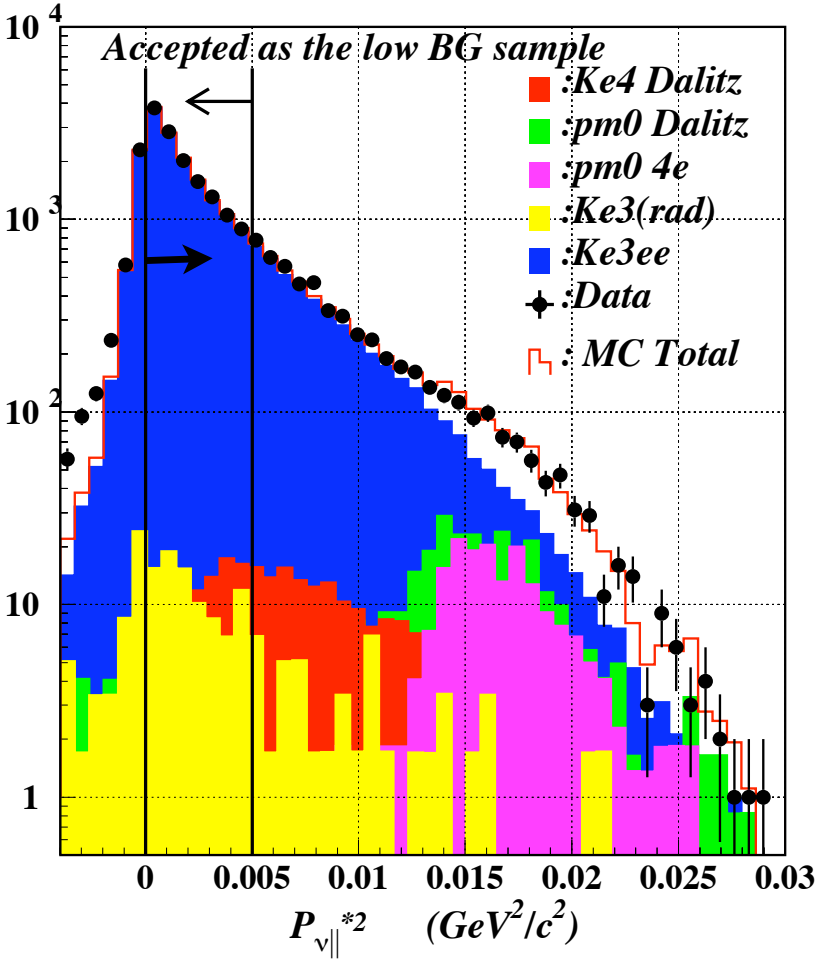
# 選択範囲

| |
|---|
| $\chi^2_{vtx} < 125$ |
| $Ek_{max} < 200$ GeV |
| 95 m < Z-vertex < 150 m |
| $E/p$ for $\pi$ track < 0.9 |
| $0.93 < E/p$ for $e^{\pm}$ track < 1.15 |
| $TRD_{prob\pi} < 0.06$ for electron track |
| $E\pi > 10$ GeV |
| $Ee^{\pm}ke3 > 10$ GeV |
| $Ee^{\pm}pair > 3$ GeV |
| $Mee > 0.005$ GeV/$c^2$ |

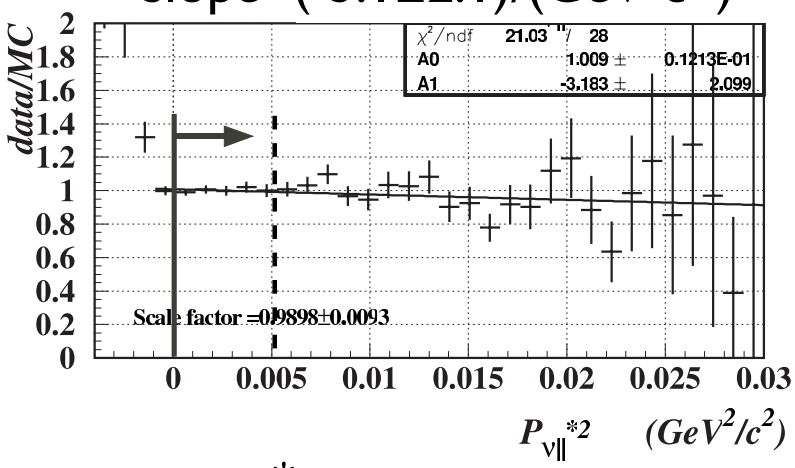
# Background

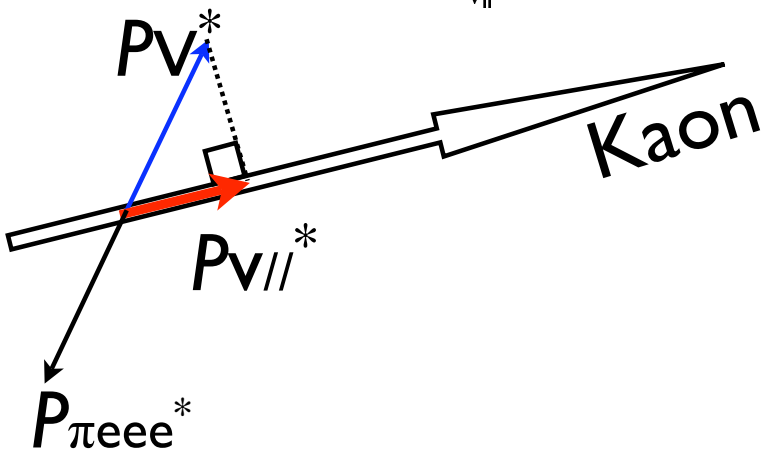
| mode | to be acceptable |
|---|---|
| $K_L \to \pi^+\pi^-\pi^0{}_D$ ($\pi^0 \to e^+e^-\gamma$) | $\pi^\pm \xrightarrow{\text{fake}} e^\pm$ |
| | $e^+e^-\gamma \to e^+e^-e^+e^-$ |
| $K_L \to \pi^+\pi^-\pi^0{}_{4e}$ ($\pi^0 \to e^+e^-e^+e^-$) | one $\pi^\pm$, one $e^\pm$ } lost |
| $K_L \to \pi^\pm e^+\nu\ \pi^0{}_D$ ($\pi^0 \to e^+e^-\gamma$) | そのまま |
| $K_L \to \pi^\pm e^+\nu\gamma$ ($\gamma \to e^+e^-$ / in materials) | そのまま |

# Longitudinal momentum of neutriono




Slope=(-3.1±2.1)/(GeV$^2$c$^{-2}$)



# The number of signal candidates

| Decay mode | Full | Low BG | High BG |
|---|---|---|---|
| Signal(inc.BG) | 20225 | 14605 | 5620 |
| MC:$K_L \to \pi^+\pi^-\pi^0{}_D$ | 350.3±13.5 | 32.8±4.1 | 317.5±12.9 |
| MC:$K_L \to \pi^\pm e^\mp \nu \pi^0{}_D$ | 320.8±6.5 | 108.7±3.8 | 211.8±5.2 |
| MC:$K_L \to \pi^+\pi^-\pi^0{}_{4e}$ | 183.7±8.9 | 3.0±1.1 | 180.7±8.8 |
| MC:RadKe3(conv) | 155.2±17.5 | 99.6±13.9 | 55.6±10.5 |
| MC:Dauble Ke3 | 7.9±1.8 | 5.8±1.6 | 2.1±0.9 |
| MC:Cascade | 1.2±0.5 | 0.2±0.2 | 1.0±0.5 |
| BG/Signal | (5.04±0.12)% | (1.71±0.10)% | (13.7±0.35)% |
| Estimated # of Ke3ee × $10^{-6}$ | 2.137±0.016 | 2.121±0.019 | 2.186±0.036 |

1.6 σ

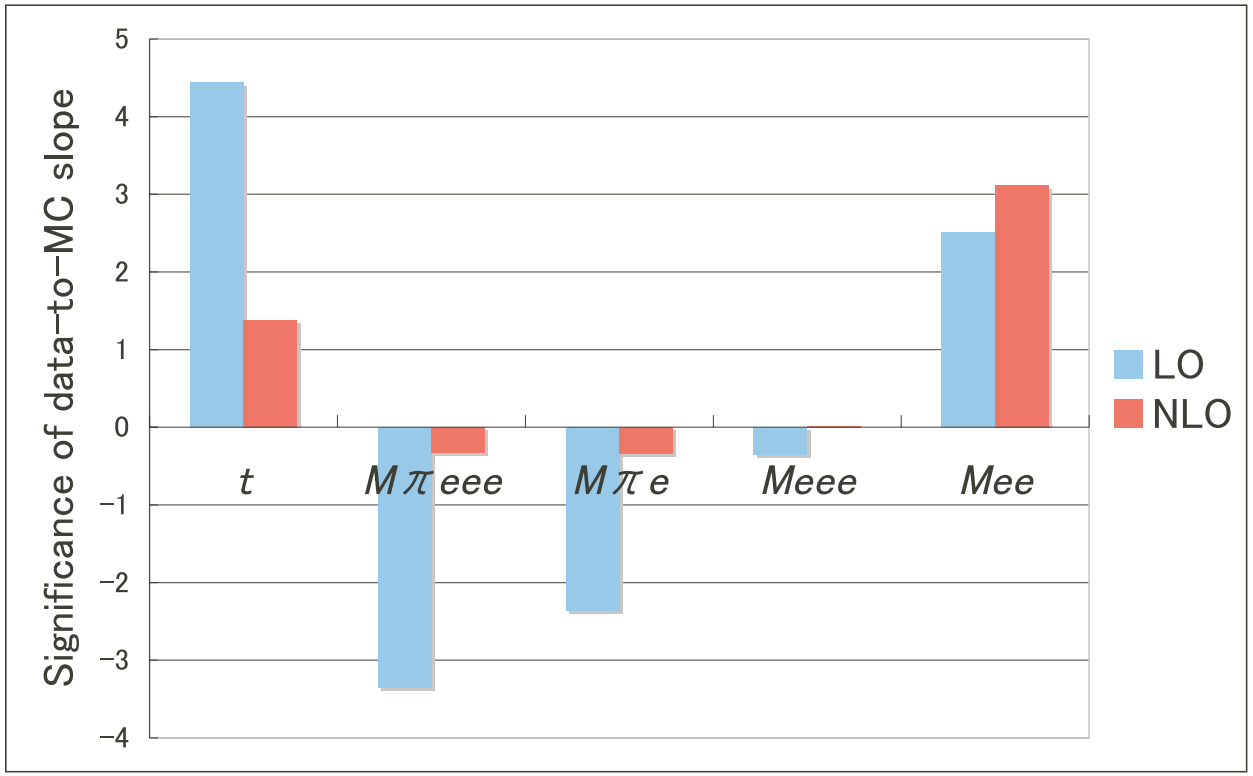
# Systematec Errors

| | |
|---|---|
| Unonbserved photon in Norm.analysis | ±1.03% |
| vertex $\chi^2$ cut | ±0.7% |
| Radiative correction | ±0.51% |
| pion loss in TRD | ±0.45% |
| Ek distribution | ±0.35% |
| MC statistics | ±0.32% |
| Cut-off on Mee | - 0.18% |
| e± inefficiency in E/p | ±0.09% |
| e± inefficiency in TRD | ±0.06% |
| e± inefficiency in E/p | ±0.03% |
| Background estimation | ±0.05% |
| External [BR($K_L \rightarrow \pi^+\pi^-\pi^0{}_D$)] | ±2.73% |

Inrernal Total ±1.51%

Total ±3.21%

# LO vs. NLO (Mass-distribution)




Mee を除いて， NLO($p^4$)はKe3ee をよく再現する