R&D on an active photon converter

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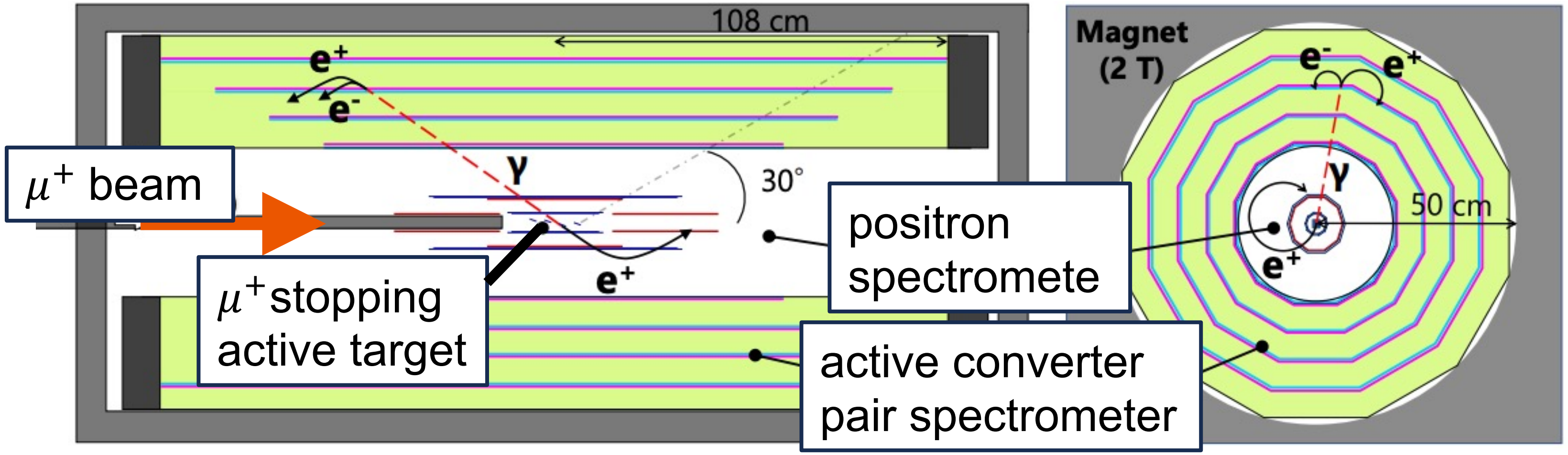
Future experiment of $\mu^+ \rightarrow e^+\gamma$ search



- The intensity of muon beam at PSI is planned to be increased to $\sim 10^{10}\ \mu^+/s$
- R&D of new detectors with good resolutions & high rate capability is necessary
- Accidental background rate :

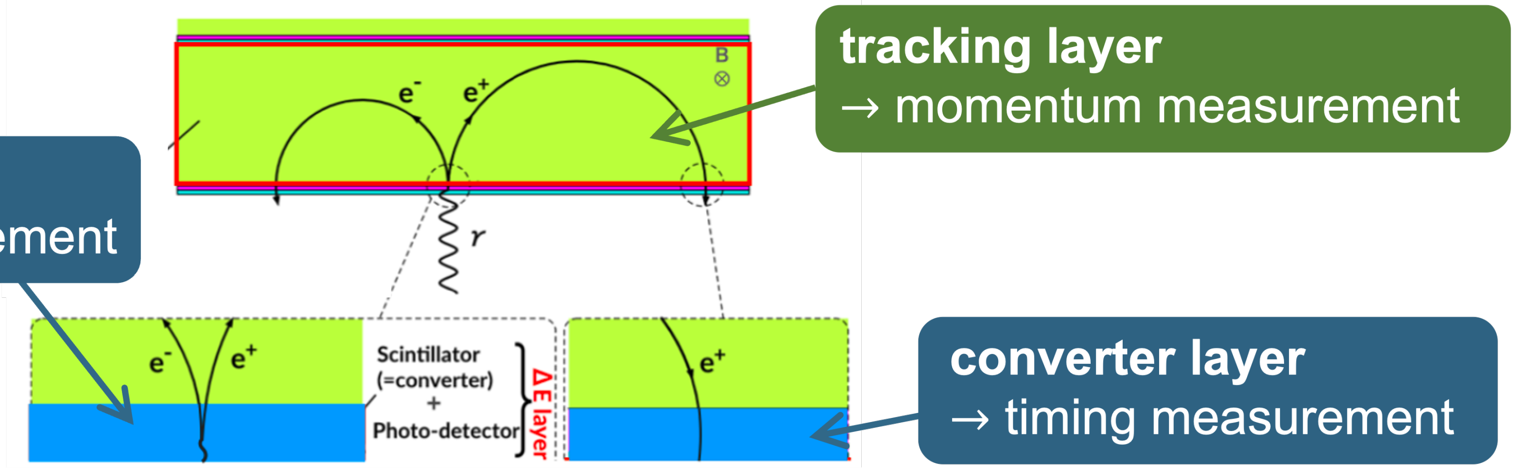
$$N_{acc} \propto R_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta p_e \cdot \Delta\theta_{e\gamma}^2 \cdot \Delta t_{e\gamma} \cdot T$$

R_μ : muon stopping rate
$\Delta E_\gamma, \Delta p_e, \Delta\theta_{e\gamma}, \Delta t_{e\gamma}$: detector resolutions
T : measurement time

$\rightarrow$ photon energy resolution is important for background suppression

- For photon measurement, pair spectrometer with active converter is under development

Pair spectrometer with active converter



<u>problem with conventional pair-spectrometer</u>

- low efficiency (compared to calorimeter) → want to increase thickness
- energy loss in converter → want to reduce thickness

➡ solution : energy measurement by converter (active converter)

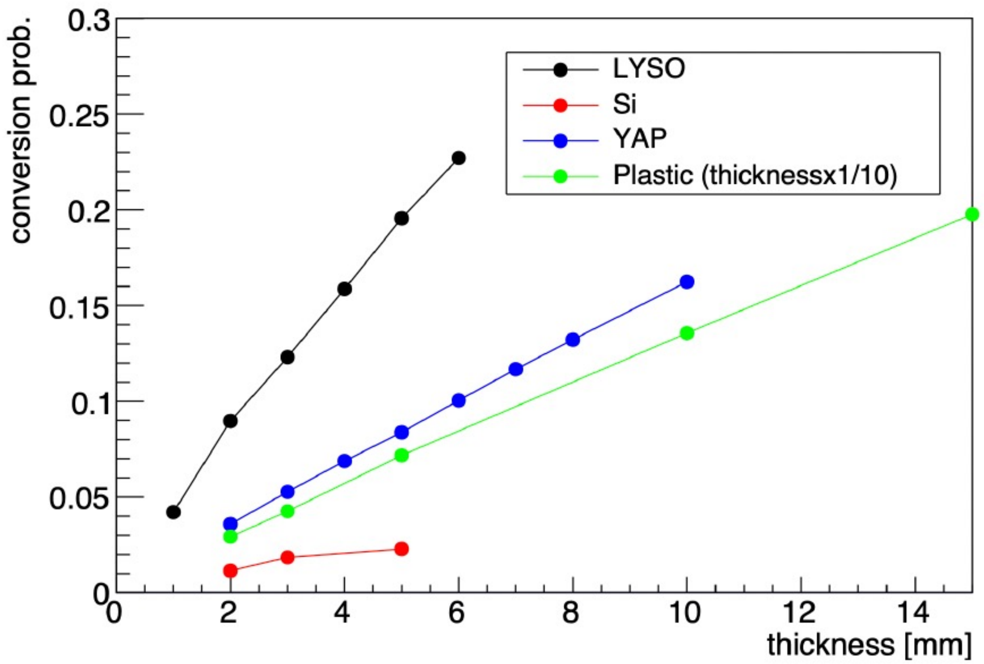
<u>requirements for active converter</u>

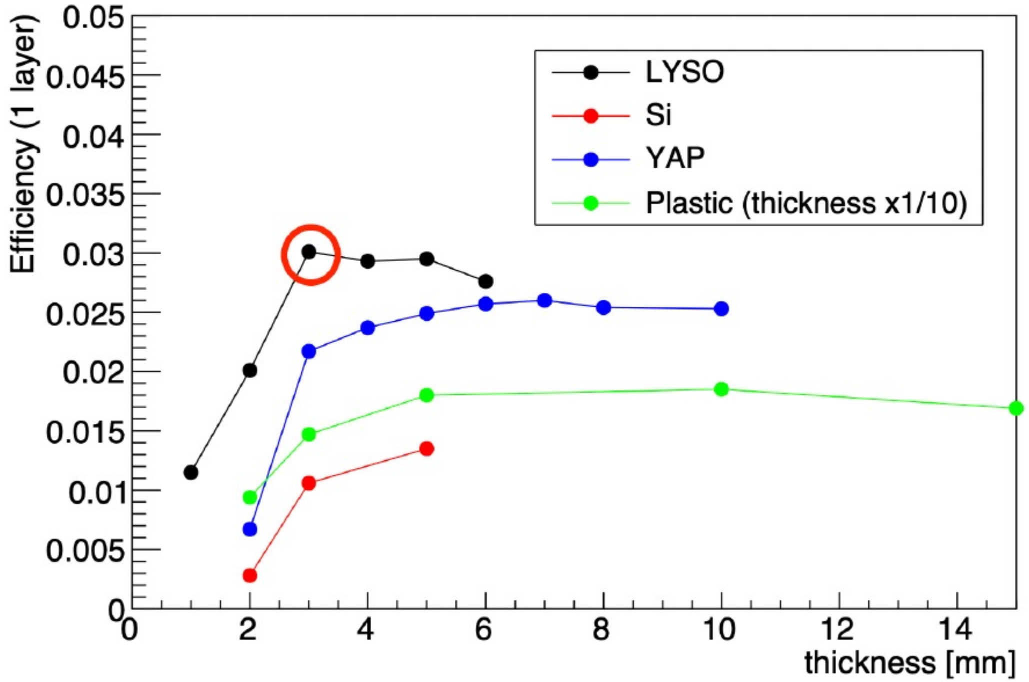
$\frac{\Delta E}{E} < 0.4\ \%$ at signal region ($E = 52.8\ \mathrm{MeV}$) & $\Delta t < 30\ \mathrm{ps}$ for pair spectrometer

⬇

$N_{\mathrm{p.e.}} > 670$ p.e. (3mm thickness converter) & $\Delta t < 30\ \mathrm{ps} \times \sqrt{2} \sim 40\ \mathrm{ps}$ for 1 MIP

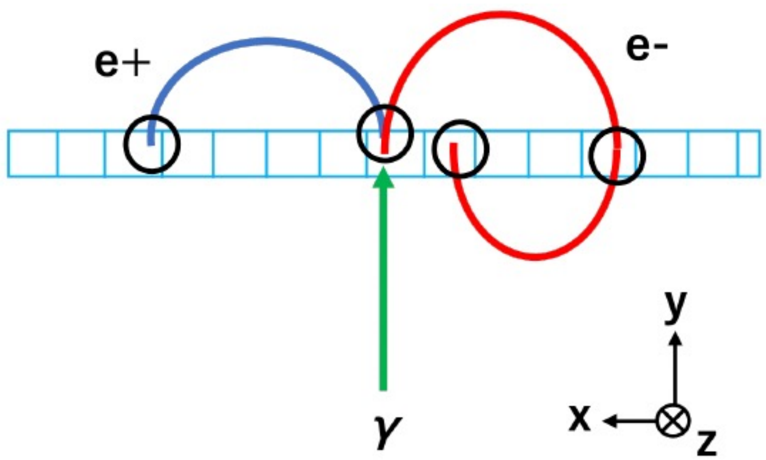
Converter material & thickness

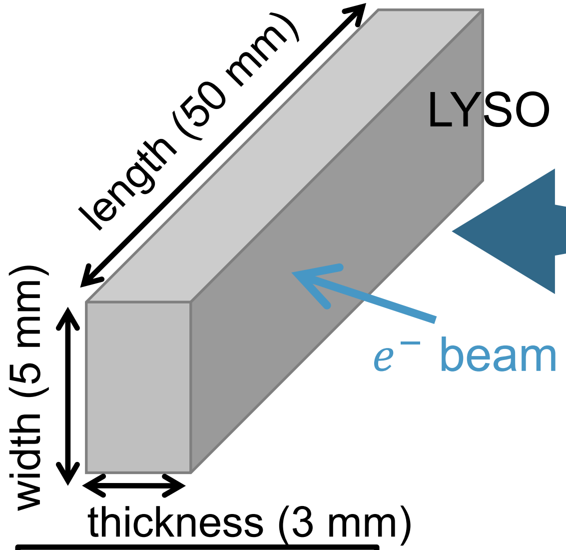




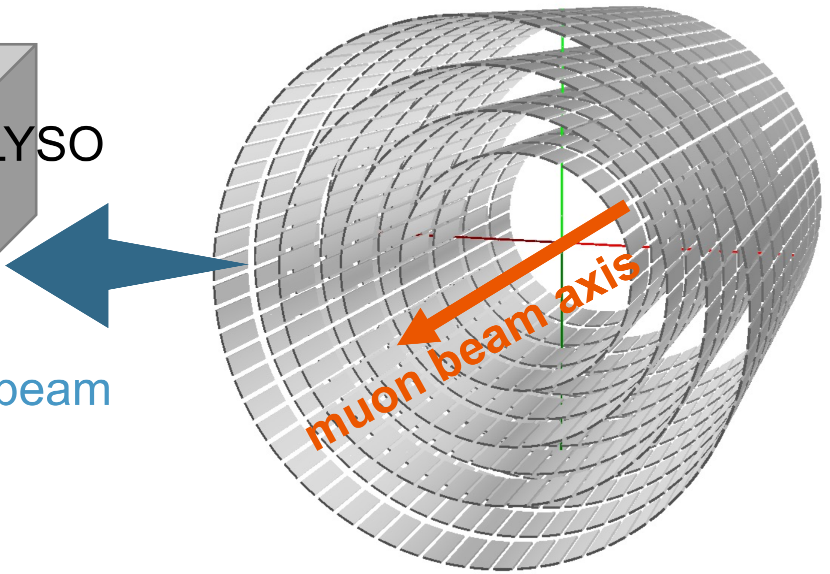
- Conversion probability and efficiency was simulated with four candidate material
- LYSO had the best performance among the candidates
- 3 mm thickness had the highest efficiency

Converter segmentation





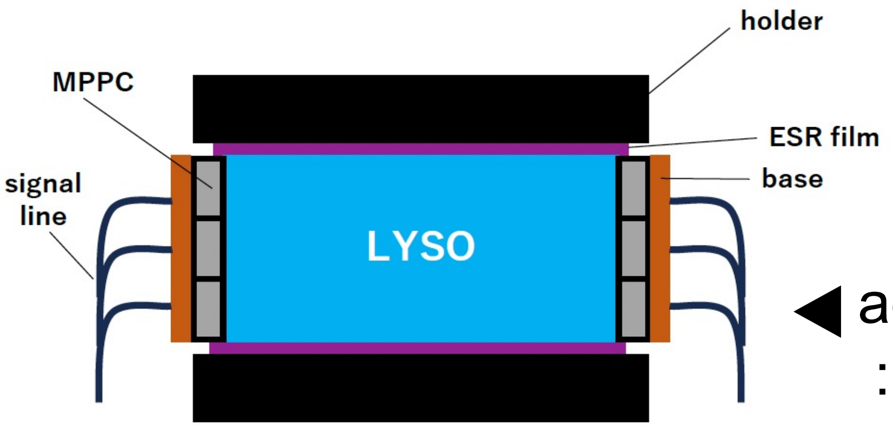
one segment
(standard size)



segmentation of converter
in the future experiment

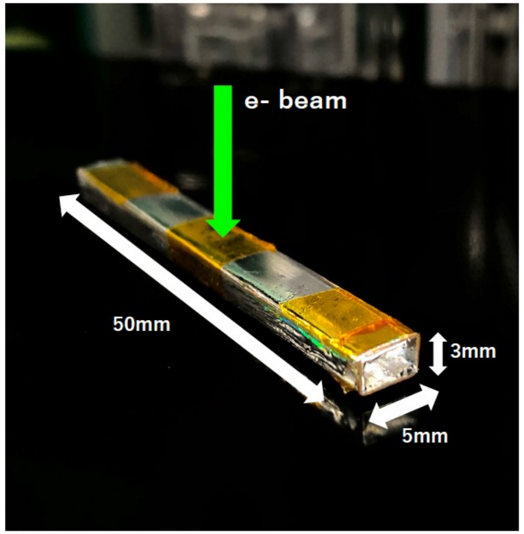
- Converter will be segmented to avoid pile-up
- From the simulation study,
  3 x 5 x 50 mm segmentation size will
  be best in terms of efficiency &number of readout channels

Active converter prototype



◀ active converter segment prototype
: LYSO + there SiPMs on both edge

standard size LYSO (+ESR) ▶



LYSO

- 3 mm thickness × 5 mm width × 50 mm length (standard size)
- FTRL type (less lightyield and faster response than normal type)

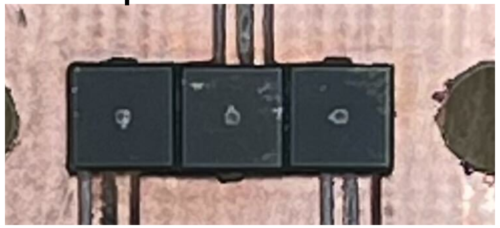
SiPM

- Hamamatsu MPPC
- Three different pixel pitch
(50 um(S14160-3050HS), 15 um(S14160-3015PS), 10 um(S14160-3010PS))

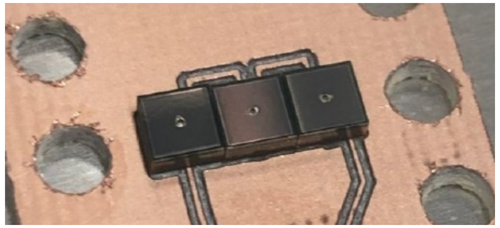
readout method

1. **independent readout** … three SiPMs readout independently
2. **series readout**…three SiPMs connected in series

independent readout



series readout

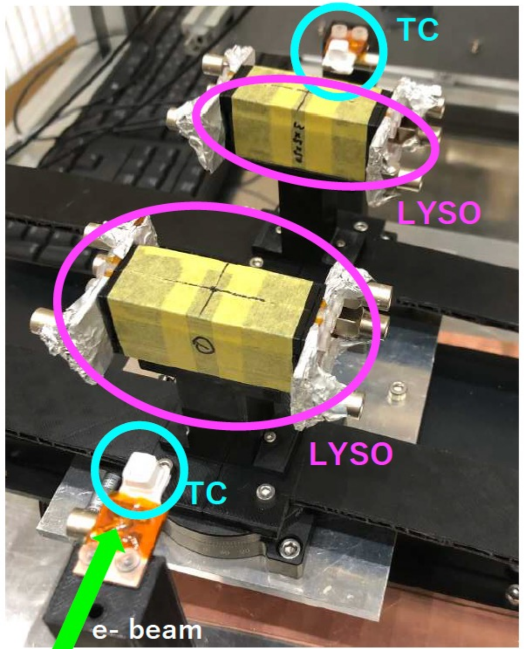


Electron beam test

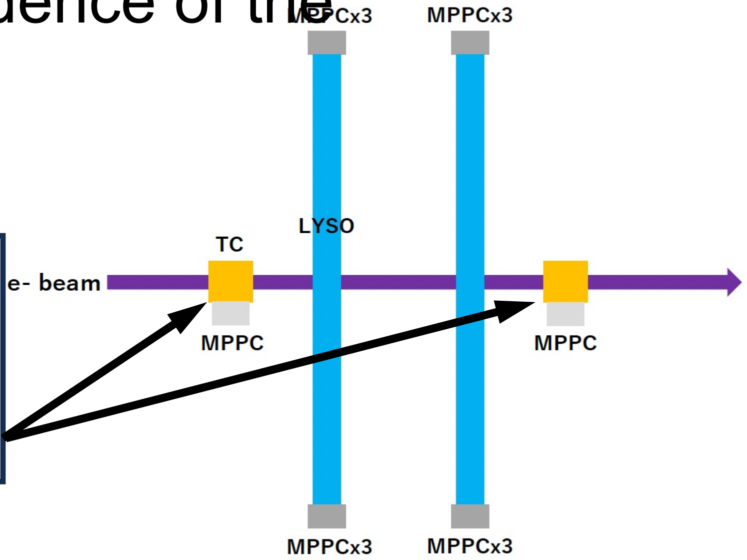
- **Electron beam at KEK PF-AR Test beam line**
  Beam momentum ~ 3 GeV
  Beam rate ~ 4.5 kHz

- **DAQ**: Wave Dream Board (sampling rate :4 GHz)

- **Studied items**
  - Comparison of various prototypes (LYSO size, readout method)
  - Investigation of injection angle/position dependence of the performance

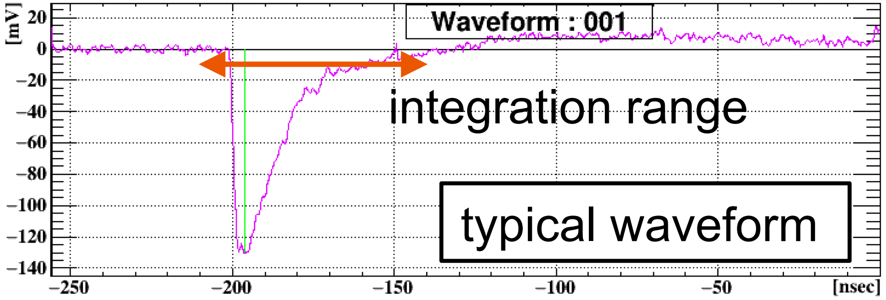


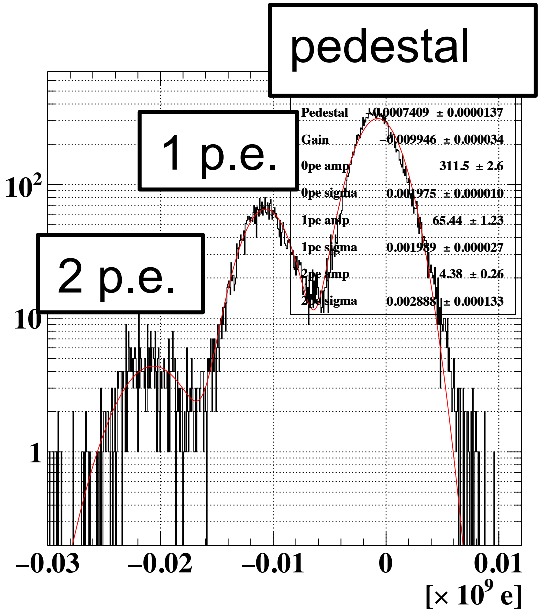
5 mm cube plastic timing counter for
- trigger (coincidence of up & down TC)
- time reference



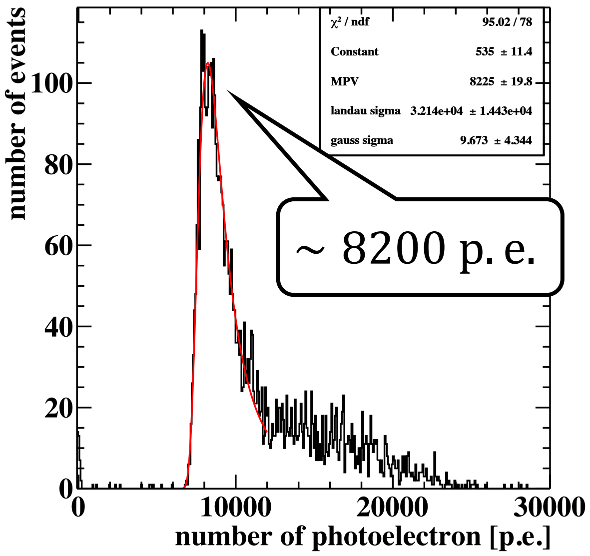
Lightyield

- 1 p.e. gain was calculated from dark count of MPPC
- Lightyield analysis was done with the low gain beam data
- Lightyield was far beyond the target (670 p.e.)

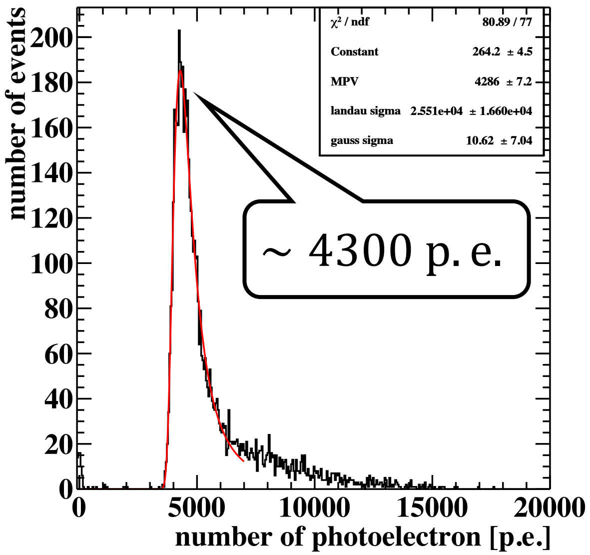




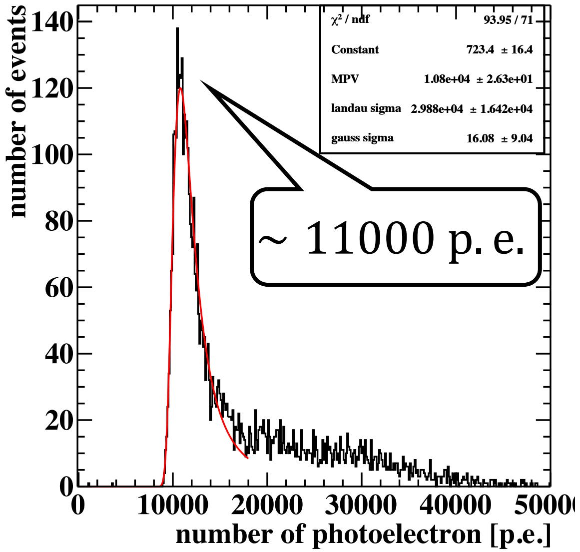
standard size
(3 mm×5 mm×50 mm)



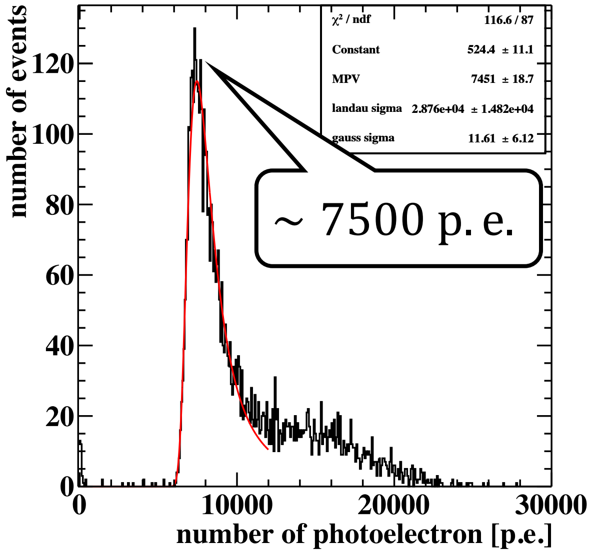
half thickness
(1.5 mm×5 mm×50 mm)



double width
(3 mm×10 mm×50 mm)



double length
(3 mm×5 mm×100 mm)

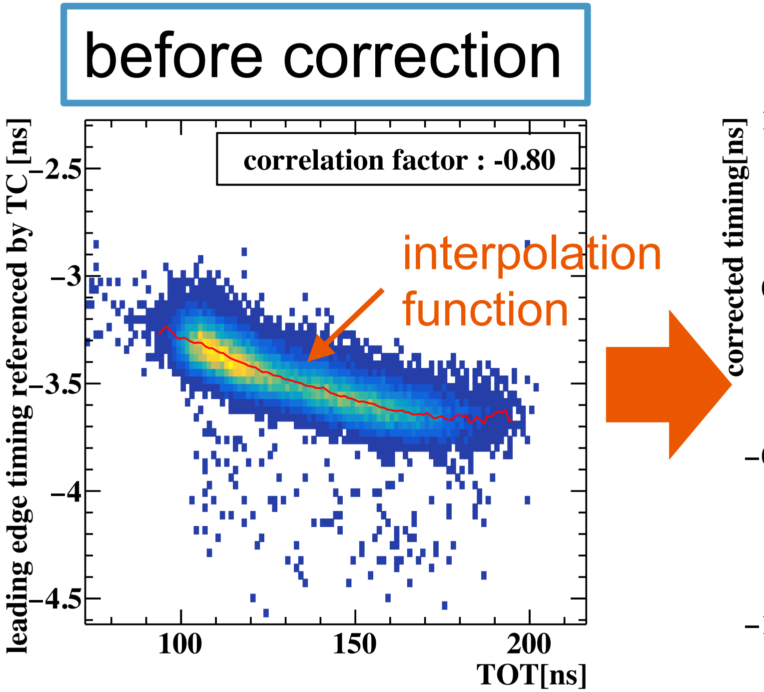


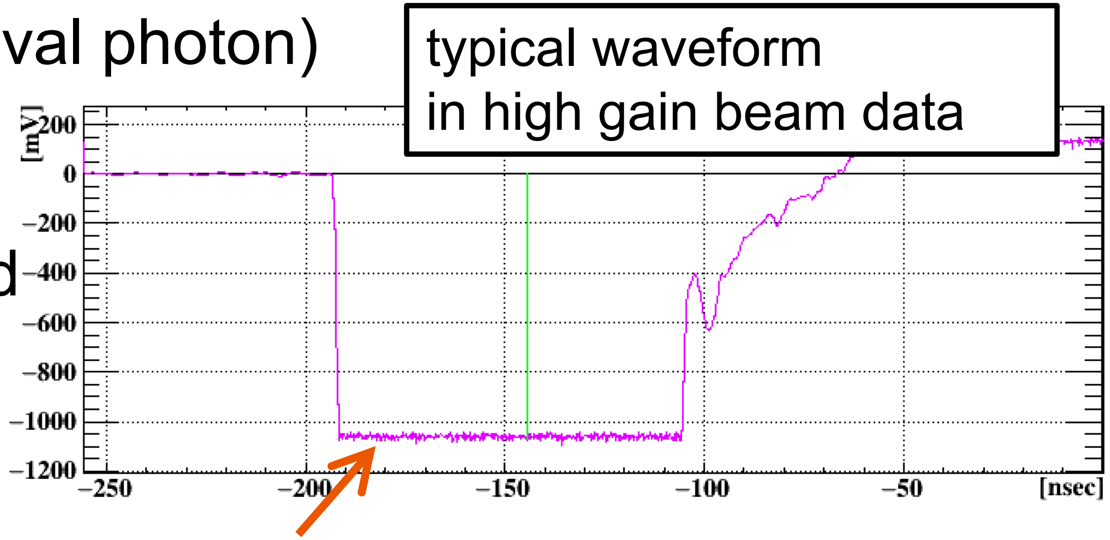
*in this analysis, gain of the electronics is assumed to be the nominal value

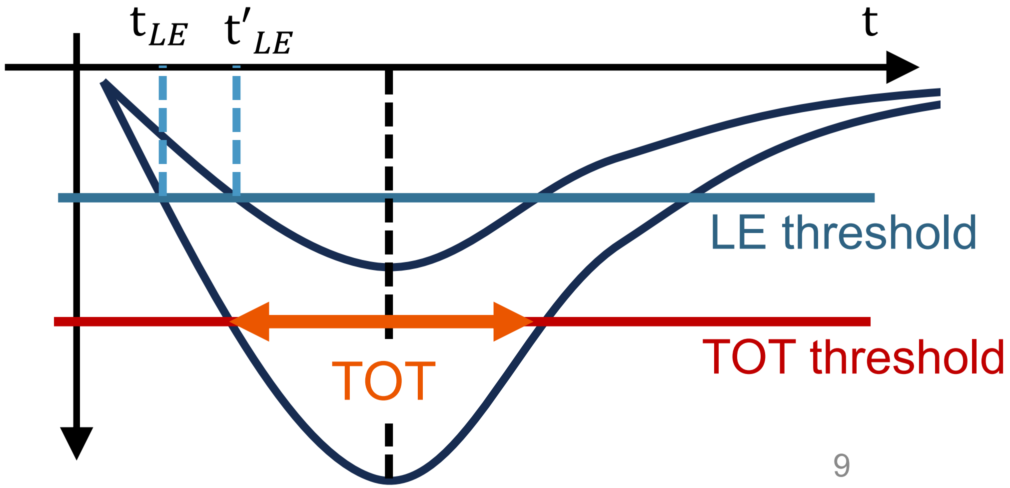
Time resolution analysis method

- Operation in high gain (to focus on the early arrival photon)

- Time pick-up : leading edge method
- Time walk correction : using time over threshold

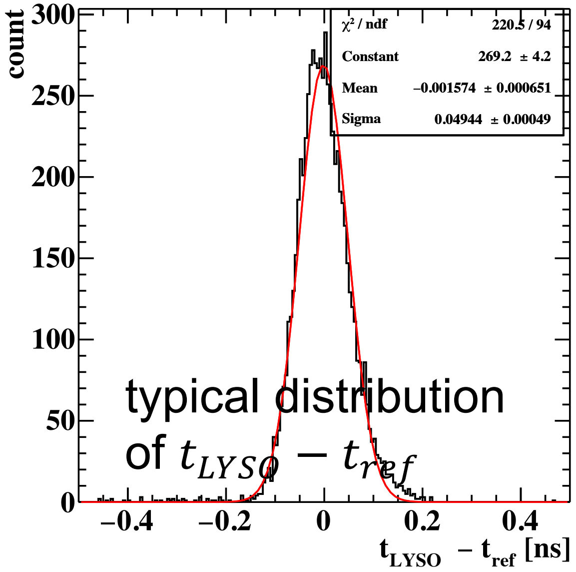






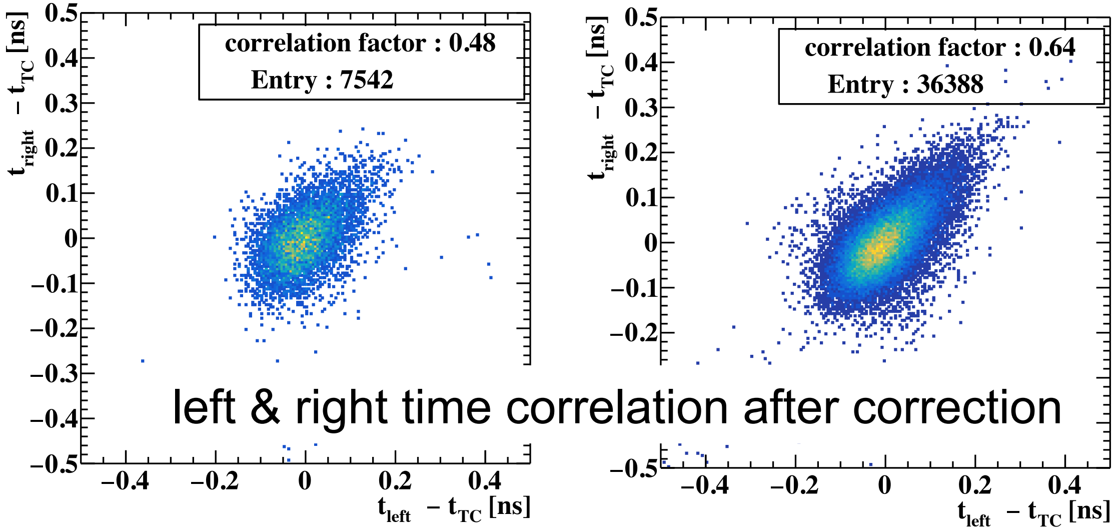
time resolution analysis result – LYSO size –

	Standard size (3 mm×5 mm×50 mm)	Half thickness (1.5 mm×5 mm×50 mm)	Double width (1.5 mm×5 mm×50 mm)	Double length (3 mm×5 mm×100 mm)
Independent readout	27.0 ps	36.1 ps	26.5 ps	30.4 ps
Series readout	29.4 ps	(no data taken)	27.6 ps	(no data taken)



typical distribution of $t_{LYSO} - t_{ref}$

- Basically, LYSO size that had larger lightyield has better time resolution
- Independent readout has slightly better resolution by a few ps
  - This is due to the difference in the remaining time walk effect after correction
  - Correlation between timing of left channels and right channels → …stronger on series connection



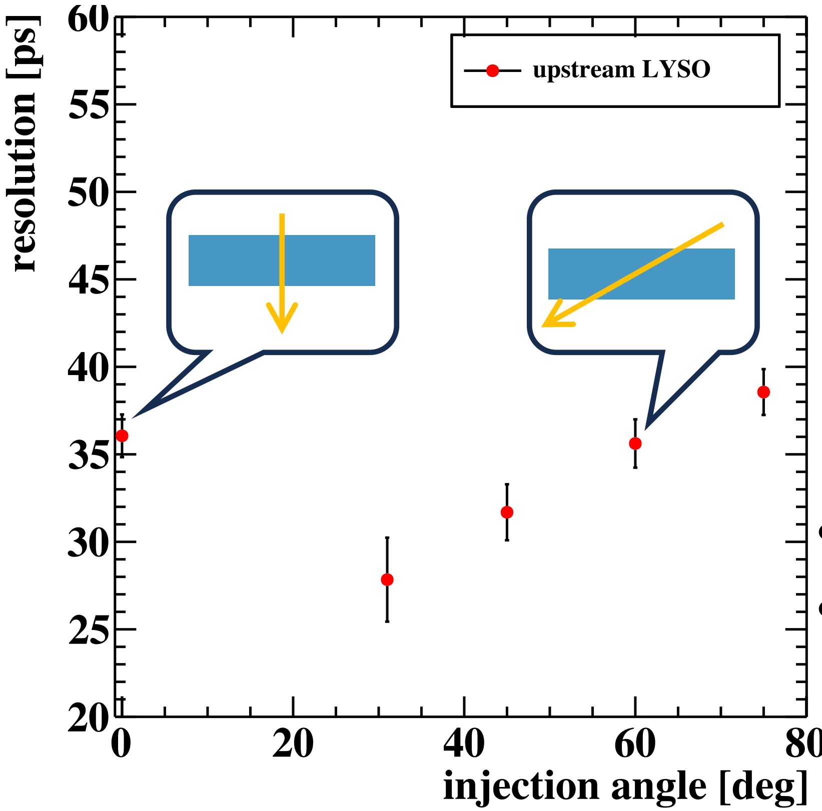
left & right time correlation after correction

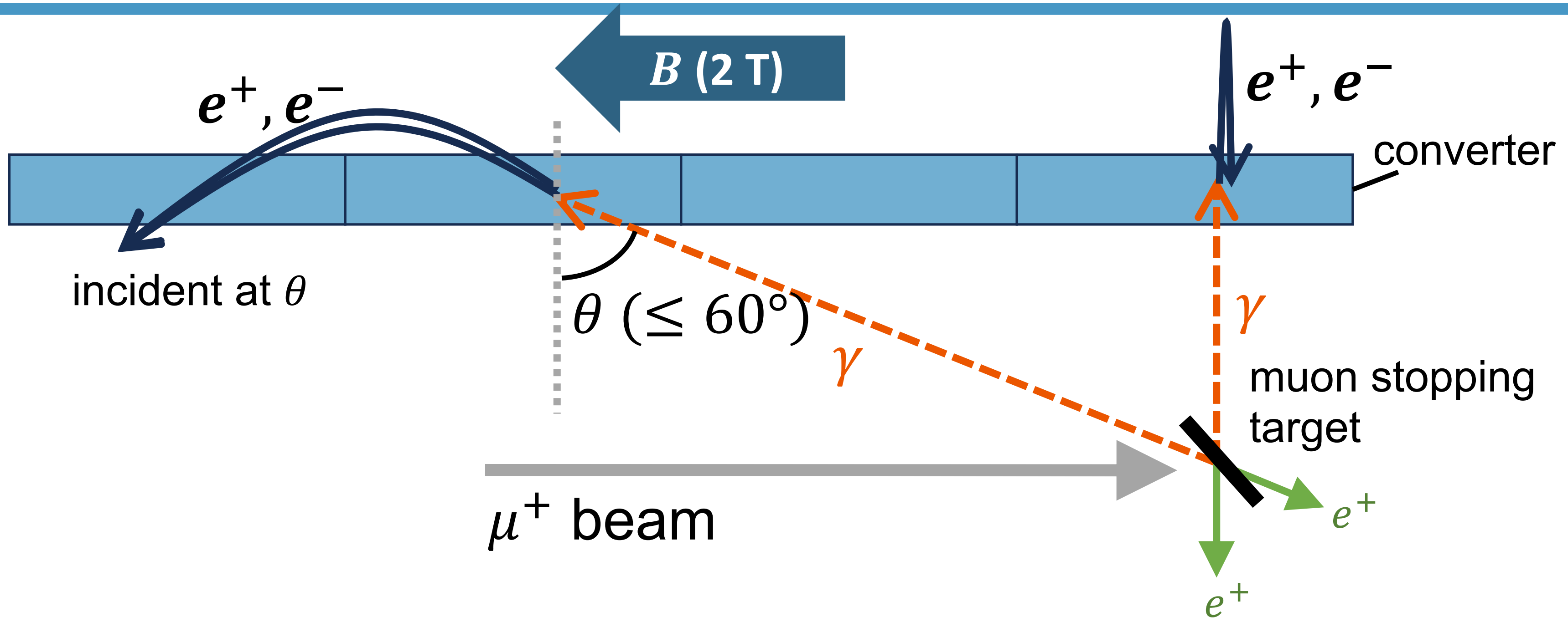
independent connection

series connection

time resolution analysis result – angle dependence –

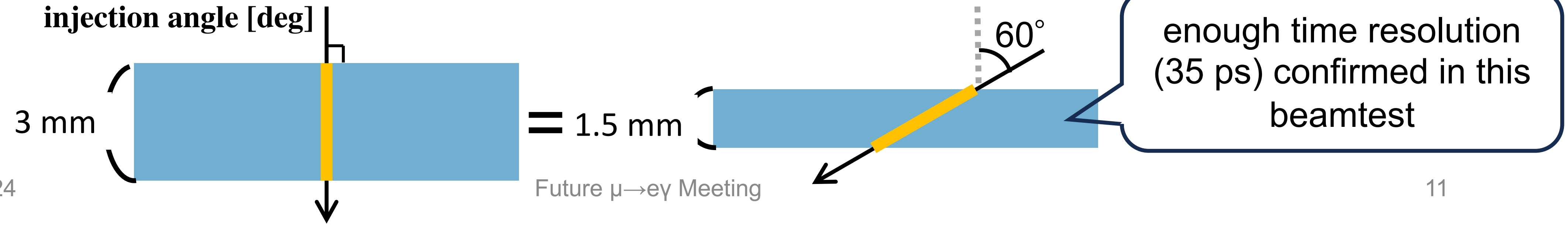
injection angle scan
(1.5 mm thickness LYSO)





- Incident angle will be steeper in the outer segments
- Steeper incident has longer effective thickness

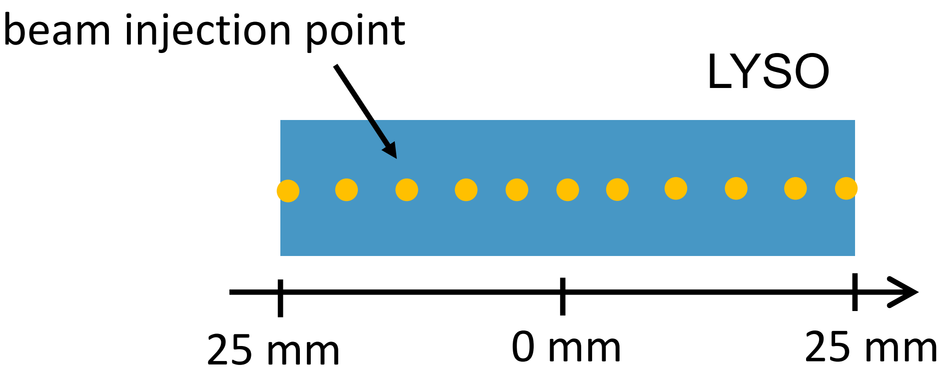
➡ Outer converter should be thinner

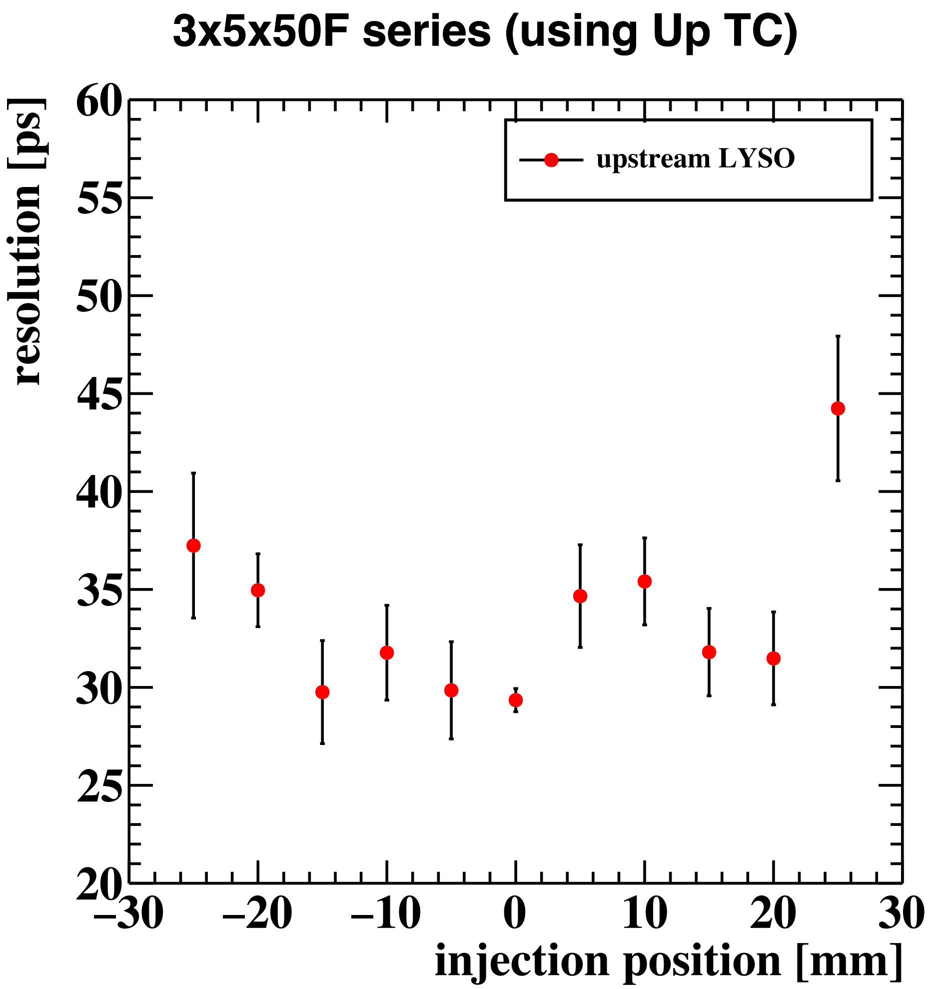


time resolution analysis result – position dependence –

Except the injection on the most edge,

LYSO achieved the goal resolution of 40 ps with all injection position

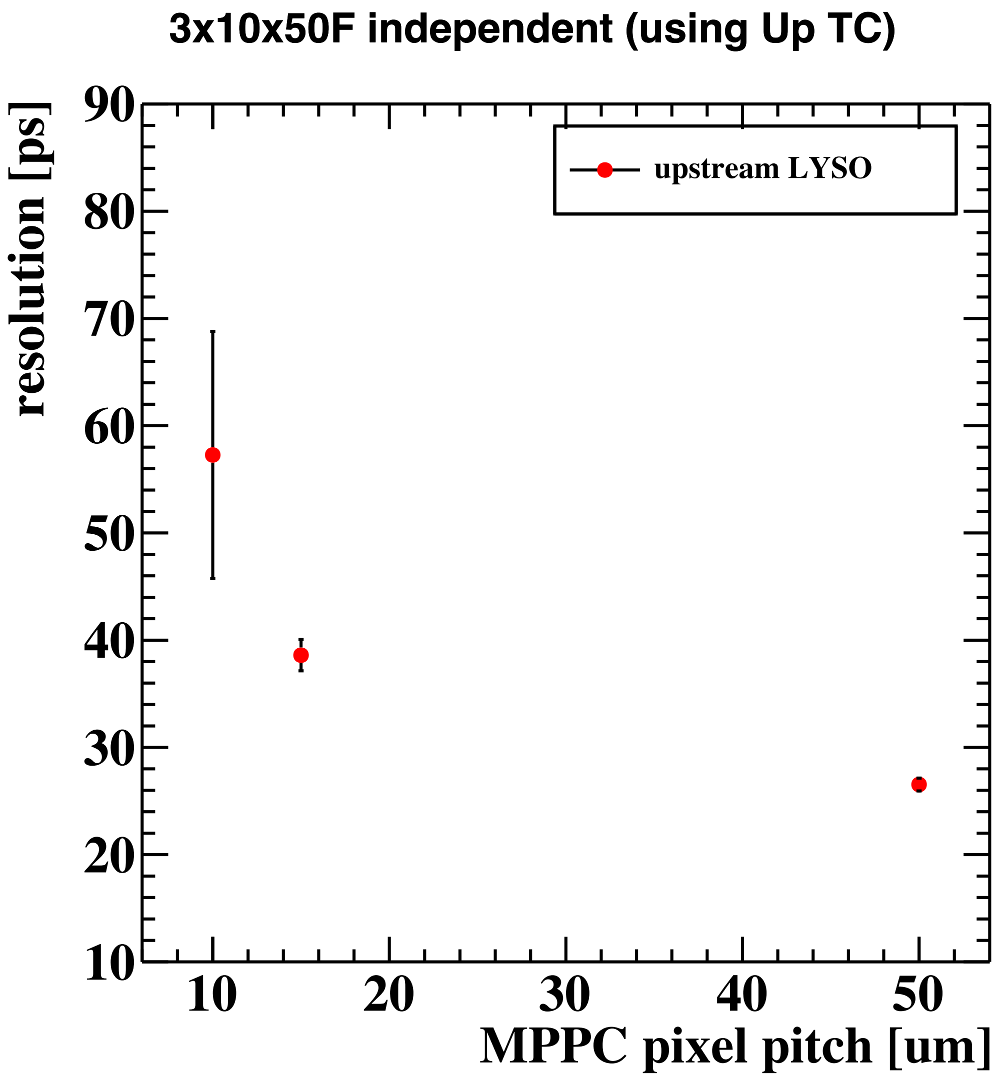




time resolution analysis result – pixel pitch comparison–

- Tested MPPCs with different pixel pitch
  - 10 μm (S14160-3010PS)
  - 15 μm (S14160-3015PS)
  - 50 μm (S14160-3050HS)

- 50 μm pixel pitch shows the best performance because of
  - high gain
  - high PDE



summary and prospect

summary

- Pair spectrometer with active converter is under R&D as a photon detector for the future experiment for $\mu^+ \to e^+\gamma$ decay search.
- The beamtest result shows that requirement of energy and time resolution for a converter can be well achieved with LYSO.

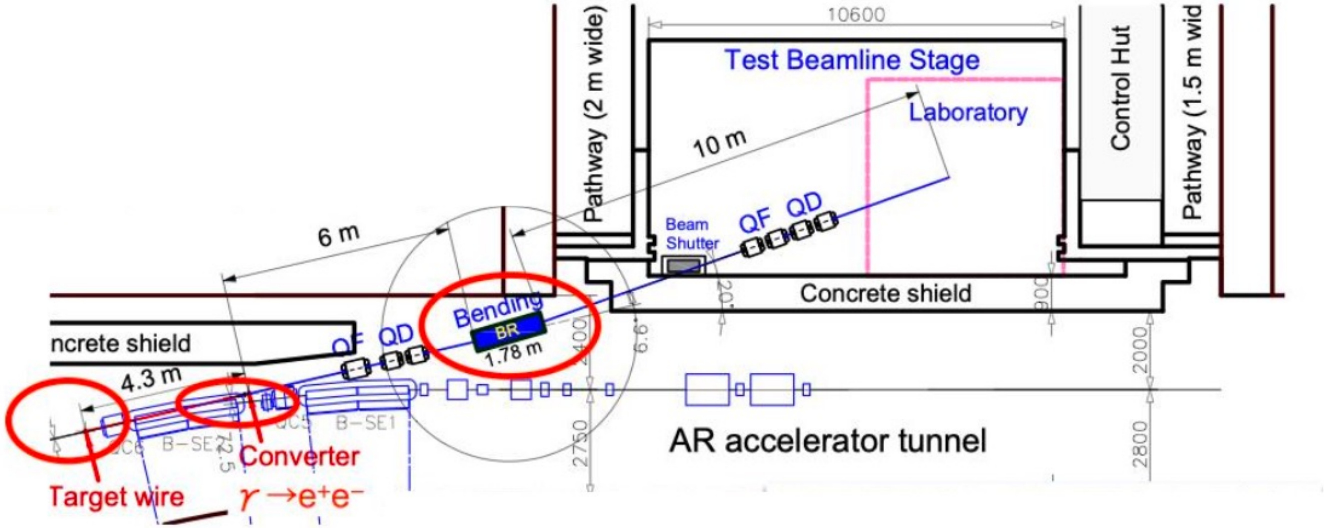
prospect

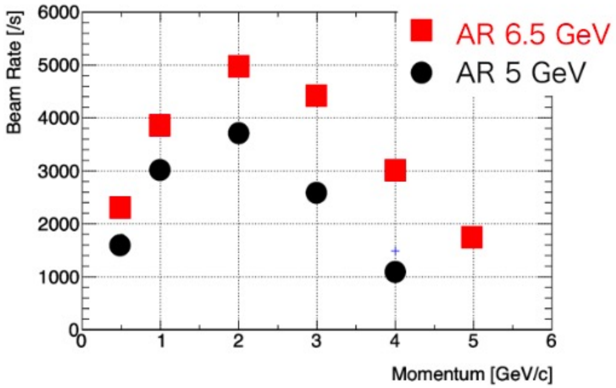
- In the future experiment, timing and energy must be measured at the same time
- Possibility of improving the time walk correction using charge information

→ Next beam test with high gain & low gain DAQ at the same time (planned in Nov – Dec 2024)

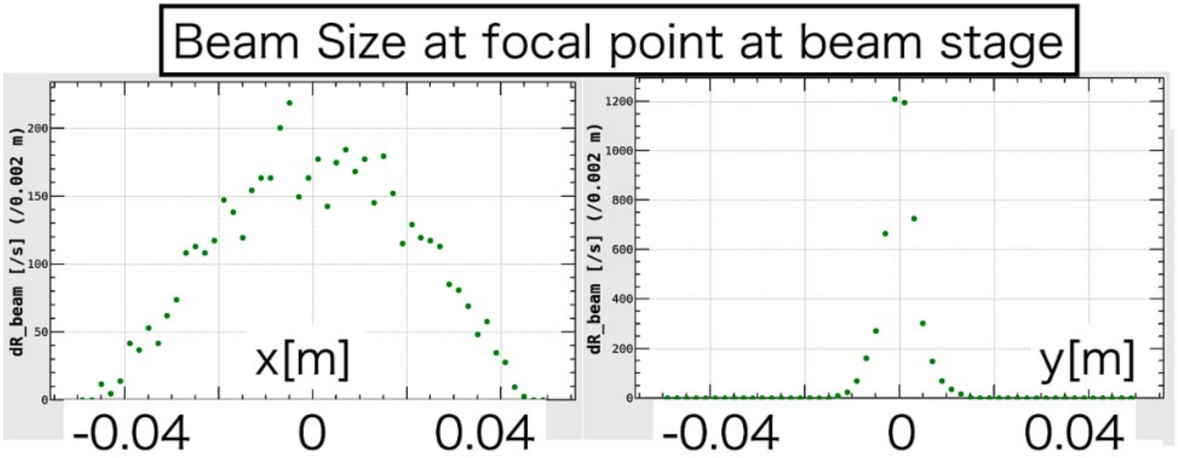
backup

KEK PF-AR test beam line

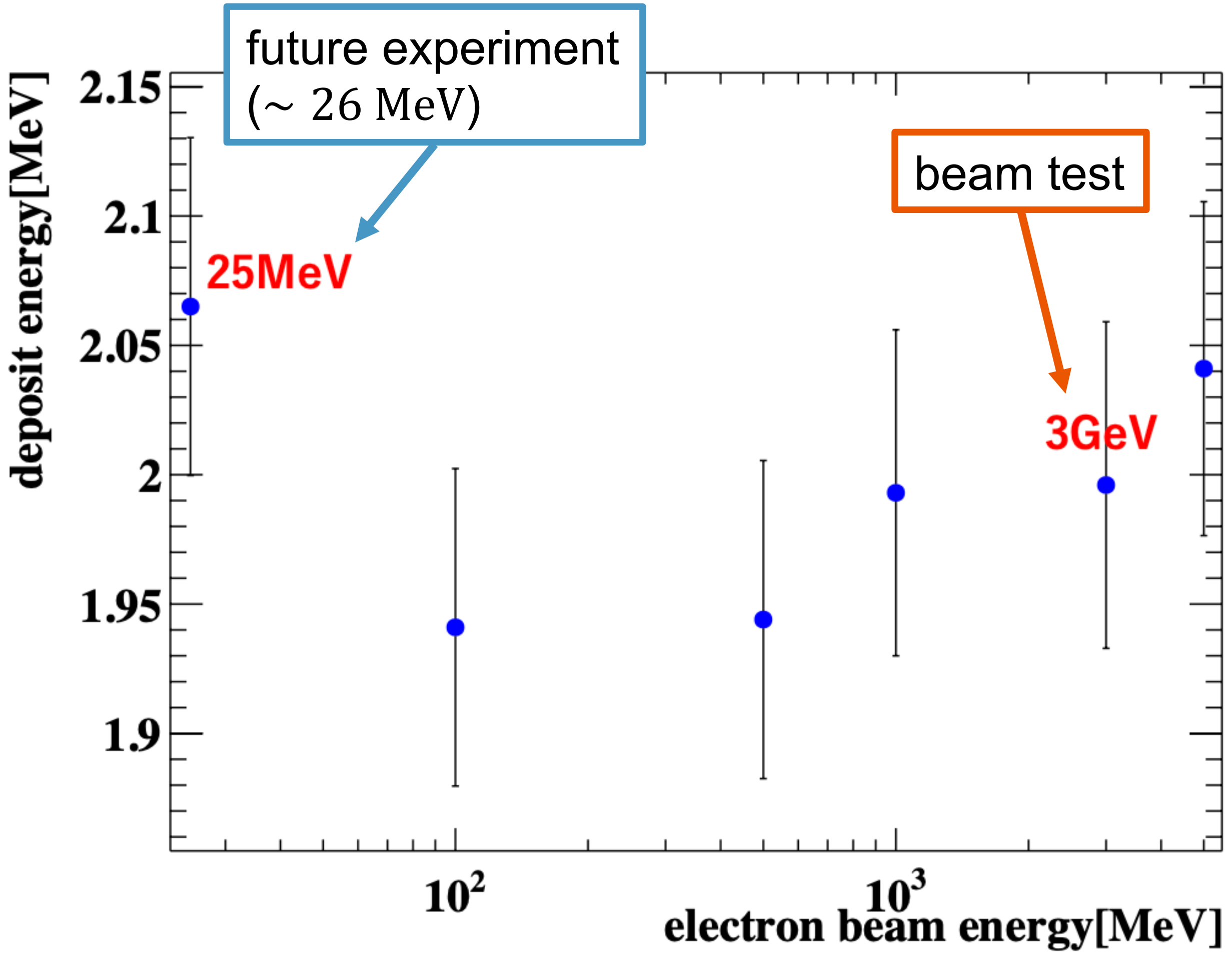




beam rate by momentum



deposit energy by electron in different energy



(R.Yokota, 2023 thesis)

- deposit energy in LYSO was simulated with various electron beam energies
- deposit energy in LYSO of 3 GeV electron was almost identical to that of 25 GeV electron

the resolution obtained in the beam test could be applied to the future experiment

requirements for the active converter

energy resolution

- $\frac{\Delta E}{E} \leq 0.4\ \%\ @E = 52.8\ \mathrm{MeV}$ for pair spectrometer
  $\rightarrow \Delta E \leq 211\ \mathrm{keV}$ for 2 MIP($e^+\ \&\ e^-$)

- deposit energy of 2 MIP:
  $E' = 1.12\ \mathrm{MeV/mm} \times 3\ \mathrm{mm} \times 2 = 6.72\ \mathrm{MeV}$ (in 3 mm thickness LYSO)
  $\rightarrow \frac{\Delta E}{E'} = \frac{1}{\sqrt{N_{\mathrm{p.e.}}}} \leq \frac{211\ \mathrm{keV}}{7.72\ \mathrm{MeV}} = 2.73\ \%$
  $\rightarrow N_{\mathrm{p.e.}} \geq 1341$ for 2 MIP
  $\rightarrow N_{\mathrm{p.e.}} \geq 671$ for 1 MIP

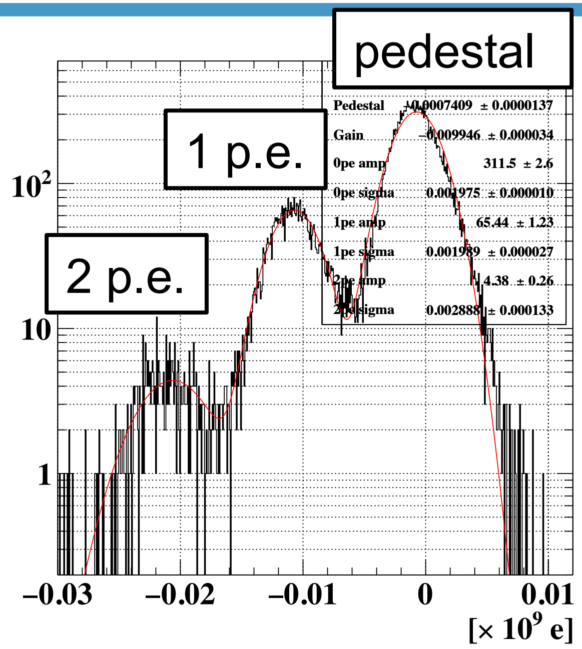
time resolution

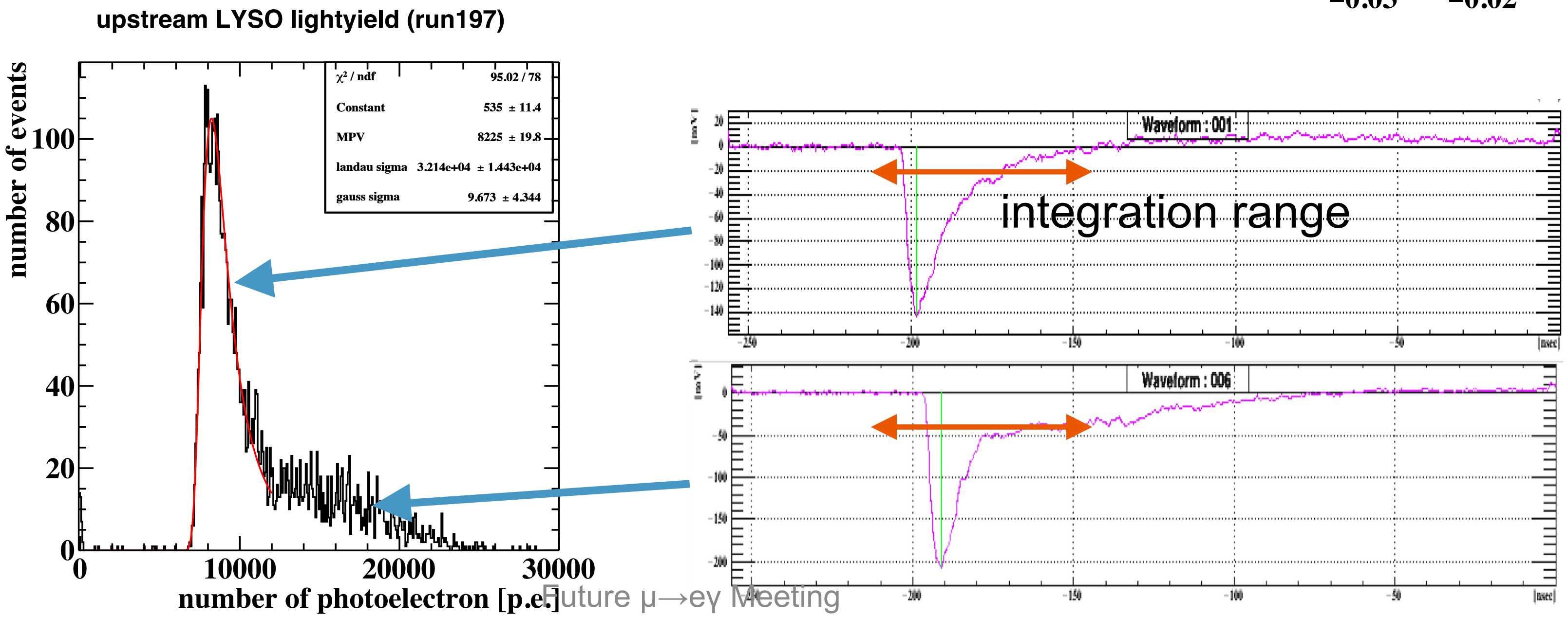
- $\Delta t = 30\ \mathrm{ps}$ for pair spectrometer $\rightarrow 30 \times \sqrt{2} = 42\ \mathrm{ps}$ for 1 MIP

lightyield analysis method

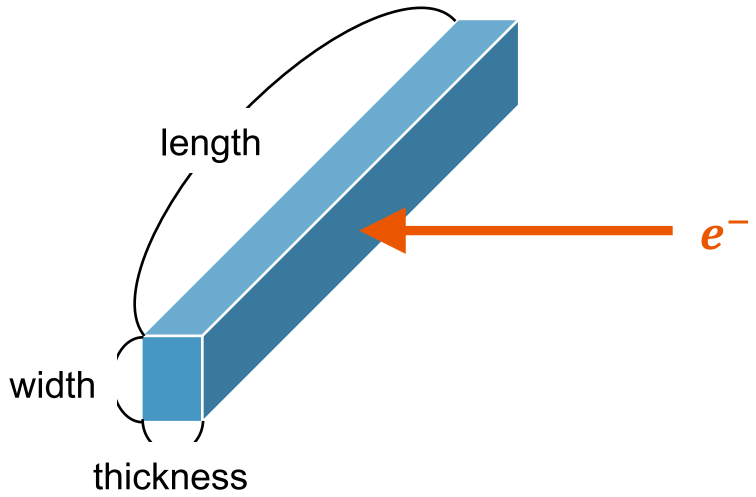
1. estimate 1 p.e. gain with the dark count of MPPC
2. obtain charge from the low gain beam where full waveform is recorded
3. estimate the detected number of photoelectrons at LYSO by

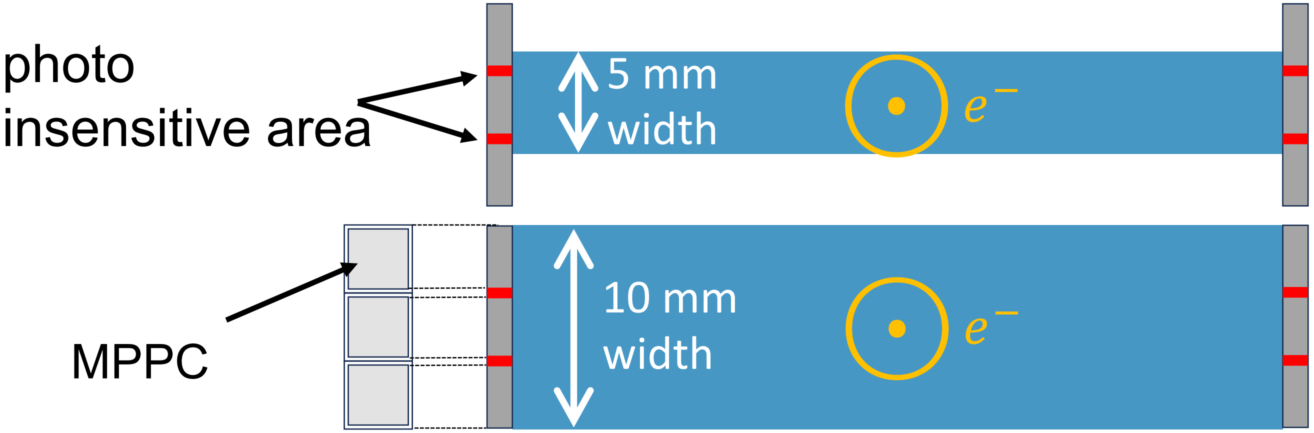
$$N_{p.e.} = \sum_{i=\text{MPPC channels}} \frac{(\text{ch } i \text{ charge})}{(\text{ch } i \text{ 1 p.e. gain})}$$





lightyield analysis result





LYSO size	Standard (3mm x 5mm x 50mm)	Half thickness	Double width	Double length
Lightyield [p.e.]	8344 ± 22	4345 ± 9	10900 ± 29	7564 ± 20

- thickness : lightyield decreases in proportion to the thickness
- width : wider LYSO have smaller ratio of photo-insensitive area
- length : longer LYSO is more susceptible to the attenuation of scintillation light

LYSO of all size achieved the goal of $N_{p.e.} > 670$

($N_{p.e.} > 168$ for half thickness)

estimation of contribution from reference counter

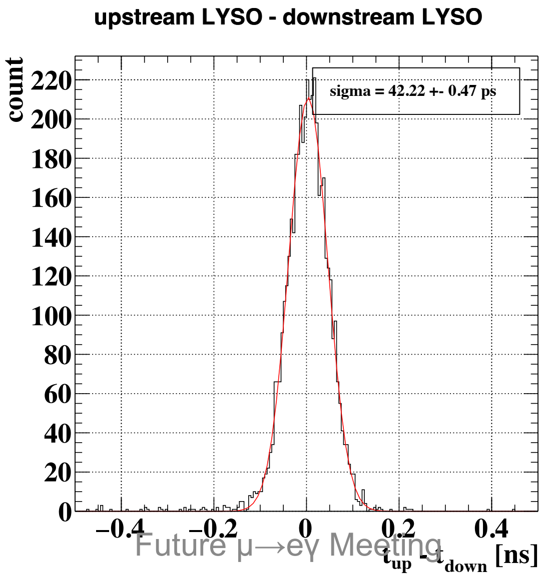
$$\sigma(t_{\mathrm{UpLYSO}} - t_{\mathrm{ref}}) = \sqrt{\sigma_{\mathrm{UpLYSO}}^2 + \sigma_{\mathrm{ref}}^2}$$

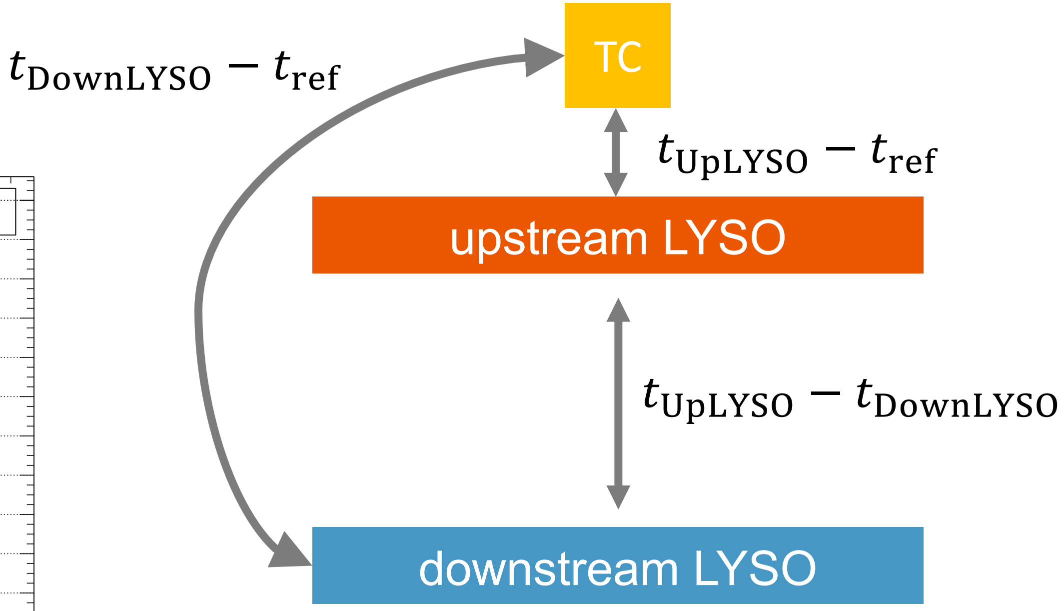
$$\sigma(t_{\mathrm{DownLYSO}} - t_{\mathrm{ref}}) = \sqrt{\sigma_{\mathrm{DownLYSO}}^2 + \sigma_{\mathrm{ref}}^2}$$

$$\sigma(t_{\mathrm{UpLYSO}} - t_{\mathrm{DownLYSO}}) = \sqrt{\sigma_{\mathrm{UpLYSO}}^2 + \sigma_{\mathrm{DownLYSO}}^2}$$

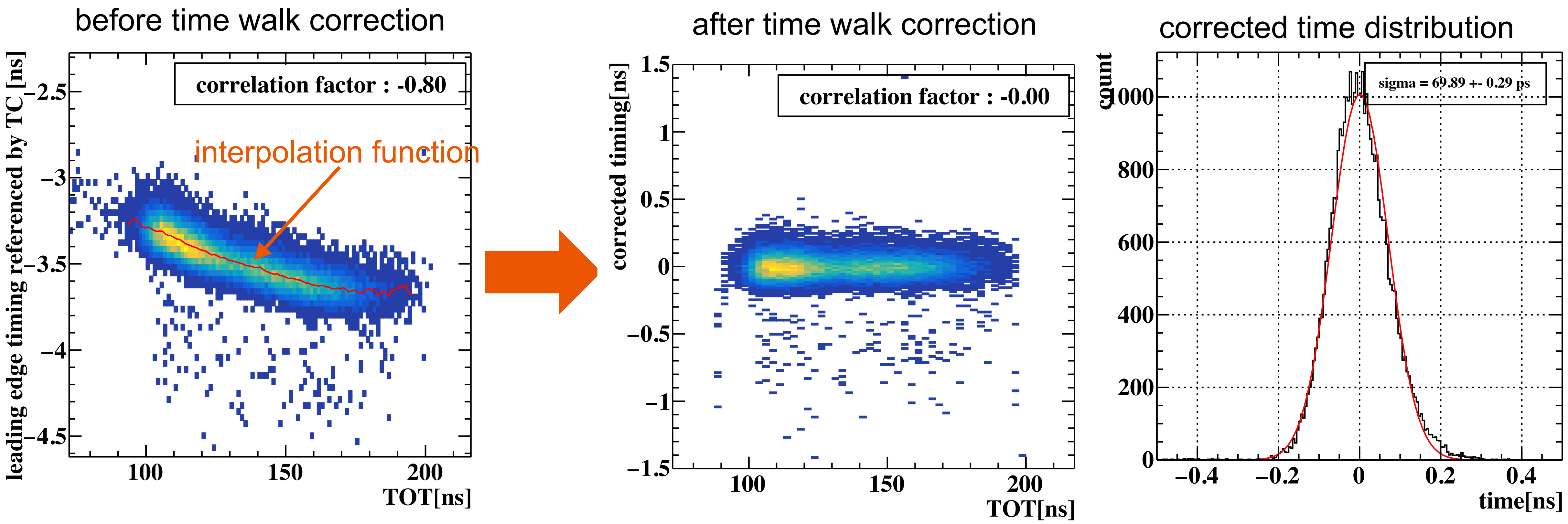
→ able to calculate each σ_{UpLYSO}, $\sigma_{\mathrm{DownLYSO}}$ and σ_{ref}

$(t_{\mathrm{UpLYSO}} - t_{\mathrm{ref}}) - (t_{\mathrm{DownLYSO}} - t_{\mathrm{ref}})$





time walk correction



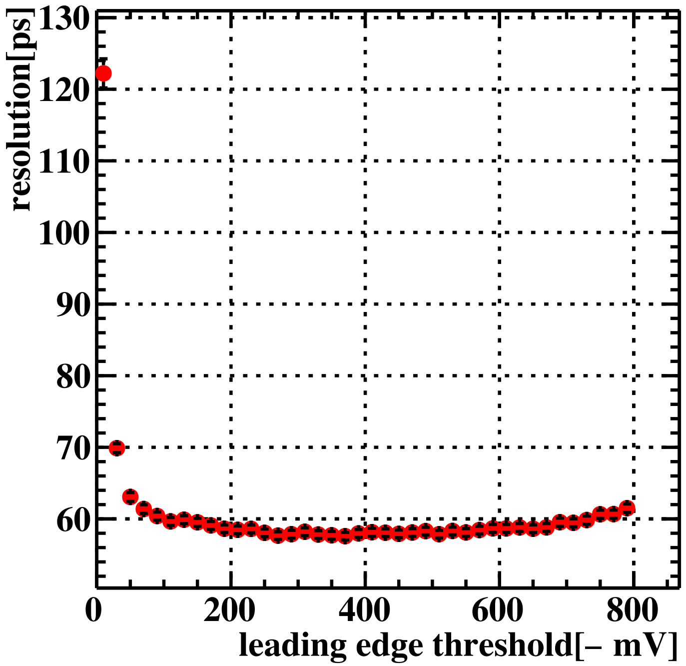
1. look at the correlation between $t_{LE} - t_{ref}$ and TOT, and get the interpolation function
2. subtract interpolation function from the datapoint
3. obtain resolution from a σ of a gaussian fit of corrected time

optimization of the thresholds

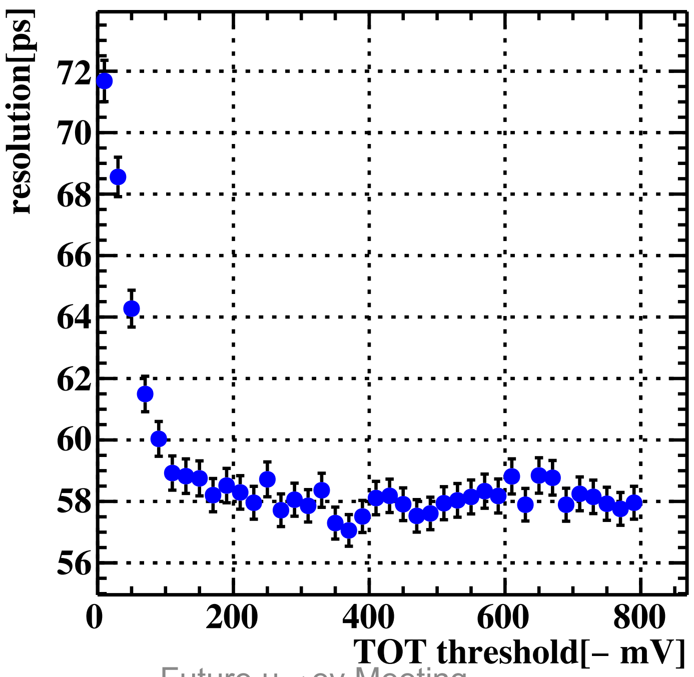
<u>thresholds to be optimized:</u>

1. leading edge threshold for each LYSO channel
2. TOT threshold for each LYSO channel
3. leading edge threshold for time reference counter

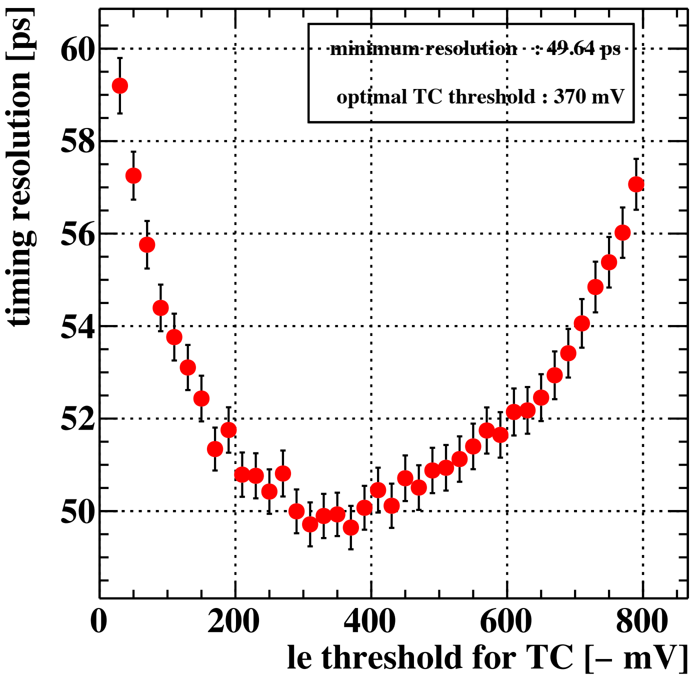
LE threshold scan



TOT threshold scan



LE threshold scan
for reference TC

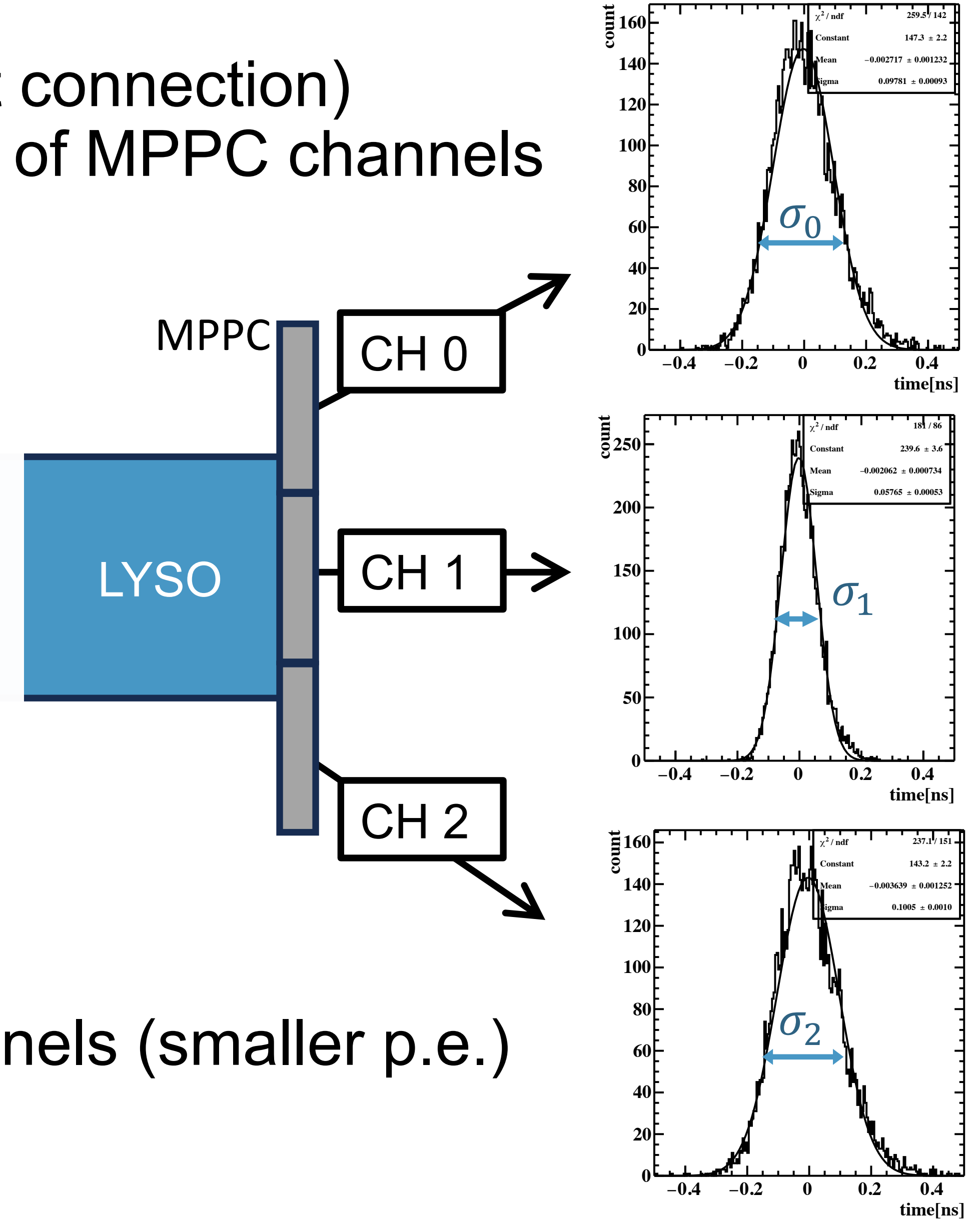


timing decision by multiple MPPC channels

- asymmetry in lightyield in 3 channels(independent connection)
  →decide timing of LYSO by the weighted average of MPPC channels

- weight $\propto 1/\sigma_i^2$
  (σ_i: time resolution of 1 MPPC channel)

$$t_{\mathrm{LYSO}} - t_{\mathrm{ref}} = \sum_{\mathrm{channels}} w_i (t_i - t_{\mathrm{ref}})$$

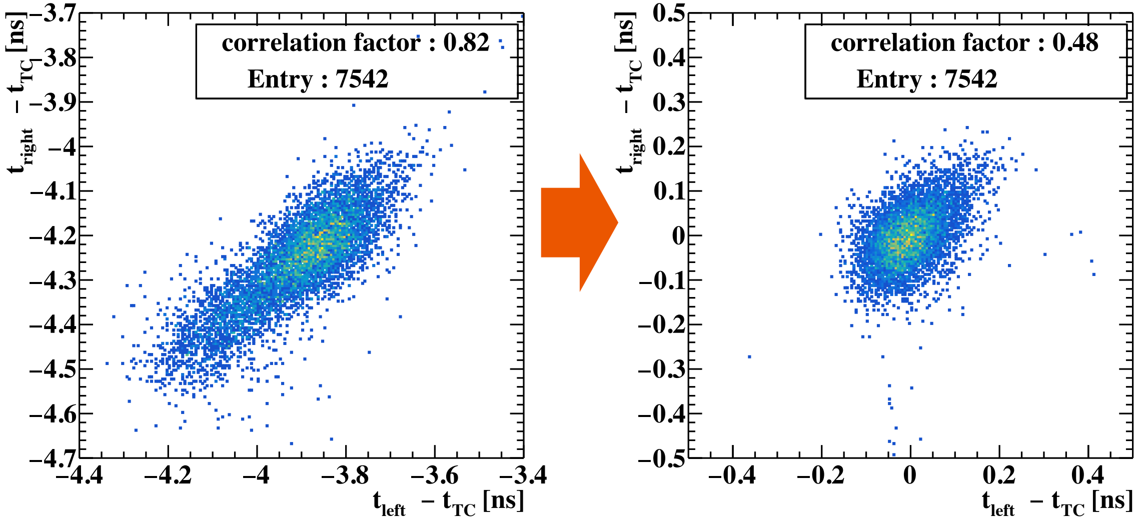


➡ center MPPC channels (larger p.e.) are weighted more than the edge MPPC channels (smaller p.e.)

remaining time walk effect

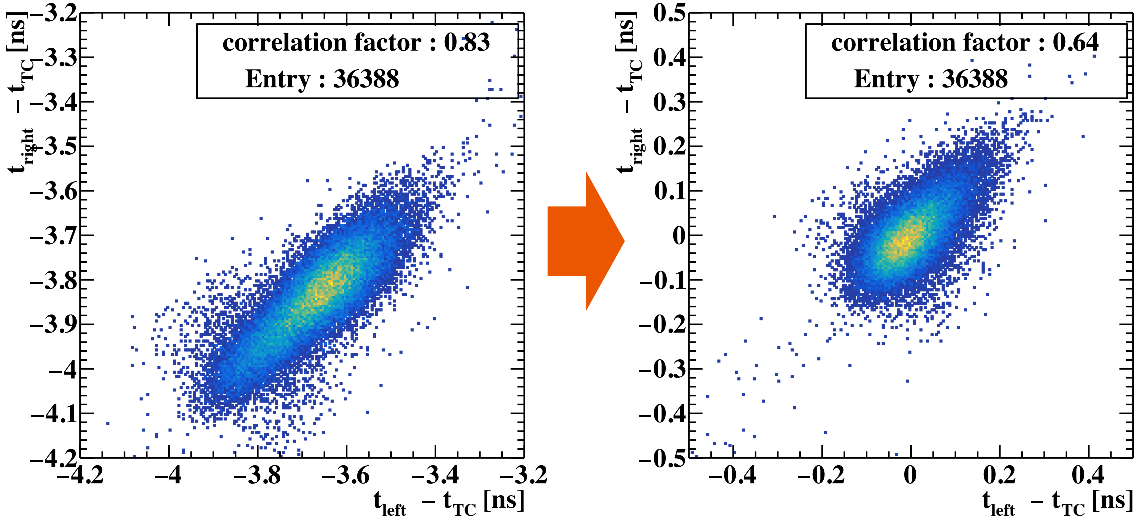
independent connection

before correction | after correction



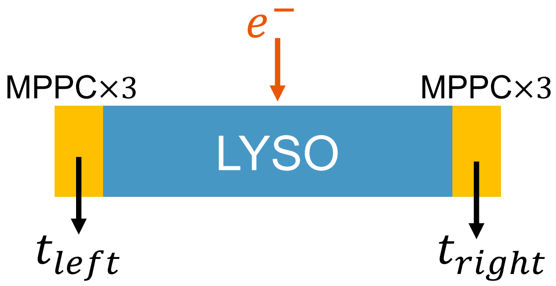
series connection

before correction | after correction



- if the time walk effect exists, t_{left} and t_{right} will correlate stronger

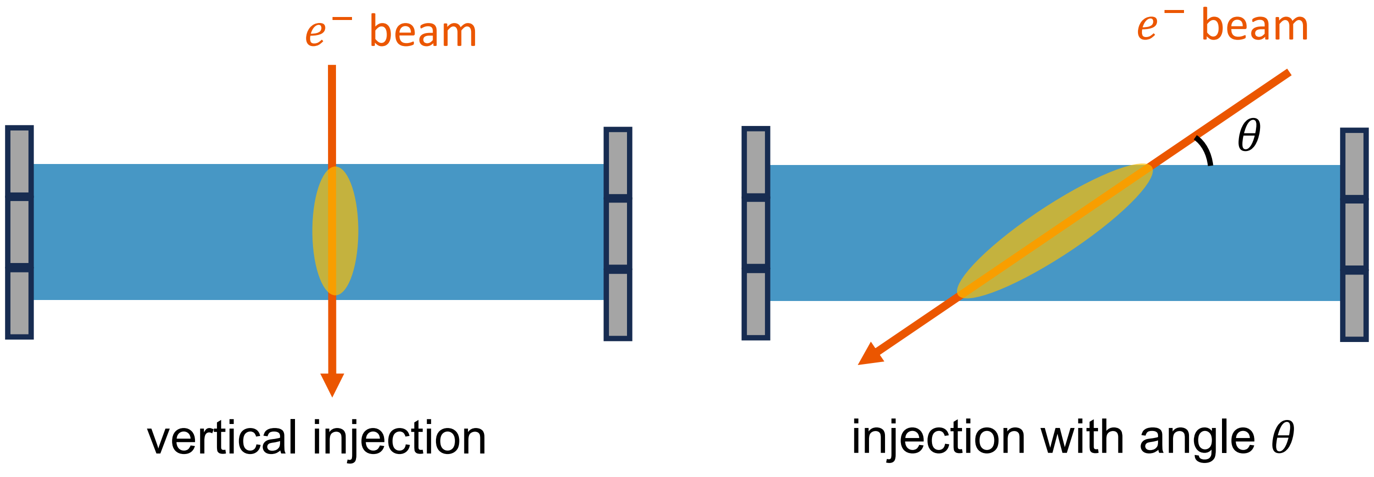
  larger lightyield → faster timing
  smaller lightyield → slower timing
  } in both sides

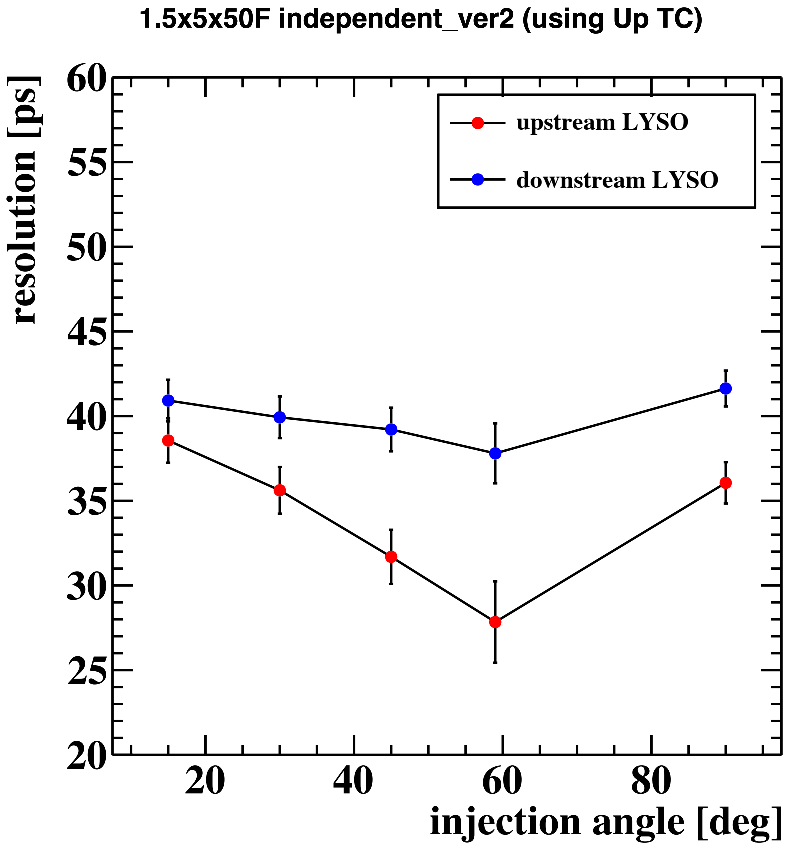


- series connection had stronger time walk effect left even after the correction by TOT

※$t_{left} - t_{TC}$ and $t_{right} - t_{TC}$ will have a small correlation even if there is no walk effect, because of t_{TC}

time resolution analysis result – angular dependence –

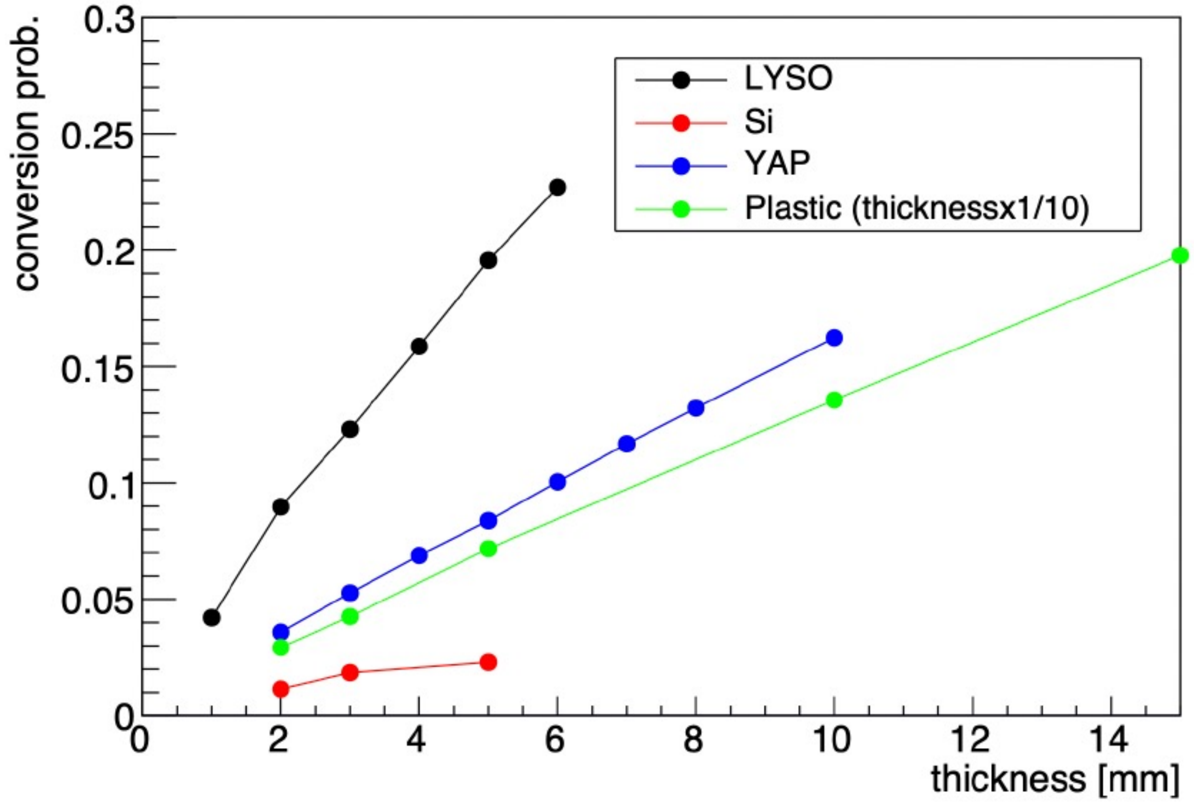




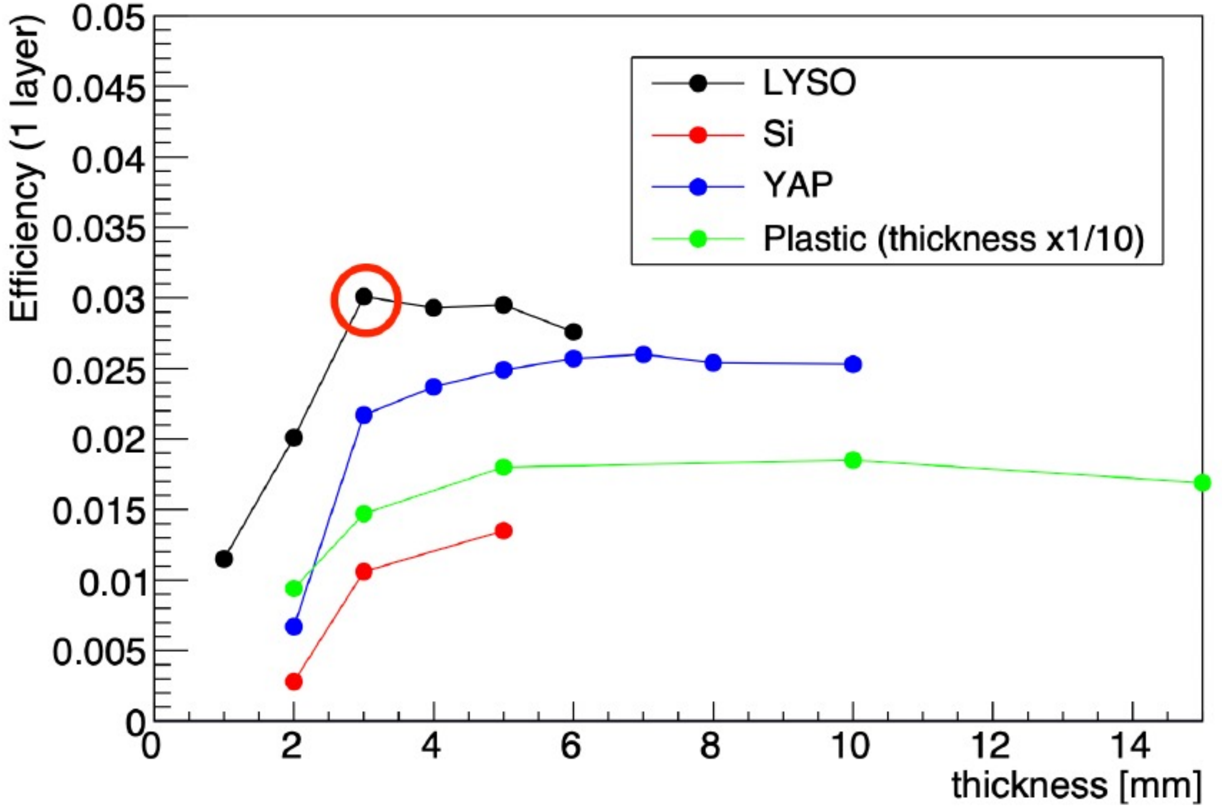
- steeper injection angle event has
  - more lightyield
    → improve time resolution
  - larger expansion in photon emission region
    → worsen time resolution

LYSO achieved the goal resolution of 42 ps with all injection angle

comparison between material & thickness



(a) 異なる材質ごとの厚みに対するコンバージョン確率

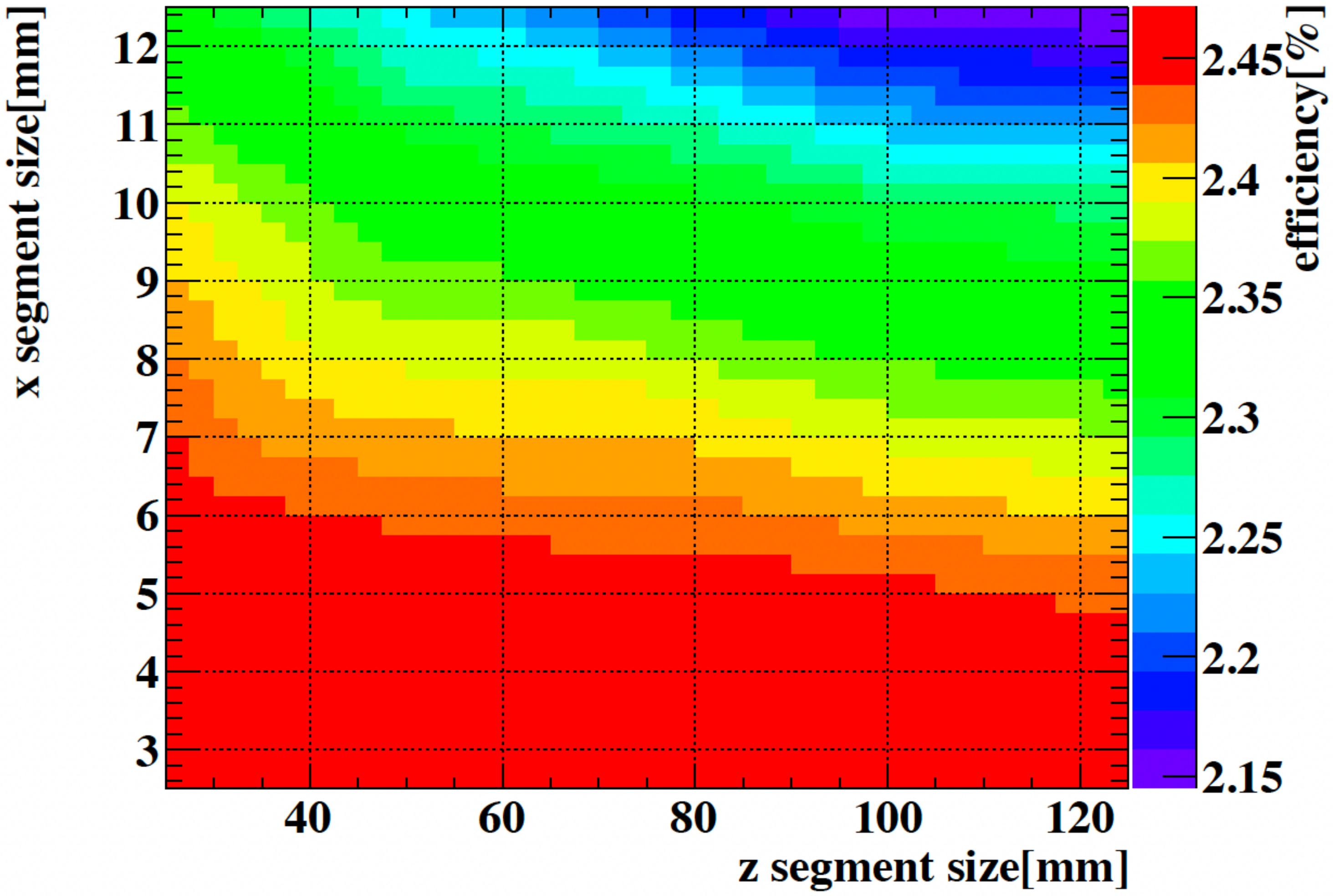


(b) 異なる材質ごとの厚みに対する検出効率

- conversion probability
- energy loss due to the bremsstrahlung

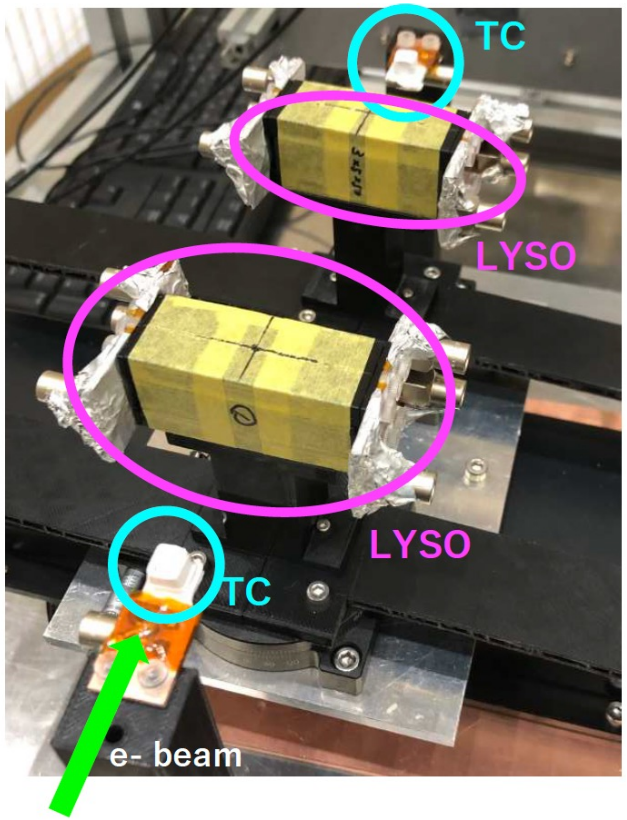
} increase with thickness

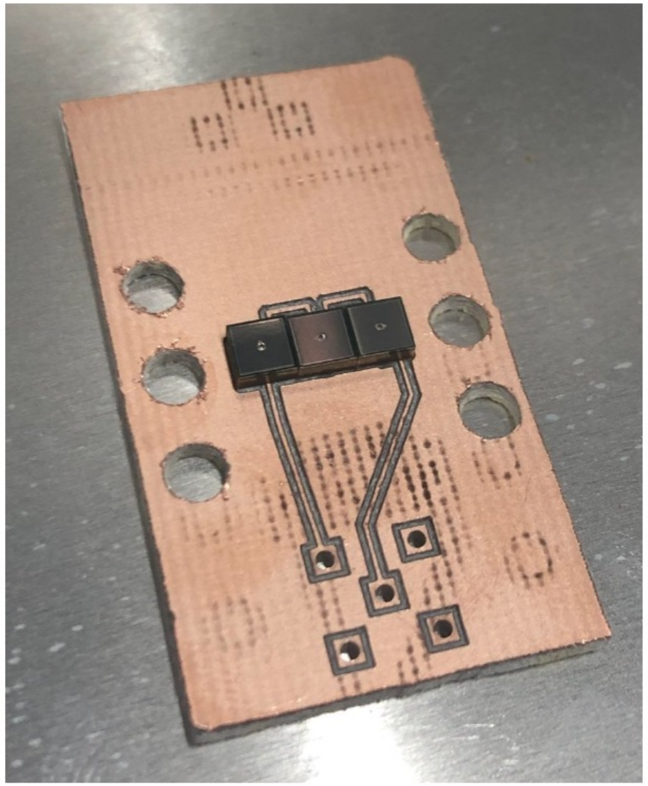
→ best balance at 3 mm thickness

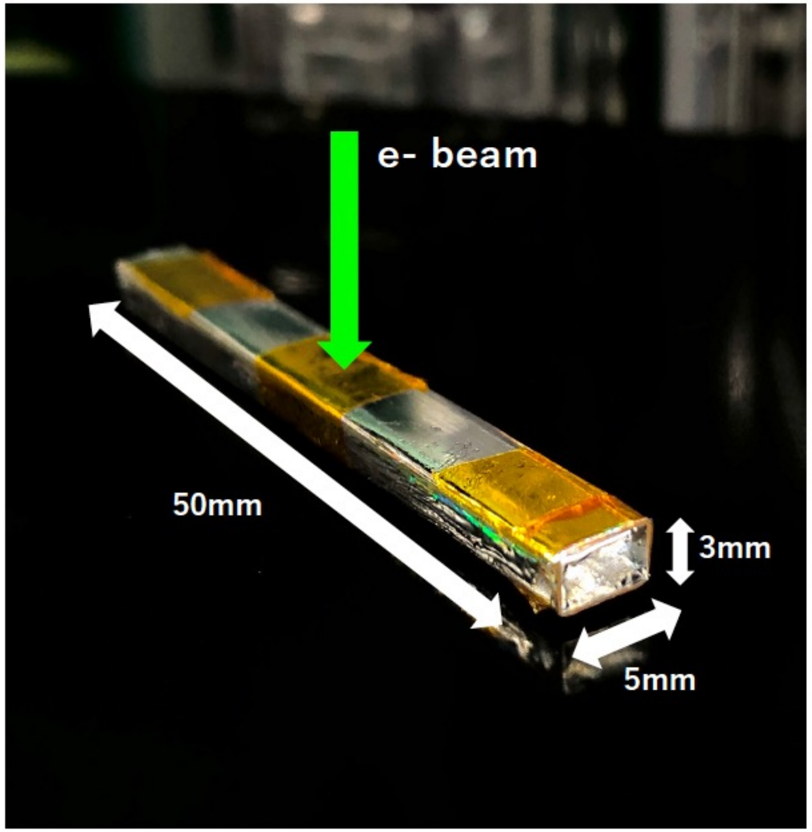


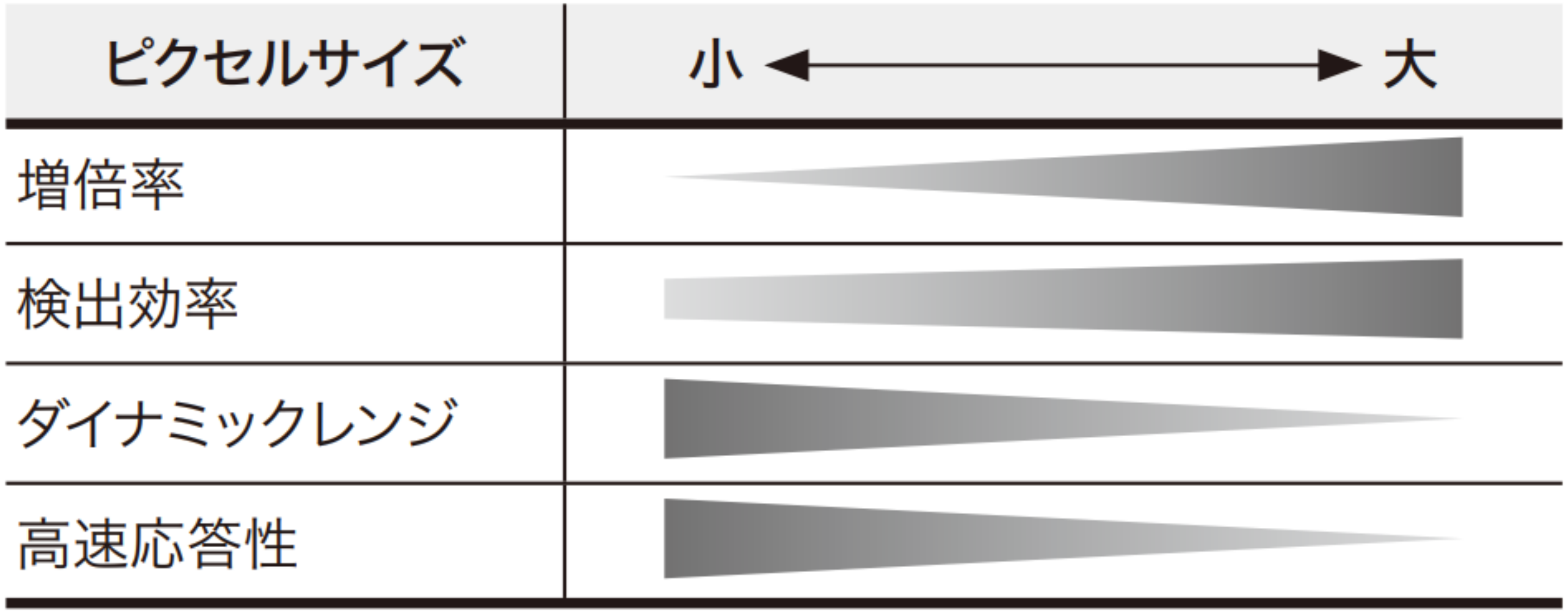
efficiency in 3 mm thickness LYSO

pictures





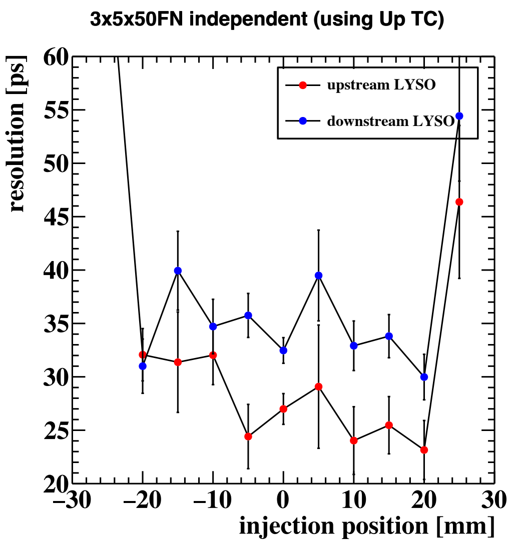


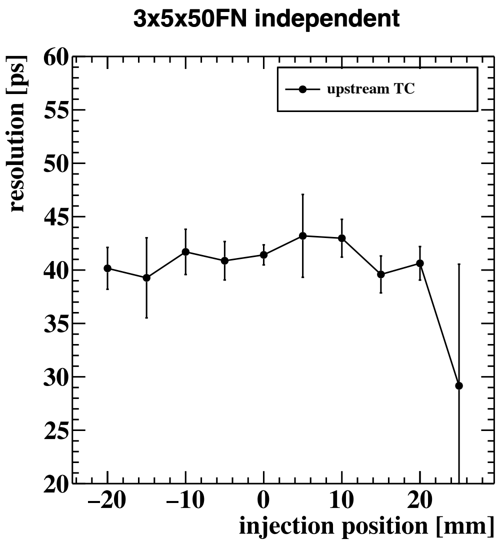

ピクセルサイズ
小
大
増倍率
検出効率
ダイナミックレンジ
高速応答性

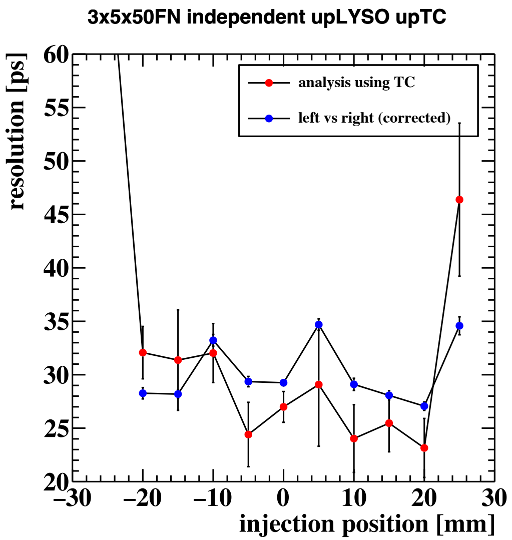
JTC's Scintillation Product Information

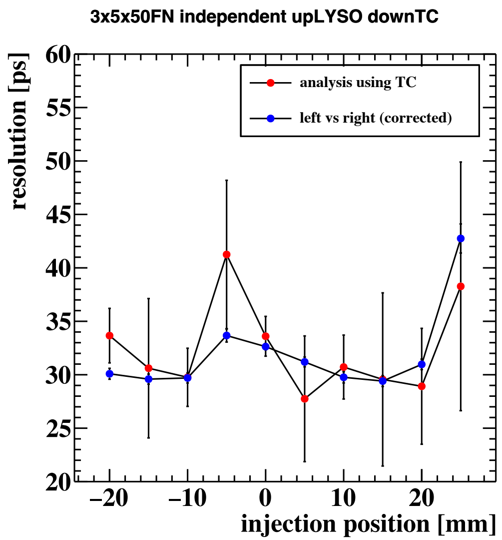
Properties	Ce:FTRL	Ce:LYSO	YSO
Coincident Time Resolution(ps) 2mm cube	96	125	
LO (Ph/MeV)	30000±10%	36000±10%	27000
Decay Time (ns)	31	40	70
Energy Resolution	8-10%	8-10%	11%
Hygroscopic	No	No	No
Wavelength of Max Emission (nm)	420	420	420
Refractive Index	1.81	1.81	1.8
Density (g/cm3)	7.2	7.2	4.5

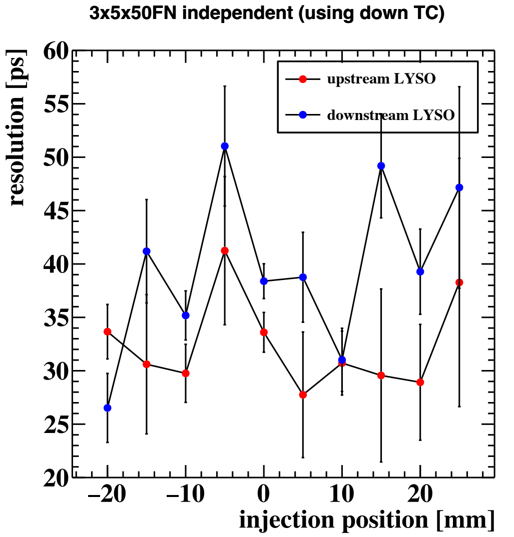
3 x 5 x 50 F&N (independent) position scan

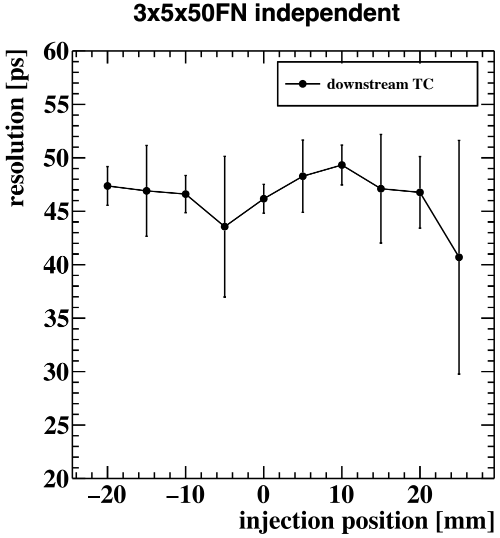


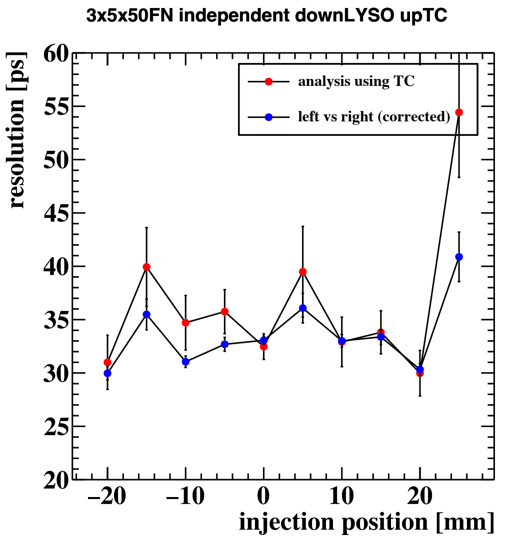


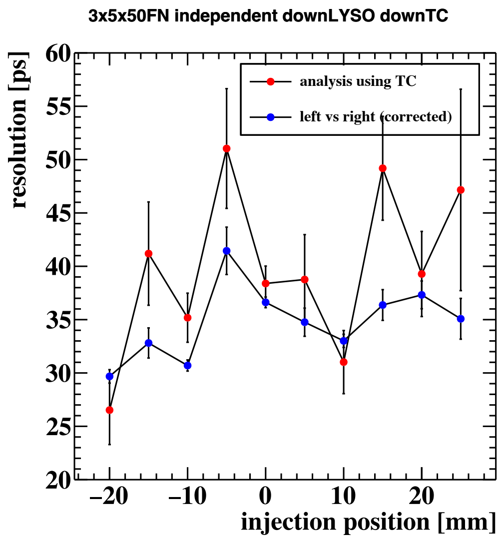




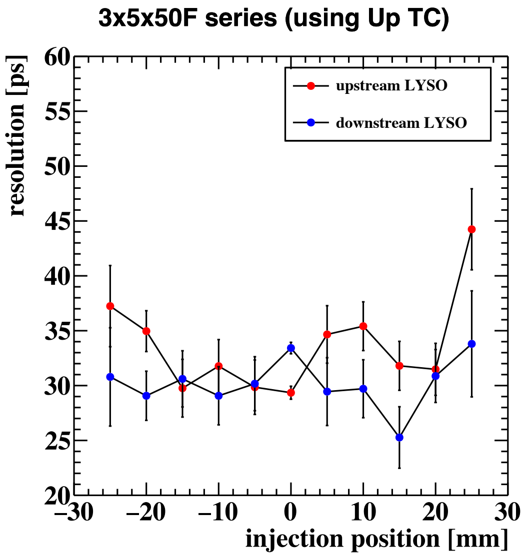


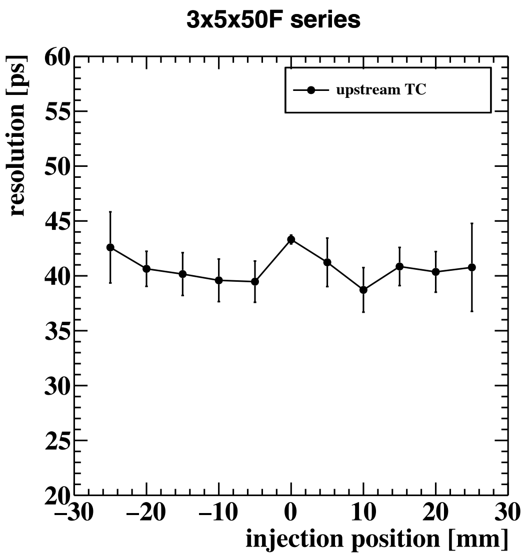


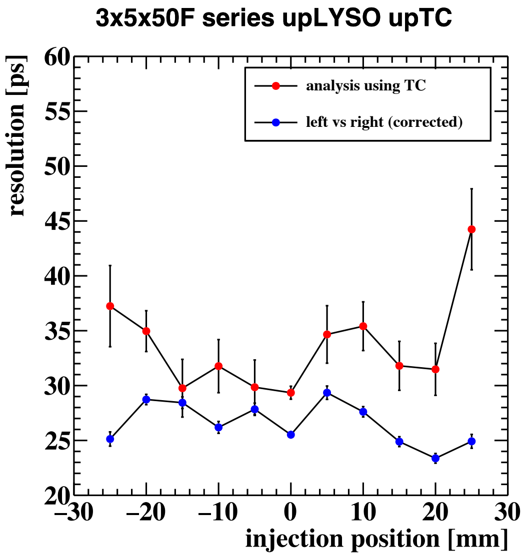


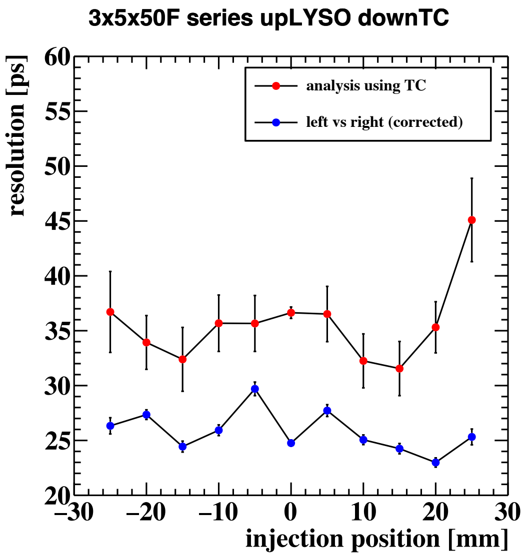


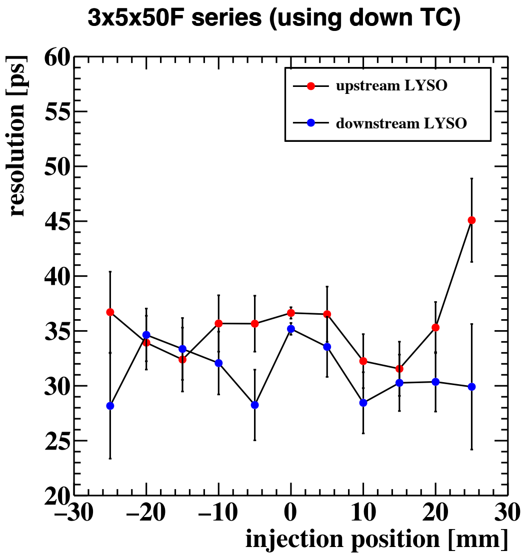
3 x 5 x 50 F (series) position scan

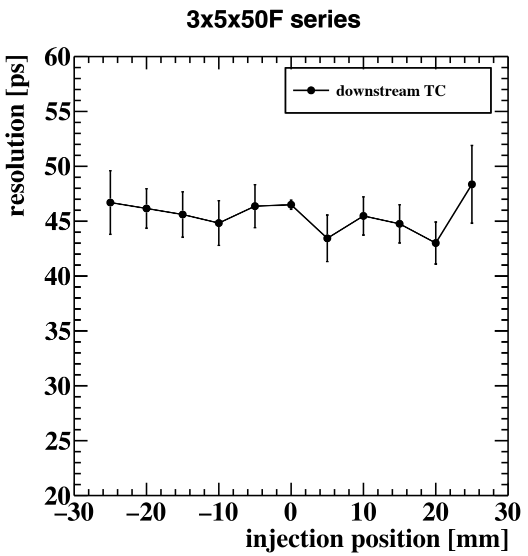


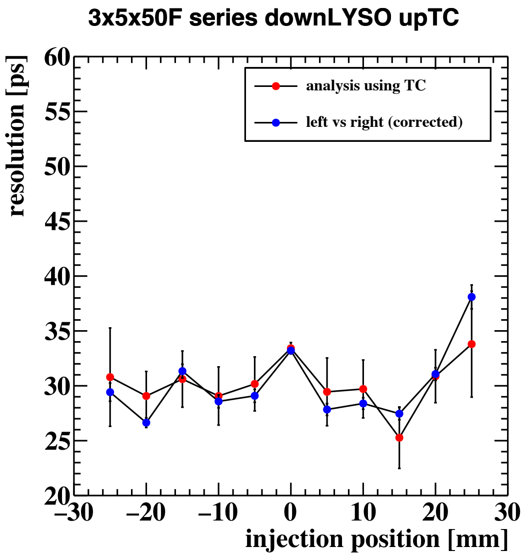


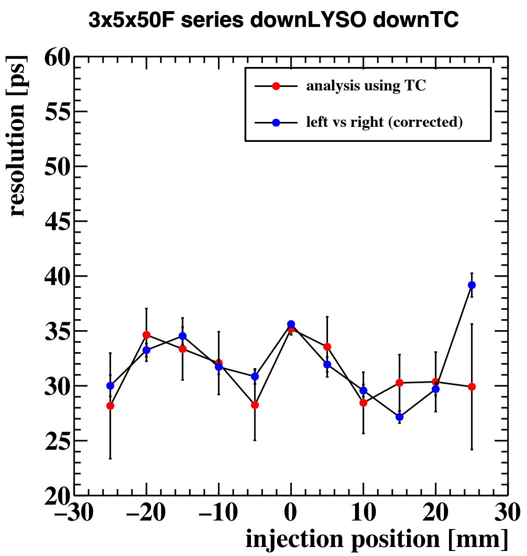




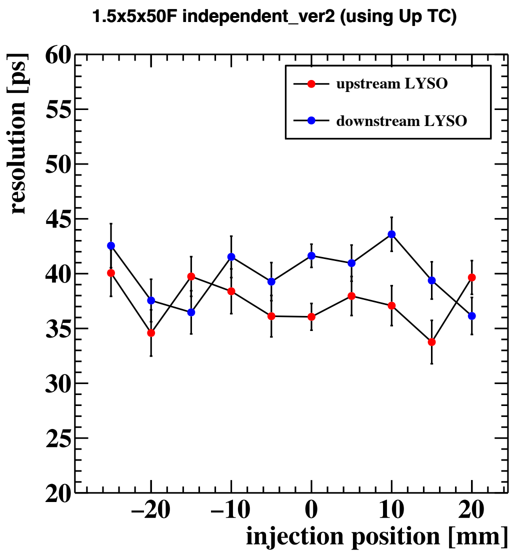


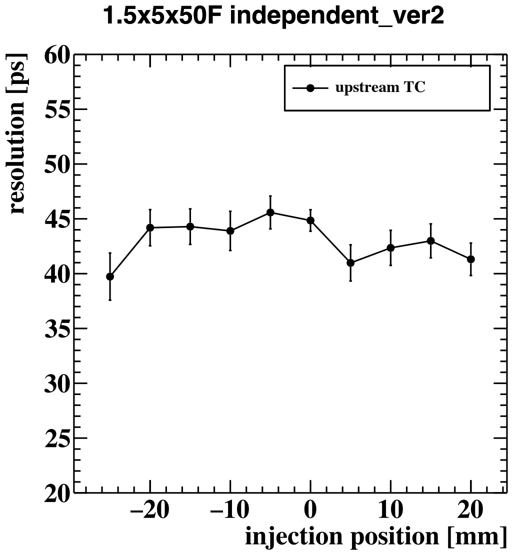


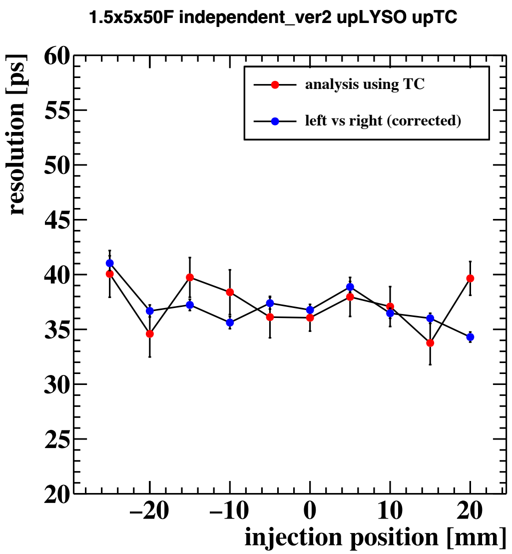


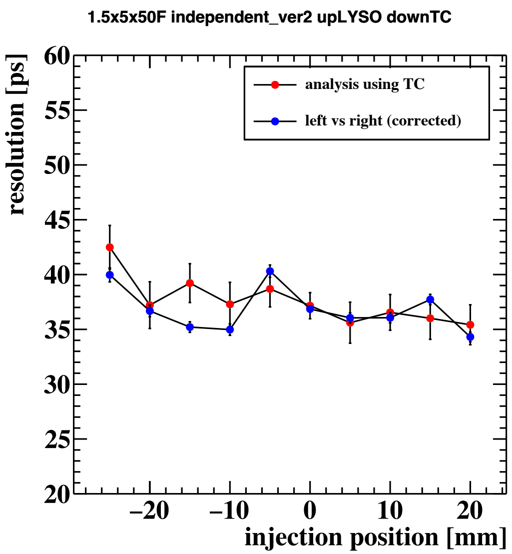


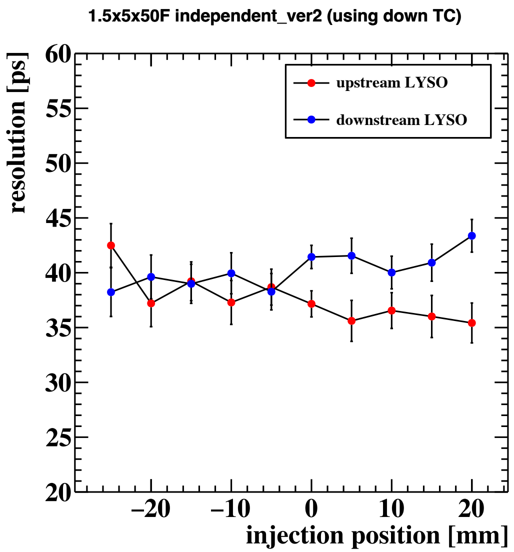
1.5 x 5 x 50 (independent) position scan

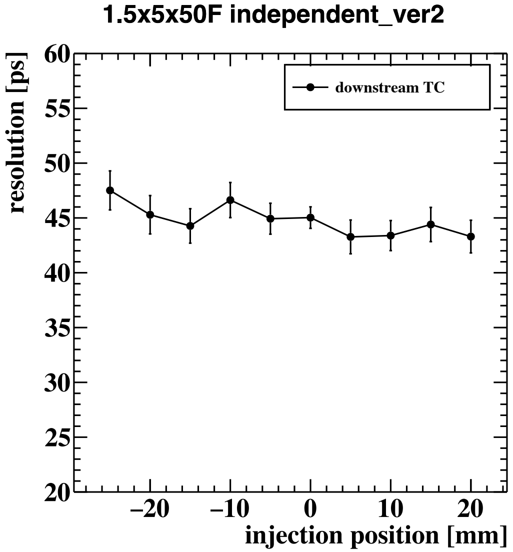


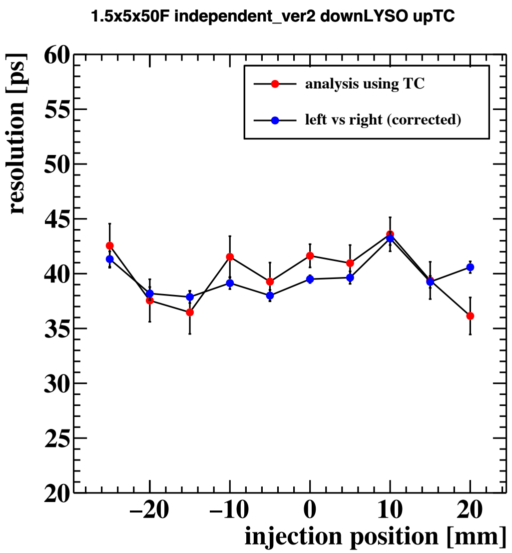


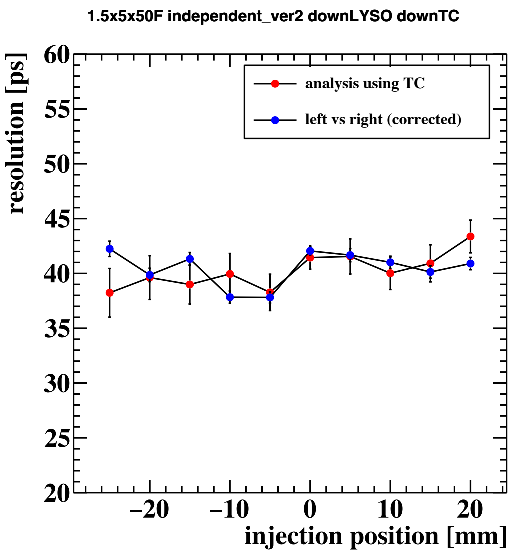




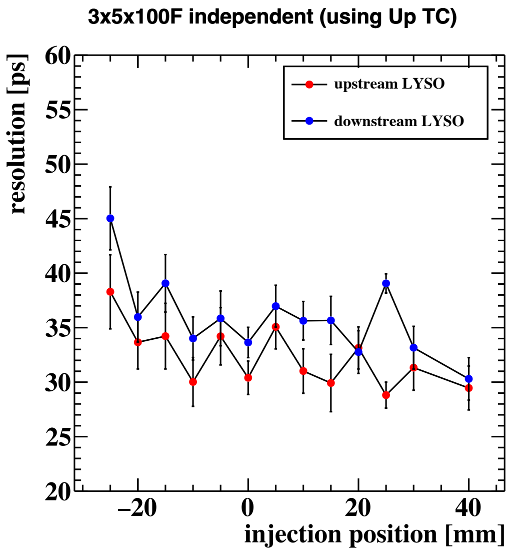


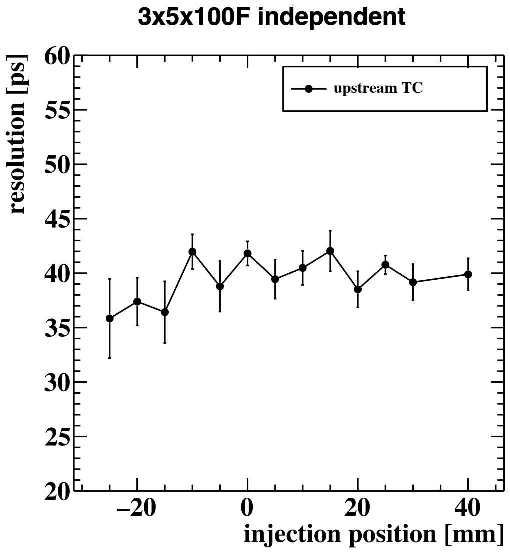


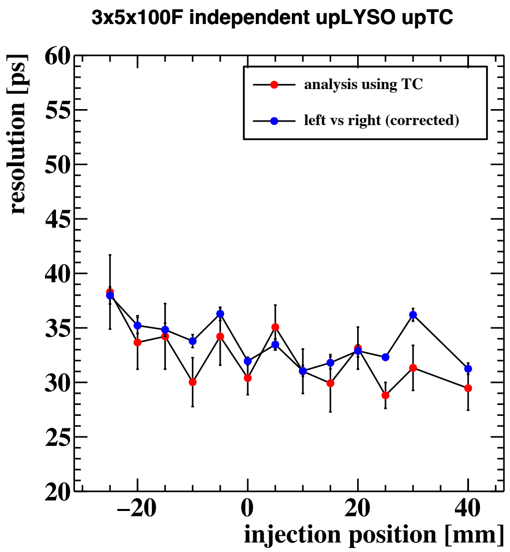


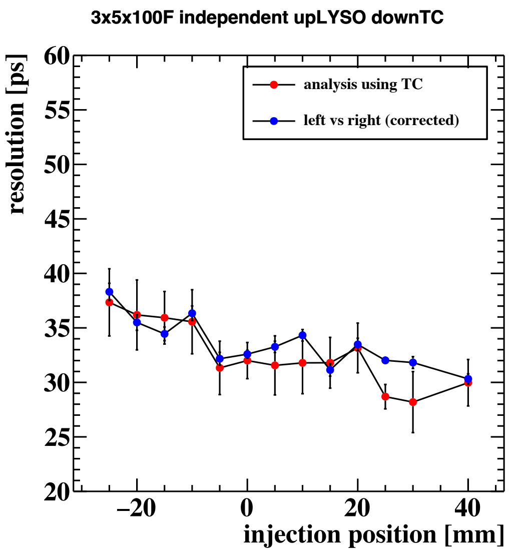


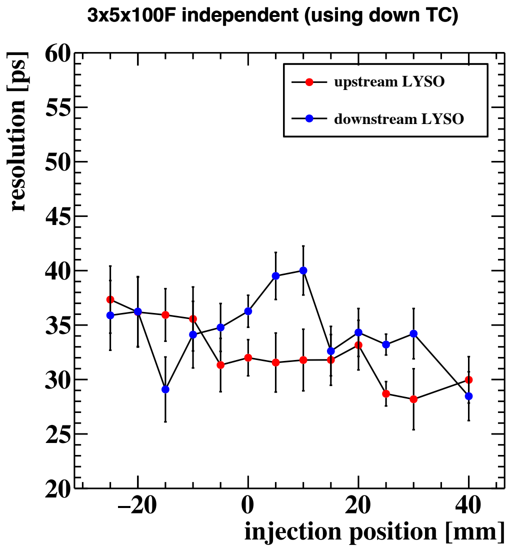
3 x 5 x 100 (independent) position scan

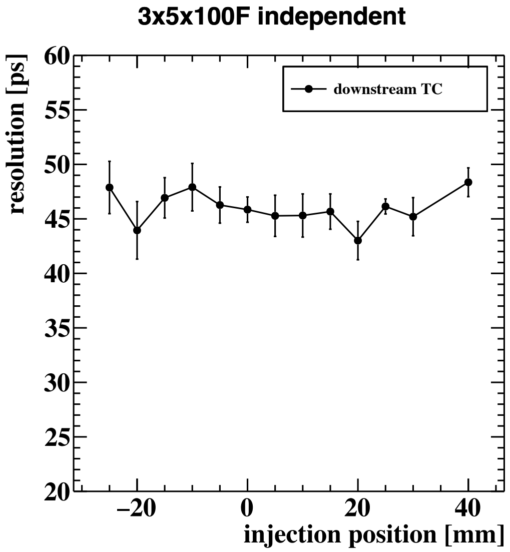


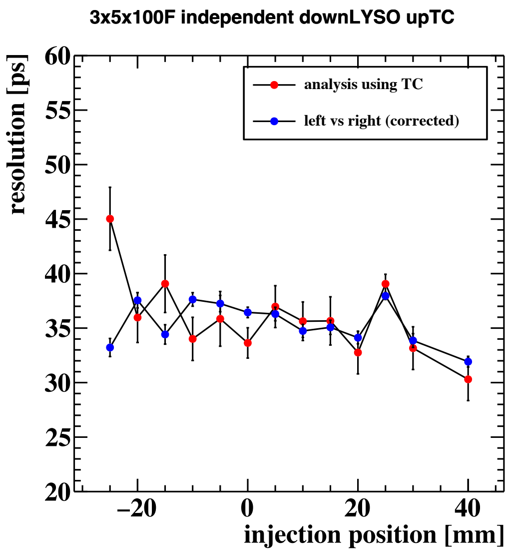


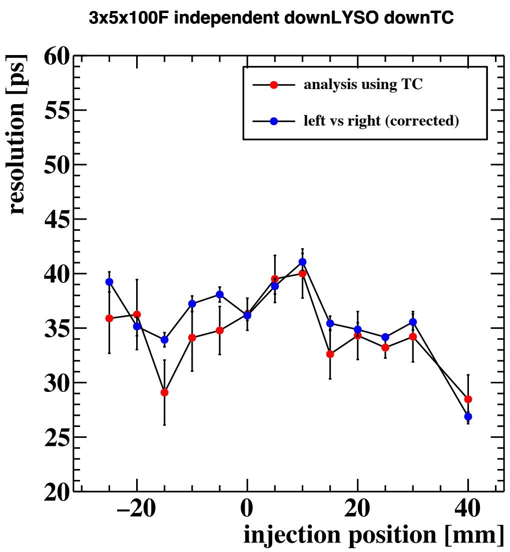




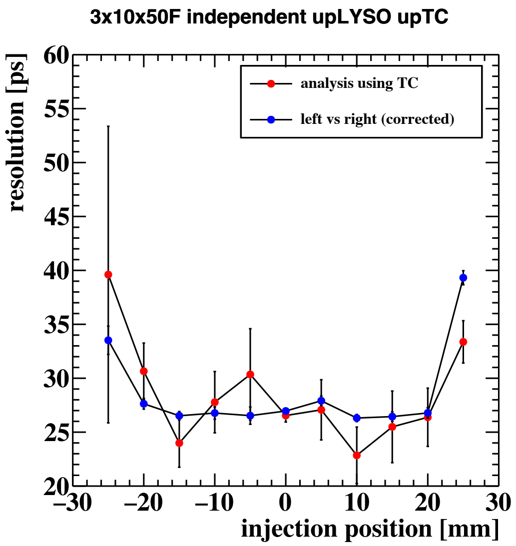


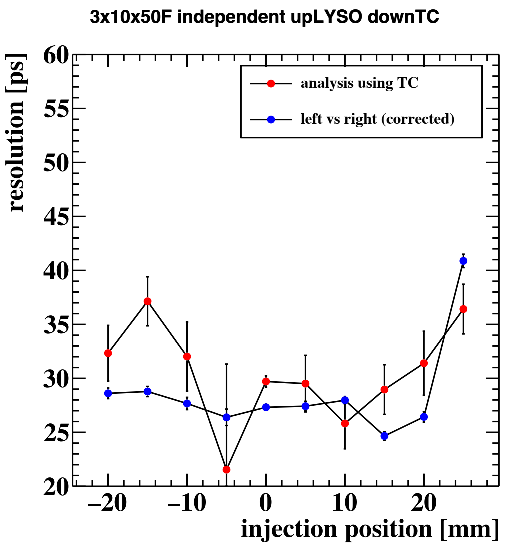


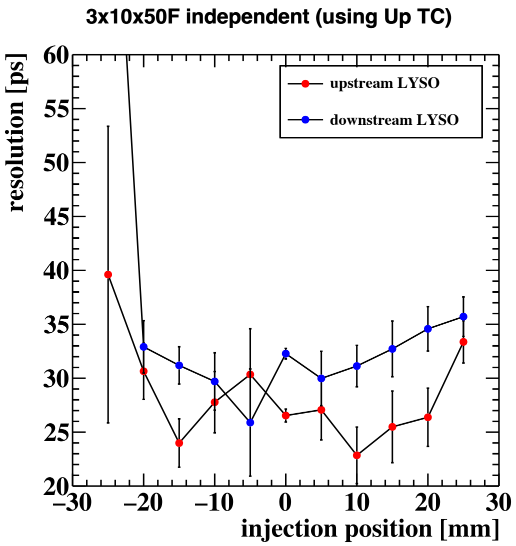


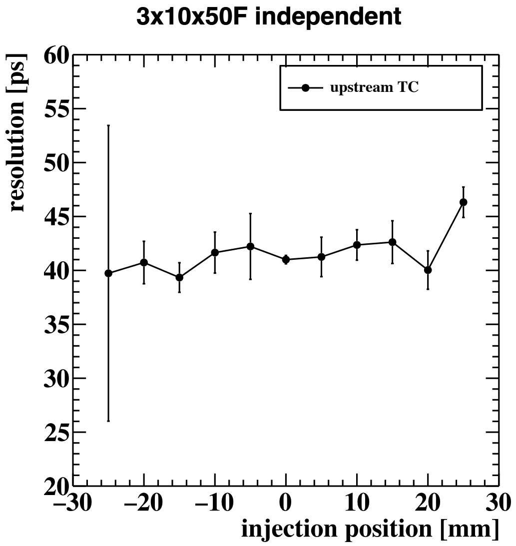


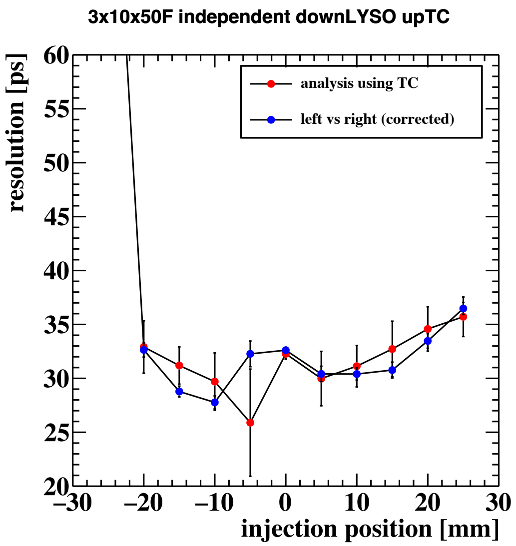
3 x 10 x 50 (independent) position scan

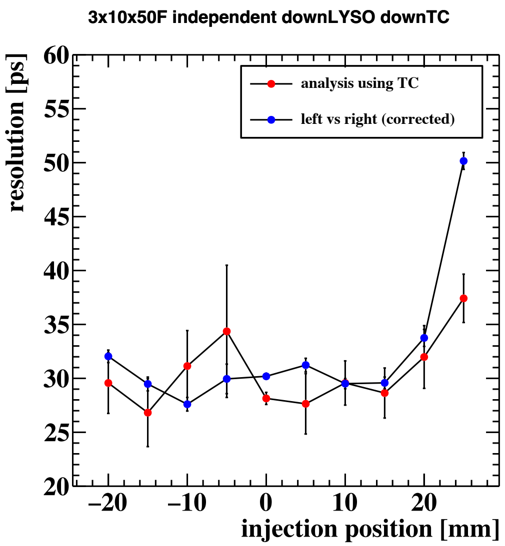


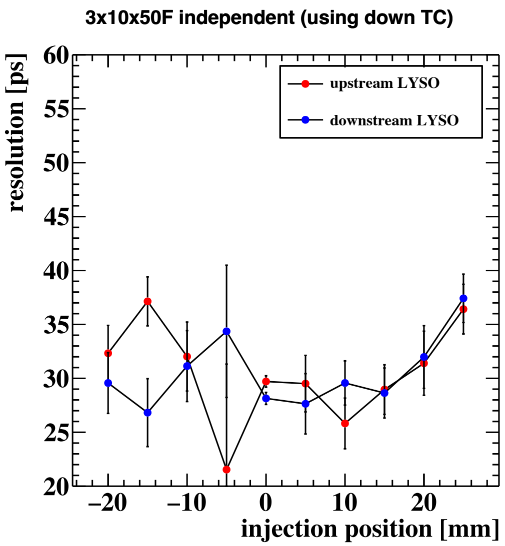


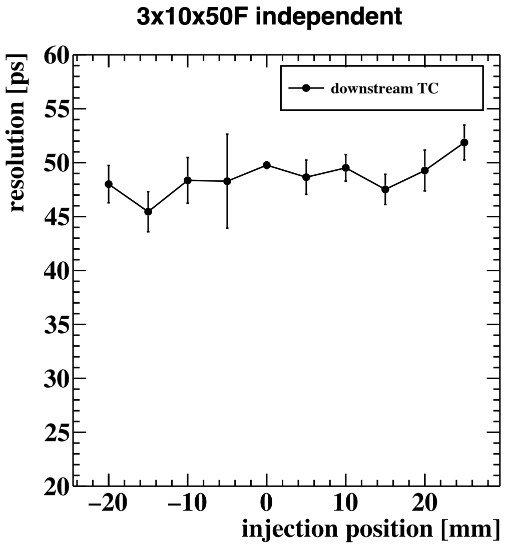




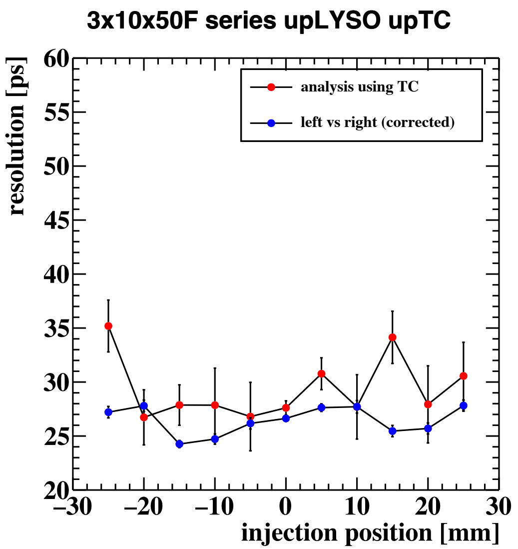


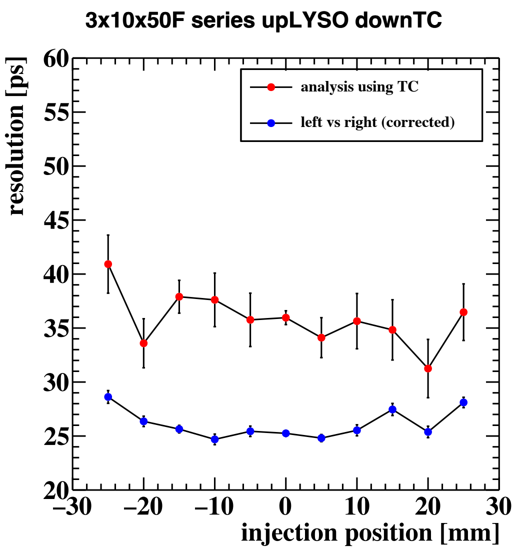


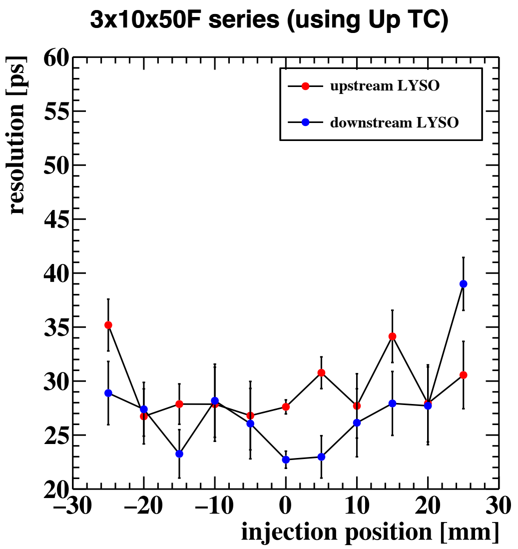


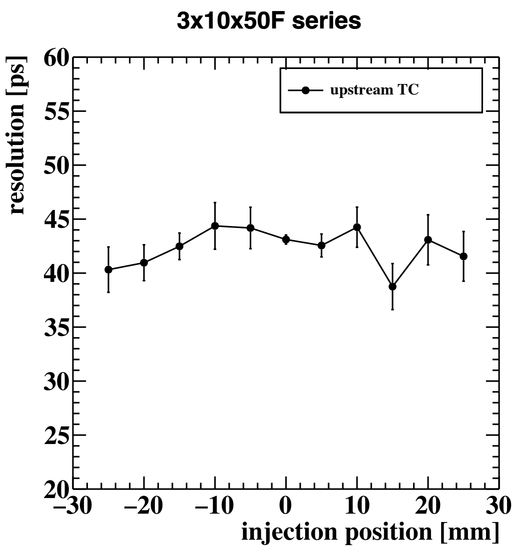


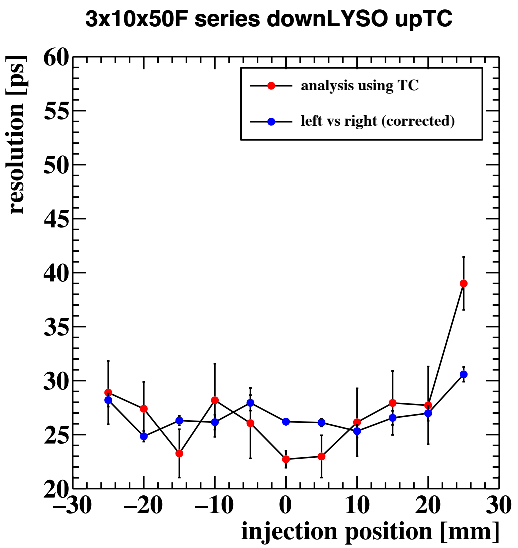
3 x 10 x 50 (series) position scan

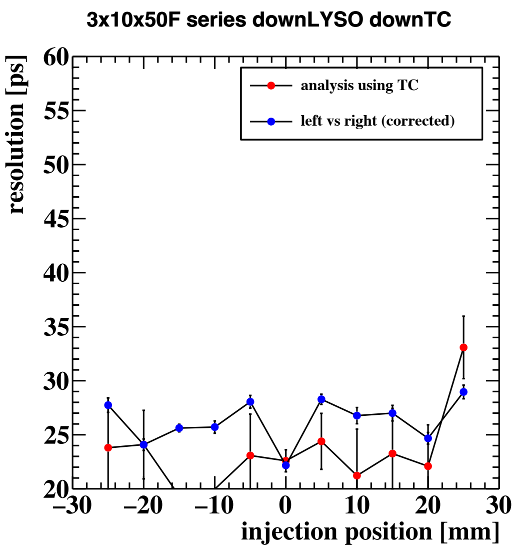


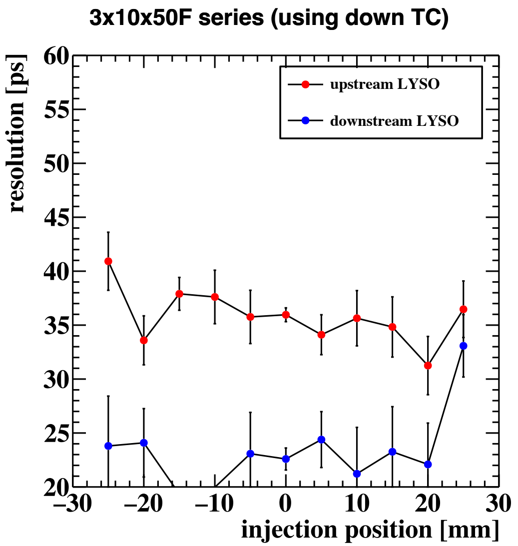


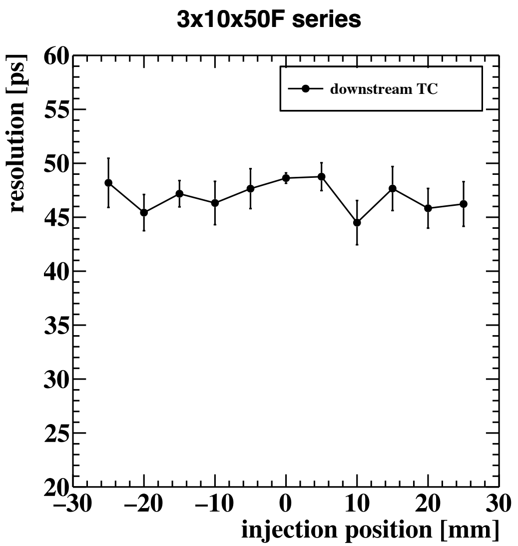




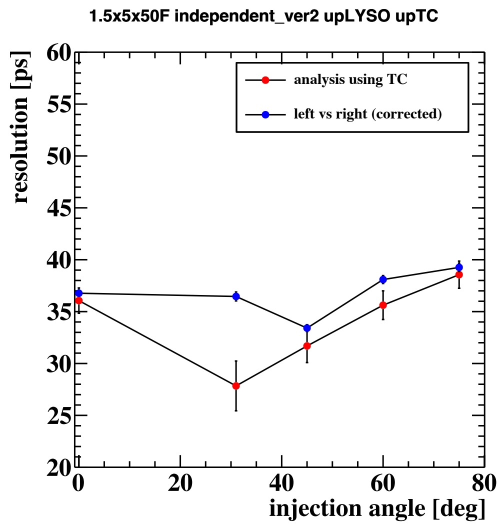


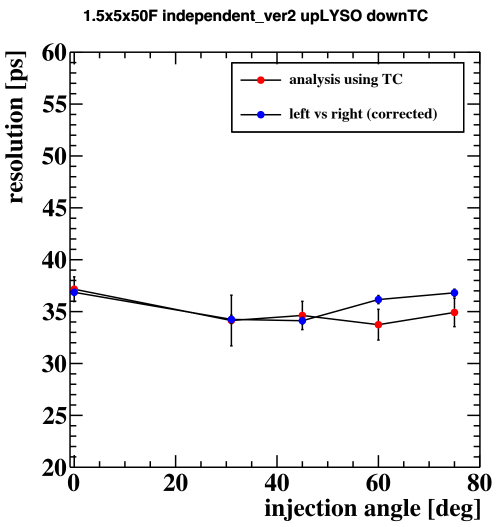


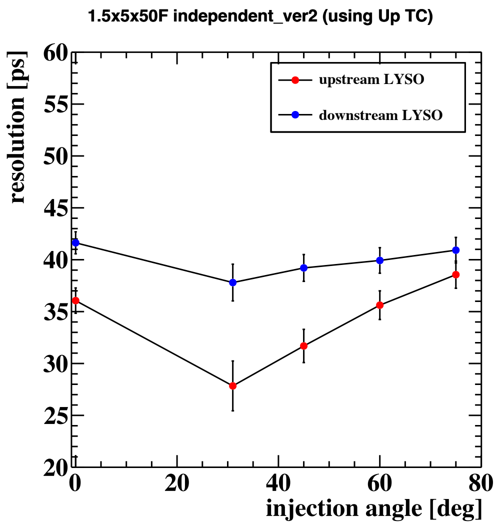


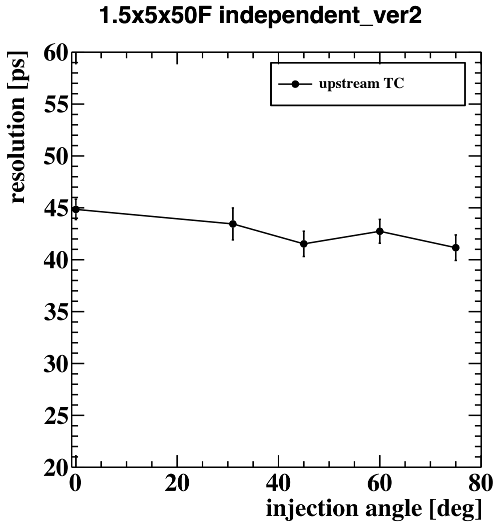


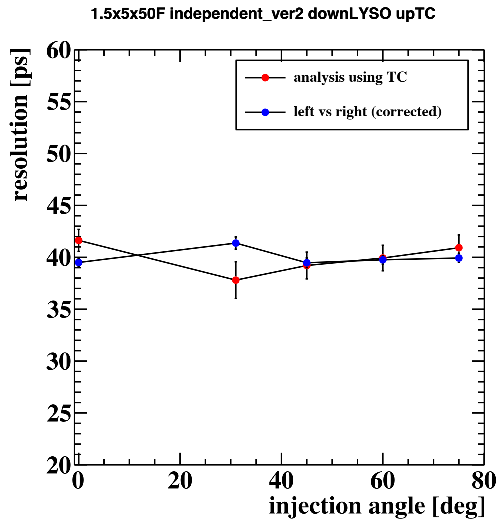
1.5 x 5 x 50 angle scan

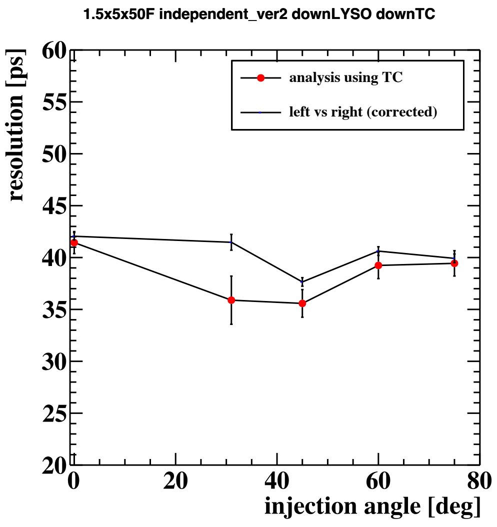


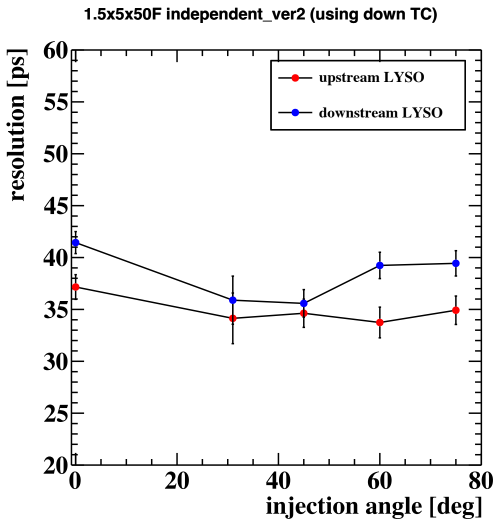


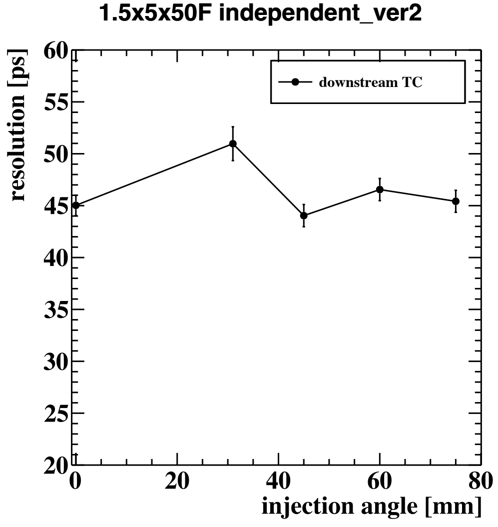












3 x 10 x 50 angle scan