Tracking performance studies for FASERν2/FASER2

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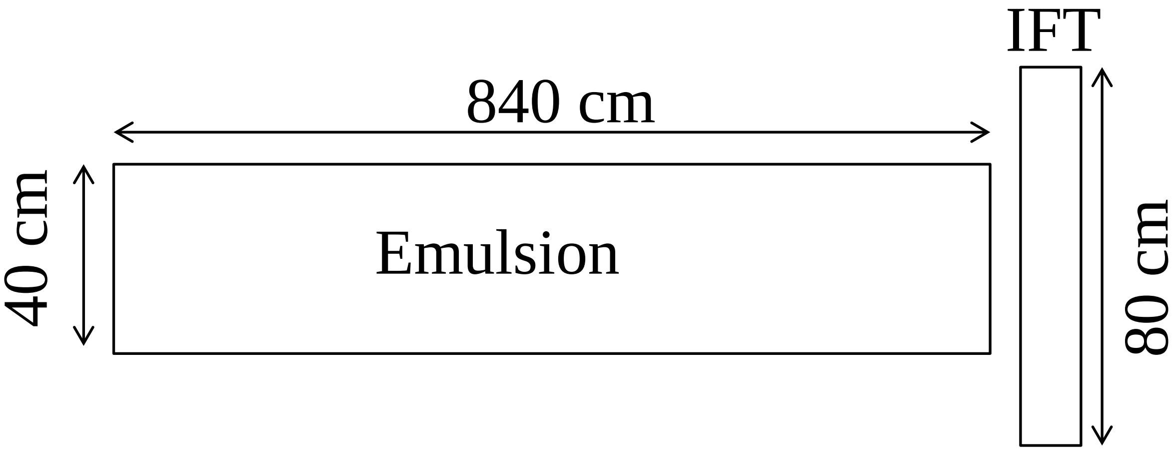
Track matching with Emulsion/IFT

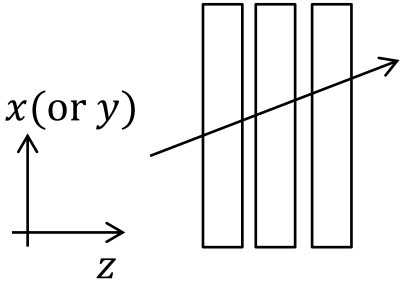
IFT for FASERν2

- IFT will be used as an interface tracker between emulsion detector and FASER2 tracker.
  - Detector candidates : silicon strip detector (SCT), scintillating fiber
- The studies on tracking performance and capability of track matching between emulsion and tracker were just started.
  - Assuming one IFT with 3 layers just behind the emulsion detector.
  - Emulsion: 40 x 40 x 840 cm^3, IFT: 80 x 80 cm^2

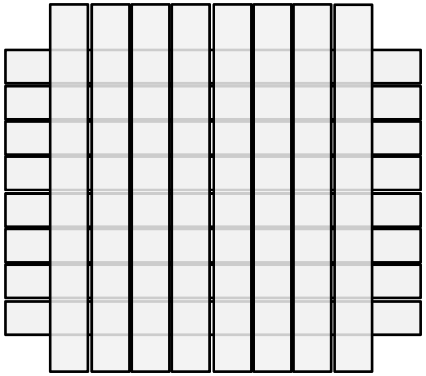


Tracking performance in IFT (1)

- Performance of the tracking with IFT only was evaluated with a linear fitting of hit positions in IFT: $x(\text{or } y) = \alpha z + \beta$



- A charged particle is assumed to come from (x, y, z)=(0,0,0) with $\vec{p}$ = (0,0, p_z).
- Fitting is done 1000 times for each p_z, fluctuating the hit position with the position resolution.
- Position resolution: 16 um (SCT), 50 and 100 um (scinti. fiber)
  - ➢ Two strip sensors in a module / scintillating fiber layers are considered to be placed with 90 degrees of the stereo-angle.



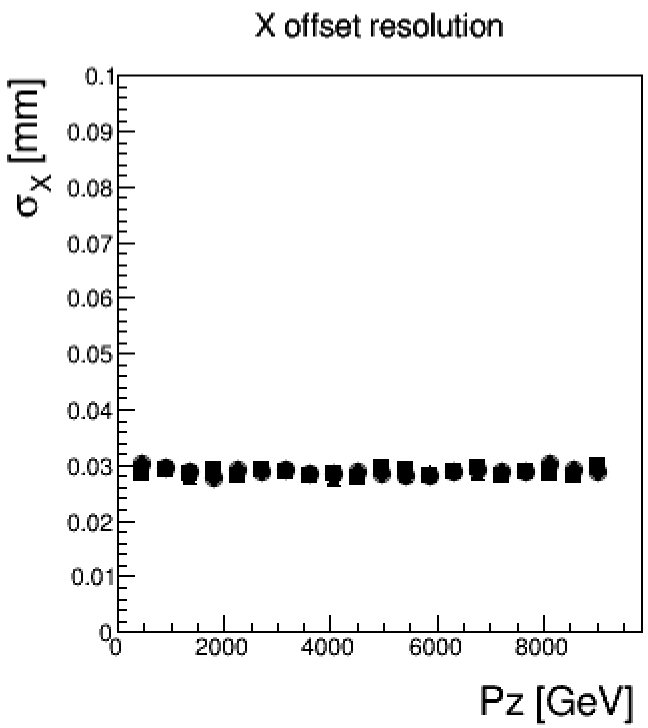
Tracking performance in IFT (2)

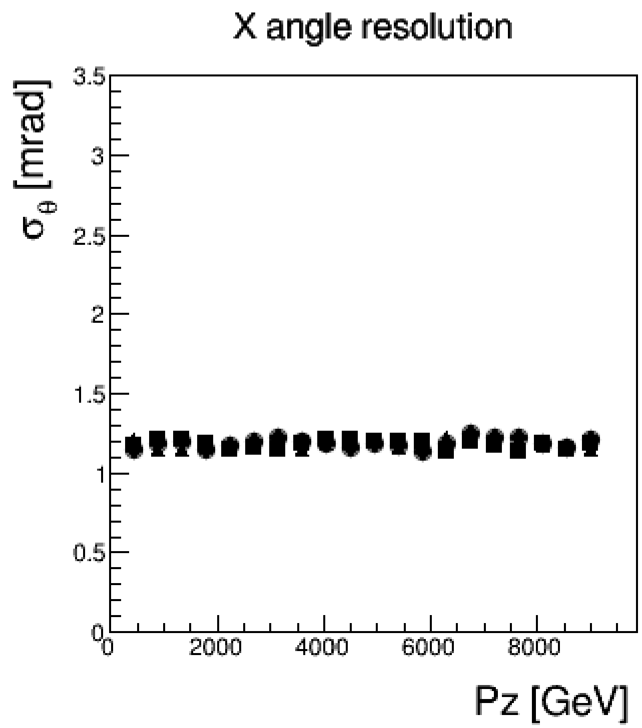
$x(\text{or } y) = \alpha z + \beta$

- σ_α: angular resolution
- σ_β: offset resolution

σ_{xy}	Offset reso.	Angular reso.
16 um	~10 um	~0.4 mrad
50 um	~30 um	~1.2 mrad
100 um	~58 um	~2.4 mrad

Offset/angular reso. with 50 um of IFT position reso.



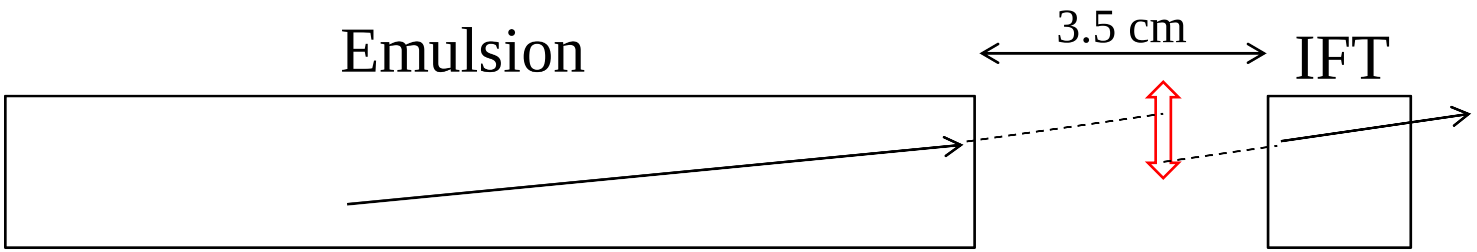


Track matching capability (Introduction)

- Matching probability of signal-signal and signal-background was studied with Emulsion and IFT ($R_{\mathrm{em}1/2} = 12.5/20$ cm).
- $\left[4k \times \frac{R_{\mathrm{em}2}^2 L_{\mathrm{em}2}}{R_{\mathrm{em}1}^2 L_{\mathrm{em}1}} \text{ signal}\right]$ v.s. $\left[40k \times \frac{R_{\mathrm{em}2}^2}{R_{\mathrm{em}1}^2} \text{ background}\right]$ (@30fb^{-1})
- The signal tracks were generated with distributions in Backup which was used for the studies on the current FASER.
  - Angular distribution: $\sigma_\theta \sim 35$ (ν_μ), 27($\bar{\nu}_\mu$) mrad.
- Backgrounds were injected with $\sigma_\theta = 2$ mrad. and uniformly in radius.
- The position and angular resolution of the emulsion are assumed to be 1 um and 0.5 mrad., respectively.
- 3.5 cm was used for the gap between the last layer of emulsion and the first layer of IFT.

Track matching capability (Method)

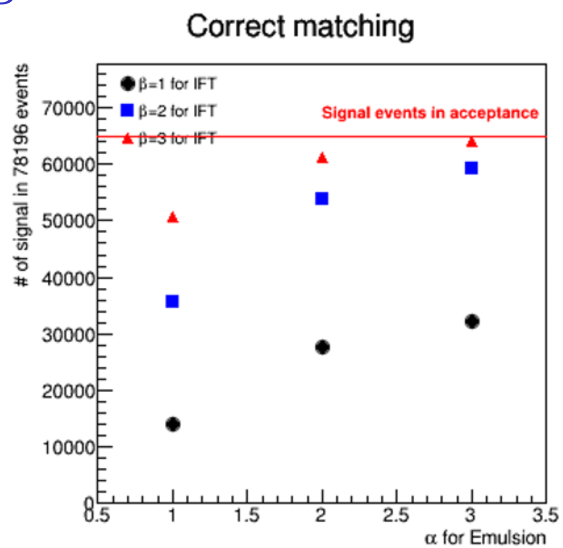
- $(x, y, \theta_x, \theta_y)$ was fluctuated by the resolutions of Emulsion and IFT, separately.
- If $(\Delta x, \Delta y, \Delta\theta x, \Delta\theta y)$ is within $(\sigma_x, \sigma_y, \sigma_{\theta x}, \sigma_{\theta y})$, the track is assumed as matching.
  - $\Delta x = x(\text{Emulsion}) - x(\text{IFT})$
  - $\sigma_{x/y} = \sqrt{(\alpha \cdot \sigma)^2_{Emulsion} + (\beta \cdot \sigma)^2_{IFT} + \sigma^{min,2}_{x/y(gap)}}$
  - $\sigma_{\theta x/\theta y} = \sqrt{(\alpha \cdot \sigma)^2_{Emulsion} + (\beta \cdot \sigma)^2_{IFT}}$
  - Matching is checked by changing α/β (=1, 2, 3).



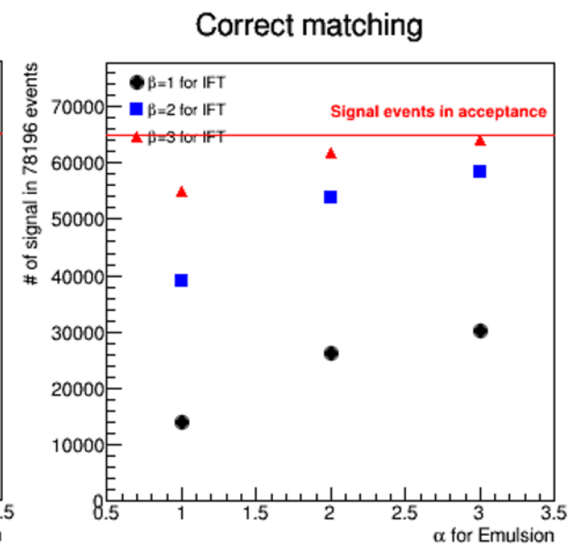
Track matching capability (ν_μ)

Signal-signal matching

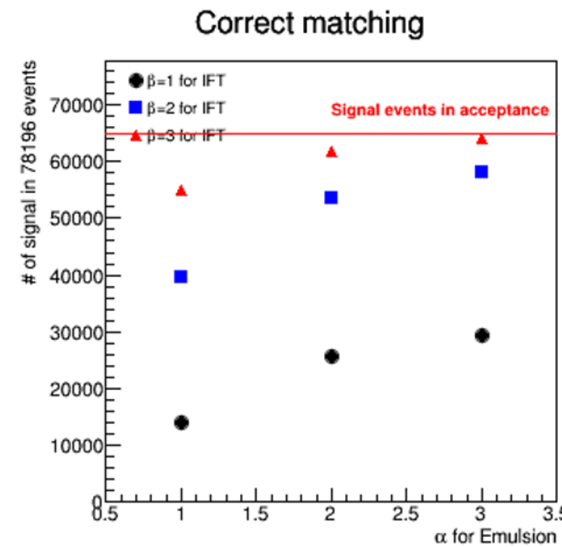
$\sigma_{xy}(\mathrm{IFT}) = 16$ um



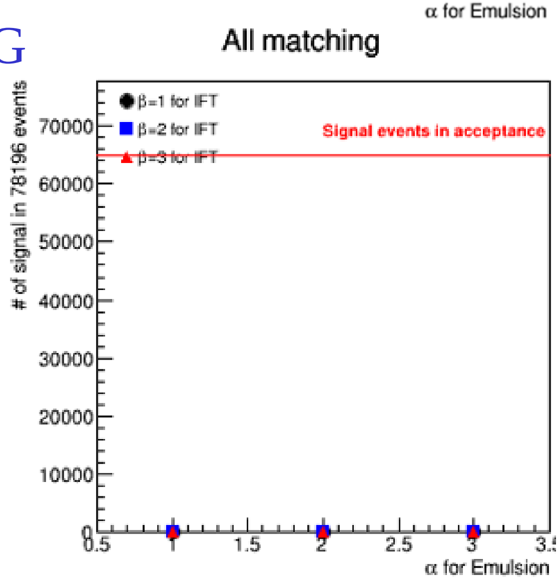
$\sigma_{xy}(\mathrm{IFT}) = 50$ um

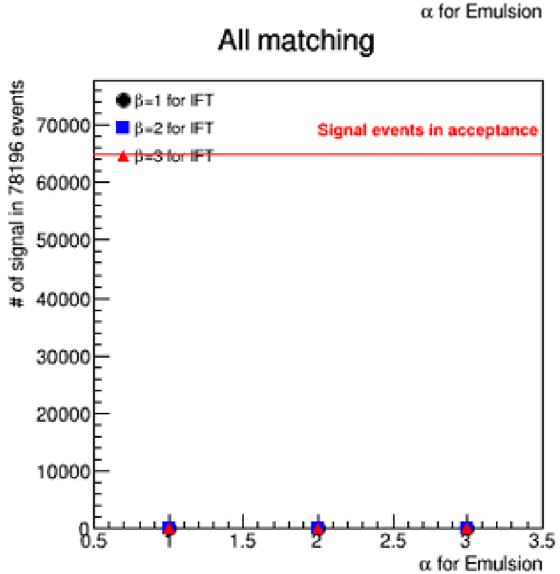


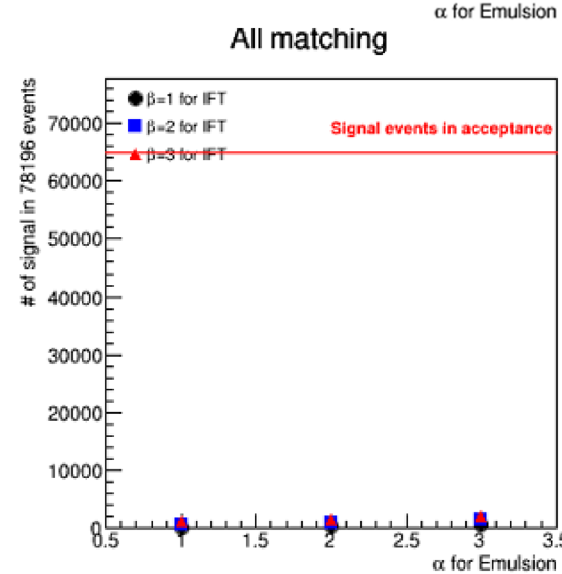
$\sigma_{xy}(\mathrm{IFT}) = 100$ um



Signal-BG matching



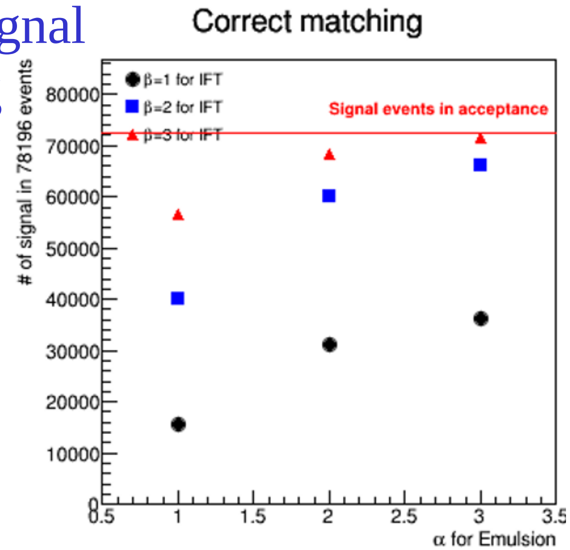


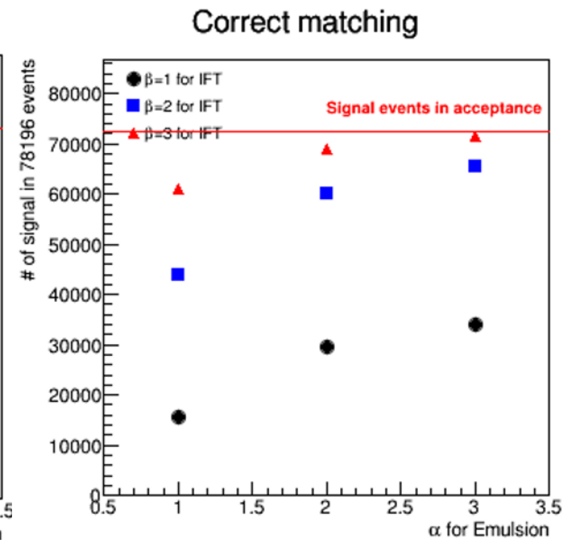


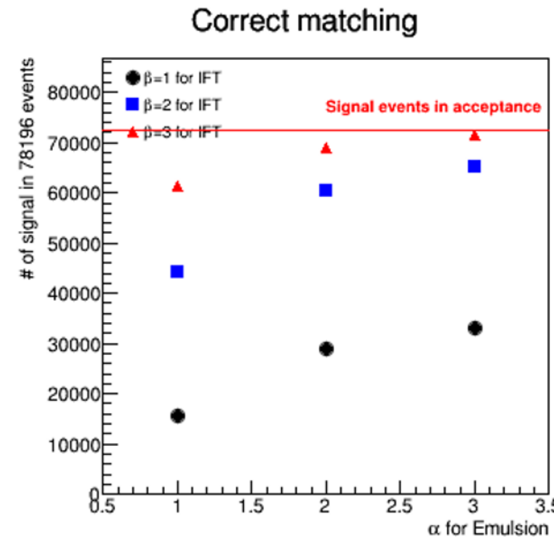
Track matching capability ($\bar{\nu}_\mu$)

$\sigma_{xy}(\text{IFT}) = 16$ um | $\sigma_{xy}(\text{IFT}) = 50$ um | $\sigma_{xy}(\text{IFT}) = 100$ um

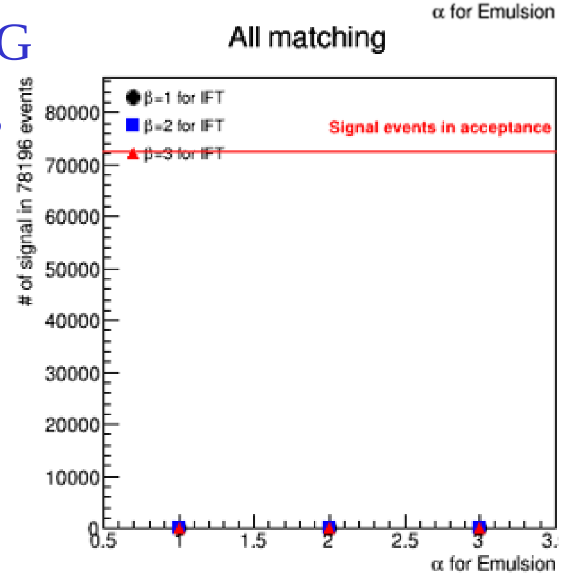
Signal-signal matching

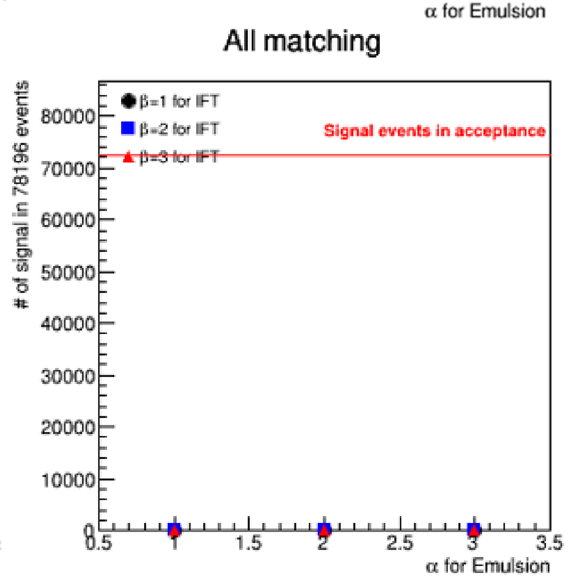


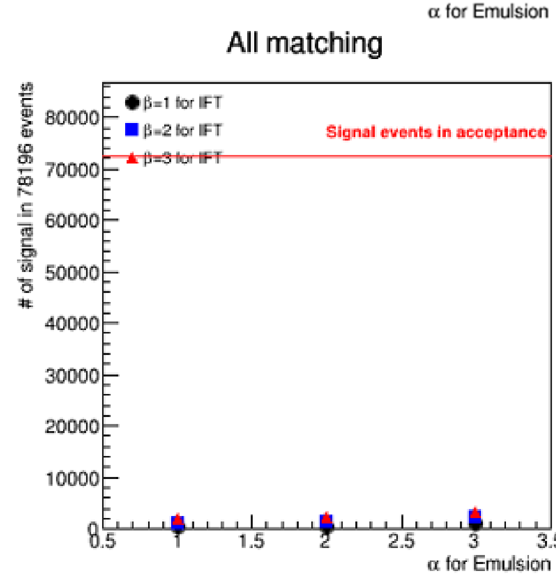




Signal-BG matching



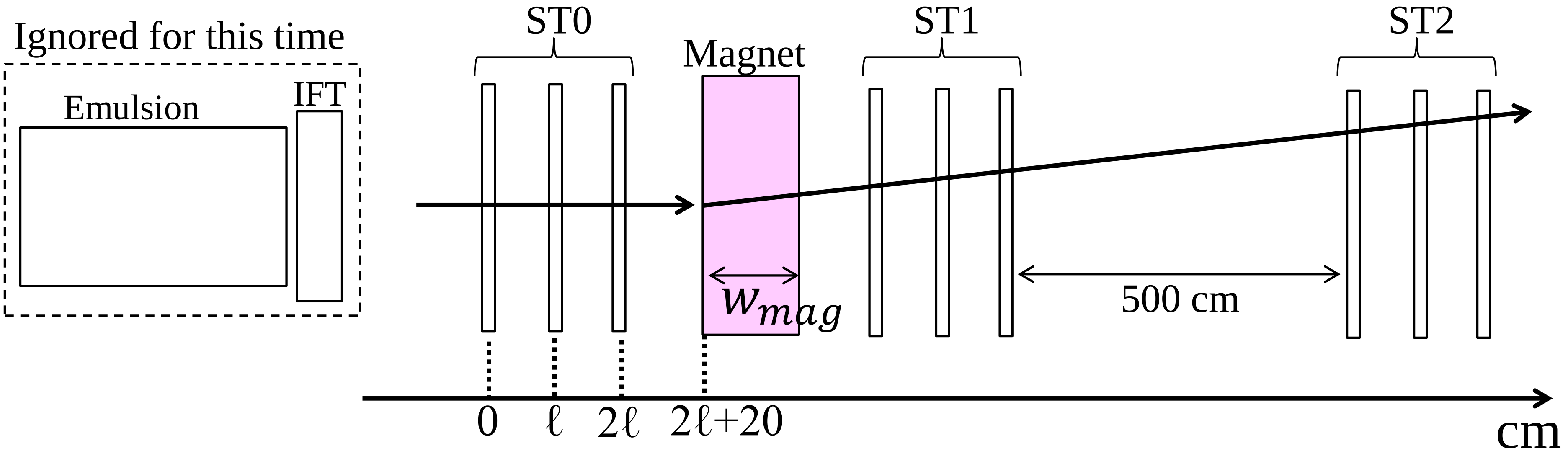




Tracking performance with FASER2 tracker

Charge ID capability and momentum resolution

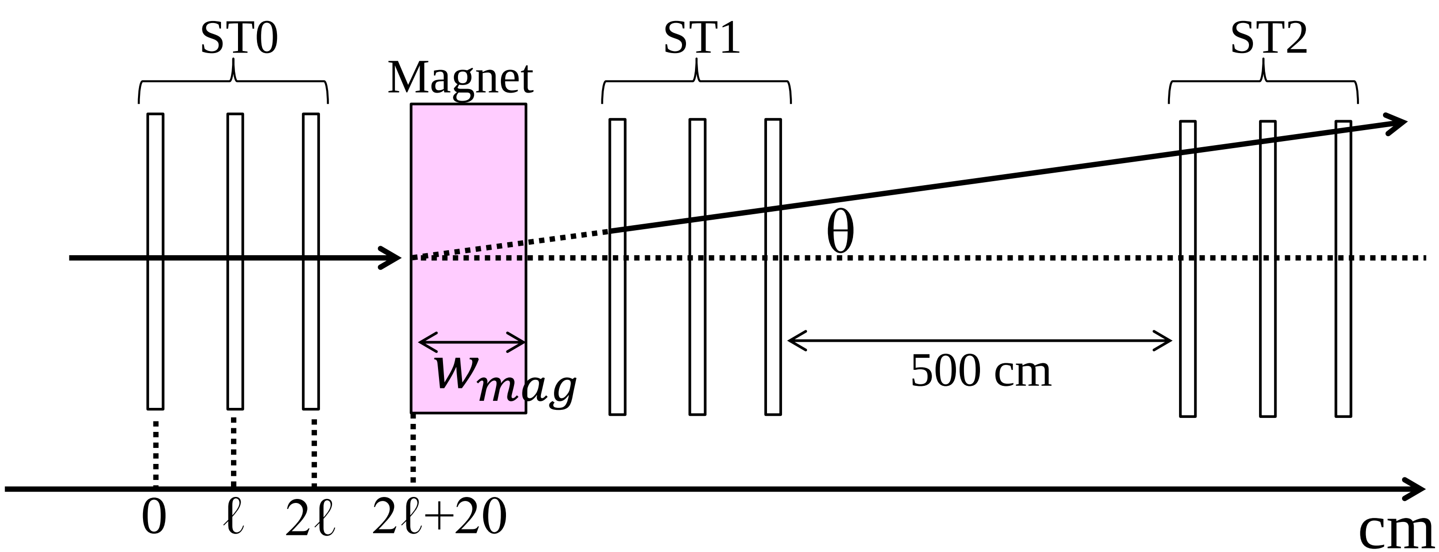
- 3 tracker stations with 3 single-layers (ST0-2) are placed before and after the magnet.
  - 80 um position resolution
  - 50 or 100 cm gap between each layer (ℓ)
  - Distance between ST1 and ST2 is set to 500 cm.
- Magnetic field is changed to 1/2/4 Tm with 50 cm length (w_{mag}).



Momentum reconstruction

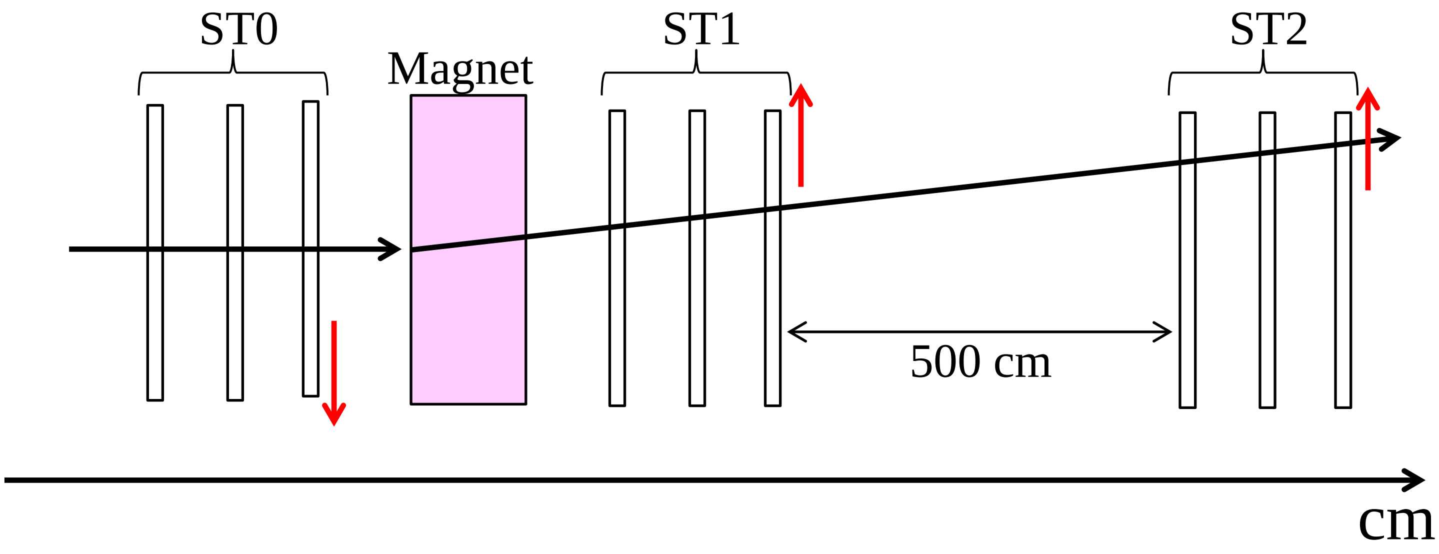
- The linear fitting is done with ST0 and ST1-2 separately.
- θ is calculated with a residual of slope of the linear function.
- The charge is identified with a sign of θ (+ or −).

$$r = \frac{w(\theta^2 + 1)}{2\theta} \Rightarrow p[\mathrm{MeV}] = 3 \cdot r[\mathrm{cm}] \cdot B[\mathrm{T}]$$



Alignment shift

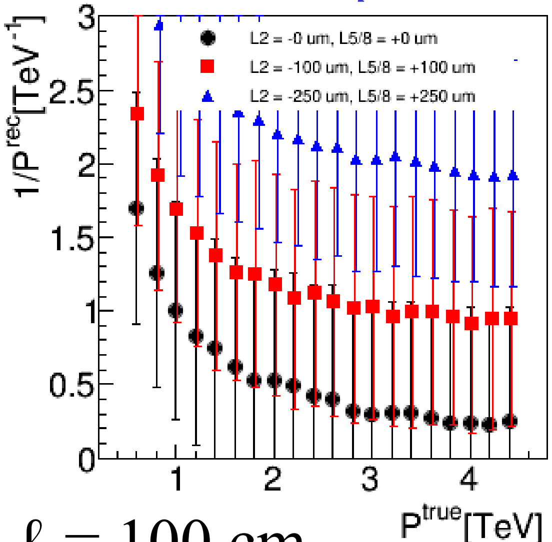
- The alignment shift (100 um and 250 um) was applied to the 3rd layers in each station.
  - “–” (down) for ST0 and “+” (up) for ST1/2



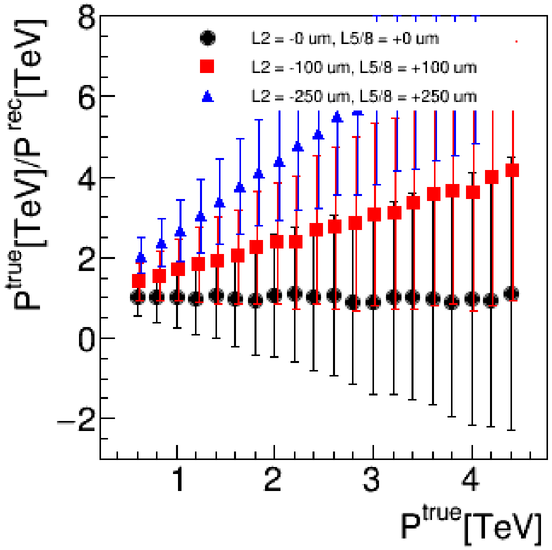
Performance (1Tm, single layer)

$\ell = 50$ cm

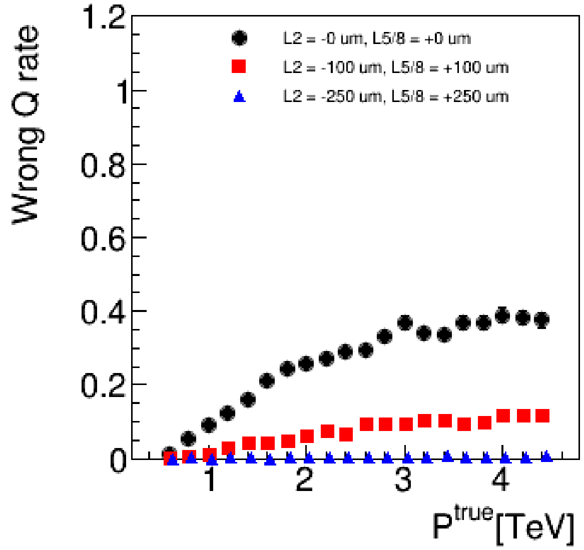
$^1/_p$ v.s. momentum



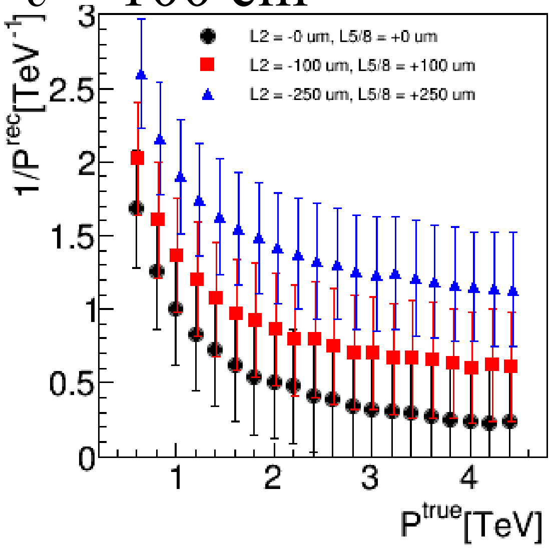
Momentum resolution

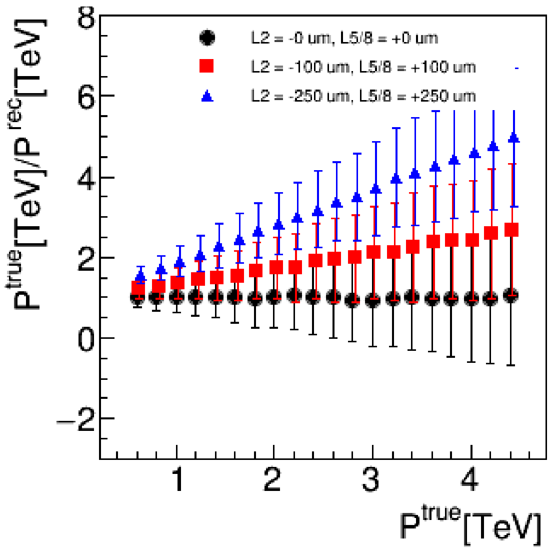


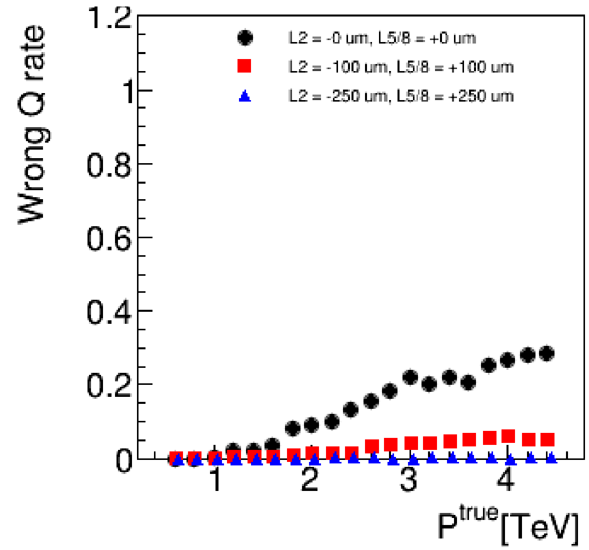
Wrong charge rate



$\ell = 100$ cm



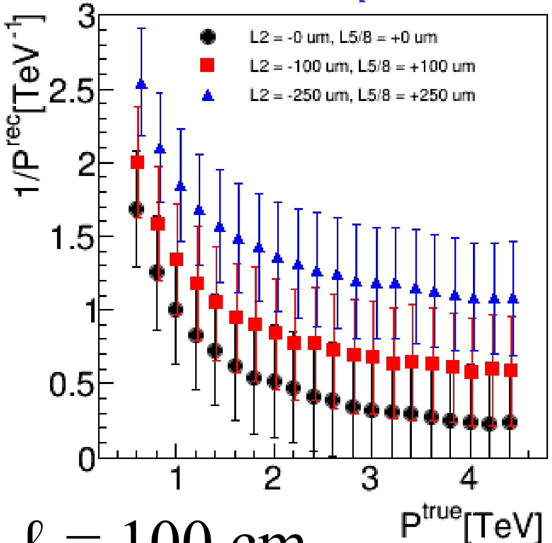




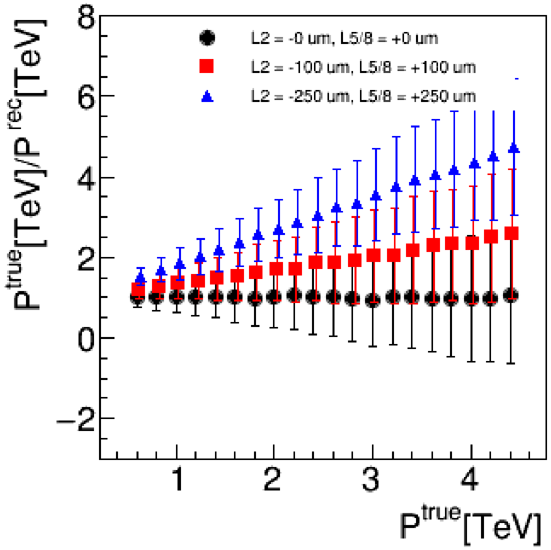
Performance (2Tm, single layer)

$\ell = 50$ cm

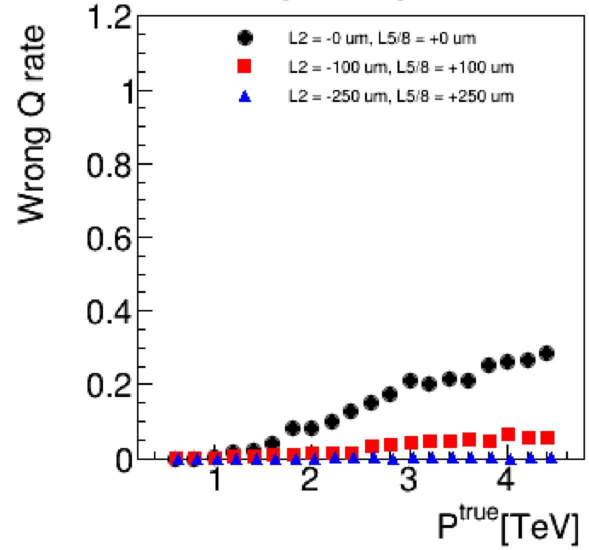
$^1/_p$ v.s. momentum



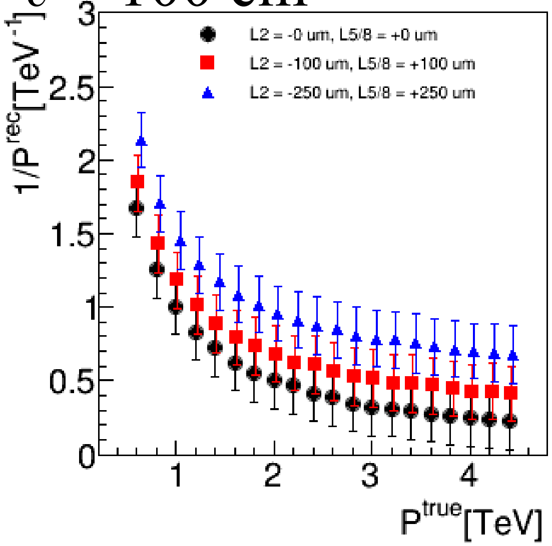
Momentum resolution

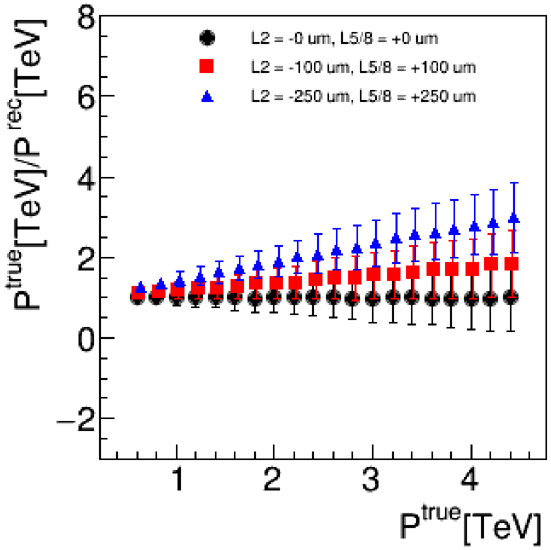


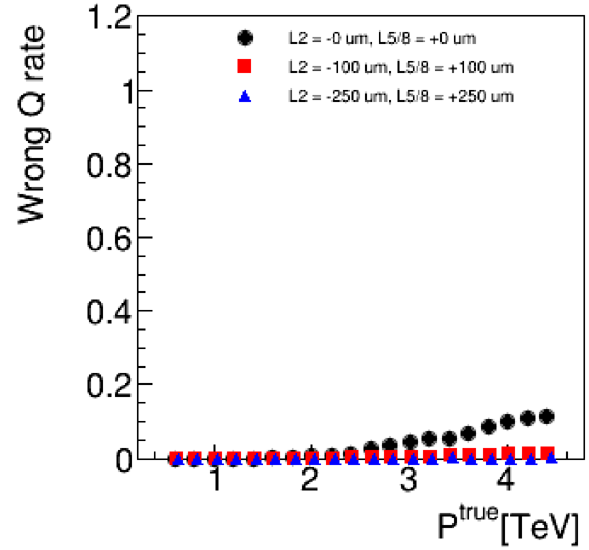
Wrong charge rate



$\ell = 100$ cm



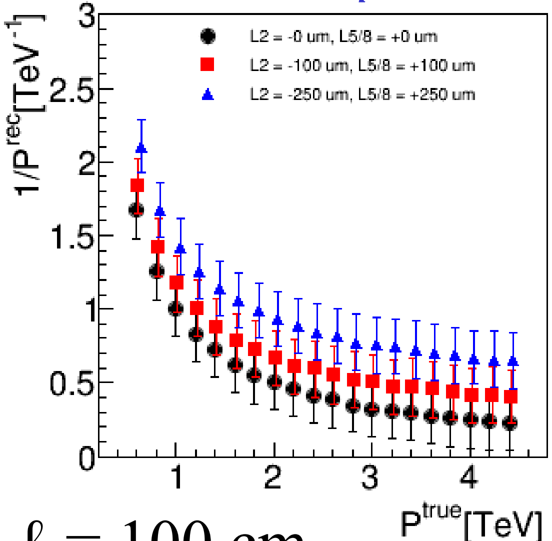




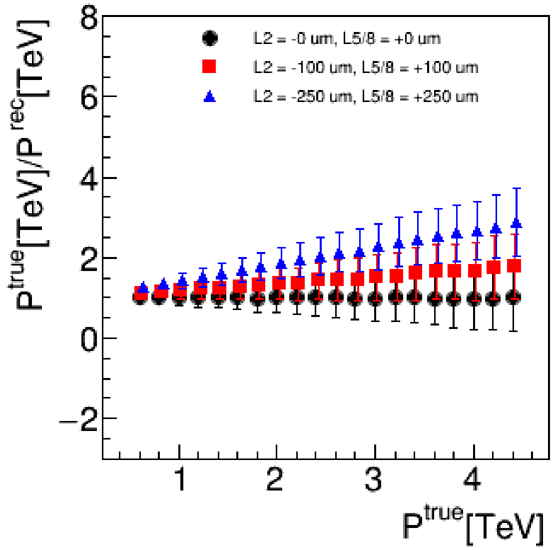
Performance (4Tm, single layer)

$\ell = 50$ cm

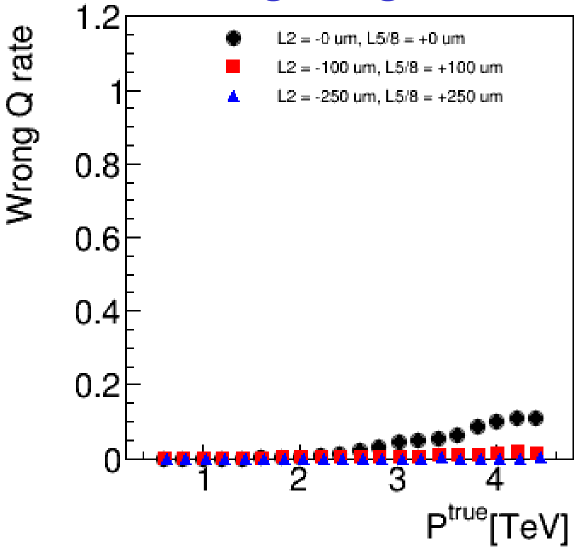
$^1/_p$ v.s. momentum



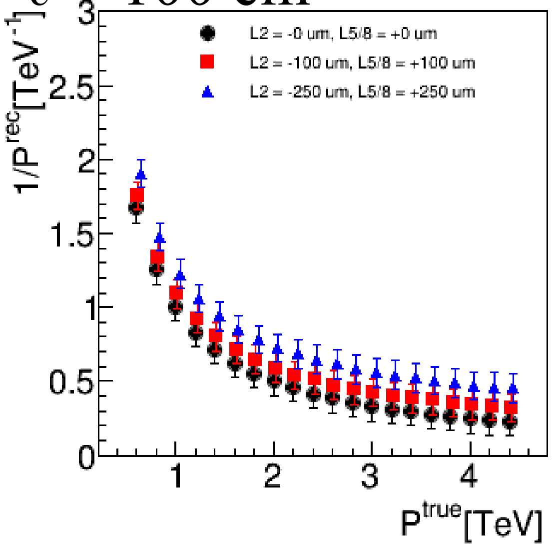
Momentum resolution

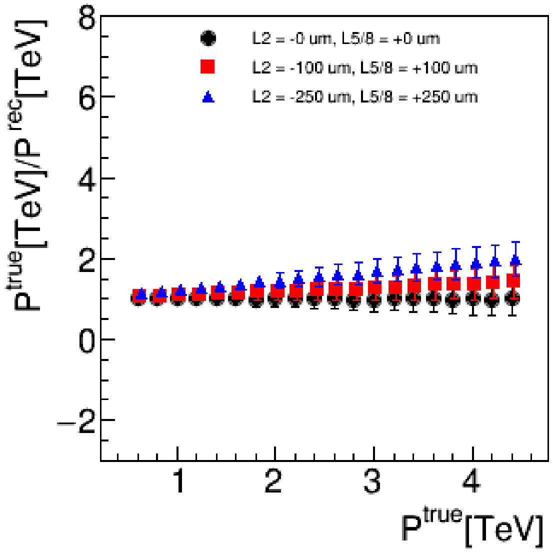


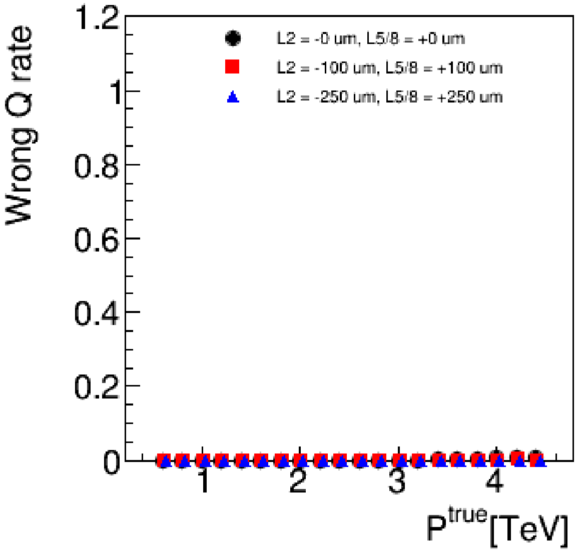
Wrong charge rate



$\ell = 100$ cm

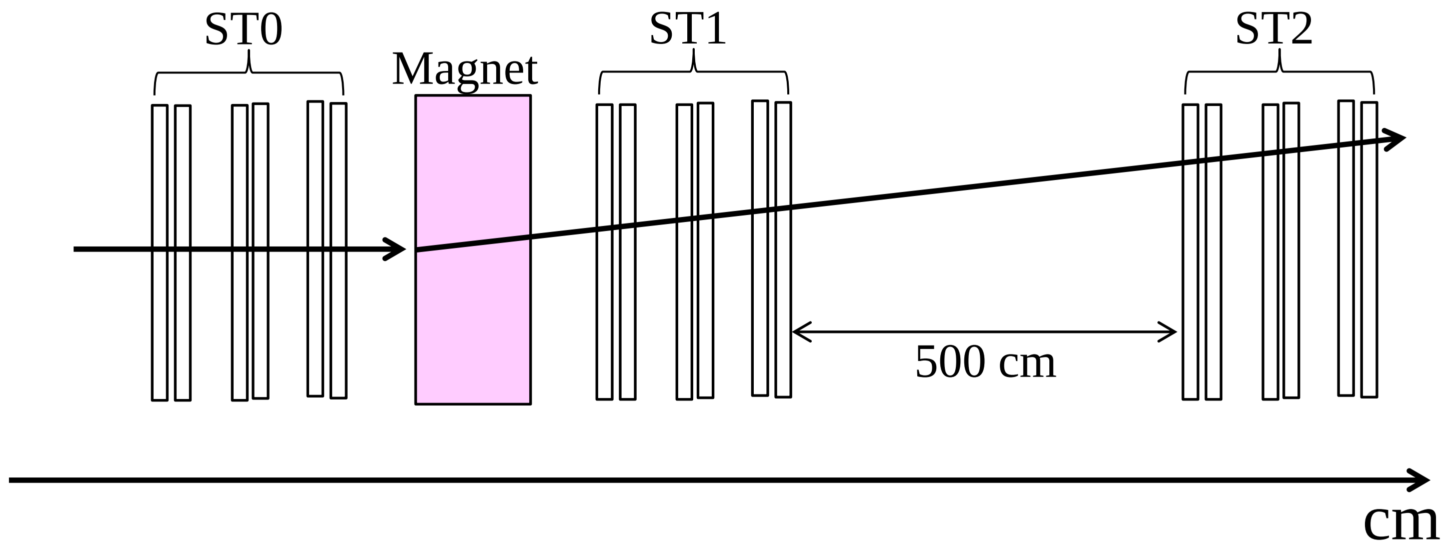






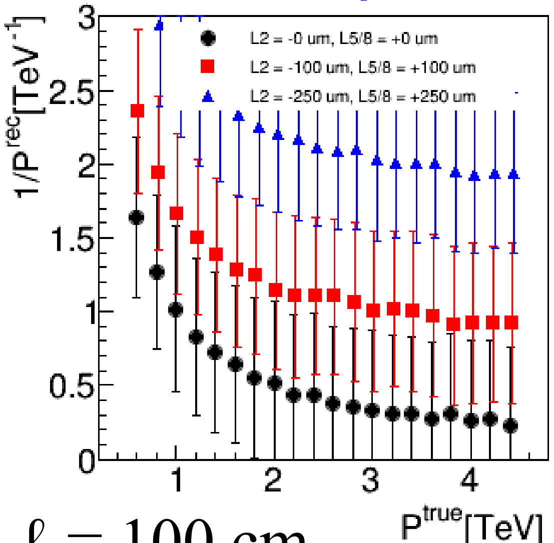
Performance with double layer

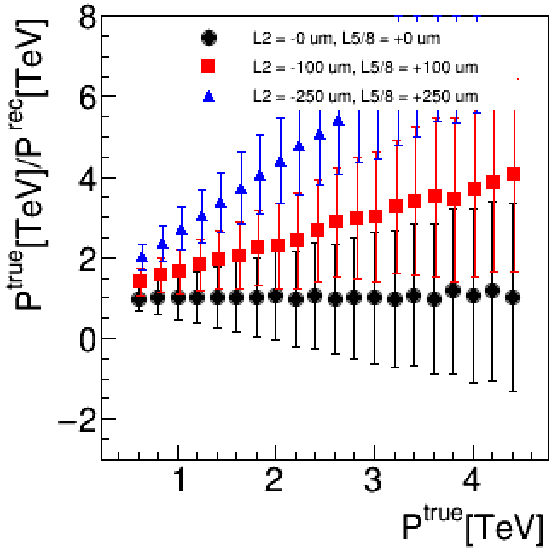
- The performance was also check with 3 tracker stations with 3 double-layers (ST0-2).
  - 3 cm gap between top and bottom layers in a double-layer.

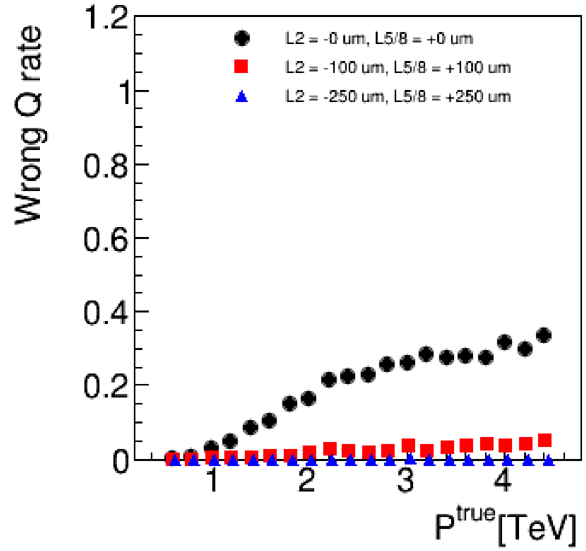


Performance (1Tm, double layer)

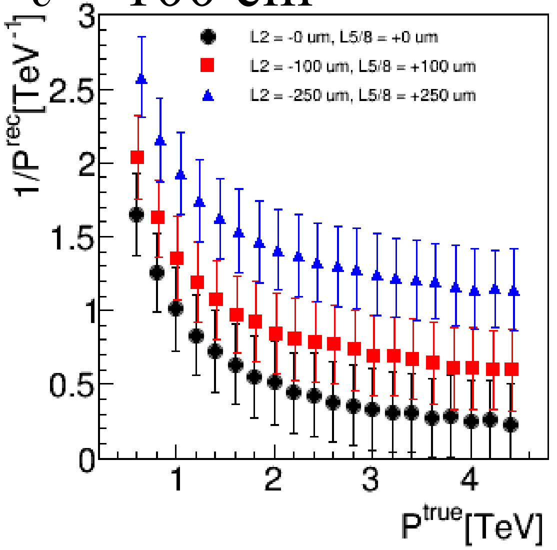
$\ell = 50$ cm $^{1}/_{p}$ **v.s. momentum** **Momentum resolution** **Wrong charge rate**

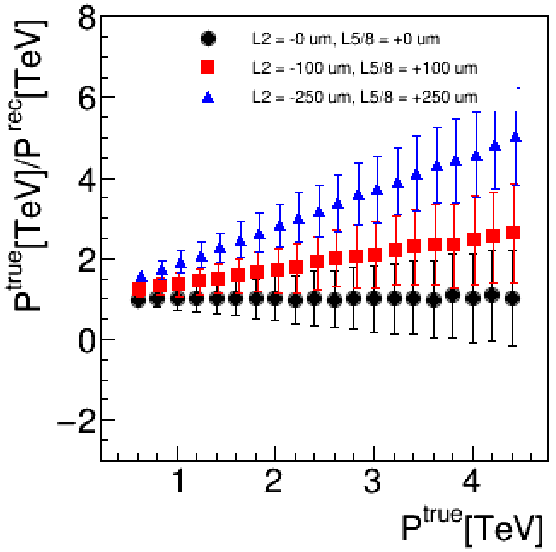


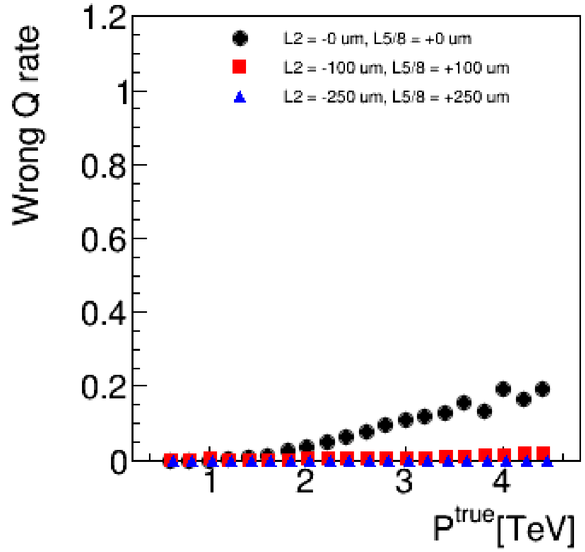




$\ell = 100$ cm

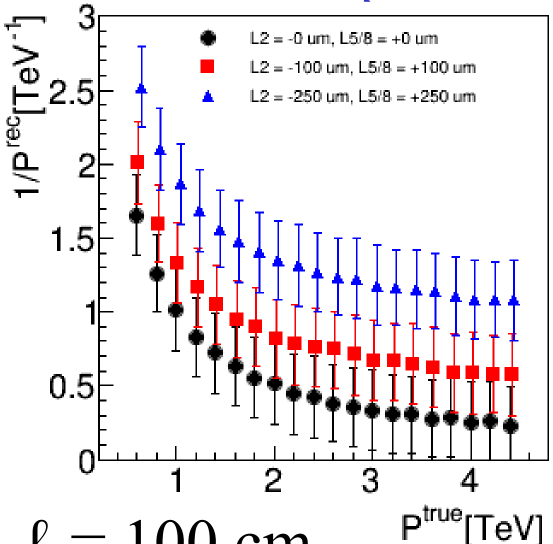


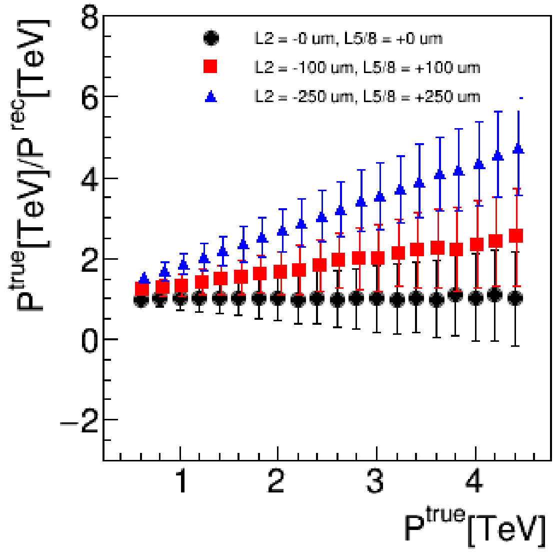


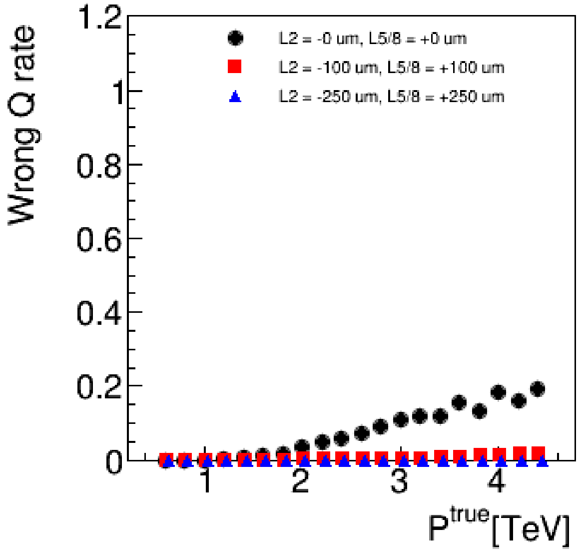


Performance (2Tm, double layer)

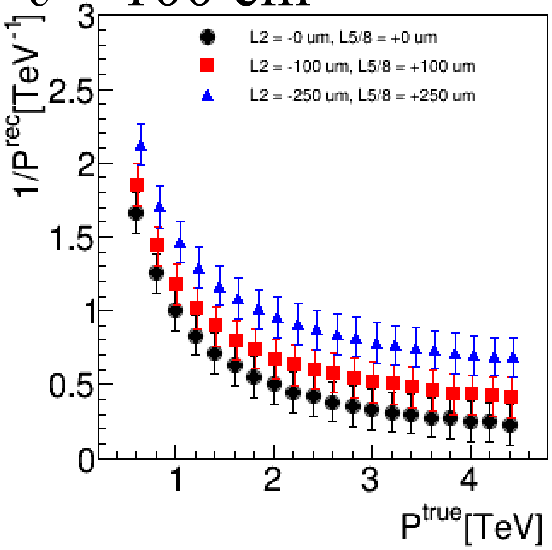
$\ell = 50$ cm **$^1/_p$ v.s. momentum** **Momentum resolution** **Wrong charge rate**

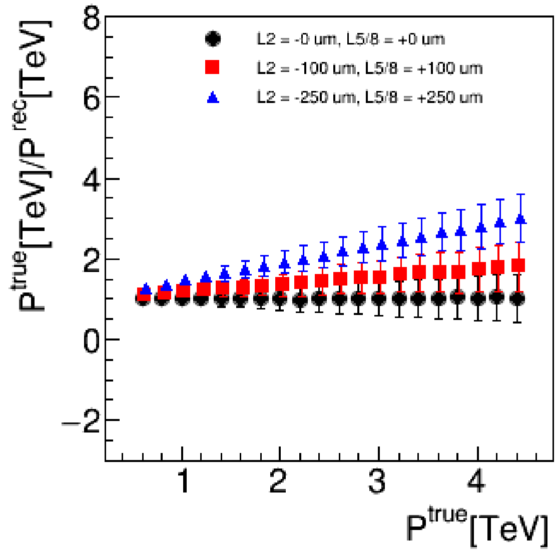


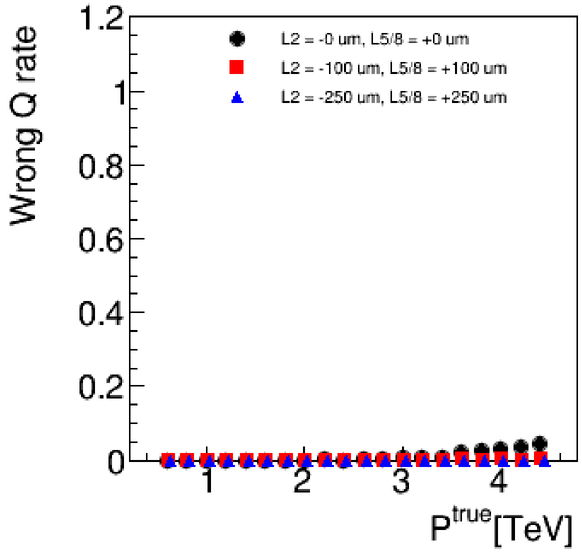




$\ell = 100$ cm



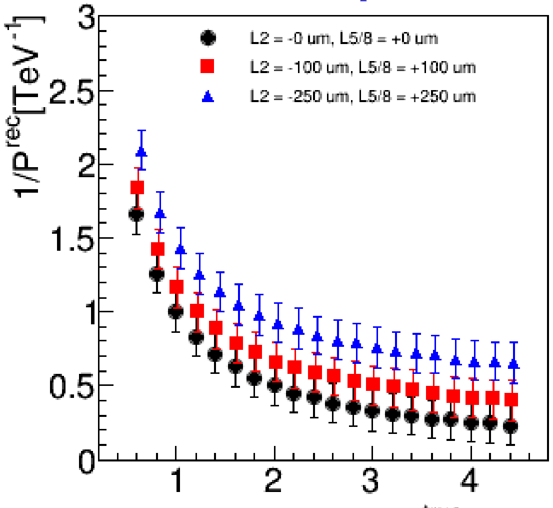




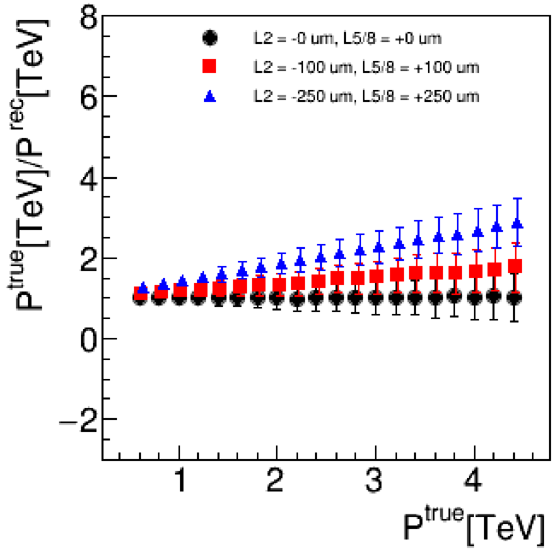
Performance (4Tm, double layer)

$\ell = 50$ cm

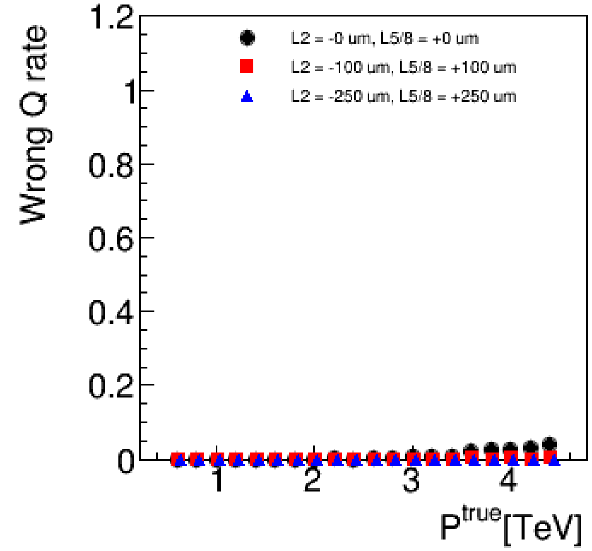
$^1/_p$ v.s. momentum



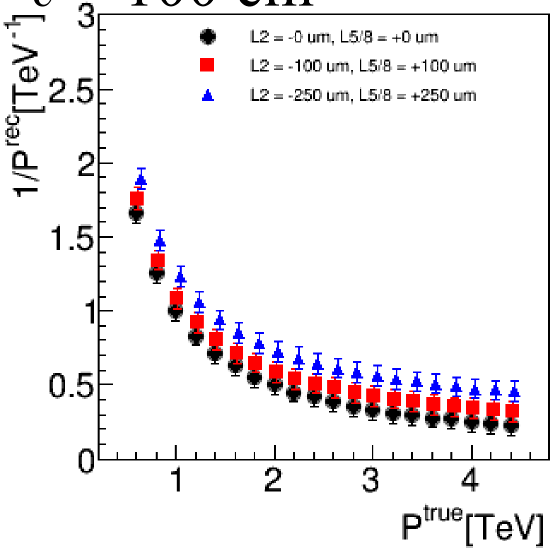
Momentum resolution

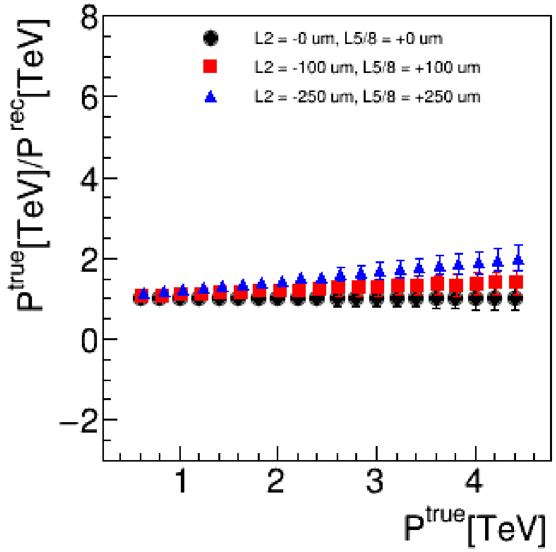


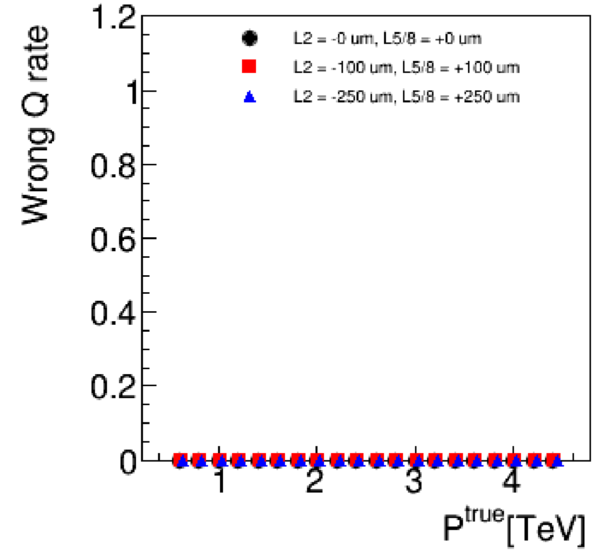
Wrong charge rate



$\ell = 100$ cm







Summary of momentum resolution

$\frac{\sigma_{1/p_T}}{1/p_T^{true}}$ is summarized here:

$\ell = 50$ cm

	Single layer			Double layer		
	1 T▪m	2 T▪m	4 T▪m	1 T▪m	2 T▪m	4 T▪m
1 TeV	0.74	0.37	0.19	0.56	0.28	0.14
2 TeV	1.53	0.76	0.38	1.10	0.55	0.27
3 TeV	2.30	1.15	0.58	1.63	0.82	0.41

$\ell = 100$ cm

	Single layer			Double layer		
	1 T▪m	2 T▪m	4 T▪m	1 T▪m	2 T▪m	4 T▪m
1 TeV	0.38	0.19	0.09	0.28	0.14	0.07
2 TeV	0.78	0.39	0.19	0.56	0.28	0.14
3 TeV	1.17	0.59	0.29	0.83	0.41	0.21

Backup

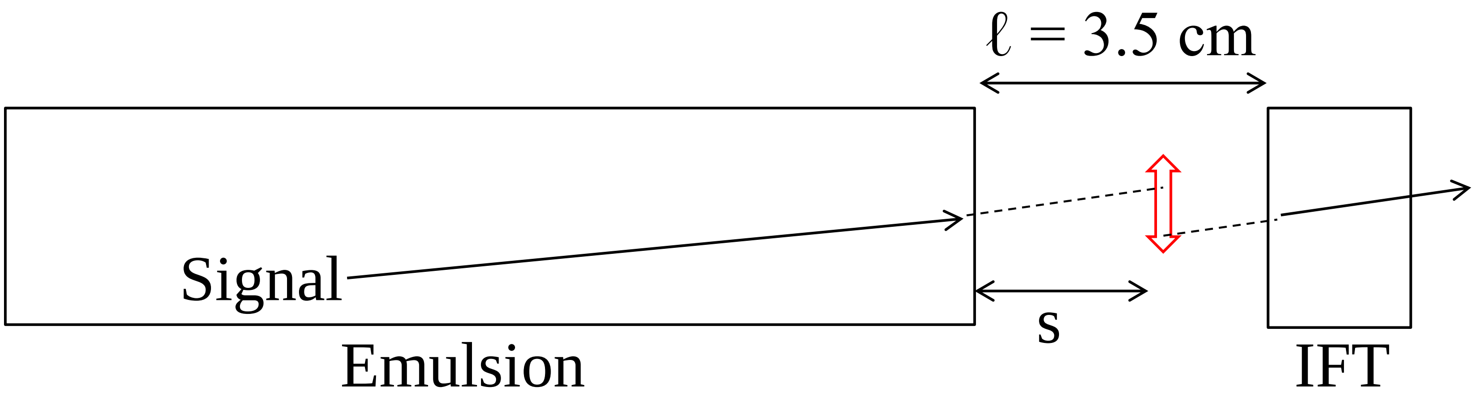
Position resolution caused by gap

- Define ℓ as gap between the last layer of emulsion and the first layer of IFT (ℓ = 3.5 or 4.5 cm was used for this study).

- Fluctuation on x/y caused by extrapolating tracks with angular resolution of emulsion/IFT:

$$\sigma_{x/y(gap)} = \sqrt{\{\sigma_{\theta(emulsion)} \cdot s\}^2 + \{\sigma_{\theta(IFT)}(\ell - s)\}^2}$$

$$\rightarrow \sigma_{x/y(gap)}^{min} = \frac{\sigma_{\theta(emulsion)} \cdot \sigma_{\theta(IFT)} \cdot \ell}{\sqrt{\sigma_{\theta(emulsion)}{}^2 + \sigma_{\theta(IFT)}{}^2}}$$



Checking items

Signal-signal matching

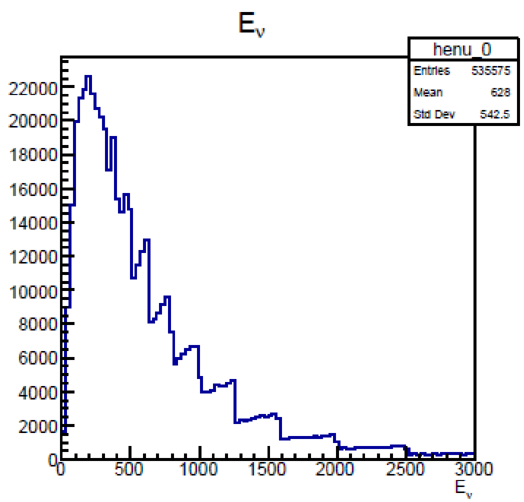
- # of signal tracks correctly matching (“Correct matching”) and matching to another signal track (“Wrong matching”)

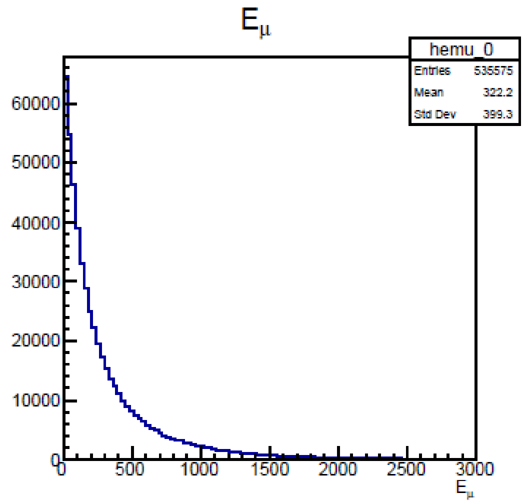
Signal-BG matching

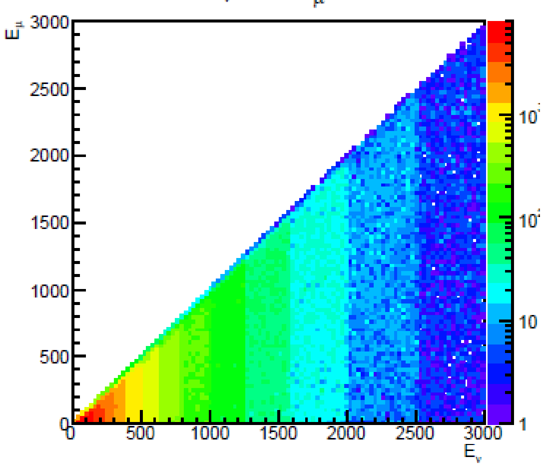
- # of signal tracks matching to a single BG track (“Single matching”), matching to more than one BG tracks (“Multiple matching”) and either of them (“All matching”).

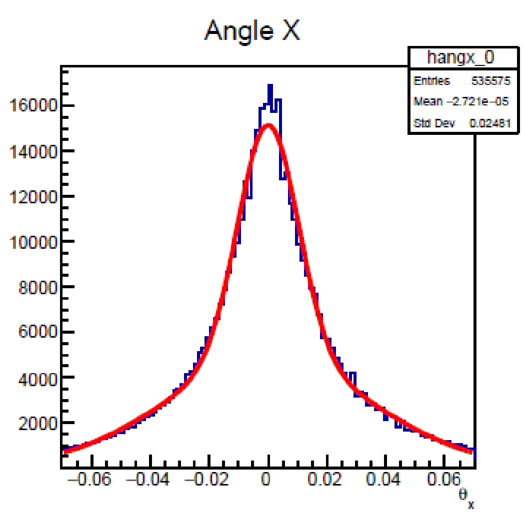
Muon distribution from neutrino

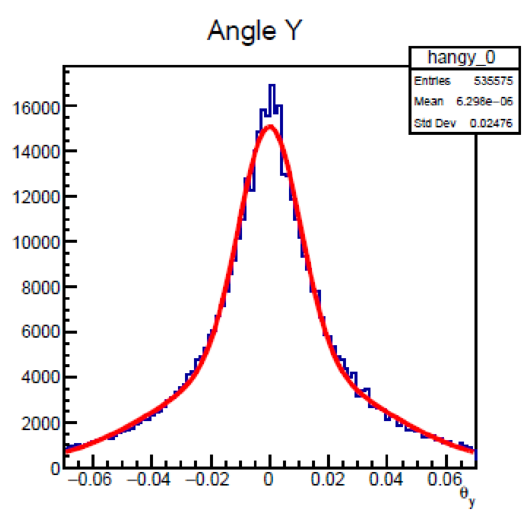
$$\frac{d\sigma_{\nu q}}{d\Omega} = \frac{G_F^2}{4\pi^2}\hat{S}$$

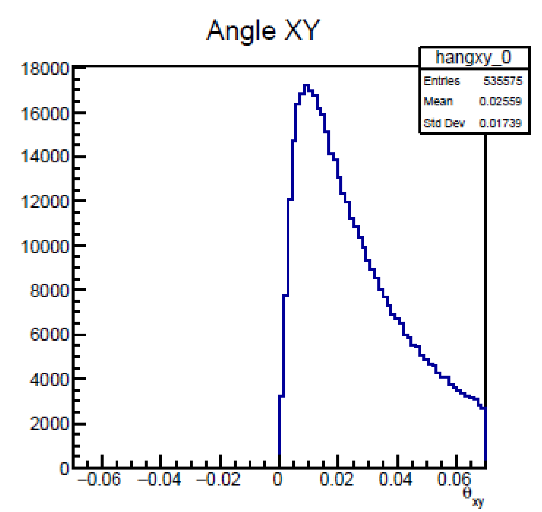






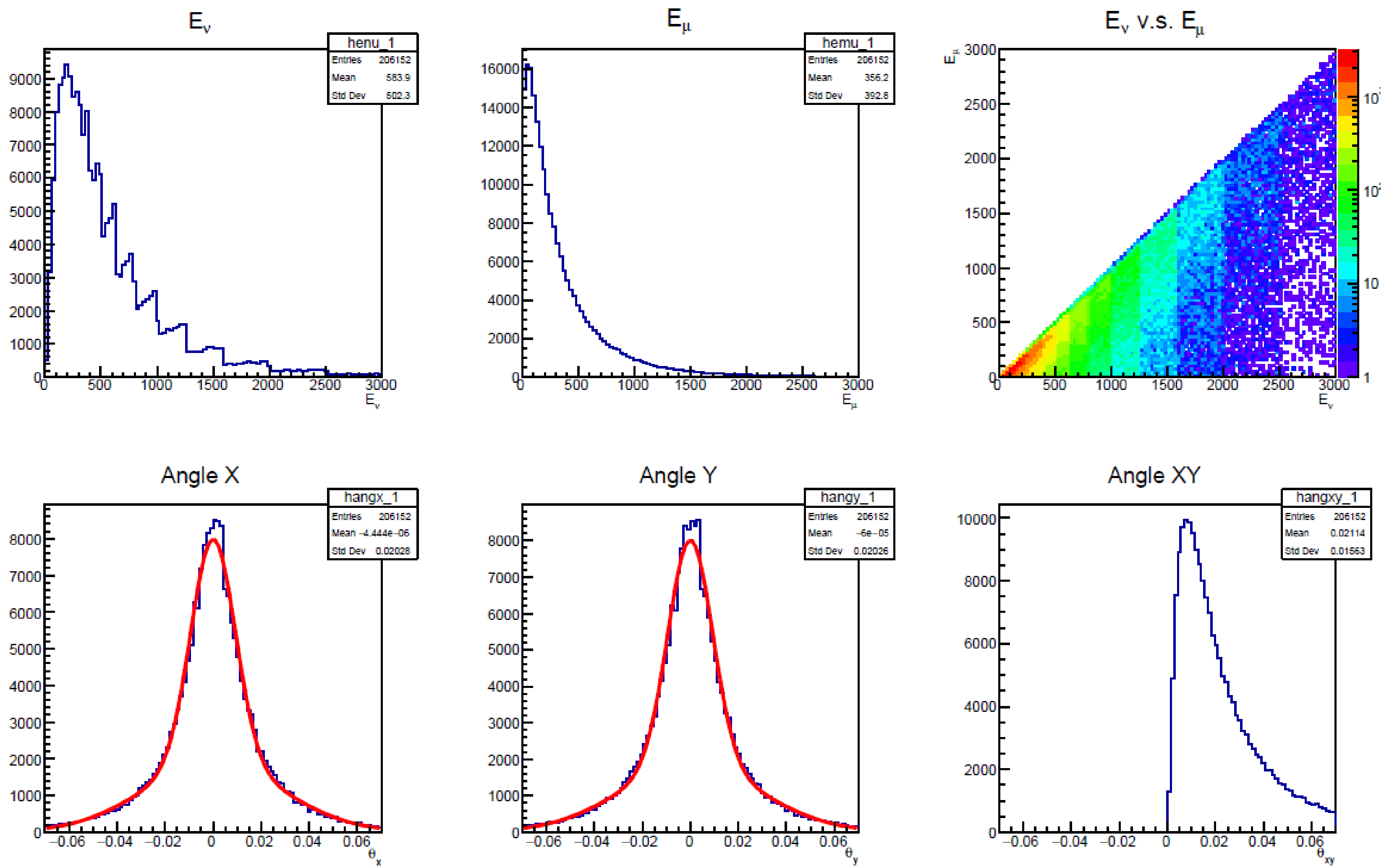






Muon distribution from anti-neutrino

$$\frac{d\sigma_{\nu q}}{d\Omega} = \frac{G_F^2}{16\pi^2}(1+cos\theta)^2\hat{s}$$



Calculation method

$$dx = r - \sqrt{r^2 - {w_{mag}}^2}$$

$$(dx - r)^2 = r^2 - {w_{mag}}^2$$

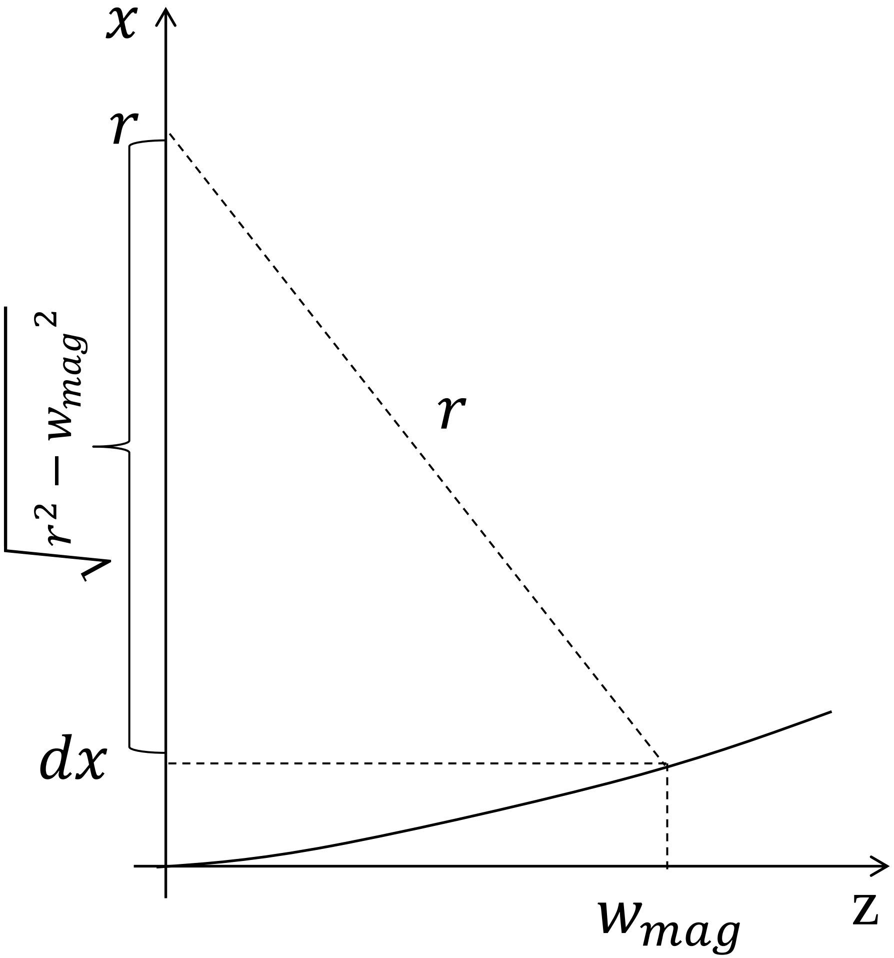
$$dx^2 - 2dx \cdot r = -{w_{mag}}^2$$

$$2dx \cdot r = dx^2 + {w_{mag}}^2$$

$$\mathrm{r} = \frac{dx^2 + {w_{mag}}^2}{2dx}$$

$$\theta = \frac{dx}{w_{mag}}$$

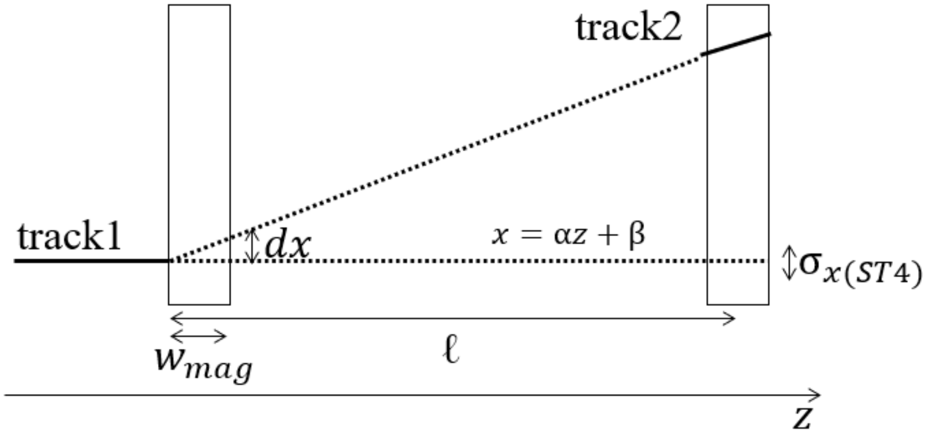
$$\mathrm{r} = \frac{w_{mag}(\theta^2 + 1)}{2\theta}$$



Confirmation by hand calculation (1)

Let's try rough estimation of momentum resolution for 1 TeV/c.

The largest uncertainty on θ comes from that of linear fitting of track1 ($x = \alpha z + \beta$).



- $\sigma_\alpha^2 = \sigma^2 \frac{n}{\Delta}$
- $\sigma_\beta^2 = \sigma^2 \frac{\sum z_i}{\Delta}$
- $\Delta = n \sum z_i^2 - (\sum z_i)^2$
- $\sigma = 100/\sqrt{3}$ [um] (i.e., position resolution of each station)
- z_i: center position of each station

- $\sigma_\alpha = 0.00041$
- $\sigma_\beta = 5.3 \times 10^{-5}$[m]

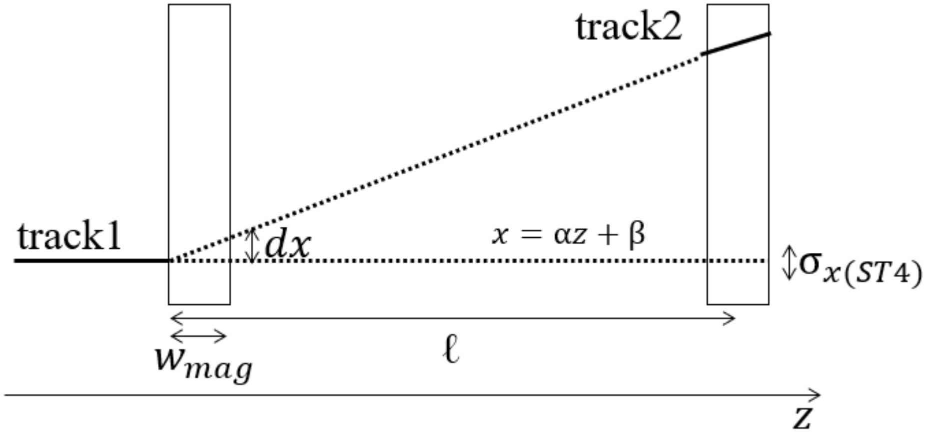
$\sigma_{x(ST4)} = 8.2$ mm

Confirmation by hand calculation (2)

$\sigma_{x(ST4)} = 8.2$ mm

$$\sigma_\theta = \frac{\sigma_{x(ST4)}}{\ell} = 4.2 \times 10^{-3}$$

The resolution of track2 is ignored since it is much smaller than $\sigma_{x(ST4)}$.



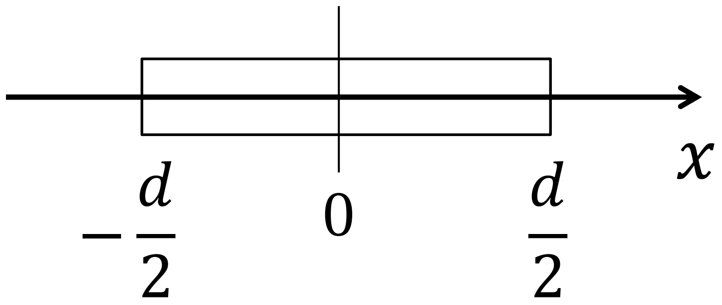
$$r = \frac{w_{mag}(\theta^2 + 1)}{2\theta}$$

$$\sigma_r = \frac{w_{mag}}{2}\left(\frac{1}{\theta^2} - 1\right)\sigma_\theta \sim 1500 \text{ [m]}$$

$$\frac{\sigma_{1/p}}{1/p} = \frac{\sigma_{1/r}}{1/r} = \frac{\sigma_r}{r} = 1.7 \ (r = 833 \text{ m at } 1 \text{ TeV})$$

Hit position resolution

If a particle penetrates a strip with the width d uniformly, the probability to pass position x is 1/d.



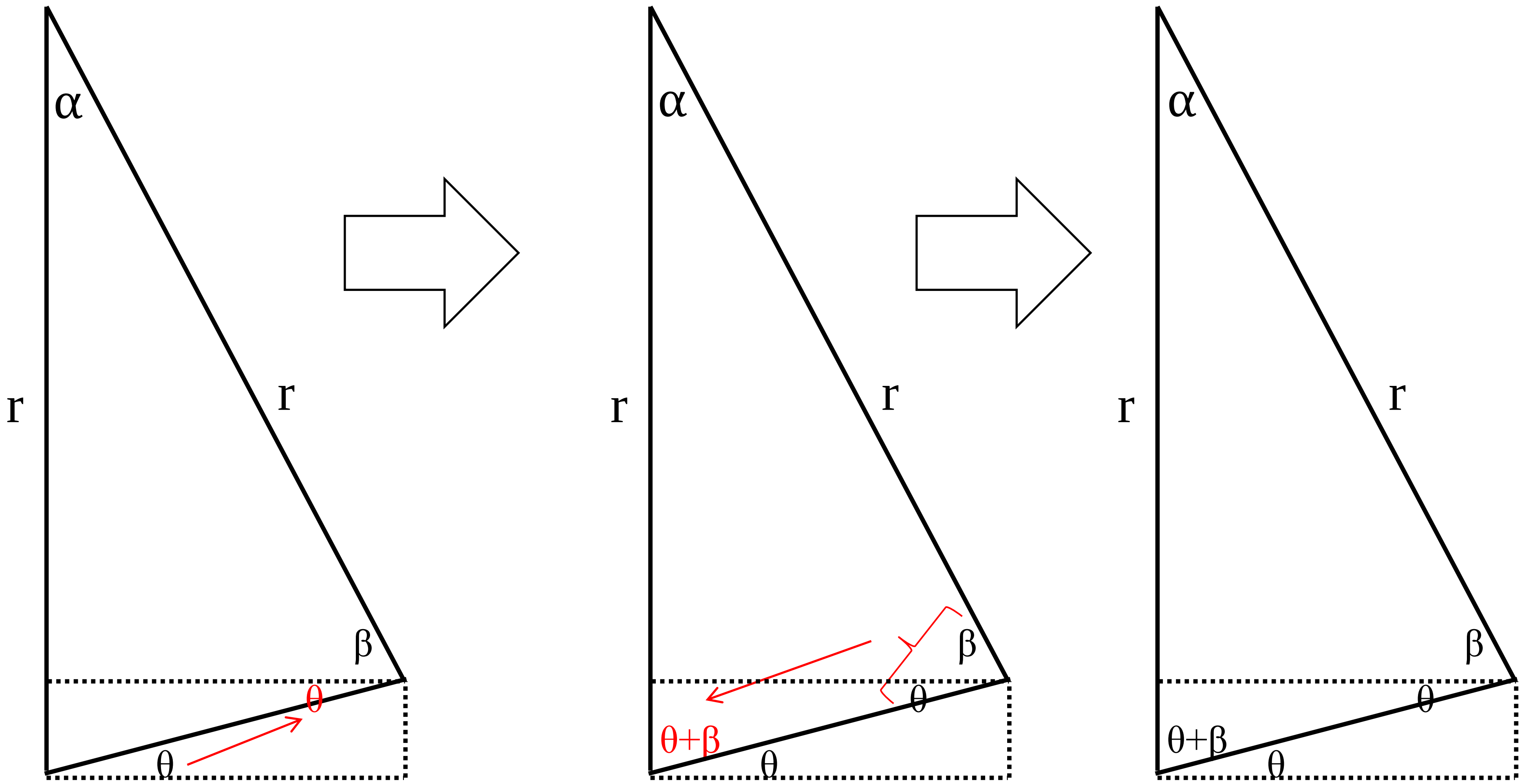
$$\sigma_x^2 = \int_{-d/2}^{+d/2} x^2 p(x)\, dx$$

$$= \int_{-d/2}^{+d/2} \frac{x^2}{d}\, dx$$

$$= \frac{d^2}{12}$$

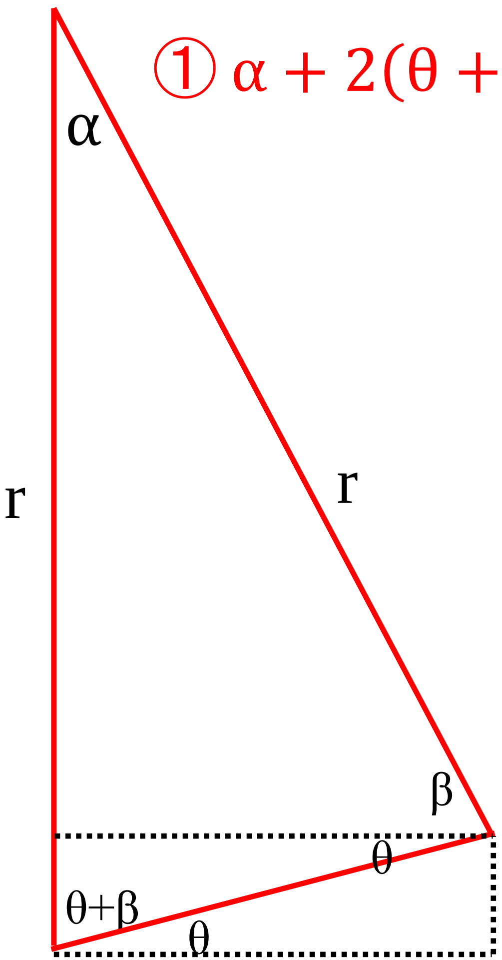
$$\sigma_x = \frac{d}{\sqrt{12}}$$

Comparison with AdvSND (1)



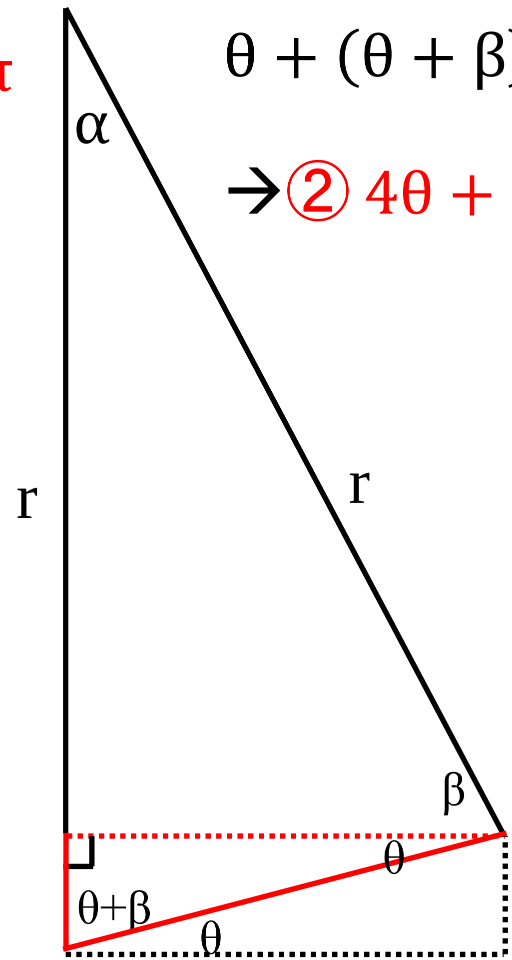
Comparison with AdvSND (2)

① $\alpha + 2(\theta + \beta) = \pi$



$$\theta + (\theta + \beta) + \frac{\pi}{2} = \pi$$

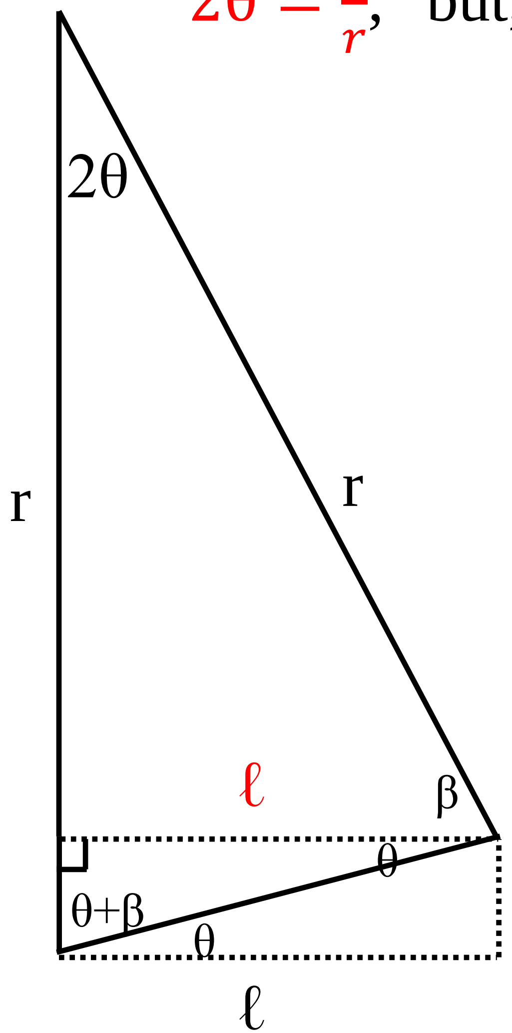
$\rightarrow$ ② $4\theta + 2\beta = \pi$



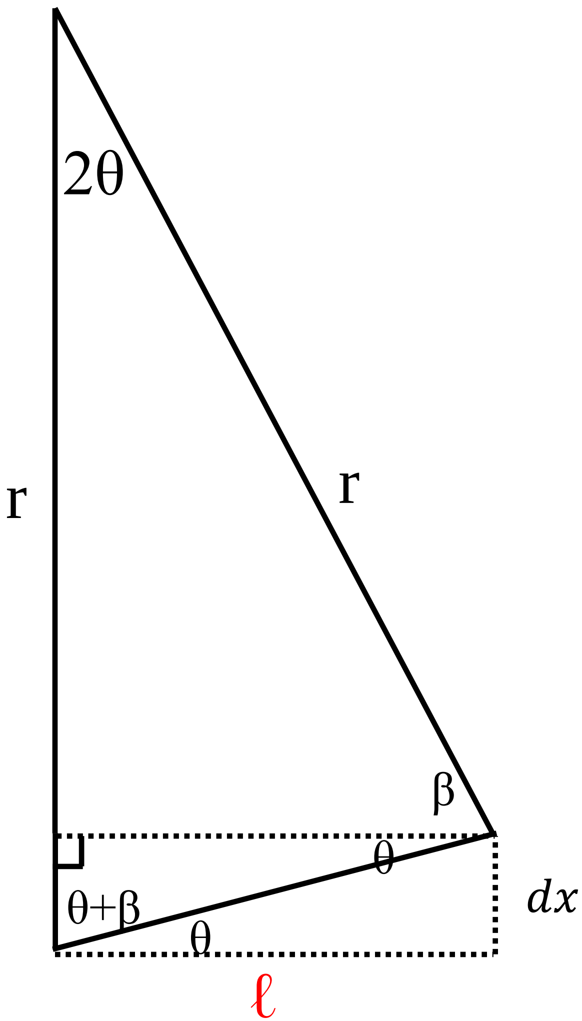
With ①+②, $2\alpha = \theta$

Comparison with AdvSND (3)

$2\theta = \frac{\ell}{r}$, but, written as $\theta = \frac{\ell}{r}$ in Sec. 3.3.2 in [FPF White Paper]



Comparison with AdvSND (4)



Anyway, let's compare with my calculation.

Condition of my calculation:

$$\begin{cases} \bullet\ \theta = \dfrac{dx}{\ell} \\ \bullet\ dx = r - \sqrt{r^2 - \ell^2} \end{cases}$$

$$dx = r - \sqrt{r^2 - \ell^2}$$

$$\rightarrow ①\ dx \sim r - r\left(1 - \frac{\ell^2}{2r^2}\right) = \frac{\ell^2}{2r}$$

$$\theta = \frac{dx}{\ell}$$

$$\rightarrow ②\ dx = \theta\ell$$

With ① and ②, $\theta\ell = \frac{\ell^2}{2r} \rightarrow 2\theta = \frac{\ell}{r}$

The result is the same as the method of AdvSND (except for factor of 2).

Comparison with AdvSND (5)

p[MeV] = 3・r[cm]・B[T]

(“3” is missing in calculation of Sec. 3.3.2 in [FPF White Paper])

→ $r = \frac{p}{3B}$

⇨ $2\theta = \frac{\ell}{r} = \frac{3B\ell}{p}$

⇨ $\theta = \frac{3B\ell}{2p}$ ($\theta = \frac{B\ell}{p}$ in Sec. 3.3.2 in [FPF White Paper])