FASER実験の最新結果とハドロン相互作用研究の今後の展望

大橋健 (ベルン大)

FASER Collaboration

Ken Ohashi — 第七回 空気シャワー観測による宇宙線の起源探索研究会 — 2024 March 27

ForwArd Search ExpeRiment (FASER) 実験

ATLAS衝突点から480m 前方に検出器を設置

Run3 2022-2025の期間にデータ取得

<u>**主な物理目標**</u>

Dark photon 探査

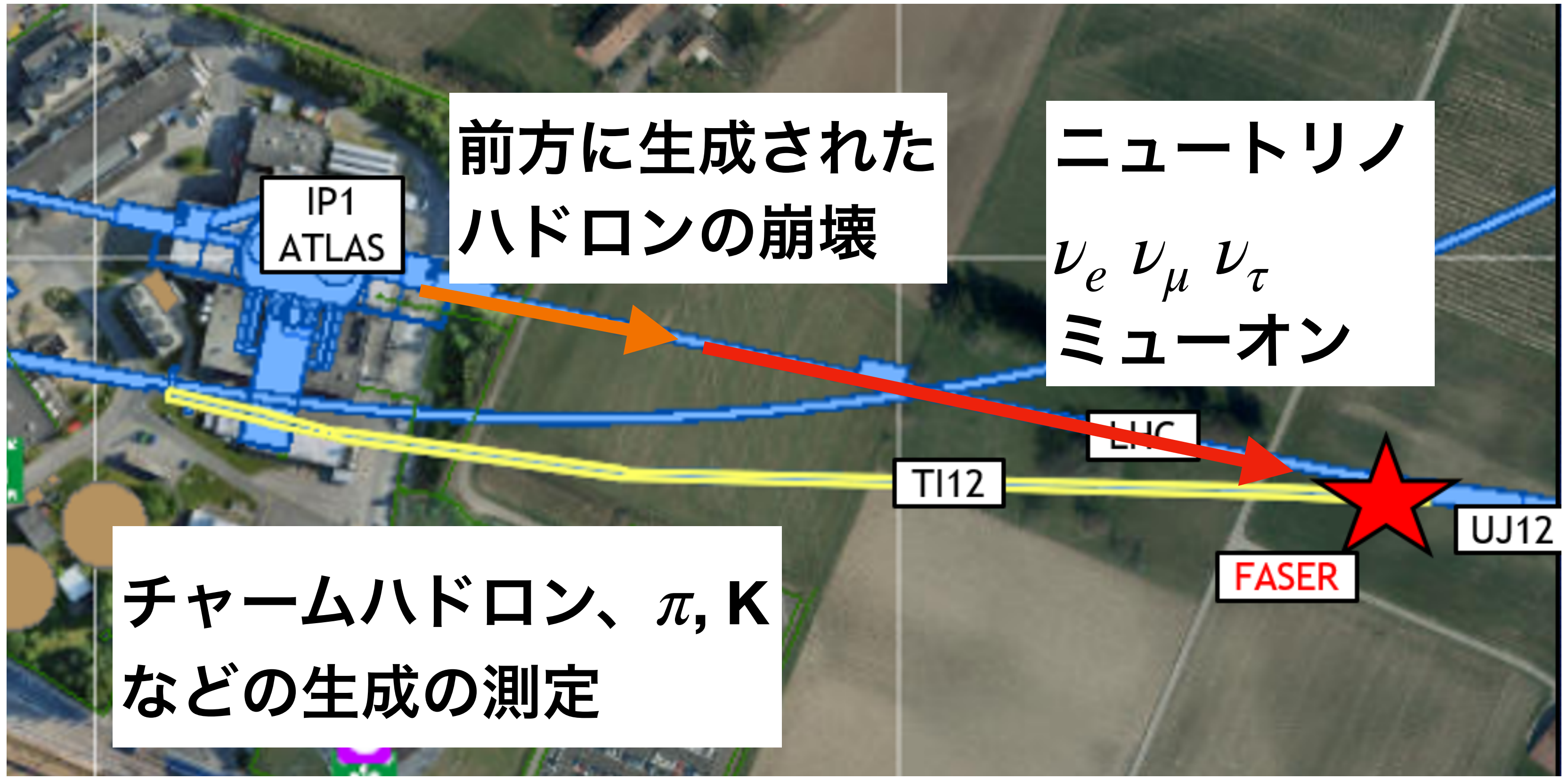
ニュートリノ測定 ($\eta > 8.8$)

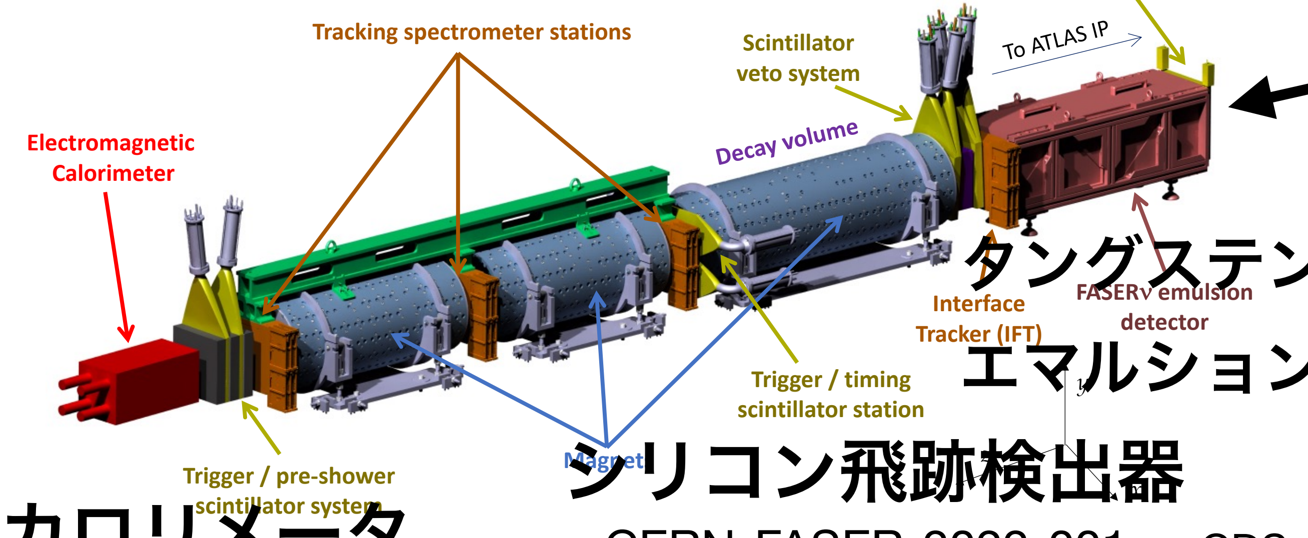
三世代ニュートリノのタングステン中での cross-section測定

Run3で想定されるイベント数:

1128 (ν_e), 5346 (ν_μ), 21.6 (ν_τ) ($150\mathrm{fb}^{-1}$)

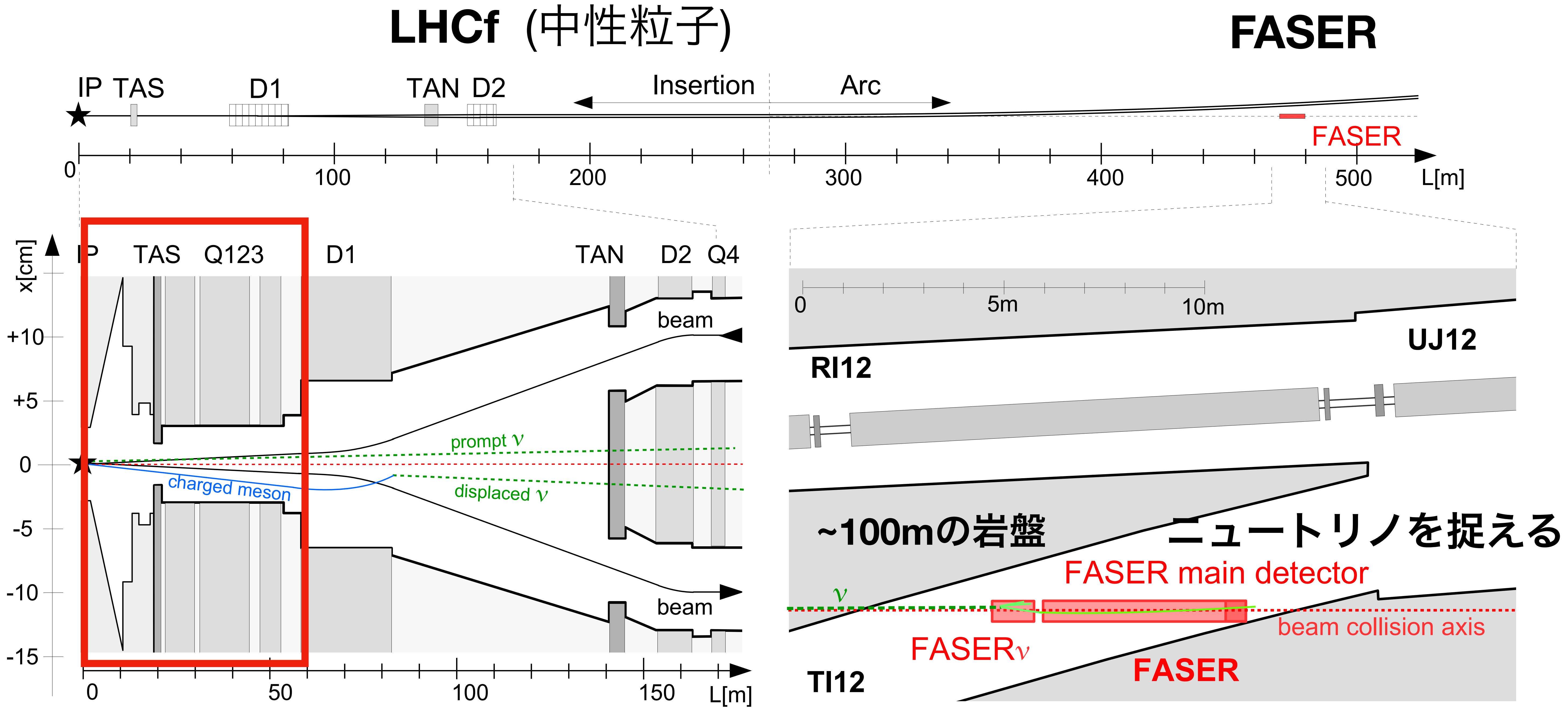
超前方ハドロン生成研究





CERN-FASER-2022-001 on CDS

荷電粒子の崩壊により生じるニュートリノを測定



Decay volume

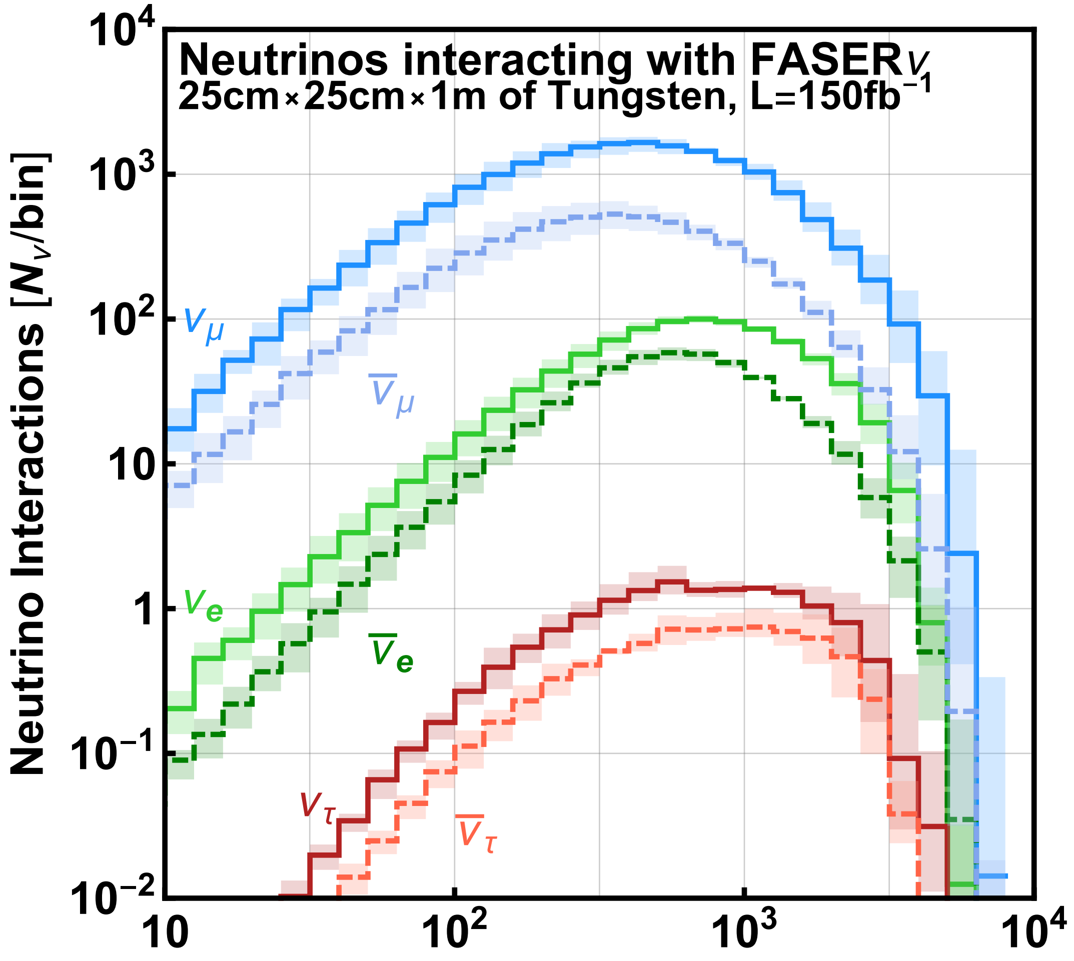
Meson decay -> neutrinos

arXiv:1908.02310

π-Kの割合をニュートリノの割合から求める

電子ニュートリノは主にKから、ミューニュートリノは主にπから

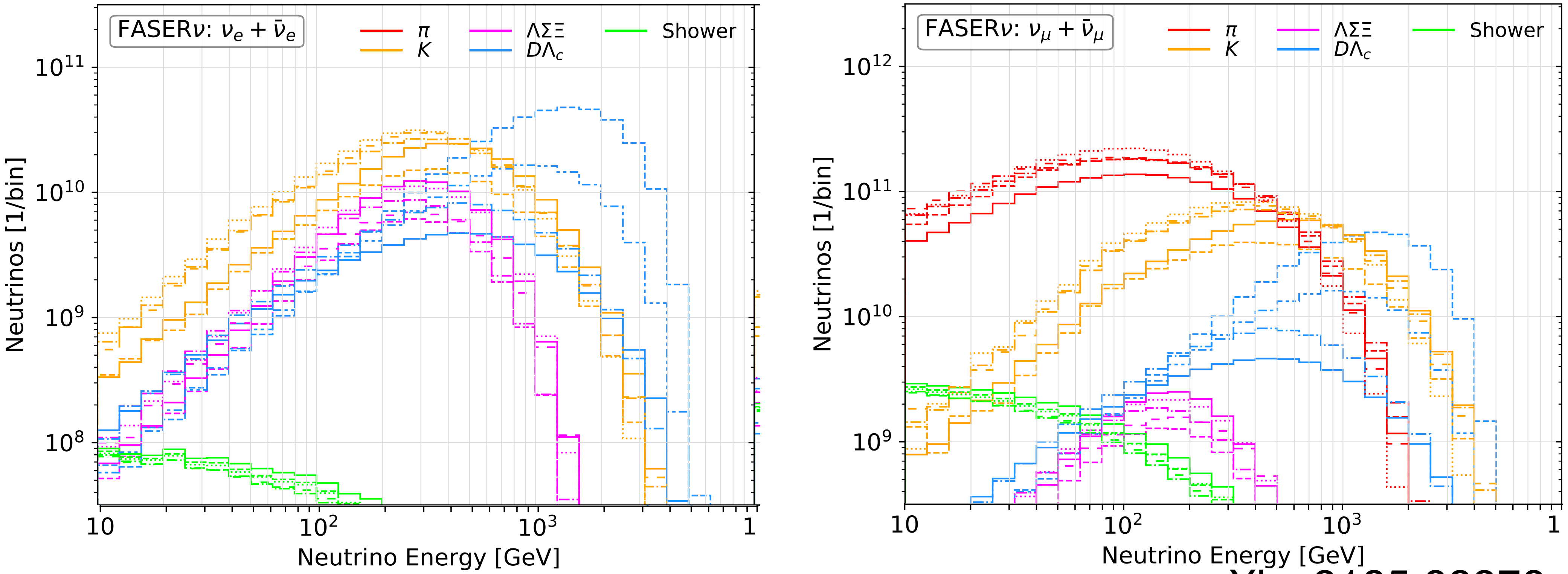
Run3で想定されるイベント数

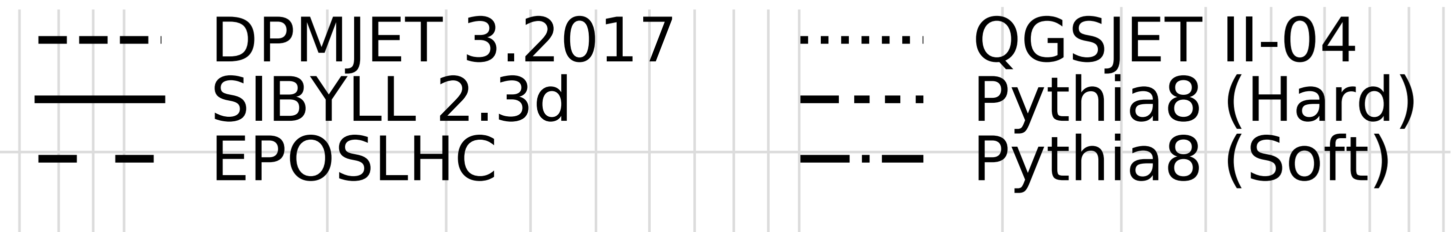


ニュートリノの

エネルギー [GeV]

検出器を通過するニュートリノ、親粒子ごとに分けて表示



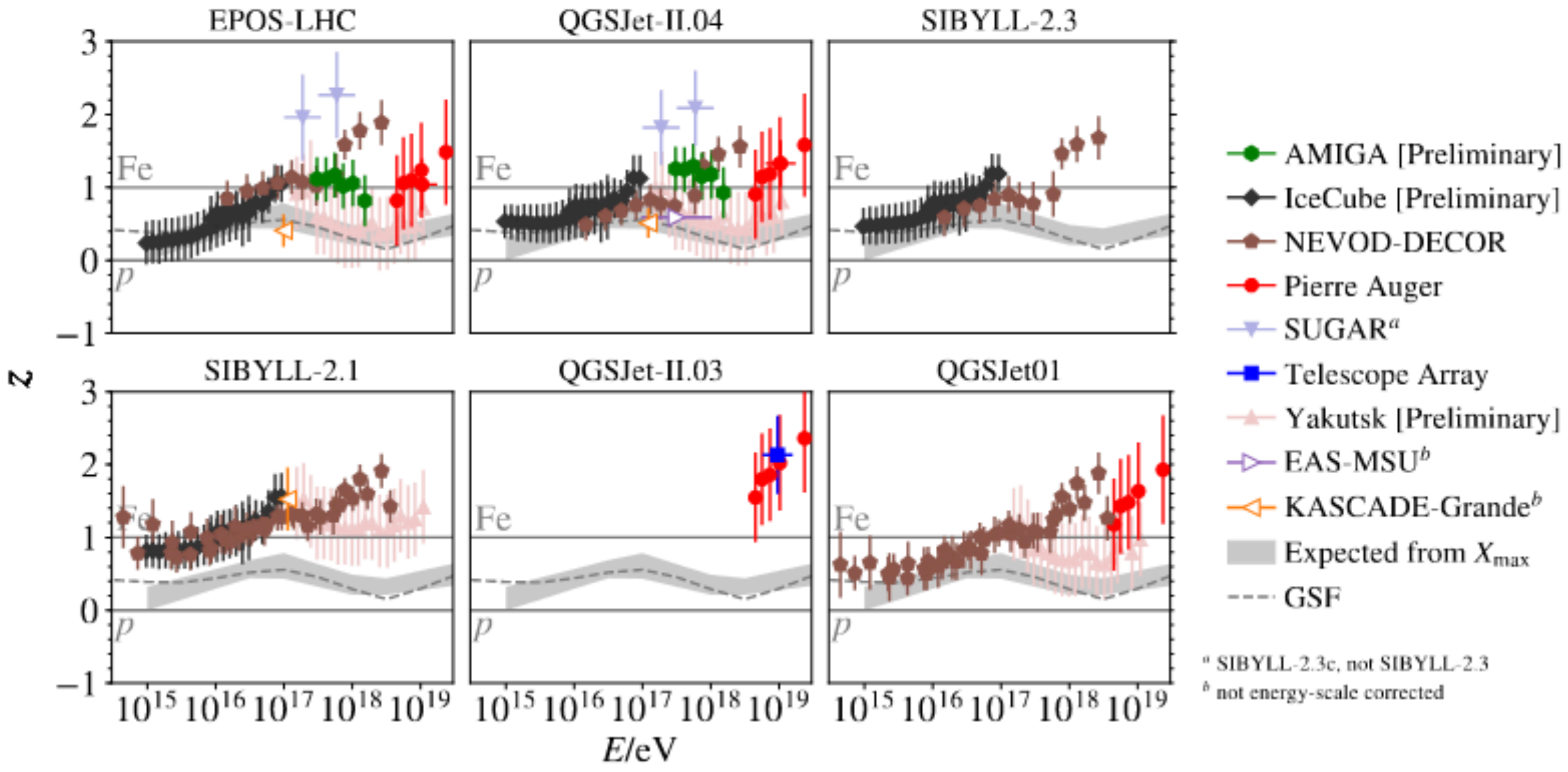


arXiv: 2105.08270

ν_eとν_μの割合を測定することで、πとKの割合を測定できる!!

μ粒子超過問題

地上でのμ粒子数がシミュレーション予測よりも多い



$$z = \frac{\ln(N_\mu) - \ln(N_{\mu,proton})}{\ln(N_{\mu,iron}) - \ln(N_{\mu,proton})}$$

L. Cazon et al., PoS(ICRC2019) 214

Ralph Engel, Forward Physics Facility 7 meeting (March 2024)

Modification of Sibyll 2.3d to study different versions of muon enhancement

- Rho meson in pion interactions (leading particle effect only) → **not seen in FPF**
- Baryon pair production (all interactions) → **not seen in FPF**
- Kaon production (all interactions) → **directly seen in FPF**

Kaon production シナリオならFASER or Future detectorで検証できる

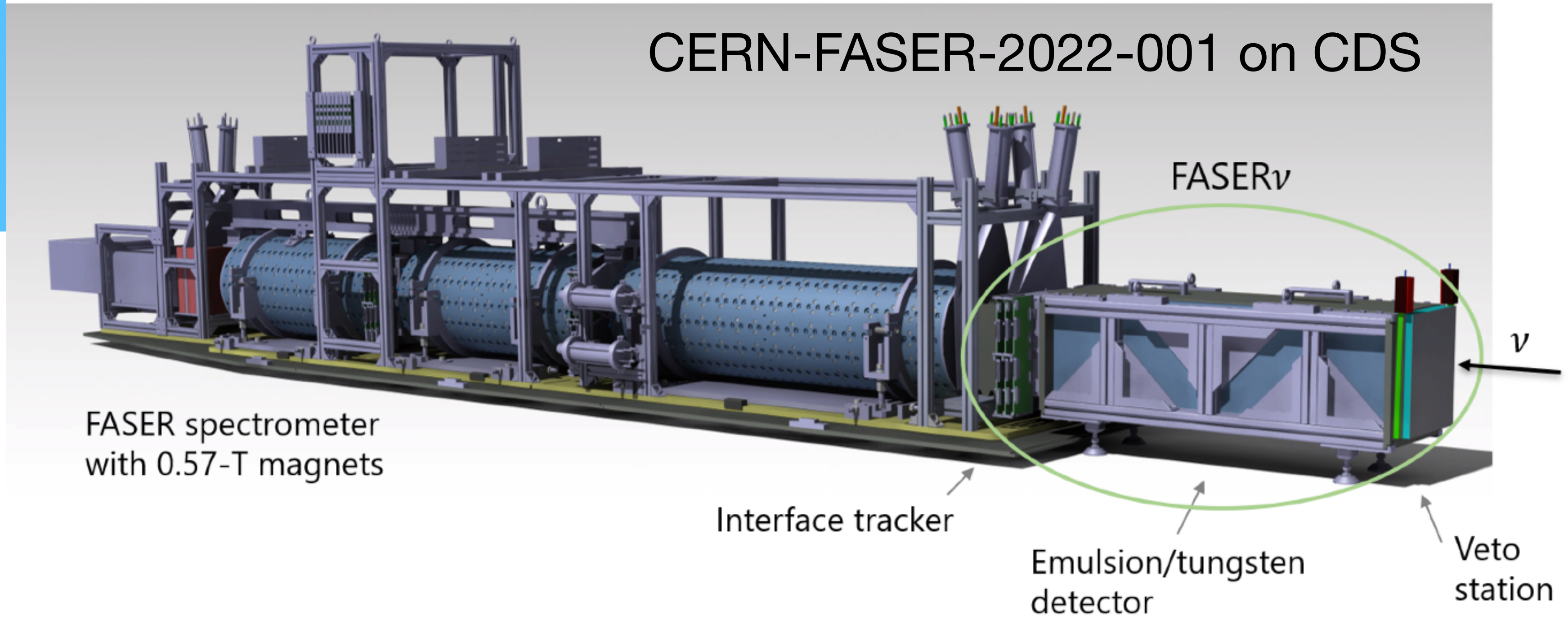
FASERν detector

原子核乾板を用いた検出器

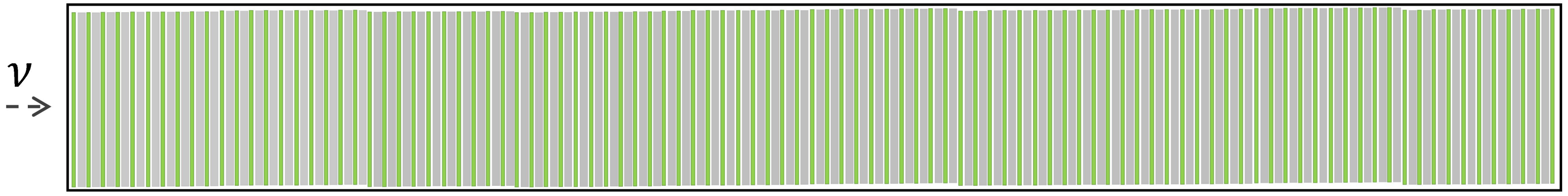
特徴

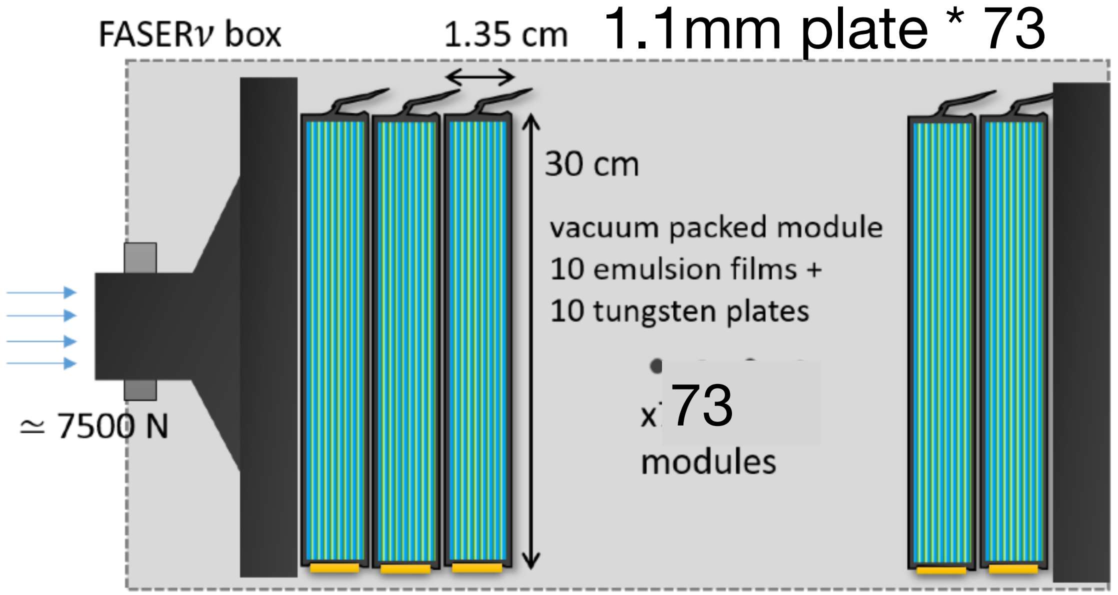
非常に高い位置分解能

ニュートリノのフレーバーの決定

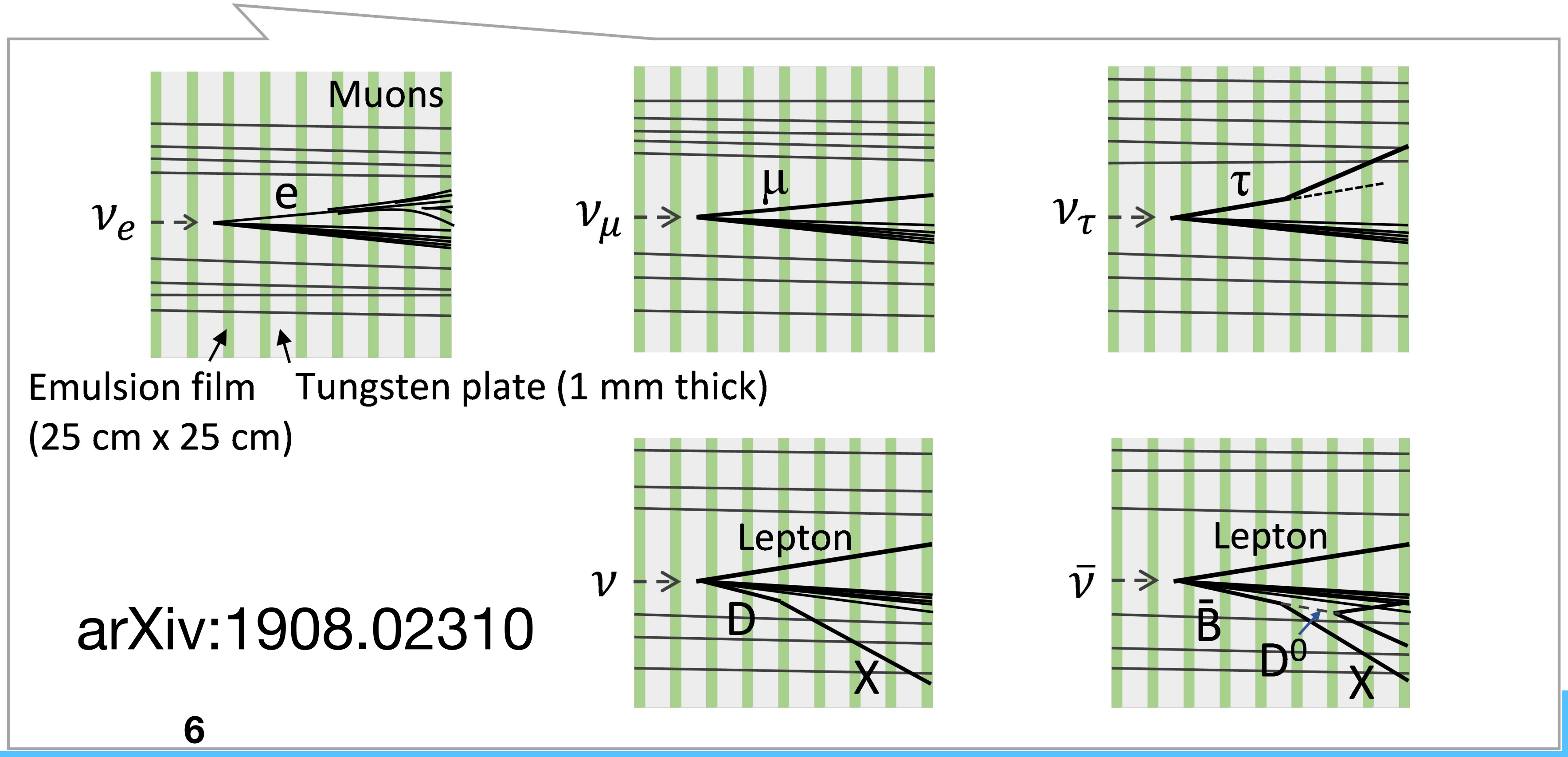


Total 1000 emulsion films interleaved with 1-mm-thick tungsten plates





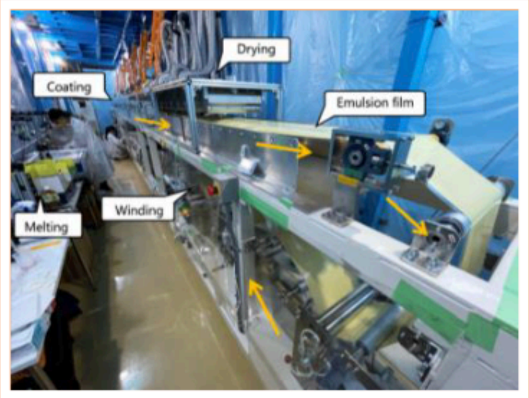
CERN-FASER-2022-001 on CDS



Slide By Jeremy Atkinson at NuFACT2023

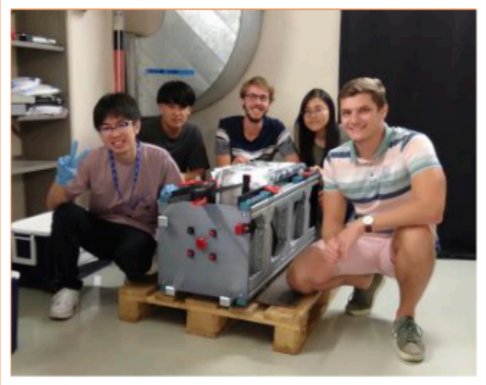
FASERν Process

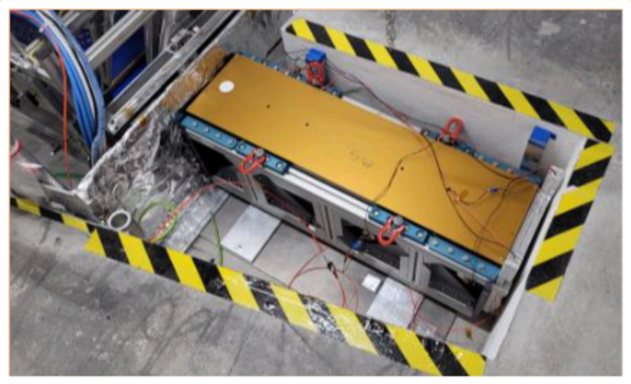
Japan

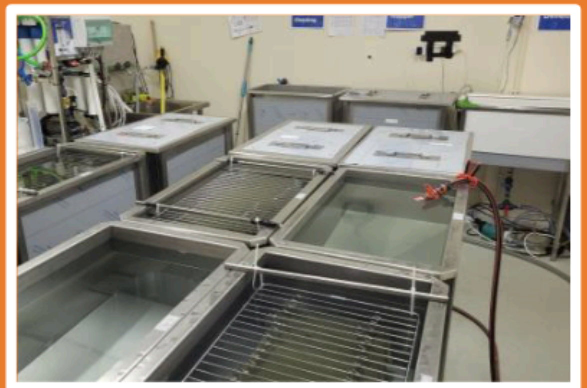


Film production

CERN

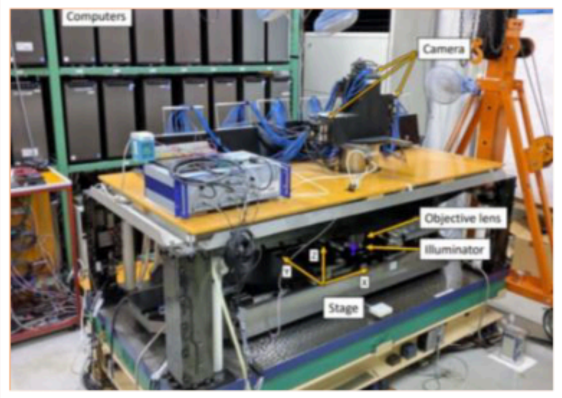






Assembly → Exposure → Disassembling → Development

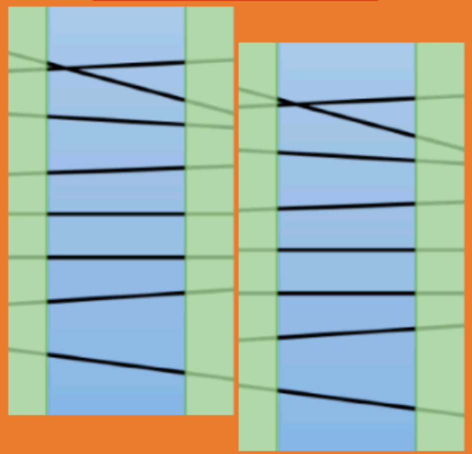
Japan

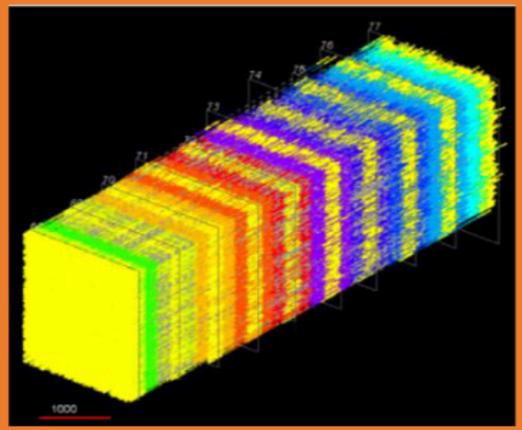


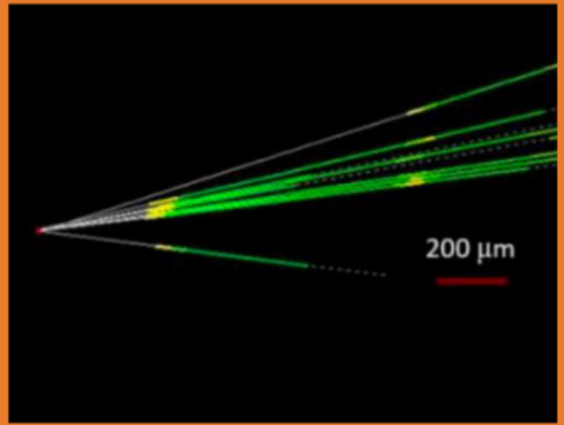
Readout

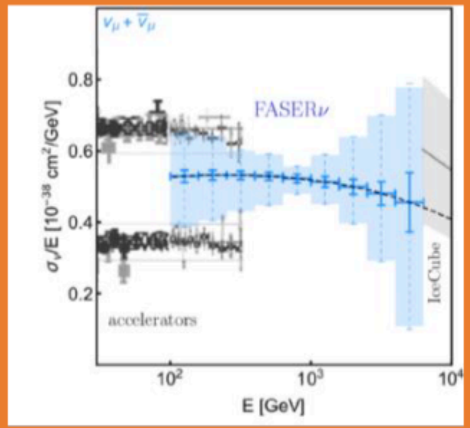
Offline analysis

Alignment → Track reconstruction → Vertex reconstruction → e, μ ID, τ decay search, charge ID, etc… → Physics analysis



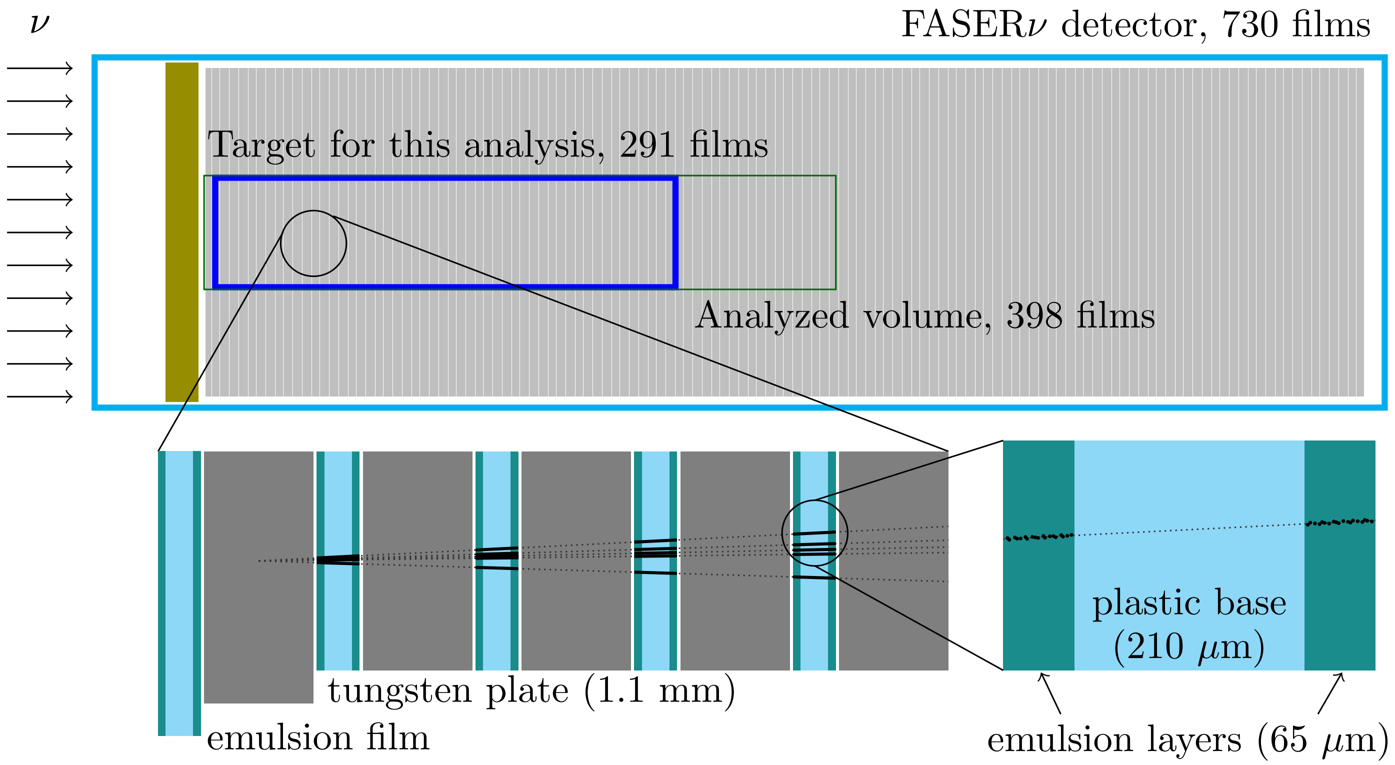


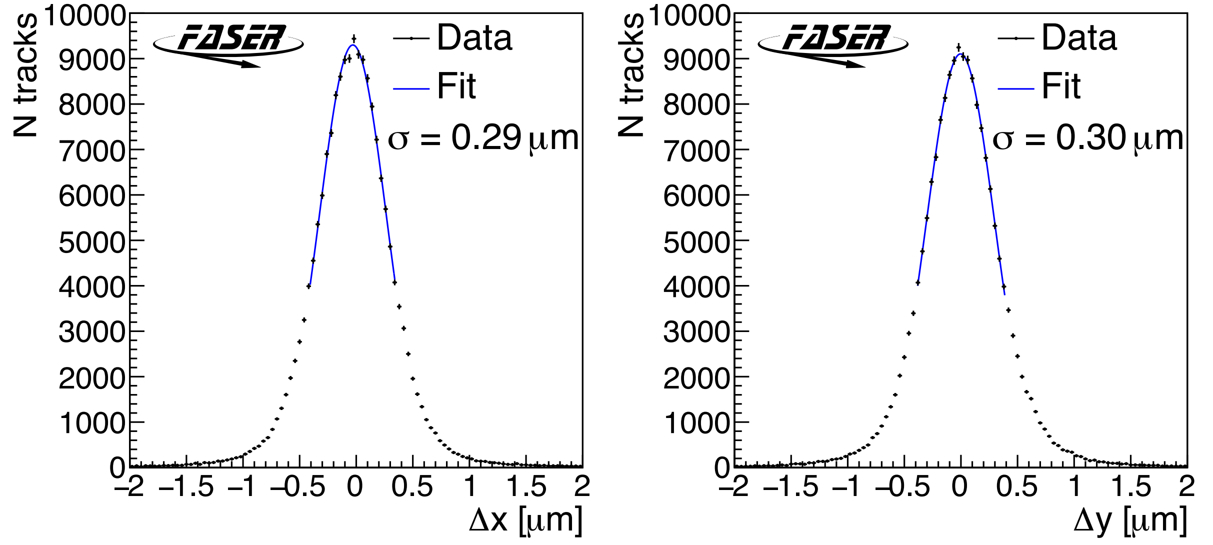


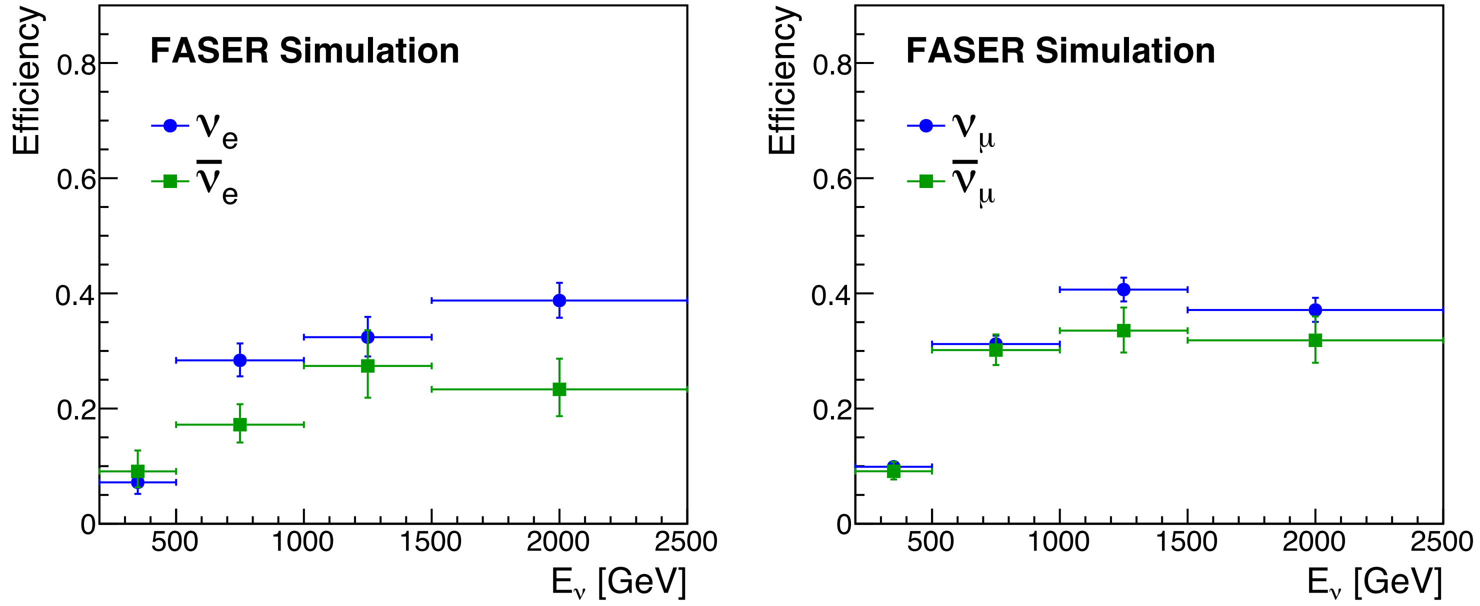


最新の物理解析結果 - ν_e & ν_μ 検出 + ν-核子反応断面積

- 2022年の2nd moduleを解析 (9.5fb^{-1})
  - Film 730枚のうち、291枚の中心部が解析領域
- 想定されるイベント数
  - 複数のハドロン相互作用モデルを考慮
    - 軽いハドロン: EPOS-LHC, QGSJET II-04, SIBYLL 2.3d, PYTHIA forward tune
    - チャームハドロン: POWHEG, pQCD のuncertaintyを考慮
  - $N_{\mathrm{expected}} = 1.68^{+1.18}_{-0.37}\ (\mathrm{flux})^{+0.51}_{-0.36}\ (\mathrm{others})$ for ν_e
  - $N_{\mathrm{expected}} = 8.64^{+1.41}_{-0.76}\ (\mathrm{flux})^{+2.65}_{-1.82}\ (\mathrm{others})$ for ν_μ

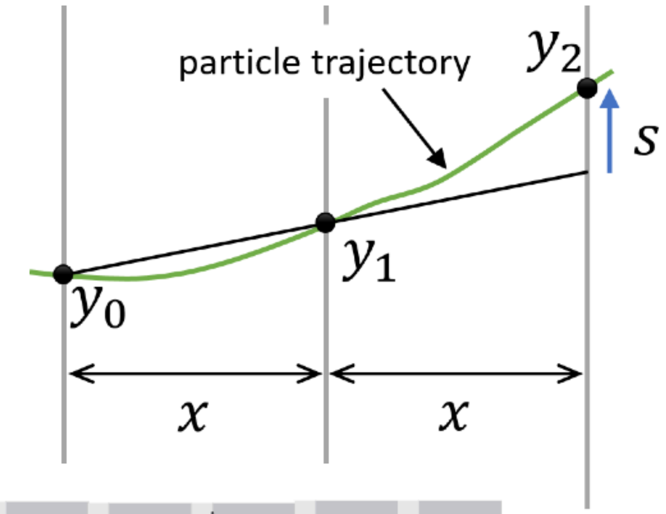


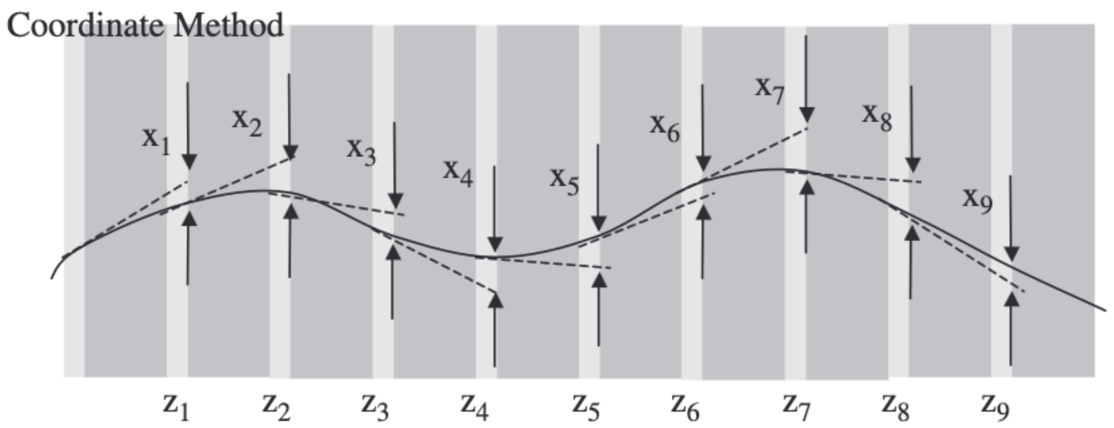




ミューオン運動量測定

Momentum dependency in the scattering angle

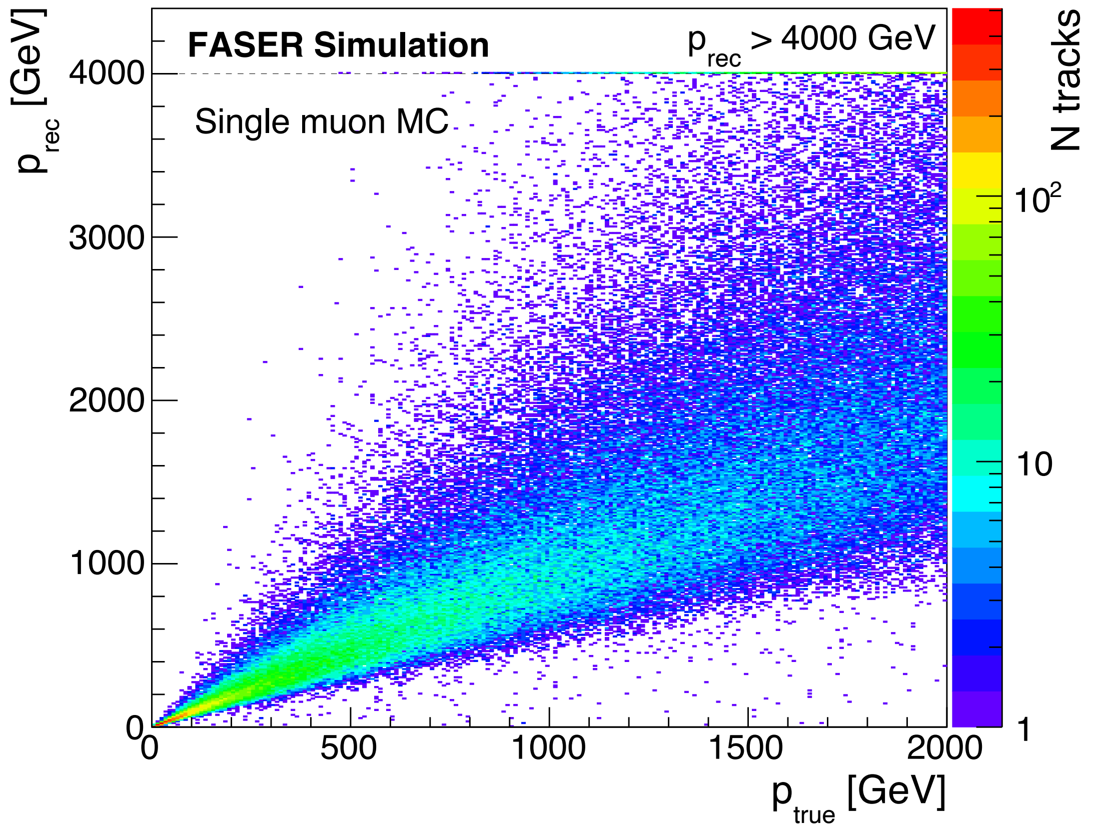




$$\theta^{RMS}_{plane} = \frac{0.0136}{\beta pc}\sqrt{\frac{z}{X_0}}\left\{1 + 0.038\ ln\left(\frac{z}{X_0\beta^2}\right)\right\},$$

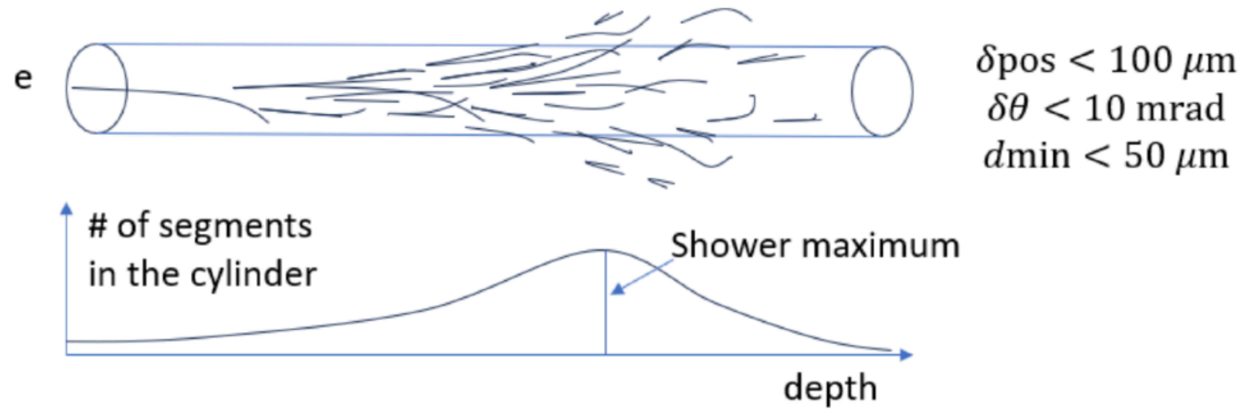
z: thickness
p: momentum

Momentum is estimated by measuring displacements for every 1 plate, every 2 plates, every 4 plates, every 8 plates, and every 16 plates and calculating RMS for each case.



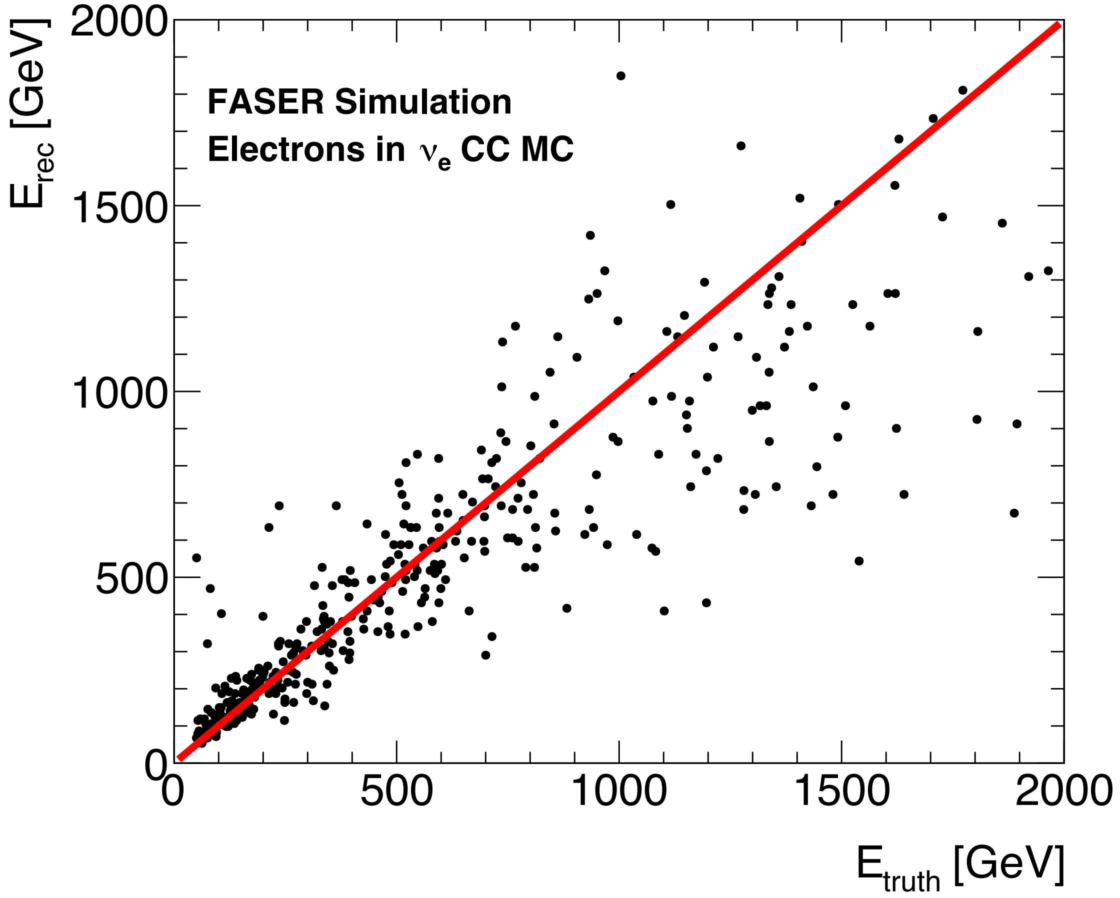
Resolution: ~20% at 200 GeV

EMシャワーエネルギー測定



Count the number of segments in ±3 films around the shower maxim (total 7 films)

The number of backgrounds was estimated and subtracted by counting the number of segments at the cylinder randomly opened.

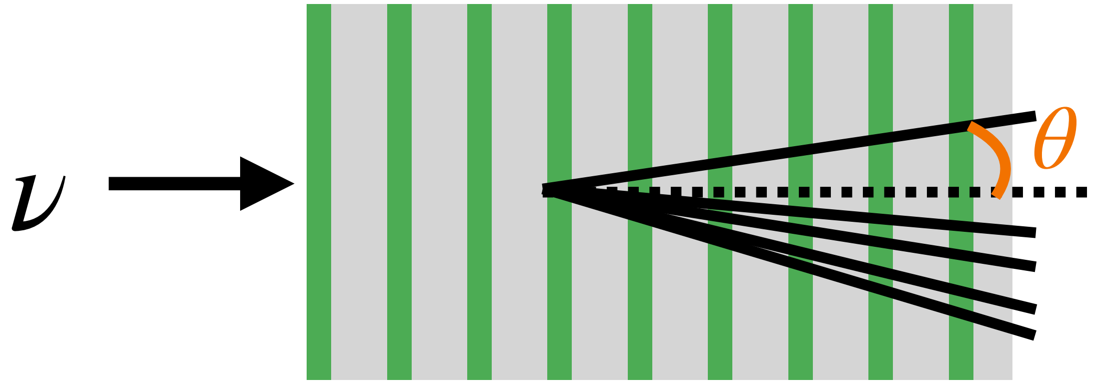


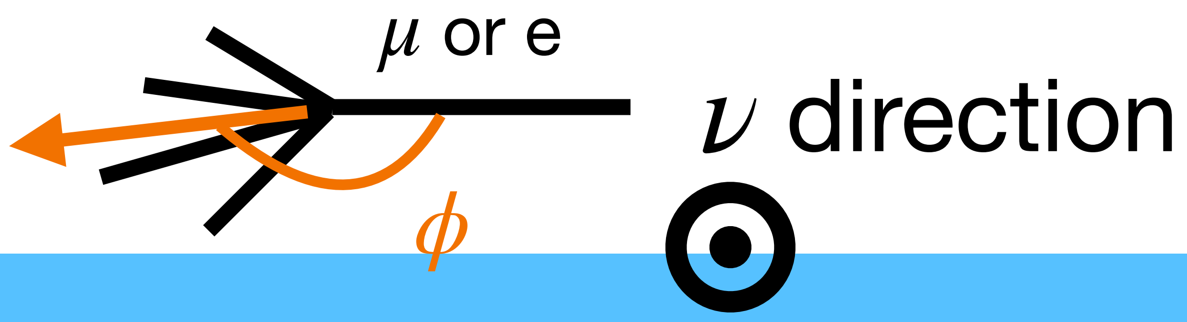
Resolution: ~25% at 200 GeV

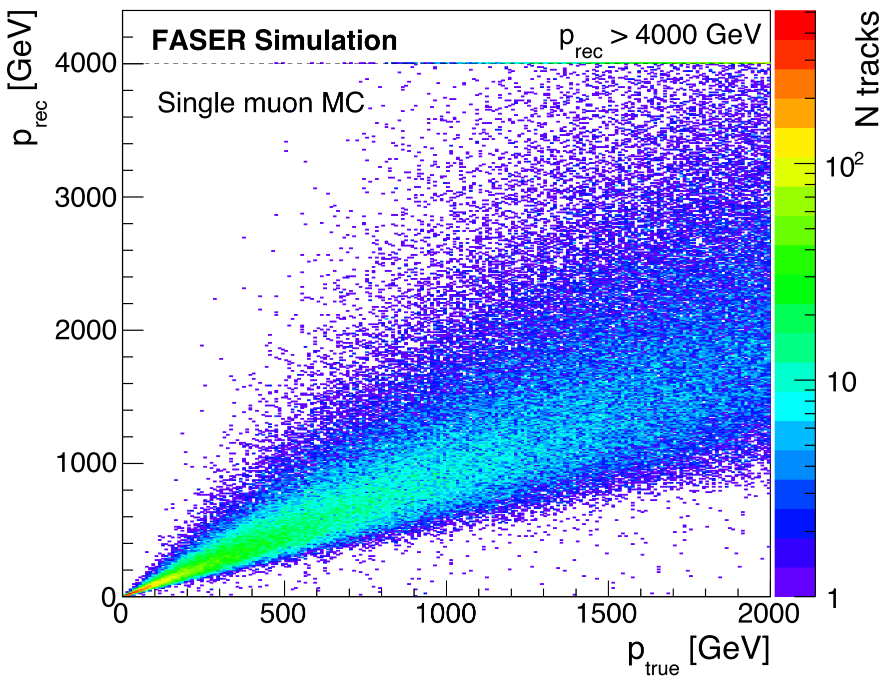
イベント選別

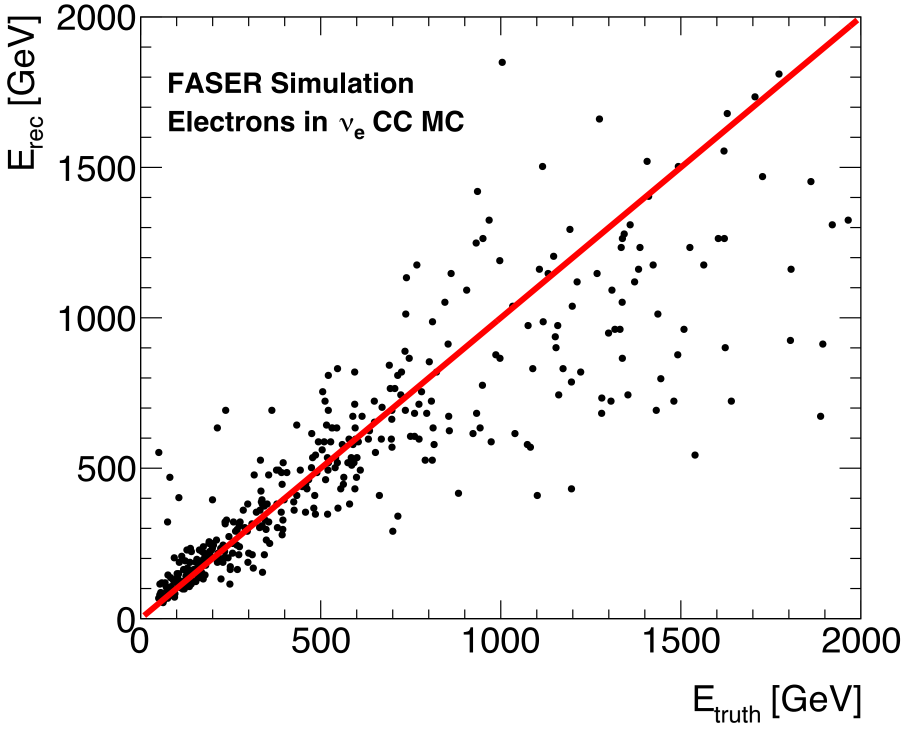
イベント選別

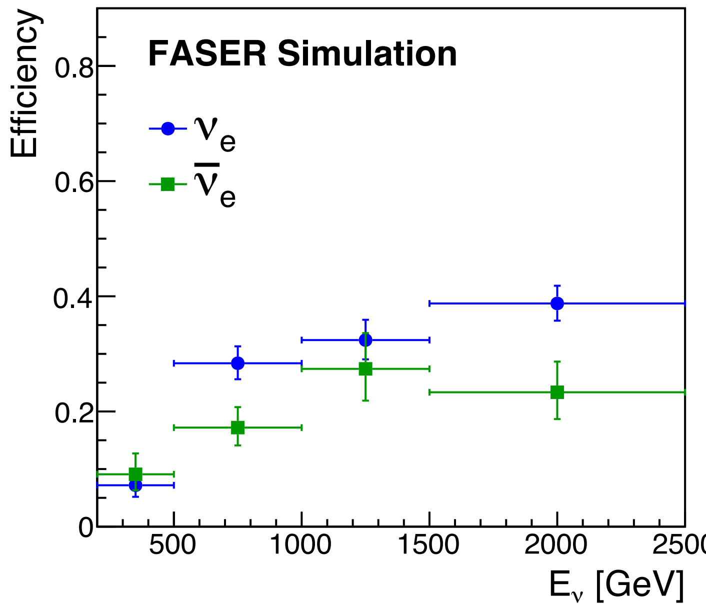
- 5 or more tracks attached to a vertex
- No charged parent track
- 4 or more tracks with $\tan_\theta < 0.1$
- $\tan\theta > 0.005$ for muon or EM shower
- An EM shower or a track of more than 200 GeV
- $\phi > 90°$

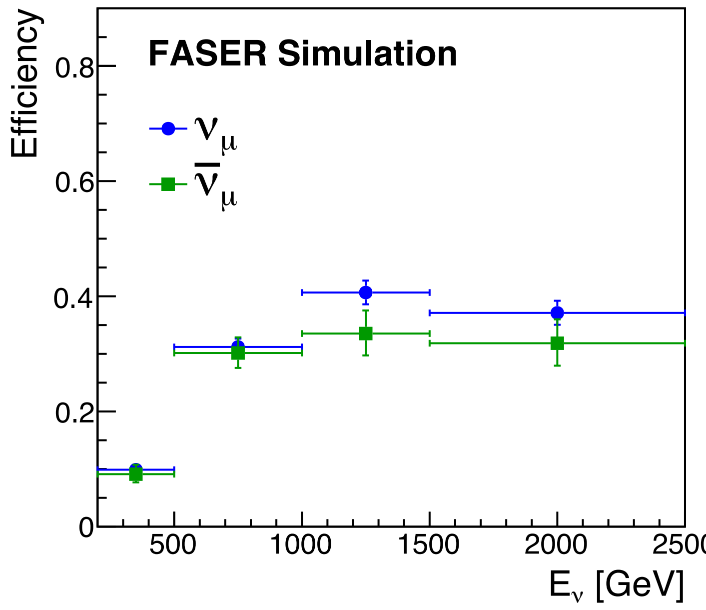












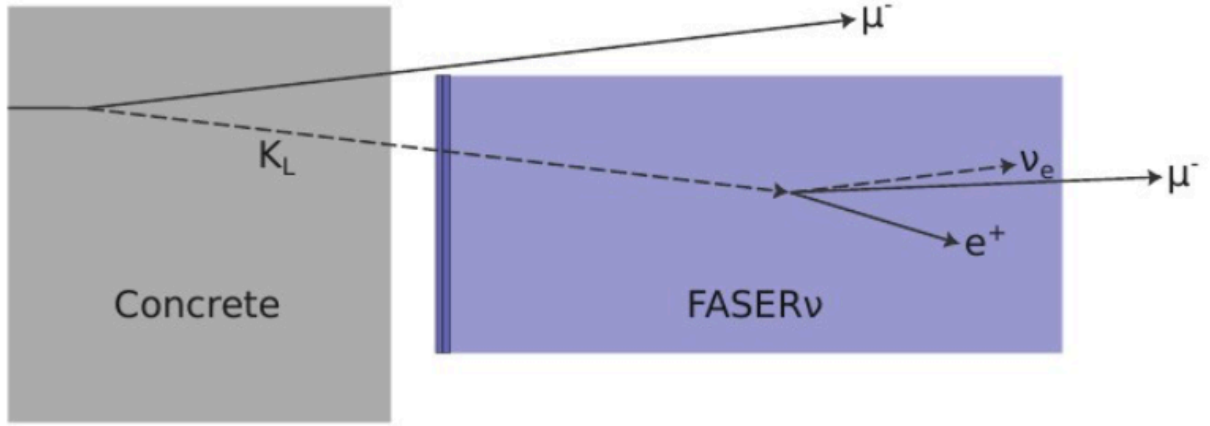
バックグラウンド

- 中性ハドロン

Hadron type	K_L	n	Λ
Events simulated (E_h >200 GeV)	13497	13191	13902
Events selected as ν_e CC	0	0	0
Events selected as ν_μ CC	6	11	5
Scaling factor (data/MC)	1/232	1/256	1/423

Hadron type	K_S	$\bar{n}$	$\bar{\Lambda}$
Events reconstructed (E_h >200 GeV)	7113	5827	5368
Events selected as ν_e CC	1	0	0
Events selected as ν_μ CC	3	3	4
Scaling factor (data/MC)	1/436	1/569	1/630

ミューオン由来の中性ハドロン生成



- ニュートリノ Neutral Current interaction

$$\nu_e: 0.008^{+0.013}_{-0.004}\ (\text{flux}) \pm 0.001\ (\text{cross}-\text{section})^{+0.007}_{-0.004}\ (\text{others})$$

$$\nu_\mu: 0.045^{+0.004}_{-0.005}\ (\text{flux}) \pm 0.003\ (\text{cross}-\text{section})^{+0.076}_{-0.024}\ (\text{others})$$

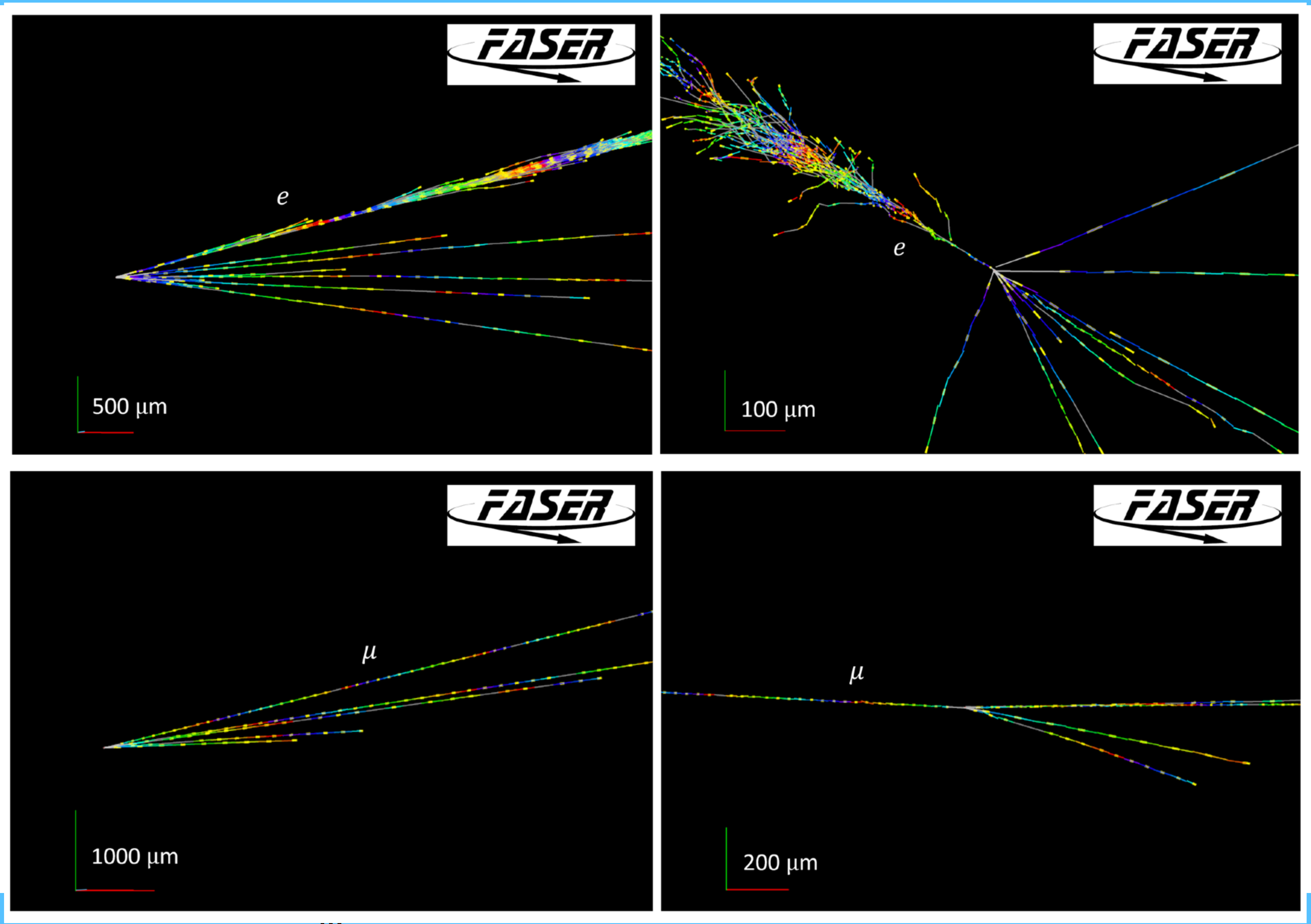
Total background

ν_e: $0.025^{+0.015}_{-0.010}$

ν_μ: $0.22^{+0.09}_{-0.07}$

ν_e candidates, ν_μ candidates

- ν_e候補: 4イベント
- ν_μ候補: 8イベント
- バックグラウンド
  - ν_e: $0.025^{+0.015}_{-0.010}$
  - ν_μ: $0.22^{+0.09}_{-0.07}$
- 10^10 toysを振って、significanceを計算
  - ν_e: 5.2 σ
  - ν_μ: 5.7 σ

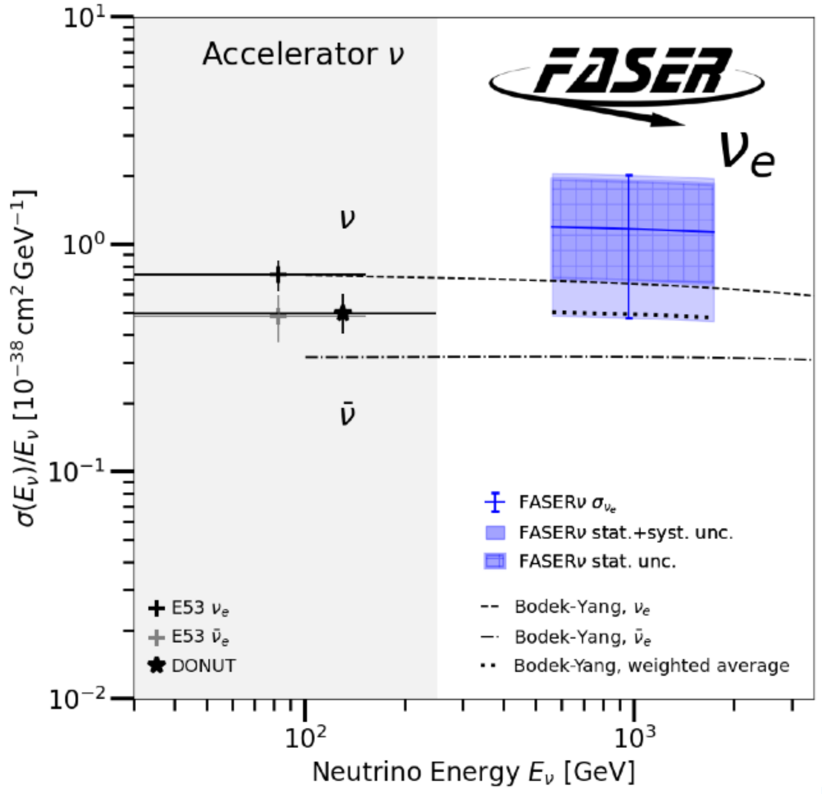


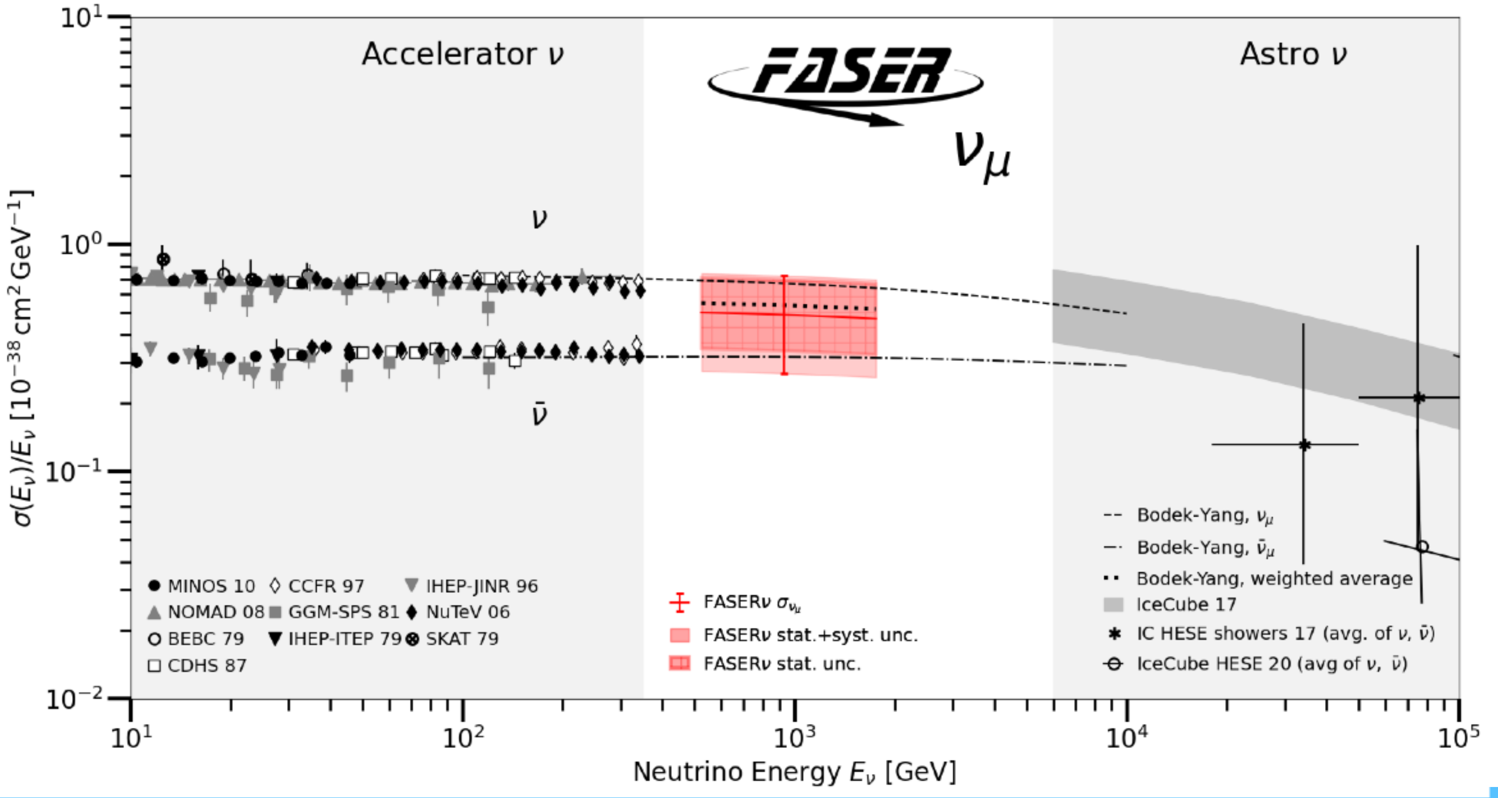
ν-核子反応断面積

- $\sigma_{\rm obs} = \dfrac{N_{\nu,\rm obs}}{N_{\rm expected}}\sigma_{\rm theory}$
  - ν_e候補: 4イベント, ν_μ候補: 8イベント
  - $N_{\rm expected} = 1.68^{+1.18}_{-0.37}\ ({\rm flux})^{+0.51}_{-0.36}\ ({\rm others})$ for ν_e
  - $N_{\rm expected} = 8.64^{+1.41}_{-0.76}\ ({\rm flux})^{+2.65}_{-1.82}\ ({\rm others})$ for ν_μ

Table 2: Systematic uncertainties related to the signal expectation.

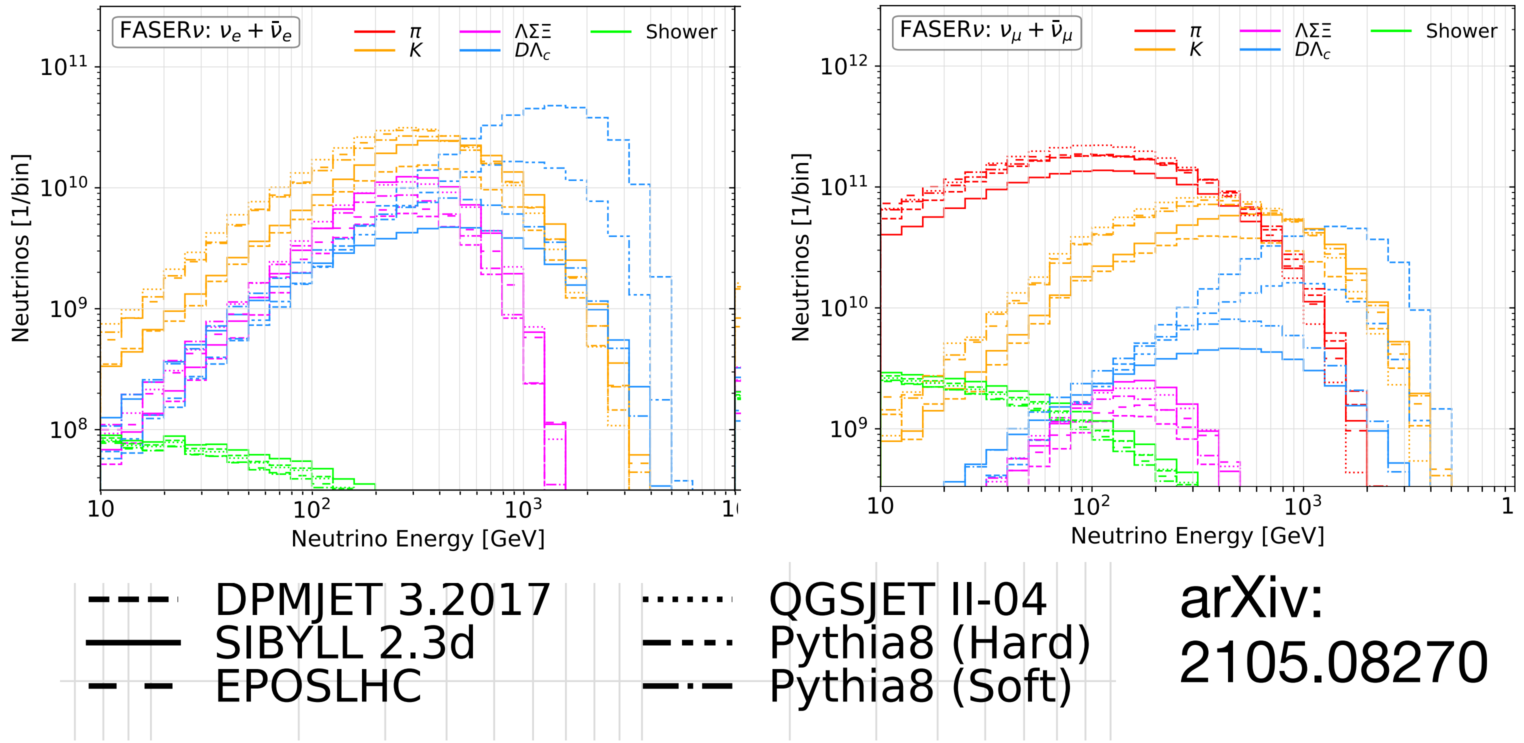
Source	Relative uncertainty ν_e	Relative uncertainty ν_μ
Luminosity	2.2%	2.2%
Tungsten thickness	1%	1%
Interactions with emulsions	$^{+3.6}_{-0}$%	$^{+3.6}_{-0}$%
Flux uncertainty	$^{+70}_{-22}$%	$^{+16}_{-9}$%
Line of sight position	$^{+2.1}_{-2.4}$%	$^{+1.9}_{-2.5}$%
Efficiency from hadronization	$^{+22}_{-5}$%	$^{+23}_{-5}$%
Efficiency from reconstruction	20%	20%
Efficiency from MC statistics	4.9%	2.8%
Total	$^{+70}_{-22}$% (flux)	$^{+16}_{-9}$% (flux)
	$^{+30}_{-21}$% (other)	$^{+31}_{-21}$% (other)



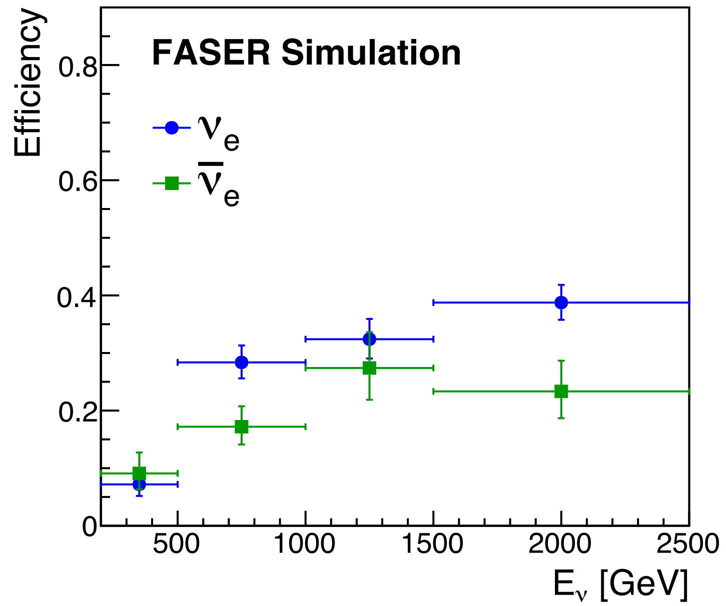


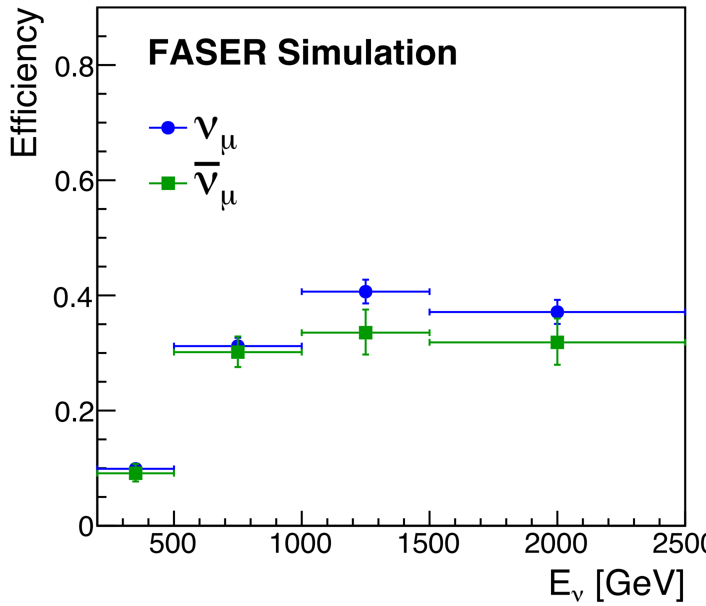
今後の展望

- ニュートリノエネルギー再構成
  - FASERν検出器での再構成手法を開発中
  - ミューオン運動量測定およびEMシャワーエネルギー測定をSPS でのテストビームにて検証
  - ハドロンの運動量やミューオン・電子のエネルギー、角度からニュートリノエネルギーを再構成する
- 2022年2nd moduleのフル解析
  - 約6倍のtarget mass
  - さらに、1 TeV以下のニュートリノの検出効率を上げる
  - 宇宙線との関係で重要なのは、100 GeV-1TeVでのν_e とν_μの 比
- バックグラウンドミューオン解析
  - p-p 衝突で生じたハドロン由来の成分を測定できれば、ハドロン相互作用モデルの検証につながる



arXiv: 2105.08270



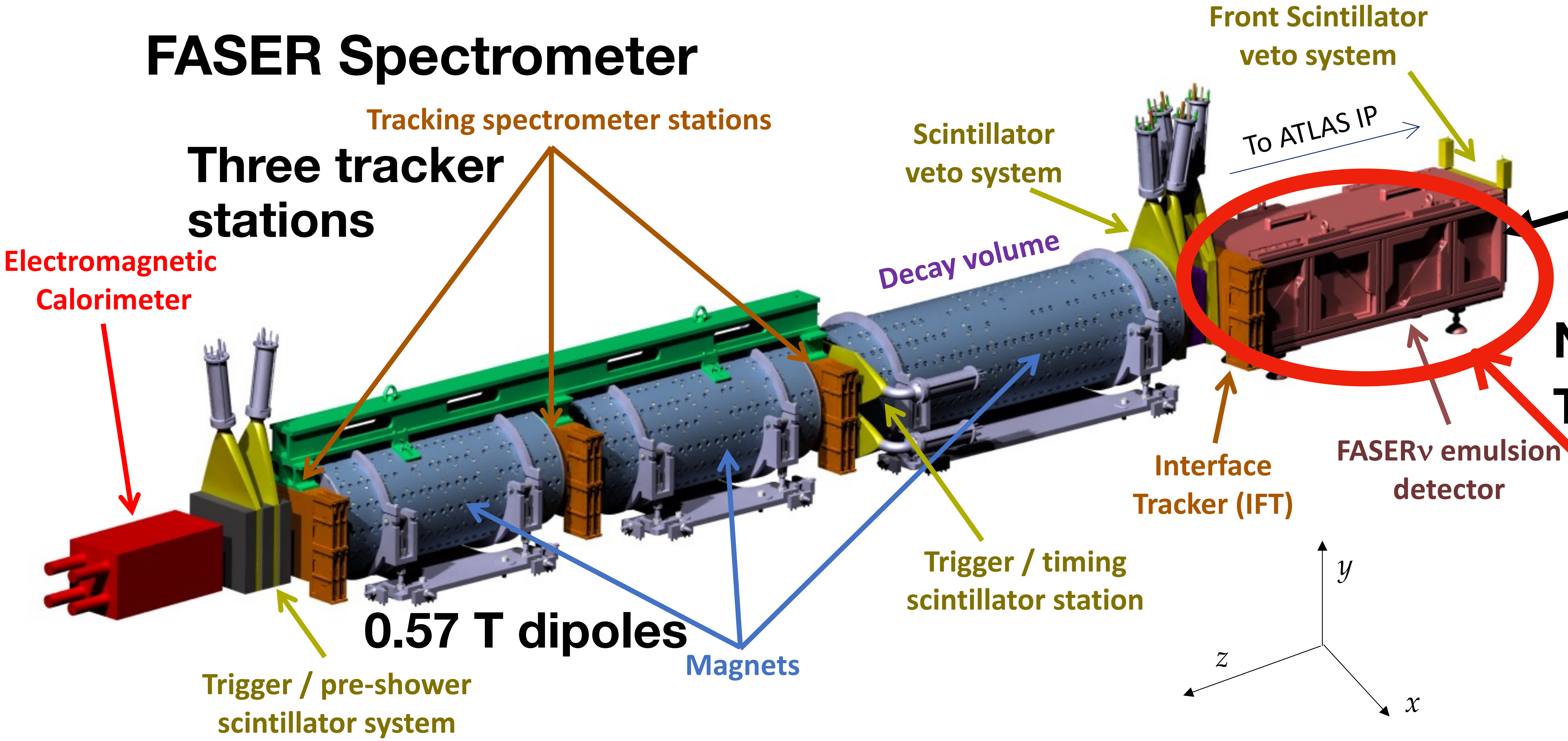


Back-up slides

The FASER detector

FASER Spectrometer

Three tracker stations

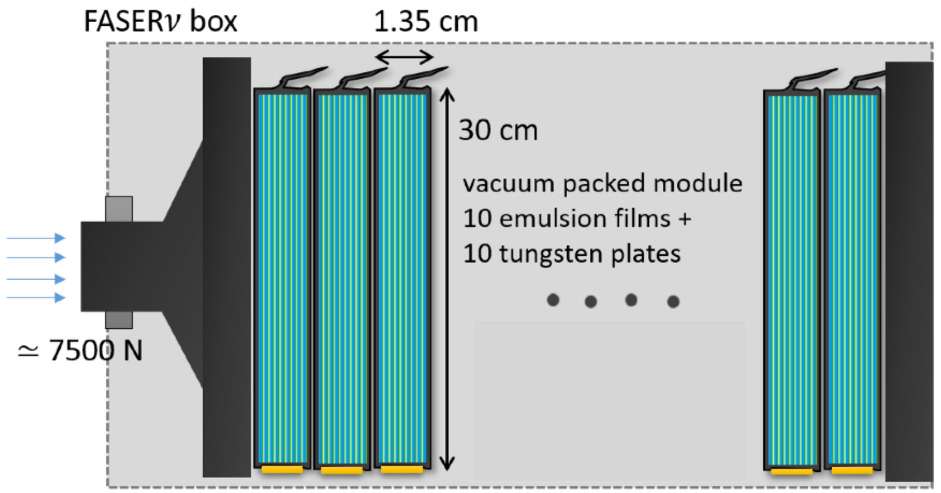


0.57 T dipoles

Neutrino interaction in Tungsten targets

FASERν detector

Emulsion films between tungsten plates



Successful data-taking during 2022 and 2023

Total ~68.4 fb^{-1}

FASERν detector was installed 5 times in total

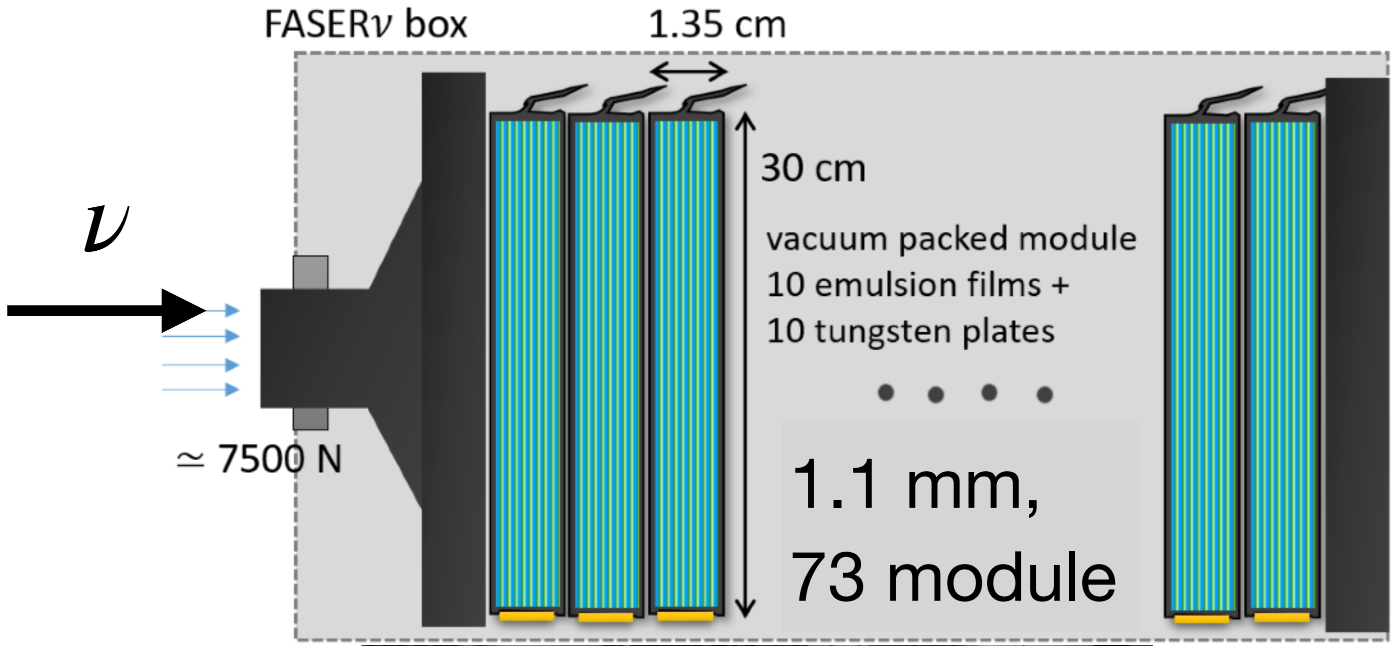
The FASERν detector

FASERν detector

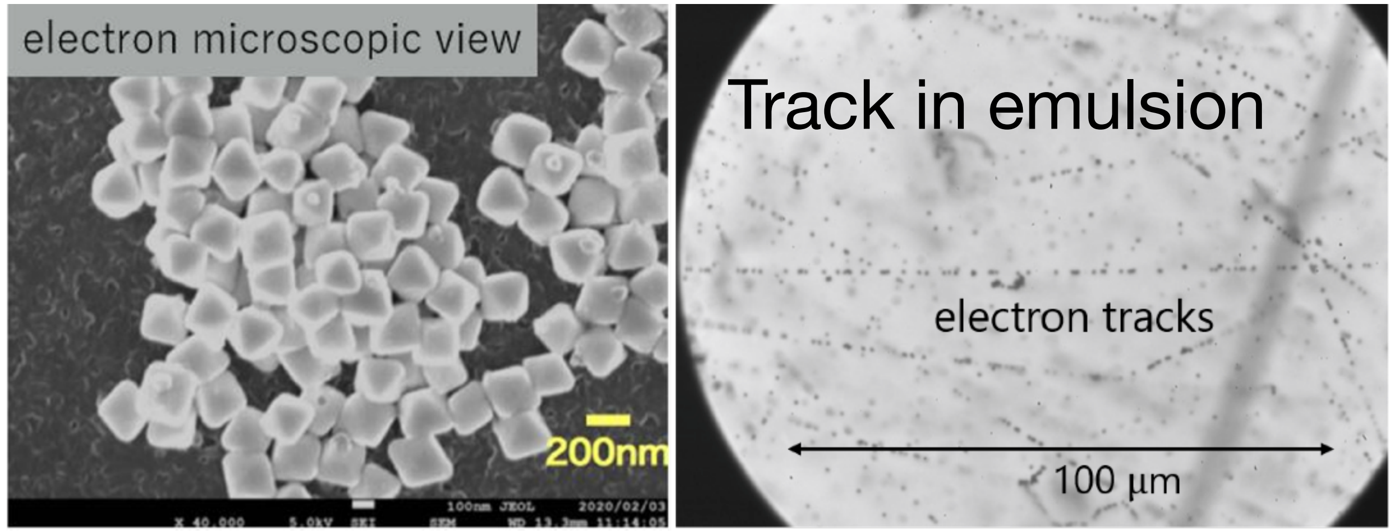
Emulsion films between tungsten plates

1.1 mm tungsten plates x 730: target

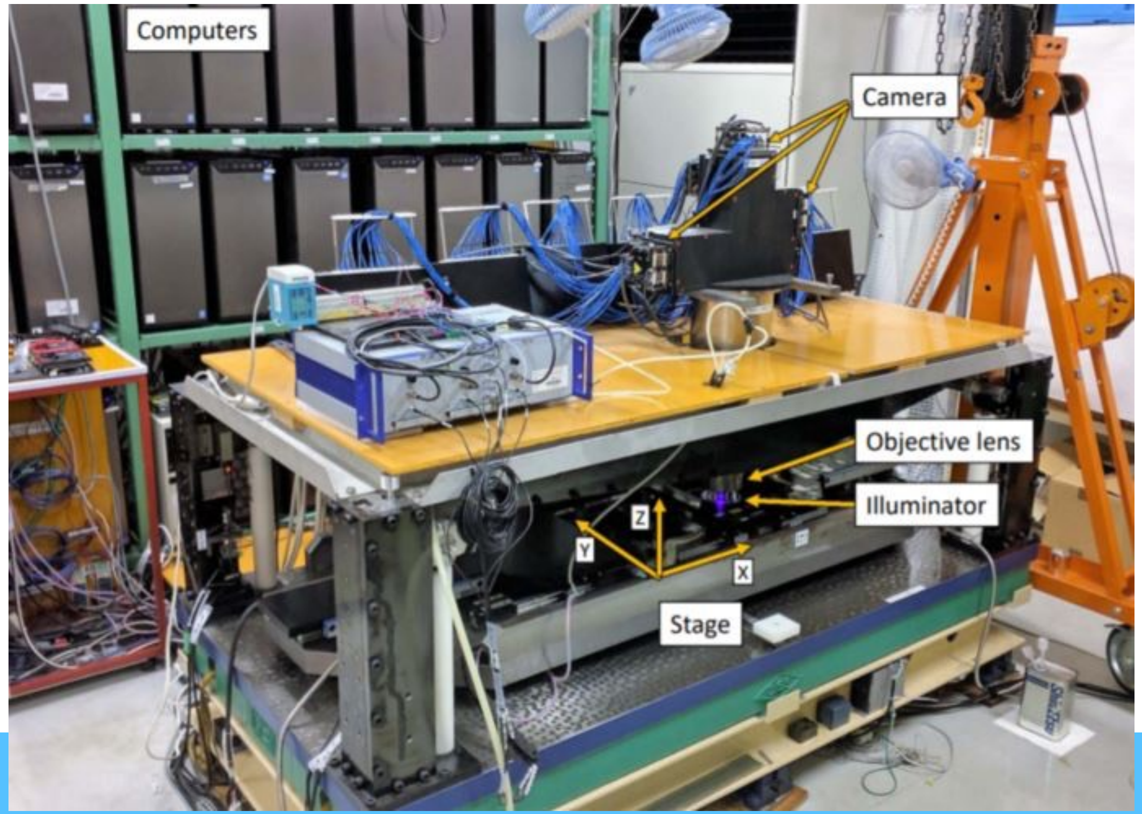
Emulsion film x 730: to measure tracks



Emulsion films (25cm x 30cm)



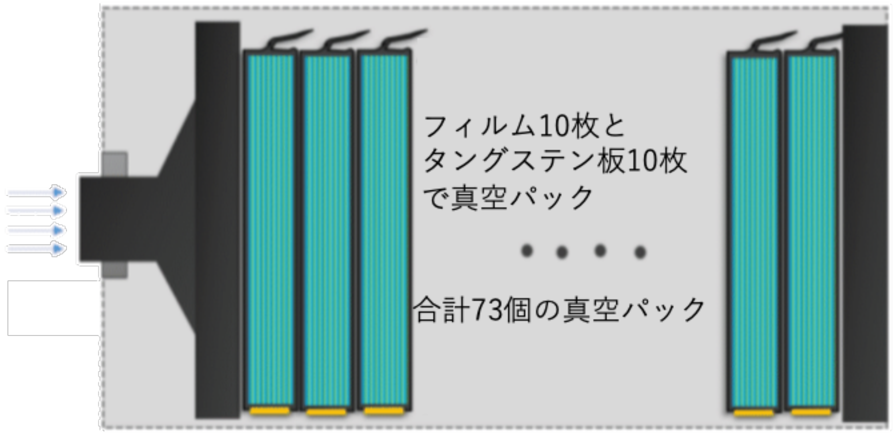
Microscope in Nagoya Univ.



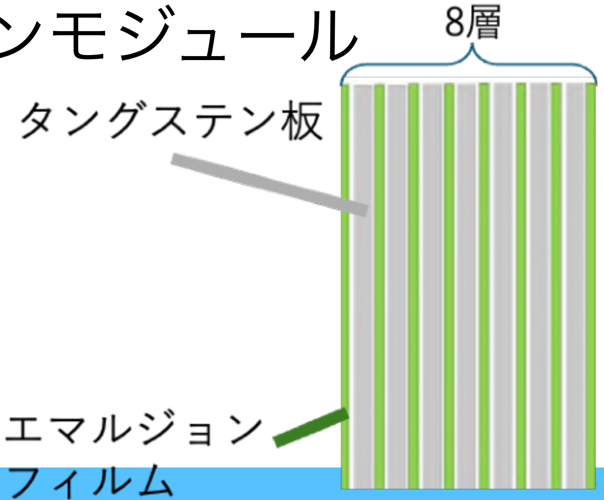
ミューオンバックグラウンドの測定

FASERν検出器および
ミューオンモジュールで
バックグラウンド測定
が行われている。

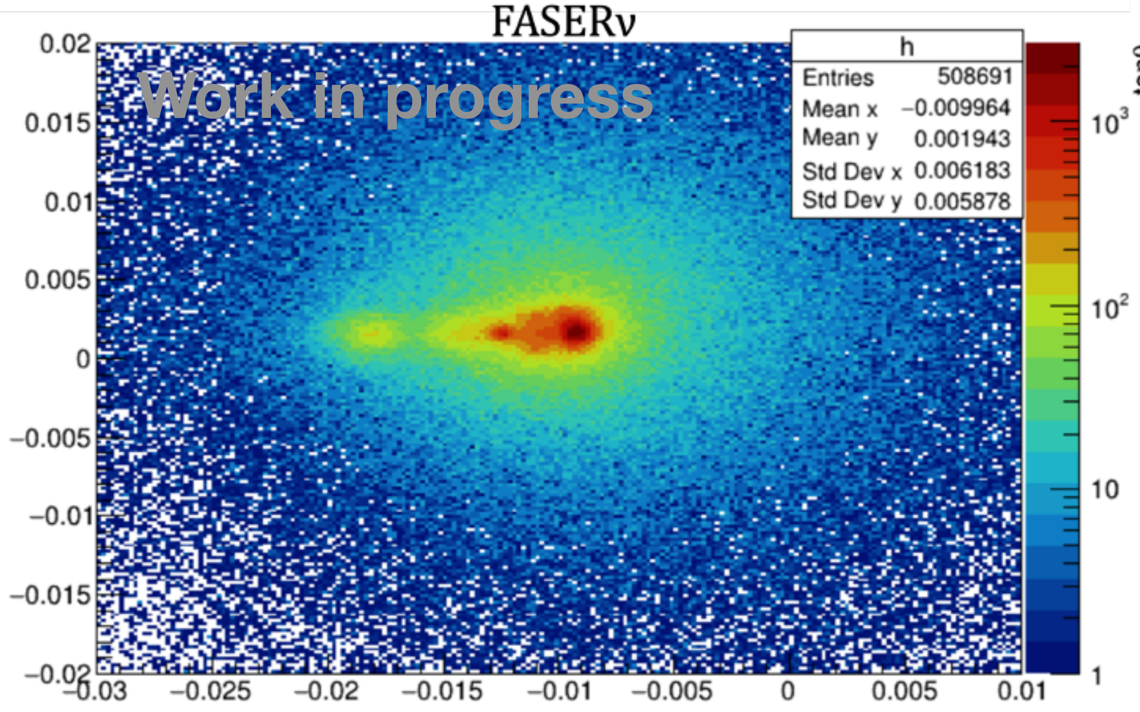
FASERν 検出器

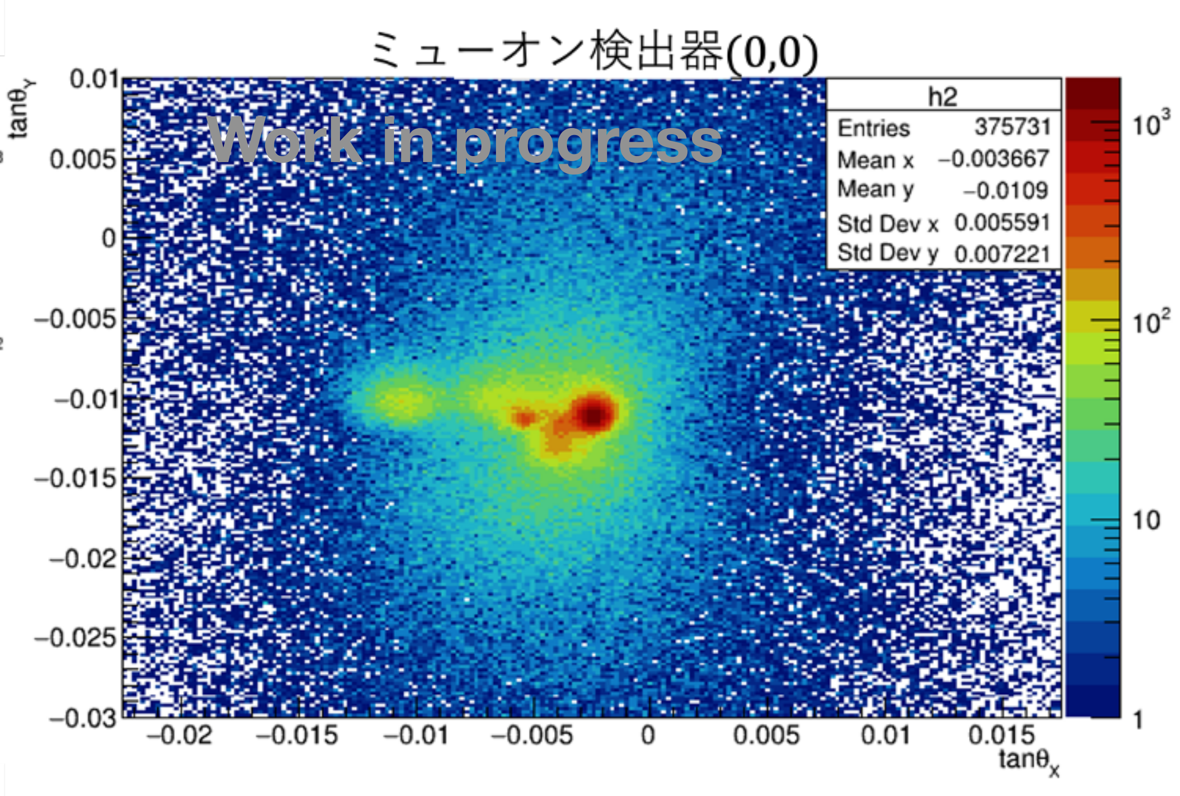


ミューオンモジュール

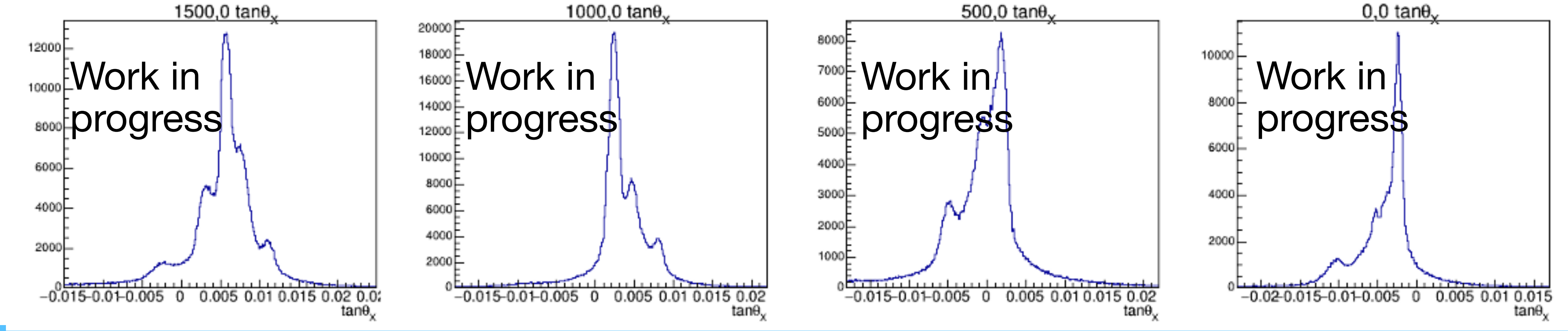


LOS(散乱角0度)での角度分布

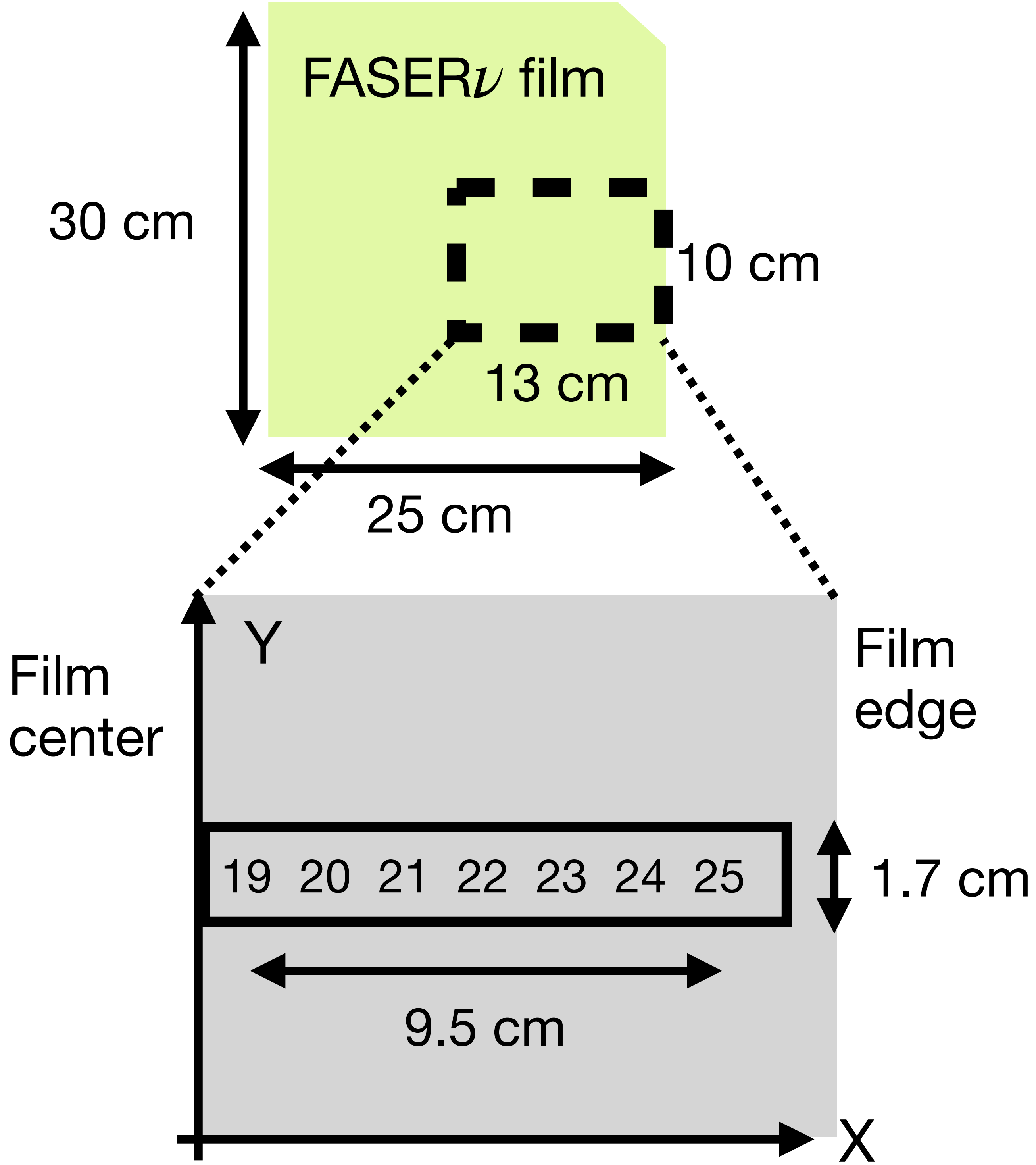




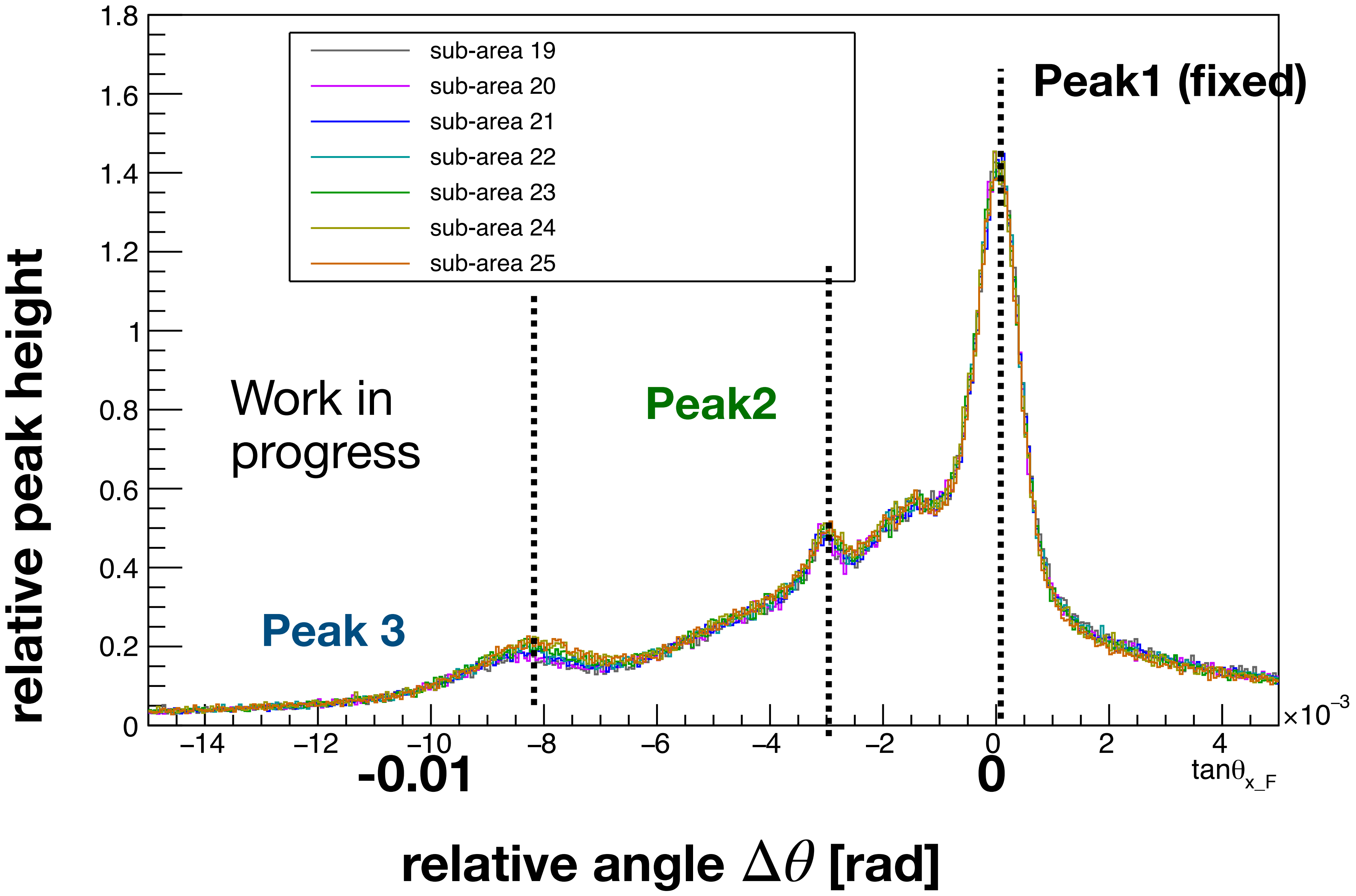
ミューオンモジュール、x = 1500, 1000, 500, 0 mm



角度分布の位置依存性

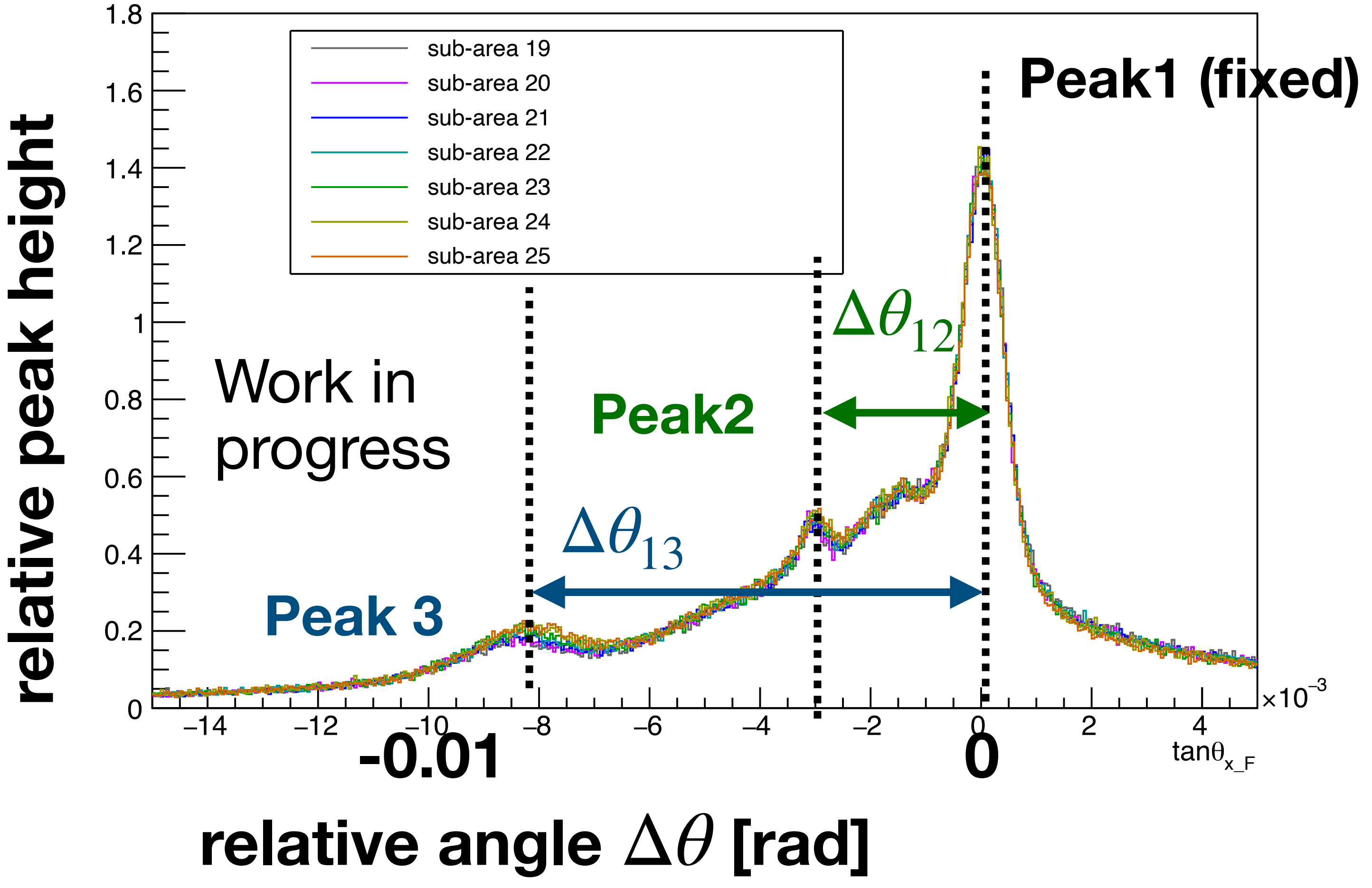


FASERν film
30 cm
10 cm
13 cm
25 cm
Y
Film center
Film edge
19 20 21 22 23 24 25
1.7 cm
9.5 cm
X



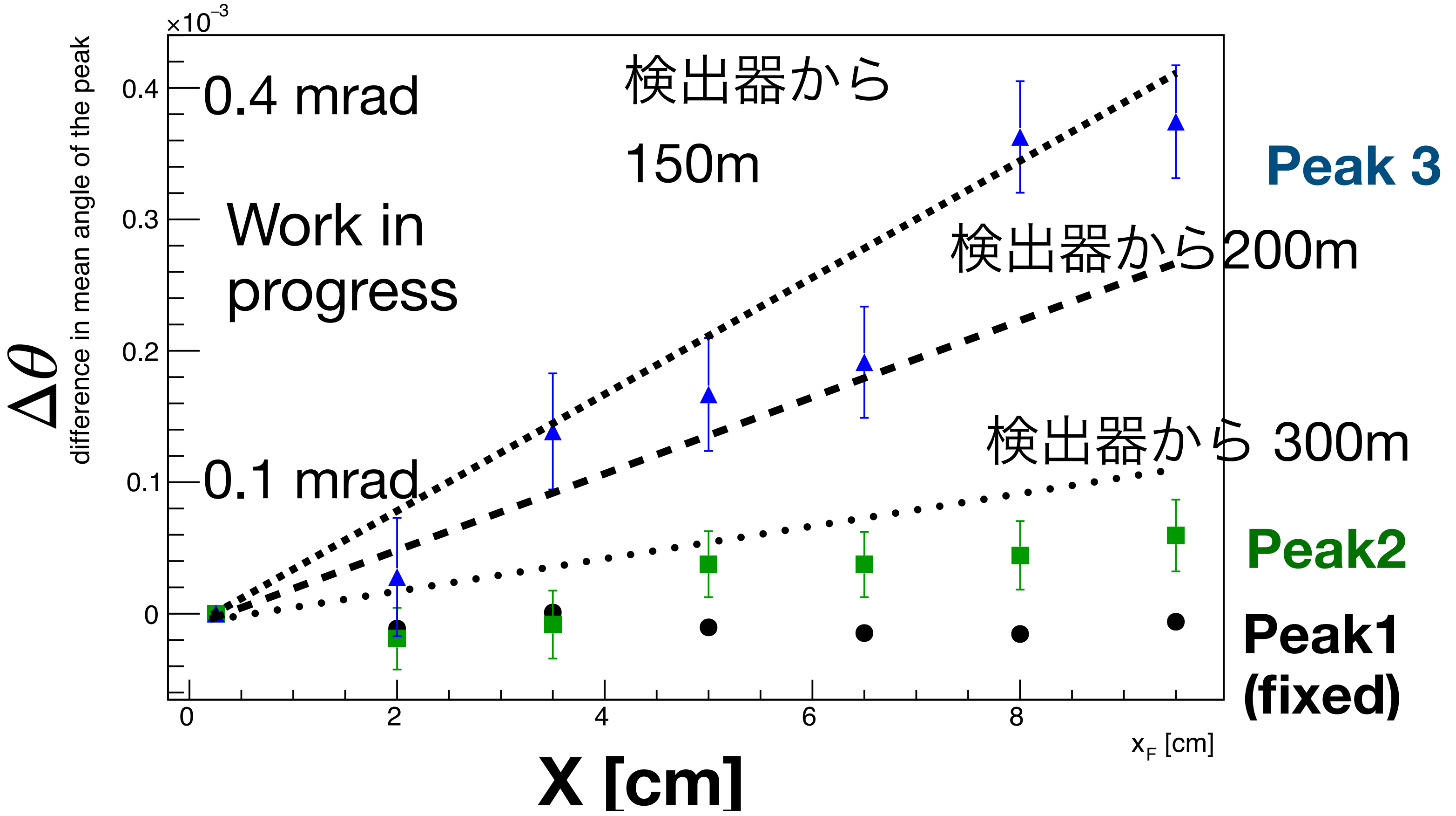
sub-area 19
sub-area 20
sub-area 21
sub-area 22
sub-area 23
sub-area 24
sub-area 25
Peak1 (fixed)
Peak2
Peak 3
Work in progress
relative peak height
relative angle Δθ [rad]
-0.01
0
$\times 10^{-3}$
$\tan\theta_{x\_F}$

角度分布の位置依存性



角度の絶対値ではなく、一番大きなピークからの相対角度で検討

点線は、一番大きなピークのミューオンが検出器から480m先で生成したと仮定した時に検出器から150m, 200m, 300m先で生成したミューオンの角度変化の想定



今後、シミュレーションとも比較しながらさらに詳しく検討する

FASERnu first analysis

Energy range from simulation

The energy range for σ_{theory} was defined as the energy range containing 68% of reconstructed neutrinos using the baseline models, which is 560–1740 GeV and 520–1760 GeV for ν_e and ν_μ, respectively.

Number of expected events

$$N_{\text{obs}} = \frac{L\rho l}{m_{\text{nucleon}}} \int \sigma(E)\,\phi(E)\,\varepsilon(E)\,\mathrm{d}A\,\mathrm{d}E,$$

$$N_{\text{expected}} = 1.68^{+1.18}_{-0.37}\ (\text{flux})^{+0.51}_{-0.36}\ (\text{others})\ \text{for}\ \nu_e$$

$$N_{\text{expected}} = 8.64^{+1.41}_{-0.76}\ (\text{flux})^{+2.65}_{-1.82}\ (\text{others})\ \text{for}\ \nu_\mu$$

- 中性ハドロン

Hadron type	K_L	n	Λ
Events simulated (E_h >200 GeV)	13497	13191	13902
Events selected as ν_e CC	0	0	0
Events selected as ν_μ CC	6	11	5
Scaling factor (data/MC)	1/232	1/256	1/423

Hadron type	K_S	$\bar{n}$	$\bar{\Lambda}$
Events reconstructed (E_h >200 GeV)	7113	5827	5368
Events selected as ν_e CC	1	0	0
Events selected as ν_μ CC	3	3	4
Scaling factor (data/MC)	1/436	1/569	1/630

- ニュートリノ Neutral Current interaction

$$\nu_e\text{: } 0.008^{+0.013}_{-0.004}\ (\text{flux}) \pm 0.001\ (\text{cross}-\text{section})^{+0.007}_{-0.004}\ (\text{others})$$

$$\nu_\mu\text{: } 0.045^{+0.004}_{-0.005}\ (\text{flux}) \pm 0.003\ (\text{cross}-\text{section})^{+0.076}_{-0.024}\ (\text{others})$$

FASERnu first analysis

$$L = P(N_{\text{obs}}|\mu) \cdot \prod_j G(\lambda_j|\mu' = 0., \sigma' = 1.) \cdot \prod_i P(N^i_{\text{MC found}}|n_i^{\text{background}}) G(f^i|\mu' = 1., \sigma' = 1.),$$

$$\mu = N_\nu + \sum_i N^i_{\text{backgrounds}}(f^i_{\text{syst}}, n_i^{\text{background}}) + N_{\text{NC}}^{\text{contamination}}(\lambda_{\text{light hadron}}, \lambda_{\text{charm hadron}}, \lambda^{\text{NC}}_{\text{syst.}})$$

$$N'_{\text{expected}}(\lambda) = \begin{cases} N_{\text{center}}\left(\frac{N_{\text{center}}+\Delta N_{\text{lower}}}{N_{\text{center}}}\right)^{|\lambda|} & (\lambda < 0) \\ N_{\text{center}}\left(\frac{N_{\text{center}}+\Delta N_{\text{upper}}}{N_{\text{center}}}\right)^{|\lambda|} & (\lambda \geq 0), \end{cases}$$

$$f_{\text{syst}}(\lambda_{\text{syst}}) = \begin{cases} \frac{N_{\text{center}}+\Delta N_{\text{lower}}|\lambda_{\text{syst}}|}{N_{\text{center}}} & (\lambda < 0) \\ \frac{N_{\text{center}}+\Delta N_{\text{upper}}|\lambda_{\text{syst}}|}{N_{\text{center}}} & (\lambda \geq 0), \end{cases}$$

$$N_{\text{expected}}(\lambda_{\text{light hadron}}, \lambda_{\text{charm hadron}}, \lambda_{\text{syst.}}) = f^{\text{light hadron}}_{\text{syst}}(\lambda_{\text{syst.}}) N^{\text{light hadron}}_{\text{expected}}(\lambda_{\text{light hadron}}) + f^{\text{charm hadron}}_{\text{syst}}(\lambda_{\text{syst.}}) N^{\text{charm hadron}}_{\text{expected}}(\lambda_{\text{charm hadron}}),$$

Table 2: Systematic uncertainties related to the signal expectation.

Source	Relative uncertainty ν_e	Relative uncertainty ν_μ
Luminosity	2.2%	2.2%
Tungsten thickness	1%	1%
Interactions with emulsions	$^{+3.6}_{-0}$%	$^{+3.6}_{-0}$%
Flux uncertainty	$^{+70}_{-22}$%	$^{+16}_{-9}$%
Line of sight position	$^{+2.1}_{-2.4}$%	$^{+1.9}_{-2.5}$%
Efficiency from hadronization	$^{+22}_{-5}$%	$^{+23}_{-5}$%
Efficiency from reconstruction	20%	20%
Efficiency from MC statistics	4.9%	2.8%
Total	$^{+70}_{-22}$% (flux)	$^{+16}_{-9}$% (flux)
	$^{+30}_{-21}$% (other)	$^{+31}_{-21}$% (other)

The posterior probability distribution of N_ν is calculated by integrating Eq. 17.

$$P(N_\nu) = \int L(N_\nu, f^i_{\text{syst}}, n_i^{\text{background}}, \lambda_{\text{light hadron}}, \lambda_{\text{charm hadron}}, \lambda_{\text{syst.}})\pi_{\text{flat}} \prod_i df^i_{\text{syst}} dn_i^{\text{background}} d\lambda_{\text{light hadron}} d\lambda_{\text{charm hadron}} d\lambda_{\text{syst.}}.$$

FASERnu first analysis

- $\sigma_{\rm obs} = \frac{N_{\nu,\rm obs}}{N_{\rm expected}} \sigma_{\rm theory}$
  - ν_e候補: 4イベント, ν_μ候補: 8イベント

The α parameter is measured to be $2.4^{+1.8}_{-1.3}$ and $0.9^{+0.5}_{-0.3}$ for ν_e and ν_μ, respectively. The energy-independent part of the interaction cross sections per nucleon, $\sigma_{\rm obs}/E_\nu$, is measured to be $(1.2^{+0.8}_{-0.7}) \times 10^{-38}$ cm^2 GeV^{-1} over the energy range of 560–1740 GeV for ν_e and $(0.5 \pm 0.2) \times 10^{-38}$ cm^2 GeV^{-1} over the energy range of 520–1760 GeV for ν_μ.

$$L = P(N_{\rm obs}|\mu) \cdot \prod_j G(\lambda_j|\mu' = 0., \sigma' = 1.) \cdot \prod_i P(N^i_{\rm MC\,found}|n_i^{\rm background}) G(f^i|\mu' = 1., \sigma' = 1.),$$

The posterior probability distribution of N_ν is calculated by integrating Eq. 17.

$$P(N_\nu) = \int L(N_\nu, f^i_{\rm syst}, n_i^{\rm background}, \lambda_{\rm light\,hadron}, \lambda_{\rm charm\,hadron}, \lambda_{\rm syst.}) \pi_{\rm flat} \prod_i df^i_{\rm syst} dn_i^{\rm background} d\lambda_{\rm light\,hadron} d\lambda_{\rm charm\,hadron} d\lambda_{\rm syst.}.$$