T2K実験の最新結果：ニュートリノビームと前置ニュートリノ検出器の解析結果

村上明(京都大学)、T2K Collaborator

2011/7/1, 「フレーバー物理の新展開」研究会2011

Contents of T2K report

- ☑ T2Kの紹介
- ☑ 最新の物理結果 — 村上
  - ☑ ビームラインモニターと前置検出器の測定結果

- ☑ 振動解析(νe appearance)の手法とスーパーカミオカンデの測定と振動解析の結果について — 坂下

T2K experiment

Super-Kamiokande
(ICRR, Univ. Tokyo)

T2K

J-PARC Main Ring
(KEK-JAEA, Tokai)

Physics run start from 2010.1.

Goals

Search for νe appearance ($\nu_\mu \rightarrow \nu_e$)

Precise measurement of νμ disappearance ($\nu_\mu \rightarrow \nu_x$)

T2K Collaboration

~500 collaborators, 59 institutions, 12 countries

ν_e appearance

Three-neutrino oscillation scenario

= U_{PMNS}

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \quad (\Delta m^2_{31} \sim \Delta m^2_{32})$$

Current measurement of mixing angle

- $\theta_{12} \sim 34°$: solar/reactor ν (Kamland, SNO)
- $\theta_{23} \sim 45°$: atmospheric/accelerator ν (Supar-K, K2K, MINOS)
- $\sin^2 2\theta_{13} < 0.15$ (90% C.L.) ← CHOOZ, MINOS

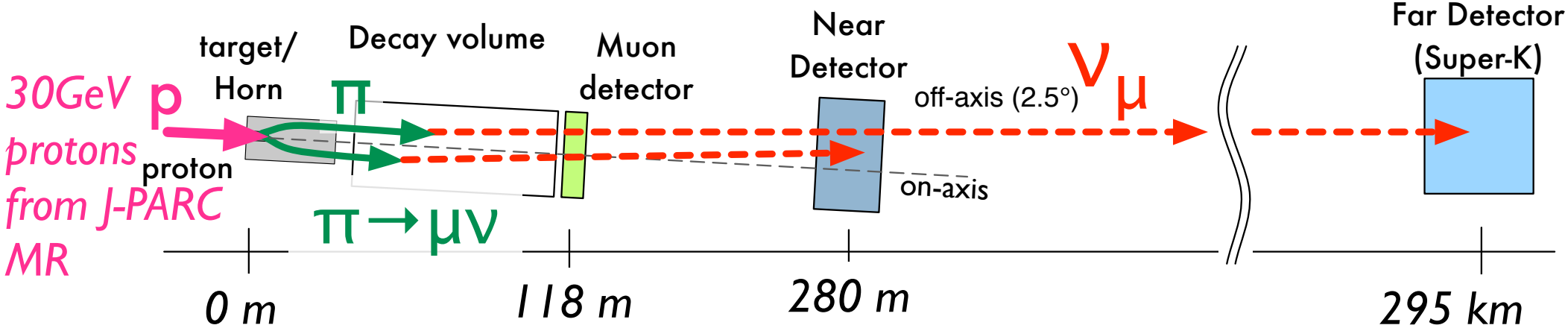
Define last unknown mixing angle.

CPV term in $P(\nu_\mu \to \nu_e) \propto \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta$

If θ_{13} measured > 0 ...

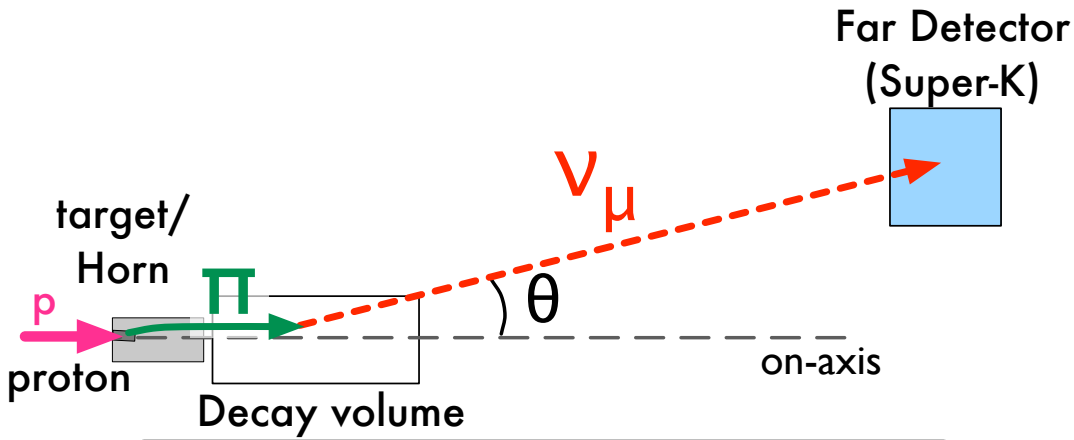
→ Possible to measure CP violation in lepton sector

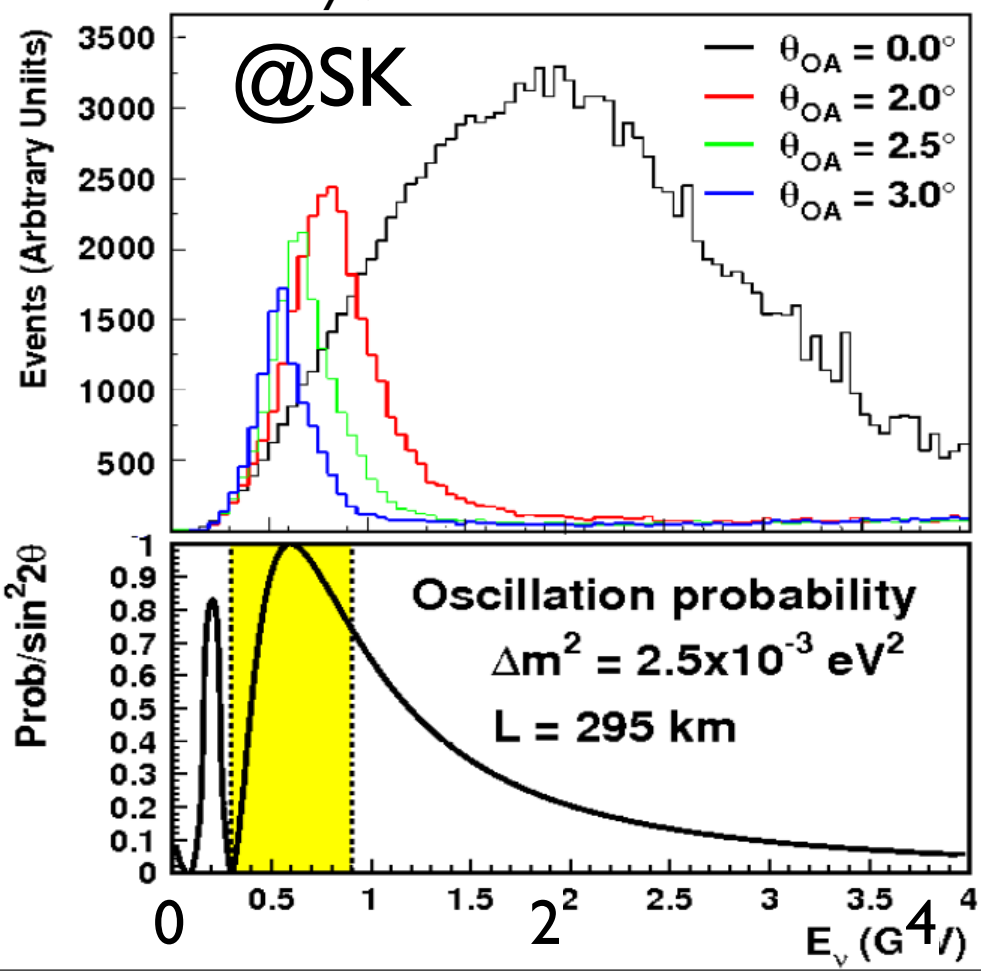
T2K overview



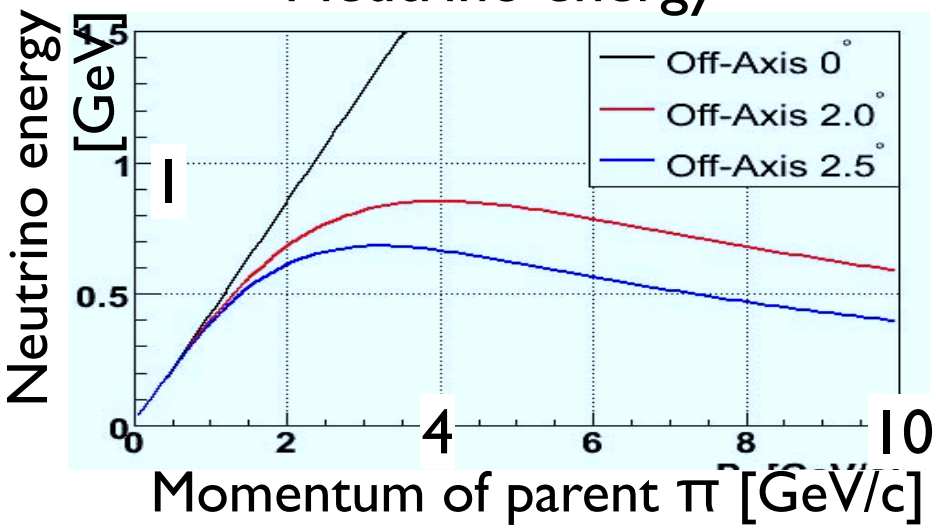
- ☑ **High stat. ν experiment** (high proton beam intensity)
- ☑ **Super-Kamiokande(SK) as far neutrino detector**
- ☑ **Off-axis beam method** (optimize to oscillation, less background)
- ☑ Event synchronization (near/far) with GPS
- ☑ **NA61(@CERN) → Precise prediction of neutrino flux for oscillation analysis**

Off-Axis beam method





Momentum of parent π vs Neutrino energy



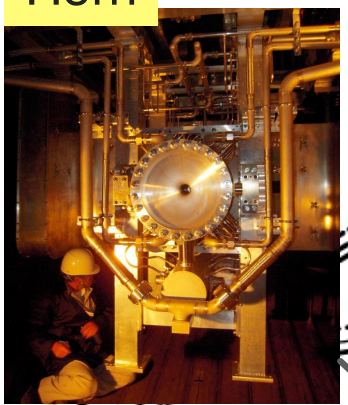
- More sensitive to oscillation.
- Less high energy neutrino tail (→ background)

Need to control beam direction precisely (**< 1mrad**)

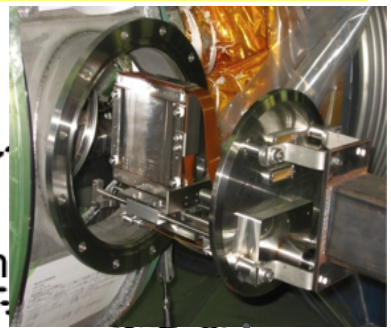
Beam line component

Muon Monitor

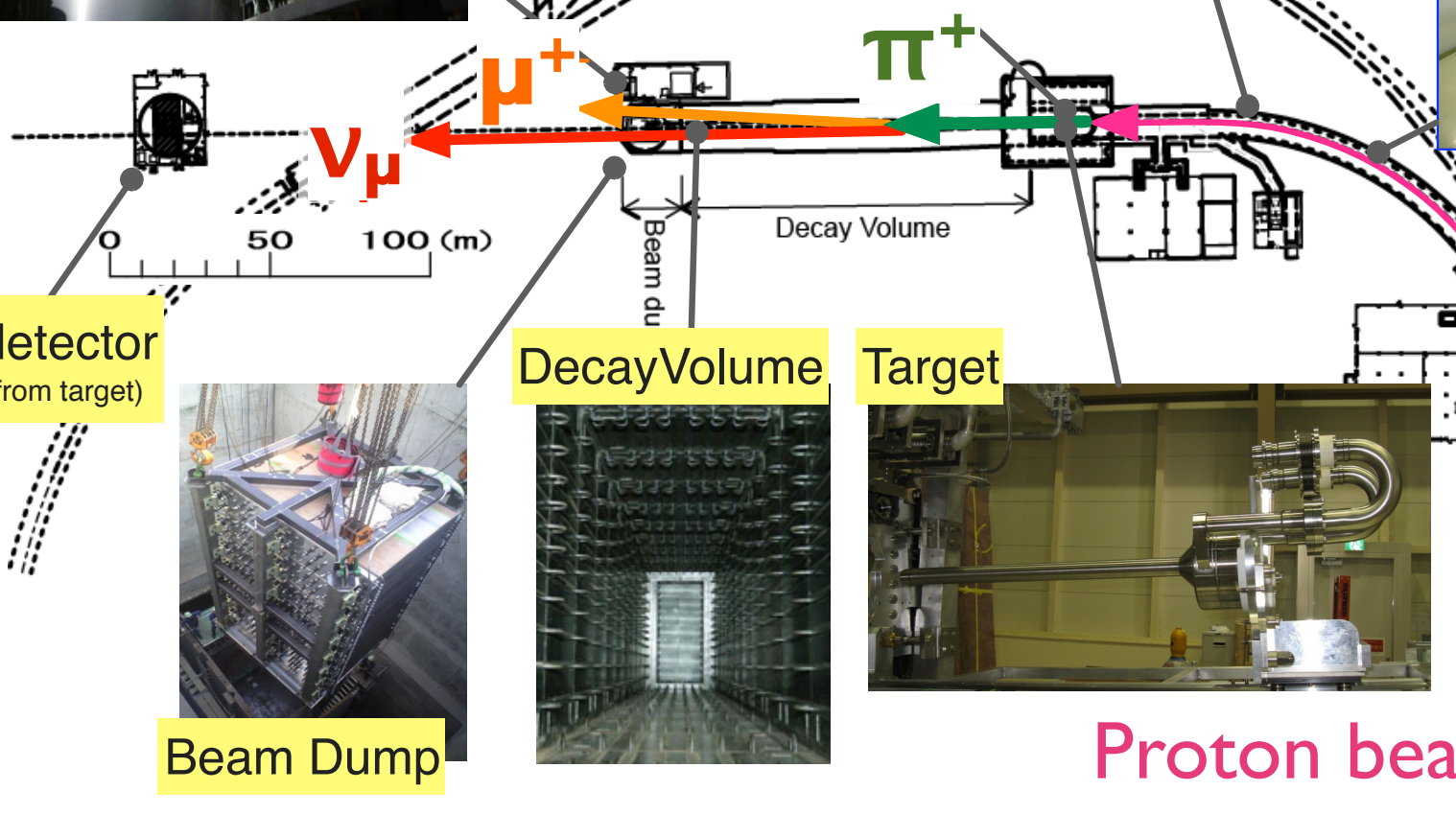
Horn



Beam monitors



Super-Conducting Magnets



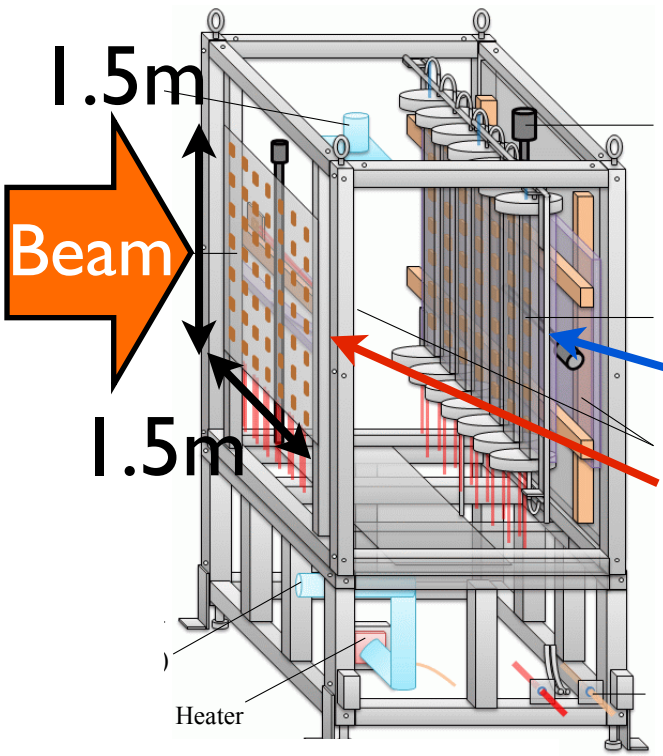
Near detector
(at 280m from target)

Beam Dump

DecayVolume

Target

Secondary beam line monitor : Muon monitor (MUMON)

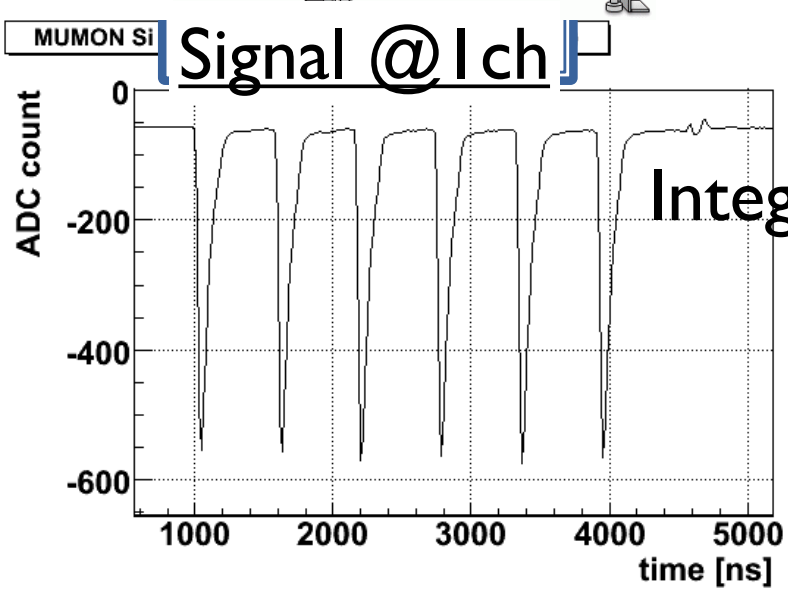


Detect decay μ from π

→Indirect measurement of ν beam direction spill-by-spill.

Ion chamber array (7×7ch)

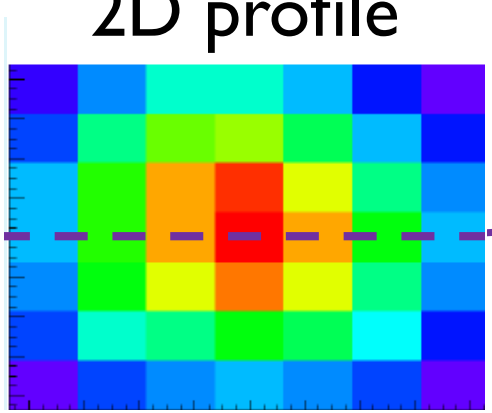
Silicon pin photo diode array (7×7ch)

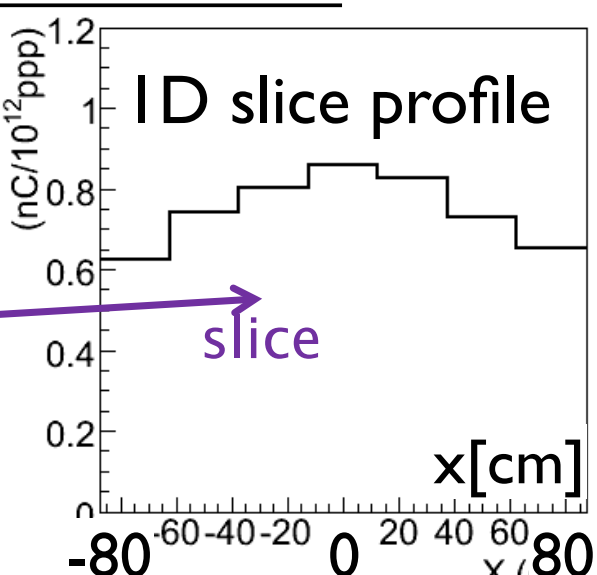


Integrate

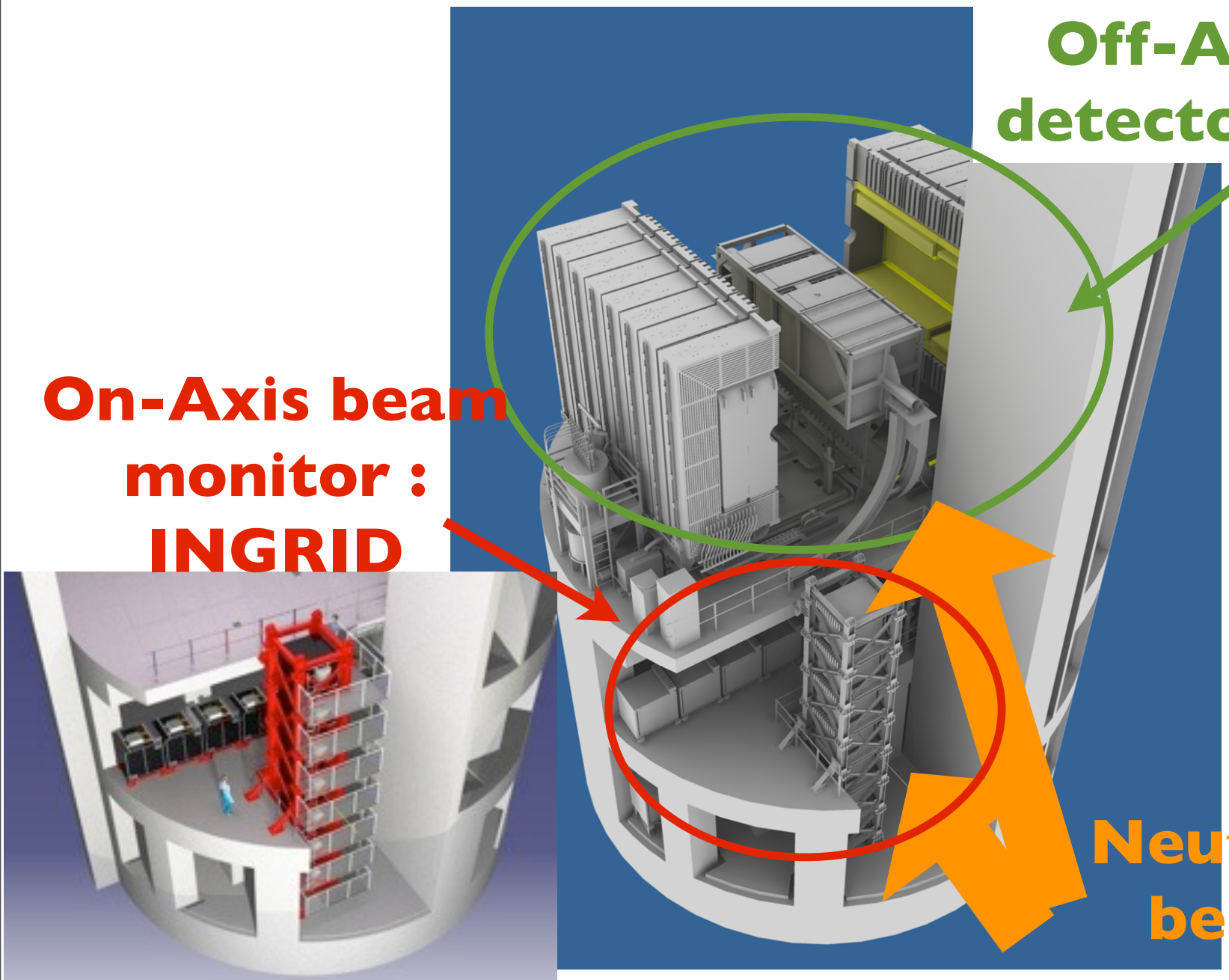
×49ch

Spill-by-spill μ beam profile by fitting with Gaussian.



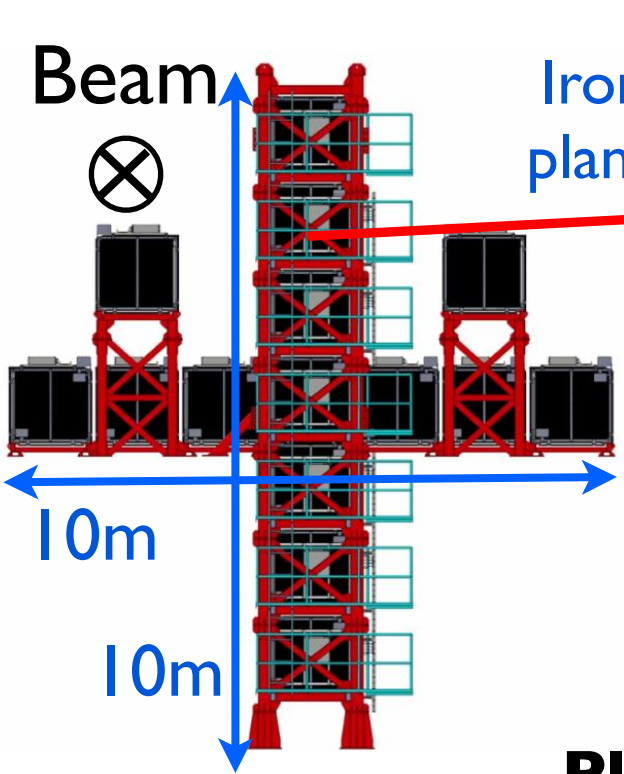


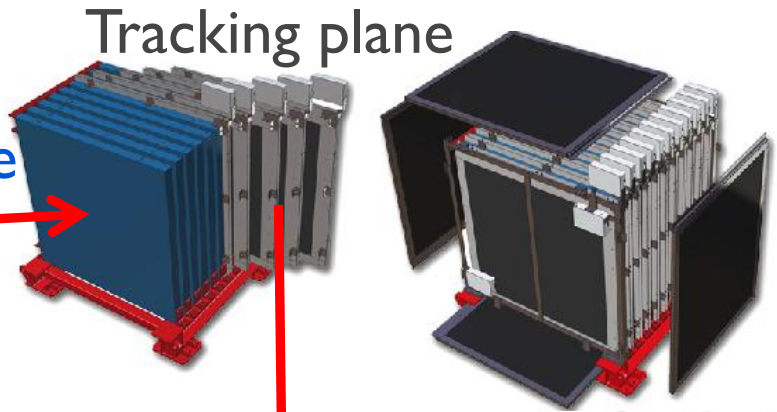
Near detector



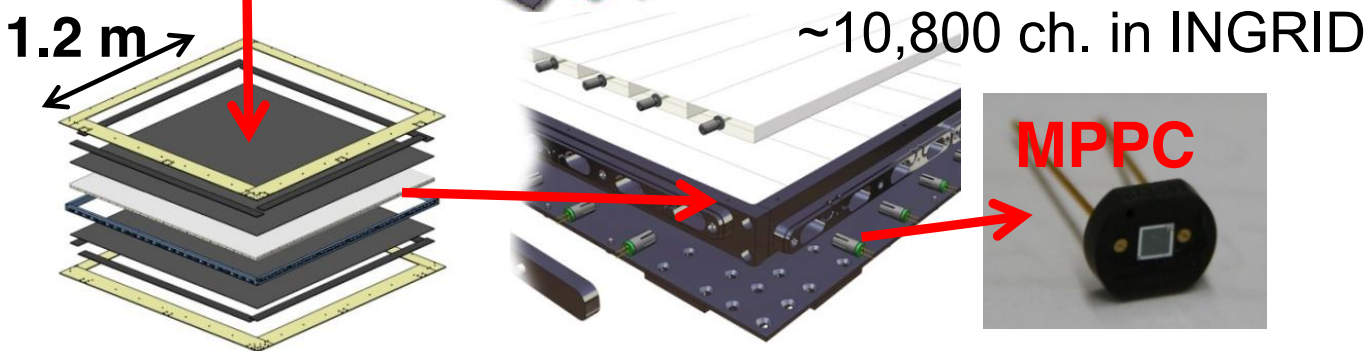
INGRID (On-axis near detector)

Neutrino beam direction/intensity monitor





First large scale application of MPPC (~56,000 MPPCs are used for ND280 /INGRID)



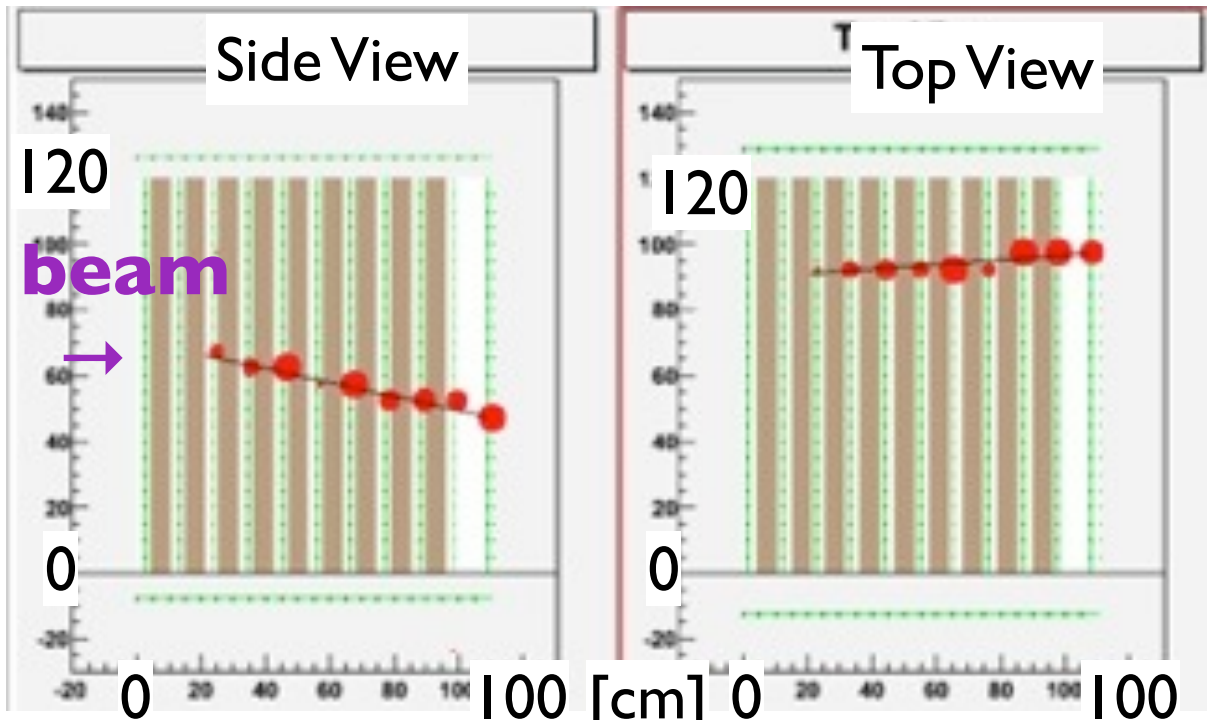
Plastic scintillator(1cm×5cm×120cm) + WLS fiber + MPPC

- 14 identical modules + 2 off-cross modules
  - Sandwiched Tracking (scintillator-layer) / Iron planes (6.5cm thickness) & VETO planes.
- Measure beam direction well better than 1 mrad.

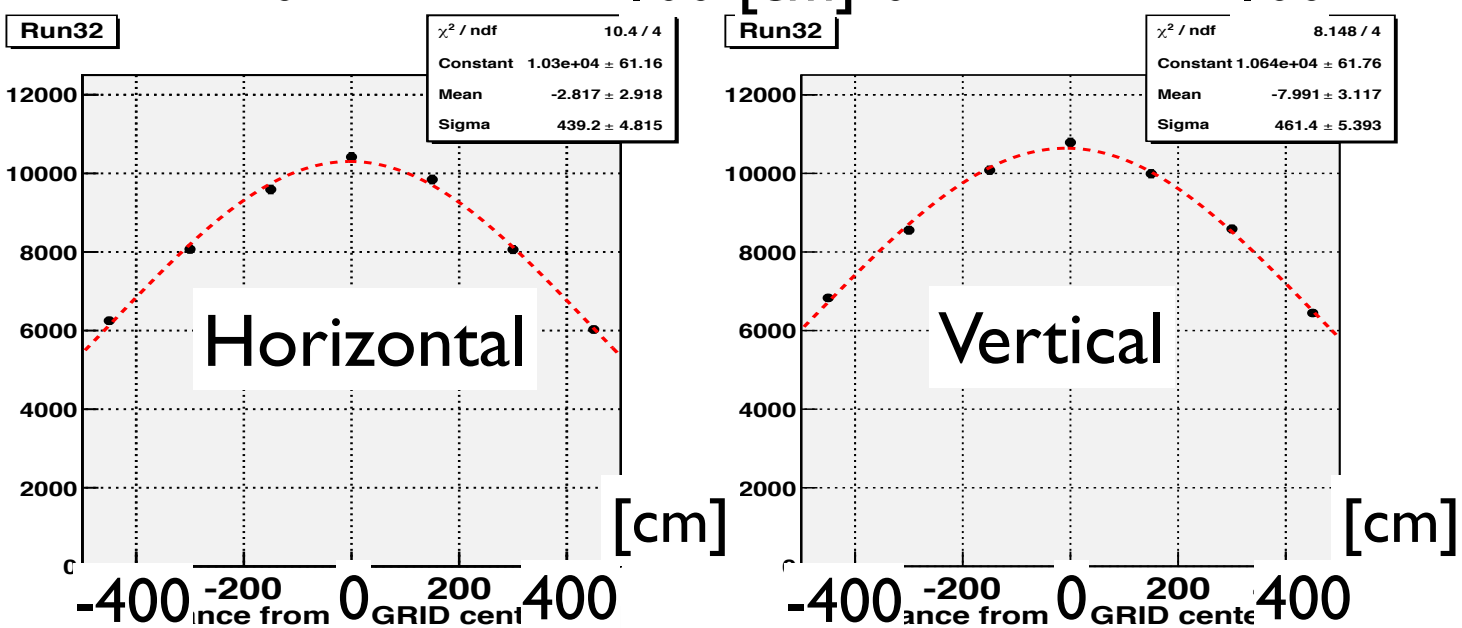
Event display of INGRID

DATA.

Neutrino event

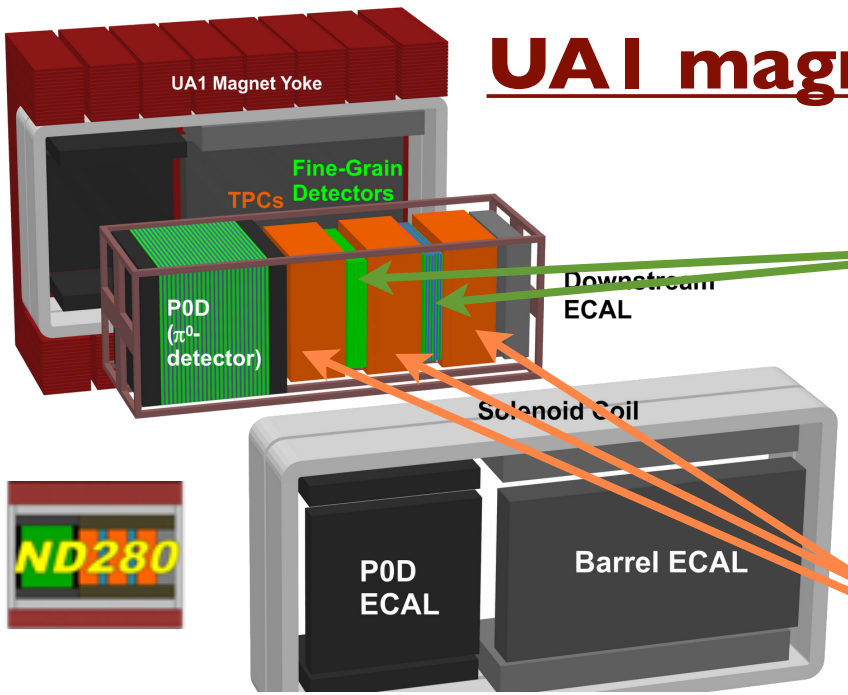


Beam profile
(~1month data)



ND280 (Off-axis near detector)

Count # of neutrino before oscillation with trackers



UA1 magnet : 0.2T (nominal)

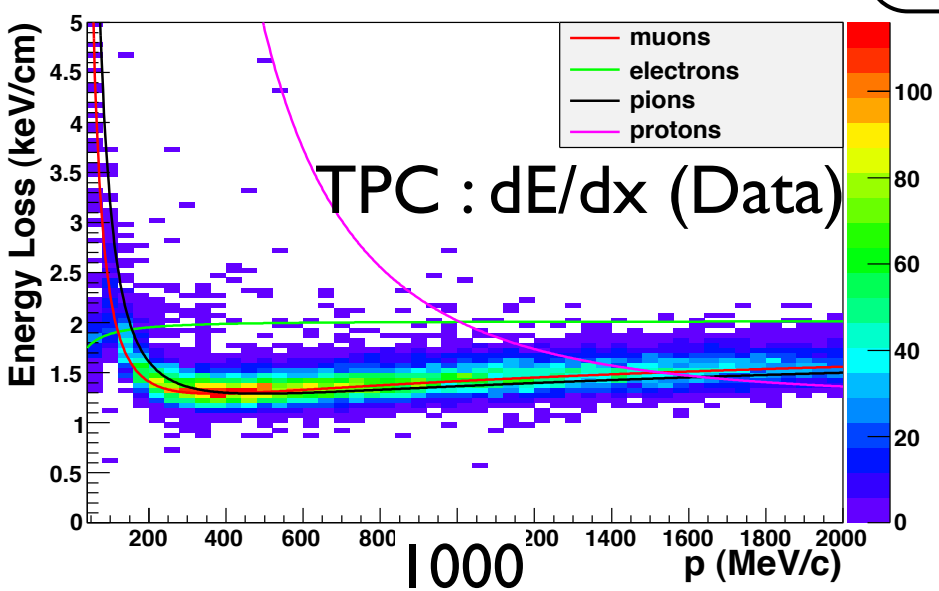
Trackers

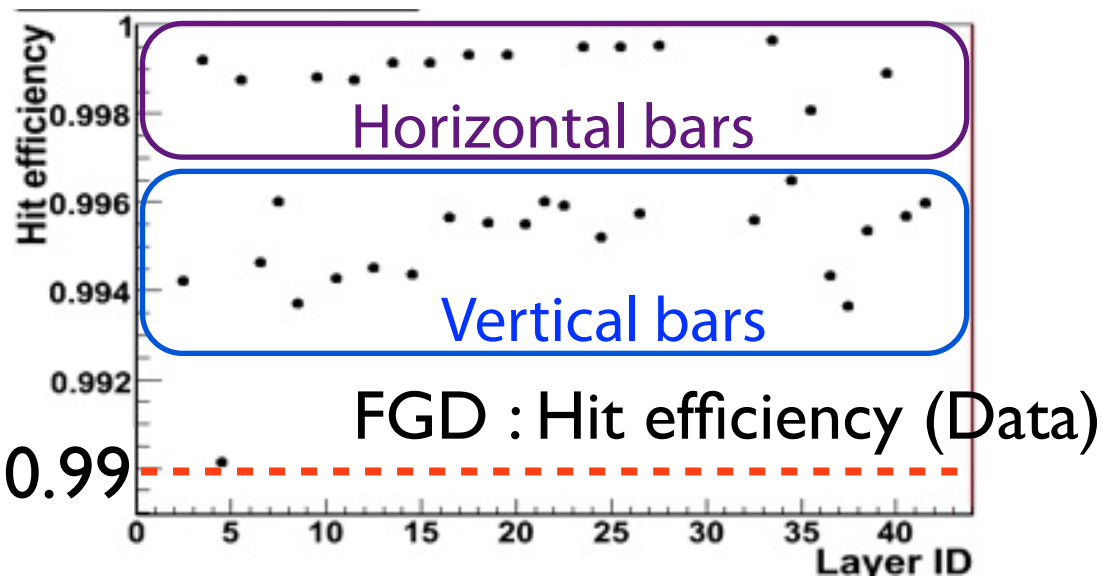
Fine Grained Detectors (FGD)

- Neutrino target (FV:1.6ton)
- Fine grain scintillator bars (1cm×1cmx186cm)

Time projection chambers (TPC)

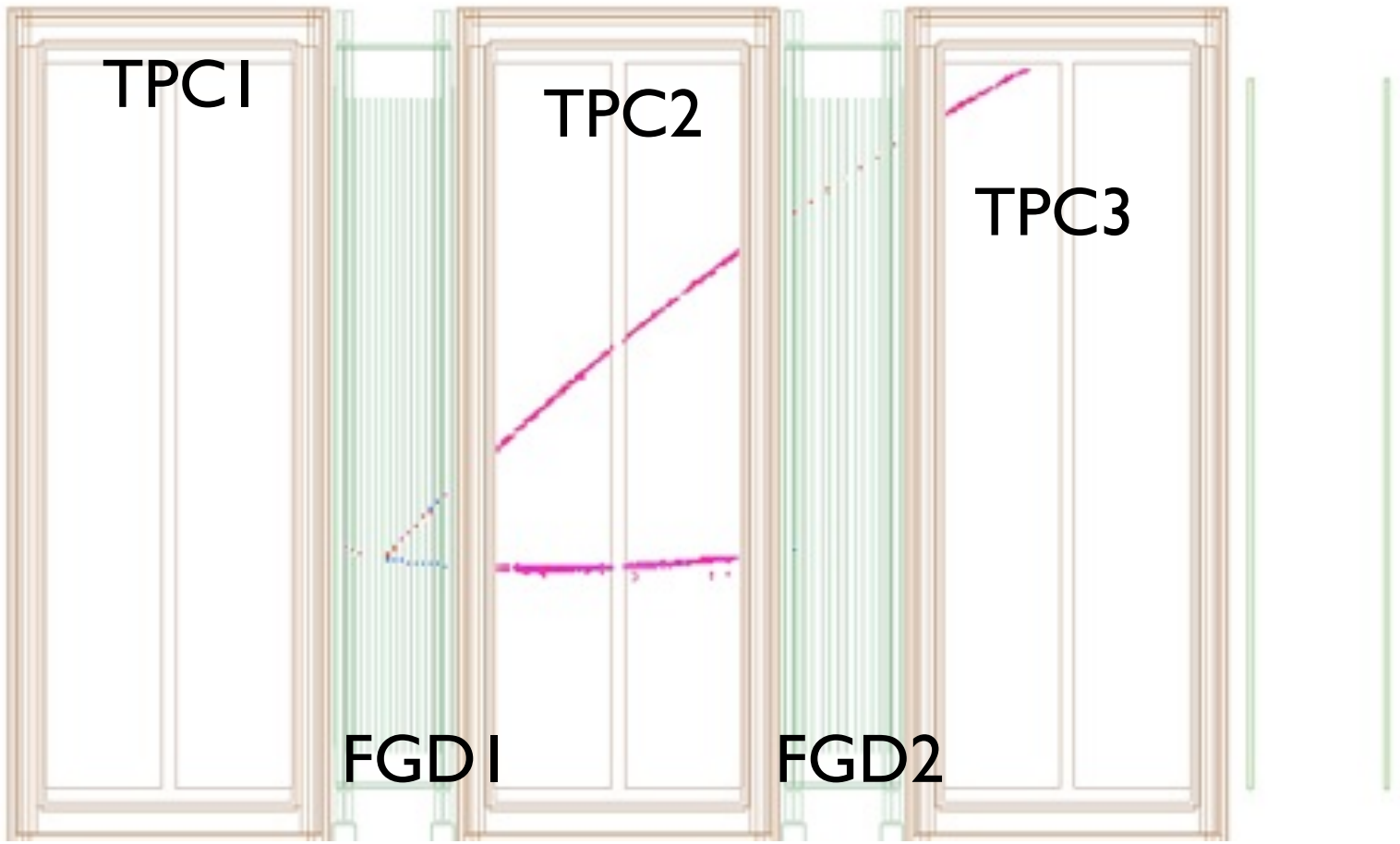
- <10% dE/dx resolution





Event display of ND280

DATA.

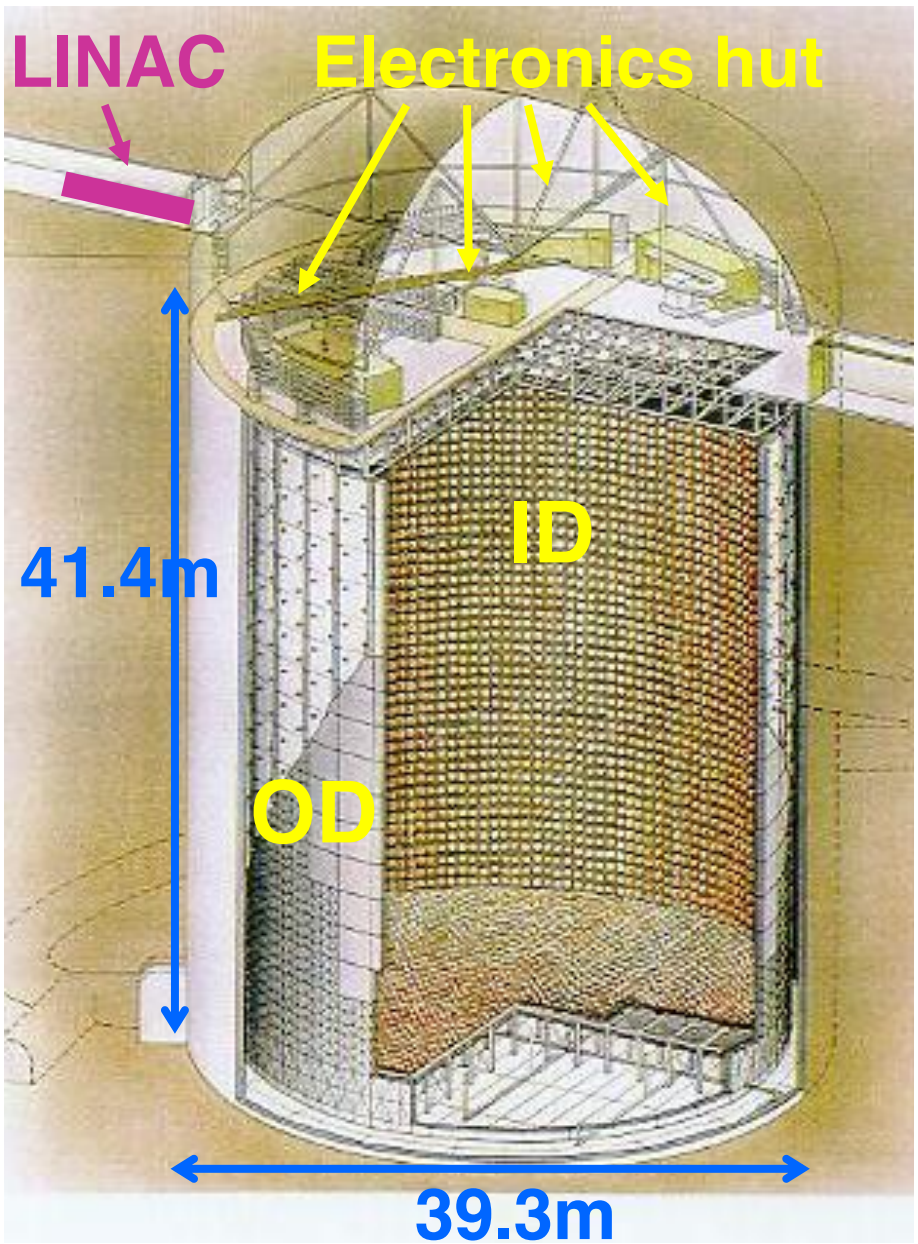


ν beam

→

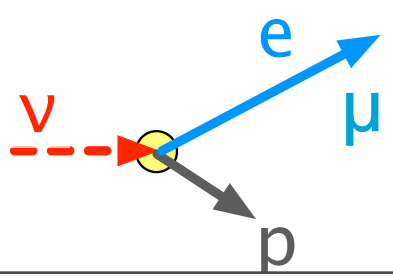
CCQE candidate ($\nu + n \rightarrow \mu^- + P$)

Far detector: Supar-Kamiokande (SK)



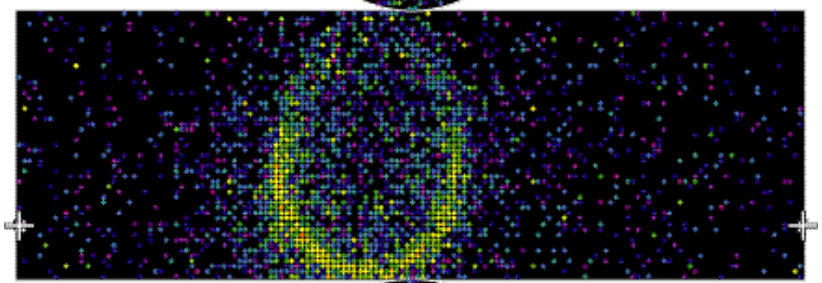
- Water Cherenkov detector w/ fiducial volume 22.5kton
- Dead-time less DAQ system (2008~)
- Detector performance is well-matched at sub GeV
  - Excellent performance for single particle event
  - Good e-like(shower ring) / μ-like separation

νe/νμ

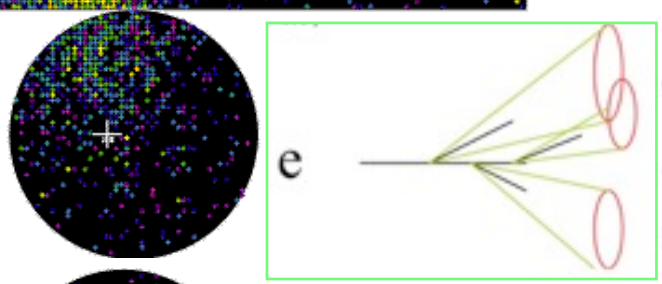


Electron-like and muon-like event at SK

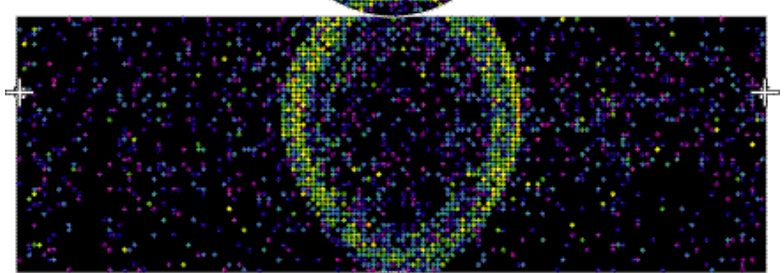
simulation



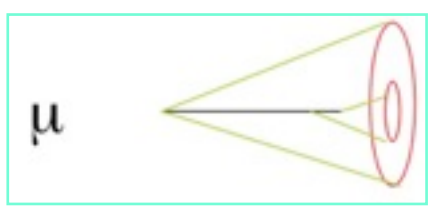
e-like



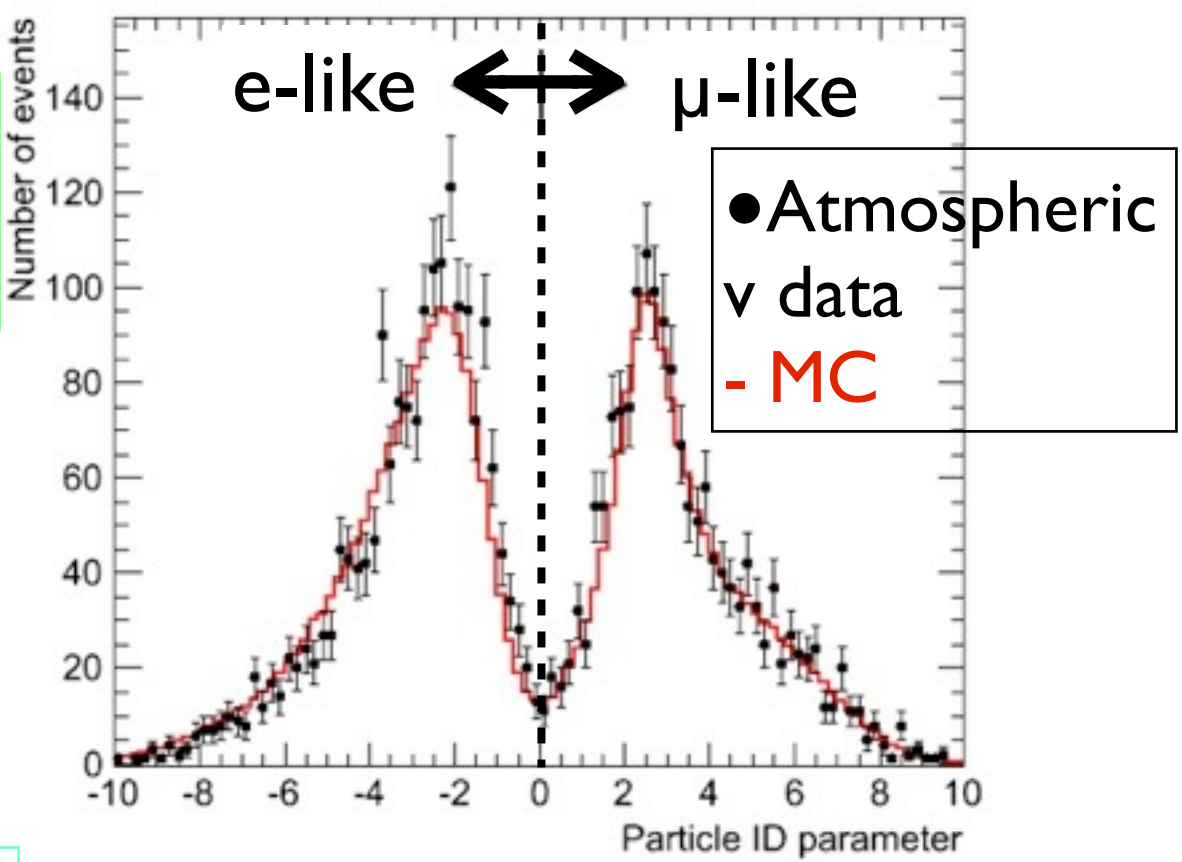
simulation



μ-like



Particle identification using ring shape & opening angle



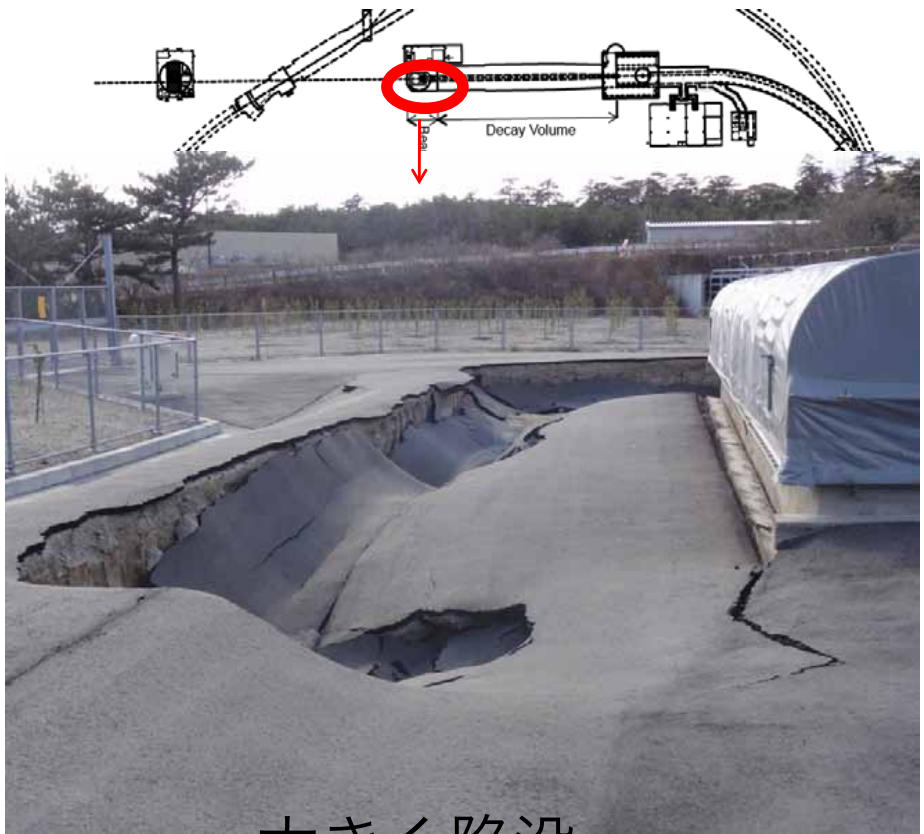
μ is mis-identified as electron : ~1%

2011.3.11 東日本大震災

私は20分ほど前まで前置検出器ホール地下で作業 → KEK東海一号館

→ 2日ほど東海村で避難生活

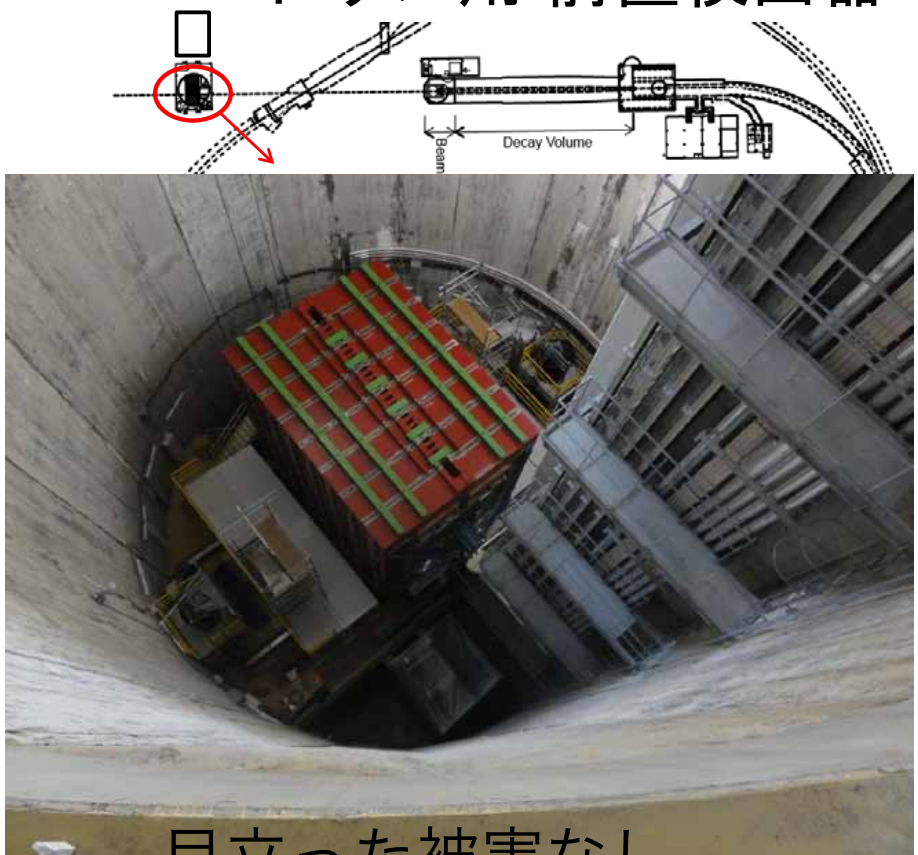
ニュートリノビームダンプ周辺



大きく陥没

→ 6月には地中の電気工事、埋め立て完了

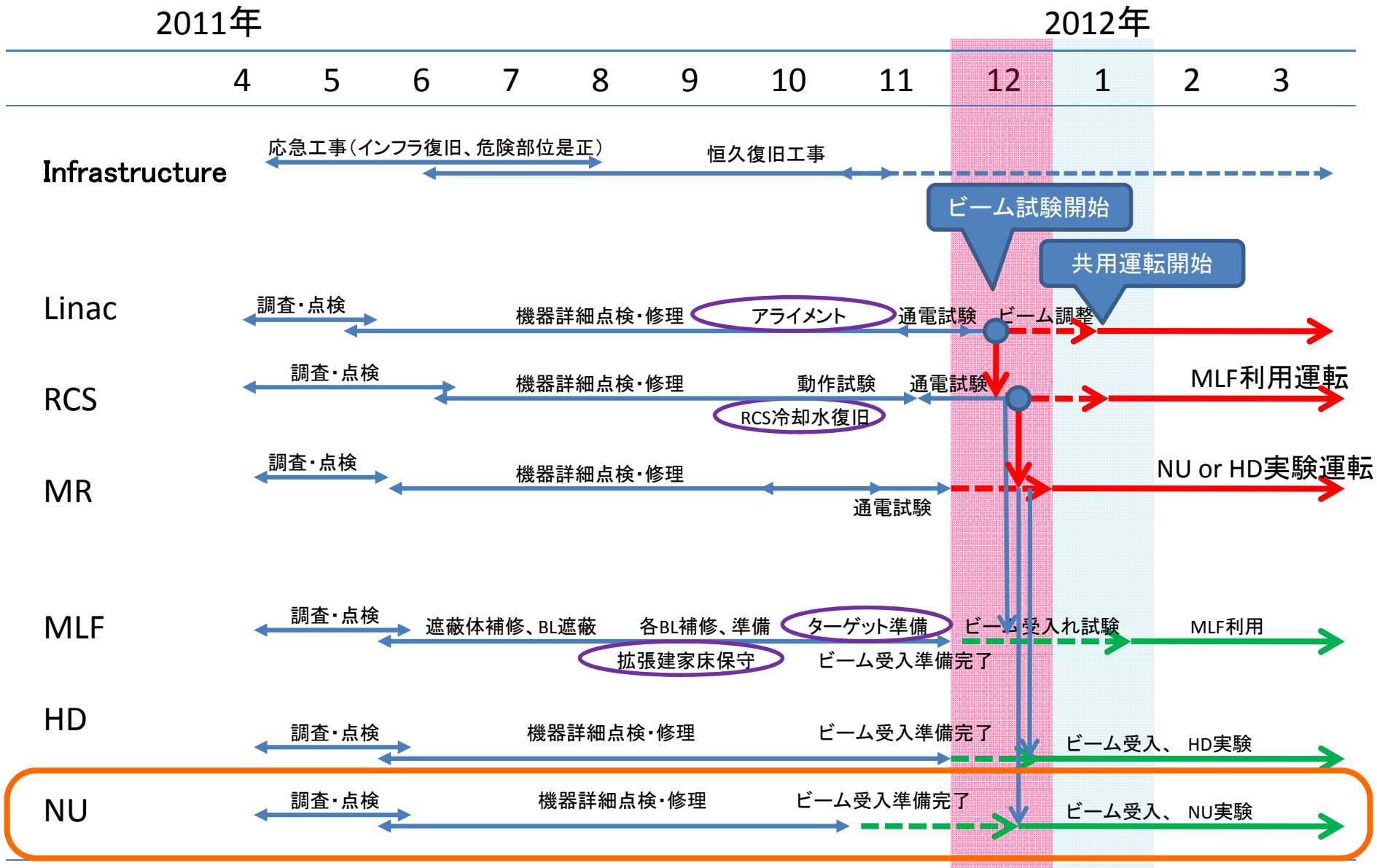
ニュートリノ用 前置検出器



目立った被害なし。

→ 宇宙線測定進行中。INGRIDなどは問題ないことを確認済み！

J-PARC復旧スケジュール （@2011.5.20）

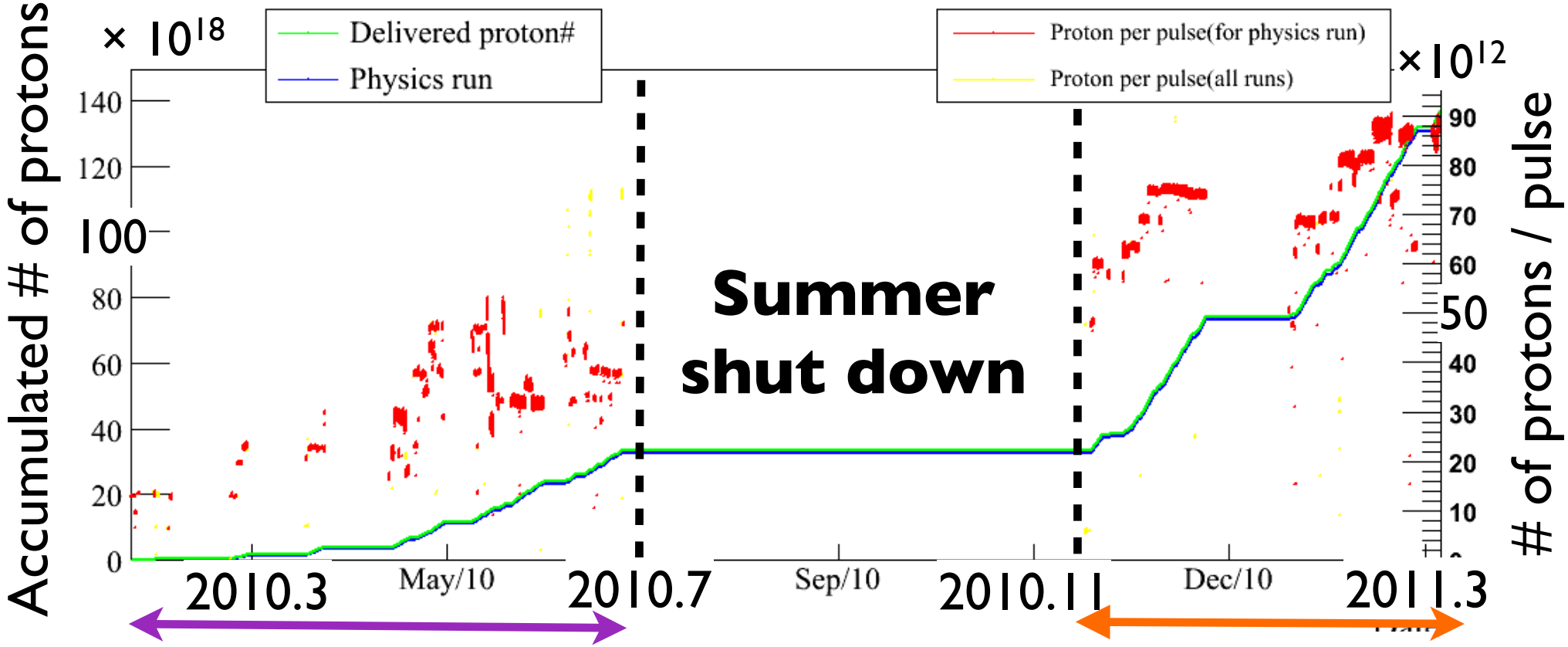


ニュートリノグループとしては11月中にビーム受け入れ準備完了！

今年中にビーム試験を開始する！

Physics Run 1&2
(2010.1~2011.3)

Accumulated # of protons



Run1 : 2010.1~6

- 6 bunch/spill, 3.52 sec cycle
- Total protons : 3.23×10^{19}
- Average power : 50kW

Run2 : 2010.10~2011.3

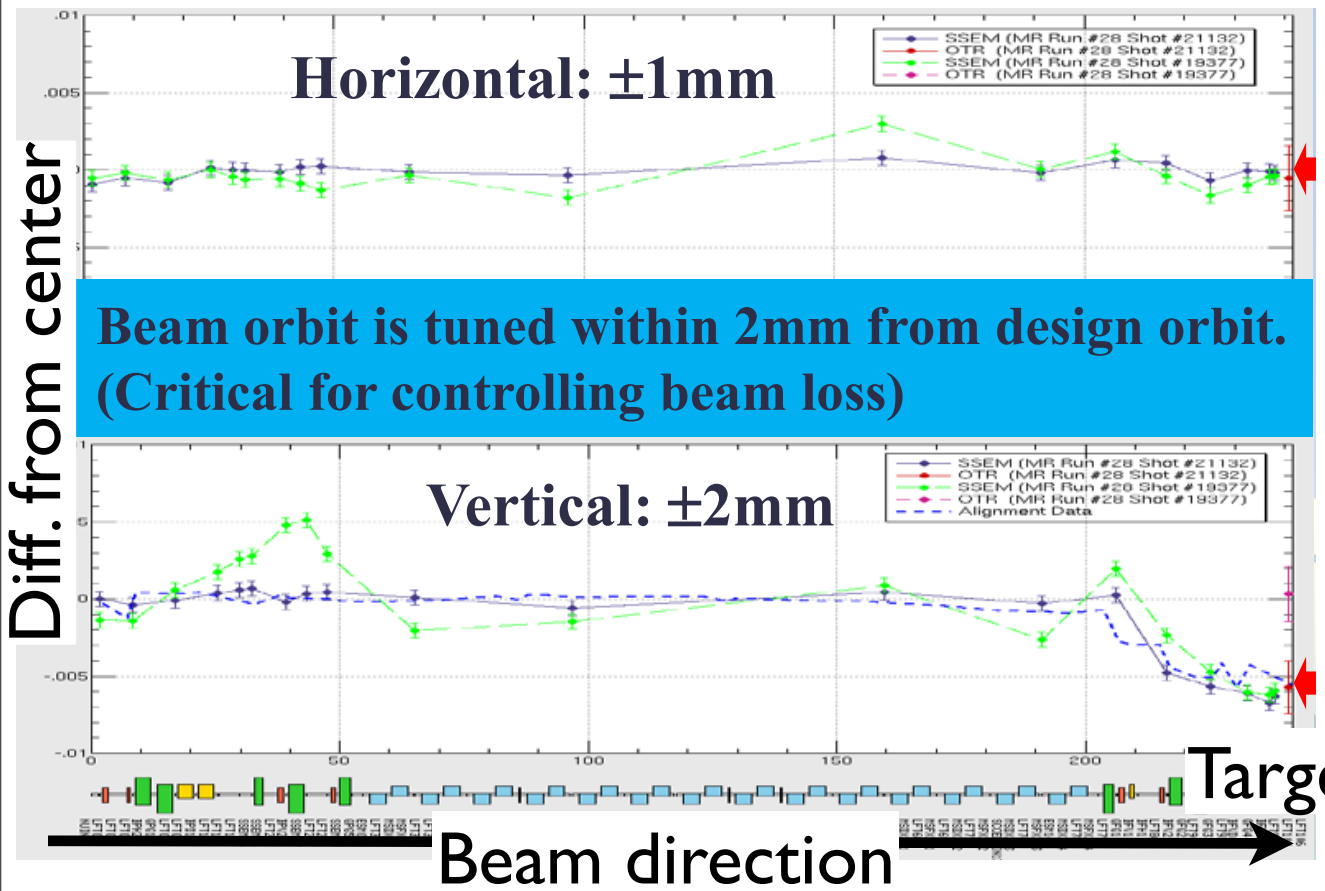
- 8 bunch/spill, < 3.2 sec cycle
- Max stable power : ~145kW
- Achieve 10^{20} protons (2011.2)

Total # of protons used for analysis is 1.43×10^{20} protons

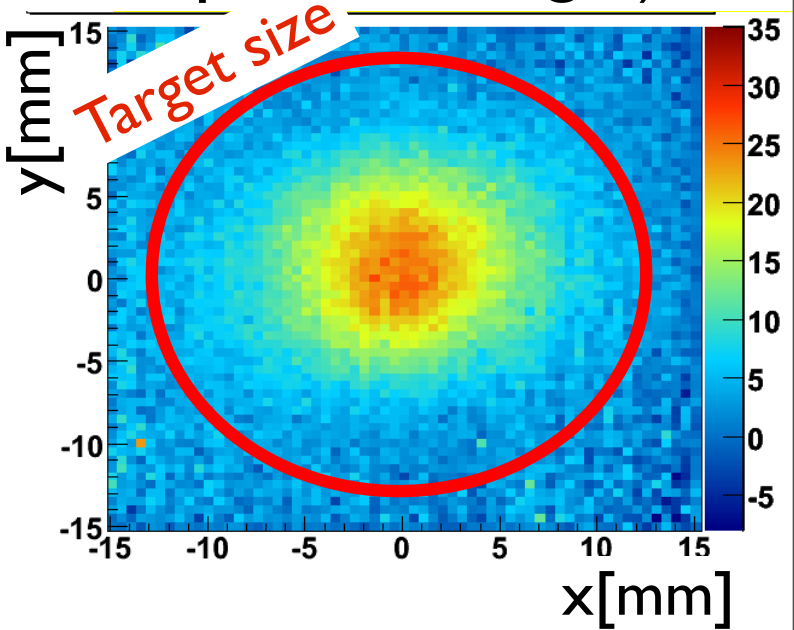
= 2% of T2K's final goal

Primary proton beam measurement

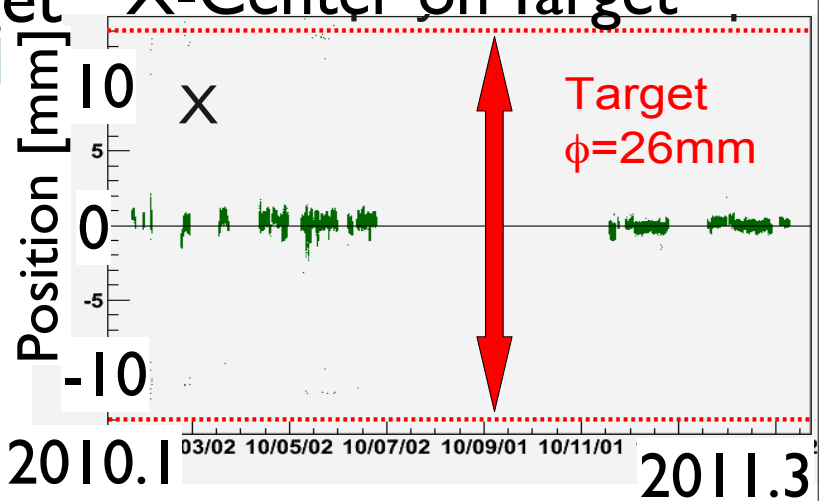
Control beam orbit (optimize before/after)



Beam profile (just upstream target)



X-Center on Target

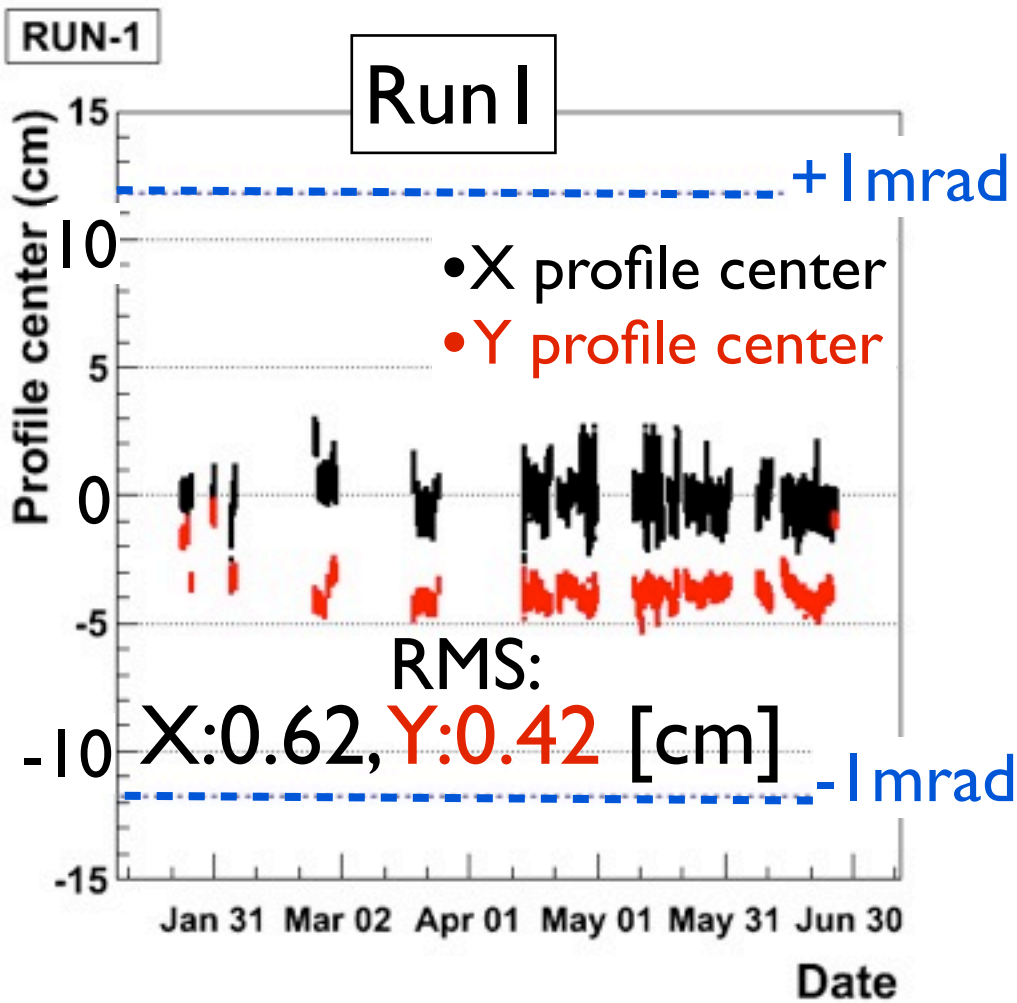


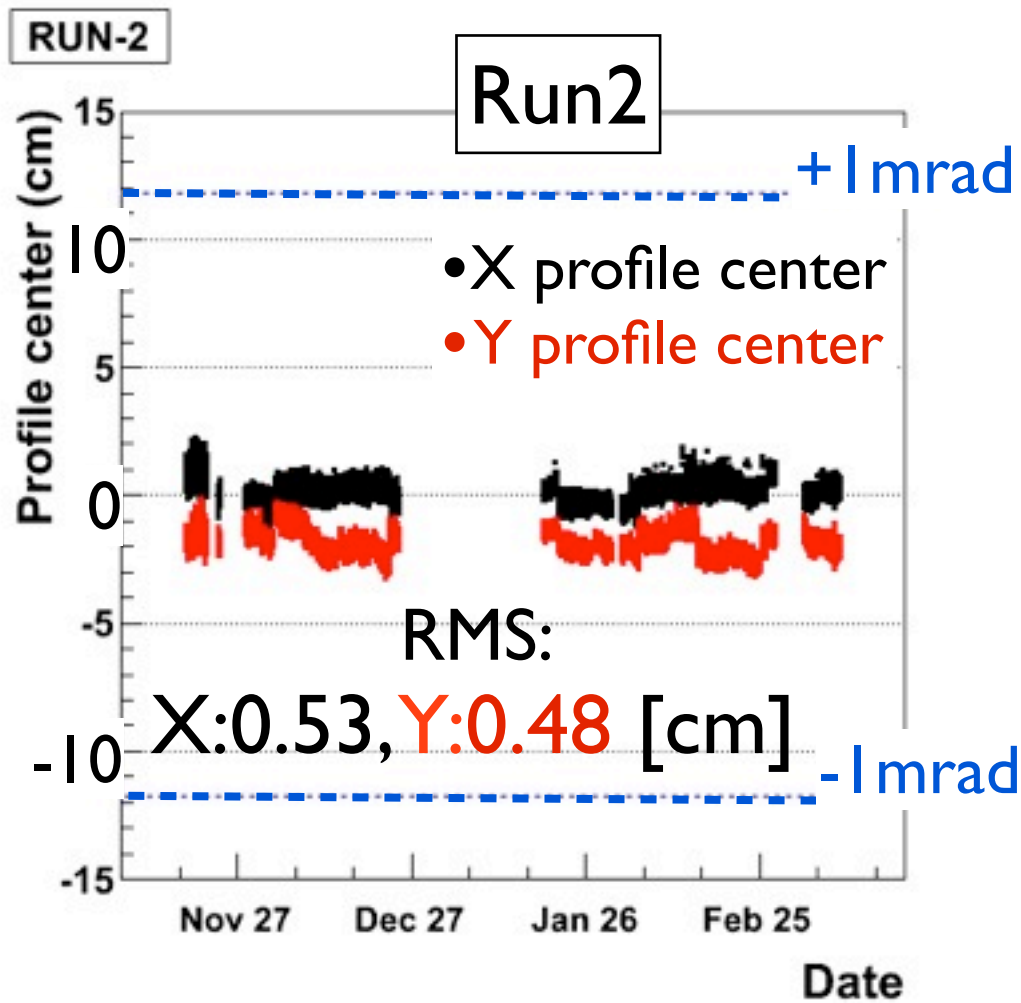
Beam position, size, angle on Target from extrapolation of profile measurements.

→ **Input of flux prediction for oscillation analysis.**

MUMON measurement

Recon. beam profile center by Si-arrays





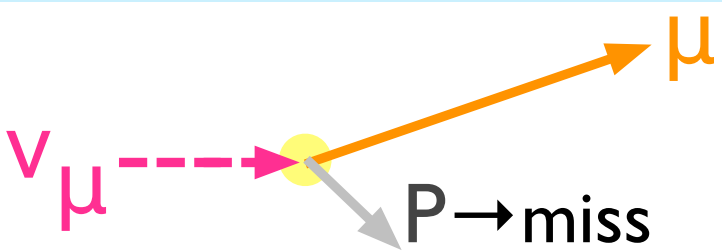
Beam direction diff. from center << 1mrad

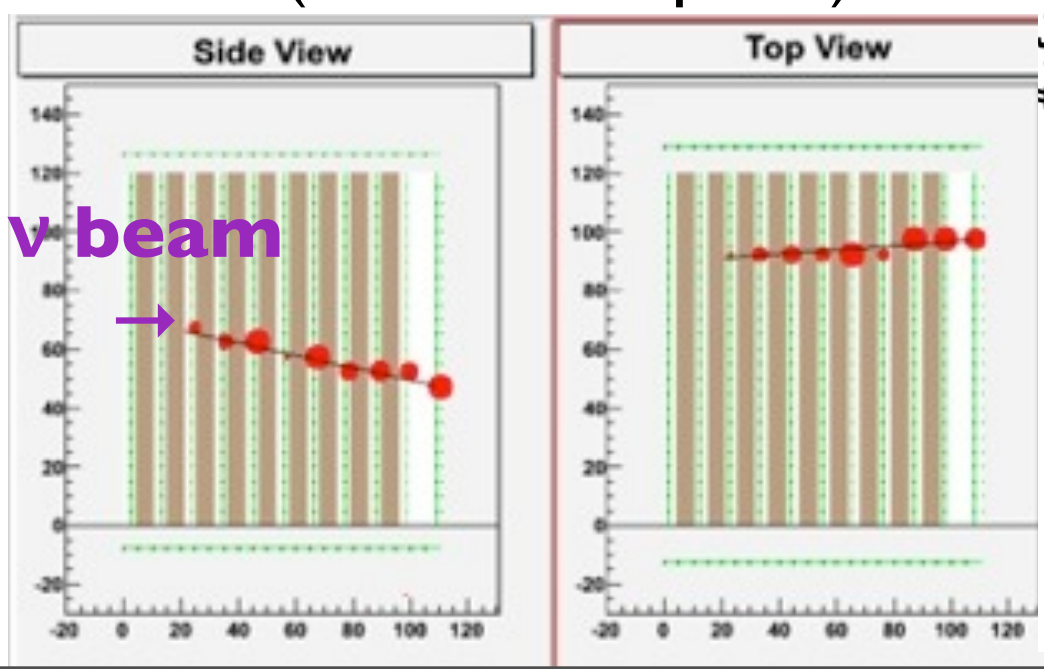
→ well-control

INGRID measurement

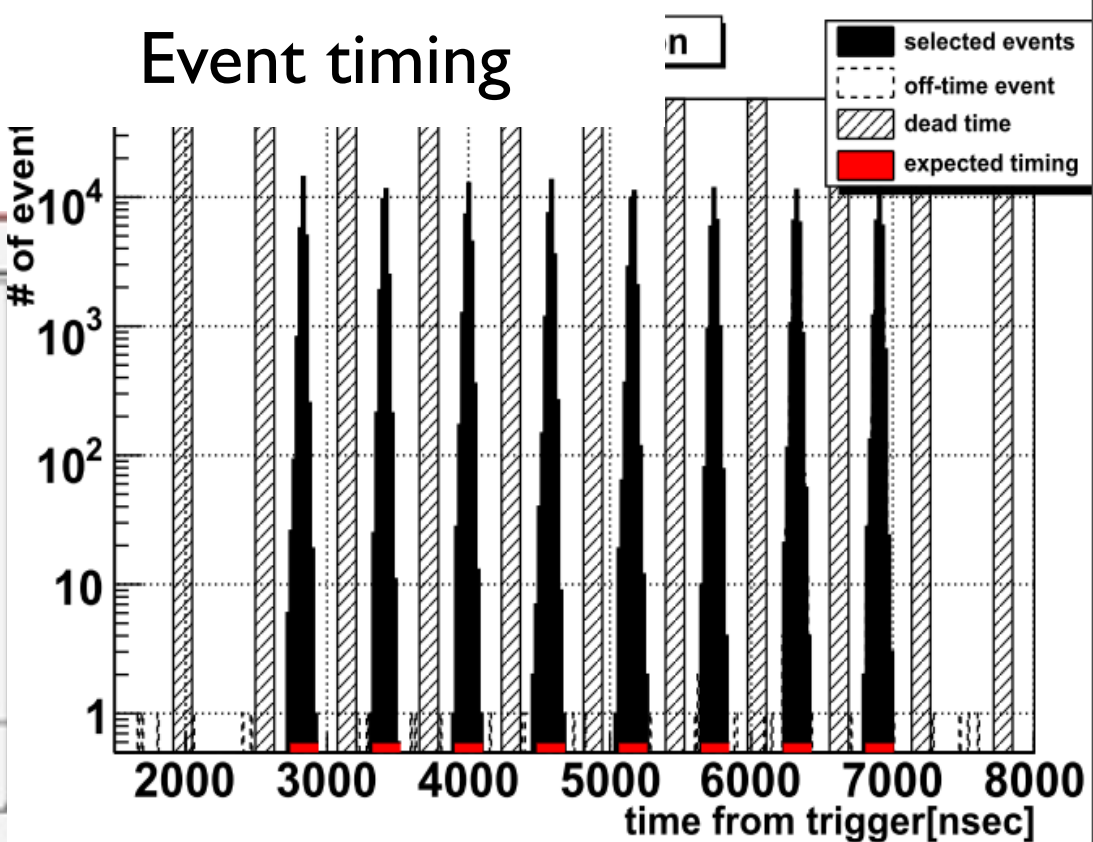
Select neutrino event in FV

- Coincident hits in X-Y plane & Timing cut → Reject accidental hits
- Reconstruct one track.
- Select vertex inside fiducial volume → Veto sand muon, cosmic



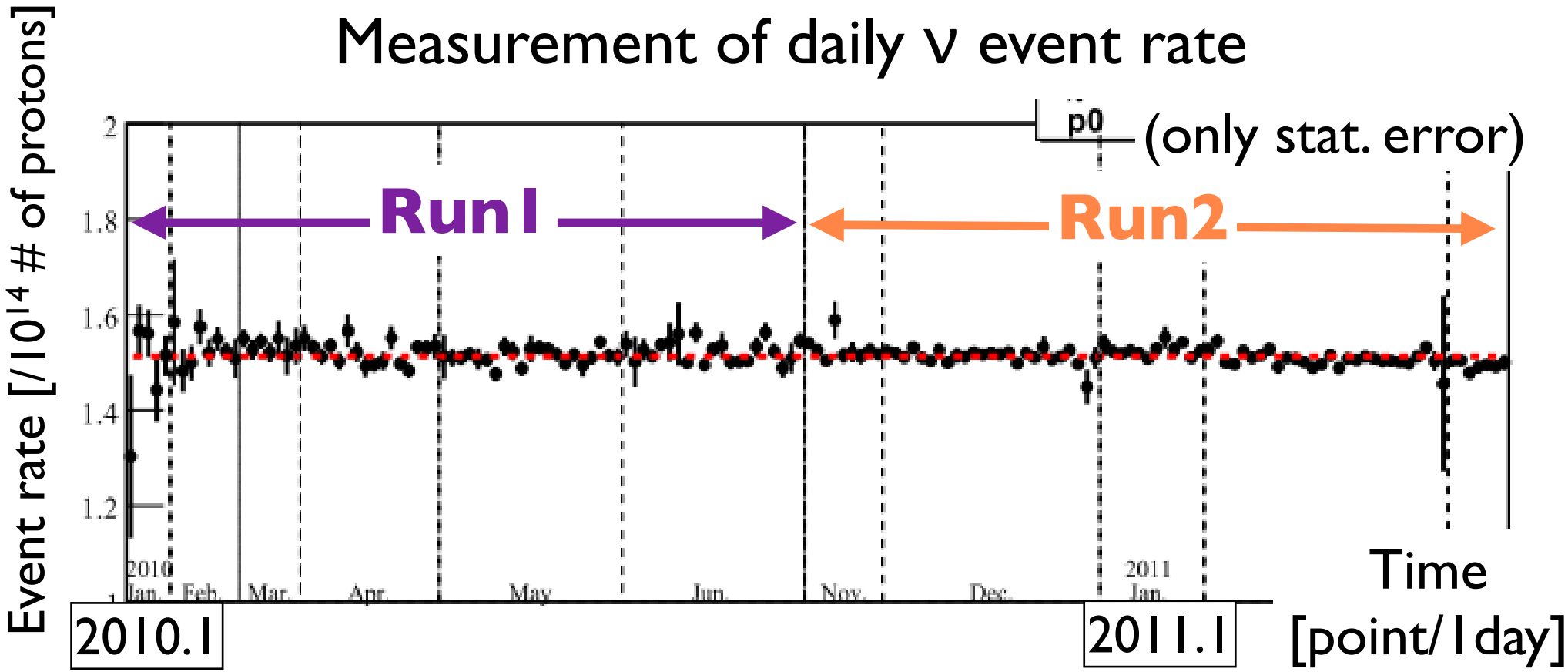


Event timing



INGRID measurement

Measurement of daily ν event rate



Event rate is stable in whole period.

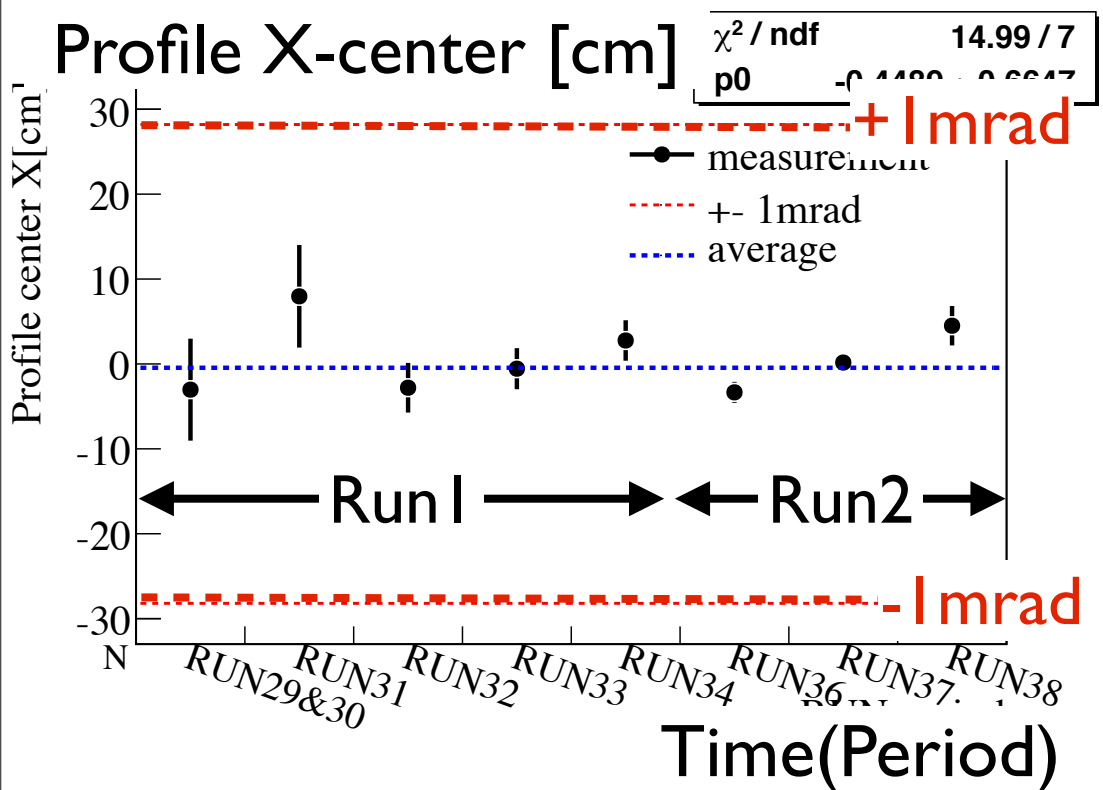
Average=1.512 /10^{14} # of protons (χ2/ndf=1.44)

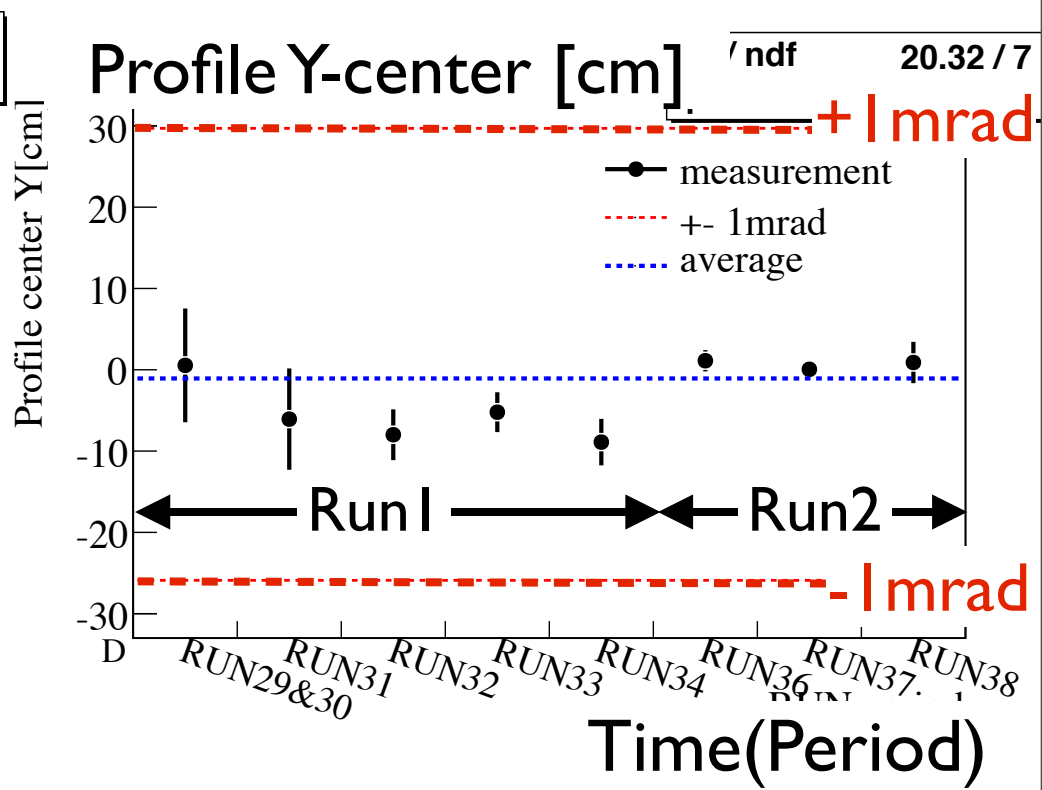
ν event rate stability: Run 1+2 / Run 1 < 1%

DATA/MC(Run1&2) = 1.057 ± 0.001(stat.) ± 0.040(syst.)

INGRID measurement

Reconstructed neutrino beam profile center (monthly)





Run1&2 Beam direction diff. form exp. << 1mrad

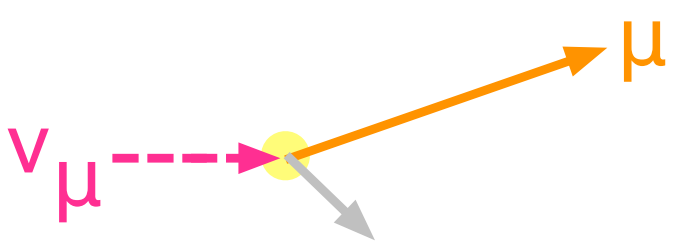
- Horizontal: **-0.014±0.025 (stat.)±0.33 (syst.)** mrad
- Vertical: **-0.107±0.025 (stat.)±0.37 (syst.)** mrad

→ Input for oscillation analysis

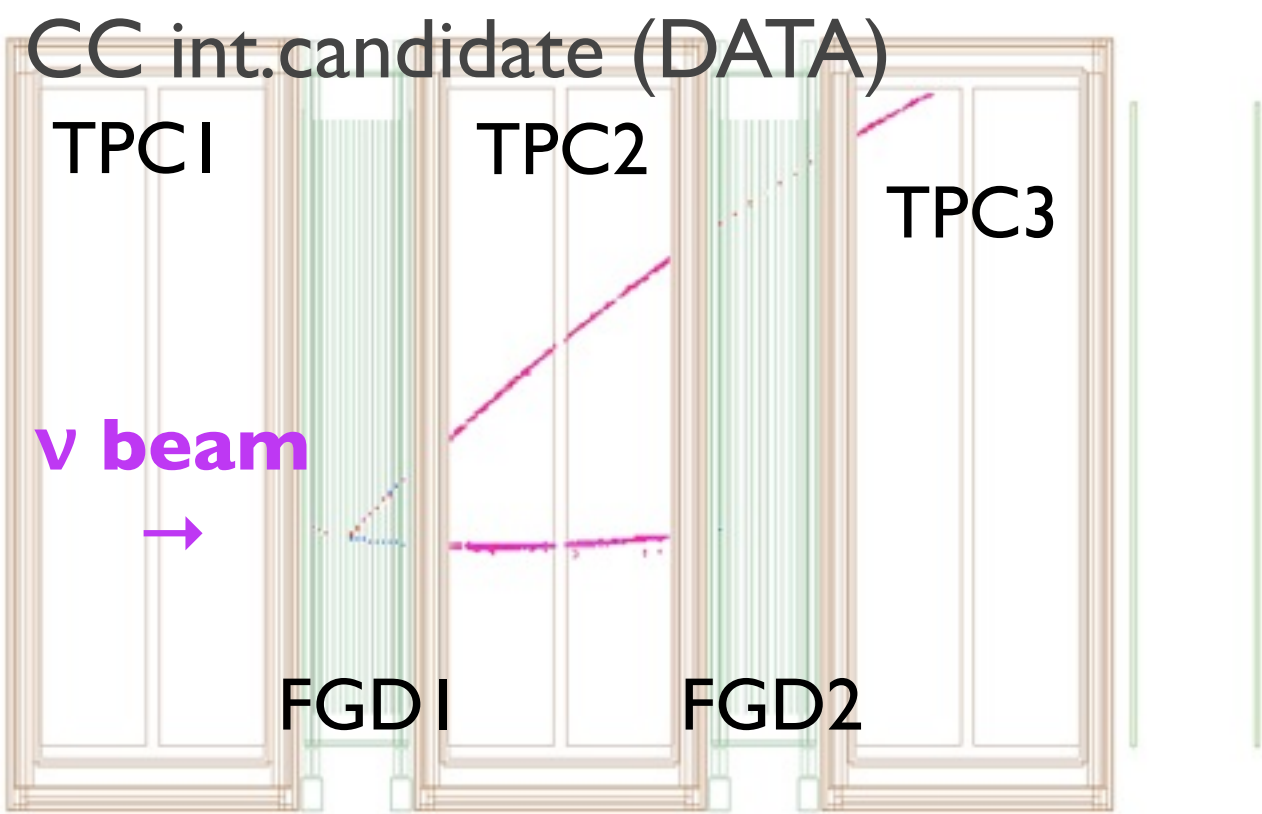
Count # of neutrino events at ND280

Inclusive ν_μ charged current (CC) events with FGD-TPC

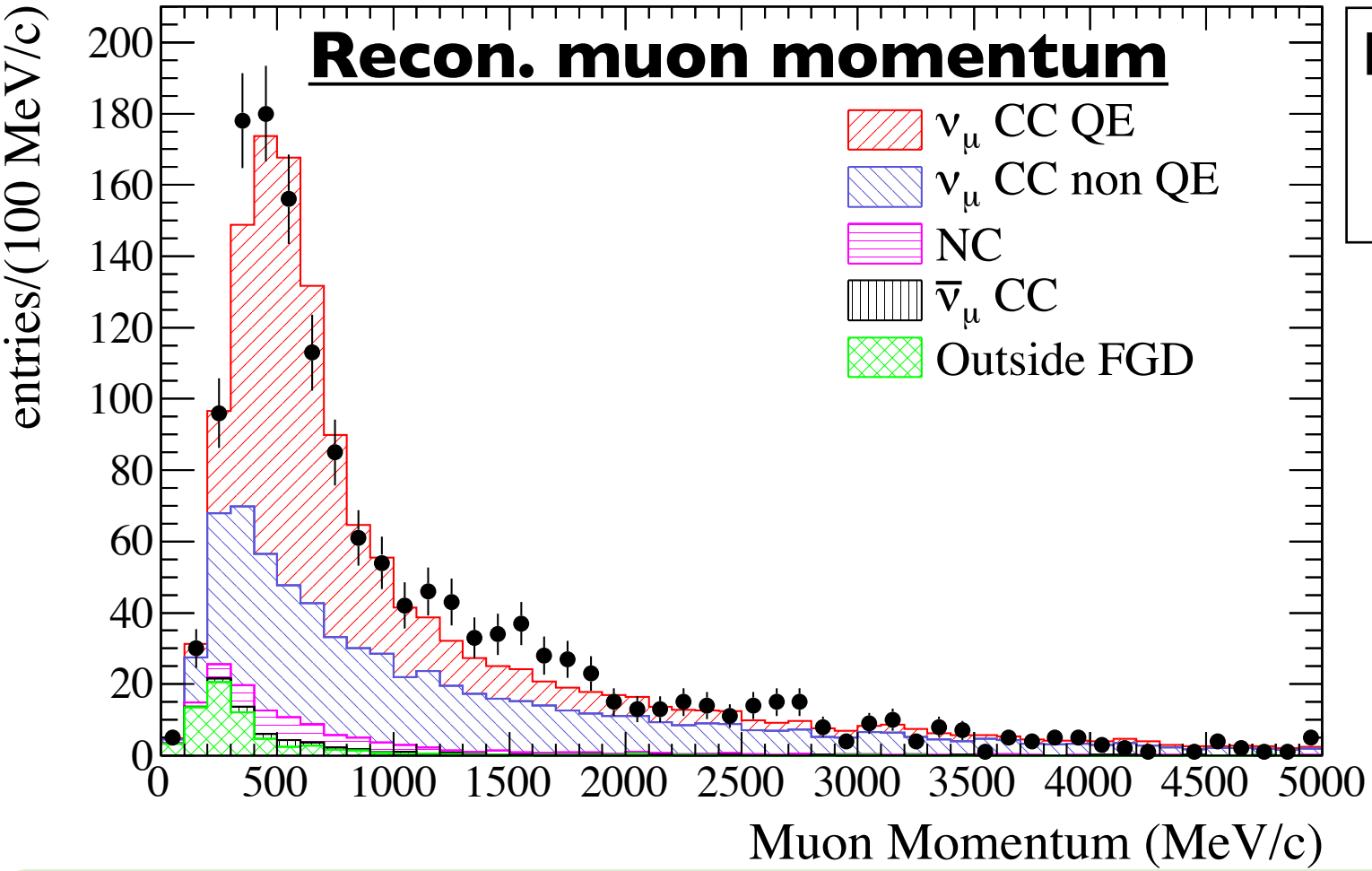
- Reconstruct track & matching of FGD-TPC
- No track in TPC1 → Veto sand muon
- ≧1 negative charge track in TPC2(or TPC3)
- Track start fiducial volume of FGD1(or FGD2)
- TPC PID → Select negative particle



High purity: 90%
ν_μ CC int.
(50% CCQE)



Count # of neutrino events at ND280



Normalized by # of protons
Only Run1 DATA

$$R_{ND}^{\mu,\,Data} = 1529 \text{ events } / \; 2.9 \times 10^{19} \text{ p.o.t.}$$

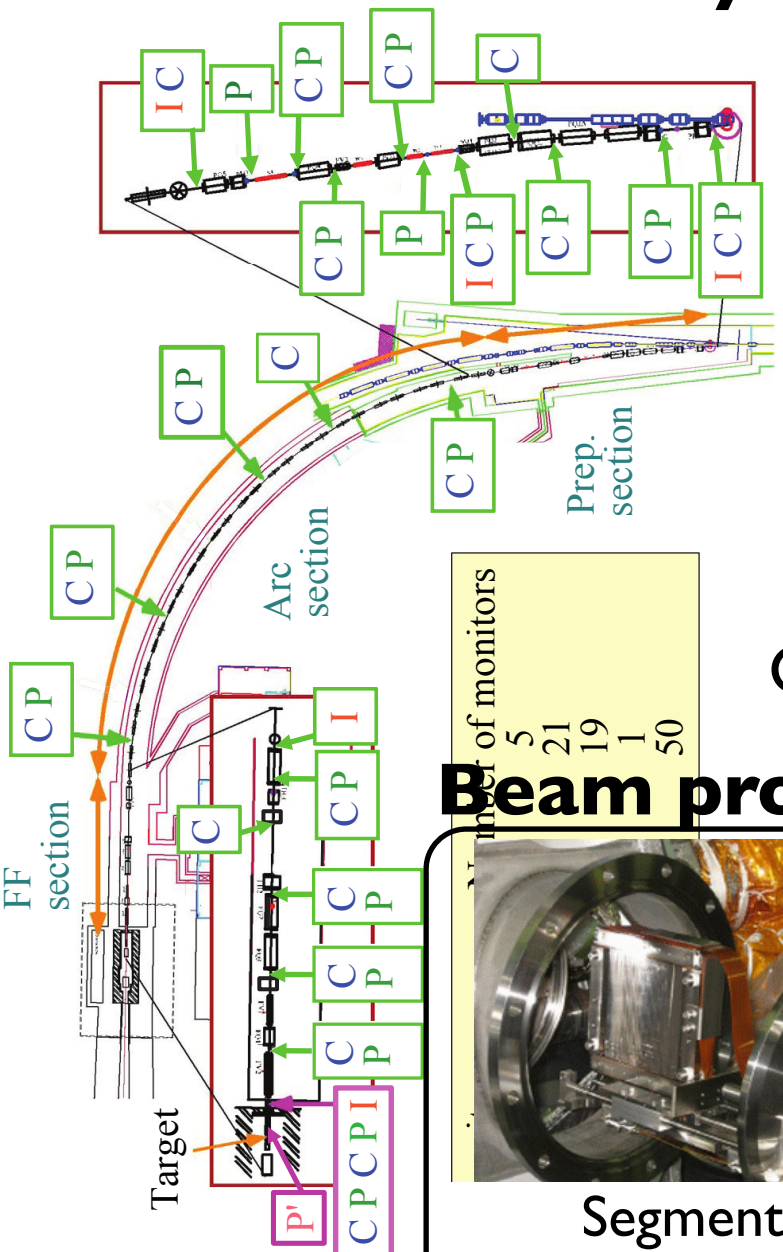
$$\frac{R_{ND}^{\mu,\,Data}}{R_{ND}^{\mu,\,MC}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

Summary of this talk

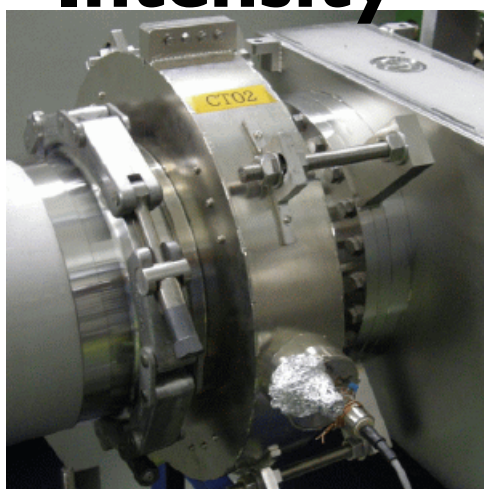
- T2K実験は2010年1月から物理ランをスタートし、2011年3月までで1.43×10^{20} # of protons (2% of design)の統計を貯めた。
  - 各検出器は期待通りに動作し、ニュートリノビームを安定して生成することができた。
- 振動解析のインプットとして以下の結果を使用する:
  - ビームラインモニターによる陽子ビームの情報
  - INGRIDによるニュートリノビームの方向
  - ND280による振動前のニュートリノ数
- 次の講演者がν_e appearanceの最新結果について報告。

Back up

Primary beam line monitor

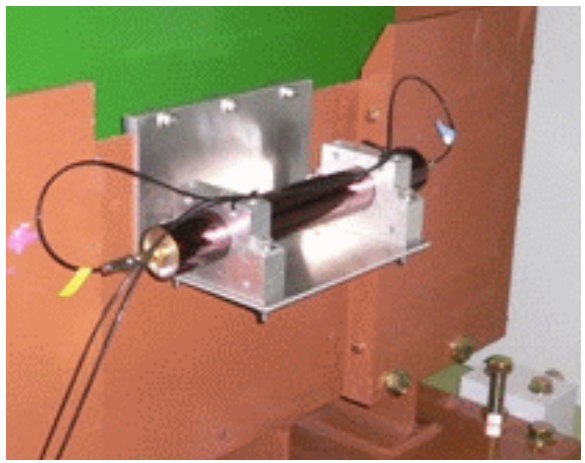


Intensity



Current transfer(×5)

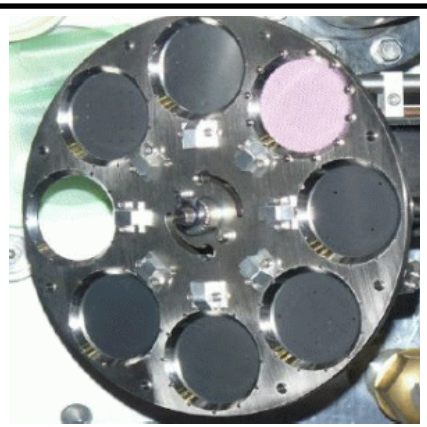
Beam loss



Beam loss monitor (×50)

Beam profile

Segmented Secondary Emission Monitor (×19)



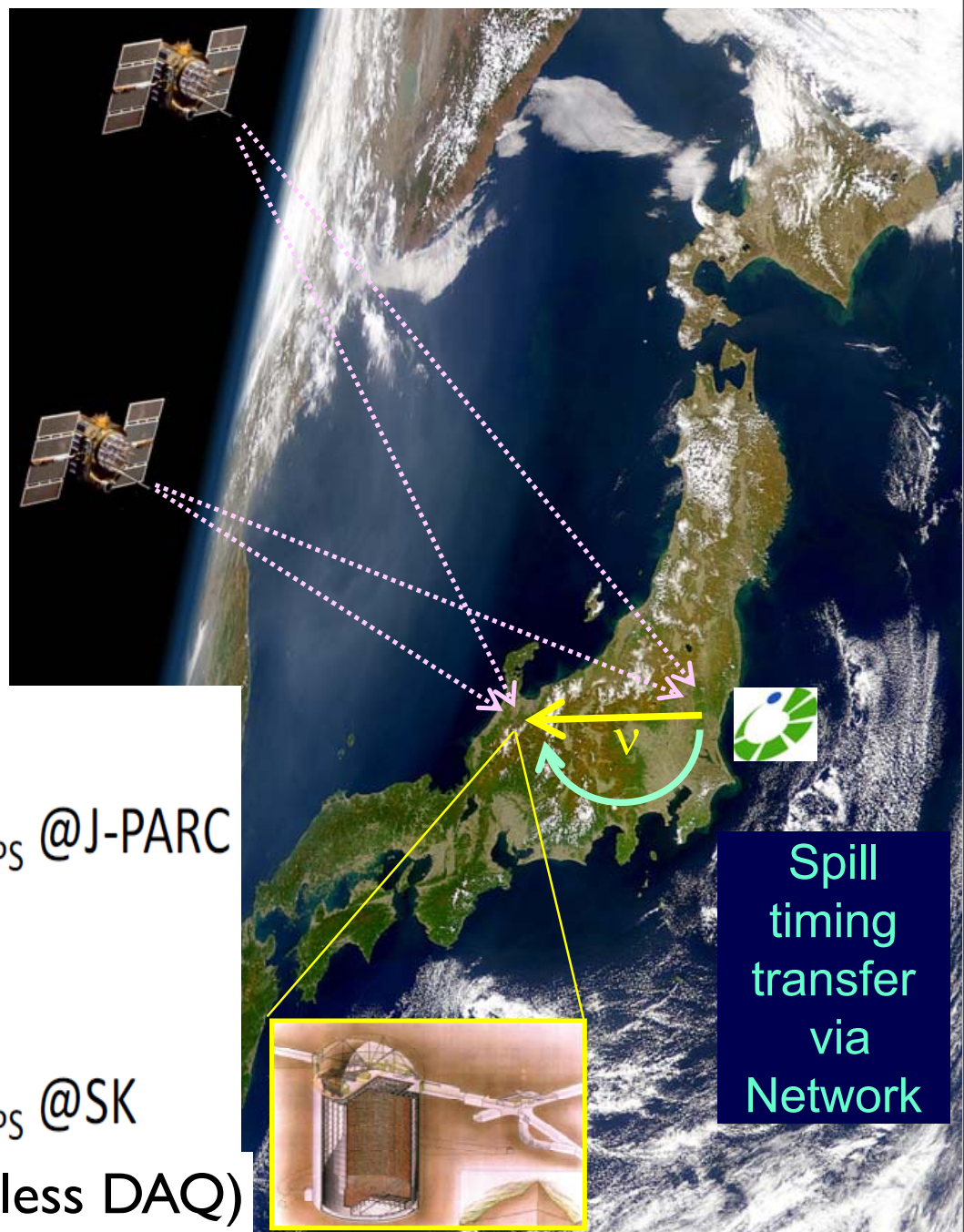
Optical Transition Radiation (@Target)

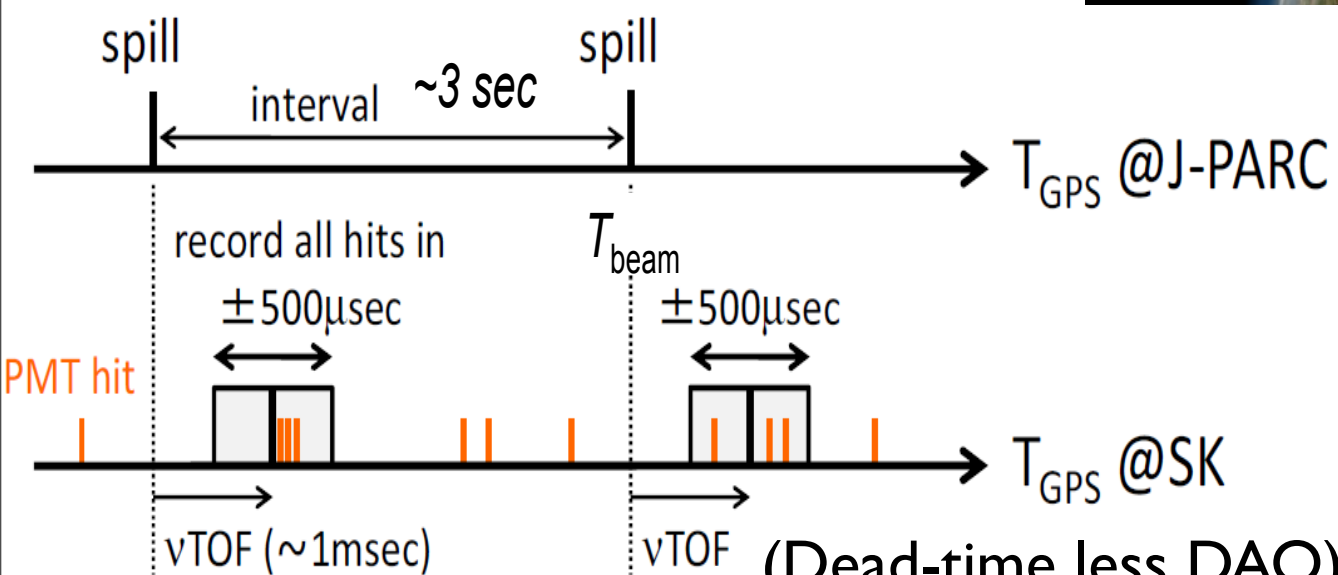
Beam position

Electro Static Monitor (×21)

Event sync. near/far with GPS

- Baseline measurement (GPS Survey)
  - L = 295,335 ± 7 m (ToF = 985.132 ± 0.02 μsec)
- **DAQ synchronization**
  - Store events in ±500μsec window from exp. beam timing at SK: "T2K beam event"

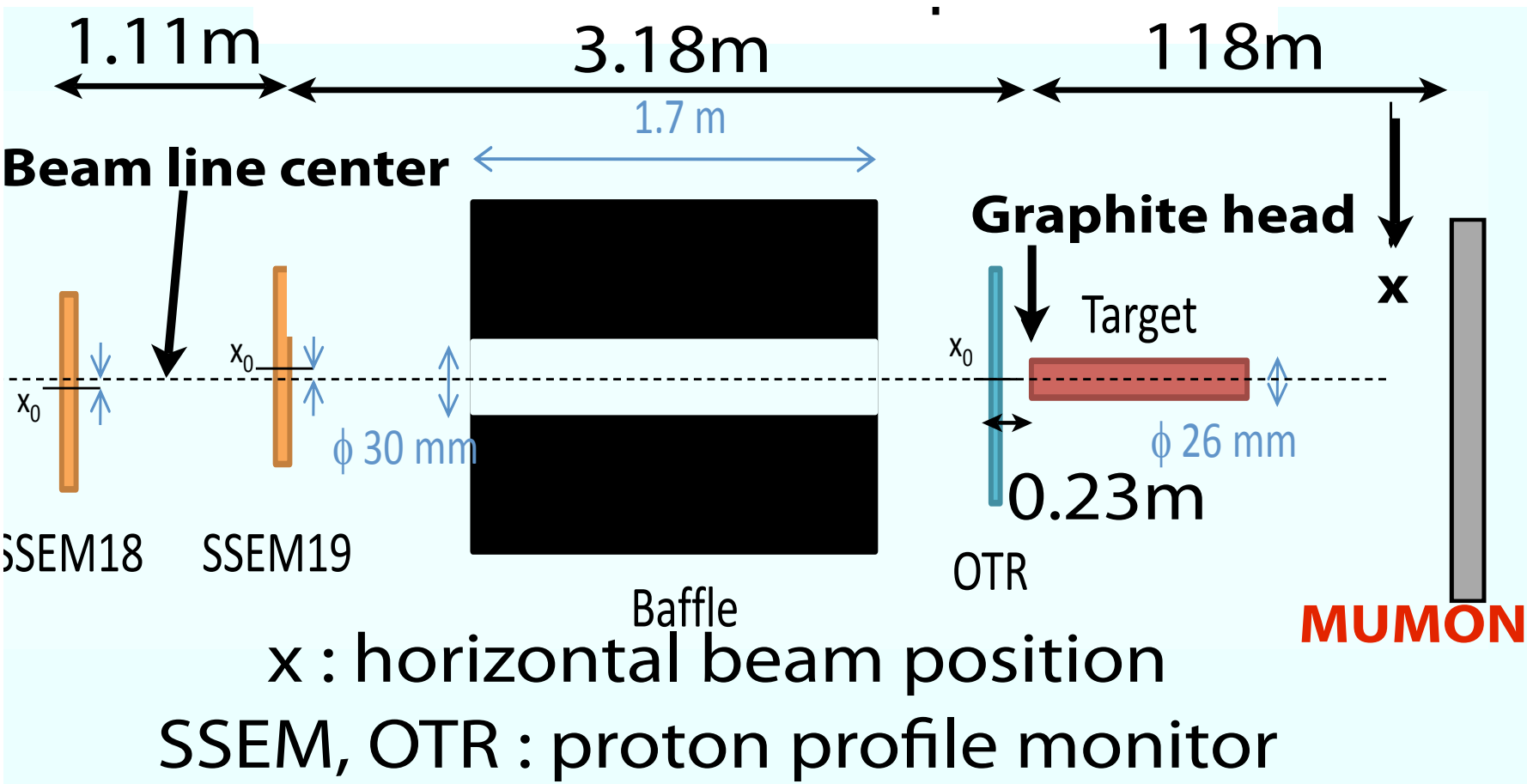




(Dead-time less DAQ)

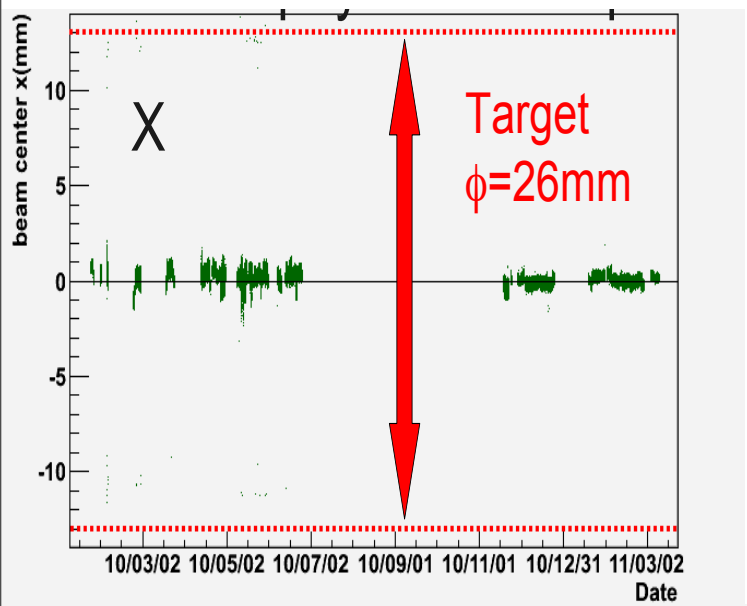
Measure proton beam @Target

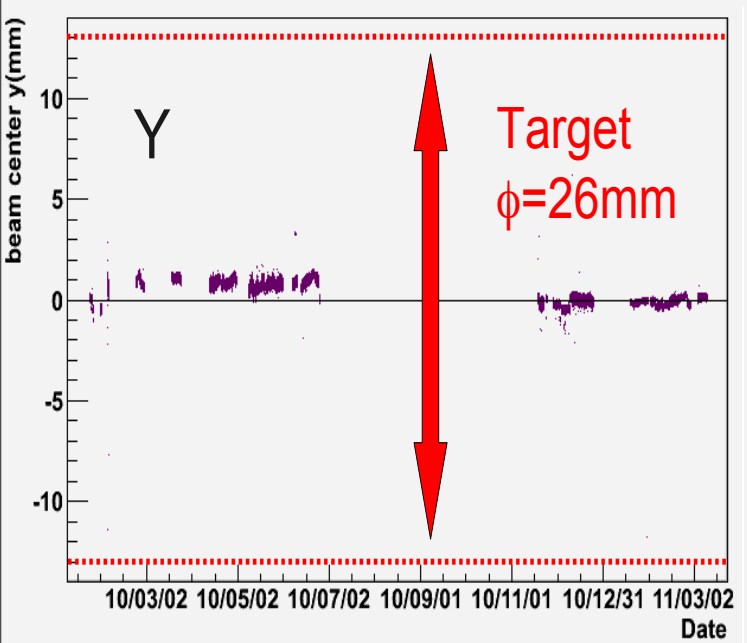
Estimate beam position, width, angle @Target by extrapolation of profile measurements.



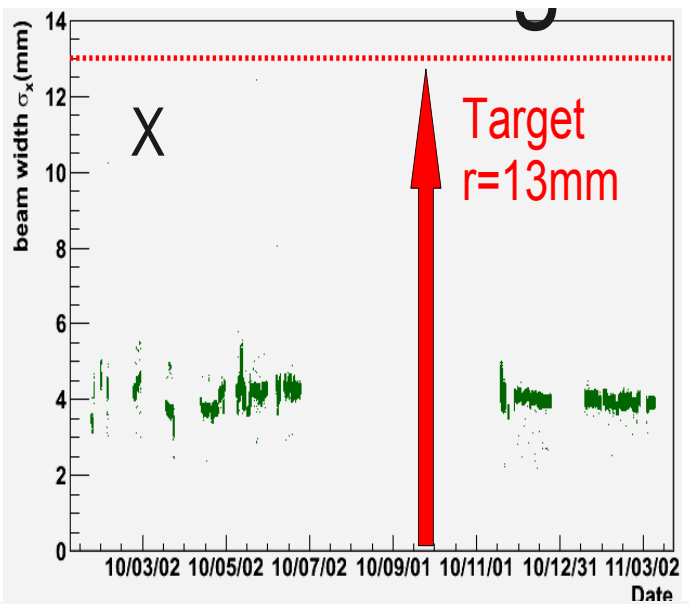
Proton beam measurement

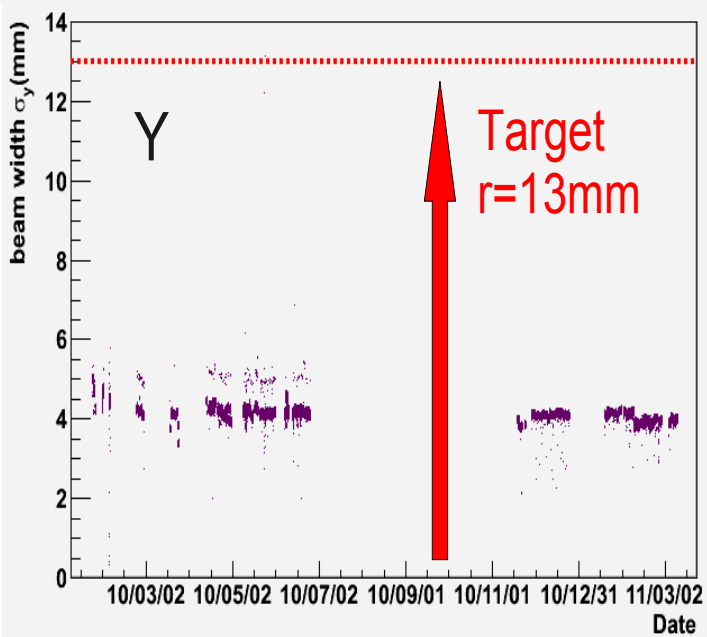
Position [mm]



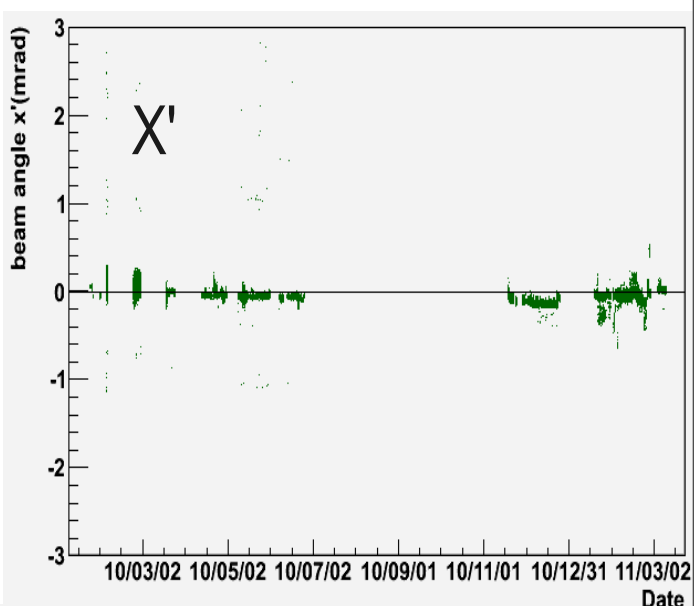


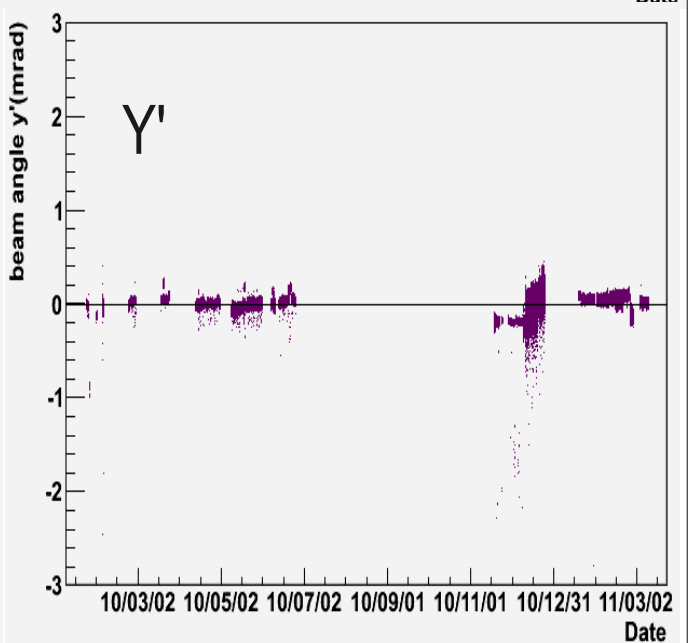
Width [mm]





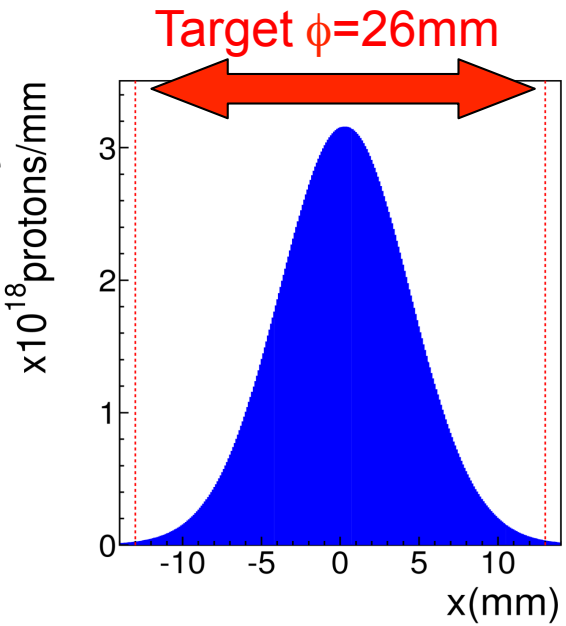
Angle [mrad]





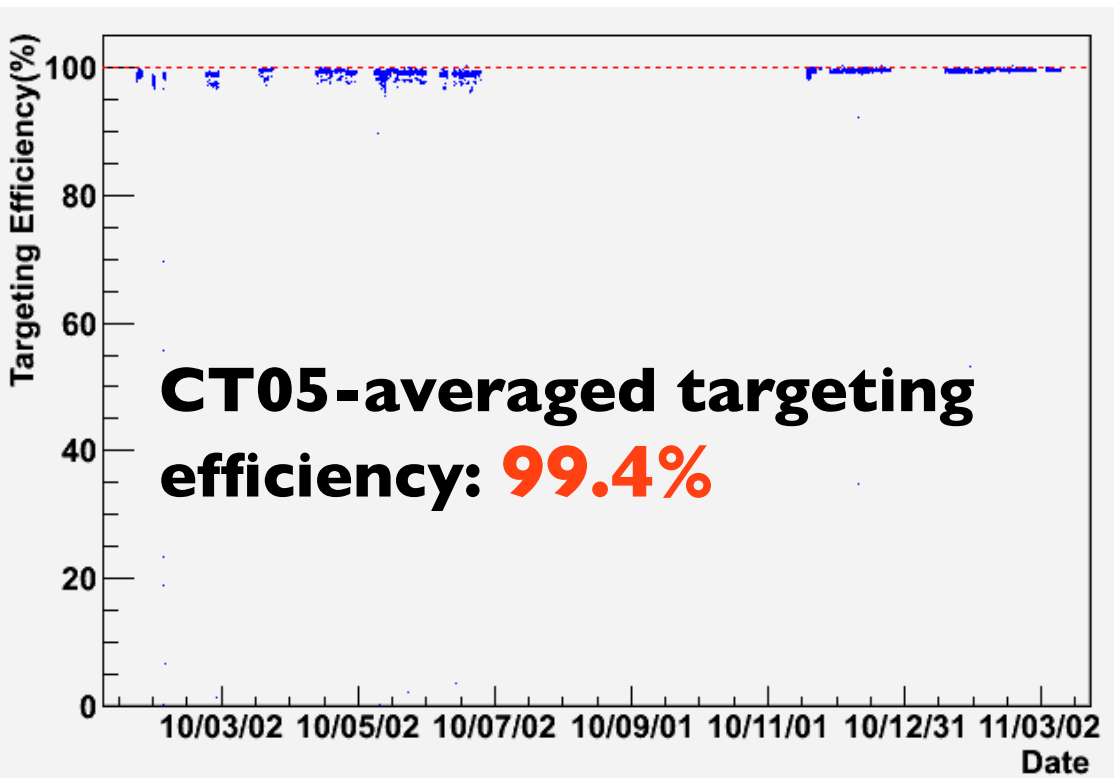
Proton beam measurement

- Shot-by-shot accumulated beam profile on target
  - Gaussian assumption for shot-by-shot beam profile
- Targeting efficiency
  - Geometrical overlap b/w 2D gaussian beam and upstream target surface.



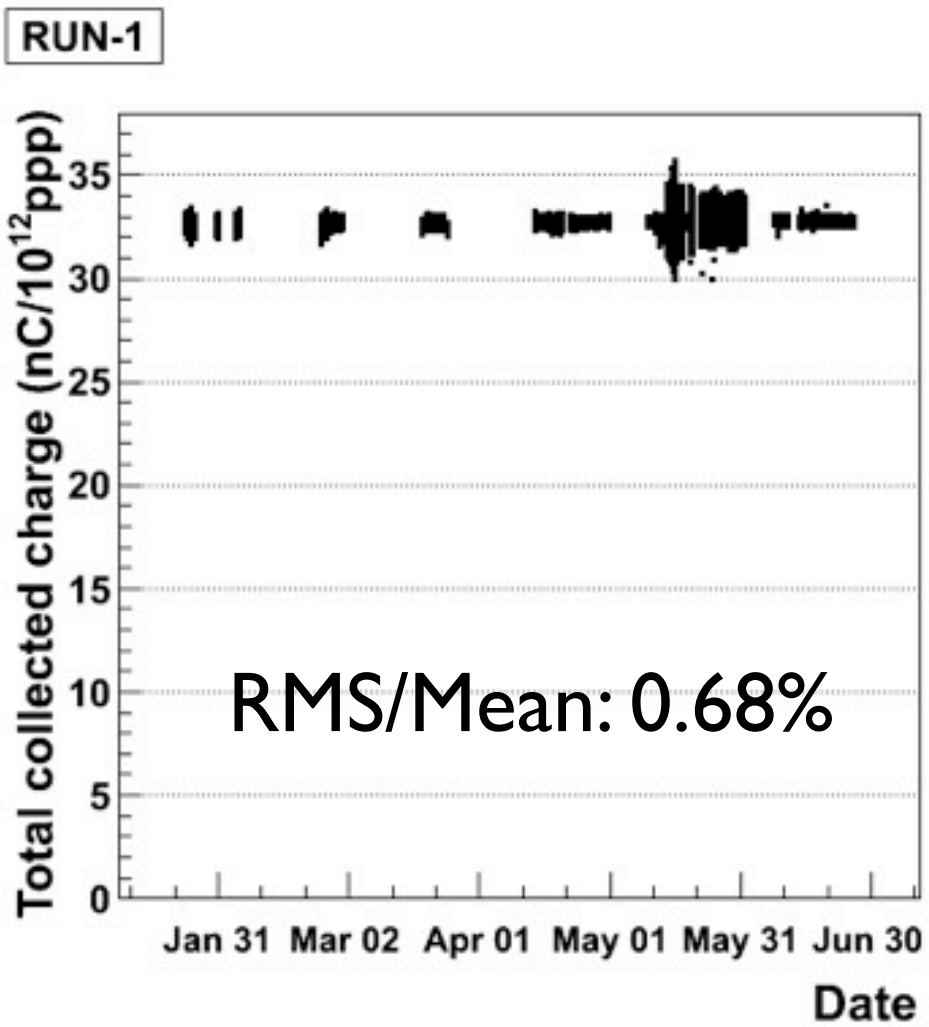
Fitted parameters			
MR-run	29-38	29-34	36-38
x(mm)	0.189	0.37	0.149
x'(mrad)	-0.071	-0.044	-0.080
σ_x(mm)	4.097	4.273	4.037
ε_x(π mm mrad)	4.68	2.13	5.27
α_x	0.20	0.60	0.16

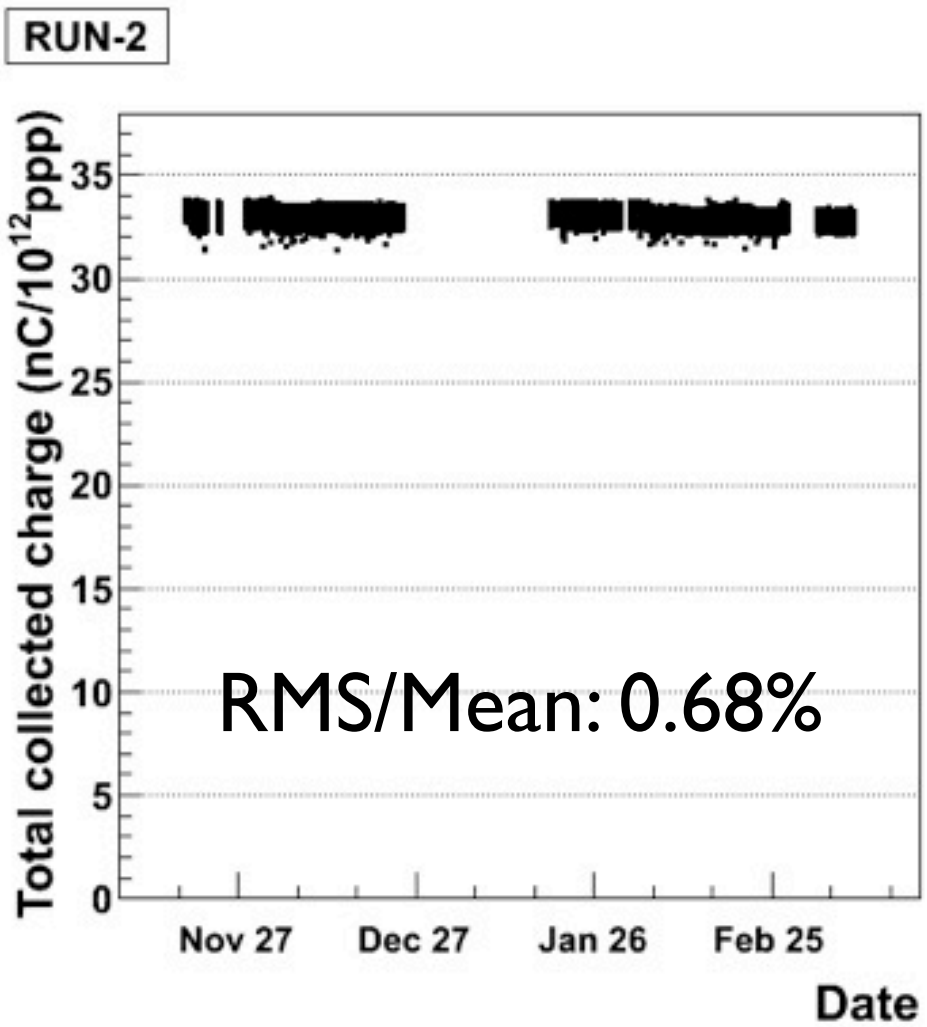
Fitted parameters			
MR-run	29-38	29-34	36-38
y(mm)	0.163	0.84	-0.052
y'(mrad)	-0.008	0.004	-0.007
σ_y(mm)	4.115	4.167	4.083
ε_y(π mm mrad)	4.63	2.29	5.17
α_y	0.09	-0.09	0.14



Beam measurement of MUMON

Total muon yield measured by Si-arrays





Beam generation is stable in whole period

Systematic error of profile center of MUMON

Error source	Profile center		Beam direction	
	Δx (cm)	Δy (cm)	$\Delta\theta_x$ (mrad)	$\Delta\theta_y$ (mrad)
Alignment	0.63	0.65	0.054	0.055
Sensor gain uncertainty	0.08	0.30	0.007	0.026
Profile asymmetry	1.25	1.12	0.106	0.095
Beam dump non-uniformity	0.38	0.38	0.032	0.032
Tilted beamline effect	–	0.22	–	0.019
Chamber/silicon discrepancy	0.55	1.77	0.047	0.150
Total	1.56	2.26	0.132	0.192

- Profile asymmetry: due to asymmetric or non-Gaussian beam profile.
- Chamber/silicon discrepancy: due to difference of nearby structure silicon moving stage(7.5mm thick aluminum plate)

good spill selection

1. physics run (run_type is “physics run” and all Horn ON)
   - exclude spills for beam tuning, beam study
2. TriggerFlag is “Beam Trigger” (it means that beam during MR operation)
3. Good GPS status
4. CT05 # of protons per spill > 1e11 in order to exclude spills which no beam in MR (due to machine interlock etc..)
5. normal condition cut
   - exclude unusable spills (e.g. PV2 unstable etc..)
6. Horn cut
   - nominal ±5kA for all the three Horns
7. Mumon cut
   - beam angle within 1mrad (abs(Si fit x) < 10cm and abs(Si fit y) <10cm)
   - Si total Q / CT05 cut : nominal ± 5%

Data taking efficiency

Select good quality data for analysis.

- DAQ alive & good event sync b/w J-PARC and SK.
- Stable beam operation & monitoring.

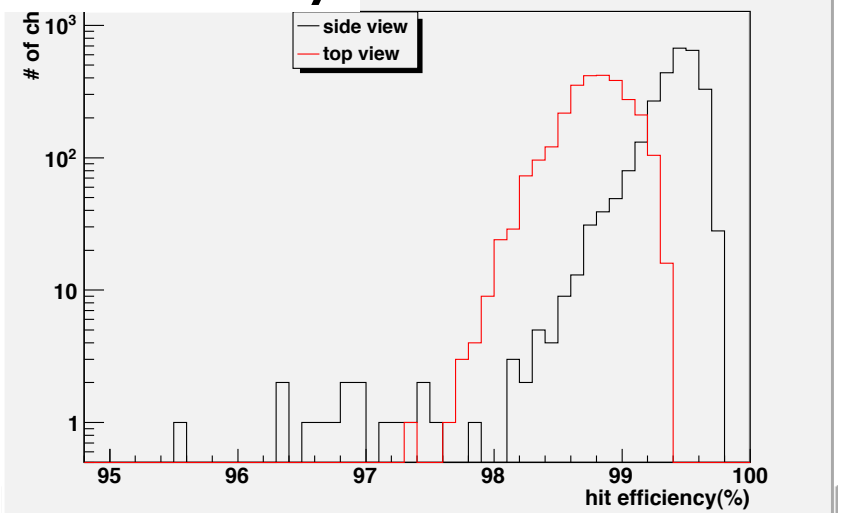
# of protons	Run1	Run2	Total
Total delivered	3.35×10^{19}	1.12×10^{20}	1.46×10^{20}
Physics Run	3.28×10^{19}	1.12×10^{20}	1.45×10^{20}
Good spill	3.26×10^{19}	1.12×10^{20}	1.45×10^{20}
SK Good spill	**3.23×10^{19}**	**1.11×10^{20}**	**1.43×10^{20}**

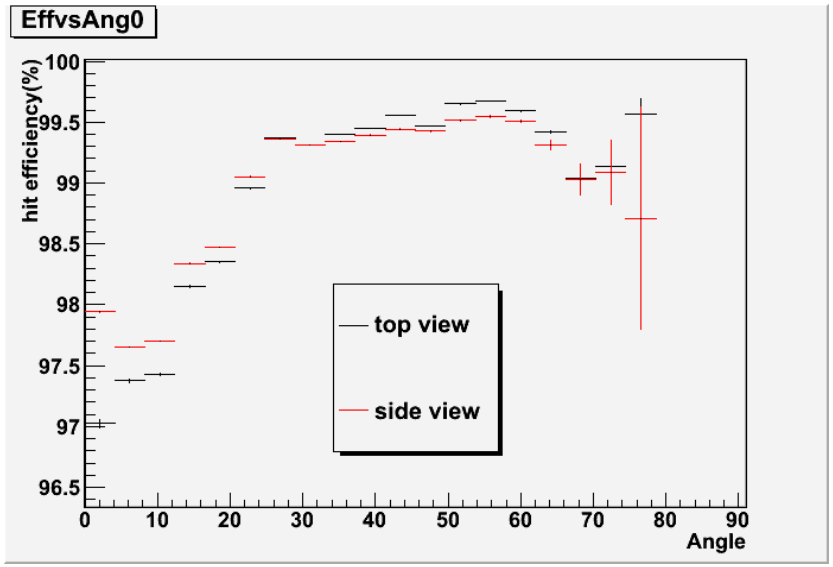
98% data used for oscillation analysis in Run1&2.

INGRID Performance

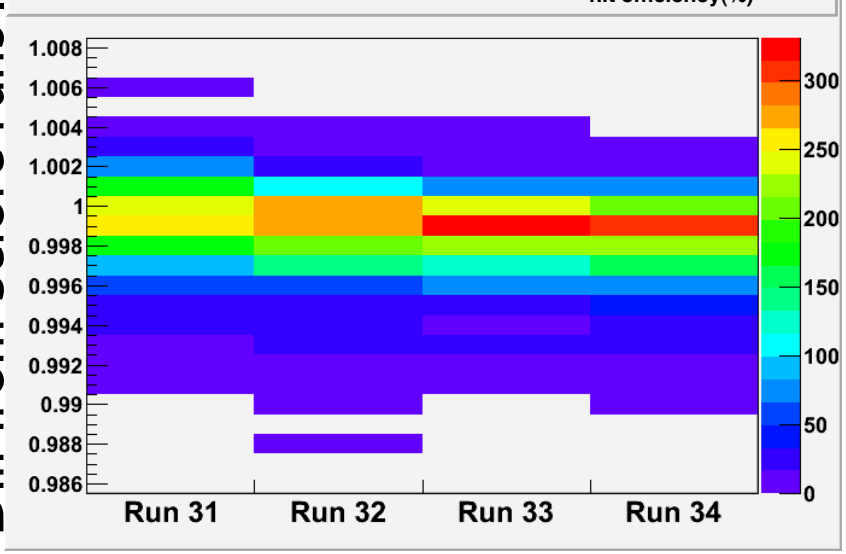
Detector	Total ch.	Bad ch.
INGRID	10796	0.17%

Hit effieiency



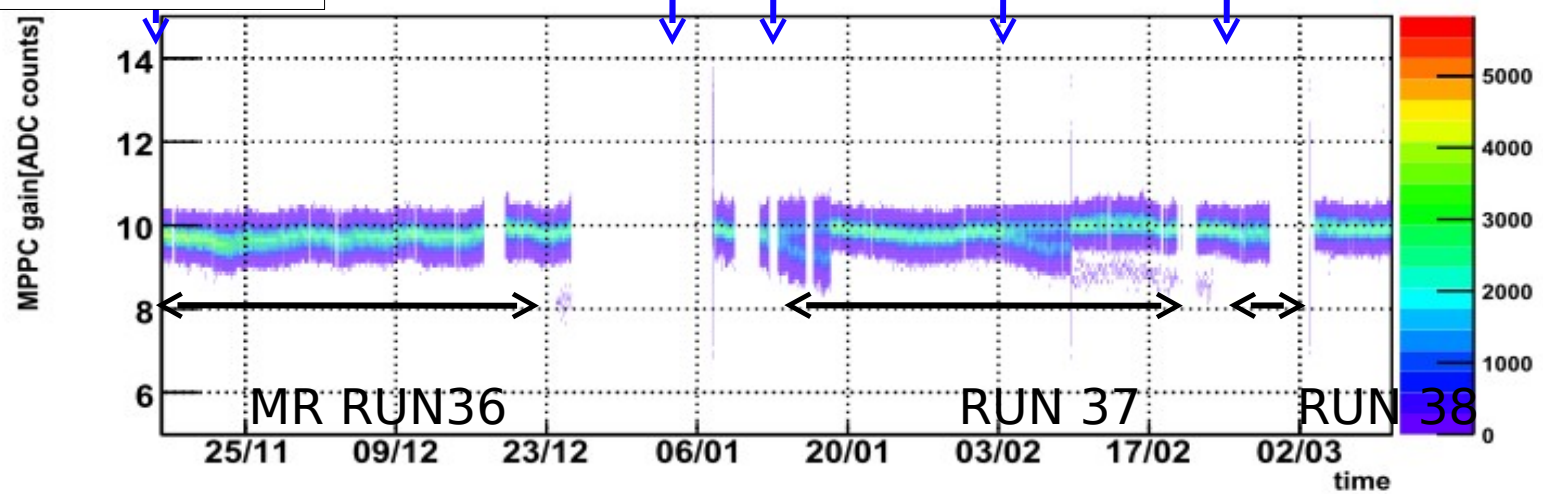


Diff from before run31

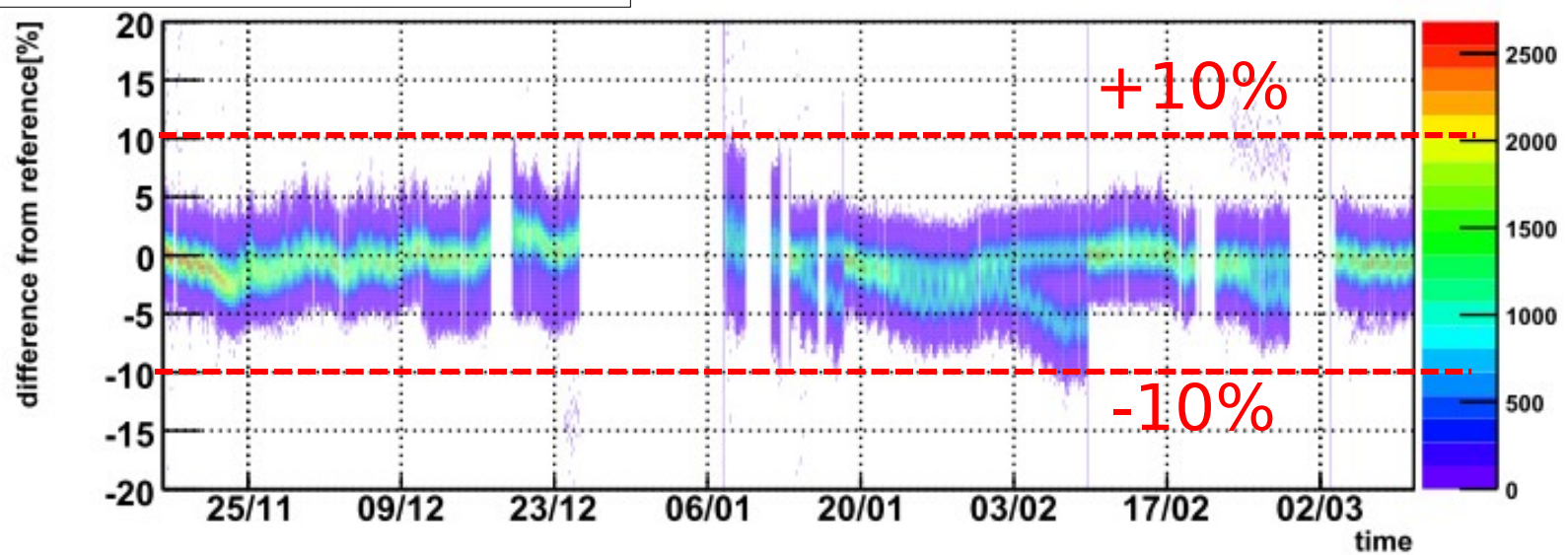


INGRID Performance

Gain history



Difference from reference gain

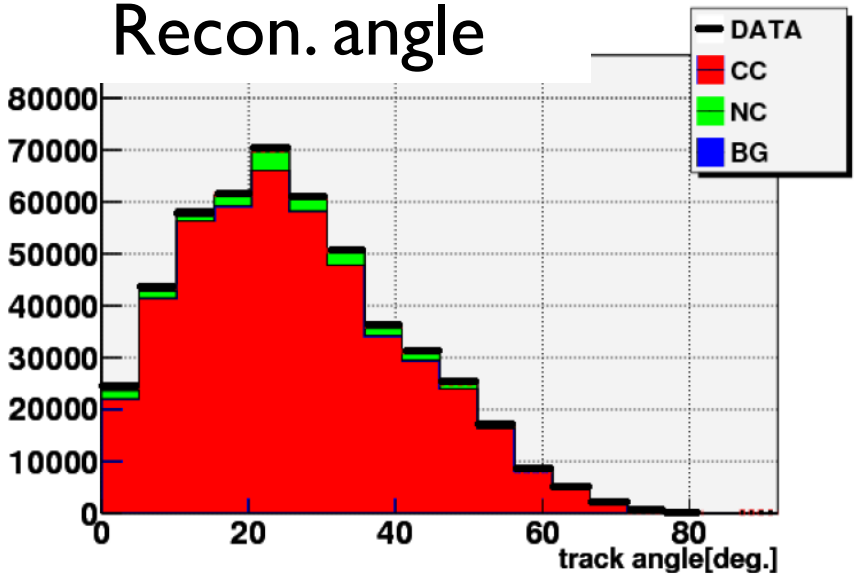


オフライン解析時には温度による補正をかける

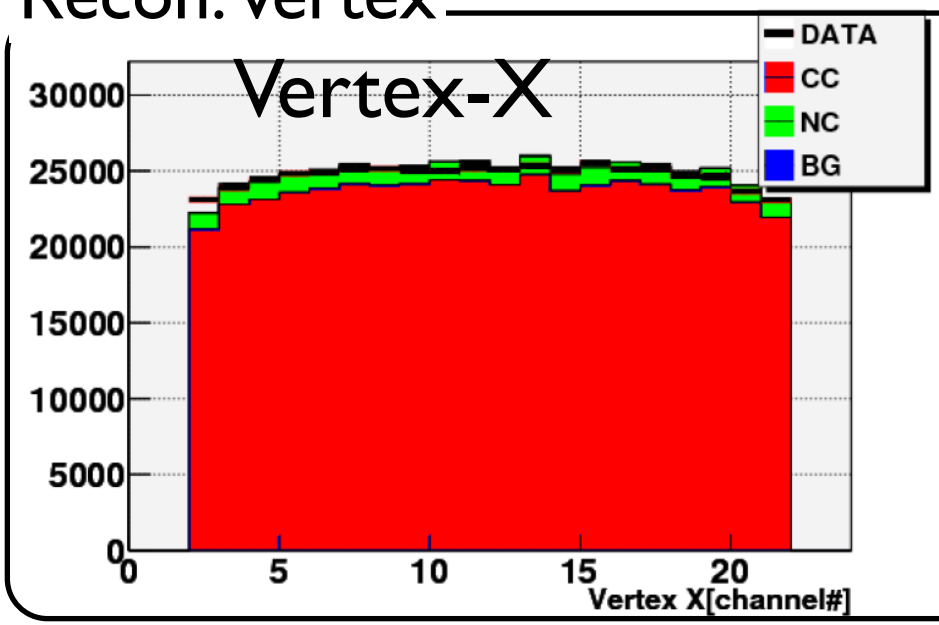
INGRID measurement

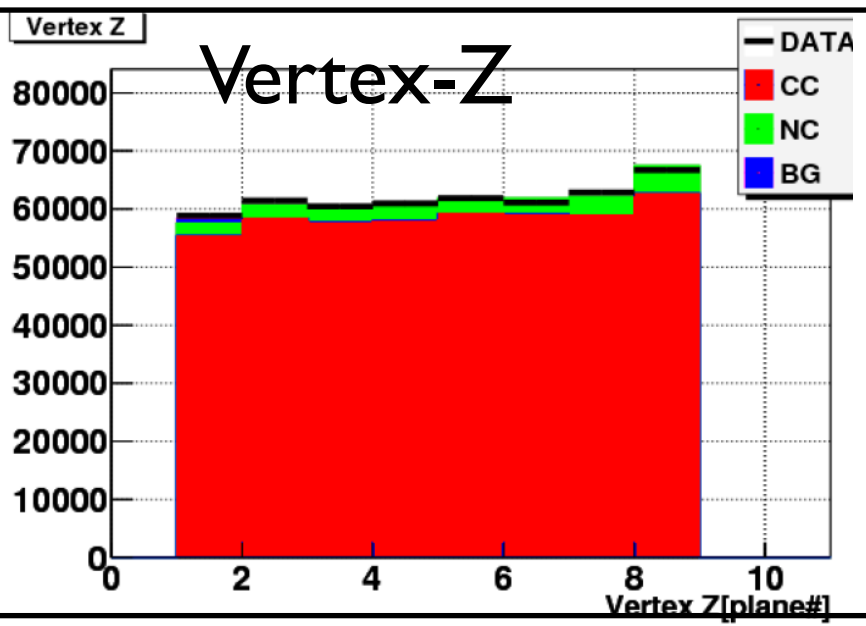
Some distribution after selection (normalized by p.o.t.)

Recon. angle



Recon. vertex

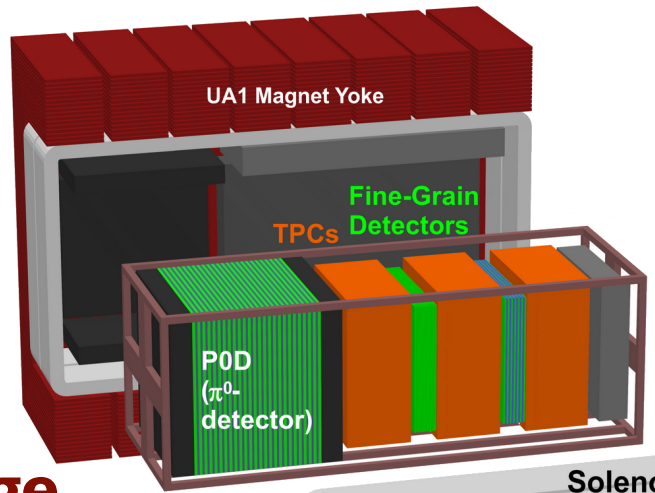




ND280

Count # of neutrino before oscillation with trackers

UA1 magnet
- 0.2T (nominal)



PiZero Detector (P0D)
- Detect π0 from νμ w/ water.
- Scintillator planes interleaved w/ water & lead/brass layers.

Side Muon Range Detector (SMRD)
- Scintillator planes in magnet
- Detect muon from inner/ outer

ECALs
- Capture γ/e/μ from P0D or tracker
- Scintillating layers & Pb absorber

Tracker

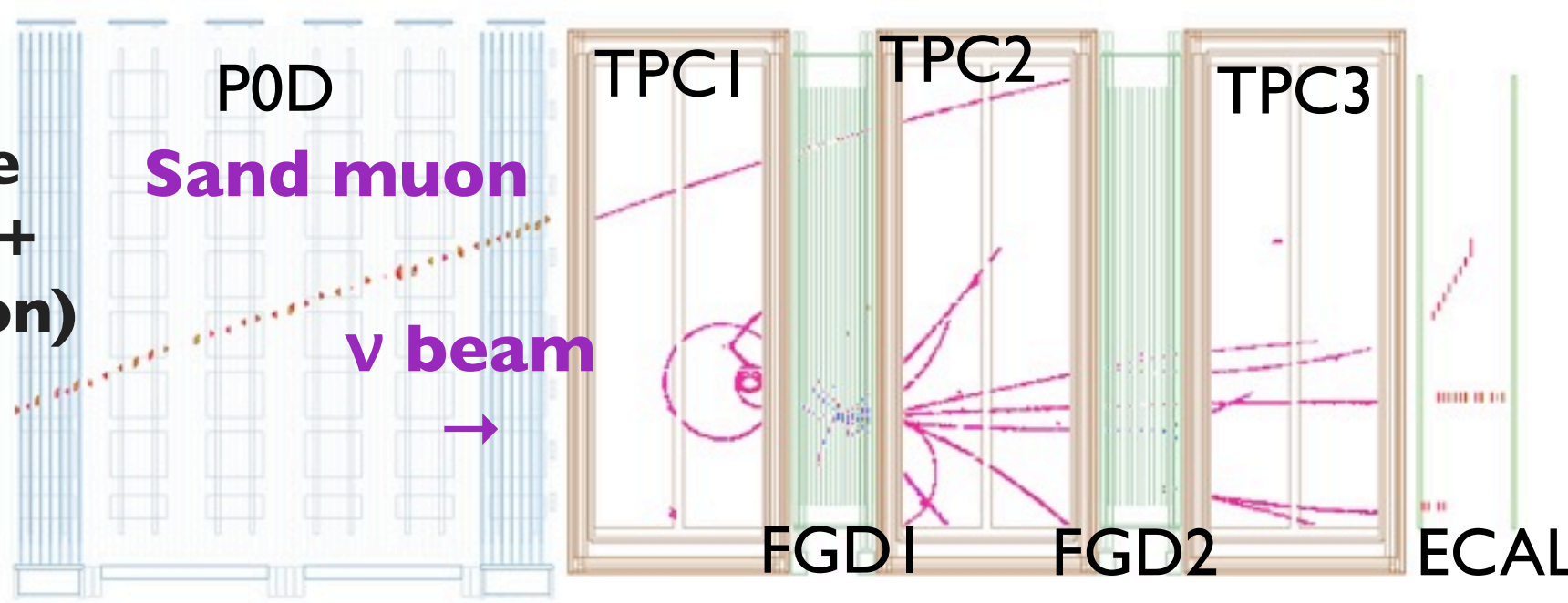
Fine Grained Detectors (FGD)
- Neutrino target (FV:1.6ton)
- Fine grain scintillator bars (1cm×1cmx186cm)

Time projection chambers (TPC)
- <10% dE/dx resolution

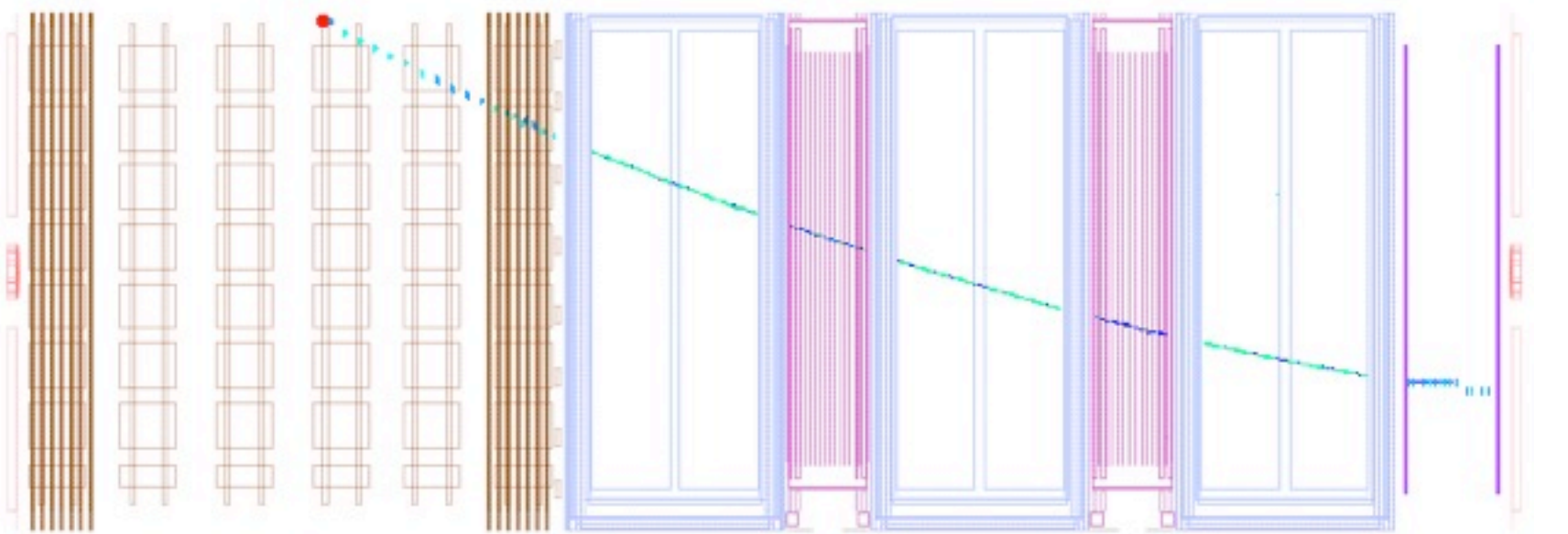
Event display of ND280

DATA.

CC DIS candidate ($\nu + n \rightarrow \mu^- +$ multi meson)

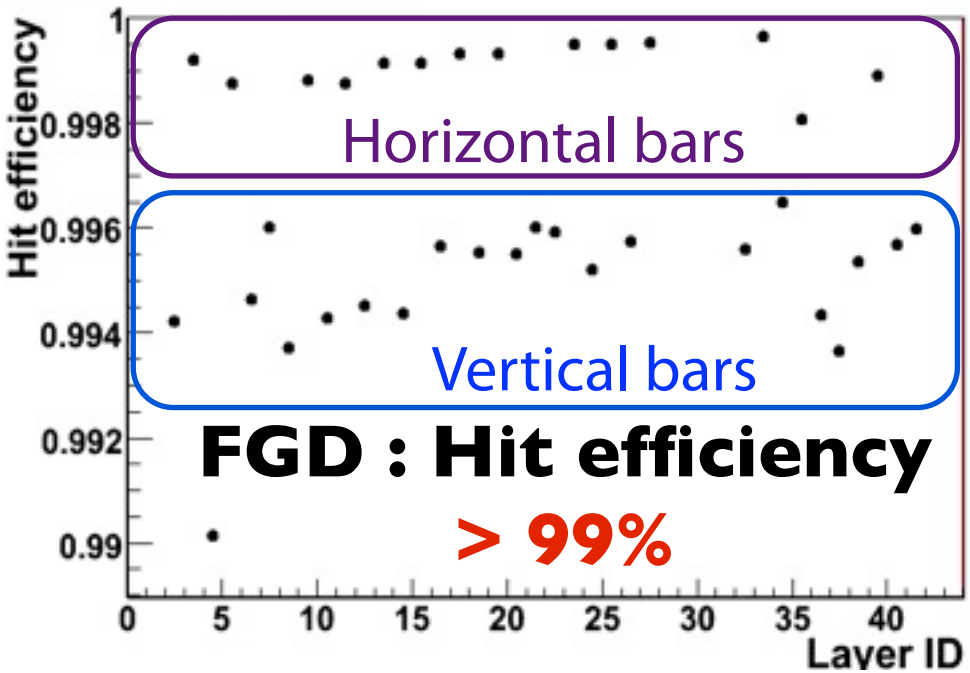


Cosmic event

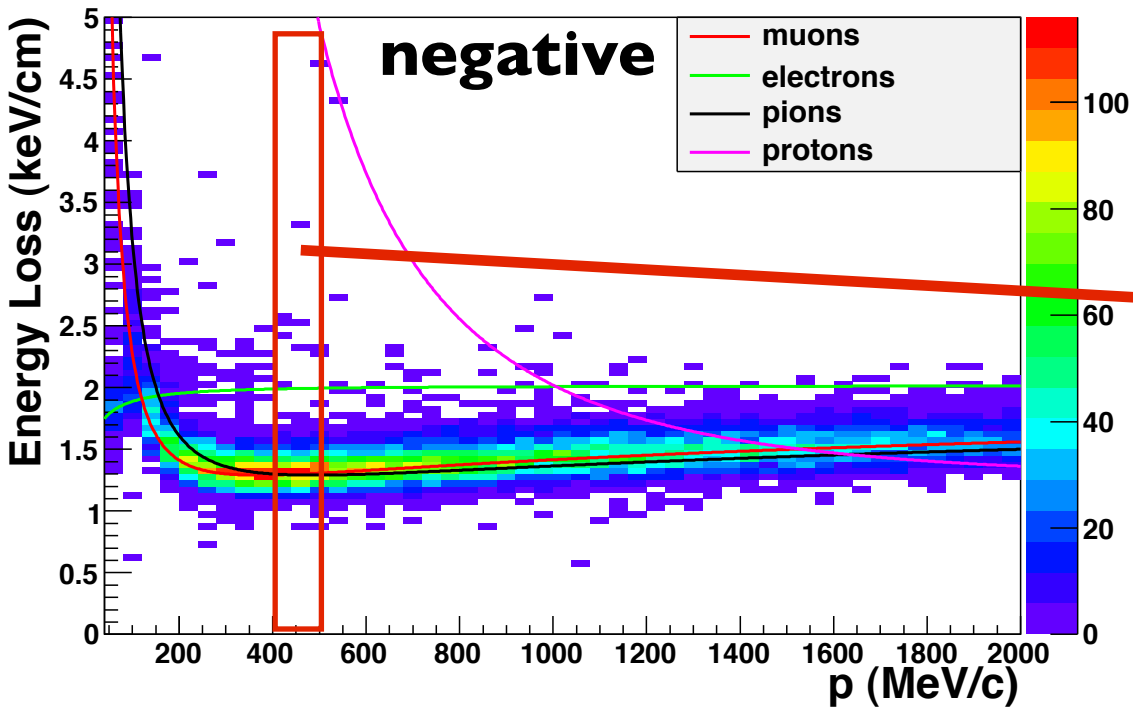


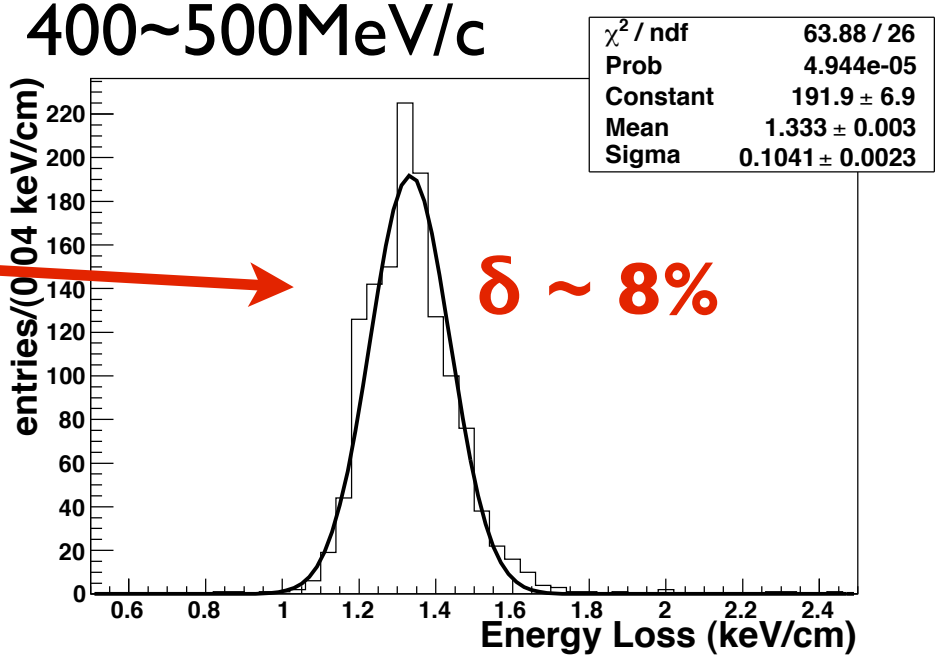
ND280 performance

Detector	Total ch.	Bad ch.
FGD	8448	0.24%
TPC	124416	0.01%
P0D	10400	0.07%
ECAL	25736	0.17%
SMRD	4016	0.17%



TPC : Recon. dE/dx

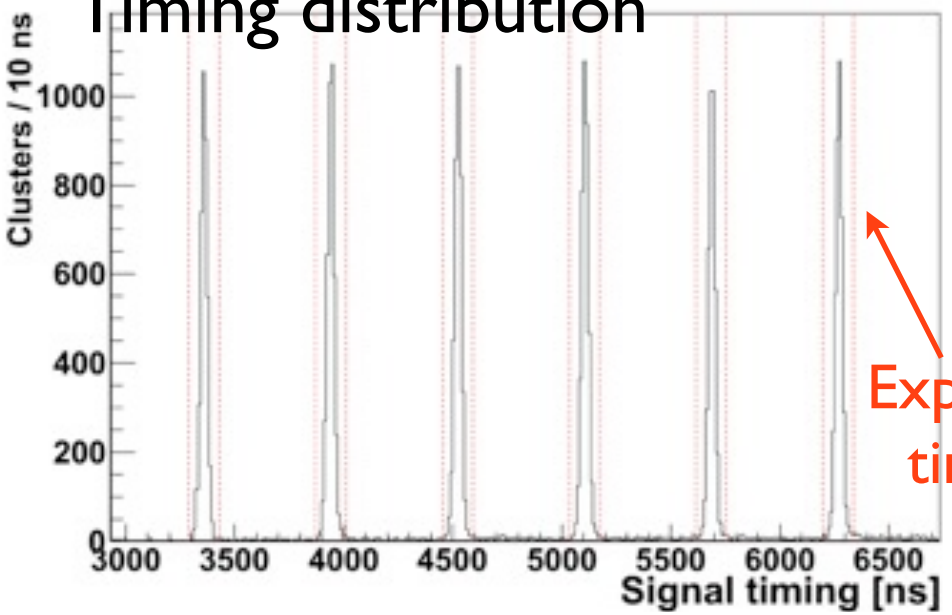




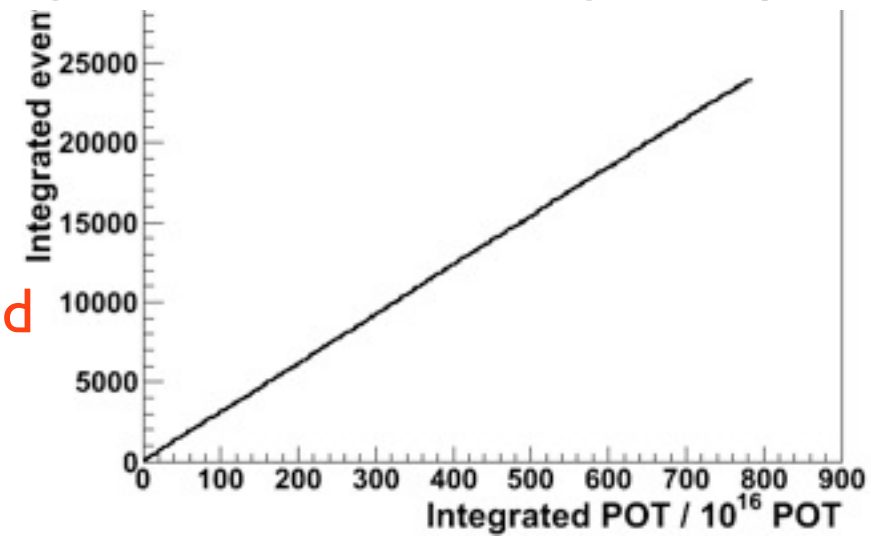
ND280 measurement

Select neutrino event at each detector (Reject accidental hit, timing cut) → Show examples of FGD (by Ieki-san).

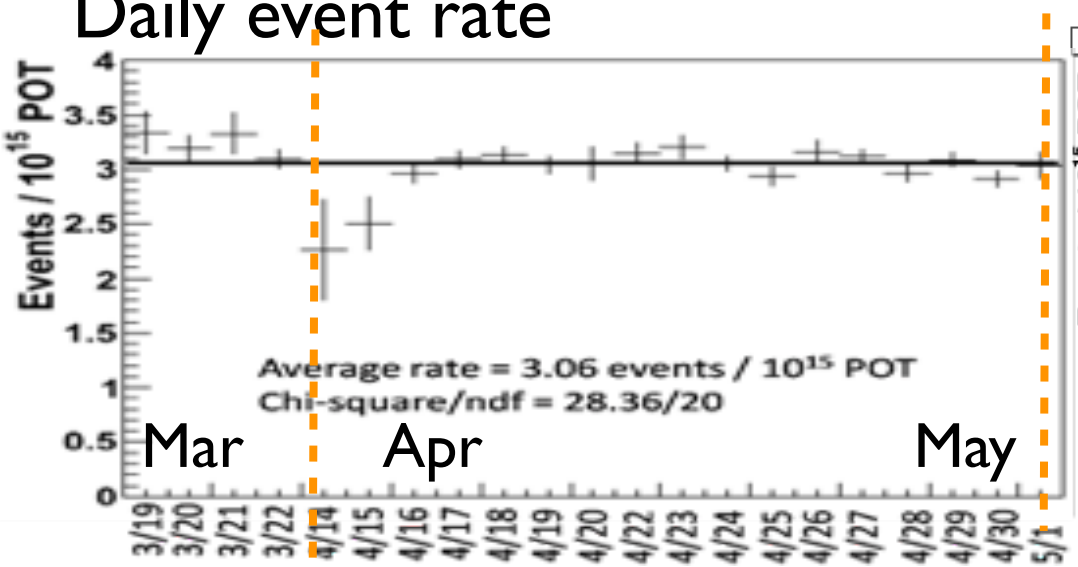
Timing distribution

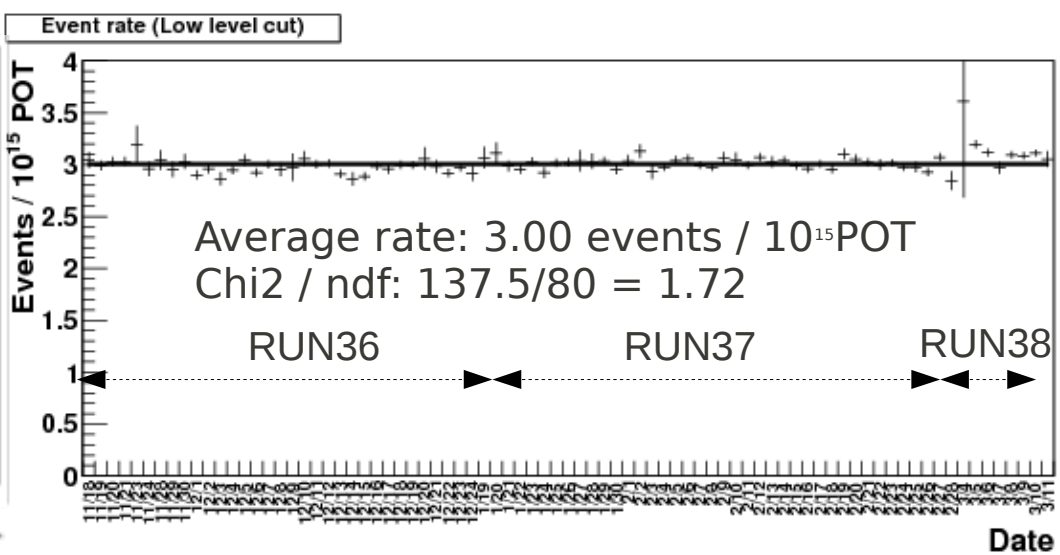


Integrated events vs integrated protons



Daily event rate





Systematic error of INGRID, ND280

INGRID

Item	Error[%]
Iron mass	0.1
Accidental MPPC noise	0.7
Beam related background	0.2
Fiducial selection	1.1
Hit efficiency	1.8
Tracking efficiency	1.4
Track matching selection	2.7
Not beam-related background	<0.1
p.e./active layer selection	<0.1
Beam timing selection	<0.1
Total	3.7

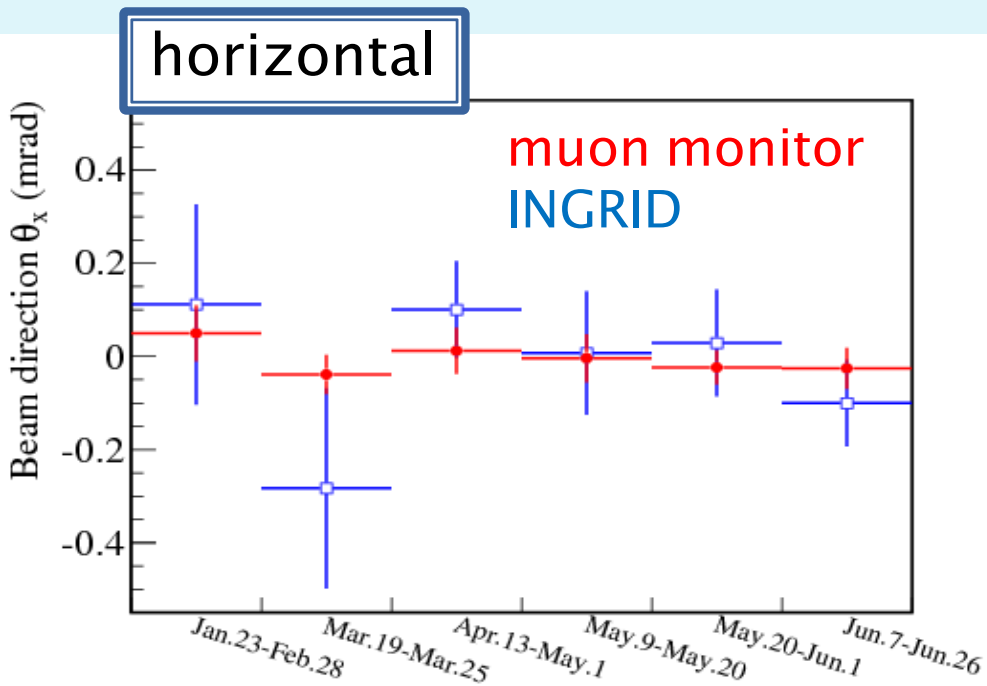
ND280

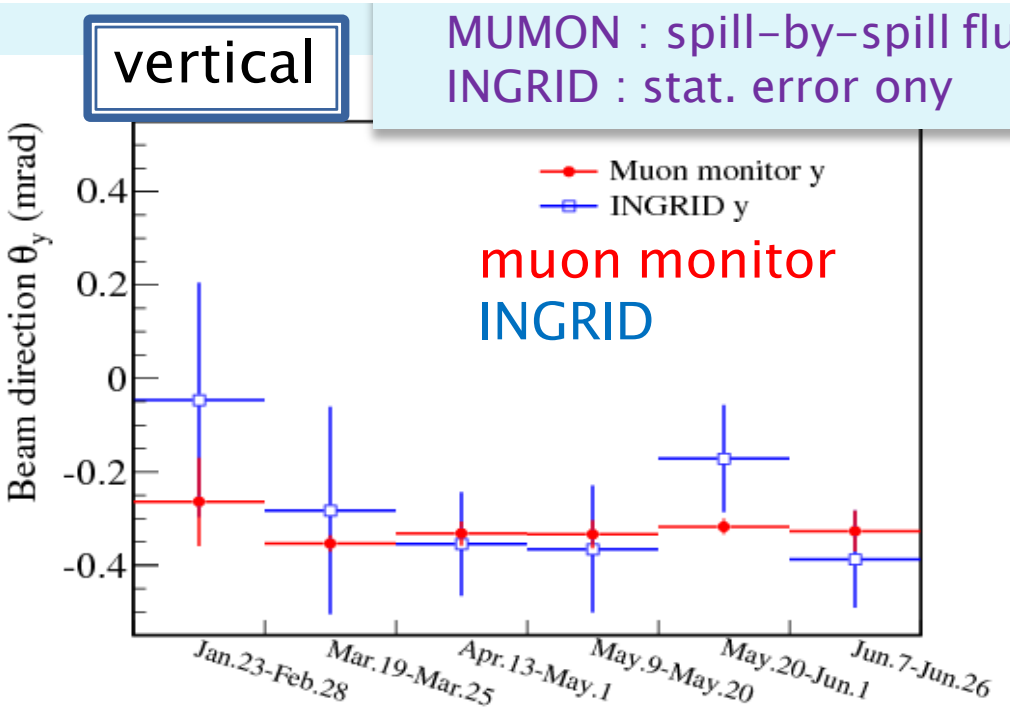
Source	Section	err. sys. +	err sys -
TPC1 veto	9.1	0.012	0.012
TPC eff	9.2	/	0.020
TPC ch misid	9.3	0.01	0.01
TPC-FGD match	9.4	0.021	0.021
FV	9.5	/	/
FGD mass	9.5	0.005	0.005
T_0	9.6	0.001	/
highest mom tk	9.7	/	/
PID pull width	9.8.3	0.030	/
Low gain MM	9.8.2	0.004	0.004
pile-up	9.9	0.009	0.009
cosmics	10.1	/	0.004
Out of FGD	10.3	0.009	0.009
Total		**0.042**	**0.036**

- Nucleon Ejection: -2.7%
- FSI tuning: $\pm 0.7\%$
- Kinematical variation $M_A + M_V$: $\pm 2.4\%$

Physics syst. = 3.7%

MUMON vs INGRID





- averaged beam center position (L≅280m)
  horizontal : +0.2±1.4(stat.)±9.2(syst.) cm
  vertical : -6.6±1.5(stat.)±10.4(syst.) cm
  corresponds to 0.37mad uncertainty
- beam direction is controlled within << 1mrad