FUTURE HADRON PRODUCTION MEASUREMENTS

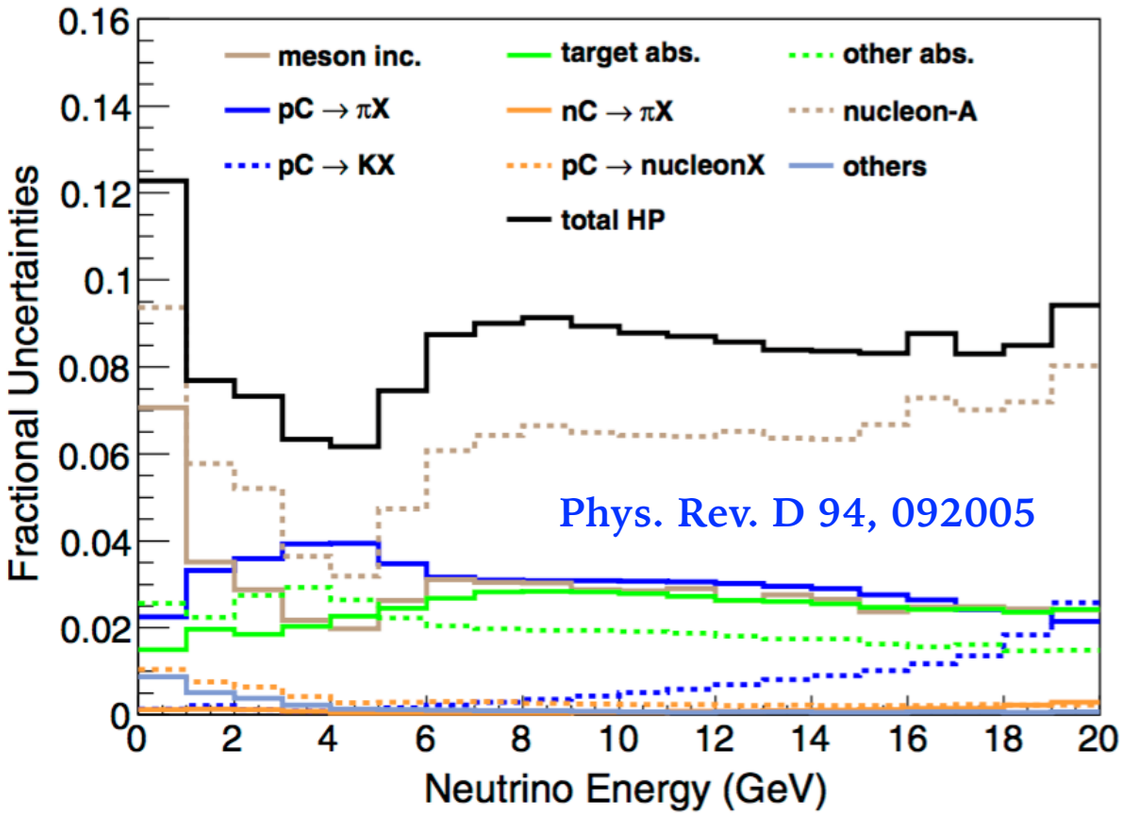
Mark Hartz
Kavli IPMU (WPI), University of Tokyo & TRIUMF

NuInt 2017, Fields Institute, University of Toronto
June 26, 2017

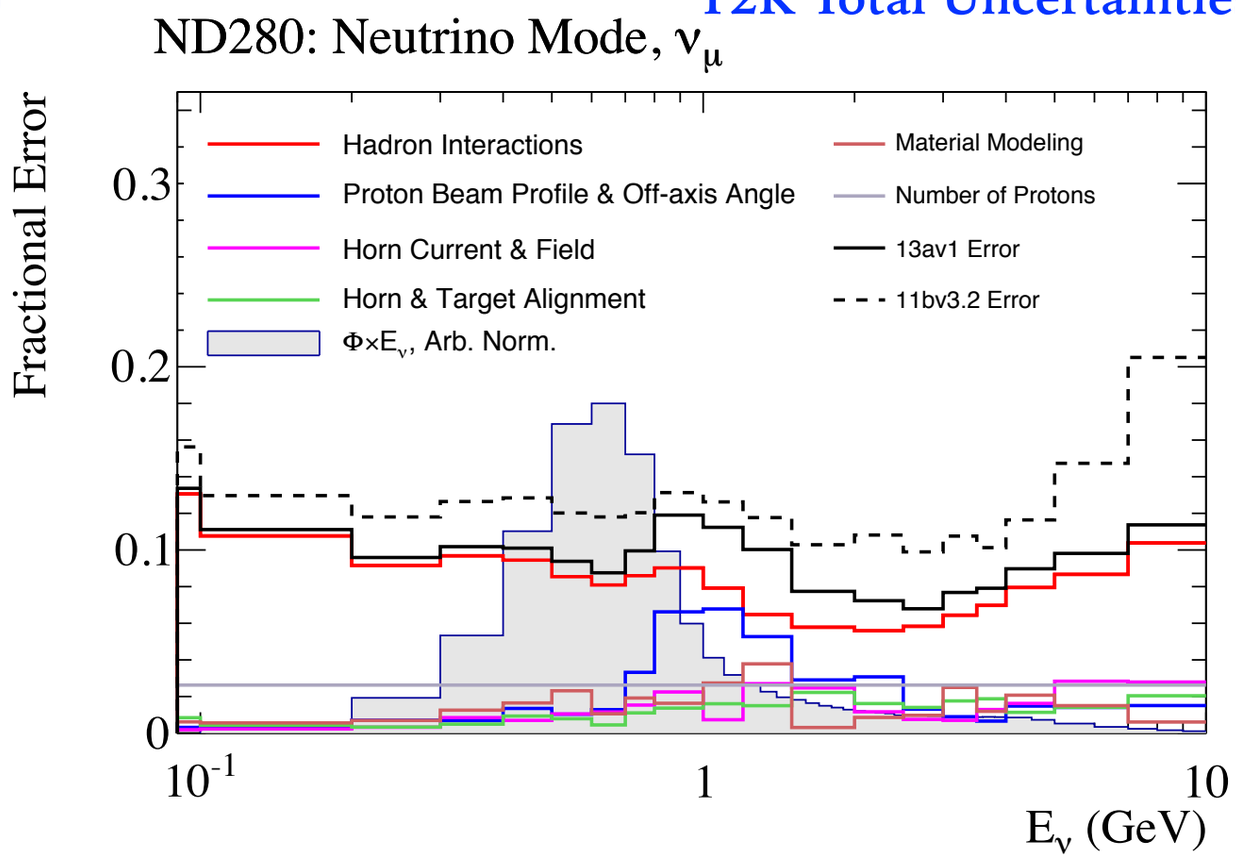
STATE OF FLUX CALCULATIONS

- The status of NuMI, T2K and DUNE flux predictions have been covered in this session
- Flux predictions with <10% errors have been achieved
  - Thanks to hadron production measurements at NA61/SHINE, MIPP, etc.

NuMI Hadron Modeling Errors (Thin Target)



T2K Total Uncertainties

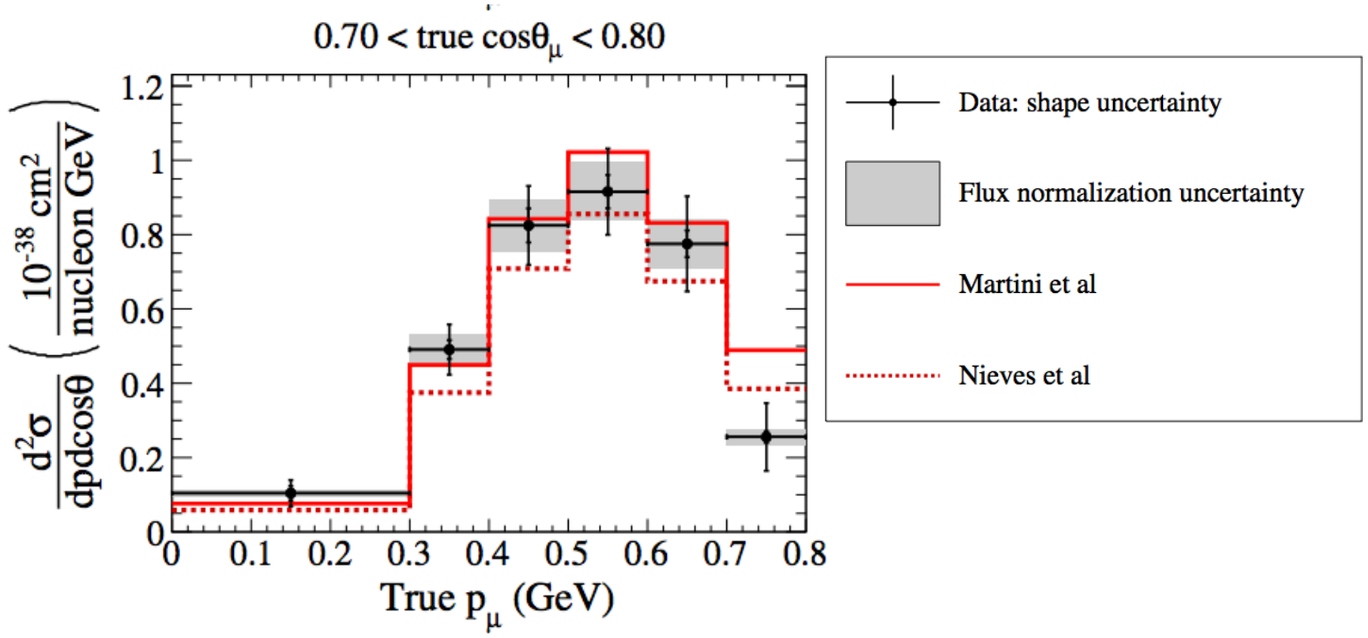


- Uncertainties on hadronic interactions dominate, but errors on alignment, focussing, material modelling, proton counting are not negligible.

NEEDED PRECISION?

- Do we need to do better than 8-10% uncertainties on flux calculations?
  - May already be sufficient precision for near-to-far extrapolations
- We can benefit from improved precision in cross-section measurements!

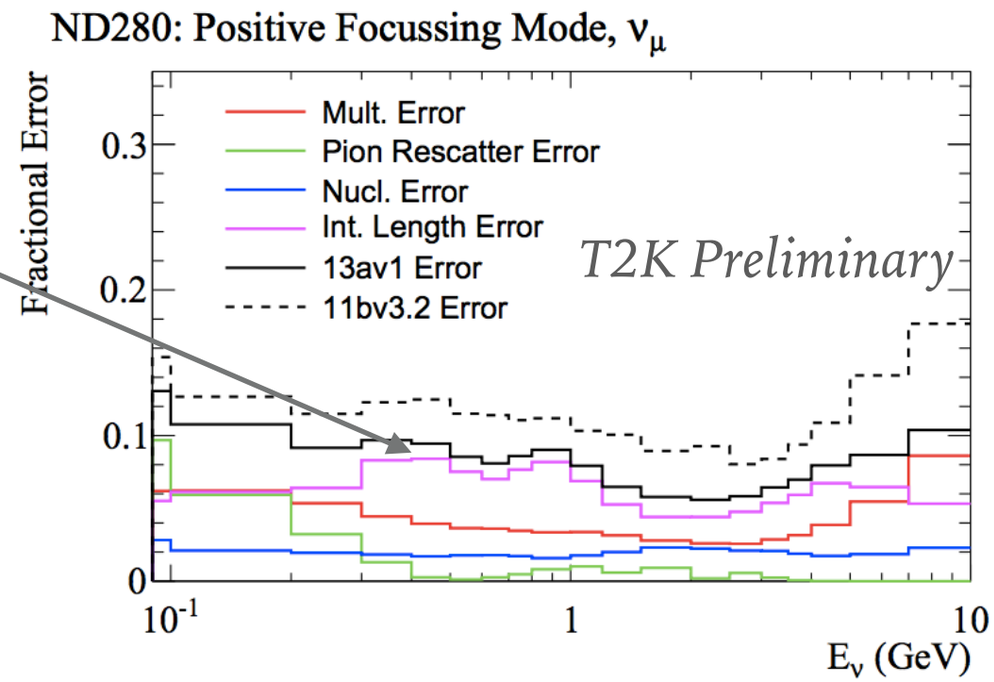
T2K CC0π: Phys.Rev. D93 (2016) 11, 112012

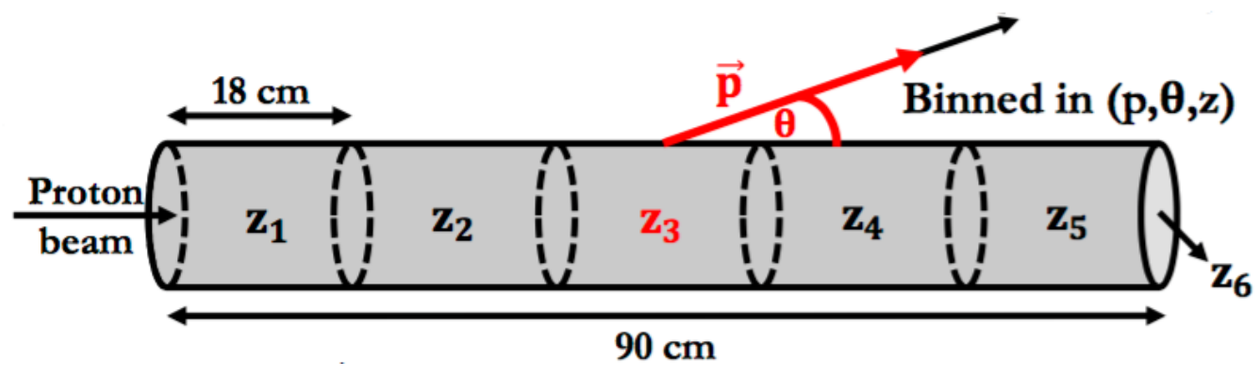


- Are data/model discrepancies due to missing enhancements or deficits in the model?
- Differences between models can be comparable to or smaller than the flux uncertainties

REPLICA TARGET MEASUREMENTS TO THE RESCUE

- Largest error in T2K from hadronic interaction lengths inside (and outside) the target
- Measure particle production in target identical to that used in neutrino experiment
  - NA61/SHINE with T2K target: **Eur. Phys. J. C76 (2016) no.11, 617**
  - MIPP with a NuMI target: **Phys. Rev. D 90, 032001 (2014)**
- Measure particle multiplicities exiting the replica target
- Remove uncertainties on the re-interaction of particles inside the target

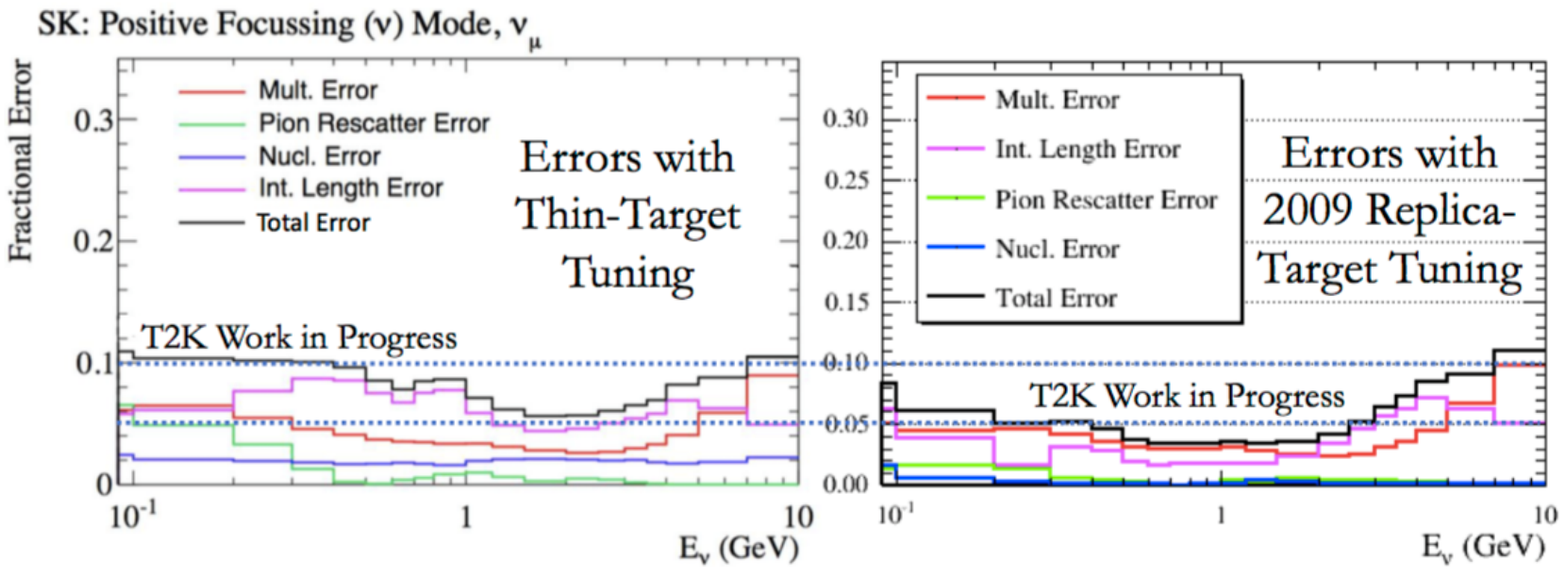




Binning for T2K Replica Target Measurement

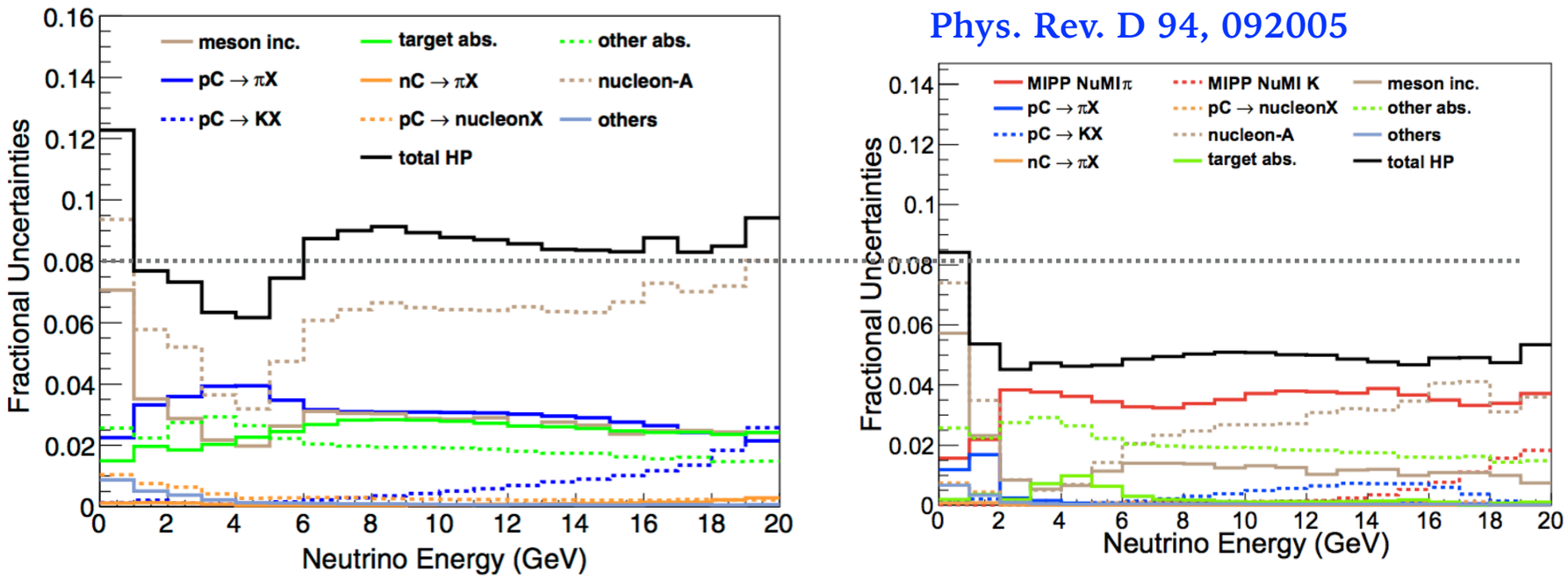
IMPROVEMENT DUE TO REPLICA TARGET IN T2K

- **Preliminary** investigation by T2K shows error reduction from ~10% to ~5% on hadron interaction modeling



See poster by T. Vladisavljevic

- ~5% error on NuMI flux error is achieved with the MIPP thick target data



FUTURE & IMPROVED HADRON PRODUCTION MEASUREMENTS?

There is still be a need for new measurements in the future:

- Current measurements are systematics limited - improve hadron production experiments to reduce systematic errors
- **Future high power target may (are likely to?) use new materials and geometry - new thin and replica target measurements will be necessary**
- Uncertainties on hadronic interactions outside of the target may become dominant - especially for wrong-sign flux components

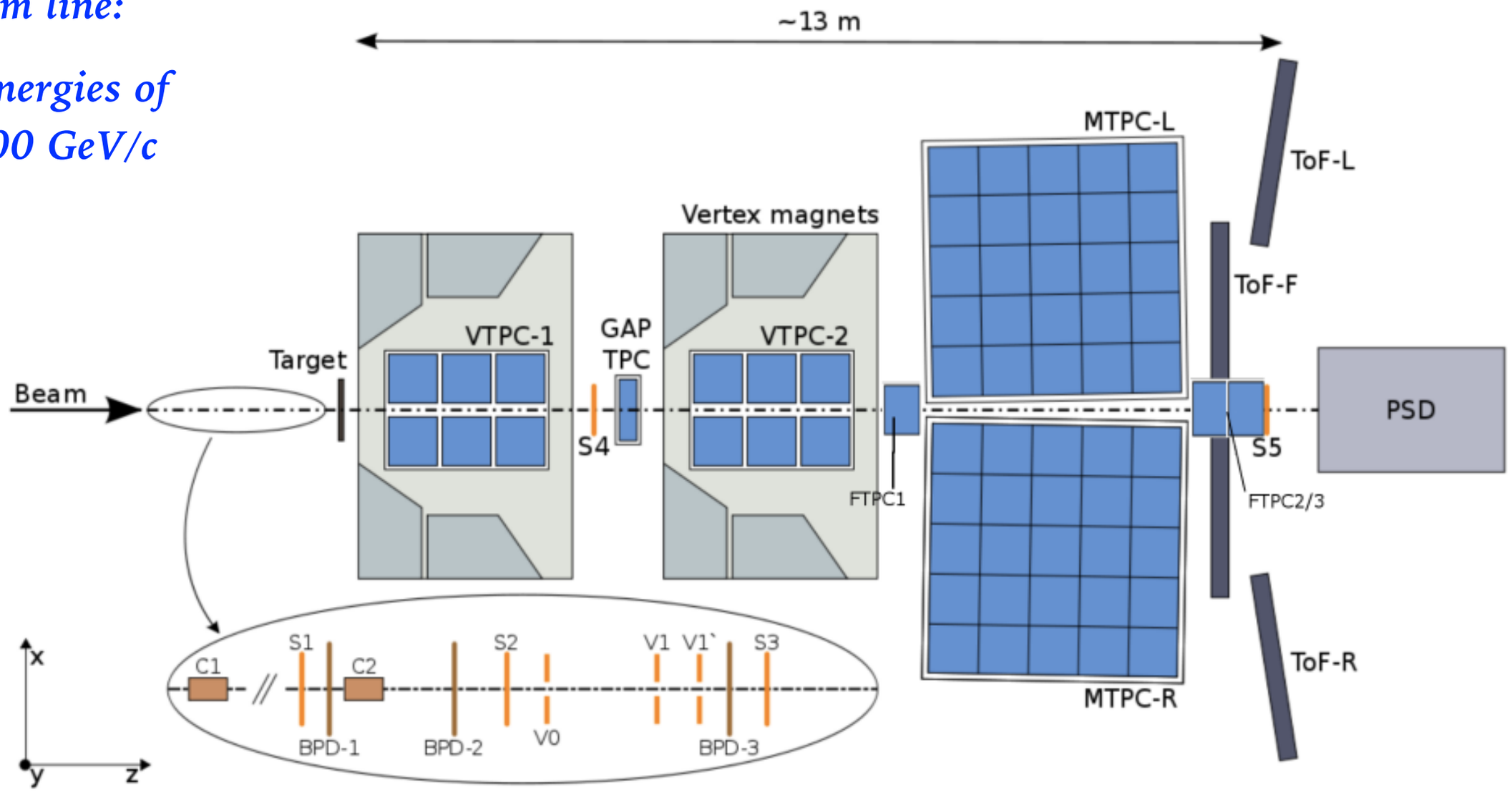
	Number of Inelastic Hadronic Interactions in Chain Producing the Neutrino		
	1 Interaction	≥2 Interactions	≥1 Out of Target Interaction
N280 ν_μ flux	63.2%	36.8%	12.6%
N280 anti-ν_μ flux	39.5%	60.5%	49.8%

- Improved precision on ν_e/ν_μ flux ratios may be necessary for electron neutrino cross section measurements
- New measurements can improve atmospheric neutrino flux predictions

NA61/SHINE EXPERIMENT

H2 Beam line:

Beam energies of ~10-200 GeV/c



Large acceptance TPCs in magnetic fields

Particle identification with dE/dx and time-of-flight

NA61/SHINE FUTURE OPERATIONS

- The status report from NA61/SHINE as well as future plans are described here: http://cds.cern.ch/record/2222876?ln=en

Beam Primary	Beam Secondary	Target	Momentum (A GeV/c)	Year	Days	Physics
p			400			
	h^+	A	40-400	2017	21 days	installation/tests
p			400			
	p	Pb	30, 40	2017	28 days	SI
p			400			
	h^+	A	30–120	2017	42 days	ν
Xe		La	13, 19, 30, 40, 75, 150	2017	60 days	SI
p			400			
	p	Pb	13, 20	2018	28 days	SI
p			400			
	h^+	A	30–120	2018	42 days	ν
Pb		Pb	20, 40, 75, 150	2018	60 days	SI

Run plan up to the long accelerator shutdown at CERN includes two periods of data taking for Fermilab neutrino beams.

Shutdown planned from July 2018 for 18 months

- Extension of the NA61/SHINE program beyond the long shutdown is now being considered

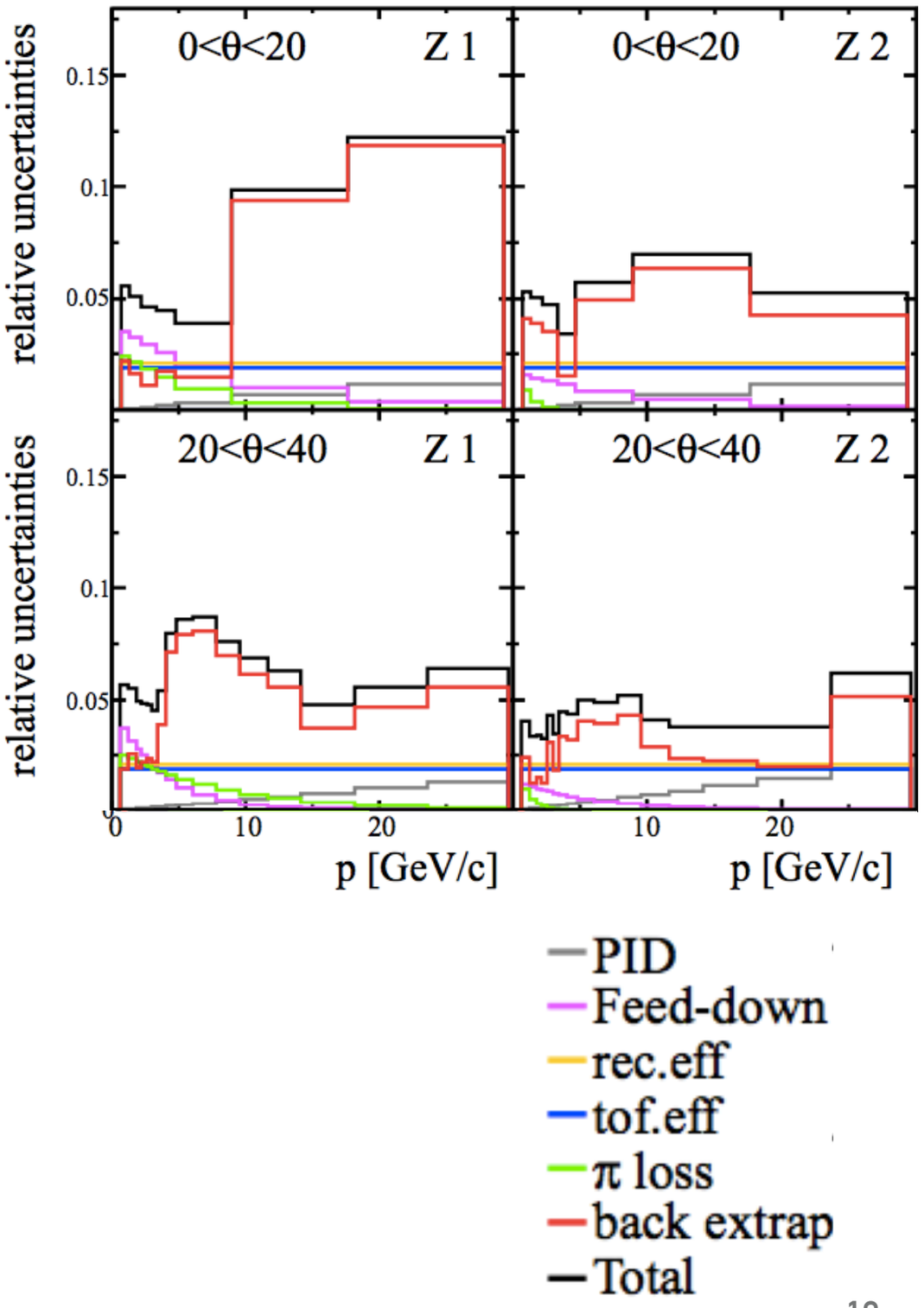
NA61/SHINE UPGRADE OPTIONS BEYOND SHUTDOWN

- Beam quality improvements
  - Reduction/removal of 50 Hz oscillation of beam intensity
  - Secondary beam line may be upgraded to handle higher ion beam intensities
- Detector upgrades being considered:
  - Tracking at the target
    - Large Acceptance Vertex Detector
  - Increased readout to 1 kHz
  - New time-of-flight detectors
  - **Tracking along replica targets for neutrino experiments**

BACKWARDS EXTRAPOLATION IN REPLICA TARGET DATA

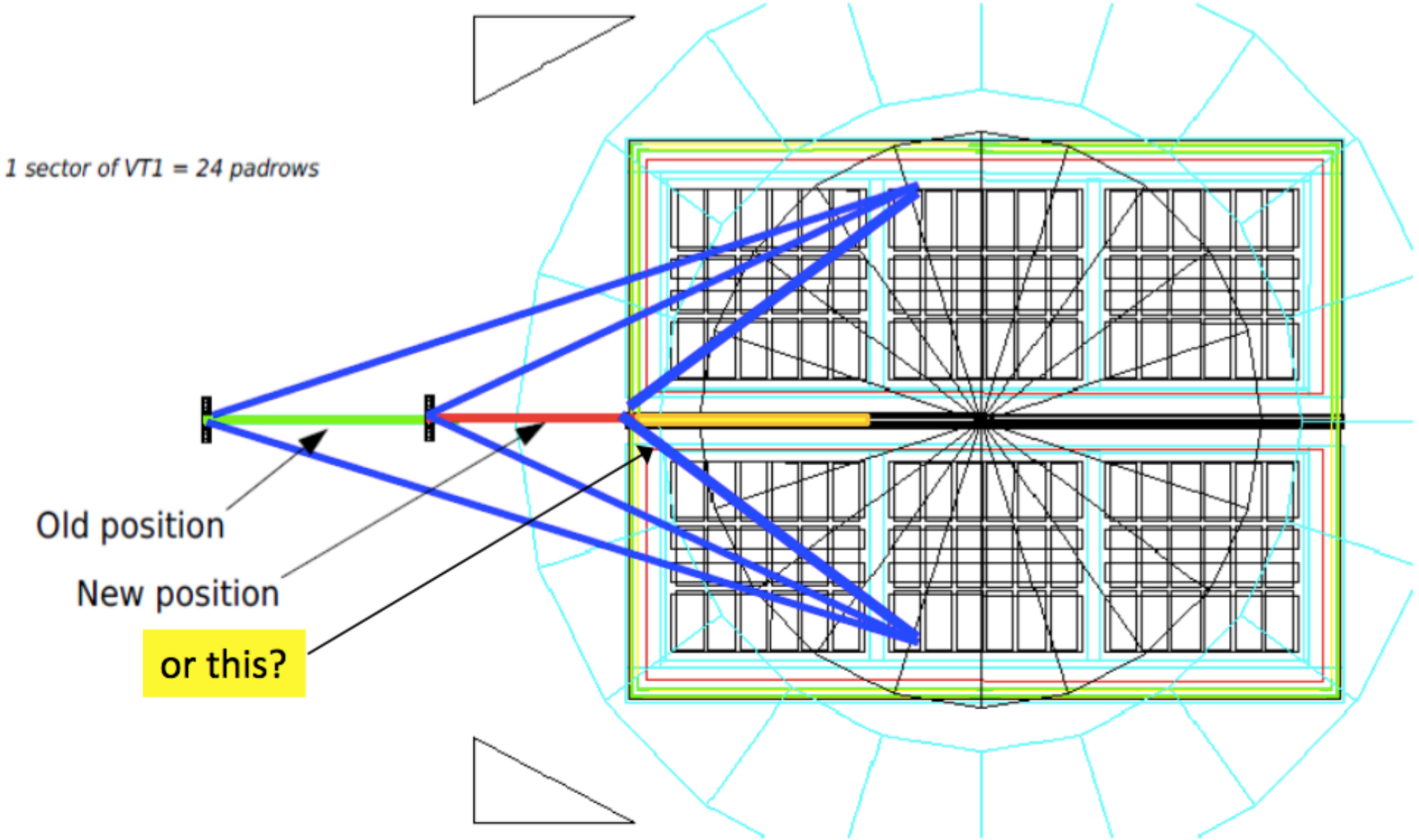
Eur. Phys. J. C76 (2016) no.11, 617

- Significant systematic uncertainty in the NA61/SHINE replica target data from backward extrapolation of track to target
- Measurement will benefit from tracking closer to the target
- Two options
  - New tracking layers near the target
  - Move the replica target into the TPC region



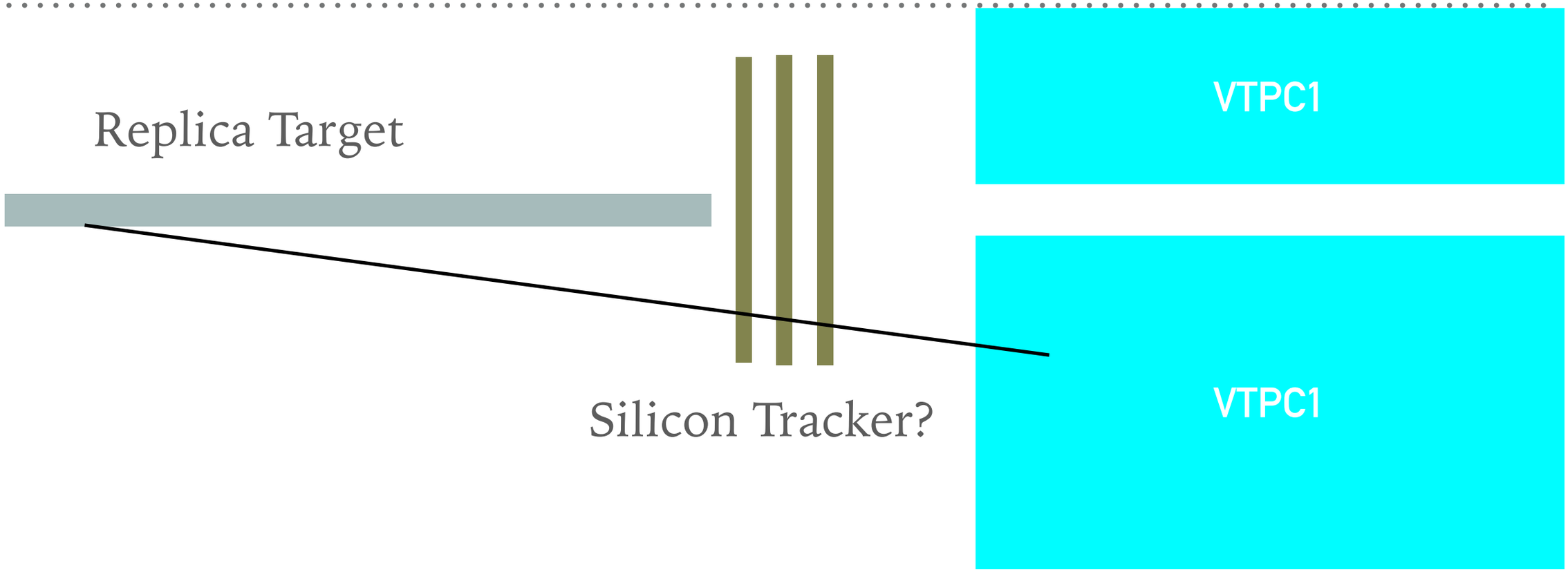
MOVING REPLICA TARGET INTO TRACKING REGION

A. Blondel



- Inserting the replica target into the VT1 region allows for better extrapolation
- Requires a target envelop to insert into the helium pipe at the center of the tracking region

NEW TRACKERS NEAR THE REPLICA TARGET?



- The addition of precision trackers near the target can improve the backwards extrapolation from the tracking region to the replica target
- One possibility is the use of silicon strip/pixel tracking layers between the replica target and TPCs

HIGH B FIELD DATA WITH REPLICA TARGET

- NA61/SHINE finds the best consistency between thin-target and replica-target multiplicities when the cross section for particle production is reduced by ~9% relative to the NA61 thin target measurement.
  Eur.Phys.J. C76 (2016) no.11, 617

- NA61/SHINE 2010 replica target data includes data collected with a high magnetic field setting
  - Forward protons exiting the downstream end of the target are tracked
  - Independent measure of the proton interaction length from the proton survival probability

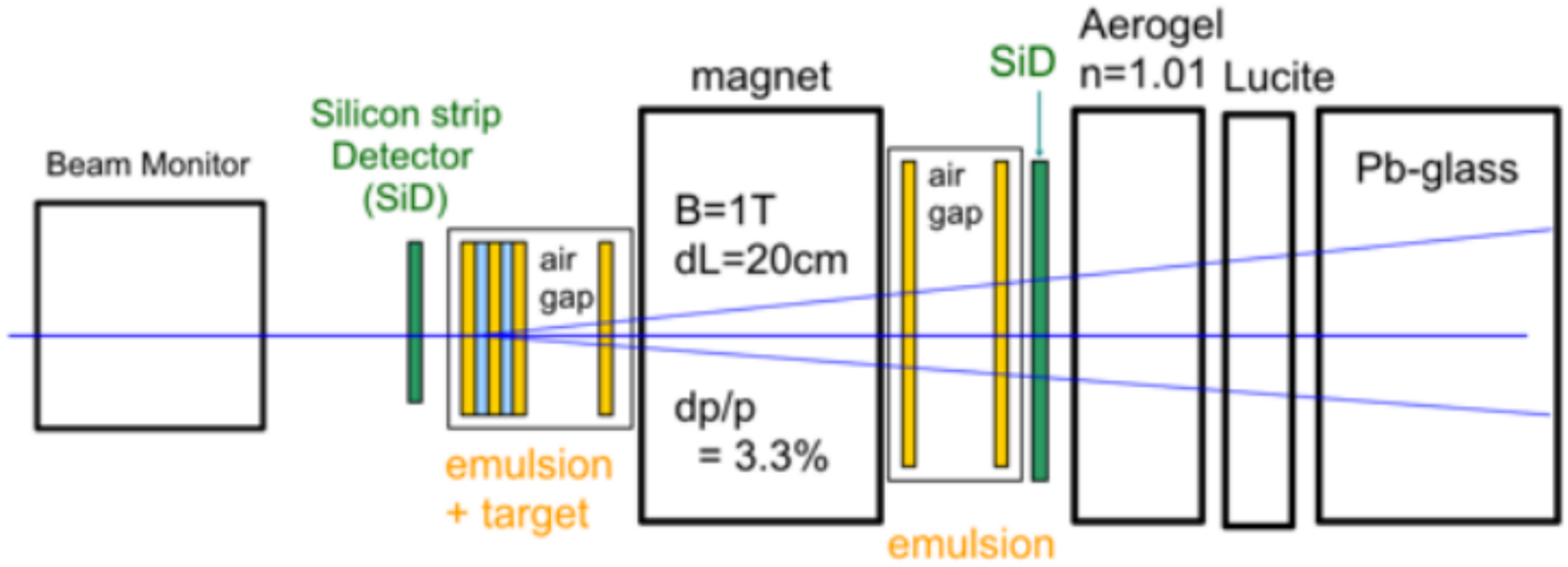
- Analysis of the high magnetic field replica target data is ongoing and may shed some light on this “tension” between thin and replica target data

WORKSHOP FOR FUTURE NA61/SHINE PROGRAM

- A workshop for NA61/SHINE beyond 2020 will be held at University of Geneva on July 26-28: https://indico.cern.ch/event/629968/

"The purpose of the workshop is to gather information about possible future measurements that may be useful and how the capabilities of the current (or possibly upgraded) detector could meet these needs. Anyone interested in hadron production, as well as prospective new collaborators, are welcome to attend."

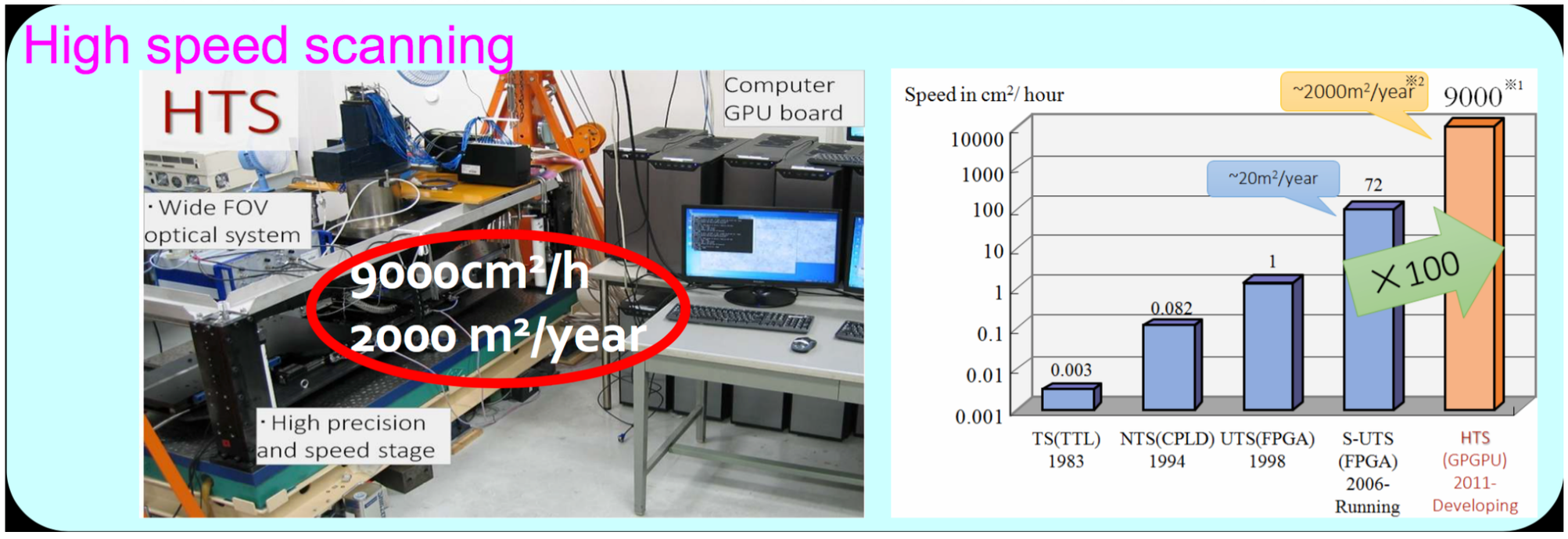
HADRON PRODUCTION WITH A HYBRID-EMULSION DETECTOR



- Collaborators in Japan and Canada working on a design of compact detector that combines nuclear emulsion tracking with electronic detectors - Now working with colleagues at Fermilab as well.

- Advantages:
  - Forward tracking of all charged particles to 0°
  - Minimize dead material between target and tracking layers
  - Target/tracking sandwich configuration
  - Can be placed in beam lines that extend to lower energy (Fermilab MTest or MCenter)
- Challenges:
  - Emulsion requires track matching with fine-grained electronic detectors to collect timing information
  - Building a compact spectrometer with the required momentum resolution
  - Development of Cherenkov ring imaging particle identification

EMULSION TECHNOLOGY



- Improvements in emulsion technology in recent years:
  - Scanning up to 9000 cm^2/hr with system at Nagoya university
    - Up to 10^5 tracks per cm^2 - can process single tracker layer from 10^7 particles on target in fraction of an hour
- High sensitivity film
  - Improved tracking and dE/dx resolution

See talk by T. Fukuda at State of Nu-tion for more details on PID (https://meetings.triumf.ca/indico/event/12/session/2/contribution/8/material/slides/0.pdf)

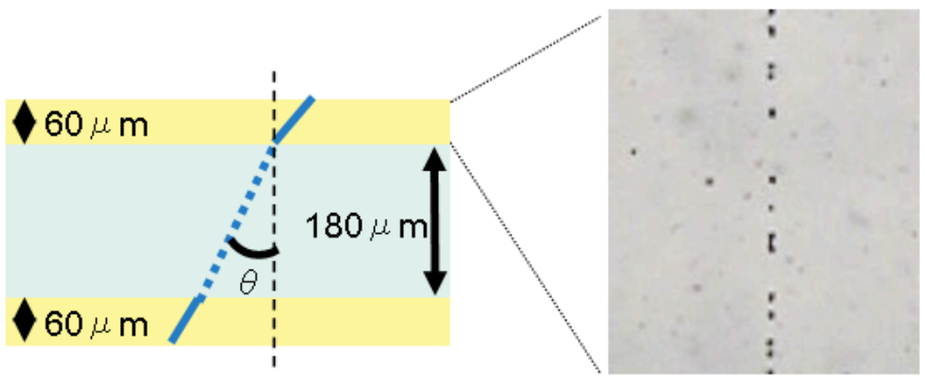
See talk by T. Fukuda on NINJA on Thursday for more detail

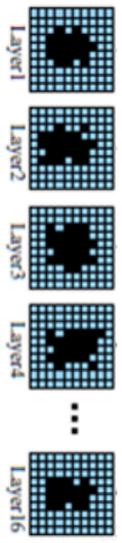
DE/DX IN EMULSION

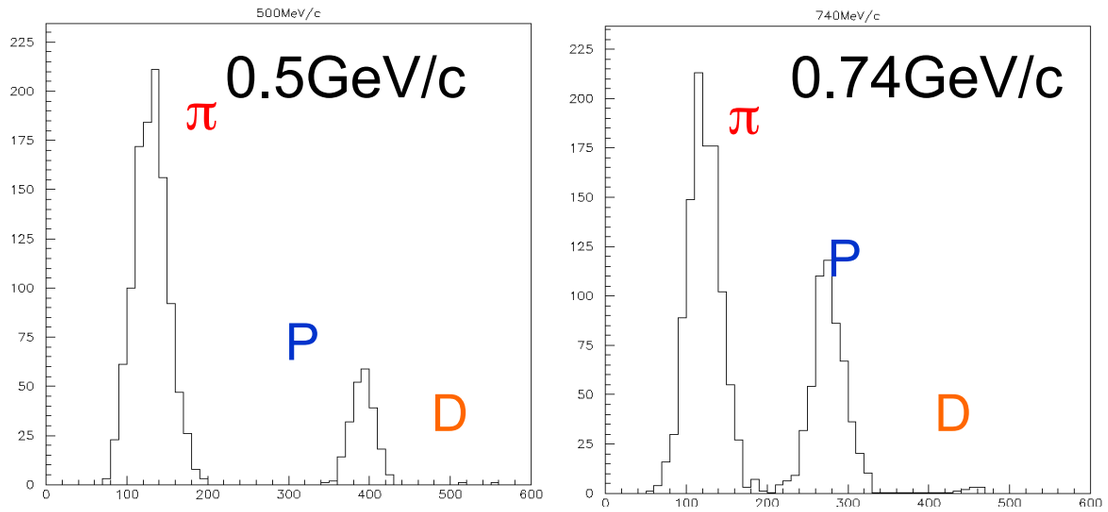
T. Fukuda (State of Nu-ation)

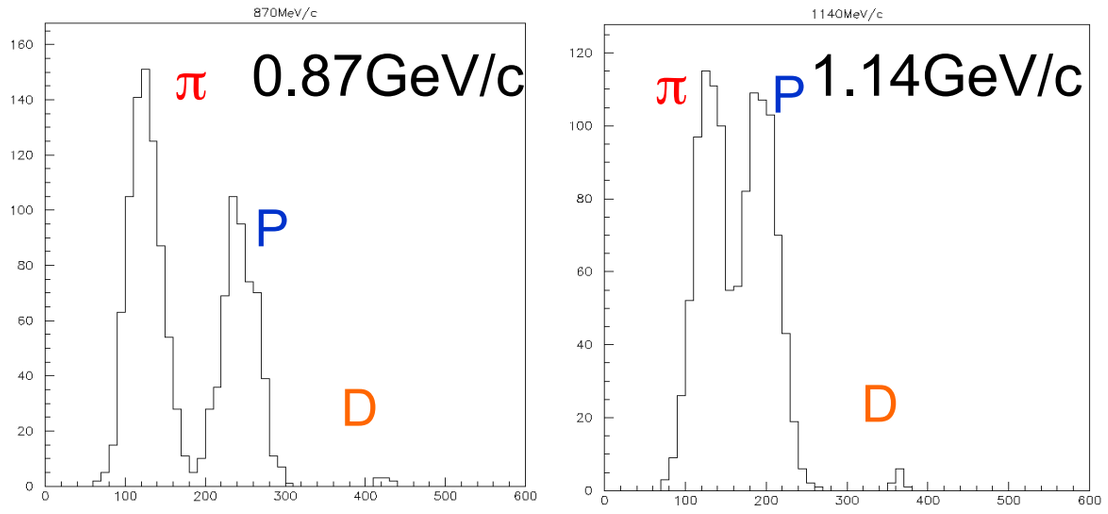
- dE/dx is inferred from the darkness of the track
- Good π/p separation below 1 GeV/c with 20 OPERA plates
- New more sensitive film should improve the resolution for the same number of layers

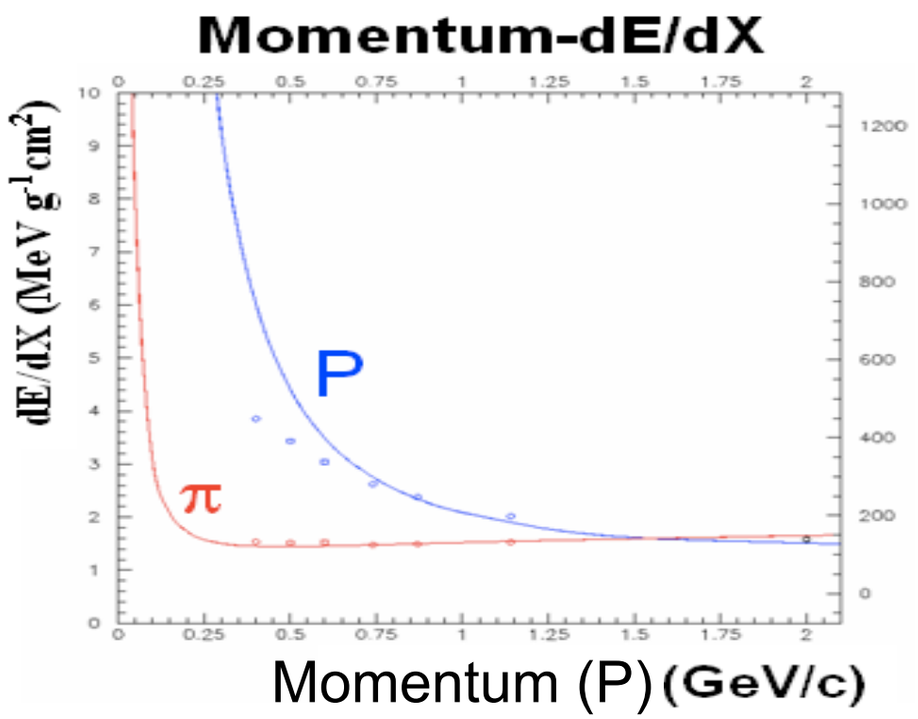
Darkness of tracks





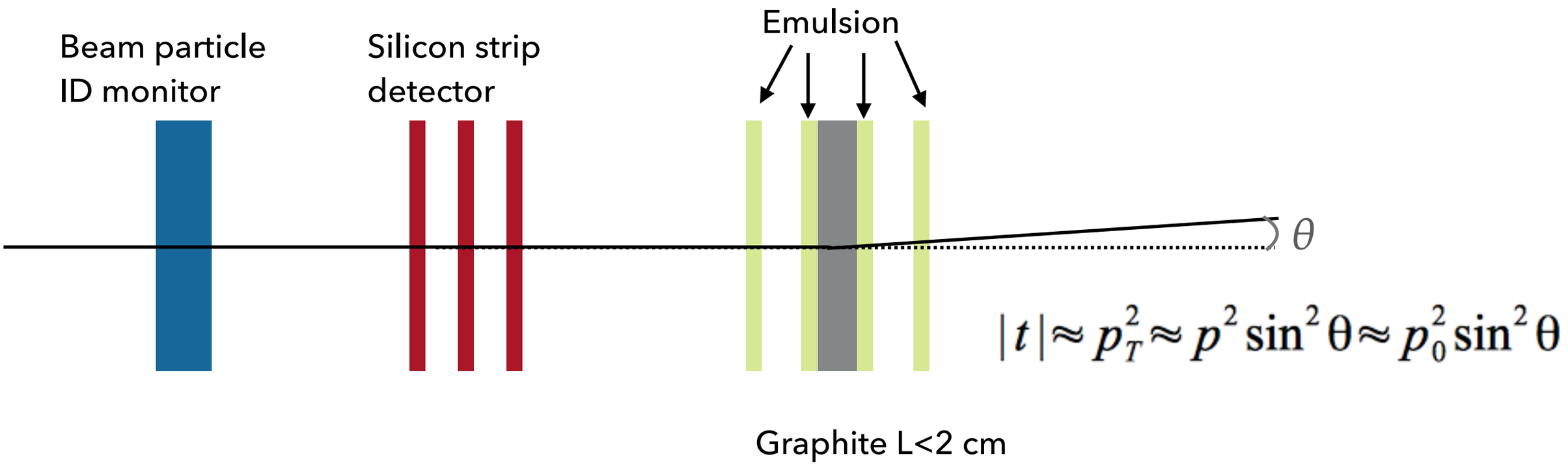




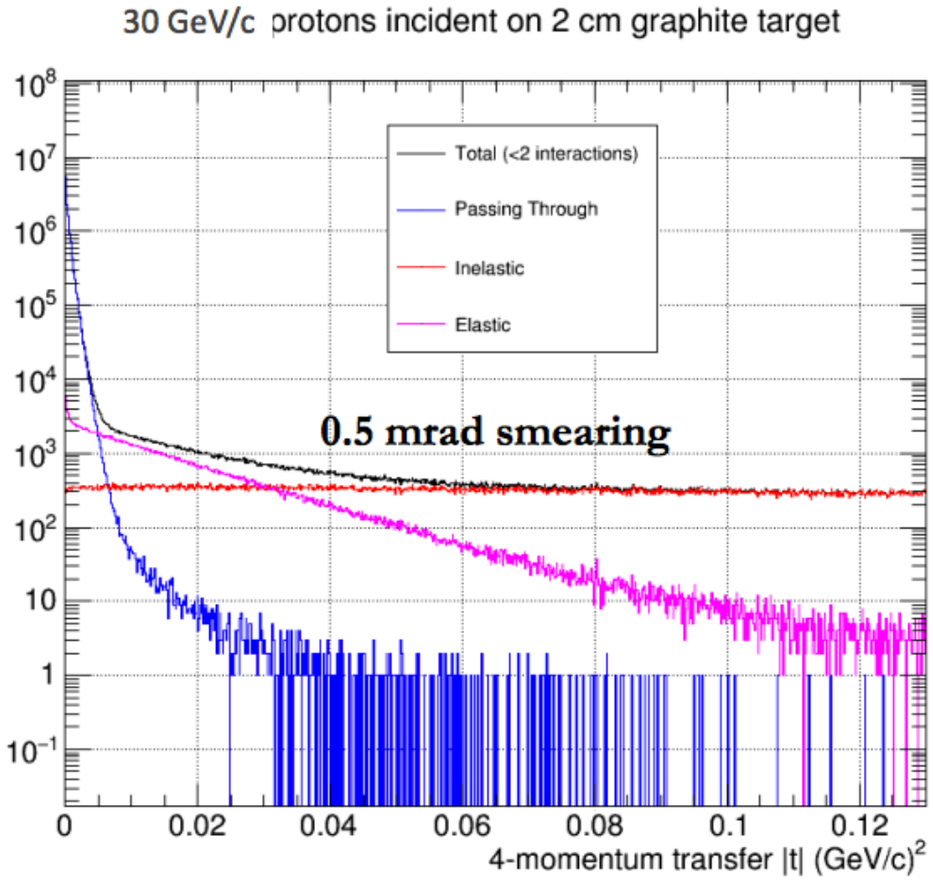


INITIAL EMULSION EXPERIMENT

- NA61 finds the best consistency between thin-target and replica-target multiplicities when the cross section for particle production is reduced by ~9% relative to the NA61 thin target measurement.
  Eur.Phys.J. C76 (2016) no.11, 617
- A ~9% reduction is beyond the thin-target measurement systematic error
- May be explained by the subtraction of scattering at low four-momentum transfer in NA61 thin target measurement
- Propose a measurement of scattering at low four-momentum transfer with 30 GeV beam:

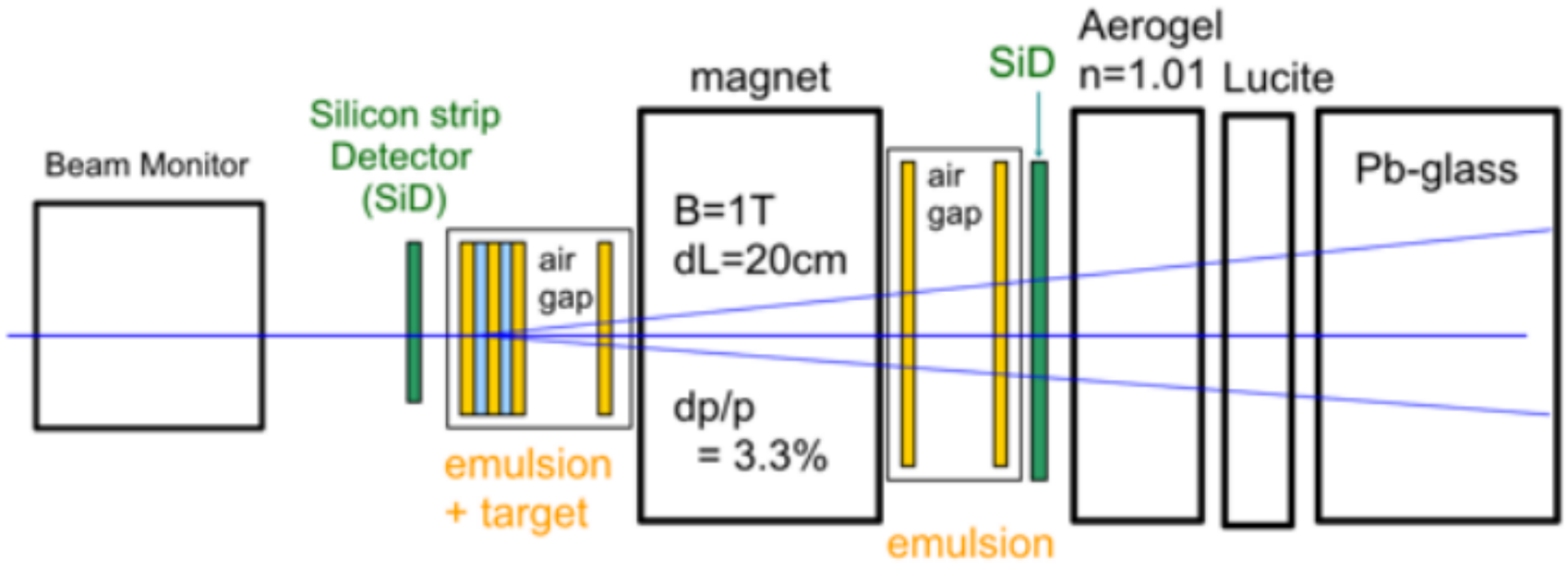


SIMULATION FOR FORWARD SCATTERING MEASUREMENT



- 0.5 mrad precision on the scattering angle is achievable with the emulsion tracker
- The elastic and inelastic contributions to the 4-momentum distribution can be measured
  - Measure the contributions from these components in the trigger acceptance region for the NA61/SHINE thin-target measurement

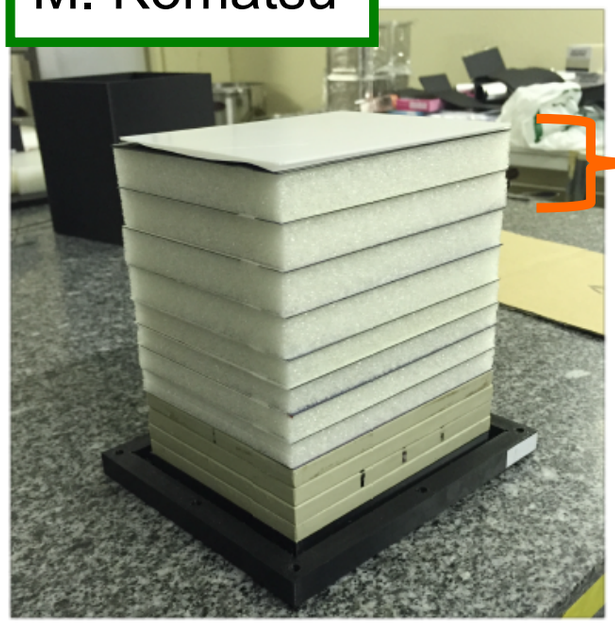
DEVELOPMENT FOR FULL HYBRID EMULSION DETECTOR



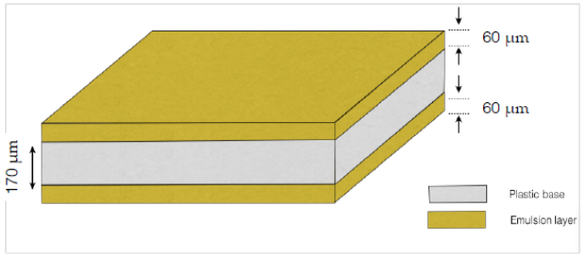
- To advance with the hybrid-emulsion detector, we need development of two key sub-systems
  - The particle spectrometer with emulsion track matching across a region with a magnetic field
  - Particle identification using a ring imaging Cherenkov detector

DEVELOPMENT OF THE EMULSION SPECTROMETER

M. Komatsu

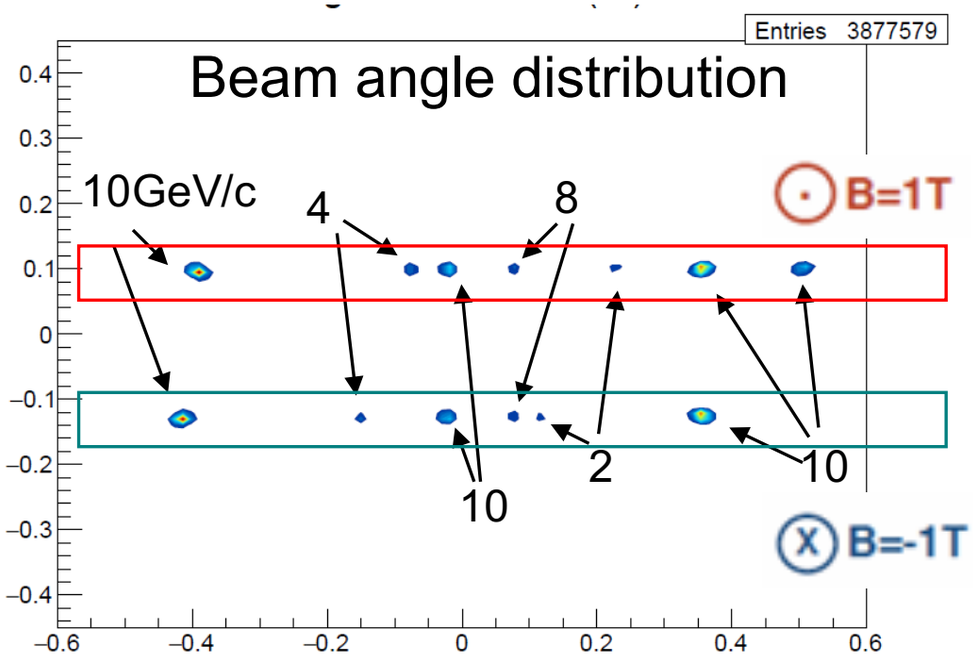


Single unit

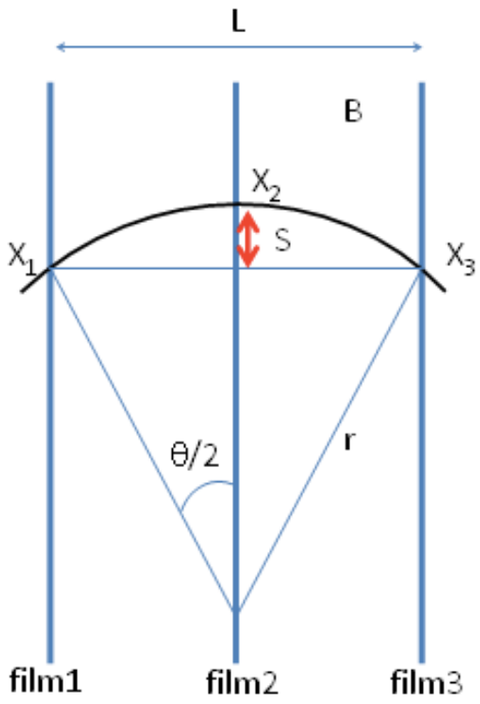


Emulsion films prepared
@ Nagoya Univ.

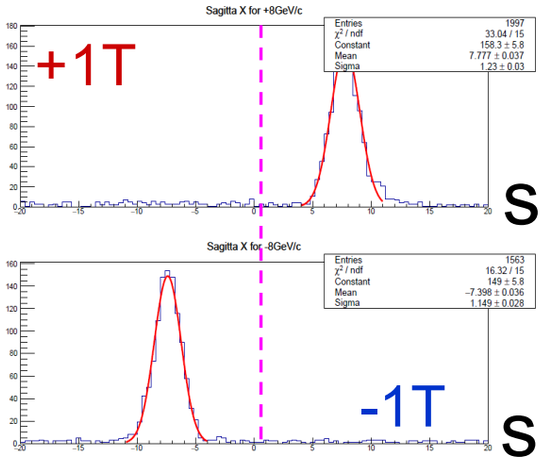
- Test beam exposure: 2015 autumn @CERN.
- π^-@T9 beamline with MNP17 magnet ($\pm$1T).



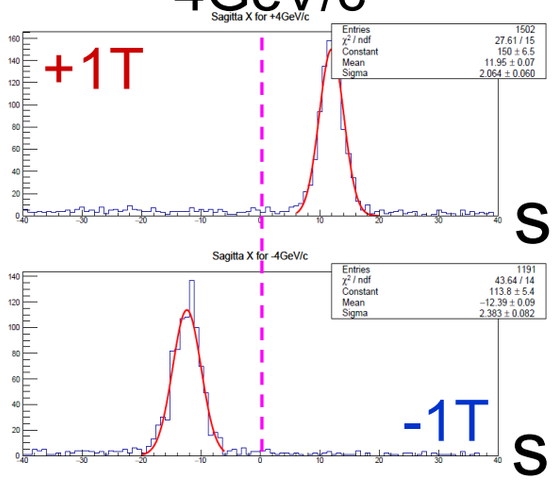
Emulsion film + 15mm thick Rohacell spacers.
Sagitta (S) is measured.



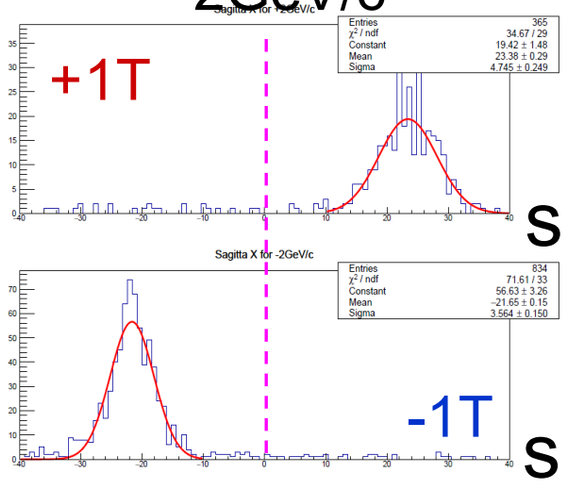
8GeV/c



4GeV/c



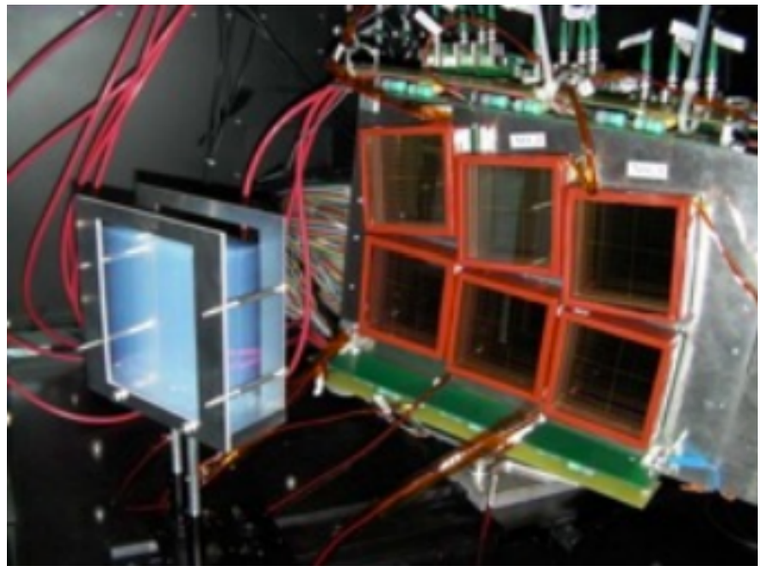
2GeV/c

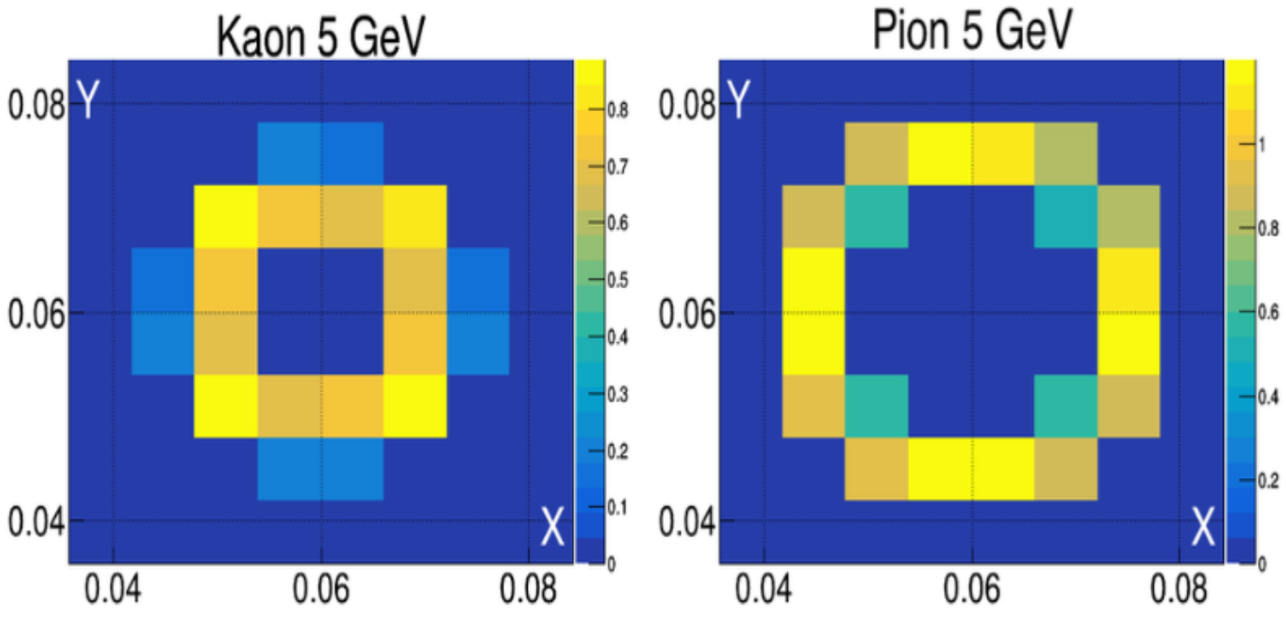


Charged sign is clearly separated for each momentum.

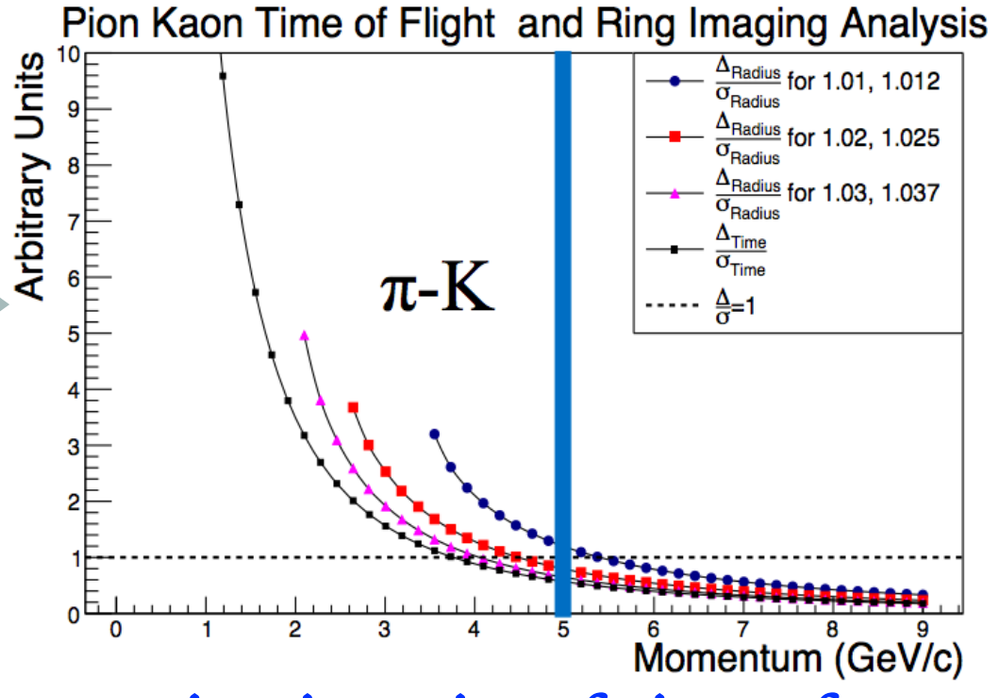
DEVELOPMENT OF RING IMAGING CHERENKOV DETECTOR

- Aerogel detector based detector can give pion/ kaon separation in the 1-5 GeV/c range
- Imaging of rings with multi-anode PMTs
- Simulation and testing of aerogels is ongoing at TRIUMF





Comparison of simulated kaon and pion rings at 5 GeV



Separation in units of sigma for different aerogel configurations

See poster by K. Gameil

PLANS FOR HYBRID EMULSION DETECTOR

- Aim to make forward scattering measurements at the MTest Fermilab beamline in early 2018
- Will have a meeting at Fermilab on July 20-21 - all that are interested are welcome to attend
- Plan to develop a long term program:
  - Development of detector components such as the spectrometer and ring imaging Cherenkov detector
  - Further measurements in the Fermilab beam lines or other beam lines

CONCLUSION

- Hadron production measurements including measurements with replica targets are pushing flux prediction errors from **10% -> 5% level!**
- Work remains for future experiments - reduced systematic errors, new target geometries and materials, secondary out-of-target interactions, etc.
- NA61/SHINE are now considering the future program and welcome input
  - **Strong motivation for community to keep the NA61/SHINE program going for DUNE and Hyper-K**
  - Meeting at University of Geneva on July 26-28
- Collaborators in Japan and Canada are considering a new hybrid emulsion technology for hadron production experiments
  - Aim for initial forward scattering measurements in 2018
- **Hadron production experiments are a lot of work and may not be highly rewarding - we shouldn't assume someone else will continue to do them in the future**