How to build (and understand) a neutrino beam

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High Energy Physics seminar
Université de Genève
17 mai 2023

Neutrino Oscillations

- Kinematic searches for neutrino mass look for missing kinetic energy in decays. They are very difficult!
  - Sub-eV sensitivity has barely been achieved even for electron neutrino (MeV scale for the other flavors).
- The phenomenon of oscillations (discovered 1998) provides a probe of much smaller masses.
- Oscillation is a probe of both the masses (actually, of m^2 differences) and the flavor mixing matrix.

Neutrino Oscillations

- ASSUME:
  - Two neutrinos (simpler than three)
  - Massive, but masses are non-degenerate
  - Mass eigenstates are NOT the same as flavor eigenstates
- This is a quantum-mechanical two-state system:

Flavor basis

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Mass basis

- ν_1 and ν_2 phases rotate at different rates:

$$|\nu_1\rangle \to e^{-im_1 t}|\nu_1\rangle \qquad (\hbar = c = 1)$$

- So, starting at t=0 with one flavor:

$$|\psi(0)\rangle = |\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

- The state evolves a component of the other flavor:

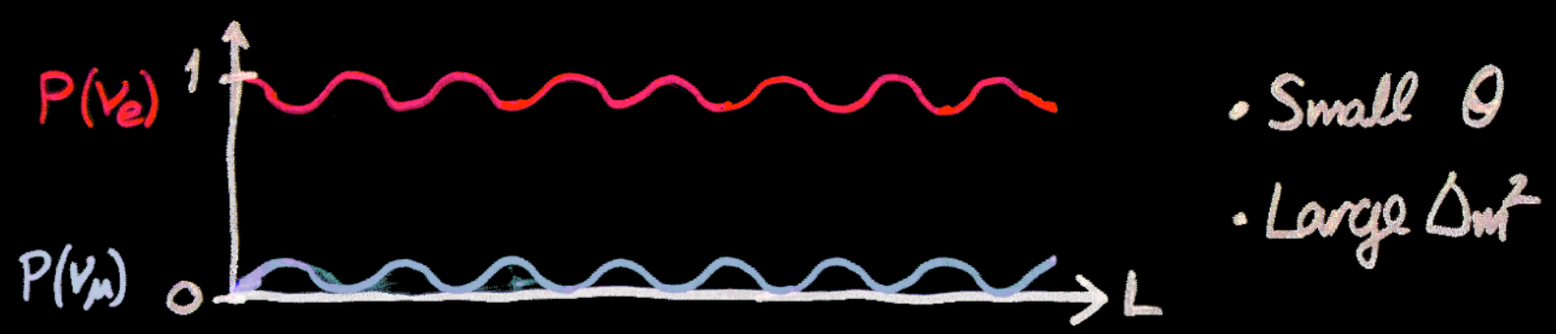
$$|\psi(t)\rangle = \cos\theta e^{-im_1 t}|\nu_1\rangle + \sin\theta e^{-im_2 t}|\nu_2\rangle$$

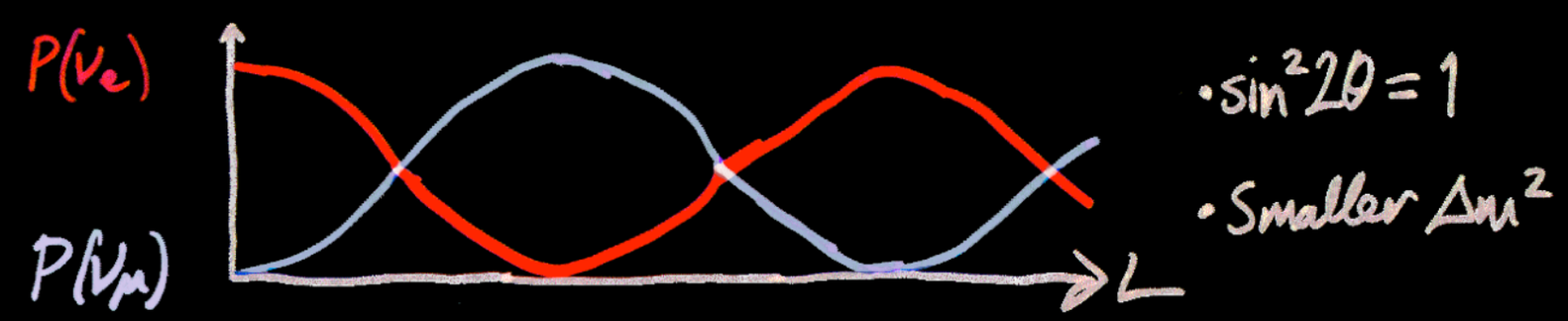
Neutrino Oscillations

- Solving and plugging in sensible units, probability of measuring ν_μ if state was created as ν_e:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

  - L = flight distance (km); E = neutrino energy (GeV); m = mass (eV/c^2)





Mass splittings are such that at accessible energies, oscillation phenomena generally occur at terrestrial or astronomical distance scales.

Neutrino oscillation probability in standard 3-neutrino picture

- The flavor eigenstates are related to the mass eigenstates by matrix *U*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Mixing Matrix (aka MNSP Matrix)

- Probability for detecting particular flavor depends on the values in *U* and the Δm^2 between the neutrino mass states. In general:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) sin^2[1.27\Delta m^2_{ij}(L/E)]$$
$$-2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) sin[2.54\Delta m^2_{ij}(L/E)]$$

L=Distance in km, E=Energy in GeV

Matrix Elements

$\Delta m^2_{ij} = m_i^2 - m_j^2$,
m=neutrino mass in eV

Parametrizing the matrix

- ***U*** is a basis transformation, and therefore a unitary matrix. Can be fully specified with four real numbers: three angles θ_{12}, θ_{13}, θ_{23} and one phase δ_{CP}:

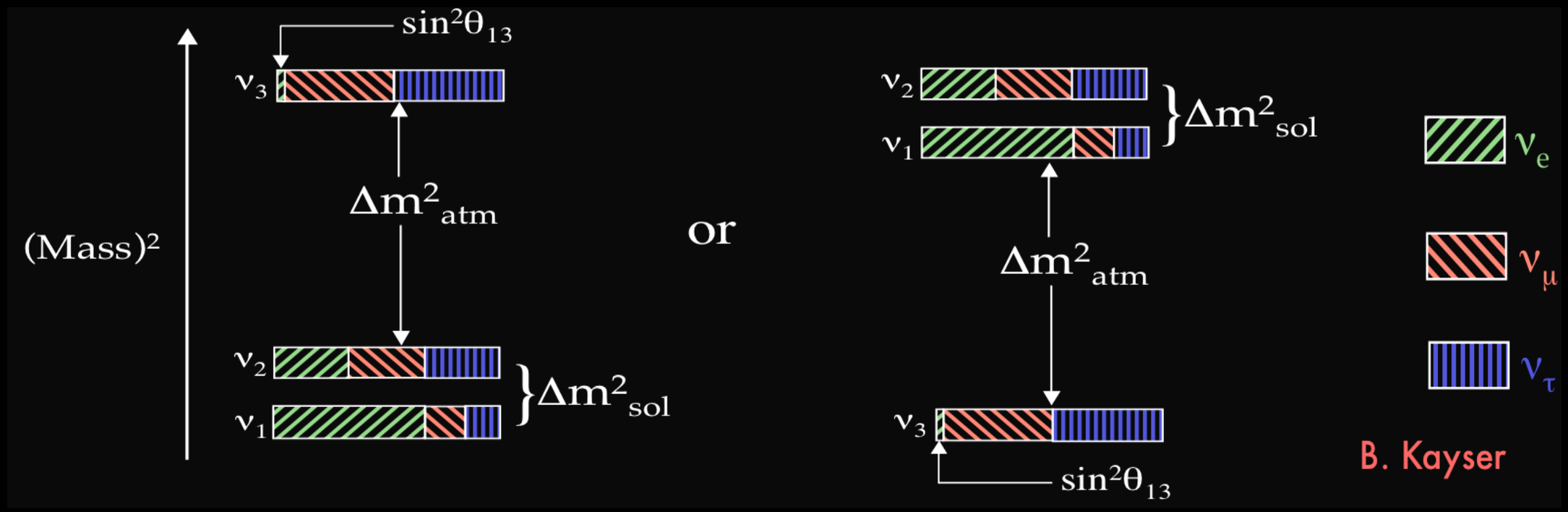
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $s_{ij} = sin(\theta_{ij})$ and $c_{ij} = cos(\theta_{ij})$

- As with quark mixing, *CP* violation is only observable if all four parameters are nonzero.

Character of the parameters

- Matrix is characterized by large mixing angles (unlike the quark sector)
- Hierarchy of masses: one mass splitting is about 30 times the other. We do not know, however, what the order is or whether there's a significant offset from zero.



"NORMAL" ORDERING "INVERTED" ORDERING

Neutrino oscillation experiments

- Important parameter is L/E
- For the larger mass splitting, first oscillation maximum sits at $L/E \sim 500$ km/GeV
- "Short-baseline" experiments with L~km and E~MeV or "long-baseline" with L~1000 km and E~GeV are appropriate for this.

How to build (and understand) a neutrino beam

- Neutrino beam physics
- NA61/SHINE neutrino program
- Current and new results
- Upcoming data sets
- New opportunities

NEUTRINO SOURCES

- Most basic demand is ***weak decays -- and lots of them!***
- Flavor composition:
  - Nuclei give you ν_e and (usually) $\bar{\nu}_e$
  - $\pi^+(\pi^-)$ give you nearly pure $\nu_\mu(\bar{\nu}_\mu)$
  - A μ^+ decay gives you one $\bar{\nu}_\mu$ and one ν_e
  - Kaons are complicated:
    - K^+: mostly ν_μ from two-body decay; softer ν_μ and ν_e from three-body decays
    - K_L: ν_μ and ν_e and their antineutrinos from three-body decays
  - For ν_τ you need a parent at least as heavy as charm

DIFFERENT SOURCES OF NEUTRINOS

- ~~Natural sources: atmospheric, solar, supernova~~
- ~~Reactors: fission products are short-lived; decay chains include beta decays that produce $\bar{\nu}_e$ in large numbers. Sources are isotropic; energies few MeV.~~
- Conventional accelerator-based beams:
  - Beam-dump sources
  - Meson decay-in-flight
    - Horn-focused
    - Other focusing systems
- ~~Future beams:~~
  - ~~Beta beams (pure $\bar{\nu}_e$)~~
  - ~~Muon storage rings ("neutrino factory")~~

Only discussing these today.

ACCELERATOR-BASED BEAMS: Beam-dump sources

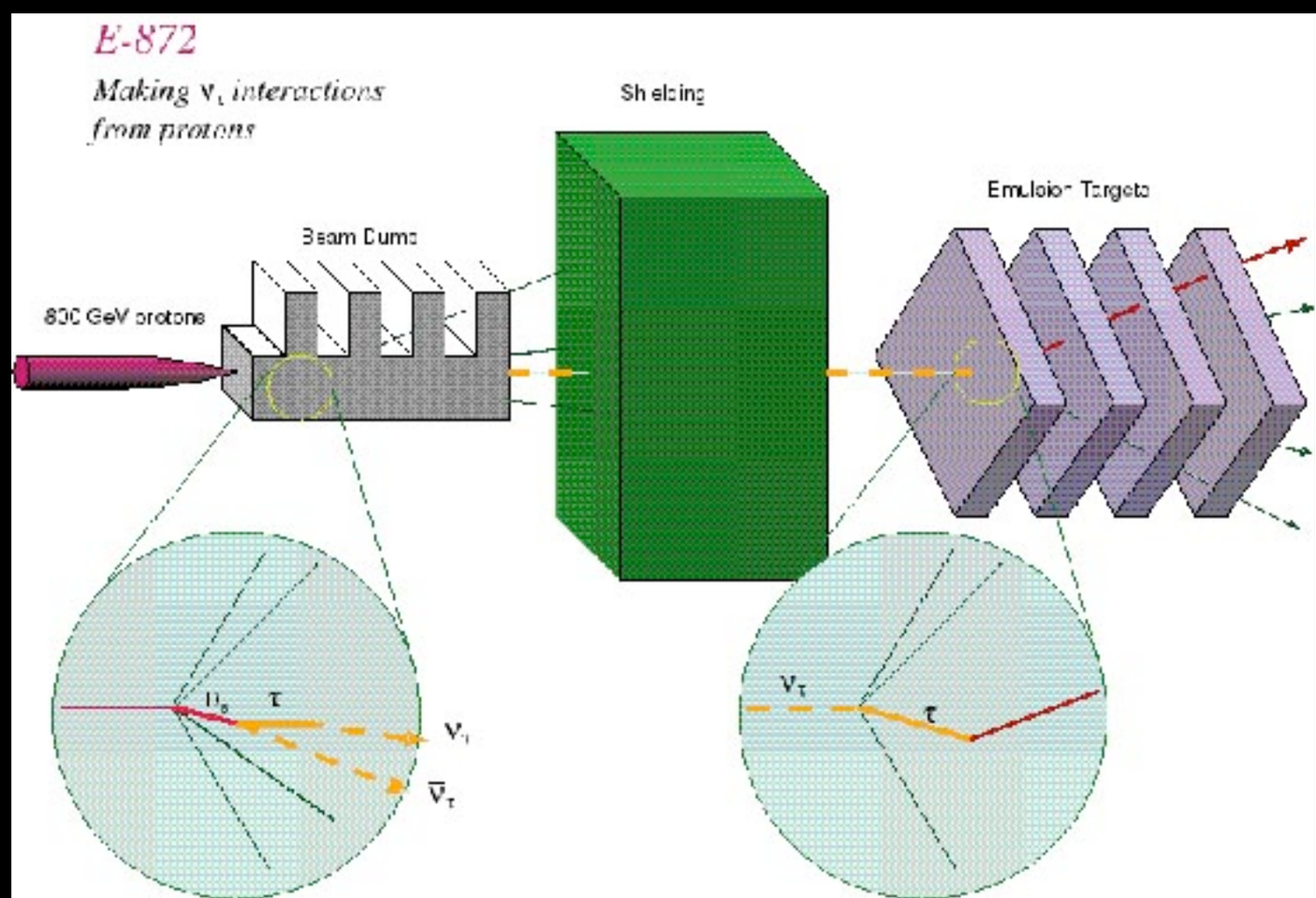
- The simplest beam to describe! The proton beam enters a thick target, and all interaction products are stopped in the target or surrounding material.
- Has been used for major experiments, for different purposes depending on the beam energy:
  - LSND (1993-98)
  - KARMEN (1990-99)
  - FNAL E872 (1996-97)
  - JSNS2 (2021-)

Low energies

- Proton beams from 800 MeV; main source of interesting neutrinos is μ^+ decays at rest to $\bar{\nu}_\mu$ with E<53 MeV.
- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations via $\bar{\nu}_e + p \rightarrow e^+ + n$
- JSNS2 uses 3 GeV protons: more complicated because it's above threshold for kaon production
- Note: decay-at-rest neutrino source is isotropic: can only study very short baselines, and requires huge proton numbers for modest neutrino statistics. LSND and KARMEN combined received >30,000 *coulombs* on target.

FNAL E872: Direct Observation of ν ("DONuT")

A source of ν_τ: D_S decays

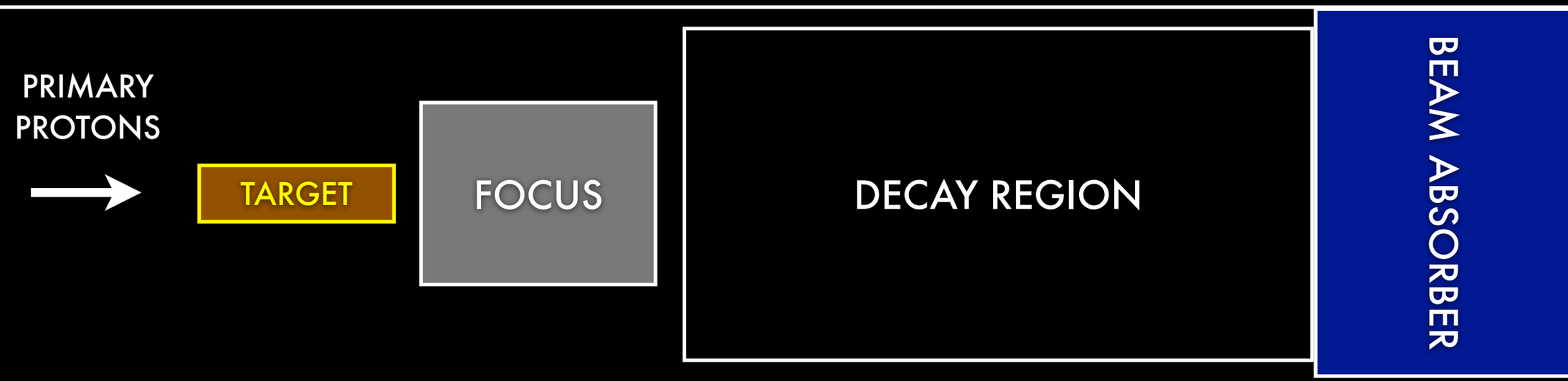


- Very high energy proton beam (800 GeV), tungsten target (highest practical nucleon density)
- D_S production cross-section is low; branching ratio to ν_τ only 7%
- D_S lifetime is very short ($\gamma c\tau$=3cm at 400 GeV), so these decays are in flight: it's a directional "beam" despite not being focused.
- Big systematic errors on flux due to cross-sections, secondary production, decay branching ratios. But for a ν_τ discovery search, this is reasonable.

Neutrino beam physics

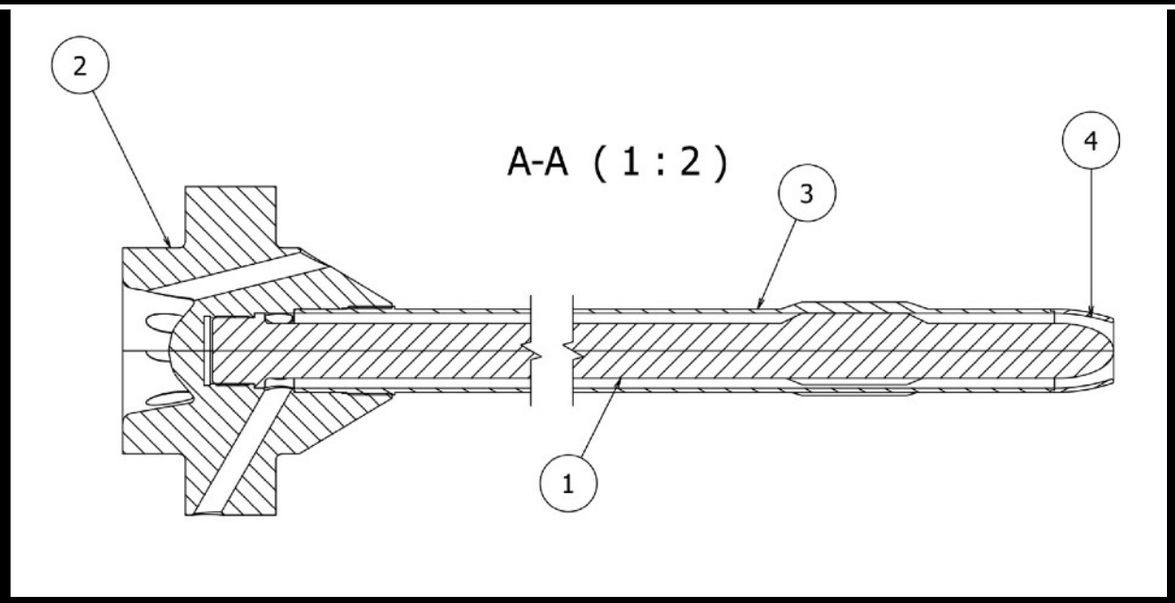
- Modern long-baseline oscillation experiments use "conventional" beams: primary protons strike a target, secondary mesons enter a decay region, and they decay in flight to neutrinos upstream of a beam stop
- All have common properties:
  - Predominantly ν_μ, with ν_e contamination at the ~1% level from muon, kaon decays.
  - Even "narrow-band" beams tend to have tails to high energy
  - Fluxes have significant systematic errors

Targets



- Target usually ~2 λ_0 in beam direction, to maximize interactions
- Should be wide enough to contain the primary beam, but narrow enough to allow interaction products with average p_T to escape the side
- Target material is generally selected to be low-A, since lighter nuclides tend to produce shorter-lived radioactive isotopes with lower gamma energies. Also, want to maximize interactions while minimizing multiple scattering: low λ_0/X_0 ratio preferred.
- Targets must handle very high beam power deposition! Modern targets need dedicated cooling; future targets may need to be liquid or powder-jet as solids may not be able to survive thermal shock.

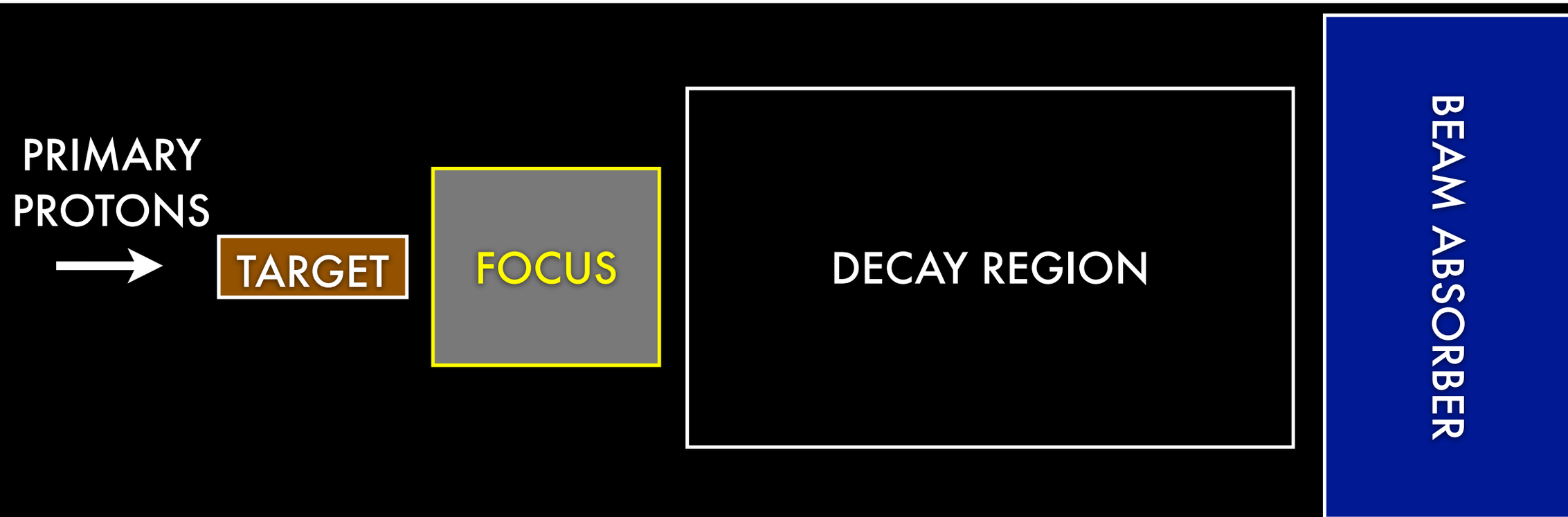
Targets



T2K target
(for illustration)

- Graphite target, like most modern beams
- 90 cm long: ~2 λ0 in beam direction, to maximize interactions
- 2.6 cm diameter
- Primary beam radius is large (6mm) to reduce local intensity and thermal shock
- Target cooled by very high-speed helium gas in closed loop

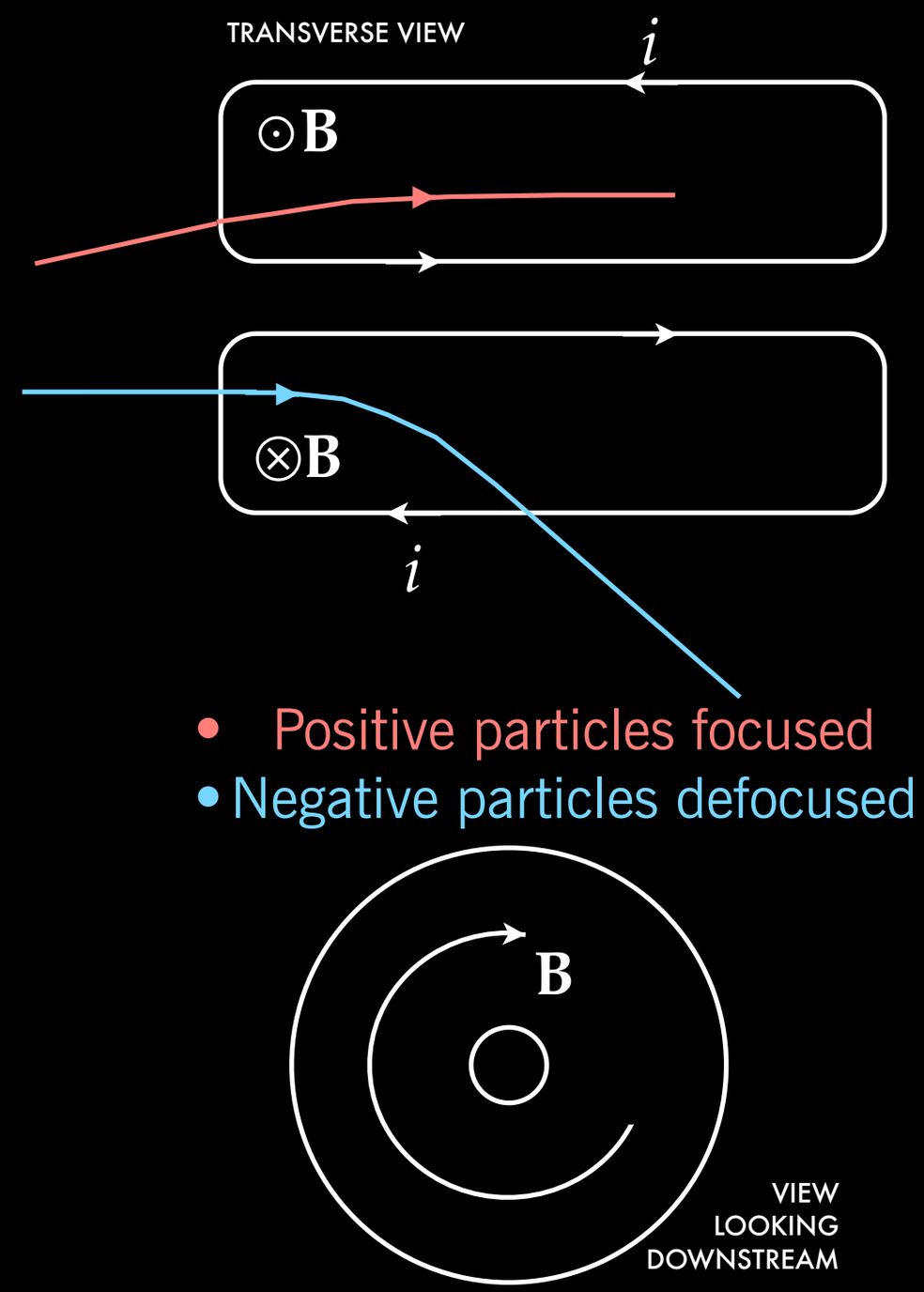
CONVENTIONAL BEAMS: Basic components



- After leaving target, charged particles may be focused before entering decay volume
  - Several focusing schemes possible
  - Focusing not strictly necessary: 1962 two-flavor neutrino discovery experiment used unfocused mesons.

Horns

- Horns first proposed by Van der Meer (1961)
- At the most basic level:
  - Two coaxial conductors: a toroidal field exists in the region radially between inner and outer conductors
  - Inner conductor is thin enough (2-3 mm) for most pions to pass through
  - Conductor currents are 100-300 kA so water cooling, pulsed operation necessary to prevent melting
  - Generally made of aluminum alloy

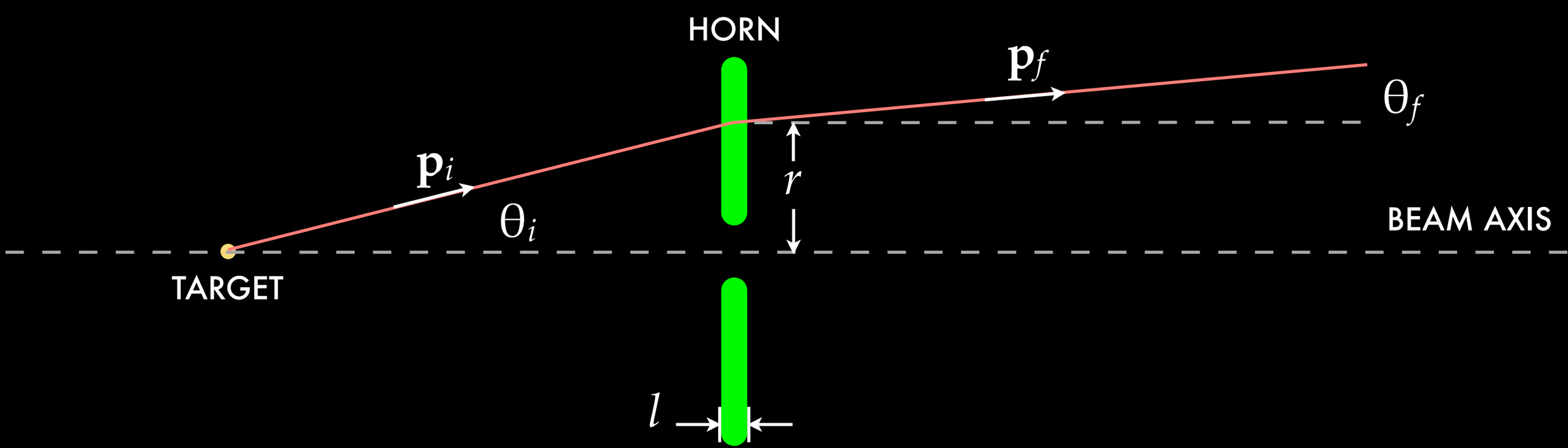


Horn field design considerations

Begin with a set of approximations (none really good):

1. The target is a point source somewhere upstream of the horn
2. Pions from the target are all at the most-probable transverse momentum (which happens to be close to the mean) from a p-N collision
3. The horn is short enough in the beam direction to where a pion's radial position does not change as it traverses the horn (the "thin lens" approximation).
4. Pions are not scattered or lost as they pass through the inner conductor

Horn field design considerations



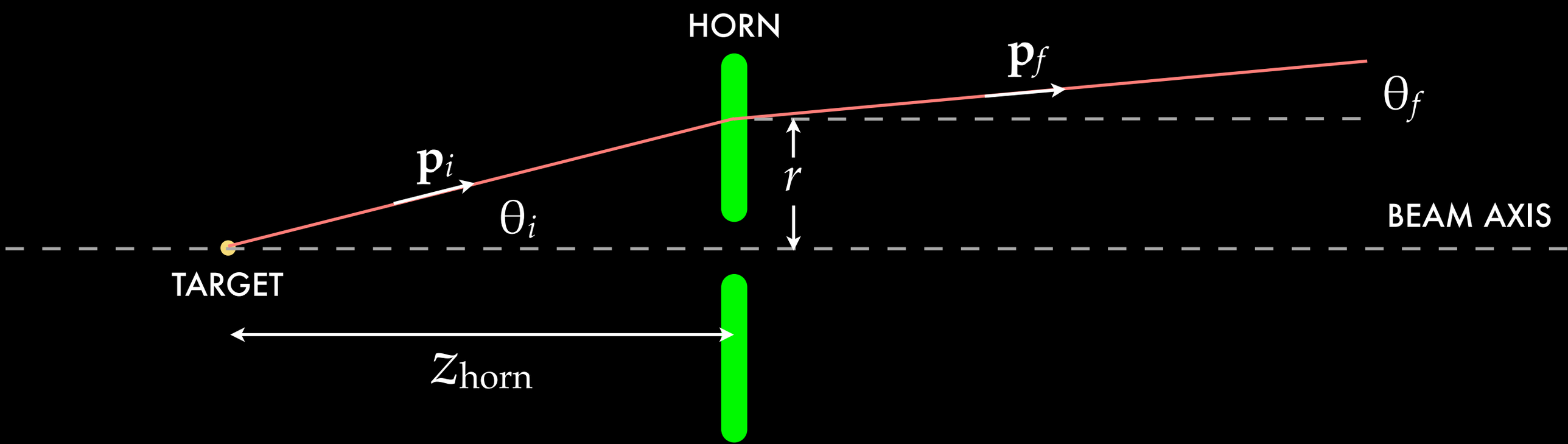
- Thin magnetic field regions can be thought of as giving a "p_T kick" to charged particles:

$$\Delta p_r = e\int_0^l dz B_\phi = eB_\phi l \text{ or } \Delta\theta \approx eB_\phi l/p$$

- Here, l is the length of the horn. It is a function of radius r, as is

$$B_\phi = \mu_0 I/2\pi r \Longrightarrow \Delta\theta \approx \mu_0 I l/2\pi r p$$

Horn field design considerations



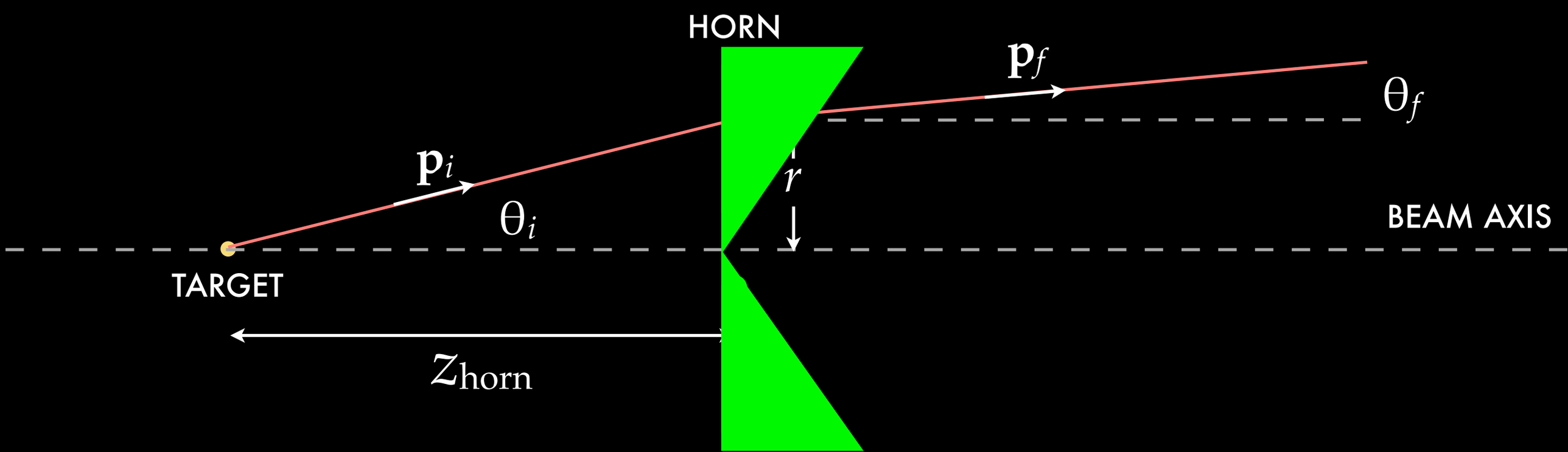
- Empirically, pion production for a wide range of proton energies is characterized by an inverse relationship between the mean production angle $\bar{\theta}$ and pion momentum: $\bar{\theta}_i \sim 0.5$ GeV / p.
- To take a particle at this angle and make it forward, we need to have $\Delta\theta = -\bar{\theta}_i$. So at the horn, substitute $\bar{p}$ for p in equation for $\Delta\theta$:

$$\bar{r} \sim z_{\text{horn}} \cdot 0.5\ \text{GeV}/p$$

$$\bar{p} \sim z_{\text{horn}} \cdot 0.5\ \text{GeV}/r$$

$$\Delta\theta = \frac{e\mu_0 I l}{2\pi r p} \sim \frac{e\mu_0 I l}{2\pi \cancel{r}} \frac{\cancel{r}}{z_{\text{horn}} \cdot 0.5\ \text{GeV}}$$

Horn field design considerations



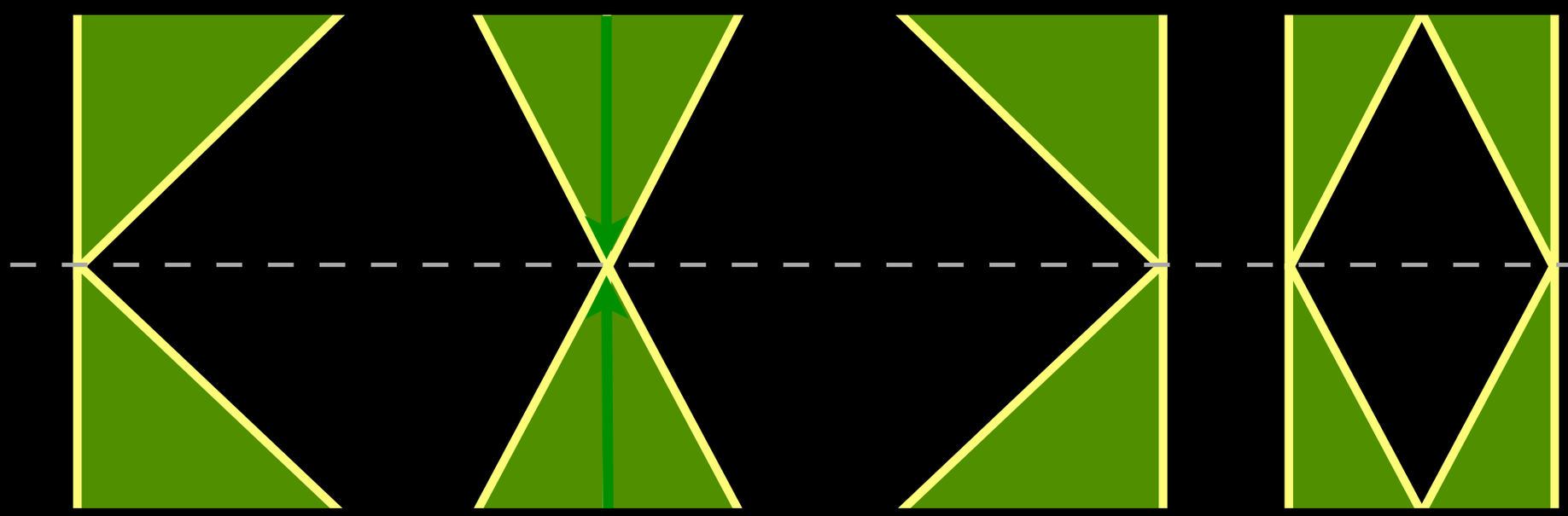
- To find ideal horn shape, set $\Delta\theta=\bar{\theta}_i$:

$$\frac{e\mu_0 I l}{2\pi z_{\mathrm{horn}} \cdot 0.5\ \mathrm{GeV}} = \frac{r}{z_{\mathrm{horn}}}$$

Length of horn $l(r) \propto r$ $\Rightarrow$ ideal inner conductor shape is a cone.

Comments

- Note that this result isn't dependent on momentum. This implies that the pion beam that results is broad-band.
- In the thin-lens approximation, a conical inner conductor has several equivalent shapes:

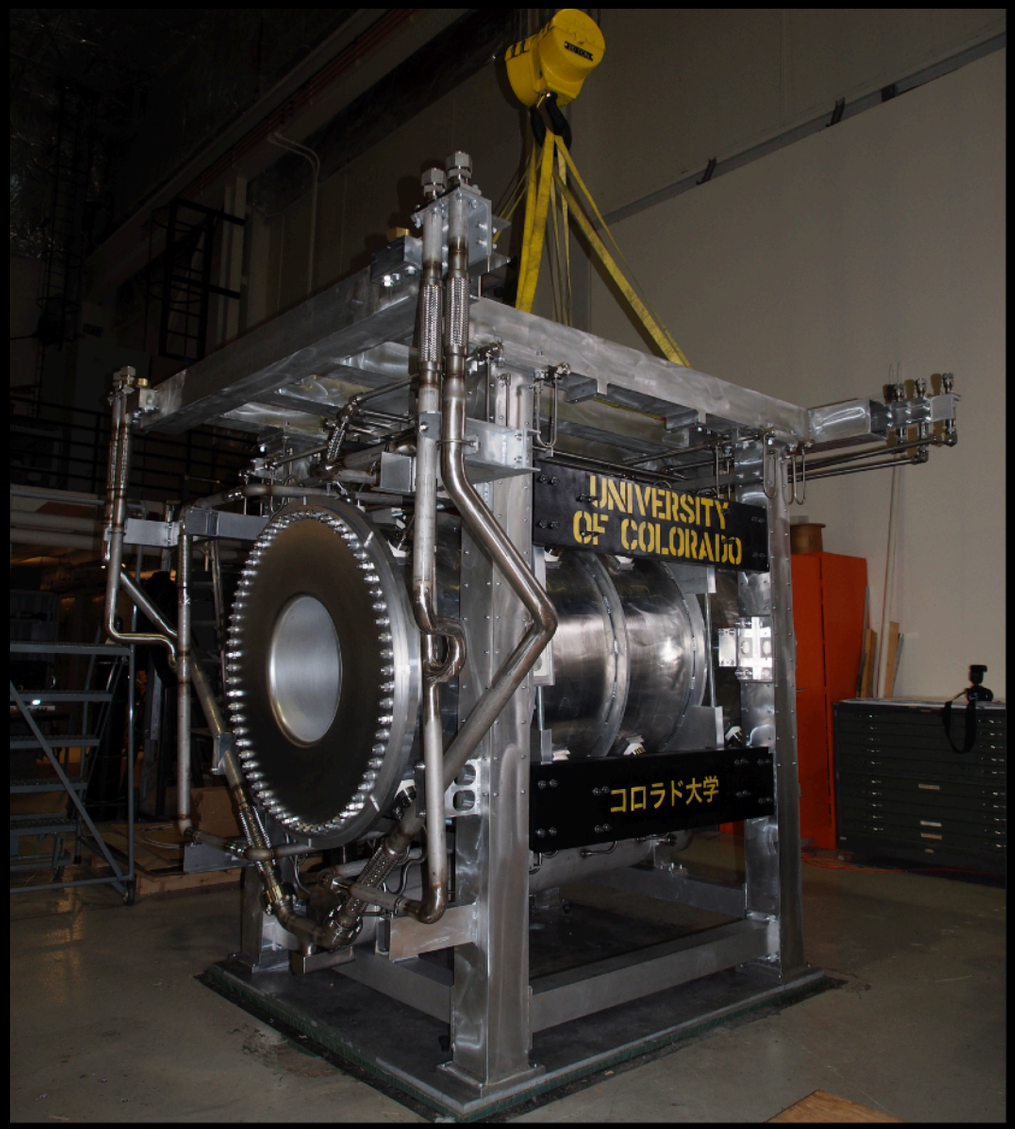


- In reality, the inner conductor radius can't get too small, or the current density will get too large. So particles at small radius cannot be focused (often not a problem, as they already have small angle).

Horns

1960s

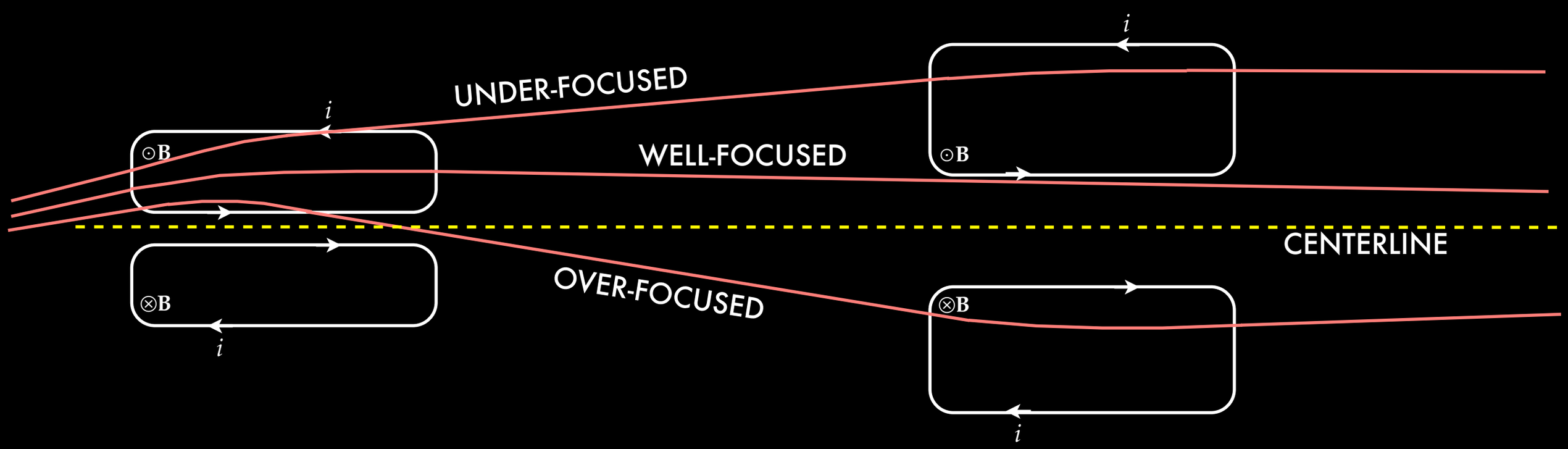
2010s



Multi-horn systems

- A single horn generally reduces the angular spread of the beam by a factor of ~2. The resulting beam, observed from far enough downstream, looks again like a point source of pions with an angular spread ⇒ it can be focused further by adding another horn.

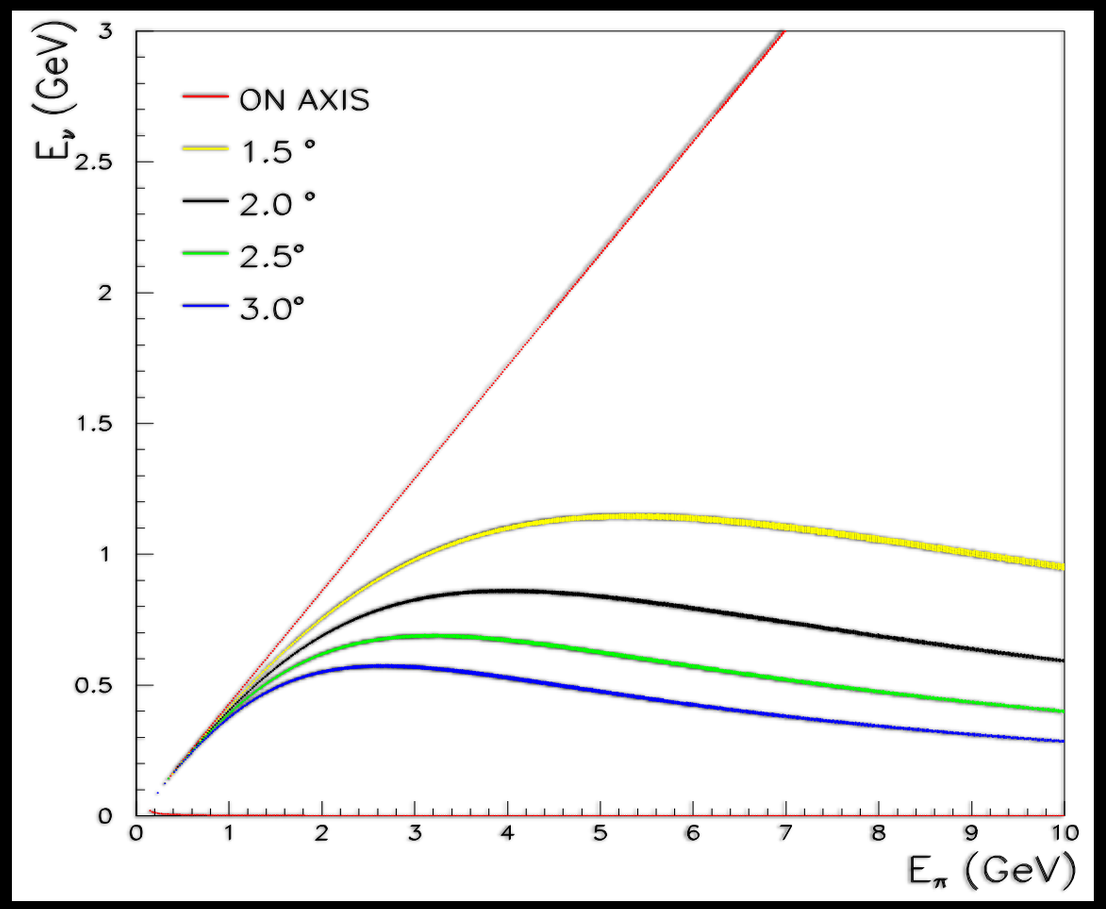
- Common for beams to be designed with two (or even three) horns in series. The downstream horns allow correction of both under- and over-focused particles:

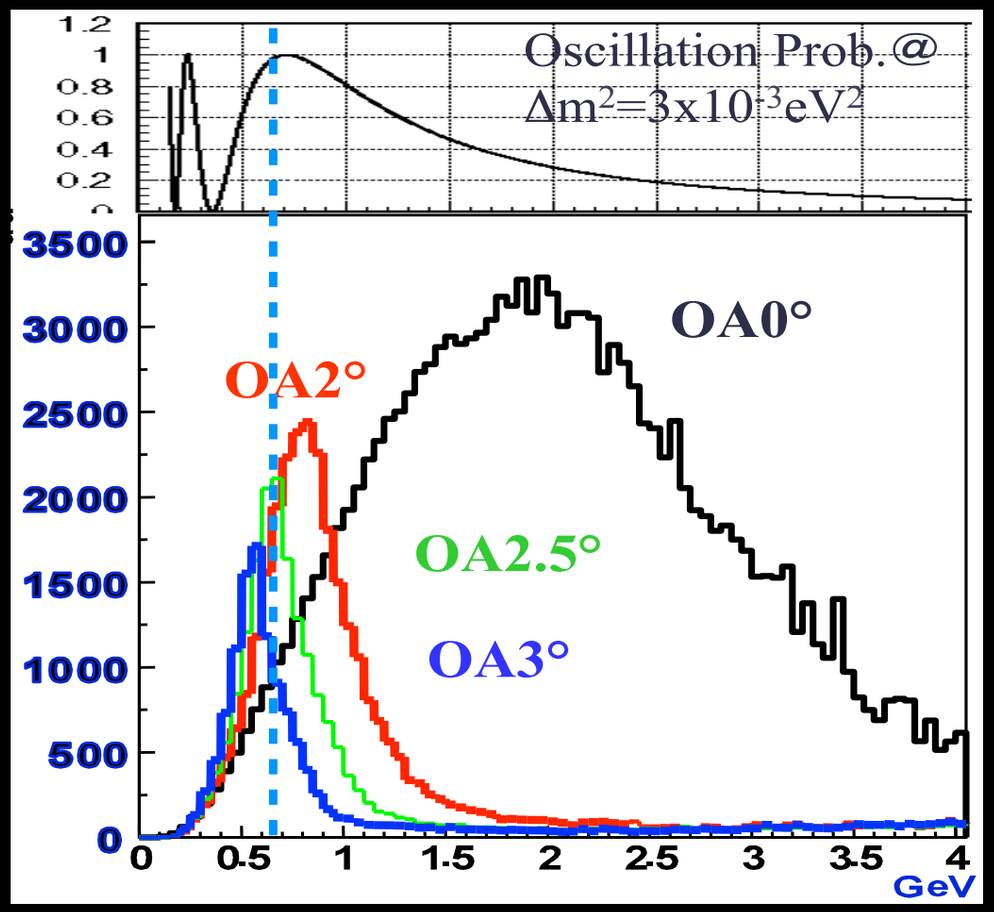


Variants on the ideal-focusing horn

- Narrow-band beams:
  - Paraboloid inner conductor surfaces present ideal thin-lens focusing of pions of a single momentum over many values of transverse momentum. (Budker)
  - Can selectively remove particles as a function of radius by inserting a "beam plug" in or near horn
  - Narrow-band neutrino beam from broad-band pion beam: go off axis! (T2K)
- Ellipsoid inner conductor surfaces
- "Magnetic fingers" (Palmer)

Off-axis beam technique





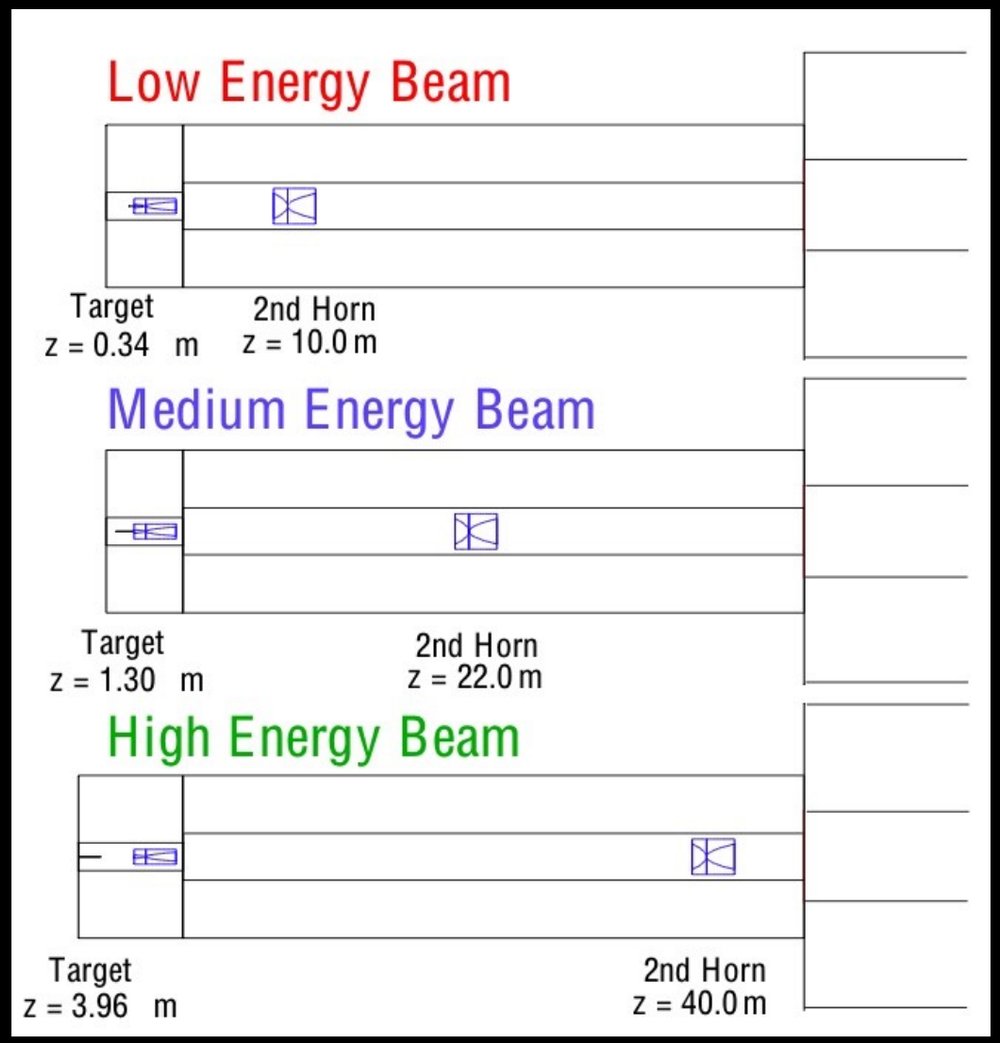
- For wide range of pion momenta, E_ν depends more on decay angle than E_π
- Exploit to make narrow-band ν_μ beams by going off-axis
- Example here is for T2K beam with 295 km baseline. First oscillation maximum is at 570 MeV for $\Delta m^2=2.4\cdot10^{-3}$ eV^2 $\Rightarrow$ T2K wants 2.5° off-axis angle

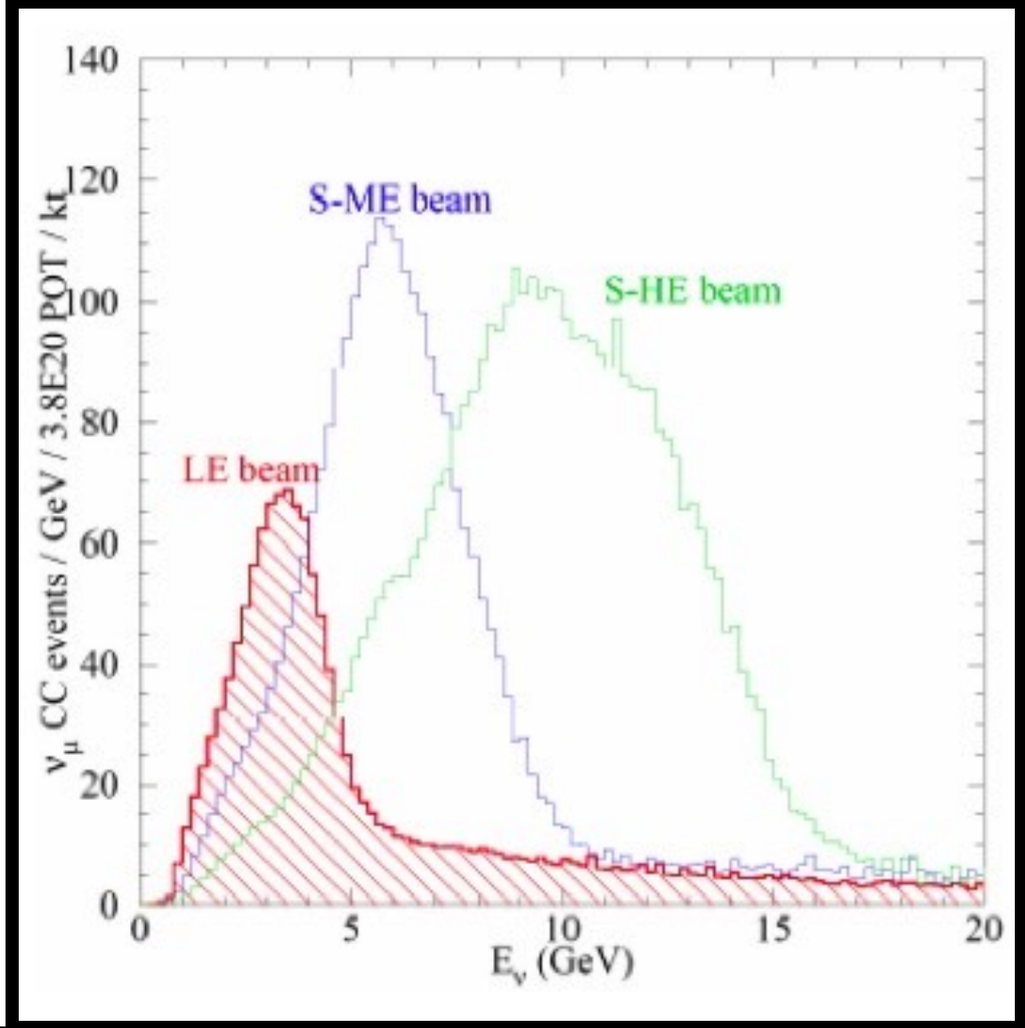
Target-horn separation

- To focus *low-energy* (≲10 GeV) pions, need to capture pions with large initial angles
- Horns can't have zero inner diameter or infinite outer diameter! So certain angles can't be focused as in the ideal cone horn.
- Given the length of the target, even if horn is immediately downstream, large-angle pions may be outside the outer conductor.
- Solution is to put the target inside the horn. In this case, the upstream point-source approximation breaks down completely → horns generally designed from numerical calculations

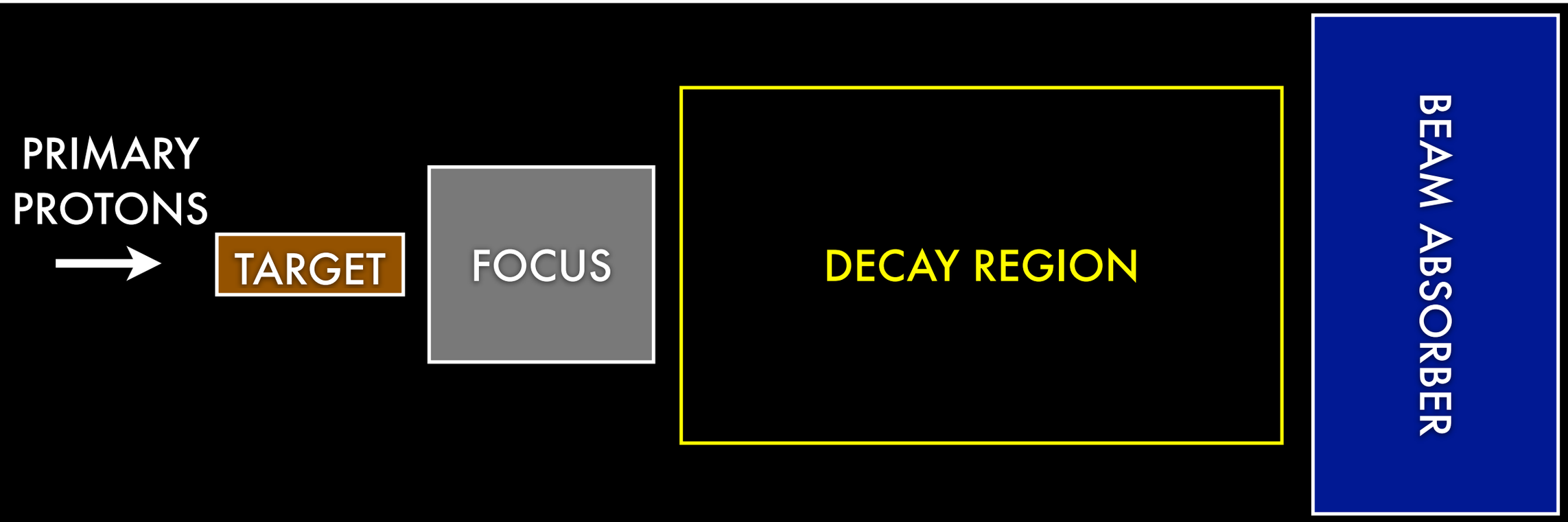
Target-horn separation

- NuMI took advantage of this effect, tuning beam energy by moving the target and (in original design) the second horn:





CONVENTIONAL BEAMS: Decay Region



- Decay region dimensions are very important for decay-in-flight beams

Decay Region

- Critical numbers for understanding physics design of decay regions:

	2 GeV	15 GeV	300 GeV
π^+	111	835	16700
μ^+	12500	94000	1.8E+06
K^+	15	113	2250
K_L	62	465	9300

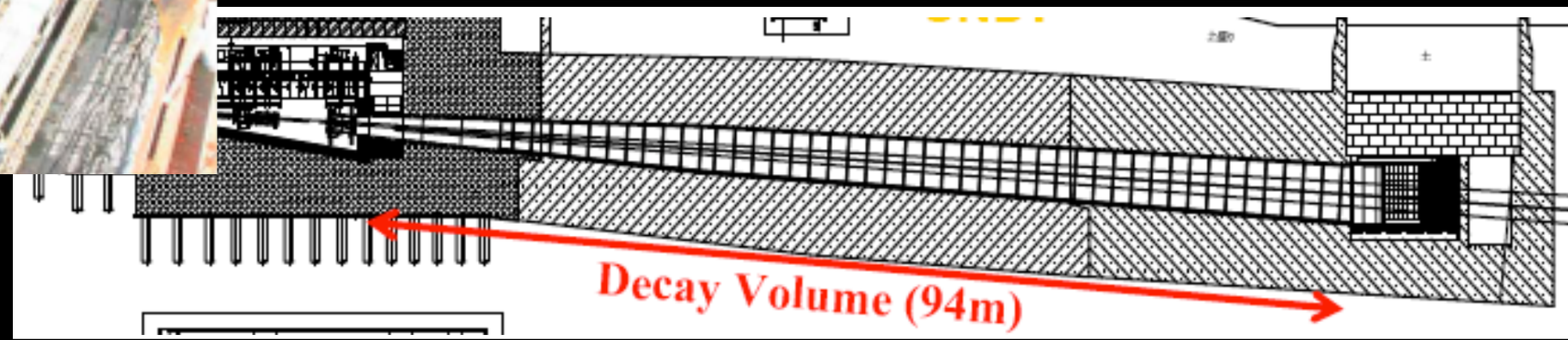
Decay length $\gamma c\tau$ (m)

- Kaons decay predominantly upstream, pions later, and muons rarely decay before the beam dump in decay-in-flight beams.

Decay Region

- If goal is maximum ν_μ flux with minimal ν_e contamination, must balance the following considerations:
  - Longer decay regions yield higher flux as more pions can decay
  - Most kaons will decay in decay region, with 5% ν_e branching ratio; a short decay region will have a higher ν_e-from-K^+ fraction
  - Very long decay regions allow muons to accumulate, increasing ν_e background a bit
  - …and of course, longer decay regions are more expensive to build.

T2K decay region



- 94 m long (starting at collimator after third horn)
- Helium-filled:
  - reduces interactions/loss of pions and increases flux
  - Reduces radioactive gas contamination

NuMI decay region

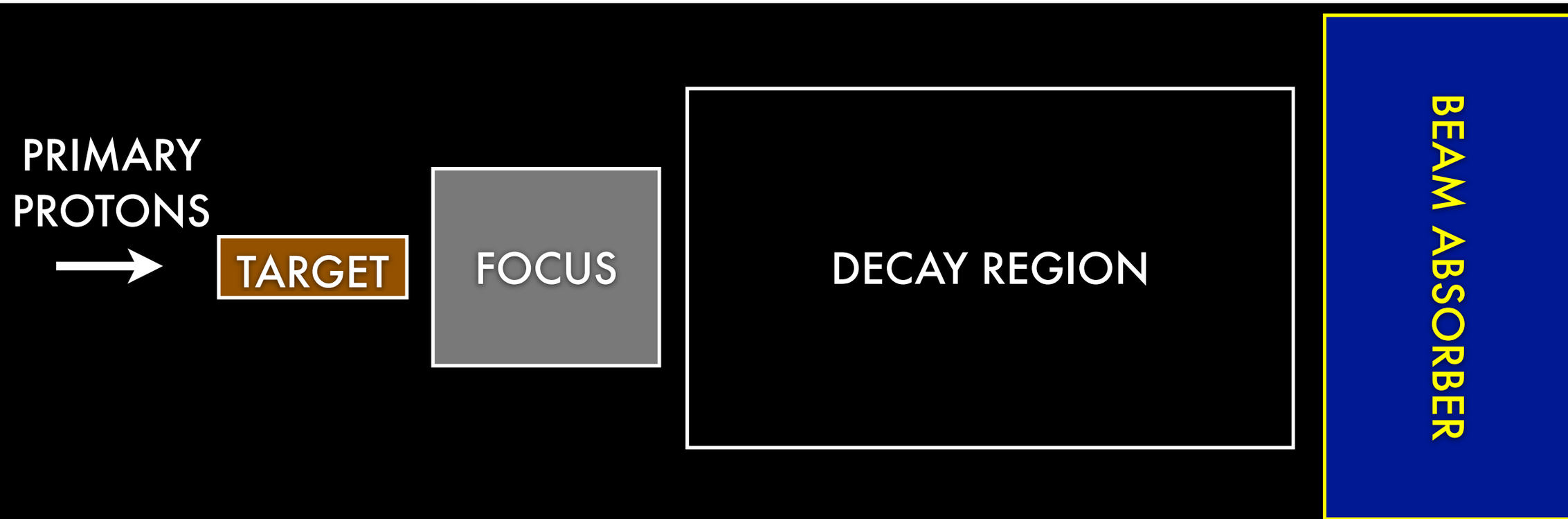
- Copper pipes provide water cooling in surrounding concrete
- Cylinder structure (2m diameter, 677m long)
- Held at ~~vacuum~~ helium
  - Entrance window is 1.5mm stainless steel

Impressive energy deposition warrants cooling:

- 63 kW in 1 cm thick steel decay pipe
- 52 kW in shielding concrete

J. Hylen
NBI02

CONVENTIONAL BEAMS: Basic components

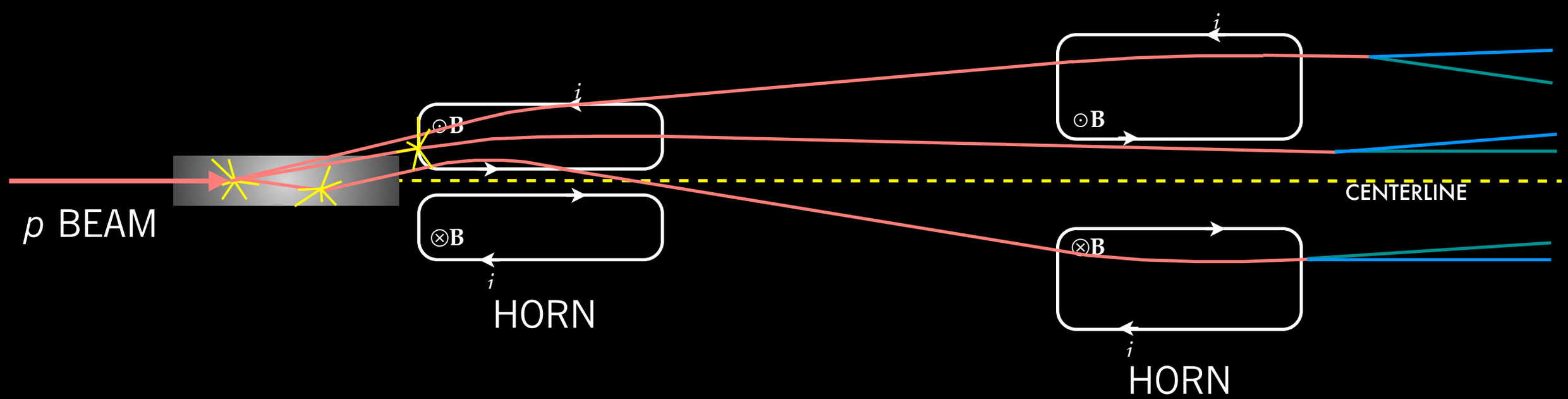


- In most beams, about 1/3 of the beam power is deposited in the absorber. Generally requires very rad-hard materials and active cooling. Must be well-engineered, because it is generally too radioactive for any active maintenance or replacement.

- Typical materials: graphite, copper, aluminum, steel (low power only)

Flux from a neutrino beam

- Neutrino flux comes from:
  - Pions, kaons produced directly from primary p+C interactions
  - Also produced from re-interactions of secondary p, π in the target
- Secondary particles from target focused in a series of horns
  - Horns contain substantial amounts of aluminum, which also acts like a secondary target
- **All of these sources of mesons contribute significantly to the neutrino flux.**

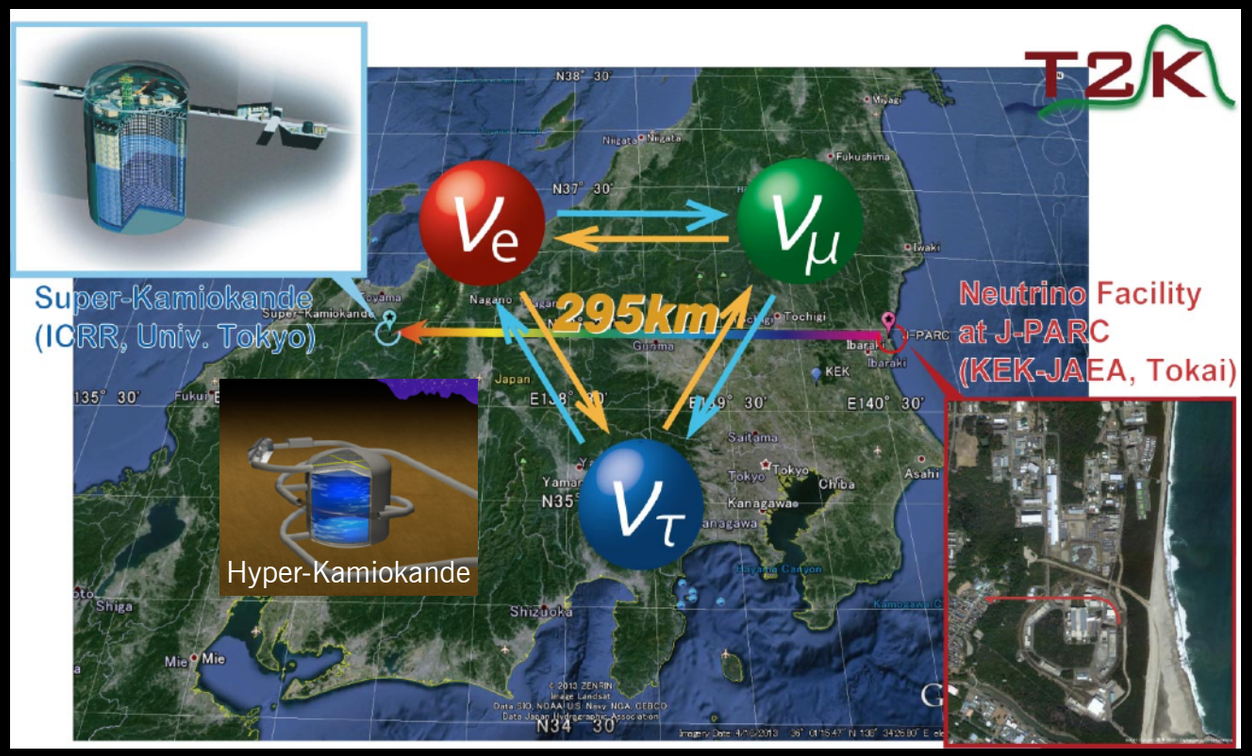


Understanding the flux

- Use Monte Carlo techniques to simulate the beam, but this is generally a very complicated and challenging environment. Uncertainties can be large: 20-50% with standard simulation tools.
- Monte Carlo must simulate:
  - Interaction of proton in target
  - Production of pions, kaons in target
  - Propagation of particles through horn (scattering, interactions, field)
  - Propagation through decay volume and loss in beam absorber
  - Meson decays to neutrinos, muons

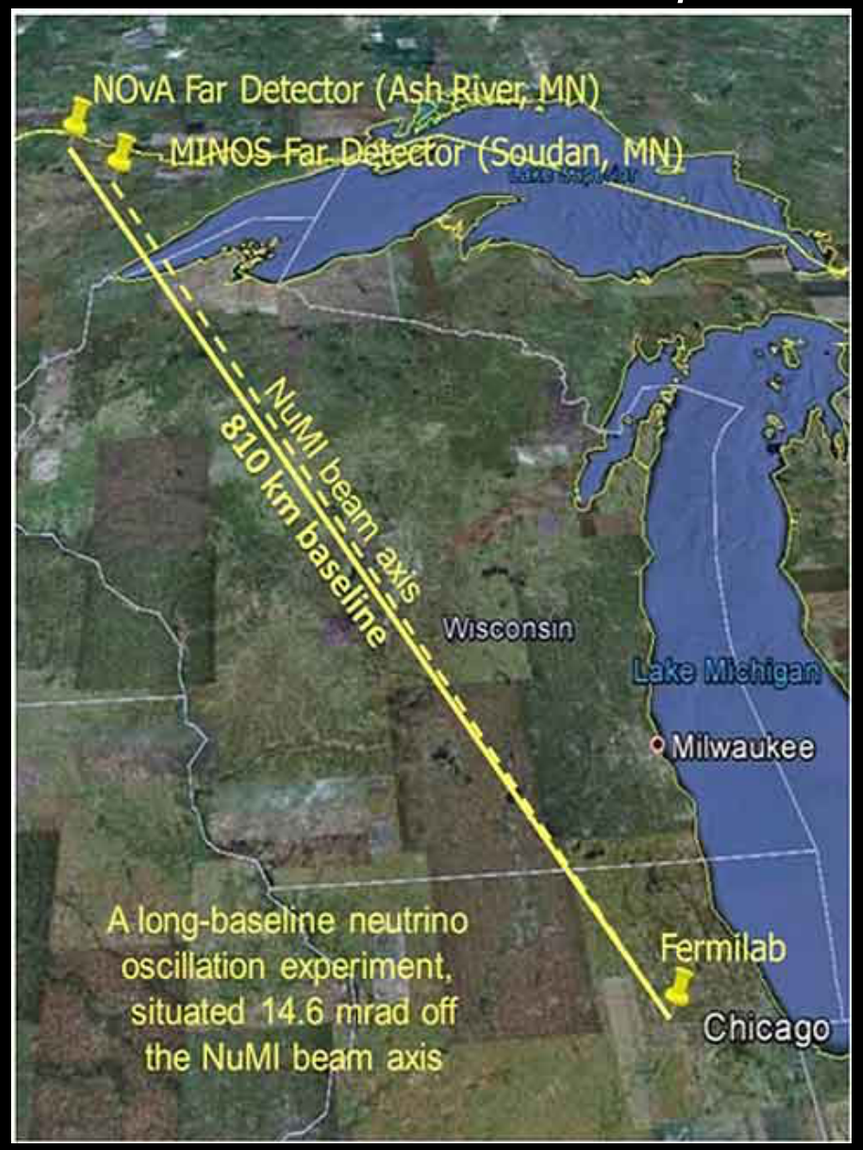
All of these require knowing hadron interaction physics!

Primary beam energies for current and near future neutrino beams

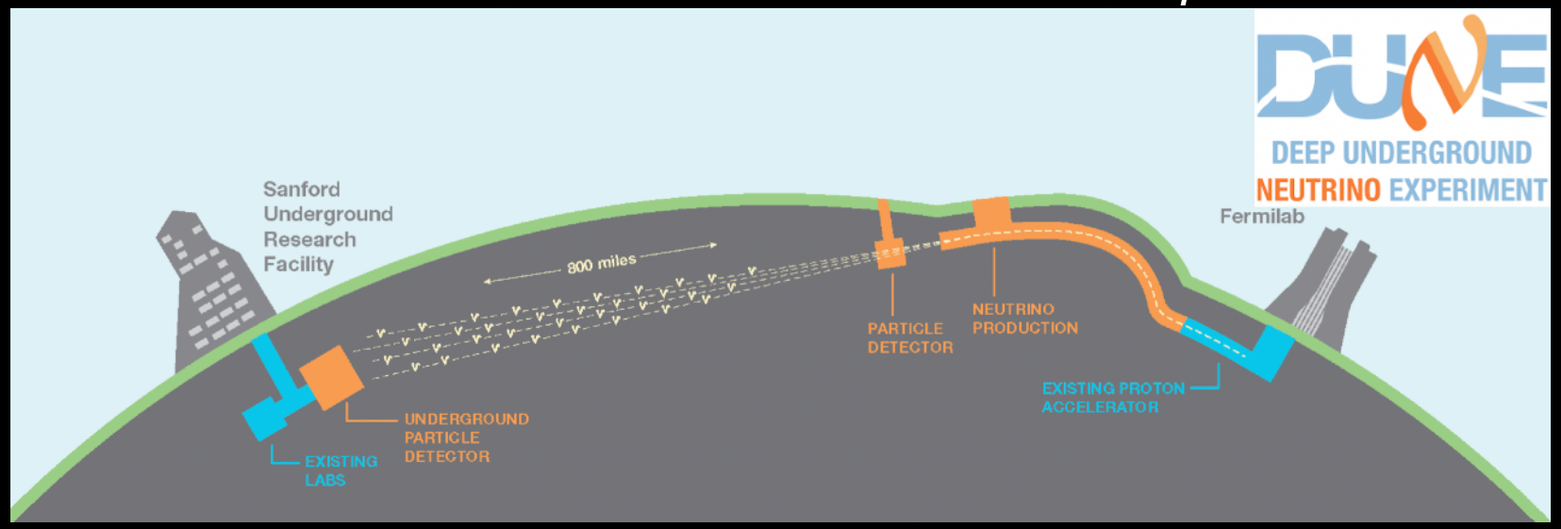


T2K, T2HK: 30 GeV/*c p*

NuMI: 120 GeV/*c p*

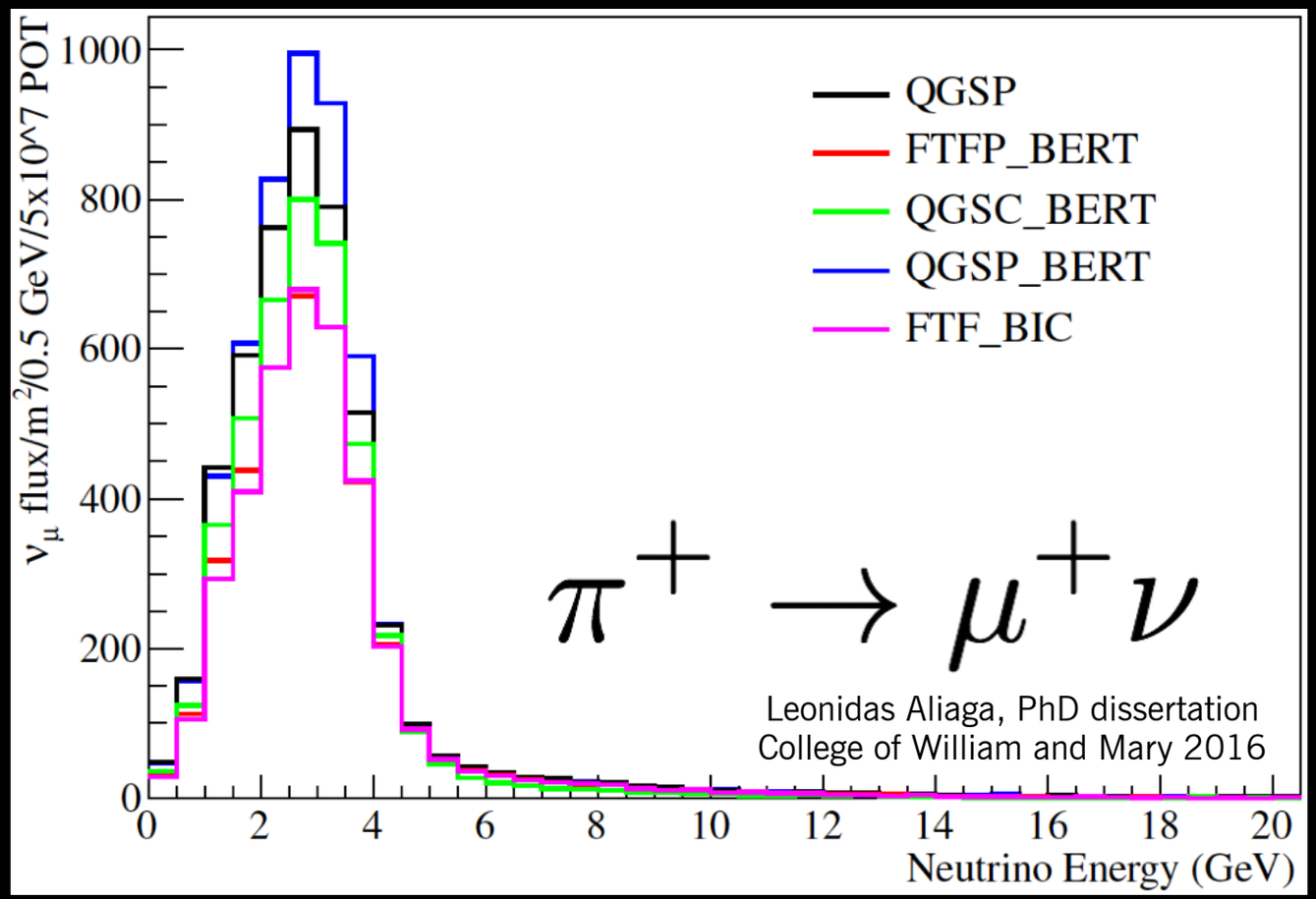


LBNF/DUNE: 60-120 GeV/*c p*



Monte Carlo generators

- Neutrino experiments use hadronic interaction generators including FLUKA, GEANT4 with various physics lists
- But these generators have **very large** disagreements with one another: 20%+ is common, or even factors of two for kaon production!
- Very important to have constraints on the hadronic processes



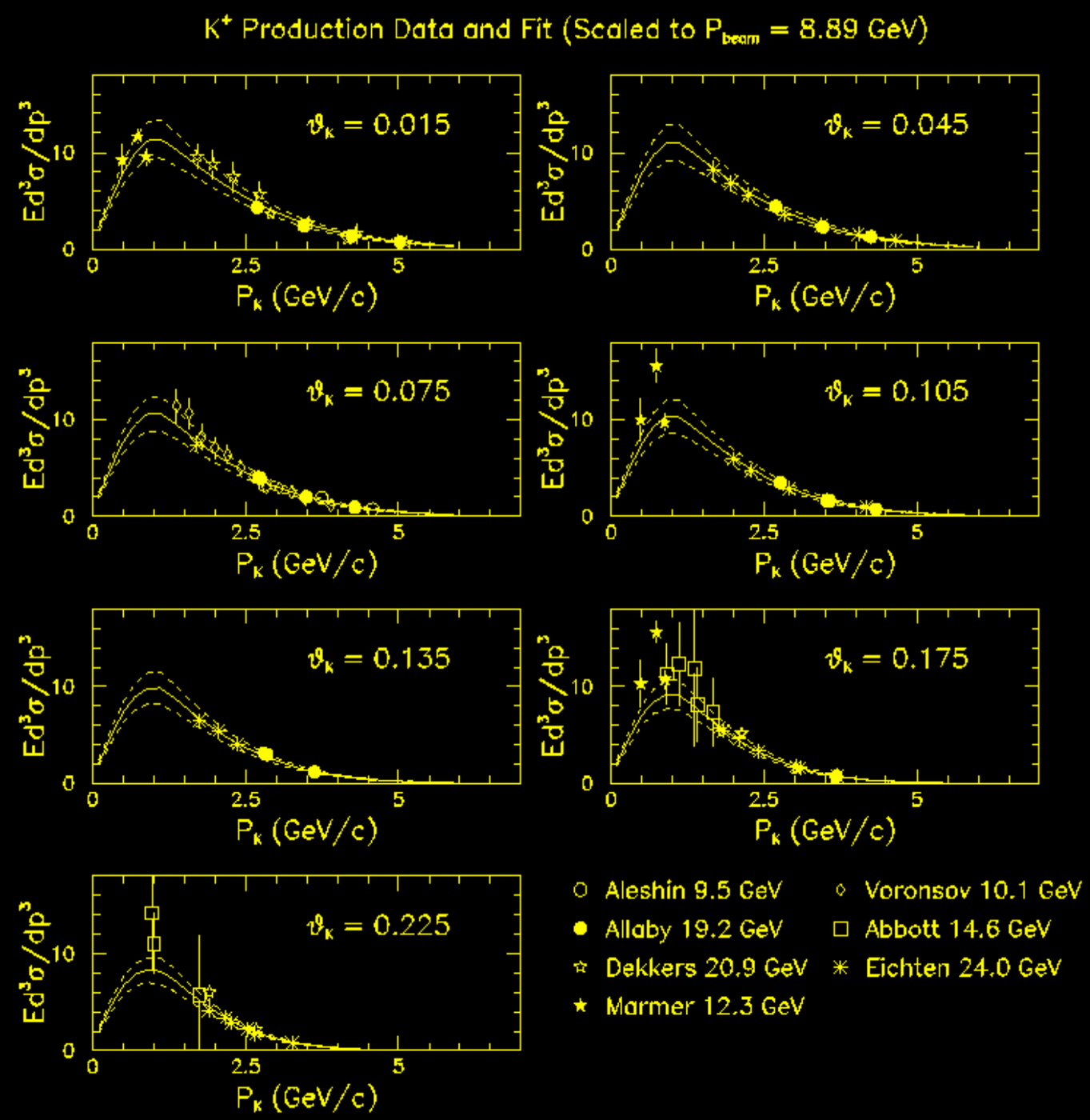
Flux of FNAL's NuMI neutrino beam with different physics generators

Inputs to beam simulations

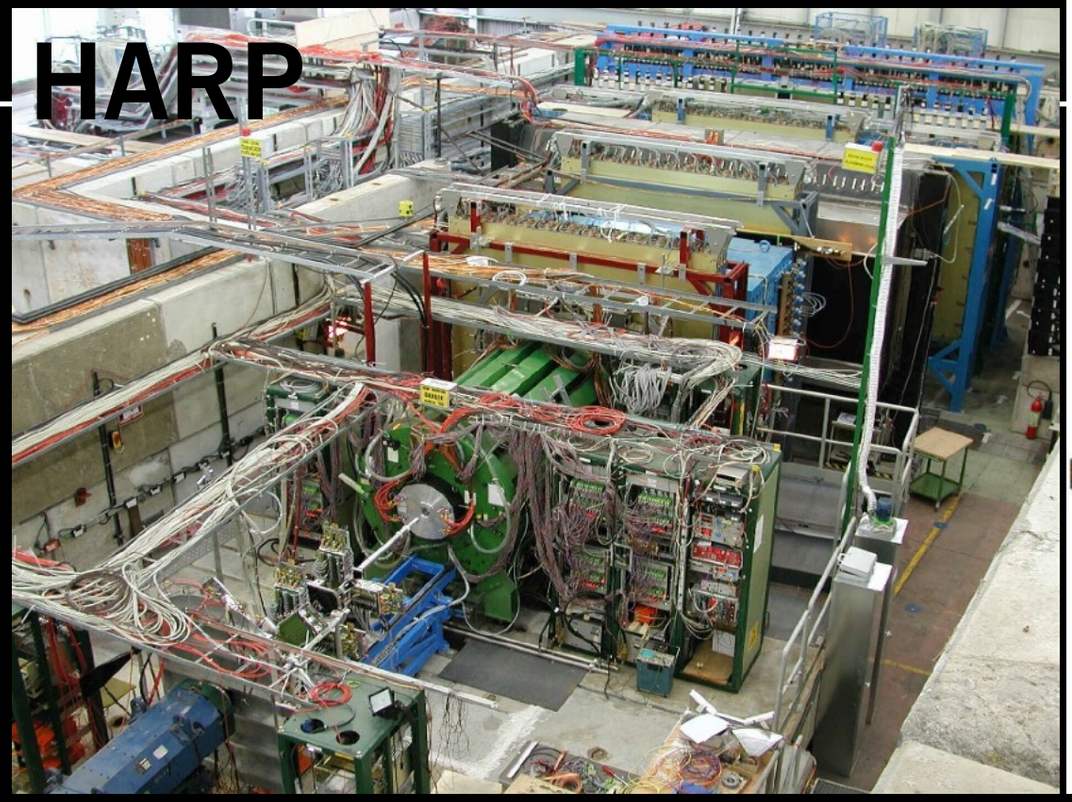
- In-situ:
  - Proton beam monitors upstream of target
  - Secondary muon monitors for indirect monitoring of pion decays
  - Near neutrino detectors: critical for making oscillation measurements! These are not perfect for constraining flux, due to neutrino cross-section and reconstruction uncertainties and parallax effects due to their sites near to extended sources
- Ex-situ:
  - Dedicated measurements of pion, kaon production in proton-target interactions

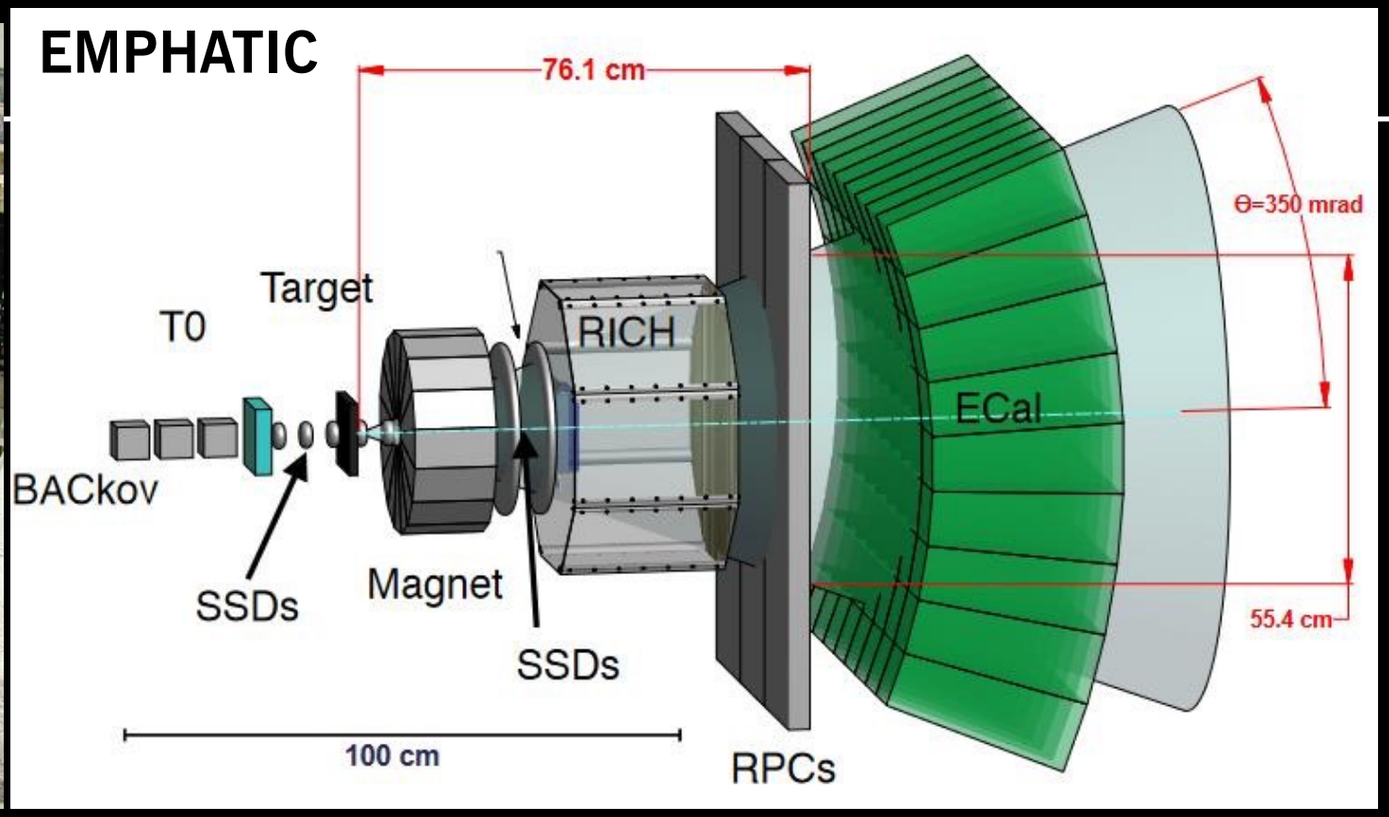
External measurements of meson production

- Until recently, depended on fits to multiple measurements at different labs with different beam energies
- These measurements were made many years ago for other purposes, and had varying applicability to neutrino beams
- Significant issues with combining systematic errors across very different experiments
- Model dependence in extrapolating from different energies, target nuclei

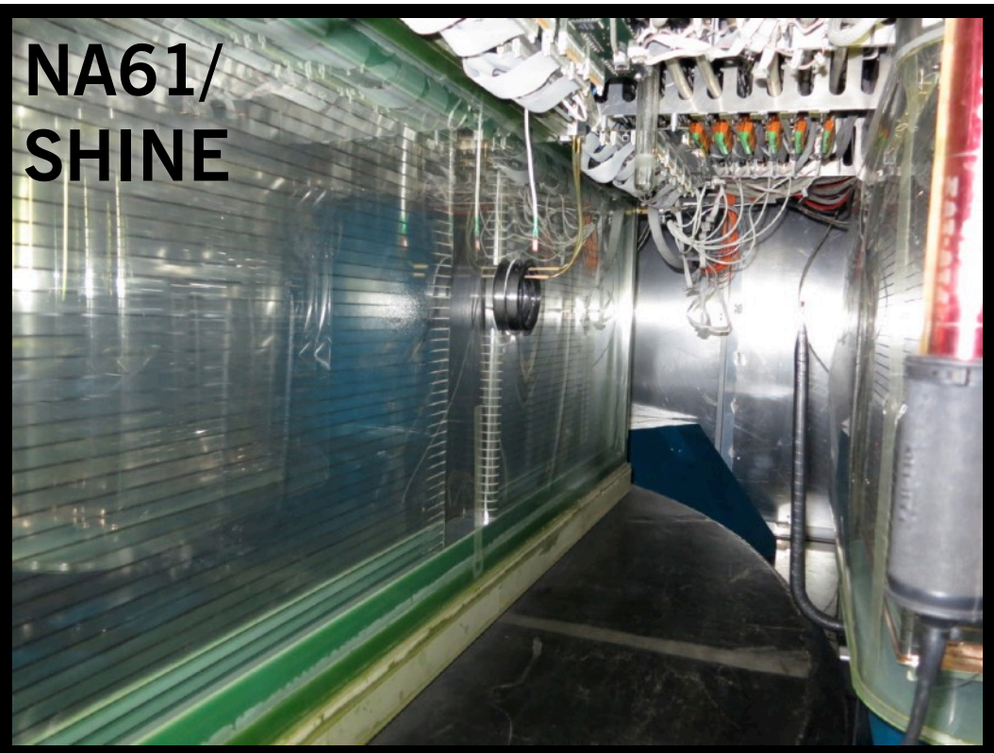


Dedicated experiments



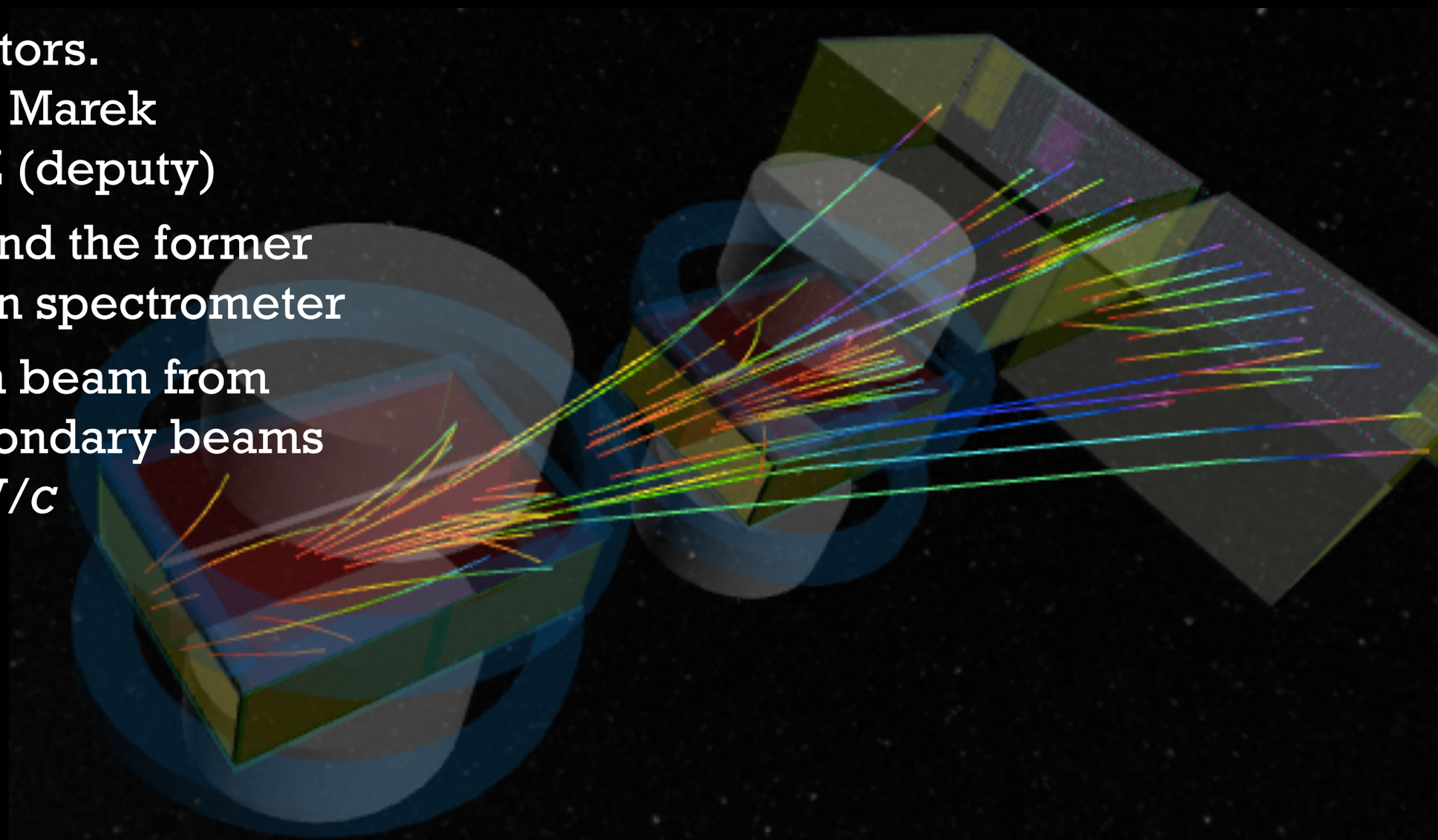


- In recent years, a loose program of hadron production measurements specifically for neutrino experiments has been underway
- HARP (CERN PS)
- EMPHATIC (FNAL MI)
- NA61/SHINE (CERN SPS)



NA61: The SPS Heavy Ion and Neutrino Experiment

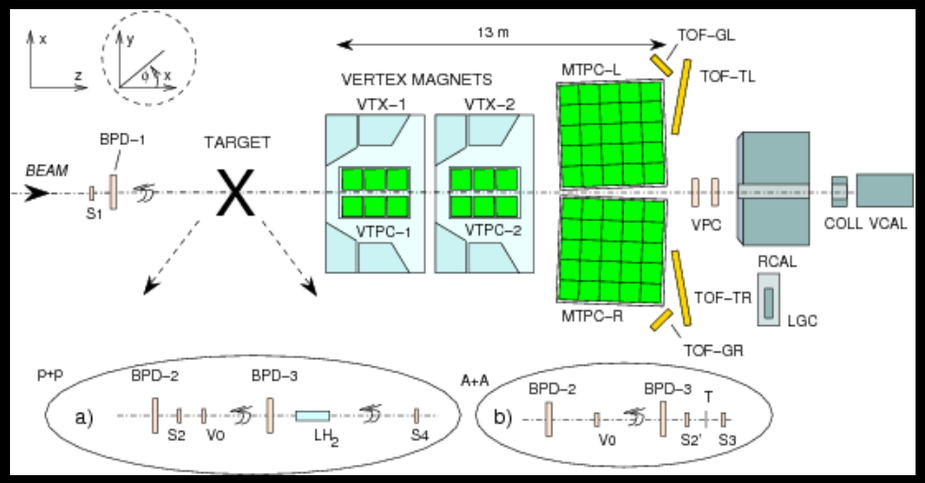
- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators. Spokespeople: Marek Gazdzicki, EDZ (deputy)
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~25 to 350 GeV/*c*



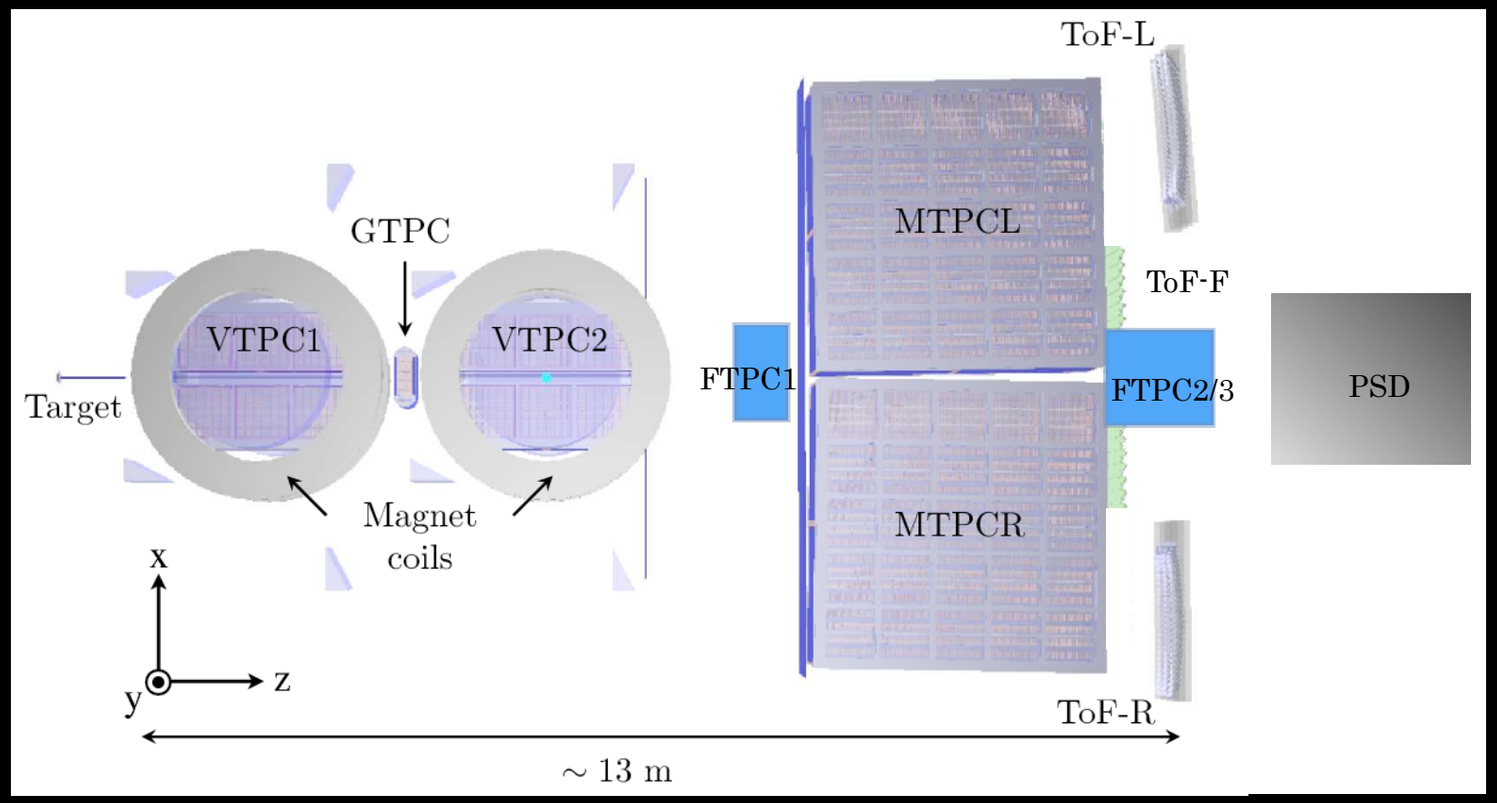
NA61: The SPS Heavy Ion and Neutrino Experiment

- Diverse physics program includes
  - Strong interactions/heavy ion physics
    - Onset of QCD deconfinement
    - Search for critical point
    - Open-charm production
  - Hadron production for neutrino beams
  - Cosmic ray production
    - Hadron production for air-shower model predictions
    - $d/\bar{d}$ production for AMS experiment
    - Nuclear fragmentation cross-sections

NA61 detector system



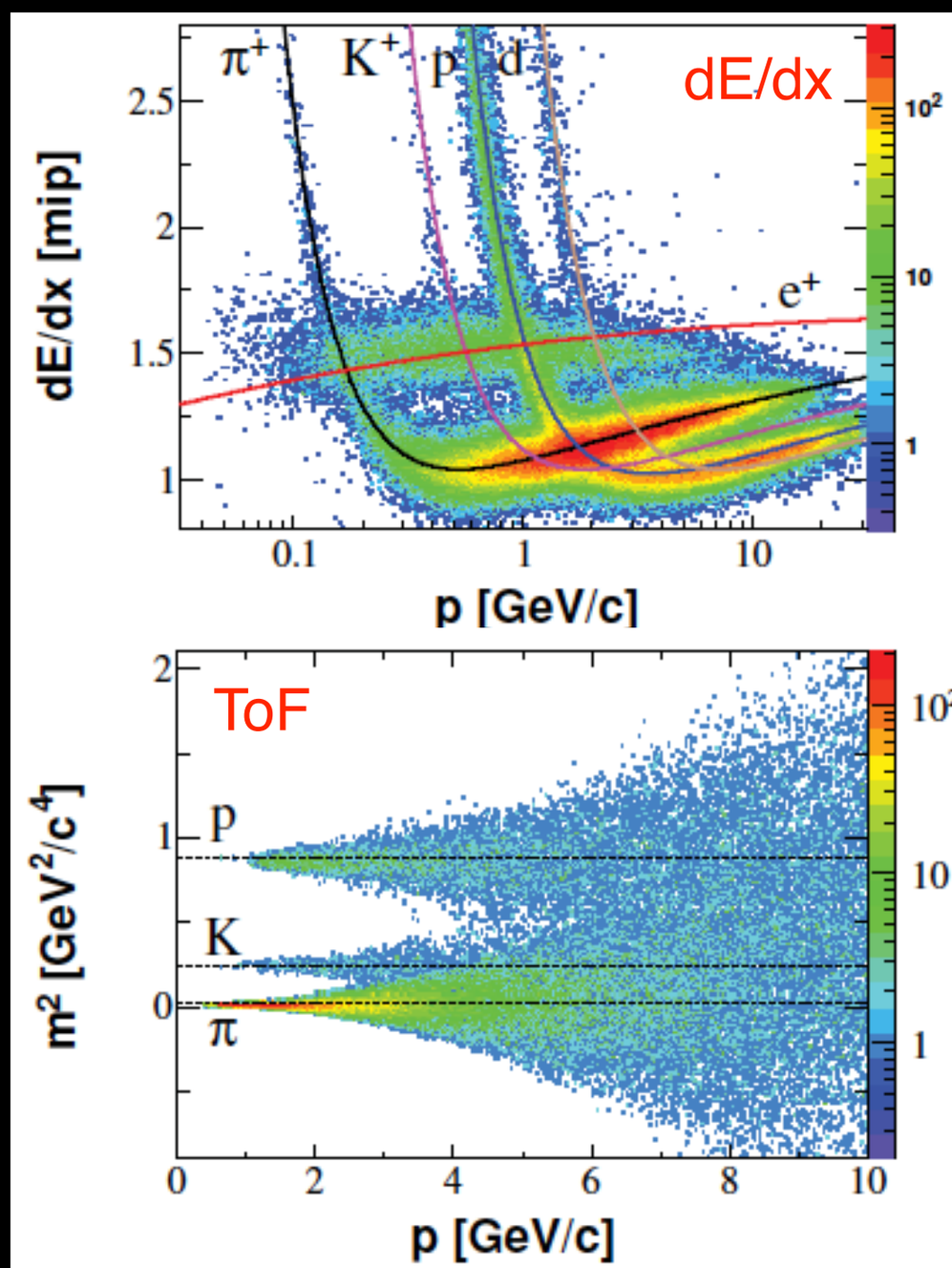
NA49



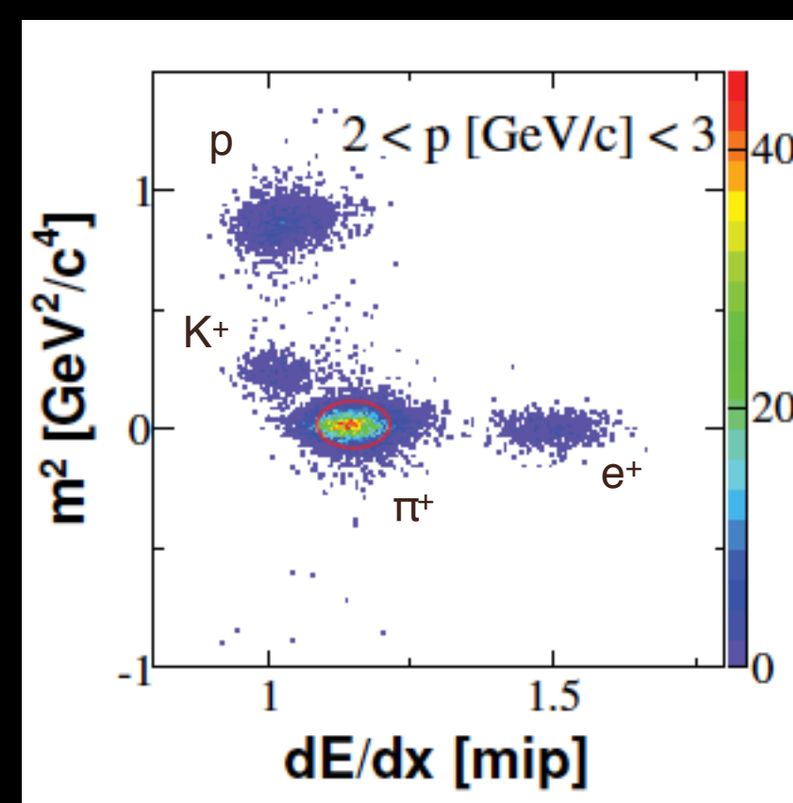
NA61

- Detailed beam instrumentation including PID and tracking before the target
- Several large-acceptance time projection chambers (TPC), two superconducting analysis magnets
- Scintillator-based time-of-flight detectors
- Projectile Spectator Detector: forward hadron calorimeter

Particle identification

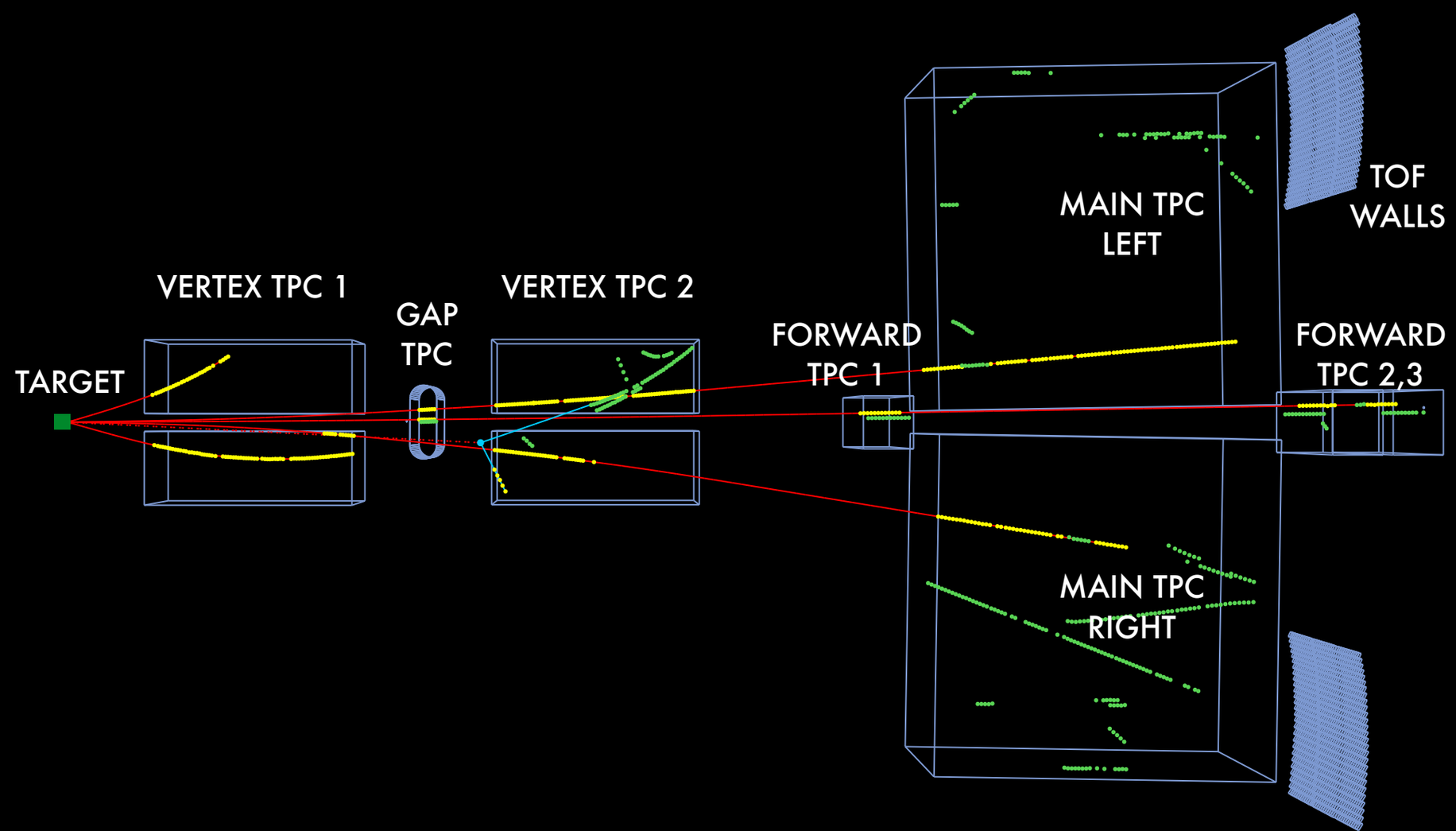


- Uses dE/dx in TPCs at higher momentum
- Transitions to TOF at lower p

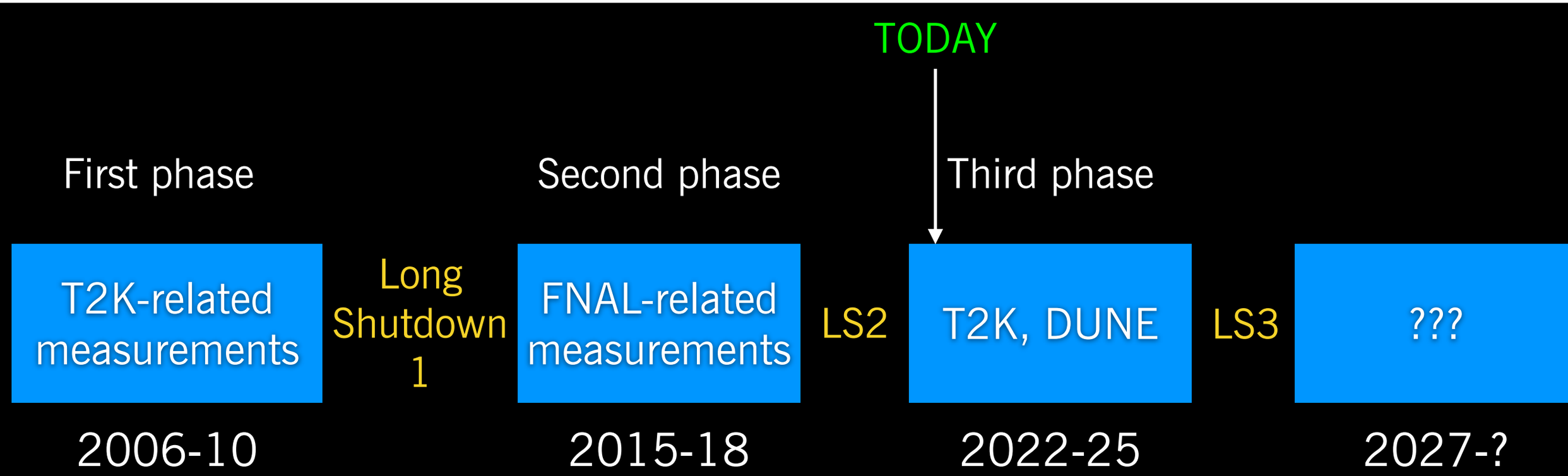


Event display

120 GeV p+C



NA61/SHINE operational eras

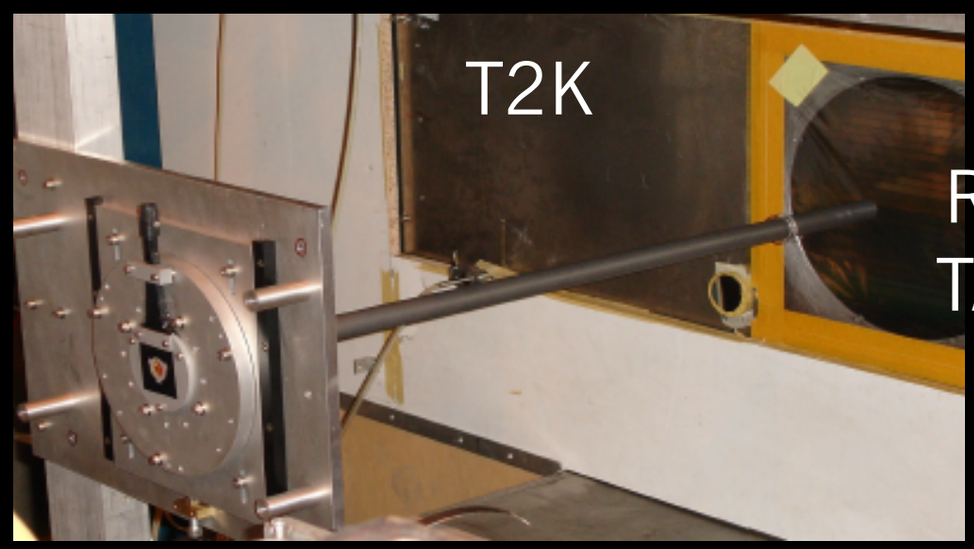


- Multi-phase program of hadron production measurements dedicated for neutrino physics
- Major upgrades during each Long Shutdown
- Plans continue to evolve for future upgrades and operations

Twin approaches: thin- and replica-target measurements

- Need thin-target measurements to measure physics cross-sections (total inelastic and production cross-sections, and differential spectra), for inputs to generators
- Need measurements on replica (~meter-long) targets of same material and geometry as neutrino production targets.
  - Measure both beam survival probability and differential yields.
  - Make measurements specifically for each neutrino beam.
  - Usually use results to re-weight particles in beam MC at surface of target

Graphite thin target
(1.5 cm, 3.1% of λ_I)



REPLICA
TARGETS

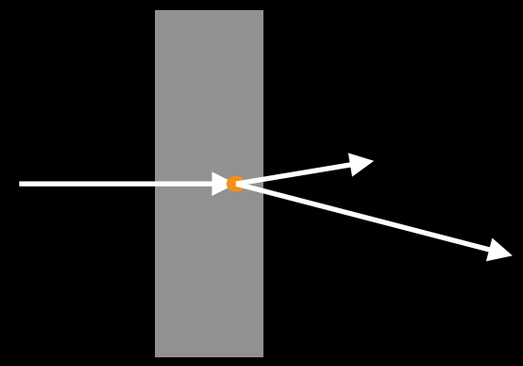
NA61/SHINE measurements for T2K

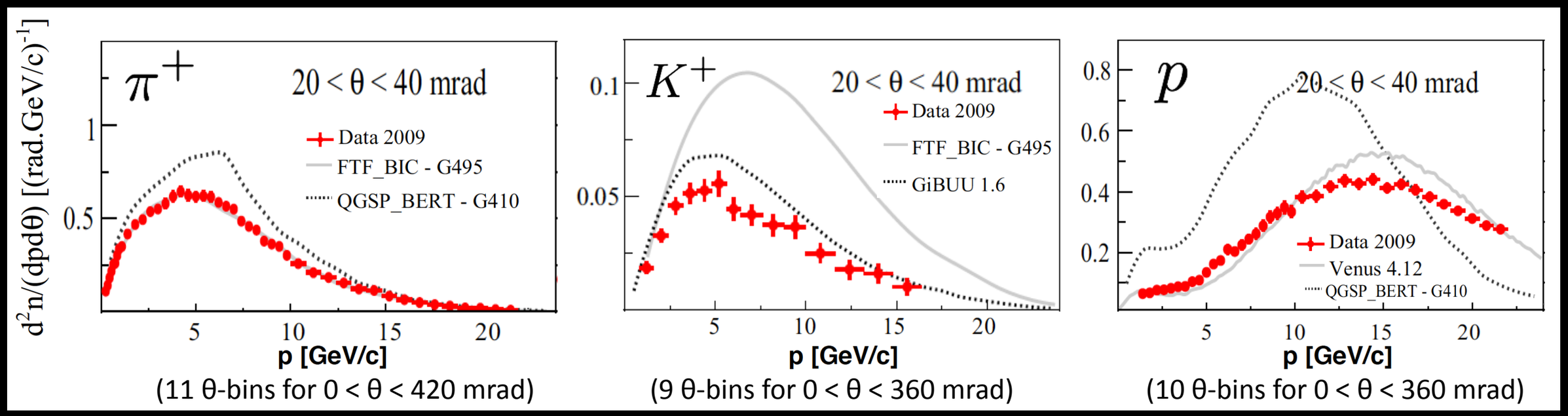
- NA61/SHINE took thin- and thick- target data with 30 GeV/*c* protons specifically for T2K in **2007 (thin) 2009 (thin and replica)**, and **2010 (replica)**.
- Eight NA61/SHINE publications have come out of these data sets

THIN TARGET	
Total xsec, pion spectra	Phys. Rev. C84 034604 (2011)
K^+ spectra	Phys. Rev. C85 035210 (2012)
K^0_S and Λ^0 spectra	Phys. Rev. C89 025205 (2014)
$\pi^\pm$,$K^\pm$, p, K^0_S, Λ^0 spectra	Eur. Phys. J. C76 84 (2016)

T2K REPLICA TARGET	
methodology, $\pi^\pm$ yield	Nucl. Instrum. Meth. A701 99-114 (2013)
$\pi^\pm$ yield	Eur. Phys. J. C76 617 (2016)
$\pi^\pm$,$K^\pm$, p yield	Eur. Phys. J. C79 100 (2019)
p beam survival probability	Phys. Rev. D103 012006 (2021)

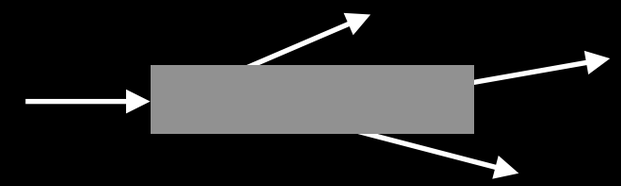
Thin-target results: p+C @ 30 GeV





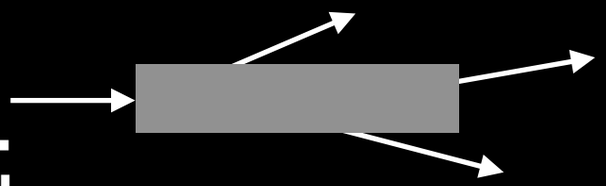
- One angle bin shown here for illustration
- MC generators fail badly for kaons and protons
- Published in Eur. Phys. J. **C76** 84 (2016): also contains yields of negative particles and neutral strange particles (V^0).

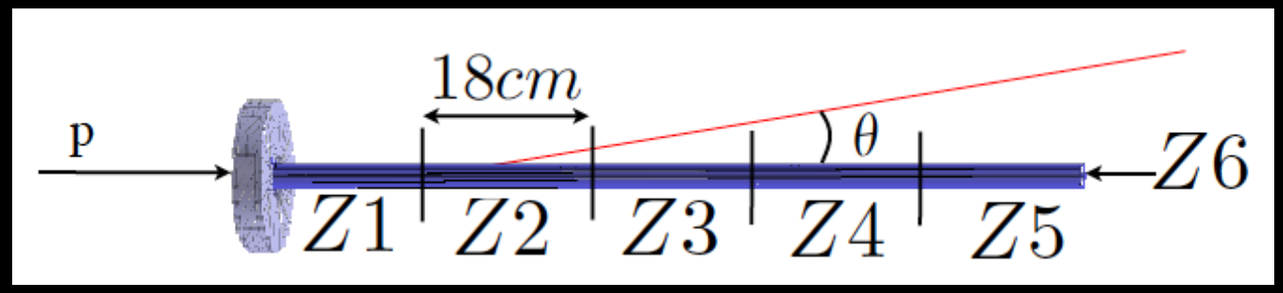
Replica-target measurements



- Exact target geometry of a particular neutrino beam (T2K: 90cm cylinder, NuMI/NOvA: 120cm of graphite fins)
- Most events have primary and secondary interactions in the target
- Measure particle yields vs not only p and θ, but also exit z along target (and possibly ϕ for targets like NuMI's that aren't cylindrically symmetric)
- Also measure beam particle survival as additional constraint on σ_{prod}
- In neutrino beam MC, apply weights to particles at surface of target in the simulation

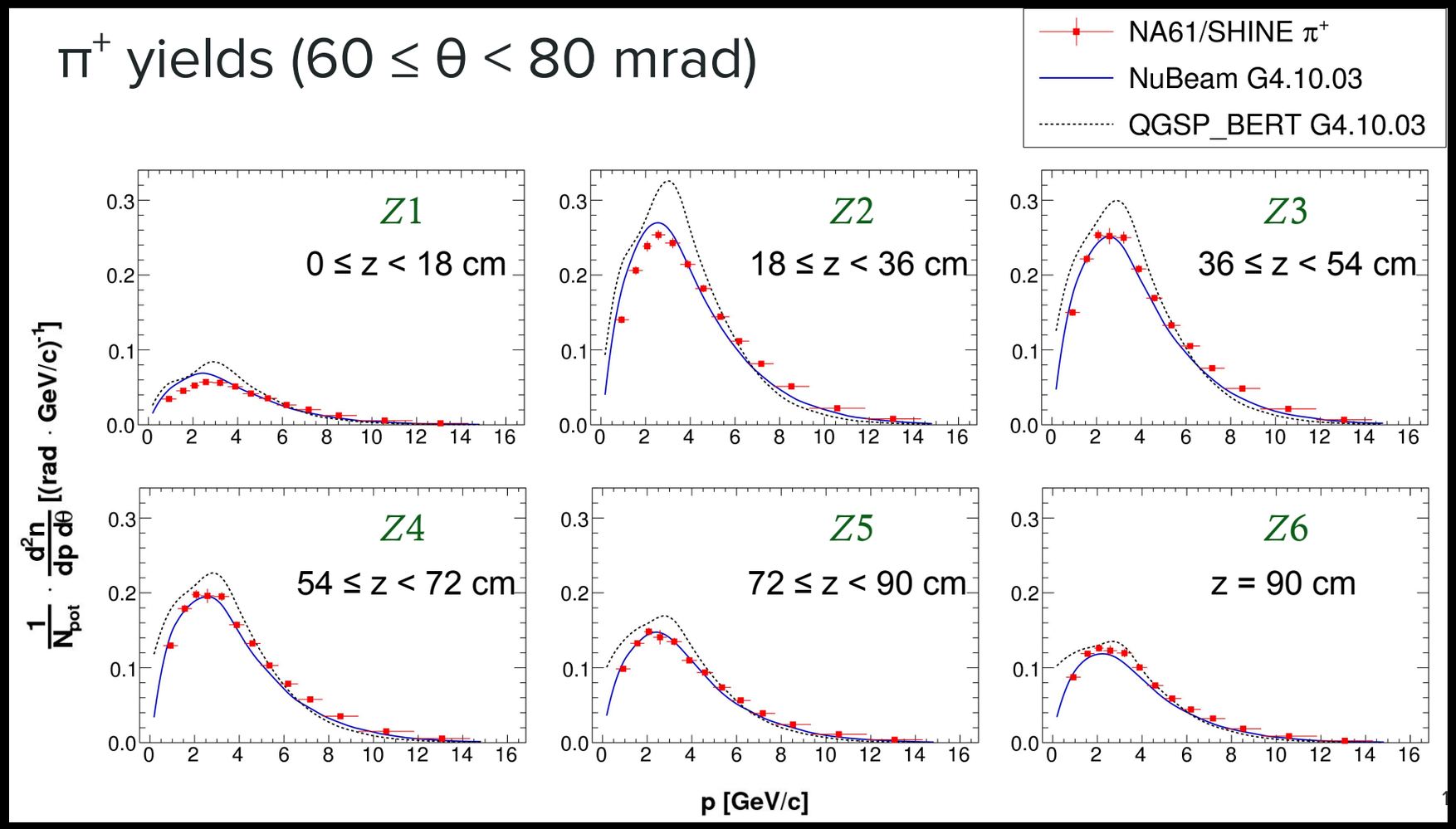
NA61 result: full differential yields from T2K replica target





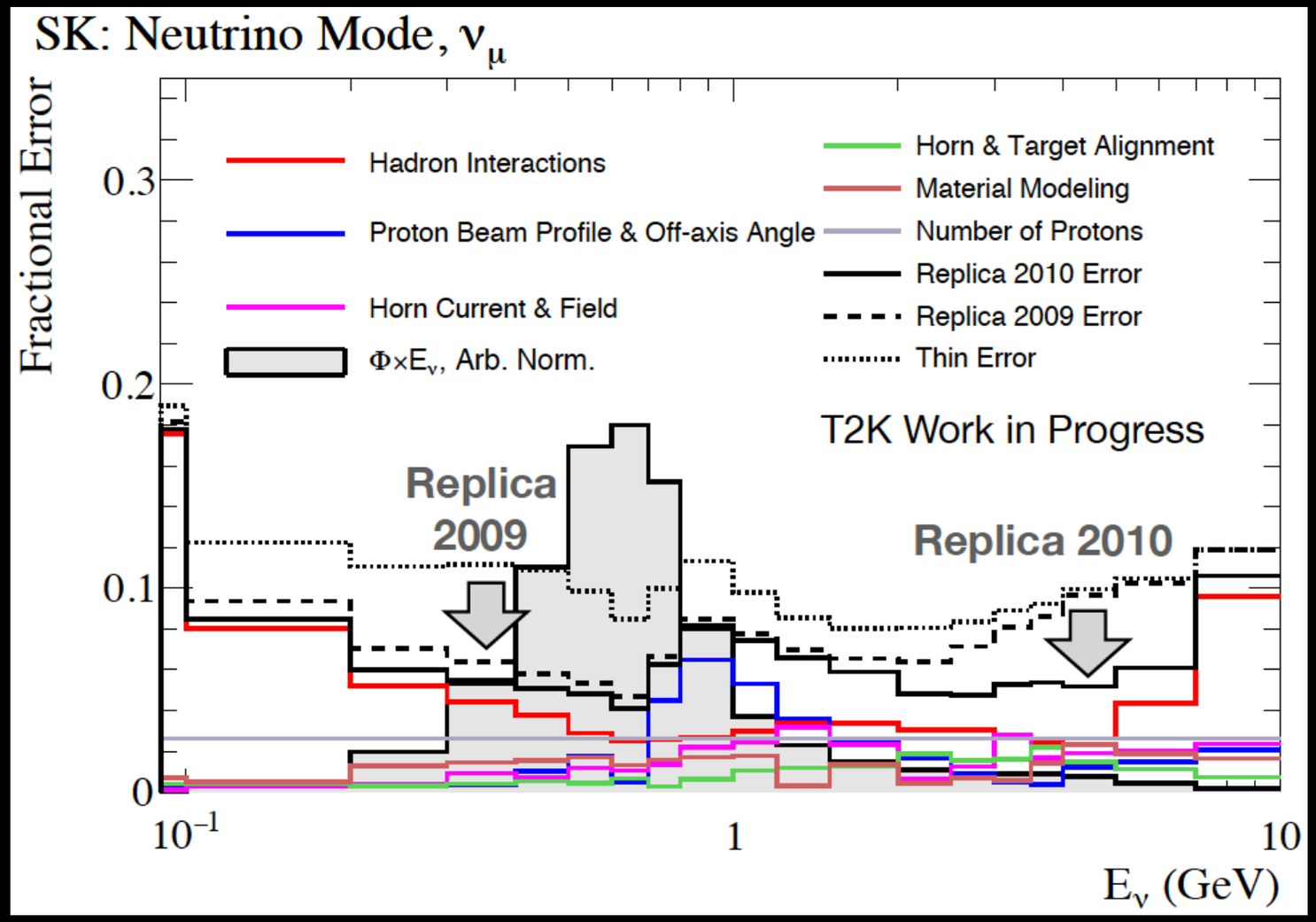
- *Eur.Phys.J.* **C 79** 2, 100 (2019)
- Showing one angle bin of π^+ for illustration.

  Also have π^-, $K^\pm$, p yields

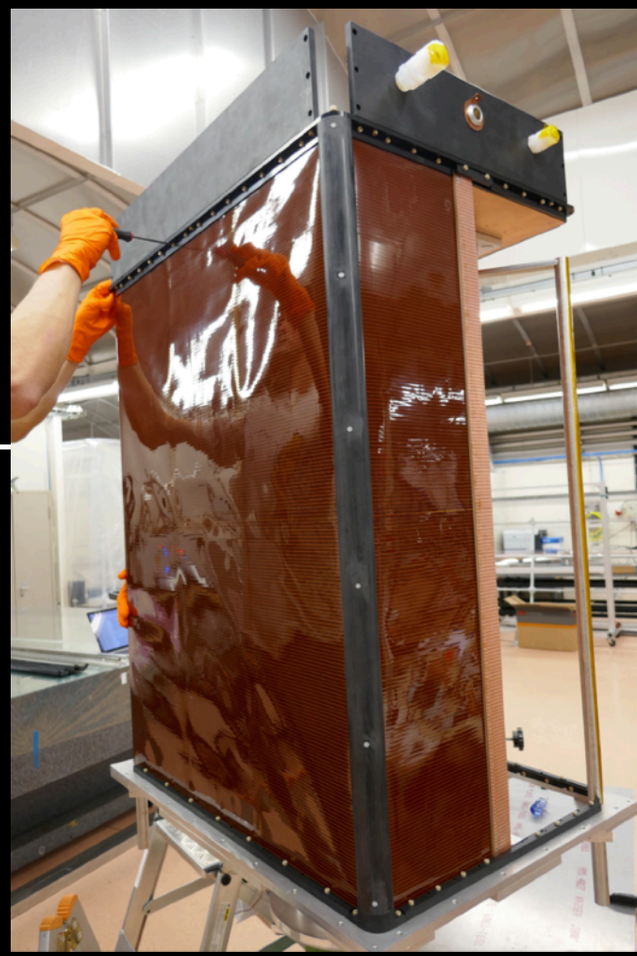


NA61/SHINE measurements for T2K

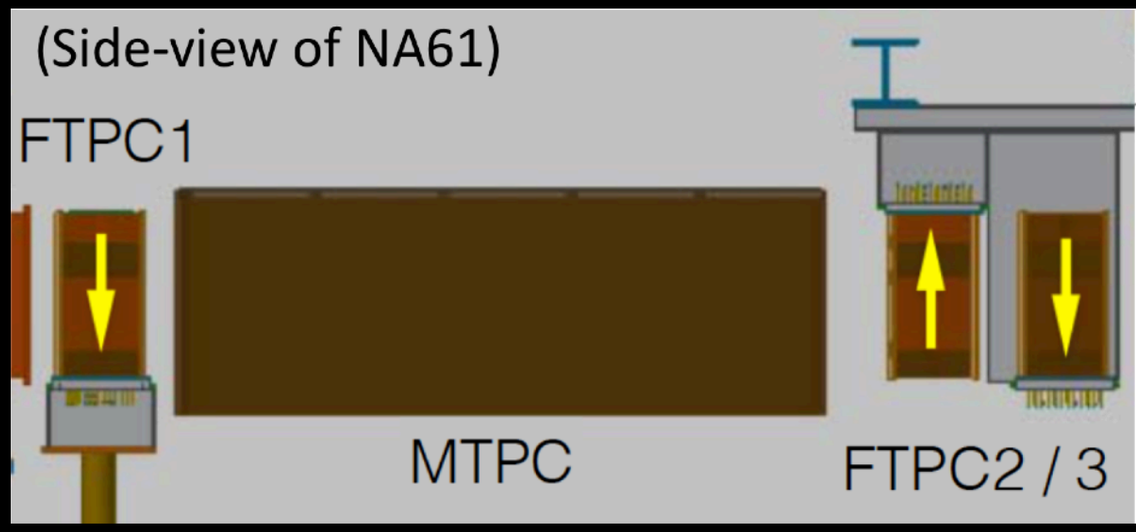
- Steady improvements to the T2K flux prediction (described in Phys.Rev. D87 (2013) no.1, 012001 and J.Phys.Conf.Ser. 888 (2017) no.1, 012064) as more NA61 data sets have been incorporated:
  - first thin-target
  - 2009 replica
  - 2010 replica data set (which added statistics and included kaon yields)



2015-18: A second phase of NA61 neutrino measurements



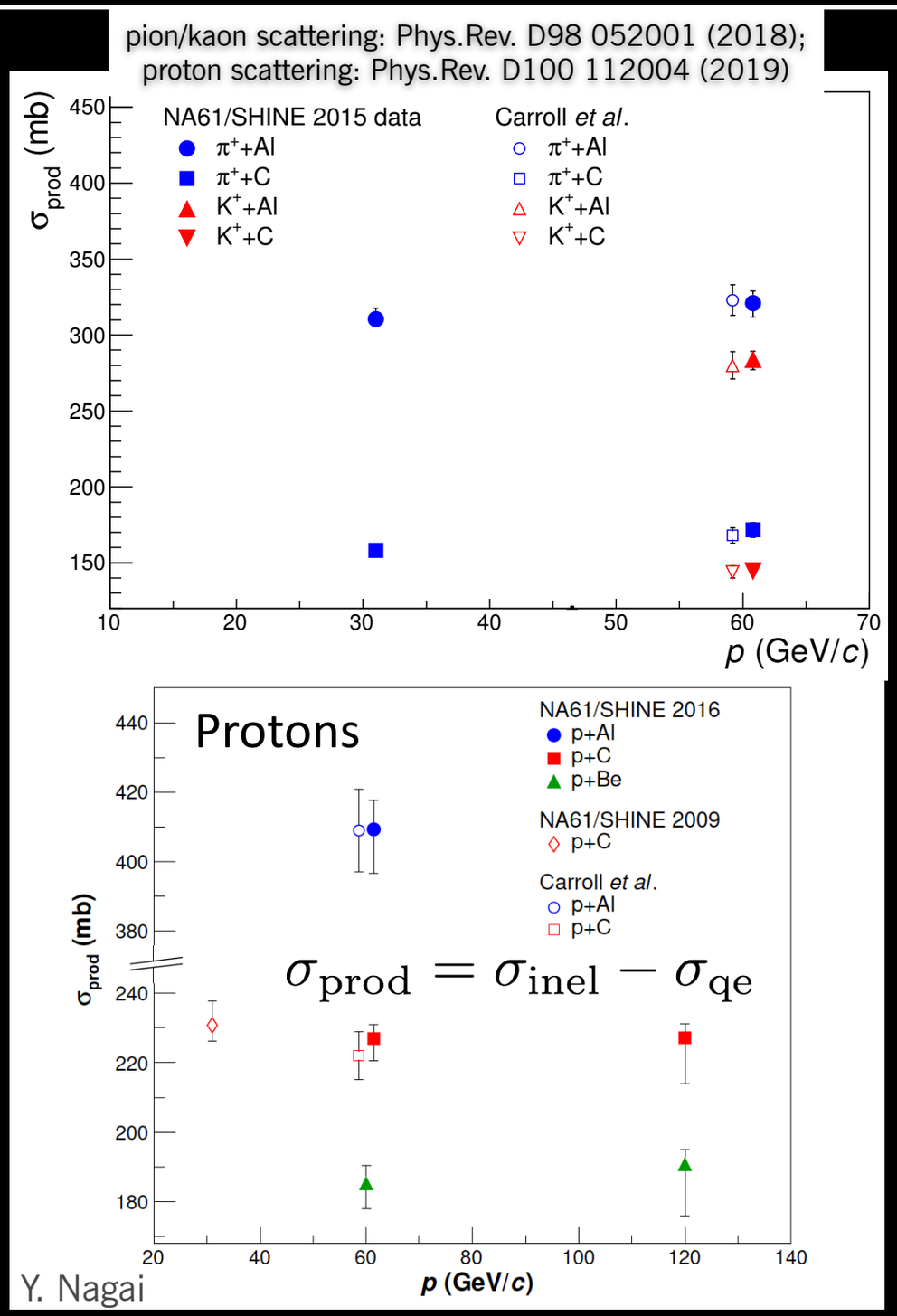
- Motivation: new coverage will be needed for future experiment DUNE, can help existing experiments as well in shorter term
- Project made specific upgrades:
  - Forward tracking system
    - New tandem TPC concept for rejecting out-of-time tracks
  - New readout electronics for time-of-flight detector
- Data collected in 2015-18 for this program



Arrows indicate drift direction

NA61/SHINE results: total production cross-sections on nuclear targets

- Pion and kaon scattering on carbon and aluminum
- Published total production and total inelastic cross section measurements for data without magnetic field
- Definitions: (terminology not always used consistently in community or in hadronic event generators.)
  - $\sigma_{prod} = \sigma_{total} - \sigma_{el} - \sigma_{qe}$, requires new hadrons to be produced.
  - $\sigma_{inel} = \sigma_{total} - \sigma_{el}$.
- Before, NuMI had 5% error on pion interactions, 10-30% for kaons, and had to extrapolate from other energies for protons



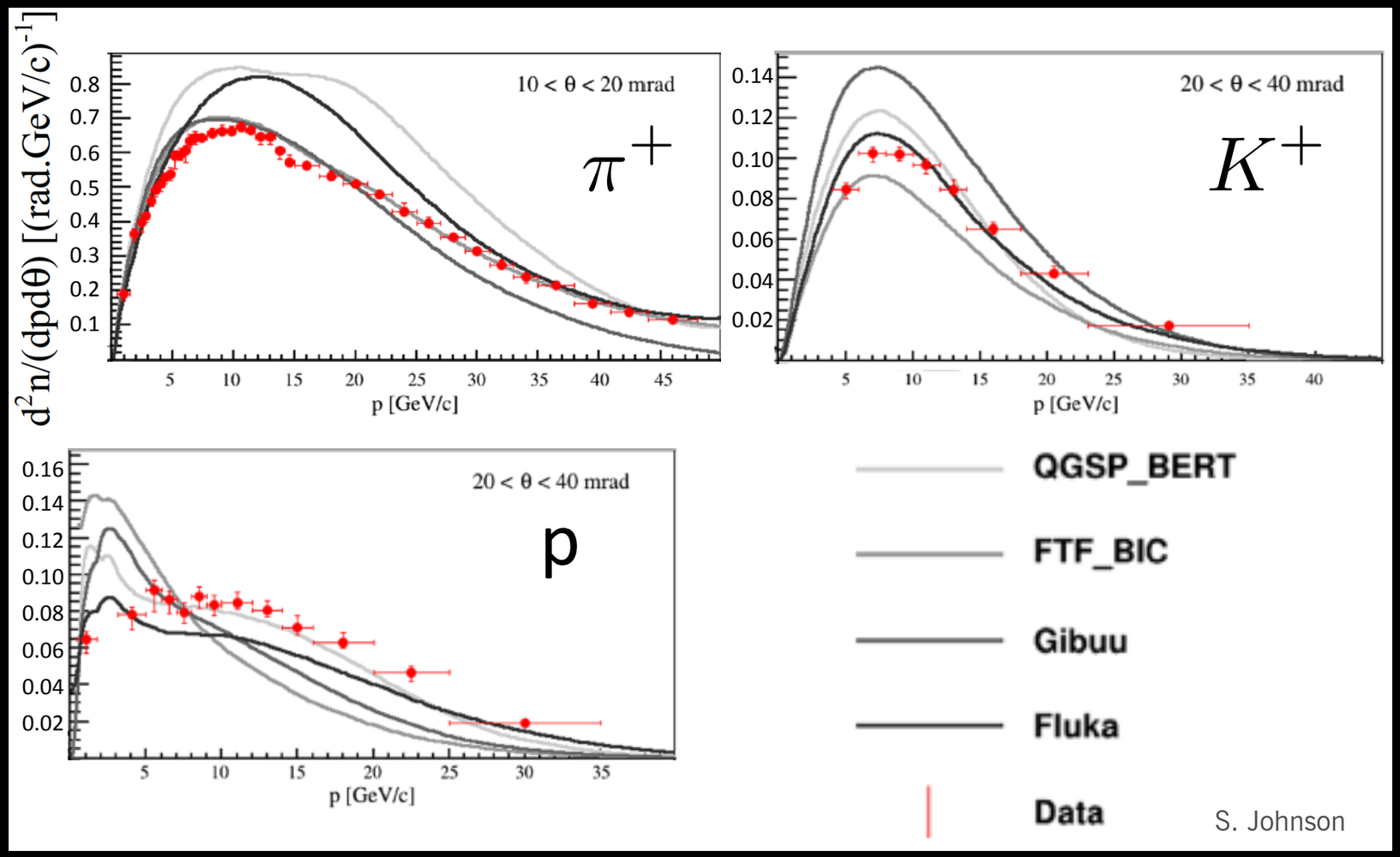
NA61 2016-17 neutrino data
Thin targets

2016	2017
p + C @ 120 GeV/c	π^+ + Al @ 60GeV/c
p + Be @ 120 GeV/c	π^+ + C @ 30 GeV/c
p + C @ 60 GeV/c	π^- + C @ 60 GeV/c
p + Al @ 60 GeV/c	p + C @ 120 GeV/c (w FTPCs)
p + Be @ 60 GeV/c	p + Be @ 120 GeV/c (w FTPCs)
π^+ + C @ 60GeV/c	p + C @ 90 GeV/c (w FTPCs)
π^+ + Be @ 60 GeV/c	

- Full particle yields and spectra from these data sets
- Goal with these measurements is to span the phase space of primary and secondary interactions in neutrino targets and surrounding materials
- Analysis is progressing on some, completed on others
- Each measurement will be a point for interpolation in MC generators

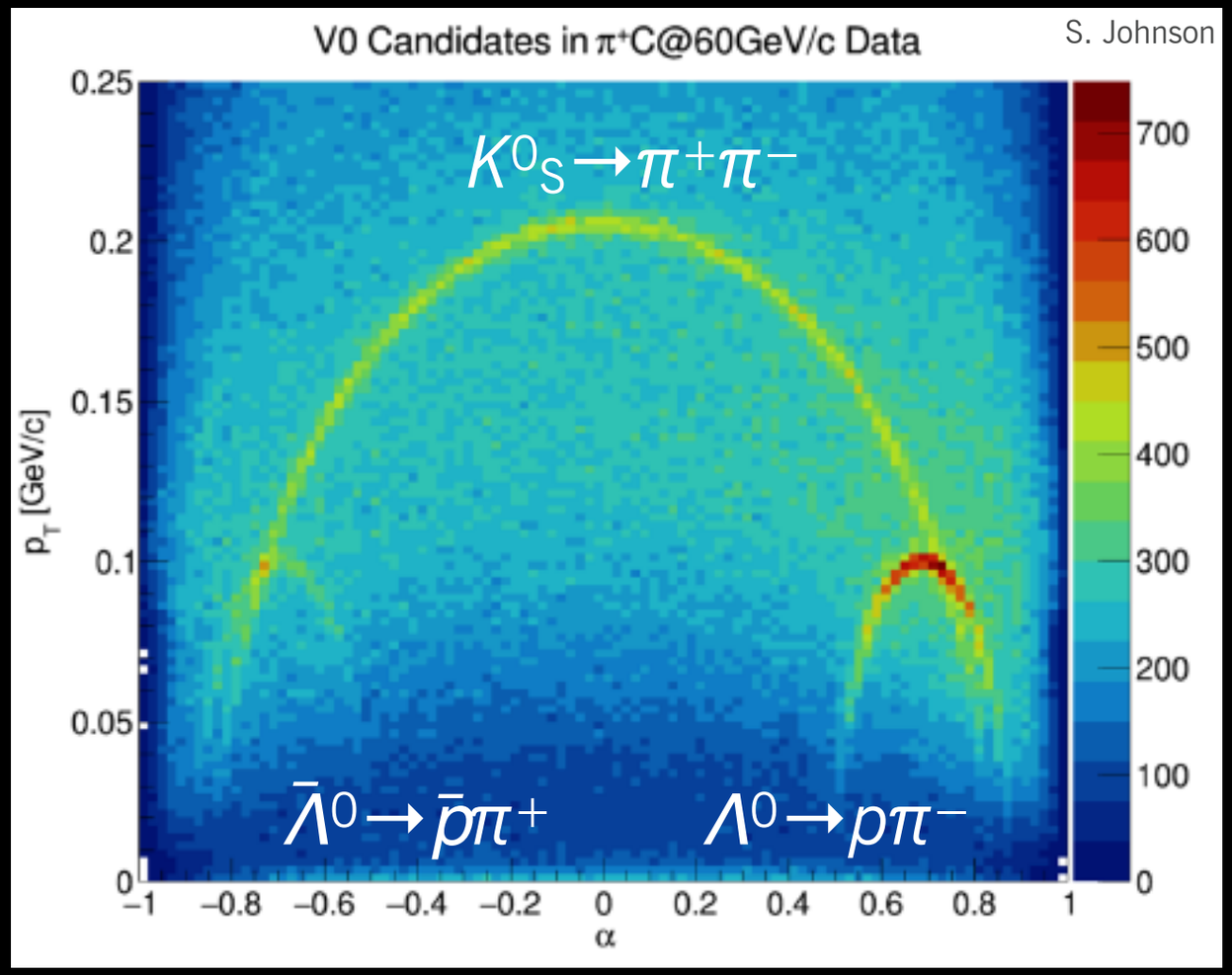
Thin-target charged hadron spectra

- Example: π^++C @ 60 GeV (Phys.Rev. **D100** 112004 (2019))
- Measured differential production yields (positively-charged shown, also measured negatives)



Thin-target neutral hadron spectra

- Analysis of decays in flight using "V^0" events: displaced vertex of two oppositely-charged particles.
- Visualize the events using Armenteros-Podolansky plots

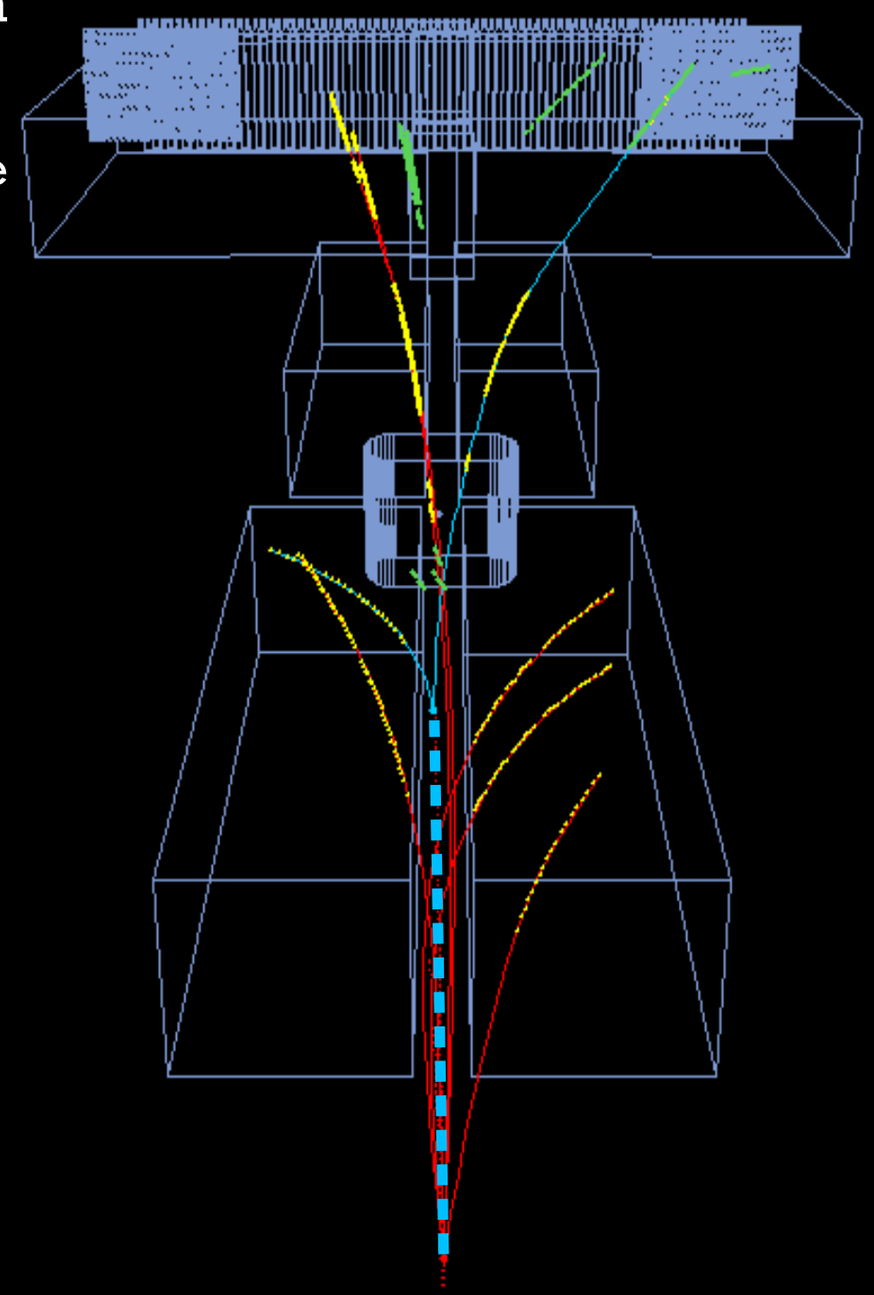


- Plot track p_T vs V trajectory against longitudinal momentum asymmetry of the tracks

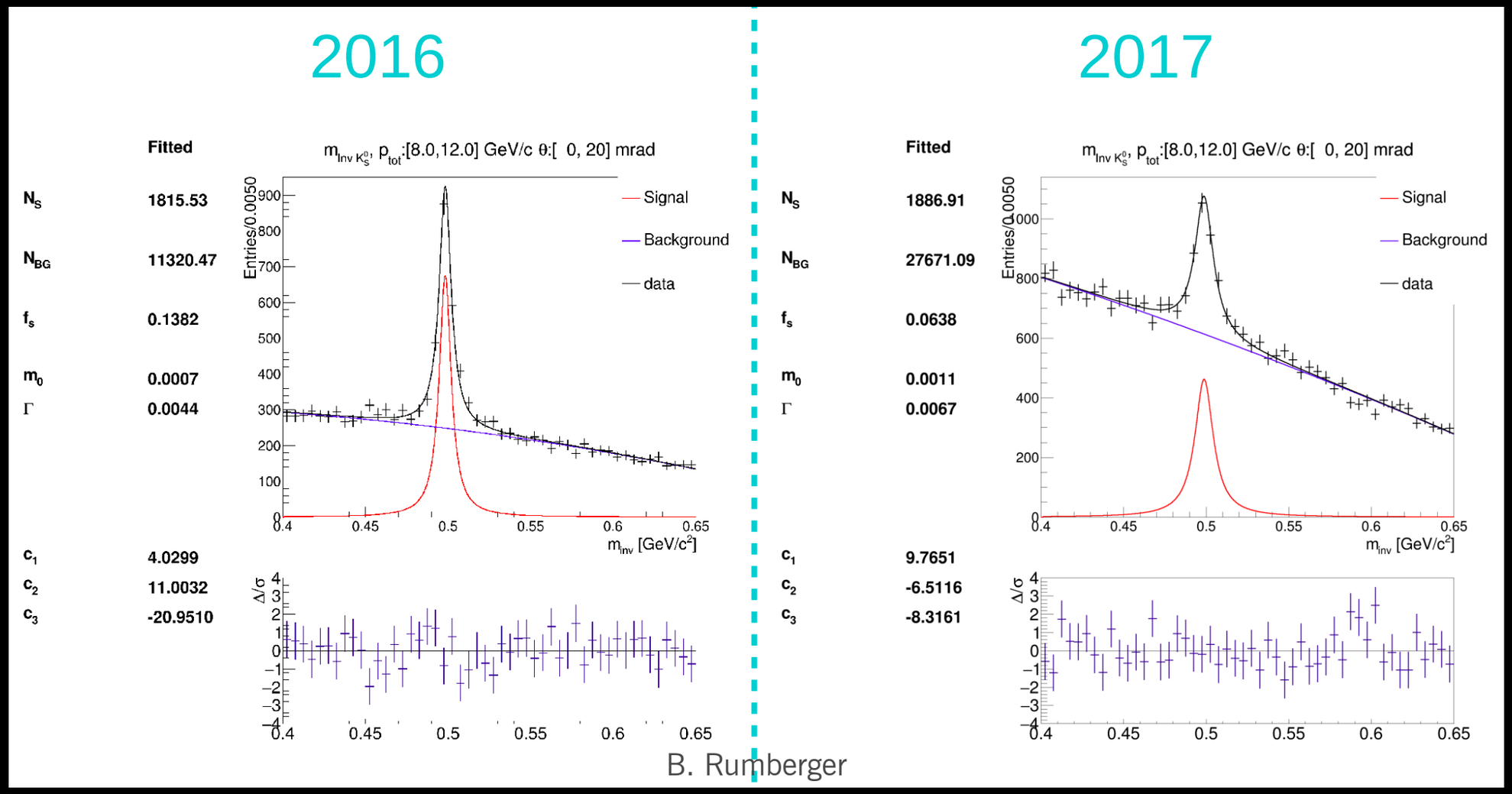
$$\alpha \equiv \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$

Thin-target p+C @ 120 GeV

- This data set is high priority: represents the primary proton interaction in NuMI/NOvA/MINERvA.
- Relies on new Forward TPCs to provide forward acceptance (magnet doesn't bend beam-energy protons into the older TPCs) to see elastic, quasi-elastic events
- New tracking algorithm is used for integrating the FTPCs into the analysis:
  - Cellular automaton-based local tracking with Kalman filter for global track fit
- Superior identification of V^0 events
- Charged and neutral particle yields from ~3 million interactions
  - Neutral particle measurements just published! Phys. Rev. **D107** 072004 (2023)
  - Charged particle measurements preliminary; will be published soon



K^0_S invariant mass fits



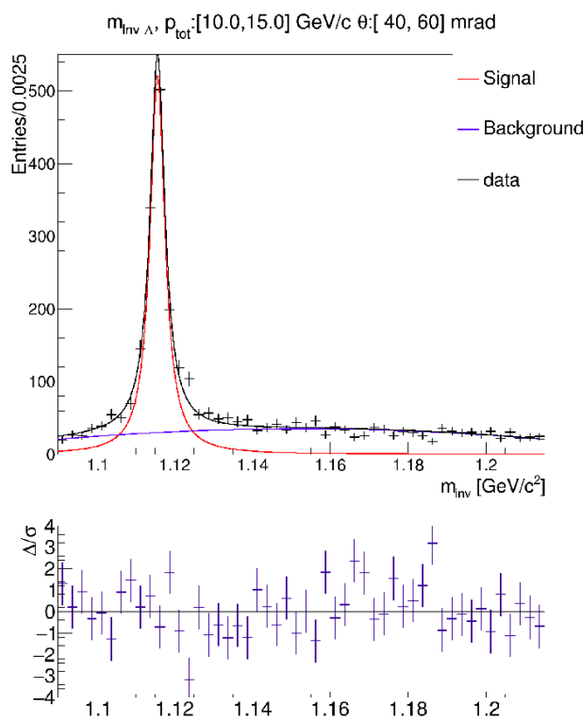
B. Rumberger

- 2016: Higher magnetic field, no forward TPCs
- 2017: Lower magnetic field, full forward TPC system

Λ^0

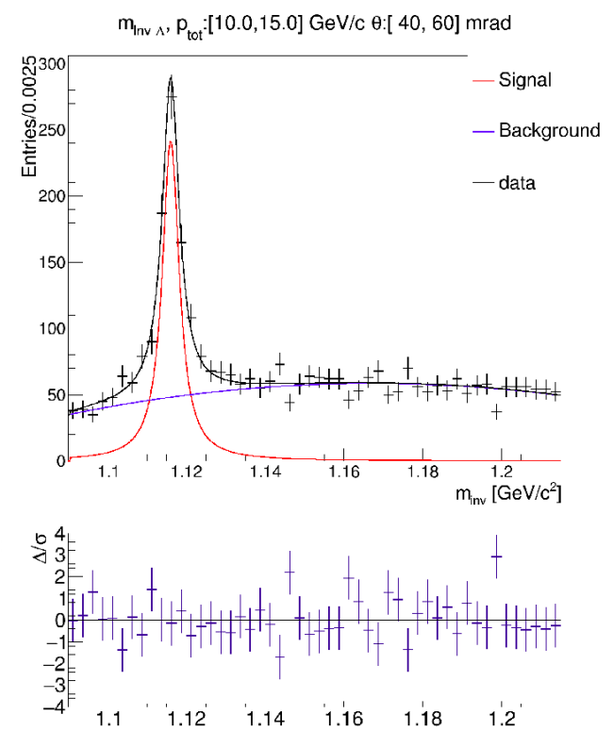
2016

	Fitted
N_S	1456.88
N_{BG}	1518.12
f_s	0.4897
m_0	0.0000
Γ	0.0023
c_1	-631.3202
c_2	1103.4291
c_3	-478.7071



2017

	Fitted
N_S	761.65
N_{BG}	2623.35
f_s	0.2250
m_0	0.0004
Γ	0.0026
c_1	-750.6588
c_2	1300.2512
c_3	-556.9631

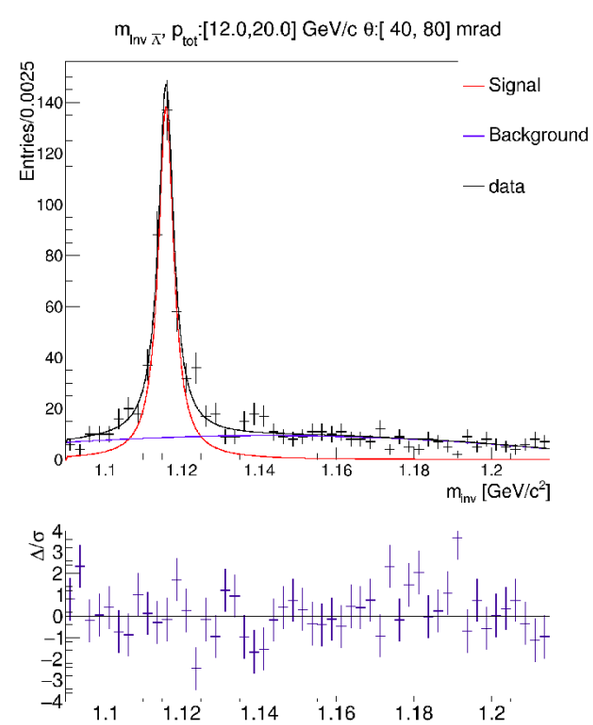


B. Rumberger

$\bar{\Lambda}^0$

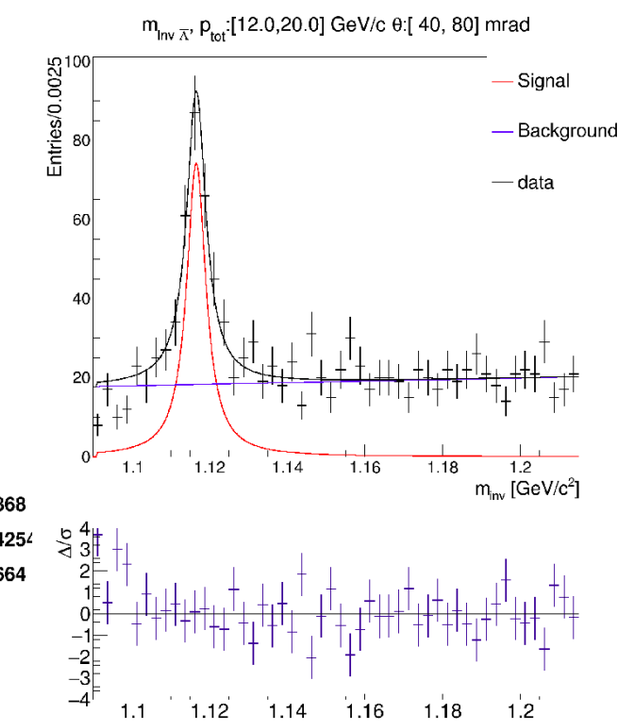
2016

	Fitted
N_S	401.00
N_{BG}	401.00
f_s	0.5000
m_0	0.0004
Γ	0.0024
c_1	-925.8070
c_2	1633.0437
c_3	-714.8490



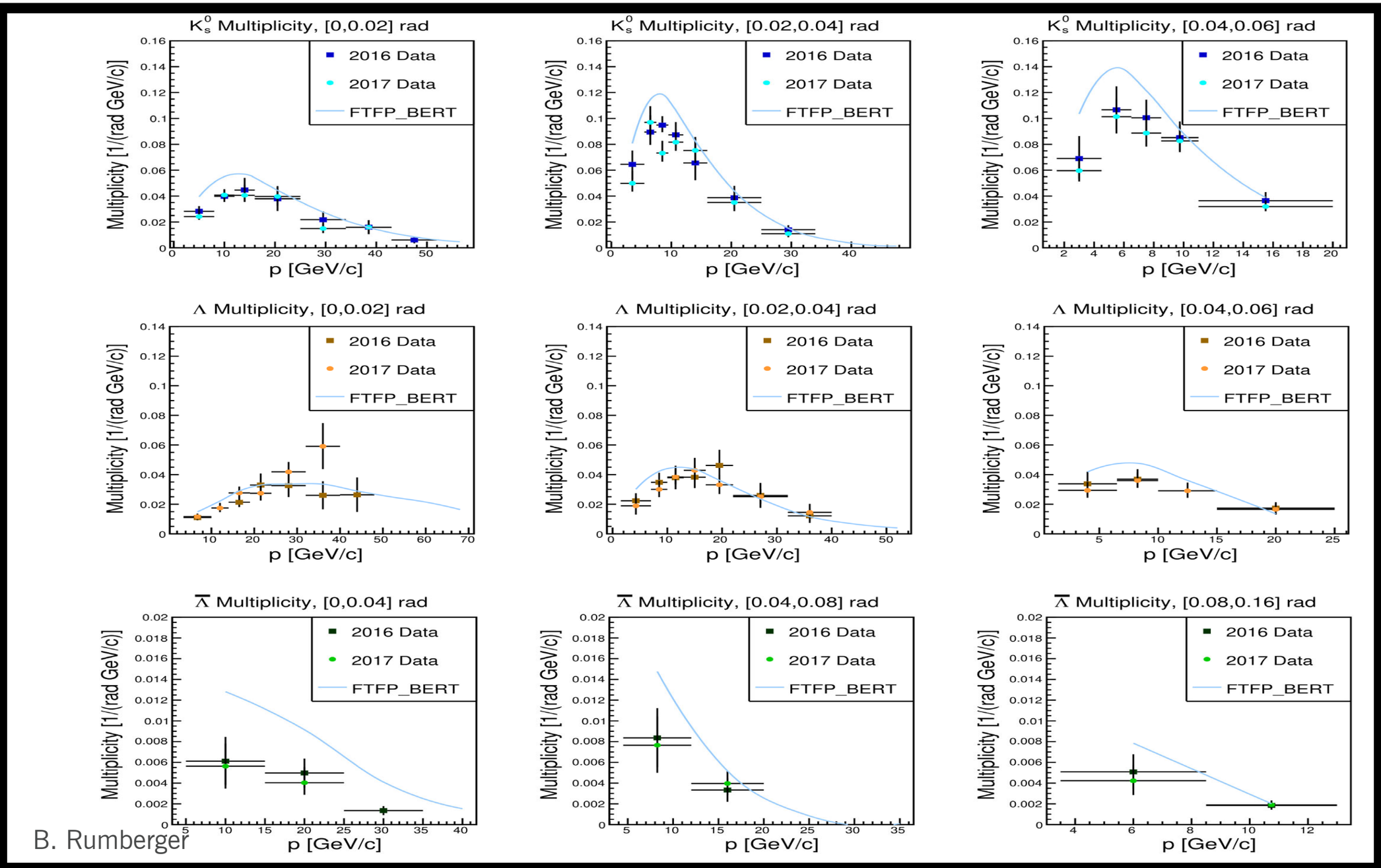
2017

	Fitted
N_S	268.42
N_{BG}	948.58
f_s	0.2206
m_0	0.0010
Γ	0.0030
c_1	6816.5868
c_2	11109.4254
c_3	9598.0664



B. Rumberger

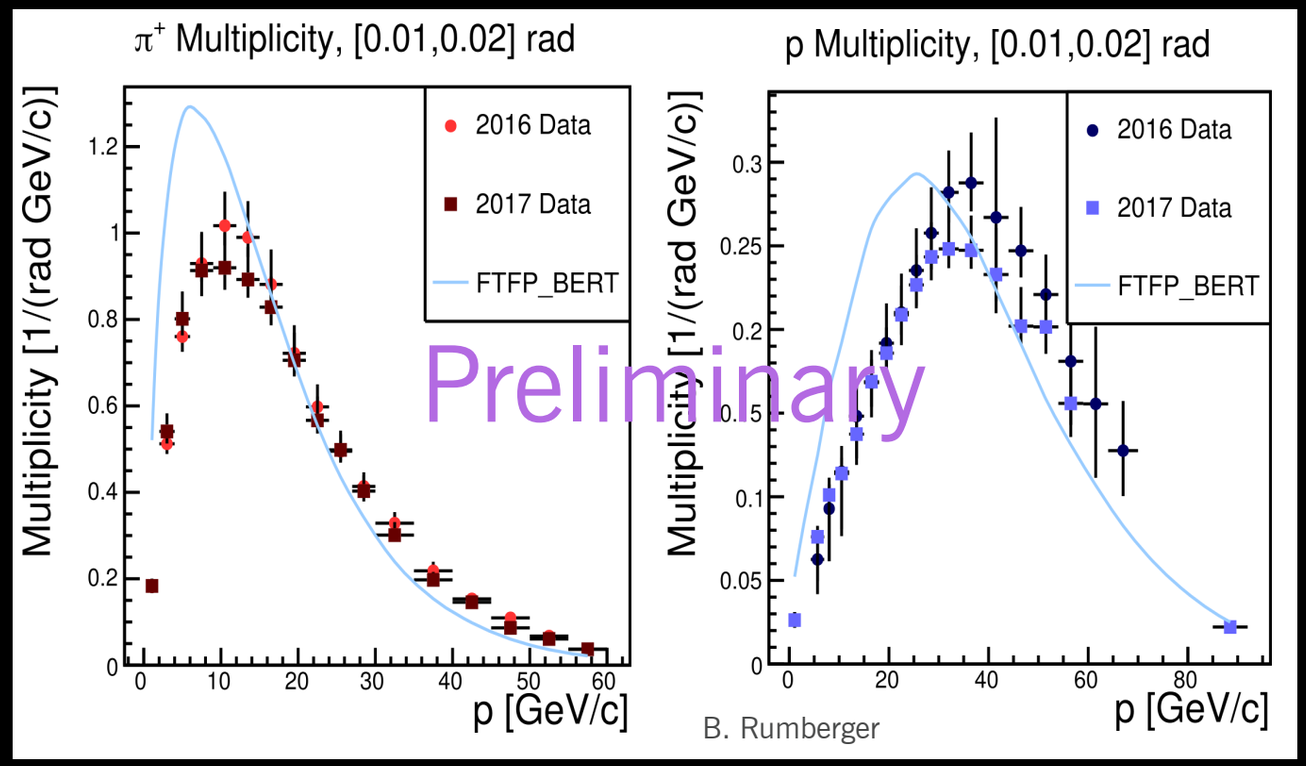
Multiplicity measurements

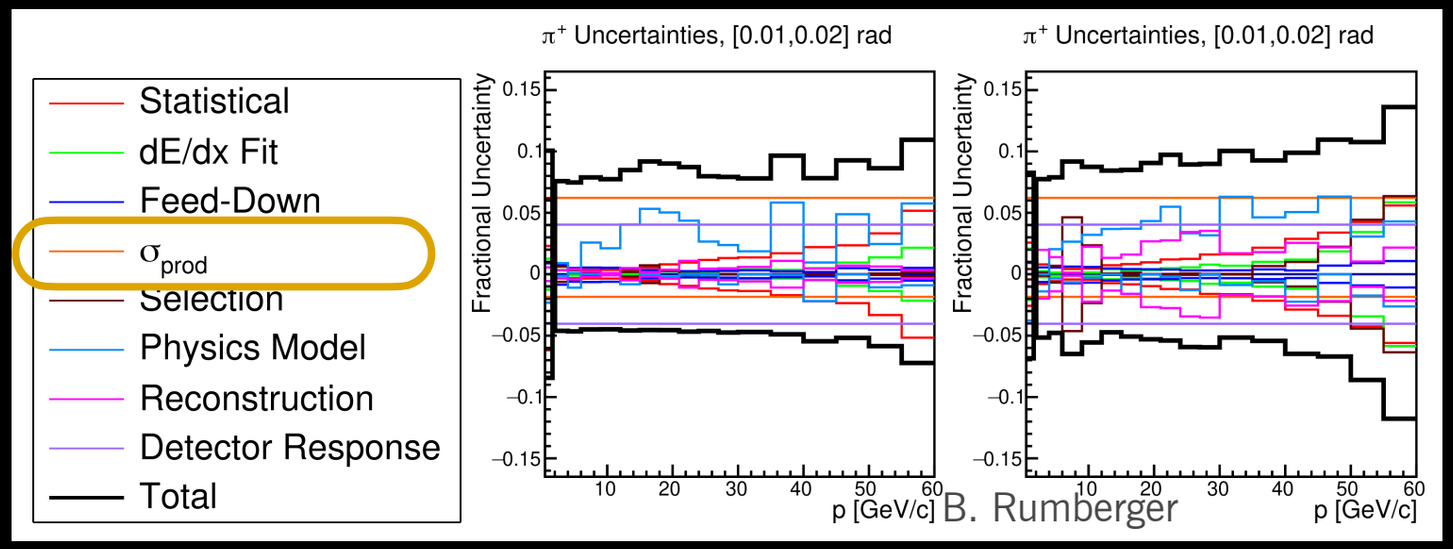


- 2016 and 2017 combined to optimize resolution while increasing phase space coverage

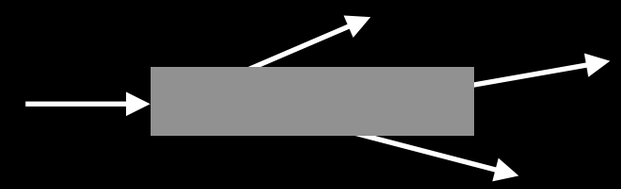
Coming soon: charged hadron multiplicities

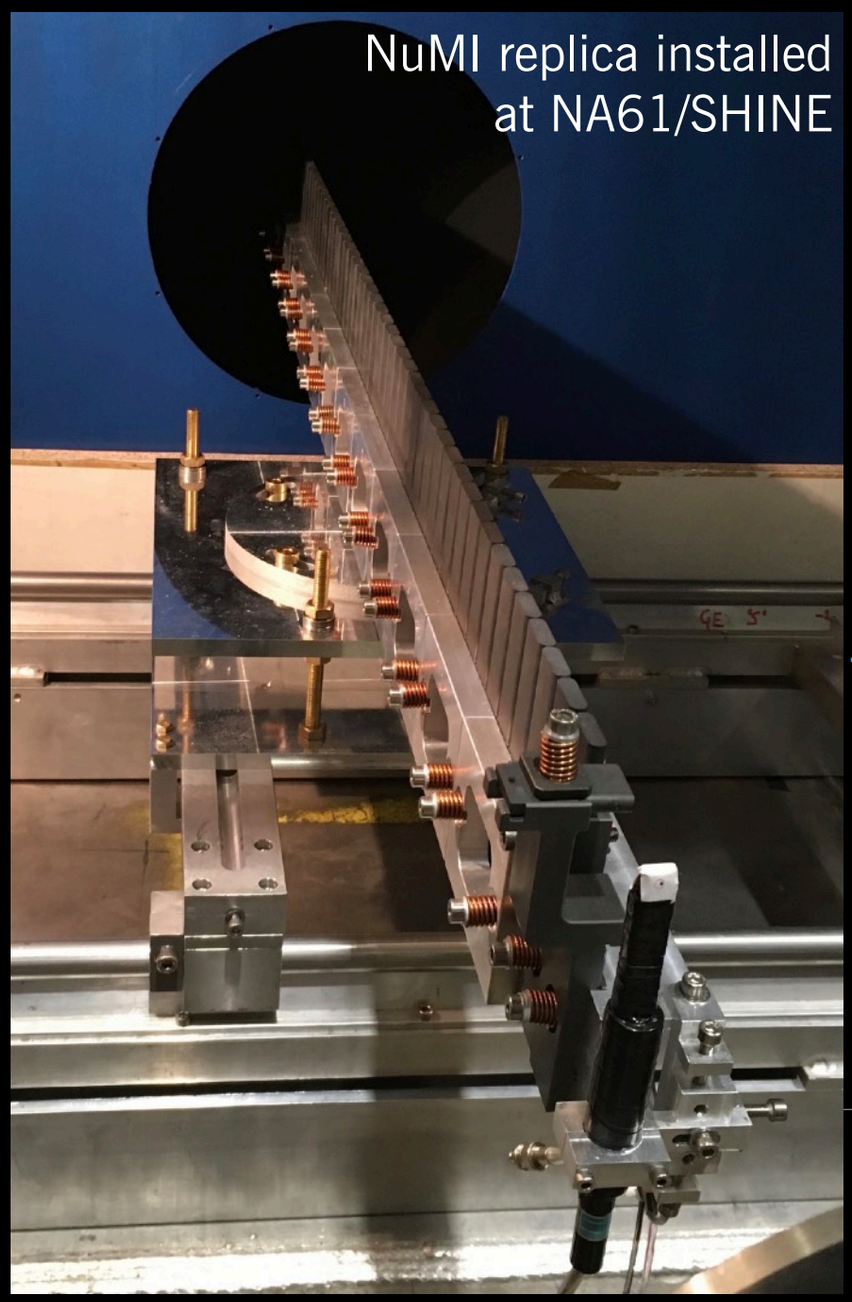
- Measured multiplicities: π^+, π^-, p, $\bar{p}$, K^+, K^-
- Neutral hadron multiplicities used to estimate backgrounds from with weak neutral decay products
- Two complementary data sets again combined for final multiplicity result
- Results will soon be used to reduce NuMI, DUNE beam flux uncertainties

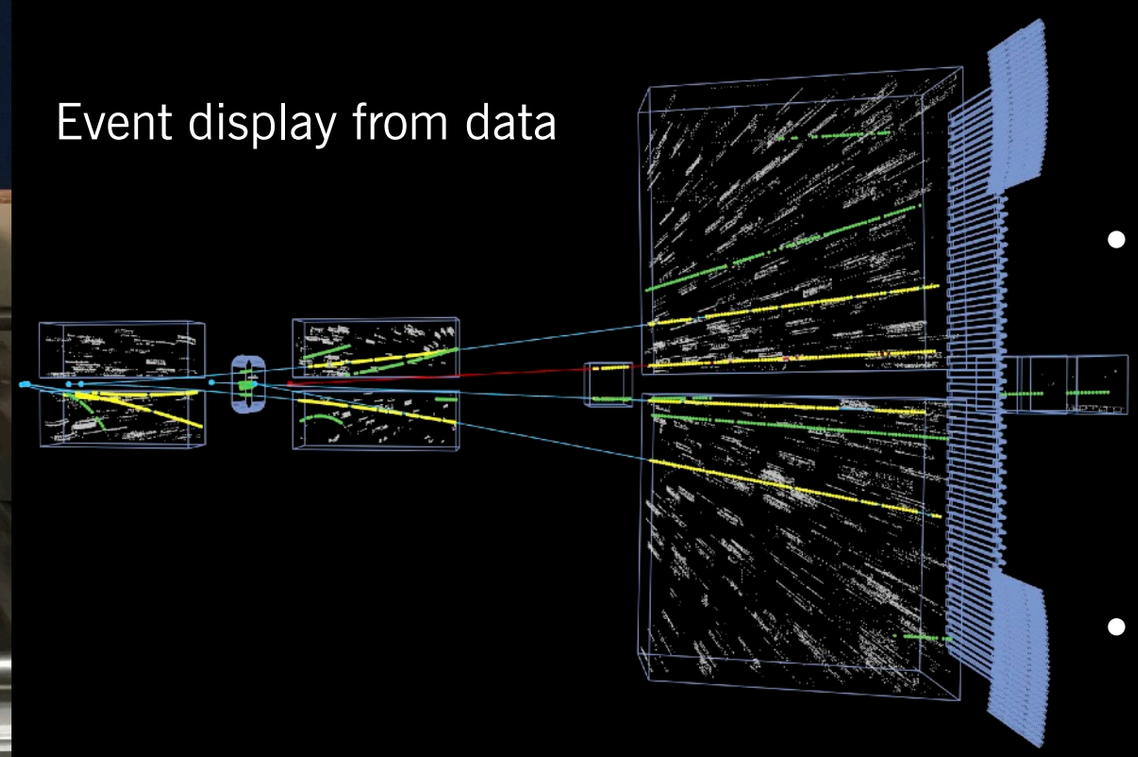




Coming soon: measurements with NuMI replica target



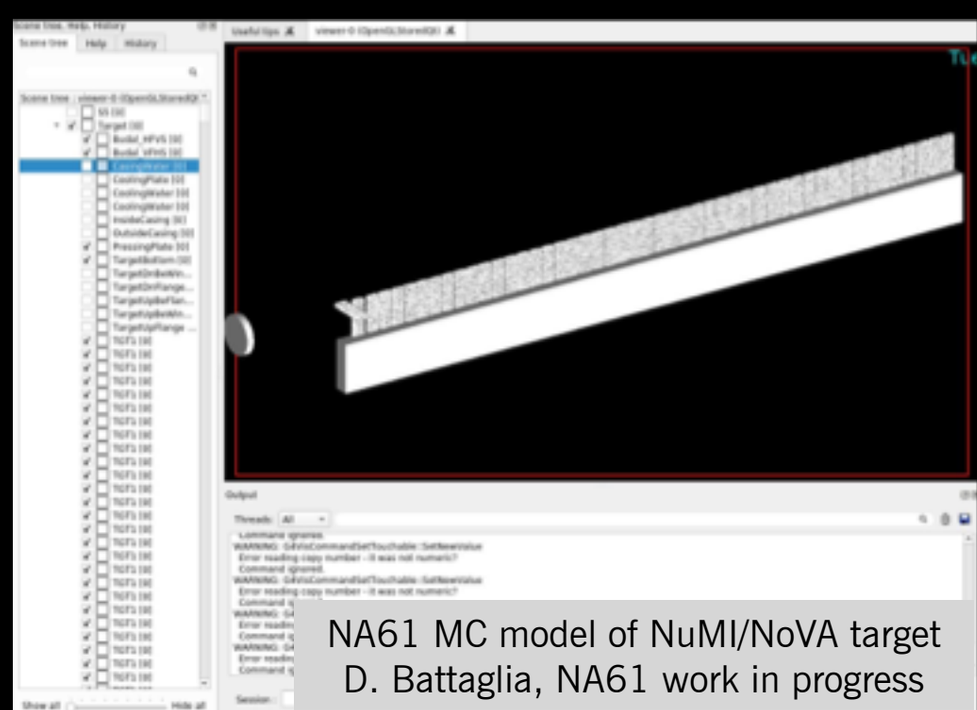




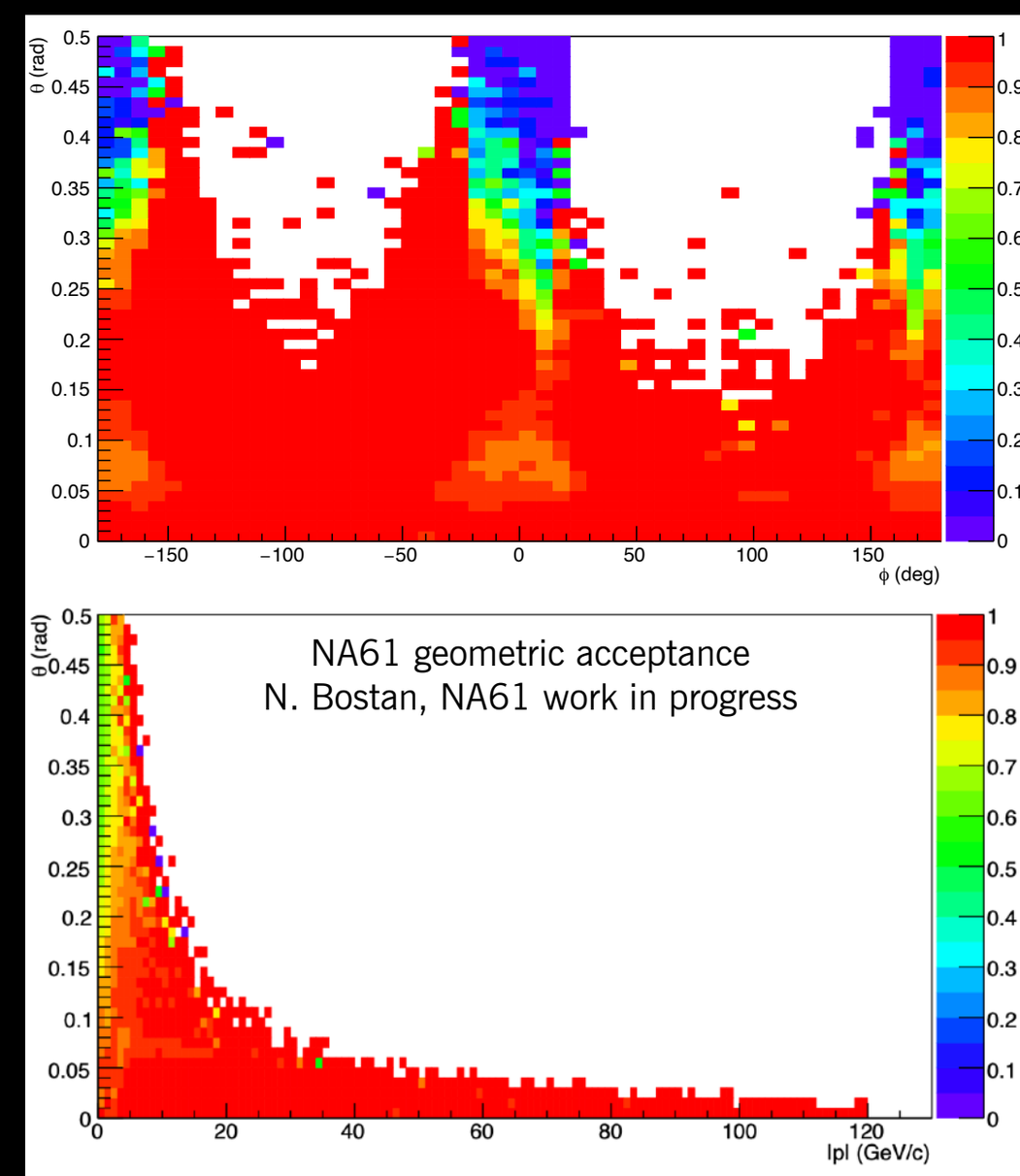
- Took high statistics (18M events) in 2018 with 120 GeV protons
- Analysis underway on hadron yields from this target
- Asymmetric design means binning in ϕ becomes important

NuMI target analysis

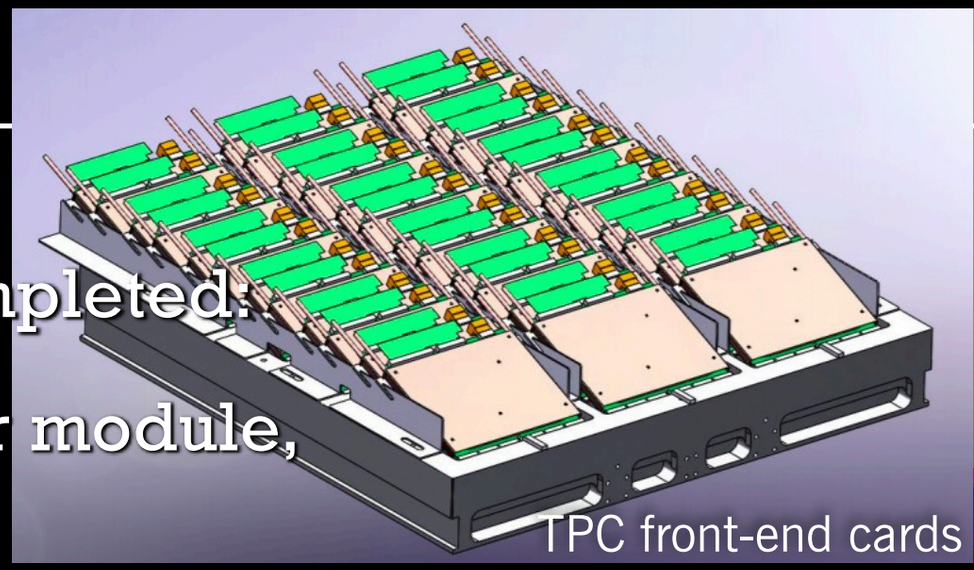
- Calibration of detectors underway
- Main challenge is the very complicated geometry of the target, with azimuthal dependence
- NA61 acceptance is not uniform due to dipole analysis magnet!



NA61 MC model of NuMI/NoVA target
D. Battaglia, NA61 work in progress



Third phase: upgraded detector



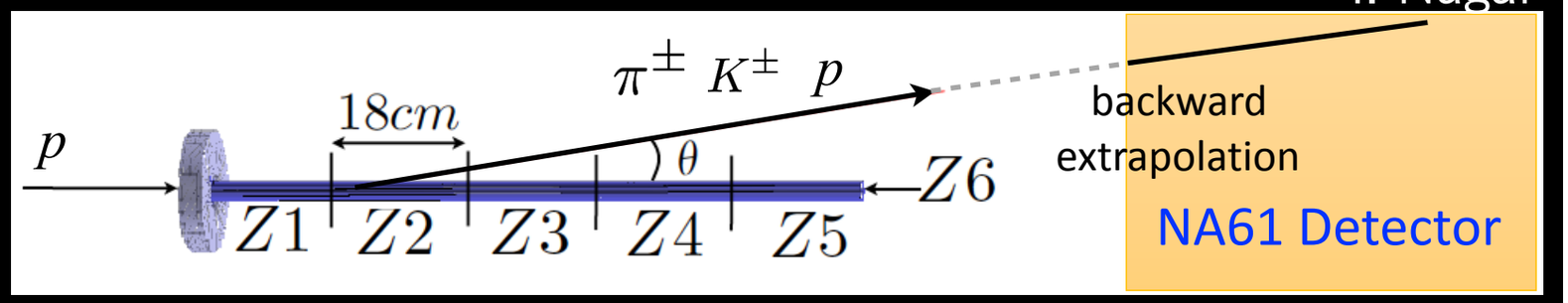
- Many major detector upgrades recently completed:
  - New forward Projectile Spectator Detector module, reconfiguration of existing detector
  - Replacement of old TPC electronics with system from ALICE
  - New silicon vertex detector for open charm studies
  - RPC-based replacement for TOF-L/R walls
  - New beam position detectors
  - New trigger/DAQ, combined with new electronics, will give a major upgrade in data collection rate (~100 Hz → ~1 kHz)

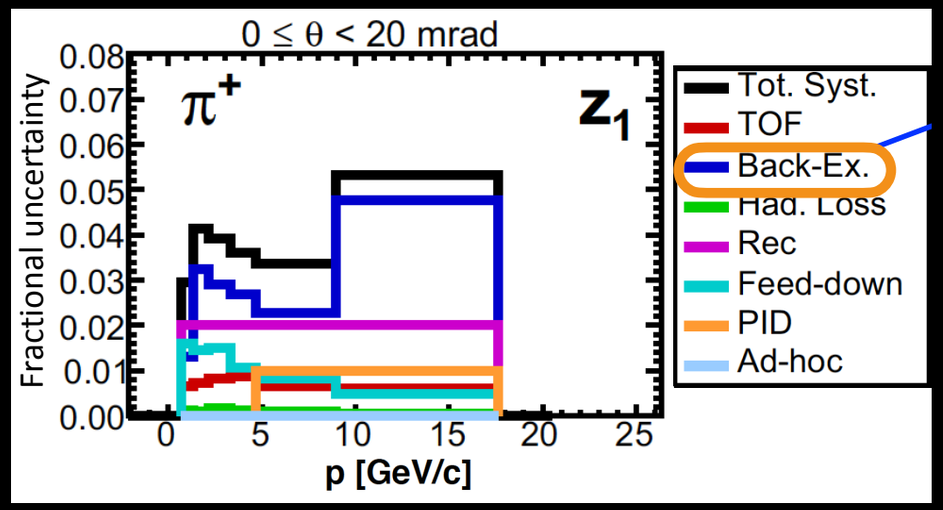
Data collection: now and near future

- **Data collection has begun!**
  - 31 GeV/c protons on T2K replica-target in 2022: 180M events (nearly 20x 2010 statistics) to measure high-momentum kaon yields
  - 2023-2025:
    - Kaon scattering with thin targets for secondary interaction modeling; 120 GeV proton on titanium
    - LBNF/DUNE replica target (2024). This target will be at least 1.5 m long and may create some challenges for reconstruction. Planning an additional close-up tracking detector to help this.
    - Improved statistics as needed on multiple measurements

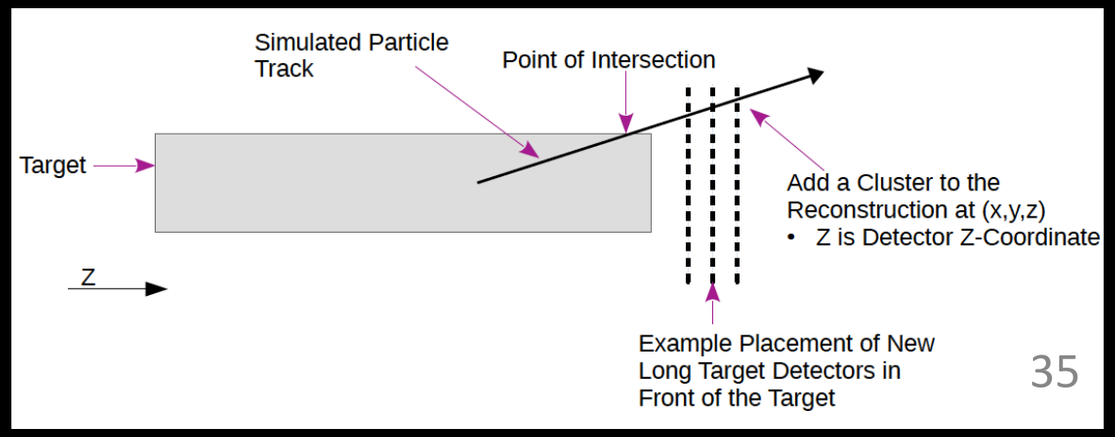
Long-target tracker

Y. Nagai





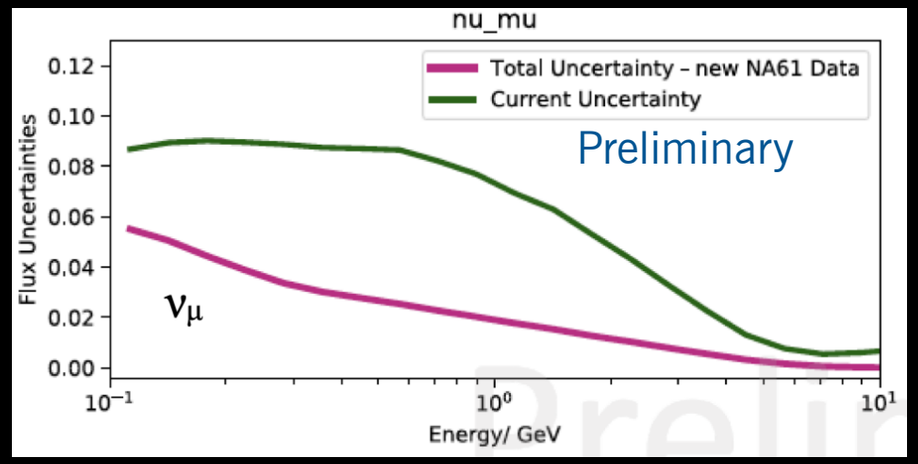
- A leading systematic error with the T2K replica target has been extrapolation of shallow-angle tracks backward to the target surface
- Additional tracking detectors at the end of the target will probably be needed for the longer LBNF/DUNE target as well as a more precise measurement for T2K
- Considering options such as silicon planes or a (more likely) a small TPC



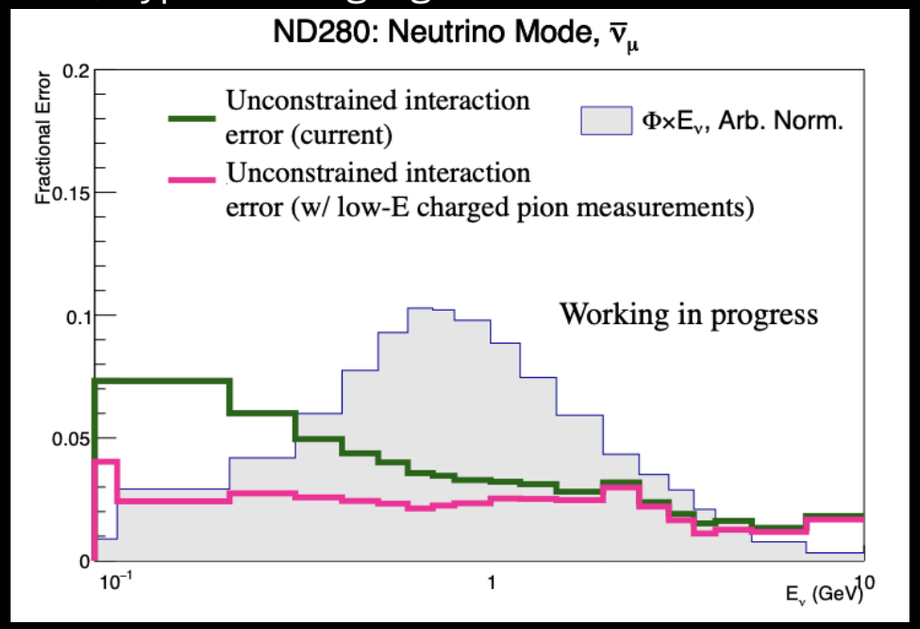
Future after LS2/3: low-energy beam?

- Many groups are interested in hadron production with beams in the 1-20 GeV region, below the range the current H2 beam is capable of providing
  - Atmospheric neutrino flux
  - T2K/HyperK secondary interactions
  - Spallation sources, cosmic rays, others…
- Beam modifications under design at CERN, project being formed now after positive response from SPSC

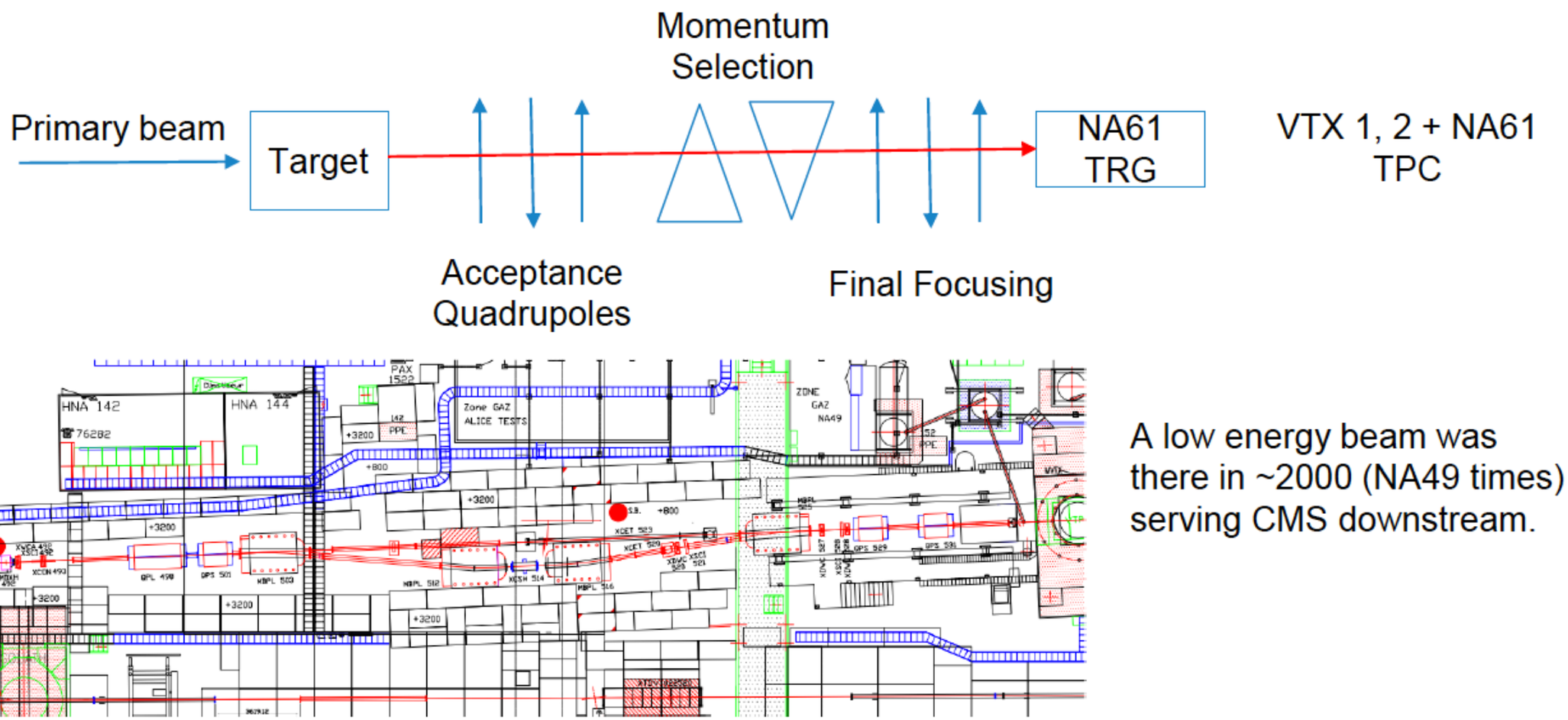
L. Cook (Bartol Group) atmospheric neutrino flux



T2K/HyperK wrong-sign flux uncertainties



Principle of a low-energy beam for NA61/SHINE



- New beam design ongoing by CERN beam group in collaboration with NA61/SHINE.
- Goal is to have beam available in 2025, and again after the next Long Shutdown

Conclusions

- Neutrino beams are a technical and operational challenge
- Neutrino beams have flux systematic errors that may limit analysis precision
- NA61/SHINE has provided unique and critical data to support the global neutrino program
  - More data sets coming in the next three years, with T2K and LBNF/DUNE targets
  - Low-energy beam and other future options under study

NBI WORKSHOP: EDITORIAL/ PLUG/ACKNOWLEDGMENT

- Neutrino Beams and Instrumentation (NBI)
- This is an excellent workshop series, with a highly practical focus. Everyone involved or interested in neutrino beams should attend! Comments overheard:
  - “There are fifty people in the world who know exactly what I do. They are all here.”
  - “In the spirit of NBI, let me tell you what went wrong as well as what went right.”
  - “The only workshop I really look forward to every year.”
- NBI is held every 1-2 years, and rotates between FNAL, CERN/Europe, and Japan.
- Last held September 2022 at Abingdon/RAL, UK. Next will be in Japan.
- Archive of talks from past workshops is a great resource.

OTHER RESOURCES

- The original van der Meer article: *"A Directive Device for Charged Particles and Its Use in an Enhanced Neutrino Beam"* CERN-61-07 (1961)
- Proceedings of CERN Informal Workshops on Neutrino Physics, 1963, 1965, and 1969
  - The 1965 proceedings are particularly useful: most of what became modern neutrino beam design and engineering is here in an accessible format!
  - R. Palmer, *"Magnetic Fingers,"* p. 141-145 gives a very accessible derivation of conical horn conductor
- A great review article: Sacha Kopp, *Physics Reports,* **439** 101-159 (2007)