Following ALICE's Footsteps: A Modern Tale of Neutrino Interactions in the Few-GeV Realm

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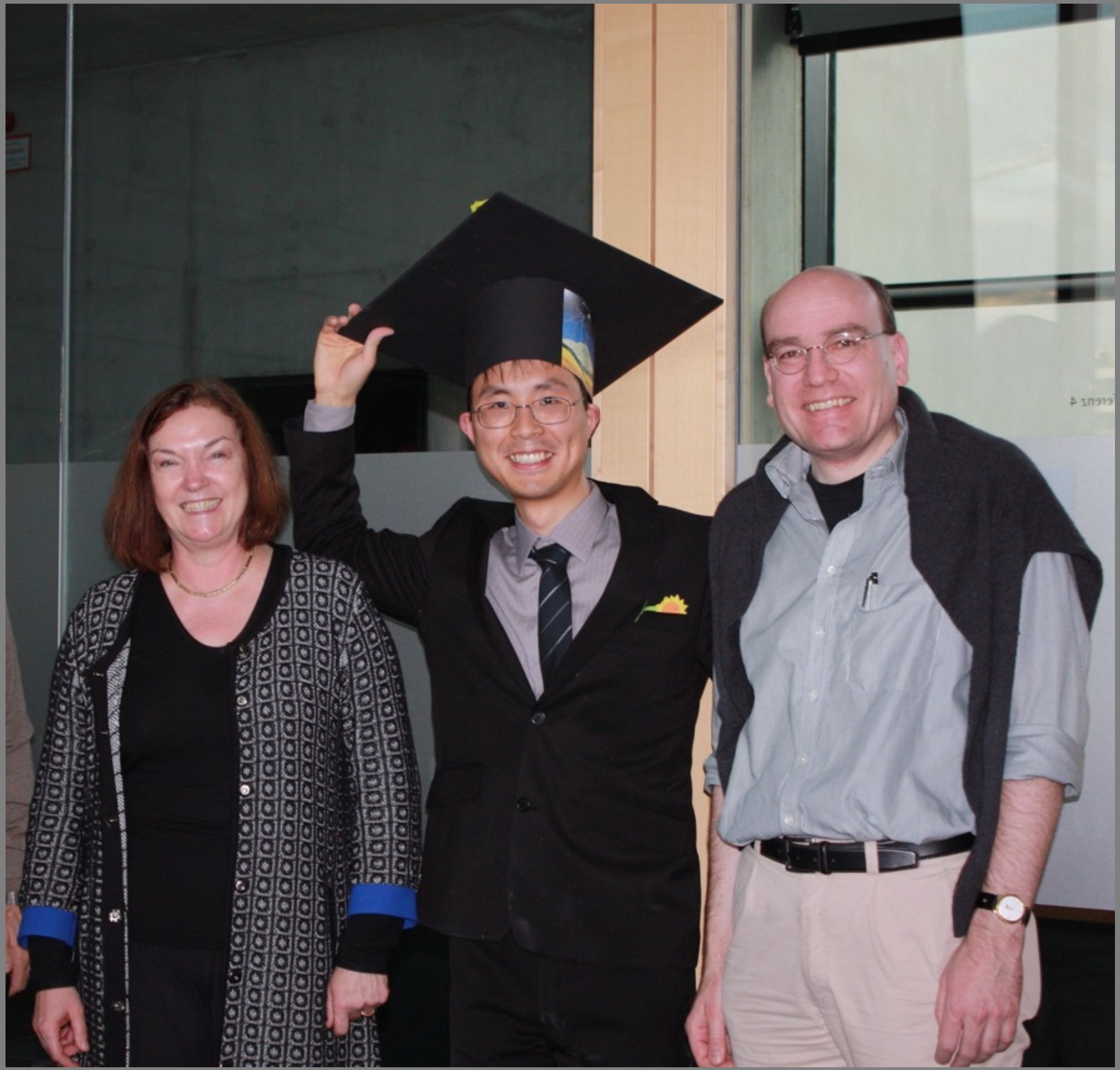
University of Warwick

Never at Rest: A Lifetime Inquiry of QGP
Celebrating the 70th birthday of Prof. Johanna Stachel

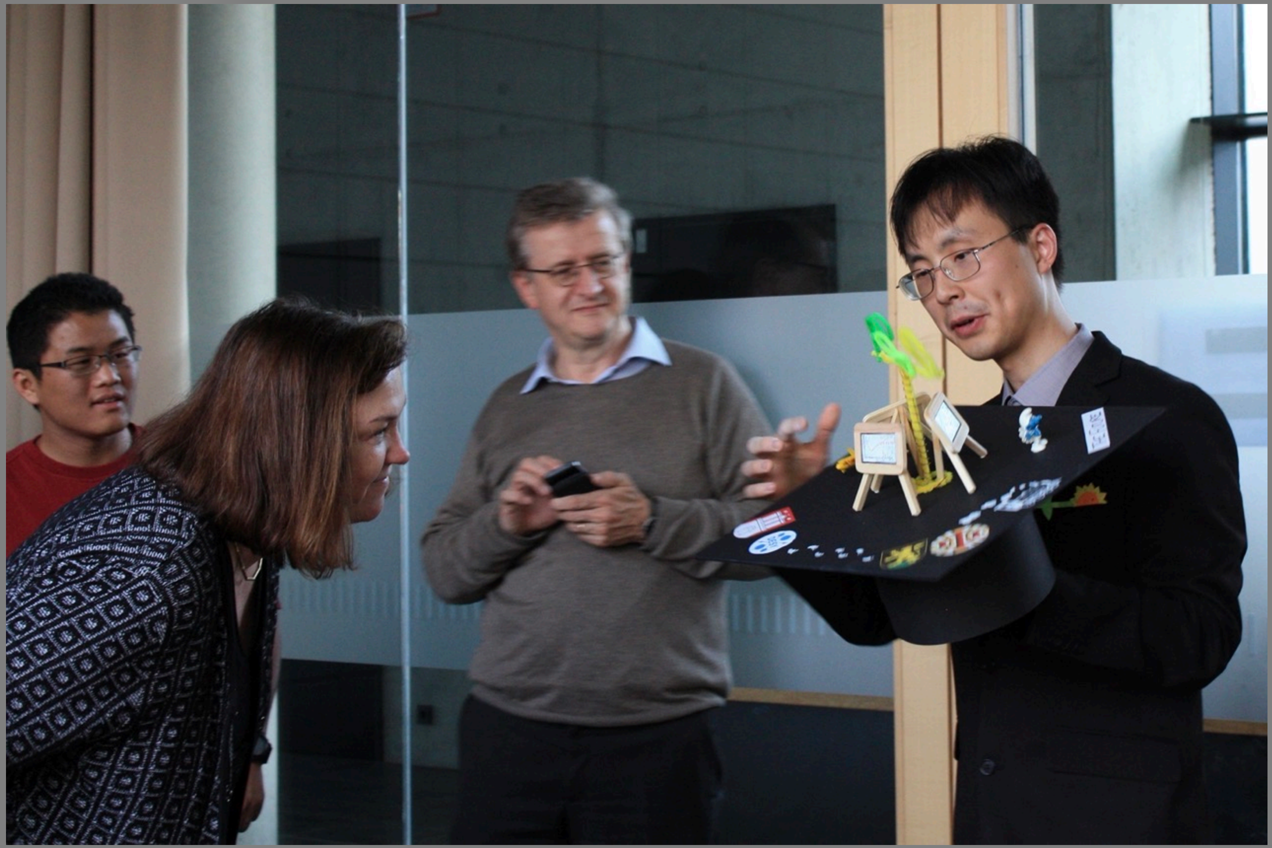
2025 February 10, Bad Honnef

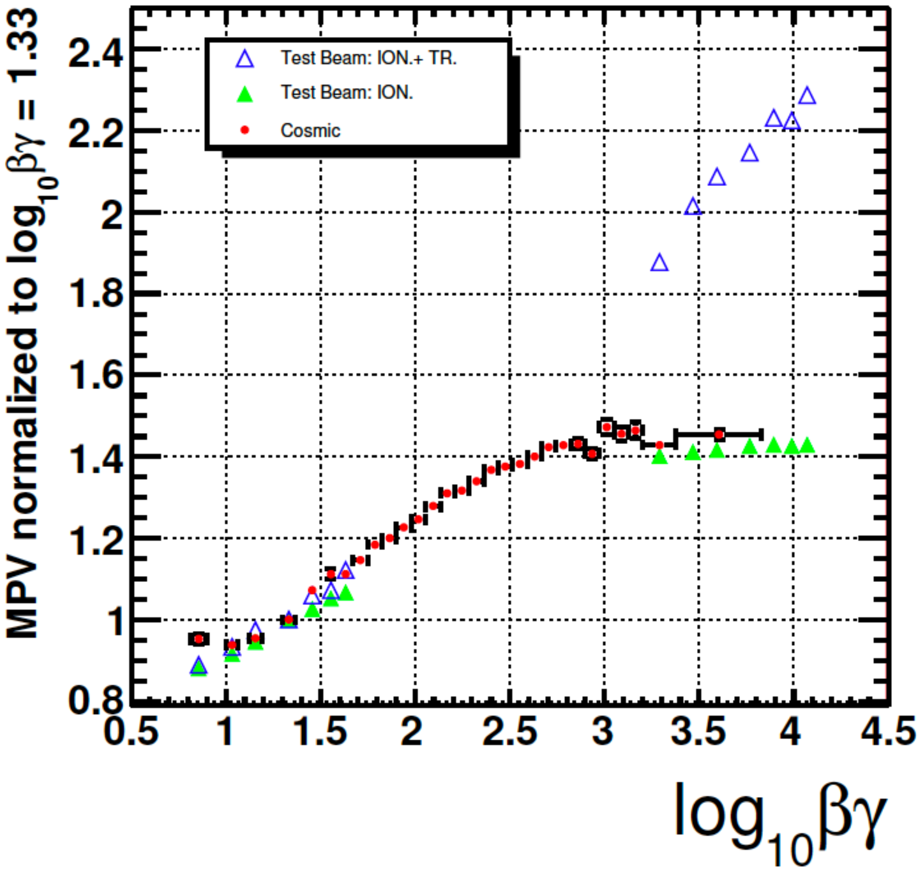


- ❑ Started PhD under Johanna in September 2009
- ❑ Thesis defence in October 2013
- ❑ First PostDoc until August 2014, then moved to neutrino

Member of neutrino experiments w/ GeV neutrinos, in particular:

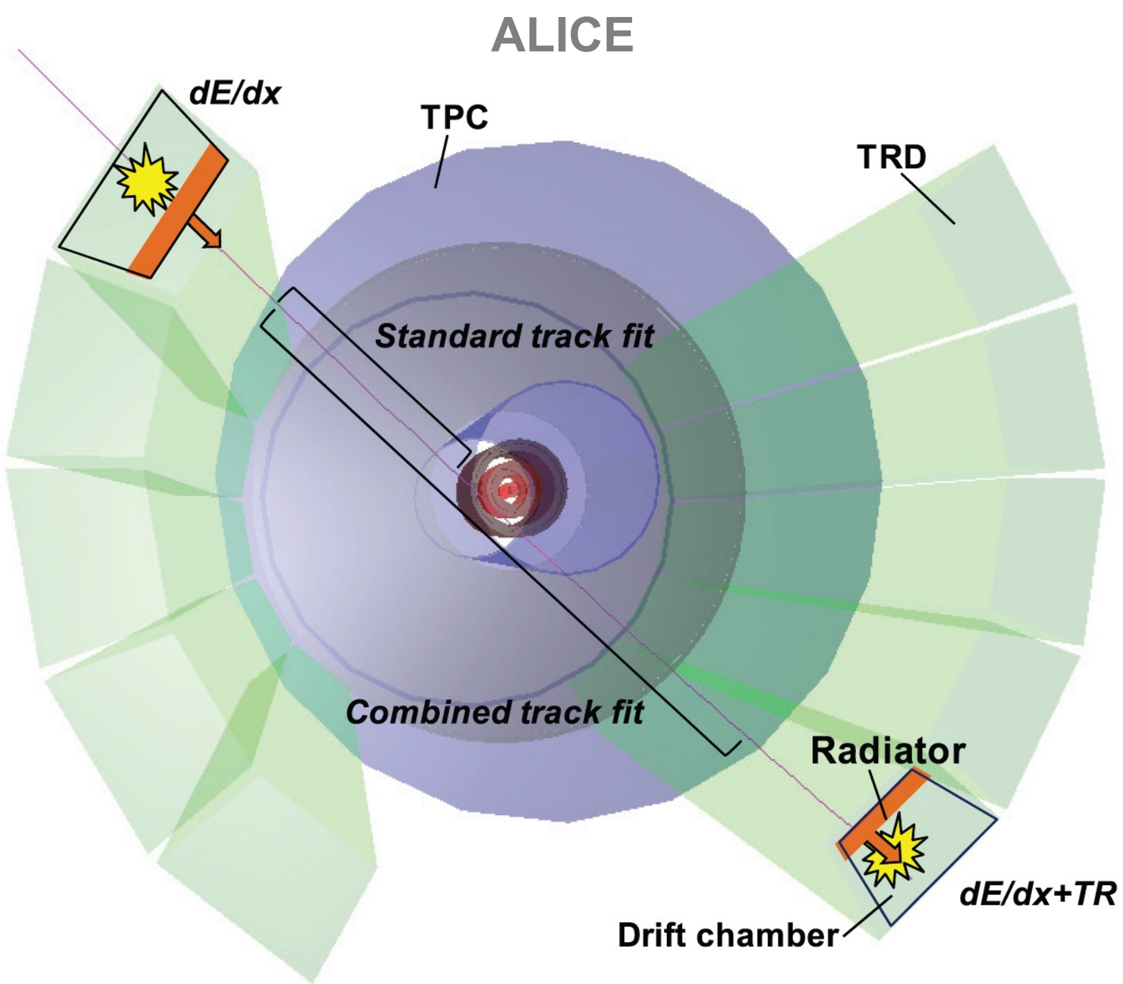
- ❖ nuSTORM (neutrinos from STORed Muons)
- ❖ JUNO (Jiangmen Underground Neutrino Observatory)

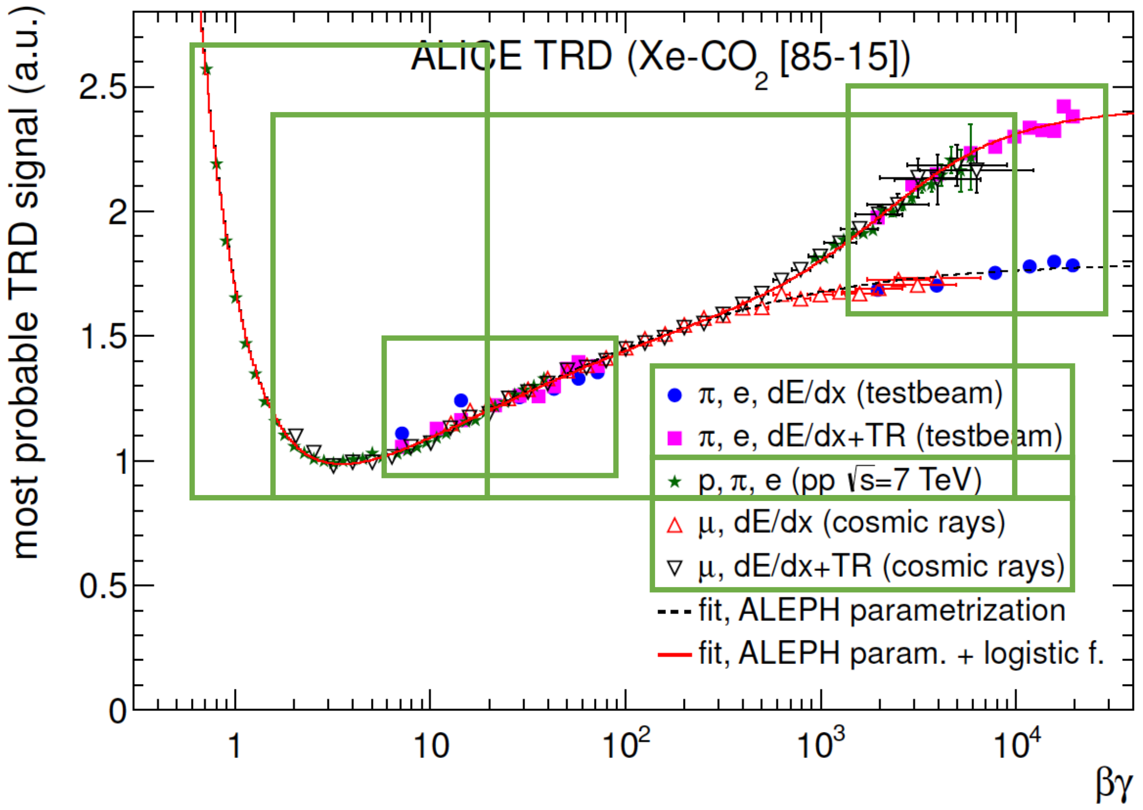




- A plot from ~ 1 June 2010
- MinJung and I were trying to understand transition radiation (TR) in full ALICE set up with cosmic muons
- We were surprised that the TRD signal was consistent with *pure* dE/dx from test beam…
- We tried very hard to understand it and in the end, I sent an email

  "Anton, do you think the *theory* of TR could be wrong?"





One of my thesis topics: ALICE TRD performance in full ALICE set up

- ❑ Turned out could measure onset of TR → in vs. out cosmics
- ❑ Need TPC tracking up to TeV → combined track fit
- ❑ Need MIP for energy scale → dedicated cosmic data with B = 0.1 T

Outline

1. Problems and opportunities with neutrino masses
   - Call for a GeV ν_e and $\bar{\nu}_e$ machine: nuSTORM

2. Using lepton-hadron correlations to study GeV neutrino interactions
   - Transverse Kinematic Imbalance (TKI)

3. JUNO news!

Neutrino Mass and Mixing

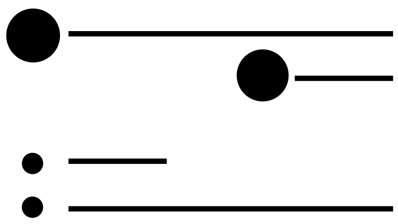
Standard Model | Beyond Standard Model

$$\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix} = \text{PMNS matrix} \begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

Mass Ordering



Normal **Inverted**

Δm^2 leads to neutrino oscillations

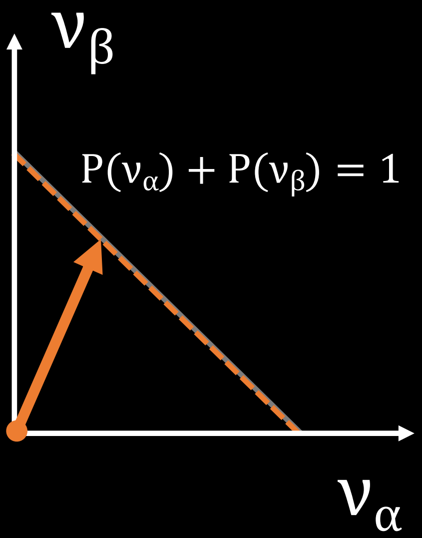
Problems

- ❑ What are the neutrino masses?
  - ❖ Mass gaps (Δm_{21}^2, $|\Delta m_{32}^2|$) and ordering (sgn Δm_{32}^2)?
- ❑ What are the mixing parameters?
  - ❖ Mixing angles (θ_{12}, θ_{23} , θ_{13}) and CP-phase (δ_{CP})?

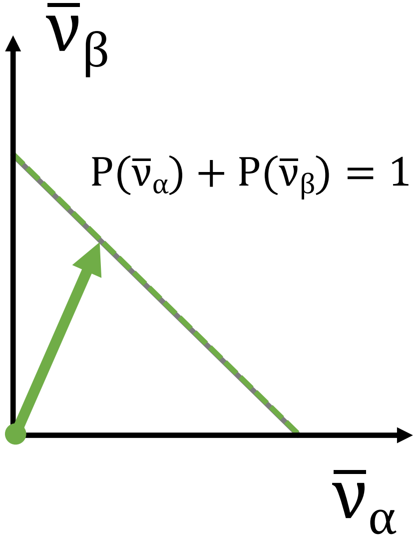
$\theta_{13} = 0$

2-flavor oscillation

Neutrinos



Antineutrinos

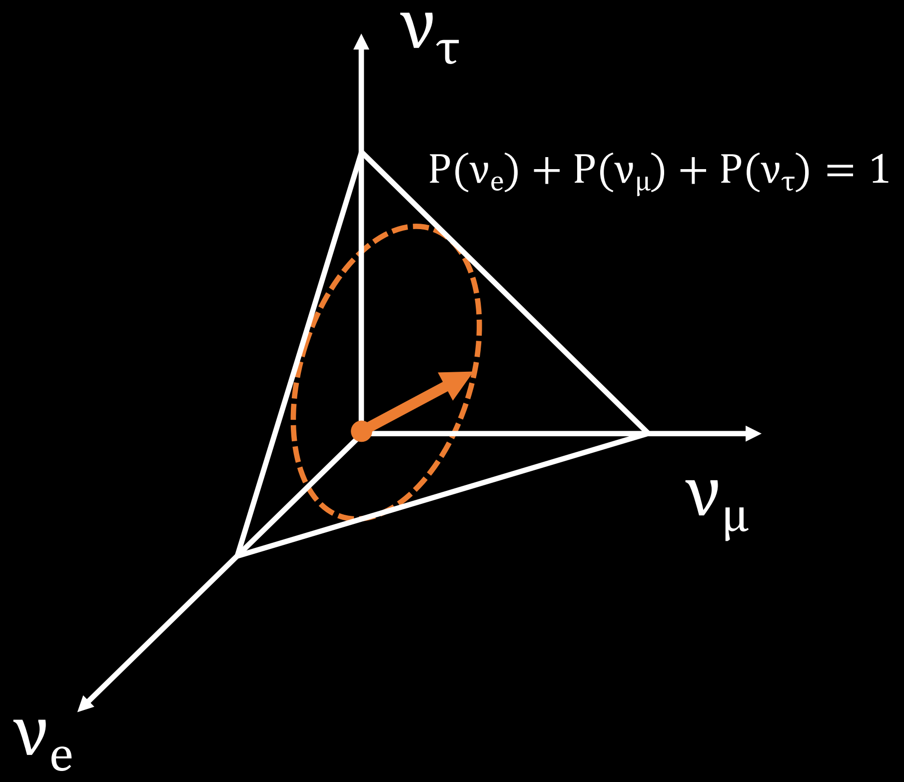


- ❑ 2-flavor oscillation: CP not observable

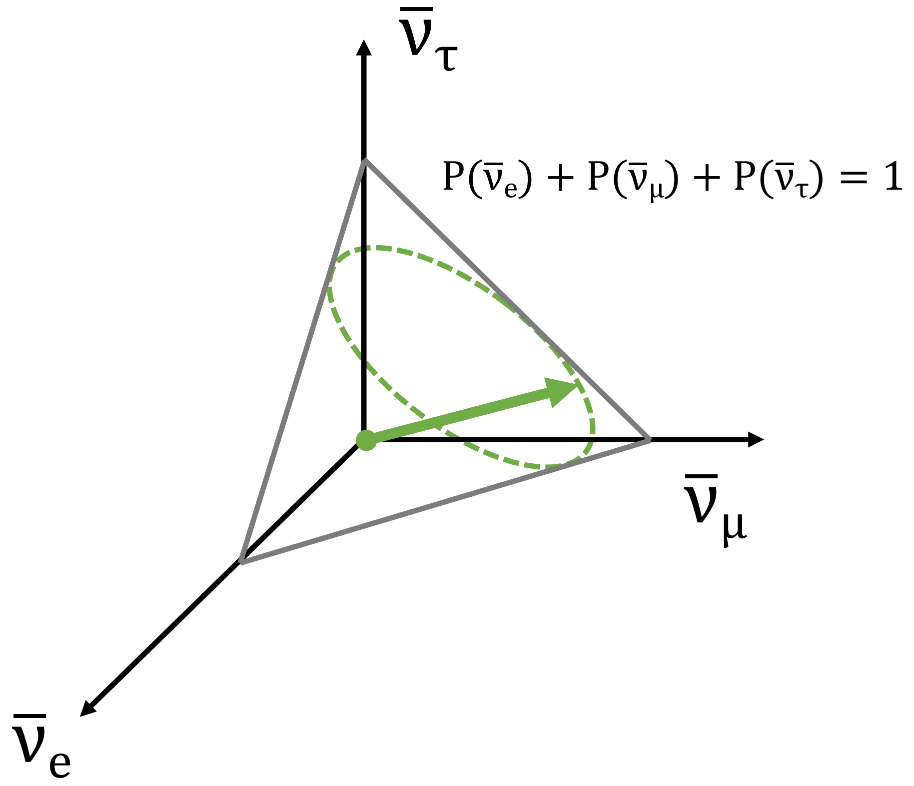
$\theta_{13} \neq 0$

3-flavor oscillation

Neutrinos



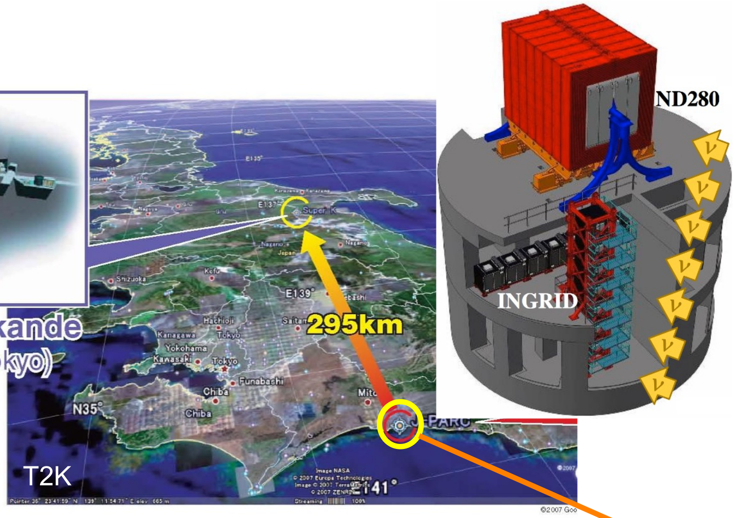
Antineutrinos



Opportunities

- ❑ 3-flavor oscillation: CP-violation possible

Accelerator Neutrino Experiments

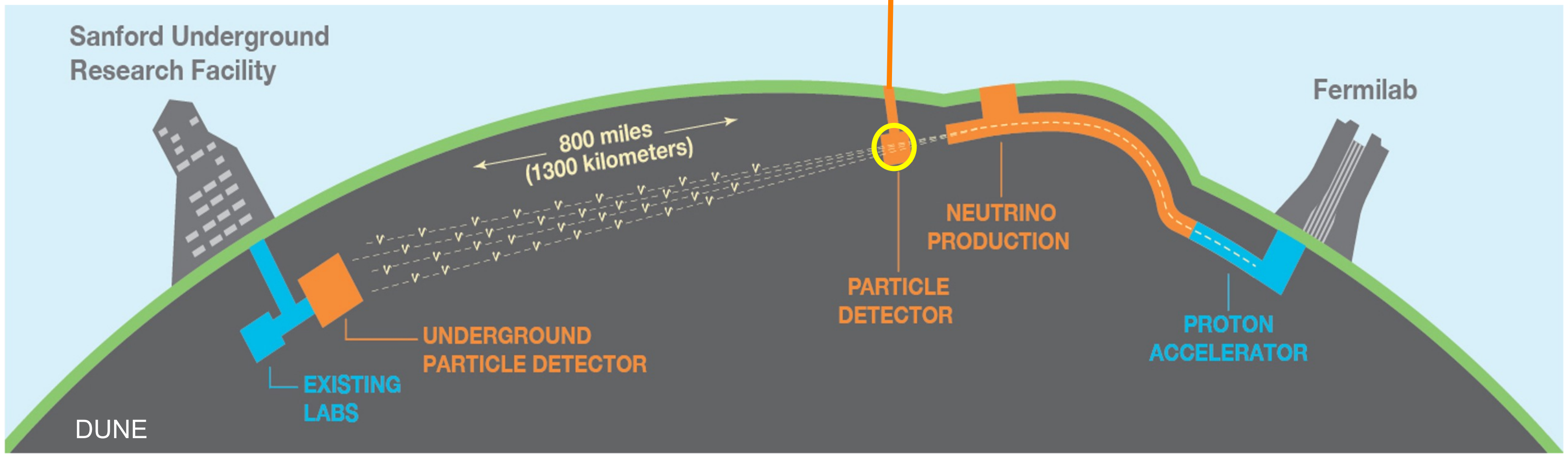


T2K / Hyper-K

NOvA

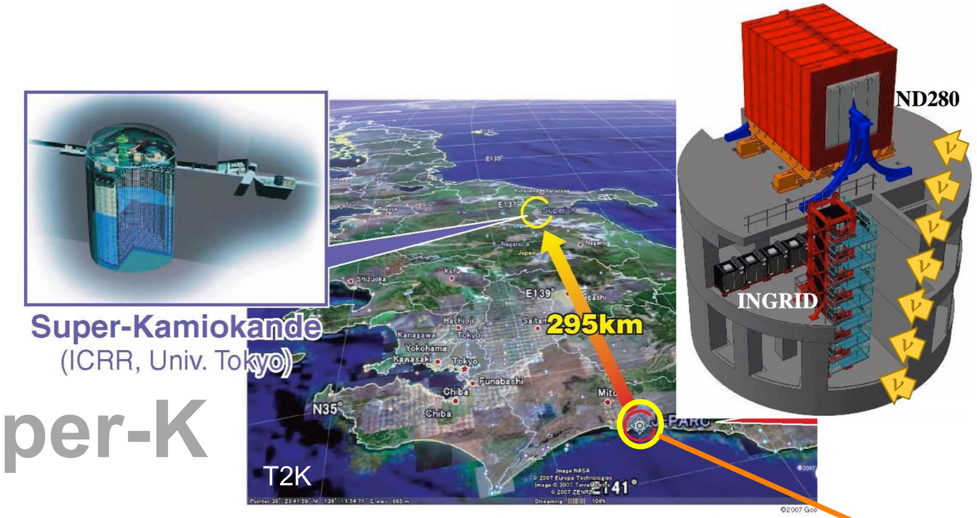
ν beams via hadron decay

DUNE



Accelerator Neutrino Experiments

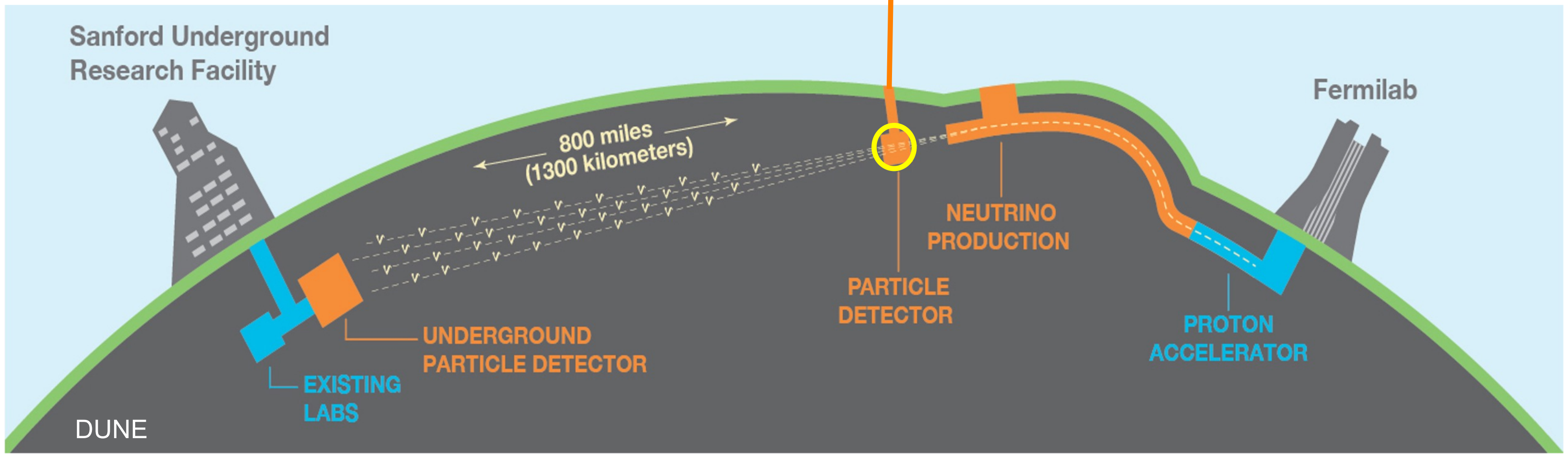
T2K / Hyper-K



NOvA

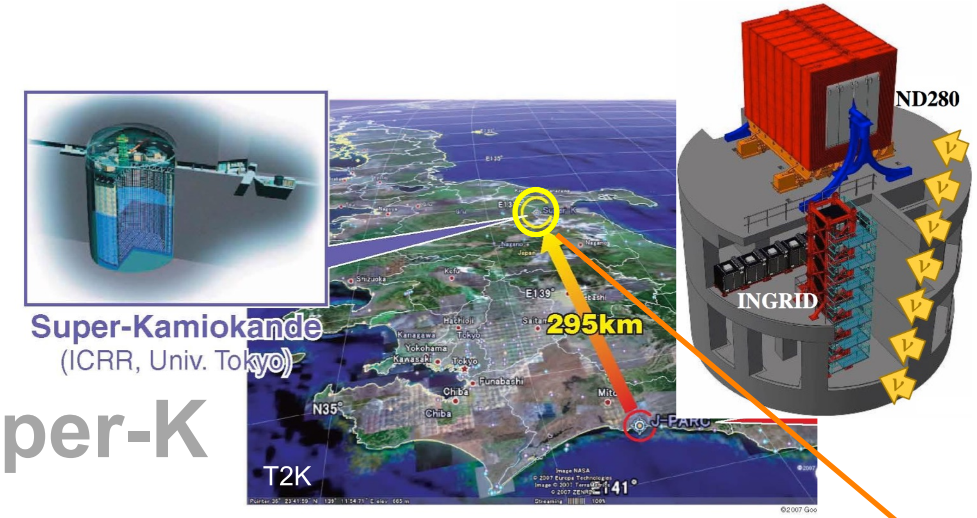
Near Detectors to constrain ν flux ***and*** cross section ***together*** (no oscillation)

DUNE



Accelerator Neutrino Experiments

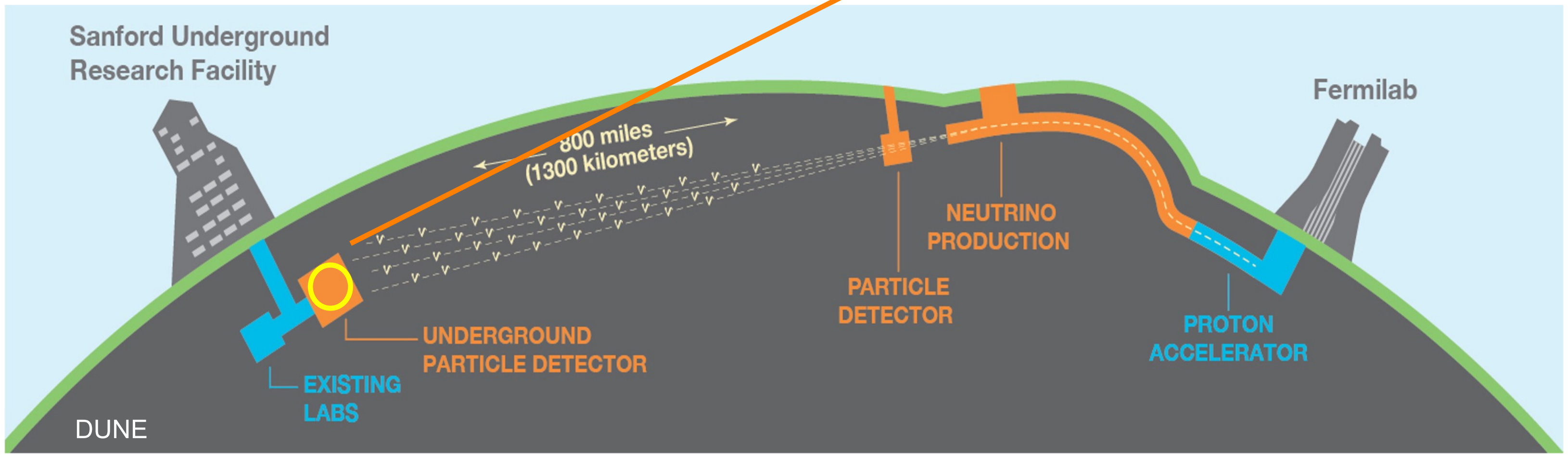
T2K / Hyper-K



NOvA

Far Detectors to measure ν oscillation

DUNE



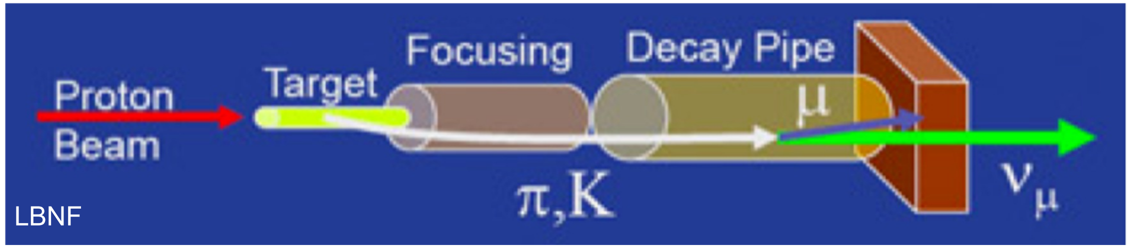
Accelerator Neutrino Experiments

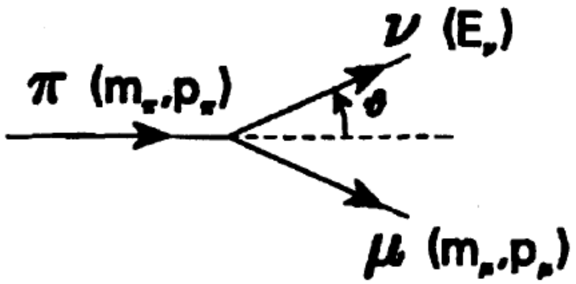
Accelerator ν Experiment	E_ν/GeV @ Flux Peak	Far Detector Technology	Target Nuclei
T2K / Hyper-K	0.6	Water Cherenkov	H_2O
NOvA	2	Liquid Scintillator	CH
DUNE	2.4	LAr TPC	Ar

Signal = (**Beam flux** · **Oscillation probability** · Cross section) ⊕ Detector effects

- ❑ Beam: ν_μ and $\bar{\nu}_\mu$
- ❑ Oscillation
  - ❖ ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - ❖ **ν_e and $\bar{\nu}_e$ appearance, then CP violation**

Accelerator Neutrino Experiments





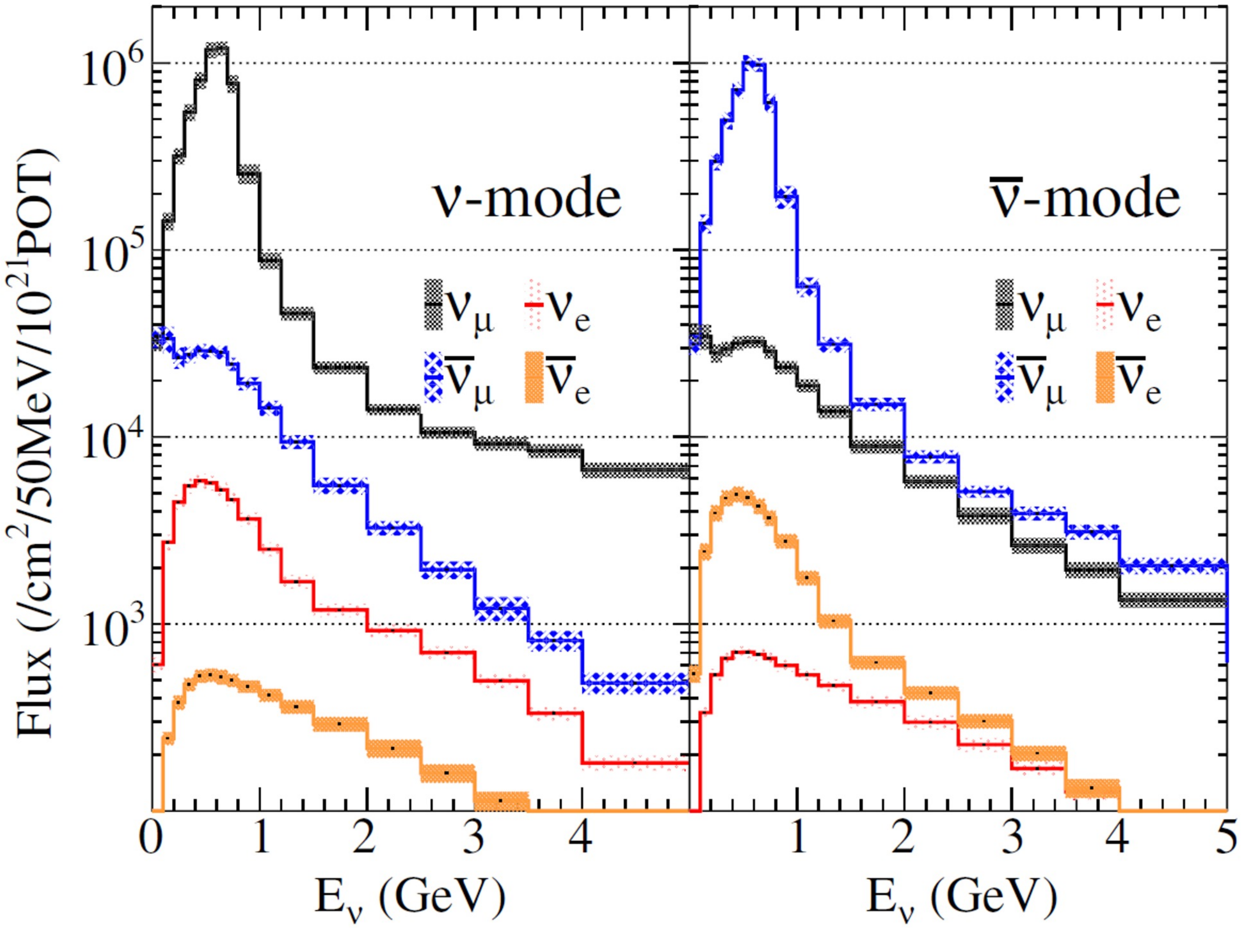
"β decay" of collision products
(ν_μ from π, ν_e from K)

Neutrino beams from accelerators
→ Directional

Charge selection on π
→ High purity ν or $\bar{\nu}$ beams

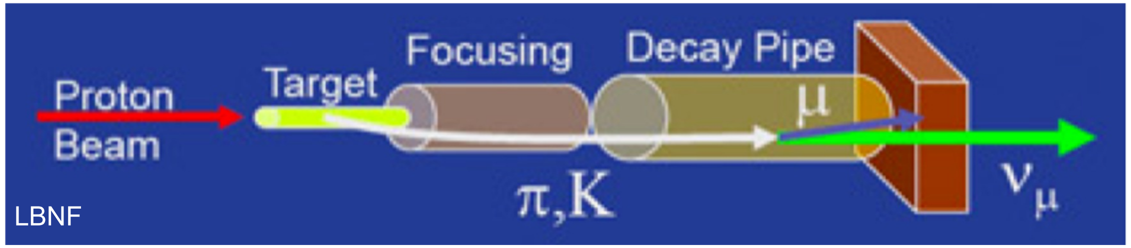
T2K flux

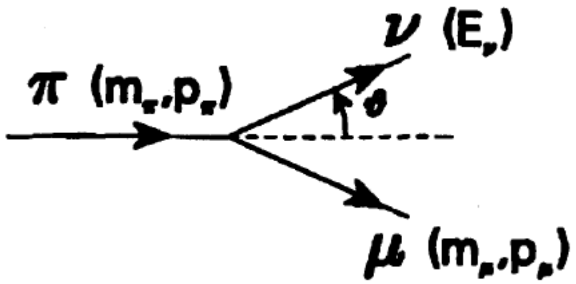
T2K, Phys.Rev.Lett. 116, 181801 (2016)



- ❑ Maximise ν_μ and $\bar{\nu}_\mu$ flux

Accelerator Neutrino Experiments





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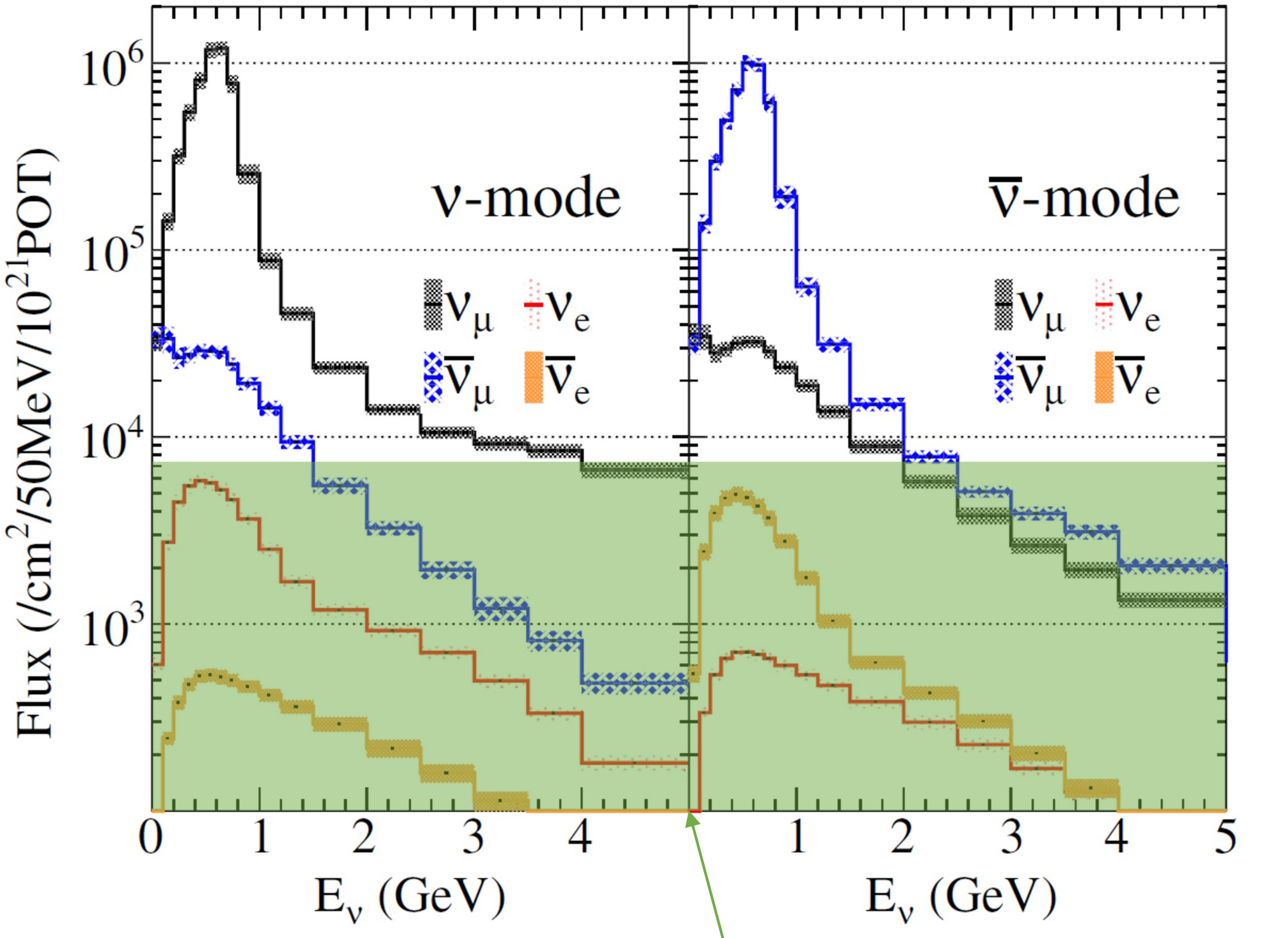


- ❑ Maximise ν_μ and $\bar{\nu}_\mu$ flux
- ❑ **Minimise ν_e and $\bar{\nu}_e$ to observe appearance**
  - ❑ **ν_e and $\bar{\nu}_e$ flux are background**

Call for a GeV ν_e and $\bar{\nu}_e$ Machine

Oscillation Signal = (Beam flux · Oscillation probability · **Cross section**) ⊕ **Detector effects**

ν_e ($\bar{\nu}_e$) cross sections: major δ_{CP} systematics

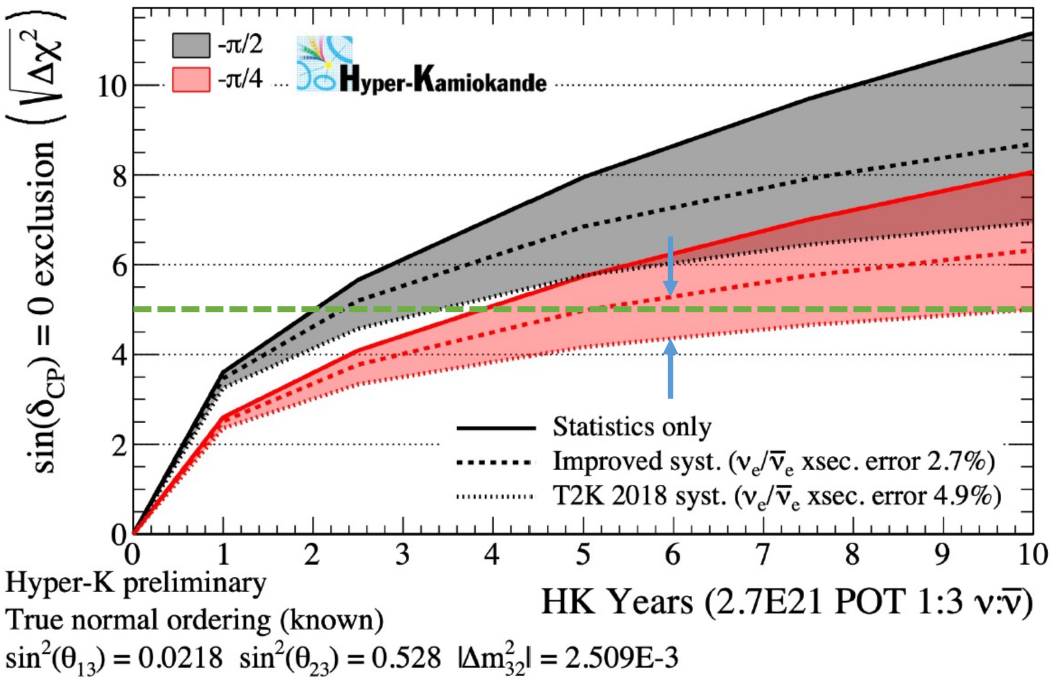
- ❑ Very few ν_e scattering data
- ❑ δ_{CP} ~ ν_e appearance ~ no ν_e in beams
  - ❖ No *in situ* ν_e measurements
- ❑ ν_μ for ν_e via lepton universality, but higher precision needed for δ_{CP}

Hyper-K example

Improving error of $\nu_e/\bar{\nu}_e$ xsec ratio 4.9% → 2.7%

- ❑ Improve δ_{CP} sensitivity by ~ 1 σ for 6 year
- ❑ **Significantly shorten running time to reach 5σ**

Jeanne Wilson, Neutrino2022



Host | Cost | Cost

Time

Call for a GeV ν_e and $\bar{\nu}_e$ Machine

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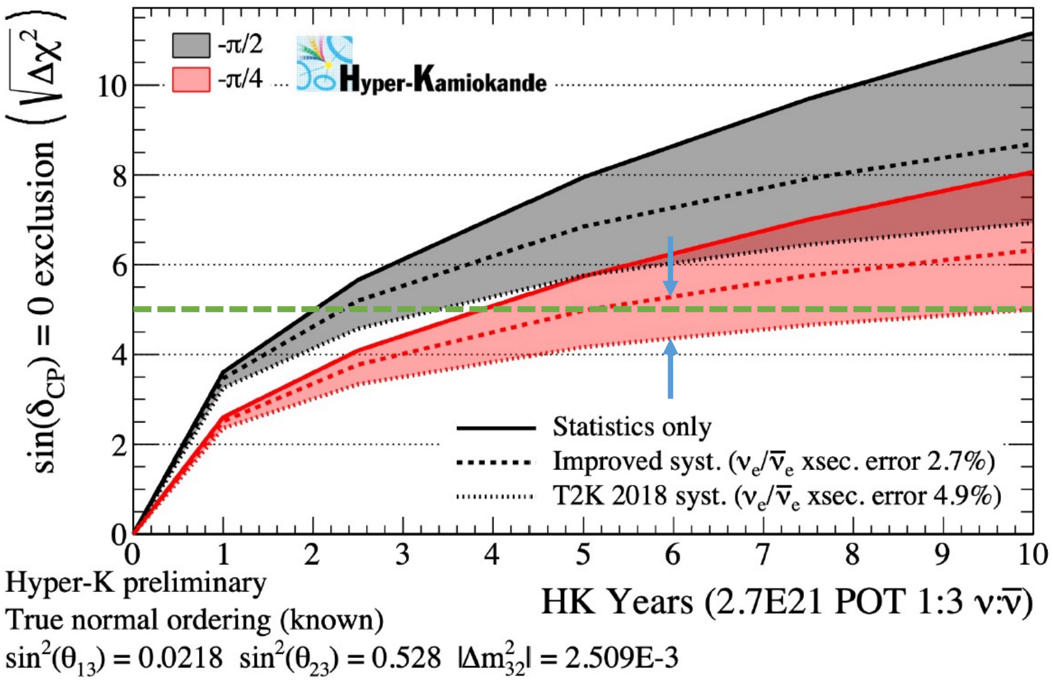

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- ❑ **Shorten running time = ~~reduce~~ share cost**

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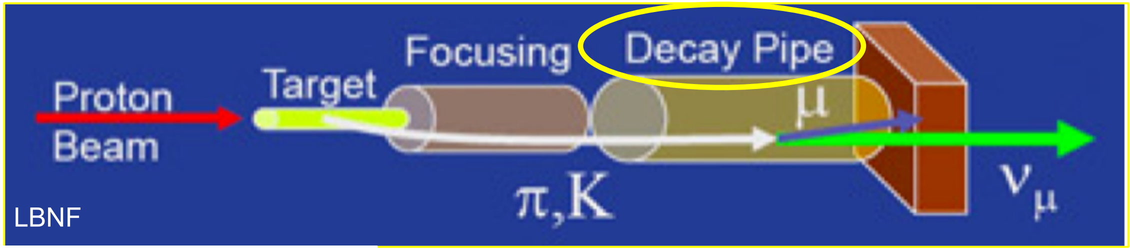
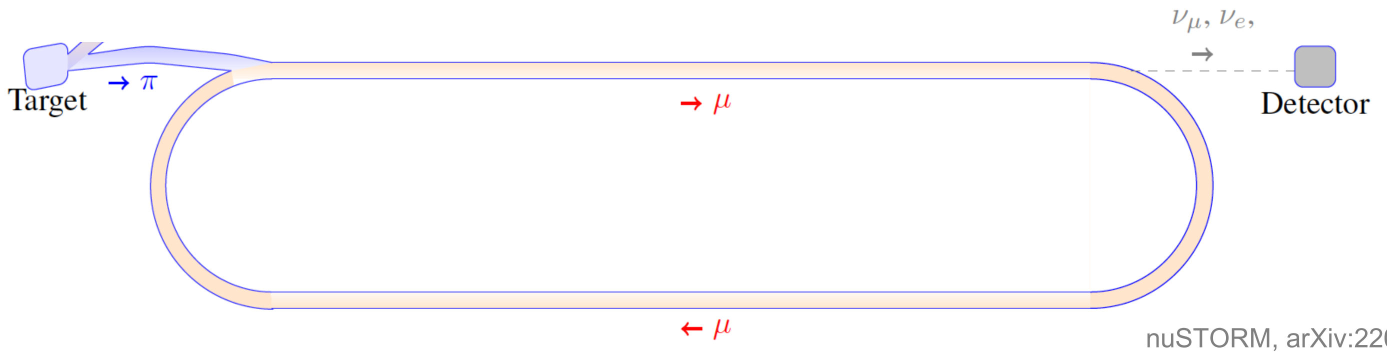
✓ Wishlist

1. **ν_e and $\bar{\nu}_e$ beams with the relevant energy for appearance**
2. **Well-understood fluxes**
3. **High statistics**
4. **Low ν_μ background**

❑ **Shorten running time = ~~reduce~~ share cost**

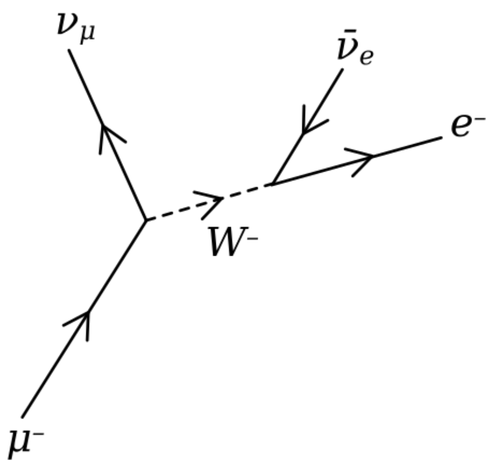
ν from STORed Muons (nuSTORM)



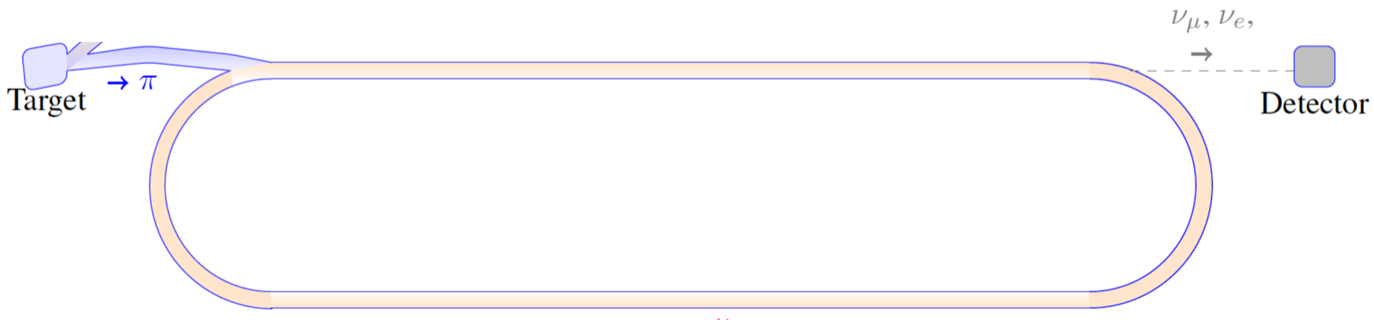


nuSTORM, arXiv:2203.07545

- π captured by storage ring → μ, instead of decay pipe → ν
- $\bar{\nu}_\mu + \nu_e$ and $\nu_\mu + \bar{\nu}_e$ fluxes from $\mu^\pm$ decays
  - **Storage ring: tunable fluxes**
  - **μ decay: perfect understanding of flux shape and normalisation**
- Scientific objectives
  - %-level ν cross sections
  - BSM searches, e.g. steriles beyond Short Baseline Neutrino program at FNAL
  - Test bed for muon collider technology

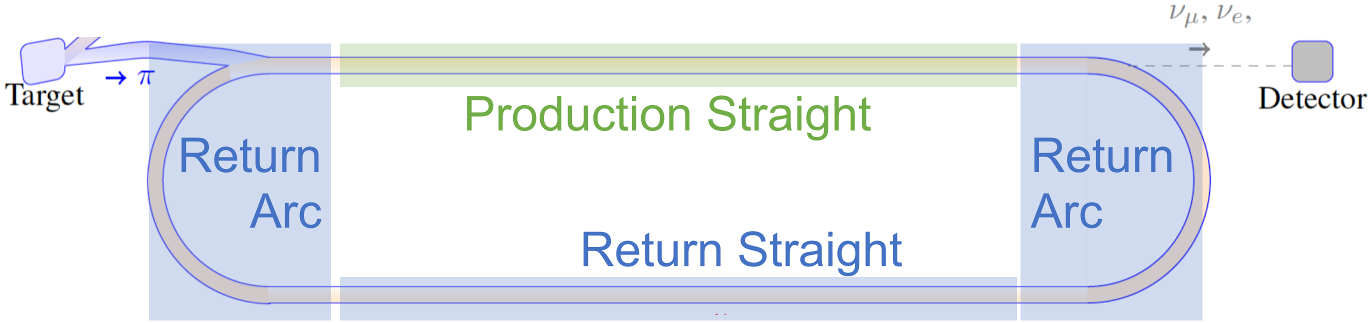


ν from STORed Muons (nuSTORM)



- **1st ν beam facility & highest ever beam power based on stored muons**
- Fine tune neutrino fluxes via μ acceptance
  - p_μ spread: flux shape
  - p_μ mean: neutrino beam energy scan (νBES)

ν from STORed Muons (nuSTORM)



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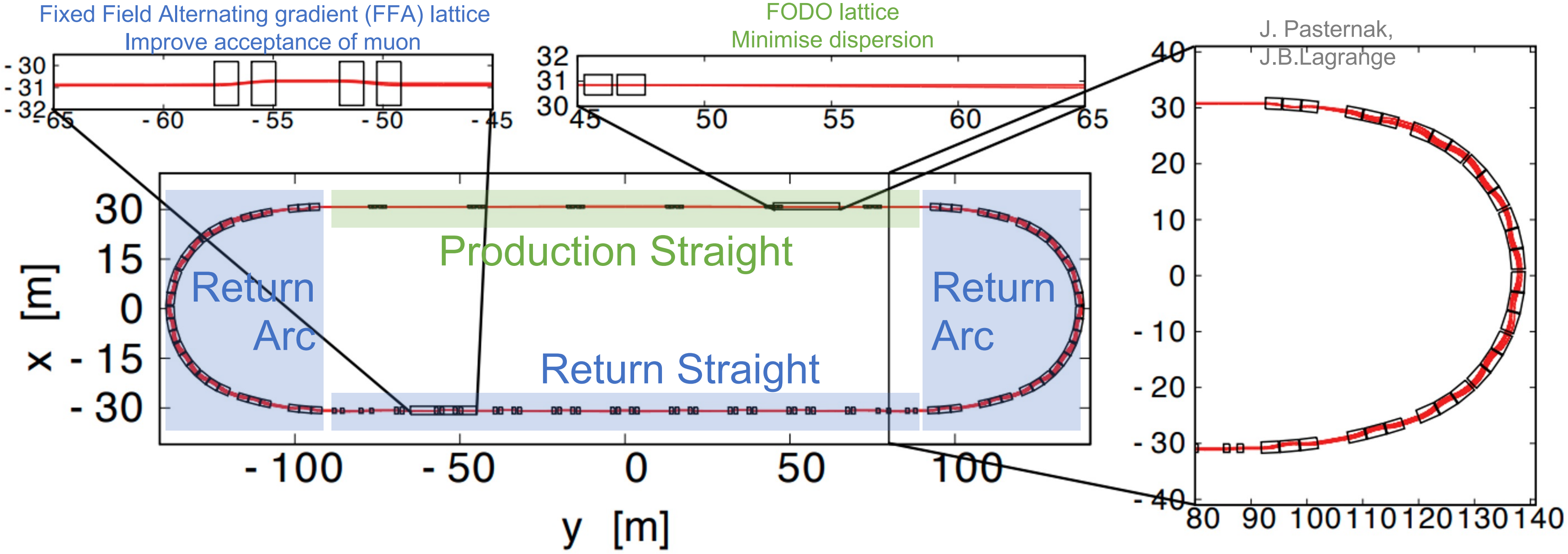
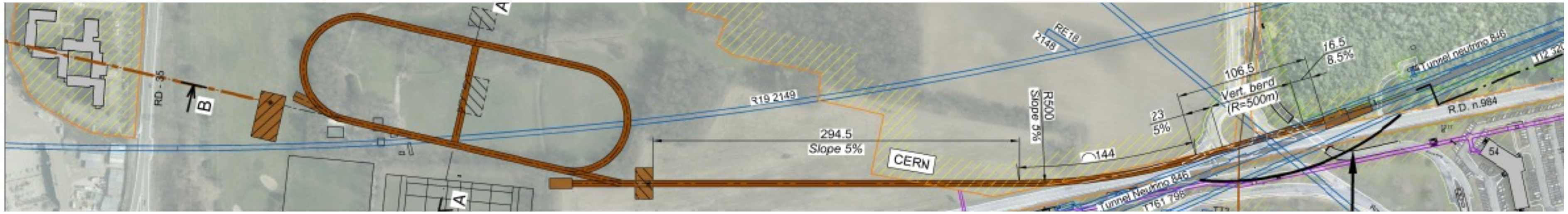


- **1st ν beam facility & highest ever beam power based on stored muons**
- Fine tune neutrino fluxes via μ acceptance
  - p_μ spread: flux shape
  - p_μ mean: neutrino beam energy scan (νBES)
- Production Straight (example w/ π^+ injection)
  - ν_μ flux from $\pi^+ \to \mu^+\nu_\mu$ ("pion flash")
  - $\nu_e + \bar{\nu}_\mu$ flux from $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$
  - Maximise μ capture efficiency
- Return Arcs and Straight
  - $<p_\mu>$ tunable between 1 and 6 GeV/c, spread ±16%

A Brief History of nuSTORM

CERN-PBC-REPORT-2019-003
DOI:10.17181/CERN.FQTB.O8QN



2012-13 LoI and Proposal to FNAL PAC [arXiv:1206.0294, arXiv:1308.6822], EoI to CERN [arXiv:1305.1419]

- Sterile neutrinos
- Neutrino-nucleus scattering
- Technology test bed for muon accelerators

2014 Steriles sensitivity [Phys.Rev.D 89, 071301 (2014)]

- nuSTORM at FNAL

2019 Feasibility of nuSTORM at CERN [CERN-PBC-REPORT-2019-003]

- SPS 100 GeV proton beam
- Optimised for neutrino-nucleus scattering, maintaining sensitivity to BSM (steriles + non-unitarity, NSI, Lorentz-invariance/CPT violation)

2022 Snowmass 2021 [arXiv:2203.07545]

- Advocating synergy with ENUBET and Muon Collider Demonstrator
  - ✓ Muon Collider demonstrator
    - ❖ 6-D cooling
  - ✓ nuSTORM as test bed for muon storage ring
    - ❖ Complete implementation for large acceptance
    - ❖ R&D for very precise determination of stored-muon energy and spread

- ❑ ***Why do we need nuSTORM?***

✓ Wishlist

1. **ν_e and $\bar{\nu}_e$ beams with the relevant energy for appearance**
2. **Well-understood fluxes**
3. **High statistics**
4. **Low ν_μ background**

- ❑ ***What other physics can we do with it?***

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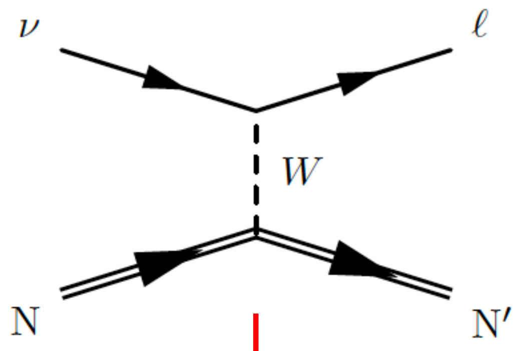
1. Problems and opportunities with neutrino masses
   - Call for a GeV νe and $\bar{\nu} e$ machine: nuSTORM

2. Using lepton-hadron correlations to study GeV neutrino interactions
   - Transverse Kinematic Imbalance (TKI)

3. JUNO news!

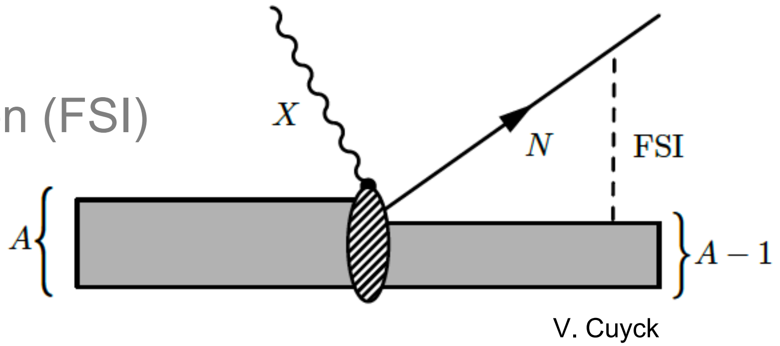
Why Neutrino Interactions?

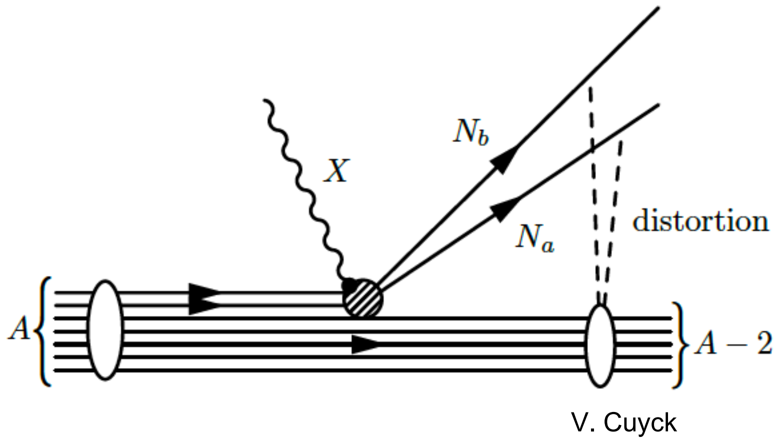
How well can we measure neutrino energy?
(reminder: oscillation very sensitive to baseline and energy, *L*/*E*)

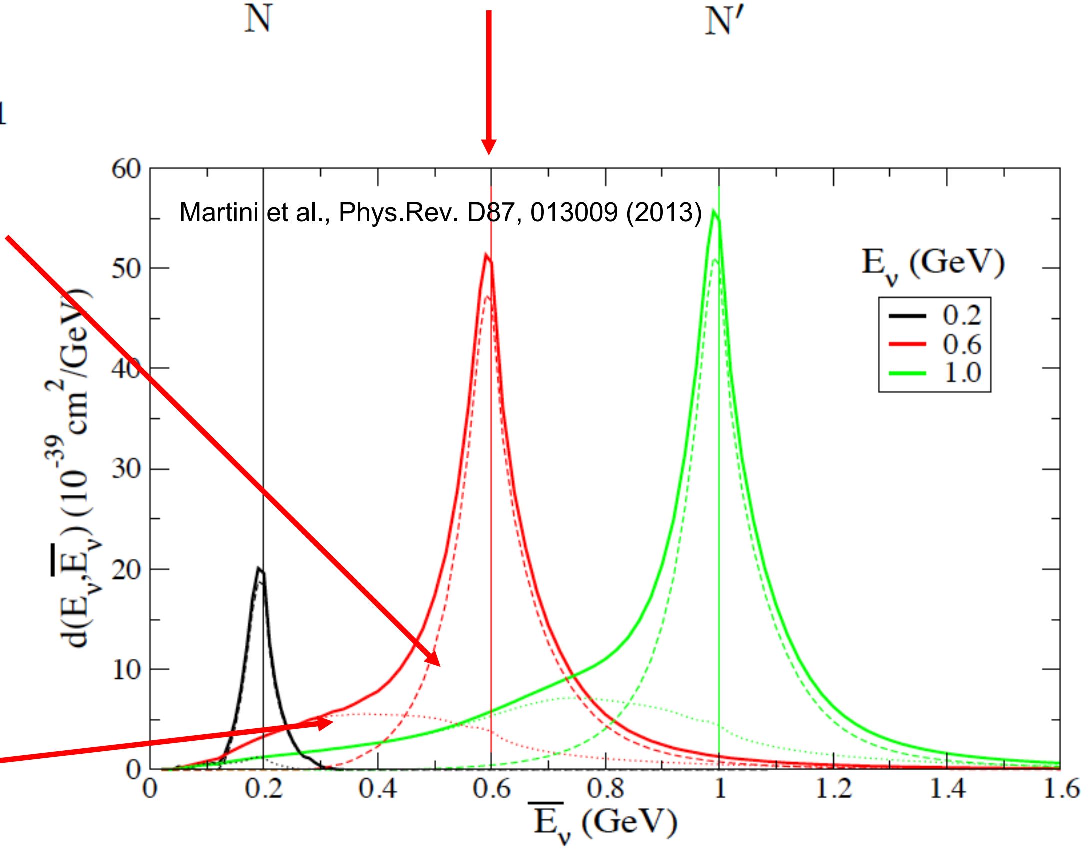


2-body reaction
❑ precise

Fermi motion,
Final State Interaction (FSI)
❑ spread





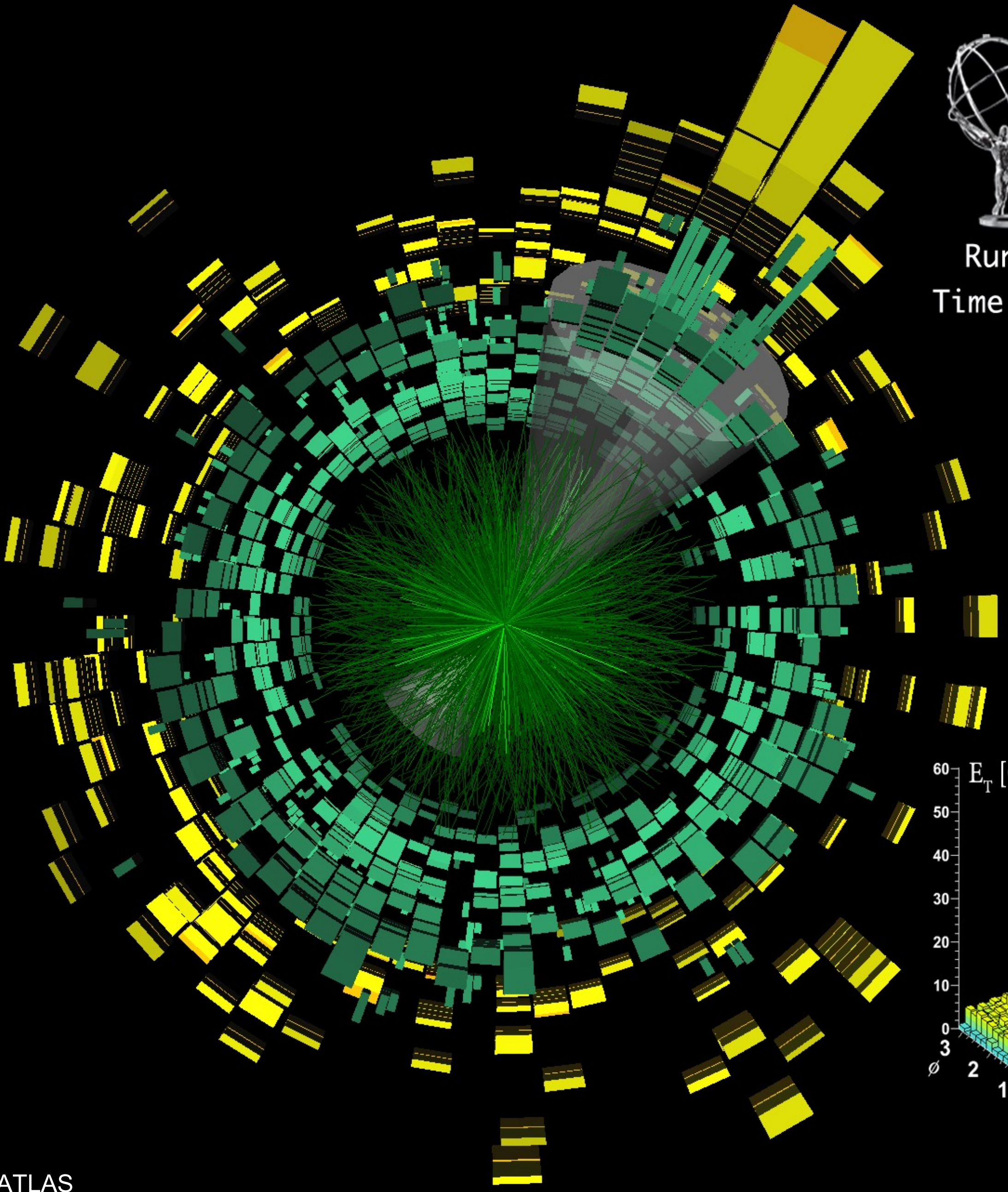


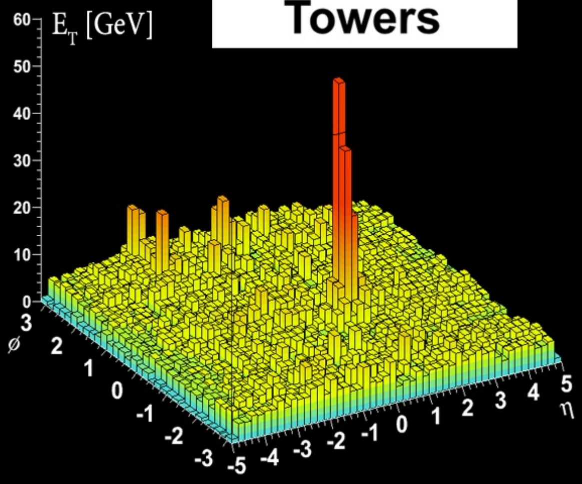
2-particle-2-hole (*2p2h*),
pion absorption (missing particles)
❑ Large fraction of large bias and spread

TKI

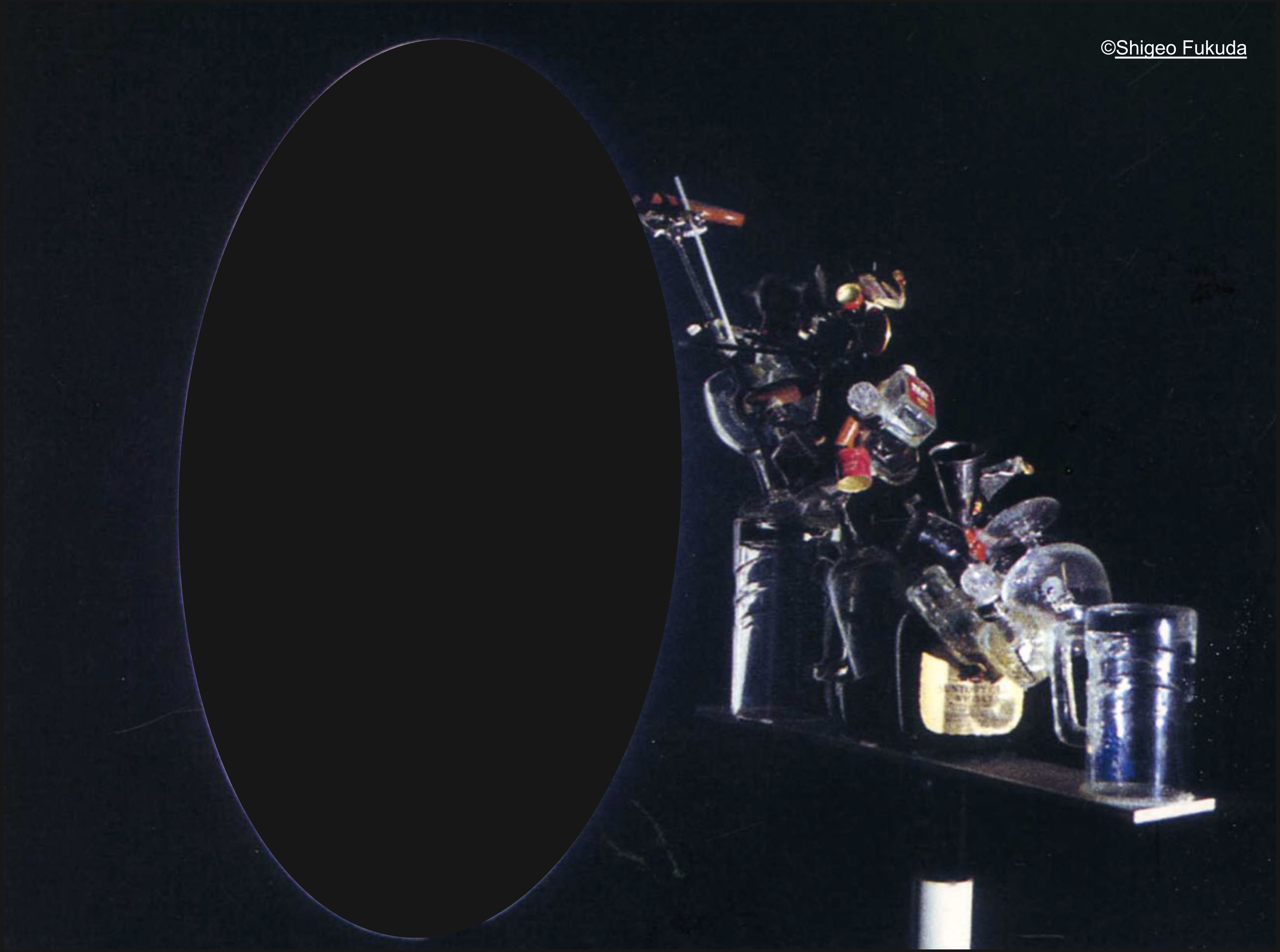
2010: Watched a live ATLAS seminar in the Tower—didn’t see what the big deal was…

- Over time in ALICE, learnt that *imbalance* & *correlations* are powerful tools for studying medium effects.
- 2014/2015: Moved into neutrinos and *started to* study neutrino interactions with hadron-lepton correlations.
- Transverse Kinematic Imbalance (TKI) now active topic in T2K, MINERvA, MicroBooNE, SBND, ICARUS with real data, and also in future projects like DUNE and nuSTORM.





@ATLAS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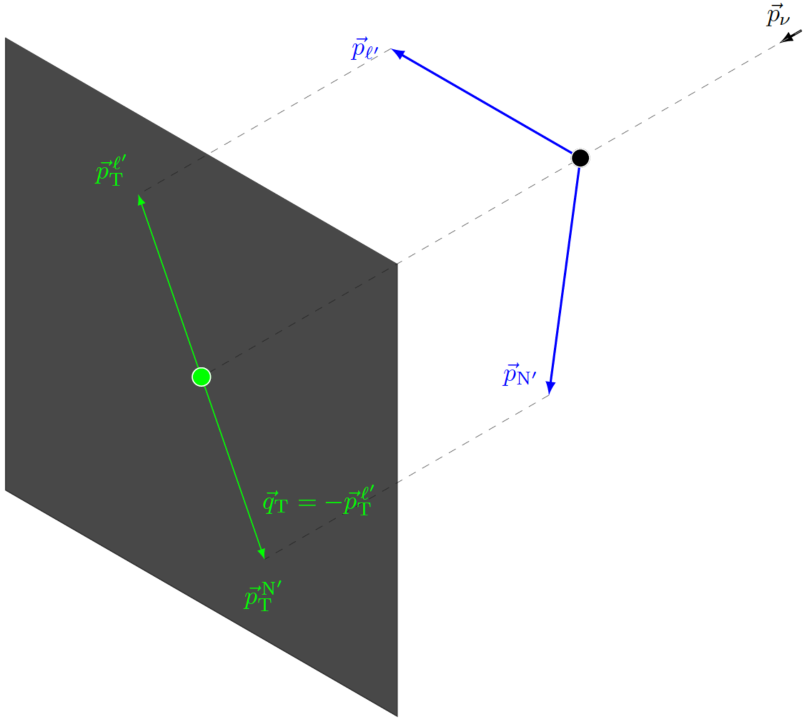
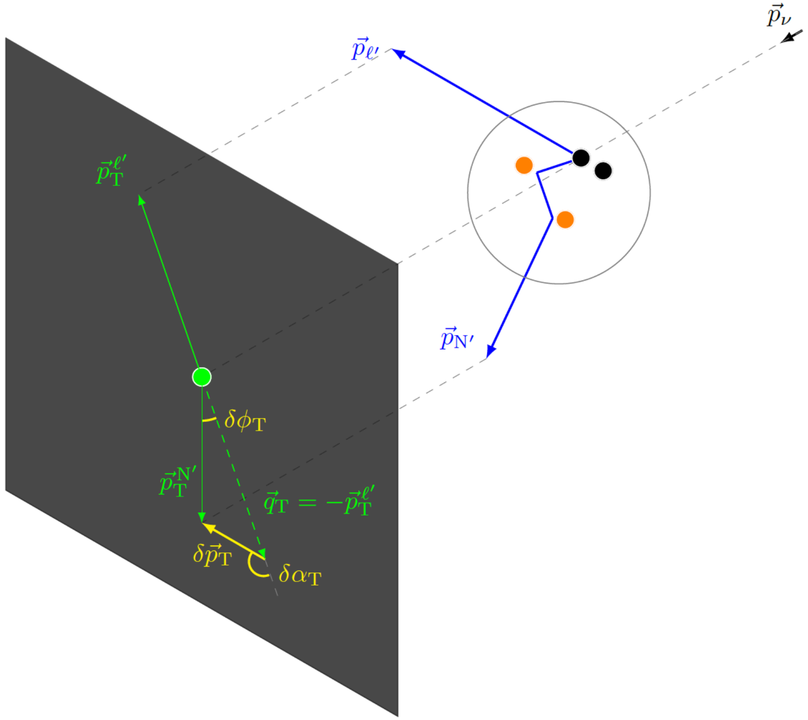
Transverse Kinematic Imbalance (TKI)



Stationary free nucleon target



Nuclear target ($A > 1$)
- ❑ Fermi motion
- ❑ Final-state interactions (FSI)
- ❑ 2-particle-2-hole (2p2h)

Missing energy

From Wikipedia, the free encyclopedia

[…]

neutrinos.[1] In general, missing energy is used to infer the presence of non-detectable particles and is expected to be a signature of many theories of physics beyond the Standard Model.[2][3][4]

[…]

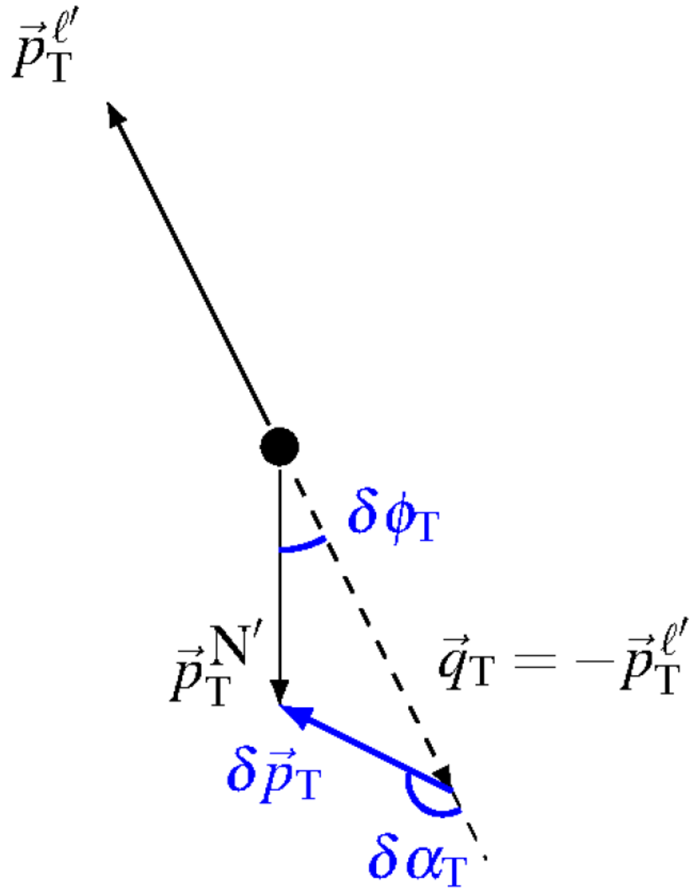
hadron colliders.[5] The initial momentum of the colliding partons along the beam axis is not known —

TKI

Multi-dimensional observation
- ❑ Momentum (magnitude)
- ❑ Angle
- ❑ Asymmetry

Lu, *et al.*, Phys.Rev.D 92, 051302 (2015)
Lu, *et al.*, Phys.Rev.C 94, 015503 (2016)
Lu & Sobczyk, Phys.Rev.C 99, 055504 (2019)
Cai, Lu, Ruterbories, Phys.Rev.D 100, 073010 (2019)

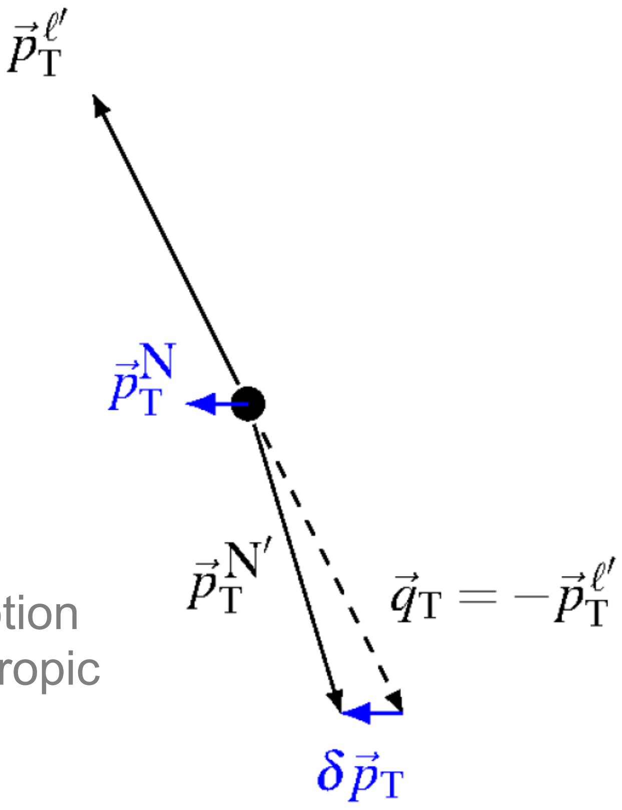
Transverse Boosting Angle $\delta\alpha_T$



if Fermi motion only

$$\delta\vec{p}_T = \vec{p}_T^N$$

$\delta\alpha_T$ is Fermi motion direction → isotropic



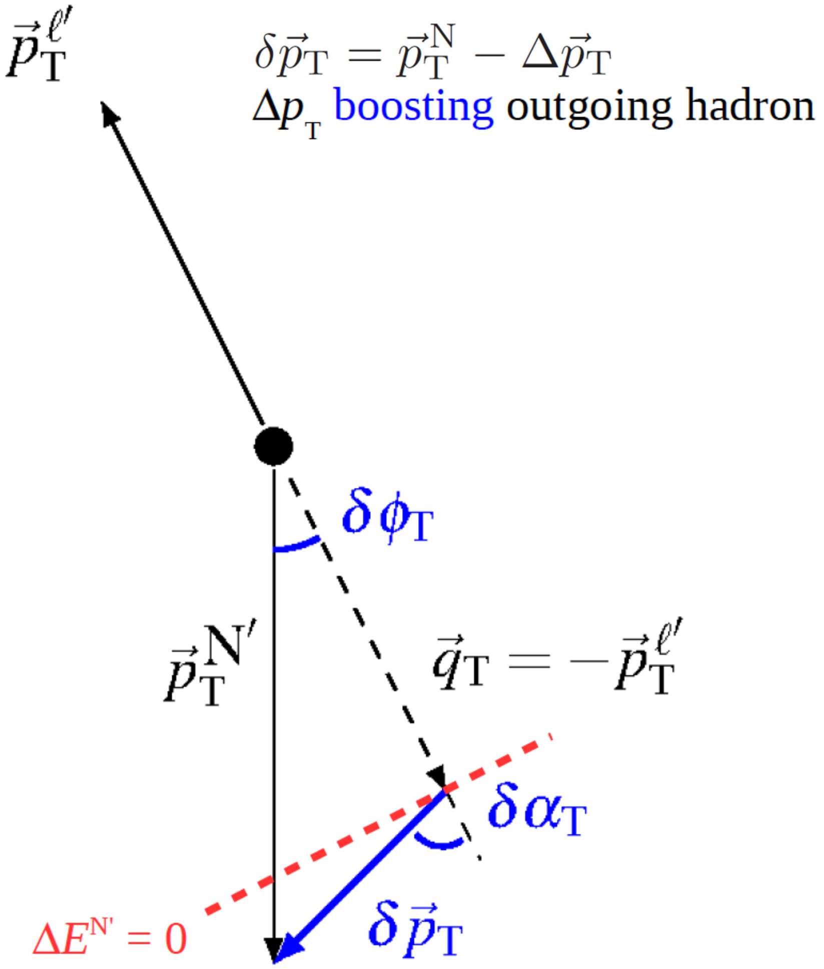
$\delta\vec{p}_T$
—total transverse momentum
—transverse momentum imbalance
—missing pT
—...

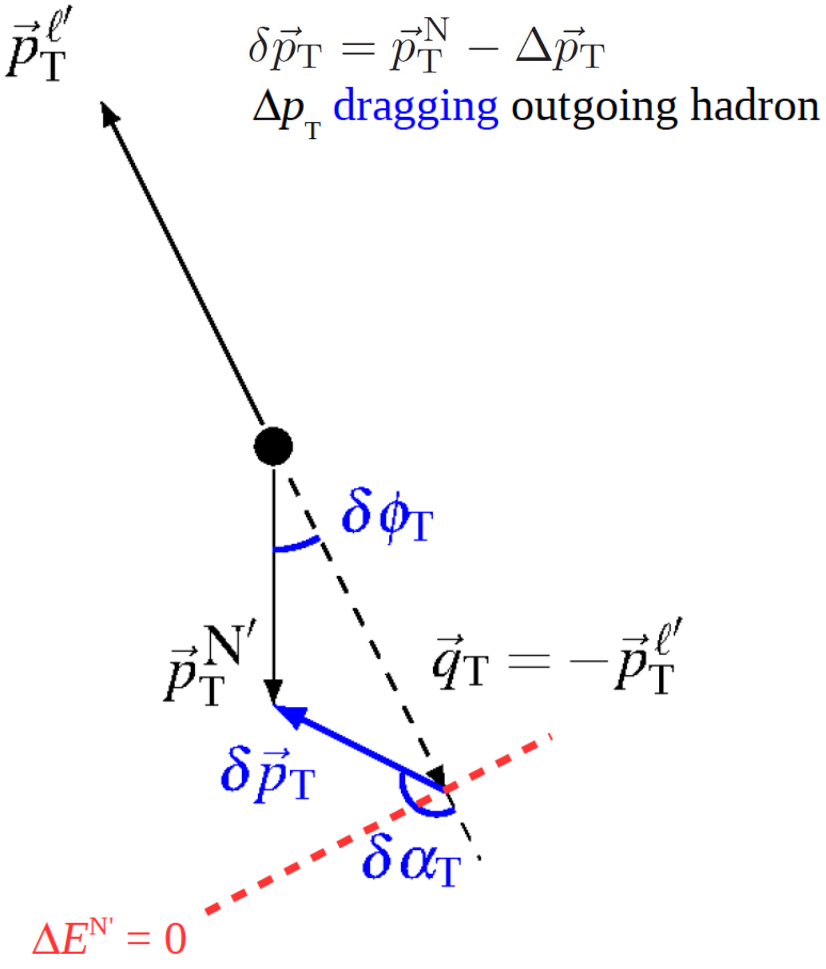
In full

$$\delta\vec{p}_T = \vec{p}_T^N - \Delta\vec{p}_T$$

FSI and missing particles

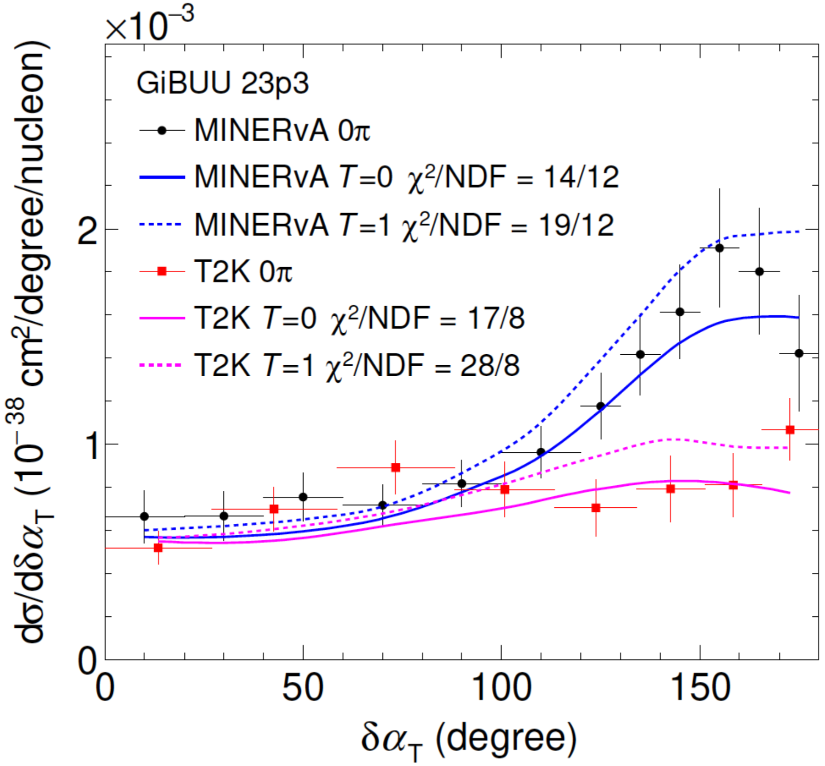
Transverse Boosting Angle $\delta\alpha_T$





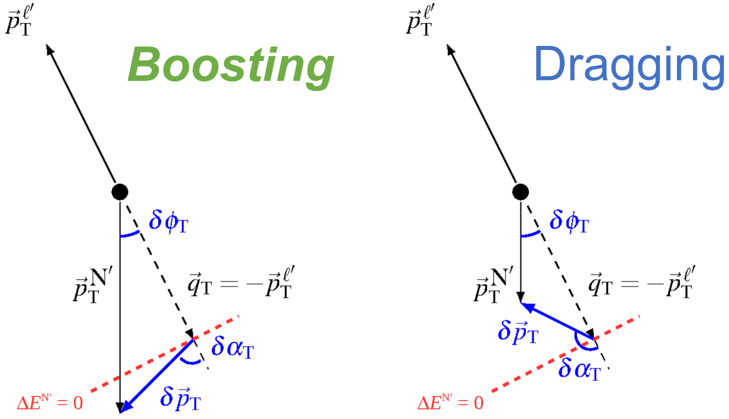
FSI and momentum sharing with extra particles
- ❑ pion absorption
- ❑ 2p2h

TKI Measurements at T2K, MINERvA, and nuSTORM

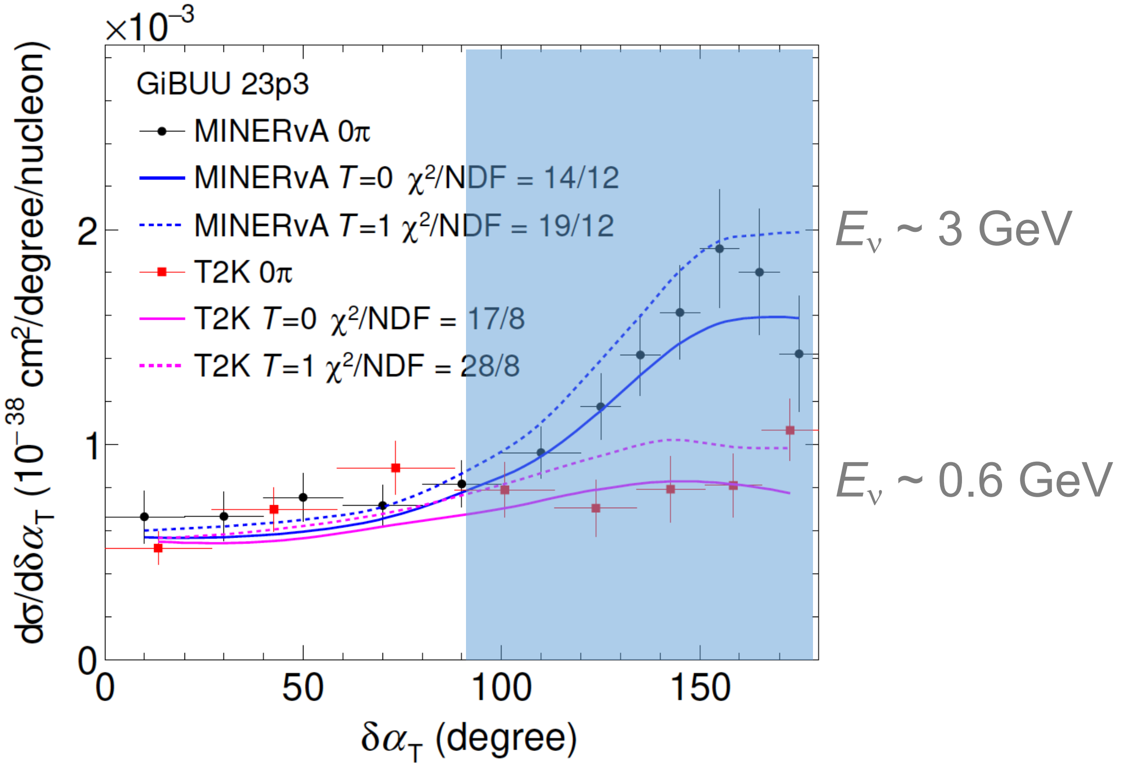


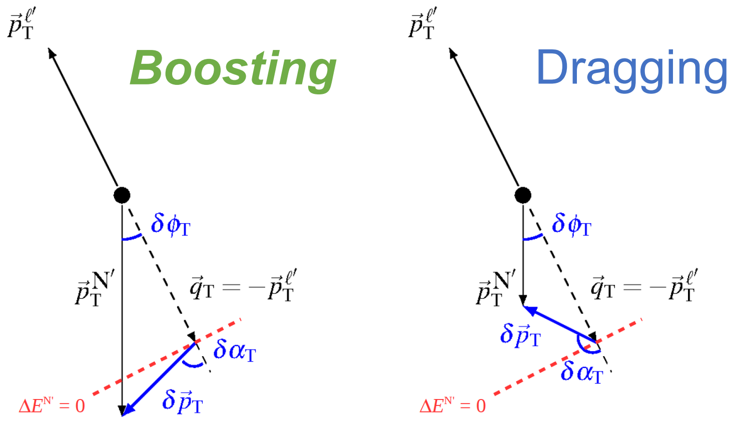
$E_\nu \sim 3$ GeV

$E_\nu \sim 0.6$ GeV



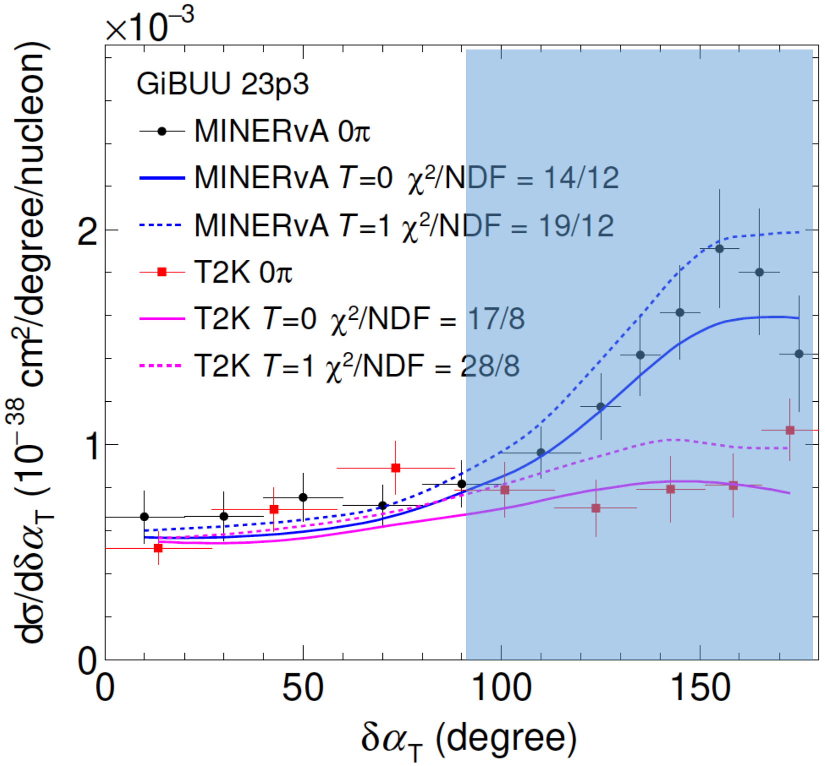
TKI Measurements at T2K, MINERvA, and nuSTORM

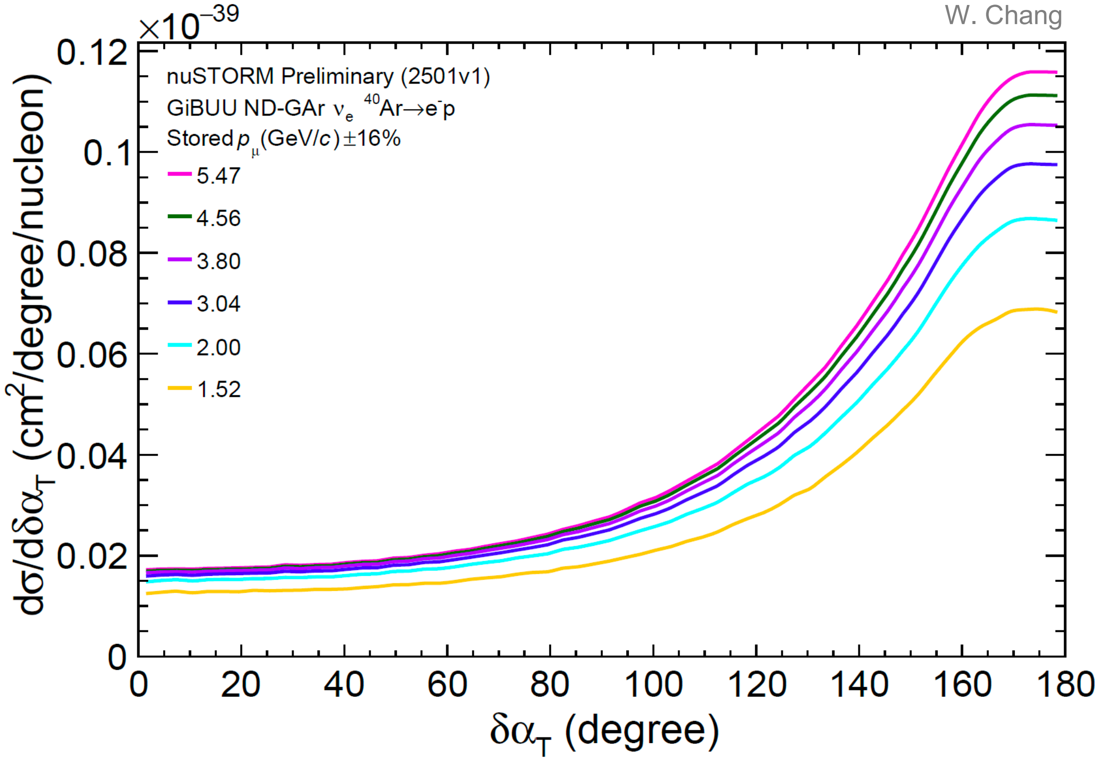


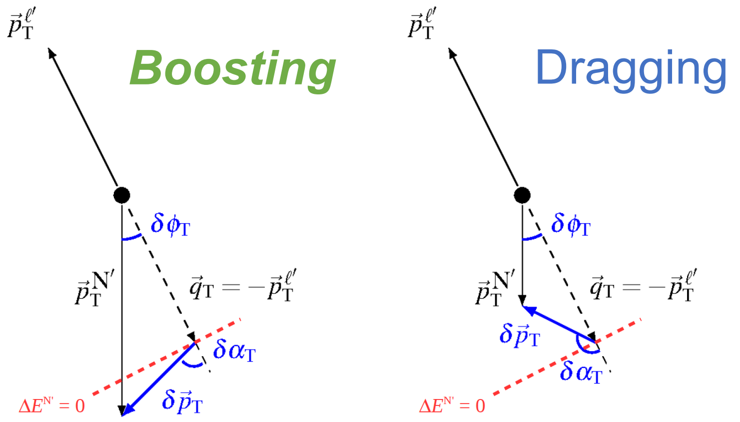


- ❑ Dissipative processes: 2p2h, FSI

TKI Measurements at T2K, MINERvA, and nuSTORM







- Dissipative processes: 2p2h, FSI
- Dynamical evolution of nuclear medium effects can be mapped out via νBES at nuSTORM

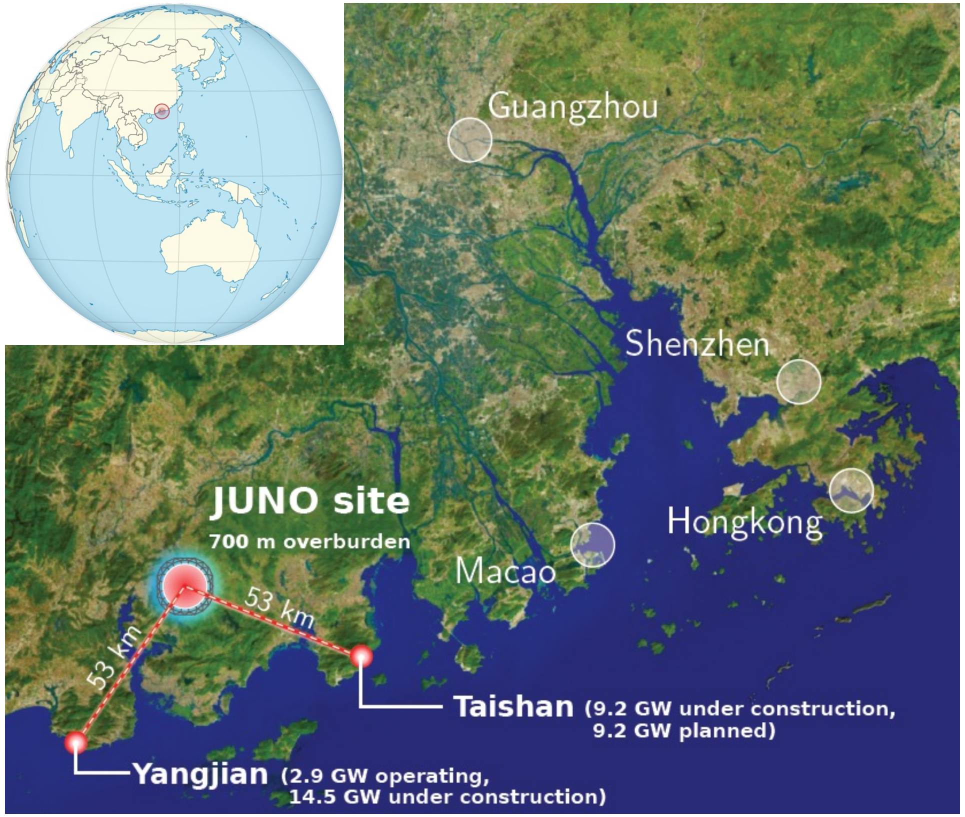
Outline

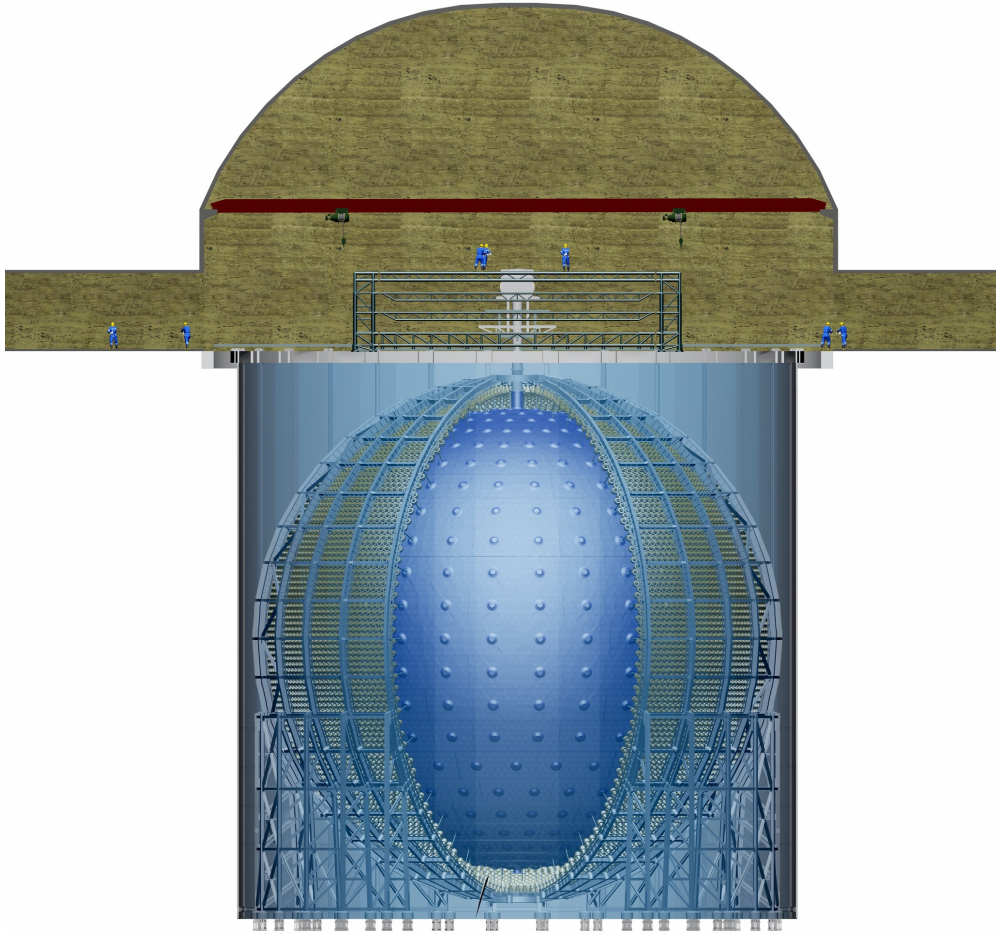
1. Problems and opportunities with neutrino masses
   - Call for a GeV νe and $\bar{\nu} e$ machine: nuSTORM

2. Using lepton-hadron correlations to study GeV neutrino interactions
   - Transverse Kinematic Imbalance (TKI)

3. JUNO news!

Jiangmen Underground Neutrino Observatory (JUNO)





- ❑ JUNO: *primarily* a reactor neutrino experiment
  - ❖ 20 kt liquid scintillator
  - ❖ 17,612 20-inch PMTs + 25,600 3-inch PMTs
    - ➢ 77.9% photocathode coverage
  - ❖ **Expected mass ordering sensitivity with reactor neutrinos: 2.9 sigma in 6 years**
- ❑ Turns out big enough to contain atmospheric ν up to 10 GeV
  - ➢ 3-10 GeV sensitive to ν mass ordering

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JUNO

https://www.nature.com/articles/d41586-024-00694-5

2022/03—2024/12

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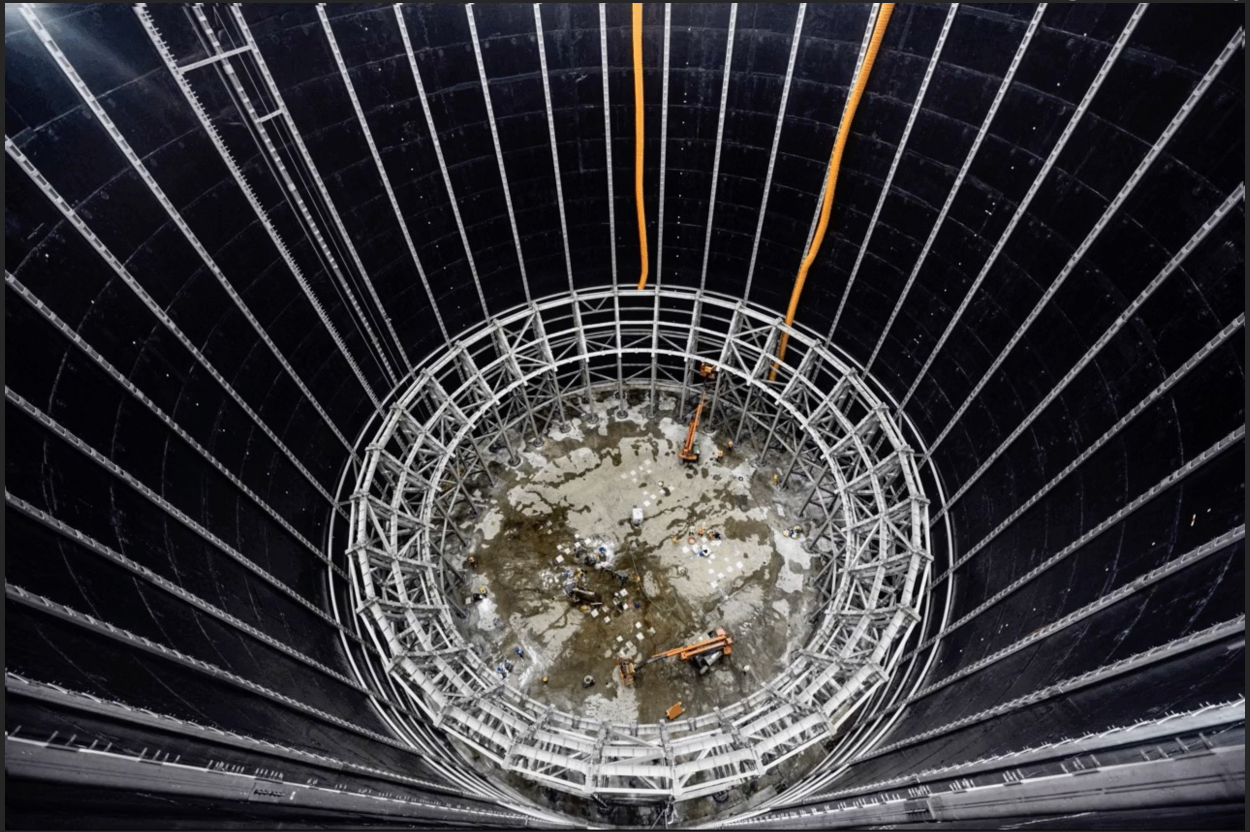

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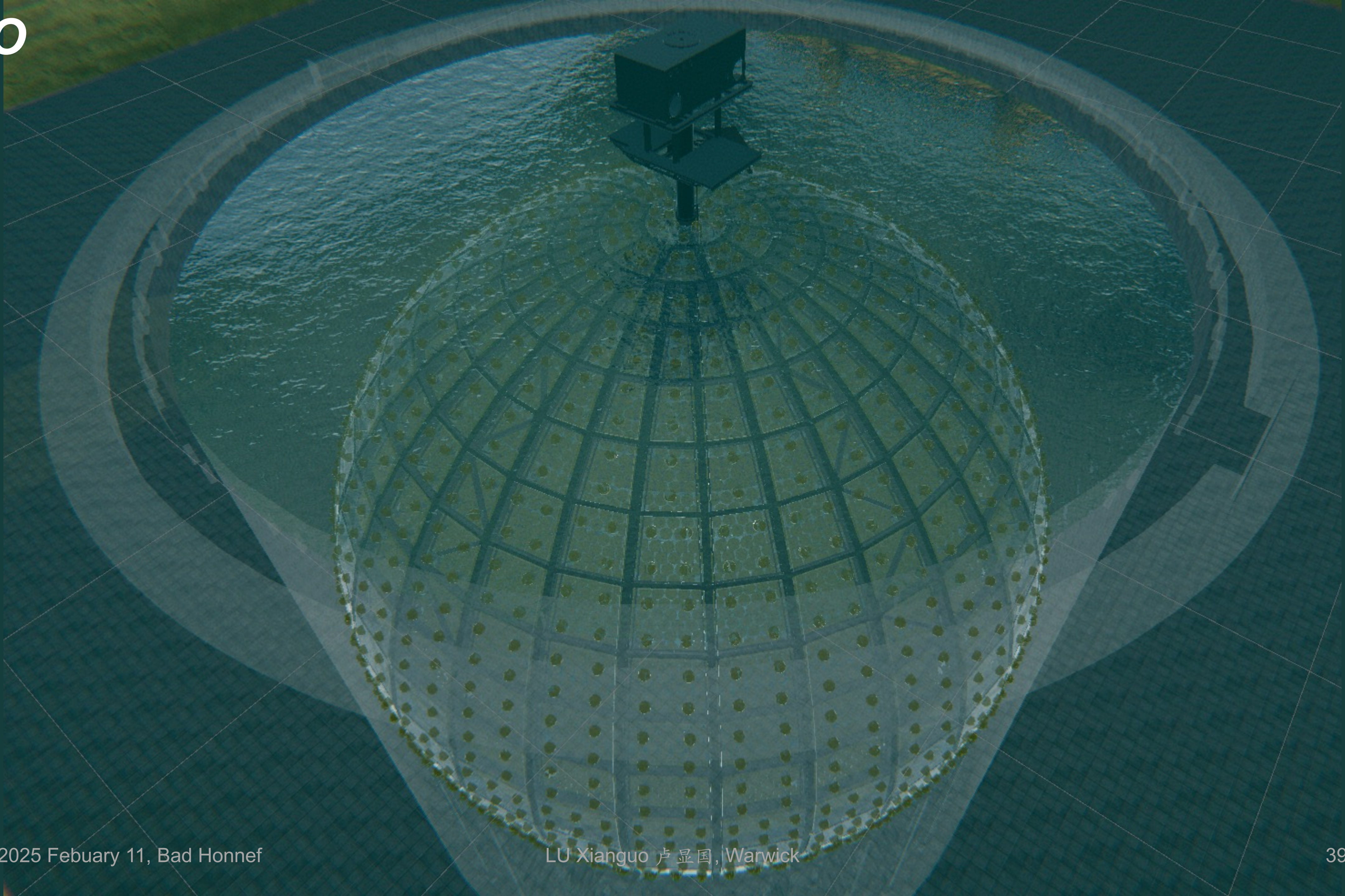

When I left Heidelberg and the field, I wasn't sure what to expect. But looking back, I realise those years had prepared me well for the journey ahead. Thank you, Johanna!

Now, let's celebrate Johanna's special day and this wonderful gathering!

2025 Febuary 11, Bad Honnef