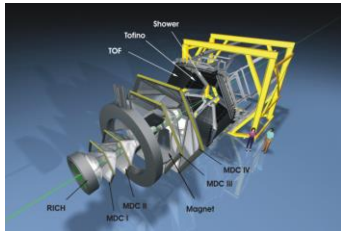
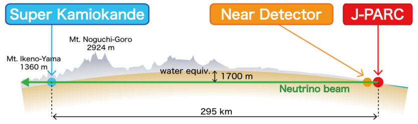
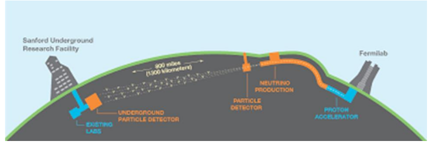
IFJ-PAN & IJCLab
PRE-PROJECT PROPOSAL



HADES-ν

Reduce uncertainty on neutrino oscillation parameters by using HADES pion beam data





B. Ramstein (IJCLab) for the *HADES-ν team*

HADES (hadronic physics)
IJCLab : Béatrice Ramstein
IFJ PAN : Izabela Ciepal

accelerator neutrino physics
IJCLab/DUNE: Fabien Cavalier, Yoann Kermaidic, Thibaut Houdy
IFJ PAN/T2K and HK: Tomasz Wąchała, Grzegorz Żarnecki, Marcela Batkiewicz-Kwasniak

Outline

- Why do Long Base Line neutrino oscillation experiments need pion-nucleus interaction data ?
- Existing HADES data: how can they be useful ?
- Detailed plan for the collaboration and PhD cotutelle

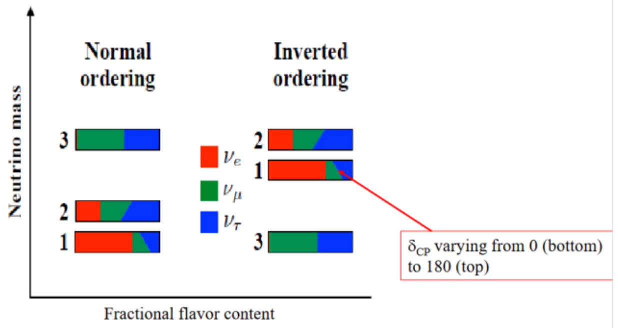
Neutrino oscillation experiments

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

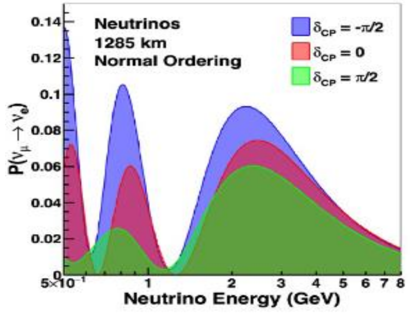
$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad (\beta \neq \alpha)$$

(for 2 flavours)

Discovery (Nobel Prize 2015) : SK (1998) + SNO(2001)

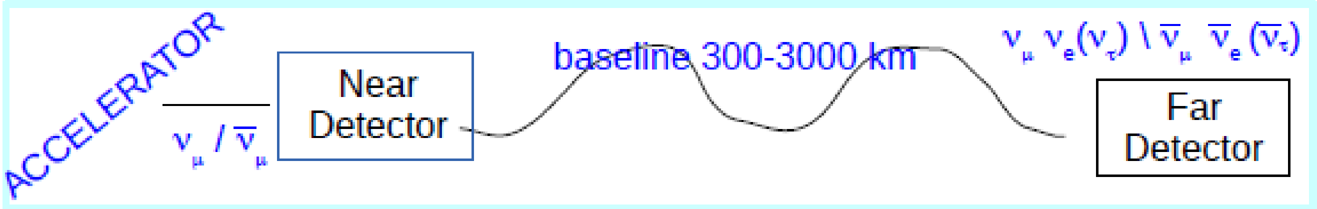


DUNE simulations



Open questions:
Neutrino mass hierarchy ?
CP violation in the leptonic sector ?

New generation Long Base Line (and utmost precise) experiments :
Higher sensitivity
Measure appearance/disappearance for ν_μ / $\bar{\nu}_\mu$
and appearance ν_e , ν_τ , $\bar{\nu}_e$, $\bar{\nu}_\tau$



Long Base Line neutrino oscillation experiments

Contributions of our labs in this worldwide effort

IFJ PAN

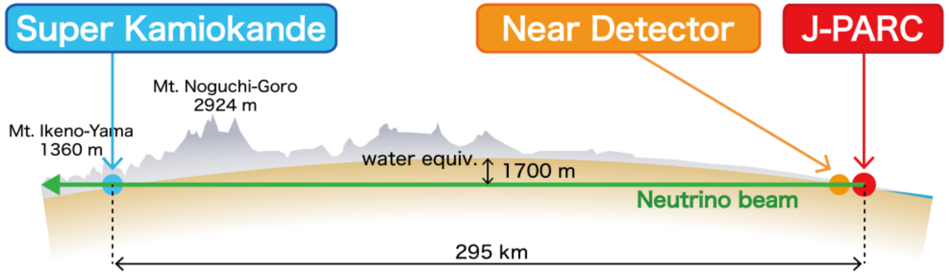
Super-Kamiokande /Hyper-Kamiokande

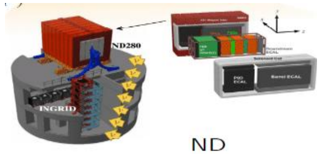
J-PARC beams

L = 295 km

T2K: operating now

HK: 2028





ND

Contributions to T2K near detector (ND280) :

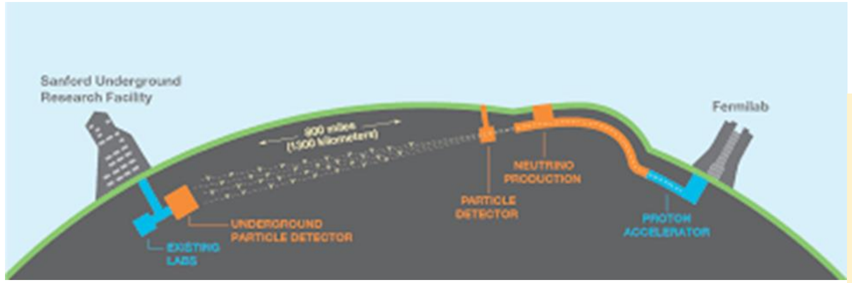
- Construction of SIDE Muon Range Detector and High Angle TPC
- Analysis and off-line software
- Studies of ν_μ / $\bar{\nu}_\mu$ interactions with CH and H_20
- Upgraded ND280 detector: starting work on interactions with pion emission in the SFGD (high granularity plastic scintillators)

DUNE

Fermilab proton beam

L = 1300 km

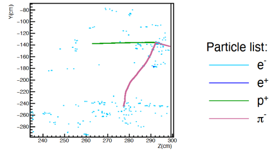
DUNE: 2031

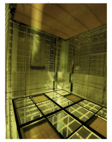


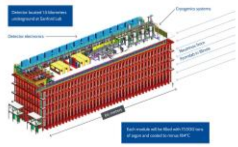
Laboratoire de Physique des 2 infinis Irène Joliot-Curie

Joined accelerator neutrino activities in 2019

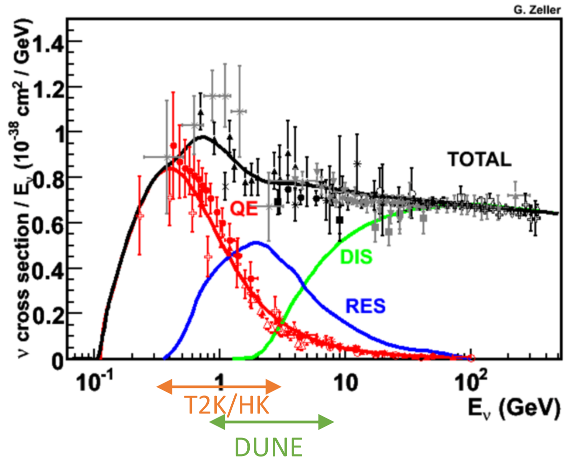
- cathode and insertion chimney construction of the vertical drift (VD) LArTPC far detector
- Construction of protoDUNE-VD
- Start data analysis: event reconstruction in LArTPC







Neutrino–nucleus interactions



ν/ $\bar{\nu}$ yields need to be precisely measured as a function of energy in Near and Far detectors

T2K/HK : $H_2$0 and CH ; DUNE Ar

- E_ν < 0.8 GeV : cross sections mostly sensitive to Quasi-Elastic process

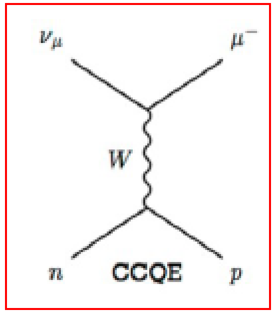
most energy carried by the outgoing lepton (models include Fermi momentum, 2p-2h, ….)

Models are well constrained.

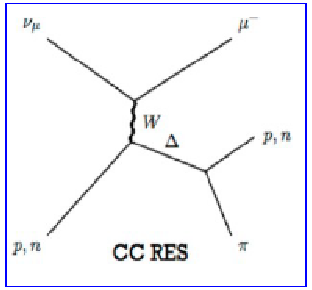
- E_ν > 0.8 GeV (DUNE) importance of pion production (Δ(1232) and higher resonances)

Large model uncertainties

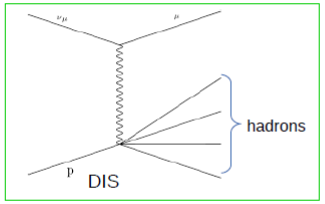
Quasi-elastic

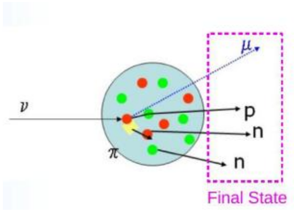


Resonance excitation
(1 pion emission)



Deep Inelastic
(multi-particle emission)



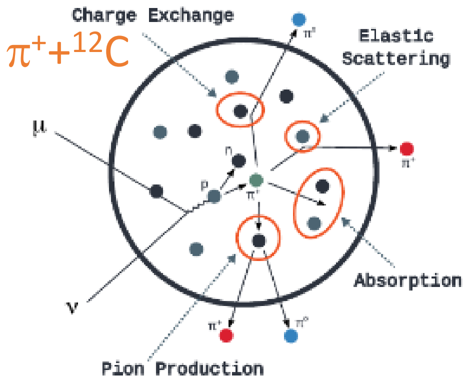


Evolution of LBL experiments :
Detect as many reaction products as possible
(proton, pions, neutrons,…)

Reliable dynamical hadronic models
(transport or intranuclear cascade models)
are needed to reconstruct neutrino energy from detected products

a large fraction (~50%) of the uncertainties on oscillation parameters is due to hadronic model dependency !

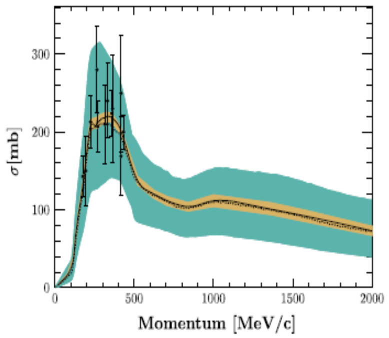
Pion induced experiments can help !



- Neutrinos and pions : different primary interactions, but similar energy dissipation processes (elastic/inelastic reactions, baryon resonance propagation, pion regeneration)
- Pion transfer a well controlled amount of energy and momentum to the nucleus
- Models needed for neutrino detection can be tuned to pion beam data !

Existing pion beam data base

- $P_\pi < 250$ MeV/c : Δ(1232) resonance region rather well-known.
- $300 < P_\pi < 500$ MeV/c : few measurements (π, πx) or (π, ππx) (LAMPF, TRIUMF, KEK) + DUET recent data
- $P_\pi > 500$ MeV/c : only σ_{tot} (Saturne-1, NIMROD, BNL) and diff. elast. cross sections (KEK).



(b) Quasi-elastic

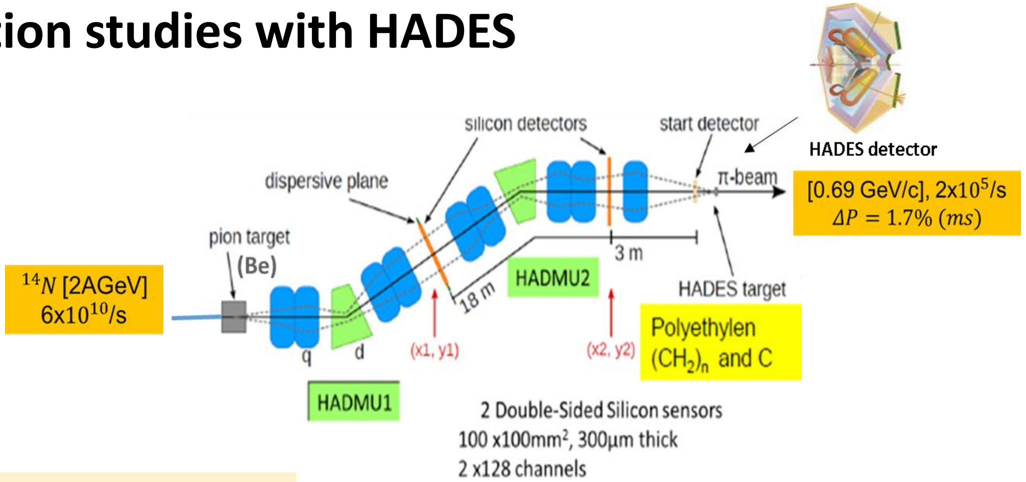
Available HADES data (p = 610-800 MeV/c) using pion beam at GSI can be useful !

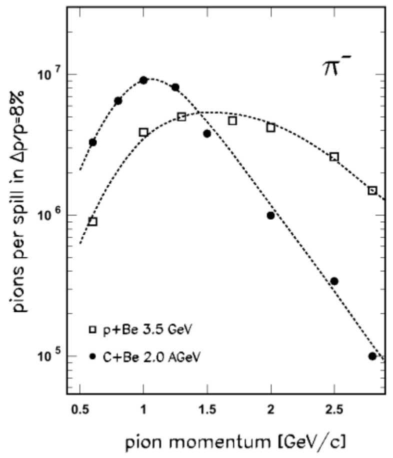
Pion beam at GSI

A facility for pion-induced nuclear reaction studies with HADES

HADES coll. Eur. Phys. J. A (2017) 53: 18

- Primary beam:
  4 × 10^{10} Nitrogen ions/s at E = 2*A* GeV
- Secondary π^- beam: 2 × 10^5 /s
- Momentum acceptance = 2 % (rms)





Momentum range
$p_\pi = 0.65 - 2$ GeV/c

Existing data :

- W and C targets p =1.7 GeV/c kaon and ϕ production
arXiv:2301.03940v2

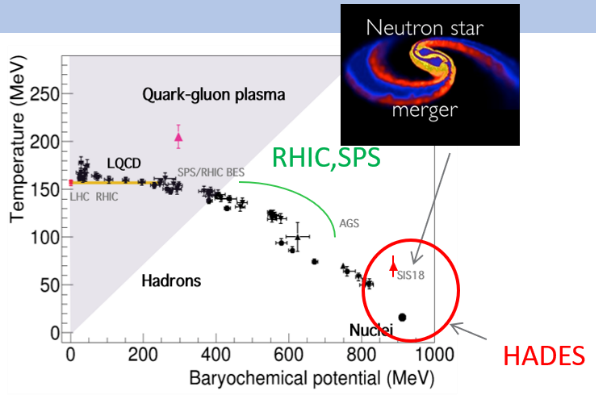
- CH2 and C targets 0.61, 0.66, 0.7, 0.75, 0.8 GeV/c
N1520 region : baryon resonance properties (vacuum and nuclear medium)
Phys.Rev.C 102 (2020) 2, 024001
arXiv:2205.15914 [nucl-ex]
arXiv: 2309.13357 [nucl-ex]
Fatima Hojeij's PhD, Paris-Saclay, Nov. 2023

Near future plans (2025?)

new experiment with the upgraded HADES detector
(5 energy points from 1 to 1.23 GeV/c)
with CH2 and C targets

Could possibly be extended to add other targets/energies ?

HADES detector at FAIR/GSI



T. Galatyuk, NPA-D-18-00411 (2018) QM18

- Study baryon-rich matter in Heavy-ion reactions (A+A),
- Reference+ cold matter studies p/π +A, p/π +p.

Role of baryonic resonances

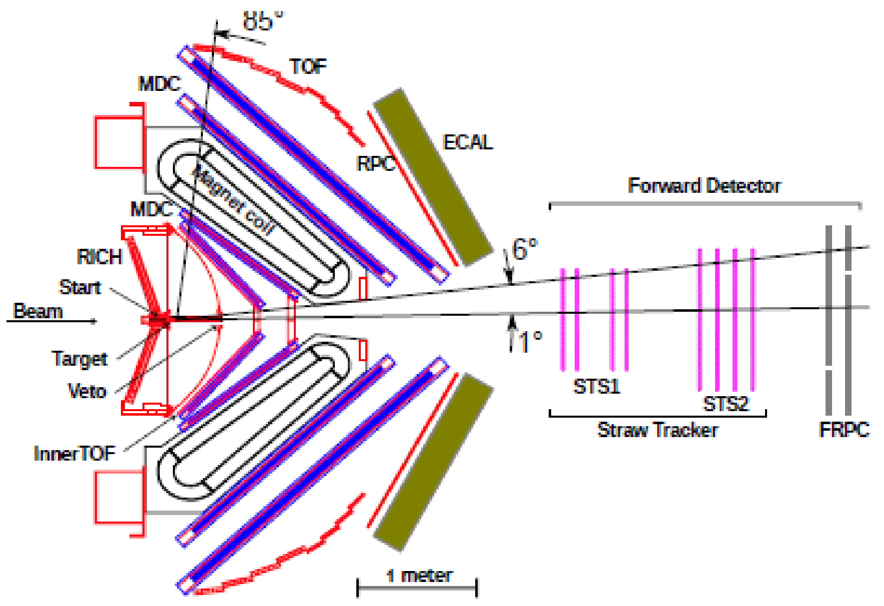
Acceptance:
Full azimuth, polar angles 18° - 85°

Momentum measurement:
Δp/p ~ 1-2 %, low material budget optimized for electron detection

Particle identification:
γ, e^+/e^-, π^+/π^- , K^+/K^-, p

Trigger: < 50 kHz

High Acceptance DiElectron Spectrometer



Polish contribution:

- Pre-Shower (replaced in 2019 by ECAL)
- ECAL (Jagiellonian University, mechanical frame)
- Forward detector (Jagiellonian University + IFJ PAN)

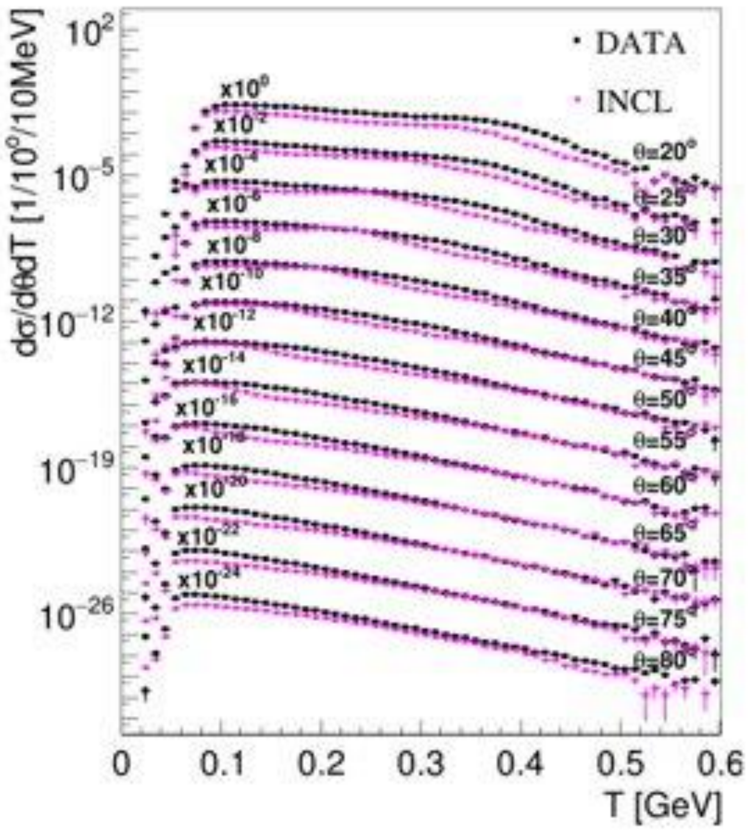
STS2 (2^{nd} straw tube station) construction

French contribution:

- MDCIV –largest MDC chamber
- Forward detector (support mechanics and STS2 financial contribution)
- Liquid Hydrogen Target

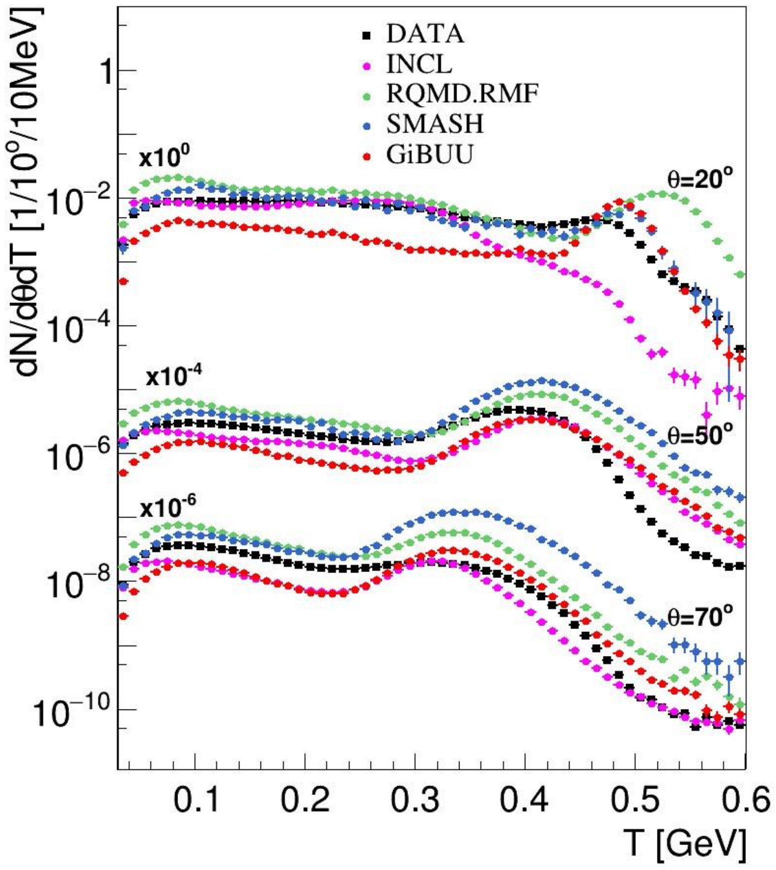
Inclusive hadronic channels in π^-+C at 0.69 GeV/c

Inclusive protons



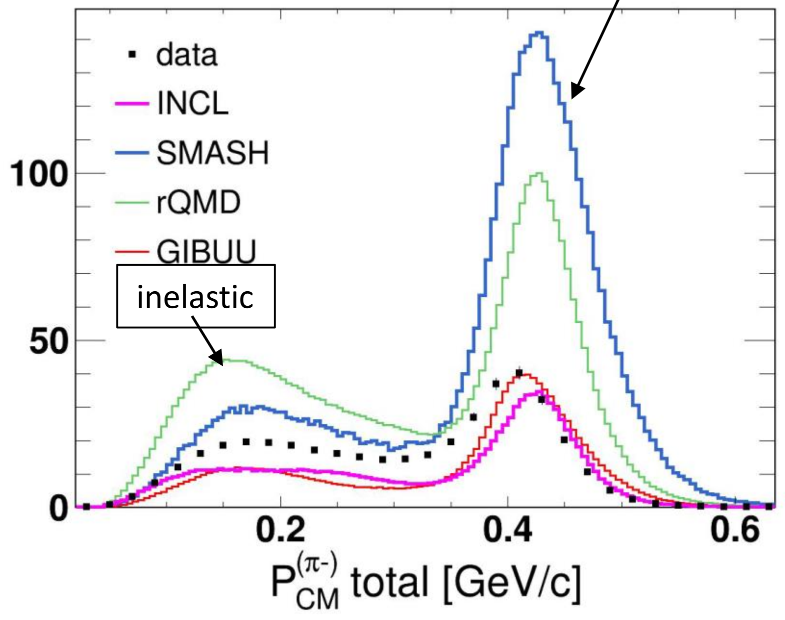
+ inclusive π^+ , d and t

Inclusive π^-

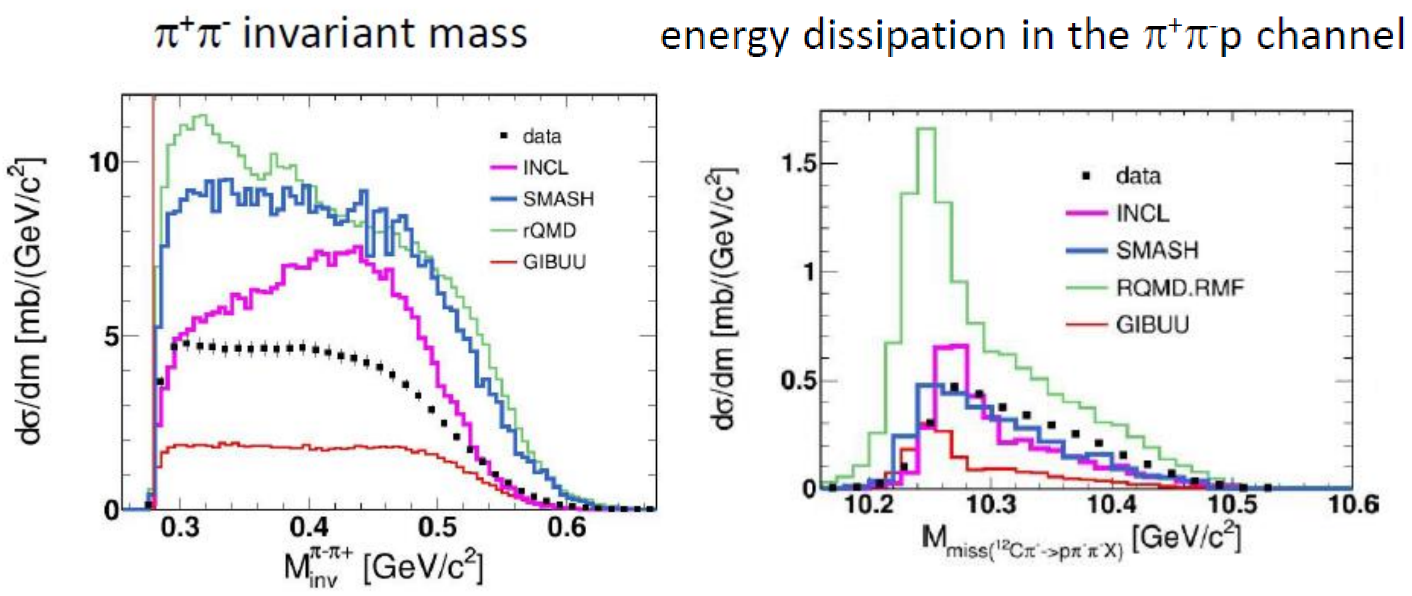


Data compared to INCL++ , GiBUU (used by the neutrino physics community !) and other transport models

Hadronic channels in $\pi^- + C$ @ 0.69 GeV.c



examples



Fatima Hojeij's PhD defended 14 Nov. 2023 at IJCLab (cosupervised by I. Ciepal), presented at NSTAR 2022, MESON 2023

- Detailed tests of various models (GiBUU and INCL++ cascade also used for simulations of neutrino-nucleus interactions)
- HADES objectives: test models for heavy-ion reactions (FAIR) $\rightarrow$ can be also useful for neutrino physics

HADES-neutrino : starting point

- June 2023: discussions between HADES and IRFU team involved in T2K and DUNE (A. Letourneau, S. Bolognesi, A. Ershova)
- S. Bolognesi member of Fatima's PhD committee
- ANR project πFORν submitted oct. 23: including IRFU (neutrino +INCL++) , IJCLab (neutrino+hadronic), LLR (neutrino)
- Nov 2023 : discussions involving IJCLab and IFJ PAN physicists

- HADES collaboration very open to connections with neutrino physics
  improvement of models can benefit to both hadronic and neutrino physics
- Leading role of IJClab and IFJ PAN teams in the pion beam experiments at GSI
- Long standing (since 2016) collaboration between IJCLab and IFJ PAN for HADES analysis, publications in the framework of IN2P3/COPIN agreements (+ P2IO + NAWA)
- Co-supervision of Fatima Hojeij's PhD

IJCLab/IFJ PAN pre-project : very timely to start a collaboration between HADES and neutrino physics teams

no existing IJCLab/IFJPan collaboration

HADES-neutrino IJCLab/IFJ PAN collaboration

HADES
IJCLab : Béatrice Ramstein
IFJ PAN : Izabela Ciepal

accelerator neutrino physics
IJCLab/DUNE: Fabien Cavalier, Yoann Kermaidic, Thibaut Houdy
IFJPAN/T2K and HK: Tomasz Wąchała, Grzegorz Żarnecki, Marcela Batkiewicz-Kwasniak

Plan for 1st year collaboration: use HADES data at 0.690 GeV/c

- Identify most important observables for neutrino reconstruction for T2K ad DUNE (topology, missing energy,..)
- quantify INCL++ and GiBUU deviation w.r.t. data for these observables

Exploit existing collaboration with INCL++ (IRFU) and GIBUU (Giessen) experts

- test other event generators used by the T2K IFJ-PAN team
- one visit in Spring in Cracow to discuss first results and further needed measurements
- One workshop in autumn in Orsay with INCL experts and T2K colleagues at IRFU.

3200 € for visits of IFJ PAN scientists 4200 € for visits of IJCLab scientists

Cotutelle PhD subject: analyze other existing HADES data : π^-+C 0.612, 0.656, 0.750, 0.800 GeV/c
test hadronic physics models used for heavy-ion and neutrino physics (INCL++ and others) and possibly improve them

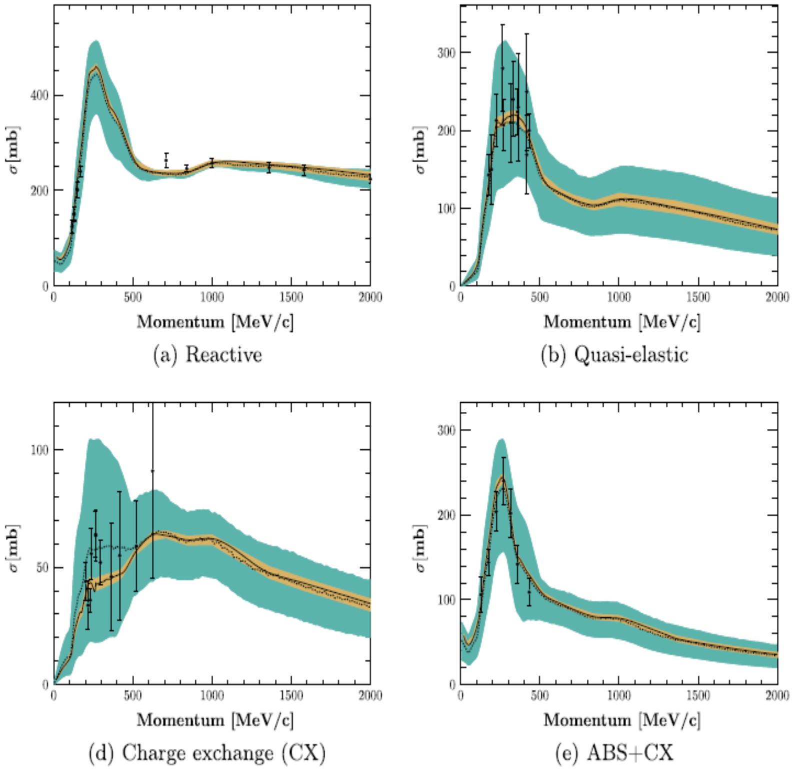
Impact:
- reduce uncertainties on neutrino osc. parameter measurement
- share expertise on T2K analysis physics and develop new methods for T2K and DUNE
- improve the visibility of our teams in our collaborations (HADES, DUNE,T2K,HK)

Thank you – Merci - Dziękuję

Data base for pion-nucleus reactions

- $P_\pi < 250$ MeV/c : Δ(1232) resonance region rather well-known.
- $300 < P_\pi < 500$ MeV/c : few measurements (π, πx) or (π, ππx) (LAMPF, TRIUMF, KEK).
- $P_\pi > 500$ MeV/c : only σ_{tot} (Saturne-1, NIMROD, BNL) and diff. elast. cross sections (KEK).

$\pi^+ + {}^{12}C$

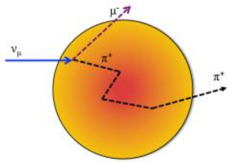


E.S. Pinzon Guerra et al., Phys. Rev. D 99, 052007 (2019)

($\pi^- + {}^{12}C$ is even more scarce !)

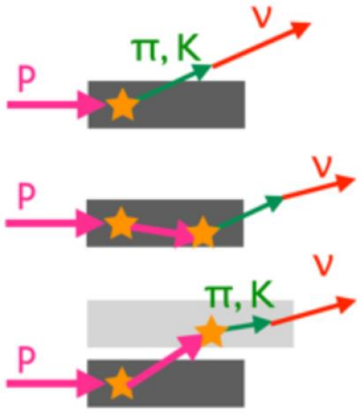
Measurements for $p_\pi > 500$ MeV/c are highly needed

- for hadronic matter studies at $\sqrt{s_{NN}} > 2.6$ GeV
- for detector studies (e.g. e/π discrimination in calorimeters)
- for neutrino physics (ν flux and ν detection)



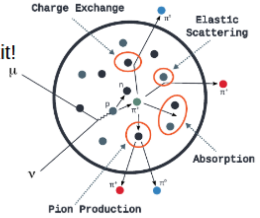
Neutrino oscillation probability and hadronic physics

Neutrino flux
(production cross sections)

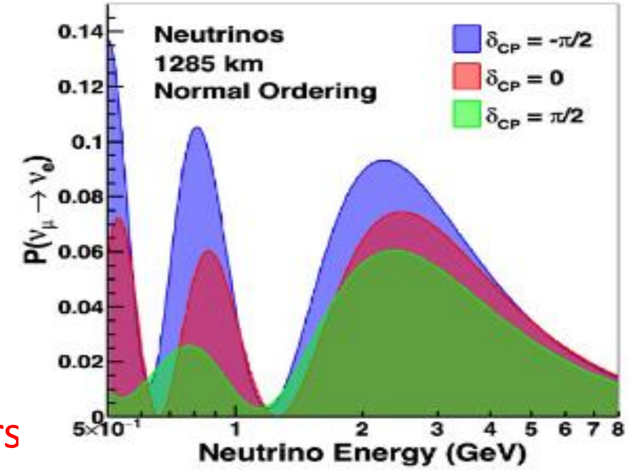


Number of neutrinos measured
in Near Detector

$$N_{ND}(E_\nu) = N_{inc}(E_\nu) \times P_{det}(E_\nu)$$



- Neutrino interaction cross sections in the detector material
- Detection efficiencies



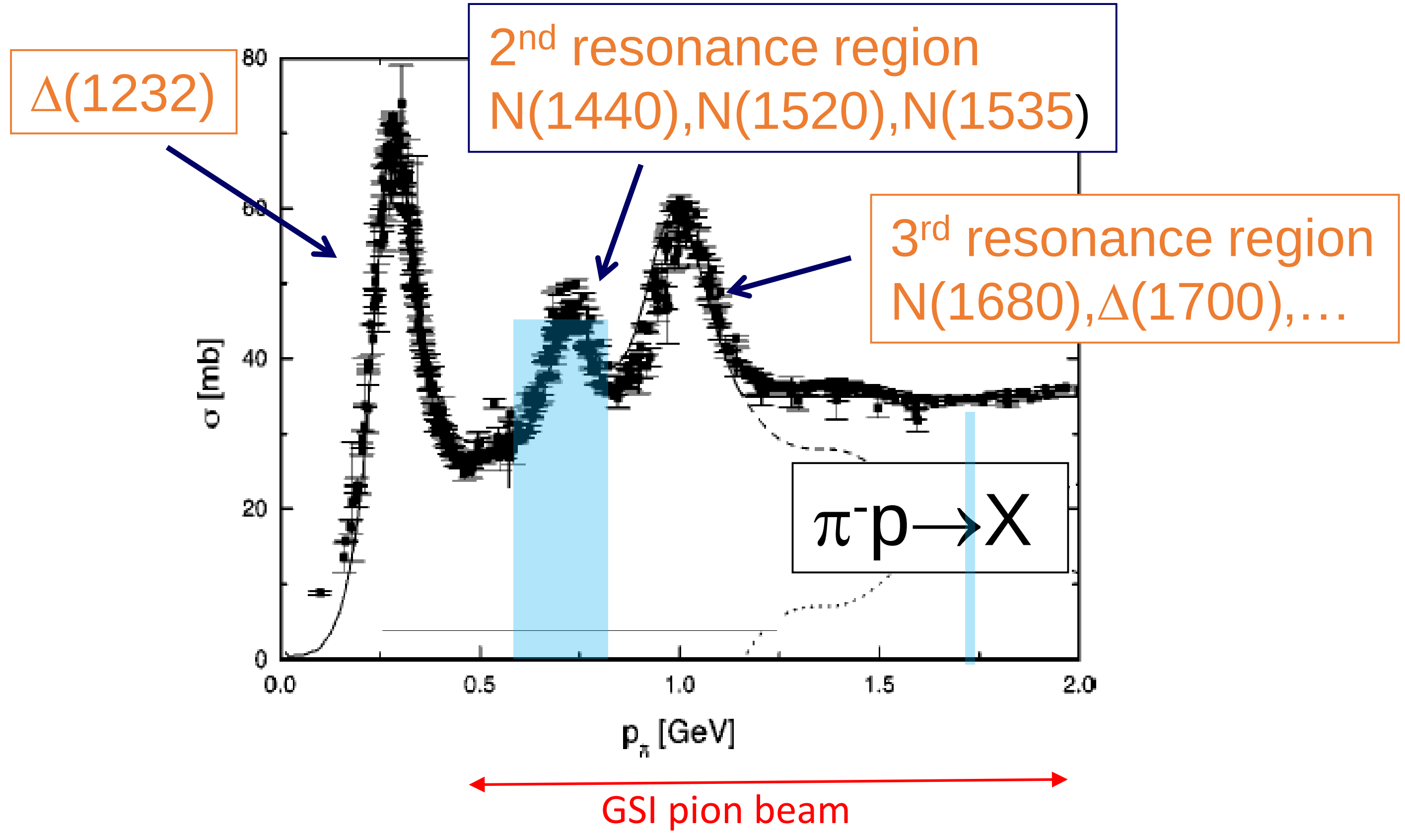
Number of neutrinos needs to be extrapolated to Far Detector and compared to number of neutrinos measured in far detector (after eff. Corrections)

$$P_{\nu_\alpha \to \nu_\beta}(E_\nu) = \frac{N^{corr}_{FD,}(E_\nu)}{N^{extrap}_{ND,\alpha}(E_\nu)}$$

ν/ ν yield needs to be precisely measured as a function of energy in Near and Far detectors

Large fraction (~50%) of the uncertainty on ν oscillation parameters due to hadronic interaction contribution !
Urgent problem of new generation LBL neutrino oscillation experiments

Unique tool to study baryon resonances :



Existing data :

W and C targets p =1.7 GeV/c $\sqrt{s}$ =2 GeV/c^2

CH2 and C targets 0.61, 0.66, 0.7, 0.75, 0.8 GeV/c
Baryon resonance in the 2nd resonance region:
π^-+p : vacuum properties
π^-+A : in-medium properties

2025: new experiment with the upgraded HADES detector at 1.17 GeV/c with CH2 and C targets

GSI pion beam momentum range

The DUNE activities at IJClab in short

- Implication in the DUNE Far Detector-Vertical Drift prototyping phase at CERN
  - Construction of the ProtoDUNE-VD cathode frame and suspension system
  - Reconstruction of events from data and simulation
    - Low-energy calibration with ^{39}Ar decay
    - Charged particle beam showers (e^-, π^-, K^-) for preparing subsequent Ar cross-section analysis

- Responsible for the delivery of the FD-VD cathode and electronics penetrations

Top PD-VD volume

anode

Cathode + photon detectors

1 GeV pion in PD-VD - G4 simulation