Standard Model neutrinos with CERN proposed and forthcoming facilities

Neutrino Workshop at CERN – January 2025

Sara Bolognesi – CEA/IRFU

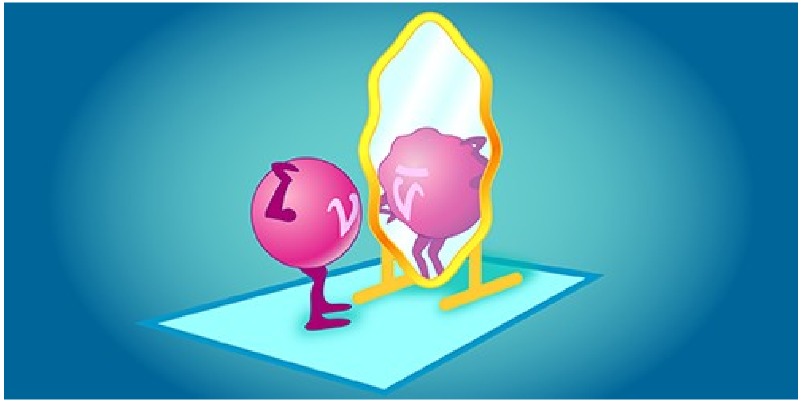
A new era for neutrino oscillations

Neutrino oscillations entered **the precision era :**

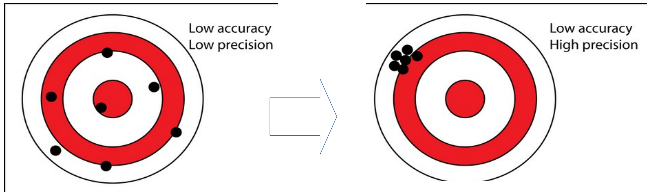
- huge statistics from neutrino **atmospherics** experiments

- neutrino from **reactors** become a benchmark to study nuclear physics

- **long-baseline experiments** enable the unique possibility to compare oscillation in controlled beams of neutrinos and antineutrinos separately



The challenge move from precision to **accuracy** !



Neutrino oscillations (at LBL)

	Today	Future
θ_{12}, Δm^2_{12}	Few %	<1% (JUNO)
θ_{13}	~1 %	~1 %
$\|\Delta m^2_{32}\|$		
θ_{23}		
CPV (δ_{CP})		
MO		

From **solar and Kamland** (no sensitivity at LBL)

Sensitivity at LBL from ν_e appearance but precision dominated by **reactors**

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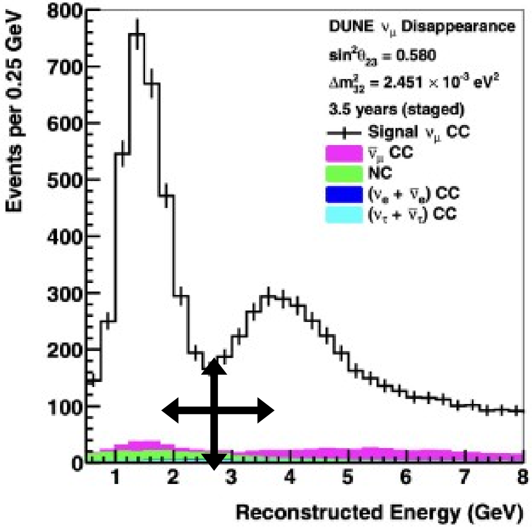
CPV (δ_{CP})		
MO		

Precision from LBL with **ν_μ disappearance**



from **rate and energy shape**

(θ_{23} octant degeneracy resolved from ν_e rate)

'Charge' selected flux of ν_μ → ν_μ ν_e ; $\bar{\nu}_\mu$ → $\bar{\nu}_\mu$ $\bar{\nu}_e$ oscilllated samples at LBL far detectors

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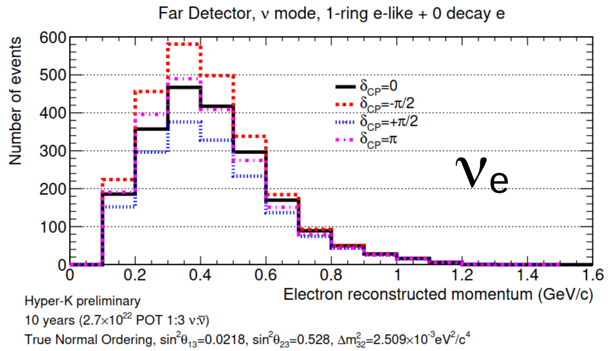
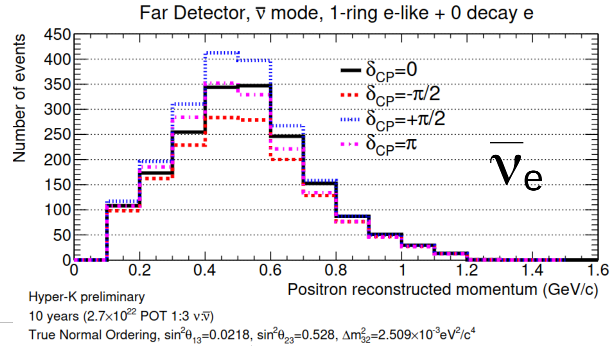
CPV (δ_{CP})	90 % CL	5σ (~5°-20°)
MO		

(Indirect sensitivity from ν_μ disappearance + θ_{13} from reactors)

Direct sensitivity from **ν_e/$\bar{\nu}_e$ rate (and ν_e shape)**





'Charge' selected flux of

$\nu_\mu \rightarrow \nu_\mu \quad \nu_e$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \quad \bar{\nu}_e$

oscilllated samples at LBL far detectors

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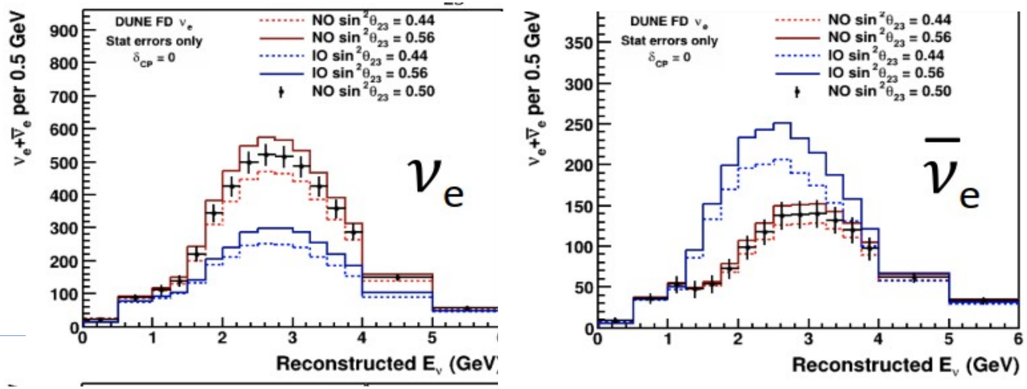
CPV (δ_{CP})	90 % CL	5σ (~5^o-20^o)
MO	1.2σ	5σ (atm&LBL&JUNO)

(Indirect sensitivity from combination of Δm^2_{ee} measured at reactors and $\Delta m^2_{\mu\mu}$ from LBL and JUNO)



Direct sensitivity at LBL with **rate of ν_e/$\bar{\nu}_e$** **(shape of ν_e** help breaking degeneracies)

‘Charge’ selected flux of

ν_μ → ν_μ ν_e

$\bar{\nu}_\mu$ → $\bar{\nu}_\mu$ $\bar{\nu}_e$

oscilllated samples at LBL far detectors

CERN support to LBL detectors

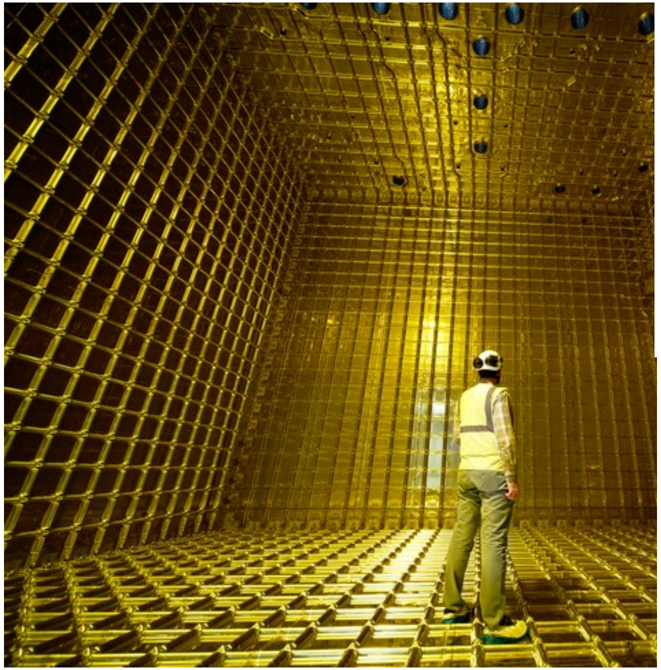
The LBL program requires development of **new detectors/technologies: large-scale efforts**

→ **crucial role of the Neutrino Platform :**

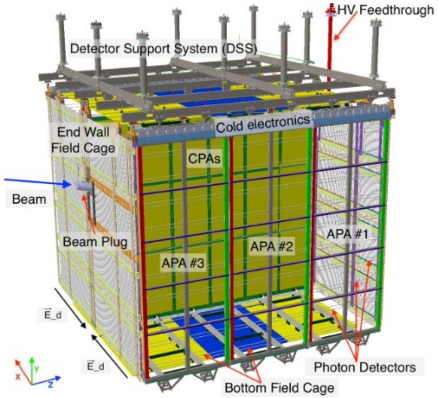
unique environment for availability of **infrastructure and expertise**

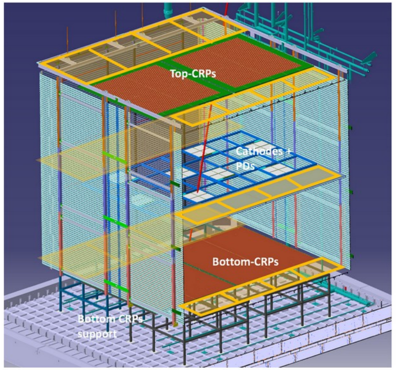
ProtoDUNE

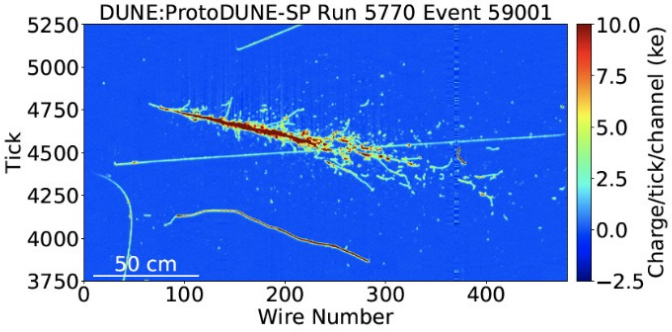
ProtoDUNE LAr modules
(>700t, >200m^3)



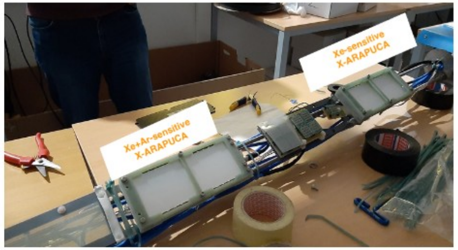
Horizontal and vertical drift



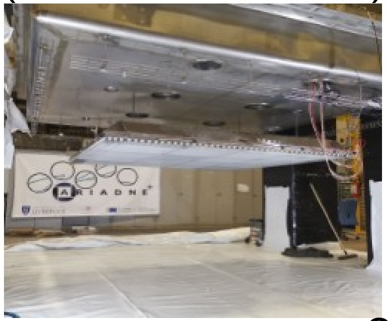




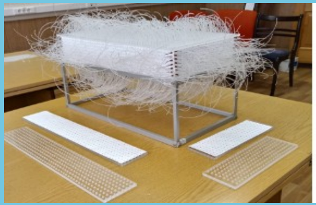
Xe-doping in PDSP
with dedicated sensors

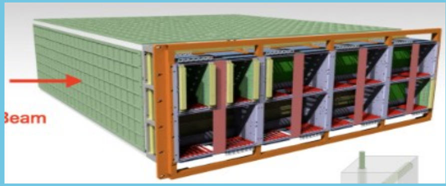


ARIADNE : TPC
optical readout
(tested in the cold-box)

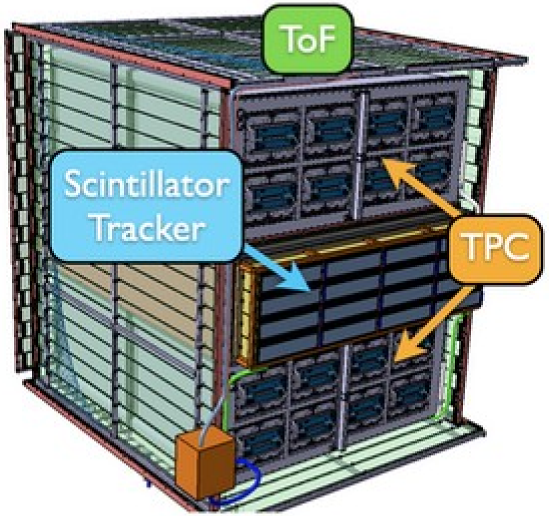


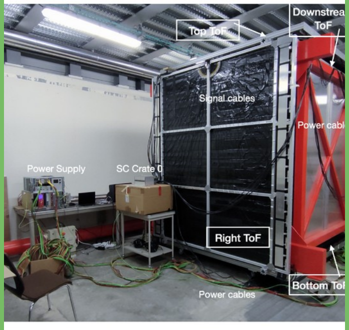
Upgrade of JPARC near detector (ND280)

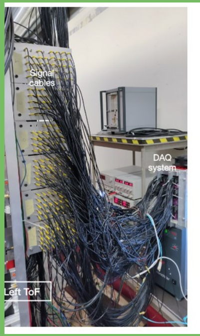




SFGD prototype test beam & mechanical tests of the box

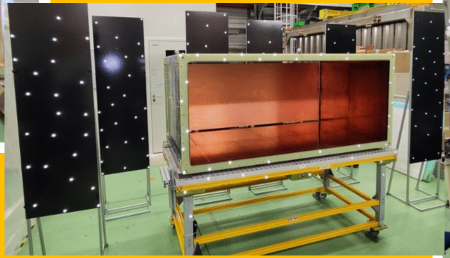
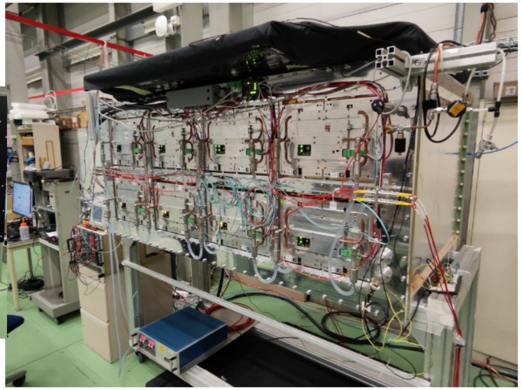






ToF prototype test beam, full assembly and test of final detector

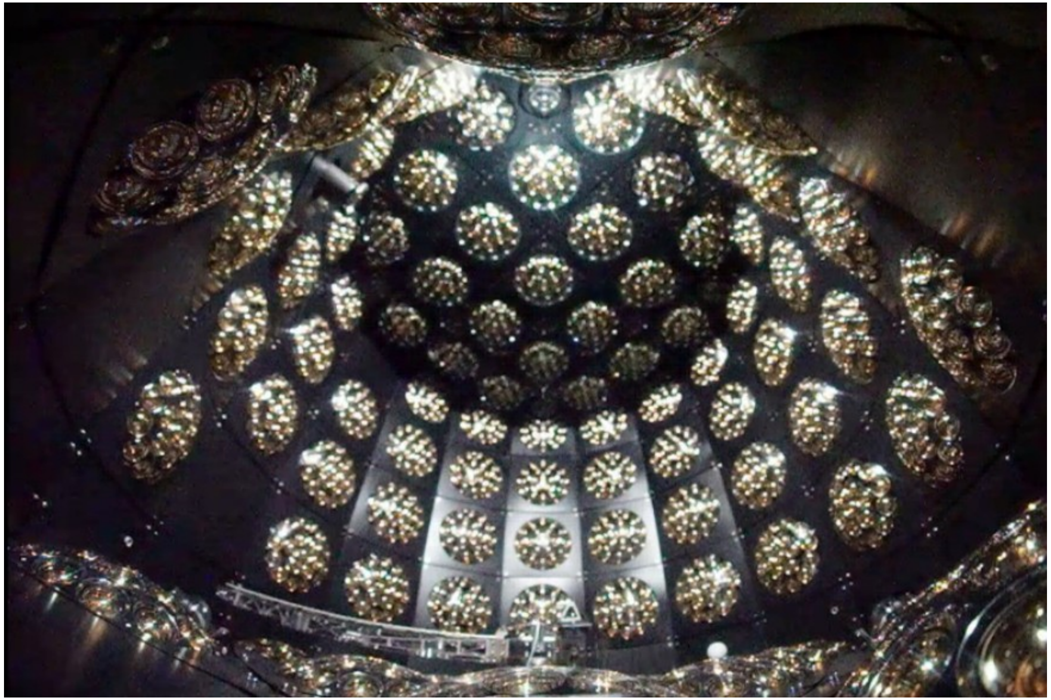


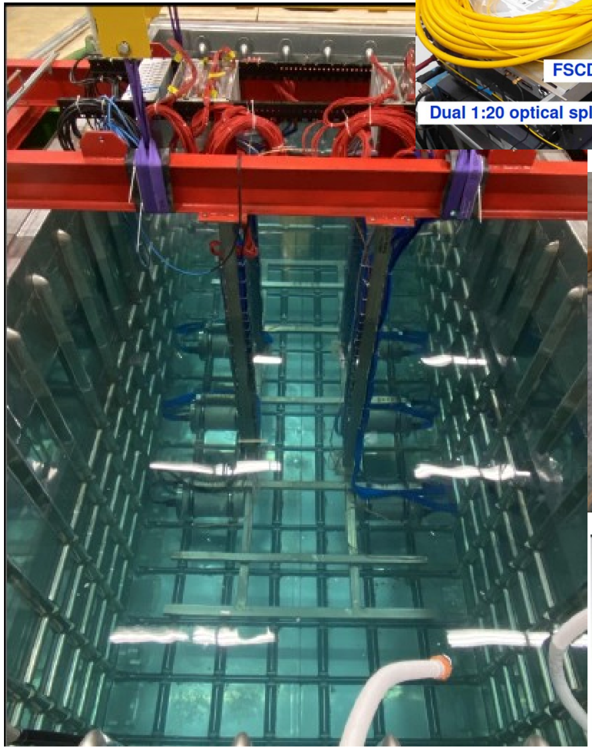



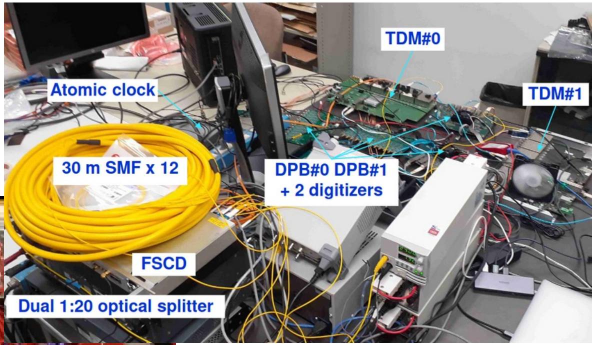
2 TPCs : multiple test-beam prototypes, Micromegas production and characterization, metrology, full assembly and test of final detector

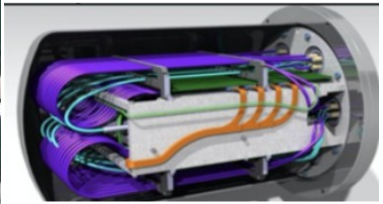
HyperKamiokande multi-PMTs and electronics

Water Cherencov Test Experiment
(4m d x 4m h) on test beam





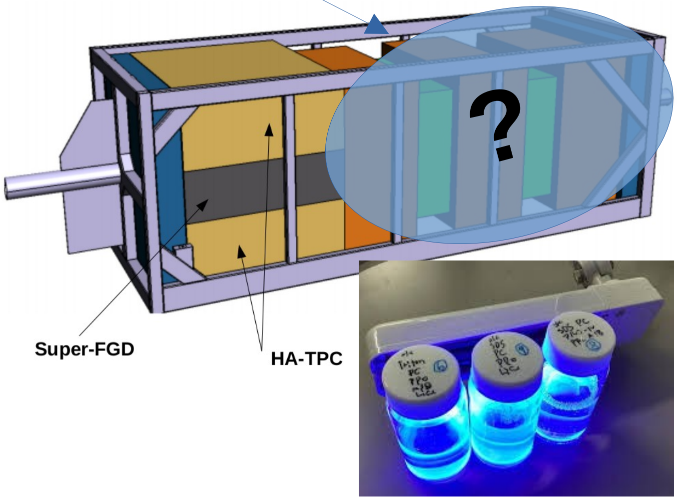


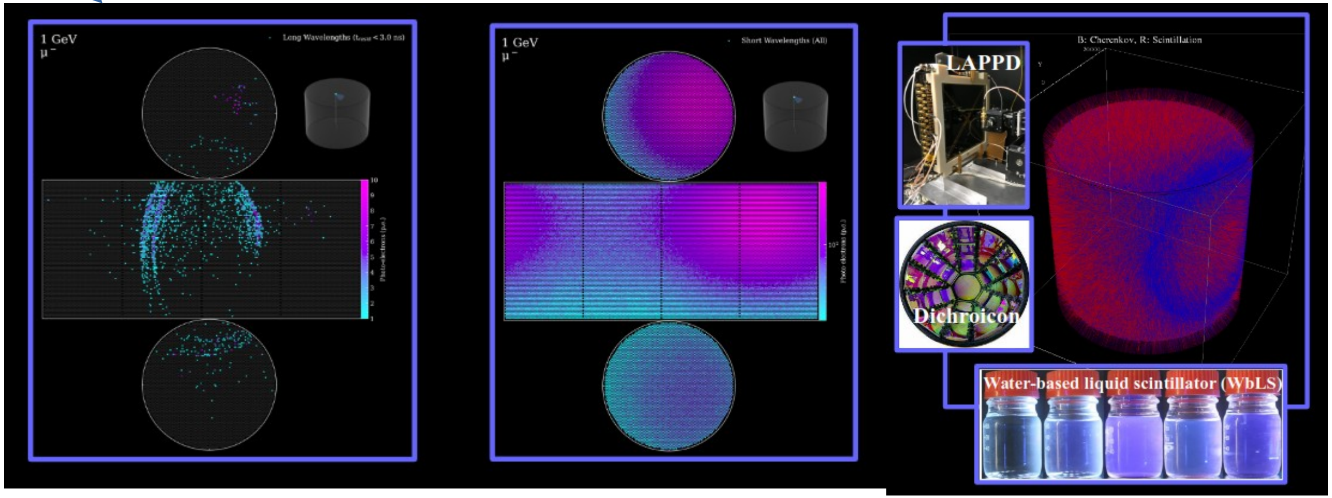


HK electronics (900 boxes, ~4500 cards) : integration, calibration, assembly and test underpressure and underwater

...and future LBL detectors

Support neutrino detector developments for further upgrades/detectors:
ND280++, DUNE Phase2 (eg, Theia), and more ...





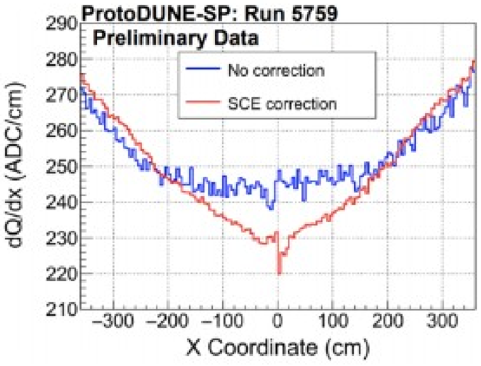
Very interesting detector developments ahead (and interesting synergy between HK and DUNE technologies)

Power is nothing w/o control

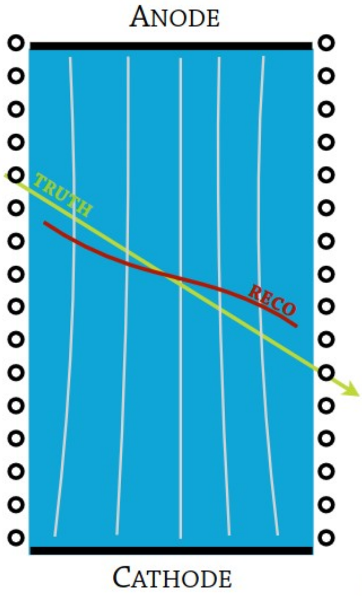
- Wonderful near and far detectors needs extremely good **control on the systematics on their response** (eg energy scale) + extremely performing **reconstruction algorithms**

- Prototypes at CERN are at the forefront of these developments : first implementation of algorithms and results on real data !

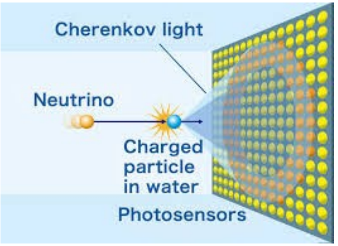
Eg, space charge effect on LAr

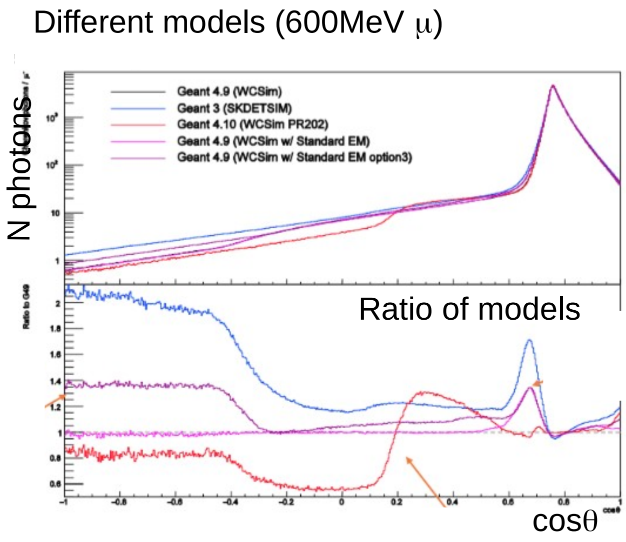


L.Zambelli (DUNE Fr workshop)



Eg, water Cherencov profile (light vs angle) with WCTE





Mo Jia (WCTE workshop)

Systematics due to nuclear physics

The neutrino oscillation measurement in a nutshell

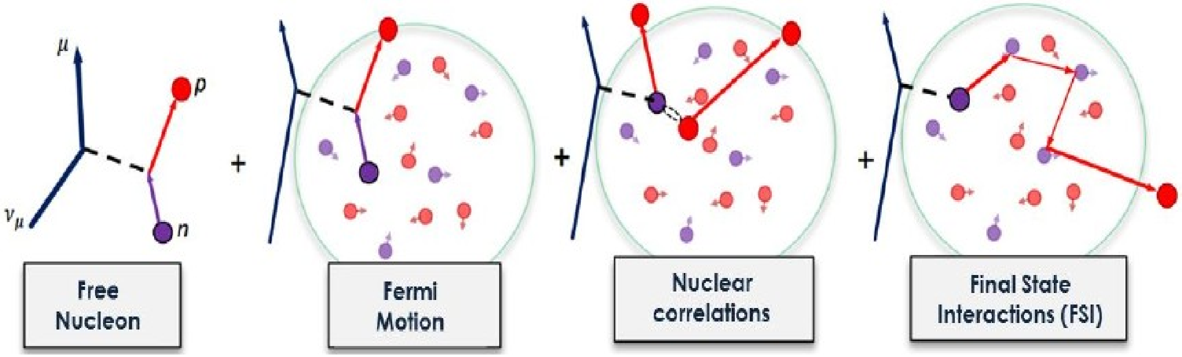
$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx \int P_{\nu_\alpha \to \nu_{\alpha'}}(E^{true}_\nu) \times \frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)} R(E^{true}_\nu - E_\nu)\, dE_\nu$$

Intrinsic systematics due to flux and xsec modelling

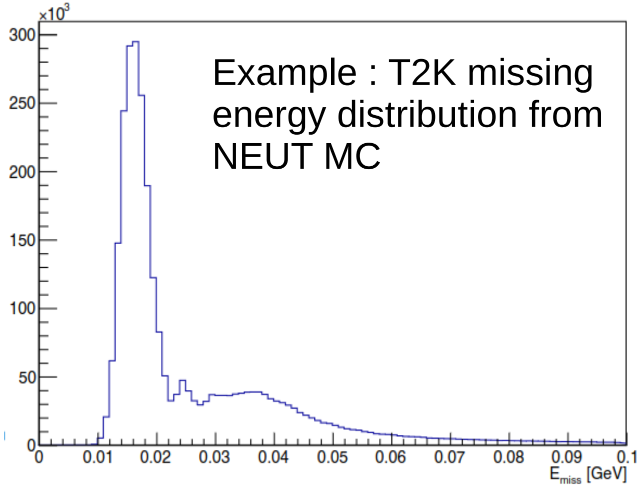
- difference between ND and FD (eg, acceptance, energy spectrum)
(and it is impossible to separate flux and xsec from ND data)

- <u>neutrino energy 'unfolding'</u>
(I will mostly focus on this aspect on the following, with 2 specific examples...)

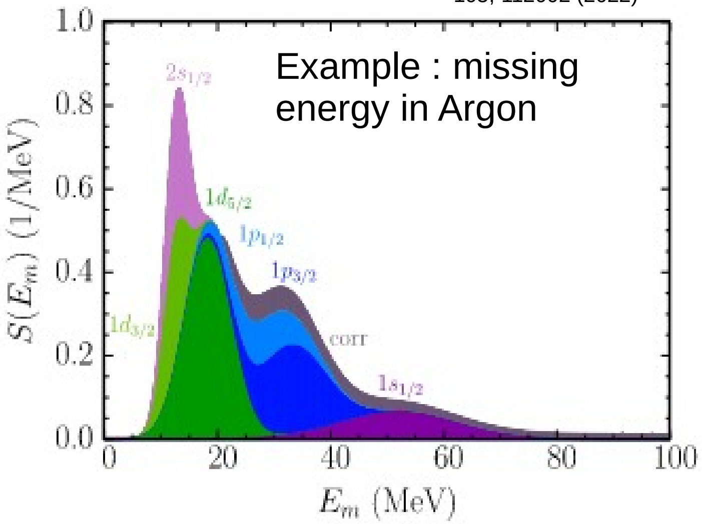
Missing energy from nuclear effects



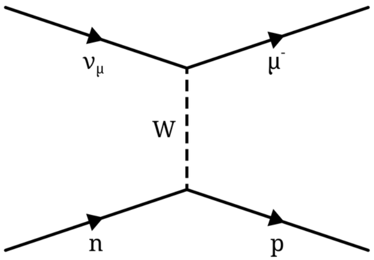
Some energy ‘lost’ to remove the nucleon from the nucleus (~tenths of MeV)
+
nucleon has already some (~hundreds of MeV/c) momentum in the nucleus

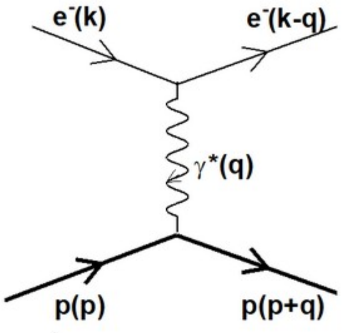


PHYSICAL REVIEW D 105, 112002 (2022)



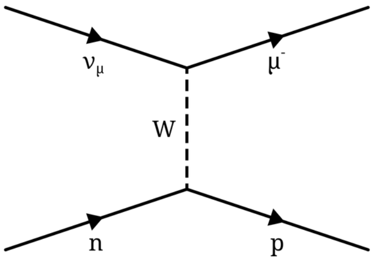
Electron-scattering

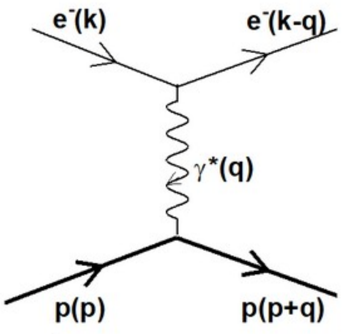




- Isn't the same thing ? Not exactly (V-A current in EWK) but still the nuclear effects ('before'/'after' the interaction) are the same… so, **shouldn't we know everything about nuclear effects already** from old e-scattering data?

Electron-scattering





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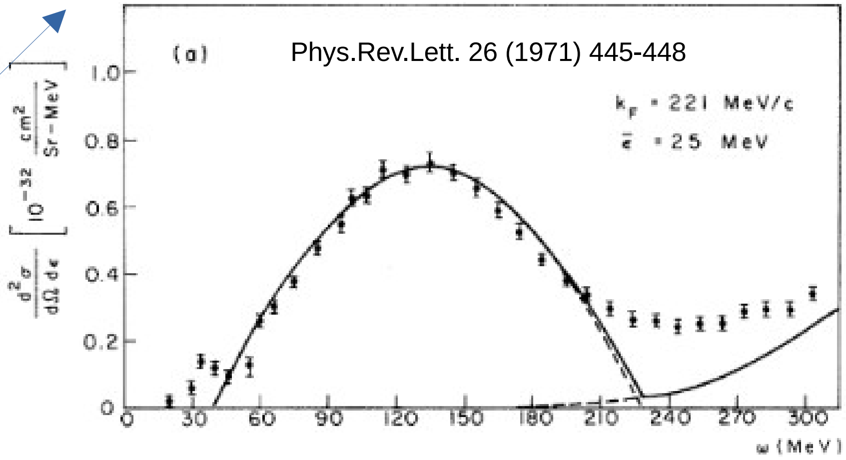
Actually e-scattering data are much more 'precise'
(you can select a monchromatic beam of e-)…
but this was actually exploited by old e-scattering experiments to focus in specific E_e regions
(eg, QE-enhanced, pion production…)

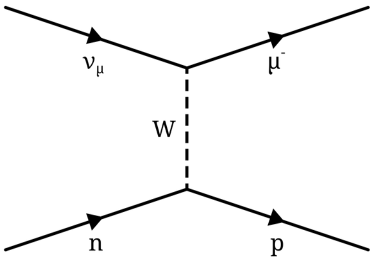
For ν scattering we need **full model of xsec for all energies** (also complex regions were different processes overlaps).

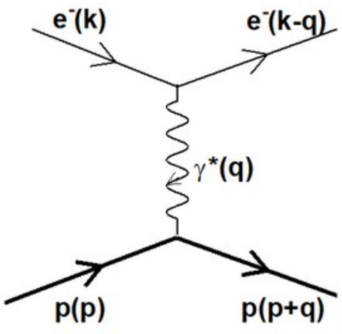
Typical example from old data/models :



Good data-model agreement for fixed E_e, fixed e' angle (only when exactly on peak of pure QE)

Electron-scattering





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- Also only sparse exclusive (e,e’p) scattering data (measuring all the final state particles are sparse)

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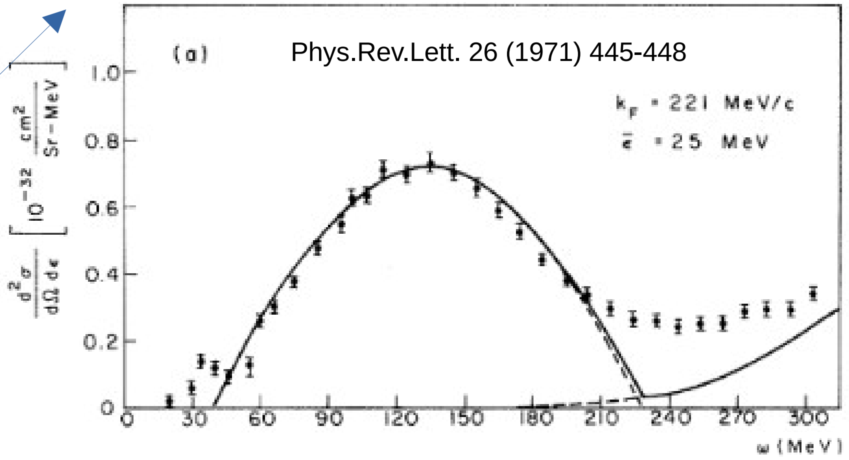

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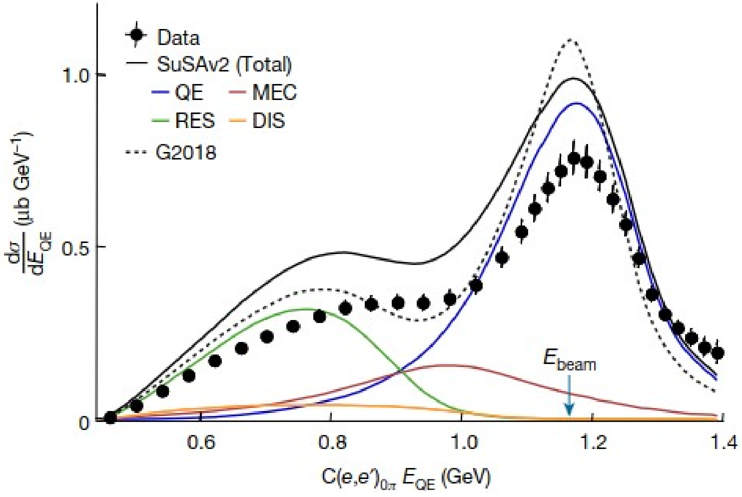
Electron test beams

More/new e-scattering measurements would be extremely useful !

Electron test beams on LBL detector prototypes would provide new measurements with modern analysis/detector techniques + casted to LBL needs

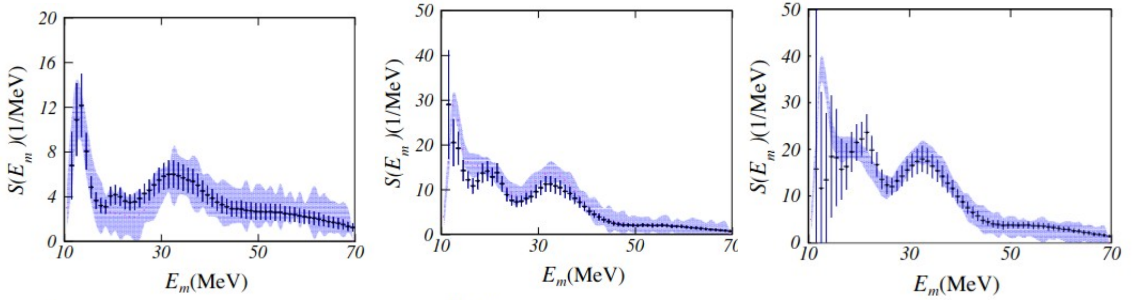
Eg, JLab recent examples :

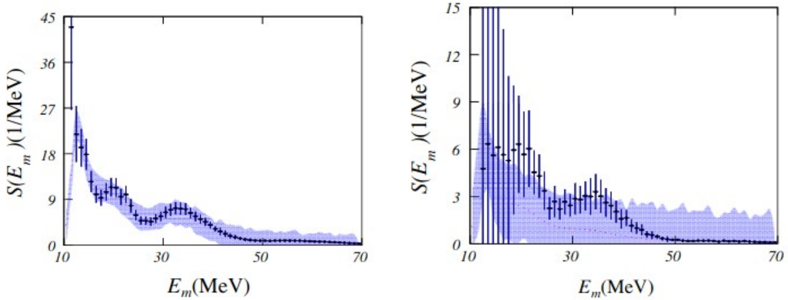
- e-C data reconstructed with ν technique → test of the models



Nature volume 599, pages 565–570 (2021)

- Tuning of model from new e-Ar exclusive (e'+p) data





Missing energy in bins of missing momentum

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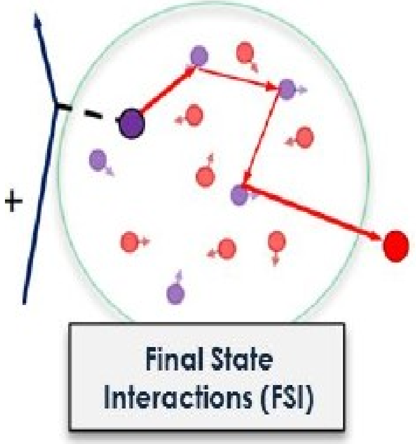
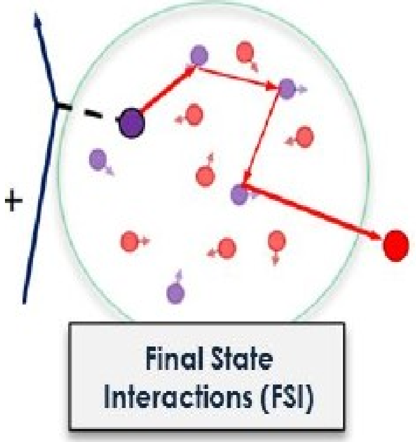
Final State Interactions: π, p test beams



Pions and protons in nuclei can change kinematics, charge or even be fully re-abosrbed

FSI Model tuned from **pion-nucleus and proton-nucleus scattering experiments.**

Final State Interactions: π, p test beams



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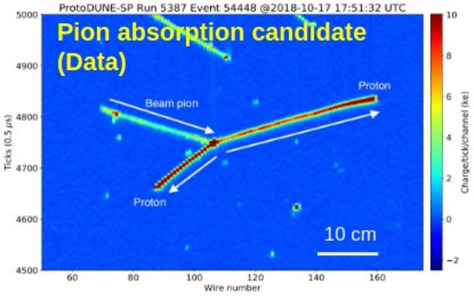
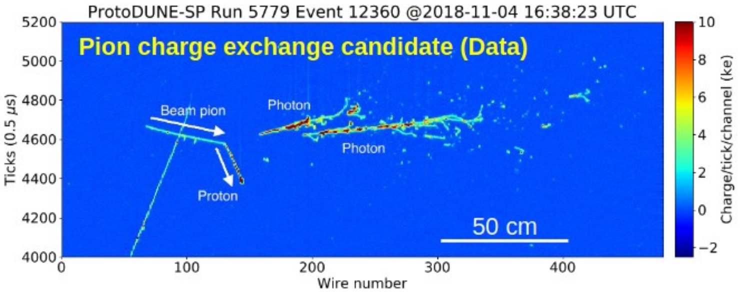
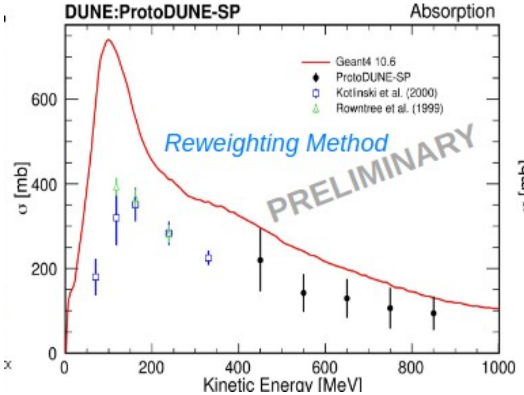
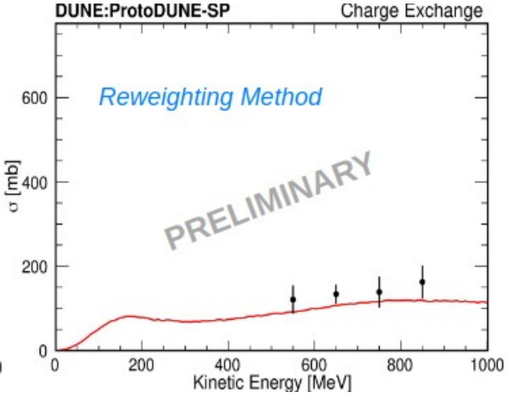




Very sparse data and mostly inclusive : no data on the kinematics of the outgoing pion/proton
→ **important measurements being done with protoDUNE data and planned with WCTE**

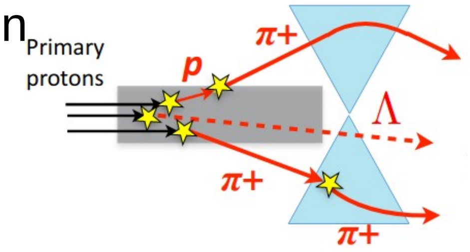




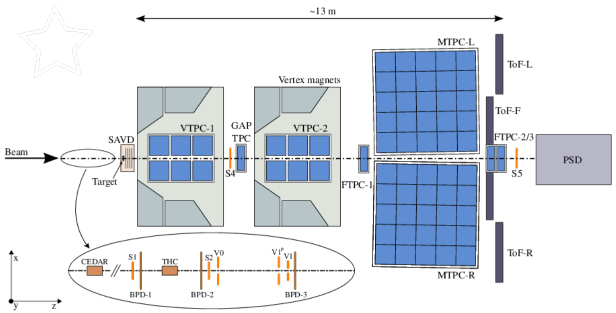
Heng-Ye Liao, ICHEP 2022

Flux : hadroproduction uncertainties

- Neutrino flux depends on hadro-production from protons hitting the target



- Tuned with dedicated experiment at CERN : NA61/SHINE



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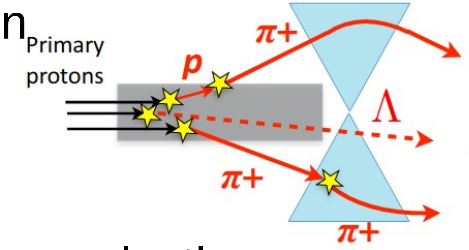

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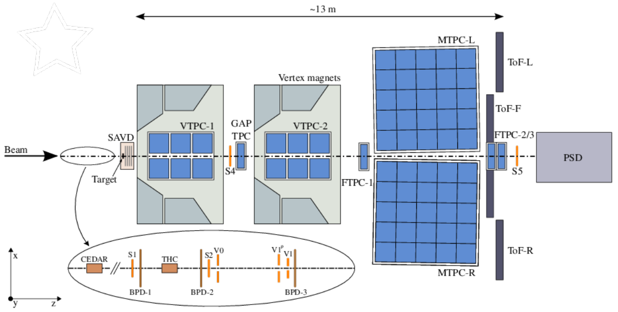
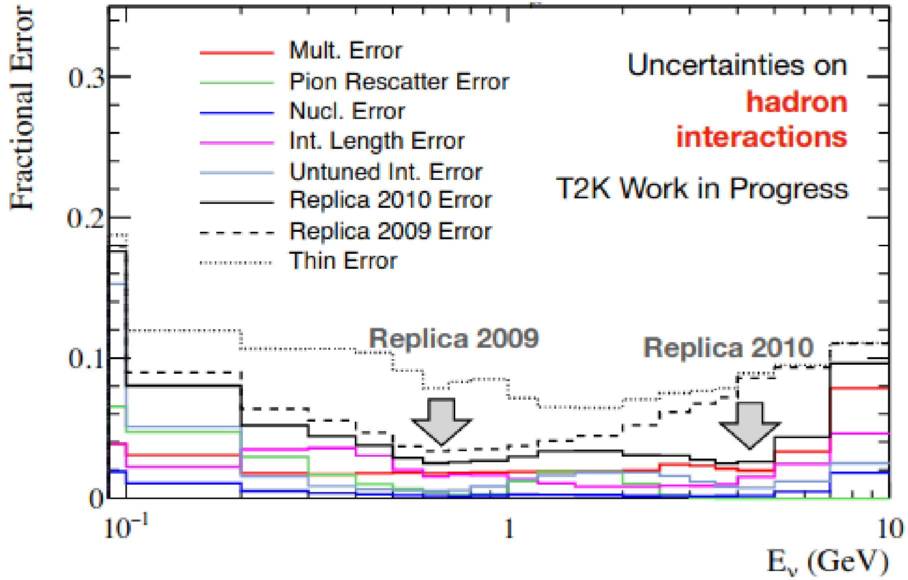


- Uncertainties from hadro-production :

T2K (as an example for the future LBL)



- **First order:** pN→ π, K multiplicity and kinematics

- With **replica target:** able to tune also re-interactions in target + minimize the impact of total proton cross-section/int. lenght uncertainty

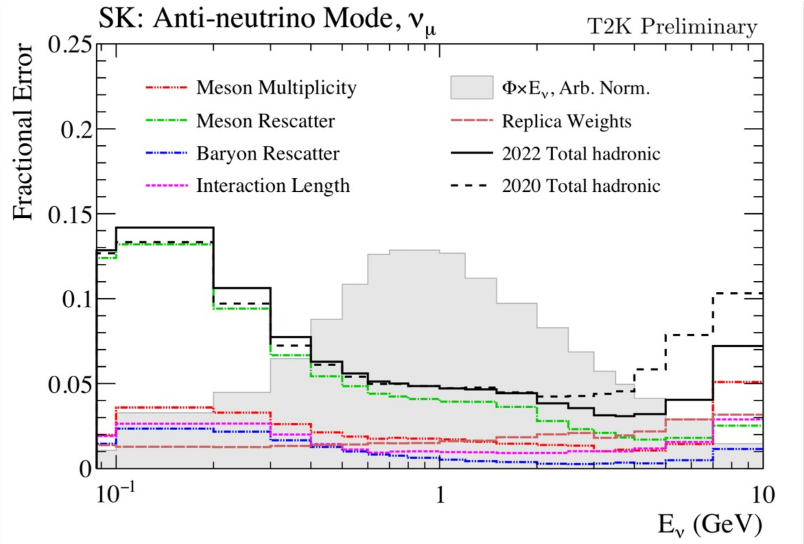
Crucial to repeat NA61 measurements on the target of the future LBL experiments, and we actually need go beyond...

NA61/SHINE for next LBL

θ_{23} Δm^2_{32} : a factors 2-3 times better → rate at better than 1 % and energy shape (eg energy peak/scale at 0.5 %)
(Energy shape also important for δ_{CP} precision measurement

CPV and MO ($\nu_e/\bar{\nu}_e$ asymmetry) : aiming to an uncertainty < 3 %

- Complex systematics comes from hadron rescattering (also in the beamline 'after' the target) and untuned interactions (outside present NA61 phase space)



Largest impact on $\nu_e/\bar{\nu}_e$ ratio comes from this meson rescattering :

rescattered pions have 'different' kinematics, more difficult to focus/defocus correctly → easier to get wrong sign comtamination

→ new measurements at lower energies and other targets is crucial

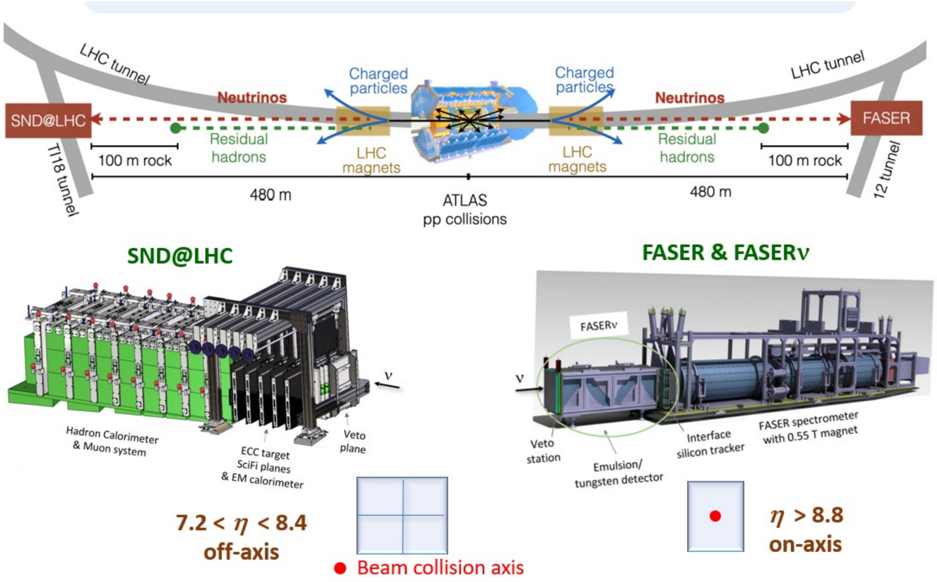
NA61/SHINE for atmospheric neutrinos

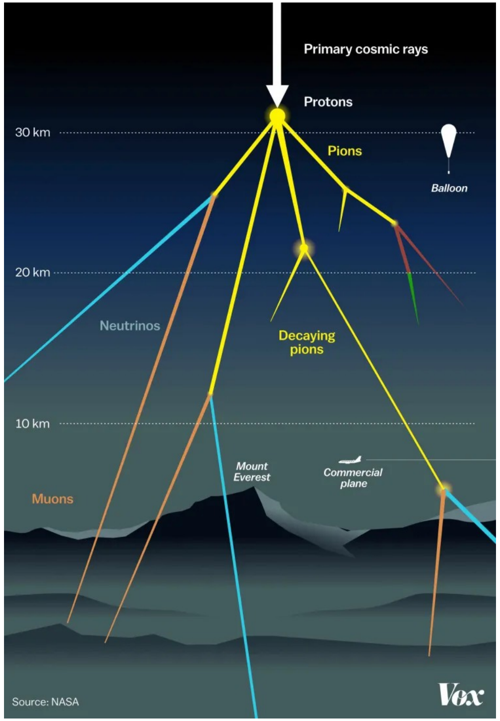
Future LBL will rely on LBL+atm and/or atm crucial for beyond-PMNS (eg NSI)
→ correlations between beam and atmospheric fluxes?
NA61 performs hadro-production measurements also for atmospherics : need to investigate needed measurements and correlations (right now very different physics models)

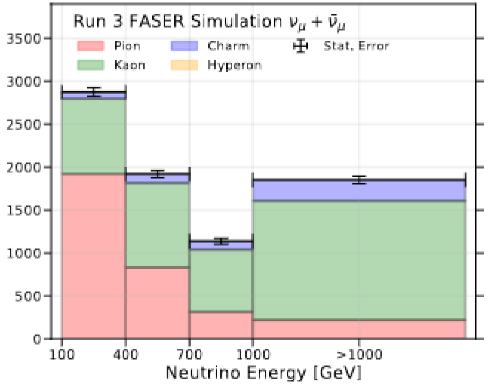
Atm flux modeling : fwd detectors at LHC

Need good control of very forward and high energy hadron production to model properly the atmospheric flux (eg, muon puzzle)

Can be measured at a new regime in LHC forward regions : FASER and SND

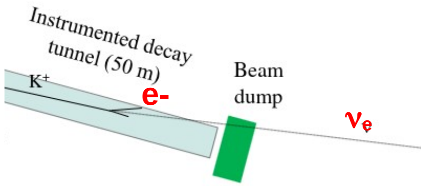






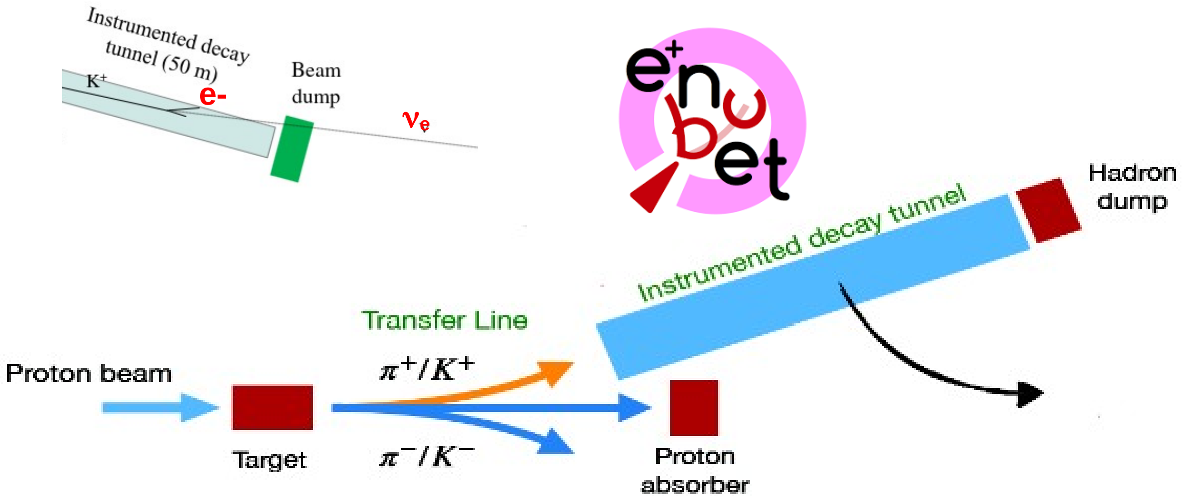
Future solution : monitored beam

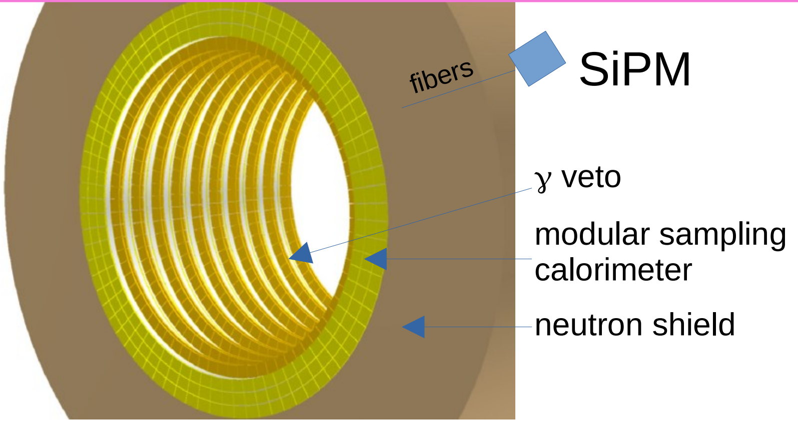
Measure the leptons in the decay tunnel ⇨ Need slow extraction (for a reasonable rate) → transfer line (instead of pulsed horns) + fast detectors (and radiation hard)



Monitored beam : R&D @ CERN

Measure the leptons in the decay tunnel ⇨ Need slow extraction (for a reasonable rate) → transfer line (instead of pulsed horns) + fast detectors (and radiation hard)



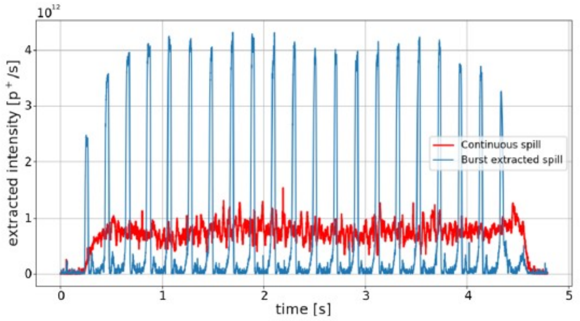


Preliminary studies : propagating hadro-production uncertainties to lepton observables → ν_μ and ν_e rate from 5 % to 1 %

Prototype succesfully tested on CERN T9 beamline

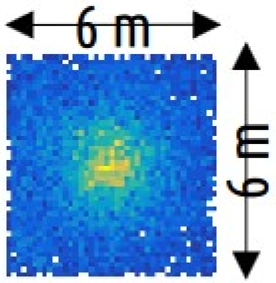
A monitored neutrino beam at protoDUNE

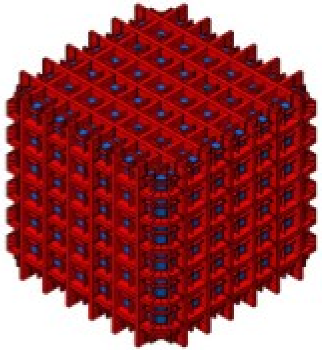
A possible implementation at CERN :

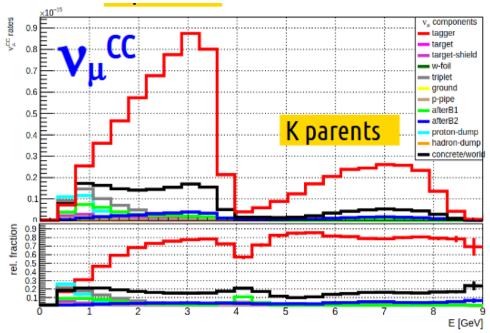


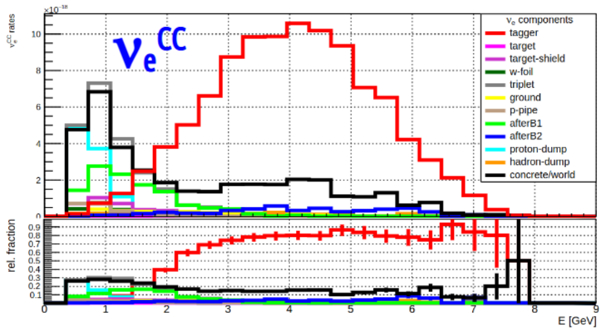
Slow extraction at SPS:
proton 400 GeV → focused π,K of 8.5 GeV ± 10 %

ProtoDUNE 50m after the hadron dump
→ 0.7M ν_μ CC with 1e20 POT → 10000 ν_e CC with ~1e20 POT
(can be further improved with beamline optimization)





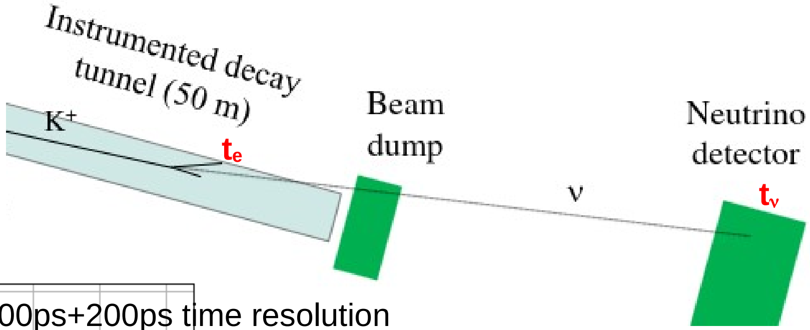


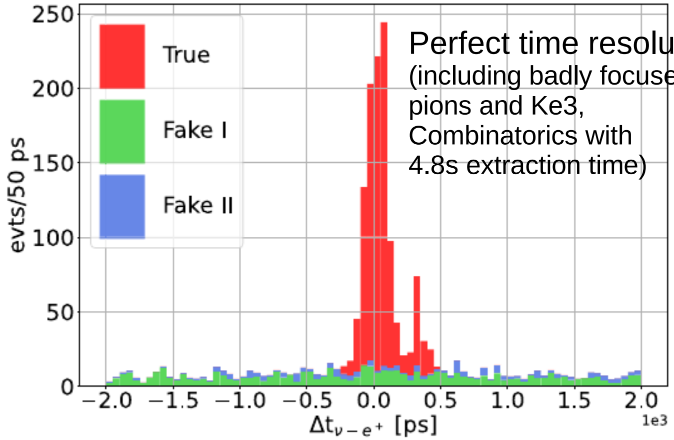


Unique return : precise neutrino cross-section measurement at protoDUNE with 1 % flux rate uncertainty !

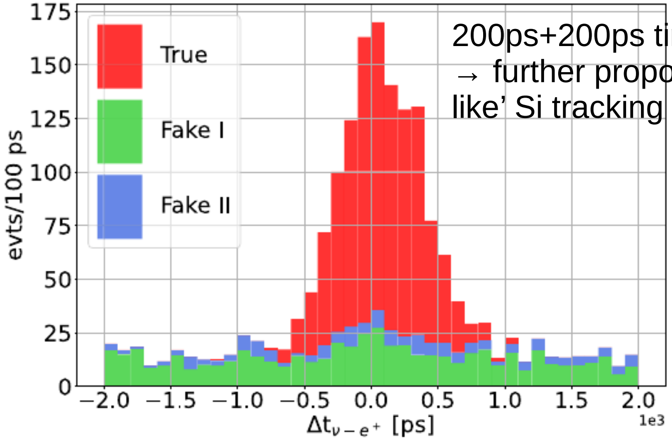
… and then a tagged neutrino beam !

Event-by-event time coincidence :
t_{lepton} in beam – t_{ν} in detector
→ virtually perfect flavour and very precise energy reconstruction of each neutrino interaction





Perfect time resolution
(including badly focused pions and Ke3, Combinatorics with 4.8s extraction time)



200ps+200ps time resolution
→ further proposal to use 'NA62-like' Si tracking (100ps)

ENUBET + NuTag → PBC short-baseline beam project (**PBC@SBN**)

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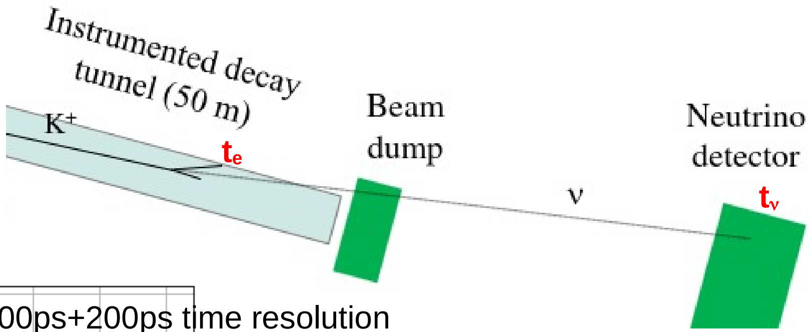

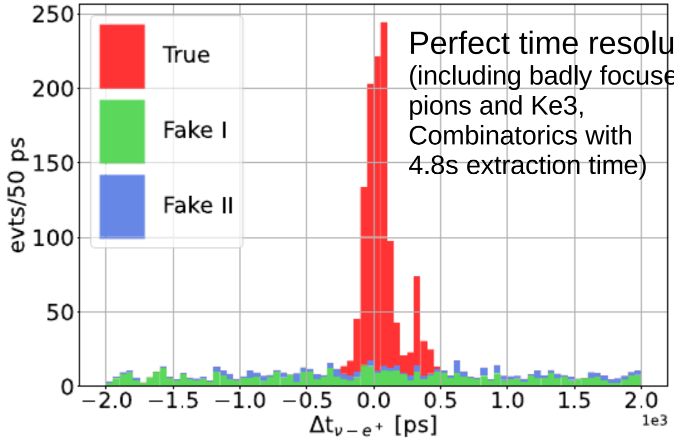

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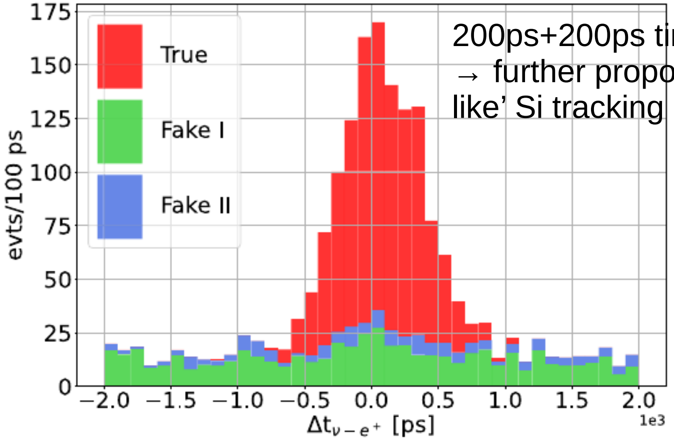

200ps+200ps time resolution
→ further proposal to use 'NA62-like' Si tracking (100ps)

ENUBET + NuTag → PBC short-baseline beam project (**PBC@SBN**)

Extremely precise xsec measurements : finally **a 'real' xsec measurement** (independent from the flux) with precision comparable to electron-scattering experiments

(This would be the **first worldwide demonstration** of this extremely powerful technique !)

Summary & prospects

- **Neutrino Platform is crucial**
  - Unique path for strong and distinct European role in overseas LBL
  - A lot to do in the next years to ensure LBL accuracy (detector development, xsec measurements) and to prepare the future technologies

Summary & prospects

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- **And more : NA61, SND/FASER, Physics Beyond Colliders inserting neutrino physics into the larger prospectives.**

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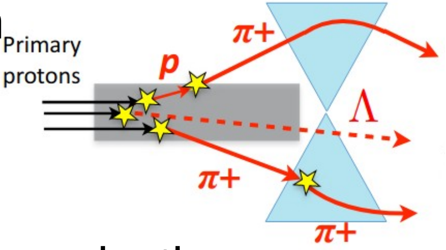
- Neutrino physics is an extremely promising **door for New Physics, crucial role for astrophysics and for cosmology.**
Neutrino oscillation is going in the next decade to produce **crucial new measurements** : notably possible discovery of Charge-Parity violation in the lepton sector !

→ Investing in the neutrino domain today is a ‘safe bet’ : **crucial opportunity for CERN to contribute to major physics results in the next decade**

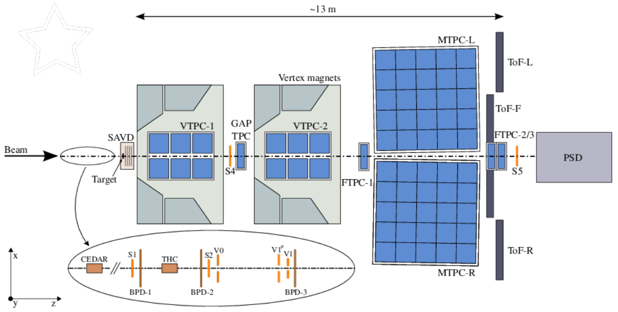
BACK-UP

Flux : hadroproduction uncertainties

- Neutrino flux depends on hadro-production from protons hitting the target



- Tuned with dedicated experiment at CERN : NA61/SHINE



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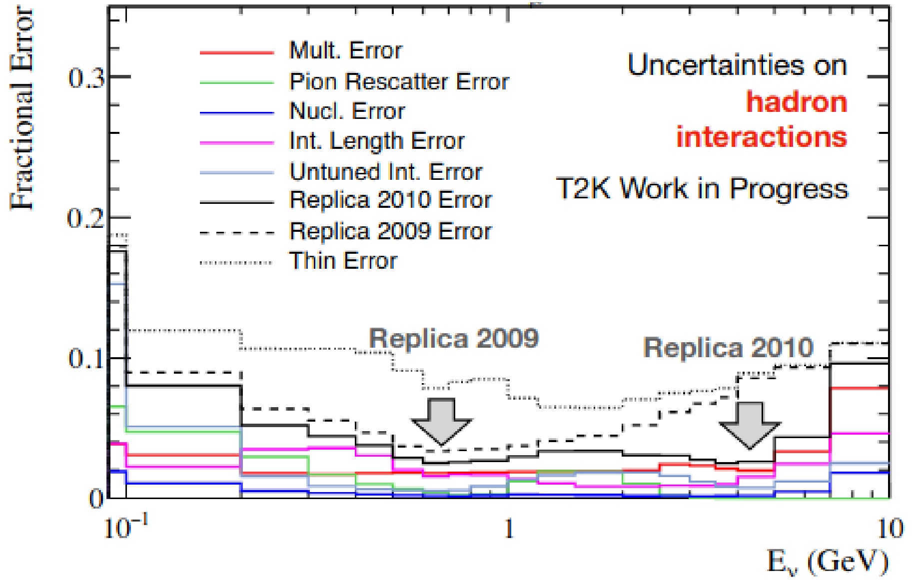
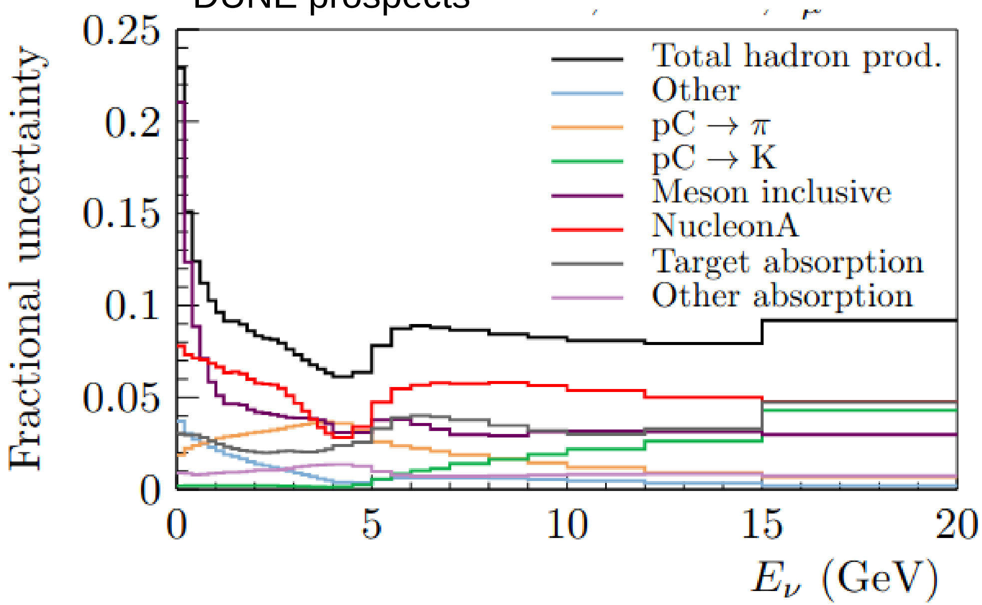


DUNE prospects



NA61/SHINE for next LBL

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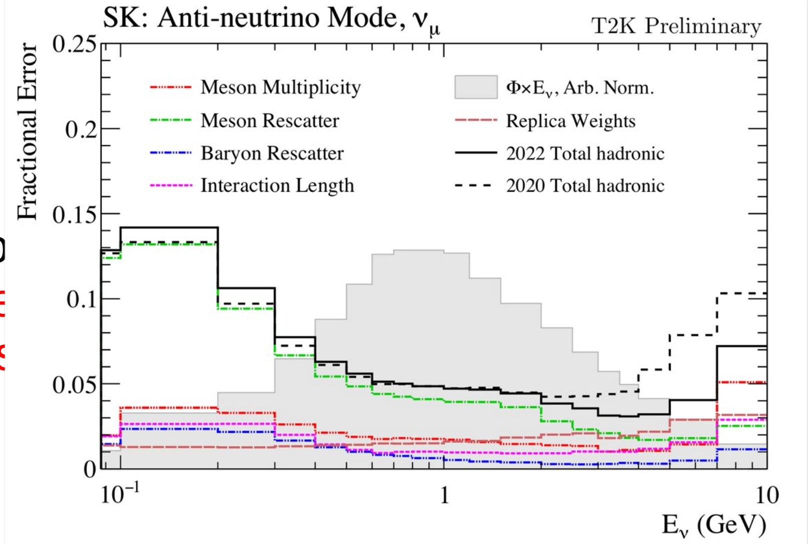
and we actually need to go beyond :

θ_{23} Δm^2_{32} : a factors 2-3 times better → need control of rate at better than 1 %
and energy shape (eg energy peak/scale at 0.5 %)
(Energy shape also important for δ_{CP} precision measurement

Challenges ahead :

- A systematics with leading impact on **total flux rate** is
(interaction length): today ~2%

- Very challenging systematics on **flux shape** comes fro
hadron rescattering error (also in the beamline 'after' the
and untuned interactions (outside present NA61 phase s

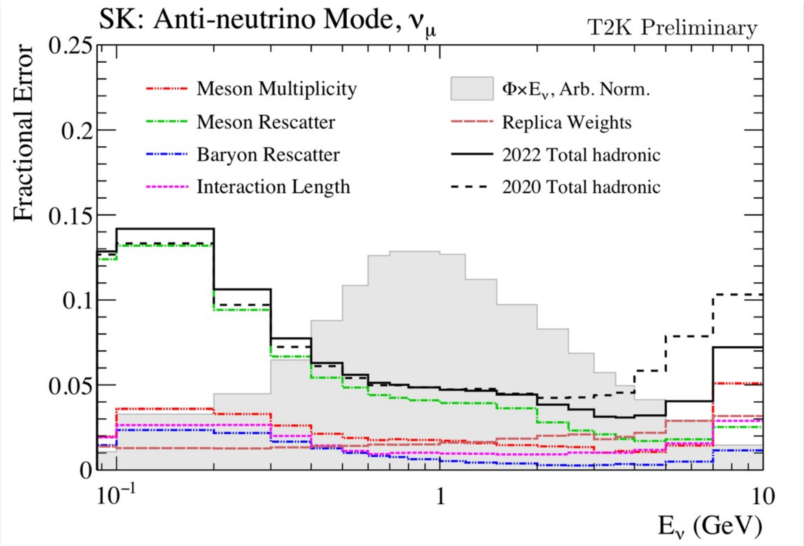


→ new measurements on other target material and on lower energies is crucial

NA61/SHINE for next LBL

Crucial to repeat NA61 measurements on the target of the future LBL experiments
and we actually need to go beyond :

CPV and MO ($\nu_e/\bar{\nu}_e$ asymmetry) :
Big correlation ν_μ to ν_e ($\pi \rightarrow \mu \rightarrow e$) and big correlation $\nu/\bar{\nu}$ (π^+/π^-) …



… but big impact of meson rescattering on $\nu_e/\bar{\nu}_e$ ratio :
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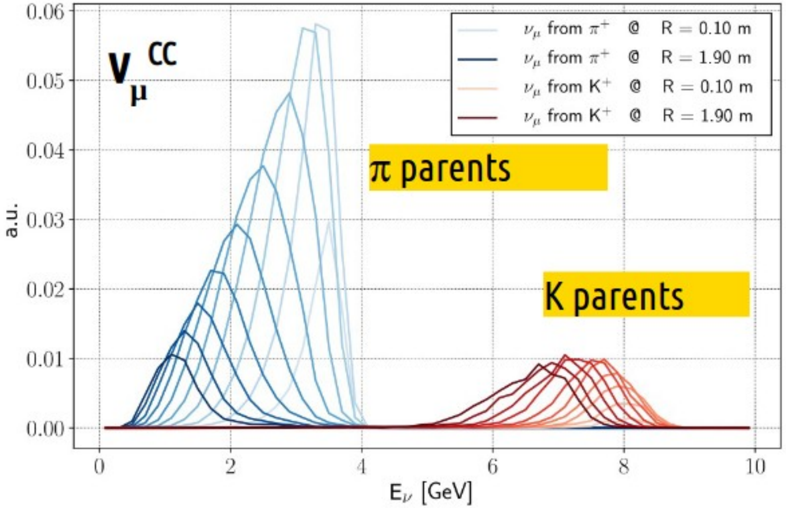
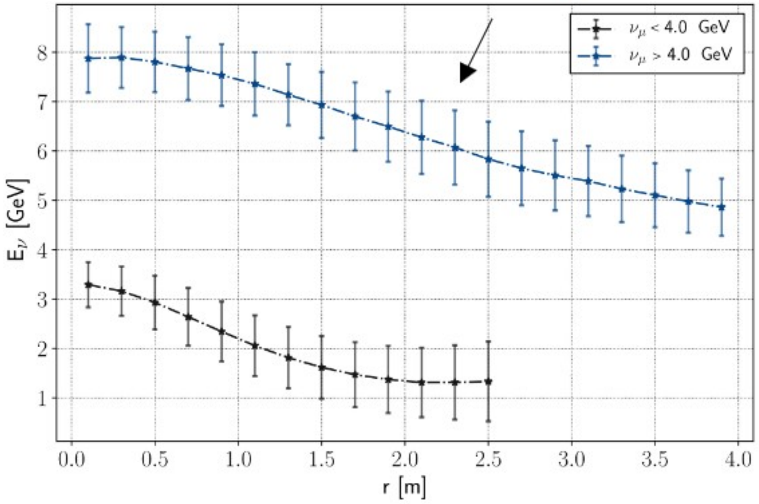
→ Correlations between beam and atmospheric fluxes?
NA61 do perform hadro-production measurements also for atmospherics : need to investigate needed measurements and correlations (right now very different physics models)

Enu from radial position

10-cm radial ‘slabs’



Error bands visualize the rms of the energy distributions



(Note : protoDUNE large enough to make a PRISM-like measurement with fixed detector, using the neutrino vertex location :

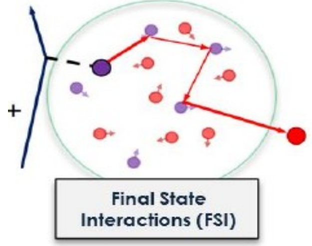
- first implementation of PRISM-like technique at DUNE energy !
- x-check of neutrino energy reconstruction !

New challenges

"Missing energy":

- **neutrons**

- **protons and pions which are re-absorbed by Final State Interactions**



- the **energy which is below tracking threshold**

- Part of this 'missing' energy could be detected **'calorimetrically' (aka vertex activity):** **all energy is ultimately emitted as low energy hadrons (π+,π-,π0,p,n) and nuclear clusters (eg α, d, t...) through FSI and nuclear de-excitation**

→ need to control the response of the detector to such different particles to 'unfold' to their kinetic energy and, ultimately sum it up to get the true Eν

From model point of view we will need to control:

- **pion, proton, neutron FSI**

- **nuclear de-excitation**

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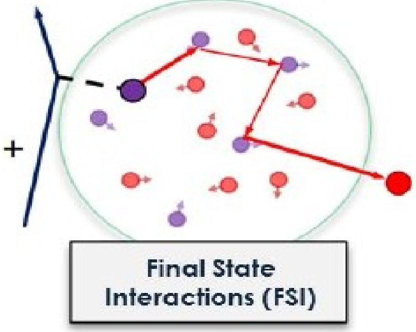
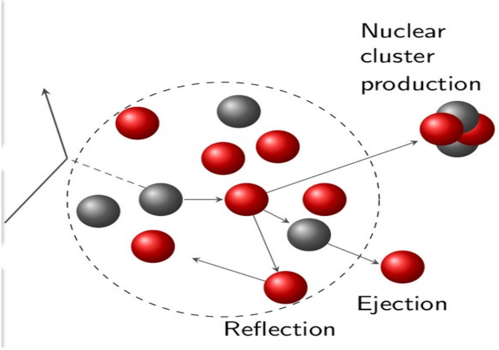
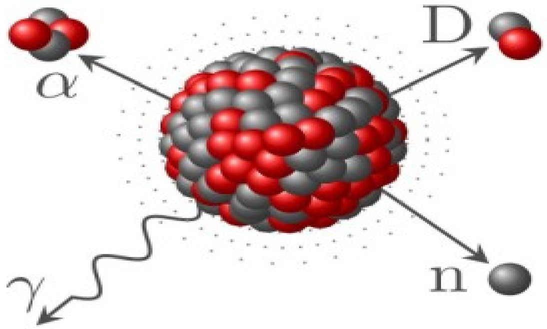
e-Print: 2309.05410 [hep-ph]

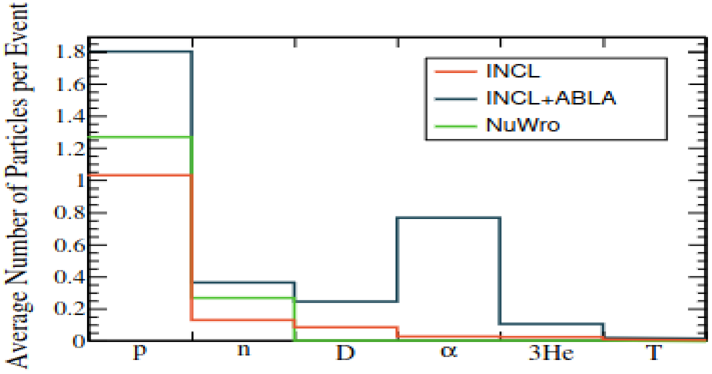
More sophisticated FSI models

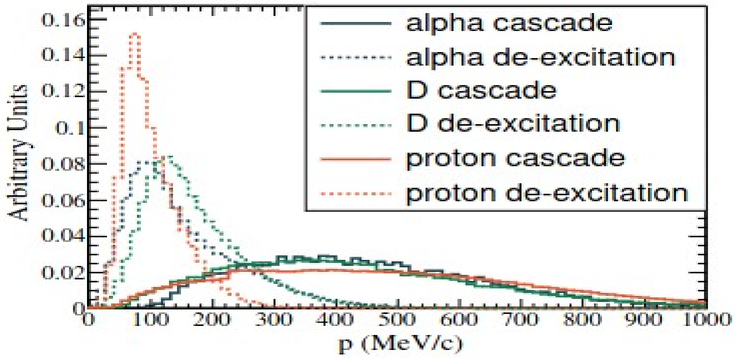
Recent study on proton FSI with more sophisticated model (INCL) put in evidence new effects: production of nuclear clusters!











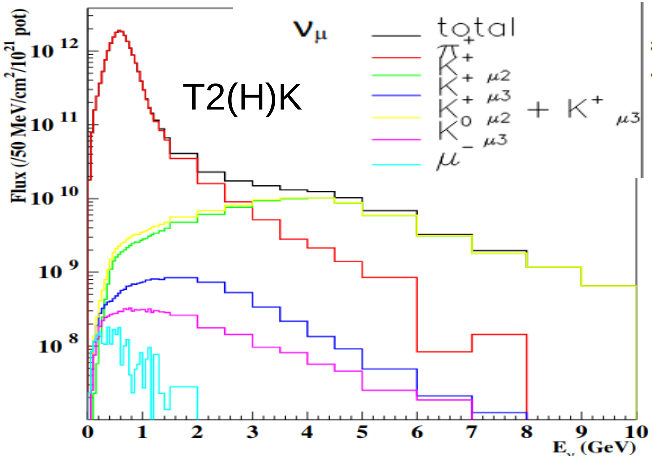
Cross-section

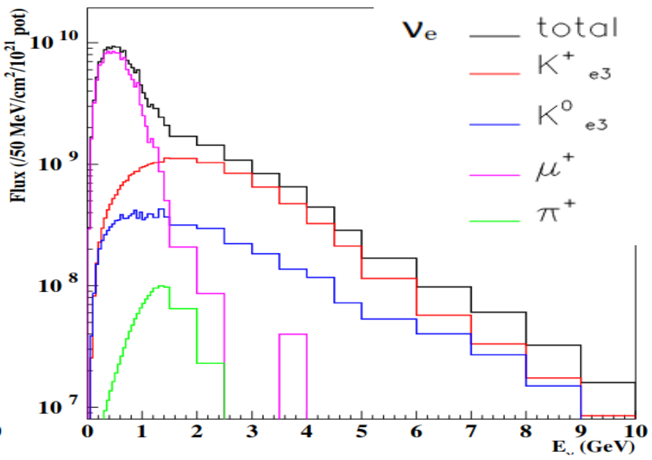
The LBL domain is moving from inclusive (lepton-only) to exclusive analysis (lepton+hadrons) analysis to improve the **resolution of neutrino energy reconstruction.**
Actually, compulsory at energy higher than CCQE as in DUNE.

Need to control new effects: **‘missing energy’**
→ important input from **ND280 upgrade neutron measurements**
→ important to **tune FSI models to external data (HADES!)** to correct for hadrons below threshold
(A joint effort of the LBL domain on FSI tuning would be welcome!)

A **‘calorimetric’ energy** reconstruction is not really inclusive given to the different response of detector to different particles: need to model exclusive final states to ‘unfold’ detector effects properly
(Recent FSI studies shows production of much more different particles: eg, nuclear clusters)

ν_e flux vs ν_μ flux





ν_e flux at the oscillation peak energy is dominated by μ decay coming from from π,K decays → correlation with ν_μ

(+ direct K decays into ν_e at higher energy,
K0 subdominant)