Hyper-Kamiokande

Status of reconstruction and selection algorithms for HK

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cnrs dépasser les frontières

ÉCOLE POLYTECHNIQUE

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IN2P3 Les deux infinis

ILANCE

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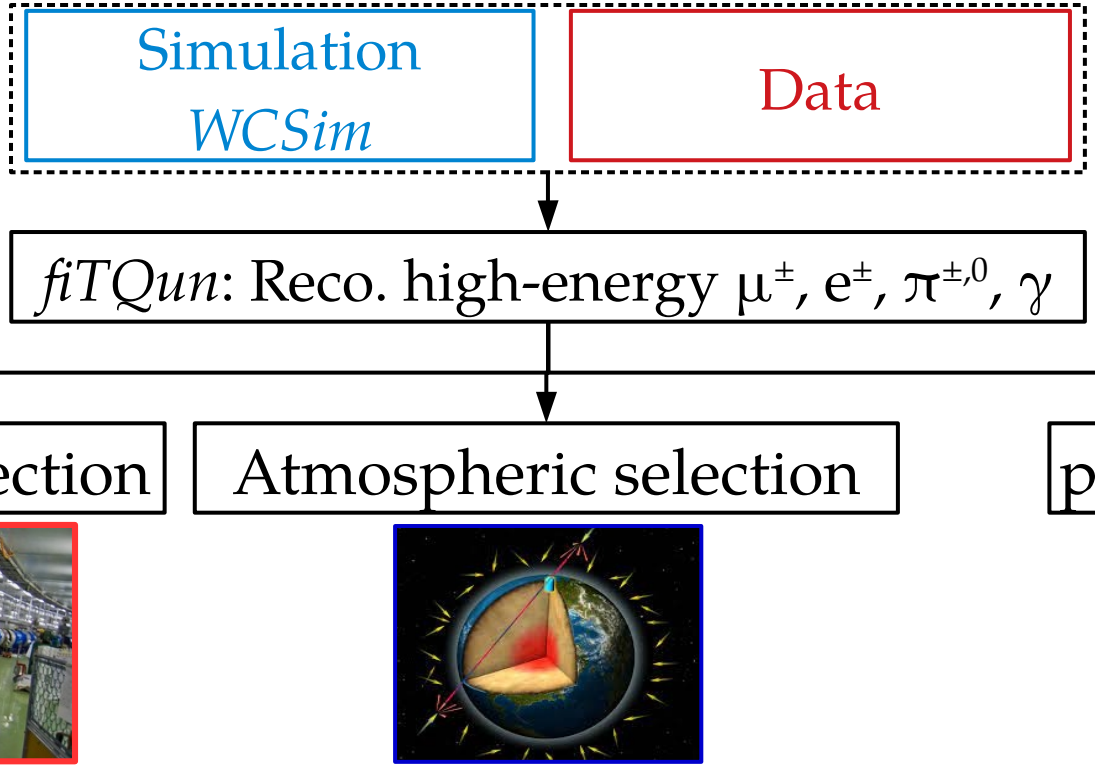
東京大学 THE UNIVERSITY OF TOKYO

HK software pre-meeting, Tokai, 2024/06/03

Reconstruction & selection overview



What do we have now :

1. fiTQun ported to HK but not optimized

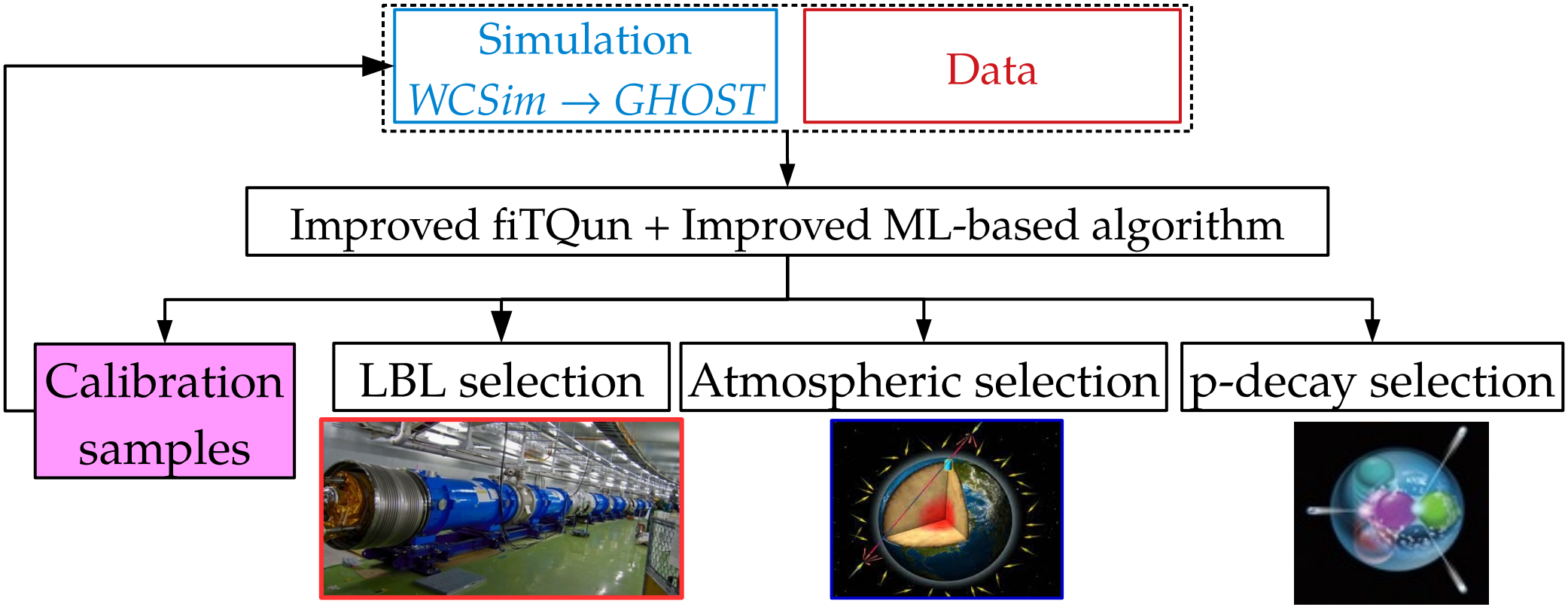
→ fiTQun tables optimized for old HK geometry.

→ fiTQun internal parameters (pre-fit search…) not reoptimized for HK.

2. LBL selection algorithm has been ported to HK.

3. Atmospheric selection software sent by our SK colleagues → Need to port it to HK/fiTQun.

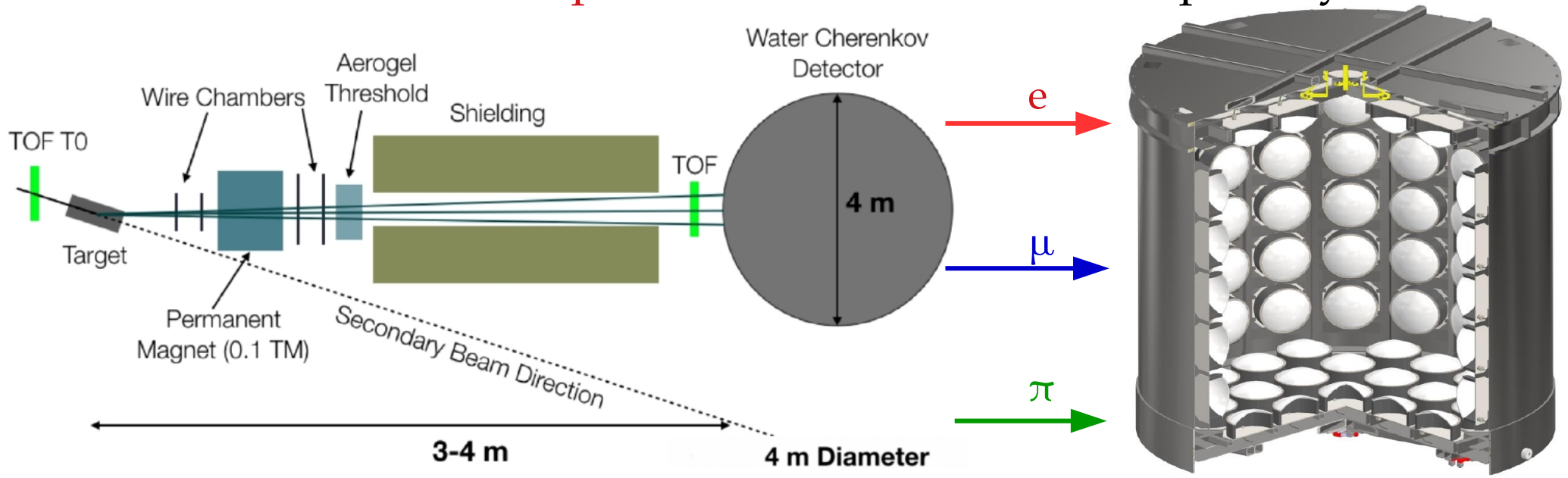
Possible future reconstruction & selection



- First HK analysis would likely use fiTQun.
  → Robust, performant… And allow to test against years of SK/T2K.
- A ML-based algorithm ready & tested by 2027 would be ideal.
  → May surpass fiTQun & help improve the later.
  → Likely much quicker : ideal for high stat productions.
- Apply reconstruction on calibration samples ⇒ Improve MC ⇒ There is a retro-active loop which take time → Need to be ready by end of 2026.

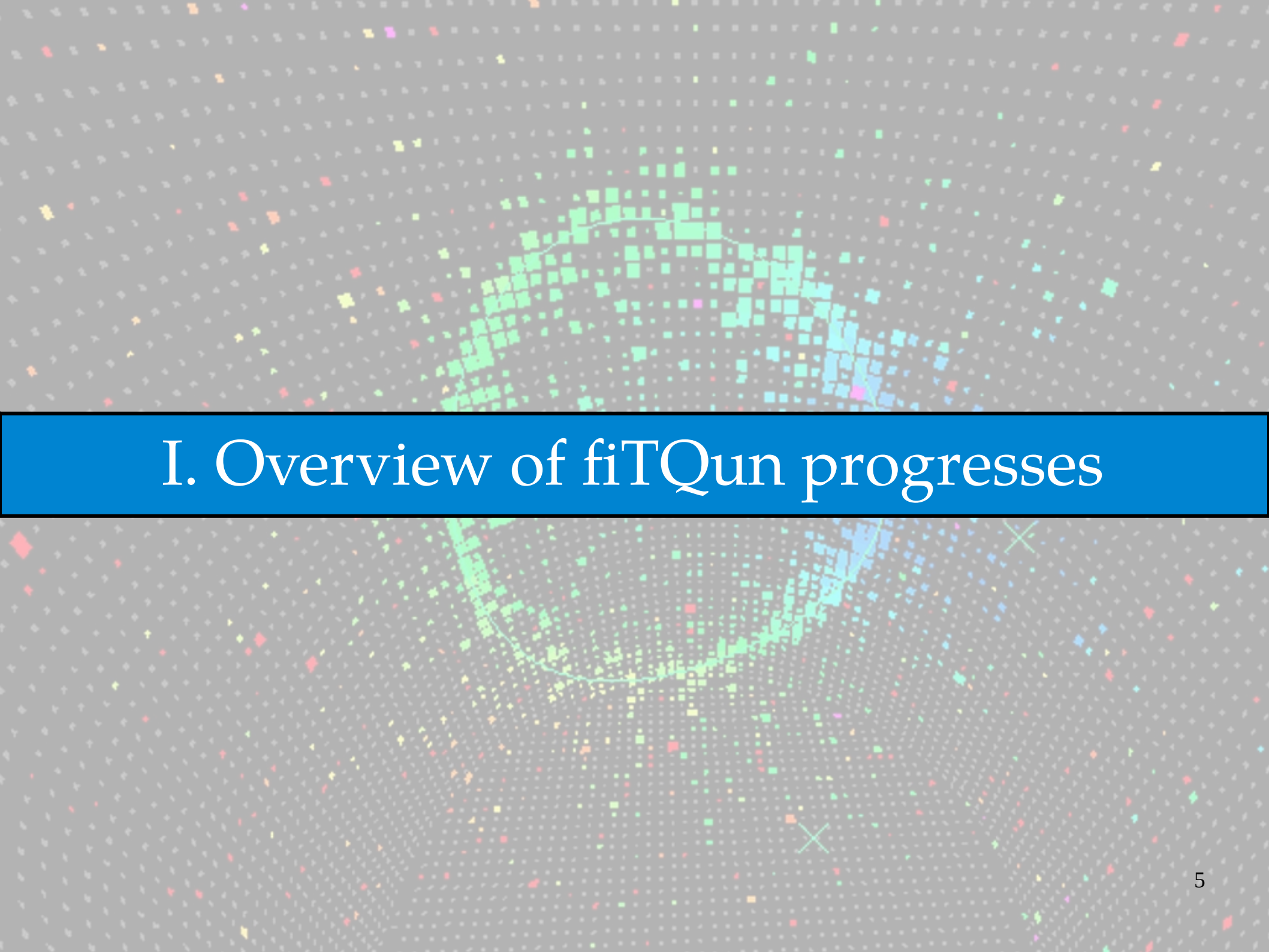
One word about WCTE

- WCTE : test our algorithms with extremely pure data in both particle type and energy for the very 1st time→ May be a crucial input for us, similar to calibration sample ⇒ Tune MC ⇒ Crucial especially for ML.



- WCTE 4m diameter : laboratory to test our algorithm @very small distance to wall → Improve software, fine tune MC (physics list etc.)

- For this reason : though WCTE is not technically in HK, we welcome work & presentations about reconstruction in WCTE at our bi-weekly reconstruction meeting (Loris, Gonzalo, Lorenzo, Anna)

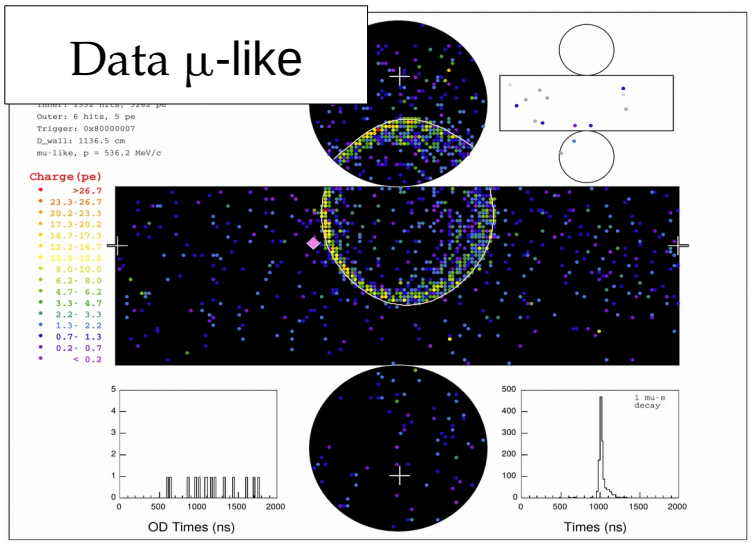


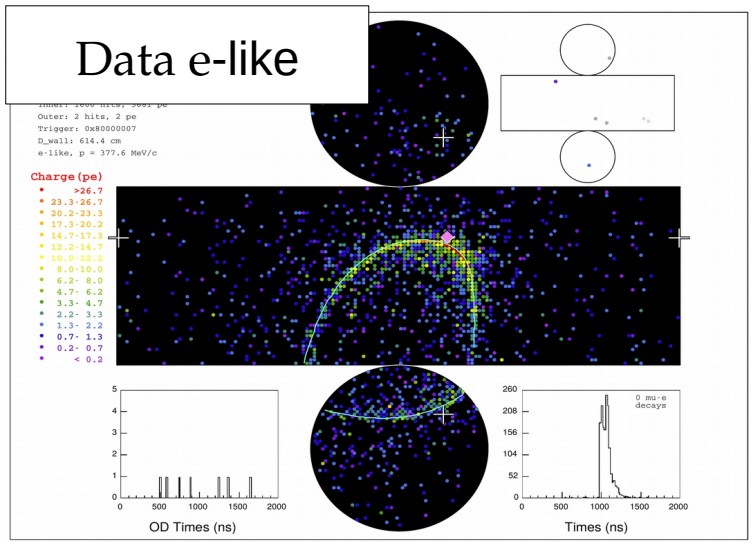
I. Overview of fiTQun progresses

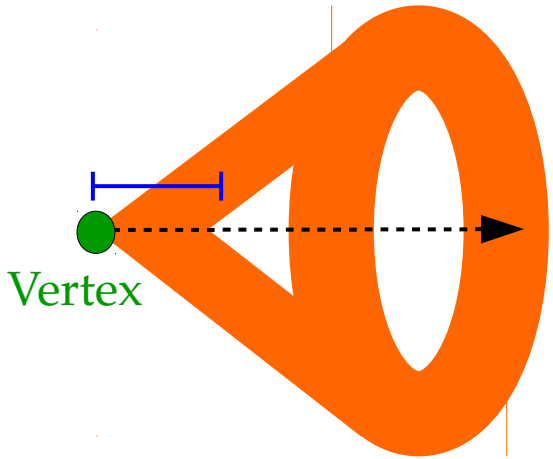
FiTQun high-energy algorithm

- Simulatenous fit of **7 parameters** using all PMTs charge&time:

  $\{X\}_i$ = (vertex position, vertex time, momentum, direction, particle type)







Likelihood-based fitter :

PMT unhit probability PMT hit probability PMT charge pdf

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

PMT timing pdf

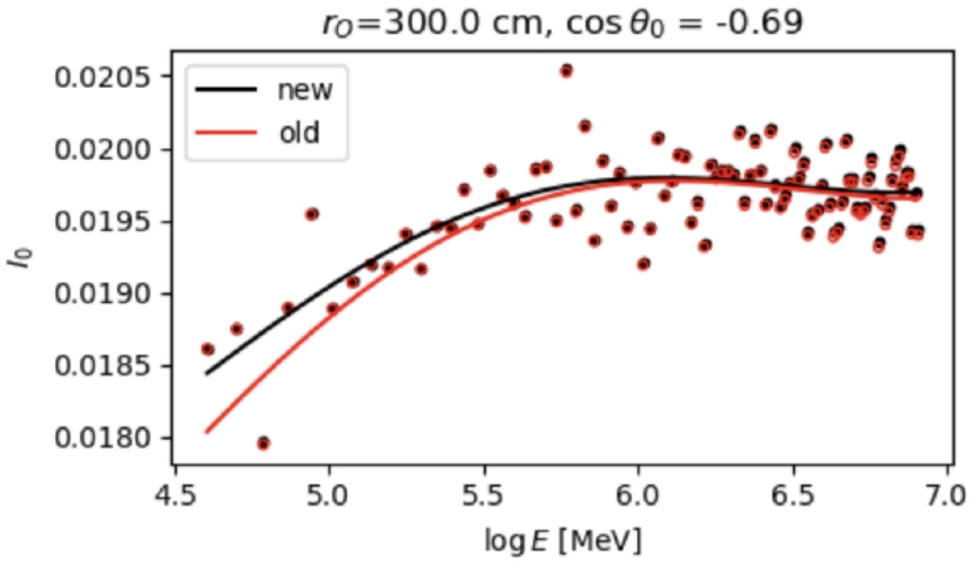
- fiTQun is performant, robust & well-tested…

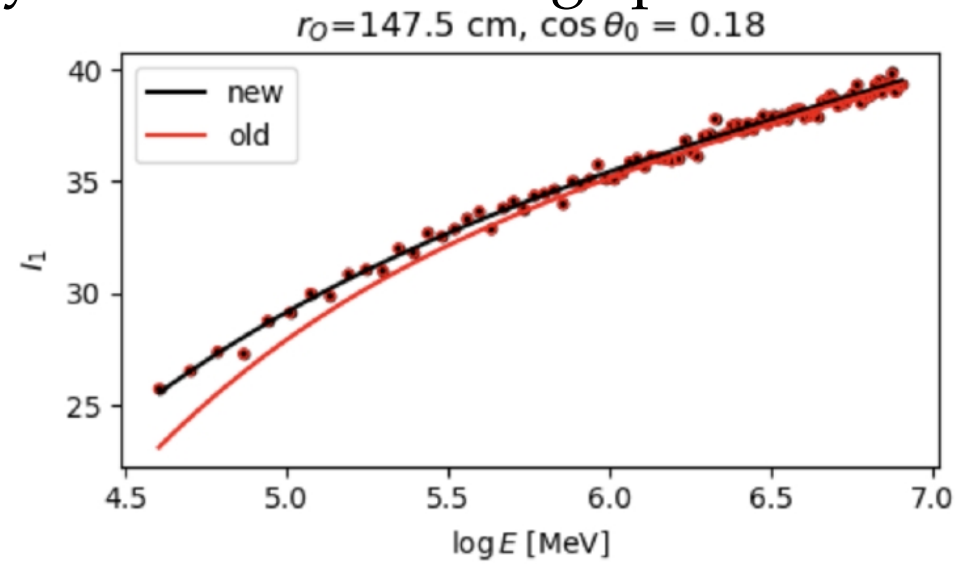
  … but is very slow : 90s per electron @500 MeV → Too slow already to optimize calibration sources e.g. to test systematic effect at 1 %.

Upgrade & modernize fiTQun towards HK

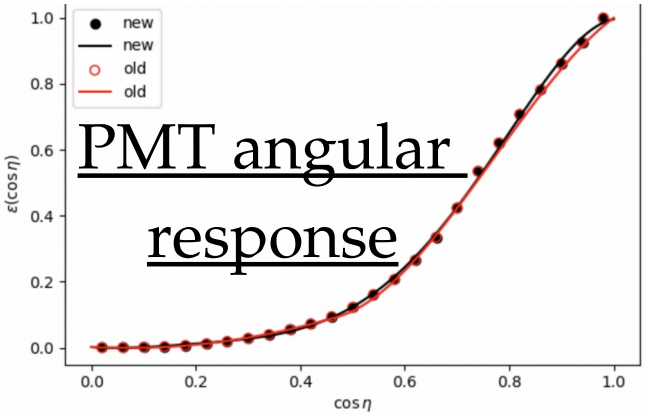
- Need to optimize fiTQun. To enhance the development towards this task, G. Diaz has re-written part of the code : Perl → Python.

- Using this tool, he observed potential room for improvements in WCTE → E.g. moving from 3 to 5-order polynomial in the charge profile fit.





- We are now testing if this effect is also seen in HK.



Optimize fiTQun vertex pre-fit

- L. Restrepo & G. Diaz : speed-up fiTQun pre-fit vertex search.

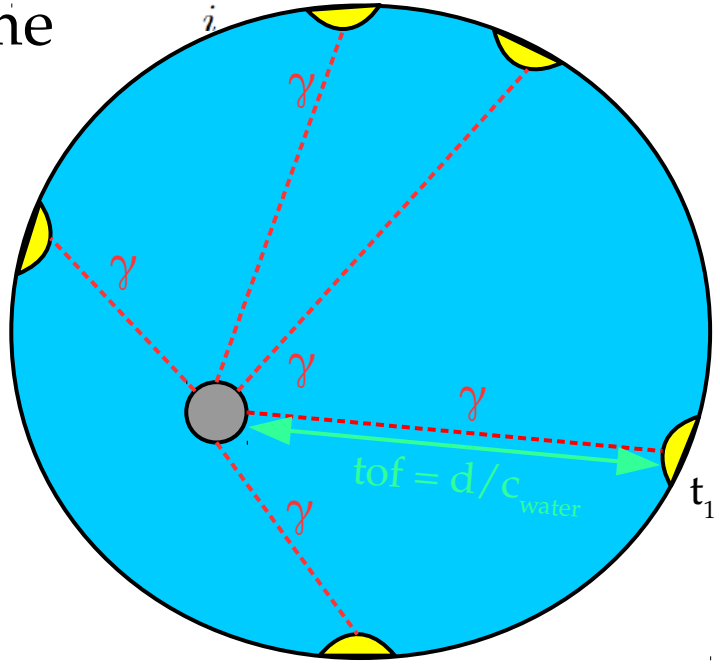
Pre-fit vertex search → (vertex is fed) → fiTQun SIMPLEX fitter

- Vertex pre-fit : mimize the time-residuals : $G(\boldsymbol{x},t) \equiv \sum_{i}^{\text{hit}} \exp(-(T^{i}_{\text{res}}/\sigma)^2/2)$

  with the time residual : T^{i}_{res} = t - tof - vertex time

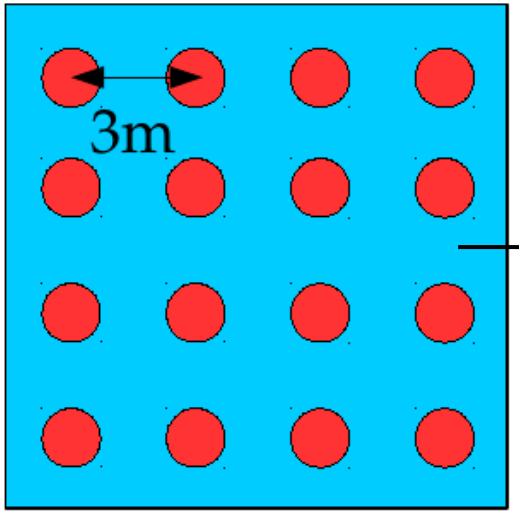
  → σ = time resolution : PMT σ (1.1 ns)

  + indirect light (scattering etc.)



- Now pre-fit operates sequentially :

1. GRID search



2. Gradient descent

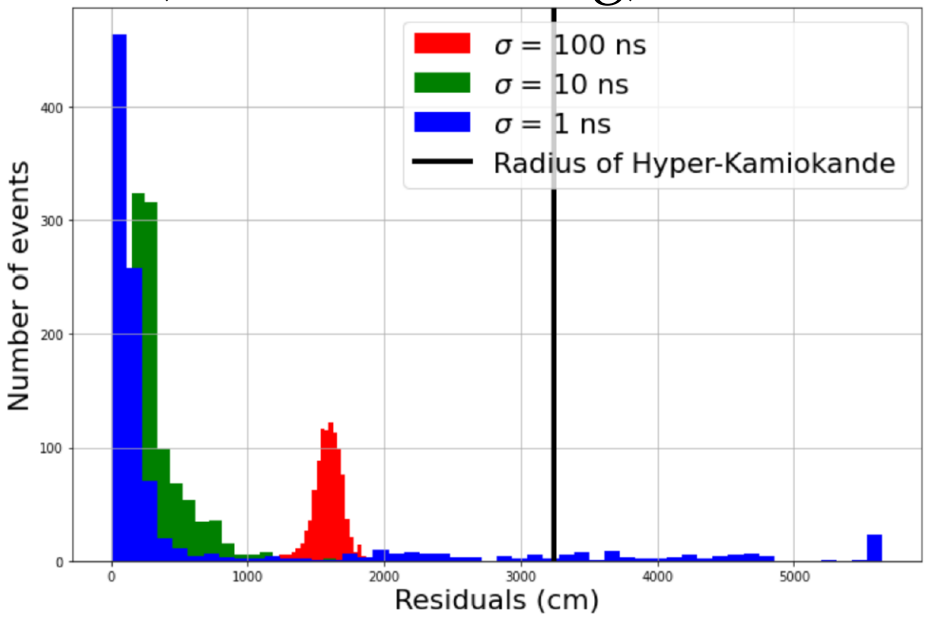
→ 4 sequential fits w/ 4 σ values

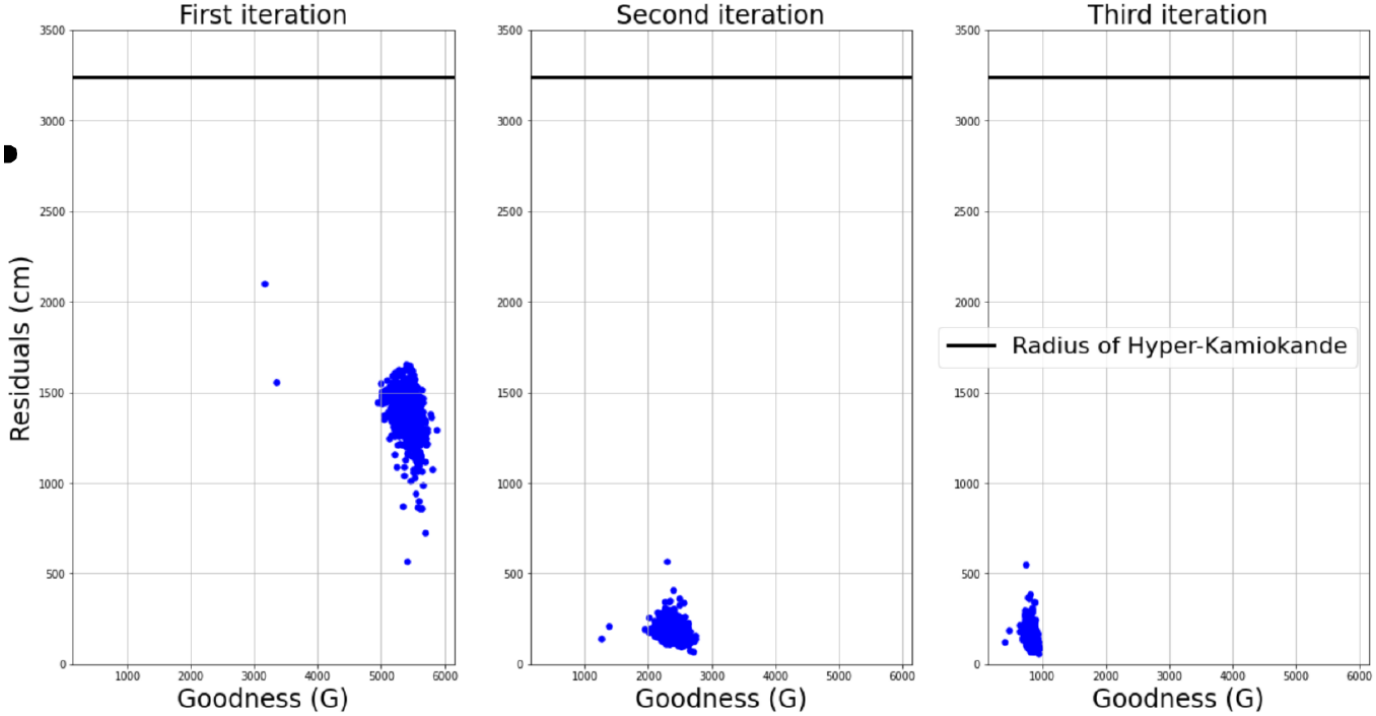
→ Reduce σ sequentially, last one is σ = 20 ns

Optimize fiTQun vertex pre-fit

- Lorenzo proposes to remove the grid-search (time consuming)
  → Perform 3 sequential descend, with σ = 80ns, 5ns and 1ns.

- Tested the effects with 500 MeV events generated at center of detector :



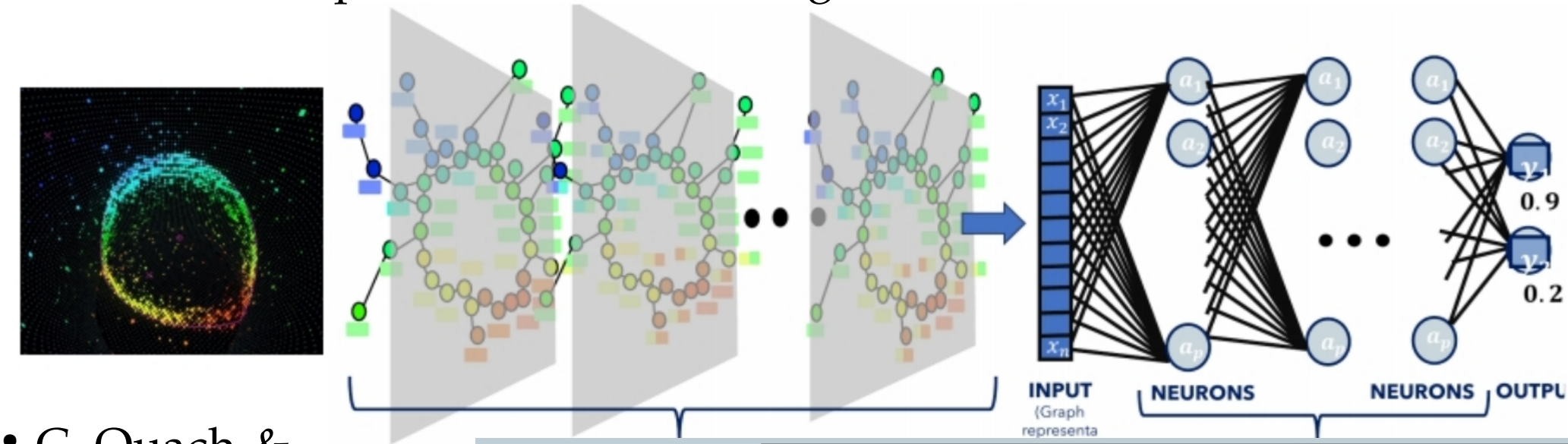


- Requires ~5 times less steps → Faster.
- Vertex res. = 1.5m
- Now need to test if method is unbiased over all detector & higher energis.

II. Overview about ML-based algorithms

The GRANT & WatChMaL algorithms

- GRANT : Graph-Neural Network algorithm → Each PMT = a node



- C. Quach & E. Le Blevec: show performances tomorrow.

- Very promising for 1R PID&E-resolution.
  → Now fighting w/ vertex resolution.

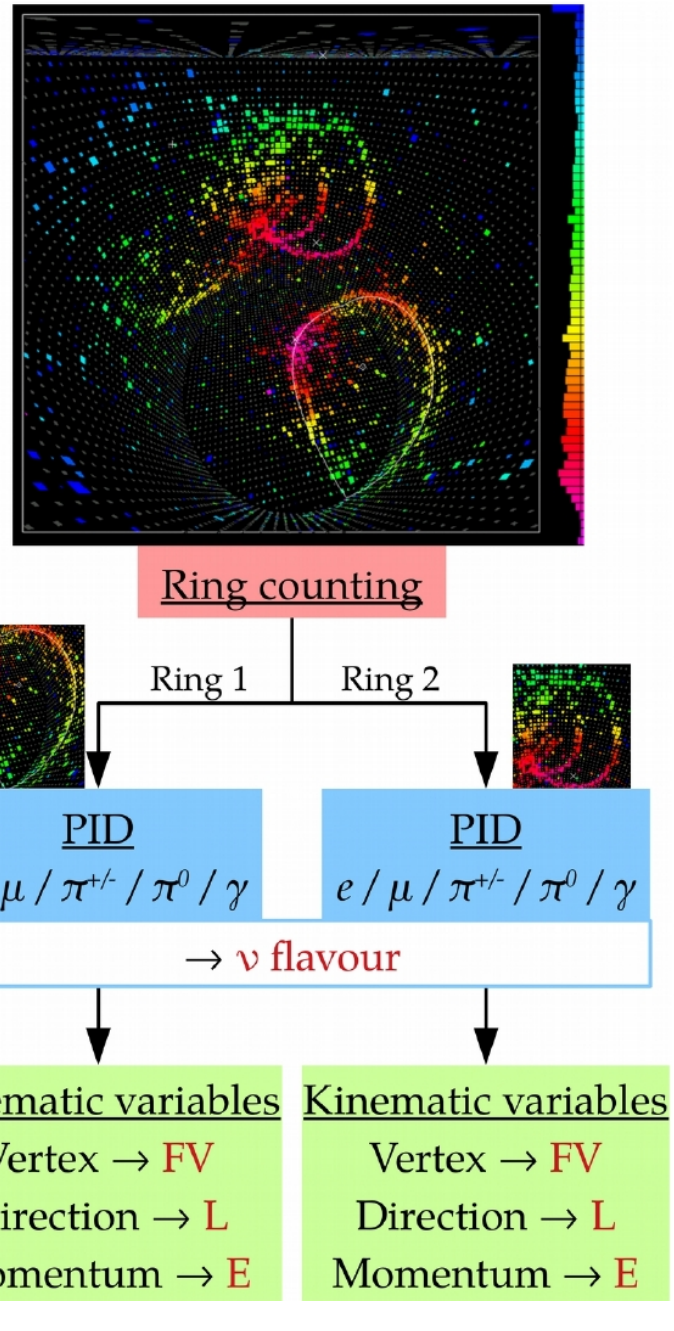
	GNN	FitQun
e/mu	99% electron efficiency at 5% muon bg acceptance, Dwall, towall analysis: After 2 m, efficiency above 99.4% !	99% electron efficiency at 5% muon bg acceptance,
e/gamma	58% efficiency at 50% bg acceptance... [Fixed energy]	None
e/pi0	98% electron efficiency at 25% pi0 bg acceptance. [Fixed energy] 78% electron efficiency at 25% pi0 bg acceptance [Spectrum of energy]	94% electron efficiency at 25% pi0 bg acceptance
Energy reconstruction for e & mu	• Electron : 5% resolution at 500 MeV, energy bias at ~4% • Muon : 7% resolution at 500 MeV, energy bias at ~7%	• Electron : 7% resolution at 500 MeV • Muon : 6% resolution at 500 MeV
Vertex reconstruction for e & mu	• Electron : 91,7 cm longitudinal resolution, 153 cm transversal resolution, • Muon : 103 cm longitudinal resolution, 181 cm transversal resolution,	

The GRANT & WatChMaL algorithms

- And extremely fast :

CPU time / event	1 ring e/μ PID	1 ring e/π⁰ PID	Energy & vertex reco.	Total
fiTQun	30s	50s	Simulatenous to PID	80s
CAVERNS	0.09s	0.07s	0.05s	0.11s

→ Could be an ideal complement to fiTQun.



- Key-point missing before complete algo. :
  → Ring counting algorithm.
  → Goal is to finalize it for 2024.

- Other developments :
  - e/γ separation.
  - μ/ π separation.
  - Improve memory usage → On-going.

The WaChMaL algorithm

- WatChMaL is a CNN-based algorithm originally developed for IWCD.

	WatChMaL	GRANT
Pros	Very powerful Can be extended beyond CNN	Very powerful Tested with HK MC
Cons	Not final Not yet optimized for HK Not tested w/ data	Not final Not tested w/ data
Speed (500 MeV e-)	??	< 1s

- On HK-FD, WatChMaL tests have been started (J. Gao, N. Prouse).
  → It is absolutely not clear which algorithm (CNN vs GNN) will give better performances/robustness for HK in 3 years.
  → To maximize our output, we would ideally have a unified framework for WatChMaL & GRANT

- E. Le Blevec will talk about it tomorrow.

III. Status of the fiTQun 2024 production

Steps for fiTQun tuning & schedule

- Changed our estimate as we use this year production to validate new tuning tools (G. Diaz) → Work for future, but take more time.

- Allow to validate that all sub parameters are correctly tuned for HK.

	May	June	July	Aug.	Sept.	Oct.
1 ring Cherenkov profile						
1 ring Angle & time PDF						
1 ring Charge PDF						
Optimisation of e/μ cut						
Optimisation of e/π0 cut						
Multi-ring 1R vs 2R						
Multi-ring Nrings						

- Will finalize the all tuning by end of September.

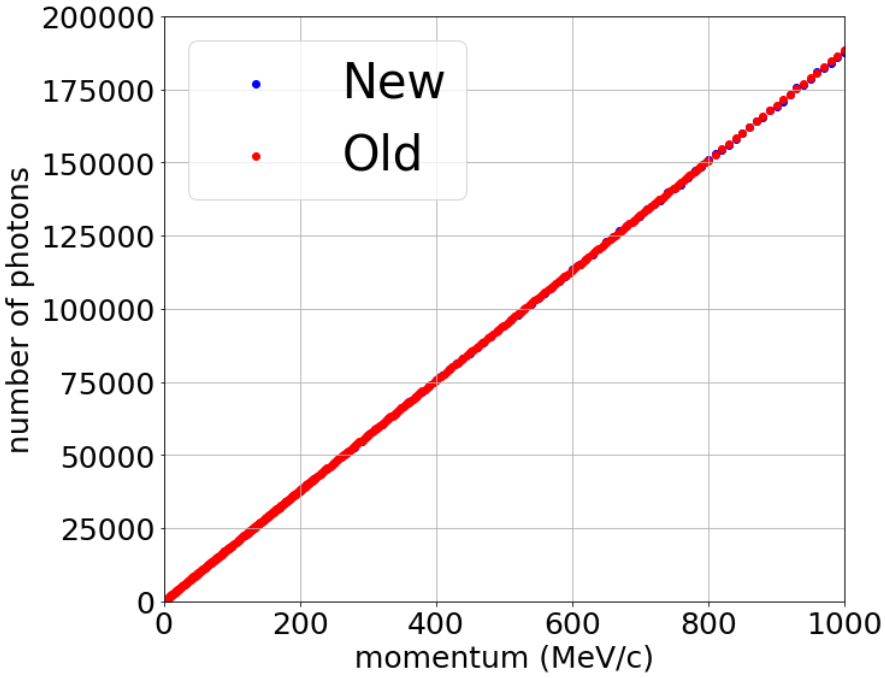
- <u>For this CM :</u> re-generate the Cherenkov profiles.

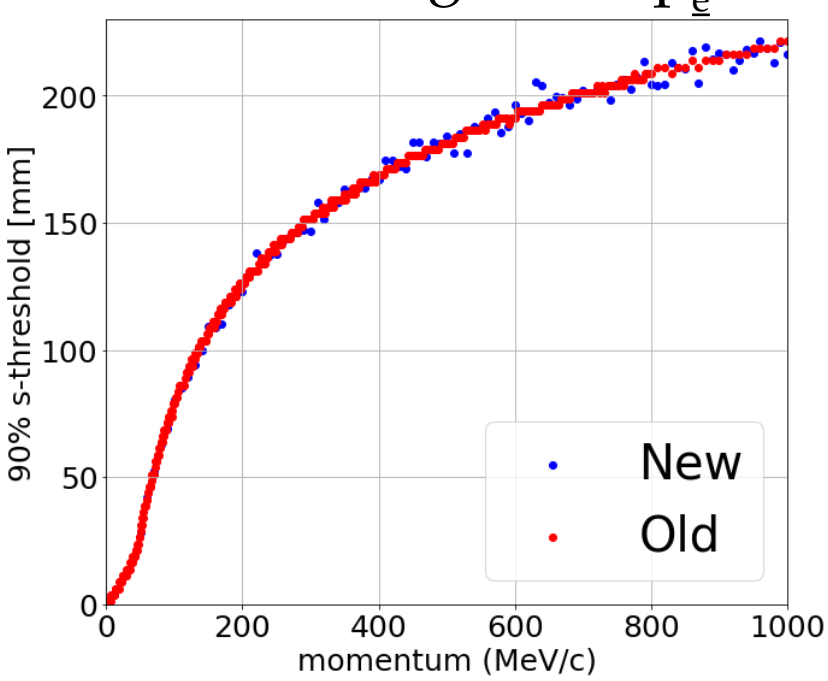
Regenerate e- & μ- Cherenkov Profiles

Photon / MeV

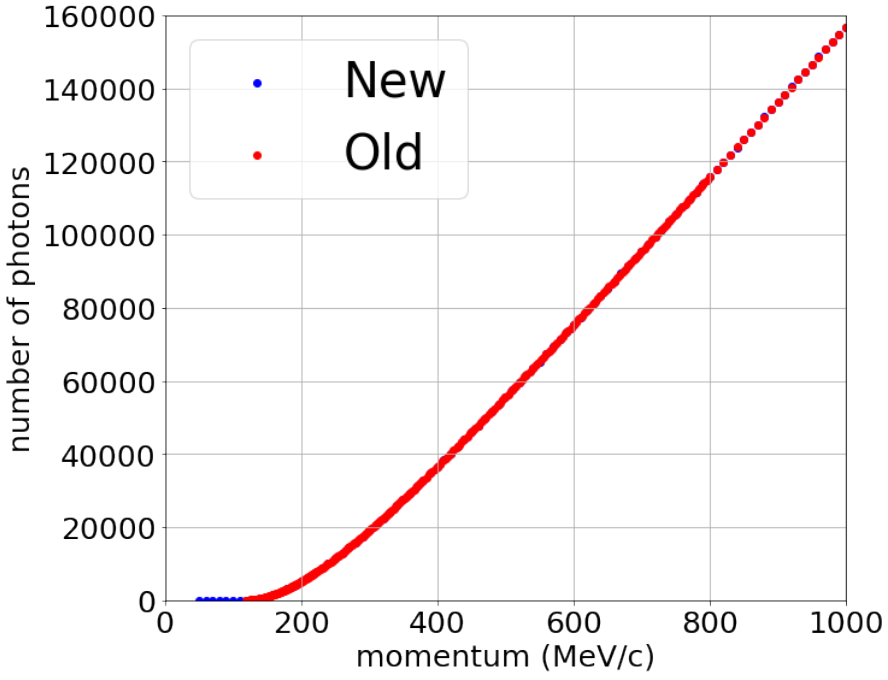
Track length wrt p_{e^-}

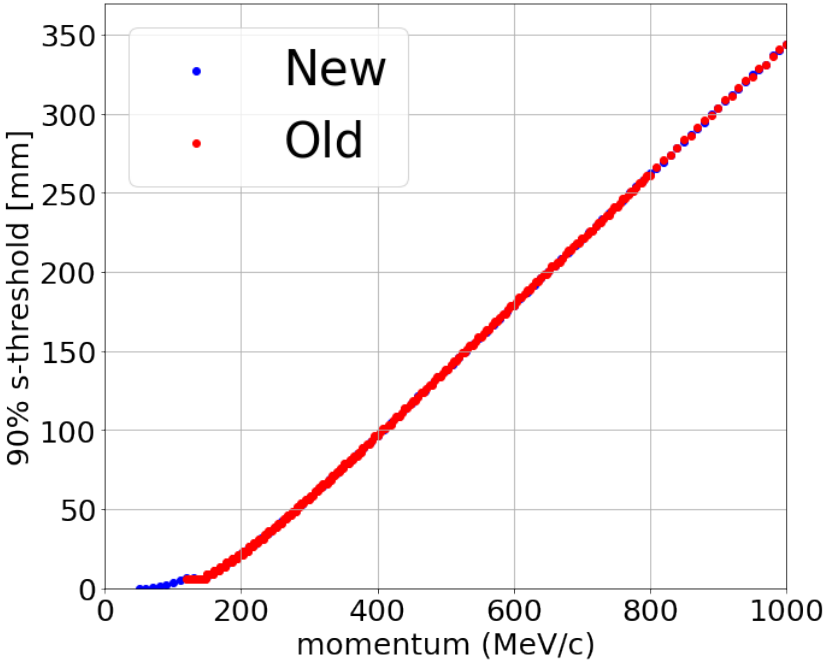
Electrons





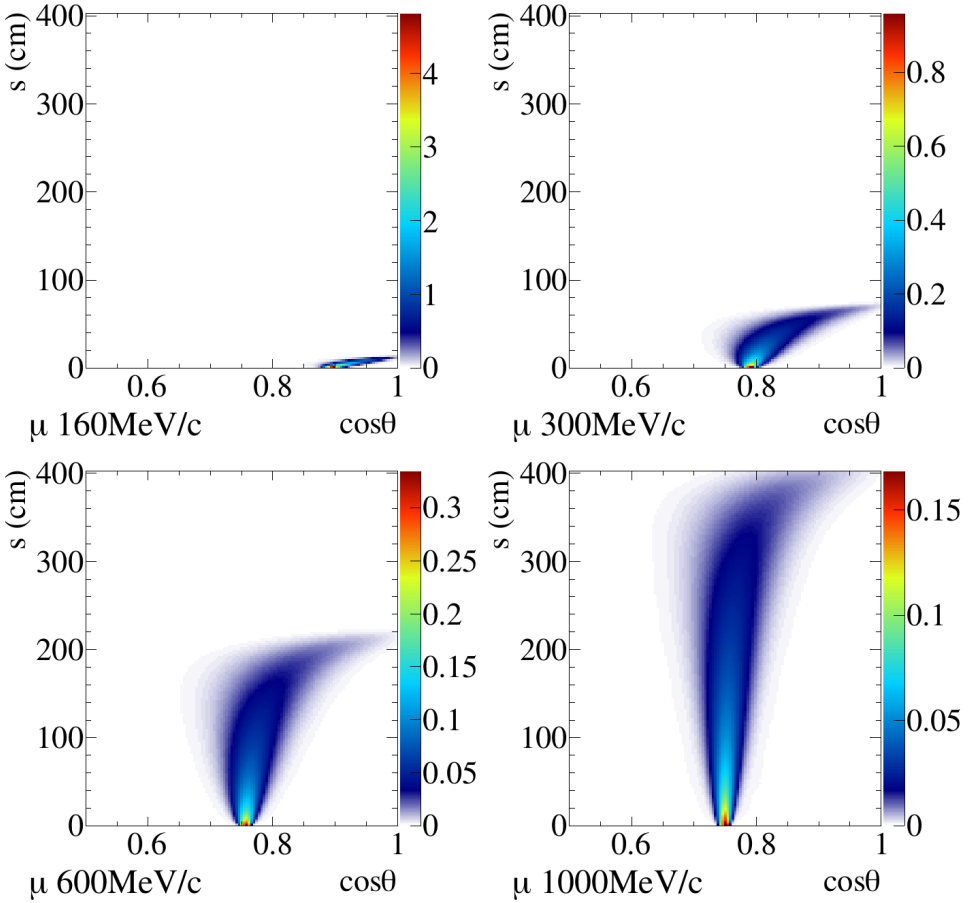
Muons



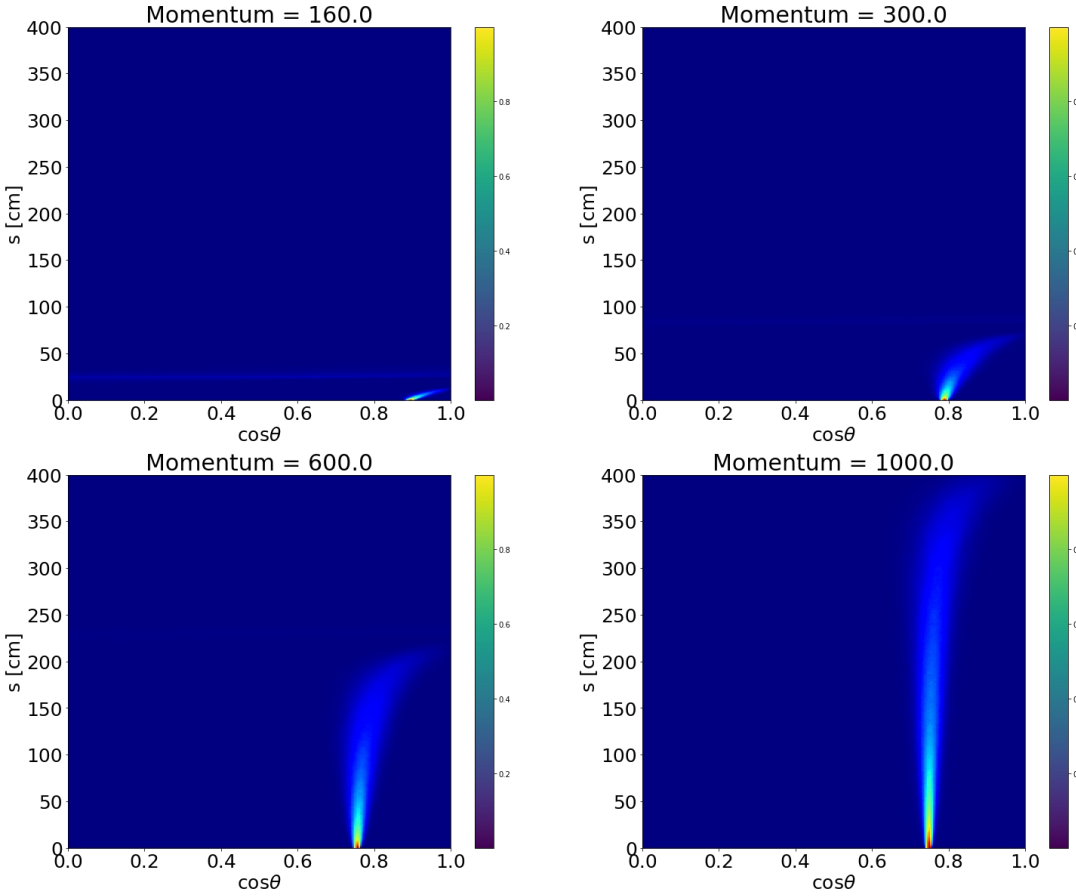


Regenerate e- & μ- Cherenkov Profiles

Old Cherenkov profiles



New Cherenkov profiles



- Excellent agreement.

- We have moved towards the reproduction of the angle & time PDFs

Conclusions

Conclusions

- The reconstruction effort is now grouping to boost our joint efforts.
  → A dedicated every 2 weeks (Thursday 17.00 JST). Both HK, SK & WCTE discussions are welcome.

- Goal : Have the best working&validated reconstruction algorithm on ~~Dec. 2027~~ summer 2027 to analyze the very first HK data !
  → « Best » : 1.High physics performances, 2.High Speed & 3.Robustness against systematics ⇒ Optimisation + Validation on MC&Data.
  → Testing on calibration data long time before ν data is crucial : in-situ for HK, WCTE etc.

- For now, the proposal is to have a complementary approach : an optimized fiTQun + a ML-based algorithm to boost our sensitivity.
  → Joint approach also allows to extract extra features from ML-reco. to improve fiTQun ⇒ This is crucial to fully understand our black box.

Conclusions

- fiTQun is being improved & tested using the new production.
  → To be fully ready by **end of September 2024**.

- GRANT & WatChMaL are showing very promising results
  → See C. Quach & E. Le Blevec (and former N. Prouse) talks.
  → Unique possibility to merge our algorithms to boost our developments for the best of HK.
  → Goal : have a fully-working ML-based algorithm in 2024 ⇒ Need to add a ring-counting algorithms (image segmentation?).

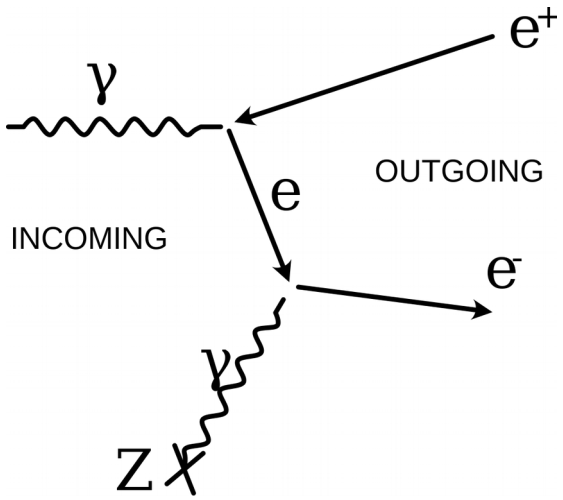
- Tutorials : we realized there is a strong need for tutorials now that number of interested newcomers is increasing.
  → Preparing a fiTQun tutorial to be released this week.
  → Hope to have a ML tutorial at October CM.

Additional slides

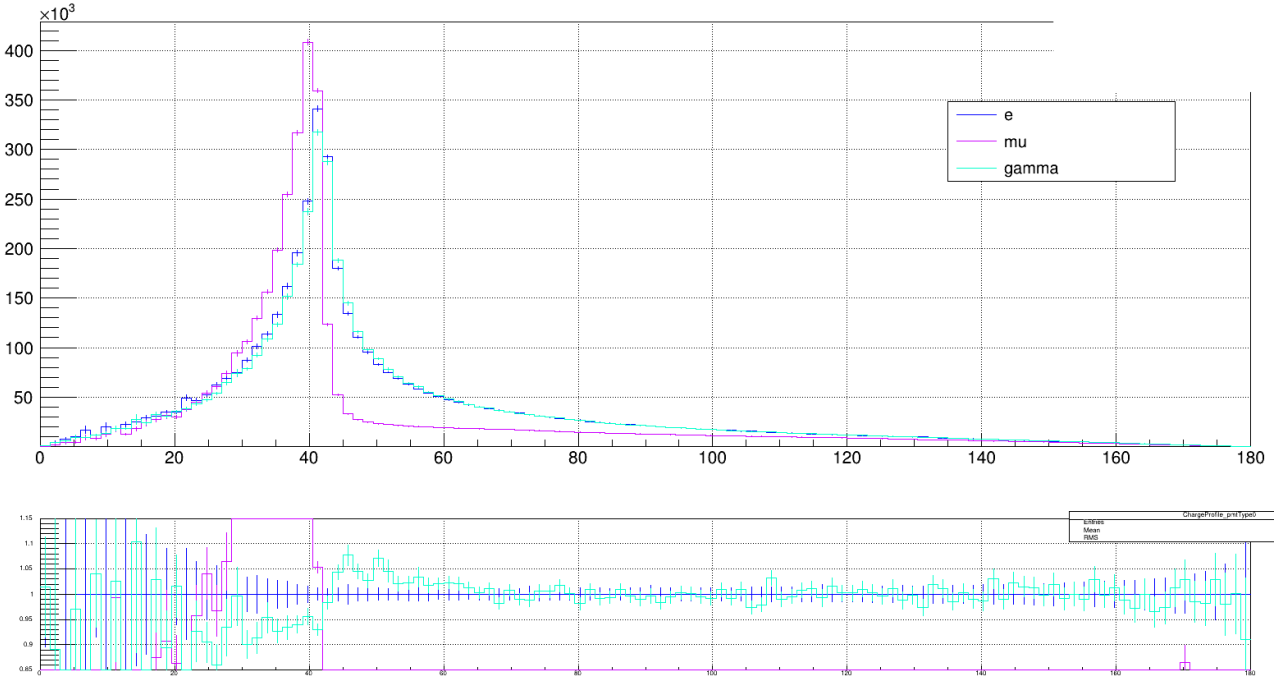
Limitations of current algorithm

- Dominant limitation is computing time : 90s / HK event @500 MeV
  → A major issue for any simulation aiming to study < 1 % systematics.
  → Goal #2 : Significantly ↓ processing time before HK starts.

- Second limitation : Fine particle identification → e/γ separation
  → Not done in fiTQun. Both provides a « shower-like » fuzzy ring.



Superposition of 2 shower-like event



→ Goal #3 : Separate e/γ them using the outer-edges of the ring.

The fiTQun algorithm

PMT unhit probability PMT hit probability PMT charge pdf

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

PMT timing pdf

- X = (x, t, p, θ, φ) : Particle hypothesis → 7 variables fit
- $\mu = \mu^{\text{dir}} + \mu^{\text{scat}}$: Poisson mean of predicted charge detected by each PMT, which is also a function of X

Normalization Integration along the particle truck

$$\mu^{\text{dir}} = \Phi(p) \int ds g(p, s, \cos\theta) \Omega(R) T(R) \epsilon(\eta)$$

Cherenkov emission profile

PMT solid angle at η=0 ~ R^{-2}

Light attenuation in water ~ $\exp(-R/L_{\text{attenuation}})$

PMT angular response