

ν_μ CC selection for ND280 Upgrade

3rd Workshop on Neutrino Near Detectors based on gas TPCs

M. Lamoureux

SPP, CEA Saclay

May 21, 2017



Motivations

Compare current ND280 performance with ND280 upgrade configurations (both reference and alternatives):

- selection efficiency
- expected statistics
- contaminations in the selection
- sensitivity to physics models

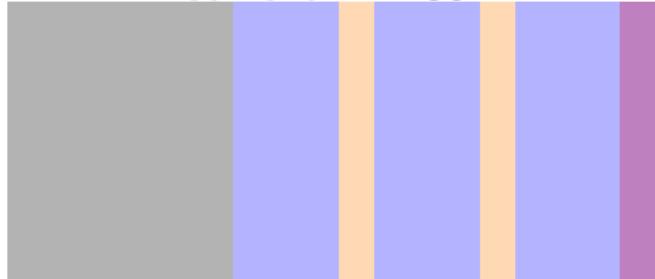
Method

All is done inside a simplified framework (with pseudo-reconstruction and simple selection criteria) with simplified geometries (current-like, upgrade-like)

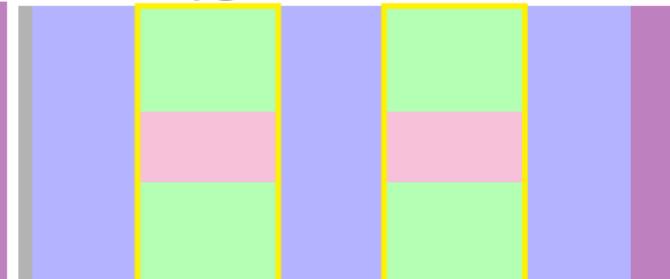
In the following, all the studies have been performed with these simplified geometries.

Different configurations

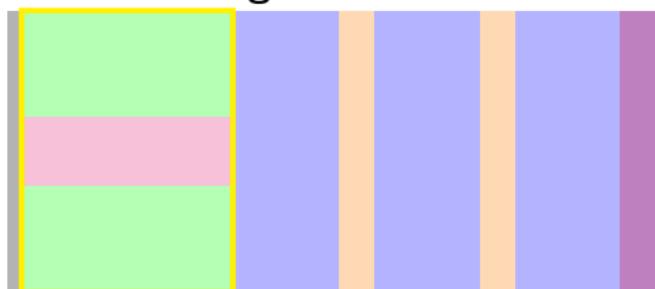
Current ND280



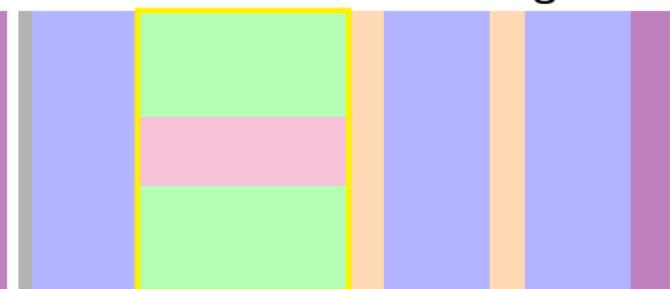
Upgrade reference



Alt.1: Target → Fwd TPC1



Alt.2: Fwd TPC1 → Target



WAGASCI-like target, FGD, VTPC, HTPC, P0D, DsECal, ToF counters

Schematics not on scale, only basket is represented

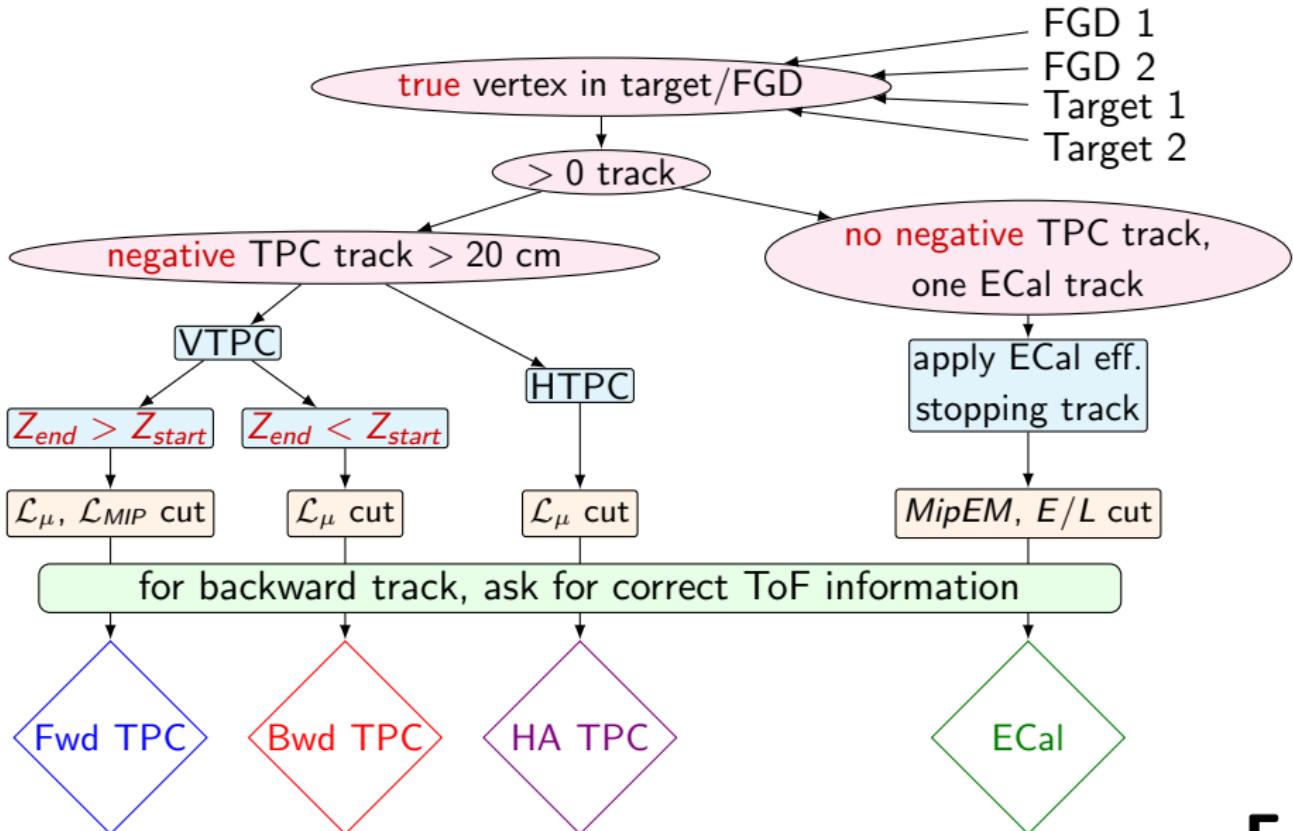
Contents

1 Efficiencies

2 ToF PID

3 Conclusion

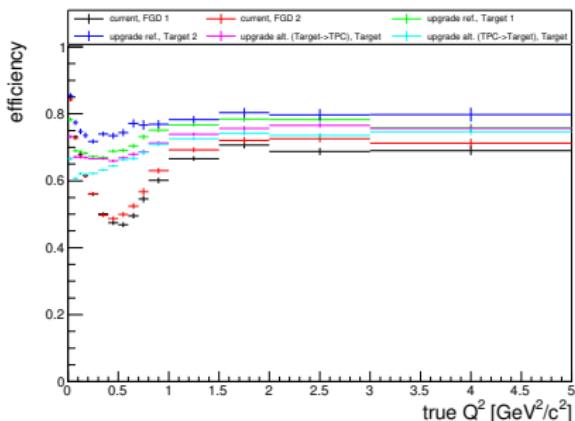
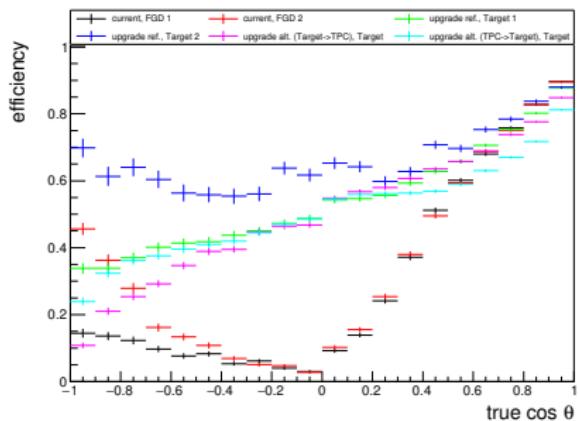
Selection in Highland



Efficiencies

ν_μ CC-inclusive selection efficiencies

How well can we select the muon from ν_μ CC interaction in FGD or Target?

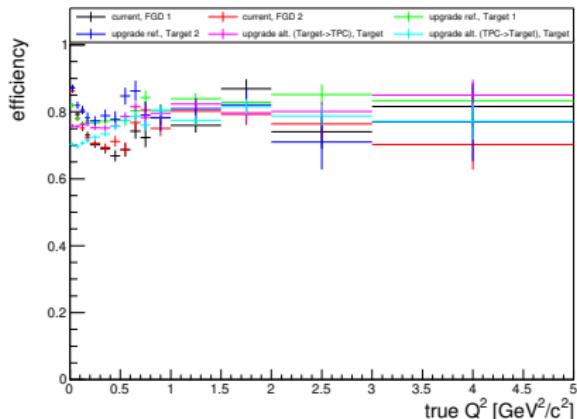
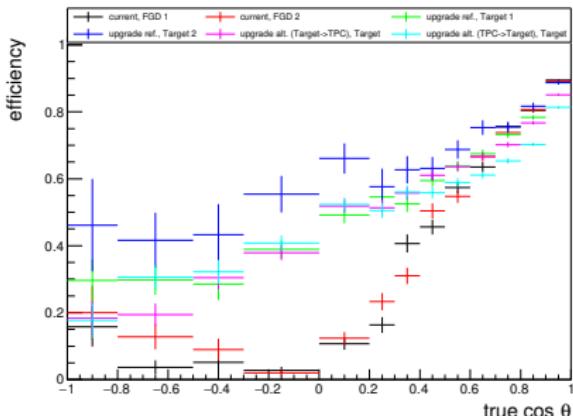


- current-like efficiencies behave as expected (low backward eff)
- upgrade fills the high-angle and backward region

*ToF are assumed with a time resolution of 600 ps

$\bar{\nu}_\mu$ CC-inclusive selection efficiencies

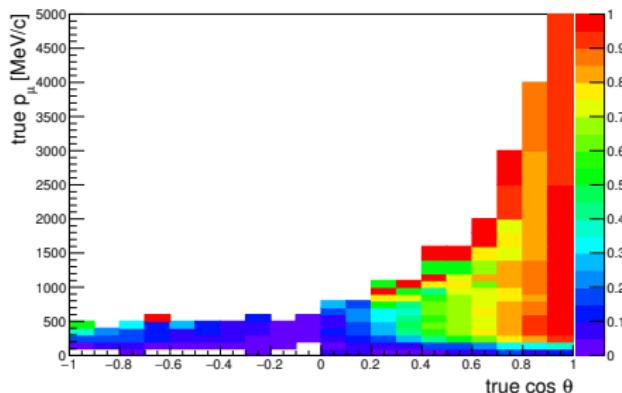
Same selection than for ν_μ , changing all the signs of charge requirement



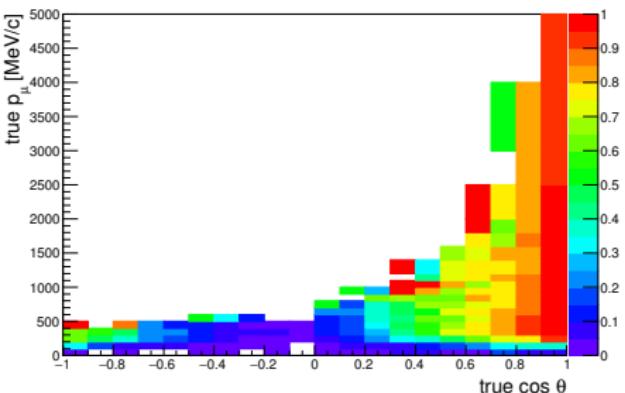
- efficiency versus $\cos \theta$ similar to ν_μ CC's
- the increase of efficiency from current-like to upgrade around $Q^2 \sim 0.5$ is less visible, as there are less backward/high-upgrade events in $\bar{\nu}_\mu$ CC (where the upgrade is more performant)

2D ν_μ CC-inclusive selection efficiencies

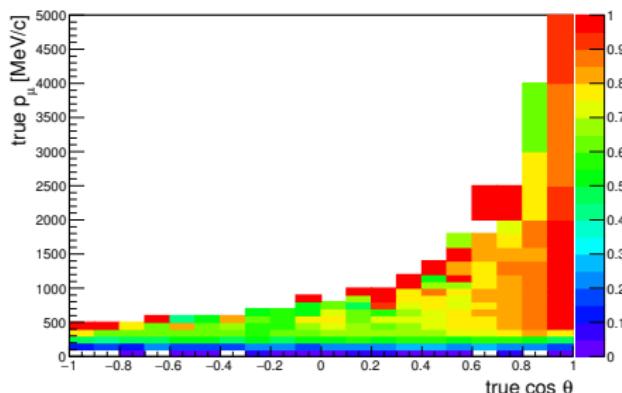
ND280 current-like, FGD 1, CC-inclusive



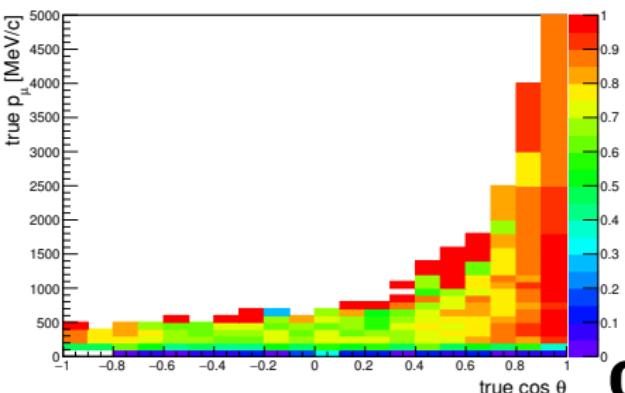
ND280 current-like, FGD 2, CC-inclusive



ND280 upgrade-like ref., Target 1, CC-inclusive



ND280 upgrade-like ref., Target 2, CC-inclusive



Pion reconstruction

Done similarly to current ND280 analysis

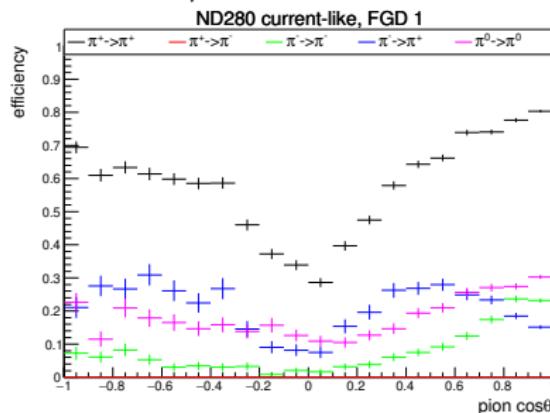
- TPC tracks: look for Target-TPC or FGD-TPC tracks
 - if charge > 0 and not proton PID
 - if $\mathcal{L}_\pi > \mathcal{L}_e \Rightarrow$ identified as $\pi^+ \Rightarrow N_{\pi^+, TPC}$
 - else \Rightarrow identified as positron from $\pi^0 \Rightarrow N_{\pi^0, e^+, TPC}$
 - if charge < 0 and not muon candidate
 - if $\mathcal{L}_\pi / (\mathcal{L}_\pi + \mathcal{L}_e) > 0.8 \Rightarrow$ identified as $\pi^- \Rightarrow N_{\pi^-, TPC}$
 - else \Rightarrow identified as electron from $\pi^0 \Rightarrow N_{\pi^0, e^-, TPC}$
- Iso-target tracks: look for Target-only tracks
 - if $L_{Target} > 5$ cm or $\Delta Z_{FGD} > 4$ cm (corresponds to four layers), it is considered perfectly identified $\Rightarrow N_{iso, \pi}$
- Michel Electrons: look for true electrons in target/FGD more than 100 ns away from vertex time
 - apply 50% efficiency on these electrons (T2K TN 104) $\Rightarrow N_{ME}$

Efficiency computation

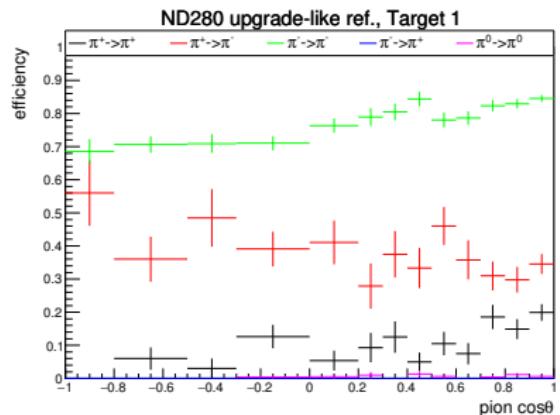
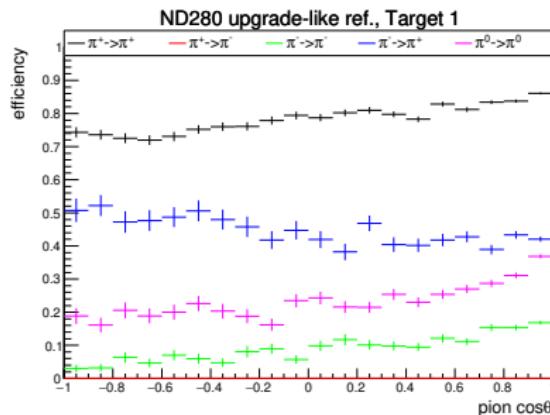
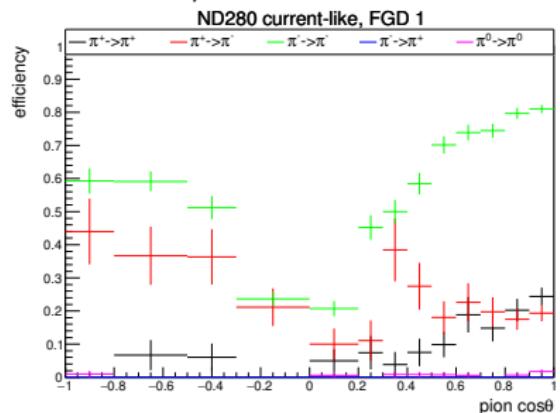
Efficiency = # of selected TPC+Iso-target+ME pions / # of true pions

Pion selection efficiency

ν_μ CC selection



$\bar{\nu}_\mu$ CC selection



CC0 π selection (FHC): composition in topologies

Selection: CC-inclusive + no pions in TPC, Target, no ME

		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG	
ν_μ CC0 π	current	FGD 1	30620	81.4	5.64	10.1	2.8
		FGD 2	30061	82.1	5.62	9.41	2.84
	ref.	Tgt 1	41970	89.1	2.3	7.11	1.52
		Tgt 2	14018	87.8	1.38	8.63	2.23
	alt.1	Tgt 1	64543	89.1	2.17	7.25	1.47
	alt.2	Tgt 1	61051	88.8	2.21	7.61	1.4

* FGD in alternative configurations have similar performance than in current-like

* If we assume target has 1cm segmentation instead of 2.5cm and 70% ME efficiency instead of 50%, the purity improved by $\sim 1.5 - 2\%$

CC0 π selection (RHC): composition in topologies

Selection: CC-inclusive + no pions in TPC, Target, no ME

		#/ 10^{21} POT	CC0 π	CC1 π	CCother	BKG		
$\bar{\nu}_\mu$ CC0 π	current	FGD 1	11318	82.2	6.89	9.28	1.63	
		FGD 2	11164	81.9	7.1	9.42	1.6	
	ref.	Tgt 1	13881	86.7	2.97	9.43	0.872	
		Tgt 2	4339	86.9	1.54	9.79	1.8	
	alt.1	Tgt 1	21349	87	2.88	9.25	0.829	
	alt.2	Tgt 1	19937	86.5	3.19	9.56	0.752	
	ν_μ CC0 π (bkg)	current	FGD 1	4120	62	11.3	21.8	4.95
			FGD 2	3954	61.8	11.5	22.4	4.25
		ref.	Tgt 1	4514	70	5.58	21.8	2.61
			Tgt 2	1425	70.1	3.09	21.5	5.26
		alt.1	Tgt 1	6855	69.4	5.31	22.6	2.67
		alt.2	Tgt 1	6558	69.2	6.07	22.4	2.27

* FGD in alternative configurations have similar performance than in current-like

CC1 π selection (FHC): composition in topologies

Selection: CC-inclusive + 1 pion in TPC or Target

		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG	
ν_μ CC1 π	current	FGD 1	9727	1.7	60.5	33.8	4.05
		FGD 2	9246	2.07	65.9	28.1	3.88
	ref.	Tgt 1	12835	1.92	66.3	29.3	2.46
		Tgt 2	4765	0.986	74.7	21.7	2.62
	alt.1	Tgt 1	19876	2.13	65.1	30.3	2.5
	alt.2	Tgt 1	18985	2.14	60.5	34.7	2.6

* If we assume target has 1cm segmentation instead of 2.5cm and 70% ME efficiency instead of 50%, the purity improved by $\sim 1.5 - 2\%$

CC1 π selection (RHC): composition in topologies

Selection: CC-inclusive + 1 pion in TPC or Target

		#/ 10^{21} POT	CC0 π	CC1 π	CCother	BKG	
$\bar{\nu}_\mu$ CC1 π	current	FGD 1	1948	0	79.1	19.3	1.64
		FGD 2	1936	0	80.5	17.5	2.07
	ref.	Tgt 1	2901	0	81.8	17.2	0.965
		Tgt 2	950	0	86.4	12.6	0.947
	alt.1	Tgt 1	4618	0	81.4	17.9	0.736
	alt.2	Tgt 1	4260	0	79.9	19.5	0.563
	current	FGD 1	2325	0.817	63.2	31.7	4.3
		FGD 2	2359	1.65	61.9	32.3	4.15
ν_μ CC1 π (bkg)	ref.	Tgt 1	3294	1.12	63.4	32	3.46
		Tgt 2	1016	1.08	65	28.5	5.41
	alt.1	Tgt 1	5208	0.634	62.8	34.2	2.34
	alt.2	Tgt 1	4918	0.508	63.2	33.8	2.5

* If we assume target has 1cm segmentation instead of 2.5cm and 70% ME efficiency instead of 50%, the purity improved by $\sim 1.5 - 2\%$

* No CC0 π contamination in antineutrino as expected, as there are no antiprotons

CC-other selection (FHC): composition in topologies

Selection: CC-inclusive + other

		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG
ν_μ CC-other	current	FGD 1	495	1.62	37.2	58.6
		FGD 2	584	2.4	34.6	59.2
	ref.	Tgt 1	603	1.82	35.3	62
		Tgt 2	288	1.04	41.7	54.9
	alt.1	Tgt 1	898	3.56	35	60.5
	alt.2	Tgt 1	736	3.26	34.9	60.6
						1
						1.22

CC-other selection (RHC): composition in topologies

Selection: CC-inclusive + other

		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG
$\bar{\nu}_\mu$ CC-other	current	FGD 1	495	1.62	37.2	58.6
		FGD 2	584	2.4	34.6	59.2
	ref.	Tgt 1	603	1.82	35.3	62
		Tgt 2	288	1.04	41.7	54.9
	alt.1	Tgt 1	898	3.56	35	60.5
	alt.2	Tgt 1	736	3.26	34.9	60.6
						1
						1.22

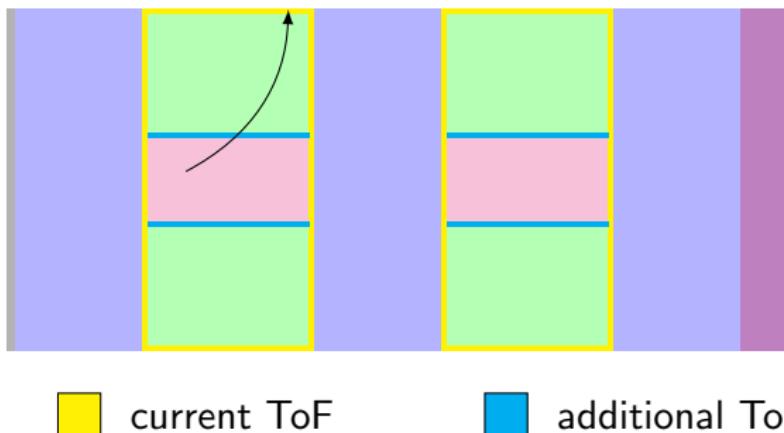
Summary of selection

- Upgrade configurations have a better coverage:
 - for high angle tracks (thanks to the new horizontal TPCs)
 - for backward tracks (thanks to the ToF counters)
- We can achieve better topology separation (better purity), even though final results will strongly depend on detector technology (that will change geometrical acceptance, Michel Electron efficiency...)
- BANFF fit uses
 - muon selection efficiency (2D, $\cos\theta$ vs momentum)
 - pion identification efficiency (2D, $\cos\theta$ vs momentum)
 - **see next presentation by Simon**

ToF PID

PID with ToF

- When two different detectors give a time for a track, we compute $m_{ToF} = p \times \sqrt{\frac{c^2(\Delta t_{reco})^2}{L^2}} - 1$, L is the length, Δt is the time of flight.
- What is the time resolution we need to separate different particle hypothesis (especially μ/e for ν_e studies)?
- Is it useful to add new ToF counters (ToF box) between the Target and the horizontal TPCs?



Available information

Smearing applied on true information

- p : we apply TPC resolution or 10% otherwise (for non-TPC tracks)
- time is smeared depending on the detector:
 - for Target/FGD: $\sigma_t = 3ns/\sqrt{N_{hits}} \oplus 0.6ns$, where $N_{hits} = L/2.5cm$
 - for ECal: $\sigma_t = 5ns$
 - for ToF counters: $\sigma_t = 600 - 150 - 50ps$
- L is smeared with 1mm if we have a TPC segment, 1cm otherwise

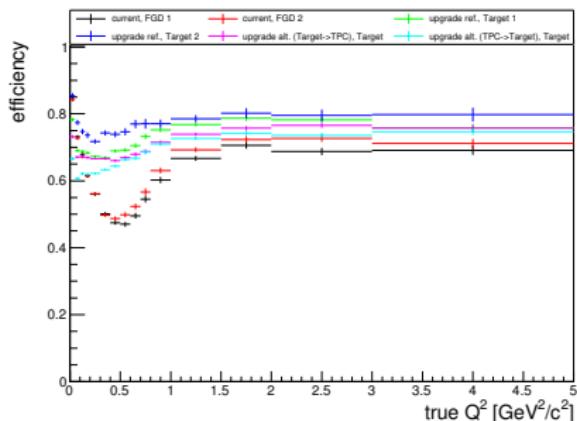
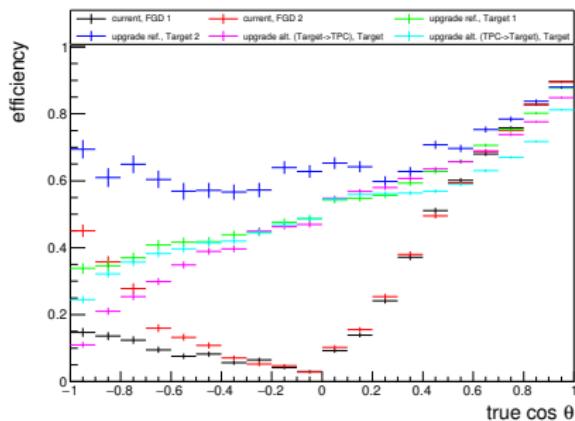
How to quantify separation?

- $\text{pull}_e^{ToF} = \frac{m_{ToF} - m_e}{\sigma_m}$, $\text{pull}_\mu \dots$
- $\mathcal{L}_e^{ToF} = \frac{e^{-(\text{pull}_e^{ToF})^2/2}}{\sum_{\text{hypo}} e^{-(\text{pull}_{\text{hypo}}^{ToF})^2/2}}$, $\mathcal{L}_\mu^{ToF} \dots$
- can be combined with TPC likelihood

Here, the selected electrons are only secondary electrons from ν_μ .

ν_μ CC-inclusive selection efficiencies (150ps ToF)

How well can we select the muon from ν_μ CC interaction in FGD or Target?



- current-like efficiencies behave as expected (low backward eff)
- upgrade fills the high-angle and backward region

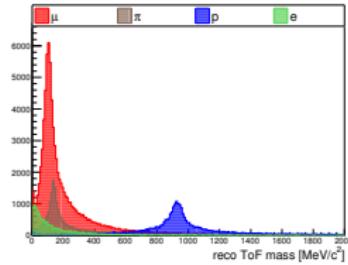
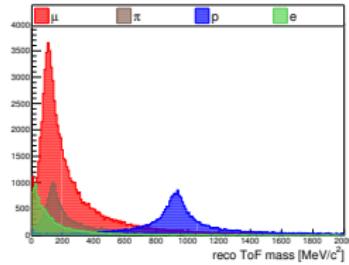
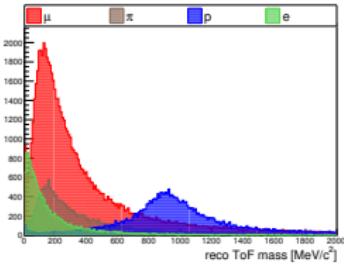
* ToF are assumed with a time resolution of 600 ps

ToF mass

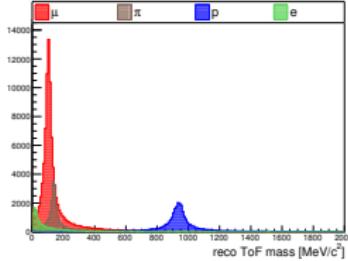
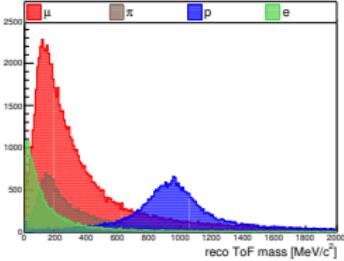
Sample of preselected ν_μ events

Look at all particles with ToF information (not only highest momentum)

reference configuration



adding ToF box between TPC and Target



$$\sigma_{ToF} = 600 \text{ ps} \uparrow$$

$$\sigma_{ToF} = 150 \text{ ps} \uparrow$$

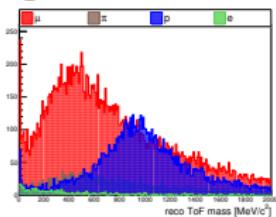
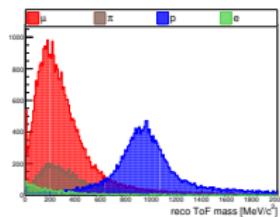
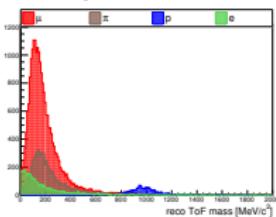
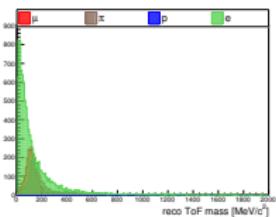
$$\sigma_{ToF} = 50 \text{ ps} \uparrow 23$$

ToF mass

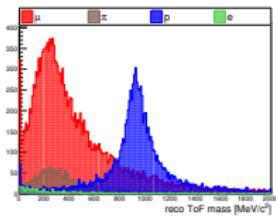
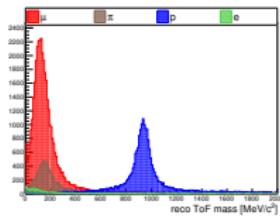
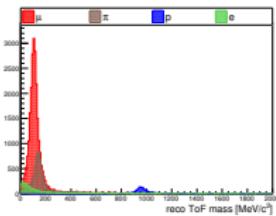
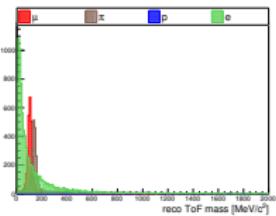
Sample of preselected ν_μ events

Look at all particles with ToF information (not only highest momentum)

$\sigma_{ToF} = 600 \text{ ps} + \text{ToF box between TPC and Target}$



$\sigma_{ToF} = 150 \text{ ps} + \text{ToF box between TPC and Target}$



$p < 200 \text{ MeV}/c$

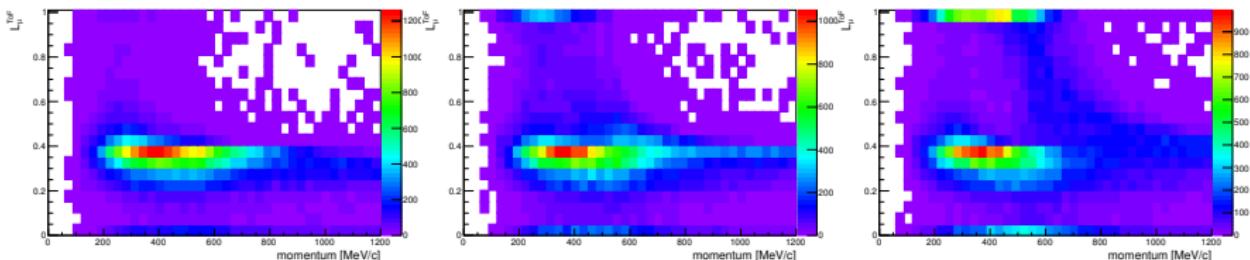
$200 < p < 400 \text{ MeV}/c$

$400 < p < 1000 \text{ MeV}/c$

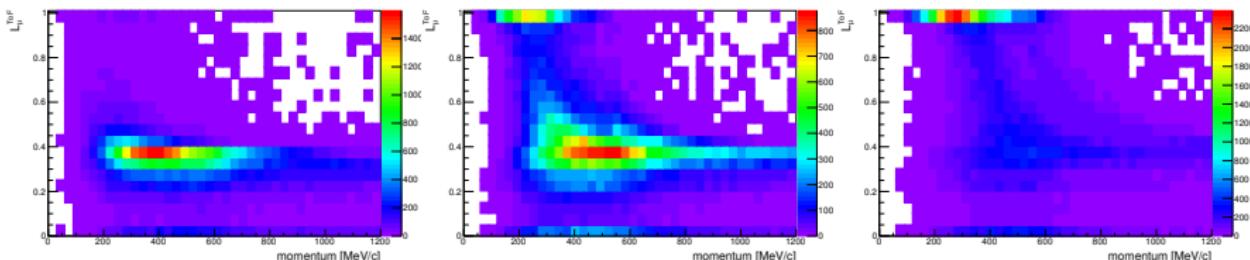
$p > 1000 \text{ MeV}/c$

\mathcal{L}_{μ}^{ToF} for true muons

reference configuration

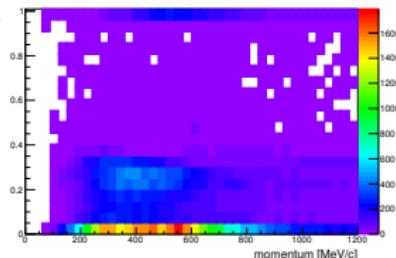
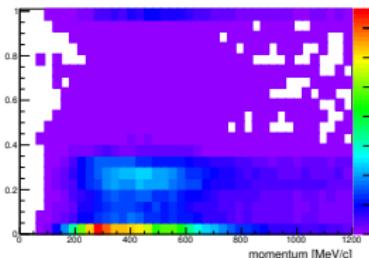
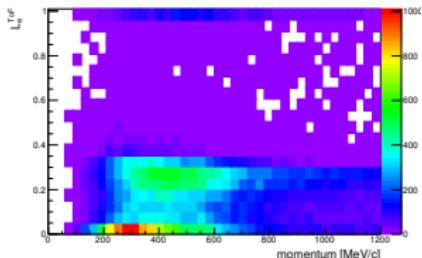


adding ToF box between TPC and Target

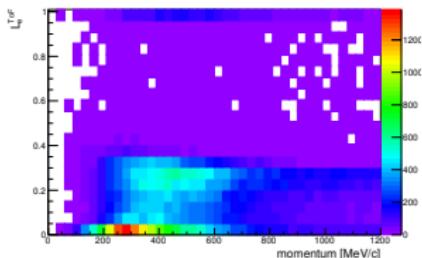

 $\sigma_{ToF} = 600 \text{ ps} \uparrow$
 $\sigma_{ToF} = 150 \text{ ps} \uparrow$
 $\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_e^{ToF} for true muons

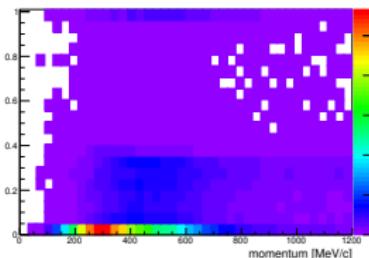
reference configuration



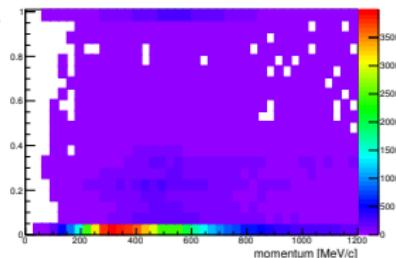
adding ToF box between TPC and Target



$\sigma_{ToF} = 600 \text{ ps} \uparrow$



$\sigma_{ToF} = 150 \text{ ps} \uparrow$



$\sigma_{ToF} = 50 \text{ ps} \uparrow$

Expected improvement of muon selection (1)

- Is it useful to add ToF information for muon PID selection?
 \Leftrightarrow Is it better to cut on \mathcal{L}_μ^{TPC} or on $\alpha \mathcal{L}_\mu^{ToF} + (1 - \alpha) \mathcal{L}_\mu^{TPC}$?
- We scan values of α and cut values (separating in different momentum bins for ToF likelihood cut optimization) and compute efficiency of selection, purity and significance

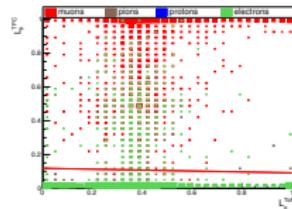
$$\varepsilon = \frac{\text{selected muons}}{\text{muons before selection}}, \rho = \frac{\text{selected muons}}{\text{selected particles}},$$

$$S = \frac{\text{selected muons}}{\sqrt{\text{selected particles}}}$$

Expected improvement of muon selection (2)

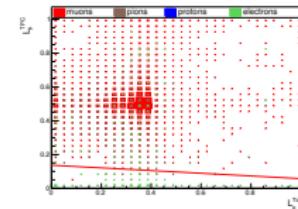
We select the best working point (cuts giving the higher significance).

Using ToF and TPC likelihoods

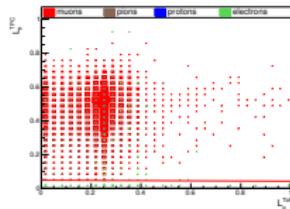


$p < 200 \text{ MeV}/c$

$200 < p < 400 \text{ MeV}/c$

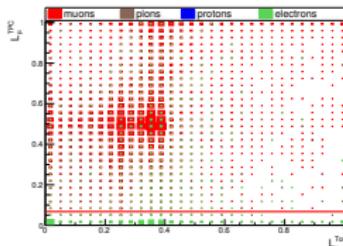


$400 < p < 1000 \text{ MeV}/c$



$p > 1000 \text{ MeV}/c$

Using TPC only



- ToF resolution of 600ps
with TPC-only: $\varepsilon = 98.3\%$, $\rho = 92.6\%$, $S = 336.4$
with TPC+ToF: $\varepsilon = 98.3\%$, $\rho = 92.3\%$, $S = 336.1$
- ToF resolution of 150ps+ToF box
with TPC-only: $\varepsilon = 98.4\%$, $\rho = 92.2\%$, $S = 340.4$
with TPC+ToF: $\varepsilon = 98.1\%$, $\rho = 92.3\%$, $S = 340.2$

Summary for ToF PID

- using the mass (and the corresponding likelihood) allows to define PID cuts
- for ν_μ analysis:
 - we looked at how well we can improve muon selection by applying cuts on \mathcal{L}_μ^{TPC} and \mathcal{L}_μ^{ToF} (no cut on MIP likelihood...)
 - we saw that the efficiency/purity/significance is not improved when adding ToF information
- for ν_e analysis:
 - we saw that muons are well separated from electron hypothesis
 - to quantify the improvement using ToF information, we would need to look at primary electrons from ν_e
- use of ToF with better resolution or use of additional ToF between TPC and Target may be critical for electron-muon separation

Conclusion

Summary

- $\nu_\mu \text{CC}/\bar{\nu}_\mu \text{CC}$ event selection:
 - current configuration performances well reproduced
 - upgrade configurations have a better coverage at high angle and backward
 - good performance of the upgrade for pion selection
 - efficiencies are then propagated to BANFF
- use of Time-of-Flight for PID
 - using \mathcal{L}^{ToF} seems convenient, because we can combine it with TPC likelihood
 - no improvement for muon selection, may be very useful for ν_e selection

Backups

ECal branch selection

ECal efficiencies

The upgrade framework does not have full ECal reconstruction (building a track from the hits).

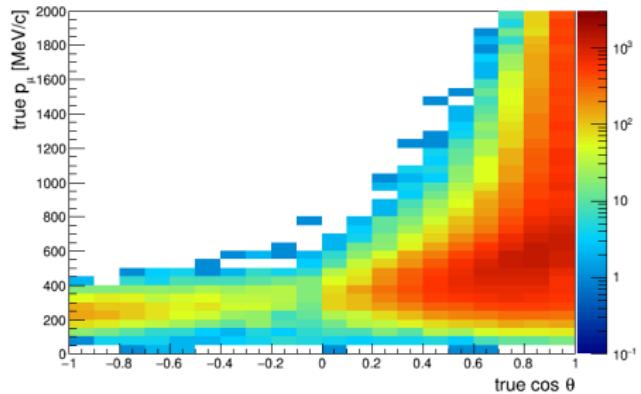
- We take all the true tracks reaching ECal
- We apply ECal efficiencies on it:
 - $\varepsilon_{reco} \sim 30\%$ for $0 < p_\mu < 300$ MeV/c
 - $\varepsilon_{reco} \sim 50\%$ for $300 < p_\mu < 900$ MeV/c
 - $\varepsilon_{reco} \sim 40\%$ for $p_\mu > 900$ MeV/c
- Same thing is done for FGD-ECal matching efficiencies (we assume same for Target-ECal matching)
- Muon is asked to stop in ECal to reconstruct momentum-by-range

ECal PID

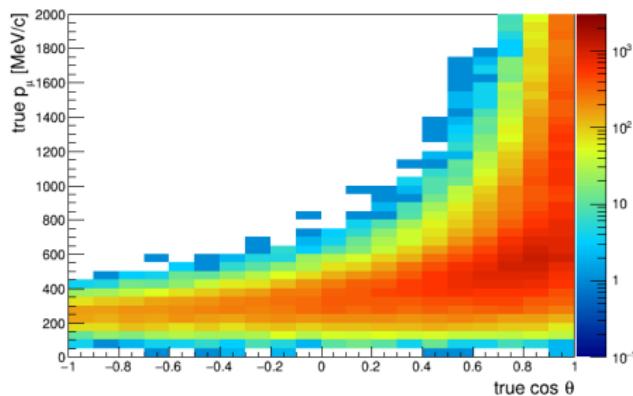
ECal PID variables MipEM and E/L are thrown randomly using pdf from current ECal reconstruction. The PID cuts are done on these variables.

2D distribution of events

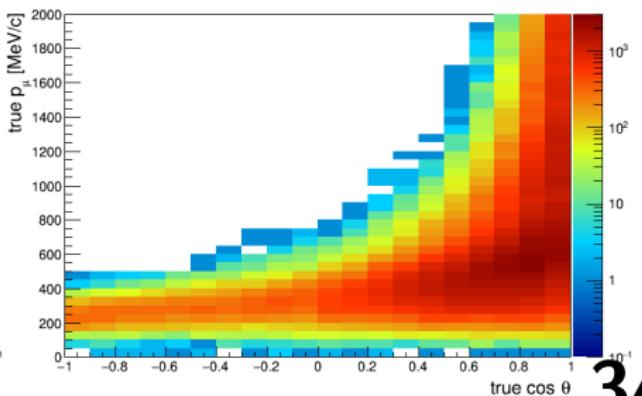
ND280 current, CC-inclusive



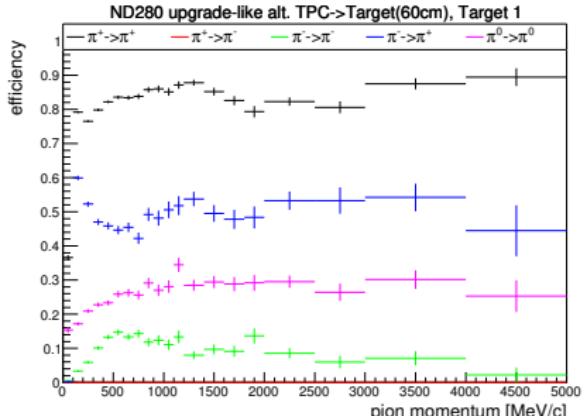
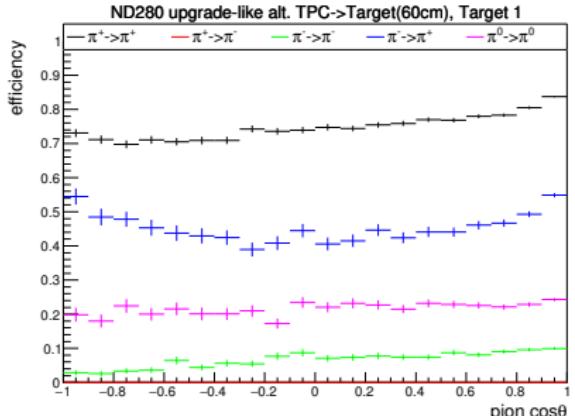
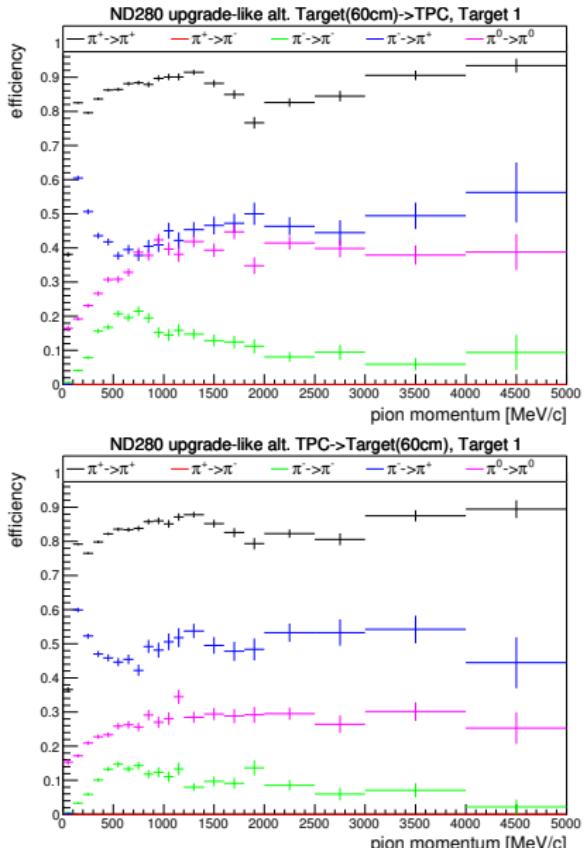
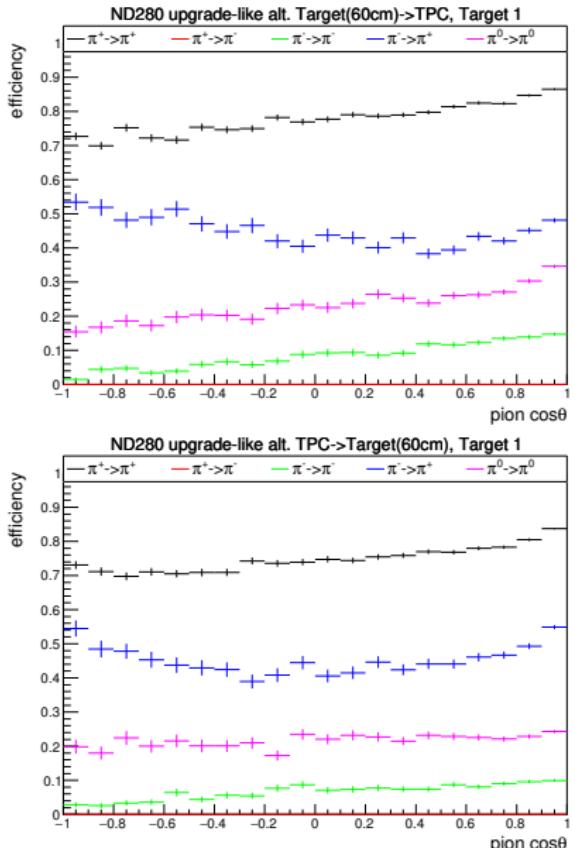
ND280 upgrade ref., CC-inclusive



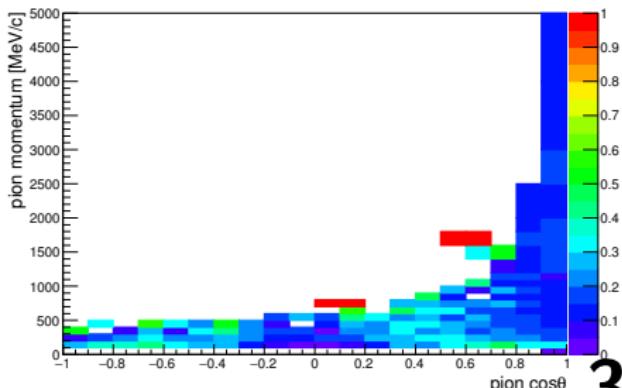
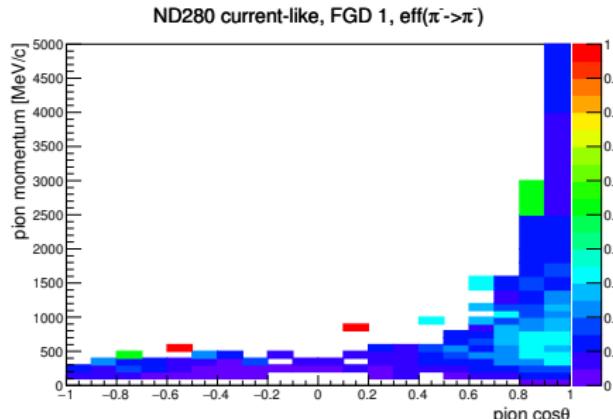
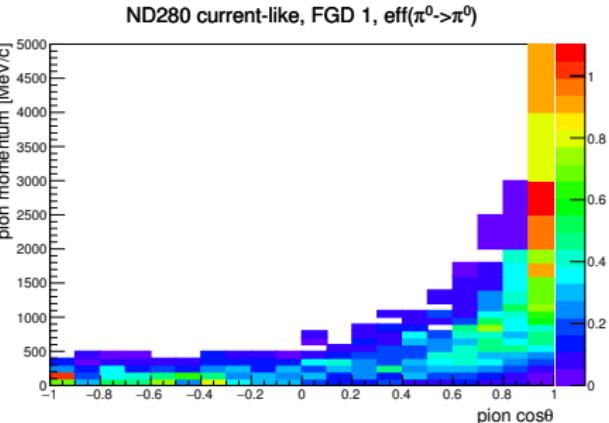
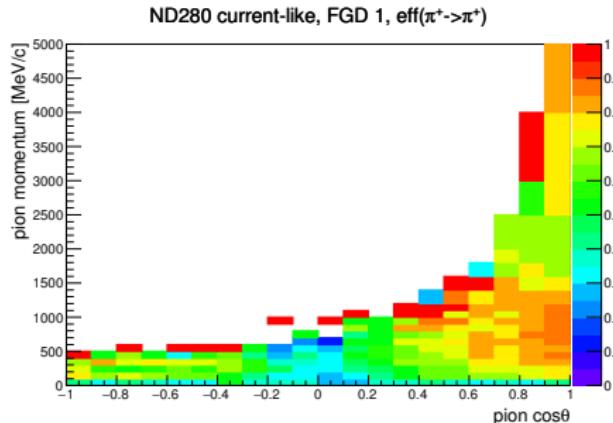
ND280 upgrade alt. Target(60cm)->TPC, CC-inclusive



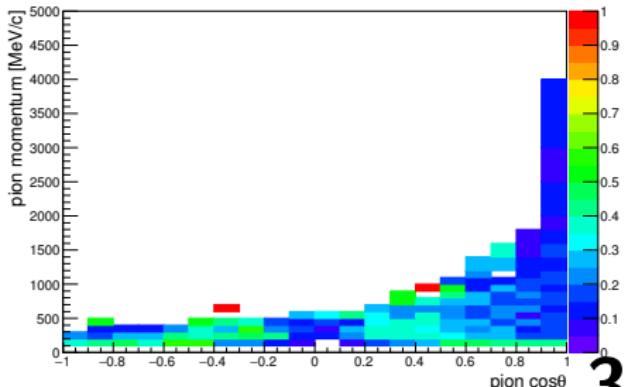
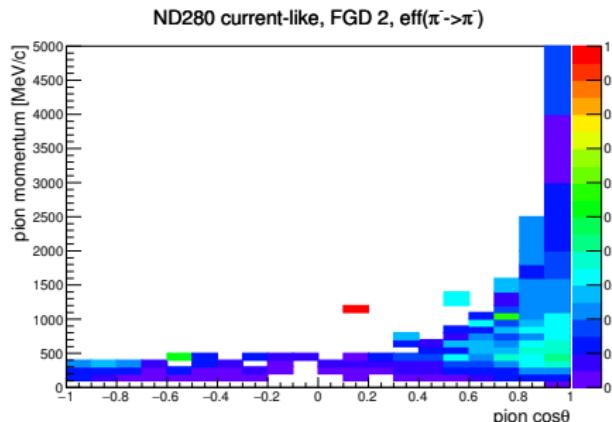
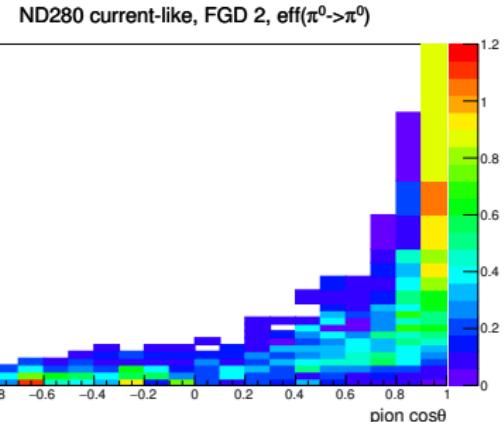
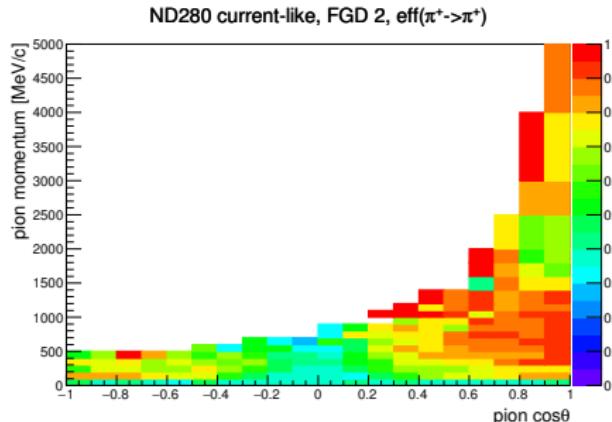
Pion selection efficiency (alternative configurations)



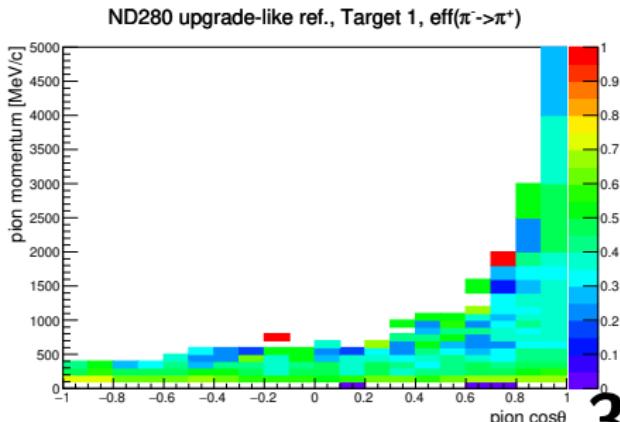
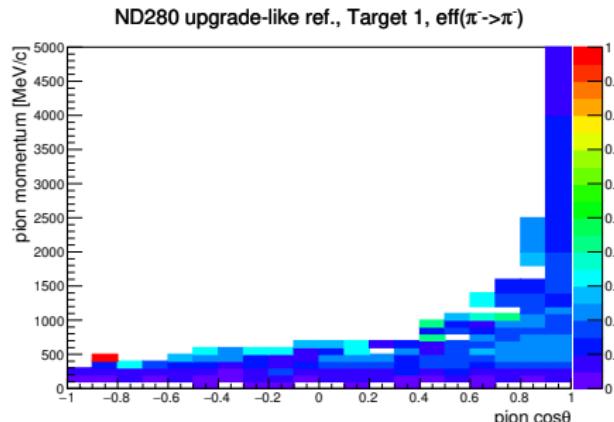
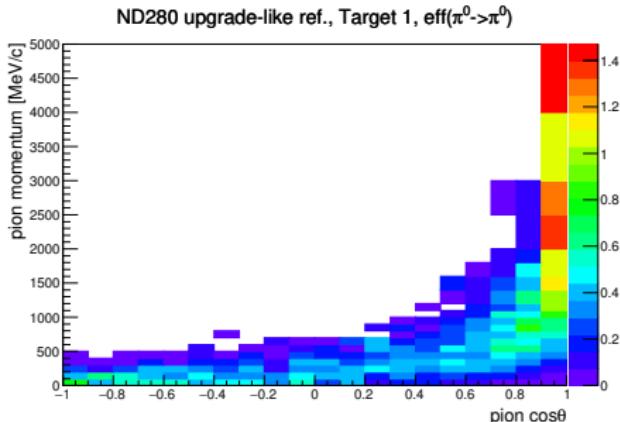
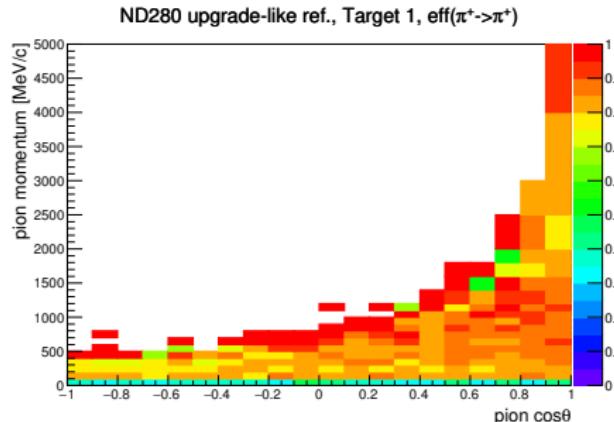
2D pion efficiencies (FGD 1, current-like)



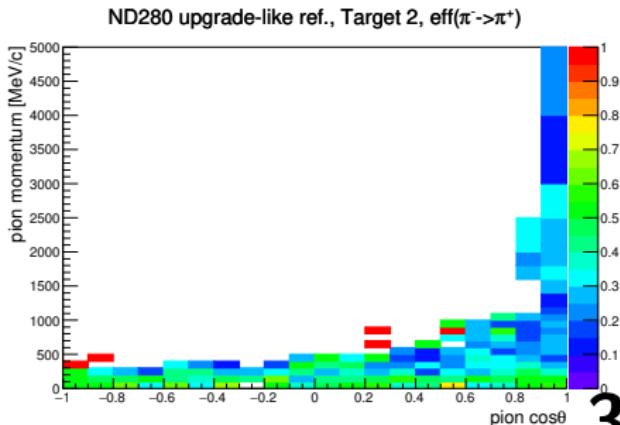
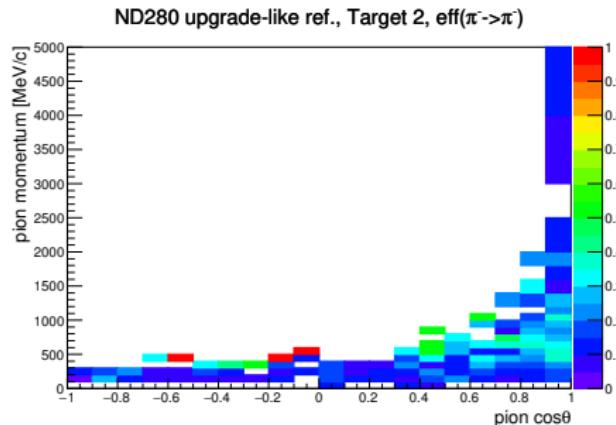
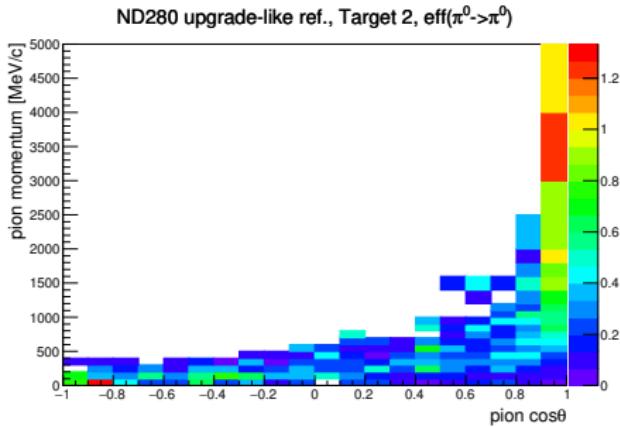
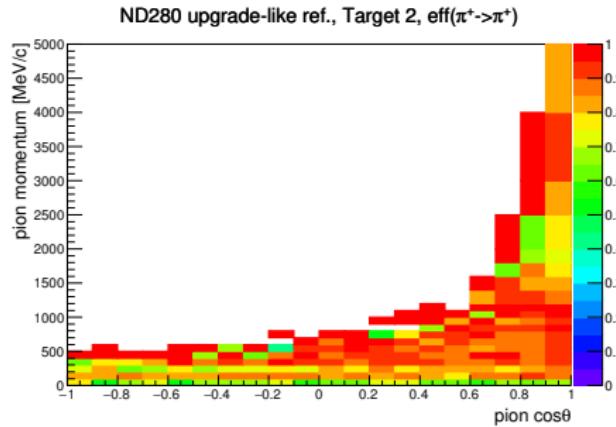
2D pion efficiencies (FGD2, current-like)



2D pion efficiencies (Target 1, reference upgrade)



2D pion efficiencies (Target 2, reference upgrade)



ν_μ CC0 π selection: composition in topologies

		ν_μ CC0 π purity in %				
		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	30620	81.4	5.64	10.1	2.8
	FGD 2	30061	82.1	5.62	9.41	2.84
ref.	Tgt 1	41970	89.1	2.3	7.11	1.52
	Tgt 2	14018	87.8	1.38	8.63	2.23
	Tgt 1'	41410	90.6	0.988	6.9	1.51
	Tgt 2'	13948	88.4	0.789	8.57	2.22
alt.1	FGD 1	31730	82.3	5.51	9.82	2.35
	FGD 2	29812	82.3	5.49	9.53	2.68
	Tgt 1	64543	89.1	2.17	7.25	1.47
	Tgt 1'	63674	90.5	0.945	7.06	1.47
alt.2	FGD 1	32999	81.9	5.52	10	2.55
	FGD 2	29967	82.7	5.29	9.36	2.63
	Tgt 1	61051	88.8	2.21	7.61	1.4
	Tgt 1'	60106	90.3	0.965	7.3	1.39

*The "prime" after target name is to say we assume target of 1cm segmentation instead of 2.5cm and 70% ME efficiency instead of 50%

ν_μ CC1 π selection: composition in topologies

		ν_μ CC1 π purity in %				
		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	9727	1.7	60.5	33.8	4.05
	FGD 2	9246	2.07	65.9	28.1	3.88
ref.	Tgt 1	12835	1.92	66.3	29.3	2.46
	Tgt 2	4765	0.986	74.7	21.7	2.62
	Tgt 1'	12702	2.28	67.4	27.8	2.46
	Tgt 2'	4802	0.979	75.3	21.1	2.6
alt.1	FGD 1	9729	1.77	60.7	33.7	3.79
	FGD 2	9135	2.06	66.2	27.9	3.82
	Tgt 1	19876	2.13	65.1	30.3	2.5
	Tgt 1'	19467	2.64	66.1	28.8	2.51
alt.2	FGD 1	9947	1.95	60.3	33.8	3.94
	FGD 2	9254	2.05	66.6	27.3	4.06
	Tgt 1	18985	2.14	60.5	34.7	2.6
	Tgt 1'	18640	2.69	61.2	33.5	2.63

*The "prime" after target name is when we assume target of 1cm segmentation instead of 2.5cm and 70% ME efficiency instead of 50%

ν_μ CC-other selection: composition in topologies

		ν_μ CC-other purity in %				
		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	8249	3.47	16.8	73.5	6.17
	FGD 2	8220	3.08	16.5	74	6.46
ref.	Tgt 1	10829	2.61	18.2	73.7	5.49
	Tgt 2	3187	2.82	20.5	71.1	5.62
	Tgt 1'	11807	2.46	21.3	70.9	5.26
	Tgt 2'	3279	2.74	21.4	70.3	5.58
alt.1	FGD 1	8283	3.63	16.2	73.7	6.43
	FGD 2	8379	3.53	17.4	72.4	6.71
	Tgt 1	18238	3.15	18.5	73.1	5.26
	Tgt 1'	19889	2.99	21.6	70.4	5.02
alt.2	FGD 1	8212	4.04	16.3	73	6.65
	FGD 2	8267	3.56	17.3	72.9	6.23
	Tgt 1	15312	2.28	19.2	73.5	5
	Tgt 1'	16988	2.21	22.7	70.3	4.78

*The "prime" after target name is when we assume target of 1cm segmentation instead of 2.5cm and 70% ME efficiency instead of 50%

$\bar{\nu}_\mu$ CC0 π selection: composition in topologies

		$\bar{\nu}_\mu$ CC0 π purity in %				
		#/ 10^{21} POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	11318	82.2	6.89	9.28	1.63
	FGD 2	11164	81.9	7.1	9.42	1.6
ref.	Tgt 1	13881	86.7	2.97	9.43	0.872
	Tgt 2	4339	86.9	1.54	9.79	1.8
alt.1	FGD 1	11264	81.7	7.17	9.65	1.47
	FGD 2	10930	82.2	6.18	9.9	1.73
	Tgt 1	21349	87	2.88	9.25	0.829
alt.2	FGD 1	11233	81.9	7.09	9.67	1.35
	FGD 2	11044	81.9	7.02	9.57	1.54
	Tgt 1	19937	86.5	3.19	9.56	0.752

$\bar{\nu}_\mu \text{CC}1\pi$ selection: composition in topologies

		$\bar{\nu}_\mu \text{CC}1\pi$ purity in %				
		#/ 10^{21} POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	1948	0	79.1	19.3	1.64
	FGD 2	1936	0	80.5	17.5	2.07
ref.	Tgt 1	2901	0	81.8	17.2	0.965
	Tgt 2	950	0	86.4	12.6	0.947
alt.1	FGD 1	2029	0	79.9	18.1	1.92
	FGD 2	1859	0	79.8	18	2.15
	Tgt 1	4618	0	81.4	17.9	0.736
alt.2	FGD 1	1986	0	78.5	19.7	1.76
	FGD 2	1986	0.0504	81	17.2	1.81
	Tgt 1	4260	0	79.9	19.5	0.563

$\bar{\nu}_\mu$ CC-other selection: composition in topologies

		$\bar{\nu}_\mu$ CC-other purity in %				
		#/ 10^{21} POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	495	1.62	37.2	58.6	2.63
	FGD 2	584	2.4	34.6	59.2	3.77
ref.	Tgt 1	603	1.82	35.3	62	0.829
	Tgt 2	288	1.04	41.7	54.9	2.43
alt.1	FGD 1	525	2.48	31.8	64	1.71
	FGD 2	523	2.49	34.6	60.2	2.68
	Tgt 1	898	3.56	35	60.5	1
alt.2	FGD 1	486	2.26	34.4	60.5	2.88
	FGD 2	527	2.66	35.9	59.8	1.71
	Tgt 1	736	3.26	34.9	60.6	1.22

$\nu_\mu \text{CC}0\pi$ selection in RHC: composition in topologies

		$\nu_\mu \text{CC}0\pi$ purity in %				
		#/ 10^{21} POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	4120	62	11.3	21.8	4.95
	FGD 2	3954	61.8	11.5	22.4	4.25
ref.	Tgt 1	4514	70	5.58	21.8	2.61
	Tgt 2	1425	70.1	3.09	21.5	5.26
alt.1	FGD 1	4033	61.6	11.4	22.4	4.61
	FGD 2	3919	61.8	11.1	22.5	4.62
	Tgt 1	6855	69.4	5.31	22.6	2.67
alt.2	FGD 1	4063	61	12.1	22.4	4.58
	FGD 2	3908	62.9	10.9	21.7	4.48
	Tgt 1	6558	69.2	6.07	22.4	2.27

$\nu_\mu \text{CC}1\pi$ selection in RHC: composition in topologies

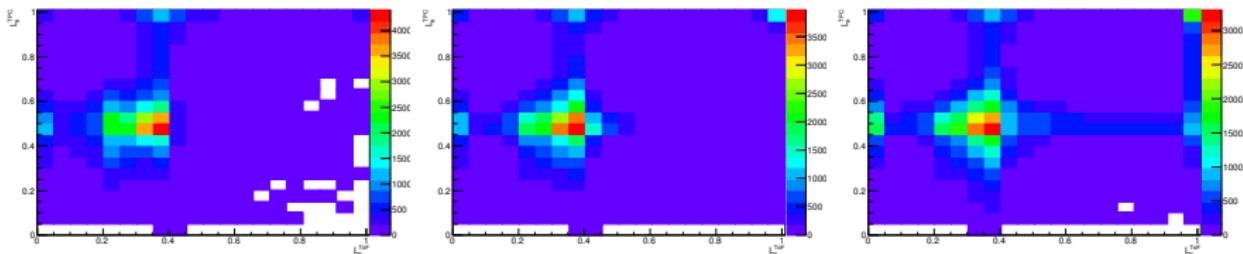
		$\nu_\mu \text{CC}1\pi$ purity in %				
		#/ 10^{21} POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	2325	0.817	63.2	31.7	4.3
	FGD 2	2359	1.65	61.9	32.3	4.15
ref.	Tgt 1	3294	1.12	63.4	32	3.46
	Tgt 2	1016	1.08	65	28.5	5.41
alt.1	FGD 1	2458	1.18	61	33.6	4.23
	FGD 2	2312	1.34	63.1	31	4.54
	Tgt 1	5208	0.634	62.8	34.2	2.34
alt.2	FGD 1	2342	1.2	60.4	33.3	5.12
	FGD 2	2315	1.17	63	31	4.84
	Tgt 1	4918	0.508	63.2	33.8	2.5

ν_μ CC-other selection in RHC: composition in topologies

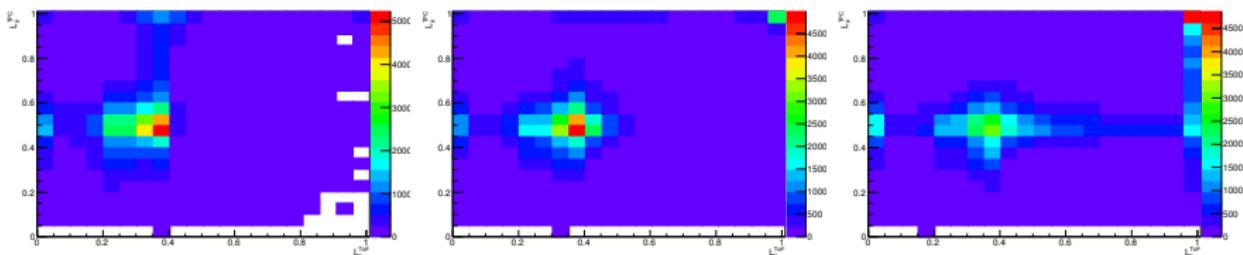
		ν_μ CC-other purity in %				
		#/10 ²¹ POT	CC0 π	CC1 π	CCother	BKG
current	FGD 1	1089	1.1	11.9	80.2	6.8
	FGD 2	1032	1.26	11.9	80	6.78
ref.	Tgt 1	1070	0.374	14	81.6	4.02
	Tgt 2	491	0.407	15.5	76.6	7.54
alt.1	FGD 1	1015	0.887	12	79.8	7.29
	FGD 2	1040	0.962	11.9	78.9	8.17
	Tgt 1	1522	0.197	15.7	80.2	3.94
alt.2	FGD 1	984	1.42	12.6	79.1	6.91
	FGD 2	1019	0.491	11.8	80.3	7.46
	Tgt 1	1296	0.54	17.1	79.1	3.32

\mathcal{L}_{ToF}^μ vs \mathcal{L}_{TPC}^μ (μ candidates)

reference configuration



adding ToF box between TPC and Target



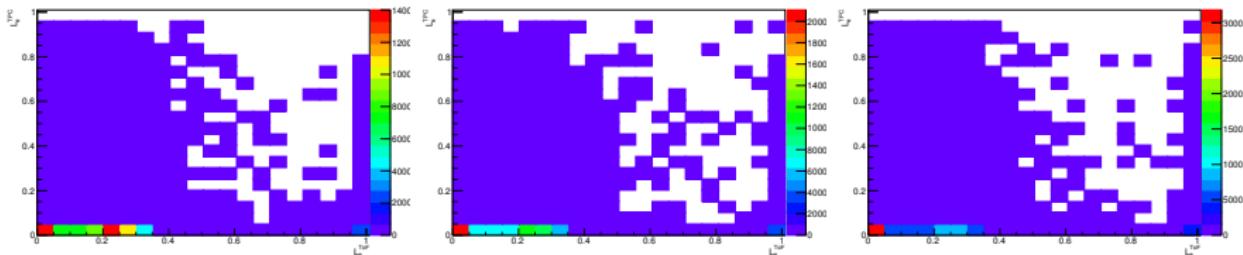
$\sigma_{ToF} = 600 \text{ ps } \uparrow$

$\sigma_{ToF} = 150 \text{ ps } \uparrow$

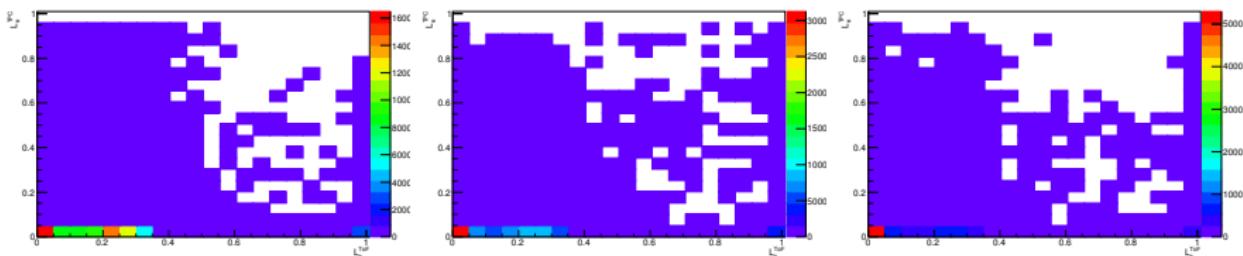
$\sigma_{ToF} = 50 \text{ ps } \uparrow$

\mathcal{L}_{ToF}^e vs \mathcal{L}_{TPC}^e (μ candidates)

reference configuration



adding ToF box between TPC and Target



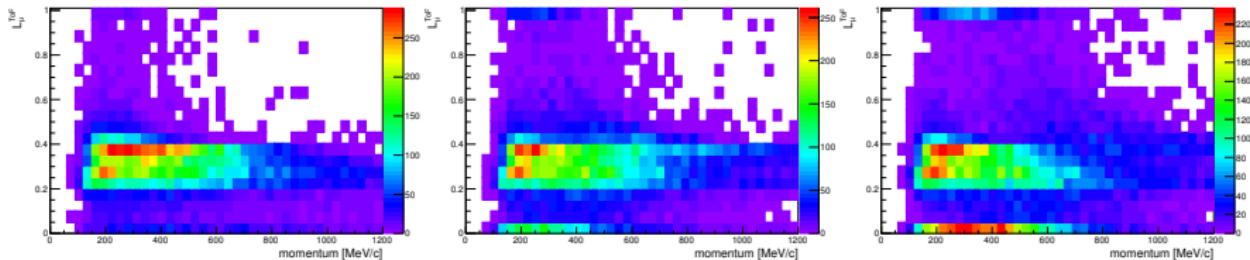
$\sigma_{ToF} = 600$ ps \uparrow

$\sigma_{ToF} = 150$ ps \uparrow

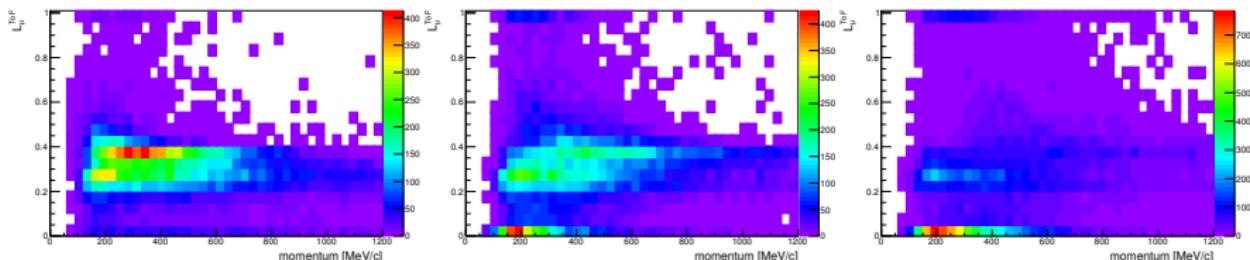
$\sigma_{ToF} = 50$ ps \uparrow

\mathcal{L}_μ^{ToF} for true pions

reference configuration



adding new ToF between Target and HTPC



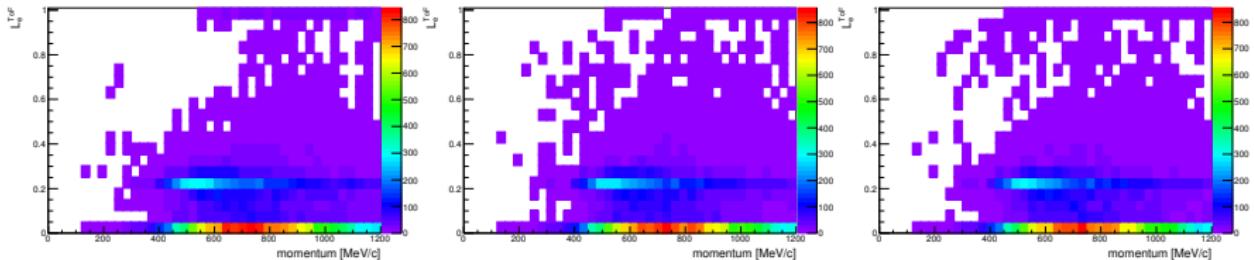
$\sigma_{ToF} = 600 \text{ ps } \uparrow$

$\sigma_{ToF} = 150 \text{ ps } \uparrow$

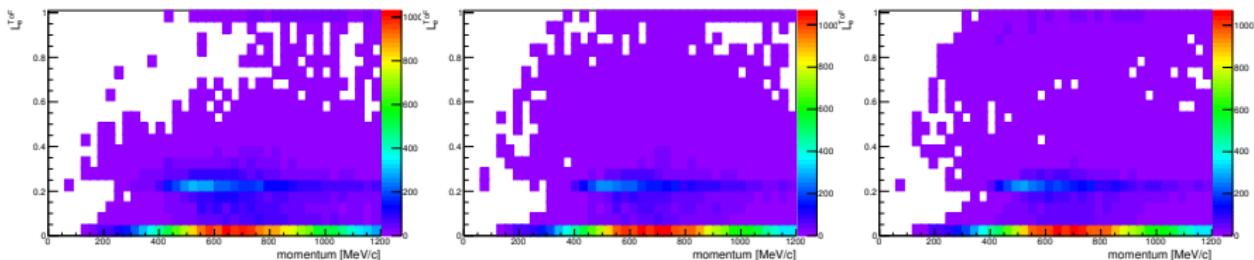
$\sigma_{ToF} = 50 \text{ ps } \uparrow$

\mathcal{L}_e^{ToF} for true protons

reference configuration



adding new ToF between Target and HTPC



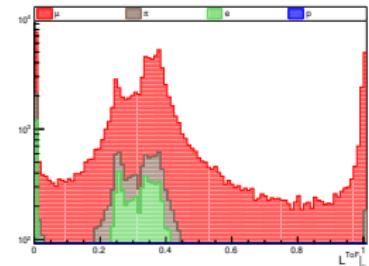
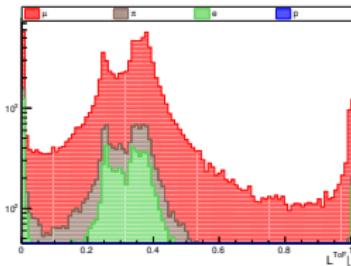
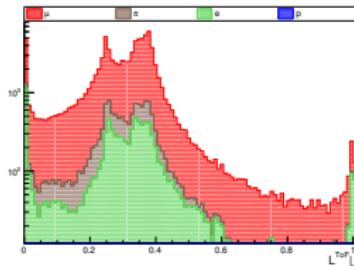
$\sigma_{ToF} = 600 \text{ ps} \uparrow$

$\sigma_{ToF} = 150 \text{ ps} \uparrow$

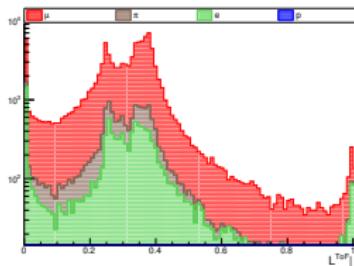
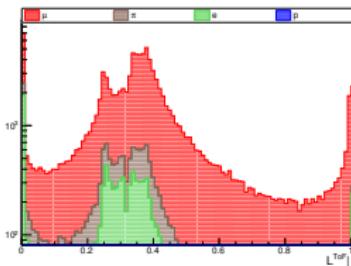
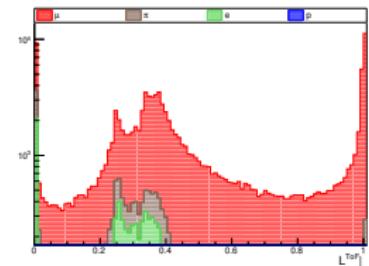
$\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_μ^{ToF} for different true PID

reference configuration

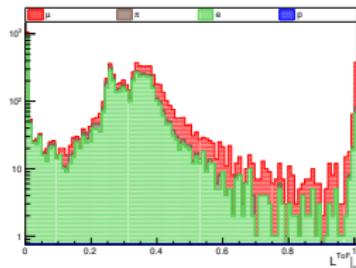
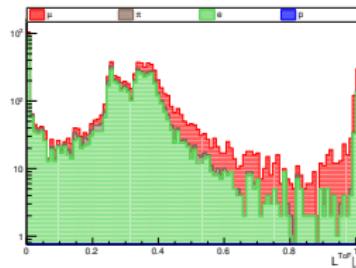
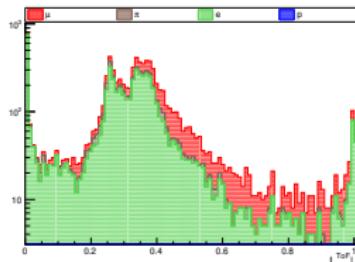


adding new ToF between Target and HTPC

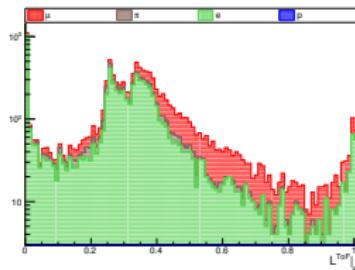
 $\sigma_{ToF} = 600 \text{ ps} \uparrow$  $\sigma_{ToF} = 150 \text{ ps} \uparrow$  $\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_μ^{ToF} for different true PID ($50 < p < 200$ MeV/c)

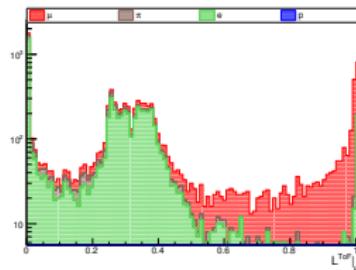
reference configuration



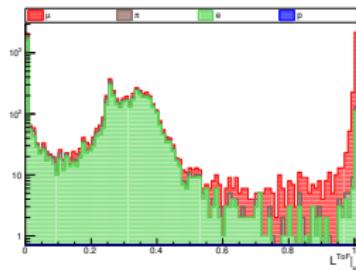
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600$ ps ↑



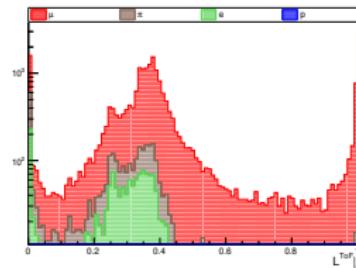
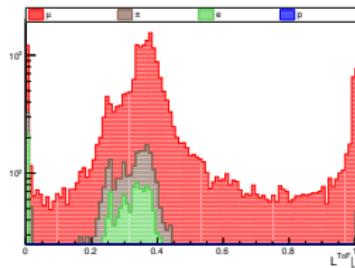
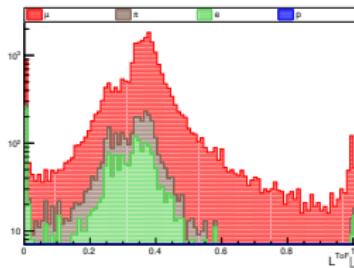
$\sigma_{ToF} = 150$ ps ↑



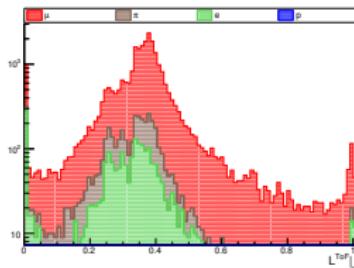
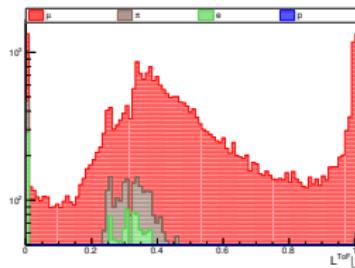
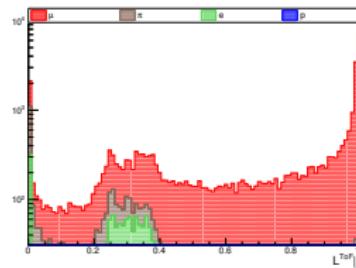
$\sigma_{ToF} = 50$ ps ↑

\mathcal{L}_μ^{ToF} for different true PID ($200 < p < 400$ MeV/c)

reference configuration

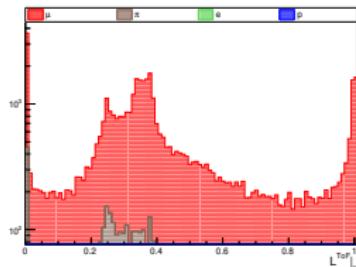
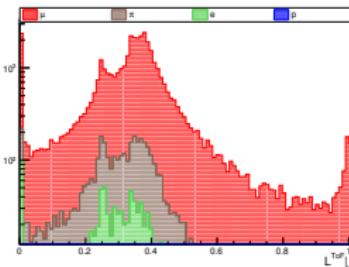
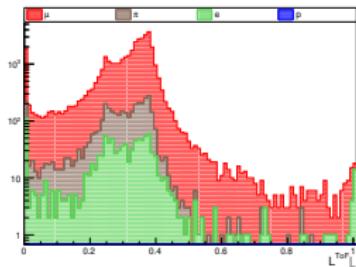


adding new ToF between Target and HTPC

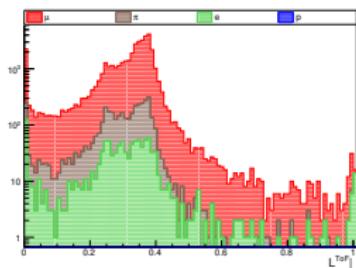

 $\sigma_{ToF} = 600 \text{ ps} \uparrow$

 $\sigma_{ToF} = 150 \text{ ps} \uparrow$

 $\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_{μ}^{ToF} for different true PID ($400 < p < 1000$ MeV/c)

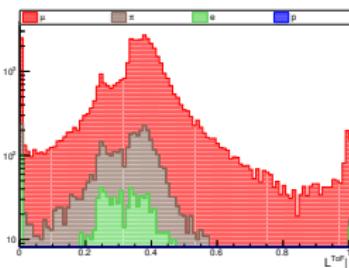
reference configuration



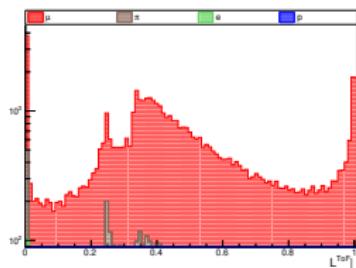
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600$ ps \uparrow



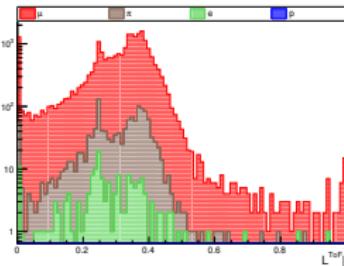
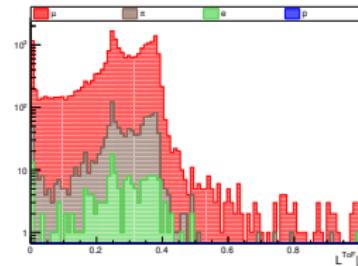
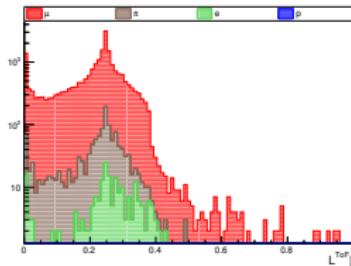
$\sigma_{ToF} = 150$ ps \uparrow



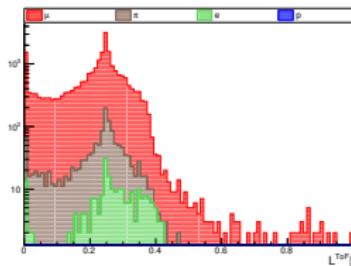
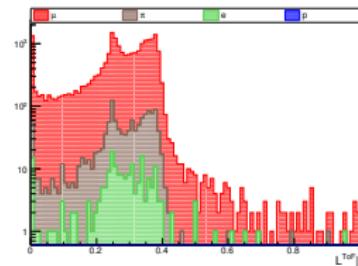
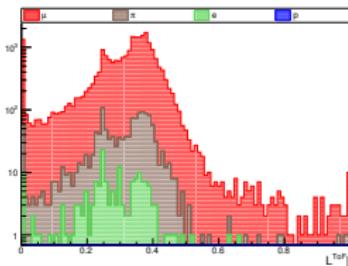
$\sigma_{ToF} = 50$ ps \uparrow

\mathcal{L}_μ^{ToF} for different true PID ($p > 1000$ MeV/c)

reference configuration

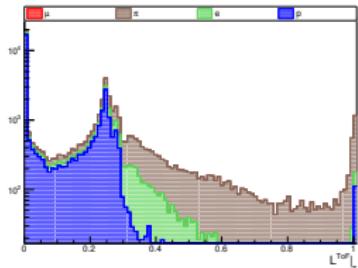
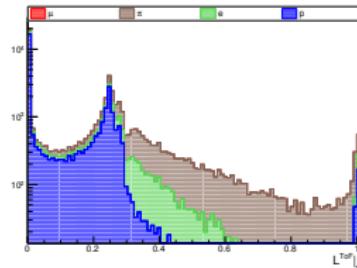
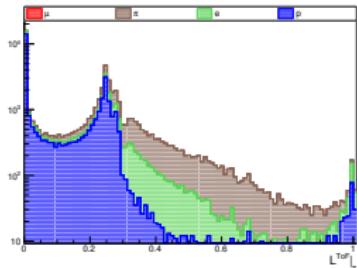


adding new ToF between Target and HTPC

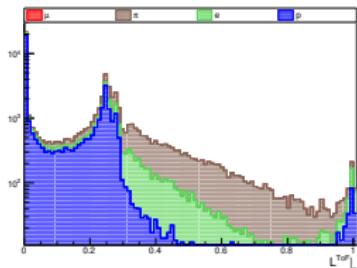

 $\sigma_{\text{ToF}} = 600 \text{ ps} \uparrow$

 $\sigma_{\text{ToF}} = 150 \text{ ps} \uparrow$

 $\sigma_{\text{ToF}} = 50 \text{ ps} \uparrow$

\mathcal{L}_{π}^{ToF} for different true PID

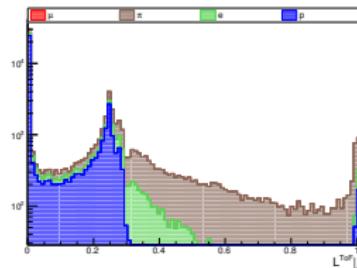
reference configuration



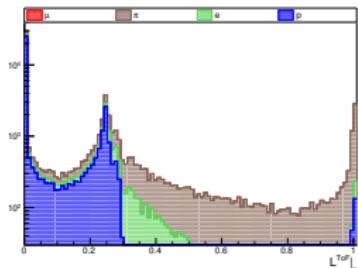
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600 \text{ ps} \uparrow$



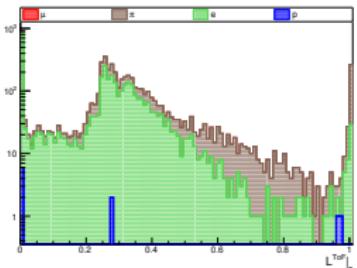
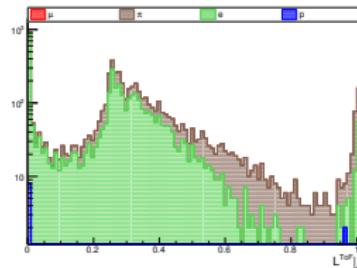
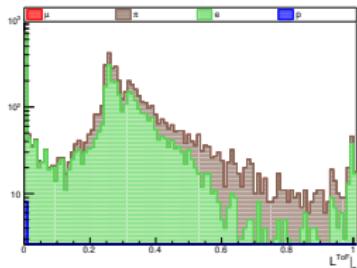
$\sigma_{ToF} = 150 \text{ ps} \uparrow$



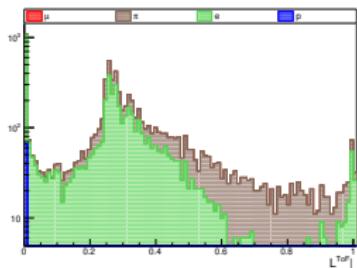
$\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_π^{ToF} for different true PID ($50 < p < 200$ MeV/c)

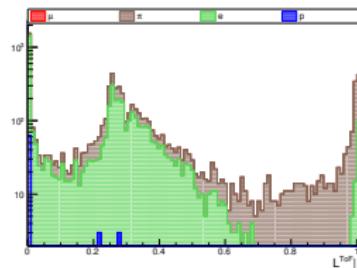
reference configuration



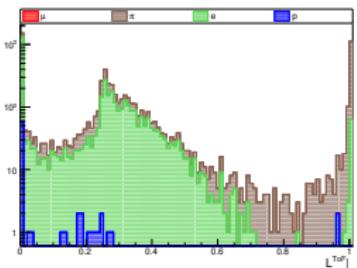
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600$ ps \uparrow



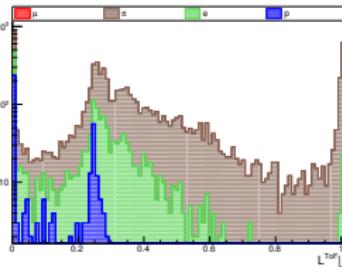
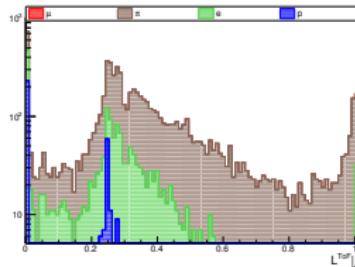
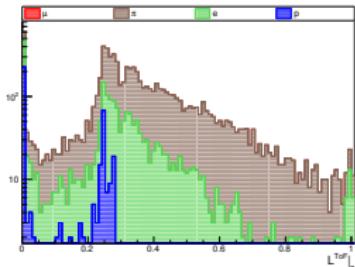
$\sigma_{ToF} = 150$ ps \uparrow



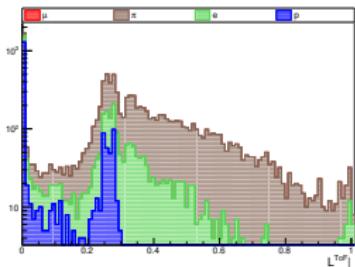
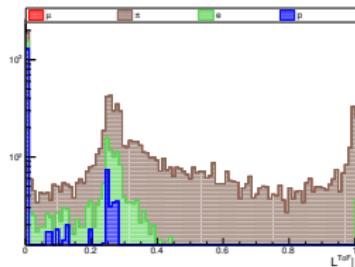
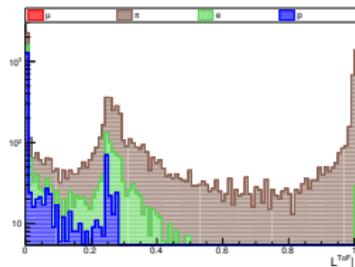
$\sigma_{ToF} = 50$ ps \uparrow

\mathcal{L}_{π}^{ToF} for different true PID ($200 < p < 400$ MeV/c)

reference configuration

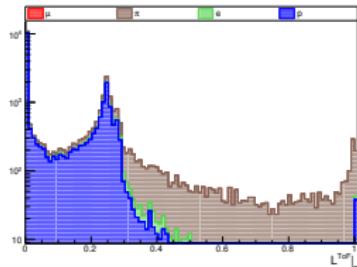
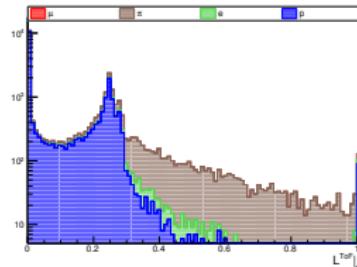
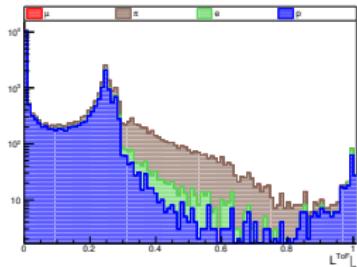


adding new ToF between Target and HTPC

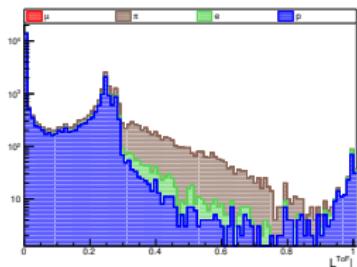

 $\sigma_{ToF} = 600 \text{ ps} \uparrow$

 $\sigma_{ToF} = 150 \text{ ps} \uparrow$

 $\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_π^{ToF} for different true PID ($400 < p < 1000$ MeV/c)

reference configuration



adding new ToF between Target and HTPC



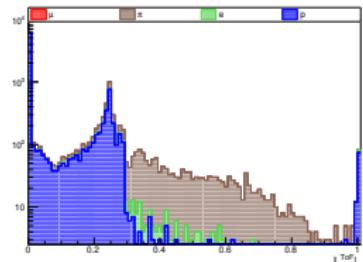
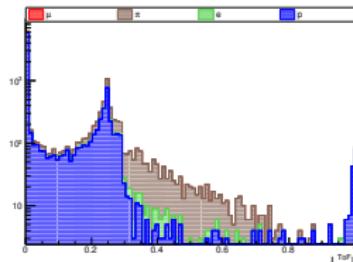
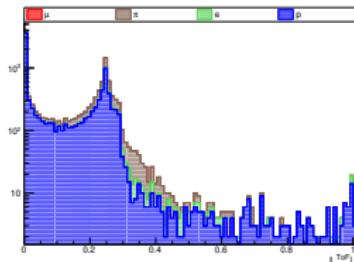
$\sigma_{ToF} = 600$ ps ↑

$\sigma_{ToF} = 150$ ps ↑

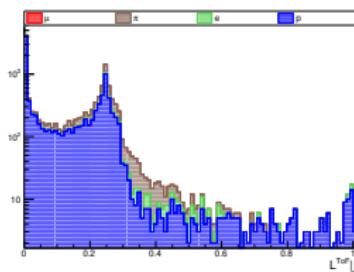
$\sigma_{ToF} = 50$ ps ↑

\mathcal{L}_π^{ToF} for different true PID ($p > 1000$ MeV/c)

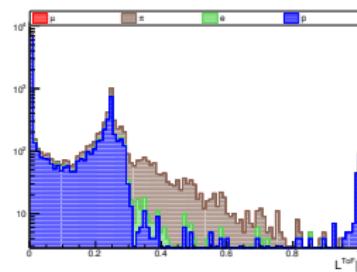
reference configuration



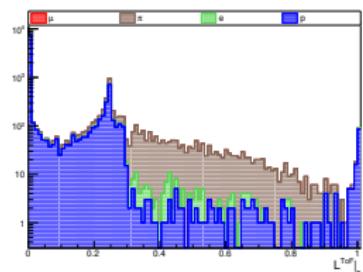
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600$ ps ↑



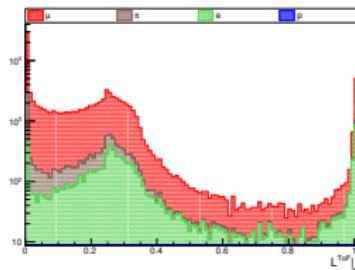
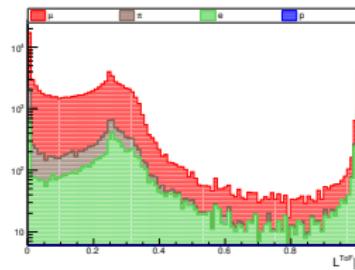
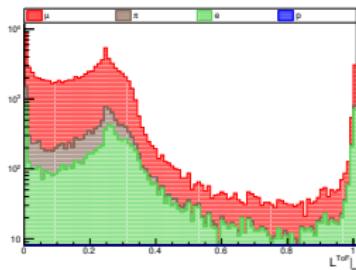
$\sigma_{ToF} = 150$ ps ↑



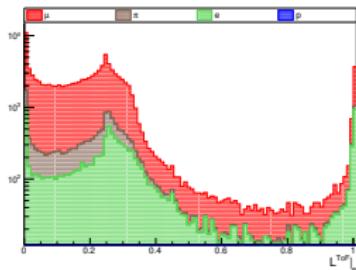
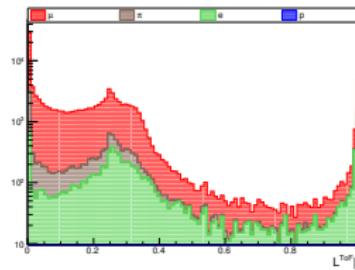
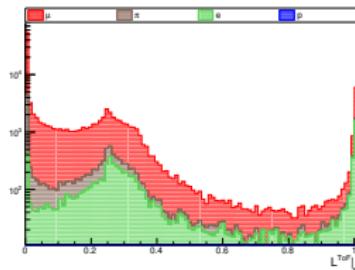
$\sigma_{ToF} = 50$ ps ↑

\mathcal{L}_e^{ToF} for different true PID

reference configuration

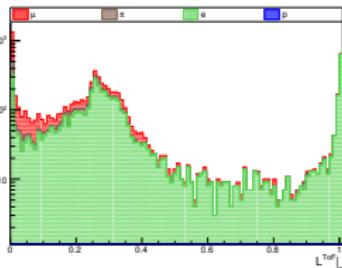
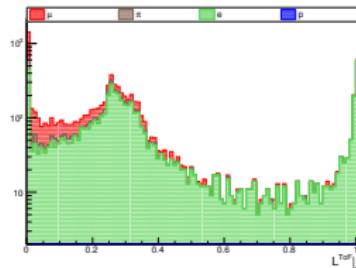
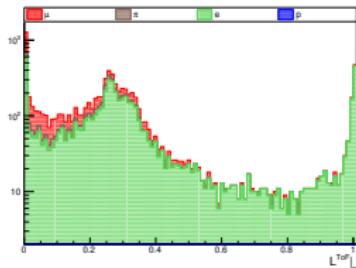


adding new ToF between Target and HTPC

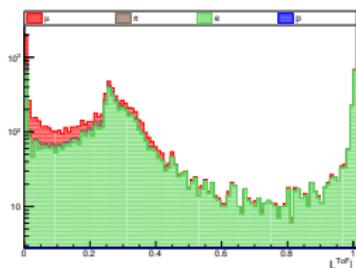
 $\sigma_{ToF} = 600 \text{ ps} \uparrow$  $\sigma_{ToF} = 150 \text{ ps} \uparrow$  $\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_e^{ToF} for different true PID ($50 < p < 200$ MeV/c)

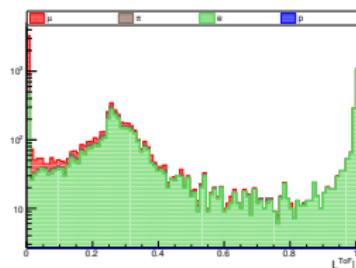
reference configuration



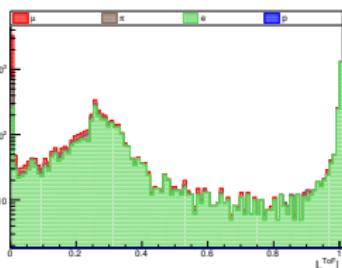
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600$ ps ↑



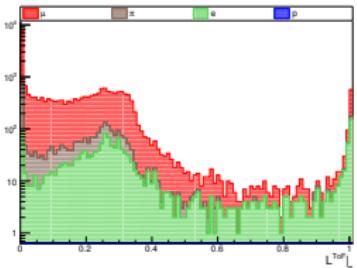
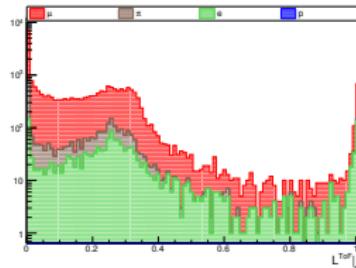
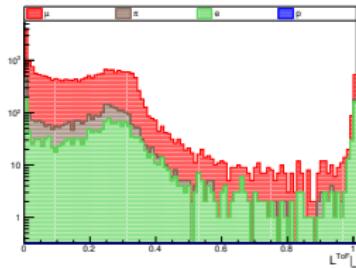
$\sigma_{ToF} = 150$ ps ↑



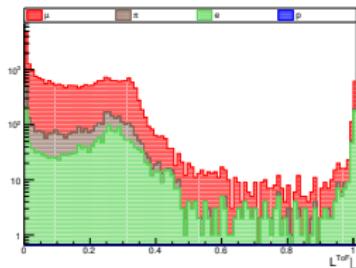
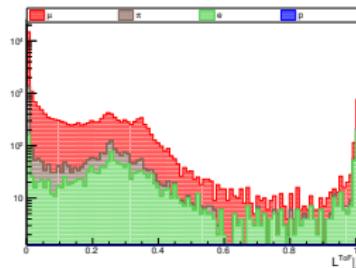
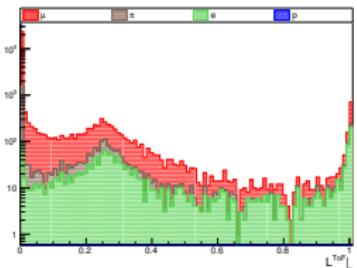
$\sigma_{ToF} = 50$ ps ↑

\mathcal{L}_e^{ToF} for different true PID ($200 < p < 400$ MeV/c)

reference configuration

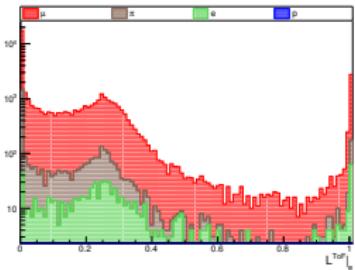
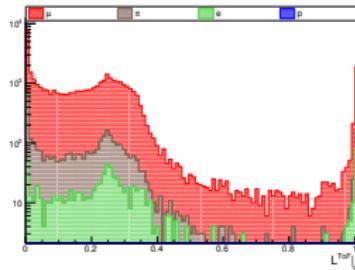
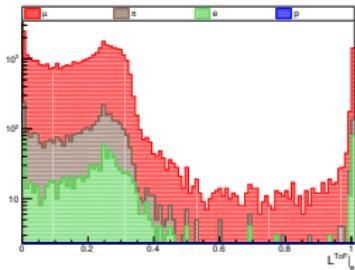


adding new ToF between Target and HTPC

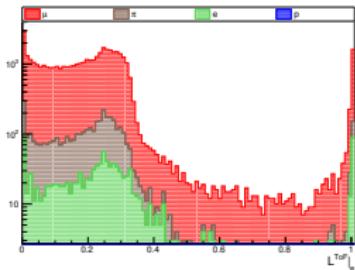

 $\sigma_{\text{ToF}} = 600 \text{ ps} \uparrow$

 $\sigma_{\text{ToF}} = 150 \text{ ps} \uparrow$

 $\sigma_{\text{ToF}} = 50 \text{ ps} \uparrow$

\mathcal{L}_e^{ToF} for different true PID ($400 < p < 1000$ MeV/c)

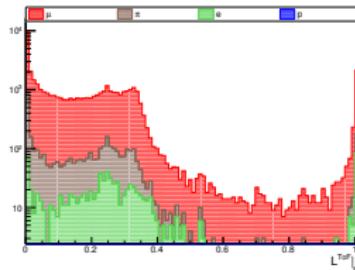
reference configuration



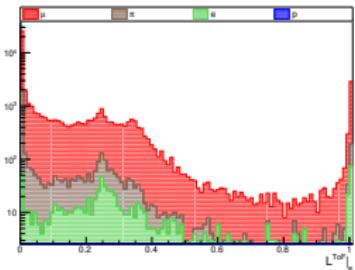
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600$ ps ↑



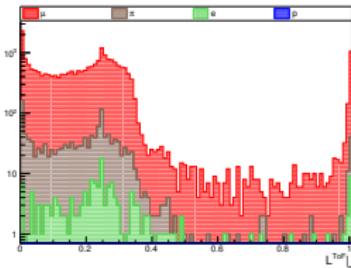
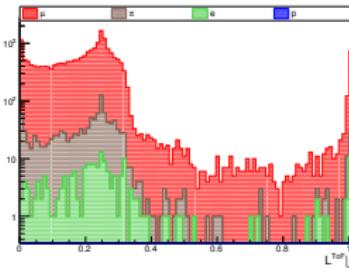
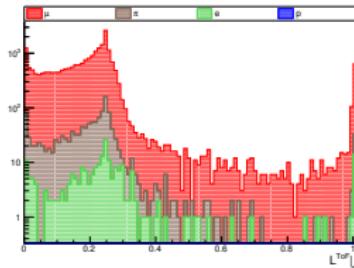
$\sigma_{ToF} = 150$ ps ↑



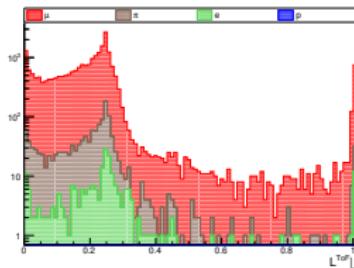
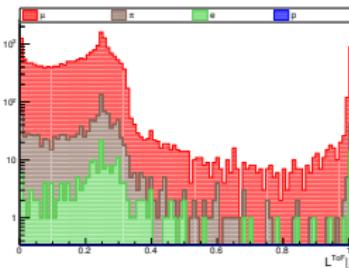
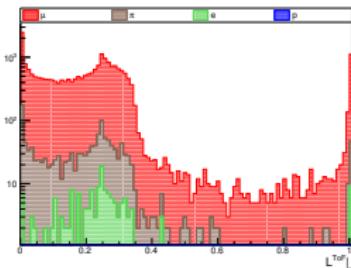
$\sigma_{ToF} = 50$ ps ↑

\mathcal{L}_e^{ToF} for different true PID ($p > 1000$ MeV/c)

reference configuration

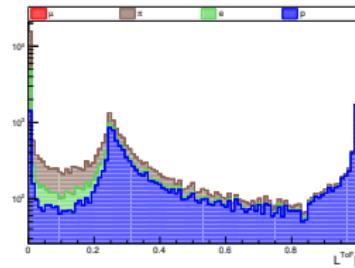
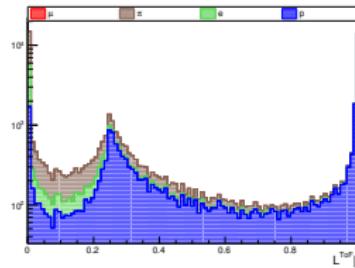
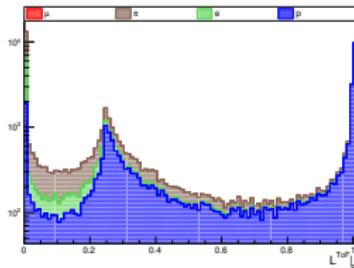


adding new ToF between Target and HTPC

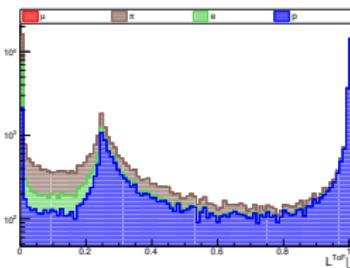
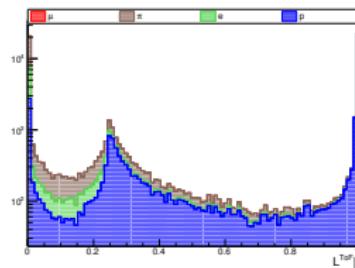
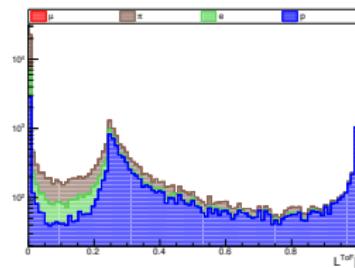

 $\sigma_{ToF} = 600 \text{ ps} \uparrow$

 $\sigma_{ToF} = 150 \text{ ps} \uparrow$

 $\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_p^{ToF} for different true PID

reference configuration

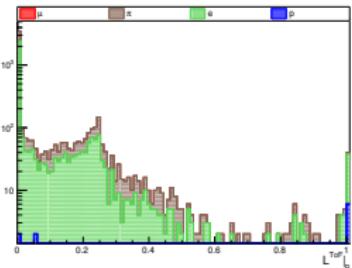
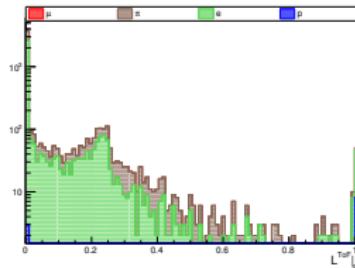
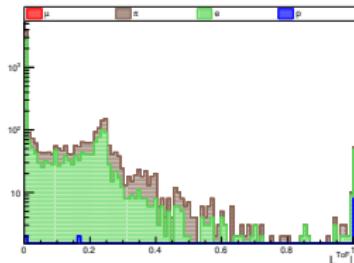


adding new ToF between Target and HTPC

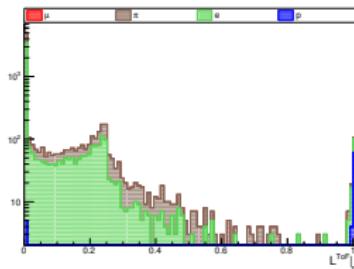
 $\sigma_{ToF} = 600 \text{ ps} \uparrow$  $\sigma_{ToF} = 150 \text{ ps} \uparrow$  $\sigma_{ToF} = 50 \text{ ps} \uparrow$

\mathcal{L}_p^{ToF} for different true PID ($50 < p < 200$ MeV/c)

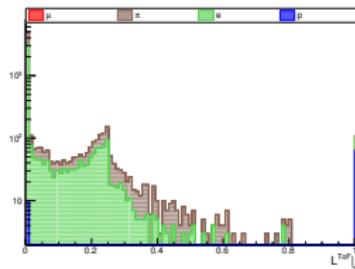
reference configuration



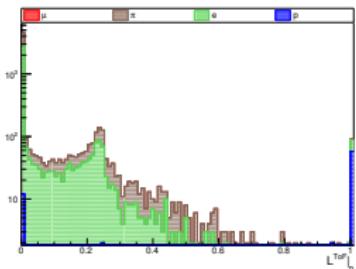
adding new ToF between Target and HTPC



$\sigma_{ToF} = 600$ ps ↑



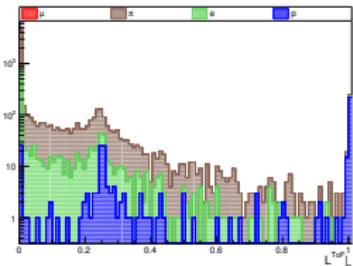
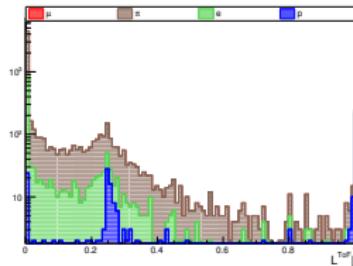
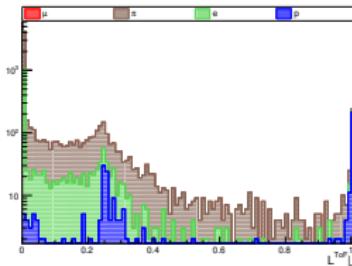
$\sigma_{ToF} = 150$ ps ↑



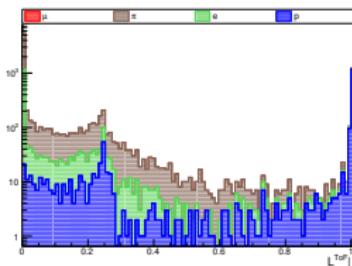
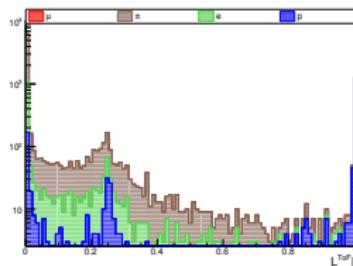
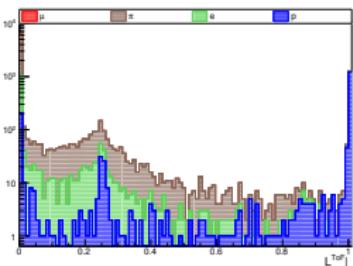
$\sigma_{ToF} = 50$ ps ↑

\mathcal{L}_p^{ToF} for different true PID ($200 < p < 400$ MeV/c)

reference configuration

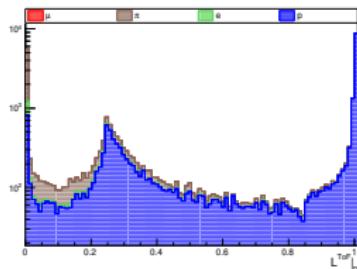
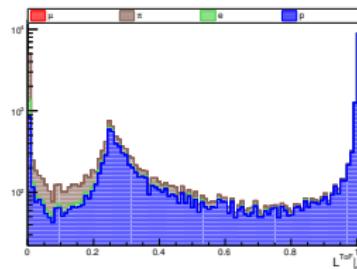
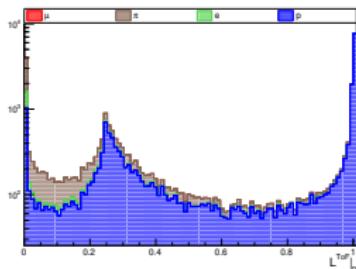


adding new ToF between Target and HTPC

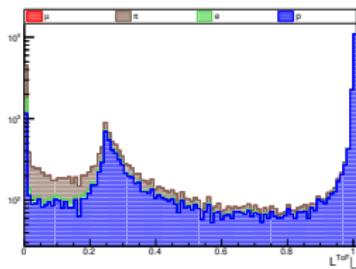

 $\sigma_{ToF} = 600$ ps \uparrow

 $\sigma_{ToF} = 150$ ps \uparrow

 $\sigma_{ToF} = 50$ ps \uparrow

\mathcal{L}_p^{ToF} for different true PID ($400 < p < 1000$ MeV/c)

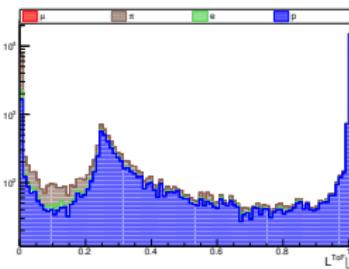
reference configuration



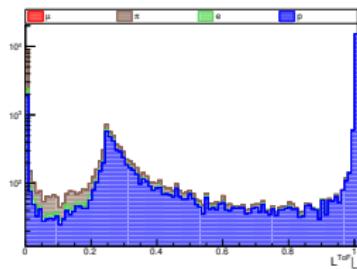
adding new ToF between Target and HTPC



$\sigma_{\text{ToF}} = 600$ ps ↑



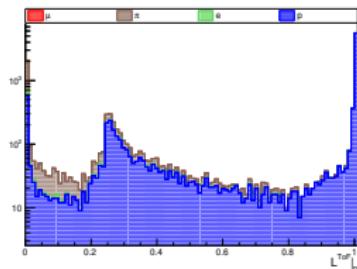
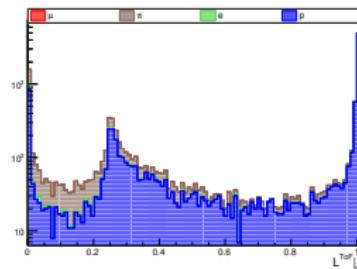
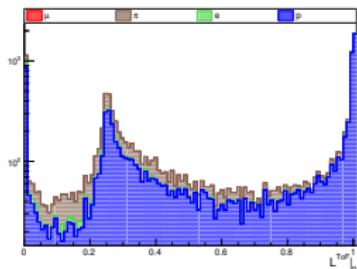
$\sigma_{\text{ToF}} = 150$ ps ↑



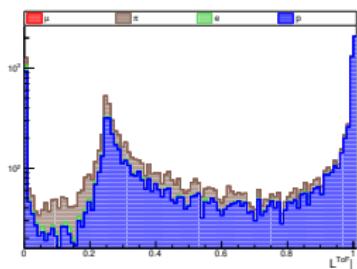
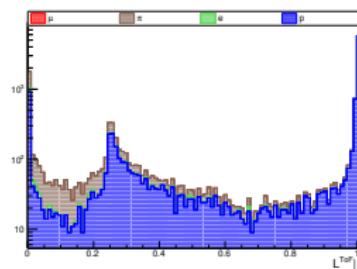
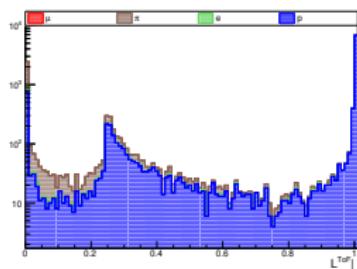
$\sigma_{\text{ToF}} = 50$ ps ↑

\mathcal{L}_p^{ToF} for different true PID ($p > 1000$ MeV/c)

reference configuration



adding new ToF between Target and HTPC

 $\sigma_{ToF} = 600 \text{ ps} \uparrow$  $\sigma_{ToF} = 150 \text{ ps} \uparrow$  $\sigma_{ToF} = 50 \text{ ps} \uparrow$