LHC Neutrinos in Surface Detectors

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In collaboration with

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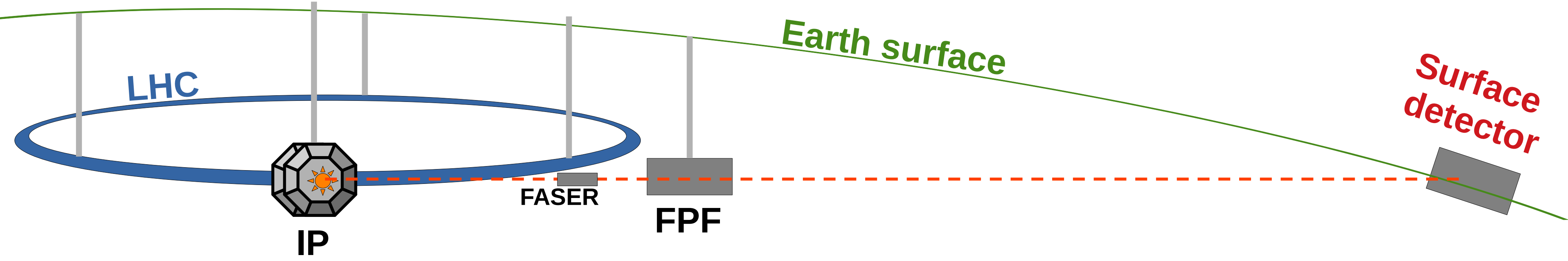
Based on arXiv:2501.06142[hep-ex]

UC Irvine

Introduction

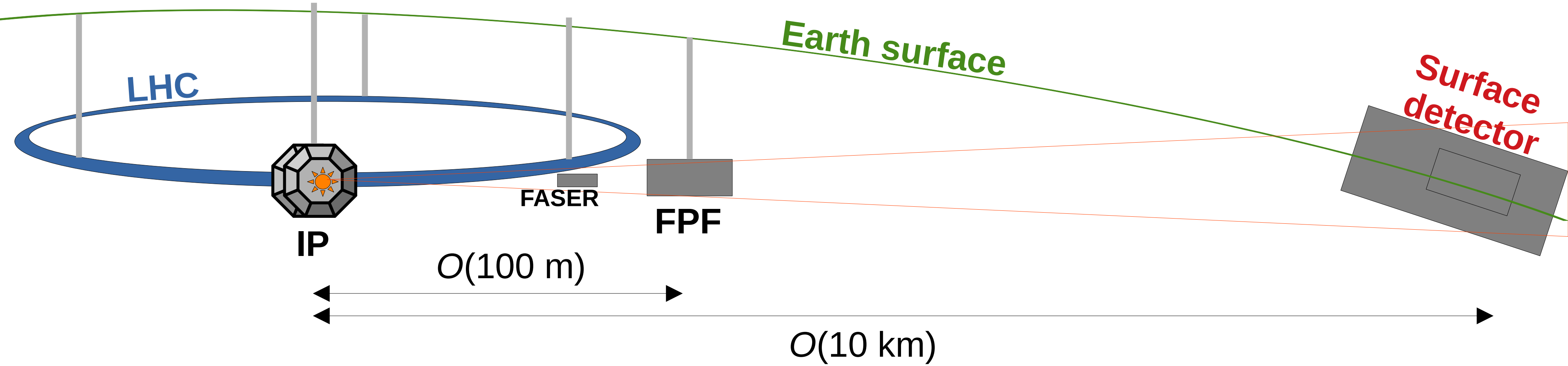
- Forward hadron decays produce neutrinos, observed by FASER & SND@LHC
- Existing & proposed forward neutrino detectors in tunnels O(100 m) from IP
- How about waiting for the neutrinos to emerge from the Earth and place detectors at surface level?



Introduction

However, at long distances...

- Neutrino flux is spread out

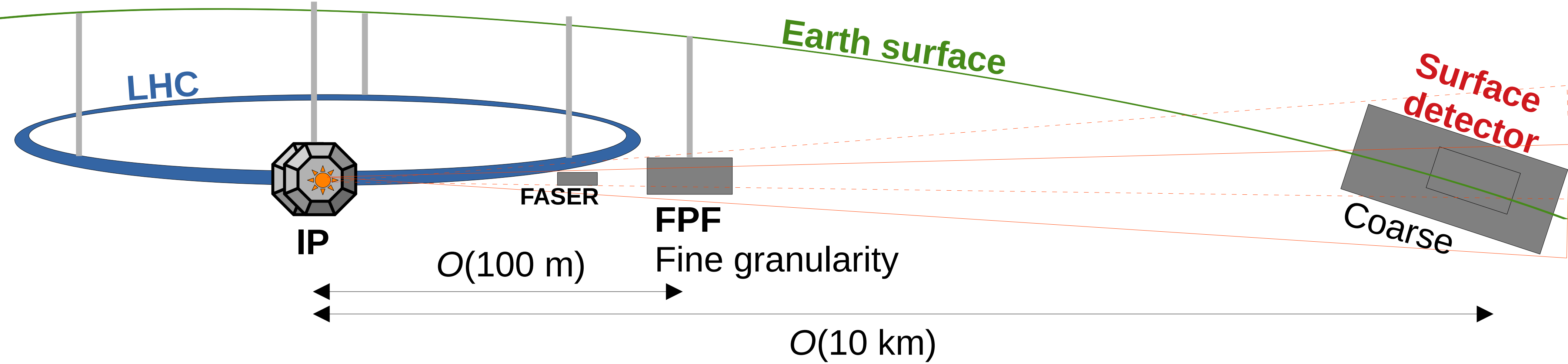


Introduction

However, at long distances...

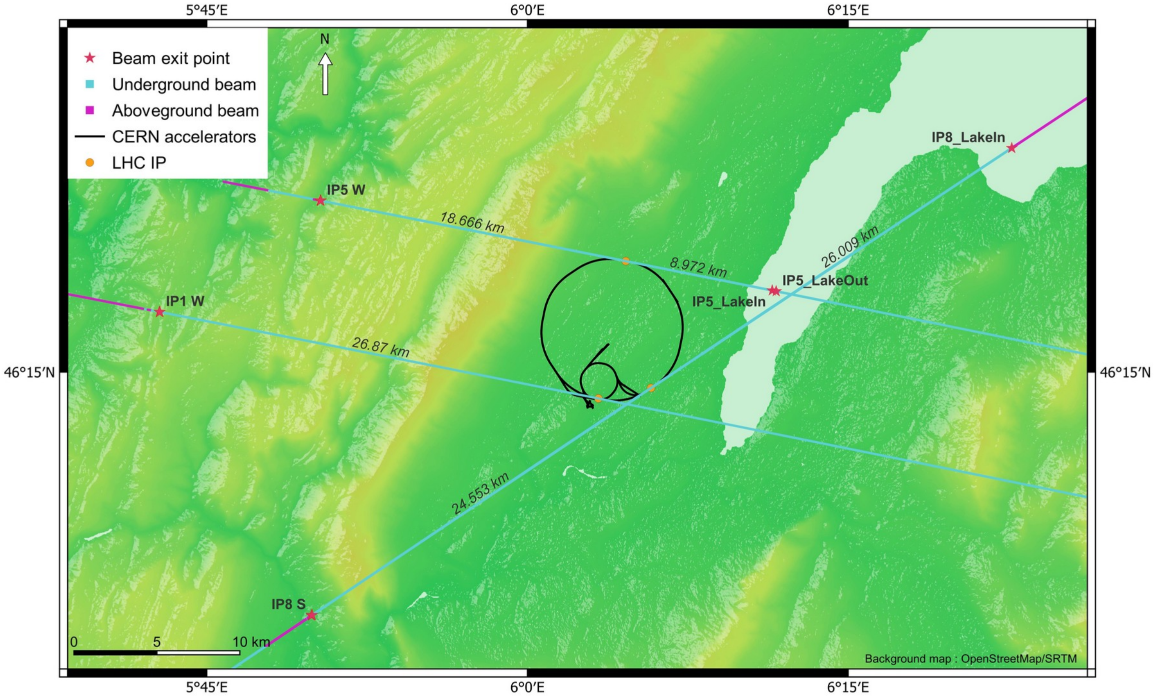
- Neutrino flux is spread out
- IP crossing angle changes play a significant role in beam position

Necessary to consider kton detectors and cost-effective materials and technologies!
▸ **Limited resolution, cannot expect FPF-level results**, but let's see what surface detectors could do



Beam LOS exit points

- The emergence points of the lines of sight from all IPs are identified
- C. Vendeuvre and B. Weyer used the most accurate model of the LHC ring and state-of-the art tools for surface / lake depth determination
- To maximize event rates, a surface detector should be as close to a high-lumi IP as possible



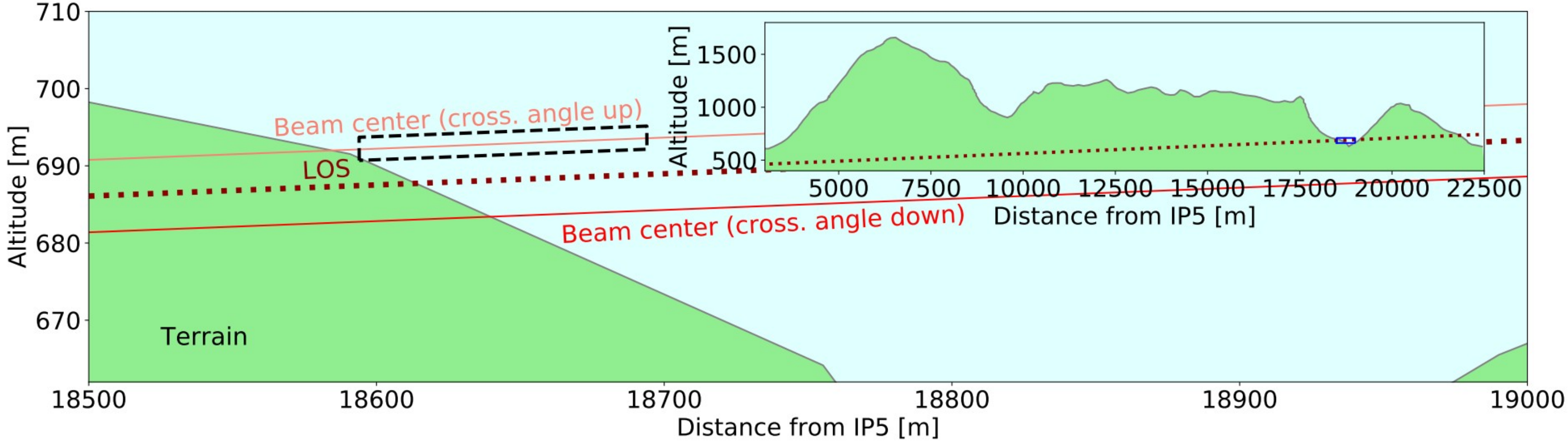
Most promising locations west of IP5, on the Jura, and east of IP5, in lake Geneva

IP/Side	luminosity	distance	relative flux	comment
IP1W (ATLAS)	3000 fb^{-1}	26.9 km	0.1	in Jura mountains
IP1E	3000 fb^{-1}	183 km	0.0025	very far
IP5W (CMS)	3000 fb^{-1}	18.7 km	0.25	in Jura mountains
IP5L	3000 fb^{-1}	9 km **Closest!**	1 **(reference)**	in lake Geneva
IP5E	3000 fb^{-1}	166 km	0.0029	very far
IP8L (LHCb)	300–600 fb^{-1}	26 km	0.0125–0.025	in lake Geneva
IP8S	300–600 fb^{-1}	24.6 km	0.0133–0.0266	in Jura mountains
FASER/SND	3000 fb^{-1}	480 m	351	TI12/TI18
FPF	3000 fb^{-1}	620 m	210	purpose-built cavern

10-20% of IP5/IP1 lumi expected at IP8!

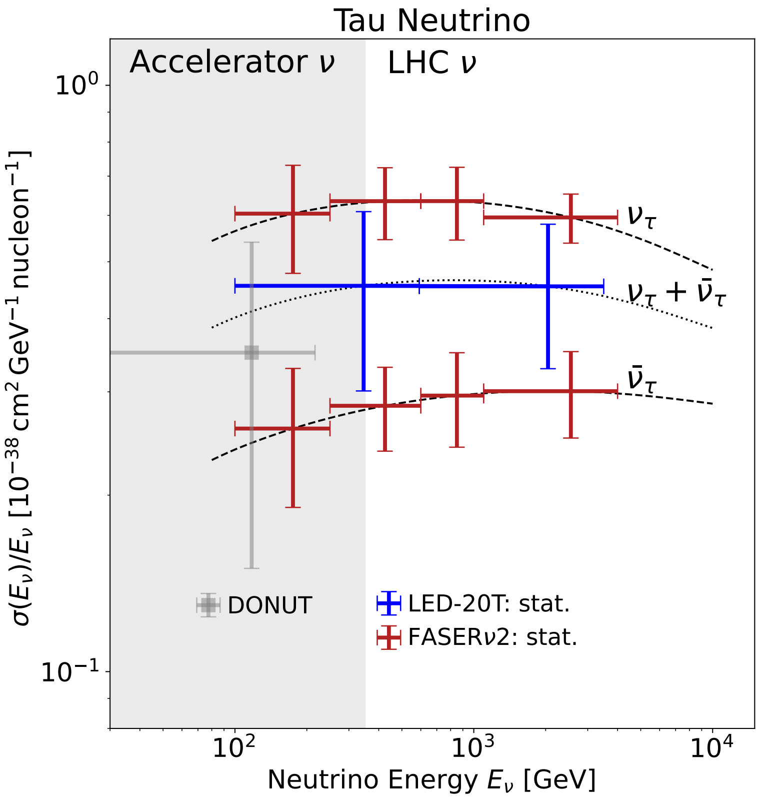
Possible detectors in the Jura mountains
West of IP5

- NuTeV or NovA -like design (690 t - 15 kt target mass)
- IP5 crossing angle configurations move ν beam up/down +/- 4.75 m from LOS
  - If data can be gathered only for one setting, 0.5 x luminosity
- Expected event rates are small and existing detector technologies well-documented, not the focus of this work



Possible detectors in Lake Geneva
East of IP5

- Submerge a small detector in a sealed volume as a lake detector prototype
  - Also a detector idea in it's own right with larger *O*(10 t – 100 t) target mass
- Lake Emulsion Detector (**LED**)
  - E.g. design similar to FASERν(2): layers of emulsion and heavy metal
  - No μ bg from LHC => long exposure
  - No magnet => no charge ID
  - Expect significantly less events than at FPF, but possible to measure e.g. $\sigma(\nu_\tau+\bar{\nu}_\tau)$

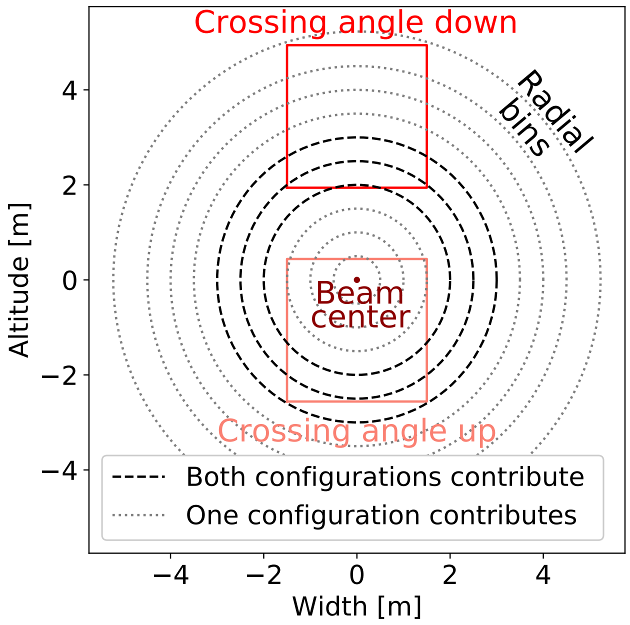


Possible detectors in Lake Geneva
East of IP5

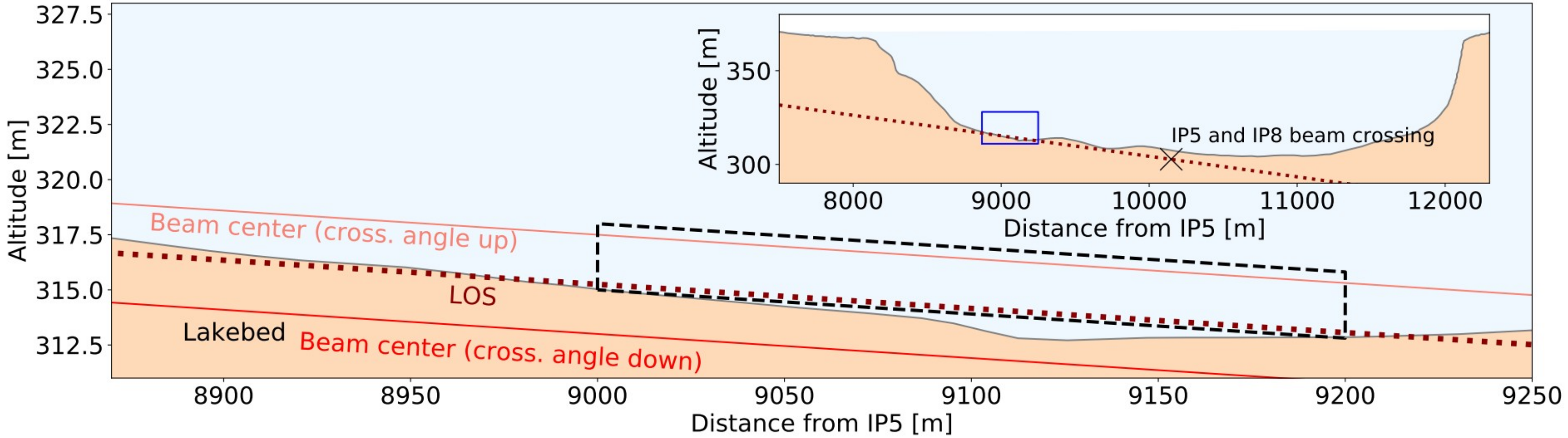
- Forward LHC Observatory Underwater for Neutrinos and the Dark sEctoR (**FLOUNDER**)
  - Water Cherenkov detector resting at the bottom
  - Strawman design
    - Purified water in sealed volume(s)
    - Outlined by photomultiplier tubes (PMT)
    - Only the beam direction needs to be long
      - Consider 9m^2 x 200 m, 1.8 kton detector
      - Veto scintillator at the front
      - Smaller track-to-PMT distance vs astrophysical ν detectors
        - Expect transverse spatial resolution ~10 cm, longitudinal ~1m

Possible detectors in Lake Geneva

East of IP5



- Crossing angle changes shift beam by +/-2.25 m from LOS
- **N.B. lake depth uncertainty ~2m**
  - Chosen position / dimensions allow gathering data with at least one crossing angle configuration in any case
  - In the remainder, focus on FLOUNDER assuming the nominal lake depth



Event rates

- A 20 ton emulsion detector in the lake would yield about 1/3 of FASERν run 3 statistics during the HL-LHC run
  - 0.5 x 3 ab^{-1}, events occur only with one crossing angle configuration

	$\mathcal{L}$	Dist.	Dimensions	Volume	M_{Target}	Rapidity	ν_e		ν_μ		ν_τ	
	ab^{-1}	km	m $\times$ m $\times$ m	m^3	ton		CC	NC	CC	NC	CC	NC
FASERν Run3	0.25	0.48	$0.25 \times 0.25 \times 1.0$	0.063	1.1	> 8.9	1.9k	590	9.2k	2.9k	34	12
FASERν HL	3	0.48	$0.25 \times 0.25 \times 1.0$	0.063	1.1	> 8.9	22k	7.1k	110k	34k	410	140
FASERν2	3	0.62	$0.4 \times 0.4 \times 6.6$	1.1	20	> 8.7	220k	69k	1.1M	340k	4.3k	1.5k
LED-20T	1.5	9.0	$0.4 \times 0.4 \times 6.6$	1.1	20	> 11	680	220	4.0k	1.2k	11	3.7
LED-200T	1.5	9.0	$1.2 \times 1.2 \times 7.3$	11	200	> 10.3	7.6k	2.4k	39k	12k	110	37
IP5W (NuTeV)	3	19	$3 \times 3 \times 10$	90	690	> 9.4	12k	3.8k	60k	19k	170	58
IP5W (NOvA)	3	19	$15 \times 15 \times 60$	13500	15000	> 8.5	130k	44k	650k	210k	2.9k	1.0k
FLOUNDER	3	9.0	$3 \times 3 \times 200$	1800	1800	> 8.2	78k	25k	380k	120k	1.6k	590
Cross.angle $\uparrow$	1.5					> 8.9	49k	16k	250k	81k	890	320
Cross.angle $\downarrow$	1.5					$8.2 - 9.1$	29k	9.4k	130k	43k	760	270

Event rates

- Reaching event rates approaching (but below) those expected at FPF requires
  - kton detectors in the lake (FLOUNDER)
  - >10 kton detectors at the Jura location (assuming relocatable detector)

	$\mathcal{L}$	Dist.	Dimensions	Volume	M_{Target}	Rapidity	ν_e		ν_μ		ν_τ	
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Cross.angle ↓	1.5					8.2 – 9.1	29k	9.4k	130k	43k	760	270

<Large volume + cost effective technologies> = coarser resolution, can't extrapolate physics potential from (even large) event rates alone

Estimated uncertainties and physics potential

- Water detector properties at TeV energies unknown, motivates further simulations
- Assume conservative uncertainty estimates based on existing H_2O detectors

Challenging to distinguish lepton track / shower from the **DIS** hadronic shower at TeV energies in water. **Signatures at LHC different to Cherenkov detectors at other energies!**

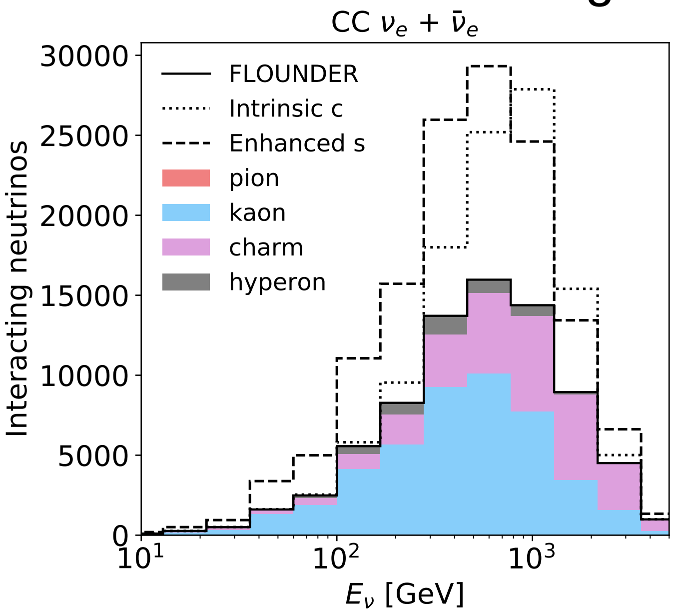
Expect higher granularity at FLOUNDER than e.g. Super-K, KM3NeT

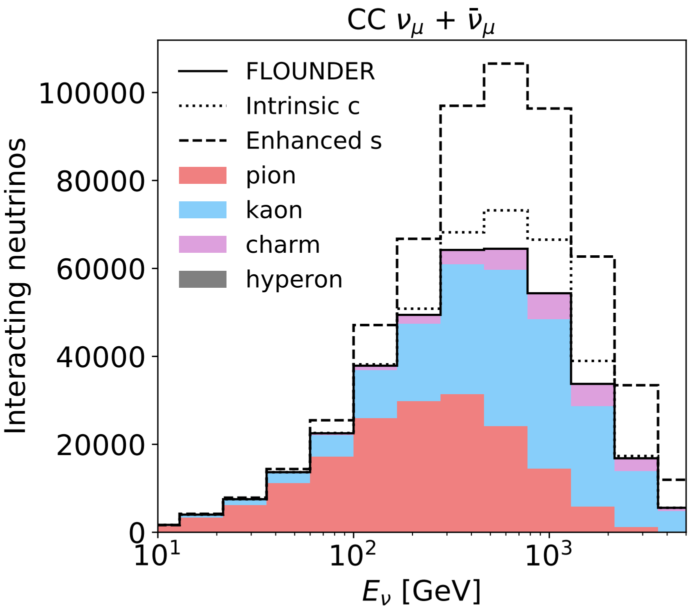
	underground detector		surface detector	
	FASERν	FLARE	LED	FLOUNDER
Technology	emulsion	LAr TPC	emulsion	water Cherenkov
Electron identification	✓	✓	✓	?
Muon identification	✓	✓	✓	✓
Tau identification	✓	?	✓	$\times$
Charm identification	✓	?, 2μ	✓	2μ
Charge identification	μ (τ)	μ (τ)	$\times$	$\times$
Muon momentum resolution	$<$20%	$<$5%	$<$20%	30%
Muon angle resolution	0.06 mrad	$\lesssim$ mrad	0.06 mrad	5 mrad
$E_{\rm had}$ resolution	30%	30%	30%	$\gtrsim$30%
ν_e energy resolution	30%	20%	30%	$\gtrsim$30%
Transverse position resolution	$\sim\mu$m	$\sim$ mm	$\sim\mu$m	$\sim$ 10 cm
Longitudinal position resolution	$<$ mm	$\sim$ mm	$<$ mm	$\sim$ 1 m
Flux (relative to FASERν)	1	0.6	0.002	0.002
Target mass (tons)	1	10	200	7500
Event rate per luminosity (relative to FASERν)	1	12	0.8	15

Flux composition and forward hadron production

Neutrino energy bins

- FLOUNDER statistics for e and μ neutrino interactions could provide information on forward hadron production and constrain models involving e.g. intrinsic charm or enhanced strangeness





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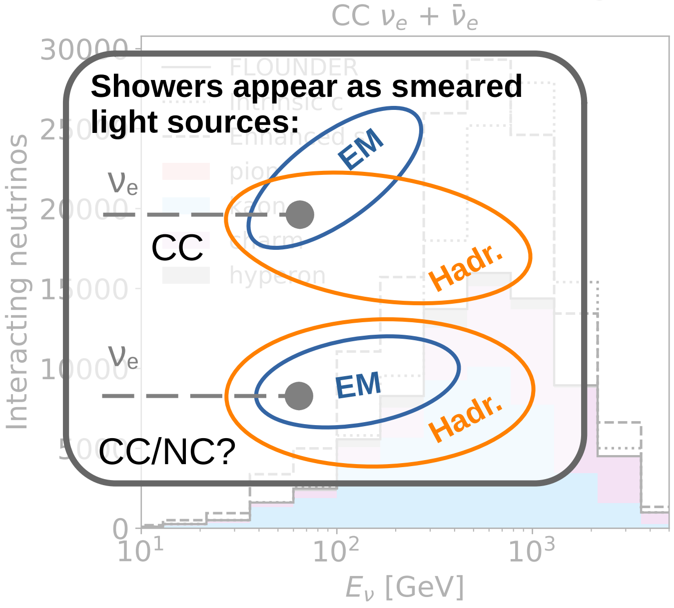
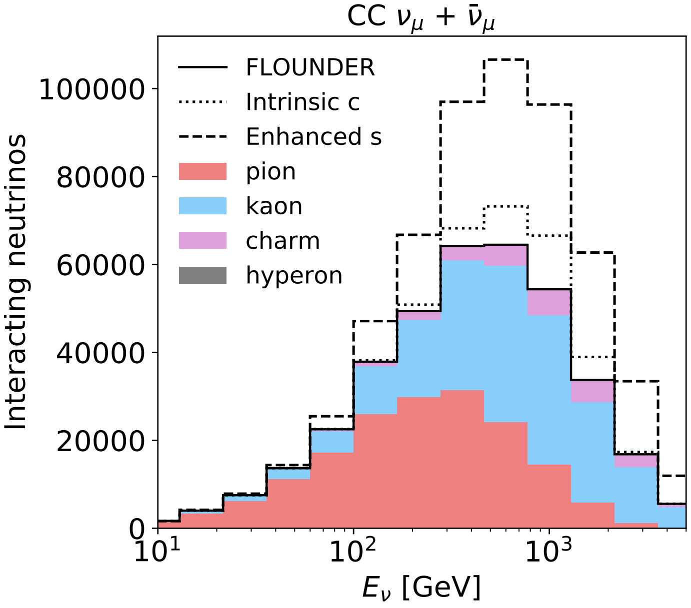
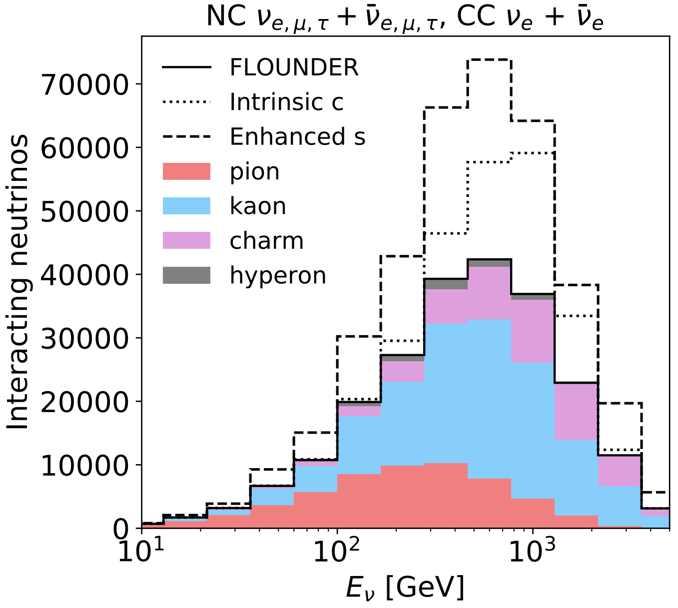




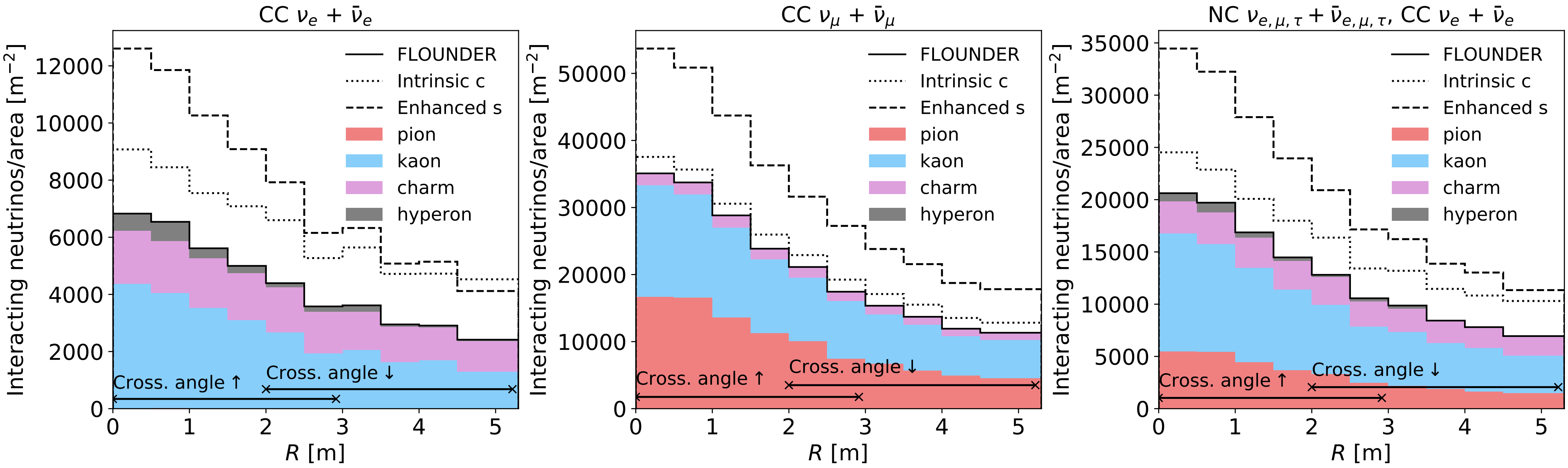


- N.B. at LHC energies, NC involving any neutrino flavor may be indistinguishable from ν_eCC, if electron not distinct from hadron shower

Flux composition and forward hadron production

Radial bins

- IP5 crossing angle effect small enough for FLOUNDER to collect data with both configurations, extending the total radial reach to η>8.2

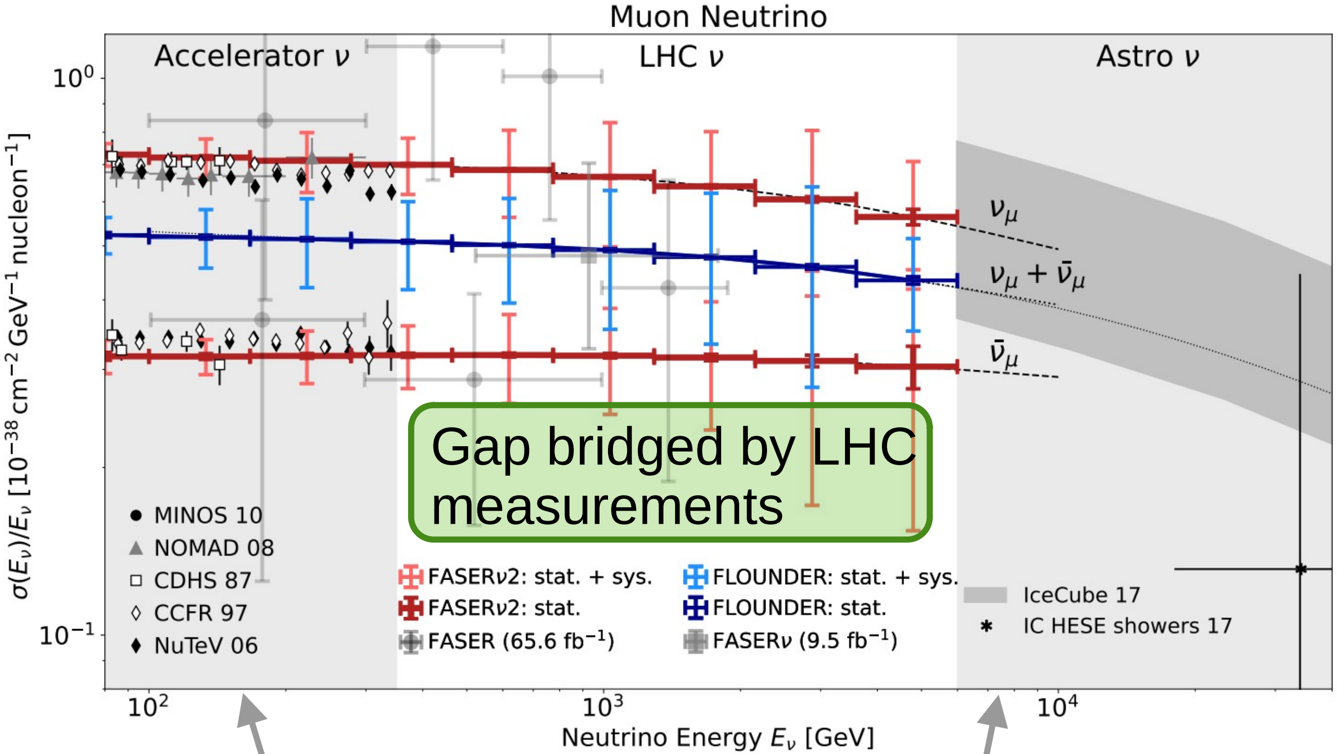


Neutrino interaction cross sections

- FLOUNDER could constrain $\nu_\mu+\bar{\nu}_\mu$ cross section

- Large statistics, measurement limited by systematics
  - flux uncertainty dominates

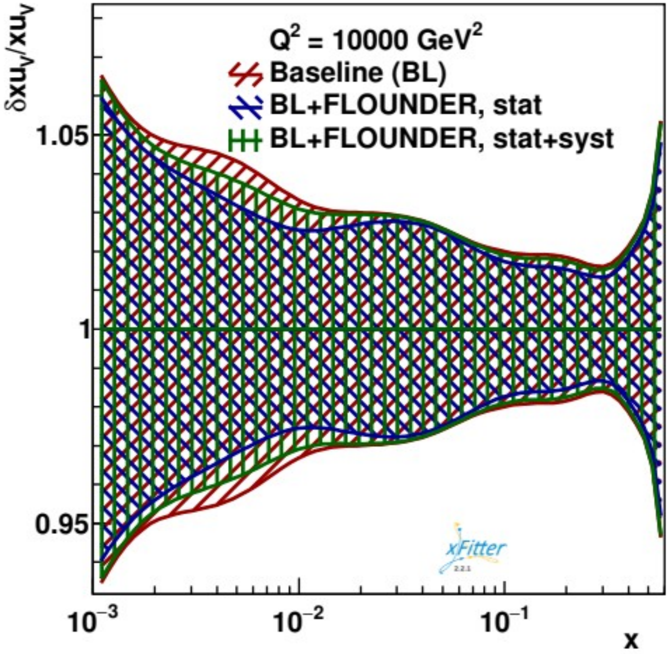
- Not measuring the same observable as FASER(2)!
  - FLOUNDER $\sigma(\nu_\mu+\bar{\nu}_\mu)$
  - FASER(2) $\sigma(\nu_\mu)$ & $\sigma(\bar{\nu}_\mu)$

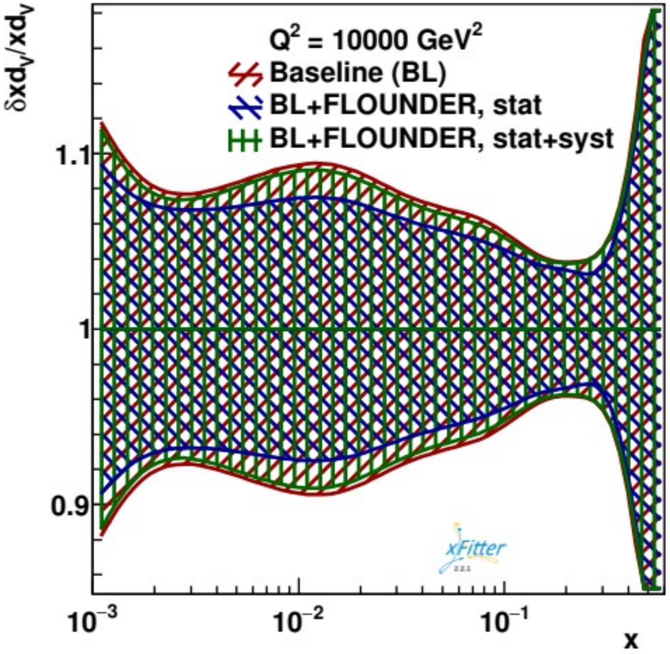


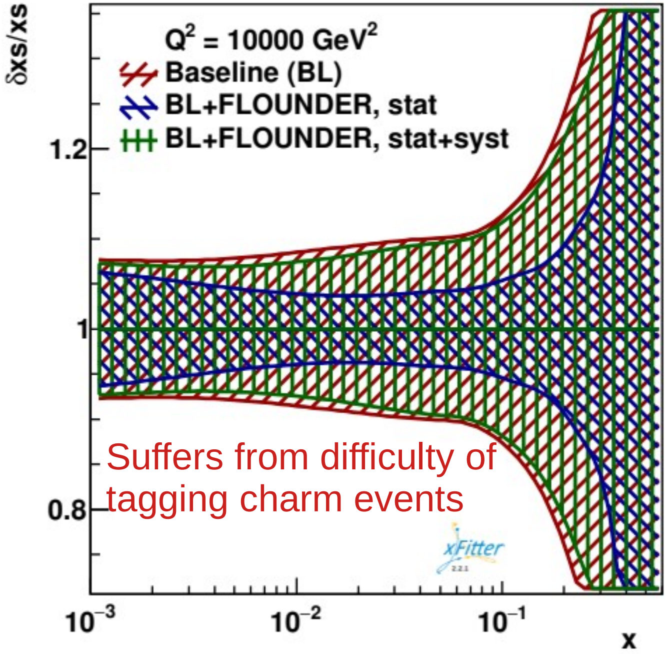
Previous measurements:
Low-E accelerators or high-E astrophysical data

Constraining PDFs

- Optimistic case accounting only for stat. unc. (blue) yields some improvement to the baseline (red, PDF4LHC21 here). Effects of including also syst. unc. (green) must be reduced if PDF studies are to be carried out at FLOUNDER





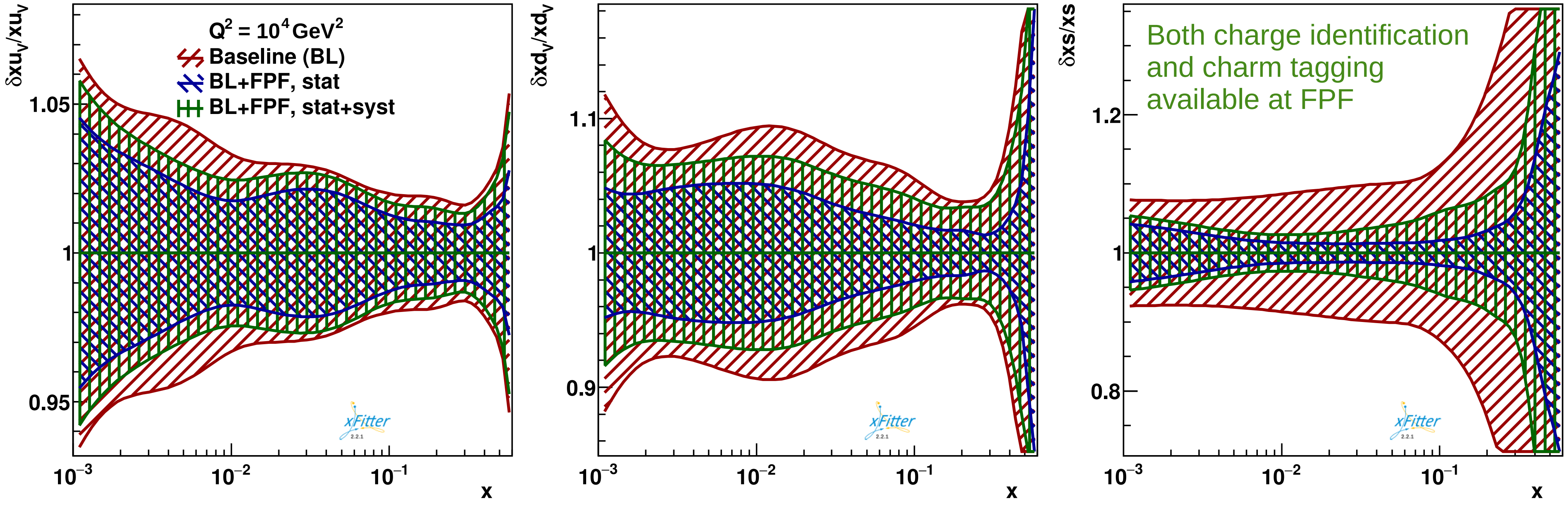


Optimistic result for illustration purposes only. Assumes free isoscalar nucleon target approximation, which doesn’t hold for water, but similar trend expected for full nuclear PDF studies.

Constraining PDFs

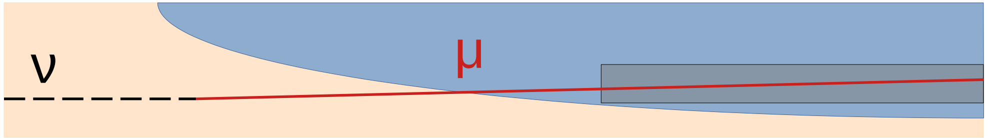
Reminder of FPF WG1 results

- PDF constraints achievable at FPF for comparison (FASERν2 + FLARE)
  DOI: 10.1140/epjc/s10052-024-12665-1

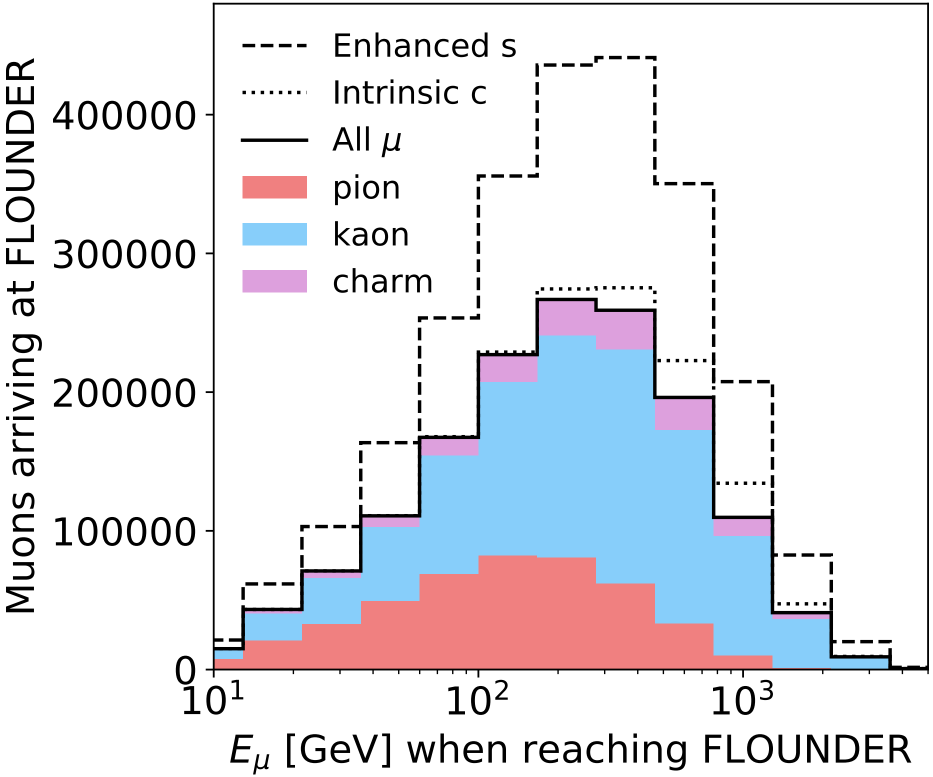


PDFs are not a strong physics case for FLOUNDER

Muons from neutrino interactions in the rock

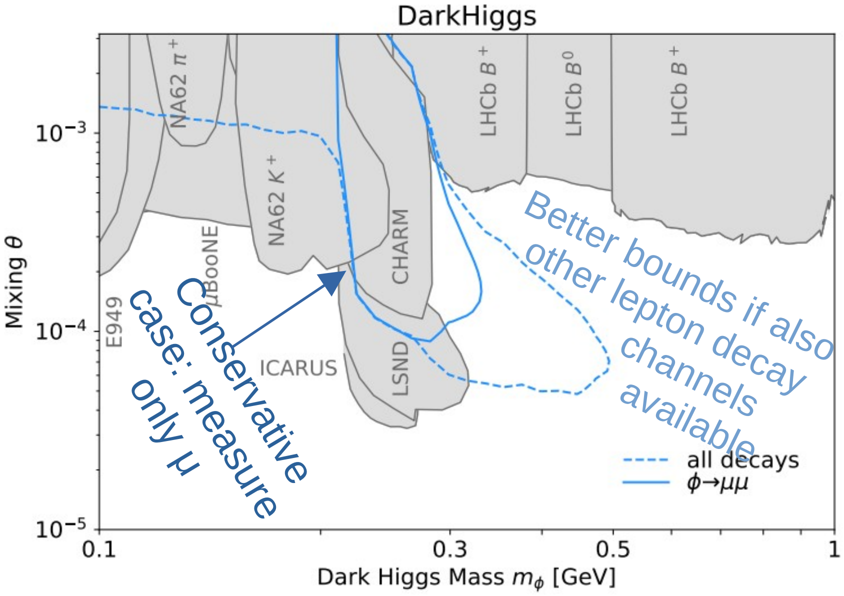


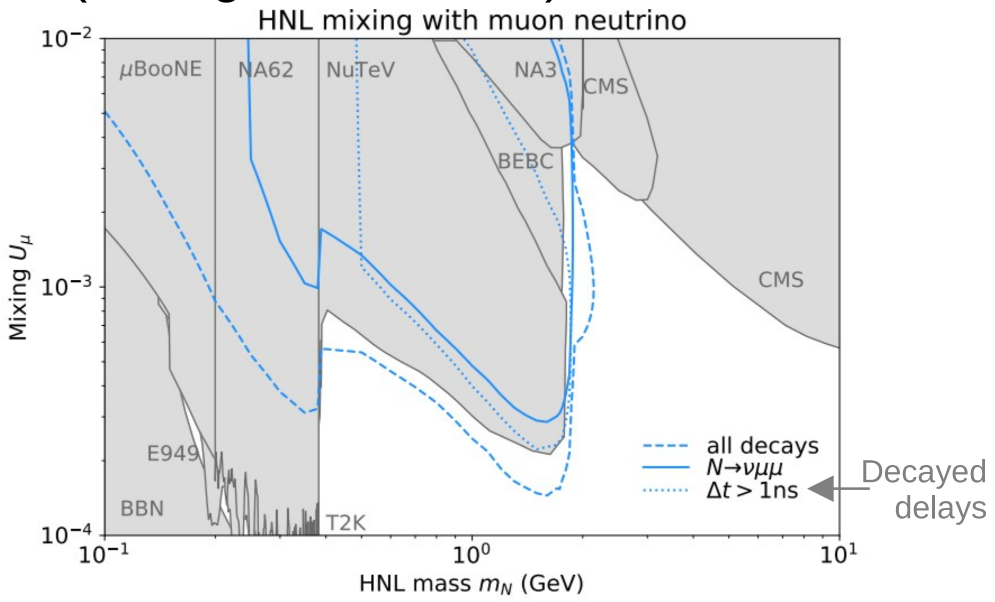
- No bg from muons produced at the LHC, but νCC interactions in ~2km of rock before the lake can produce muons entering FLOUNDER
- Significant bg for BSM studies: not possible to probe models with DM decaying outside of FLOUNDER
- Potentially additional handle for constraining the forward hadron flux
  - ν from K decays typically more energetic, muons produced in their interactions travel further



The dark sector

- FLOUNDER could search for long-lived particles decaying to muons
  - Investigated several models typically considered at forward LHC experiments, presenting most promising ones
- Small increase in sensitivity to a dark Higgs (scalar, mixes w/ Higgs, couplings to SM particles) or heavy neutral leptons (mixing w/ neutrinos)

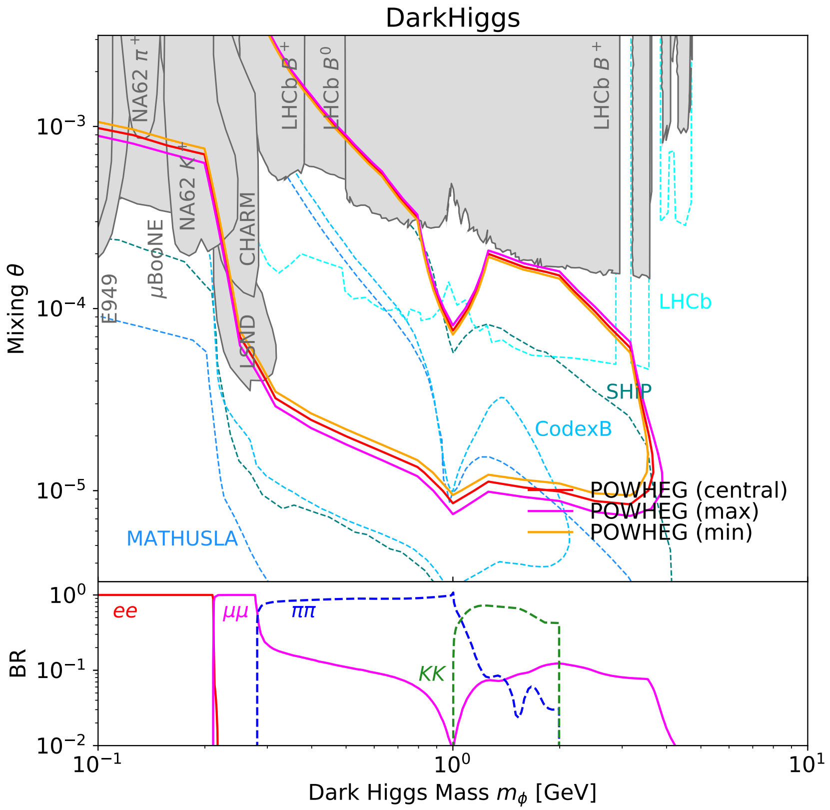


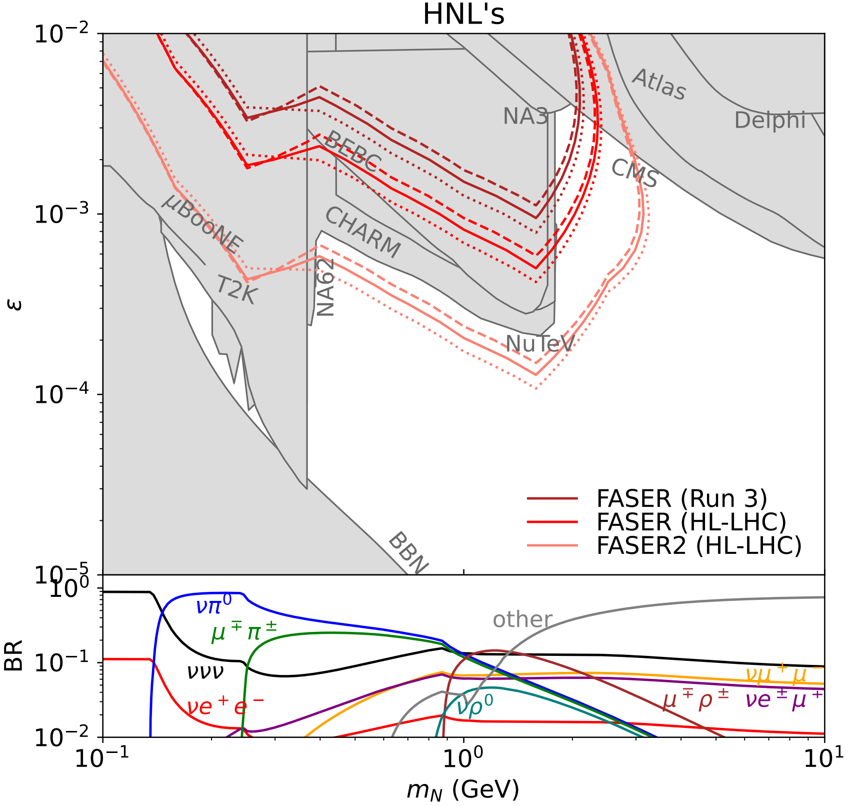


The dark sector
FASER(2) comparison

FLOUNDER will not compete with FPF dark sector program

- FASER(2) bounds for comparison, with FORESEE





Comparing FLOUNDER to UNDINE

2501.08278[hep-ex]

- N. Kamp et al. published shortly after us, introducing UNDINE in lake Geneva (water Cherenkov, IP8 beam) and SINE in the Jura mountains (IP5 beam)
  - No discussion on IP crossing angle effect: can reduce statistics by 50%
- SINE: ν_μ from CMS interact in the rock. Observe produced μ only. Lake detectors can also do this

(Slide 19)

- UNDINE: LHCb ν beam, ~30 km from IP8, Luminosity 380/fb (FLOUNDER 9km from IP5, 3/ab)
  - **Larger detector**: +12 m detector radius, 30 kton (FLOUNDER 3x3 m^2, 1.8 kton)
    - **Smaller rapidity range** than FLOUNDER and FLARE
    - Larger track-to-PMT distance than FLOUNDER
      - Both coarse, expect similar performance limitations
  - Similar to FLOUNDER results, CC event rates only approx. **48k $\nu_e+\bar{\nu}_e$, 190k $\nu_\mu+\bar{\nu}_\mu$, 1.2k $\nu_\tau+\bar{\nu}_\tau$**
    - Order of magnitude below FASERν2, and FPF will have many experiments

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- UNDINE: LHCb ν beam, ~30 km from IP8, Luminosity 380/fb (FLOUNDER 9km from IP5, 3/ab)
  - **Larger detector: 12m detector radius, 30 kton (FLOUNDER 1x3 m², 1.8 kton)**
    - **Smaller rapidity range than FLOUNDER and FLARE**
    - Larger track-to-PMT distance than FLOUNDER
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    - Order of magnitude below FASERν2, and FPF will have many experiments

Surface detectors offer interesting challenges, but cannot replace the LHC "near detectors"

Differences to 2501.08278[hep-ex]

Conclusion clear although assuming different properties at water Cherenkov detectors

- Particle identification capabilities in a hitherto unstudied energy range
  - Identify e and μ events, measure $\nu_e+\bar{\nu}_e$ and $\nu_\mu+\bar{\nu}_\mu$ cross sections
  - Charm tagging (necessary to improve s PDF)

Not necessarily possible in water *at LHC energies*, no simulation exists

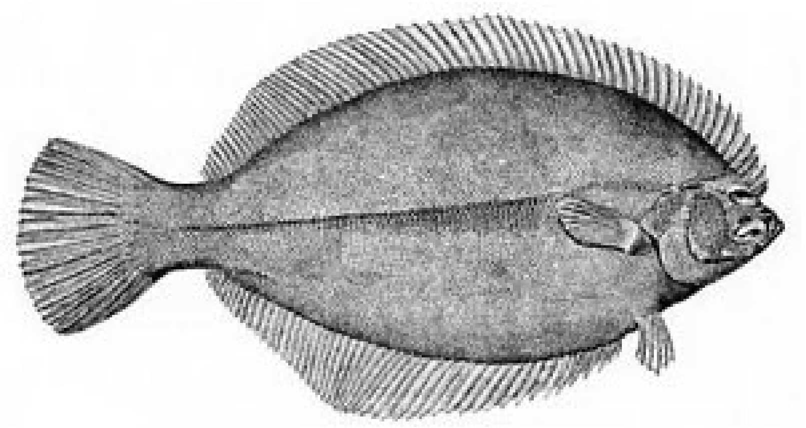
- Possibilities to constrain DM / HNLs mentioned, bg considerations left for future work
  - We found e.g. muons from interactions in the rock before the lake & NC important bg.
  - DM must decay within detector volume, also limiting possible models at FLOUNDER
  - **We investigated a variety of models, considered the backgrounds, and did not find one where FLOUNDER would outperform the FPF**
- Flux uncertainties obtained in 2501.98278 from the Cramer-Rao bound
  - Framework developed for assessing *model difference contributions* to flux uncertainty
  - For estimating *most stringent bounds*, not for cross section measurements

Summary

- Flux dilution requires kton targets + affordable tech => coarse resolution
  - IP crossing angle changes have drastic consequences at *O*(10 km)
  - Such challenges cannot be overcome when detectors are far and large
- A lake detector may perform SM measurements e.g. $\nu_\mu+\bar{\nu}_\mu$ cross sections and constrain forward hadron production, although not at FPF precision
  - No neutrino/antineutrino ID
  - Likely no electron neutrino ID
  - No charm tagging, significantly reduces applicability to PDF studies
  - Only limited reach for DM models considered at LHC forward experiments
  - No physics case found where FASER/FPF would be outperformed
- Further investigation of (LHC) water detectors requires more simulation work (new E regime) + accurate lake depth characterization (possible time variations)

Thanks for your attention!

Back-up



Earth surface and lake depth determination

- The collision axis LOS is used for estimating the ν beam exit points. Account for LHC position, tilt, etc
- Account for terrain variations using digital terrain models:
  - France: RGEALTI
    - 5 m resolution
  - Switzerland: SwissALTI3D, and swissBATHY3D for lake Geneva depth
    - 2 m resolution for both
  - Italy: Tinitaly
    - 10 m resolution
  - Global accuracy 3.5 m in Italy, better than 1 m in Switzerland and France
  - Larger uncertainty in mountainous areas