Physics opportunities with BDF/SHiP at the SPS ECN3 beam facility

R. Jacobsson

on behalf of the SHiP Collaboration of 38 institutes from 15 countries and CERN

BDF/SHIP references to reports/publications

- *17 submitted to SPSC and ESPPSU2020*
- *26 on the facility development*
- *37 on the detector development*
- *11 on physics studies*
- *20 on theory developments dedicated to SHiP*
- *20 PhD thesis, a few more in pipeline*

Future physics prospects

SM describes both what we observe and what we do **not** observe directly

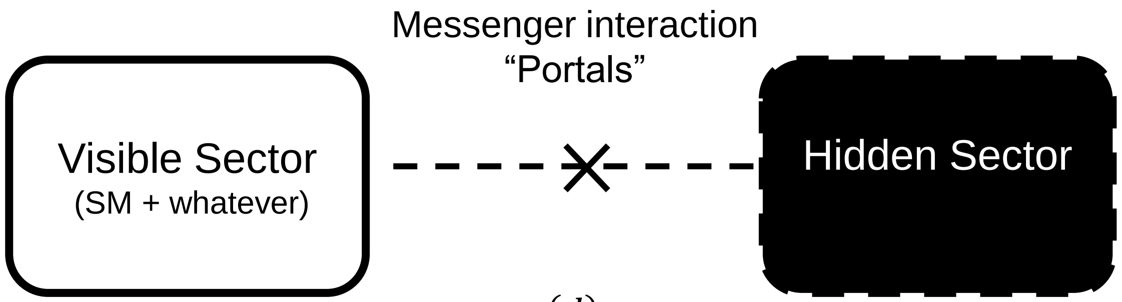
$$\mathcal{L} = (\mathcal{L}_{gauge} + \mathcal{L}_{Higgs})_{dim\leq 4} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda_{NP}^{d-4}} \mathcal{O}^{(d)}$$

With sizeable couplings
$\Lambda_{NP}^{d-4} \gg$ EW scale

- No definitive unambiguous guidance from experiments or theory!
- *New opportunities offered by the equivalence of mass scale and coupling scale!*
  - ➔ Possible guidance from cosmology and astrophysics!
- Exploration of Feebly Interacting Particles up to now mainly as by-product of experiments built for other purposes – post-analyses, data mining, often limited to exclusion capability
- Enough reasons to build a dedicated accelerator-based facility to explore FIPs, optimized for discovery
  - We are sharing the Universe already with feebly coupled and not-understood neighbours!
  - Light feebly coupled sector can provide solutions to well-established problems!
  - Essential complementarity with projects in launch/commissioning on the cosmofrontier
  - One of the main objectives of HL-LHC will be exploring FIPs…

Feebly interacting particles

Hidden Sector may have their own (hidden/dark) charges and interactions



$$\mathcal{L} = \mathcal{L}(\psi_{SM}, A_{SM}, H_{SM})_{dim\leq 4} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda_{NP}^{d-4}} \mathcal{O}^{(d)} + \mathcal{L}(\psi_{HS}, A_{HS}, H_{HS}) + \mathcal{L}_{portal}$$

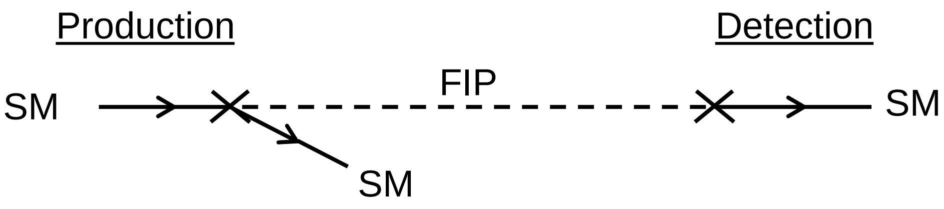
Lowest dimension makes up “portals” between visible and Hidden Sector

Portals may “drive” dynamics observed in the Visible Sector!

- Dark Matter (trivial)
- Neutrino mass and oscillations
- Matter-Antimatter asymmetry
- Higgs mass
- Structure formation
- Inflation and Dark Energy
- ….

➔ Plethora of alternative SM extensions!

Detect directly FIPs at accelerators



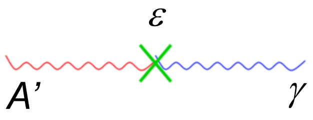
New Physics prospects in Hidden Sector

Composite operators as "portals":

D = 2: Vector portal

- Kinetic mixing with massive dark/secluded/paraphoton A' : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$

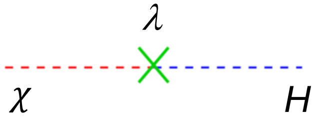
➔ Motivated in part by idea of "mirror world" restoring L/R symmetry, dark matter, g-2 anomaly, …



D = 2: Scalar portal

- Mass mixing with dark singlet scalar χ : $(g\chi + \lambda\chi^2)H^\dagger H$

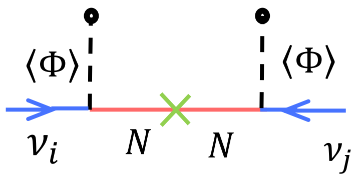
➔ Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter,…



D = 5/2: Neutrino portal

- Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell} H^\dagger \bar{N}_I L_\ell$

➔ Neutrino oscillation and mass, baryon asymmetry, dark matter

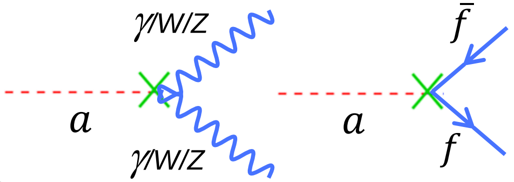


D = 4: Axion portal

- Mixing with Axion Like Particles, pseudo-scalars pNGB : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

➔ Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F

➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…



Also light SUSY (Neutralino, sgoldstino, axino, saxion, hidden photinos…)

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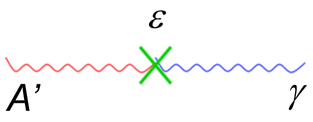

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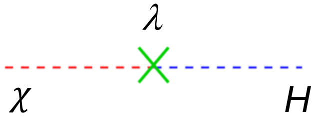

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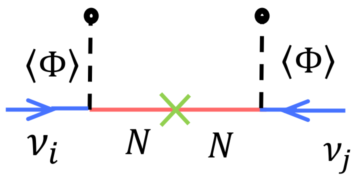

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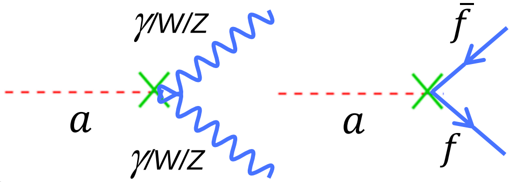


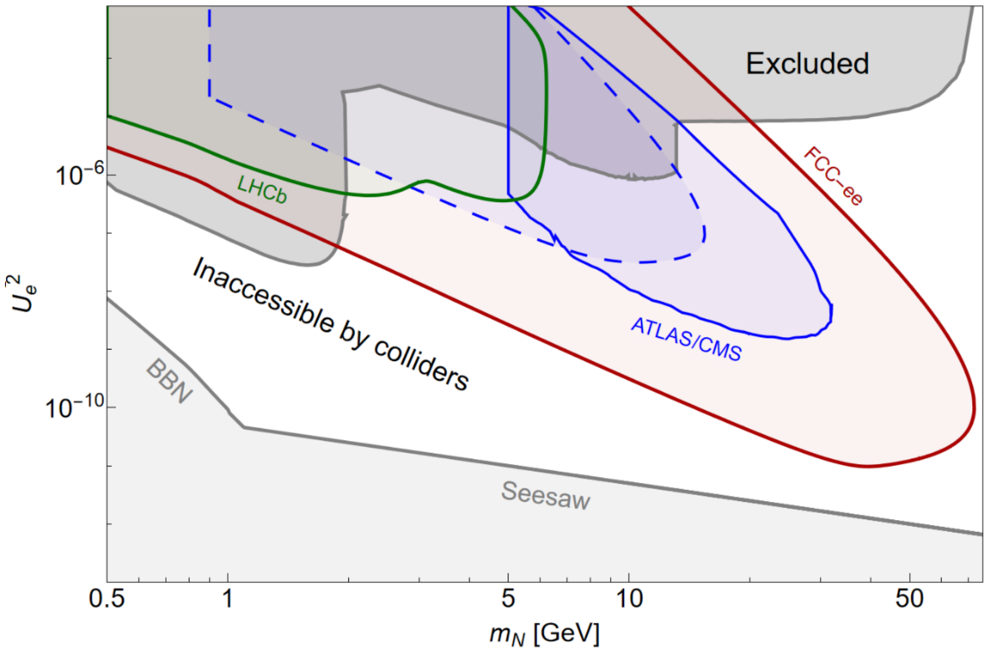
- **Also light S**

Bottom line: We need large production of $\gamma, q/g, c, b, W, Z, H$!

SHiP vision

- Initiative to identify
  - Full exploitation of unique physics potential of SPS available since CNGS (*Rep. Prog. Phys.* **79** (2016)124201)
  - Rich and relevant physics programme with the injectors at CERN going beyond LHC, bridging gap to next collider
  - ➔ SPS suitability for a beam dump facility to explore FIPs – open new programme at CERN

E.g. Heavy Neutral Leptons



➔ Region that can *only* be explored by optimized beam-dump experiment

- ➔ Optimise for maximum production of charm, beauty and electromagnetic processes, and acceptance
- ➔ SPS energy and intensity provide unique *direct discovery potential in the world*
- ➔ Capable of reaching "physical floor" or "technical/background floor"

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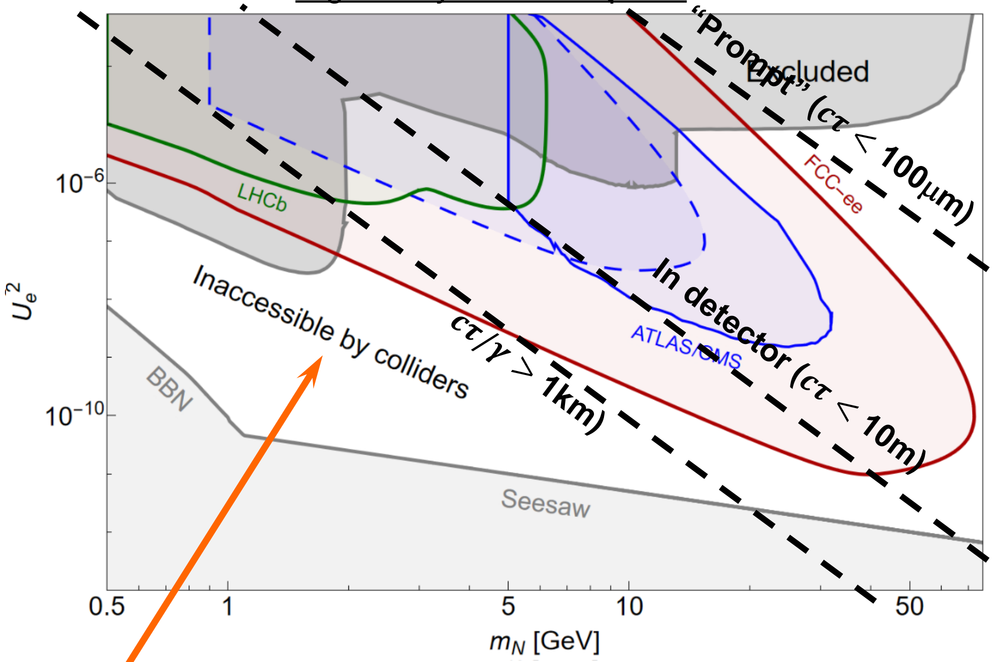

Similar behaviour $\tau_{FIP} \propto \frac{1}{\epsilon_{FIP}^{x} m_{FIP}^{y}}$

for all types of FIPs

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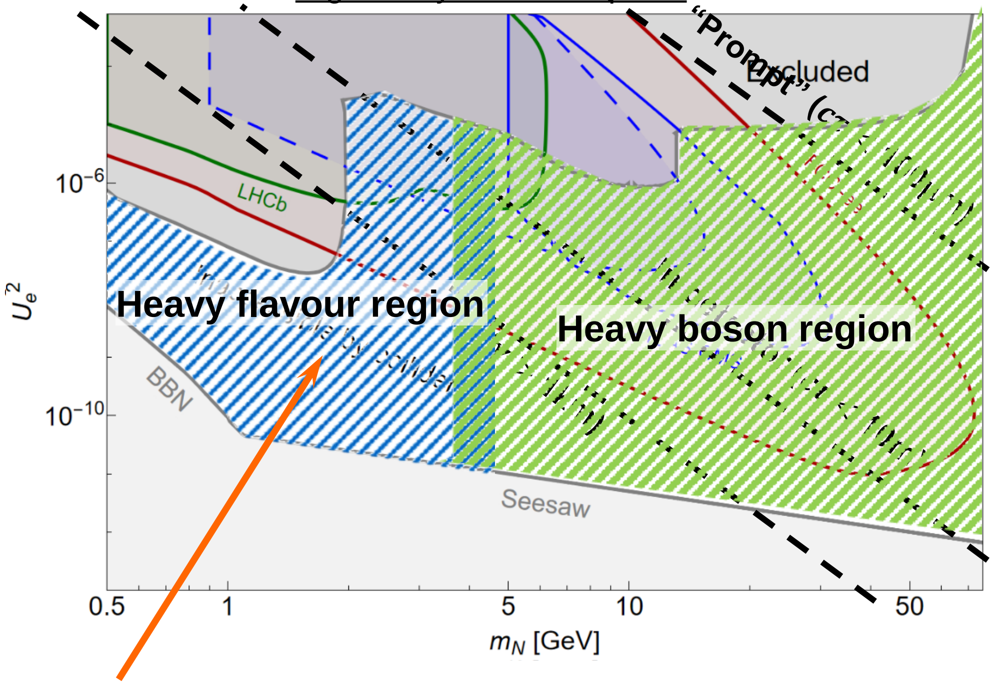

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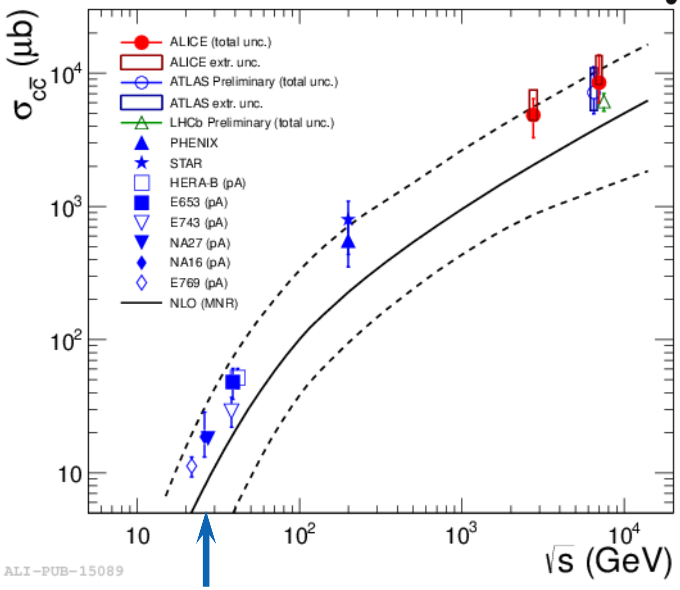
Beam dump optimisation

- Target design for signal/background optimisation:
  - Very thick → use full beam and secondary interactions (12λ)
  - High-A&Z → maximise production cross-sections (Mo/W)
  - Short λ (high density) → stop pions/kaons before decay

➔ BDF luminosity for a very thick target (e.g. >1m Mo/W) with 4×10^{19} protons on target per year *currently available* in the SPS

➔ BDF@SPS $\mathcal{L}_{int}[year^{-1}]$ = >4 x 10^{45} cm^{-2} (cascade not incl.)

➔ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = 10^{42} cm^{-2}



$BDF\ @\ \sqrt{s} = 27\ GeV$

➔ BDF/SHiP ***annually*** access to yields towards detector acceptance:
- ~ 2×10^{17} charmed hadrons (>10 times the yield at HL-LHC)
- ~ 2×10^{12} beauty hadrons
- ~ 2×10^{15} tau leptons
- $\mathcal{O}(10^{20})$ photons above 100 MeV

σ(pp→ssbar X)/σ(pp→X) ~ 0.15
σ(pp→ccbar X)/σ(pp→X) ~ 2×10^{-3}
σ(pp→bbbar X)/σ(pp→X) ~ 1.6 $\times 10^{-7}$
Cascade effect, e.g. >2 for charm

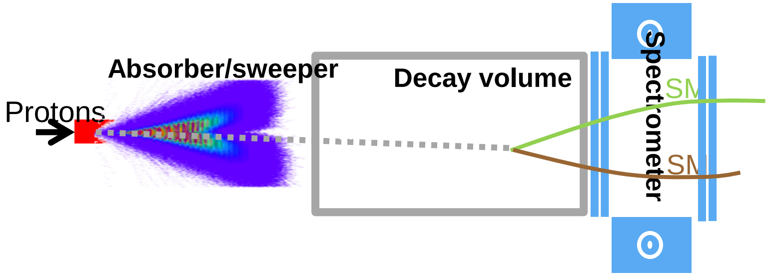
- Large number of neutrinos *detected* with 3t-W ν-target:

  $3500\ \nu_\tau + \bar{\nu}_\tau$ *per year*, and 2×10^5 $\nu_e + \bar{\nu}_e$ / 7×10^5 $\nu_\mu + \bar{\nu}_\mu$ *per year* despite target design

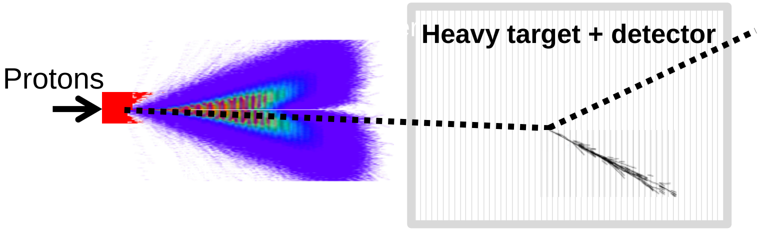
➔ *No technical limitations to operate beam and facility with 4×10^{19} protons/year for 15 years*

BDF/SHiP experimental techniques

Visible decay to SM particles



Scattering off atomic electrons and nuclei



Also suitable for neutrino interaction physics with all favours

- Sensitivity depends on three factors
  - √ Yields (protons on target)
  - ➔ Acceptance (lifetime & angular coverage)
  - ➔ Background level

- Exhaustive search should aim at a model-independent detector setup
  - Full reconstruction and identification of both fully and partially reconstructible modes
    ➔Sensitivity to partially reconstructed modes also proxy for the unknown
  - In case of discovery ➔ make precise measurements to discriminate between models and test compatibility with hypothetical signal

➔ **FIP decay search in background-free environment and LDM scattering**

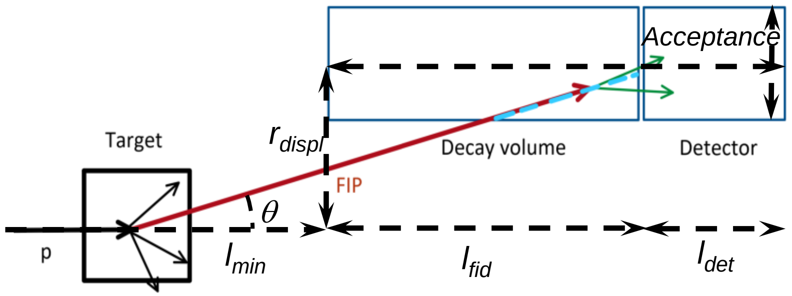
➔ **Rich "bread and butter" neutrino interaction physics with unique access to tau neutrino**

Experimental acceptance

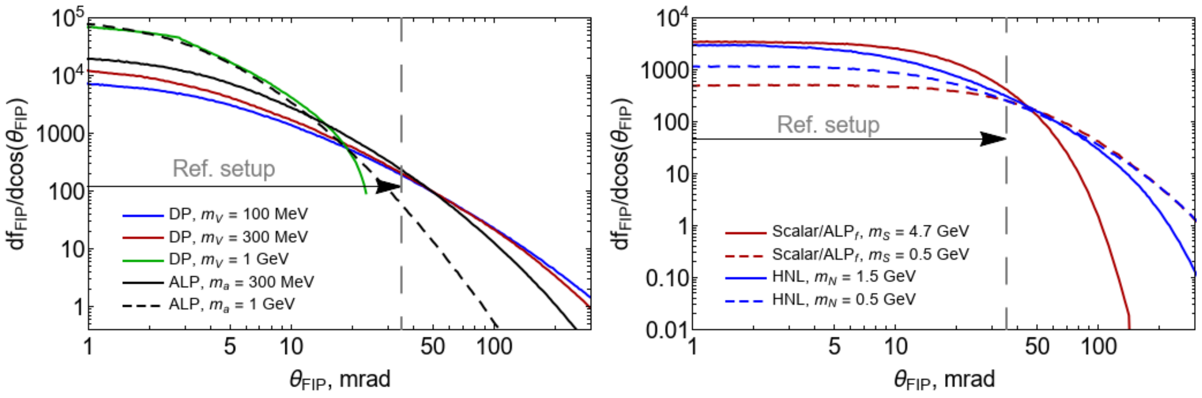
- Hidden particles travel unperturbed through ordinary matter → Filtering out beam induced background
- Production angles → Decay volume as close as possible
- Long-lived objects → Long decay volume

arXiv:2304.02511, submitted to EPJC

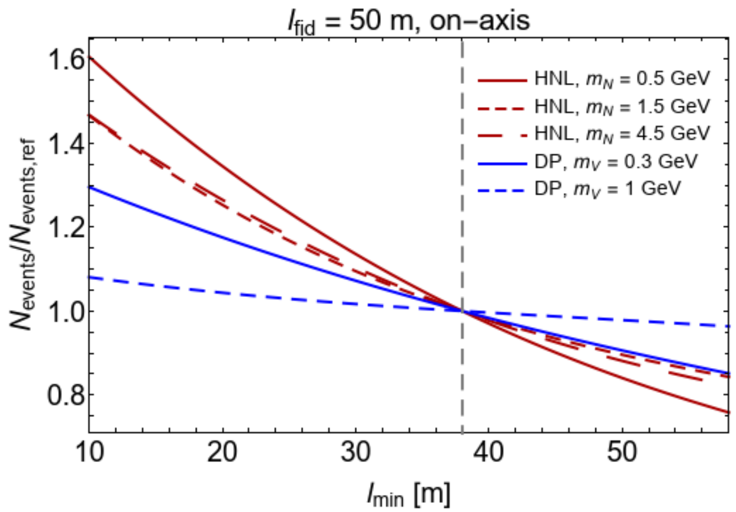
Generic setup



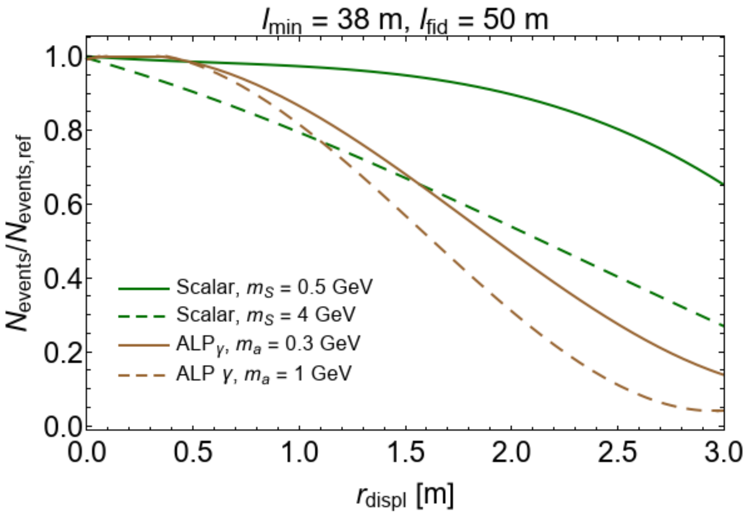
Differential acceptance



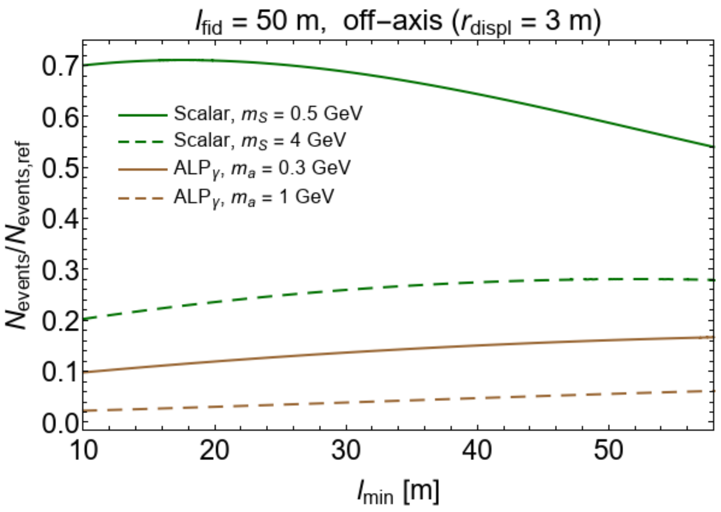
Varying distance to target



Varying offset

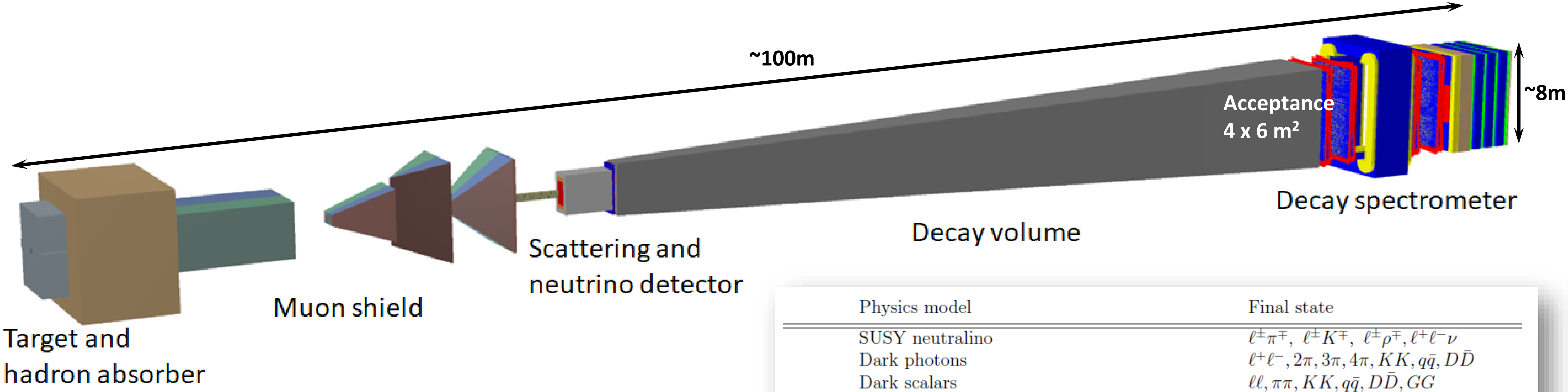


Varying distance to target with offset



General purpose experiment

Two separate detector systems: “SND” and “HSDS”

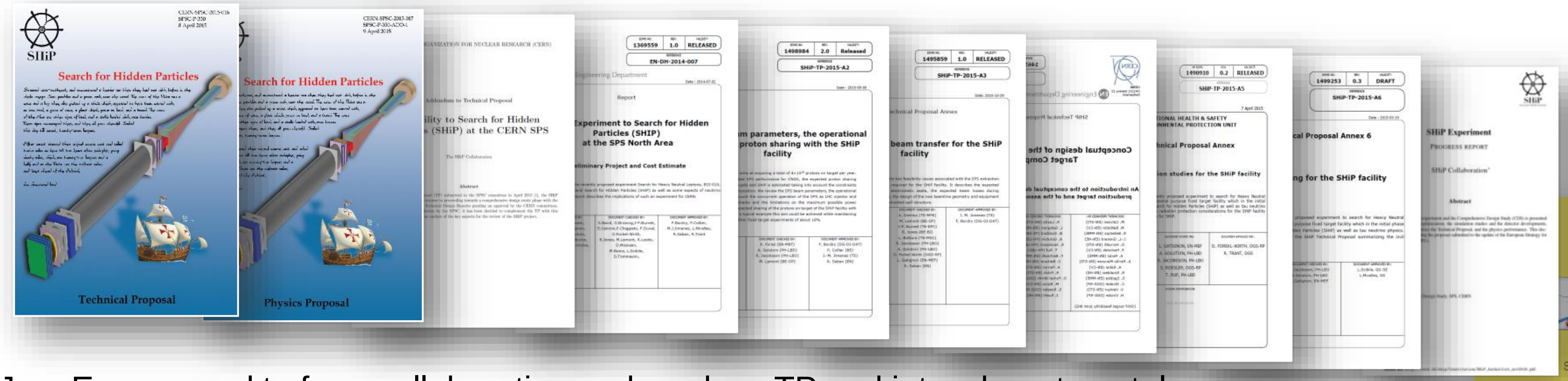


	Physics model	Final state
HSDS	SUSY neutralino	$\ell^\pm\pi^\mp,\ \ell^\pm K^\mp,\ \ell^\pm\rho^\mp, \ell^+\ell^-\nu$
	Dark photons	$\ell^+\ell^-, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
	ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
	HNL	$\ell^+\ell'^-\nu, \pi l, \rho l, \pi^0\nu, q\bar{q}'l$
	Axino	$\ell^+\ell^-\nu$
	ALP (photon coupling)	$\gamma\gamma$
	SUSY sgoldstino	$\gamma\gamma, \ell^+\ell^-, 2\pi, 2K$
SND	LDM	electron, proton, hadronic shower
	ν_τ, $\overline{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^\pm$, $D^\pm$, D^0, $\overline{D^0}$, Λ_c^+, $\overline{\Lambda_c}^-$

BDF/SHiP initially proposed in the context of a new SPS underground area (CDS report on ECN4)

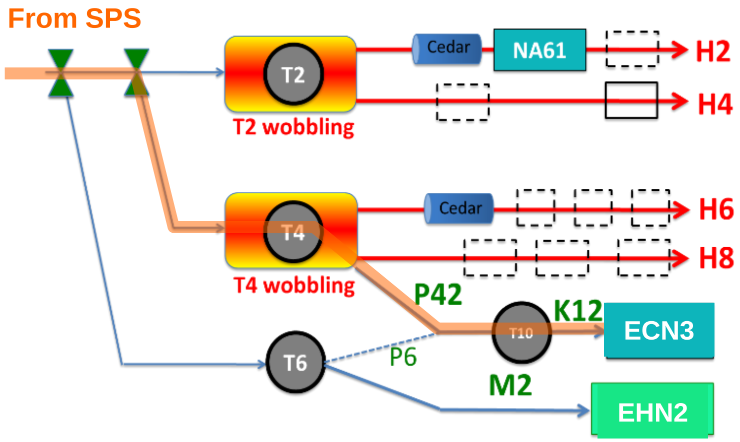
BDF/SHiP development history

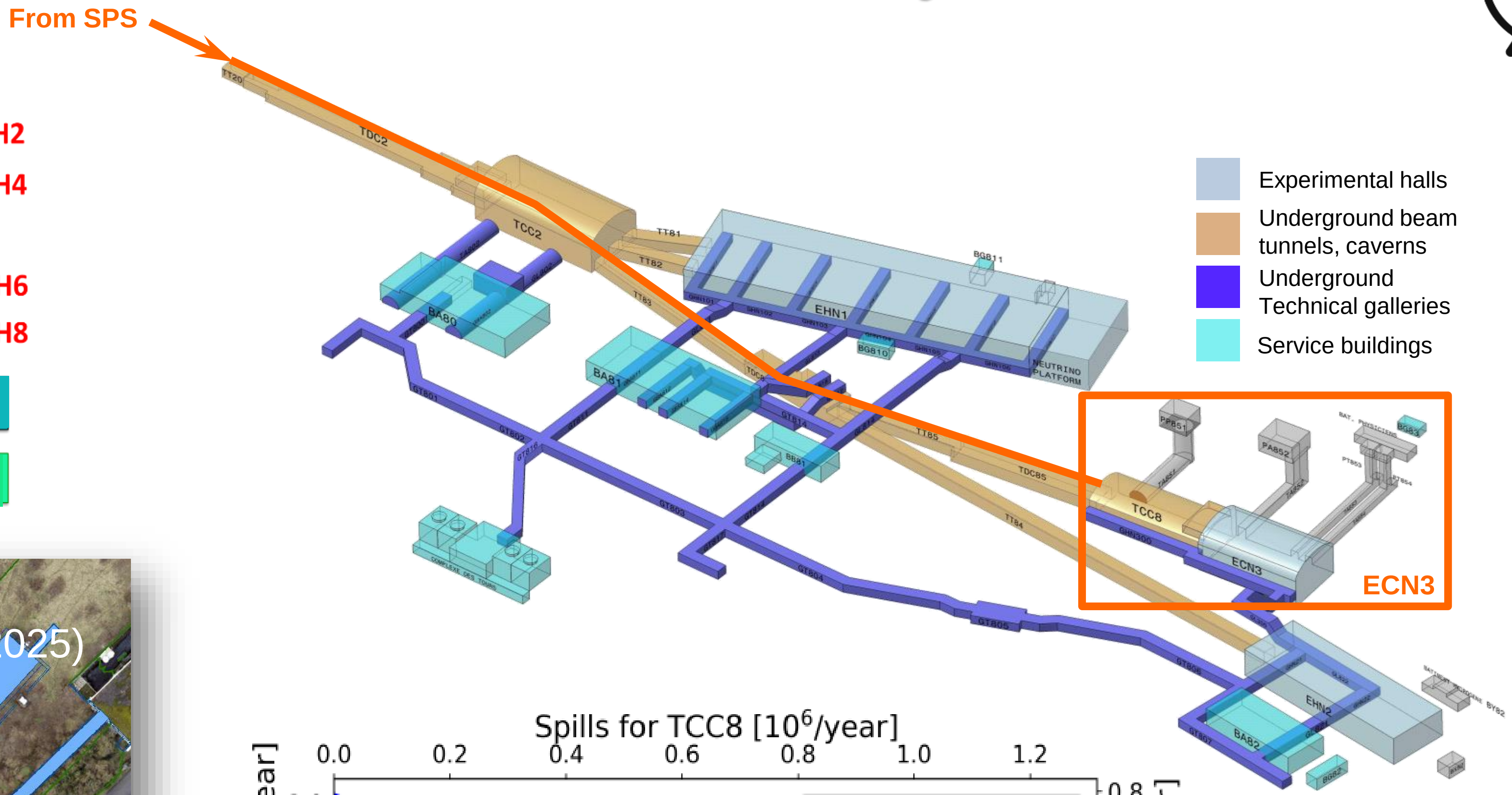
- 2013 Oct: EOI with SHiP@SPS North Area as a new high intensity facility
  ...following brainstorming SHiP@CNGS, SHiP@WANF, SHIP@ECN3

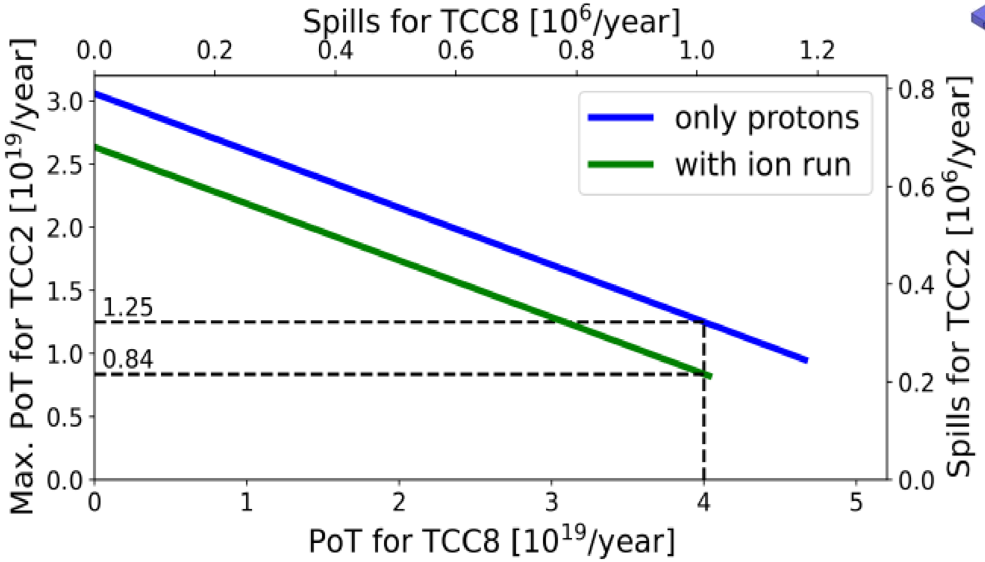


- 2014 Jan: Encouraged to form collaboration and produce TP and inter-departmental task force setup to study feasibility of facility
- 2015 Apr: TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments
- 2016 Jan: Recommendation by SPSC to proceed to Comprehensive Design Study (CDS)
- 2016 Apr: CERN management launch of Beyond Collider Physics study group
  - SHiP experimental facility included under PBC as Beam Dump Facility
- 2018 Dec: EPPSU contribution submitted by SHiP and BDF, and SHiP Progress Report to SPSC
- 2019 Dec: CDS reports on BDF (Yellow Book) and SHiP submitted to SPSC
- 2020 Sep: CERN launches continued BDF/SHiP R&D
  ➔ Location and layout optimization study recommending ECN3
- 2022 Jul: CERN launches dedicated decision process over 2022-23 for future physics programme in ECN3

SPS ECN3 beam facility







Status of ECN3 Decision Process

- Strong interest to return SPS to its full potential for fixed-target physics
  - Synergy with NA Consolidation in LS3 (2026 – 2028)
- ECN3 Beam Delivery Task established feasibility/cost of exploiting ECN3 for higher beam intensities
- SPSC ECN3 Task Force to referee all experiment proposals to be given to the CERN Research Board

➔ ECN3 high-intensity upgrade well received by CERN Scientific Policy Committee (March 2023):
  - Positive recommendation going forward to Finance Committee & CERN Council

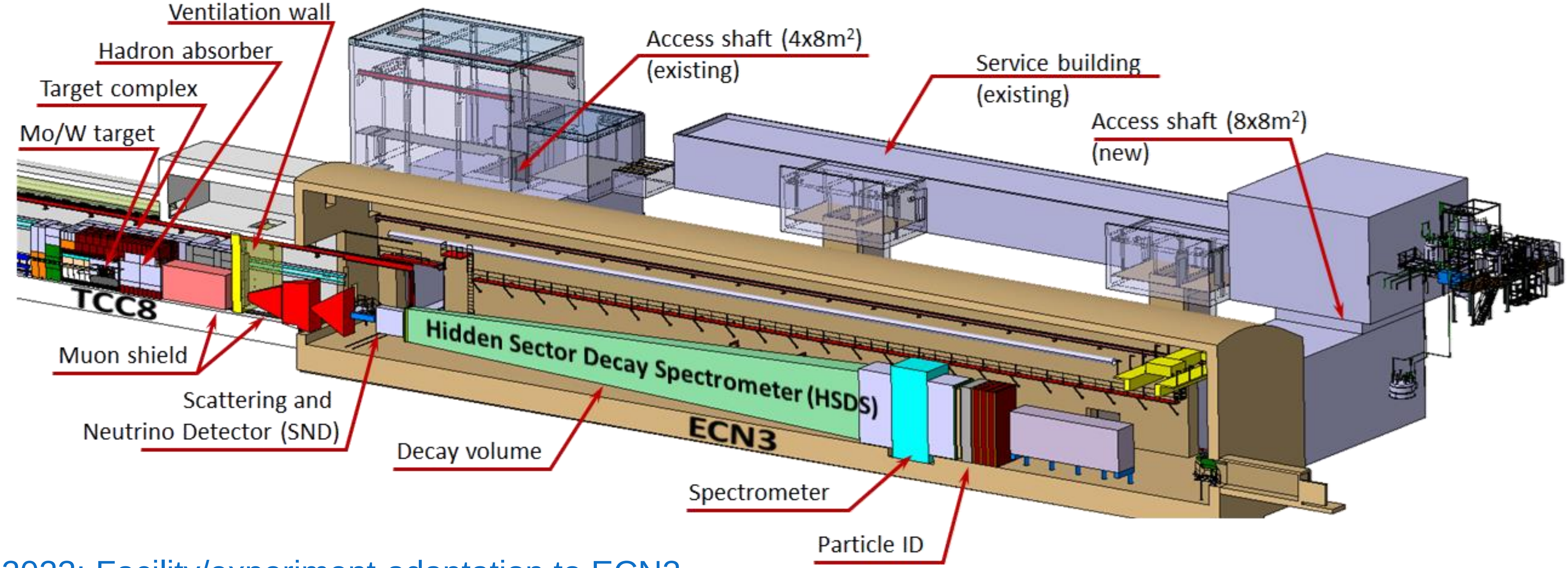
➔ Draft Medium Term Plan 2023 well received:
  - Immediate support (2023/24 items) for ECN3 discussed but not disputed

- Additional allocation for NA-CONS Phase 1, and allocation for Phase 2 out to 2033 accepted without noticeable reservation

➔ **MTP2023, including high-intensity beam delivery, approved in June’s Council meeting**

➔ **Approval of experiment at CERN Research Board, December 6, 2023**

BDF/SHiP in ECN3 proposal



2020-2023: Facility/experiment adaptation to ECN3

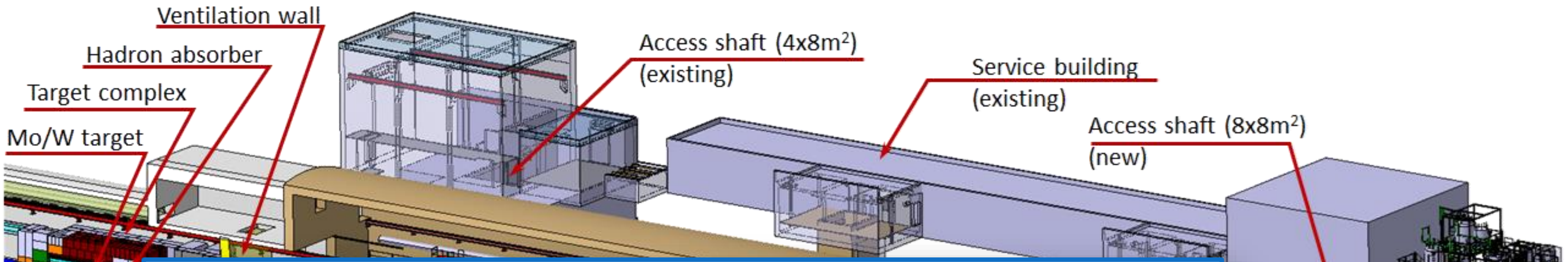
➔ Reduction in transversal size of detector w.r.t. original CDS/ECN4

➔ Shortening of the muon shield

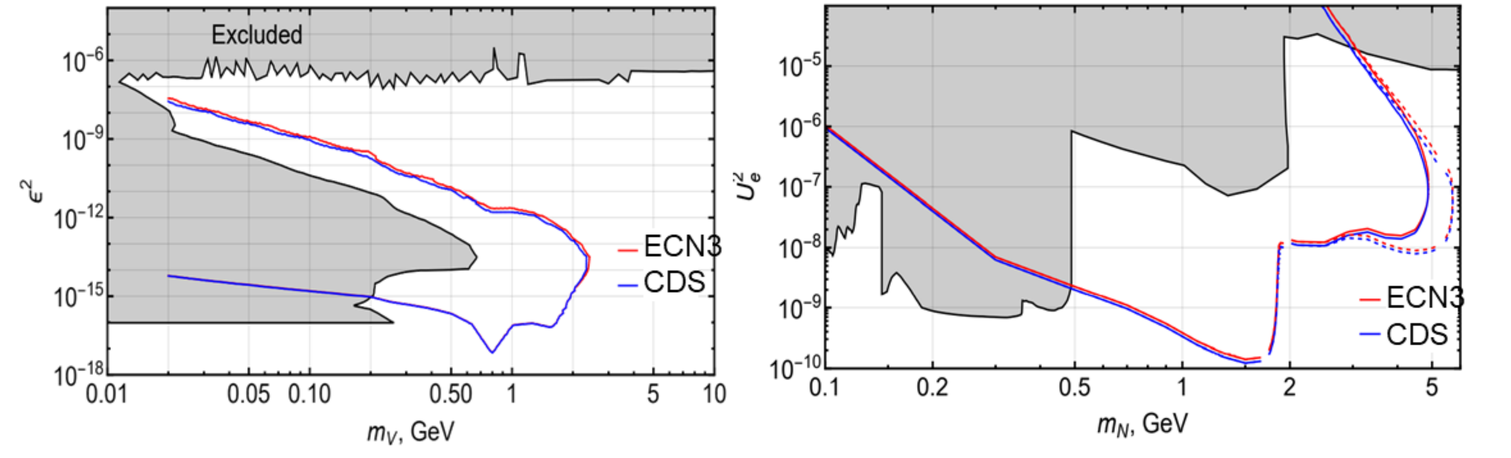
 ➔ Background suppression is combined effect of upstream shielding ⊗ detector

 ➔ Further improvement by use of superconducting technology for muon shield

BDF/SHiP in ECN3 proposal



Comparison of LoI configuration in ECN3 with original design (CDS for ECN4) with 2x10[20]pot



2020-2023: Fac

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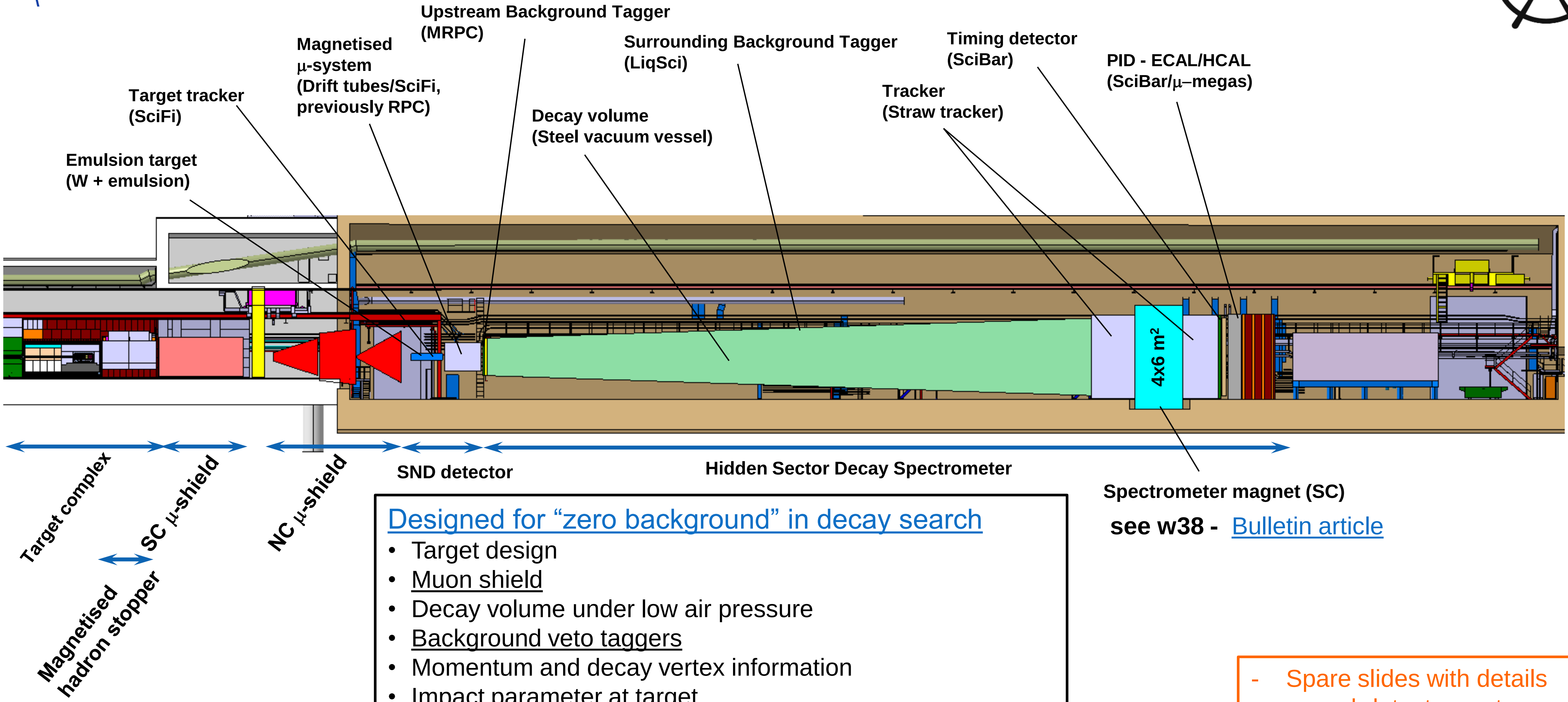
➔ Shortening of the muon shield

➔ Background suppression is combined effect of upstream shielding ⊗ detector

➔ Further improvement by use of superconducting technology for muon shield

➔ Physics programme and sensitivities same as in original proposal at new SPS beam facility

SHiP detector in more detail



see w38 - Bulletin article

Designed for "zero background" in decay search

- Target design
- Muon shield
- Decay volume under low air pressure
- Background veto taggers
- Momentum and decay vertex information
- Impact parameter at target
- Coincidence timing

- Invariant mass
- Particle identification

} Not currently used in background suppression

- Spare slides with details on subdetector systems
- CERN detector seminar schedule on October 13

Background simulations

Optimization and background challenges studied with complete experimental setup implemented in GEANT (FairShip)
➔ Simulation tuned with detector performance parameters measured in test beam on prototypes

- Large rejection power needed
  - $\mathcal{O}(10^{11})$ muons (>1 GeV/c) per spill of $4\text{x}10^{13}$ protons
  - 1.3×10^{19} neutrinos and $9\text{x}10^{18}$ anti-neutrinos in acceptance in 6×10^{20} proton on target

  ➔ Requires large sample of simulated events

  ➔ Muon spectrum validated in measurement at SPS with BDF/SHiP prototype target - agreement within 30%

(Eur. Phys. J. C 80 (2020) 284)

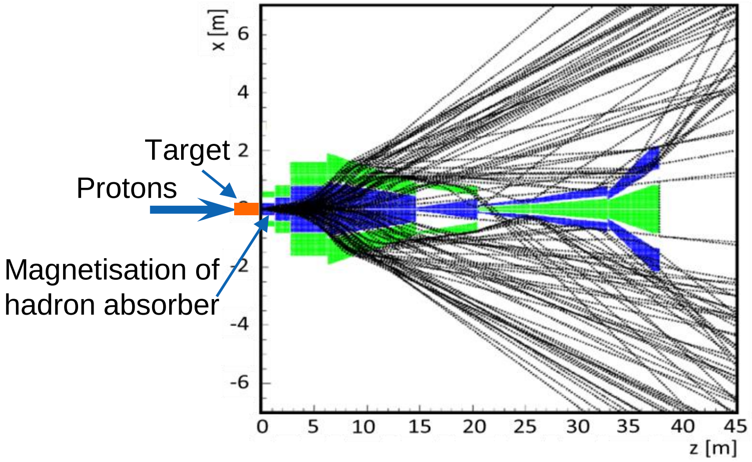
➔ ***Rates*** of neutrinos and muons efficiently suppressed by high-A&Z target and muon shield

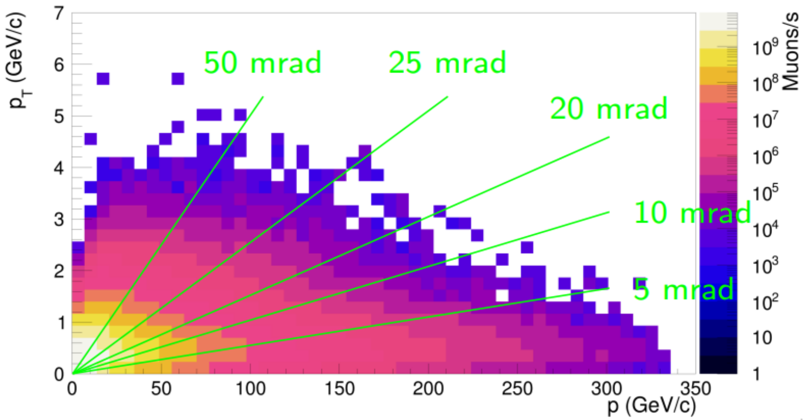
- Most "dangerous" signal-type muons are produced in charm and beauty decays, and in QED resonance decays (e.g. $\rho \rightarrow \mu\mu$).
  - Dedicated samples of charm and beauty decays with Pythia6, and resonance decays enhanced by two orders of magnitude

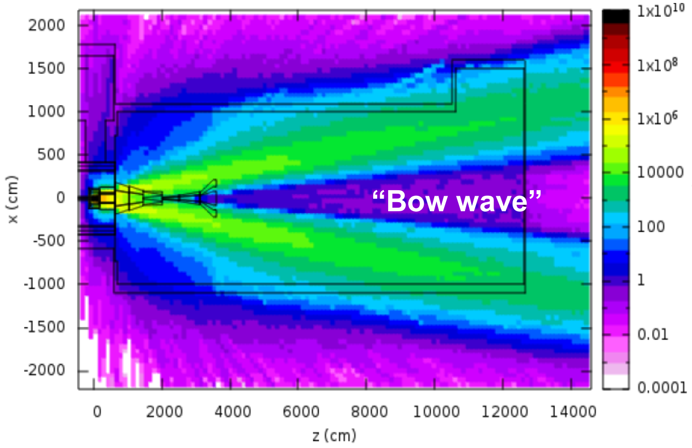
- Muon and neutrino DIS processes
  - Use Pythia6 to generate muon DIS events and GENIE generator for neutrino DIS events in material
  - Boost statistics by forcing each muon and neutrino to interact according to the material distribution

Muon shield principle

Suppress muon flux by ~6 orders of magnitude by magnetic sweeper system (illustrations from earlier studies)

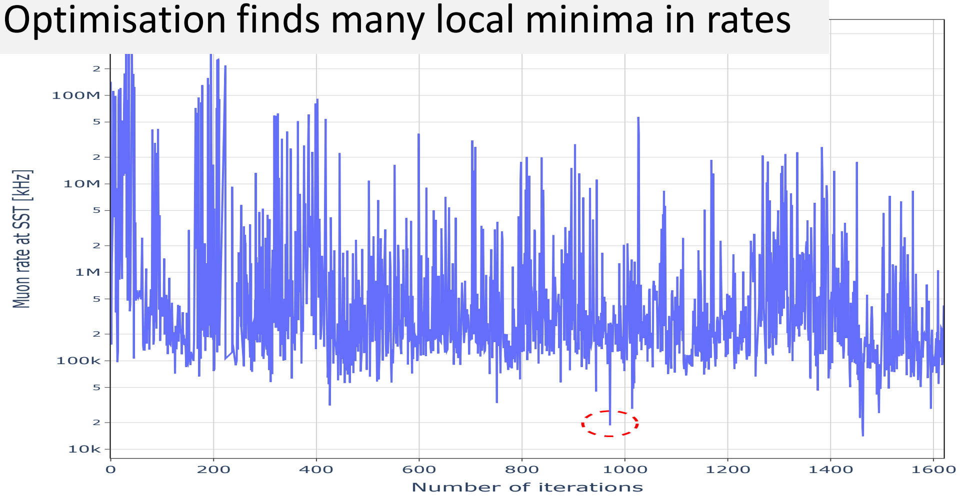






Field configuration optimised by machine learning
with the large sample of muons simulated with PYTHIA/GEANT

Optimisation finds many local minima in rates



Different configurations with similar performance

- Demonstrates robustness against systematics and engineering
- Engineering studies will be used to further constrain optimization and select final configuration

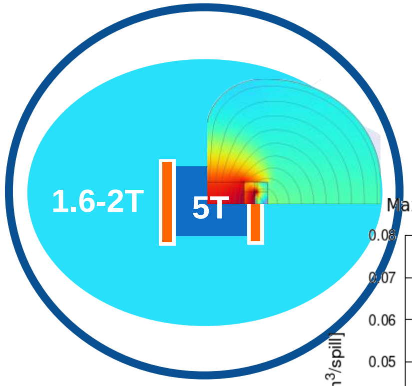
Muon shield in ECN3

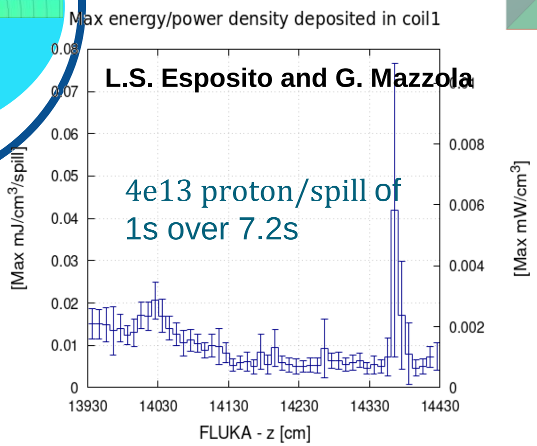
- ECN3 Letter of Intent focused on purely normal conducting (NC) magnets
  - Total length ~25m, 5m shorter than in original design
  - Provided an acceptable rate of muons of 67 kHz in the main tracker and 2 Hz/cm^2 in SND
  - ➔ Robust NC option of the muon shield at ECN3 confirmed
  - ➔ SND shorter by 3m and HSDS spectrometer 4 x 6 m^2, same length as in CDS but located 8m closer to BDF/SHiP target
  - ➔ SHiP sensitivity similar to CDS/ECN4

- Since LoI, focus on hybrid superconducting (SC) / NC configuration

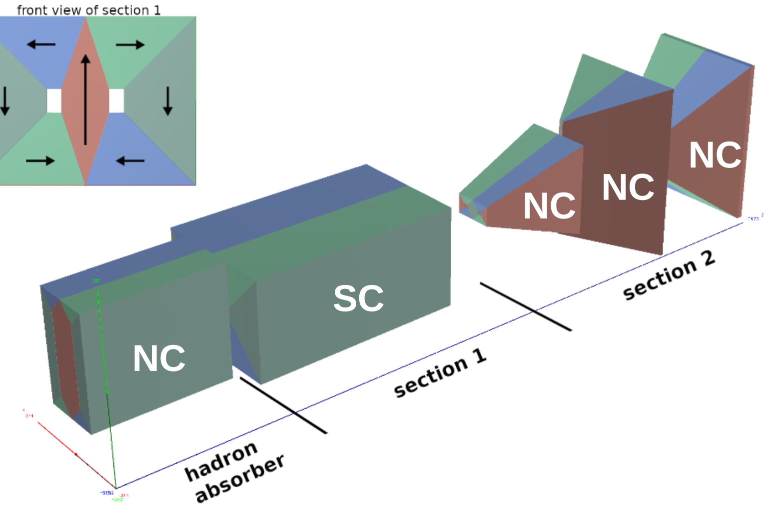
Conservative starting parameters:

- Core aperture in range 0.5 x 0.5 – 1.0 x 1.0 m^2
- Iron/air core field 5T over 4 – 8m
- NbTi @ 4.5K
- ~50 A/mm^2
- Low beam-related heating (muons) - Fluka
- Cryostat around yoke or around coil?
- Cooling options under investigation
- ➔ Challenge in assembly
- ➔ Al-stabilized co-extrusion production line currently not available



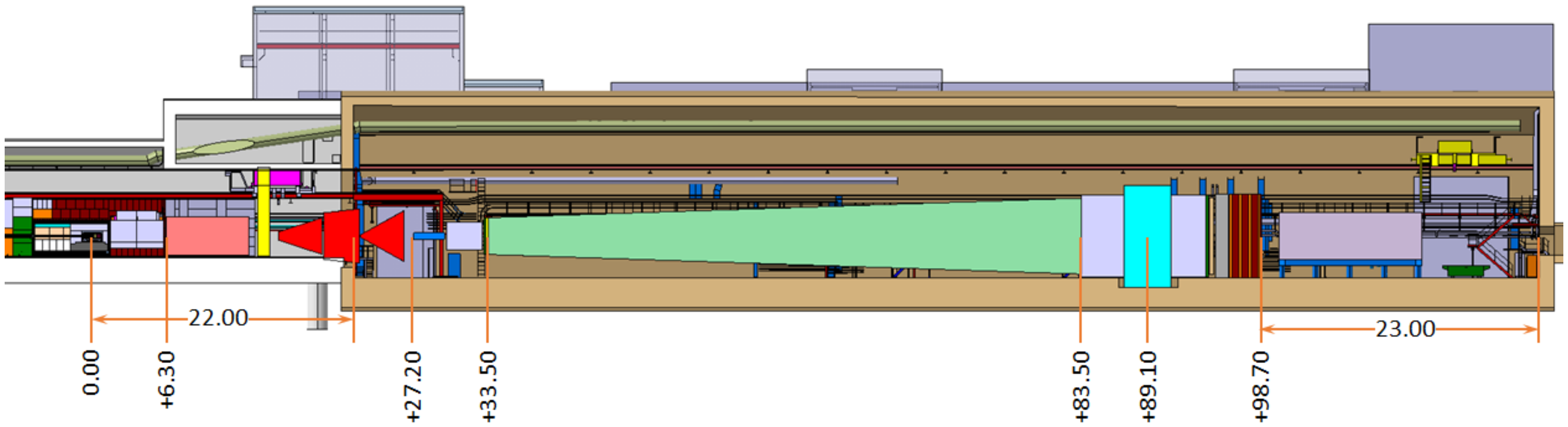


Optimisation runs converges at 18 – 21m



BDF/SHiP layout in ECN3

- With SC/NC hybrid muon shield
  - Further reduced in length by 5m compared to LoI
  - HSDS decay volume closer to the target by 13m compared to CDS/ECN4 design

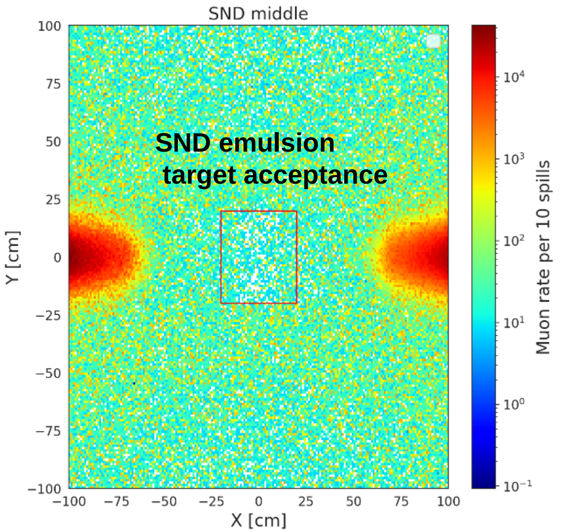


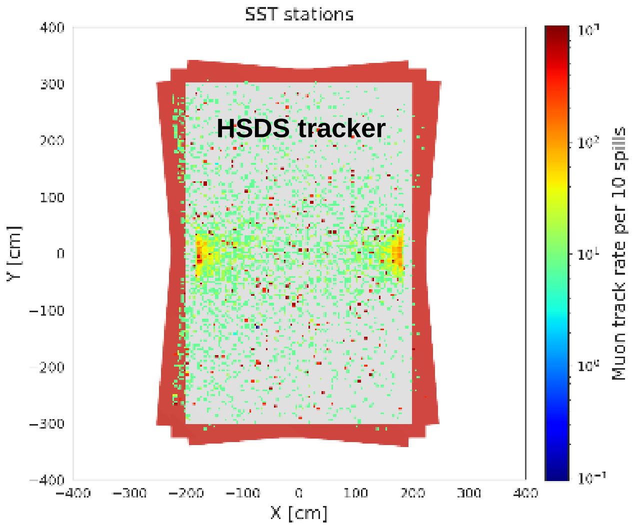
SND: New layout
→ SND is closer and sees higher flux of neutrinos
→ More compact detector (3t W, 145 m^2 of emulsion, just 3x more than SND@LHC)

HSDS: Surround Background Tagger
→ Reduced thickness of Liquid Scintillator (30 → 20cm)
→ Good spatial and time resolution demonstrated with prototypes

HSDS: Single PID system
→ Merging ECAL and Muon detectors

- Low rates of residual muons
  - ~12 kHz in the HSDS tracker
  - ~1 Hz/cm^2 in SND

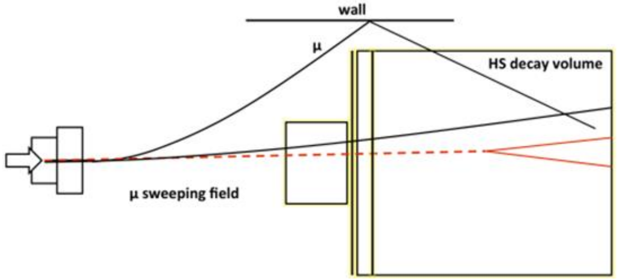




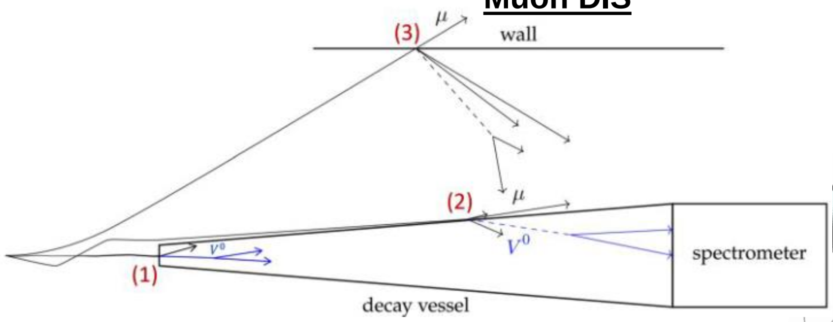
HSDS: FIP decay search background evaluation

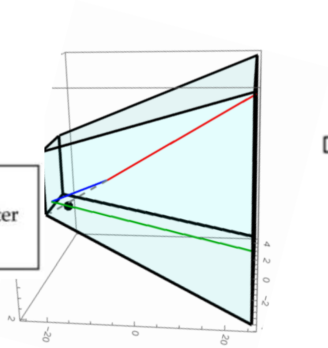
Background estimation based on full GEANT-based MC

Muon combinatorial

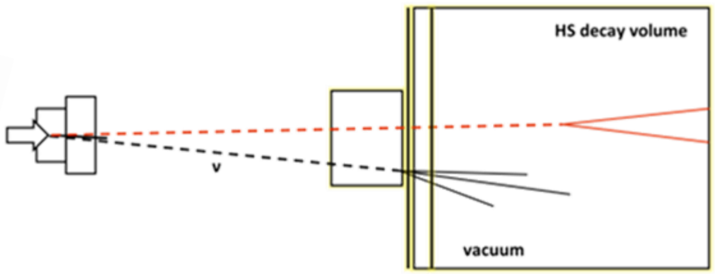


Muon DIS





Neutrino DIS



- Backgrounds from muon and neutrino DIS are dominated by random combinations of secondaries, not by V^0s

➔ Very simple and common selection for both fully and partially reconstructed events – model independence

➔ Possibility to measure background with data, relaxing veto and selection cuts, muon shield, decay volume

Selection

Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall
	$> 100\,\mathrm{cm}$ from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact parameter w.r.t. target (partially reconstructed)	$< 250\,\mathrm{cm}$

+ Time coincidence + UBT/SBT

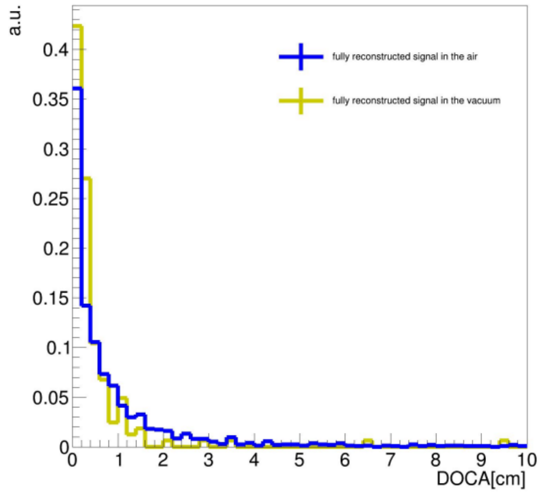
Expected background is <1 event for 6×10^{20} pot (15 years of operation)

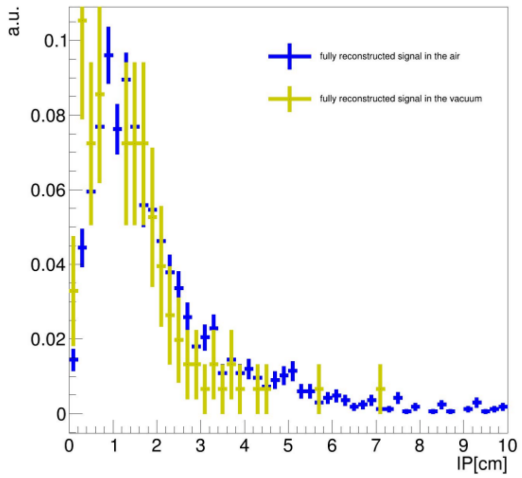
Background source	Expected events
Neutrino DIS	< 0.1 (fully)/$<$ 0.3(partially)
Muon DIS (factorisation)*	$< 5 \times 10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

Backgrounds in FIP decay search

- Background sufficiently low that He @ 1atm being considered in decay volume
  - ➔Significant simplification in HSDS spectrometer section
  - ➔➔ Needs further study

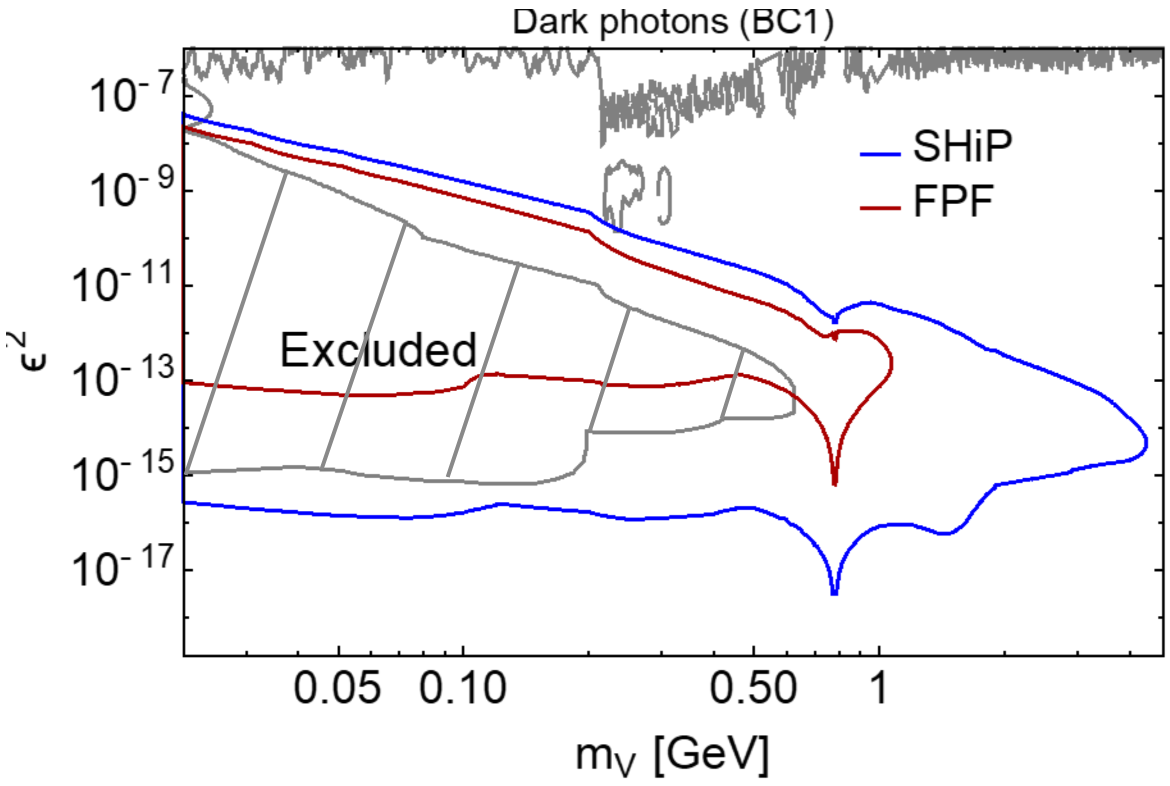
Check of signal resolution
air vs vacuum

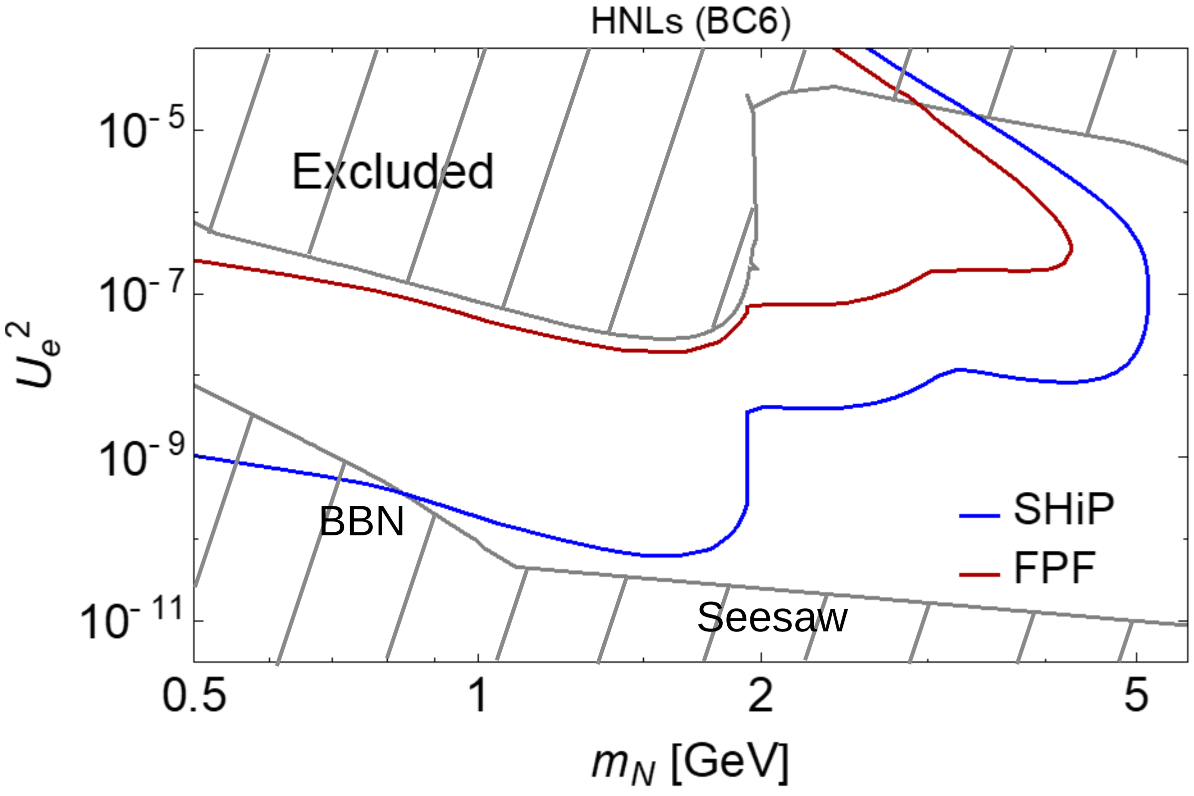




HSDS: FIP decay search performance

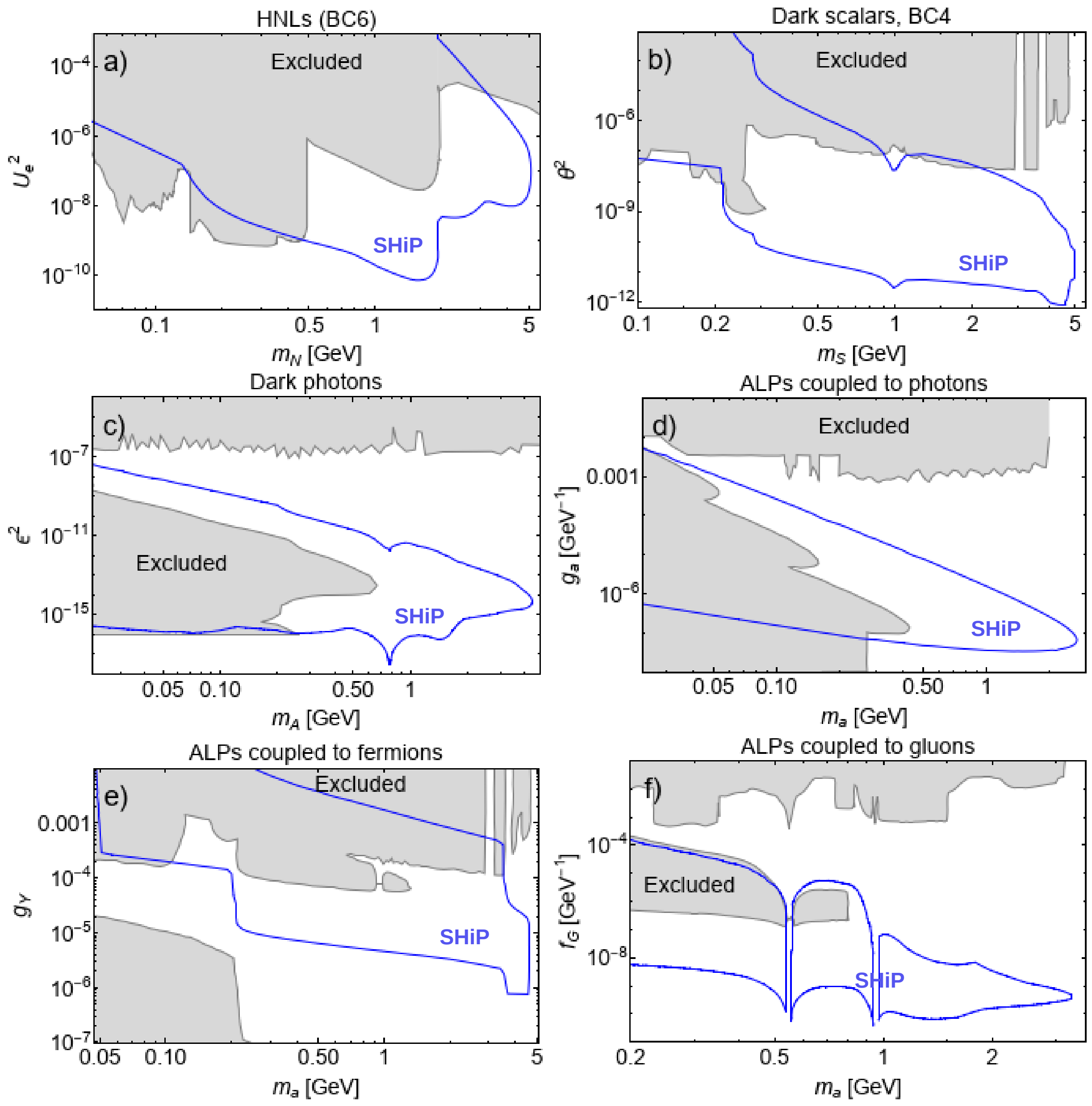
➔ SHiP sensitivity is not limited by backgrounds in 6 x 10^{20} PoT

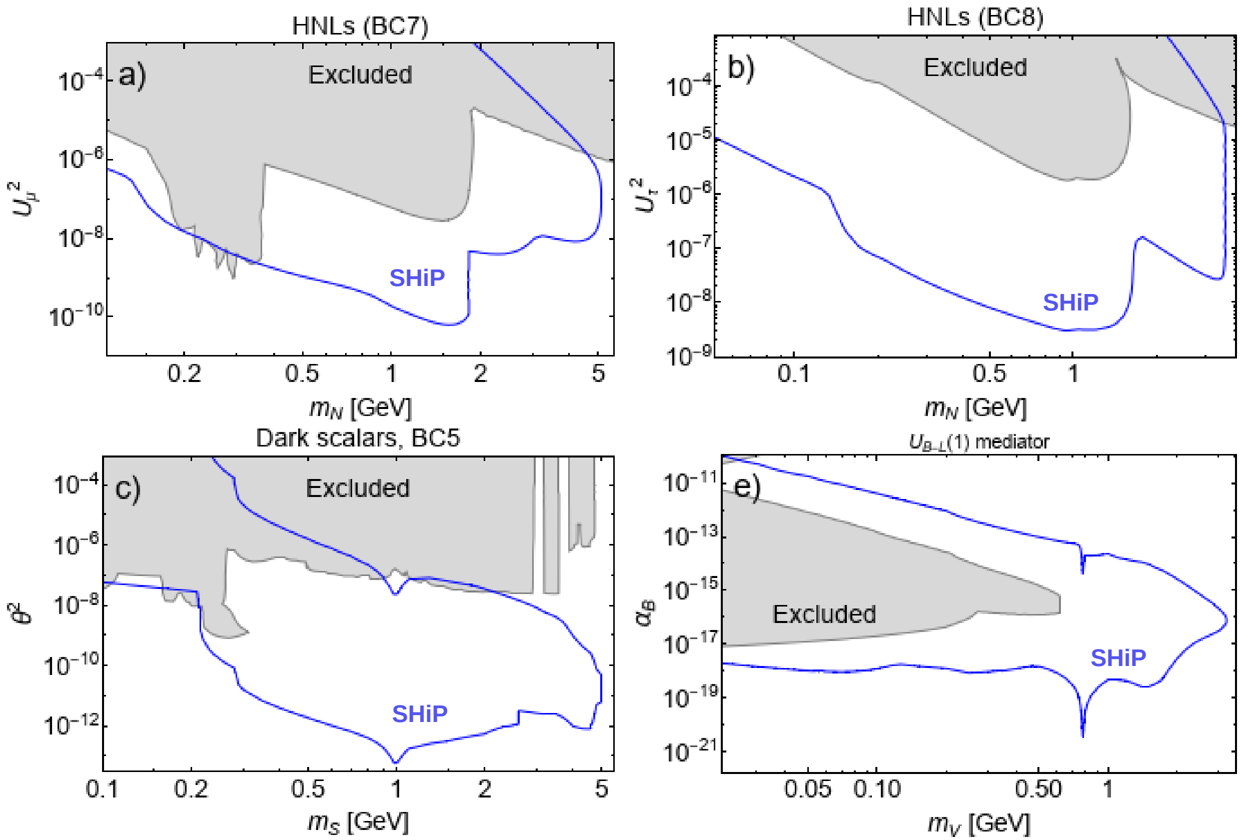




SHiP sensitivities to FIPs are orders of magnitude better than competing projects, including Forward Physics Facility

HSDS: FIP decay search performance, all benchmarks

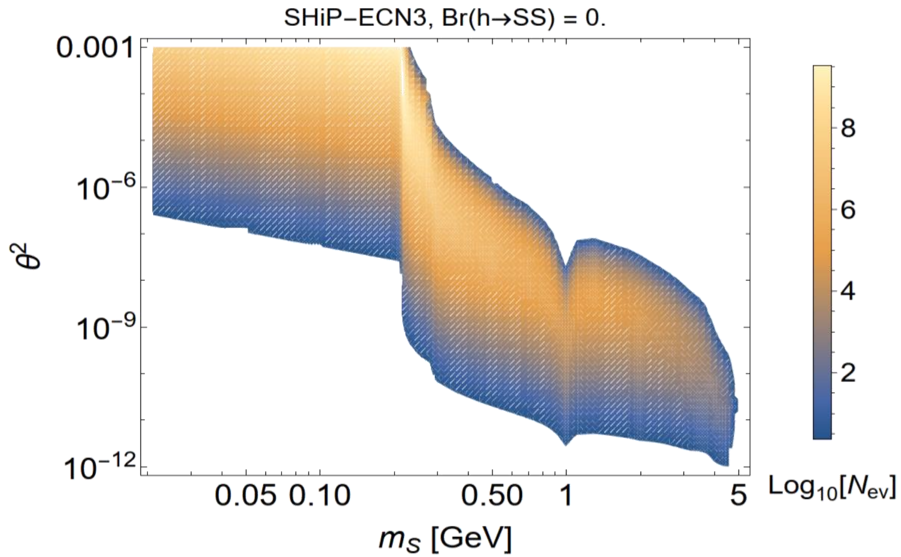




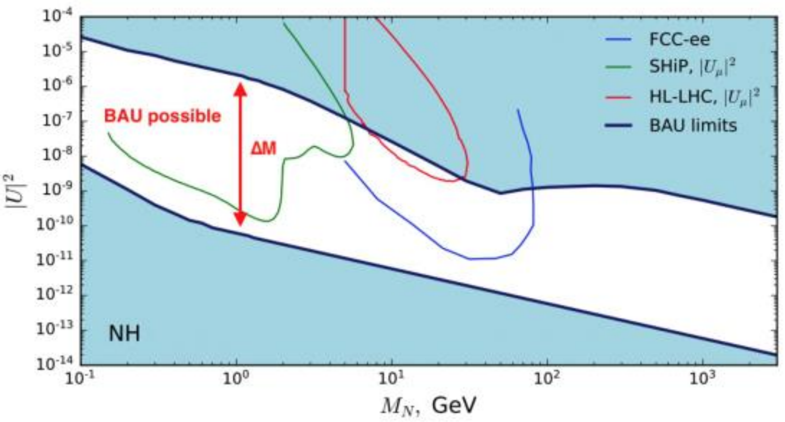
Physics sensitivities – FIPs cont'd

Experiment aimed at discovery and measurements ➔ Number of events (6x10[20] pot)

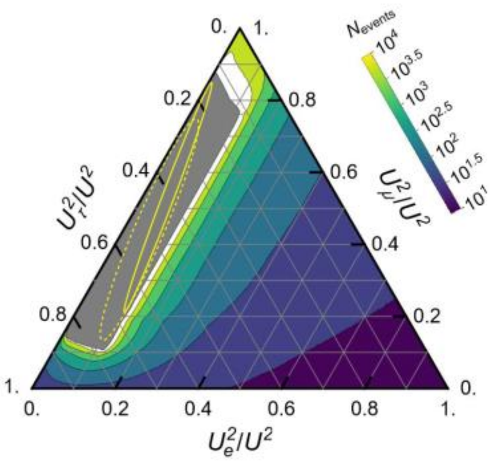
E.g. Dark scalar



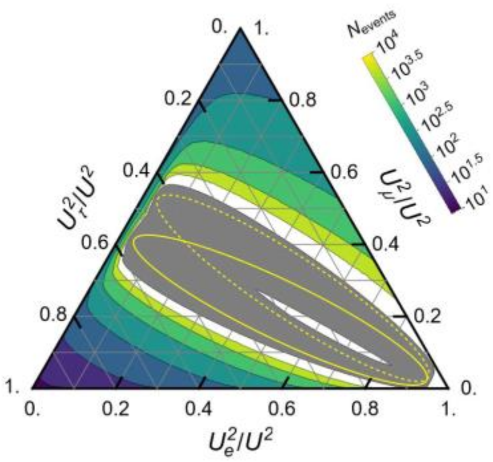
E.g. HNL, check if mixing patter fits flavour oscillations and lepton number violation (2x10[20] pot)

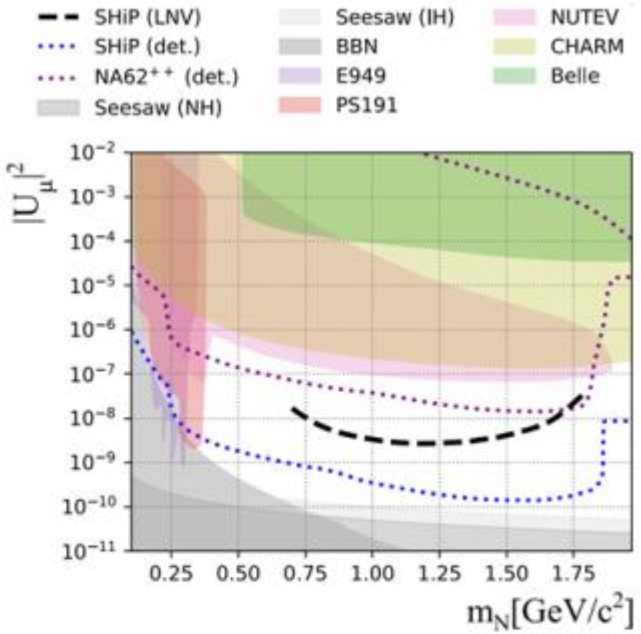


Normal hierarchy



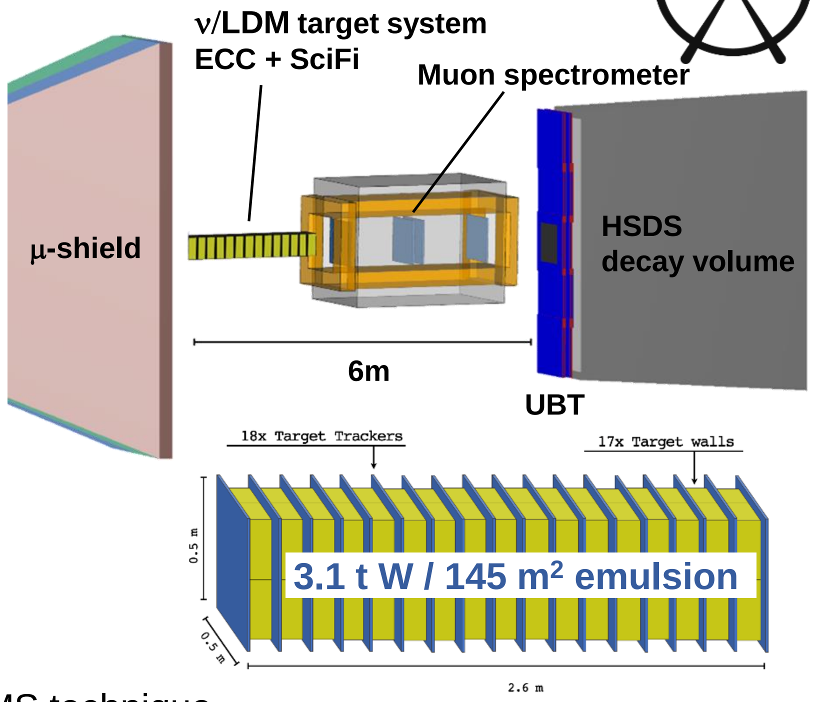
Inverted hierarchy



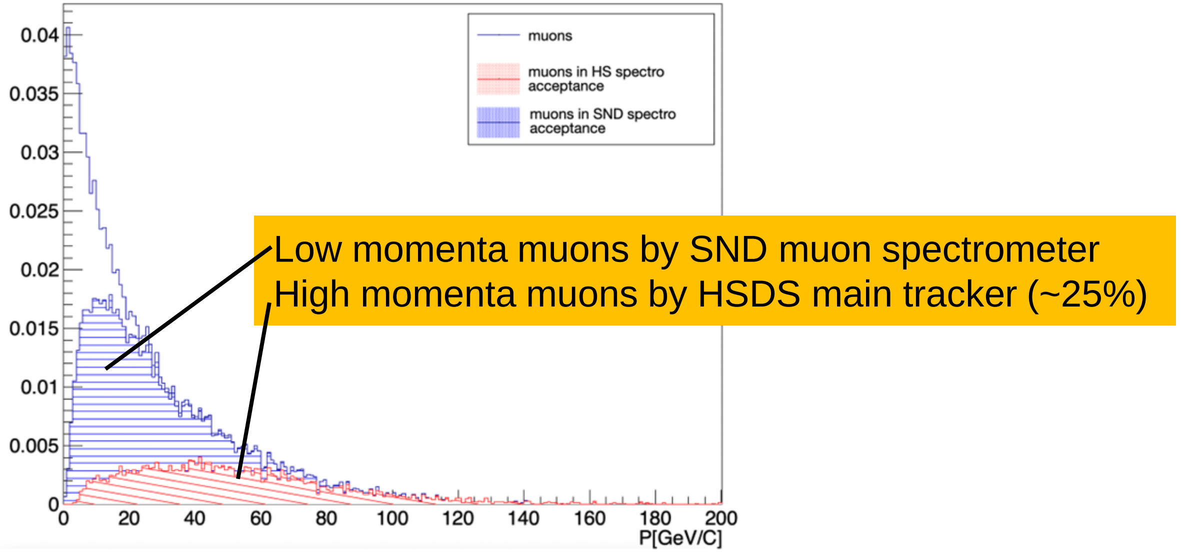


SND detector

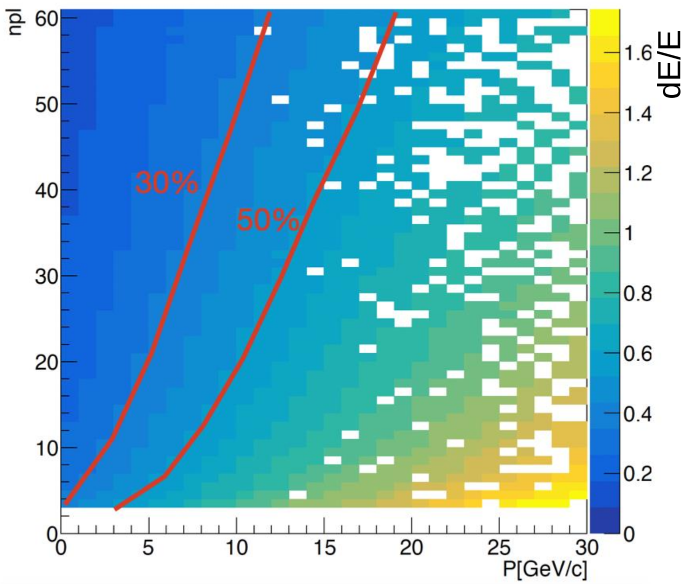
- LDM/neutrino W-target instrumented with layers of emulsion films
  - Micrometric accuracy is crucial for detecting tau neutrino by tau lepton decay vertices, and detecting charm decay vertices
- Target trackers provide time stamping and help reconstructing em-showers
- SND muon spectrometer and HSDS main tracker measures charge and momenta of muons
  - 10% accuracy with 1T magnetic field over 3m and 100μm position resolution
- Momenta of pions and kaons measured using their Multiple Scattering (MS) in the target (~40% accuracy for p_h < 15 GeV/c)



(Emulsion 3 x SND@LHC)



Hadronic energy via MS technique



SND detector

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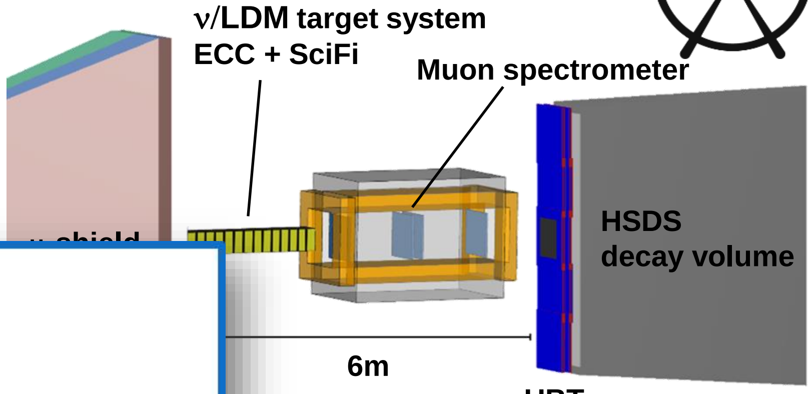
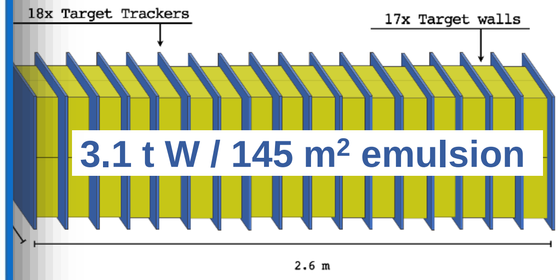
  - Micrometric accuracy is crucial for detecting tau neutrino by tau lepton decay vertices, and detecting charm decay vertices
- Target trackers pr
- SND muon spectr
  momenta of muon
  - 10% accuracy v
- Momenta of pions
  the target (~40% a





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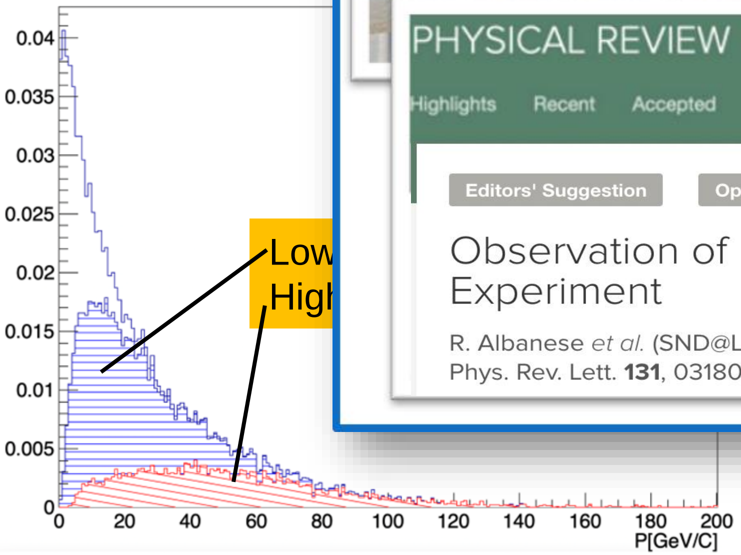

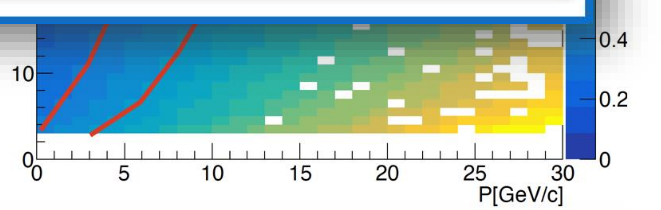

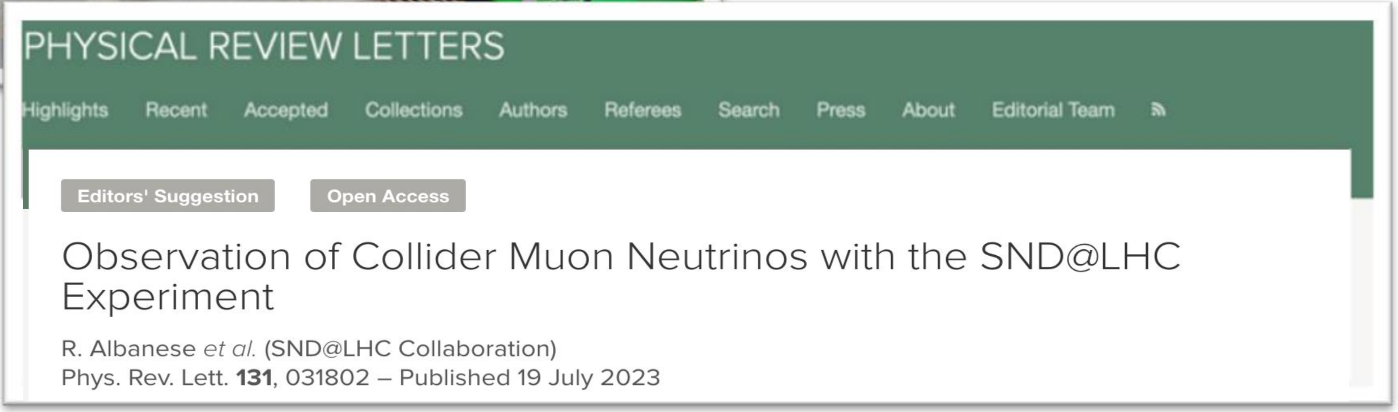
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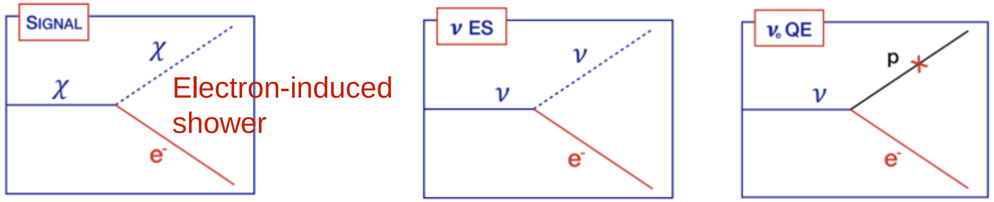
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

R. Albanese *et al.* (SND@LHC Collaboration)
Phys. Rev. Lett. **131**, 031802 – Published 19 July 2023

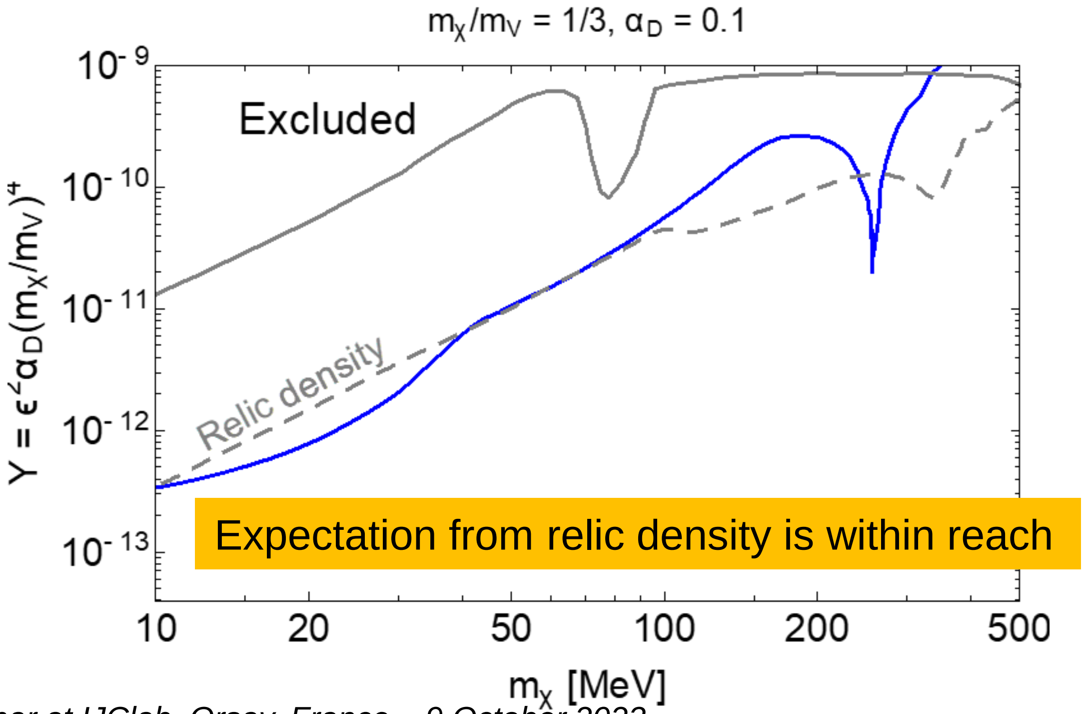
SND: Light dark matter search

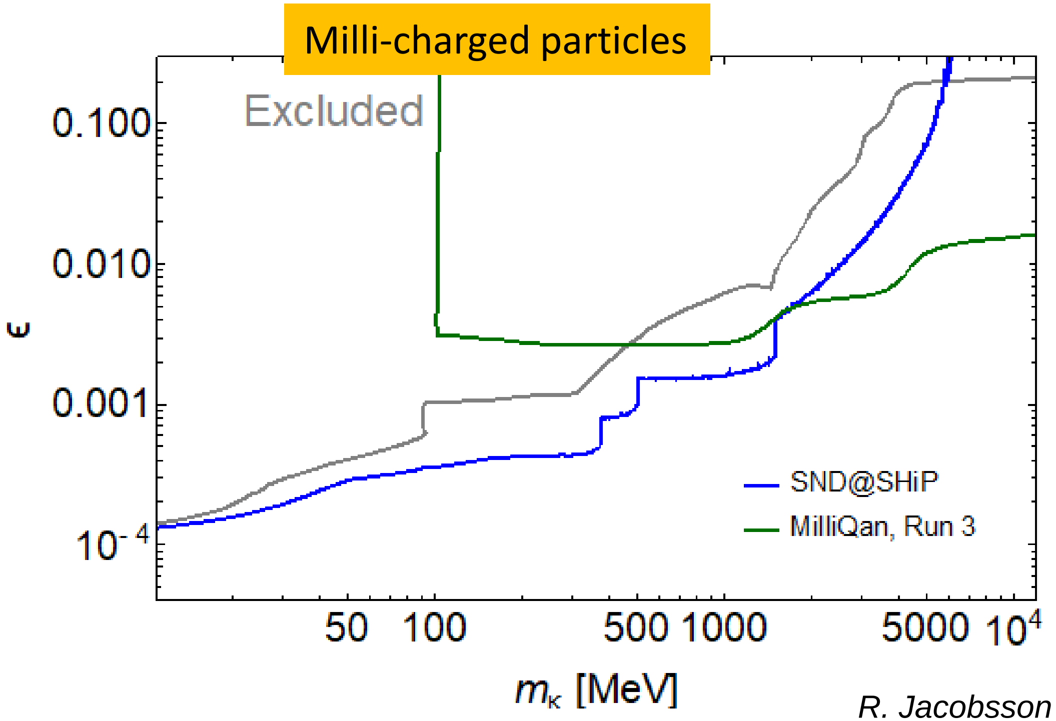
- *Direct search through scattering*, sensitivity to ϵ^4 instead of indirect searches ϵ^2 ($\not{E}$ technique)



- Background is dominated by neutrino elastic and quasi-elastic scattering, for 6 ×10^20 PoT:

6 ×10^20	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	156	81	192	126	555
Quasi - elastic scattering	-	27			27
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	156	108	192	126	582



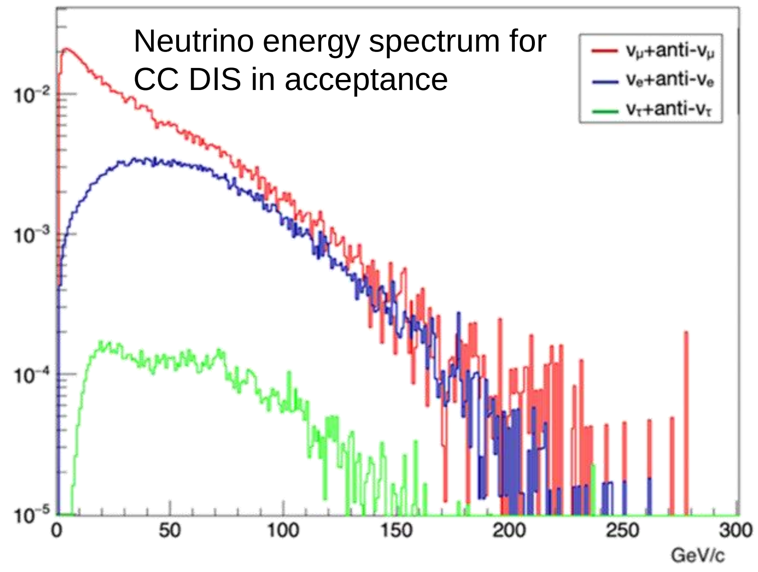


SND: Neutrino interaction physics (1)

Comes (almost) for free!

- Huge sample of tau neutrinos available at BDF/SHIP via $D_s \rightarrow \tau\nu_\tau$
  - Despite target design to suppress pion&kaon decays, statistically valid sample for interaction physics with electron, muon neutrinos as well
  - Measure kinematic variables in both CC and NC DIS
  - $\sigma_{stat} < 1\%$ for all neutrino flavours

	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	63	2.8×10^6
N_{ν_μ}	2.6	5.4×10^{18}	40	8.0×10^6
N_{ν_τ}	9.0	2.6×10^{16}	54	8.8×10^4
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	49	5.9×10^5
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	33	1.8×10^6
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	74	6.1×10^4



Incl. reconstruction efficiencies

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \rightarrow \mu$	4×10^3	3×10^3
$\tau \rightarrow h$	27×10^3	
$\tau \rightarrow 3h$	11×10^3	
$\tau \rightarrow e$	8×10^3	
total	53×10^3	

Systematic uncertainty from knowledge of ν_τ flux

1. D_s production cross-section at SPS
   - Currently 10%, but NA65 expects to reconstruct ~1000 events
2. BR($D_s \rightarrow \tau\nu_\tau$) ~3-4%
3. Cascade production of charm in thick target
   - SHiP plans dedicated experiment to measure J/ψ and charm production using muons in targets of variable depths

➔ Plan to reach ≤5% uncertainty in ν_τ flux seems realistic

➔ Also plan <5% uncertainty in ν_e, ν_μ flux

SND: Neutrino interaction physics (2)

➔ LFU in neutrino interactions

- $\sigma_{stat+syst}$~1 - 3% accuracy in ratios: ν_e/ν_μ , ν_e/ν_τ and ν_μ/ν_τ

➔ Measurement of neutrino DIS cross-sections up to 100 GeV

- E_ν< 10 GeV as input to neutrino oscillation programme
- ν_τ cross-section input to cosmic neutrino studies
- $\sigma_{stat+syst}$< 5%

➔ Test of F_4 and F_5 ($F_4 \approx 0,\ F_5 = F_2/2x$ with $m_q \to 0$) structure functions in $\sigma_{\nu-CC\ DIS}$

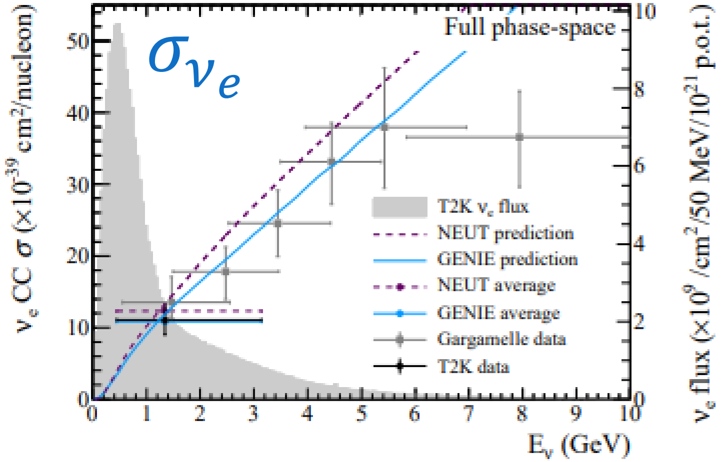
- Never measured, only accessible with tau neutrinos
  [C.Albright and C.Jarlskog, NP B84 (1975)]

➔ Exotics, …

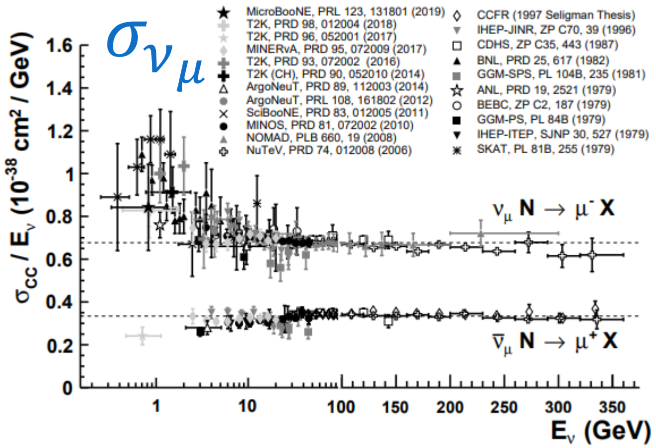
$$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} = \frac{(\nu_e \text{ events observed})}{(\nu_\mu \text{ events observed})} \frac{\int E_{\nu_\mu}(\nu_\mu \text{ flux})dE}{\int E_{\nu_e}(\nu_e \text{ flux})dE}$$

$$= 1.09 \pm 0.17 .$$ ➔ 15%!

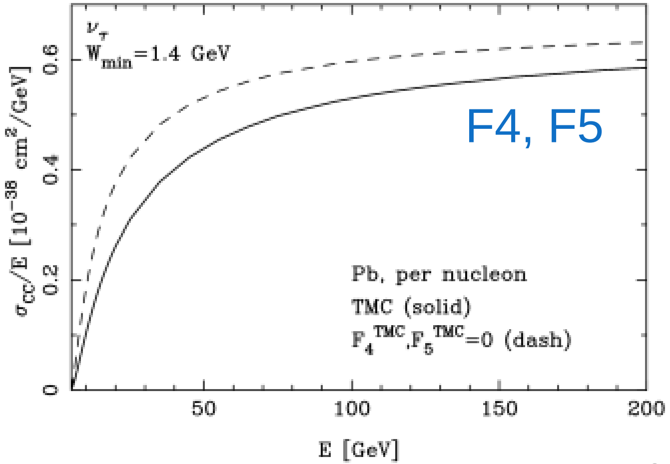
Phys.Rev. D41, 2653 (1990)



Phys.Rev.Lett 113(24). (2014)



PDG



Rep. Prog. Phys. 79 (2016)124201

SND: Neutrino interaction physics (3)

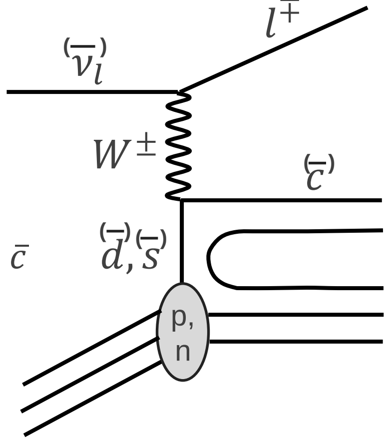
Neutrino-induced charm production to probe PDF

- Expect ~6×10[5] neutrino induced charm hadrons for 6×10[20] pot
  - More than an order of magnitude larger than currently available
- Anti-charmed hadrons are predominantly produced by anti-strange content of proton (~90%)
  - Understanding of nucleon strangeness is critical for precision tests of SM at LHC

➔ Improvement on $|V_{cd}|$ by directly identifying inclusive charm

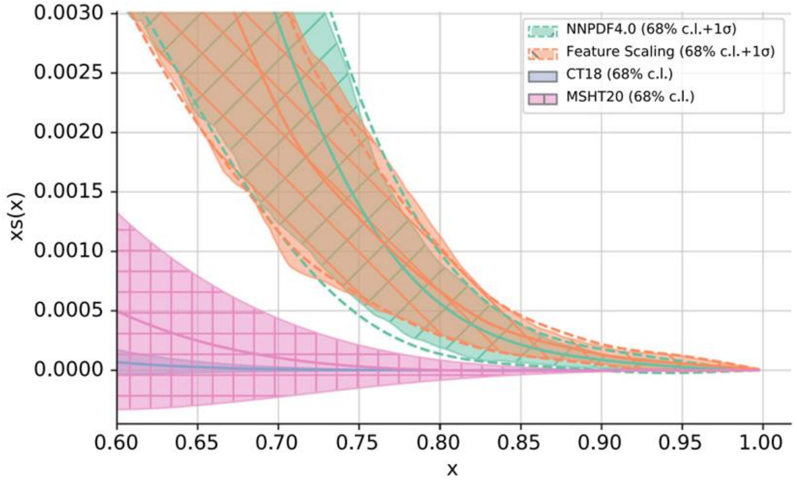
	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	57	3.5×10^5
N_{ν_e}	71	1.7×10^5
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	0.3×10^5
total		6.2×10^5

}90% from $\bar{s} \to \bar{c}$



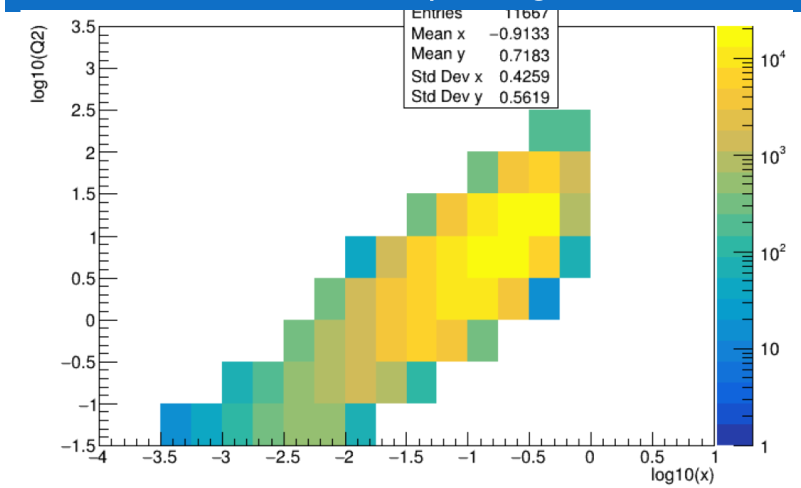
No charm candidate from ν_e and ν_τ interactions ever reported

Current status of the proton strangeness (NuTeV/CCFR data) at high x

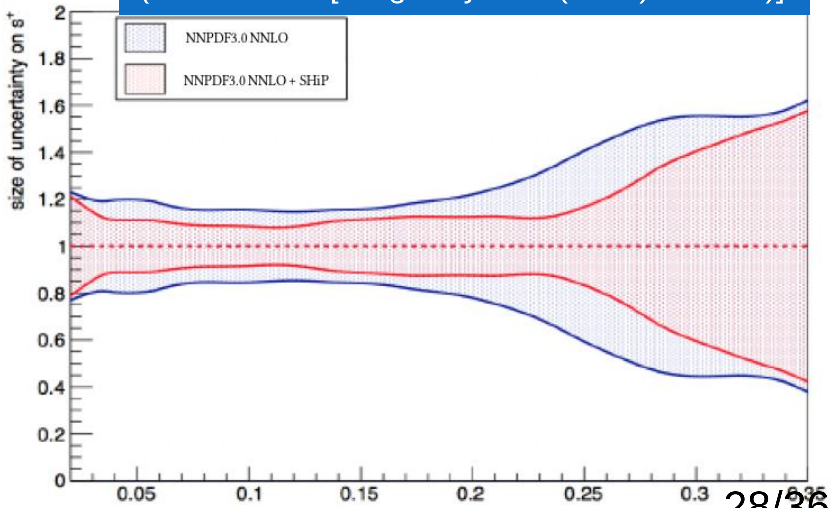


Eur. Phys. J. C 82 (2022) 163

Large data samples at SHiP will greatly improve current measurements up to high values of x



SHiP sensitivity to PDF for x < 0.35
(evaluated in [Prog. Phys. 79 (2016) 124201)]



SND: Neutrino interaction physics (3)

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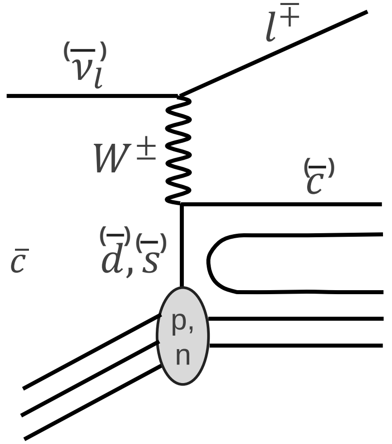

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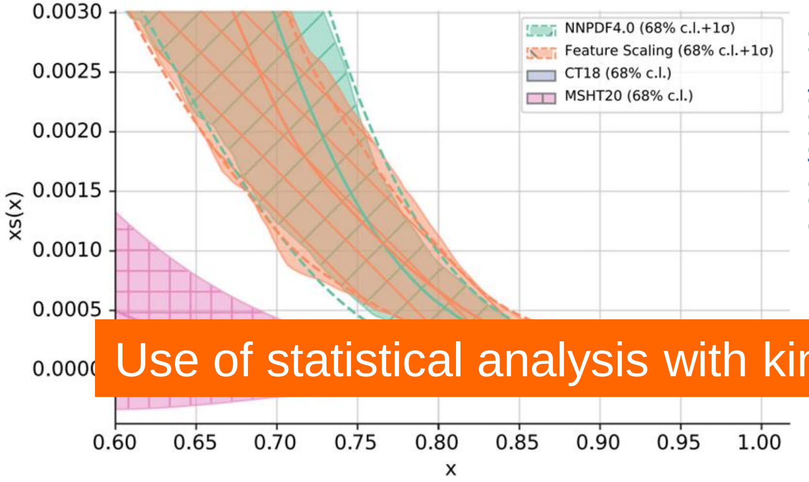

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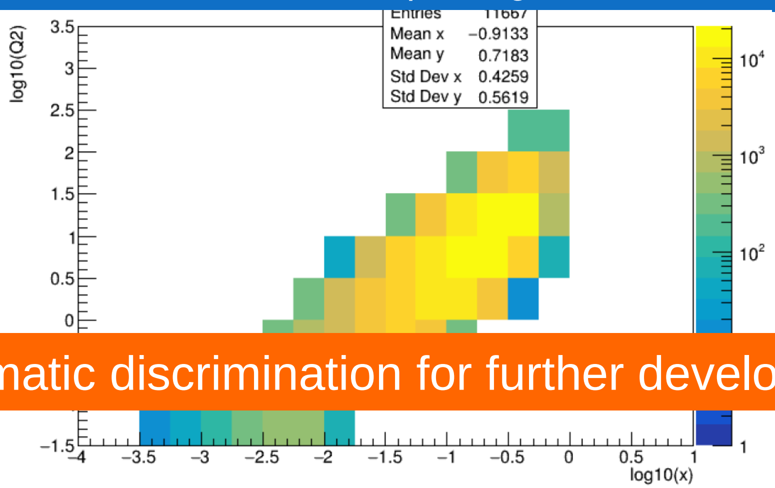

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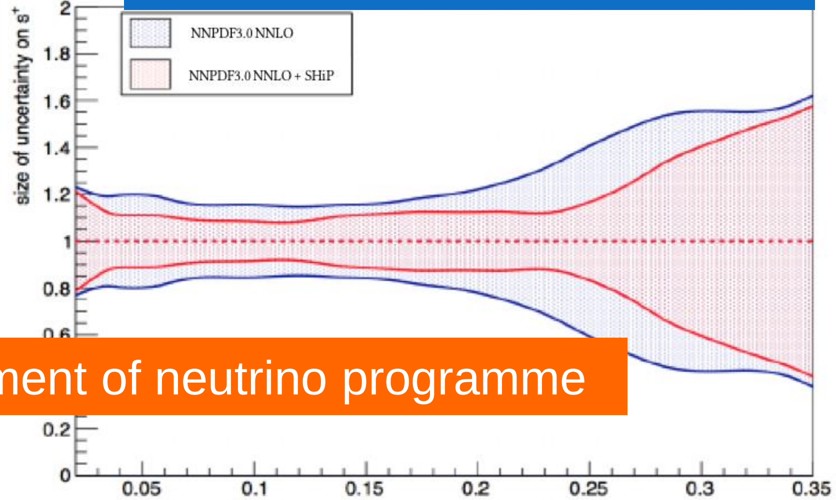
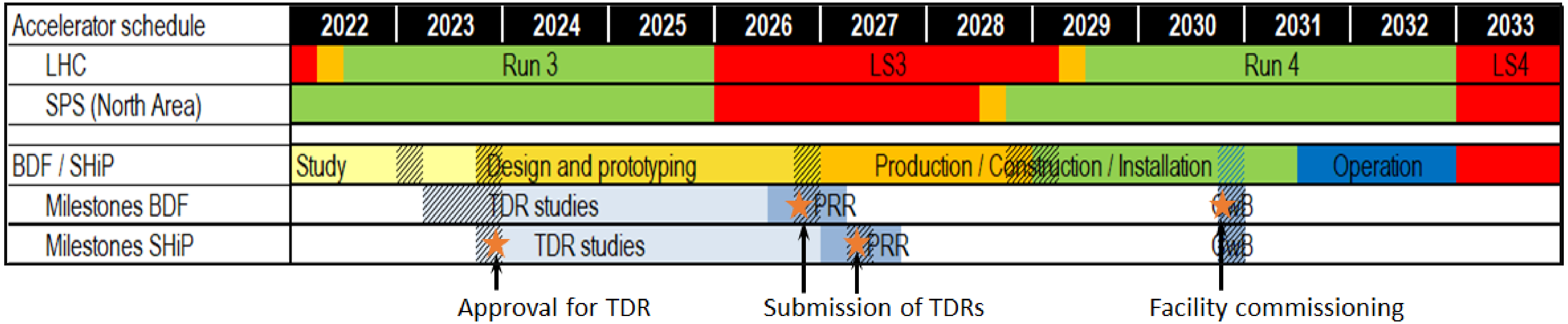
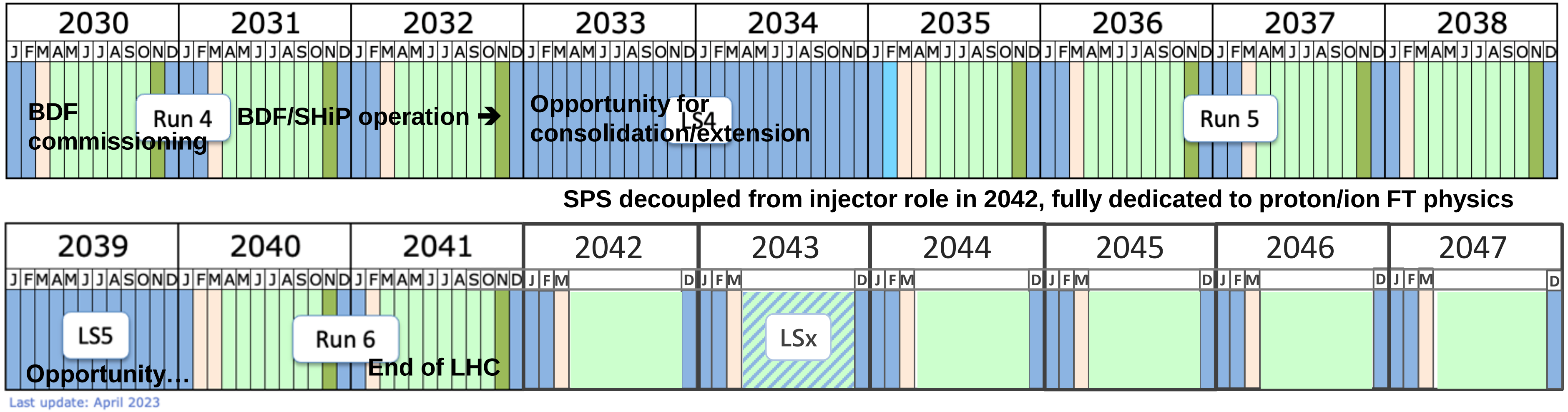


Use of statistical analysis with kinematic discrimination for further development of neutrino programme

BDF/SHiP preliminary schedule

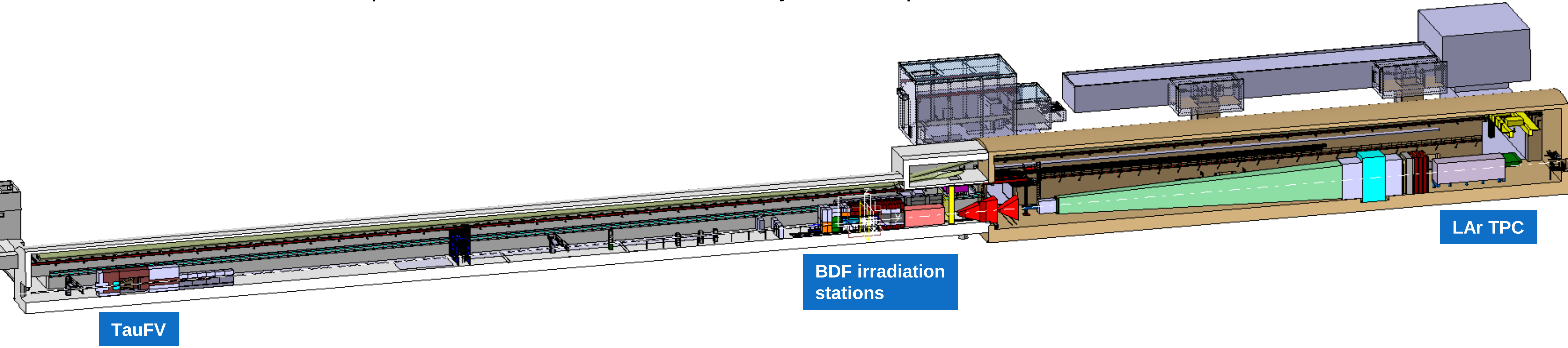


- ~3 years for detector TDRs (approval in 2023 is critical to ensure timely funding)
- Construction / installation of facility and detector is decoupled from NA operation
- Availability of test beams challenging
- Important to start data taking >1 year before LS4
- Several upgrades/extensions of the BDF/SHiP in consideration over the operational life



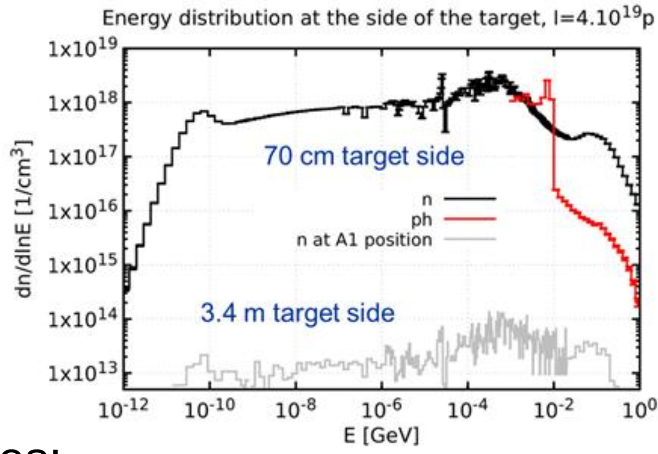
Overview of BDF extensions

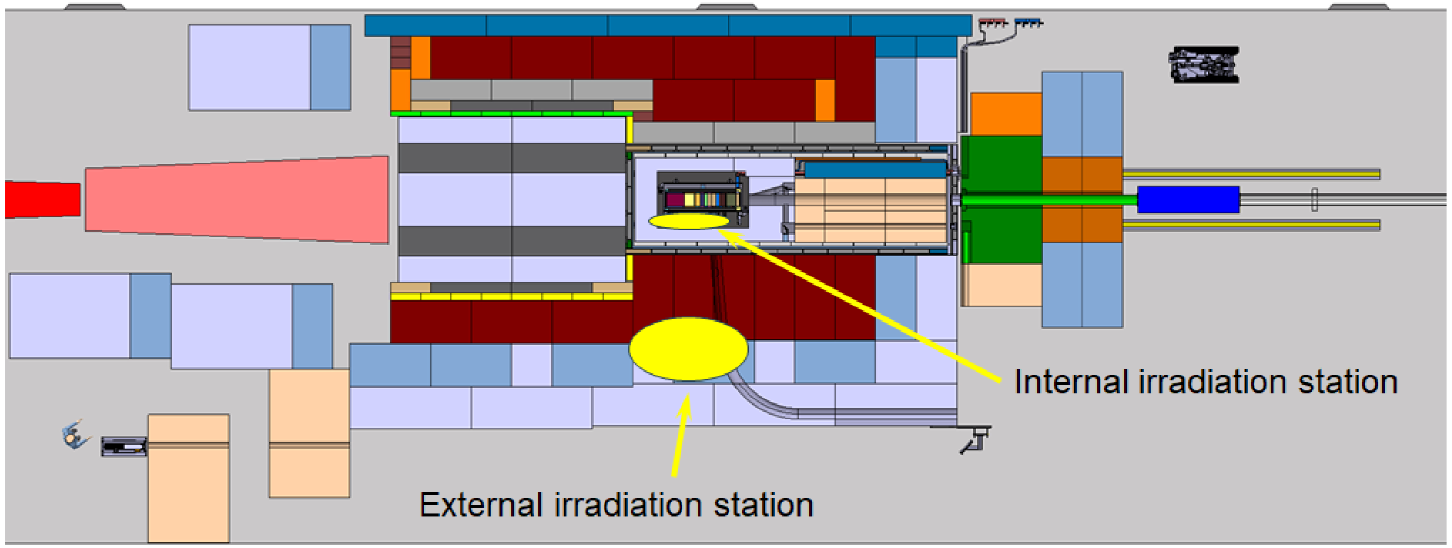
- Preliminary studies of opportunities to extend BDF's physics programme *synergetically with SHiP*:
  - Irradiation stations (nuclear astrophysics and accelerator / material science applications)
  - LArTPC to extend search for FIPs using different technology
  - TauFV to search for lepton flavour violation and rare decays of tau leptons and D-mesons



Extensions: Irradiation stations

- Can be exploited synergetically with SHiP as complementary radiation facility
  - Similar profile of radiation as at spallation neutron sources
  - A flux of ~10^{13} - 10^{14} neutrons/cm^2/pulse in the proximity of the BDF target ranging from thermal neutrons up to 100 MeV
  - Unparalleled mixed field radiation near target ~400 MGy and 10^{18} 1MeV neq/cm^2 per year





<u>Two zones:</u>

- Internal: 100-400 MGy / year adapted for irradiation of small volumes
- External: Larger zone of O(m^2) with lower radiation level

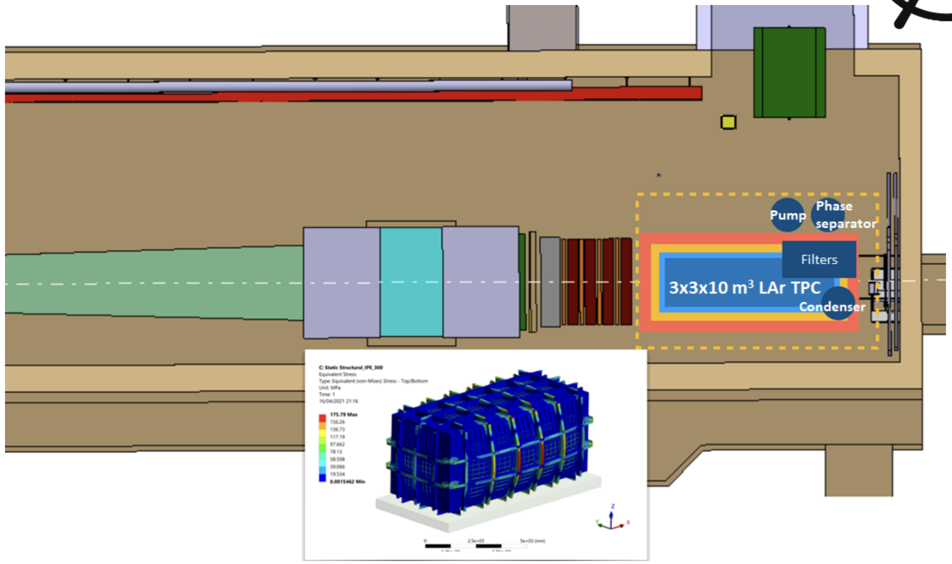
- Cross-sections important for nuclear astrophysics
- Radiation tolerance test of materials and electronic components at extreme conditions expected at FCC

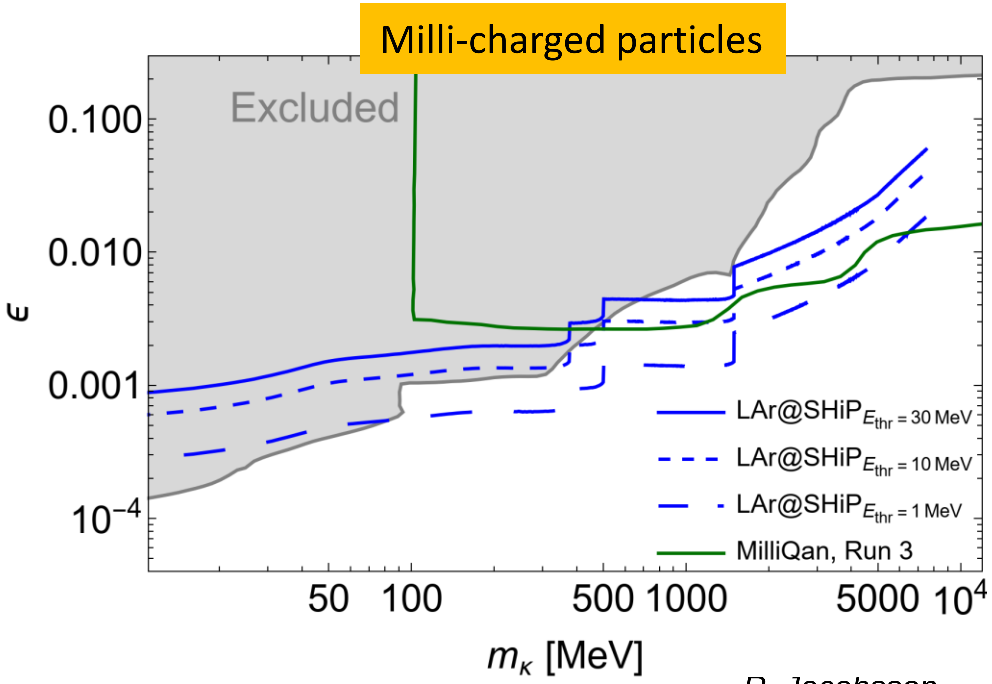
Extensions: FIP searches with LAr TPC detector

LArTPC technology is currently used in neutrino and cosmic Dark Matter search experiments

- Large experience at CERN with building 700 t detectors for DUNE
- Space available behind SHiP allows installation of LArTPC with an active volume ~3×3×10 m^3 (~130 t) and associated infrastructure

➔ Extends SHiP's physics reach using different technology



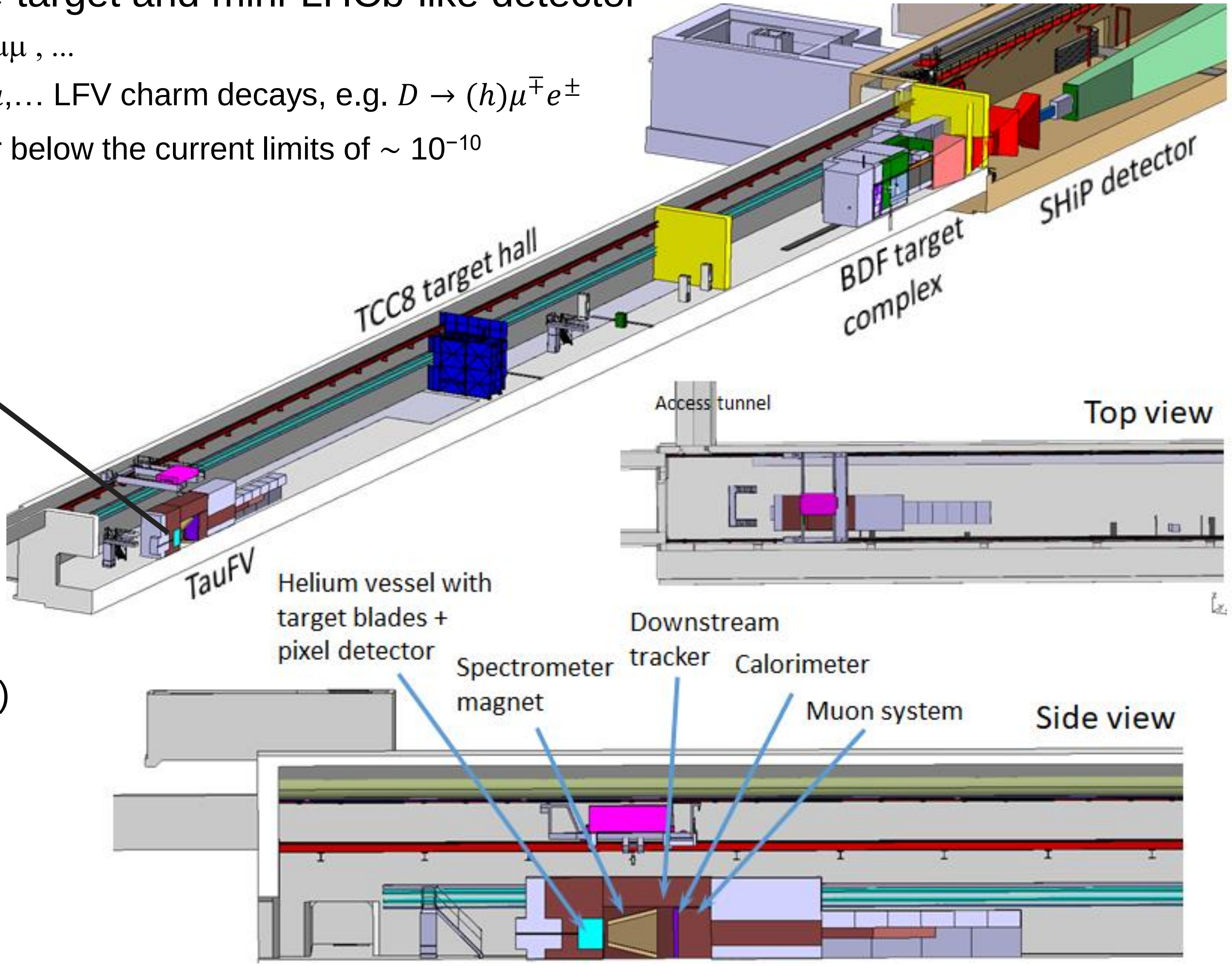


Extensions: Tau flavour violation experiment

Intercepting 1-2% of protons in BDF line with wire target and mini-LHCb-like detector

- n_τ [year^{-1}] ~ O(10^{13}) : $\tau \rightarrow 3\,\mu$, $\tau \rightarrow \mu\,\gamma$, $\tau \rightarrow ee\mu$, $\tau \rightarrow e\mu\mu$, ...
- $n_{D\ mesons}$ [year^{-1}] ~ O(10^{15}) : Also opportunity for $D \rightarrow \mu\mu, \ldots$ LFV charm decays, e.g. $D \rightarrow (h)\mu^{\mp}e^{\pm}$
- $n_{K\ mesons}$ [year^{-1}] ~ O(10^{18}) : $K_L^0, K^+ \rightarrow \pi\mu^{\mp}e^{\pm}$ probed far below the current limits of $\sim 10^{-10}$

~5 x (0.4mm x 2mm) tungsten wires (actually "blades")



➔ $\tau \rightarrow \mu\mu\mu$ yields with *5 years* of operation and assuming branching ratio 10^{-10}
(TauFV acceptance * preselection efficiency = 5%)

Experiment	PoT / $\int \mathcal{L}dt$	Yield
TauFV	4×10^{18}	800
Belle II	$50\,\text{ab}^{-1}$	1
LHCb Upgrade I	$50\,\text{fb}^{-1}$	14
LHCb Upgrade II	$300\,\text{fb}^{-1}$	84

Experimental context

Limited theoretical guidance is not new…

Nucl. Phys. B106 (1976)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Summary

- New programme at “Coupling frontier” at CERN with synergy between accelerator-based searches and searches in astrophysics/cosmology
  - First hints might come with breadth of modern earth/space-based telescopes

- BDF/SHiP capable of covering the heavy flavour region of parameter space, out of reach for collider experiments
  - Capability not only to establish existence but to measure properties such as precise mass, branching ratios, spin, etc
  - Complementary to FIP searches at HL-LHC and future $e+e^-$ - collider, where FIPs can be searched in boson decays

- Rich “biscuit’n’rhum” neutrino physics programme, including fundamental tests of SM in tau neutrino interactions.

- ECN3 decision process should conclude by end of 2023 with TDR work starting

- Many interesting areas of developments where recent upgrade efforts or R&D for future detectors may have application on medium term

  ➔ Call for interest from groups in the community

Acknowledgement

Huge thanks for the support from the ATS sector and HSE, and in particular the BDF WG

The SHiP Collaboration wishes to thank the Castaldo company (Naples, Italy) for their contribution to the development studies of the decay vessel. The support from the National Research Foundation of Korea with grant numbers of 2018R1A2B2007757, 2018R1D1A3B07050649, 2018R1D1A1B07050701, 2017R1D1A1B03036042, 2017R1A6A3A01075752, 2016R1A2B4012302, and 2016R1A6A3A11930680 is acknowledged. The support from the FCT - Fundação para a Ciencia e a Tecnologia of Portugal with grant number CERN/FIS-PAR/0030/2017 is acknowledged. The support from the TAEK of Turkey are acknowledged.

We are greatly indebted to the support of the Beam Dump Facility Working Group (below).

Outside of the SHiP collaboration and the BDF WG, we acknowledge in particular, for their contribution to:

- magnetisation of hadron stopper: V. Bayliss, J. Boehm, G. Gilley,
- muon shield superconducting magnet: B. Cure, M. Mentink, A. Milanese, E. Todesco,
- superconducting spectrometer magnet: H. Bajas, D. Tommasini,
- BDF irradiation station: S. Danzeca, A. Mengoni, N. Pacifico, F. Ravotti, R. Garcia Alia,
- LAr TPC: F. Resnati,
- TauFV: P. Collins, G. Wilkinson,
- and to the development of the SHiP detectors: M. Andreini, H. Danielsson.

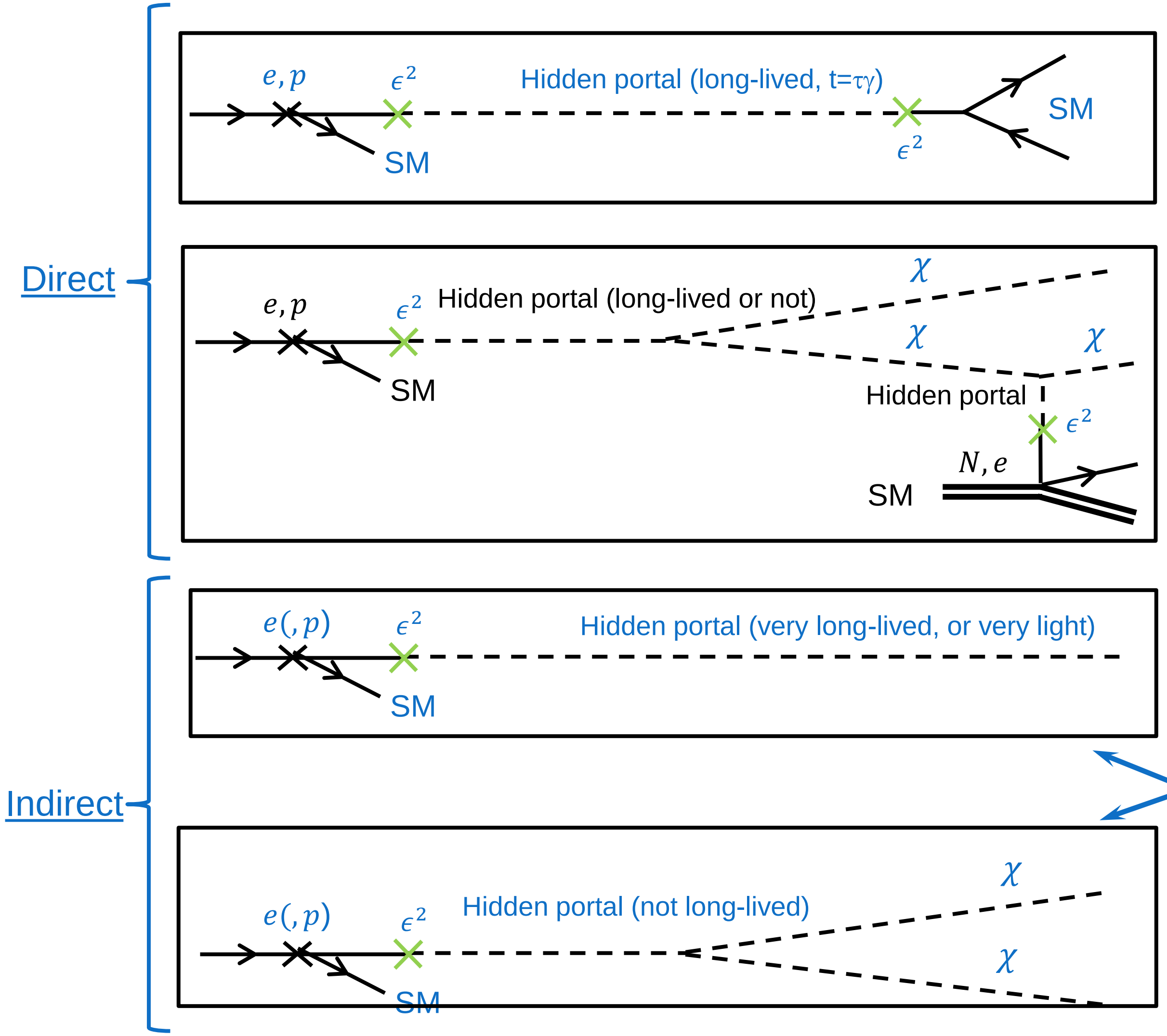
BDF Working Group[30]

O. Aberle, C. Ahdida, P. Arrutia, K. Balazs, M. Calviani, Y. Dutheil, L.S. Esposito, R. Franqueira Ximenes, M. Fraser, F. Galleazzi, S. Gilardoni, J.-L. Grenard, T. Griesemer, R. Jacobsson, V. Kain, L. Krzempek, D. Lafarge, S. Marsh, J.M. Martin Ruiz, G. Mazzola, R.F. Mena Andrade, Y. Muttoni, A. Navascues Cornago, P. Ninin, J. Osborne, R. Ramjiawan, F. Sanchez Galan, P. Santos Diaz, F. Velotti, H. Vincke, P. Vojtyla

SPARE SLIDES

Experimental techniques

Production / Detection



Decay signature ("displaced vertex")
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
→ Measurement of properties

MATHUSLA
ANUBIS
CODEX-b

NA62
NA64
FASER
SHiP

Dark matter scattering
Model-dependent interpretation
Recoil against electron or nuclei
Probability $\propto \epsilon^4$

SHiP
SND@LHC

Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

NA64
LDMX

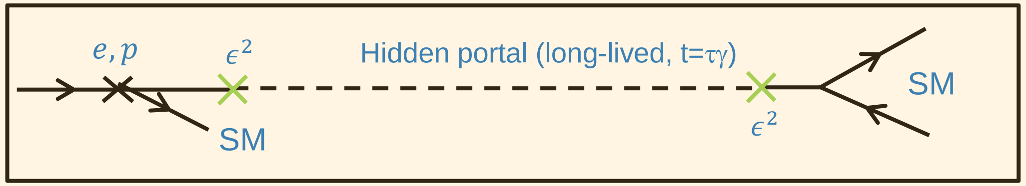
→ Background situation very different in the different techniques!!

Use of electrons limits search to Dark Photon mediator (&ALPs)

SHiP experimental technique

Production | Detection

Direct



Decay signature ("displaced vertex")
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+
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MATHUSLA
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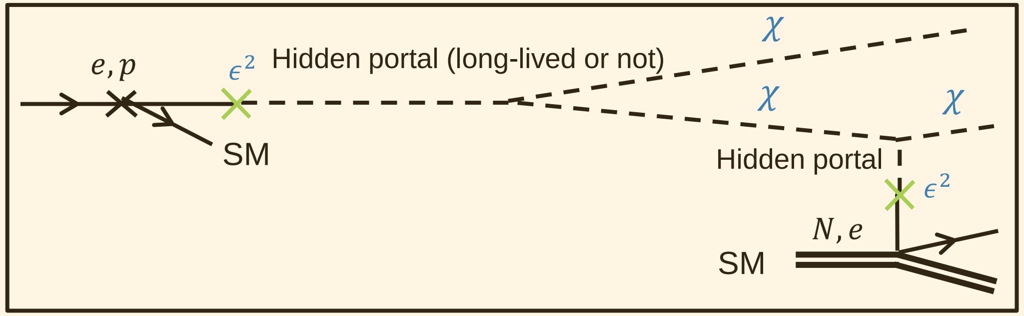
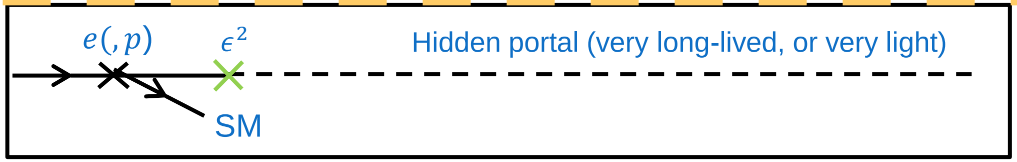


Dark matter scattering
Model-dependent interpretation
Recoil against electron or nuclei
Probability $\propto \epsilon^4$

SHiP
SND@LHC

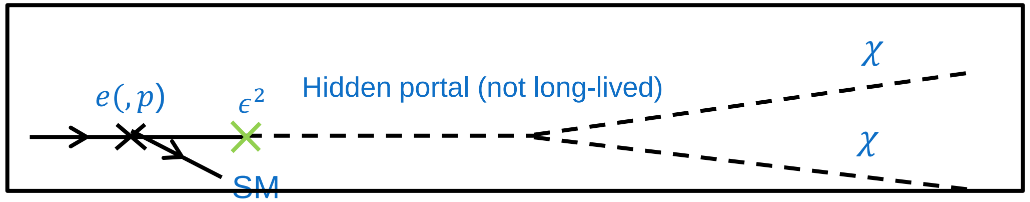
SHiP with protons

Indirect



Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation



If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

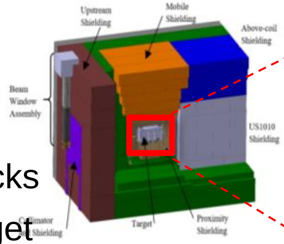
NA64
LDMX

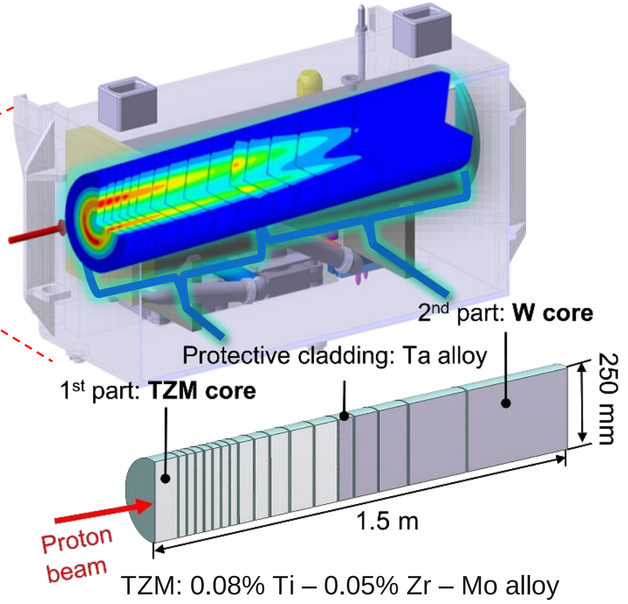
→ Background situation very different in the different techniques!!

Use of electrons limits search to Dark Photon mediator (&ALPs)

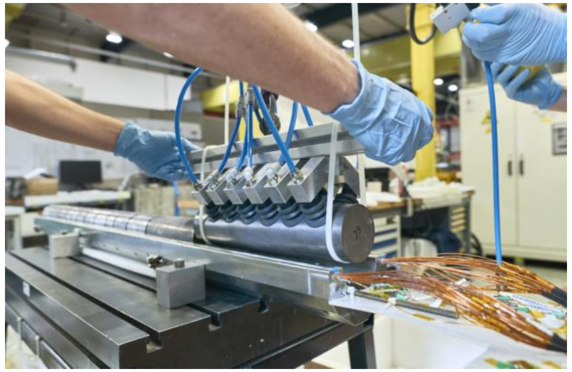
BDF/SHiP Target

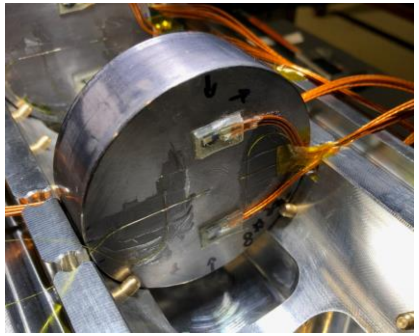
- Challenges
  - High A/Z target with high beam power of up to 2.56 MW during the 1 s spill and 320 kW on average
  - ➔ High-A/Z material resilience to high flow of cooling water
  - ➔ Target block cladding behaviour under thermo-mechanical stress
  - ➔ Integrated design of target assembly for fully remote handling

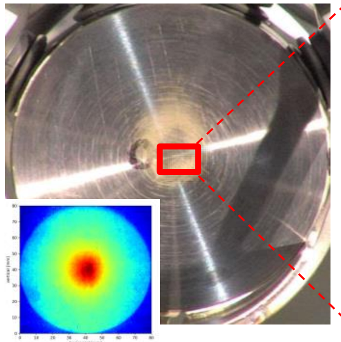


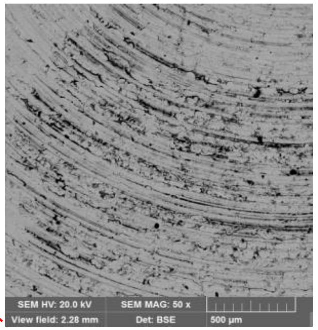


- Prototyping and beam test
  - Manufacturing validation of Ta-cladded W & TZM blocks
  - Reproduce thermo-mechanical conditions of final target
  - Cross-check FEM simulations
  - Test target online instrumentation
  - Perform detailed post-irradiation examination
  - Beam tests in 2018 with a total of 2.4 x10^{16} protons on target
  - Good agreement with simulations





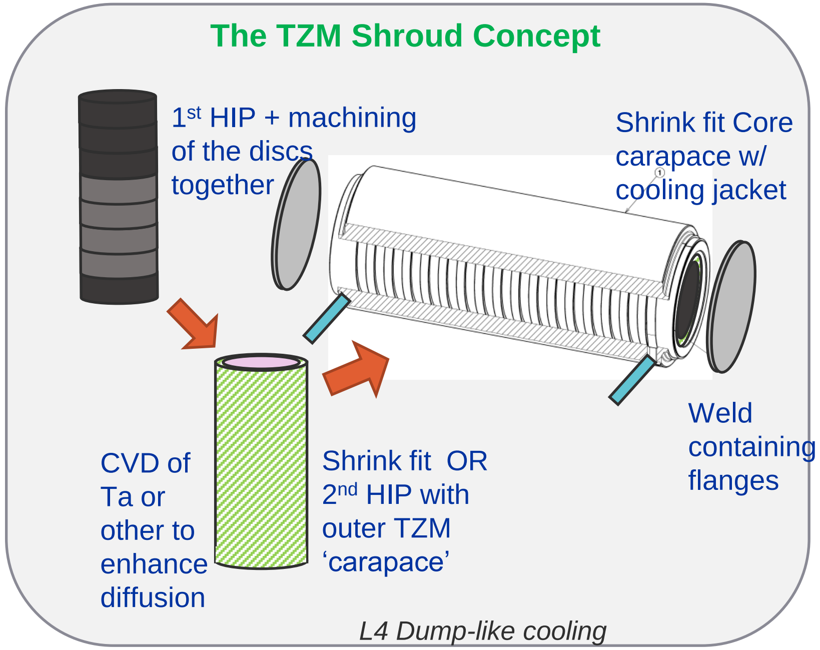


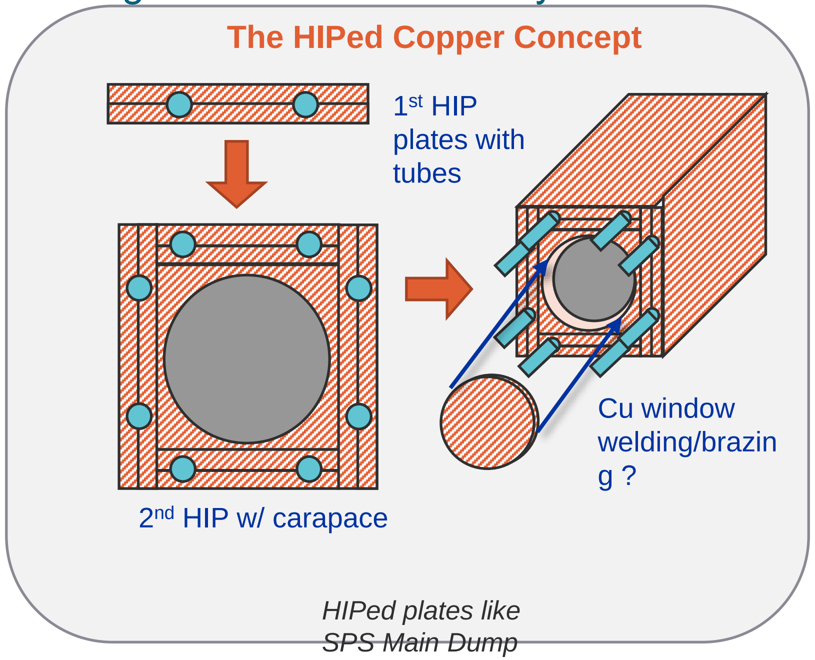


Prototype instrumentation. Visual and optical microscopy inspections during the PIE.

BDF/SHiP target – new ideas

- No water gaps between TZM & W blocks → Compact target
- Highly confined core, possibly increasing thermo-mechanical robustness → more W
- Manufacturing know-how already existent → Not starting from unknown territory



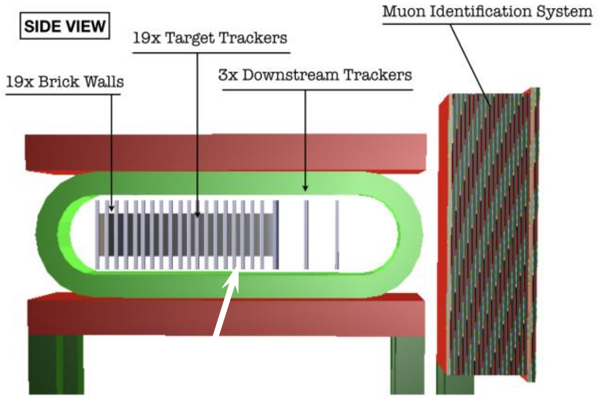


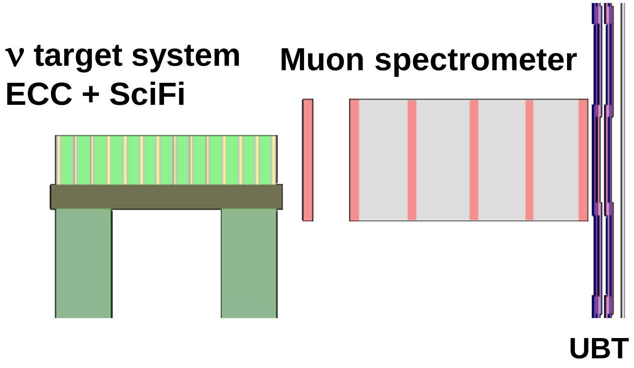
L4 Dump-like cooling serpentine jackets (welded beforehand)

HIPed plates like SPS Main Dump TIDVG5

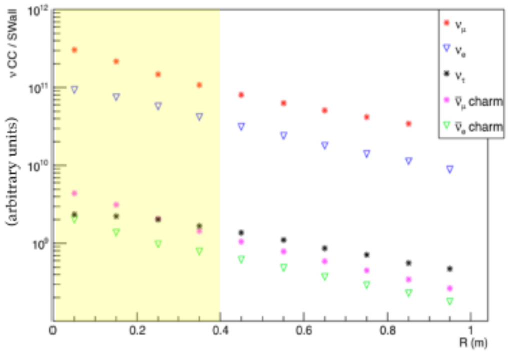
Scattering and neutrino detector

- Revised configuration
  - Magnetisation of muon system (ECN3) instead of target system (ECN4)

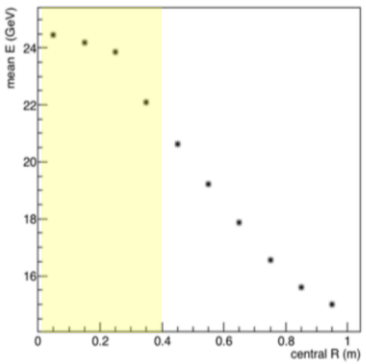




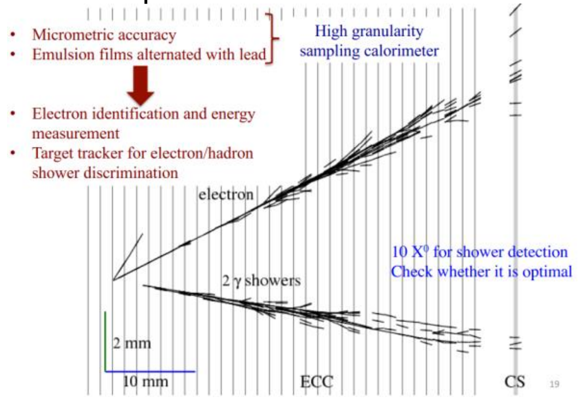
Neutrino yield density versus the radial distance



Mean energy of ν_τ



ν_e event in Opera



ECN3/ECN4 ν yield and track density of up to $6x10^5/cm^2$ from SND@LHC experience:

- ECN4 (CDS): 8 tonnes with 2 replacements per year
- ECN3 closer setup: 3.1 tonnes with 2 to 4 replacements per year → on average less emulsions

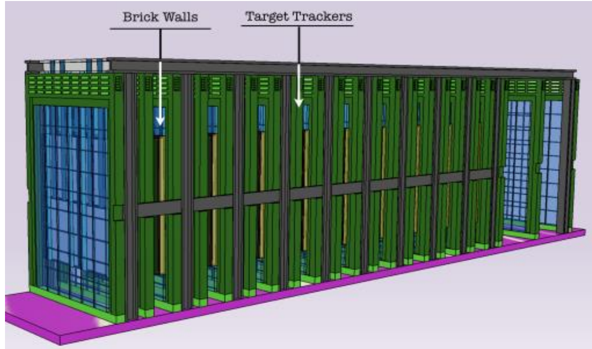
SND ECC + Target tracker

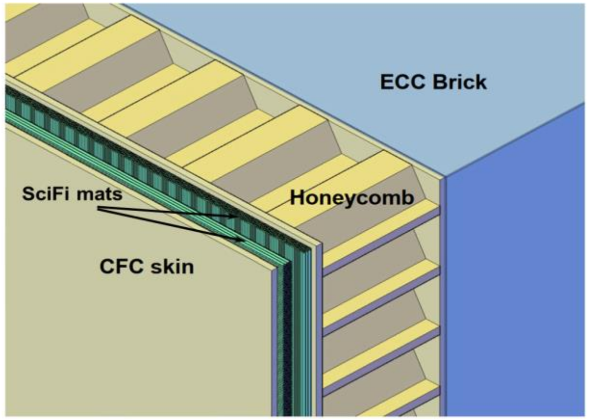
- Purpose: Neutrino/LDM vertex detector and neutrino energy with hadrons and electrons

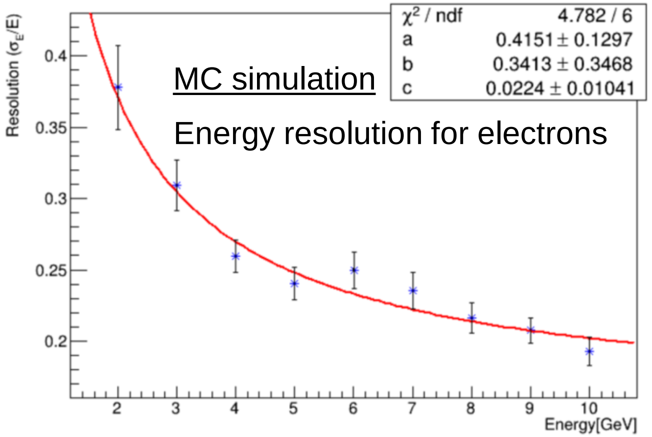
- Emulsion Cloud Chamber brick characteristics
  - Bricks of 40x40 cm^2
  - Thickness ~8 cm (57 films/lead plates → ~10 X_0)
  - Weight ~100 kg
  - Scanning speed 200 cm^2/h, 10x faster than Opera

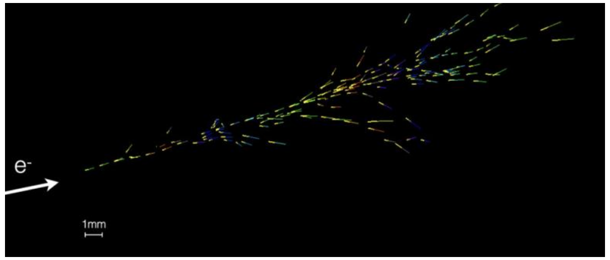
- SciFi target tracker characteristics
  - $\sigma_{x,y}$~30-50 μm resolution
  - Six scintillating fibre layers, total 3mm thickness ~ 0.05 X_0
  - Multi-channel SiPM at one end, ESR foils as mirrors on other
  - Time resolution <0.5ns
  - Extended with silicon (study in SND@HL-LHC)?

- Emulsion + TT beam test at DESY in 2019
  - Emulsion: electron identification and directionality
  - Emulsion + TT: Electron energy and time resolution



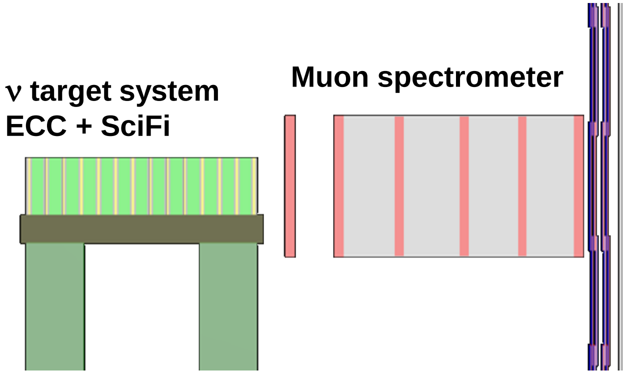


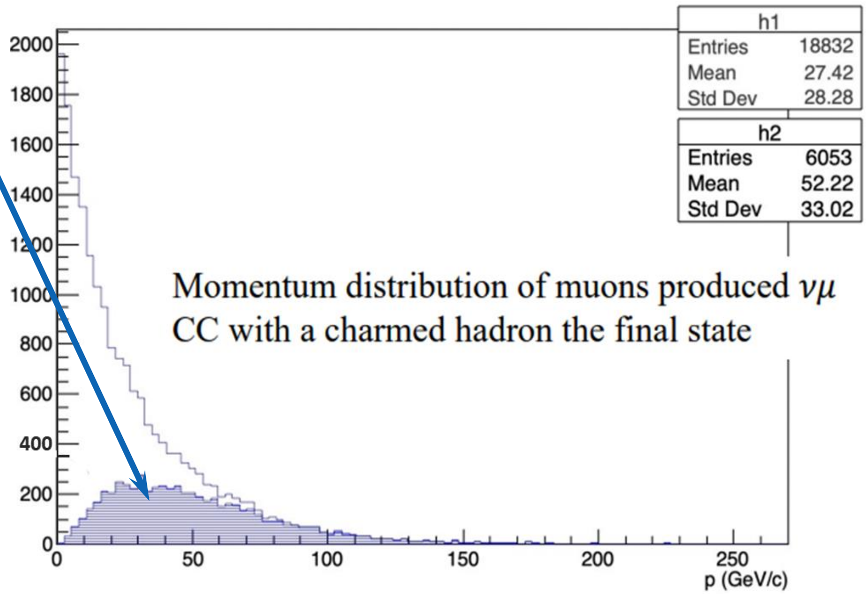




SND Muon spectrometer

- Purpose: Track and identify muons, measure charge/momenta
- Magnetised air/iron over ~3m with ~1 T
- Momentum coverage split in two/three momentum ranges
  - Position resolution of ~100 μm
  - Hidden sector acceptance is about 1/3 and correlated with high energy muons





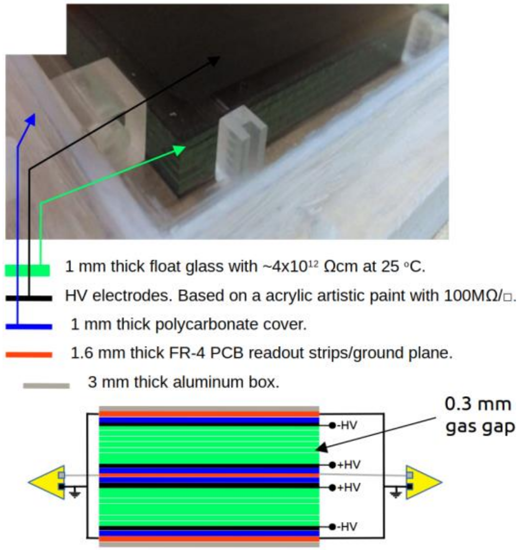
➔ Possible detector options with drift tubes or SciFi

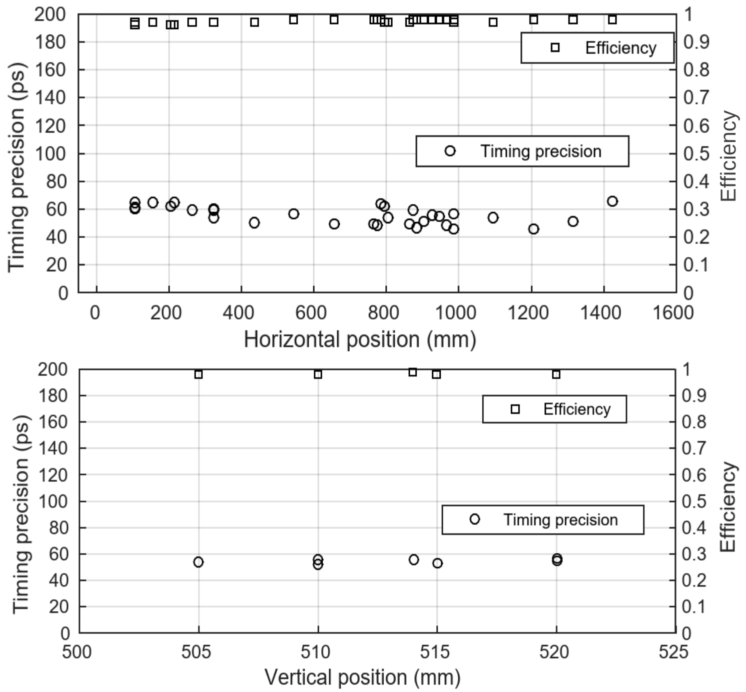
Upstream Background Tagger

- Purpose: Veto in front of decay volume
  - ➔ High efficiency, <100ps resolution, ~cm resolution

- Characteristics with 3-layer MRPC
  - Multi-gap RPC structure: six gas gaps defined by seven 1 mm thick float glass electrodes of about 1550 × 1250 mm^2, separated by 0.3 mm nylon mono-filaments
  - Two identical sensitive modules sandwiched with a plane of pick-up electrodes, consisting of 1600×30 mm^2 Cu strips

2m^2 prototype in beam test at PS





Decay volume and SBT

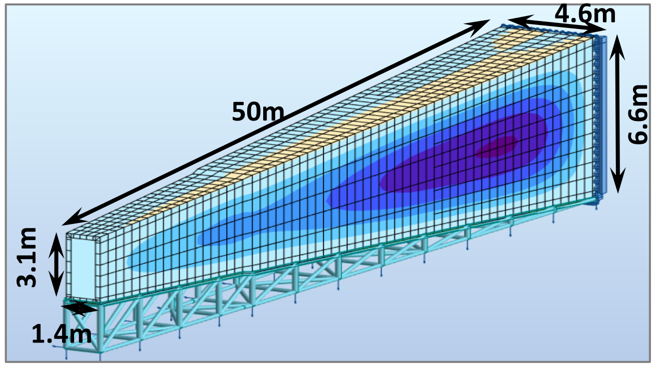
Per spill of 4x10^{13} protons

- 9 ×10^{11} and 6x10^{11} ➔ Suppress to <10 interactions per spill with decay volume under vacuum

➔ Evacuated to ~mbar air – ~bar He

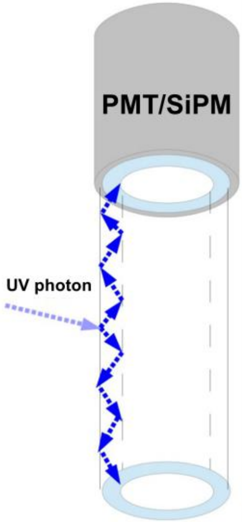
➔ Liquid scintillator veto in surrounding compartments

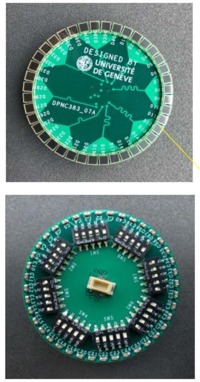
- Purpose: Tagging charged particles entering decay volume and tagging ν and μ interactions in the vacuum chamber walls
  - ➔ >99% efficiency and ~1ns time resolution



~2000 cells,
~80 x ~80 cm,
thickness ~20cm

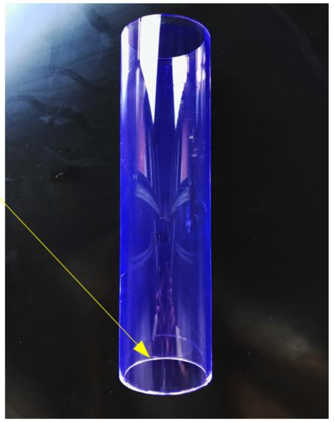
- Characteristics
  - Liquid scintillator based: linear alkylbenzene (LAB) together with 2.0 g/l diphenyl-oxazole (PPO) as the fluorescent
  - WOMs with SiPM readout Hamamatsu S14160-3050PE (40x 3x3mm²) and surrounded by PMMA vessel

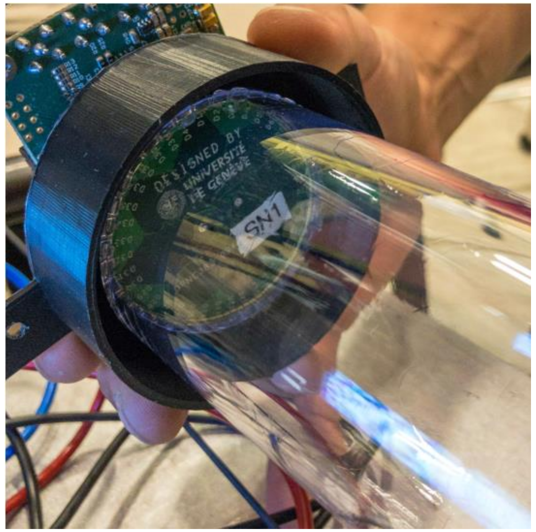


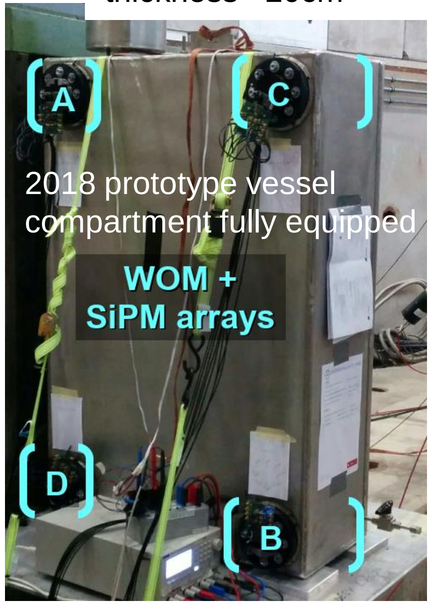


40-SiPMs array built by Geneva

WOM w/o lightguide



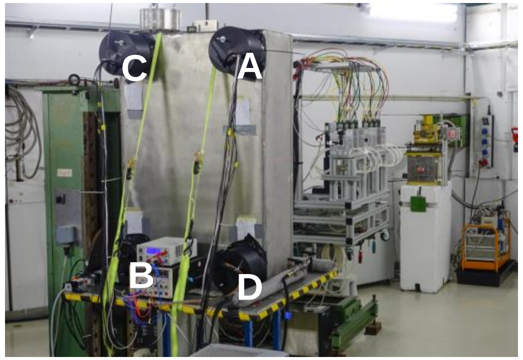


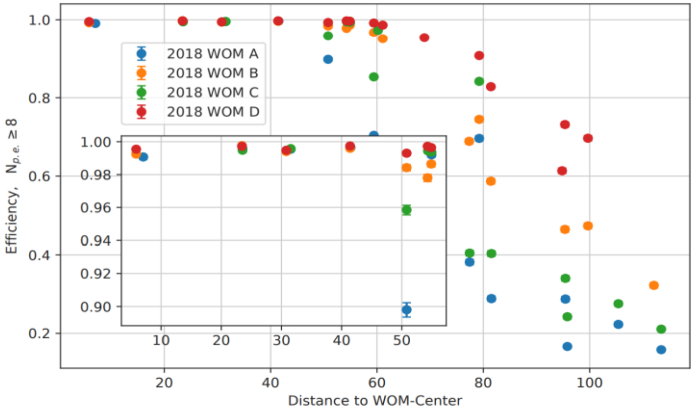


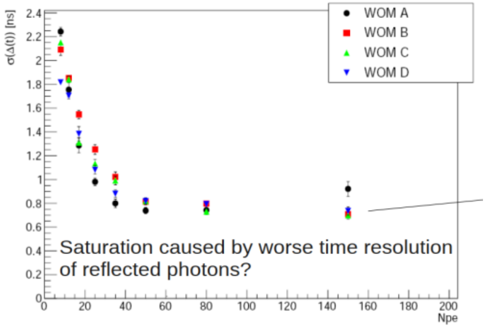
2018 prototype vessel compartment fully equipped

HS Surrounding Background Tagger

<u>'Prototype 0': 2018 test beam results</u>







➔ >99% efficiency (>45 MeV deposited), time resolution of 1 ns

<u>'Prototype 1':</u>

- 240 litre cell: Corten steel
- $BaSO_4$ reflective coating
- LHS prototype
- Improved mechanical & optical coupling
- 2 WOMs (SiPM readout)

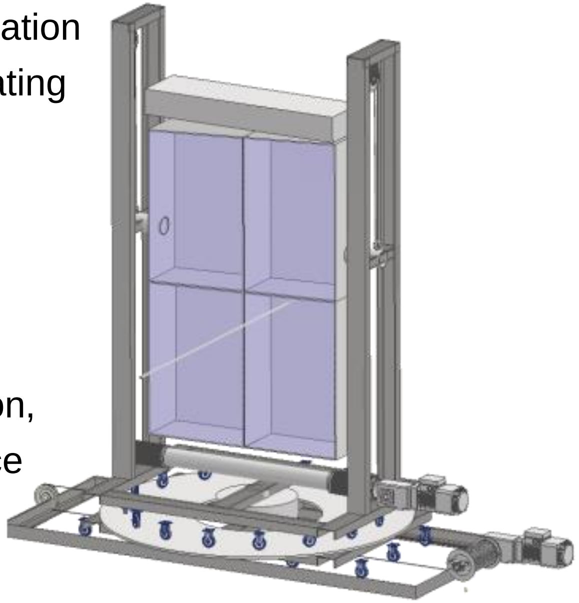
➔2022 DESY: e-

<u>'Module 0' – 4-cell demonstrator</u>

- LS handling system
- Improved mechanical integration
- Optimised cell reflective coating
- Updated readout & DAQ
- Multi-dimensional event reconstruction:

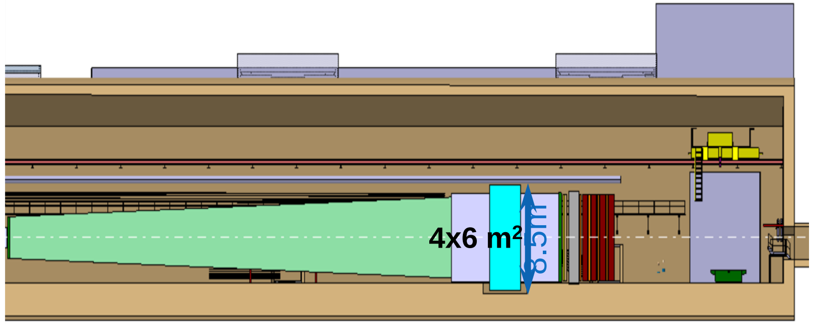
➔CERN test beam: 2023-Q4

- Light yield, energy deposition,
- spatial information, incidence angle...

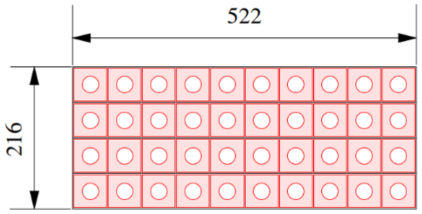


SHiP spectrometer section

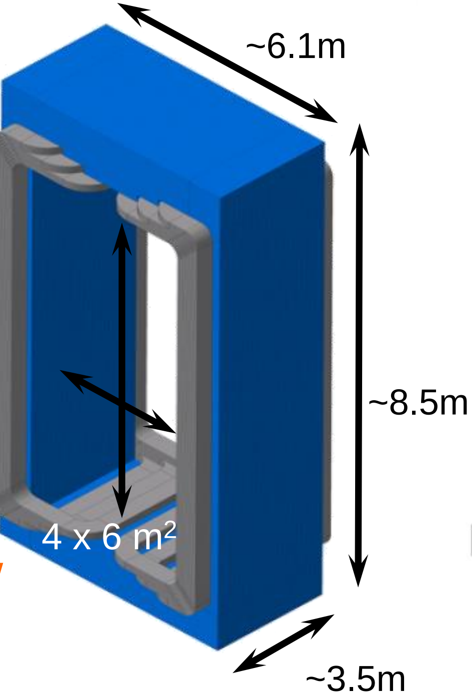
- Initial studies with aperture 5x10m^2 ➔ now 4x6m^2
  - H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020)
  - P. Wertelaers, CERN-SHiP-INT-2019-008

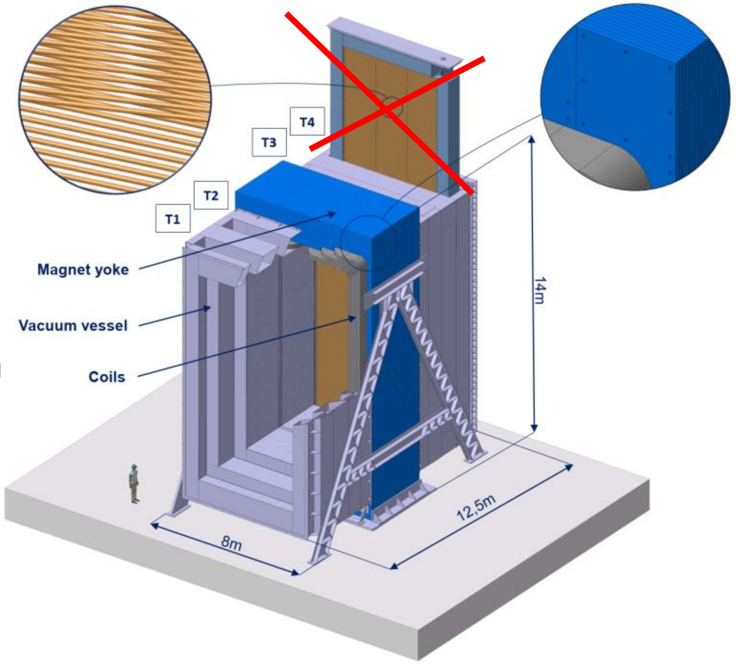


- Requirements:
  - Physics aperture 4 x 6 m^2
  - Bending field 0.6-0.7 Tm , nominal on axis ~0.15T
  - Integration of vacuum chamber



Coil's cross-section
Aluminium hollow conductor



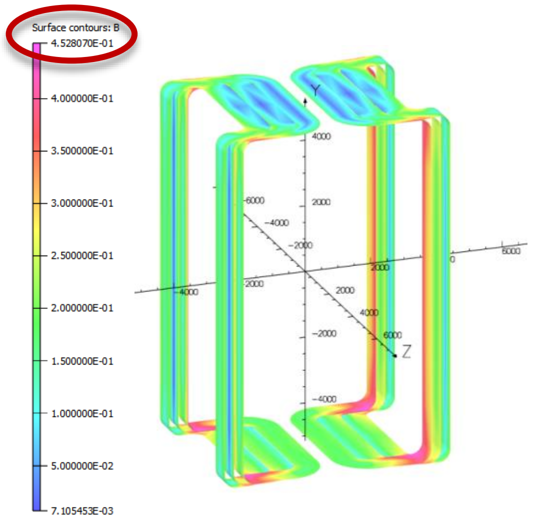


- Resistive baseline option 0.5 MW

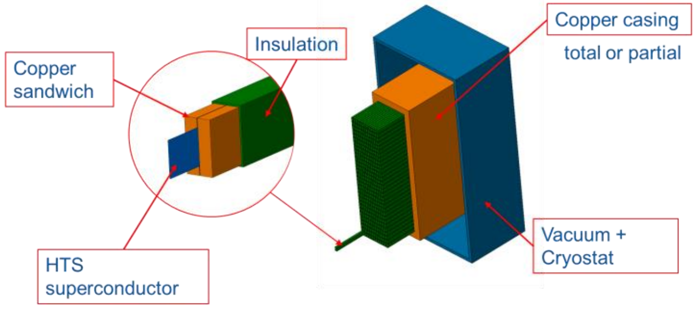
- What about superconductive with coil of same dimensions?

“Super-copper”

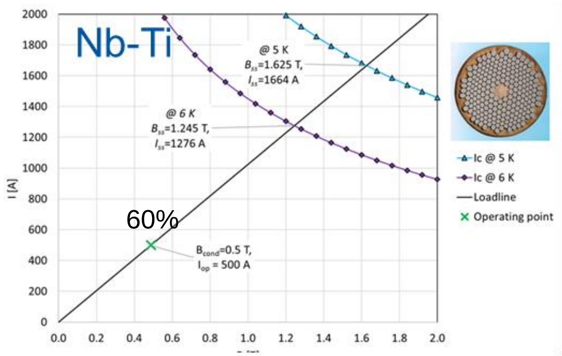
- H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020) - study of NbTi or Nb3Sn or MgB2 or ReBCO

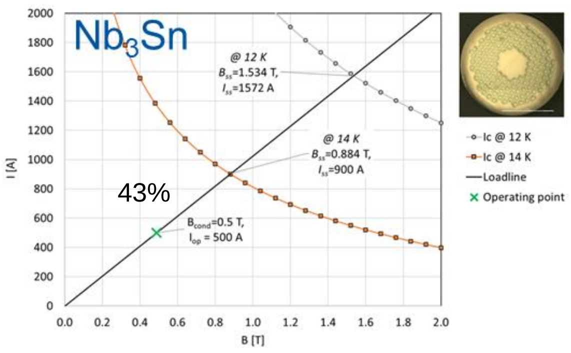


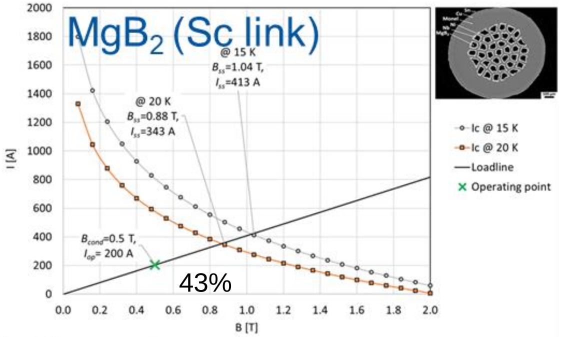
B_{peak} of 0.5 T ➔ NI_{tot} = 360 kA.turn

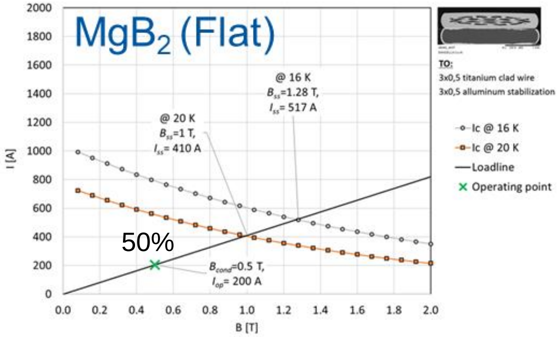


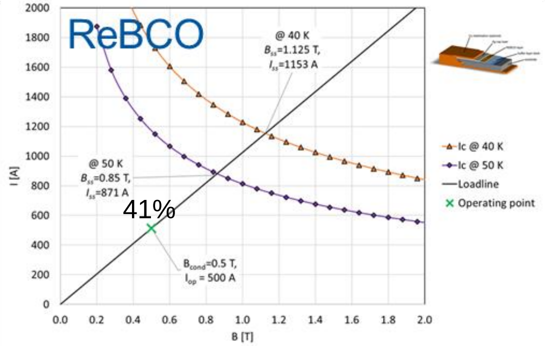
Courtesy Philip Schwarz, April 2019





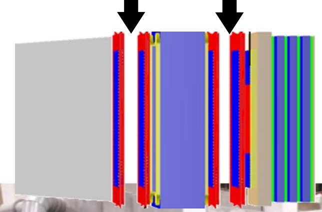




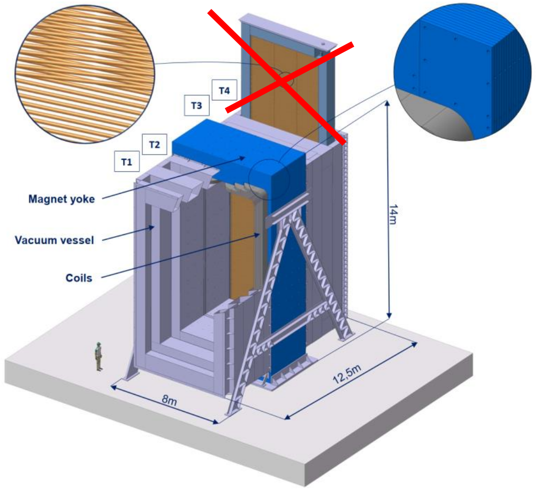


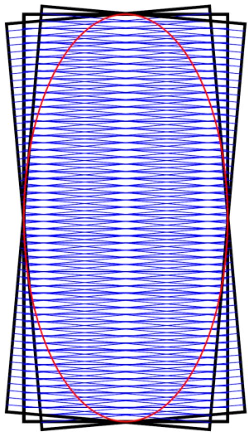
- Existing and future spectrometer magnets with large apertures will be required for many years to come!

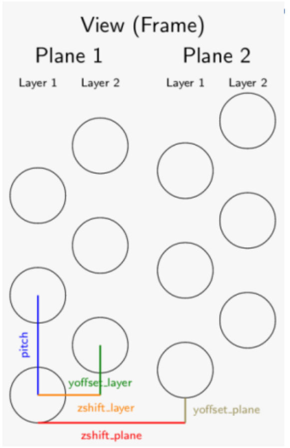
HS Straw Tracker

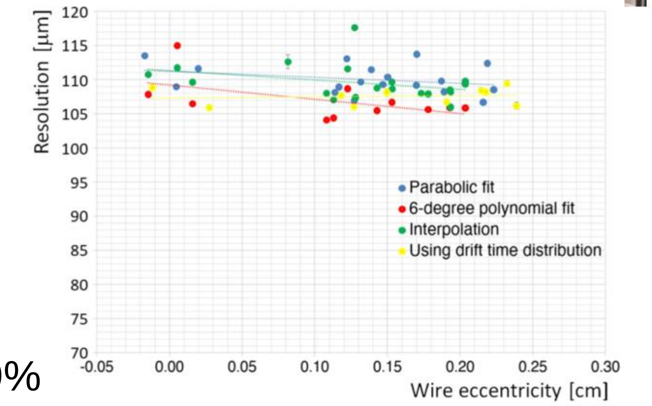


- Purpose: Track reconstruction and momentum, reconstruction of origin of neutral particle candidate. Match hits in timing detector
- Technology developed for the NA62 experiment
  - ➔ SHiP strategy: decoupling supporting frames from vacuum envelope
  - ➔ Horizontal orientation of tubes ➔ mechanical challenge
  - ➔ Lower rate allows increasing straw diameter (highest rate ~10 kHz)
- Characteristics
  - 4 x 6 m^2 sensitive area
  - 5m long 20mm diameter 36μm thick PET film coated with 50nm Cu and 20nm Au operated at 1 bar, produced and tested
  - Four stations, each with four views Y-U-V-Y, ~9600 straws



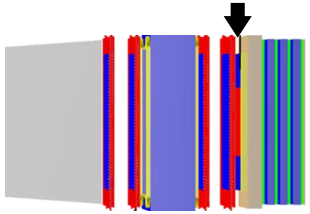




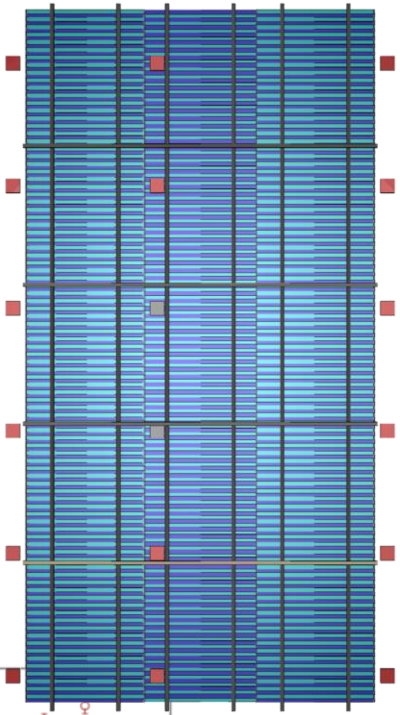


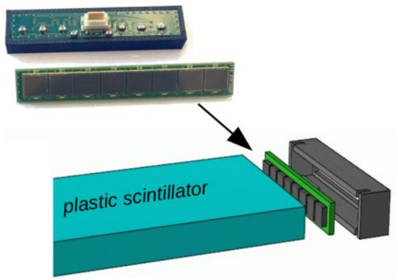
Test beams confirm 120μm hit resolution with hit efficiency >99%

HS Timing Detector

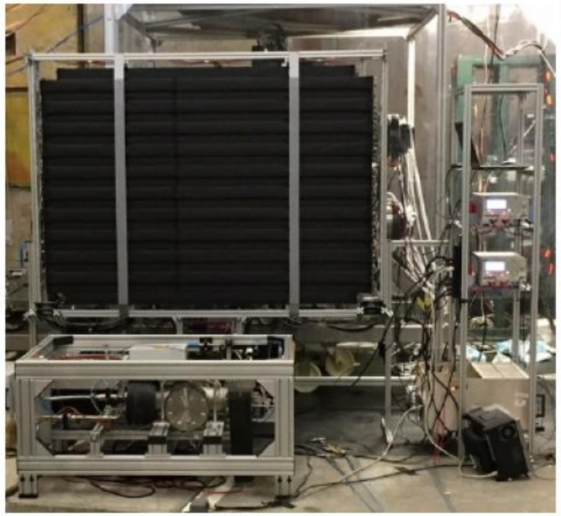


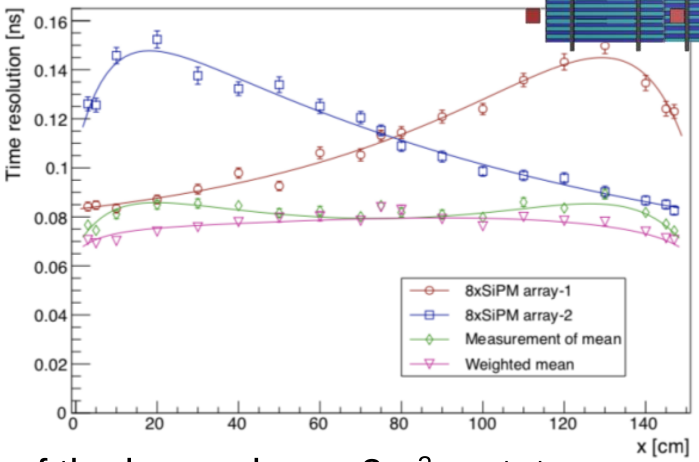
- Purpose: Provide precise timing (<100 ps) of each track to reject combinatorial background
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 135cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed
  - 330 bars and 660 channels





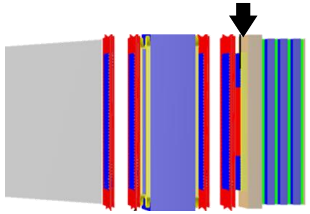
22x 168cm bar (44 channels) prototype tested at PS





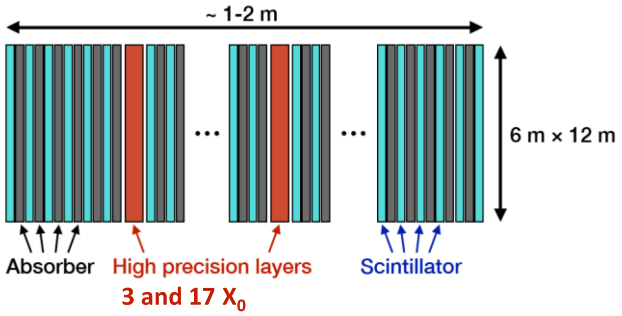
Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

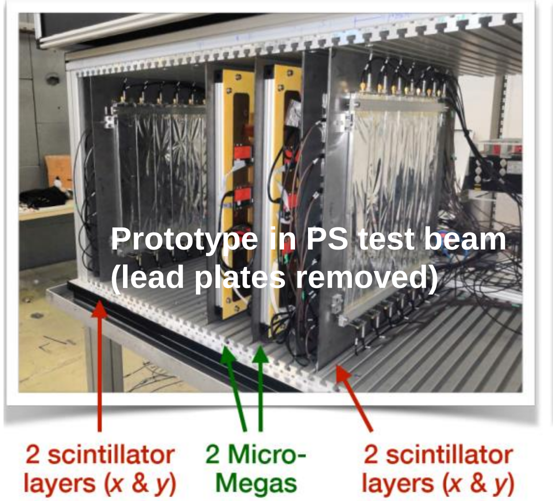
HS ECAL ("SplitCal")

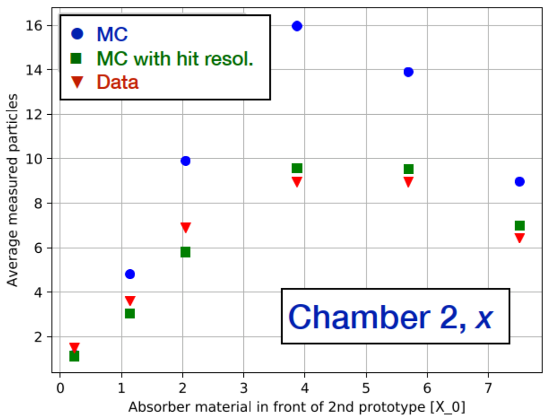


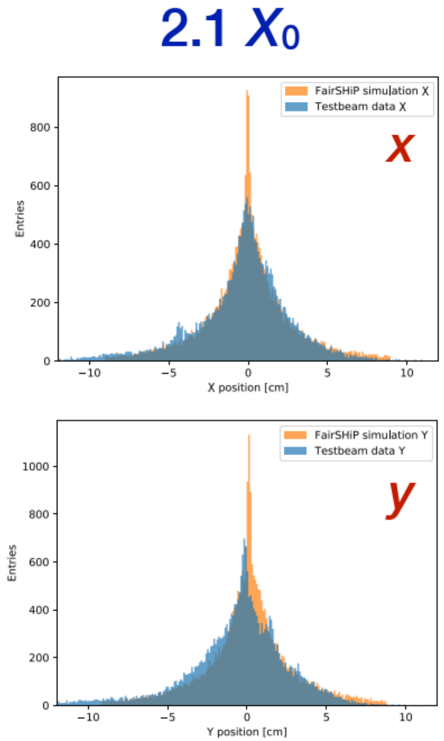
- Purpose: e/γ identification, π^0 reconstruction, photon directionality ~5mrad for ALP→ $\gamma\gamma$ (coincidence timing)
- Characteristics
  - 25 X_0 longitudinally segmented calorimeter with coarse and fine space resolution active layers
  - Coarse layers: 40-50 planes of scintillating bar readout by WLS + SiPM (0.28cm / 0.5X_0 lead + 0.56 cm plastic)
  - Fine resolution layers: 3 layers (1.12cm thick), first at 3X_0, and two layers at shower maximum to reconstruct transverse shower barycentre, with resolution of ~200μm micro-pattern or SciFi detectors, to provide photon angular resolution.

➔ 3 mrad for 20 GeV, 5 mrad for 10 GeV and 9 mrad for 6 GeV photons





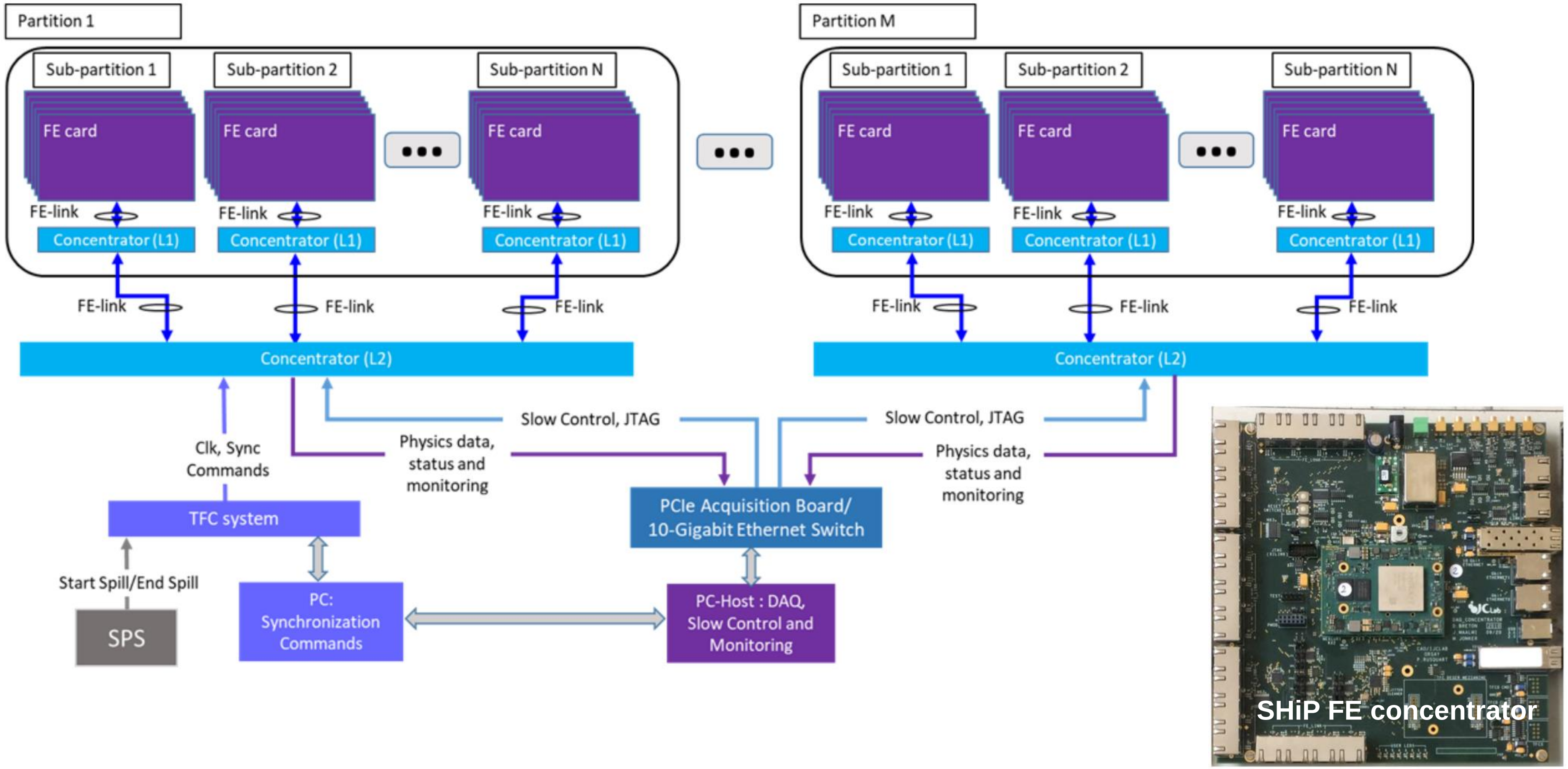




Reconstruction challenge: satellite showers in the long transverse tails

Electronics and readout

- Subsystem architecture – aiming for common electronics
- DAQ system simulation with proper occupancy and time distribution



- ECN4 CDS detector, it is estimated that
  - About 300 concentrator boards, 25 DAQ links, 12 FEH and 42 EFF computers.