



Physics programme with SHiP

SHiP Physics group

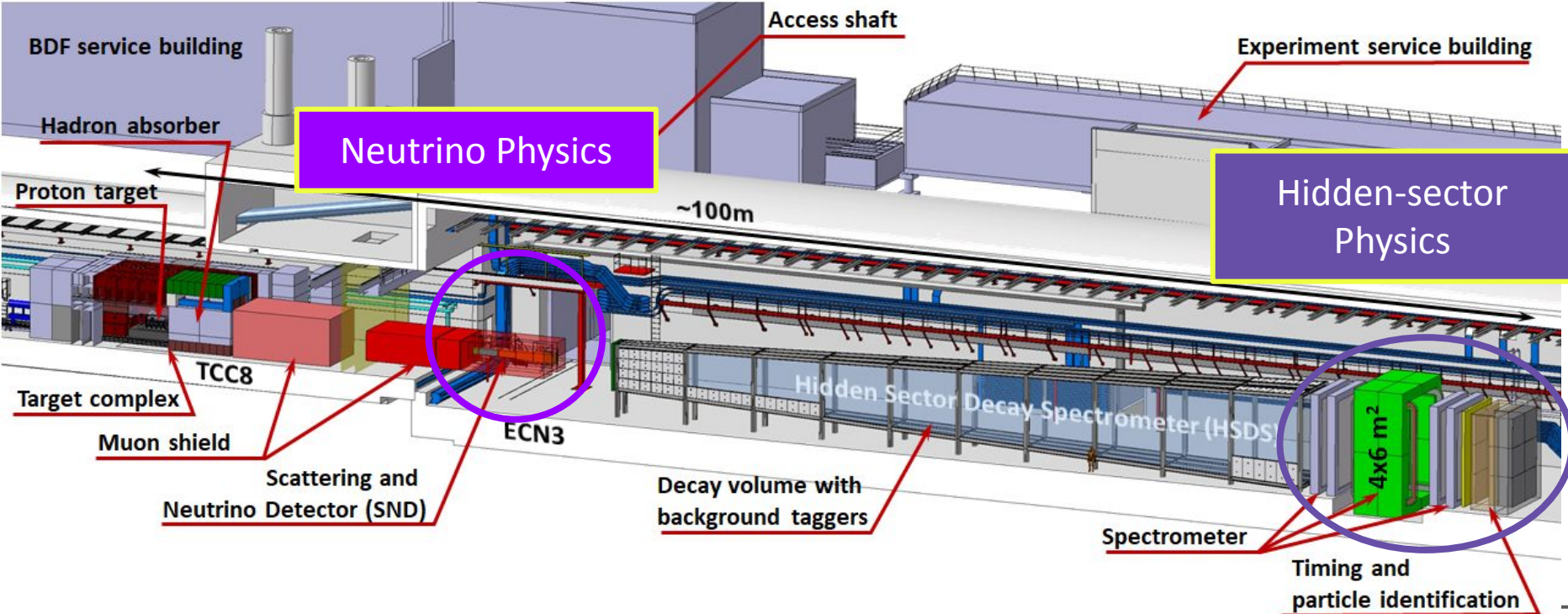
Coordinator: Lesya Shchutska (EPFL)

Deputy: Anne-Marie Magnan (IC)

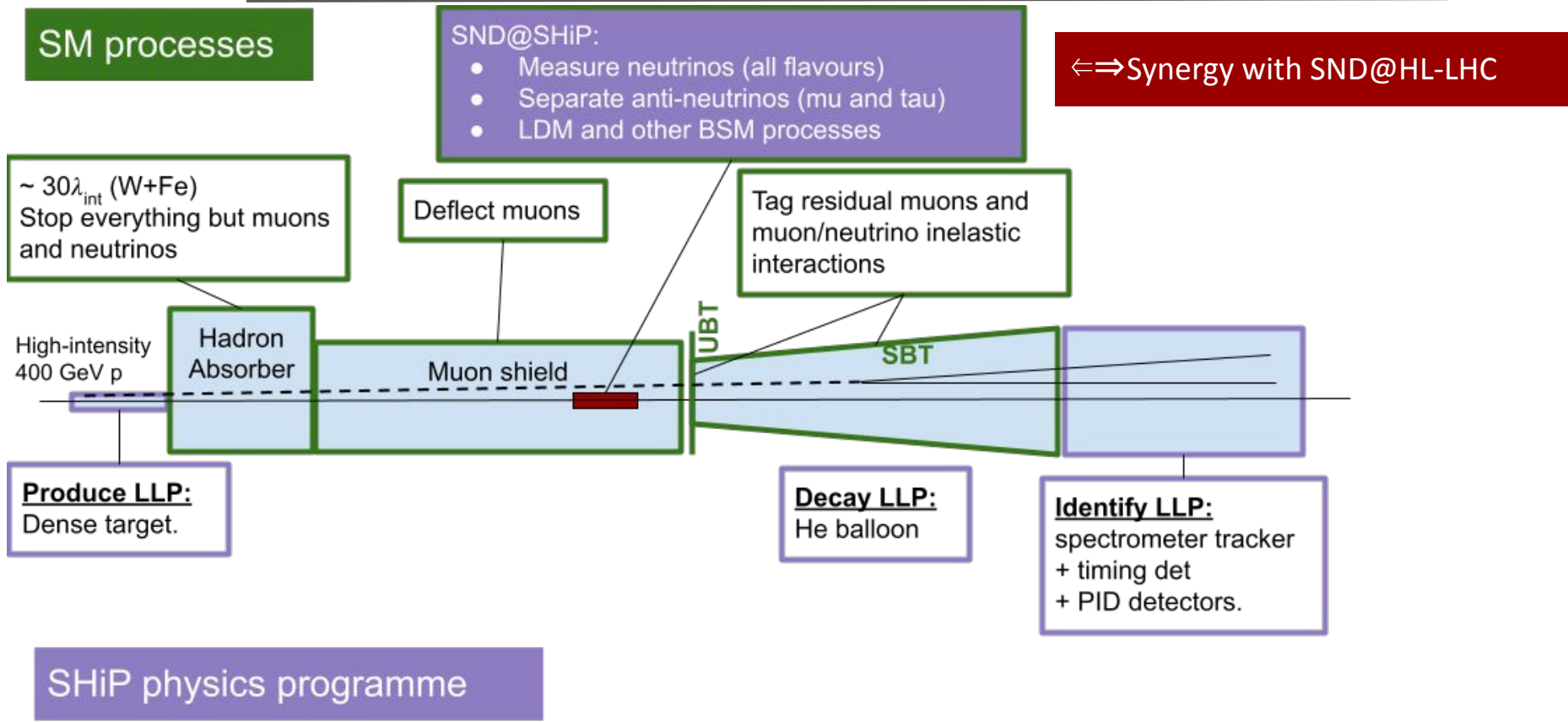
Members ~ 89 registered to
ship-physics e-group.

- Weekly meetings Tue 10-12
- Working meetings on
 - + Simulation (biweekly Thu 10.30)
 - + Veto detectors (weekly Mon 14.30)
 - + Software (weekly Fri 15.00)
 - + SND detectors (biweekly Wed 16.00)
 - + Muon shield (Wed 10.00), SBT, ...

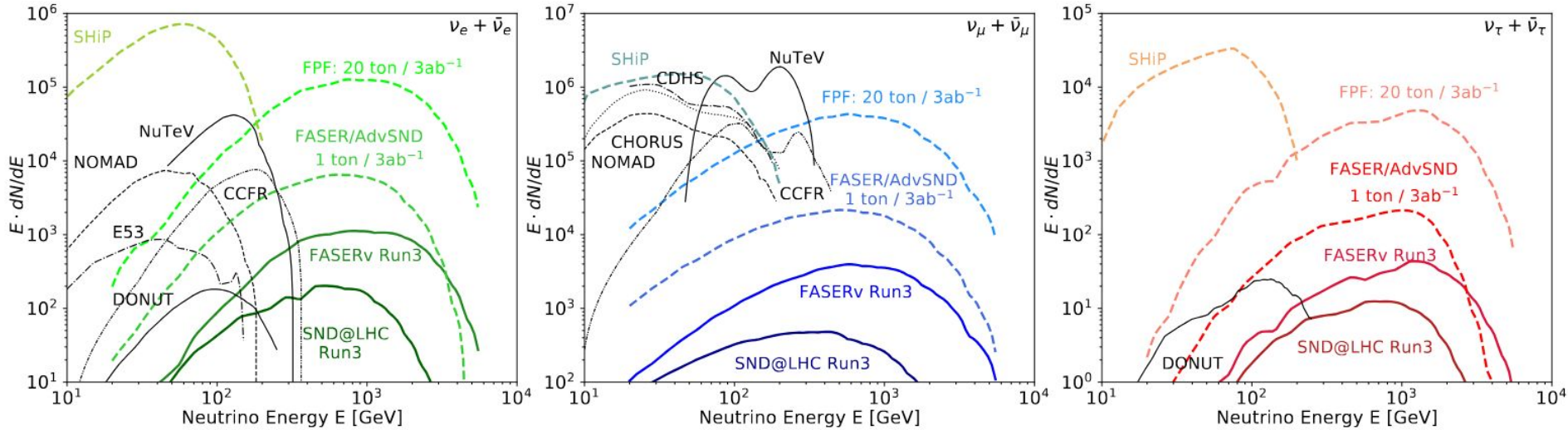
The SHiP experiment



The SHiP experiment



Neutrino physics



— running experiments

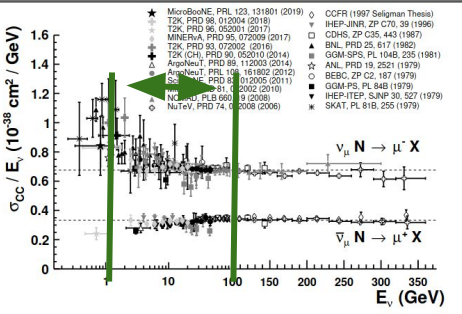
--- planned experiments

CERN-PBC-REPORT-2025-003

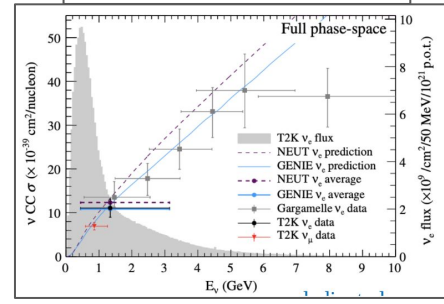
Very complementary projects. **Unique sensitivity of SHiP for tau neutrinos up to O(100) GeV.**

Neutrinos @ SHiP

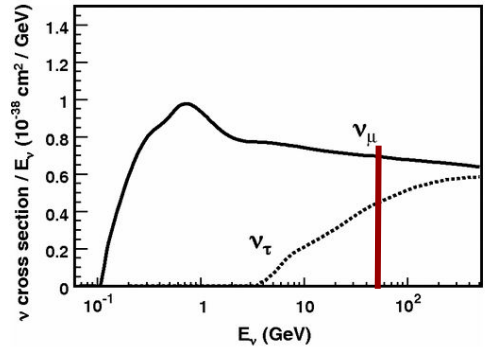
PDG - nu_mu data
 $\sigma_{CC}/E(\nu_e, \nu_\mu) \approx 0.68 \times 10^{-38} \text{ cm}^2/\text{GeV}$



Existing data for nu_e
 Only low E...

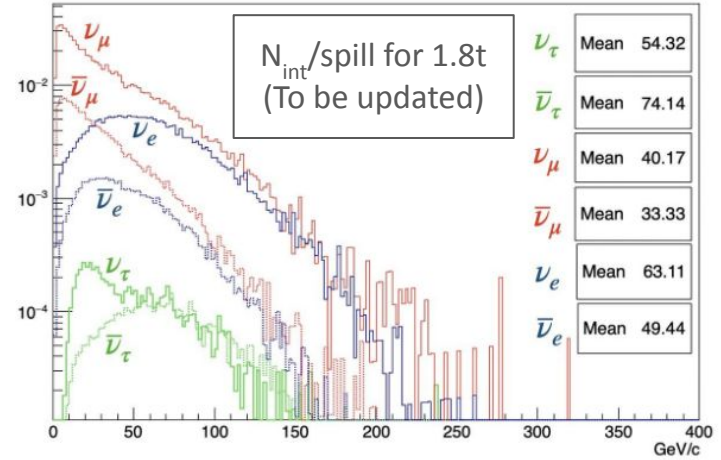


Rev. Mod. Phys. **84**, 1307



No data for nu_tau
 $\sigma(\nu_\tau) \sim 0.6 \times \sigma(\nu_e, \nu_\mu)$

- 6e29 nucleons per ton of target, W or Fe
- $N_{int}(\nu_e, \nu_\mu) \sim \text{Flux (nu/cm}^2) \times 4.1e-9 \times E(\text{nu})[\text{GeV}]$
- $\sigma(\text{antiv}) = 0.5 \times \sigma(\nu)$
- ν_μ from pi/K decays,
- ν_e/ν_τ from charm, higher $\langle E \rangle$.



A detector concept within the muon shield magnets

- 2 sections, **3 technologies**:
 - **SiStrip-W/SiPad-W** high granularity calo (HGC)
 - SiPad-Fe/**SciFi+scintillator tiles**-Fe magnetized tracking calo (MTC)
- **PS: Emulsion**: too high constraint from experimental rate

Magnetised Tracking Calorimeter:

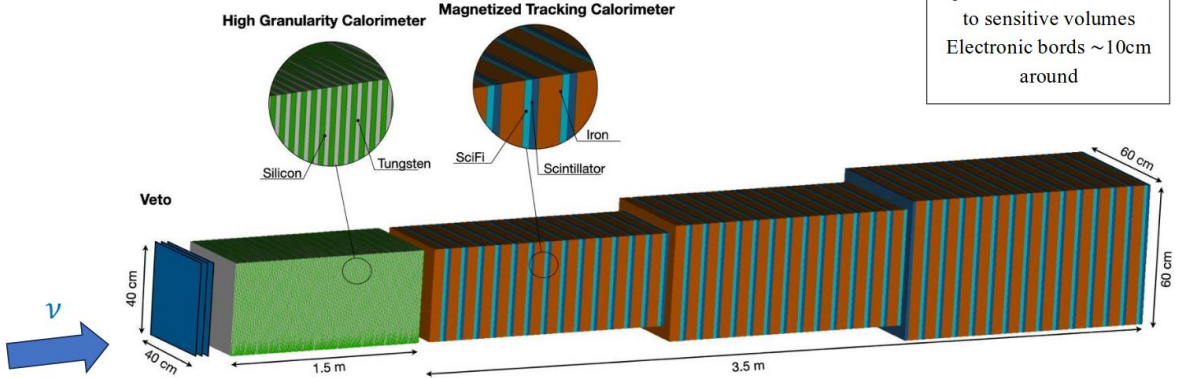
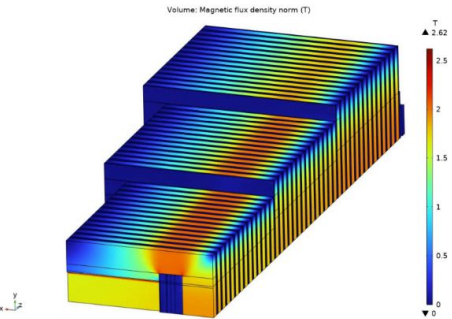
- 4.24 tons Fe (baseline)
- $B \sim 1.9$ T (in Fe)
- $12 \lambda_{in}$
- $\sim 3 X_0$ per layer,
- Moliere radius ~ 1.7 cm for Fe

High-Granularity Calorimeter:

- 1.3 tons W (baseline),
- $B=0$,
- $4 \lambda_{int'}$
- $1 X_0$ per layer,
- Moliere radius ~ 1 cm for W

⇔ Synergy with SND@HL-LHC

quoted dimensions refer to sensitive volumes
Electronic boards ~ 10 cm around



HIGH GRANULARITY CAL	
Tungsten	120
Silicon	120
Weight	1.3 tonnes

MAGNETIZED TRACKING CAL	
Iron	42
Scintillator	42
SciFi	42
Weight	4.2 tonnes

42 Fe slabs, 5 cm each
 $\geq 10 \lambda$
[Bd] ~ 3 Tm

Expected statistics per year — To be updated!

1.3 W tons in the Si/W

Interactions/year (i.e. 4.5×10^{19} pot)

	CC DIS (W)	Charm CC DIS (W)
N_{ν_e}	6.8×10^4	4.1×10^3
N_{ν_μ}	2.0×10^5	8.7×10^3
N_{ν_τ}	2.1×10^3	1.2×10^2
$N_{\bar{\nu}_e}$	1.4×10^4	7.4×10^2
$N_{\bar{\nu}_\mu}$	4.4×10^4	1.7×10^3
$N_{\bar{\nu}_\tau}$	1.5×10^3	8.6×10^1

4.2 Fe tons in the MTC

Interactions/year

	CC DIS (Fe)	Charm CC DIS (Fe)
N_{ν_e}	1.6×10^5	9.8×10^3
N_{ν_μ}	4.6×10^5	2.0×10^4
N_{ν_τ}	5.1×10^3	2.8×10^2
$N_{\bar{\nu}_e}$	3.7×10^4	1.9×10^3
$N_{\bar{\nu}_\mu}$	1.1×10^5	4.1×10^3
$N_{\bar{\nu}_\tau}$	3.8×10^3	2.1×10^2

From 2018 target simulation
1 GeV cut, “withCharm” cascade

- $\sigma_{\text{stat}} < 1\%$ for all neutrino flavours.
- Need to focus on systematics

To be updated with new
target production!

Few highlights of the neutrino physics programme

Charm-tagging and strange PDF

- Differential cross section for each neutrino type,
- anti-nu separation for nu_mu and nu_tau where lepton charge can be measured in MTC.

+ Other Standard Model measurements...

G. De Lellis et al. / Physics Reports 399 (2004) 227–320

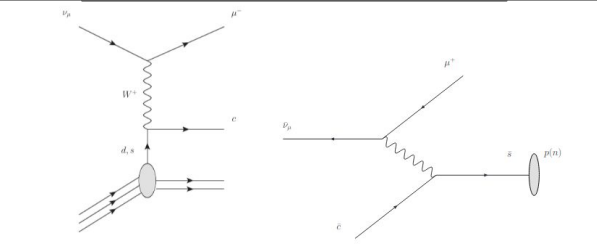
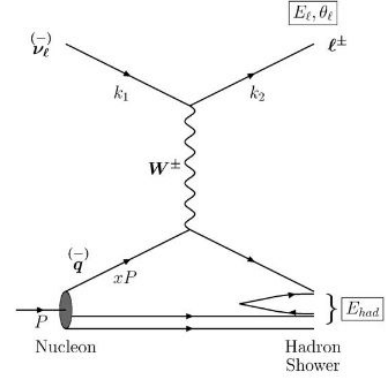
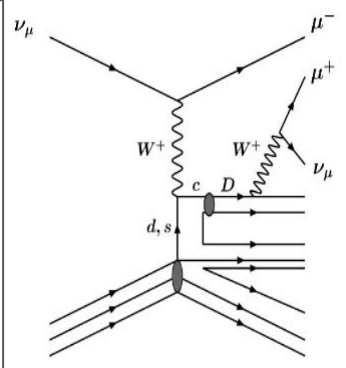


Figure 5.32: Diagram for charm production in neutrino (left) and anti-neutrino (right) charged-current interactions.



$$v = \frac{p \cdot q}{M} \equiv E_{\text{had}} ,$$

$$Q^2 = -q^2 \equiv 2E_\mu(E_{\text{had}} + E_\mu)(1 - \cos \theta_\mu) ,$$

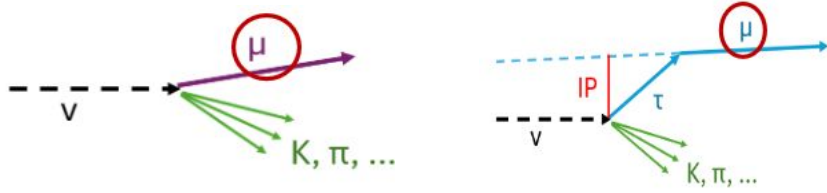
$$x = \frac{Q^2}{2p \cdot q} \equiv \frac{E_\mu(E_{\text{had}} + E_\mu)(1 - \cos \theta_\mu)}{ME_{\text{had}}} ,$$

$$y = \frac{p \cdot q}{p \cdot k_1} \equiv \frac{E_{\text{had}}}{E_{\text{had}} + E_\mu} ,$$

$$W^2 = (p + q)^2 \equiv M^2 + 2ME_{\text{had}} + 2E_\mu(E_{\text{had}} + E_\mu)(\cos \theta_\mu - 1) ,$$

+ Light dark matter
+ Other BSM signatures

Main challenges for the SND detector



Tau decay	Branching ratio	Signature	Background
$\tau \rightarrow \mu \nu \nu$	17.4%	Missing P_T	$CC\nu_\mu$
$\tau \rightarrow e \nu \nu$	17.8%	EM shower & Missing P_T	$CC\nu_e$
$\tau \rightarrow \pi^- \nu$	10.8%	Hadron shower & Missing P_T	
$\tau \rightarrow \pi^- \pi^0 \nu$	25.5%	Hadron & EM showers & Missing P_T	$NC\nu_\ell$
$\tau \rightarrow \pi^- \pi^0 \pi^0 \nu$	9.3%		
$\tau \rightarrow \pi^- \pi^+ \pi^- \nu$	9.3%		
$\tau \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu$	4.6%		

- Demonstrate **ability** of our design choices for **identifying different types of neutrinos**:
 - Separate/identify **electron shower within DIS hadronic shower**
 - Identify tau_had within DIS hadronic shower
 - Perform **leakage corrections** event-by-event to recover good missingET resolution.
 - Tag mu in HGC for nu_mu events with mu going out of acceptance before MTC.
 - Separate nu_e, nu_mu from nu_tau, tau → e, mu decay (missingET, IP reco)
 - Limit **background from NC interaction with fake lepton** reconstructed within DIS shower.
- **Detector optimisation**
 - Within tight constraints from the magnet design, TDR due early 2027
 - Overall design for the final detector configuration
 - Within overall design, placement of layers for an initial configuration with limited budget.

Physics channels

	Physics model	Final state
	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)	$\ell^+ \ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
HSDS	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	$\gamma\gamma, \ell^+ \ell^-, 2\pi, 2K$
	LDM	electron, proton, hadronic shower
SND	$\nu_\tau, \bar{\nu}_\tau$ measurements	τ^\pm
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^\pm, D^\pm, D^0, \bar{D}^0, \Lambda_c^+, \bar{\Lambda}_c^-$

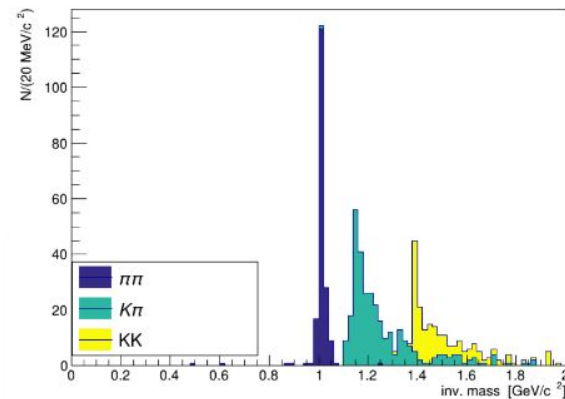
Signal reconstruction

- Tracking to reconstruct decay vertex of charged FS.
- Calorimeters to measure neutral candidates and invariant mass.
- Particle identification to further distinguish models.

Background rejection

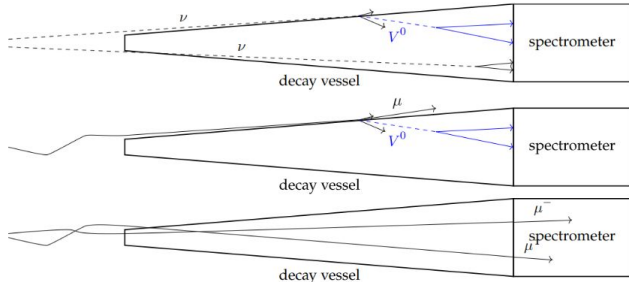
- Background taggers: upstream and surrounding.
- Timing detectors.

- With high statistics, can also further separate models using invariant mass.

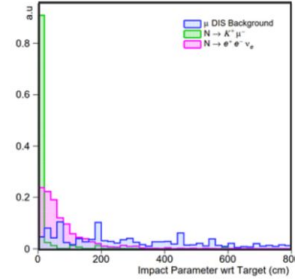
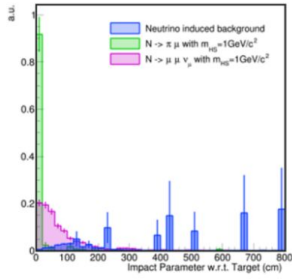
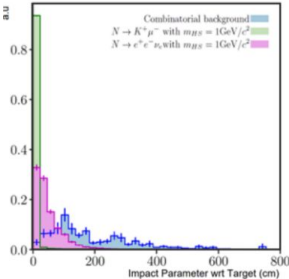


Background rejection strategy

- Use simple criteria to suppress backgrounds whilst keeping high signal efficiency, valid for all signals.
- Optimisation still ongoing.



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



To be re-optimised.

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

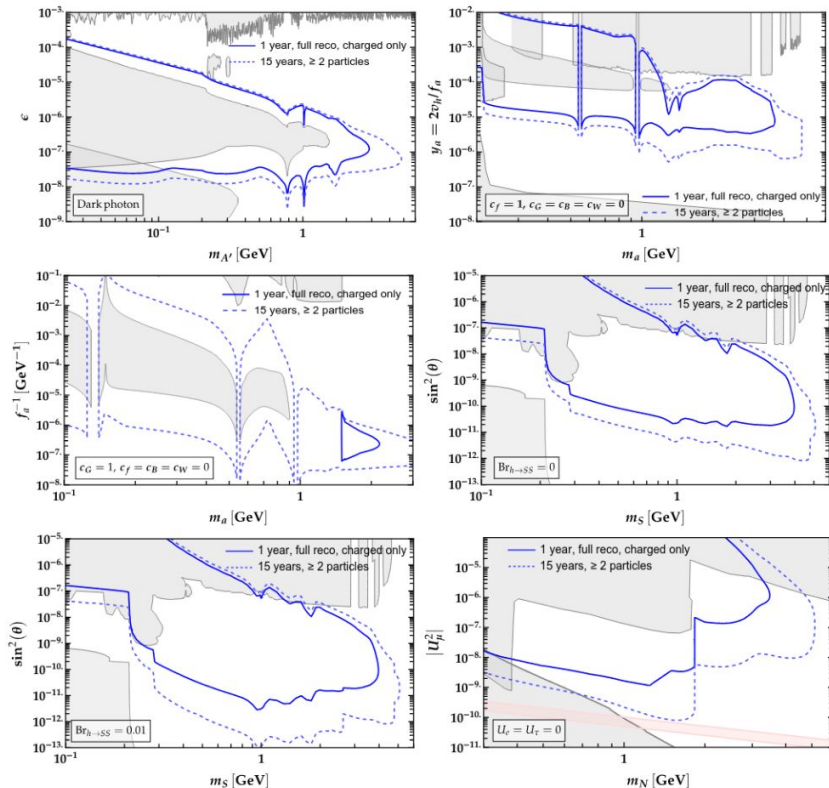
Sensitivity

SHiP's sensitivity (Figure):

- Dark photons (top-left) [BC1].
- Axion-like particles with universal couplings to fermions (top-right) [BC11].
- Axion-like particles coupled to photons (center-left) [BC10].
- Dark scalars without hSS coupling (bottom-right) [BC4].
- Dark scalars with hSS coupling fixed $\text{Br}(h \rightarrow \text{SS}) = 0.01$ (bottom-left) [BC5].
- Heavy neutral leptons mixing with ν_e (bottom-right) [BC7].

Broad Physics Reach:

- SHiP improves existing constraints by orders of magnitude
- distinguishes between theoretical models
- measures parameters relevant to cosmology.



Sensitivity projections for various benchmark models defined by Physics Beyond Colliders working group

Challenges for 0-background strategy

- Understanding of the muon shield and impact of exact muon flux
- Systematics on neutrino and muon DIS production and kinematics of the decay products:
 - Identify “dangerous” muons, “dangerous” neutrinos.
 - GENIE / PYTHIA6 / ...
- Tagging of particles in UBT (muons, pre-UBT DIS vertices)
 - Overall efficiency, including EM debris from muon shield exit face.
 - Matching with the SST tracks - multiple scattering effects.
 - False-veto rates
- Tagging of DIS products in SBT
 - Overall hit rate including muon flames and EM debris
 - DIS within SBT itself and supporting structures
 - False-veto rates

Challenges for the signal and reconstruction

- Inclusion of all pileup sources, event builder.
- Performance of SST track reconstruction
 - Impact of EM debris
- Vertex reconstruction and resolution
 - For full and partial final states.
- Impact of cascade factors at production level
- Combination of information from all detectors: SND, UBT, SBT, SST, TD, Calo...
- Multiparticle final states wrt veto detectors
 - Dedicated signal/background separation methods to not veto signal.

To do list

- Physics potential of the initial “Run 4” detector configuration
 - Full simulation with final target + Run-4 and Run-5 detector configurations
 - Physics TDR - 2027–2028
- Plans for initial background measurements:
 - Magnetic-shield OFF, low intensity
 - ...?
- Calibration strategies
- Commissioning with SM physics signals
- Validation of the MC
- SHiP-charm ?
 - Cascade factor has huge impact on neutrino (=HNL!) predicted rate.

Backups

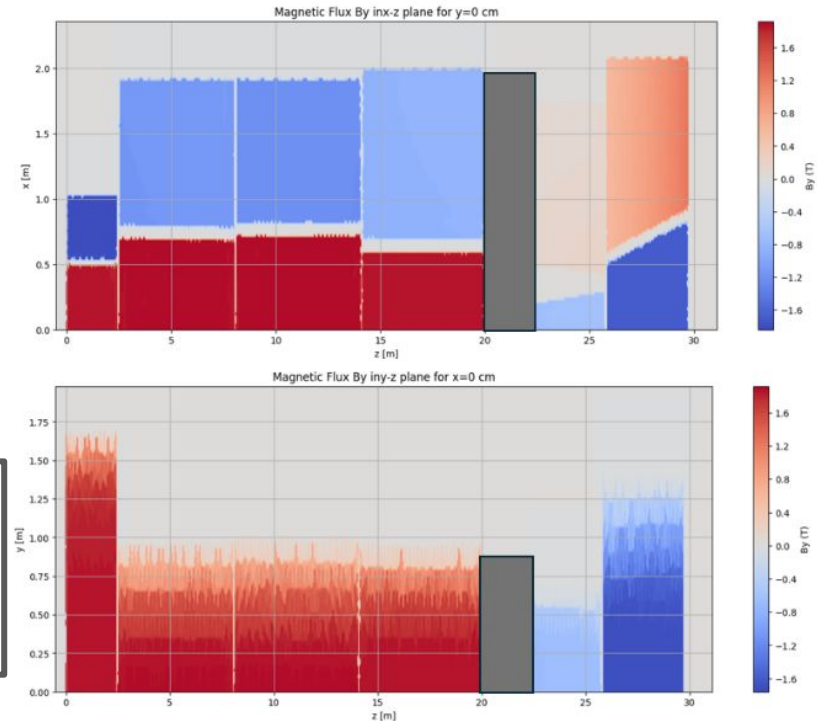
Configuration of SND within the MS optimisation

Guglielmo Frisella

The configuration of the SND inside the MS has been revised:

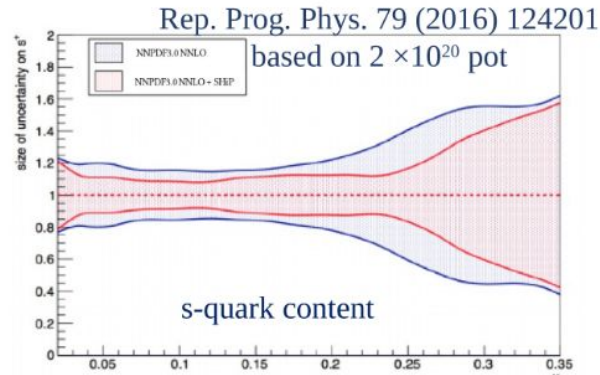
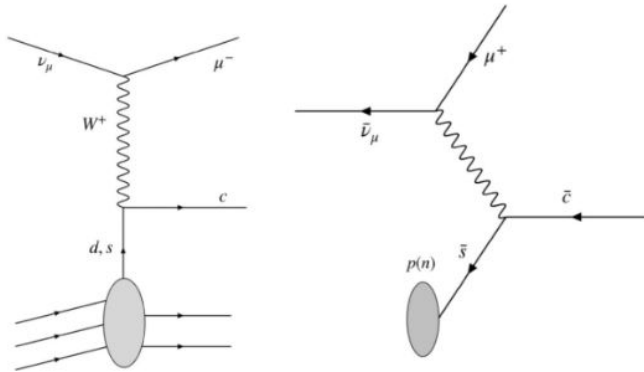
1. The SND is placed upstream of the final magnets (M4, M5).
2. The SiT is located in the passive M4 layer and can be extended up to 2.28 m.
3. The HCal is installed in M5.
4. The effective magnetic field in the HCal is assumed to be 1.1 T, accounting for the fraction of non-magnetic material.

Moved by 3m
upstream: factor O
(10%) gain in flux?



Neutrino induced charm production

- Charm production via anti-neutrinos dominated by s-quarks
- Via neutrinos shared 50/50 between d (valence) and s (sea)

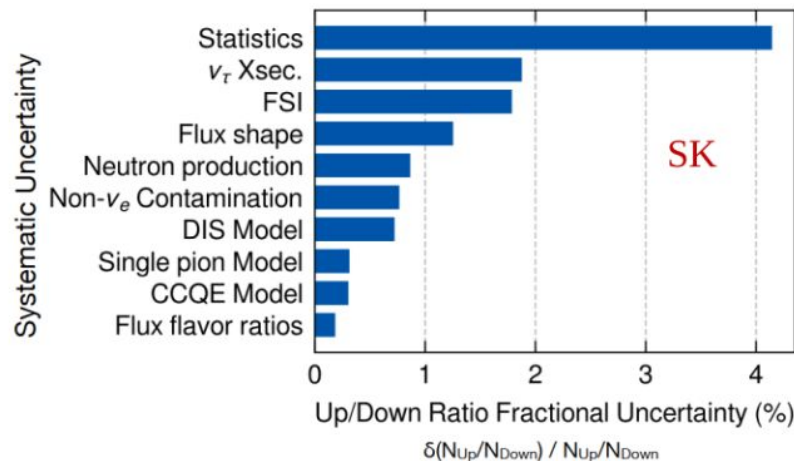
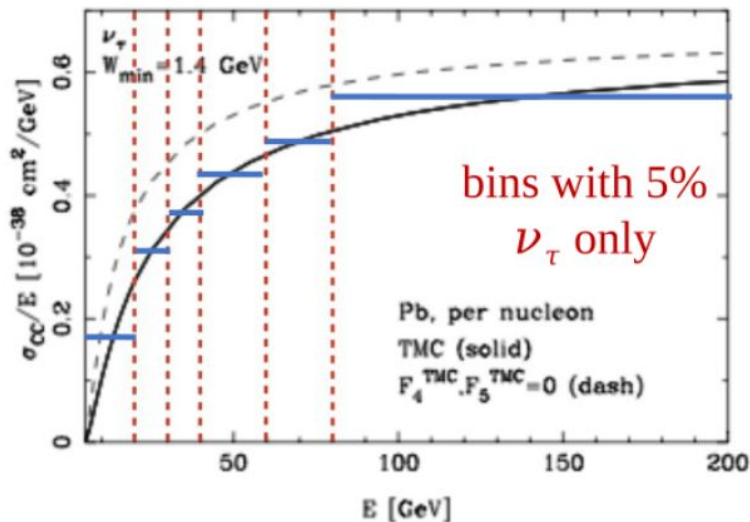


Study strange quark content of the nucleon

- $|V_{cd}| = 0.230 \pm 0.011$ (PDG 2022 value from neutrinos)
- Goal: to measure V_{cd} with <2% accuracy

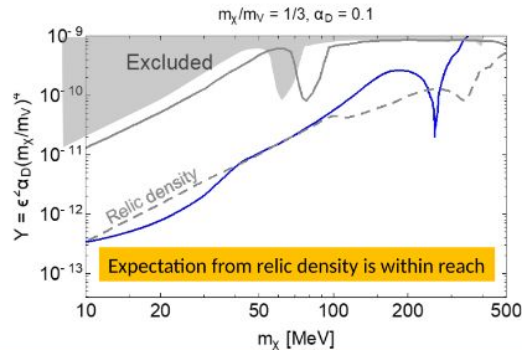
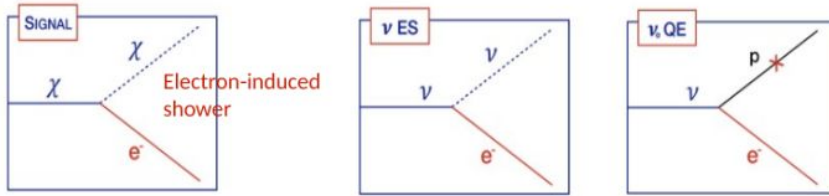
Tau neutrino cross section measurements

- Measurement of F4 and F5 structure functions
- Impact on oscillation studies, at SK/HK and IceCube



Light Dark Matter Scattering

- Direct search through scattering (Maksym sensitivity studies)
- Background dominated by neutrino elastic (Martina)



$6 \cdot 10^{20}$	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

To be updated with new target production!

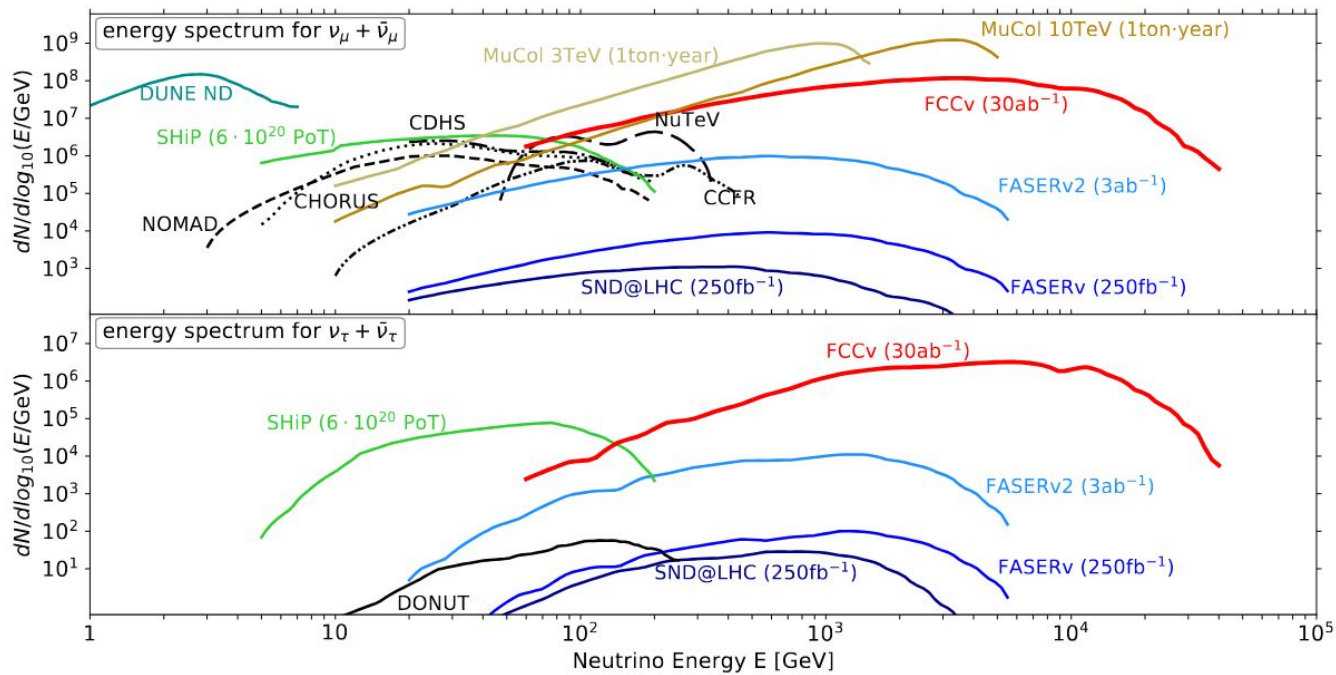
Hadronic shower reconstruction

- Nominally only $4 \lambda_{\text{int}}$ in HGC: leakage in MTC - or transverse.
- Fraction MTC/HGC dependant on interaction z .
- Lateral leakage factor (+ corrections): early interaction -> more leakage...
- Hadronic shower E resolution in HGC: similar for SiStrip and SiPad, $O(40\%/ \sqrt{E})$.
- Hadronic shower E resolution in MTC:
 - Scintillator tiles: $\sim 60\%/ \sqrt{E}$
 - SiPad could be better with smaller sampling.
- Charm tagging: exclusive decays / dilepton, probably better in HGC, final states with muons better in MTC.
- Issue of overlapping lepton-hadronic shower: best granularity will help.

SND Optimisation: summary and work ahead

- Reduce parameter space:
 - Fix total target weight for fair comparisons
 - Fix envelop for transverse size:
 - Cost + constraints from magnet: baseline design is probably the best we can do...
- Varying sampling in MTC for inclusion of SiPad layers:
 - Understand better impact on magnet + B field! Ratio $\frac{5}{8}$...
- Back layers: wherever we stop looking for neutrino vertices, should choose the cheapest technology with muon tracking capability + shower tail catcher.
- Study of mixture of different technologies:
 - Cost, technology constraints, power/DAQ constraints
 - vs. muon neutrino vertex reco (IP)
 - vs. lepton reco capacity within hadronic shower
 - vs. hadronic shower E reco
 - vs. electron E reco / charge measurement?
 - vs. tau identification, reco and charge measurement
 - vs. charm-tagging capabilities
 - vs. ??





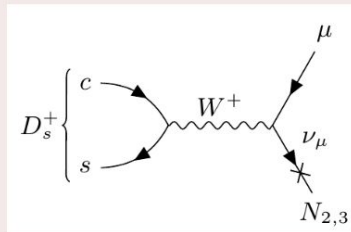


Weakly-coupled new physics

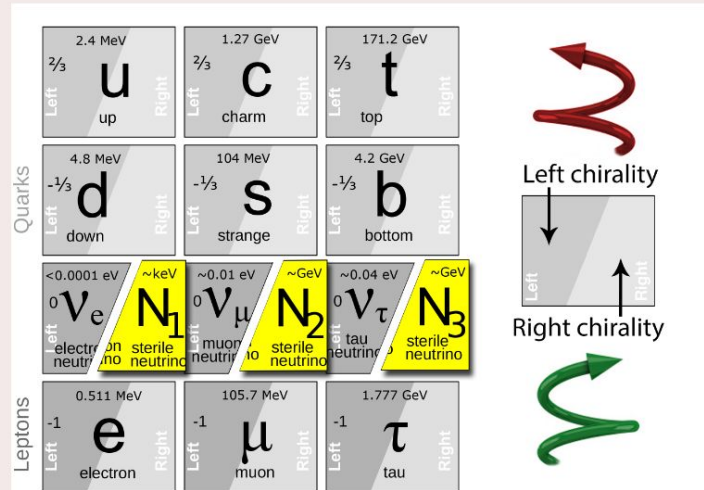
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\text{Mediator}} + \mathcal{L}_{HS}$$

- Scalar portal: e.g. dark scalar, dark Higgs.
- Vector portal: e.g. dark photon.
- Axion-Like Particles (ALP) portal.
- Fermion portal: e.g. heavy neutral leptons (HNL).

Example of production in charm decay



Example: the ν MSM



- Minimal extension: add 3 right-handed Majorana neutrinos.
- N_1 : dark matter candidate.
- N_2/N_3 : set active neutrino masses, create baryon asymmetry via leptogenesis.

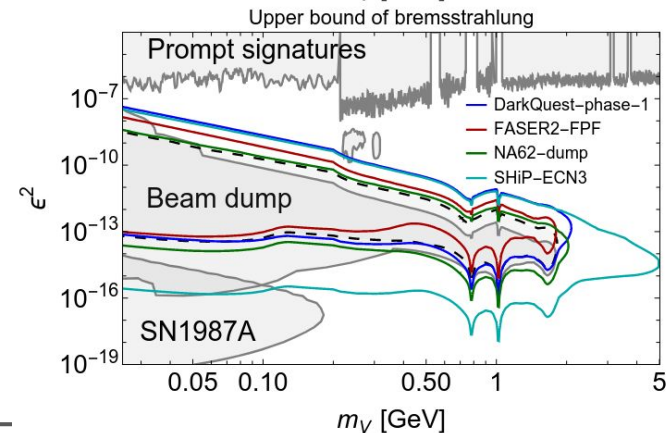
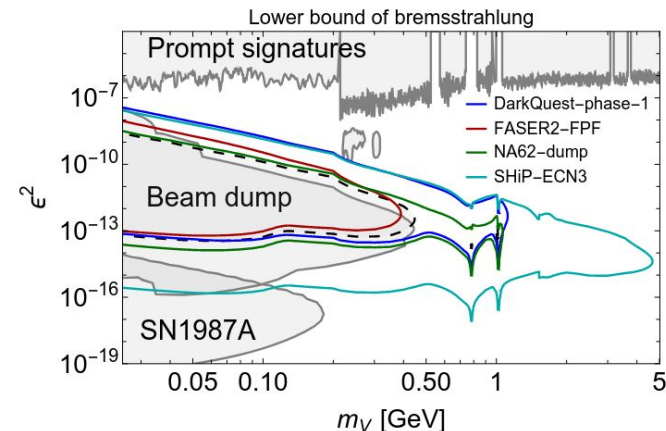
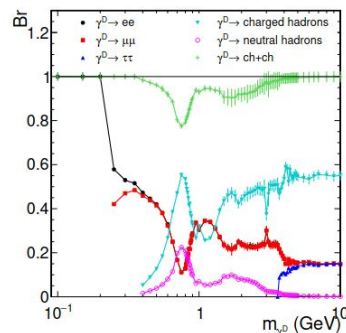
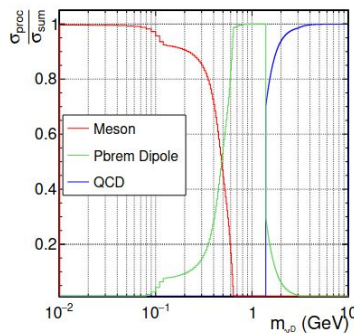
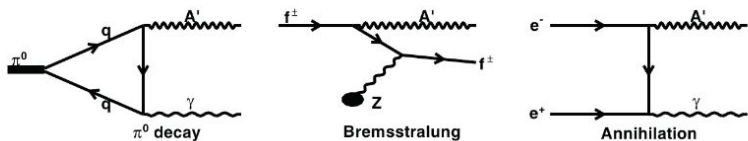
Dark photons - Vector portal

M. Ovchinnikov et al.
Phys. Rev. D 111, 015030 (2025)

- Kinetic mixing ϵ

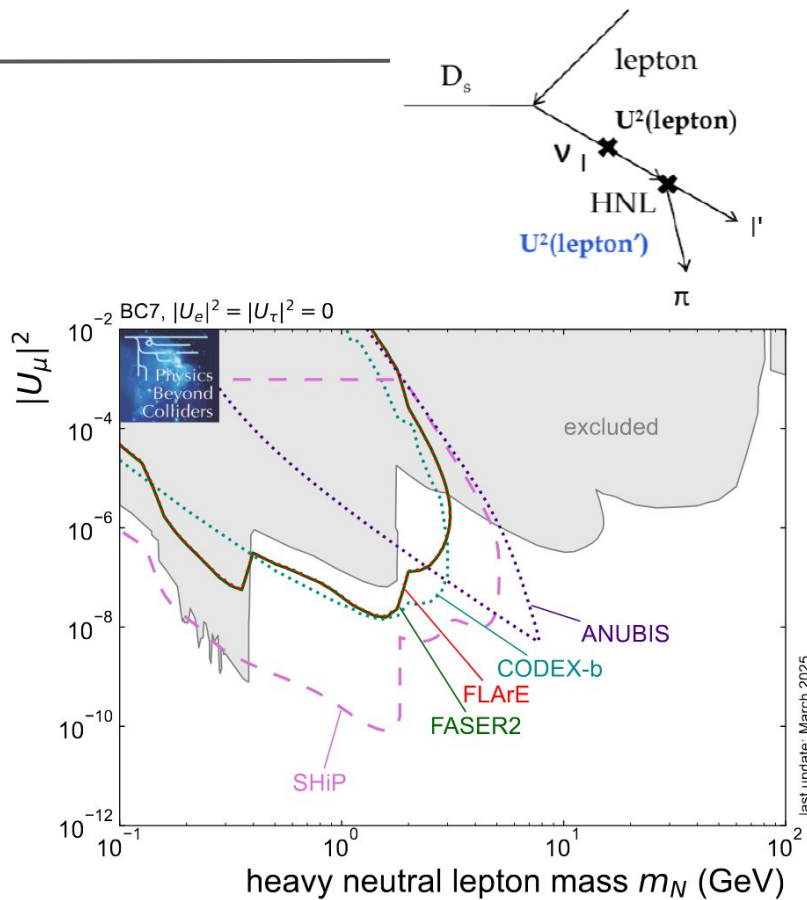
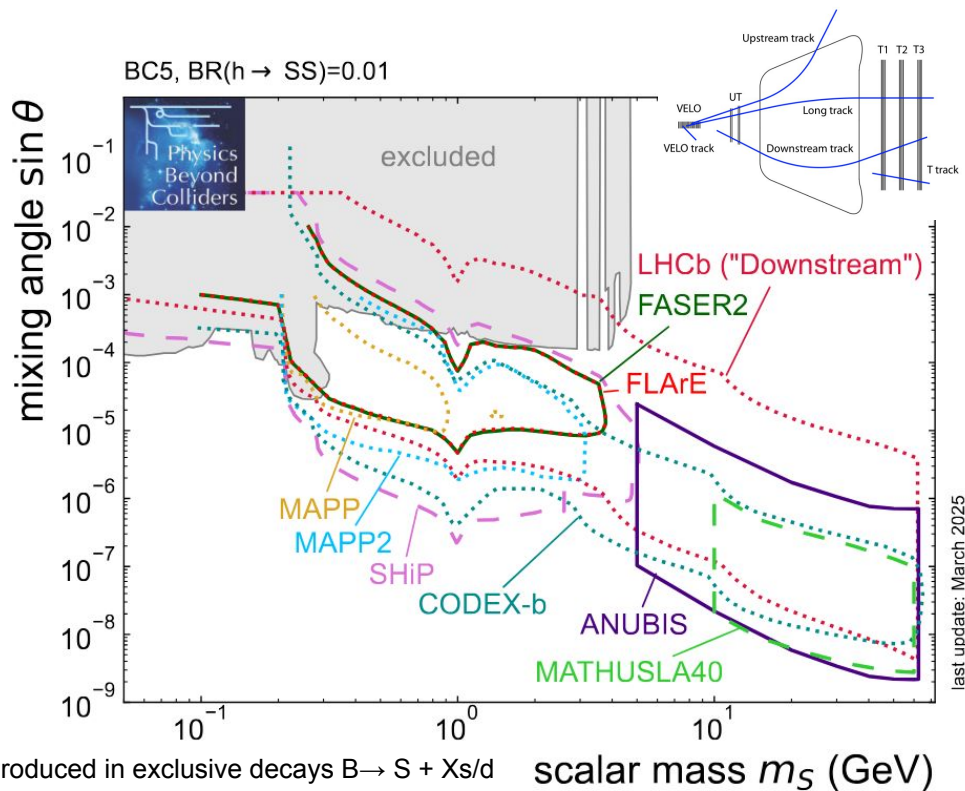


- Produced in QCD, bremsstrahlung or meson decays.
- Decays to visible particles.



EPJC 81 (2021)5

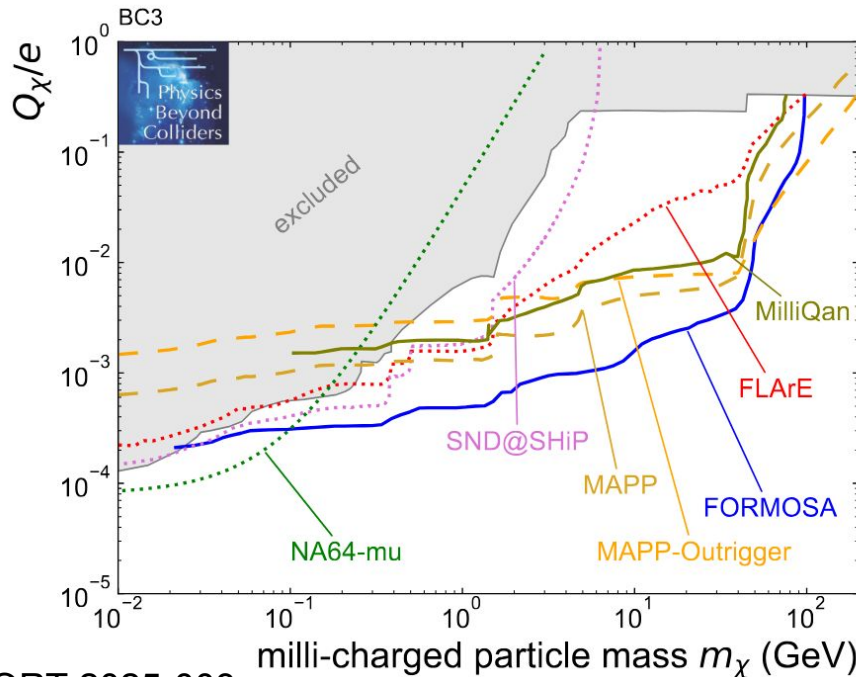
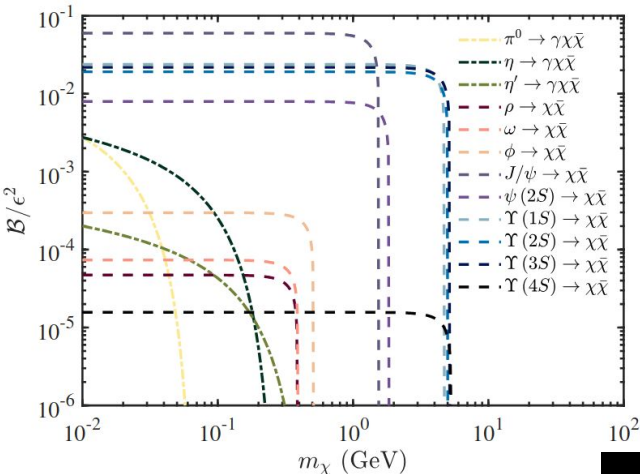
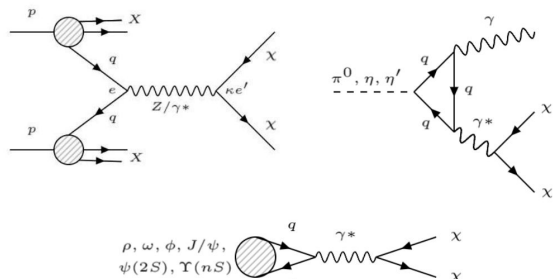
Dark scalars and HNLs



GERN-PBC-REPORT-2025-003

Millicharged particles

JHEP **2024**, 137 (2024)



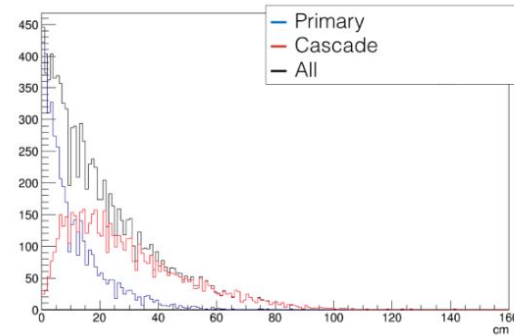
CERN-PBC-REPORT-2025-003

milliQan results—Phys. Rev. D 104, 032002 (2021); FORMOSA results—Phys. Rev. D 104, 035014 (2021)

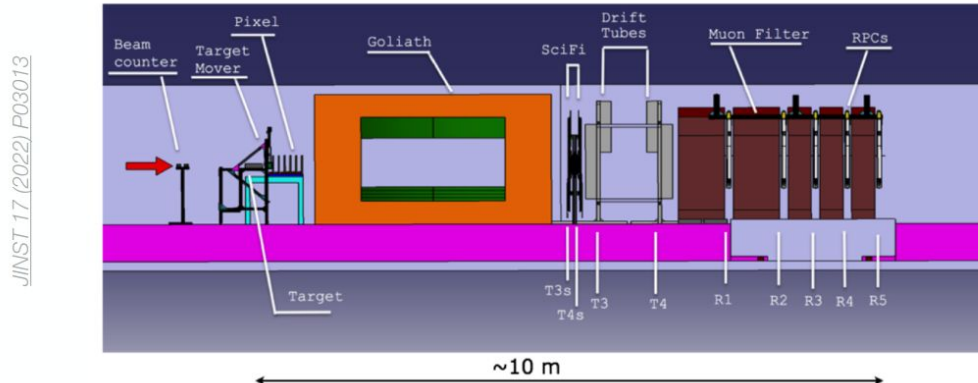
last update: March 2025

SHiP-Charm

- A **dedicated pilot experiment** (2018) to study charm production cross section at SPS
- Aimed to measure differential charm production cross section including **hadronic cascade production**
- **Demonstration of matching** between emulsions and electronic detectors in reconstruction
- **New project developments:** associate charm production with di-muon J/Psi decays



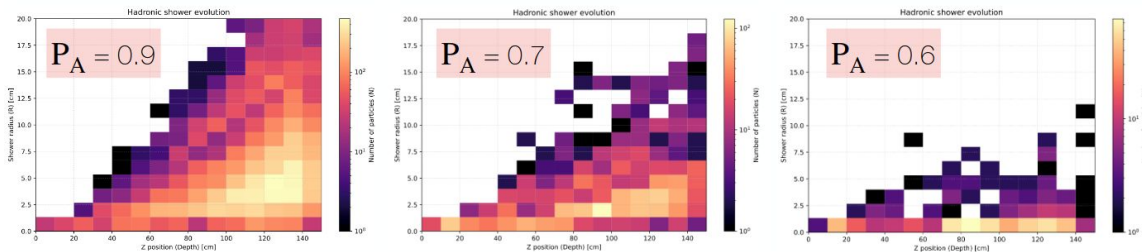
CERN-SPSC-2017-033



Courtesy of Kirill Skovpen (U. Gent)

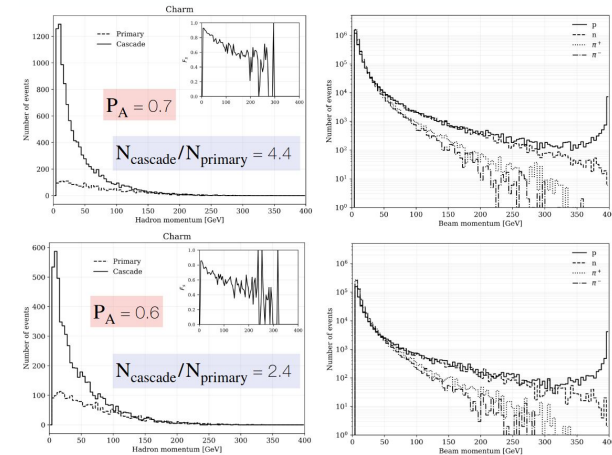
Tuning Pythia8

- A more aggressive model for underlying event (tuned for LHC) in **Pythia8**
- Simple geometric hadron-nucleus model giving thinner showers in **Pythia6**
- Tuning internal parameters (e.g. aLund) is **tricky** (and not enough) - would also affect the x_F distribution
- Use particle « **absorption** » probability (P_A) to control shower evolution in space
- $P_A = 0.9$: $z_{max} \approx 120$ cm, $N \approx 2000$, $R \approx 6$ cm
- $P_A = 0.7$: $z_{max} \approx 90$ cm, $N \approx 300$, $R \approx 4$ cm
- $P_A = 0.6$: $z_{max} \approx 80$ cm, $N \approx 100$, $R \approx 1$ cm

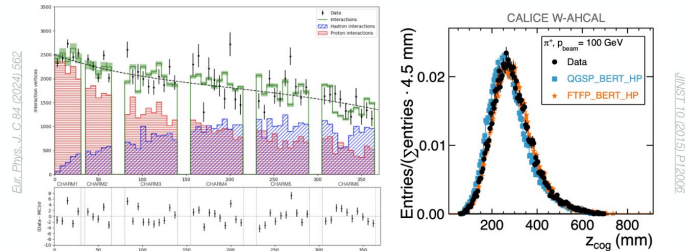


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Charm production



Shower evolution



- The $P_A = 0.7$ is more consistent with the depth of the shower development measured in SHiP-Charm (**hadronic shower component**) with proton beams - should be best suited for thick targets and proton beams
- The $P_A < 0.6$ better matches **shower maximum** as measured by CALICE using pion

Charm in cascades

Summary

- **PythiaCascade** enables the fast heavy hadron cascade generation in Pythia8
- Pythia8 produces significantly more secondary hadrons than Pythia6 → **shower dominates** the beam for the charm/heavy production
- Pythia6 is better suited for **fixed-target experiments** but some choices are still rather arbitrary
- **More tuning** is needed for Pythia8
- Both Pythia6 and Pythia8 have to be **tuned** in « opposite directions »
- Towards a **hybrid** approach?
 - GEANT4 for stochastic propagation
 - At hadron collision point call Pythia8 to generate charm/beauty
 - Hand back the interaction products to GEANT4

Courtesy of Kirill
Skovpen (U.
Gent)