The SHiP Experiment

Anne-Marie Magnan, Imperial College London

IMPERIAL

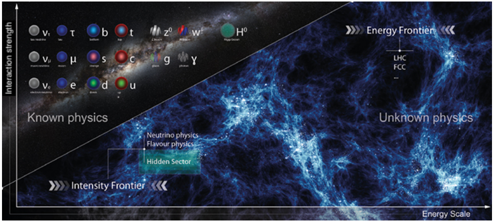
SHiP
Search for Hidden Particles

on behalf of the
SHiP Collaboration

1$^{\mathrm{st}}$-5$^{\mathrm{th}}$ July 2024,
LLP 2024, Tokyo, Japan

Physics motivation

- Standard Model verified in many ways, but many fundamental questions left:
    - Neutrino masses and their origin,
    - Dark Matter,
    - Baryon asymmetry in the universe.



- Where is the new Physics ?
    - SHiP: look for very small SM couplings / couplings through portals, small masses (below few GeV), long-lived particles ($c\tau \simeq 50 - 100$m).
    - Wide physics program:
        - Indirect evidence of new physics through precision measurements in the neutrino sector.
        - FOCUS OF THIS TALK: Direct searches for particles in the "hidden sector".

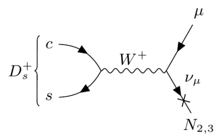
Hidden sectors and portals

Weakly-coupled new physics

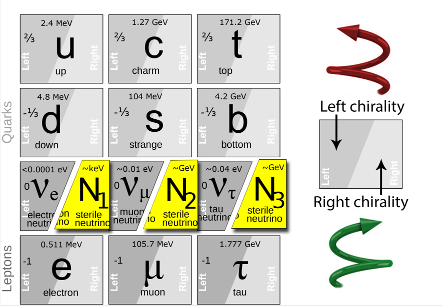
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\text{Mediator}} + \mathcal{L}_{\mathcal{HS}}$$

- 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



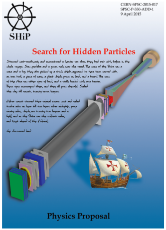
Example: the νMSM



- Minimal extension: add 3 right-handed Majorana neutrinos.
- N1: dark matter candidate.
- N2/N3: set active neutrino masses, create baryon asymmetry via leptogenesis.

Some history of SHiP

- 2013: Letter of Intent ⇒ arXiv:1310.1762
- 2015: Technical+Physics Proposals ⇒ arXiv:1504.04956/CERN-SPSC-2015-040
- 2019: Comprehensive Design Study Report ⇒ CERN-SPSC-2019-049
- 2023: BDF/SHiP at the ECN3 high-intensity beam facility ⇒ CERN-SPSC-2023-033.
- Unless stated otherwise, all figures taken from CERN-SPSC-2023-033.

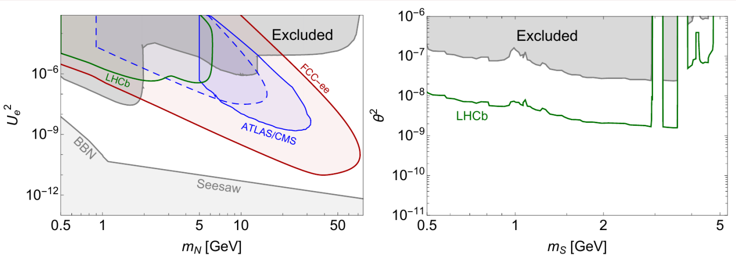

CERN-SPSC-2015-017
SPSC-P-350-ADD-1
9 April 2015

SHiP

Search for Hidden Particles

Physics Proposal

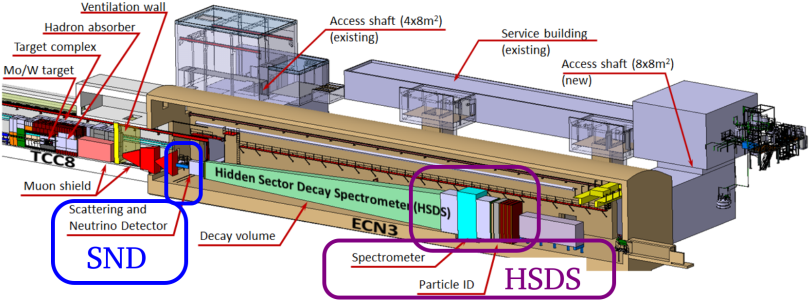
HNLs **Dark scalars mixing with H**



From Project to Experiment

- Approved by CERN in March 2024 ⇒ Moving to the Technical Design Report phase !
- Main update: change from planned ECN4 to existing ECN3 cavern configuration: downstream detector size reduced from 10 × 5 m^2 to 6 × 4 m^2.
- The SHiP collaboration in April 2024:

SHiP: a beam dump experiment



- Beam: SPS 400 GeV protons with 4×10^{19} protons-on-target (PoT) per year
- Full physics program: 15 years of running $\Rightarrow 6 \times 10^{20}$ PoT.
- Detector will seat in existing "TCC8/ECN3" caverns.

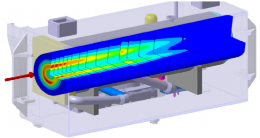
Each year, the target will produce:

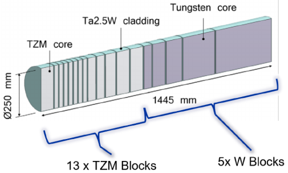
- $\simeq 10^{17}$ charmed hadrons,
- $\simeq 10^{13}$ beauty hadrons,
- an unprecedented sample of $\nu_\tau/\bar{\nu_\tau}$

Design of the Target

- Target made with Ti-Zr-Mo alloy followed by pure W. Total: 12λ, followed by 5m-long hadron absorber.

Sim. temperature rise during pulse

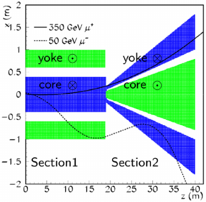


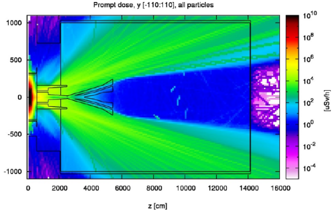


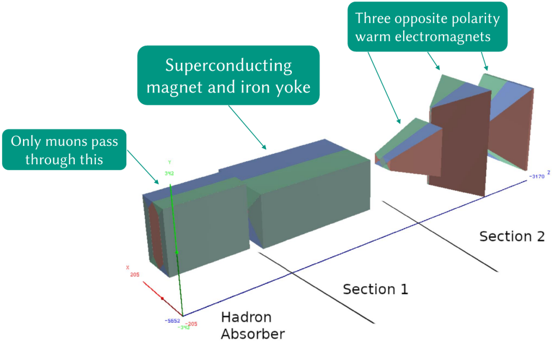

Prototype for 2018 beam test

Design of the Muon Shield

- From simulation, $\simeq 2 \times 10^{10}$ muons/spill out of hadron absorber with E$>$ 10 GeV.
- New constraints on size from TCC8 cavern.
- Considering now Hybrid option $\Rightarrow$ Design will be re-optimised for TDR.







Three opposite polarity warm electromagnets

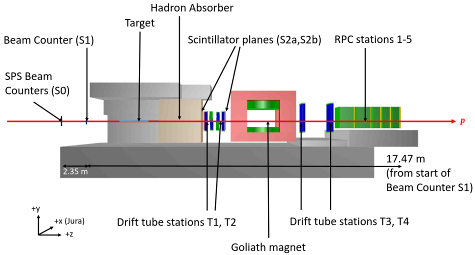
Superconducting magnet and iron yoke

Only muons pass through this

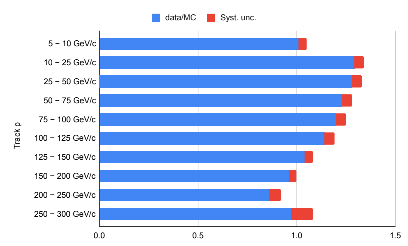
Muon flux measurement

EPJC 80 (2020) 3

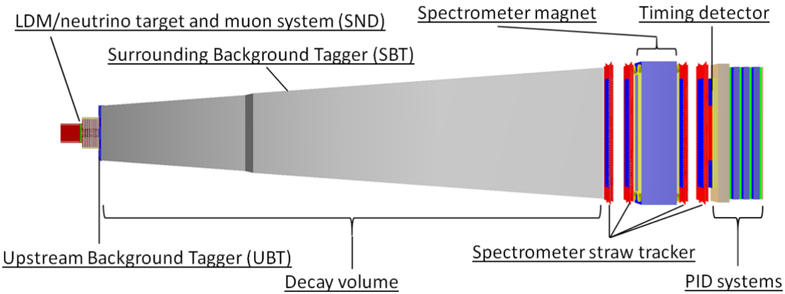
- Key aspect to control shield design + estimate remaining muon background after shield.
- Measured the flux at the H4 CERN SPS beamline, in 2018
- Obtained reasonably good agreement !
- Will rely heavily on the simulation for the final optimisation of the shield.



Number of reco tracks



Overall detector design



Physics coverage

	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 $(\nu_e, \nu_\mu, \nu_\tau)$	$D_s^\pm$, $D^\pm$, D^0, $\overline{D^0}$, Λ_c^+, $\overline{\Lambda_c}^-$

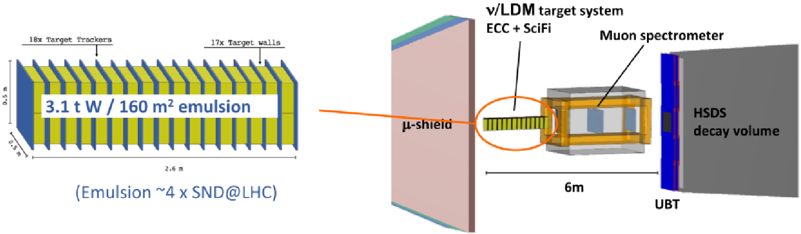
Signal reconstruction

- 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.

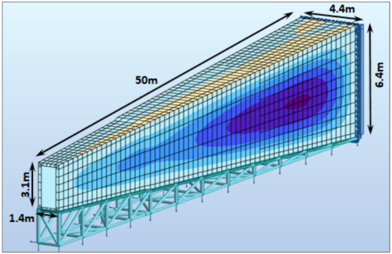
The Scattering and Neutrino Detector - SND

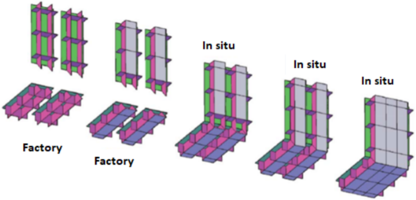


- Baseline design similar to SND@LHC ⇒ See presentation from Masahiro Komatsu on Friday.
- Undergoing re-optimisation for neutrino physics and light dark matter.
- Advantage @ SHiP: large (anti-)neutrino yields expected: $\simeq 10^6[\nu_e + \bar{\nu_e}] + 10^7[\nu_\mu + \bar{\nu_\mu}] + 10^5[\nu_\tau + \bar{\nu_\tau}]$.

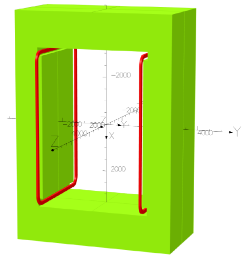
The decay volume and surrounding background taggers - SBT

- The big question of this year: vacuum or helium ?
- Design highly dependent on pressure required inside.
- Still, main challenge is to minimise μ and ν interactions in the walls.
- Instrument the surrounding volume with efficient background taggers.
- $\Rightarrow$ double-wall structure with liquid scintillator-based system with good timing and spatial resolution.





The spectrometer magnet and straw tracker



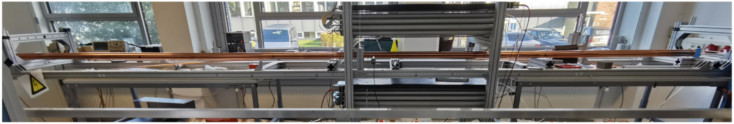
cable length: ~ 3 km

Spectrometer magnet

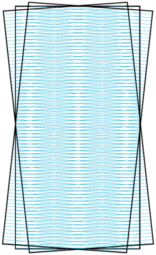
- Design: driven by physics aperture, 4×6 m^2 and vertical bending power > 0.65Tm over 4 tracking stations.
- Baseline design with normal-conducting materials. Studies ongoing for using superconducting technologies.

Straw tracker

- 4-layer straw tracker ⇒ Measure trajectories and momenta of particles, reconstruct decay vertices and impact parameter at proton target.
- Inspired by NA62 design.
- Main challenge: mechanical properties of straw tubes.
- Being redesigned for ECN3 dimensions.



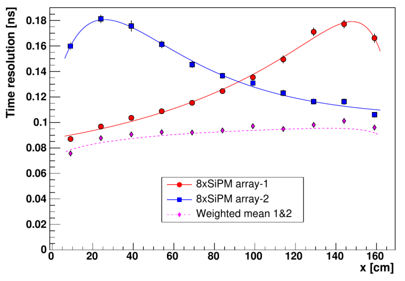
Four-straw prototype with carbon fibre suspension under test in Hamburg.



The Timing and PID detectors

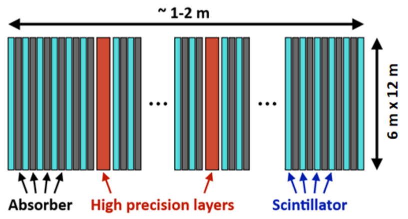
Timing detector

- Made of scintillators+SiPM.
- Measure coincidences ⇒ reject combinatorial bkg.
- Need time resolution < 100 ps.
- For TDR: validate calibration procedure and readout electronics.
- WIP: measure time-of-flight for $p < 10\,\text{GeV}$ tracks ⇒ use in PID.



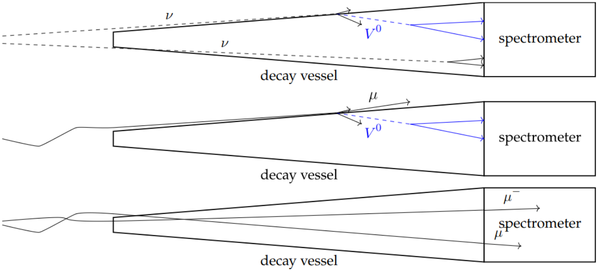
PID system

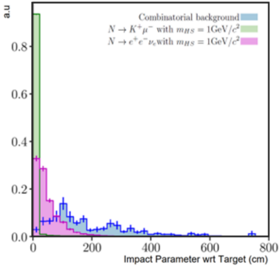
- Requirements:
  - Reconstruct e and γ showers with angular resolution $\simeq 5$ mrad for $\gamma\gamma$ FS.
  - Discriminate between hadrons and muons.
- CDS design: EM calorimeter + muon detectors.
- Re-optimisation ongoing.

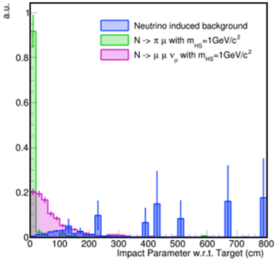


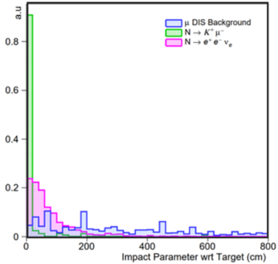
A Zero background experiment

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









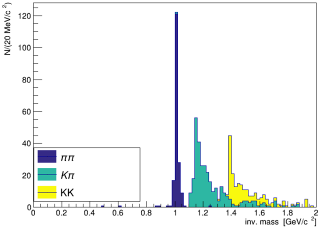
Global analysis strategy

- Searches for HNL, dark photons and RPV SUSY designed with full simulation.
- In good agreement with SensCalc tool `https://zenodo.org/record/8034735`, used for other channels and further optimisation.
- All results for 15 years of running ⇔ 6.10^{20} PoT, 90%CL limits (⇒2.3 events for 0 bkg).
- Results for other experiments from arXiv:2305.01715.

Background estimates

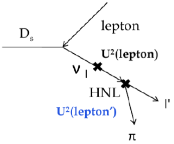
Background source	Expected events
Neutrino DIS	< 0.1 (fully)/< 0.3(partially)
Muon DIS (factorisation)	$< 5 \times 10^{-3}$ (fully) / < 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

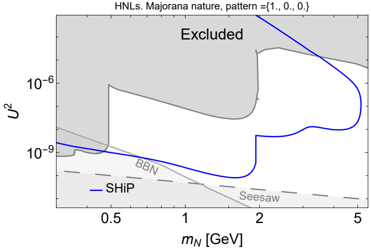
- With high statistics, can also further separate models using invariant mass.

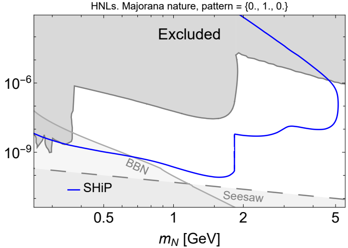


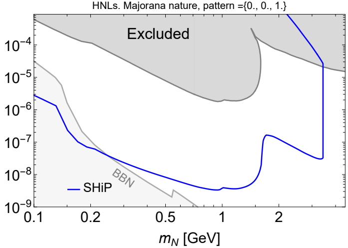
Updated sensitivity to HNLs - fermion portal

[Full study in JHEP 04 (2019) 077]




HNLs. Majorana nature, pattern ={1., 0., 0.}


HNLs. Majorana nature, pattern = {0., 1., 0.}

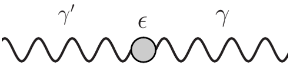

HNLs. Majorana nature, pattern ={0., 0., 1.}

Dark Photons - vector portal

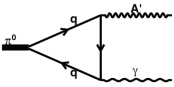
- Minimal hidden U(1) extension of the SM:

$$L_{eff} = L_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_{\mu}A'^{\mu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

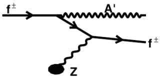
- Kinetic mixing ϵ



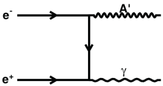
- Produced in QCD, bremstrahlung or meson decays.
- Decays to visible particles.



π^0 decay

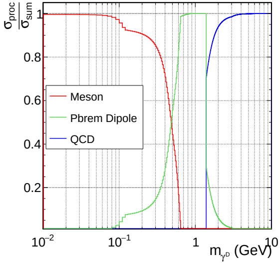


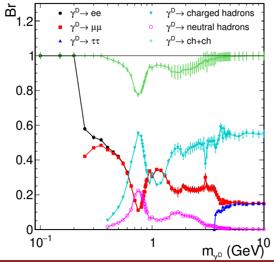
Bremsstralung



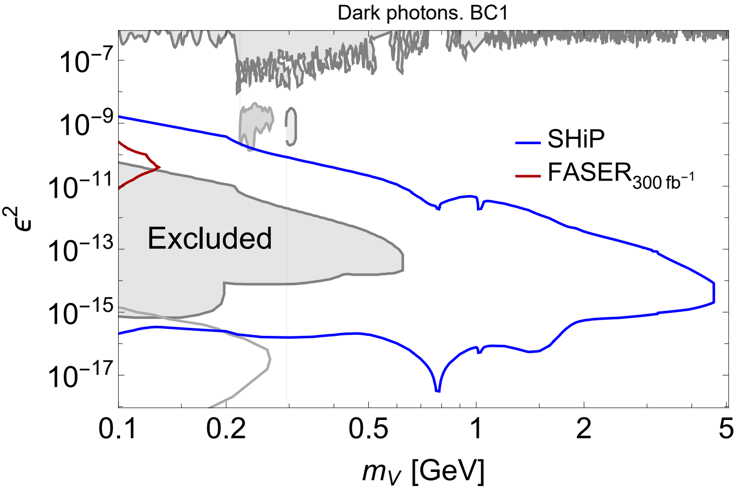
Annihilation

[Full study in EPJC 81 (2021) 5]





Updated sensitivity to Dark Photons

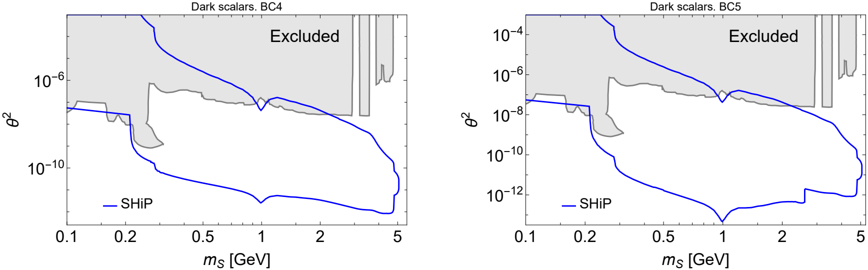


Updated sensitivity to Dark Scalars

Produced in exclusive decays B→ $S + X_{s/d}$

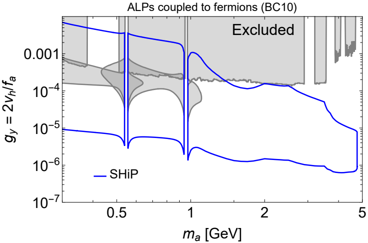
BR(H→SS) $= 0$

BR(H→SS) $= 0.01$



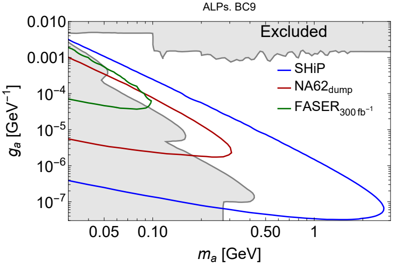
Updated sensitivity to Axion-Like-Particles

Exclusive couplings to fermions



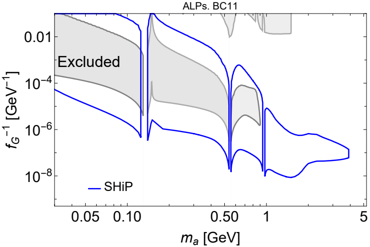
ALPs coupled to fermions (BC10)

Exclusive couplings to γ



ALPs. BC9

Exclusive couplings to gluons



ALPs. BC11

Conclusion

- TDR is expected by 2027 for commissioning starting in 2031.
- The real work starts now, plenty of opportunities available !

Thank you for your attention

[When we don't know where we're going, we should go there!!... and as fast as possible.]

Backups

BACKUPS

Basic selection in CDS report

To be re-optimised.

Criterion	Requirement
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)	$< 250\,\mathrm{cm}$