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SHiP Overview

SHiP is currently a collaboration of 49 institutes, 5 associate institutes from 16 countries, CERN and JINR

Outline:

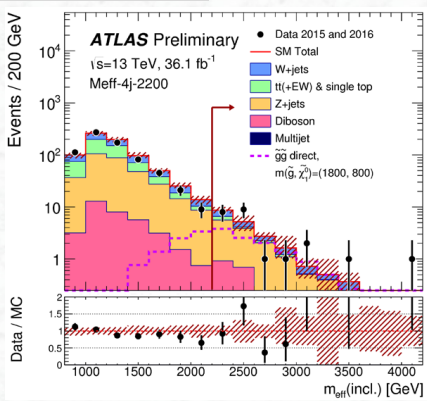
- ✓ *Brief summary on "Standard" SHiP layout and sensitivities*
- ✓ *Possible extension of SHiP physics programme*
- ✓ *Main goals of the SHiP optimization*
- ✓ *Important measurements towards TDR*

More details in the talks of Gaia Lanfranchi and Richard Jacobsson

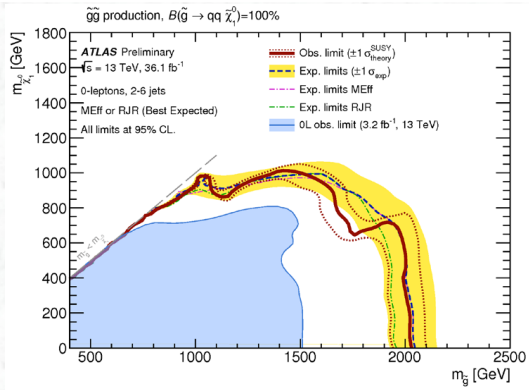
Standard Model is great but it is not a complete theory

Direct searches for NP at ATLAS & CMS have not been successful so far

ATLAS-CONF-2017-022



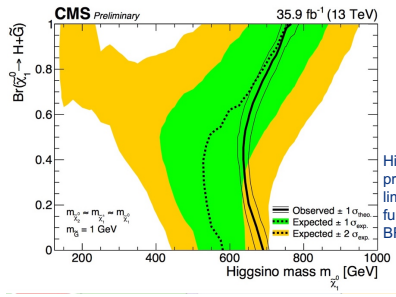
Data well described by expectations from SM processes



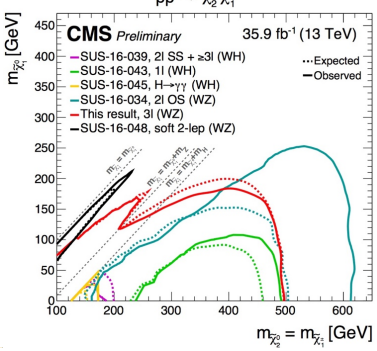
Gluino mass limit beyond 2 TeV, $m(\chi^0) = 0$

- Broad program: **23 SUSY searches completed with full 2016 CMS dataset**
- several already submitted to journals
- Probing different models: inclusive production, strong and **electroweak production**, and 3rd generation sparticles (stops, staus), high ΔM, compressed, …
- Recent highlight: "EWK combination"

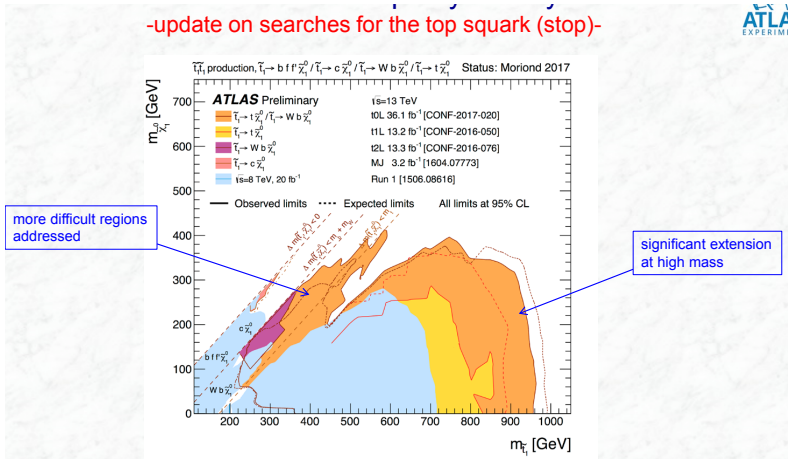
Search	Signal topology WZ	WH	ZZ	ZH	HH
1ℓ 2b		✓			
4b					✓
2ℓ on-Z	✓		✓	✓	
2ℓ soft	✓				
2ℓ SS, ≥ 3ℓ	✓	✓	✓	✓	✓
H(γγ)		✓		✓	✓



Higgsino-production limits as function of BR(N1→H G~)



-update on searches for the top squark (stop)-



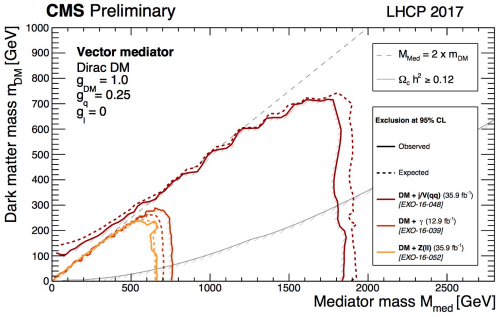
- Stop mass limit beyond 0.9 TeV, $m(\chi^0) = 0$
- Also progress in difficult parameter regions

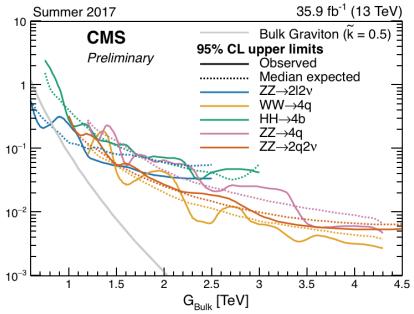
SUSY limits in a nutshell:

- **Gluinos > ~2 TeV**
- **Stops > ~1 TeV**
- **EWKinos > ~0.5 TeV**

Other searches for exotics:

- Some focus on **boosted topologies** (eg. X decaying to pairs of W/Z/H/tops)
- Also focus on combining searches targeting **DM** (the "mono-X" class)





Parameter space for popular BSM models is being rapidly decreased, but only < 5% of the complete HL-LHC data set has been delivered so far

→ NP discovery still may happen !

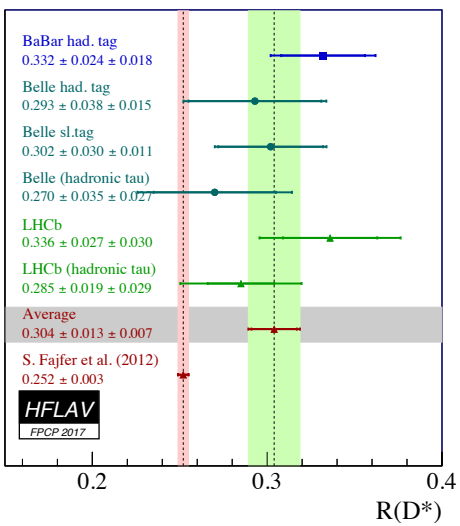
Interesting hints on violation of Lepton Flavour Universality (LFU)

in two classes of decays:

$b \to c l \nu$

LHCb combination [FPCP 2017]:

$R(D^*) = 0.306 \pm 0.016 \pm 0.022$ 2.1σ above the SM

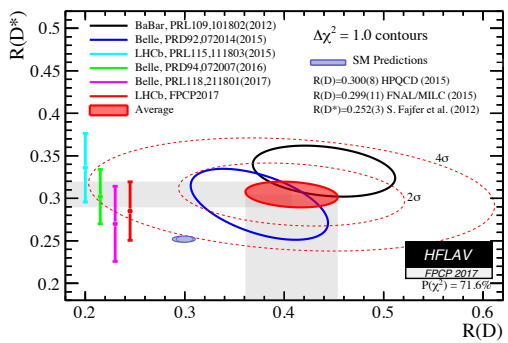


World average [HFLAV]:

$R(D^*) = 0.304 \pm 0.013 \pm 0.007$

(3.4σ from SM)

$R(D) \oplus R(D^*)$ is 4.1σ from SM!



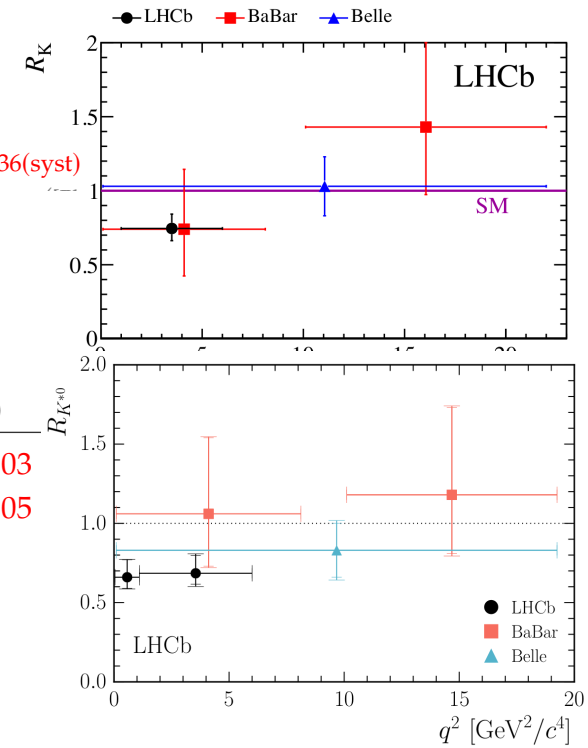
$b \to s l l$

$R_{LHCb}(K) = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$

2.6σ away from SM

q^2 bin	$R_{LHCb}(K^*)$
Low	$0.66^{+0.11}_{-0.07} \pm 0.03$
Central	$0.69^{+0.11}_{-0.07} \pm 0.05$

2.5σ away from SM



Clear evidence of BSM physics if substantiated with further studies!

Many models predict enhanced LFV effects (some close to the current experimental limits) in the 3rd generation

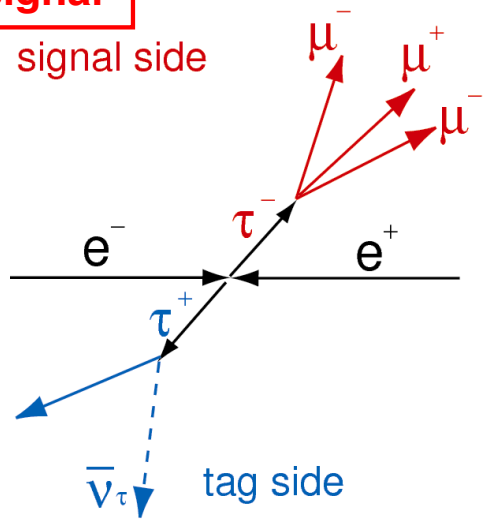
Search for non-LFU tau decays @ BELLE / BELLE II
(extrapolation to BELLE II depends on background)

Main sources of background:

- $e^+e^- \rightarrow \tau^+ \tau^-$
  - 1 prong tau decay (BR~85%)

signal

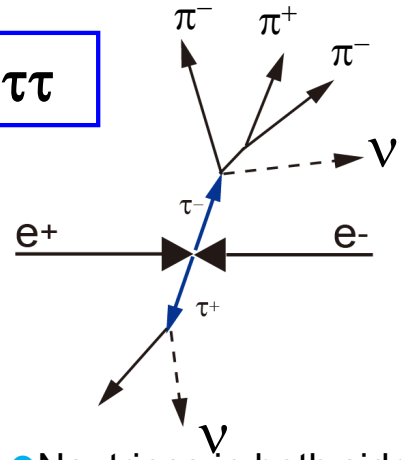
signal side



tag side

- Neutrino(s) in both side
- Particle ID
- (Mass of mesons)

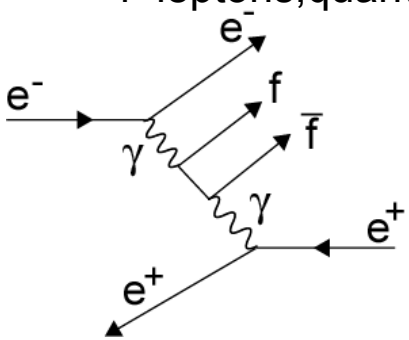
ττ



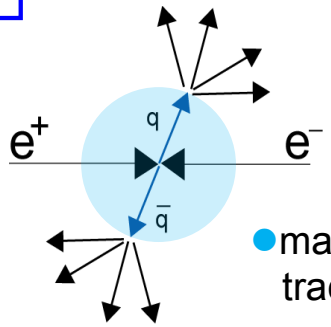
- Neutrinos in both side
- Missing energy in signal side

2photon process

f=leptons,quarks

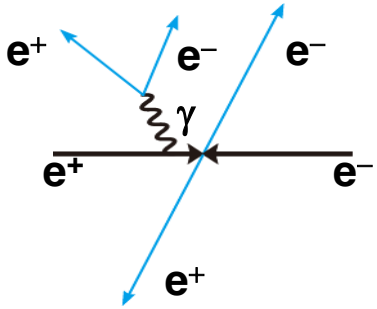


qq̄



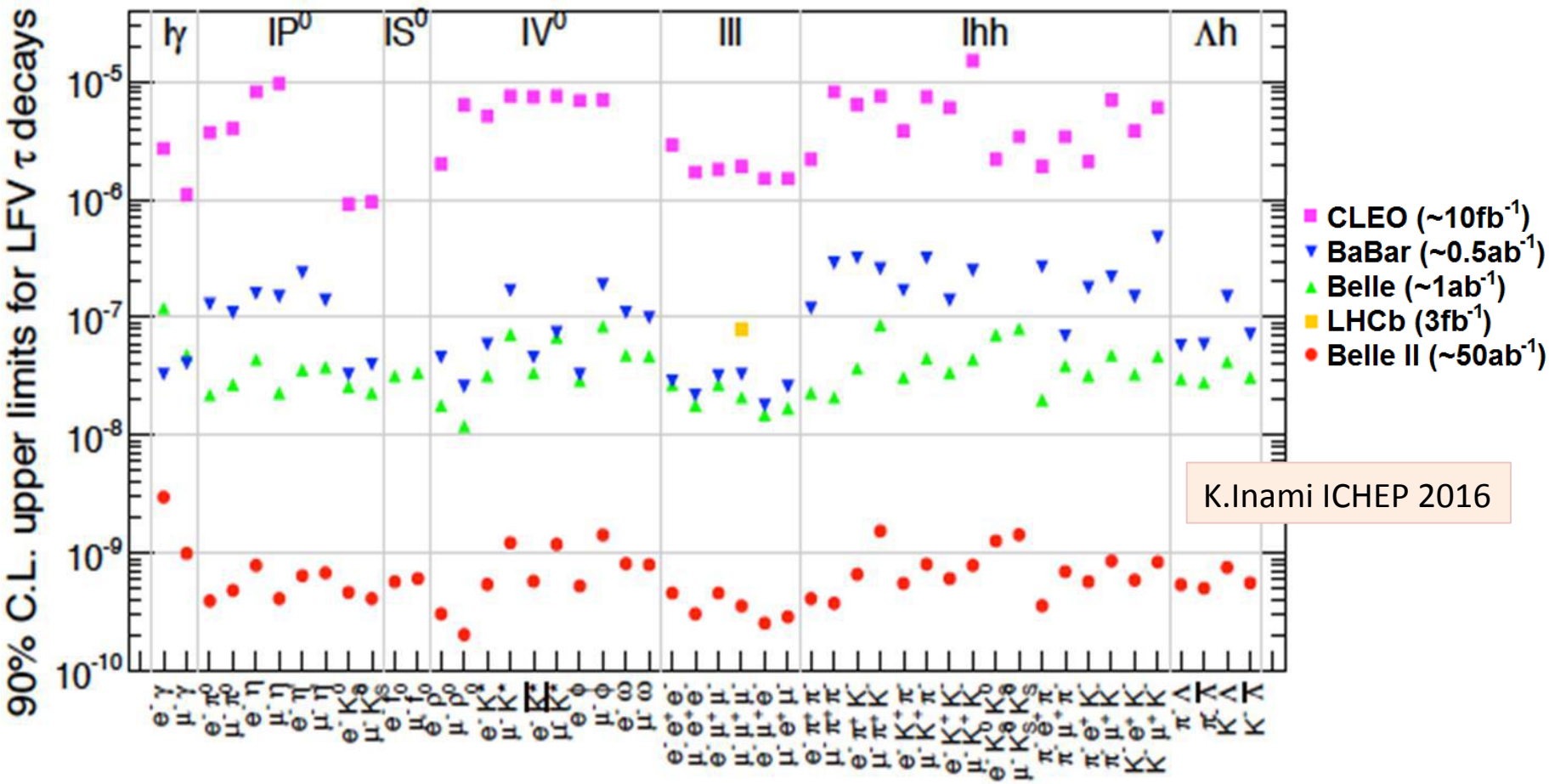
- many tracks

radiative Bhabha process



Current and expected sensitivities

- ✓ *BELLE reached O(10^{-8}) sensitivity using ~10^9 $\tau\tau$ events*
- ✓ *BELLE II plans to collect ~5×10^{10} $\tau\tau$ events*
- ✓ *Expected sensitivity for UL ($\tau\rightarrow3\mu$) varies from 10^{-9}(BELLE II TDR) to few$\times10^{-10}$*



K.Inami ICHEP 2016

Sensitivity scales as 1/√L or 1/L depending on the level of background (beam related background may become an issue)

Physics Beyond Colliders *(covered by Claude)*
(complementary to LHC search for NP at CERN)

"Physics Beyond Colliders" Study Group established in March 2016

Mandate
Explore opportunities offered by the (very rich) CERN accelerator complex to address outstanding questions in particle physics through projects:

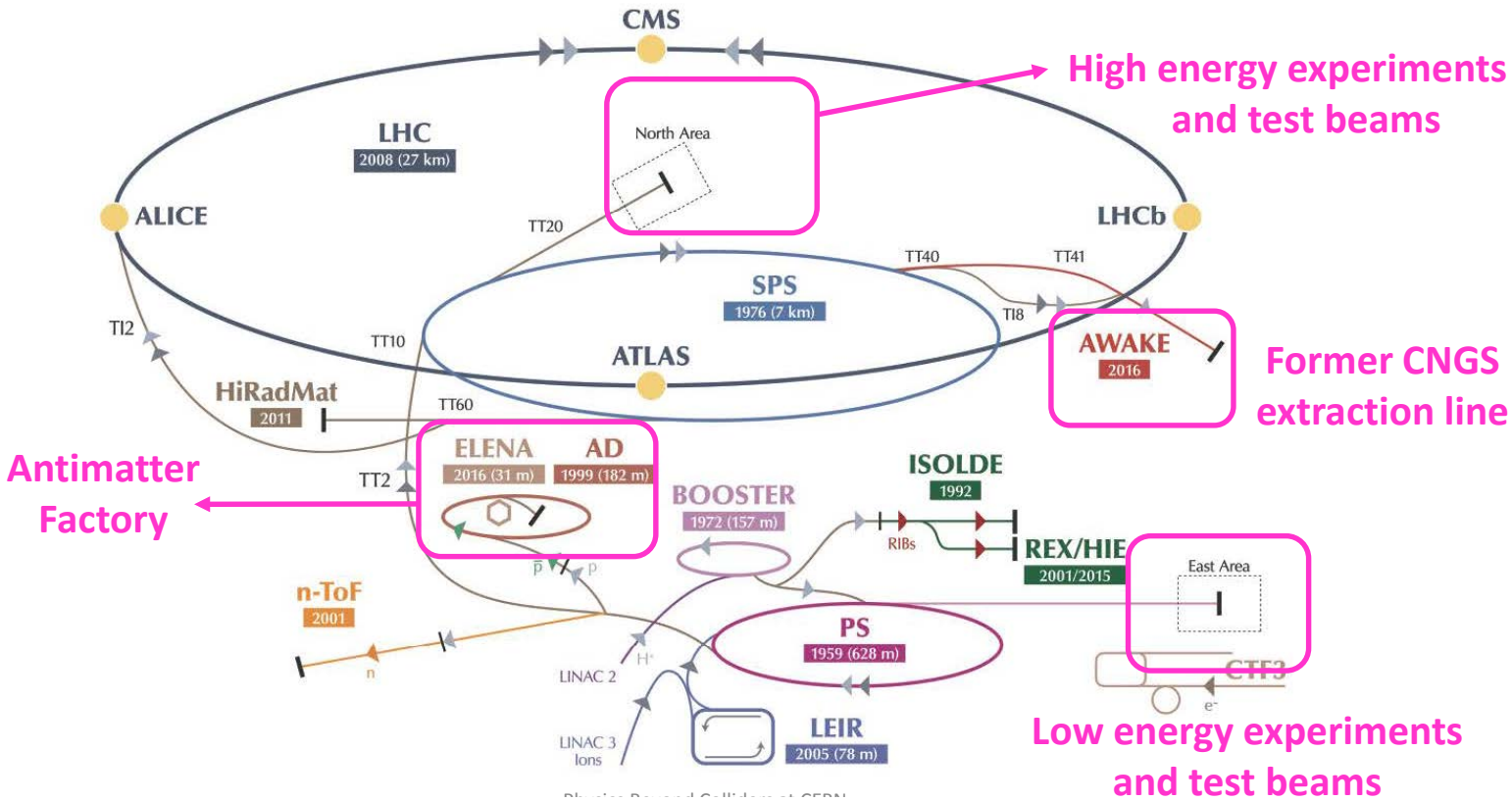
- ❑ complementary to high-energy colliders (studied at CERN: HE-LHC, CLIC, FCC)
  → we know there is new physics, we don't know where it is → we need to be as broad as possible in our exploratory approach
- ❑ exploiting the unique capabilities of CERN accelerator complex and infrastructure and complementary to other efforts in the world:
  → optimise the resources of the discipline globally

BSM program includes Search for Hidden Sector at the CERN SPS proton (SHiP & NA62++) and electron (NA64) beams

Many theoretical ideas predict new light particles, which can be tested experimentally [Rep. Progr. Phys. 79(2016) 124201 (137pp)]
(see talk of Misha Shaposhnikov)

Thanks to stable LHC operation and long lifetime of the LHC beams significant fraction of the SPS protons, and its time, are available for physics at the North Area !

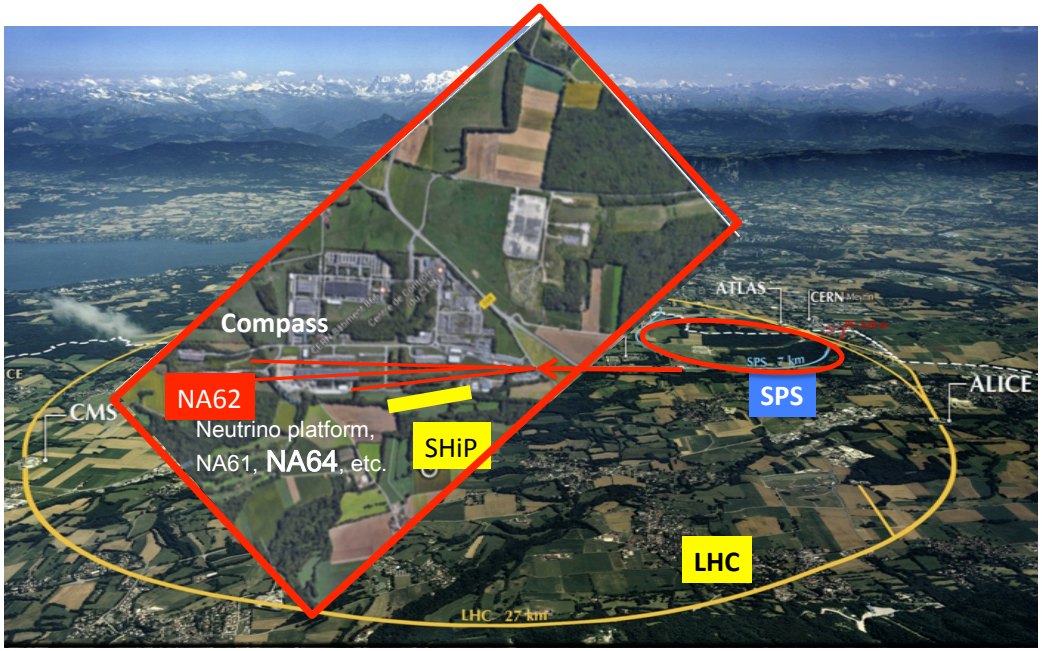
THE PRESENT CERN ACCELERATOR COMPLEX



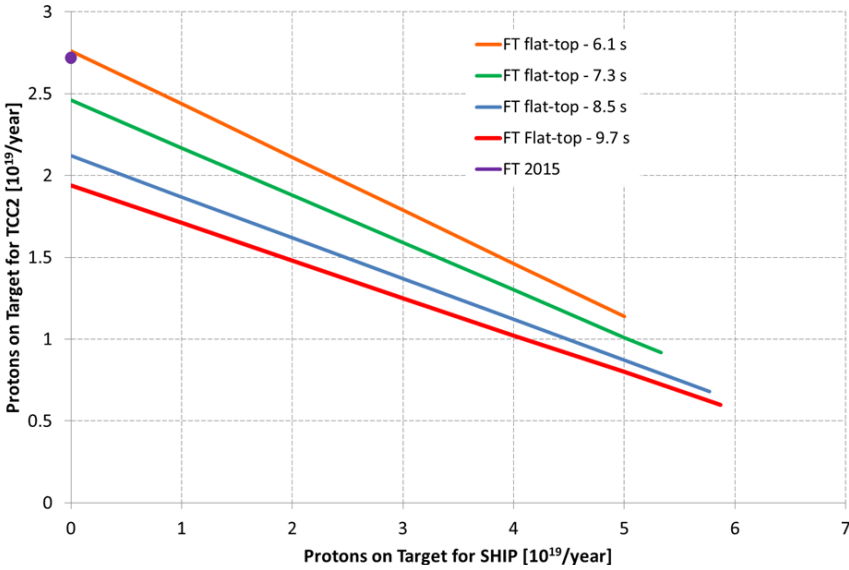
Nominal year of the SPS operation → 200 days with typical machine availability ~80%; 20% of the SPS physics time to run LHC and 80% - to run fix target programme

The Beam Dump Facility at the SPS at Prevessin North Area site
is being actively studied within the PBC framework

Very intense proton beam with highest in the world energy delivered to fixed target exp. at CERN SPS. ***The aim is to deliver with 4×10^{13} protons / spill (at slow extraction)***



Sharing of pot between current fixed target exp. and planned BDF



Proposed implementation is based on minimal modification to the current SPS complex

Search for Hidden Sector (HS) *or very Weakly Interacting Massive Particles (vWIMP)*

$$L = L_{SM} + L_{mediator} + L_{HS}$$

Visible Sector

Mediators or portals to the HS: vector, scalar, axial, neutrino

Hidden Sector

Naturally accommodates Dark Matter (may have rich structure)

- ✓ *HS production and decay rates are strongly suppressed relative to SM*
  - *Production branching ratios O(10^{-10})*
  - *Long-lived objects*
  - *Interact very weakly with matter*

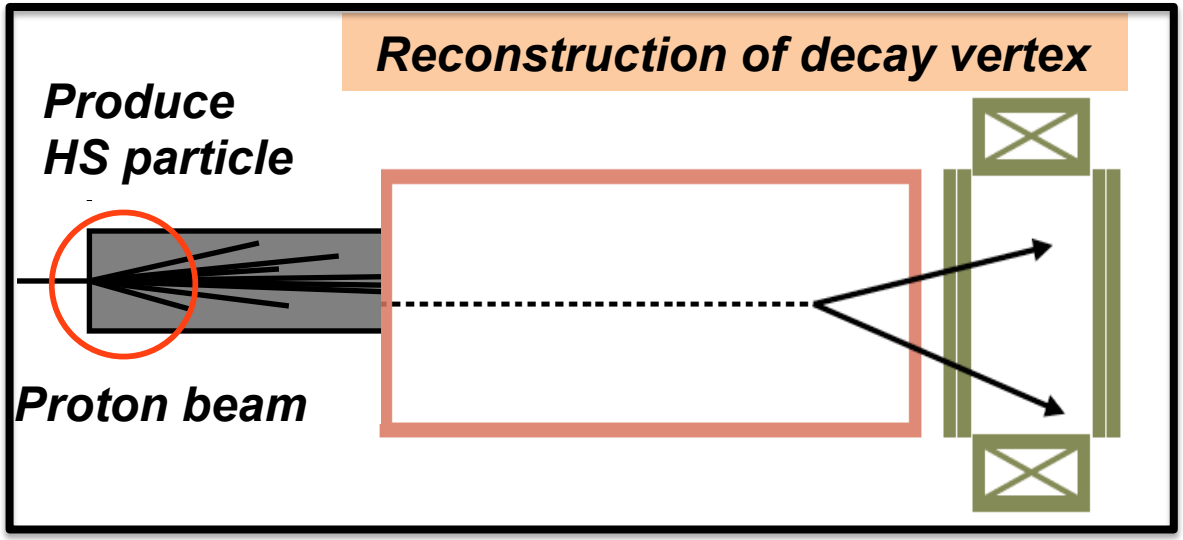
Models	***Final states***
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+ \rightarrow \pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

Full reconstruction and PID are essential to minimize model dependence

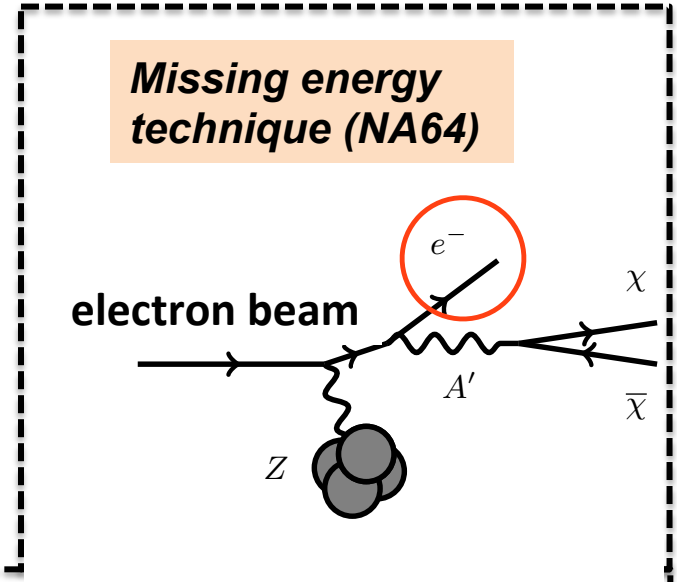
Experimental challenge is background suppression
(see Gaia's talk)

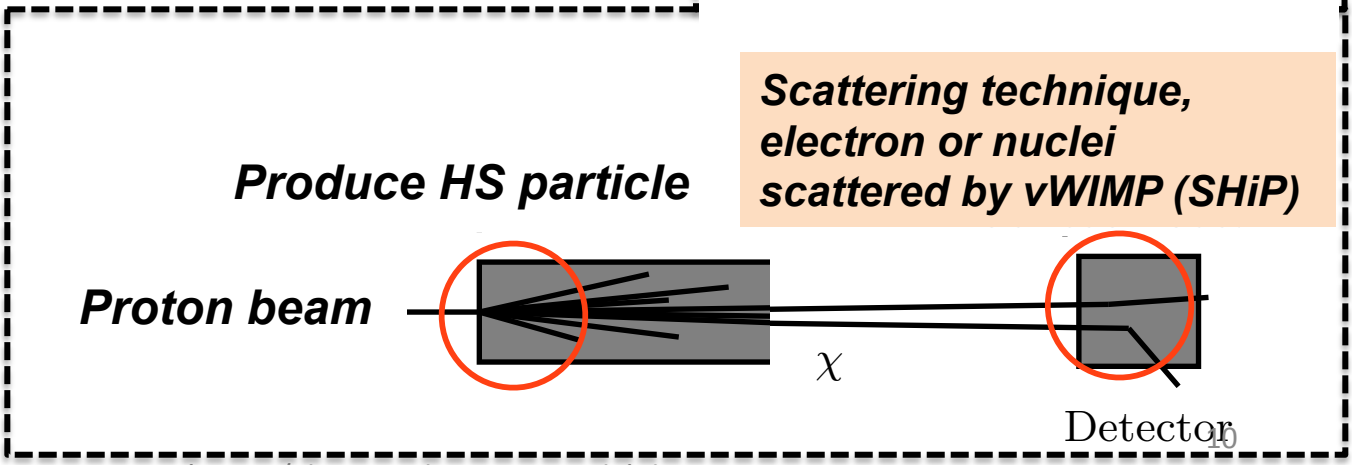
Two strategies at CERN SPS

Direct observation (SHiP & NA62++)



Indirect detection (SHiP & NA64)





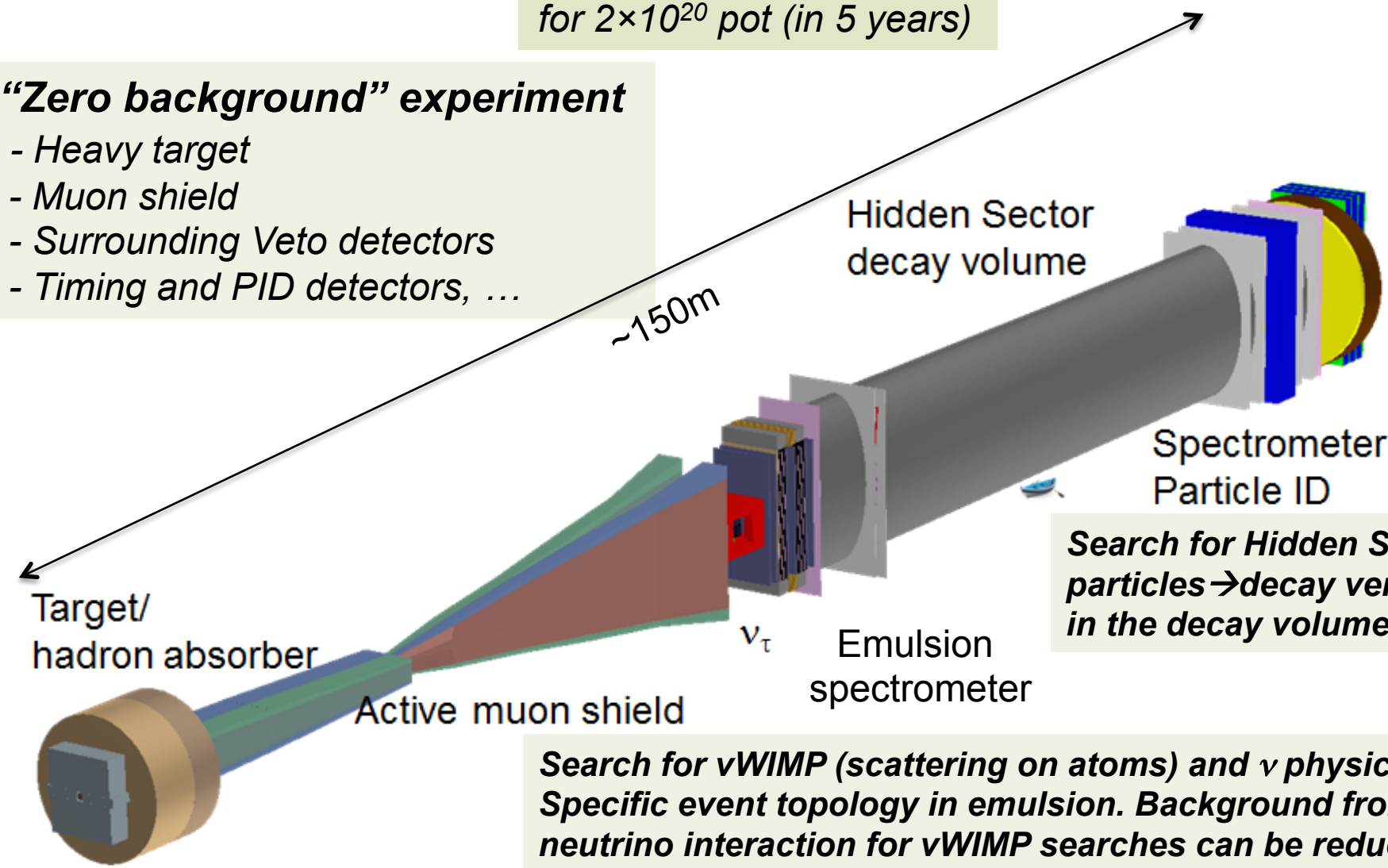
Note:
Missing mass technique Is applicable only if dark photon mediator

The SHiP experiment at SPS
(to search for HS and νWIMPs with O(10 GeV) masses)

SHiP Technical Proposal: 1504.04956

$>10^{18}$ D, $>10^{16}$ τ, $>10^{20}$ γ
for 2×10^{20} pot (in 5 years)

"Zero background" experiment
- *Heavy target*
- *Muon shield*
- *Surrounding Veto detectors*
- *Timing and PID detectors, …*



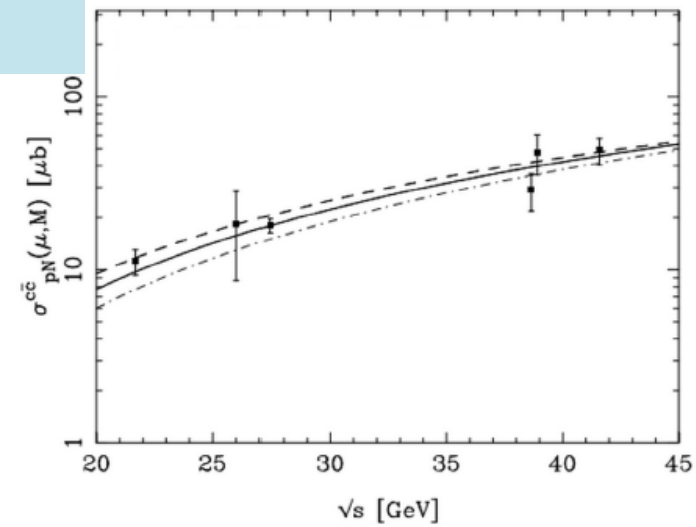
Search for Hidden Sector particles→decay vertex in the decay volume

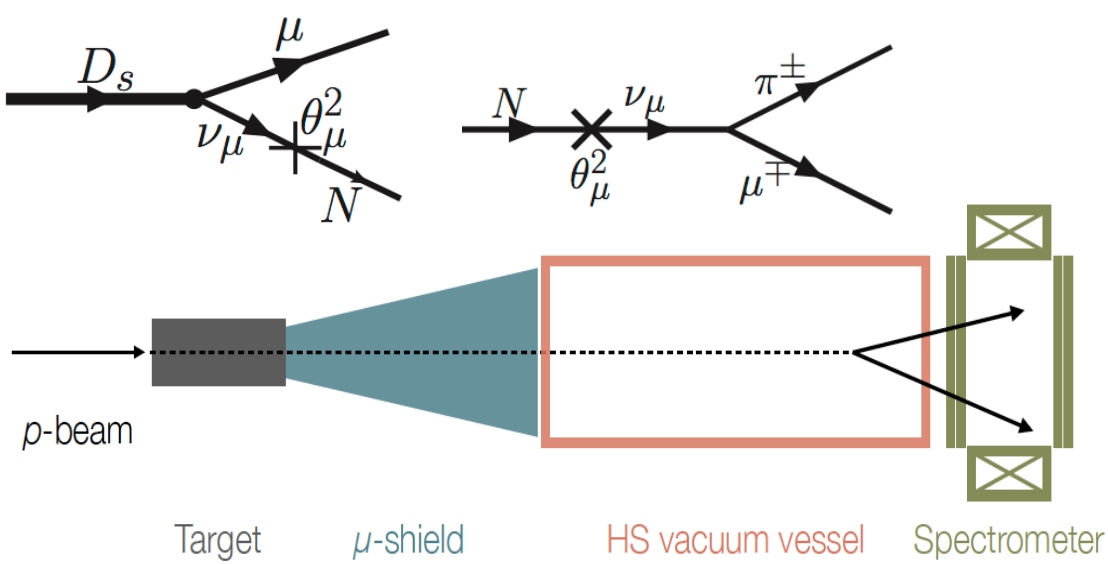
Search for νWIMP (scattering on atoms) and ν physics Specific event topology in emulsion. Background from neutrino interaction for νWIMP searches can be reduced to a manageable level

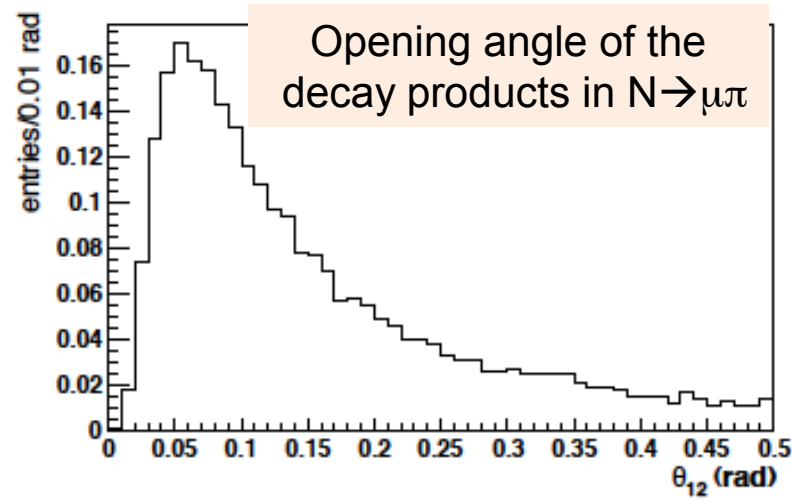
General experimental requirements
to search for HS at beam dump experiment

- ✓ *Search for HS particles in Heavy Flavour decays*
  Charm (and beauty) cross-sections strongly depend on the beam energy

- ✓ *HS produced in charm and beauty decays have significant P_T*







Detector must be placed close to the target to maximize geometrical acceptance. Effective (and "short") muon shield is the key element to reduce muon-induced backgrounds

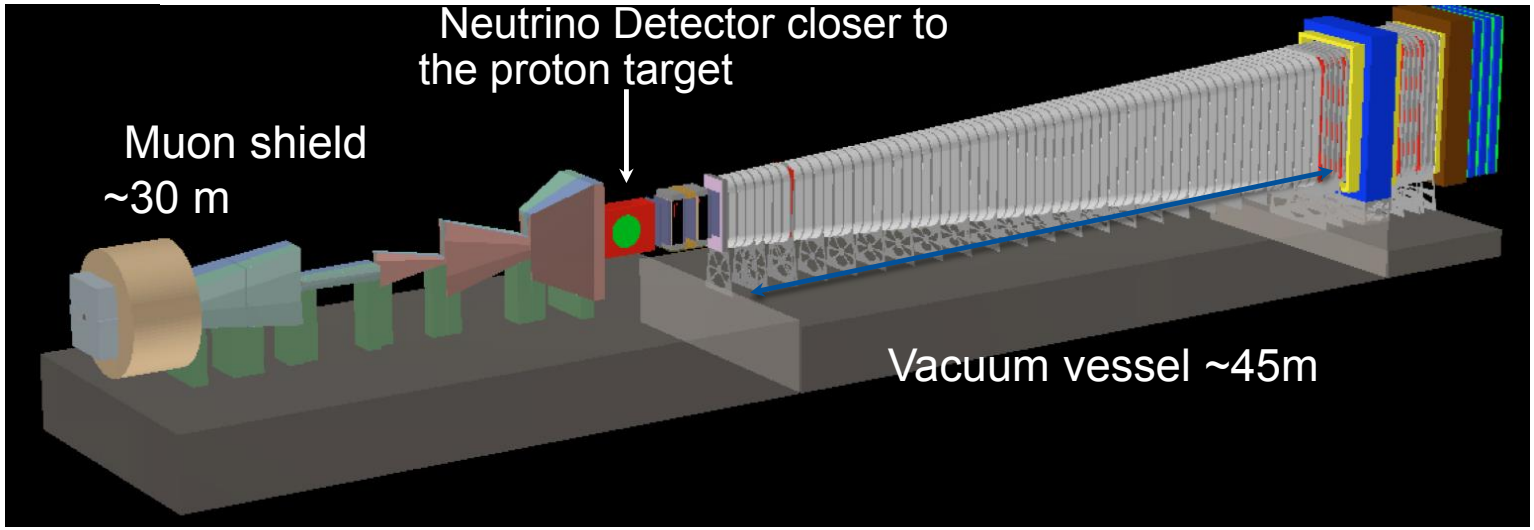
Brief history and current status of SHiP

- ✓ *Letter Of Intent - October 2013*
- ✓ *Technical Proposal & Physics Paper - April 2015*
- ✓ *Reviewed by the SPSC and CERN RB by March 2016, and recommended to prepare a Comprehensive Design Study (CDS) by 2018*
  → Input to the European strategy consultation to take a decision about construction of SHiP in 2019/2020

***CDS will improve SHiP TP version** respecting cost constraints*

Main goals of the SHiP optimization for the CDS

- ✓ *Further optimization of the target*
- ✓ *Configuration of the muon shield, including magnetization of the hadron stopper (**MC to be validated with data**)*
- ✓ *Shape, dimension and evacuation of the decay volume*

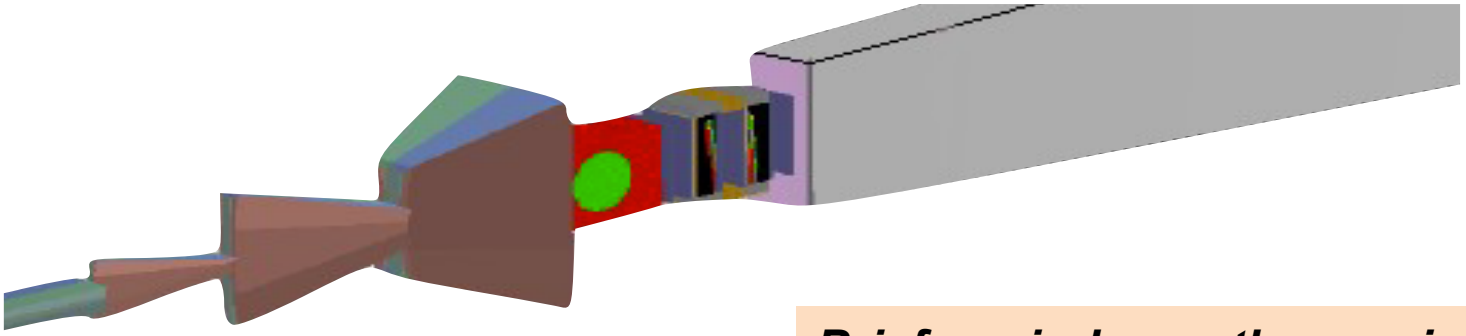


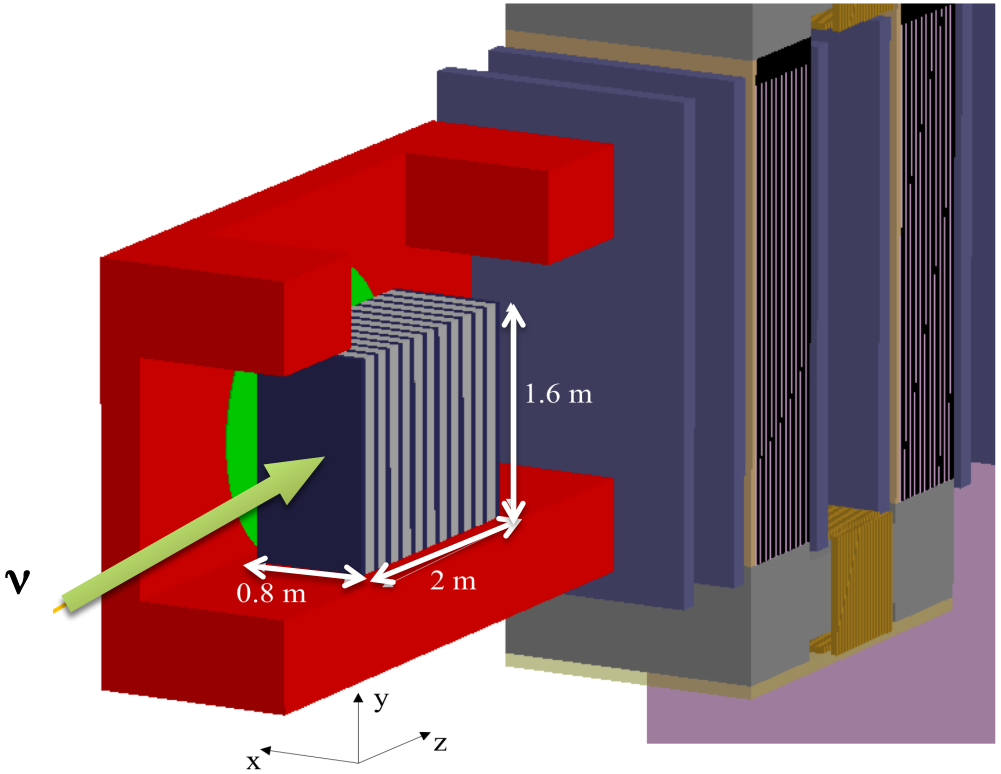
- ✓ *Optimization of physics performance for various sub-detectors*
- ✓ *Revisit detector technologies, including new sub-detectors, to further consolidate background rejection and extend PID (see Walter's talk)*
- ✓ ***Optimization of the emulsion detector to search for LDM***

Updated background estimates and signal sensitivities, and cost

- ✓ *Contribution from the secondary interactions in the target improves signal yield by ~50% (**to be validated with data**)*

Optimization of the emulsion spectrometer
TP layout





Brief reminder on the requirements:

- ✓ *High spatial resolution to observe the τ decay (~1 mm)*

→ ***EMULSION FILMS***

- ✓ *Electronic detectors to provide the time stamp to the event and match tracks from the emulsion target down to the muon spectrometer*

→ ***TARGET TRACKER PLANES***

- ✓ *Magnetized target to measure the charge of hadrons from τ decays*

→ ***DIPOLAR MAGNET***

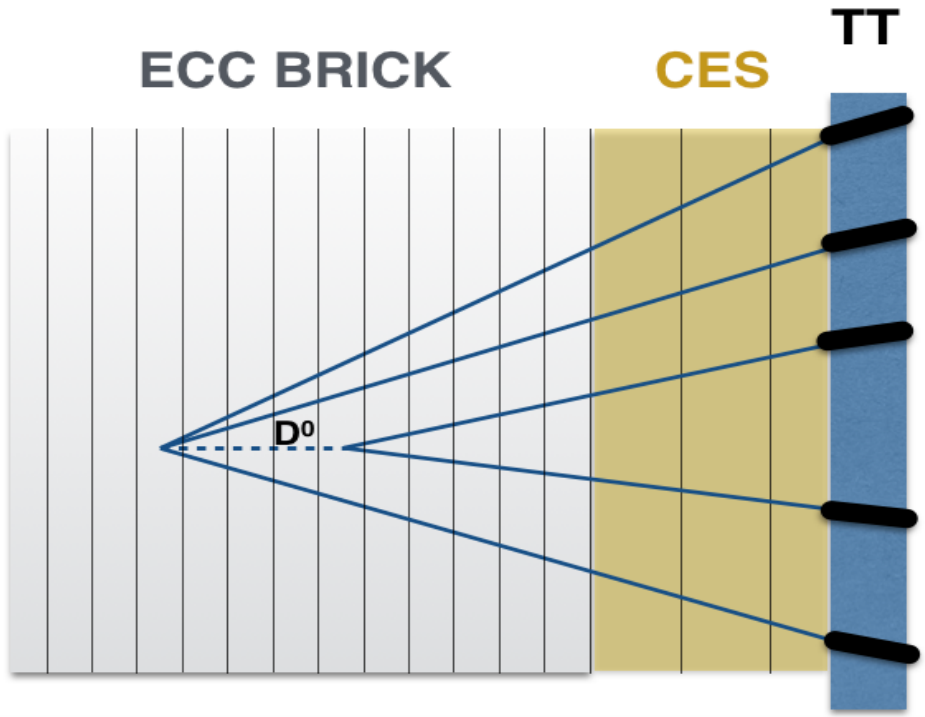
- ✓ *Magnetic spectrometer to perform muon identification and measure its charge and momentum*

→ ***MUON SPECTROMETER***

TT: Target Trackers *(12 planes, 0.8×1.6 m² each)*

Technology is to be chosen!

- ✓ *Provide time stamp of the neutrino interaction in the brick*
- ✓ *Matching between the electronic detectors and the emulsion tracker in high density environment (long integration time of the emulsion films)*
- ✓ *Matching the muon track with the downstream muon spectrometer*



Requirements:

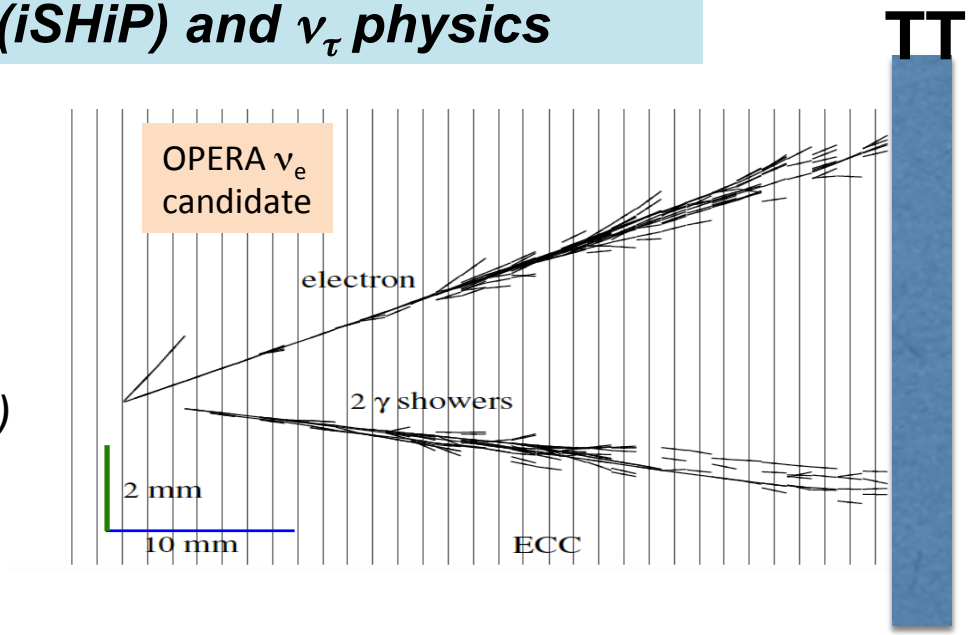
- *Spatial resolution: 100 um*
- *Maximum thickness for a plane: 5 cm*
- *Distance between TT plane and ECC to be small (a few mm) and uniform (constant tracking capabilities)*
- *Small dead spaces (max 1 mm) to be matched with ECC dead spaces*
- *High efficiency (>99%)*
- *Good performances in magnetized region*
- *Angular information*

Note: *Good spatial resolution needed, e.g. to discriminate between 2-vertices topology (D^0-decay) and two neutrino interactions occurring at the same time stamp*

Optimization of the SHiP emulsion spectrometer for νWIMP searches (iSHiP) and ν_τ physics

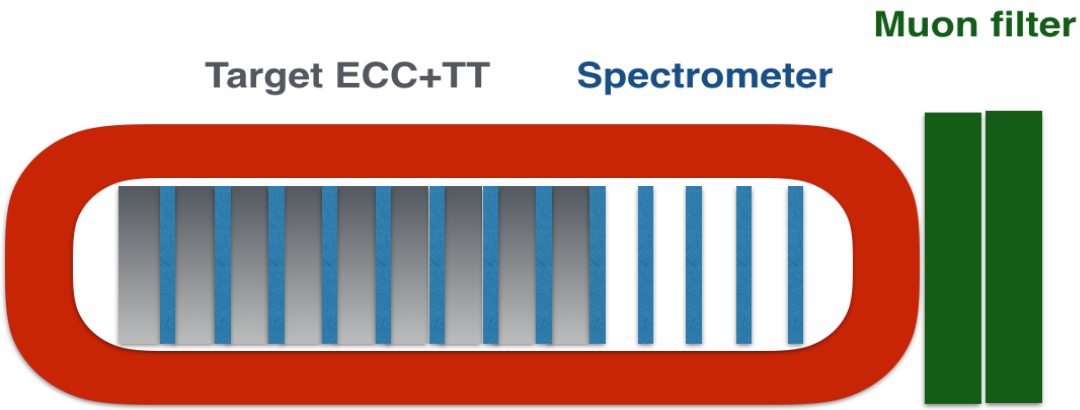
Possible improvements:

- ✓ *Analog readout of TT to provide calorimetric information*
- ✓ *Optimize the distance between consecutive TT planes (currently ~10X_0)*
- ✓ *Use a combination of TT and ECC to measure electromagnetic and hadronic showers in the event*

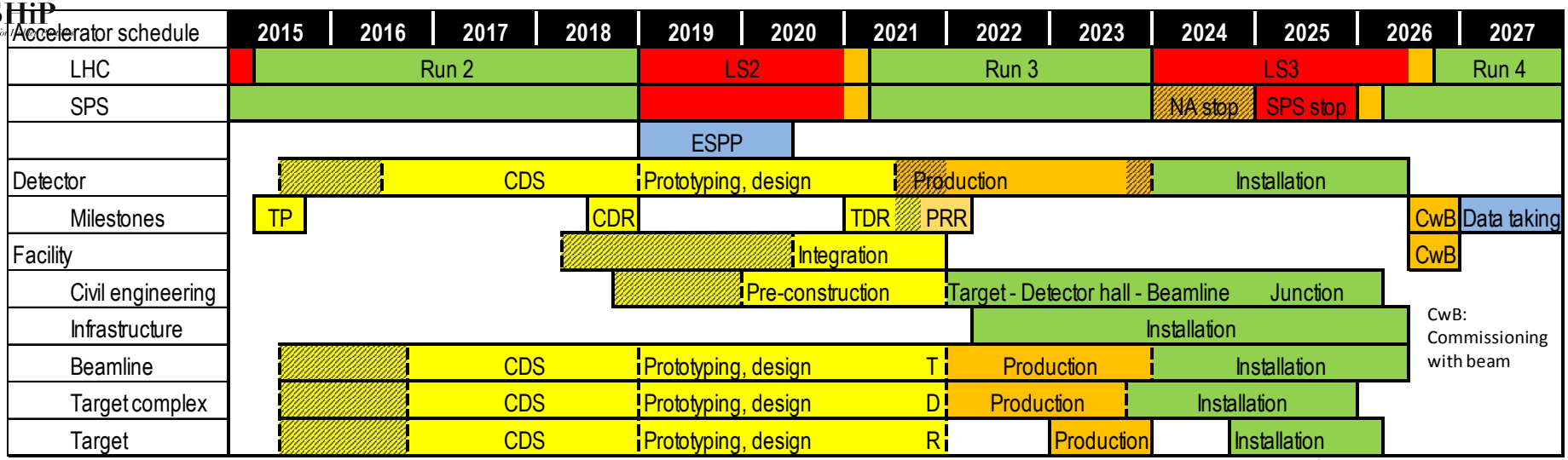


New layout is under study

- ✓ *Single long magnet hosting the emulsion and muon spectrometer*
- ✓ *Muon identification using a filter outside the magnet*



Global SHiP schedule

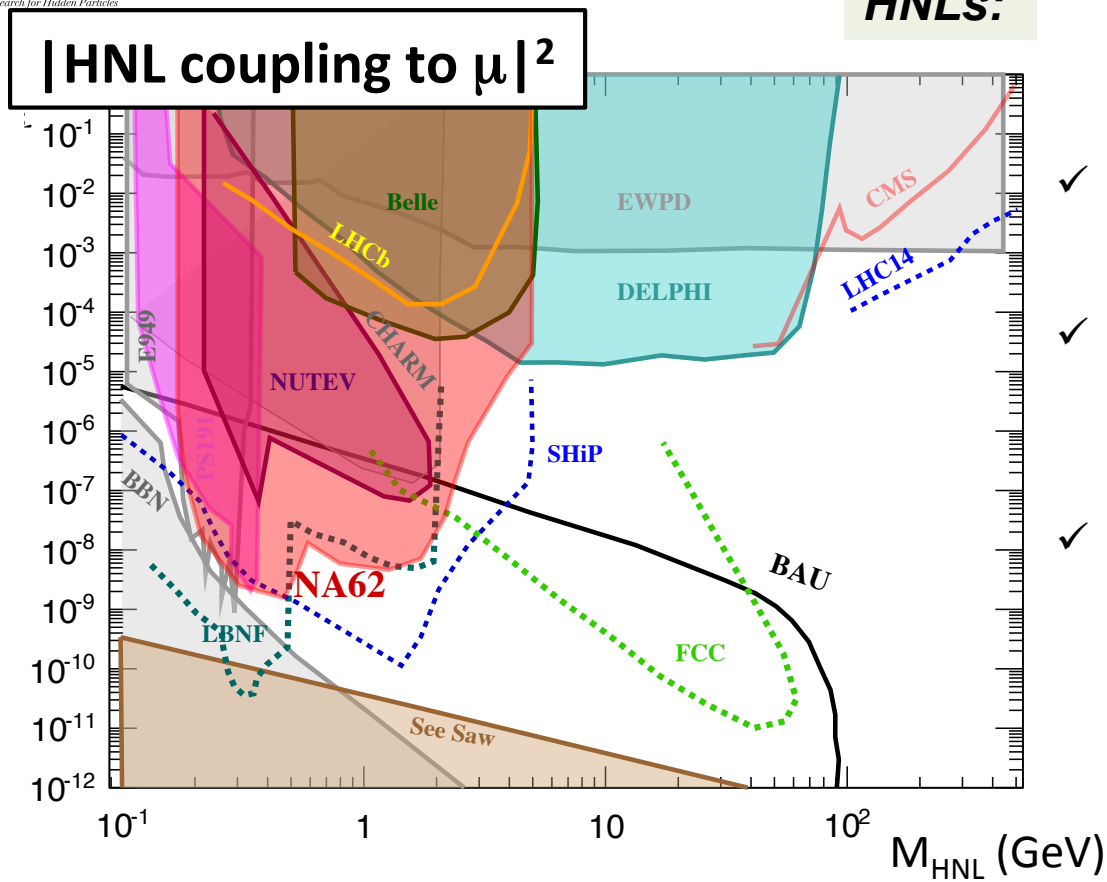


- ✓ ***Planning very well aligned with***
  - *Update of European strategy 2019/2020*
  - *Accelerator schedule (to be followed closely)*
  - *TDRs by 2021*
  - *Production Readiness Reviews (PRR) 2021Q2 – 2022Q1*
  - *Construction / production 2021Q2 →*
  - *Data taking (pilot run) 2026 (start of LHC Run 4)*

- ✓ ***Main current priority: Comprehensive Design Study by 2018***

Future prospects and comparison with other facilities

HNLs:



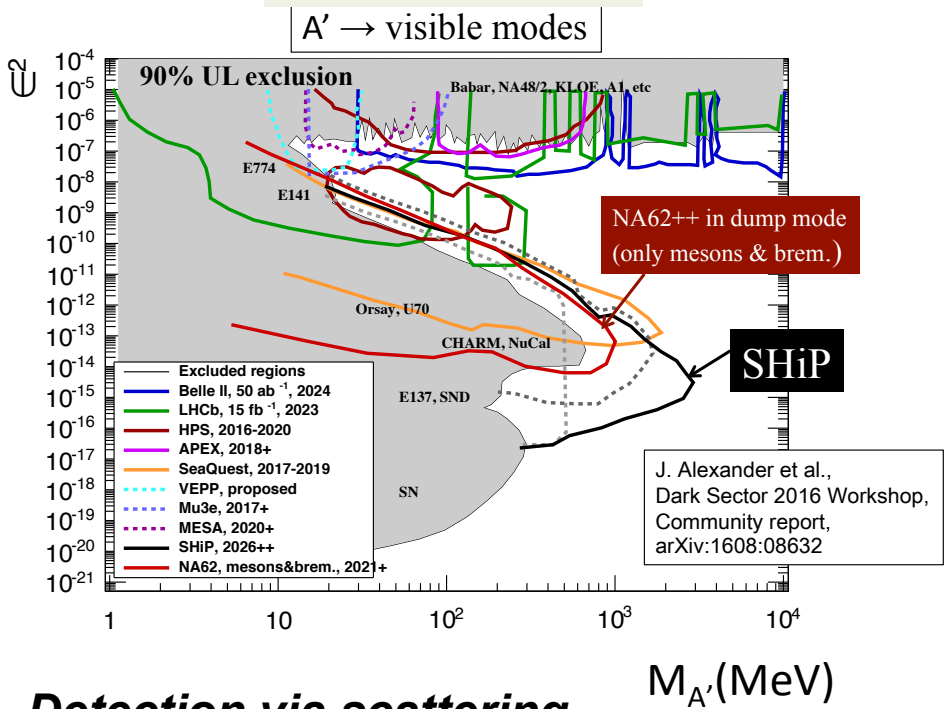
- ✓ $M_{HNL} < M_b$ LHCb, Belle2
  SHiP will have much better sensitivity
- ✓ $M_b < M_{HNL} < M_Z$ ***FCC in e^+e^- mode***
  (improvements are also expected from ATLAS / CMS)
- ✓ $M_{HNL} > M_Z$ ***Prerogative of ATLAS/CMS @ HL LHC***

SHiP sensitivity covers large area of parameter space below B mass moving down towards ultimate see-saw limit

SHiP will also have the best prospects for HS particles produced in heavy flavour decays, e.g. hidden scalars *(see Gaia's talk)*

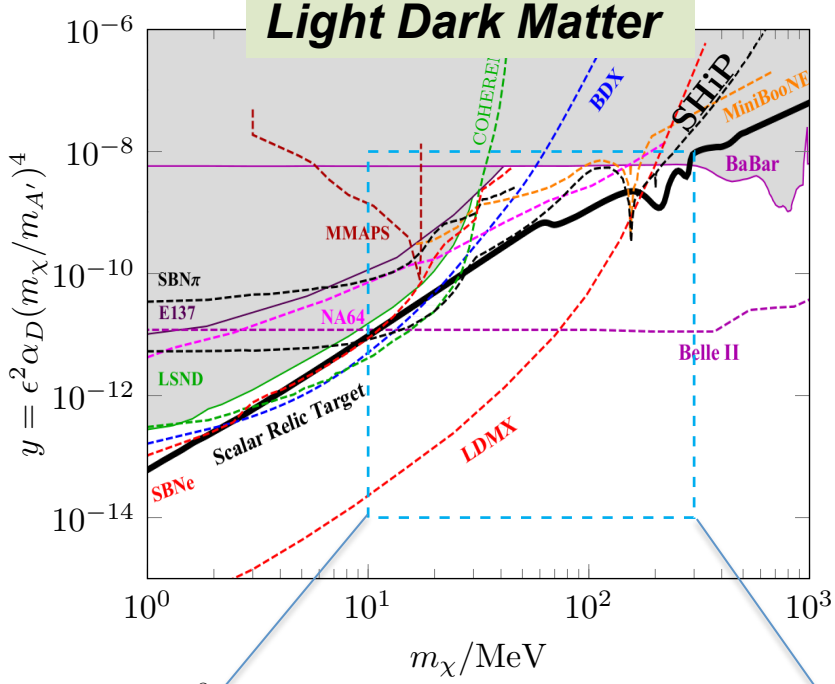
Future prospects and comparison with other facilities

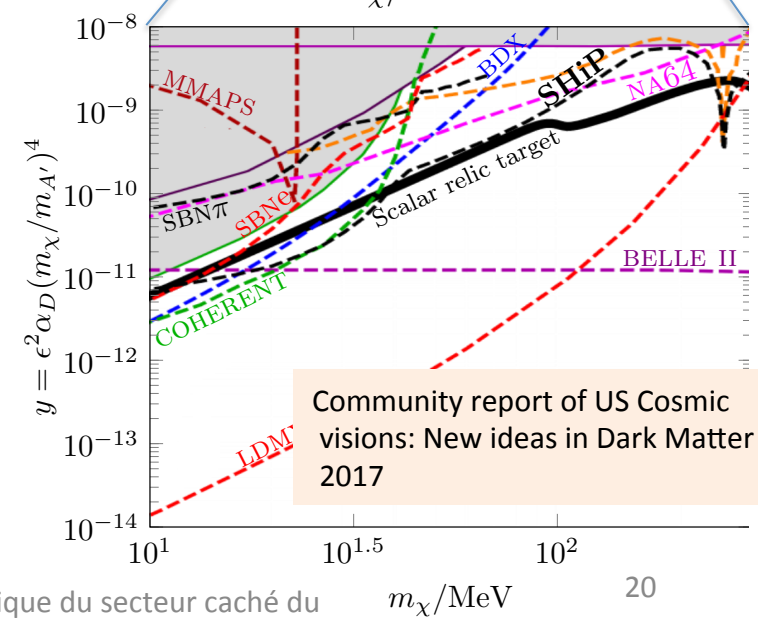
Dark photons:



J. Alexander et al., Dark Sector 2016 Workshop, Community report, arXiv:1608:08632

Light Dark Matter





Community report of US Cosmic visions: New ideas in Dark Matter 2017

Detection via scattering

- *SHiP has the best sensitivity in 20 – 200 MeV*
  Optimization is ongoing
  COHERENT, BDX and SBNe in US

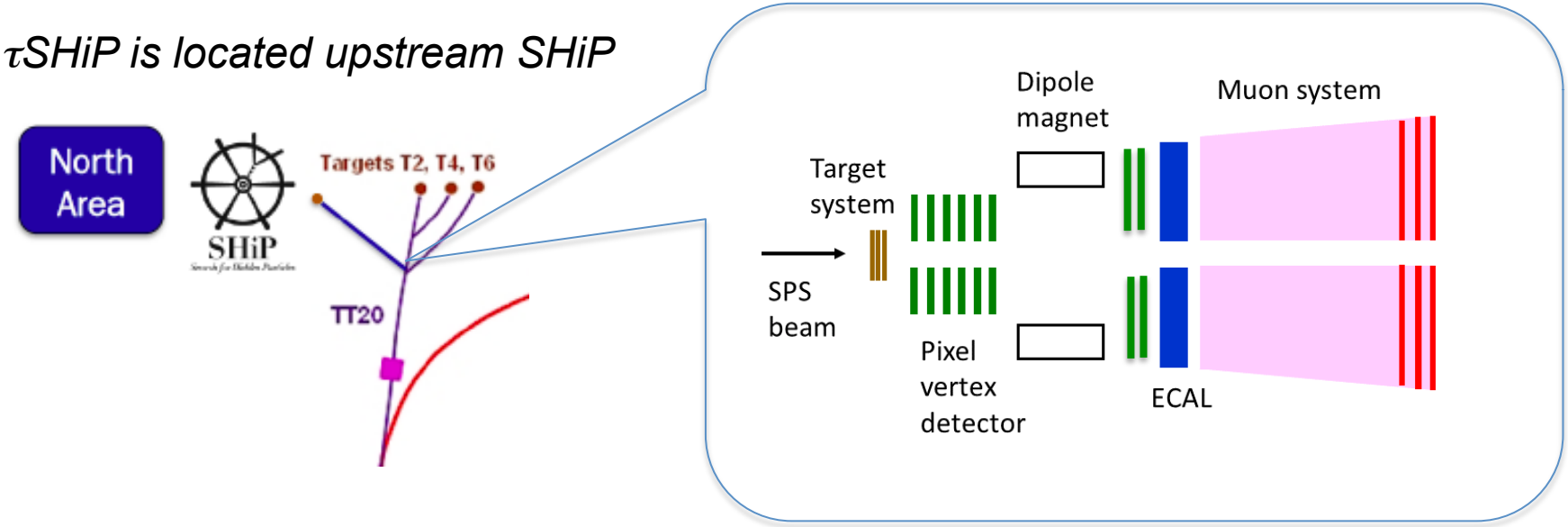
Missing mass / energy technique

- *Belle II with 50 ab^{-1} provided that low energy mono-photon trigger works*
- *LDMX (under discussion at SLAC) has the best prospects for M_χ< 100 MeV*

Search for $\tau \rightarrow \mu\mu\mu$ (τSHiP) at possible extension of SHiP facility

Currently at the pre-EOI stage (see SHiP Physics Paper)

τSHiP is located upstream SHiP



- ✓ *Thin (~1mm thick) W target(s) → τ-decay vertex in the air*
- ✓ *~ 5×10^{13} τ leptons produced in 5 years*
- ✓ *Backgrounds include*
  - *Combinatorial bckg., mainly from muons produced in em decays of η, ρ, ω, …*
  - *Bckg. from various semileptonic D decays, e.g. $D^+ \rightarrow \eta\mu^+\nu$, $\eta \rightarrow \mu^+\mu^-$*
- ✓ *Estimated sensitivity: UL on BR($\tau \rightarrow 3\mu$) better than 10^{-10} (SHiP Physics Paper)*

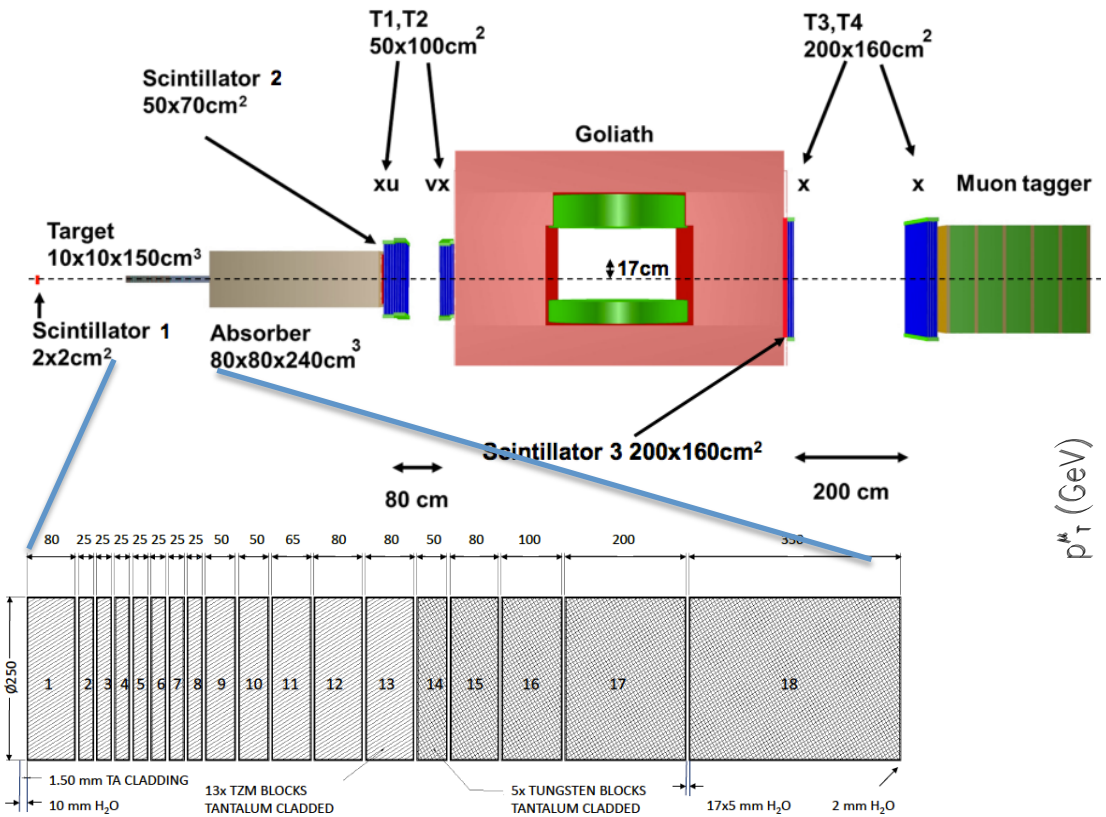
BUT: Great improvements in detector technologies are required

Synergy with LHCb tracking and calorimetry for future upgrades

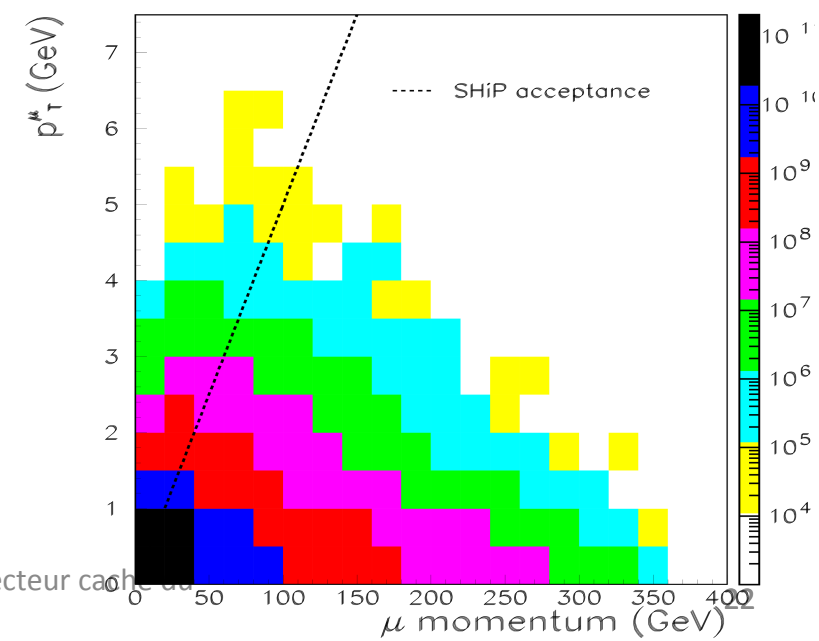
Important measurements towards TDR

(test beam program and prototypes will be covered by Richard)

✓ ***Measurement of muon flux expected at SHiP in 2018***
Replica of the SHiP target followed by a muon spectrometer



✓ ***SHIP target***, *10×10 cm² Mo/W replica*
✓ ***Spectrometer*** *to measure momentum and charge of the muons*
✓ ***Muon tagger*** *to identify muons*



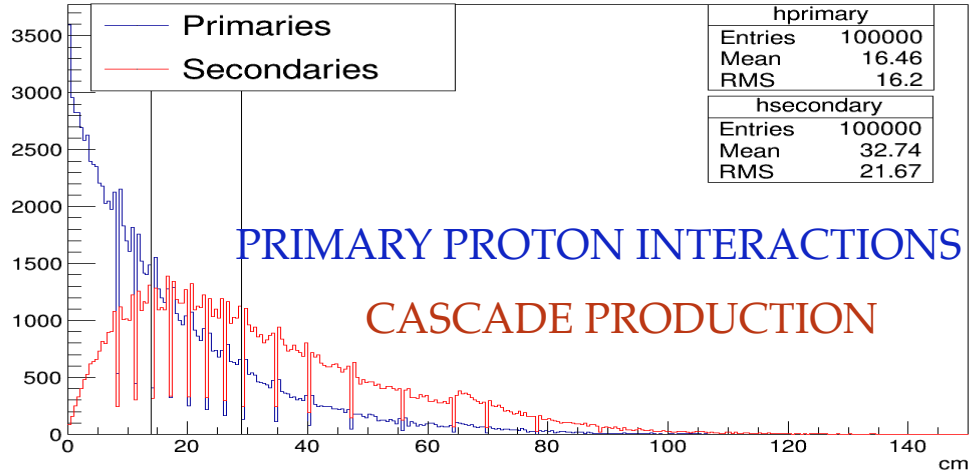
10^{11} pot → 10 times more data than in SHiP MC
Validate simulation in "dangerous" corners of the muon phase space

EoI-016 submitted to the SPSC

Associated charm production

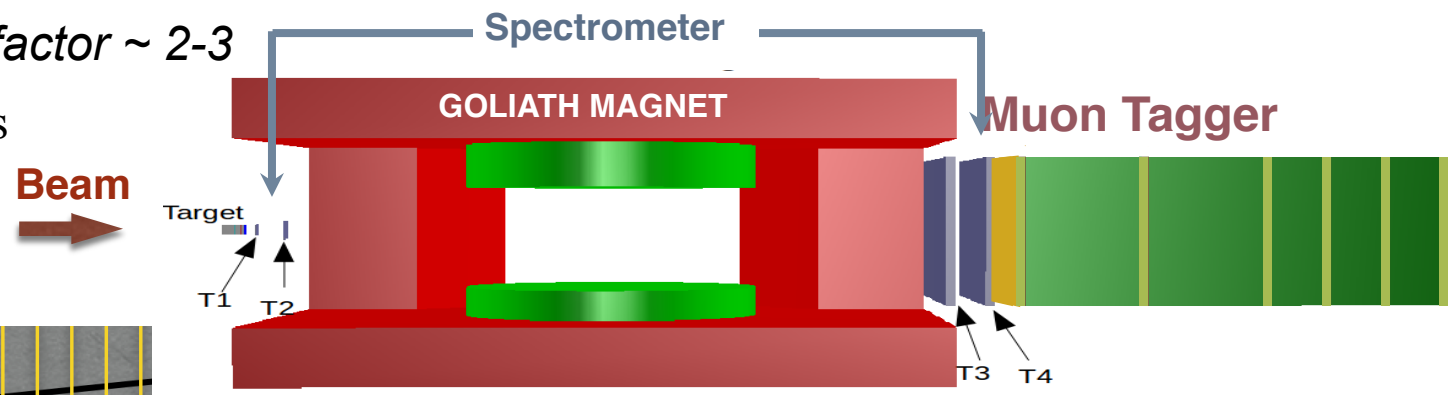
Measurement of inclusive $d^2\sigma / dEd\theta$ charm cross section in SHiP-like target *(to validate cascade production in the target) in 2018-2021*

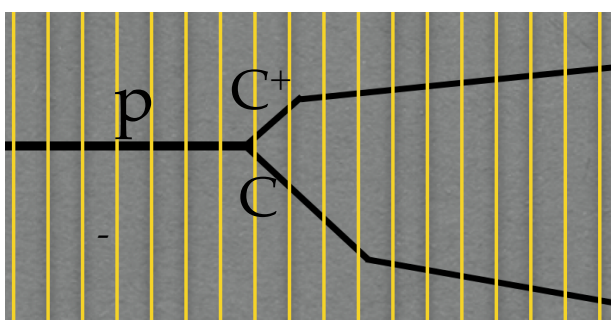
- ✓ ***SHIP target**, 10×10 cm² Mo/W blocks (few mm)interleaved with emulsion to identify charm topology*
- ✓ ***Spectrometer** to measure momentum and charge of the charm daughters*
- ✓ ***Muon tagger** to identify muons*



Cascade effect → a factor ~ 2-3

400 GeV protons





5 x 10^7 pot → ~ 10000 charmed hadron pairs

EoI-017 submitted to the SPSC

Conclusions

- ✓ ***Physics case to search for Dark Sector is very timely !***
  No NP finding at LHC, *but many theoretical models offer a solution for the BSM experimental facts with light very weakly-interacting particles.* ***Must be tested !***

- ✓ ***CERN is ideal place to search for Dark Sector at high energy and high intensity SPS beams.*** *Two complementary strategies are being explored, direct observation of the decay vertex and indirect detection via scattering on atoms*

- ✓ ***New possibilities to search for LFV in tau decays at the SHiP facility***

- ✓ ***SHiP is an ideal experiment to search for new phenomena in < O(10 GeV) range in "no background" environment***
  Complementarity between two detection techniques:
  - Reconstruction of the decay vertices in the decay volume
  - Detection of interactions with atoms in the emulsion spectrometer

- ✓ ***The rich physics programme to search for Dark Sector at the SPS North Area at CERN nicely complements searches for NP at the LHC***