The Intensity Frontier Physics
&
SHiP

이강영
경상대학교

@서울대학교 2018.09.05

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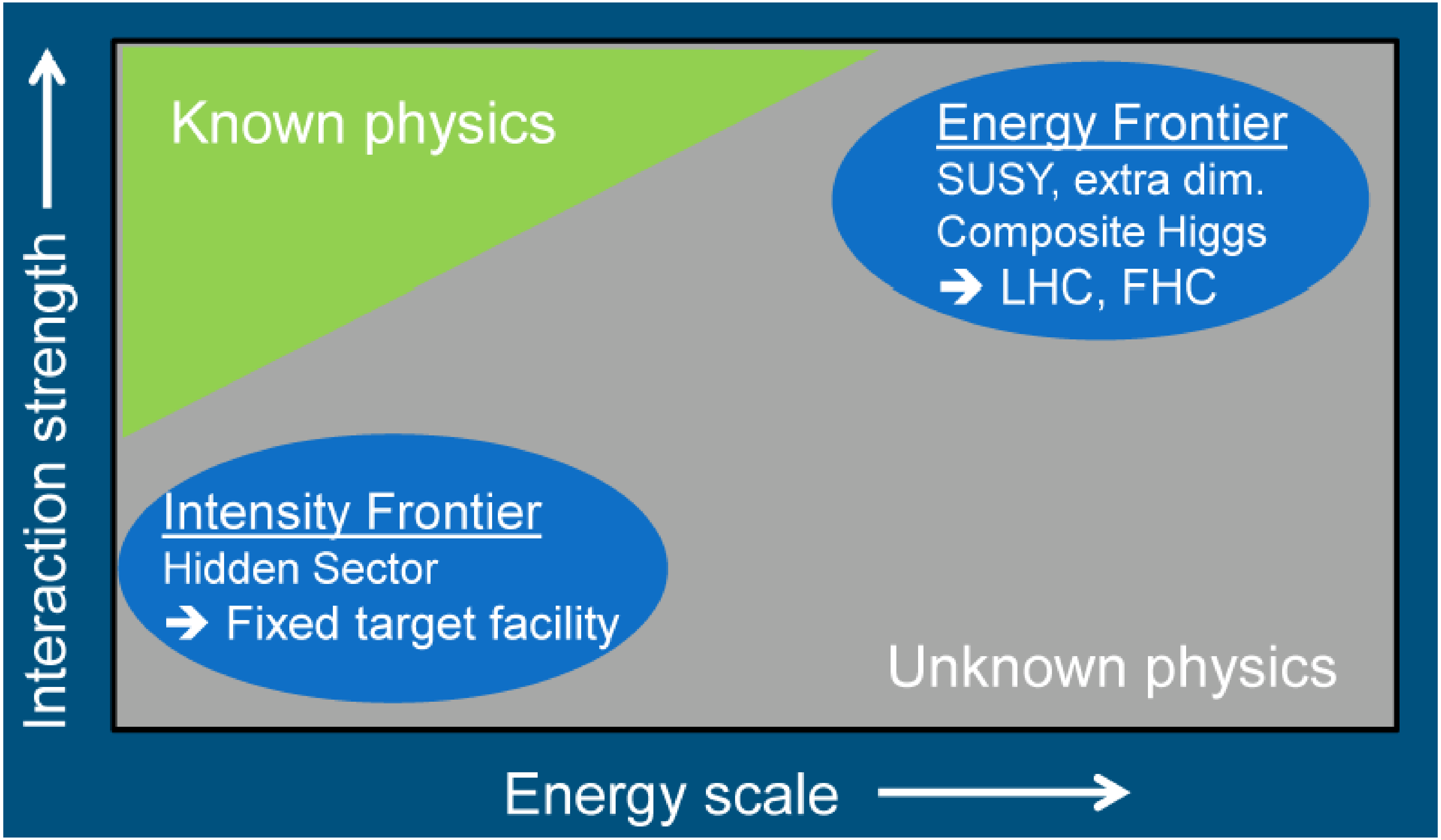
Energy Frontier vs. Intensity Frontier



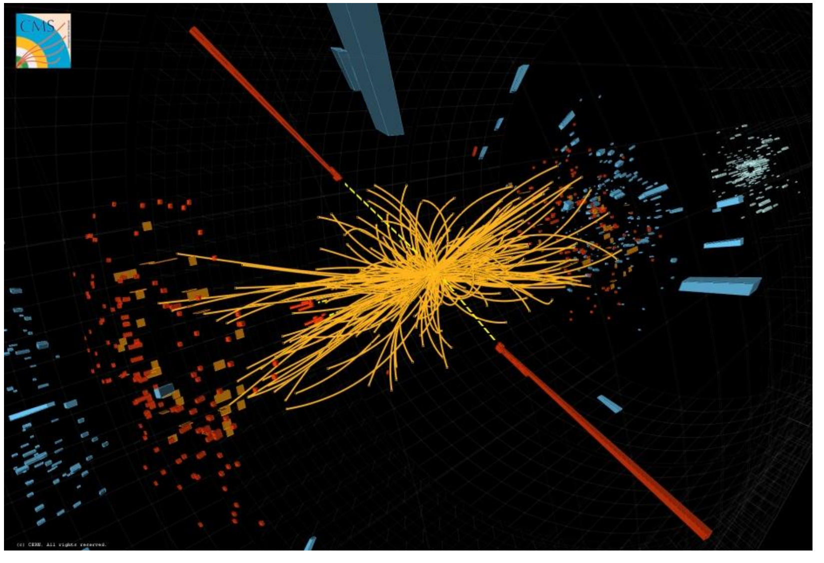
Energy Frontier

$$E^2 = m^2c^4 + p^2c^2$$

에너지 ↔ 질량

High Energy ↔ Heavy Mass

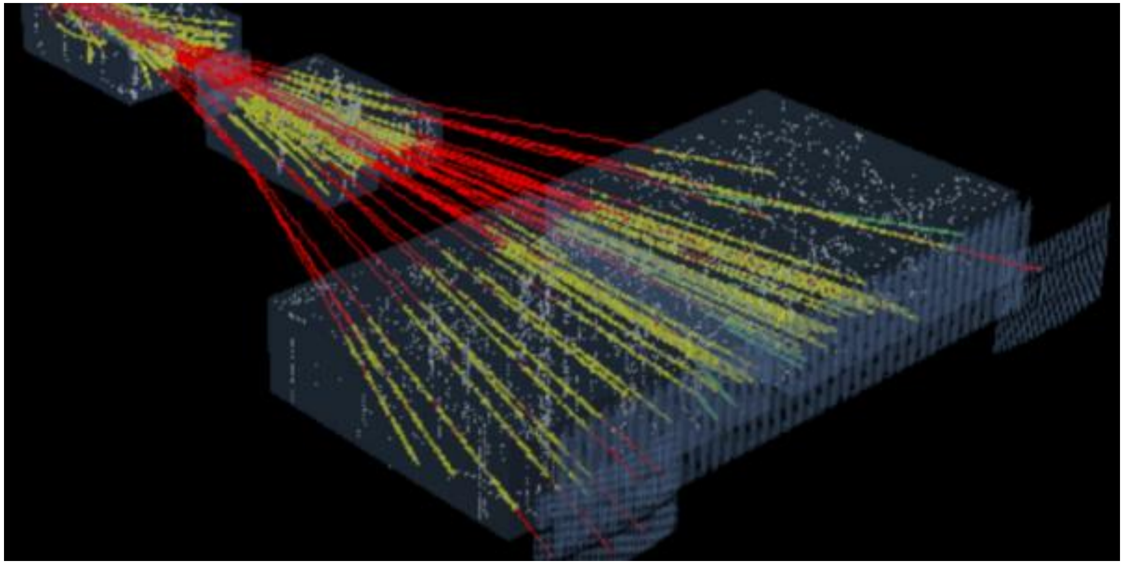
입자를 만들 수 있어야 입자를 볼 수 있다.



Intensity Frontier

사건 수 = 발생할 확률 X 시행 횟수

사건이 일어나야 사건을 볼 수 있다.

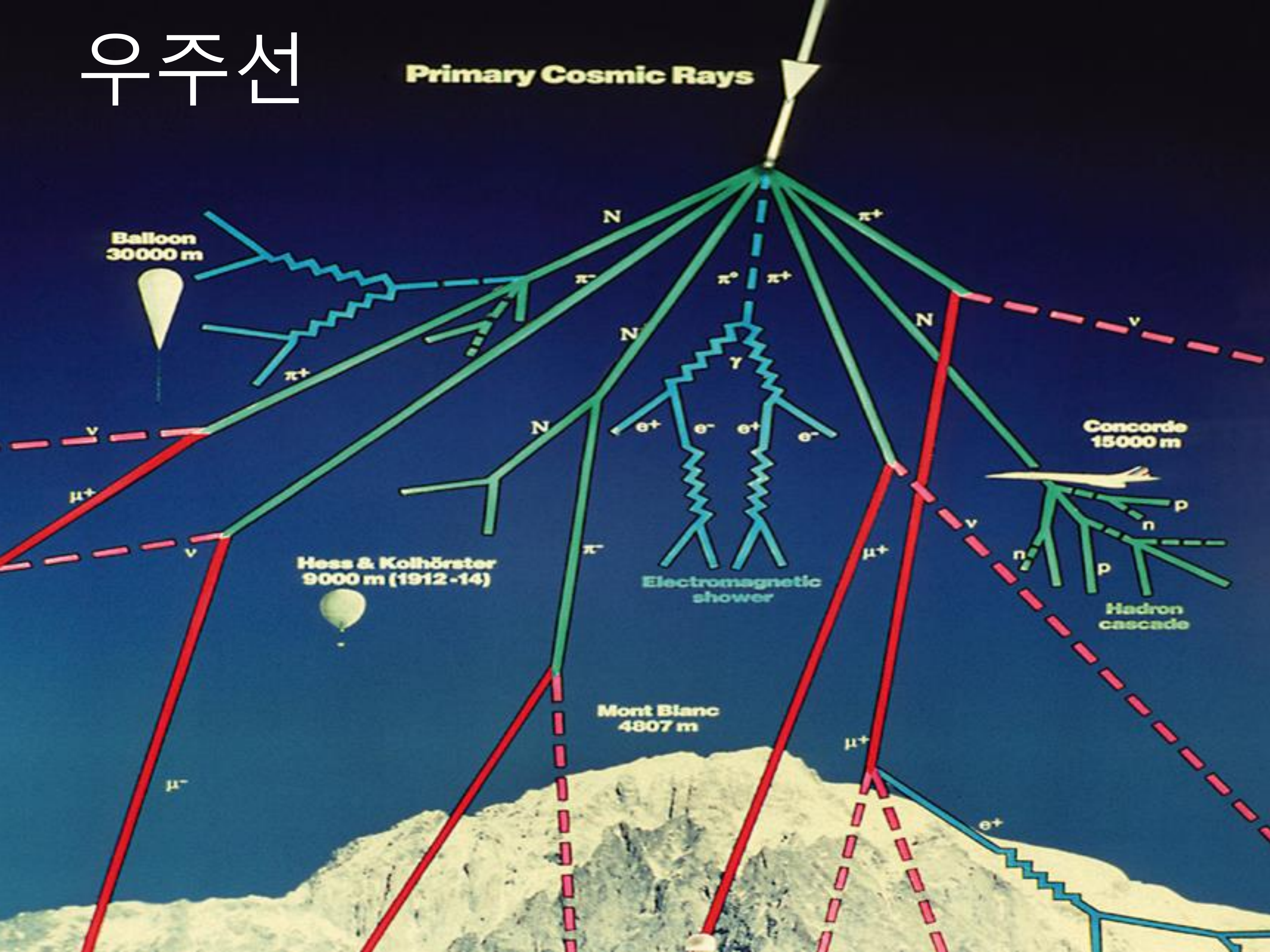


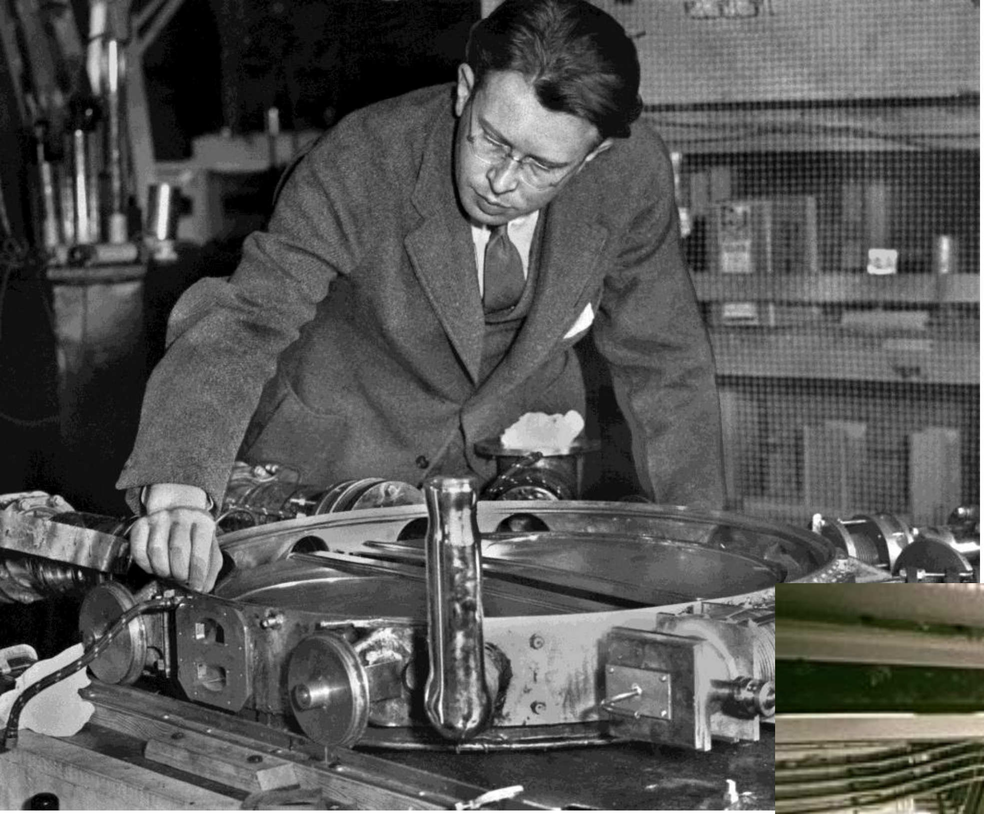
Energy Frontier Physics

역사적으로

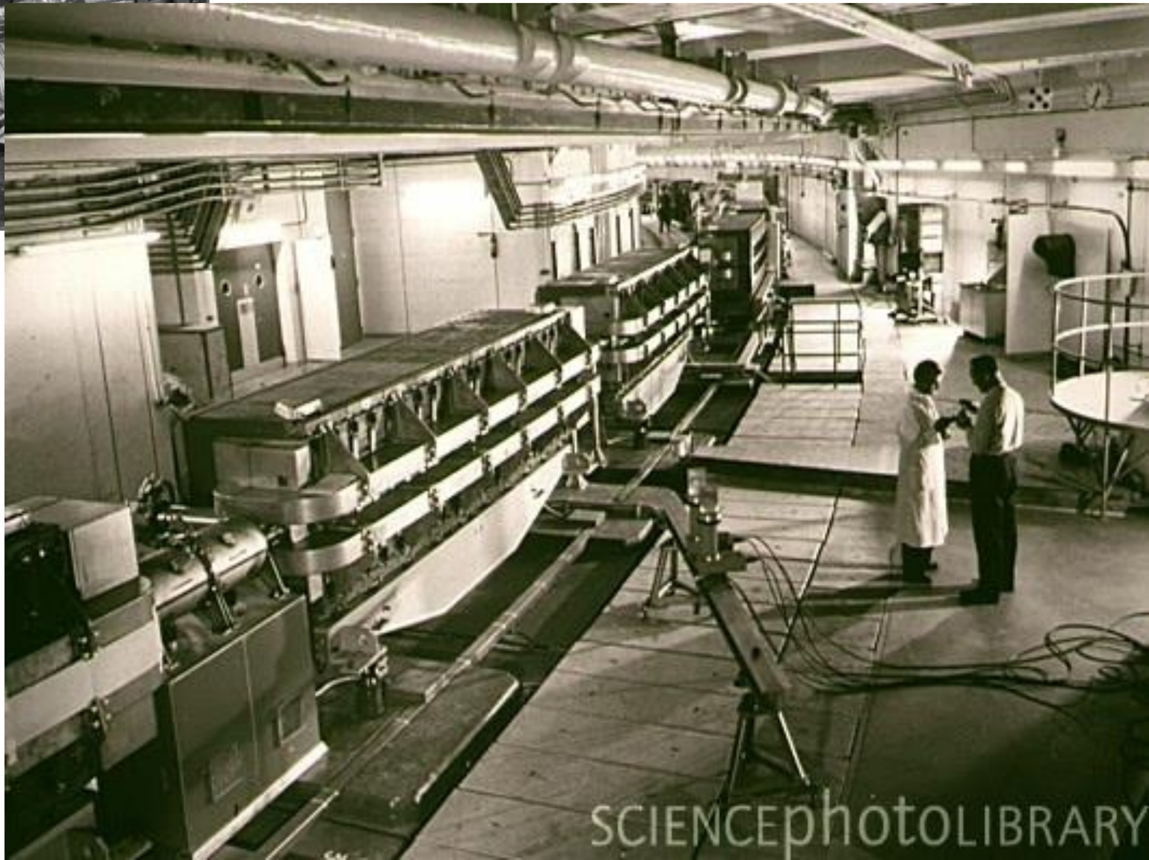
- 우주선 Cosmic Ray
- 가속기 Accelerator
- 충돌기 Collider

우주선


Primary Cosmic Rays
Balloon
30000 m
N
π+
π-
π°
π+
N
N
γ
e+
e-
e+
e-
N
ν
μ+
ν
Concorde
15000 m
p
n
n
p
Hadron
cascade
Hess & Kolhörster
9000 m (1912-14)
π-
Electromagnetic
shower
μ+
ν
Mont Blanc
4807 m
μ+
μ-
e+

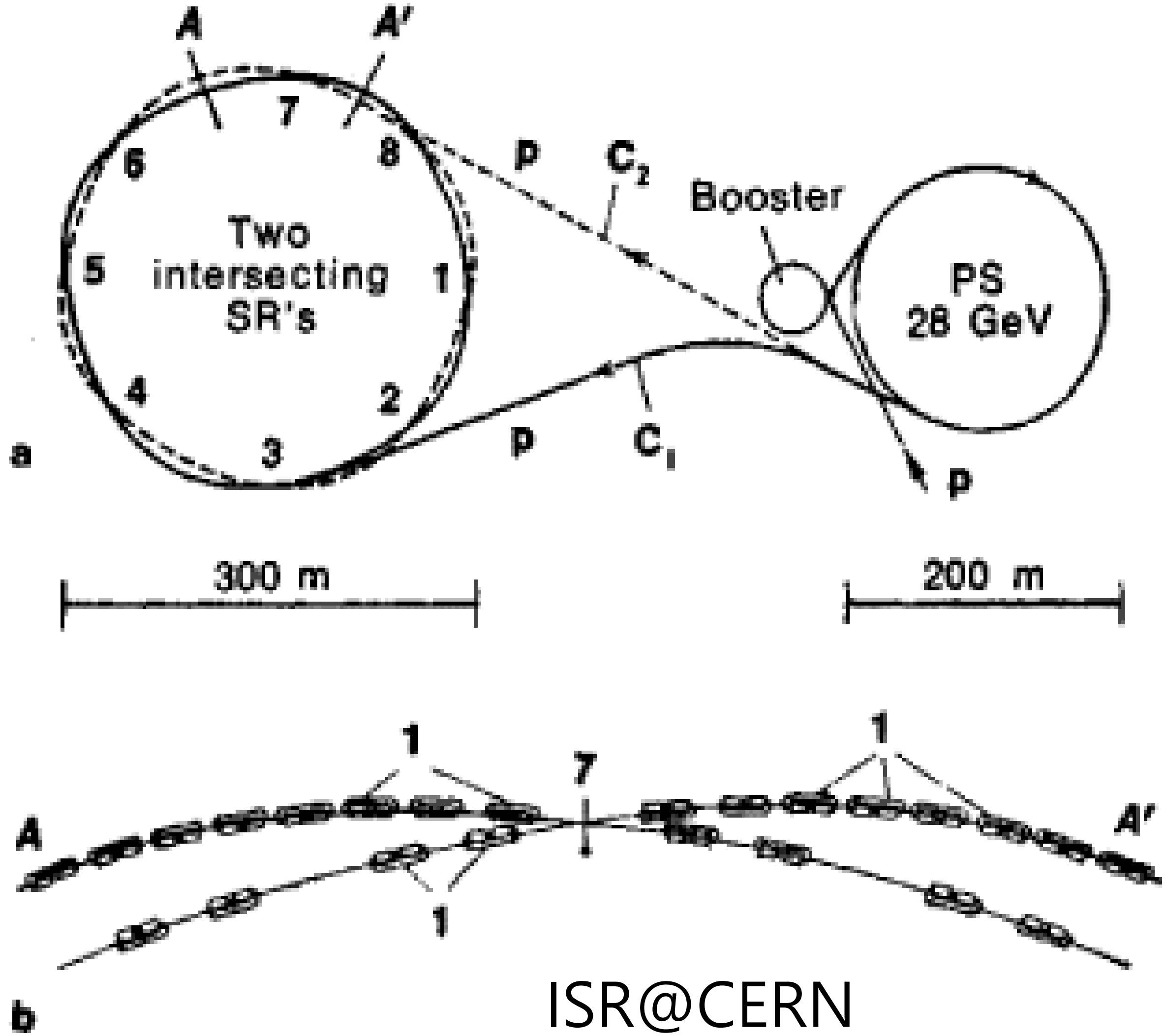


Cyclotron

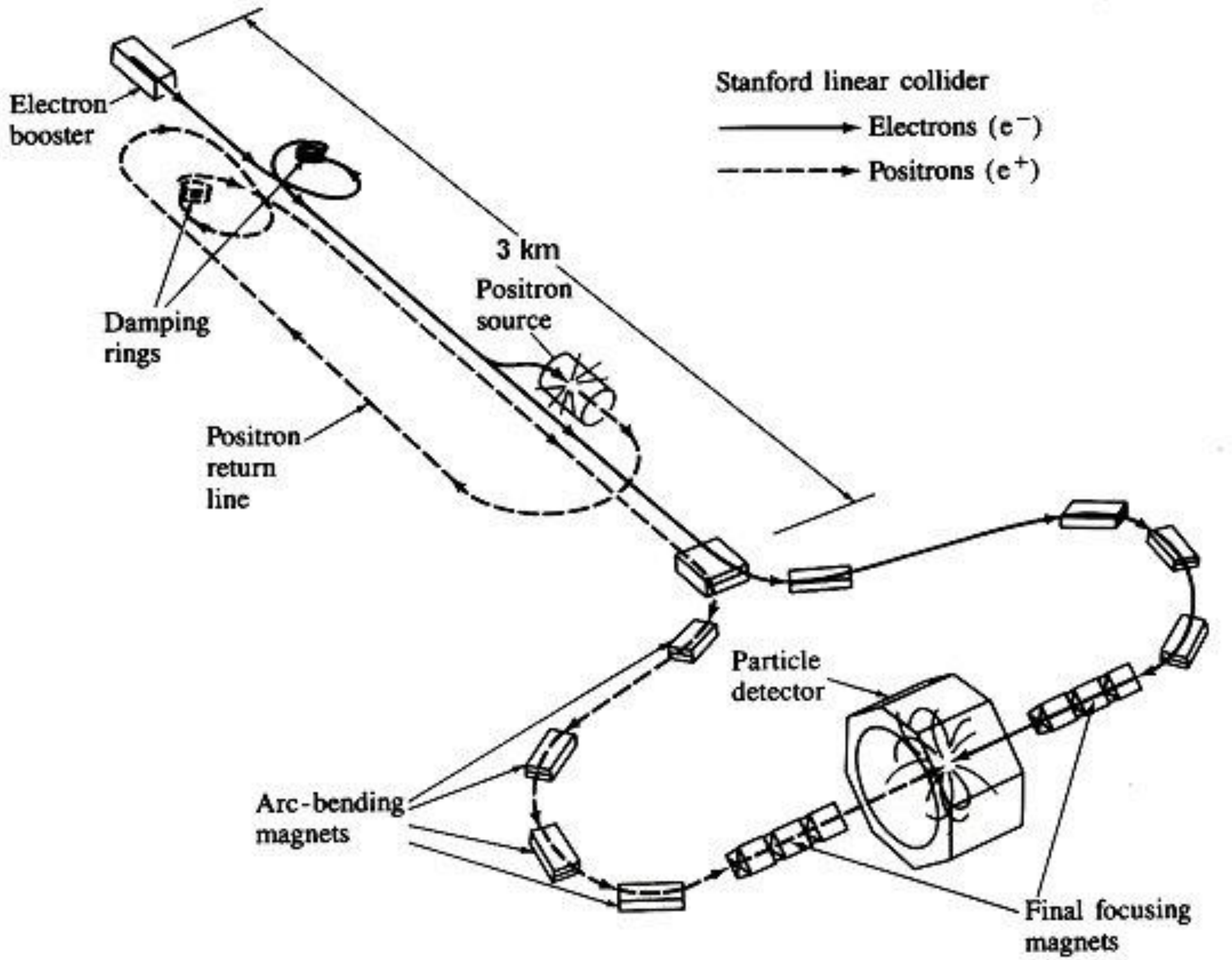


Synchrotron

Collider



ISR@CERN
최초의 양성자-양성자 충돌장치



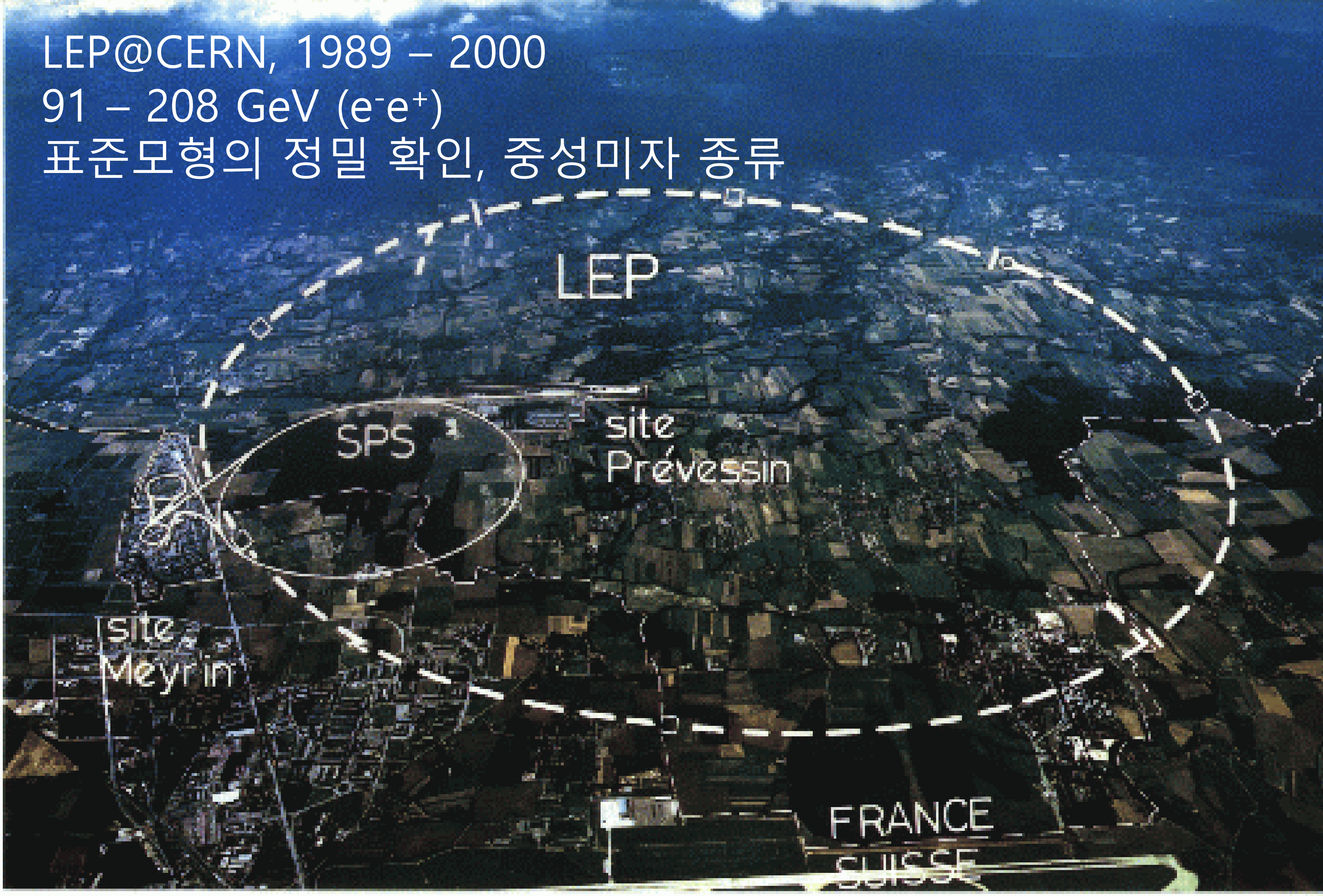
SLAC의 전자-양전자 충돌장치

테바트론
@페르미 국립 가속기 연구소, 1999-
1.96 TeV (proton-antiproton)
톱쿼크 발견

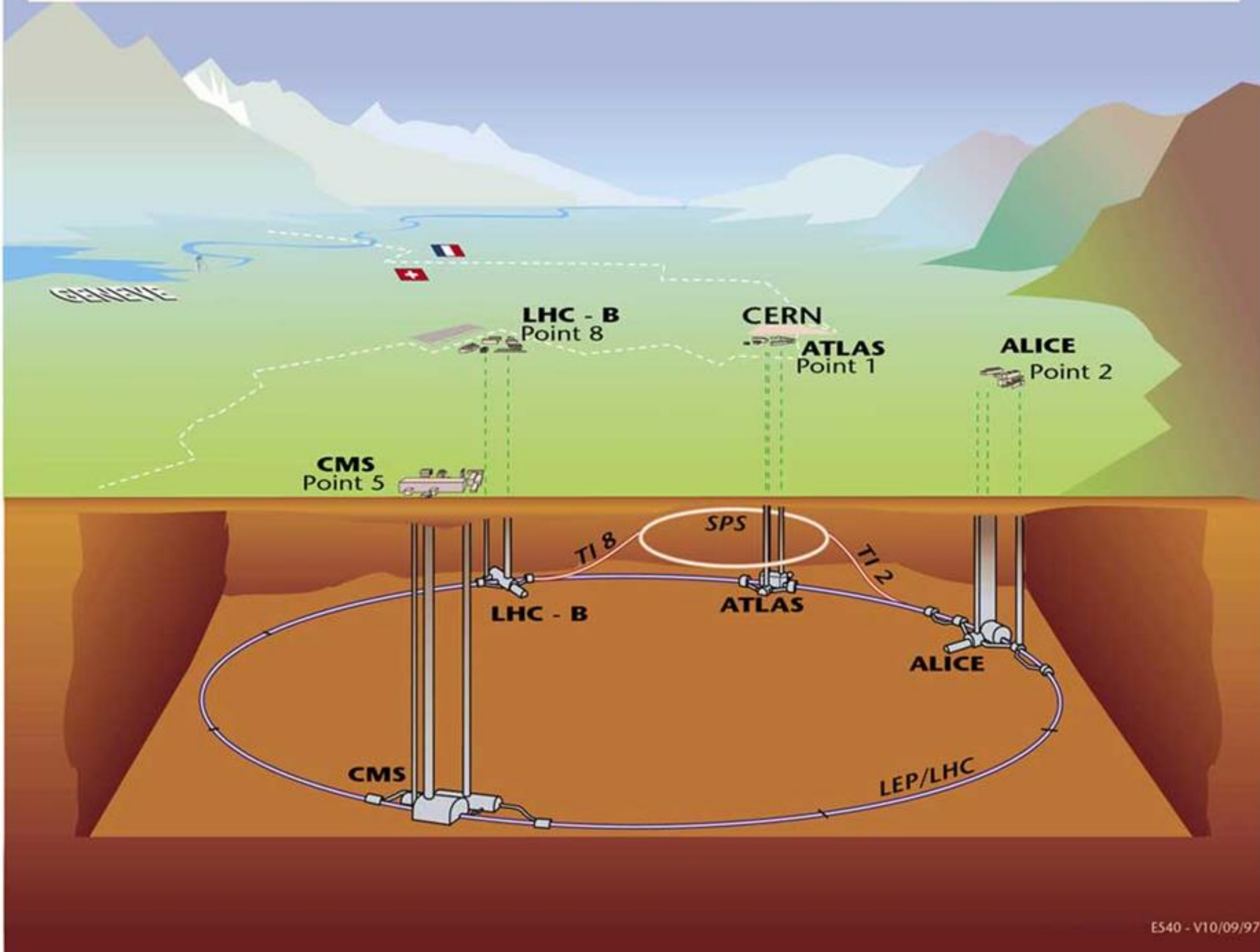
LEP@CERN, 1989 – 2000

91 – 208 GeV (e^-e^+)

표준모형의 정밀 확인, 중성미자 종류



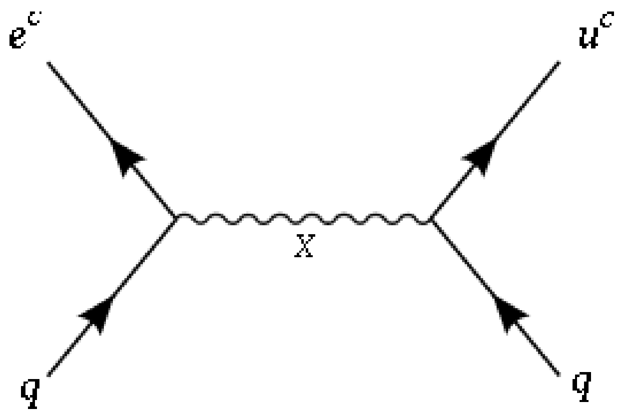
Overall view of the LHC experiments.

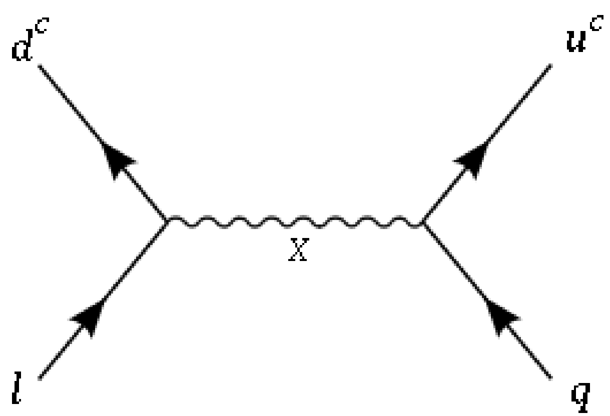


Intensity Frontier Physics

- 양성자 붕괴
- B-factory
- 암흑물질 검출
- 중성미자 물리학

양성자 붕괴



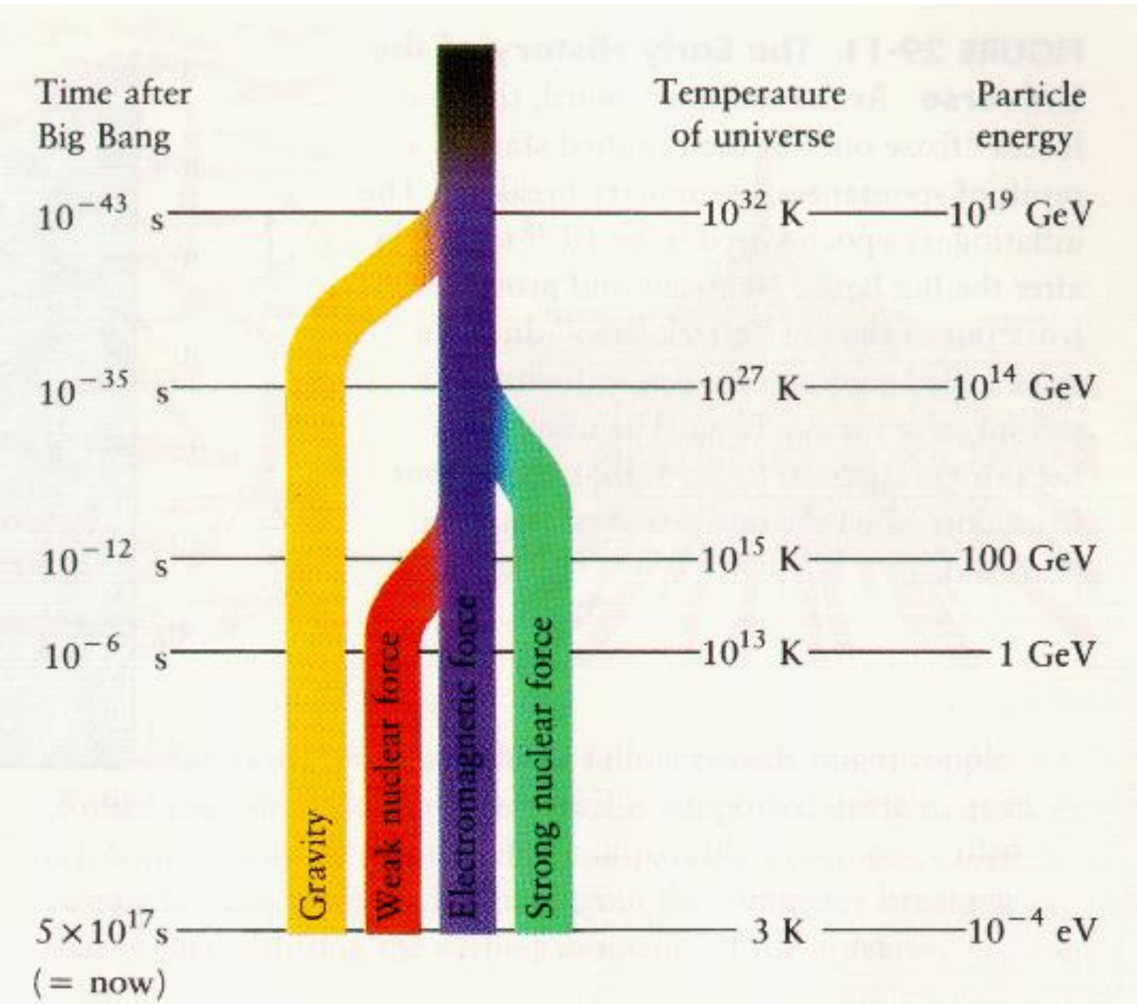


양성자 → 렙톤

표준모형 No

대통일 이론 Yes

대통일 이론의 자연스런 귀결

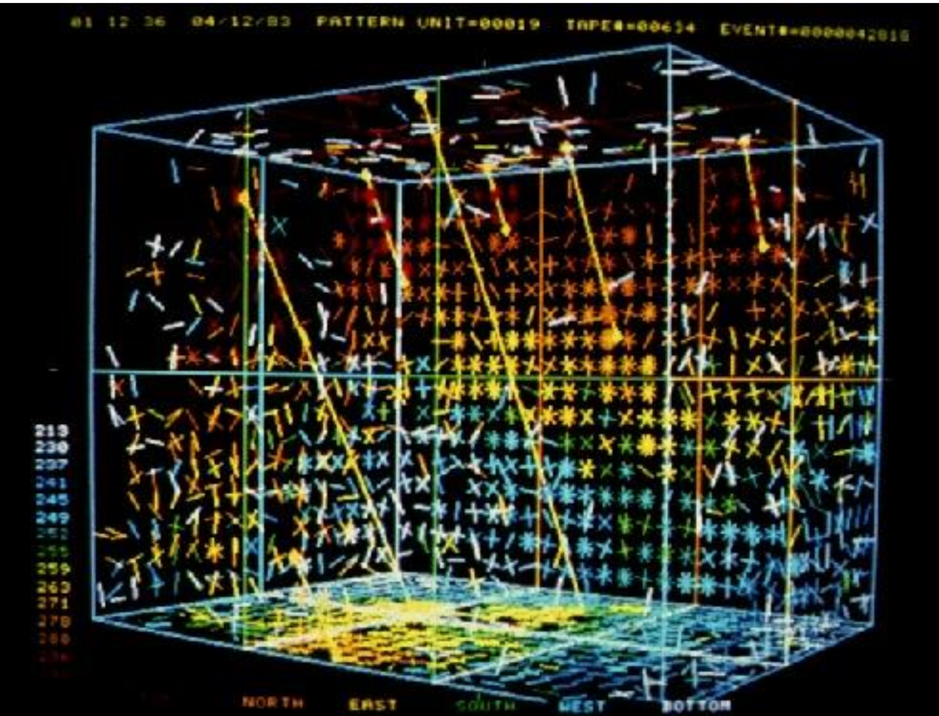


모든 힘이 통일되면 그 힘을 통해서 쿼크와 렙톤이 상호 작용할 수 있다.

e.g.

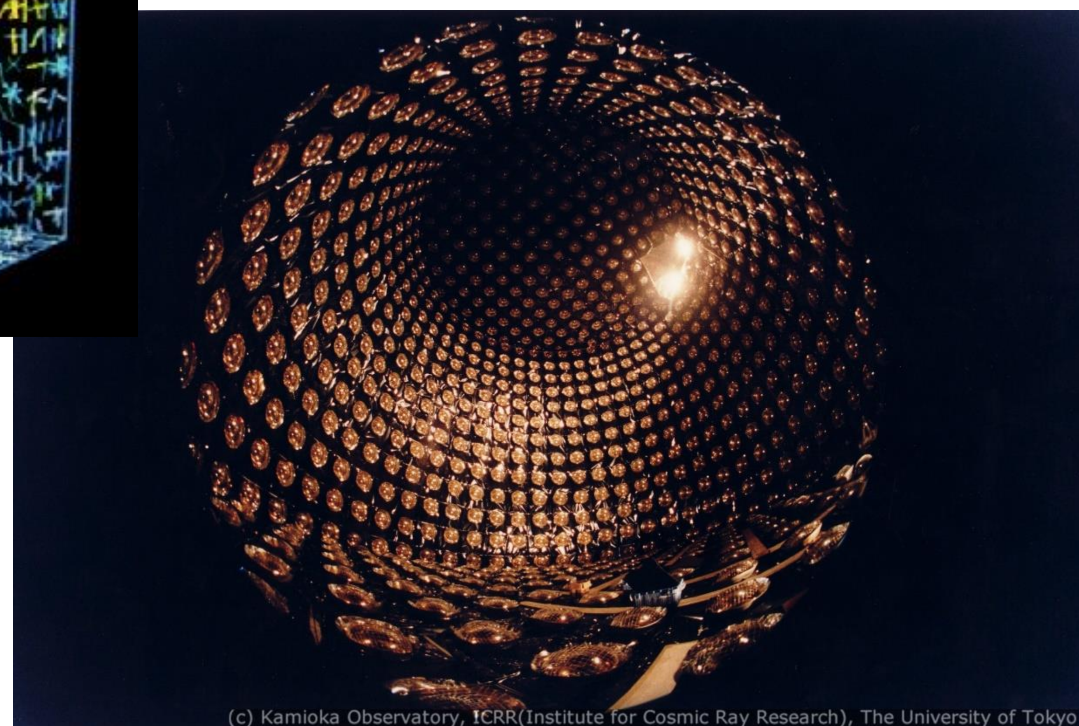
$p \rightarrow \pi^0 e^+ \rightarrow \gamma\ \gamma\ e^+$

IMB vs. Kamiokande



IMB

Kamiokande



e. g.

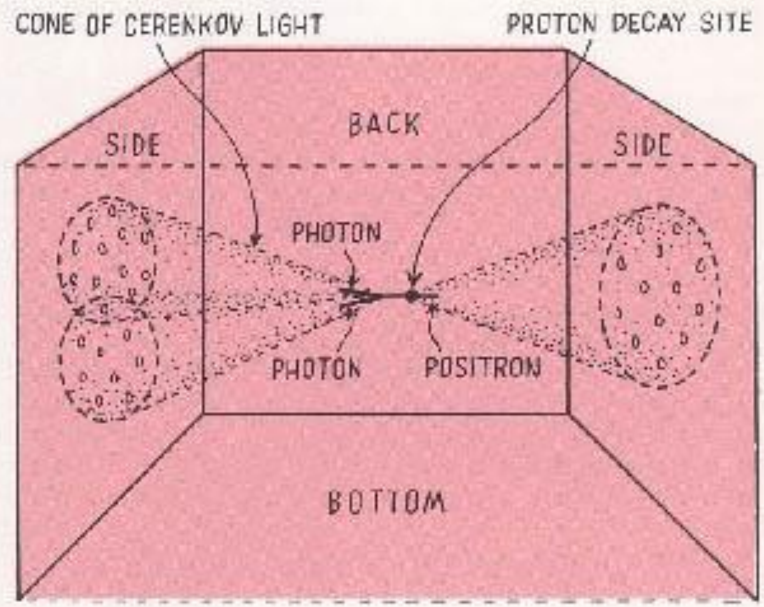
$p \rightarrow \pi^0 e^+ \rightarrow \gamma\ \gamma\ e^+$

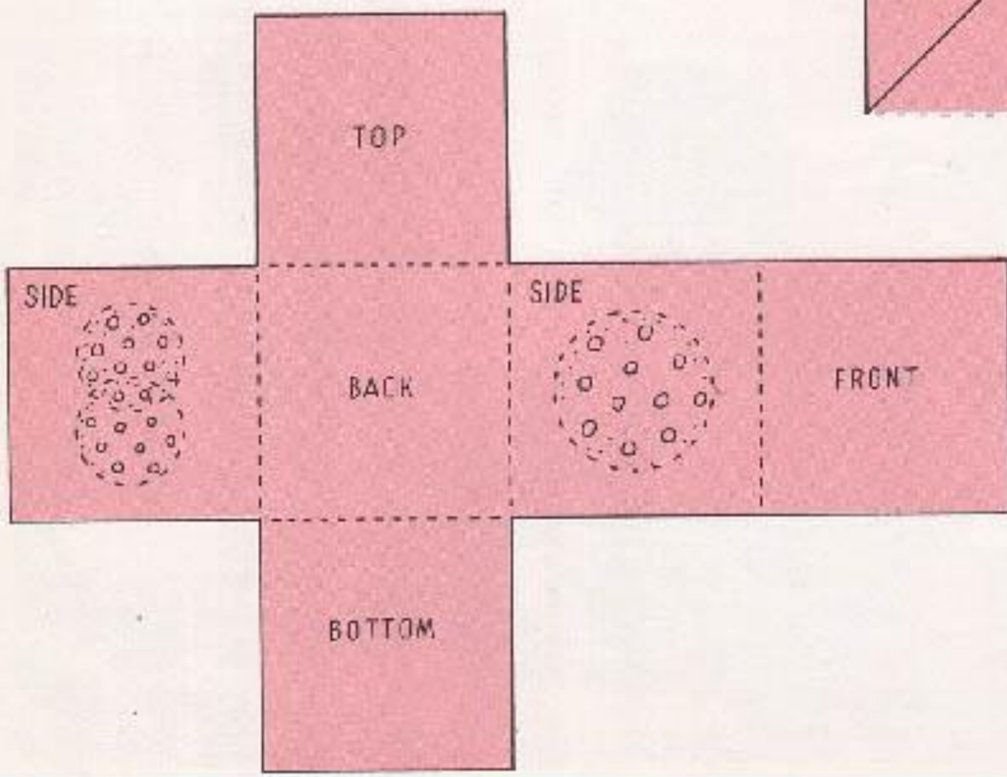
$p \rightarrow K^0 \mu^+ \rightarrow \pi^+ \pi^- \mu^+ \rightarrow \mu^+ \nu\ \mu^- \nu\ \mu^+$

$p \rightarrow K^+ \nu \rightarrow \mu^+ \nu\ \nu$

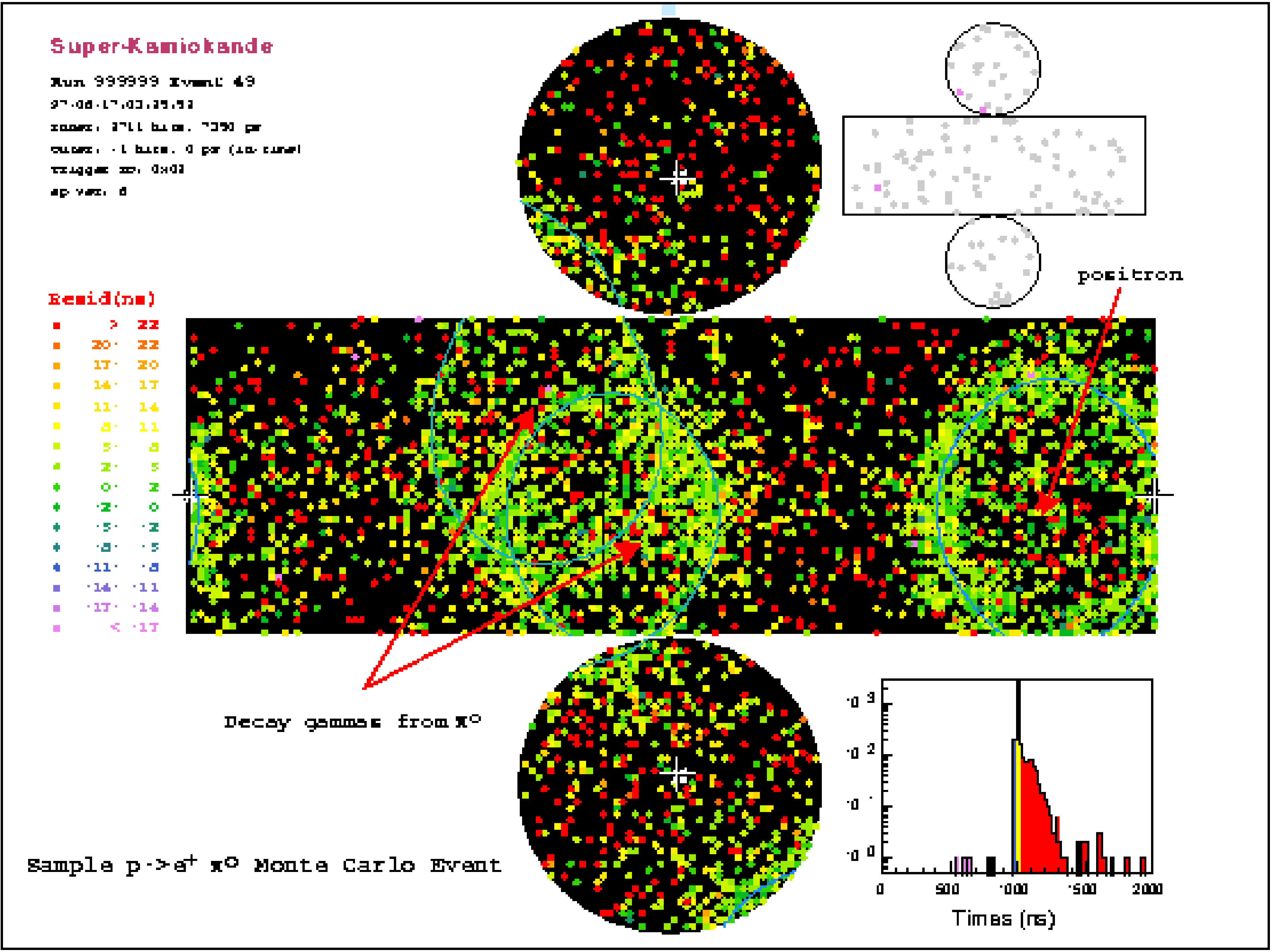
This is how it works

Cerenkov radiation from a proton decay event will create three back-to-back cones of light in the detector. The left cone actually includes two cones resulting from decay of a pi meson. The right cone results from the track of the positron. The light cones will trigger photomultiplier tubes on the faces of the detector. No other event will display this particular pattern of light. ▶



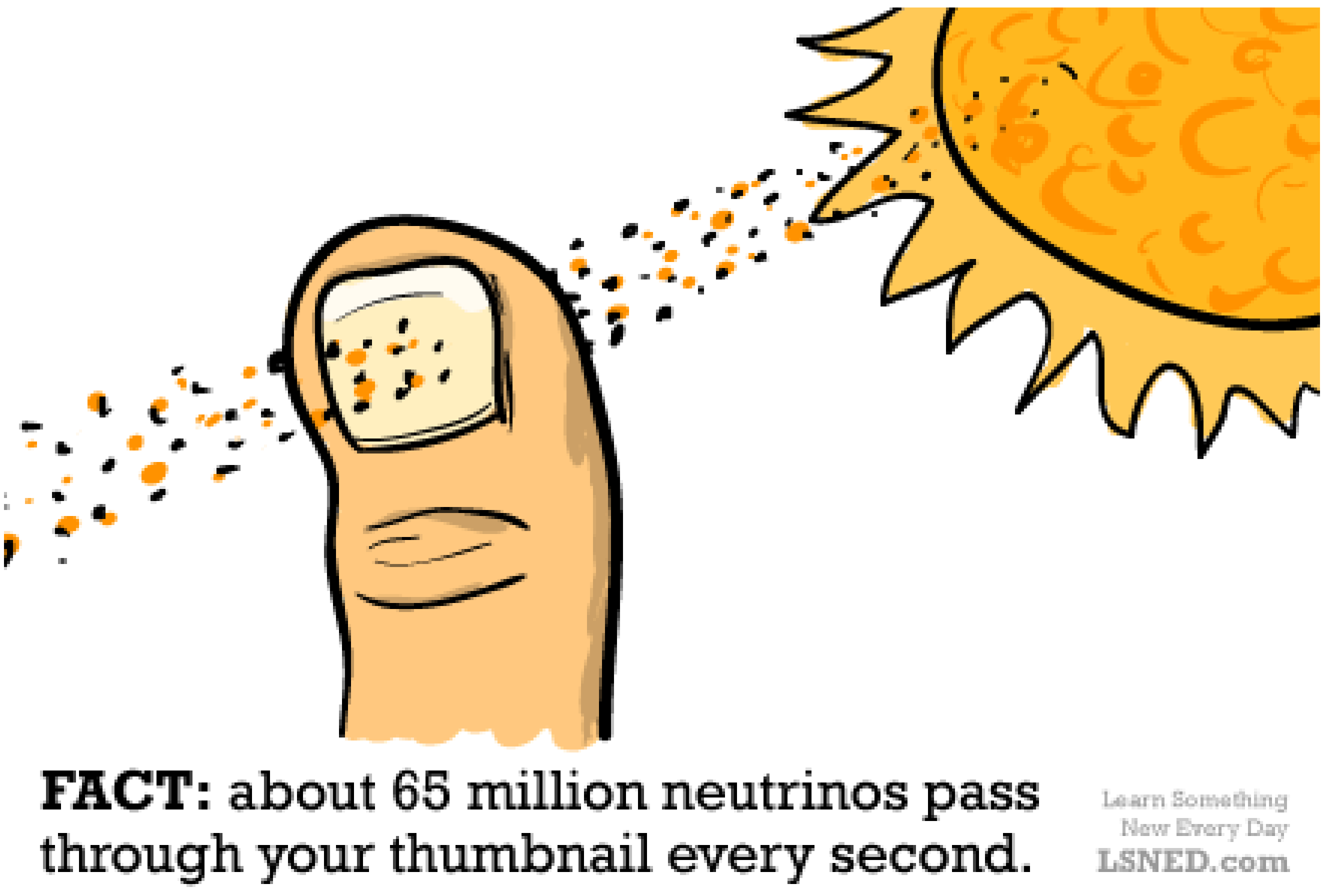


◀ The computer graphic pattern resulting from a proton decay in the detector would look something like this. Each rectangle represents one face of the cube. If you cut it out and folded it, you would have a mini-detector. The dots represent the photomultiplier tubes which would be lit up in an idealized proton decay. Each dot on the graph would provide energy intensity, timing and location data to the researchers.



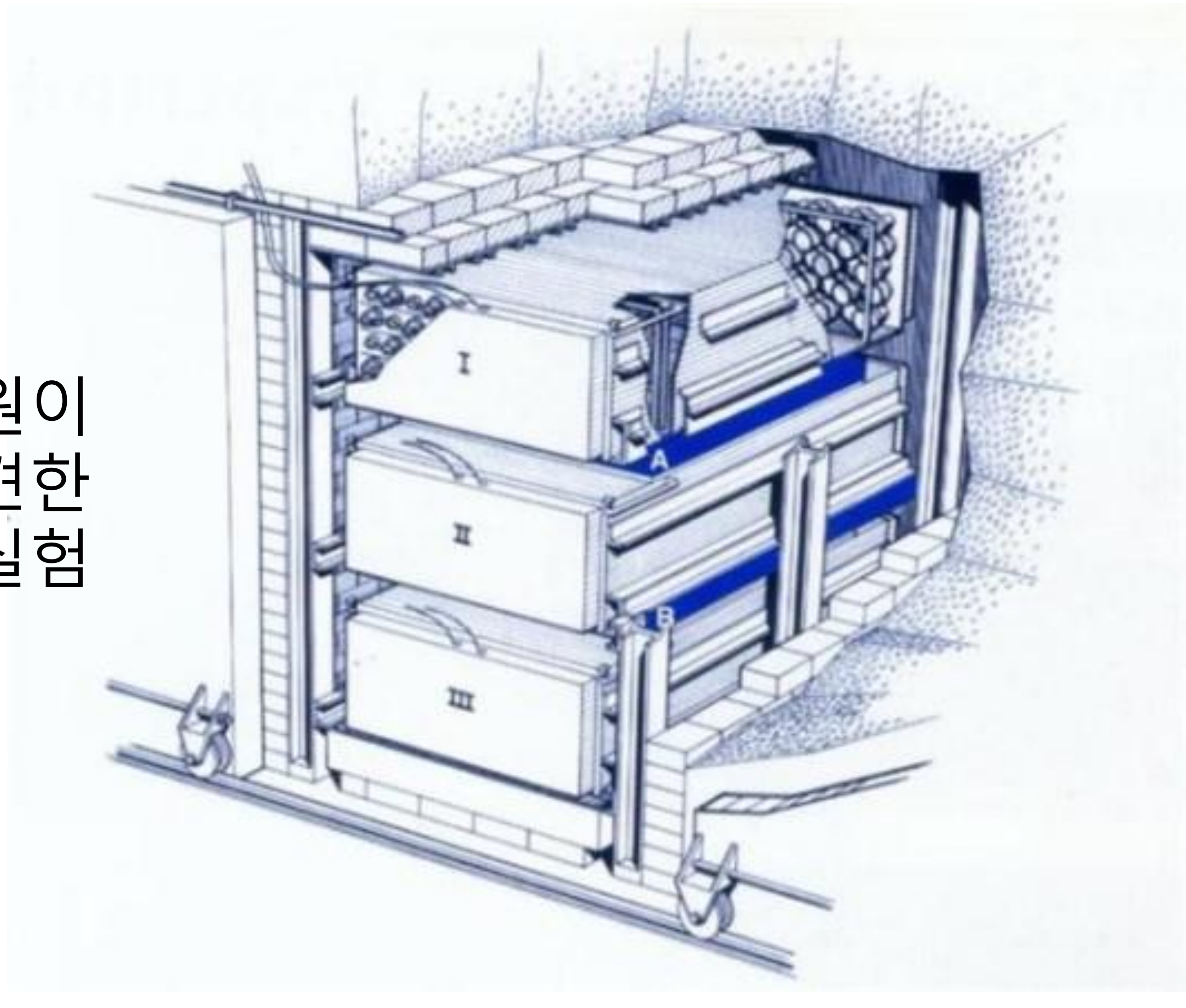
Sample p->e+ π0 Monte Carlo Event

중성미자 물리학


FACT: about 65 million neutrinos pass through your thumbnail every second.
Learn Something New Every Day
LSNED.com

중성미자는 본질적으로 Intensity Frontier Physics다.

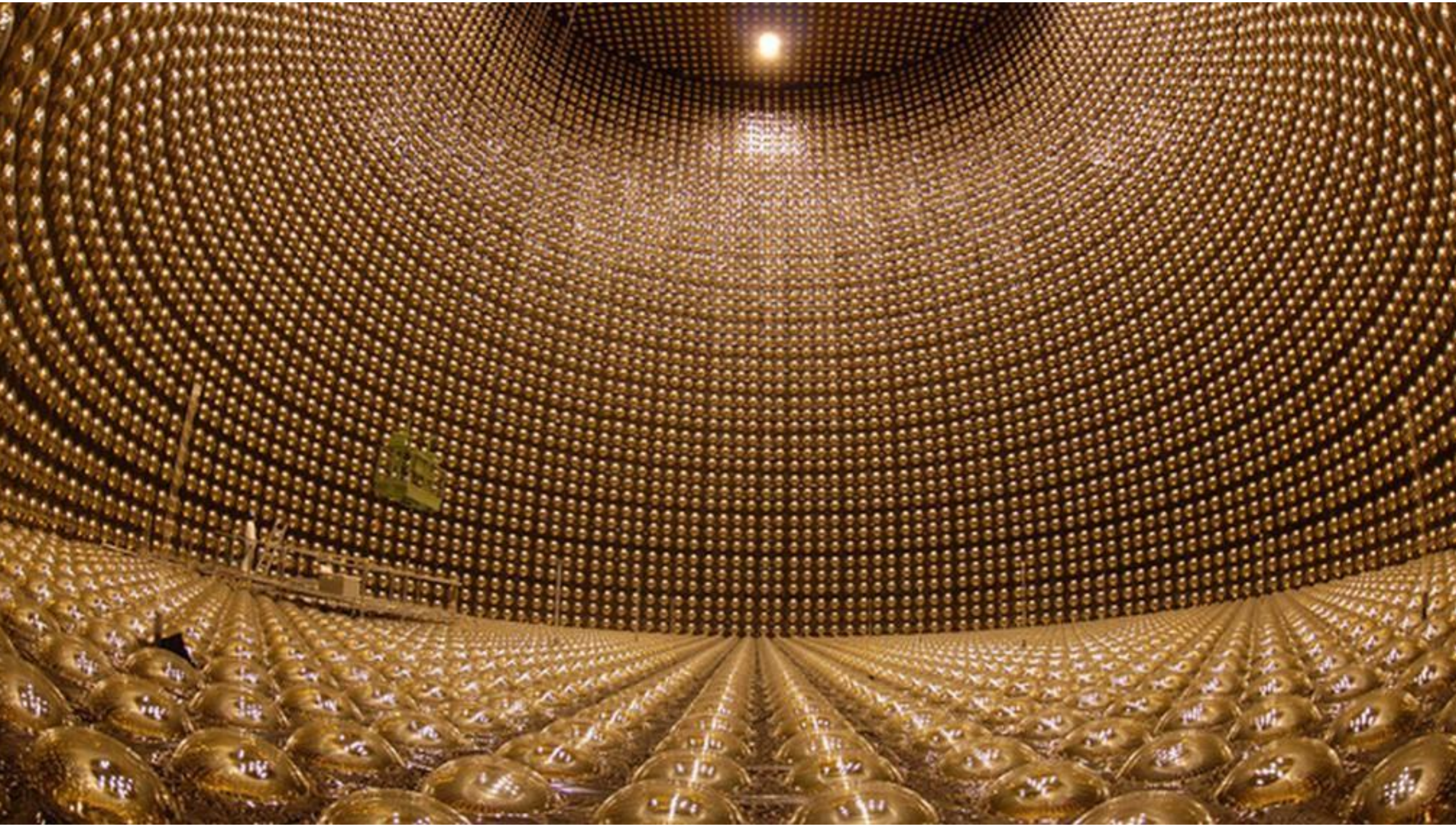
라이네스와 코원이
중성미자를 처음 발견한
사바나 강 실험



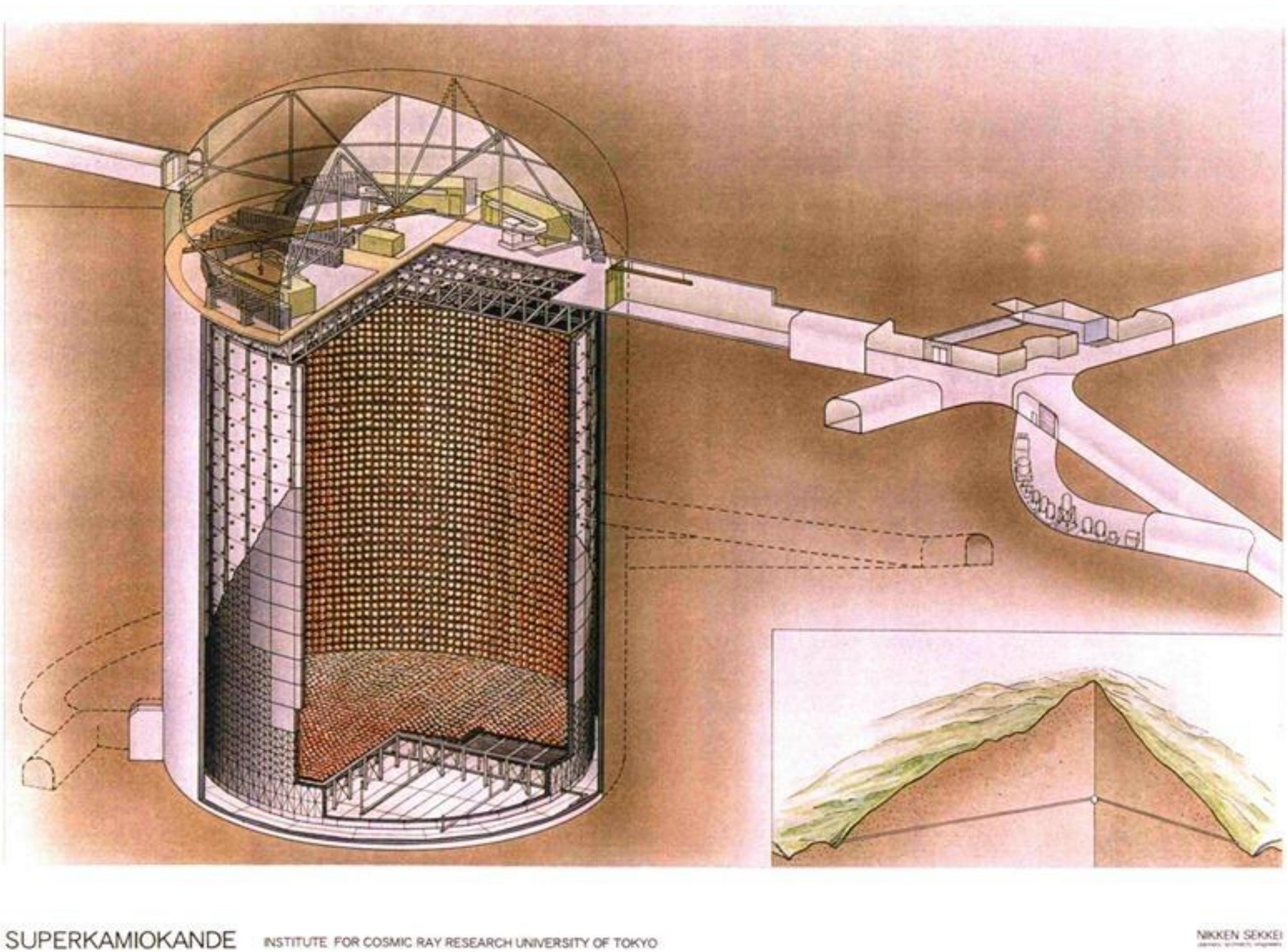
- 태양 중성미자 ~6500만/초/cm^2
- 발전소 중성미자 ~10^{20}/초
- 가속기 중성미자

  proton-nucleon → π → μ + ν

Super-Kamiokande



Kamiokande의 후속 실험

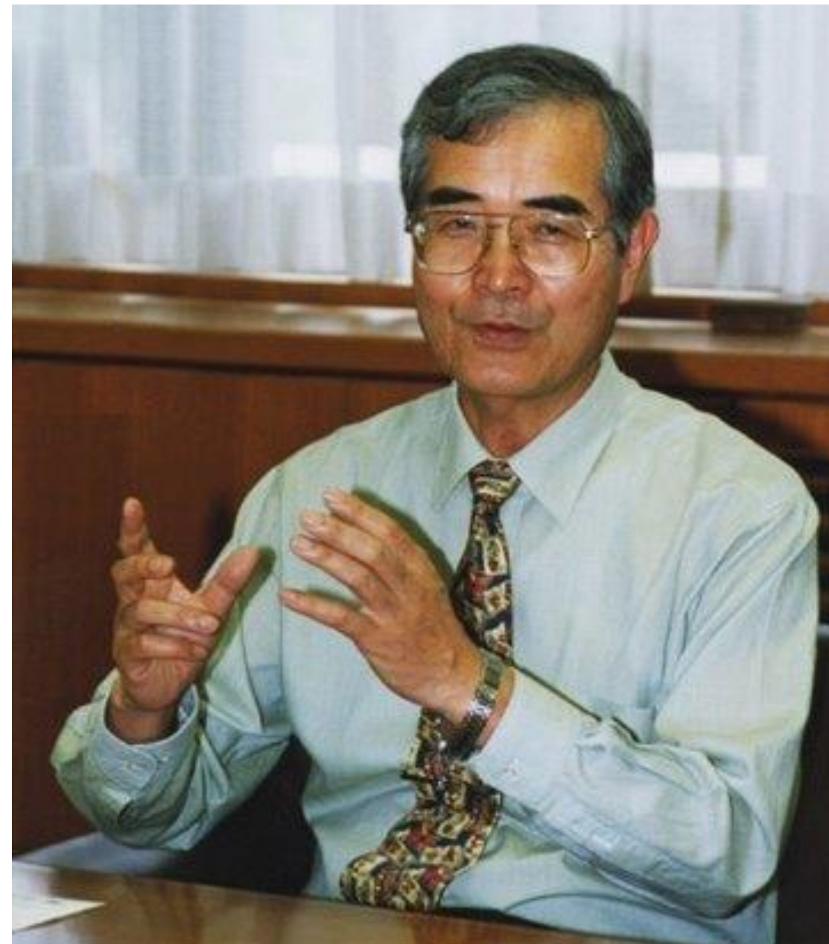


물 5만 톤.

11,200개
광자 증배관

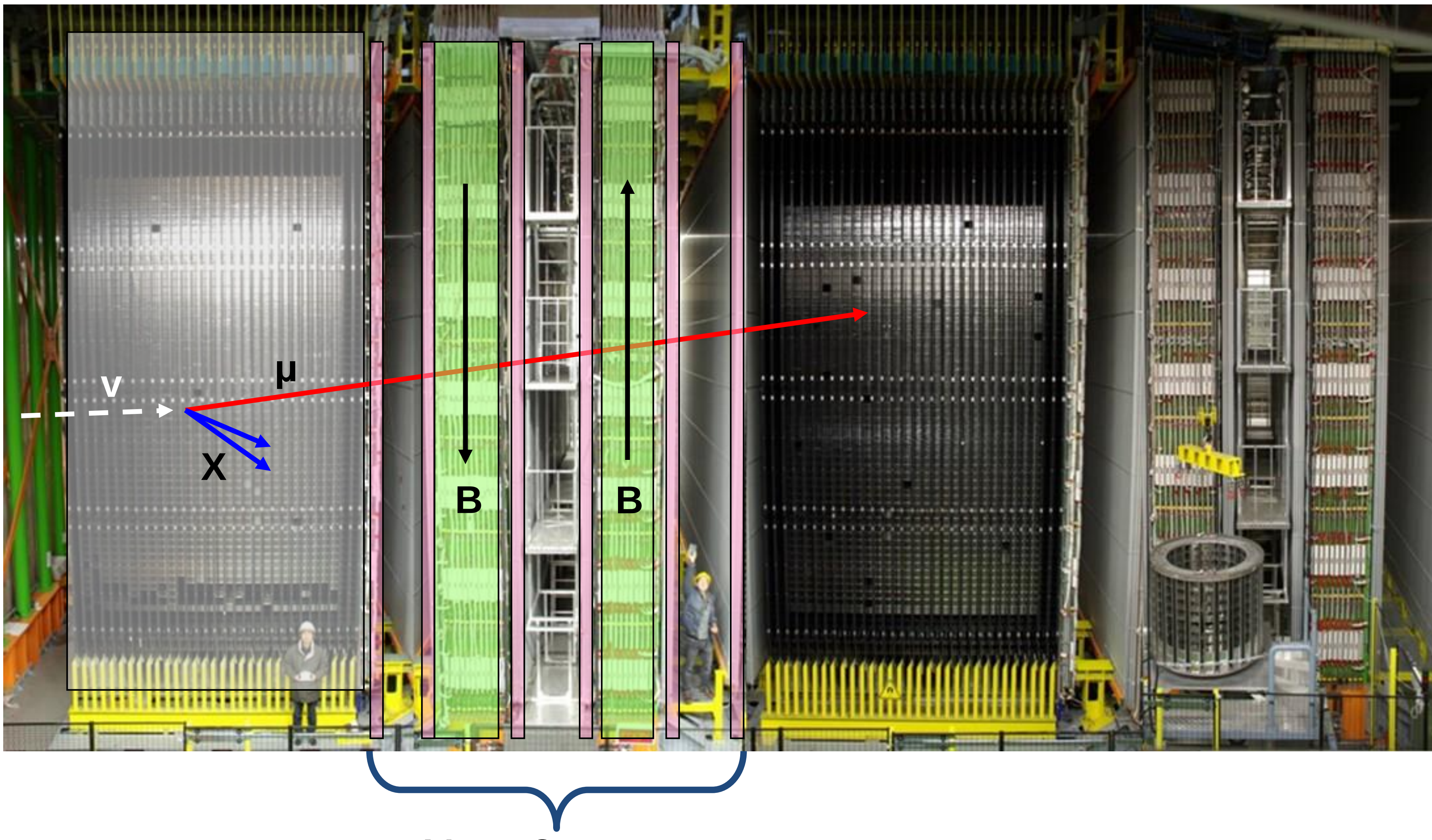
Kamiokande - Kamiokande II - Super-Kamiokande

일본 물리학의 영광



Opera

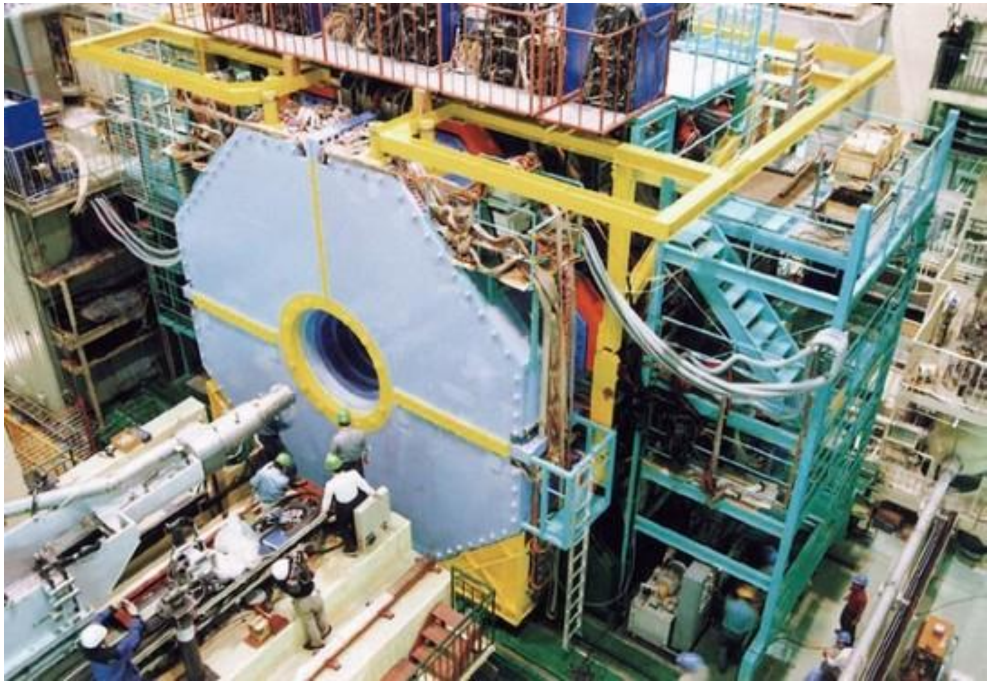
57장의 핵건판/블록, 3300개 블록/벽, 31*2중 벽



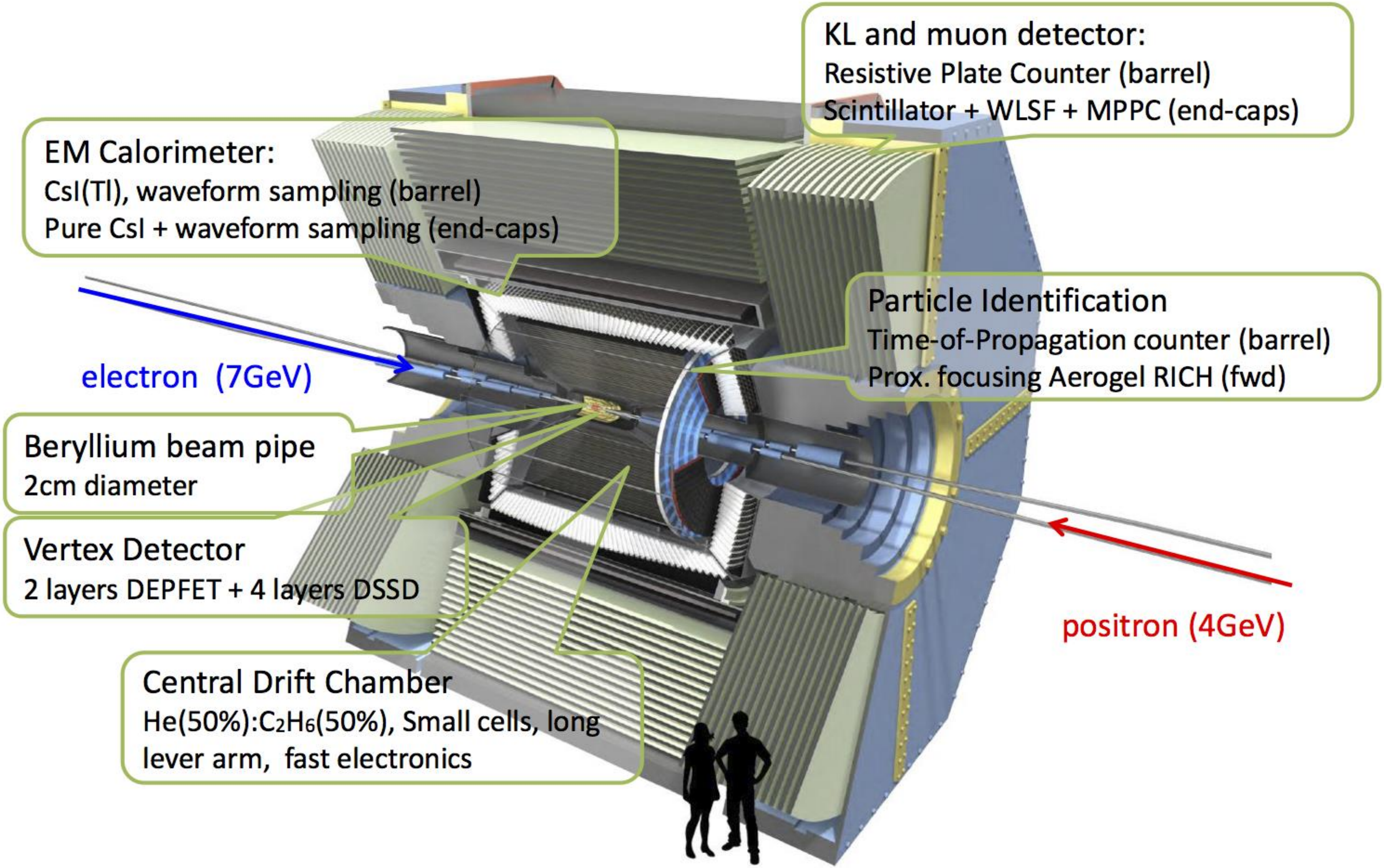
B factory

Belle at KEK
(Japan)

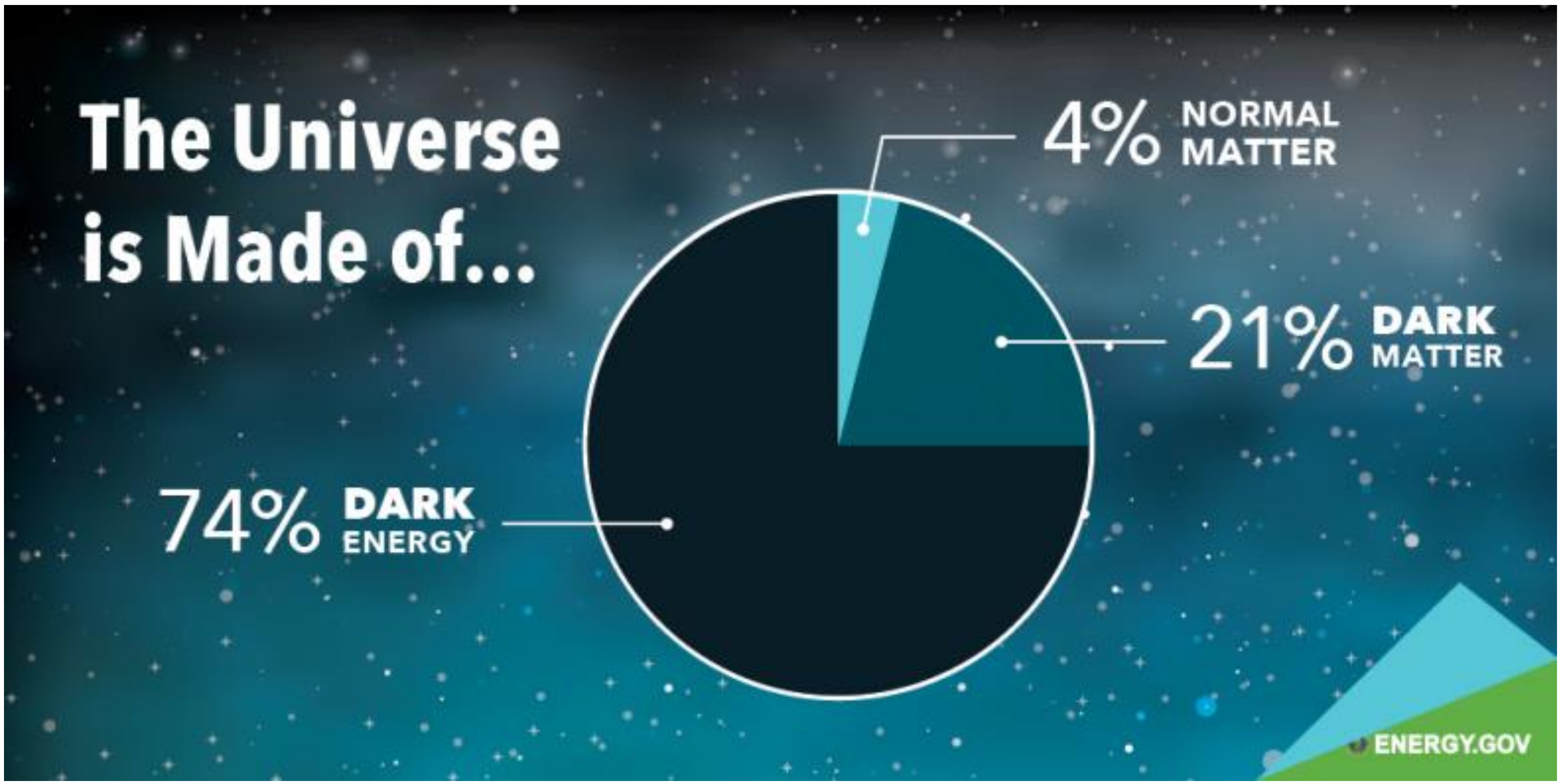
SLD at SLAC
(USA)



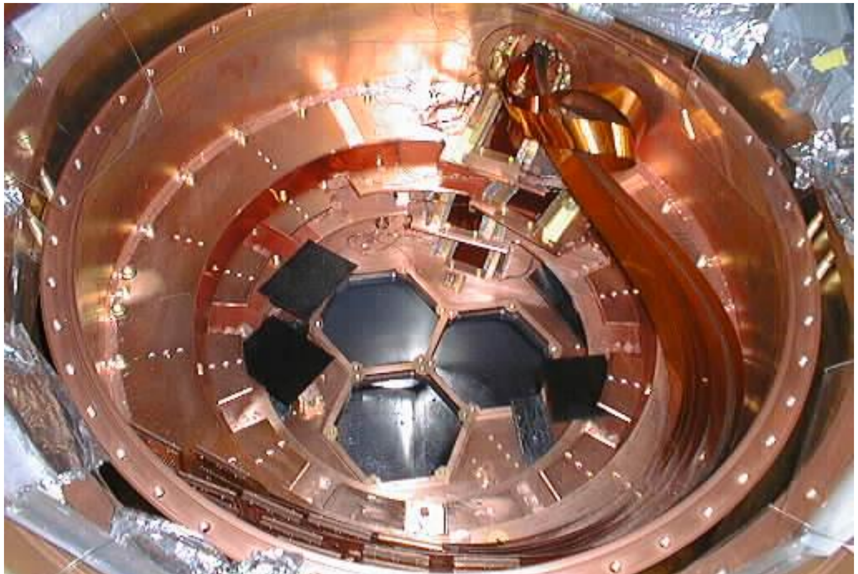
Belle II Detector

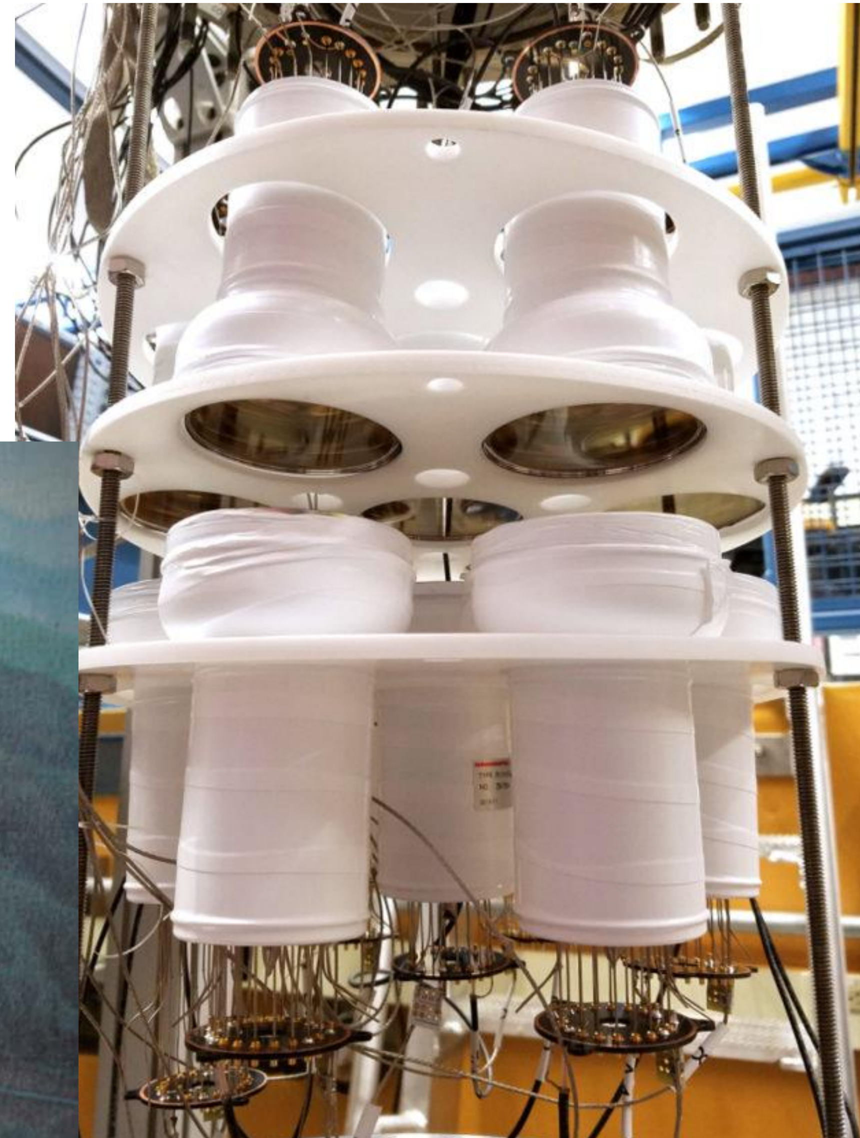


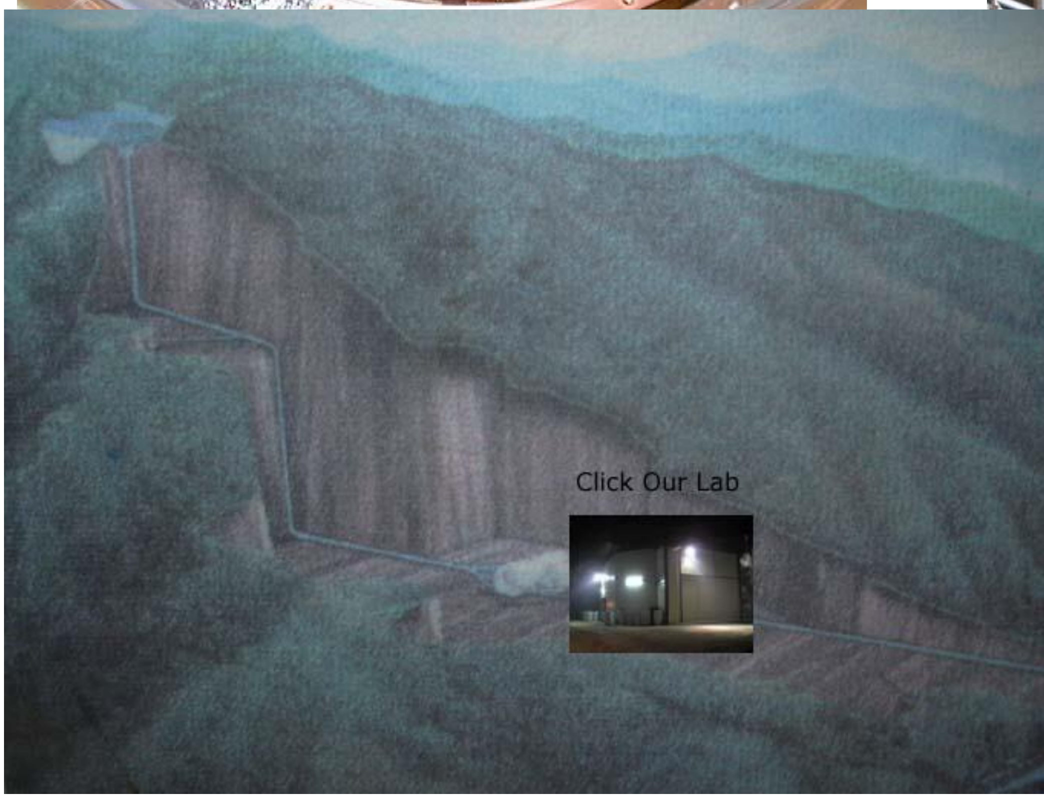
암흑물질 검출

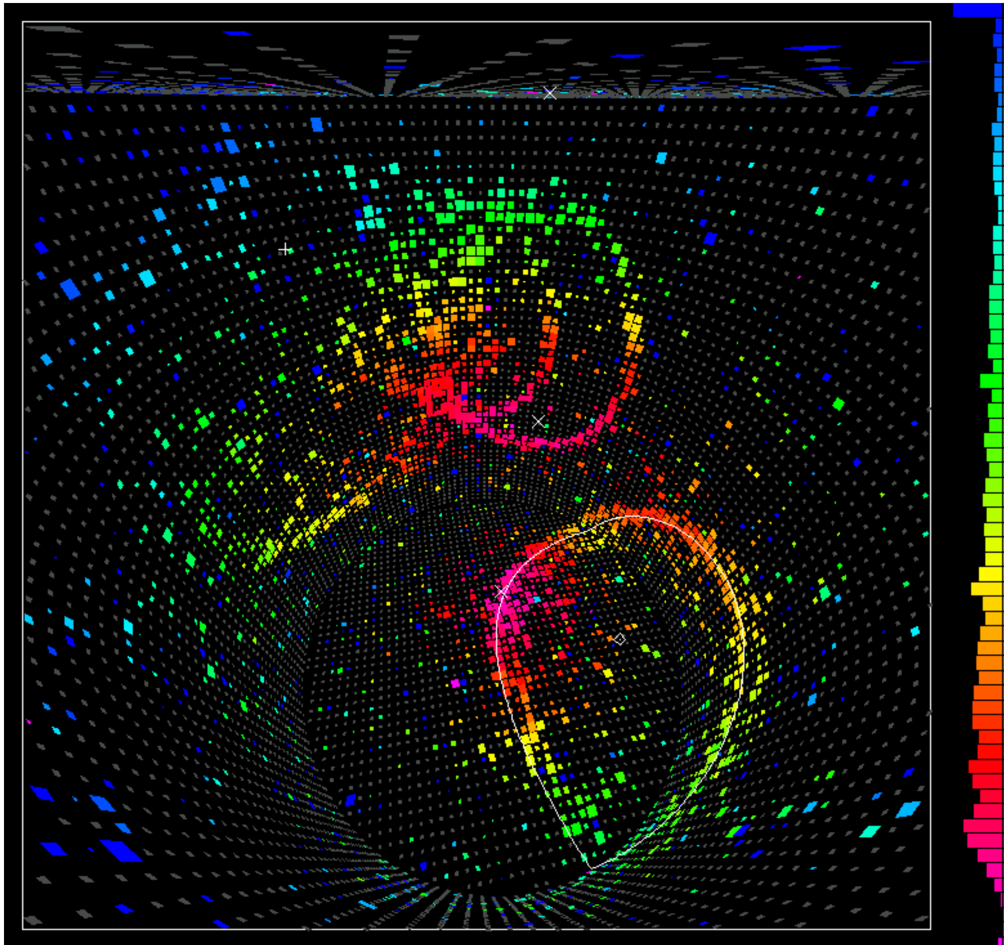


천체물리학에서 중력 이상 현상 + 우주론에서 새로운 물질 필요

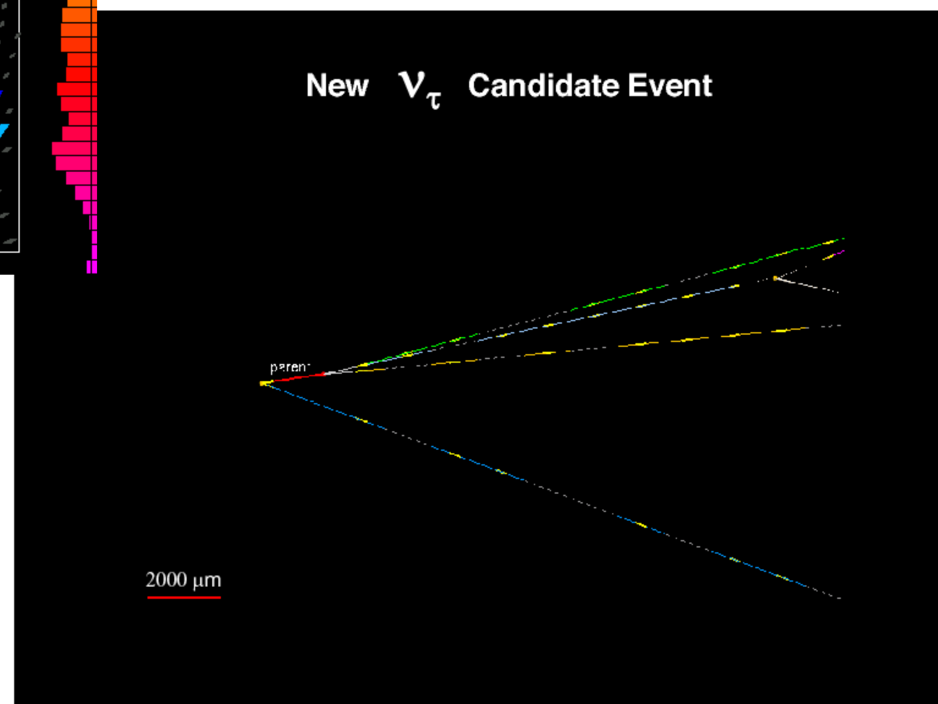





Click Our Lab



Intensity frontier 실험에서는 사건 하나 하나가 소중하다.



B-factory는 예외

SHiP – Search for Hidden Particles

SHiP 은

LHC와 상호보완적으로

GeV 정도의 질량을 갖고,

아주 약하게 상호작용하면서

수명이 긴 입자를 발견하기 위한

고정 표적 충돌 실험이다.

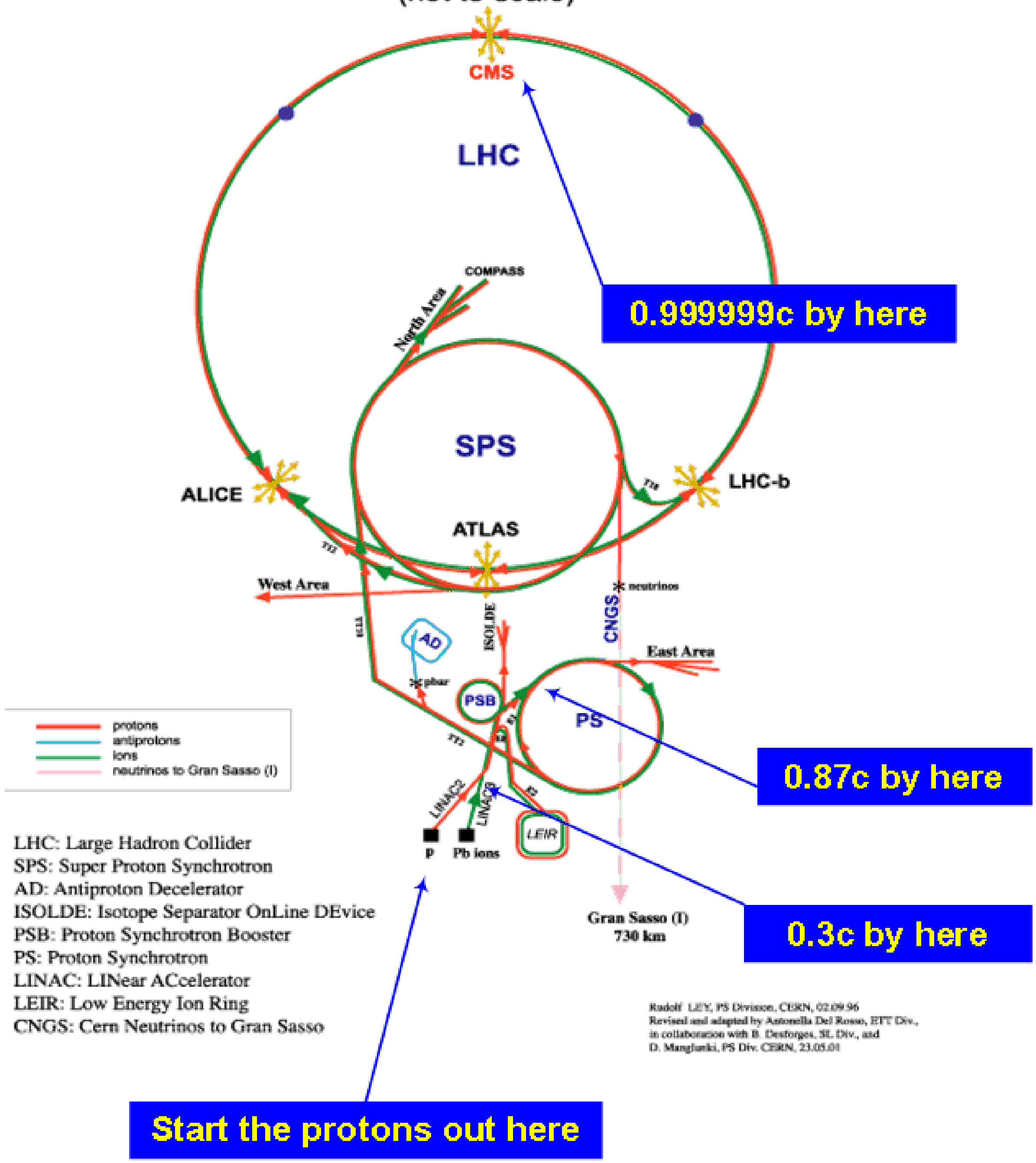
이용하는 가속기 : SPS

Super Proton Synchrotron (1976~)

The second-largest machine in CERN's accelerator complex.

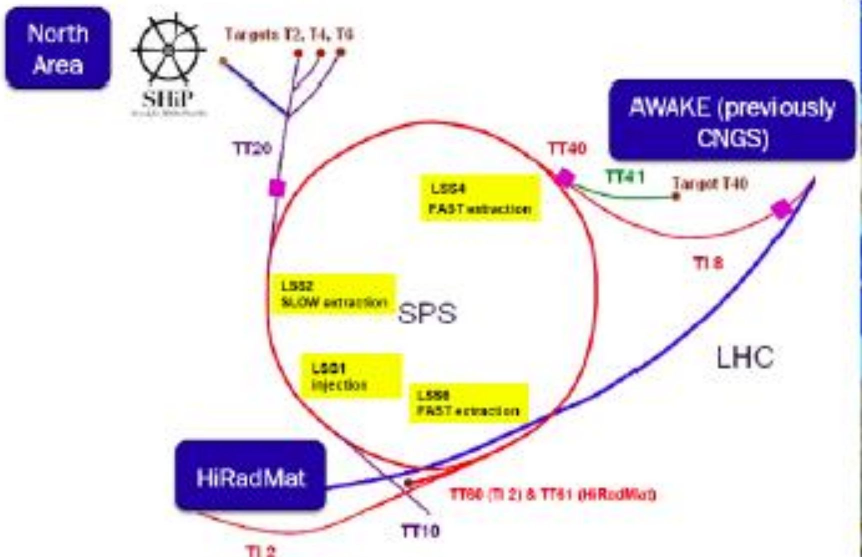
Nearly 7 kilometres in circumference, operated at up to 450 GeV.

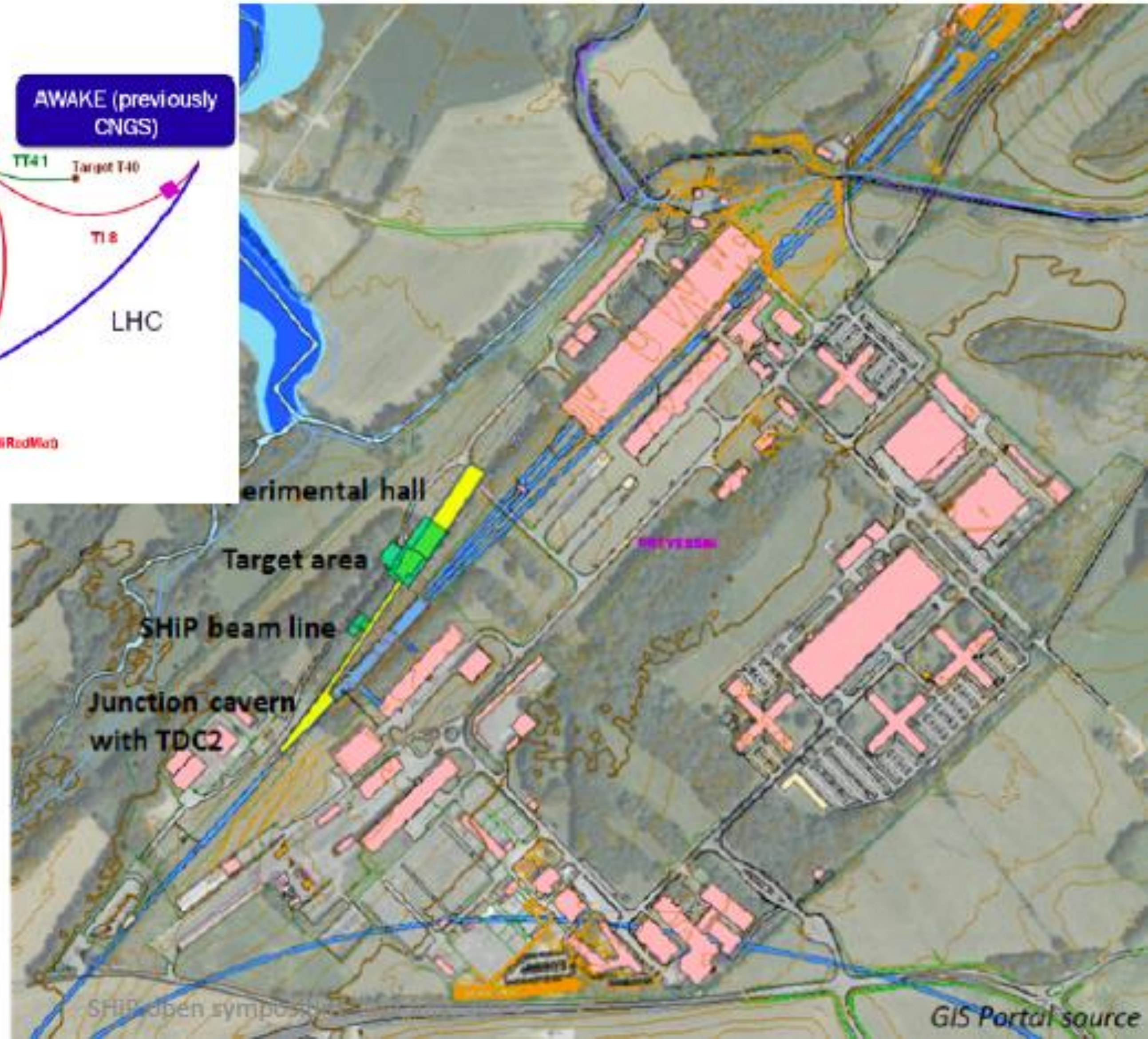
CERN Accelerators
(not to scale)



The Fixed-target facility at the SPS: Prevessin North Area site
(see talk of Lau)

Proposed implementation is based on minimal modification to the SPS complex

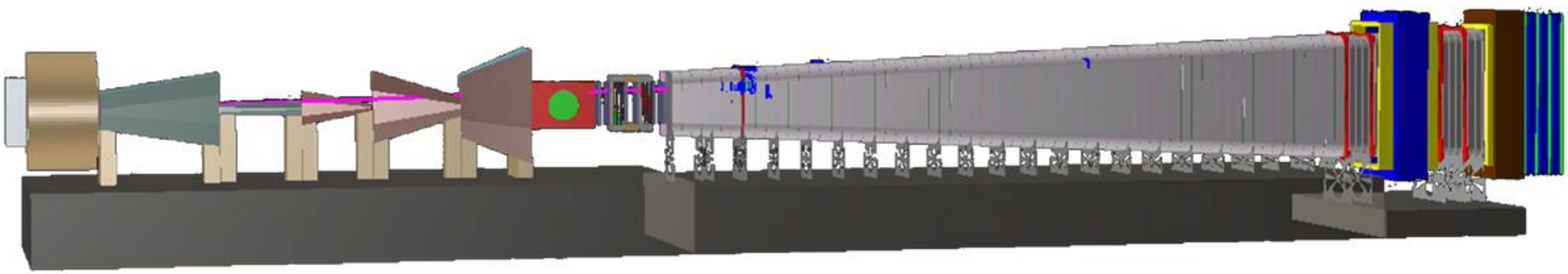




The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes

SHiP

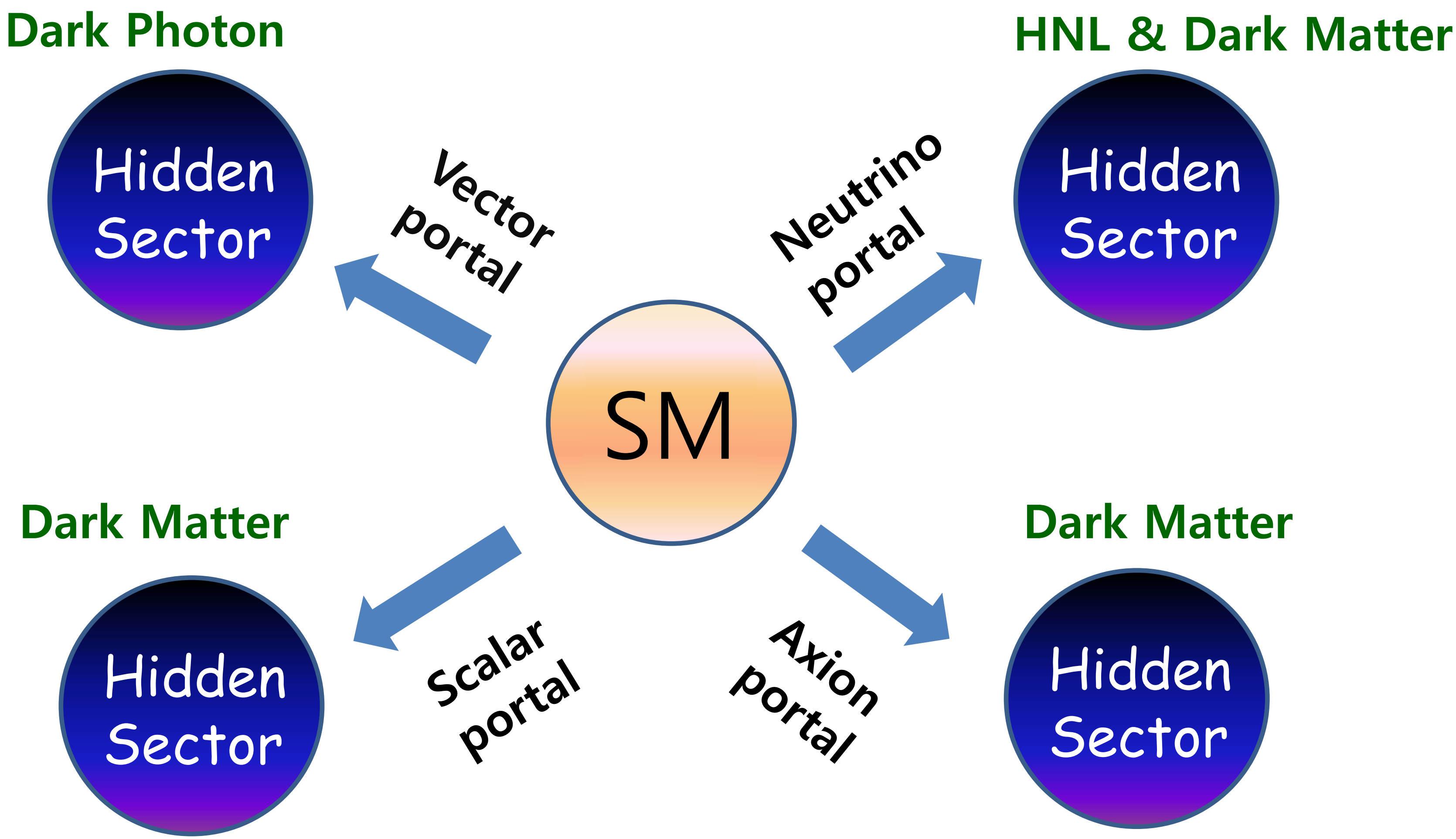
Search for Hidden Particles



～150m

- 왜 이렇게 실험장치가 긴가?
  → 수명이 긴 입자를 찾기 위해서
- 왜 입자의 수명이 긴가?
  → 입자의 상호작용이 작아서
- 왜 상호작용이 작은 입자를 보려고 하는가?
  → 암흑물질과 관련이 있는 입자이므로

Extensions of SM



Many hidden sector models often include **low mass particles below the GeV scale** (dark matter candidates).

Hidden Sector Models

- Vector Portal $\epsilon B_{\mu\nu} F'^{\mu\nu}$
- Scalar Portal $(\alpha_1 S + \alpha S^2) H^\dagger H$
- Neutrino Portal $Y H^T \bar{N} L$
- Others $\frac{a}{f_A} G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad \frac{a}{f_A} \partial_\mu J^\mu, \quad etc$

An Example : Neutrino Portal

Neutrino = neutral lepton
= electrically and strongly neutral fermion

Neutrino portal = gauge singlet fermion coupled
= Sterile Neutrino coupled

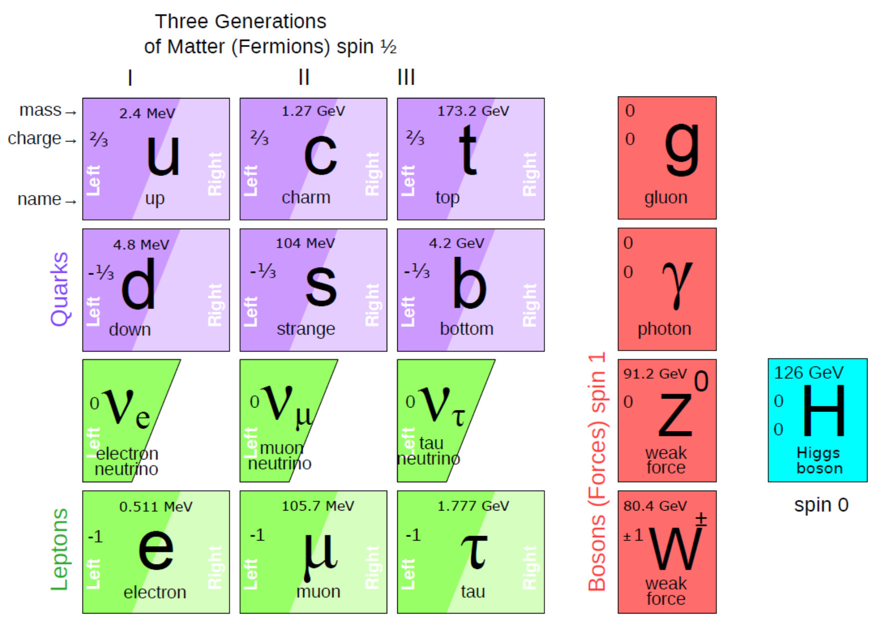
$$\mathcal{L}_{\text{Neutrino portal}} = F_{\alpha I}\,(\bar{L}_\alpha \cdot \tilde{\Phi}) N_I + \text{h.c.}\,,$$

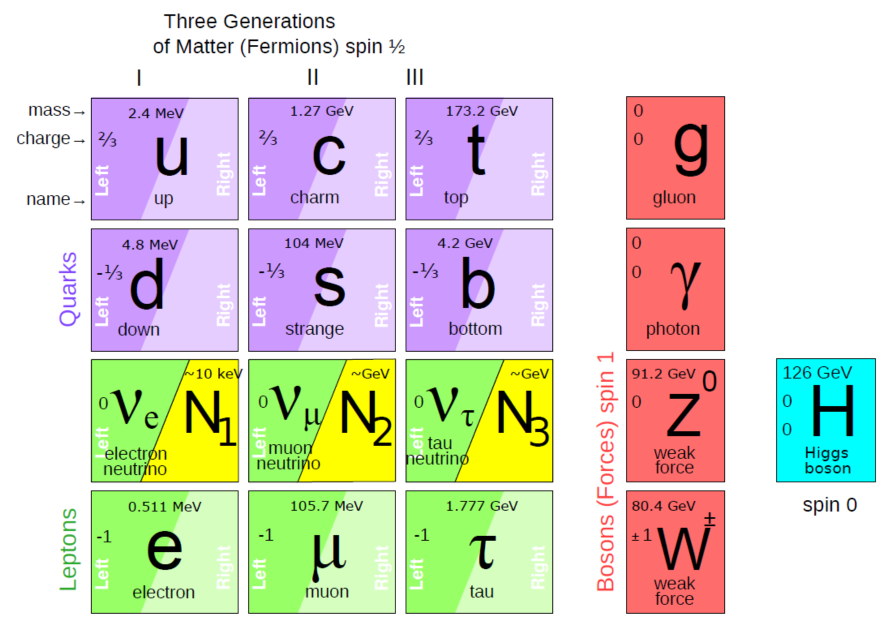
$$\tilde{\Phi}_a = \epsilon_{ab}\Phi_b \qquad \tilde{\Phi} = \frac{1}{\sqrt{2}}\begin{pmatrix} v \\ 0 \end{pmatrix}$$

νMSM

= SM + sterile neutrinos

: The economical extension of the SM





Why sterile neutrinos in this model?

- Smallness of neutrino masses by see-saw
- Dark matter candidate
- New CP phases → Baryogenesis

Phenomenological prediction

Heavy Neutral Leptons (HNL)

→ **SHiP**

The Lagrangian

$$L_{\rm singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha^c - M_I \bar{N}_I{}^c N_I + \text{h.c.},$$

Independent parameters

3 Dirac masses,
3 Majorana masses,
6 mixing angles,
6 CP phases

Dark Matter Candidate

If N_1 mass < electron mass

→ N_1 decays into only active neutrinos

$$\tau_{N_1} = 5 \times 10^{26}\ \mathrm{s} \left(\frac{M_1}{1\ \mathrm{keV}} \right)^{-5} \left(\frac{\bar{\Theta}^2}{10^{-8}} \right)^{-1}$$

$$\Omega_N h^2 \sim 0.1 \sum_I \sum_{\alpha = e, \mu, \tau} \left(\frac{|\Theta_{\alpha I}|^2}{10^{-8}} \right) \left(\frac{M_I}{1\ \mathrm{keV}} \right)^2$$

Long lived N_1 → warm dark matter candidate

$$2 \lesssim M_I \lesssim 5\ \mathrm{keV}$$

- HNL mass > 10^9 GeV

  GUT, LR model motivated
  Baryogenesis OK, no Dark Matter
  no Experimental signature, hierarchy problem

- HNL mass ~ TeV

  No underlying model motivated
  Baryogenesis OK, no Dark Matter
  Experimental signature at the LHC, no hierarchy problem

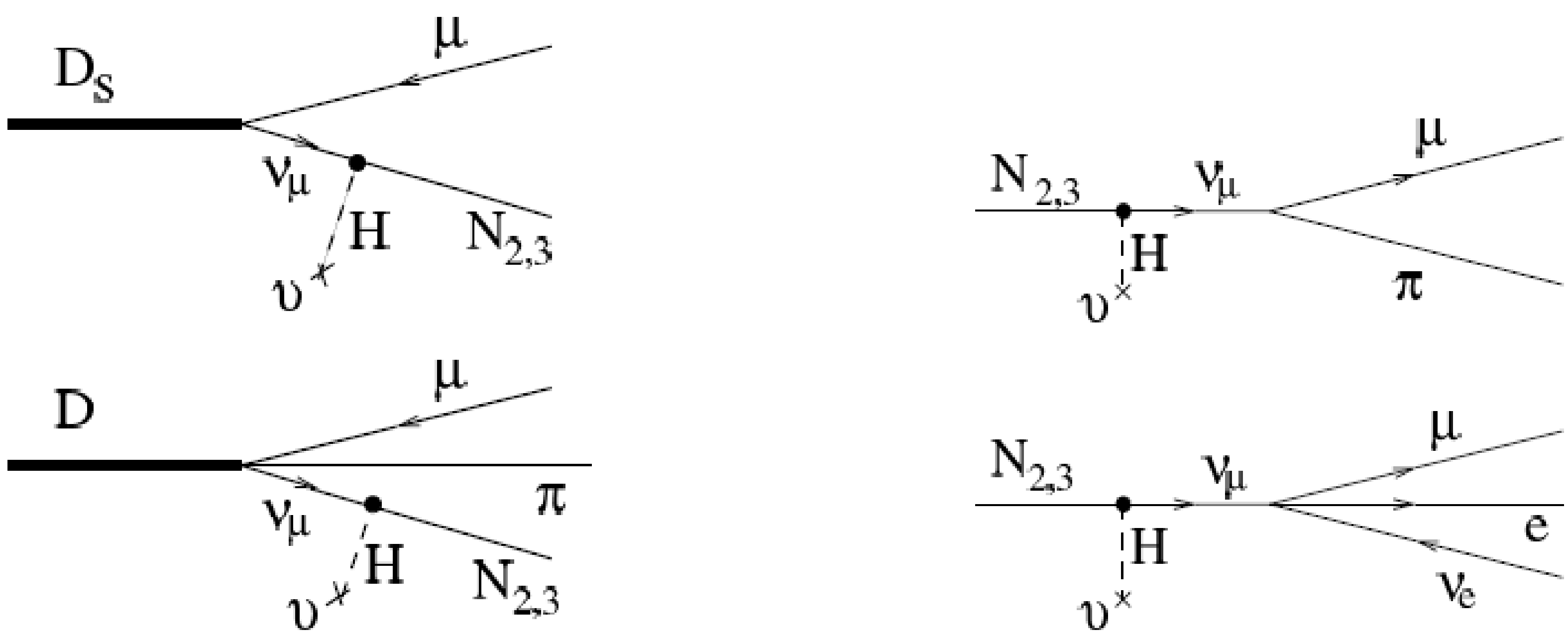
- HNL mass ~ GeV → **SHiP**

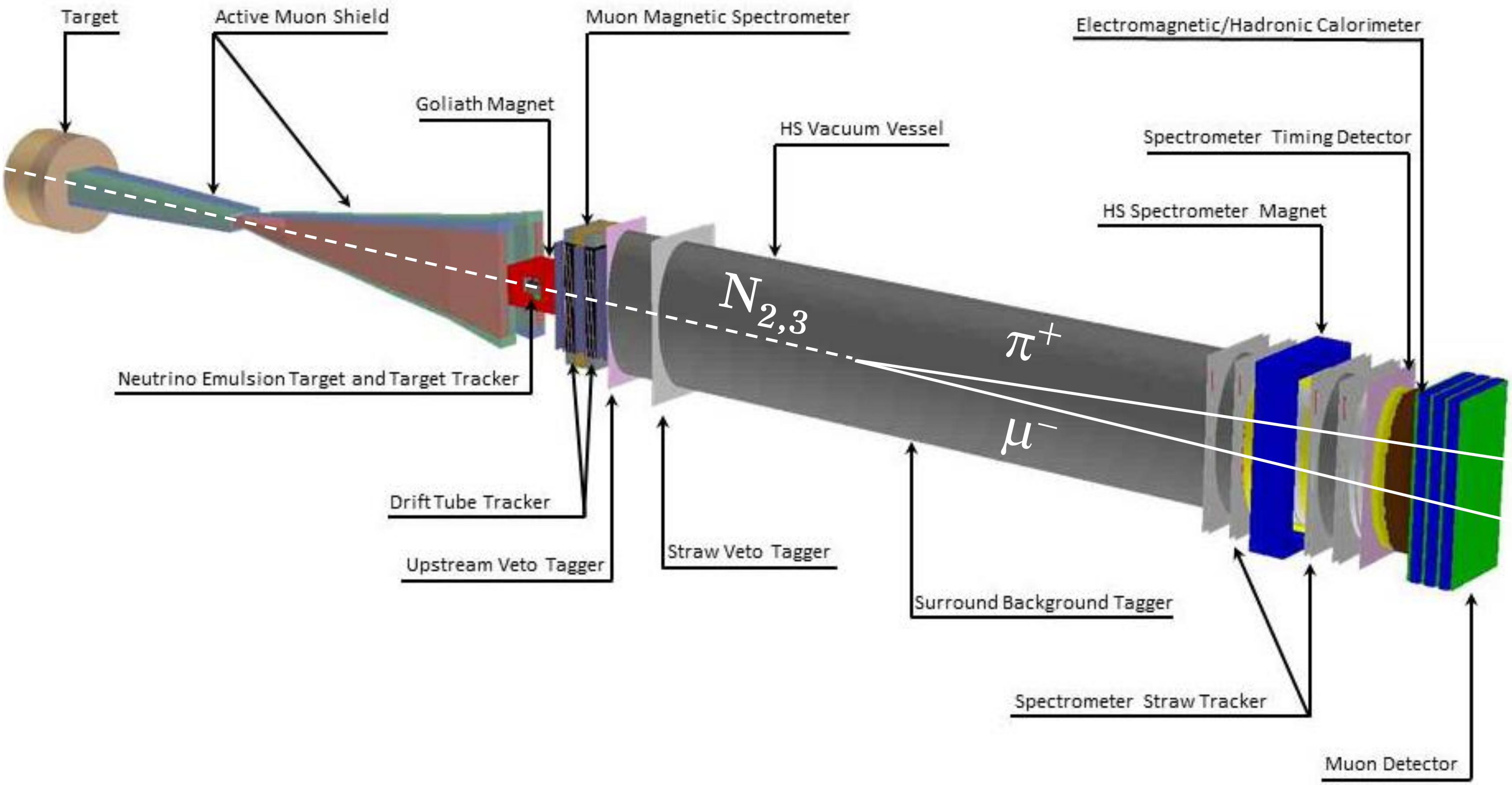
No underlying model motivated
Baryogenesis OK, Dark Matter OK
Experimental signature at the **SHiP**, no hierarchy problem

- HNL mass ~ eV

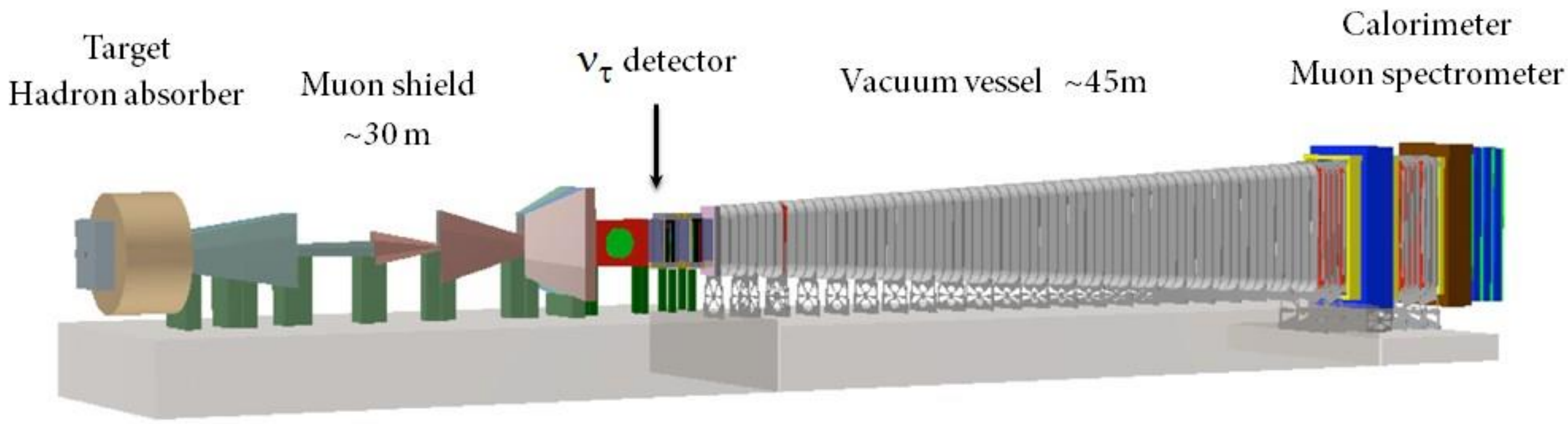
No underlying model motivated
no Baryogenesis, no Dark Matter
Experimental signature at many neutrino experiments
no hierarchy problem

- Subsequent decay of *N* to SM particles

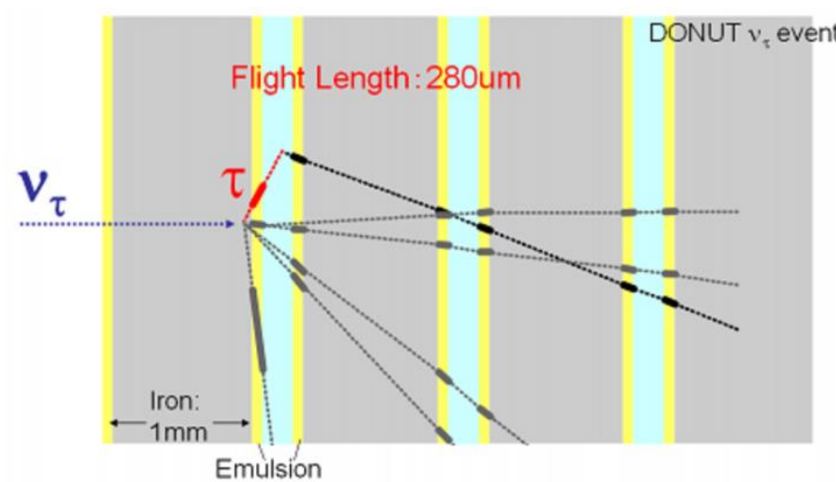



Target
Active Muon Shield
Muon Magnetic Spectrometer
Electromagnetic/Hadronic Calorimeter
Goliath Magnet
HS Vacuum Vessel
Spectrometer Timing Detector
HS Spectrometer Magnet
$N_{2,3}$
π^+
μ^-
Neutrino Emulsion Target and Target Tracker
Drift Tube Tracker
Upstream Veto Tagger
Straw Veto Tagger
Surround Background Tagger
Spectrometer Straw Tracker
Muon Detector

Hidden particle detector



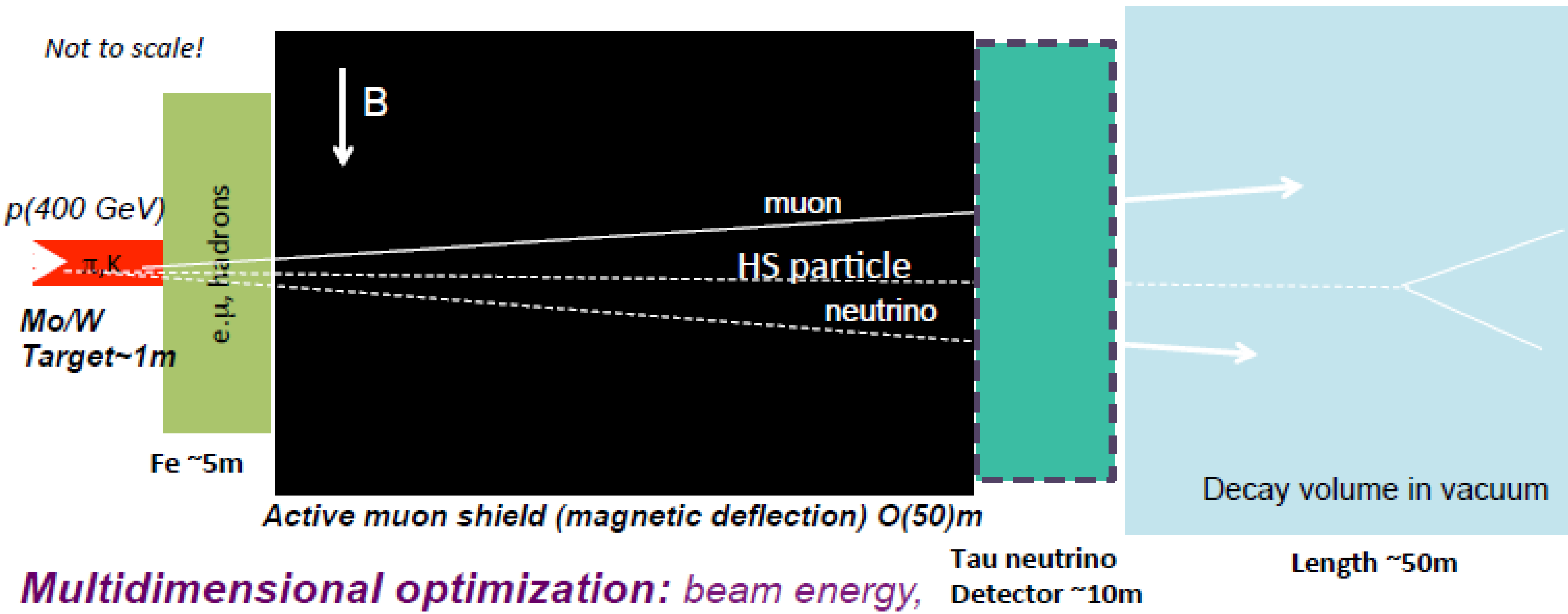
Tau Neutrino detector



SHiP beam-line
(incompatible with conventional neutrino facility)

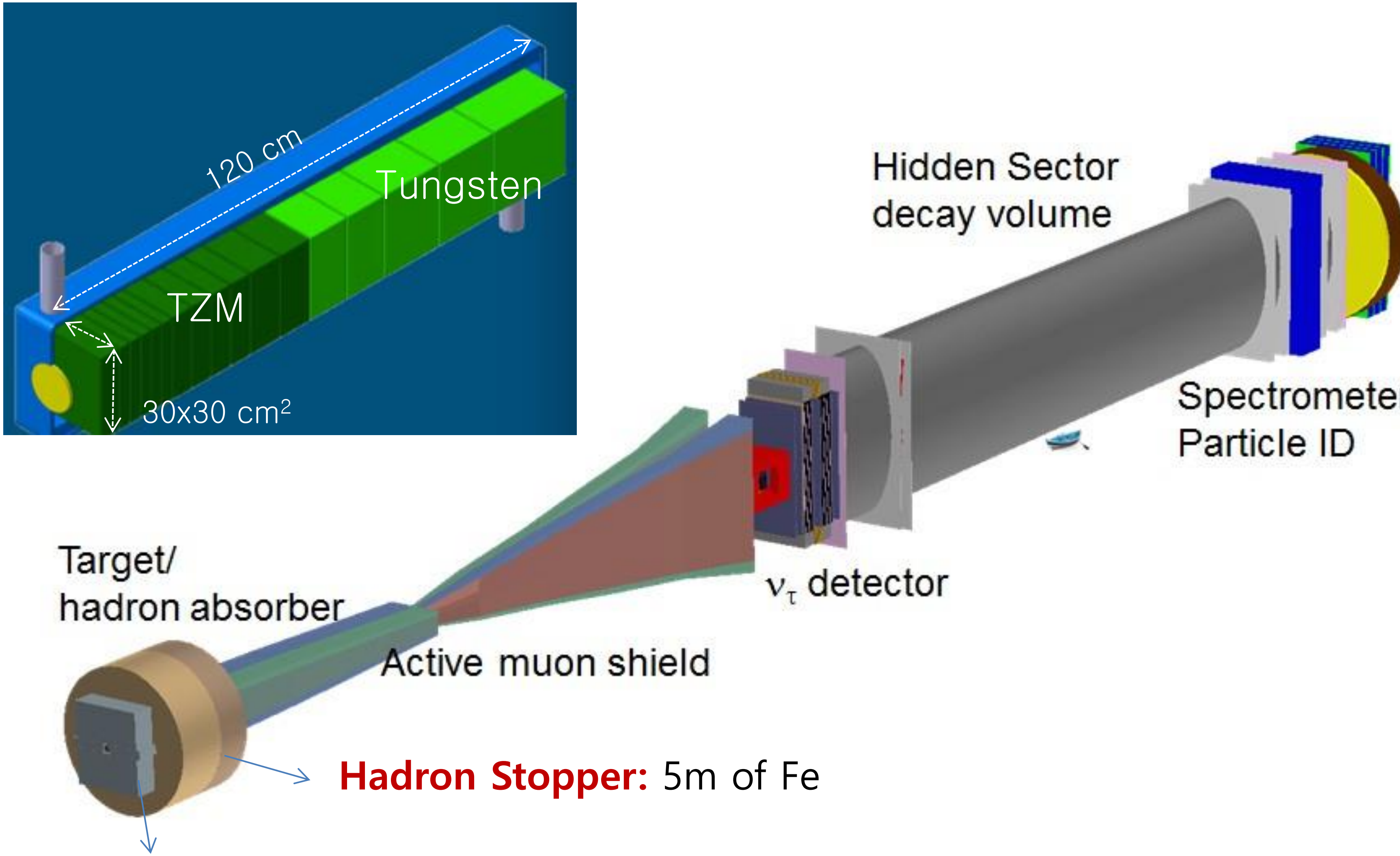
Initial reduction of beam induced backgrounds

- *Heavy target to maximize Heavy Flavour production (large A) and minimize neutrinos from $\pi/K \rightarrow \mu\nu$ decays (short λ_{int})*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~10^{10} per spill of 5×10^{13} pot)*
- *Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector*



***Multidimensional optimization:** beam energy, beam intensity, background conditions and detector acceptance*

8



Hadron Stopper: 5m of Fe

Hybrid target:
Blocks of Titanium Zirconium doped Molybdenum (TZM) followed by blocks of pure Tungsten

High A/Z target to maximize D, B production and to stop p, K before decay

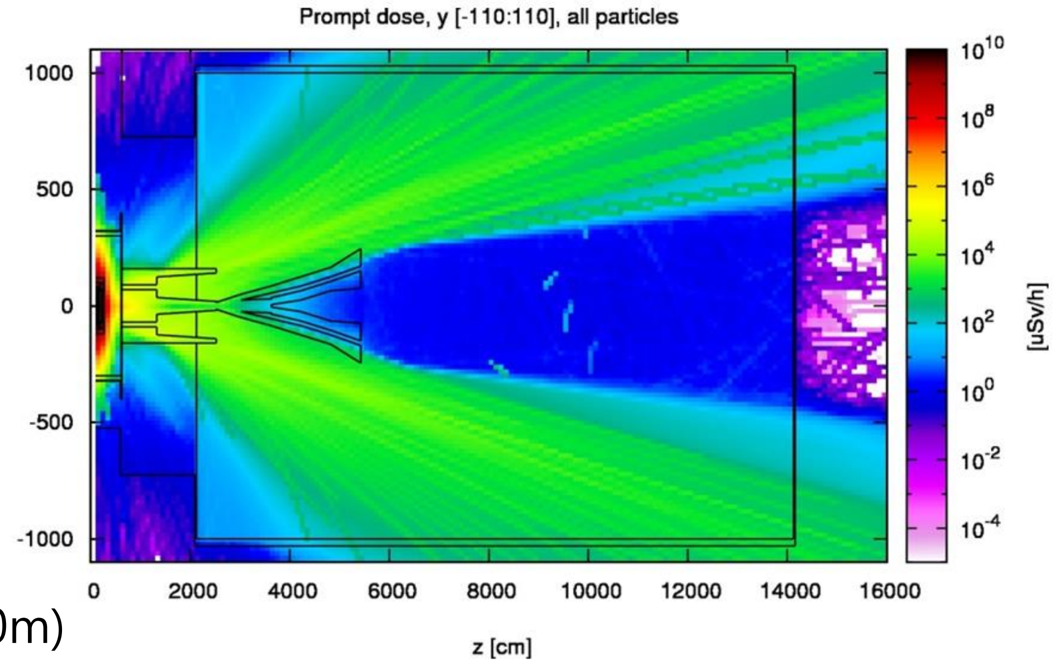
Hadron stopper

→ eliminate 2ry mesons

Muon Shield

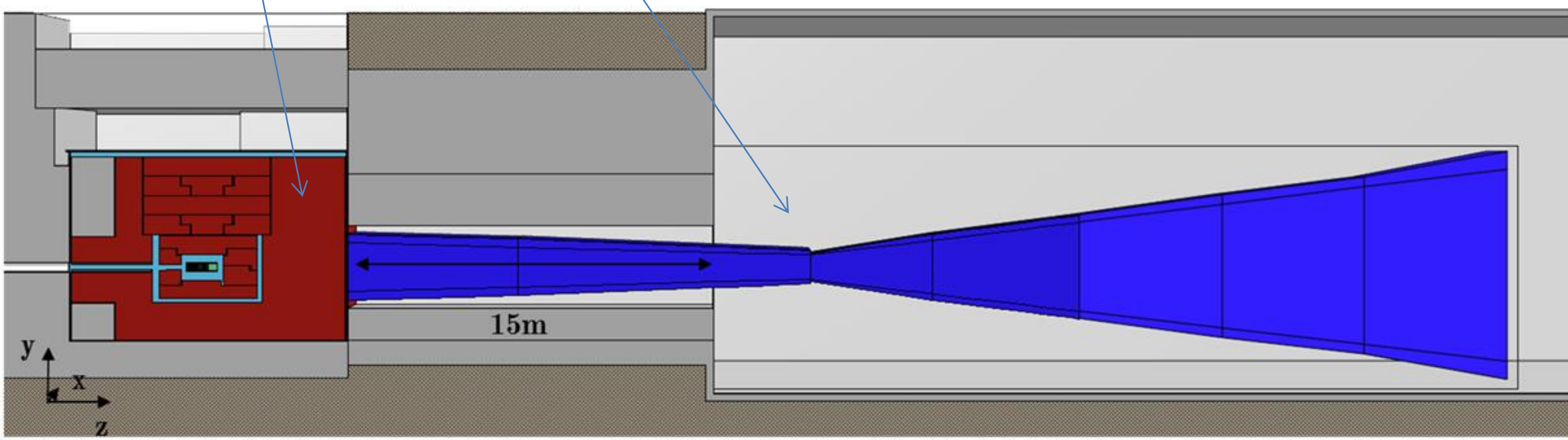
→ deflect muons from 2ry meson decay

like DONuT exp

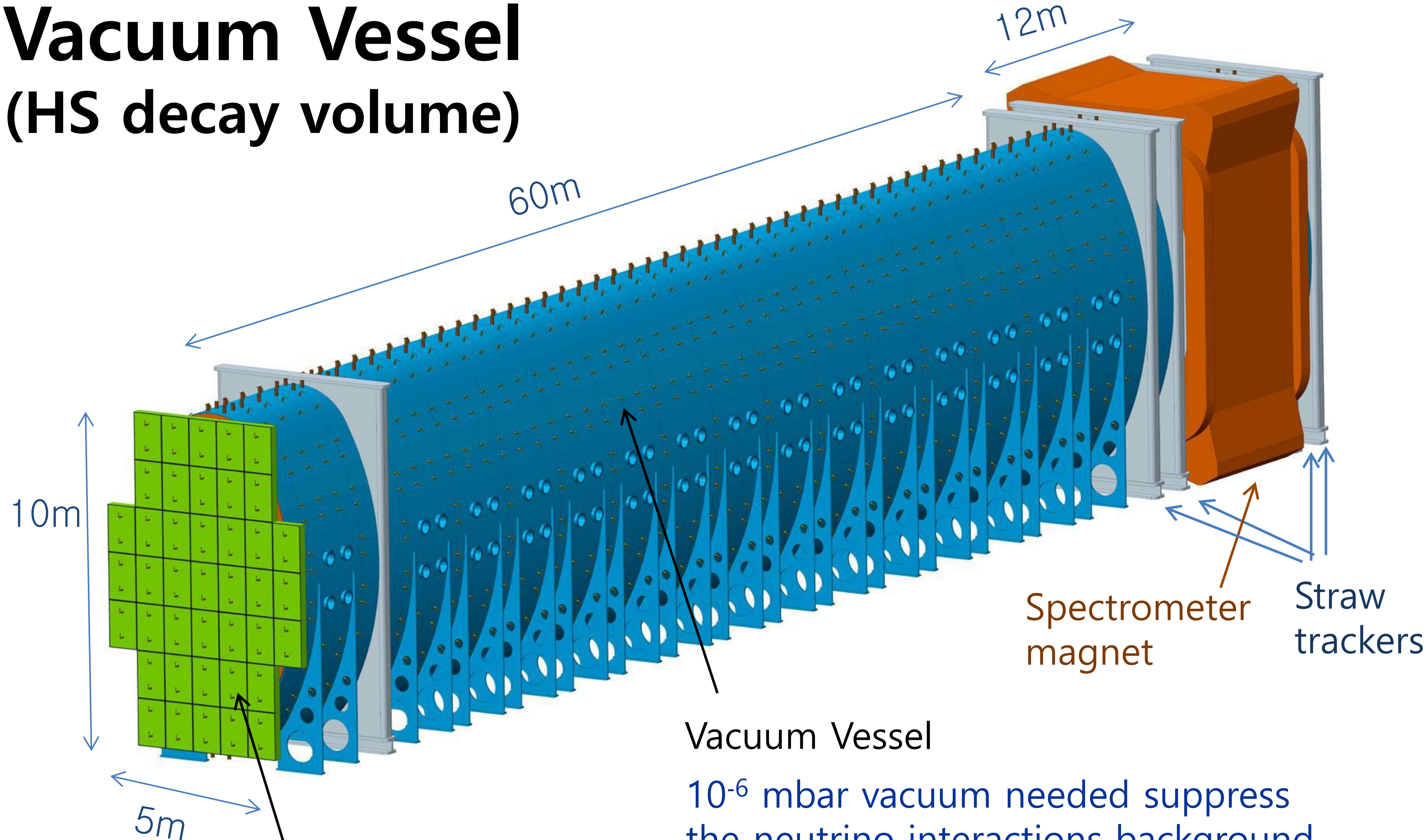


Hadron stopper

Active shield (~50m) (using magnet)



Vacuum Vessel
(HS decay volume)



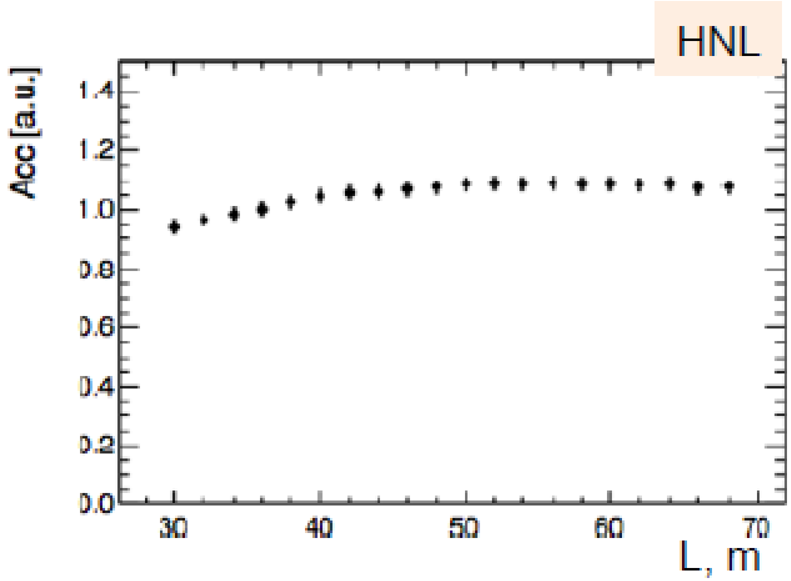
10^{-6} mbar vacuum needed suppress the neutrino interactions background.

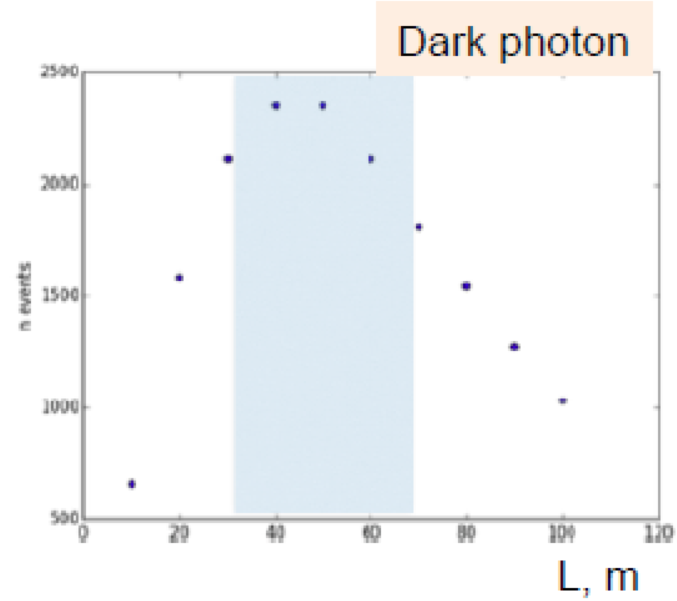
Upstream Veto tagger

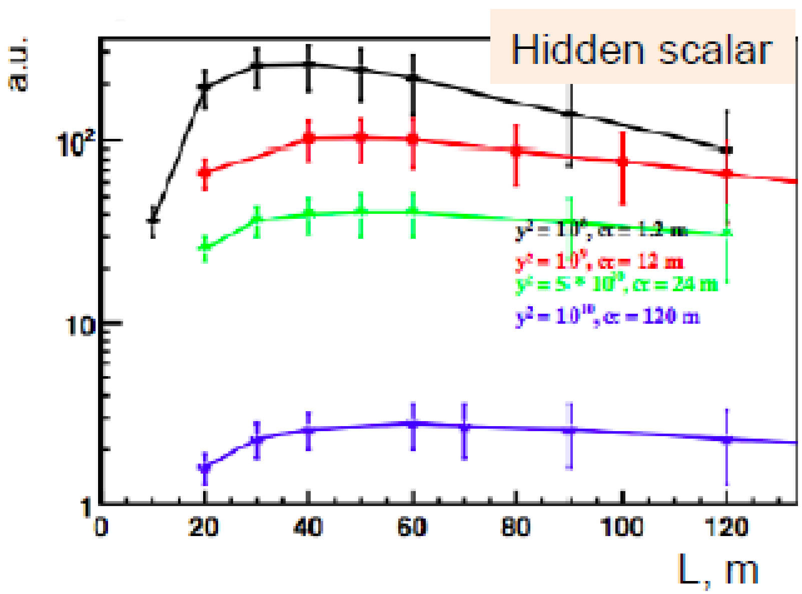
located just after ν_τ detector
to tag **neutral K** produced by ν and μ int
and **μ** entering the vessel from the front

Optimization of the HS decay volume

Geometrical acceptance as function of the decay volume length for given cross section 5 × 10 m (M_{HS} = 1 GeV)





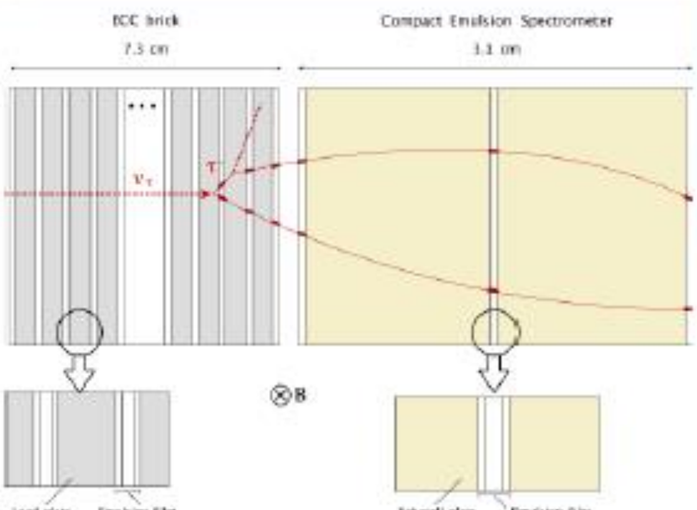


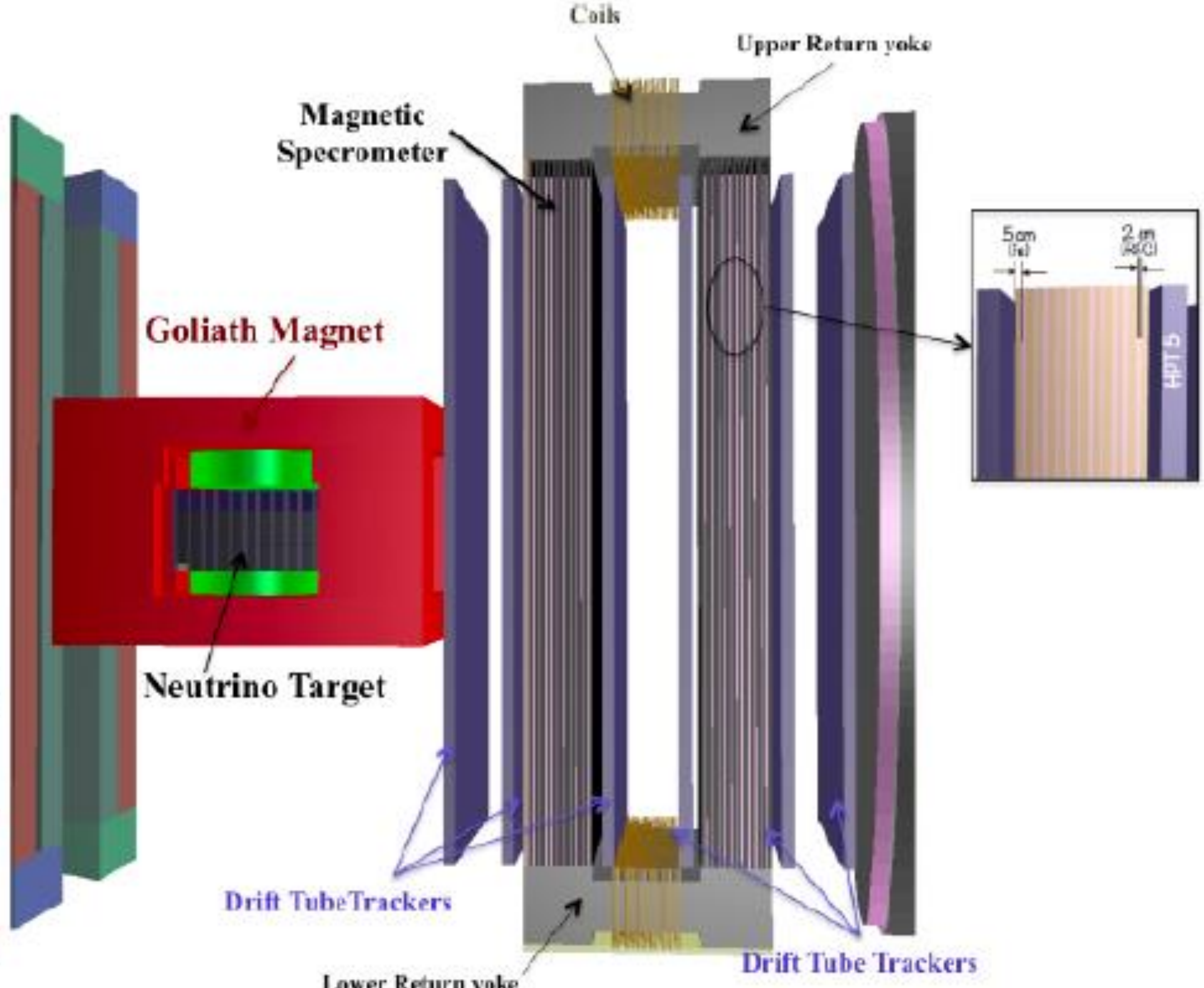
Acceptance saturates at

- *- 48 m for HNL*
- *- 40 m for dark photon*
- *~ 40 m is also ok for hidden scalars with shorter life times*

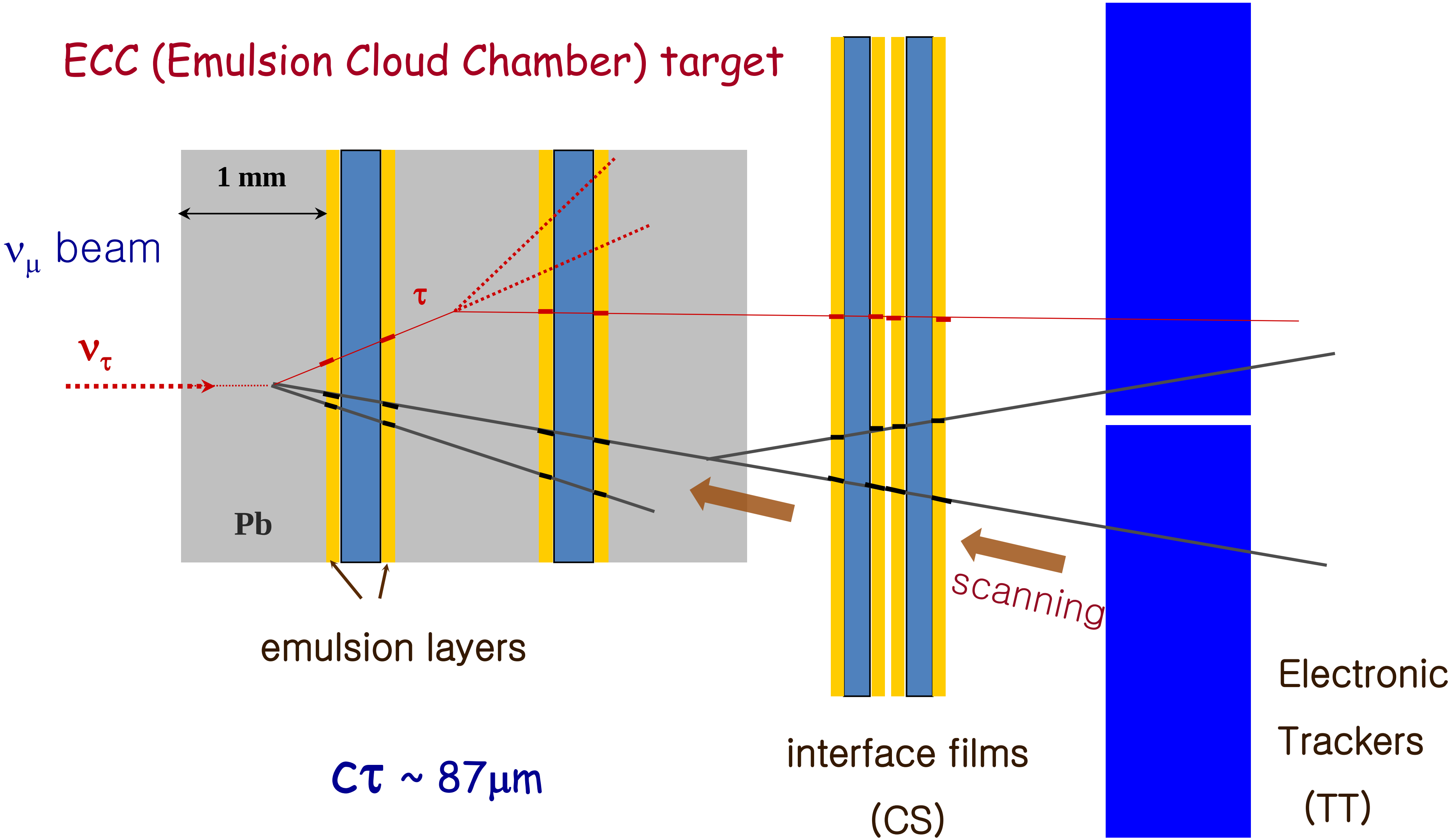
ν_τ detector follows the concept of OPERA

Emulsion Cloud Chamber Is a key element of ν_τ detection



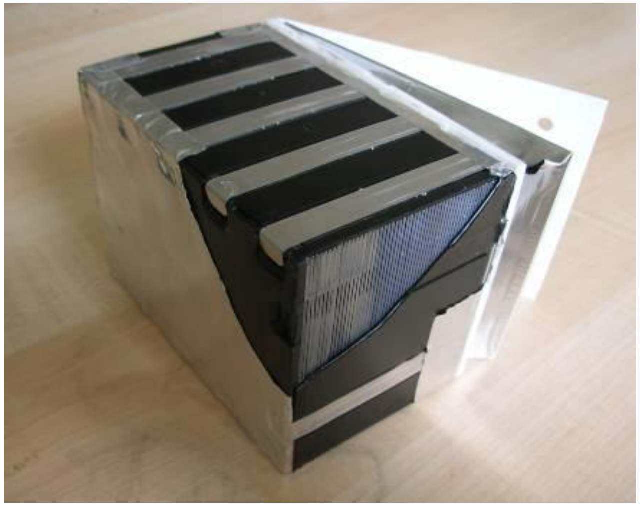


ν_τ detection by identification of Tau lepton



$c\tau \sim 87\mu m$

Tau Neutrino detector



ECC
(Emulsion film + Pb)

ECC (Emulsion Cloud Chamber)

TT & Muon Spectrometer

Nuclear emulsion

- Spatial resolution → sub micron
- PID → electron, proton, pion …
- Momemtum measurement – using MCS

→ **Application to various fields**

Neutrino exp, DM search, S=-2 nuclei, Gamma ray telescope, Muon radiography …

Neutrino detection at SHiP

✓ ***Unique capability of detecting all three neutrino flavours***

- $\nu_\tau / \bar{\nu}_\tau$ → *ν interaction and τ decay vertices in emulsion target*
- ν_e → *electrons producing em shower in emulsion target*
- ν_μ → *muons identified by TT, DTT and the muon spectrometer of the tau neutrino detector*

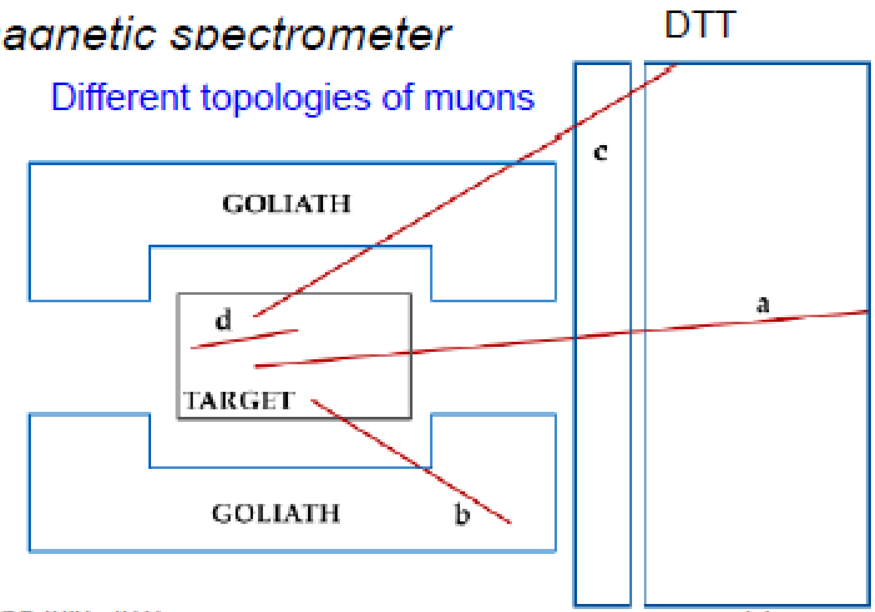
	ε_{tot} (%)
$\tau \to \mu X$	60
$\tau \to hX$	62
$\tau \to 3hX$	63
$\tau \to eX$	56

✓ ***Separation between tau and anti tau-neutrinos by the charge measurement***

- *charge of hadrons is measured by CES*
- *charge of muons is measured by CES and magnetic spectrometer*

	$\tau \to hX$	$\tau \to 3hX$	$\tau \to \mu X$
Correct charge	70%	49%	94%
Wrong charge	0.5%	1.0%	1.5%

Different topologies of muons



HS Signal yield

The same procedure applied to all physics signals, outlined here for HNLs:

$$n(HNL) = N(\text{p.o.t}) \times \chi(pp \to HNL) \times \mathcal{P}_{\text{vtx}} \times \mathcal{A}_{\text{tot}}(HNL \to \text{visible})$$

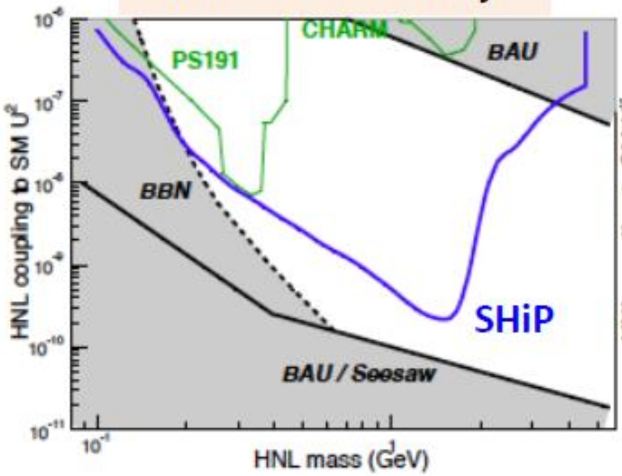
- ✓ *N(p.o.t.) = 2×10^{20}*
- ✓ $$\chi(pp \to HNL) = 2 \times [\chi(pp \to c\bar{c}) \times \mathcal{BR}(c \to HNL) + \chi(pp \to b\bar{b}) \times \mathcal{BR}(b \to HNL)] \times U^2$$
    - *χ(pp → cc) = 1.7×10^{-3}, χ(pp → bb) = 1.6×10^{-7} are production fractions for 400 GeV proton colliding on a Mo target*
    - *$U^2 = U^2_e + U^2_\mu + U^2_\tau$ (ratio between different LF is model dependent)*
- ✓ *$\mathcal{P}_{vtx}$ - probability that HNL (of a given mass and couplings) decays in the SHiP fiducial volume*
- ✓ *$\mathcal{A}_{tot}$ (HNL→visible) – detector acceptance for all HNL final states, HNL → 3ν, $\pi^0\nu$, π^+l^-, $\rho^0\nu$, ρ^+l^-, $l^+l^-\nu$*

$$\mathcal{A}_{\text{tot}}(HNL \to \text{visible}) = \sum_{\text{i=visible channel}} \mathcal{BR}(HNL \to i) \times \mathcal{A}(i)$$

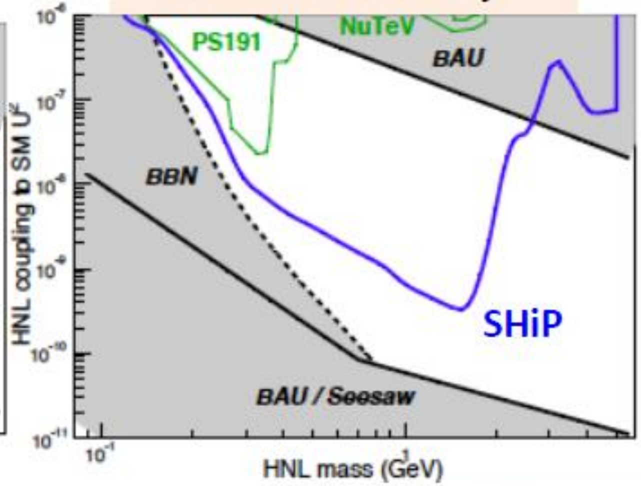
HNL prospects @ SHiP

BAU constraint is model-dependent (shown below for νMSM)

$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$
Inverted hierarchy



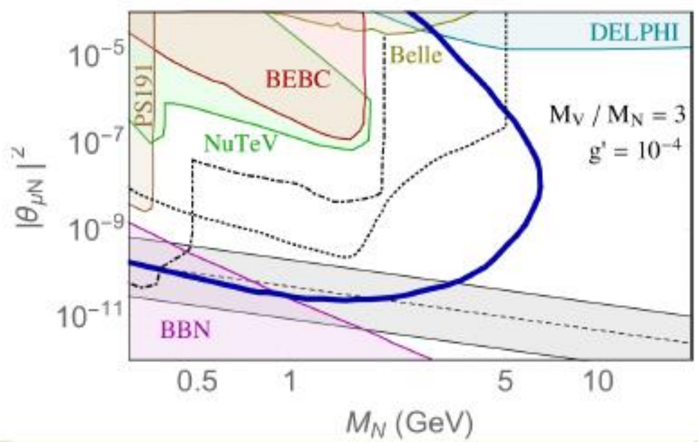
$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$
Normal hierarchy



Further studies:
Drewes et al. (2016)
Hernandez et al. (2016)
Hernández (2015)
Drewes & Garbrecht (2012)
Abada et al. (2015)

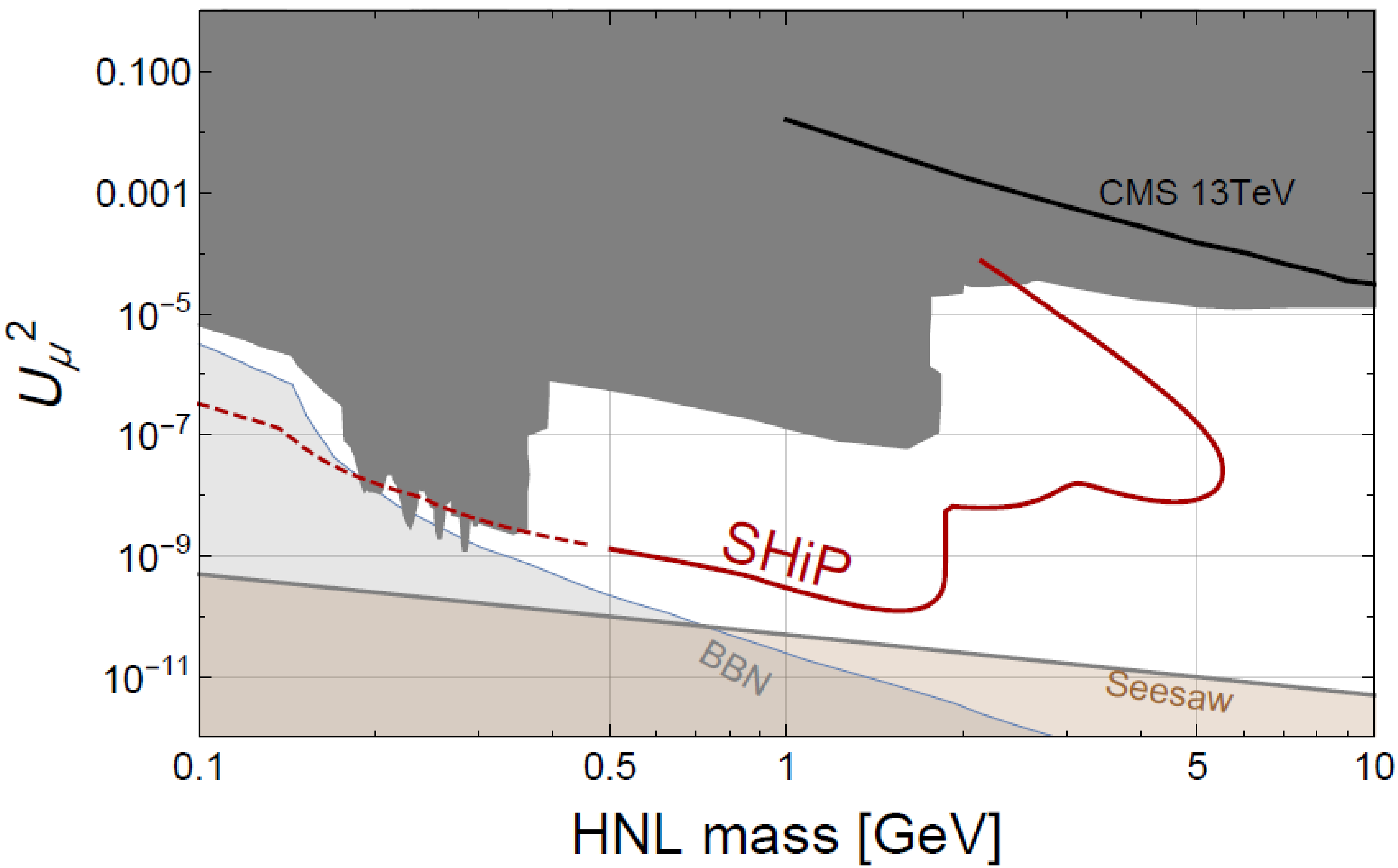
Enhanced HNL production
(B-L gauge symmetry)

Batell, Pospelov, Shuve 1604.06099



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

Comparison with previous bounds



And others…

- Scalar portal models
- Vector portal models

- R-parity violating SUSY
- Bulk singlet neutrinos in the extra dimension models
- Unparticles

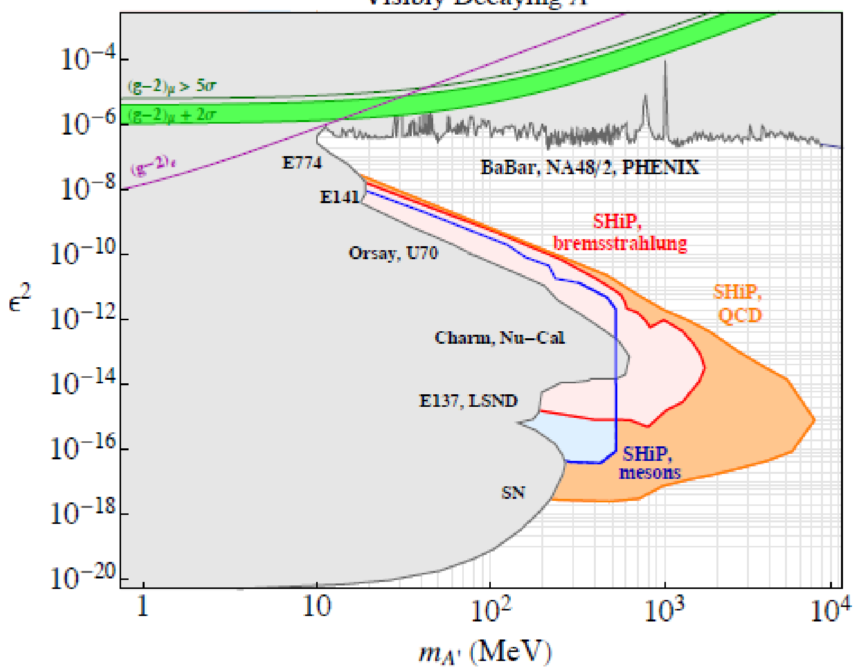
- And more…

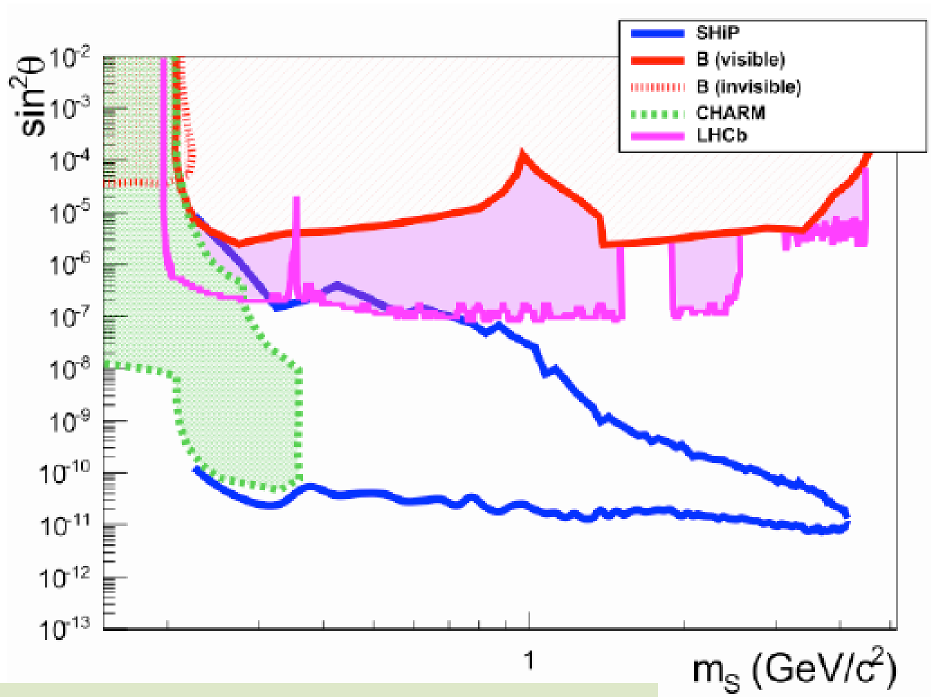
SHiP sensitivity to hidden-sector mediators

- ✓ ***Dark photons*** *→ U(1) associated particle* ***A' (γ')*** *in HS that can have non-zero mass and mix with the SM photon with* ε
  Produced in QCD processes or in decays of $\pi^0 \to \gamma'\gamma$, $\eta \to \gamma'\gamma$, $\omega \to \gamma'\pi^0$ *and* $\eta' \to \gamma'\gamma$
- ✓ ***Hidden scalars, S,*** *can mix with the SM Higgs with* $\sin^2\Theta$
  Mostly produced in penguin-type B and K decays

Search for ***the decay vertex*** *into a pair of SM particles into* e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^+$, *KK,* $\eta\eta$, $\tau\tau$, *DD, …*

Visibly Decaying A'





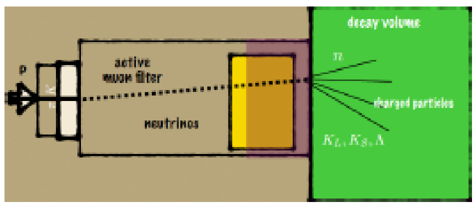
SHiP probes unique range of couplings and masses

SHiP is a "background-free experiment"

SPSC –P350-ADD-2

Accurate control of backgrounds is critical for SHiP physics performance
Bkg. estimation is based on FairSHiP → data samples comparable to the expected ones simulated with Pythia, Genie and run through full GEANT4

Neutrino induced



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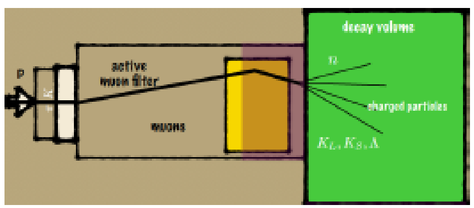
Muon inelastic



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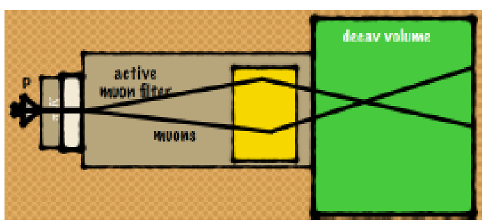
Muon Comb.



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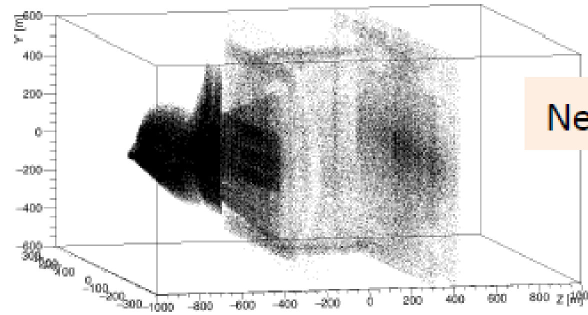
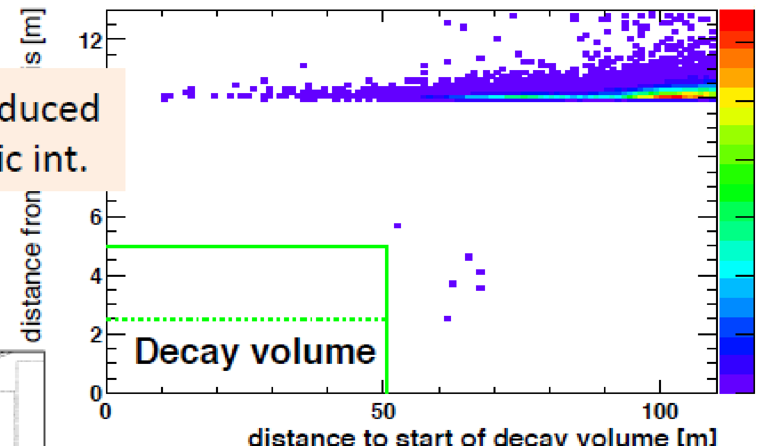
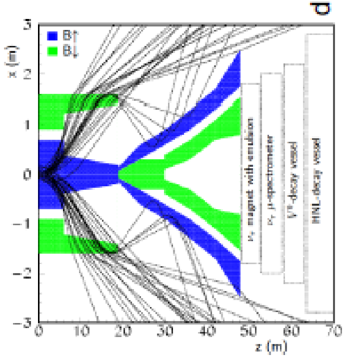
Cosmics



Neutrino tomography



Origin of V_0 produced in muon inelastic int.



Muon trajectories

No evidence for any irreducible background !

SHiP in the world

~250 scientific authors

16 member countries: Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Korea, Portugal, Russia, Sweden, Switzerland, Turkey, United Kingdom, Ukraine, United States of America + CERN, DUBNA

48 member institutes: Sofia, Valparaiso, Niels Bohr Institute Copenhagen, LAL Orsay, LPNHE Paris, Berlin, Humboldt University Hamburg, Mainz, Bari, Bologna, Cagliari, Ferrara, Lab. Naz. Gran Sasso, Frascati, Naples, Rome, Aichi, Kobe, Nagoya, Nihon, Toho, Gyeongsang, LIP Coimbra, Dubna, ITEP Moscow, INR Moscow, P.N. Lebedev Physical Institute Moscow, Kurchatov Institute Moscow, IHEP Protvino, Petersburg Nuclear Physics Institute St. Petersburg, Moscow Engineering Physics Institute, Skobeltsyn Institute of Nuclear Physics Moscow, Yandex School of Data Analysis, Stockholm, Uppsala, CERN, Geneva, EPFL Lausanne, Zurich, Middle East Technical University Ankara, Ankara University, Imperial College London, University College London, Rutherford Appleton Laboratory, Bristol, Warwick, Taras Shevchenko National University Kyiv, Florida

5 associated institutes: Jeju, Gwangju, Chonnam, National University of Science and Technology "MISIS" Moscow, St. Petersburg Polytechnic University

52 institutes from 17 countries

Andrey Golutvin
Spokesman

Korea SHiP Group

@제주대학교 2018. 8. 21

History of Korean Group

- 2015 결성
- 2015 경상대학교 정식멤버로 참가
- 2016 새물리 암흑물질 특집호 총설논문
- 2017 고려대학교 정식멤버로 참가
- 2017 PS beam test 참가 (윤천실, 이강영)
- 2018 예비실험에 RPC 제작 지원
- 2018 예비실험 참가 (윤천실)
- KPS meeting에서 총 14회 발표
- ICHEP 2018 포스터 발표
- SHiP collaboration meeting 참가
- 총 13회 local meeting 개최

Conclusions

- ✓ ***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*
  - *Interactions with atoms in the emulsion spectrometer*

- ✓ ***Physics case is very timely !***
  *Many theoretical models offer a solution for the BSM experimental facts with light very weakly-interacting Particles. **Must be tested !***

- ✓ *SHiP is based on existing technologies and can be built in time to start data-taking in 2026 (in line with the LHC schedule)*
  This requires approval in ~2020!

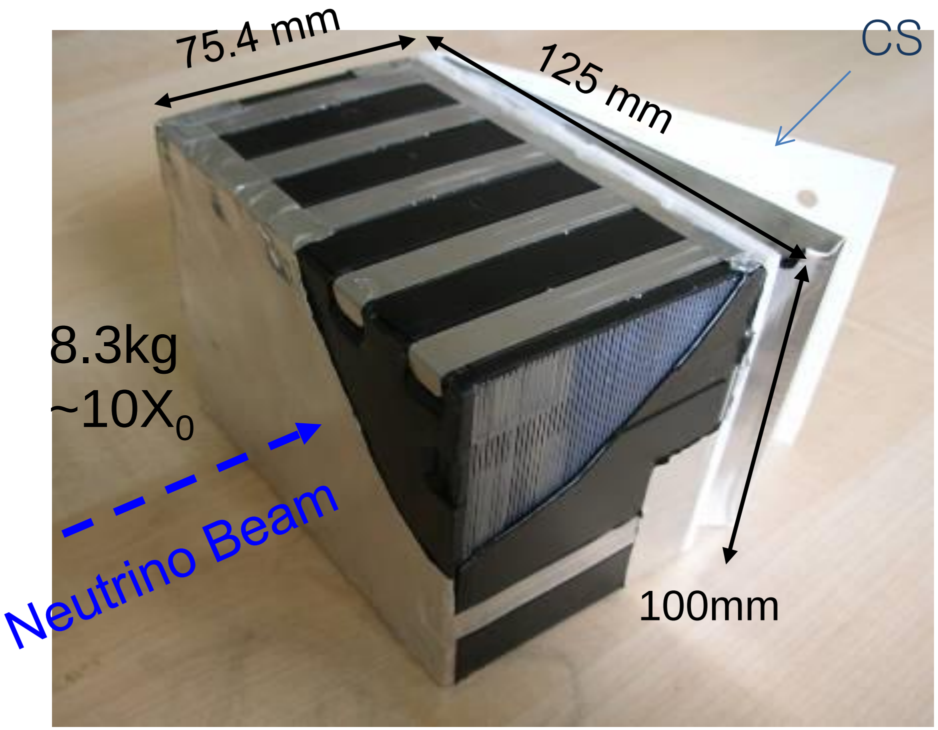
- ✓ ***No existing, or near future facility could make the proposed physics programme**, which nicely complements searches for NP at the LHC*

감사합니다.

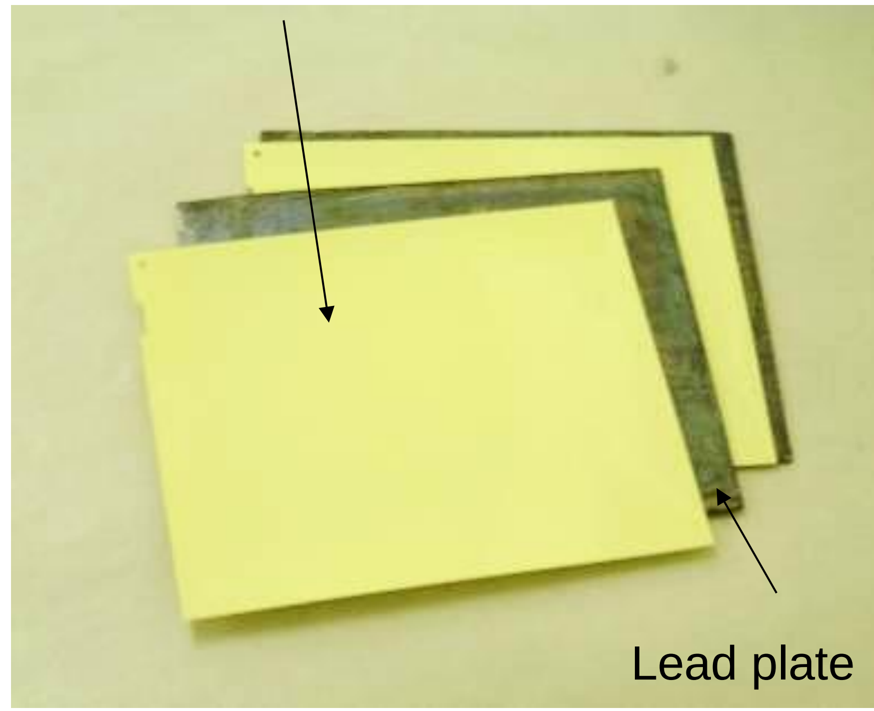
Backup Slides

SHiP experiment is
a fixed target experiment
complementary to the LHC
to search for new particles of order GeV, very weakly interacting and long-lived.

ECC (Emulsion Cloud Chamber)



Emulsoin film (before development)



Sandwich structure
57 nuclear emulsion films
56 lead plates (1mm thick)

(Golutvin's) Summary

- ✓ *SHiP is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with masses O(10) GeV*
- ✓ *Also unique opportunity for ν_τ physics*
- ✓ *Sensitivity improves previous experiments by O(10000) for Hidden Sector and by O(200) for ν_τ physics*
- ✓ ***The technical feasibility of the SHiP facility has been demonstrated by the CERN Task Force. Great thanks !***
- ✓ ***The impact of the discovery of a new light hidden particle is hard to overestimate !***
- ✓ ***SHiP will greatly complement searches for New Physics at energy frontier at CERN***

Active ν Phenomenology

Mixings and Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\rm PMNS}(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \alpha_1, \alpha_2) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) \;=\; & \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin^2\left(\frac{(m_j^2 - m_i^2)L}{4E}\right) \\
& - \; 2\sum_{i<j} \mathrm{Im}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin\left(\frac{(m_j^2 - m_i^2)L}{2E}\right).
\end{aligned}
$$

$N_{2,3}$ production

Interaction with the Higgs v.e.v. —>mixing with active neutrinos with U^2

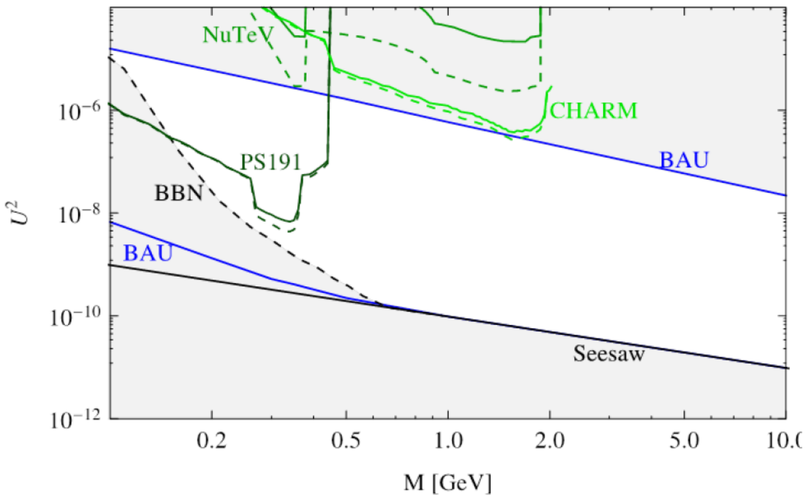
in the νMSM strong limitations in the parameter space (U^2,m)

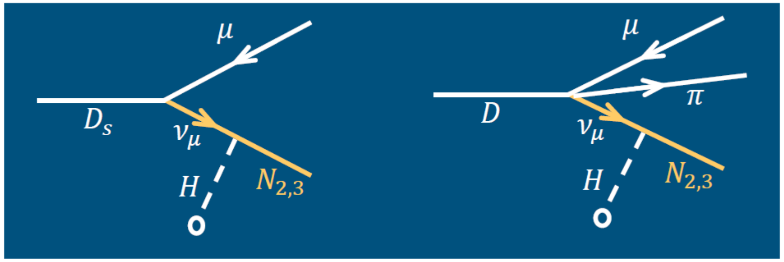
a lot of HNL searches in the past but, for $m>m_K$, with a sensitivity not of cosmological interest (e.g. LHCb with B decays obtained $U^2 \approx 10^{-4}$, arXiv:1401.5361)

this proposal: search in D meson decays (produced with high statistics in fixed target p collisions at 400 GeV)

Taking into account the existing beams and those possibly existing in the near future, this is the best experiment to problem the cosmologically interesting region

inverted mass hyerarchy

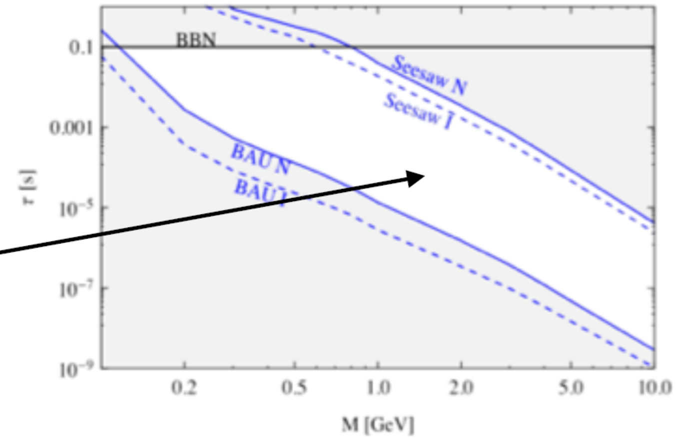




$N_{2,3}$ decays

Very weak HNL-active ν —>$N_{2,3}$ have very long life-time

decay paths of O(km)!: for $U^2_\mu=10^{-7}$, $\tau_N=1.8\times10^{-5}$ s

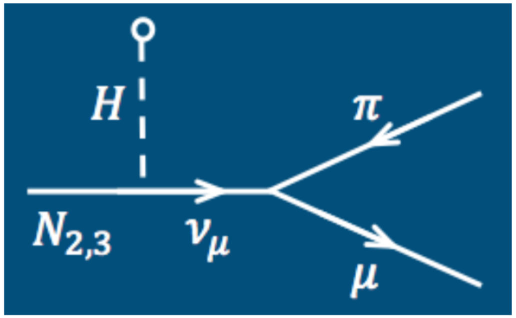


Various decay modes : the BR's depend on flavor mixing

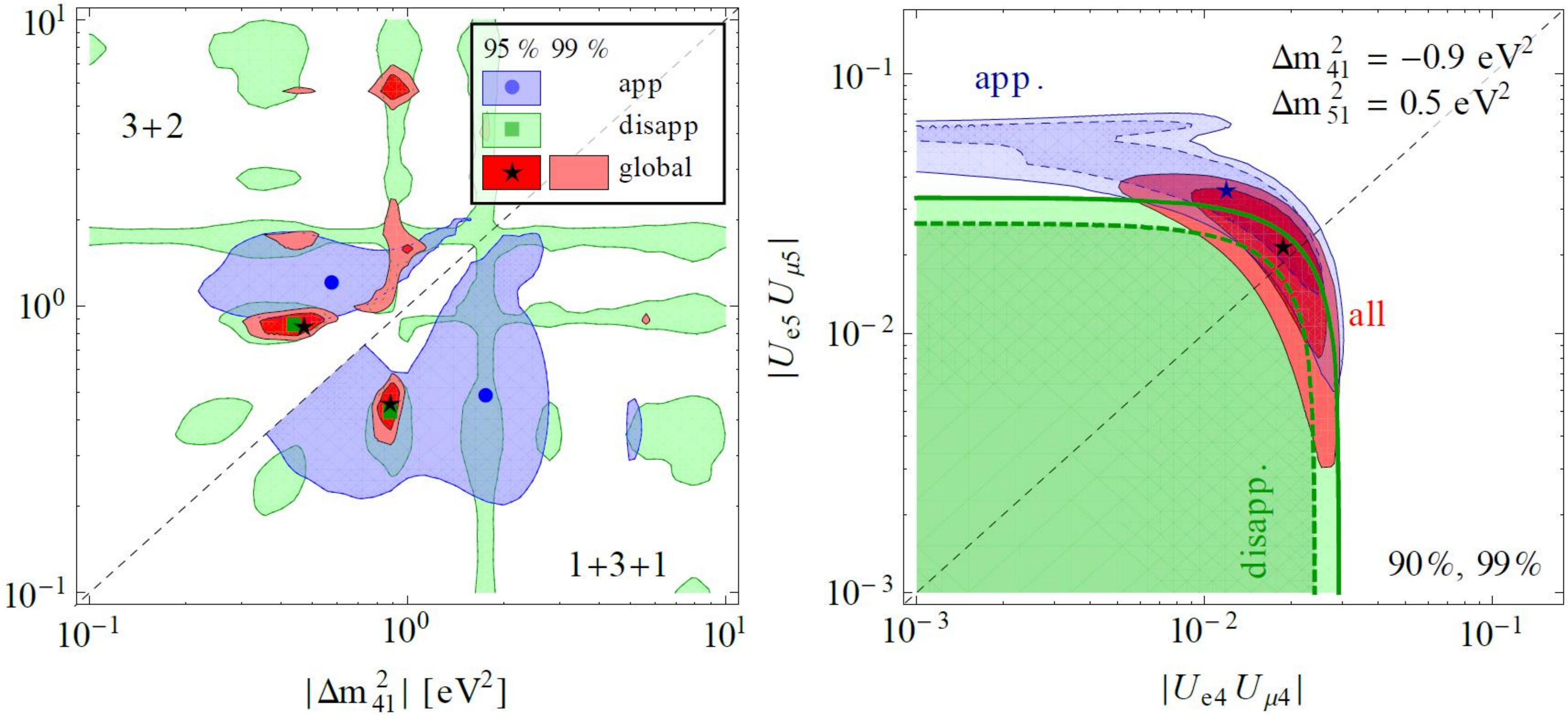
Decay mode	Branching ratio
$N_{2,3} \to \mu/e + \pi$	0.1 - 50 %
$N_{2,3} \to \mu^-/e^- + \rho^+$	0.5 - 20 %
$N_{2,3} \to \nu + \mu + e$	1 - 10 %

The probability that $N_{2,3}$ decays within the fiducial volume of the experiment $\propto U_\mu^2$

—> number of events $\propto U_\mu^4$



	$\Delta m^2_{\odot}(\mathrm{eV}^2)$	$\Delta m^2_{\mathrm{atm}}(\mathrm{eV}^2)$	$\theta_{12}(^\circ)$	$\theta_{23}(^\circ)$	$\theta_{13}(^\circ)$	$\delta(^\circ)$
NH	$7.5(2)\ \times 10^{-5}$	$2.46(5)\ \times 10^{-3}$	33.5(8)	$42.3^{+3}_{-1.6}$	8.5(2)	306^{+39}_{-70}
IH	idem	$-2.45(5)\ \times 10^{-3}$	idem	$49.5^{+1.5}_{-2.2}$	idem	254^{+63}_{-62}



See-saw

See-saw masses $$m_\nu \sim \frac{m_D^2}{M}$$

with $m_D \sim Y_{I\alpha} v$

M ~ 1 GeV, m_ν ~ 0.05 eV

→ m_D ~ 10 keV, Y ~ 10^{-7}

mixings

$$U^T M^\nu U = M^\nu_{\mathrm{diag}} = \mathrm{diag}(m_1, m_2, m_3)$$

$$\nu_\alpha = U_{\alpha i} \nu_i + \Theta_{\alpha I} N_I^c \text{ where } \Theta_{\alpha I} = (M^D)^\dagger_{\alpha I} M_I^{-1} \ll 1$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\bar{N}_I \partial\!\!\!/ N_I - \left(F_{\alpha I} \bar{L}_\alpha N_I \tilde{\Phi} + \frac{M_I}{2} \bar{N}_I^C N_I + h.c. \right)$$

$$\mathcal{M}_{\nu,N} = \left(\begin{array}{c|c} 0 & m_D \\ \hline m_D^T & M_I \end{array} \right),$$

$$\frac{c_{\alpha\beta} v^2}{\Lambda} \equiv (\mathcal{M}_\nu)_{\alpha\beta} = -\sum_I (m_D)_{\alpha I} \frac{1}{M_I} (m_D)_{\beta I}.$$

$$U_{\alpha I}^2 \equiv \frac{v^2 |F_{\alpha I}|^2}{M_I^2} \ll 1.$$

$$\text{Number of HNL parameters} = 7 \times \mathcal{N} - 3$$

$$U^2 = 5.0 \times 10^{-11} \left(\frac{m_\nu}{m_{\text{atm}}}\right) \left(\frac{1\ \text{GeV}}{M_N}\right) \qquad \text{One HNL case}$$

$$U_I^2 \geq \frac{m_2 m_3}{m_2 + m_3} \frac{1}{M_I} \simeq \frac{m_{\text{atm}}}{M_N} \begin{cases} \dfrac{m_\odot}{m_{\text{atm}}}, & \text{NH} \\ \dfrac{1}{2}, & \text{IH} \end{cases}$$

$$U^2 \geq \frac{\sum_\nu m_\nu}{3(M_I)_{\max}}$$

- Sterile neutrino = Heavy Neutral Lepton
  = gauge singlet fermion

- Direct search – mass & Yukawa

- Indirect search – lepton flavour violation

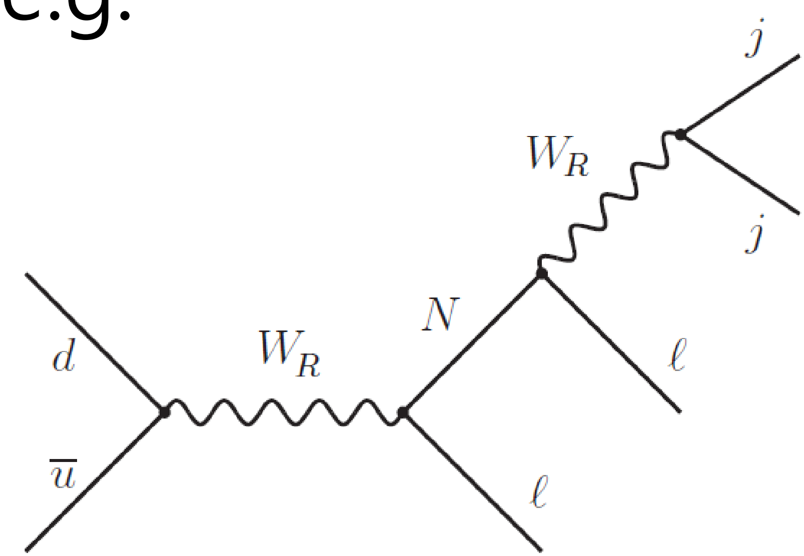
- If it carries lepton number, only Dirac mass term exists

LRSM

See-saw is naturally realized in the LRSM.

$$\Phi = \begin{bmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & -\phi_2^{0*} \end{bmatrix} \quad \Delta_{L,R} = \begin{bmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{bmatrix}_{L,R}$$

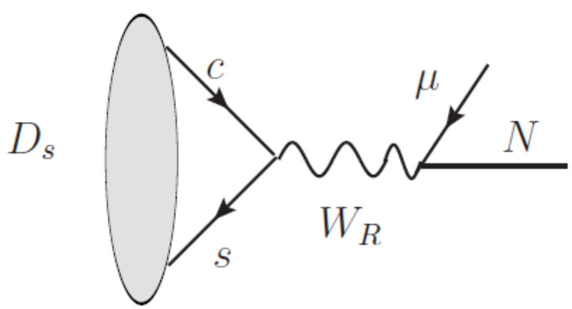
(Heavy) HNL phenomenology expected at the LHC, e.g.

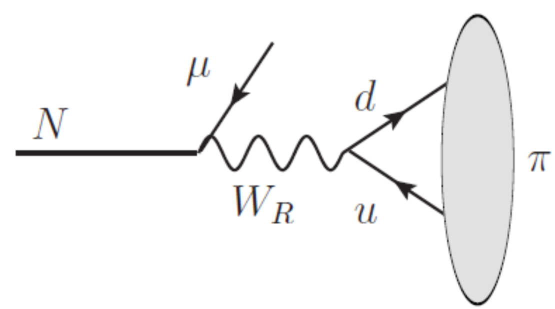


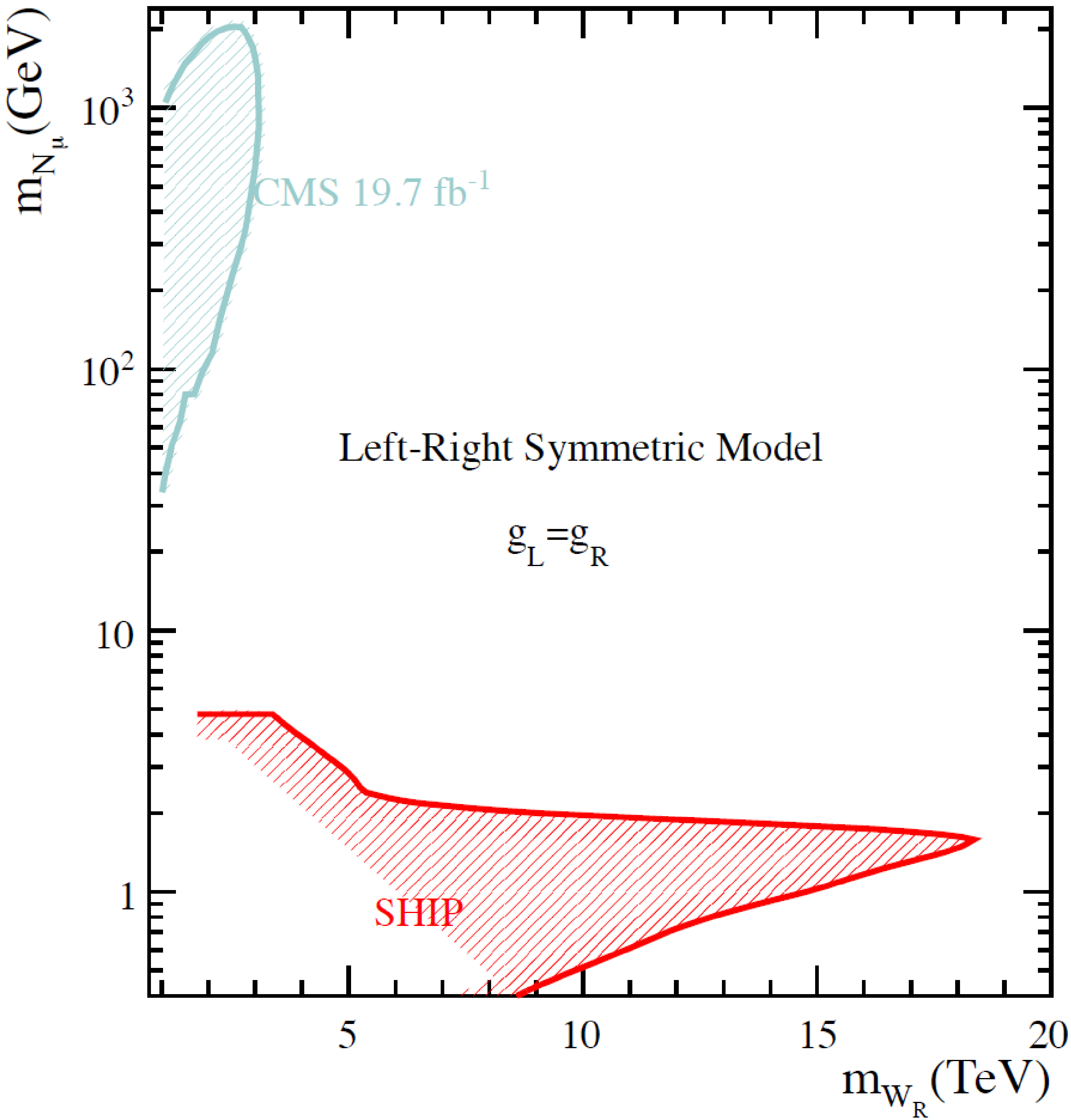
LRSM with GeV HNL?

$$L = c\bar{\gamma}\tau_N \simeq 12\ \bar{\gamma}\ \left(\frac{1\text{GeV}}{m_N}\right)^5 \left(\frac{m_{W_R}}{1\ \text{TeV}}\right)^4 [m].$$

SHiP can probe it!





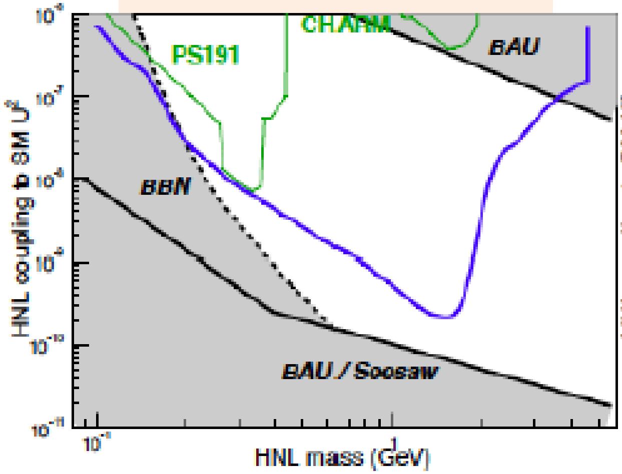


m_{N_μ}(GeV)
10^3
10^2
10
1
CMS 19.7 fb^{-1}
Left-Right Symmetric Model
$g_L = g_R$
SHIP
5
10
15
20
m_{W_R}(TeV)

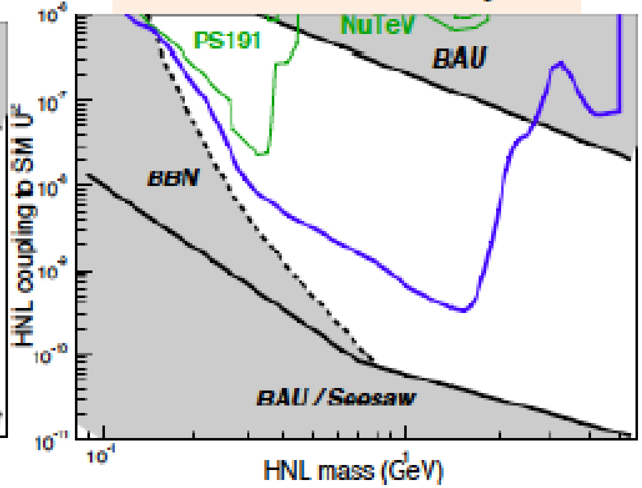
Sensitivity to HNLs for representative scenarios

(moving down to ultimate see-saw limit)

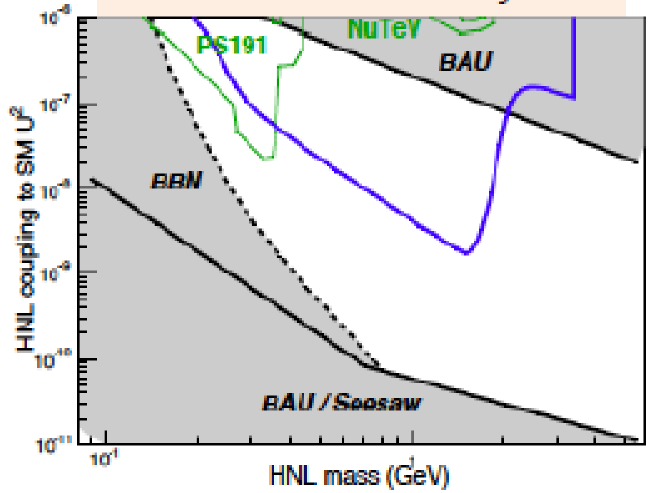
$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$
Inverted hierarchy



$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$
Normal hierarchy

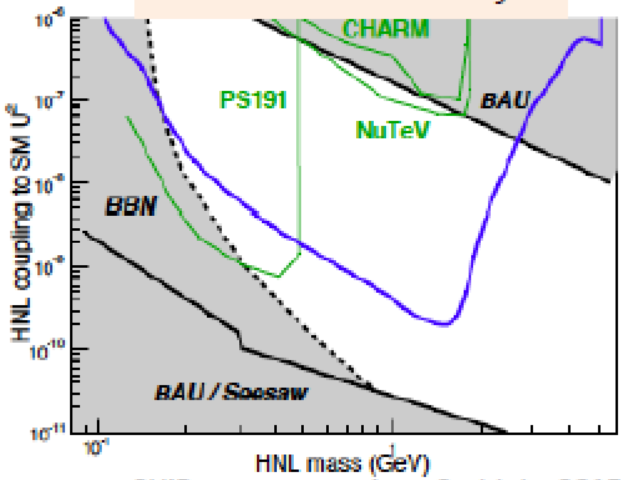


$U^2_e : U^2_\mu : U^2_\tau \sim 0.061:1:4.3$
Normal hierarchy

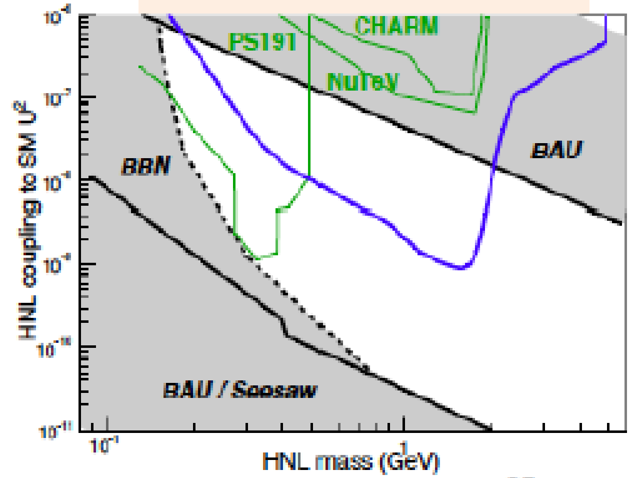


Scenarios for which baryogenesis was numerically proven

$U^2_e : U^2_\mu : U^2_\tau \sim 48:1:1$
Inverted hierarchy



$U^2_e : U^2_\mu : U^2_\tau \sim 1:11:11$
Normal hierarchy



Sensitivity to dark photons

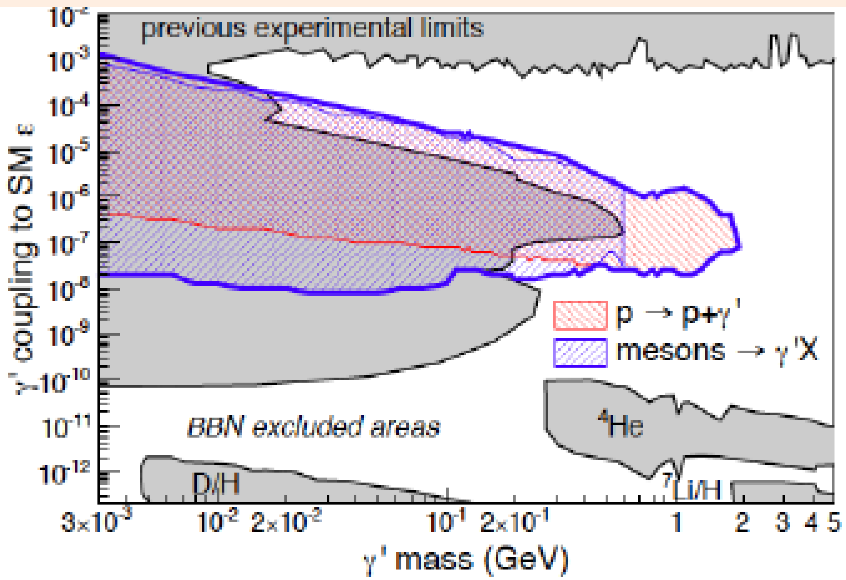
✓ **Production:**

- *mainly decays of $\pi^0 \rightarrow \gamma'\gamma$, $\eta \rightarrow \gamma'\gamma$, $\omega \rightarrow \gamma'\pi^0$ and $\eta' \rightarrow \gamma'\gamma$*
- *a la proton bremsstrahlung (above Λ_{QCD} one should consider parton bremsstrahlung, currently is approximated by the form factor)*

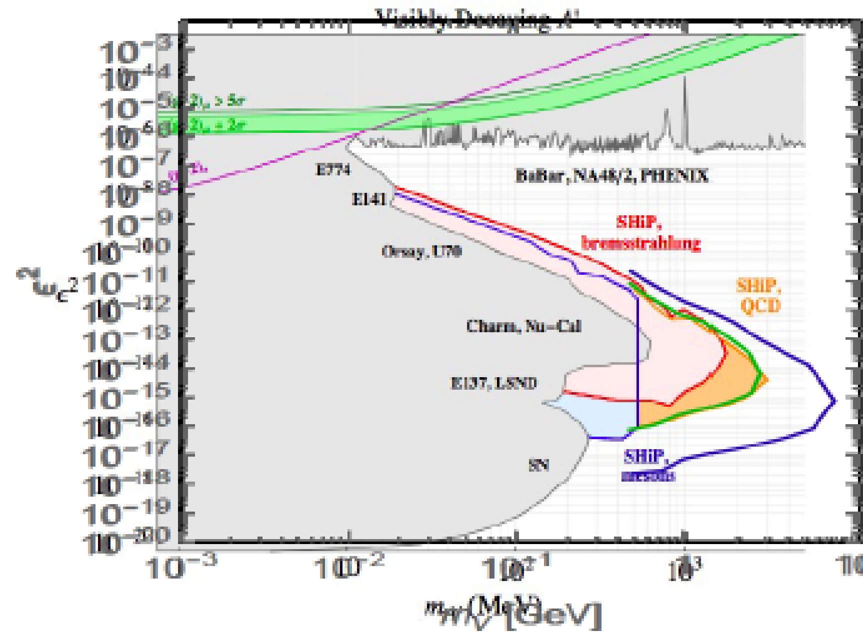
✓ **Decay**

into a pair of SM particles by mixing again with the SM photon

SHiP sensitivity (only p-bremsstarhlung)



With new QCD calculations (still in progress) actual sensitivity extends to higher masses O(10 GeV)



Sensitivity to hidden scalars
(mixing with the SM Higgs with $\sin^2\Theta$)

✓ ***Production:***

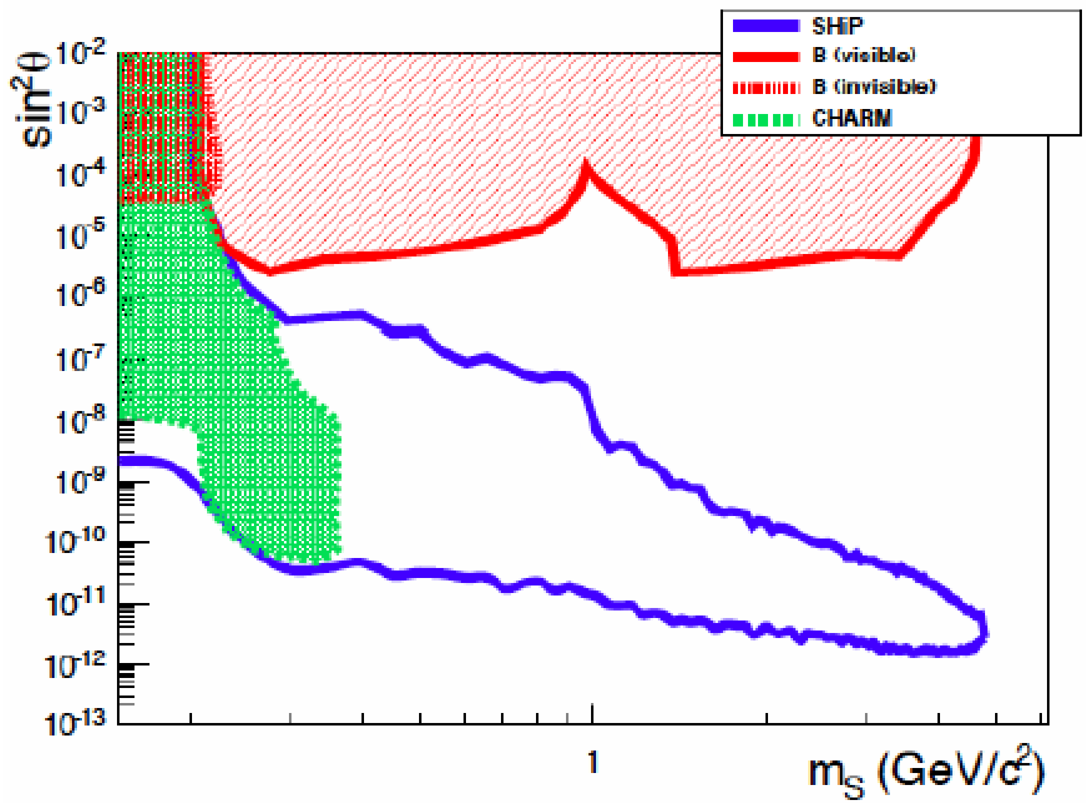
- mostly penguin-type decays of B and K decays (D decays are strongly suppressed by CKM)

✓ ***Decay***

into e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^+$, KK, $\eta\eta$, $\tau\tau$, DD, …

SHiP sensitivity

SHiP probes unique range of couplings and masses, thus complementing existing limits from CHARM and B-factories



Korean group

1. **GNU (Gyeongsang National University)**

    C.S. Yoon (Research professor, CR)

    K.Y. Lee (Professor)

    S.H. Kim (Senior Researcher)

    B.D. Park (Researcher)

2. **JNU (Jeju National University)**

    J.K. Wu (Professor)
    J. Ko (Ph. D. student)
    D. Liu (Ph. D. student)

3. **GNUE (Gwangju National University of Education)**

    Y.G. Kim (Professor)

4. **KASI (Korea Astronomy and Space Science Institute)**

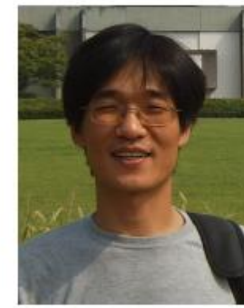
    K.Y. Choi (Senior researcher)

GNU (Gyeongsang National University)

C.S. Yoon
Research professor

K.Y. Lee
Professor

S.H. Kim
Senior researcher



B.D. Park
Researcher

Search for Singlet Fermionic DM

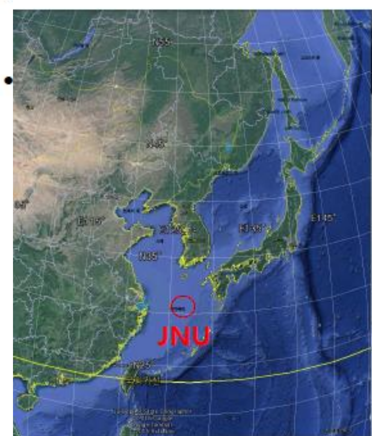
Y.G. Kim (GNUE)

K.Y. Lee (GNU)

SHiP
Search for Hidden Particles

Jeju National University (JNU)

제주대학교
JEJU NATIONAL UNIVERSITY



J. Ko
Ph. D. student

J.K. Woo
Professor

D. Liu
Ph. D. student

K.Y. Choi
KAI (Korea Astronomy and Space Science Institute)
One of the authors of the SHiP physics proposal

I am interested in the search for the dark photon model at the SHiP

Cost and resources

Detector breakdown

Item	Cost (MCHF)	
Tau neutrino detector		**11.6**
Active neutrino target	6.8	
Fibre tracker	2.5	
Muon magnetic spectrometer	2.3	
Hidden Sector detector		**46.8**
HS vacuum vessel	11.7	
Surround background tagger	2.1	
Upstream veto tagger	0.1	
Straw veto tagger	0.8	
Spectrometer straw tracker	6.4	
Spectrometer magnet	5.3	
Spectrometer timing detector	0.5	
Electromagnetic calorimeter	10.2	
Hadronic calorimeter	4.8	
Muon detector	2.5	
Muon iron filter	2.3	
Computing and online system		**0.2**
Total detectors		**58.7**

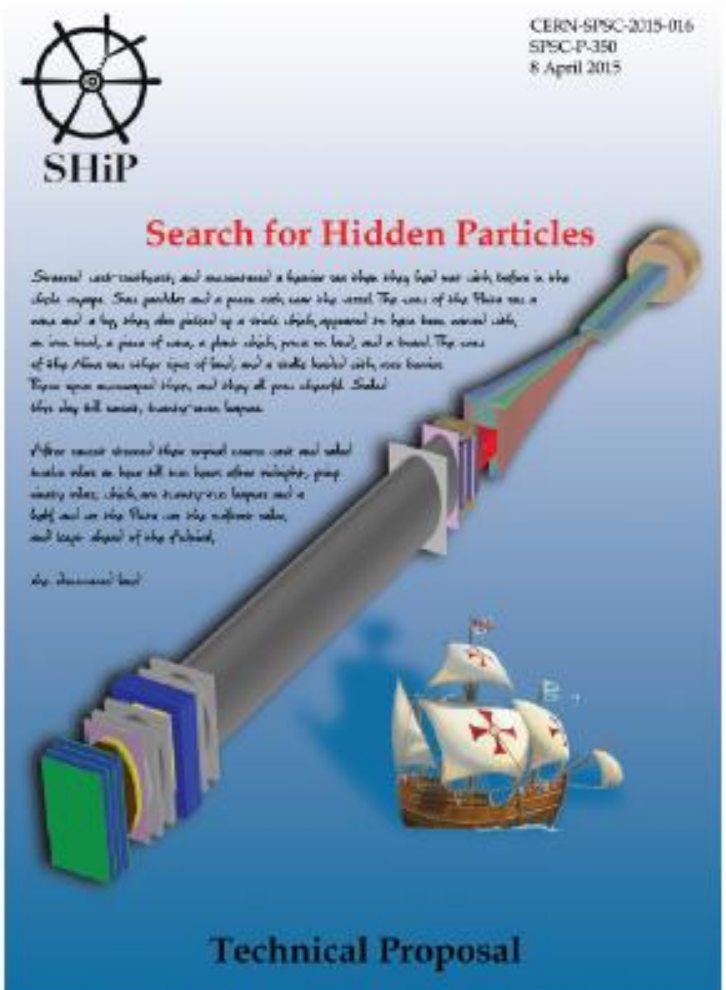
Overall cost of SHiP facility

Item	Cost (MCHF)	
Facility		**135.8**
Civil engineering	57.4	
Infrastructure and services	22.0	
Extraction and beamline	21.0	
Target and target complex	24.0	
Muon shield	11.4	
Detector		**58.7**
Tau neutrino detector	11.6	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**

- ✓ *CERN manpower for preparation of entire facility and installation: 103 FTEs*
  - Fellows (6.3 MCHF) included in cost
- ✓ *CERN resource requirements for TDR phase (3years) excluding integration and CE : ~3.2 MCHF and 12.5 FTEs*
- ✓ *CE preparatory cost (integration, design, EIA, permit, tendering, 2.5 years)*
  → 2.5 MCHF and 12.5 FTEs

Andrey Golutvin
Imperial College London

SHiP conceptual design and performance

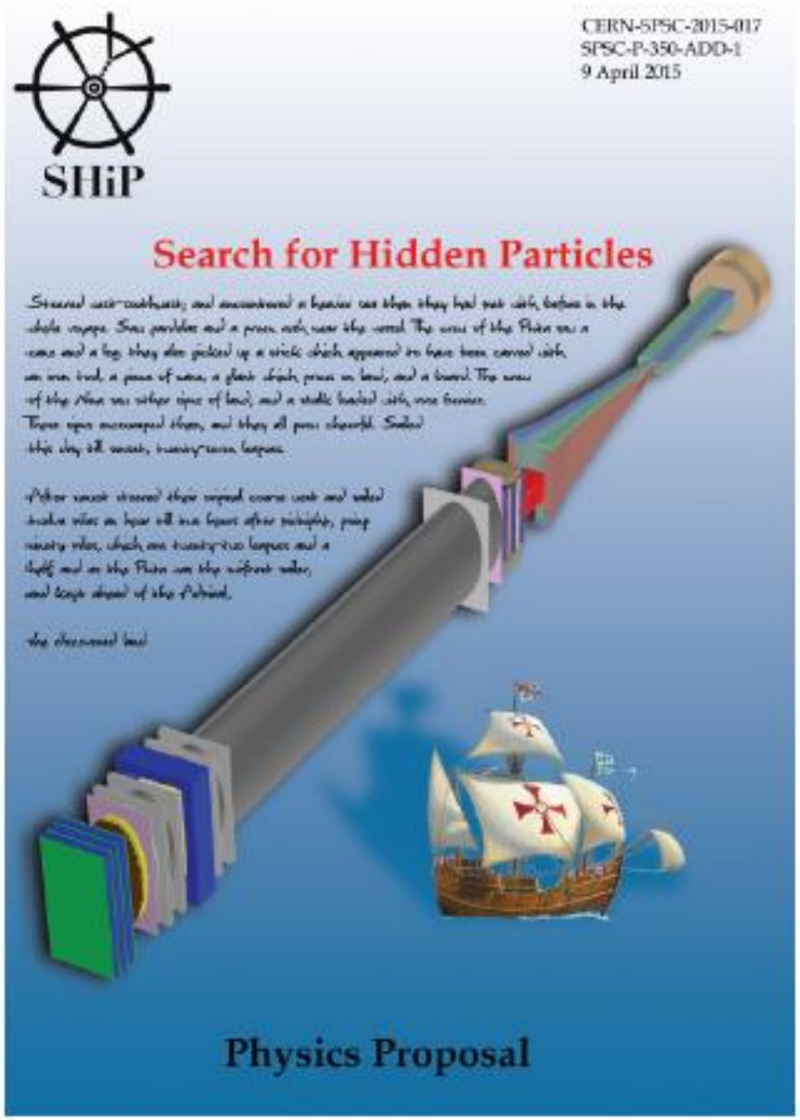


Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

[1] *Faculty of Physics, Sofia University, Sofia, Bulgaria*
[2] *Universidad Técnica Federico Santa María and Centro Científico Tecnológico de Valparaíso, Valparaíso, Chile*
[3] *Niels Bohr Institute, Copenhagen University, Copenhagen, Denmark*
[4] *LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*
[5] *LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France*
[6] *Humboldt-Universität zu Berlin, Berlin, Germany*
[7] *Universität Hamburg, Hamburg, Germany*
[8] *Sezione INFN di Bari, Bari, Italy*
[9] *Sezione INFN di Bologna, Bologna, Italy*
[10] *Sezione INFN di Cagliari, Cagliari, Italy*
[11] *Sezione INFN di Ferrara, Ferrara, Italy*
[12] *Sezione INFN di Napoli, Napoli, Italy*
[13] *Laboratori Nazionali dell'INFN di Gran Sasso, L'Aquila, Italy*
[14] *Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy*
[15] *Sezione INFN di Roma La Sapienza, Roma, Italy*
[16] *Aichi University of Education, Kariya, Japan*
[17] *Kobe University, Kobe, Japan*
[18] *Nagoya University, Nagoya, Japan*
[19] *Nihon University, Narashino, Chiba, Japan*
[20] *Toho University, Funabashi, Chiba, Japan*
[21] *Joint Institute of Nuclear Research (JINR), Dubna, Russia*
[22] *Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[23] *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*
[24] *P.N. Lebedev Physical Institute (LPI), Moscow, Russia*
[25] *National Research Centre Kurchatov Institute (NRC), Moscow, Russia*
[26] *Institute for High Energy Physics (IHEP), Protvino, Russia*
[27] *Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*
[28] *Moscow Engineering Physics Institute (MEPhI), Moscow, Russia*
[29] *Skobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU), Moscow, Russia*
[30] *Yandex School of Data Analysis, Moscow, Russia*
[31] *Stockholm University, Stockholm, Sweden*
[32] *Uppsala University, Uppsala, Sweden*
[33] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[34] *University of Geneva, Geneva, Switzerland*
[35] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[36] *Physik-Institut, Universität Zürich, Zürich, Switzerland*
[37] *Middle East Technical University (METU), Ankara, Turkey*
[38] *Ankara University, Ankara, Turkey*
[39] *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[40] *Department of Physics, University of Warwick, Coventry, United Kingdom*
[41] *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[42] *Imperial College London, London, United Kingdom*
[43] *University College London, London, United Kingdom*
[44] *Taras Shevchenko National University of Kyiv, Kyiv, Ukraine*
[45] *University of Florida, Gainesville, Florida, United States*
[a] *Università di Bari, Bari, Italy*
[b] *Università di Bologna, Bologna, Italy*
[c] *Università di Cagliari, Cagliari, Italy*
[d] *Università di Ferrara, Ferrara, Italy*
[e] *Università di Napoli "Federico II", Napoli, Italy*
[f] *Università di Roma La Sapienza, Roma, Italy*
[g] *Also at N.A. Dollezhal Research and Development Institute of Power Engineering - NIKIET, Moscow, Russia*
[h] *Also at Tomsk State University and Tomsk Polytechnic University, Tomsk, Russia*

On behalf of the SHiP theory: The hidden sector Mikhail Shaposhnikov/EPFL



A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

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Sergey Alekhin,[1,2] Wolfgang Altmannshofer,[3] Takehiko Asaka,[4] Brian Batell,[5] Fedor Bezrukov,[6,7] Kyrylo Bondarenko,[8] Alexey Boyarsky*,[8] Nathaniel Craig,[9] Ki-Young Choi,[10] Cristóbal Corral,[11] David Curtin,[12] Sacha Davidson,[13,14] André de Gouvêa,[15] Stefano Dell'Oro,[16] Patrick deNiverville,[17] P. S. Bhupal Dev,[18] Herbi Dreiner,[19] Marco Drewes,[20] Shintaro Eijima,[21] Rouven Essig,[22] Anthony Fradette,[17] Björn Garbrecht,[20] Belen Gavela,[23] Gian F. Giudice,[5] Dmitry Gorbunov,[24,25] Stefania Gori,[3] Christophe Grojean[§],[26,27] Mark D. Goodsell,[28,29] Alberto Guffanti,[30] Thomas Hambye,[31] Steen H. Hansen,[32] Juan Carlos Helo,[11] Pilar Hernandez,[33] Alejandro Ibarra,[20] Artem Ivashko,[8,34] Eder Izaguirre,[3] Joerg Jaeckel[§],[35] Yu Seon Jeong,[36] Felix Kahlhoefer,[37] Yonatan Kahn,[37] Andrey Katz,[5,38,39] Choong Sun Kim,[36] Sergey Kovalenko,[11] Gordan Krnjaic,[3] Valery E. Lyubovitskij,[40,41,42] Simone Marcocci,[16] Matthew Mccullough,[5] David McKeen,[43] Guenakh Mitselmakher ,[44] Sven-Olaf Moch,[45] Rabindra N. Mohapatra,[46] David E. Morrissey,[47] Maksym Ovchynnikov,[34] Emmanuel Paschos,[48] Apostolos Pilaftsis,[18] Maxim Pospelov[§],[3,17] Mary Hall Reno,[49] Andreas Ringwald,[27] Adam Ritz,[17] Leszek Roszkowski,[50] Valery Rubakov,[24] Oleg Ruchayskiy*,[21] Jessie Shelton,[51] Ingo Schienbein,[52] Daniel Schmeier,[19] Kai Schmidt-Hoberg,[27] Pedro Schwaller,[5] Goran Senjanovic,[53,54] Osamu Seto,[55] Mikhail Shaposhnikov*,[§],[21] Brian Shuve,[3] Robert Shrock,[56] Lesya Shchutska[§],[44] Michael Spannowsky,[57] Andy Spray,[58] Florian Staub,[5] Daniel Stolarski,[5] Matt Strassler,[39] Vladimir Tello,[53] Francesco Tramontano[§],[59,60] Anurag Tripathi,[59] Sean Tulin,[61] Francesco Vissani,[16,62] Martin W. Winkler,[63] Kathryn M. Zurek[64,65]

Abstract: This paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (*Search for Hidden Particles*) experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the Fermi scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used later to look for decays of tau-leptons with lepton flavour number non-conservation, $\tau \to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physics beyond the Standard Model and describe interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different models, manifesting themselves via these interactions, and how they can be probed with the SHiP experiment and present several case studies. The prospects to search for relatively light SUSY and composite particles at SHiP are also discussed. We demonstrate that the SHiP experiment has a unique potential to discover new physics and can directly probe a number of solutions of beyond the Standard Model puzzles, such as neutrino masses, baryon asymmetry of the Universe, dark matter, and inflation.

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*Editor of the paper
§Convener of the Chapter

What we have done ...

CHORUS - Emulsion scanning for Nu_tau search at GNU
- X-ray mark for connection predicted track in the emulsion by using counter information
- Grid mark for alignment of emulsion plates

DONuT - Emulsion scanning for nu_tau search
- Grid mark for alignment of emulsion plates
- Nu_e search & momentum measurement in ECC

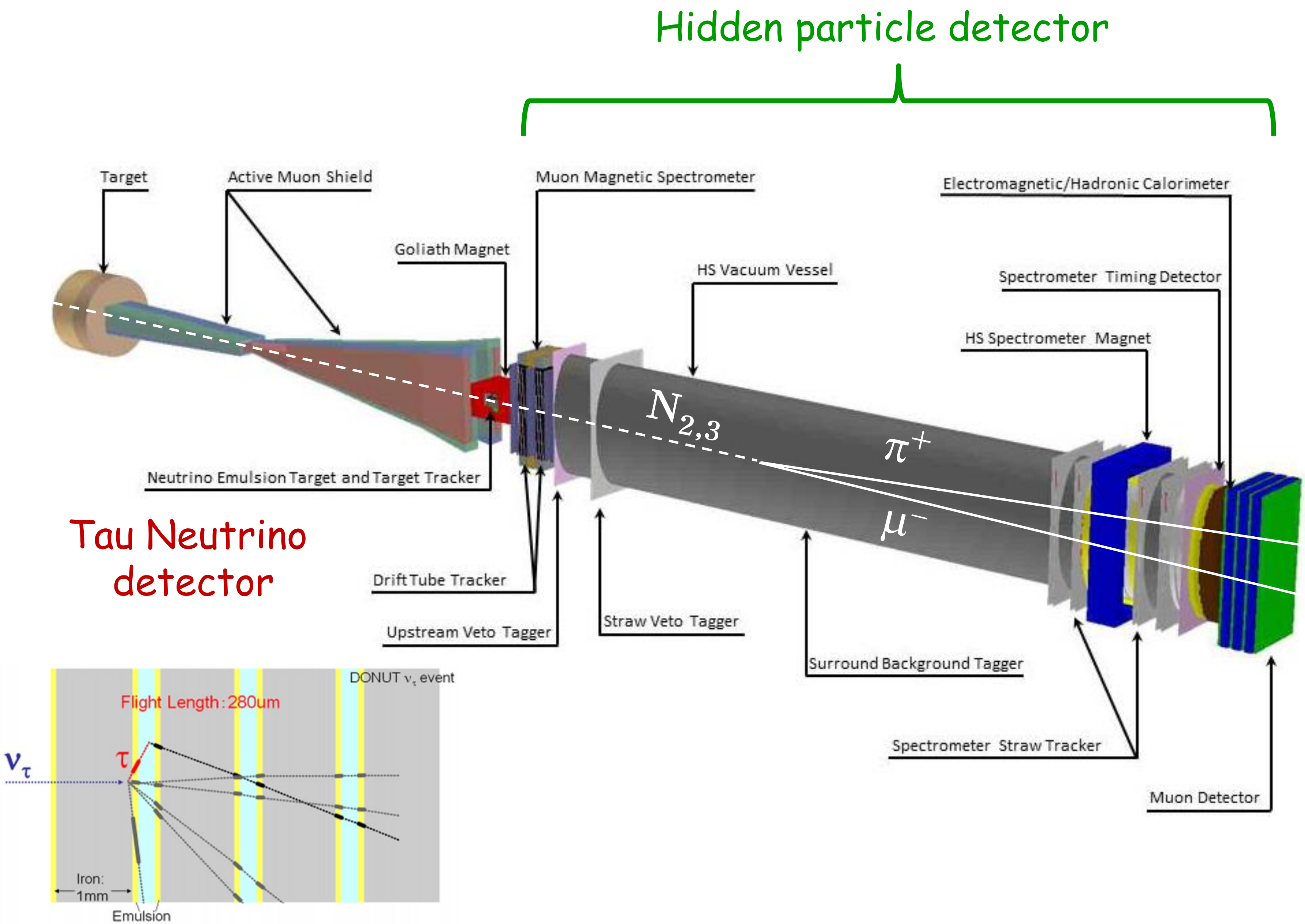
OPERA - Emulsion scanning for Nu_tau search at Nagoya (CS scan, Scan-Back, Decay search)
- Brick X-ray mark for alignment of emulsion films
- Brick handling at Gran Sasso

What we will be able to contribute in the SHiP ...

Emulsion scanning for Nu_tau and anti Nu_tau (and also Nu_e) at Nagoya **(GNU)**

X-ray marking **(GNU)**

MC & Physics analysis etc. **(JNU, GNUE, KAI, GNU)**


Hidden particle detector
Target
Active Muon Shield
Muon Magnetic Spectrometer
Electromagnetic/Hadronic Calorimeter
Goliath Magnet
HS Vacuum Vessel
Spectrometer Timing Detector
HS Spectrometer Magnet
$N_{2,3}$
π^+
μ^-
Neutrino Emulsion Target and Target Tracker
Tau Neutrino detector
Drift Tube Tracker
Upstream Veto Tagger
Straw Veto Tagger
Surround Background Tagger
Spectrometer Straw Tracker
Muon Detector
DONUT ν_τ event
Flight Length: 280um
ν_τ
τ
Iron: 1mm
Emulsion

OPERA scanning shift at F-lab in Nagoya Univ.

J.H.Kim

S.H.Kim

C.S.Yoon

B.D.Park

Automatic scanning systems in GNU

DOMS interface & TS (for CHORUS, DONuT)

Semi-auto system (KEK E373)
S=-2 nuclei search

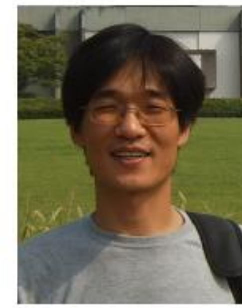
Full-auto system
(J-PARC E07)
S=-2 nuclei search

GNU
(Gyeongsang National University)

C.S. Yoon
Research professor

K.Y. Lee
Professor

S.H. Kim
Senior researcher

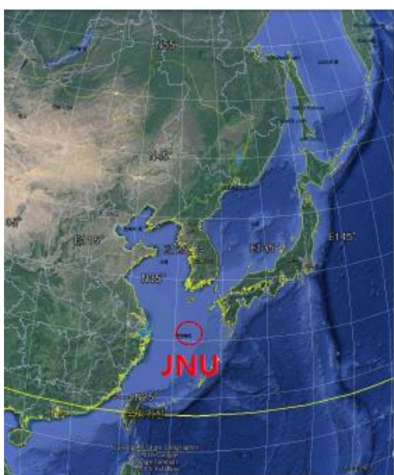


B.D. Park
Researcher

SHiP
Search for Hidden Particles

Jeju National University (JNU)

제주대학교
JEJU NATIONAL UNIVERSITY



J. Ko
Ph. D. student

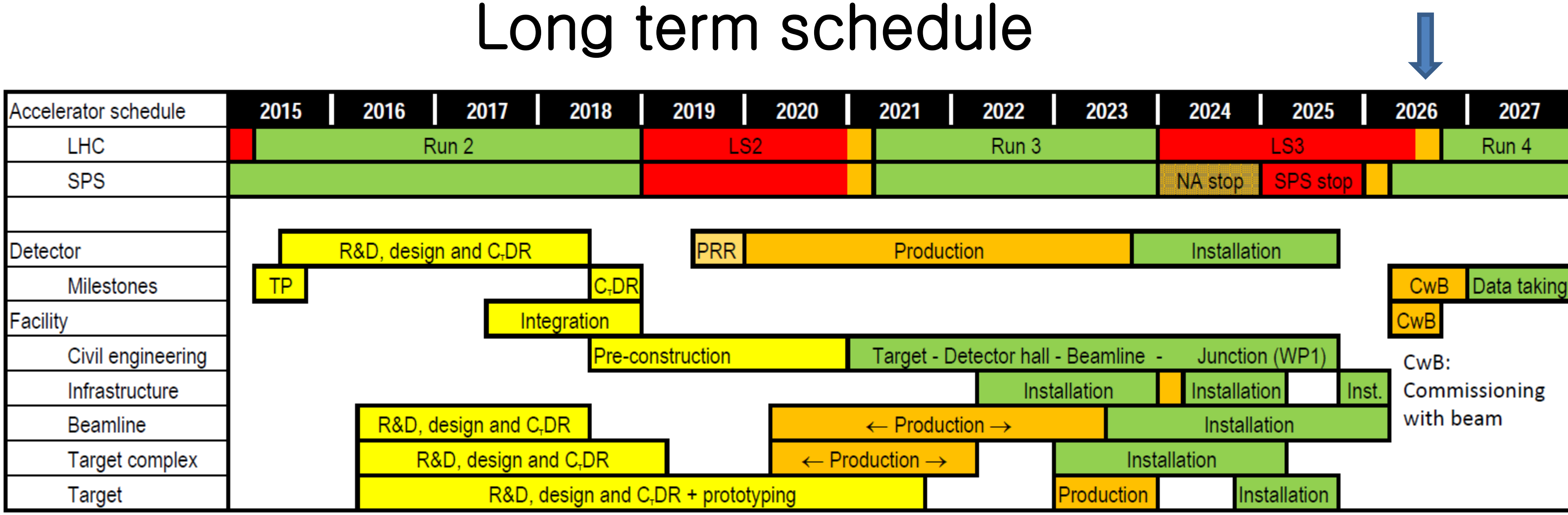
J.K. Woo
Professor

D. Liu
Ph. D. student

K. Choi (CNU)

Y.G. Kim (GNUE)

Long term schedule



2016-2019: CDR (Comprehensive Design Report) phase

Approval is made after CDR

From 2021: Civil engineering for 5 years after Approval

In parallel, Detector construction for 3 years,

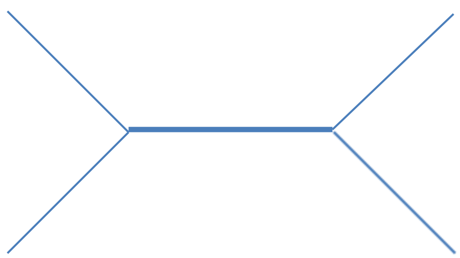
Detector installation and commissioning for 2 years

From 2026 : Beam exposure (data taking) after LS3 for LHC for 5 years

Alternatively,

$$\text{HNL Majorana mass term} = M_I \bar{N}_I^C N_I + \text{h.c.}$$

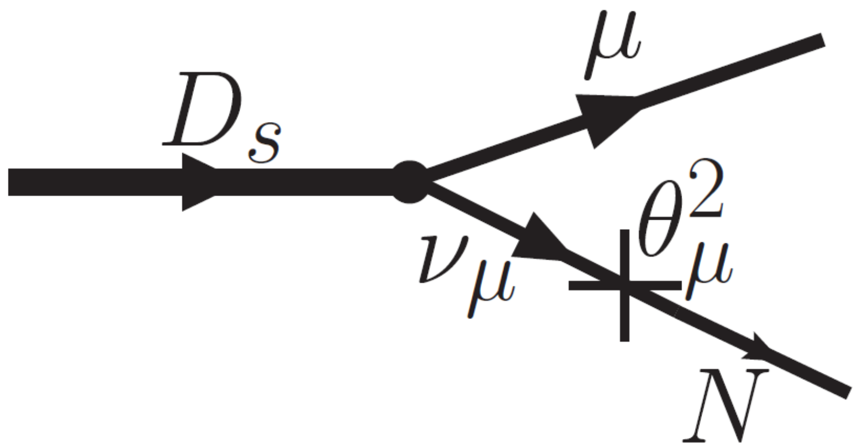
$$\Delta\mathcal{L}_{\rm osc} = c_{\alpha\beta}\frac{(\bar{L}_\alpha^C \cdot \tilde{\Phi})(\tilde{\Phi} \cdot L_\beta)}{\Lambda}$$



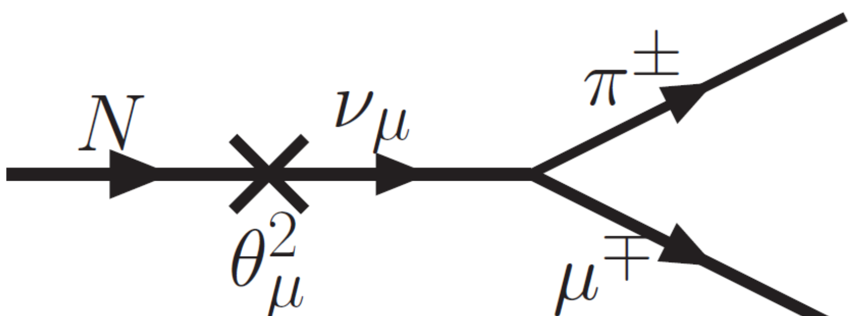
$\Lambda \sim 10^{15}$ GeV

# of HNL ≥ 2

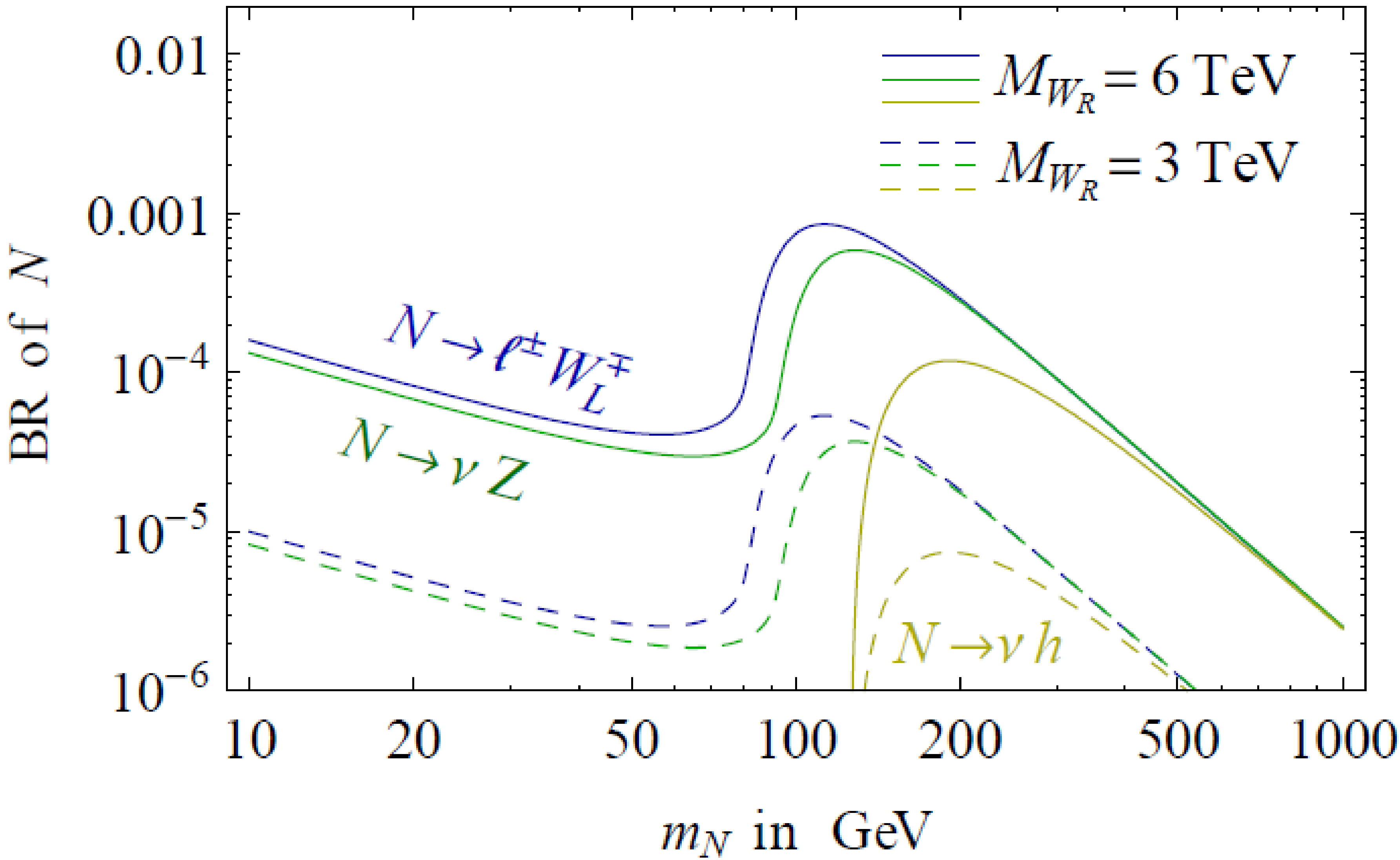
$$\sum_{\alpha,I} |F_{\alpha I}|^2 \geq \frac{M_{\min} \sum m_\nu}{3v^2} = 5.5 \times 10^{-16} \left[\frac{\sum m_\nu}{0.1\,\mathrm{eV}}\right] \left[\frac{M_{\min}}{1\,\mathrm{GeV}}\right]$$



D_s
μ
ν_μ
θ_μ^2
N



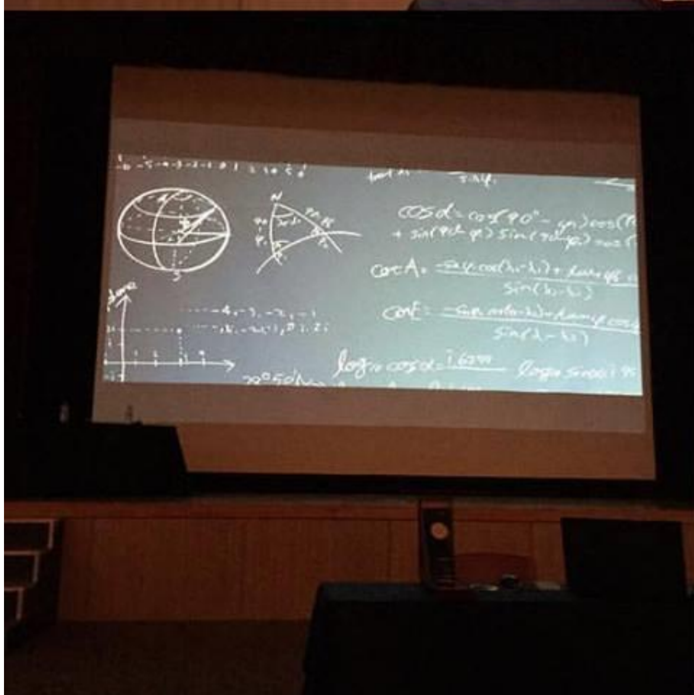
N
ν_μ
θ_μ^2
$\pi^\pm$
$\mu^\mp$



$M_{W_R} = 6$ TeV
$M_{W_R} = 3$ TeV
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
BR of N
$N \to \ell^{\pm} W_L^{\mp}$
$N \to \nu Z$
$N \to \nu h$
10
20
50
100
200
500
1000
m_N in GeV

2016 한국물리학회 가을 학술논문발표회


KEEP
CALM
BECAUSE
I AM
THE BEST




내
물리학
이 세상을
바꾼다
5인5색 과학 설전


PHYSICS
The Korean Physical Society
2016 황금 이빨상
대 상
(사)한국물리학회
The Korean Physical Society
아시아태평양이론물리센터