SHiP

Search for Hidden Particles

A Facility for Hidden Sector Exploration

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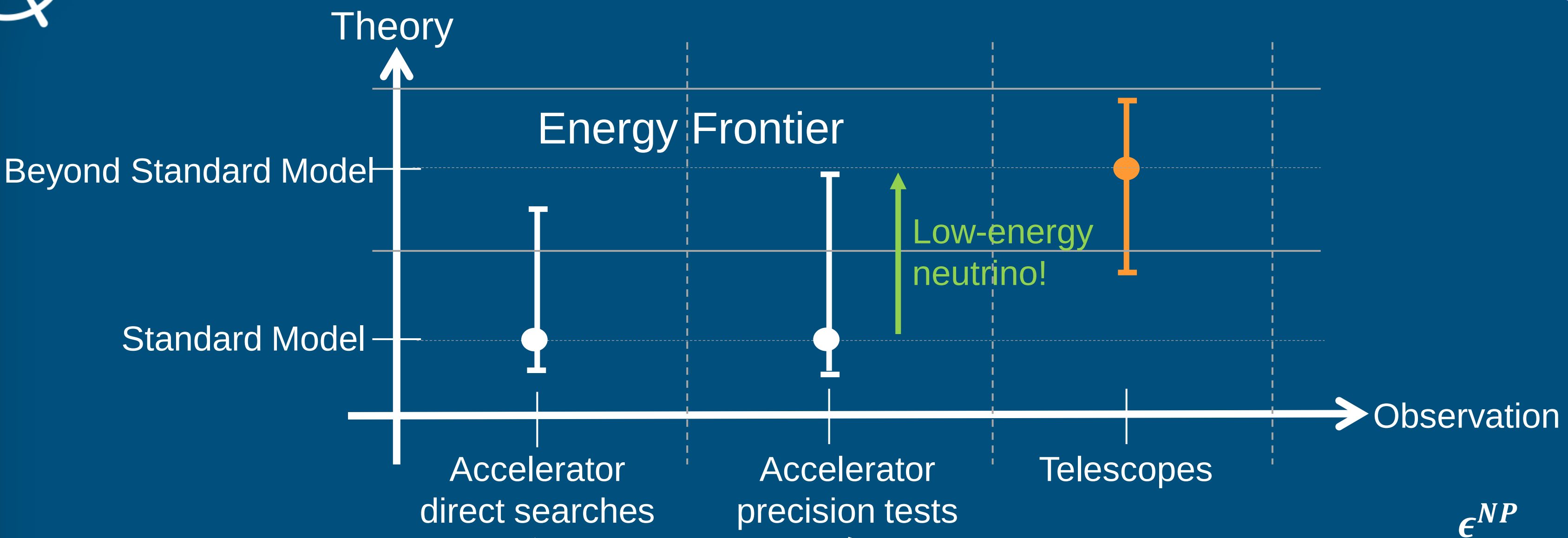
on behalf of the SHIP Collaboration

Seminar at LAL, Orsay, France, January 29, 2015

Introduction

Physics Scenario after LHC Run 1



Theory

Energy Frontier

Beyond Standard Model

Low-energy neutrino!

Standard Model

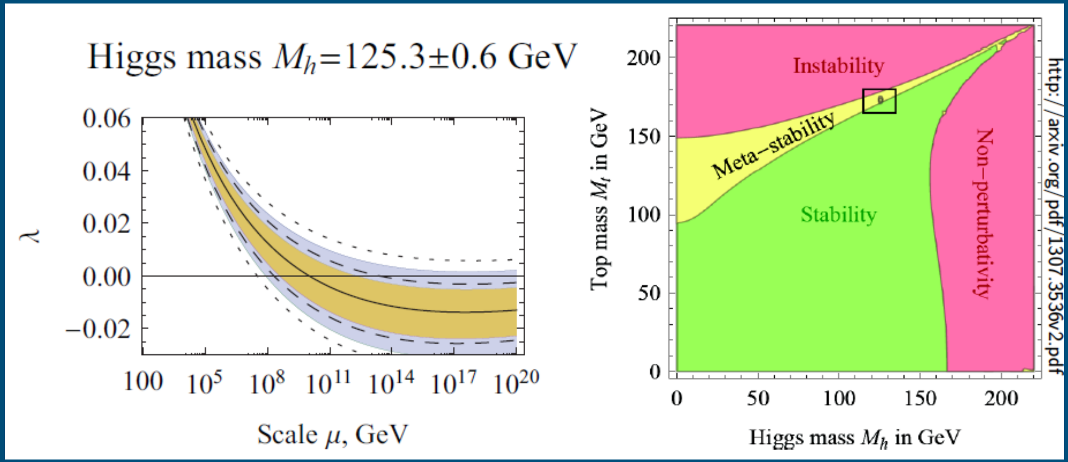
Observation

Accelerator direct searches

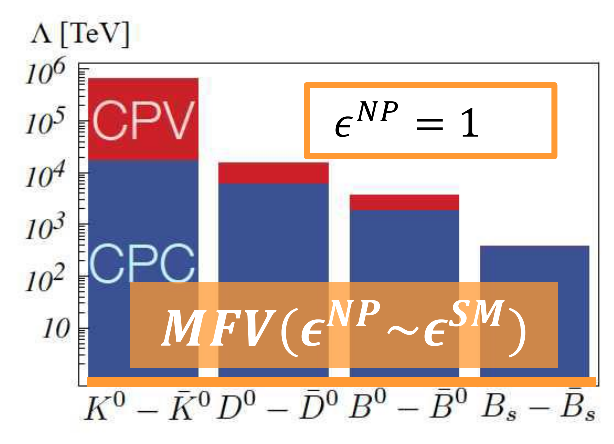
Accelerator precision tests

Telescopes

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta C[\frac{\epsilon^{NP}}{\Lambda_{NP}^2}]$$



arXiv:0906.0954



- All predicted particles found and SM unitarity OK
- No tangible evidence for the scale of the new physics!

Physics Situation after LHC Run 1

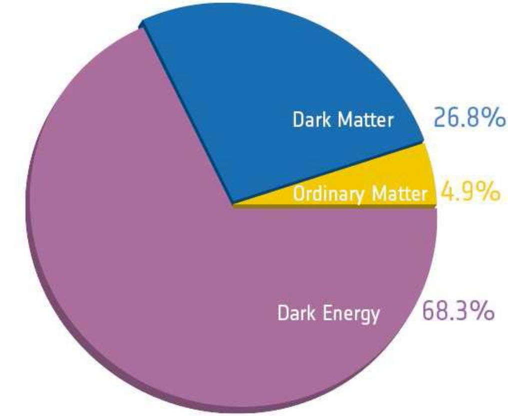
- *With a mass of the Higgs boson of 125 − 126 GeV, the Standard Model may be a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles*
  - ➔ No *need* for new particles *up to* Planck scale!?

Experimental evidence for New Physics

1. Neutrino oscillations: *tiny* masses and flavour mixing
   - → Requires new degrees of freedom in comparison to SM
2. Baryon asymmetry of the Universe
   - → Measurements from BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim \left\langle \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \right\rangle_{T \gtrsim 1\ GeV} \sim 6 \times 10^{-10}$
   - → Current measured CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!
3. Dark Matter from indirect gravitational observations
   - → Non-baryonic, neutral and stable or long-lived
4. Dark Energy and Inflation

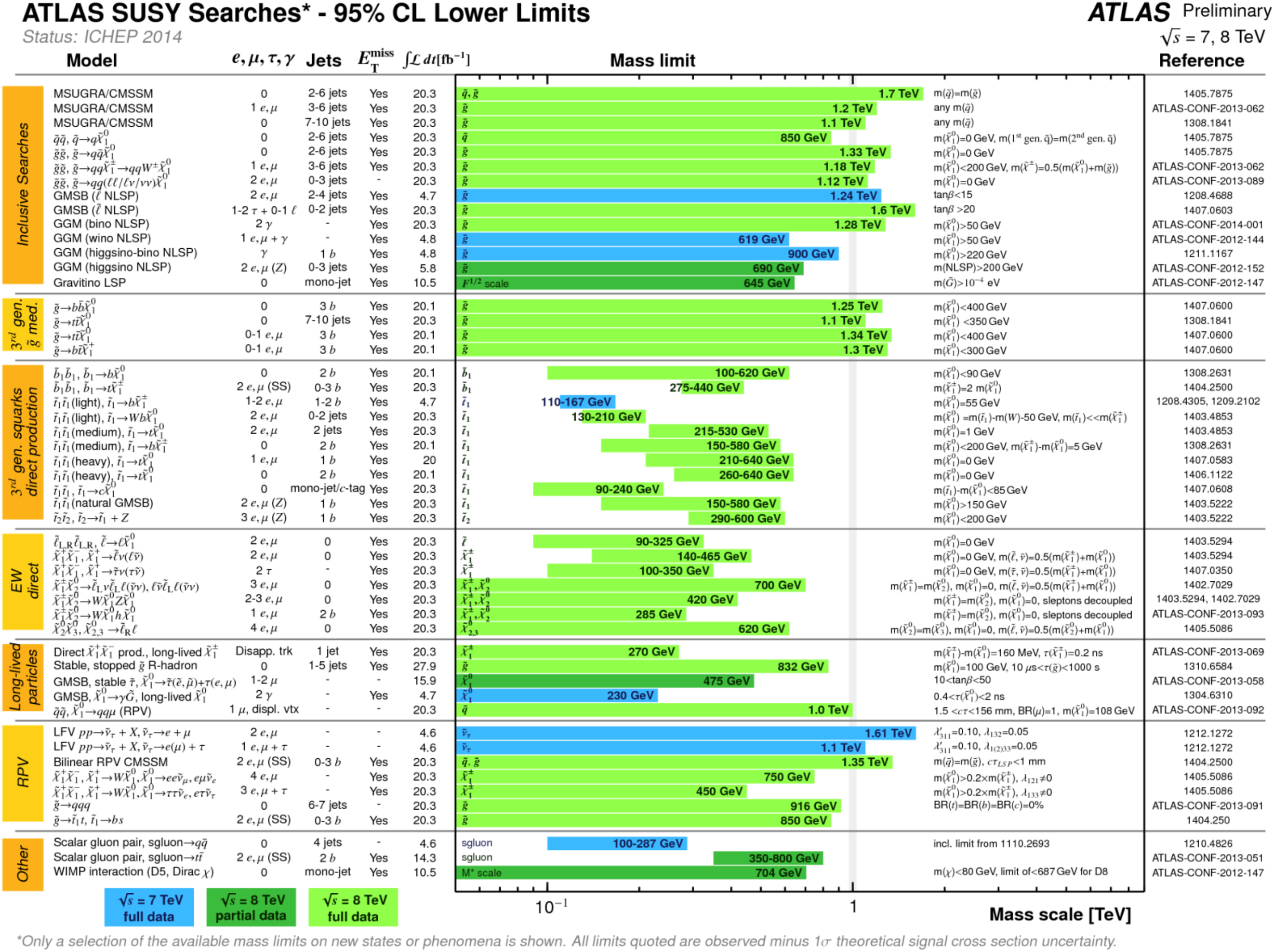
Theoretical "evidence" for New Physics

1. Hierarchy problem and stability of Higgs mass
2. SM flavour structure
3. Strong CP problem
4. Unification of coupling constants
5. Gravity
6. ….



➔ *While we had unitarity bounds for the Higgs, no such indication on the next scale….*

Naturalness?



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

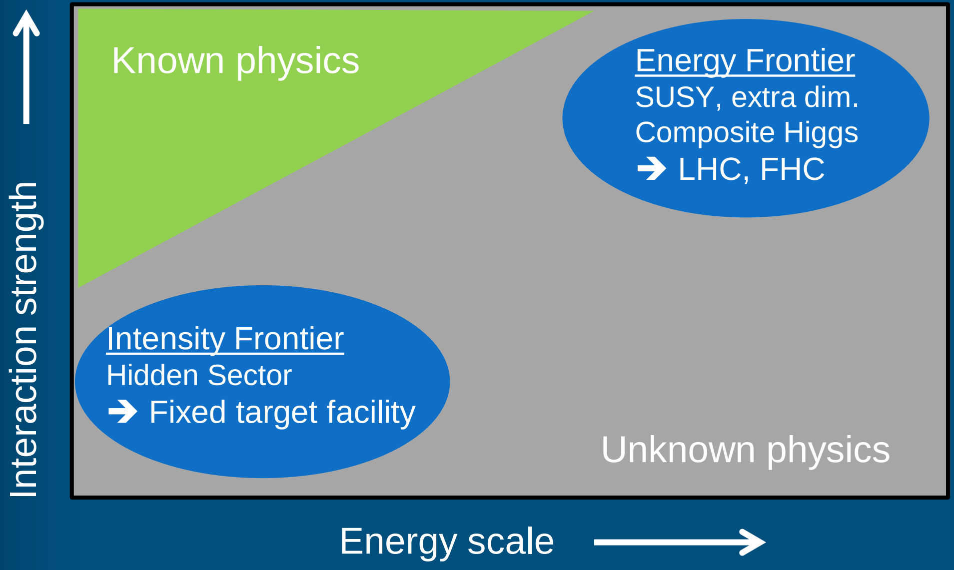
	Model	e,μ,τ,γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g},\ \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g},\ \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g},\ \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1,\ \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1,\ \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$	210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$	260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2,\ \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}},\ \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu),\ \ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	285 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0,\ \tilde{\chi}_{2,3}^0\to\tilde{\ell}_{\mathrm{R}}\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q},\ \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X,\ \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X,\ \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to W\tilde{\chi}_1^0,\ \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu,\ e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to W\tilde{\chi}_1^0,\ \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e,\ e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t,\ \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

- What should we learn from Naturalness?
  - Electroweak fine tuning

What if...?

What about solutions to (some/all) these questions *below Fermi scale* $E < G_F^{-1/2}$?



Known physics

Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC

Intensity Frontier
Hidden Sector
➔ Fixed target facility

Unknown physics

Interaction strength

Energy scale

➔ "Intensity Frontier" much less attention recently:

- PS 191: early 1980s
- CHARM: 1980s
- NuTeV: 1990s
- DONUT: late 1990s - early 2000

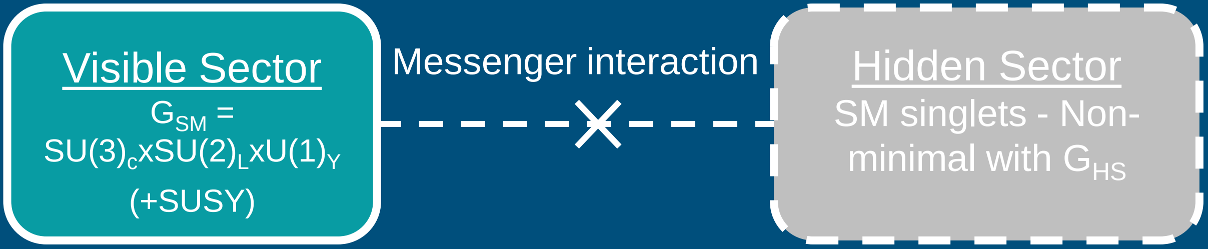
◉ Must have very weak couplings ➔ "*Light* Hidden Sector"

- Not the first time! Neutrino is QED gauge singlet with SM Portal $(\bar{p}\gamma^{\mu}n)(\bar{e}\gamma_{\mu}\nu)$

➔ Dark Matter (and Dark Energy) are already "proofs" of Hidden Sector, what about "Dark Forces"?

New Physics prospects in Hidden Sector

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



Visible Sector

G_{SM} = $SU(3)_c xSU(2)_L xU(1)_Y$ (+SUSY)

Messenger interaction

Hidden Sector

SM singlets - Non-minimal with G_{HS}

- New light hidden particles are singlet under the SM gauge group
- Composite operators (hoping there is not just gravity…) $\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)}\mathcal{O}_{SM}^{(l)}}{\Lambda^n}$

  ➔ Conventionally lowest dimension SM operator makes up “portals” to the Hidden Sector

➔ *Dynamics of Hidden Sector may drive dynamics and anomalies of Visible Sector!*

  ➔ *Dark Matter candidates comes for free – stable or unstable – and together with other cosmological observations impose powerful constraints*

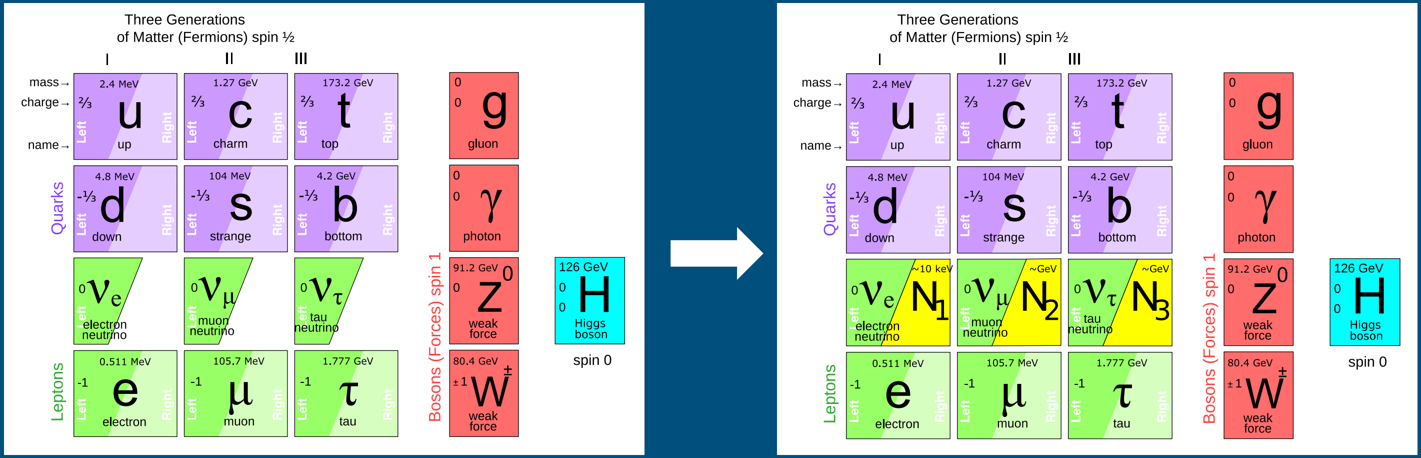
- Two possibilities:
  1. SM + light Hidden Sector is all there is up to Planck scale – no new scale
  2. Wider theory exist at new energy scale (SUSY, extra dim.,etc) including *inherent* light Hidden Sector

➔ Development of experimental facility and detector concept, and initial sensitivity studies used neutrino portal and vector portal as case studies

Some <u>groups</u> of physics models for SHiP

D=GeV$^{5/2}$: Neutrino Portal

- Standard Model "portal" through neutrino Yukawa coupling with right-handed neutrinos



- Introduce three right-handed Majorana leptons N_I with Majorana mass $m_I^R \equiv$ "Heavy Neutral Leptons (HNL)"
    - Make the leptonic sector similar to the quark sector
    - No electric, strong or weak charges ➔ "sterile"

Minkowski 1977
Yanagida 1979
Gell-Mann, Ramond, Slansky 1979
Glashow 1979

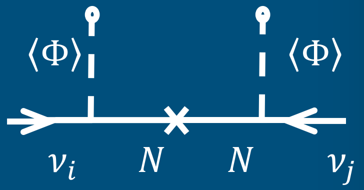
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\substack{I=1,2,3; \\ \ell=1,2,3(e,\mu,\tau)}} i\overline{N}_I\partial_\mu\gamma^\mu N_I - Y_{I\ell}H^\dagger\overline{N}_I L_\ell - m_I^R\overline{N}_I^c N_I + h.c$$

where L_ℓ are the lepton doublets, Φ is the Higgs doublet, and $Y_{I\ell}$ are the corresponding new Yukawa couplings

- Discovery of Higgs vital for the see-saw type I model! ➔ Responsible for Yukawa couplings!

Type I See-saw

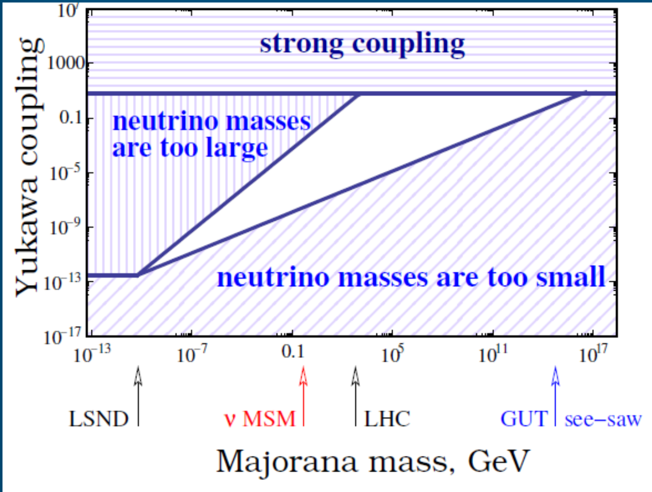
- $Y_{I\ell} H^\dagger \overline{N}_I L_\ell$ lepton flavour violating term results in mixing between N_I and SM active neutrinos when the Higgs SSB develops the $< VEV > = v \sim 246\ GeV$
    - ➔ Oscillations in the mass-basis and CP violation



- Type I See-saw with $m^R >> m_D (= Y_{I\ell} v)$ ➔ superposition of chiral states give
    - ➔ Active neutrino ($\nu = U_\nu(\nu_L + \theta\nu_R^c)$) mass in mass basis $\tilde{m}_1 \sim \frac{m_D^2}{m^R} \sim m_\nu$
    - ➔ Heavy singlet fermion mass in mass basis $\tilde{m}_2 \sim m^R \left(1 + \frac{m_D^2}{m^{R2}}\right) \sim m^R \sim M_N$

- Four "popular" N mass ranges:

arXiv:1204.5379



	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

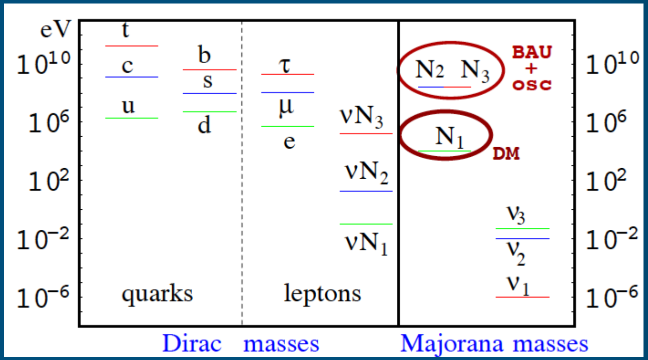
E.g. HNLs in νMSM (Asaka, Shaposhnikov)

Role of N_1 with a mass of $\mathcal{O}$(keV)
➔ Dark Matter

Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and BAU

➔ Assumption that N_I are $\mathcal{O}(m_q/m_l)$: No new energy scale!

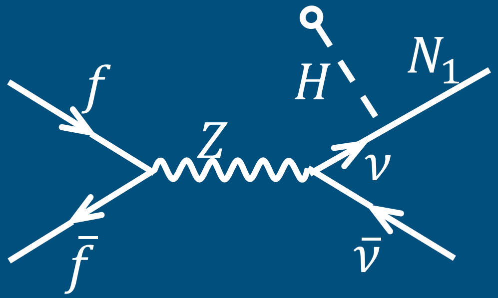
- $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm} m_I^R}}{v}\right) \sim 10^{-8} \quad (m^R = 1\ GeV, m_\nu = 0.05\ eV)$
- $\mathcal{U}^2 \sim 10^{-11}$ ➔ Intensity Frontier!



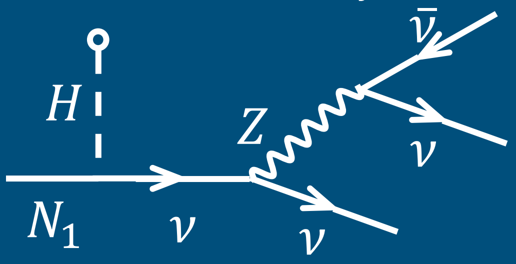
νMSM N_1 = Dark Matter

- Assume lightest singlet fermion N_1 has a very weak mixing with the other leptons
  - Mass $M_1 \backsim \mathcal{O}(keV)$ and very small coupling
    - ➔ Sufficiently stable to act as Dark Matter candidate
    - ➔ Give the right abundance
    - ➔ Decouples from the primordial plasma very early
  - Produced relativistically out of equilibrium in the radiation dominant epoque ➔ erase density fluctuations below free-streaming horizon ➔ sterile neutrinos are redshifted to be non-relativistic before end of radiation dominance (Warm Dark Matter → CDM)
    - ➔ Decaying Dark Matter

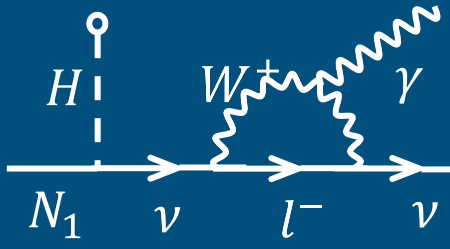
Production from υ ↔ N oscillations



Dominant decay



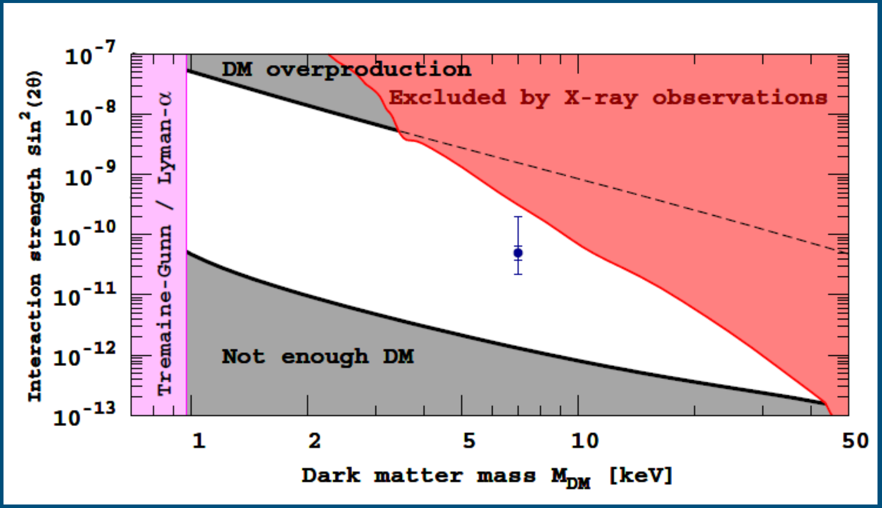
Subdominant radiative decay

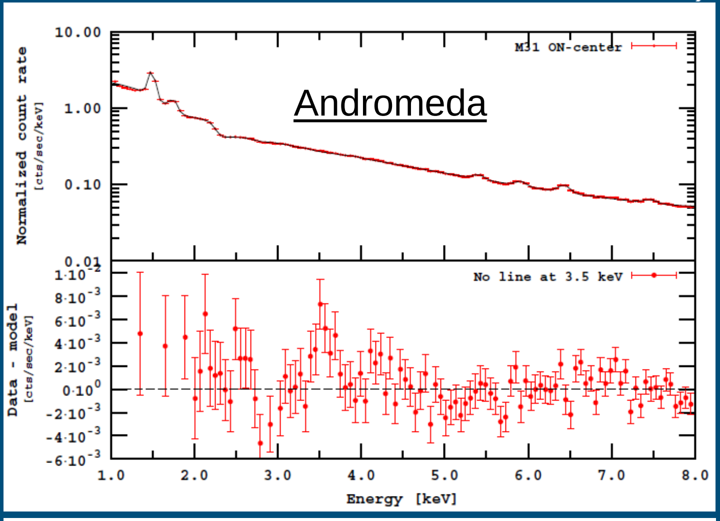


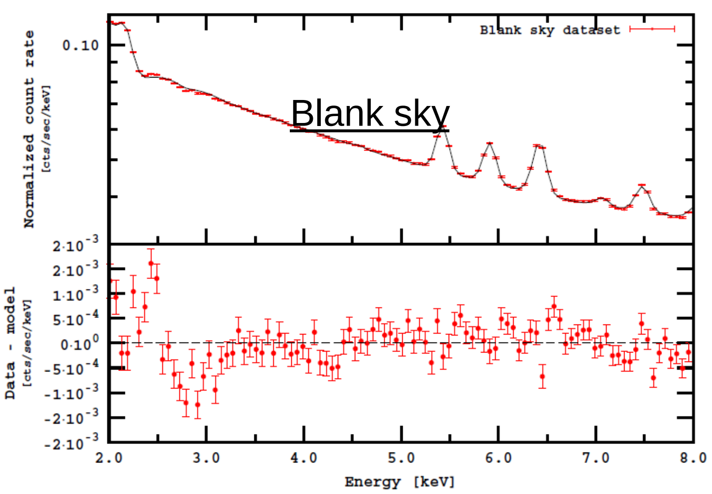
$$E_\gamma = \frac{M_{N_1} c^2}{2}$$

(Intriguing hints from galaxy spectrum?)

- Two recent publications:
  - ➔ arXiv:1402.2301 : Detection of an unidentified emission line in the stacked XMM-Newton X-ray spectra of Galaxy Clusters at $E_\gamma \sim (3.55 - 3.57) \pm 0.03 keV$
  - ➔ arXiv:1402.4119 : An unidentified line in the X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster at $E_\gamma \sim 3.5\ keV$





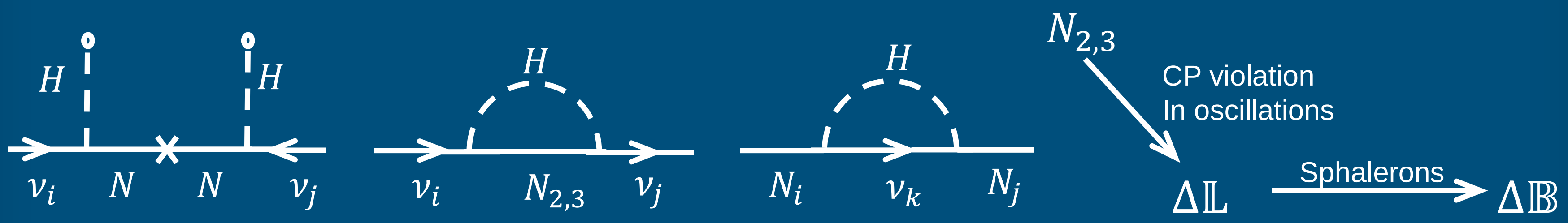


- XMM-Newton's has granted 1.4 Mega-seconds (10% of time budget) to further verification!
- Confirmation by Astro-H with better energy resolution in the future

N_2 and N_3 in νMSM

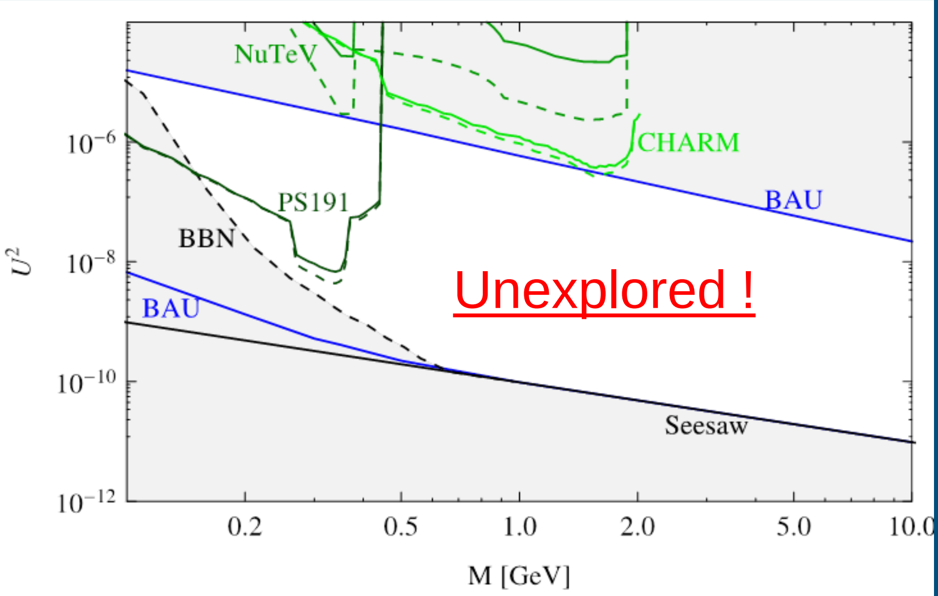
- N_1 as DM ($M_{N_1} \ll M_{N_2} \approx M_{N_3}$) gives no contribution to active neutrino masses
  - ➔ Neglect for the rest
  - ➔ Reduces number of effective parameters for Lagrangian with $N_{2,3}$
    - 18 parameters ➔ 11 new parameters with 3 CP violating phases
      - ➔ Two mixing angles related to active neutrinos and mass difference measured in low-energy neutrino experiment

- Generation of BAU with degenerate N_2 and N_3 (Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov)
  1. Leptogenesis from coherent resonant oscillations with interference between CP violating amplitudes
     - ➔ Two fermion singlets should be quasi-degenerate
  2. Out of equilibrium ($\Gamma_{N_{2,3}}$ < Hubble rate of expansion) at the E.W. scale above sphaleron freeze-out
  3. Lepton number of active left-handed neutrinos transferred to baryon number by sphaleron processes
     - $\mathbb{L}_\ell - \frac{\mathbb{B}}{3}$ remain conserved while $\mathbb{L}_\ell$ and $\mathbb{B}$ are violated individually



N_2 and N_3 Constraints in νMSM

1. See-saw: Sufficient mixing to produce oscillations and masses
2. BAU: Guarantee out-of-equilibrium oscillations ($\Gamma_{N_{2,3}}$ < H)
3. BBN: Decays of N_2 and N_3 must respect current abundances of light nuclei
   - ➔ Limit on lifetime $\tau_{N_{2,3}} < 0.1s \ \ (T > 3\ MeV)$
4. Experimental: No observation so far…
   - ➔ Constraints 1-3 now indicate that previous searches were largely outside interesting parameter space



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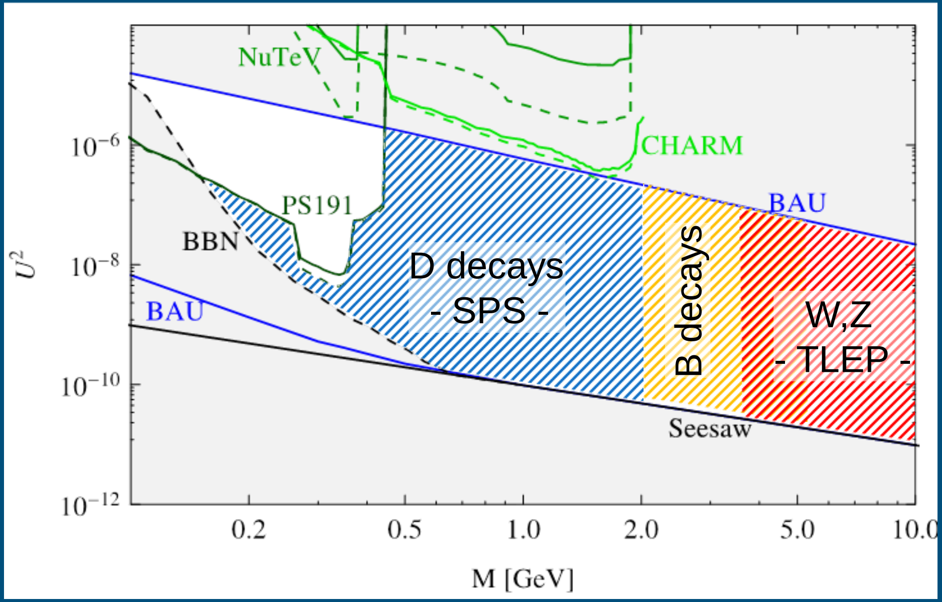
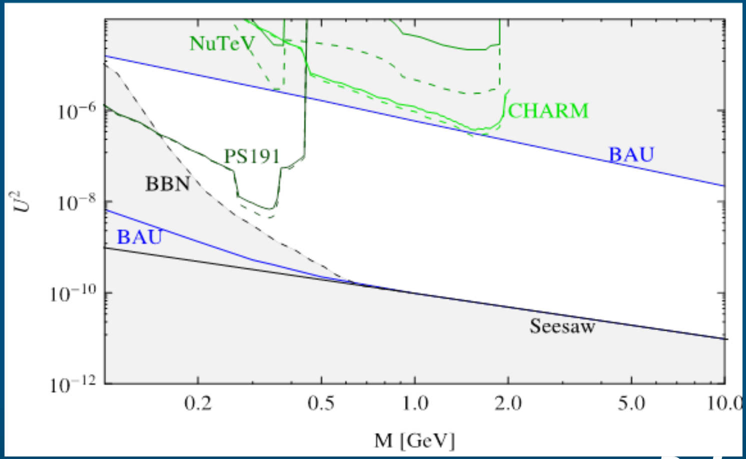


Constraints in variants with HNLs

HNLs is not “just one model”:

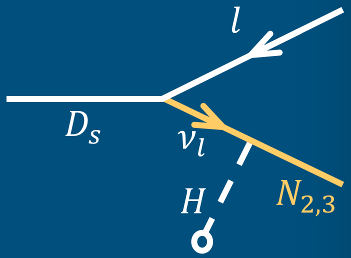
1. νMSM: HNLs are required to explain neutrino masses, BAU, and DM
    - $\mathcal{U}^2$ is the most constrained
2. HNLs are required to explain neutrino masses and BAU
    - N_1 , N_2 and N_3 are available to produce neutrino oscillations/masses and BAU
3. HNLs are required to explain neutrino masses
    - Only experimental constraints remain
4. HNLs are required to explain Dark Matter
5. HNLs are helpful in cosmology and astrophysics
    - E.g. HNL may influence primordial abundance of light elements
    - E.g. HNL with masses below 250 MeV can facilitate the explosions of the supernovae
6. HNLs are not required to explain anything - just so
    - Contributions of the HNL to the rare lepton number violating processes μ → e, μ → eee



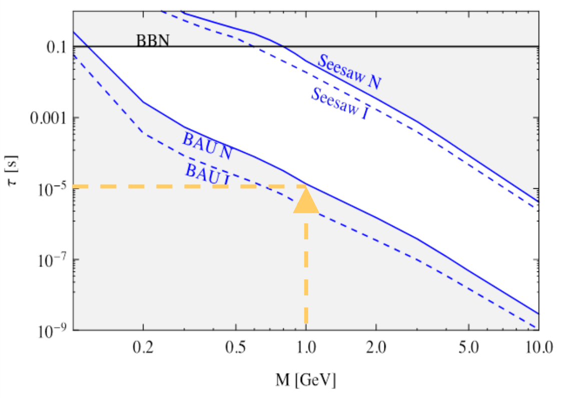
$N_{2,3}$ Production and decay

- Predominant production in mixing with active neutrino from leptonic/semi-leptonic weak decays of heavy mesons
  - $D_s \to lN,\ (\tau \to X\nu_\tau)$ $U^2_{e,\mu,\tau}$ and $N_N \leq M(D_s) - m_l,\ (N_N \leq M(\tau) - M(X))$
  - $D \to lKN$ $U^2_{e,\mu}$ and $N_N \leq M(D_s) - m_l$
  - $B_{(s)} \to D_{(s)} lN$ $U^2_{e,\mu,\tau}$ and $N_N \leq M\left(B_{(s)}\right) - M(D_{(s)}) - m_l$
  - $B \to lN\ \ (B \to l\pi N)$ $U^2_{e,\mu,\tau}$ and $N_N \leq M(B) - m_l$ $,Br \propto V^2_{ub}/V^2_{cb}$

E.g.

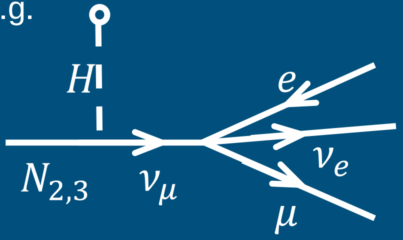


- Very weak HNL-active neutrino mixing → $N_{2,3}$ much longer lived than SM particles
  - → Typical lifetimes > 10 μs for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$



- Decay modes
  - $N \to h^0\nu,\ with\ h^0 = \pi^0, \rho^0, \eta\ \ , \eta'$
  - $N \to h^\pm l^\mp,\ with\ h^\pm = \pi^\pm, \rho^\pm$
  - $N \to 3\nu$
  - $N \to l^\pm l^\mp \nu$

E.g.

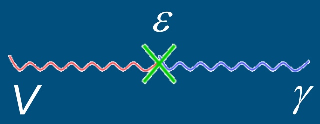


Decay mode	Branching ratio
$N_{2,3} \to \mu/e + \pi$	*0.1 - 50 %*
$N_{2,3} \to \mu^-/e^- + \rho^+$	*0.5 - 20 %*
$N_{2,3} \to \nu + \mu + e$	*1 - 10 %*

- For both, total rate depend on $\mathcal{U}^2 = \sum_{\substack{I=2,3 \\ \ell=e,\mu,\tau}} |\mathcal{U}_{\ell I}|^2$
  - → Relation between $\mathcal{U}_e{}^2, \mathcal{U}_\mu{}^2$ and $\mathcal{U}_\tau{}^2$ depends on exact flavour mixing

D = GeV²: Vector portal

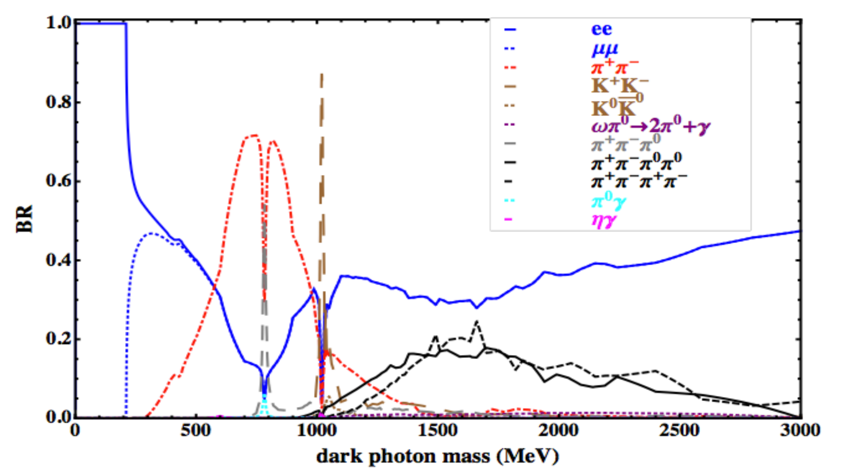
- Massive dark (hidden, secluded, para-) photon
  - Motivated in part by idea of "mirror world" restoring symmetry between left and right and constituting dark matter, g-2 anomaly
  - SM portal through kinetic mixing with massive dark/secluded/paraphoton V

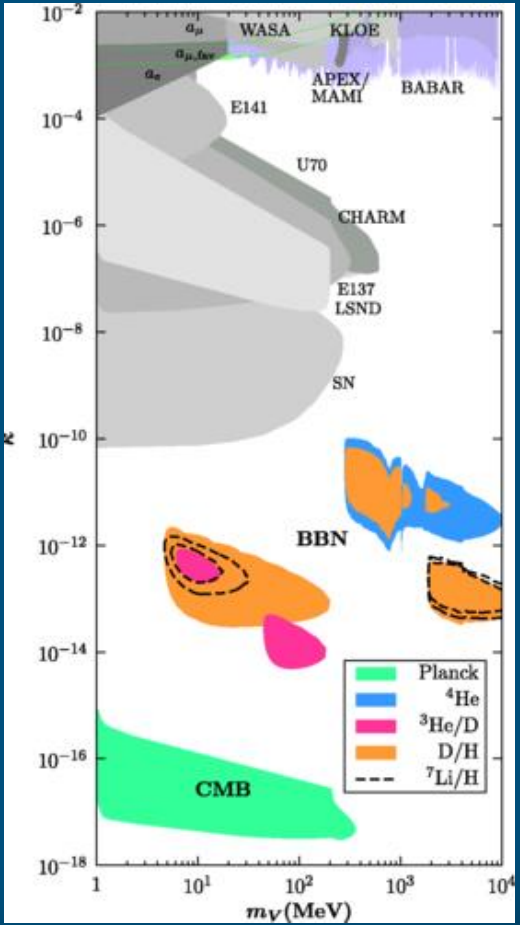


$$\mathcal{L} = \frac{1}{2}\varepsilon F^{SM}_{\mu\nu} V^{\mu\nu}_{HS}$$, also mixing with Z

- Predominant dark photon production at SPS
  - Proton bremsstrahlung
  - Pseudo-scalar meson decays $(\pi^0, \eta,\ \omega,\ \eta', \ldots)$
  - Lifetime limit from BBN: $\tau_\gamma < 0.1s$
- Dark photon decays
  - $e^+e^-, \mu^+\mu^-, q\bar{q}\ (\pi^+\pi^-, \ldots), \ldots$

Decay branching ratios





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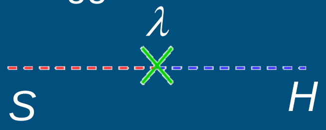
D=GeV^2: Scalar portal

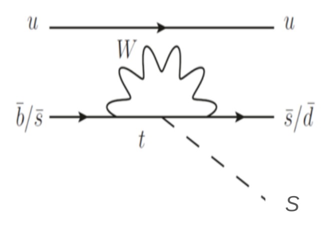
- Real singlet dark scalar S
  - ➔ Motivated by possibility of inflaton in accordance with Planck and BICEP measurements, giving mass to Higgs boson and right-handed neutrinos
  - ➔ SM portal through mass mixing with the SM Higgs:

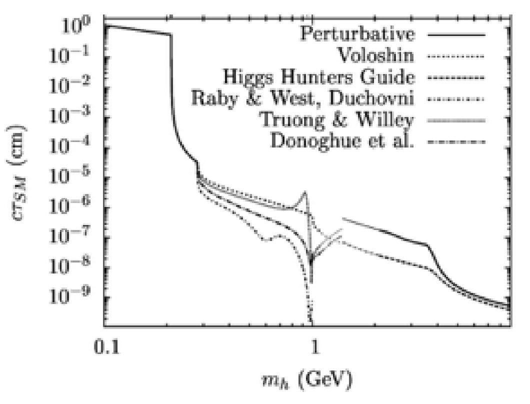
$$\mathcal{L} = (gS + \lambda S^2)H^\dagger H$$

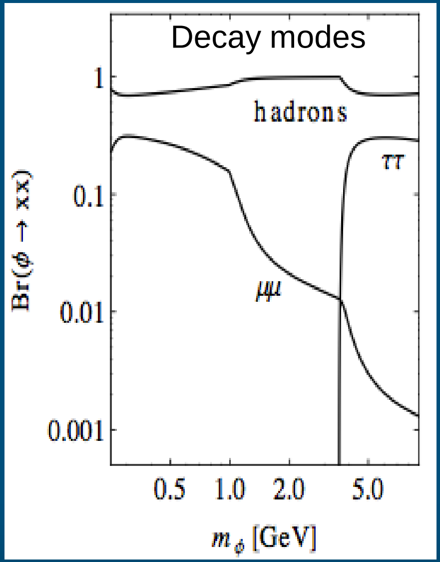


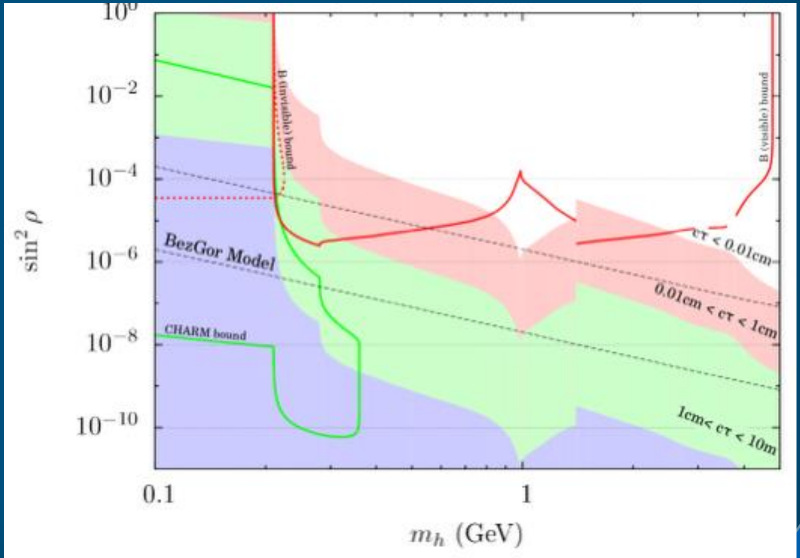
$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$$

- Production
  - Direct $p + target \rightarrow X + S$
  - Decay of heavy meson e.g. $B \rightarrow K$S
  - ➔ Lifetime $\tau \propto \sin^{-2}\rho$







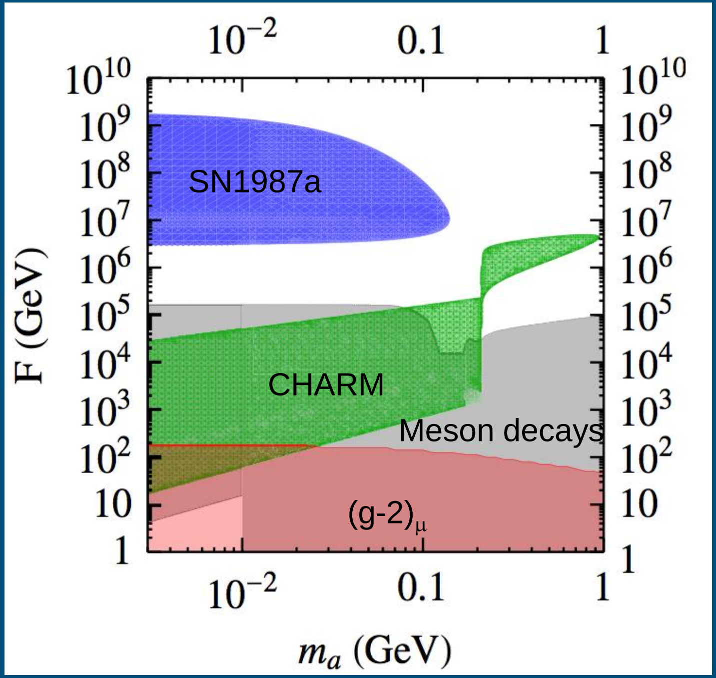


D≥GeV^4: Axion portal

- Axion Like Particles, pseudo-scalars pNGB, axial vectors a
  - Motivated by possibility of inflaton, SUSY,
  - SM portal through mixing

$$\mathcal{L} = \frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}, \frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi \text{ , etc}$$

  - Interaction to fermions $\mathcal{L} = \frac{m_a}{F} a\bar{\psi}\psi$
  - Generically light pseudo-scalars arise in spontaneous braking of approximate symmetries at a high mass scale F
  - Production from meson decays, mixing with neutral pion (beam dump)
  - Decays to $e^+e^-, \mu^+\mu^-$, hadrons above 1 GeV



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SUSY with light long-lived partners

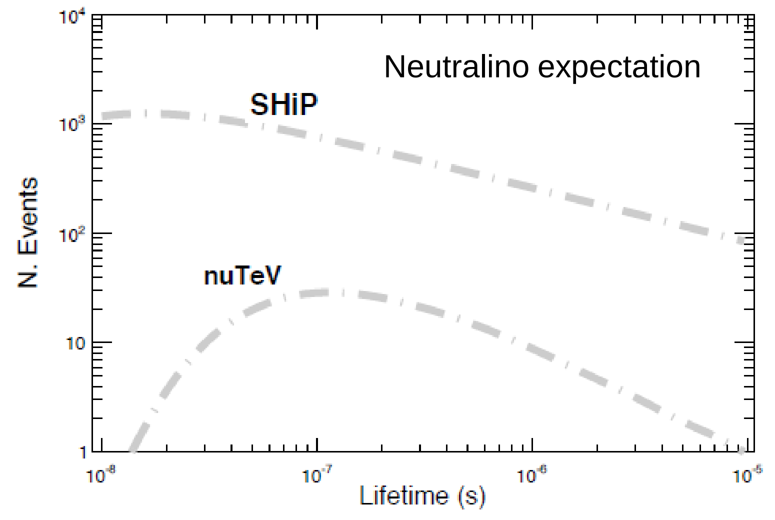
- The absence of SUSY below TeV and the relatively large Higgs mass leads to increasing electro-weak fine-tuning of the SUSY parameters
  - How to make SUSY natural?

  ➔ Lowering breaking scale $\sqrt{F}$ in hidden sector to few TeV leads to different gravitino/goldstino and DM sectors ➔ light, possibly long-lived particles

  ➔ Less fine-tuning due to additional quartic Higgs couplings

- Sgoldstino
  - Massless at tree level but massive via loop corrections
  - Naturally light in no-scale SUGRA and GMSB
  - Production: heavy hadron decays $D \to \pi X, \ \ D_s \to K^+ X$
  - Decay: $X \to \pi^+\pi^-, \pi^0\pi^0, l^+l^-, \gamma\gamma$

- R-Parity Violating SUSY: Neutralino
  - LSP can decay into SM particles
  - Light neutralino with long lifetime $\tau_{\tilde{\chi}} < 0.1s$ (BBN)
  - Production: heavy meson decays $D \to \nu\tilde{\chi}, \ \ D^\pm \to l^\pm\tilde{\chi}$
  - Decay: $\tilde{\chi} \to \ l^+l^-\nu$



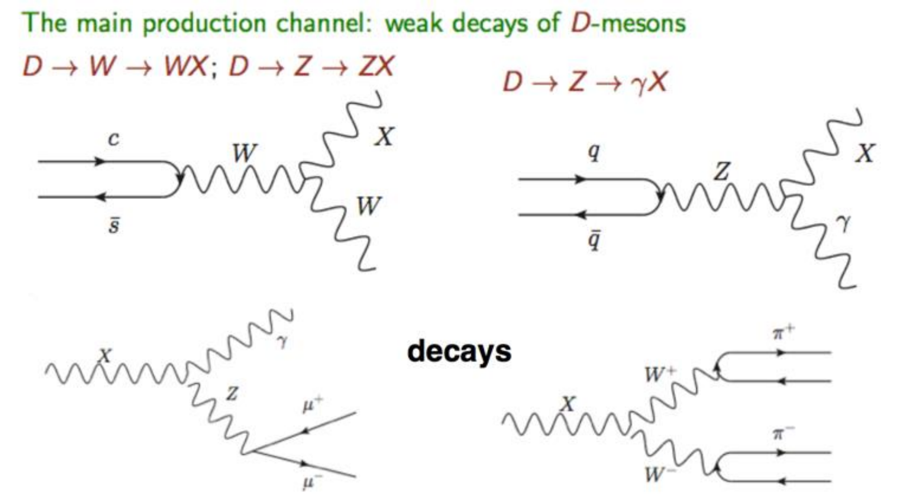
- Natural SUSY with light higgsinos leading to natural mass degeneracy between chargino and LSP neutralino

  ➔ Long-lived light chargino

- Hidden Photinos; Axinos and saxions; Light flavoured SUSY

And more....

- Chern-Simons Portal:

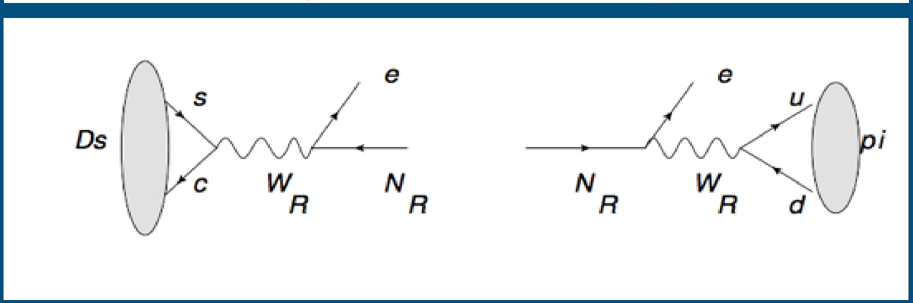


The main production channel: weak decays of D-mesons

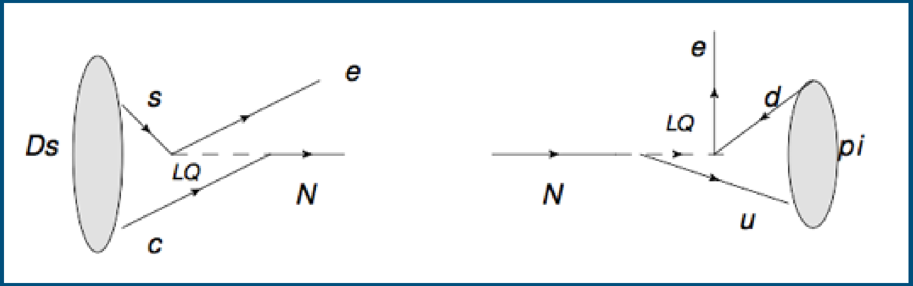
$D \to W \to WX$; $D \to Z \to ZX$

$D \to Z \to \gamma X$

- Left-right symmetric models:



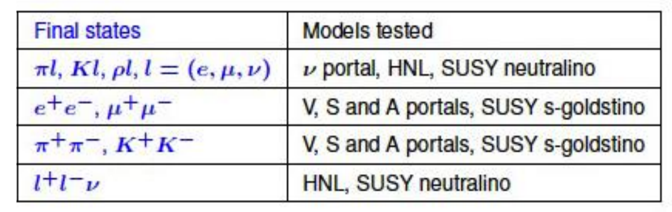
- Lepto-quarks



- Setting limits is “easy” but theorist home work:
  - In case of discover, how do we call the new particle(s)!?

HS Common experimental features

- Cosmologically interesting and experimentally accessible $m_{HS} \sim \mathcal{O}(MeV - GeV)$
  - ➔ Production through meson decays (π, K, D, B), proton bremsstrahlung,…
  - ➔ Decays



Final states	Models tested
$\pi l, Kl, \rho l, l = (e, \mu, \nu)$	ν portal, HNL, SUSY neutralino
$e^+e^-, \mu^+\mu^-$	V, S and A portals, SUSY s-goldstino
$\pi^+\pi^-, K^+K^-$	V, S and A portals, SUSY s-goldstino
$l^+l^-\nu$	HNL, SUSY neutralino

  - ➔ Full reconstruction and particle ID aim at maximizing the model independence

- Production and decay rates are very suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects
  - Travel unperturbed through *ordinary* matter
  - ➔ Challenge is background suppression➔ requires $\mathcal{O}$(0.01) carefully estimated

➔ Fixed-target (“beam-dump”) experiment

- ➔ Large number of protons on target and large decay volume not too far away!
- ➔ Side benefit: Optimizing for heavy meson decays also optimizes facility for $\nu_\tau(\nu_e, \nu_\mu)$ physics
  - $Br(D_s \to \tau \; + \nu_\tau) \sim$ 5.6% : 10^{15}

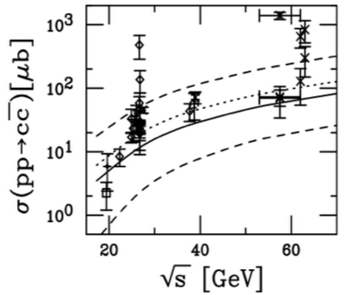
➔ Complementary physics program to searches for new physics by LHC!

The SHiP experiment

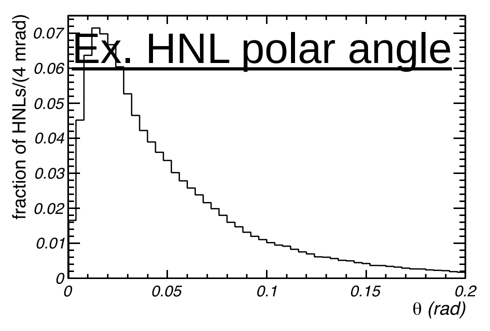
Experimental Requirements/Challenges

Proposal: *fixed-target (beam dump like) experiment at the SPS*

1. E.g. sensitivity to HNL ∝ $\mathcal{U}^4$ → Number of protons on target (p.o.t.)
   - ➔ SPS: 4x10^{13} / 7s @ 400 GeV = 500 kW → 2x10^{20} in 5 years (similar to CNGS)
2. Preference for slow beam extraction of $1s$ to reduce detector occupancy
   - ➔ Reduce combinatorial background



3. As uniform extraction as possible for target and combinatorial background/occupancy
4. Heavy material target to stop π, K before decay to reduce flux of active neutrinos
   - ➔ Blow up beam to dilute beam energy on target
5. Long muon shield to range out flux of muons
6. Away from tunnel walls to reduce neutrino/muon interactions in proximity of detector
7. Vacuum in detector volume to reduce neutrino interactions
8. Detector acceptance compromise between lifetime and production angles
   - …and length of shield to filter out muon flux

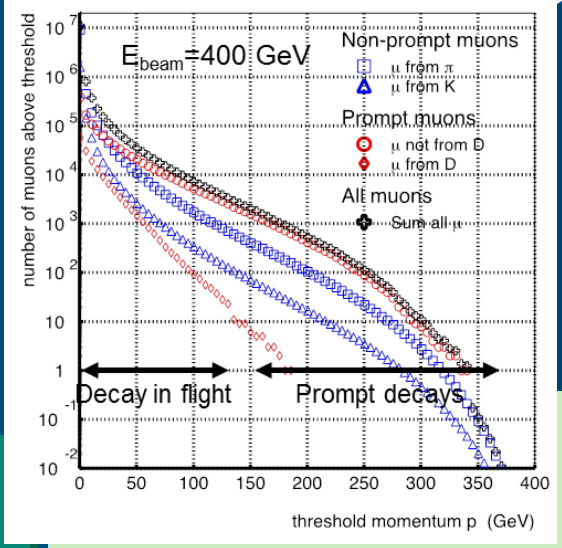


➔ Defines the list of critical parameters and layout for the sensitivity of the experiment

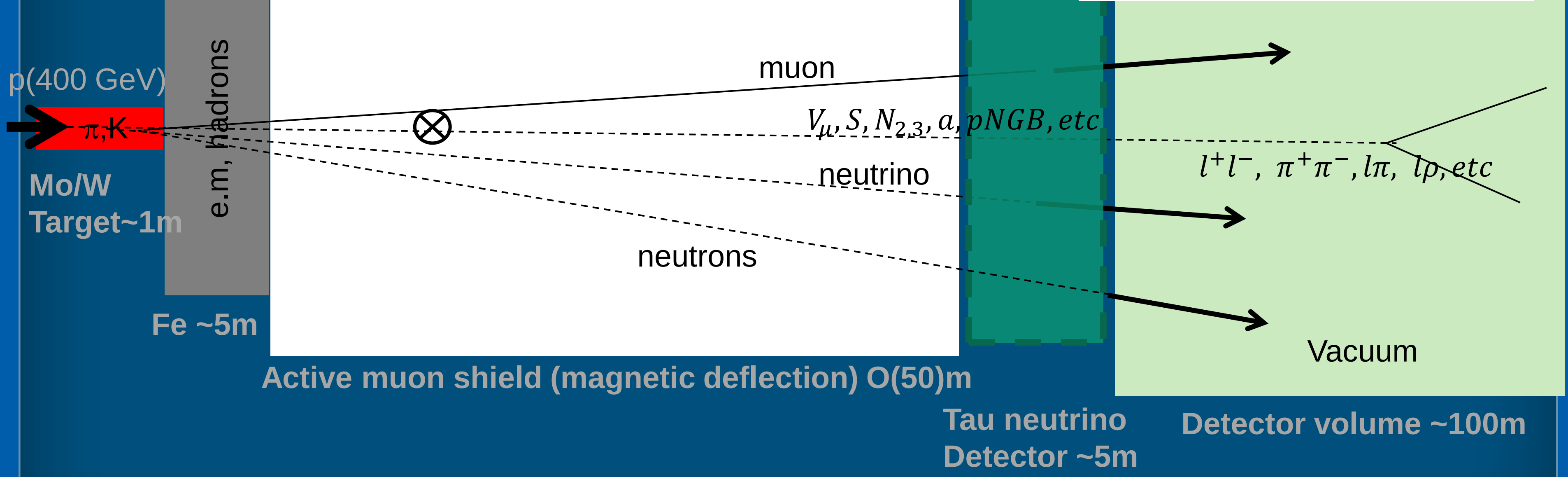
- ➔ Incompatible with conventional neutrino facility
- ➔ But a very powerful general-purpose facility for now and later!

Schematic Principle of Experimental Setup

- Initial reduction of beam induced background:
  - Heavy target
  - Hadron absorber
  - Muon shield (Without: Rate at detector 5x10^9 muons / 5x10^{13} p.o.t.)



Not to scale!

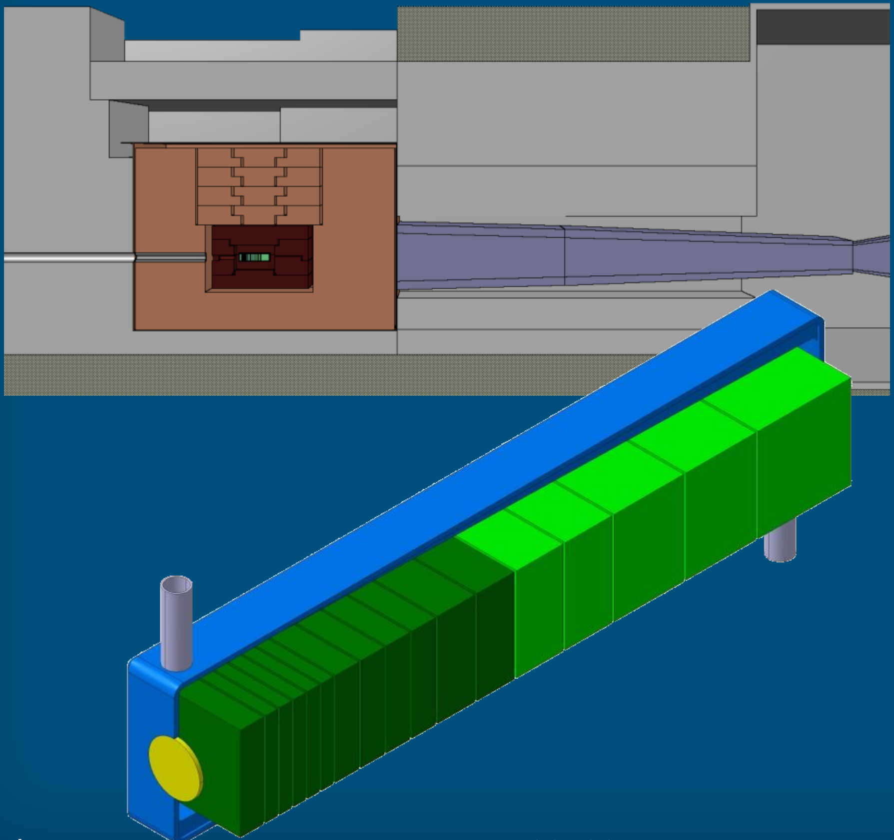


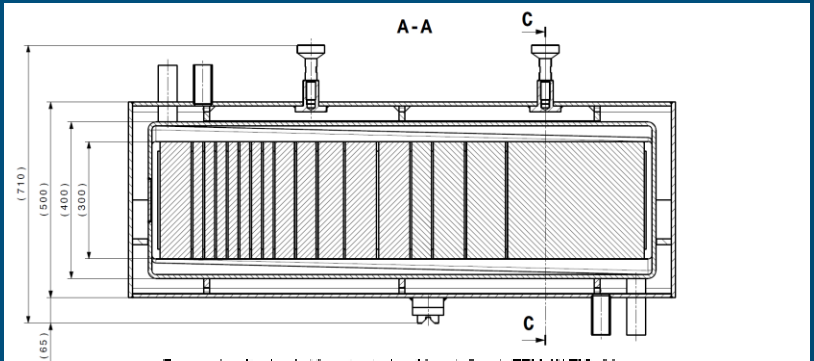
➔ Multi-dimensional optimization: Beam energy is compromise between σ_{charm}, beam intensity, background conditions, acceptance, detector resolution

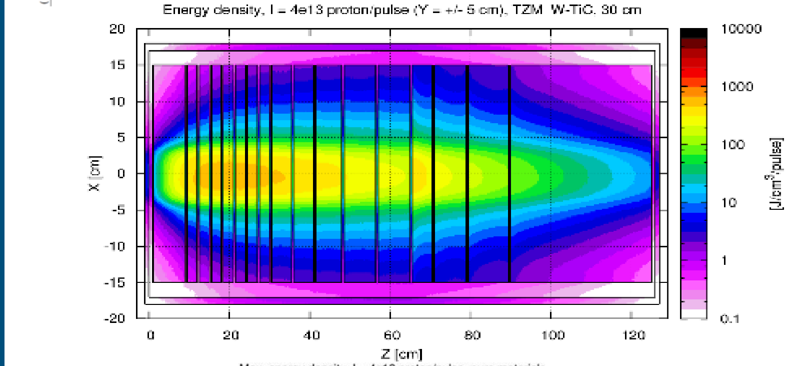
SHiP target

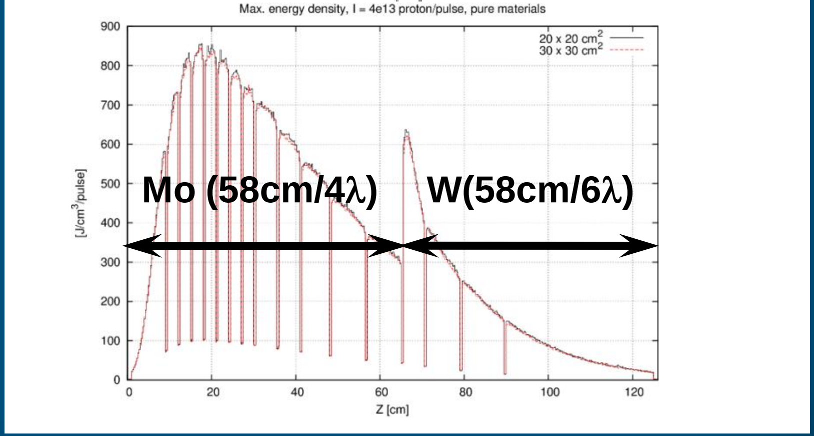
Design considerations with 4×10^{13} p / 7s → 400 kW

- High temperature
- Compressive stresses
- Atomic displacement
- Erosion/corrosion
- Material properties as a function of irradiation
- Remote handling (Initial dose rate of 50 Sv/h…)



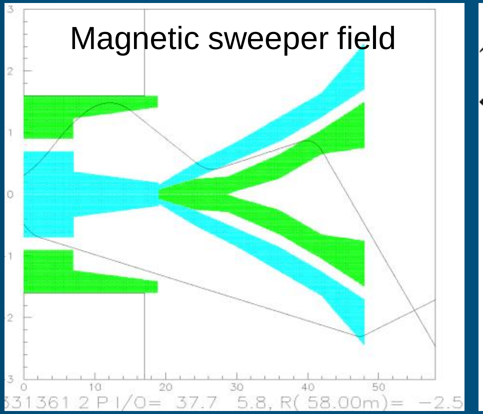


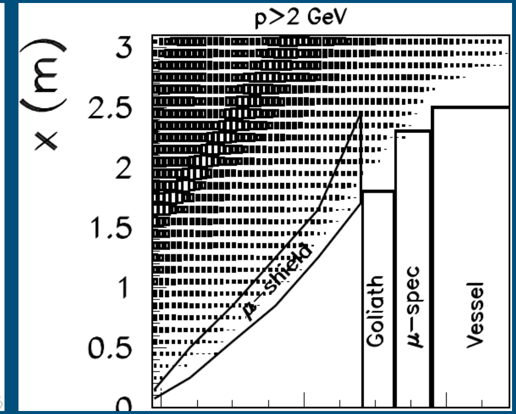


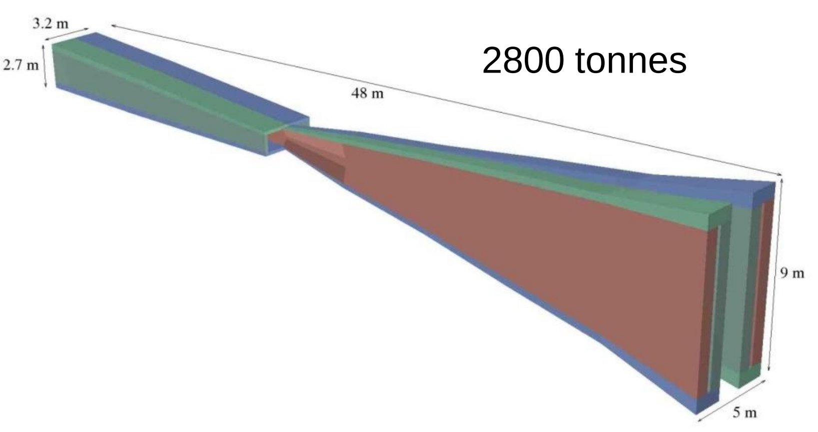


Active muon shield

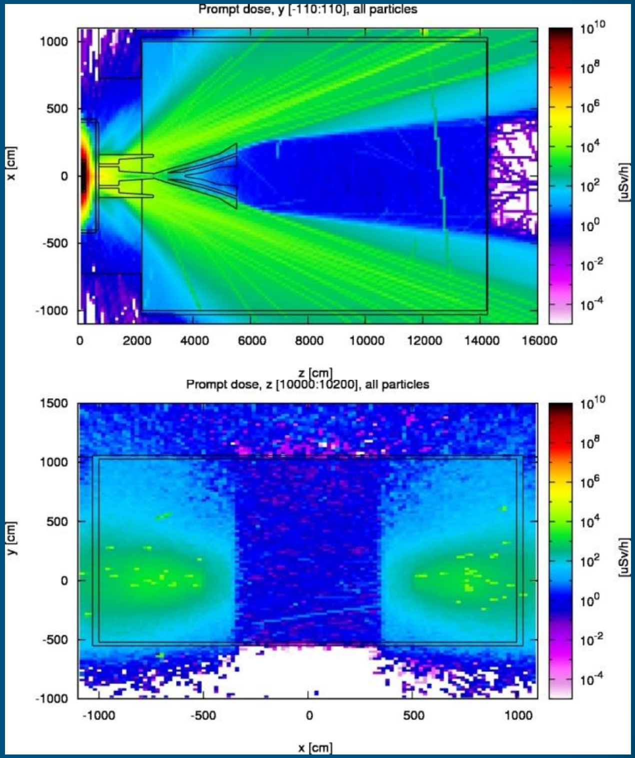
- Muon flux limit driven by emulsion based ν-detector and “hidden particle” background
- Studies of purely passive and combination of magnet sweeper/passive absorber:
  - Conclusion: Muon shield based entirely on magnetic sweeping
  - ➔ <100k muons / spill (E_{muon} > 3 GeV) which can potentially produce V0 (K_L)
  - ➔ Negligible occupancy
  - ➔ Realistic design of sweeper magnets in progress
  - Challenges: Flux leakage, constant field profile, Modelling magnet shape





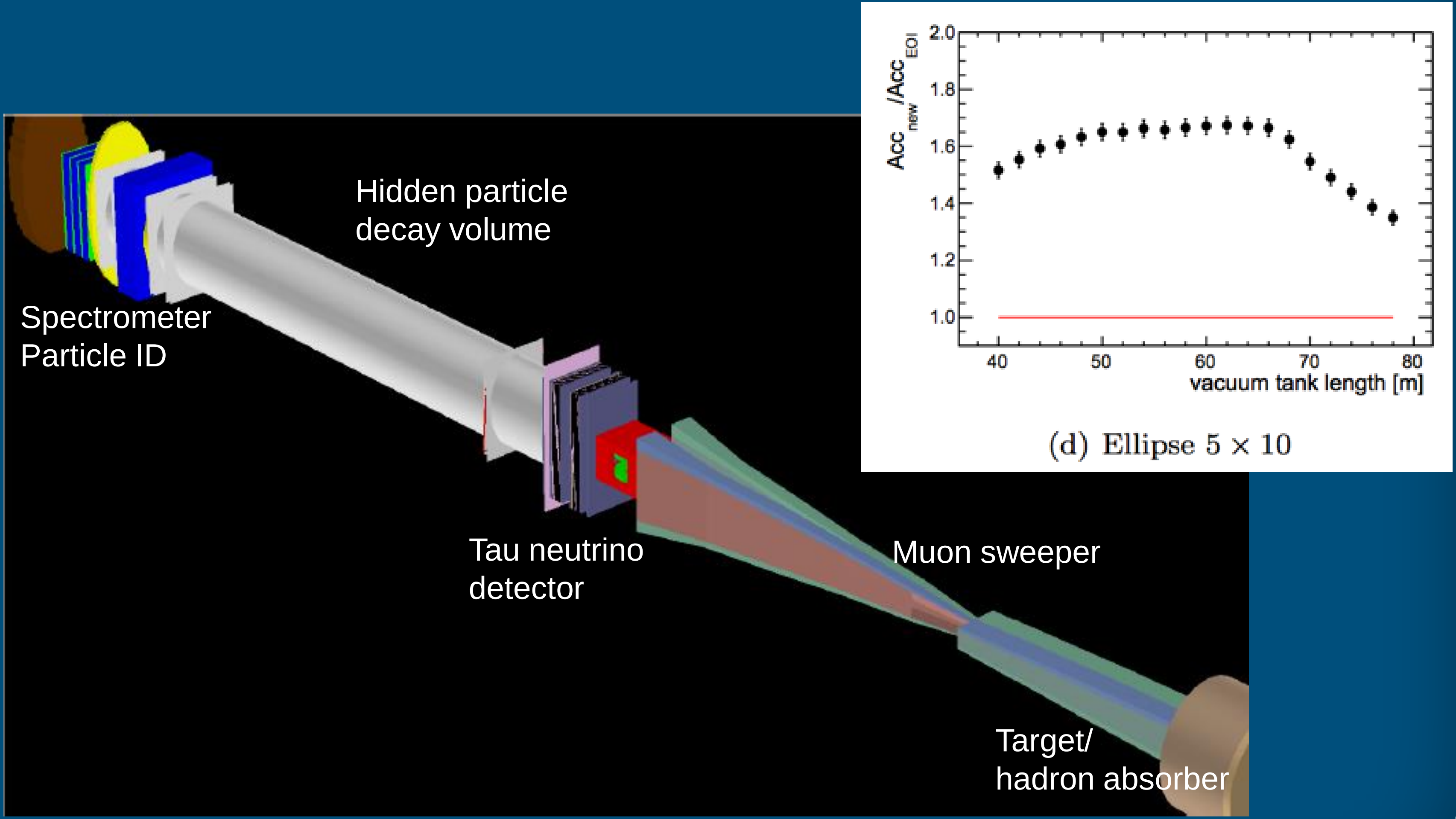


Prompt dose rates in the experimental hall 4x13 p.o.t. / 7s



Detector Geometry

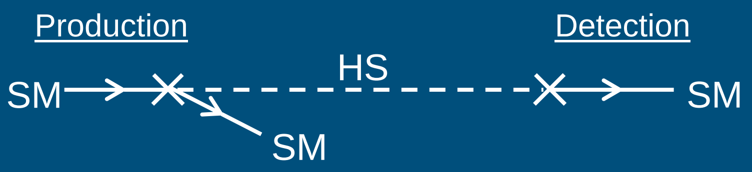
- From optimization of active muon shield and acceptance:
  - ➔ Single detector element W:5m x H:10m
  - Geometric acceptance saturates for a given lifetime as a function of the detector length



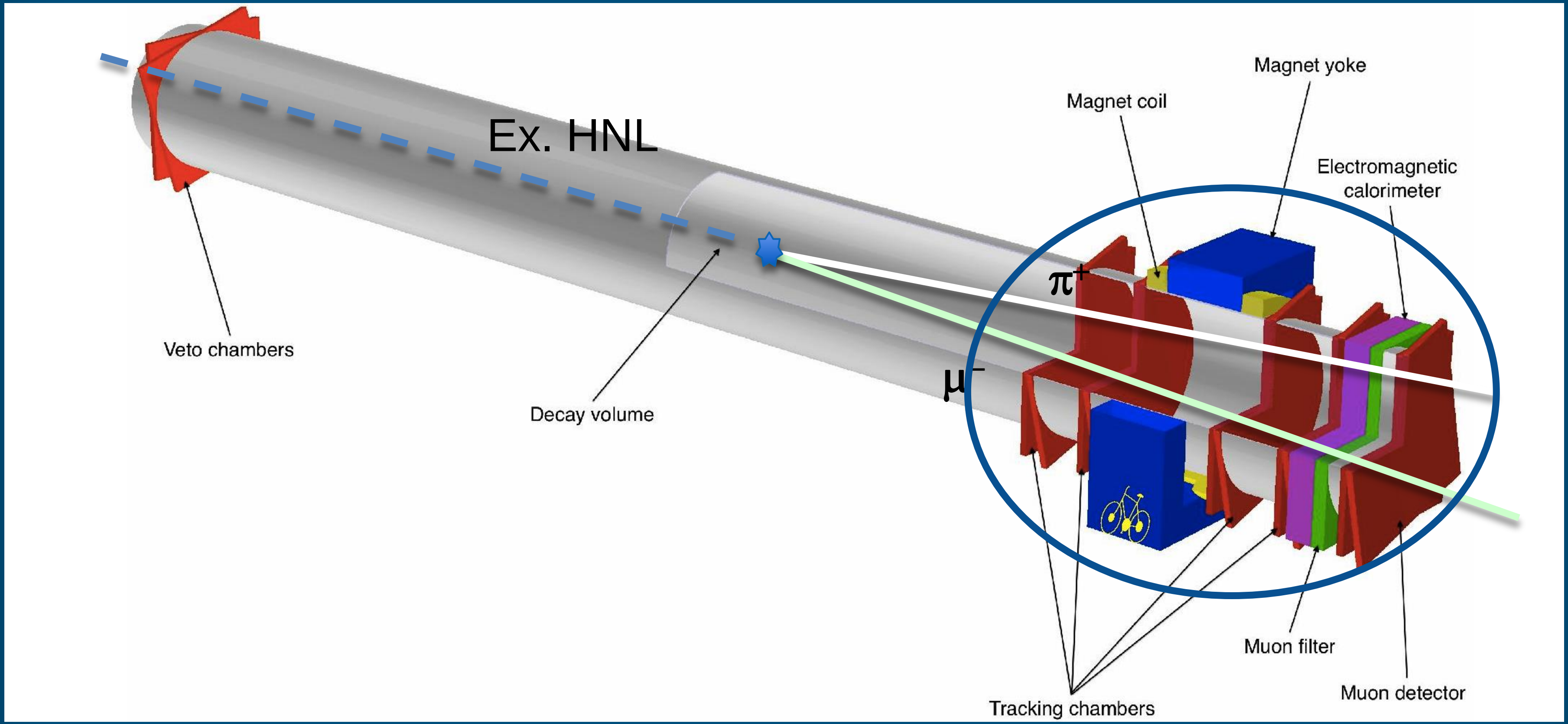
(d) Ellipse 5 × 10

Reminder: Detector Concept

- Direct detection of Hidden Sector Portals:



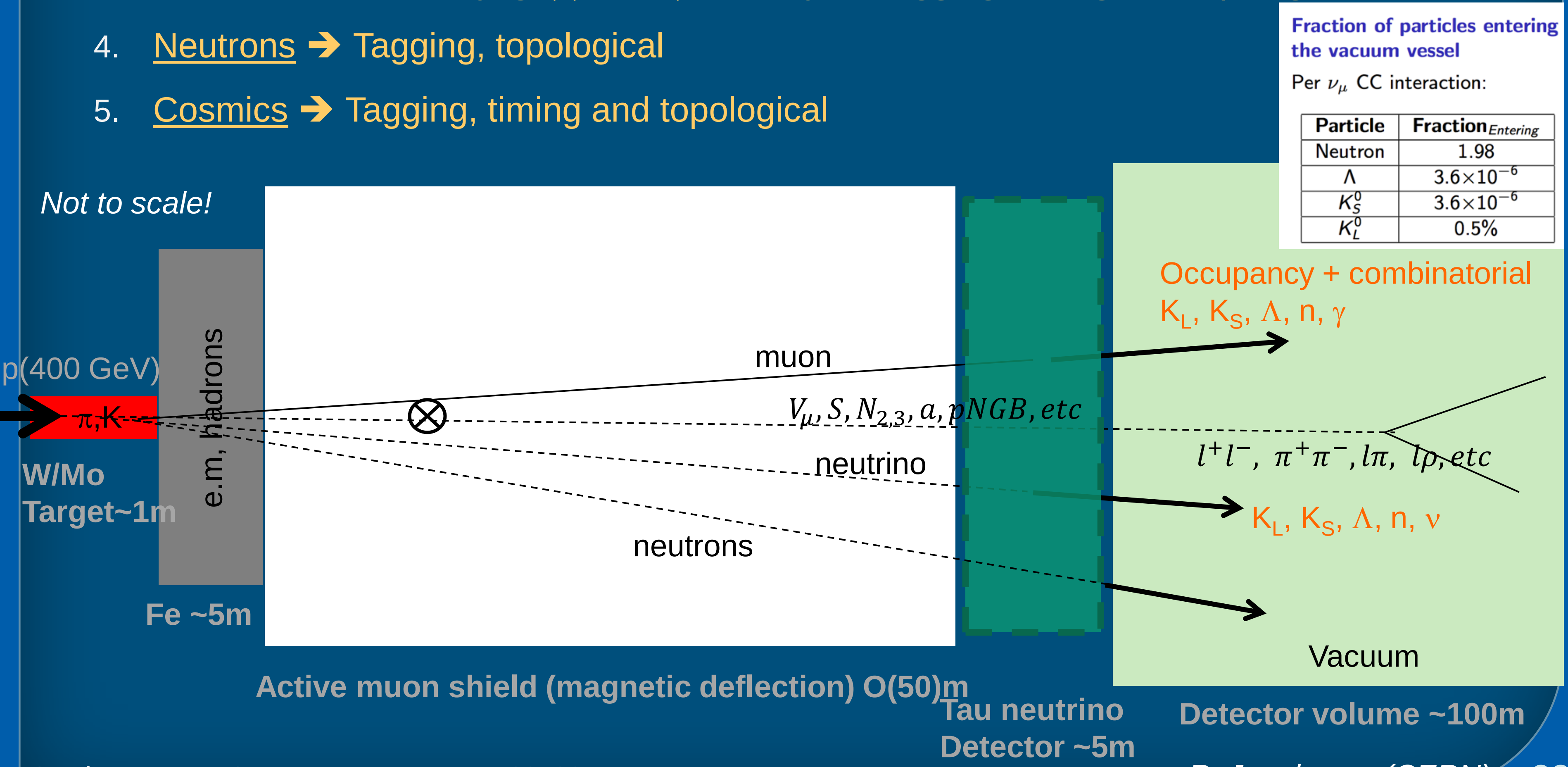
- ➔ Full reconstruction and particle identification of final states with e, $\mu, \pi^{\pm}, \gamma$ ($\pi^0, \rho^{\pm}$), (ν), and decays in flight
- ➔ Large decay volume, magnetic spectrometer, electromagnetic calorimeter, hadron calorimeter/muon detector



- ➔ Virtually background free experiment required!

Background sources

- Residual backgrounds sources:
  1. Neutrino inelastic scattering (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$) ➔ Detector under vacuum, accompanying charged particles (tagging, timing), topological
  2. Muon inelastic scattering ➔ Accompanying charged particles (tagging, timing), topological
  3. Muon combinatorial (e.g. μμ with μ mis-ID) ➔ Tagging, timing and topological
  4. Neutrons ➔ Tagging, topological
  5. Cosmics ➔ Tagging, timing and topological



Fraction of particles entering the vacuum vessel

Per ν_μ CC interaction:

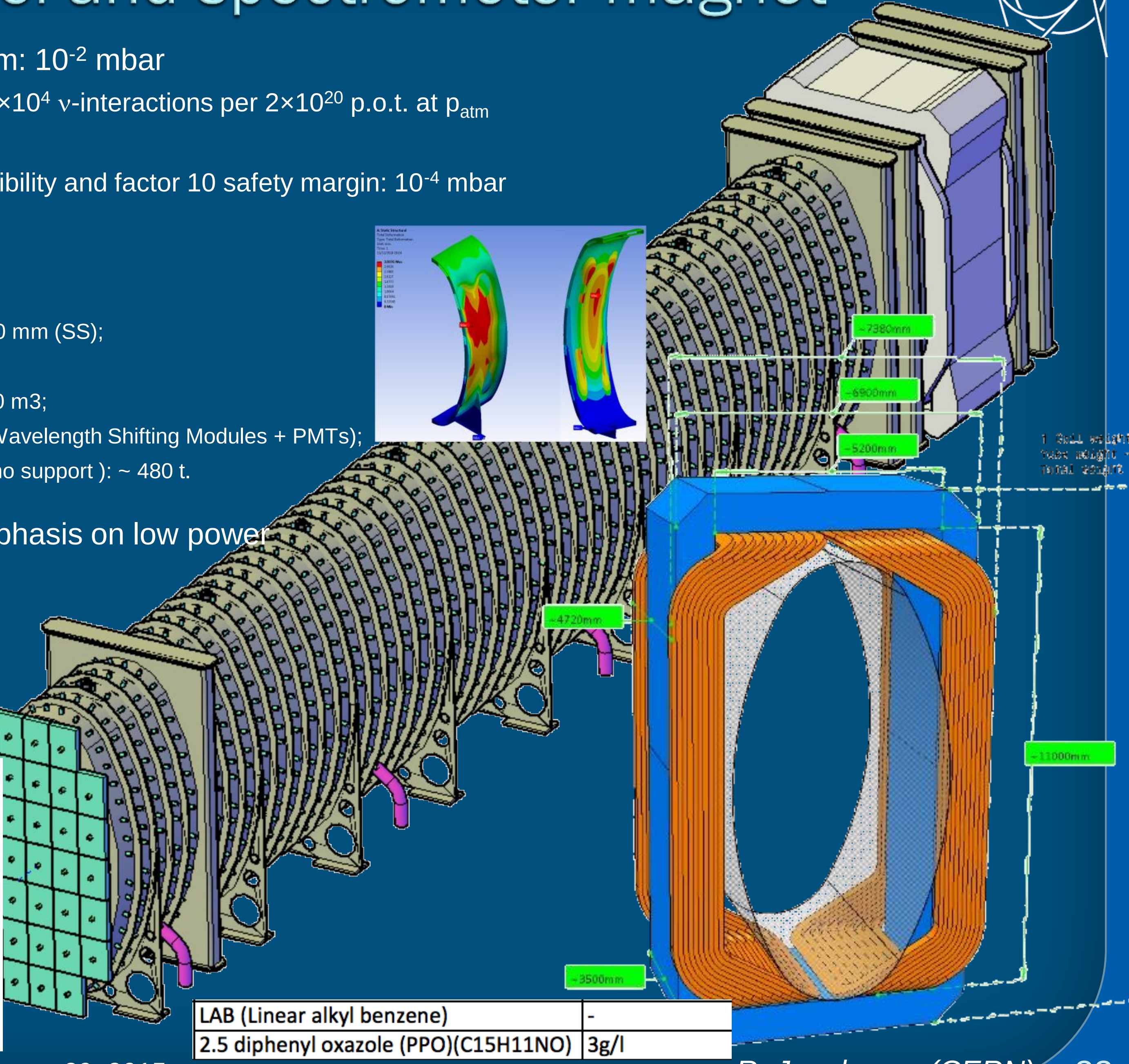
Particle	Fraction$_{Entering}$
Neutron	1.98
Λ	3.6×10^{-6}
K^0_S	3.6×10^{-6}
K^0_L	0.5%

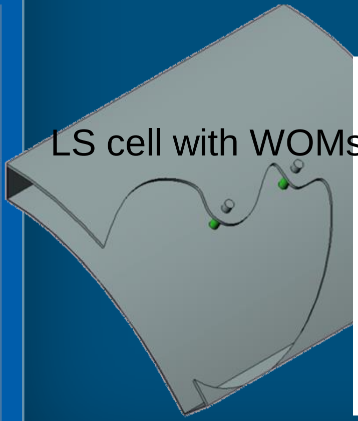
Vessel and spectrometer magnet

- Estimated need for vacuum: 10^{-2} mbar
  - Based on neutrino flux: 2×10^4 ν-interactions per 2×10^{20} p.o.t. at p_{atm}
  - ➔ Negligible at 0.01 mbar
  - Design with factor 10 flexibility and factor 10 safety margin: 10^{-4} mbar

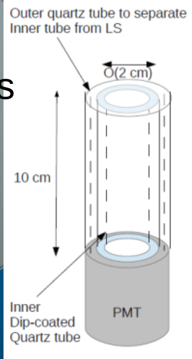
- Vacuum vessel
  - 10 m x 5 m x 60 m;
  - Walls thickness: 8 mm (Al) / 30 mm (SS);
  - Walls separation: 100 mm;
  - Liquid scintillator volume: ~120 m3;
  - 1500 WOMs (8 cm x Ø 8 cm Wavelength Shifting Modules + PMTs);
  - Metal weight (stainless steel, no support): ~ 480 t.

- Magnet designed with emphasis on low power
  - Power consumption < 1 MW
  - Field integral: 0.65Tm over 5m
  - Current 2500 A (1.7 A/mm2
  - Weight ~800 tonnes





LS cell with WOMs



LAB (Linear alkyl benzene)	-
2.5 diphenyl oxazole (PPO)(C15H11NO)	3g/l

Background suppression

- Residual backgrounds sources:
  1. Neutrino inelastic scattering (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$) ➔ Detector under vacuum, accompanying charged particles (tagging, timing), topological
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  3. Muon combinatorial (e.g. $\mu\mu$ with μ mis-ID) ➔ Tagging, timing and topological
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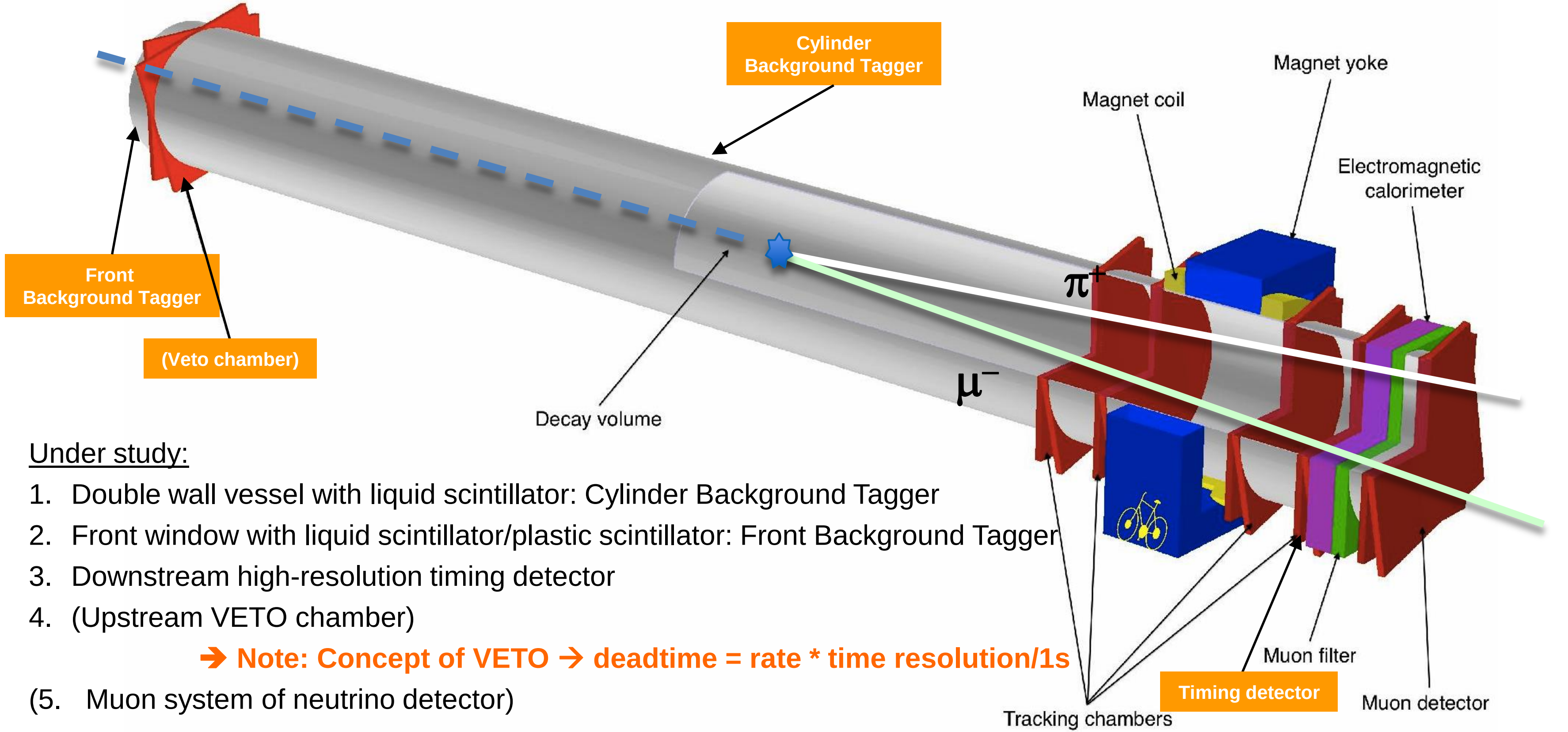


Under study:
1. Double wall vessel with liquid scintillator: Cylinder Background Tagger
2. Front window with liquid scintillator/plastic scintillator: Front Background Tagger
3. Downstream high-resolution timing detector
4. (Upstream VETO chamber)

➔ Note: Concept of VETO ➔ deadtime = rate * time resolution/1s

(5. Muon system of neutrino detector)

CERN Task force

Initiated by CERN Management after SPSC encouragement in January 2014

Detailed investigation

- Physics motivation and requirements
- Experimental Area
- SPS configuration and beam time
- SPS beam extraction and delivery
- Target station
- Civil engineering
- Radioprotection

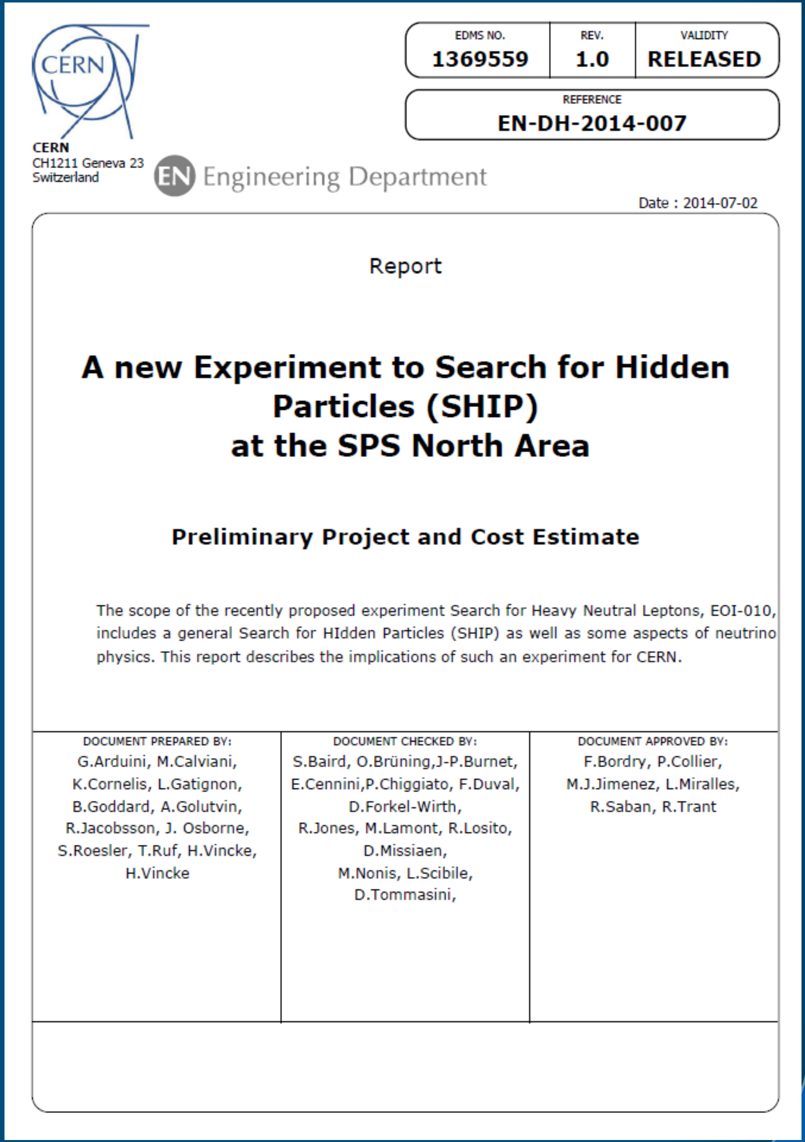
➔ Aimed at overall feasibility, identifying options/issues, resource estimate

➔ Document completed with 80 pages on July 2

➔ Detailed cost, manpower and schedule

➔ Compatible with commissioning runs in 2022, data taking 2023

◉ Working group responsible for providing design of facility for Technical Proposal



CERN
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1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

EN Engineering Department

Date : 2014-07-02

Report

A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area

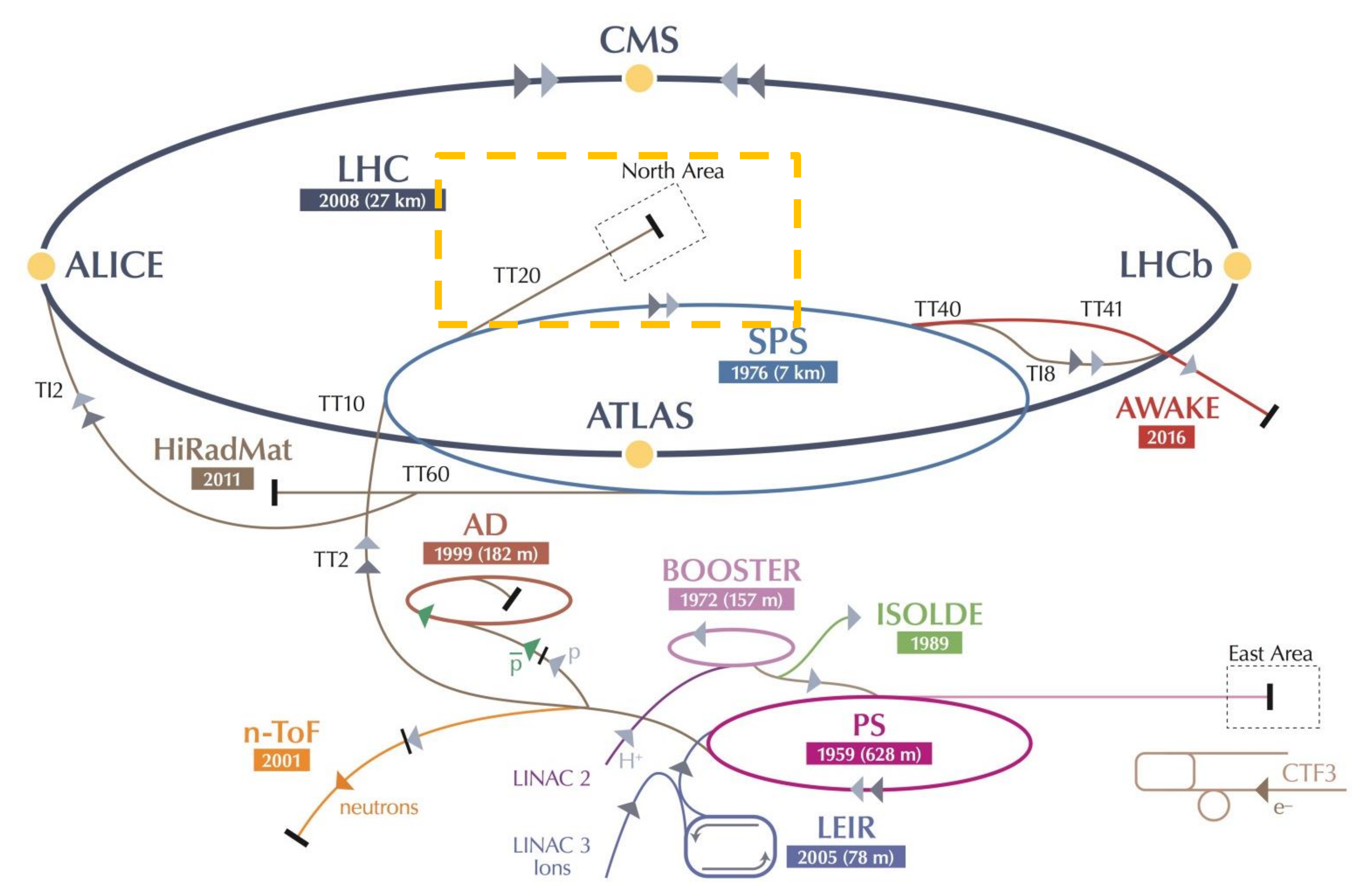
Preliminary Project and Cost Estimate

The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

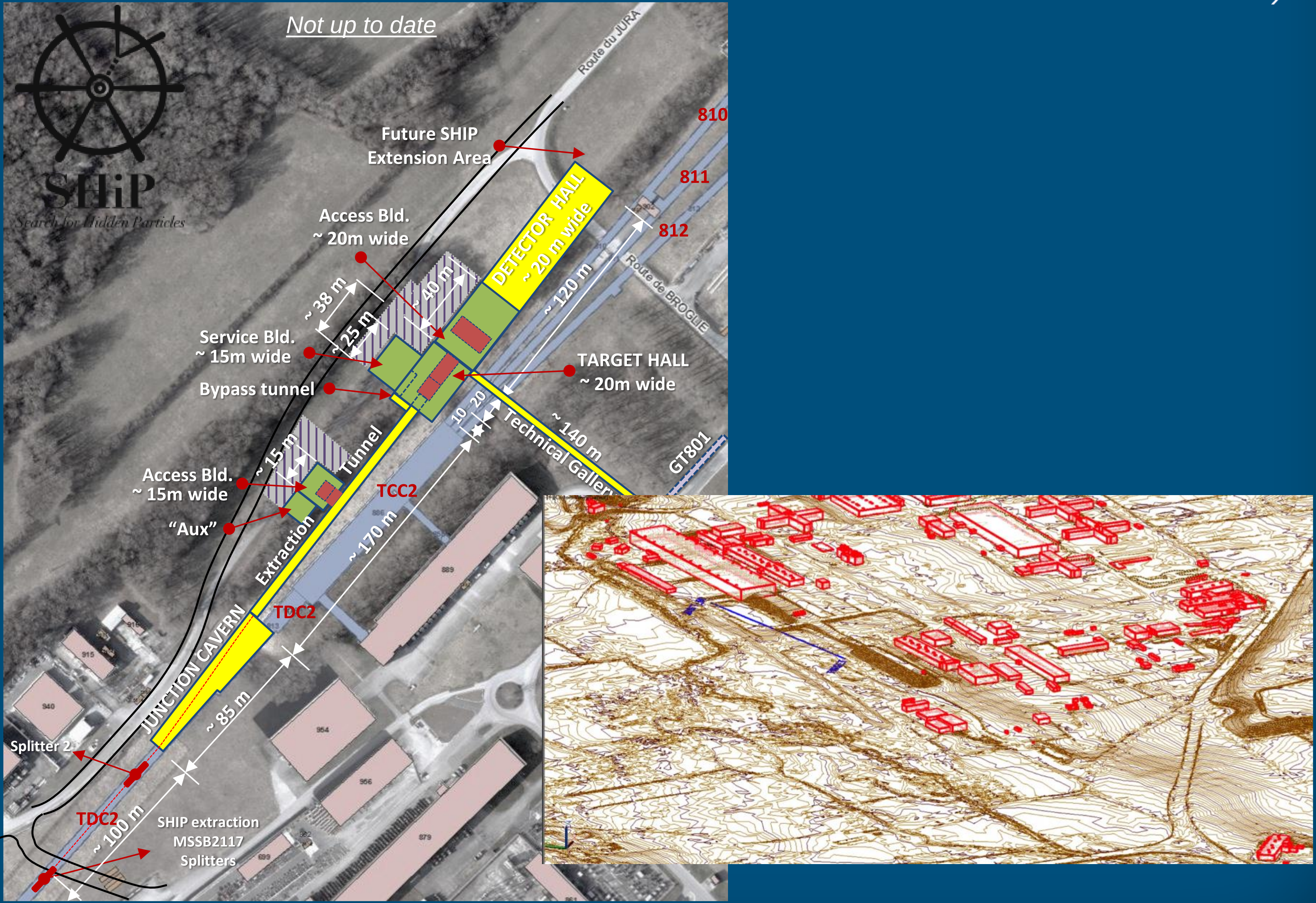
DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
G.Arduini, M.Calviani, K.Cornelis, L.Gatignon, B.Goddard, A.Golutvin, R.Jacobsson, J. Osborne, S.Roesler, T.Ruf, H.Vincke, H.Vincke	S.Baird, O.Brüning,J-P.Burnet, E.Cennini,P.Chiggiato, F.Duval, D.Forkel-Wirth, R.Jones, M.Lamont, R.Losito, D.Missiaen, M.Nonis, L.Scibile, D.Tommasini,	F.Bordry, P.Collier, M.J.Jimenez, L.Miralles, R.Saban, R.Trant

SHiP Location

- Proposed location by CERN beams and support departments



Prevessin North Area site



Some sensitivities

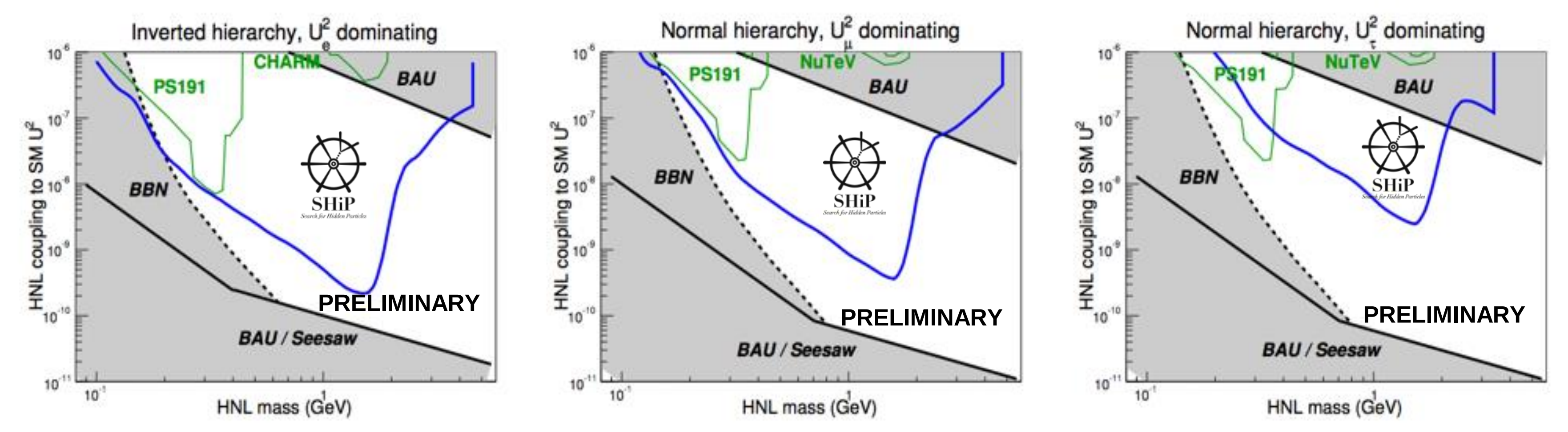
Ex. Expected Sensitivity to $N_{2,3}$

Sensitivity based on current SPS with 2×10^{20} p.o.t in ~5 years of CNGS-like operation

- Visible decays = At least two tracks crossing the spectrometer
  - Ex. $\mathcal{U}_\mu^2 = 10^{-7}$ (corresponding to strongest current experimental limit for $M_{N_{2,3}} = 1\ GeV$) ($\tau_N = 18\ \mu s$)

➔ ~12k fully reconstructed $N_{2,3} \rightarrow \mu\pi$ events are expected for $M_{N_{2,3}} = 1\ GeV$

➔ ~120 events for cosmologically favoured region: $\mathcal{U}_\mu^2 = 10^{-8}$ and $\tau_N = 180\ \mu s$



I $U_e^2 : U_\mu^2 : U_\tau^2 \approx 52 : 1 : 1$, inverted hierarchy

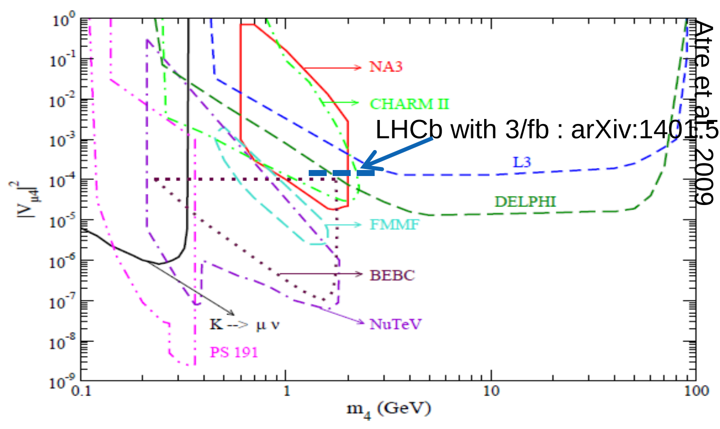
II $U_e^2 : U_\mu^2 : U_\tau^2 \approx 1 : 16 : 3.8$, normal hierarchy

III $U_e^2 : U_\mu^2 : U_\tau^2 \approx 0.061 : 1 : 4.3$, normal hierarchy

HNL sensitivity in other experiments

- Colliders out of luck with low mass / long lifetimes
  - LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1}, i.e. 3-4 years: ~ 2x10^{16} D's in 4π
  - SPS@400 ($\sqrt{s}$ = 27 GeV) with 2x10^{20} pot, i.e. ~5 years: ~ 2x10^{17} D's
  - BELLE-2 using $B \rightarrow XlN$, where $N \rightarrow l\pi$ and X reconstructed using missing mass may go well below 10^{-4} in 0.5<M$_N$<5 GeV

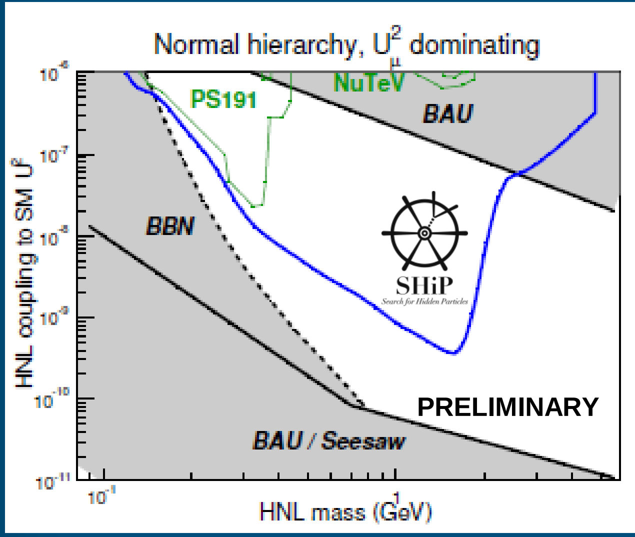
Summary of past Searches for N_I



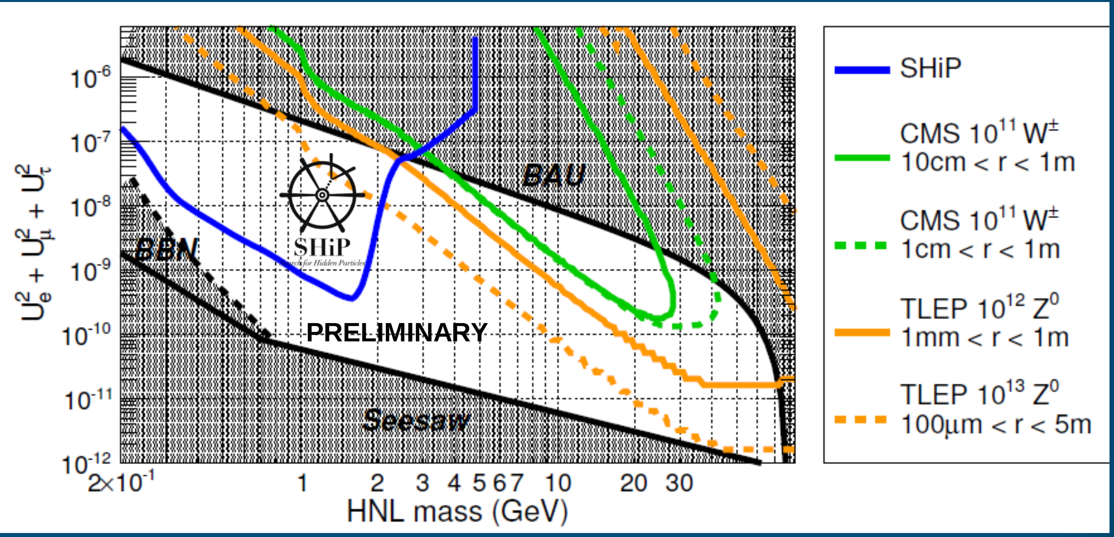
LHCb with 3/fb : arXiv:1401.5361

Atre et al. 2009

- SHiP sensitivity based on current SPS with 2x10^{20} p.o.t at 400 GeV in ~5 years of nominal CNGS-like operation



PRELIMINARY

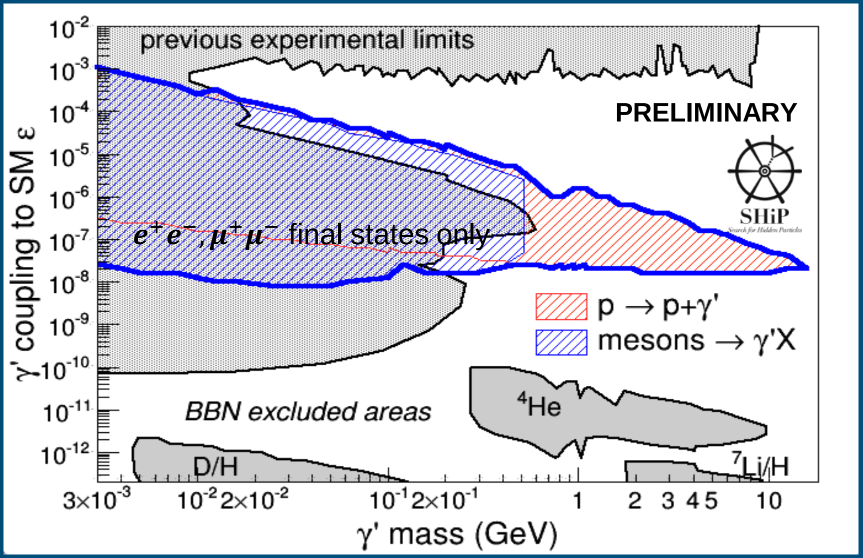


PRELIMINARY

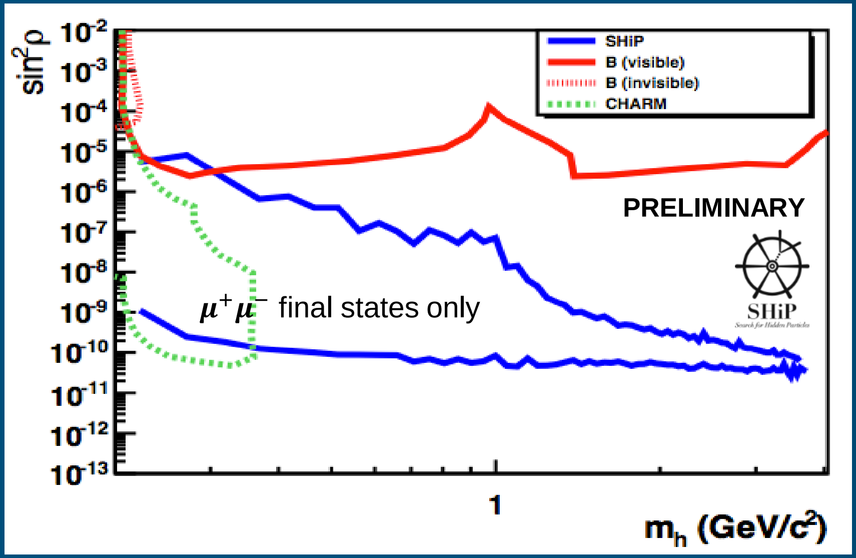
- W ➔ ℓN at LHC: extremely large BG, difficult triggering/analysis.
- Z ➔ Nν at e$^+$e$^-$ collider [M. Bicer et al. 2013]: clean

SHiP Sensitivities

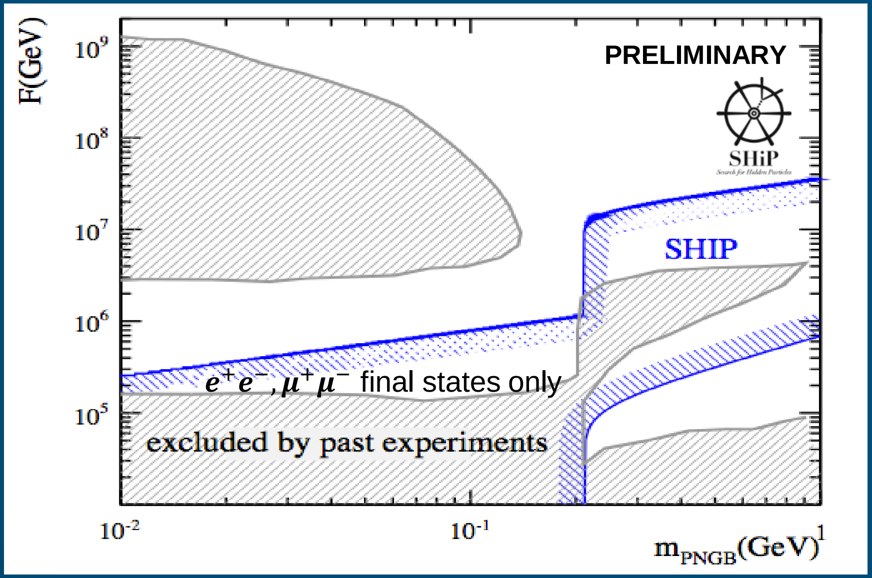
Dark photon



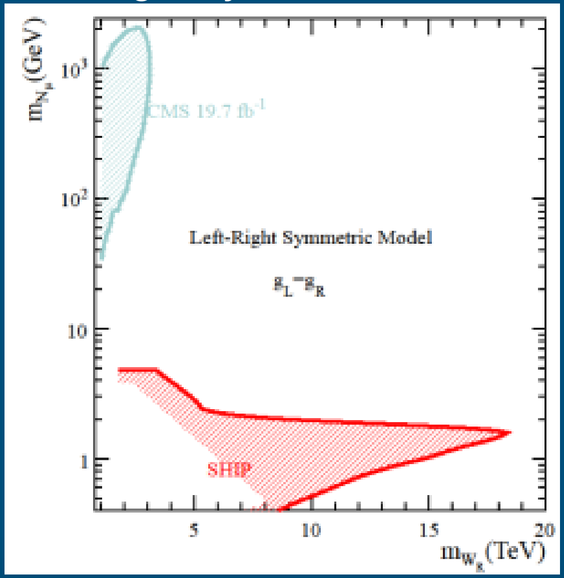
Dark scalar



pNGB



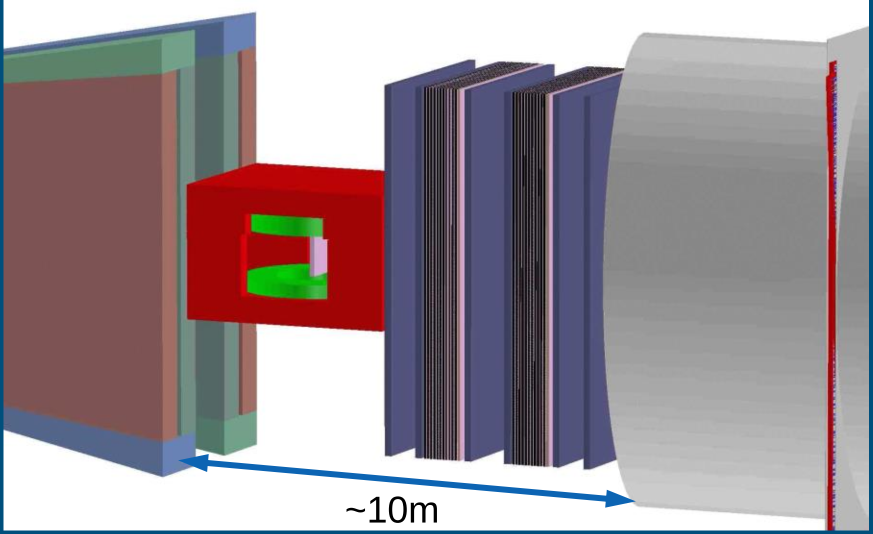
Left-right symmetric models

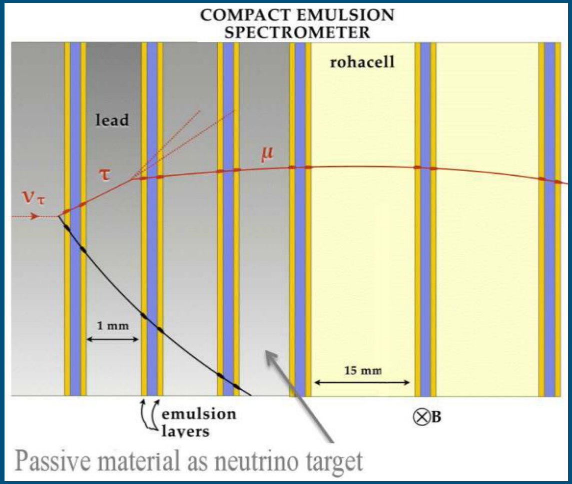


SM Physics: Prospects for ν_τ ($\nu_{e,}$ ν_μ)

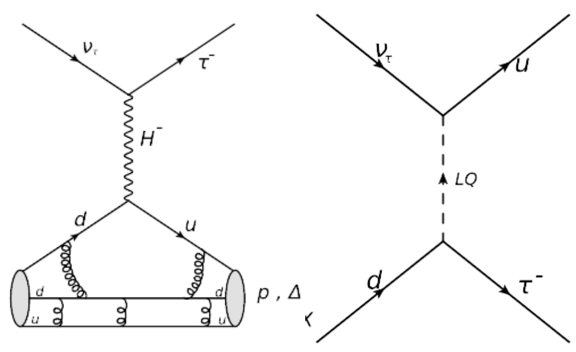
ν-detector and other

SM Physics: Prospects for ν_τ (ν_e, ν_μ)





- Expecting $\mathcal{O}(3500)$ $\nu_\tau/\bar{\nu}_\tau$ interactions in 6 tons of emulsion target
- Physics objectives:
  - First observation of $\bar{\nu}_\tau$
  - ν_τ and $\bar{\nu}_\tau$ cross-section measurements
  - Structure function study
  - ν_τ flux estimation
  - Charm physics with neutrinos and anti-neutrinos
  - Associated charm production
  - Exotic states (e.g. multi-quark)
  - ➔ Normalization for hidden particle search with ν_e from Ds!



Neutrino induced charm production

- Large charm production in ν_μ^{CC} and ν_e^{CC} interactions
- Fraction of neutrino-induced charm events:

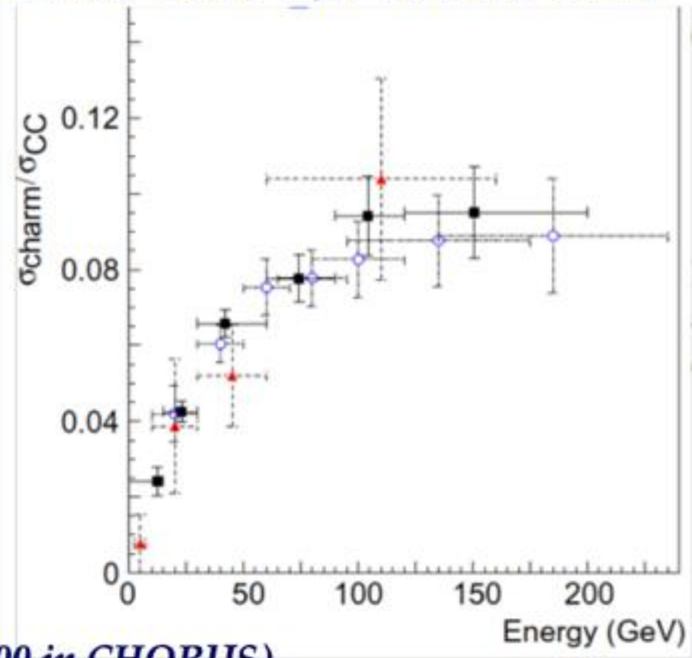
ν_μ^{CC}

$$f(charm) = \frac{\int \Phi_{\nu_\mu}\sigma^{CC}_{\nu_\mu}\left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_\mu}}\right)dE}{\int \Phi_{\nu_\mu}\sigma^{CC}_{\nu_\mu}dE} \approx 2\%$$

ν_e^{CC}

$$f(charm) = \frac{\int \Phi_{\nu_e}\sigma^{CC}_{\nu_e}\left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_e}}\right)dE}{\int \Phi_{\nu_e}\sigma^{CC}_{\nu_e}dE} \approx 4.6\%$$

CHORUS, New J. Phys. 13 (2011) 093002



- Expected ν_μ-induced charm events:

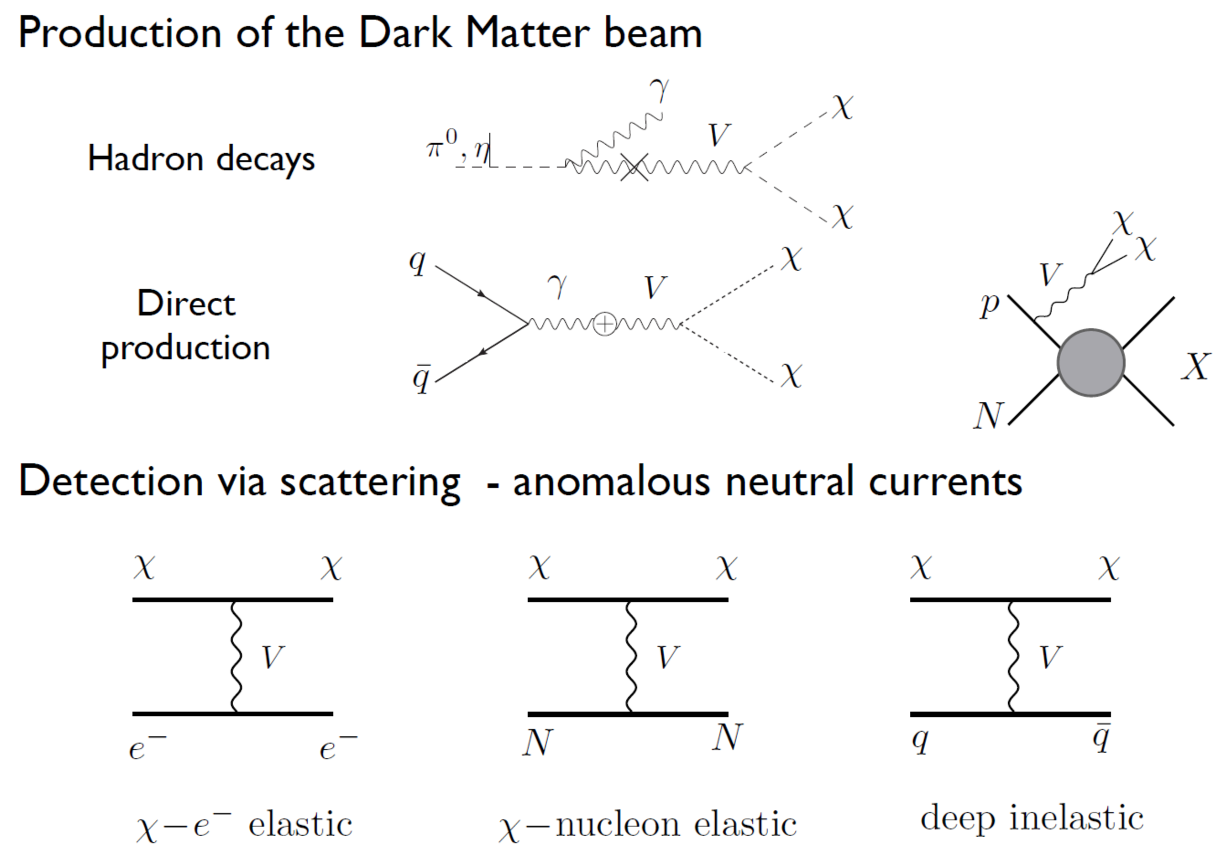
$$N_{charm} = N_{\nu int} \times f_{charm} \times \frac{CC}{NC+CC} \times \epsilon_{decay}$$
$$= (2\times 10^6)\times 0.02 \times 0.7 \times 0.4 \sim 11000$$ *(~2000 in CHORUS)*

- Expected anti-ν_μ-induced charm events: → separate the contribution of valence (absent in the anti-neutrino case) and sea quarks

$$N_{anti-charm} = N_{charm} \times \frac{\Phi_{\overline{\nu}_\mu}}{\Phi_{\nu_\mu}} \times \frac{\sigma_{\overline{\nu}_\mu}}{\sigma_{\overline{\nu}_\mu}}$$
$$= 11000 \times 0.63 \times 0.5 \sim 3500$$ *(~32 in CHORUS)*

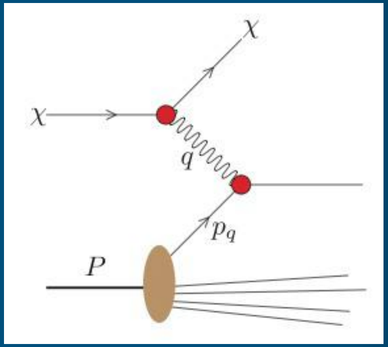
Future: Direct DM Search

- Relativistic beam of light Dark Matter with 2x10^20 pot!



Production of the Dark Matter beam

Detection via scattering - anomalous neutral currents



- The signature of dark matter is a neutral current scattering event
  - Very similar to neutrino induced neutral current event!
  - Deep inelastic: energetic jets, hadrons

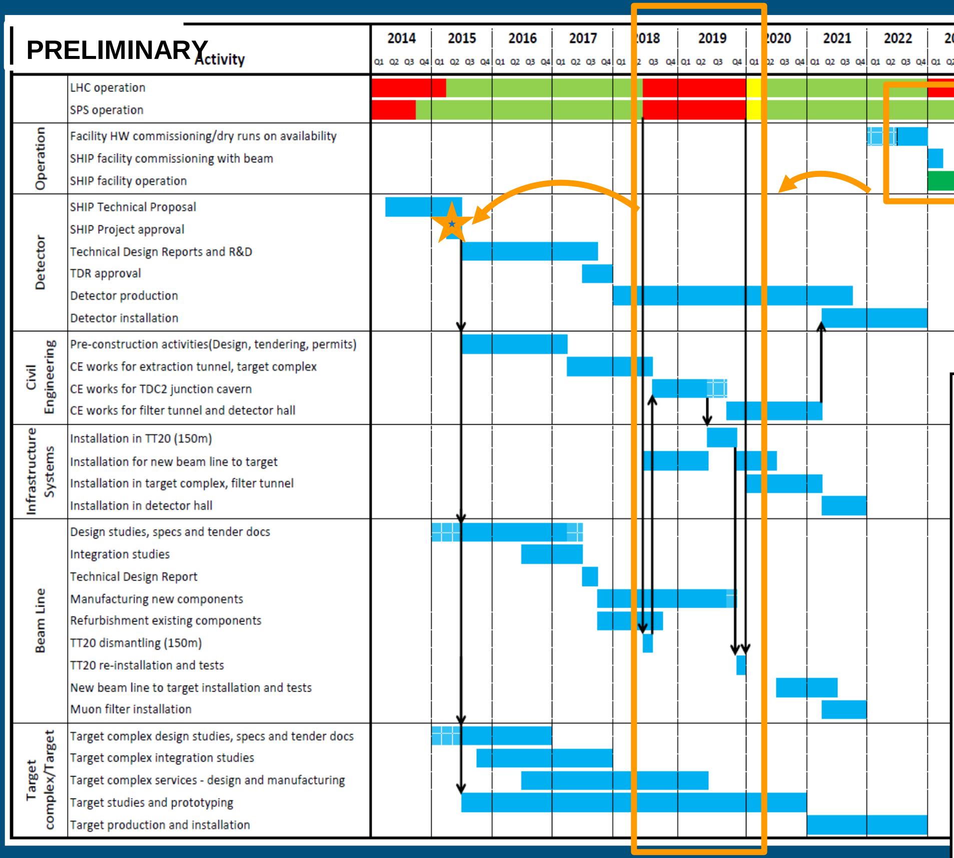
Status and plans

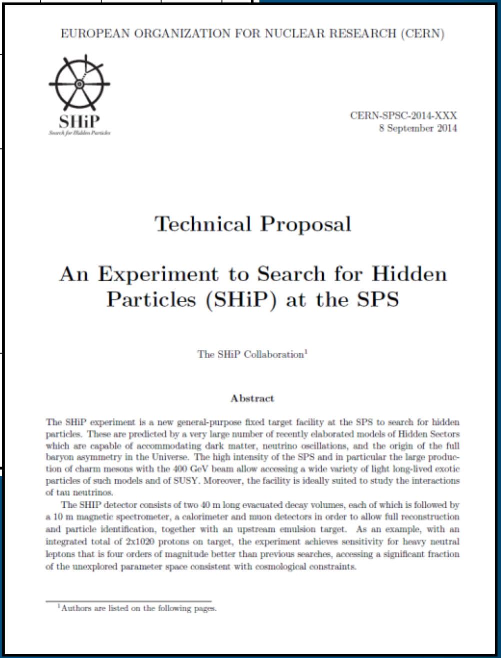
History and Current Status

- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010
  - ➔ EOI stimulated a lot of interest
- January 2014: EOI discussed at SPSC
  - Encouraged to produce "*an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration."*
- January 2014: Meeting with CERN Research Director S. Bertolucci
  - ➔ Proposed a task force to evaluate feasibility and required resources at CERN within ~3months
  - ➔ Supportive to the formation of a proto-Collaboration and agreed to CERN signing
- Work towards Technical Proposal in full swing
  - Extension of physics program
  - Signal background studies and optimization
  - Detector specification, simulation and even some detector R&D
  - Optimization of Experimental Facility - beam line, target, and muon filter, RP, overall layout
- 1st SHiP Workshop in Zurich in June with a 100 experimentalists and theorists
  - 41 institutes from 14 countries expressed interest to contribute to the Technical Proposal
- 2nd SHiP Workshop/Collaboration meeting at CERN September 24-26
  - Revise progress in Working Groups towards Technical Proposal
  - Extend physics for a general purpose facility: Tau neutrino, LFV and direct Dark Matter search
- 3rd SHiP Collaboration meeting at CERN December 15
  - Revise progress towards TP and Physics Proposal
  - Formalize Collaboration as proposed by CERN management with 44 institutes from 14 countries
- 4th SHiP Collaboration meeting in Naples, February 9-11
  - Finalize contents and decision for TP, first raw draft ready

Technical Proposal and beyond

- Aim full force at submitting TP by March 31, 2015
  - Design of facility must start second half of 2015 (CE, beam, target, infra)





EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2014-XXX
8 September 2014

Technical Proposal

An Experiment to Search for Hidden Particles (SHiP) at the SPS

The SHiP Collaboration[1]

Abstract

The SHiP experiment is a new general-purpose fixed target facility at the SPS to search for hidden particles. These are predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. The high intensity of the SPS and in particular the large production of charm mesons with the 400 GeV beam allow accessing a wide variety of light long-lived exotic particles of such models and of SUSY. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

The SHIP detector consists of two 40 m long evacuated decay volumes, each of which is followed by a 10 m magnetic spectrometer, a calorimeter and muon detectors in order to allow full reconstruction and particle identification, together with an upstream emulsion target. As an example, with an integrated total of 2x1020 protons on target, the experiment achieves sensitivity for heavy neutral leptons that is four orders of magnitude better than previous searches, accessing a significant fraction of the unexplored parameter space consistent with cosmological constraints.

---

[1] Authors are listed on the following pages.

We expect CERN to decide on the strategy for the SHIP beam within a year after TP submission

- Technical Design Report: 2018
- Construction and installation: 2018 – 2022
- Data taking and analysis of 2×10^{20} p.o.t.: 2023 – 2028++

Conclusion

- Proposed GP experiment for HS exploration in largely unexplored domain
  - Very much increased interested for Hidden Sector after LHC Run 1
  - A very significant physics reach beyond past/current experiments in the cosmologically interesting region
  - Also unique opportunity for ν_τ physics, direct Dark Matter search, and LFV,…

  ➔ Statistical sensitivity $\mathcal{O}$(10000x) previous experiments on hidden particles and $\mathcal{O}$(200x) for ν_τ physics

- Work towards Technical Proposal in full swing
  - Signal background studies and optimization, detector specification, simulation and some detector R&D

    ➔ Full detector including muon filter and surrounding structures implemented in GEANT: FairSHIP!
  - Optimization of Experimental Facility - beam line, target, and muon filter, RP, overall layout

- TP will be complemented by a “Physics Proposal”
  - Prepared mainly by a large group of invited theorists
  - Contains a description of the complete physics program, and extensions beyond SHiP

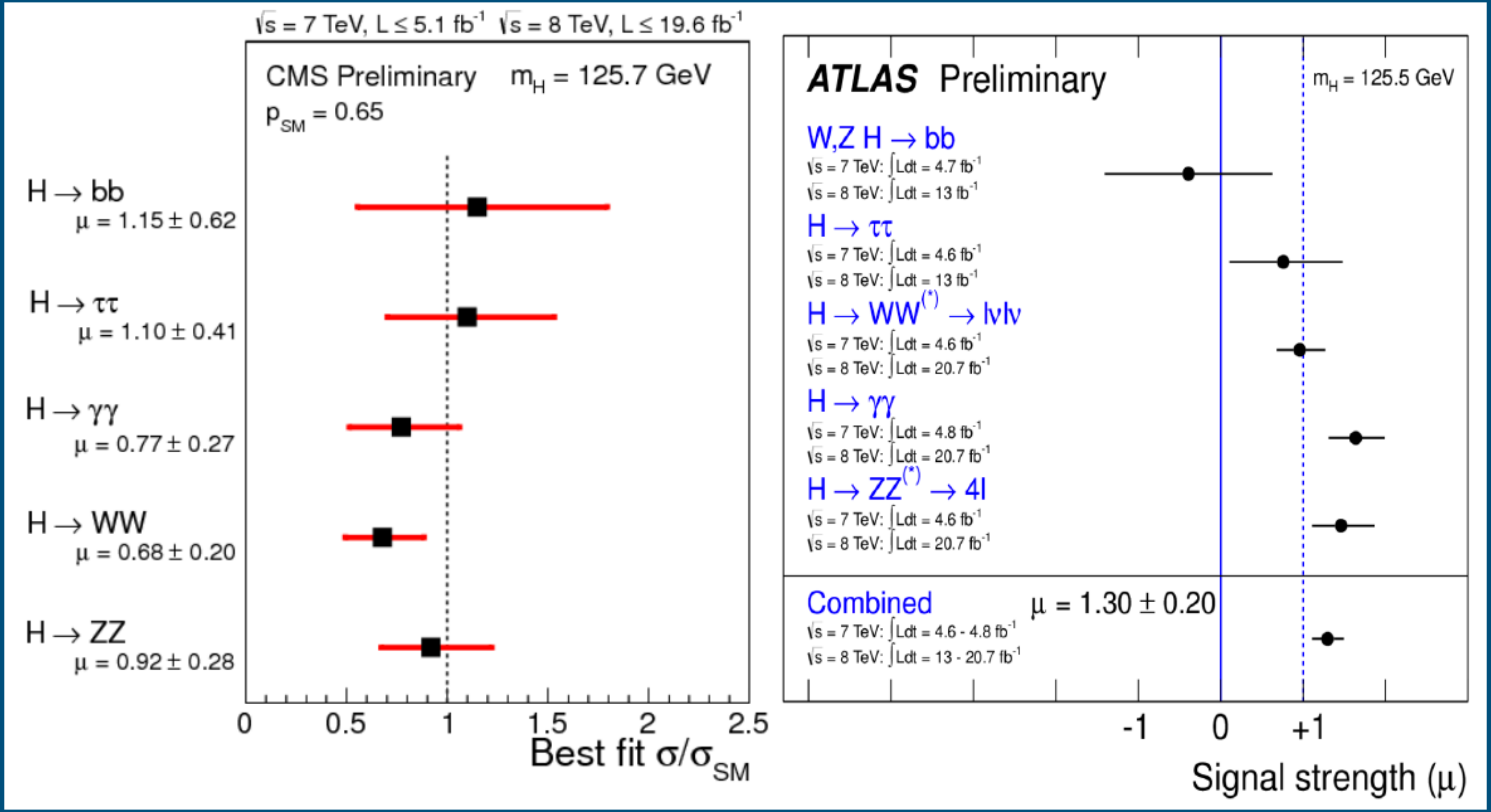
- Facility and physics case based on the current injector complex and SPS
  - $2\text{x}10^{20}$ at 400 GeV in 5 nominal years by “inheriting” CNGS share of the SPS beam time from 2023

- *Proposed experiment perfectly complements the searches for New Physics at the LHC*

Spare slides

Higgs Discovery

- It looks very much like THE Higgs boson:



- To be done
  - Measure more precisely fermion couplings
  - Measure triple and quartic gauge couplings to reconstruct vacuum potential

Dark Matter Constraint and Search

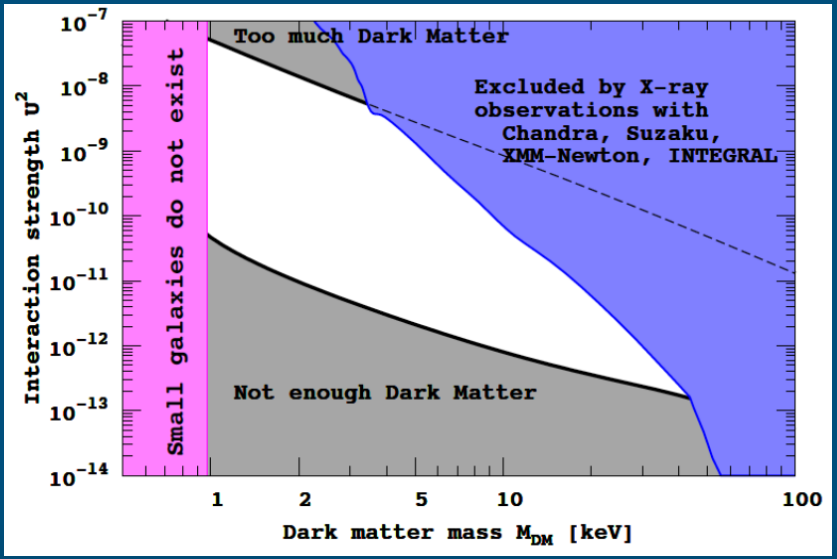
1. Tremaine-Gunn bound: average phase-space density for fermionic DM particles cannot exceed density given by Pauli exclusion principle

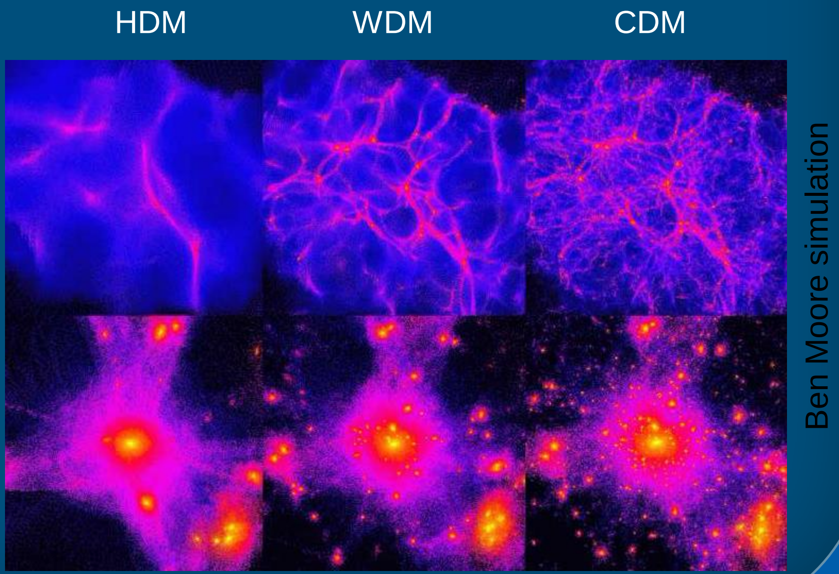
   ➔ For smallest dark matter dominated objects such as dwarf spheroidal galaxies of the Milky Way

2. X-ray spectrometers to detect mono-line from radiative decay
   - Large field-of-view ~ ~ size of dwarf spheroidal galaxies ~ 1°
   - Resolution of $\frac{\Delta E}{E} \sim 10^{-3} - 10^{-4}$ coming from width of decay line due to Doppler broadening

   ➔ Proposed/planned X-ray missions: Astro-H, LOFT, Athena+, Origin/Xenia

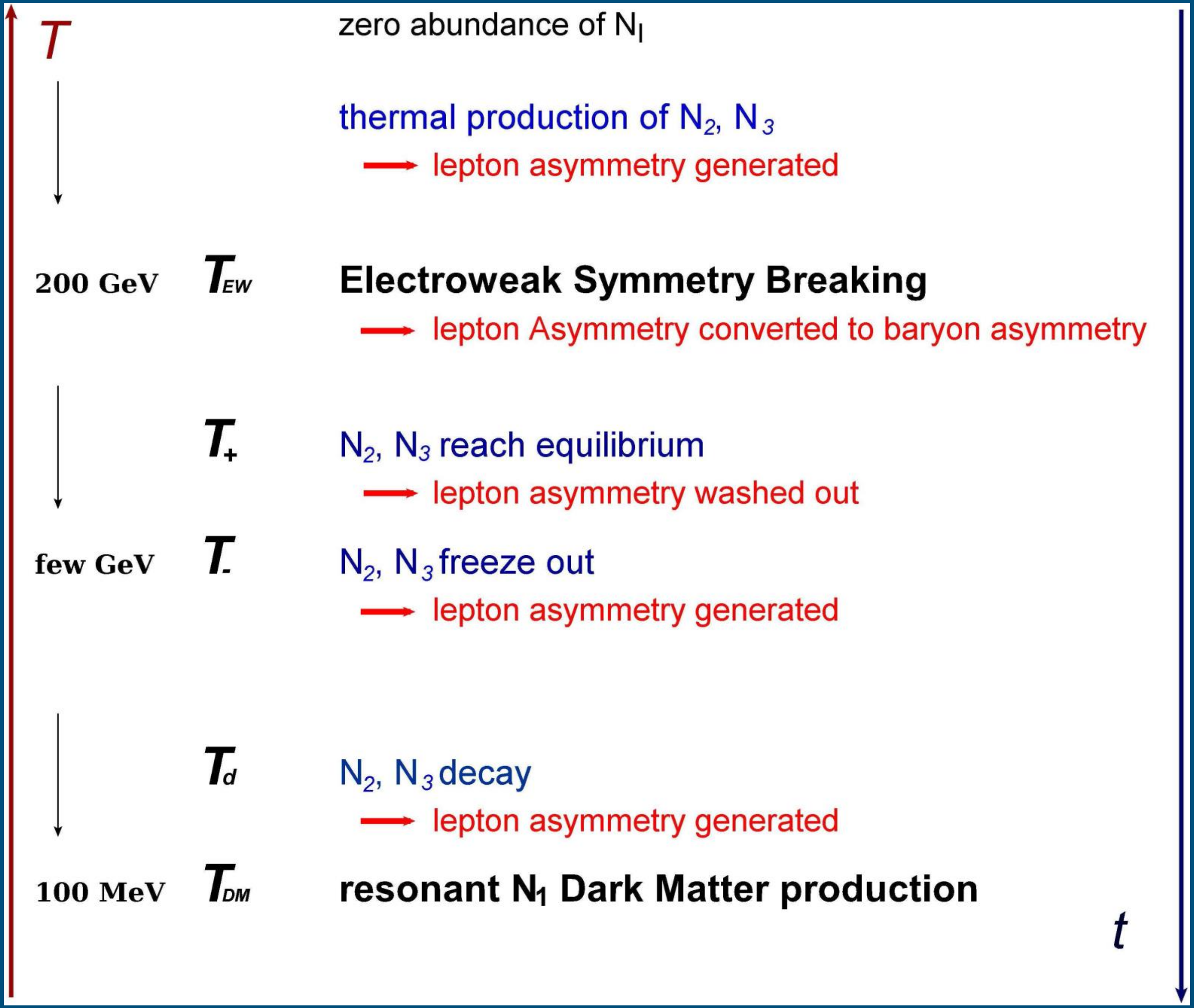
3. Lyman-α forest
   - Super-light sterile neutrino creates cut-off in the power spectrum of matter density fluctuations due to sub-horizon free-streaming $d_{FS} \sim 1\ \mathrm{Gpc}\ m_{eV}^{-1}$
   - Fitted from Fourier analysis of spectra from distant quasars propagating through fluctuations in the neutral hydrogen density at redshifts 2-5





Ben Moore simulation

Thermal History in νMSM



T

zero abundance of N_I

thermal production of N_2, N_3
→ lepton asymmetry generated

200 GeV T_{EW} **Electroweak Symmetry Breaking**
→ lepton Asymmetry converted to baryon asymmetry

T_+ N_2, N_3 reach equilibrium
→ lepton asymmetry washed out

few GeV T_- N_2, N_3 freeze out
→ lepton asymmetry generated

T_d N_2, N_3 decay
→ lepton asymmetry generated

100 MeV T_{DM} **resonant N_1 Dark Matter production**

t

(arXiv:1208.4607)

Ex. Expected Event Yield $N_{2,3} \rightarrow \mu\pi$

- Integral mixing angle $\mathcal{U}^2 = \mathcal{U}_e^2 + \mathcal{U}_\mu^2 + \mathcal{U}_\tau^2$
- Estimate of the sensitivity is obtained by considering different scenarios for the hierarchy of flavour coupling (arXiv:0605047)
  - Conservative: Consider only the decay $N_{2,3} \rightarrow \mu\pi$ with production mechanism $D \rightarrow \mu N_{2,3} X$, which probes $\mathcal{U}_\mu^4$
- Expected number of signal events

$$N_{signal} = n_{pot} \times 2\chi_{cc} \times Br(\mathcal{U}_\mu^2) \times \varepsilon_{det}(\mathcal{U}_\mu^2)$$

$n_{pot} = 2 \times 10^{20}$
$\chi_{cc} = 0.45 \times 10^{-3}$

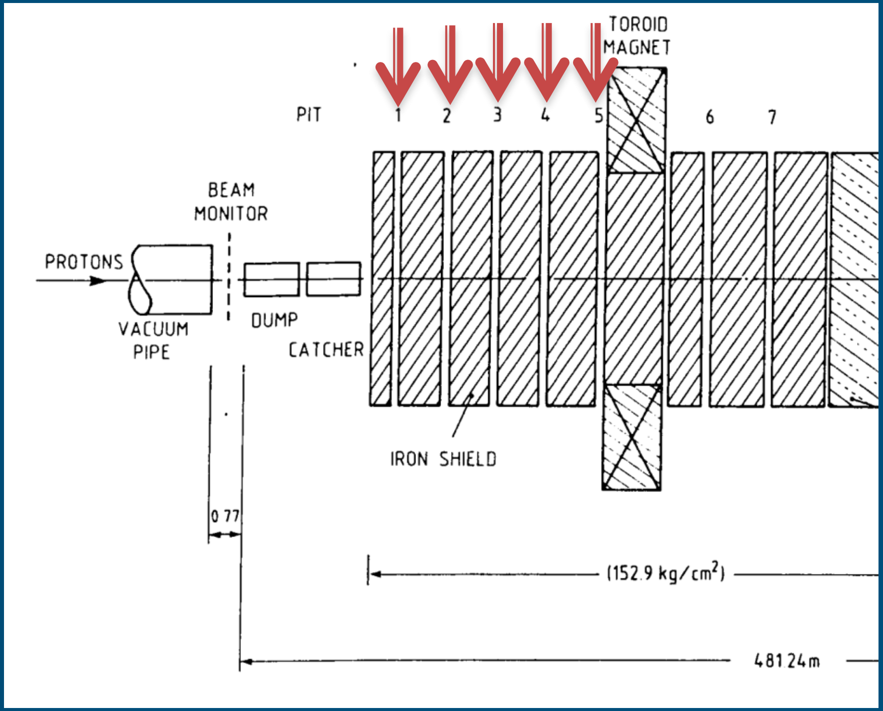
- $Br(\mathcal{U}_\mu^2) = \mathrm{Br}(D \rightarrow \mu N_{2,3} X) \times Br(N_{2,3} \rightarrow \mu\pi)$,
  - $Br(N_{2,3} \rightarrow \mu\pi)$ is assumed to be 20%
  - Br$(D \rightarrow NX) \sim 10^{-8} - 10^{-12}$
- $\varepsilon_{det}(\mathcal{U}_\mu^2)$ is the probability that $N_{2,3}$ decays in the fiducial volume, and μ and π are reconstructed

  ➔ Detection efficiency entirely dominated by the geometrical acceptance (8×10^{-5} for $\tau_N = 1.8 \times 10^{-5} s$)

(Validation of MC for SHiP)

- Critical to have high confidence on background studies
- CHARM experiment had a similar configuration of the beam line to SHiP
  - Muon flux measurements in each pit up to magnet

➔ Validation by reproducing mu flux with GEANT checking different EM generators and QCD string models

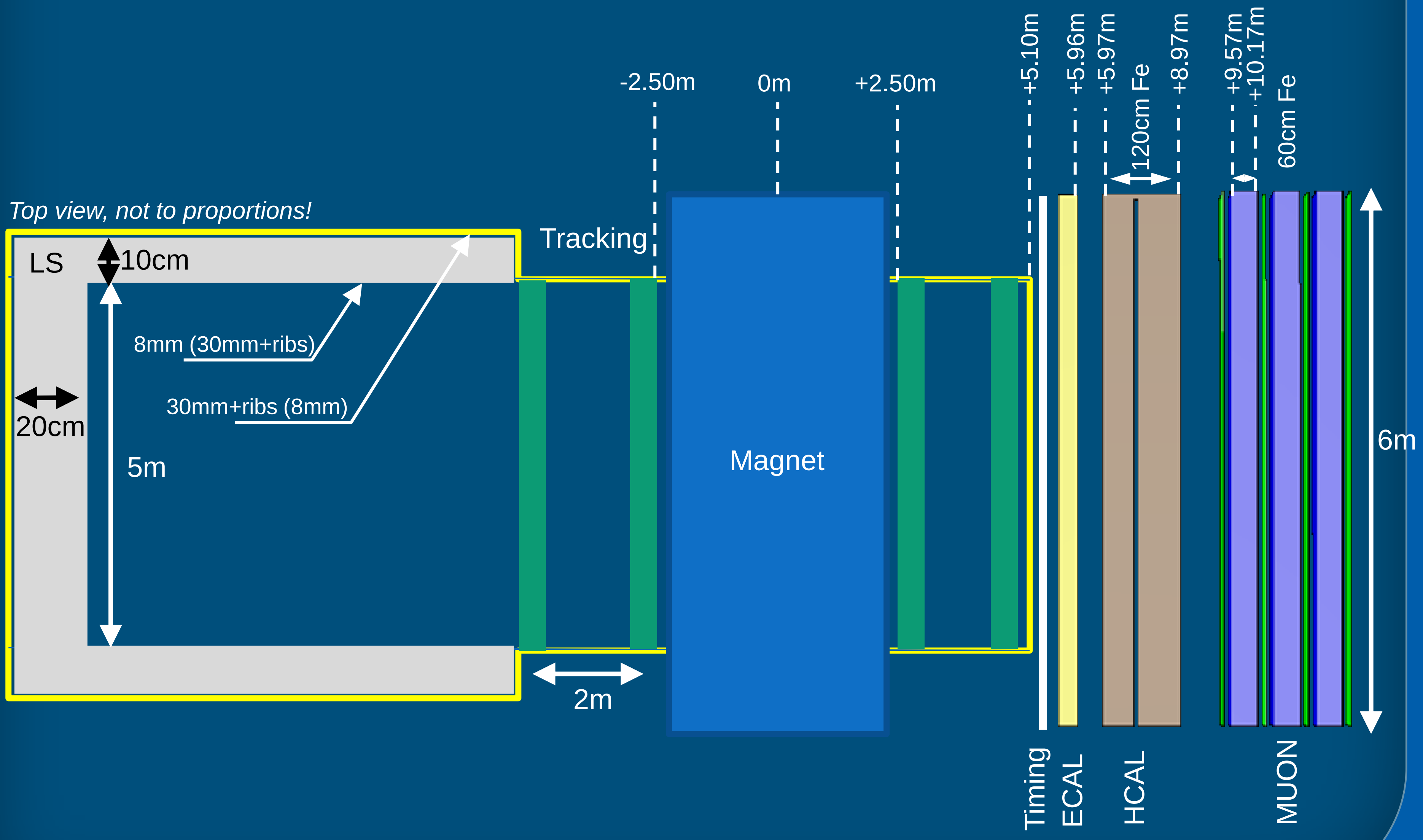


Number of muon per 10^7 p.o.t. in each pit

	data	MC			
Type	CHARM	EMV		EMX	
		QGSP	FTFP	QGSP	FTFP
Pit 1	8200	8460	9254	8650	9252
Pit 2	655	647	639	730	659
Pit 3	137	164	172	237	169
Pit 4	33.1	52	57	65	50
Pit 5	6.1	21	10	27	13

Looks good

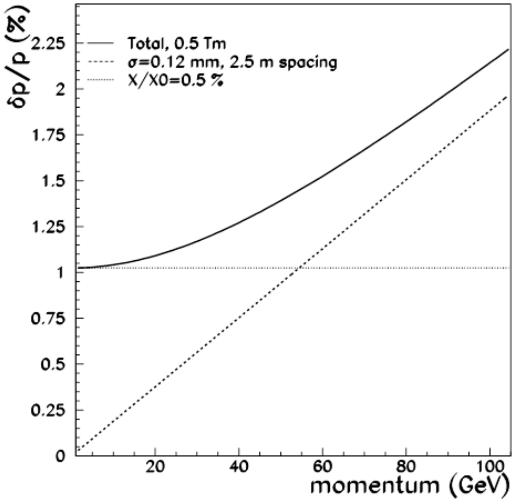
(More in detail....)

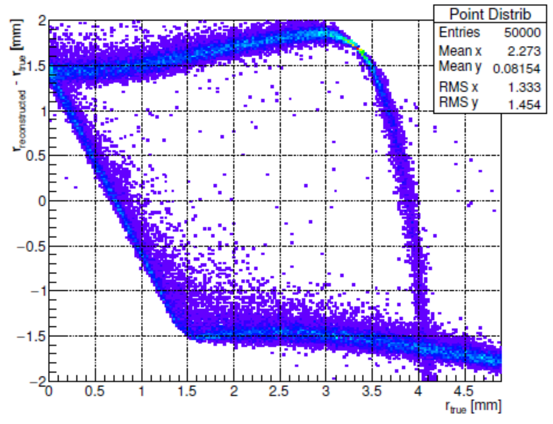


Spectrometer: Tracking

- Based on NA62 straw tube technology
  - Straw tubes with 120 μm resolution and 0.5% $\frac{X_0}{X}$ of material budget

Item	NA62	SHiP
Vessel width	2.5 m	**5 m**
Design rate max	500kHz/straw	2kHz/straw (ø1cm)*
Vacuum requirement p <	1e-5 mbar	1e-2 mbar
Views	X, X+45°, X-45°, Y	**Y, Y+few°, Y-few°, Y**
Spatial resolution per coord per space point	 ≤ 130um ≤ 80um	same
Average track efficiency	near 100%	same

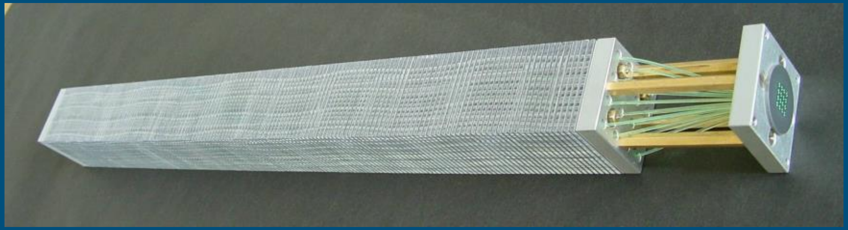




- Challenges to be studied
  1. Straightness (sagging of straw, sagging of wire)
     ➔ How much sagging can we tolerate ?
  2. Readout of signal, attenuation, two-sided ?

PID: ECAL

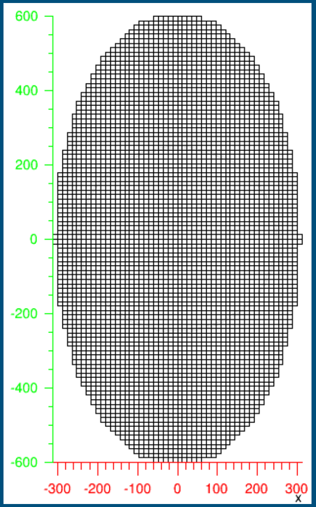
- Based on spiral-fibre Shashlik module



  - Dimensions 38.2x38.2 mm^2
  - Radiation length 17.5mm
  - Moliere radius 36mm
  - Radiation thickness 22.5 X0
  - Scintillator/lead thickness 1.5mm/0.8mm
  - Energy resolution 6.5%/√E ⊕ 1%

W:6m x H:12m x D:50 cm

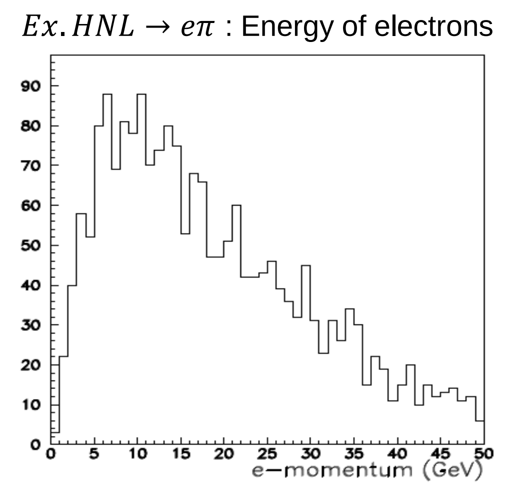
- 4064 modules
- 36576 readout channels



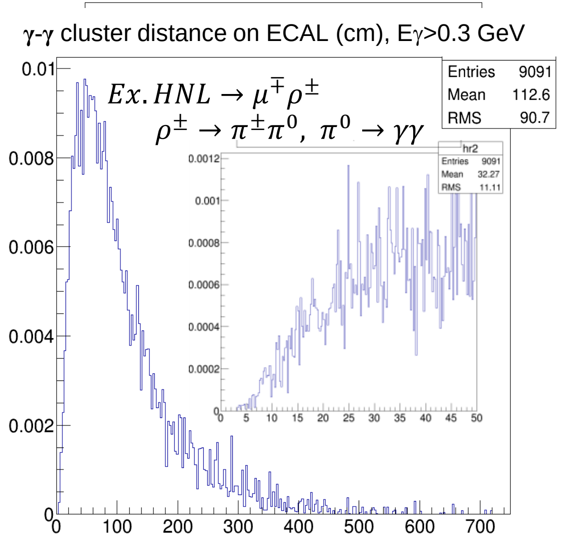
- Main challenge is calibration
  - 2 x 10^9 μ /day (MIP) and 1.3 x 10^6 e /day (from μ→e)

➔ Equalization on MIP, energy scale with E/p for electrons per each cell

➔ ~50 electroncs/cell/day ➔ 1% calibration accuracy



$Ex.HNL \to e\pi$: Energy of electrons



γ-γ cluster distance on ECAL (cm), Eγ>0.3 GeV

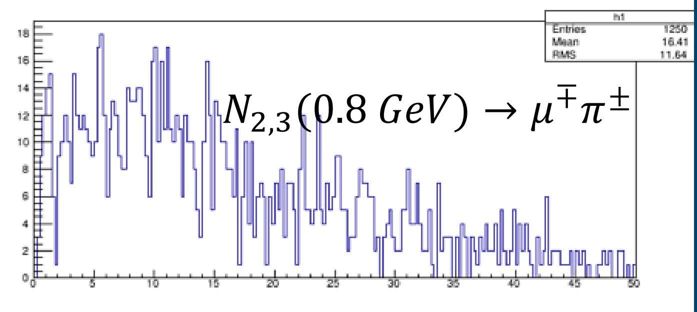
$Ex.HNL \to \mu^{\mp}\rho^{\pm}$

$\rho^{\pm} \to \pi^{\pm}\pi^{0},\ \pi^{0} \to \gamma\gamma$

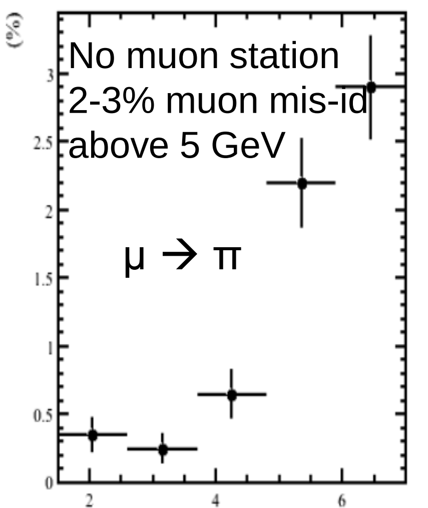
PID: MUON/HCAL

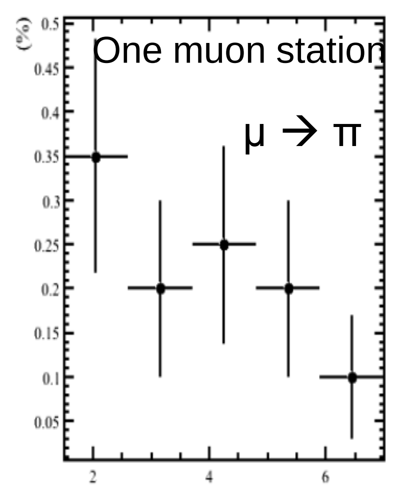
- Challenge
  - For muons, high detection eff and low mis-id as pions
  - For pions, high detection eff and low misid as muons

    ➔Tough as pions decay in flight before PID system
    - 20% of the pions at 2GeV, 10% at 5GeV, 4% at 30GeV



- Two configurations under considerations
  1. **ECAL + MUON (4 stations)**
  2. **ECAL+ HCAL + MUON (1 station)** ⟶
  - **Option 2 being optimized now**



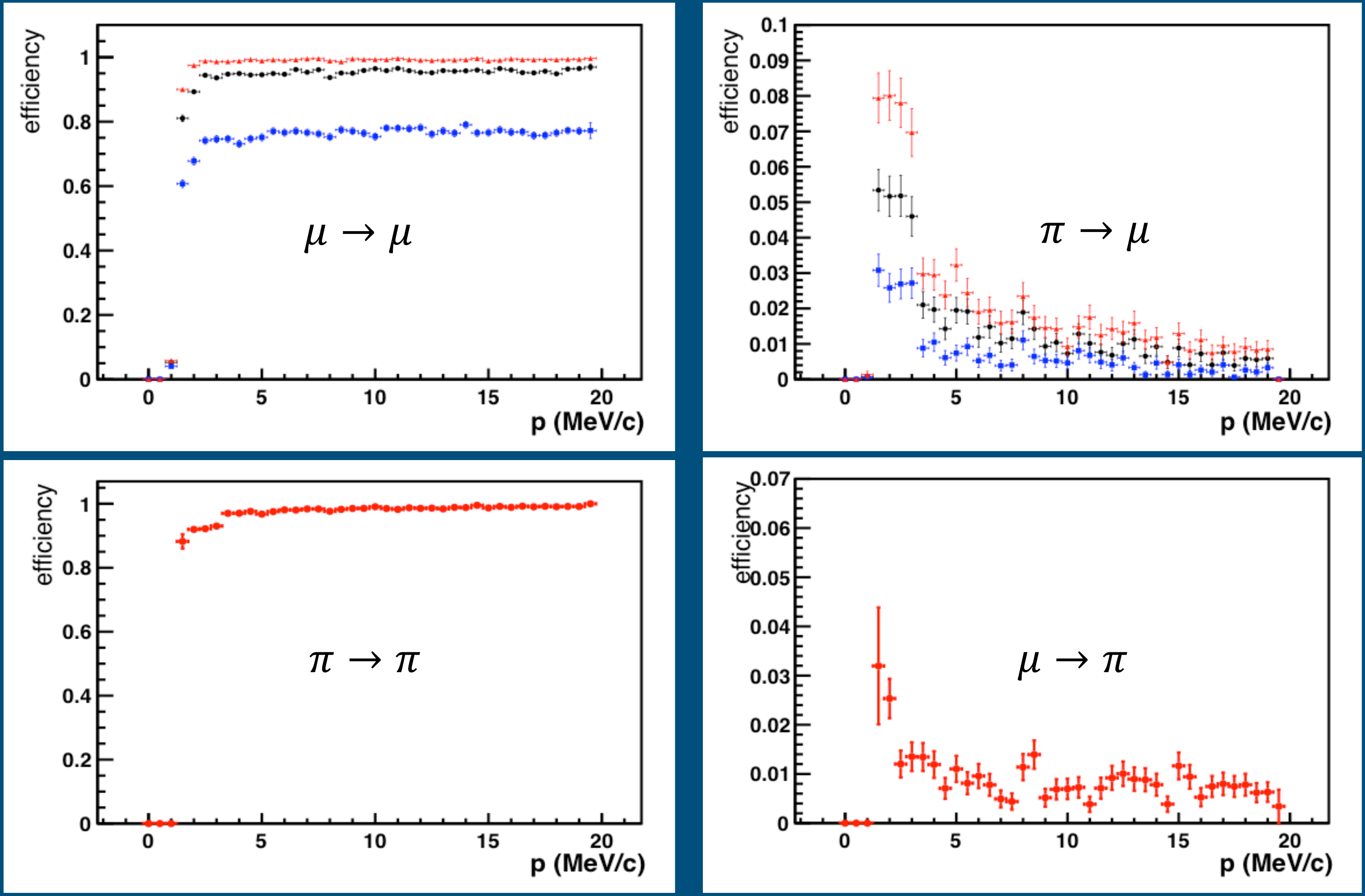


- MUON system
  - Four active stations (1 cm scintillator) interleaved with 60 cm (3.6 λ_I) iron filters
  - Strips W:5cm x H:2cm x L:270cm
  - Option 2 (W:6m x H:12m): 800 (H)+800 (V) = 1600 strips/station
  - Two RO channels / strip ➔ 4800 strips / 9600 RO channels

- HCAL system
  - 2 segment HCAL: 3.8 λ +6.2 λ = 8 λ (to be optimized with MUON)
  - 24 x 24 cm^2 modules (baseline)
  - Option 2 (W:6m x H:12m): 2012 readout channels

PID: MUON/HCAL

- Preliminary performance with no HCAL (no decays in flight)
  - >95% muon efficiency for < 0.7% misidentification probability > 3 GeV/c

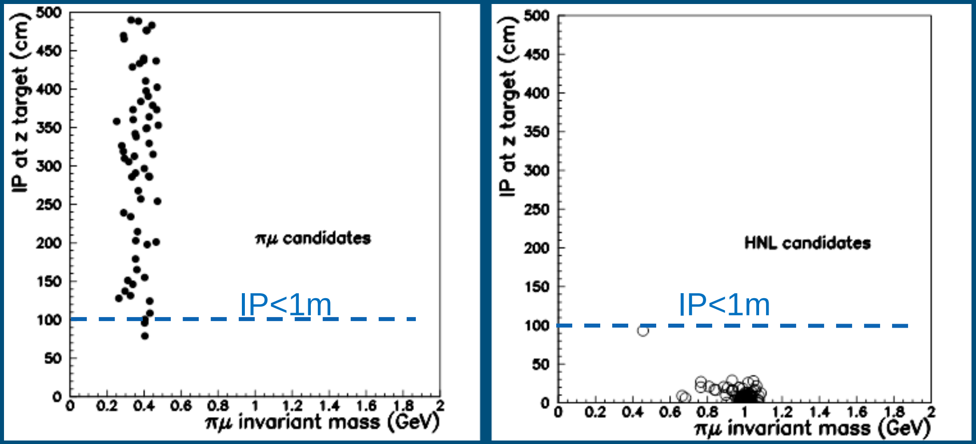


- Optimization of field of interest to tune id/mis-id
  - FOI(x,y) = a[i]/p where a[i], for i=1,4 depends on the stations

Ex. Background Suppression

- 2×10^4 neutrino interactions per 2×10^{20} p.o.t. in the decay volume at atmospheric pressure
  - ➔ Becomes negligible at 0.01 mbar
- Neutrino (muon) interactions in the final part of the muon shield
  - $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$
  - Yields CC(NC) rate of ~$6(2)\times10^5$ / λ_{inter} / 2×10^{20} p.o.t.
  - ~10% of neutrino interactions produce Λ or K^0 in acceptance
  - Majority of decays occur in the first 5 m of the decay volume
  - ➔ Requiring μ-identification for one of the two decay products: 150 two-prong vertices in 2×10^{20} p.o.t.
  - For 0.5 Tm field integral σ_{mass} ~ 40 MeV for p < 20 GeV

➔ E.g. background reduction by impact parameter



- The IP cut will also be used to reject backgrounds induced by neutrino interactions in the material surrounding the detector, cosmics etc
- Similar for muon inelastic interactions in the vicinity of the detector