

# SHIP

# SEARCH FOR HIDDEN PARTICLES

## A NEW EXPERIMENT PROPOSAL



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# Theoretical motivation

- Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model  
The SM may work successfully up to Planck scale ! 
- SM is unable to explain:
  - Neutrino masses
  - Excess of matter over antimatter in the Universe
  - The nature of non-baryonic Dark Matter
- All three issues can be solved by adding three new fundamental fermions, right-handed Majorana **Heavy Neutral Leptons (HNL)**:  **$N_1$ ,  $N_2$  and  $N_3$**

**vMSM:** T.Asaka, M.Shaposhnikov **PL B620** (2005) 17

Three Generations of Matter (Fermions) spin $\frac{1}{2}$			Bosons (Forces) spin 1		
I	mass → 2.4 MeV charge → $\frac{2}{3}$ name → <b>u</b> Left up Right	II	mass → 1.27 GeV charge → $\frac{2}{3}$ name → <b>c</b> Left charm Right	III	mass → 173.2 GeV charge → $\frac{2}{3}$ name → <b>t</b> Left top Right
Quarks			0 0 <b>g</b> gluon		
	mass → 4.8 MeV charge → $-\frac{1}{3}$ name → <b>d</b> Left down Right		0 0 <b><math>\gamma</math></b> photon		
	mass → 104 MeV charge → $-\frac{1}{3}$ name → <b>s</b> Left strange Right		91.2 GeV 0 0 <b>Z</b> weak force	126 GeV 0 0 <b>H</b> spin 0	80.4 GeV $\pm 1$ 0 <b>W</b> weak force
Leptons	0 <b><math>\nu_e</math></b> electron neutrino Left Left Right	0 <b><math>\nu_\mu</math></b> muon neutrino Left Left Right	0 <b><math>\nu_\tau</math></b> tau neutrino Left Left Right	0 <b><math>\nu_e N_1</math></b> electron neutrino Left Left Right	0 <b><math>\nu_\mu N_2</math></b> muon neutrino Left Left Right
	0.511 MeV $e^-$ Left electron Right	105.7 MeV $\mu^-$ Left muon Right	1.777 GeV $\tau^-$ Left tau Right	~10 keV $e^-$ Left $\nu_e N_1$ Right	~GeV $\mu^-$ Left $\nu_\mu N_2$ Right

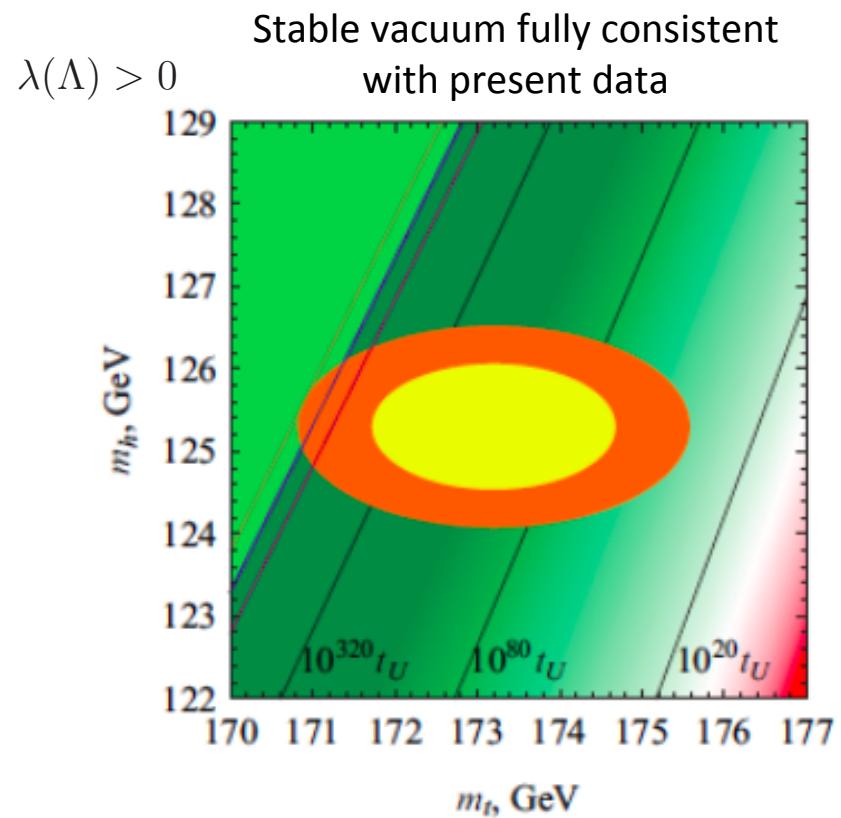
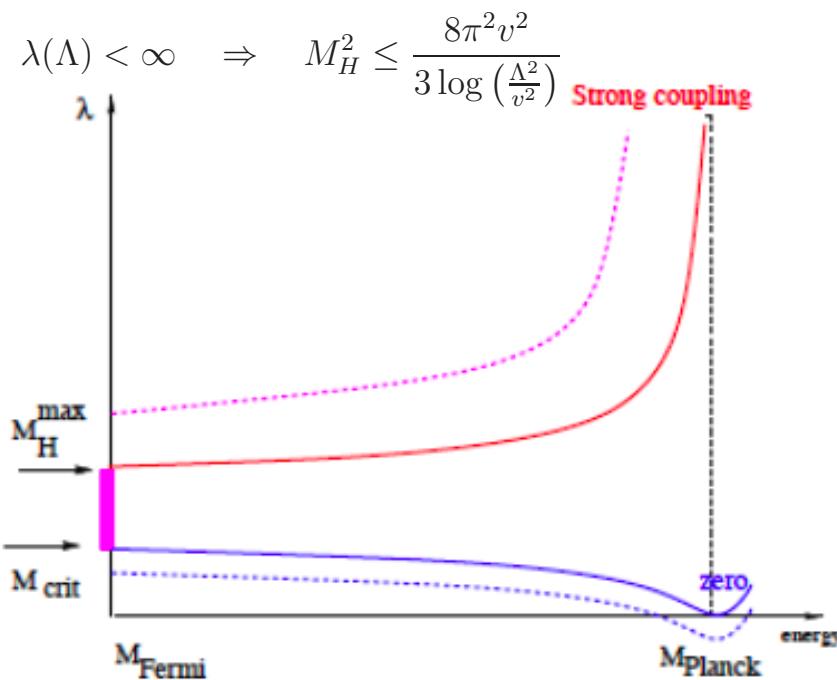


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# ***SM may well be a consistent effective theory all the way up to the Plank scale***

- ✓  $M_H < 175 \text{ GeV} \rightarrow \text{SM is a weakly coupled theory up to the Plank energies !}$
- ✓  $M_H > 111 \text{ GeV} \rightarrow \text{EW vacuum is stable or metastable with a lifetime greatly exceeding the age of our Universe (Espinosa et al)}$

See e.g. arXiv:1405.3781



- ✓ No sign of New Physics seen

# No sign of New Physics seen

## What is not found..

### ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$$

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

Model	e, $\mu$ , $\tau$ , $\gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	1.7 TeV m( $\tilde{q}$ )=m( $\tilde{g}$ )
	MSUGRA/CMSSM	1 e, $\mu$	3-6 jets	Yes	20.3	any m( $\tilde{q}$ )
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	any m( $\tilde{q}$ )
	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{q}^0$	0	2-6 jets	Yes	20.3	1.2 TeV m( $\tilde{q}^0$ )=0 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}^0$	0	2-6 jets	Yes	20.3	1.1 TeV m( $\tilde{q}^0$ )=0 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}^0 \rightarrow qqW^{\pm}\tilde{l}^0$	1 e, $\mu$	3-6 jets	Yes	20.3	740 GeV m( $\tilde{q}^0$ )=>200 GeV, m( $\tilde{l}^0$ )=>0.5(m( $\tilde{q}^0$ )+m( $\tilde{g}$ ))
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}^0 \rightarrow q\ell\ell/\ell\nu\tilde{l}^0$	2 e, $\mu$	0-3 jets	-	20.3	m( $\tilde{q}^0$ )=0 GeV tan $\beta$ <15
	GMSSB ( $\tilde{\tau}$ NLSP)	2 e, $\mu$	0-2 jets	Yes	4.7	1.18 TeV tan $\beta$ >18
	GGM (bino NLSP)	1-2 $\tau$	0-2 jets	Yes	20.7	1.12 TeV m( $\tilde{\tau}$ )>50 GeV
	GGM (wino NLSP)	2 $\gamma$	-	Yes	4.8	1.24 TeV m( $\tilde{\tau}$ )>200 GeV
3 <sup>rd</sup> gen. & med.	GGM (higgsino-bino NLSP)	1 e, $\mu$ + $\gamma$	-	Yes	4.8	1.07 TeV m( $\tilde{\tau}$ )>50 GeV
	GGM (higgsino-bino NLSP)	2 $\gamma$	1 b	Yes	4.8	619 GeV m( $\tilde{\tau}$ )>200 GeV
	GGM (higgsino NLSP)	2 e, $\mu$ (Z)	0-3 jets	Yes	5.8	900 GeV m( $\tilde{\tau}$ )>200 GeV
	Gravitino LSP	0	mono-jet	Yes	10.5	690 GeV m( $\tilde{\tau}$ )>10 <sup>-4</sup> eV
3 <sup>rd</sup> gen. direct production	$\tilde{g}\rightarrow b\bar{b}\tilde{l}^0$	0	3 b	Yes	20.1	1.2 TeV m( $\tilde{l}^0$ )<600 GeV
	$\tilde{g}\rightarrow t\bar{t}\tilde{l}^0$	0	7-10 jets	Yes	20.3	1.1 TeV m( $\tilde{l}^0$ )<350 GeV
	$\tilde{g}\rightarrow t\bar{t}\tilde{l}^0$	0-1 e, $\mu$	3 b	Yes	20.1	1.34 TeV m( $\tilde{l}^0$ )<400 GeV
	$\tilde{g}\rightarrow b\bar{b}\tilde{l}^0$	0-1 e, $\mu$	3 b	Yes	20.1	1.3 TeV m( $\tilde{l}^0$ )<300 GeV
EW direct	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{l}^0$	0	2 b	Yes	20.1	100-820 GeV m( $\tilde{l}^0$ )<90 GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow t\tilde{l}^0$	2 e, $\mu$ (SS)	0-3 b	Yes	20.7	275-430 GeV m( $\tilde{l}^0$ )>2 m( $\tilde{b}_1$ )
	$\tilde{b}_1\tilde{b}_1(\text{light}), \tilde{b}_1\rightarrow b\tilde{l}^0$	1-2 e, $\mu$	1-2 b	Yes	4.7	110-167 GeV m( $\tilde{l}^0$ )>55 GeV
	$\tilde{b}_1\tilde{b}_1(\text{light}), \tilde{b}_1\rightarrow W\tilde{l}^0$	2 e, $\mu$	0-2 jets	Yes	20.3	130-220 GeV m( $\tilde{l}^0$ )>m( $\tilde{b}_1$ )-m(W)-50 GeV, m( $\tilde{b}_1$ )<<m( $\tilde{l}^0$ )
	$\tilde{b}_1\tilde{b}_1(\text{medium}), \tilde{b}_1\rightarrow t\tilde{l}^0$	2 e, $\mu$	2 jets	Yes	20.3	225-525 GeV m( $\tilde{l}^0$ )>0 GeV
	$\tilde{b}_1\tilde{b}_1(\text{medium}), \tilde{b}_1\rightarrow b\tilde{l}^0$	0	2 b	Yes	20.1	150-580 GeV m( $\tilde{l}^0$ )>200 GeV, m( $\tilde{l}^0$ )-m( $\tilde{b}_1$ )>5 GeV
	$\tilde{b}_1\tilde{b}_1(\text{heavy}), \tilde{b}_1\rightarrow t\tilde{l}^0$	1 e, $\mu$	1 b	Yes	20.7	200-610 GeV m( $\tilde{l}^0$ )>0 GeV
	$\tilde{b}_1\tilde{b}_1(\text{heavy}), \tilde{b}_1\rightarrow b\tilde{l}^0$	0	2 b	Yes	20.5	320-660 GeV m( $\tilde{l}^0$ )>m( $\tilde{b}_1$ )<85 GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow c\tilde{l}^0$	0	Monö-jet/c-tag	Yes	20.3	90-200 GeV m( $\tilde{l}^0$ )>150 GeV
	$\tilde{b}_1\tilde{b}_1(\text{natural GMSSB})$	2 e, $\mu$ (Z)	1 b	Yes	20.7	500 GeV m( $\tilde{l}^0$ )>180 GeV
Long-Lived Particles	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{l}^0$	3 e, $\mu$ (Z)	1 b	Yes	20.7	271-520 GeV m( $\tilde{l}^0$ )>180 GeV
	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow \tilde{\ell}^0\tilde{\ell}^0$	2 e, $\mu$	0	Yes	20.3	85-315 GeV m( $\tilde{\ell}^0$ )>0 GeV
	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow \tilde{\ell}^0(\tilde{\nu})$	2 e, $\mu$	0	Yes	20.3	125-450 GeV m( $\tilde{\ell}^0$ )>0 GeV, m( $\tilde{\ell}^0$ )>0.5(m( $\tilde{\ell}^0$ ))+m( $\tilde{\ell}^0$ )
	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow \tilde{\ell}^0\tilde{\ell}^0$	2 $\tau$	-	Yes	20.7	180-330 GeV m( $\tilde{\ell}^0$ )>0 GeV, m( $\tilde{\ell}^0$ )>0.5(m( $\tilde{\ell}^0$ ))+m( $\tilde{\ell}^0$ )
RPV	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow \ell\tilde{\nu}_1, \ell\tilde{\nu}_1$	3 e, $\mu$	0	Yes	20.7	600 GeV m( $\tilde{\ell}^0$ )>m( $\tilde{\ell}^0$ ), m( $\tilde{\ell}^0$ )>0, sleptons decoupled
	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow W\tilde{l}^0 Z\tilde{l}^0$	3 e, $\mu$	0	Yes	20.7	315 GeV m( $\tilde{\ell}^0$ )>m( $\tilde{\ell}^0$ ), m( $\tilde{\ell}^0$ )>0, sleptons decoupled
	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow W\tilde{l}^0_1 h\tilde{l}^0_1$	1 e, $\mu$	2 b	Yes	20.3	285 GeV m( $\tilde{\ell}^0$ )>m( $\tilde{\ell}^0$ ), m( $\tilde{\ell}^0$ )>0, sleptons decoupled
	Direct $\tilde{\chi}_1^- \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	270 GeV m( $\tilde{\ell}^0$ )-m( $\tilde{\ell}^0$ )>160 MeV, $\tau(\tilde{\ell}^0)>0.2$ ns
Other	Stable, stopped R-hadron	0	1-5 jets	Yes	22.9	822 GeV m( $\tilde{\ell}^0$ )>190 GeV, 10 $\mu\text{e} < \tau(\tilde{\ell}^0) < 1000$ s
	GMSSB, stable $\tilde{\tau}$ , $\tilde{\tau}^0 \rightarrow \tilde{\tau}(e, \tilde{\mu}) + \tau(e, \mu)$	-	-	-	15.9	475 GeV 10 < tan $\beta$ < 50
	GMSSB, $\tilde{\tau} \rightarrow \gamma G$ , long-lived $\tilde{\tau}_1$	2 $\gamma$	-	Yes	4.7	230 GeV 0.4 < tan $\beta$ < 2 ns
	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{q}u$ (RPV)	1 $\mu$ , dispel. vtx	-	-	20.3	1.0 TeV 1.5 < cr<158 mm, BR( $\mu$ )<1, m( $\tilde{\tau}^0$ )>108 GeV
RPV	LFV $pp\rightarrow \tilde{\tau}_1 + X, \tilde{\tau}_1\rightarrow e + \mu$	2 e, $\mu$	-	-	4.6	1.61 TeV $\lambda_{121}=-0.10, \lambda_{122}=0.06$
	LFV $pp\rightarrow \tilde{\tau}_1 + X, \tilde{\tau}_1\rightarrow e(\mu) + \tau$	1 e, $\mu + \tau$	-	-	4.6	$\lambda_{311}=-0.10, \lambda_{1212}=0.05$
	Bilinear RPV CMSSM	1 e, $\mu$	7 jets	Yes	4.7	$m(\tilde{\tau}^0)>m(\tilde{\ell}^0)$ , $c\tau_{250}<1$ mm
	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow W\tilde{l}^0_1 \tilde{l}^0_2 + ee\tilde{\nu}_e, ee\tilde{\nu}_e$	4 e, $\mu$	-	Yes	20.7	$m(\tilde{\ell}^0_1)>300$ GeV, $\lambda_{321}>0$
	$\tilde{\chi}_{1,0}^0, \tilde{\chi}_{1,0}^0\rightarrow W\tilde{l}^0_1 \tilde{l}^0_2 + \tau\tau\tilde{\nu}_\tau, \tau\tau\tilde{\nu}_\tau$	3 e, $\mu + \tau$	-	Yes	20.7	$m(\tilde{\ell}^0_1)>80$ GeV, $\lambda_{313}>0$
	$\tilde{g}\rightarrow q\tilde{q}q$	0	5-7 jets	-	20.3	$BR(\tau)=BR(b)+BR(c)=0\%$
	$\tilde{g}\rightarrow b\tilde{t}_1, \tilde{t}_1\rightarrow bs$	2 e, $\mu$ (SS)	0-3 b	Yes	20.7	ATLAS-CONF-2013-007
	Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	-	4.6	Incl. limit from 1110.2693
Other	Scalar gluon pair, sgluon $\rightarrow t\tilde{t}$	2 e, $\mu$ (SS)	1 b	Yes	14.3	1210.4826
	WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	ATLAS-CONF-2013-051
$\sqrt{s} = 7 \text{ TeV}$ full data					$\sqrt{s} = 8 \text{ TeV}$ full data	
$\sqrt{s} = 7 \text{ TeV}$ partial data					$\sqrt{s} = 8 \text{ TeV}$ partial data	

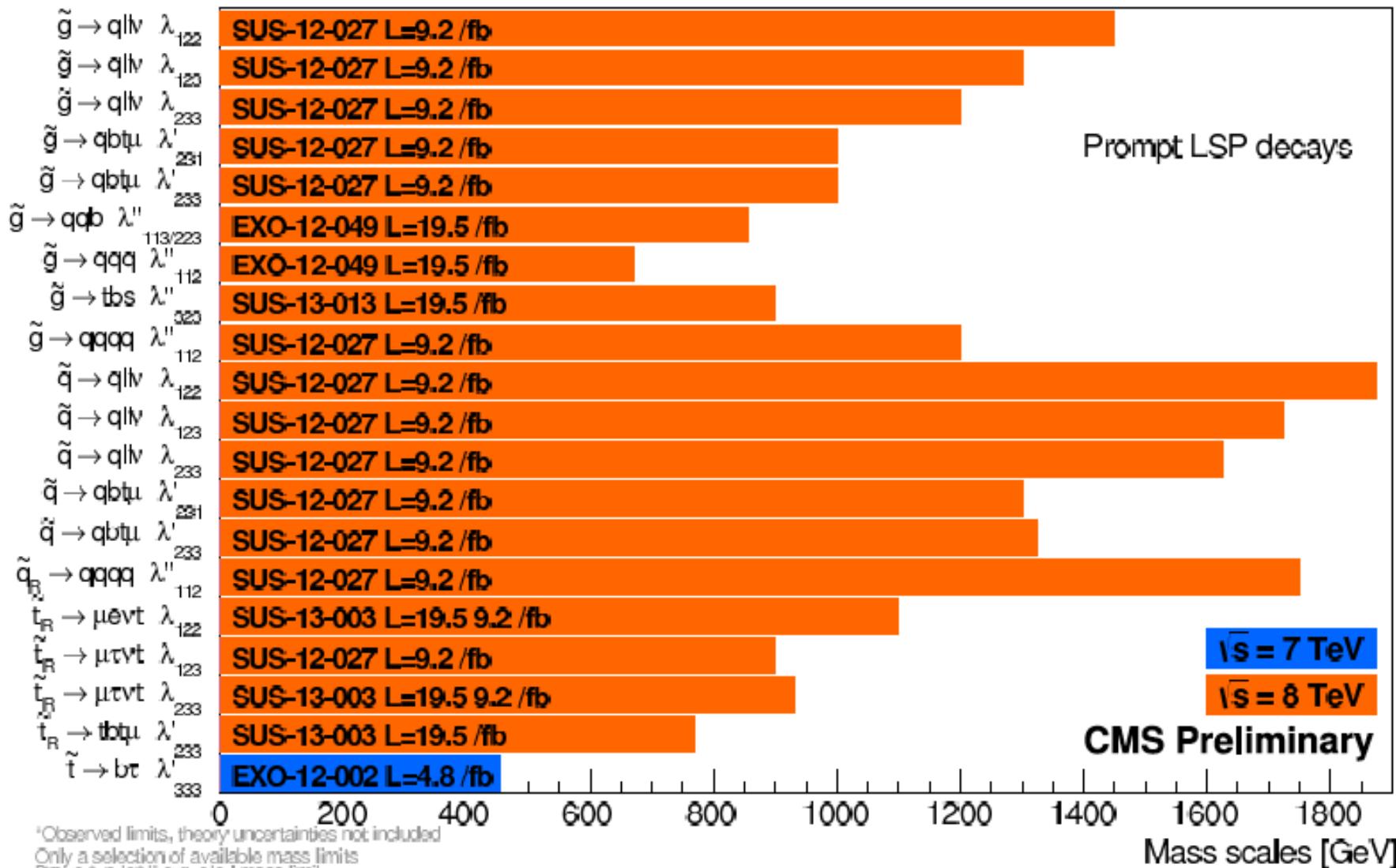
10<sup>-1</sup> 1 Mass scale [TeV]

# No sign of New Physics seen

## What is not found..

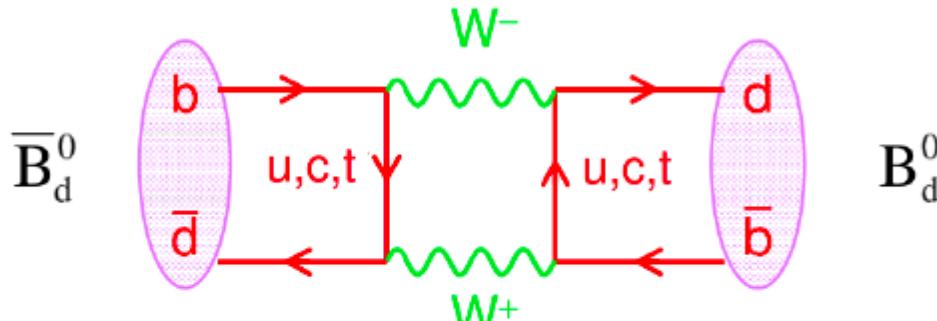
### Summary of CMS RPV SUSY Results\*

EPSHEP 2013

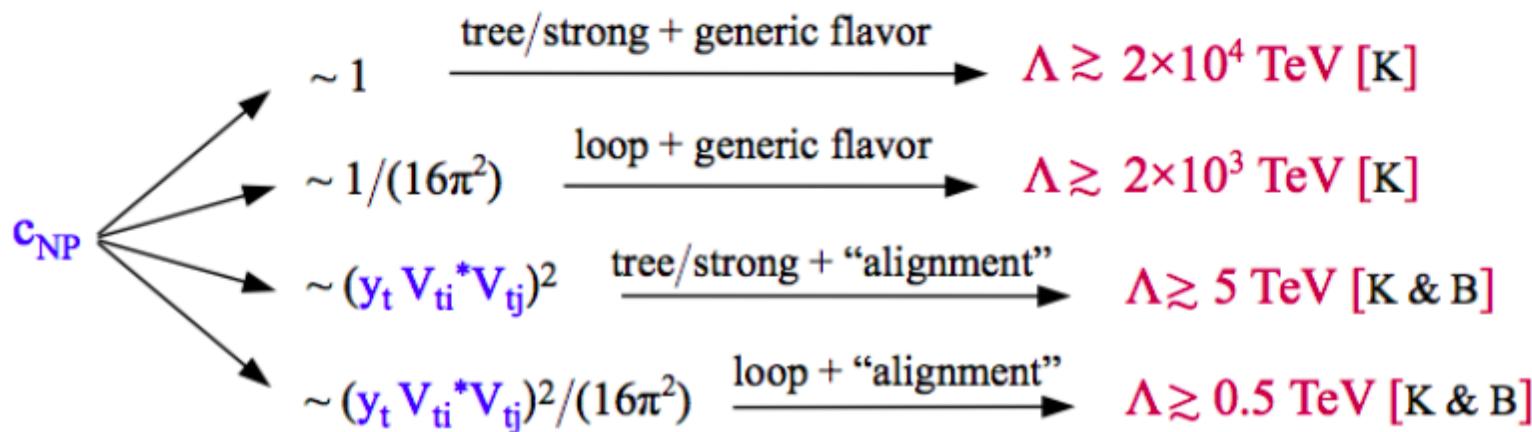
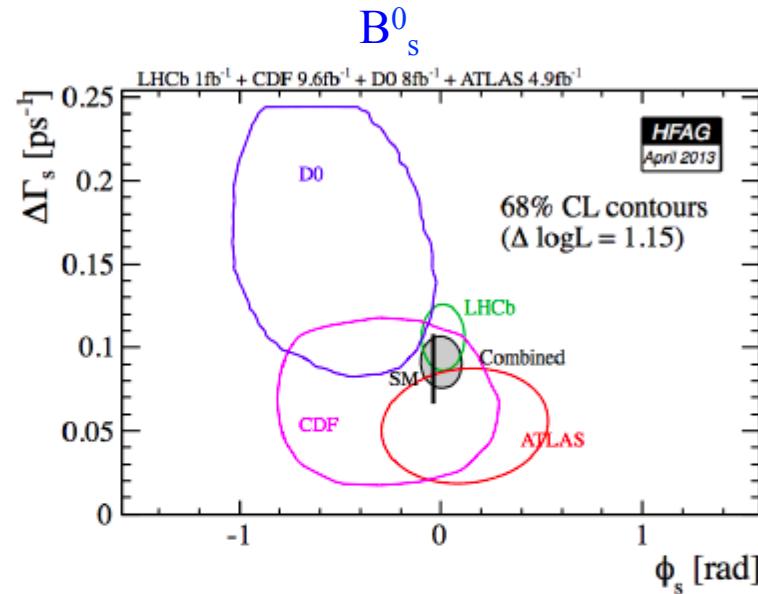


# Bounds on the scale of New Physics

Most stringent limits come from observables in  $B\bar{B}$  mixing



$$M(B_d^0 - \bar{B}_d^0) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP} \frac{1}{\Lambda^2}$$



# Theoretical motivation

- Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model  
The SM may work successfully up to Planck scale !
- SM is unable to explain:
  - Neutrino masses & oscillations
  - Excess of matter over antimatter in the Universe
  - The nature of non-baryonic Dark Matter
- All three issues can be solved by adding three new fundamental fermions, right-handed Majorana Heavy Neutral Leptons (HNL):  $N_1$ ,  $N_2$  and  $N_3$



**vMSM:** T.Asaka, M.Shaposhnikov PL B620 (2005) 17

Three Generations of Matter (Fermions) spin ½					
	I	II	III		
mass →	2.4 MeV	1.27 GeV	173.2 GeV		
charge →	2/3	2/3	2/3		
name →	u up	c charm	t top		
Quarks	I	II	III		
mass →	4.8 MeV	104 MeV	4.2 GeV		
charge →	-1/3	-1/3	-1/3		
name →	d down	s strange	b bottom		
Leptons	I	II	III		
mass →	0.511 MeV	105.7 MeV	1.777 GeV		
charge →	-1	-1	-1		
name →	e electron	$\mu$ muon	$\tau$ tau		
Bosons (Forces) spin 1	I	II	III		
mass →	91.2 GeV	0	126 GeV		
charge →	0	0	0		
name →	Z weak force	H Higgs boson	W weak force		



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mass →	0.511 MeV	105.7 MeV	1.777 GeV		
charge →	-1	-1	-1		
name →	e electron	$\mu$ muon	$\tau$ tau		
Bosons (Forces) spin 1	I	II	III		
mass →	91.2 GeV	~10 keV	126 GeV		
charge →	0	~GeV	0		
name →	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino		
Bosons (Forces) spin 0	I	II	III		
mass →	80.4 GeV	80.4 GeV	80.4 GeV		
charge →	+1	+1	+1		
name →	Z weak force	H Higgs boson	W weak force		

# See-saw generation of neutrino masses

Most general renormalisable Lagrangian of all SM particles (+3 singlets wrt the SM gauge group):

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

Yukawa term: mixing of  $N_I$  with active neutrinos to explain oscillations

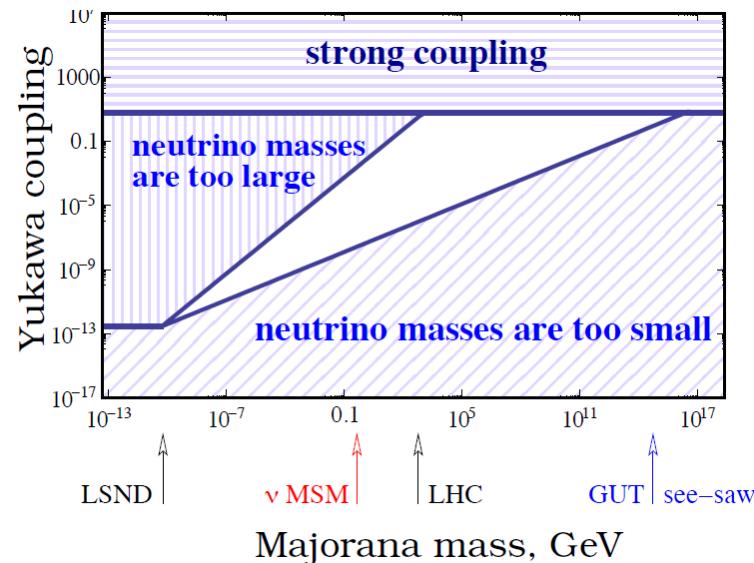
Majorana term which carries no gauge charge

The scale of the active neutrino mass is given by the see-saw formula:  $m_\nu \sim \frac{m_D^2}{M}$  where  $m_D \sim Y_{I\alpha} v$  - typical value of the Dirac mass term

$$v \sim 246 \text{ GeV}$$

## Example:

For  $M \sim 1 \text{ GeV}$  and  $m_\nu \sim 0.05 \text{ eV}$  it results in  $m_D \sim 10 \text{ keV}$  and Yukawa coupling  $\sim 10^{-7}$



# The $\nu$ MSM model

Three Generations of Matter (Fermions) spin $\frac{1}{2}$			Three Generations of Matter (Fermions) spin $\frac{1}{2}$												
I	II	III	I	II	III										
mass → charge → name →	2.4 MeV $\frac{2}{3}$ u up Left Right	1.27 GeV $\frac{2}{3}$ c charm Left Right	173.2 GeV $\frac{2}{3}$ t top Left Right	mass → charge → name →	2.4 MeV $\frac{2}{3}$ u up Left Right	1.27 GeV $\frac{2}{3}$ c charm Left Right	173.2 GeV $\frac{2}{3}$ t top Left Right	mass → charge → name →	2.4 MeV $\frac{2}{3}$ u up Left Right	1.27 GeV $\frac{2}{3}$ c charm Left Right	173.2 GeV $\frac{2}{3}$ t top Left Right				
Quarks	d down Left Right	s strange Left Right	b bottom Left Right	d down Left Right	s strange Left Right	b bottom Left Right	d down Left Right	s strange Left Right	b bottom Left Right	d down Left Right	s strange Left Right	b bottom Left Right			
Leptons	$\nu_e$ electron neutrino Left Right	$\nu_\mu$ muon neutrino Left Right	$\nu_\tau$ tau neutrino Left Right	$\nu_e$ electron neutrino Left Right	$\nu_\mu$ muon neutrino Left Right	$\nu_\tau$ tau neutrino Left Right	$\nu_e$ electron neutrino Left Right	$\nu_\mu$ muon neutrino Left Right	$\nu_\tau$ tau neutrino Left Right	$\nu_e$ electron neutrino Left Right	$\nu_\mu$ muon neutrino Left Right	$\nu_\tau$ tau neutrino Left Right			
	0.511 MeV -1 e electron Left Right	105.7 MeV -1 $\mu$ muon Left Right	1.777 GeV -1 $\tau$ tau Left Right	0.511 MeV -1 e electron Left Right	105.7 MeV -1 $\mu$ muon Left Right	1.777 GeV -1 $\tau$ tau Left Right	0.511 MeV -1 e electron Left Right	105.7 MeV -1 $\mu$ muon Left Right	1.777 GeV -1 $\tau$ tau Left Right	0.511 MeV -1 e electron Left Right	105.7 MeV -1 $\mu$ muon Left Right	1.777 GeV -1 $\tau$ tau Left Right			
Bosons (Forces) spin 1	0 g gluon	0 $\gamma$ photon	91.2 GeV 0 Z weak force	126 GeV 0 H Higgs boson	spin 0	0 g gluon	0 $\gamma$ photon	91.2 GeV 0 Z weak force	126 GeV 0 H Higgs boson	spin 0	0 g gluon	0 $\gamma$ photon	91.2 GeV 0 Z weak force	126 GeV 0 H Higgs boson	spin 0
Bosons (Forces) spin 1	$\pm 1$ W weak force					$\pm 1$ W weak force				$\pm 1$ W weak force				$\pm 1$ W weak force	

N = Heavy Neutral Lepton - HNL

Role of  $N_1$  with mass in keV region: dark matter

Role of  $N_2$ ,  $N_3$  with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

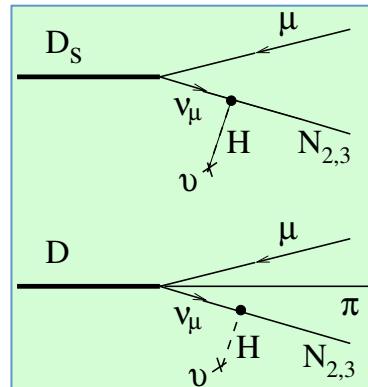
# Masses and couplings of HNLs

- $N_1$  can be sufficiently stable to be a DM candidate,  $M(N_1) \sim 10\text{keV}$
  - $M(N_2) \approx M(N_3) \sim \text{a few GeV} \rightarrow \text{CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)}$
- Very weak  $N_{2,3}$ -to- $\nu$  mixing ( $\sim U^2$ )  $\rightarrow N_{2,3}$  are much longer-lived than the SM particles

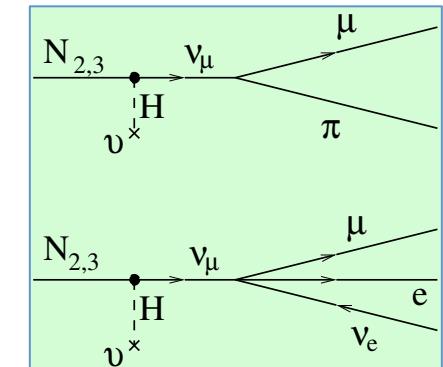


**Example:**

$N_{2,3}$  production in charm

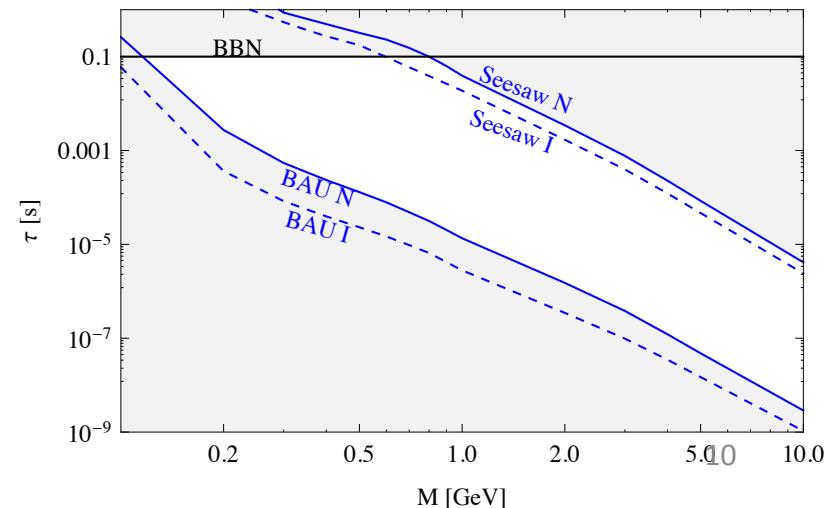


and subsequent decays



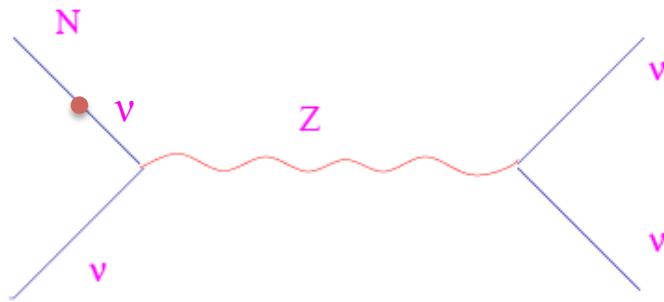
- Typical lifetimes  $> 10\ \mu\text{s}$  for  $M(N_{2,3}) \sim 1\ \text{GeV}$   
Decay distance  $O(\text{km})$
- Typical BRs (depending on the flavour mixing):

$$\begin{aligned} Br(N \rightarrow \mu/e \pi^-) &\sim 0.1 - 50\% \\ Br(N \rightarrow \mu/e^- \rho^+) &\sim 0.5 - 20\% \\ Br(N \rightarrow \nu \mu e^-) &\sim 1 - 10\% \end{aligned}$$



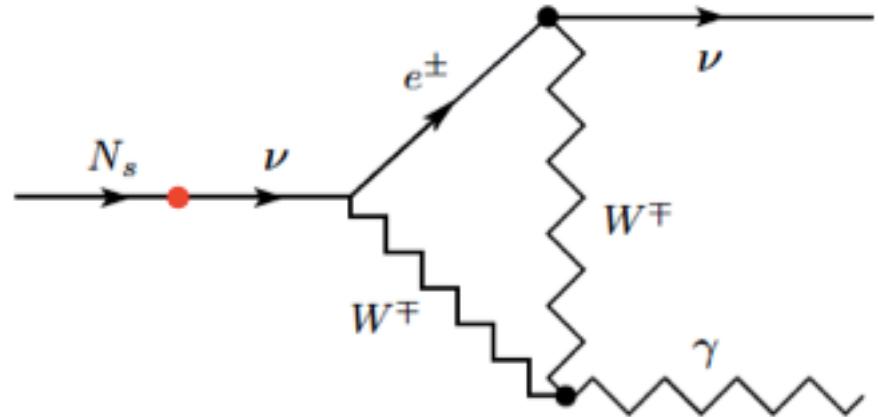
# *Dark Matter candidate HNL $N_1$*

Yukawa couplings are small →  
 $N$  can be very stable.



Main decay mode:  $N \rightarrow 3\nu$ .

Subdominant radiative decay channel:  $N \rightarrow \nu\gamma$ .



Photon energy:

$$E_\gamma = \frac{M}{2}$$

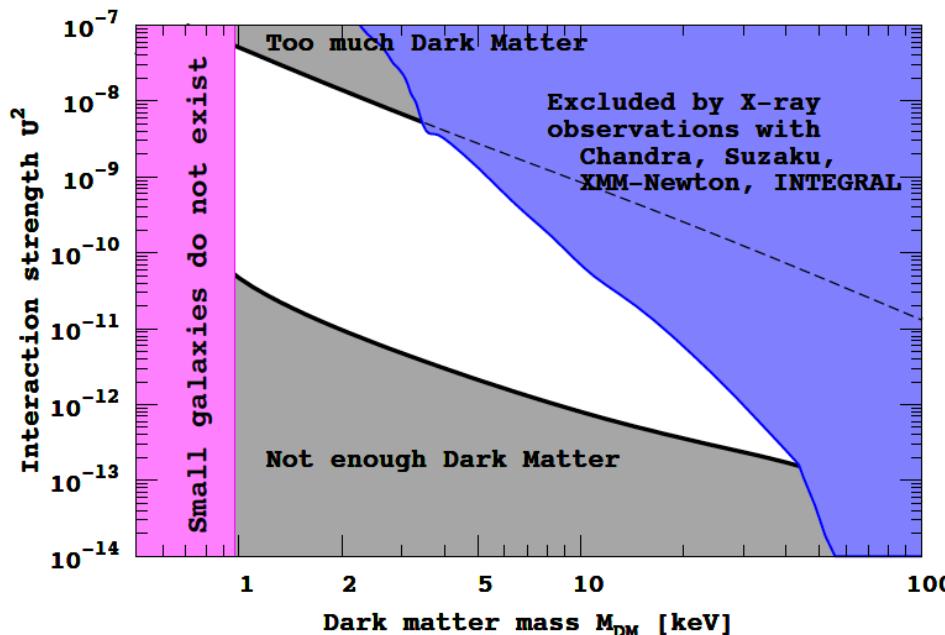
Radiative decay width:

$$\Gamma_{\text{rad}} = \frac{9 \alpha_{\text{EM}} G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) M_N^5$$

Interaction strength

# Constraints on DM HNL $N_1$

- ✓ **Stability** →  $N_1$  must have a lifetime larger than that of the Universe
- ✓ **Production** →  $N_1$  are created in the early Universe in reactions  
 $l\bar{l} \rightarrow \nu N_1$     $q\bar{q} \rightarrow \nu N_1$  etc. Need to provide correct DM abundance
- ✓ **Structure formation** →  $N_1$  should be heavy enough! Otherwise its free streaming length would erase structure non-uniformities at small scales ( Lyman- $\alpha$  forest spectra of distant quasars and structure of dwarf galaxies )
- ✓ **X-ray spectra** → Radiative decays  $N_1 \rightarrow \gamma\nu$  produce a mono-line in photon galaxies spectrum.



# Searches for DM HNL $N_1$ in space

- Has been previously searched with *XMM-Newton*, *Chandra*, *Suzaku*, *INTEGRAL*
- Spectral resolution is not enough (required  $\Delta E/E \sim 10^{-3}$ )
- Proposed/planned X-ray missions with sufficient spectral resolution:

**Astro-H**



**LOFT**



**Athena+**



**Origin/Xenia**



# New line in photon galaxy spectrum ???

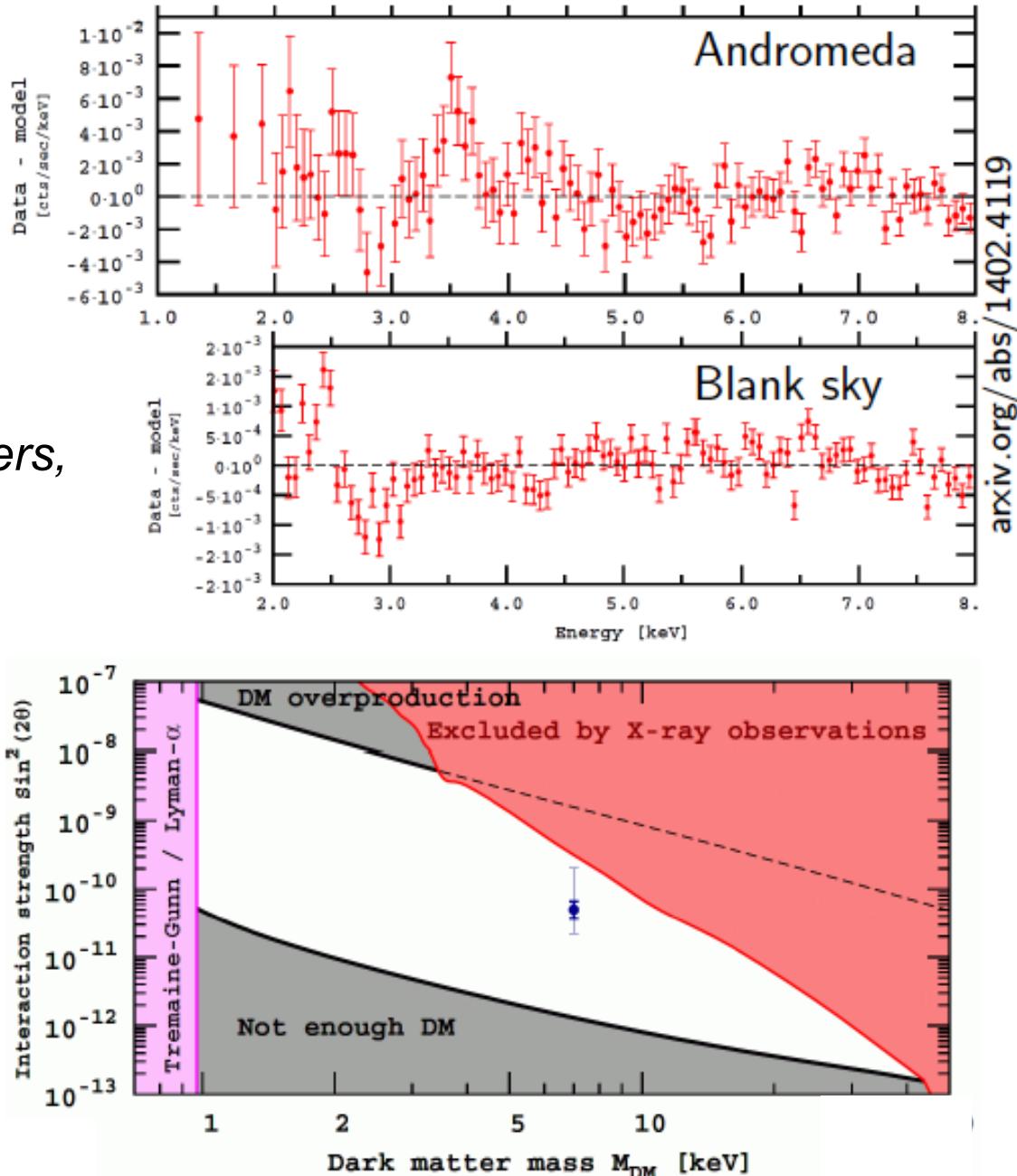
Two recent publications in arXiv:

- arXiv 1402.2301

*Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters,  $E_\gamma \sim 3.56$  keV*

- arXiv 1402.4119

*An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster,  $E_\gamma \sim 3.5$  keV*

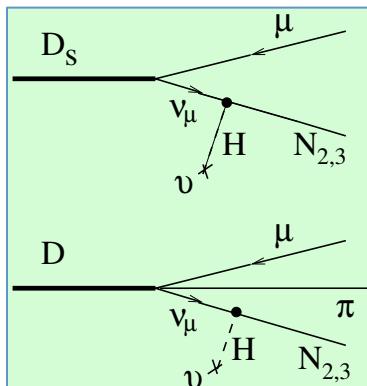


**Will soon be checked by Astro-H with higher energy resolution**

# Masses and couplings of HNLs

**Very weak  $N_{2,3}$ -to- $\nu$  mixing ( $\sim U^2$ )  $\rightarrow N_{2,3}$  are much longer-lived than the SM particles**

- Produced in semi-leptonic decays,  
 $K \rightarrow \mu\nu, D \rightarrow \mu\pi\nu, B \rightarrow D\mu\nu$

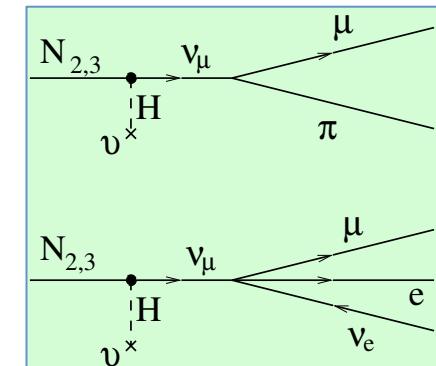


**Example:**

$N_{2,3}$  production in charm

- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

and subsequent  
decays

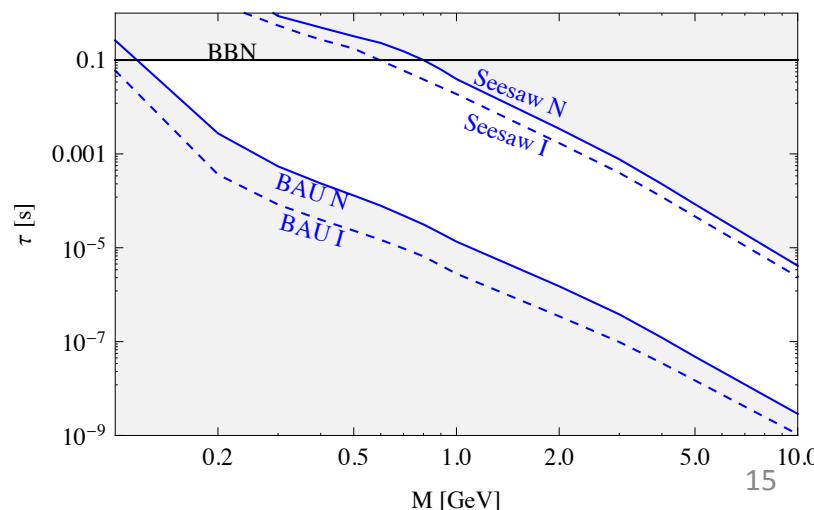


- Typical lifetimes  $> 10 \mu\text{s}$  for  $M(N_{2,3}) \sim 1 \text{ GeV}$   
 Decay distance  $O(\text{km})$
- Typical BRs (depending on the flavour mixing):

$$Br(N \rightarrow \mu/e \pi) \sim 0.1 - 50\%$$

$$Br(N \rightarrow \mu/e^- \rho^+) \sim 0.5 - 20\%$$

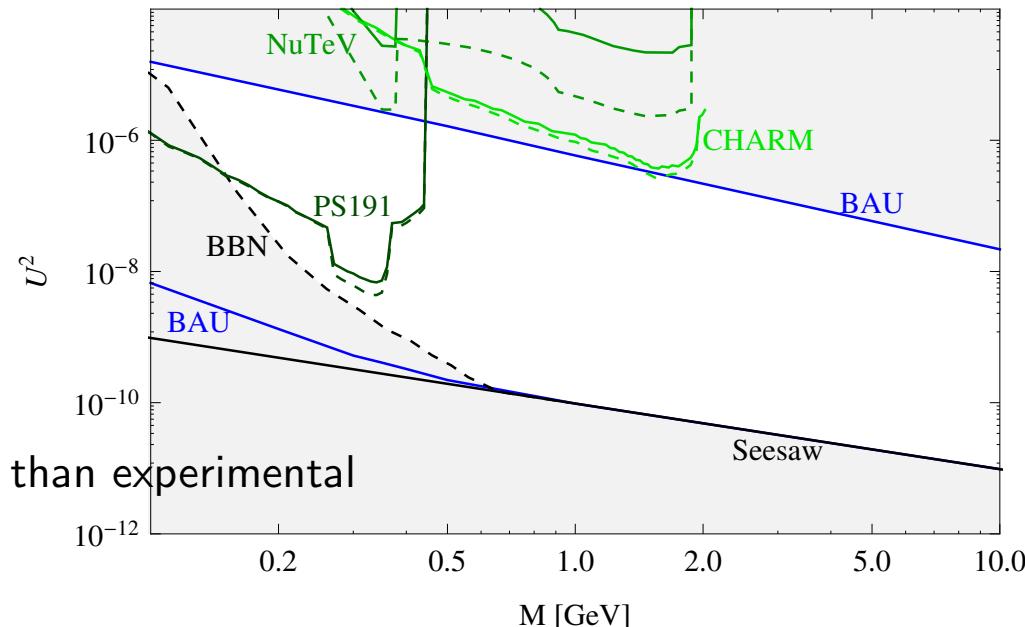
$$Br(N \rightarrow \nu\mu e) \sim 1 - 10\%$$



# Experimental and cosmological constraints

Already searches in K/D-decay performed:

- PS191('88)@PS 19.2 GeV,  
 $1.4 \times 10^{19}$  pot, 128 m from target.
- CHARM('86)@SPS 400 GeV,  
 $2.4 \times 10^{18}$  pot, 480 m from target.
- NuTeV('99)@Fermilab 800 GeV,  
 $2.5 \times 10^{18}$  pot, 1.4 km from target.
- BBN, BAU and Seesaw constrain more than experimental  
searches for  $M_N > 400$  MeV.



## - Recent progress in cosmology

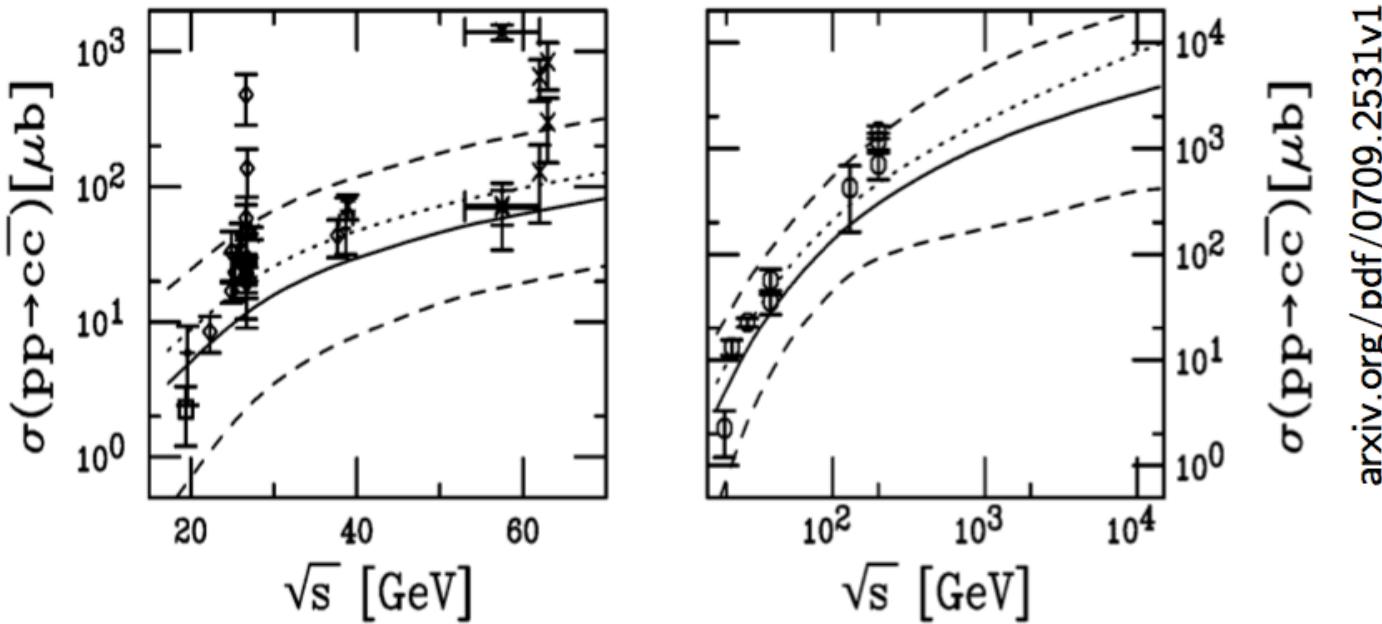
- The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass
- Strong motivation to explore cosmologically allowed parameter space

**Proposal for a new experiment at the SPS, SHIP to search for new long-lived particles produced in charm decays**  
(see <http://ship.web.cern.ch/ship>)

Experimentally this domain has not been well explored!

# Sensitivity for $N_{2,3} \propto U^4$

- PS-191: Used K decays  $\rightarrow$  limited to 500 MeV (PLB 203 (1988) 332)
- Goal: Extend mass range to  $\sim 2$  GeV by using charmed hadron decays
- B-decays: 20÷100 smaller  $\sigma$ , and  $B \rightarrow D\mu\nu$ , i.e. limited to 3 GeV still



Where to produce charmed hadrons?

LHC ( $\sqrt{s} = 14$  TeV): with  $1 ab^{-1}$  ( $\sim 3\text{-}4$  years):  $\sim 2 \times 10^{16}$  in  $4\pi$

SPS (400 GeV  $p$ -on-target (pot)  $\sqrt{s} = 27$  GeV): with  $2 \times 10^{20}$  pot ( $\sim 3\text{-}4$  years):  $\sim 2 \times 10^{17}$

Moreover, the acceptance of a beam dump facility can be much larger for long lived particles

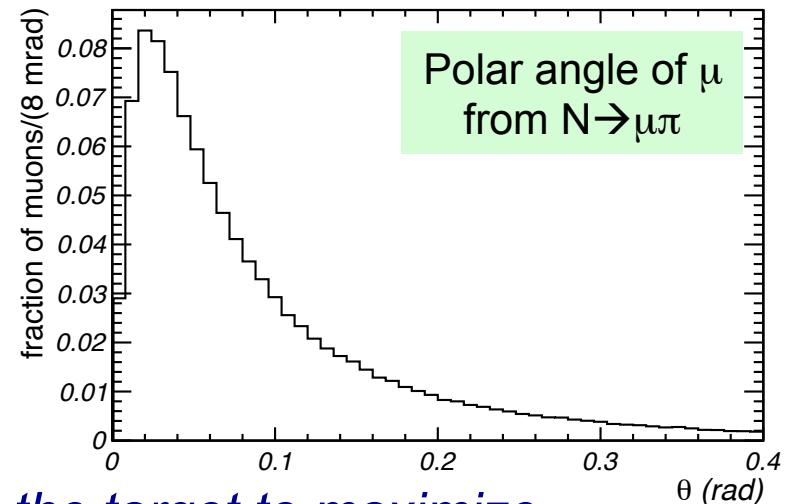
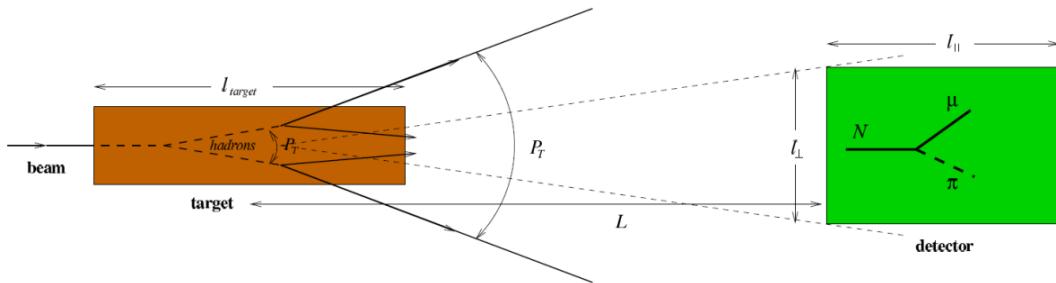
# Experimental requirements

- Search for HNL in Heavy Flavour decays



Beam dump experiment at the SPS with a total of  $2 \times 10^{20}$  protons on target (pot) to produce a large number of charmed hadrons  
CNGS:  $1.8 \times 10^{20}$  pot, 2011 run:  $4.8 \times 10^{19}$  pot

- HNLs produced in charm decays have significant  $P_T$



Detector must be placed close to the target to maximize geometrical acceptance



Effective (and “short”) muon shield is essential to reduce muon-induced backgrounds (mainly from short-lived resonances accompanying charm production)

# Secondary beam-line

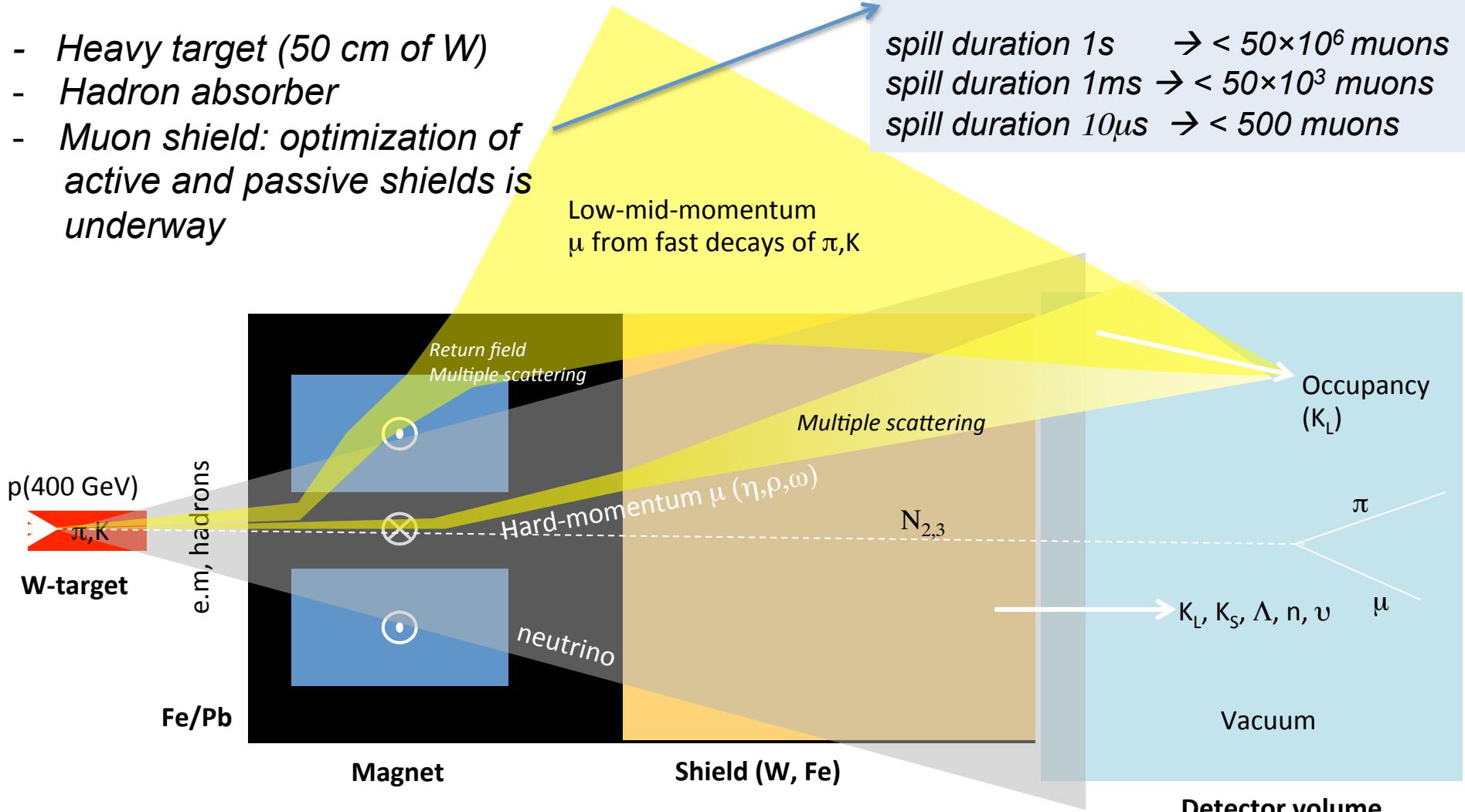
(different from a conventional neutrino facility)

## Initial reduction of beam induced backgrounds

- Heavy target (50 cm of W)
- Hadron absorber
- Muon shield: optimization of active and passive shields is underway

Acceptable occupancy <1% per spill  
of  $5 \times 10^{13}$  p.o.t.

spill duration 1s →  $< 50 \times 10^6$  muons  
spill duration 1ms →  $< 50 \times 10^3$  muons  
spill duration 10 $\mu$ s →  $< 500$  muons

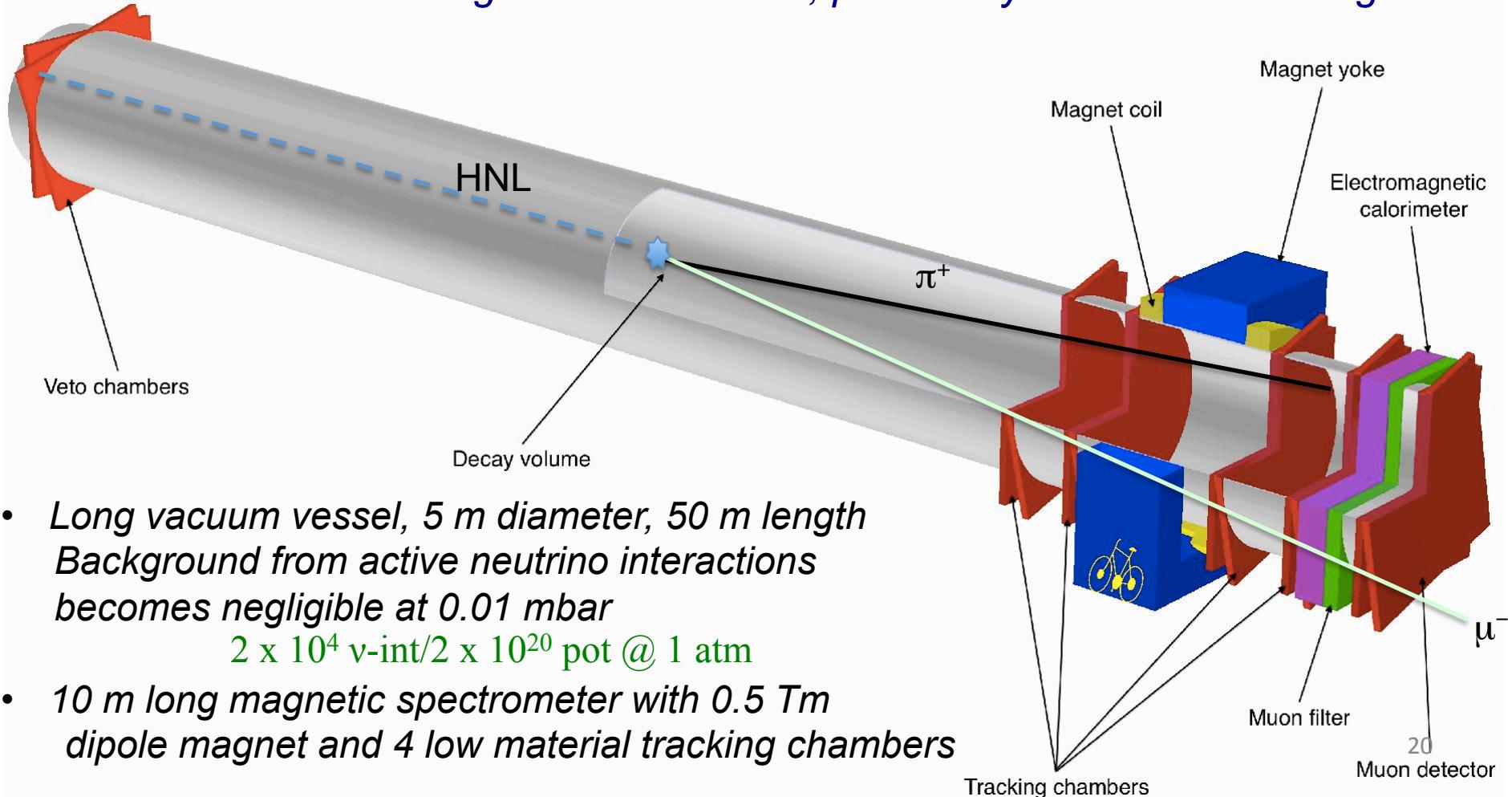


Generic setup, not to scale!

# Detector concept

(based on existing technologies)

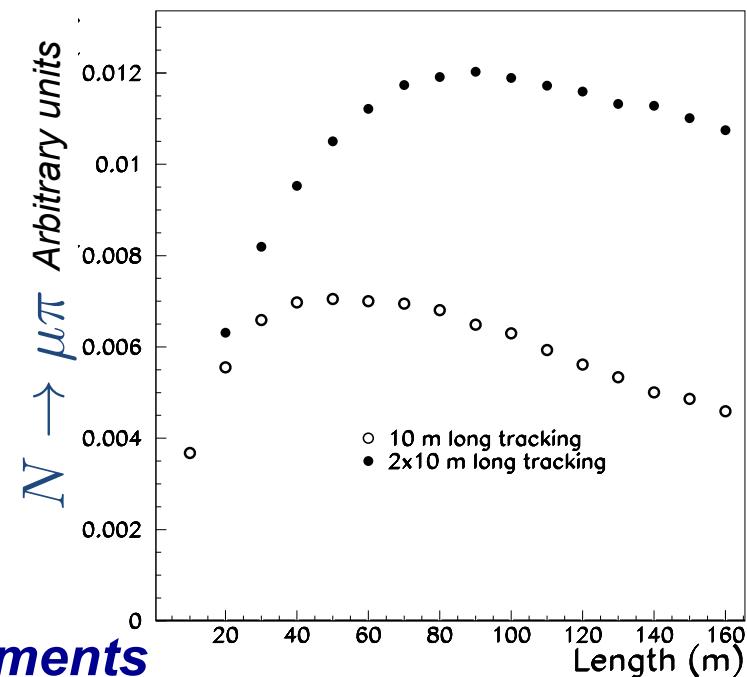
- Reconstruction of the HNL decays in the final states:  $\mu^-\pi^+$ ,  $\mu^-\rho^+$  &  $e^-\pi^+$
- Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building



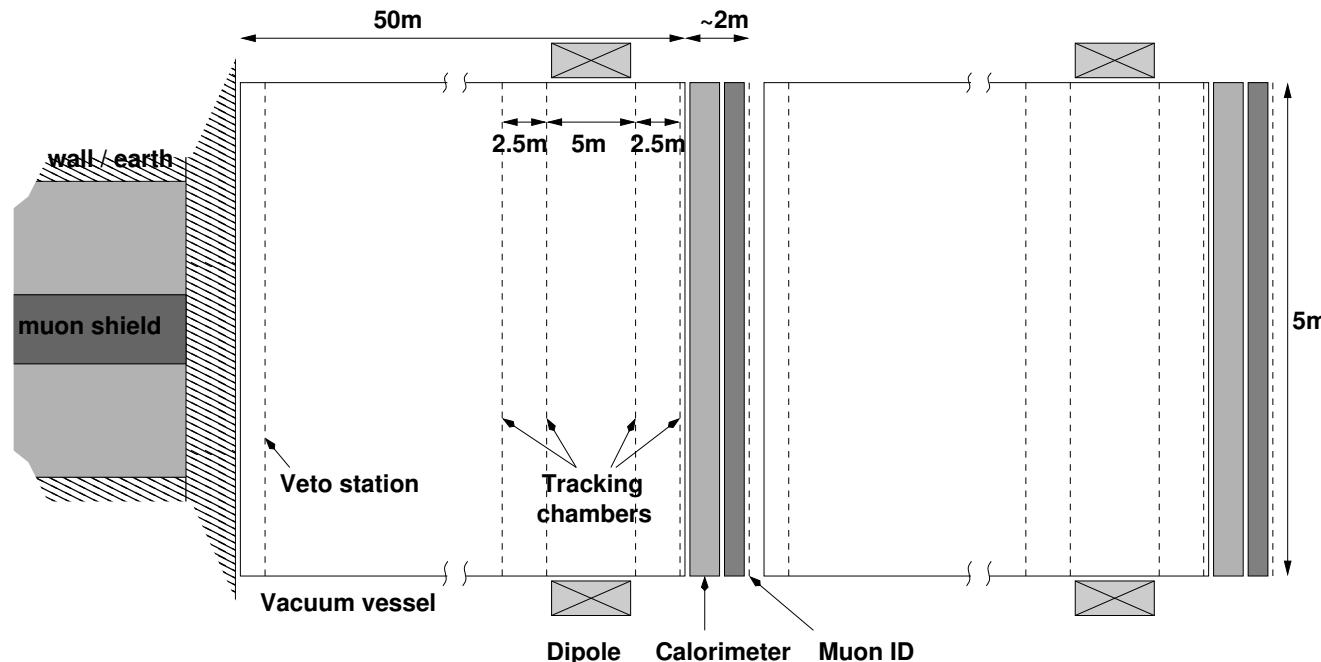
# Detector concept (cont.)

## Geometrical acceptance

- Saturates for a given HNL lifetime as a function of detector length
- The use of two magnetic spectrometers increases the acceptance by 70%



→ Detector has two almost identical elements



# Tracking chambers

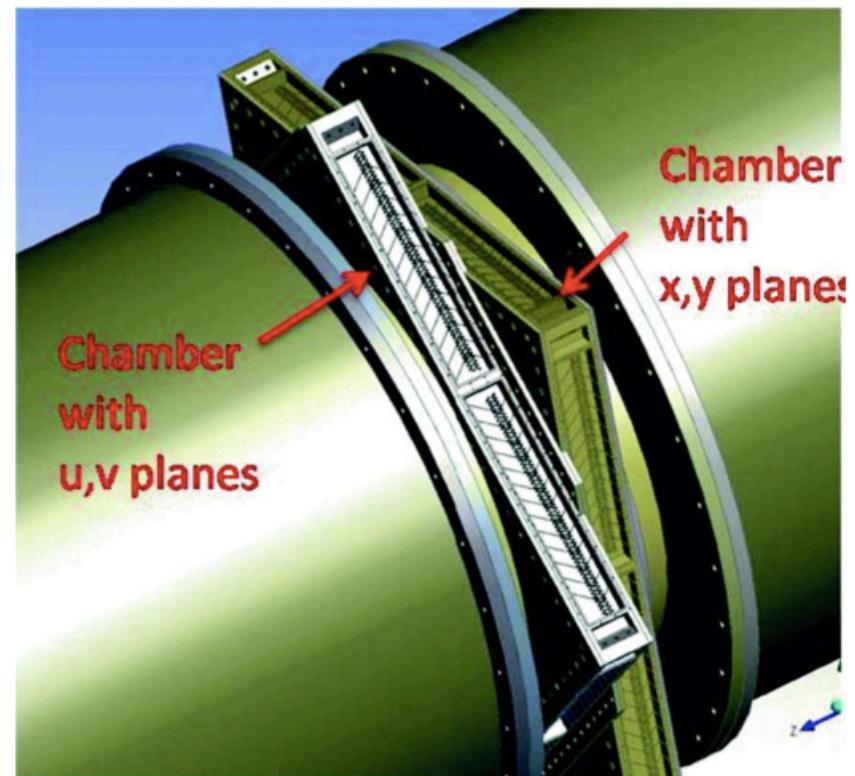
Same as NA62 ( $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ )

2m diameter vessel at 0.01  $\mu\text{bar}$

10 mm diameter straws made of PET → working well in vacuum

$X/X_0 = 0.5\%$  for 4 view stations

120  $\mu\text{m}$  resolution/straw



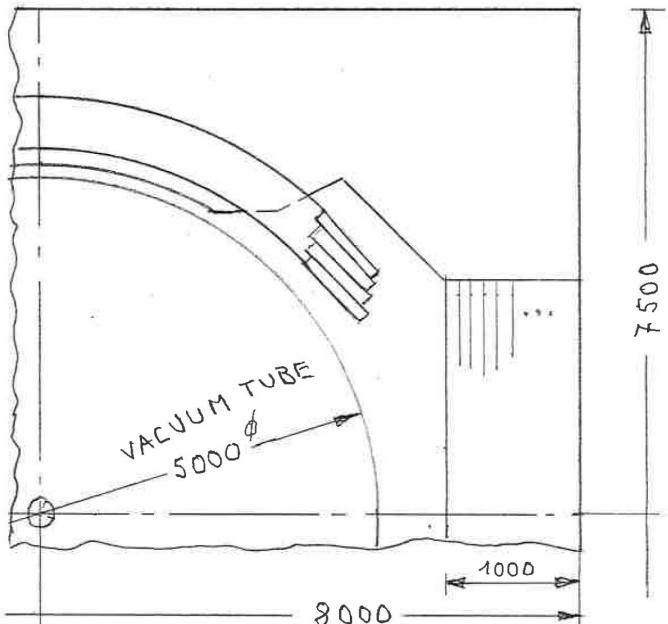
# Magnet and e.m. calo

- With  $X/X_0=0.5\%$  chambers: modest 0.5 Tm
- Need  $\sim 20\text{ m}^2$  aperture.

LHCb magnet: 4 Tm, 16 m<sup>2</sup> aperture

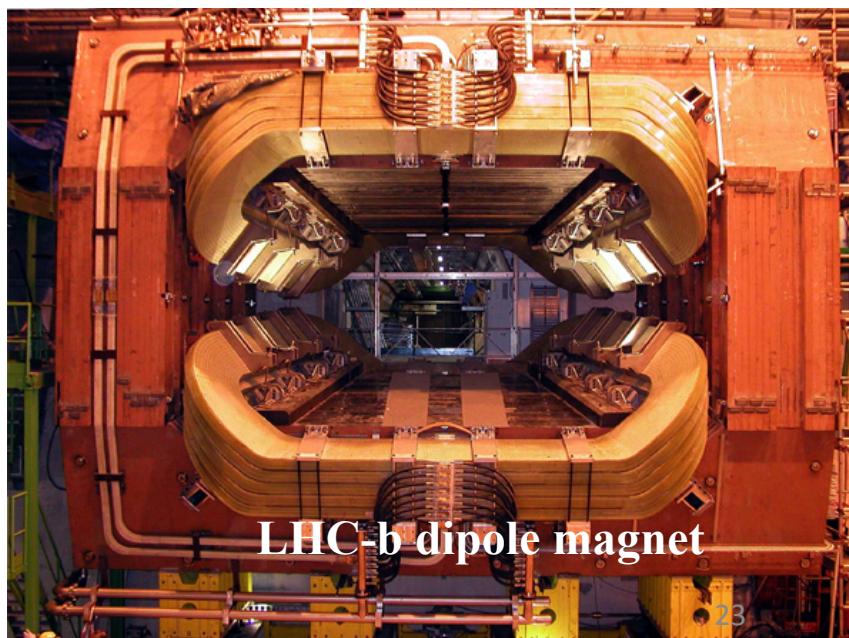
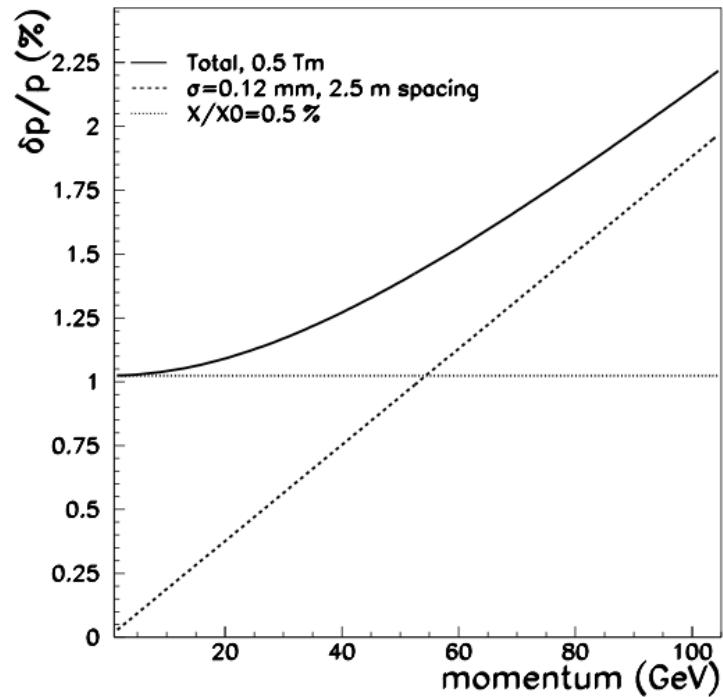
Preliminary calculations (W.Flegel):

- Needs 30 % less iron/yoke than LHCb.
- Consumes 3 times less power.



LHCb Shashlik ECAL:

- $6.3 \times 7.8\text{ m}^2$
- $\frac{\sigma(E)}{E} < 10\%/\sqrt{E} \oplus 1.5\%$

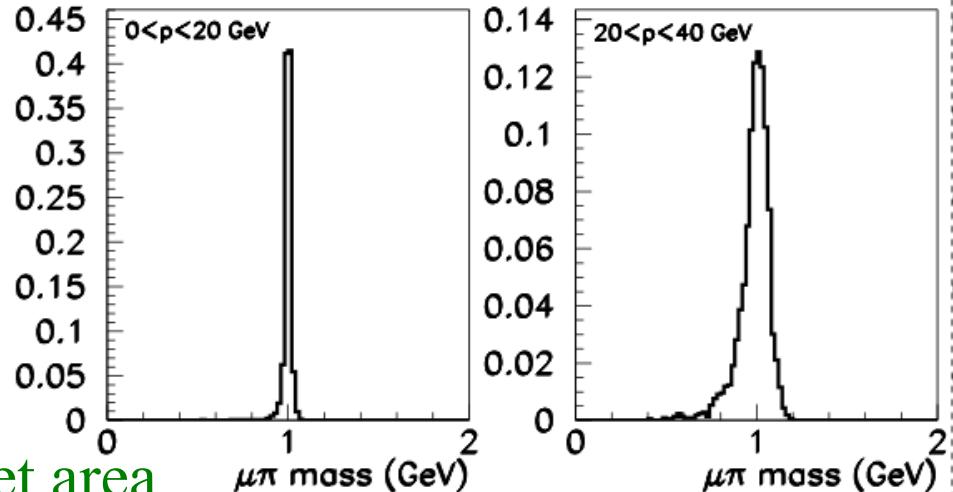


LHC-b dipole magnet

# Mass resolution

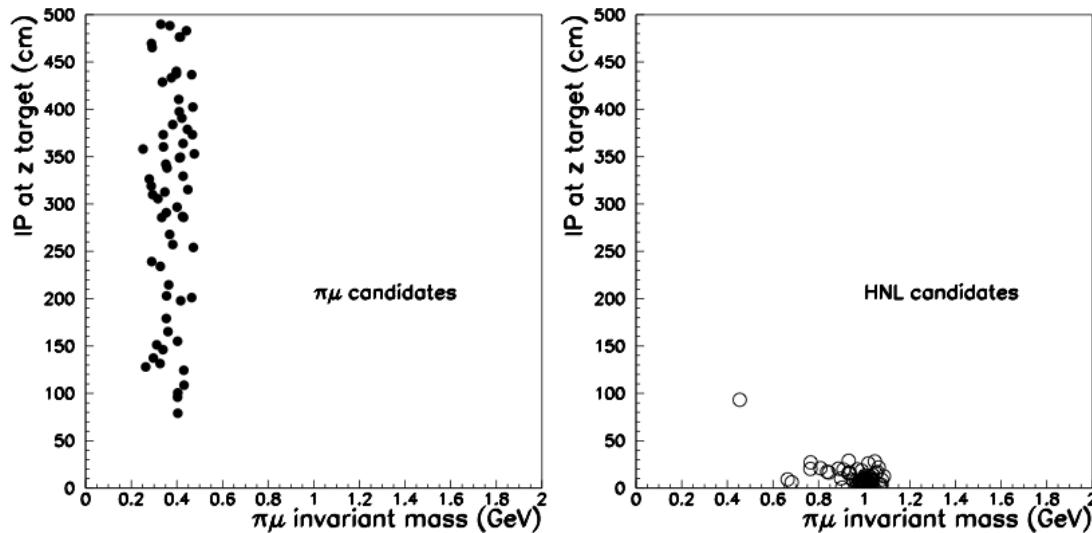
Expected resolution for 1 GeV  $N \rightarrow \mu\pi$   
 $\langle p_N \rangle = 25 \text{ GeV}$

- $\sigma_{\text{mass}} \sim 40 \text{ MeV}$  for  $P < 20 \text{ GeV}$



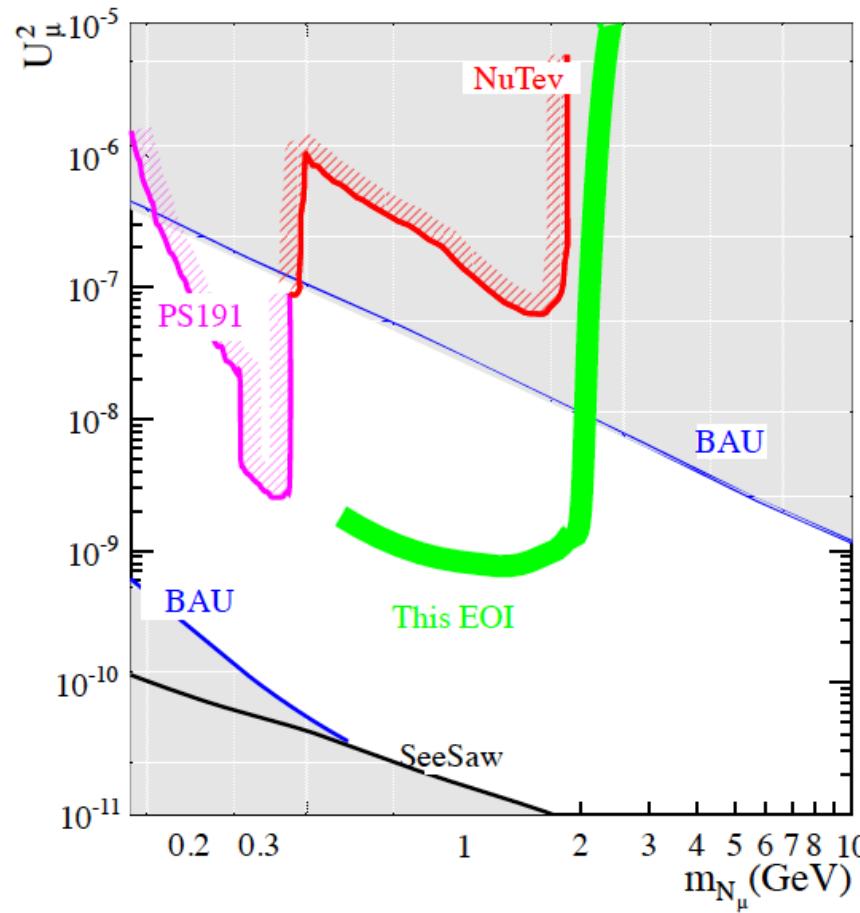
$K^0_L$  background suppression

- Use pointing of candidates to target area
- Detect CC via extra  $\mu$  in coincidence with  $\mu\pi$
- Instrument  $\mu$ -filter to tag CC/NC shower



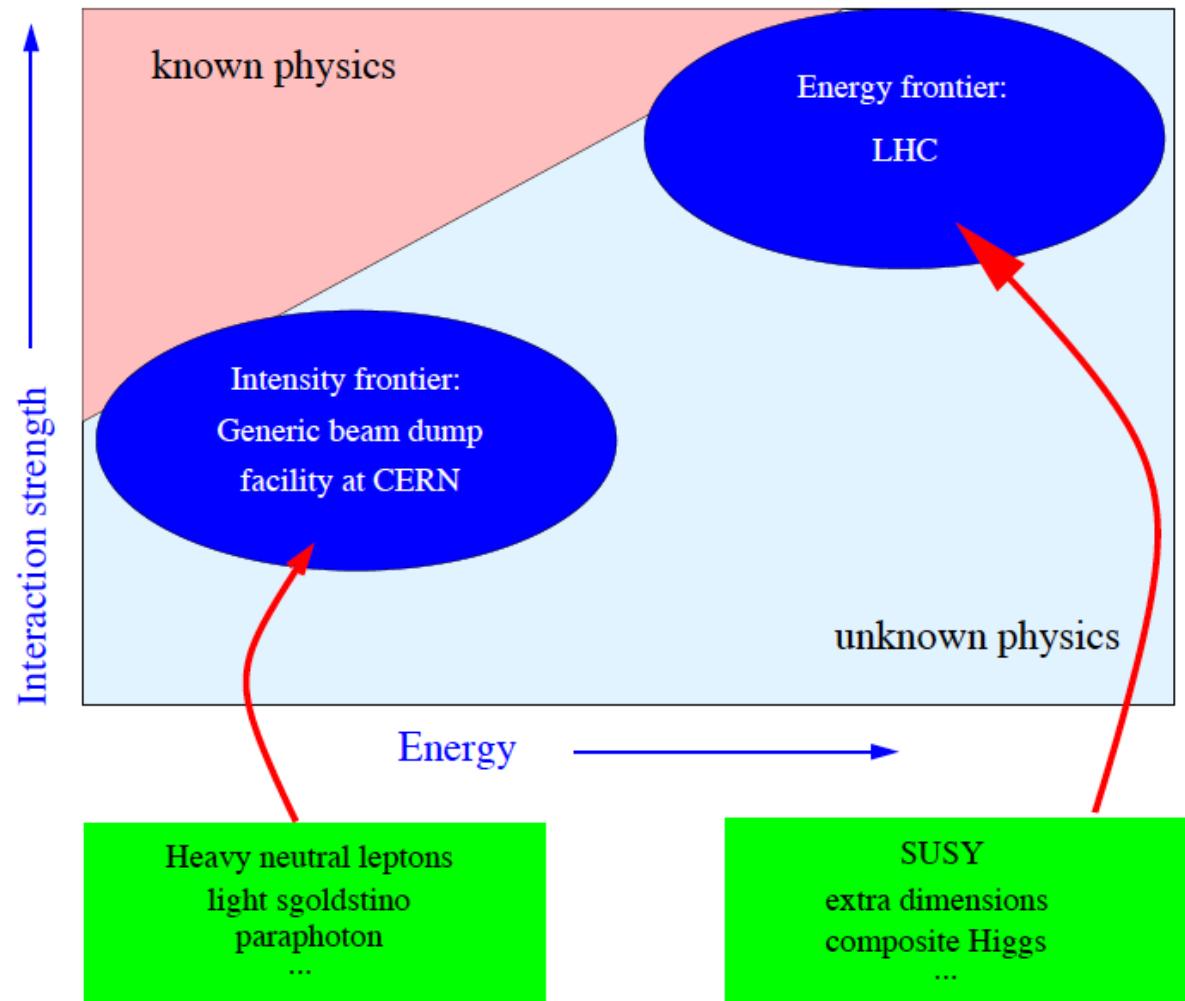
# Expected event yield

Assuming  $U_\mu^2 = 10^{-7}$  (corresponding to the strongest experimental limit currently for  $M_N \sim 1$  GeV) and  $\tau_N = 1.8 \times 10^{-5}$  s  
~12k fully reconstructed  $N \rightarrow \mu^- \pi^+$  events are expected for  $M_N = 1$  GeV



120 events for cosmologically favoured region:  $U_\mu^2 = 10^{-8}$  &  $\tau_N = 1.8 \times 10^{-4}$  s

# Physics case for general beam dump facility



hidden sector:

HNL: baryon asymmetry of the Universe, dark matter, neutrino masses

sgoldstino, light neutralino: SUSY

paraphoton: mirror matter, dark matter

# **Physics case for general beam dump facility**

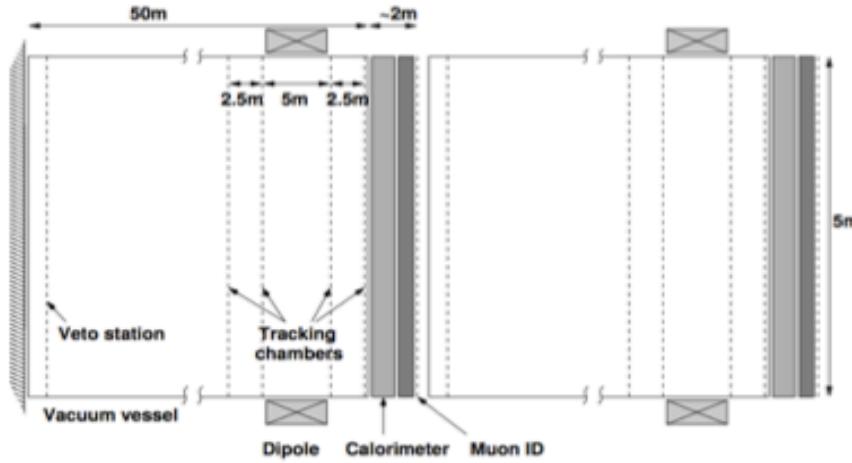
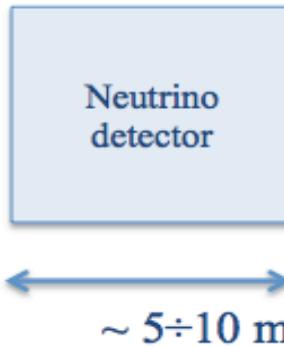
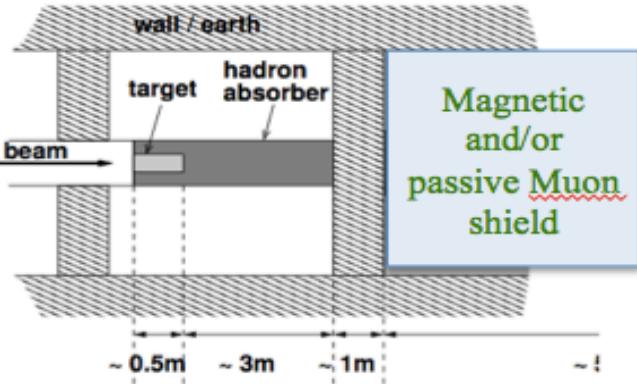
- ✓ ***Study of  $\nu_\tau$  interactions (guaranteed SM physics)***

*Ideally suited since  $\nu_\tau$  is produced in  $D_s \rightarrow \tau \nu_\tau$  with similar to HNL kinematics. DONUT 9 events, OPERA 4 events (from oscillations)*

- ✓ *Search for any weakly interacting yet unstable particles produced in very rare charm (or hyperon) decays such as low mass SUSY or paraphotons or ...*
- ✓ *Review of the SHIP sensitivities for  $\nu_\tau$  physics and wide class of models with hidden portals is ongoing*

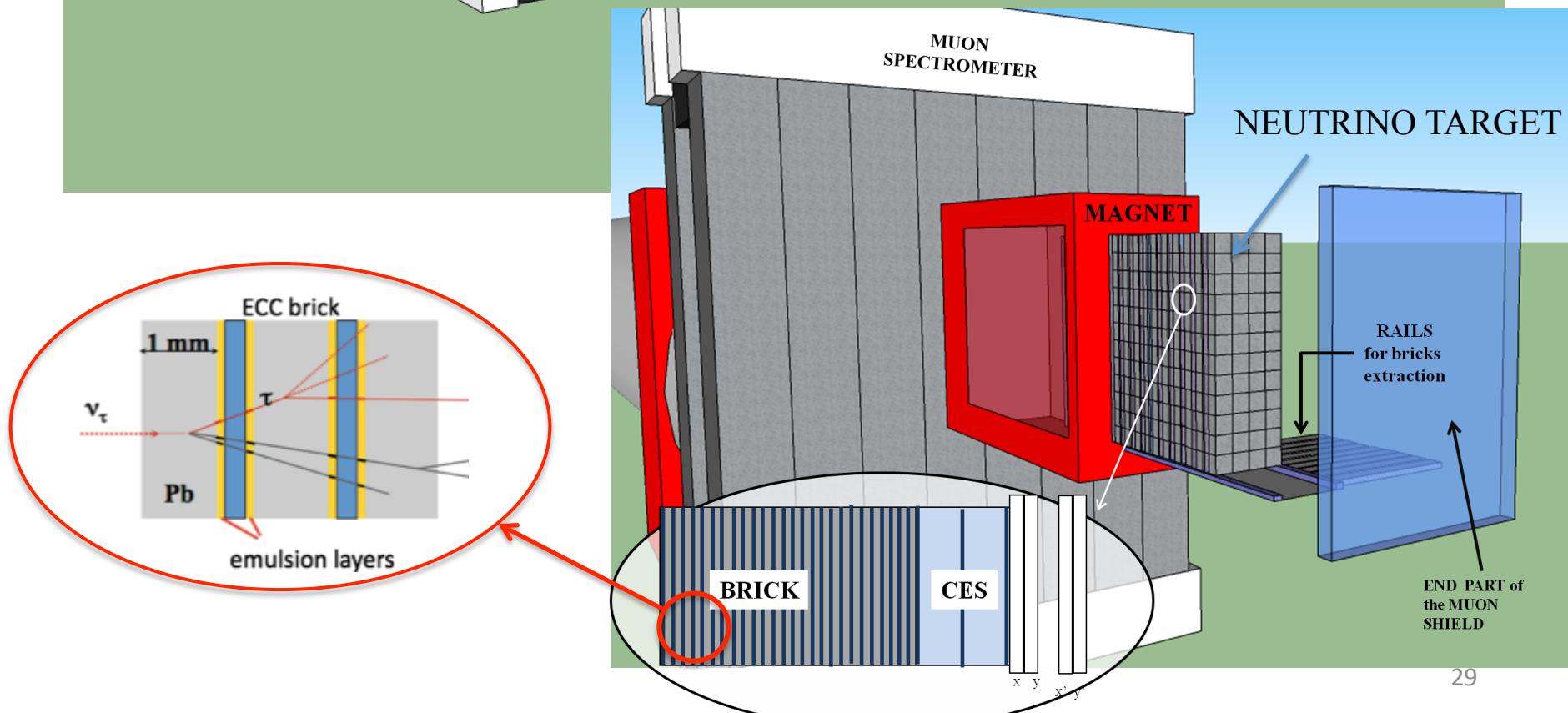
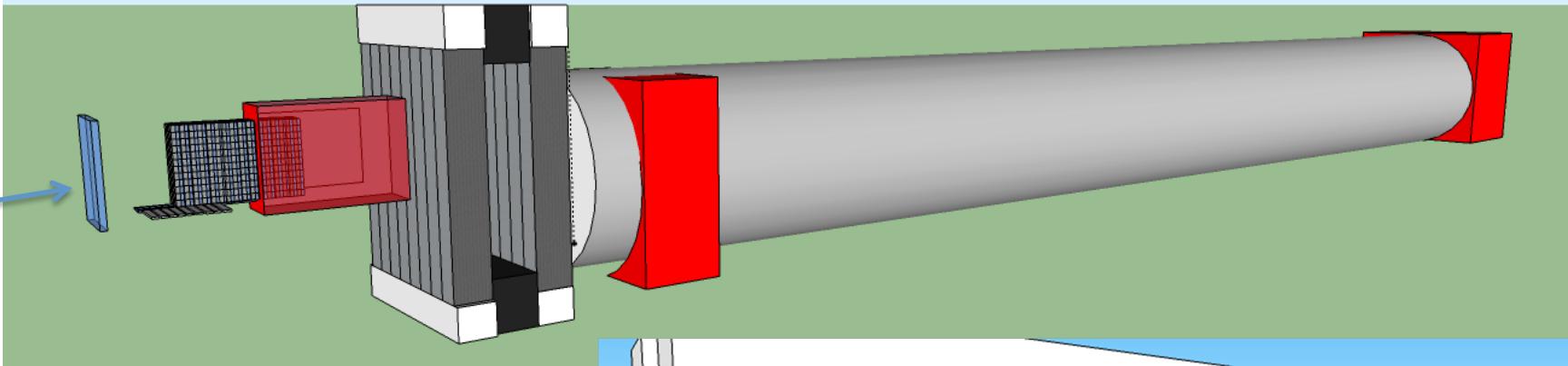
***Expect significant improvement of currently available measurements and constrains everywhere!***

# SM: $\nu_\tau$ physics with $2 \times 10^{20}$ pot

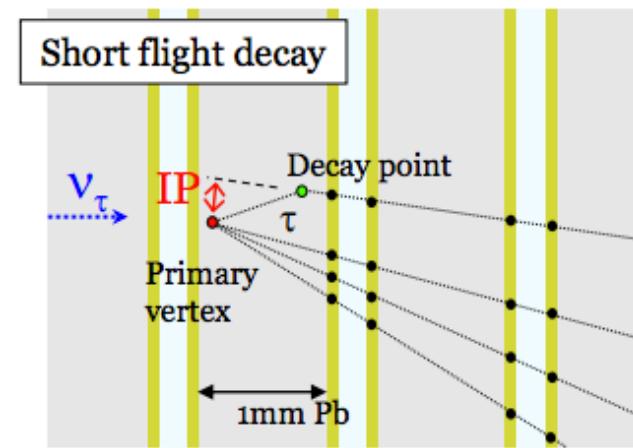
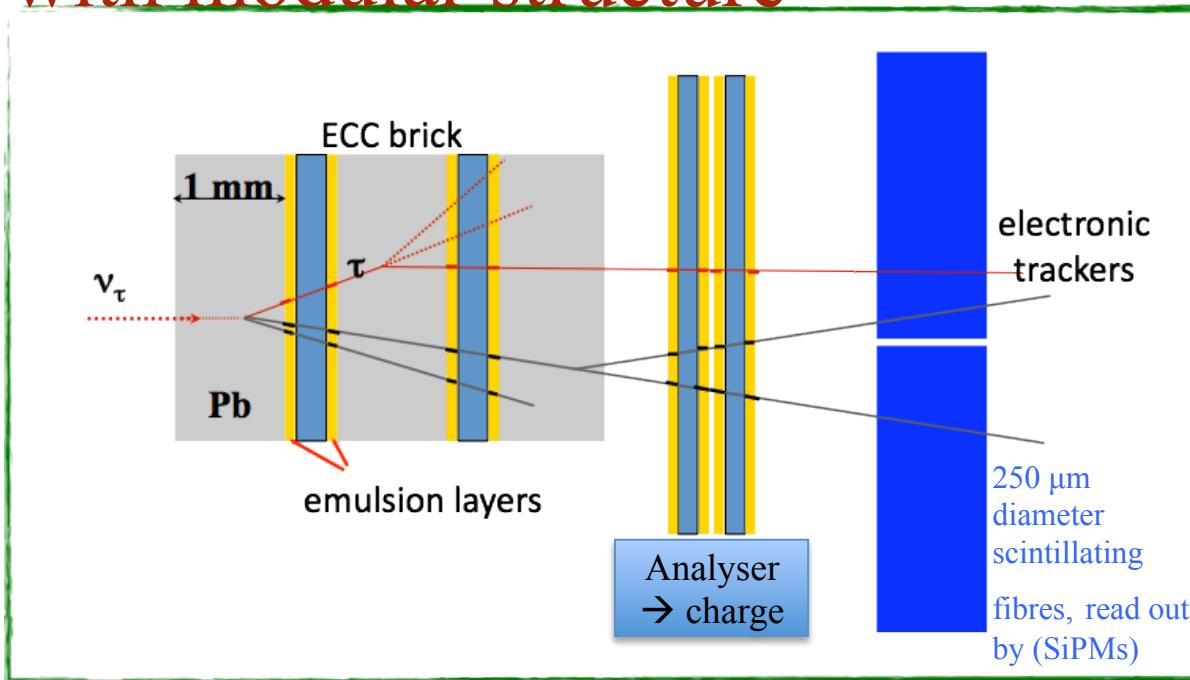


- Good physics program with a compact neutrino detector
- Expect  $\sim 3400$   $\nu_\tau$  interactions in 6 tons emulsion target (5% of the OPERA emulsion films)
- Tau neutrino and anti-neutrino (never seen) physics
- Charm physics with neutrinos and anti-neutrinos
- Electron neutrino studies (high energy cross-section, only low energy studies for oscillations) and  $\nu_e$  induced charm ( $\sim 1000$  events)
- $\nu_\tau$ : a probe of non-standard interactions PRD 87 (2013) 013002

# A neutrino detector upstream



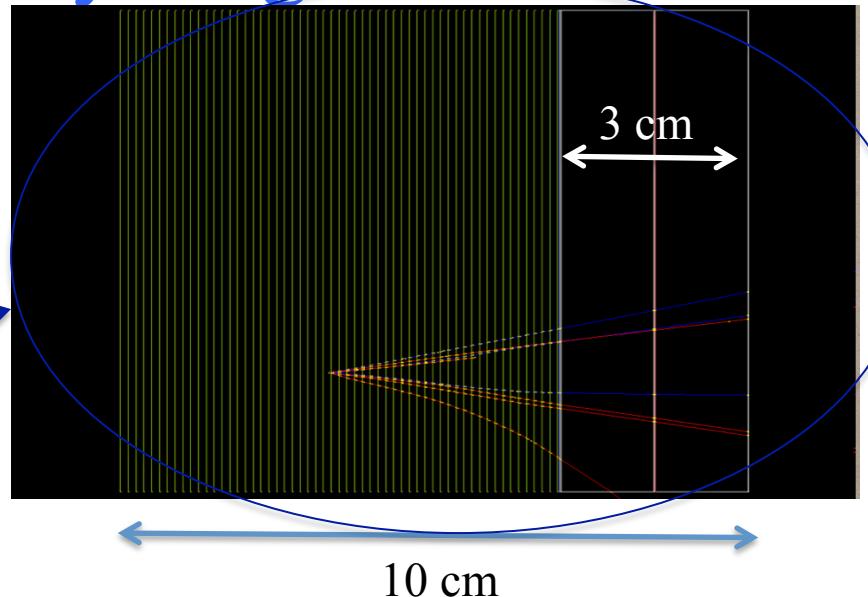
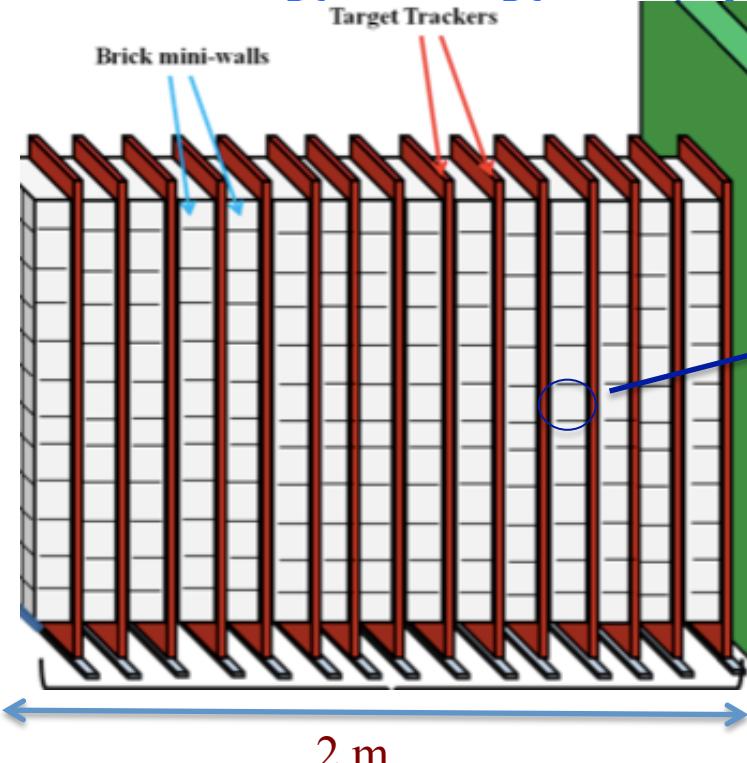
# THE PRINCIPLE: hybrid detector with modular structure



- Micrometric space resolution with nuclear emulsions as trackers
- Detect  $\tau$ -lepton production and decay
- Electronic detectors to provide the “time stamp ” and reconstruct  $\mu$  charge/momentum
- Option: target in a magnetic field to measure the leptonic number ( $\nu_\tau$  and  $\bar{\nu}_\tau$ )

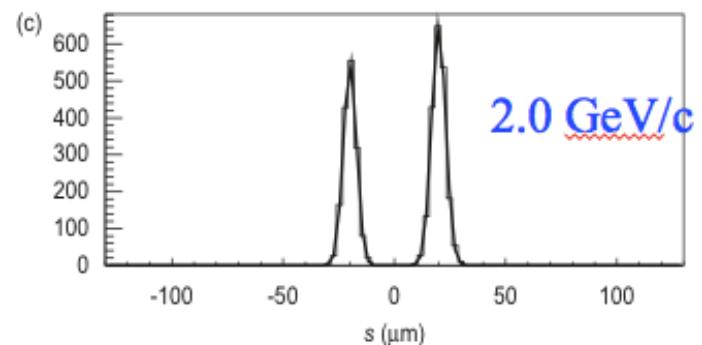
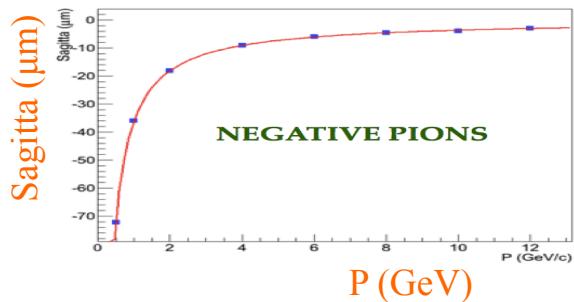
$\tau$ DECAY CHANNEL	BR (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	30 15.0

# Target region, possibly magnetised



Sagitta measurement with  
3 cm thick chamber,  
3 films and 1 Tesla field

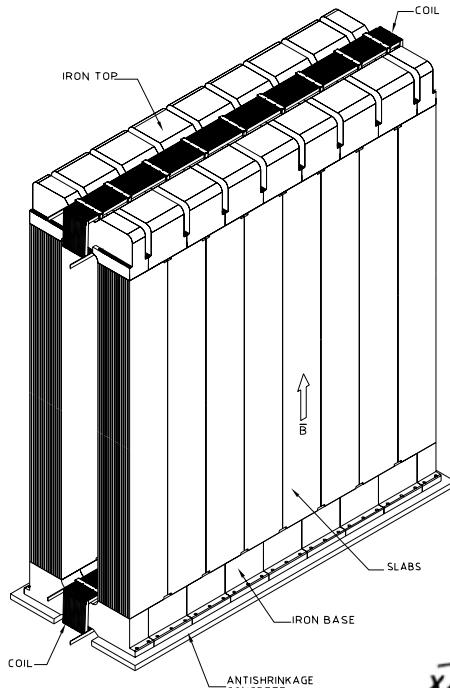
- Charge and momentum of hadrons
- tau lepton charge  $\rightarrow \nu$  and anti- $\nu$
- Part of the muons, complemented by a downstream spectrometer



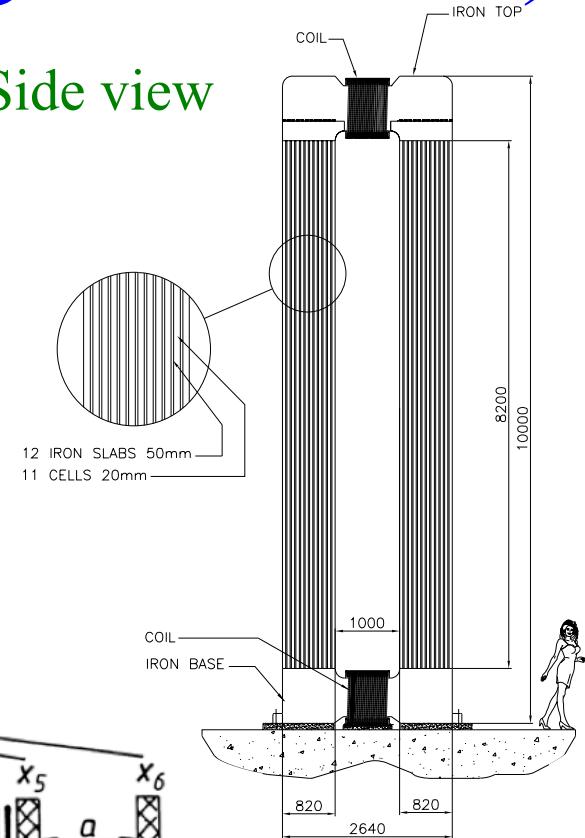
NIM A592 (2008) 56

# OPERA spectrometer (magnetised iron)

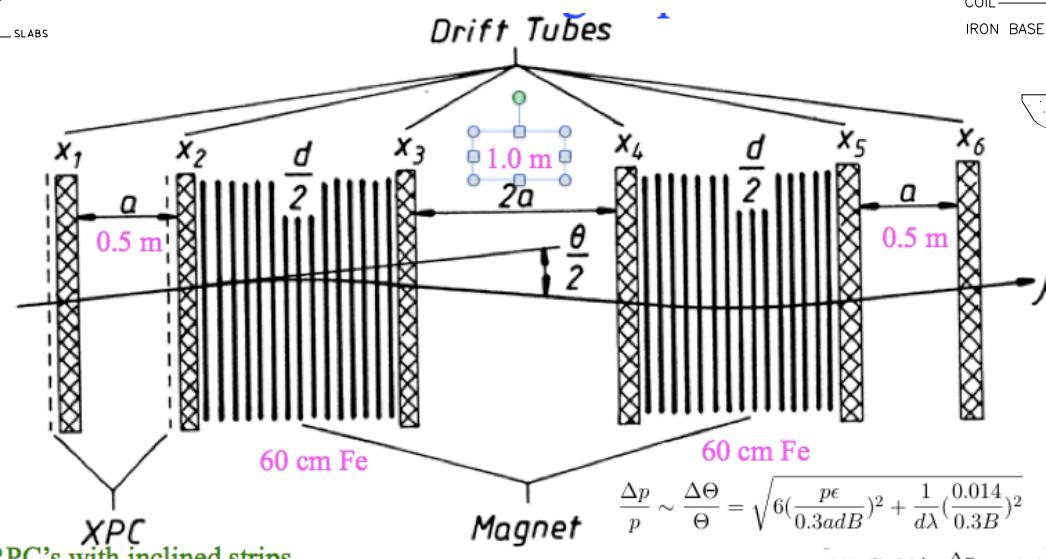
Isometric view



Side view



Reduced surface  $\sim 22 \text{ m}^2$



RPC's with inclined strips

$$\frac{\Delta p}{p} \sim \frac{\Delta \Theta}{\Theta} = \sqrt{6\left(\frac{pe}{0.3adB}\right)^2 + \frac{1}{d\lambda}\left(\frac{0.014}{0.3B}\right)^2}$$

for a momentum of  $25 \text{ GeV}/c$   $\frac{\Delta p}{p} = 0.24$ .

Intrinsic resolution of drift tubes  $\xi = 0.3 \text{ mm}$ ,  $\rightarrow 0.5 \text{ mm}$  including alignment

# ***Status of the SPSC review***

- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010. - 2013
- SPSC assigned 4 referees, who came with a list of questions.
- 3/1/2014: answers to questions: [snoopy.web.cern.ch/snoopy/EOI/SPSC-EOI-010\\_ResponseToReferees.pdf](http://snoopy.web.cern.ch/snoopy/EOI/SPSC-EOI-010_ResponseToReferees.pdf)
- 15/1/2014: SPSC discussed our proposal.

17/1/2014: The official feedback from the Committee is as follows :

"The Committee received with interest the response of the proponents to the questions raised in its review of EOI010.

The SPSC recognises the interesting physics potential of searching for heavy neutral leptons and investigating the properties of neutrinos.

Considering the large cost and complexity of the required beam infrastructure as well as the significant associated beam intensity, such a project should be designed as a general purpose beam dump facility with the broadest possible physics programme, including maximum reach in the investigation of the hidden sector.

To further review the project the Committee would need an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration."

Cheers,

Gavin, Lau, Matthew and Thierry  
(for the SPS Committee).

# **Conclusion and Next steps**

- *The proposed experiment will search for NP in the largely unexplored domain of new, very weakly interacting particles with masses below the Fermi scale*
- *Detector is based on existing technologies  
Ongoing discussions of the beam lines with experts*
- *The impact of HNL discovery on particle physics is difficult to be overestimated!*
- *The proposed experiment complements the searches for NP at the LHC and in neutrino physics*
- *Tau neutrino physics and charm physics with neutrinos*

**A Collaboration is currently being setup. The first collaboration meeting in June. Let us know if you are interested to join!**