SHiP
Search for Hidden Particles

SHIP

SEARCH FOR HIDDEN PARTICLES

A NEW EXPERIMENT PROPOSAL

Giovanni De Lellis

Università Federico II and INFN Naples

Italy

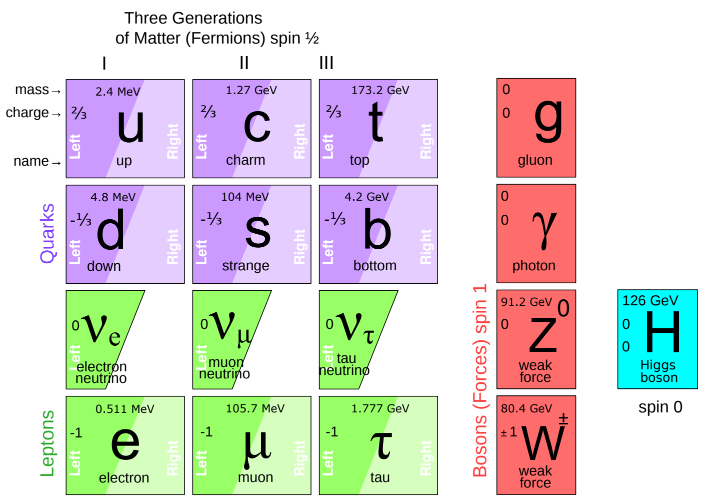
Theoretical motivation

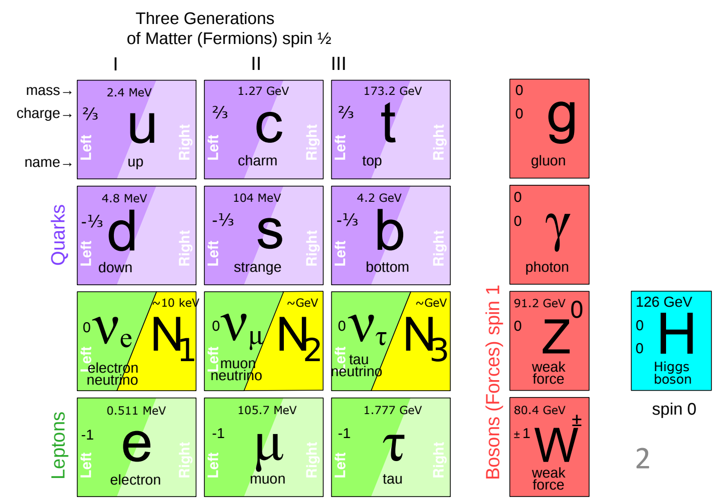
- *Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model The SM may work successfully up to Planck scale !*

- *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 **H**eavy **N**eutral **L**eptons (HNL)**: N$_1$, N$_2$ and N$_3$***

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





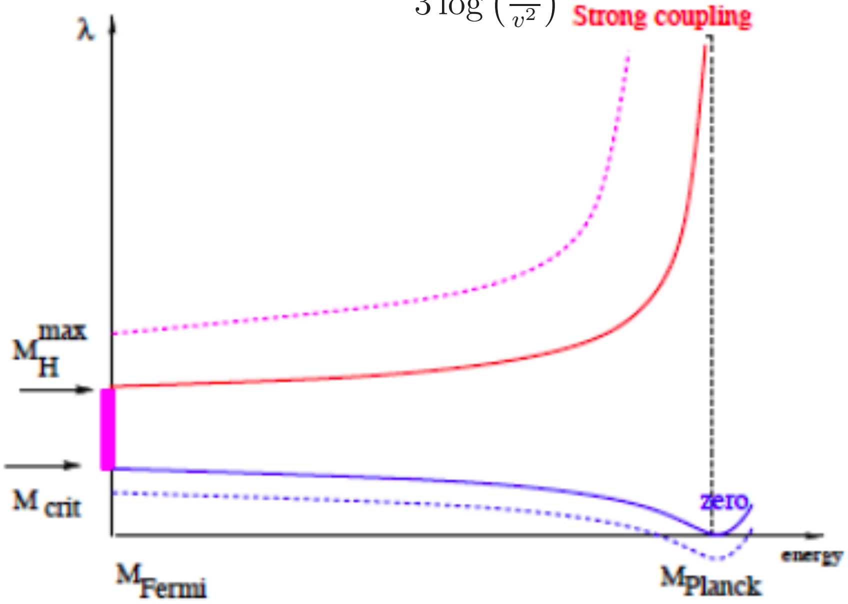
SM may well be a consistent effective theory all the way up to the Plank scale

✓ *M_H < 175 GeV → SM is a weakly coupled theory up to the Plank energies !*

✓ *M_H > 111 GeV → EW vacuum is stable or metastable with a lifetime greatly exceeding the age of our Universe (Espinosa et al)*

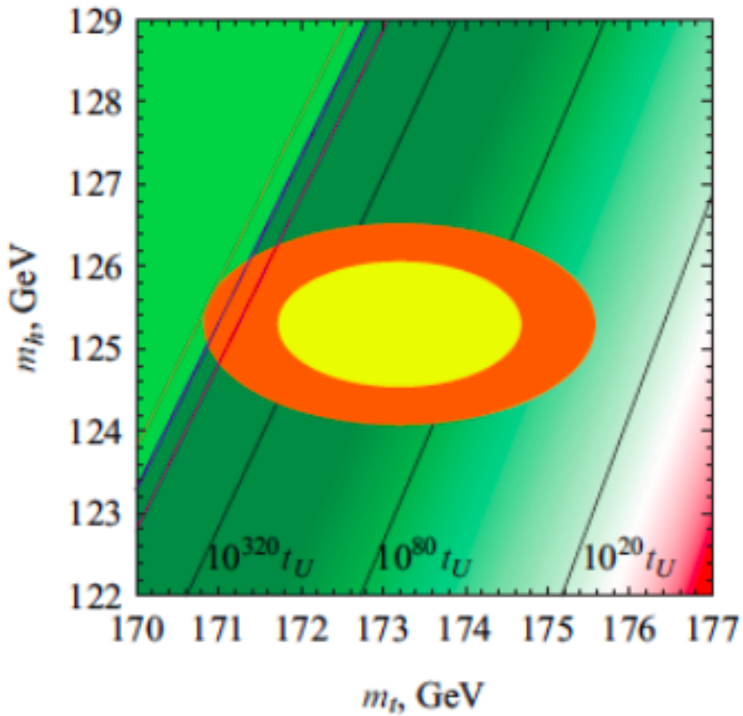
See e.g. arXiv:1405.3781

$$\lambda(\Lambda) < \infty \quad \Rightarrow \quad M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$



Stable vacuum fully consistent with present data

$$\lambda(\Lambda) > 0$$

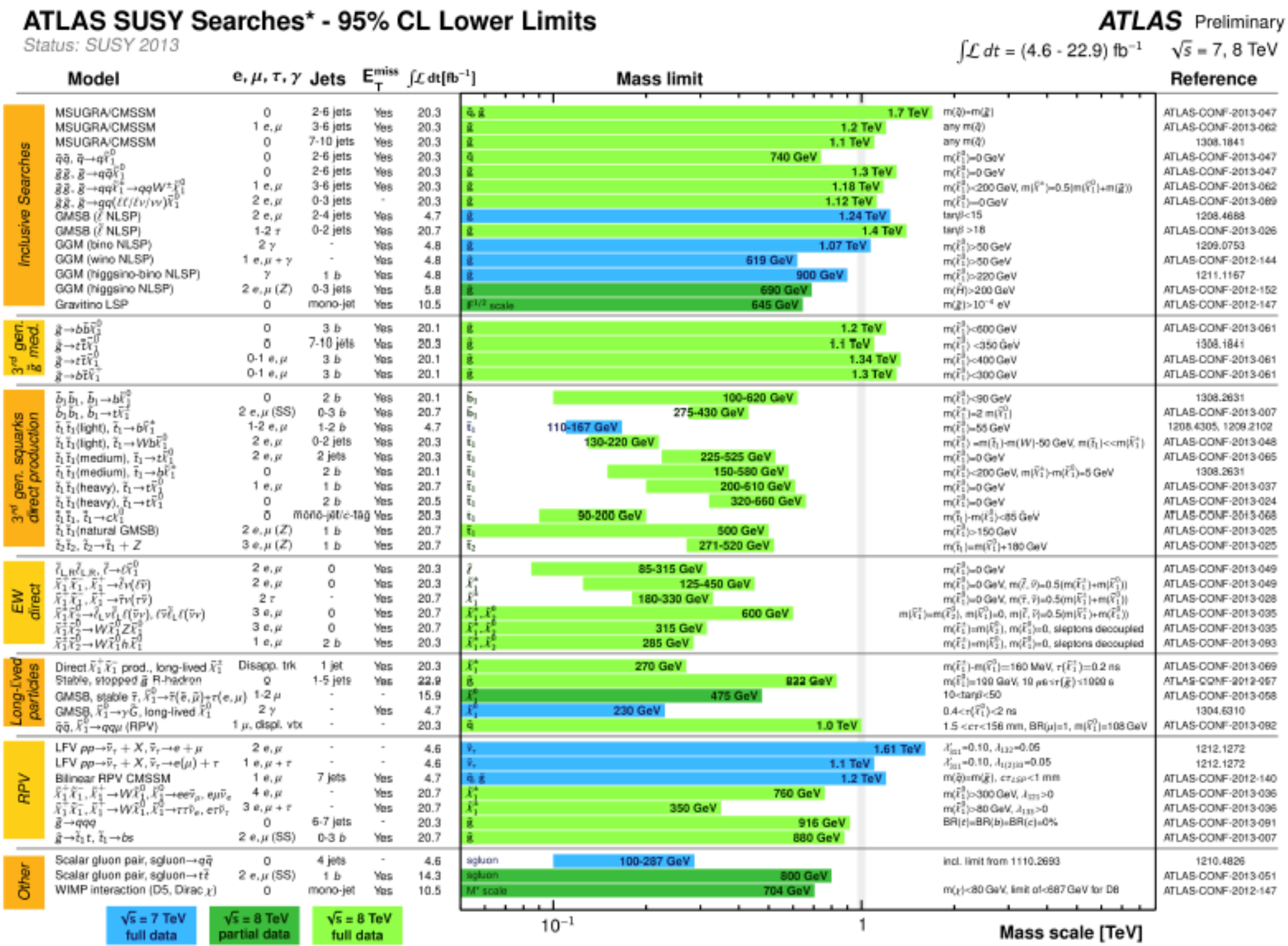


✓ *No sign of New Physics seen*

3

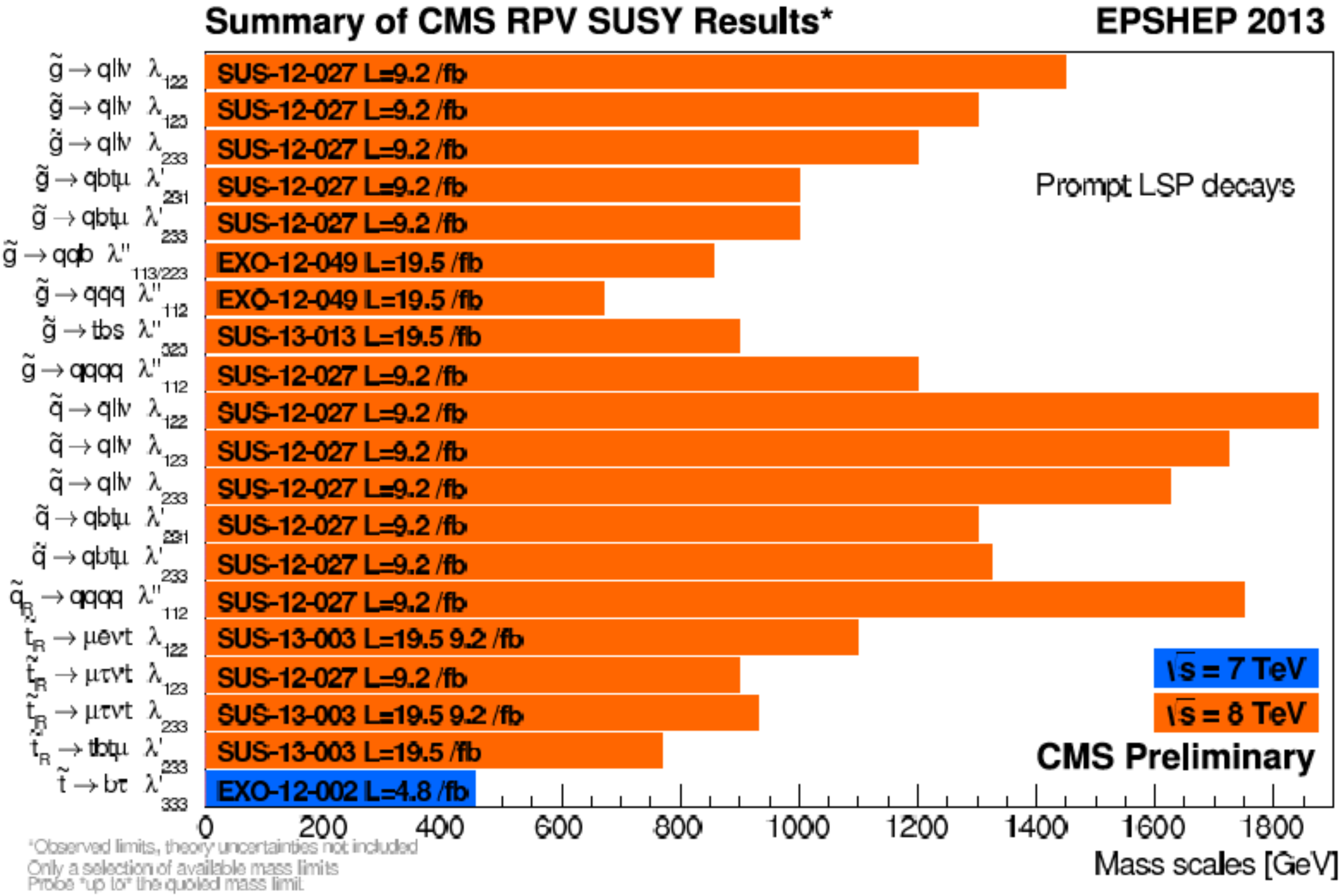
No sign of New Physics seen

What is not found..



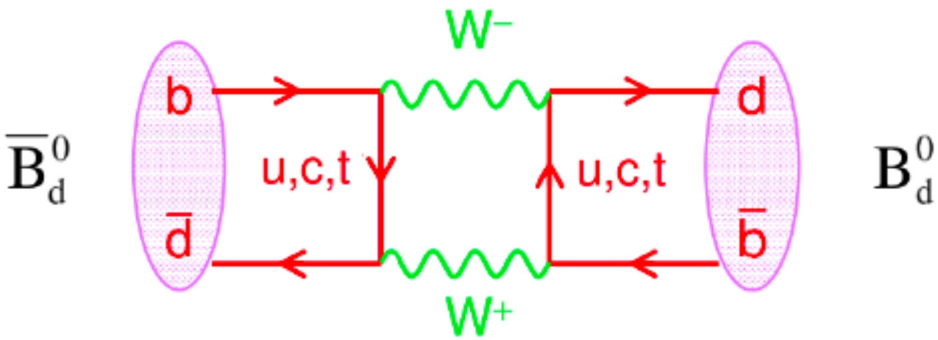
No sign of New Physics seen

What is not found..



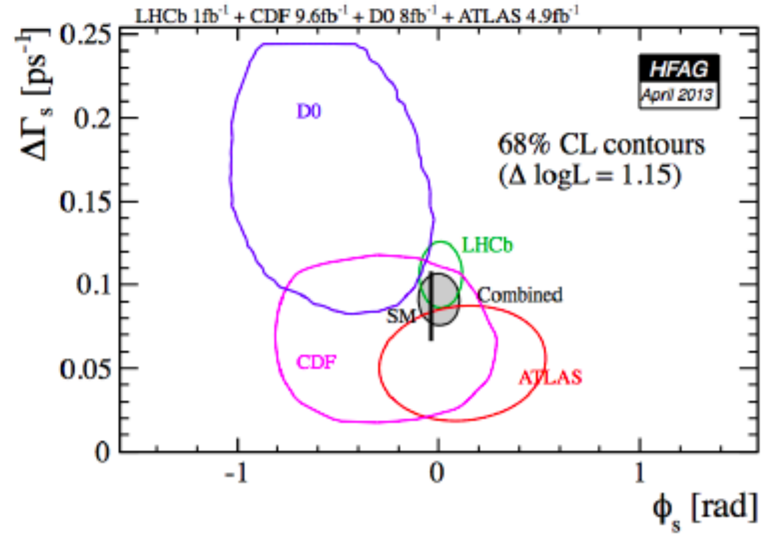
Bounds on the scale of New Physics

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



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

B^0_s



c_{NP}:

- $\sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2 \xrightarrow{\text{tree/strong + “alignment”}} \Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + “alignment”}} \Lambda \gtrsim 0.5$ TeV [K & B]

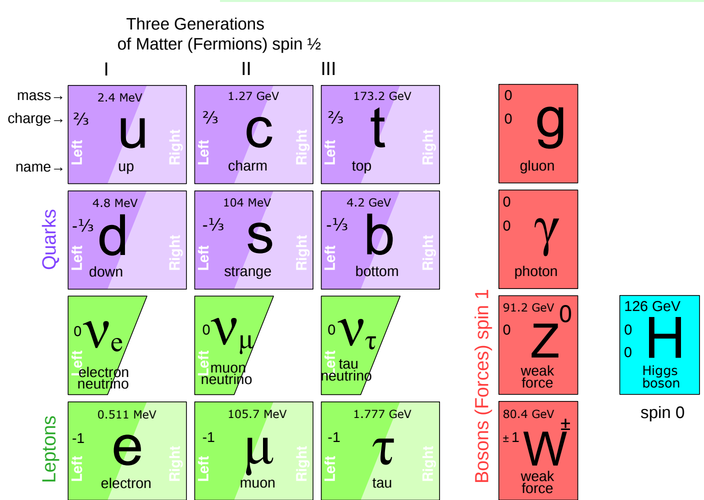
Theoretical motivation

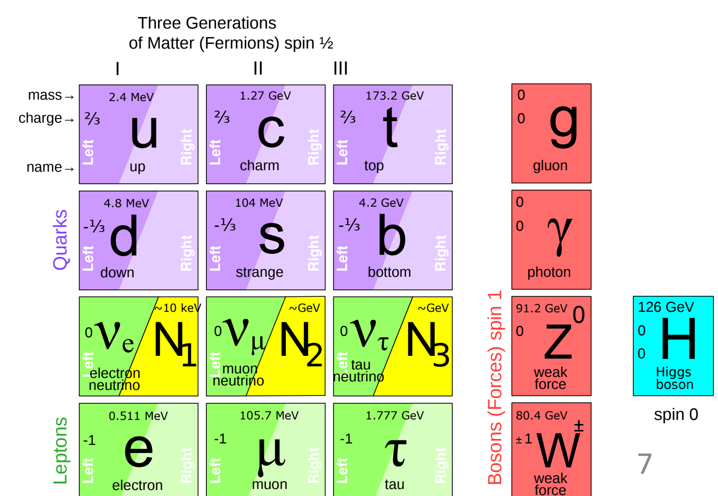
- *Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model The SM may work successfully up to Planck scale !*

- ***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 **H**eavy **N**eutral **L**eptons (HNL): N_1, N_2 and N_3*

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





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

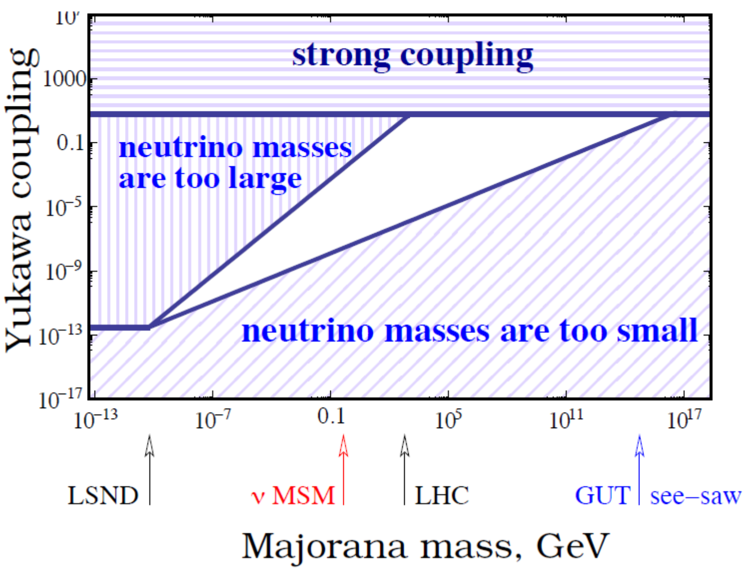
Majorana term which carries no gauge charge

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*

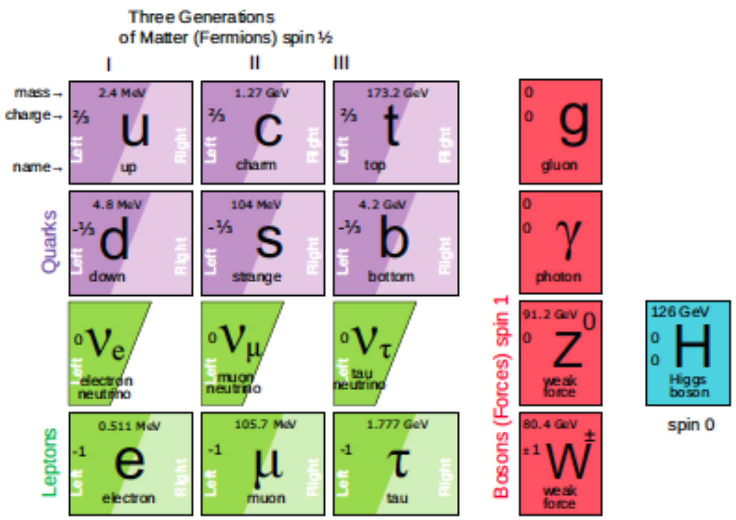
$v \sim 246$ GeV

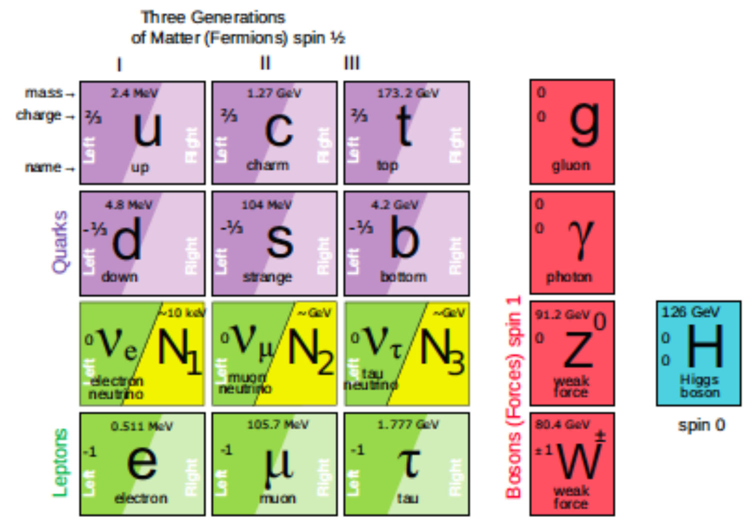
Example:

For M ~ 1 GeV and m_ν ~ 0.05 eV it results in m_D ~ 10 keV and Yukawa coupling ~ 10^{-7}



The νMSM model





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

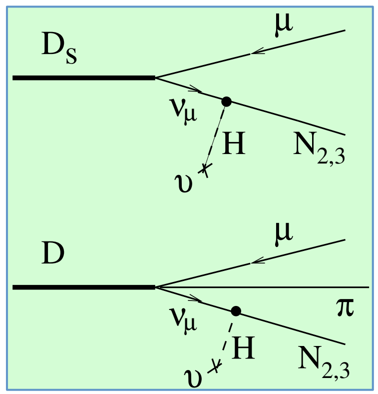
Masses and couplings of HNLs

- ***N_1 can be sufficiently stable to be a DM candidate, $M(N_1)$~10keV***

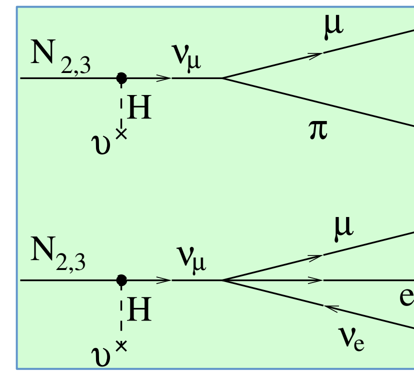
- *$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)*

Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than the SM particles

Example:
$N_{2,3}$ production in charm



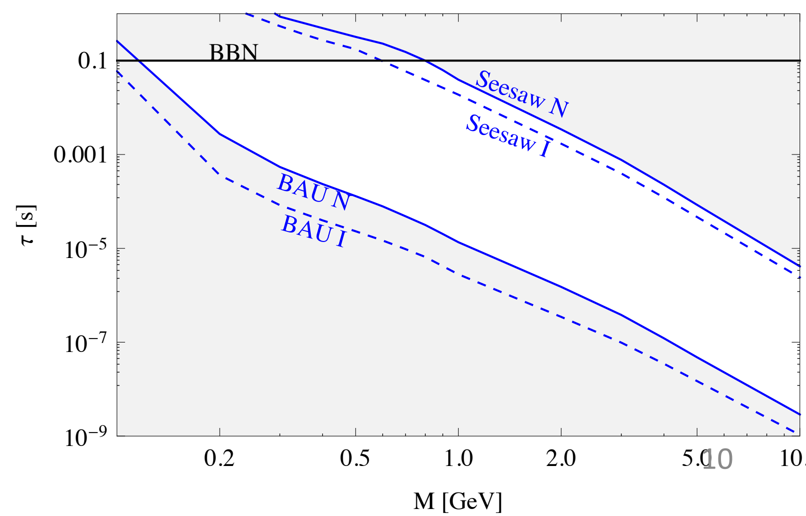
and subsequent decays



- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV Decay distance O(km)*

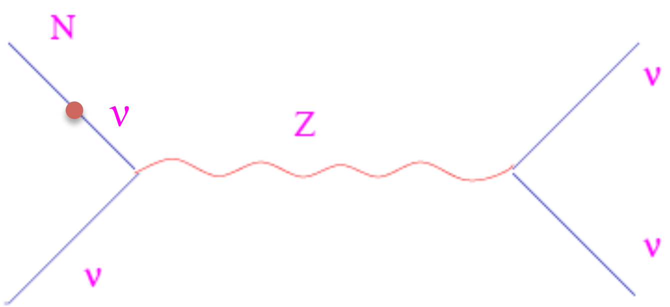
- *Typical BRs (depending on the flavour mixing):*

$Br(N \to \mu/e\ \pi)$ ~ 0.1 – 50%
$Br(N \to \mu^-/e^-\ \rho^+)$ ~ 0.5 – 20%
$Br(N \to \nu\mu e)$ ~ 1 – 10%



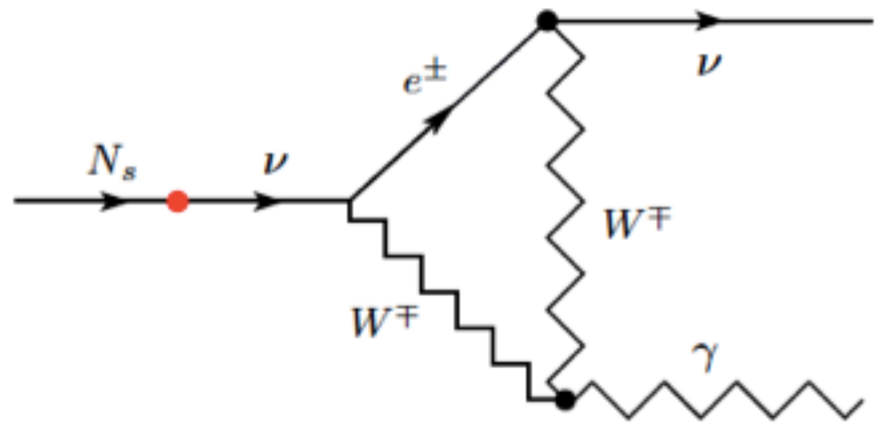
Dark Matter candidate HNL N_1

Yukawa couplings are small $\rightarrow$ N can be very stable.



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

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



Photon energy:

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

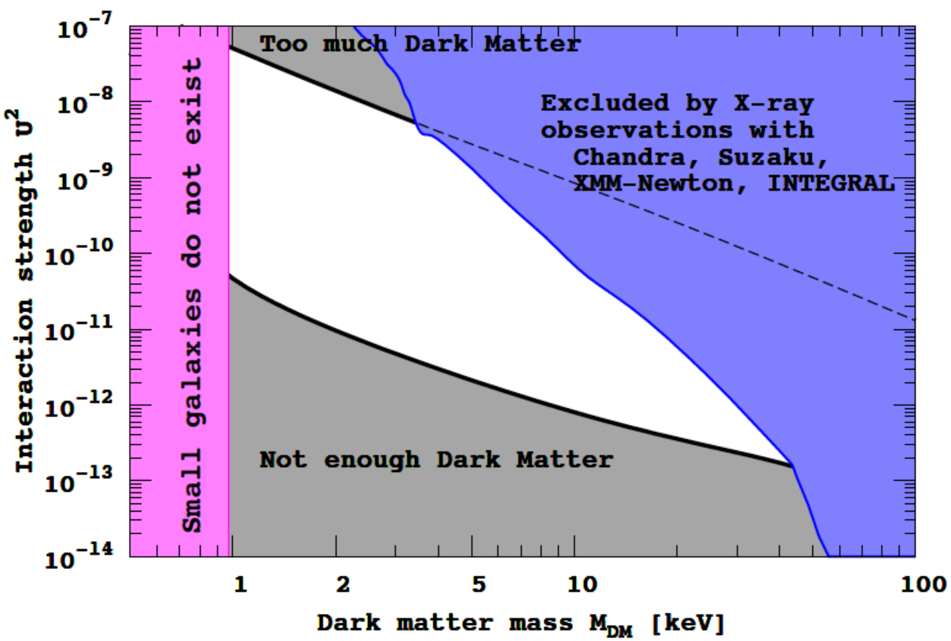
Radiative decay width:

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

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* $l\bar{l} \to \nu N_1 \quad q\bar{q} \to \nu N_1$ *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-α forest spectra of distant quasars and structure of dwarf galaxies)*
- ✓ ***X-ray spectra*** → *Radiative decays $N_1 \to \gamma\nu$ produce a mono-line in photon galaxies spectrum.*



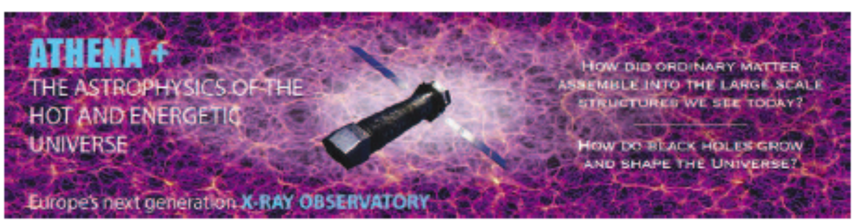
Searches for DM HNL N_1 in space

- 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:

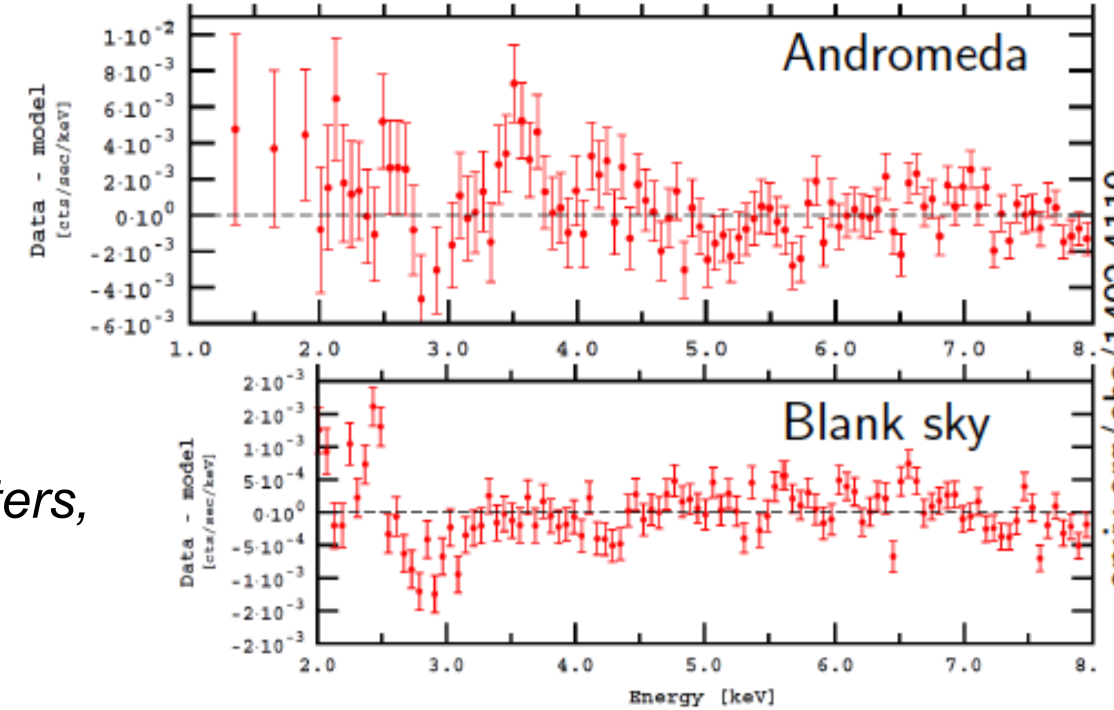
- *arXiv 1402.2301*

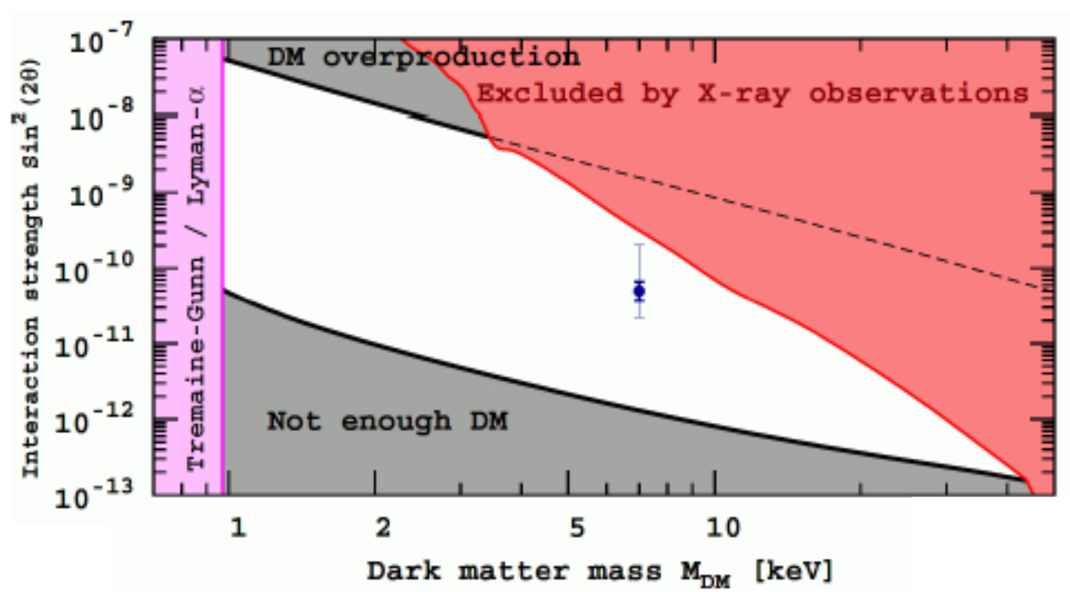
Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters, $E_\gamma \sim 3.56$ keV

- *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





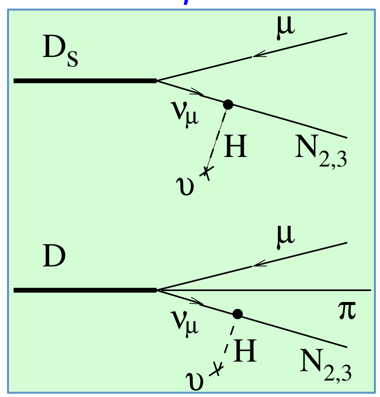
Masses and couplings of HNLs

- ***M(N_2) ≈ M(N_3) ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)***

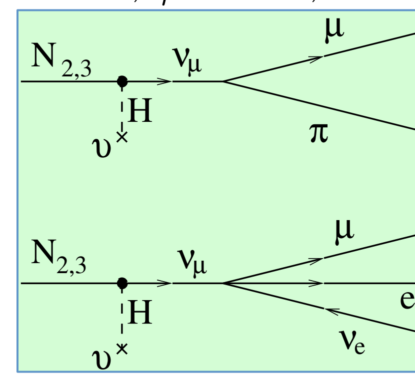
Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than the SM particles

- Produced in semi-leptonic decays, $\mathrm{K} \to \mu\nu,\ \mathrm{D} \to \mu\pi\nu,\ \mathrm{B} \to \mathrm{D}\mu\nu$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

Example:
$N_{2,3}$ production in charm



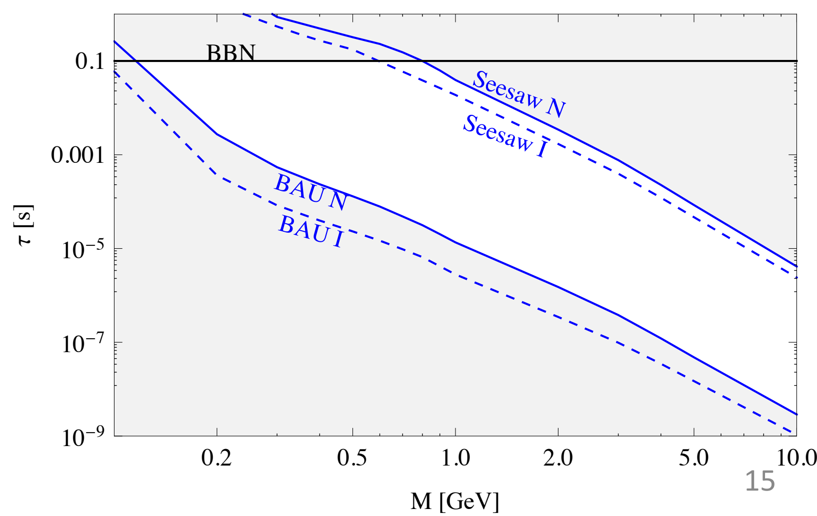
and subsequent decays



- *Typical lifetimes > 10 μs for M($N_{2,3}$) ~ 1 GeV Decay distance O(km)*

- *Typical BRs (depending on the flavour mixing):*

Br(N → μ/e π) ~ 0.1 – 50%
Br(N → $\mu^-/e^-\ \rho^+$) ~ 0.5 – 20%
Br(N → νμe) ~ 1 – 10%



Baryon asymmetry

Sakharov conditions:

- *C and CP are not conserved in νMSM*

  6 CPV phases in the lepton sector and 1 CKM phase in the quark sector (to be compared with only one CKM phase in the SM)

- *Deviations from thermal equilibrium*

↓

✓ ***HNL are created in the early Universe***

✓ ***CPV in the interference of HNL production and decay***

✓ ***Lepton number goes from HNL to active neutrinos***

✓ ***Then lepton number transfers to baryons in the equilibrium sphaleron processes***

PS *Explanation of DM with N_1 reduces a number of free parameters*
→ Degeneracy of $N_{2,3}$ masses is required to ensure sufficient CPV

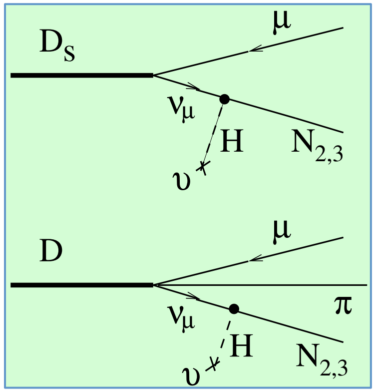
Masses and couplings of HNLs

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

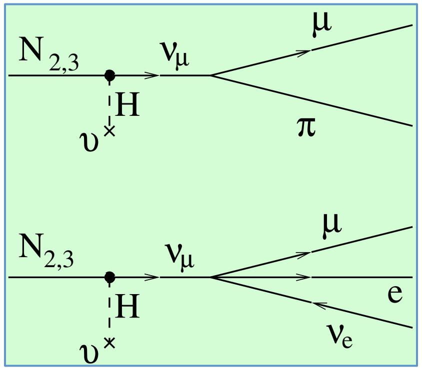
- Produced in semi-leptonic decays, $\mathrm{K} \to \mu\nu$, $\mathrm{D} \to \mu\pi\nu$, $\mathrm{B} \to \mathrm{D}\mu\nu$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

Example:

$N_{2,3}$ production in charm



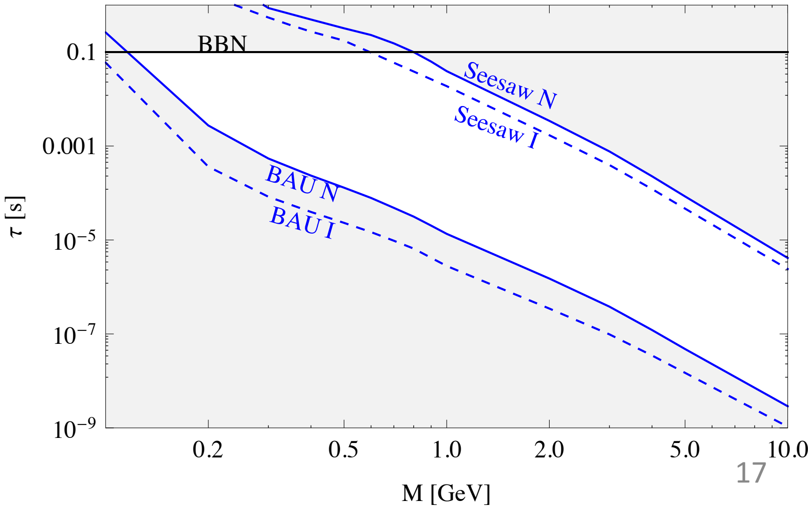
and subsequent decays



- *Typical lifetimes > 10 μs for $M(N_{2,3}) \sim 1$ GeV*
  Decay distance O(km)

- *Typical BRs (depending on the flavour mixing):*

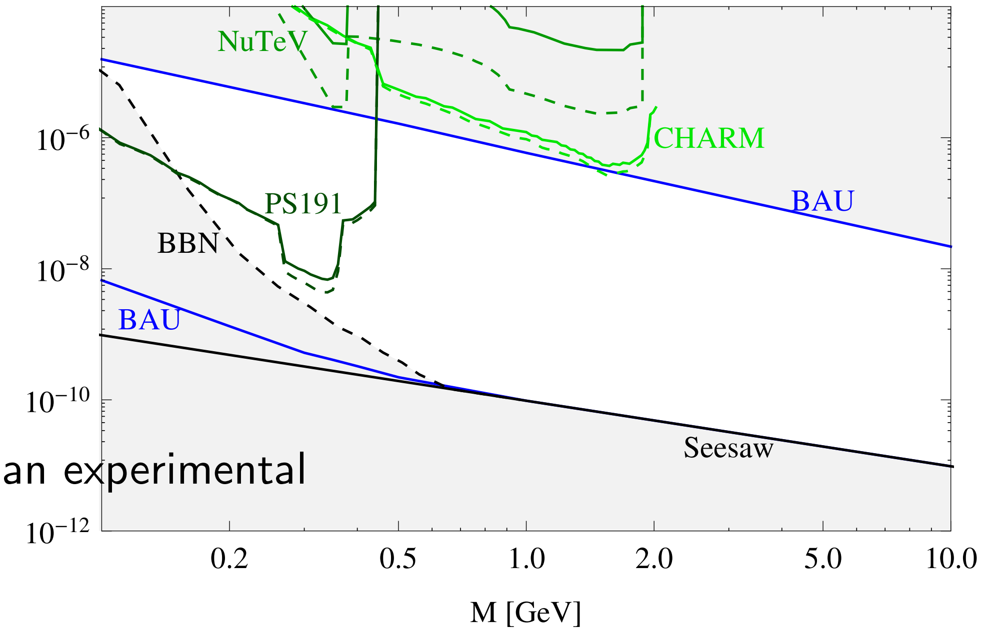
  $Br(N \to \mu/e\ \pi) \sim 0.1 – 50\%$
  $Br(N \to \mu^-/e^-\ \rho^+) \sim 0.5 – 20\%$
  $Br(N \to \nu\mu e) \sim 1 – 10\%$



Experimental and cosmological constraints

Already searches in K/D-decay performed:

- PS191('88)@PS 19.2 GeV,
  1.4×10^{19} pot, 128 m from target.
- CHARM('86)@SPS 400 GeV,
  2.4×10^{18} pot, 480 m from target.
- NuTev('99)@Fermilab 800 GeV,
  2.5×10^{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***

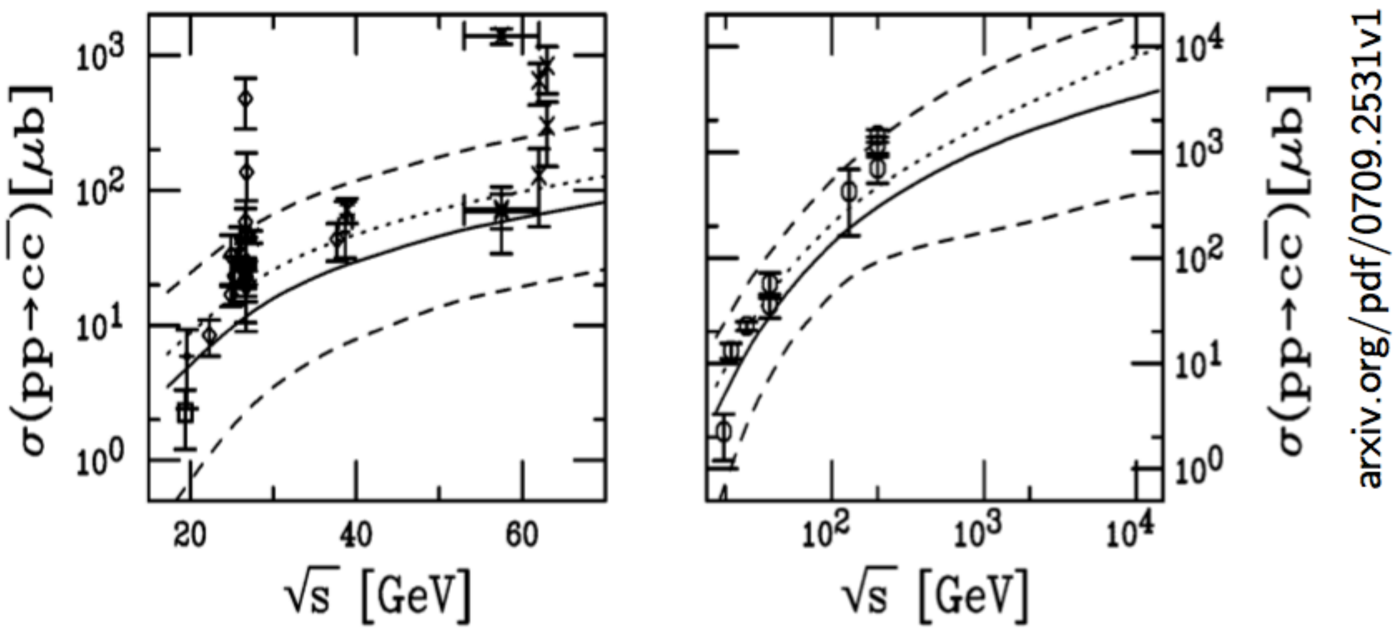
  - *The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass*

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 → limited to 500 MeV (PLB 203 (1988) 332)
- Goal: Extend mass range to ~ 2 GeV by using charmed hadron decays
- B-decays: 20÷100 smaller σ, and B → Dμν, i.e. limited to 3 GeV still



Where to produce charmed hadrons?

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

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

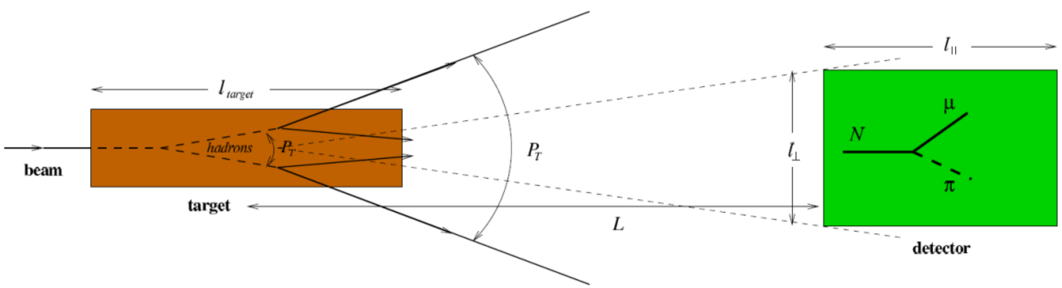
Moreover, the acceptance of a beam dump facility can be much larger for long lived particles

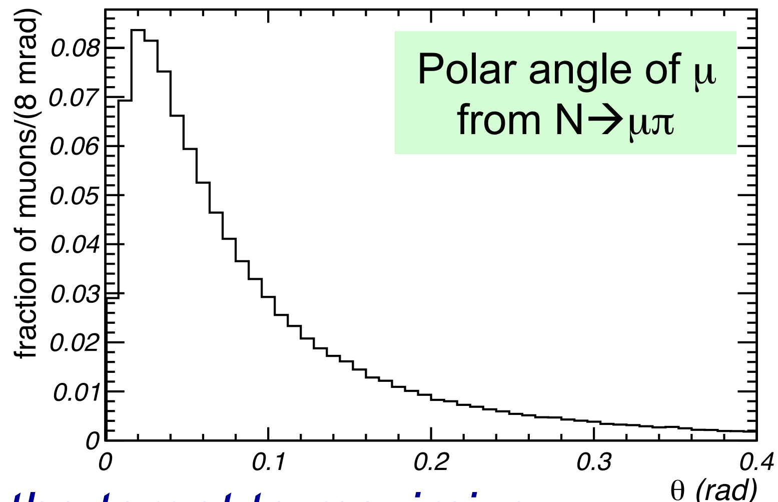
Experimental requirements

- *Search for HNL in Heavy Flavour decays*

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

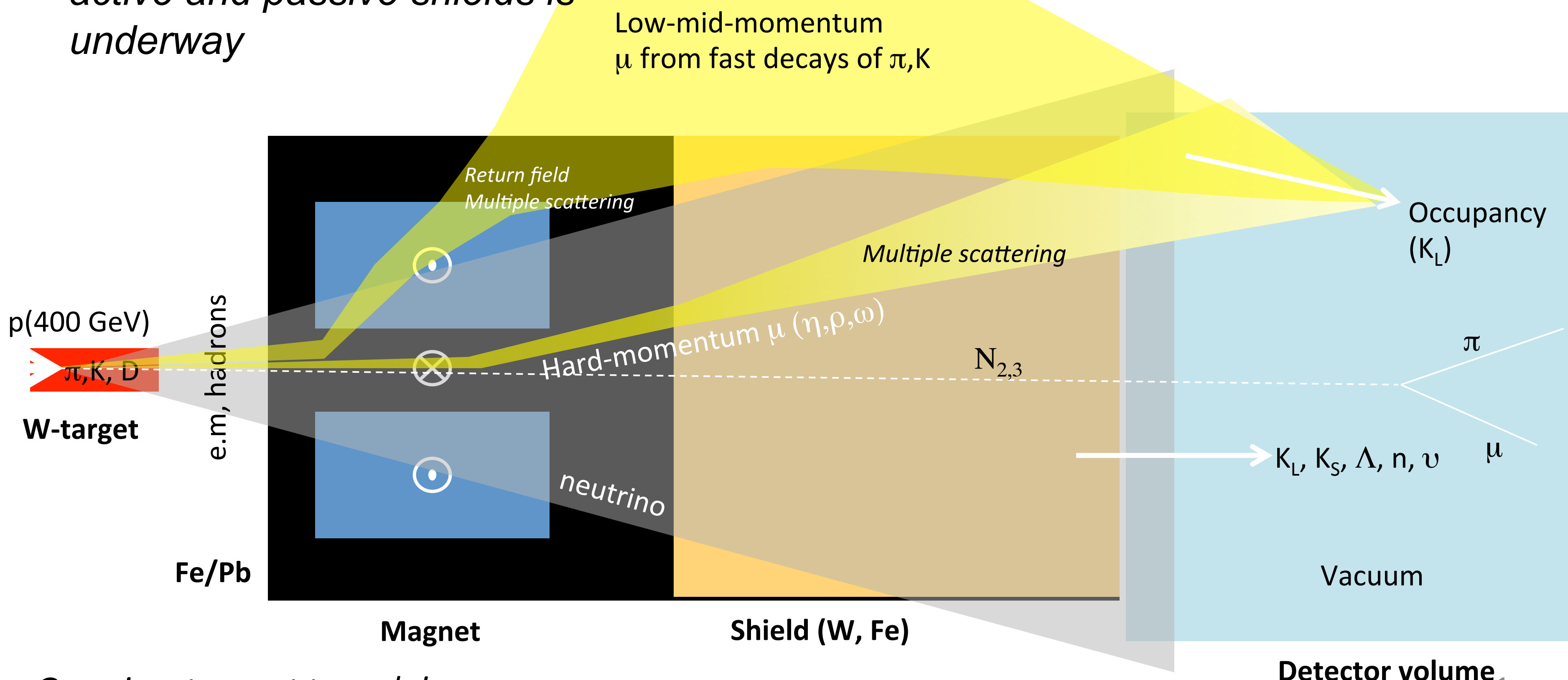
(different from a conventional neutrino facility)

Initial reduction of beam induced backgrounds

- *Heavy target (50 cm of W)*
- *Hadron absorber (5m Fe)*
- *Muon shield: optimization of active and passive shields is underway*

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

spill duration 1s → $< 50\times10^{6}$ muons
spill duration 1ms → $< 50\times10^{3}$ muons
spill duration $10\mu s$ → < 500 muons

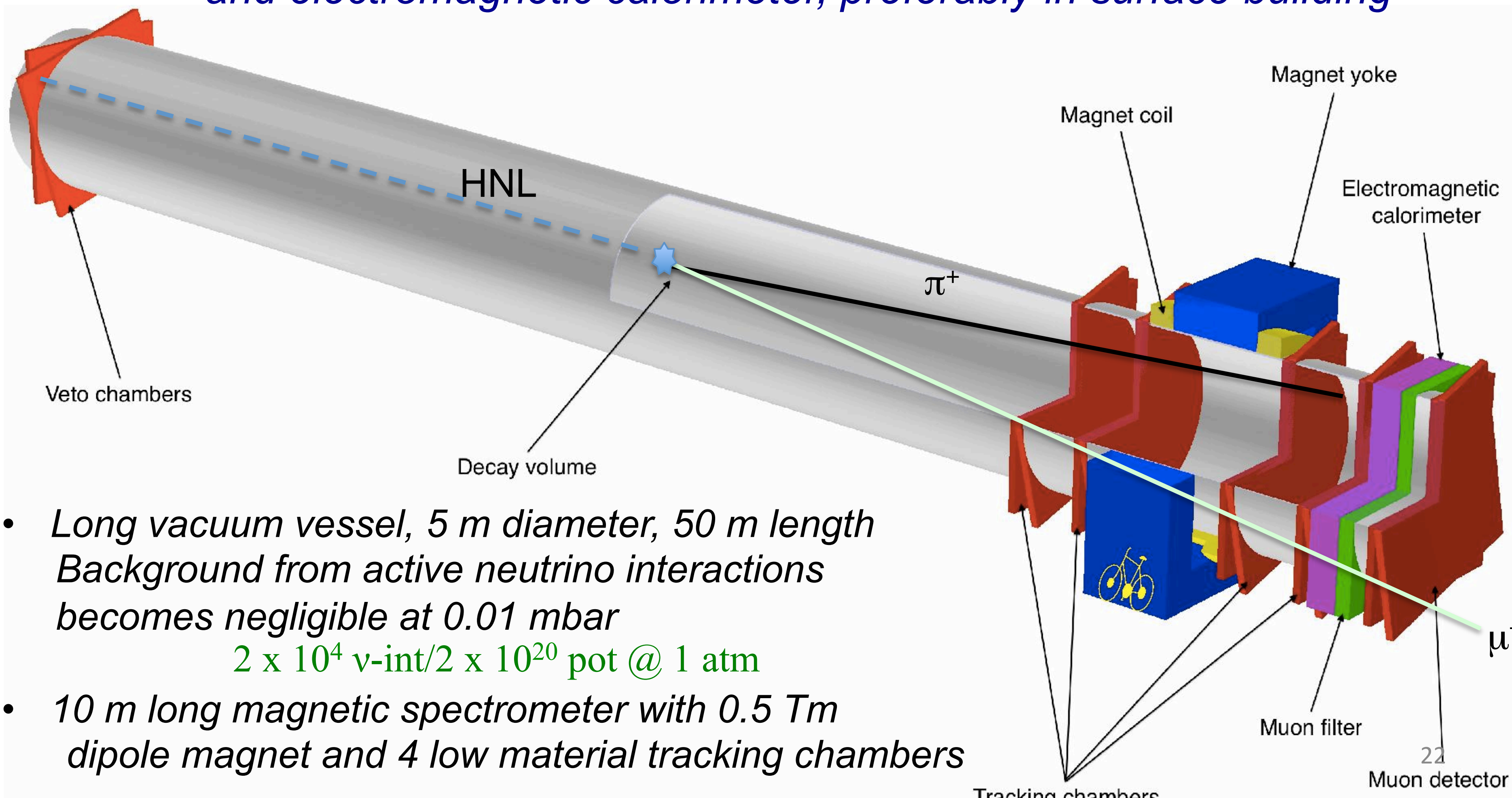


Generic setup, not to scale!

Detector concept
(based on existing technologies)

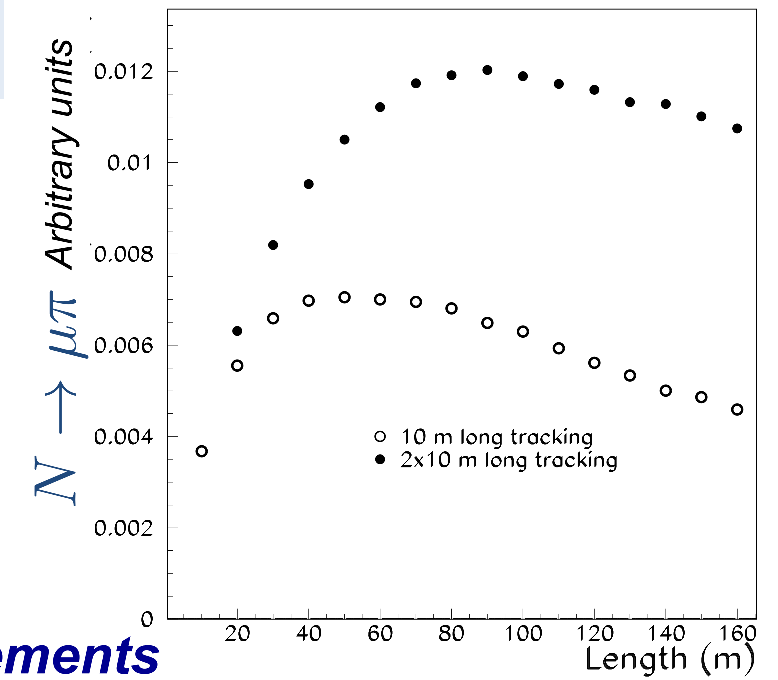
- Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$

→ Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building



- Long vacuum vessel, 5 m diameter, 50 m length
  Background from active neutrino interactions becomes negligible at 0.01 mbar
  2×10^4 ν-int/2×10^{20} pot @ 1 atm
- 10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers

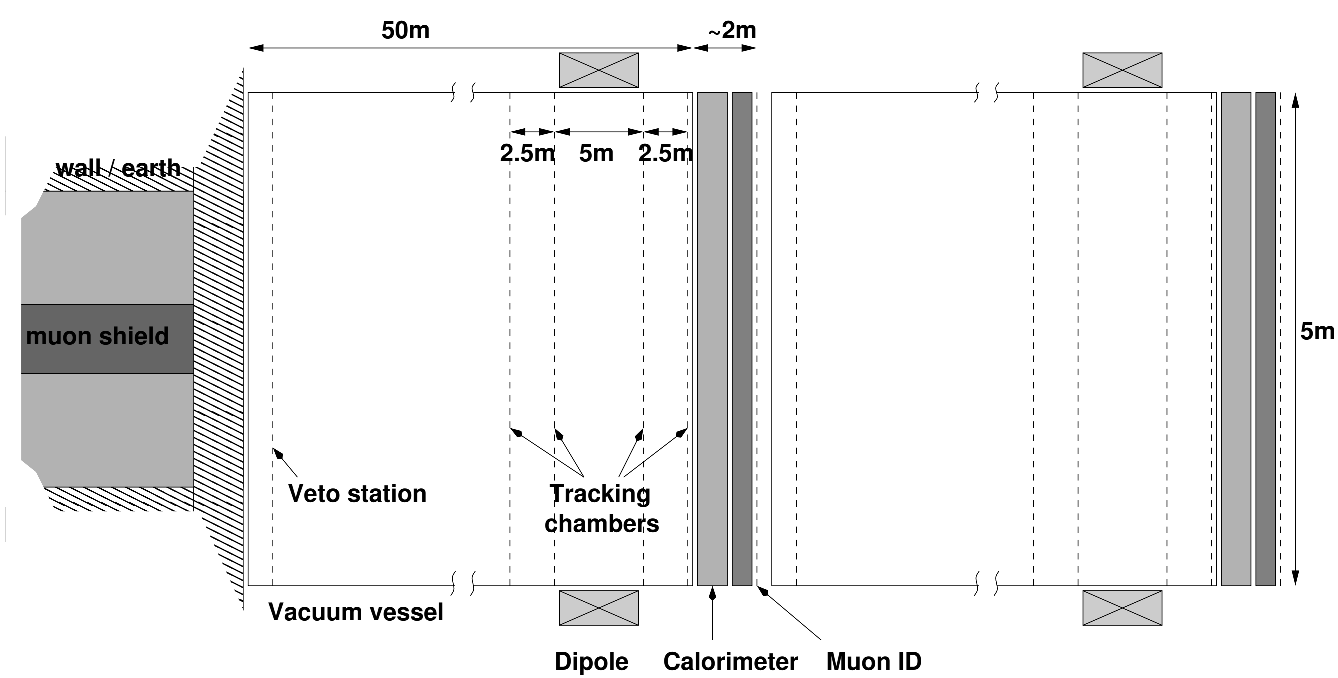
Detector concept (cont.)



Geometrical acceptance

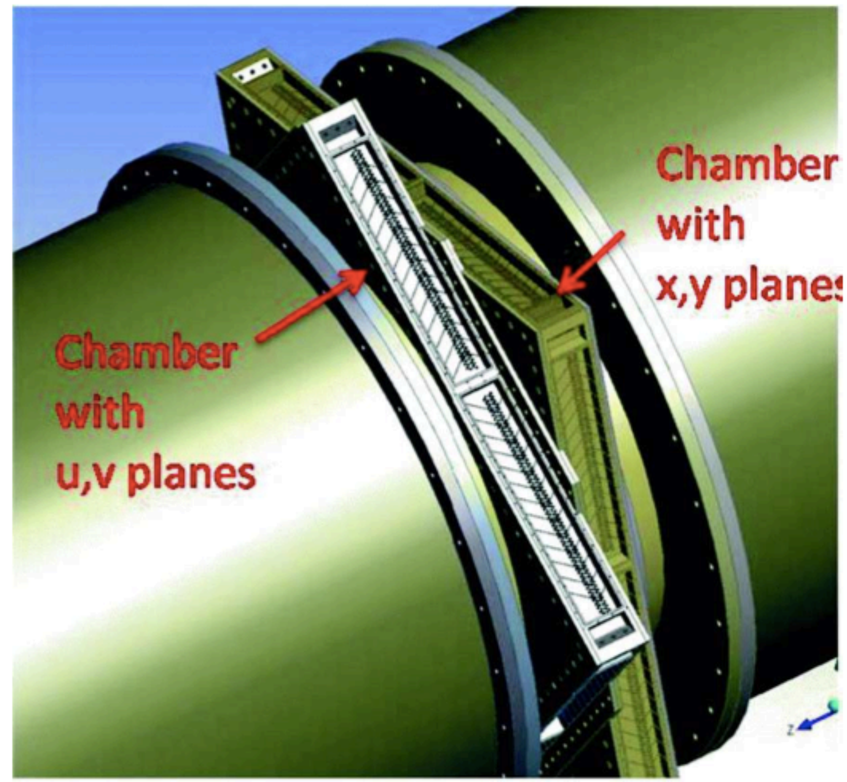
- *Saturates for a given HNL lifetime as a function of detector length*
- *The use of two magnetic spectrometers increases the acceptance by 70%*

Detector has two almost identical elements



Tracking chambers

Same as NA62 $(K^+ \to \pi^+ \nu \bar{\nu})$
2m diameter vessel at 0.01 μbar
10 mm diameter straws made of PET → working well in vacuum
X/X_0 = 0.5% for 4 view stations
120 μm resolution/straw



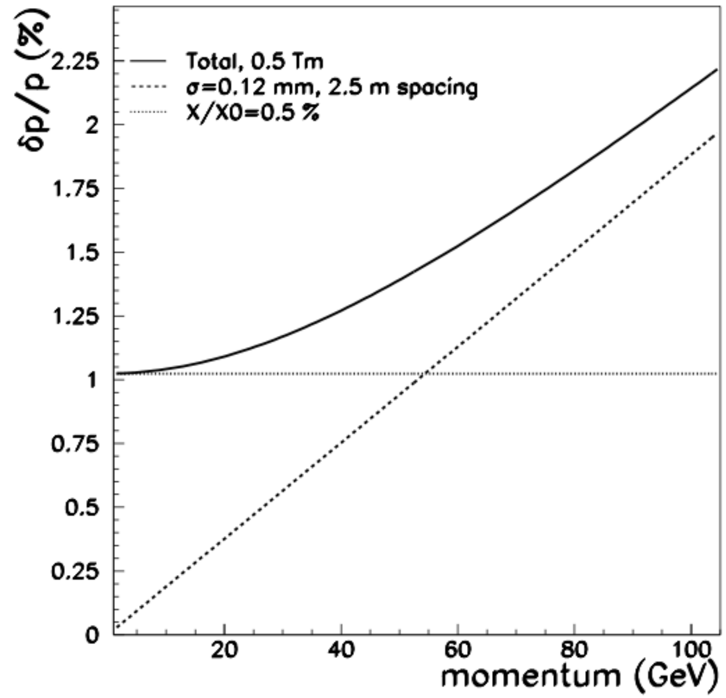
Magnet and e.m. calo

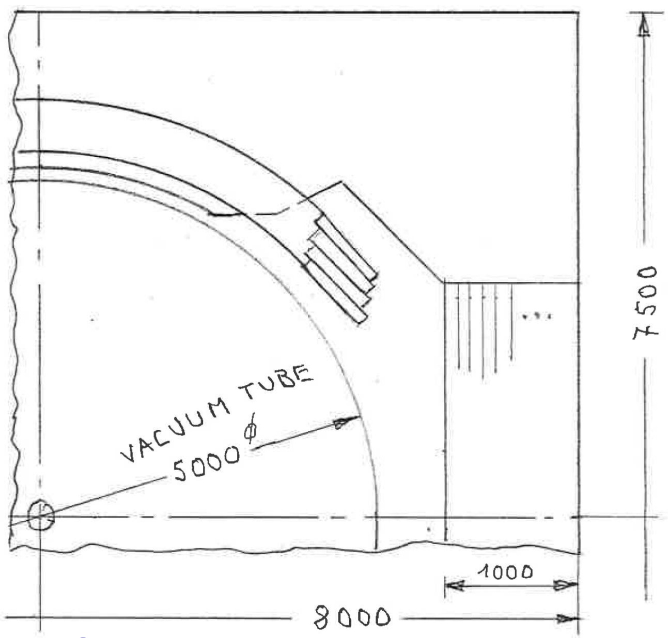
- With X/X0=0.5 % chambers: modest 0.5 Tm
- Need $\sim 20\ \mathrm{m}^2$ aperture.

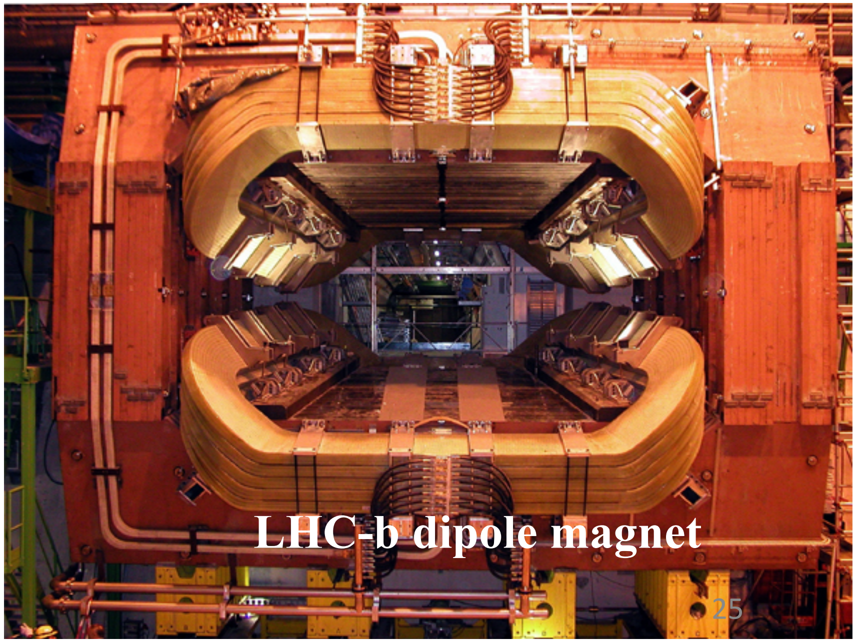
LHCb magnet: 4 Tm, $16\ \mathrm{m}^2$ aperture

Preliminary calculations (W.Flegel):

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







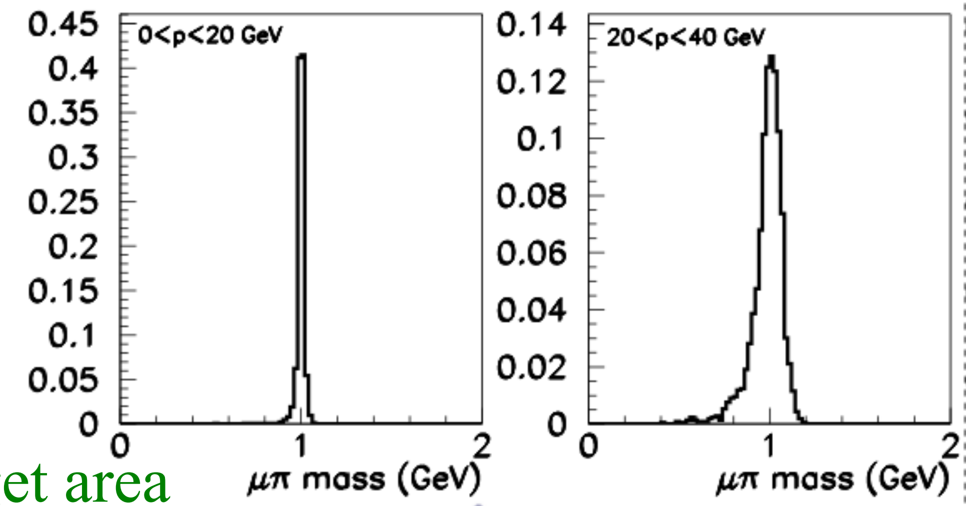
LHCb Shashlik ECAL:

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

Mass resolution

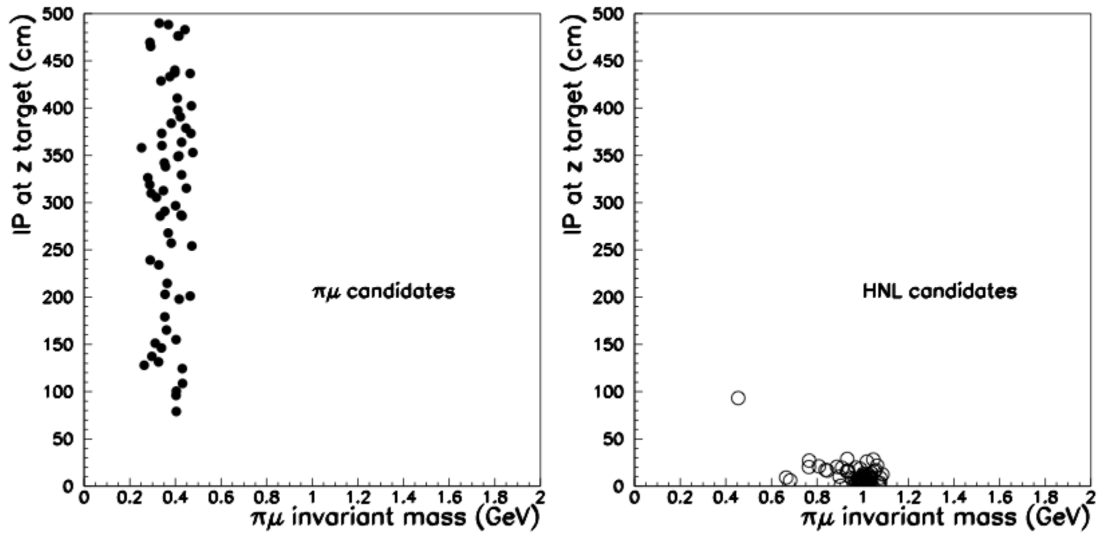
Expected resolution for 1 GeV N $\rightarrow \mu\pi$
$\langle p_N \rangle = 25$ GeV

- σ_{mass} ~ *40 MeV for P < 20 GeV*



K^0_L background suppression

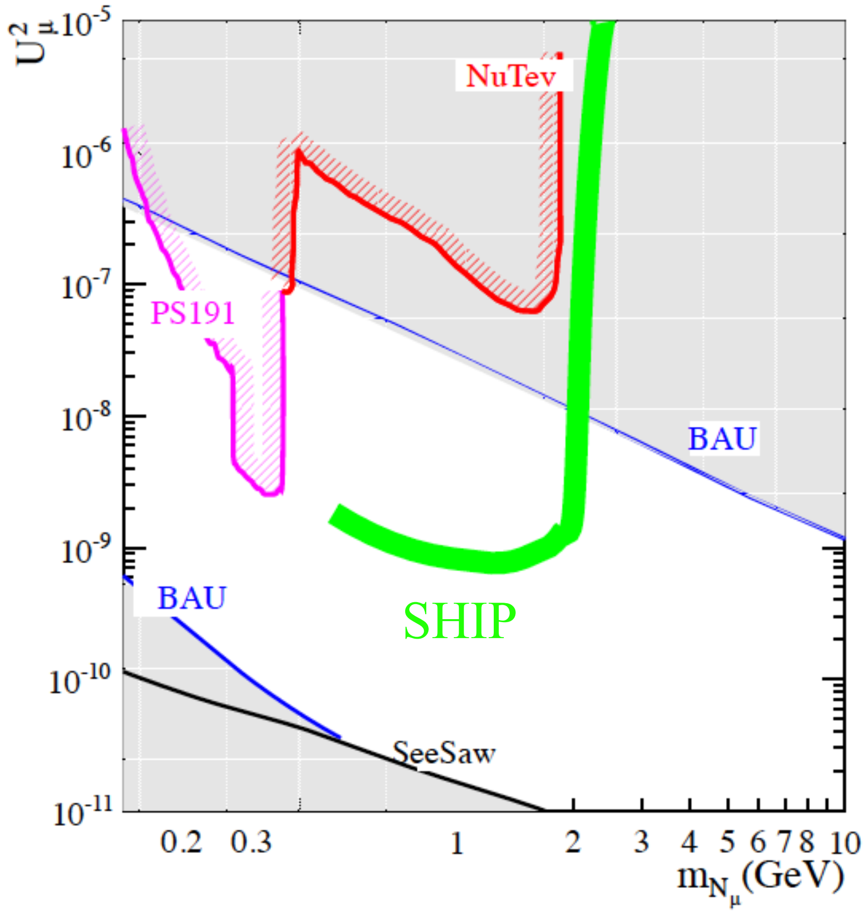
- Use pointing of candidates to target area
- *Detect CC via extra μ in coincidence with μπ, upstream tagger*
- *Instrument μ-filter to tag CC/NC shower*



Expected event yield

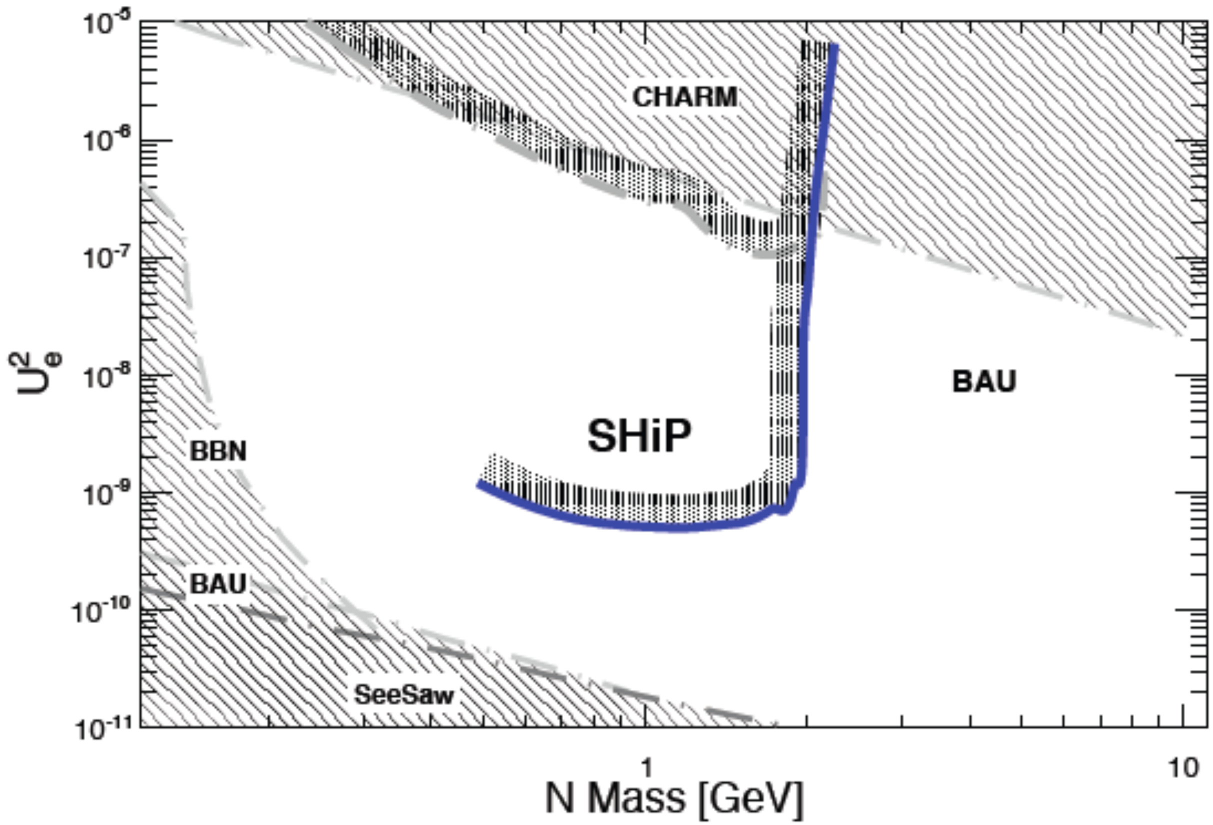
Assuming $U_\mu^2 = 10^{-7}$ (corresponding to the strongest experimental limit currently for $M_N \sim 1$ GeV) and $\tau_N = 1.8\times10^{-5}$ s

~12k fully reconstructed $N \rightarrow \mu^-\pi^+$ events are expected for $M_N = 1$ GeV



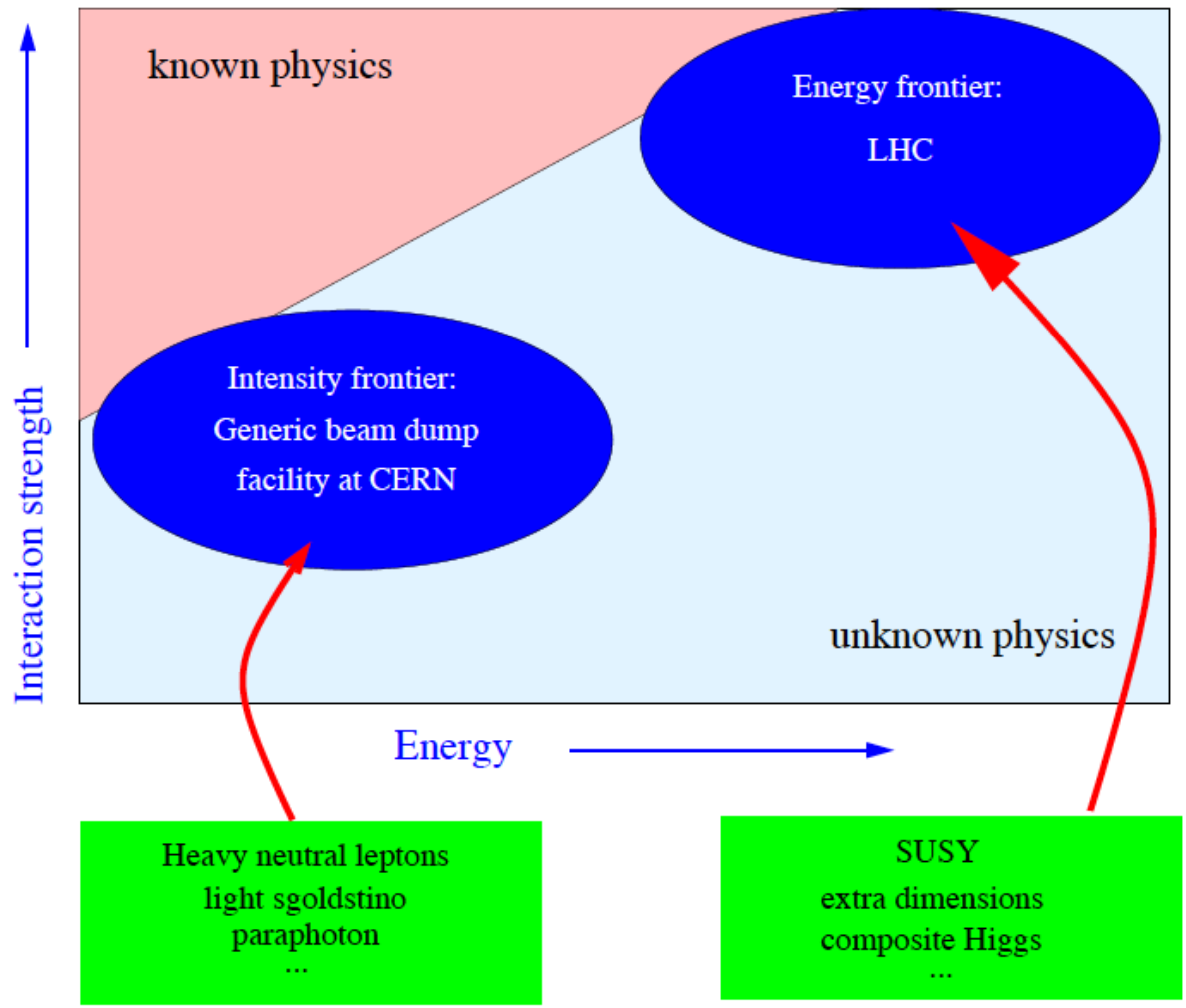
120 events for cosmologically favoured region: $U_\mu^2 = 10^{-8}$ & $\tau_N = 1.8\times10^{-4}$s

Sensitivity to HNL: U_e



Decay Channels: $N \to \pi e$ and $N \to e\rho$

Physics case for a 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 ν_τ interactions (guarantied SM physics)***

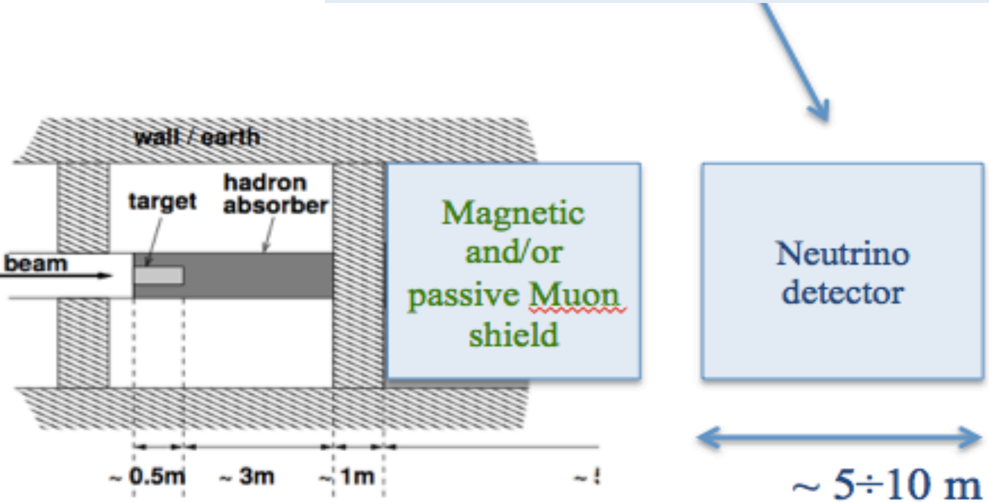
  Ideally suited since ν_τ is produced in $D_s \rightarrow \tau\, \nu_\tau$ with similar to HNL kinematics. DONUT 9 events, OPERA 4 events (from oscillations)

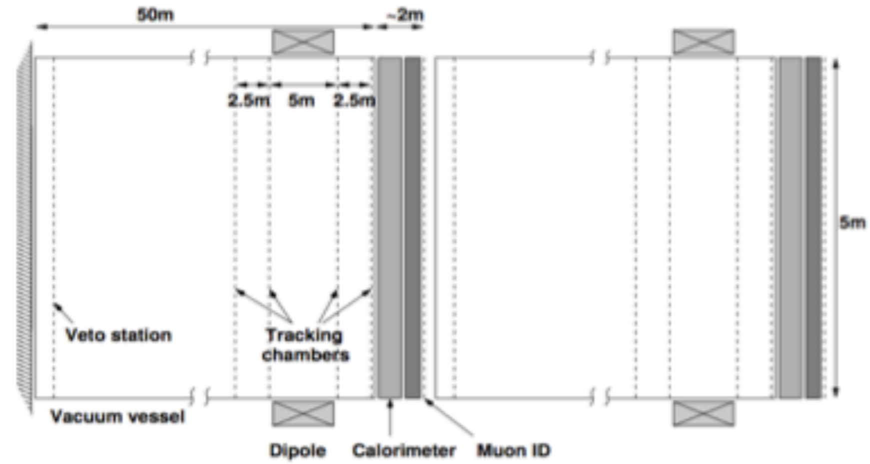
- ✓ *Search for any weakly interacting yet unstable particles produced in very rare charm (or hyperon) decays such as low mass SUSY or paraphotons or …*

- ✓ *Review of the SHIP sensitivities for ν_τ physics and wide class of models with hidden portals is ongoing*

Expect significant improvement of currently available measurements and constrains everywhere!

SM: ν_τ physics with 2×10^{20} pot





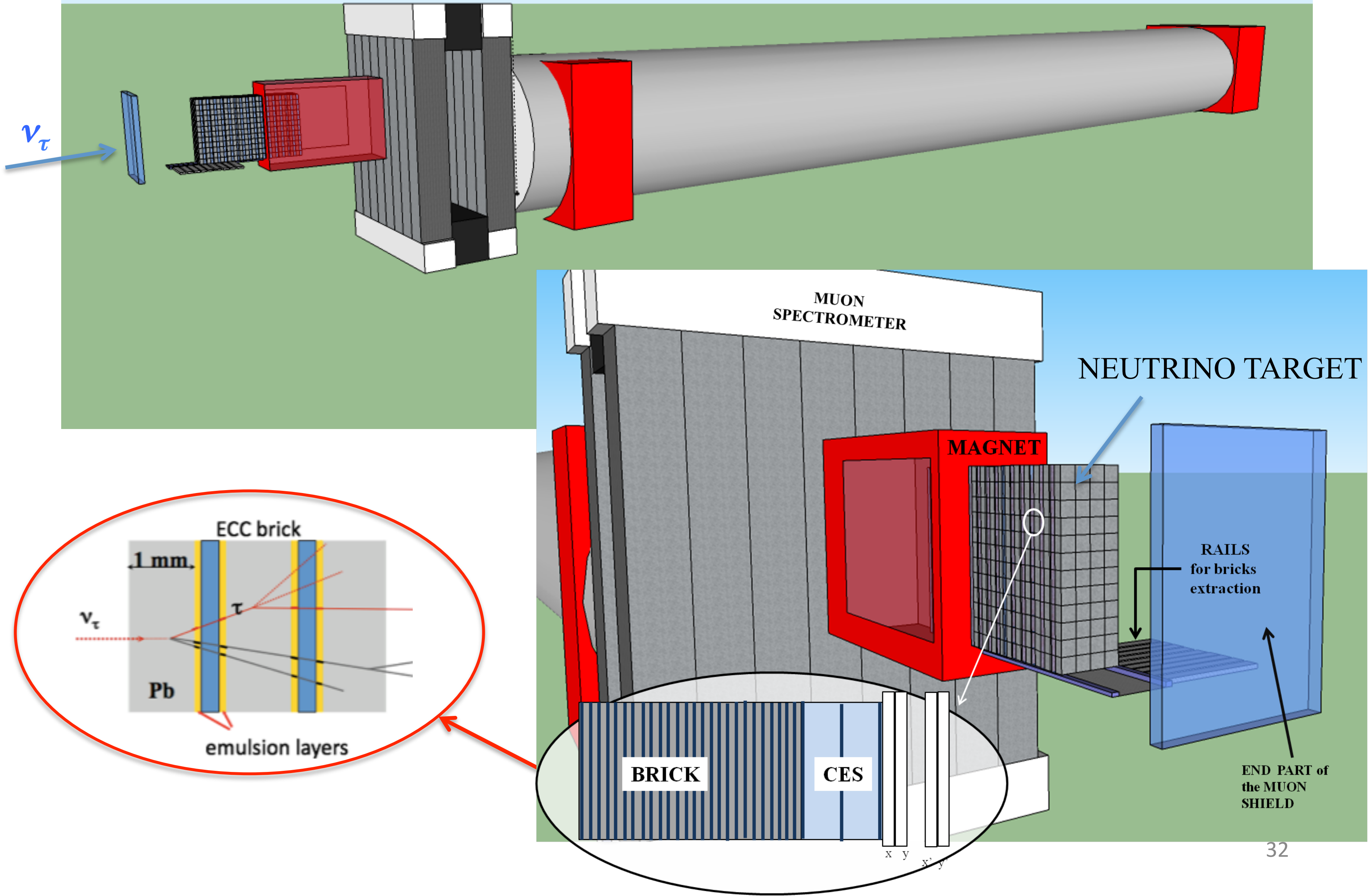
A powerful source of neutrinos originated by charm decays, $D_s \rightarrow \tau\, \nu_\tau$

Present configuration, flux rates: $\nu_e \sim 7.1\%$, $\nu_\mu \sim 92.5\%$, $\nu_\tau \sim 0.4\%$

Anti-ν_μ /$\nu_\mu \sim 62\%$, Anti-ν_e /$\nu_e \sim 1$, Anti-ν_τ /$\nu_\tau = 1$

- Expect ~ 3400 ν_τ 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
- ν_τ: a probe of non-standard interactions PRD 87 (2013) 013002

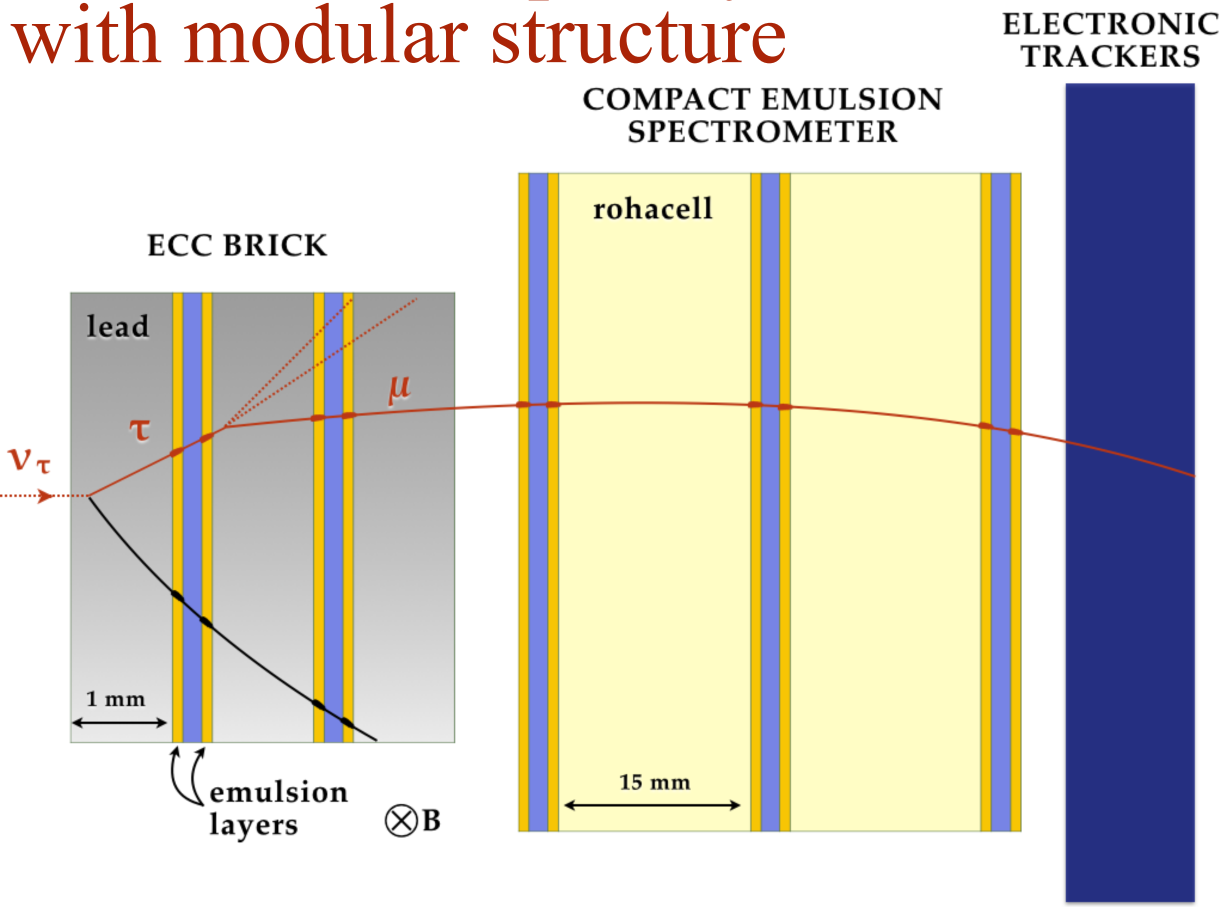
A neutrino detector upstream

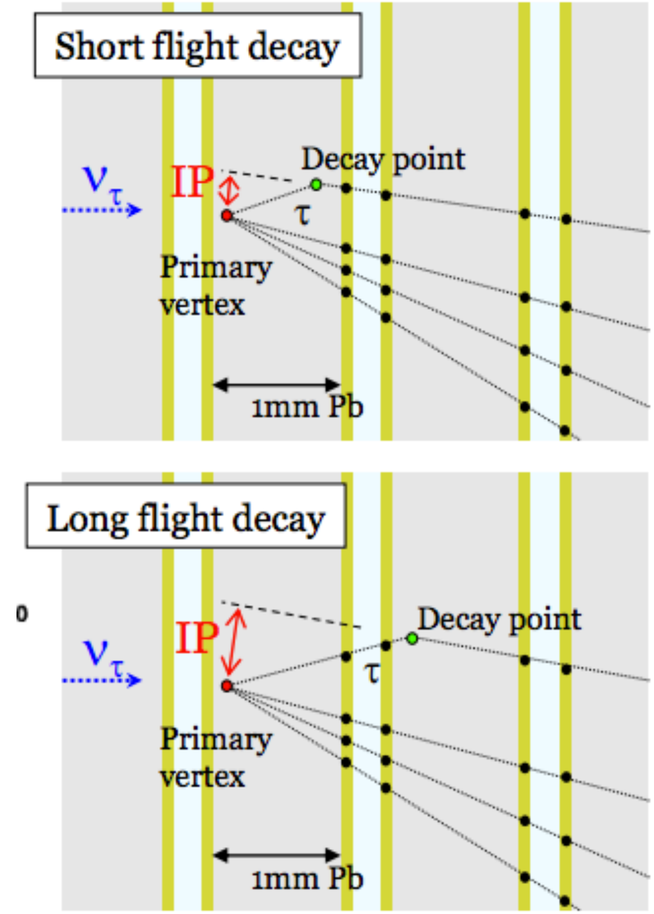


Detector choice

- Neutrino target: high density material (lead) alternated with emulsions (Emulsion Cloud Chamber).
- Vertex detector: emulsions as micrometric tracking device to see both the neutrino interaction and τ decay vertices.
- Nuclear fragments $\rightarrow$ reduce background from hadronic int. (track angles up to $\vartheta \sim \pi/2$)
- Momentum measurement of hadrons (several GeV) by Multiple Coulomb Scattering with ~ 20% accuracy in the several GeV range
- High resolution tracker to provide the time stamp and reconstruct the μ track in the target (~ 100 μm)
- Muon spectrometer to measure charge and momentum. Focus on the acceptance to low energy and large angle μ (as μ from ν_μ int., charmed interactions particularly important)

Detector Principle: hybrid detector with modular structure





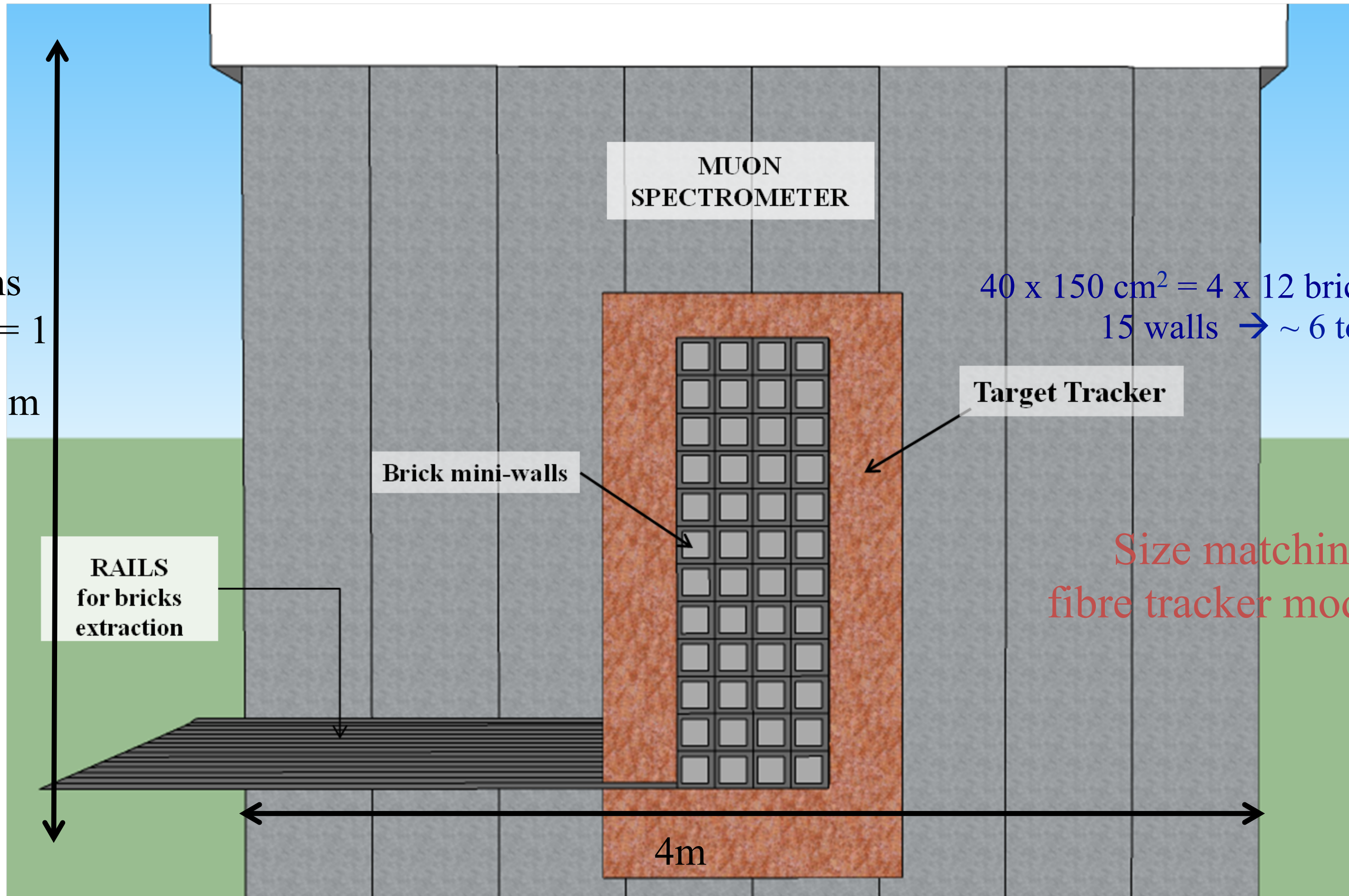
- Nuclear emulsions acting as trackers with micrometric resolution
- Detect τ-lepton production and decay vertices
- An option: Compact emulsion spectrometer to measure charge
- Electronic detectors to provide the“time stamp ” and reconstruct μ charge/momentum

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

Detector design, beam view

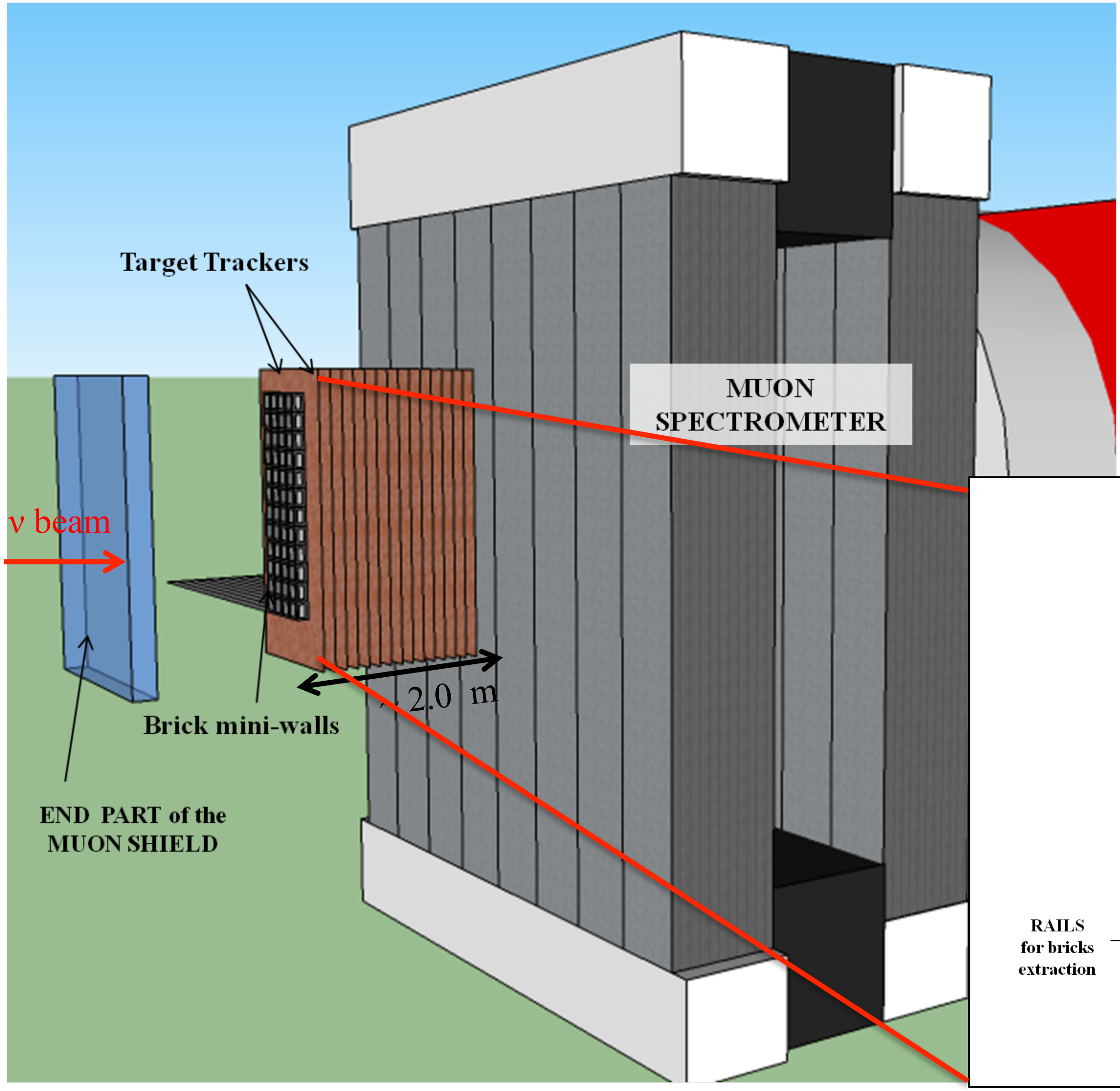
Magnetic muon shield → elongate the target along the magnetic field
→ rectangular shape

Detect muons
up to tan(ϑ) = 1



Squared or circular shape could be used in case of passive shield

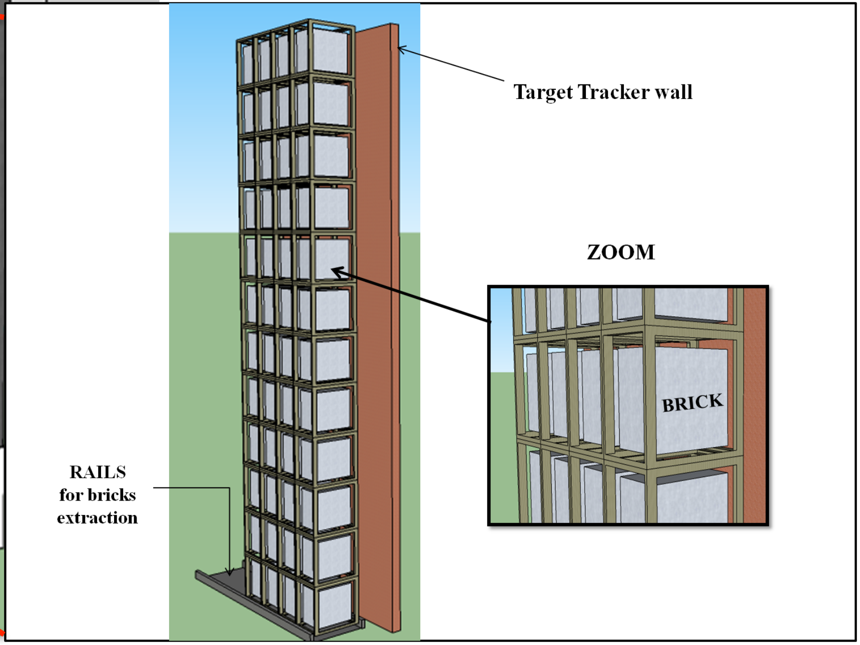
Detector design: first option



Target region: 15 mini-walls
One wall contains 48 bricks
target mass ~ 8.3 x 48 x 15 kg ~ 6 ton

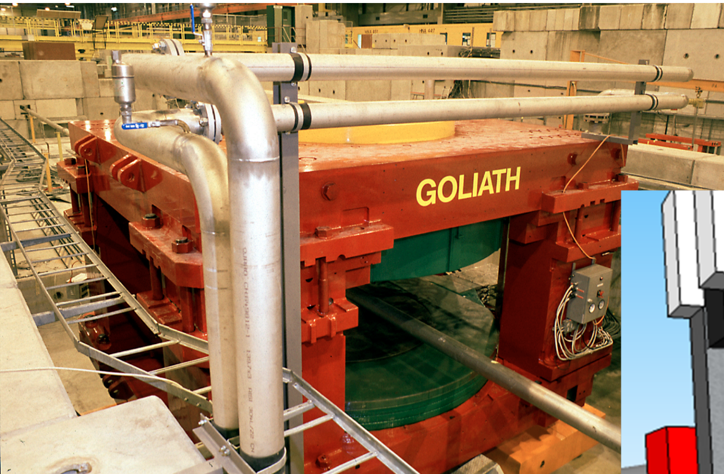
TARGET TRACKER:

- Scintillating fibres (250 μm diameter), read out by SiPMs,
- GEM

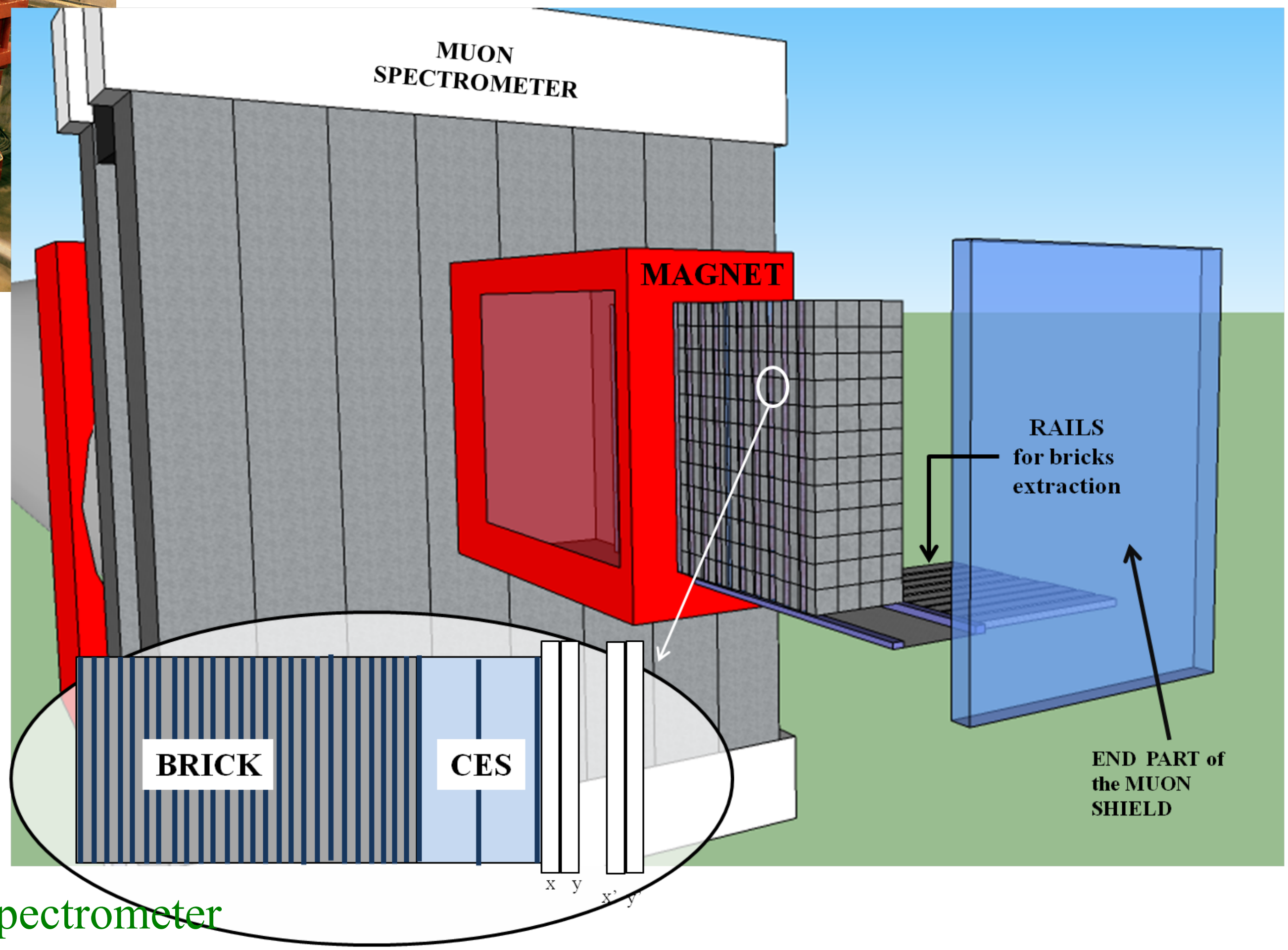


Wall thickness ~ 13 cm: 8 cm brick + 5 cm tracker plane

Detector design: second option with a magnetized target

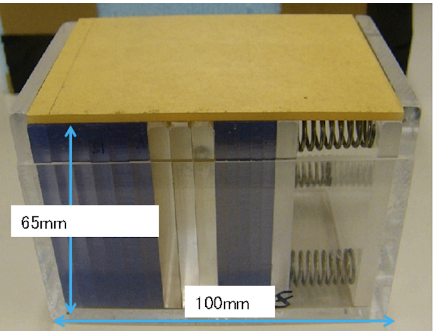


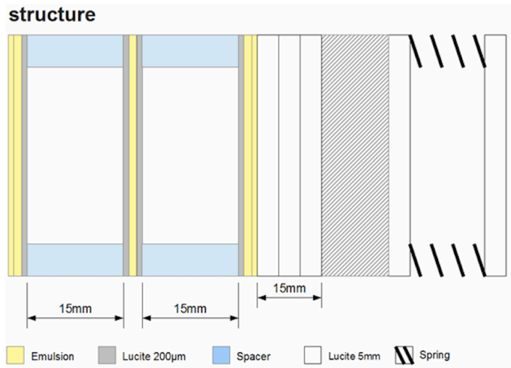
Magnet available at CERN



CES = Compact Emulsion Spectrometer

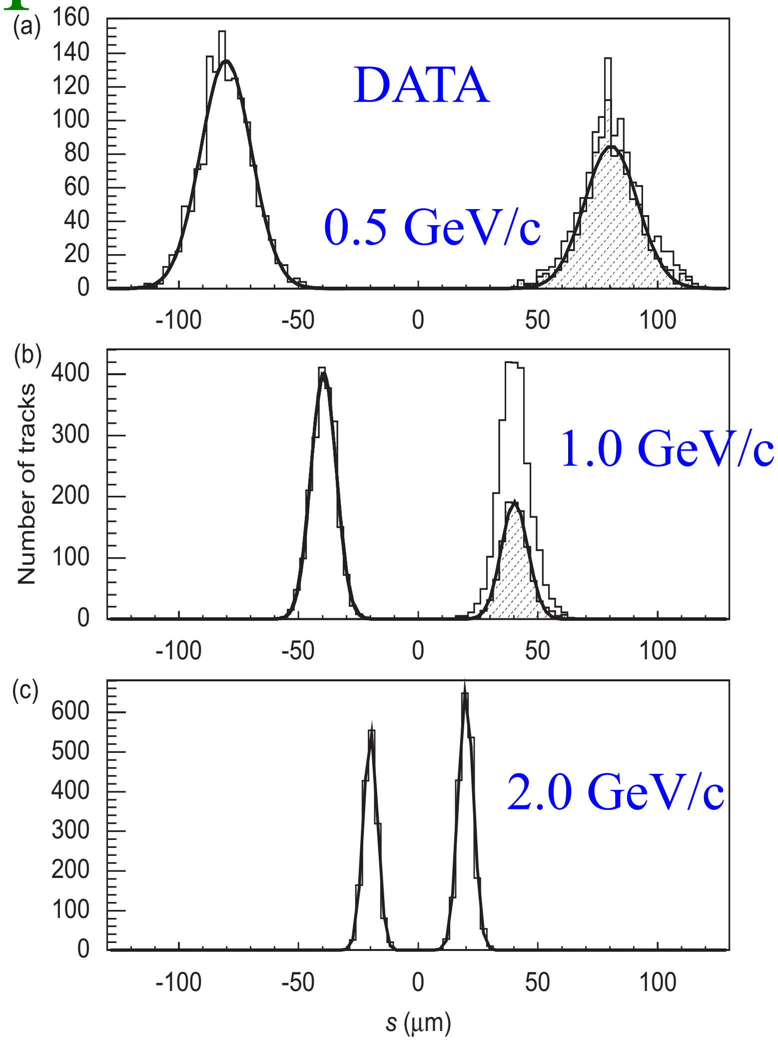
Compact emulsion spectrometer CES





3 emulsion films interleaved with 1.5 cm air gap in a magnetic field (~ 1T), 3cm thick device, H. Shibuya et al NIM A592 (2008) 56

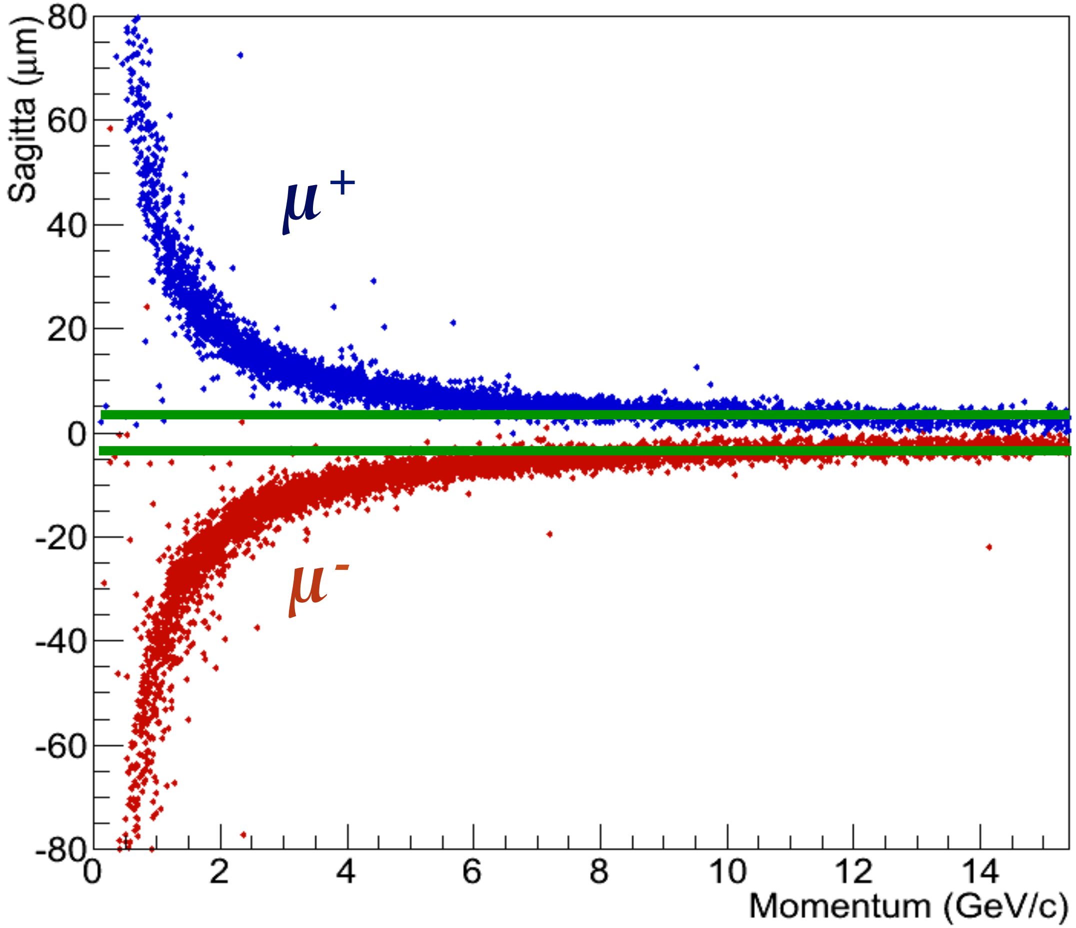
- Emulsion films alternated by low density material (Rohacell, 30÷100 kg/m^3)
- With a good alignment, by means of high energy μ, the charge of 10 GeV muons detectable (±4 μm displacement).



Sagitta measurement

Charge Measurement with CES

Geant4 simulation



$\tau^- \to \mu^-$	$\tau^+ \to \mu^+$
58.3 ± 0.6 %	61.8 ± 0.6 %
93.1 ± 0.3 %	94.9± 0.3 %

with muon spectrometer

$\tau^- \to h^-$	$\tau^+ \to h^+$
56.5± 0.3 %	49.3± 0.3 %

Statistical gain due to the CES $$\frac{\sum_{i=1}^{N} br_i \varepsilon_i}{br_\mu \varepsilon_\mu} \simeq \frac{18 \cdot 0.95 + 50 \cdot 0.53 + 15 \cdot 0.53^2}{18 \cdot 0.9} \simeq 3$$

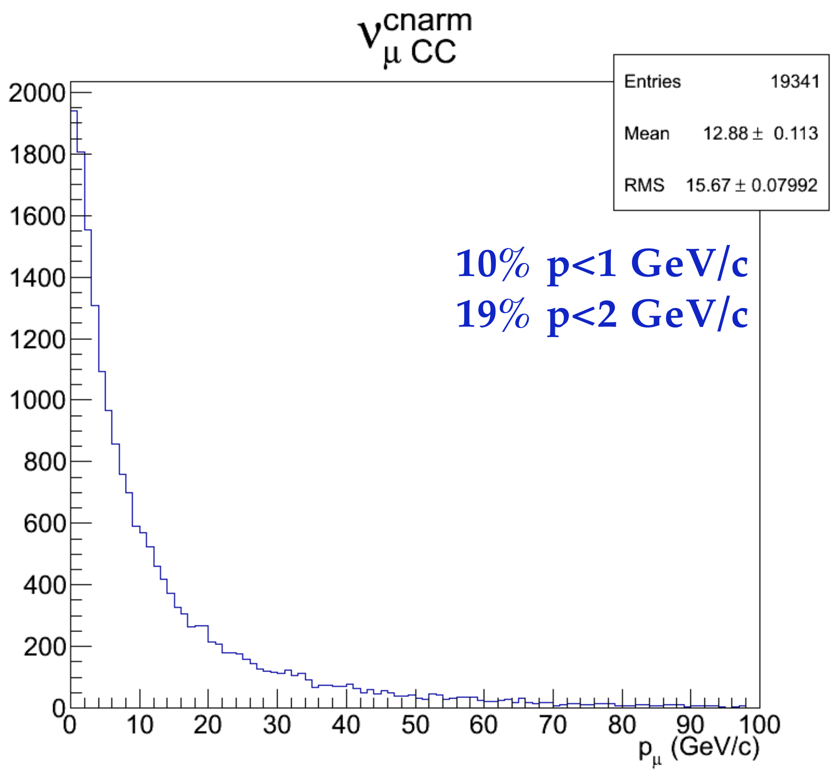
Neutrino Event Generator tuned with NOMAD data

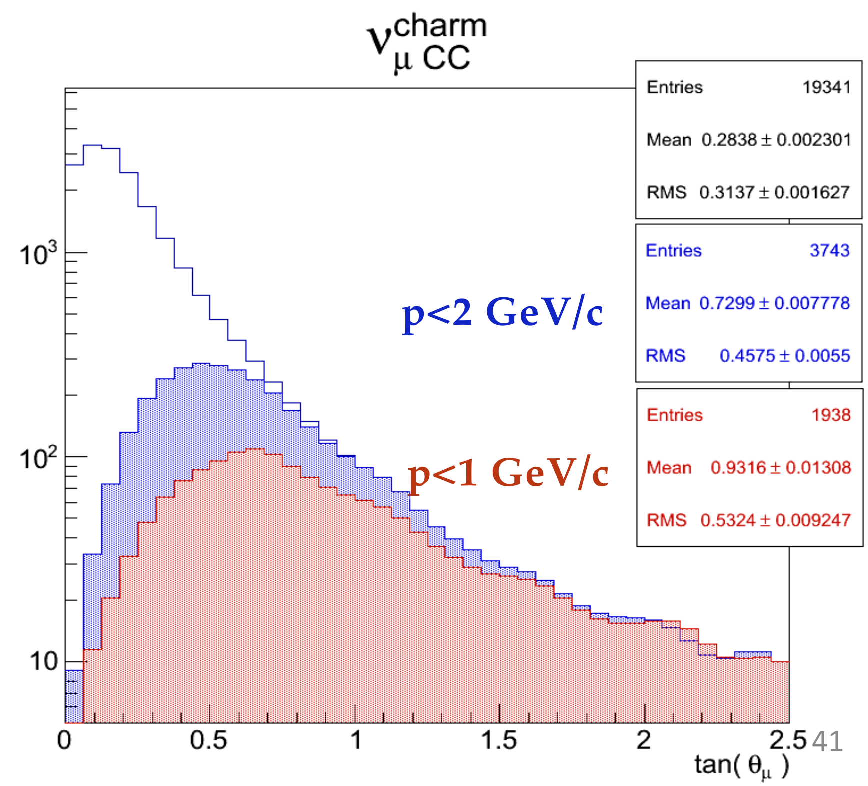
Real-time electronic detectors

- Time stamp of the event, association of tracks in emulsions with tracks in the target tracker
- In an environment with high interaction rate, a high resolution (~ 100 μm) is needed. Identified options: 250 μm scintillating fibre tracker; GEM; MicroMegas.
- The muon spectrometer has to identify μ with high efficiency
- Charm background from μ mis-identification.
- Charge measurement is less important than μ identification in this respect
- Charge measurement important for ν_τ and anti-ν_τ separation

Muon detector requirements

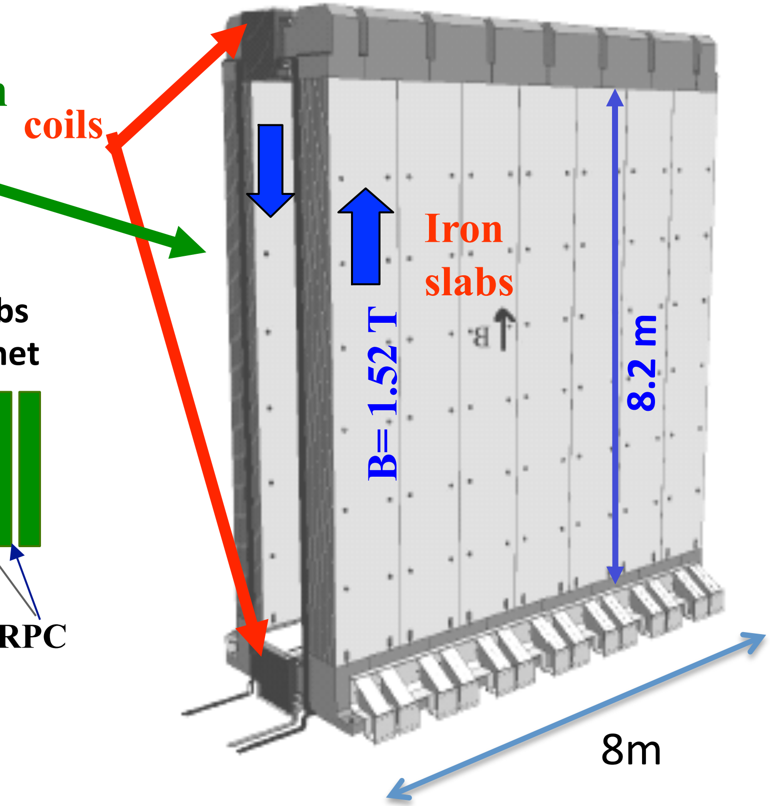
- Detector performances driven by the background rejection → minimise muon misidentification
- Soft and large angle muons → difficult to be identified
- Large acceptance and fine graining to identify P < 2 GeV
- 4 x 5.5 m^2 to detect angles up to $\tan(\vartheta) \leq 1$
- High sampling to use momentum/range correlation





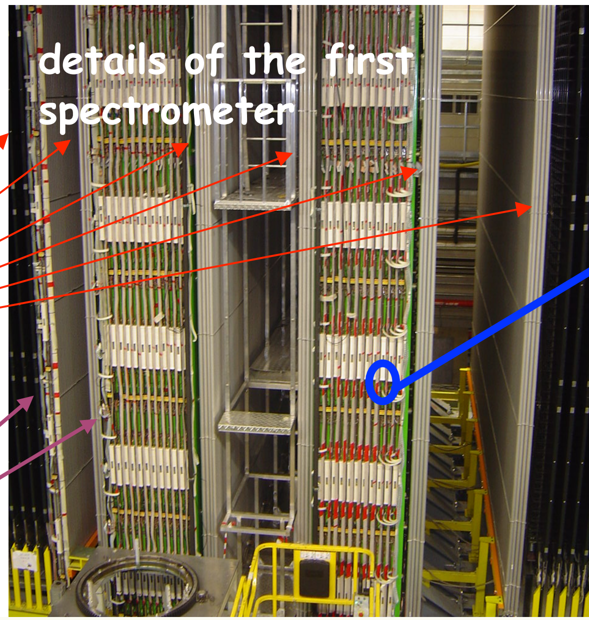
The magnetic spectrometer (OPERA one is an option)

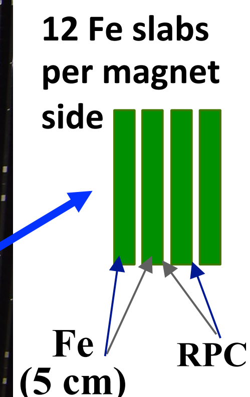
One spectrometer is composed by:
1 dipolar magnet (1.52 T)
22 RPC layers as inner tracker inside magnetized iron
6 drift tubes stations (PT stations)
2 external XPC stations (RPCs with strips at ±43º)

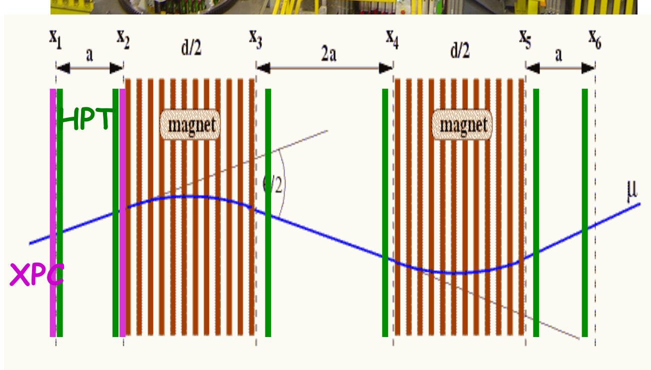


Precision
Trackers
(drift tubes)

XPCs







Charm bkg rejection in ν_μ CC events
Muon identification (with TT) > 95%
$\Delta p/p$ < 20% for p<30 GeV
Charge misidentification < 0.3%

OPERA RPC's

1 RPC row:
3 chambers in a series (~9 m^2)
Basic unit of gas flow and HV

I > 4 μA / 9 m^2

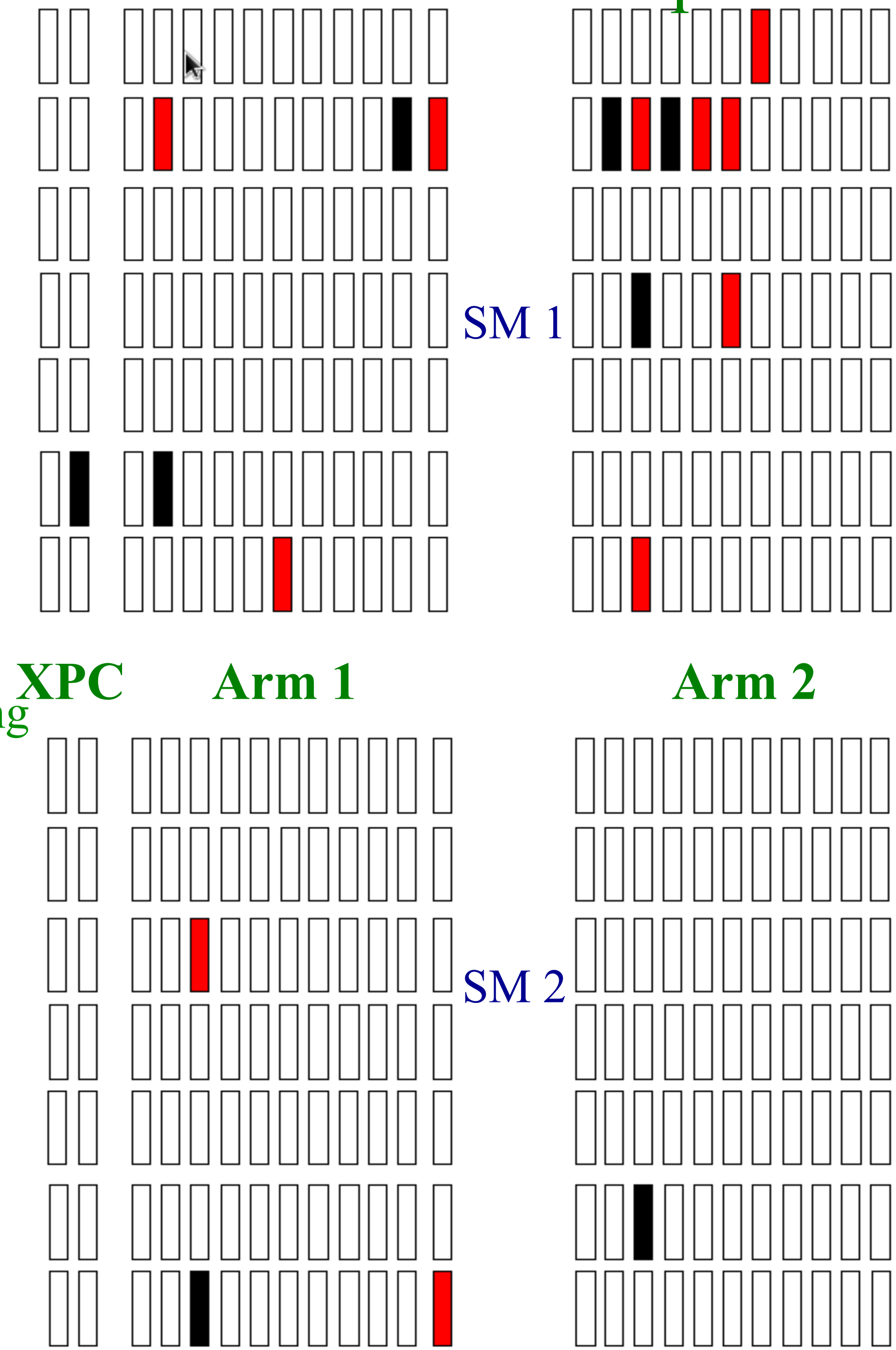
HV cable failure (thin cables)

- 1008 RPC chambers for a surface ~3200 m^2
- 22+2 layers (RPC+XPC) for each SM
- 1 layer = 21 RPCs of 2.9*1.1 m^2
- Read-out strips of ~8 m, 2.6 cm pitch for bending and 3.5 cm pitch for orthogonal view
- Total digital electronics channels ~ 28000

Typical current/rates:
500 nA/row / 1 kHz/layer

In SM2
2/168 (1.2%) rows I > 4 μA/9m^2
Rates of high current layers: 10 kHz
2 RPC rows (1.2%) off because of HV failures (cable insulation)

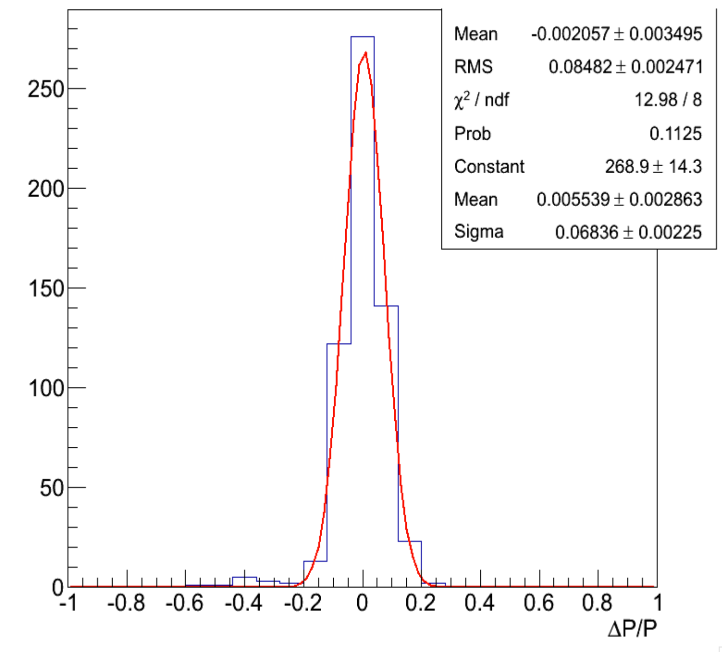
Current map



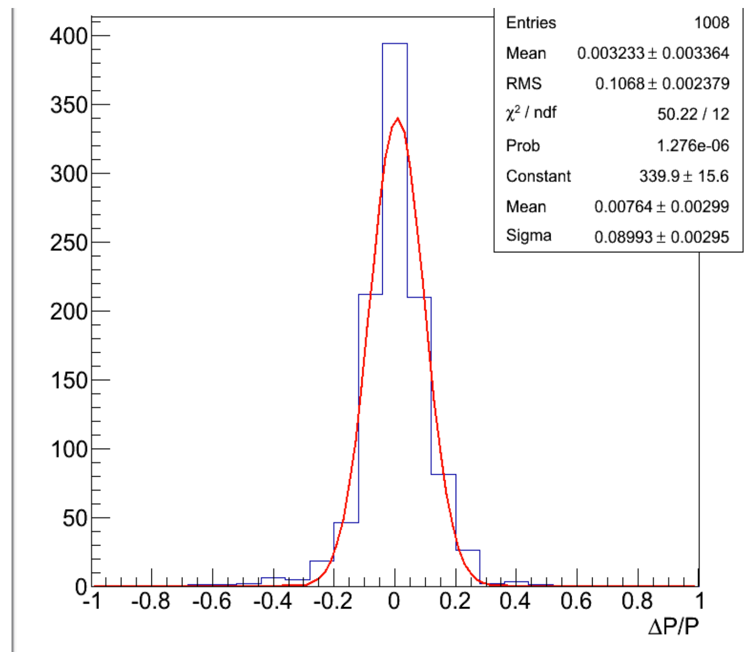
Muon identification

- Same configuration as OPERA, 5 cm iron slabs interleaved with active (RPC) trackers, 4 x 5.5 m^2
- Exploit the momentum-range correlation
- $\varepsilon_\mu \sim 92\%$ for charm ν_μ events (~3% out of acceptance)
- $\varepsilon_\mu \sim 94\%$ for $\tau \rightarrow \mu$ events

Momentum resolution by range in the second arm ~7%



Momentum resolution by range in the first arm ~ 9%



Signal to noise

In ν_τ interactions

$$\frac{\nu_\tau}{\bar{\nu}^{charm}_{\mu CC}} = \frac{\int \phi_{\nu_\tau} \cdot \sigma_{\nu_{\tau CC}} dE}{\int \phi_{\bar{\nu}_\mu} \cdot \sigma_{\bar{\nu}^{charm}_{\mu CC}} \cdot \eta_{mis} dE} \sim \frac{6 \times 10^{-3} \times 300}{8 \times 10^{-2}} \sim 20$$

In anti-ν_τ interactions

$$\frac{\bar{\nu}_\tau}{\nu^{charm}_{\mu CC}} = \frac{\int \phi_{\bar{\nu}_\tau} \cdot \sigma_{\bar{\nu}_{\tau CC}} dE}{\int \phi_{\nu_\mu} \cdot \sigma_{\nu^{charm}_{\mu CC}} \cdot \eta_{mis} dE} \sim \frac{3.7 \times 10^{-3} \times 90}{8 \times 10^{-2}} \sim 4$$

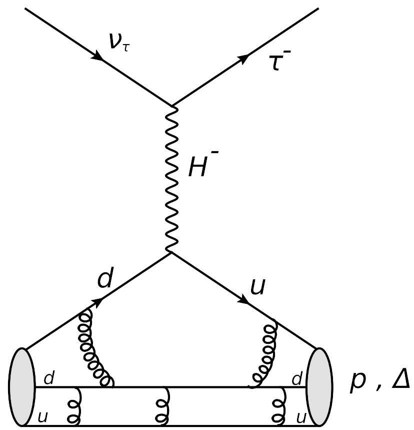
Effect of the angular acceptance not accounted
Kinematical selection not included

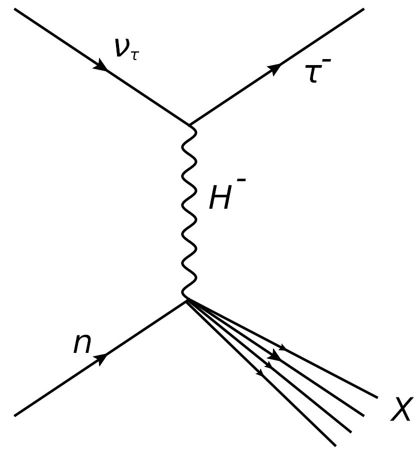
In OPERA Signal/noise ~ 10 on average
Signal/noise ~ 30 in the leptonic channels ($\varepsilon_\mu \sim 98\%$)

New physics in ν_τ scattering

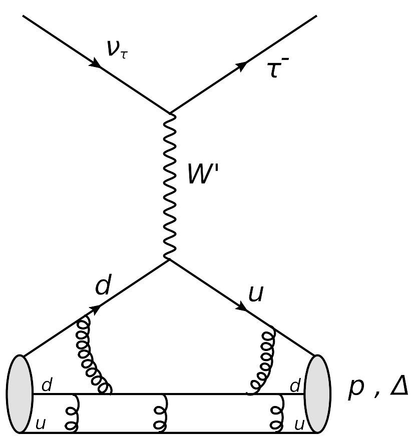
A. Datta et al., PRD 87 (2013) 013002

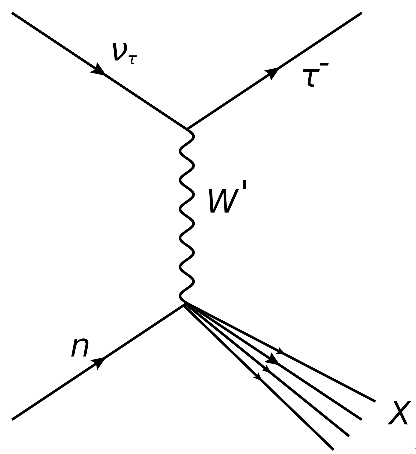
Several new physics models may contribute to ν_τ scattering

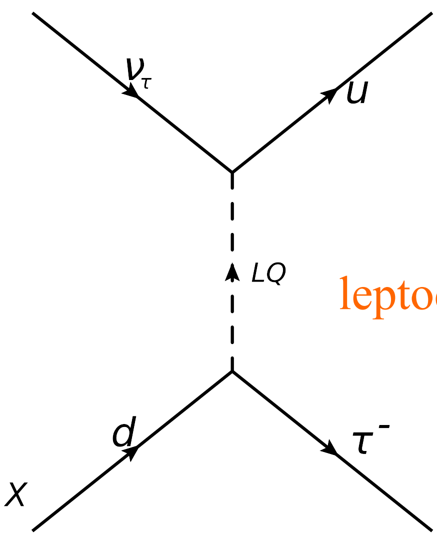




2HDM





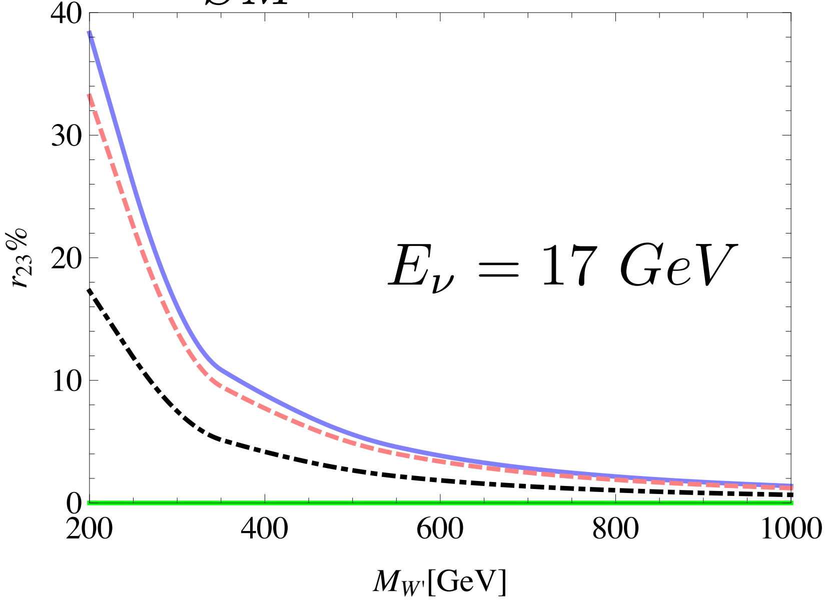


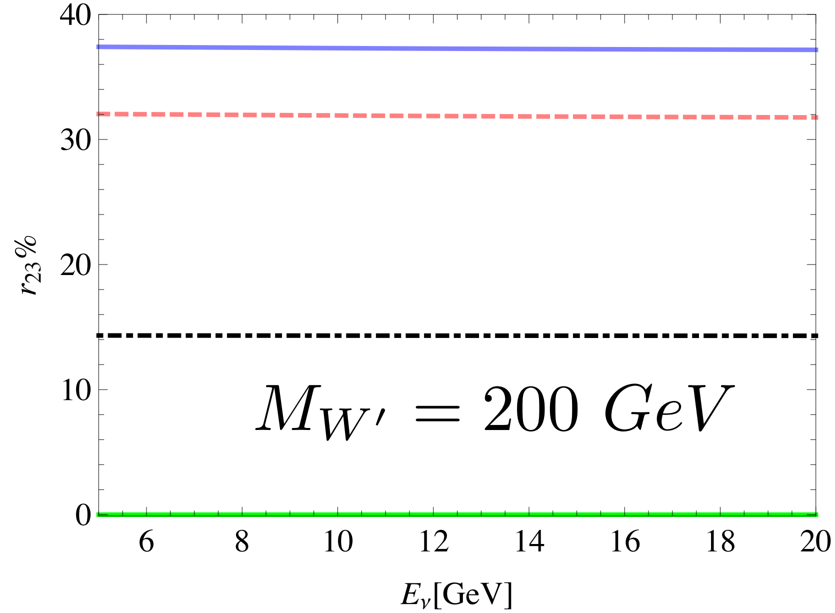
leptoquark

W' in deep-inelastic scattering

$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{f'f} \bar{f}' \gamma^{\mu} (g_L^{f'f} P_L + g_R^{f'f} P_R) f W'_{\mu} + h.c..$$

$$r_{W'} = \frac{\sigma_{NP}}{\sigma_{SM}}$$





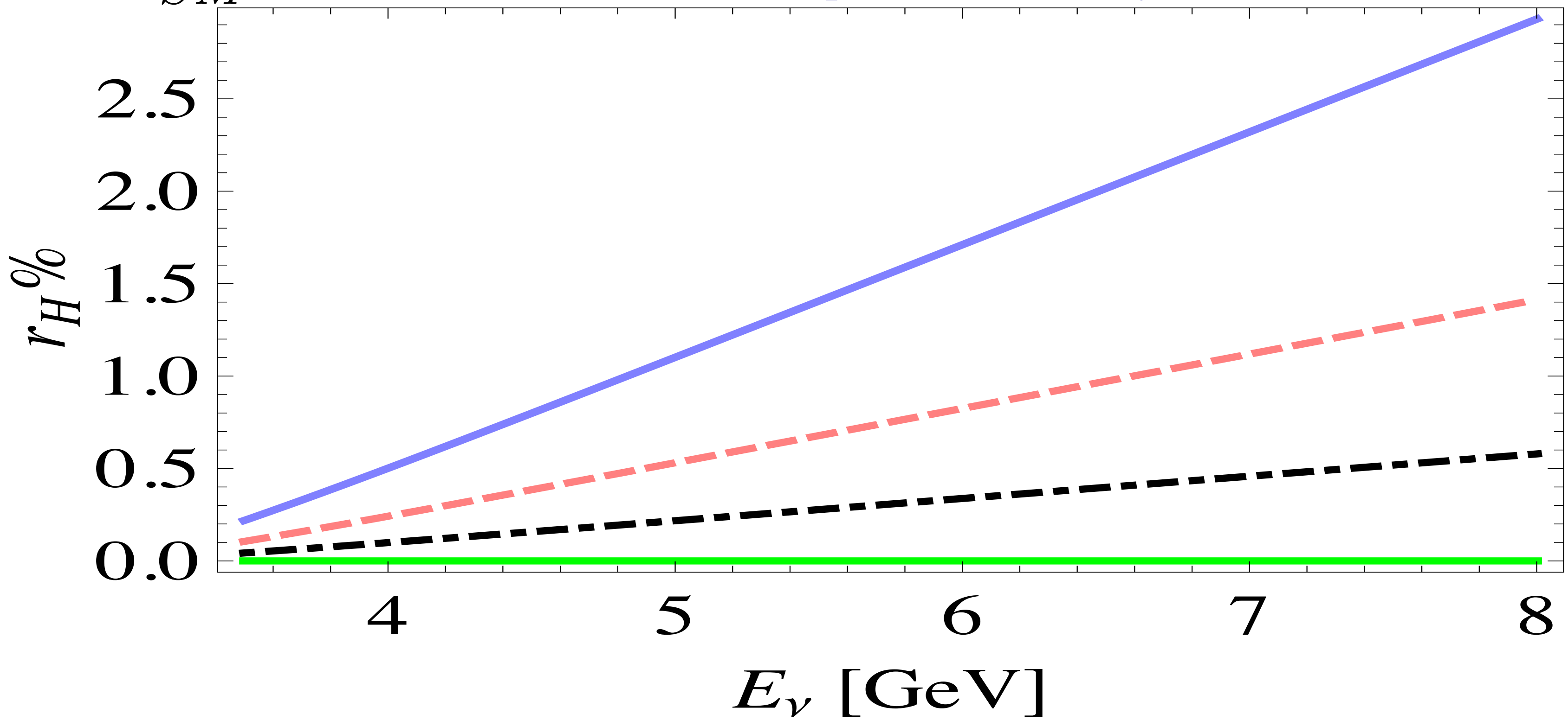
The lines correspond to different sets of the couplings $(g_L^{\tau\nu_\tau}, g_L^{ud}, g_R^{ud})$.

Charged Higgs in quasi-elastic scattering

$$\nu_\tau n \to \tau^- p$$

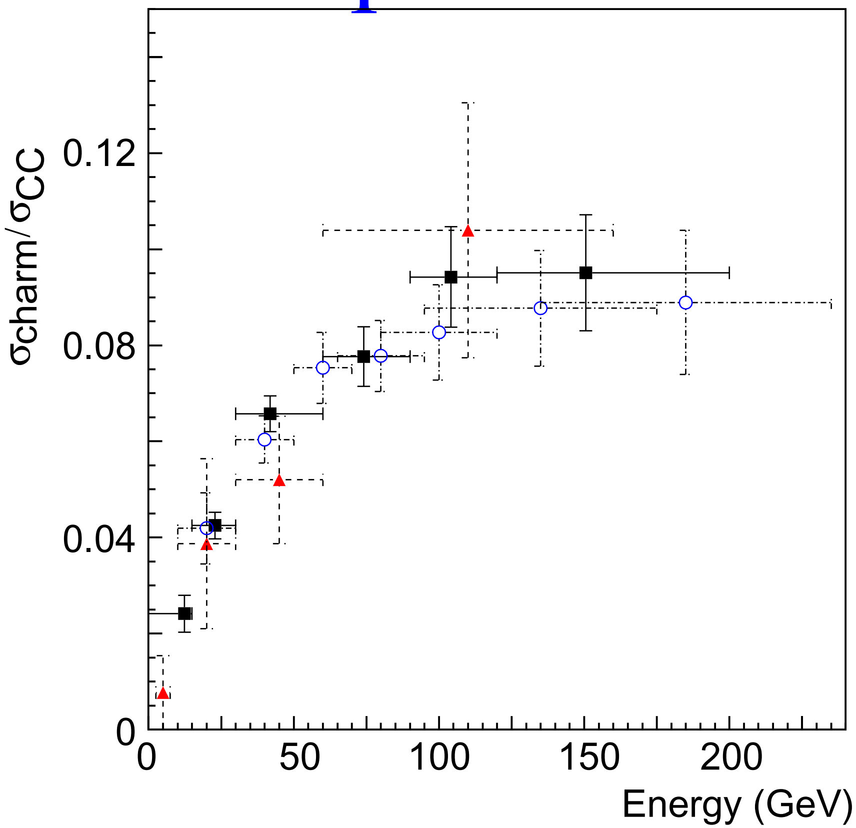
$$r_H = \frac{\sigma_{NP}}{\sigma_{SM}}$$

Much less sensitive, require an accuracy <<1%



The lines correspond to different values of $\tan\beta$ (ratio of VEV's)

Expected ν-induced charm events



CHORUS , New Journal of Physics 13 (2011) 093002

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

In ν_μ interactions: $\sigma_{charm} \sim 2\%$, CC/(NC+CC) = 0.7
$\varepsilon_{decay} \sim 40\%$ → 2 x 10^6 x 0.02 x 0.7 x 0.4 ~ 11000 charm

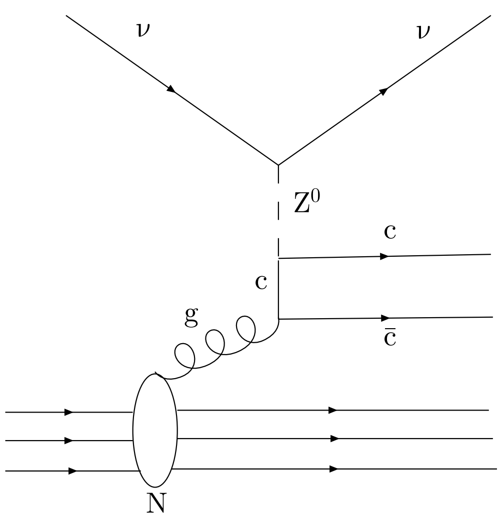
In anti-ν_μ interactions:
anti-ν_μ /ν_μ ~ 63%, $\sigma_{\nu\text{-bar}}/\sigma_\nu$ = 0.5 ~ 3500 events expected, 32 observed by CHORUS

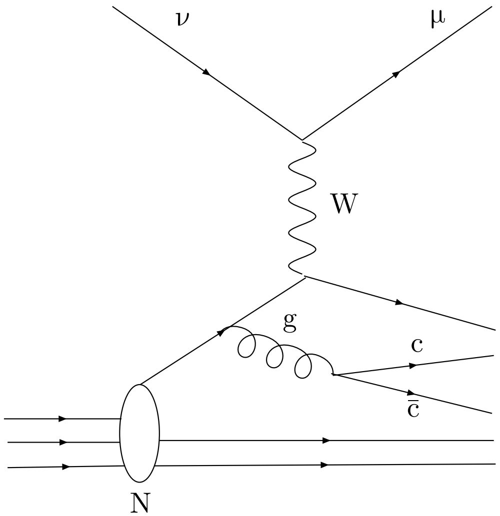
Charm production in ν_e interactions

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

Charm background in the ν_τ search from electron mis-identification (ν_e ~ 10%)

Associated charm production





Only gluon bremsstrahlung in CC interactions
Both processes in NC

Fig. 1. Feynman diagrams for boson-gluon fusion (*left*) and gluon bremsstrahlung processes (*right*)

3 events in NC and 1 in CC processes, another CC event observed with a different search

$$\frac{\sigma(c\bar{c}\nu)}{\sigma_{\mathrm{NC}}^{\mathrm{DIS}}} = (3.62^{+2.95}_{-2.42}(\mathrm{stat}) \pm 0.54(\mathrm{syst})) \times 10^{-3}.$$

$$\frac{\sigma(c\bar{c}\mu^-)}{\sigma_{\mathrm{CC}}} < 9.69 \times 10^{-4},$$

~ 30 events expected

Double charm in NC interactions sensitive to the existence of Z' bosons

Charm production induced by ν_τ interactions is competing

Same topology, kinematics to be exploited

Search for multi-quark states in ν interactions: charmed pentaquarks

Weakly decaying charmed hadron (below 2.8 GeV)

Unlike other processes like e+ e- scattering, the θ^0_c production in anti-neutrino interactions is favoured by the presence of three valence quarks

G. De Lellis et al. / Nuclear Physics B 763 (2007) 268–282

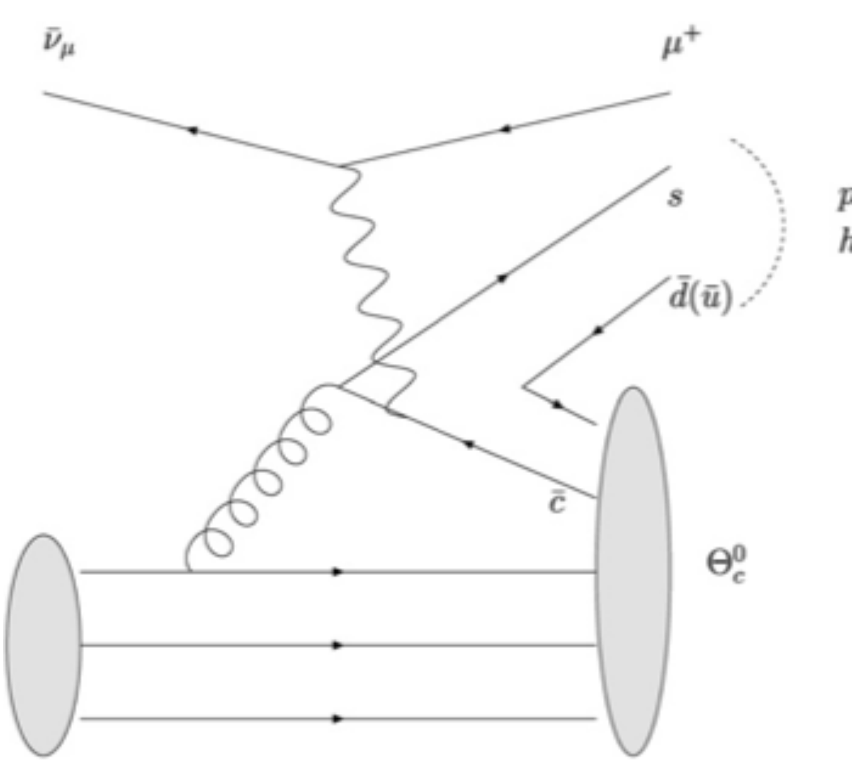


Fig. 1. Θ^0_c production in $\bar{\nu}_\mu$ interactions.

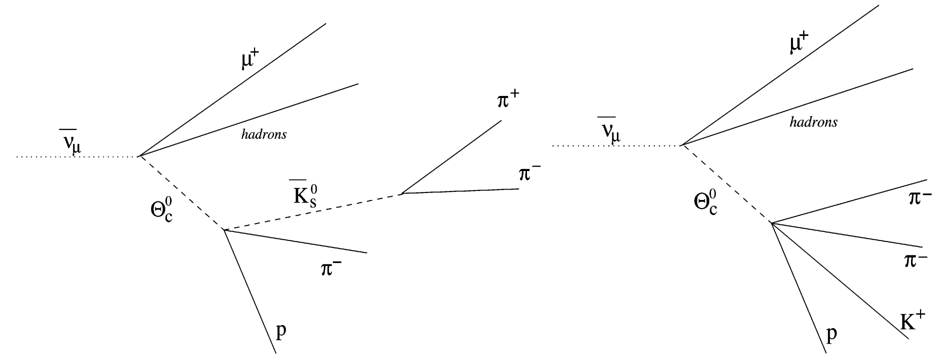


Fig. 2. Decay topology of Θ^0_c events produced in $\bar{\nu}_\mu$ interactions with two and four prongs.

$$\sigma_{\Theta^0_c}/\sigma_{\bar{\nu}} < 0.039 \text{ at } 90\% \text{ C.L.}$$

lifetime equal to $0.5\tau_{D^0}$

Not a tight bound, larger than D^0 prod,
Limited by the anti-nu statistics

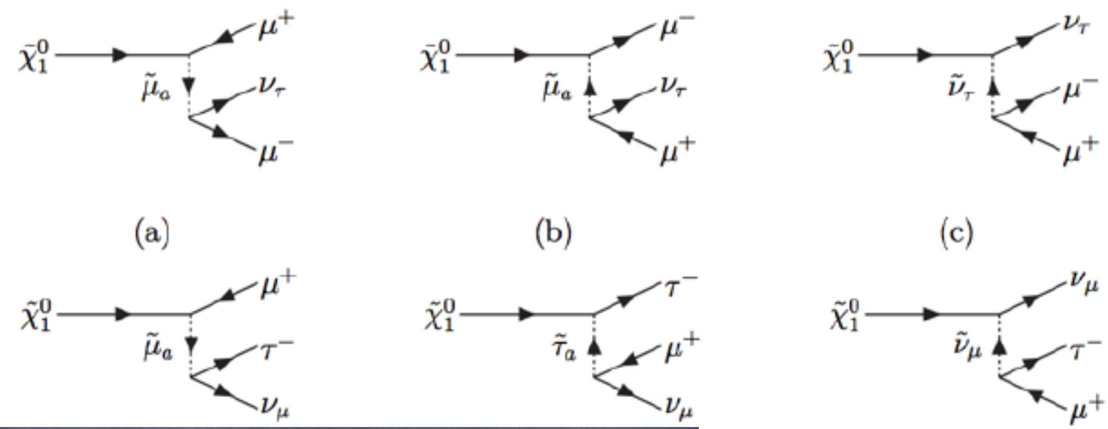
New physics portals

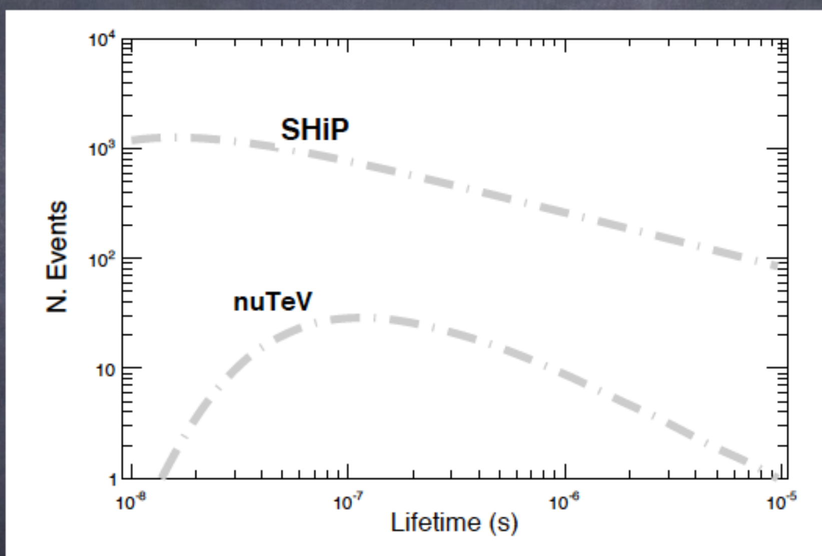
- Fermion portal
  - HNL in general
  - SUSY: Low mass neutralinos
- Scalar portal
  - Light inflaton
- Vector portal
  - Paraphoton
- Axion portal
  - SUSY: Light sgoldinos

In general: sensitive to very weakly interacting and long lived particles

Light neutralinos

- *Can be produced in charm decays, e.g.* $D^0 \rightarrow \nu\,\chi_0$, $D^+ \rightarrow \mu^+\,\chi_0$
- *Decay final states:*





Number of events for $BR(B^+ \rightarrow \ell^+\chi_0) = 10^{-7}$ which is equivalent to $BR(D^+ \rightarrow \ell^+\chi_0) = 10^{-9}$ and $\chi \rightarrow \ell^+\ell^-\nu$

Hidden photons

- Assuming no lighter hidden particles, γ' decay into SM particles through a virtual photon:

$$\gamma' \to e^+e^-, \quad \mu^+\mu^-, \quad q\bar{q}, \ldots$$

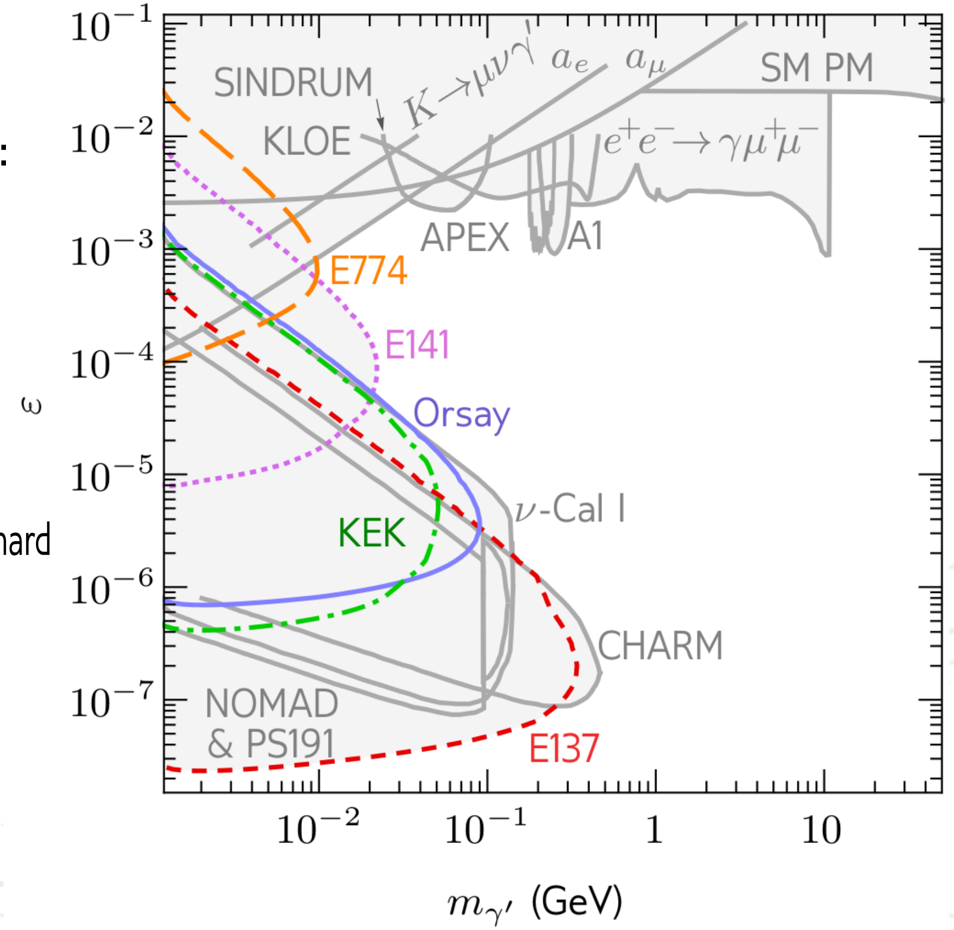
- decay length $c\tau \sim \varepsilon^{-2} m_{\gamma'}^{-1}$
- cosmological constraints (nucleo-synthesis): $\tau < 0.1$ s $\Rightarrow \varepsilon^2 m_{\gamma'} > 10^{-21}$ GeV

γ' production

- proton bremsstrahlung:
  - initial-state radiation from the incoming proton, followed by a hard proton-nucleus interaction
- secondary particles decay:

Mass interval (GeV)	Process	$n_{\gamma'}/p.o.t$
$m_{\gamma'} < 0.135$	$\pi^0 \to \gamma\gamma'$	$\varepsilon^2 \times 5.41$
$0.135 < m_{\gamma'} < 0.548$	$\eta \to \gamma\gamma'$	$\varepsilon^2 \times 0.23$
$0.548 < m_{\gamma'} < 0.648$	$\omega \to \pi^0\gamma'$	$\varepsilon^2 \times 0.07$
$0.648 < m_{\gamma'} < 0.958$	$\eta' \to \gamma\gamma'$	$\varepsilon^2 \times 10^{-3}$

Present limits



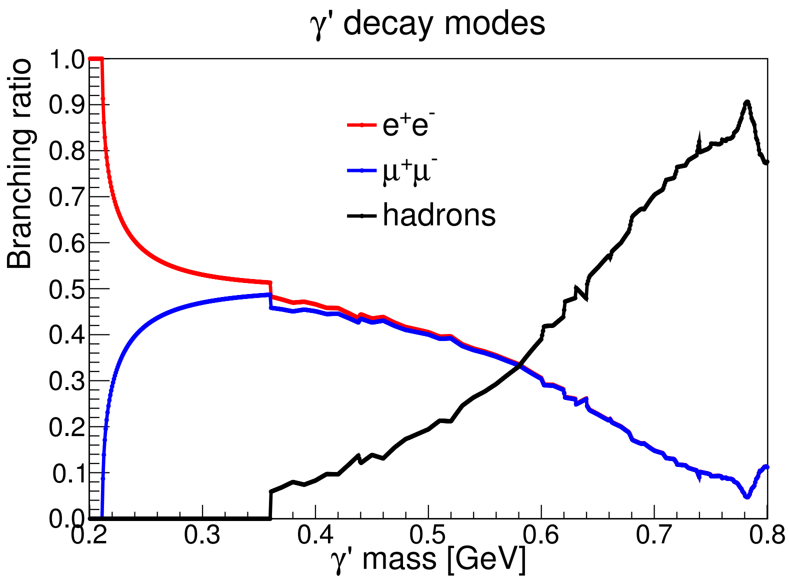
γ' decays

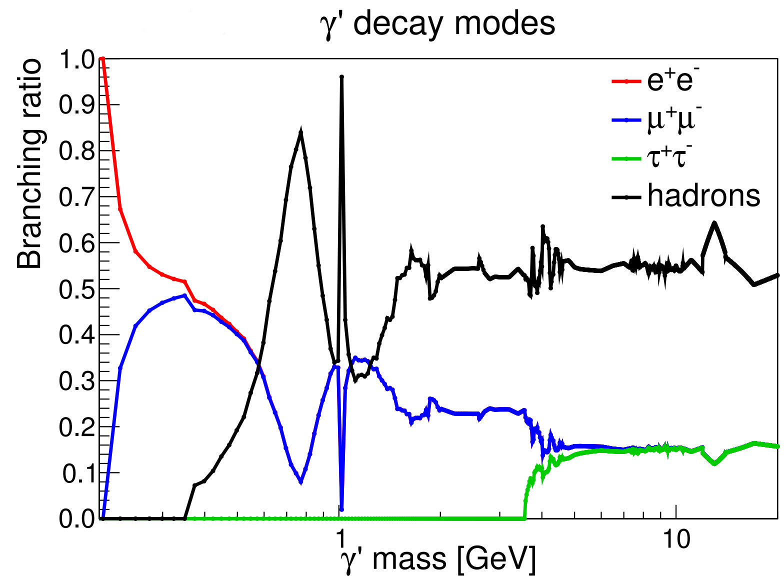
Phys. Lett. B731 (2014) 320

$$\Gamma\left(\gamma' \to \ell^+\ell^-\right) = \varepsilon^2 \frac{\alpha_{QED}}{3} m_{\gamma'} \times \sqrt{1 - \frac{4m_\ell^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_\ell^2}{m_{\gamma'}^2}\right)$$

$$\Gamma\left(\gamma' \to q\bar{q}\right) = \varepsilon^2 \frac{\alpha_{QED}}{3} m_{\gamma'} \times R\left(m_{\gamma'}\right)$$

$$R\left(\sqrt{s}\right) = \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)}$$



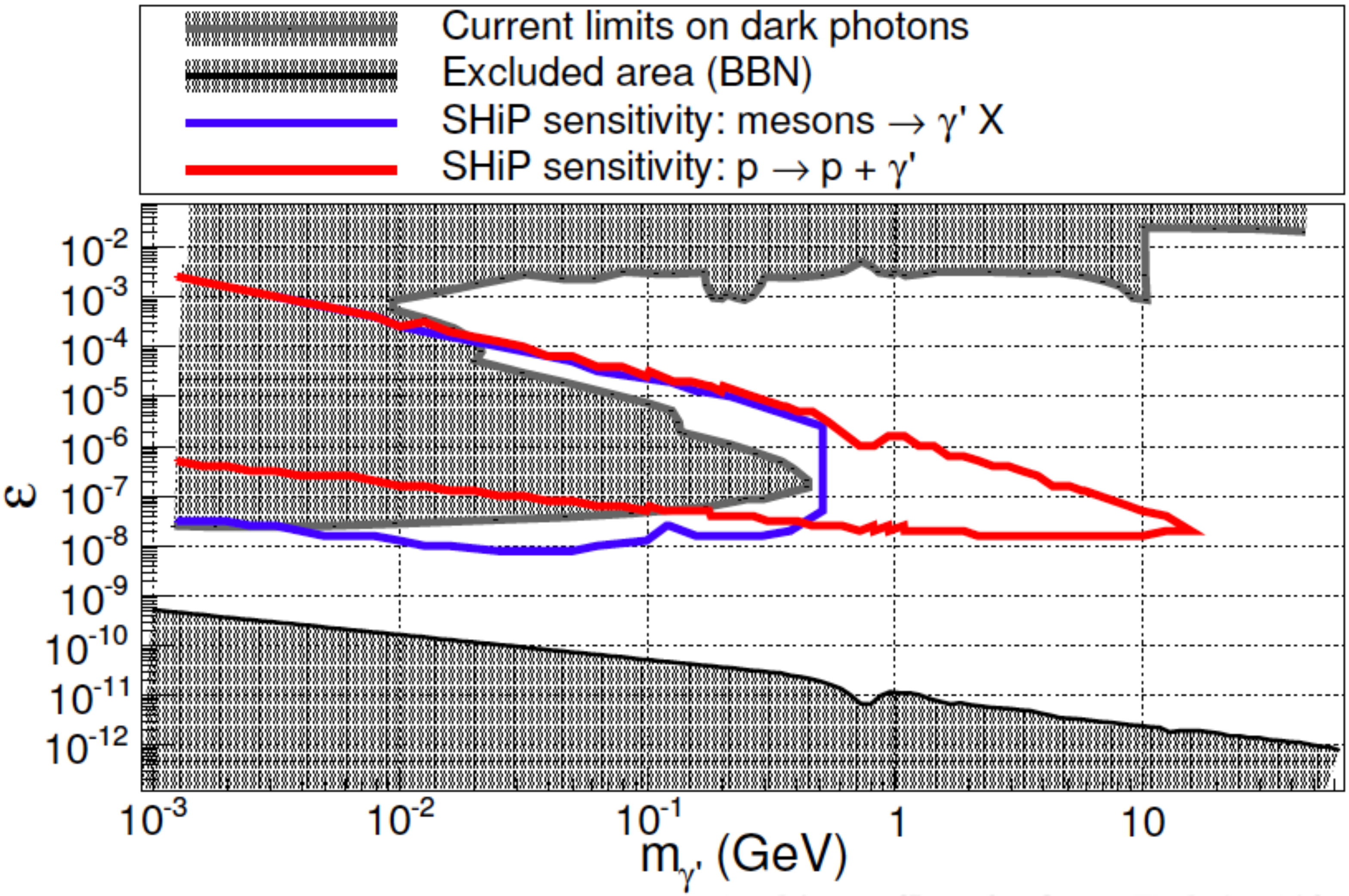


Only e^+e^- and $\mu^+\mu^-$ decays considered here

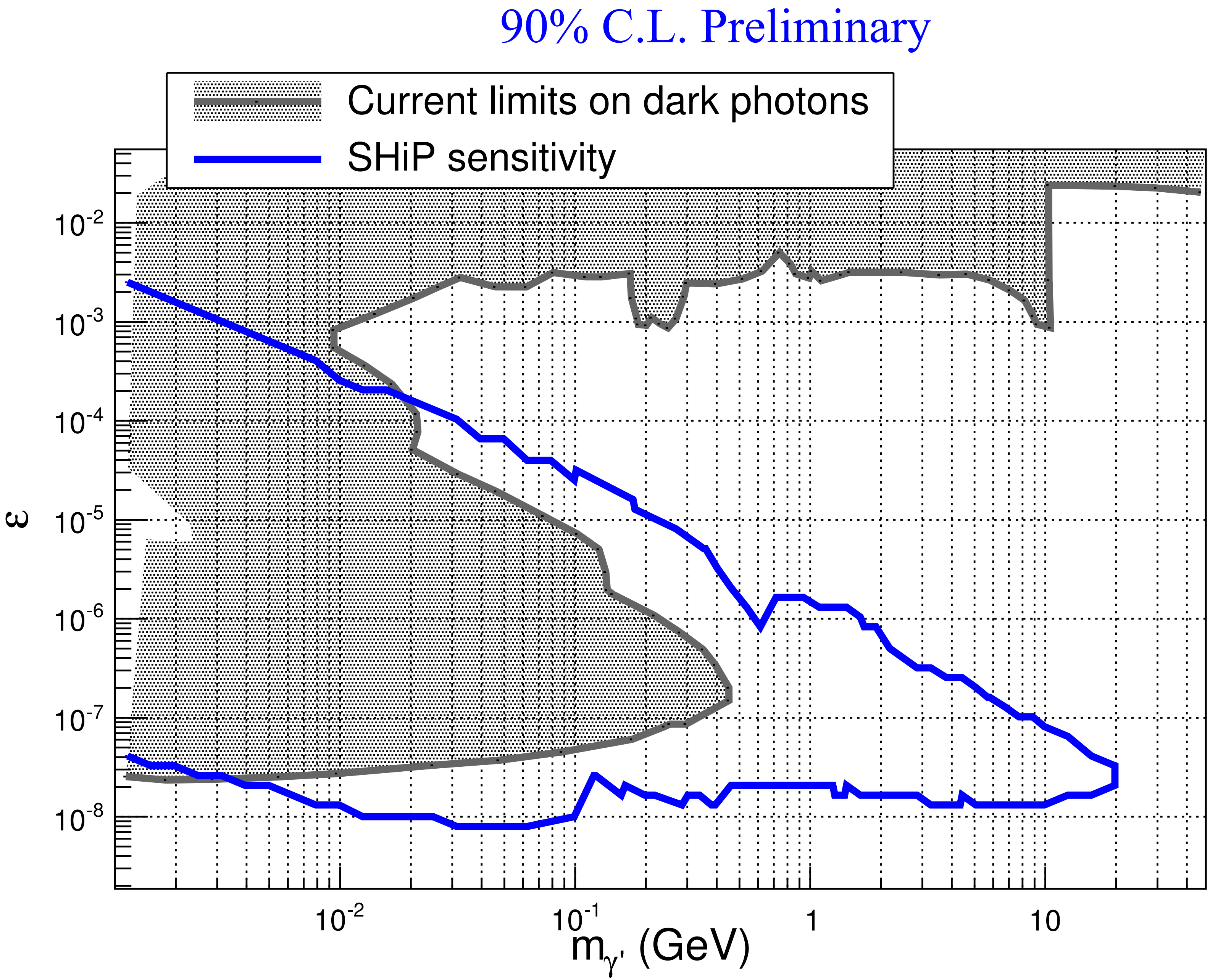
R used to compute the dark photon lifetime

Sensitivity to Dark photons

Preliminary result: 90% C.L. limit



Sensitivity to Dark photons



Status of the SPSC review

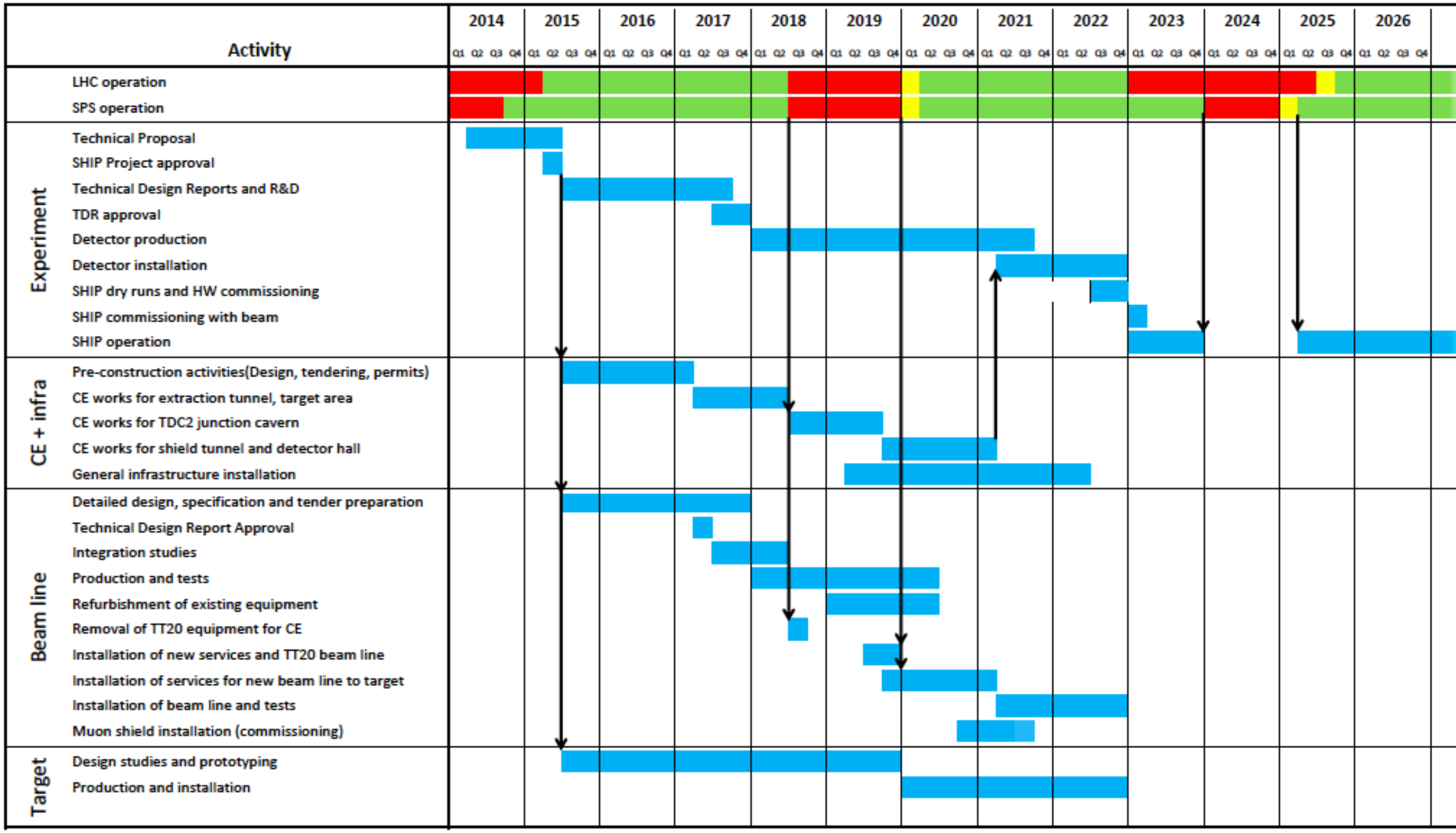
- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010. - 2013
- SPSC assigned 4 referees, who came with a list of questions.
- 3/1/2014: answers to questions: snoopy.web.cern.ch/snoopy/EOI/SPSC-EOI-010_ResponseToReferees.pdf
- 15/1/2014: SPSC discussed our proposal.

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).

Planning schedule of the SHIP facility



A few milestones:

- ✓ ***Form SHIP collaboration*** → ***June-September 2014***
- ✓ ***Technical proposal*** → ***2015***
- ✓ *Technical Design Report* → *2018*
- ✓ *Construction and installation* → *2018 – 2022*
- ✓ *Commissioning* → *2022*
- ✓ *Data taking and analysis of 2×10^{20} pot* → *2023 - 2027*

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 was held in June. Let us know if you are interested to join!