



Search for Heavy Neutral Leptons @ the SPS

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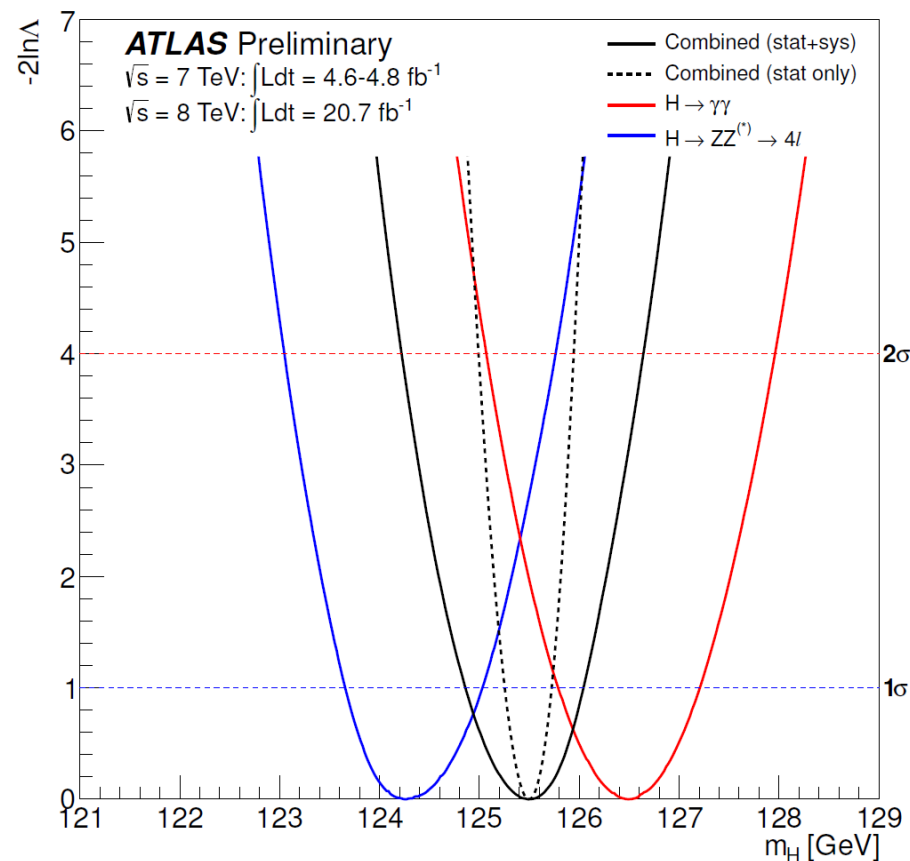
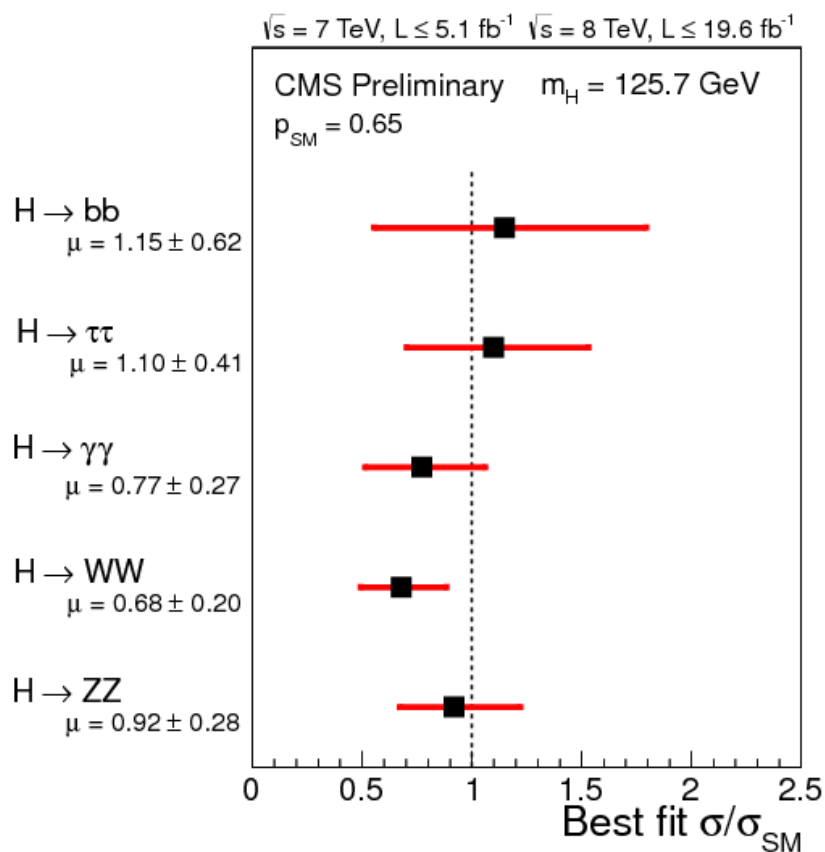
(‡) *retired*

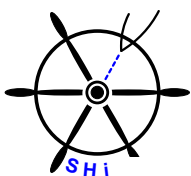
- How does this proposal fit in the physics landscape?
- Why HNLs?
- How to produce/detect HNLs.
- Backgrounds.
- The experimental set-up.
- Symbiosis with “active” ν physics.
- Conclusions.



Triumph of SM: Higgs found!

- Boson found consistent with SM-Higgs.
- Atlas: $M_H = 125.5 \pm 0.2_{stat} \pm 0.5_{syst} \text{ GeV}$
- CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst} \text{ GeV}$

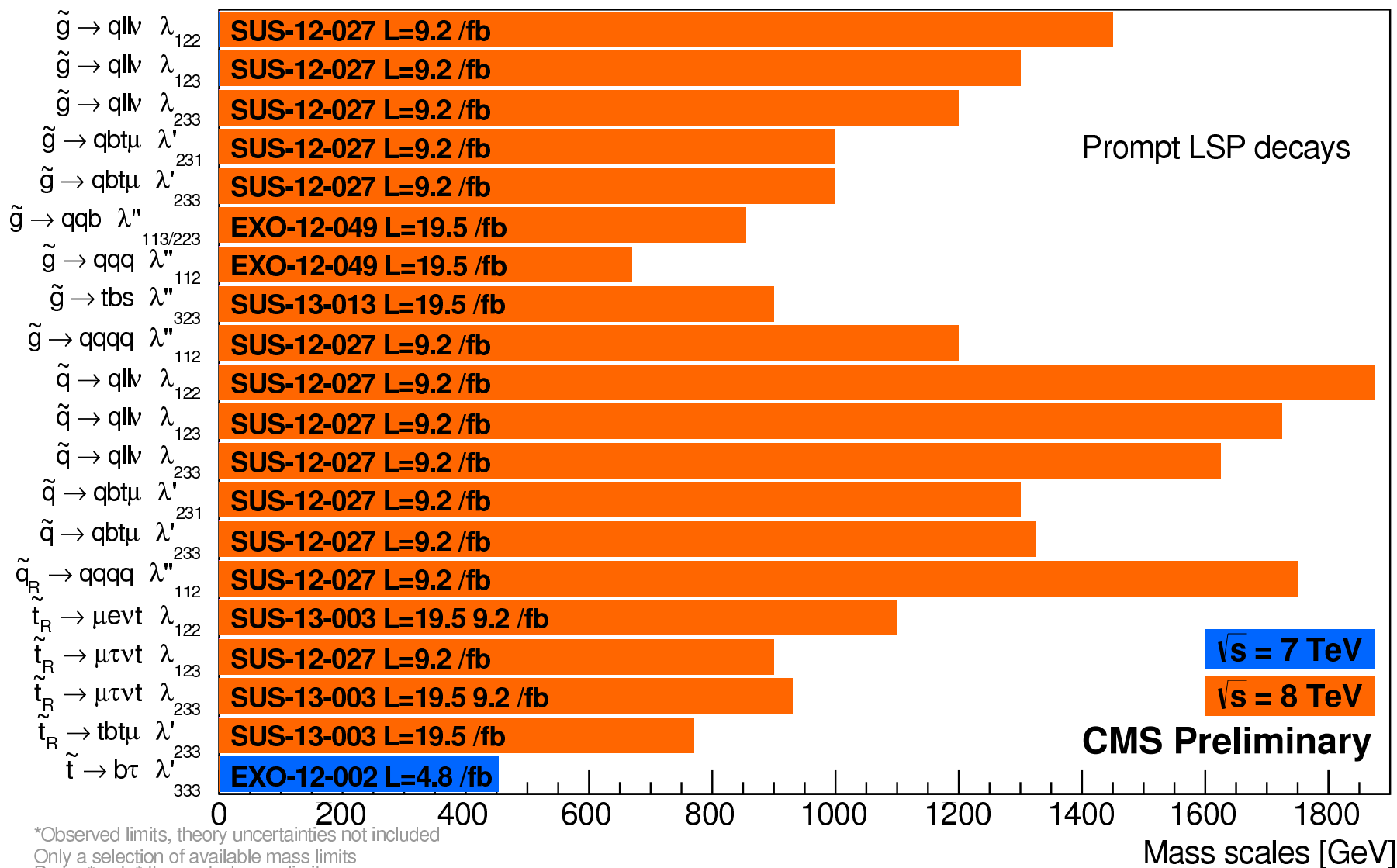




What is not found..

Summary of CMS RPV SUSY Results*

EPSHEP 2013



*Observed limits, theory uncertainties not included
 Only a selection of available mass limits
 Probe *up to* the quoted mass limit



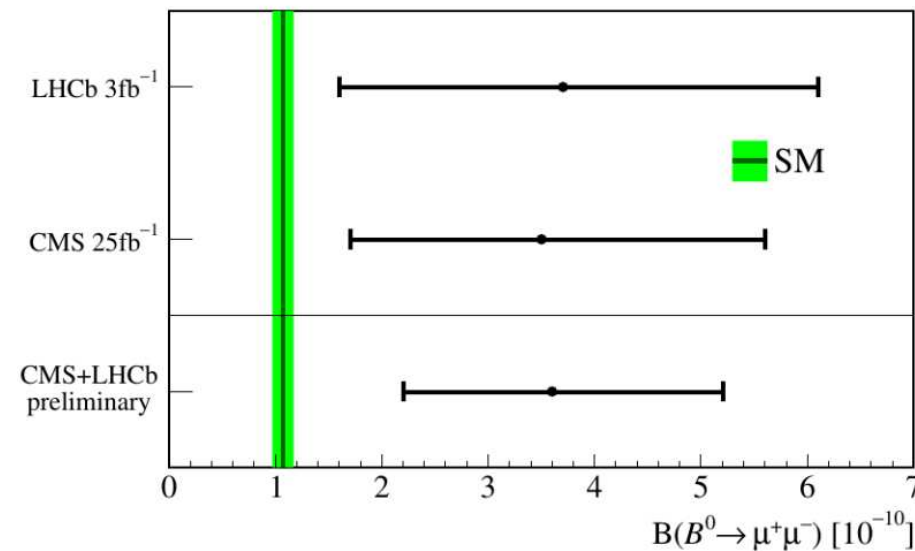
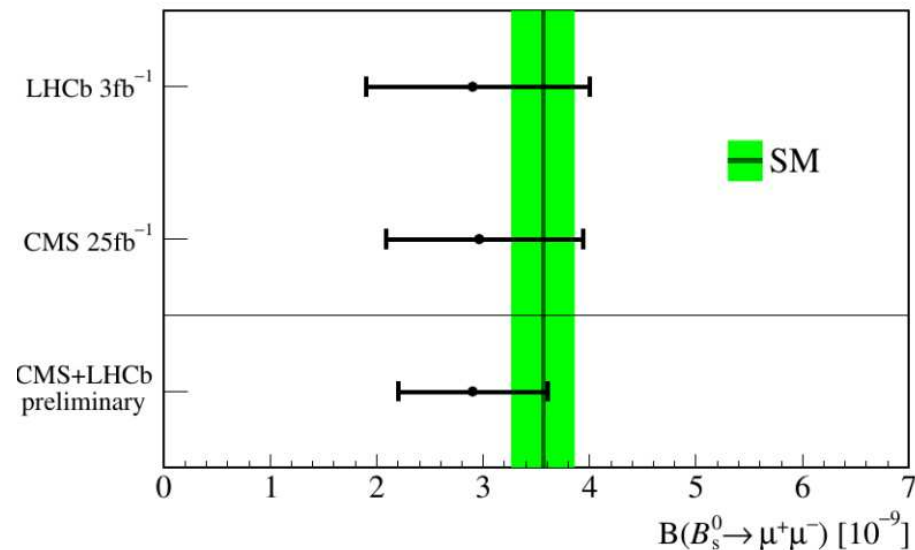
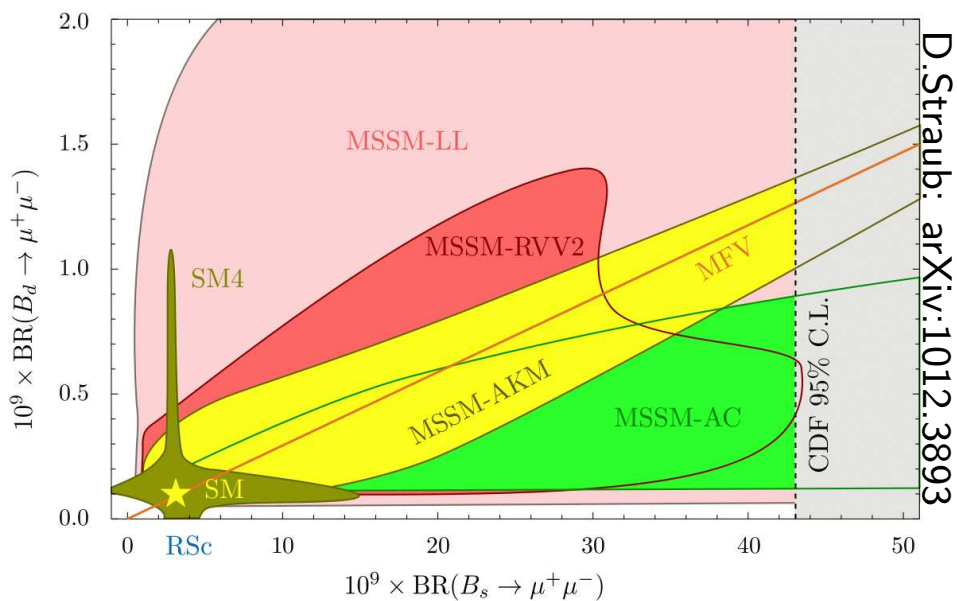
$B_s \rightarrow \mu\mu$ found and \equiv SM

SM:

- No tree level decay
- Helicity suppressed
- Expected: $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$
(Phys. Rev. Lett. 109 (2012) 041801)

NP:

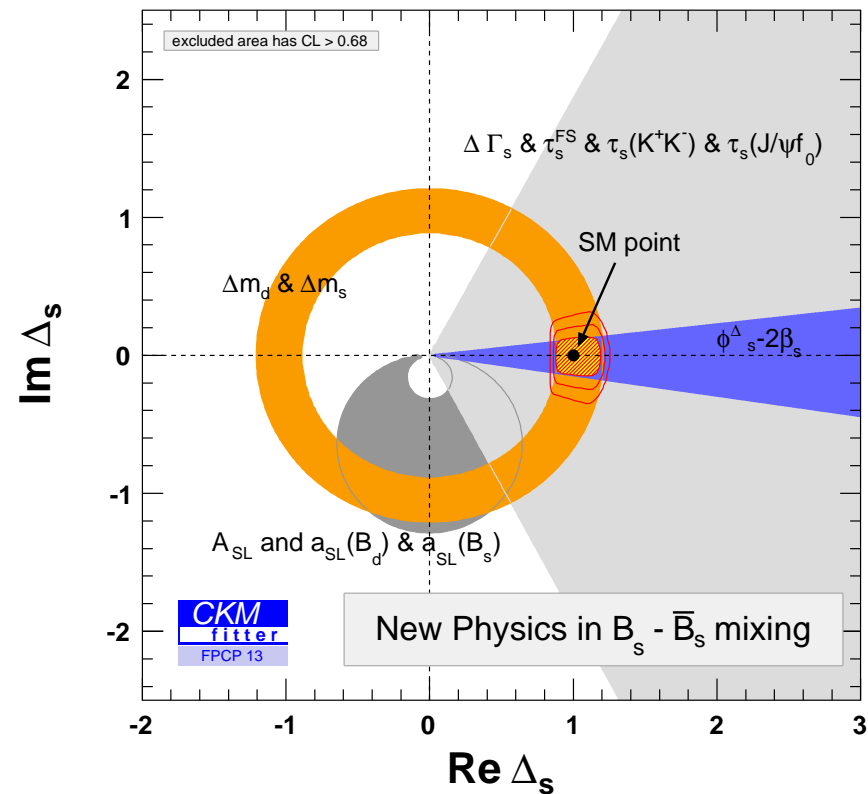
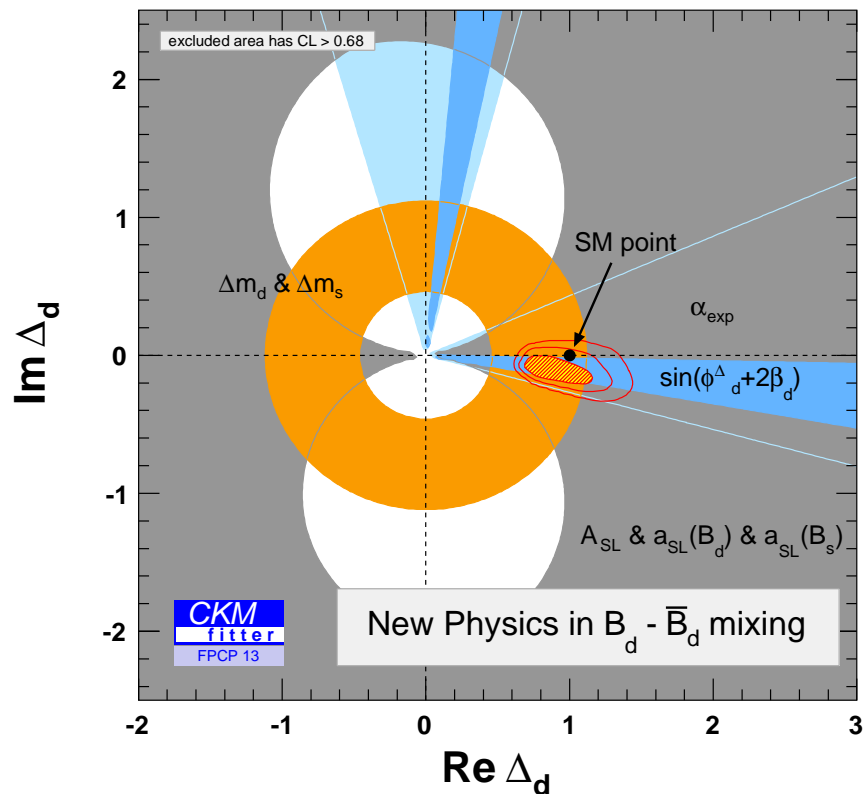
- MSSM: $\mathcal{B} \propto \tan^6\beta/M_{A^0}^4$
- Pre-LHC parameter space example:





NP from quark flavour observables

CKM-fitter

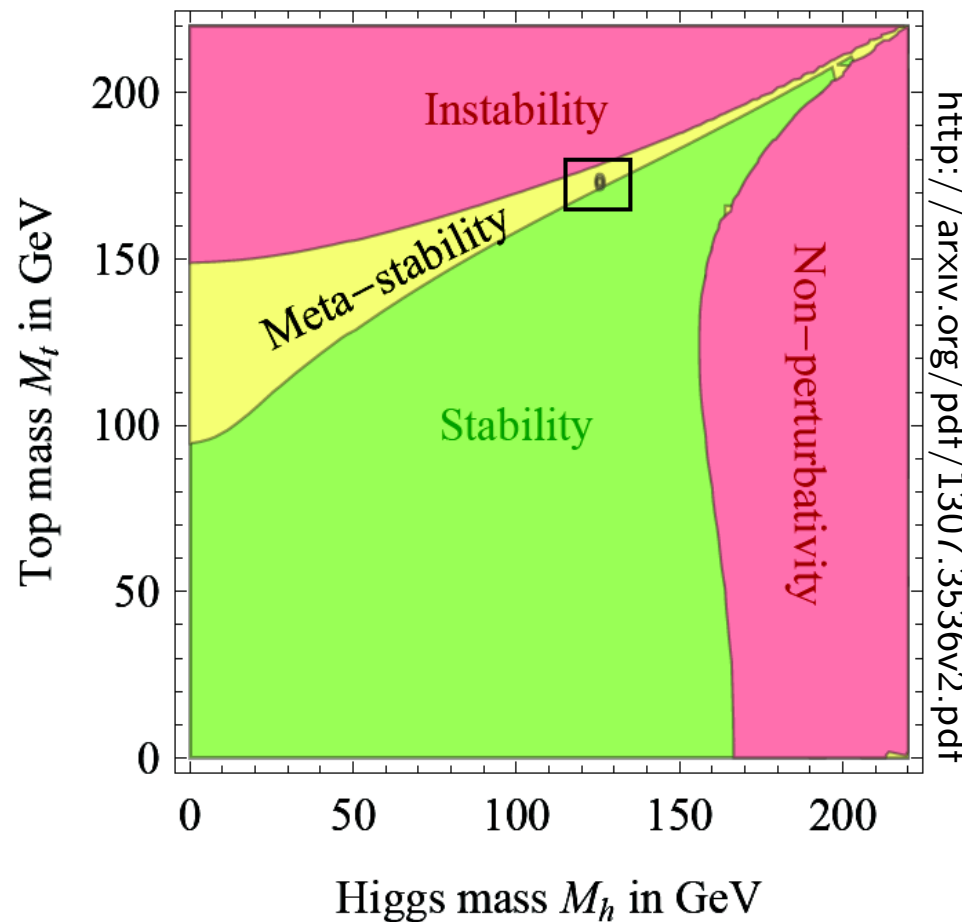
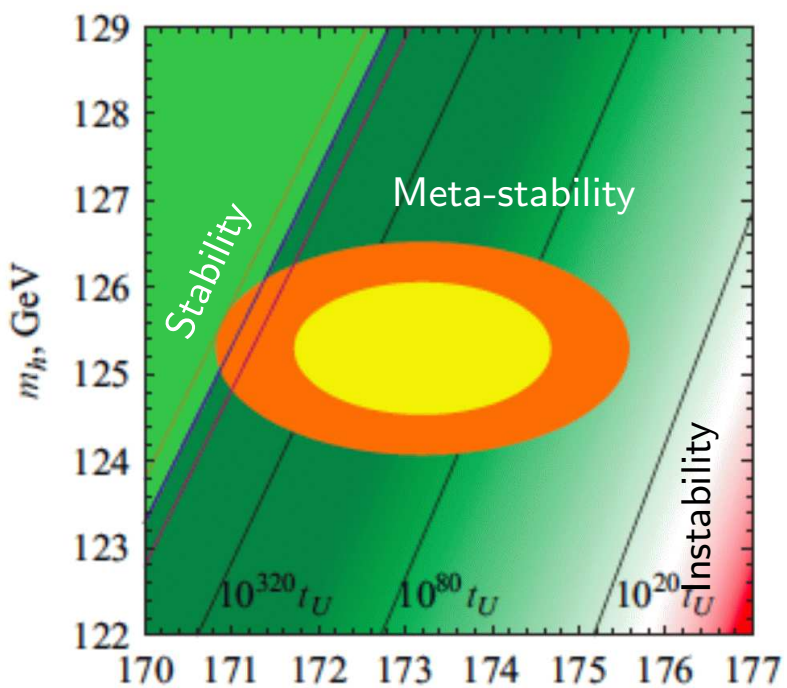


Scale of NP in $B\bar{B}$ -mixing: $> 0.5 - 10^4$ TeV depending on assumptions of couplings.

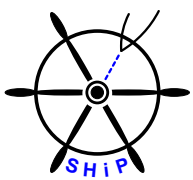


Higgs and Vacuum Stability

- Higgs mass is “fine tuned”?
 - SM located in narrow meta-stability wedge.
 - Most likely “multiverse” near such a wedge?
 - Vast majority of sand-dunes have a slope angle roughly equal to the so-called “angle of repose”.
 - Not anthropic, but $P(\text{multiverses})$ peaks near wedge?
- Vacuum might be stable, or has a $\tau \gg \tau_{\text{universe}}$
- SM may work successfully up to Planck scale, i.e. no need for a new mass scale



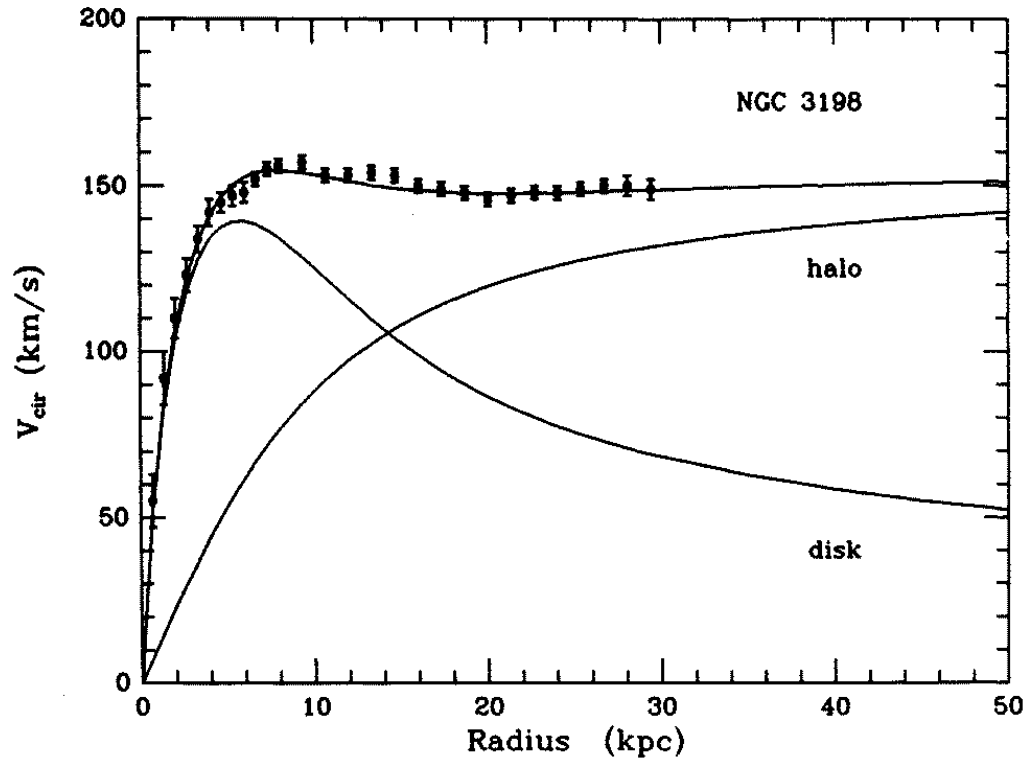
<http://arxiv.org/pdf/1307.3536v2.pdf>



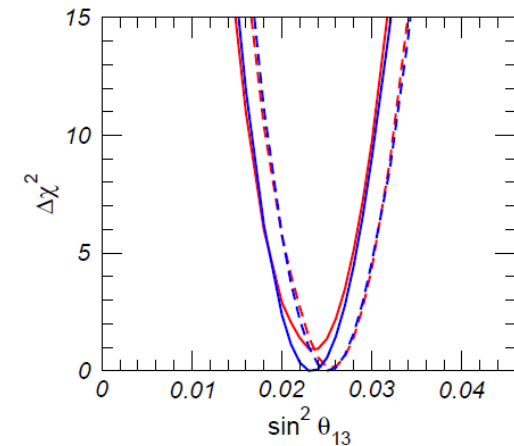
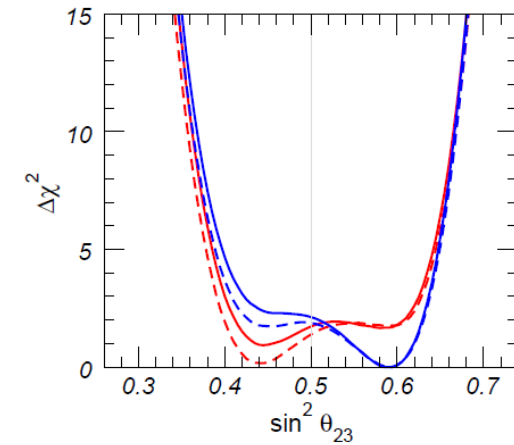
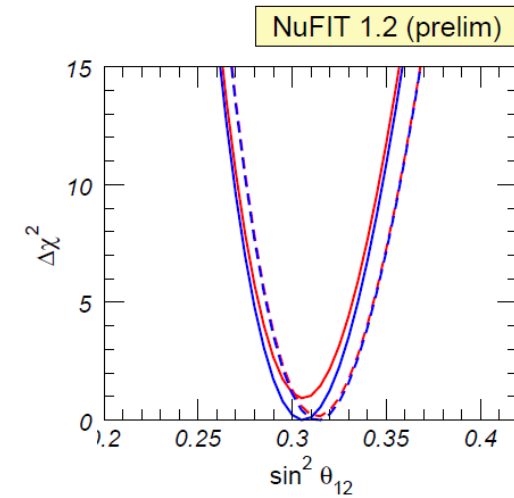
SM case closed?

NO, SM unable to explain:

- Matter anti-matter asymmetry in universe
- Neutrino mixing \rightarrow masses
- Non-baryonic dark matter



Astrophysical Journal, Vol. 295, Aug. 15, 1985





Ptolomy (~90-168 AD):

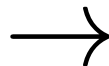
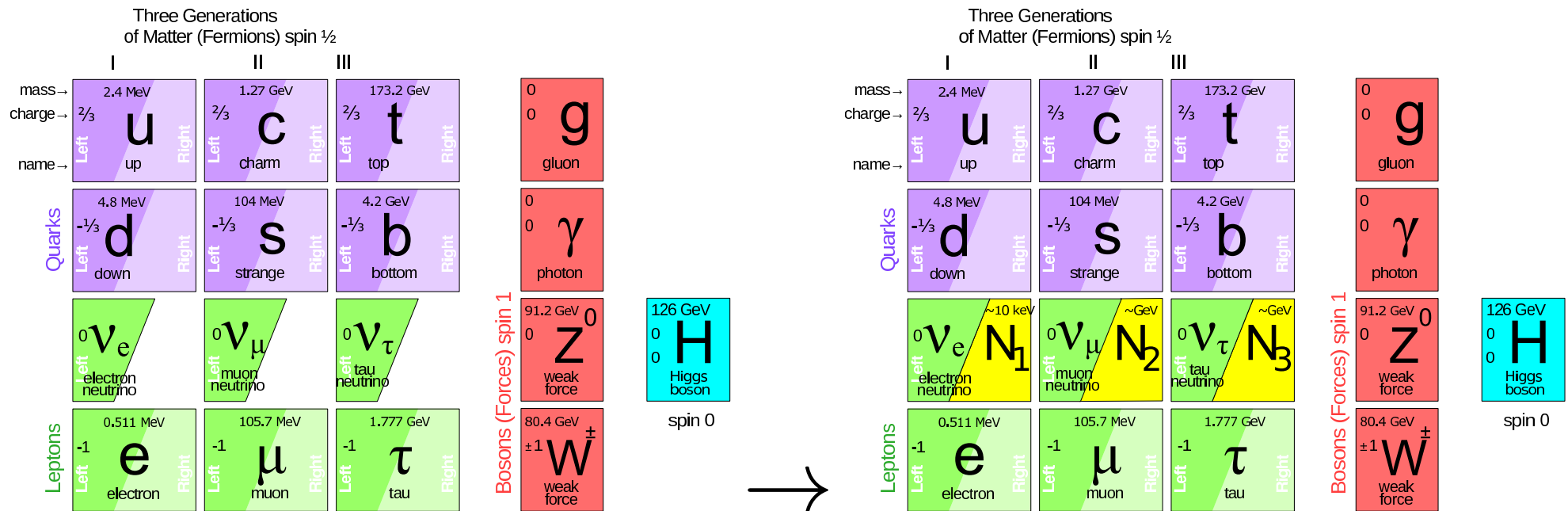
It is a good principle to explain phenomena by the simplest hypothesis possible!

MSM: T.Asaka, M.Shaposhnikov

PL B620 (2005) 17

Adding three right-handed Majorana Heavy Neutral Leptons (HNL): N_1 , N_2 and N_3 :

- N_1 can provide dark matter candidate
- $N_{2,3}$ can provide neutrino masses via Seesaw mechanism
- $N_{2,3}$ can induce leptogenesis \rightarrow baryogenesis.





ν MSM: closer look at N_1

N_1 can provide dark matter candidate:

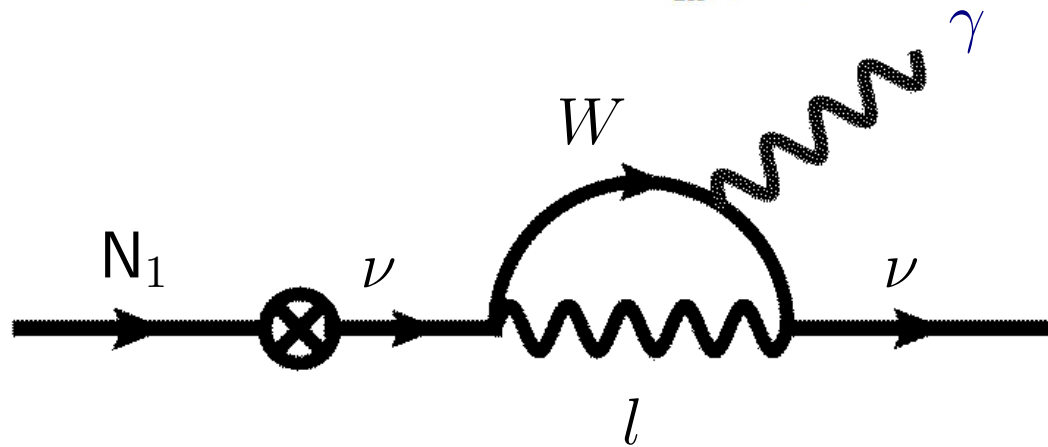
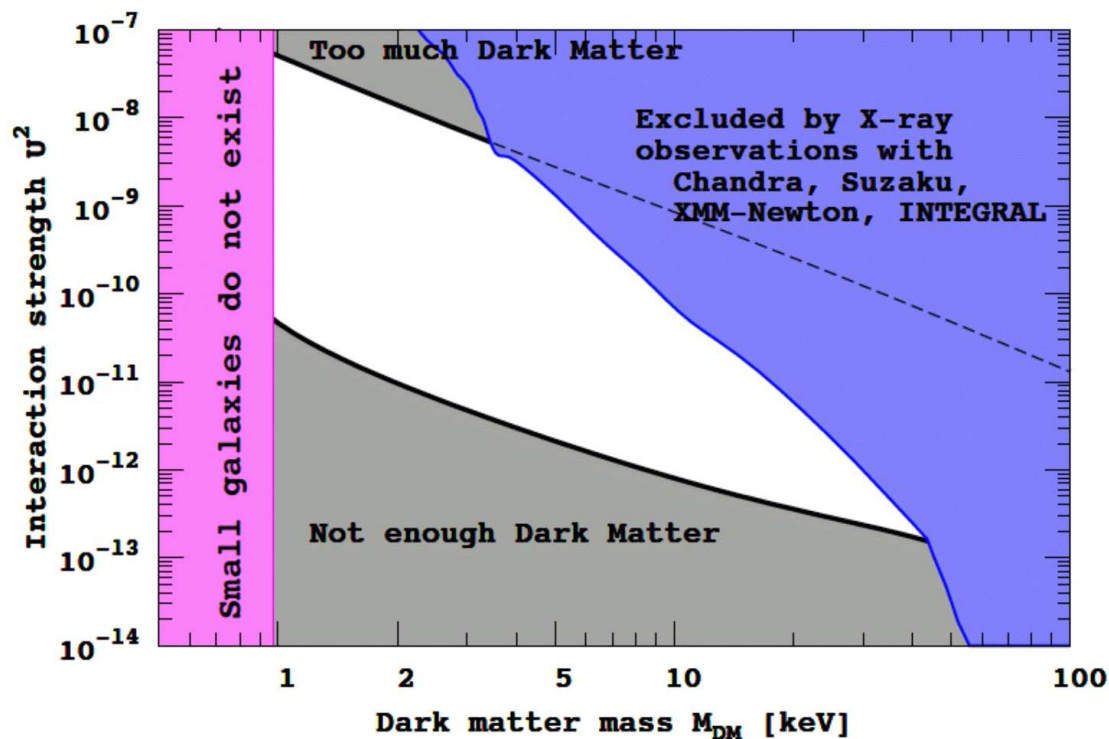
- very weak mixing with other leptons
- hence, stable enough for dark matter
- Seesaw: one $M_{\nu\text{-active}} \sim 10^{-5}$ eV

- Radiative decay: $\tau > \tau_{\text{universe}}$

- $E_\gamma = \frac{M_{N_1}}{2}$

- X-ray detection:

- View dwarf spheroidal galaxies
- $\frac{\Delta E}{E} \sim 10^{-3} - 10^{-4}$
- Proposed missions: Astro-H, LOFT, Athena+, Origin/Xenia



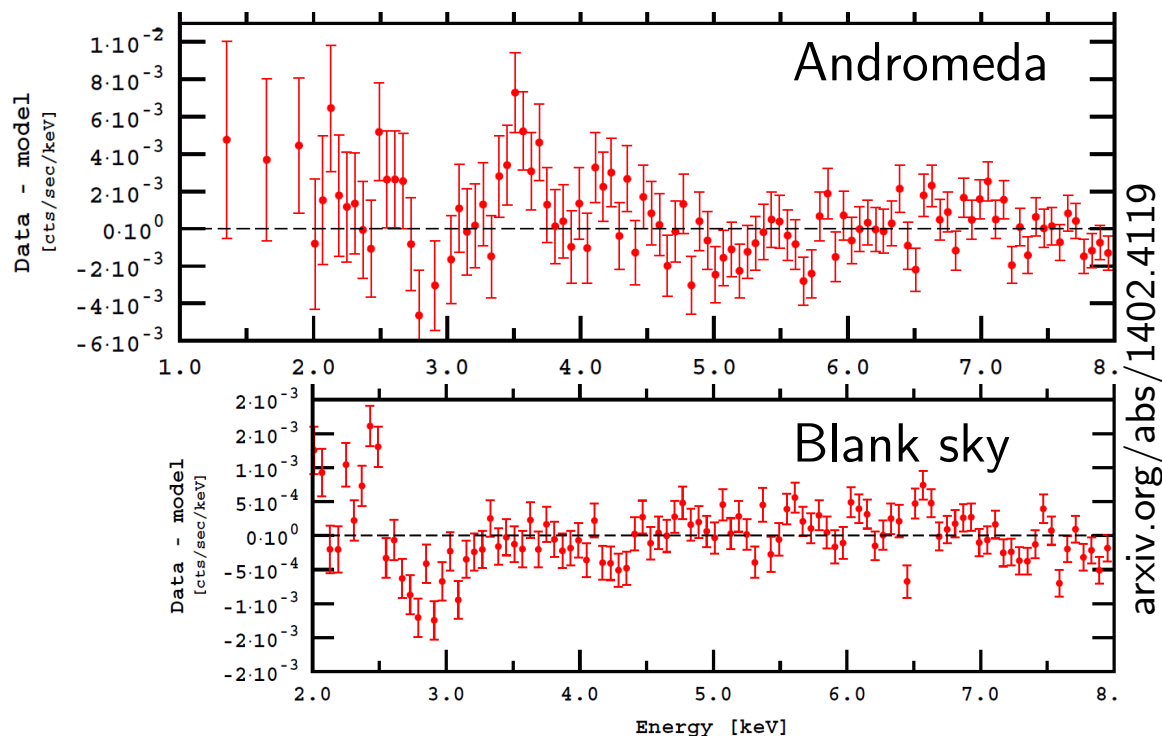


N_1 : stop the press...

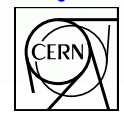
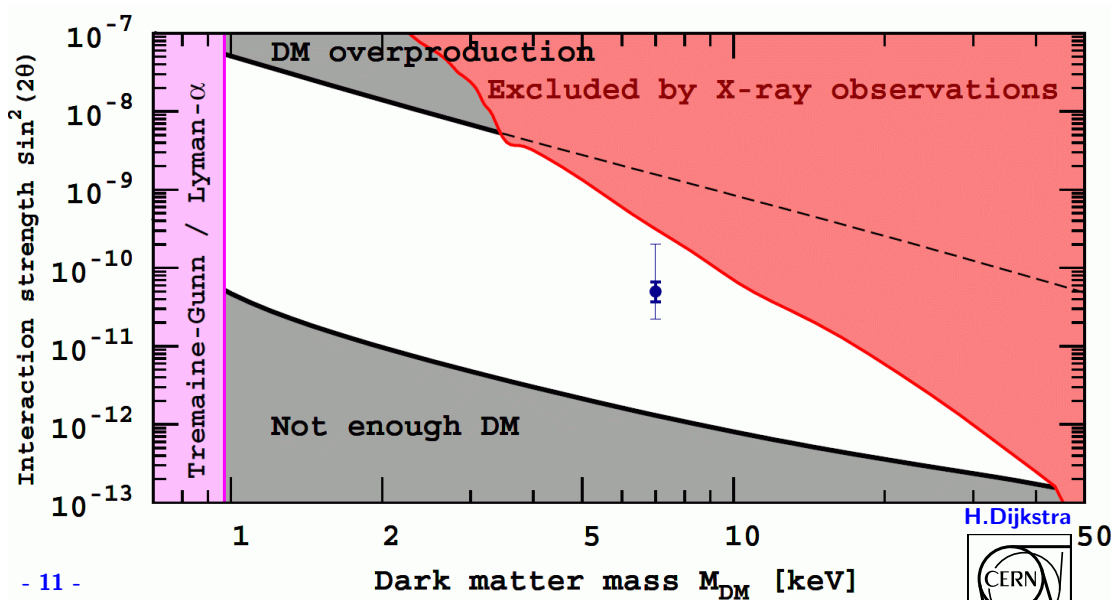
Recently two papers on ArXiv:

- 10/2/14: arxiv.org/abs/1402.2301:
Detection of an Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters
 $E_\gamma \sim 3.56$ keV
- 17/2/14: arxiv.org/abs/1402.4119:
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster
 $E_\gamma \sim 3.5$ keV

Both papers refer to Astro-H
(with Soft X-Ray Spectrometer, 2015 launch)
to confirm/rule-out the DM origin of this signal.



arxiv.org/abs/1402.4119



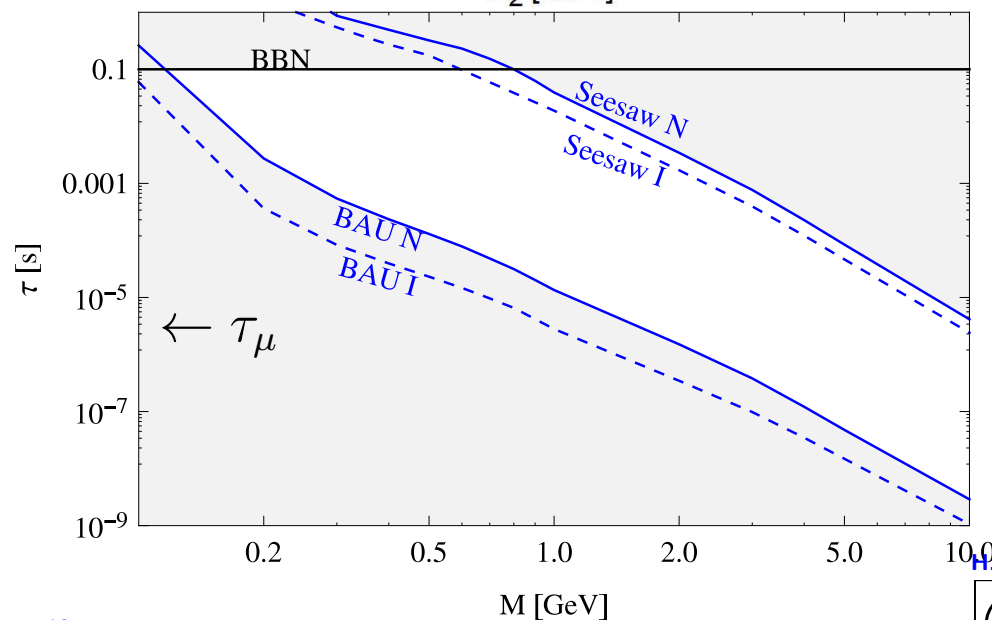
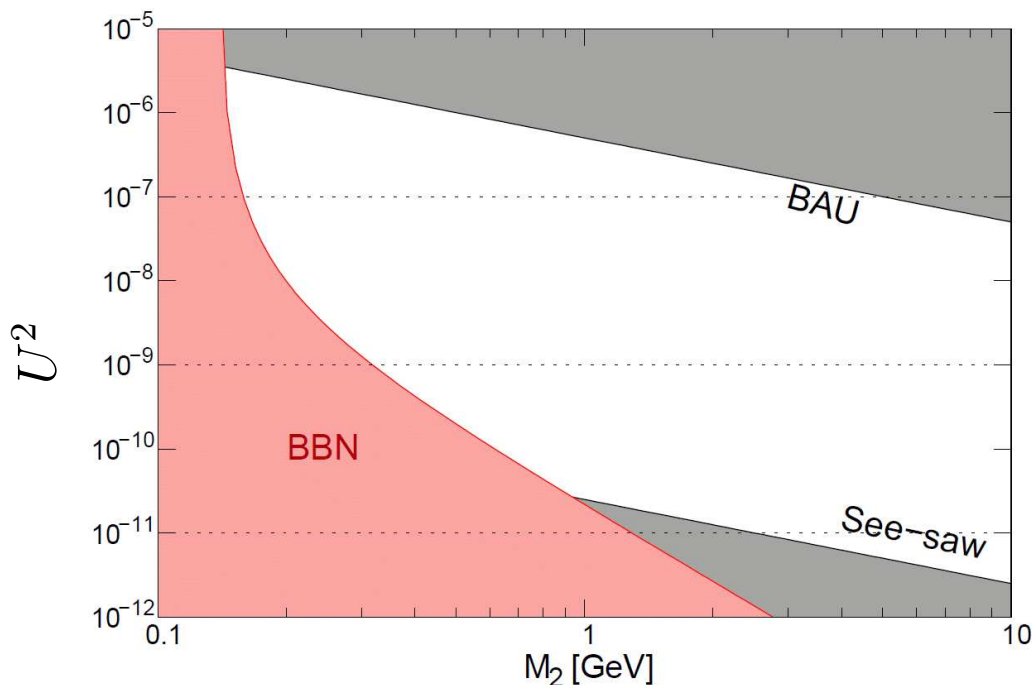


Use $N_{2,3}$ to explain:

- ν masses:
Seesaw constrains Yukawa coupling and $M_{N_{2,3}}$, i.e. $M_\nu \propto U^2/M_{N_{2,3}}$
- Baryo(Lepto)genesis: make N_2 nearly degenerate with N_3 , and tune CPV-phases to explain baryon asymmetry of universe (BAU).
- Coupling (U^2) and $M_{N_{2,3}} \rightarrow \tau_{N_{2,3}}$
- $\tau_{N_{2,3}} < 0.1$ s, otherwise Big Bang Nucleosynthesis (BBN, $\sim 75/25$ % H-1/He-4) would be affected by $N_{2,3}$ decays.

These are the particles we are after!

$N_{2,3}$



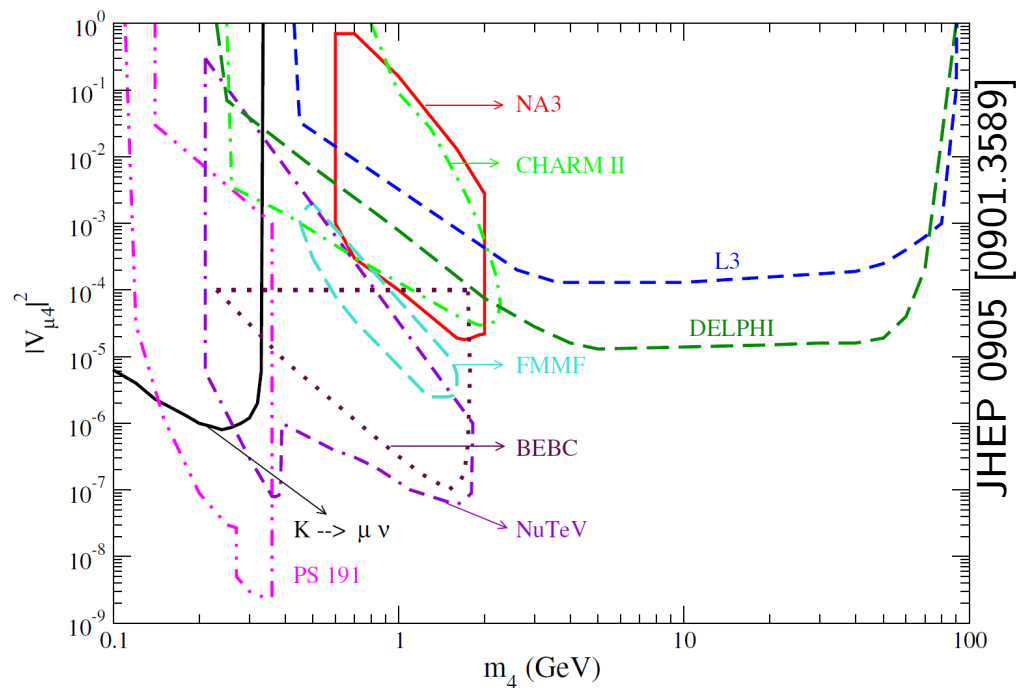


If Ptolomy was wrong?

Model	1	2	3	4	5
ν -masses	✓	✓	✓		
BAU	✓	✓			
Dark Matter	✓			✓	

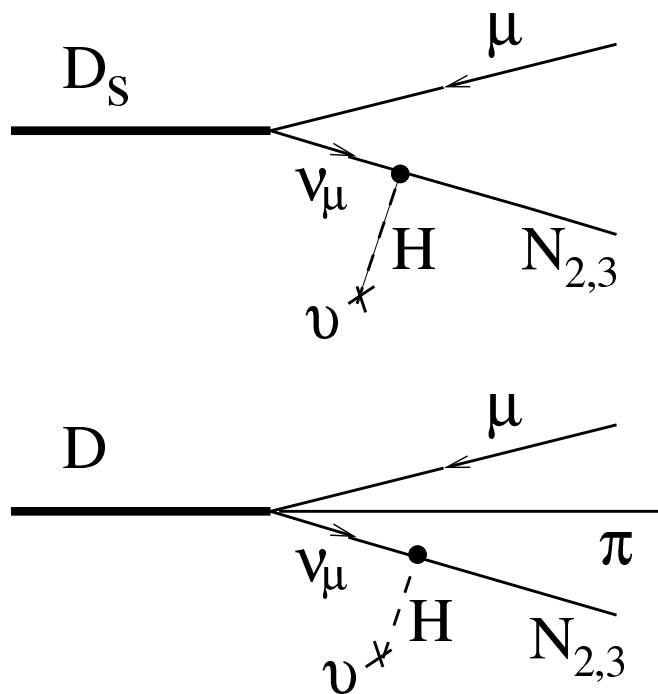
1. ν MSM: strongest parameter constraints
2. All active ν could be “heavy”, and
 - No $M_2 \leftrightarrow M_3$ degeneracy necessary.
 - U^2 constraint relaxed, up to $U_\mu^2 \sim 10^{-3}$
3. Still $U^2 \gtrsim 10^{-10}$
4. HNL as dark matter only
 - with keV mass: $\tau \gg \tau_{\text{universe}}$
 - Can only be found with X-ray telescopes.
5. Many (cosmology) papers still use HNLs

HNL (U_μ) searches:



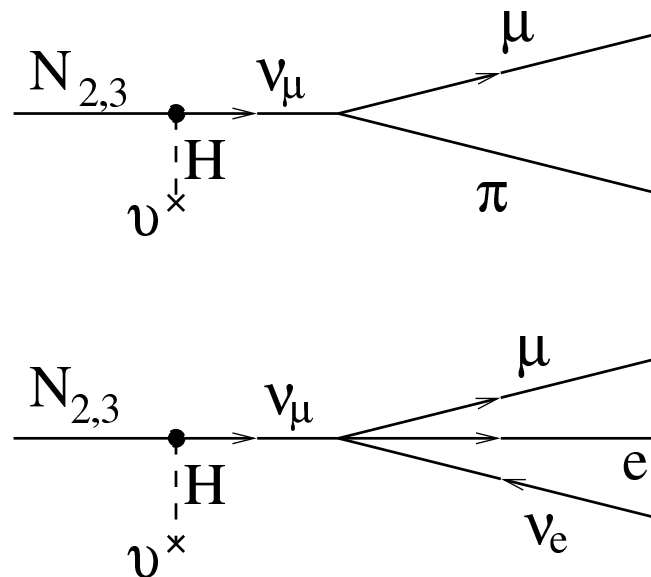


$N_{2,3}$ production and decay



- $N_{2,3}$ mix with ν
- Produced in semi-leptonic decays, f.i. $K \rightarrow \mu\nu$, $D \rightarrow \mu\nu X$, $B \rightarrow \mu\nu X$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

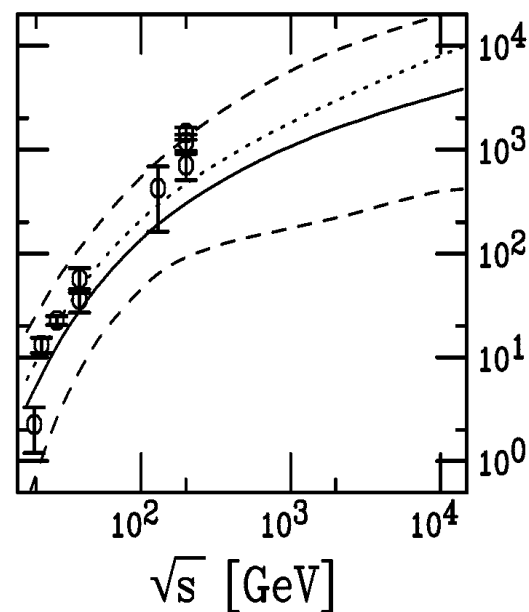
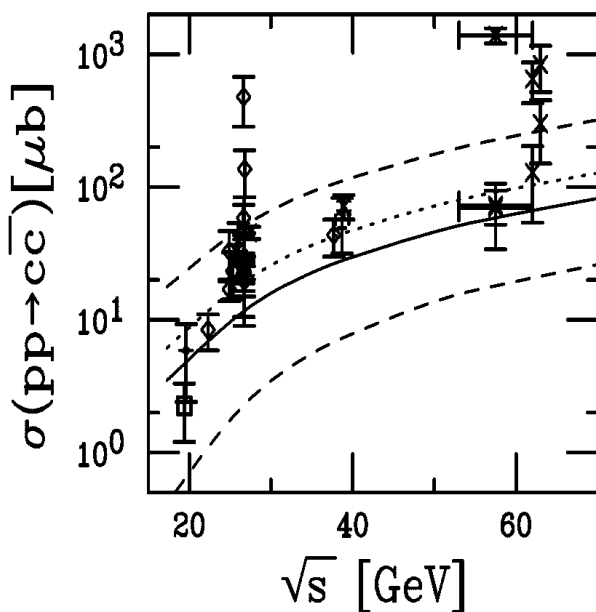
- $\mathcal{B}(N \rightarrow \mu/e \pi)$: $\sim 0.1 - 50 \%$
- $\mathcal{B}(N \rightarrow \mu/e \rho)$: $\sim 0.5 - 20 \%$
- $\mathcal{B}(N \rightarrow \nu\mu e)$: $\sim 1 - 10 \%$
- $\tau_{N_{2,3}} \propto U^{-2}$, i.e. $c\tau \sim O(\text{km})$





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

- Look for HNL from D -decays, i.e. $M < 2$ GeV
- B-decays: 20-100 smaller σ , and $\rightarrow D\mu\nu$, i.e. still limited to ~ 3 GeV.



$\sigma(pp \rightarrow c\bar{c}) [\mu\text{b}]$
 arxiv.org/pdf/0709.2531v1

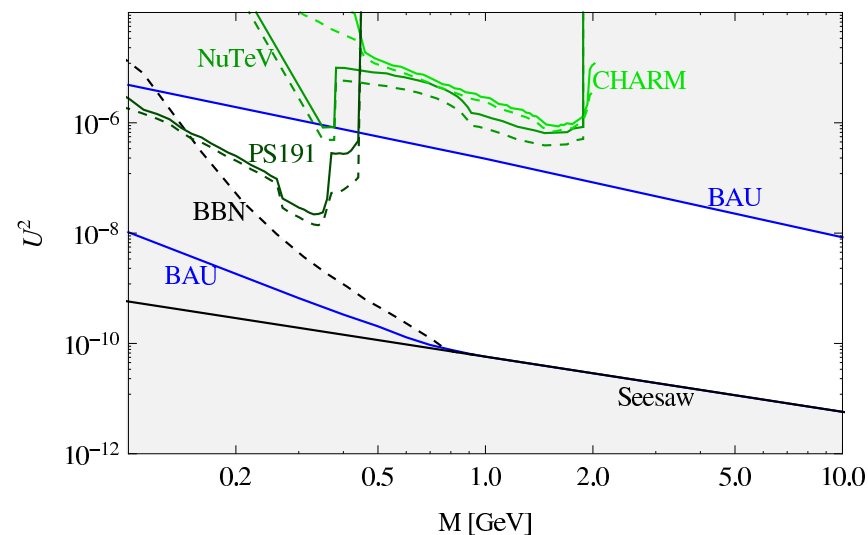
- Where to produce charm?
 - LHC ($\sqrt{s} = 14$ TeV): with 1 ab^{-1} (i.e. 3-4 years): $\sim 2 \cdot 10^{16}$ in 4π .
 - SPS (400 GeV p-on-target (pot) $\sqrt{s} = 27$ GeV): with $2 \cdot 10^{20}$ pot (i.e. 3-4 years): $\sim 2 \cdot 10^{17}$
 - Fermilab: 120 GeV pot, $10\times$ smaller $\sigma_{c\bar{c}}$, $10\times$ pot by 2025 for LBNE..



Experimental status on searches

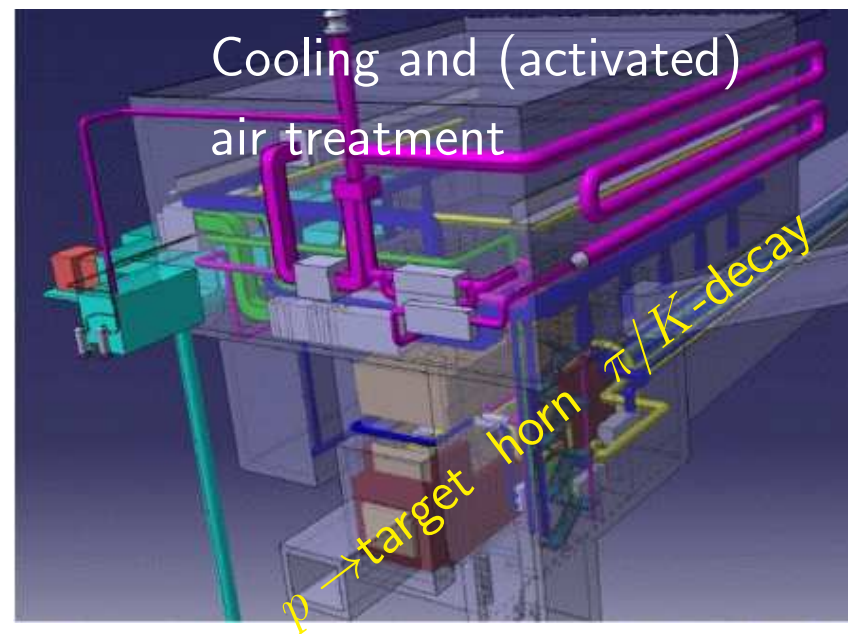
Already searches in K/D-decay performed:

- 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.



What has been achieved, is being prepared:

- CNGS: 1.8×10^{20} pot, 2011: 4.8×10^{19}
- CERN neutrino R&D platform.
Design of target area in progress.

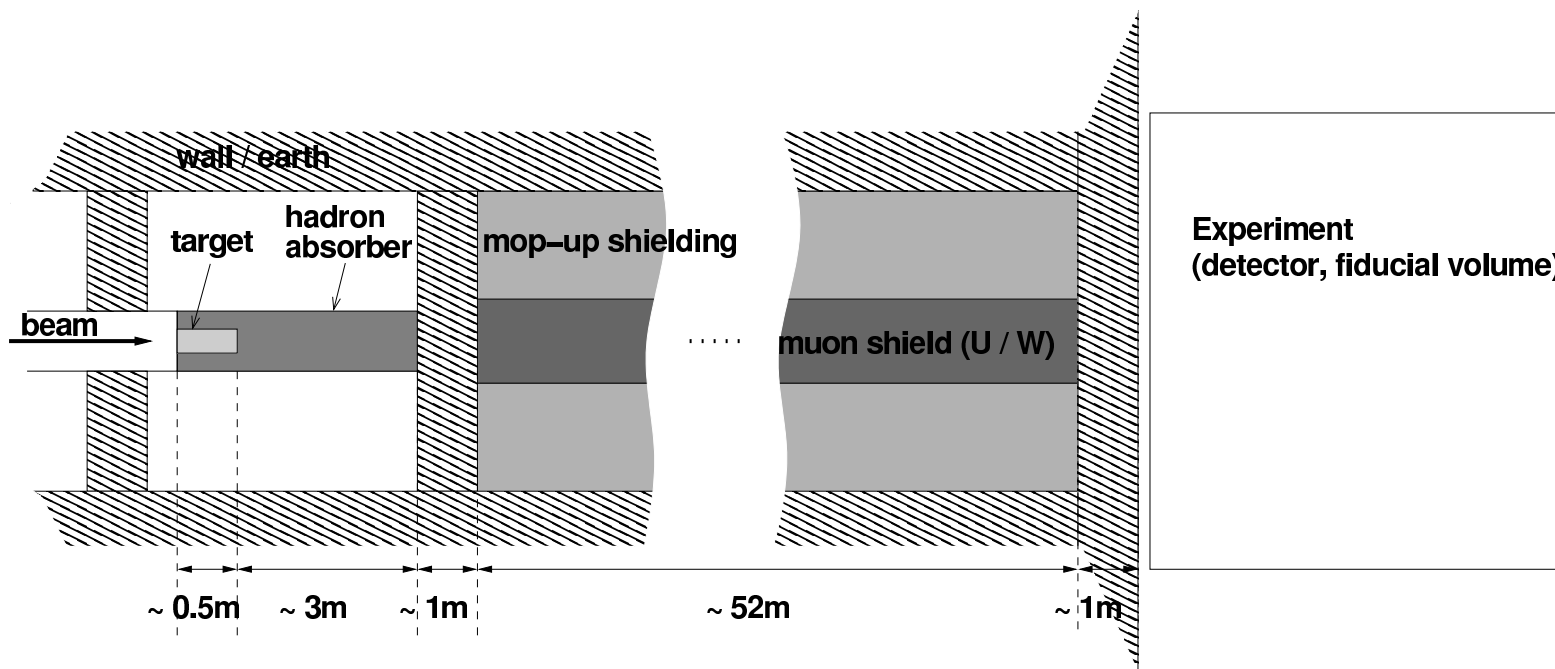
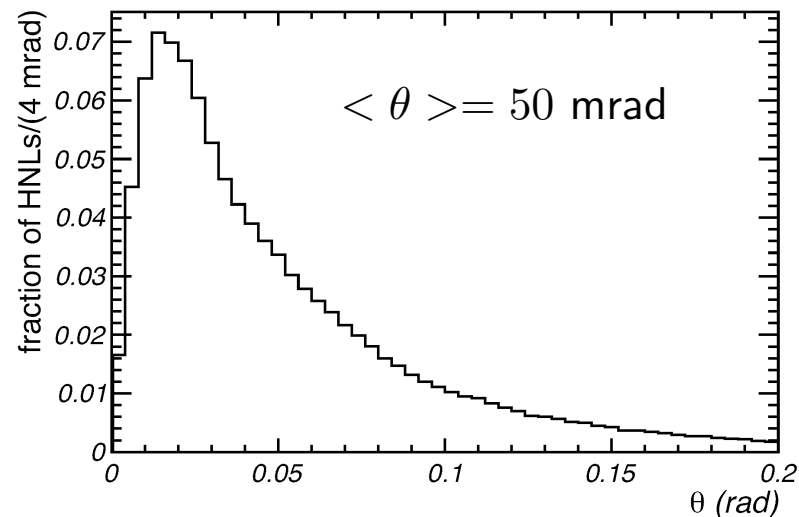




2×10^{20} 400 GeV pot

HNL search is different from ν_μ , ν_e physics (but ν_τ similar):

- ν_μ , ν_e cause background:
heavy (W) target to avoid π/K -decay.
Example: Cu iso W-target doubles ν -background!
- Place detector as close as possible to target as background (huge μ -flux!) allows, i.e. ~ 60 m?

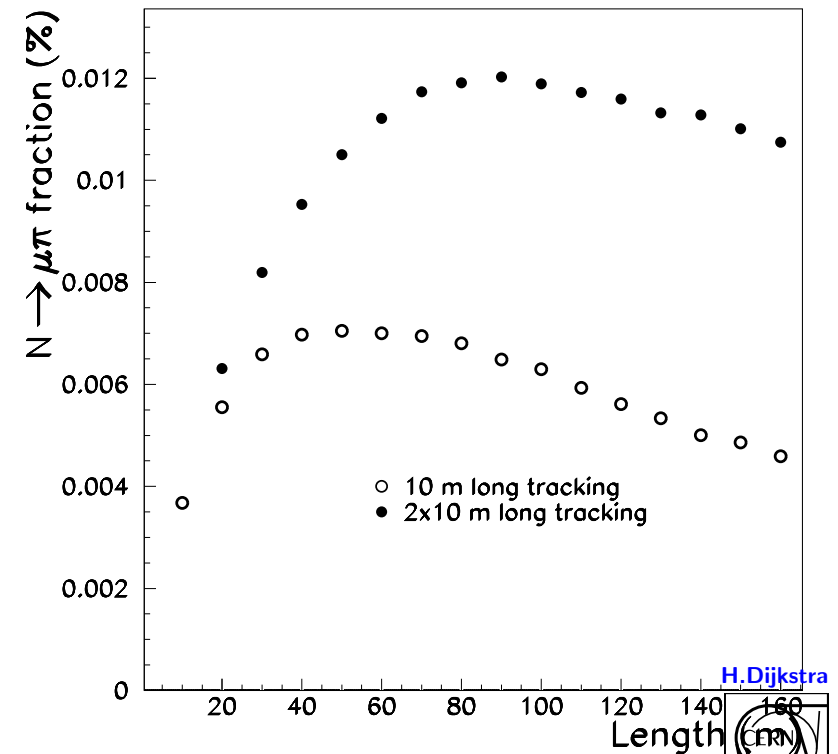
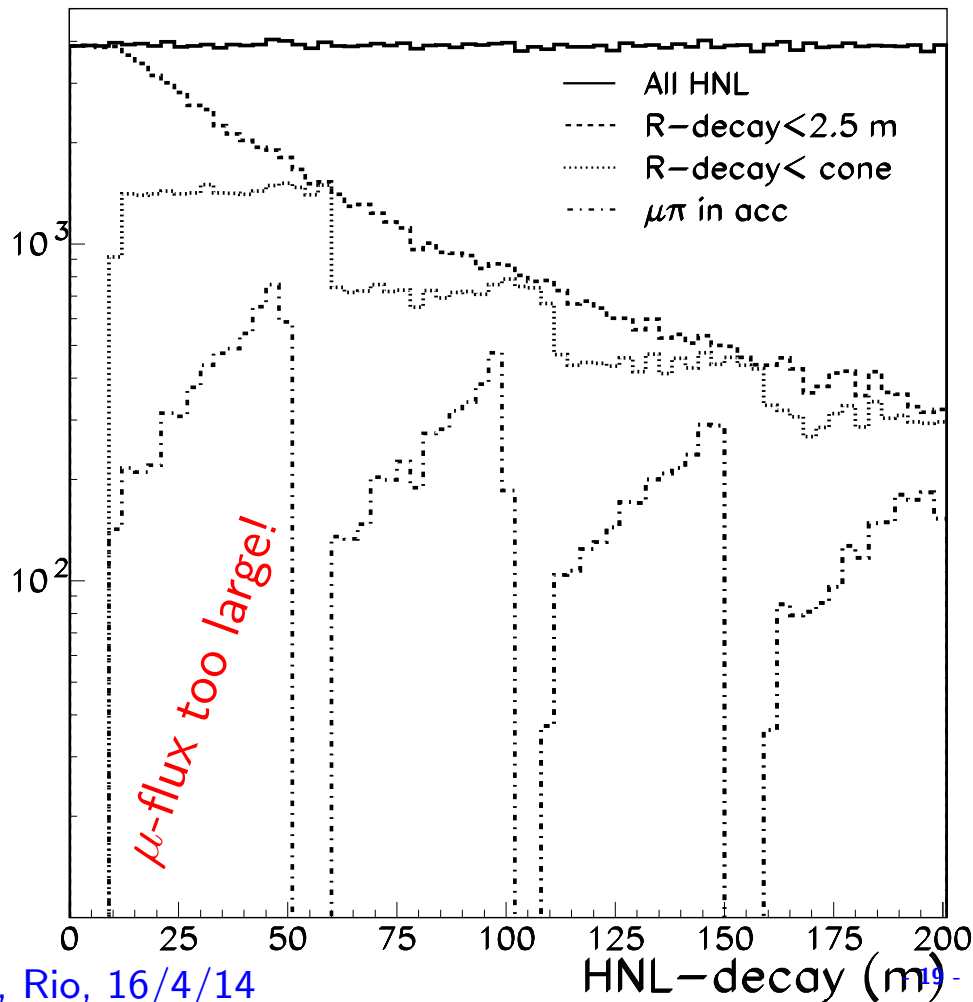
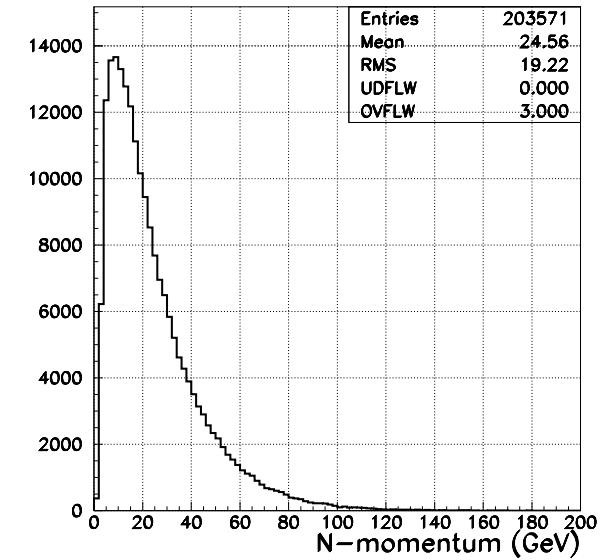






Designing the Spectrometer

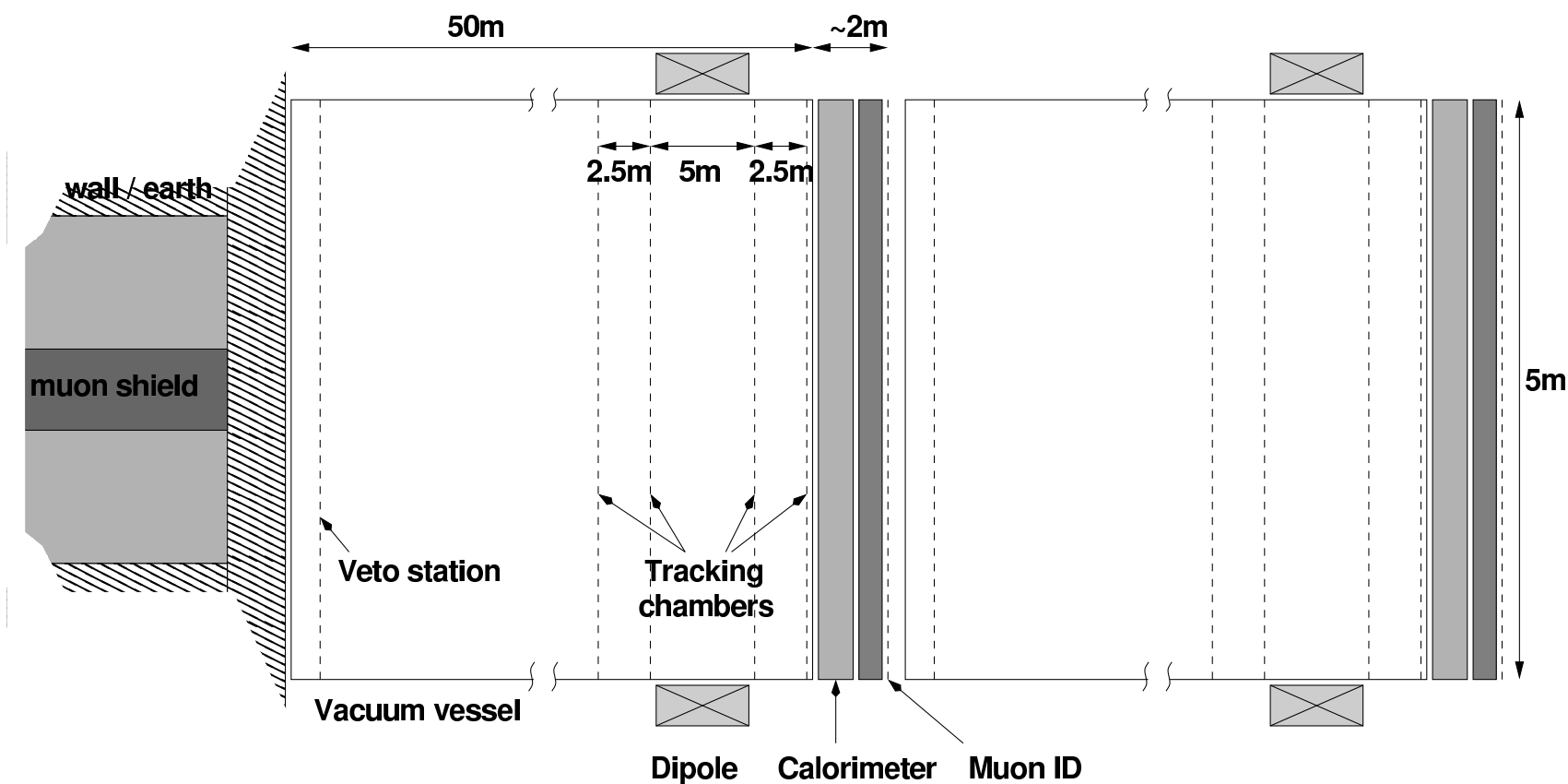
- Take $N_{2,3} \rightarrow \mu\pi$, mass=1 GeV as proxy.
- $c\tau_N$ is kms, $\langle p \rangle = 25$ GeV!
- Assume spectrometer $\varnothing = 5$ m.
- Decay volume length saturates at ~ 40 m.
- 2nd spectrometer of 50 m adds 70 % in acceptance.





Spectrometer(s)

- ~ 40 m long decay volume, $\varnothing = 5$ m, 10 m long spectrometer
- Go for exclusive decays: $N \rightarrow \mu \pi$, $\rightarrow e \pi$, $\rightarrow \mu \rho(\pi\pi^0)$
- measure momenta of decay particles \rightarrow mass-peak and impact parameter,
- identify μ , e , measure γ momentum.
- Put two behind each other to increase acceptance.





Background: μ Flux

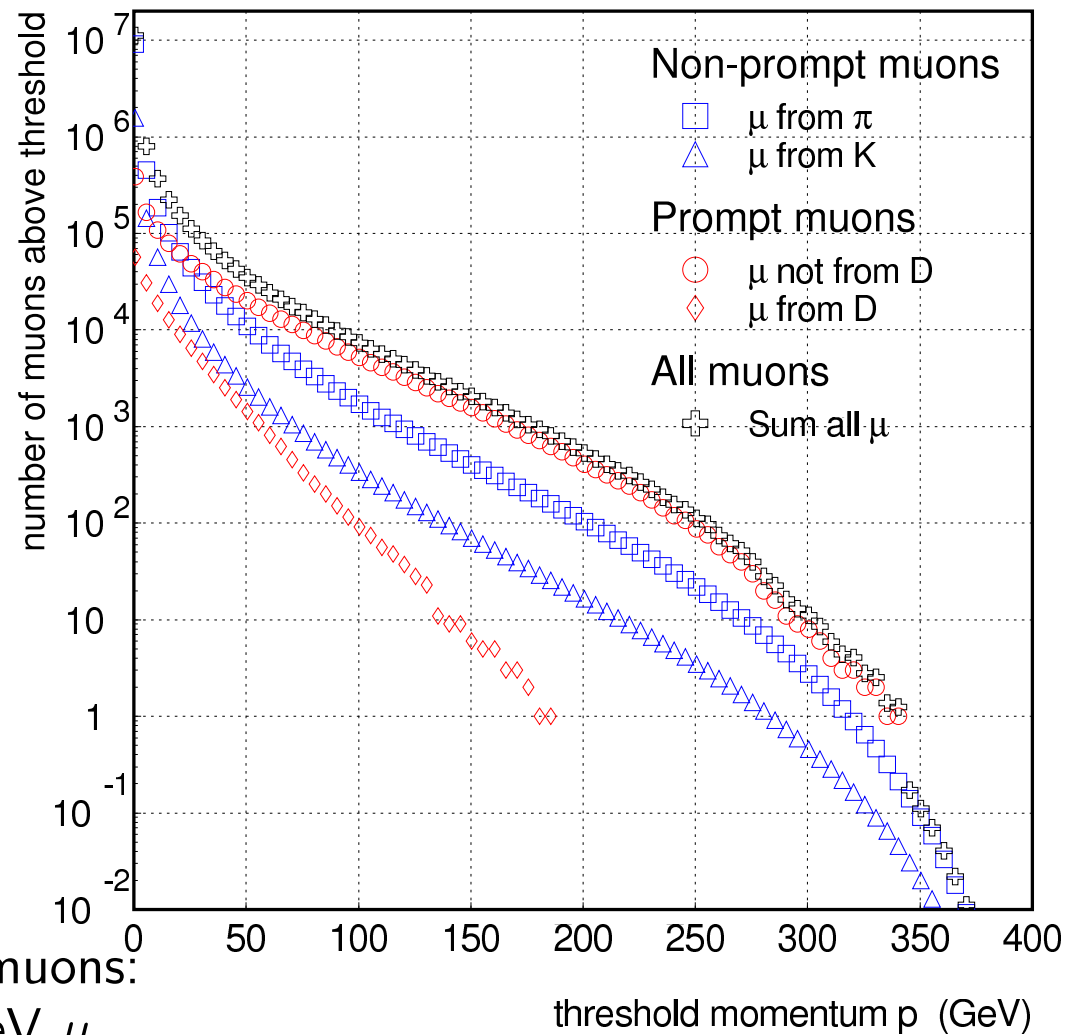
Without μ -filter:

5×10^9 /SPS-spill (5×10^{13} pot)

- Low-p: still from π/K -decay
- High-p: ω/ρ -decays to $\mu\mu$
- Reduce background from μ -interactions to below ν -background (see later)
- Acceptable μ rate $\sim 10^5$ /spill.

Two alternatives for filter:

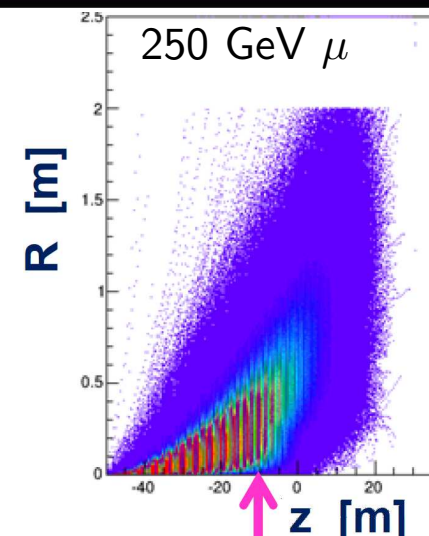
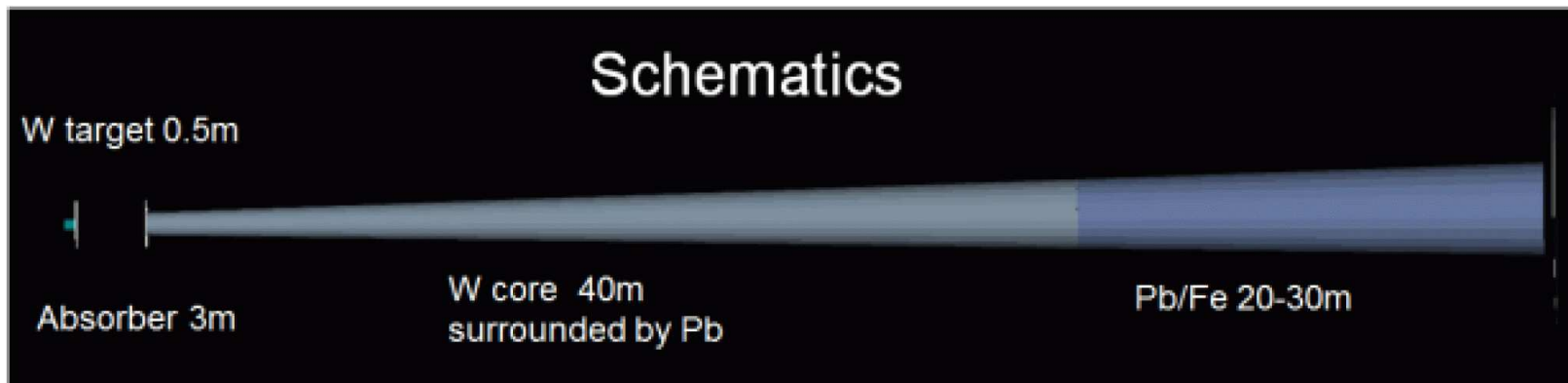
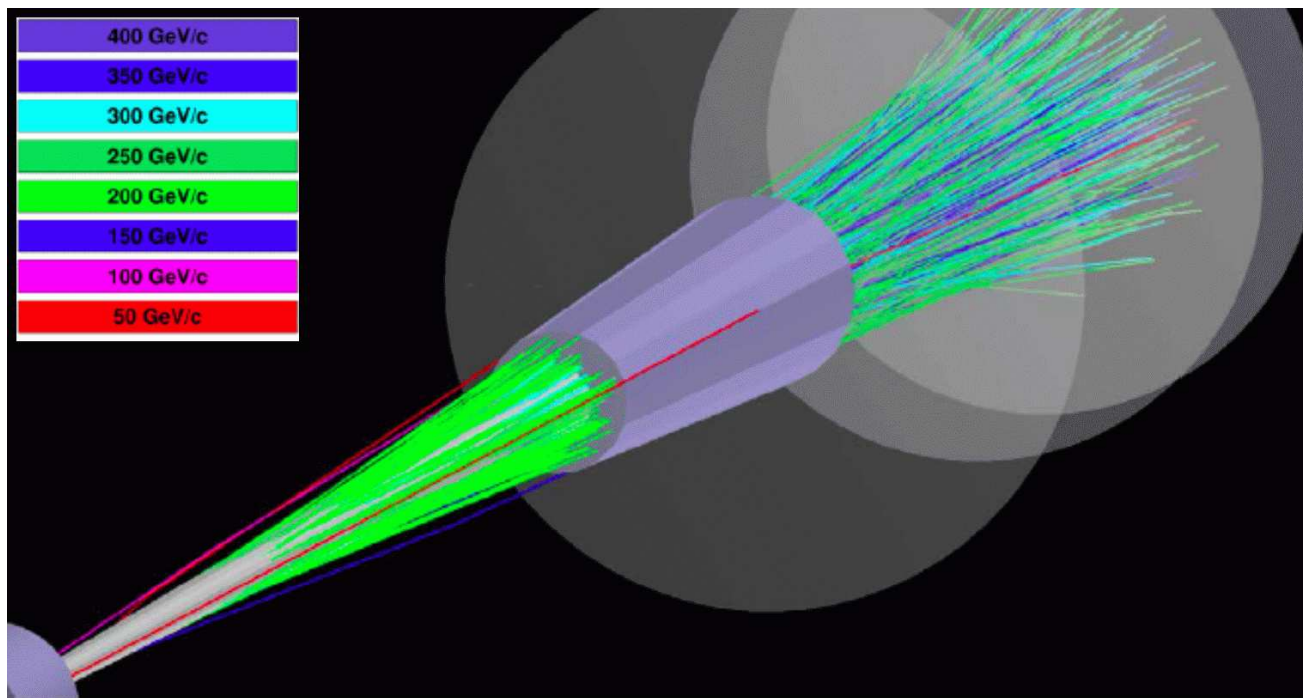
- Passive: i.e. use high Z material to stop muons:
Example: need 54 m of W to stop 400 GeV μ .
- Active (+passive): use magnets to deflect muons:
Example: need 40 Tm to deflect 400 GeV μ outside acceptance.



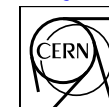


Passive μ -filter

- Geant studies to estimate flux.
- MS and ϵ : limit W-length to 40 m.
- High-p at small θ : $W\varnothing$ 12-50 cm
- +20-30 m of Pb/Fe :
- reduction to $< 10^5 \mu$ /spill possible.
- Robust/easy to operate



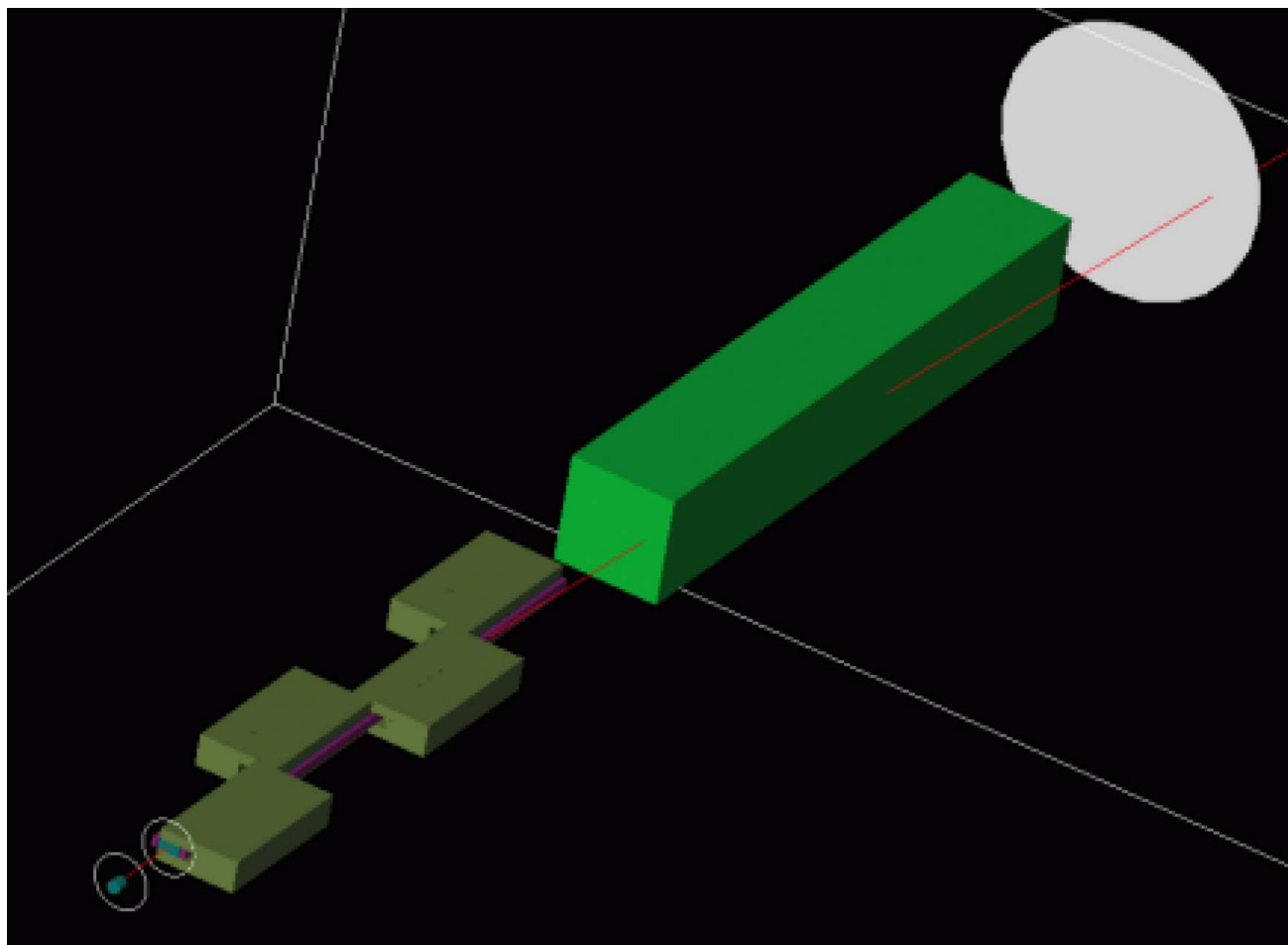
H.Dijkstra





Alternative: Active (+passive) μ -filter

- Use 6 m long C-shaped magnets.
- Produces 40 Tm total field with 4 magnets: high-p swept out.
- Problem: return-B of low-p μ :
 - alternate return-B left/right
 - Add passive Fe-shield
- reduction to $< 5 \cdot 10^5 \mu/\text{spill}$ possible.



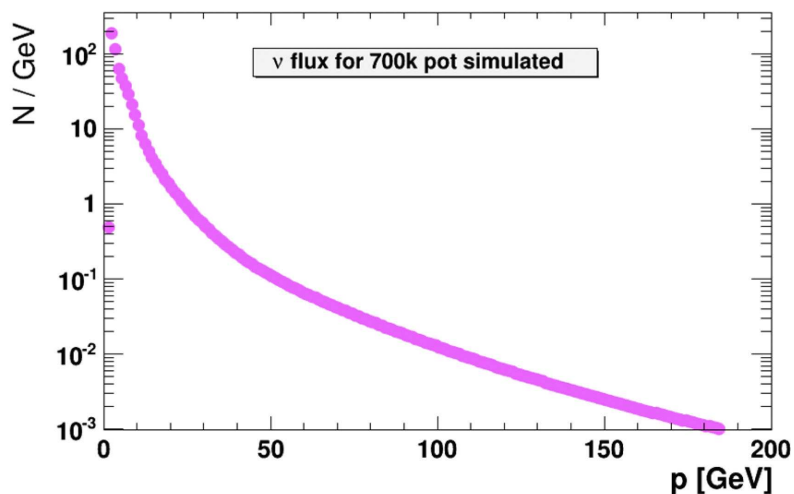
Work in progress.



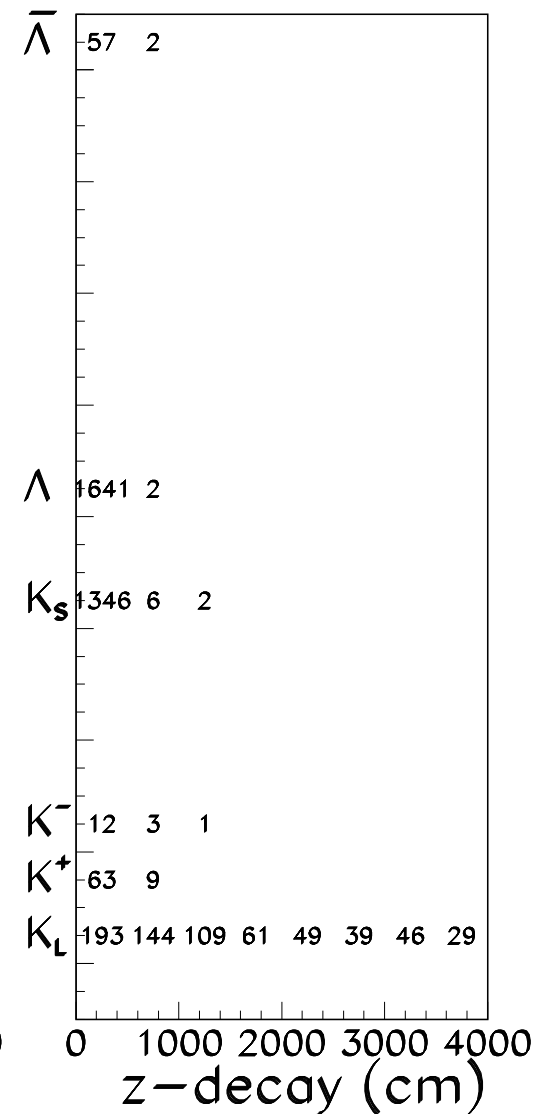
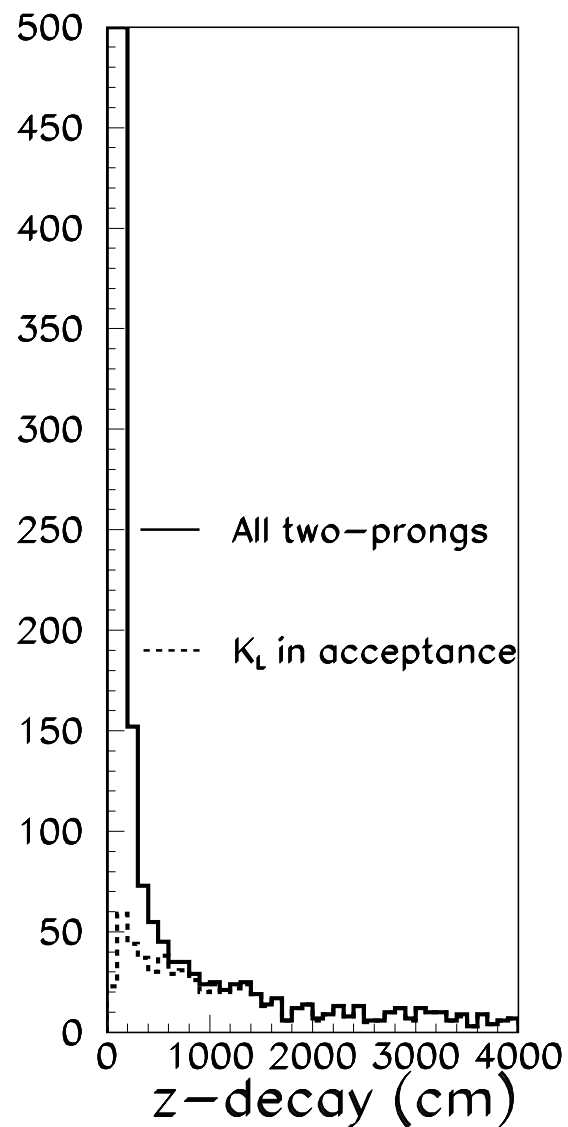
ν -Background

Pythia/Genie/Geant, compare to CHARM:

- ν -flux at end of μ -filter ($/2 \times 10^{20}$ pot):
CC+NC 8×10^5 interactions/ λ

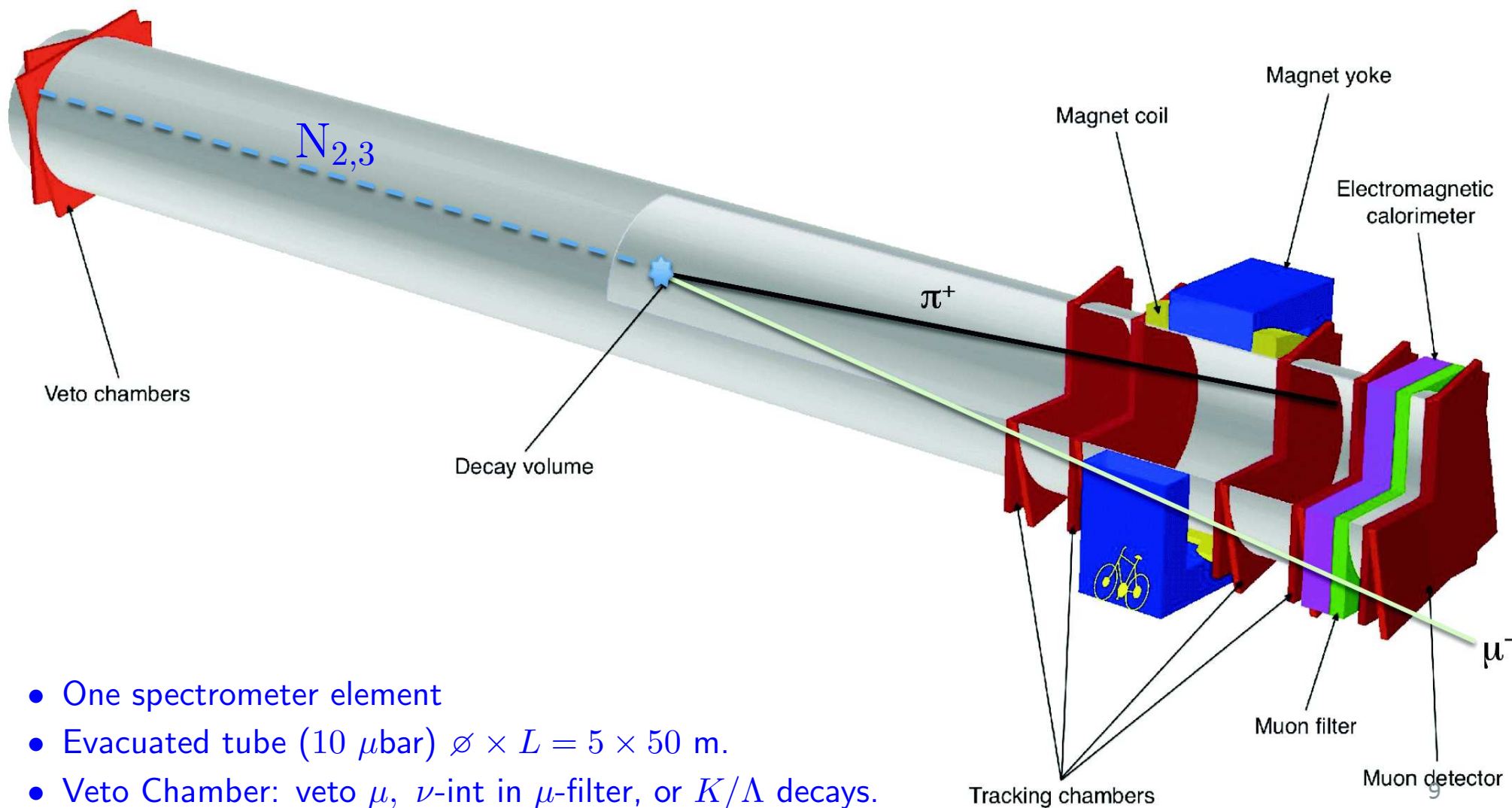


- 1 bar air in decay volume:
 2×10^4 ν -int/ 2×10^{20} pot
- Reduce pressure to $10 \mu\text{bar}$!
- ν -interactions in μ -filter:
 - Use veto-station to suppress short lived.
 - $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$ main background.





Spectrometer



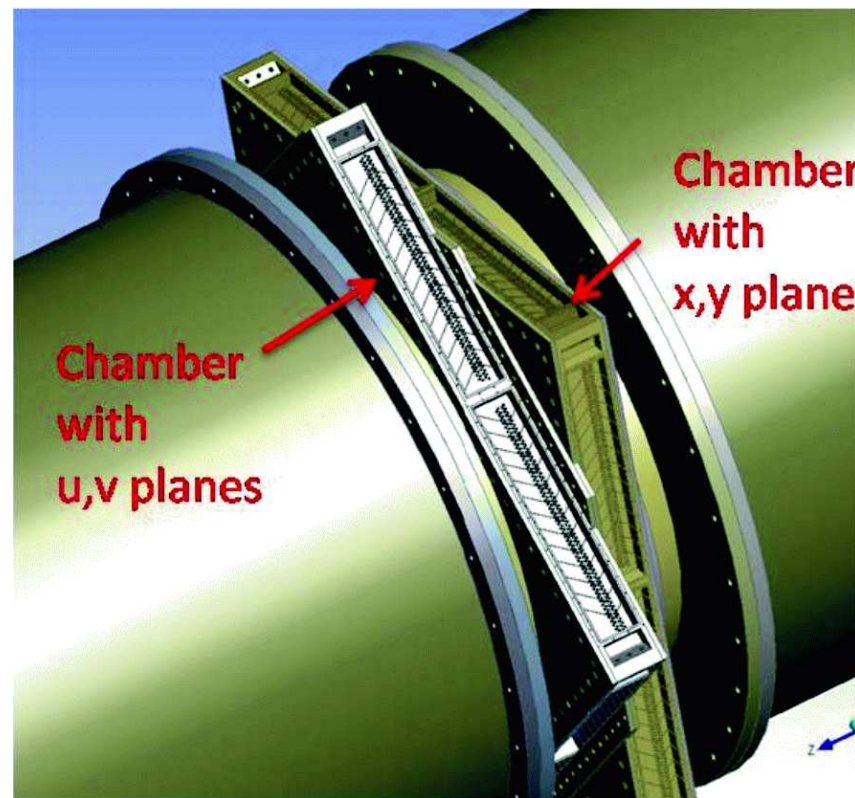
- One spectrometer element
- Evacuated tube ($10 \mu\text{bar}$) $\varnothing \times L = 5 \times 50 \text{ m}$.
- Veto Chamber: veto μ , ν -int in μ -filter, or K/Λ decays.
- Tracking chambers (thin!) and magnet for momentum measurements
- Ecal and muon filter/chambers at the end.



Tracking Chambers

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

- 2 m \varnothing vessel @0.01 μ bar.
- 10 mm \varnothing straws made of PET.
- Demonstrated to work in vacuum.
- $X/X_0=0.5$ % for 4 view station!
- 120 μ m resolution/straw.





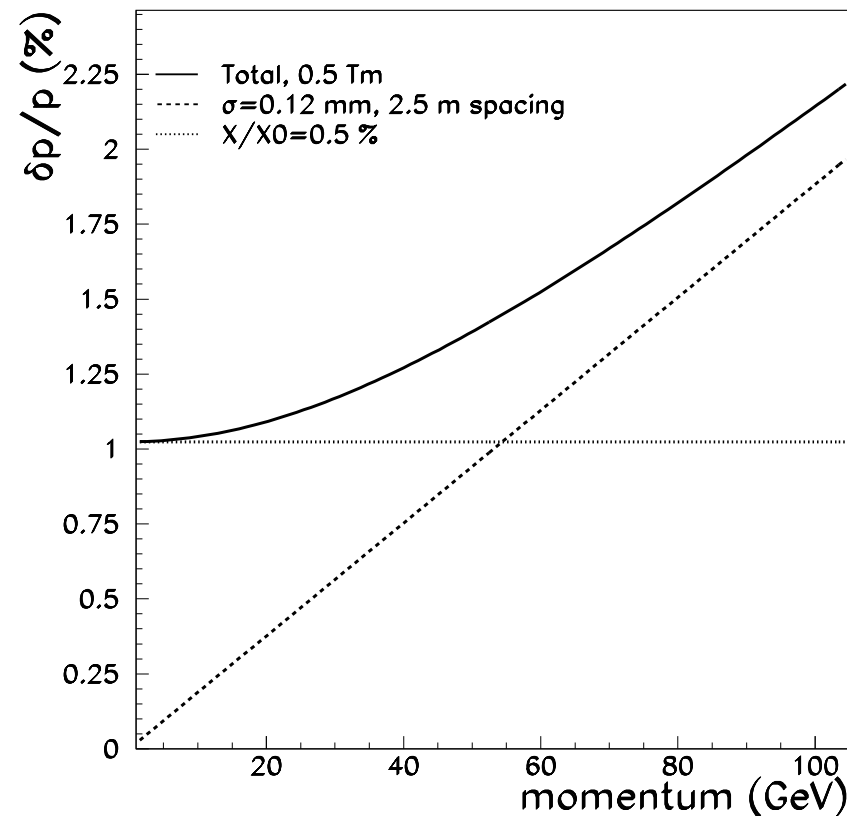
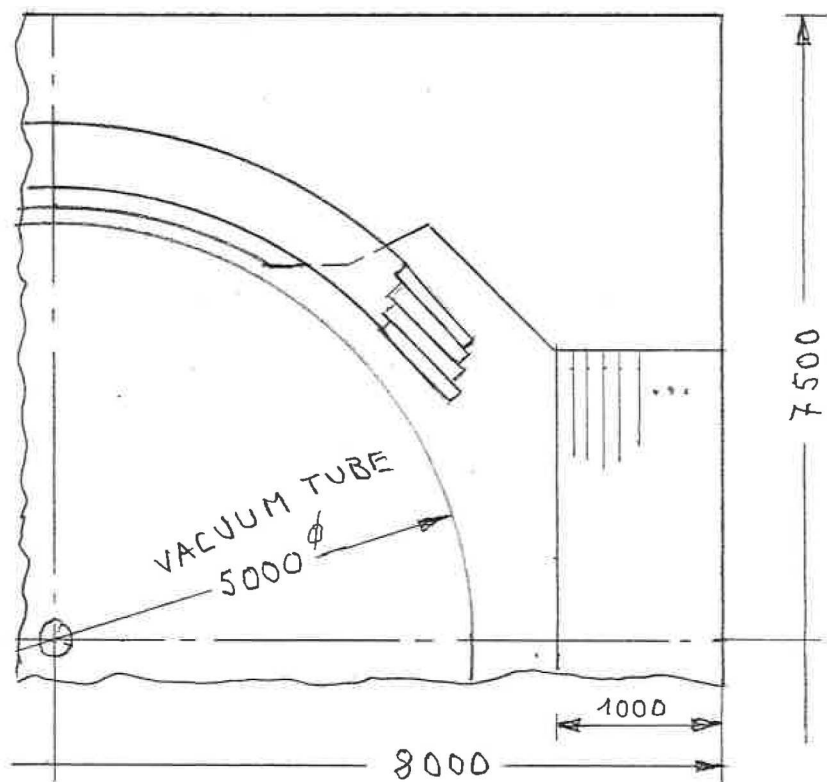
Magnet

- With $X/X_0=0.5$ % chambers: modest 0.5 Tm
- Need ~ 20 m² aperture.

LHCb magnet: 4 Tm, 16 m² exit-aperture

Preliminary calculations (W.Flegel):

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



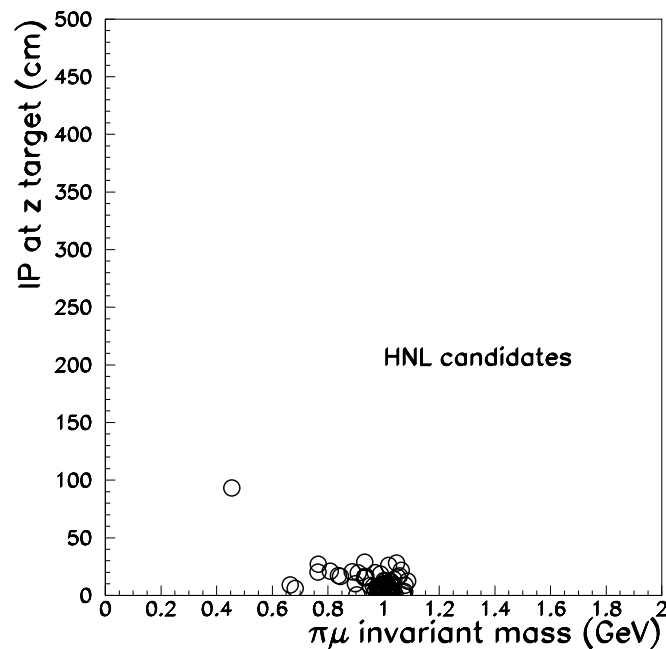
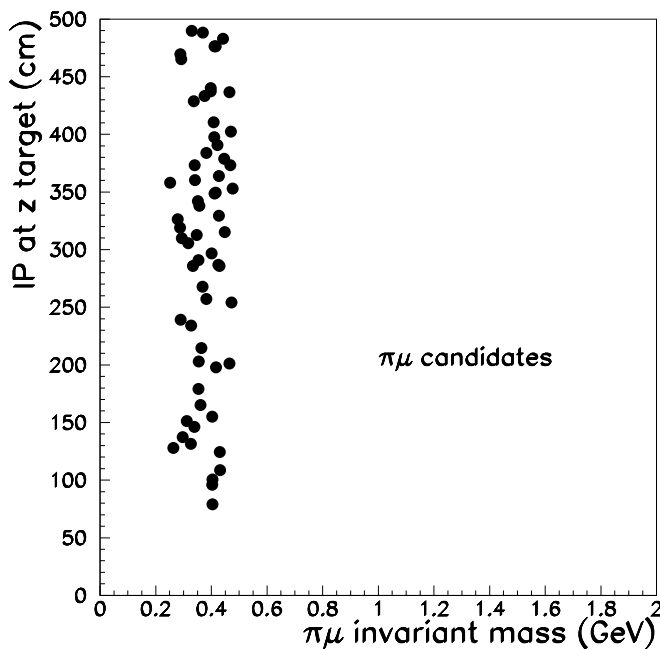
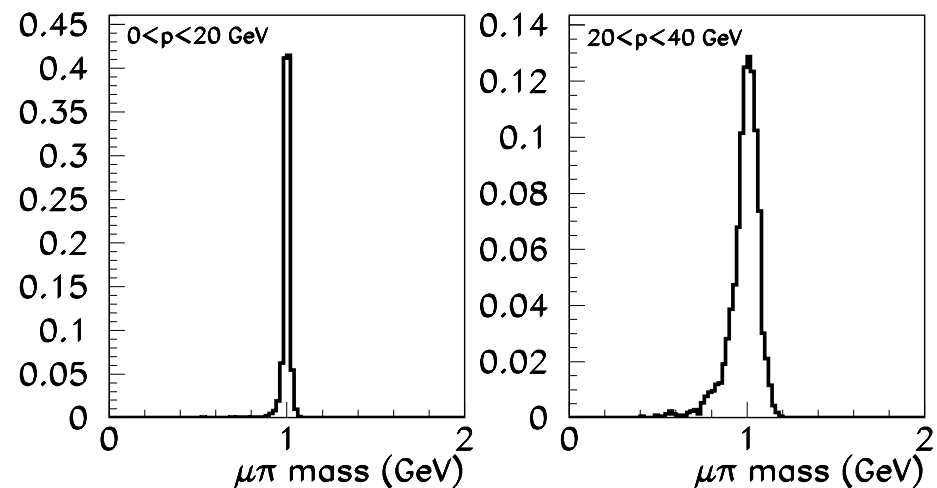


Mass resolution

- Expected resolution for 1 GeV $N \rightarrow \mu\pi$

K_L background suppression:

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





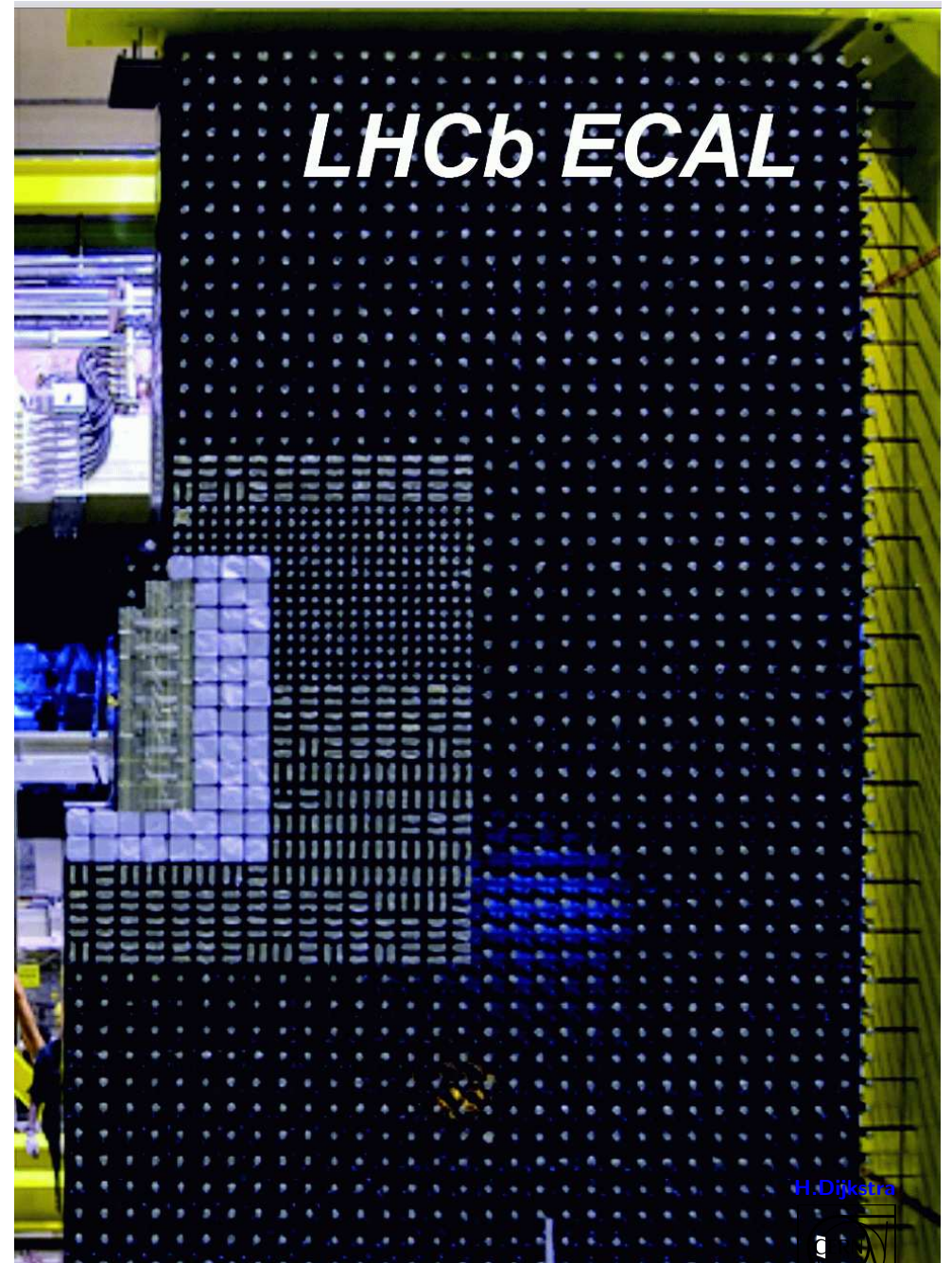
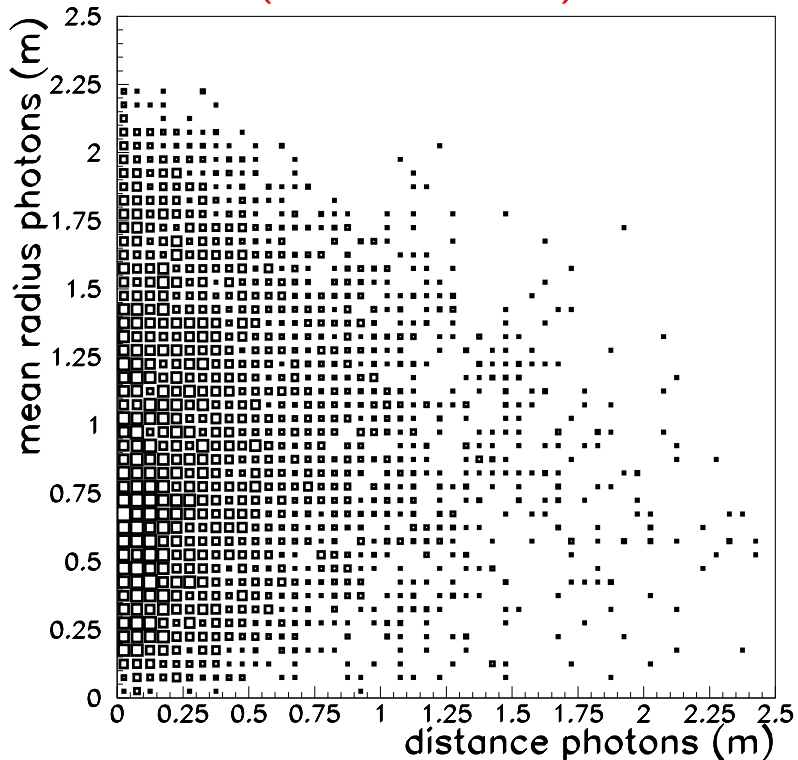
Electromagnetic Calo

LHCb Shashlik ECAL:

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

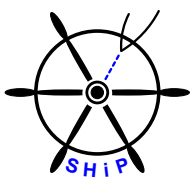
Larger/better than required.

But for $N \rightarrow \mu\rho(\pi\pi^0(\gamma\gamma))$
need small ($10 \times 10 \text{ cm}^2$) cells everywhere.



H.Dijkstra





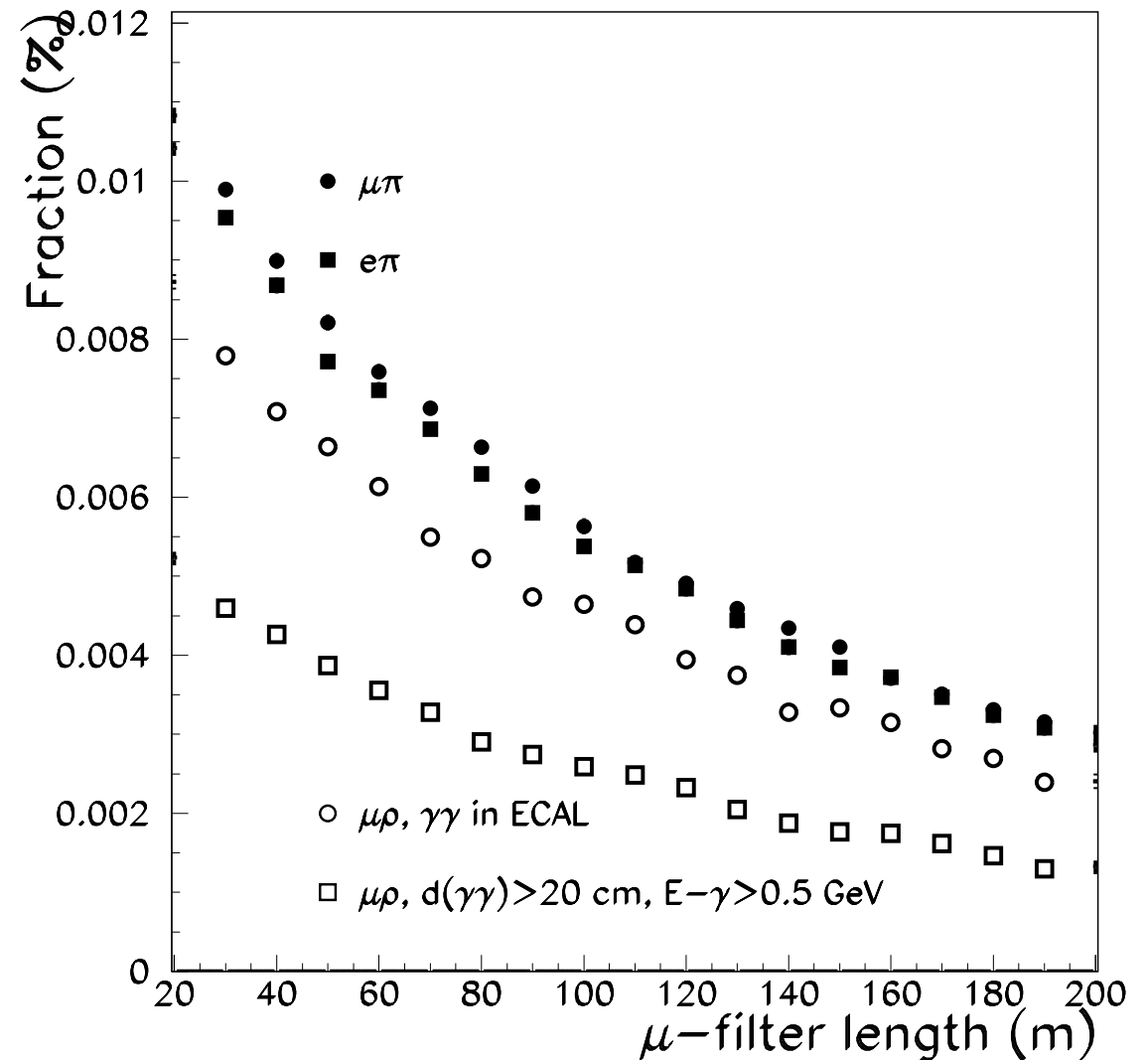
Expected acceptance/channel

$N \rightarrow \mu/e \pi, \rightarrow \mu \rho(\pi\pi^0):$

- $\tau_{\text{HNL}} = 1.8 \times 10^{-5}$ s, mass=1 GeV.
- Our standard double 40+10 m vessel.

Conclusion:

- Acceptance $e\pi \sim \mu\pi$
- $\mu\rho \sim 45\%$ reco-eff compared to $\mu\pi$.





Expected HNL Sensitivity

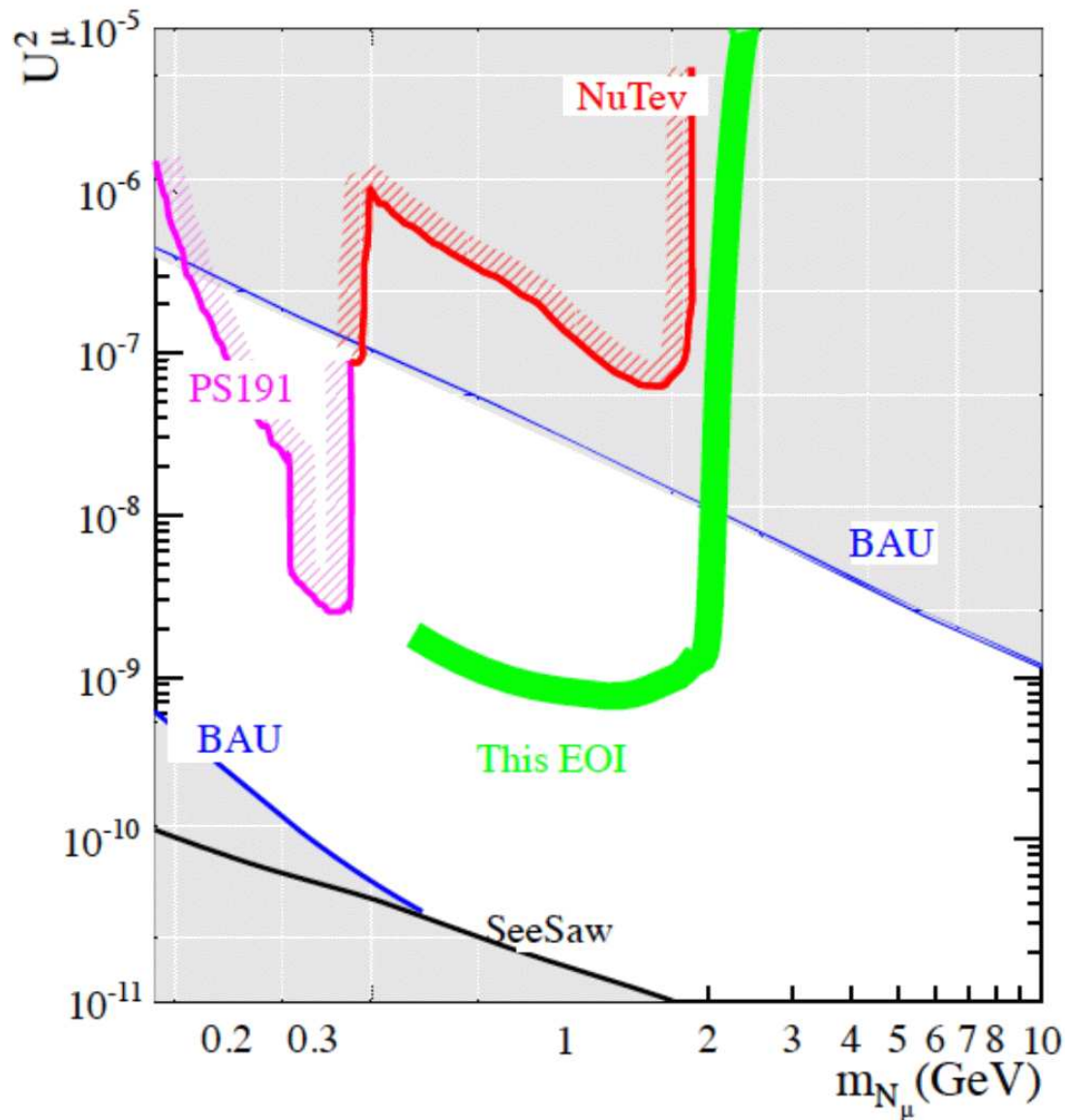
- Only consider $N_{2,3} \rightarrow \mu\pi$, i.e. U_μ^2
- 400 GeV pot = 2×10^{20}
- $\mathcal{B}(N \rightarrow \mu\pi) = 20\%$

For $M_N = 1$ GeV:

U_μ^2	τ_N	$\mu\pi$ events
10^{-7}	1.8×10^{-5} s	12000
10^{-8}	1.8×10^{-4} s	120
10^{-9}	1.8×10^{-3} s	1

For $U_\mu^2 = 10^{-10}$ need:

- 10× more pot (and/or $\sqrt{(s)}$?), AND
- 10× larger acceptance!





Extended Physics Program

Experiment designed for HNL studies in ν MSM, but..

- Ideally suited for studying interactions of ν_τ , since they are produced from D_s -decay, hence have similar kinematics as HNLs. \rightarrow next slides

- Can search for any other weakly interacting, yet unstable particles with $100 < M < 2000$ MeV.

Example of “hidden sector” models on the “market”:

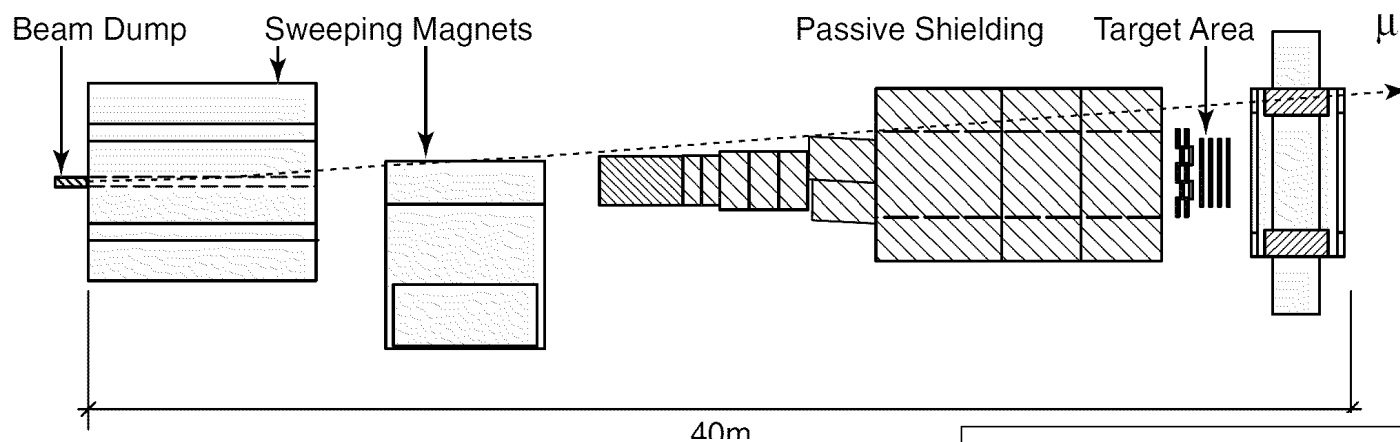
- Light SUSY goldstinos (hep-ph/000735):
 - * Production/decay might be like HNL, i.e. $D \rightarrow \pi X$, $X \rightarrow \pi\pi$
 - * $c\tau_X$ $O(\text{km})$?
- Light R-parity violating neutralinos in SUSY (hep-ph/0106199):
 - * $D \rightarrow X\chi^0$, $\chi^0 \rightarrow \mu^+\mu^-\nu$
 - * LSP, with R-parity “slightly” violated: BBN: $\tau_{\chi^0} < 0.1$ s
- Dark/massive/para photons (hep-ph/0606202):
 - * Produced via p-Bremstrahlung, $\gamma' \rightarrow e^+e^-$, $\mu^+\mu^-$.
 - * BBN limit: $\tau_{\gamma'} < 0.1$ s.
- Insert your “favourite” model here...
- Still need to evaluate hidden-sector models (more) quantitatively.



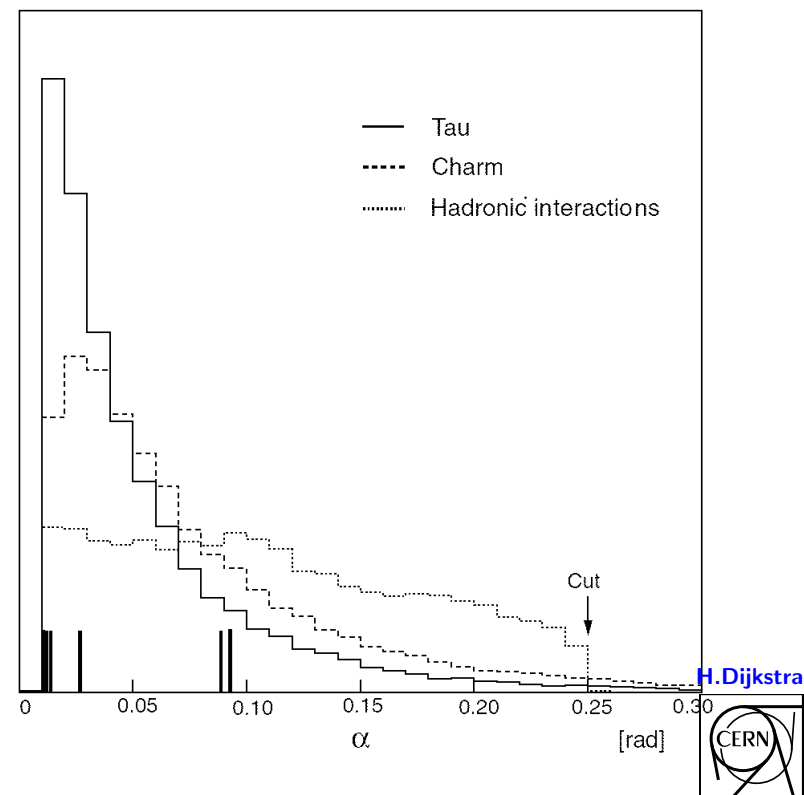
ν_τ Physics

Experimental status: DONUT results (PR D 78, 052002 (2008))

- 1997: 3.6×10^{17} pot, 800 GeV, using 260 kg emulsion ν -target.



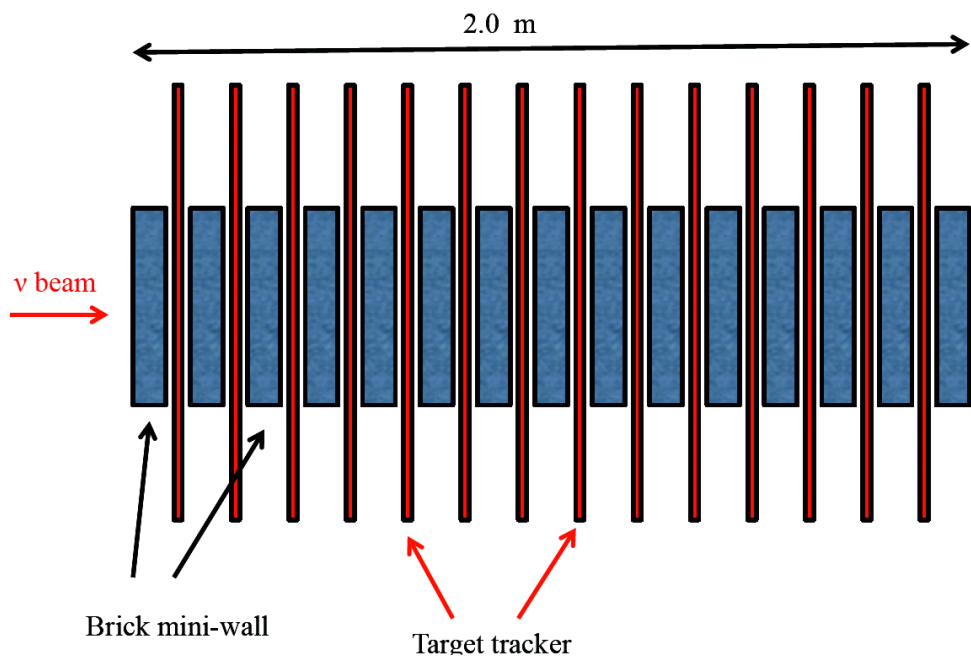
- α_{kink} from τ -decay in CC interactions.
- Charm/hadronic-interaction background.
- 9 candidates, including 1.5 background.





ν_τ Physics with 2×10^{20} pot

- Scaling from DONUT: 20 times more CC with same ν -target mass.
- But can increase ν -target mass “easily”, let's say to 3 % of OPERA emulsion surface:



- Only requires limited space along beam-line, hence “no” loss for HNL acceptance.
- HNL spectrometer is forward spectrometer of ν -physics program.
- ν -target allows to tag K_L which coincide with ν -interactions.
- Expect 1500-2000 CC ν_τ interactions.
- In addition: $5 \times \nu_\mu$ CC charm production than CHORUS (2k).



SPSC status

- 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: ship.web.cern.ch/ship/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).



Next Steps

Following the endorsement of the SPSC:

- The CERN directorate has set-up a task force to assess the implications of the Heavy Neutral Lepton Experiment at the SPS. The deliverable that the DG is expecting for this summer is a report including the layout and the resources which are required to set-up the beam-dump and its calendar .
(Draft report already circulating ...)
- Our (proto) collaboration called SHiP (Search for Hidden Particles^a, CERN, Universität Zürich, EPFL Lausanne, INFN Cagliari, Universit Federico II and INFN Napoli, Imperial College London) is organising a workshop:
June 10-12 at Zürich
<http://ship.web.cern.ch/ship/collmtg10062014.htm>
- SHiP needs reinforcements to undertake this experiment. Hence, the meeting in June aims at attracting experimental groups which are interested in participating.

^aLogo to be decided



Conclusions

- SHiP will search for NP in the largely unexplored domain of new, very weakly interacting neutral particles.
- Detector is based on existing technologies.
Ongoing discussions of the beam lines with experts.
CERN directorate has set-up task force to study accelerator part.
- The impact of HNL discovery on particle physics is difficult to overestimate!
Discovery would shed light on BSM physics:
 - The origin of the baryon asymmetry of the Universe
 - The origin of neutrino mass
 - The nature of Dark Matter, did we get a hint?

The SHiP collaboration is being setup, first collaboration meeting June 10-12.

Who would like to join?