very preliminary

Muon/Pion Capture and the Search for Light Exotics

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http://www.npl.washington.edu/muon/

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Outline

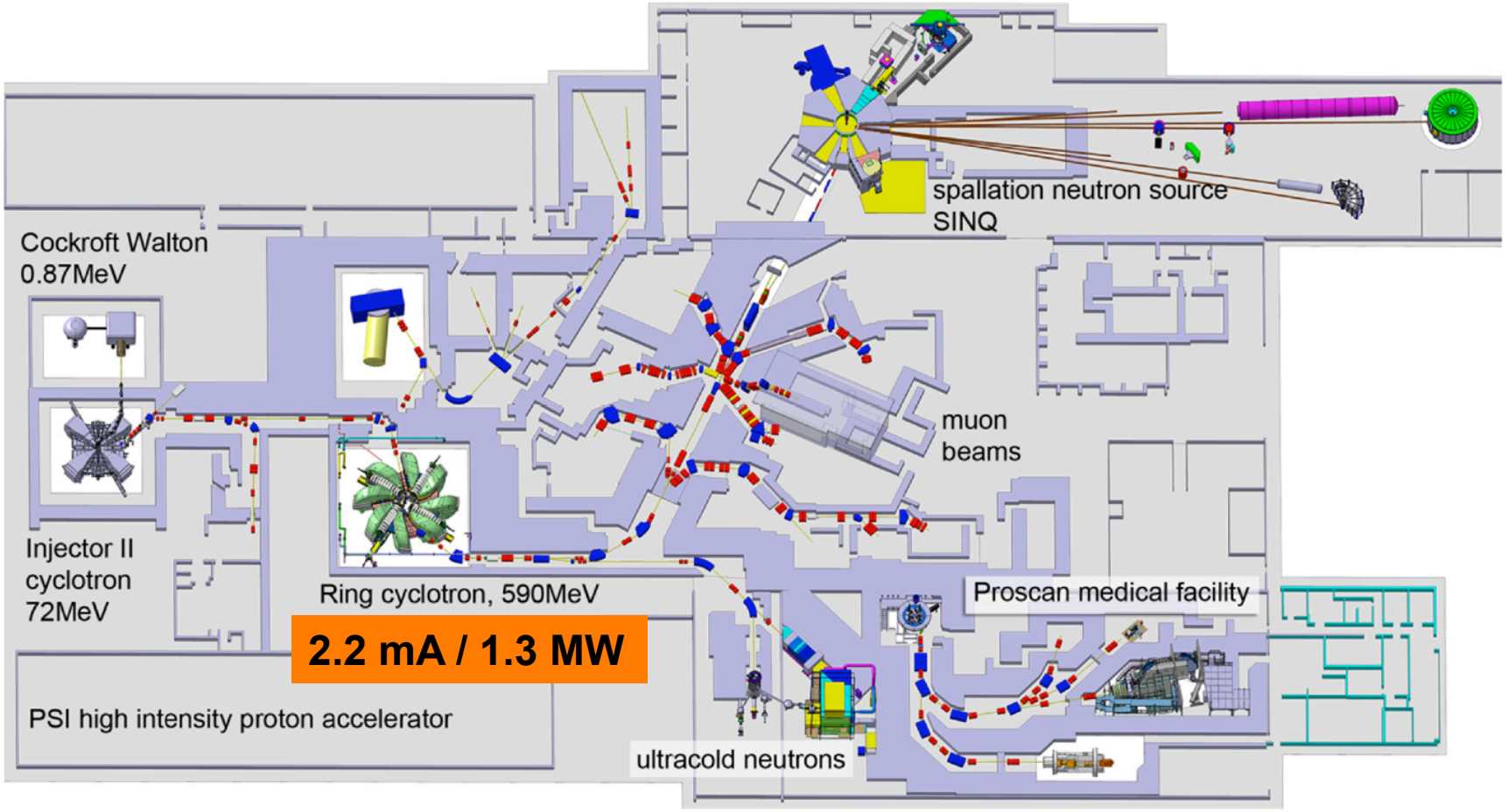
Introduction: Current Muon Capture Program

- PSI
- MuX trilogy and techniques

Light Exotics in Muon and Pion Capture

- Motivation
- Kinematics
- Heavy neutrino search
- Dark photon search


PAUL SCHERRER INSTITUT
PSI

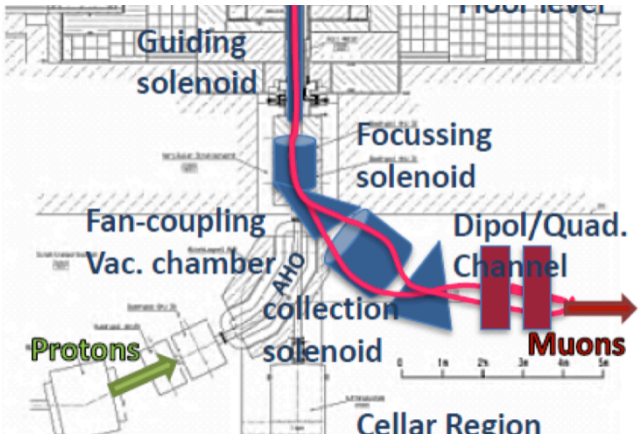

spallation neutron source
SINQ
Cockroft Walton
0.87MeV
muon
beams
Injector II
cyclotron
72MeV
Ring cyclotron, 590MeV
2.2 mA / 1.3 MW
Proscan medical facility
PSI high intensity proton accelerator
ultracold neutrons

Paul Scherrer Institute

Laboratory/ Beam Line	Energy/ Power	Present Surface μ^+ Rate Hz	Future estimated μ^+/μ^- Rate Hz
PSI (CH)	(590 MeV, 1.3MW, DC)		
- LEMS	"	$4 \cdot 10^8$	
- πE5	"	$1.6 \cdot 10^8$	
- HiMB	(590 MeV, 1 MW DC)		$\sim 10^{10}$ (μ+) (for cf. only)
J-PARC (JP)	(3 GeV, 1MW Pulsed) currently 300kW		
- MUSE D-line	"	$4.5 \cdot 10^6$	$1.5 \cdot 10^7$ (μ+) 2013
- MUSE U-Line	"	$1.5 \cdot 10^8$	$2 - 5 \cdot 10^8$ (μ+) 2013
- COMET	(8 GeV, 56kW Pulsed)		10^{11} (μ-) 2019/2020
- PRIME/PRISM	(8 GeV, 300 kW Pulsed)		$10^{11\text{-}12}$ (μ-) >2020
FNAL (FermiLab) (USA)			
Mu2e	(8GeV, 25kW Pulsed)		$5 \cdot 10^{10}$ (μ-) 2019/2020
Project X Mu2e	(3GeV, 750kW Pulsed)		$2 \cdot 10^{12}$ (μ-) >2022
TRIUMF (CA)	(500 MeV, 75kW, DC)		
-M20		$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW Pulsed)		
- Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160kW, Pulsed)		
- RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400W DC)		
- MUSIC	currently max 4W		10^8 (μ+) * 2012
			* (≡ > 10^{11} per MW!!!)
DUBNA (RU)	(660 MeV, 1.65kW Pulsed)		
- Phasotron Ch:I-III		$3 \cdot 10^4$	

HiMB Science Case Workshop

- **Wednesday Feb 11 – Friday Feb 13, 2015**



Central Momentum [MeV/c]	Momentum-byte [%] FWHM	Estimated Muon Rate (Below SINQ Target) [Hz] I_P = 2.4 mA Tg E
28 (Surface muons)	Full	$(7\pm1)\cdot10^{10}$
28 (Surface muons)	10	$(3\pm1)\cdot10^{10}$
26 (sub-surface muons)	10	$(3\pm1)\cdot10^{10}$

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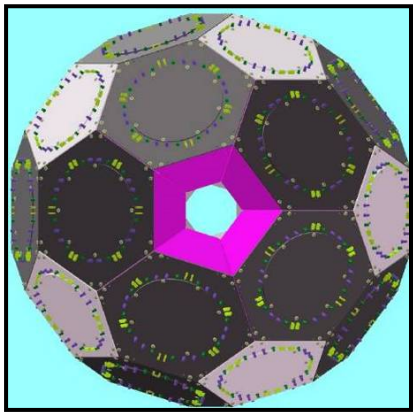
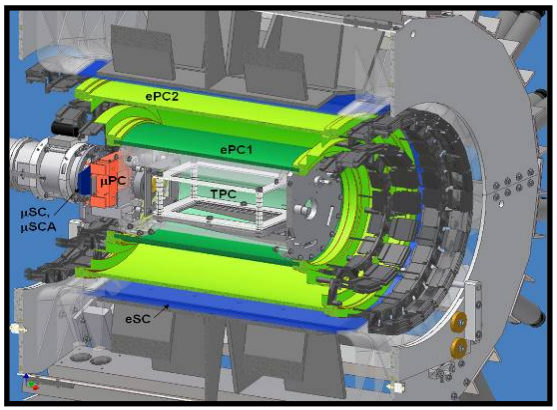
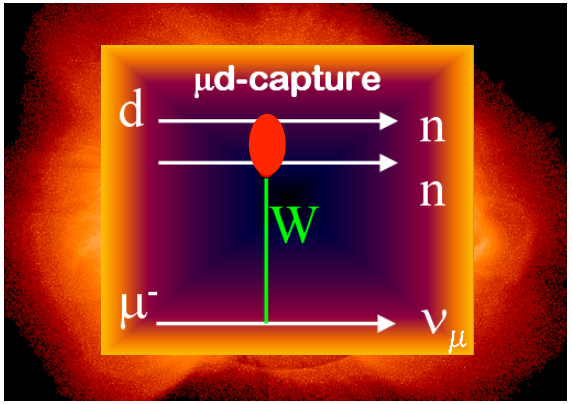
MuX Trilogy

Fermi Constant	QCD Symmetries	"Calibrating the Sun"
MuLan	**MuCap**	**MuSun**



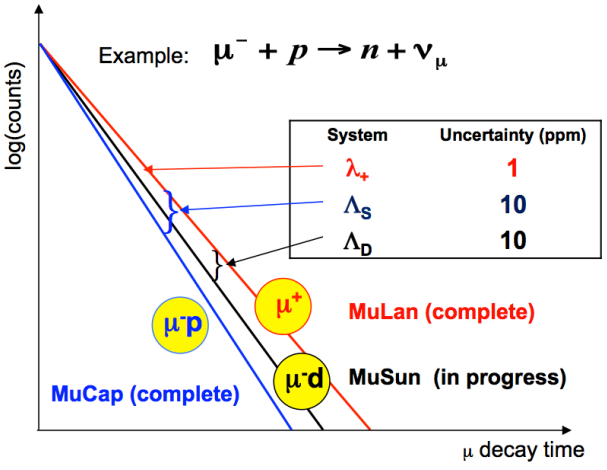




$\mu \rightarrow e\,\bar{\nu}\,\nu$ $\quad$ $\mu+p \rightarrow n+\nu$ $\quad$ $\mu+d \rightarrow n+n+\nu$

"Muon lifetime technique"

- capture rate
  $\Lambda_S = 1/\tau_{\mu^-} - 1/\tau_{\mu^+}$
- special active target technique



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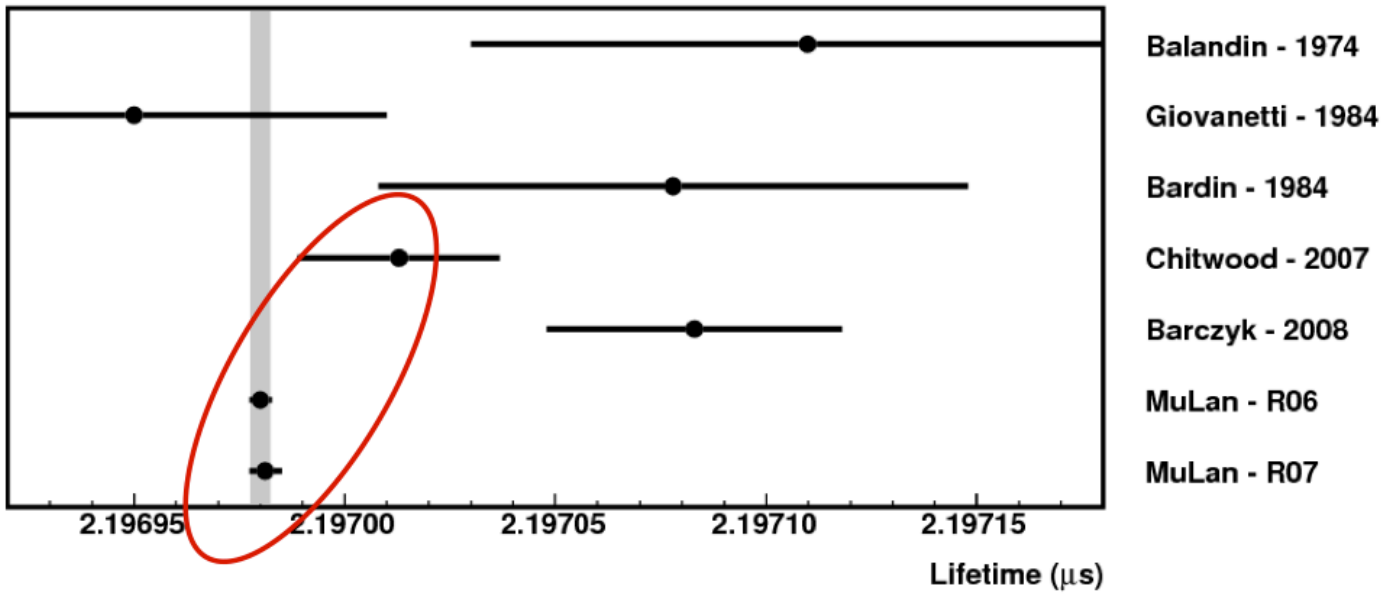
MuLan Final Results



τ(MuLan) = 2 196 980.3 ± 2.2 ps (1.0 ppm)

The most precise particle or nuclear or atomic lifetime ever measured

New G_F (30x improved since 1999 PDG)

G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

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Muon Capture on the Nucleon: MuCap

Muon Capture $\mu + p \rightarrow n + \nu$ rate Λ_S

$$H_{weak} = \frac{G_F}{\sqrt{2}} V_{ud} L_\mu (V^\mu - A^\mu)$$

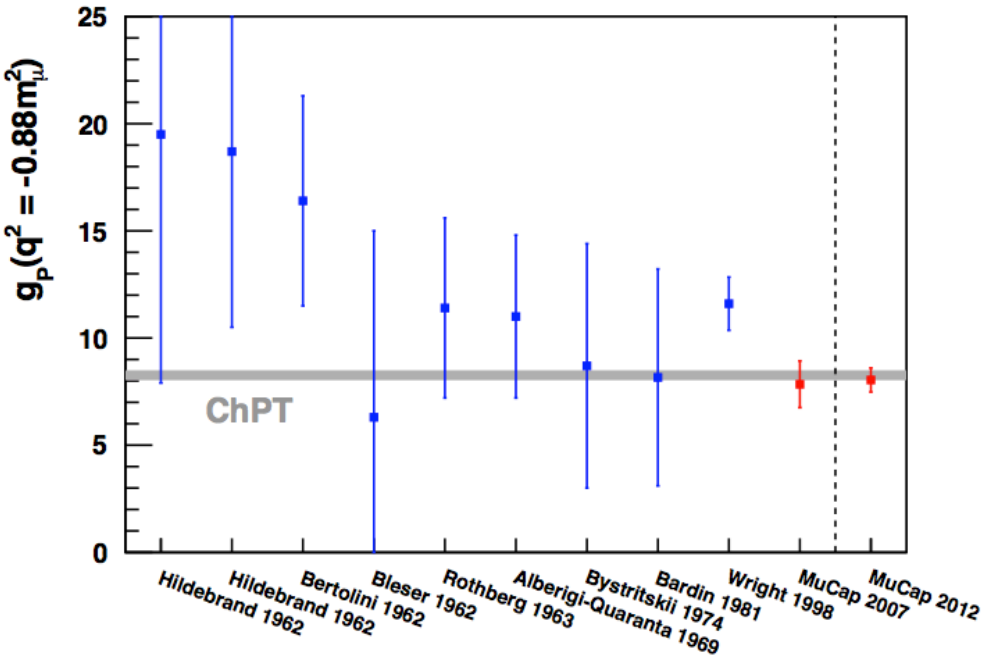
$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \frac{g_P(q^2)}{m_\mu}\,q_\alpha\,\gamma_5$$

χPT parameter free prediction: $g_P = 8.26 \pm 0.23$

MuCap final result: $g_P = 8.06 \pm 0.55$

verifies basic prediction of low energy QCD



PRL 110, 012504 (2013)
APS Editor's spotlight
Physics World

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Muon Capture on the Deuteron: MuSun

$$\mu + d \rightarrow n + n + \nu$$

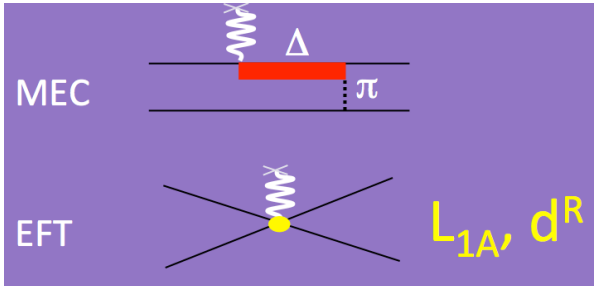
measure rate Λ_d to 1.5%

Measure weak coupling of two-body axial current

EFT

pion less EFT, L_{1A}

HB χ PT, d^R sole unknown LEC up to N^{3}LO



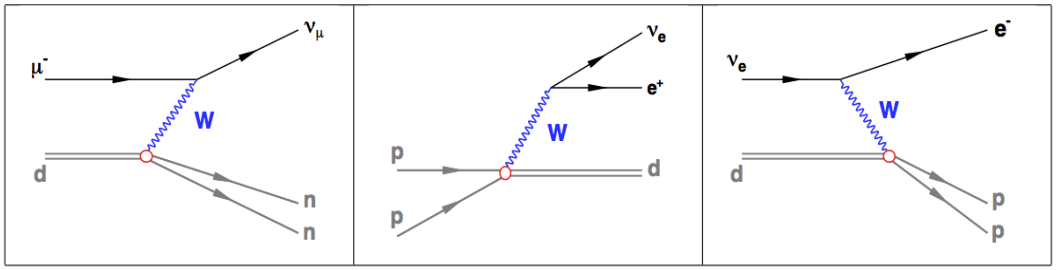
Model independent connections via d^R

- 2N weak processes

  Sun $p\,p \rightarrow d\,e^+\nu$

  SNO $\nu_e\,d \rightarrow p\,p\,e^-$ (CC)

  $\nu_x\,d \rightarrow p\,n\,\nu_x$ (NC)



- Nuclear forces

  Three-body forces, nn scattering length

"Calibrating the Sun"

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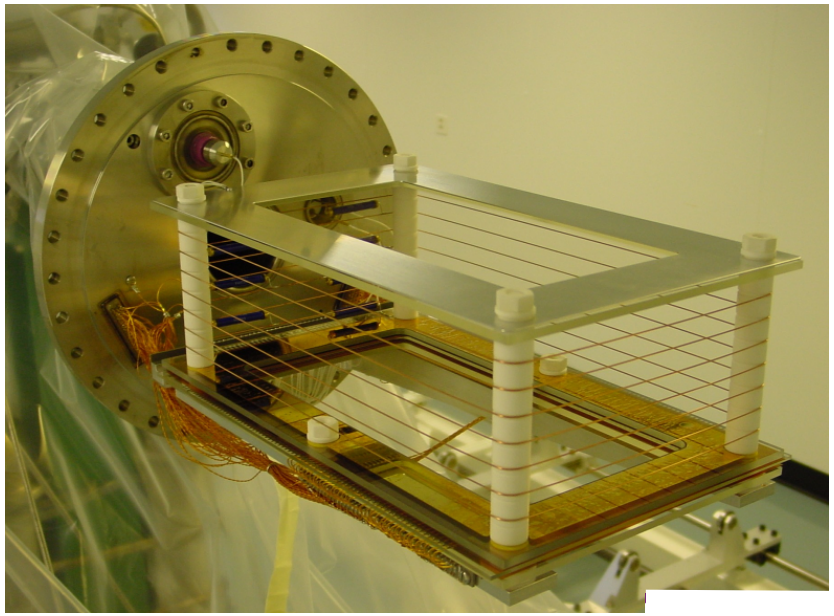
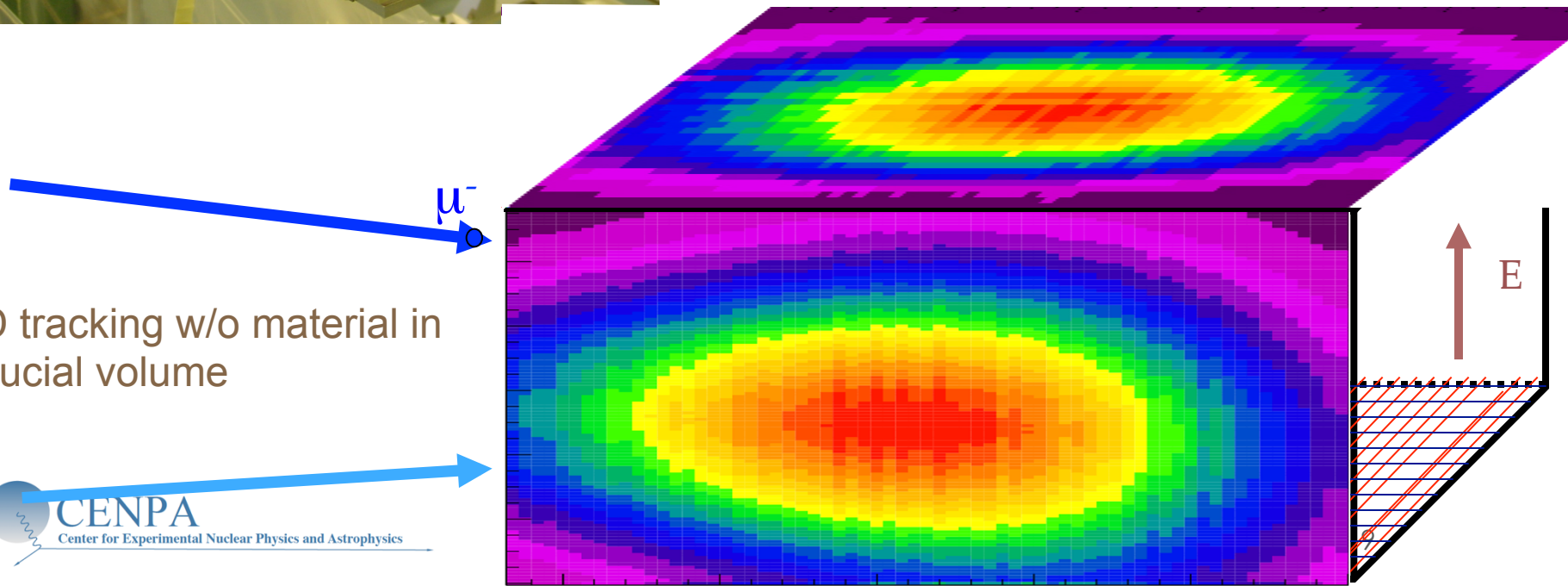
MuCap: Active TPC Target



to prevent muon stops in walls
(Capture rate scales with ~Z^4)

10 bar ultra-pure hydrogen, 1.12% LH_2
2.0 kV/cm drift field
~5.4 kV on 3.5 mm anode half gap
bakeable glass/ceramic materials

Observed muon stopping distribution



3D tracking w/o material in fiducial volume

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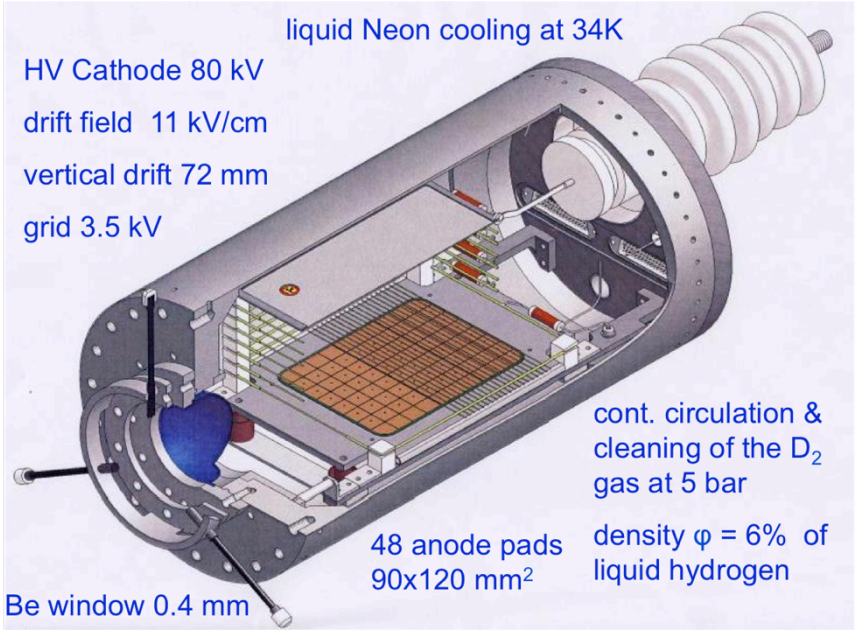
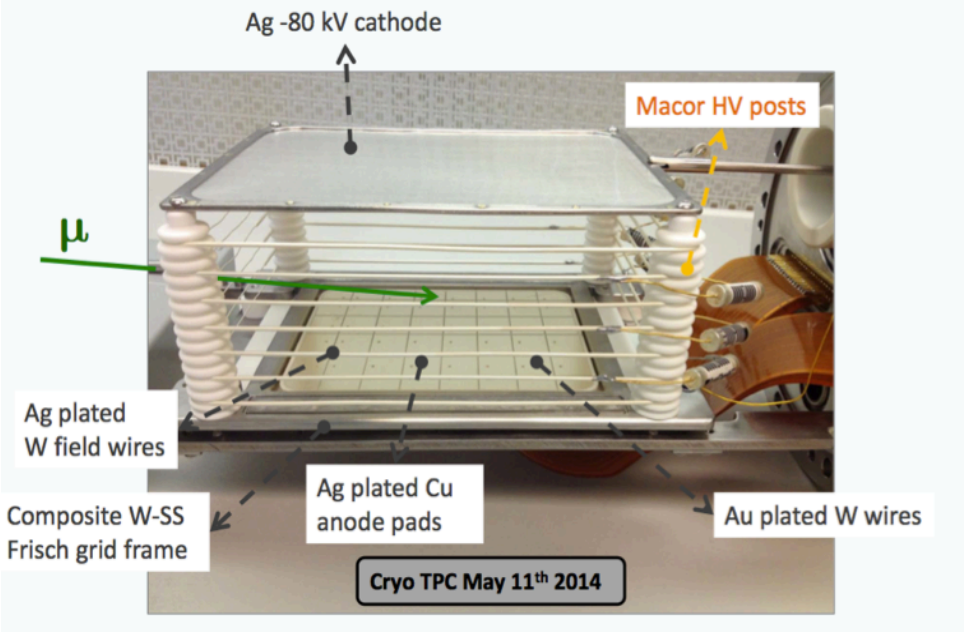
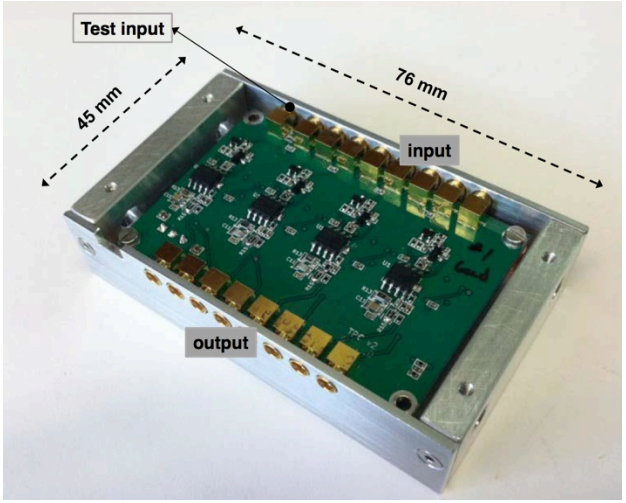
MuSun: High Density Cryo TPC





- ionization chamber with no gas gain
- new cryo-preamp designed by UW achieve 10 keV electronic resolution.



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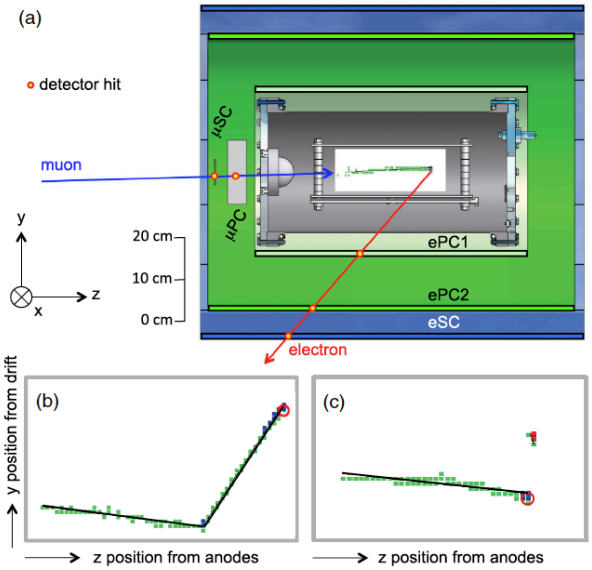
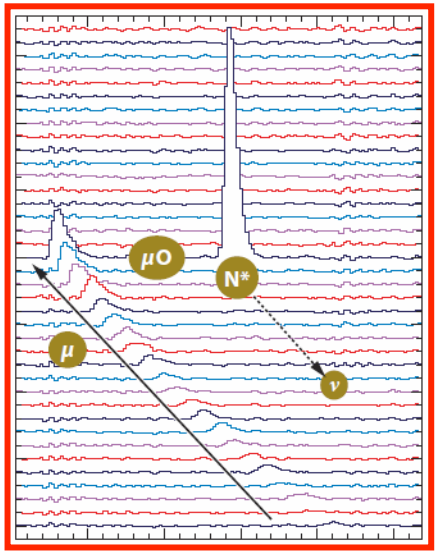
Comparison

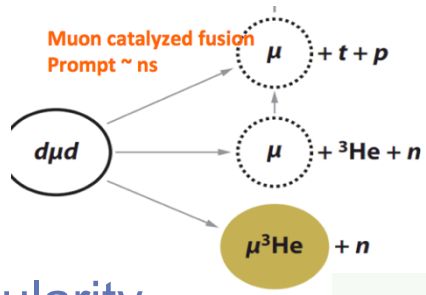
MuCap

- high granularity
- low threshold
- 10% energy resolution

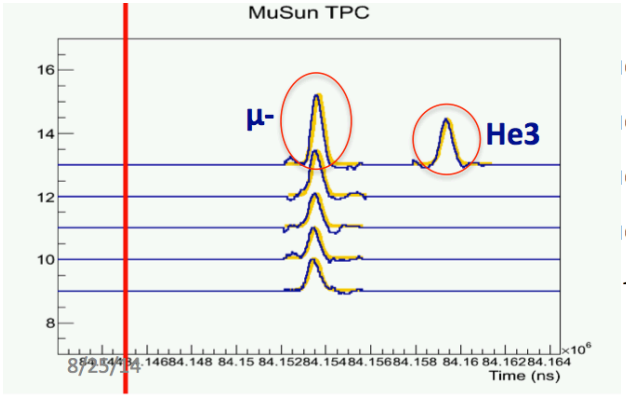


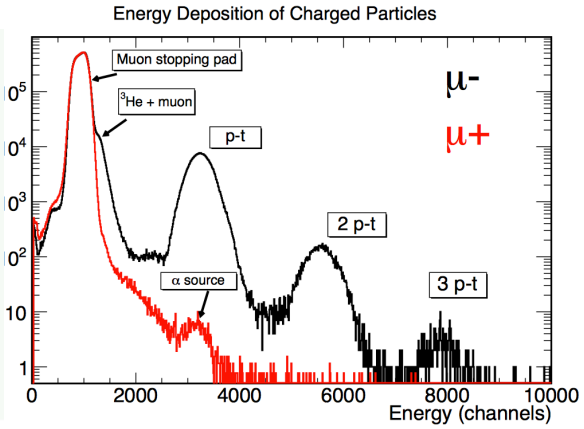


MuSun



- lower granularity
- excellent 20 keV energy resolution





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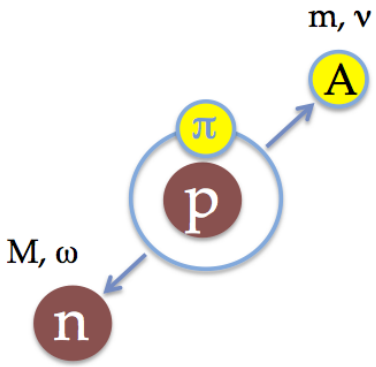
Ideas only

Search for Light Exotics

μ/π capture provides O(100 MeV) energy

Generic



$$\omega = \frac{s - m^2 + M^2}{2\sqrt{s}}$$

$$\nu = \frac{s - M^2 + m^2}{2\sqrt{s}}$$

$$\Delta m_A = -\frac{\sqrt{s}}{m_A}\Delta\omega$$

Reactions

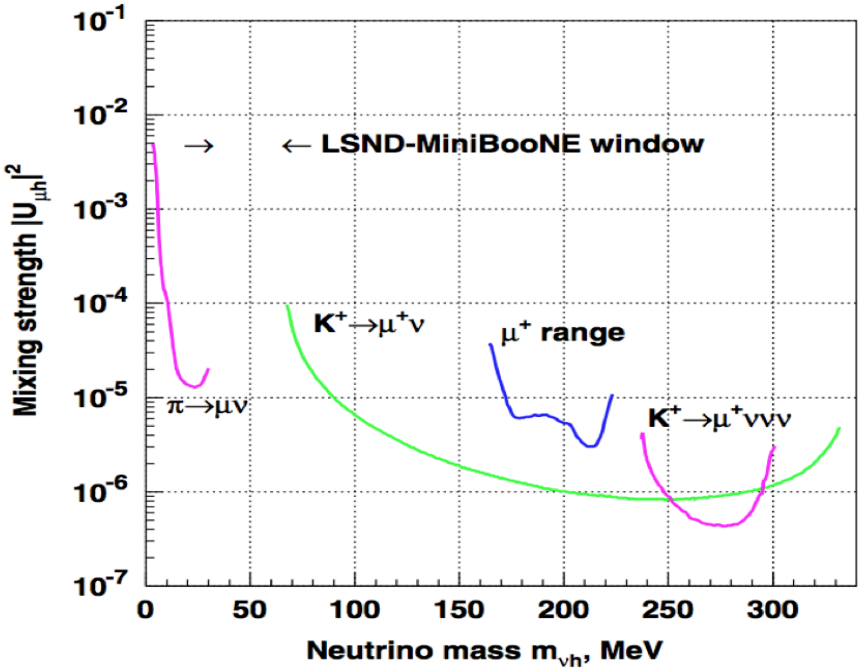
- muon
- pion

reaction	$\sqrt{s}$	p	ν	T_ν	ω	T_ω	BR	Ref
$\mu + p \to \nu + n$	1043.93	99.15	99.15	99.15	944.78	5.22	1.57×10^{-3}	[10]
$\mu + {}^3He \to \nu + t$	2914.04	103.22	103.22	103.22	2810.82	1.89	3.28×10^{-3}	[11]
$\mu + {}^4He \to \nu + t + n$	3833.03	83.60	83.60	83.60	3749.43	0.932	$\sim 0.5\times10^{-3}$	[12]
$\pi + p \to \gamma + n$	1077.84	129.40	129.40	129.40	948.44	8.87	0.394	[13]
$\pi + p \to \pi^0 + n$	1077.84	28.03	137.86	2.88	939.98	0.418	0.605	[13]
$\pi + {}^3He \to \gamma + t$	2947.95	135.74	135.74	135.74	2812.21	3.23	0.069	[14]
$\pi + {}^3He \to \pi^0 + t$	2947.95	32.49	138.83	3.86	2809.12	0.188	0.158	[14]

Ideas only

Heavy ν Search

Generic

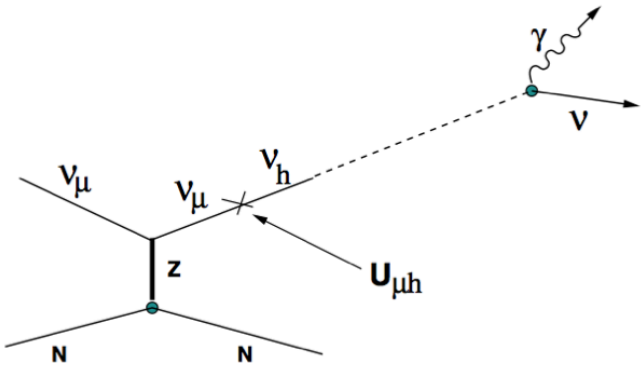


Gninenko model

explains LSND not as $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation but as NC reaction with sterile ν_h consistent with Karmen (MiniBoone??)

40 MeV < m_h < 80 MeV

$|U_{\mu h}|^2 \sim 10^{-3} - 10^{-2}$!!



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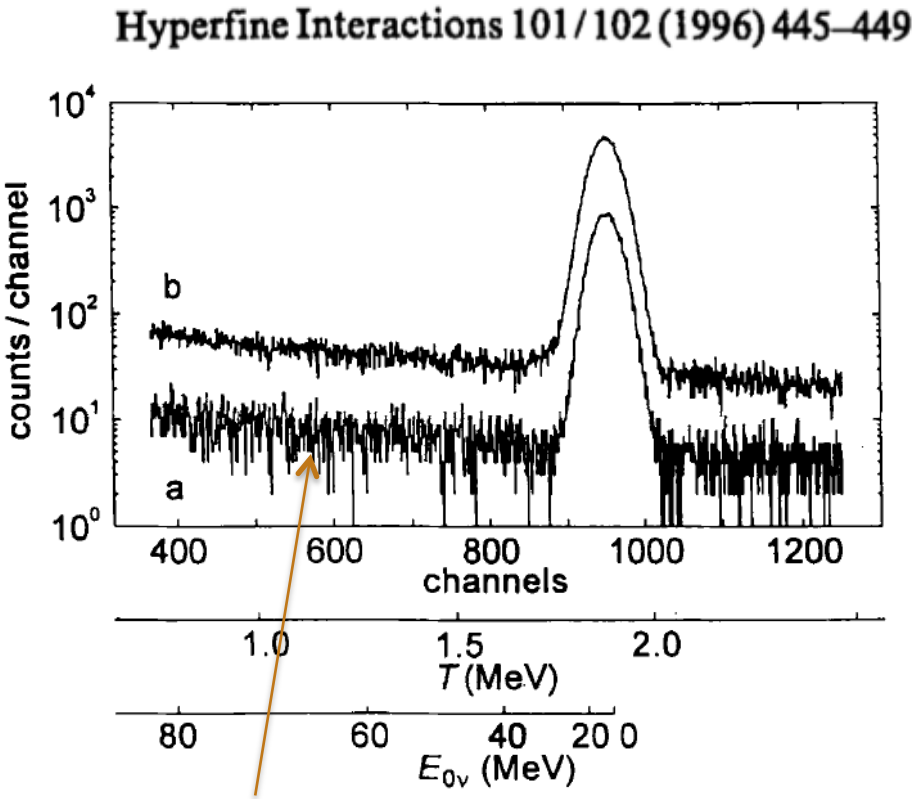
Heavy ν at PSI?

Early experiment:

$\mu + {}^3He \rightarrow t + \nu \quad (70\%)$

- rms resolution 25 keV
- $|U_{\mu h}|^2 \leq 10^{-3}$



Key improvements MuSun

- TPC size and cryo operation
- Resolution
- Digitizer and DAQ
- γ Detection ?

background:
$\mu + {}^3He \rightarrow d + n \quad (20\%)$
$\rightarrow d + 2n \quad (10\%)$

Large improvement potential

Good test case for more difficult pion experiment

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Dark Photons

Standard Model ⟷ (messenger) Hidden Sector

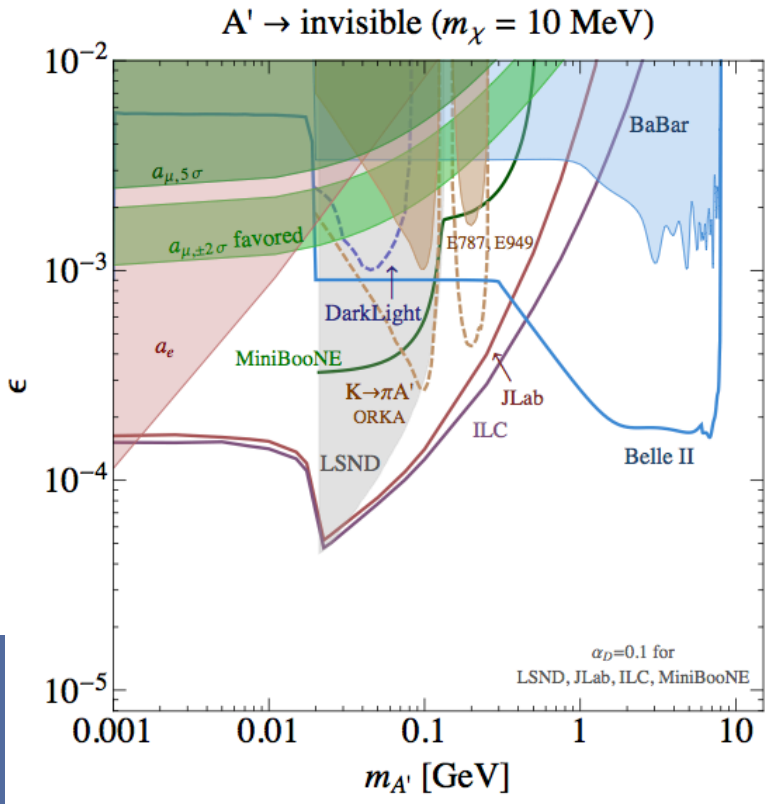
Popular scenario: SU(3) x SU(2) x U(1) x U'(1)

V coupling via kinetic mixing: $L_{int} = \varepsilon\, e\, J_{u}\, V_{u}$

- connection to DM
- "explains" muon g-2 anomaly

Worldwide effort

- Bump hunt in $A' \rightarrow l^+l^-$
- Unseen decay
  missing energy
  scattering of χ
  ??



Discussion
- exp. competition
- model dependence

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Ideas only

Dark Photons at PSI?

Kammel, Pospelov

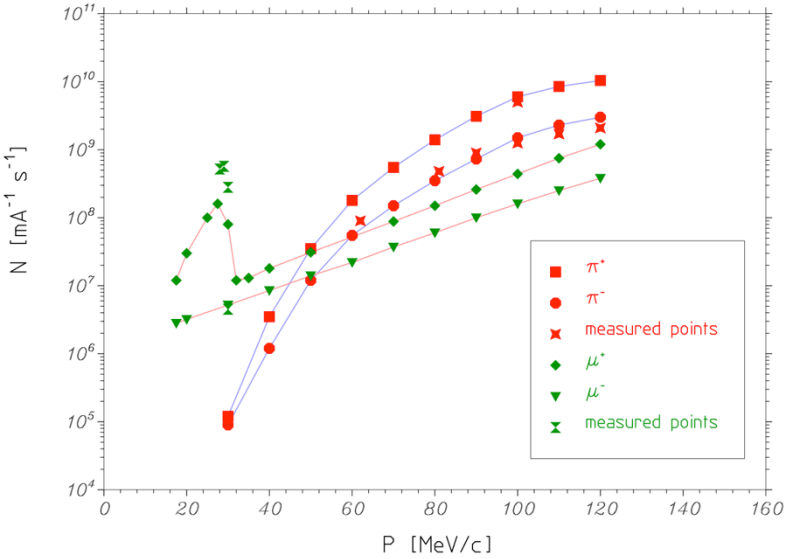
Capabilities

- Excellent π beams
- Simple, clean and low energy reactions
- Two body recoil with high resolution ^{3}He TPC: model-independent search for unseen mode

Ideas only

Beam & Rates

πE5 @ PSI

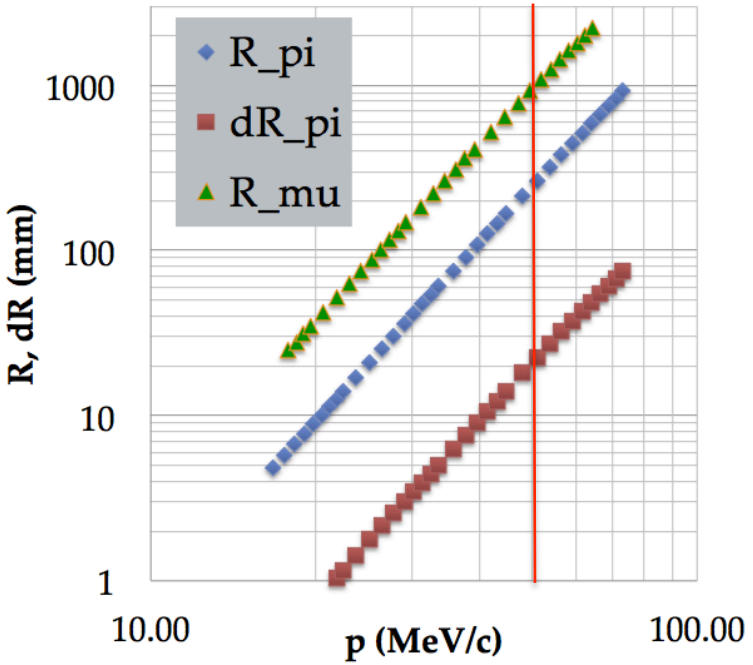


μ/π range R and width ΔR in mm He

- assume MuSun density
- 2% Δp/p
- how clean is beam at low p ?

example

- 10^6 π^-/s stop in 20mm @ p=50 MeV/c



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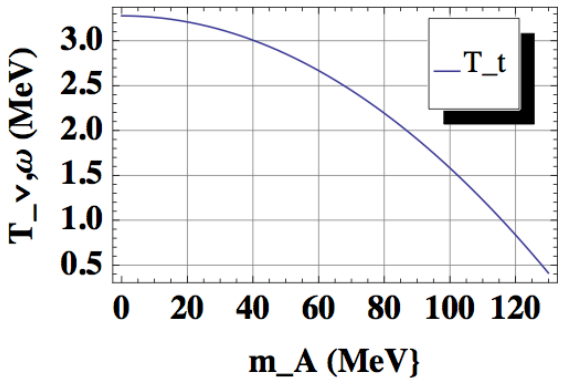
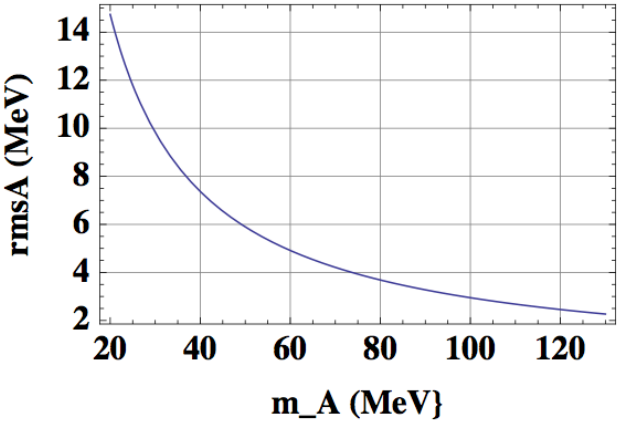
Detector

assume

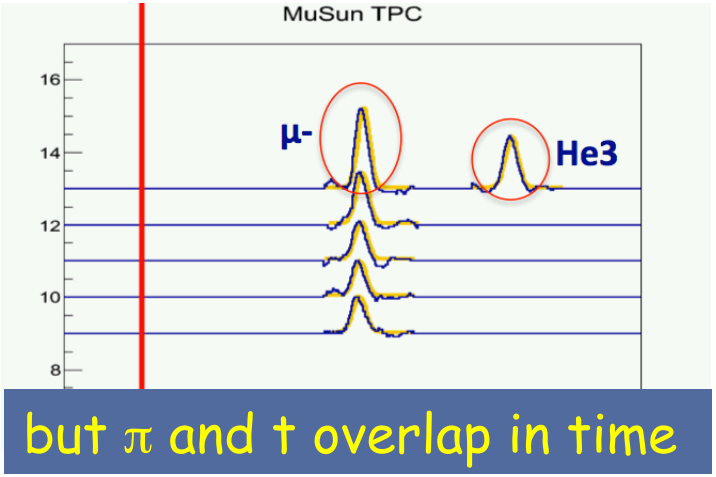
- MuSun TPC
- 100 keV rms resolution
- 4-8 mm pixel



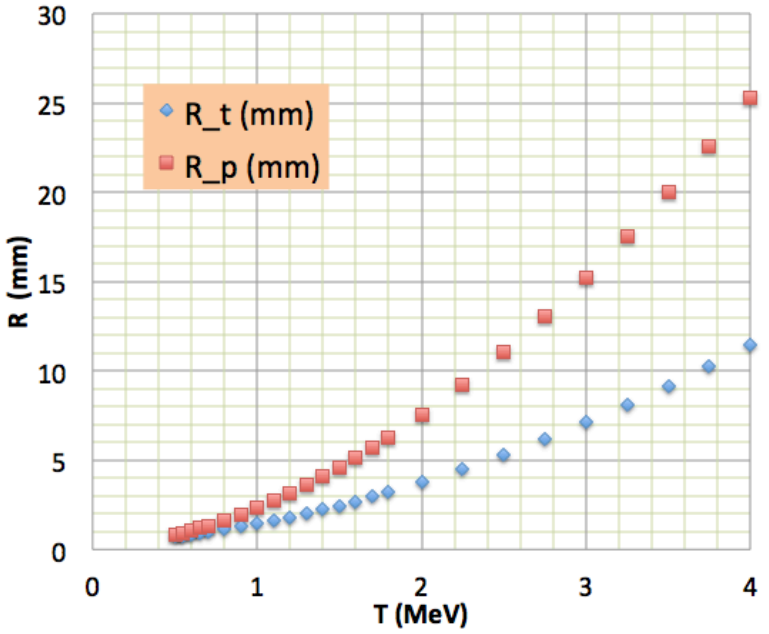


Main issue is good energy resolution

- correct for π energy in stop pixel



triton range



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Systematics & Statistics

Systematics

- optimize for excellent energy resolution !
- SM background
  TPC suppresses continuum

$$\begin{aligned} \pi + {}^3He &\rightarrow {}^3H\pi^0 \ (17.8\%) \\ &\rightarrow {}^3H\gamma \ (6.6\%) \\ &\rightarrow dn\gamma + pnn\gamma \ (7.4\%) \\ &\rightarrow dn + pnn \ (68.2\%) \end{aligned}$$

- rad. corrections ?
- wall stops, muons, electrons?

Statistics

- conservatively assume R_π ~10^5 π/s (single π in TPC)
- R(^{3}H,γ)= 7 kHz
- 2 months: >10^{10} events

Exciting, but basic homework still needs to be done to check whether ideas survive some scrutiny.

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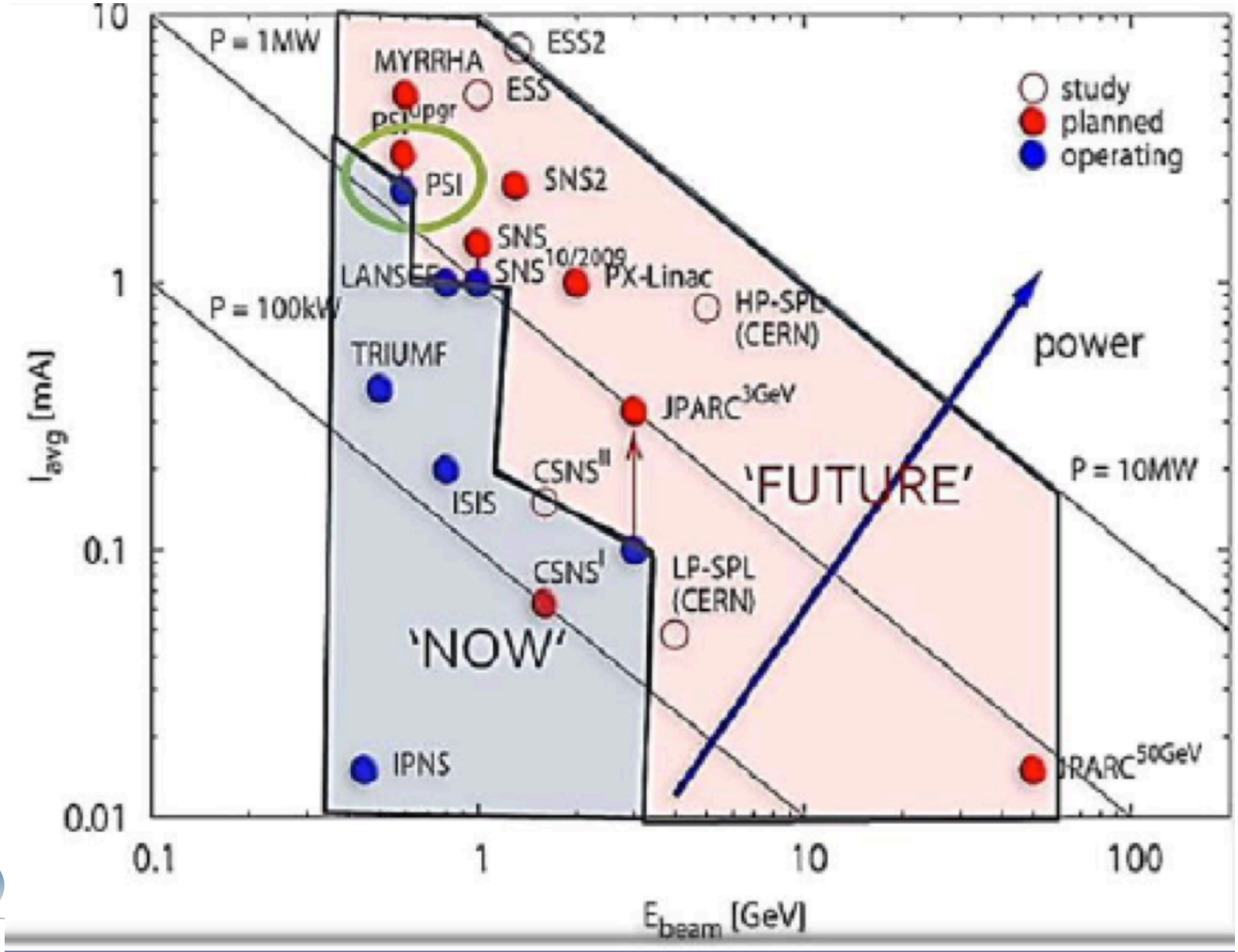
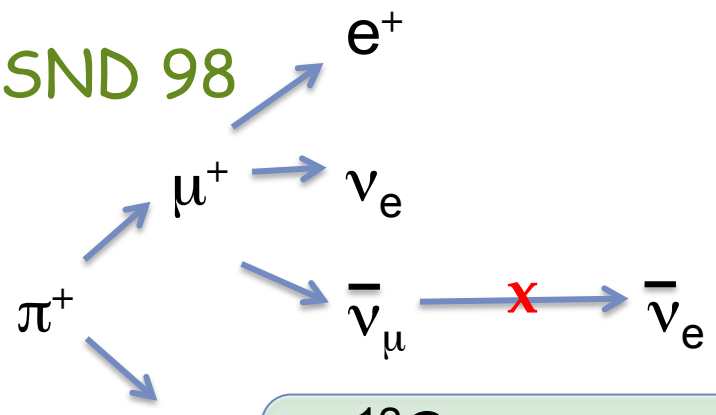
Backup


P = 1MW
P = 100kW
P = 10MW
MYRRHA
ESS2
ESS
PSI
SNS2
SNS
SNS 10/2009
LANSCE
PX-Linac
HP-SPL (CERN)
TRIUMF
JPARC 3GeV
CSNS II
ISIS
'FUTURE'
CSNS I
LP-SPL (CERN)
'NOW'
IPNS
JPARC 50GeV
study
planned
operating
power
I_{avg} [mA]
E_{beam} [GeV]
10
1
0.1
0.01
0.1
1
10
100

Ideas only

Part II: Heavy ν Search

LSND 98



$\bar{\nu}_e\, p \rightarrow n\, e^+$ (CC)

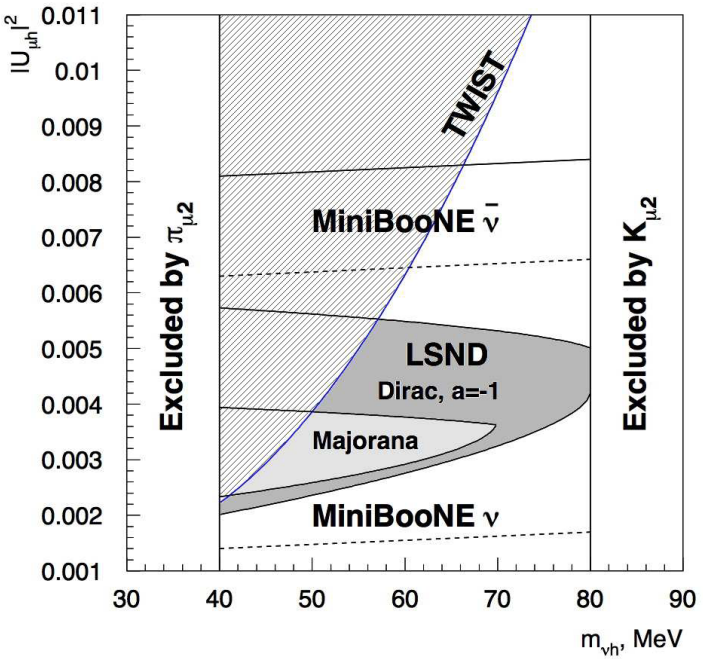
$n\, p \rightarrow d\, \gamma$

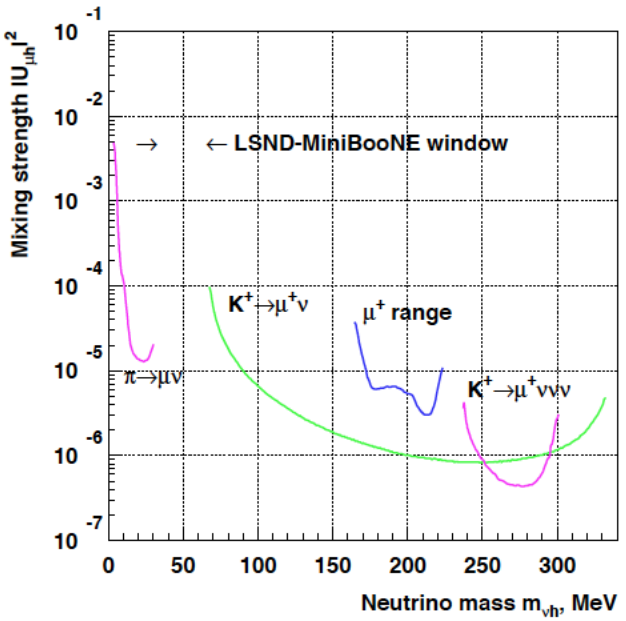
$+ {}^{12}C \rightarrow \nu_h + n + {}^{11}C$ (NC)

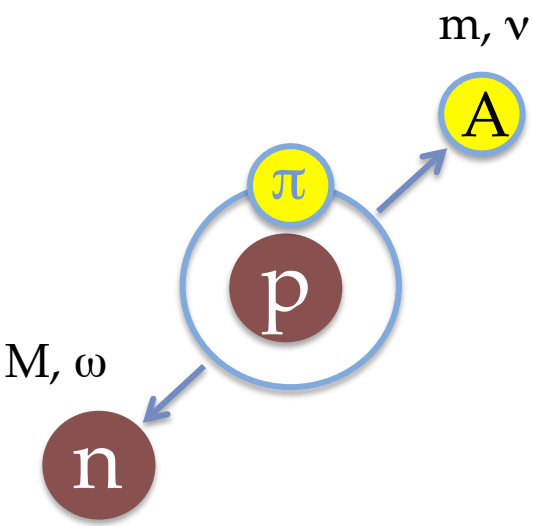
$\nu + \gamma$

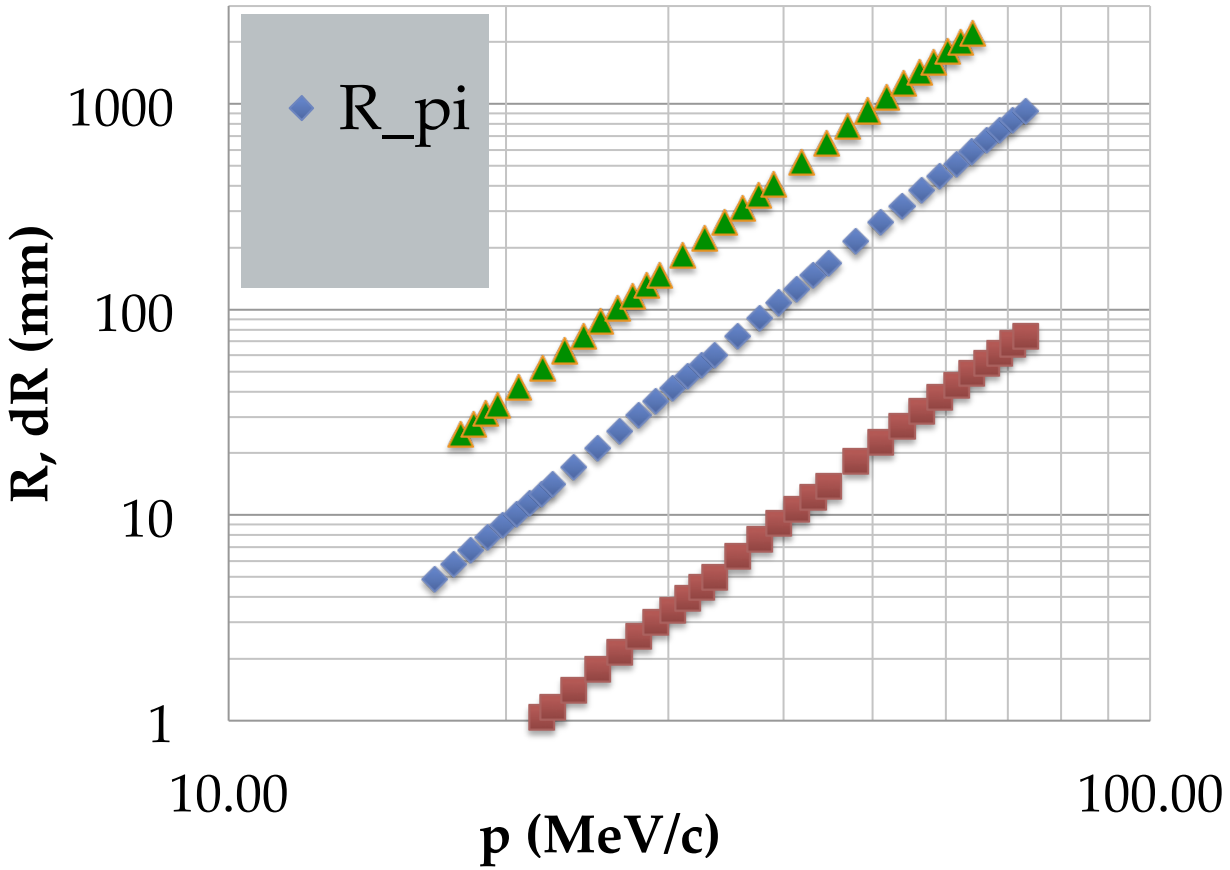
Gninenko 11
consistent with
Karmen, MiniBoone

$\tau_h < 10^{-9}$s









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