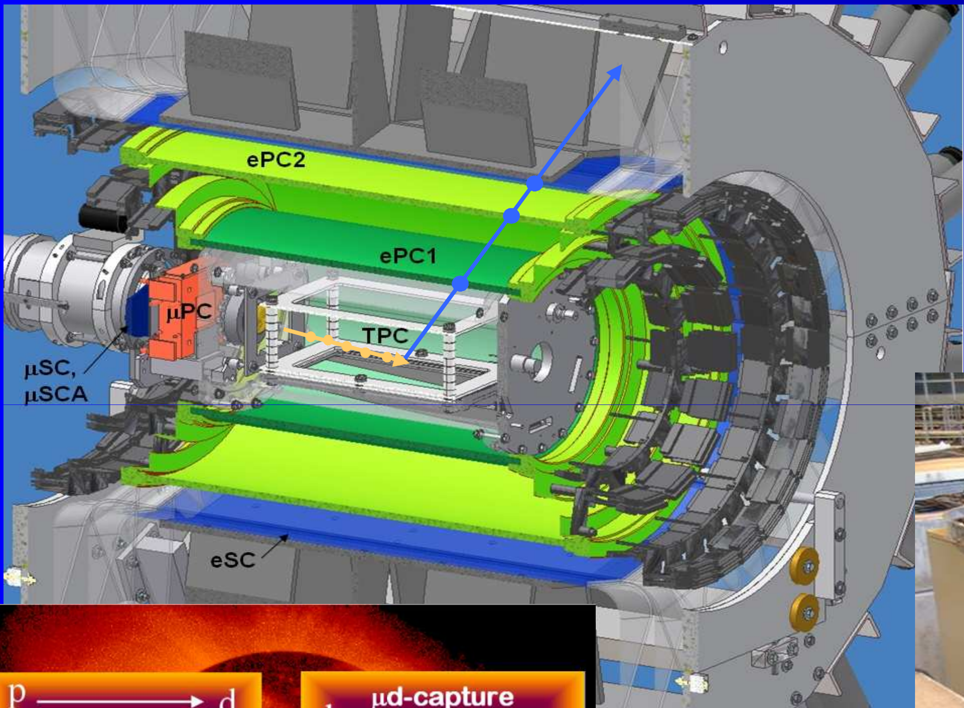
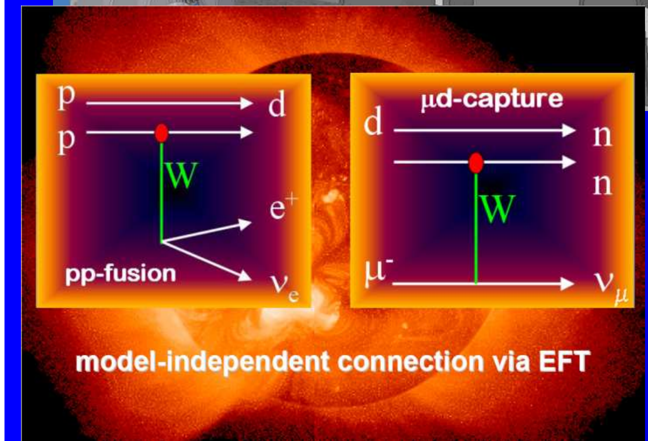
In a muon's lifetime: From Fermi's constant to calibrating the sun



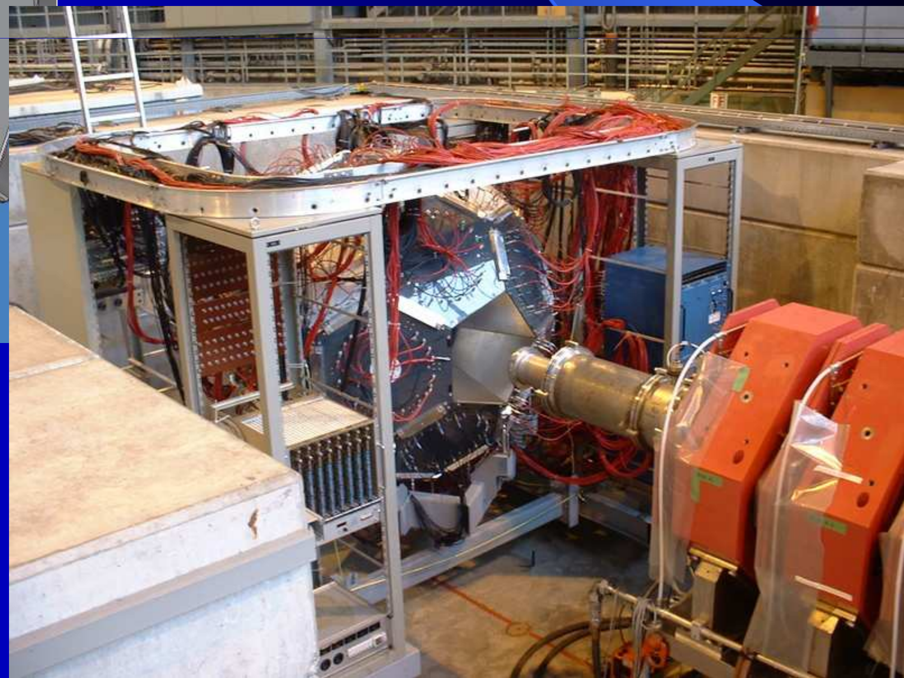


L_{1A} / d_R

g_P

Peter Winter

University of Illinois
at Urbana-Champaign

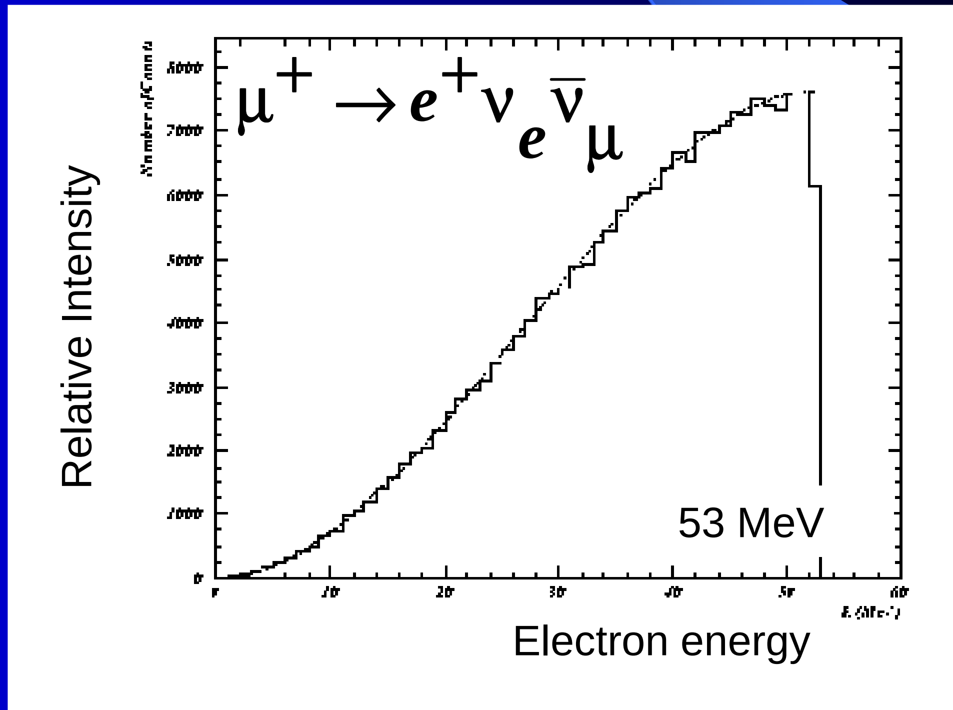


τ_μ

The muon

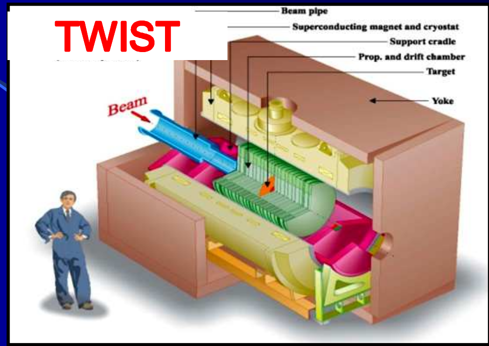
- Mass 207· m_e
- Lifetime ~2.2 μs
- Main decay $\mu \rightarrow e\ \nu_e\ \nu_\mu$
- Parity violating decay

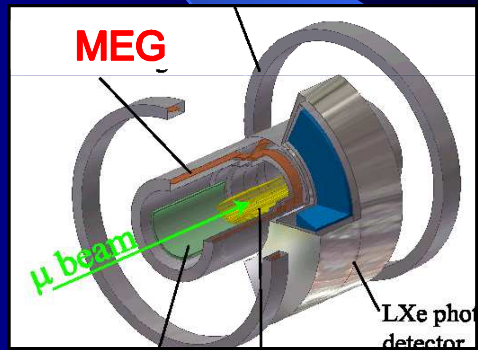
L. Michel

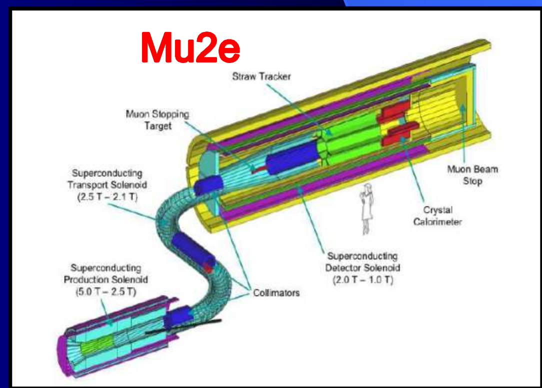


Muon physics efforts worldwide

- **Lifetime – Fermi constant**
  - 2 "precision" experiments: MuLan & FAST
- **Decay parameters**
  - Michel – TWIST $\rho, \delta, \eta, P_{\mu}\xi$
  - Transverse polarization (η) – PSI
- **Capture**
  - MuCap: g_P, pseudoscalar coupling
  - MuSun: basic EW interaction in 2N system
- **Anomalous magnetic moment (g-2)**
  - New g-2FiNALe experiment in planning
- **Lepton Flavor Violation**
  - $\mu \rightarrow e\gamma$ – MEG at PSI taking data now
  - μe conversion – $\mu A \rightarrow eA$ Mu2e at FNAL new high-priority project
- **EDM**
  - E821 PRD in prep ~10^{-21} e·cm
  - Modest efforts toward small dedicated ring at PSI
- **Lorentz / CPT violation tests**
  - E821 g-2 PRL 2007; precession vs. sidereal day
- **Muonic Lamb shift – in progress (QED)**
  - Finite size effects aids to hydrogen Lamb shift effort







Outline

Muon Lifetime Analysis (MuLan)

- Motivation
- MuLan experiment
- Main systematics and result

Muon capture on the proton (MuCap)

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Muon capture on the deuteron (MuSun)

- Motivation and outlook

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Three electro-weak input parameters

- Fine structure constant

  $\Delta\alpha / \alpha \approx 0.37$ ppm [Gabrielse et al, 2008]

- Neutral weak boson mass

  $\Delta M_Z / M_Z \approx 23$ ppm [LEP EWWG *2005*]

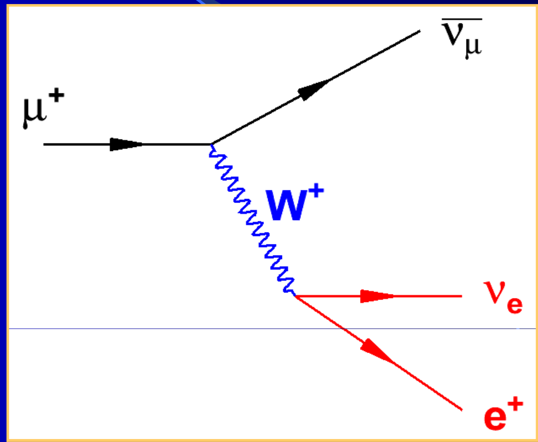
- Fermi constant

  $\Delta G_F / G_F \approx 9$ ppm [Giovanetti et al, 1984, Bardin et al., 1984]

Fermi constant G_F

Implicit to all EW precision physics

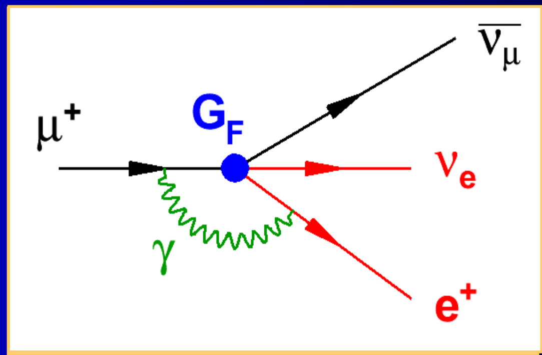
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \Delta r(m_t, m_H, \ldots)\right)$$



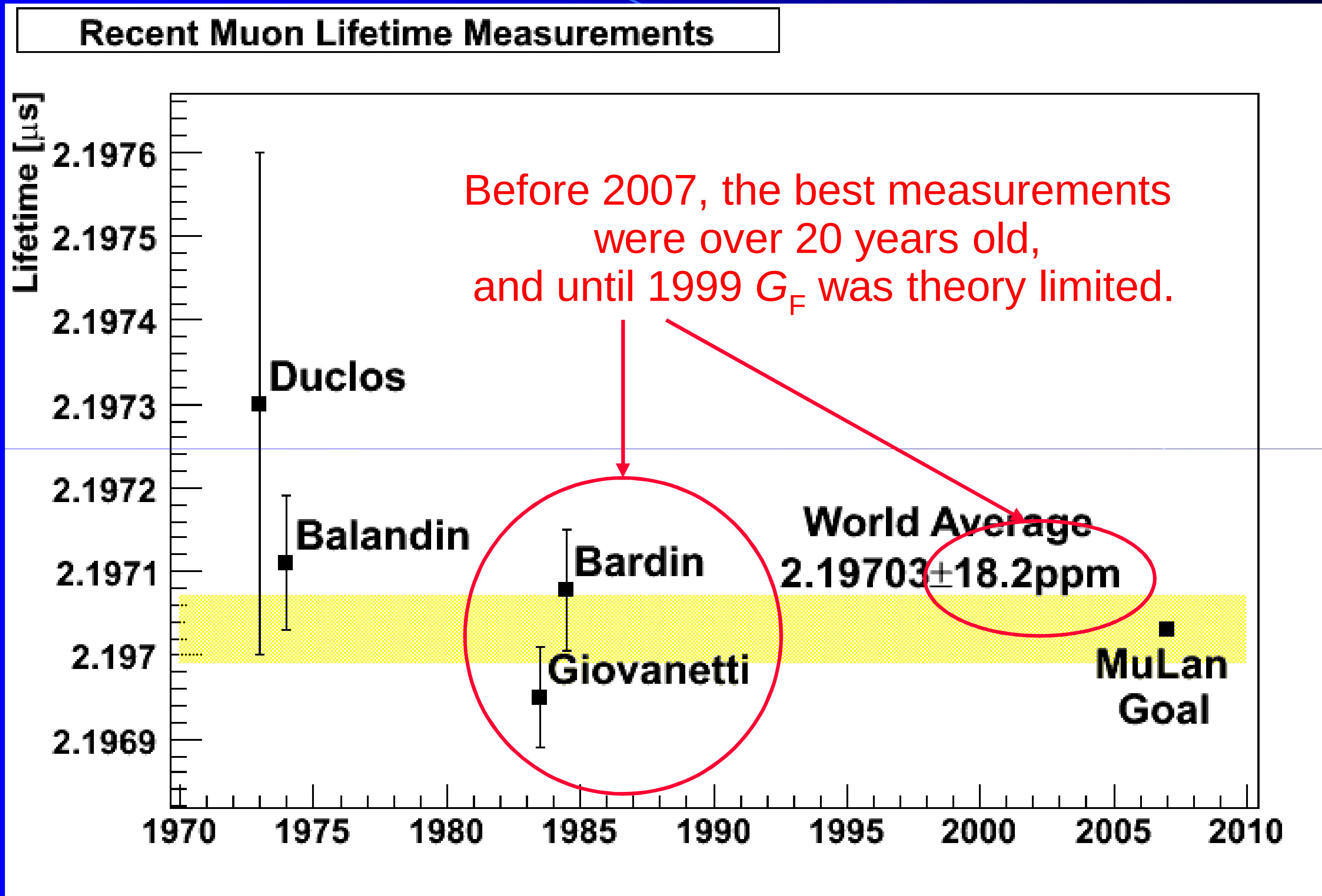
Uniquely defined by muon decay

$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}\left(1 + q\right)$$

PS, QED and hadr. rad.



Brief history of τ_μ / G_F



G. Bardin et al., Phys. Lett. B 137, 135 (1984)
K. Giovanetti et al., Phys. Rev. D 29, 343 (1984)

Extraction of G_F no longer theory limited

$$\frac{\delta G_F}{G_F} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau}{\tau}\right)^2 + \left(\frac{\delta\Delta q}{\Delta q}\right)^2}$$

Future: **0.5 ppm** **1 ppm** **<0.3 ppm**

Lifetime error is the limit

2 loop QED corrections

T. van Ritbergen and R. G. Stuart, Nucl. Phys. B564, 343 (2000)

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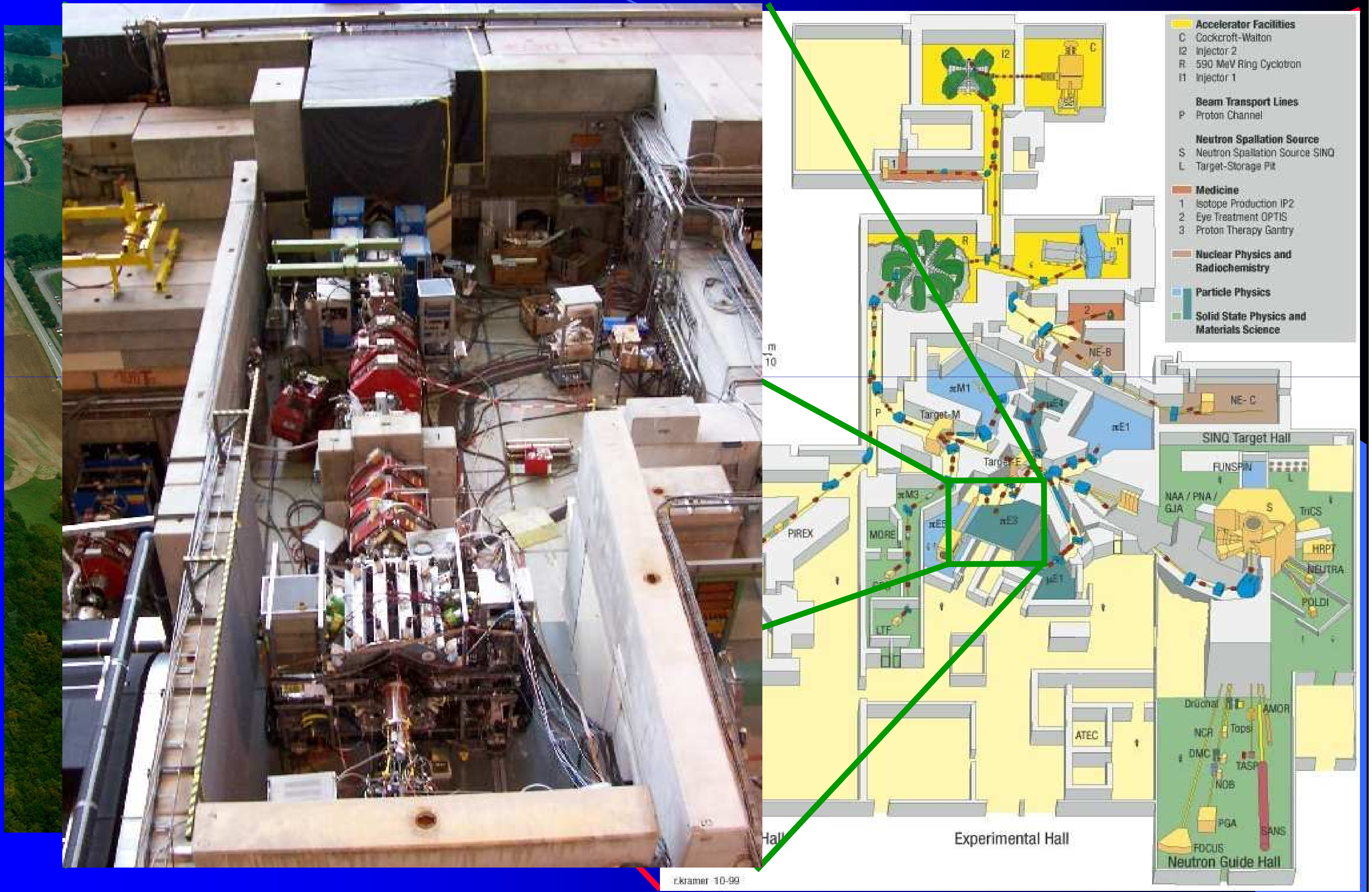
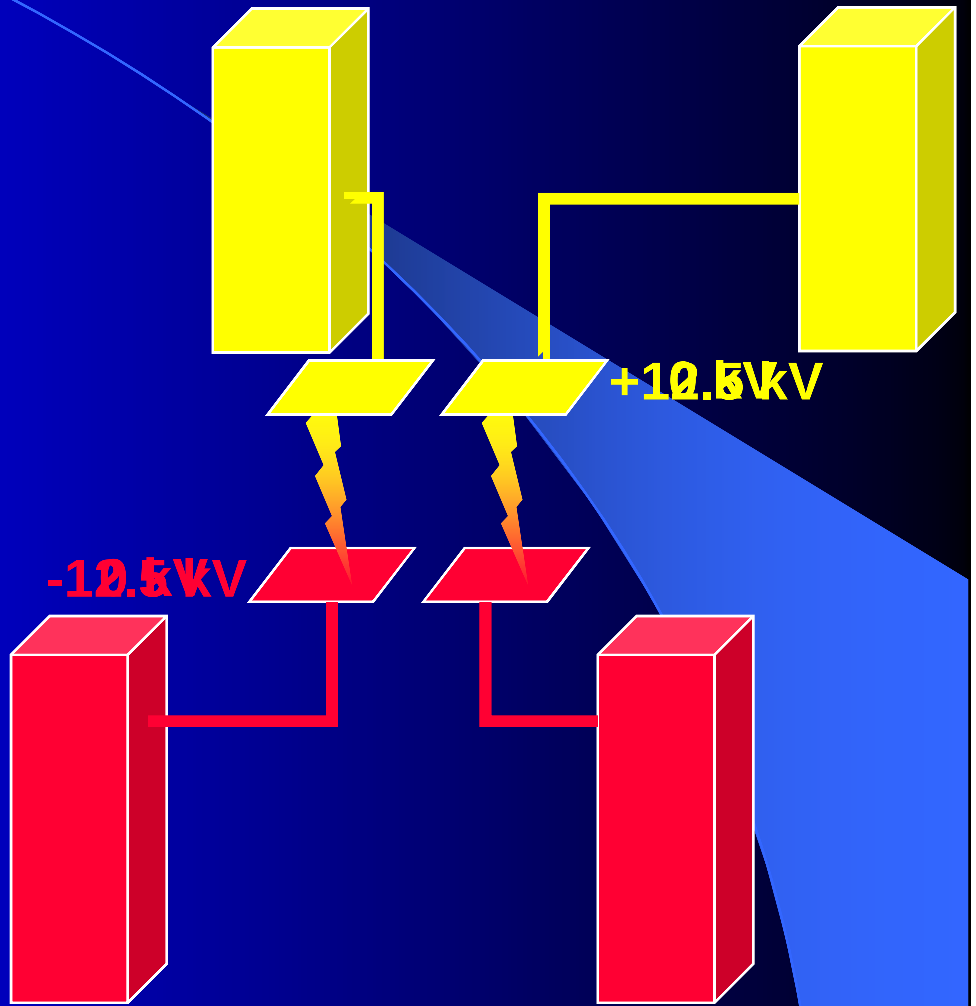
The facility: πE3 beamline at PSI



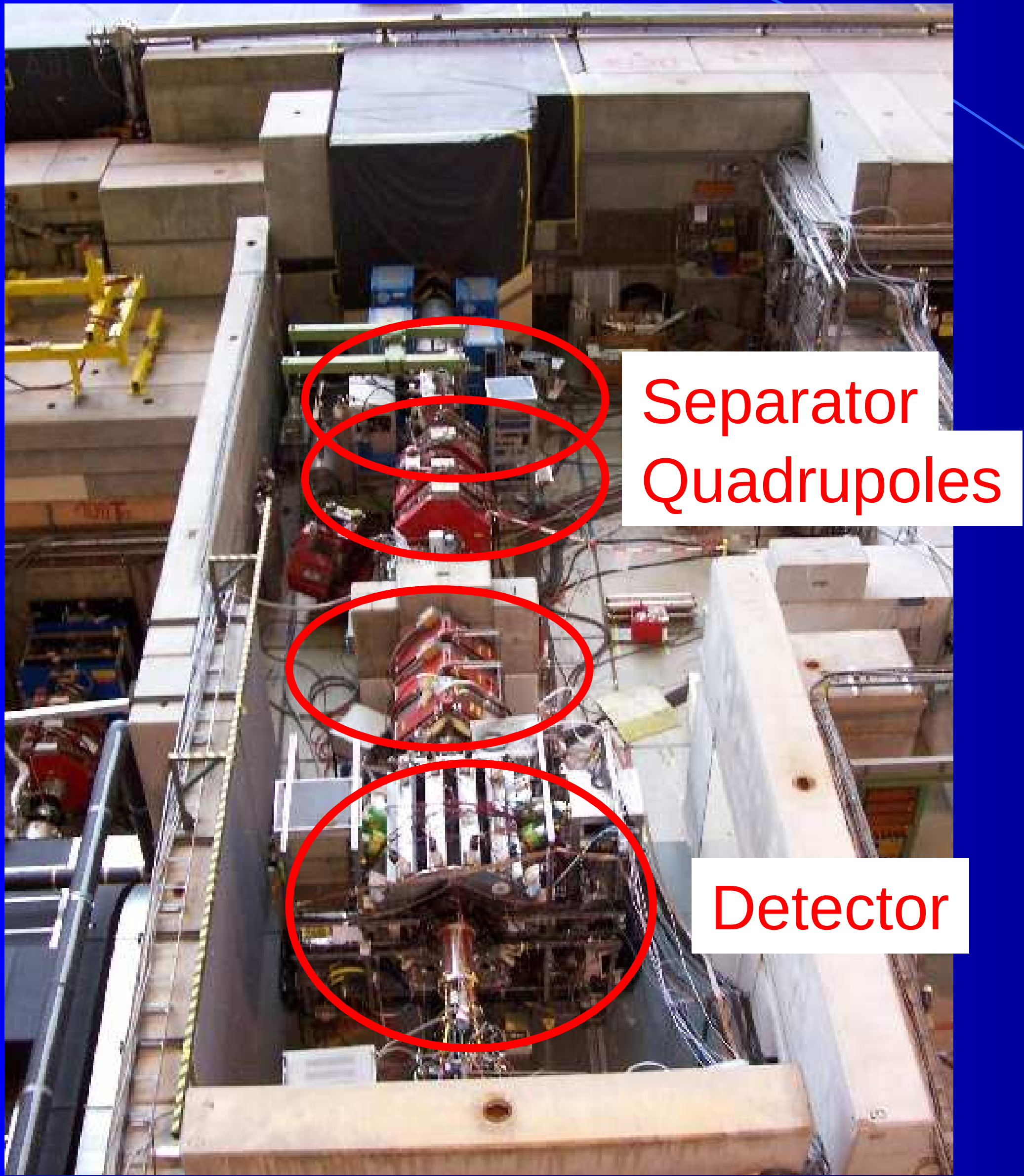
The Kicker

- Design at TRIUMF
- MOSFET based
- 50 ns switching time

The Kicker

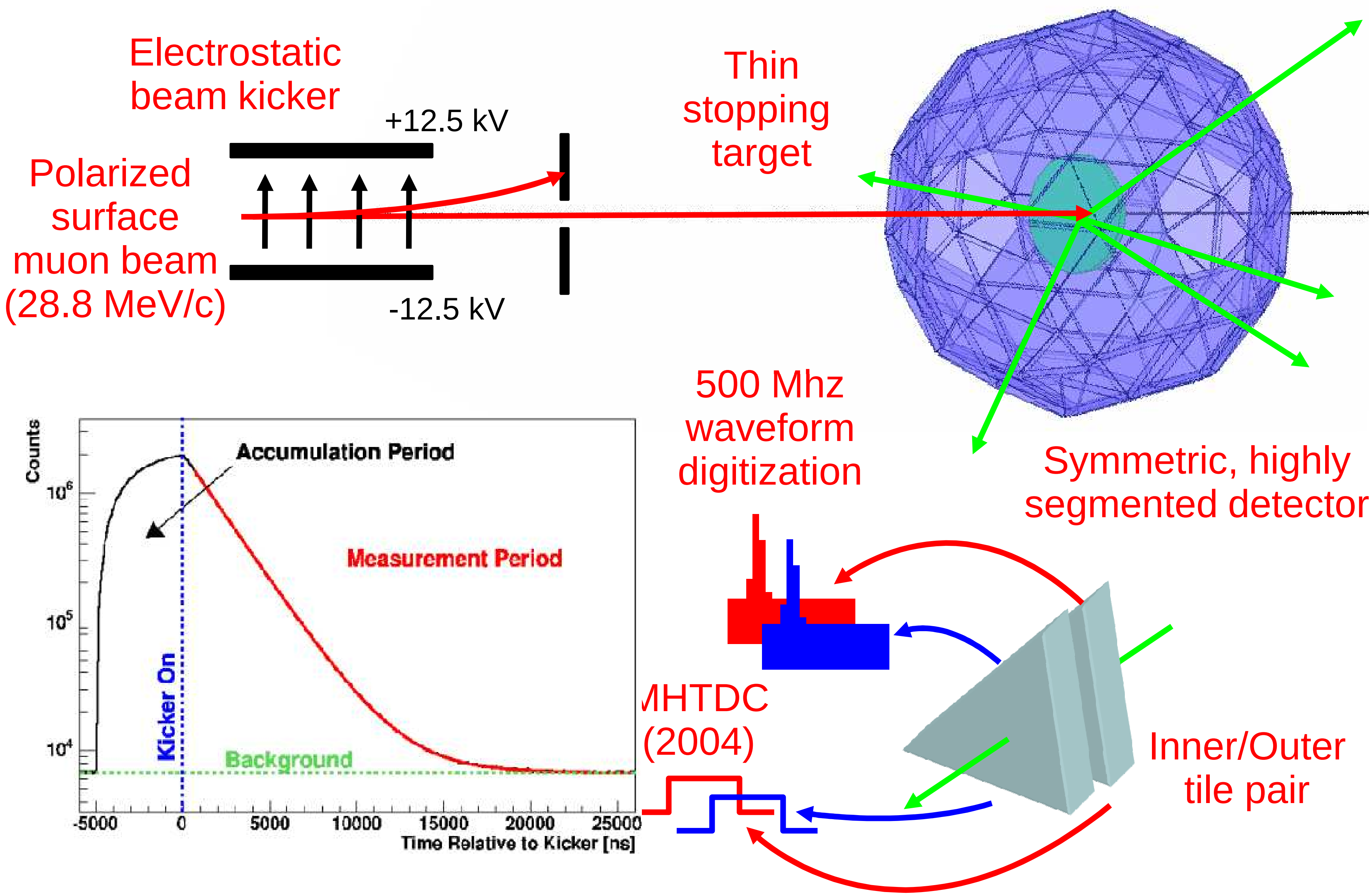


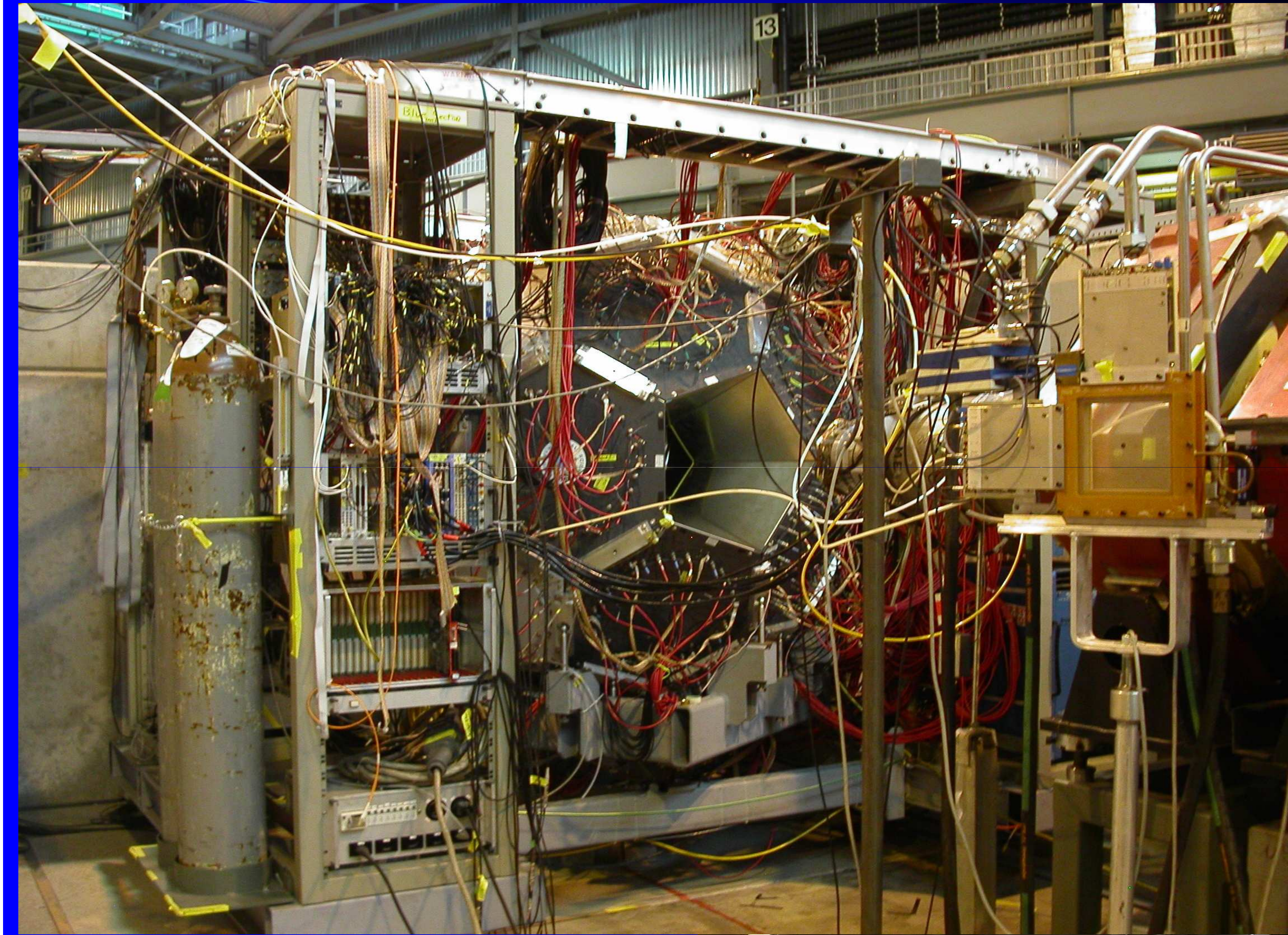
Other elements



Separator:
Suppression of e^+ or e^- in beam

MuLan experiment




13

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Main systematics

Any early-to-late effect:

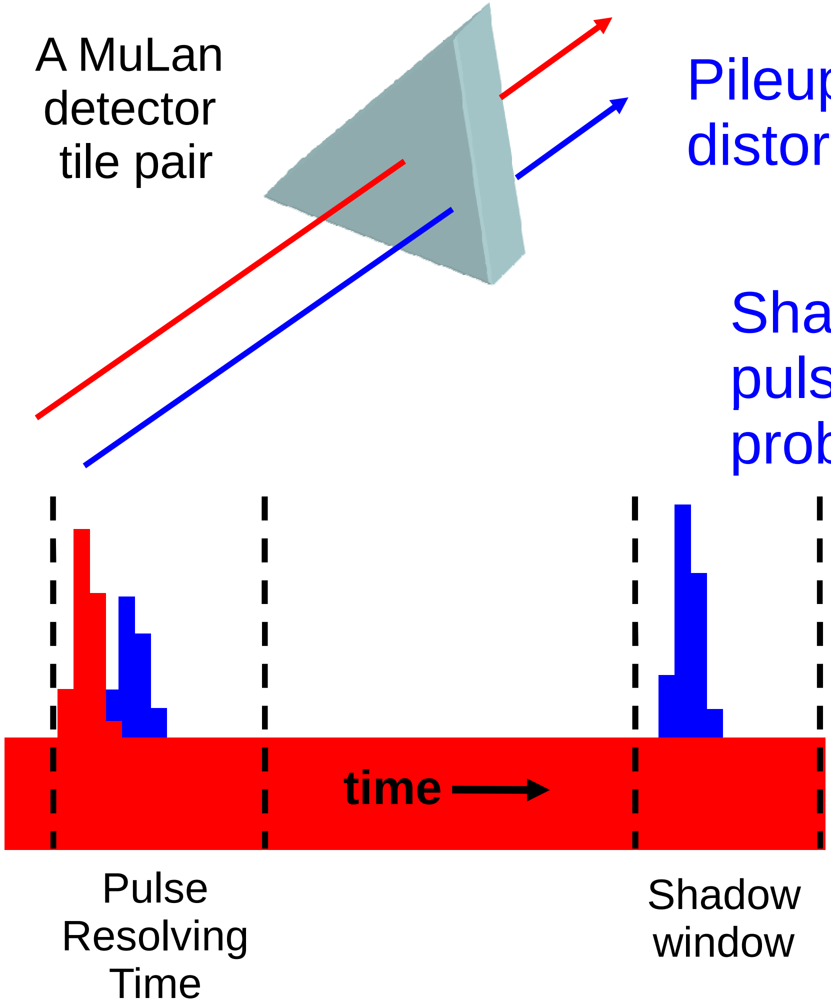
Instrumental issues

- Pileup pulses
- Non-flat background
- PMT gain change
- ....

Physics issues

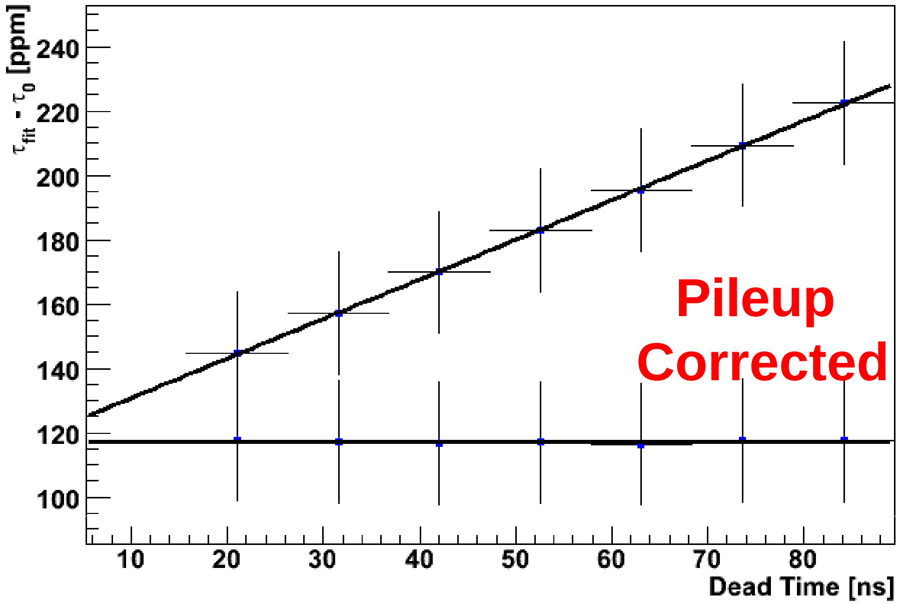
- Polarization
- Longitudinal relaxation
- ....

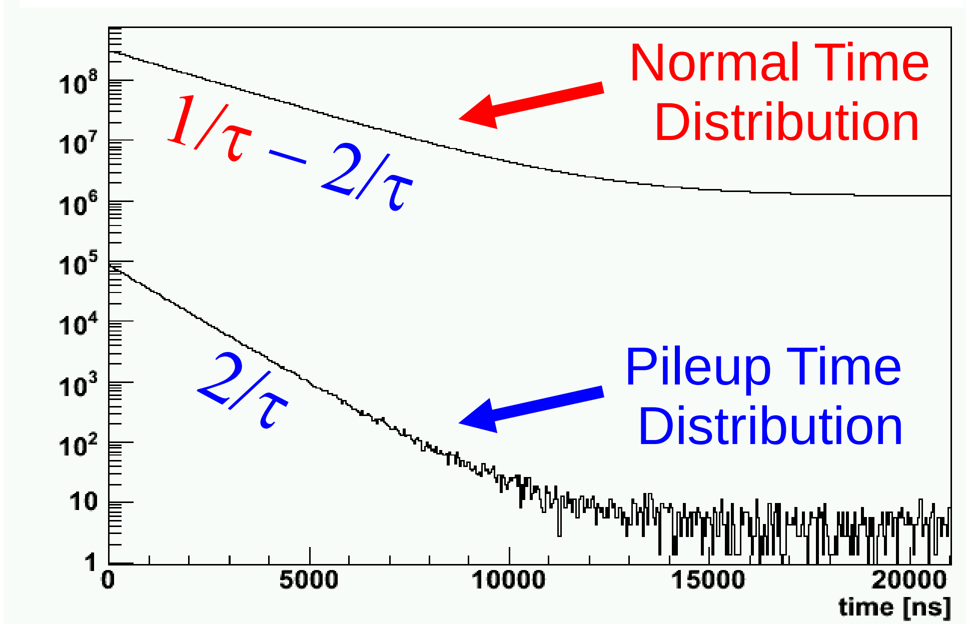
Pileup corrected from the data



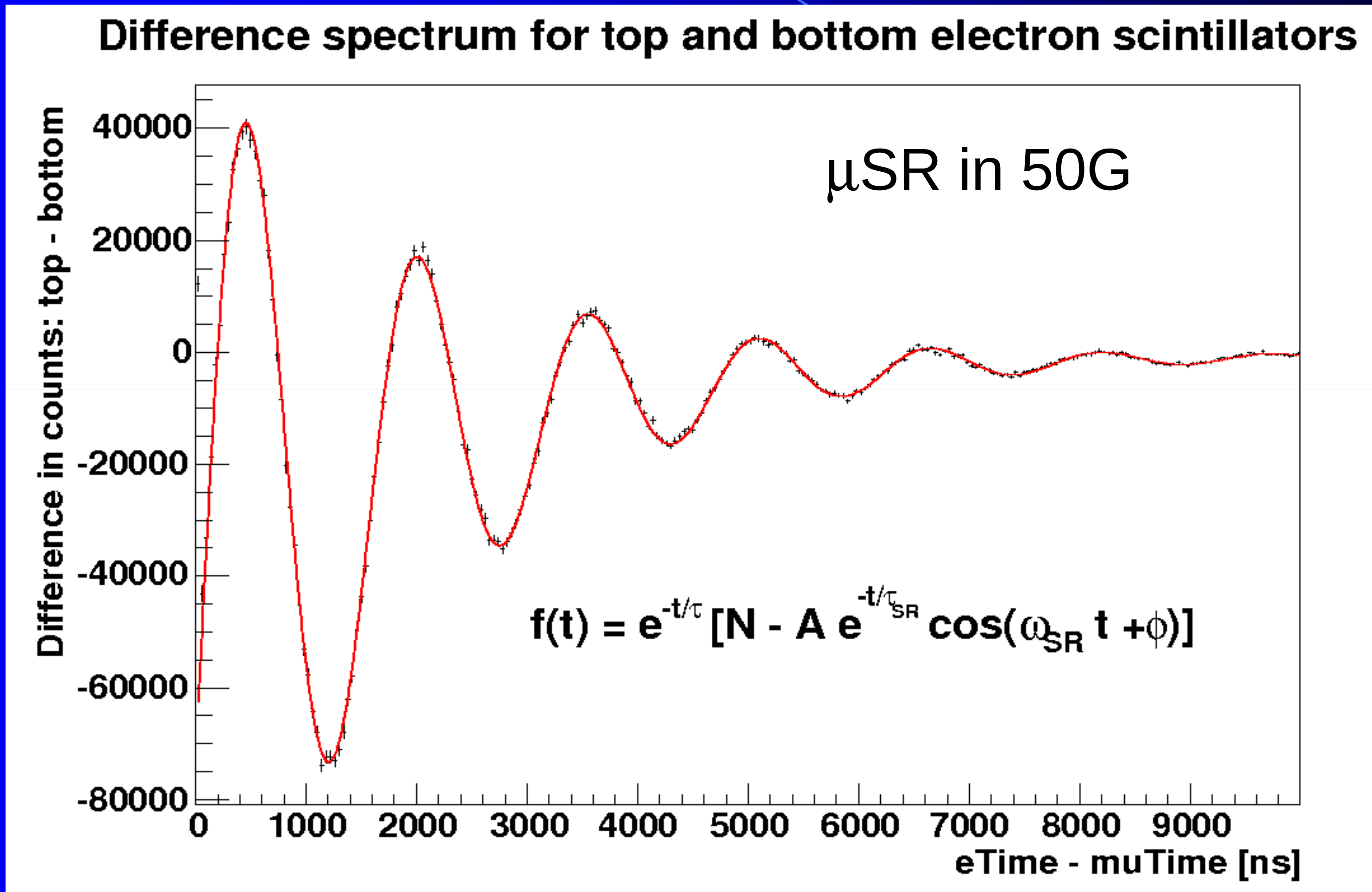
Pileup pu
distort the

Shadow
pulses
probabi





Polarization



How do we control polarization?

- Point-like symmetry + large solid angle coverage reduce effects
  - Polarization destroying ferromagn. target AK3 in 2006
    - Polarization preserving quartz target in 2007 with external field
  - Reduce errant muon stops with vacuum beam corridor to target

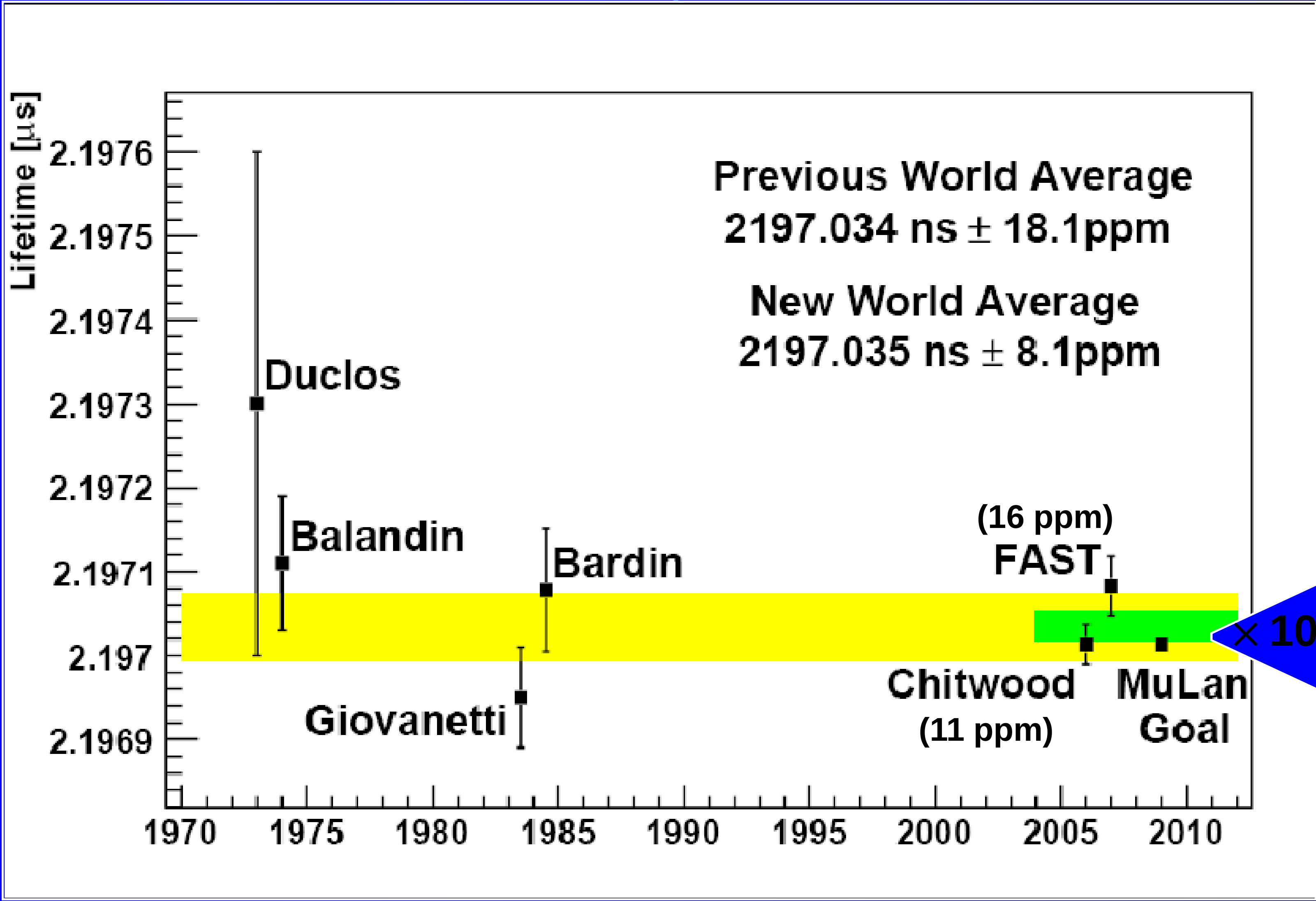
Error contributions (2004)

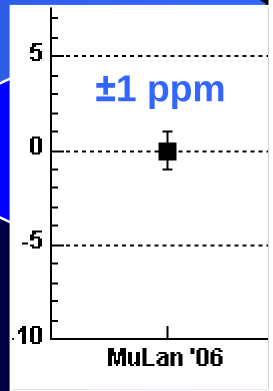
Statistics: 1.8×10^{10} (9.6 ppm)

Source	Size (ppm)
Extinction stability	3.5
Dead time correction	2.0
TDC response	1.0
Gain stability	1.8
Errant muon stops	2.0
Duplicate words (+1 ppm shift)	1.0
Queuing loss	0.7
Multiple hit timing shifts	0.8
Total	5.2

Clearly statistics limited

New world average





$G_F = 1.166367(5) \times 10^{-5}\ \text{GeV}^{-2}$ (4.1 ppm)

Summary MuLan

- First result with 11ppm published 2007
- Data analysis of two sets with each 10^{12} decays on its way
- Plan to publish 1ppm result end of 2009

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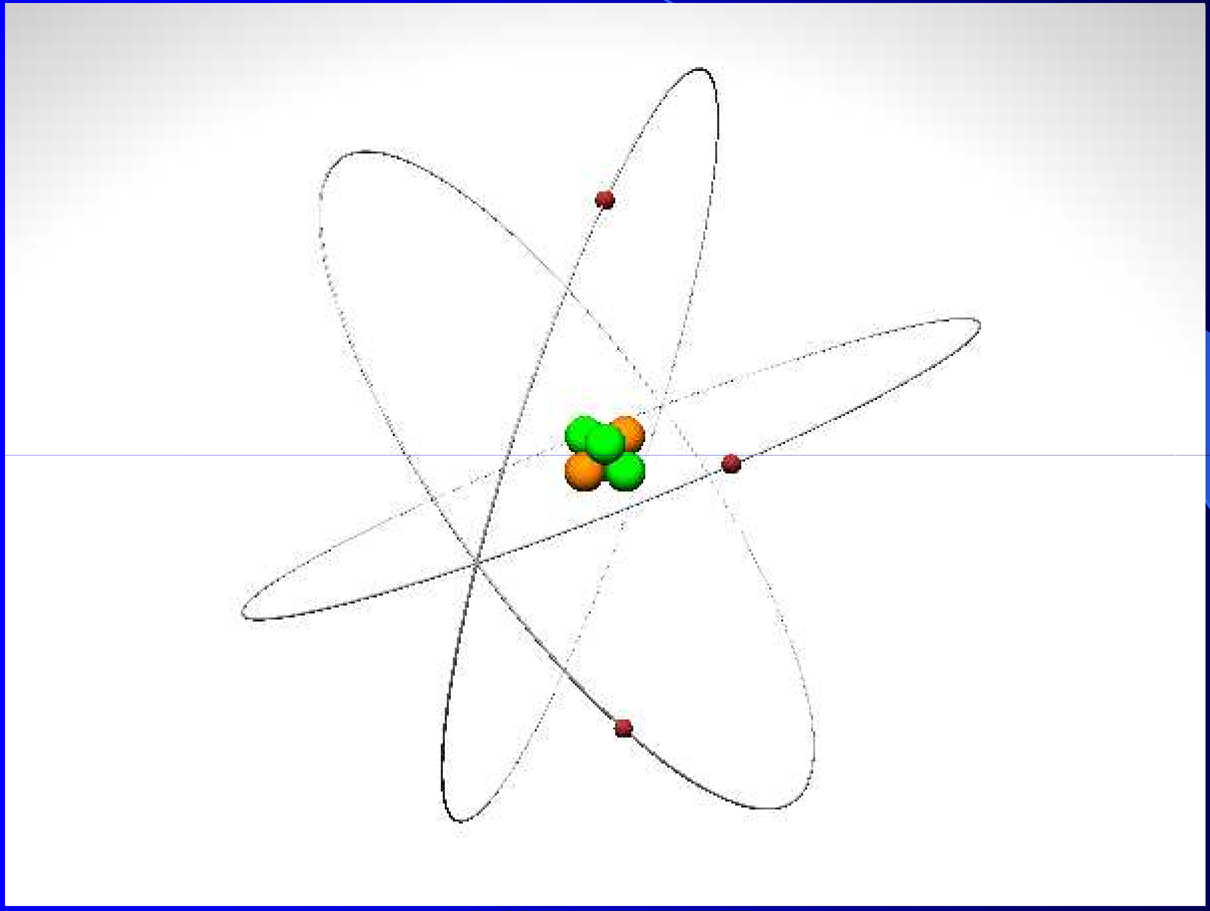
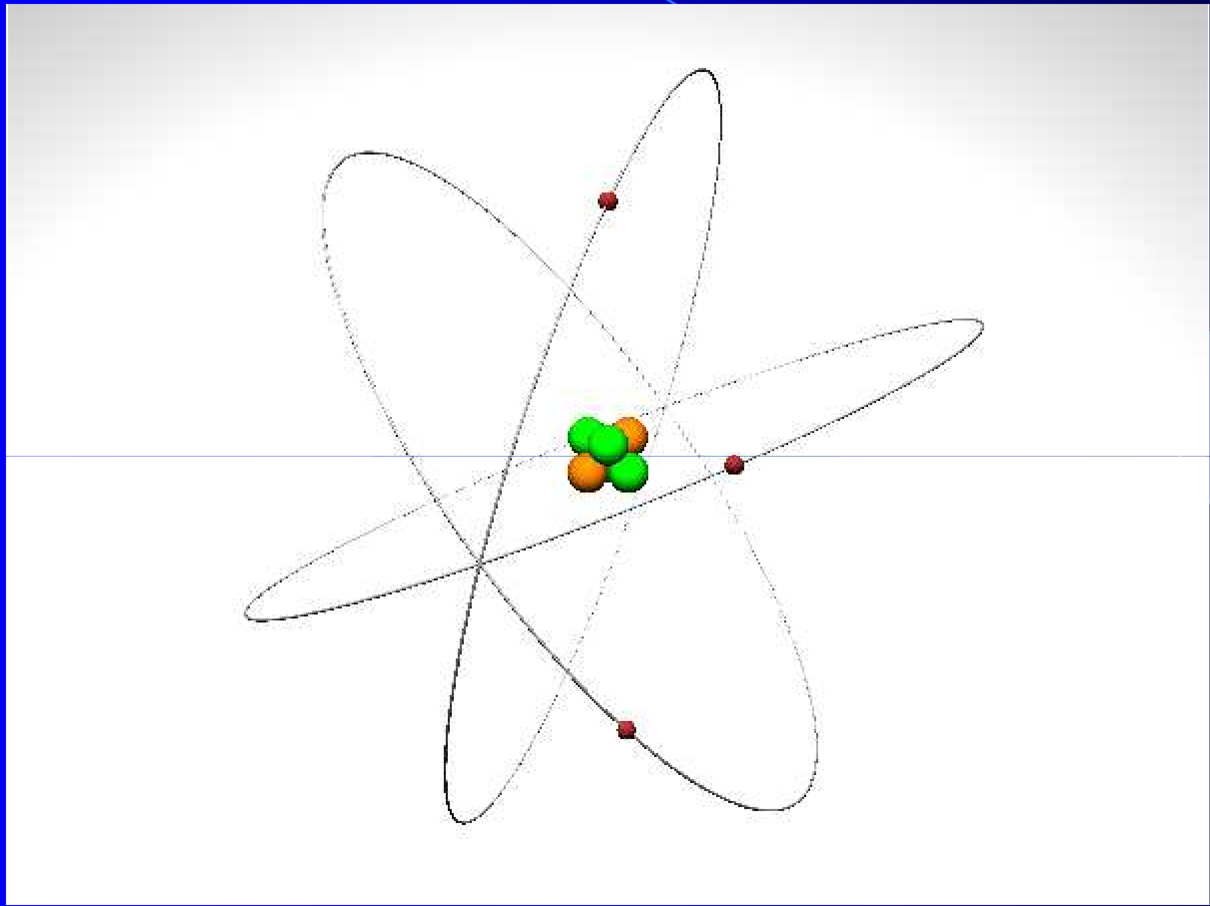
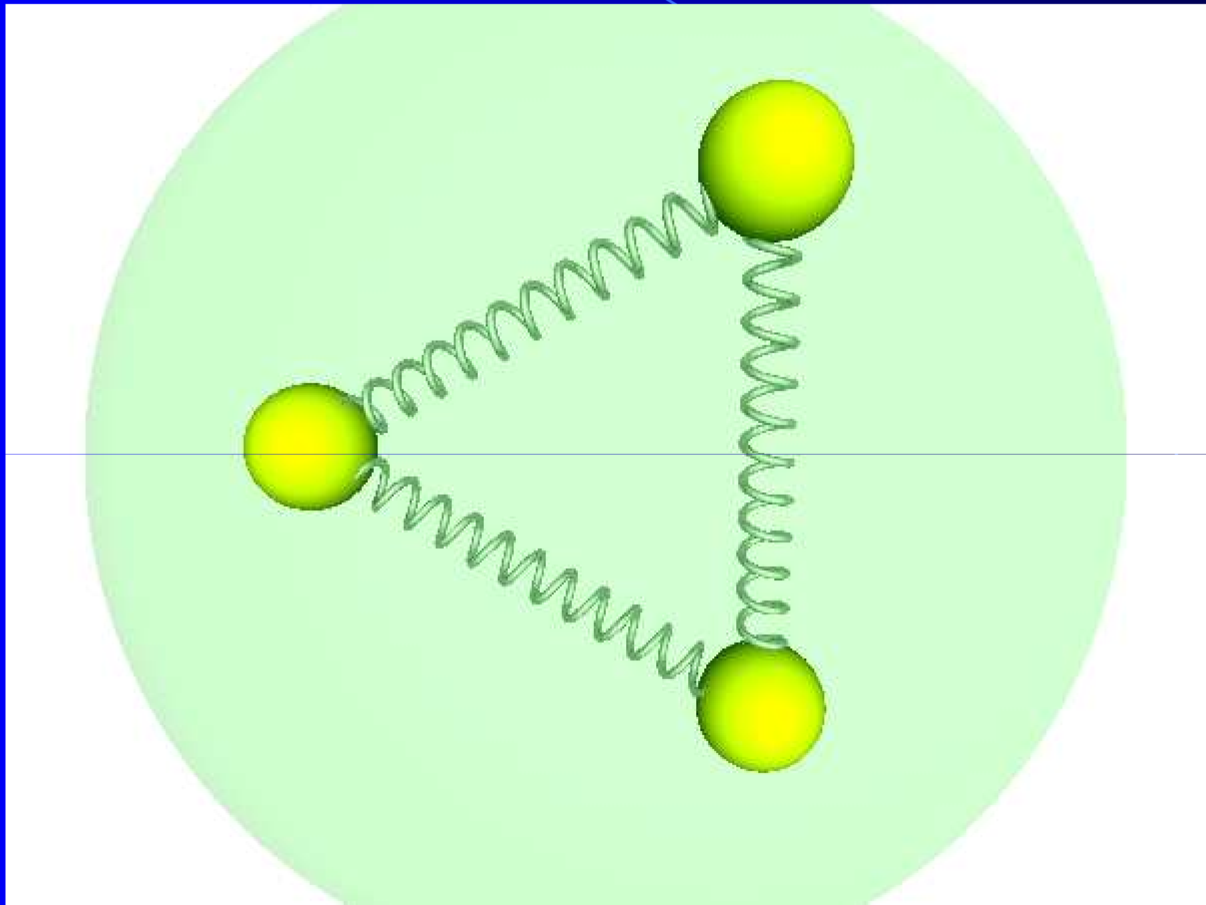
The nucleon



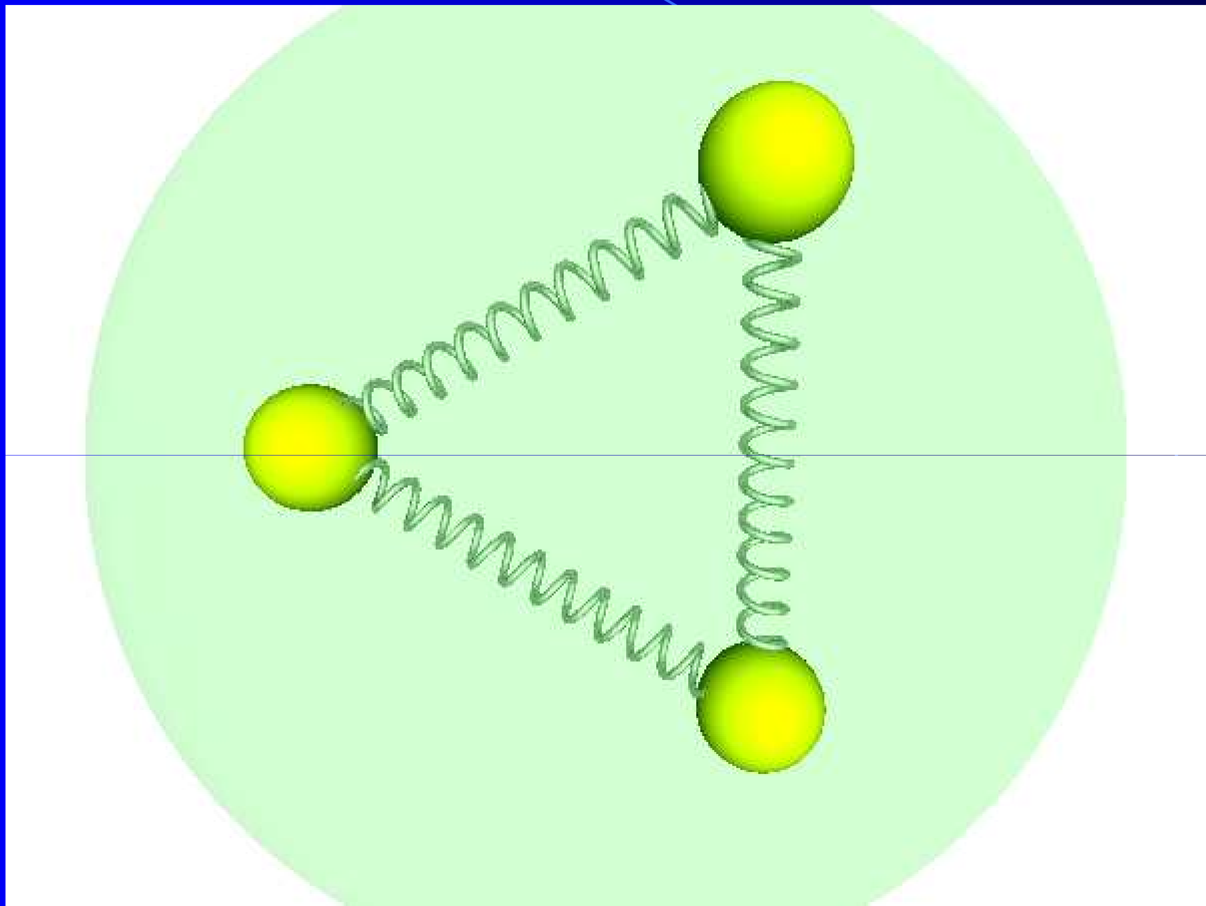
The nucleon



The nucleon

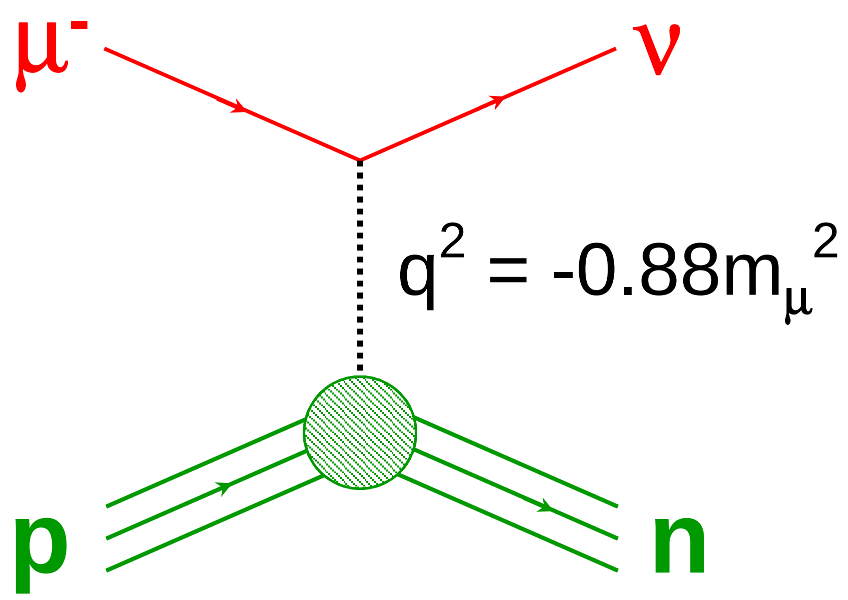


The nucleon



Nucleon form factors

$$\mu^- + p \rightarrow n + \nu$$



$$M \sim G_F V_{ud} \cdot \psi_\nu \gamma_\alpha (1-\gamma_5) \psi_\mu \cdot \psi_n (V^\alpha - A^\alpha) \psi_p$$

Nucleon form factors

$$M \sim G_F V_{ud} \cdot \psi_\nu \gamma_\alpha (1-\gamma_5) \psi_\mu \cdot \psi_n (V^\alpha - A^\alpha) \psi_p$$

$$V^\alpha = g_V(q^2)\,\gamma^\alpha$$
$$+\, i\, g_M(q^2)\,\sigma^{\alpha\beta} q_\beta / 2M_N$$
$$+\, \cancel{g_S(q^2)\, q^\alpha / m_\mu}$$

Conserved Vector Current and isospin symmetry

$\Rightarrow \quad g_S(q^2) = 0$

g_V, g_M: strong program JLab, Mainz, ...

Nucleon form factors

$$M \sim G_F V_{ud} \cdot \psi_\nu \gamma_\alpha (1-\gamma_5) \psi_\mu \cdot \psi_n (V^\alpha - A^\alpha) \psi_p$$

$$A^\alpha = \quad g_A(q^2)\, \gamma^\alpha \gamma_5$$
$$+\, i\, \cancel{g_T(q^2)\, \sigma^{\alpha\beta}} q_\beta / 2M_N \gamma_5$$
$$+\, g_P(q^2)\, q^\alpha / m_\mu \gamma_5$$

Second class current suppressed by isospin

$\Rightarrow\ g_T(q^2) = 0$

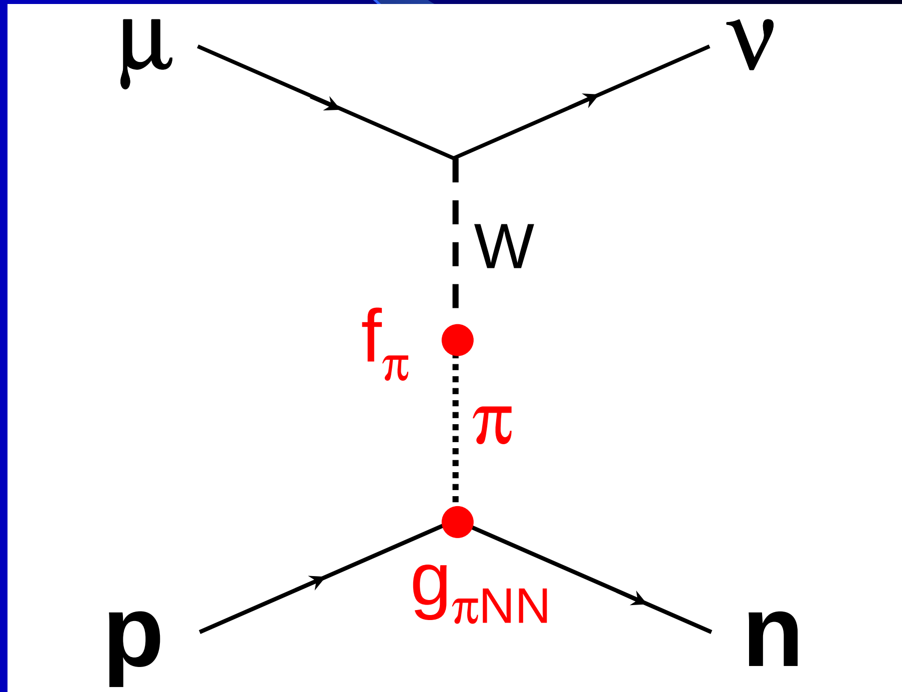
$g_A(q^2)$ measured in neutron decay

Pseudoscalar form factor g_P

$$A^\alpha = g_A(q^2)\,\gamma^\alpha\gamma_5 + g_P(q^2)\,q^\alpha/m_\mu\gamma_5$$

Dominant diagram

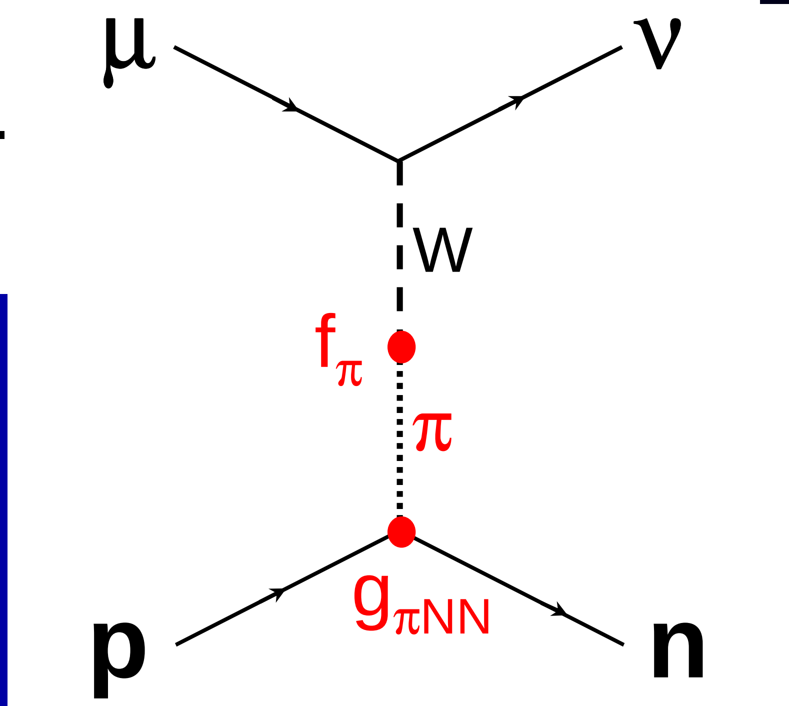
$$\sim -f_\pi\, g_{\pi NN}\, q^\alpha\gamma_5 \,/\, (q^2 - m_\pi^2)$$



PCAC: $\partial_\mu A^\mu = 0$ for $m_\pi \rightarrow 0$

Pseudoscalar form factor g_P

$$g_P(q^2) = -\frac{2m_N m_\mu g_A(0)}{q^2-m_\pi^2} -$$



PCAC pole term

(Adler, Dothan, Wolfenstein)

g_P = (8.74 ± 0.23) - (0.48 ±

- solid QCD prediction via ChPT (2-3% level)
- NNLO < 1%: N. Kaiser, PRC67 (2003)
- basic test of QCD symmetries

Recent reviews:

T. Gorringe, H. Fearing, Rev. Mod. Physics 76 (2004) 31

V. Bernard et al., Nucl. Part. Phys. 28 (2002), R1

Values of relevant quantities

g	$q^2=0$	$q^2 = -0.88m_\mu^2$	
g_V	1	0.9755(5)	from e+p scat.
g_M	3.71	3.5821(25)	from e+p scat.
g_A	1.2695(29)	1.245(4) (PDG)	n decay, r_A from νN scat. and π elect.prod.
g_P		$8.3 \pm 50\%$	
V_{UD}	0.97377(27)	0.97377(27)	superallowed $0^+ \rightarrow 0^+$ beta decay

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Sensitivity of Λ_S

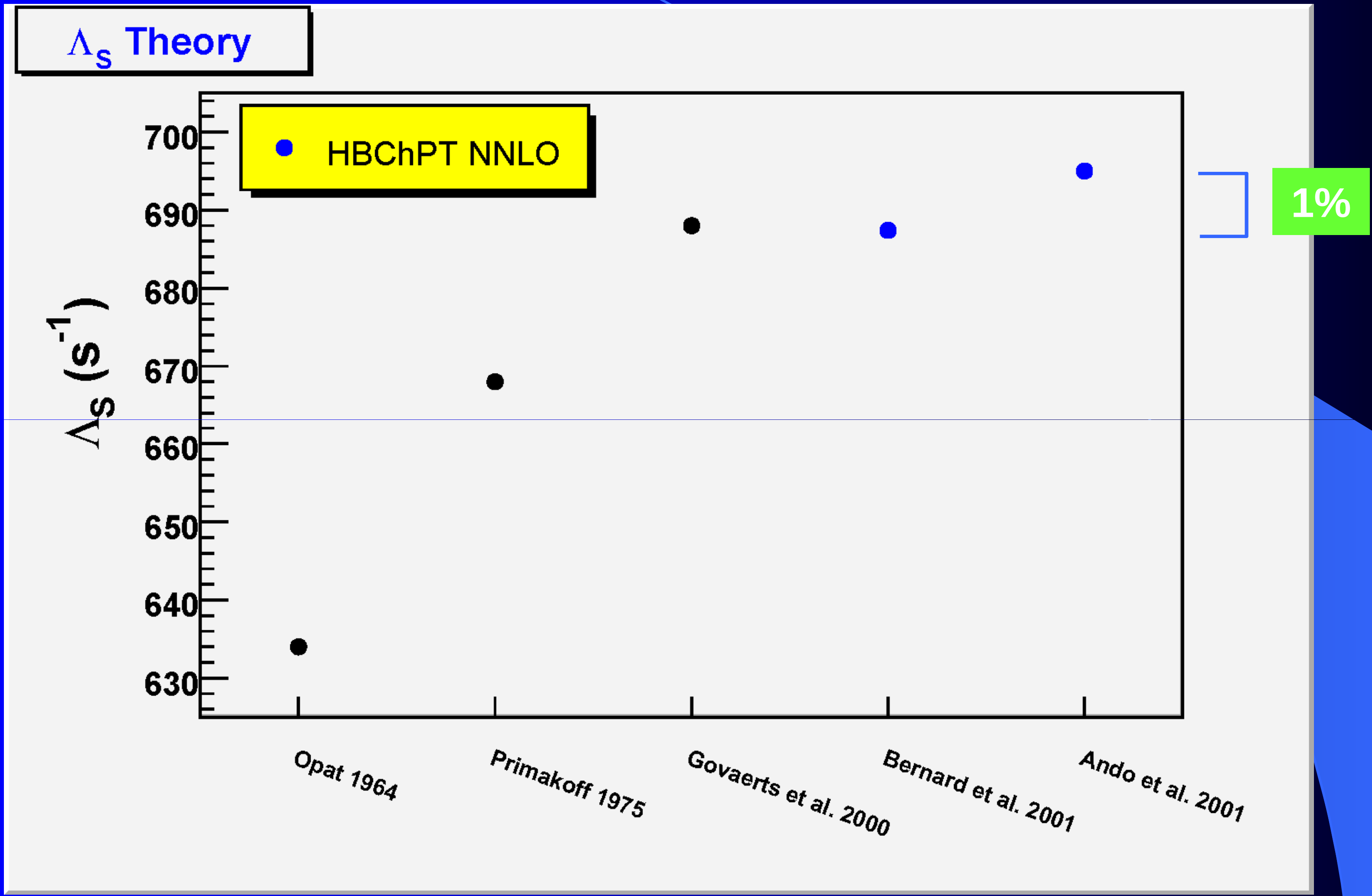
$\frac{\delta\Lambda_S}{\Lambda_S}$	$\Rightarrow$	$\frac{\delta g_P}{g_P}$
2.4%		13.6%
1.0%		6.1%
0.5%		3.8%

$$\frac{\delta\Lambda_S}{\Lambda_S} = 2\frac{\delta V_{ud}}{V_{ud}} + 0.466\frac{\delta g_v}{g_v} + 0.151\frac{\delta g_m}{g_m} + 1.567\frac{\delta g_a}{g_a} - 0.179\frac{\delta g_p}{g_p}$$

Contributes 0.45% uncertainty to Λ_S^{theory}

$\frac{\Lambda_S}{\partial x}\frac{x}{\Lambda_S}$ from Govaerts, Lucio-Martinez, Nucl.Phys.A678 (2000), 110

Calculation of Λ_S



Inclusion of radiative corrections later

How to access g_P?

In principle any process directly involving axial current:

- β decay: Not sensitive since g_P term ~ q
- ν scattering difficult to measure

$\Downarrow$

Muon capture most direct source for g_P

Experiments: Observed Processes

- Ordinary muon capture (OMC): $\mu^- p \rightarrow \nu n$
  - BR = ~10^{-3}, 8 exps with 4-15% precision in Λ_S
  - Liquid or gaseous hydrogen target
  - Neutron counting or "lifetime" method

- Radiative muon capture (RMC): $\mu^- p \rightarrow \nu n \gamma$
  - BR = ~10^{-8} for E_γ>60 MeV
  - Theoretical connection to g_P more complicated
  - 279 ± 25 events (Wright et al., 1998)

- $\mu^- {}^3He \rightarrow \nu {}^3H$ or other nuclei

- Pion electroproduction

Experiments: Observed Processes

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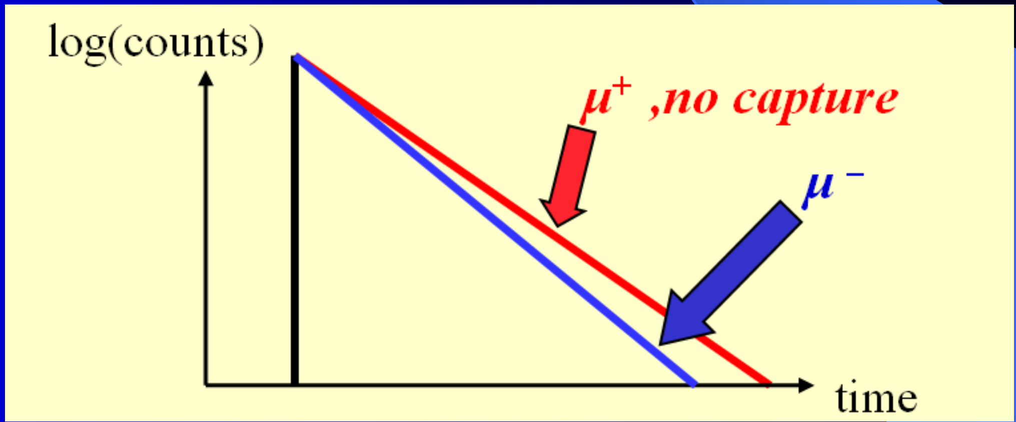
OMC: Methods to measure

Neutron experiments:

- Measure outgoing neutrons N_N
- Requires knowledge of neutron efficiency
- Separation of decay γ's from neutrons
- Typical experiments 8-13% precision in Λ_S

Lifetime method:

- $\Lambda_S = 1/\tau_- - 1/\tau_+$

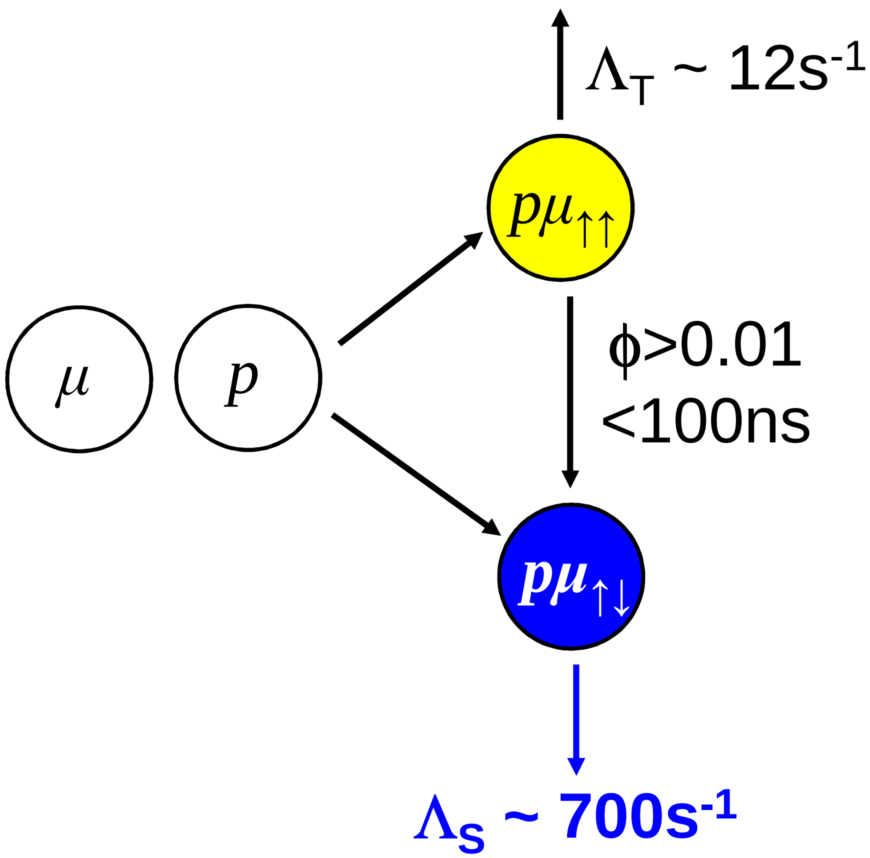


General requirements:

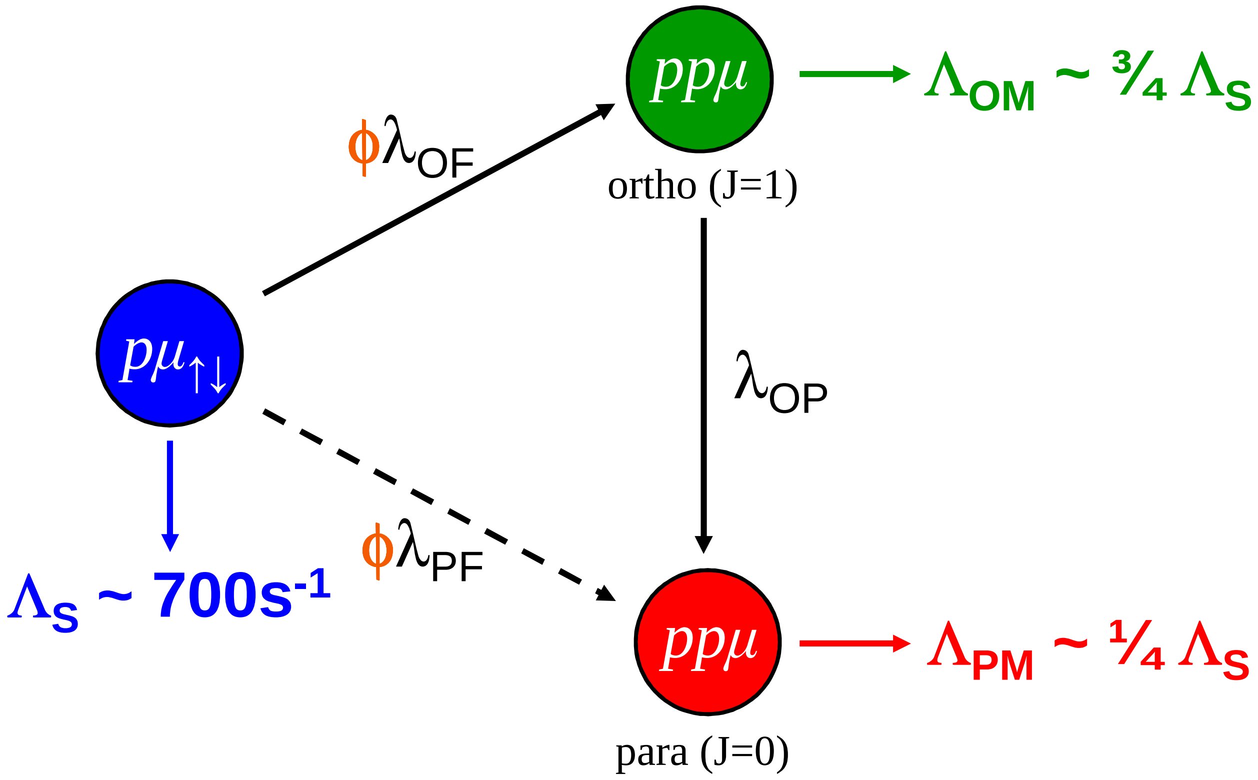
- Good muon stop identification
- Avoid Z>1 and deuterium contamination

Muon kinetics

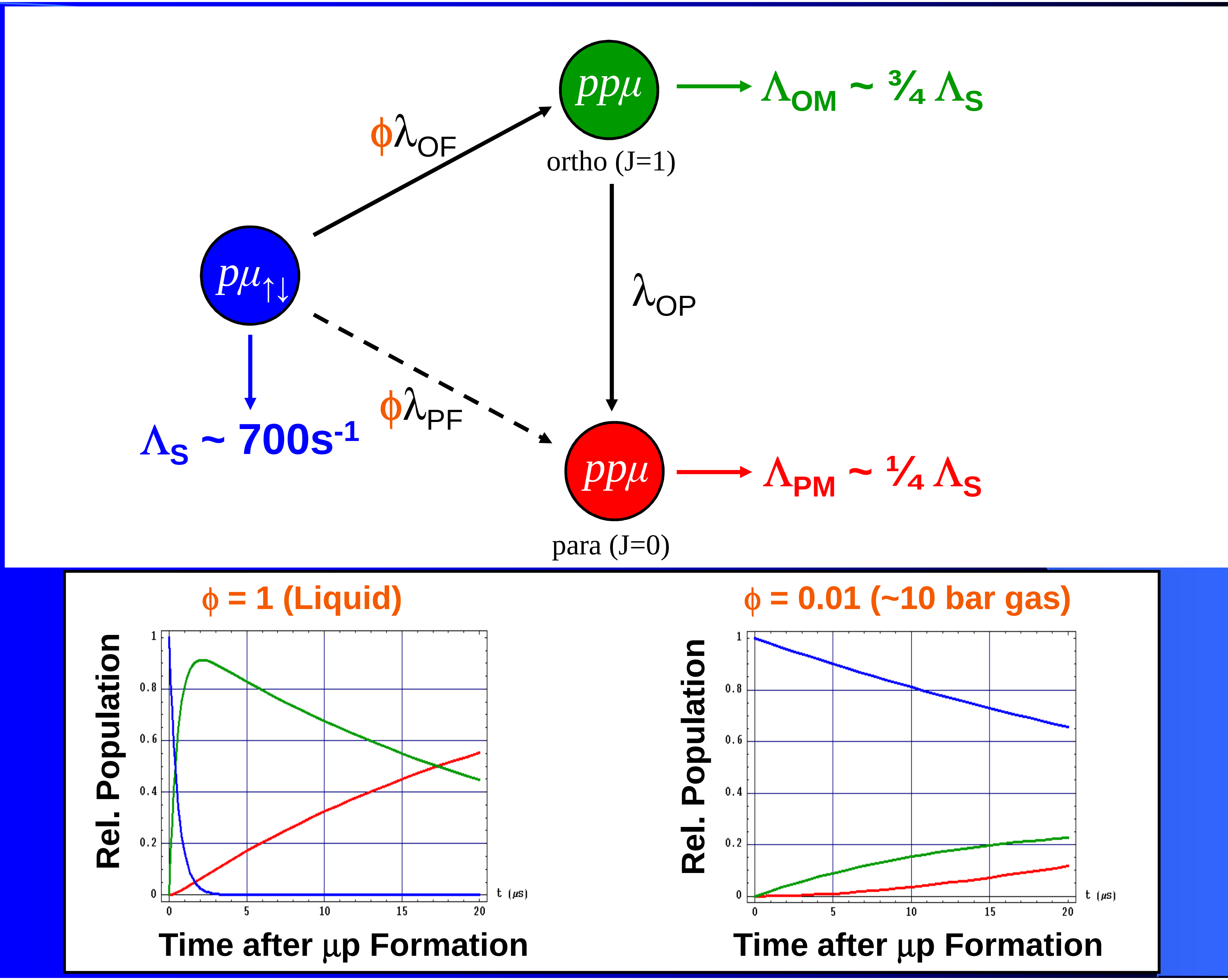
ϕ: Hydrogen density, (LH_2: ϕ=1)



Muon kinetics

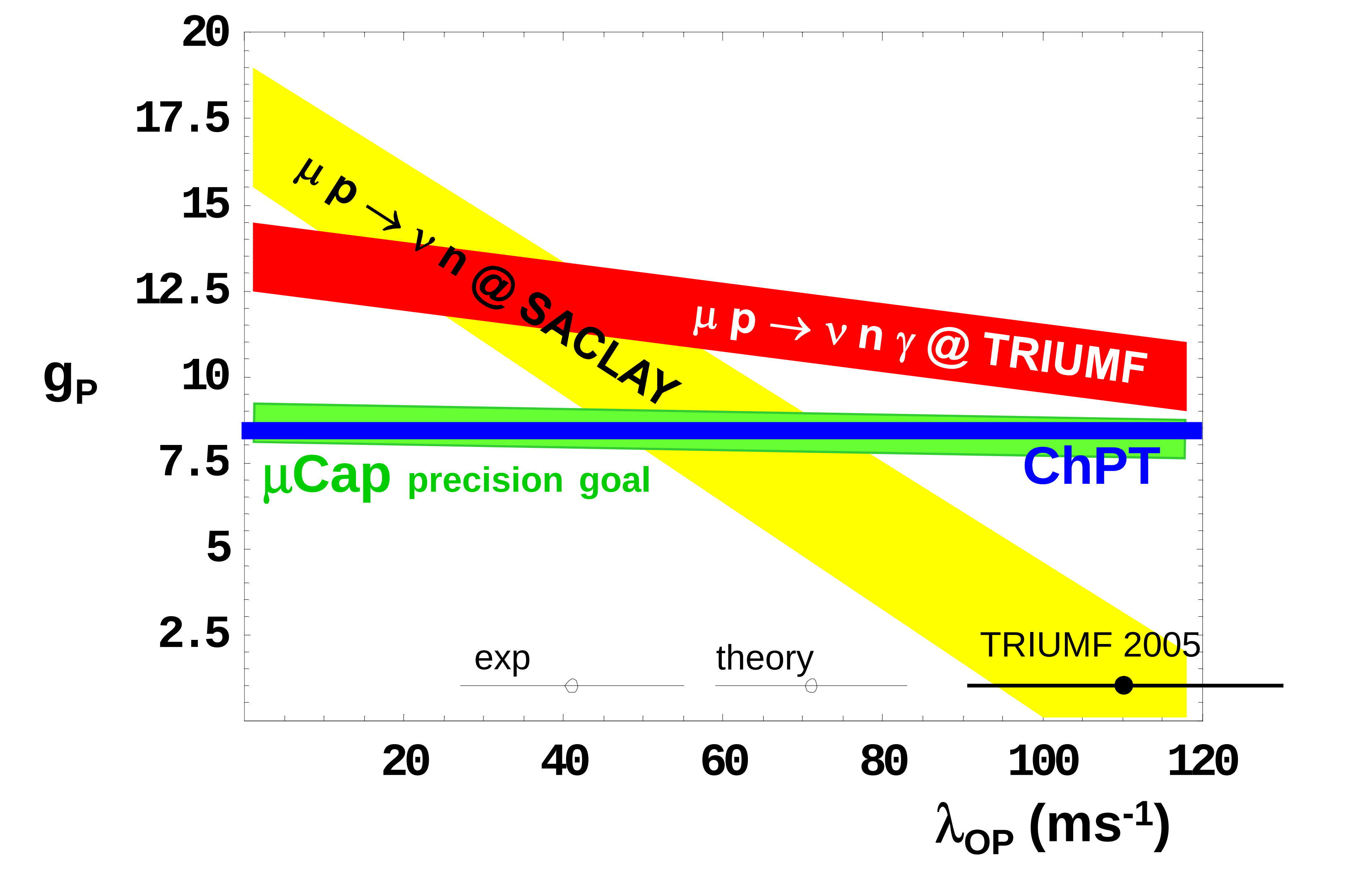


- $pp\mu$ formation depends on density ϕ
- Interpretation requires knowledge of Λ_{OM}, Λ_{PM} and λ_{OP}



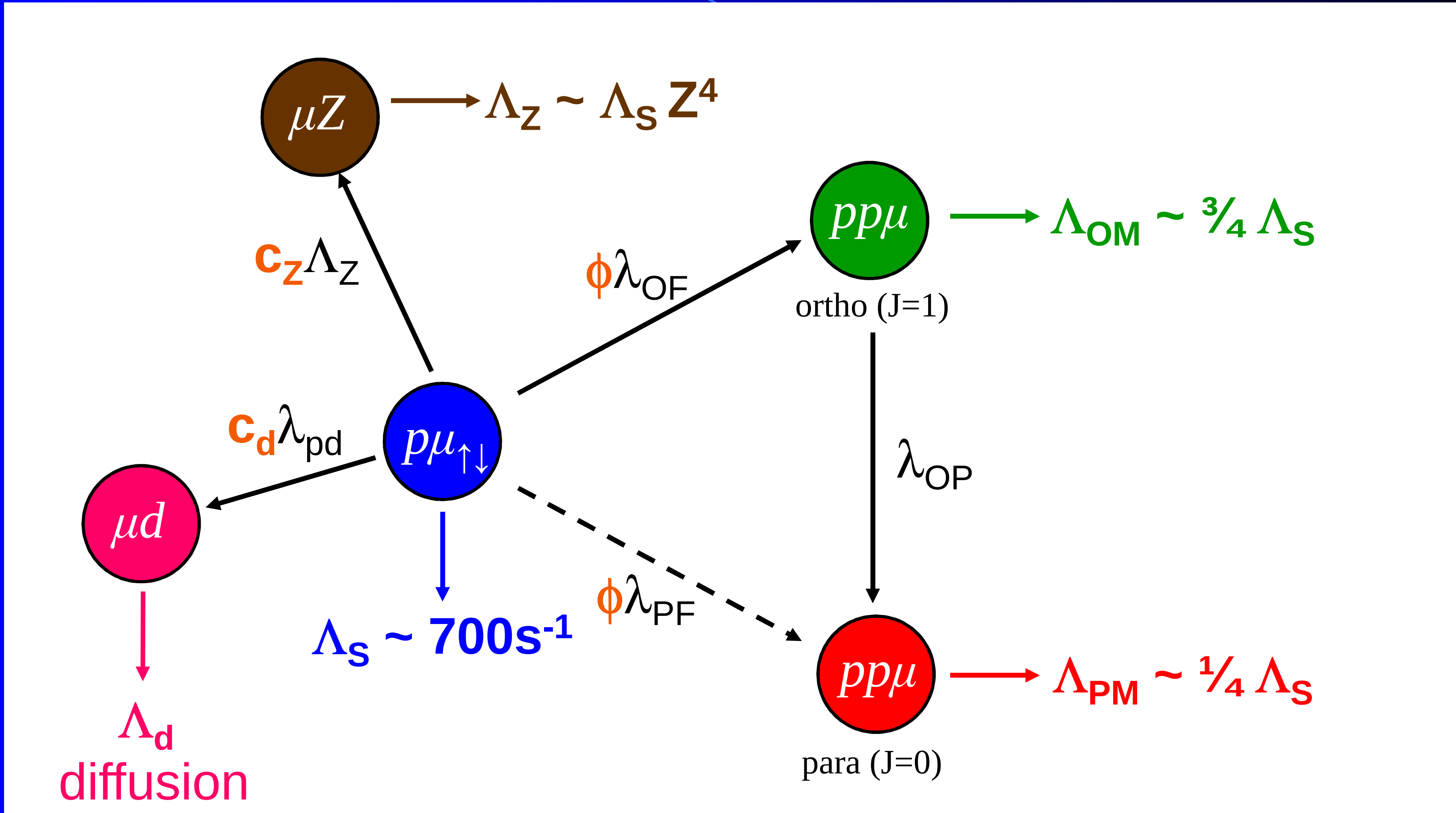
ppμ
ortho (J=1)
Λ_OM ~ ¾ Λ_S
φλ_OF
pμ↑↓
λ_OP
Λ_S ~ 700s^-1
φλ_PF
ppμ
para (J=0)
Λ_PM ~ ¼ Λ_S
φ = 1 (Liquid)
Rel. Population
Time after μp Formation
t (μs)
φ = 0.01 (~10 bar gas)
Rel. Population
Time after μp Formation
t (μs)

Previous results



- no overlap theory, OMC & RMC
- large uncertainty in $\lambda_{OP} \Rightarrow g_P \pm 50\%$

Requirement of clean target



⇒ Isotopically and chemically pure H_2, ideally:

c_d<1 ppm, c_Z<10 ppb

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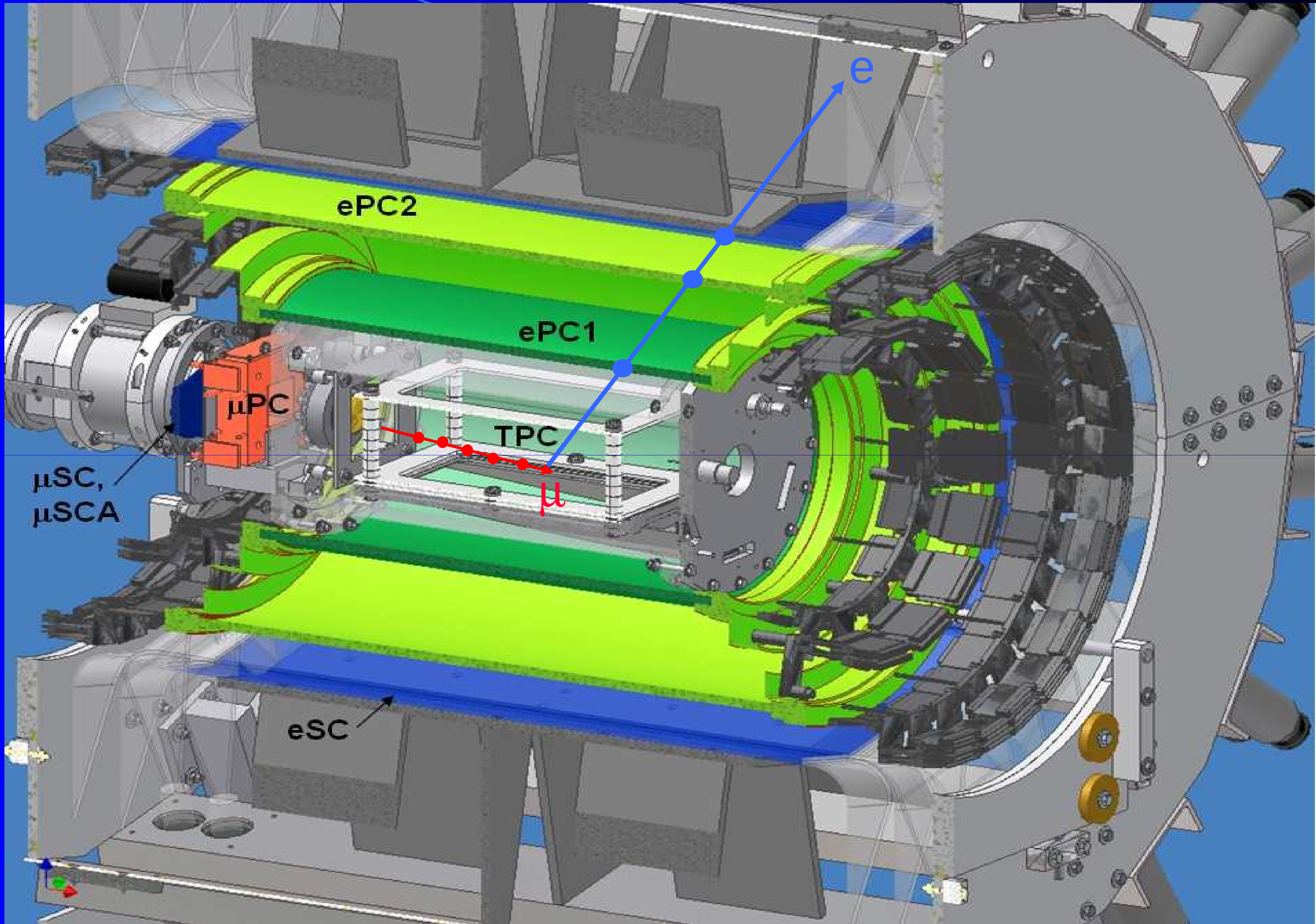
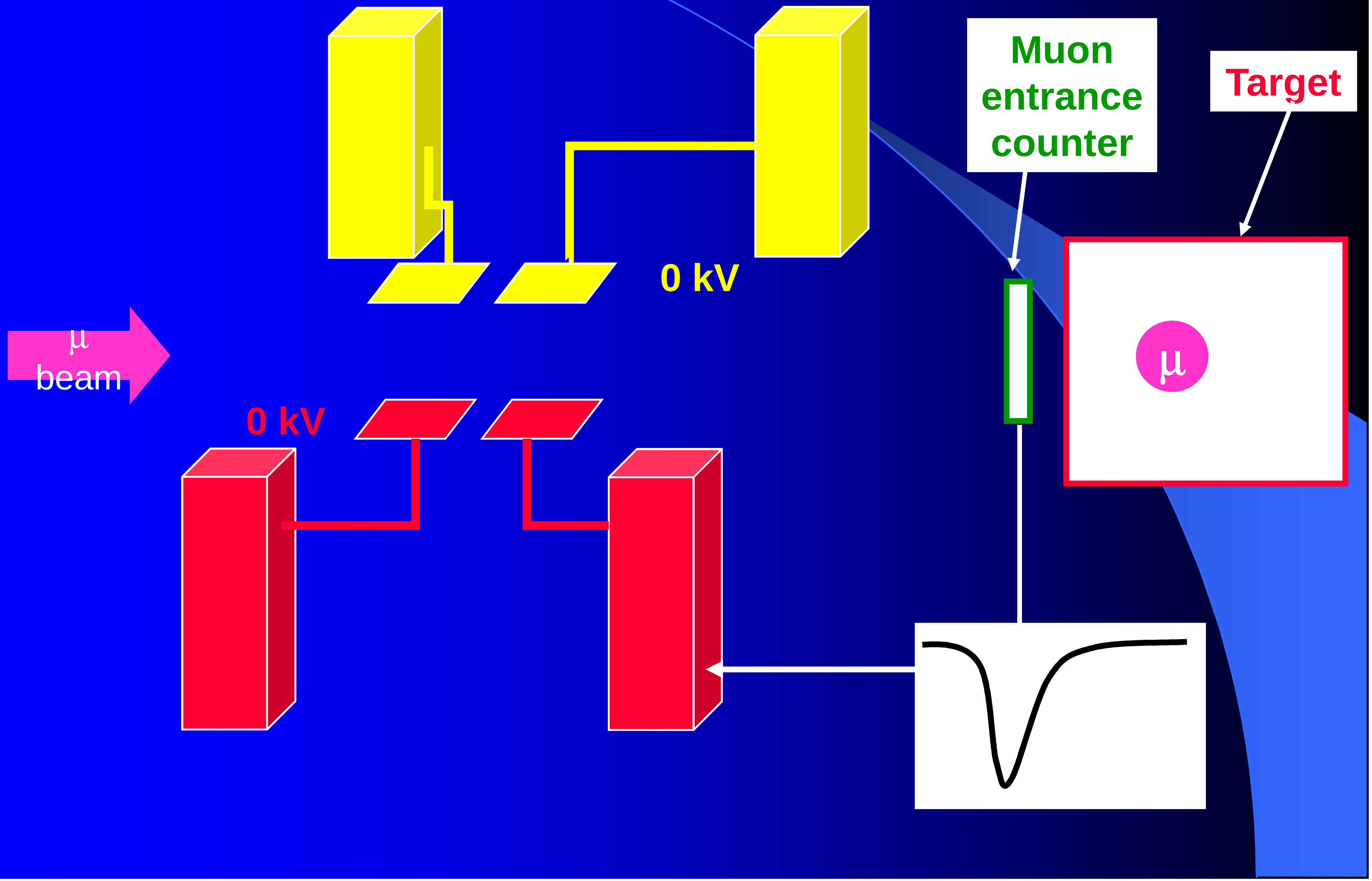
MuCap: General overview

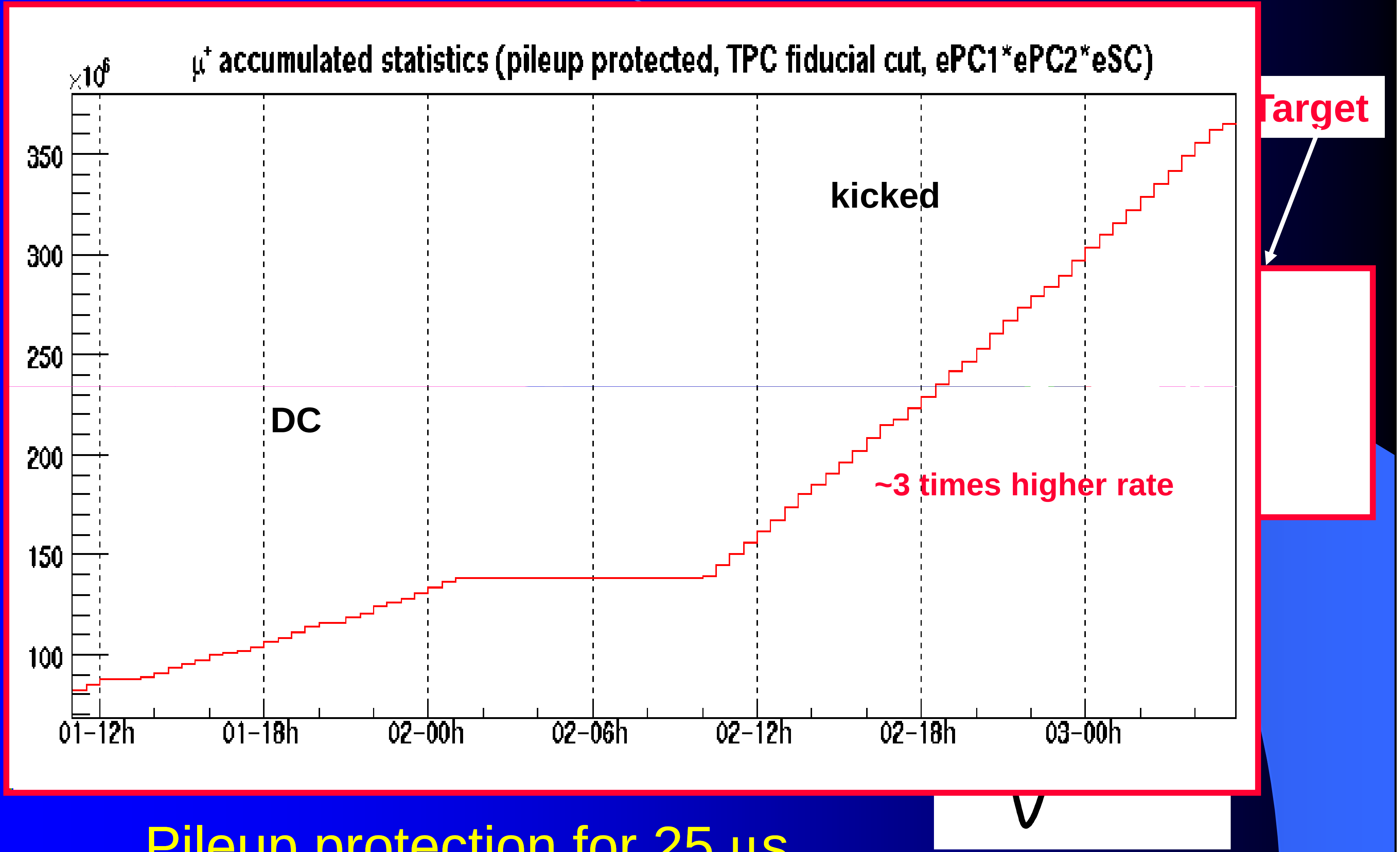
- Lifetime method:
  10^{10} μ decays $\Rightarrow$ Λ_S to 1% precision
- Low gas density $\Rightarrow$ Capture mostly from F=0
- Active gas target (TPC) $\Rightarrow$ Clean μ stop
- Ultra pure gas system with in-situ monitoring
  $c_Z \sim 10 - 30$ ppb   ($Z = N_2$, H_2O)
- Isotopically pure "protium"
  $c_d \sim 0.1 - 2$ ppm   (deuterium separation)


e
ePC2
ePC1
µPC
TPC
µSC,
µSCA
µ
eSC

Muon-On-Demand

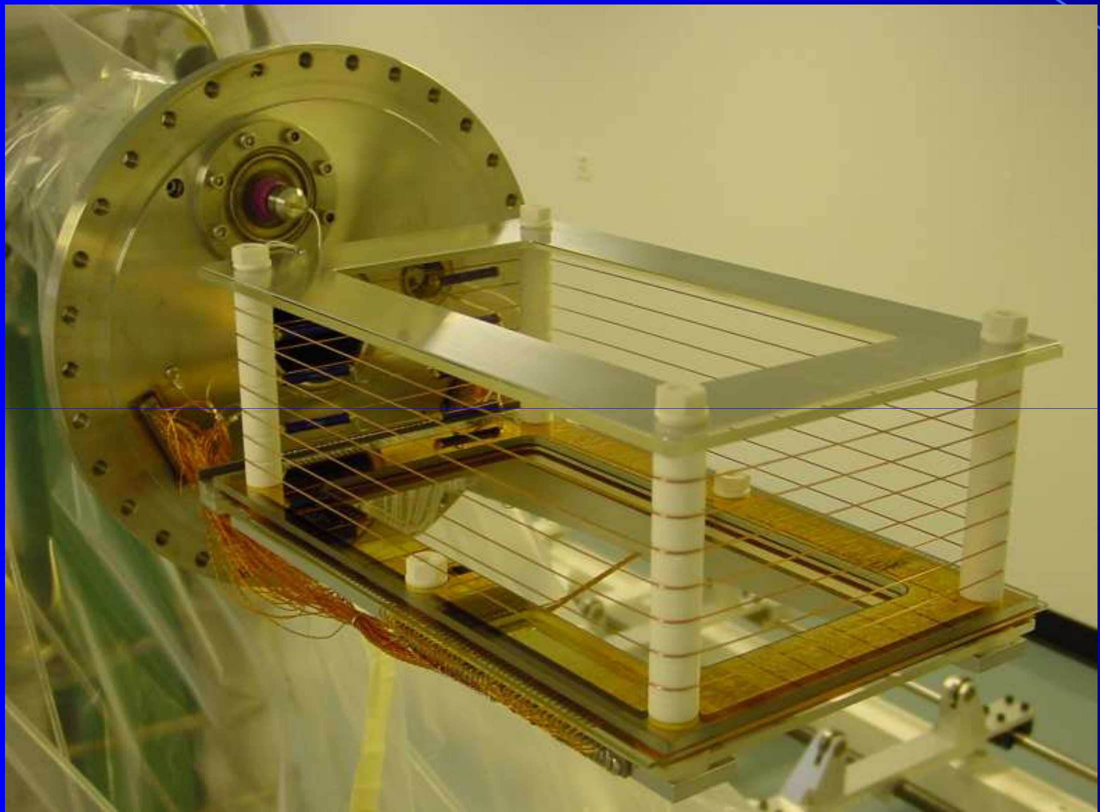


Muon-On-Demand



Pileup protection for 25 μs

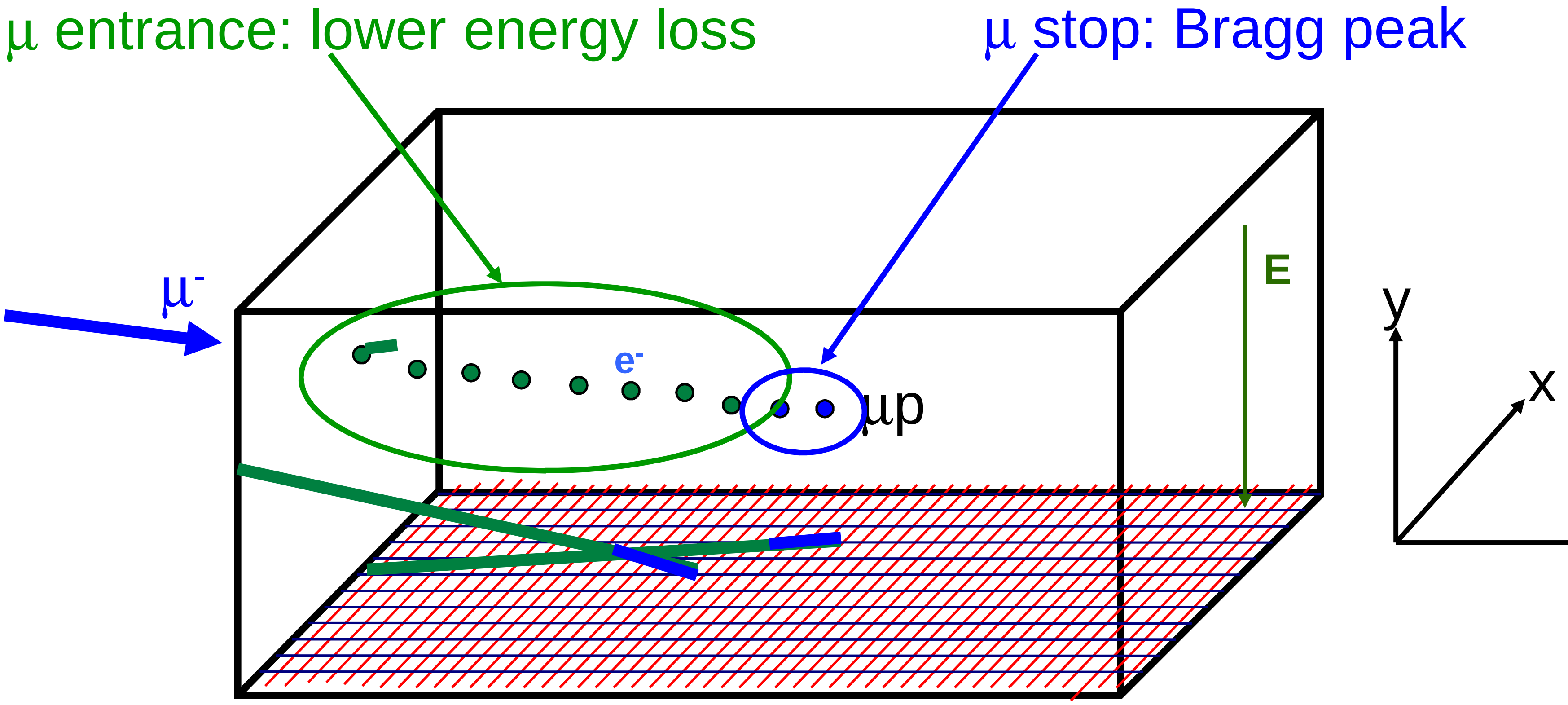
TPC - the active target



- 10 bar ultra-pure hydrogen, ϕ = 1.16%
- 2.0 kV/cm drift field
- ~ 5.4 kV on 3.5 mm anode half gap
- bakeable glass/ceramic materials

Operation with pure H_2 challenging, R&D @ PNPI, PSI

TPC - the active target



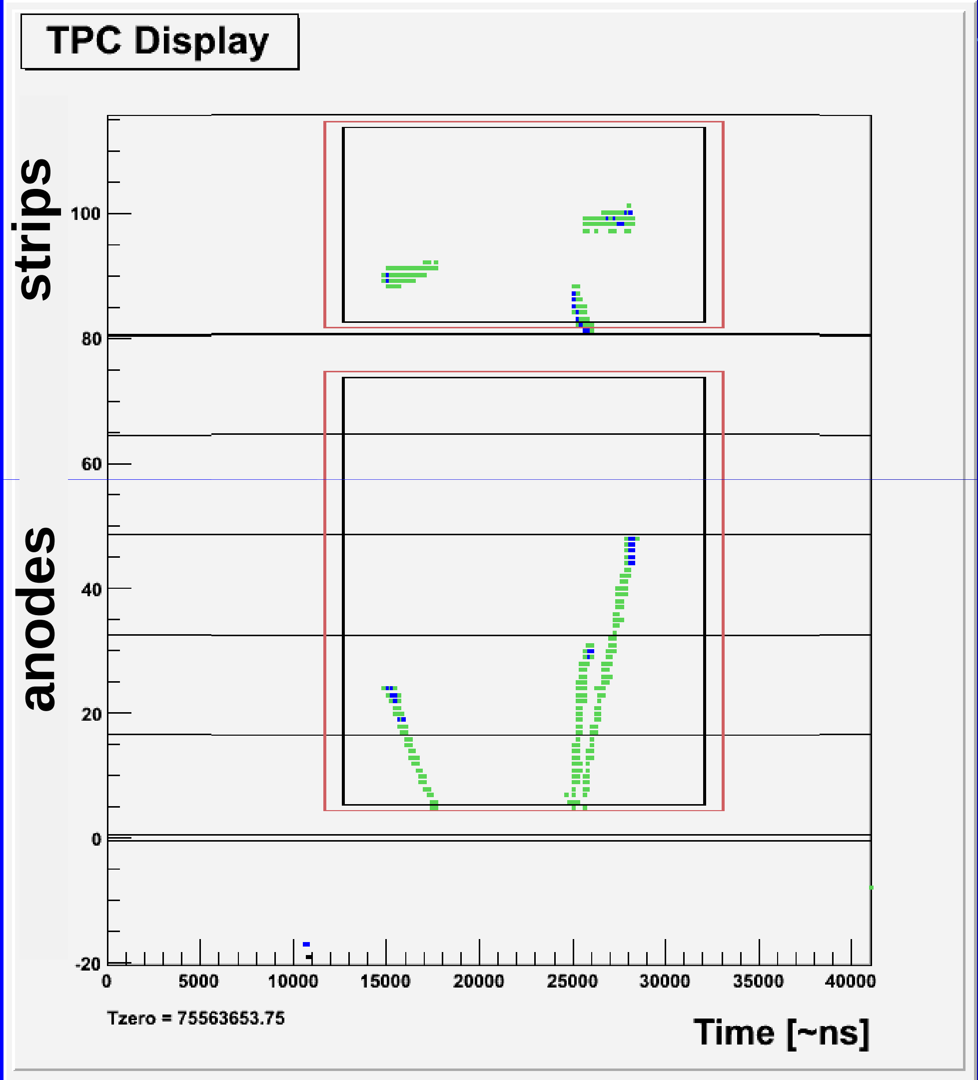
xz projection from anodes and strips

zy projection from anodes and drift time

xy projection from strips and drift time

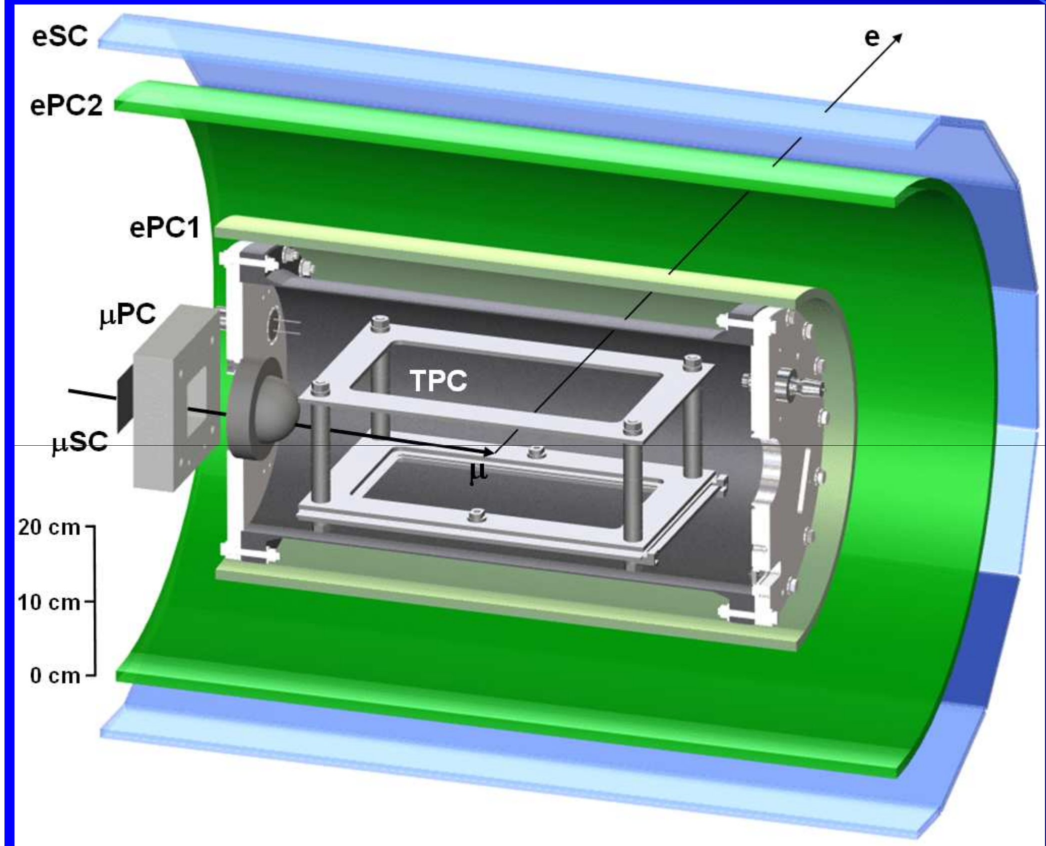
- 3d tracking without material in fiducial volume
- Clean muon stop definition

The clean μ stop definition



- Connected muon pixels
- Clear Bragg peak
- Only muon stops well away from the wall accepted
- Reject pileup events

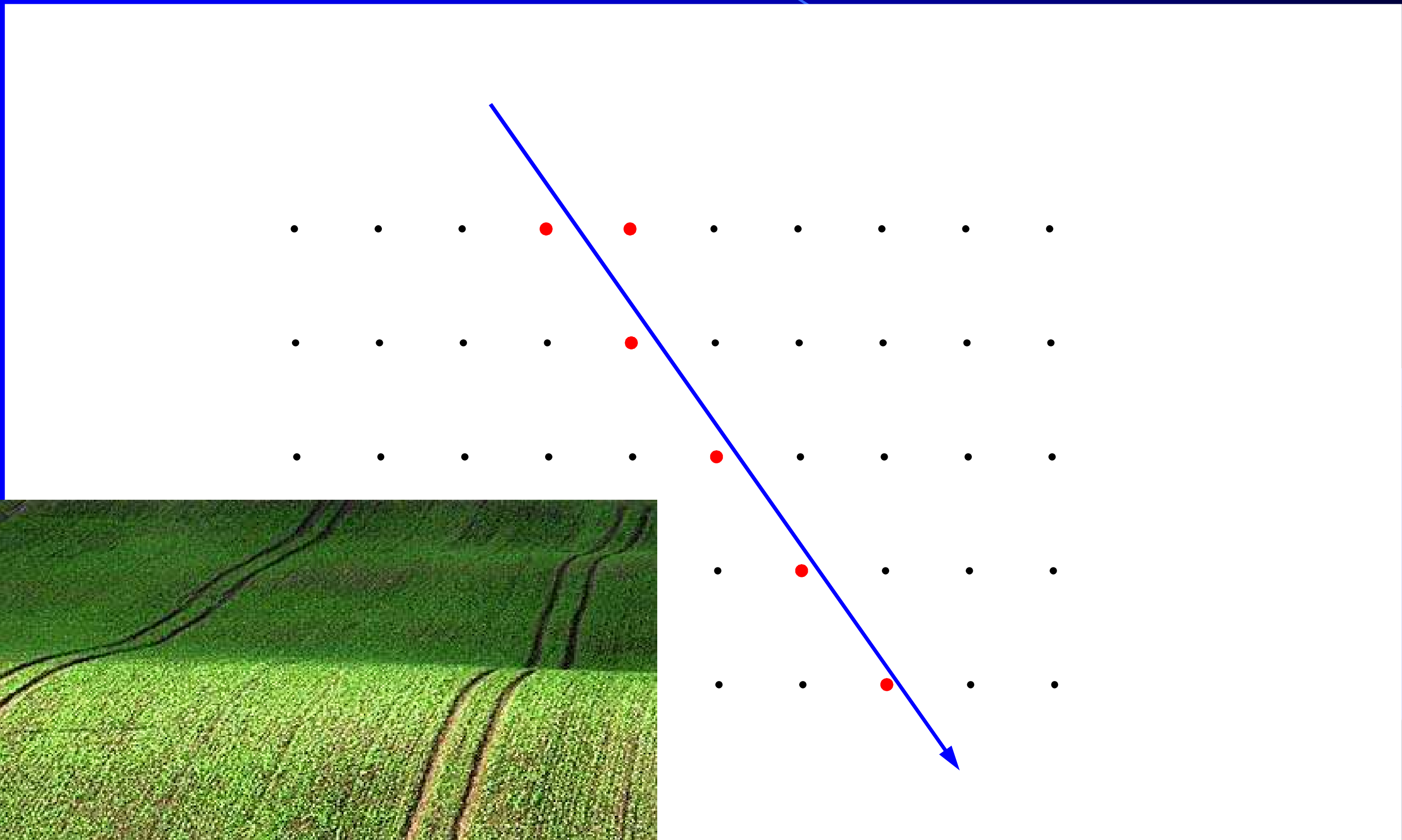
Electron detectors



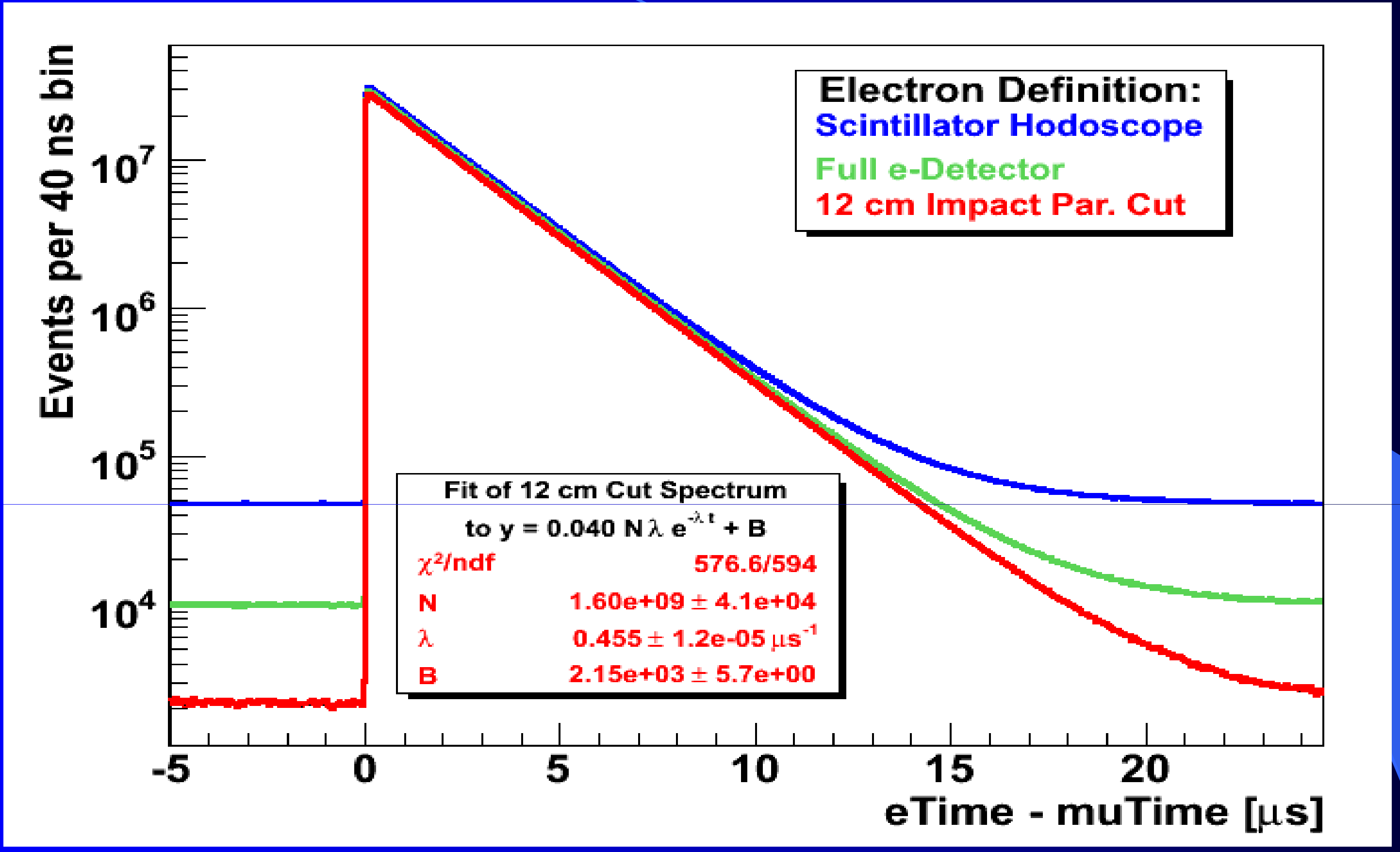
- Timing from scintillator (eSC)
- Temporal and spatial coincidences with wire chamber planes (ePC1 and ePC2)
- Full 3d tracking of electron

The impact parameter b is the distance of closest approach of the muon stop and electron track

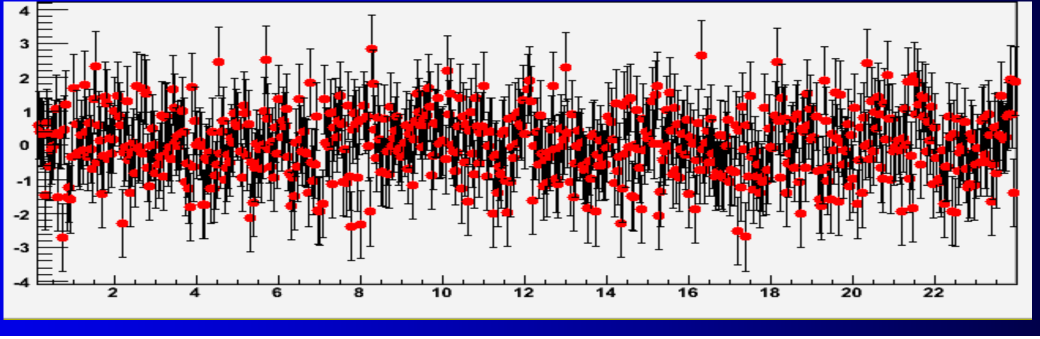
Drift chamber



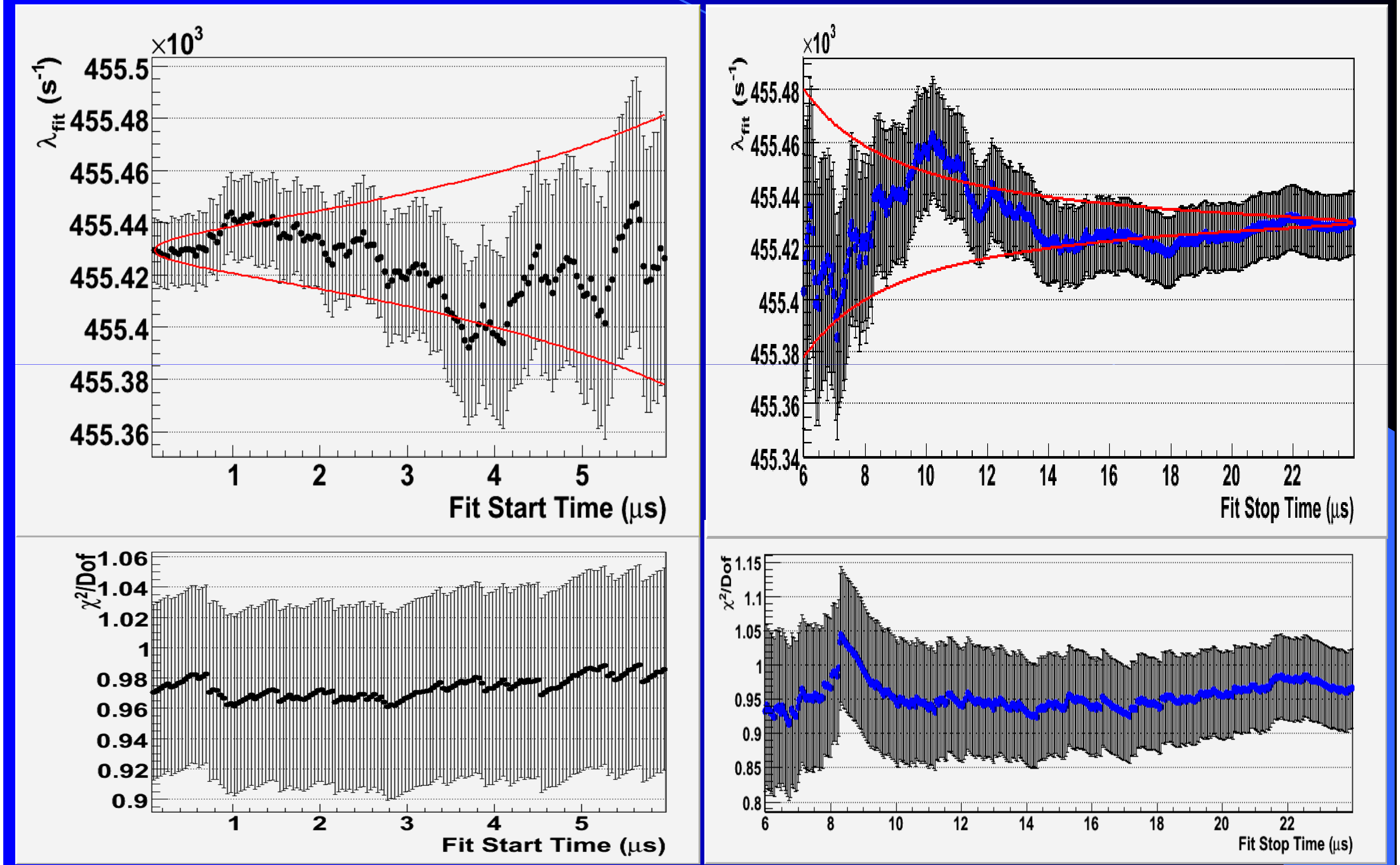
Lifetime spectra

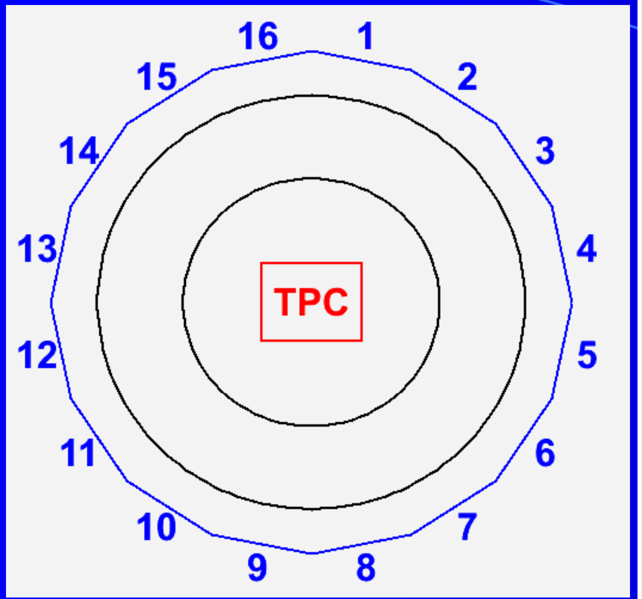


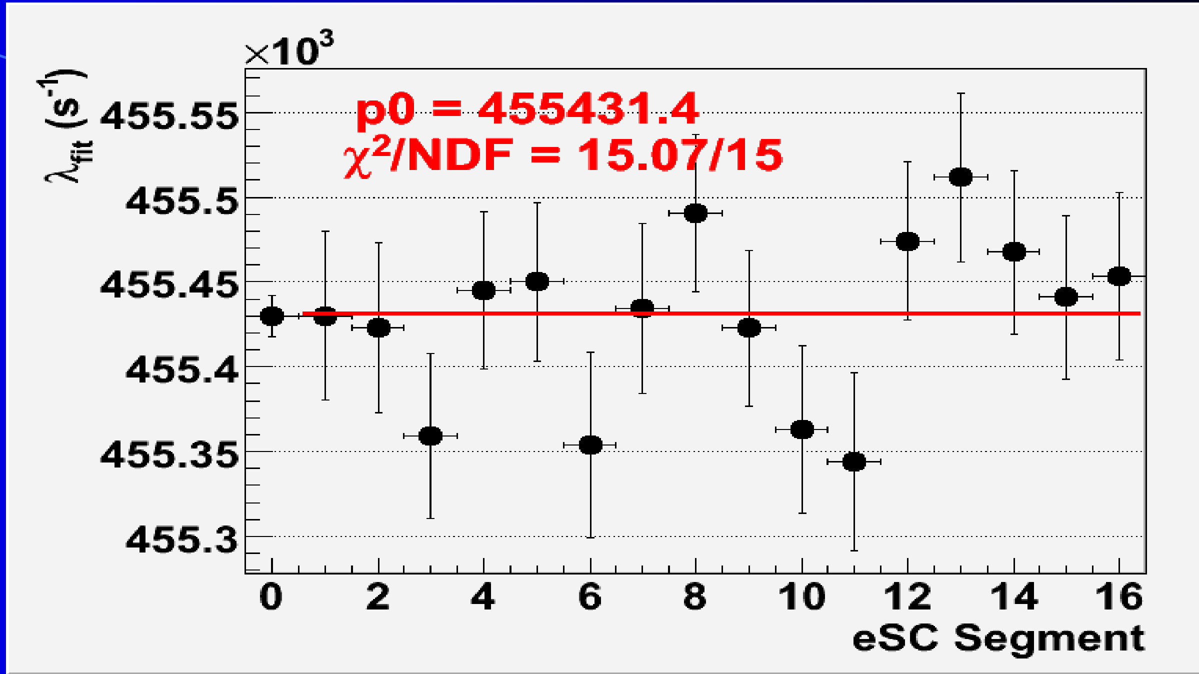
Normalized residuals

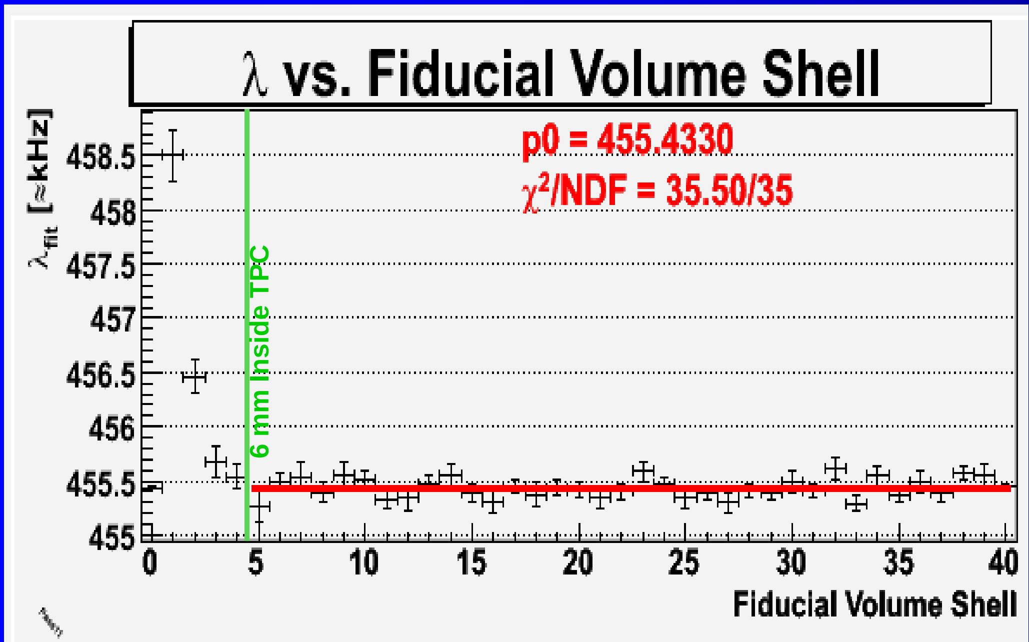


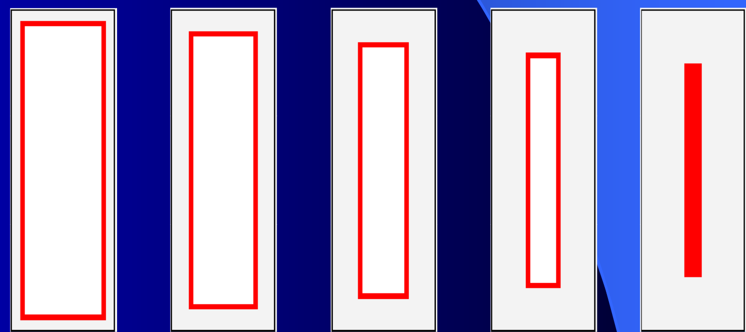
Consistency checks





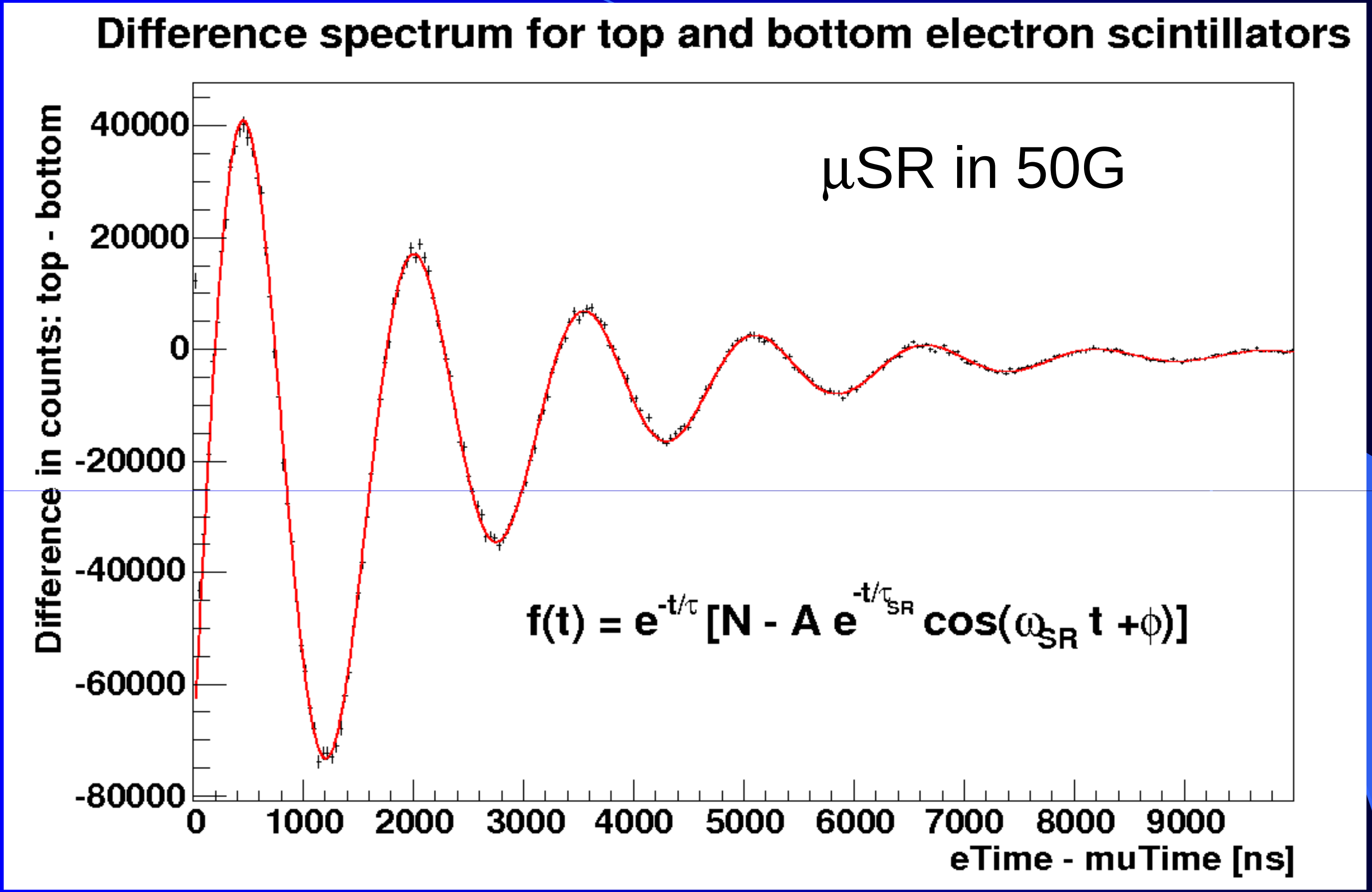






Non overlapping TPC volume shells

μ^+ as reference



- Measurement with μ^+ has identical detector systematics
- Cross check with world average τ_+:
  ~1ppm precision in the future (MuLan and FAST @ PSI)

What do we have so far?

μ^- lifetime: τ_- ✓

Consistency checks ✓

μ^+ lifetime: τ_+ ✓

Is that it for $\Lambda_S = 1/\tau_- - 1/\tau_+$?

Not yet...

... but almost!

Outline

Muon Lifetime Analysis (MuLan)

- Motivation
- MuLan experiment
- Main systematics and result

Muon capture on the proton (MuCap)

- Motivation and general overview
- MuCap experiment
- Systematics and results

Muon capture on the deuteron (MuSun)

- Motivation and outlook

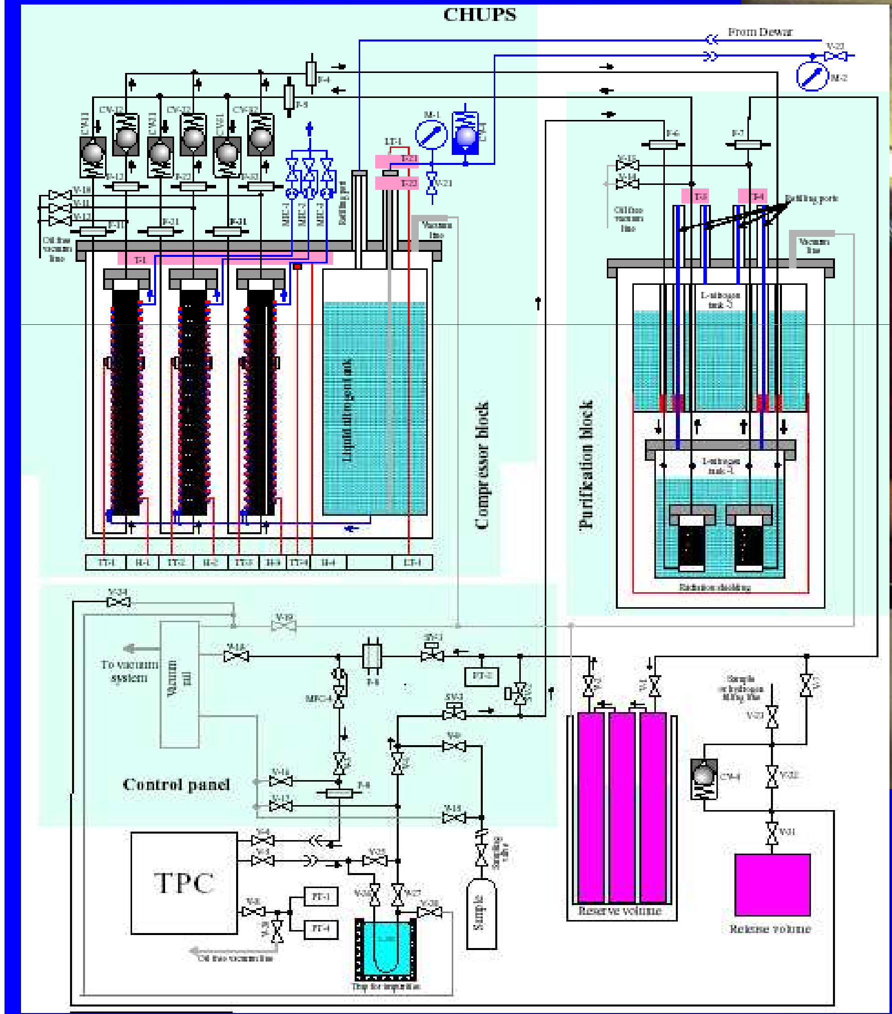
Internal corrections to λ_-

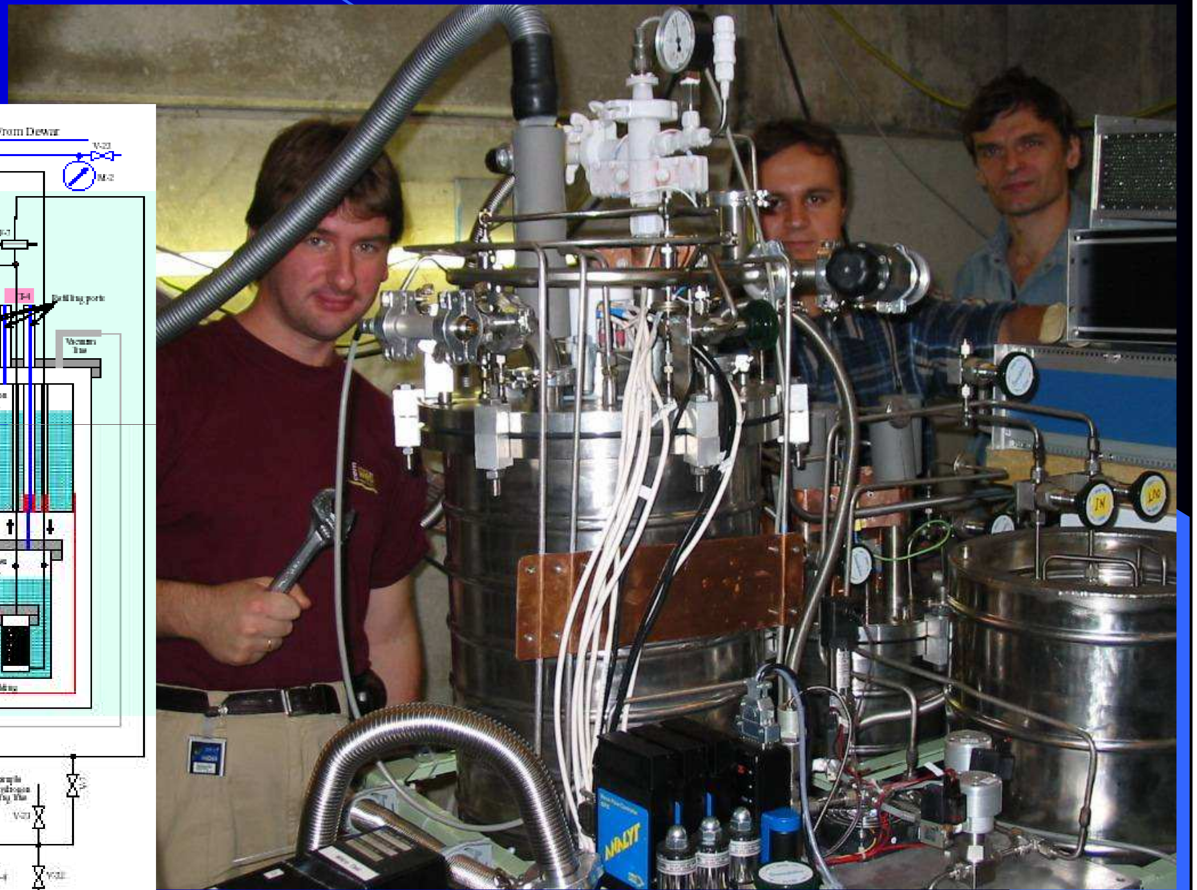
Source	Correction (s^{-1})	Uncertainty (s^{-1})
$Z > 1$ impurities ($\Delta\lambda_Z$)	-17.4	4.6
Deuterium ($\Delta\lambda_d$)	-12.1	1.8
μp Diffusion ($\Delta\lambda_k$)	-3.1	0.1
Unseen $\mu + p$ scatters ($\Delta\lambda_{\mathrm{sc}}$)	0.0	3.0
μ stop definition ($\Delta\lambda_{\mathrm{tr}}$)	0.0	2.0
μ pileup veto inefficiency ($\Delta\lambda_\kappa$)	0.0	3.0
Analysis methods ($\Delta\lambda_{\mathrm{Ana}}$)	0.0	5.0
Total	-32.6	± 8.4

(statistical uncertainty of λ_-: 13.7 s^{-1})

CHUPS

Continous H_2 Ultra-Purification System

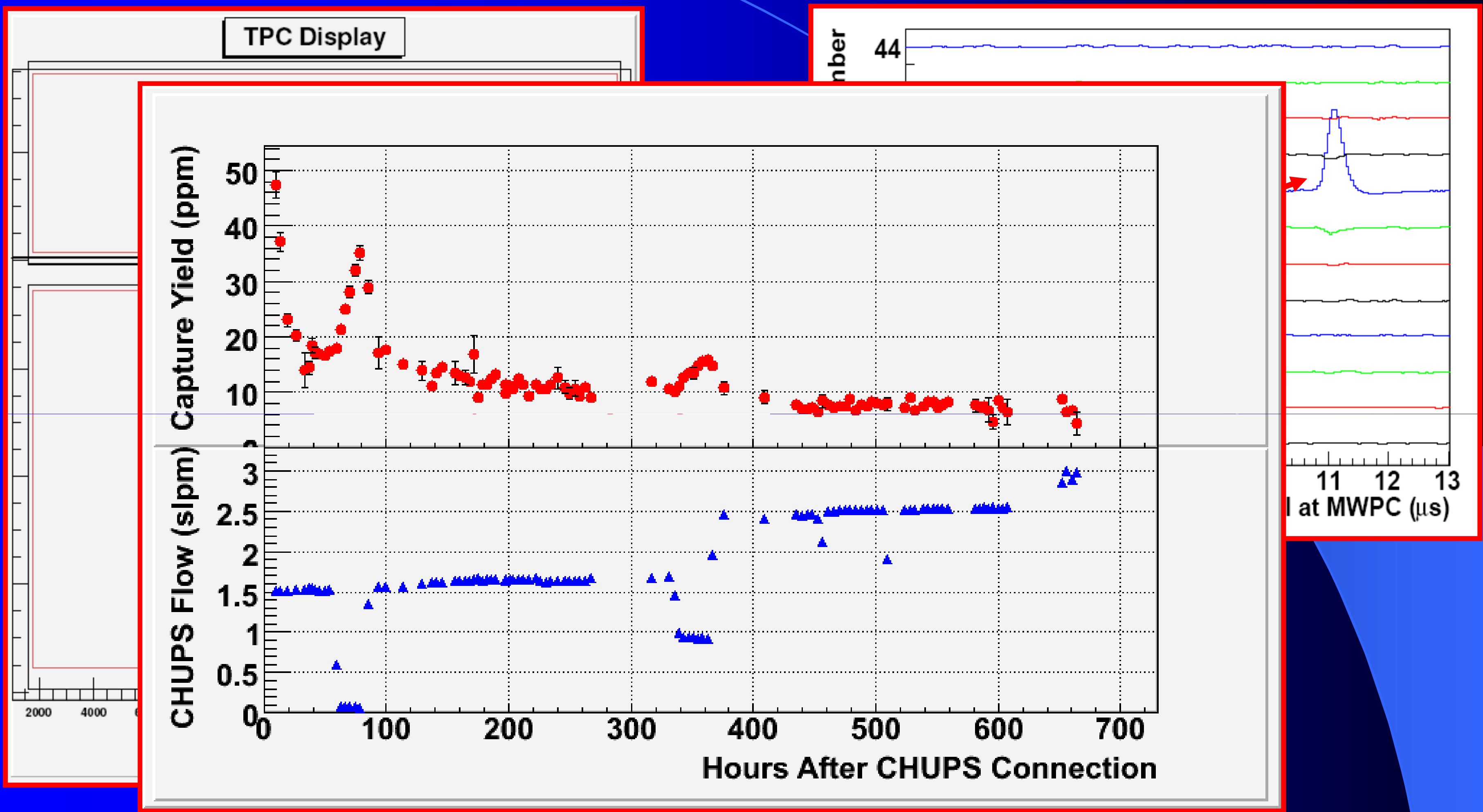




c_{N2}, c_{O2} < 10 ppb

NIM A578 (2007), 485

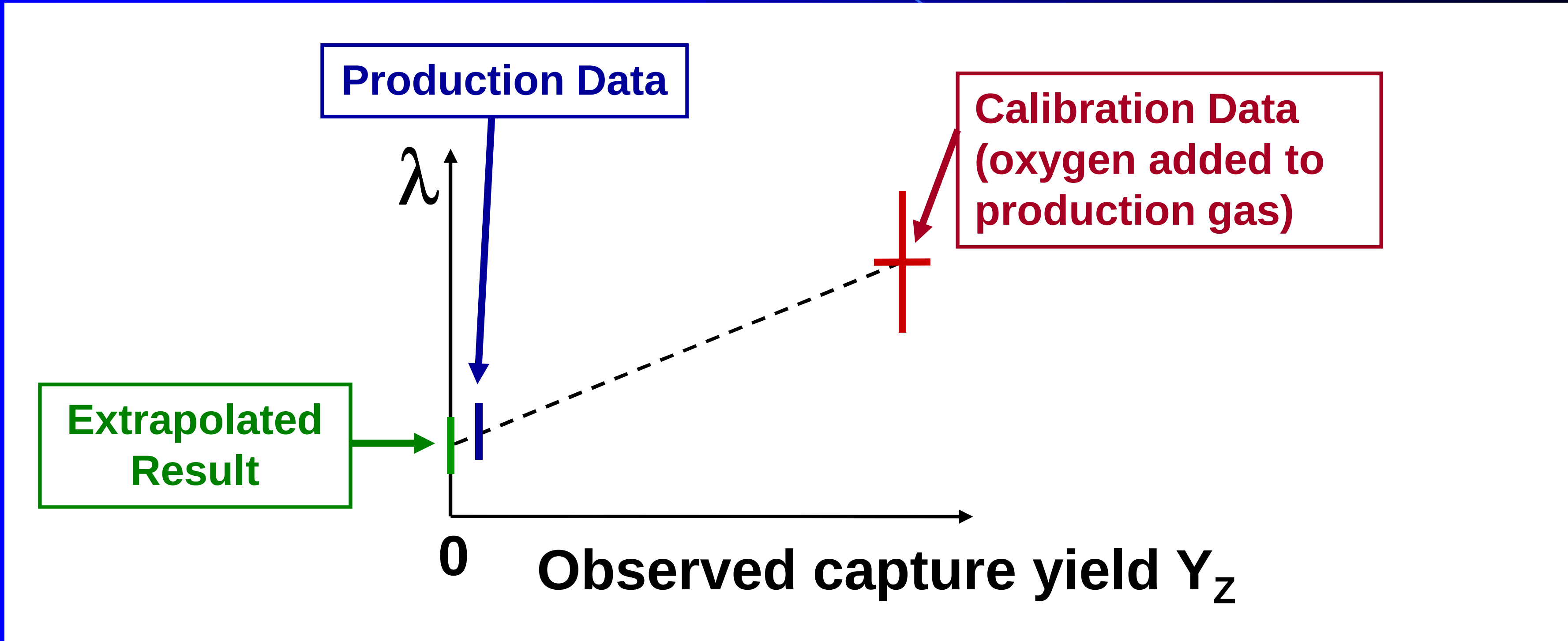
Impurity monitoring



2004 run: c_N, c_O < 7 ppb, c_{H2O}~30 ppb

2006/2007 runs: c_N, c_O < 7 ppb, c_{H2O}~10 ppb

Final high-Z impurity correction



Lifetime deviation is linear with the Z>1 capture yield.

Internal corrections to λ_-

Source	Correction (s^{-1})	Uncertainty (s^{-1})
$Z > 1$ impurities ($\Delta\lambda_Z$)	-17.4	4.6
Deuterium ($\Delta\lambda_d$)	-12.1	1.8
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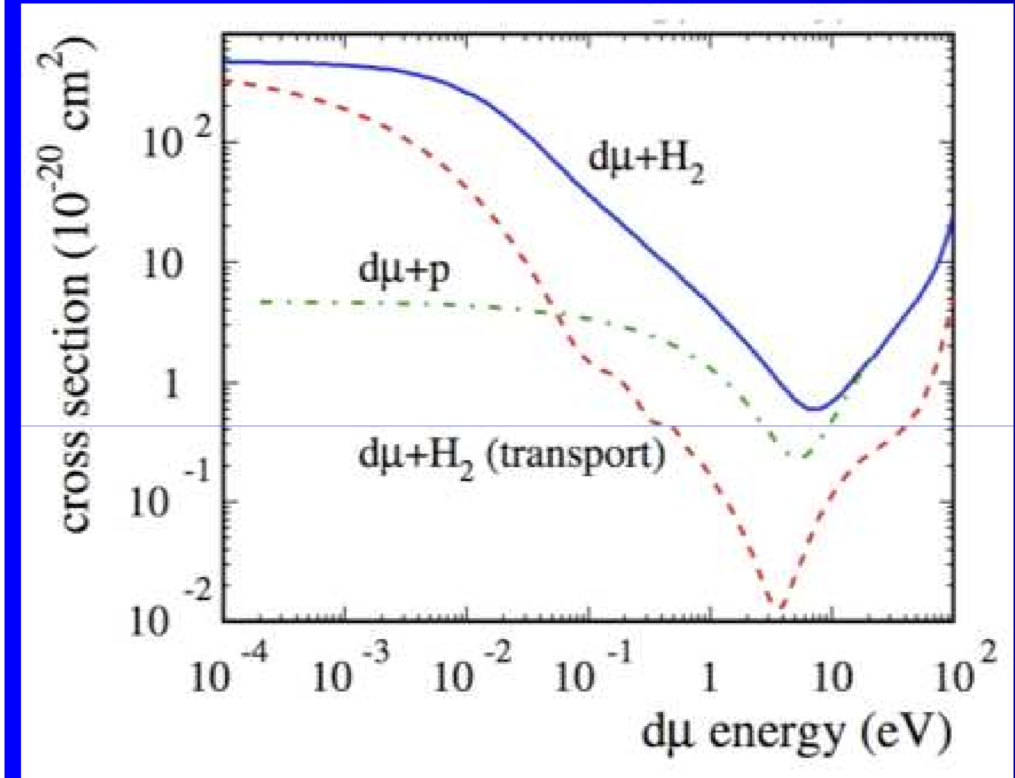
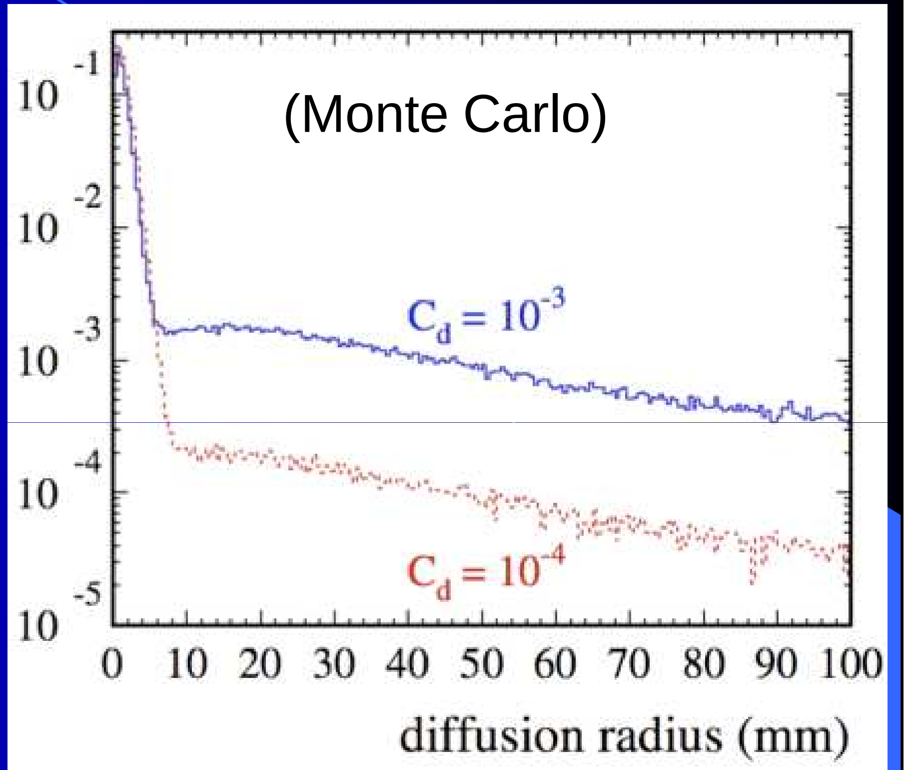
Total	-32.6	± 8.4

(statistical uncertainty of λ_-: 13.7 s^{-1})

μd diffusion

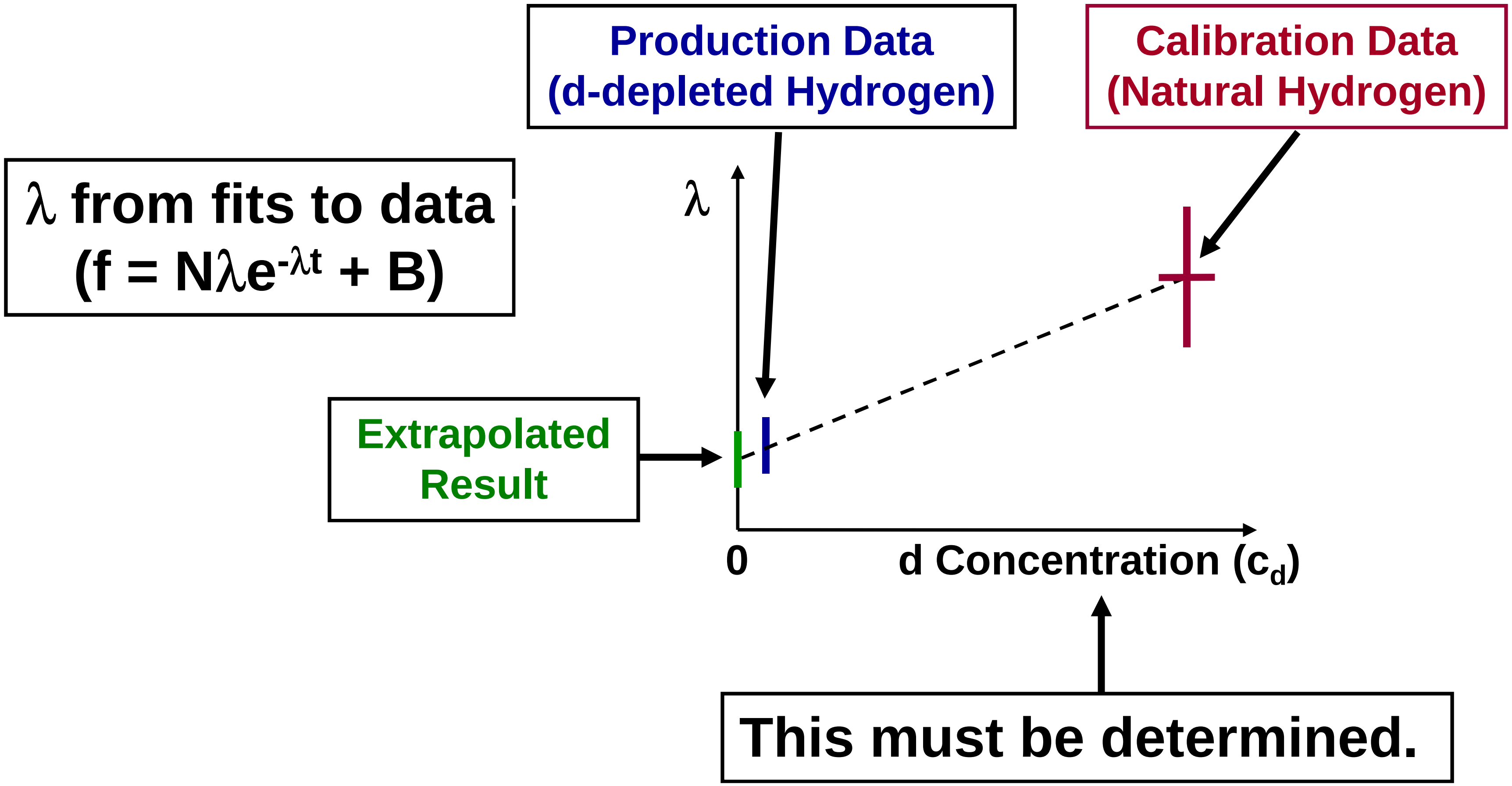




- Ramsauer-Townsend minimum in the scattering cross section
- μd can diffuse ~10 cm before muon decay, possibly into walls

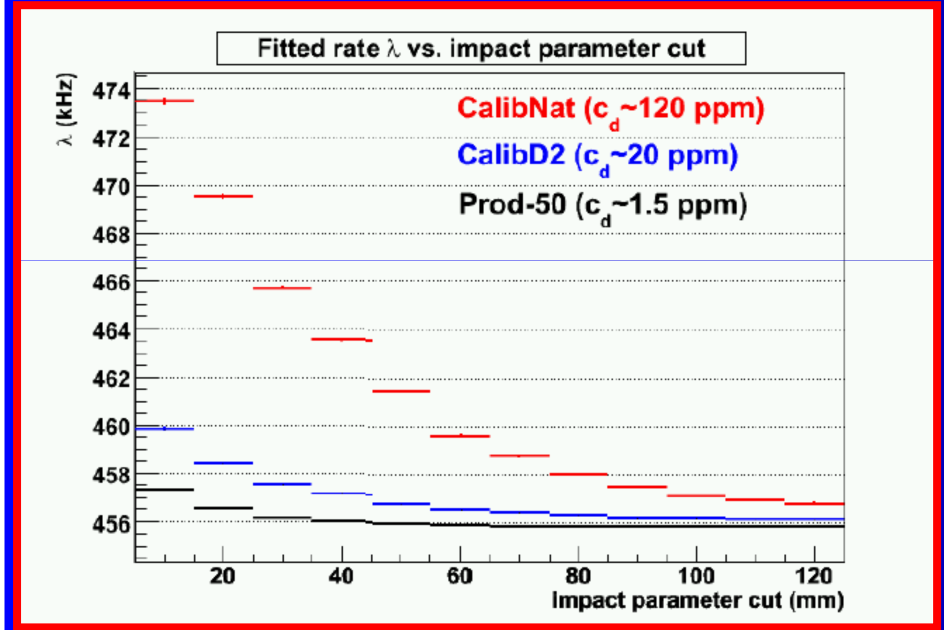
Deuterium correction

Again zero extrapolation procedure



μd: MuCap's unique capability

- Data: λ versus impact parameter cut

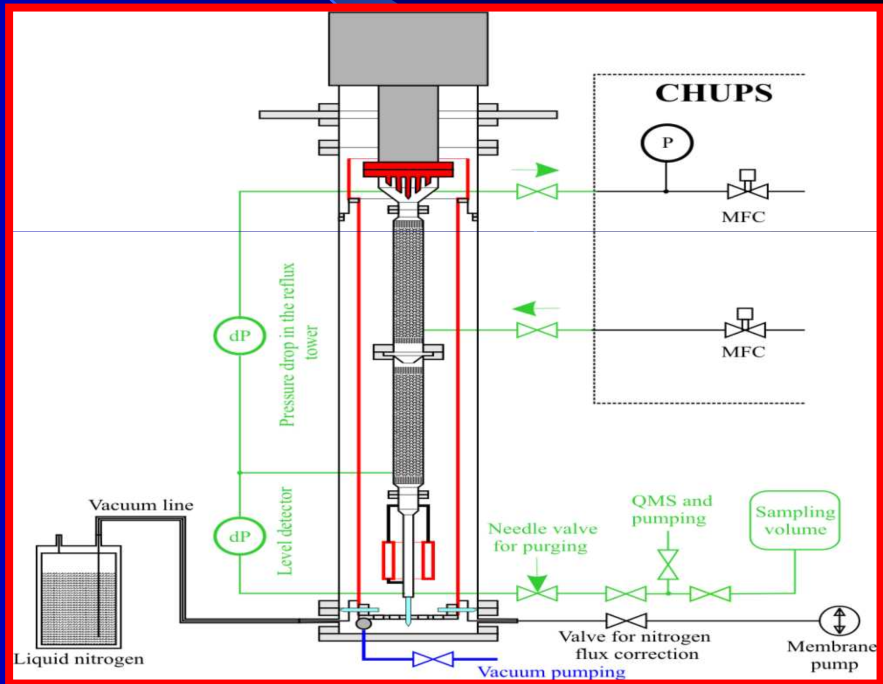


$c_d = 1.49 \pm 0.12$ ppm

- AMS, ETH Zurich

$c_d = 1.44 \pm 0.15$ ppm

On site purification since 2006



World Record: c_d < 100 ppb

External corrections to λ-

$$\lambda_\mu^- = \lambda_0 + \Lambda_S + \Delta\lambda_{p\mu p}$$

molecular formation

$$\lambda_\mu^+ + \Delta\lambda_{\mu p}$$

bound state effect

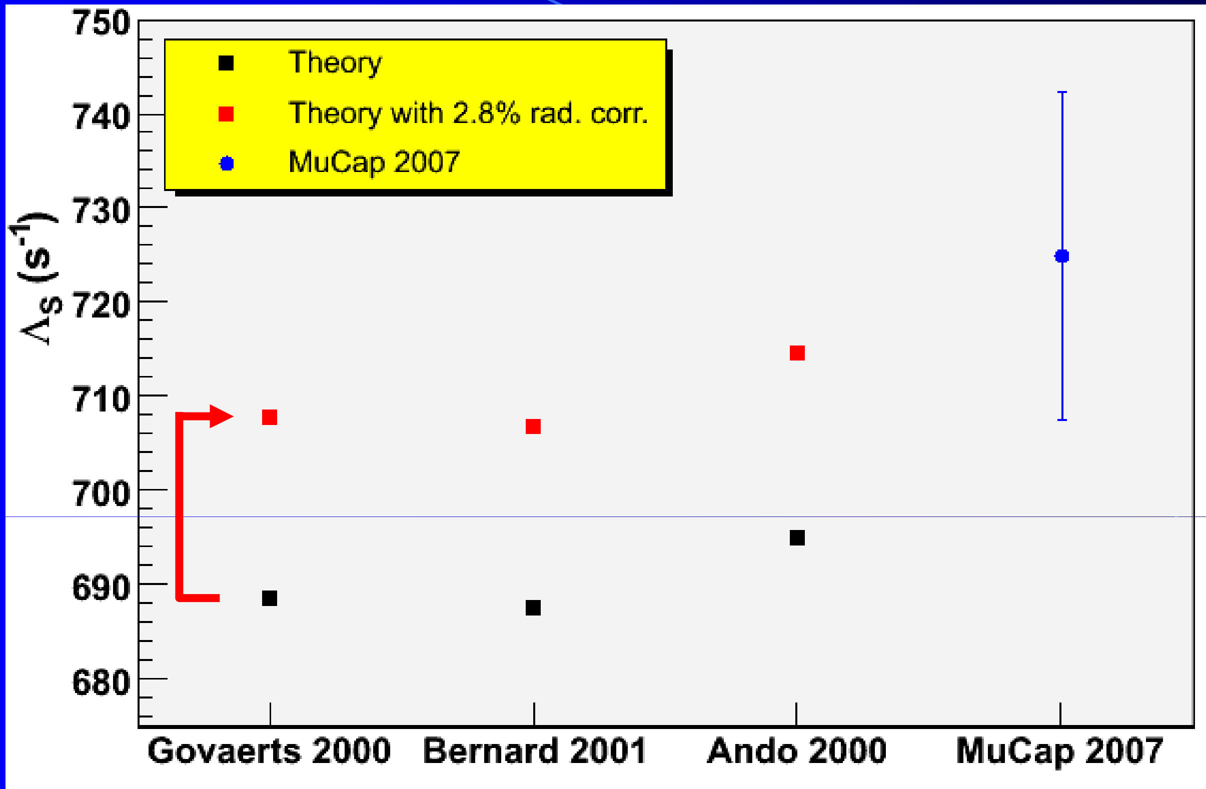
	Value (s^{-1})	Uncertainty (s^{-1}) Stat.	Syst.
Molecular Formation (λ_{OF}) Correction	17.3		4.7
Molecular Transitions (λ_{OP}) Correction	5.7		3.4
Bound State Correction ($\Delta\lambda_{\mu p}$)	12.3		

Here we are...

$$\Lambda_S = 725.0 \pm 13.7_{stat} \pm 10.7_{syst}\ s^{-1}$$

V.A. Andreev et al., Phys. Rev. Lett. 99, 032002 (2007)

MuCap and Λ_S calculations



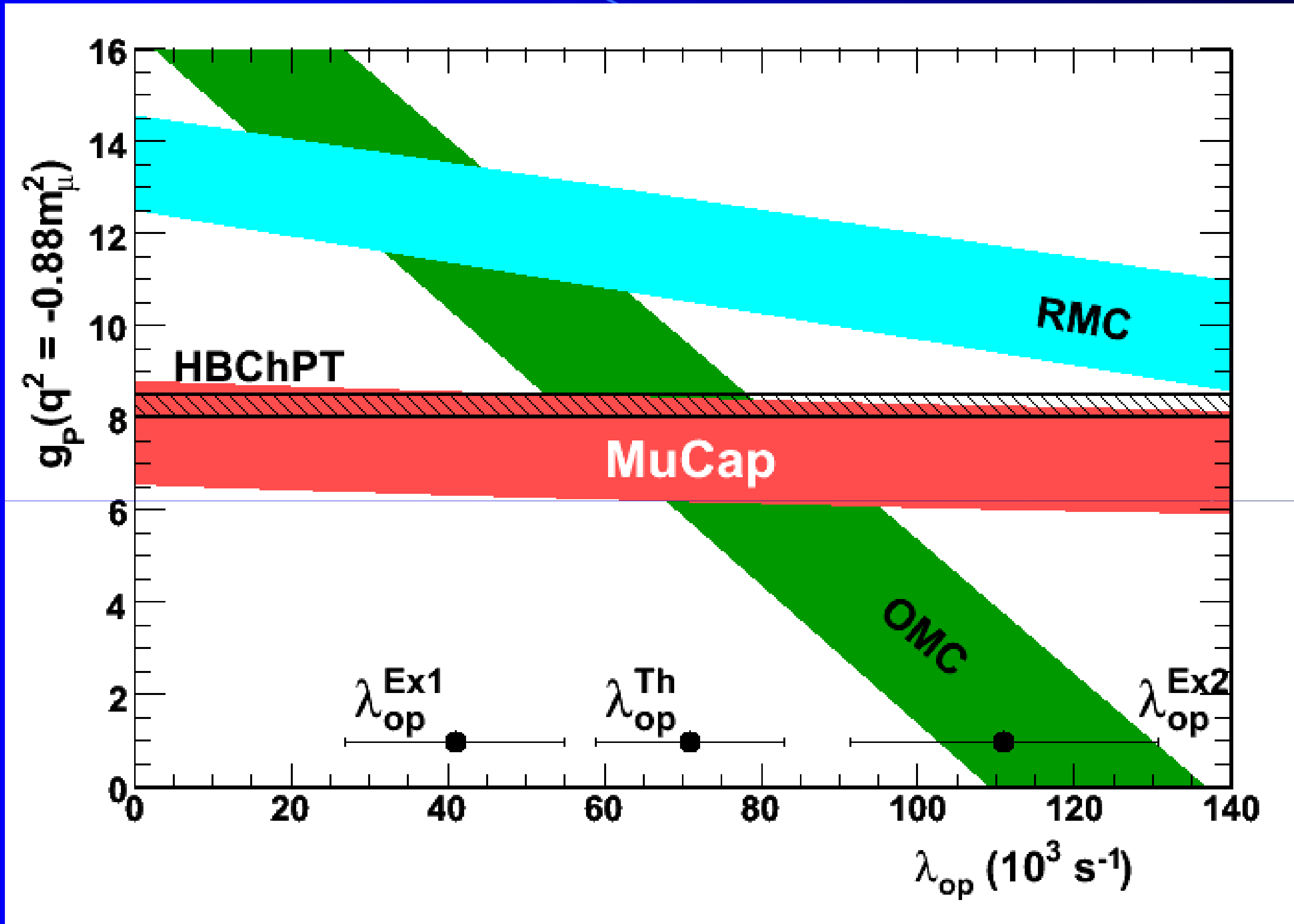
Rad. corrections: Δ_R = 2.8%

A. Czarnecki, W.J. Marciano, A. Sirlin, PRL99, 032003 (2007)

$$\Lambda_S = 725.0 \pm 13.7_{stat} \pm 10.7_{syst}\ s^{-1}$$

V.A. Andreev et al., Phys. Rev. Lett. 99, 032002 (2007)

MuCap and g_P



$g_P = 7.3 \pm 1.1$

First precise and unambigous result

Summary for μ^- p capture

- Active hydrogen target for clean muon stop
- Muon-On-Demand mode for pileup rejection
- Ultra clean running conditions
- In-situ high-Z capture monitoring
- First precise result and almost independent of λ_{OP}
- Final precision of $\Delta g_P/g_P$ = 7% in progress

Outline

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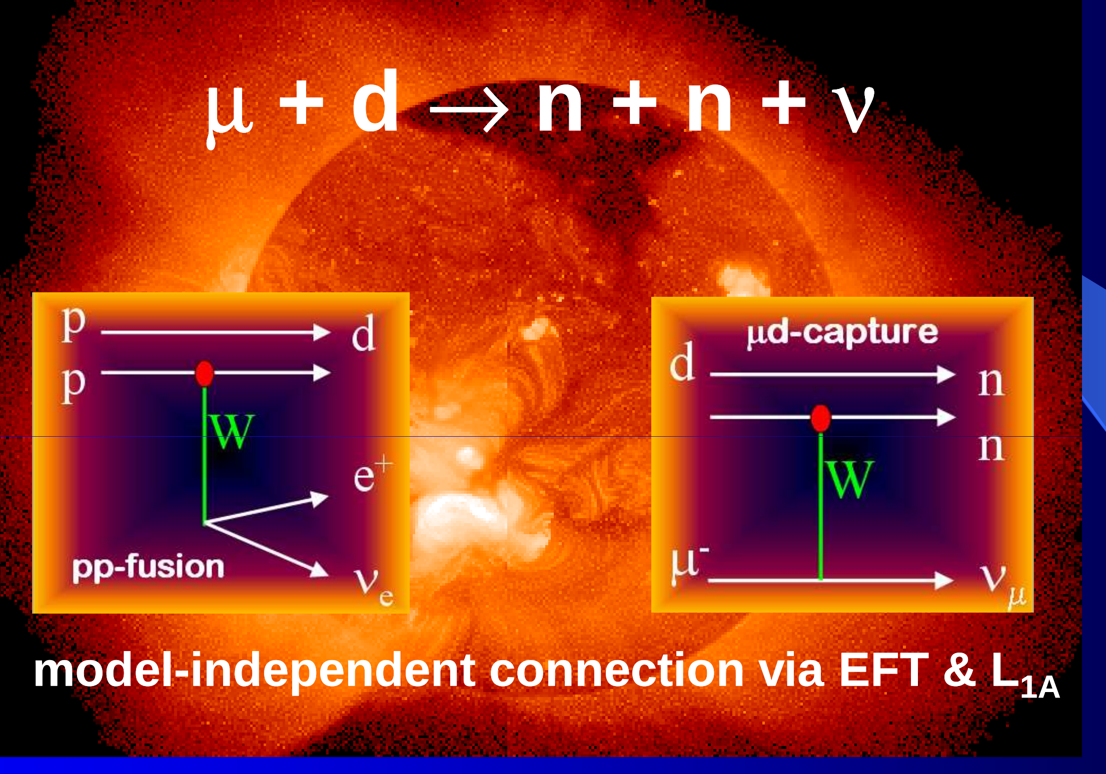
Muon capture on the proton (MuCap)

- Motivation and general overview
- MuCap experiment
- Systematics and results

Muon capture on the deuteron (MuSun)

- Motivation and outlook

MuSun: "Calibrating" the sun



Aim: Measure rate Λ_d from $\mu d(\uparrow\downarrow)$ to < 1.5 %

Motivation: $\mu^- d \rightarrow n\, n\, \nu$

- Aim:

  Measure rate Λ_d from $\mu d(\uparrow\downarrow)$ to < 1.5 %

- Simplest weak interaction in a nucleus allowing for precise theory & experiment

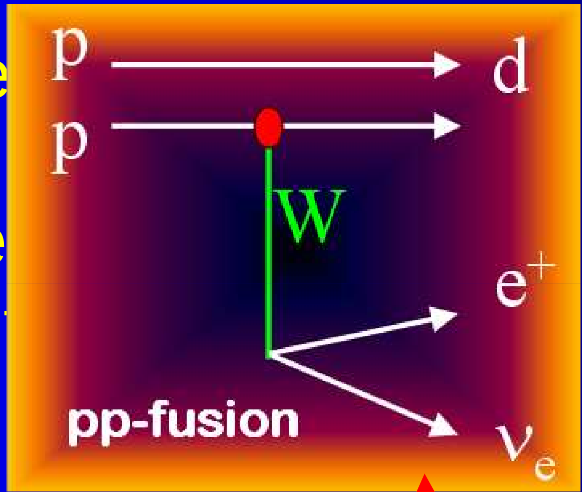
- Close relation to neutrino/astrophysics

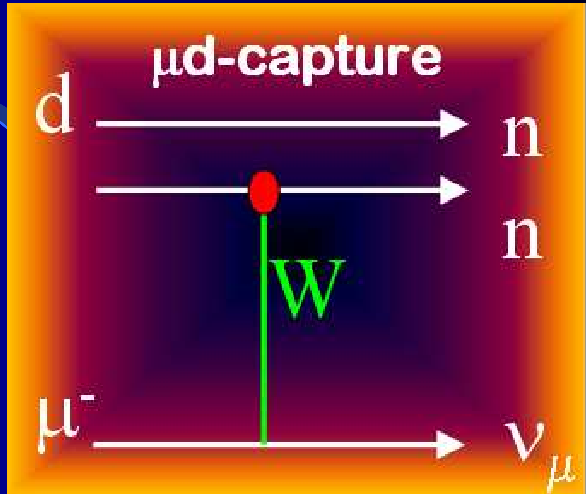
- Broader Impact on modern nuclear physics

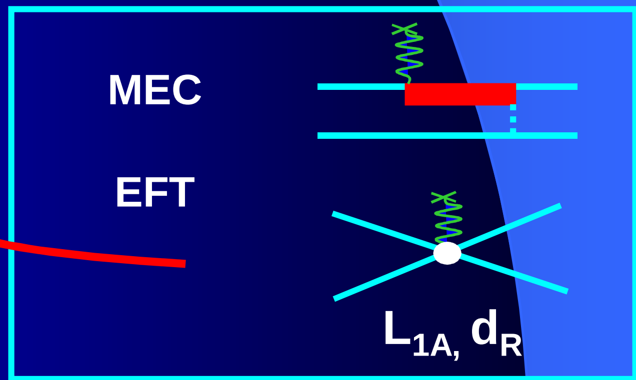
  EFT relates μd to strong processes like $\pi d \rightarrow \gamma nn$, a_{nn}

Theory

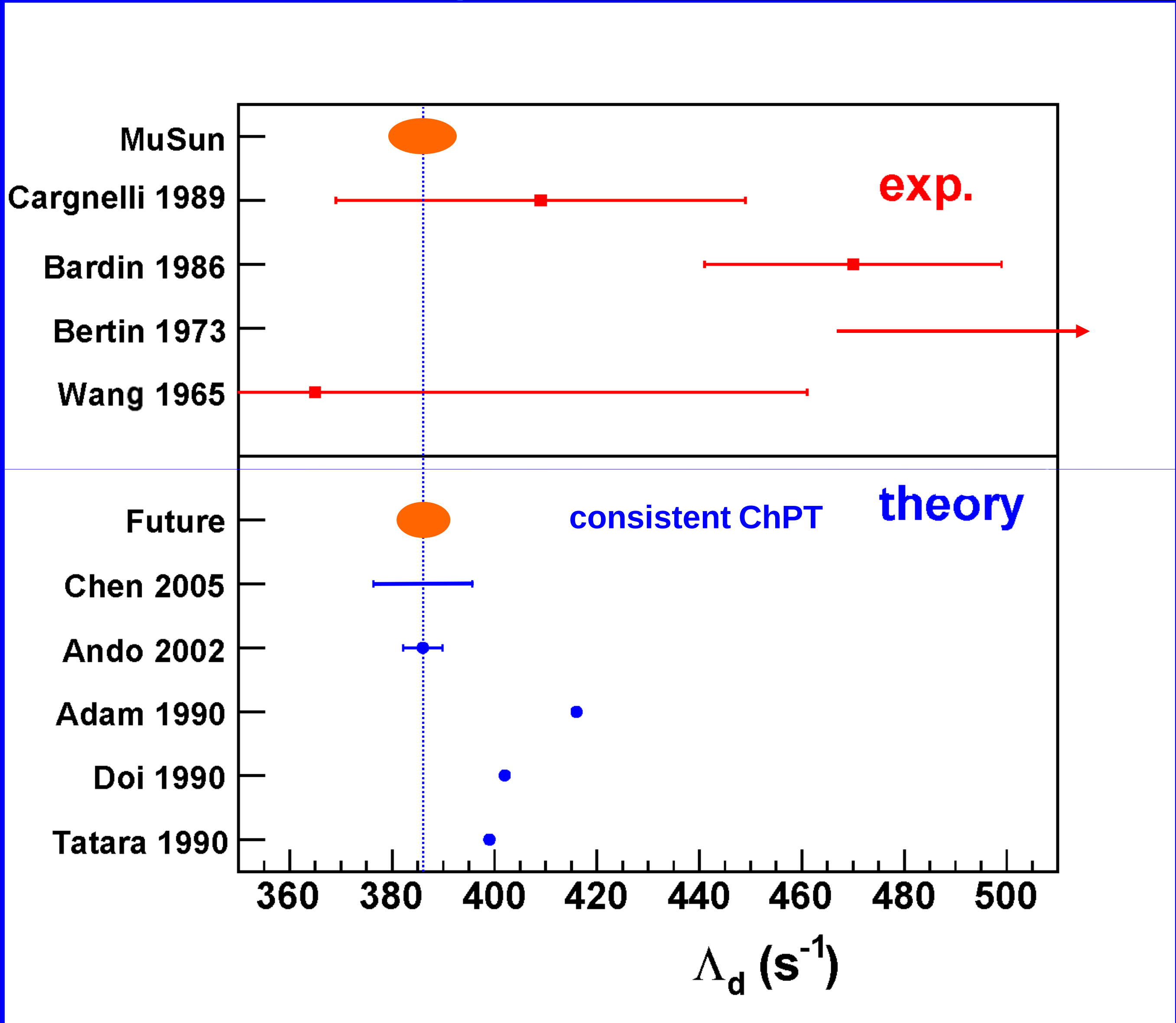
- Axial current reaction (Gamov-Teller $^3S_1 \rightarrow {}^1S_0$)
- One body curre
- Two body curre constrained by
- Methods:
  Potential model + MEC
  hybrid EFT (L_{1A} / d_R)
- Muon capture soft enough to relate to solar reactions



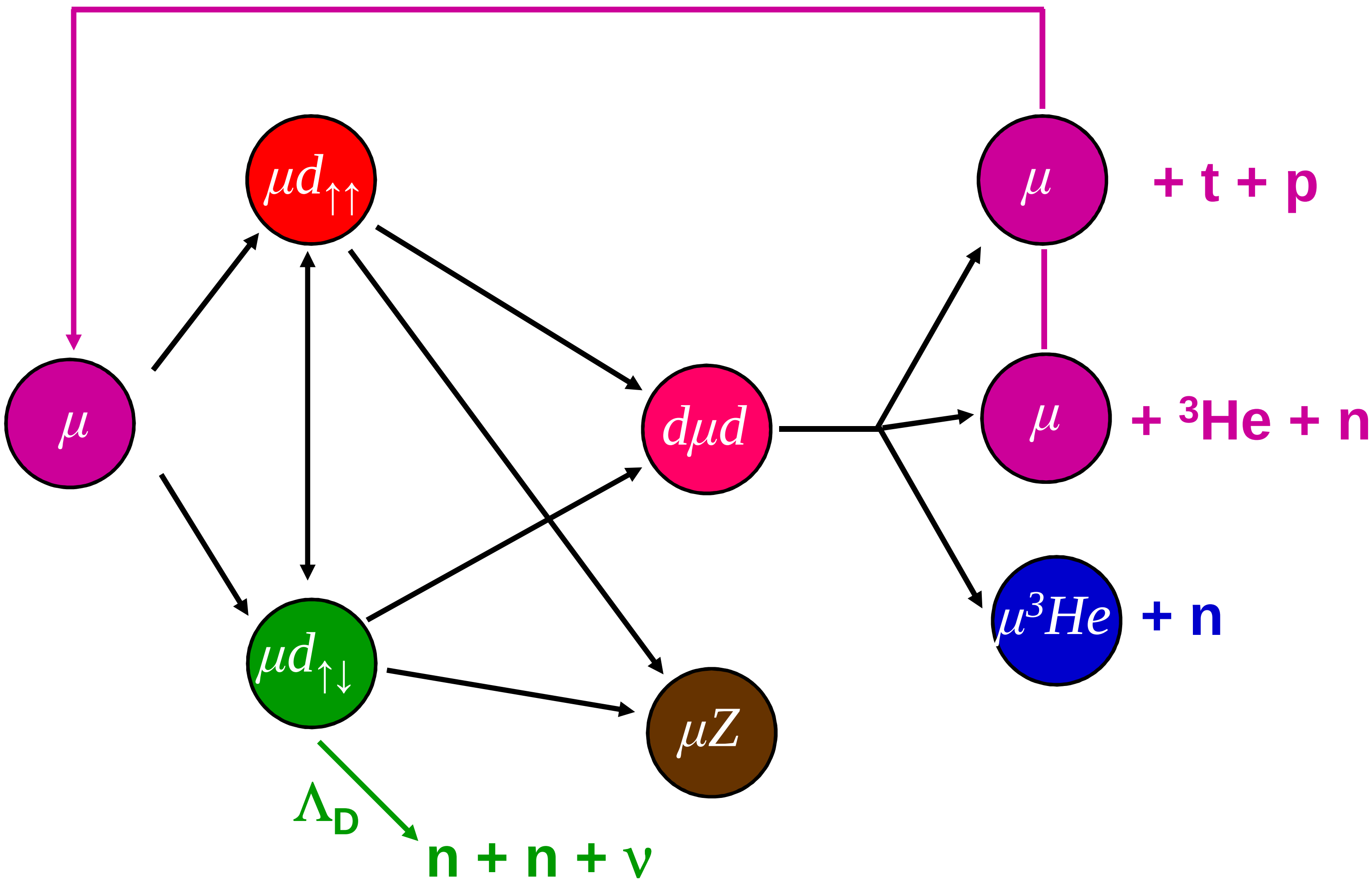




Precise experiment needed

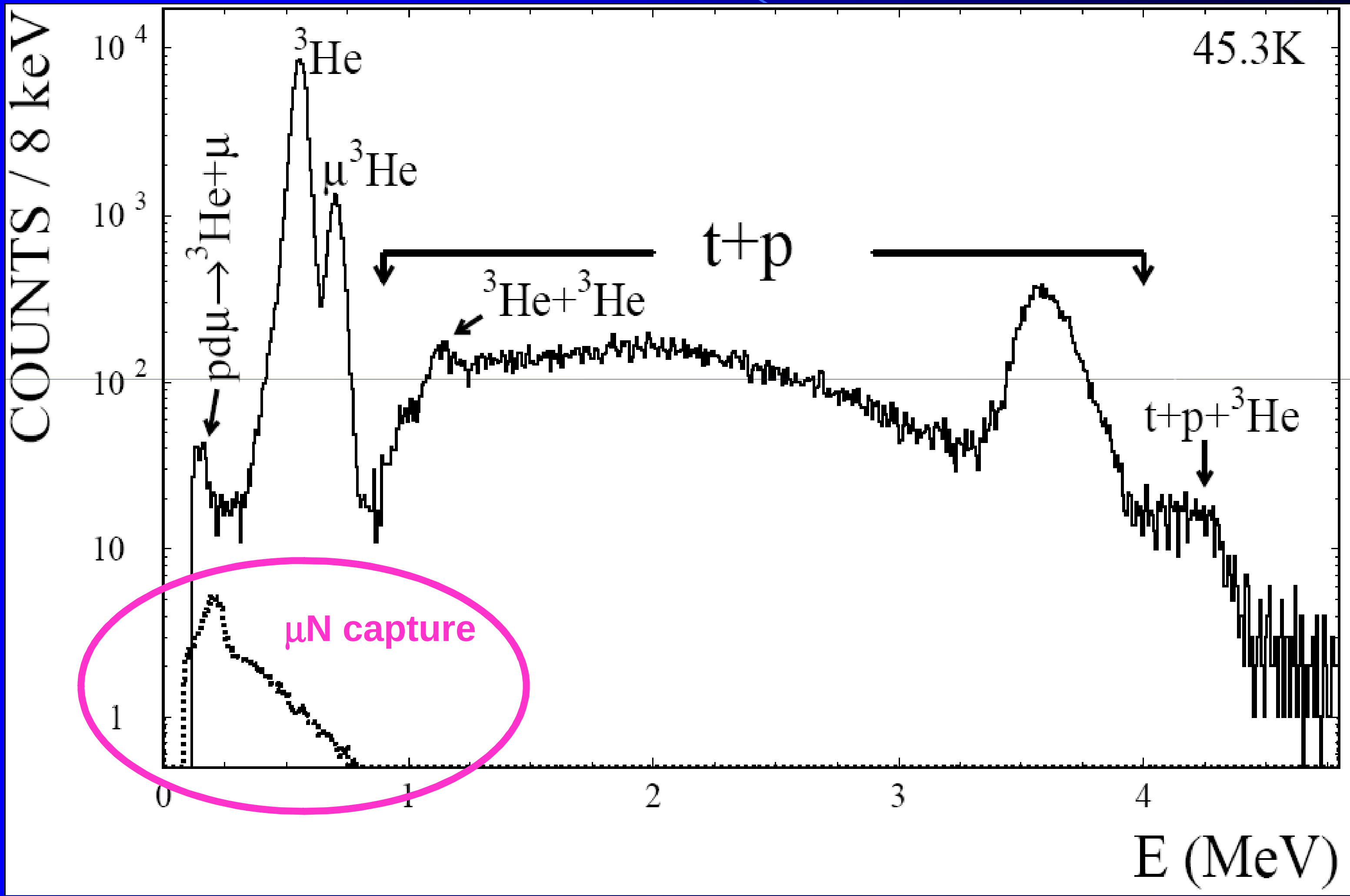


μd kinetics

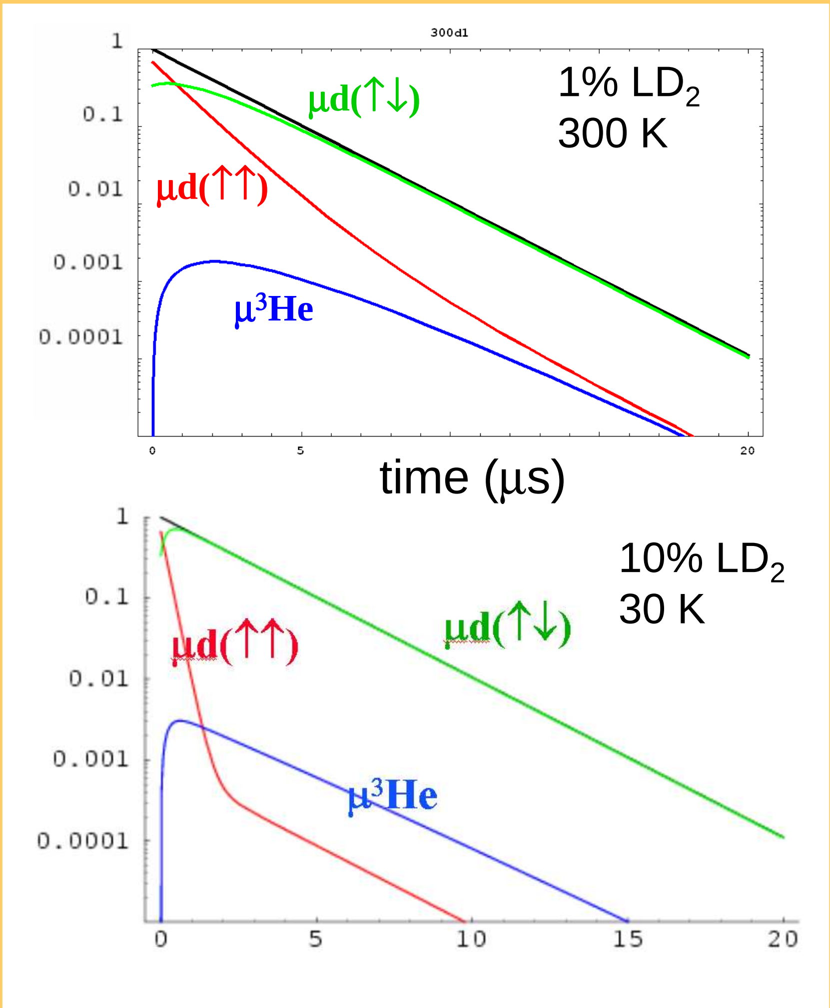


$\mu d_{\uparrow\uparrow}$
μ
$d\mu d$
$\mu d_{\uparrow\downarrow}$
μZ
μ
+ t + p
μ
+ ^{3}He + n
μ^3He
+ n
Λ_D
n + n + ν

Energy spectrum (from MCF exp.)



Approved proposal by PSI



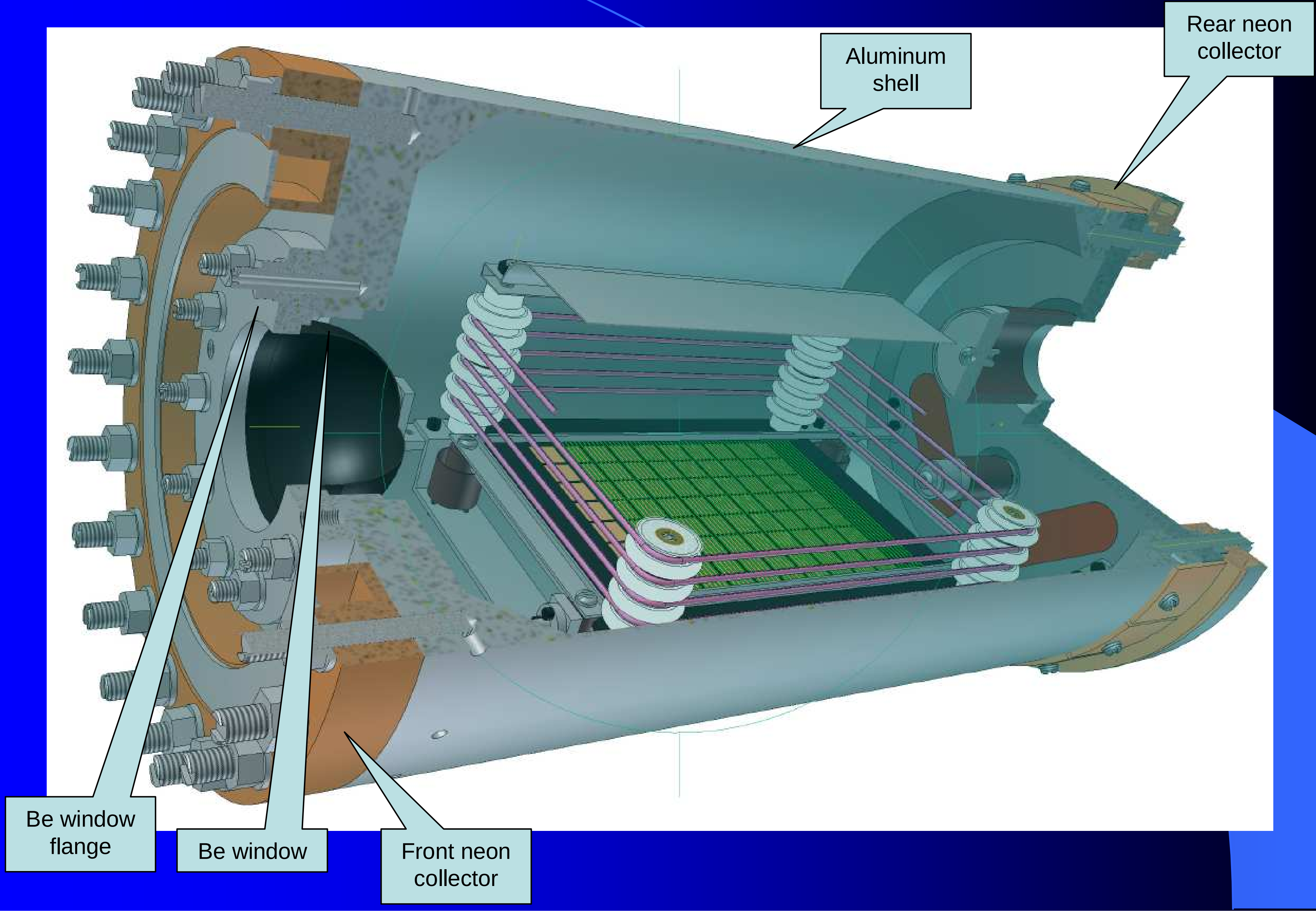
Stage 1:

- MuCap setup with 1% LD_2 and 300 K
- Prove excellent energy resol.
- Understand fusion and impurity events
- Measure nitrogen transfer rate
- Run finished end of 2008

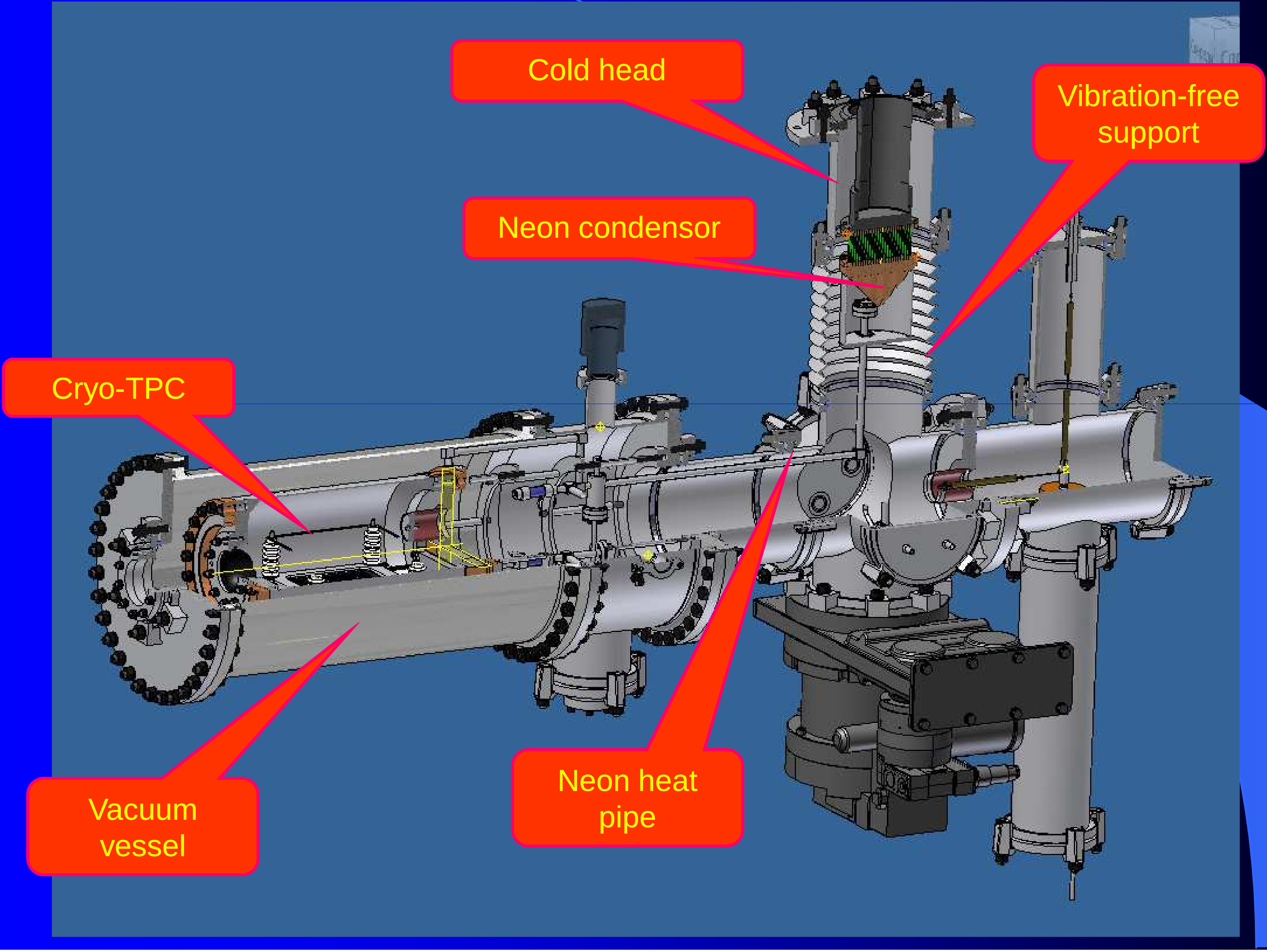
Stage 2:

- Measure Λ_D at >5% LD_2 and 30 K
- Cryo TPC development

Cryo-TPC development

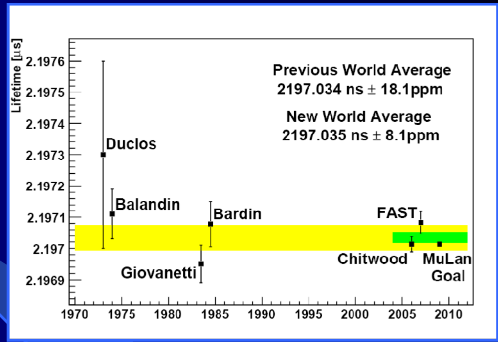


Cryo-TPC development

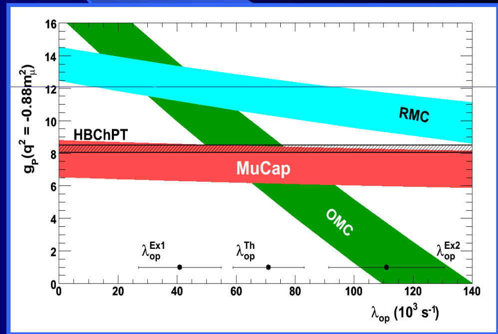


Overall summary

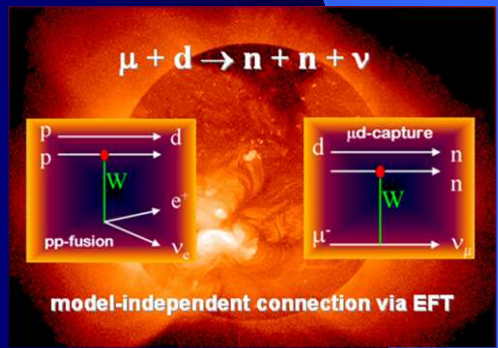
- MuLan:
  - First G_F update in 23 years – 2.5x improvement
  - **Factor 10 additional improvement on the way**



- MuCap:
  - First precise g_P with clear interpretation
  - Consistent with ChPT expectation, clarifies long-standing puzzle
  - **Factor 3 additional improvement on the way**



- MuSun
  - **Muon-deuteron capture with 10x higher precision**
  - Calibrates basic astrophysics reactions and provides new benchmark in axial 2N reactions



- ***Petersburg Nuclear Physics Institute, Gatchina, Russia***
- ***Paul Scherrer Institute, CH***
- ***University of California, Berkeley, USA***
- ***University of Illinois at Urbana-Champaign, USA***
- ***Université Catholique de Louvain, Belgium***
- ***University of Kentucky, Lexington, USA***
- ***Boston University, USA***
- ***James Madison University, USA***
- ***Regis University, Colorado, USA***

Science and arts belong

to the whole world,

and before them vanish

the barriers of nationality.

J. W. von Goethe

EXTRA Slides

- Non flat background: MuLan - kicker

Phenomenological calculation

$$dW = \delta(E_p - E_n + E_\mu - E_\nu) d^3p_\nu \; |M|^2/4\pi^2$$

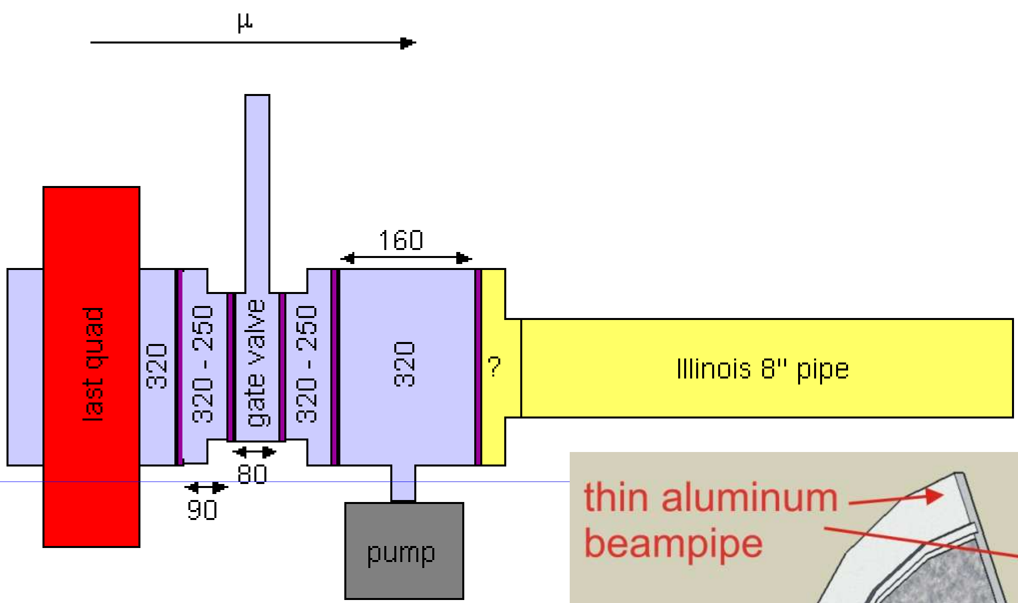
$$W = \frac{C_p^2}{2\pi^2 a_0^3} \frac{E_\nu^2}{1 + E_\nu/\sqrt{m_n^2 + E_\nu^2}} G_V^2 (1 + 3\eta) \left(1 - \frac{\langle \vec{\sigma} \cdot \vec{\sigma}_\Lambda \rangle \xi}{1 + 3\eta} \right)$$

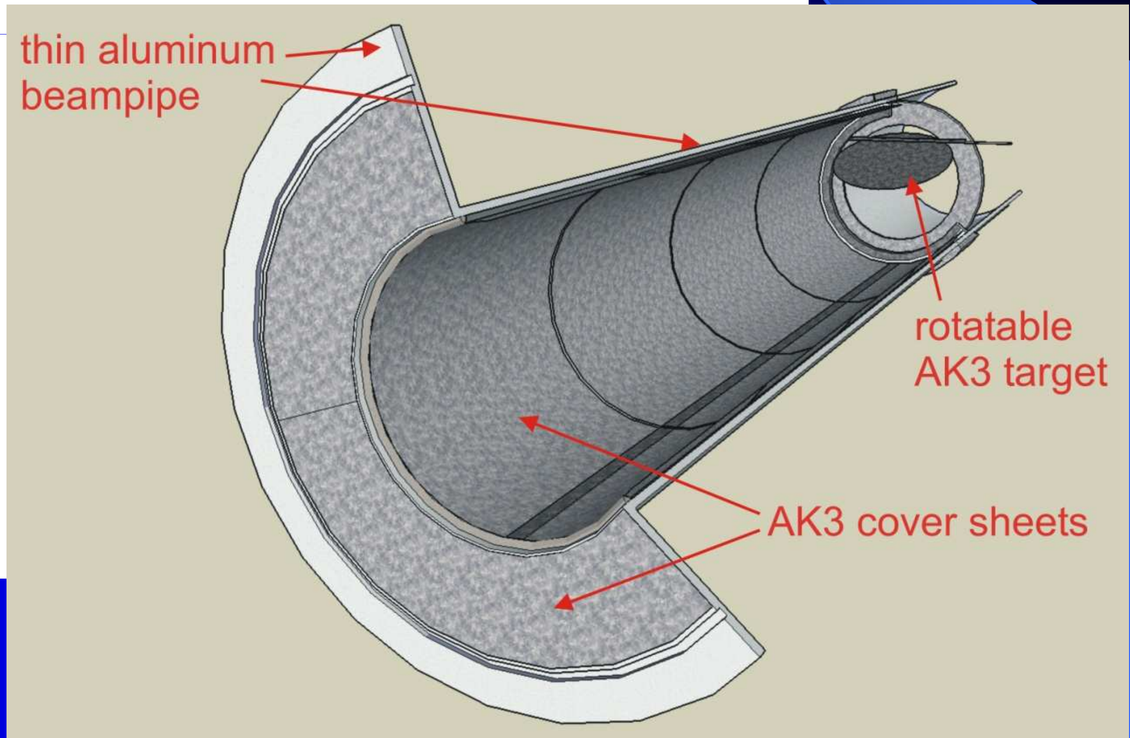
μp spin dependence

$$\Lambda_S = W_{F=0} = 690.0 \text{ s}^{-1}$$

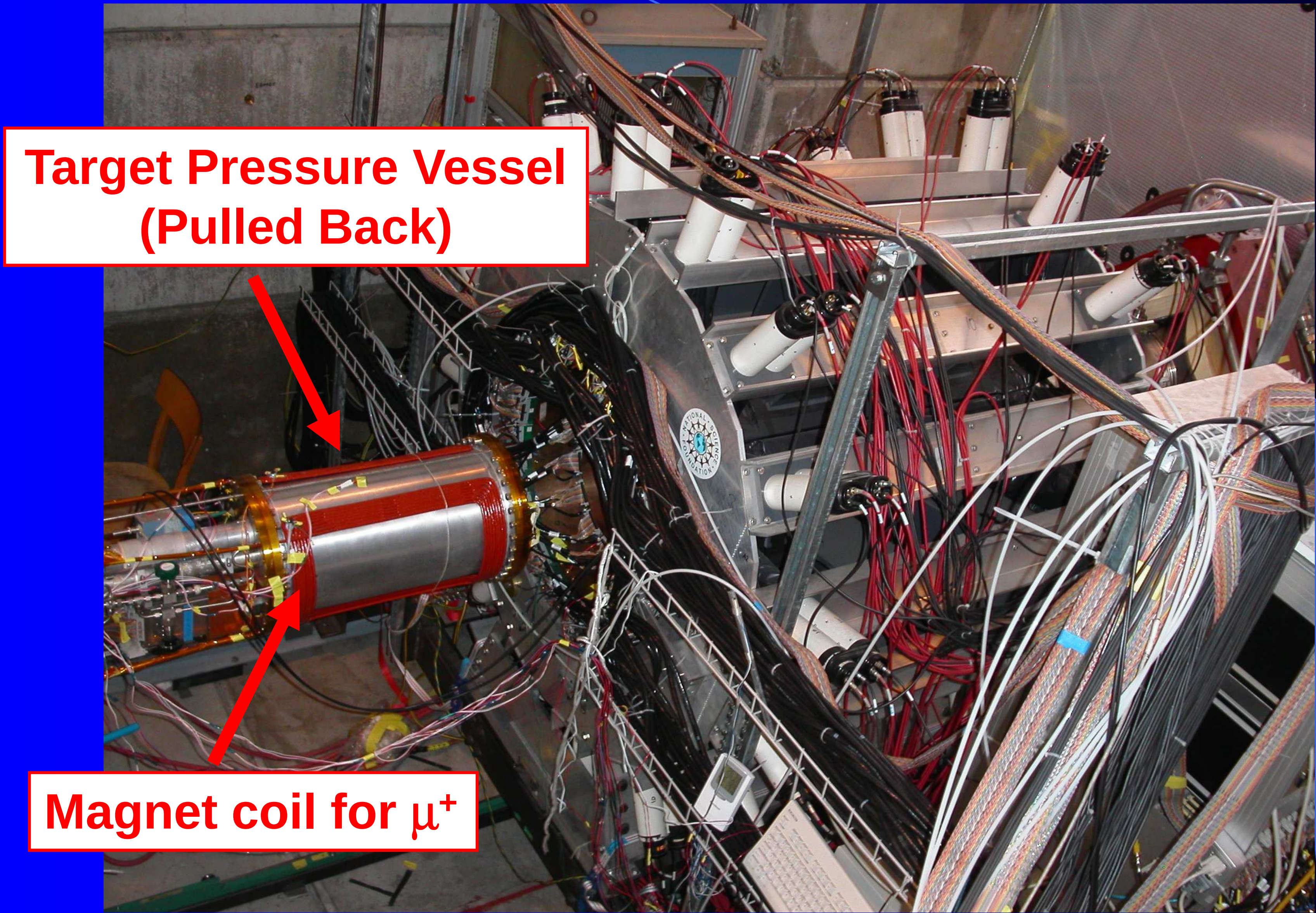
$$\Lambda_T = W_{F=1} = 11.3 \text{ s}^{-1}$$

Muon vacuum corridor

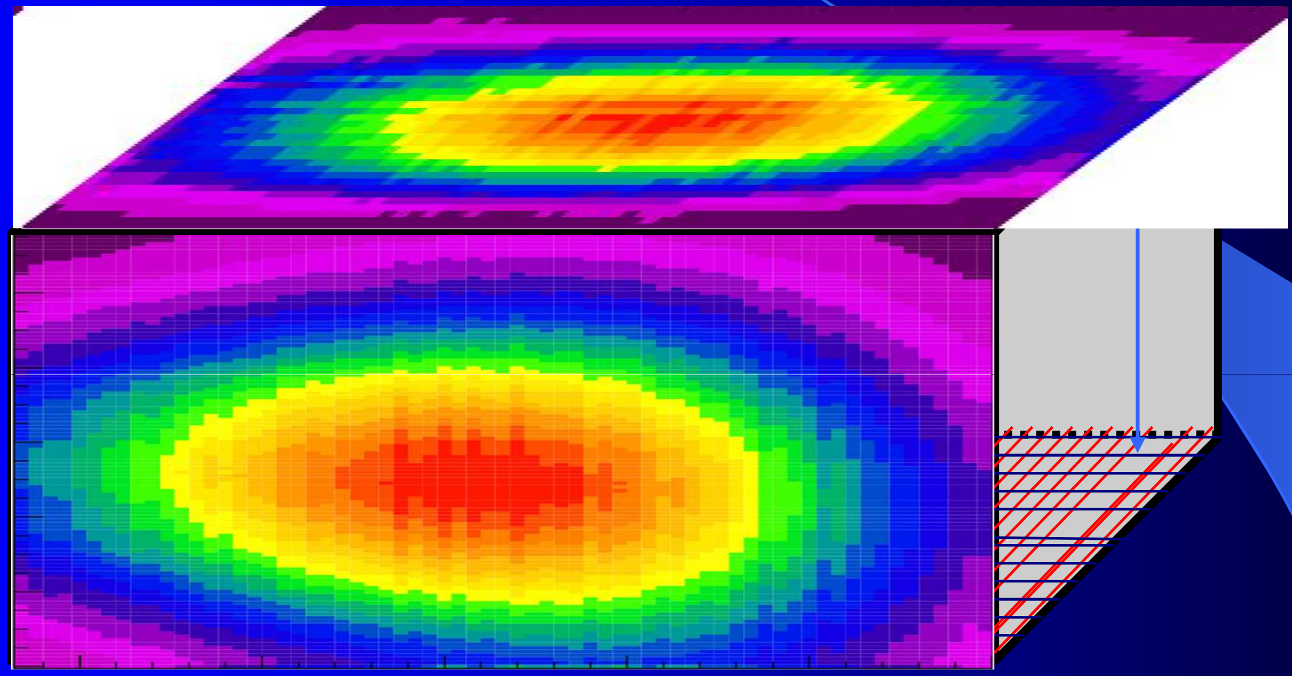




The MuCap detector



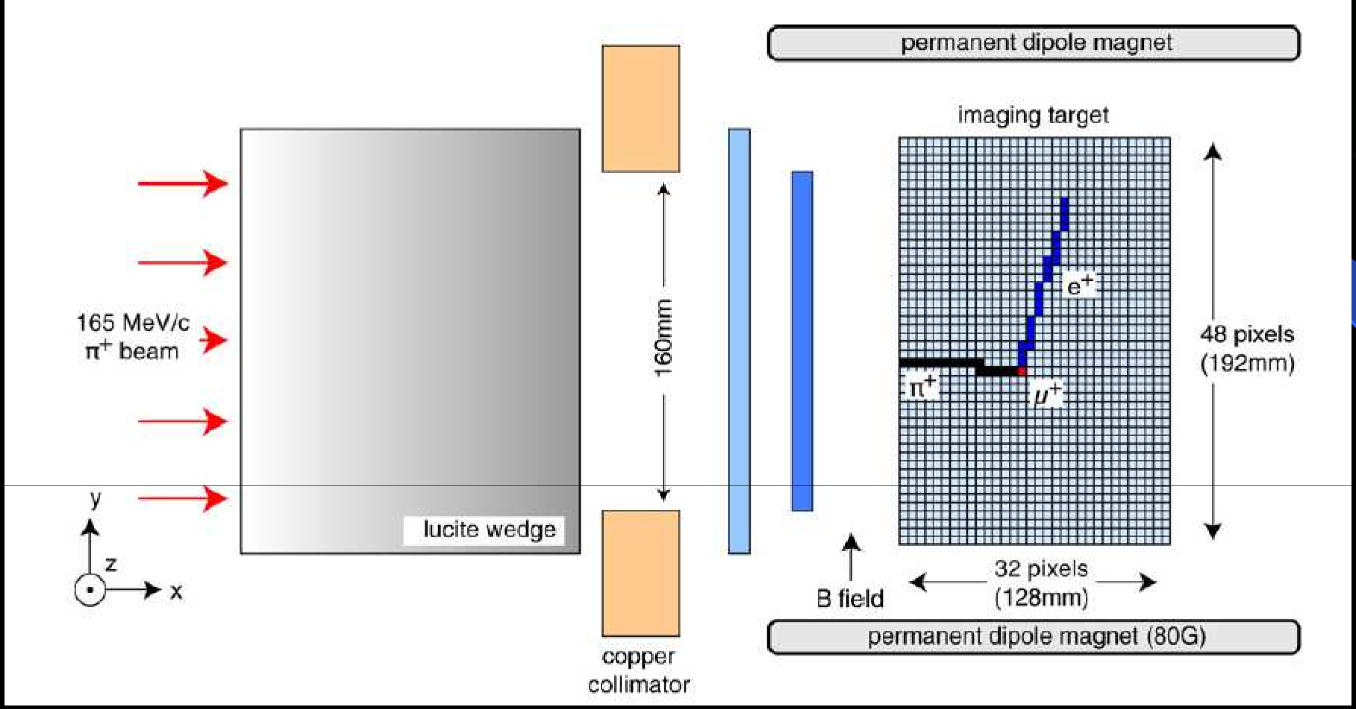
Stopping distribution

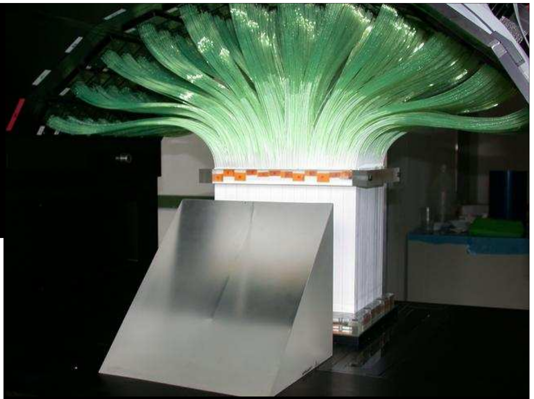


$\sigma_Z = 8$ cm

$\sigma_x = \sigma_y = 3.1$ cm

FAST Experiment





- **Fast imaging target** of 4x4x200 mm³ scintillators, PSPMs
- **Trigger: L1 selects π, L2 selects π → μ → e decay chain**
- **Essentially many small decay detectors in parallel**
- **Proof-of-principle measurement 16 ppm published 2008, 30 kHz L2**
- **One year run in 2008 to obtain 2 ppm τ result** (with improved L2)

Connection to Neutrino/Astrophysics

- Basic solar fusion reaction

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

- Key reactions for Sudbury Neutrino Observatory

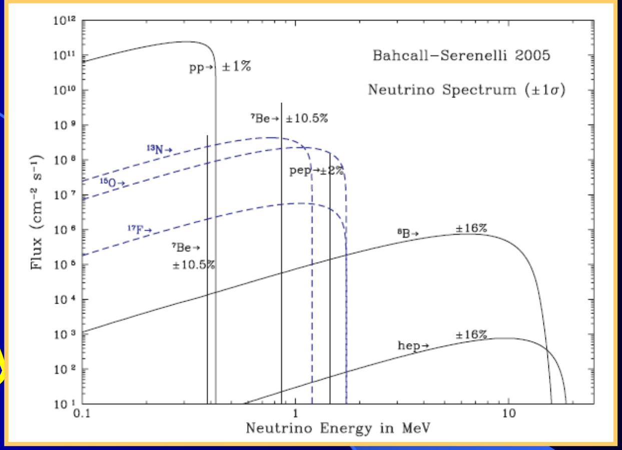
  $\nu_e + d \rightarrow p + p + e^-$ (CC)

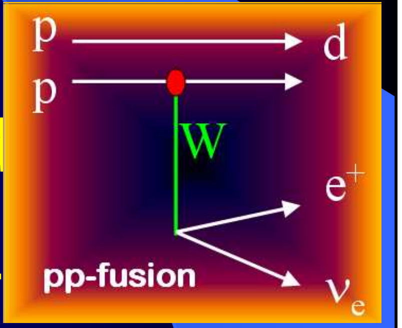
  $\nu_x + d \rightarrow p + n + \nu_x$ (NC)

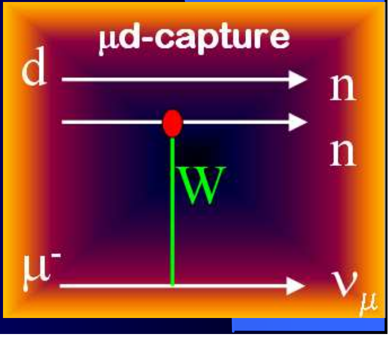
- Intense theoretical studies, scarce direct d
- EFT connection to m+d capture via LEC L

$$\sigma \approx \sigma_0 (1 + 0.013 \frac{L_{1A}}{fm^3})$$

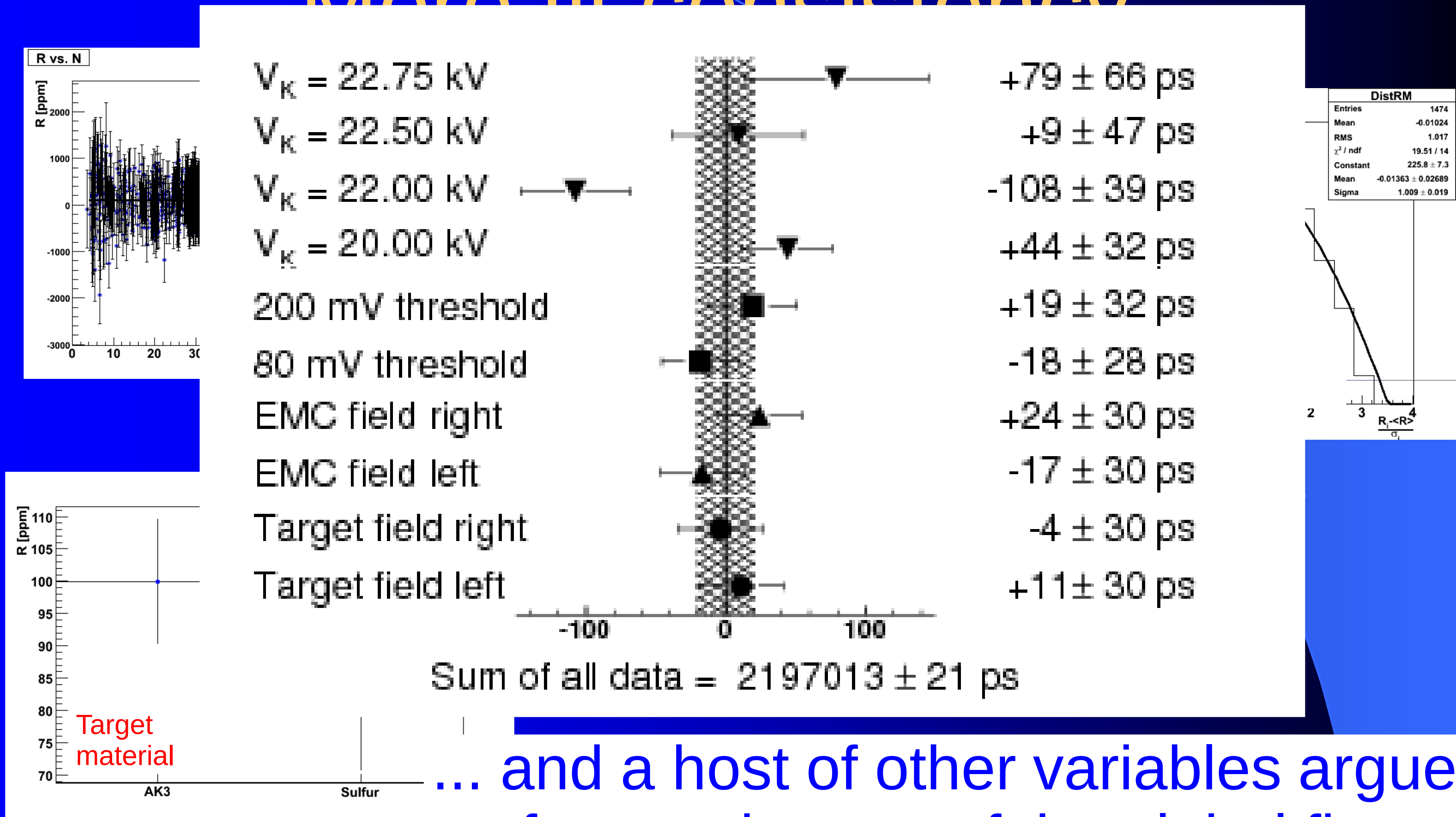
- Muon capture soft enough to relate to solar reactions





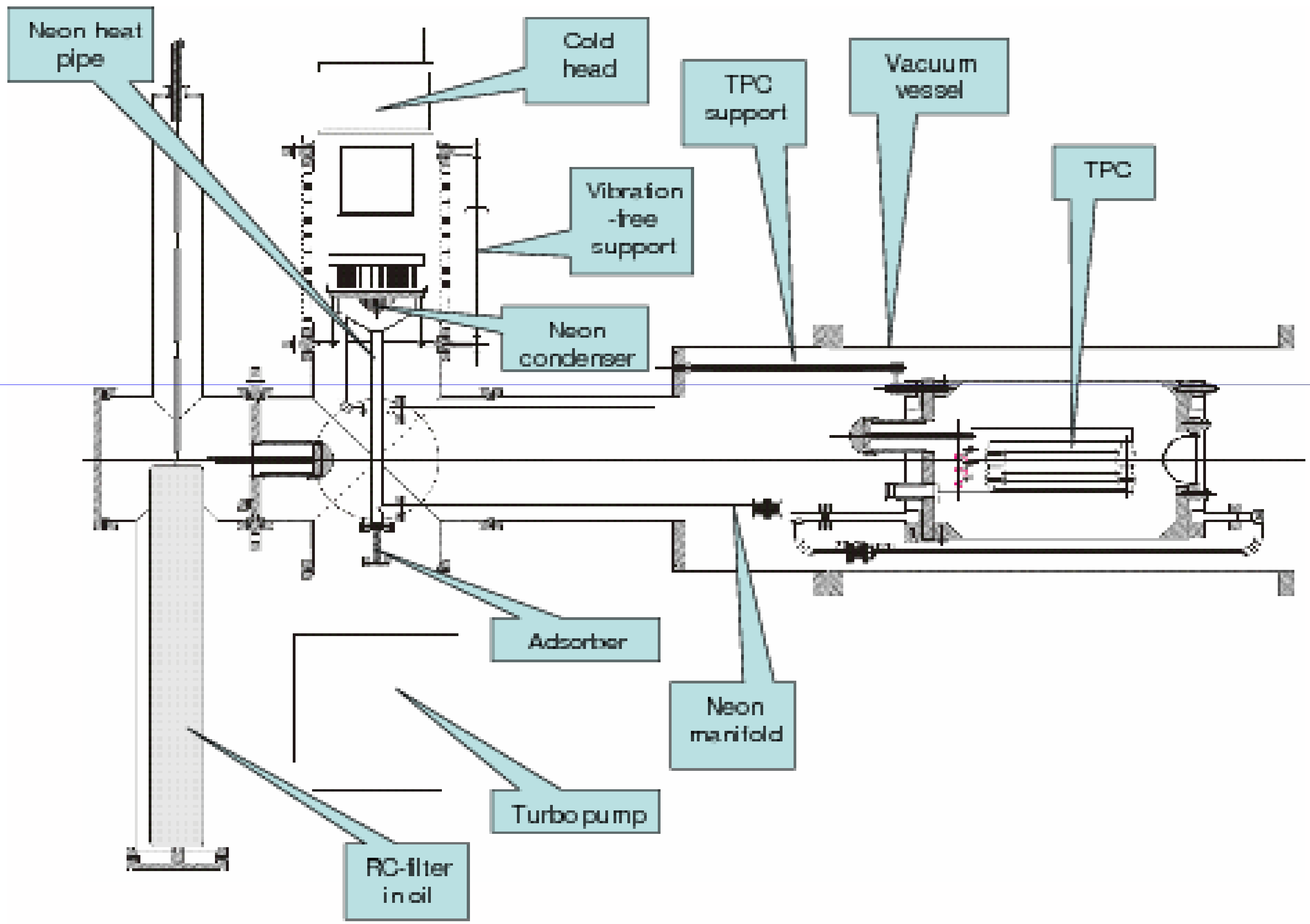


More fit consistency



... and a host of other variables argue for consistency of the global fit.

Cryo-TPC development



Neutrino flux SNO

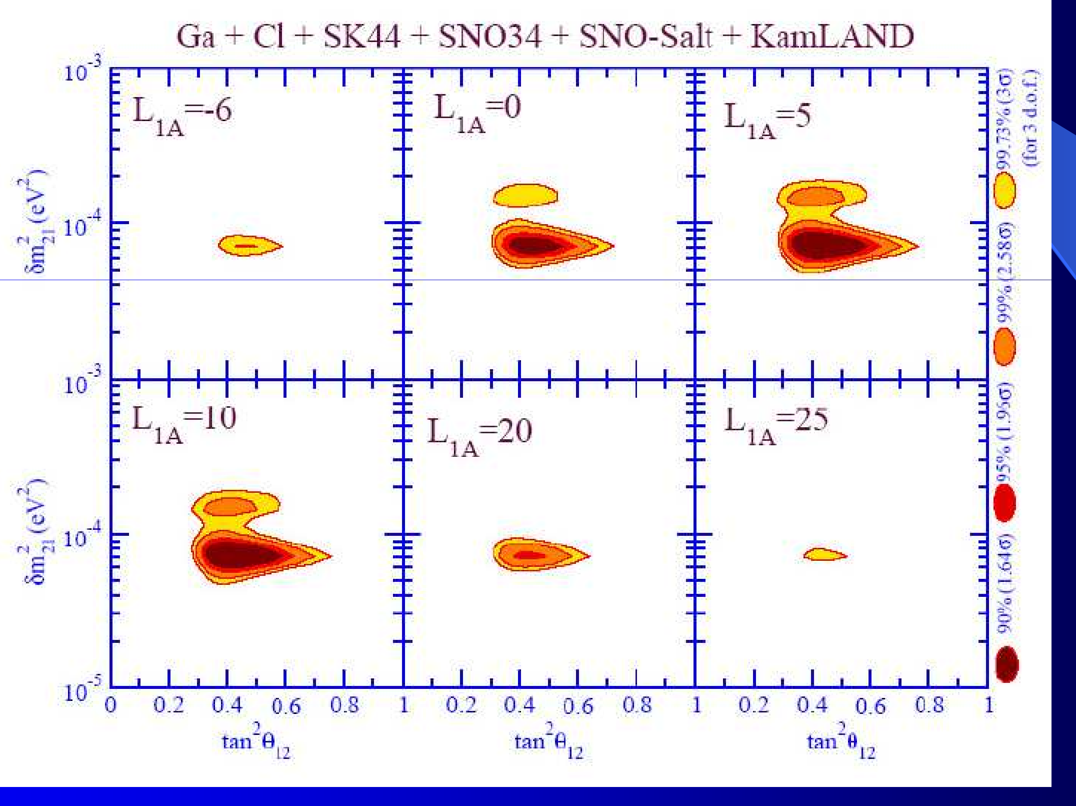
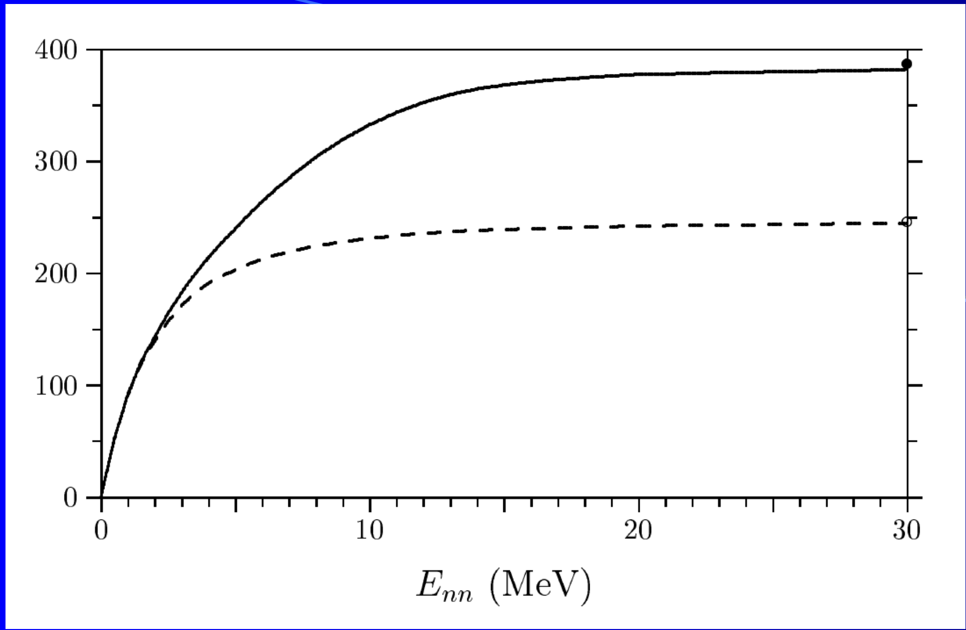
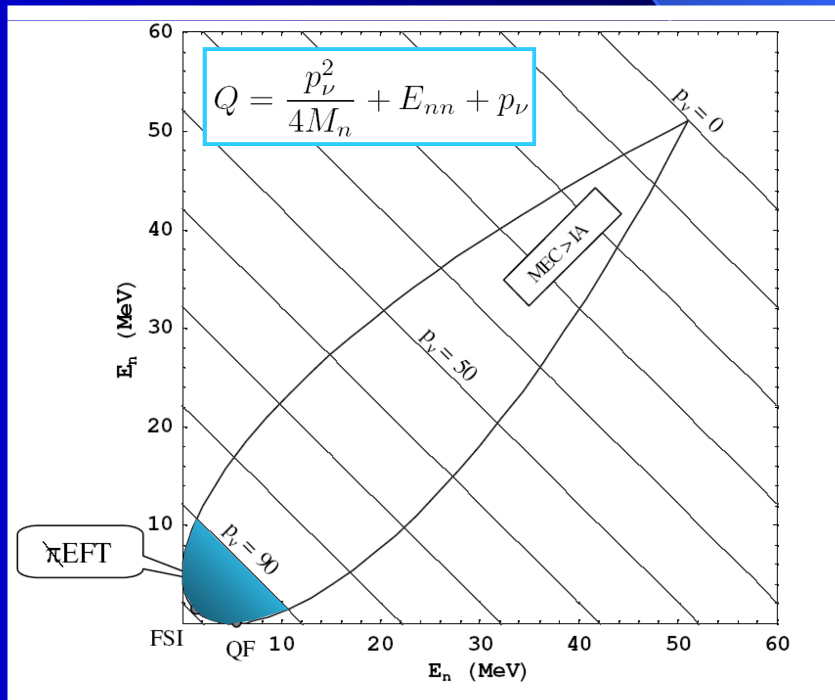


TABLE I. Numerical values of the parameters and derived quantities used in the text and in our evaluations of rates for comparison with experiment.

Symbol	Description	Value	Reference
F_π	pion decay constant	92.4 ± 0.3 MeV	Particle Data Group (2000)
$g_{\pi NN}(m_\pi^2)$	pion nucleon coupling	13.05 ± 0.08	de Swart *et al.* (1997)
$G_F V_{ud}$	Fermi constant for β decay	$1.135\,48 \times 10^{-5}$ GeV^{-2}	Particle Data Group (2000)
$g_a(0)$	axial coupling from β decay	1.2670 ± 0.0035	Particle Data Group (2000)
r_A^2	rms radius squared for g_a	0.44 ± 0.02 fm^2	Liesenfeld *et al.* (1999)
g_p^{PCAC}	PCAC value, $g_p(-0.88 m_\mu^2)$	$6.87\, g_a(0) = 8.70$	Eq. (5), leading term only
	PCAC value, NLO constant term included	$6.50\, g_a(0) = 8.23$	Eq. (5), including NLO correction
$\Lambda_{p\mu p}$	$p\mu p$ molecular formation rate	2.5×10^6 s^{-1}	average, Wright *et al.* (1998)
$\Lambda_{p\mu p}^{ortho}/\Lambda_{p\mu p}^{para}$	ratio of ortho to para molecular formation	240:1	Faifman and Men'shikov (1999)
Λ_{op}	ortho to para transition rate	$4.1 \pm 1.4 \times 10^4$ s^{-1}	Bardin *et al.* (1981a)
$2\gamma^{ortho}$	ortho-molecular overlap factor	1.009 ± 0.001	Bakalov *et al.* (1982)
$2\gamma^{para}$	para-molecular overlap factor	1.143 ± 0.001	Bakalov *et al.* (1982)
$g_m(0)$	weak magnetism coupling, $\kappa_p - \kappa_n$	3.705 89	Particle Data Group (2000)
r_m^2	rms radius squared for g_m	0.80 fm^2	Mergell *et al.* (1996)
r_v^2	rms radius squared for g_v	0.59 fm^2	Mergell *et al.* (1996)

	method	L_{1A} (fm^3)	comment
two-body			
	reactor $\bar{\nu} + d$	3.6 ± 5.5 [11]	i)
	ES, CC, NC in SNO	4.0 ± 6.3 [41]	ii)
	MuSun proposal	**±1.25**	
three-body			
	tritium beta decay	4.2 ± 3.7 [11], 4.2 ± 0.1 [41]	iii)
other			
	helioseismology	4.8 ± 6.7 [42]	iv)


400
300
200
100
0
0
10
20
30
E_{nn} (MeV)


$Q = \frac{p_\nu^2}{4M_n} + E_{nn} + p_\nu$
$p_\nu = 0$
MEC > IA
$p_\nu = 50$
$p_\nu = 90$
π̸EFT
FSI
QF
E_n (MeV)
E_n (MeV)
10
20
30
40
50
60