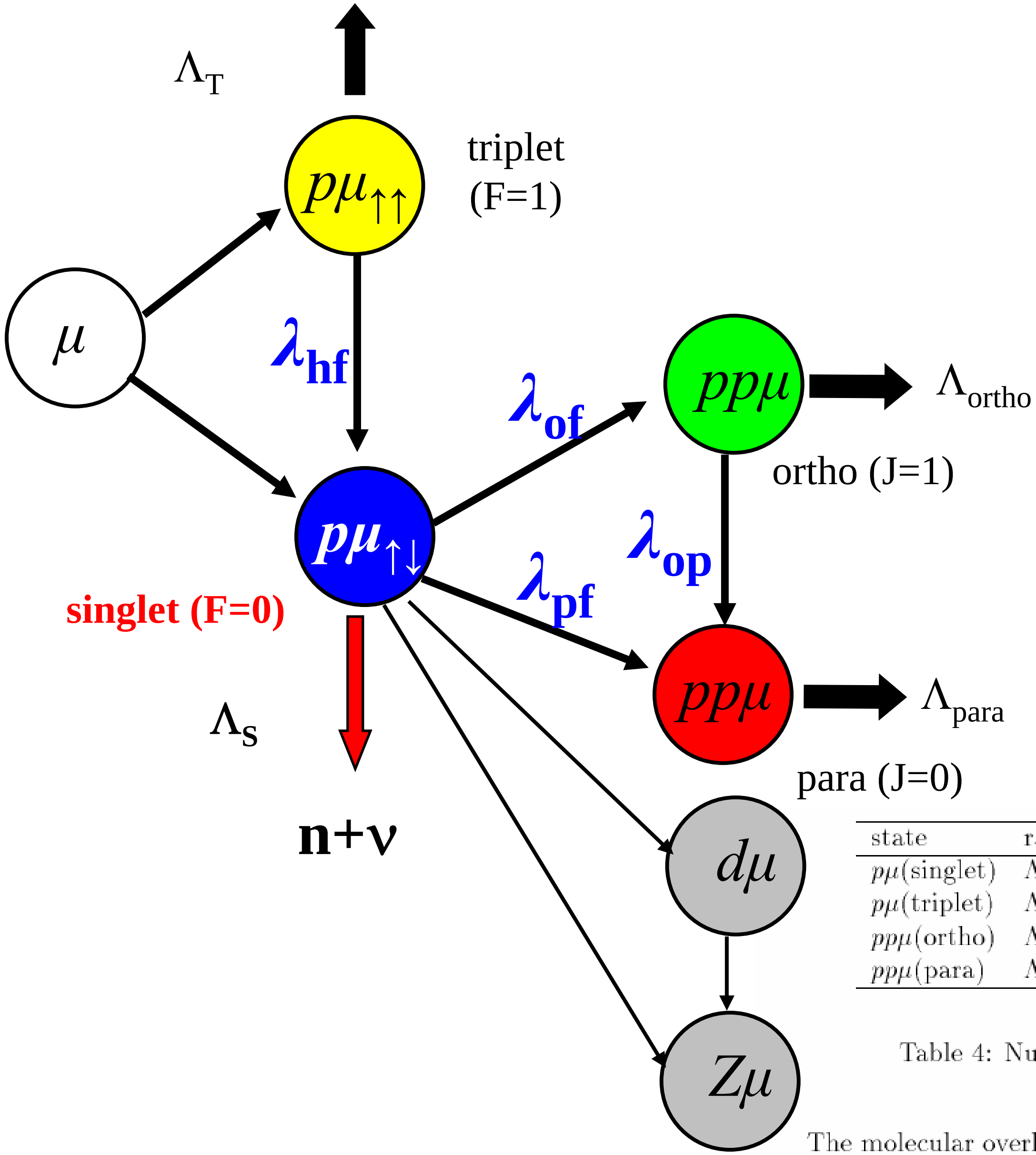
Physics: Interpretation

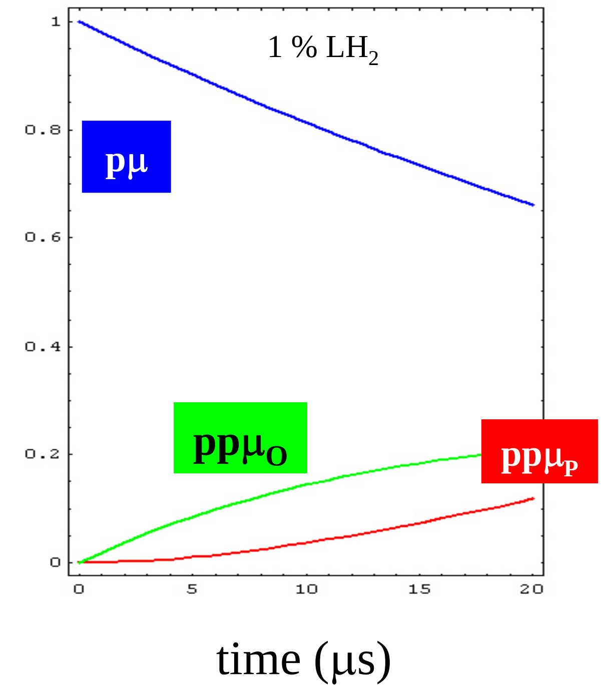
$\delta\lambda$

- **Experimental issues**
  - λ_{op} — **neutron detectors** — $\pm$ **5 ppm**
  - λ_{pp} — **measure 2007** — $\pm$ **9 ppm**
  - λ_{hfs} — **start time scan** — **small**

- **Other issues**
  - **consistency Λ_S calcs**
  - **new neutron lifetime measurement**
  - **radiative corrections**
  -

Kinetics: Overview





95.2% pμ

state	rate	theoret. prediction (s^{-1})
$p\mu$(singlet)	Λ_s	664
$p\mu$(triplet)	Λ_t	12
$pp\mu$(ortho)	$\Lambda_{om} = 2\gamma_o(0.75\Lambda_s + 0.25)\Lambda_t$	506
$pp\mu$(para)	$\Lambda_{pm} = 2\gamma_p(0.25\Lambda_s + 0.75)\Lambda_t$	200

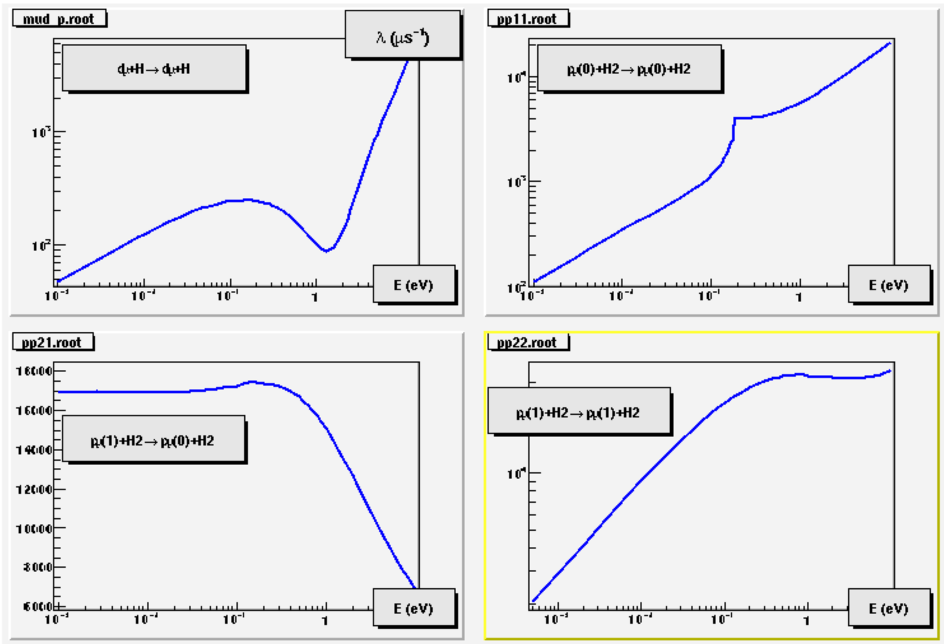
Table 4: Nuclear capture rates in $p\mu$ atoms and $pp\mu$ molecules.

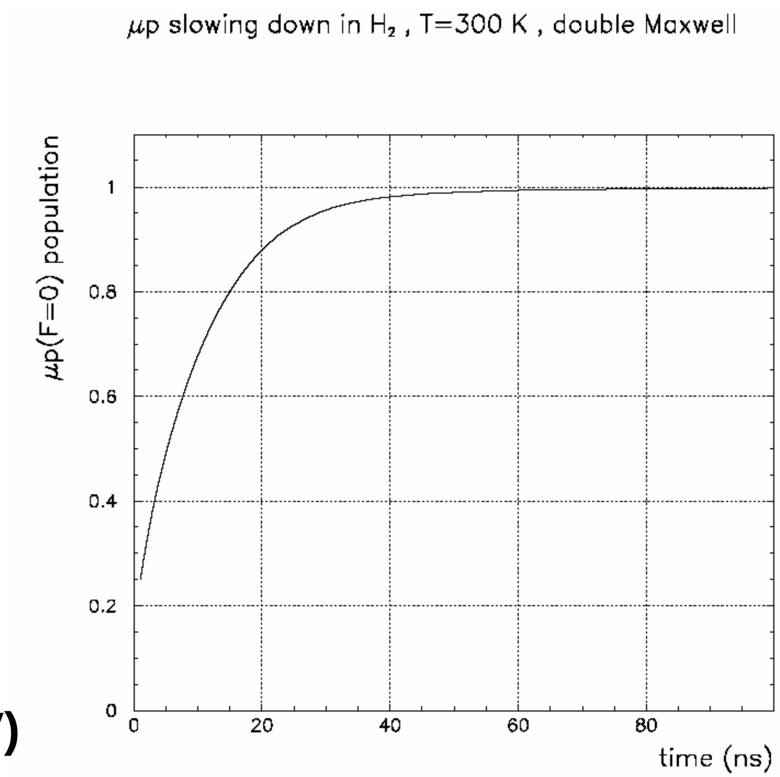
The molecular overlap factors are calculated by theory as $2\gamma_o = 1.009 \pm 0.001$ and $2\gamma_p = 1.143 \pm 0.001$ [8]. Further relativistic corrections might lead to $1-2\%$ corrections

hfs transition

- **Theory**

the hfs energy splitting is 0.182 eV





from MuScat, T=30K, PK check, **μx T(eV)**

λ_{hf}= 170 MHz = 1/(5.9ns)

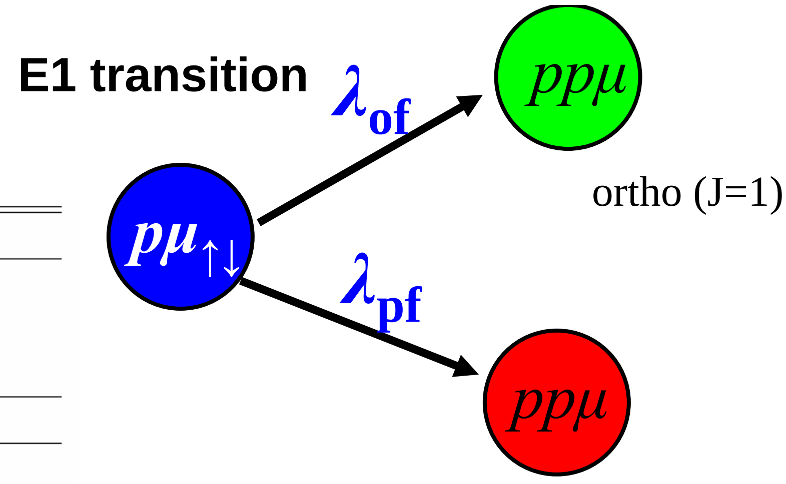
- **Experiment: fairly uncertain, Siegel, Mulhauser**
- **Run8: check experimentally with different λ_{hf}**

PK finish study, T&S Fit

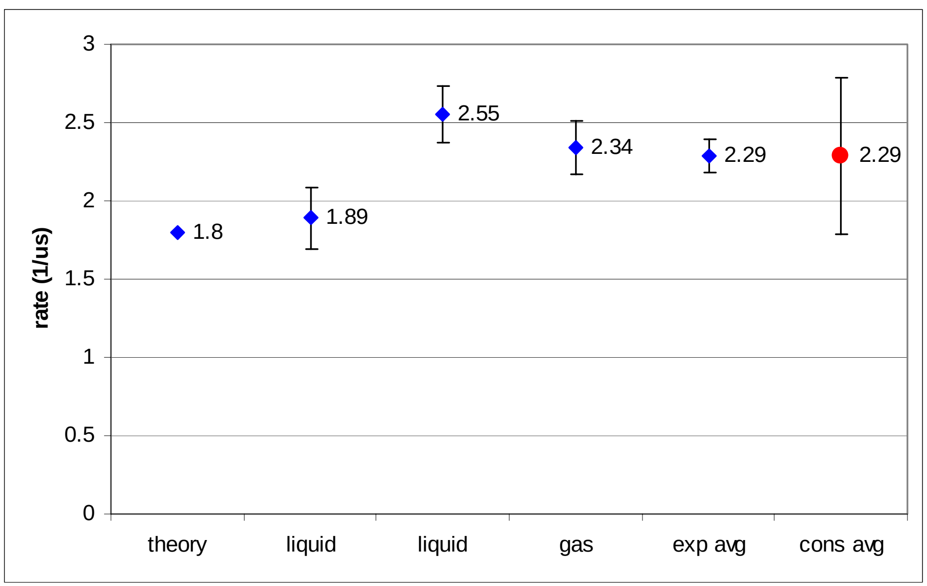
ppμ formation

Theory	Rate ($10^6\ s^{-1}$)		Ref.
	2.6		[7]
	3.9		[44]
	2.2		[9]
	1.8		[8]
Experiment	**Rate ($10^6\ s^{-1}$)**	**Conditions**	**Ref.**
	$0.6^{+0.8}_{-0.5}$	Gas	[45]
	1.89 ± 0.20	Liquid	[18]
	2.55 ± 0.18	Liquid	[37]
	2.74 ± 0.25	Gas	[38]
	2.34 ± 0.17	Gas	[39]
	$3.56 \pm (0.38)_{stat} \pm (0.17)_{syst}$	Solid	[40]
	$3.21 \pm (0.10)_{stat} \pm (0.14)_{syst} (^{+0}_{-0.06})_{model}$	Solid	this work

λ_{of}	1.8	theory[23]
λ_{pf}	0.0074	theory[23]



F. Mulhauser et al., Phys. Rev. A 53, 3069-3080 (1996)

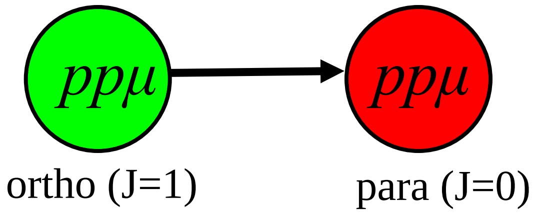


conservative average

2.29±0.5 MHz (22%)

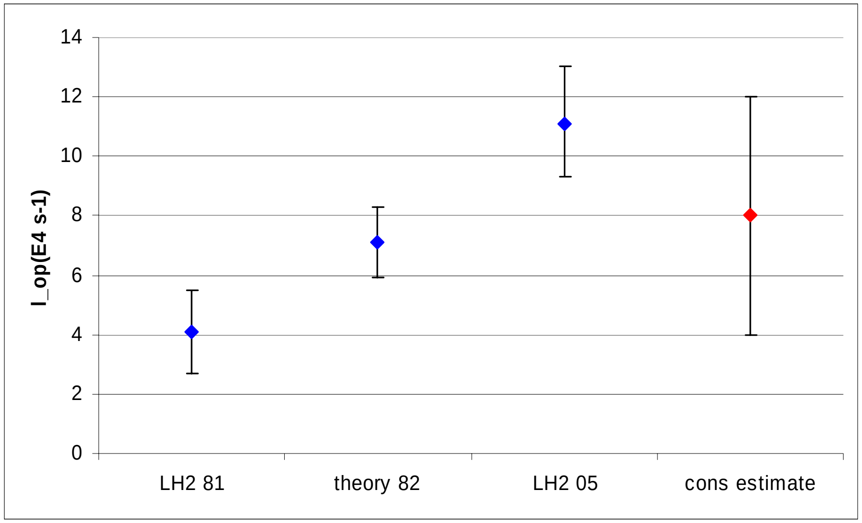
Francoise, please evaluate references and check

o-p transition



- **results**

year	Method	λ_{op} (10^4/s)
1981	Exp LH2	4.1(1.4)
1982	Theory	7.1(1.2)
2005	Exp LH2	11.1±1.7+0.9-0.6



- **MuCap limit with neutron detectors run10 ?**
  - **The situation is confused and not much guidance available from the literature.**
  - **MuCap uses 1% of LH2 density which, though not expected, might change λ_{op} from the measured value(s) at LH2**

Equations

$$
\begin{aligned}
&n1'[t] == (-r0 - ph\ rpp - Rs)\ n1[t] \\
&n2'[t] == ph\ rpp\ n1[t] + (-r0 - Rom - rop)\ n2[t] \\
&n3'[t] == rop\ n2[t] + (-r0 - Rpm)\ n3[t] \\
&\{n1[0],\ n2[0],\ n3[0]\} == \{1,\ 0,\ 0\}
\end{aligned}
$$

Rom and Rpm can be expressed by Rs as shown in previous slide.

solutions

$$
\begin{pmatrix}
e^{-(ph\ rpp+Rs)\ t} \\
\dfrac{\left(e^{-(Rom+rop)\ t} - e^{-(ph\ rpp+Rs)\ t}\right) ph\ rpp}{-Rom-rop+ph\ rpp+Rs} \\
\dfrac{e^{-(Rom+rop+Rpm+ph\ rpp+Rs)\ t}\ ph\ rop\ rpp\ \left(e^{(Rom+rop+Rpm)\ t}\ (Rom+rop-Rpm) + e^{(Rpm+ph\ rpp+Rs)\ t}\ (Rpm-ph\ rpp-Rs) + e^{(Rom+rop+ph\ rpp+Rs)\ t}\ (-Rom-rop+ph\ rpp+Rs)\right)}{(Rom+rop-Rpm)\ (Rom+rop-ph\ rpp-Rs)\ (Rpm-ph\ rpp-Rs)}
\end{pmatrix}
$$

μp: **Power(E,-((ph*rpp + Rs)*t))**

μppO:((Power(E,-((Rom + rop)*t) - Power(E,-((ph*rpp + Rs)*t)))*ph*rpp)/ (-Rom - rop + ph*rpp + Rs)

μppP: (ph*rop*rpp*(Power(E,(Rom + rop + Rpm)*t)*(Rom + rop - Rpm) + Power(E,(Rpm + ph*rpp + Rs)*t)*(Rpm - ph*rpp – Rs) + Power(E,(Rom + rop + ph*rpp + Rs)*t)*(-Rom - rop + ph*rpp + Rs)))/ (Power(E,(Rom + rop + Rpm + ph*rpp + Rs)*t)*(Rom + rop - Rpm)*(Rom + rop - ph*rpp - Rs)*(Rpm - ph*rpp - Rs))

Kinetics study

Sensitivity studies

- **original proposal**
- **neutron detector proposal**
- **Steve's new fits**

The results are summarized in the following table.

Kinetic assumption Rates in μs^{-1}	Relative change in **electron** disappearance rate (ppm)	Relative change in **neutron** disappearance rate (ppm)	
λ_{op}=0.0, λ_{pp}=2	0	0	moment method
	0	0	fit method (0.05-20 µs)
λ_{op}=0.08, fit 0.05-20us	-11	5569	moment method
	-12	5482	fit method
λ_{op}=0.20	-23	10468	moment method
	-21.6	10330	fit method
λ_{op}=0.20, fit 0.05-10us	-15	9306	fit method !
λ_{pp}*1.5	-18.4	7054	moment method
	-17.6	6899	fit method

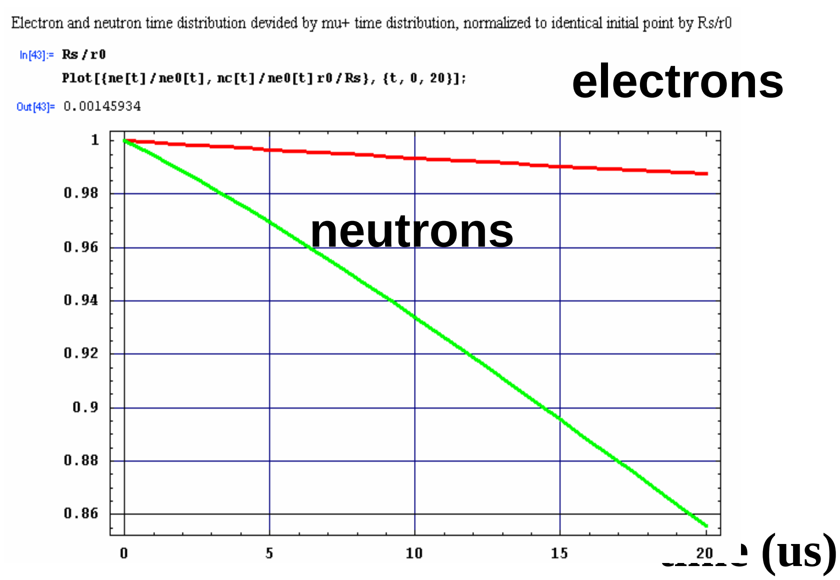
systematically calculate λ_e, λ_n as function of λpp (0-3 /µs) PK, Steve, Tom

http://kaon.physics.berkeley.edu:8080/run9-prep/12
I will post update

$\Delta\lambda_e$= 10 ppm ≈ $\Delta\lambda_n$= 5 10^{-3}

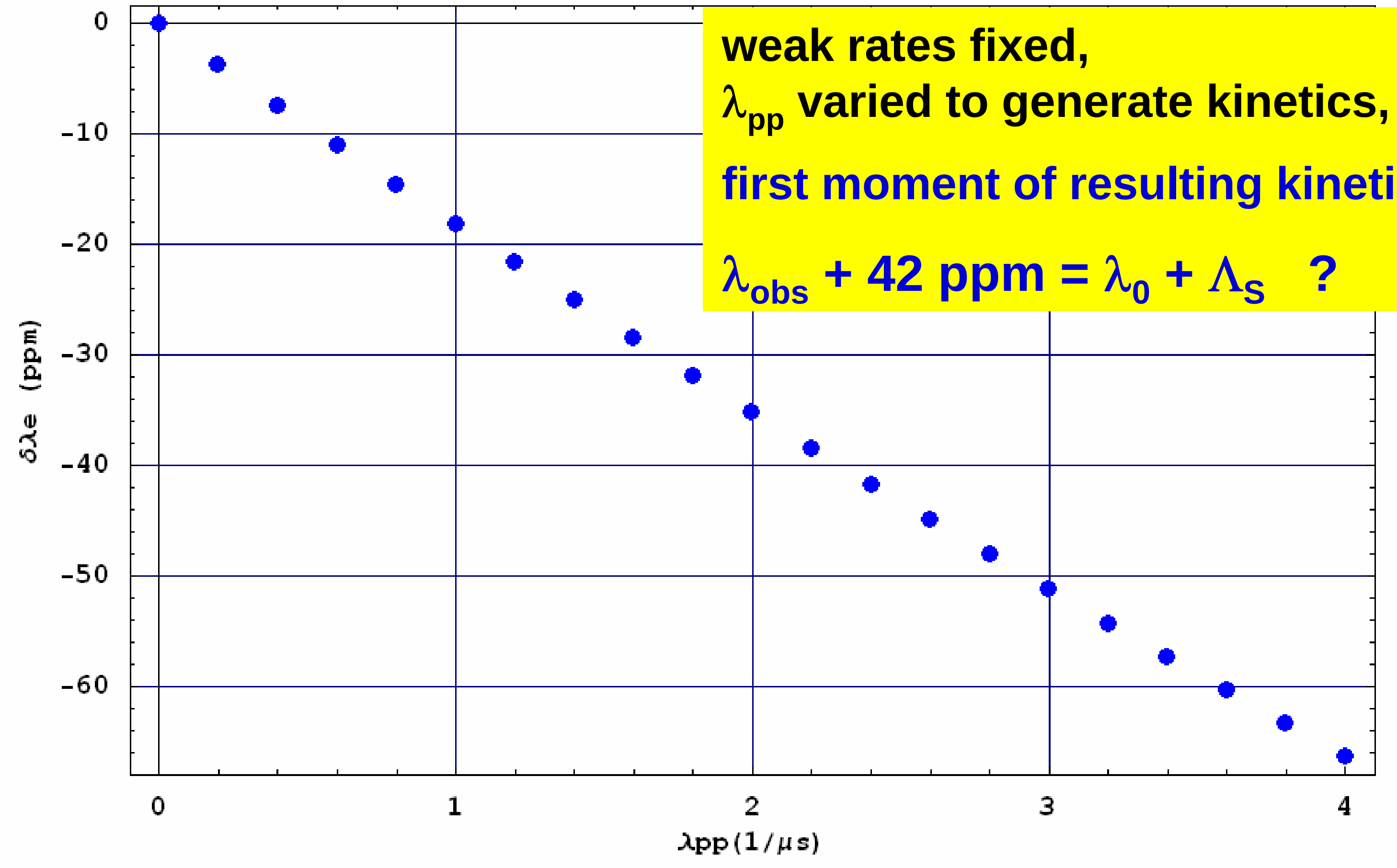
We need to measure $\Delta\lambda_n$ to ~3 10^{-3}!

(At present $\Delta\lambda_n$= xx 10^{-3}, Tim)



e decay rate vs λ_{pp}

first moment method



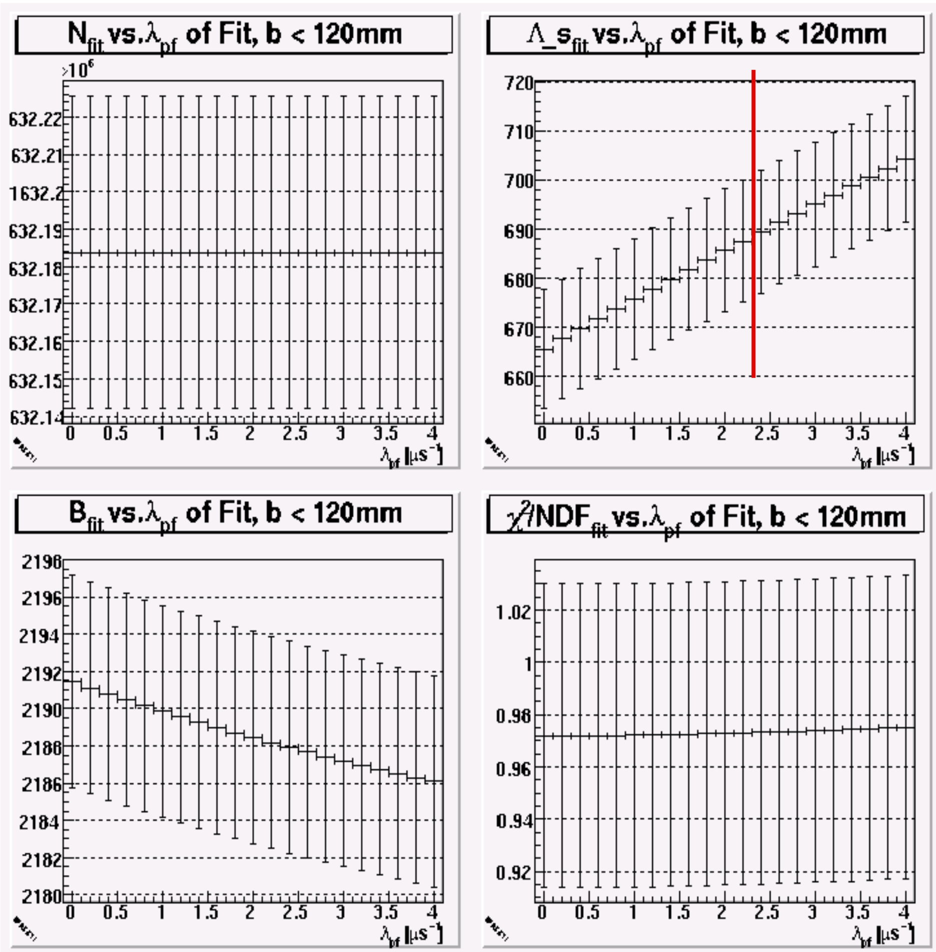
weak rates fixed,
λ_{pp} varied to generate kinetics,

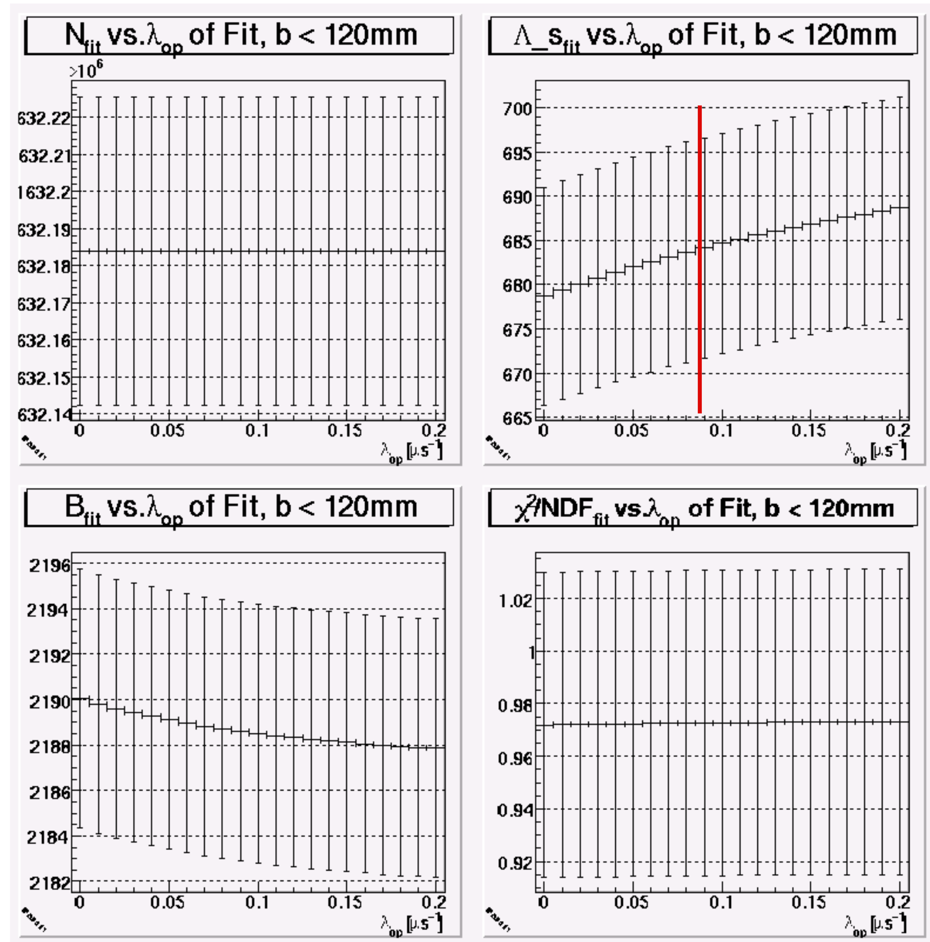
first moment of resulting kinetics calculated.

λ_{obs} + 42 ppm = $\lambda_0 + \Lambda_S$?

last moment exercise. Check analytically, and with fit of MC and real data to investigate consistency and start/stop time dependence.

Steve's fit to prod-50 data





18 Hz (40ppm) change for λ_{pp}=2.3 /μs

l_pf = 0.0074 MHz
l_op = 0.08 MHz
phi = 0.0116

5 Hz (11ppm)change for λ_{op}=0.08 /μs

l_pf = 0.0074 MHz
l_of = 1.80 MHz
phi = 0.0116

Correction and uncertainty

- **Approximate correction** $\delta\lambda = \lambda_2 - \lambda_1$

  $\delta\lambda_{op}$= (0.1-0.) MHz $\approx$ -13.7 ppm $\delta\lambda_e/\lambda_e$

  $\delta\lambda_{pp}$=(3-2) MHz $\approx$ -18 ppm $\delta\lambda_e/\lambda_e$

  $$\frac{\partial \lambda e}{\lambda e \ \partial \lambda op} = -137 \text{ ppm } \mu s \quad @ \quad \lambda op=0.08$$

  $$\frac{\partial \lambda e}{\lambda e \ \partial \lambda pp} = -18 \text{ ppm } \mu s \quad @ \quad \lambda pp=2.0, \text{LH2}$$

- **Perform fit to final corrected time spectra**

  Solution as given in appendix of proposal and this talk using

  analytical correction for $\delta\lambda_e/\lambda_e$ observed

  λ_{op}= 0.08 MHz **+11 ppm**

  λ_{pp}= 2.3 MHz **+42 ppm**

  FM check best value

- **Calculate uncertainty as**

  $\delta\lambda_e/\lambda_e$= ± 5 ppm from $\delta\lambda_{op}$ = ± 0.04 MHz

  $\delta\lambda_e/\lambda_e$= ± 9 ppm from $\delta\lambda_{pp}$ = ± 0.5 MHz

- **Parametrize correction**

  $\delta\lambda_e/\lambda_e$= + 137 ($\lambda_{op}$(new) – 0.08) ppm

  $\delta\lambda_e/\lambda_e$= + 18 ($\lambda_{pp}$(new)-2.3) ppm

  if new results for λ_{op} and λ_{pp} (MHz) become available.