Frictional Cooling

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Studies at Columbia University/Nevis Labs
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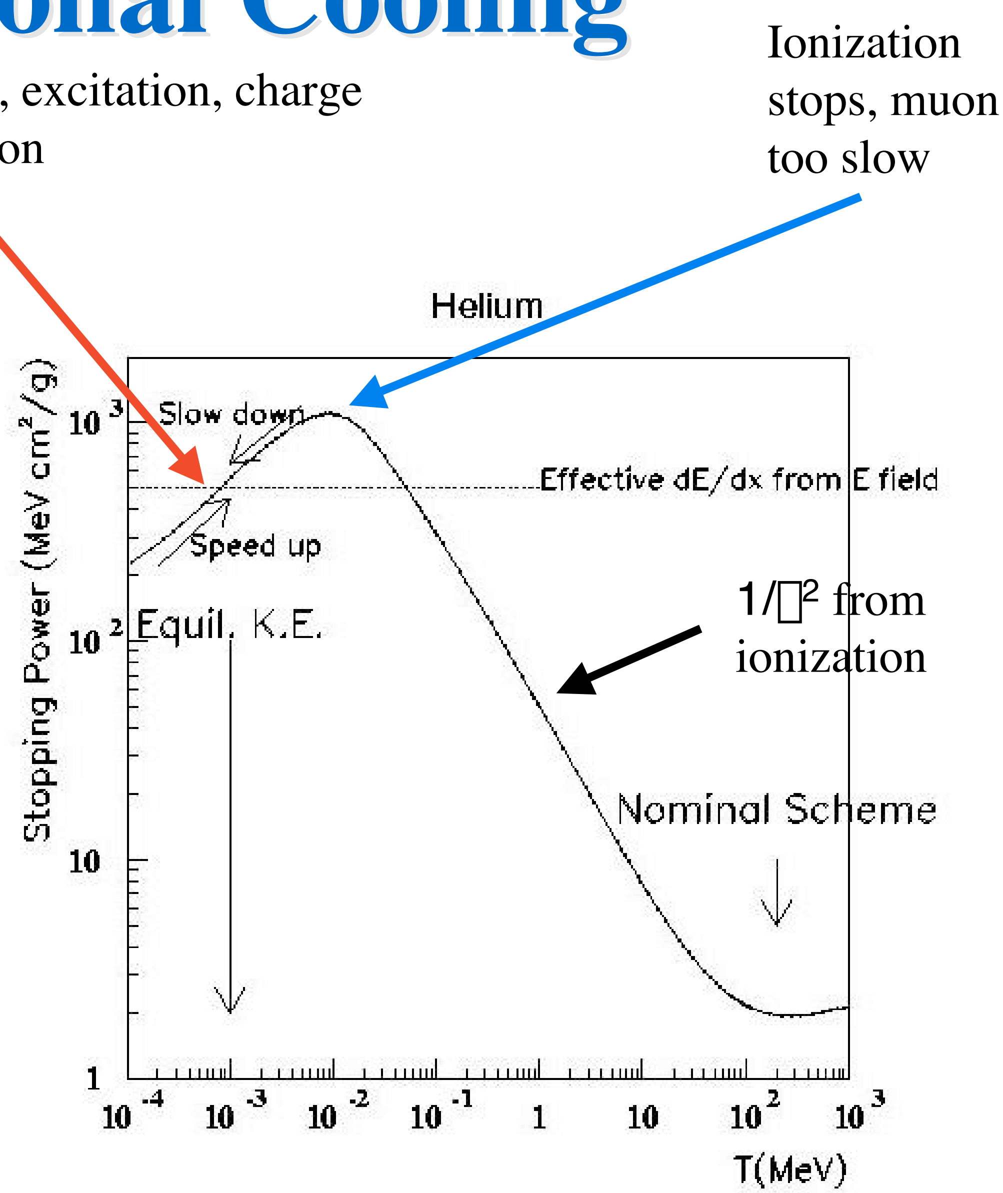
- Brief introduction
- Muon Collider based on Frictional Cooling
- Frictional Cooling with protons
- Conclusions and future work

How to reduce beam Emmittance by 10^6?

$\epsilon_{6D,N} = 1.7\ 10^{-10}\ (\pi m)^3$

Frictional Cooling

- Bring muons to a kinetic energy (T) where dE/dx increases with T
- Constant E-field applied to muons resulting in equilibrium energy
- Big issue – how to maintain efficiency
- First studied by Kottmann et al., PSI



Problems/comments:

- large dE/dx @ low kinetic energy

  □ **low average density (gas)**
- Apply **E** □ **B** to get below the dE/dx peak

$$\vec{F} = q(\vec{E} + \vec{v} \,\square\, \vec{B}) \,\square\, \frac{dT}{dx}\hat{r}$$

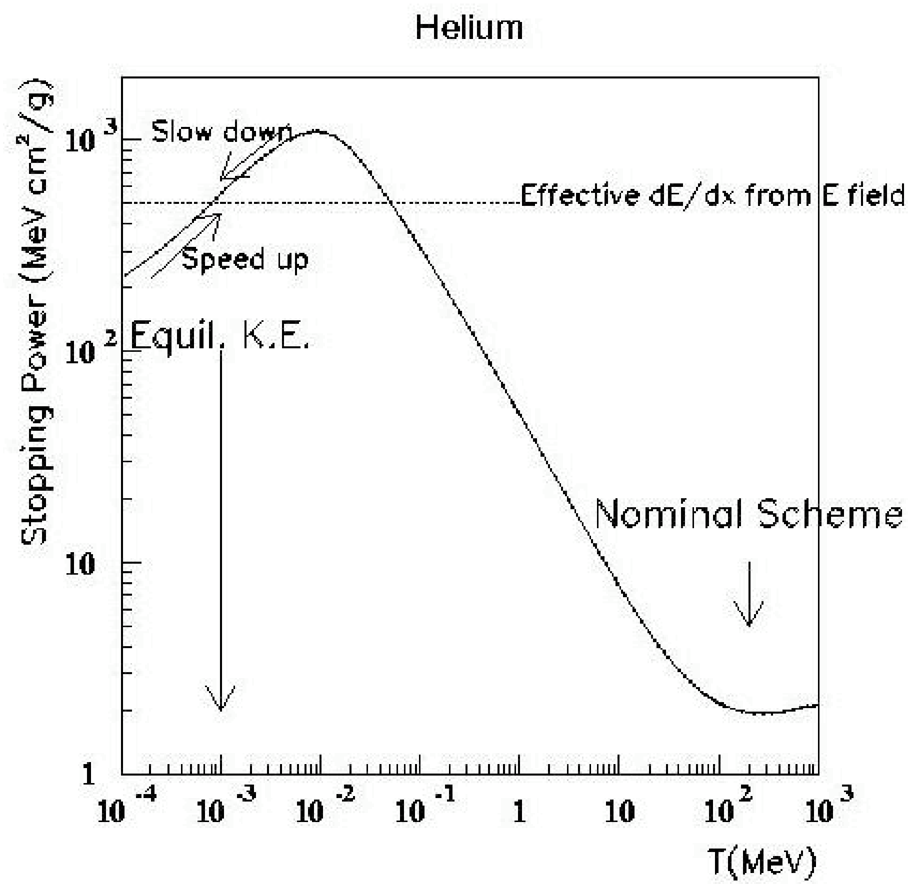
- □+ has the problem of Muonium formation

  □(□ □) dominates over e-stripping in all gases except He
- □□ has the problem of Atomic capture

  □ small below electron binding energy, but not known
- Slow muons don’t go far before decaying

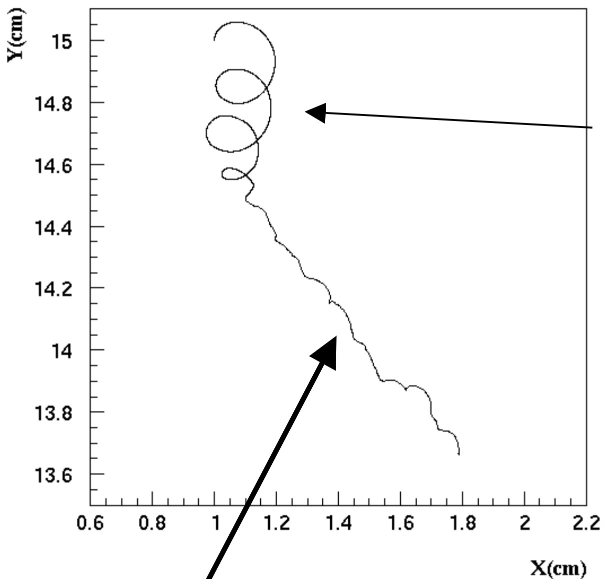
  d = 10 cm sqrt(T) T in eV

  so extract sideways (**E** □ **B**)

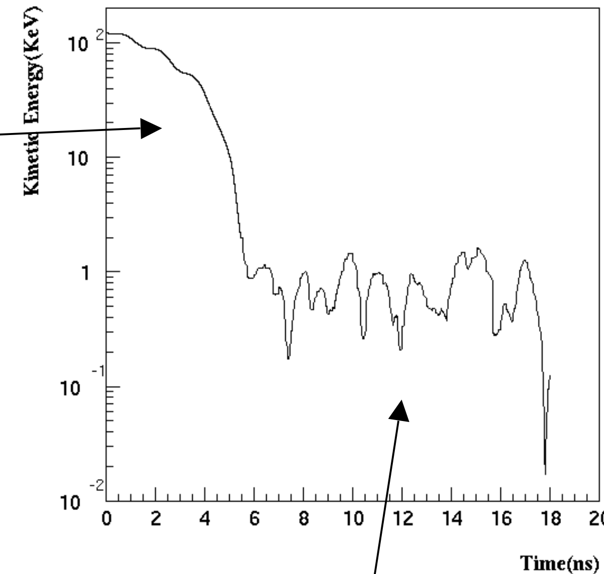


Trajectories in detailed simulation

Transverse motion



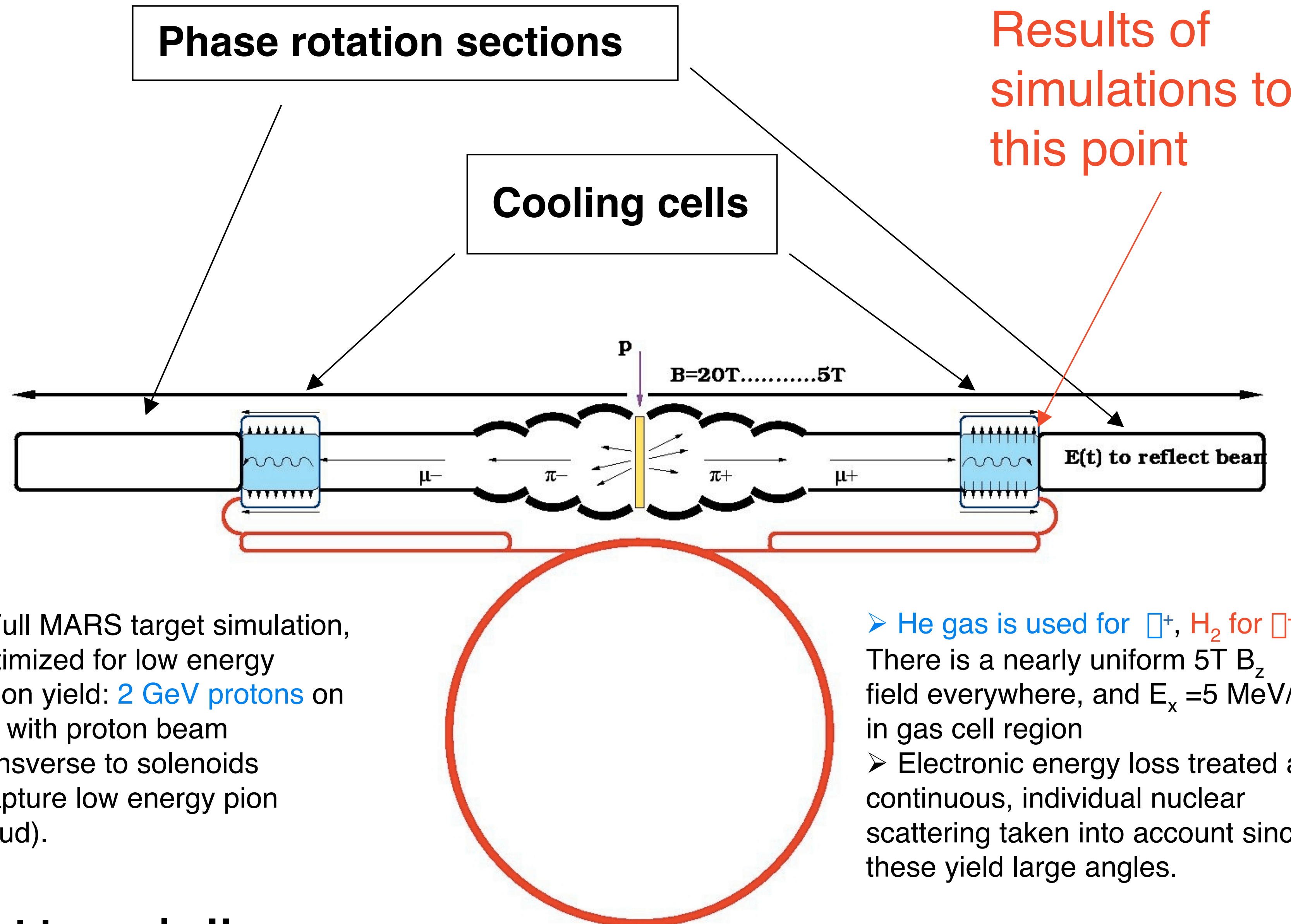
Motion controlled by **B** field



Lorentz angle drift, with nuclear scattering

Fluctuations in energy results in emittance

Final stages of muon trajectory in gas cell



- Full MARS target simulation, optimized for low energy muon yield: 2 GeV protons on Cu with proton beam transverse to solenoids (capture low energy pion cloud).

- He gas is used for □$^+$, H_2 for □$^-$. There is a nearly uniform 5T B_z field everywhere, and E_x =5 MeV/m in gas cell region
- Electronic energy loss treated as continuous, individual nuclear scattering taken into account since these yield large angles.

Not to scale !!

Yields & Emittance

Results as of NUFACT02

Look at muons coming out of 11m cooling cell region after initial reacceleration.

Yield: approx 0.002 □ per 2GeV proton after cooling cell.
Need to improve yield by factor 3 or more.

Emittance: rms

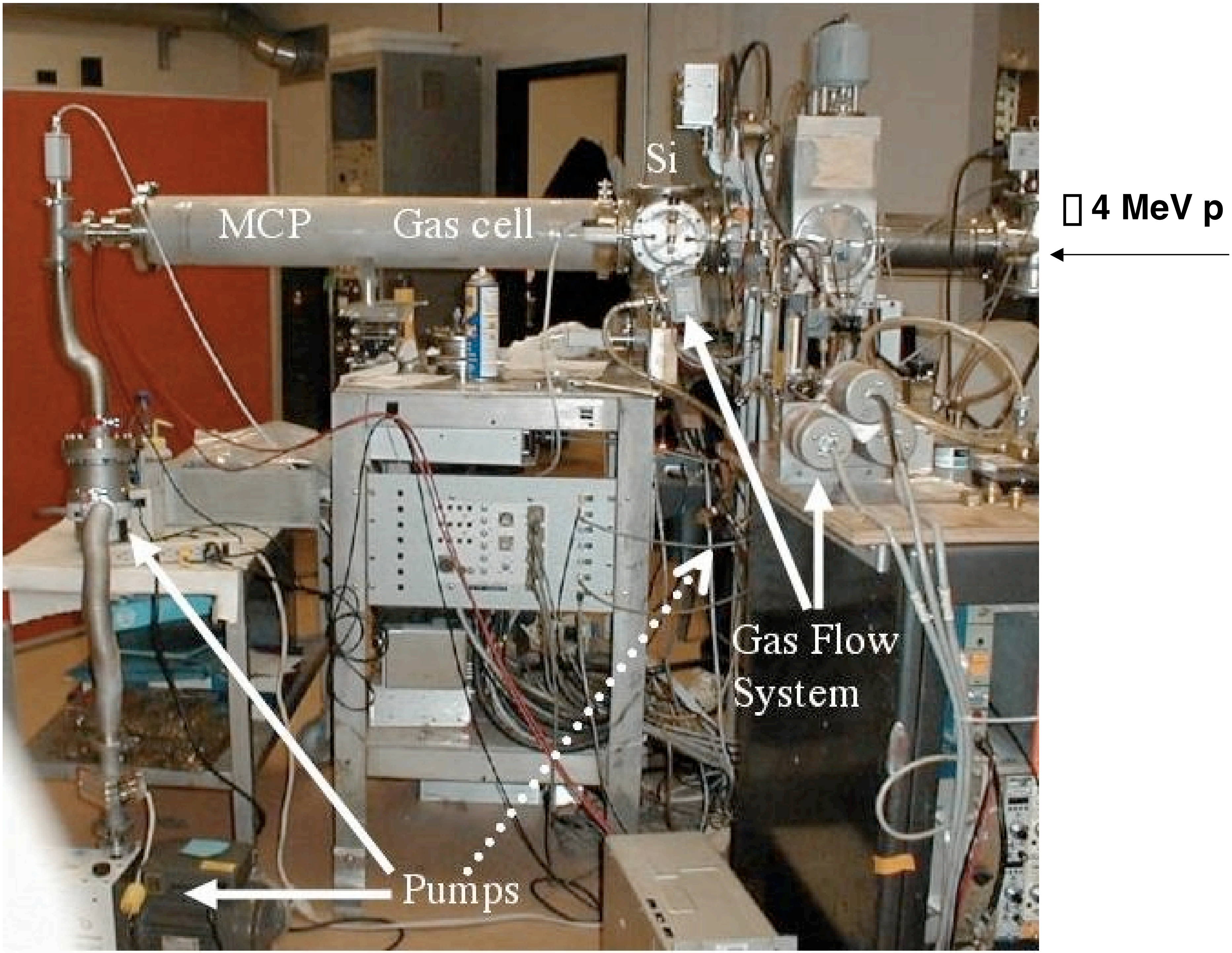
$x = 0.015$ m
$y = 0.036$ m
$z = 30$ m (actually □ct)
$P_x = 0.18$ MeV
$P_y = 0.18$ MeV
$P_z = 4.0$ MeV

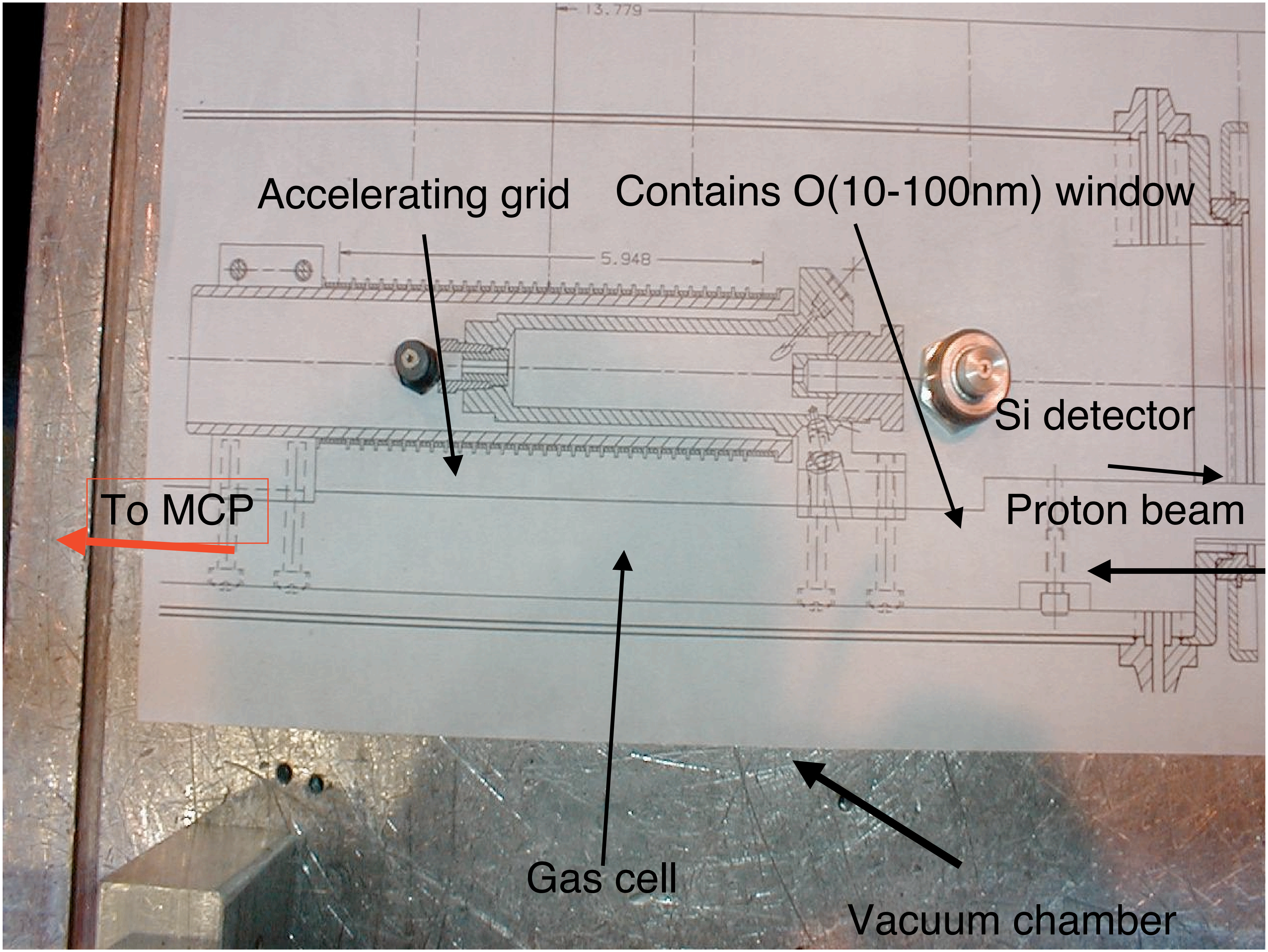
$□_{6D,N} = 5.7\ 10^{-11}$ (□m)^3 $□_{6D,N} = 1.7\ 10^{-10}$ (□m)^3

RAdiological Research Accelerator Facility

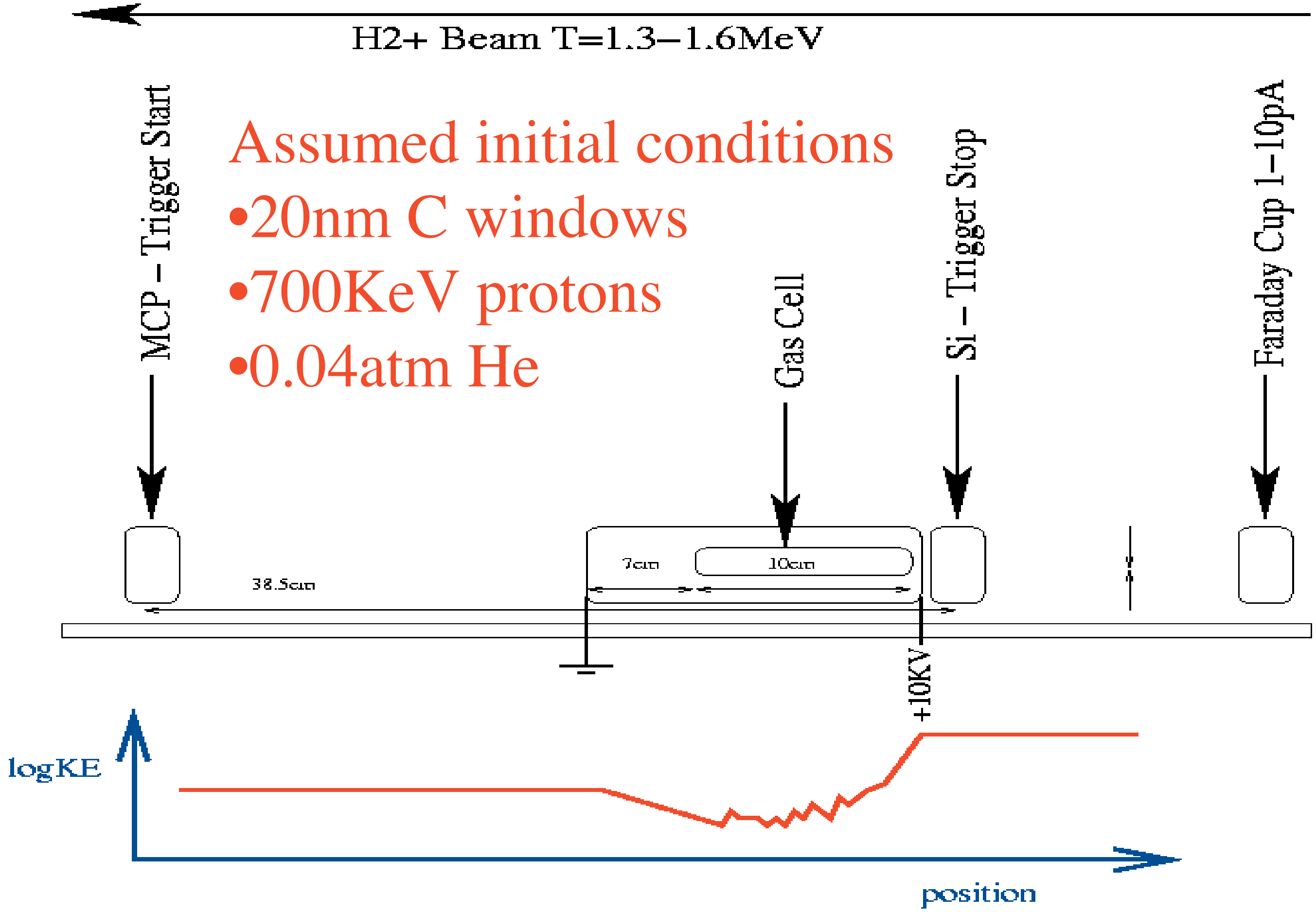
- Perform TOF measurements with protons
  - 2 detectors START/STOP
  - Thin entrance/exit windows for a gas cell
  - Some density of He gas
  - Electric field to establish equilibrium energy
  - NO B field so low acceptance

- Look for a bunching in time
  - Can we cool protons?


Si
MCP
Gas cell
Gas Flow
System
Pumps
4 MeV p



Accelerating grid
Contains O(10-100nm) window
5.948
13.779
Si detector
To MCP
Proton beam
Gas cell
Vacuum chamber



Assumed initial conditions

- 20nm C windows
- 700KeV protons
- 0.04atm He

$TOF = T0 - (T_{si} - T_{MCP})$ → speed → Kinetic energy

Summary of Simulations

- Incorporate scattering cross sections into the cooling program
  - Born Approx. for T>2KeV
  - Classical Scattering T<2KeV
- Include μ^- capture cross section using calculations of Cohen (Phys. Rev. A. Vol 62 022512-1)
- Difference in μ^+ & μ^- energy loss rates at dE/dx peak
  - Due to extra processes charge exchange
  - Barkas Effect parameterized data from Agnello et. al. (Phys. Rev. Lett. 74 (1995) 371)
- Only used for the electronic part of dE/dx
- Energy loss in thin windows
- For RARAF setup proton transmitted energy spectrum is input from SRIM, simulating protons through Si detector

(J.F. Ziegler http://www.srim.org)

DATA SETS AQUIRED

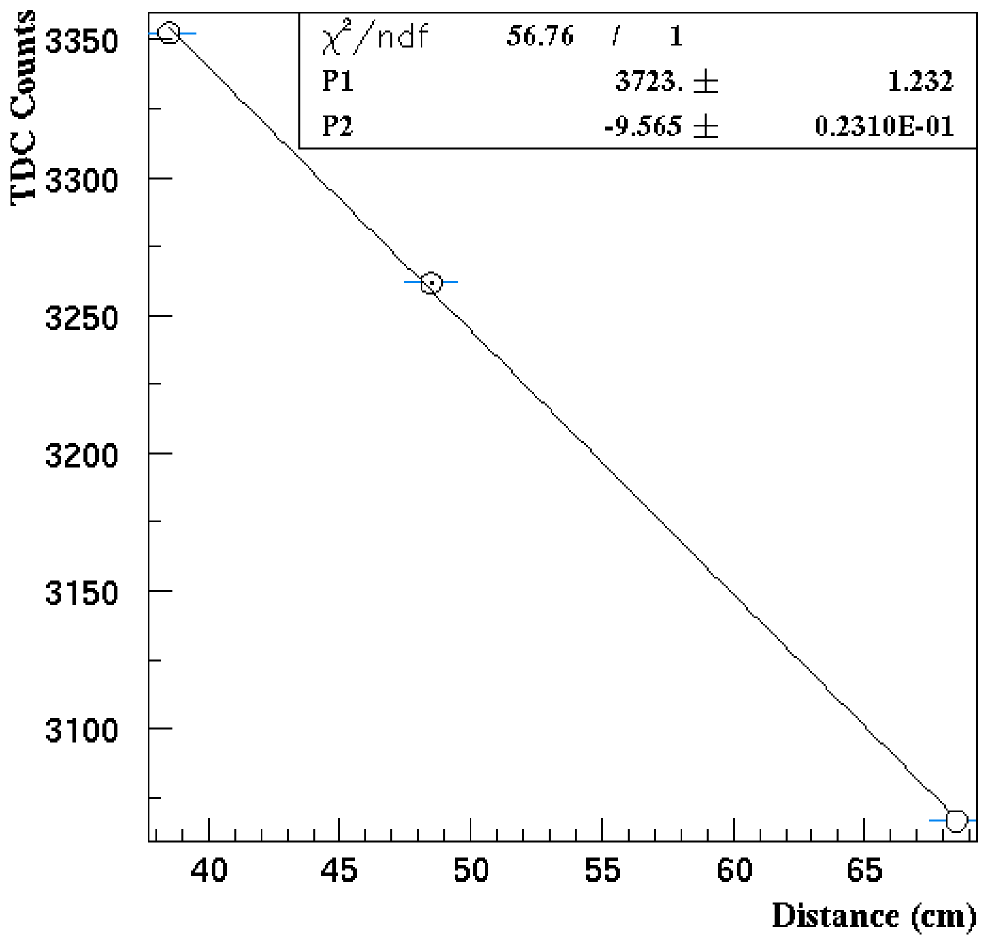
$T(H_2^+)$ (MeV)	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.6	1.6	1.6	1.6	1.5	1.3
He Gas	✘	✘	✘	✔	✔	✘	✘	✔	✔	✘	✘	✔	✔
Acc. Grid (~60KV/m)	✘	✘	✘	✔	✘	✔	✘	✔	✘	✔	✘	✔	✔
TOF Dist. (cm)	38.5	48.5	68.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5
Number of Events	60K	31K	59K	31K	7K	4K	3K	81K	2K	3K	3K	977	3K

✔ON ✘No Gas Cell/Acc. Grid installed

✘ OFF Nominal Dataset

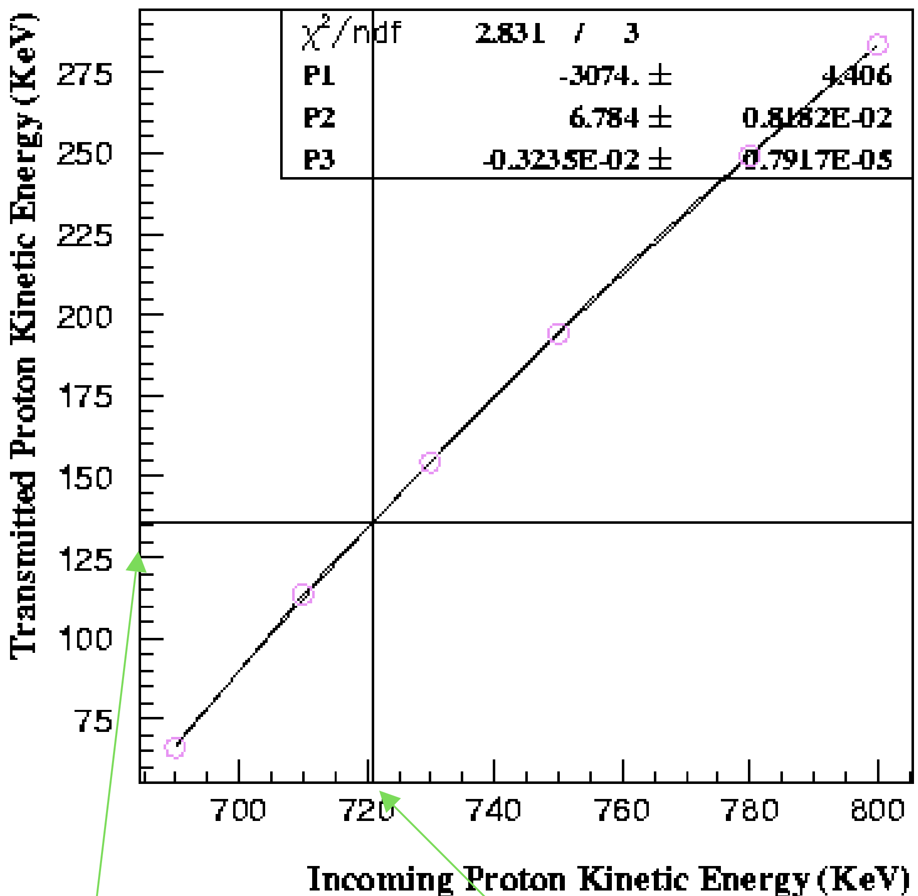
T0 Calibration

✘No Gas Cell/Acc. Grid installed

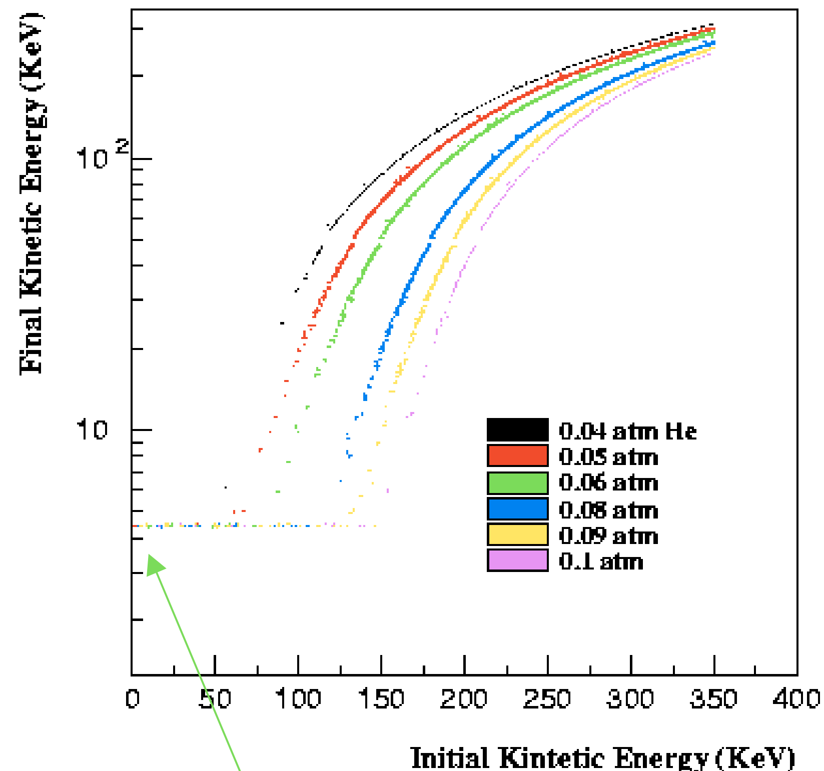


- 3xDistances used to Calibrate TDC offset
- P2=-9.565Counts/cm is <Velocity>=0.5cm/ns or T=136KeV.

Protons through 9μ Si



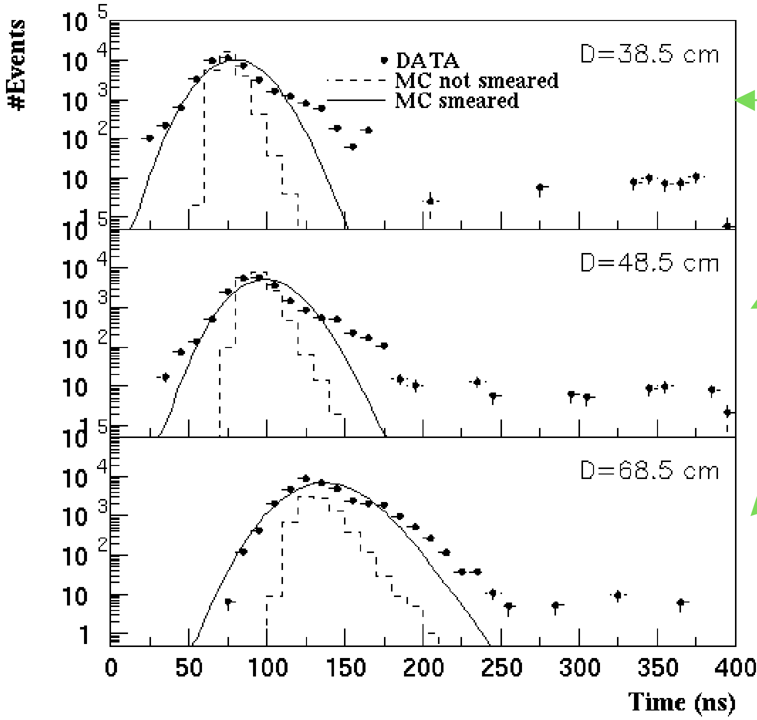
20nm C windows



<T>=136KeV

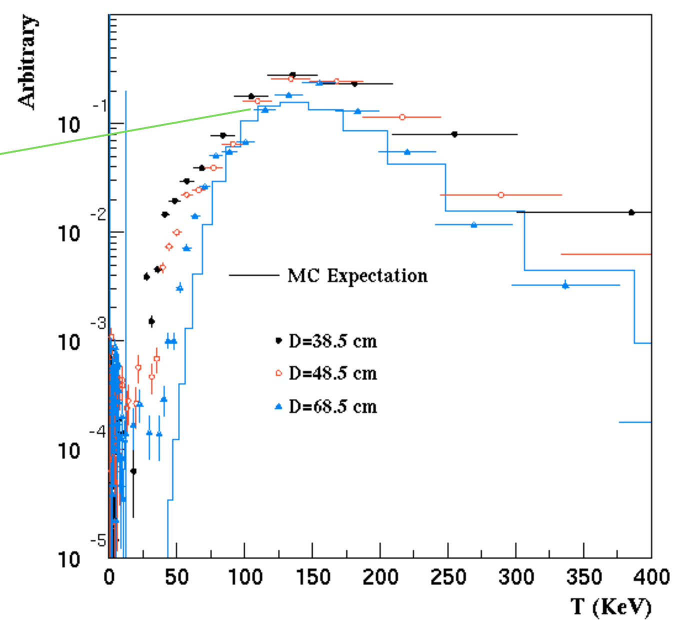
<T(proton)>=721KeV

Cooling effect
4.4KeV from 7.3cm of reacceleration



σ=13ns
σ=15ns
σ=17ns

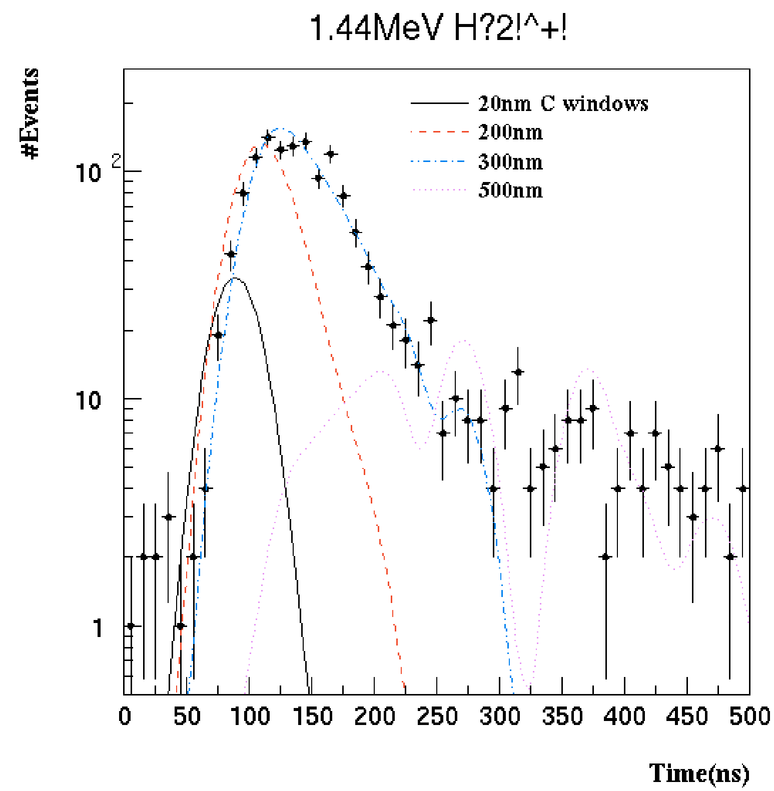
$$Pm = \int Pt * G(t,\sigma)dt$$



Do the Peaks line up?

- 1.44MeV H_2^+ corresponds to <721KeV> protons
- Add windows & check data without gas or grid
    - Put in gas cell & grid but do not flow gas & do not turn on the grid

300nm C windows

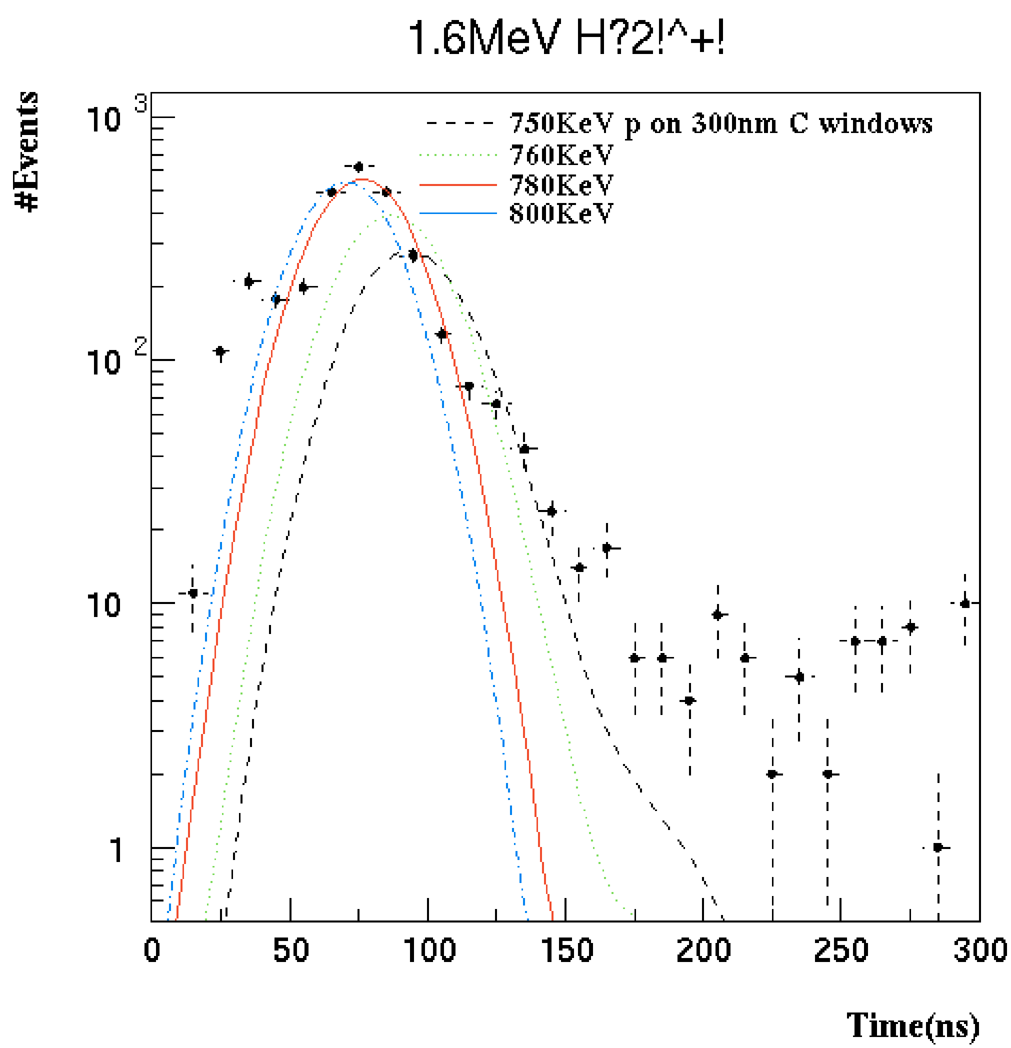


No background subtraction

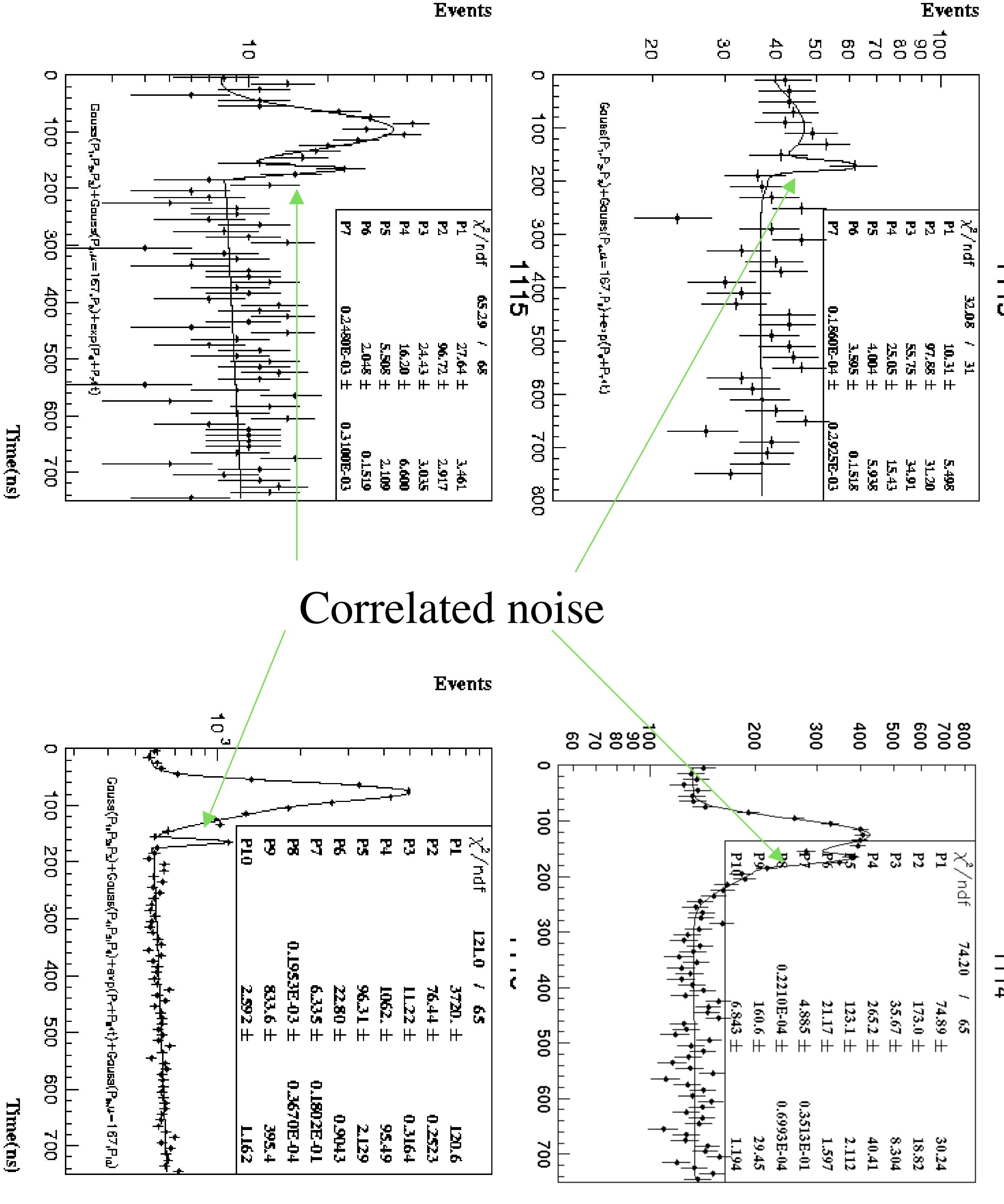
- 1.44MeV H_2^+ corresponds to <721KeV> protons
- 300nm C windows

1.6MeV H2+ corresponds to <780KeV> protons

Now add Gas and look for cooling?



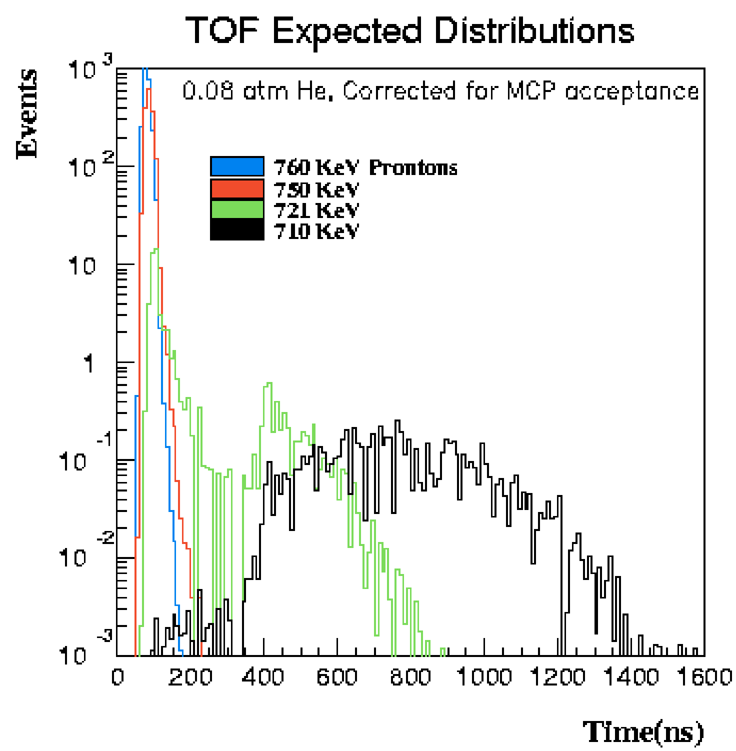
No background subtraction


1113
1114
1115
Events
Time(ns)
Correlated noise

- 1.44MeV H_2^+ corresponds to <721KeV> protons
- 300nm C windows
- 1.6MeV H_2^+ corresponds to <780KeV> protons

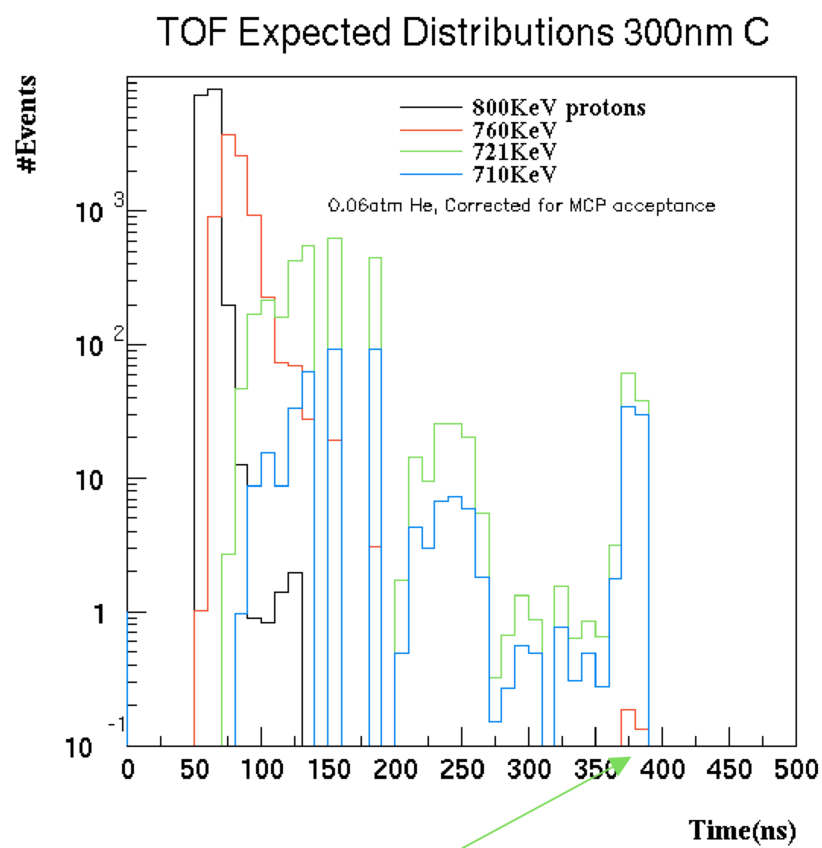
Now add Gas and look for cooling?
How much?

20nm C windows



0.08atm based on 1000000 generated events
0.06atm based on 1000000 generated events

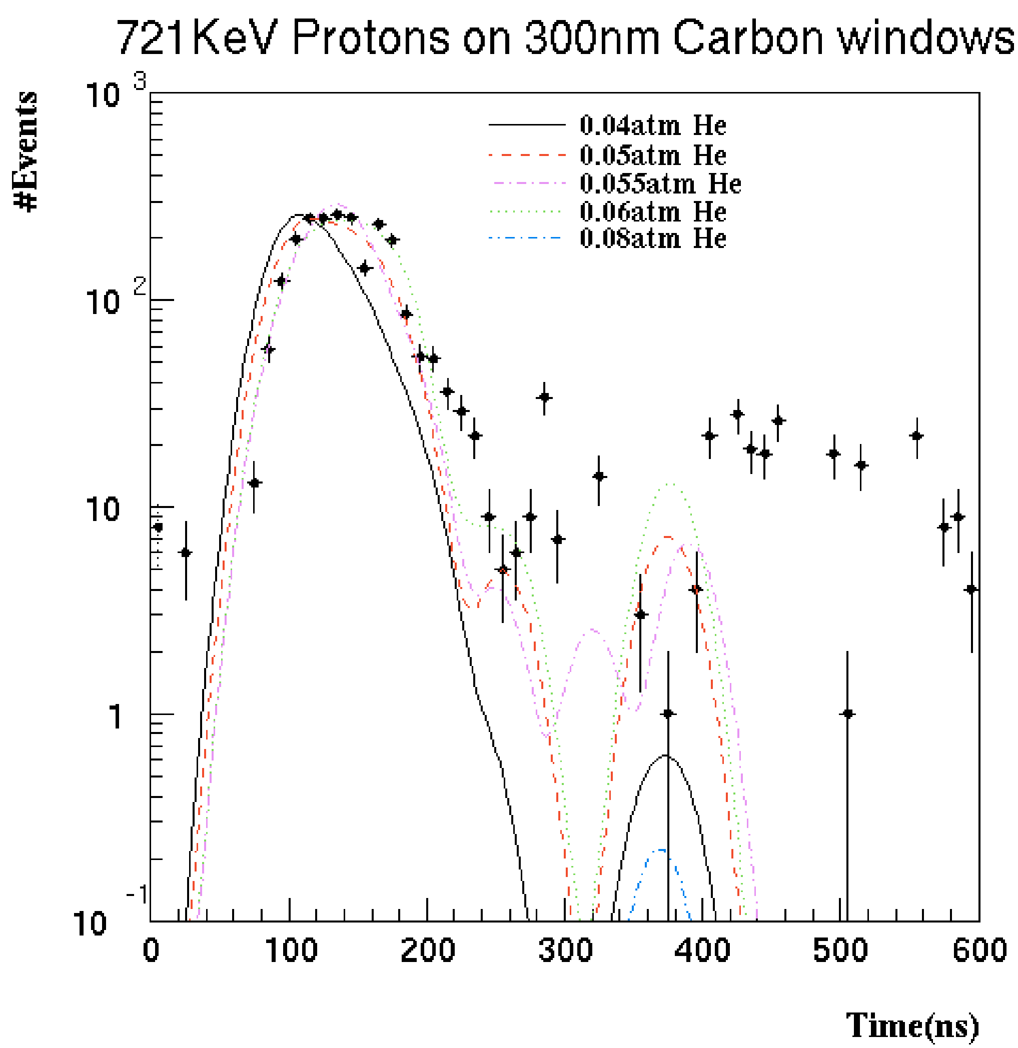
- 1.44MeV H_2^+ corresponds to <721KeV> protons
- 300nm C windows
- 1.6MeV H_2^+ corresponds to <780KeV> protons



Now add Gas and look for cooling?
How much?

Thicker windows introduce cutoff

0.08atm based on 1000000 generated events
0.06atm based on 1000000 generated events



Subtract constant Background & fit for the pressure of He gas in the cell.

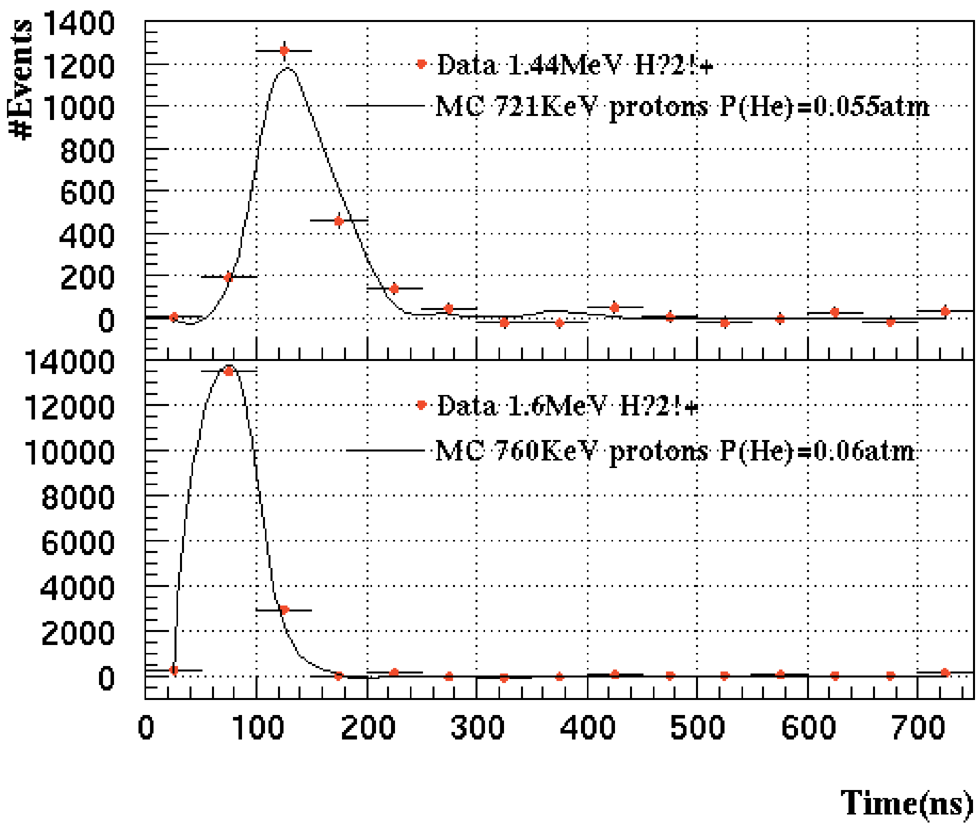
0.055 or 0.06 atm He!

- No geometric MCP Acceptance in MC.
- No high MC statistics

Cool protons???

Flat constant Background

MC exp



Background exponential with m>0

$$Events = \sum_{i=300ns}^{750ns} N_i = 58 \pm 82(55)$$

$$Events = \sum_{i=300ns}^{400ns} N_i = \square 5 \pm 45(49)$$

$$Events = \sum_{i=200ns}^{750ns} N_i = 55 \pm 194(77)$$

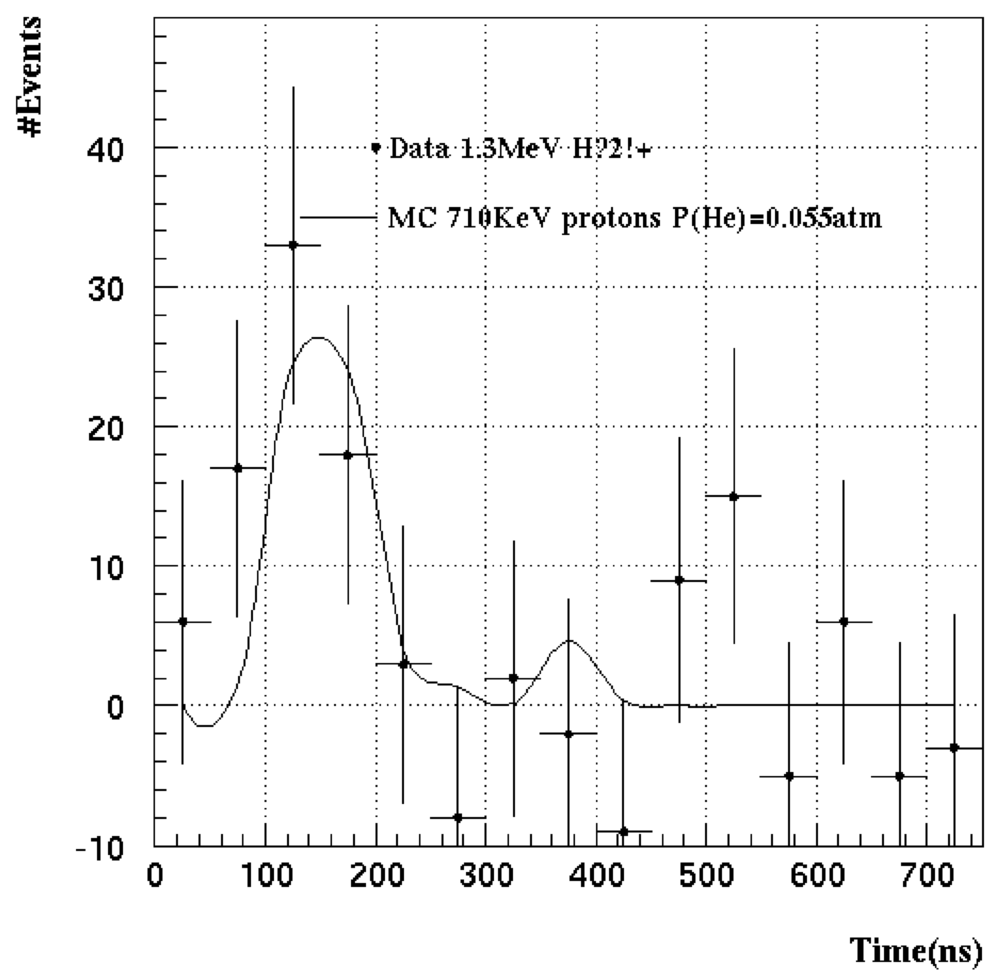
$$Events = \sum_{i=200ns}^{400ns} N_i = \square 42 \pm 124(77)$$

Other low statistics datasets?

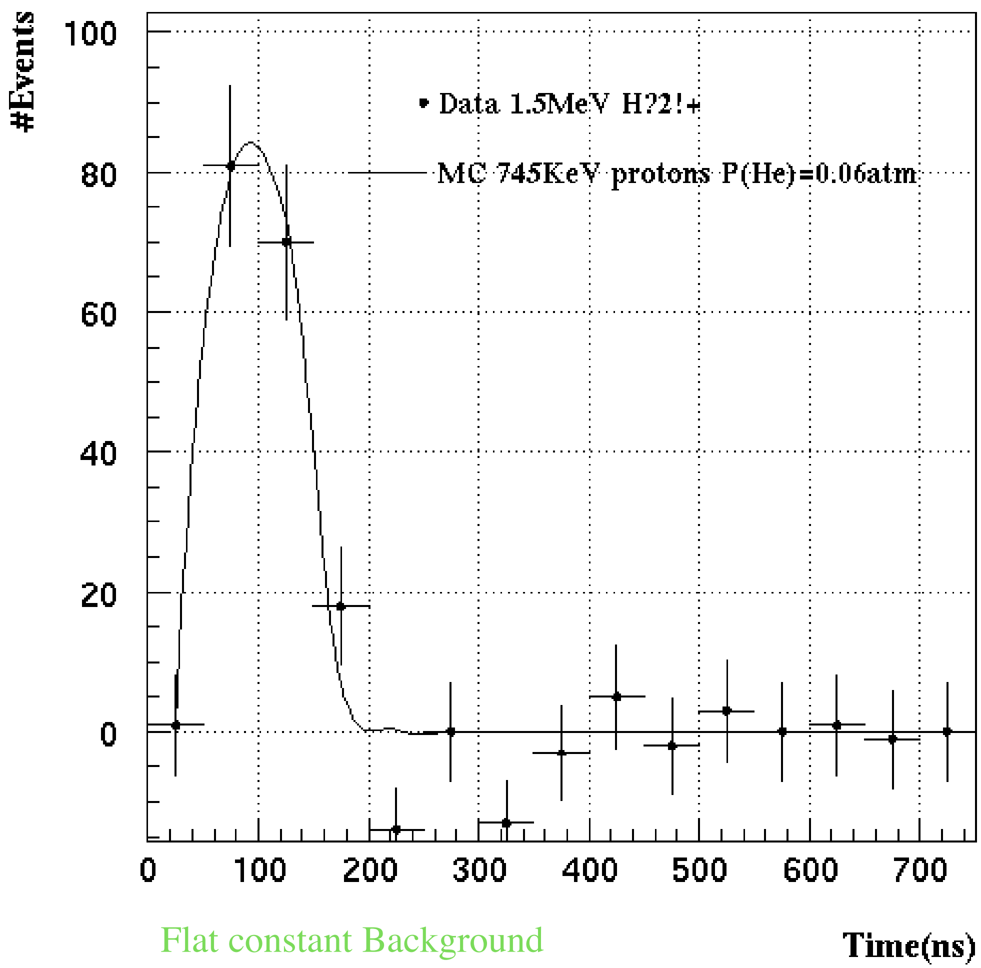
$$\# \, Events = \sum_{i=300ns}^{750ns} N_i = 0 \pm 31(8)$$

$$\# \, Events = \sum_{i=300ns}^{400ns} N_i = -8 \pm 16(7)$$

Flat constant Background



Cooled protons cont'd…



Flat constant Background

$$\# Events = \sum_{i=200ns}^{750ns} N_i = -6 \pm 24(9)$$

$$\# Events = \sum_{i=200ns}^{400ns} N_i = -12 \pm 15(9)$$

Conclusions

- No clear sign of cooling but this is expected from lack of Magnetic field & geometric MCP acceptance alone
- The Monte Carlo simulation can provide a consistent picture under various experimental conditions
- Can use the detailed simulations to evaluate Muon Collider based on frictional cooling performance with more confidence….still want to demonstrate the cooling
- Work at MPI on further cooling demonstration experiment using an existing 5T Solenoid and develop the $\square^-$ capture measurement

A lot of interesting work and results to come.