Neutrino Factories and Muon Colliders

First results from MuScat

W. Murray
CCLRC

How well do we understand neutrinos?

- Neutrino flavour changing well-established
  - Atmospheric ν_μ decrease: Super-K, Soudan, IMB, K2K etc.
  - Solar ν_e deficit: Homestake, Sage, Super-K, Kamland etc.
  - Solar $\Sigma\nu$ correct: SNO
- Oscillations per se *much* less well established
- But what else can it be? We know what we are seeing...we never got neutrinos wrong before...

Evolution and the age of the Earth?

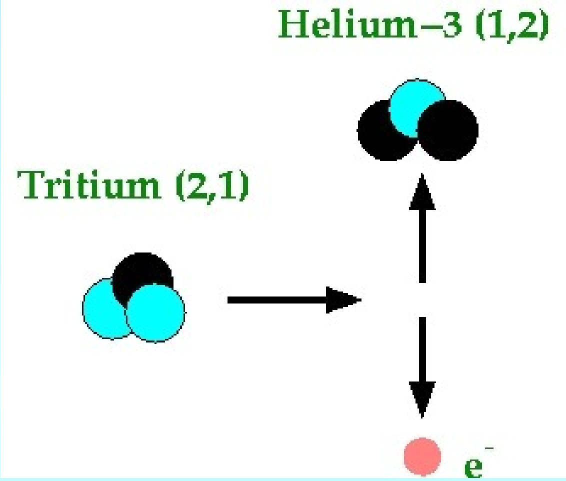
- The Physicists thought they knew what they were talking about:

Wrong

  - W.Thomson: Sun age less than tens of millions of years
  - And Earth too hot only 1million years ago for life

Darwin: "Thomson's views on the recent age of the world have been for some time one of my sorest troubles."

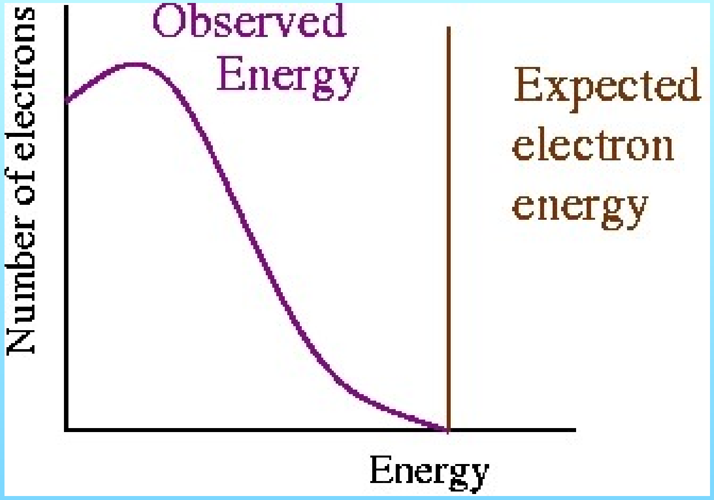
Radioactivity



$$n \rightarrow p + e^-$$

The energy of the electron should be fixed

1914: Chadwick measures electron energy



Violation of energy conservation??

Wrong

Neutrino Postulated by Pauli

1934: **Bethe and Peierls calculate probability of neutrino interactions with nuclei: billions of times smaller than for an electron**

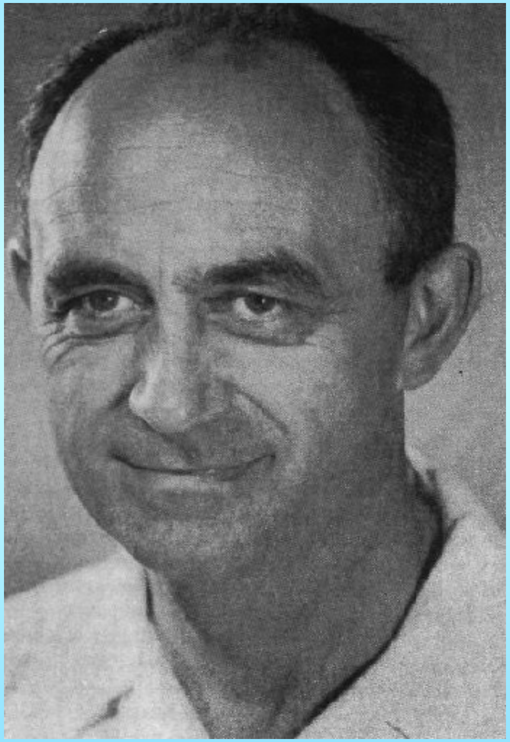
⇨ **50% probability requires 4 Light Years of lead!**

Rudolf Peierls

Pauli: "I have done something very bad today in proposing a particle that cannot be detected. It is something no theorist should ever do."

Wrong

Theory of β decay



Enrico Fermi

1933: **Fermi calls the particle the neutrino.**

Builds theory of beta-decay (weak interaction).

Mass was known to be small so set to zero

Wrong

Neutrino Interactions:

$n \rightarrow p+e^-+\bar{\nu}_e$

$p+e^-+p \rightarrow d+\nu_e$

$\mu \rightarrow e^-+\nu_\mu+\bar{\nu}_e$

- A neutrino can be made (destroyed) if a e/ μ/τ is destroyed (made) at the same time.
- Other proces pair create/destroy

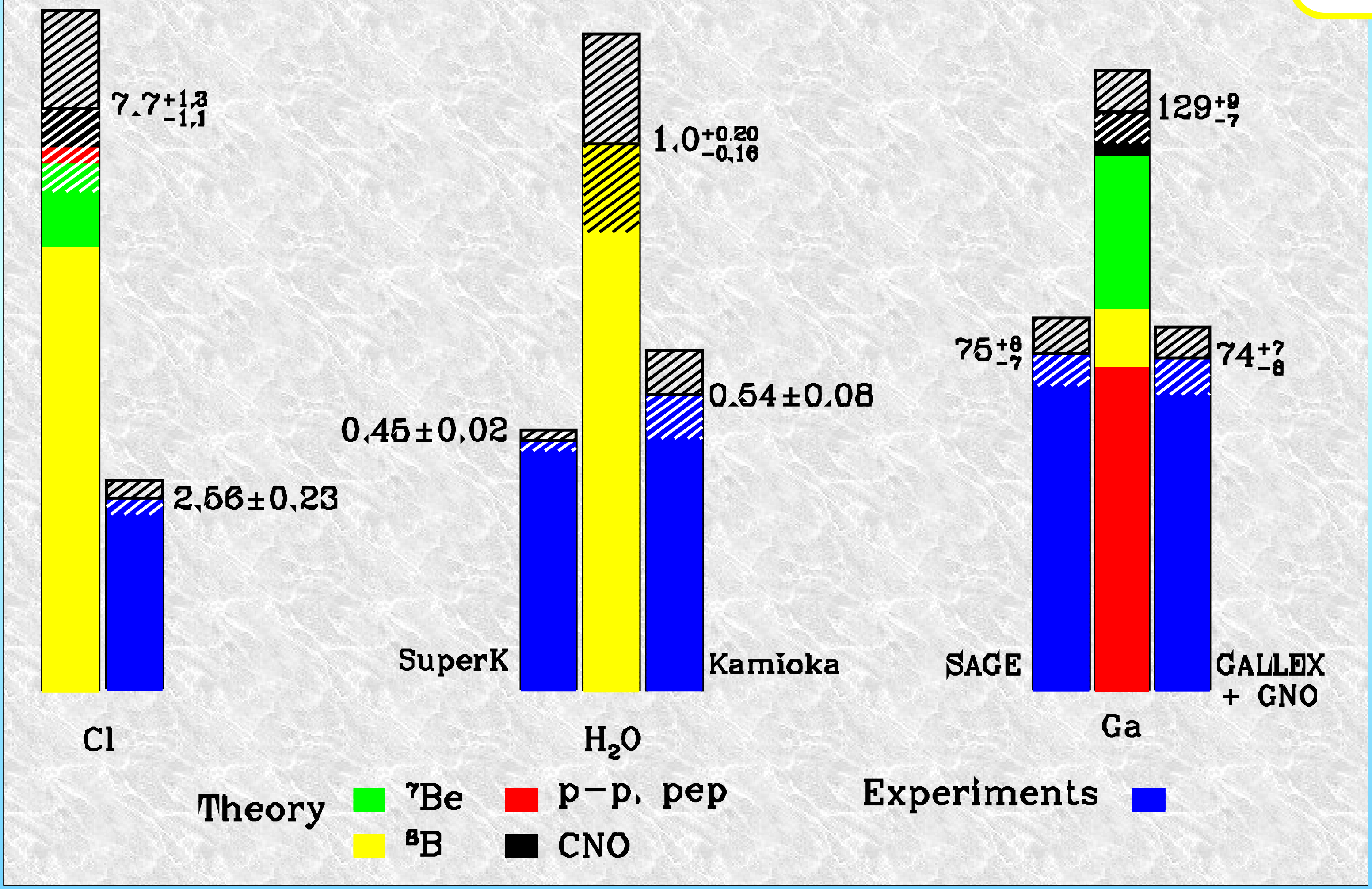
Conservation of electron number

Wrong

Solar rates

Total predicted rate greatly exceeds observed!

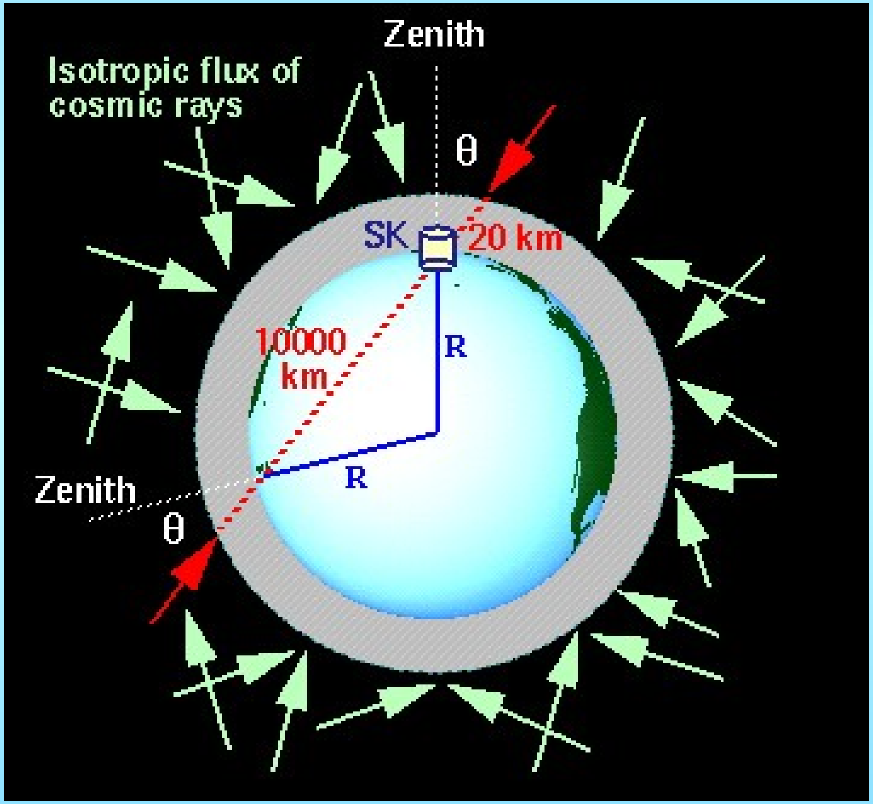
Wrong

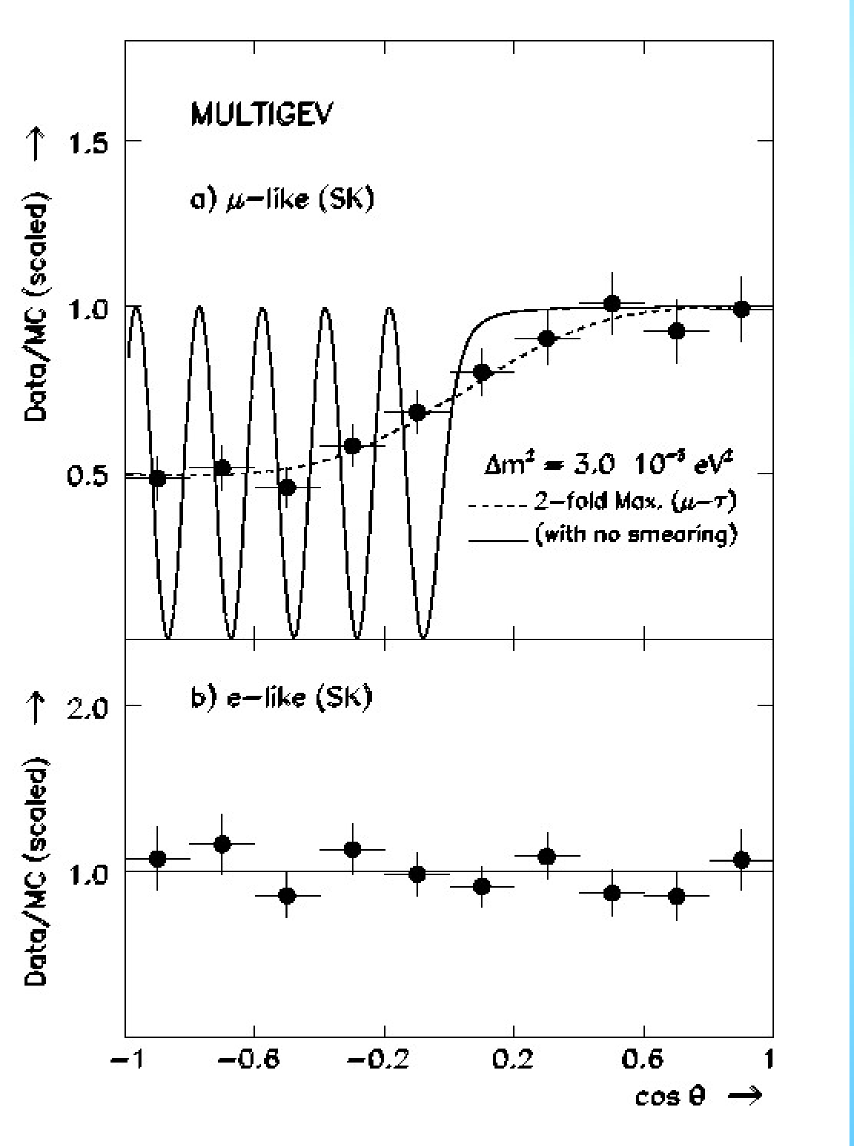


Atmospheric angle distribution

First claim to observe oscillations: Super-Kamiokande

Zenith Angle Distribution in 1998





$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23} L}{4E_\nu}\right)$$

SNO Results

SNO measures:

$$\nu_e + d \rightarrow p + p + e^-$$
$$\nu_x + d \rightarrow p + n + \nu_x$$
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

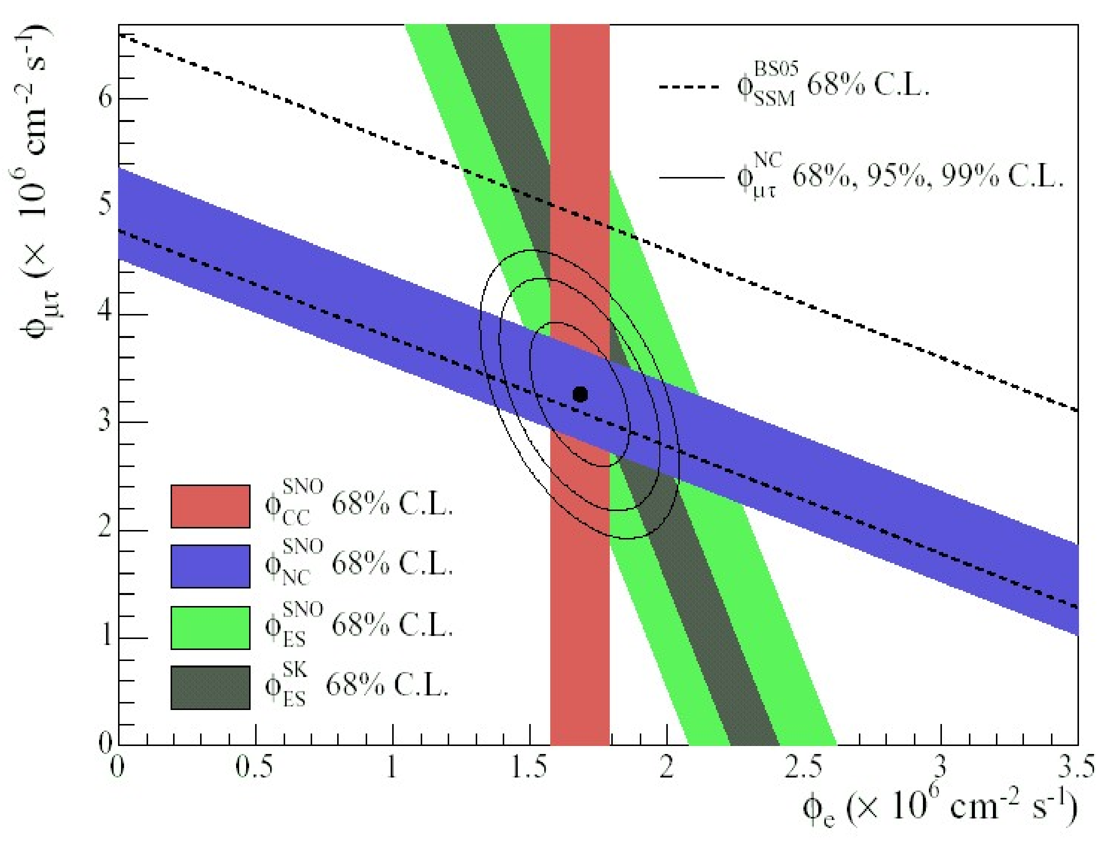
CC - ν_e only

NC - ν_e, ν_μ and ν_τ equally

ES - ν_e + 0.154(ν_μ + ν_τ)

Difference ⇒ more than just ν_e in the neutrinos from the Sun.

$$\phi_{CC} = 1.72^{+0.05+0.11}_{-0.05-0.11}$$
$$\phi_{NC} = 4.81^{+0.19+0.28}_{-0.19-0.27}$$
$$\phi_{NC} = 4.81^{+0.19+0.28}_{-0.19-0.27}$$



Neutrinos must have changed on the way.

Summary of Neutrinos:

- Flavour changing of neutrinos well established
  - Requires neutrino mass (Majorana? Dirac?)
  - Proof of oscillations still thin
- Good description of all (bar LSND) with:

parameter	best fit	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	8.1	7.3–8.7	7.2–9.1
Δm^2_{31} [10^{-3}eV^2]	2.3	1.7–2.9	1.4–3.3
$\sin^2\theta_{12}$	0.30	0.25–0.34	0.23–0.38
$\sin^2\theta_{23}$	0.50	0.38–0.64	0.34–0.68
$\sin^2\theta_{13}$	0.00	≤ 0.028	≤ 0.047

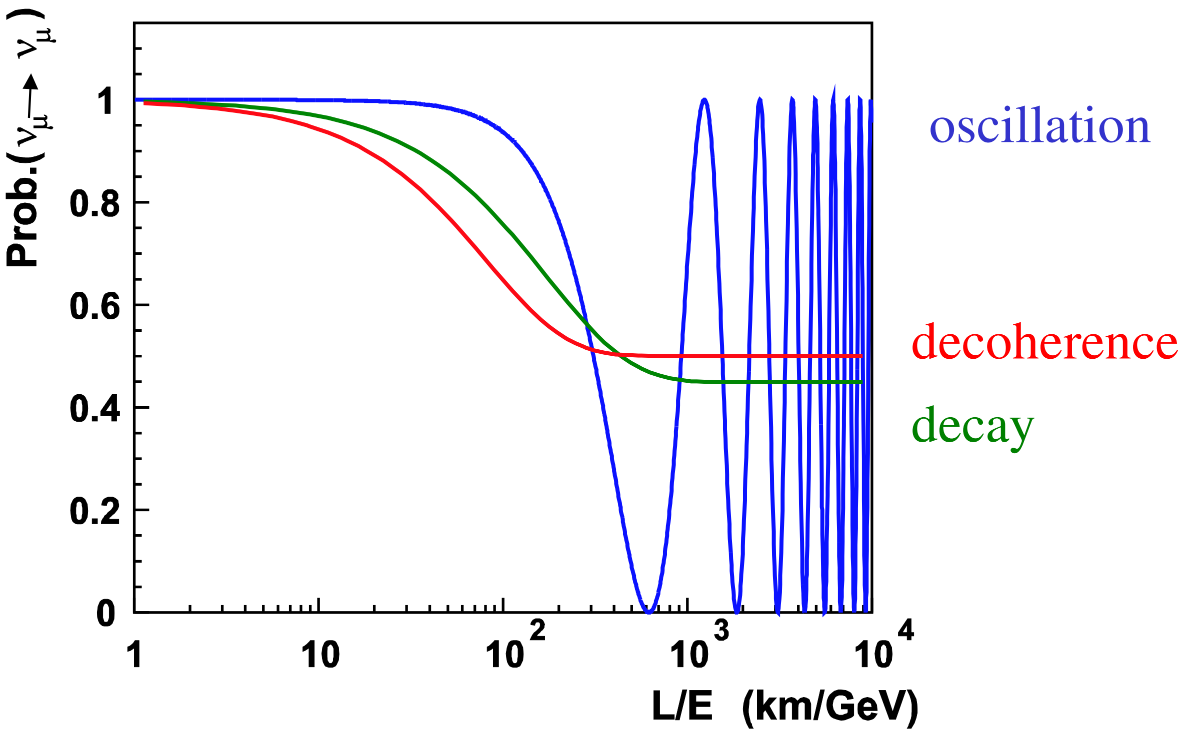
'Solar'

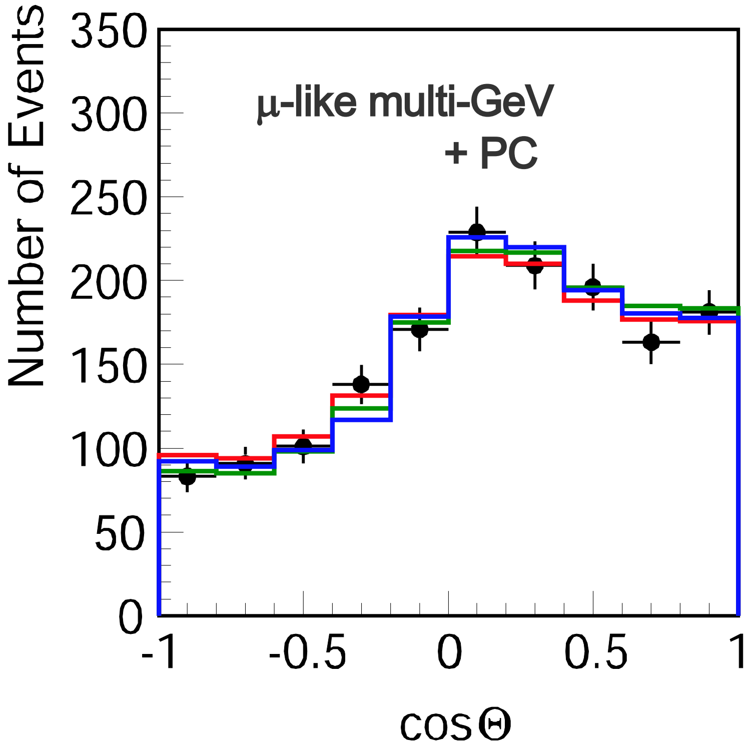
'Atmospheric'

Needed!

Super-K L/E analysis

SK collab. hep-ex/0404034

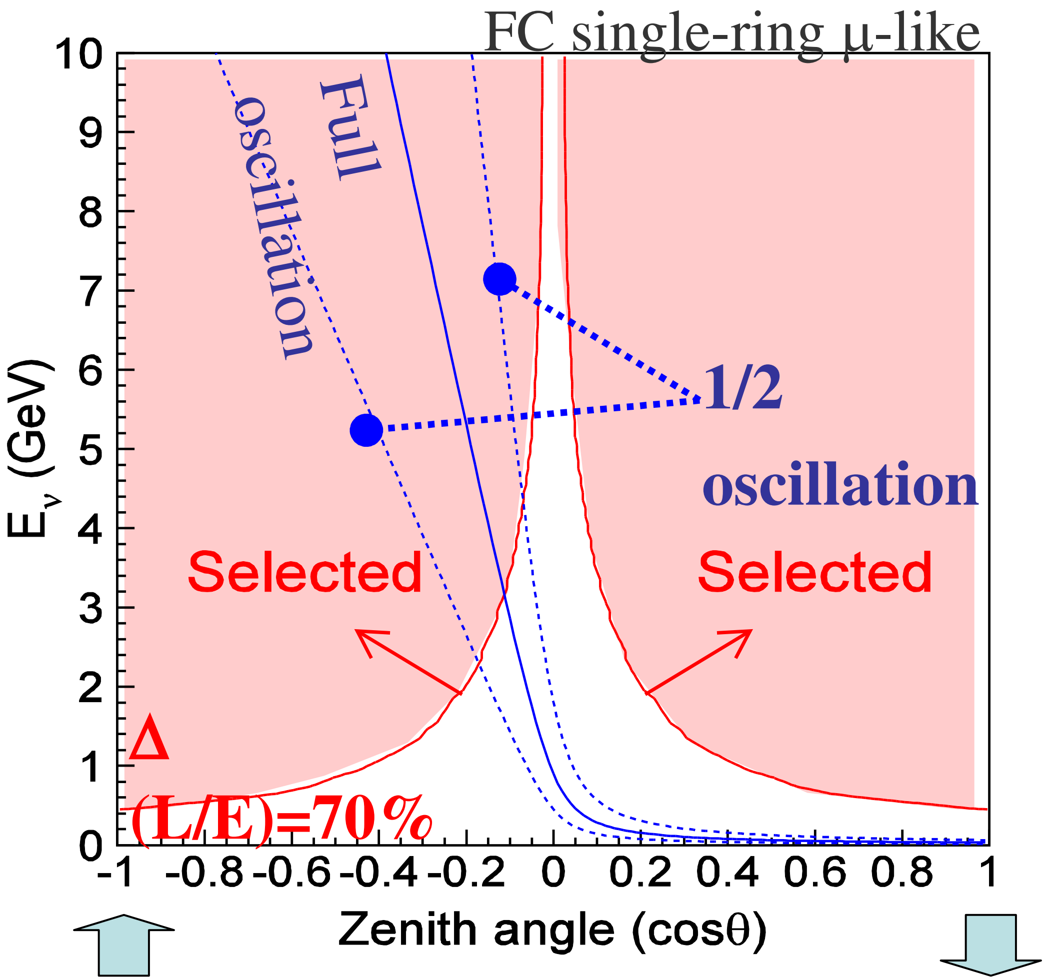




Should observe this dip!

- → Further evidence for oscillations
- → Strong constraint on oscillation parameters, especially Δm^2

Selection criteria



Similar cut for: FC multi-ring μ-like,

OD stopping PC, and

OD through-going PC

Select events with high L/E resolution

(Δ(L/E) < 70%)

Following events are not used:

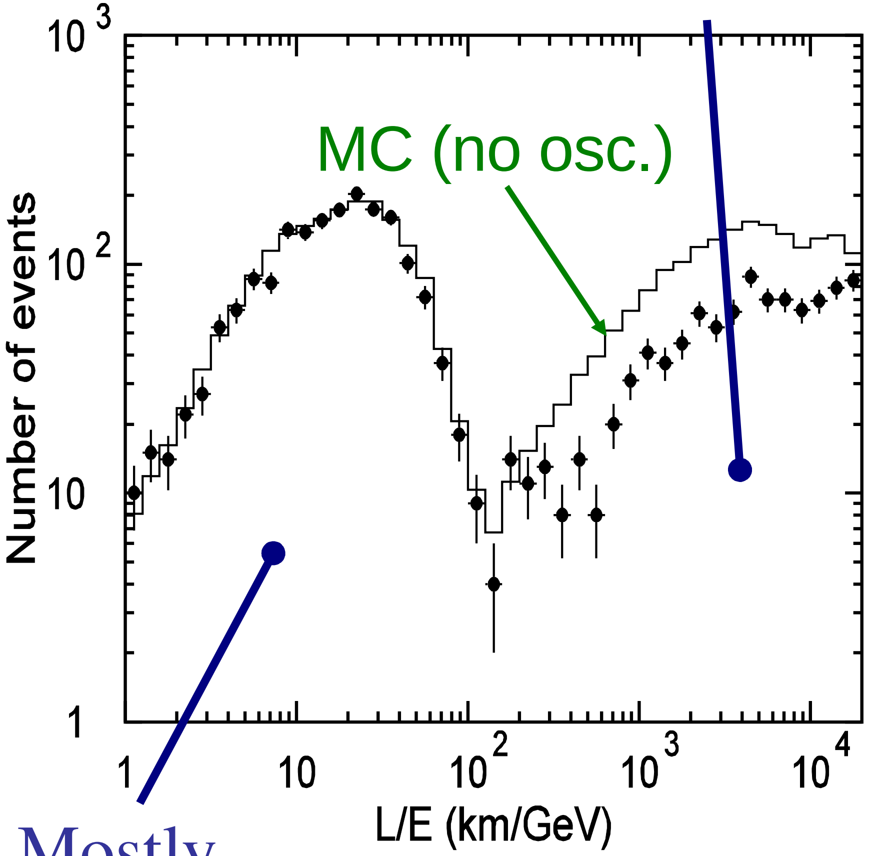
- horizontally going events
- low energy events

2121 FC μ-like and

605 PC

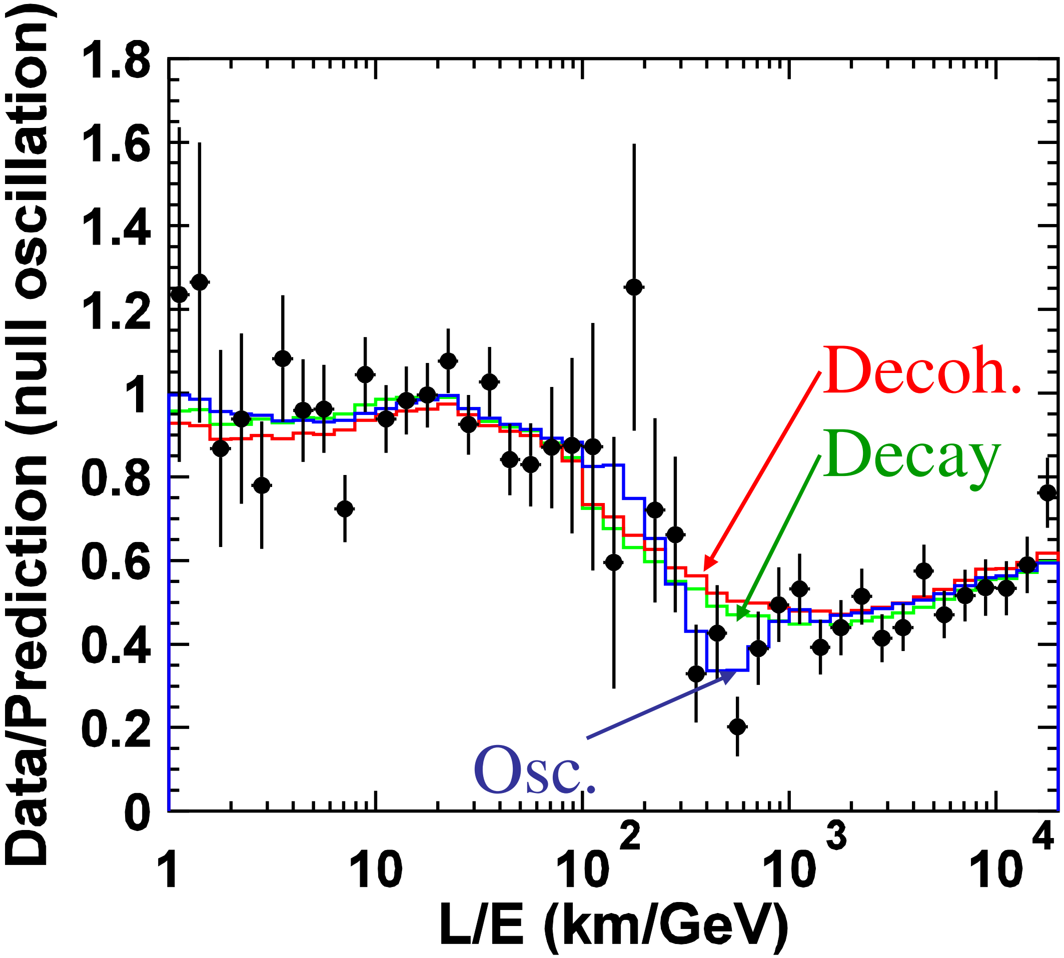
L/E distribution

1489 days FC+PC
(Super-K)



Mostly up-going

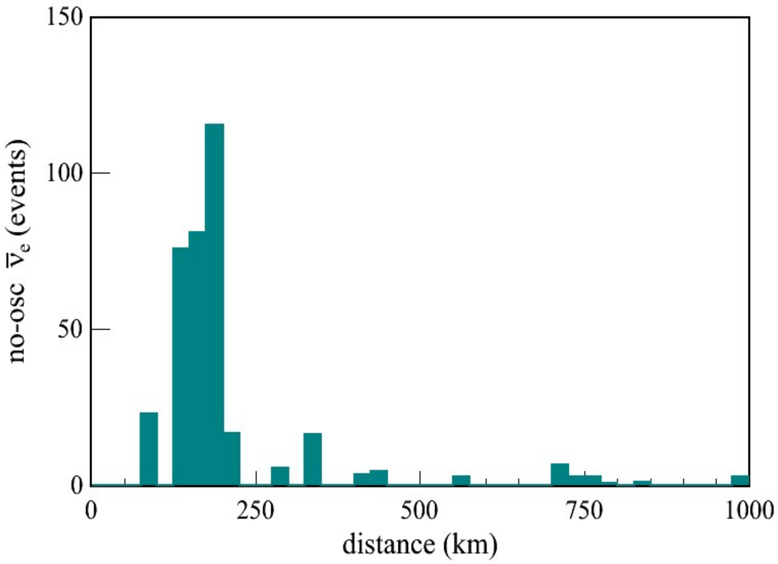
Mostly down-going

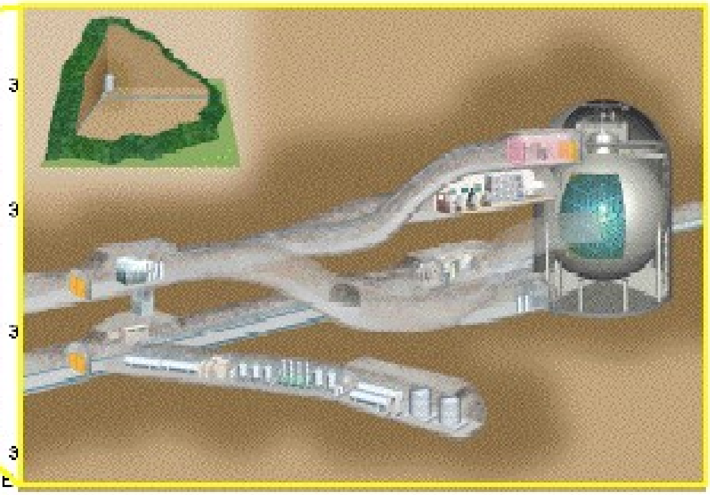


➔Evidence for oscillatory signature

Decay and decoherence disfavored at 3.4 and 3.8σ level, respectively.

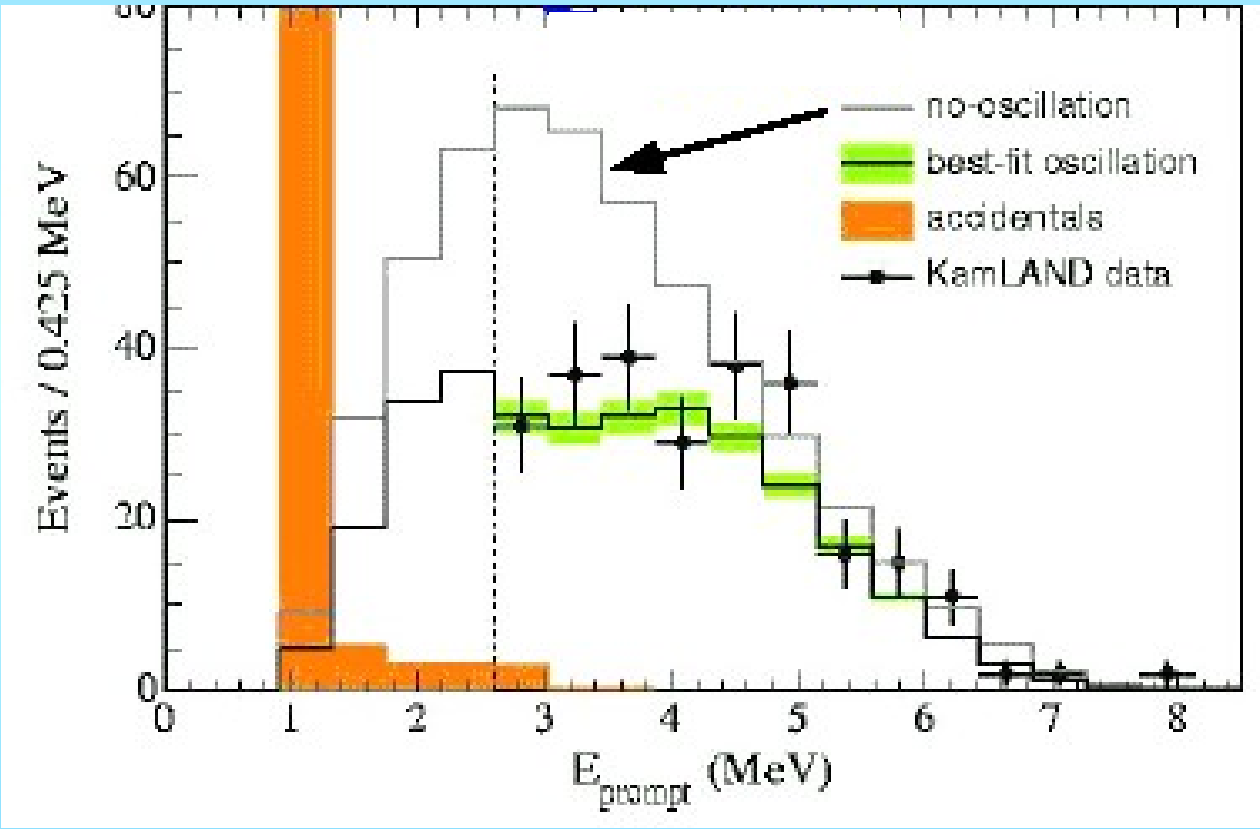
Kamland: ν_e disappearance





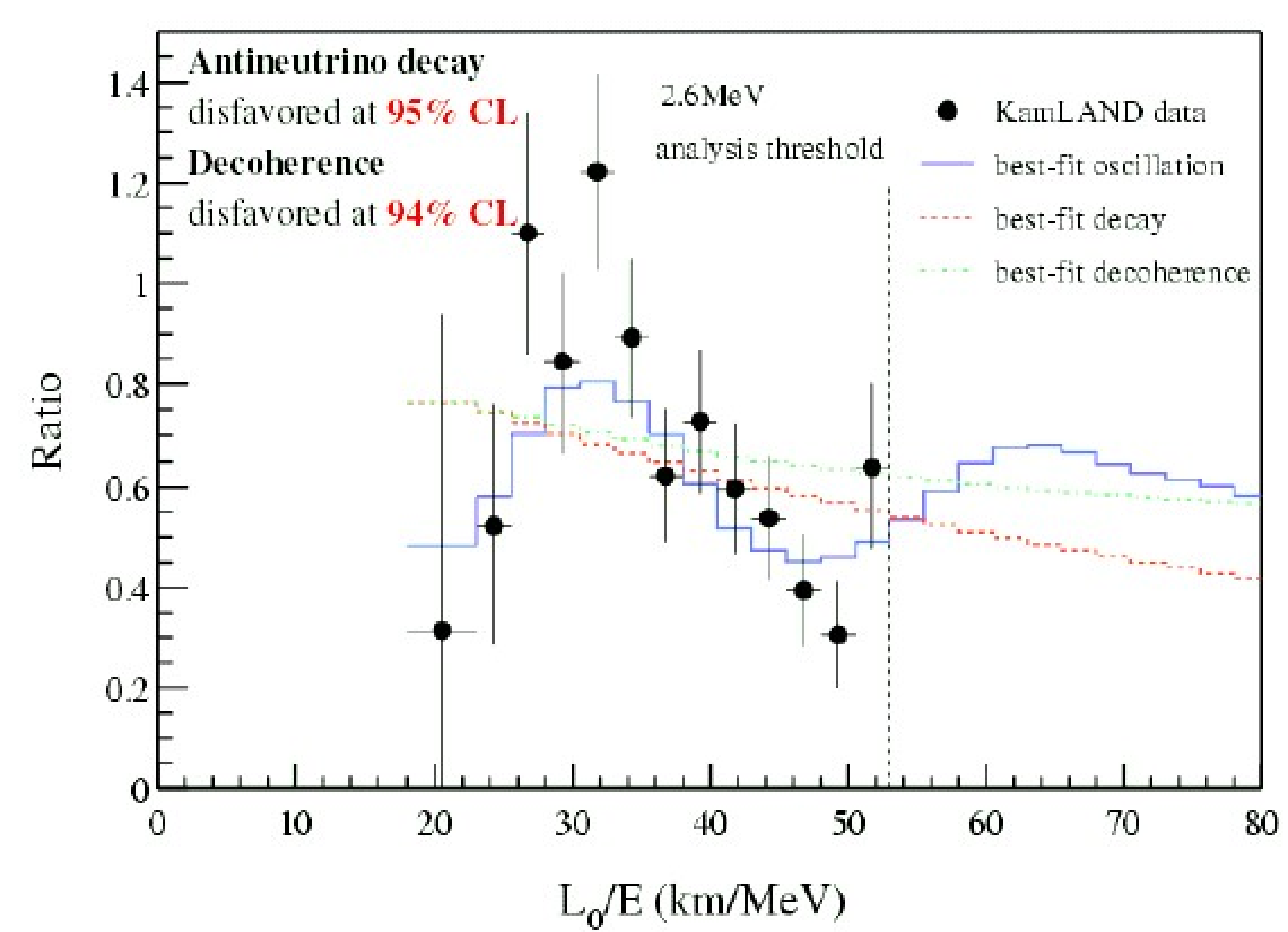
Kamland data: Energy spectrum

- Clear suppression
- energy dependent



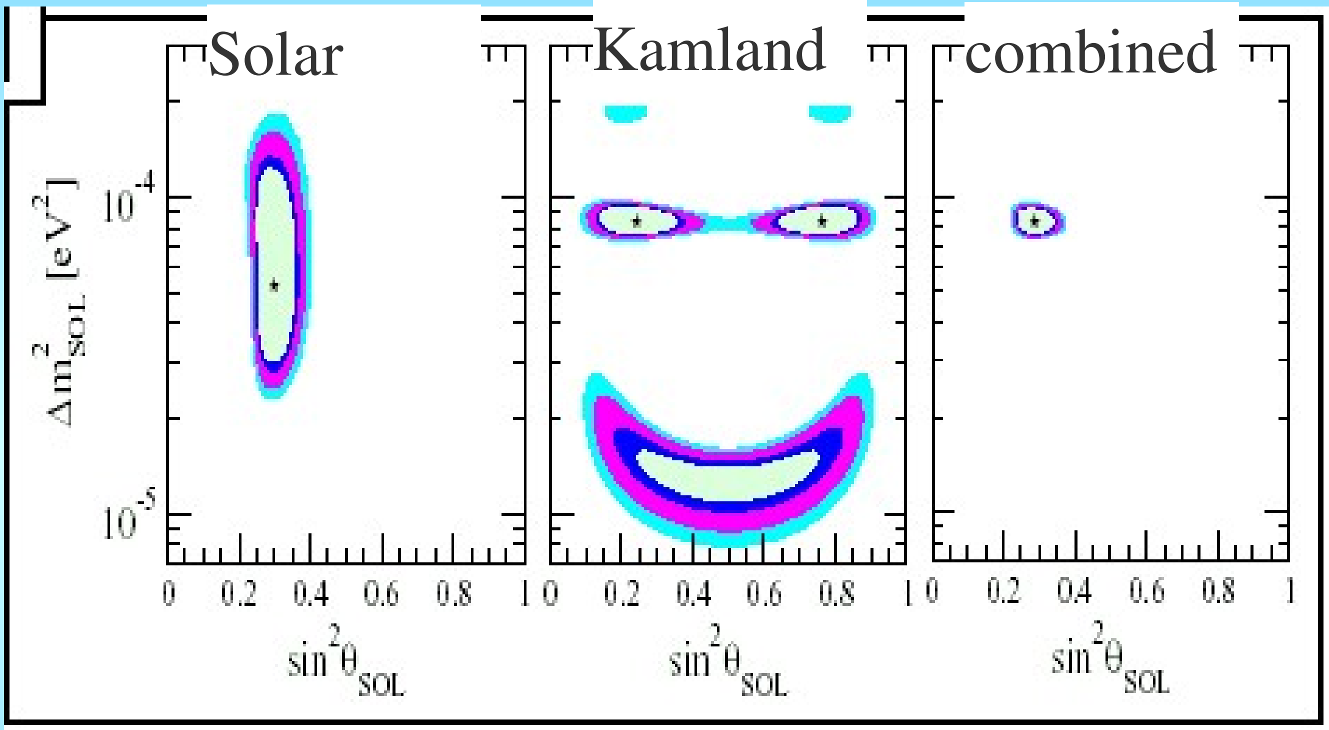
Kamland data: L/E

- Two-sigma evidence for oscillation peaks



Kamland data: LMA

- Happy face
  - ΔM^2 v θ_{12}
- 5.6 sigma exclusion of bi-maximal mixing
- limits on θ_{13}



How do neutrino oscillations work?

- Neutrinos are produced via Weak interactions:

  $Wl\nu_l$ vertex

- Propogate as mass eigenstates
  - Each mass eigenstate admixture of all flavours
    - e/mu/tau conservation broken at each neutrino production
  - Coherent mixture of states
  - Summed amplitude of the 'wrong' states zero at W vertex
  - Oscillations de-phase the states – if velocities different

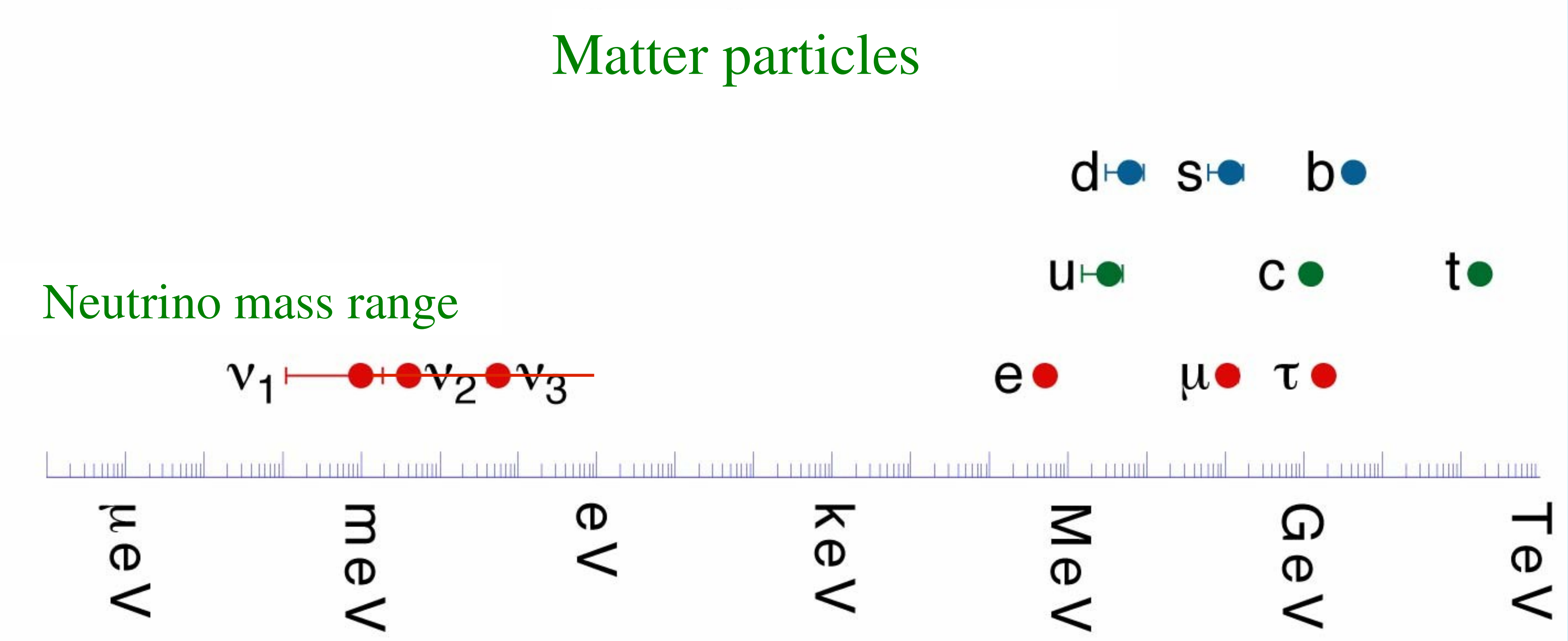
Why don't quarks oscillate?

- B_s oscillates, but this is $b\bar{s} \rightarrow \bar{b}s$
- $b\bar{s} \rightarrow d\bar{s} \rightarrow b\bar{s}$ does not happen, b →sγ does
- One mass eigenstate, not several
  - Quarks interact (QED, QCD) allowing observation of which mass eigenstate produced
  - Mass differences observable from production kinematics
  - (Quarks normally MADE in mass eigenstates)

Neutrino Propagation

- Neutrinos *can* decay
  - $\nu_2 \rightarrow \nu_1 \gamma$
  - Lifetime is very long
  - If neutrino masses were larger decay would be visible
- Decoherence stop neutrino oscillation
  - If New Physics^{TM} allows in-flight mass determination.
  - Kinematics does not ($\pi \rightarrow \mu \nu_\mu$) allow production tagging

Mass Spectrum



Small mass crucial to phenomenology

Dark energy and Neutrinos

- Dark energy – 73% of Universe, totally unknown
  - **Idea:** Neutrinos make lousy CDM candidate because they don't clump
  - Dark Energy doesn't clump
  - Maybe neutrinos are the dark energy?
  - Requires neutrino mass to depend upon density
    - Perhaps mixing with ν_R gives sensitivity to environment?
    - It is certainly a novel window on gut-scale physics...
  - Dark energy scale very close to solar neutrino scale

astro-ph/0309800

hep-ph/0401099

hep-ph/0405141

Do Neutrinos oscillate in air?

- To date there is no proof that they do.
- Only weak upper bounds on ΔM^2 in rock
  - Super-K might be seeing LSND scale oscillations!

- Can accommodate all data, and explain dark energy.

Lessons/predictions

- **Document and consider environment of neutrino in neutrino oscillation experiments**
  - θ_{13} measurements in reactor experiments
  - Consider environment in direct mass search and $0\nu\beta\beta$ measurements

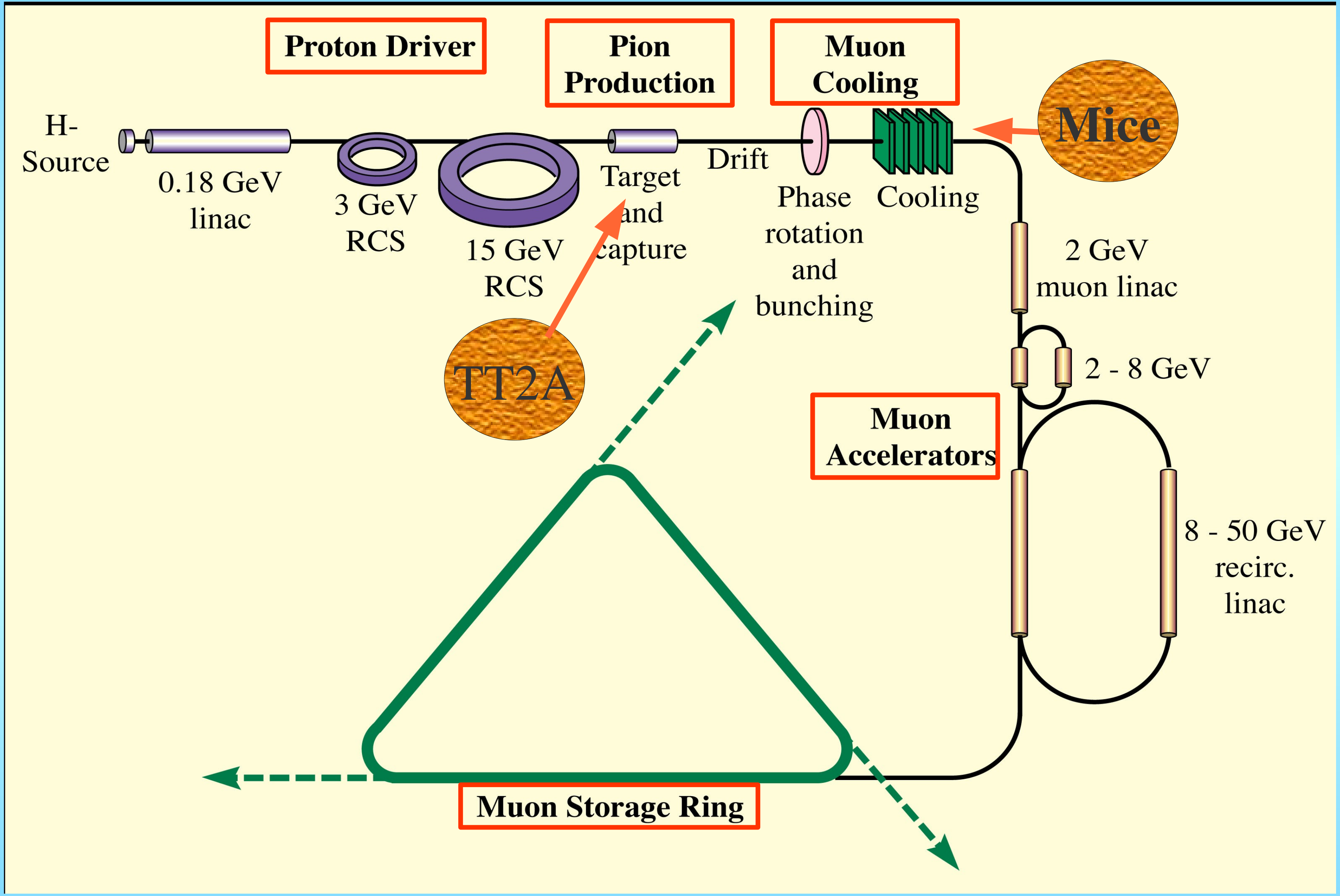
Predictions:

- Tritium endpoint searches for absolute ν mass depends on density of source?
- A MiniBooNE signal for ν_μ disappearance or ν_e appearance

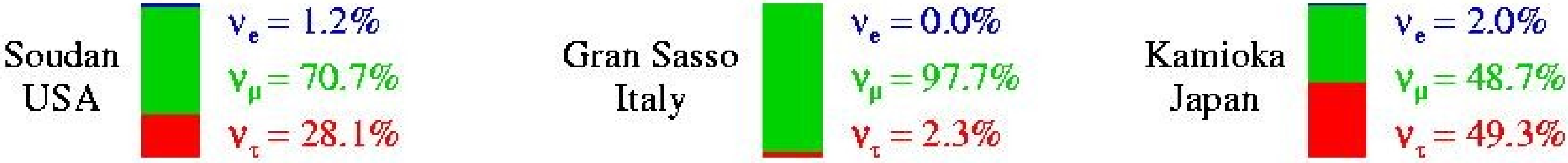
The Neutrino Factory

- Use μ to $e\nu_\mu\bar{\nu}_e$ as source of known neutrino beams: 10^{21}/yr
- 4MW protons at 2-20GeV on dense target
- Efficient collection of π, allow decay to μ
- Cool muons for injection into accelerator: LH_2 absorber
- Fast acceleration to 20-50GeV: Linac? RCS?
- Storage ring with straight sections pointing at detectors 2000-8000km away
- Large detector, at least sensitive to muon charge, tau ID or electron charge useful bonus.

The Neutrino Factory



Possible beamlines



Soudan
USA

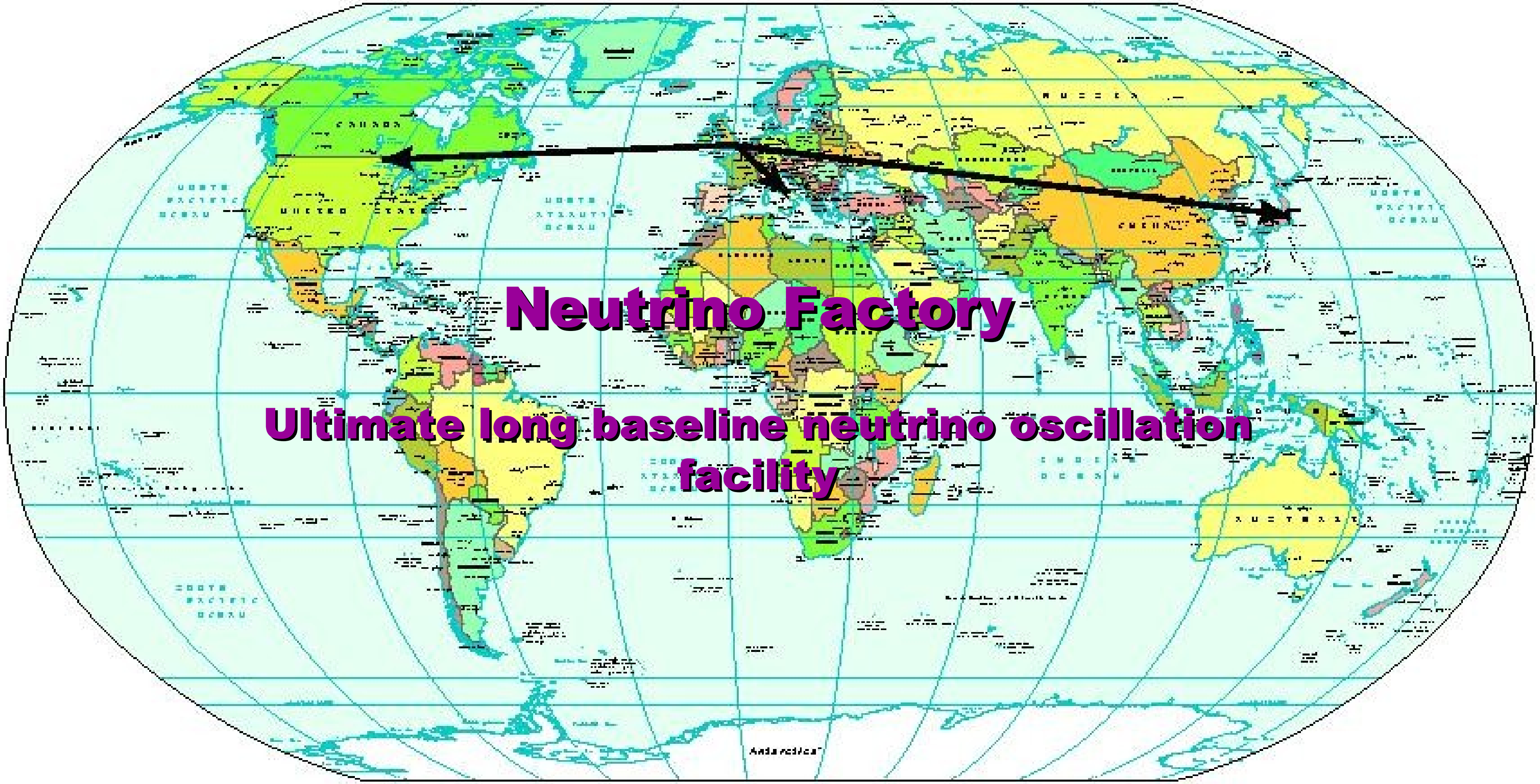
$\nu_e = 1.2\%$
$\nu_\mu = 70.7\%$
$\nu_\tau = 28.1\%$

Gran Sasso
Italy

$\nu_e = 0.0\%$
$\nu_\mu = 97.7\%$
$\nu_\tau = 2.3\%$

Kamioka
Japan

$\nu_e = 2.0\%$
$\nu_\mu = 48.7\%$
$\nu_\tau = 49.3\%$



Neutrino Factory

Ultimate long baseline neutrino oscillation facility

Neutrino Factory: I & II

- **define benchmark neutrino factories:**

	P(MW)	μ's/year	$T_\nu+T_\nu$ (y) –	M(kt)
Neutrino factory I:	0.75	10^{20}	5	10
Neutrino factroy II:	4.00	$5.3*10^{20}$	8	50

- **baseline 3000km**
- **magnetized iron detector ➔ wrong sign μ's**

simulations of various options:

Barger, Geer, Raja, Whisnant, Marfatia, ...

Cervera, Donini, Gavela, Gomez-Cadenaz, Hernandez, Mena, Rigolin, ...

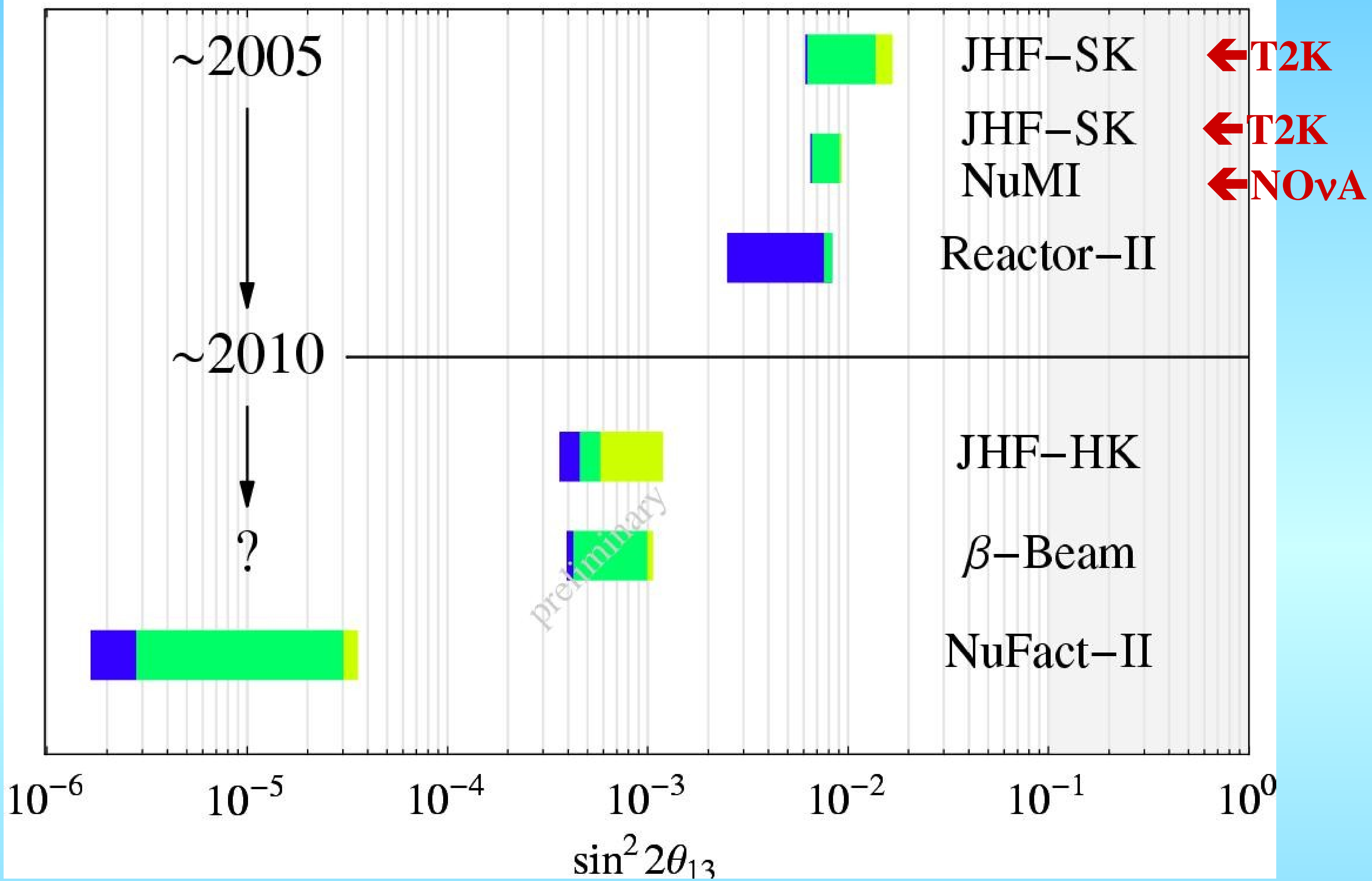
Bueno, Campanelli, Rubbia, ...

Minakata, Yasuda, ...

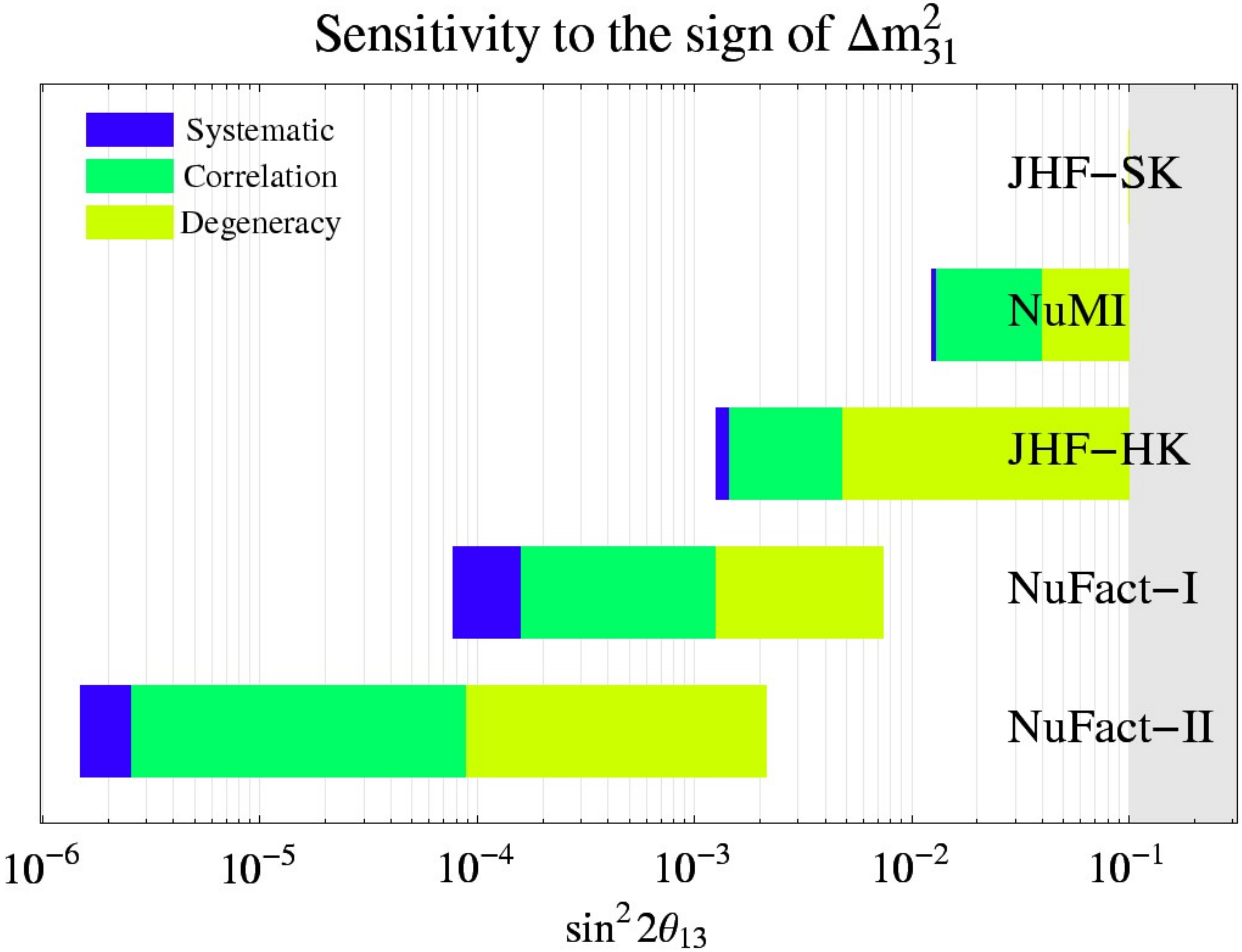
Freund, Huber, ML, Winter, ...

...

Sensitivity to $\sin^2 2\theta_{13}$ at 90% cl



- **different sensitivity reductions by systematics**
- **correlations & degeneracies lead to severe sensitivity reductions**
- **break C&D by combining different experiments of comparable potential**

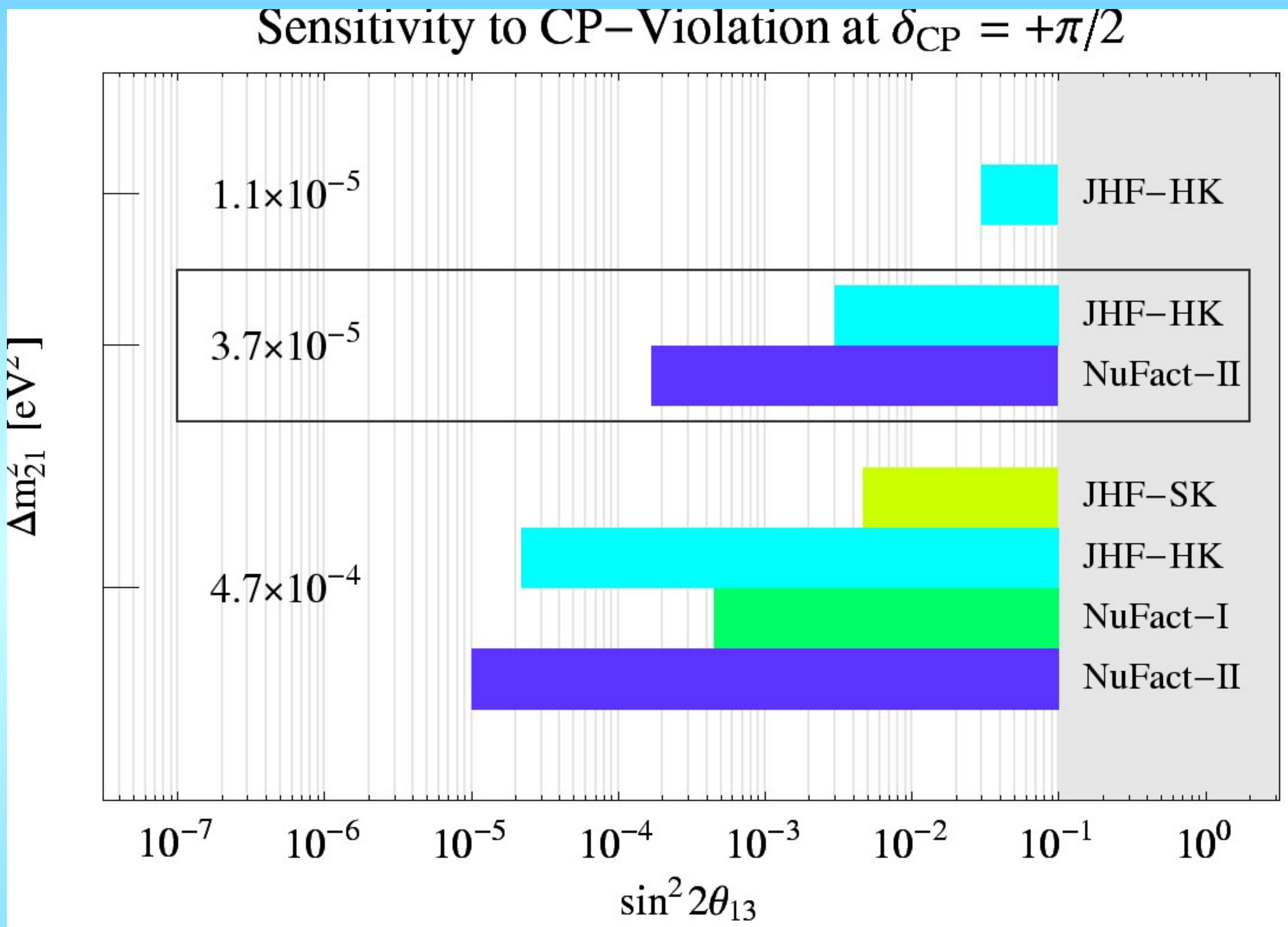


- $sign(\Delta m^2_{31})$ very hard to determine with superbeams
- degeneracies with δ_{CP} are the main problem

$\Rightarrow$ combine experiments!

Huber, ML, Winter, hep-ph/0204352

Measurement of CP Violation



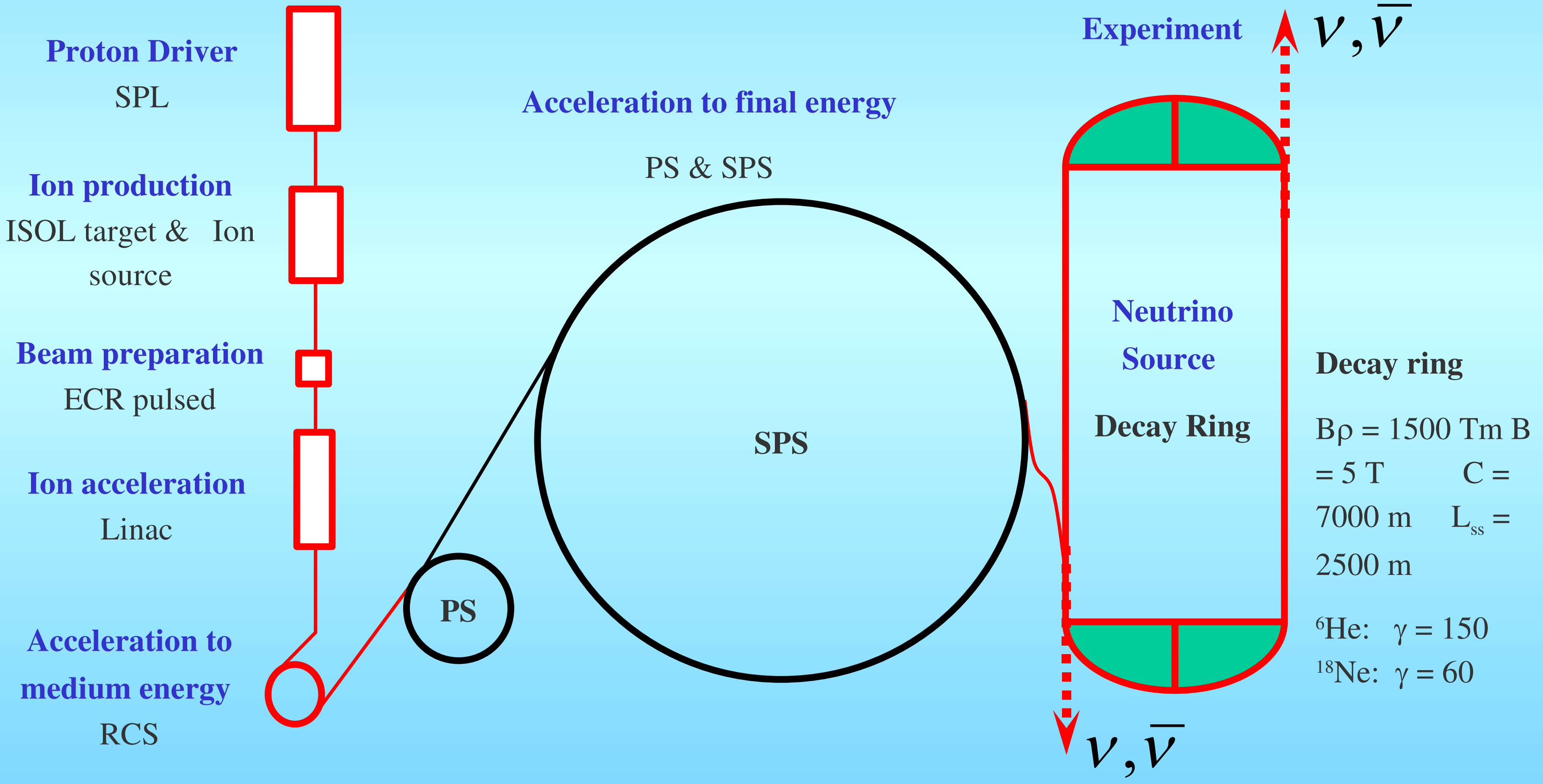
- CP violation with high luminosity superbeams feasable
- sensitivity is δ_{CP} dependent

Huber, ML, Winter, hep-ph/0204352

Beta beams

- β beams: Nucleii which release neutrinos
  - If muons can be boosted before decay, why not ions?
  - longer lifetime, only 1 flavour of muon
  - SPL at CERN as source, SPS/LHC as accelerator, just need storage ring.
  - Need very high energy to get high neutrino energy
- Does beta beam augment a ν factory?
  - No.
  - Nor does it fully replace one

Beta-beam baseline design



Ion production

Proton Driver
SPL

Ion production
ISOL target & Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac

Acceleration to medium energy
RCS

Acceleration

Acceleration to final energy
PS & SPS

PS

SPS

Neutrino source

Experiment

$\nu, \bar{\nu}$

Neutrino Source

Decay Ring

$\nu, \bar{\nu}$

Decay ring

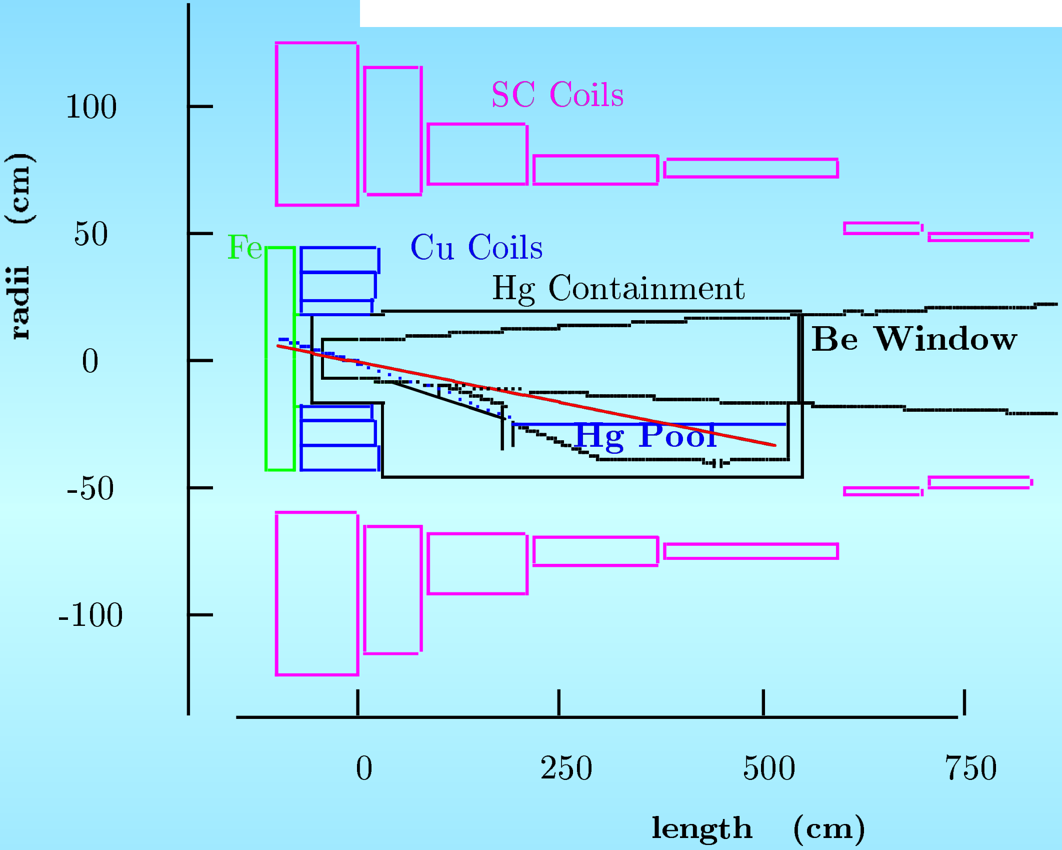
$B\rho = 1500$ Tm $B = 5$ T $C = 7000$ m $L_{ss} = 2500$ m

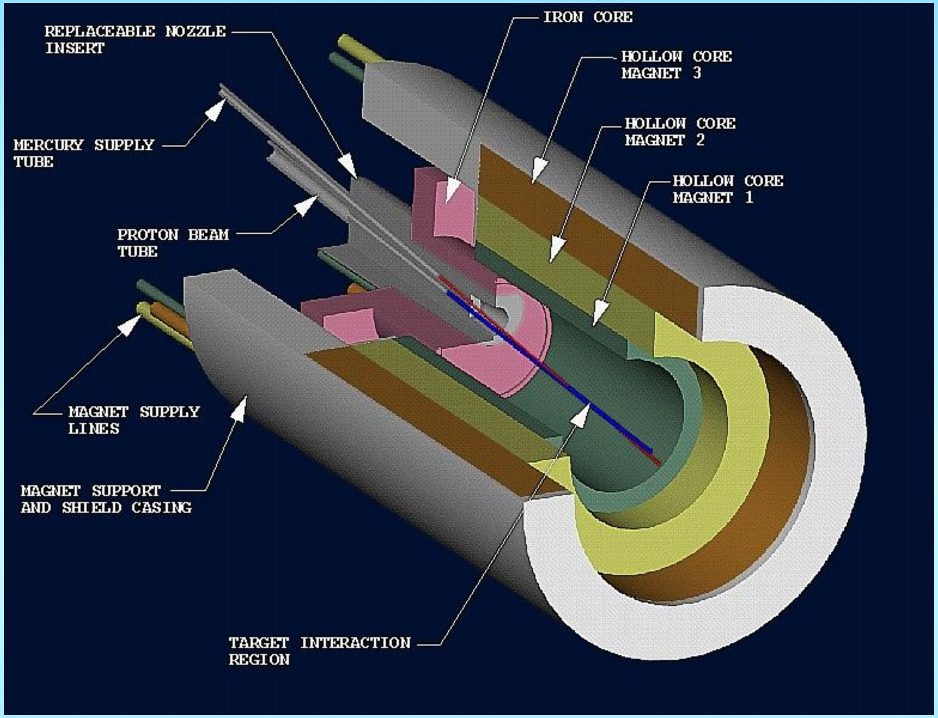
^{6}He: $\gamma = 150$
^{18}Ne: $\gamma = 60$

Targetry

- Aim if for 4MW power on small target
- Roger Bennett: Solid targets
  - magic properties do not last when exposed to beams
  - Prospects not good right now: Wait for more results
- Harold Kirk, liquid metal jet
  - Designed 15T pulsed solenoid, delivery Nov. 2004
  - Experiment TT2A 2006??

Neutrino Factory Targetry Concept





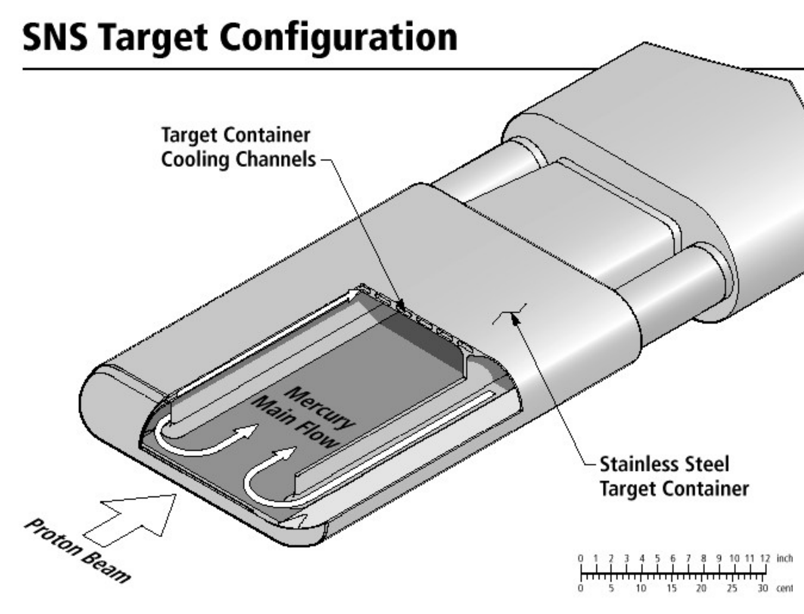
Capture low P_T pions in a high-field solenoid

Use Hg jet tilted with respect to solenoid axis

Use Hg pool as beam dump

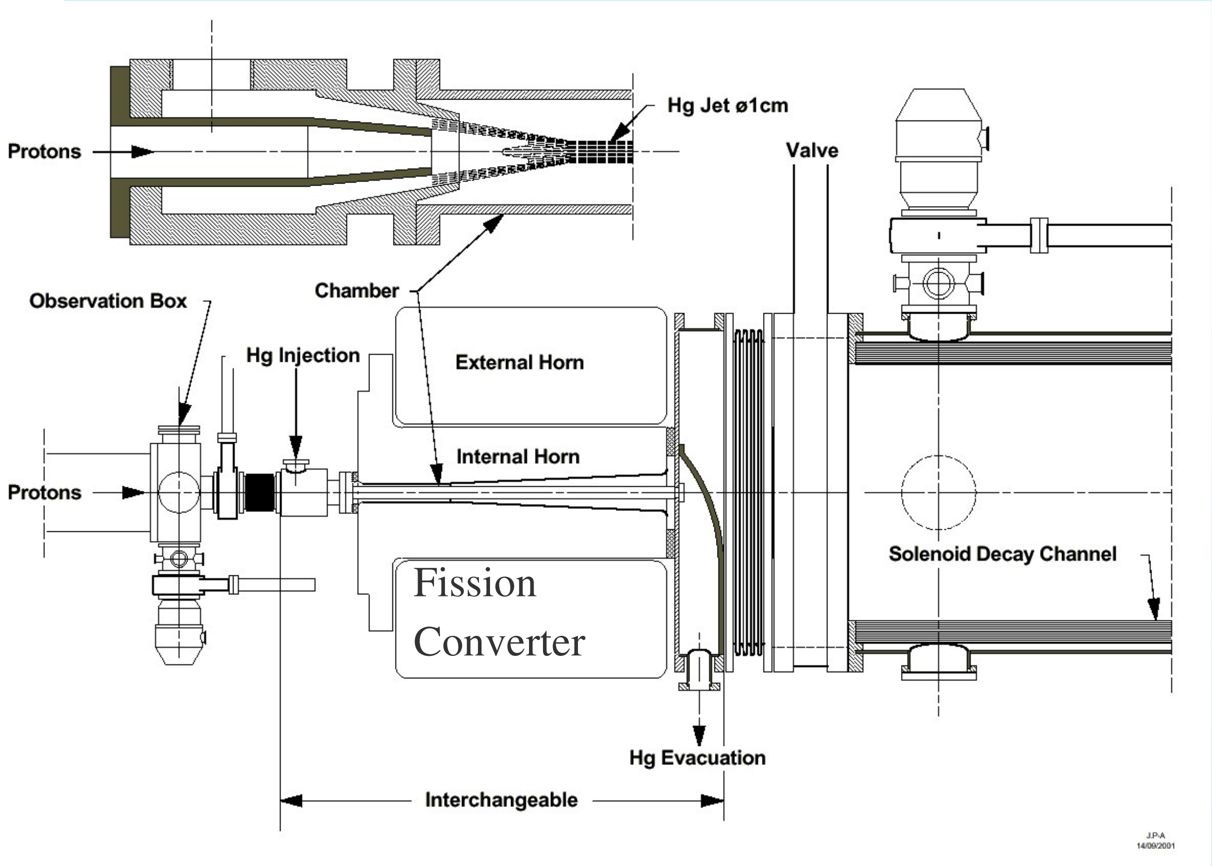
TT2A experiment at CERN aims to test all important elements in 2006

Neutron Production using Hg

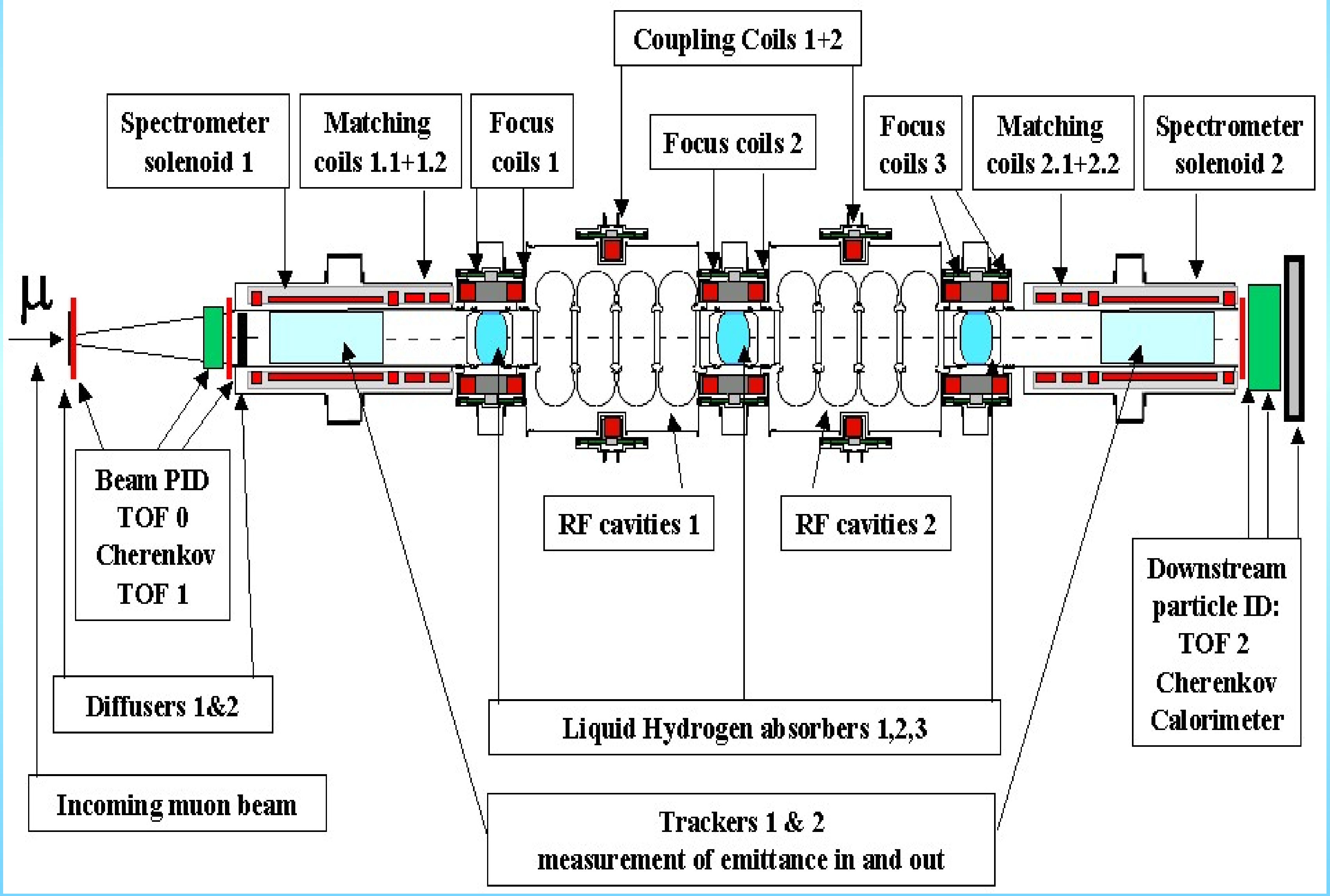


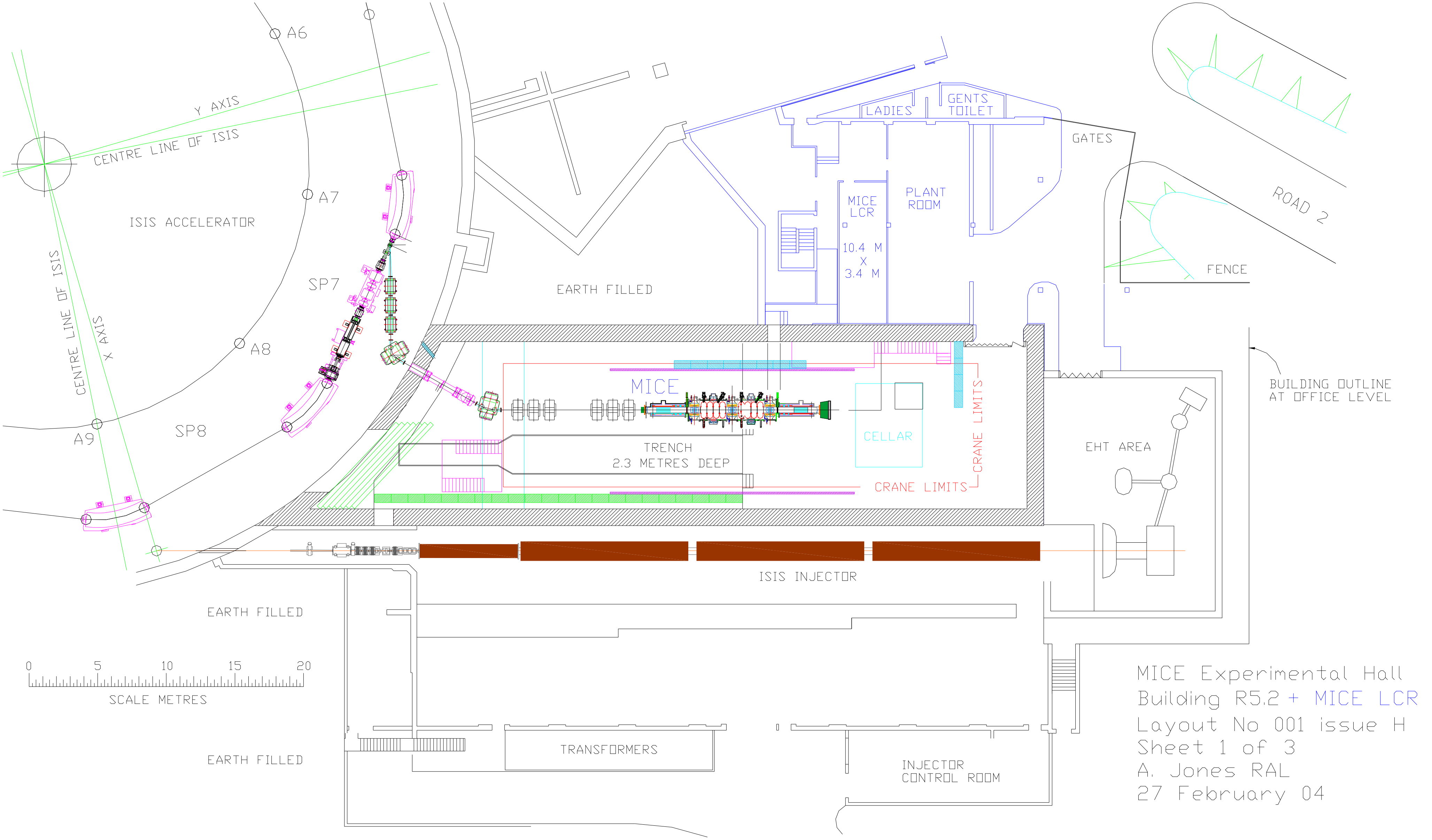
SNS Neutron Spallation Target

Beta Beams



Mice


Coupling Coils 1+2
Spectrometer solenoid 1
Matching coils 1.1+1.2
Focus coils 1
Focus coils 2
Focus coils 3
Matching coils 2.1+2.2
Spectrometer solenoid 2
μ
Beam PID
TOF 0
Cherenkov
TOF 1
RF cavities 1
RF cavities 2
Downstream particle ID:
TOF 2
Cherenkov
Calorimeter
Diffusers 1&2
Liquid Hydrogen absorbers 1,2,3
Incoming muon beam
Trackers 1 & 2
measurement of emittance in and out



MICE Experimental Hall
Building R5.2 + MICE LCR
Layout No 001 issue H
Sheet 1 of 3
A. Jones RAL
27 February 04

MICE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT

MICE HALL

Beam hole!

Mice has now been approved

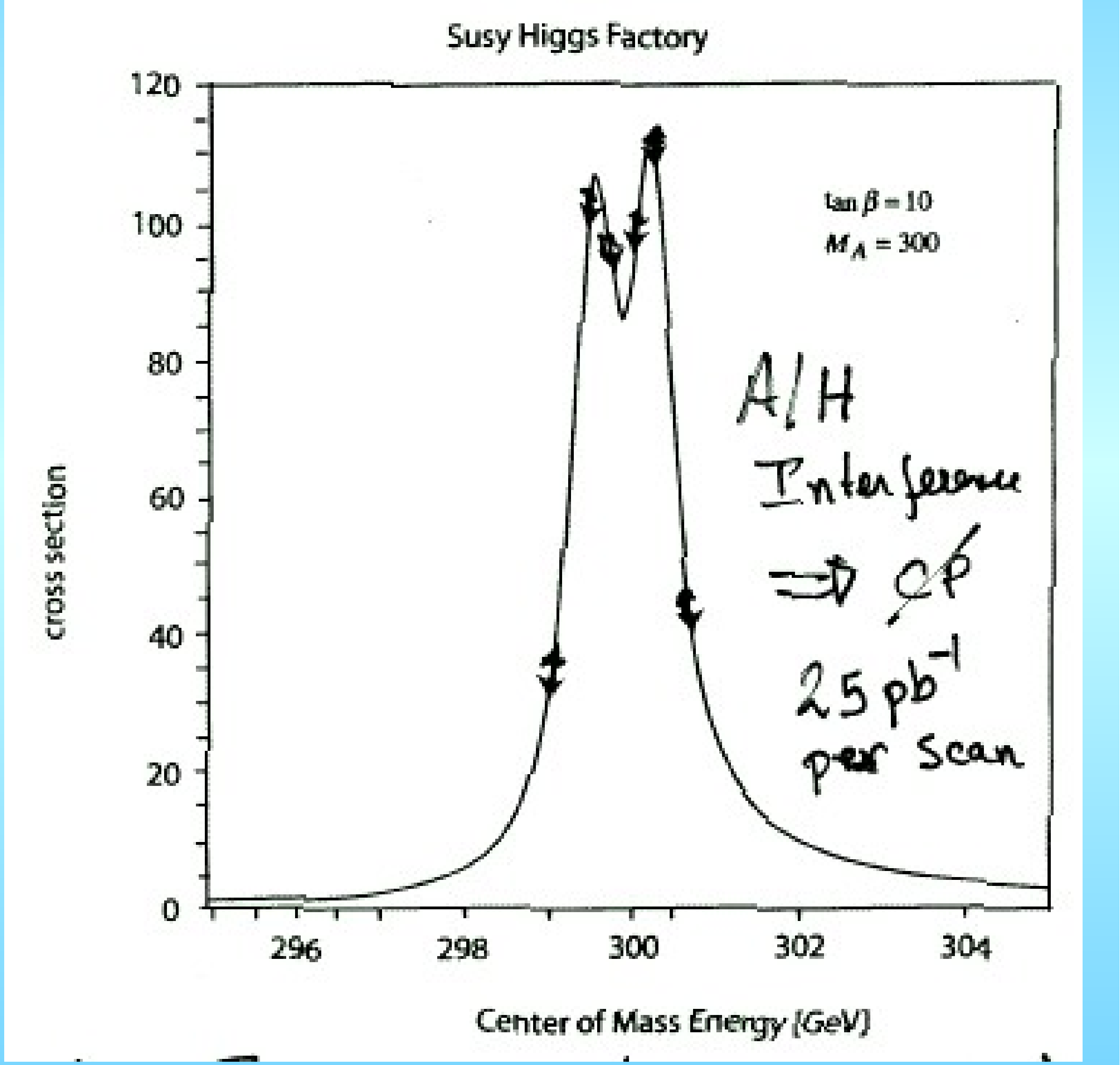
- Lord Sainsbury announced phase I a month ago.
- ~£10M investment in accelerator technology

Muon Colliders

- D. Cline persuing Muon collider potential
  - precise, high energy collisions; no beamstrahlung
  - Collider beam time structure different from Neutrino Factory
  - A/H discovery at LHC would mandate muon collider
  - Progress on ring coolers makes them possible

A/H factory

- Heavy SUSY Higgses quasi-degenerate
- Only muon collider scans peaks
- Can test CP violation in Higgs sector



A Garren
H Kirk
Steve Kahn

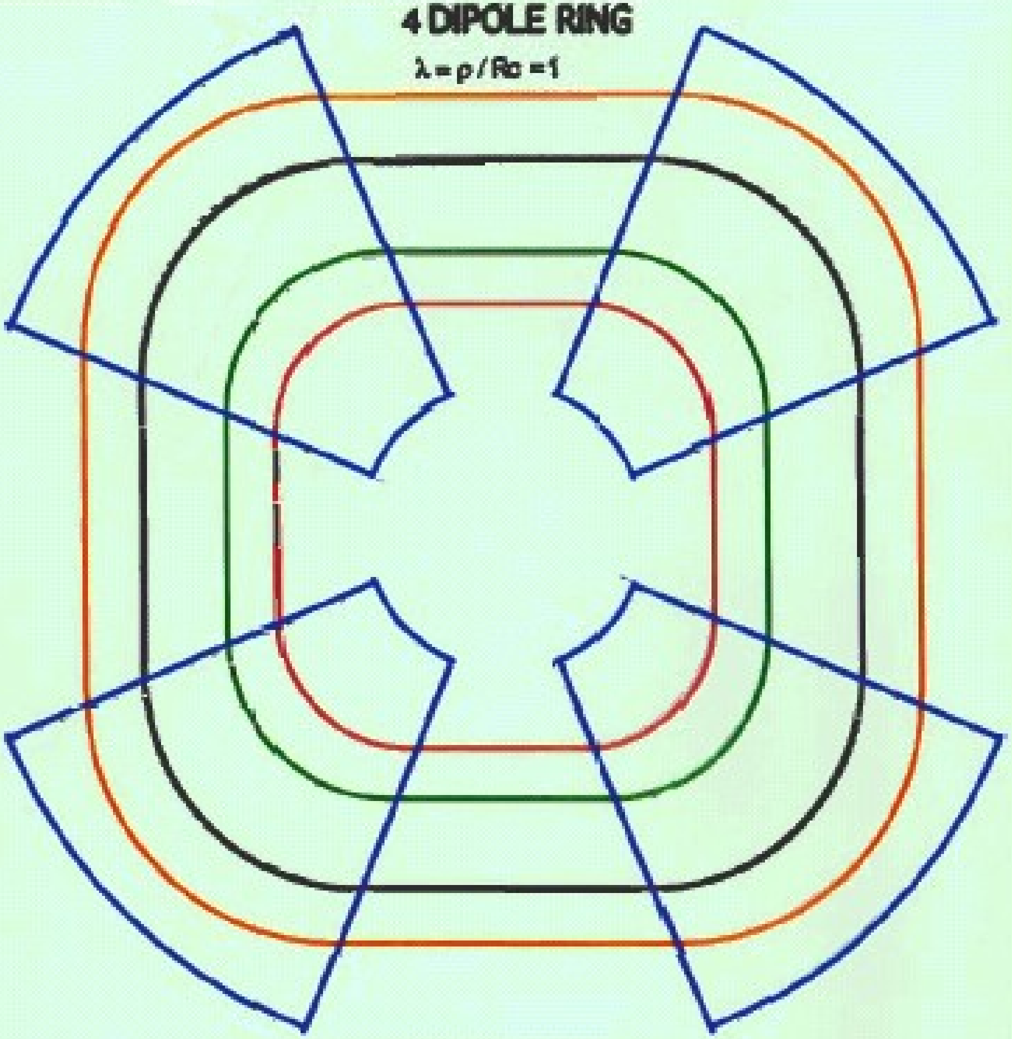
6D Cooling in Gas-filled Rings

Closed orbits scale such that the path length of each orbit is proportional to the particle momentum.

6D Merit = Transmission x

$(\varepsilon_x \varepsilon_y \varepsilon_z)_{initial} / (\varepsilon_x \varepsilon_y \varepsilon_z)_{final}$

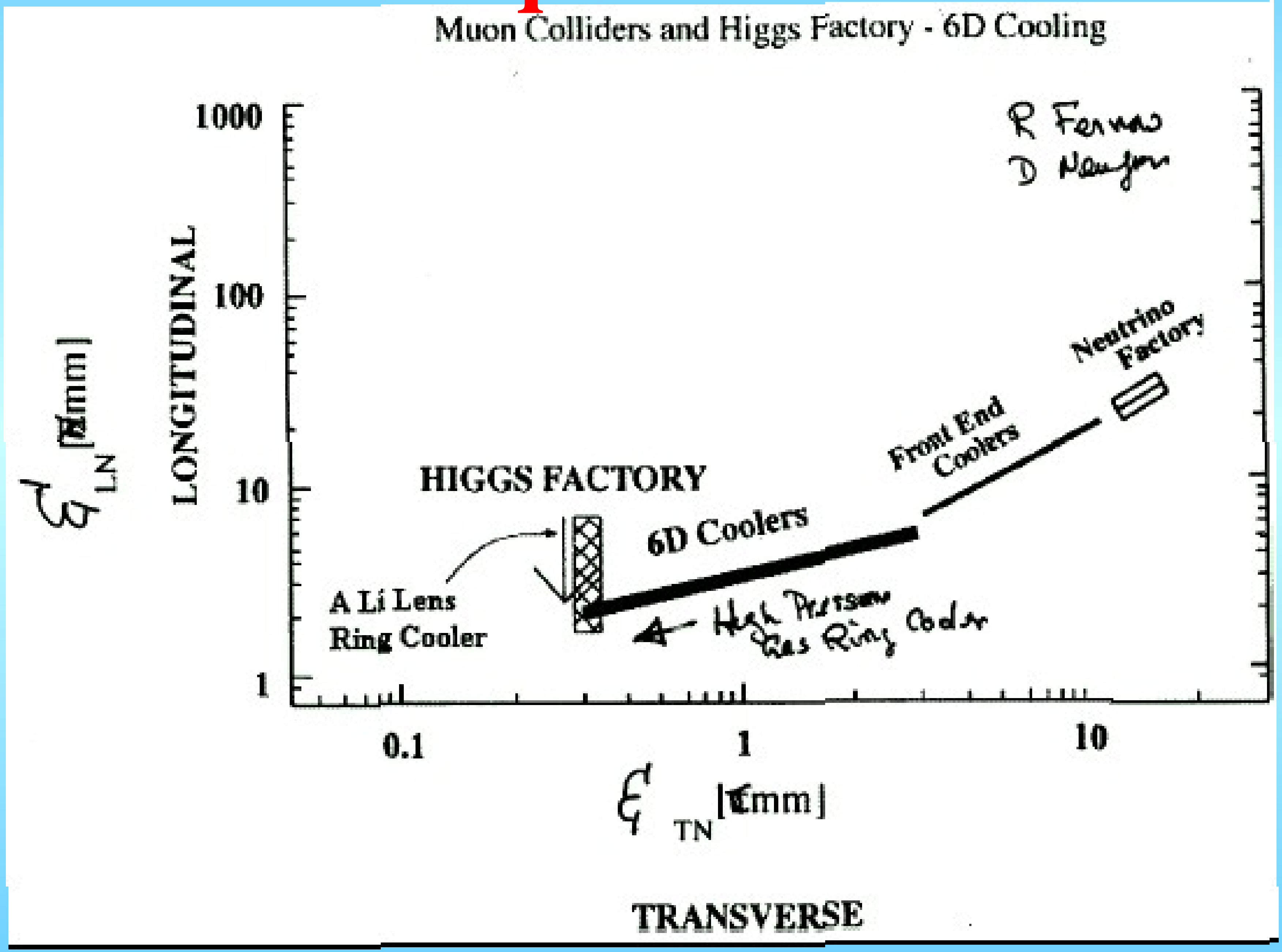
Key Issue: Gas filled RF Cavities



BROOKHAVEN NATIONAL LABORATORY

Harold G. Kirk

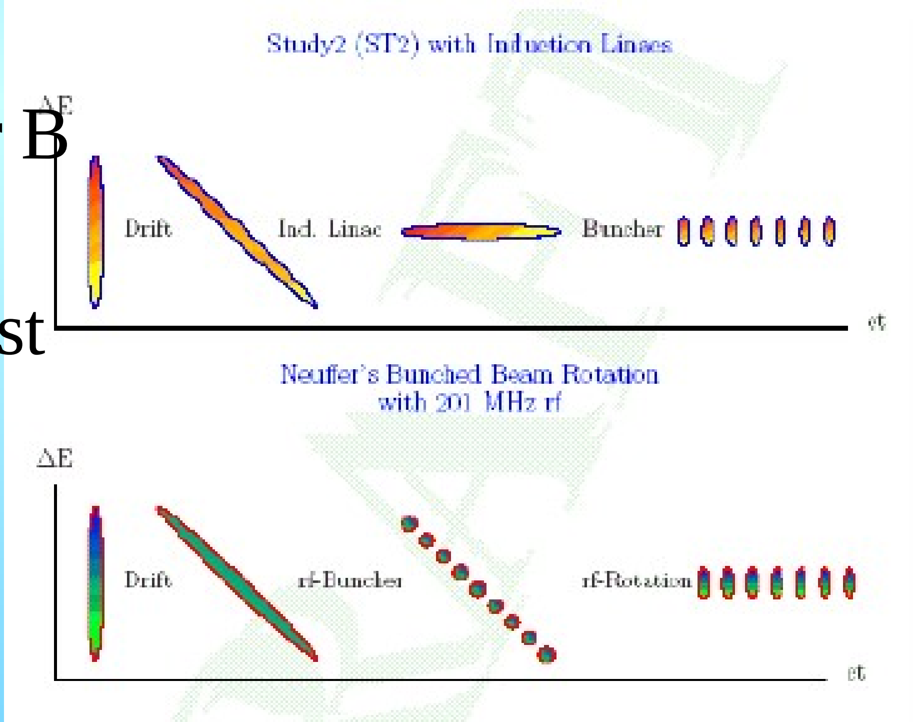
Reach required emittance?



Study 2a - Fernow

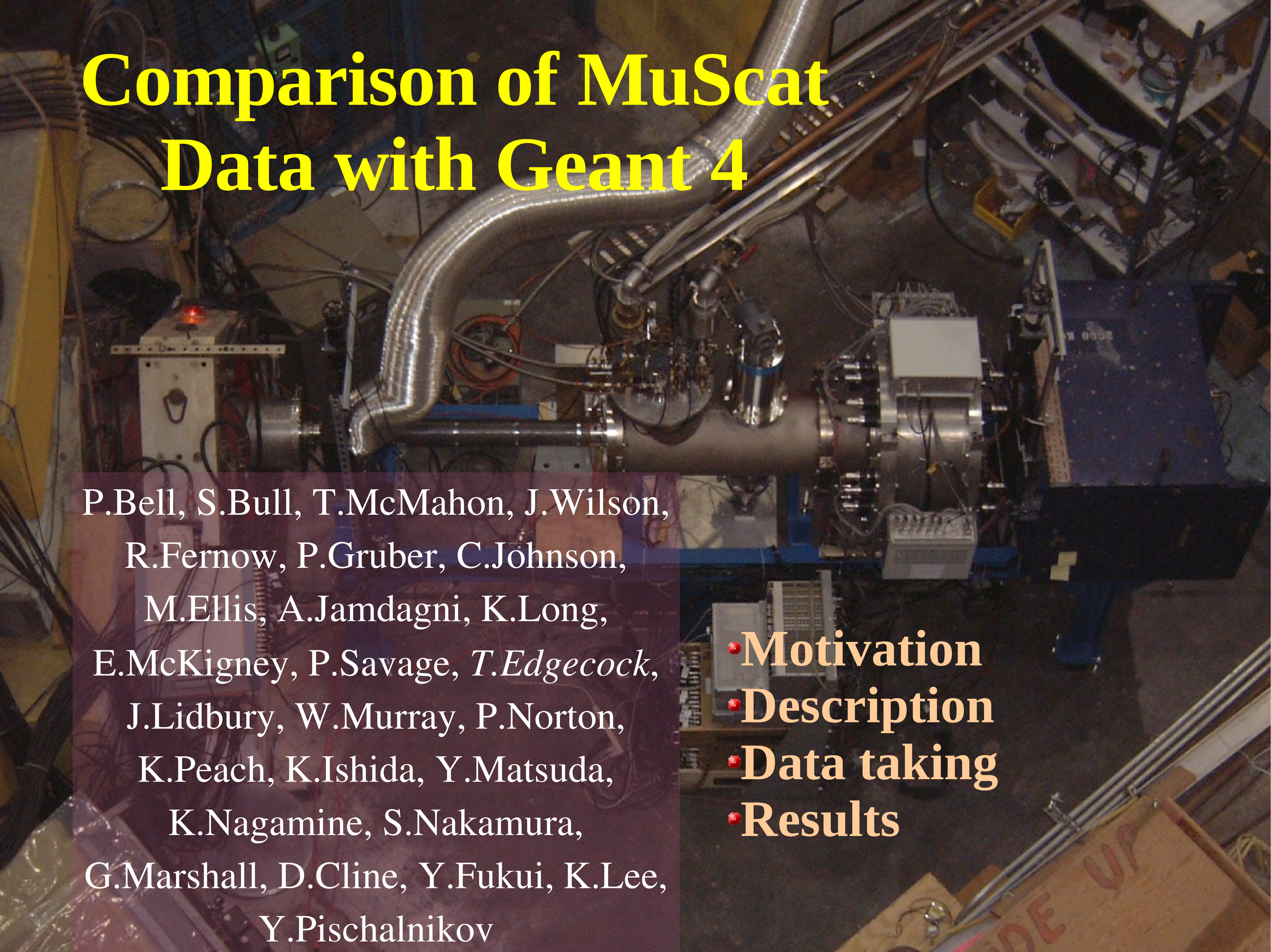
- Studys 1 & 2: Fermilab/BNL NuFact schemes
- Study 2a tries to reduce cost from study 2.

- Adiabatic RF bunching – no induction Linac
- simplified cooling cooling, lower B fields
- Similar perfomance, front end cost 53%: Overall 67%
- μ^+ μ^- beams: Good or bad?
  - Separation only metres



Communique from NuFact 04

- Communiqué from the 6th International Workshop on Neutrino Factories and Superbeams, 26th July – 1st August 2004, Osaka, Japan
- About 160 particle and accelerator physicists from Europe, Japan and the US met in Osaka (Japan) from 26th July to 1st August 2004, to discuss progress in neutrino physics and options for producing intense beams of neutrinos to explore their properties in detail, to make new discoveries about neutrinos, and thereby to understand better their nature. One of the highlights of the meeting was the strong indication that the cost of the most powerful facility, the Neutrino Factory, could be reduced by at least one third, compared with previous estimates.
- There are three new schemes for producing these intense beams of neutrinos – “superbeams”, “beta beams” and the “neutrino factory”. ....
- There is a clear programme of R&D for the next five years to take the key technologies from design to prototype.
- As chair of the final session, Dr Steve Geer (Fermilab, USA) said that “the scientific case for new experiments with intense beams of neutrinos over long baselines becomes stronger with each workshop”.



Comparison of MuScat Data with Geant 4

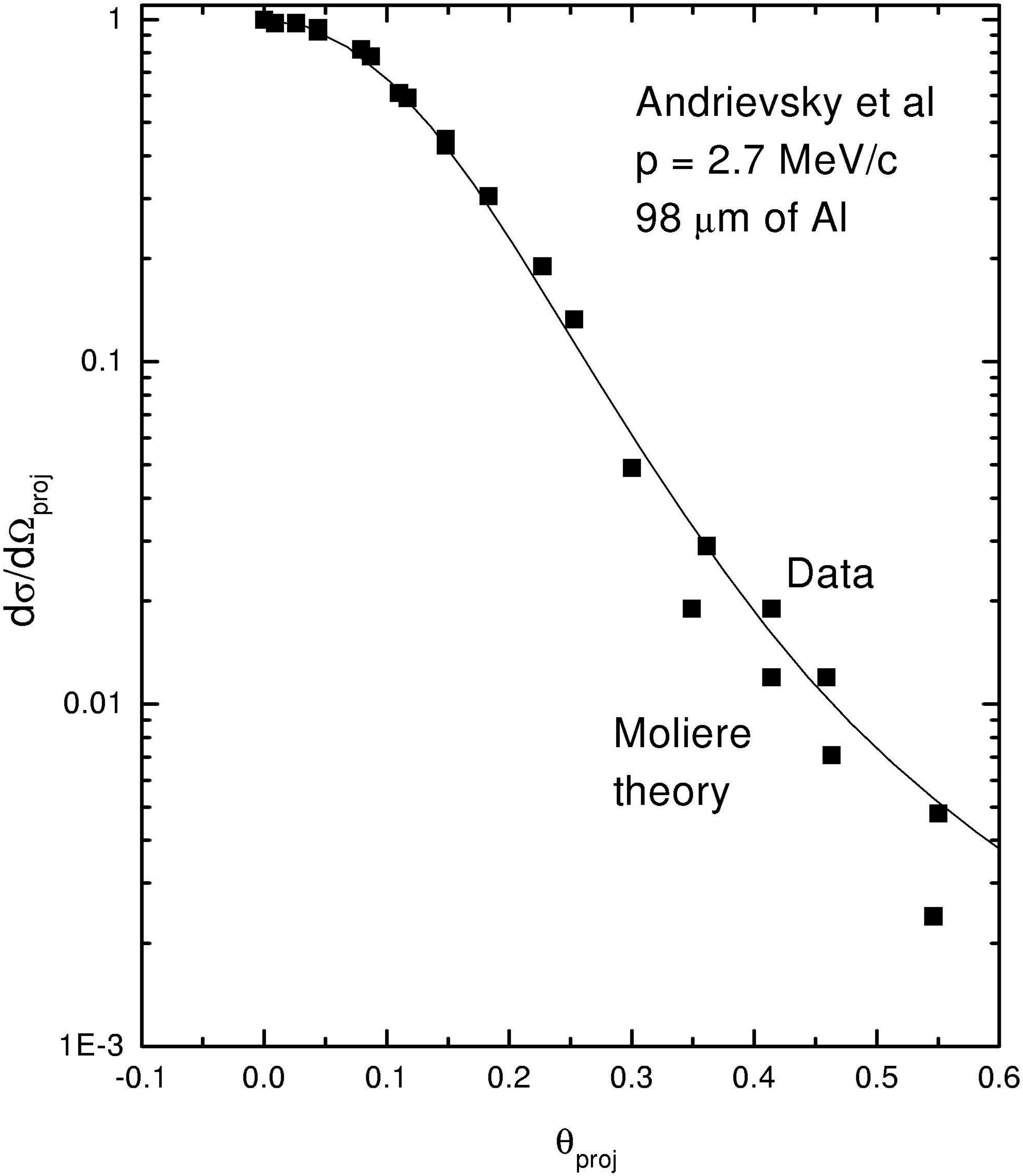
P.Bell, S.Bull, T.McMahon, J.Wilson,
R.Fernow, P.Gruber, C.Johnson,
M.Ellis, A.Jamdagni, K.Long,
E.McKigney, P.Savage, *T.Edgecock*,
J.Lidbury, W.Murray, P.Norton,
K.Peach, K.Ishida, Y.Matsuda,
K.Nagamine, S.Nakamura,
G.Marshall, D.Cline, Y.Fukui, K.Lee,
Y.Pischalnikov

- **Motivation**
- **Description**
- **Data taking**
- **Results**

The History

- MuScat to check multiple scattering of Muons at ~100MeV/c
  - Low Z materials for Ionisation cooling
  - Key is liquid Hydrogen
- Engineering run, Triumf 2000
  - Solid targets
  - MWPC problems
- Decide to build new fibre tracker for Autumn 2001
- Missed slot, re-allocated Spring 2003
- Data *still* being analysed, preliminary results here

Why check Multiple Scattering?



Ionization cooling is an interaction between cooling and heating

No published data on muon scattering at relevant energies

Electron data from 1942 are the most relevant.

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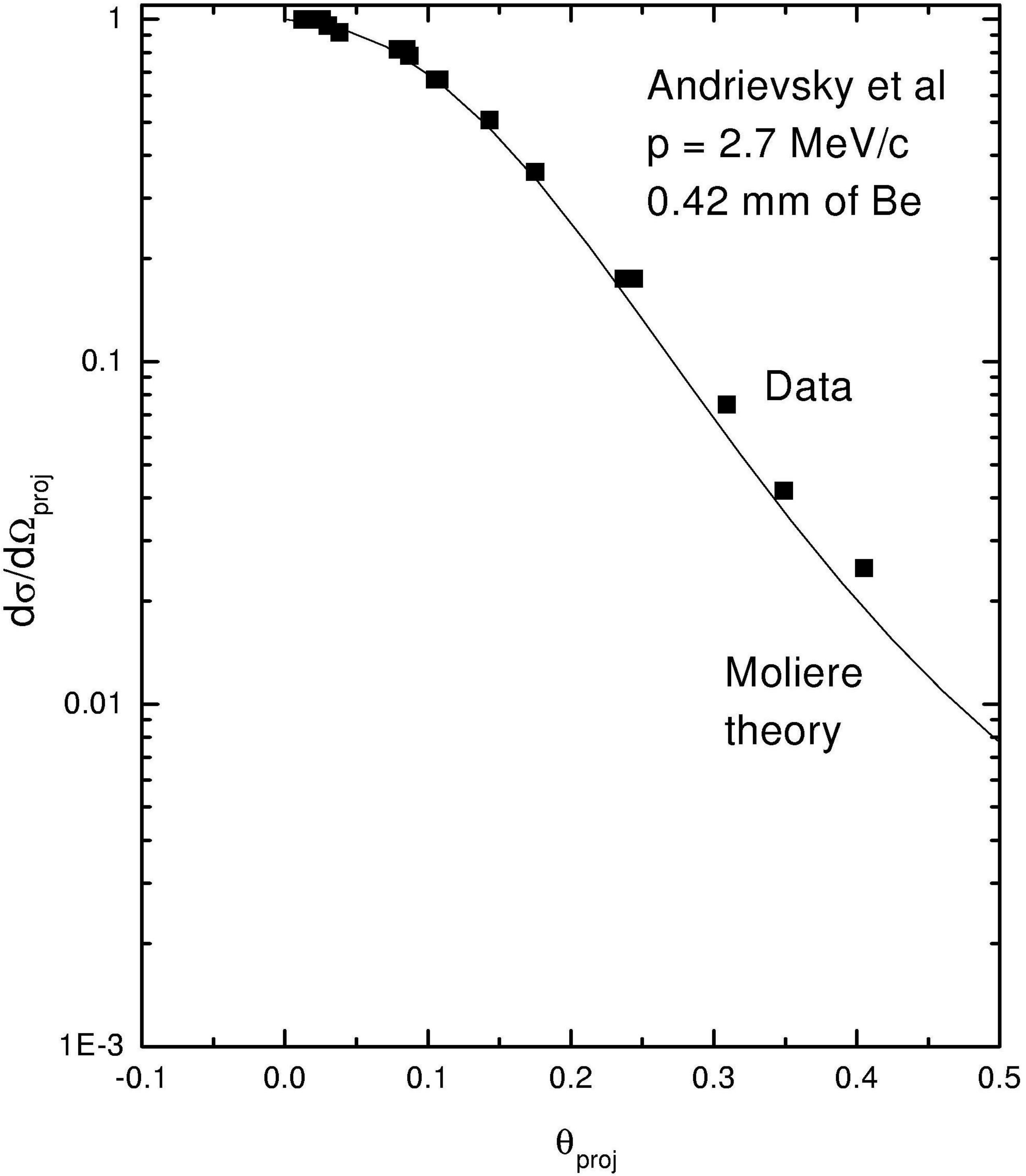

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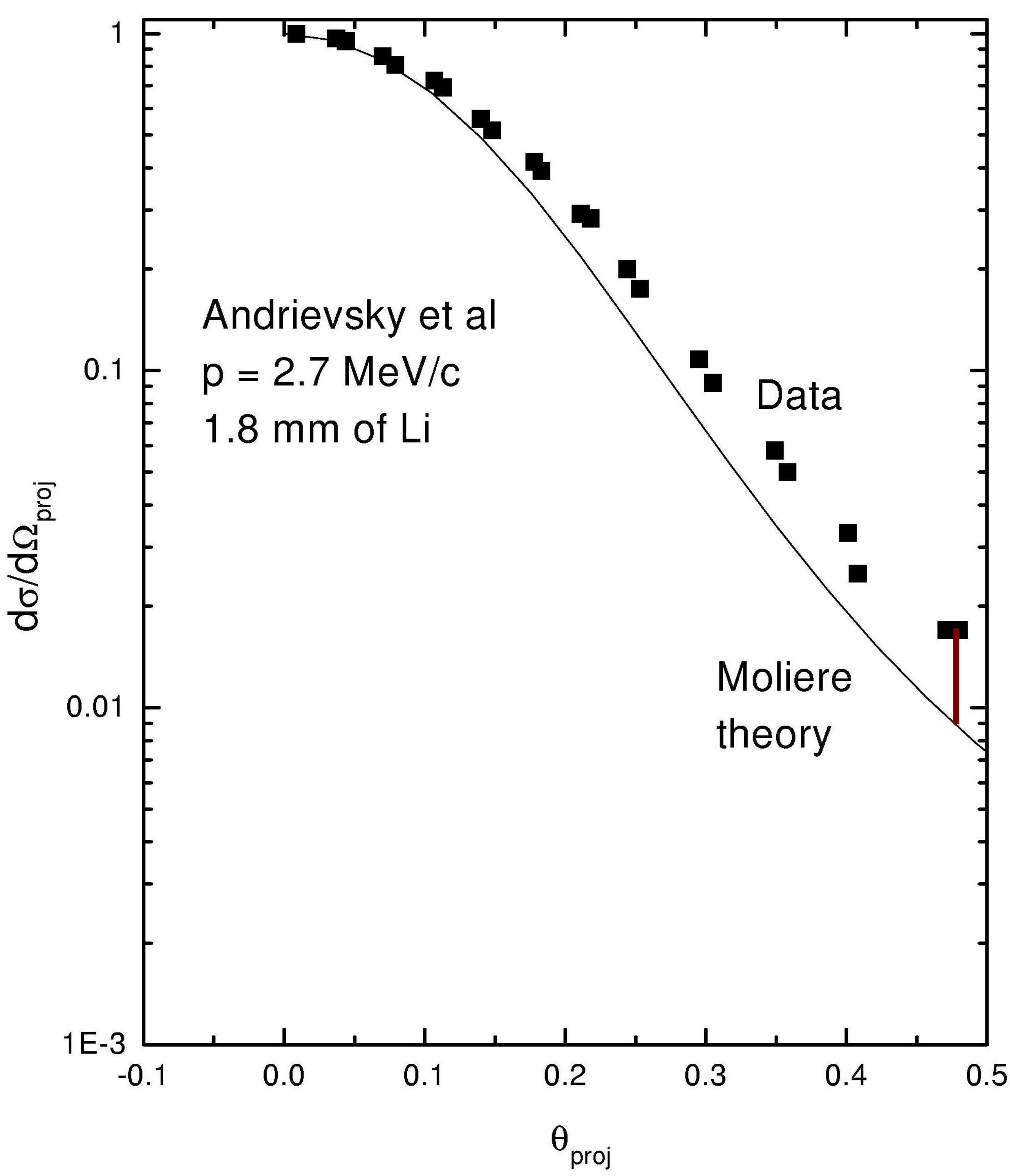

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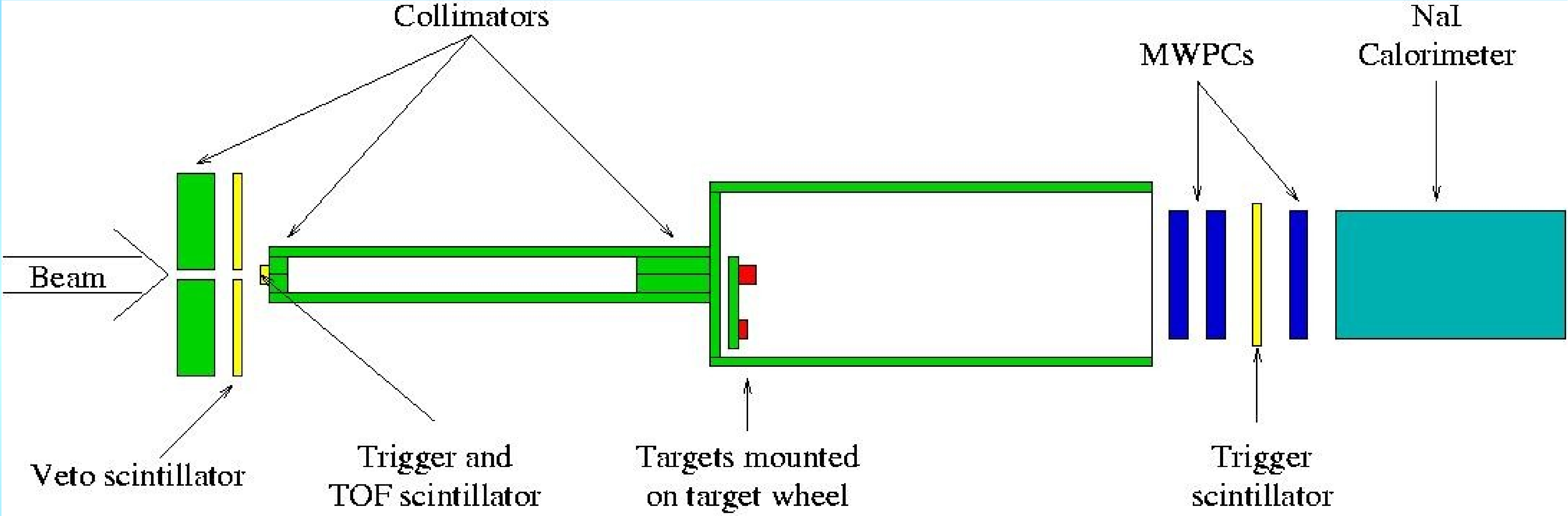
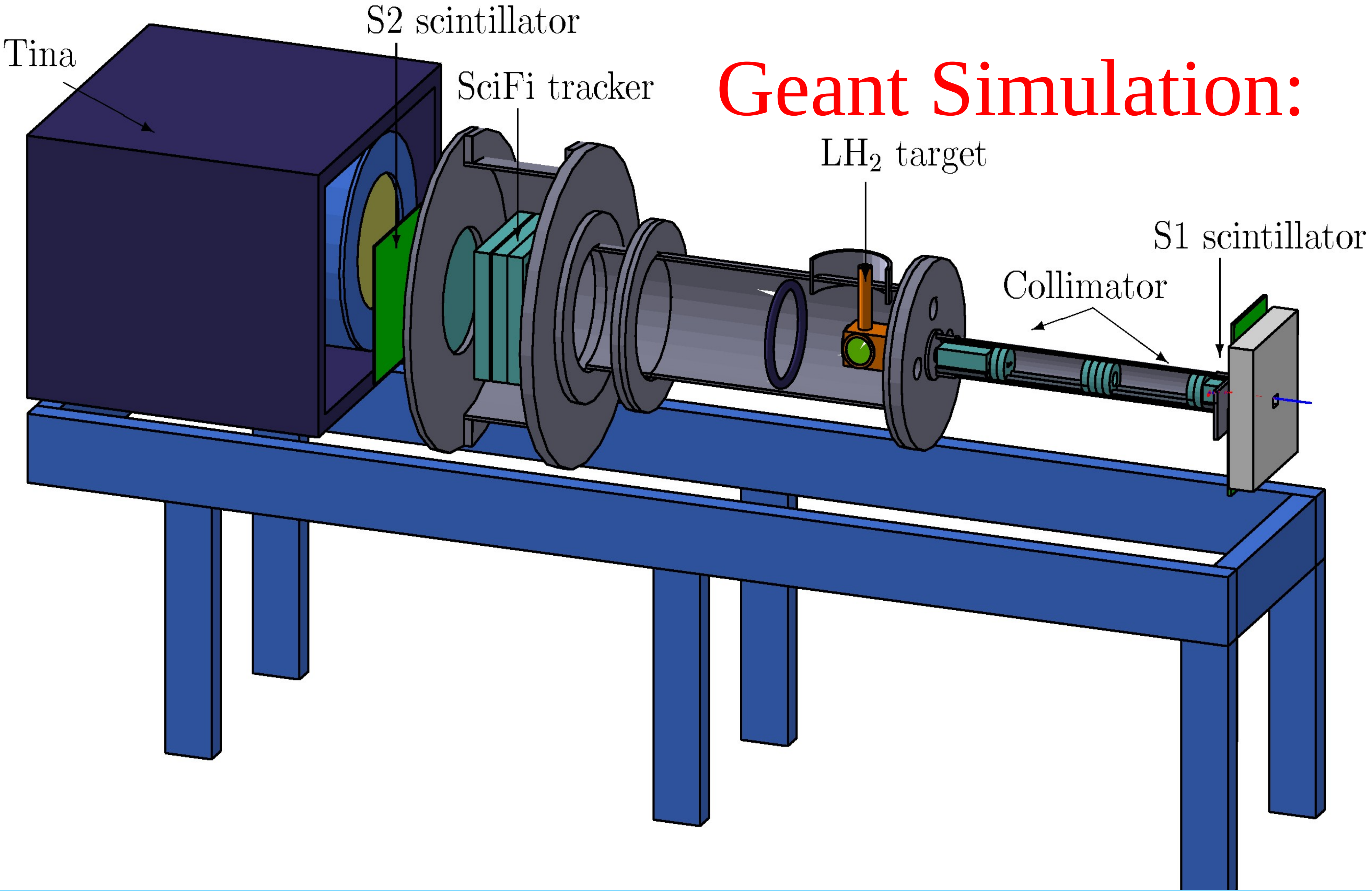
The Basic Muscat design

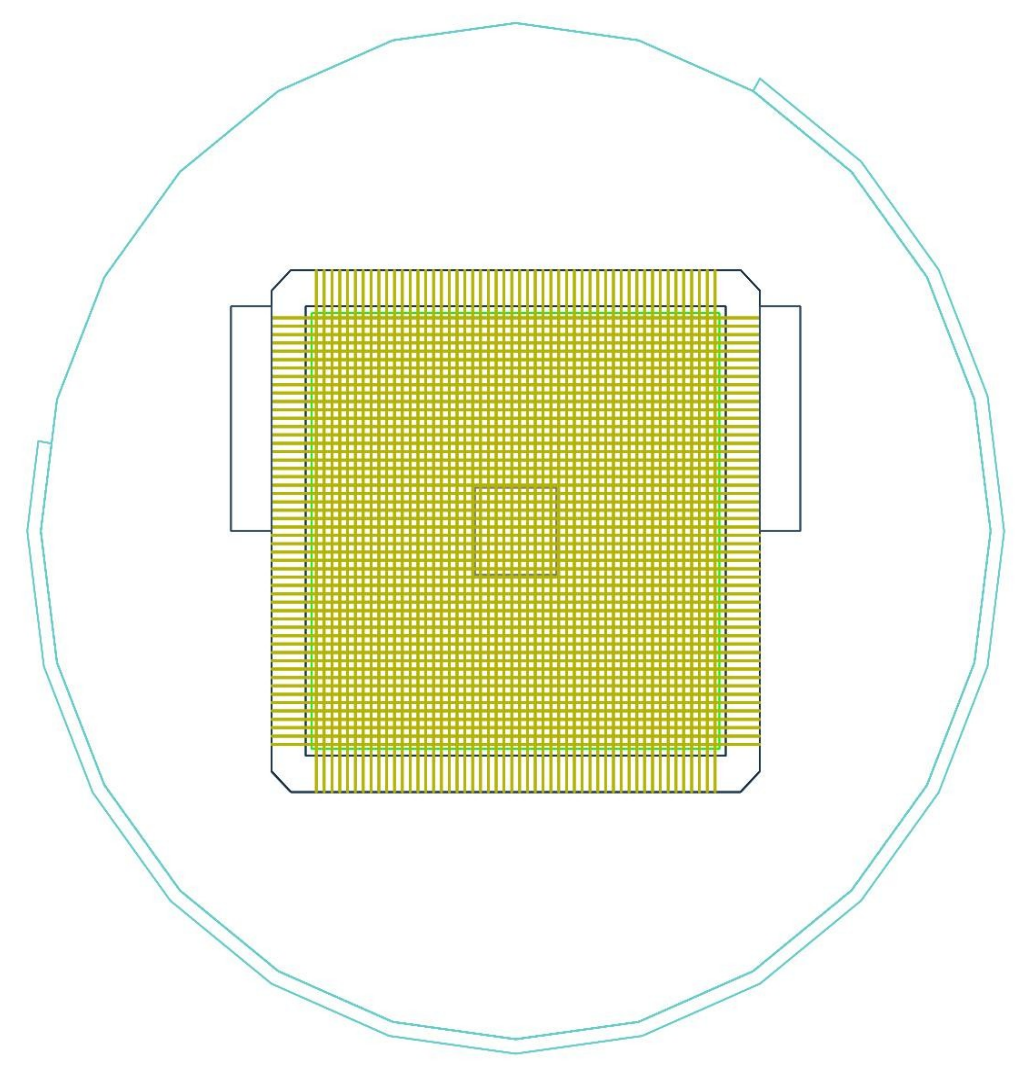


- This is a cartoon of the experiment in June 2000
- MWPCs replaced with the Sci-Fi tracker.

Geant Simulation:

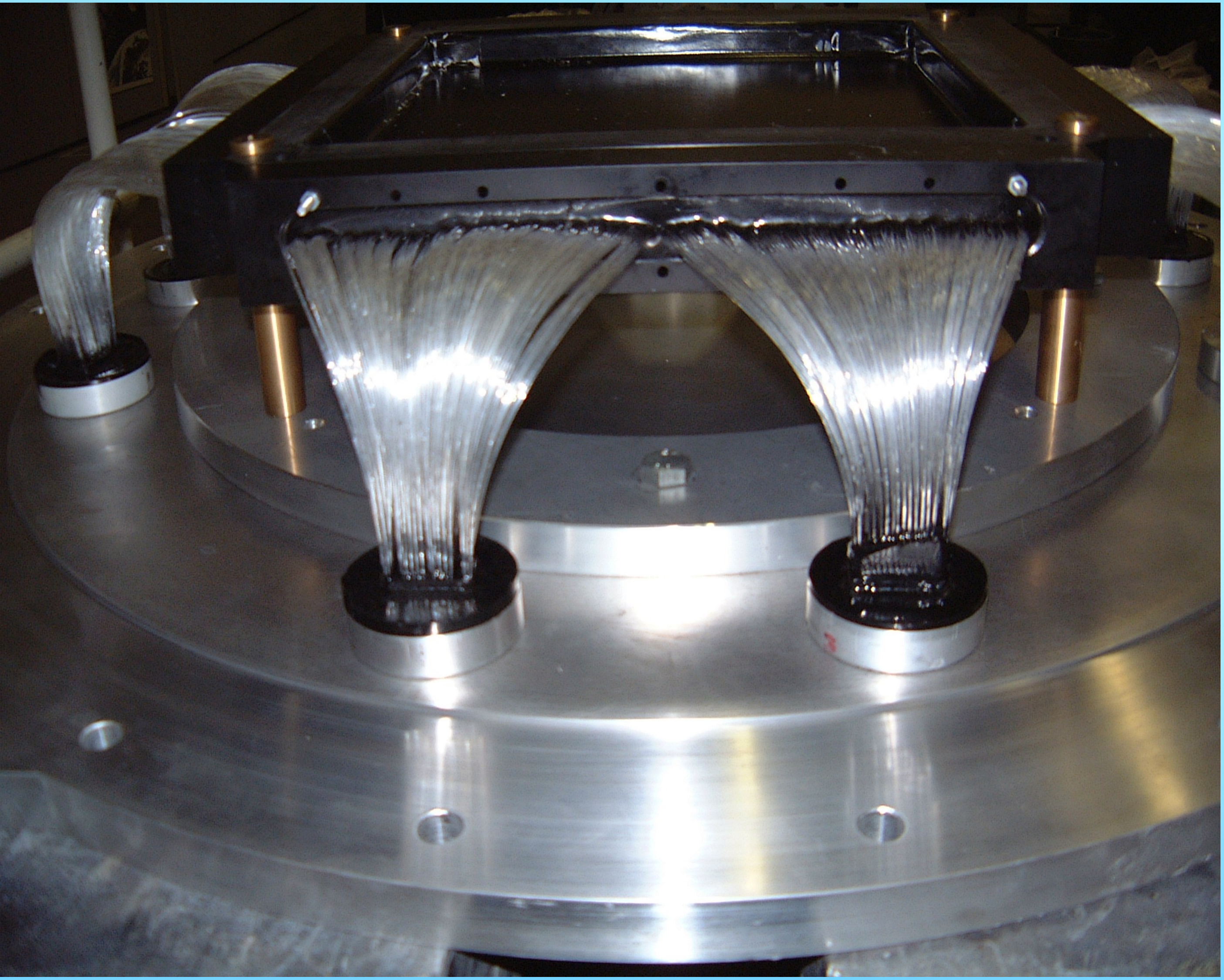


The Fibre Tracker



- 512 scintillating fibres in x and y
- Fibre diameter 1mm, spacing 0.6mm, covers 30cm^2
- 3 planes, 3096 fibres
  - A lot of rubber bands!
- Fibres potted in dark resin
  - too much material for Mice

One Mounted Plane

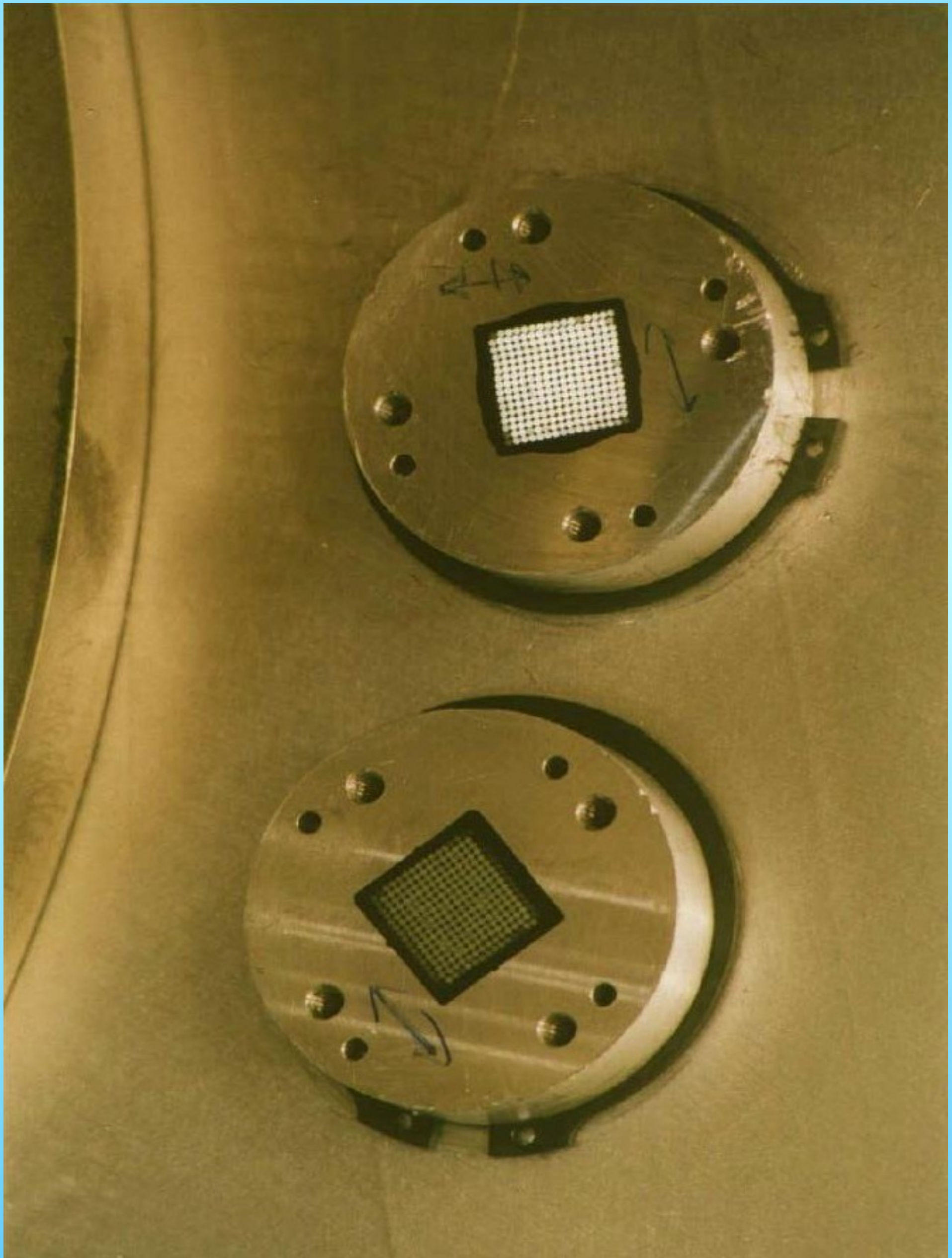


- 3 double planes
- Each with 8 fibre bundles
- Mounted in dedicated vacuum vessel
- Black resin in case of cross-talk or light leaks.

The Clear Fibre Bundles

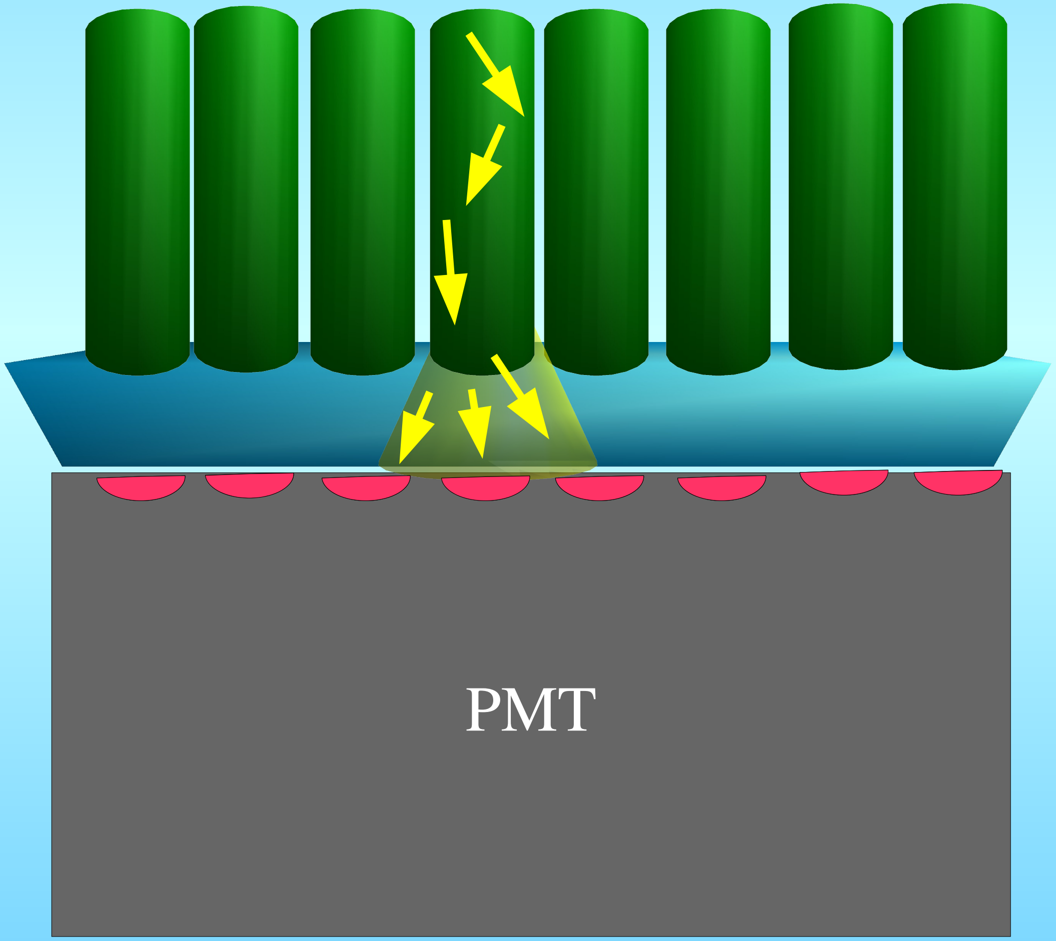
- 512 scintillating fibres grouped as 256x2
- Readout with clear fibre
  - One end match to detector edge
  - Other end potted into vacuum feedthrough/PMT interface
- 24 bundles, with 6000 fibres

The Clear Fibre Bundles II



- Each in 16mm^2 grid
- Feeding 256 fibres to 16 anode HPK PMT
- Anodes 16mm by 1mm
- Hard to keep round fibres in square grid
    - ~50% success
- Readout at both SciFi ends gives fibre mapping.

Bundle – PMT mating



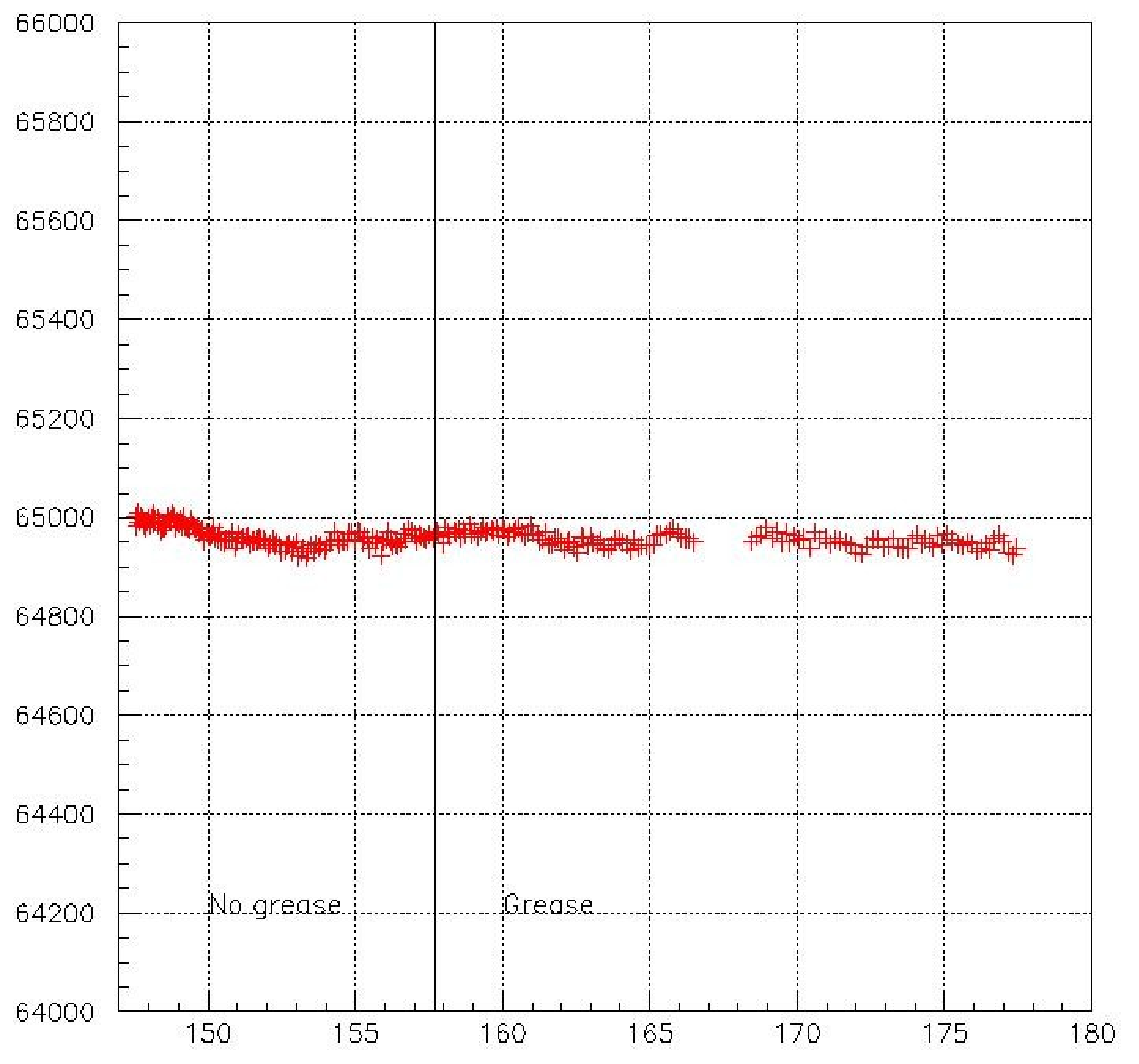
- Fibre 1mm diameter
- Anode spaced 1mm
- But..1.5mm of glass separating
- Cone angle 29^{o} in glass
  - Up to 0.8mm transverse movement
  - 35% of light on neighbours

Digitization Electronics

- Sample and hold system, 24 ADCs
- Works well for all channels
- Electronic noise low
  - Easy to select single photon

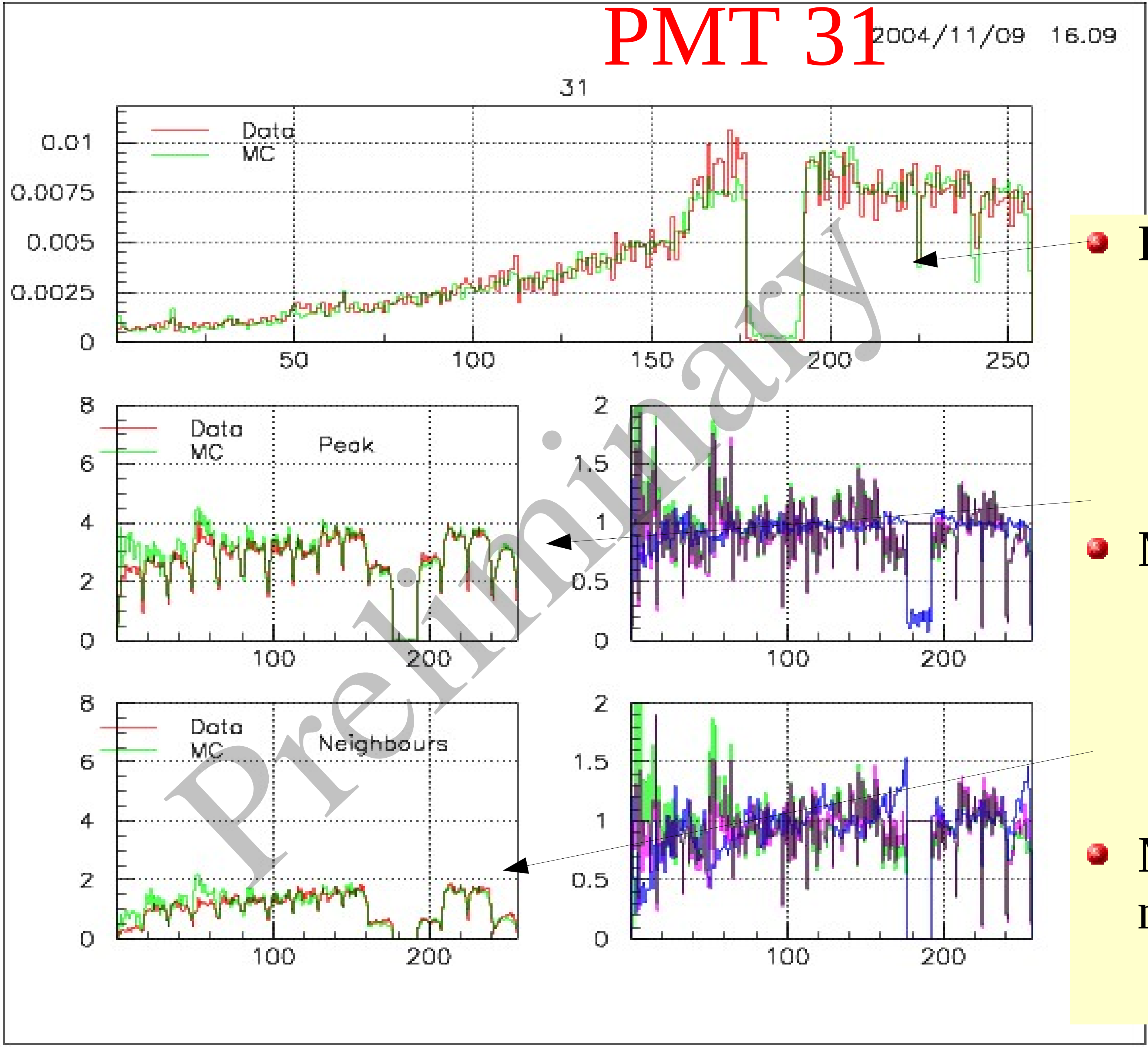
- Very happy

Stability of pedestals



- Pedestal drift over 30 days of cosmic data taking
- Stable to about 30 counts
- This is about 1% of the signal from one photon
- No problem

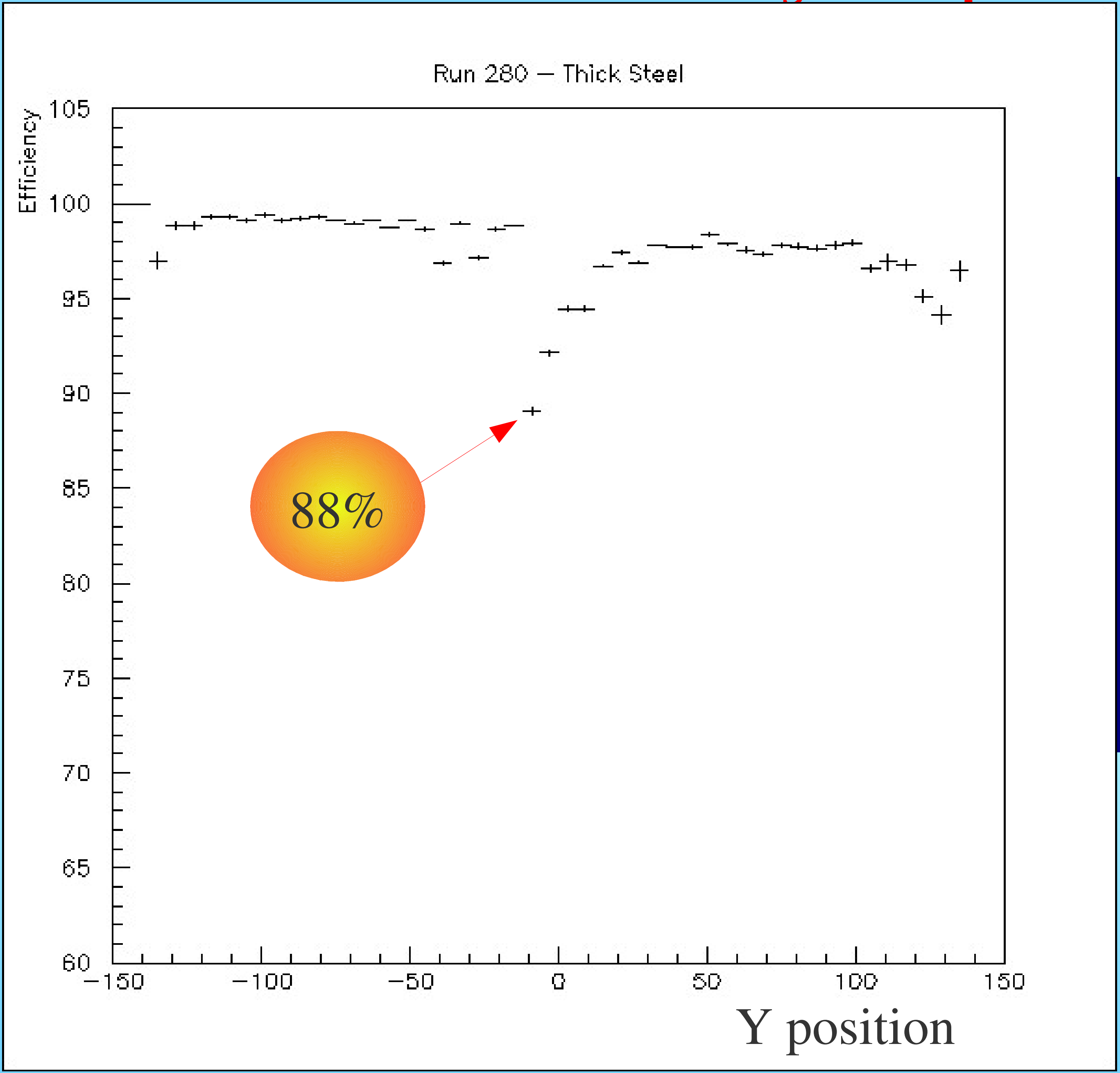
PMT 31



- Hit distribution
  - This PMT has 1 dead anode
- Mean signal size
  - Fixed in simulation
- Mean signal on neighbours
  - not fixed

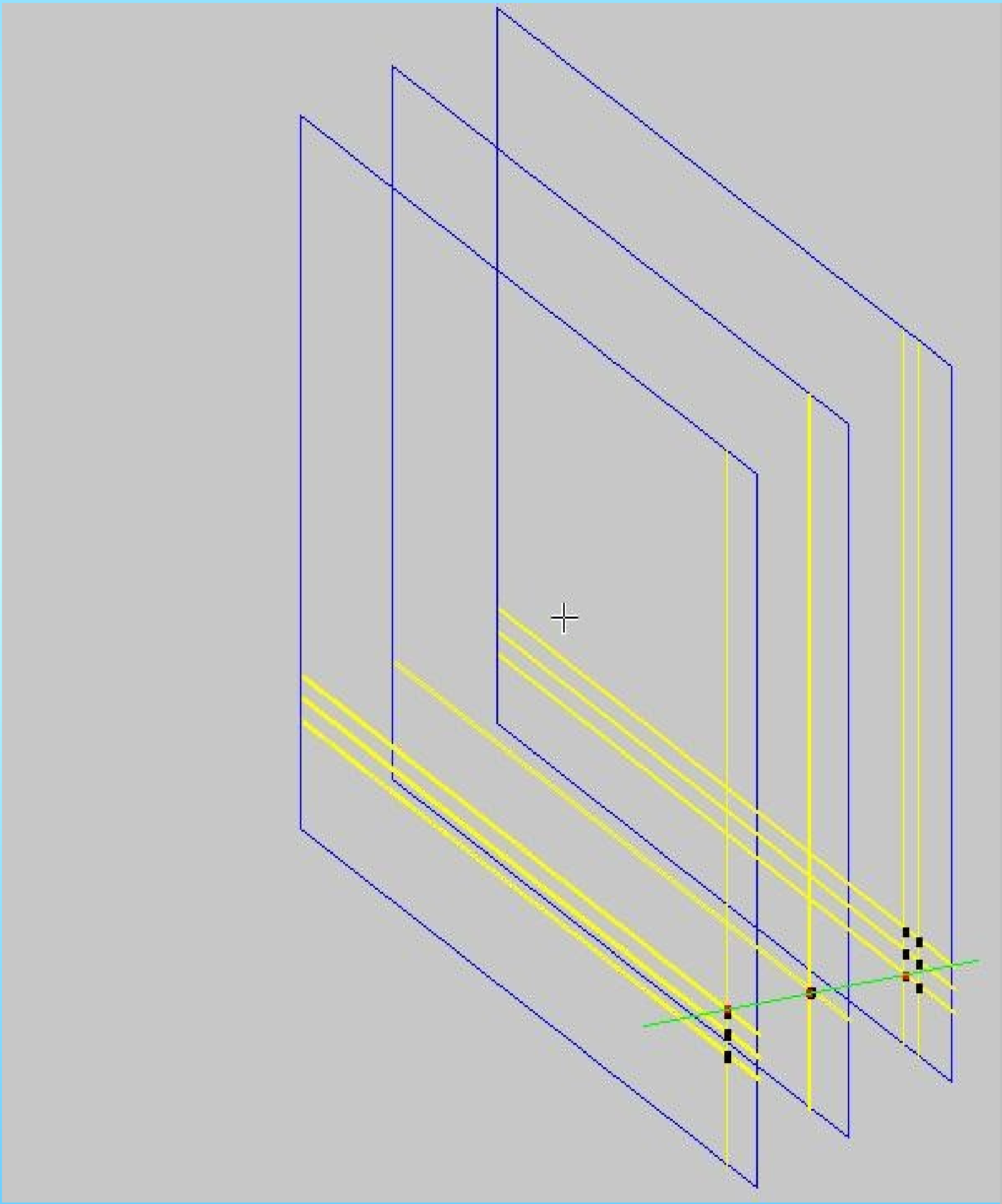
CCLRC
Rutherford Appleton Laboratory

Efficiency of plane 1



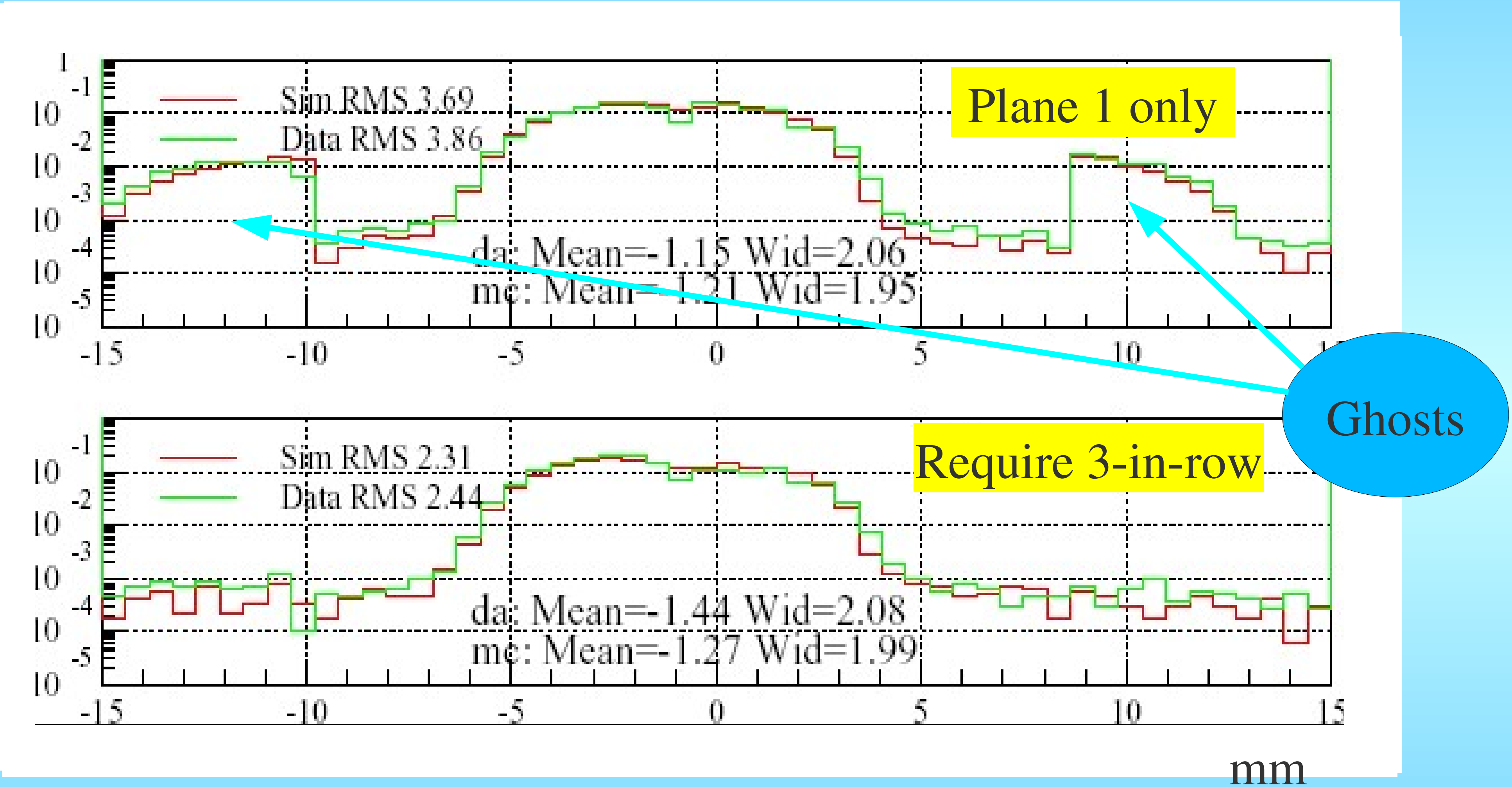
- Efficiency generally good,
  - but with dips
- This is simulated via the pulse heights

Reconstruct tracks



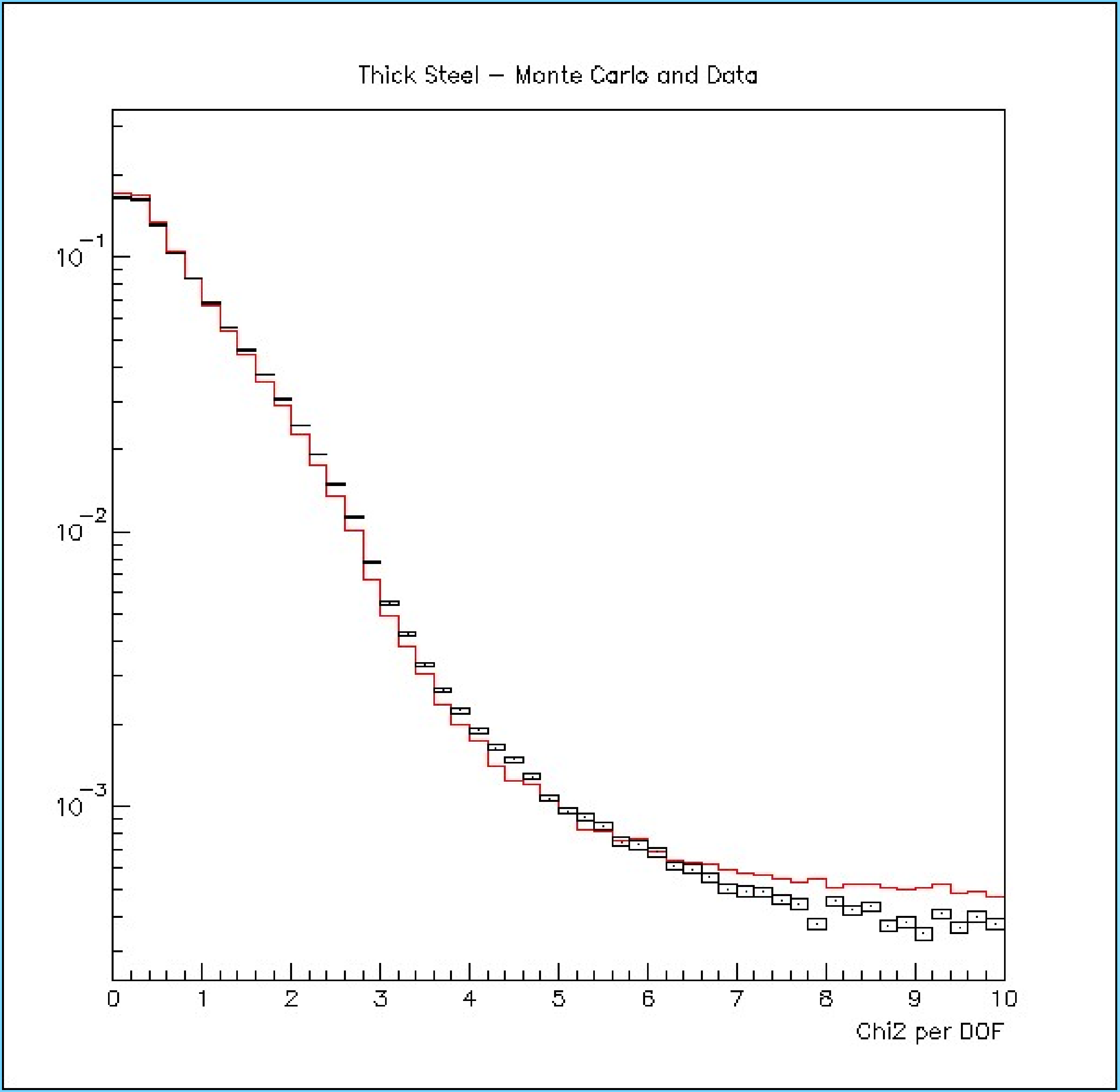
- Example cosmic ray
- 1-3 hits on each plane
- Ambiguity solved in track
  - *Much* easier with 4th point (target)
- Using just one plane would give problems

Cross-talk between anodes in PMT



- Distribution in SciFi plane 1, with no target, just collimator
- Ghosts due to cross-talk understood and suppressed

Track chi2



- Fit with target plus 3 planes
  - Demonstrates alignment
  - Tails not perfect

Sci Fi Summary

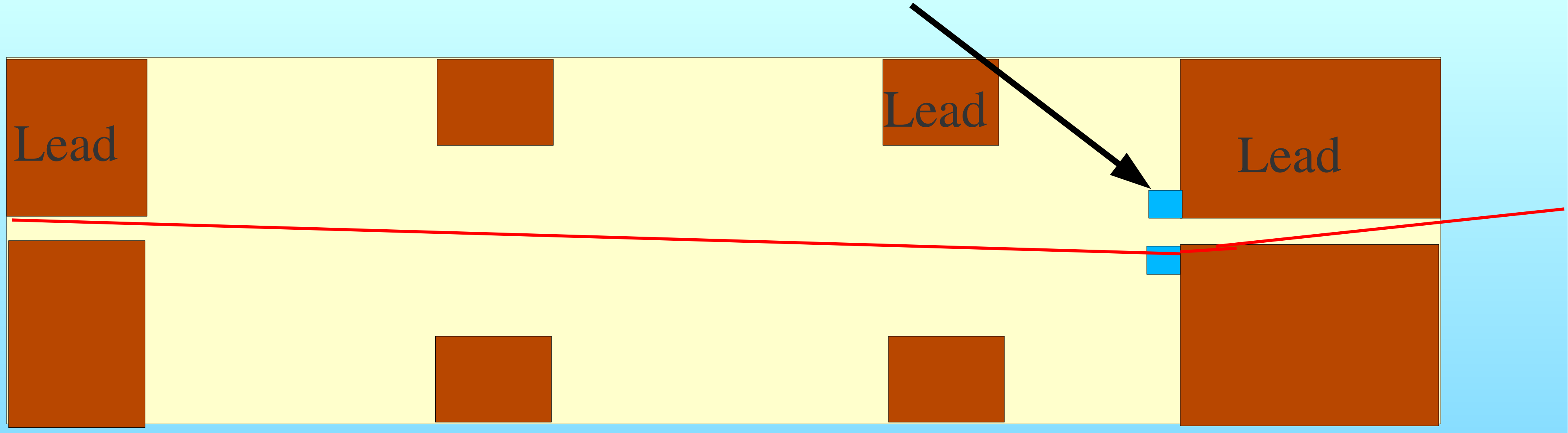
- Detector was a lot of work to build
  - **Stable** for the run
- Number of P.E. marginal, but OK
- Some cross-talk between channels
  - Quite well understood
- It works

Collimator system

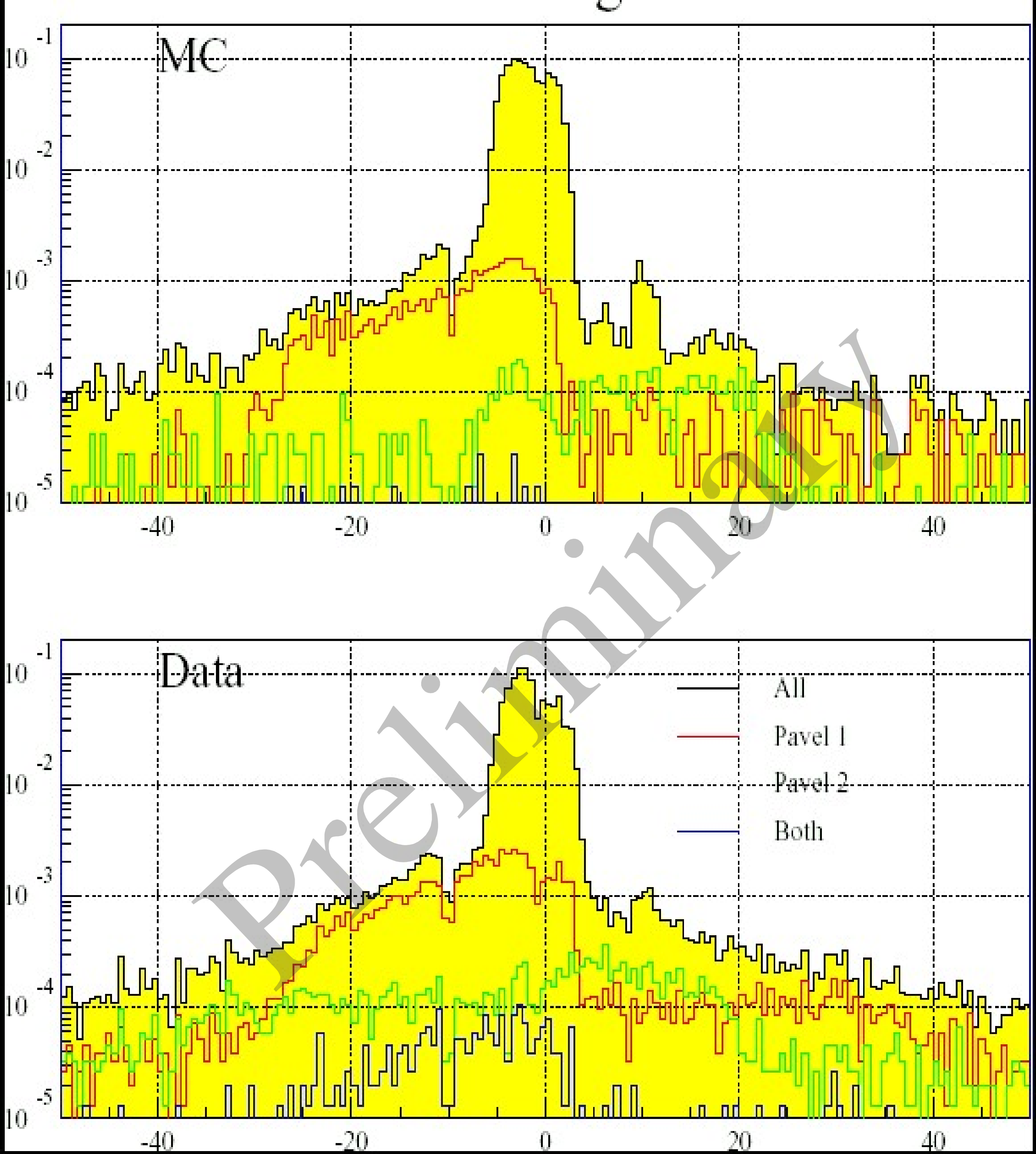
- Built in Birmingham
- Used angled surfaces to minimize direct bounces

Active collimator

- Muons can penetrate collimator
  - give tails on distribution
- Use Scintillator as active collimator

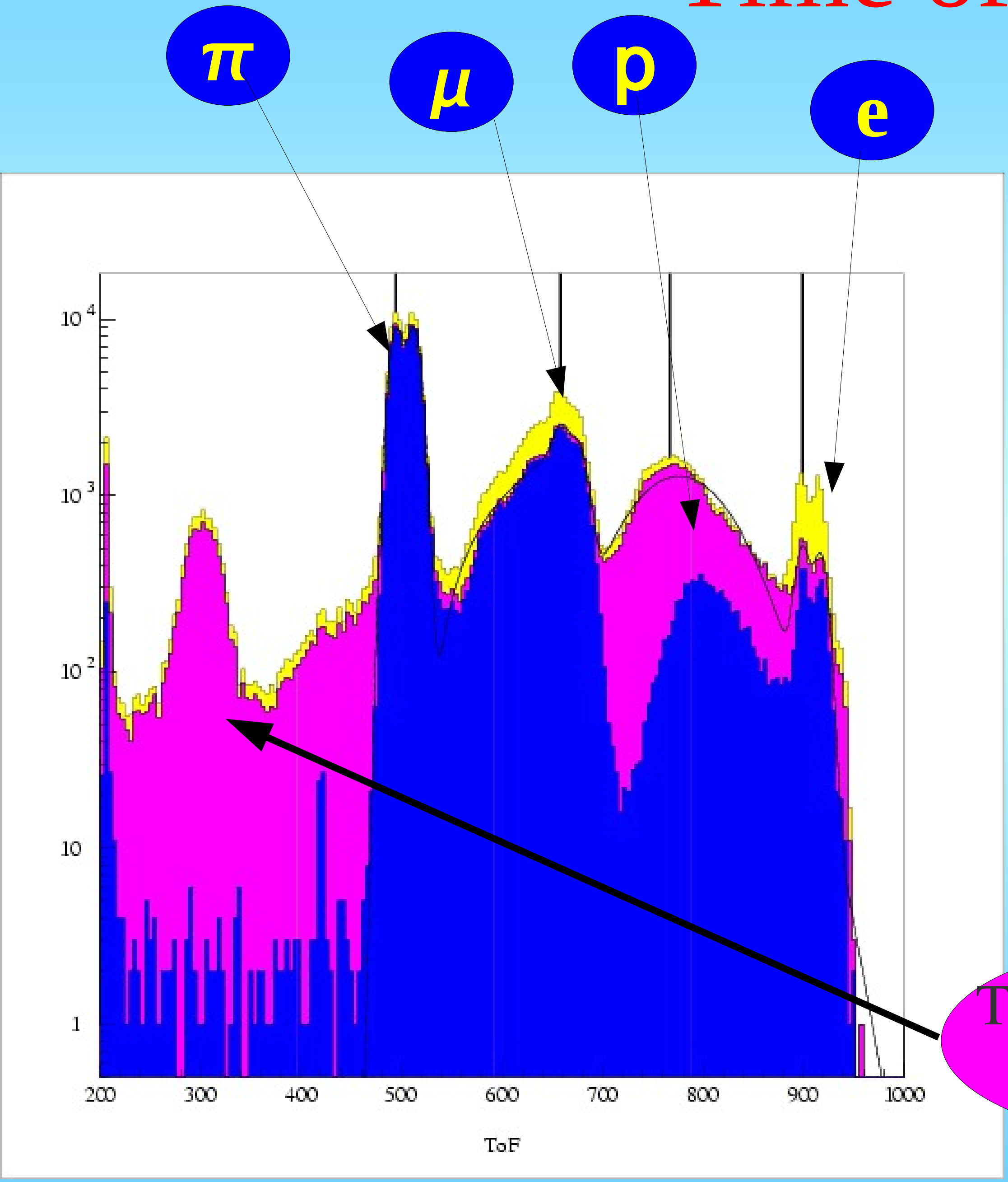


Active Collimator response



- Yellow is hits in plane 1
- red line have hit in one
- green hit in other
- Collimators have slipped ~100µm

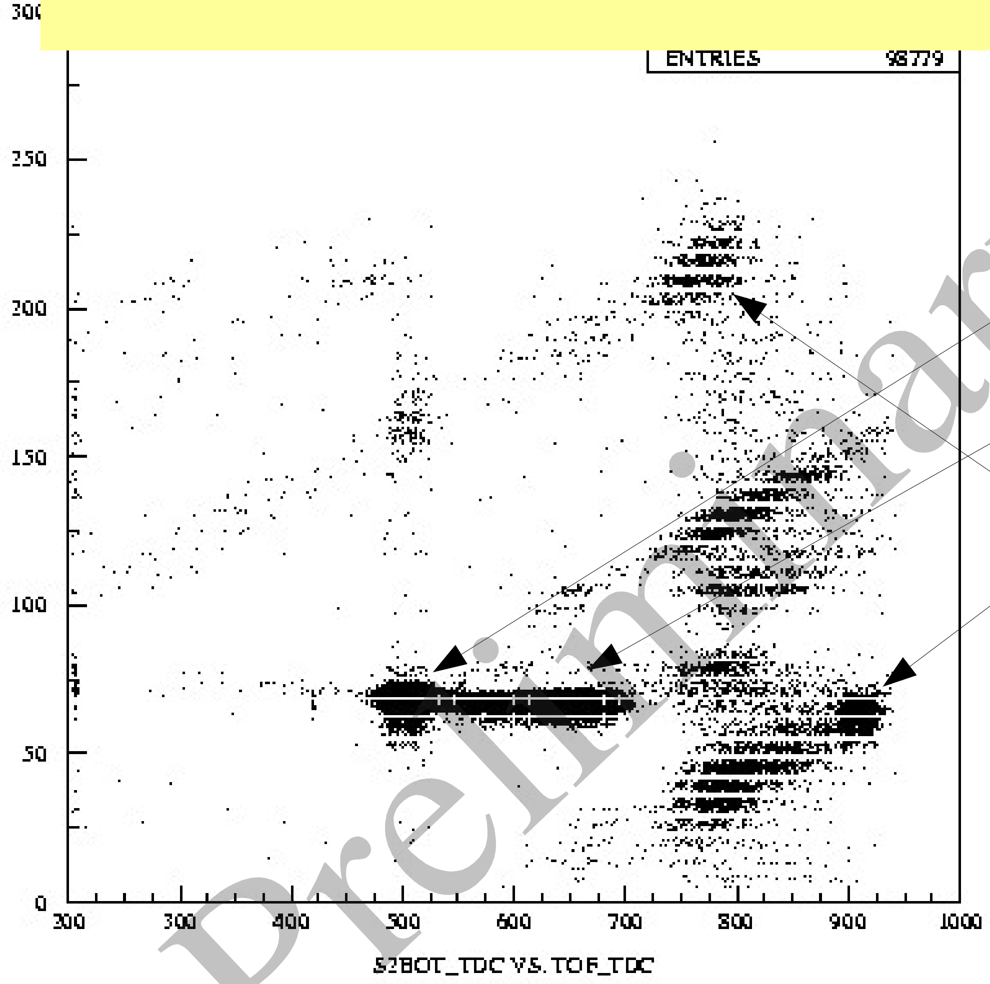
Time of flight



Timing problems, removed

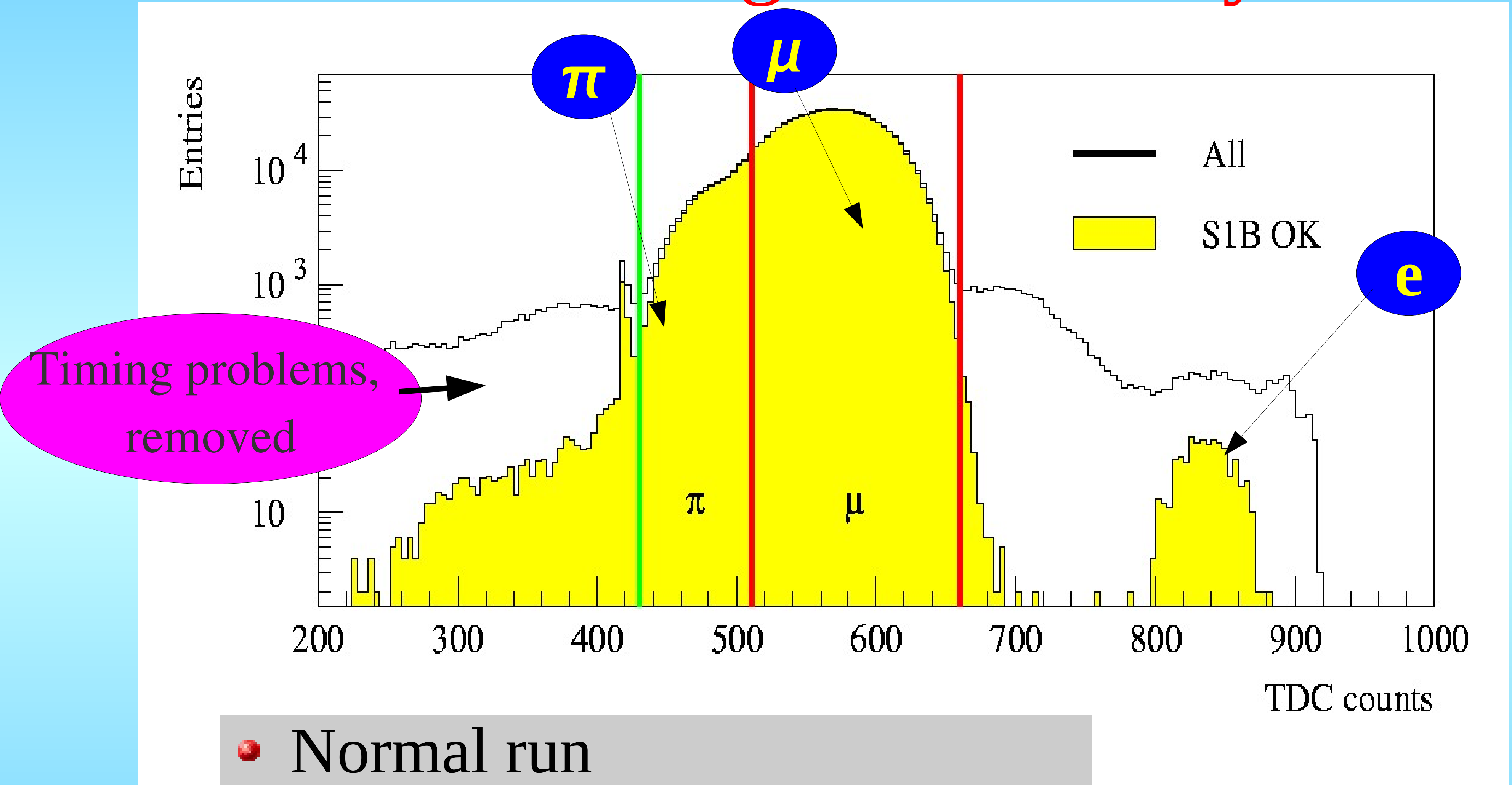
- Special run with mixed particle beam
- Used to calibrate momentum
- P=172±2MeV/c

Flight time v arrival time



- pions
- muons
- electrons
- proton overlaps

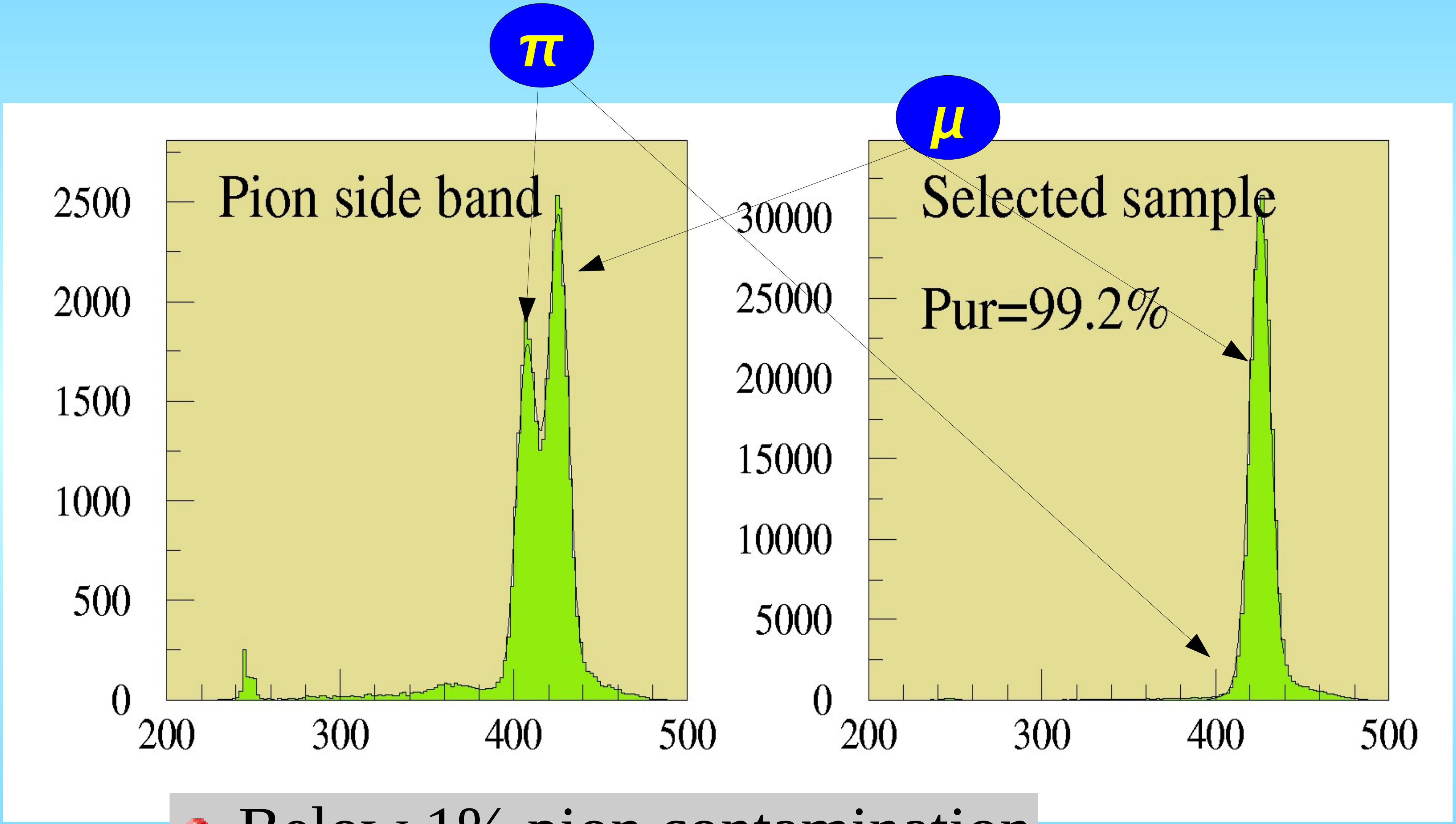
Time of flight – normally



Timing problems, removed

- Normal run
- Pion shoulder on muon beam

Contamination from Tina



- Below 1% pion contamination
- Allowed for in analysis

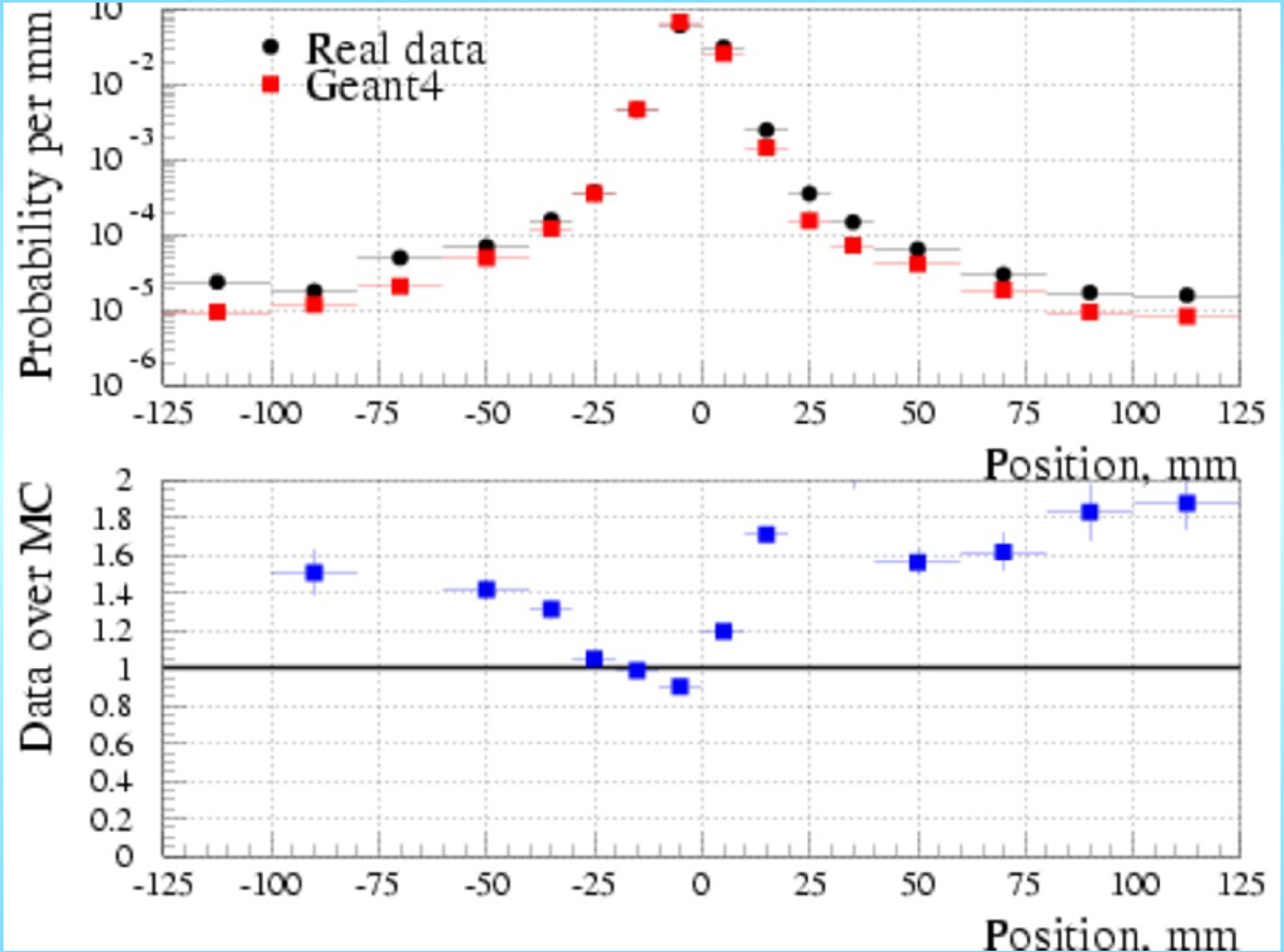
Targets

Millions of events were collected with each of the following targets.

Pink targets are shown now

No.	Target	Thickness, mm	X0, %
0/12			
1			
2			
3	Lithium 2	12.72	0.81
4			
5	Beryllium	3.73	0.53
6			
7	Carbon	2.5	1.53
8	Aluminium	1.5	1.69
9	None		
10	Iron	0.24	1.36
11	Iron	5.05	28.68
LH2			
LH2	Long, full	150	1.53
LH2			
LH2			

No target: check collimator



Tails in data exceed simulation

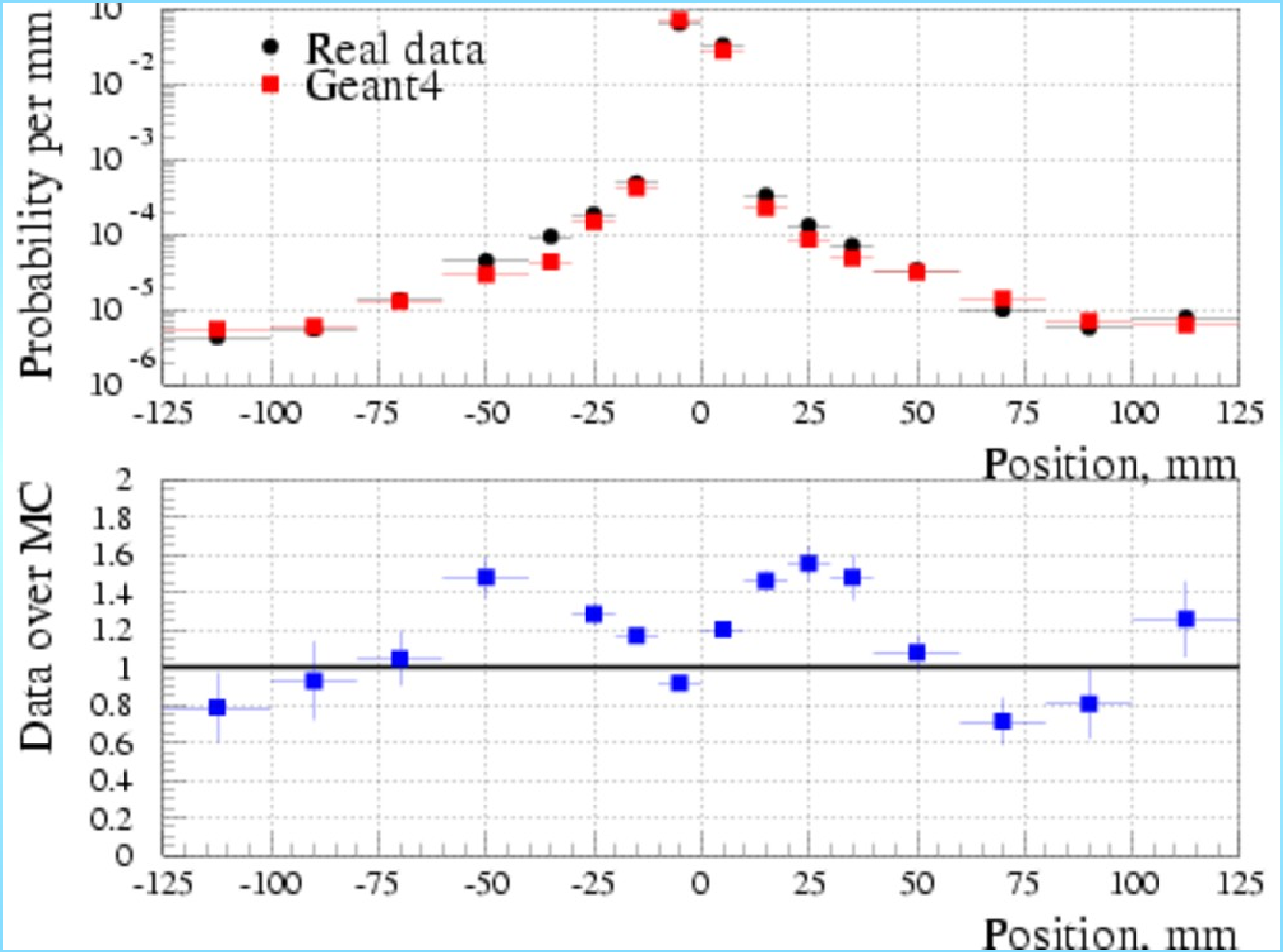
This is not understood:

neutrons?

noise?

~~tracks~~

No target: check collimator

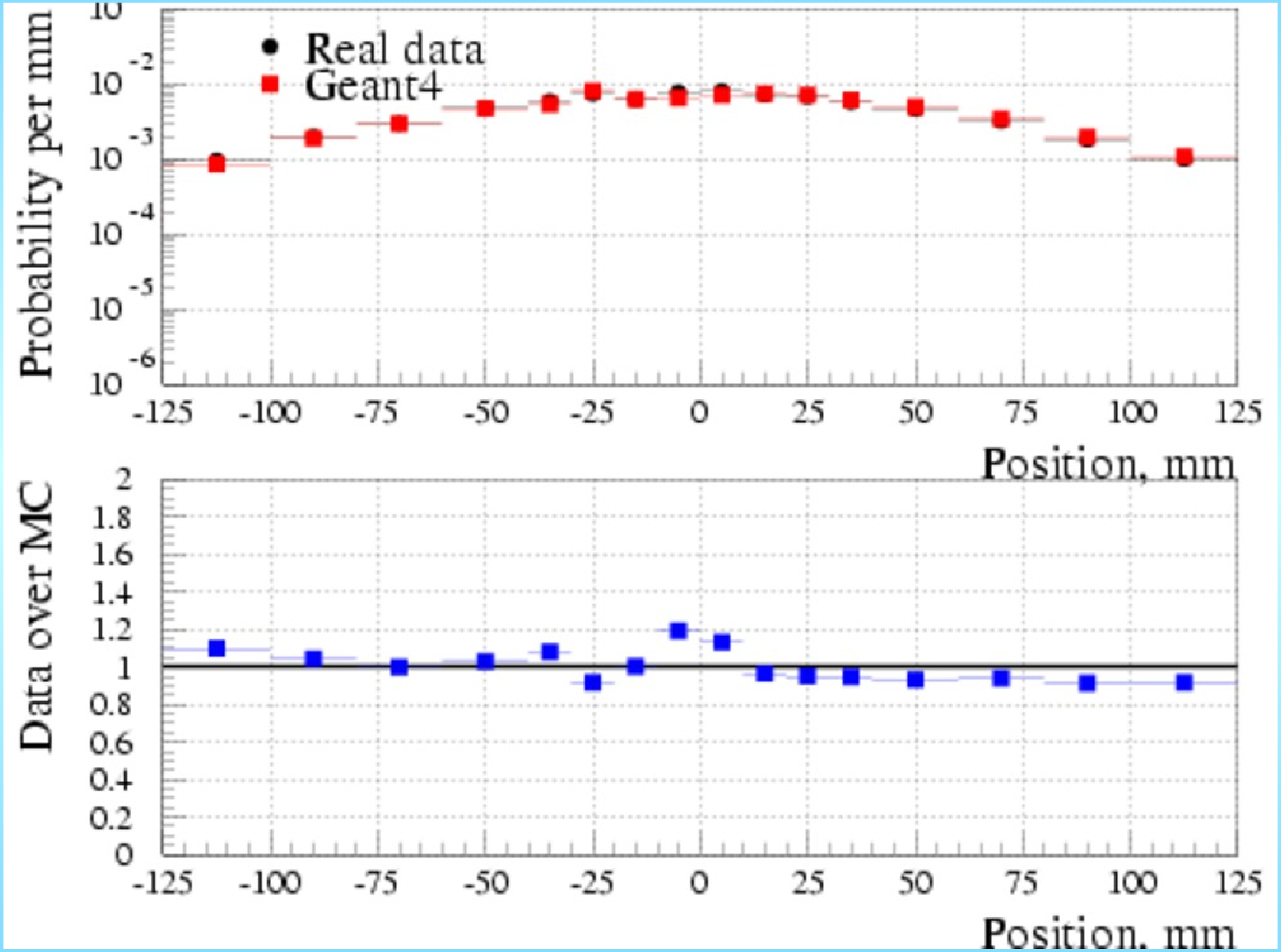


Require planes 1 and 3 gives consistent answers

Tails smaller, Discrepancy smaller

Problem is 4 10^{-5} @30mm

Thick steel target, 28% X0

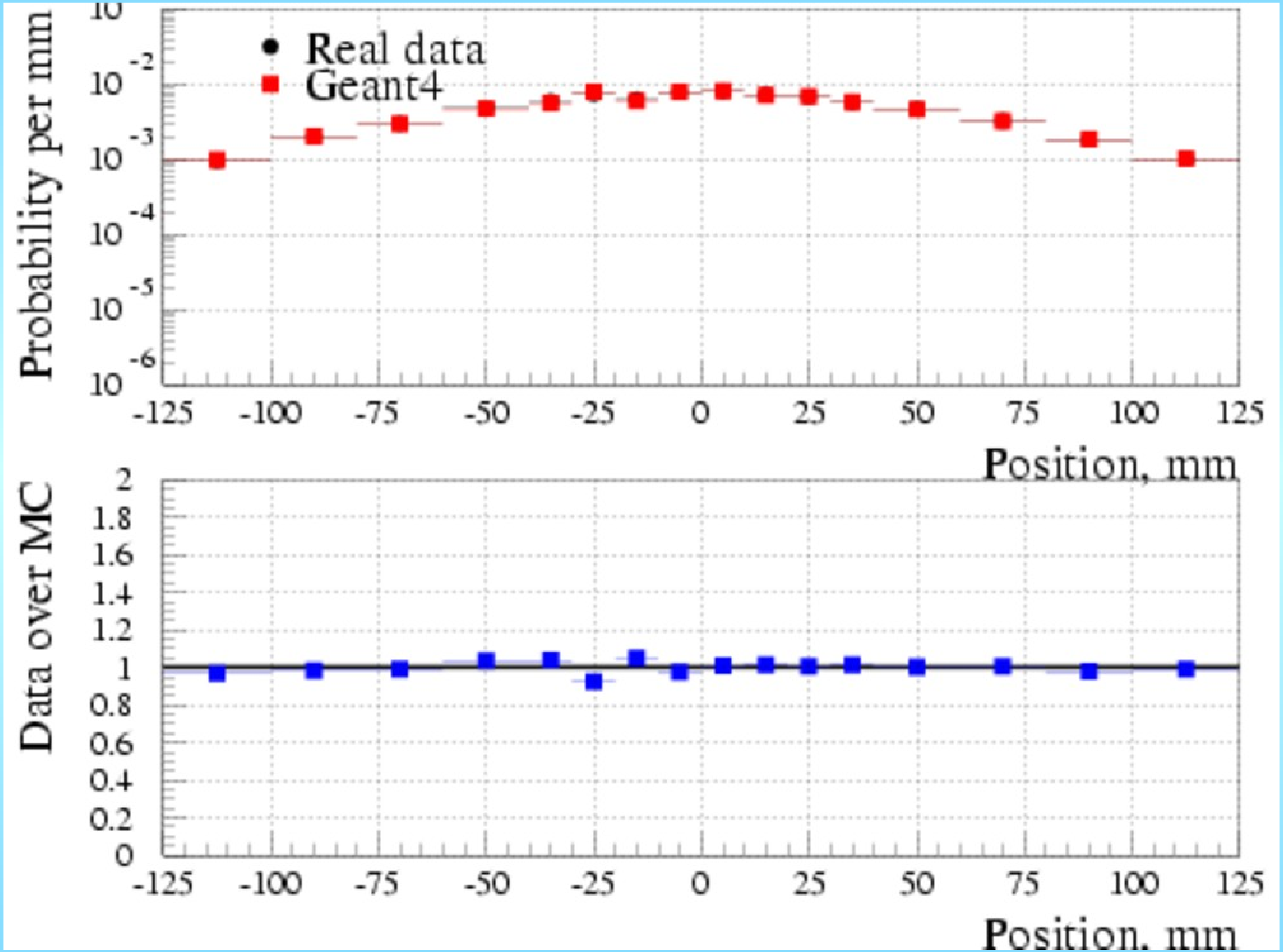


Geant 4.6.1 description good

Used to study detector response:

Efficiency modeled reasonably well

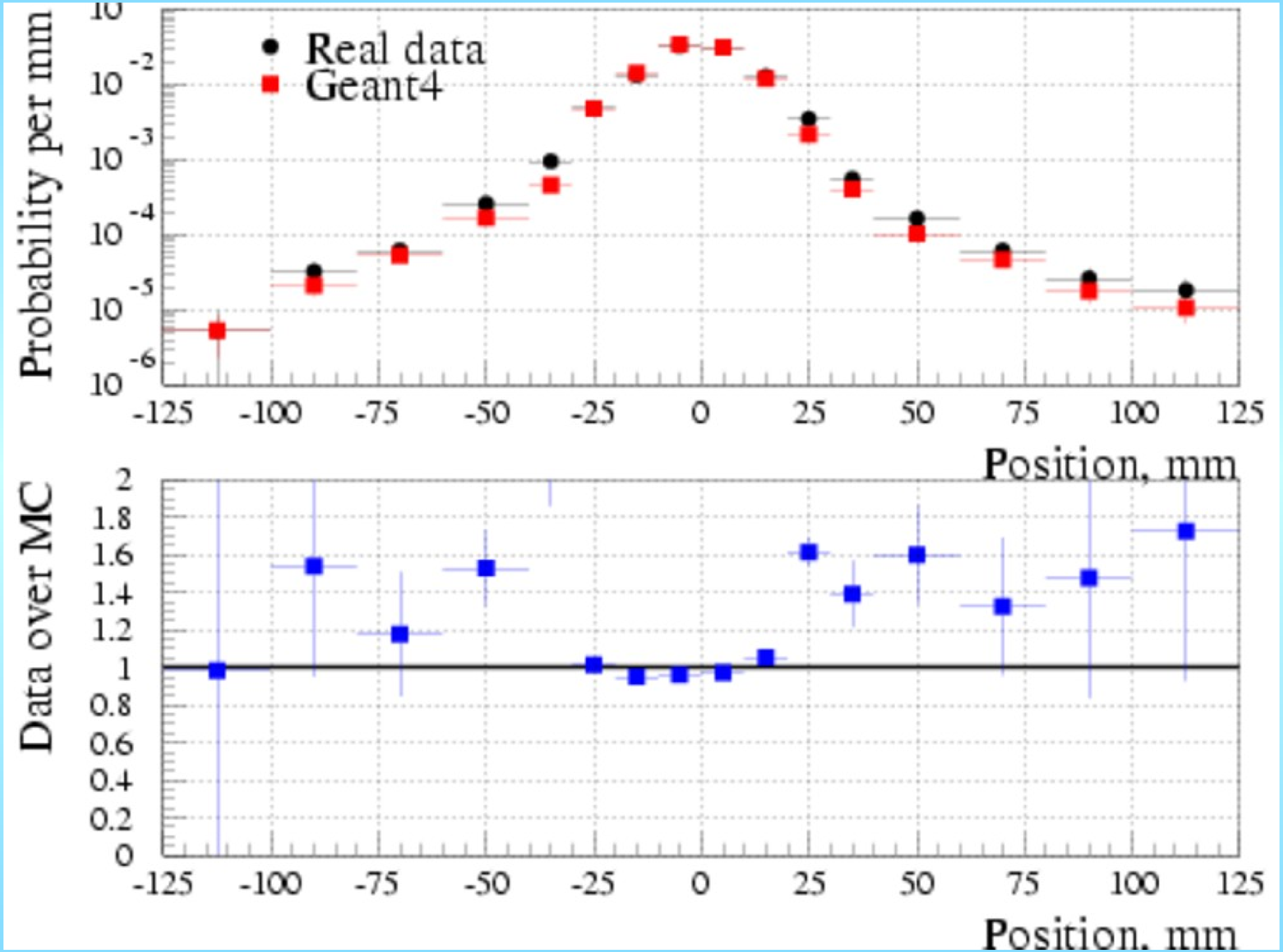
Thick steel target



Extra Efficiency correction applied

Residual error below 10%

Thin Steel



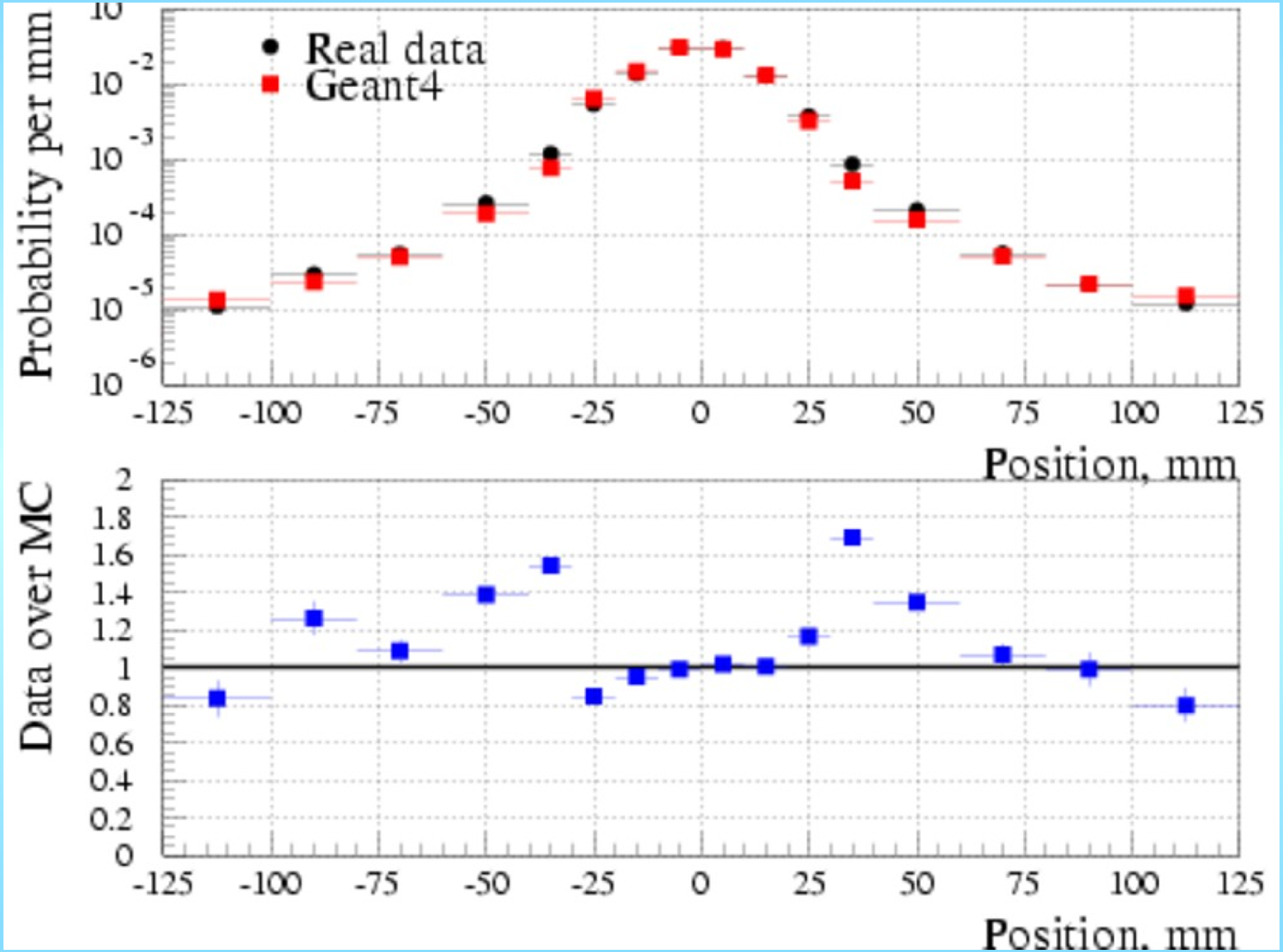
Good in core

Difference from 25mm

Problem is 4 10^{-4} @30mm

Geant underestimates tails [MC sample small here]

Aluminium

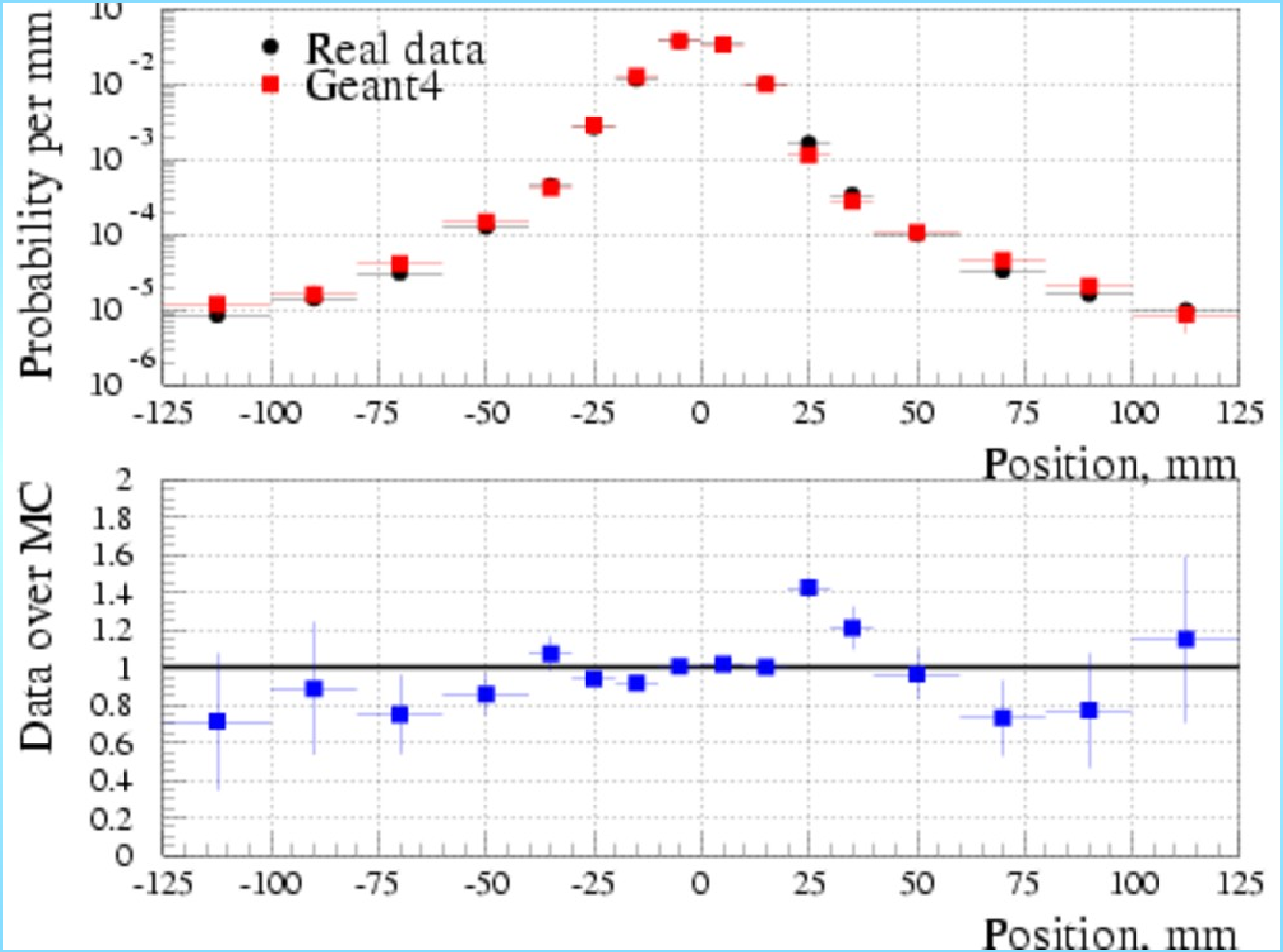


Good in core

Difference at 30mm

Problem is 4 10^{-4} @30mm

Carbon

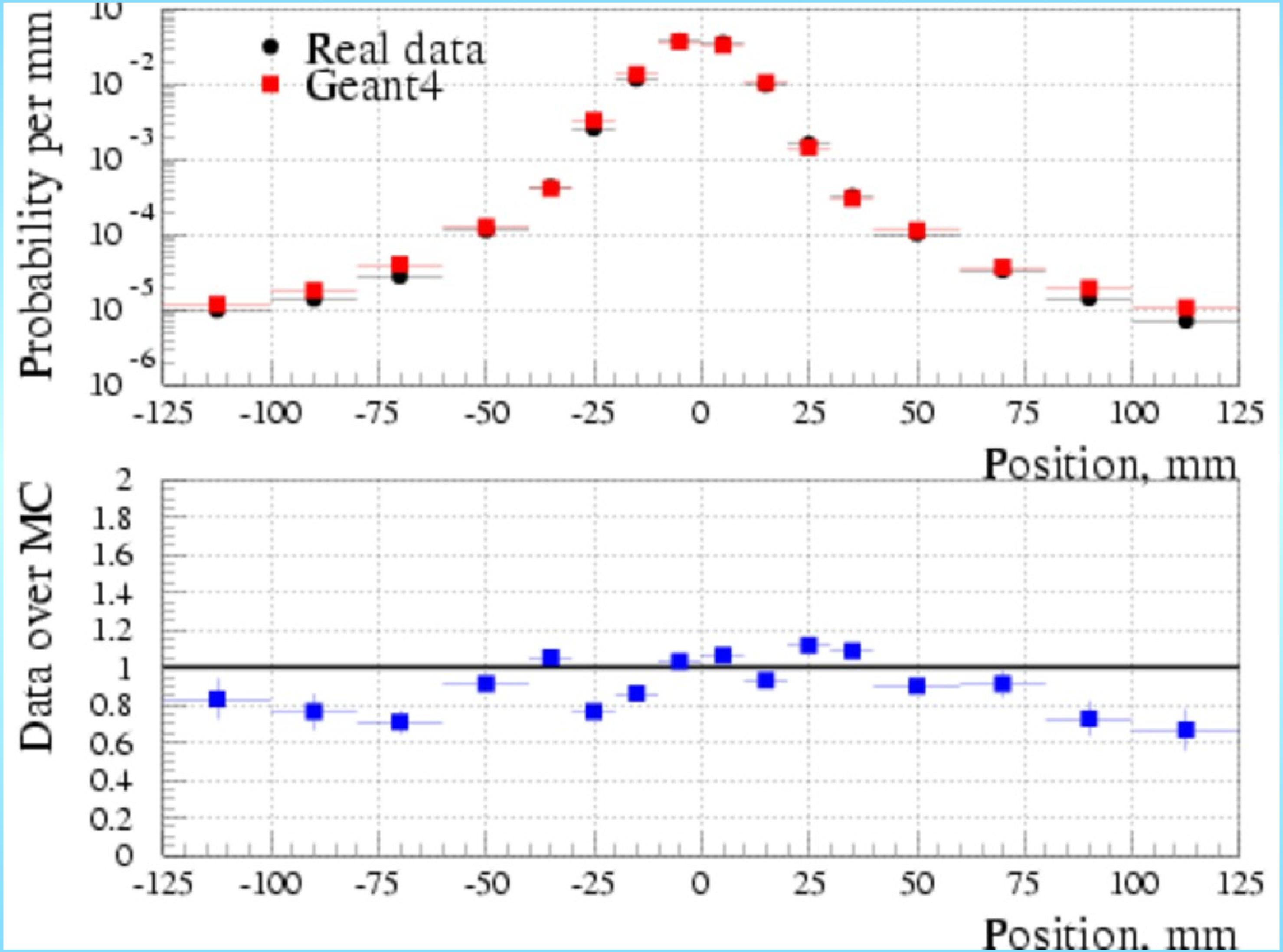


Good in core

Some hint of difference at 30mm

[MC sample small here]

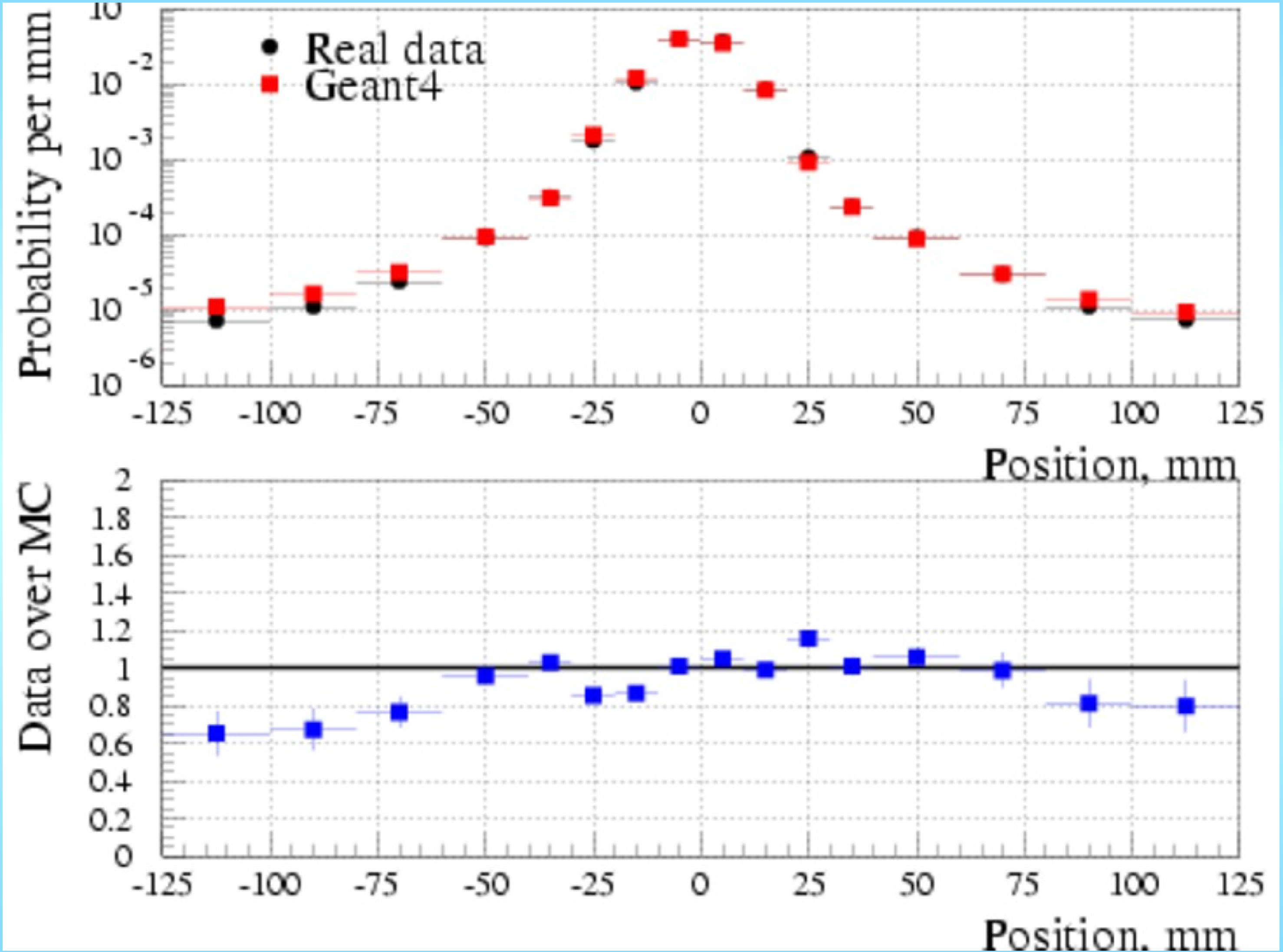
Thick Beryllium



Very satisfactory agreement

20% effects are not significant at this stage

Thick Lithium

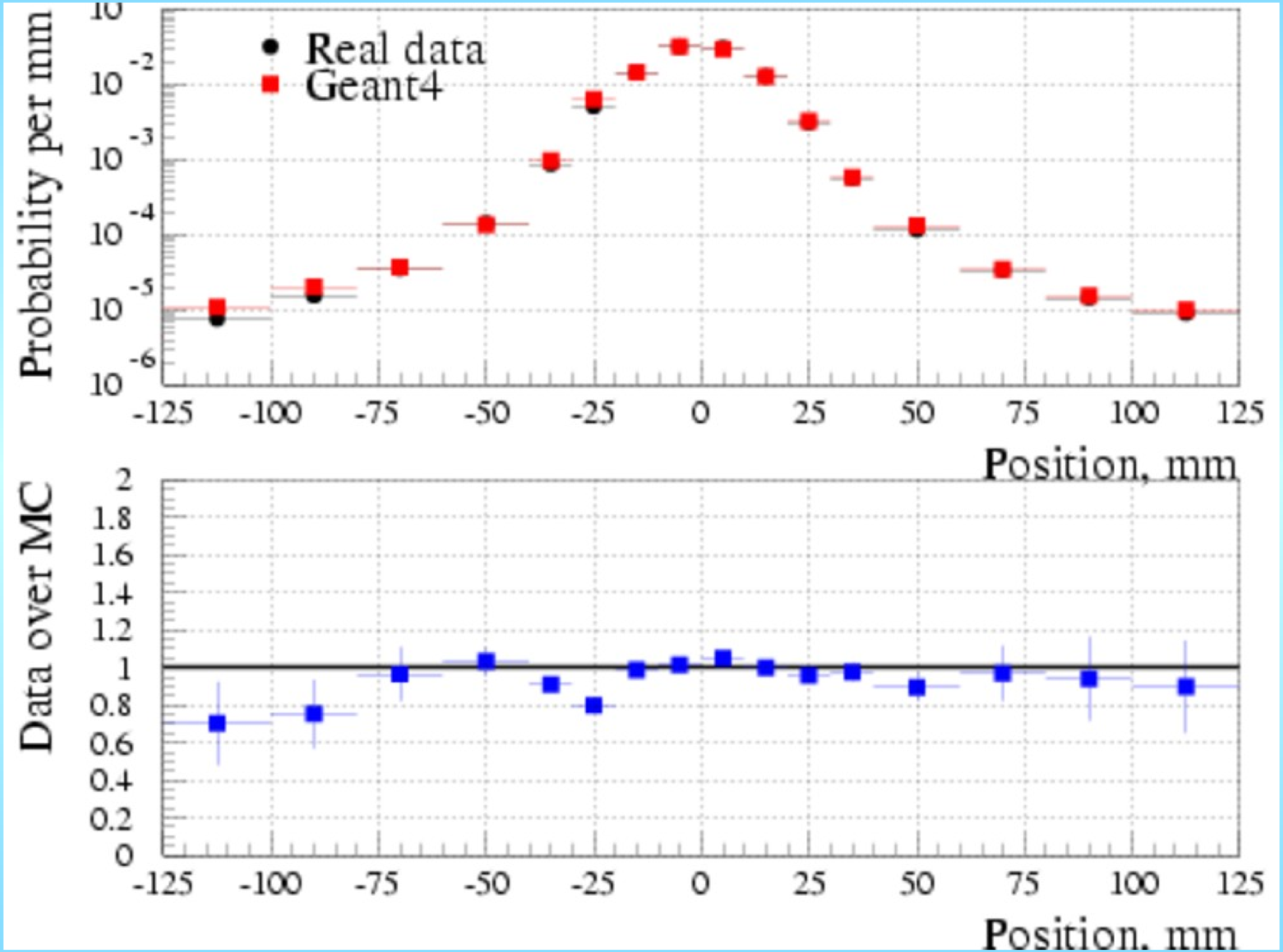


Tails lower in data?

Very similar to the Beryllium

Andrievsky's factor 2 at 1% not seen

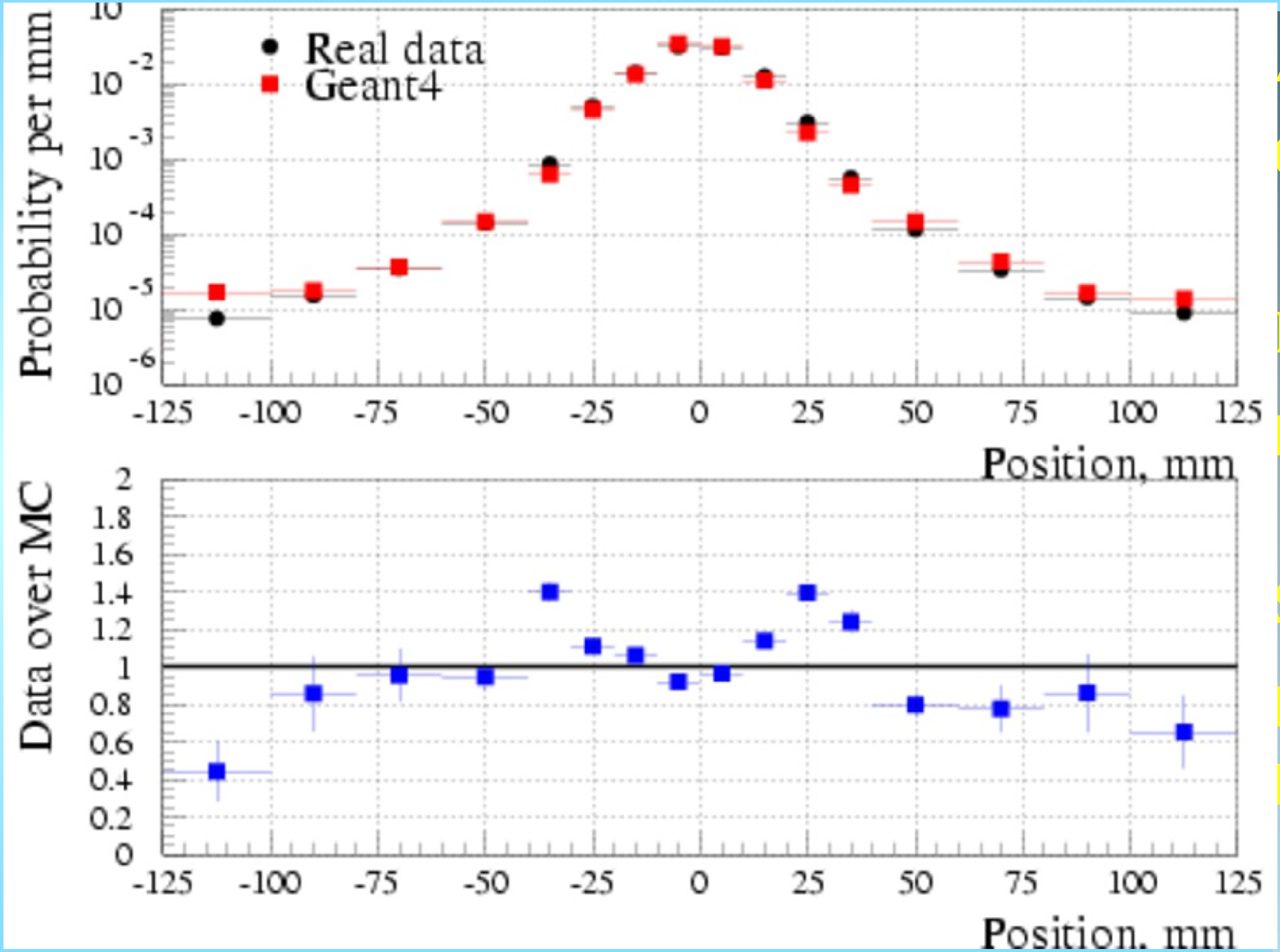
15cm liquid hydrogen



Tails *possibly* lower in data

Excellent agreement

15cm liquid hydrogen: tail 50%



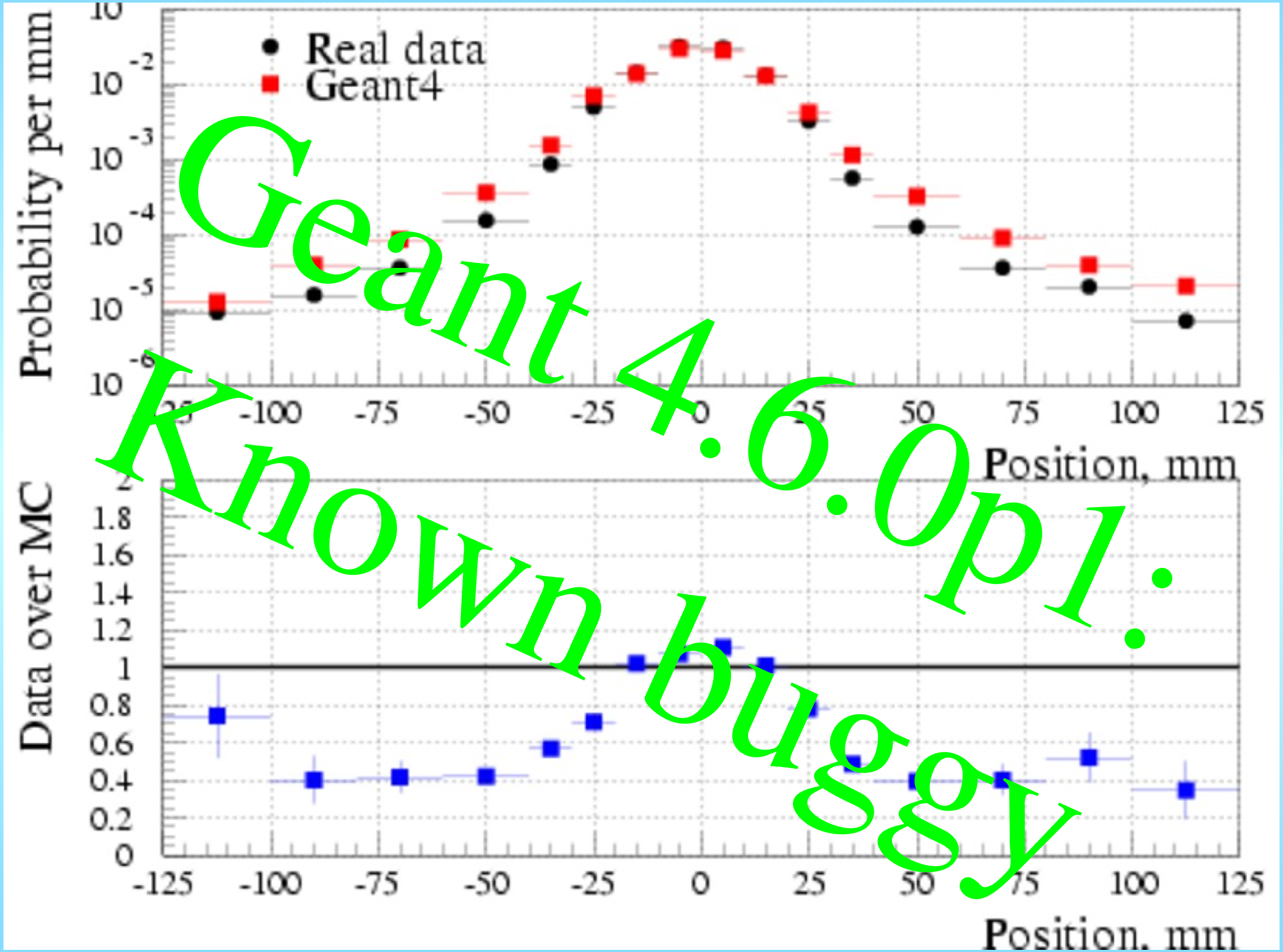
Adjust G4's MSC tail parameter

Distribution shows peaks around 30cm

Same place problems seen in high-Z materials

►Tuning might help those?

15cm liquid hydrogen: G4.6.0p1



Geant 4.6.0p1: Known buggy

Tails overstated by a factor 2 or more

MuScat Outlook

- **80Million events recorded; data being analysed**
  - **Detailed efficiency calculation**
  - **Deconvolution of detector from data**

- **Geant 4.6.1 is a GOOD description of multiple scattering in this region**
  - **For *High* Z materials may be some tuning to do?**
- **Andrievsky discrepancy for Lithium not confirmed**

Conclusions

- The neutrino has proved physicists wrong
  - Not once, but many times
  - It may do it again.
- *Neutrino mass may be responsible for our existence*
- Neutrino factory
  - Required whatever the truth is.
  - Could be a UK hosted project
  - Cost much less than a linear collider