Lepton Flavor Violating Decays
Review & Outlook

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I mostly focus on:

Experimental review & outlook on Lepton Flavor Violation (LFV) in ***charged leptons***

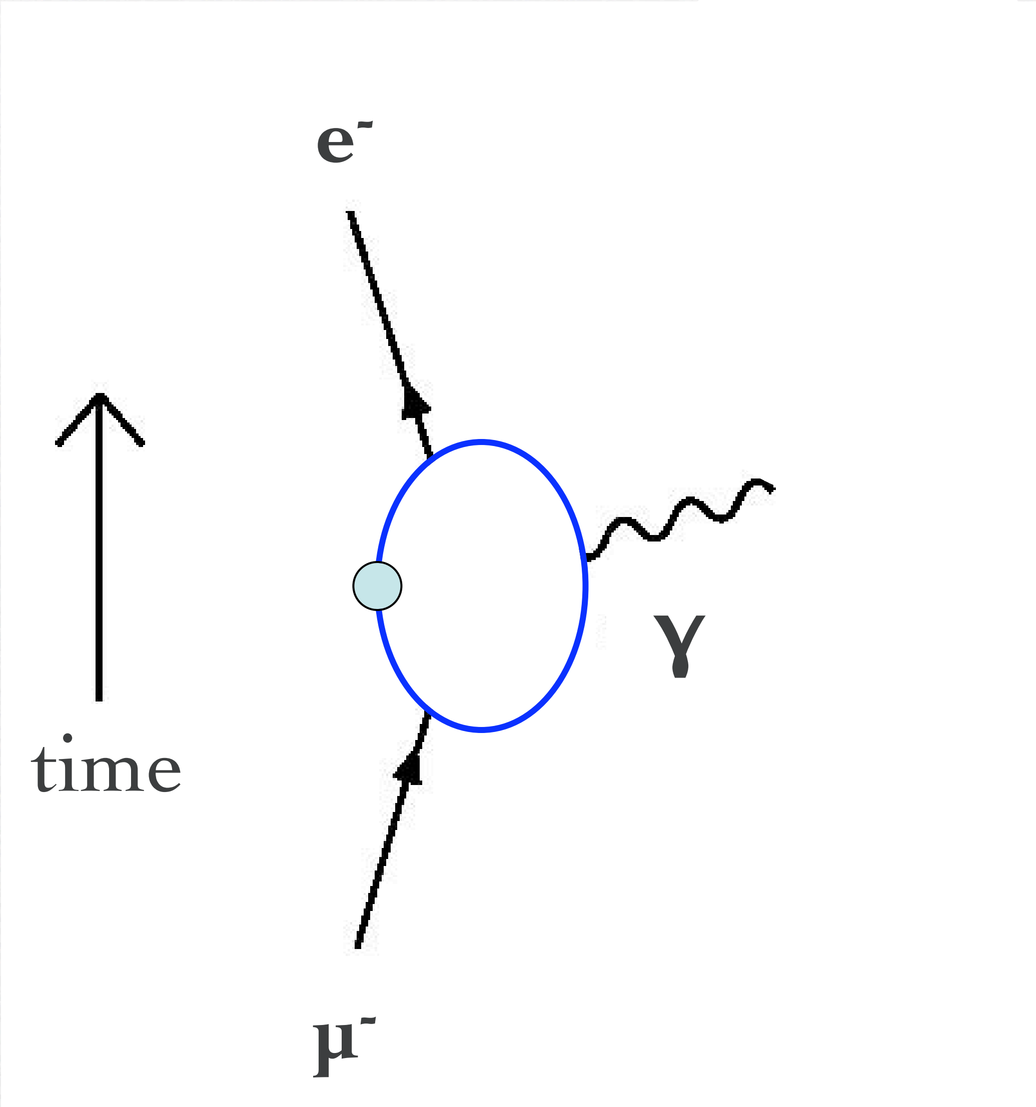
Topics to Cover

- Why Is Lepton Flavor Violation Interesting?
- "Tau Processes" :
  - ✓ Tau Decays at B Factories
  - ✓ Studies at Hadron Machines
    - LHC, Fixed target experiments
- "Muon Processes" :
  - ✓ Muon to Electron Conversion
  - ✓ Muon Decay to Electron and Gamma
    - MEG experiment

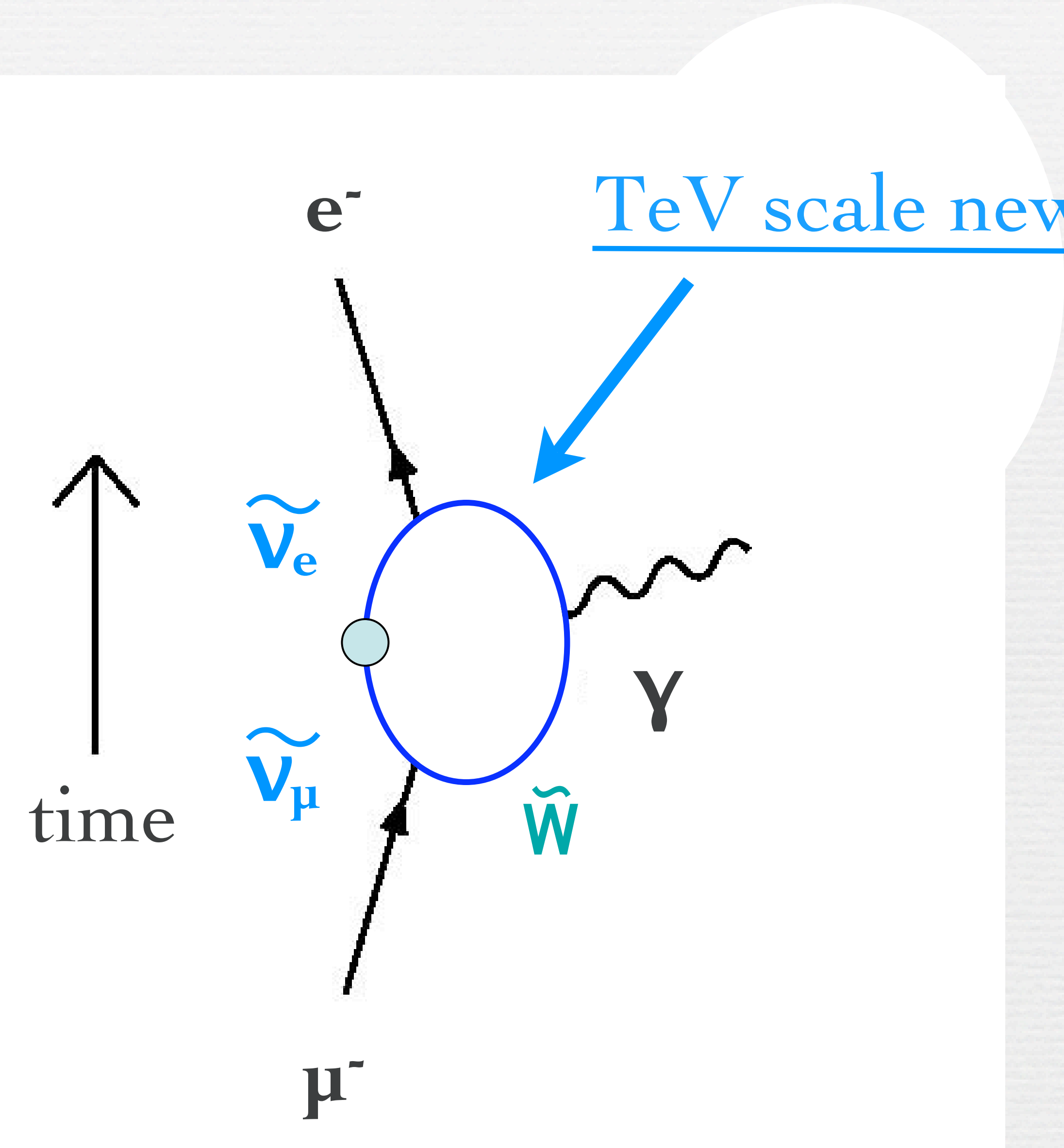
Why LFV interesting?

- Neutrino LFV --> charged leptons !
- Quark FV is generally contaminated by SM.
  - ✓ Looking for tiny deviations is not easy.
- LFV in charged leptons Is NEW PHYSICS.
  - ✓ Some experiments are already sensitive to SUSY GUTs, seesaw, and possibly more.
  - ✓ So just find it!

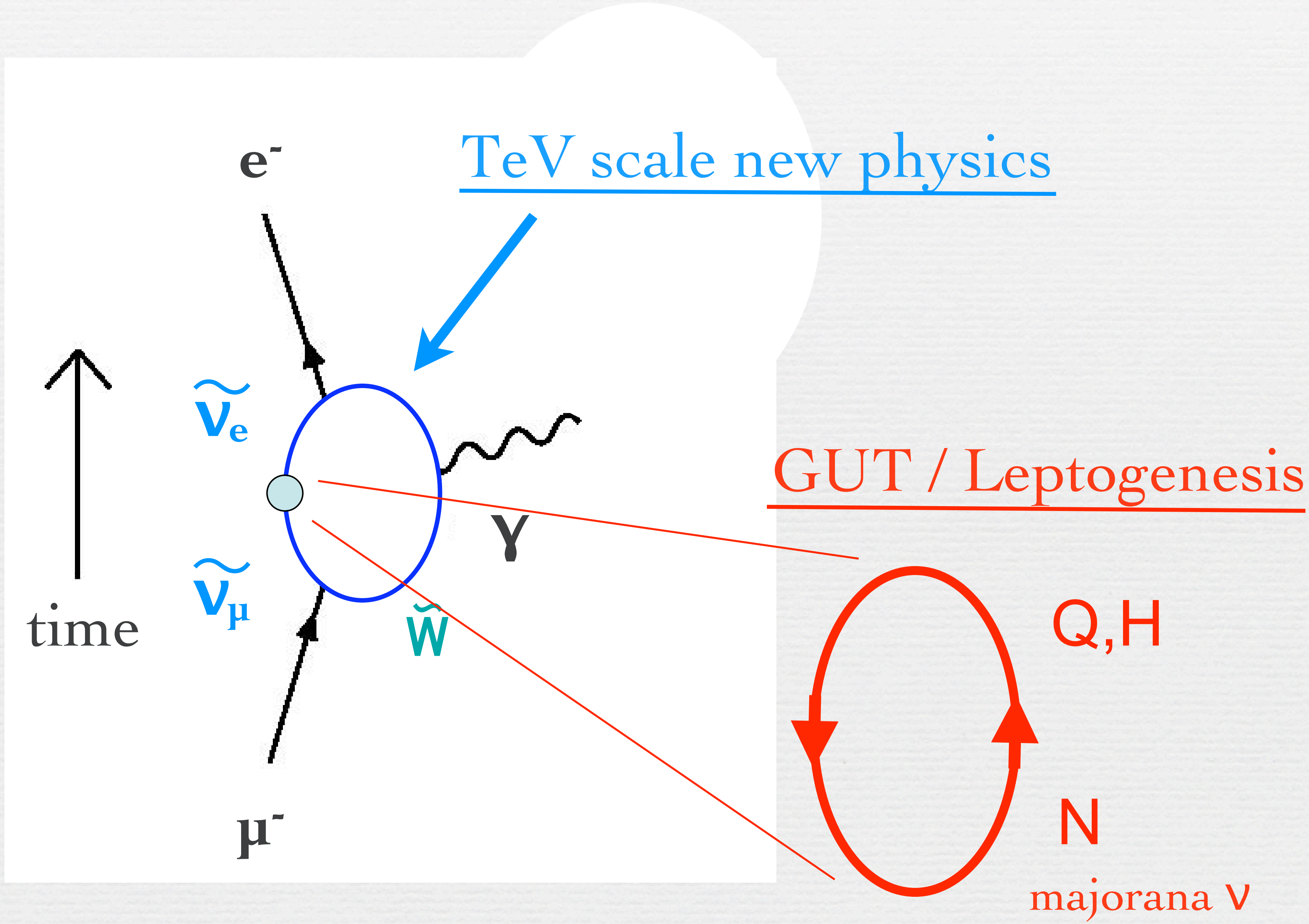
Origin of Lepton Flavor Violation

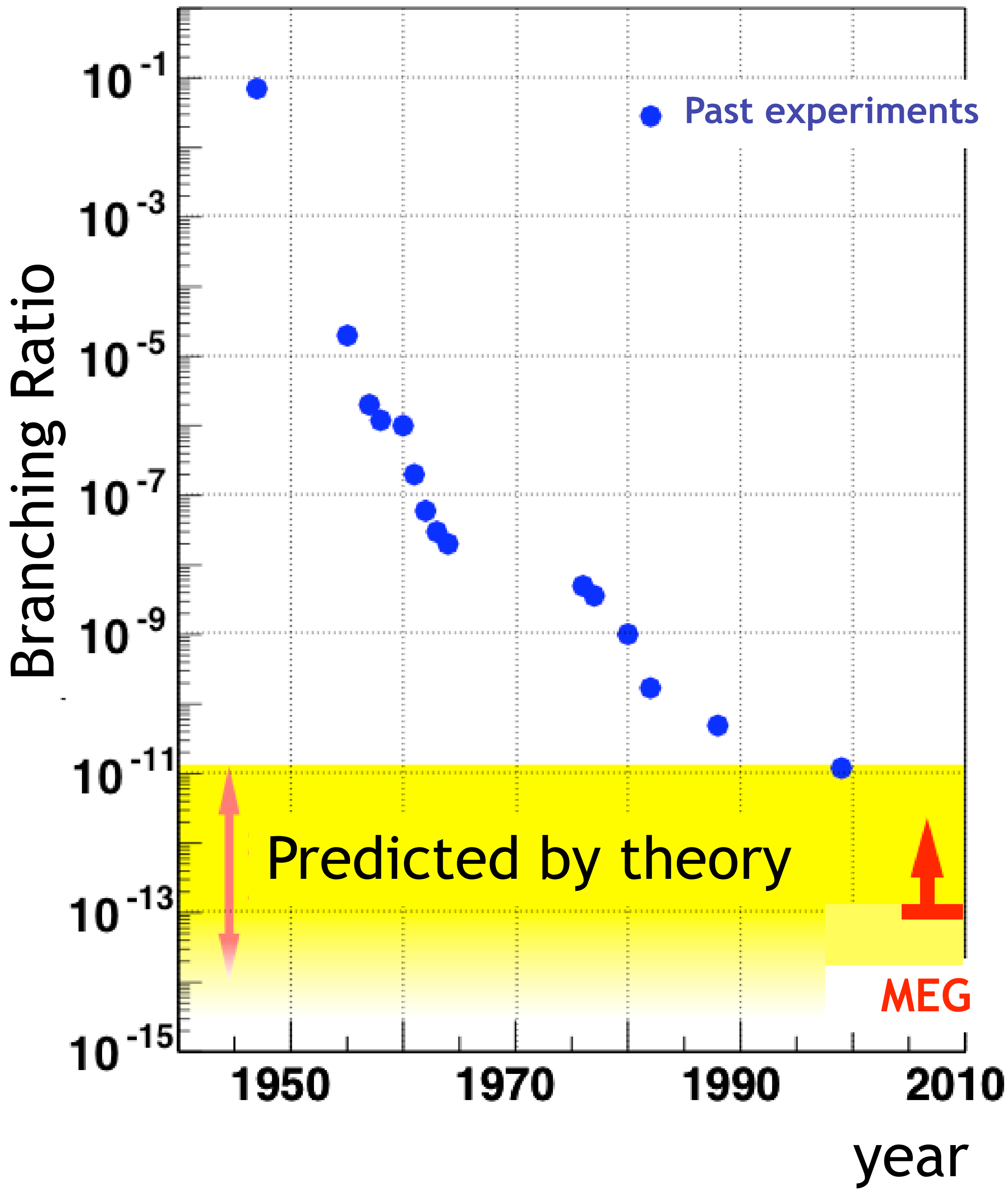


Origin of Lepton Flavor Violation



Origin of Lepton Flavor Violation





Search for $\mu \rightarrow e\gamma$ decays

already constraining new physics strongly

Experimental reach ~comparable w/ LHC e.g. SO(10) GUT

“Tau Processes”

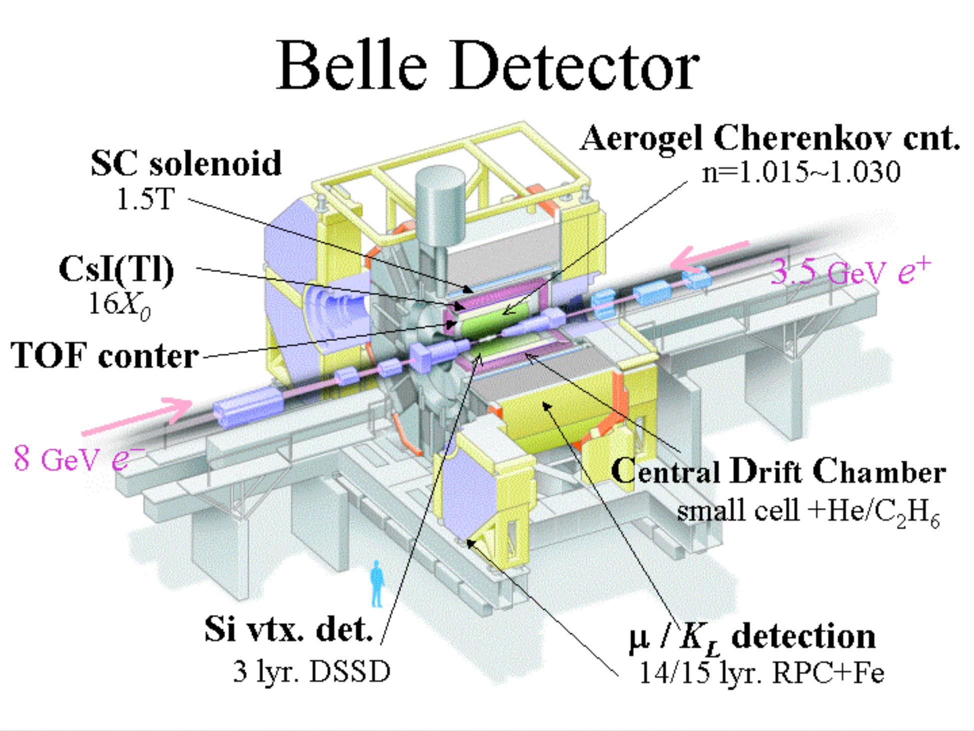
LFV Tau Decays at B Factories

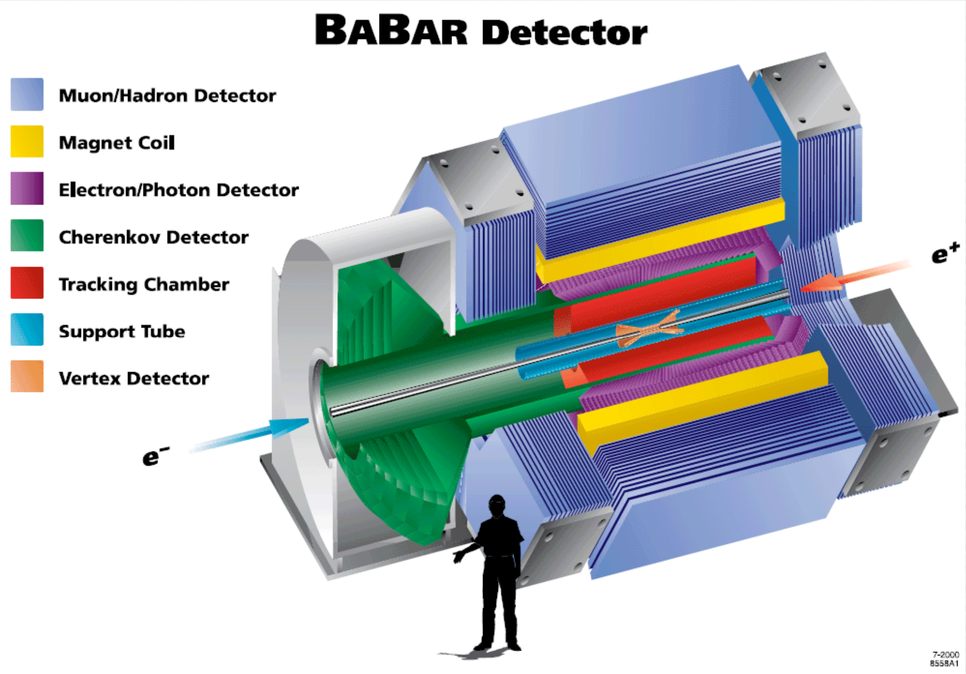
Special thanks to K.Inami /Nagoya-Belle

B Factory Experiments

F/B asymmetric detectors

Good vertex resolution and particle ID ability





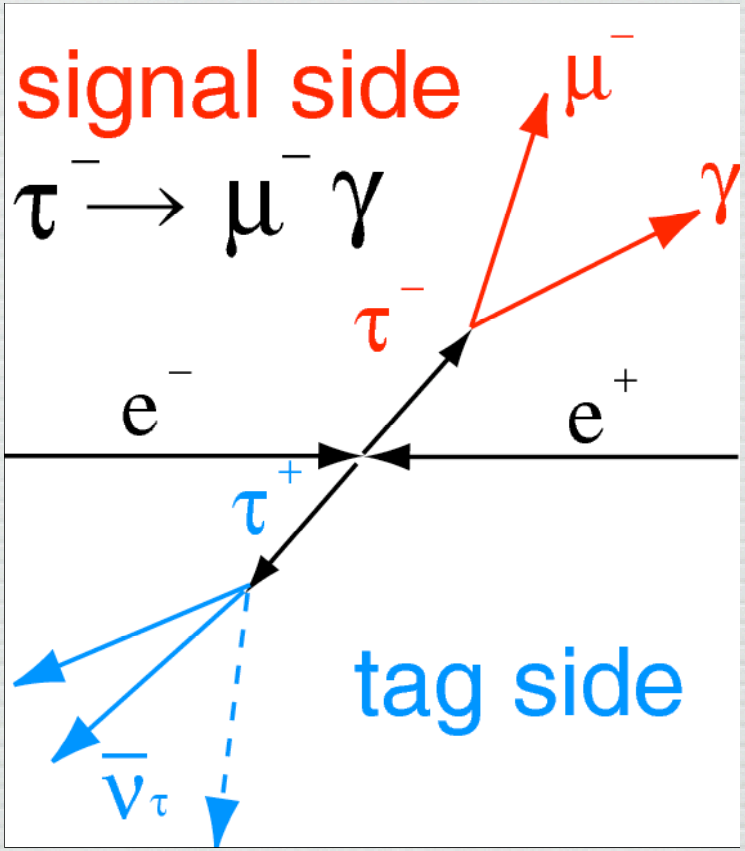
Accumulated data:

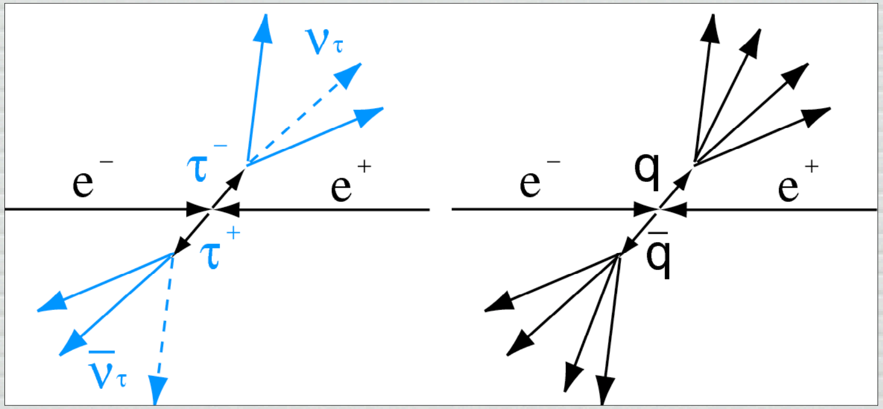
$>4.5\times10^{8}$ τ-pairs at Belle, $>3.0\times10^{8}$ τ-pairs at BaBar

Br~O(10^{-8}) sensitivity!

Analysis method

- Event Selection
  - Low multiplicity events
  - Separate into hemispheres
    - Signal and tag sides
  - Missing momentum
    - Low missing mass
  - Small Nγ
  - Lepton tag etc.

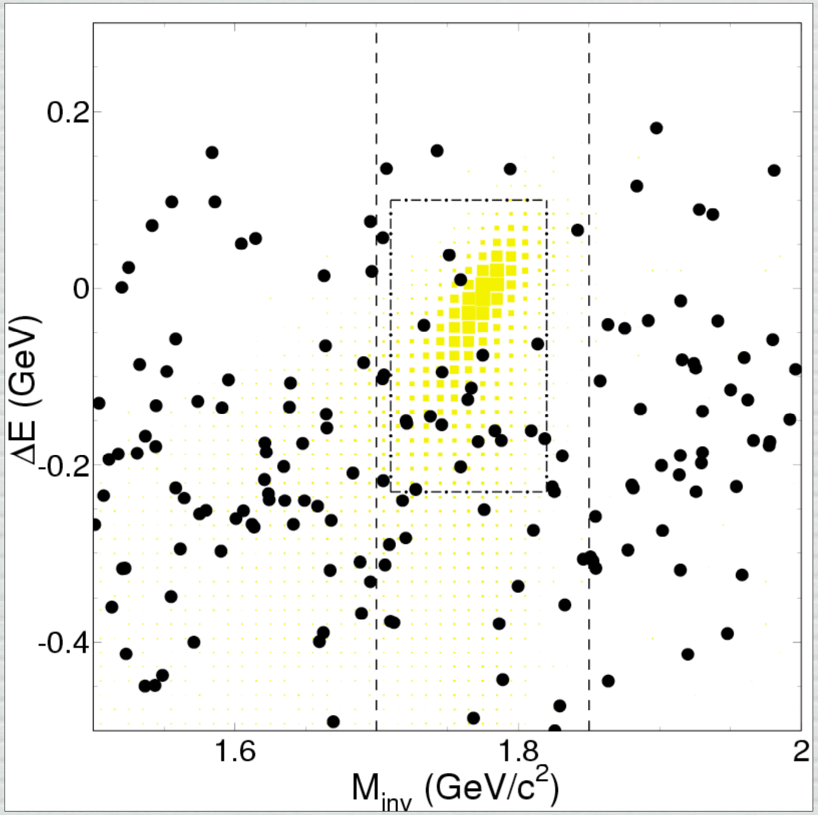




$\tau \to \mu\gamma$

Belle

86.3fb^{-1} data

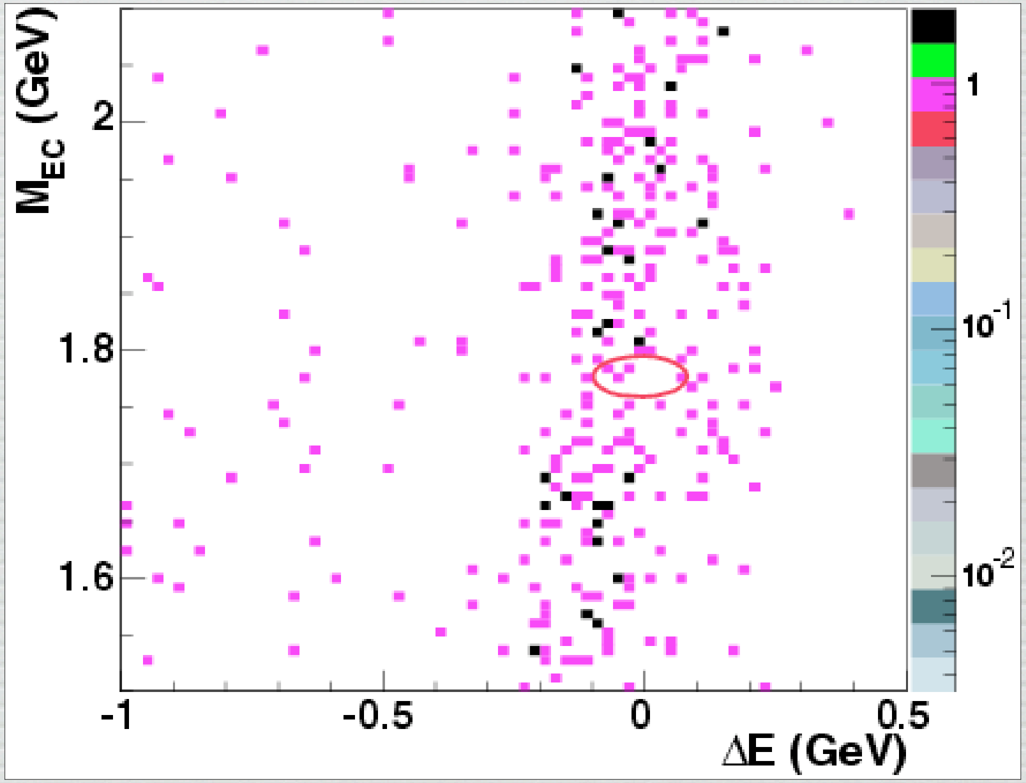


Br<3.1x10^{-7} at 90%C.L.

PRL 92, 171892 (2005).

BaBar

232fb^{-1} data



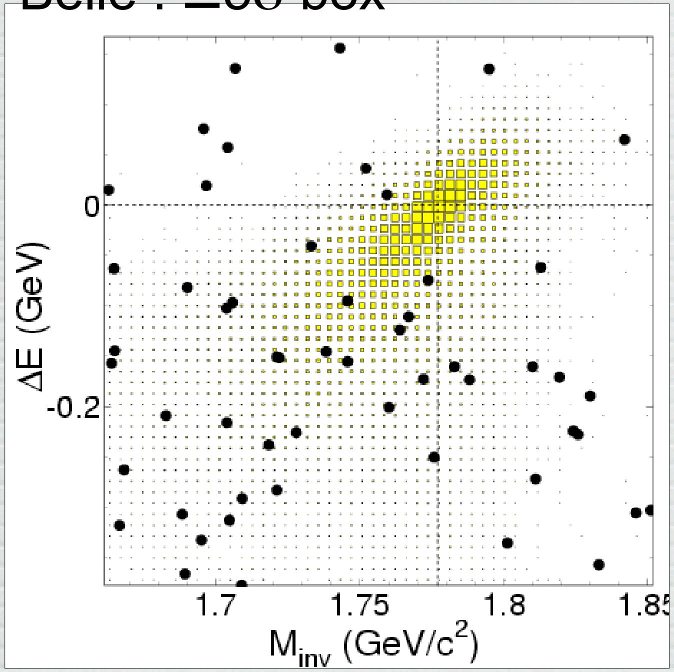
Br<0.68x10^{-7}

PRL 95, 041802 (2005).

- Background: $\tau \to \mu\nu\nu$ + ISR
  - Small contamination of $\mu\mu$ BG in $\Delta E>0$

$\tau \rightarrow \mu\gamma$: Belle vs BaBar

Belle : ±5σ box



Belle : $Br<3.1\times10^{-7}$ / 86.3 fb^{-1}

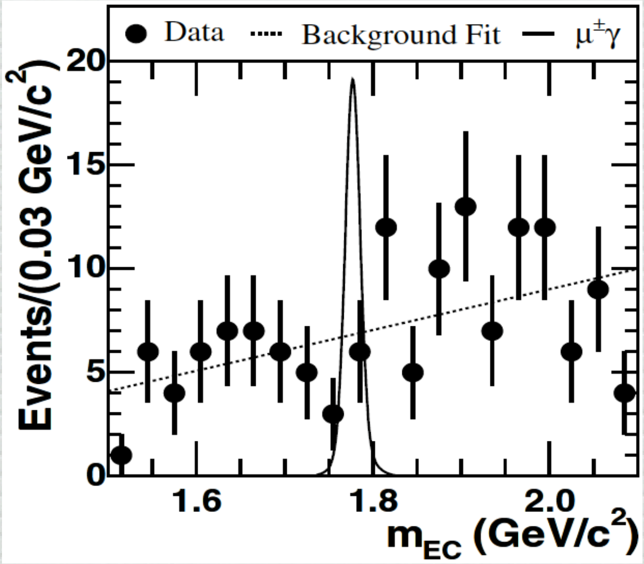
e = 11.1%

2D EML fit with 5σ signal box

N_{signal}= 0, NBG= 54

N_{signal} is constrained to be 0.

BaBar : ±2σ band



BaBar : $Br<0.68\times10^{-7}$ / 232 fb^{-1}

e = 9.4%

1D EML fit with 2σ DE band

N_{signal}= $\underline{-2.2}$, NBG= 143

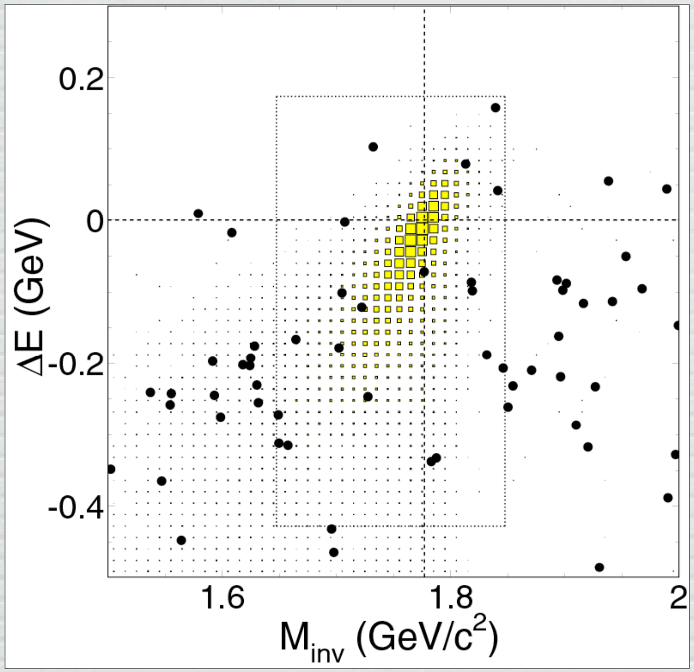
N is allowed to be negative.

Negative yield gives lower U.L. than expected.

$\tau \rightarrow e\gamma$

Belle

86.7fb^{-1} data

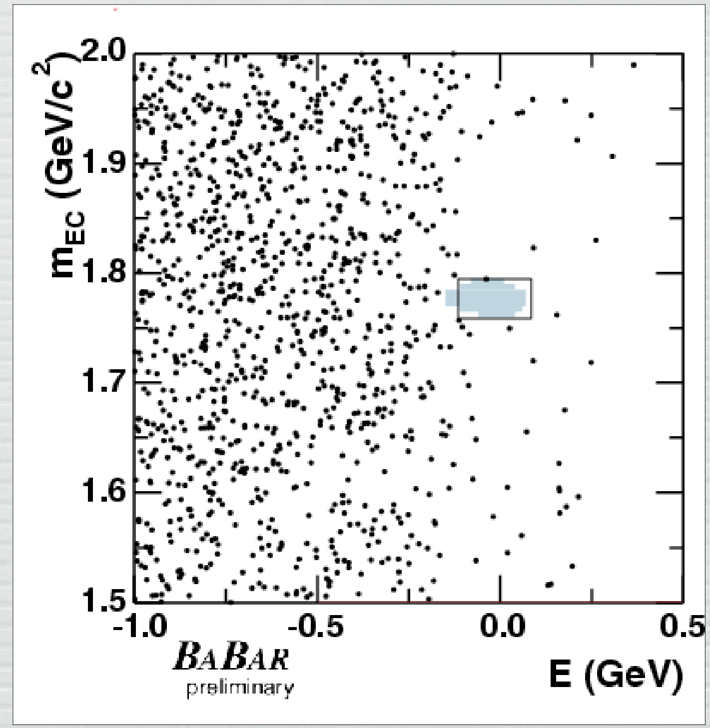


Br<3.9x10^{-7} at 90%C.L.

PLB 613, 20 (2005).

BaBar

232fb^{-1} data



Br<1.1x10^{-7}

PRL 96, 041801 (2006).

- Background: $\tau \rightarrow e\nu\nu$ + ISR

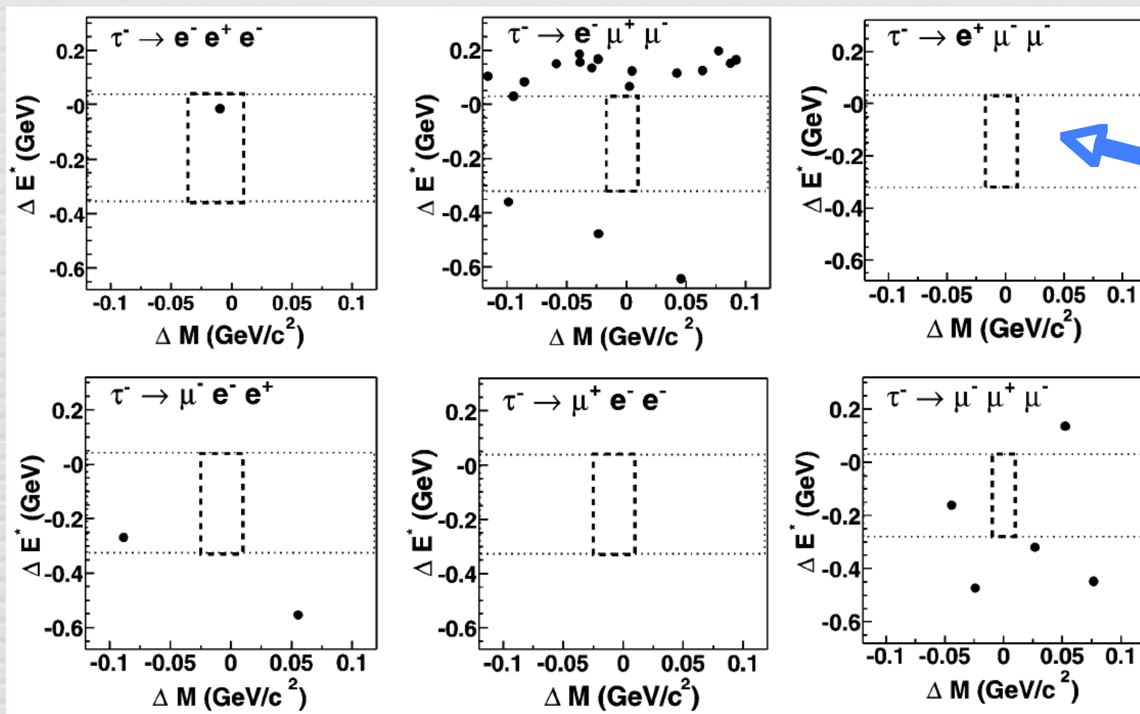
$\tau \rightarrow 3l$

Belle: 87.1fb^{-1}, BaBar: 91.5fb^{-1}

PLB 598, 103 (2004), PRL 92, 121801 (2004).

Br<(1.1~3.5)x10^{-7} at 90%C.L.

Belle's results



Signal region

Background: low level

qq around $\Delta E<0$, QED($\mu\mu$ or Bhabha) around $\Delta E>0$

$\tau \rightarrow l\pi^0/\eta/\eta'$

Lepton + Pseudoscalar meson

Belle: 154fb^{-1}

Br($\tau \rightarrow \mu\eta$)<1.5x10^{-7}

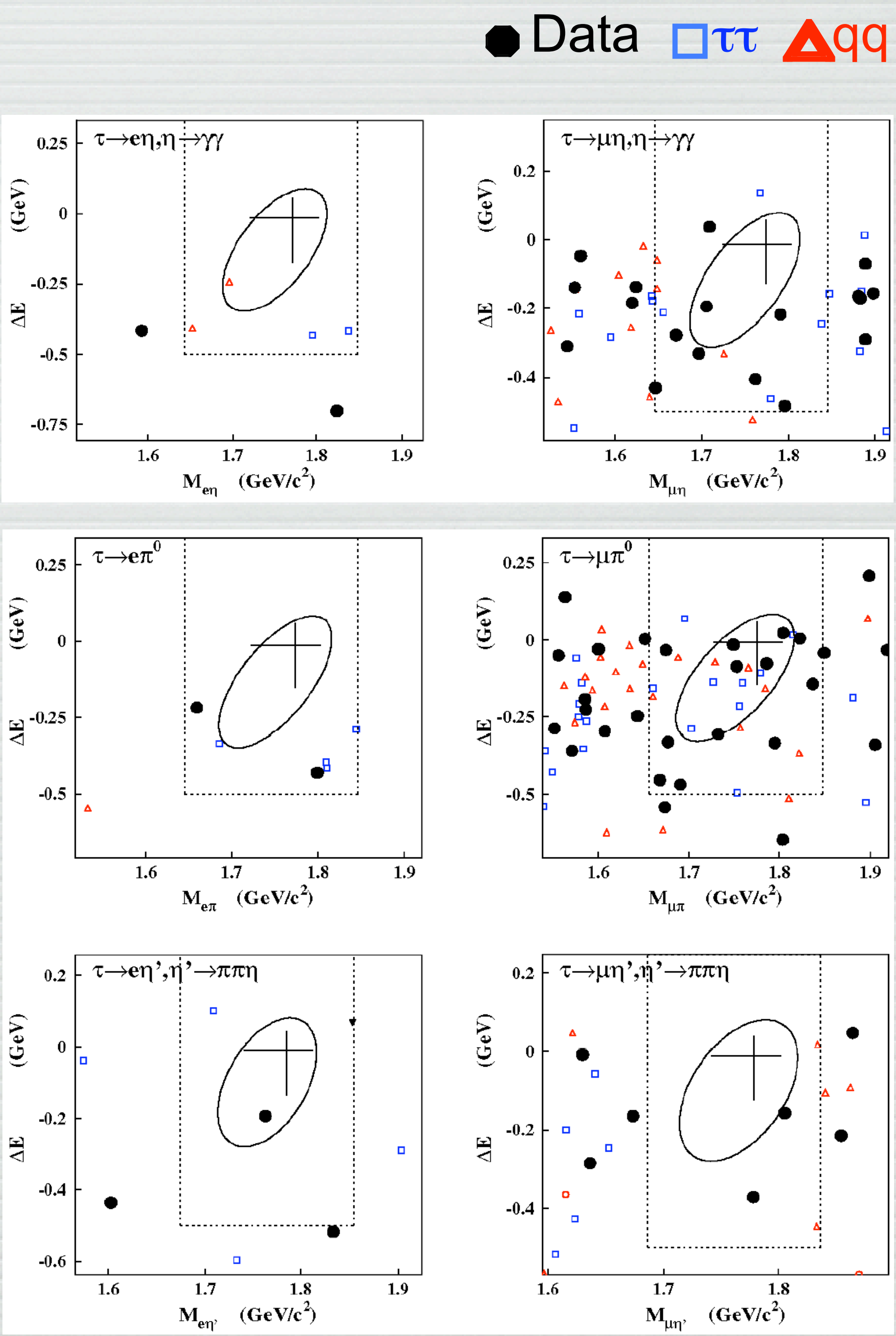
Br < (1.5~10)x10^{-7}

PLB 622, 218 (2005).

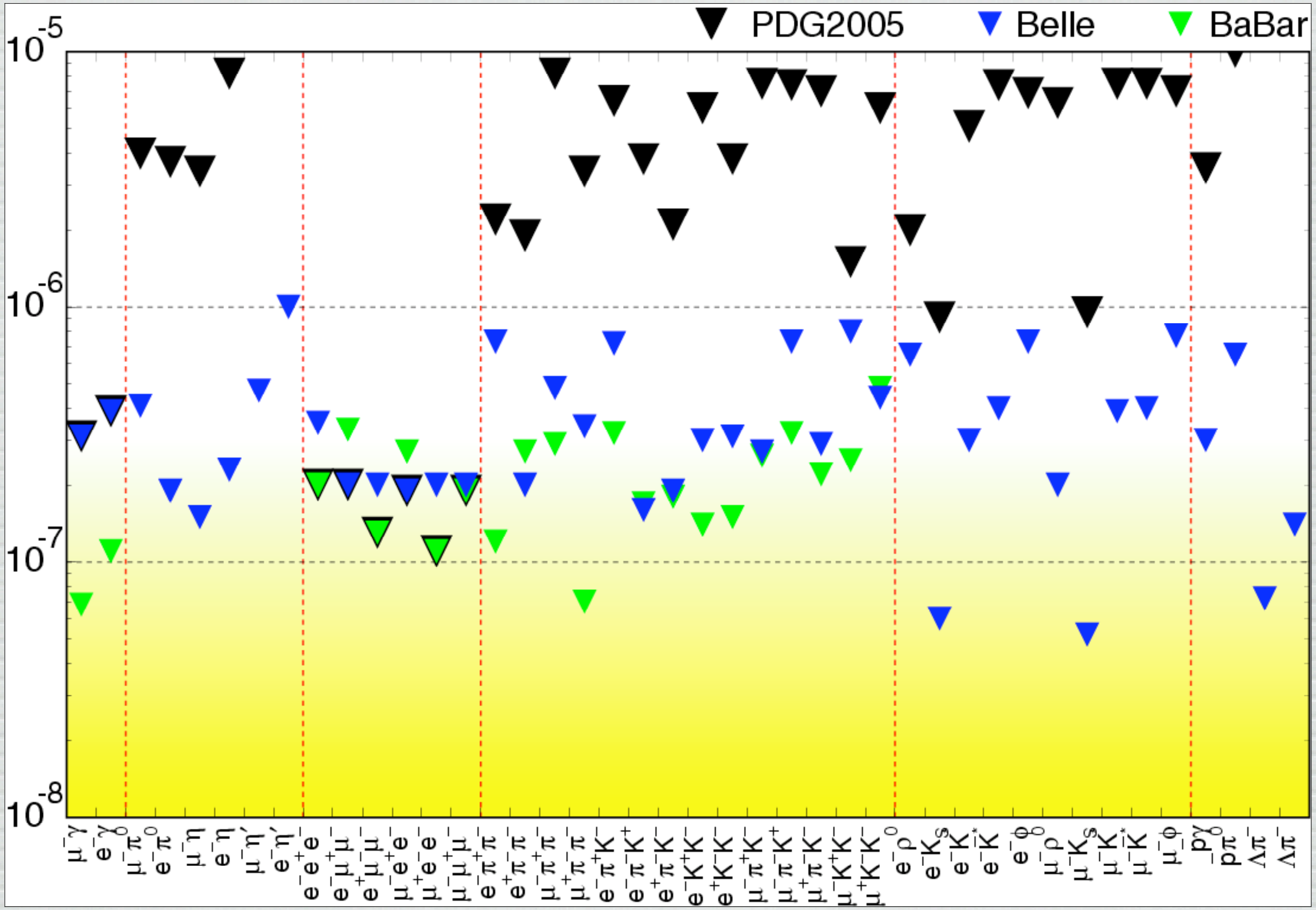
Background

μ: ττ + qq

e: negligible



Branching Ratios Summary



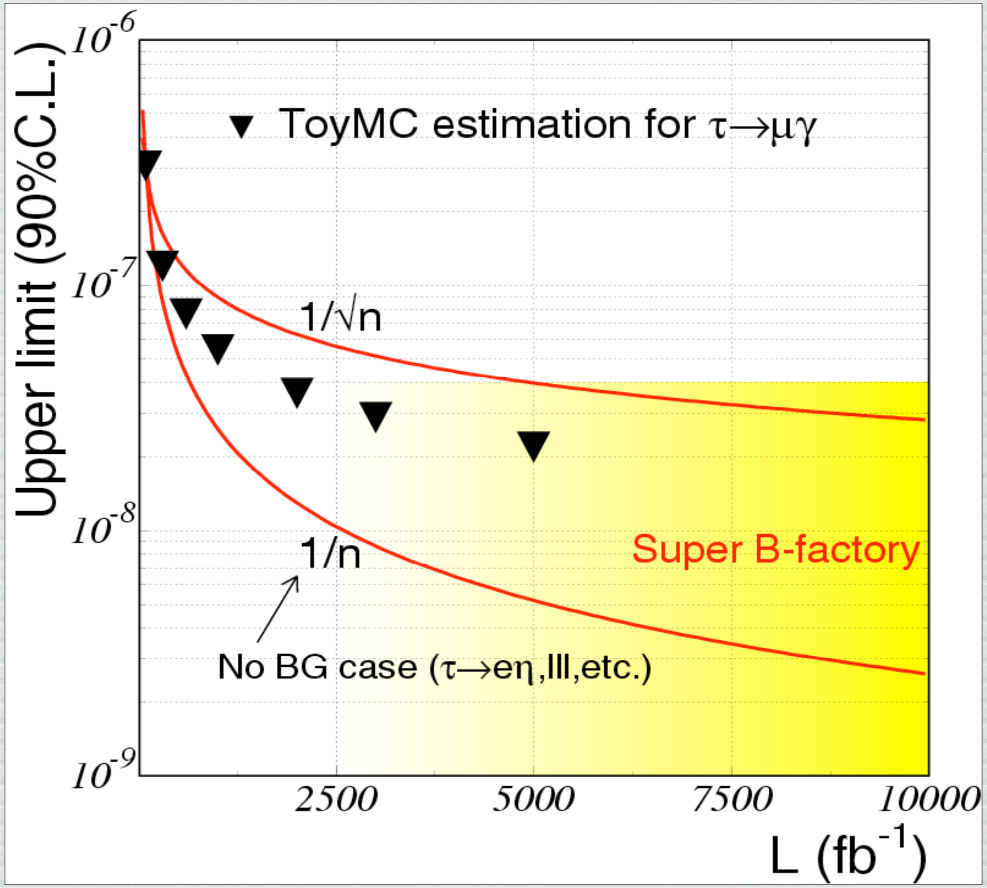
Br = O(10^{-6}) in PDG (by CLEO)
Br = O(10^{-7}) by Belle and BaBar

Future Prospects

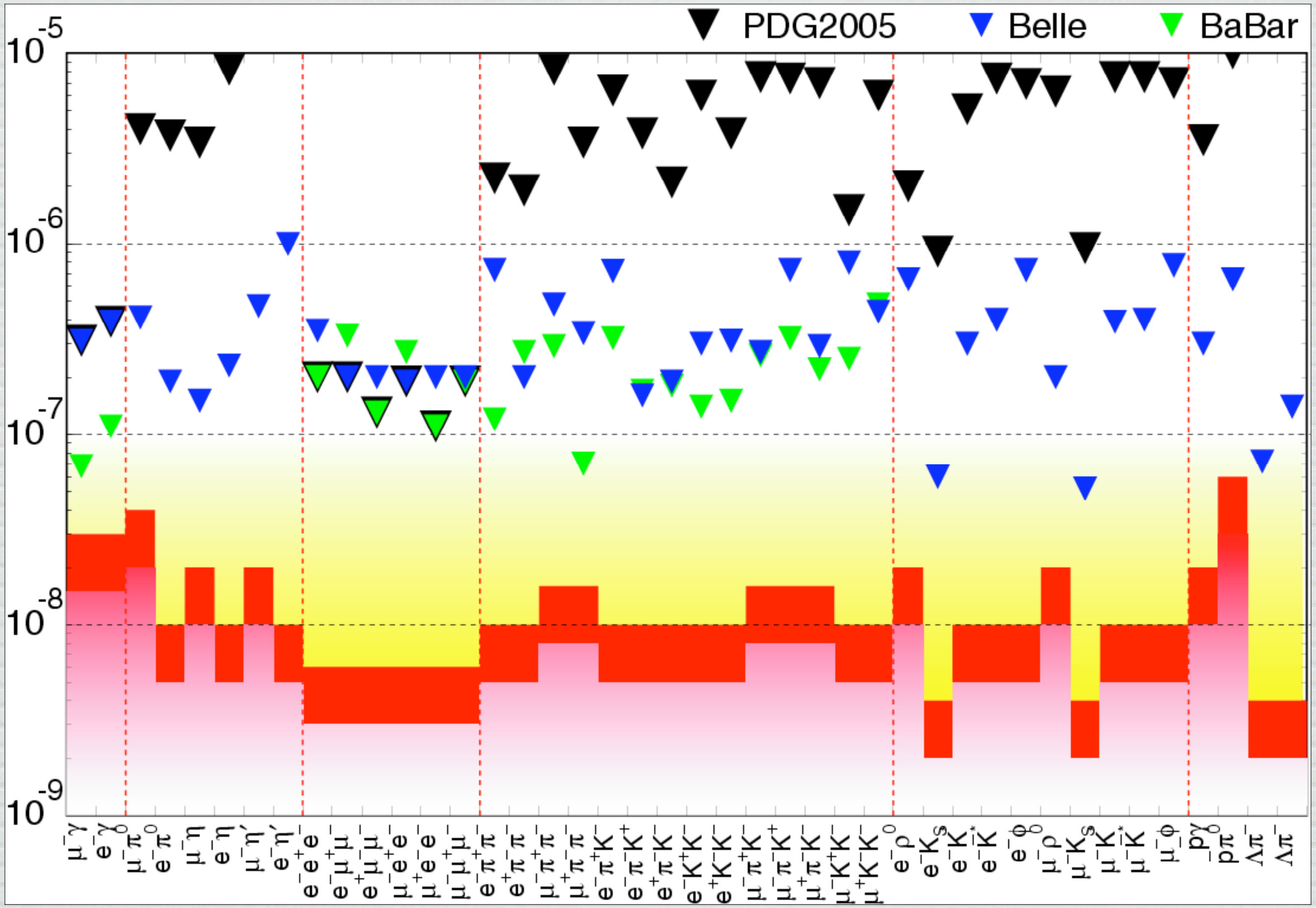
Already >7.5×10^8 τ-pairs
in two B-factories

Backgrounds are starting to
limit the sensitivity

Need better μ/π separation
Low energy τ-factory?
smaller ISR and qq background



Expectation for Super B Factory

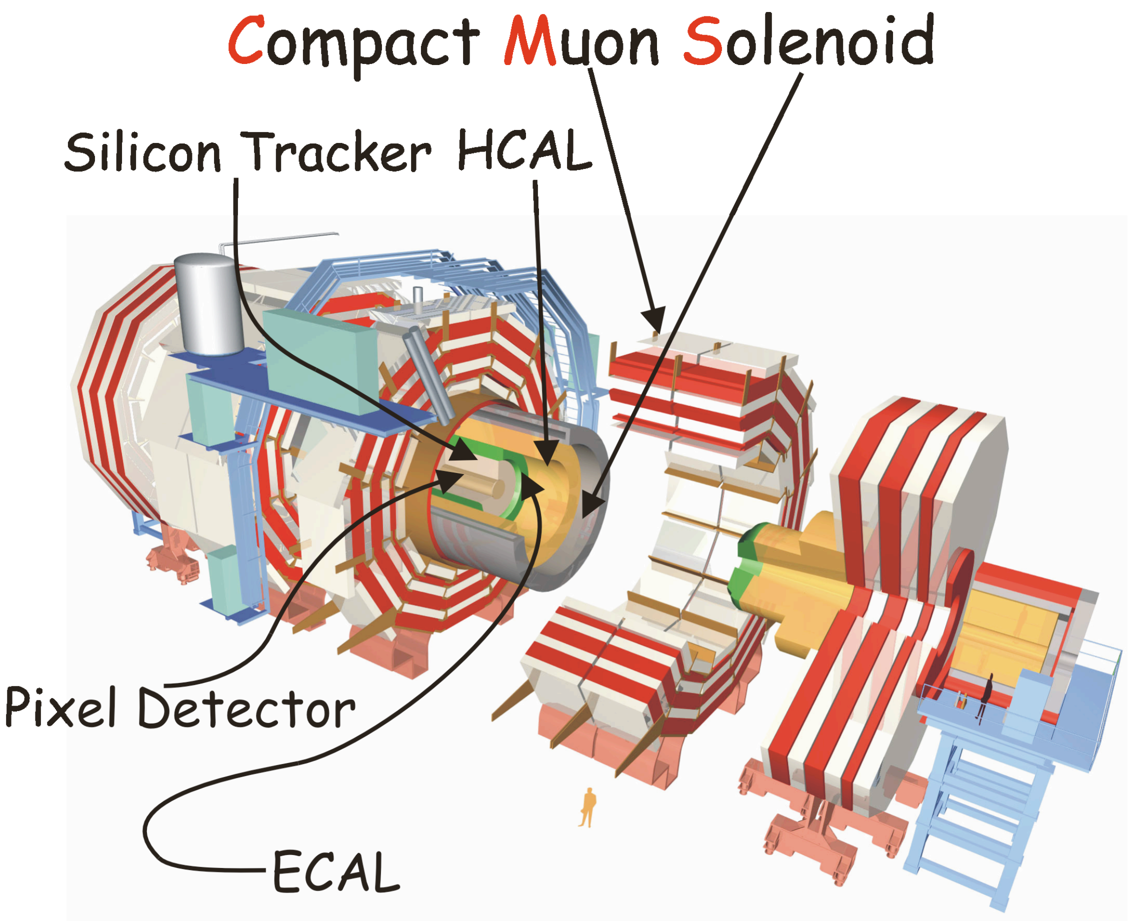


5-10ab^{-1}

The real issue is not "setting limits"
but making a discovery!

LHC experiment

The CMS detector



Well suited for studying $\tau \longrightarrow 3\mu$:

- vertexing
- large muon system

Presented at
"Flavour at the era of LHC"
Feb 2006

Luminosity goals:

2007:	$1\,\mathrm{fb}^{-1}/\mathrm{y}$	(initial operation)
2009:	$10 - 30\,\mathrm{fb}^{-1}/\mathrm{y}$	(low lumi)
2010:	$100 - 300\,\mathrm{fb}^{-1}/\mathrm{y}$	(high lumi)

LFV in τ-decays at CMS

Possible decay channels@low lumi

- $\tau \rightarrow \mu\gamma$ (seems to be hopeless!)
- $\tau \rightarrow \mu\mu\mu$

At high lumi?

- More pile-up
- More stringent trigger

Other LFV τ-decays like $\tau \rightarrow e\gamma$, $\tau \rightarrow eee$, $\tau \rightarrow \mu ee$, $\tau \rightarrow \mu + \mathrm{hadrons}$ probably not detectable at CMS, but this needs to be studied.

τ-sources at the LHC

decay channel	N_τ/y (low lumi)
$W \rightarrow \tau\nu_\tau$	$1.7 \cdot 10^8$
$Z \rightarrow \tau\tau$	$8.0 \cdot 10^8$
$B^0 \rightarrow \tau X$	$4.0 \cdot 10^{11}$
$B^\pm \rightarrow \tau X$	$3.8 \cdot 10^{11}$
$B_s \rightarrow \tau X$	$7.9 \cdot 10^{10}$
$D_s \rightarrow \tau X$	$1.5 \cdot 10^{12}$

Trigger at CMS (L1)

- single muon $p_t > 14\,\mathrm{GeV}$
- di-muon $p_t > 3\,\mathrm{GeV}$

High Level Trigger (HLT)

- single muon $p_t > 19 GeV$
- di-muon $p_t > 7\,\mathrm{GeV}$

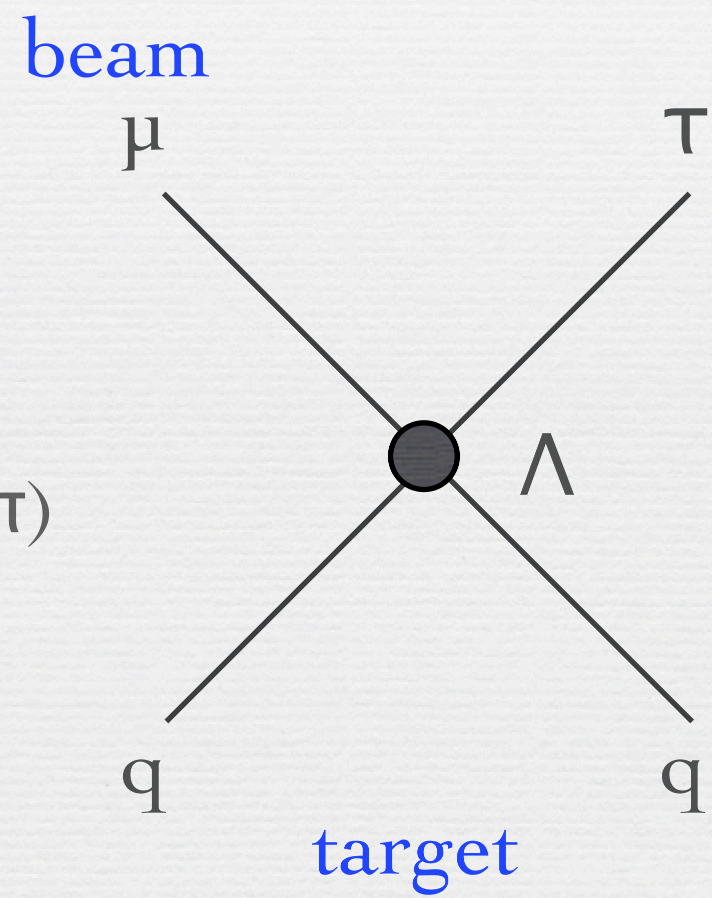
Needs more study

But looks very tough

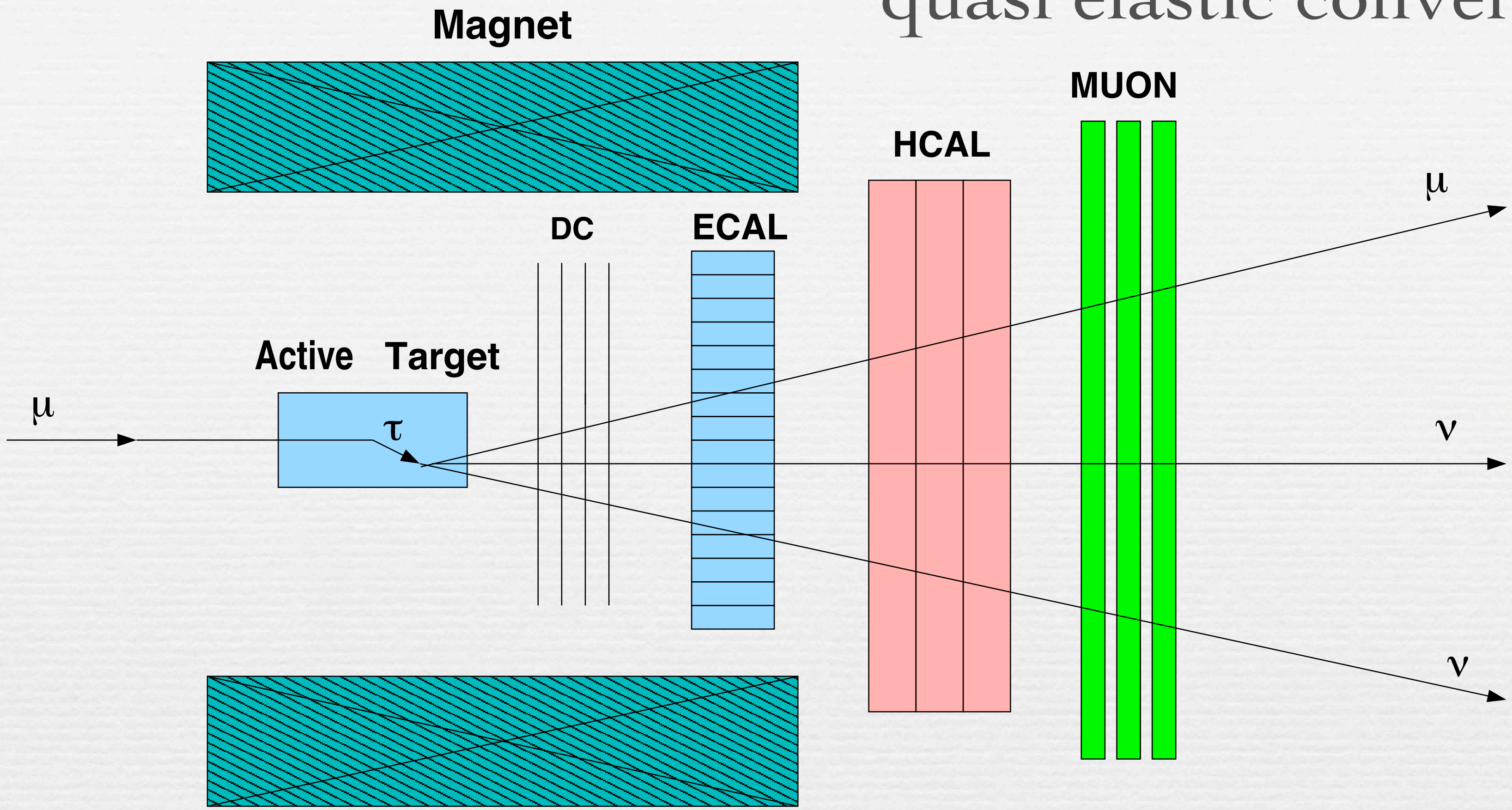
Fixed Target Experiments

Mu - Tau Conversion

- Look for effective LFV couplings:
  - ✓ that are only loosely constrained by tau decays (scalar by $\tau \to \mu\pi\pi$)
  - ✓ that are not constrained by tau decays: (qq) = (uc), etc.



quasi elastic conversion

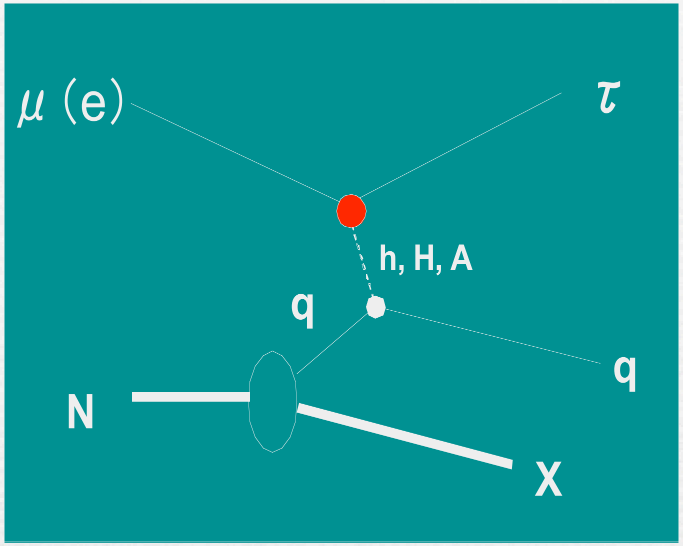


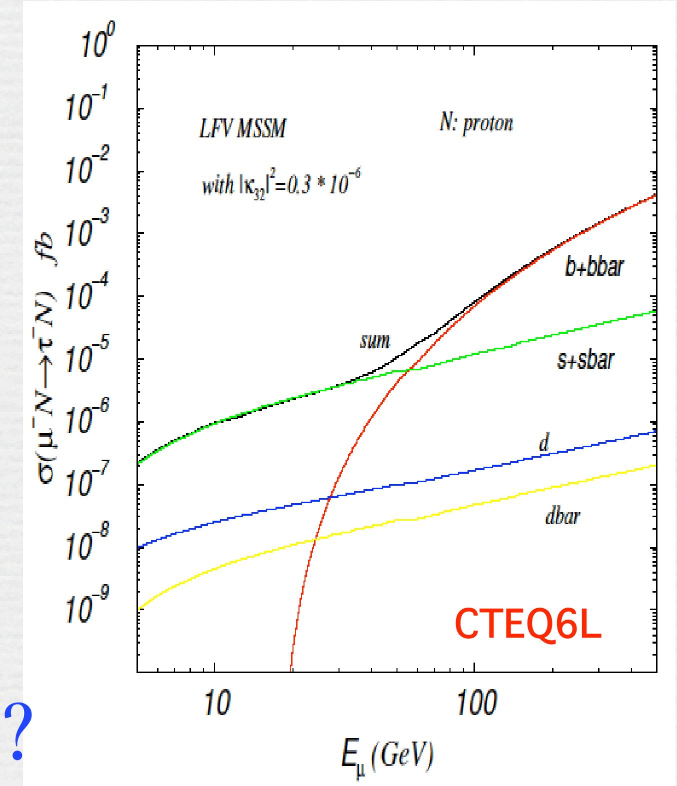
Less constrained coupling as large as 0.5fb at 50GeV could yield signal events for ~10^{15} muons/year on ~100g/cm^2 target

Experimental Feasibility at SPS or Neutrino Factory?

Deep Inelastic Conversion

- In SUSY models, possible enhancement due to Higgs mediation
  Constrained by τ→μη, 3μ
  ~100ρ events for 10^{20} muons at 50GeV; more for higher E
- For above 60GeV, b-quark subprocess dominates and increases the cross-section
- Gauge-boson mediation strongly constrained by τ→μγ





Feasibility at ILC or Muon Collider?

Really feasible?

LFV in Kaon Decays

$$R_K = \frac{K \to e\,\nu}{K \to \mu\,\nu}$$

- cancels theoretical uncertainties
- sensitive to LFV couplings if measured at 1% level:

$$\tau \to e\gamma < 10^{-11} \qquad \tau \to e\eta < 10^{-10}$$

~exceeding the B factory sensitivity

- does not prove LFV if such deviation found

A.Masiero et al. hep-ph/0511289

NA48/2

2003 data:

$2.416 \pm 0.043 \pm 0.024$

cf. SM: 2.472 ± 0.001

@EPS2005, Lisbon

2004 data at least double the statistics.

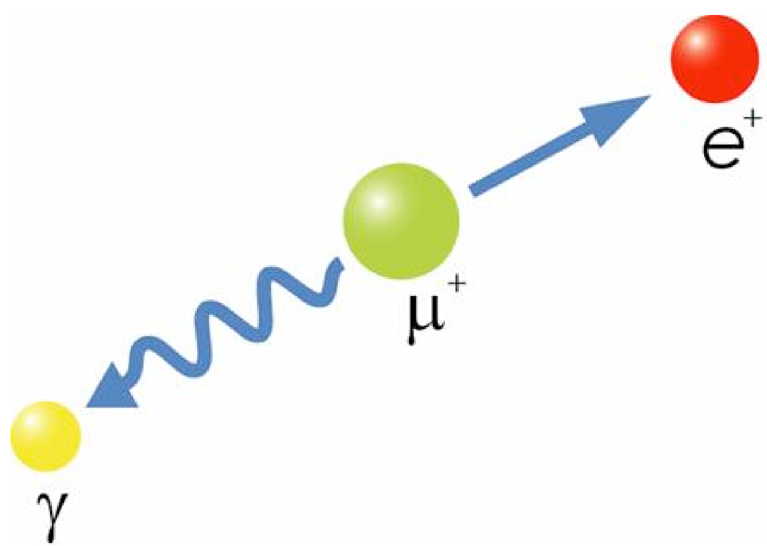
More data taking?

“Muon Processes”

Muon to Electron

- Most sensitive to SUSY GUT and SUSY Seesaw models
  - ✓ $\tau \to \mu\gamma < 10^{-9}$ for SUSY SO(10)
- Predicted branching ratios are within the reach of the next experiments !
- Two processes: $\mu \to e$ conversion vs. $\mu \to e\gamma$

$\mu \rightarrow e\, \gamma$



Clear 2-body kinematics

Use μ^+ to avoid capture inside stopping target

Background dominated by Accidental coincidence

→ lower μ rate is better

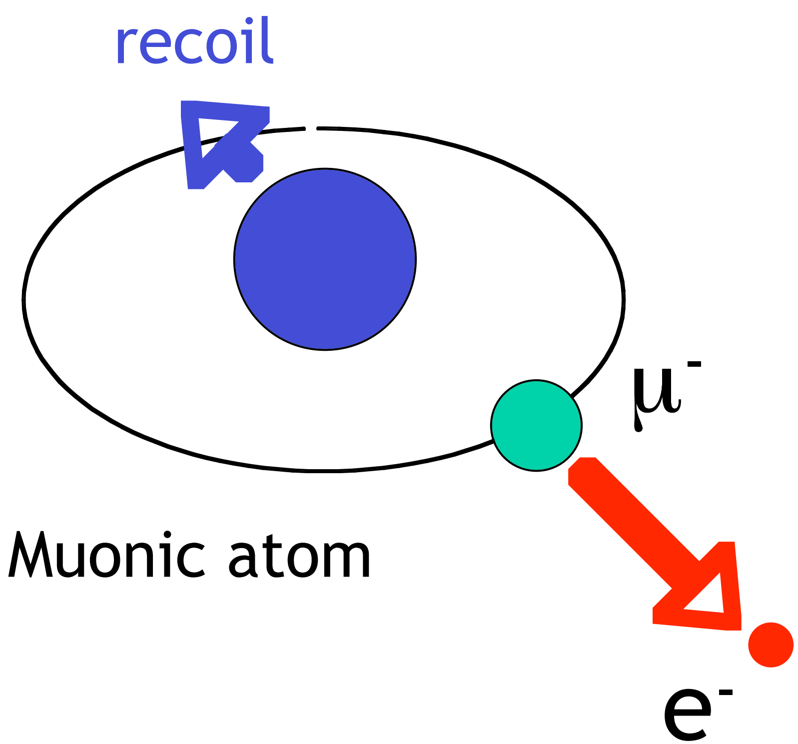
→ DC μ beam is best

"surface muon beam": 100% polarized

Good detector system Is essential

MEG Experiment

$\mu \rightarrow e$ conversion



μ^- to make a muonic atom

a single electron with

$$E_e = M_\mu - \delta$$

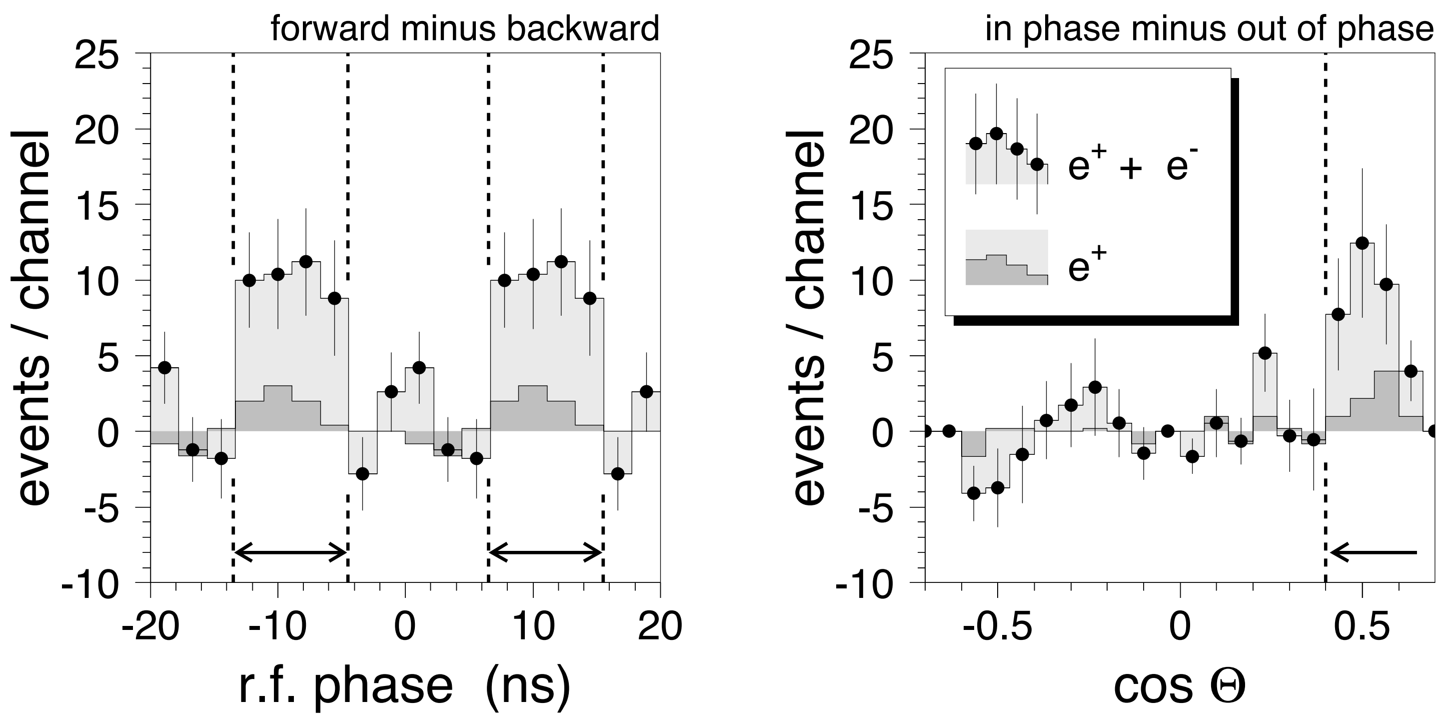
Background:

- Decay in orbit
  $\sim(E_{max} - E_e)^5$
- Beam related
  $\rightarrow$ next page

μ → e conversion

Prompt Beam Induced Background

SINDRUM II @PSI

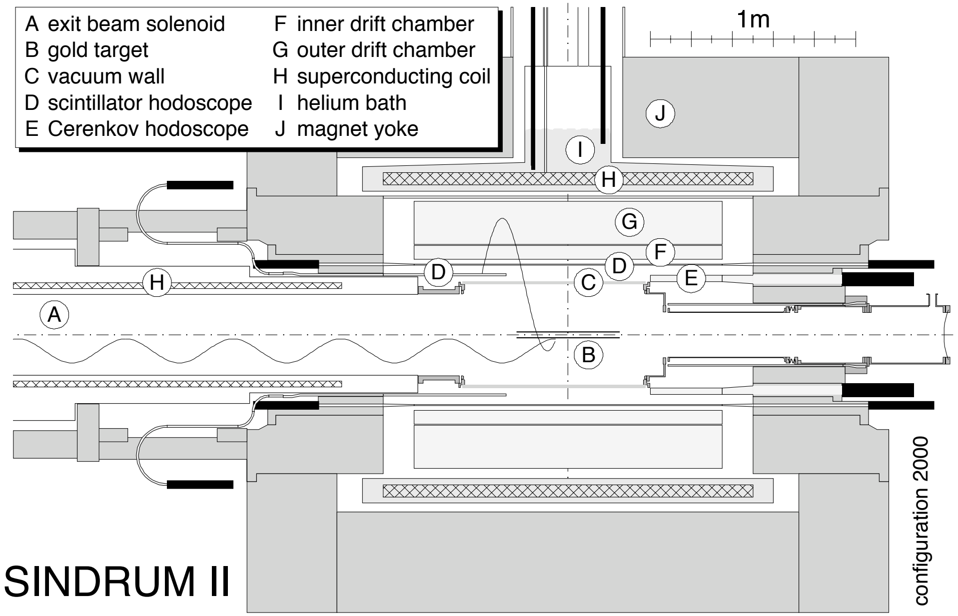


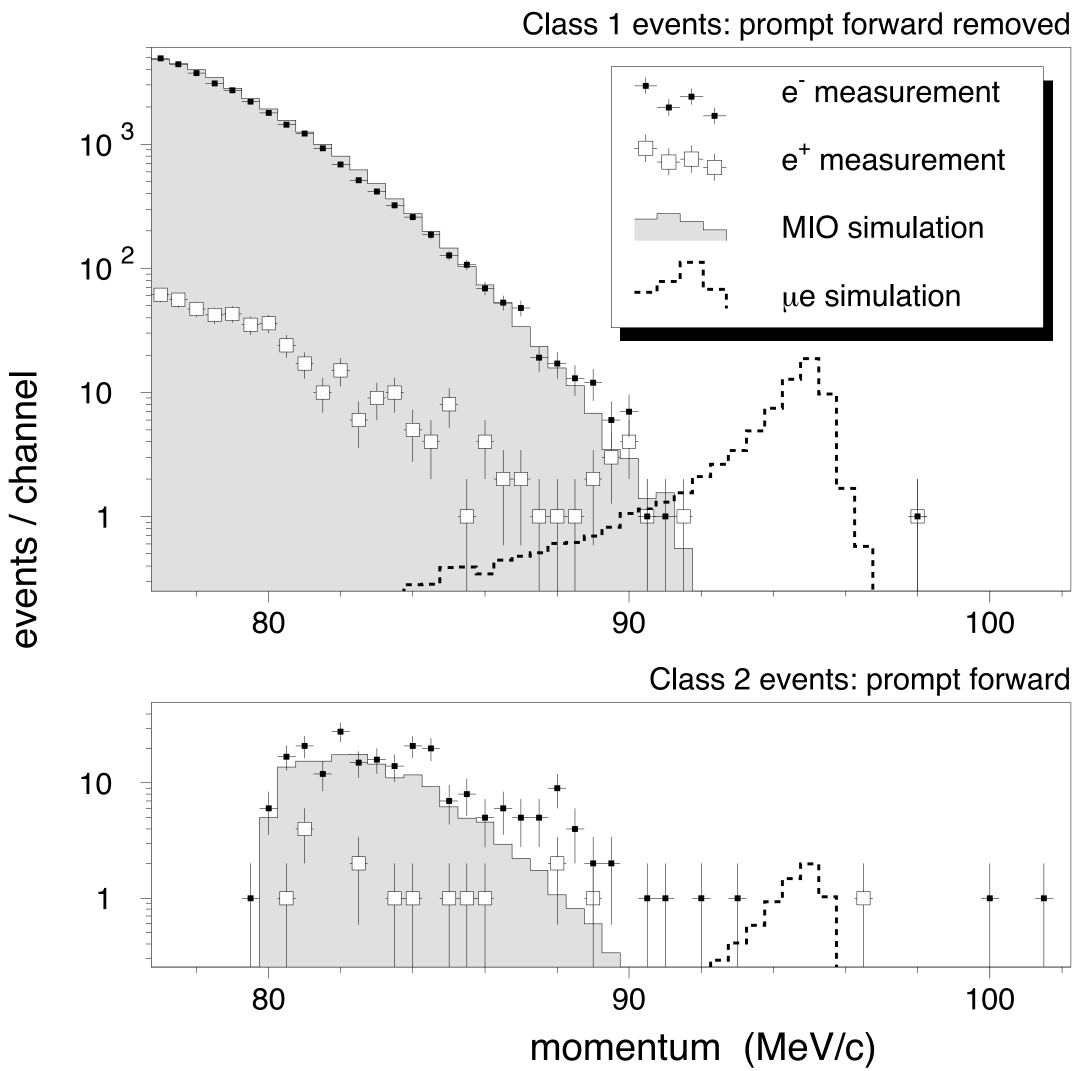
in coincidence with 20nsec Cyclotron RF

~ pion decay in flight

SINDRUM II

@ PSI





Final result on mu - e conversion on Gold target is being prepared for publication

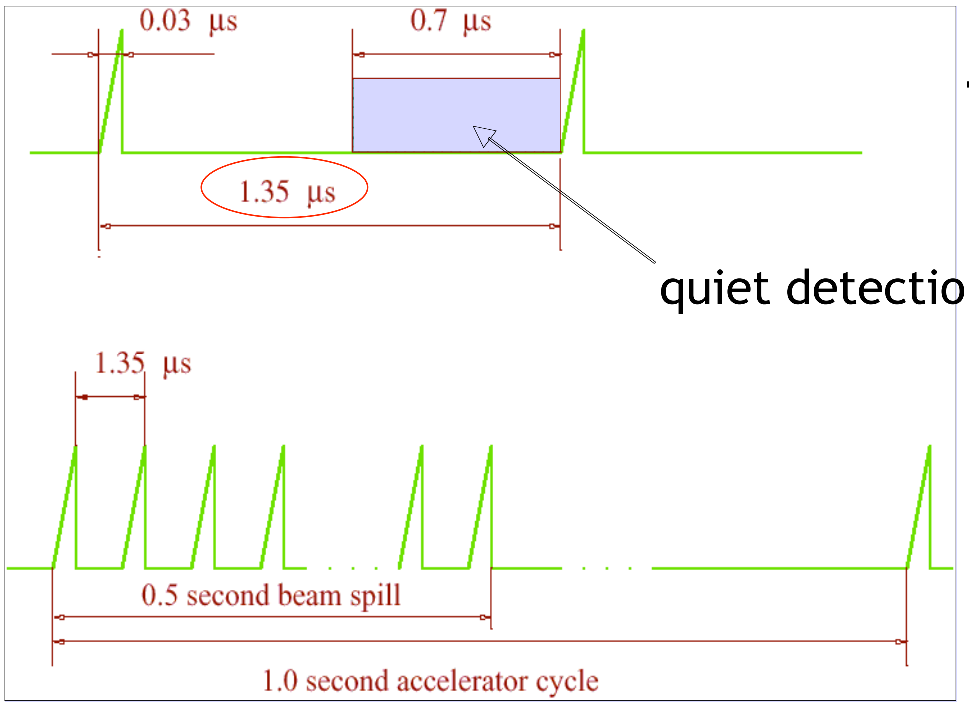
$< 7 \times 10^{-13}$ 90%CL

MECO Experiment @BNL

Beam-related background

e.g. radiative pion capture

Proton beam



quiet detection time

→ Use pulsed beam
Measure only in between

"beam extinction"

Note:
muon capture ~ Z^4

Effective μ lifetime

0.9 μs	for Al
0.3 μs	Ti
0.06 μs	Pb

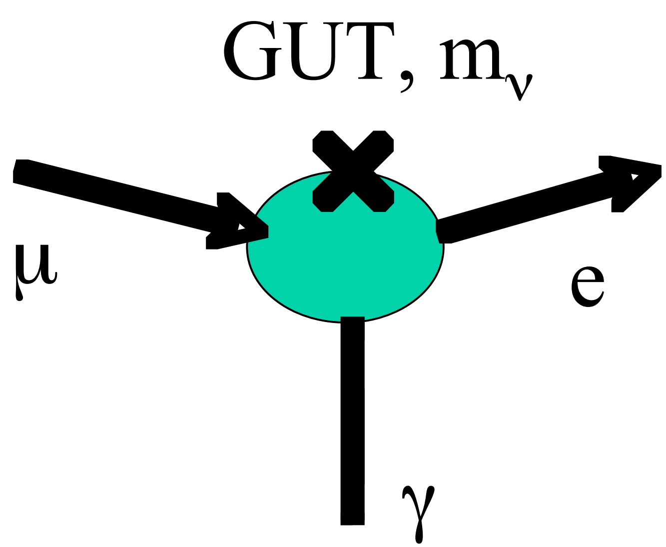
MECO @AGS
Uses Al target

Good beam is essential

$\mu \rightarrow e\,\gamma$ vs $\mu \rightarrow e$ conversion

Physics sensitivity

$$\frac{\mu \rightarrow e\,\gamma}{\mu \rightarrow e \text{ conversion}} = \begin{cases} \sim 390 & \text{Al target} \\ \sim 240 & \text{Ti} \\ \sim 340 & \text{Pb} \end{cases}$$



1×10^{-14} $\mu \rightarrow e\gamma$

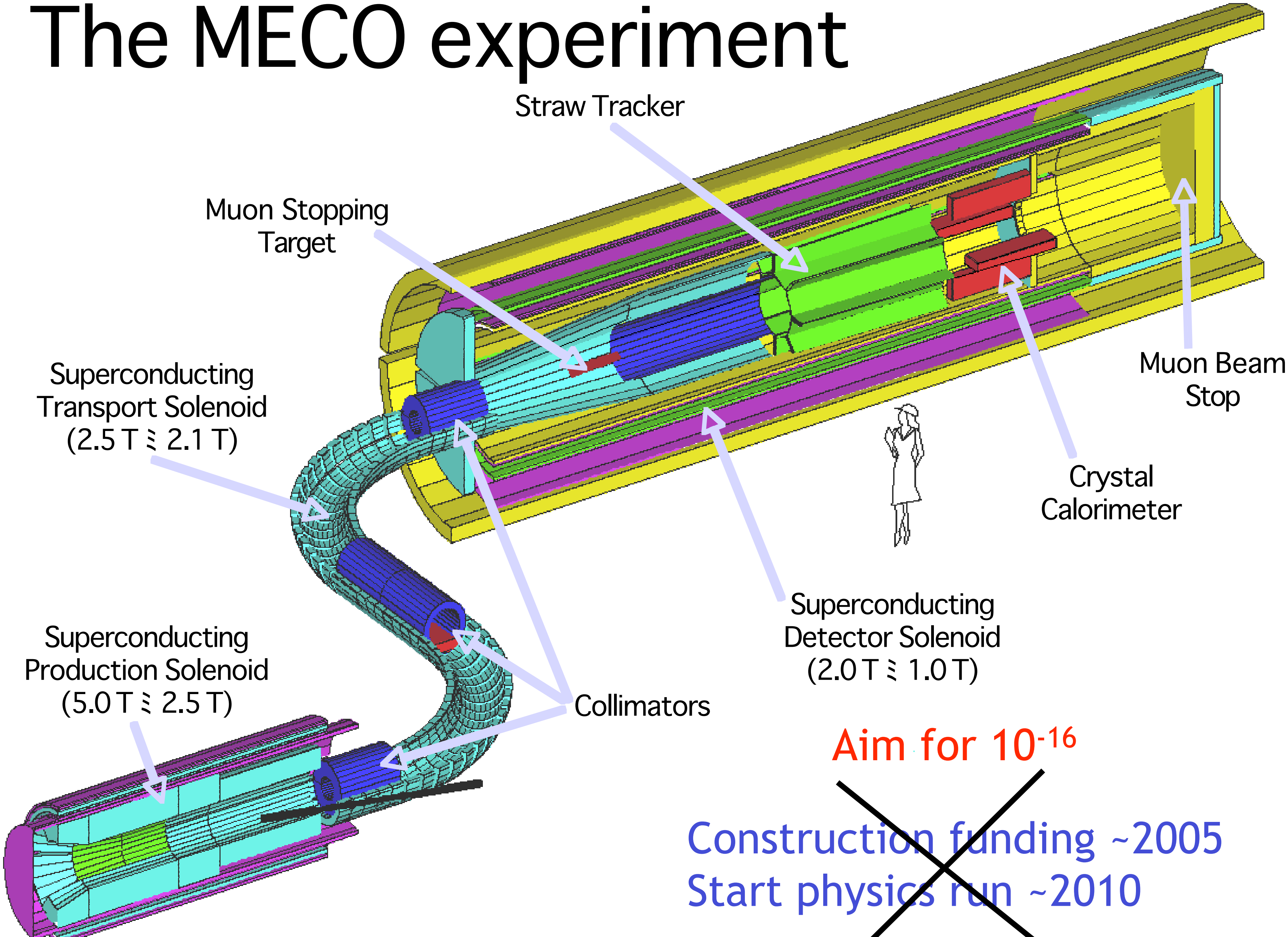
10^{8}/sec DC beam

⬇

$\sim 3 \times 10^{-17}$ $\mu \rightarrow e$ conv

10^{11}/sec pulse beam

The MECO experiment



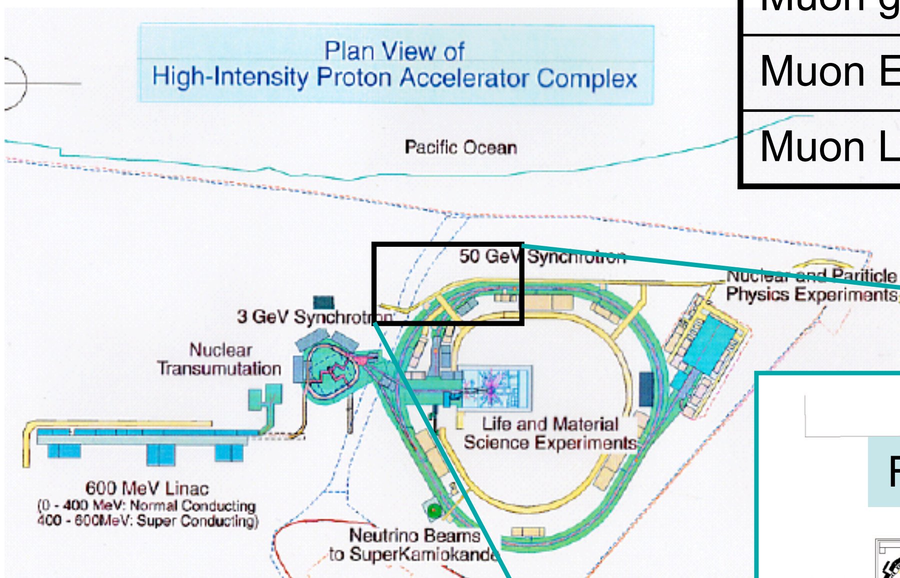
Aim for 10^{-16}

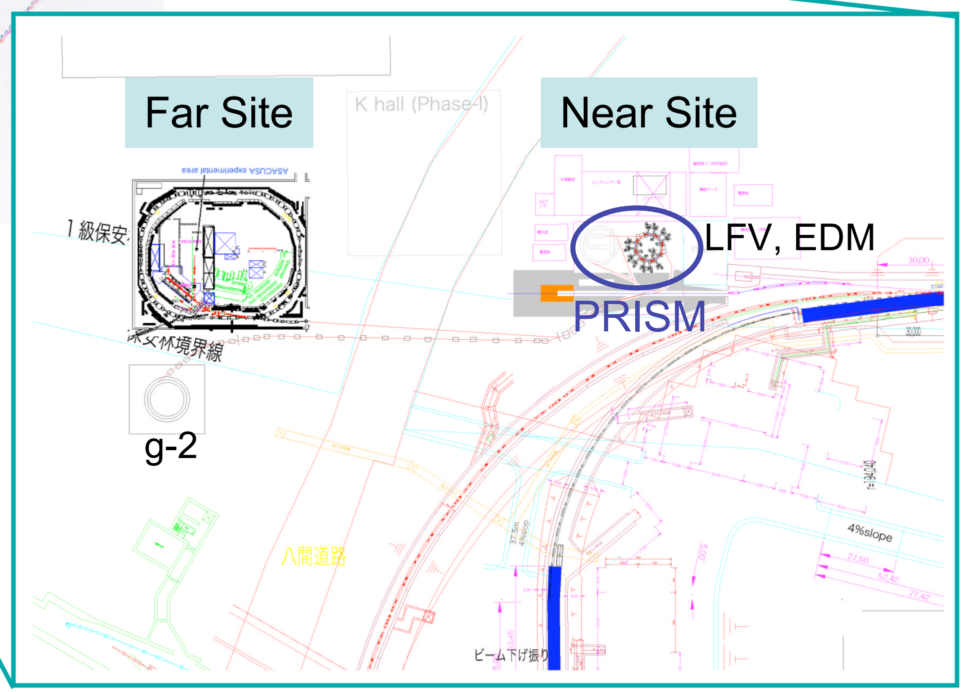
~~Construction funding ~2005~~
~~Start physics run ~2010~~

CANCELLED

Proposed Muon Facility at J-PARC

mode	Present	Goal
Muon g-2	0.5 ppm	0.05 ppm
Muon EDM	10^{-19}ecm	10^{-24}ecm
Muon LFV (m-e conv.)	< 2×10^{-13}	< 10^{-18}

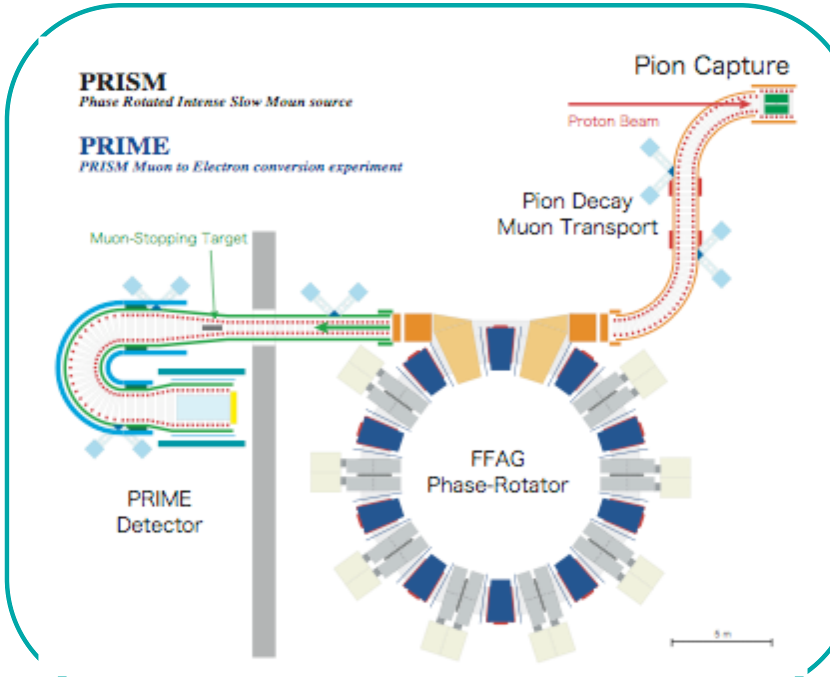




PRISM/PRIME for $\mu^- N \rightarrow e^- N$

A high-quality beam is essential to carry out $\mu^- N \rightarrow e^- N$ at high sensitivity.

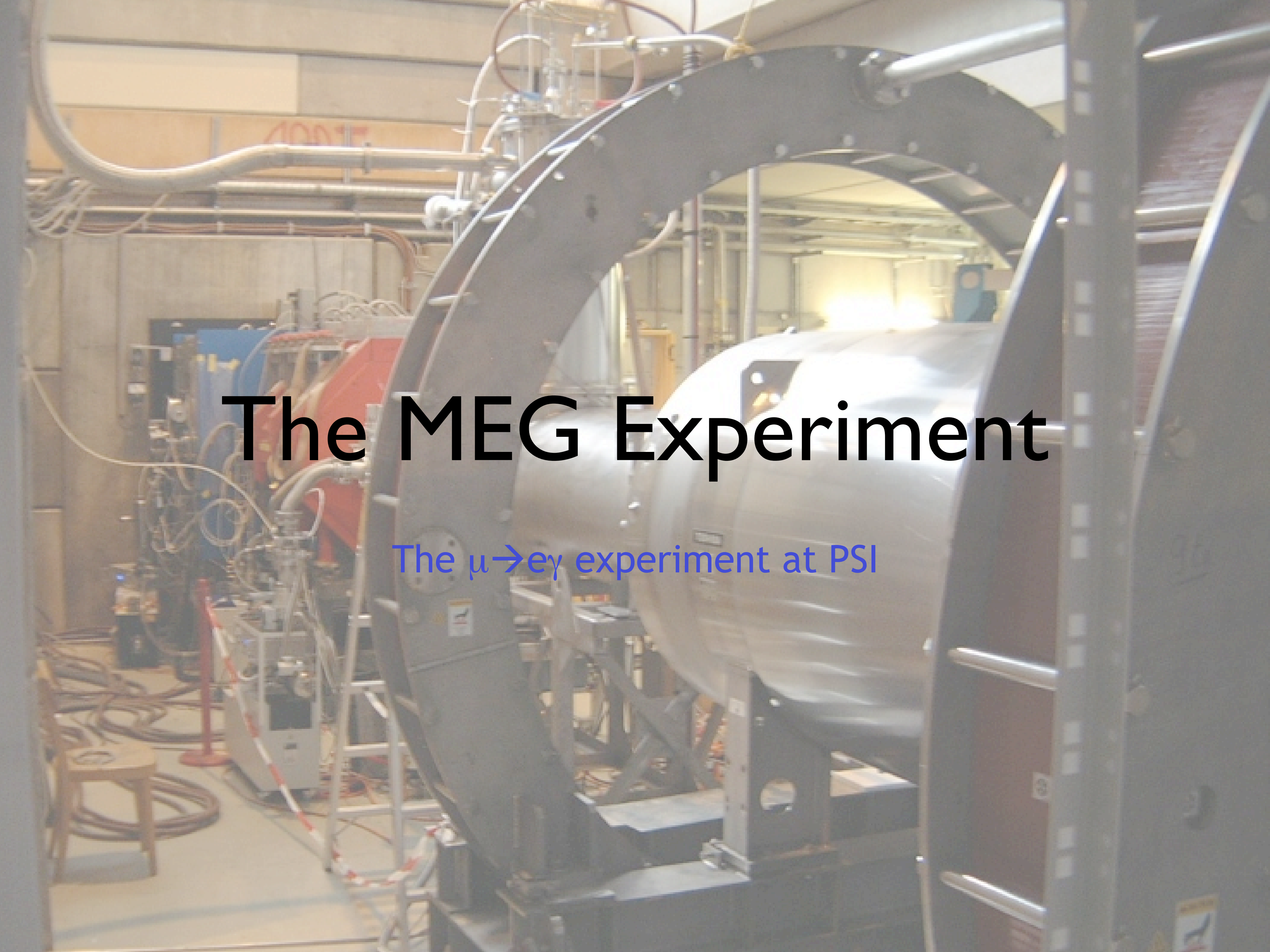
- PRISM
- (=Phase Rotated Intense Slow Muon source)
- High muon intensity
  - 10^{11} - 10^{12} μ^-/sec
- Low energy 68 MeV/c
- Pulsed beam
  - Rejection of background coming from proton
- Narrow energy spread (by phase rotation)
  - **ΔE/E** = ±0.5~1.0 MeV
  - thinner muon-stopping target
  - Better e^- momentum/energy resolution while keeping high muon stopping efficiency
- Less beam contamination
  - Practically no pion contamination **$\pi/\mu \sim 10^{-18}$**



- Year 2003-2007
  - PRISM-FFAG (phase rotator) is under construction
- Phase-I : construction and test of PRISM
- Phase-II : installation of PRISM to high intensity proton machine for mu-e. search.

- **GOAL: B($\mu^- N \rightarrow e^- N$) < 10^{-18}**

Not Funded



The MEG Experiment

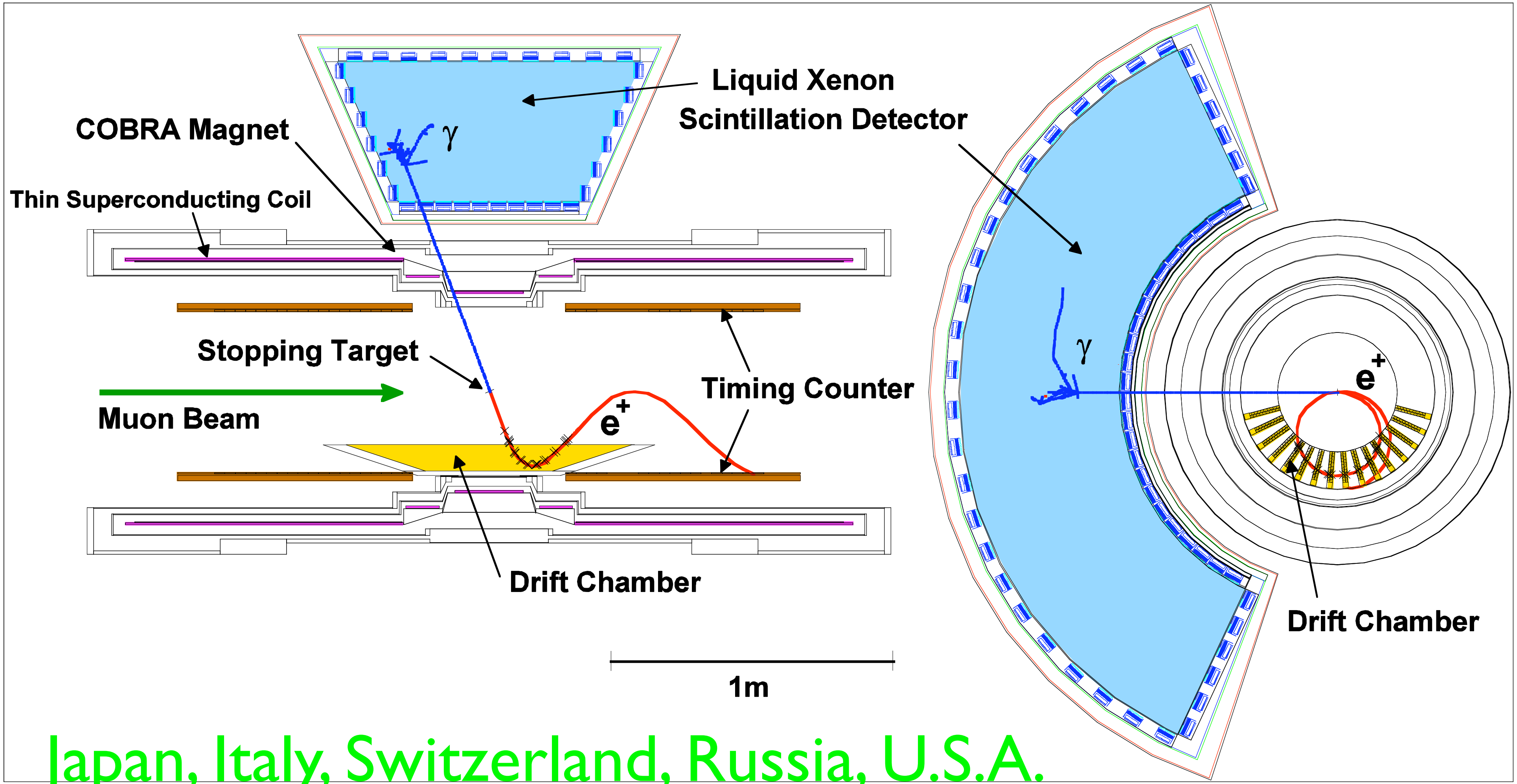
The $\mu \rightarrow e\gamma$ experiment at PSI

The MEG experiment

Approved at Paul Scherrer Institut, Switzerland in 1999

Start physics run in 2006

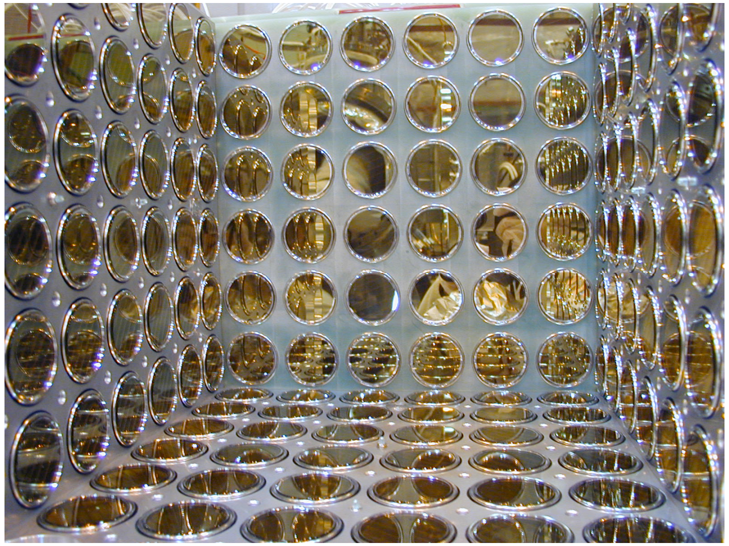
Initial aim at 10^{-13} eventually down to 10^{-14}



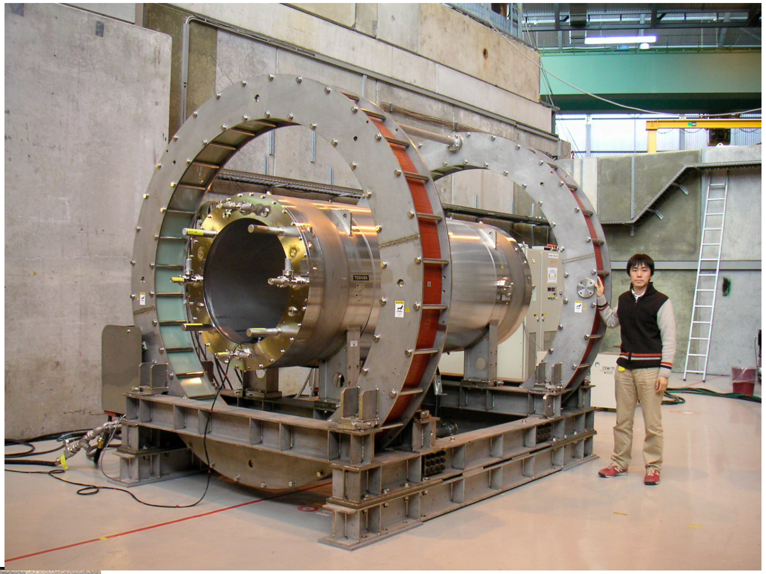
Japan, Italy, Switzerland, Russia, U.S.A.

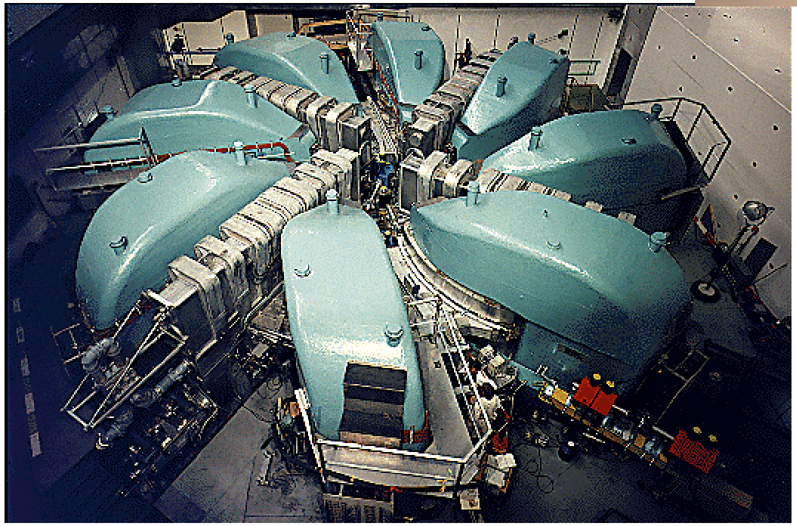
3 Techniques that enabled the experiment

LXe scintillation γ-ray detector



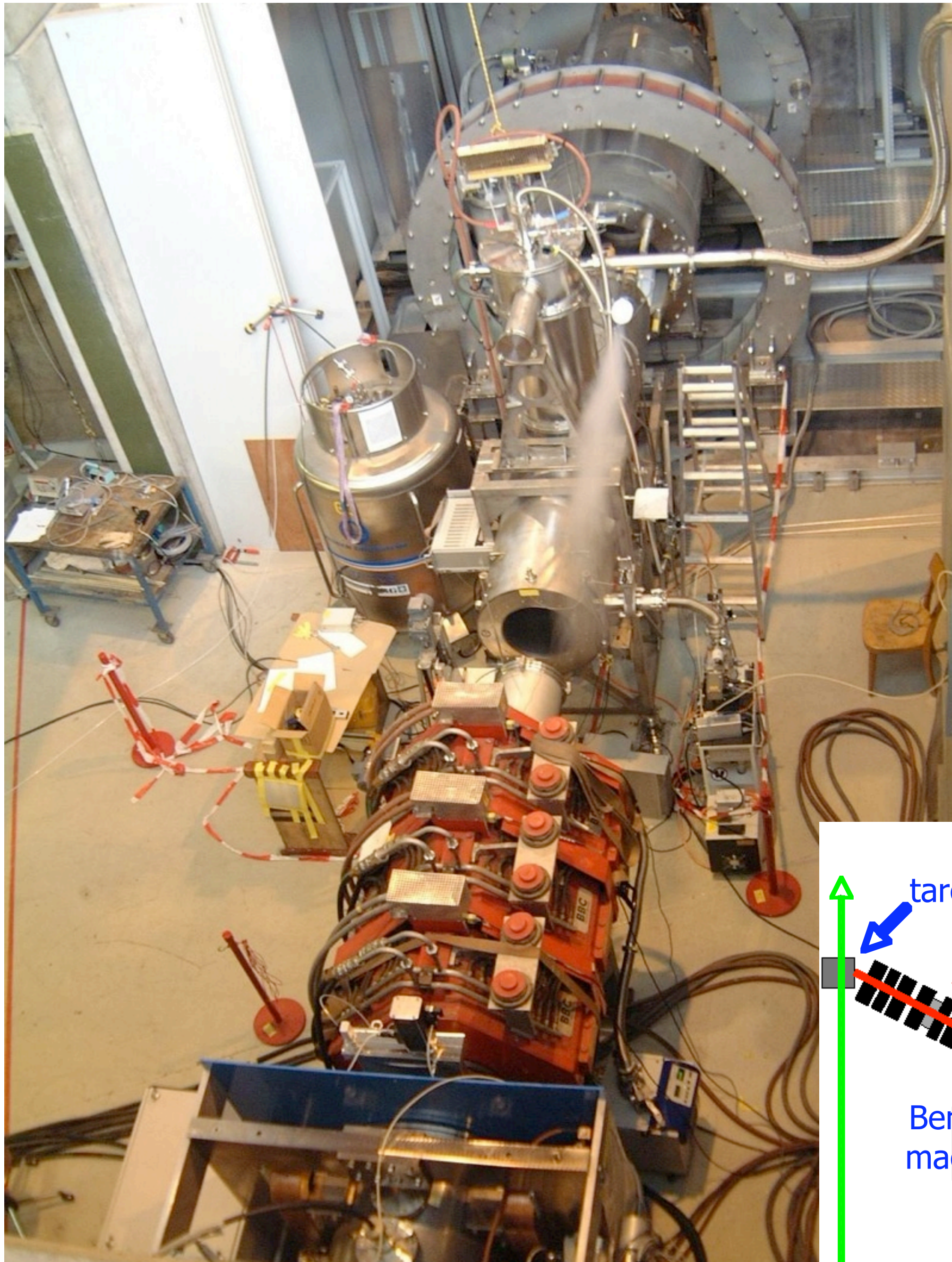
COBRA magnet
w/ graded B field





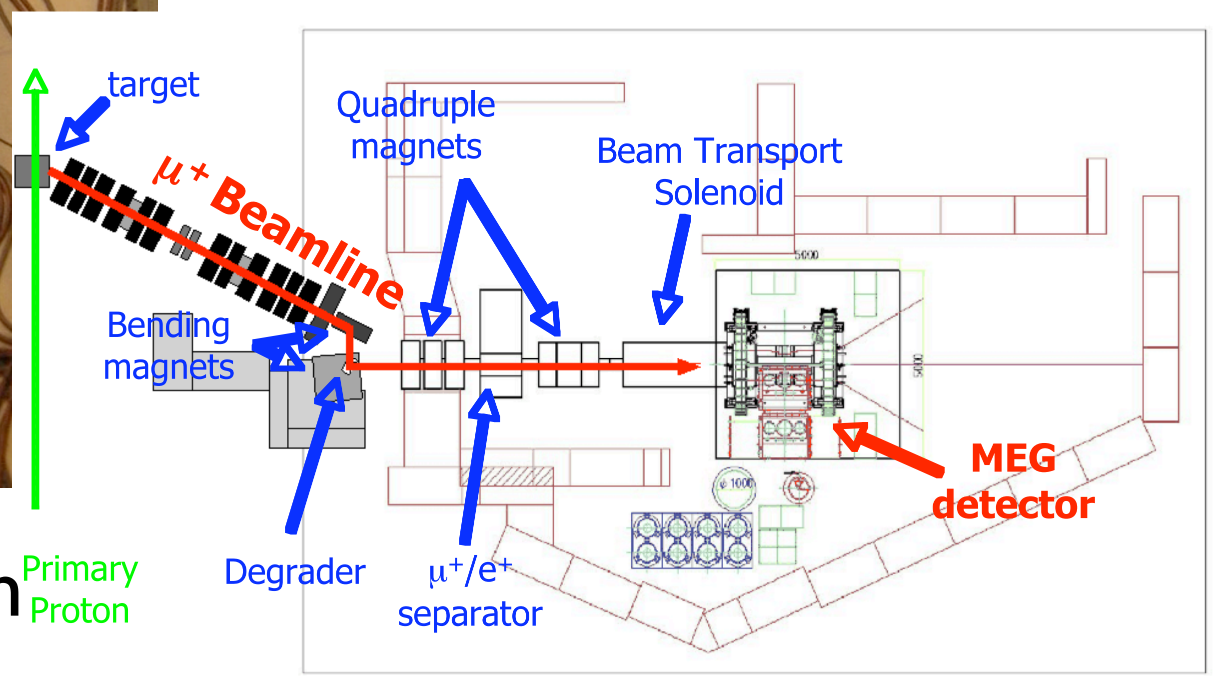
Most intensive DC muon beam (10^8/sec)

πE5 area @PSI



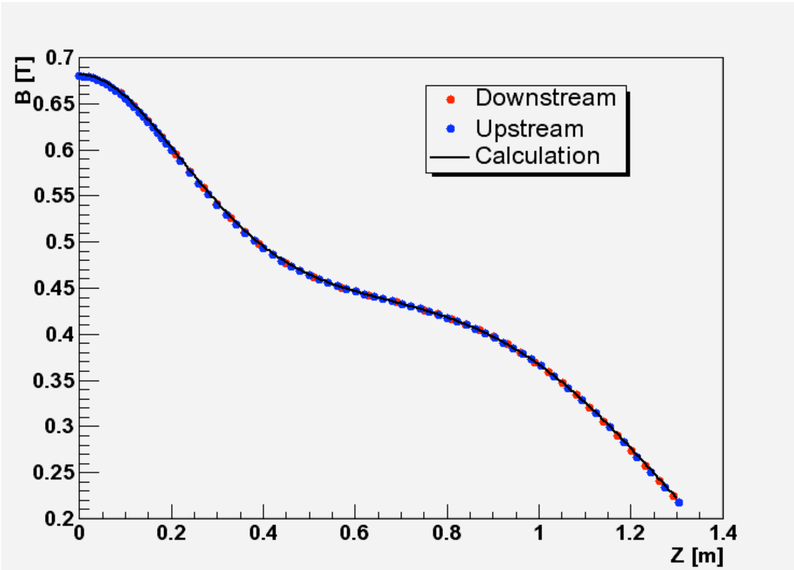
Presently tuning the beam down to the target position

10^8 muon stops /sec
~10mm spot size



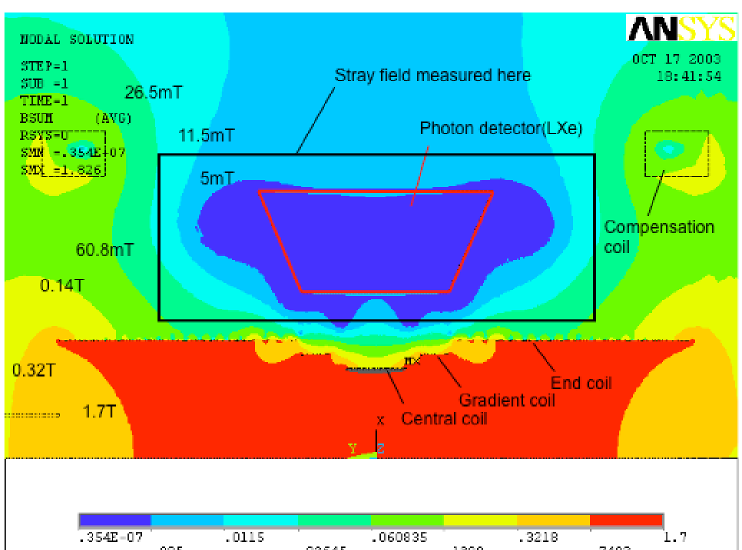
PSI Proton Cyclotron
590MeV, >1.8mA

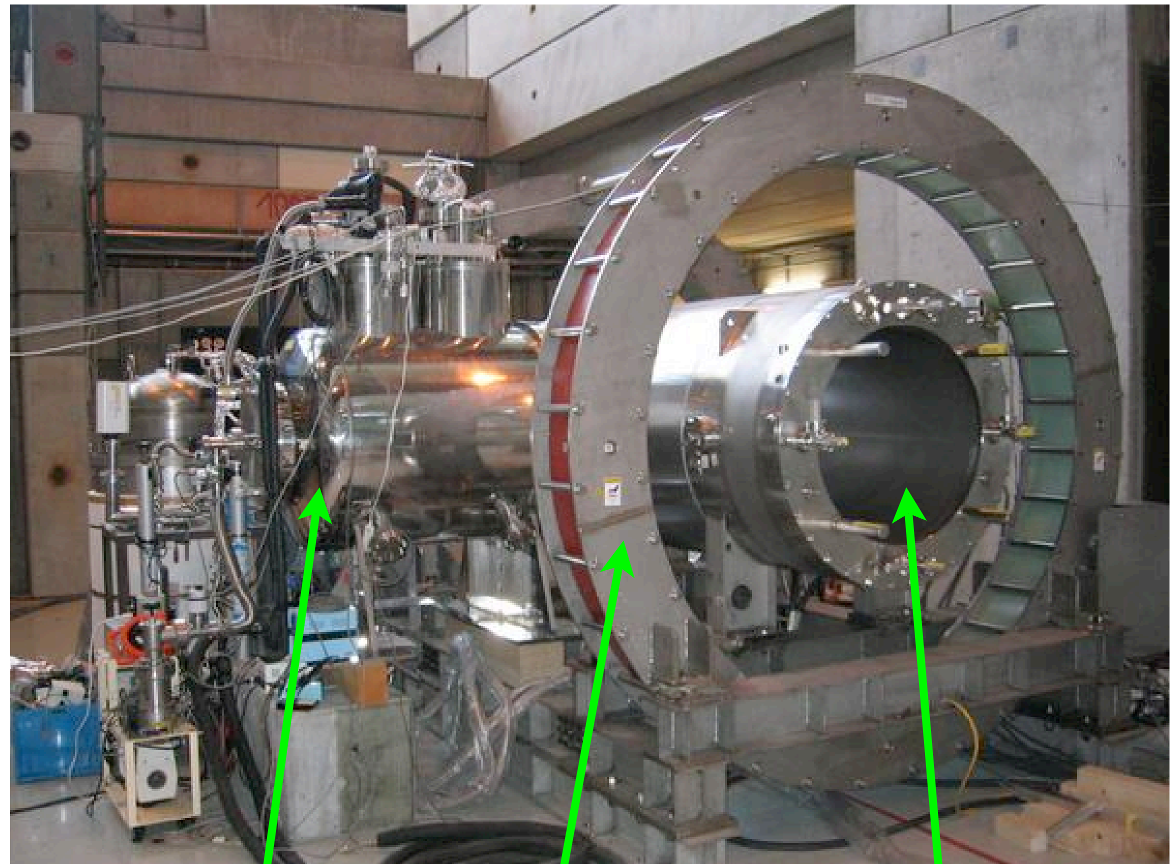
The COBRA Spectrometer



specially graded B field

low B field at LXe detector

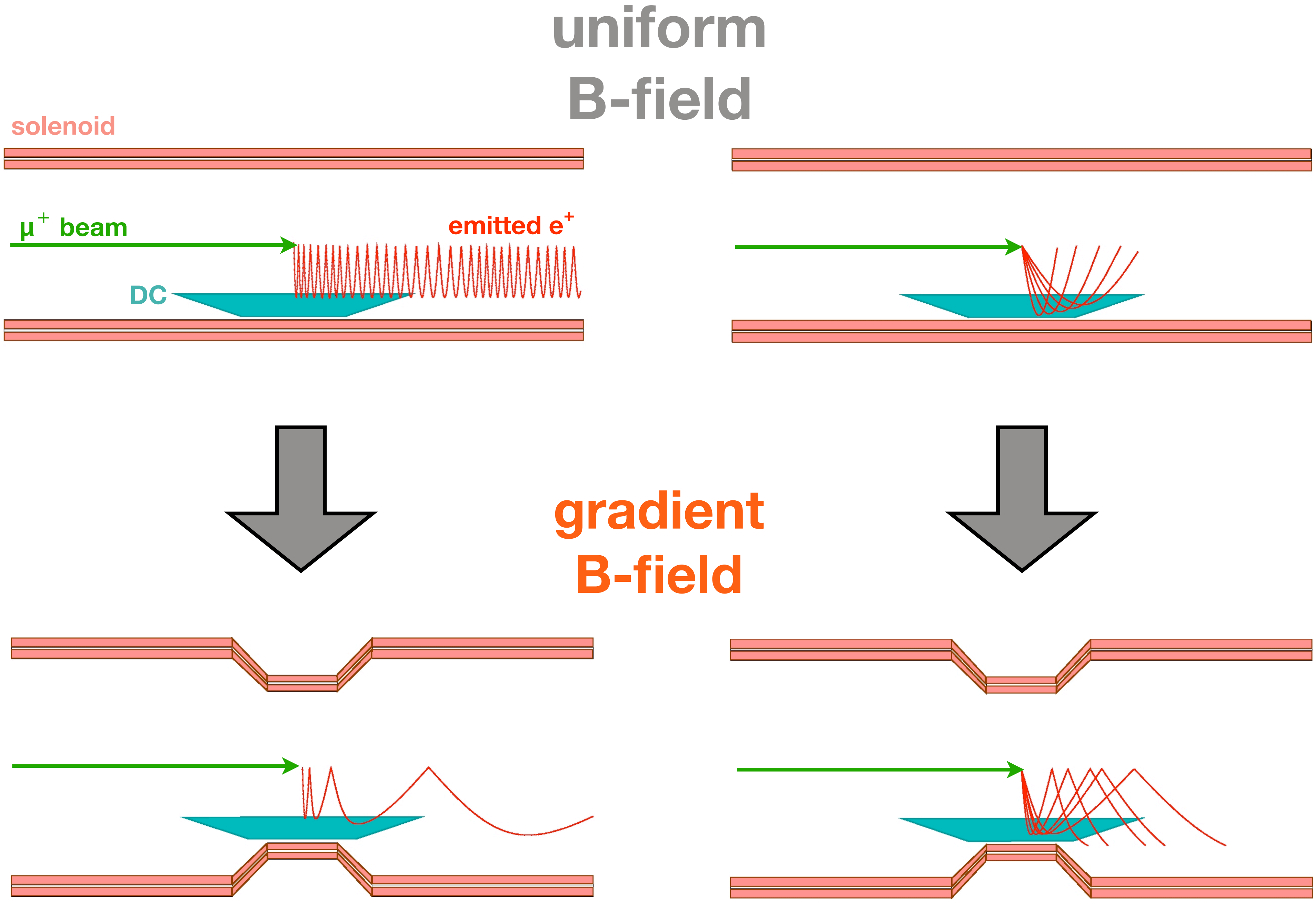




compensation coils

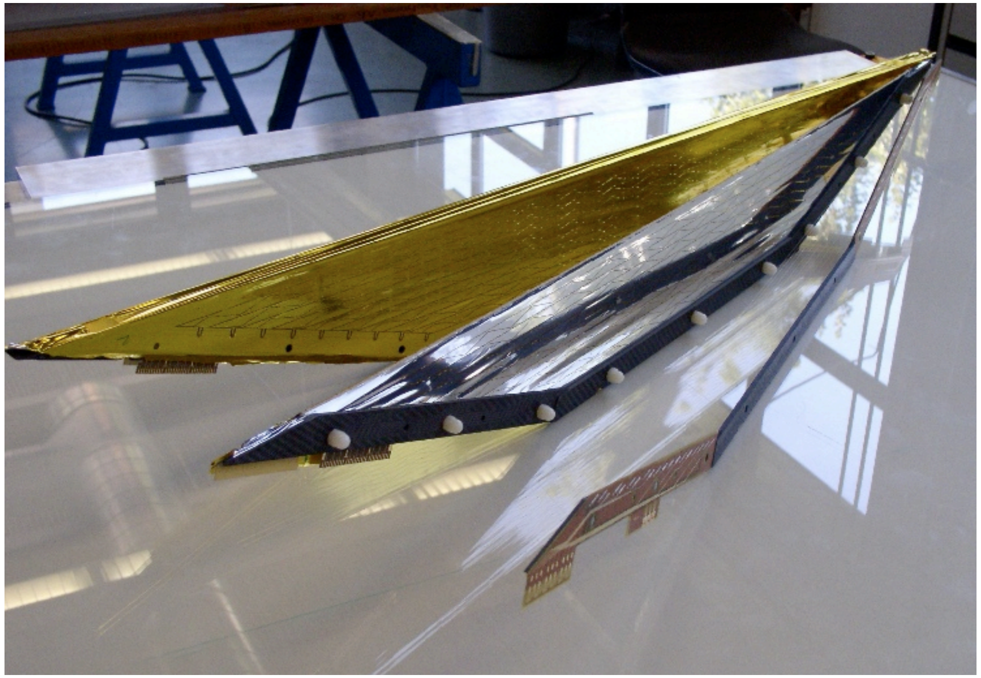
LXe detector prototype

COBRA magnet



Low energy positrons quickly swept out

Constant bending radius independent of emission angles



Drift Chambers for Positrons

very low material to avoid multiple scattering and positron annihilation in flight

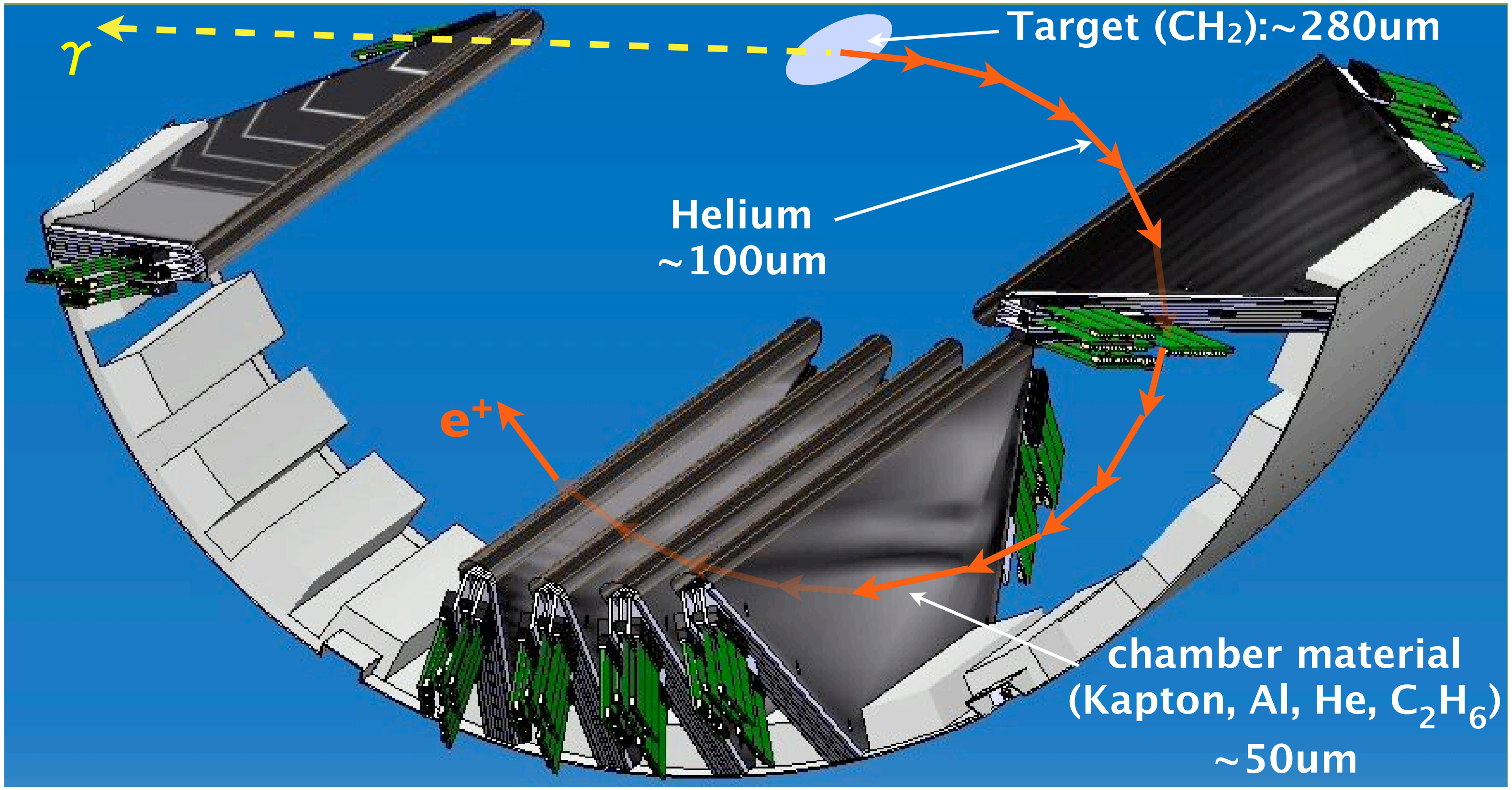
special vernier pads for z measurement

mom resolution
0.7-0.9%

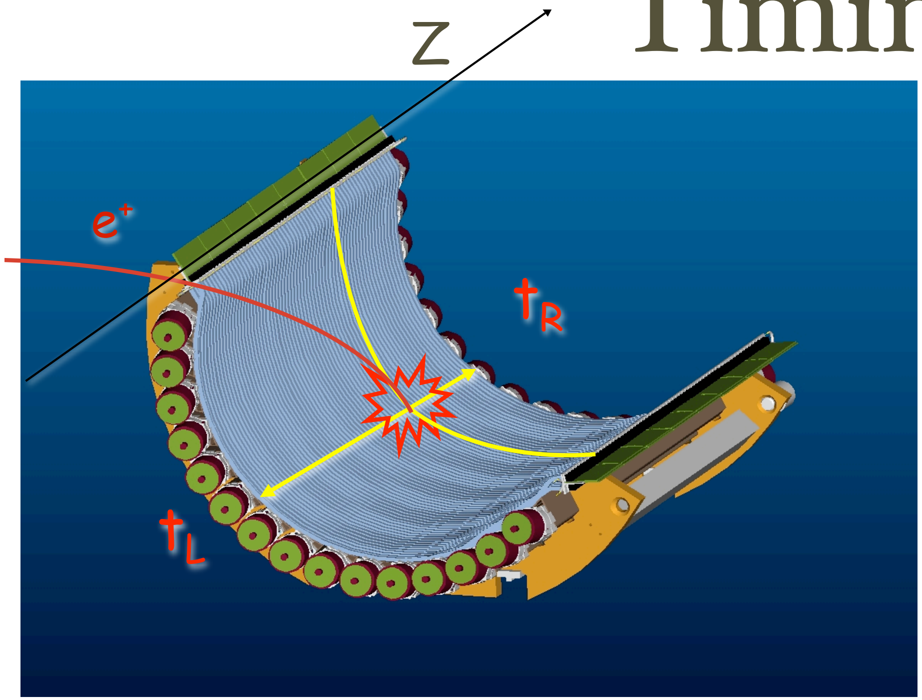
angle
9-12mrad

vertex
2.1-2.5mm

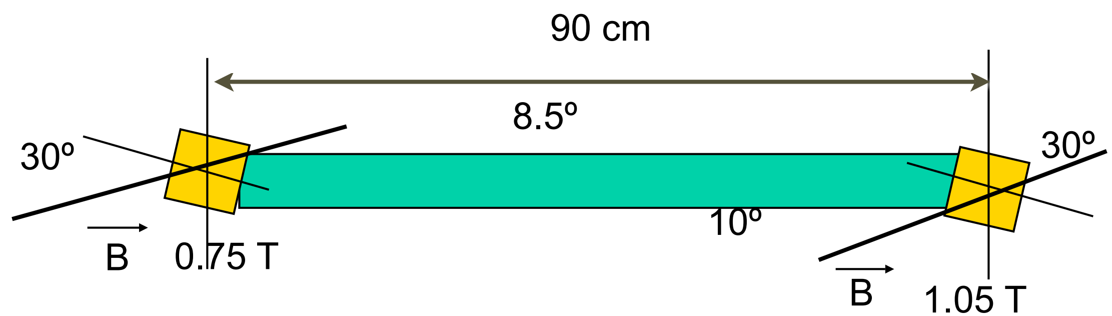
FWHM

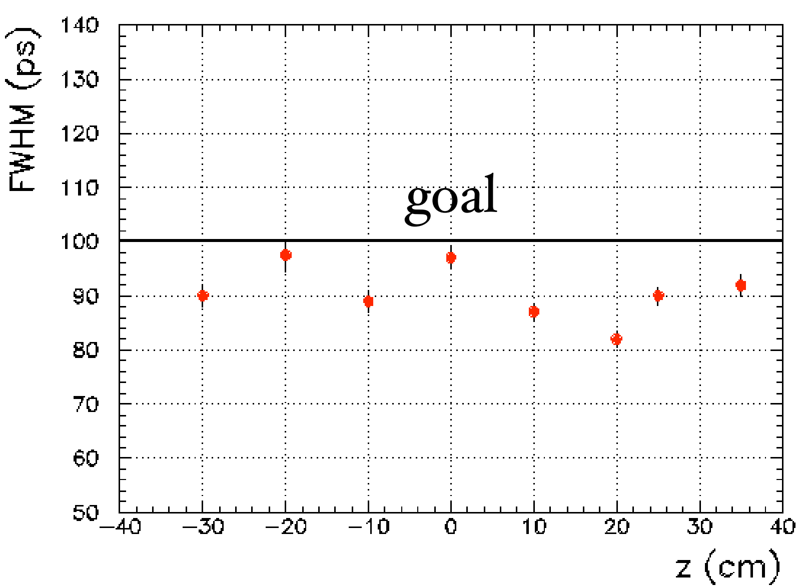


Timing Counter



- Two layers of scintillators:
  Outer layer, read out by PMTs: timing measurement
  Inner layer, read out with APDs at 90°: z-trigger
- Obtained goal σ_{time}~ 40 psec (100 ps FWHM)





Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	4.2 x 13 x 400	BC412	R1828	300	210	240
R. Stroynowski	2 x 3 x 300	SCSN38	XP2020	180	180	420
Belle	4 x 6 x 255	BC408	R6680	250	90	143
MEG	**4 x 4 x 90**	**BC404**	**R5924**	**270**	**38**	

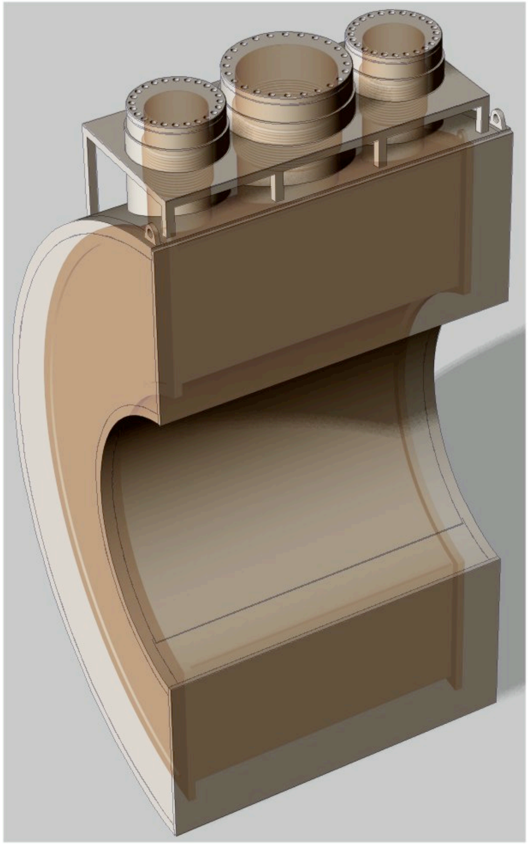
Best existing TC

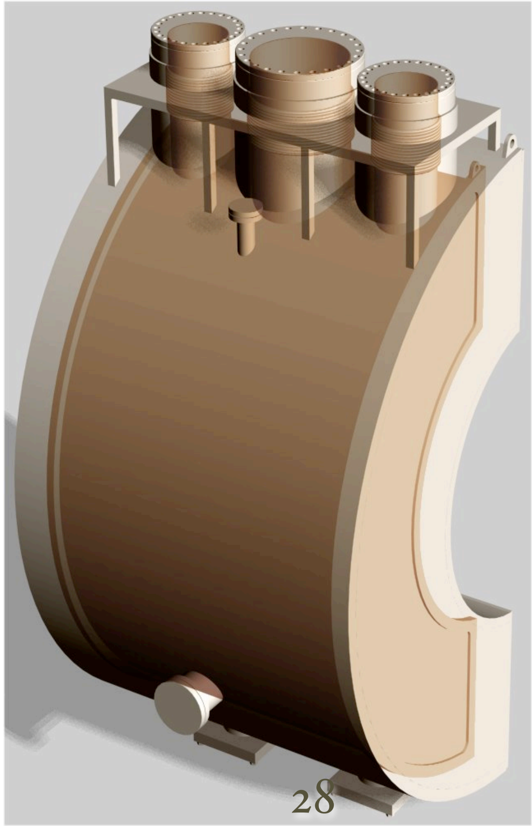
assembly test of scintilator bars

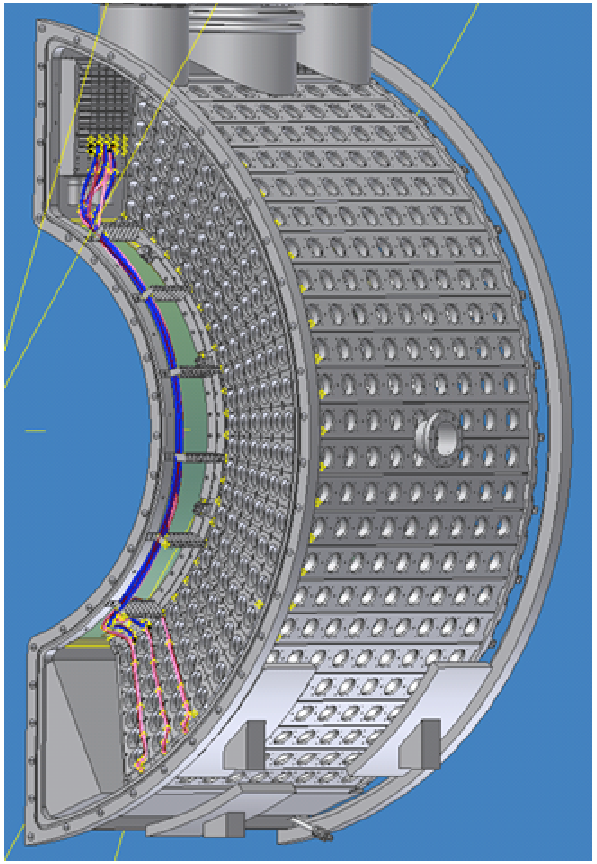
z-measuring fibers

LXe Gamma Ray Detector

LXe Scintillation: High Light Yield, Fast Signal
Measures Energy, Time and Position of Gamma Rays
3 ton LXe with ~850 PMTs
waveform digitizing to reject pile-up

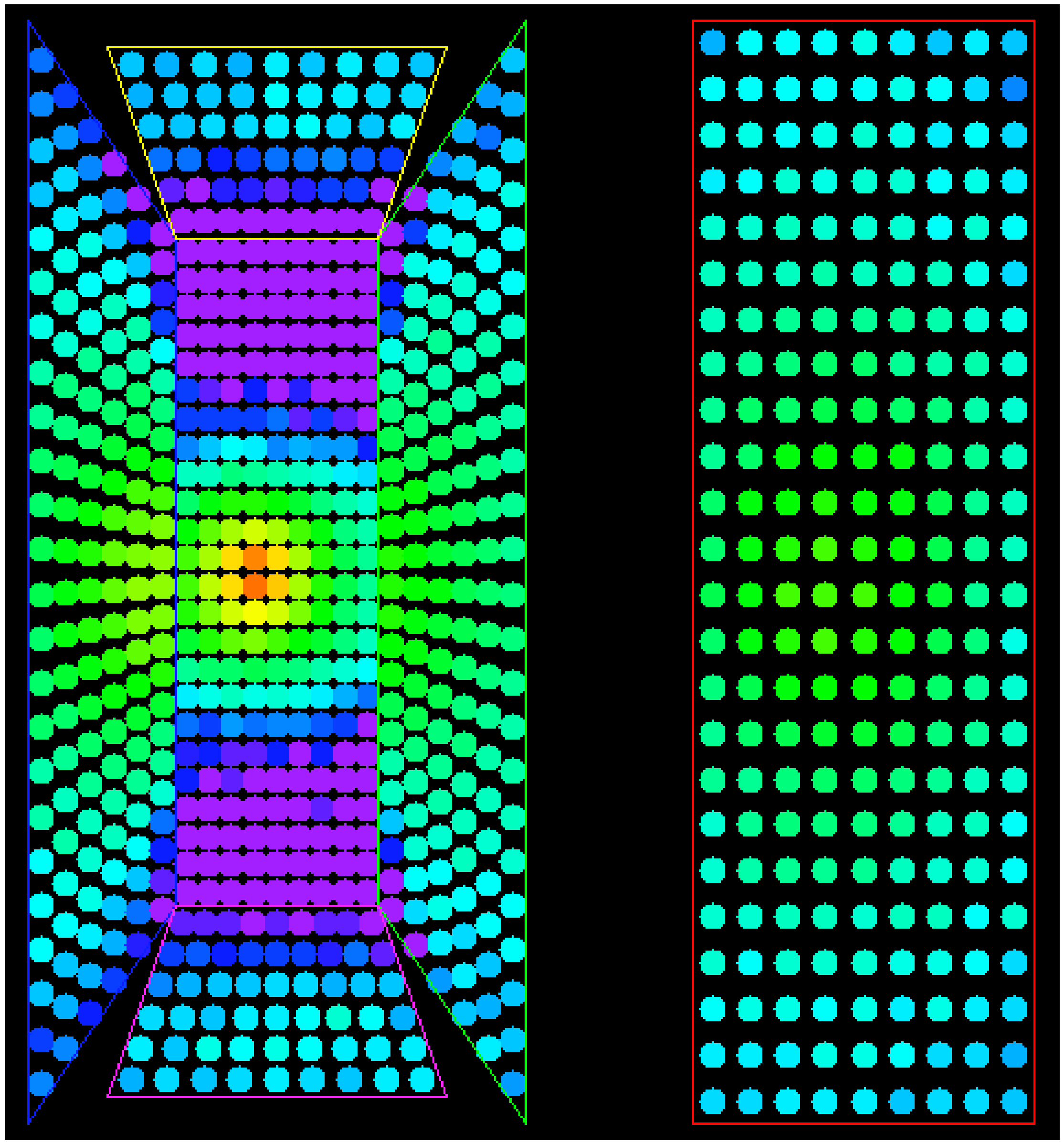






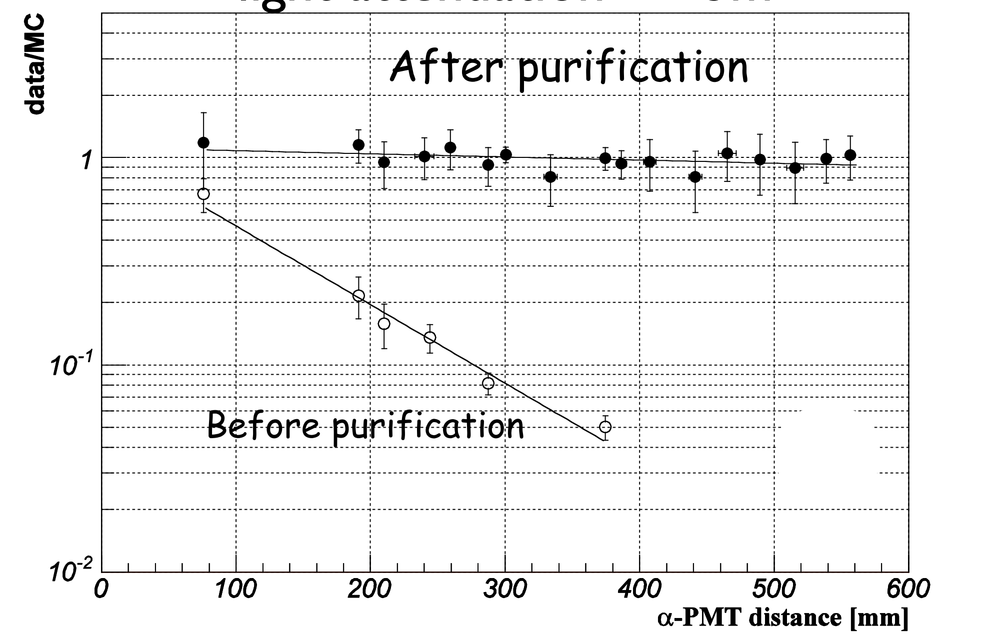
low temperature 165K, VUV light

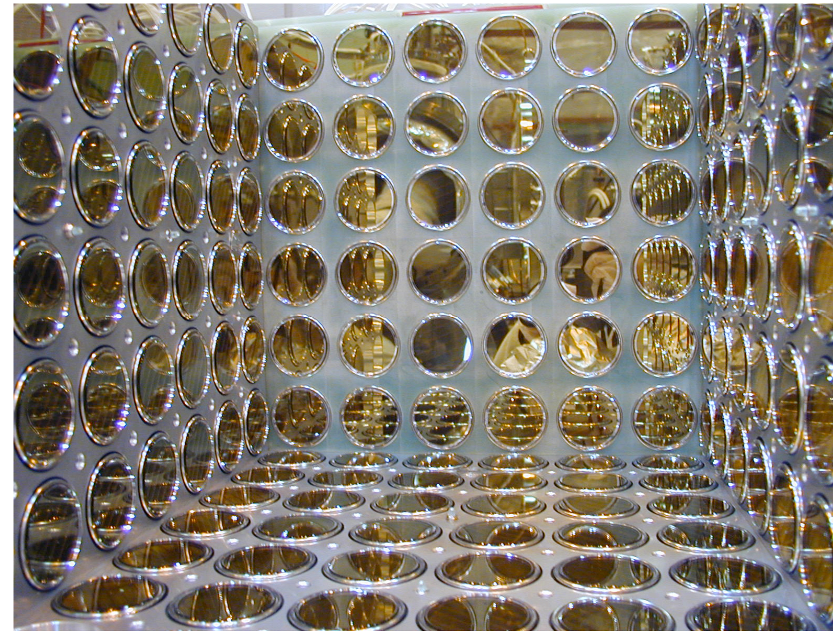
A Simulated Event



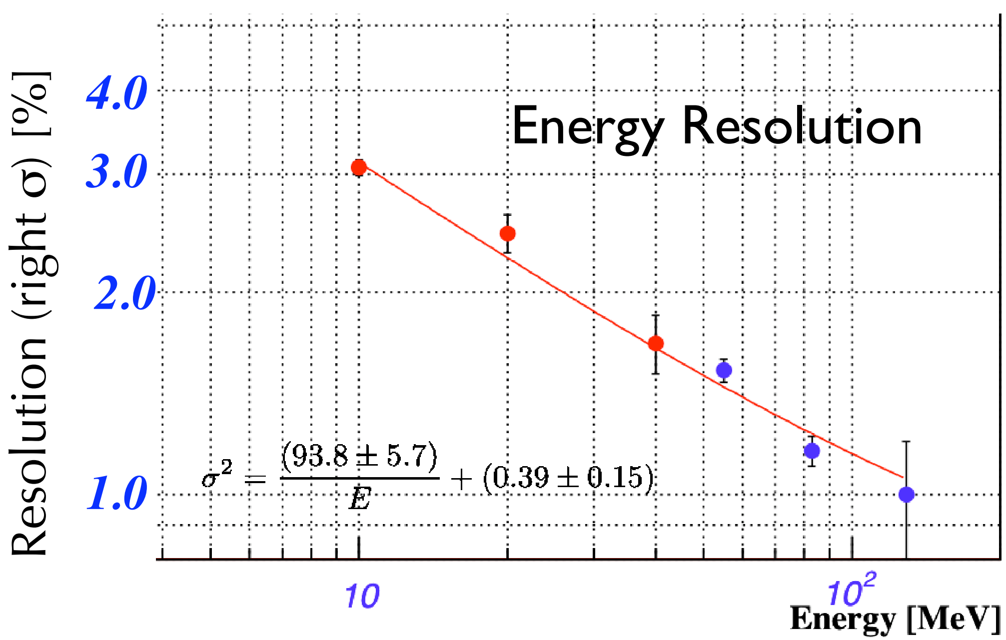
Detector Performance Verified

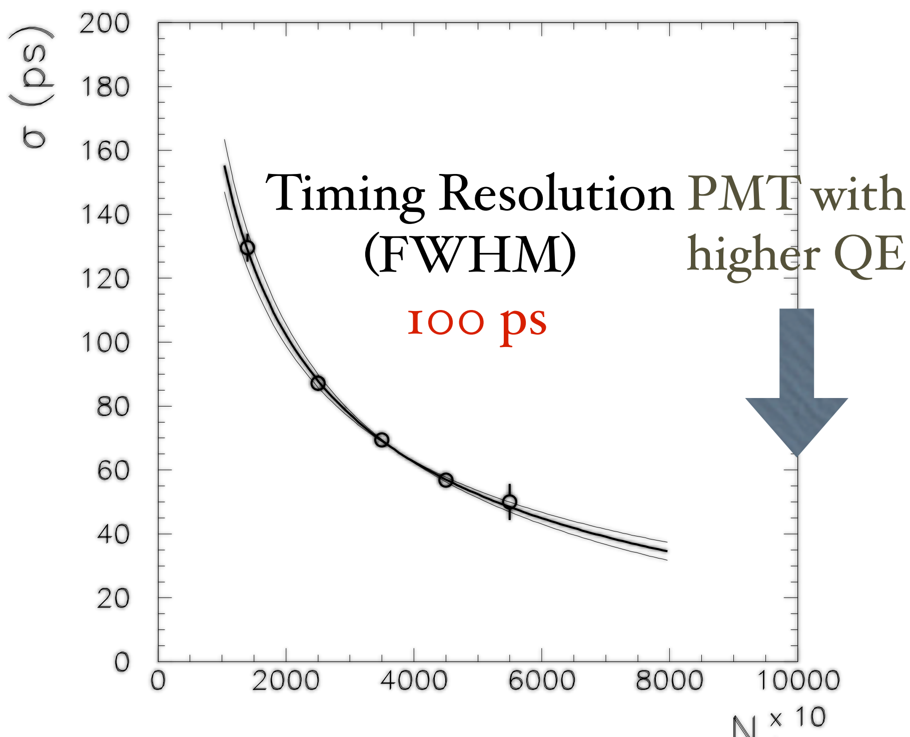
light attenuation > ~3m





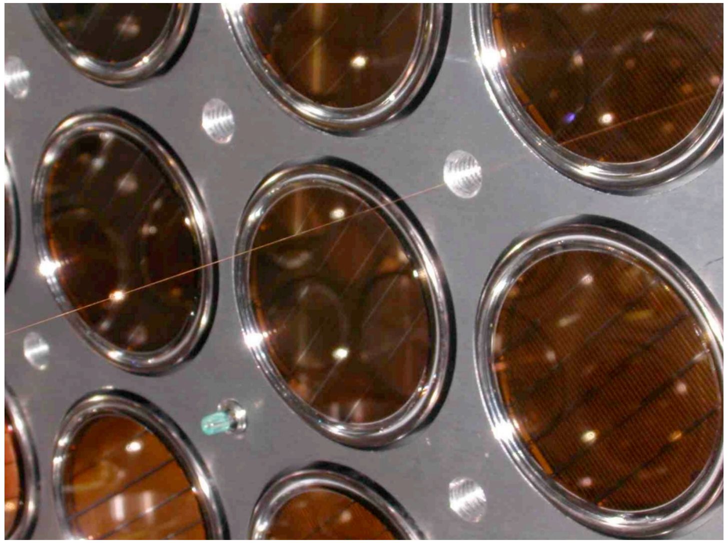
100 liter Prototype Detector

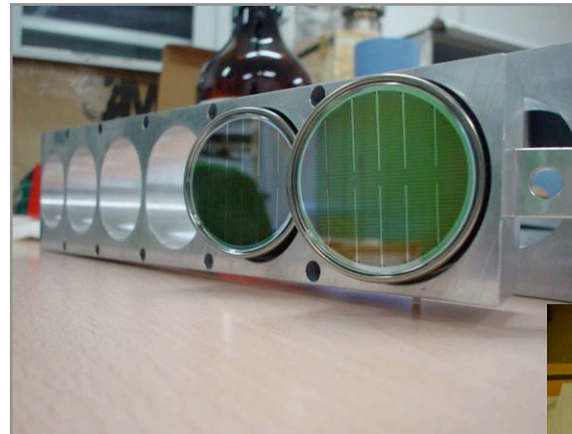


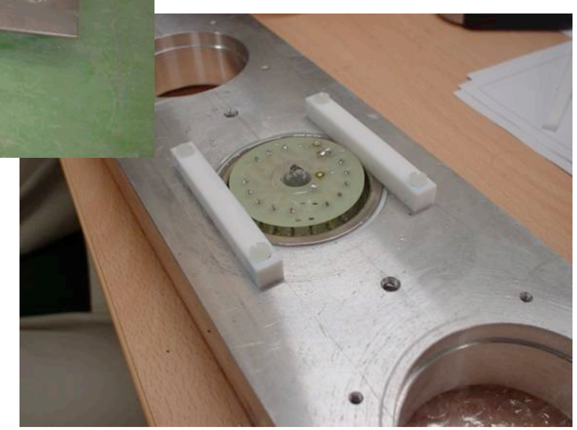


Calibration of LXe Detector

- alpha Sources (on wires and wall)
- Proton accelerator $^{7}\mathrm{Li}(p, \gamma_{17.6})^{8}\mathrm{Be}$ design under way
- Neutron generator $^{58}\mathrm{Ni}(n, \gamma_{9})^{59}\mathrm{Ni}$
- Charge exchange reaction (Panofsky) $\pi^{-} p \rightarrow \pi^{0} n$

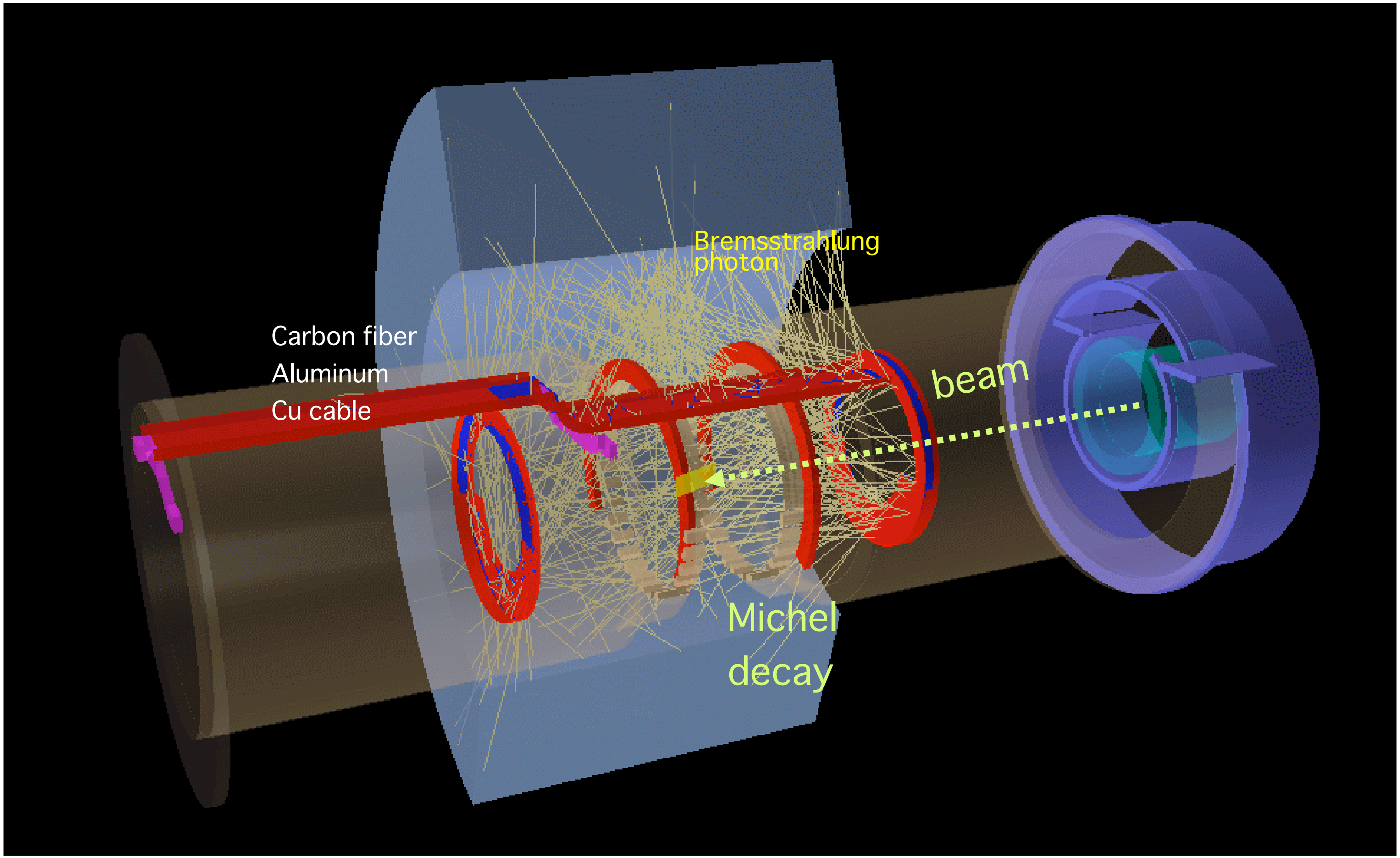






Now Under Construction

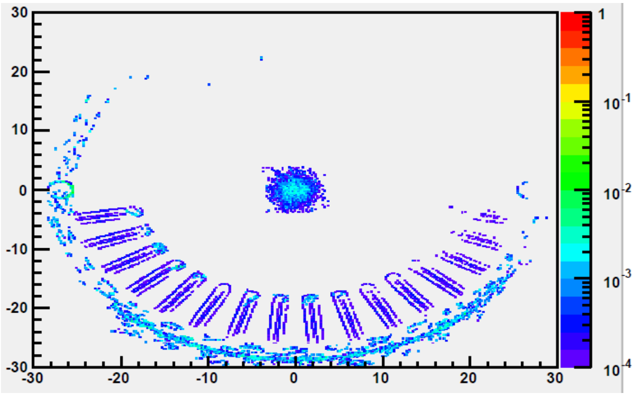
Detailed background studies are underway

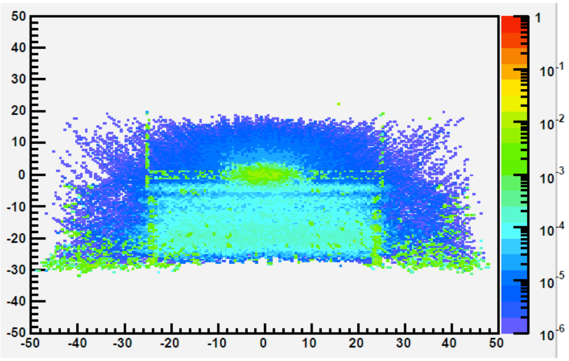


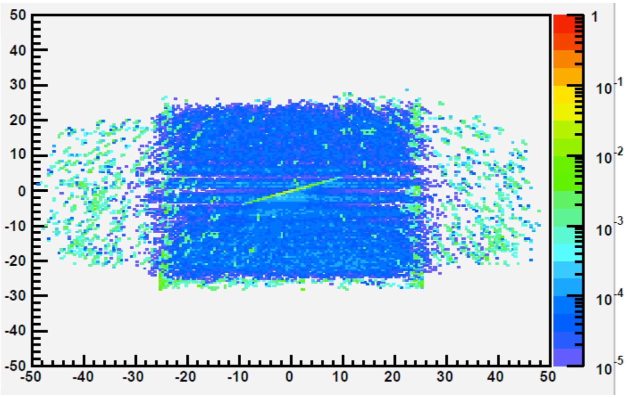
background gamma rays from the drift chamber cable ducts

Study of sources of gamma rays by e^+ annihilation in flight

Xe events
Egam>45MeV



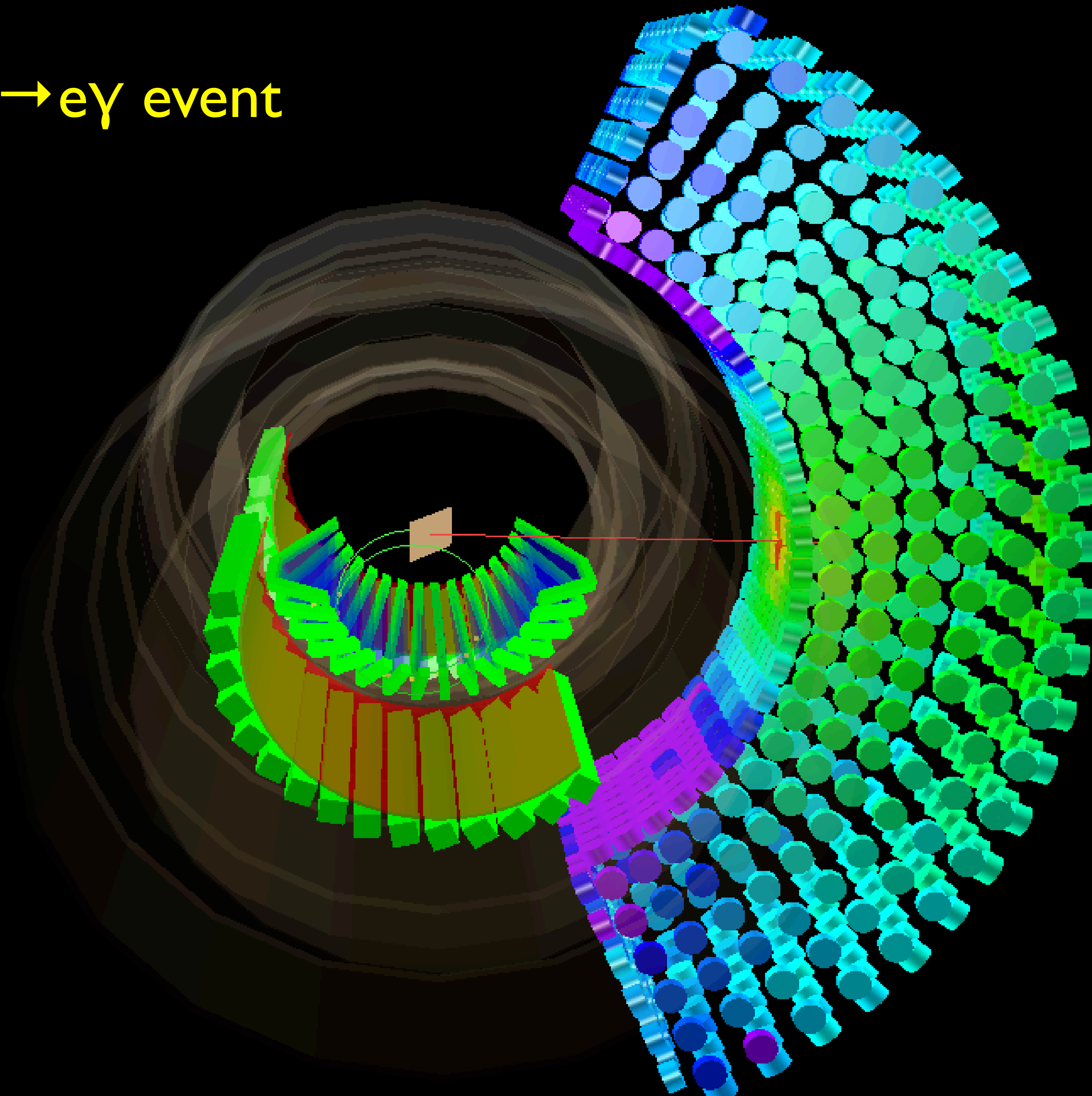


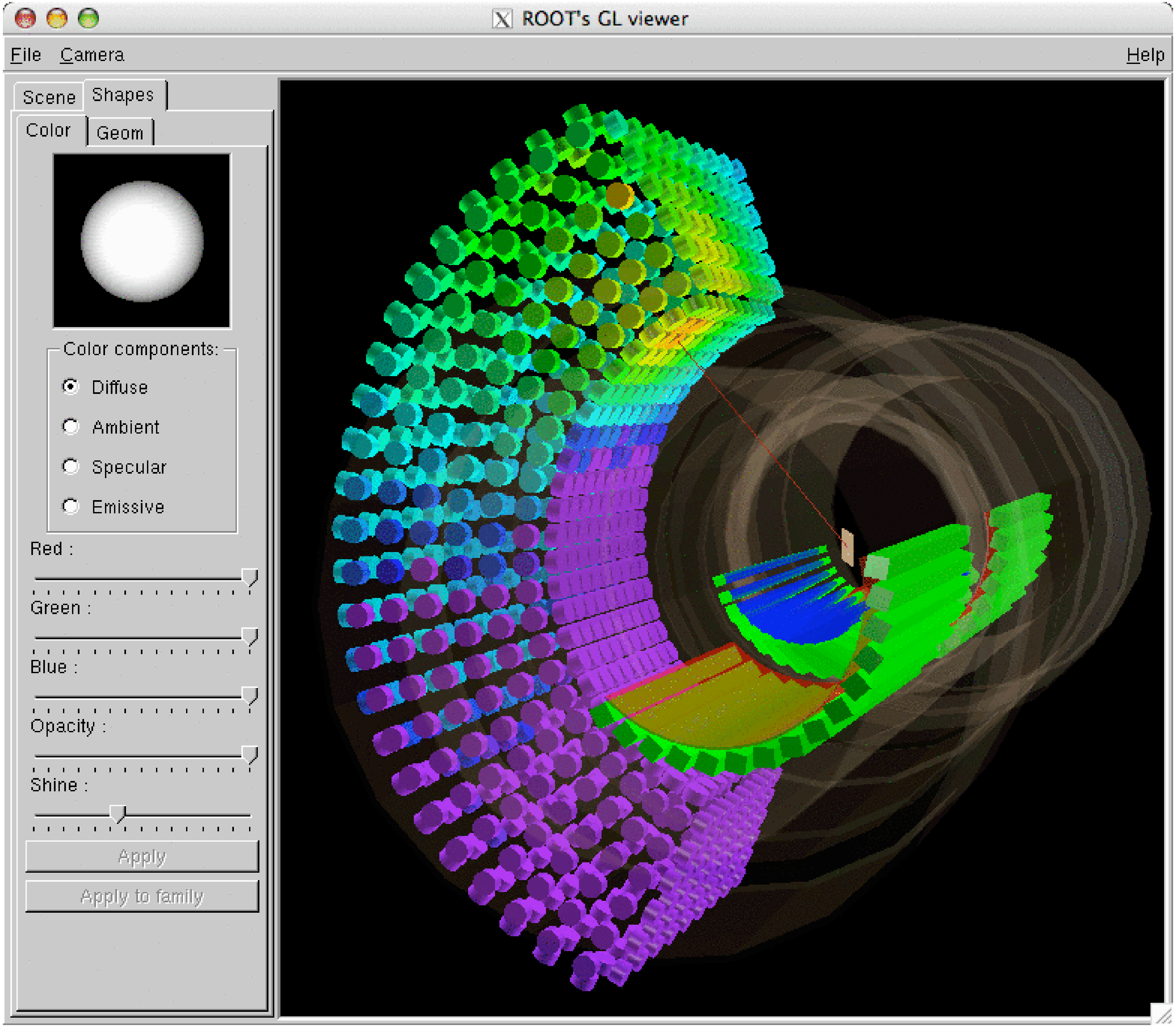


MEG Prospects

- Detectors are presently under construction and will be ready later this year (2006).
- Data taking takes ~2 years with muon beam of (1-3) x 10^{7} /sec to reach ~1 x 10^{-13} sensitivity (90% CL) with ~no background.

a $\mu \rightarrow e\gamma$ event





ROOT's GL viewer
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Shapes
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Geom
Color components:
Diffuse
Ambient
Specular
Emissive
Red :
Green :
Blue :
Opacity :
Shine :
Apply
Apply to family

Conclusion

- LFV is a clean & clear signal of new physics
  -- TeV physics & beyond (GUT, seesaw)
- The B Factories have greatly improved the τ LFV limits but start to suffer background events.
- The MEG experiment is expected to start running toward the end of this year. Stay tuned.