MEG COMET DeeMe

2nd workshop on muon g-2 & EDM in the LHC Era, LPNHE Paris, 25.May.2012

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Introduction

- **Muon Physics** in the LHC Era
  - **Keyword** : "**COMPLEMENTARY**"

LHC ⟷ Muon Physics

COMPLEMENTARY !

Within the "Muon Physics", all experiments should be COMPLEMENTARY, too!!

Introduction

Muon Physics

Past

- Michel Parameter / Lifetime *etc.*
  - $g_{S,V,T,A,P}$, G_F determined
  - > SM has been established

Present & Future

- g-2 / EDM / LFV
  - so called **Muon Trio**
  - > Search for New Physics !!

Muon Exp. in the LHC Era

Muon Trio → g-2

Muon Trio → EDM

Muon Trio → LFV

MEG	DeeMe	COMET
(running)	(planning)	(planning)

Physics Motivation

Search for New Physics

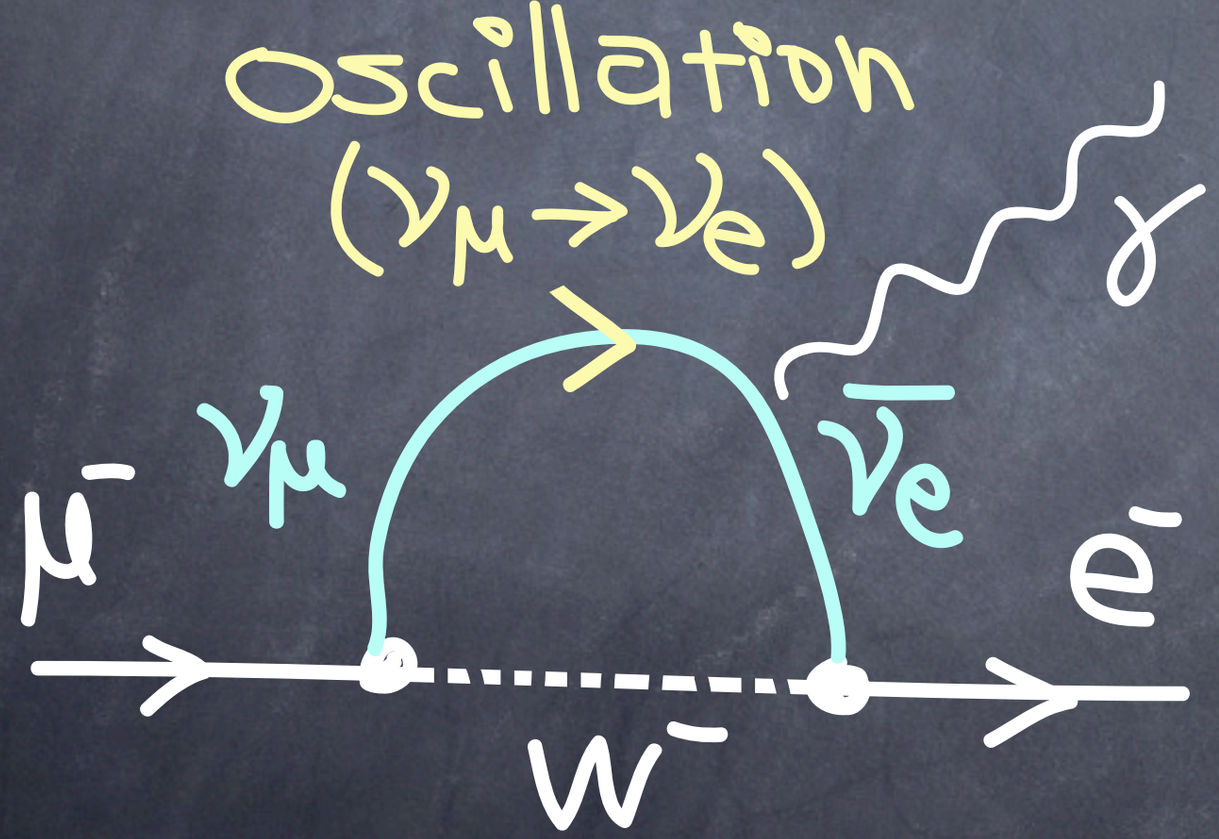
- Probes to Search for New Physics by using **Muon**
  - **Muon** "g-2"
  - **Muon** "EDM"
  - **Muon** "LFV"

  } muon trio

- **Significantly Important** to Search for New Physics
- And also, **Closely Related** one another in some cases of New Physics (*eg*. SUSY, Ext-D., Little H, lepto-quark, *etc*.)
- Physics Motivation of **Muon Trio** should be robust for the **Era of LHC** (even after the LHC !!)

Lepton Flavour Violation (SM)

- *eg.*; "$\mu \to e\gamma$" in SM



- Possible by the minimally extended SM to account for **neutrino oscillation**.
- Strongly Suppressed by "***leptonic***" GIM mechanism.
- Calculated Branching Ratio:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\Sigma_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2$$

$$<\sim 10^{-50}!!$$

- **No Sizable Contribution**

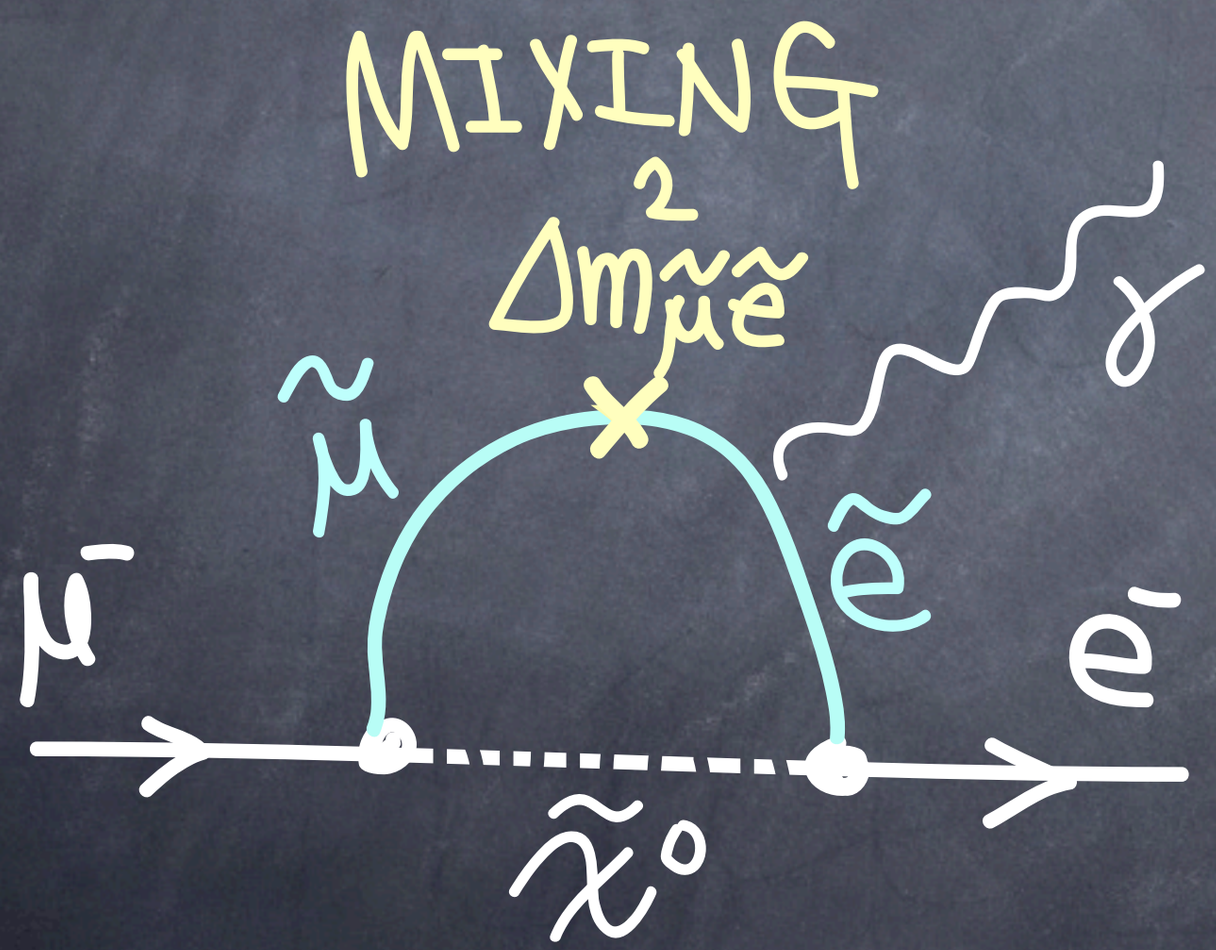
BSM : eg. SUSY Scenario

- ***Scalar-lepton*** Mass Matrix

$$\left\{ \begin{array}{ccc} m^2_{\tilde{e}\tilde{e}}, & \Delta m^2_{\tilde{e}\tilde{\mu}}, & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}}, & m^2_{\tilde{\mu}\tilde{\mu}}, & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}}, & \Delta m^2_{\tilde{\tau}\tilde{\mu}}, & m^2_{\tilde{\tau}\tilde{\tau}} \end{array} \right\}$$

Lepton Flavour Violation (BSM)

- *eg.*; "$\mu \to e\gamma$" in SUSY



- Enhanced by any new physics models beyond SM
- No Strong Suppression
- Calculated Branching Ratio:

$$\mathcal{B}(\mu \to e\gamma) = \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$

$$= 10^{-14} \sim 10^{-11}$$

- **Sizable Contribution !!!**

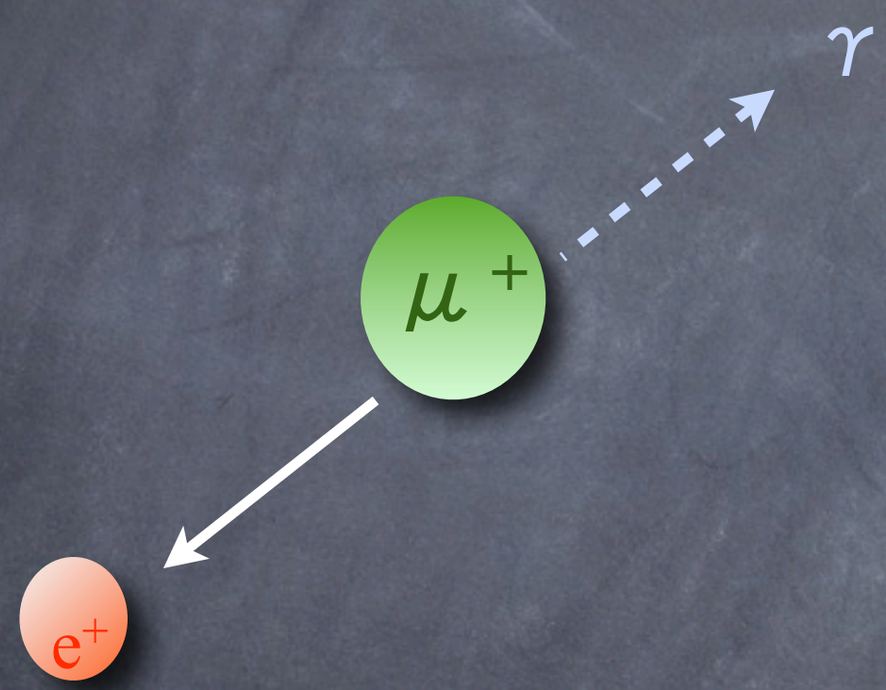
Muon LFV is so Attractive

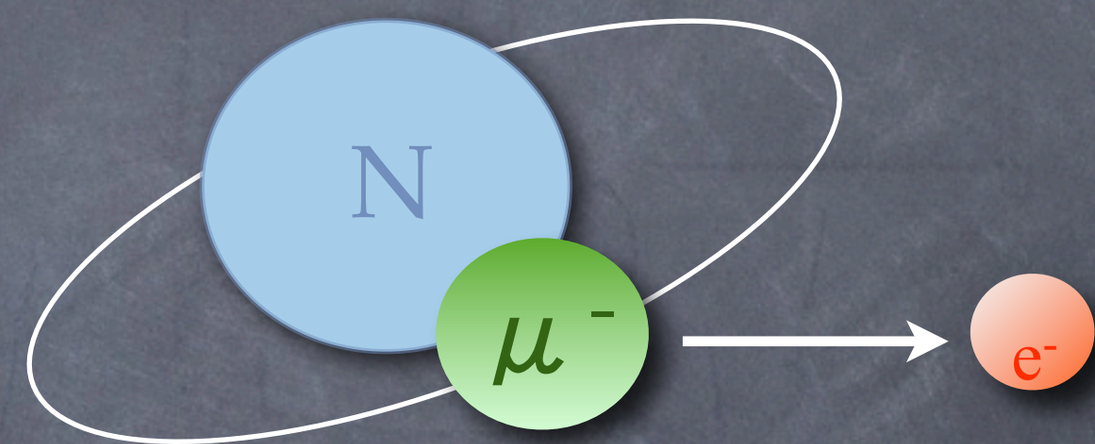
- Only charged LFV has never been observed while,
  - Neutrino Oscillation is possible by "SM + ν mass"
  - Quark Mixing is generally contaminated by SM.

Charged LFV "IS" New Physics

- Experimental Upper Limit is already sensitive to predicted region
- Search for Muon Rare Decay is the most suitable.
  - Once we have a powerful proton driver, muon can be generated very easily.

Two Muon LFV processes

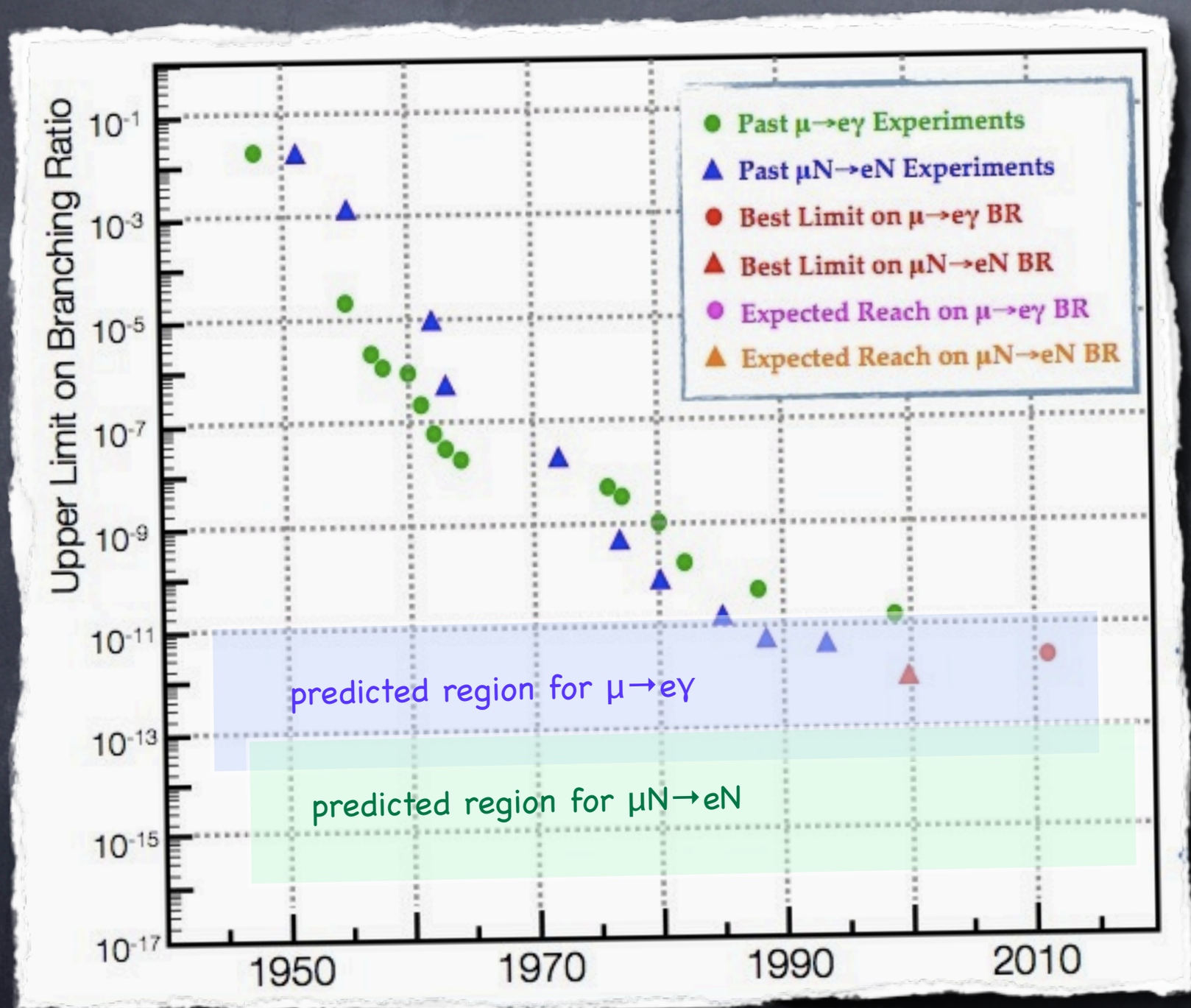




$\mu \to e\gamma$

$\mu N \to eN$

History of Muon LFV Search

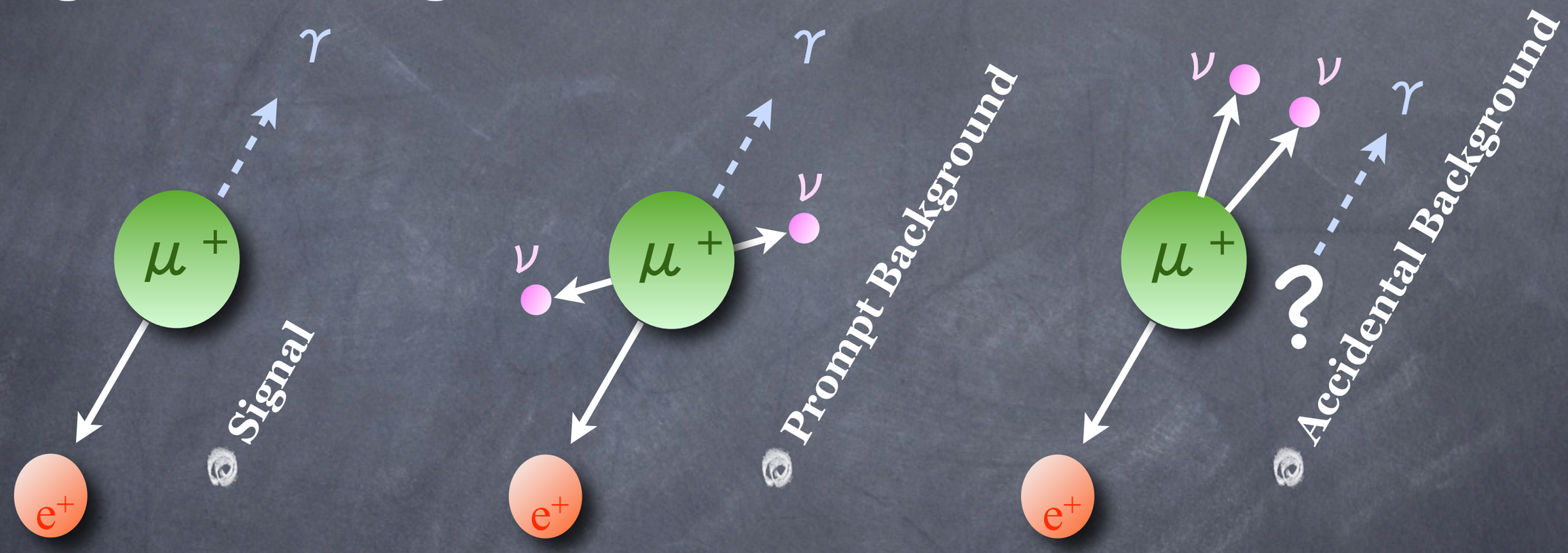


- Long Tradition on the $\mu \to e\gamma$ / $\mu N \to eN$ Search Experiment
- Started right after the muon discovery
- $\mu \to e\gamma$ has already entered the predicted region !!
- $\mu N \to eN$ is standing at just in front of the predicted region !!
- **NOW VERY VERY ATTRACTIVE !!!!!**

$\mu \rightarrow e\gamma$

Search for "$\mu \to e\gamma$"

- Signal and Backgrounds



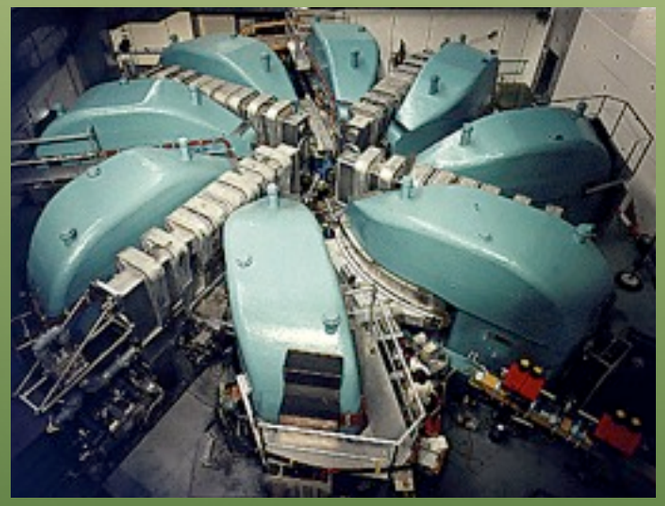
- Clear 2-Body Decay; ($E_e = E_\gamma = 52.8$MeV, $\theta_{e\gamma} = 180°$, Time Coincidence)
- Experimental Sensitivity is limited by Accidental Overlaps

Use DC beam
(No Pulsed Beam !!)

Good Resolution for E, x and t
Operational at Very High Rate

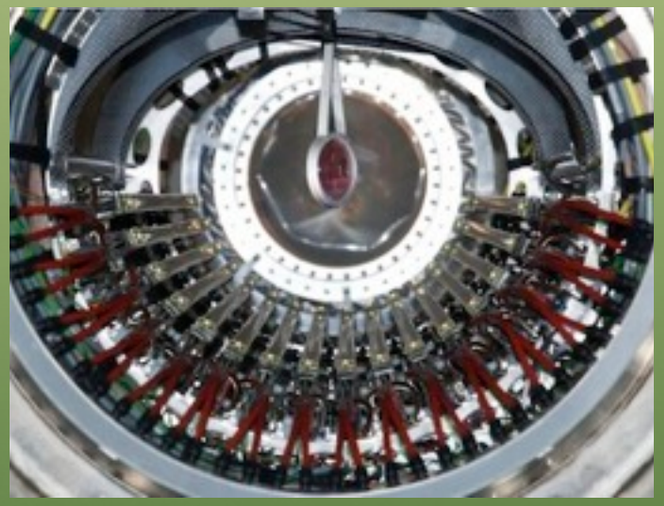
MEG Experiment

- Experimental Sensitivity is limited by Accidental Overlaps
  - Use DC beam
  - Good Resolution for E, x and t, Operational at Very High Rate



World Most Intense
DC Muon Beam at PSI
10^8 muon/sec

Liquid Xenon
Scintillation Detector
(gamma)

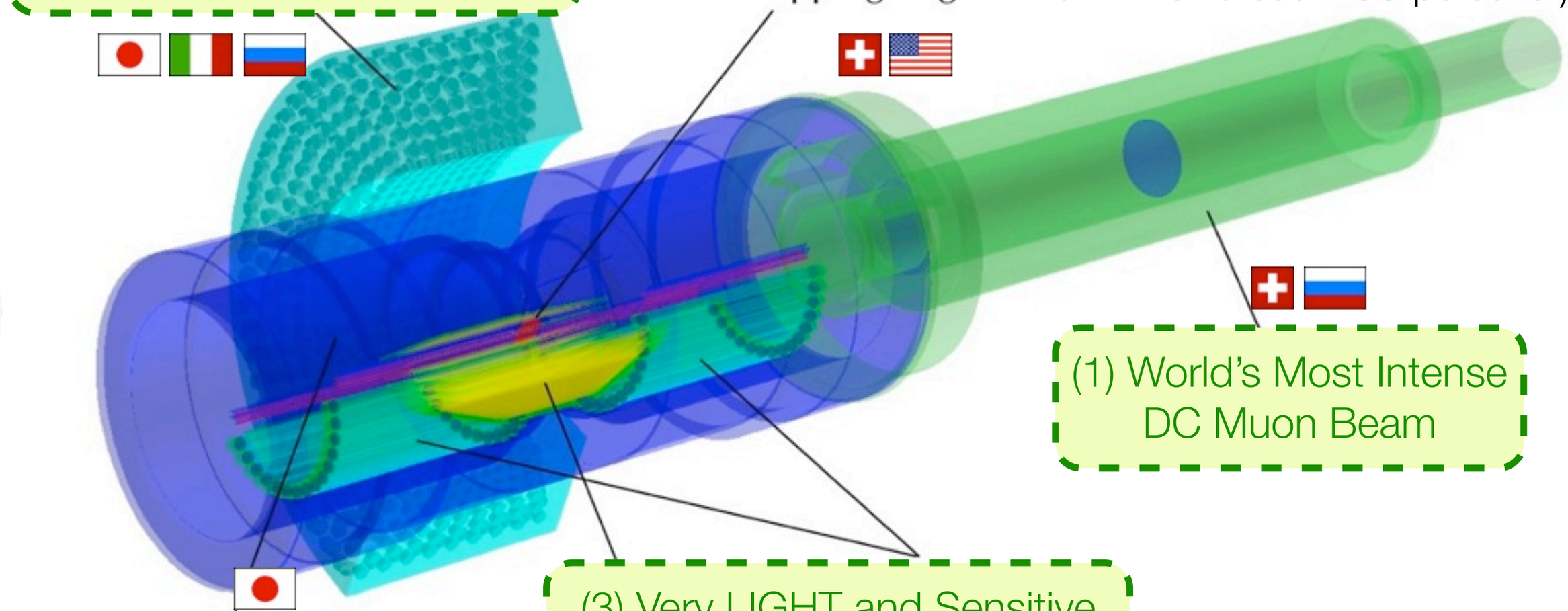


COBRA Spectrometer
(positron)

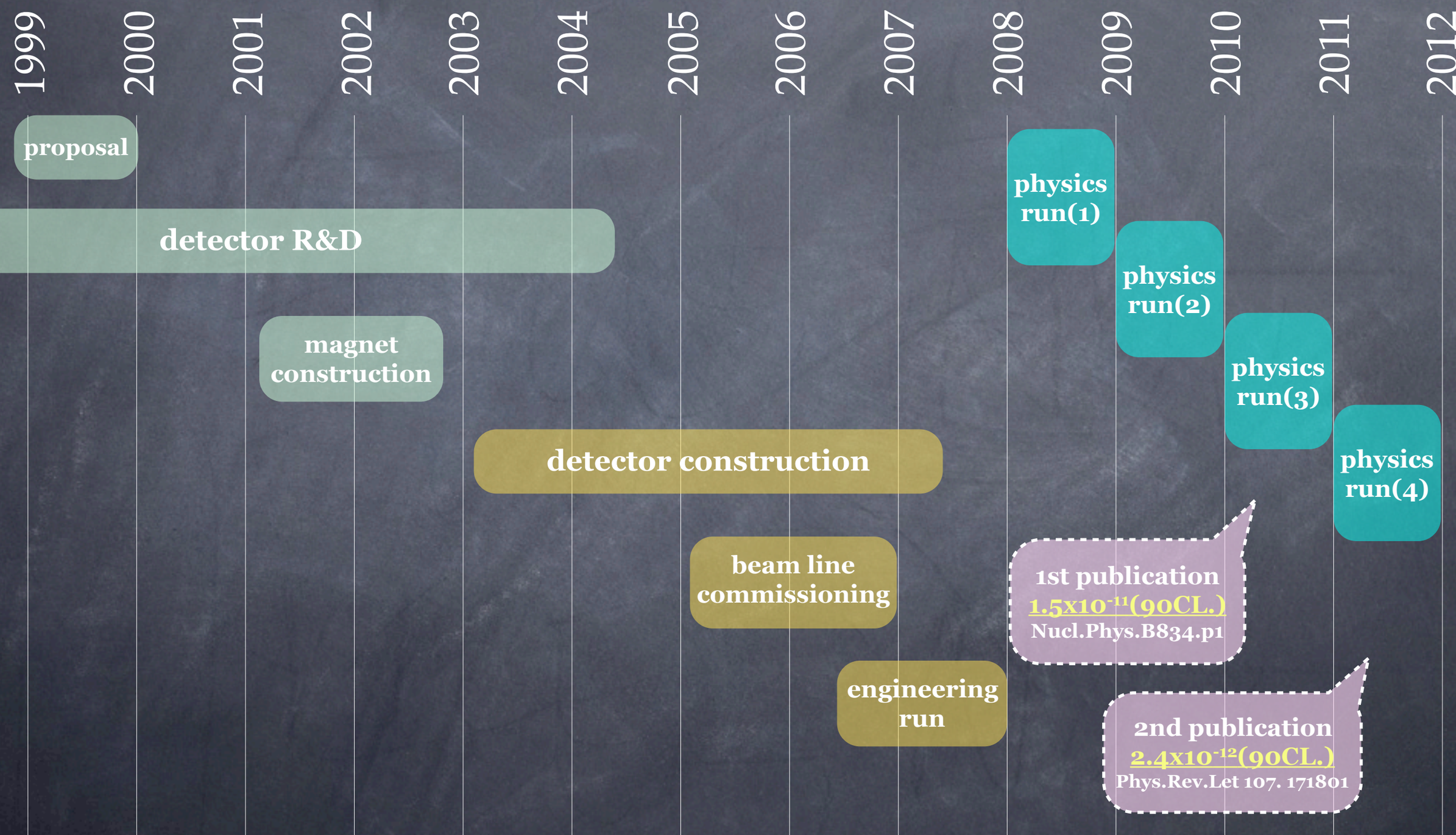
MEG - Detector Apparatus

The MEG Collaboration

(5 countries /12 institutes / ~60 persons)



MEG - TimeLine

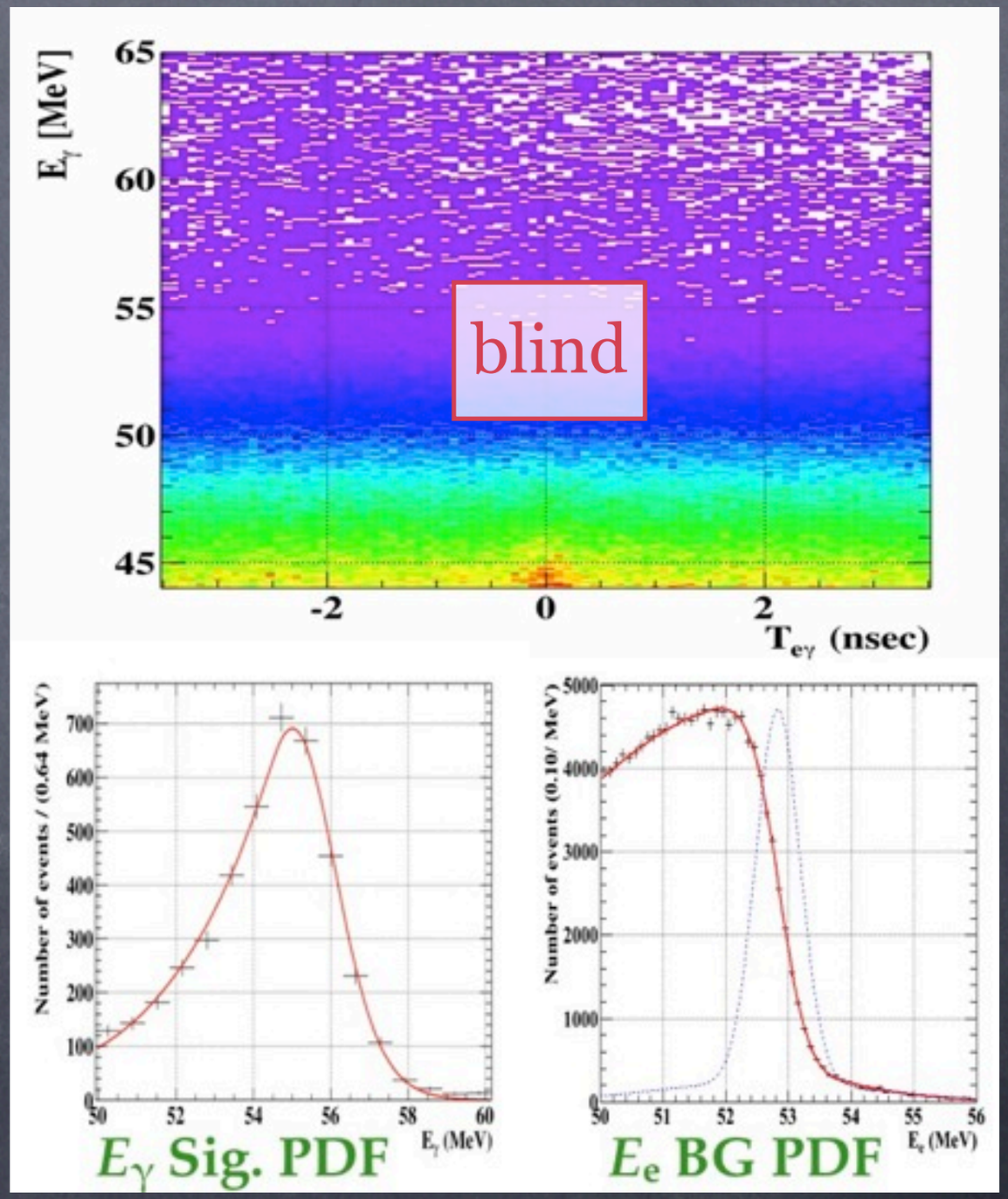


MEG - Analysis

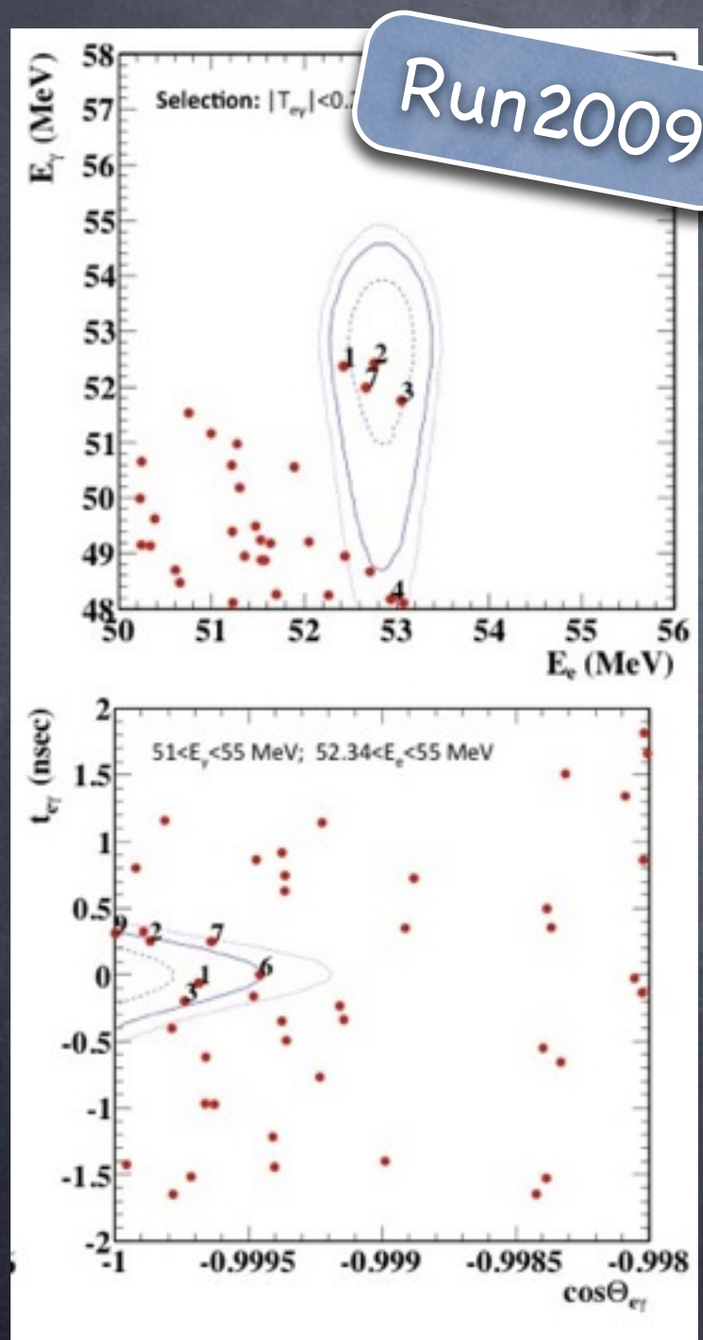
- **Blind Analysis**
  - Signal region blinded. Detector Calibration and Performance evaluation, BG estimation are done in sideband data.
- **Muon # Normalization**
  - Dedicated Trigger to count the # of Michel e+ is mixed within Physics Trig.
- **Likelihood Fitting**

$$\mathcal{L}(N_{sig}, N_{RD}, N_{BG}) = \frac{N^{N_{obs}} e^{-N}}{N_{obs}} \prod_{i=1}^{N_{obs}} \left[\frac{N_{sig}}{N} S + \frac{N_{RD}}{N} R + \frac{N_{BG}}{N} B \right]$$

  - Fit Parameter : N_{sig}, N_{RD}, N_{BG} (N= N_{sig}+ N_{RD} + N_{BG})
  - Five Observables : E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$, and $\theta_{e\gamma}$
  - PDF (Signal/BG both) are built by the data
  - Done for wide region (10σ) for Sig/BG simultaneously
  - N_{RD} and N_{BG} in sideband is good control sample
- **Three Independent Analysis Groups**



MEG - Latest Result



- **2009+2010 Combined Analysis:**
  - **Consistent with Null-Signal (90%CL.)**
  - **Best Limit is Updated**

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 2.4\times10^{-12}$$

  - **Factor 5 Stronger Restriction to the BSM**
  - **Further detailed plot, See backup slides**

- **Analysis on 2011 data is ongoing**
  - **Stepping into the world of *O*(-13) !**

MEG - World Best Limit

PRL 107, 171801 (2011) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2011

New Limit on the Lepton-Flavor-Violating Decay $\mu^+ \to e^+\gamma$

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(Received 31 July 2011; published 17 October 2011)

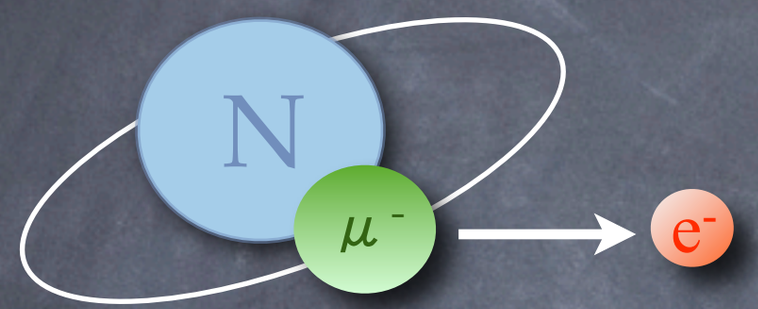
We present a new result based on an analysis of the data collected by the MEG detector at the Paul Scherrer Institut in 2009 and 2010, in search of the lepton-flavor-violating decay $\mu^+ \to e^+\gamma$. The likelihood analysis of the combined data sample, which corresponds to a total of 1.8×10^{14} muon decays, gives a 90% C.L. upper limit of 2.4×10^{-12} on the branching ratio of the $\mu^+ \to e^+\gamma$ decay, constituting the most stringent limit on the existence of this decay to date.

DOI: 10.1103/PhysRevLett.107.171801 PACS numbers: 13.35.Bv, 11.30.Hv, 12.10.Dm, 12.60.Jv

$\mu N \rightarrow eN$

Search for "μN→eN"

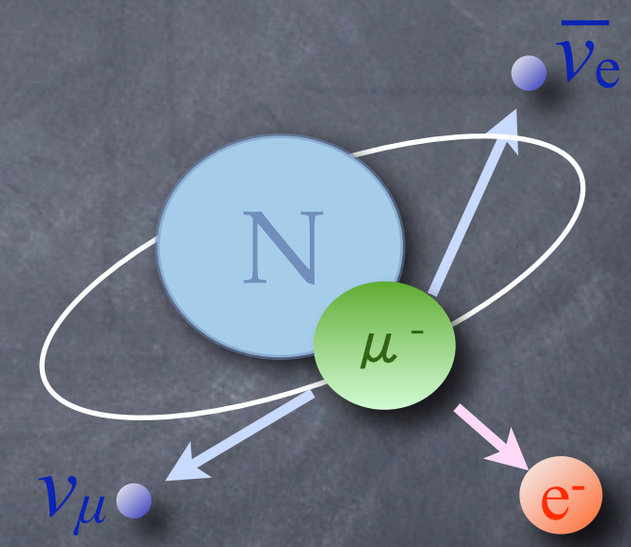
- **Signal**



- $E_e = m_\mu - B_\mu \sim$ 105MeV
- Coherent Process ($Z_{ini}=Z_{end}$)

Signal : Single Mono-Energetic Electron
Sensitivity : Limited by Beam Quality
- **Wait until Pion decays**
- **Pulsed Beam is the BEST**

- **Backgrounds**
  - **muon decay in orbit (DIO)**

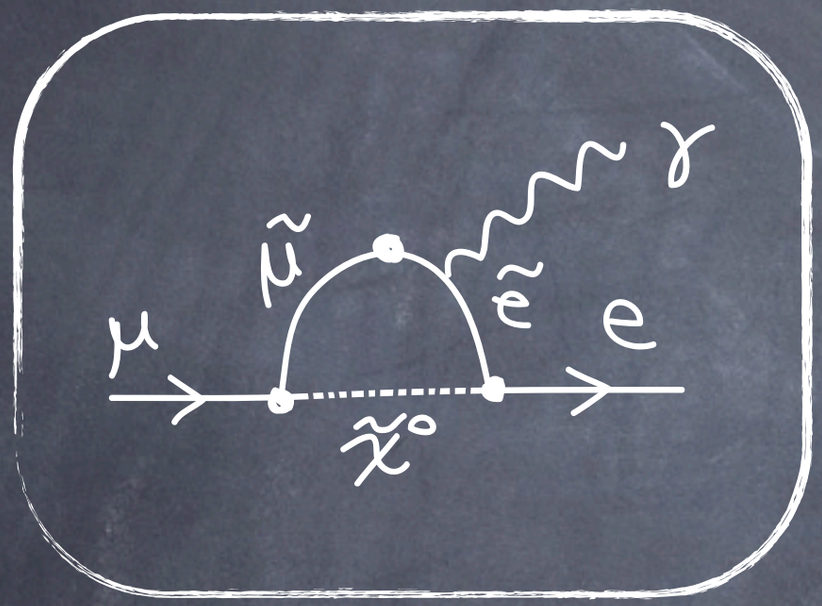


- **radiative muon capture**
- **radiative pion capture**
- **electrons from muon DiF**
- **cosmic rays**

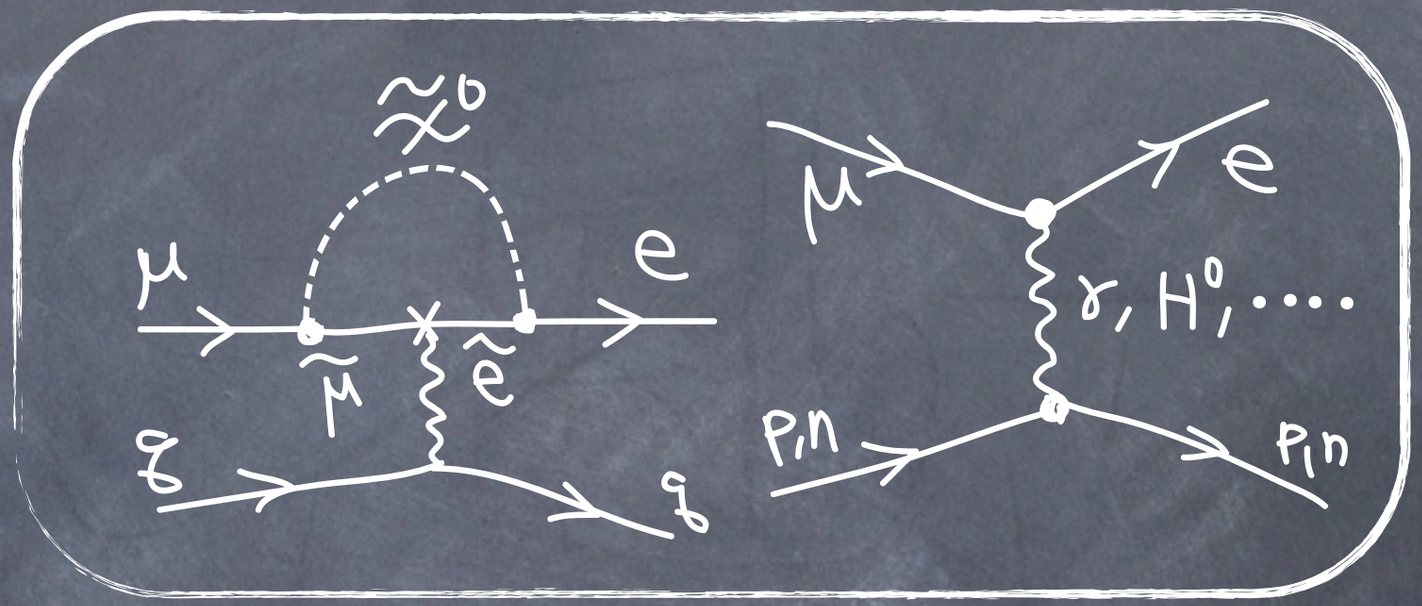
"$\mu \to e\gamma$" vs. "$\mu N \to eN$"

Physics Point of view

- **Sensitivity for "photonic" and "non-photonic" processes is different.**



vs.



	$\mu \to e\gamma$	$\mu N \to eN$
photonic (*eg*. SUSY-base models, *etc*.)	**YES** (on-shell)	**YES** (off-shell)
non-photonic (*eg*. Extra-D, Little-H, *etc*.)	**NO**	**YES !!**

- ***eg*. SUSY-based case, $\mathcal{B}(\mu \to e\gamma)/\mathcal{B}(\mu N \to eN) \sim O(100)$ (depends on N)**

"$\mu \to e\gamma$" vs. "$\mu N \to eN$"

Experimental Point of view

	$\mu \to e\gamma$	$\mu N \to eN$
Dominant B.G.	Accidental	Beam related
Challenge	Detector Performance	Beam Quality
Suitable Muon Source	DC Muon Beam	Pulsed Muon Beam
Beam Intensity	(almost) Limited	No Limitation

- $\mu \to e\gamma$: accidental B.G. $\propto$ (rate)2
  - MEG (and its upgrade) may be the final experiment

discovery

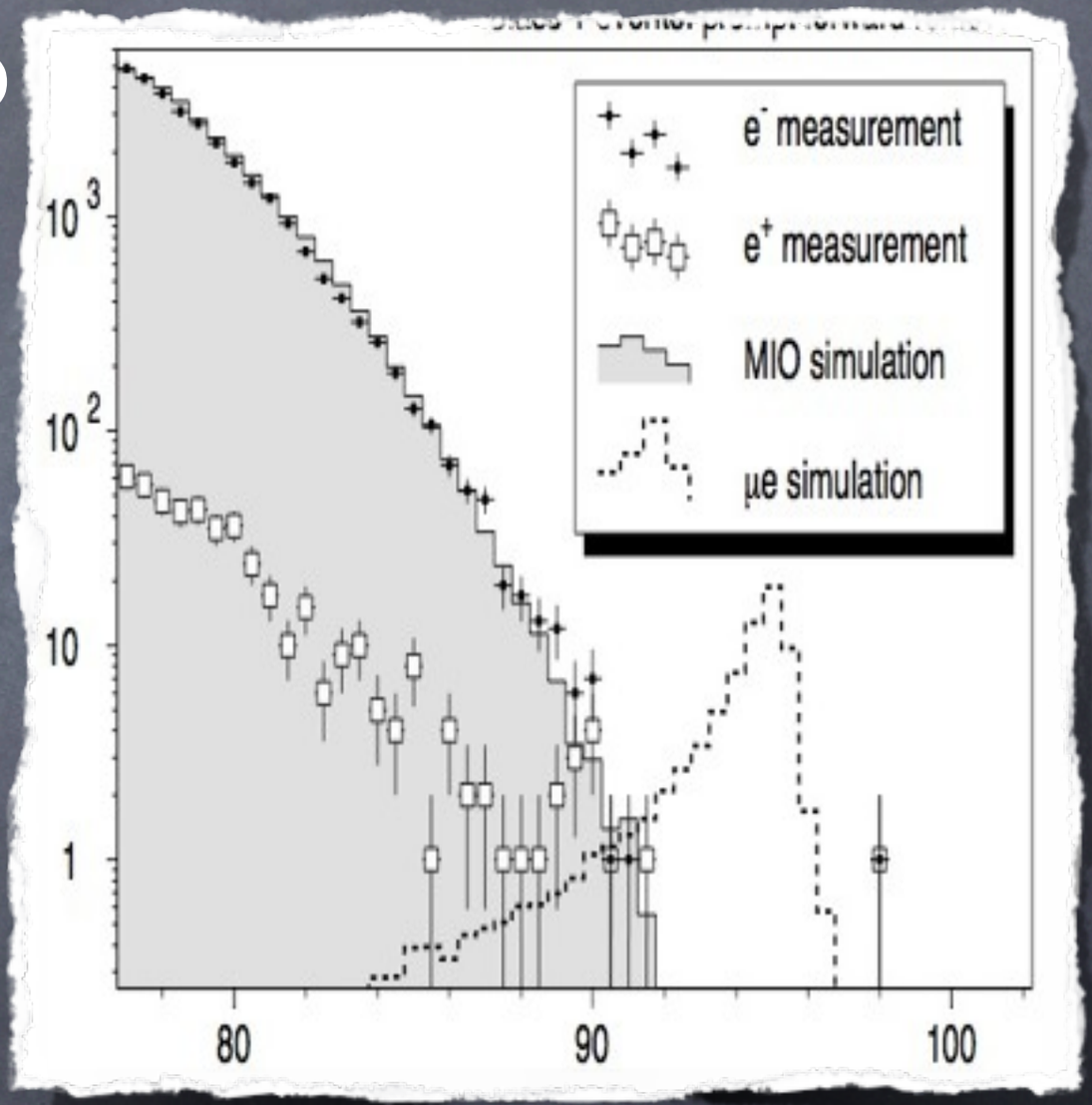
- $\mu N \to eN$: Required Beam is recently / finally achievable
  - Once we get a required beam, $\mu N \to eN$ experiment might be a next experiment after the MEG.

measurement

Present Best Limit on "μN→eN"

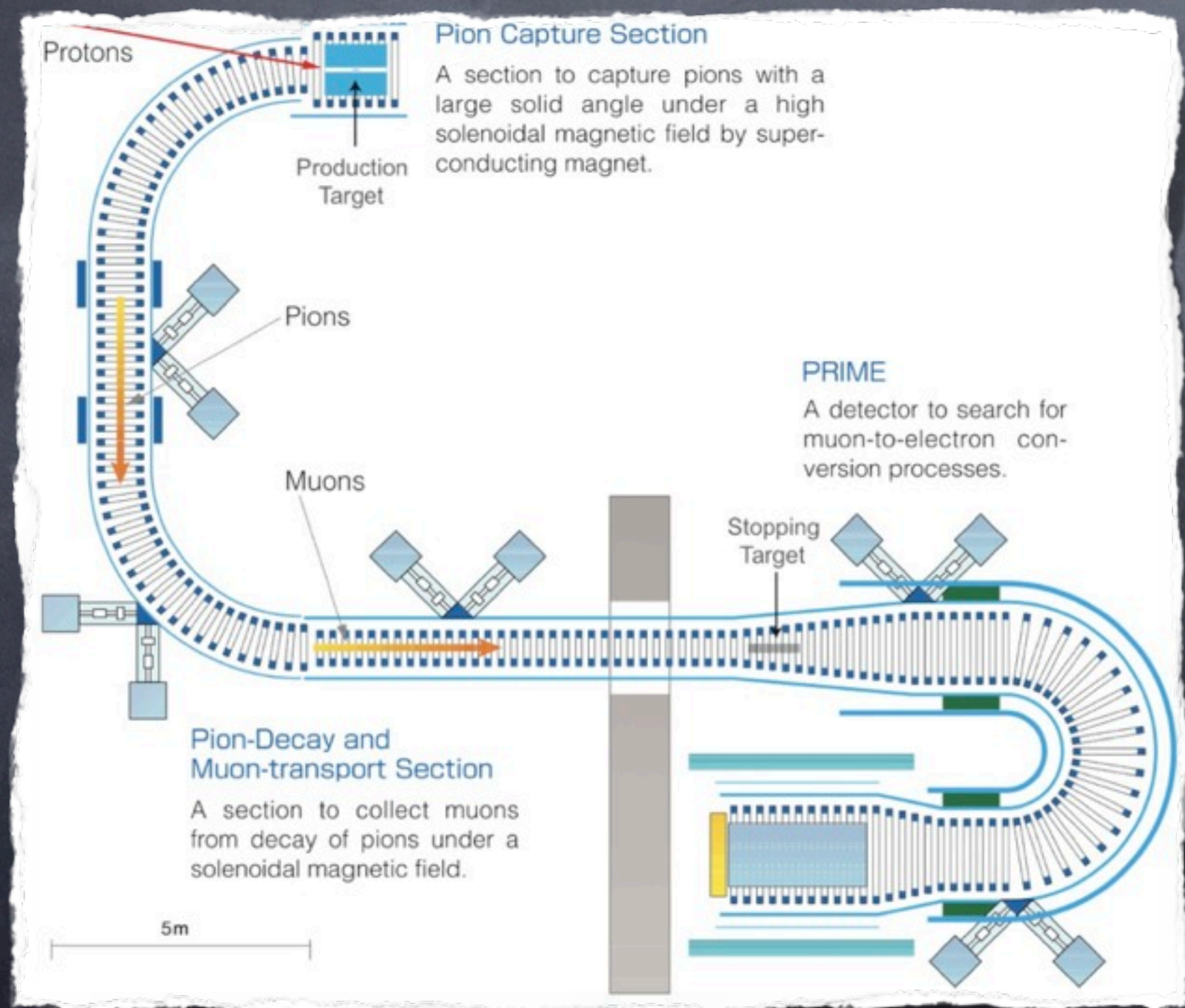
- SINDRUM-II (present record holder)
  - 1989-1993 @ PSI
  - DC Beam with Beam Veto Counters
- Results
  - $\mathcal{B}(\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}) < 6.1\times10^{-13}$ (1993)
  - $\mathcal{B}(\mu^- \mathrm{Au} \to e^- \mathrm{Au}) < 7\times10^{-13}$ (2000)

Significant BG.
Rate Limited !!



Electron Momentum Spectrum (SINDRUM-II)

COMET Experiment

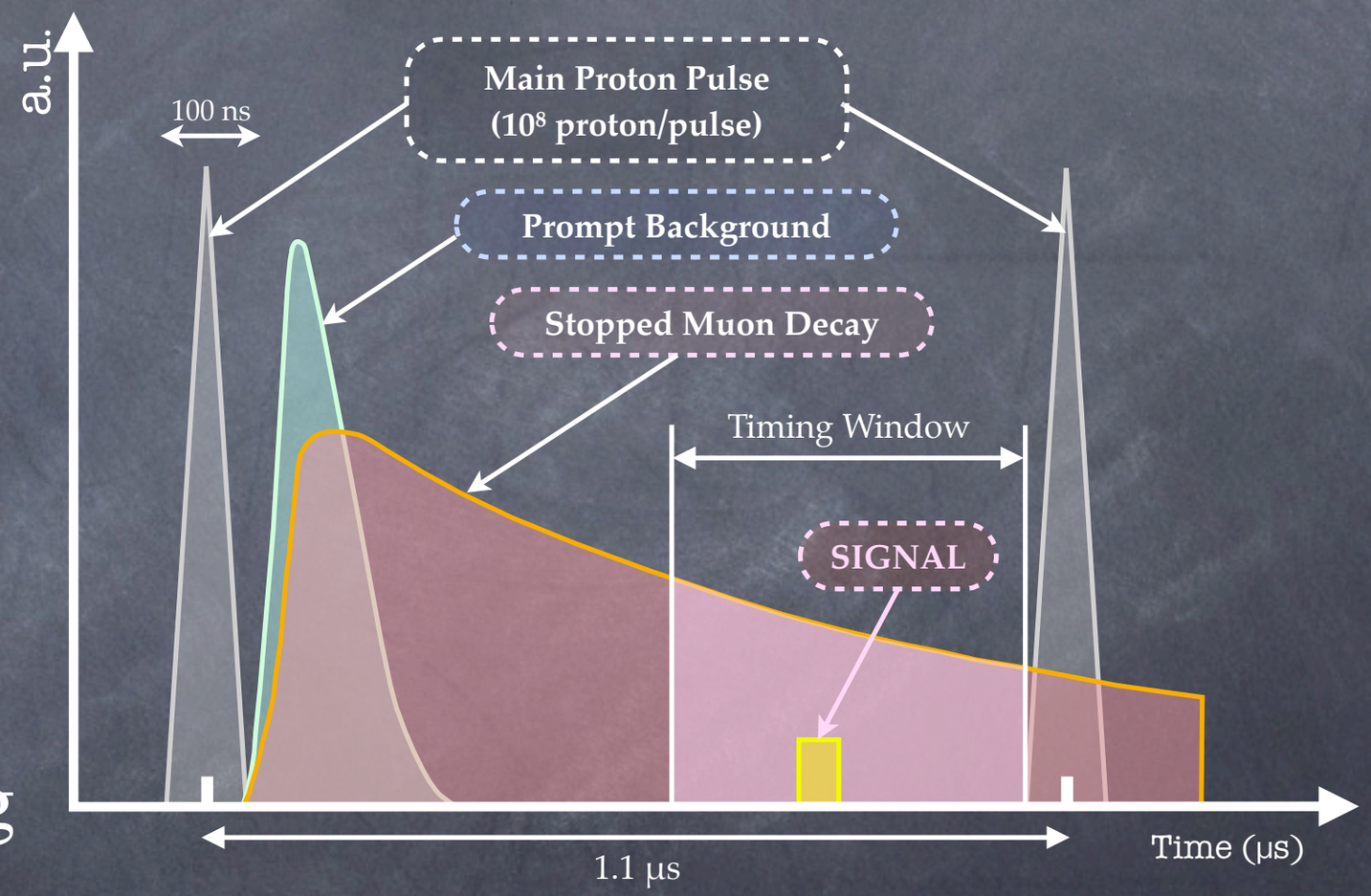


- Pulsed Proton Beam @ J-PARC Main Accelerator ①
- Utilize backward pions with pion capture solenoid ②
- Select low-p muons (and reject high-p pions) using C-Shaped Transport Solenoid, and Select high-p electron (reject low-p backgrounds) using C-shaped Detector Solenoid ③
- High Resolution Tracker & Calorimeter ④

J-PARC

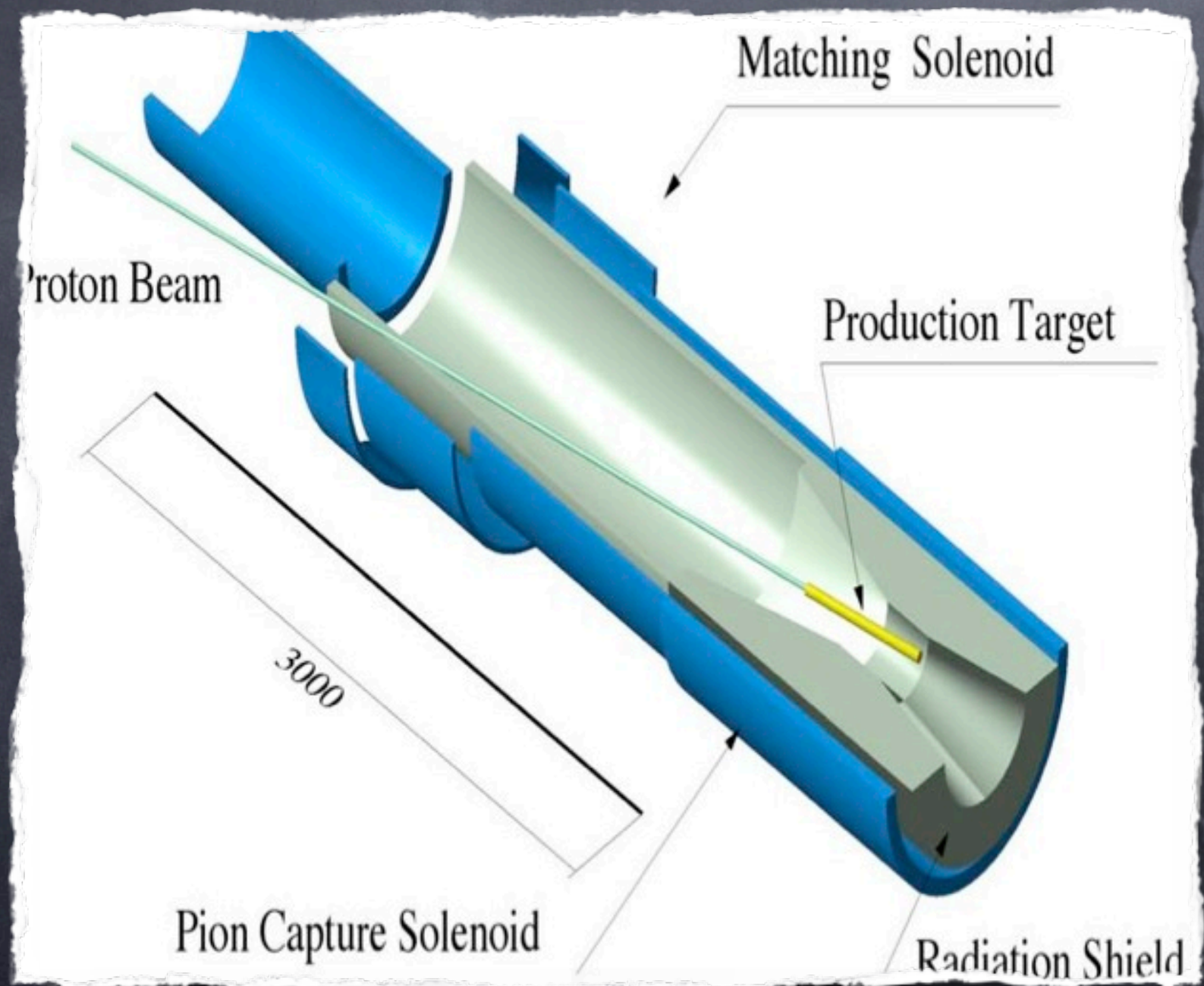
Proton Extinction

- Extinction = "Residual protons in between the pulses"
- Dominant Backgrounds
  - Beam Pion Capture
    - π+(A,Z)→(A,Z-1)* →γ+(A,Z-1), γ→e^+e^-
    - Prompt Timing
    - *cf.* $\tau_{(\text{muonic Al})} = 0.88\ \mu s$
  - Muon DIO, e^- scattering



Extinction should be <10^{-9} : To achieve 10^{-17} Single Event Sensitivity

Pion Capture Solenoid

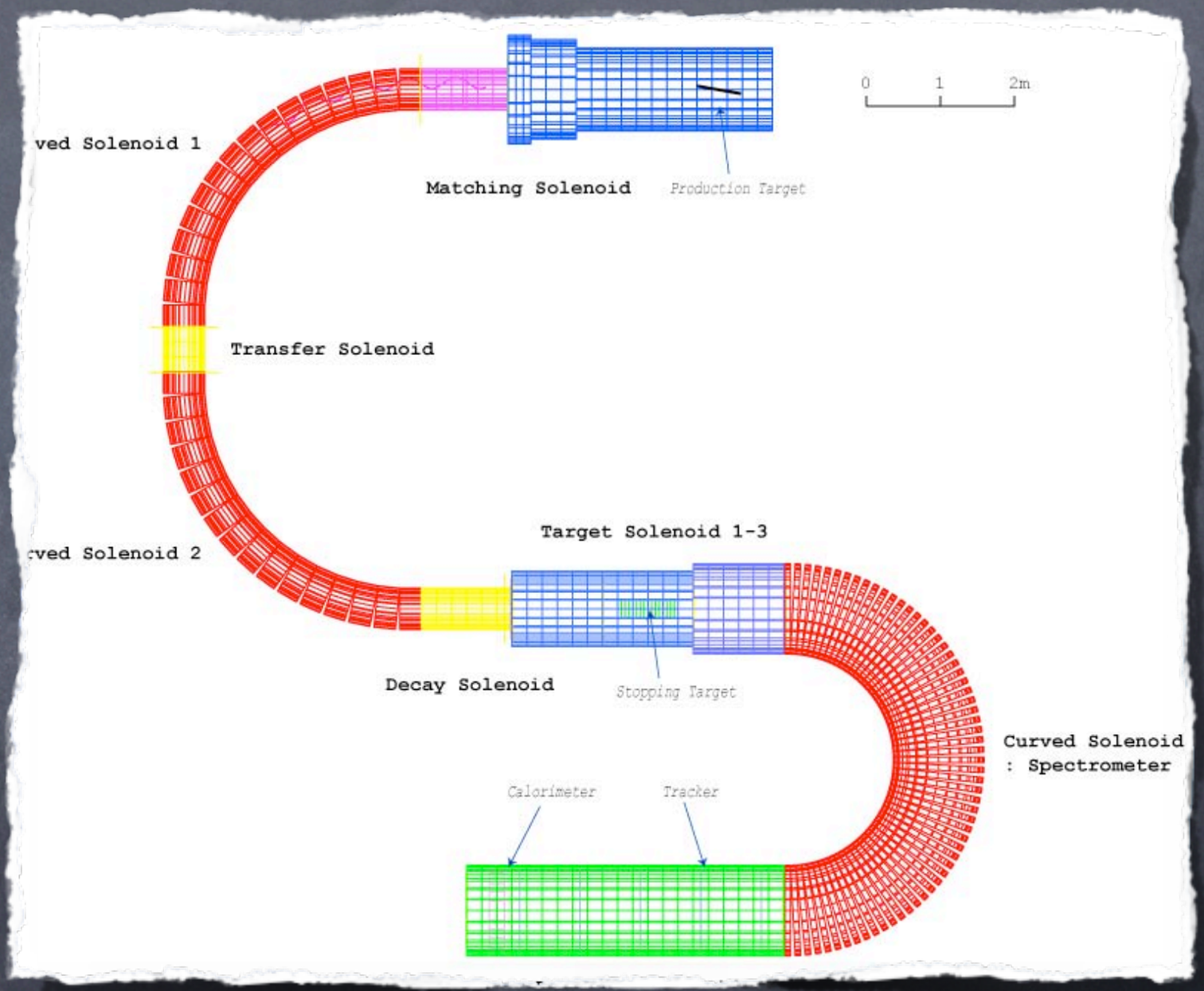


- Large muon yield by Large Solid Angle
  - powerful Solenoid
  - Surround p target
- Superconducting solenoidal magnet
  - 15cm radium bore
  - 5T
  - 30 cm thick W shield
- Issue : Heat Load

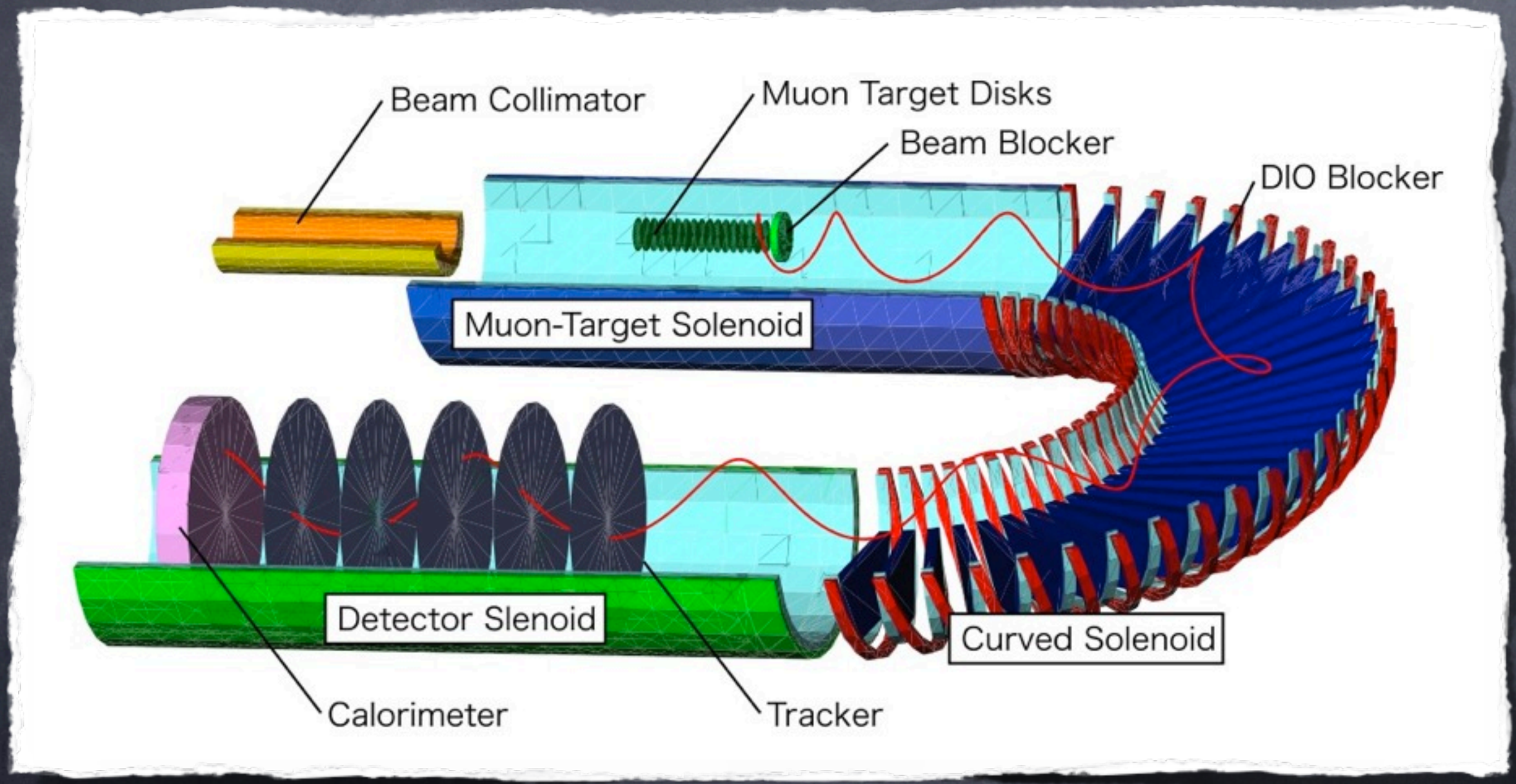
Curved Solenoid

- Requirements:
- Long enough for pions to decay to muons (>20m)
- High transport efficiency (P_μ~40MeV/c)
- Negative charge selection
- Low momentum selection (P_μ<75MeV/c)

Curved Solenoid Design is Suitable.

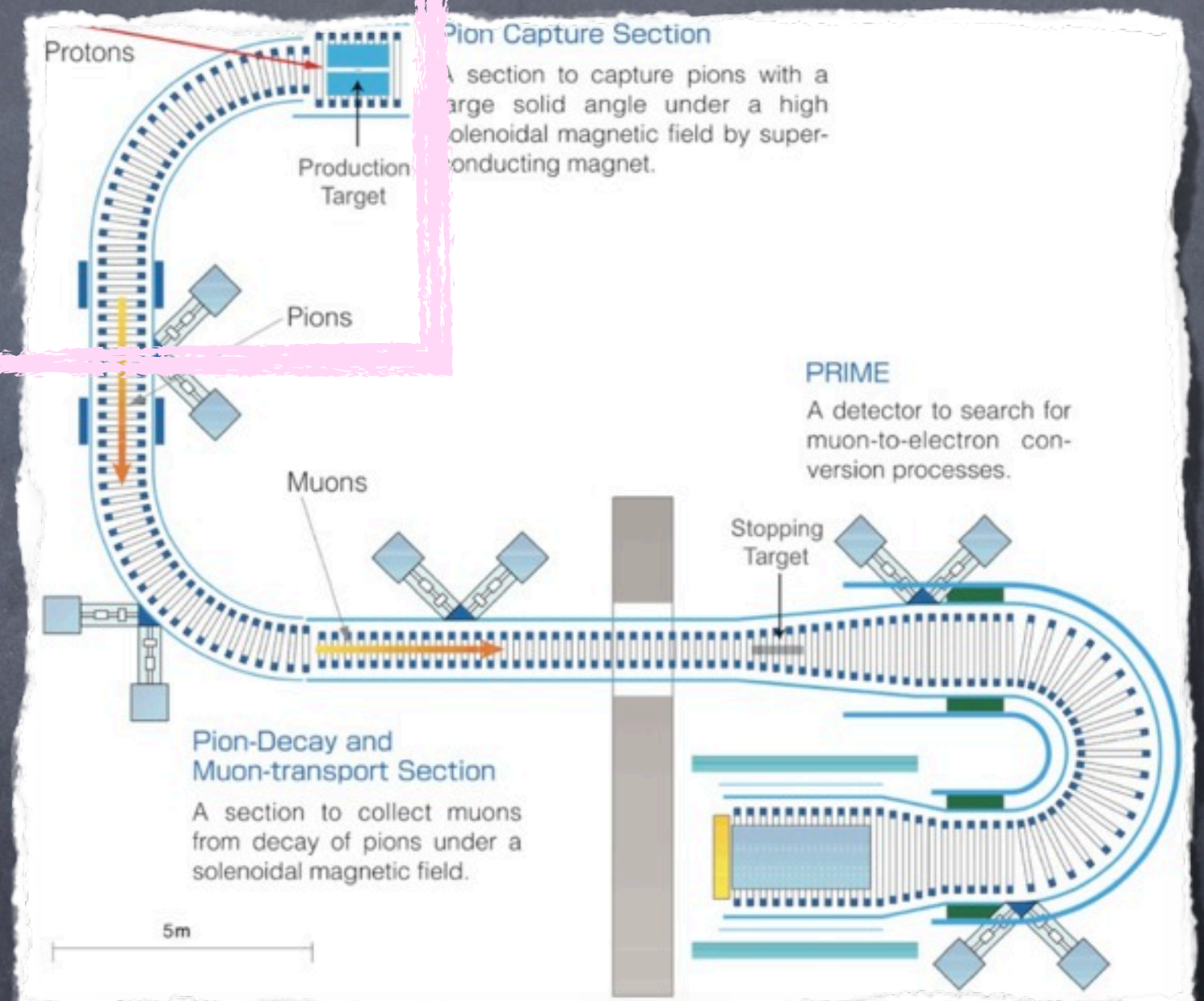


Detector Section



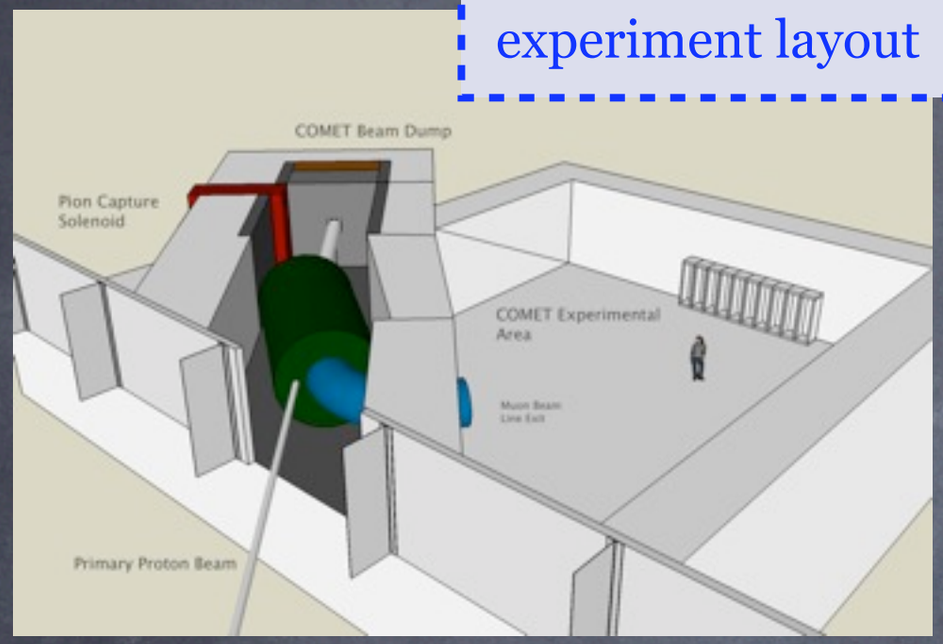
Staging Approach

COMET
Phase-I



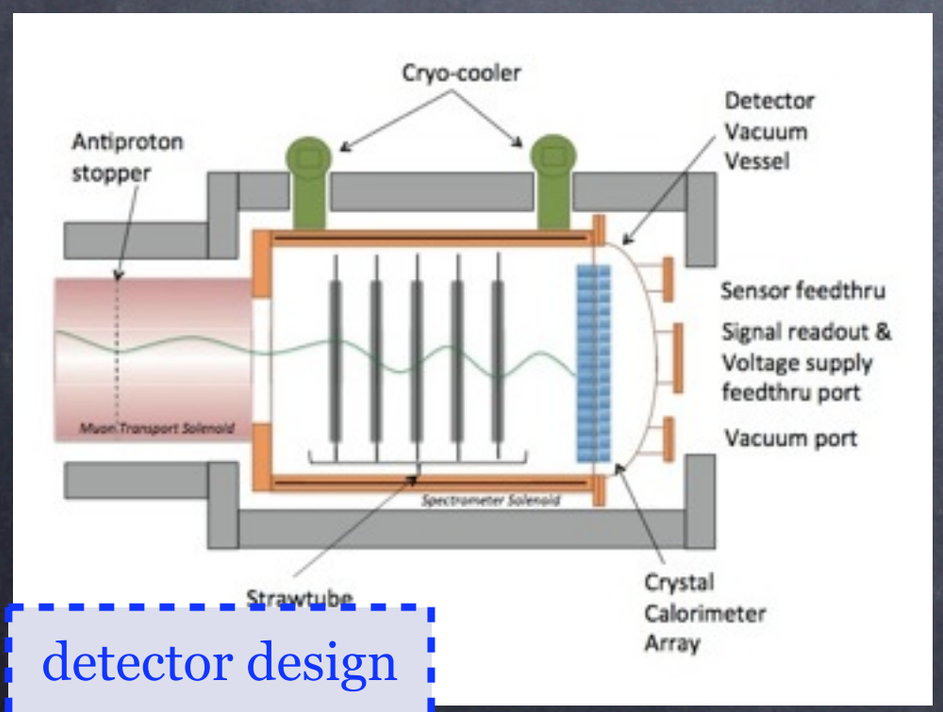
- **Beam BG Study**
- **μN→eN Search**

Beam Measurement @ phase-I

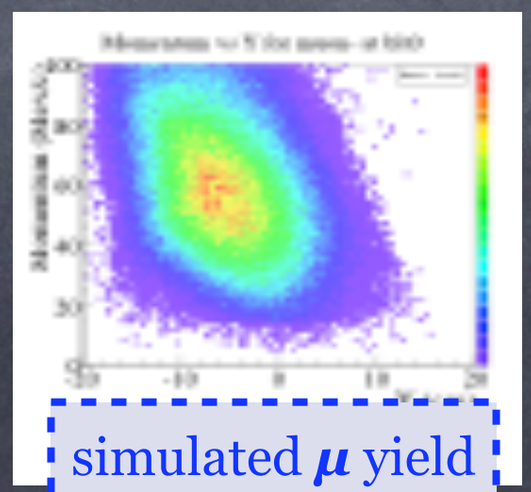


experiment layout

- Measure almost all particles
- Same detector technology used in COMET
  - SC spectrometer solenoid
  - Straw tube transverse tracker
  - Crystal Calorimeter
- Particle ID with dE/dx and E/p
  - anti-p with event shape
  - γ direction

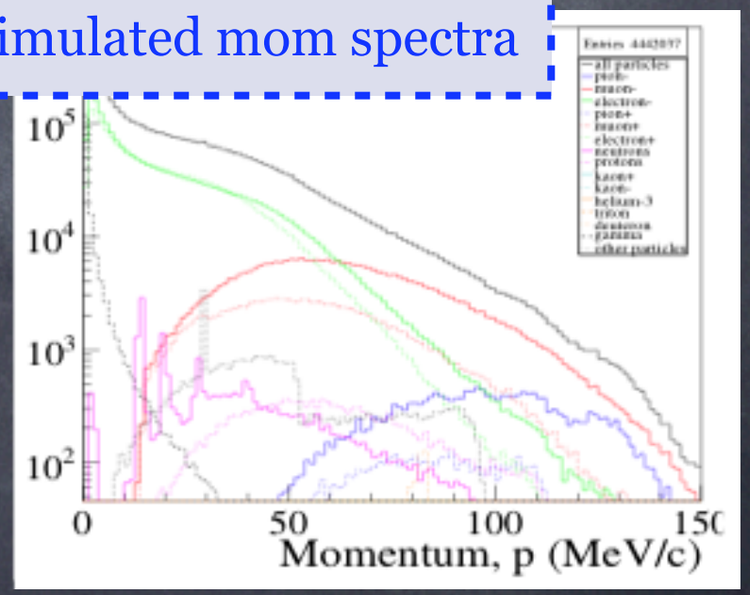


detector design



simulated μ yield

simulated mom spectra

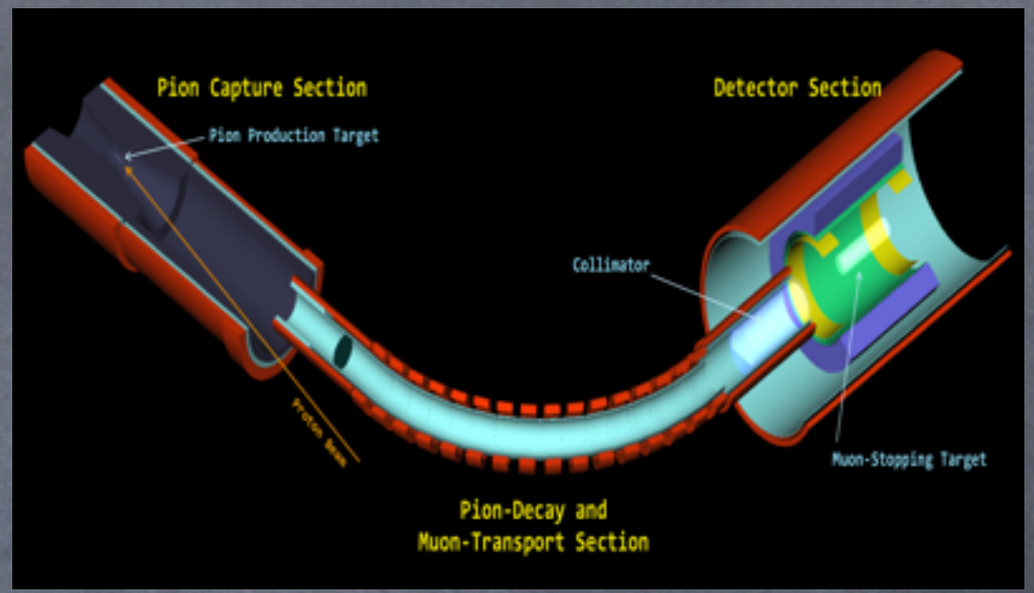


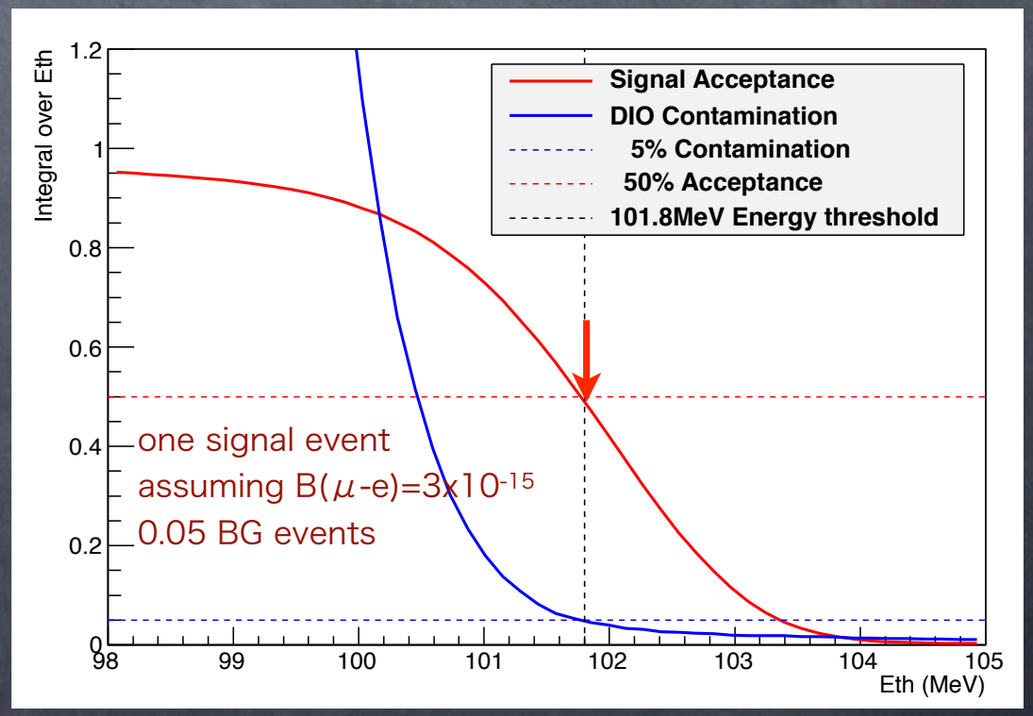
Search for $\mu N \rightarrow eN$ @ phase-I

- 8GeV, 3.2kW proton beam is assumed
  - 2.5×10^{12} protons/sec
  - 10^{-9} of extinction is supposed
- 12 days (10^6 sec) running time
- Expected single event sensitivity

$$\mathcal{B}(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}) = \frac{1}{N_\mu^{stop} \cdot f_{cap} \cdot \mathcal{A}_{\mu-e}}$$

  - $\mathcal{B}(\mu+\mathrm{Al}\rightarrow e+\mathrm{Al}) = 3.2\times10^{-15}$
- Upper limit at 90% C.L.
  - $\mathcal{B}(\mu+\mathrm{Al}\rightarrow e+\mathrm{Al}) < 7.2\times10^{-15}$
  - *cf.* present limit $< 7\times10^{-13}$ (SINDRUM-II)

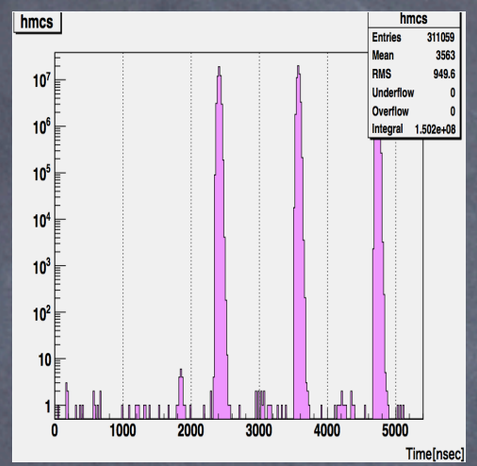




COMET : Current Status (1)

- Proton Extinction -

O(-7) is confirmed w/o any extinction treatment



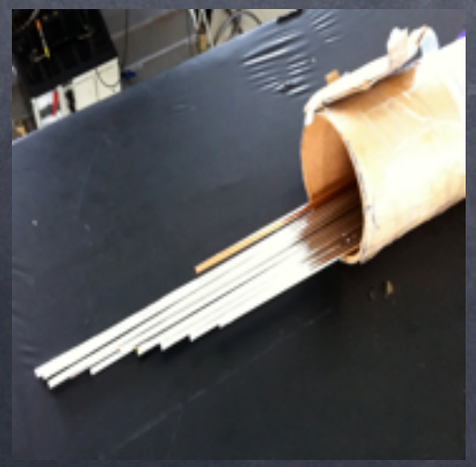
Specially dedicated injection is currently being tested.

- π Capture Solenoid -

High yield π capture is demonstr-ated at Osaka Uni.

- Straw Tracker -

Operated within vacuum successfully



Actual implementa-tion is under development

- Calorimeter -

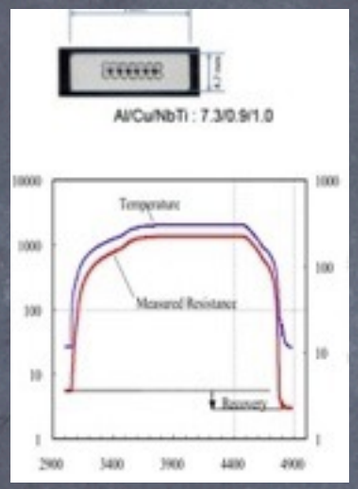
Several Crystals were investigated with test-beam.

Next testbeam is being prepared with developed front-end

COMET : Current Status (2)

- Curved Solenoid -

Super-Cond-uctor is being developed and irradiation test performed



Conductor test is ongoing, and solenoid design is almost fixed.

- Front-end Electronics -

1st prototype was delivered and being tested now.

2nd prototype design work is ongoing

- Laboratory approval -

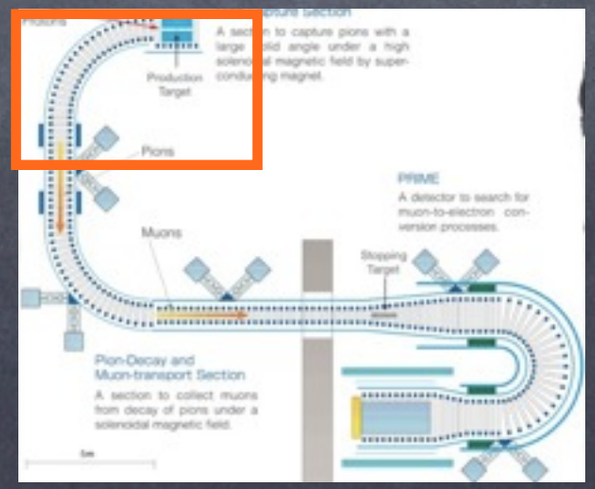
LoI for Phase-I was submitted and discussed by PAC

Letter of Intent for Phase-I of the COMET Experiment at J-PARC

March 22, 2012

Proposal for Phase-I is under preparation

- Funding -



Phase-I budget request is under way (See Next Slide)

COMET : phase-I cost estimation

		Budget request	KEK internal	External funding	Optional	Future funding	Comments
Building		8.0					
Beam dump		1.0	0.5				
SC magnet		8.0					to first 90° bend
						20.0	remaining beam line
	W shield					2.0	for higher power
Power supply					2.0		if purchased
			0.5				installation
						2.5	for upgrade
refrig-erator					2.0		if constructed
			0.5				installation
Beam line	magnet		0.5				installation
						5.0	for higher power
	piping	0.3	0.3				
	cabling	0.6	0.6				
	vacuum	0.6	0.6				
Radiation shielding	NP-hall	1.5					for 3 kW operation
						6.5	for high power
Safety			0.5				
π target				0.8			experimental group
Detector	magnet		0.5	0.5			for Phase-I
	μ target			0.1			experimental group
	μ monitor			1.5			experimental group
	tracker			1.1			experimental group
	ECAL			1.6			experimental group
	CR veto			5.7			experimental group
	DAQ			0.5			experimental group
Total		20.0	4.5	11.8	4.0	36.0	72.3+4.0

building 9.5M€

magnet 9.0M€

beam line 6.3M€

detector 11.5 M€

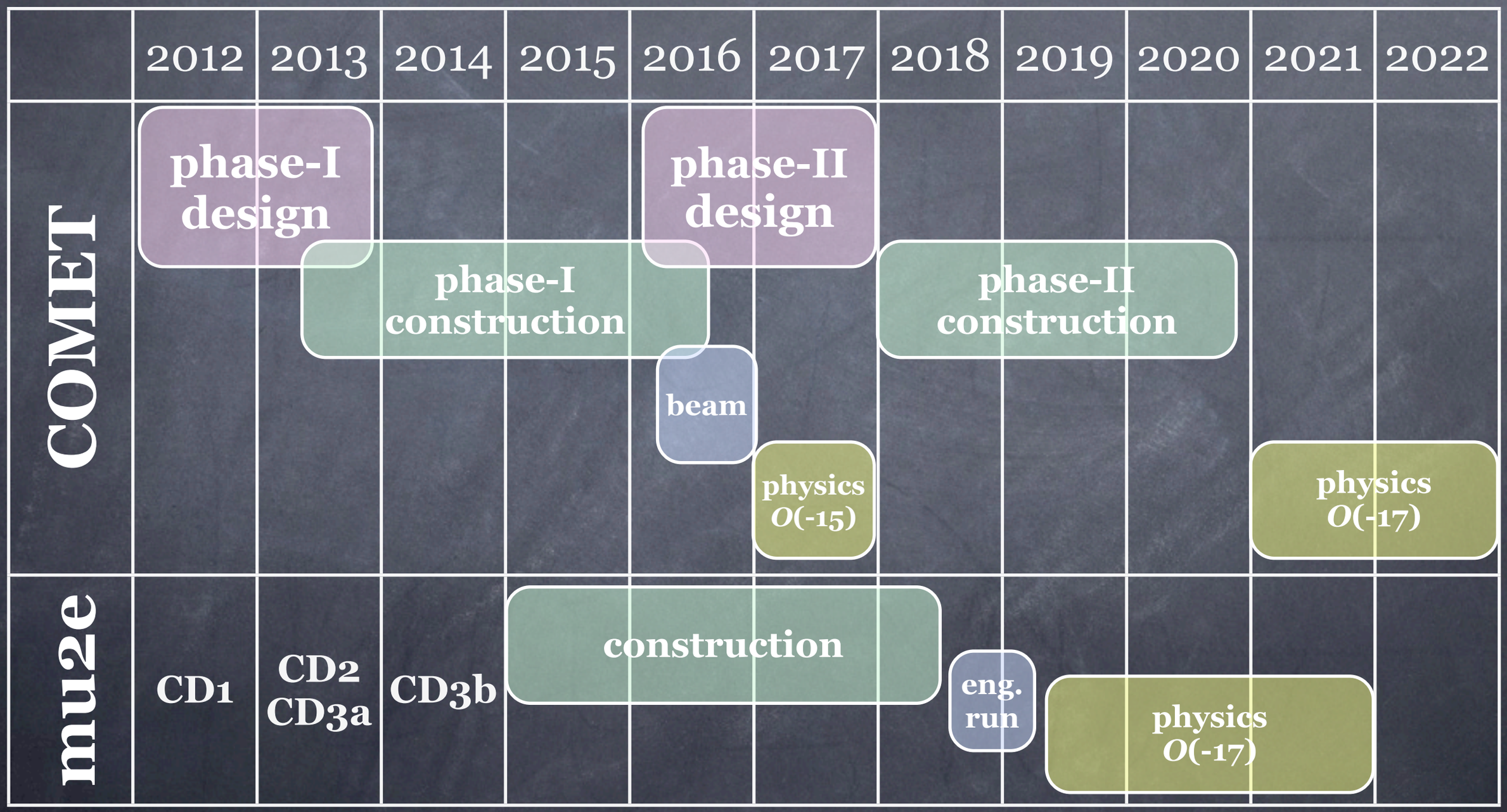
budget request 20 M€

J-PARC project budget 4.5 M€

Experimental Group 11.8 M€

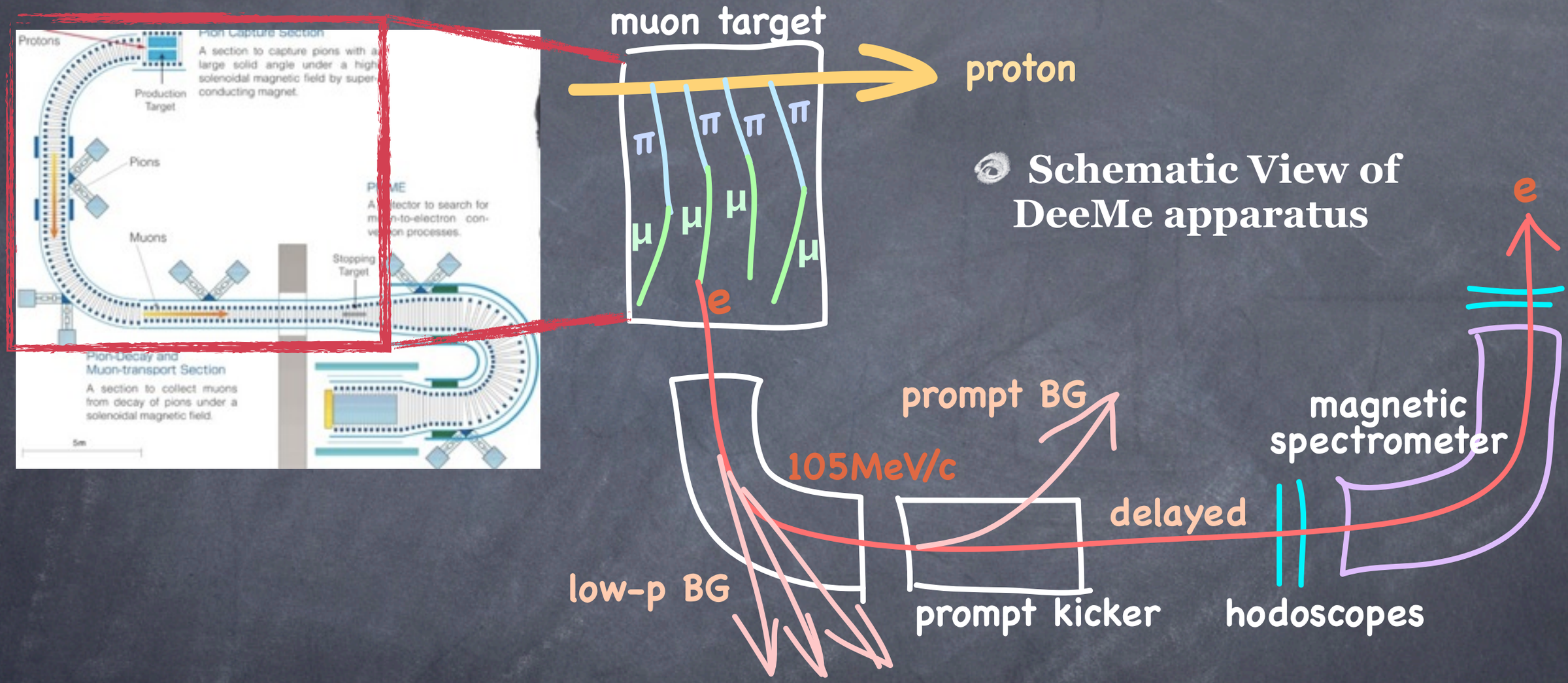
- Unit : M € (= Oku ¥)
- Based on
  - KEK facility division estimation
  - Toshiba magnet design
- **Budget request 20 Oku JPY** (=20 M€) includes building, beam line, magnet (up to 1st 90° bending)
- Expect Support from J-PARC project budget
- Detector construction needs external funding by experimental group's effort
- Additional funding is required to upgrade to the phase-II (full COMET)

COMET : Schedule (vs. mu2e)



(!) Referred Sensitivity is not UL(90CL.) sensitivity, but the order of feasible SES.

DeeMe : Another Approach



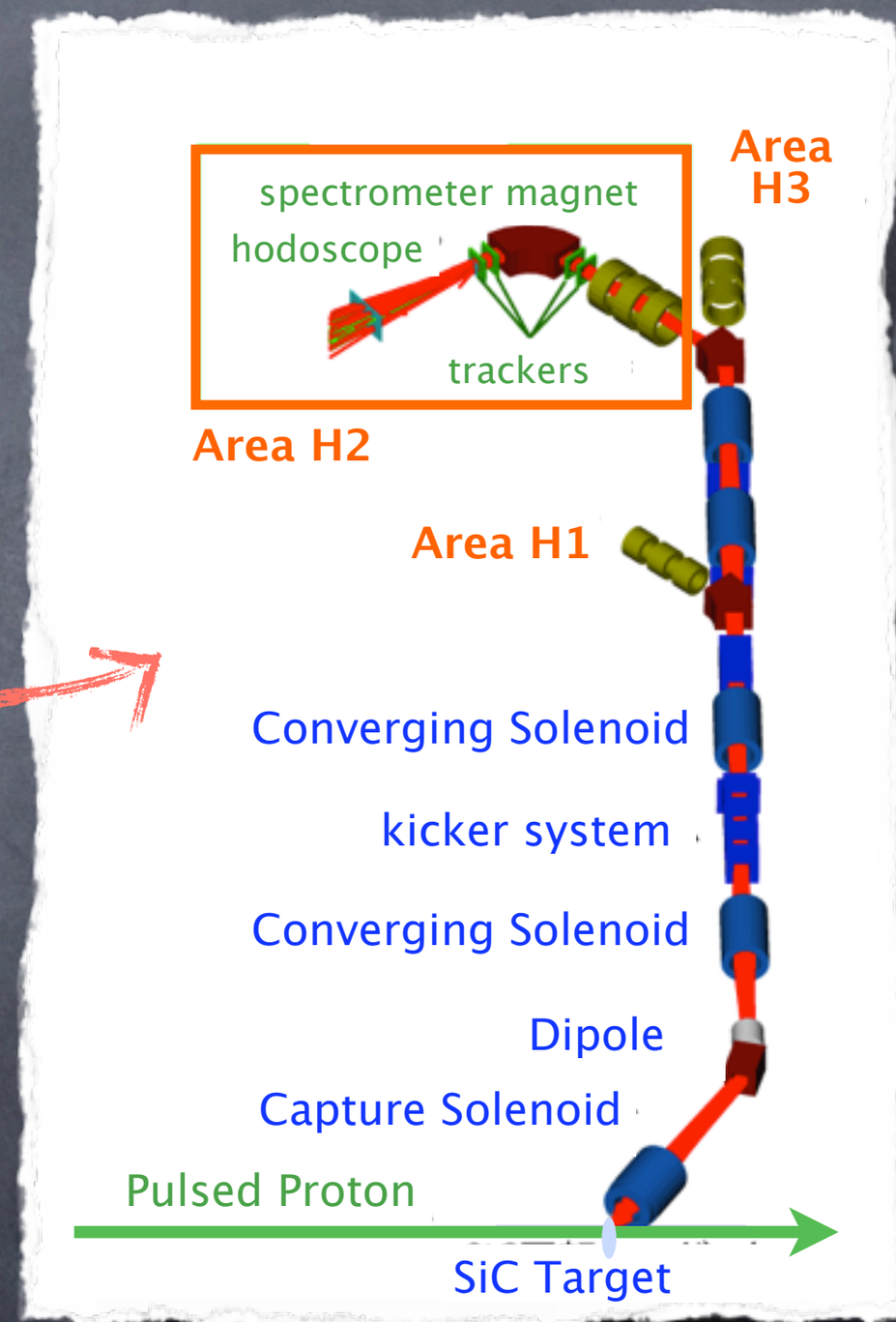
- Schematic View of DeeMe apparatus

- In the thicker target, pion production -> decaying to muon is possibly done within the target (analogy to the surface muon production)
  - Idea : "mu-e conversion electron may directory come from the target "
- "Fast" and "Low Cost" : Good 1st discovery potential !!

H-Line at J-PARC MLF

- **MUSE : MUon Science Establishment at J-PARC**
- **Muon Beam Lines (D/U/S and H-lines)**
  - **H-line is being designed for "particle physics experiments", large solid angle, large momentum acceptance.**
  - **H-line is under discussion and planned to be shared by three experiments;**

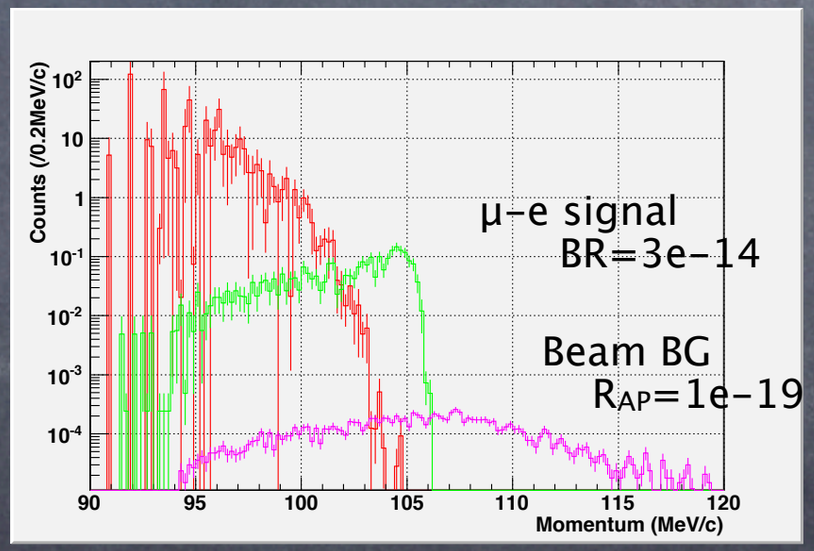
    "muonium HFS", "muon g-2/EDM", and "DeeMe"
  - **Need to be decided ASAP.**

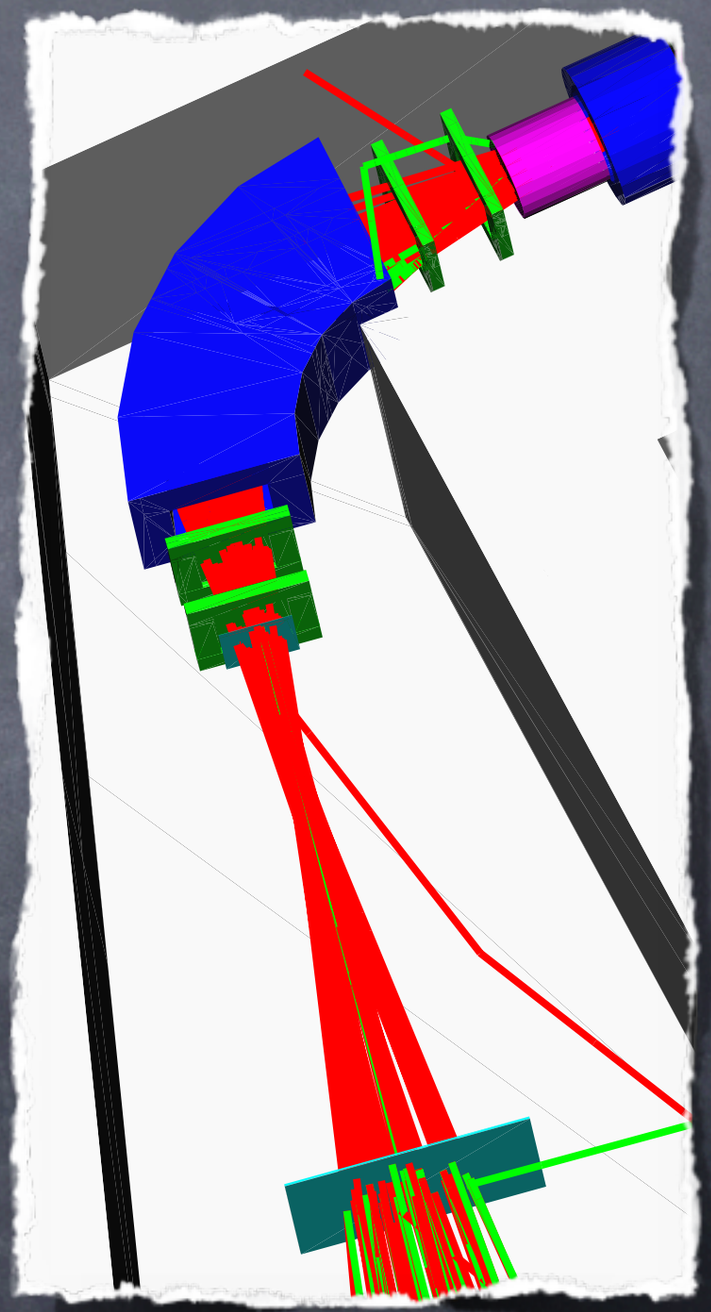


DeeMe : Sensitivity & BG.

- Signal Sensitivity
  - S.E.S. = 2×10^{-14}
  - 2×10^{7} sec running assumed
- Background
  - RAP=10^{-19} (currently under measurement)
  - Detector live-time duty = 1/20,000

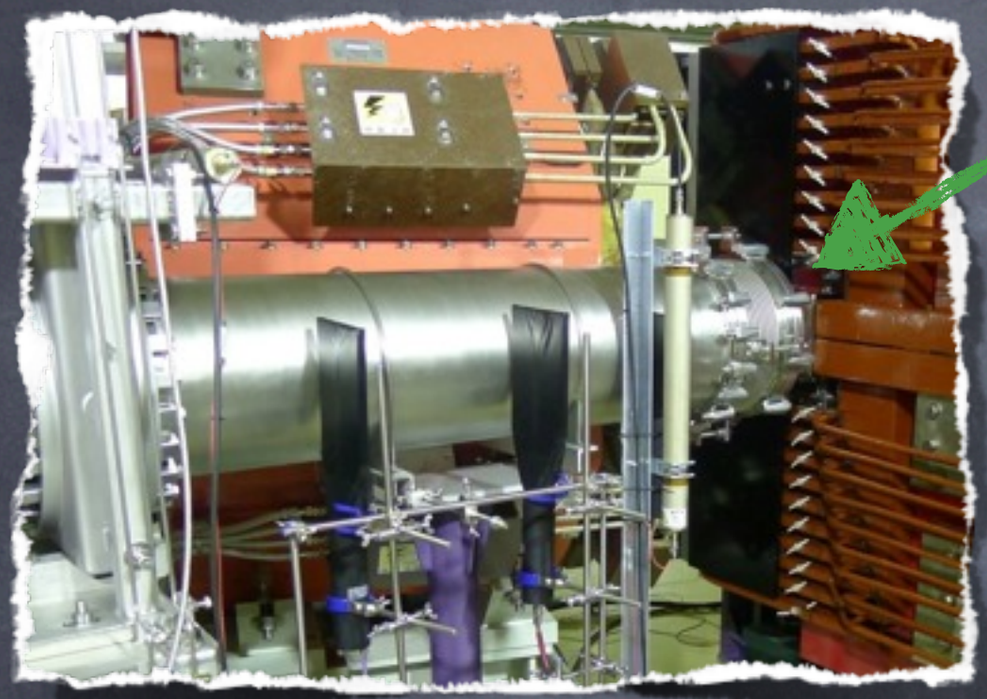
DIO	0.09
beam related	<0.01
cosmic muon induced e	<0.018
cosmic muon induced μ	<0.001





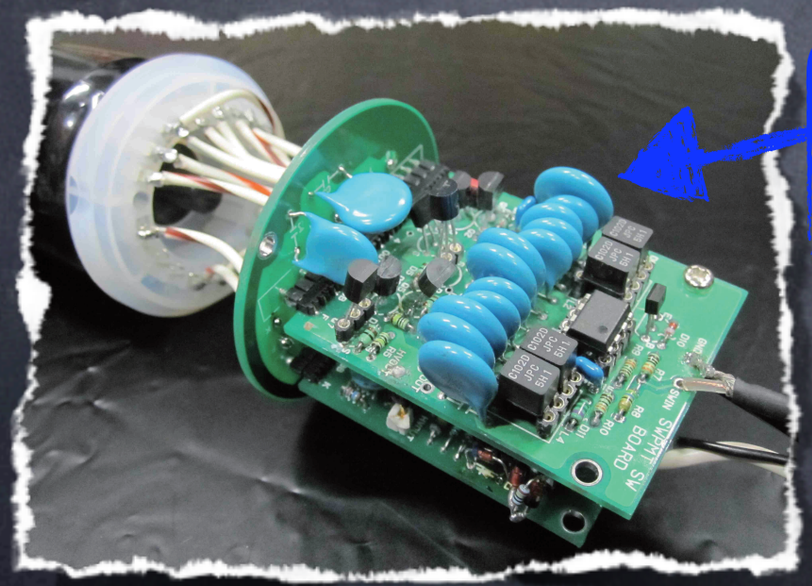
- Sensitivity is still not limited by Background, and thus we have an option to prolong the run time to achieve better sensitivitiy
  - *eg*. suppose 8×10^{7} sec of physics run → S.E.S. = 5×10^{-15}

DeeMe : Current Status



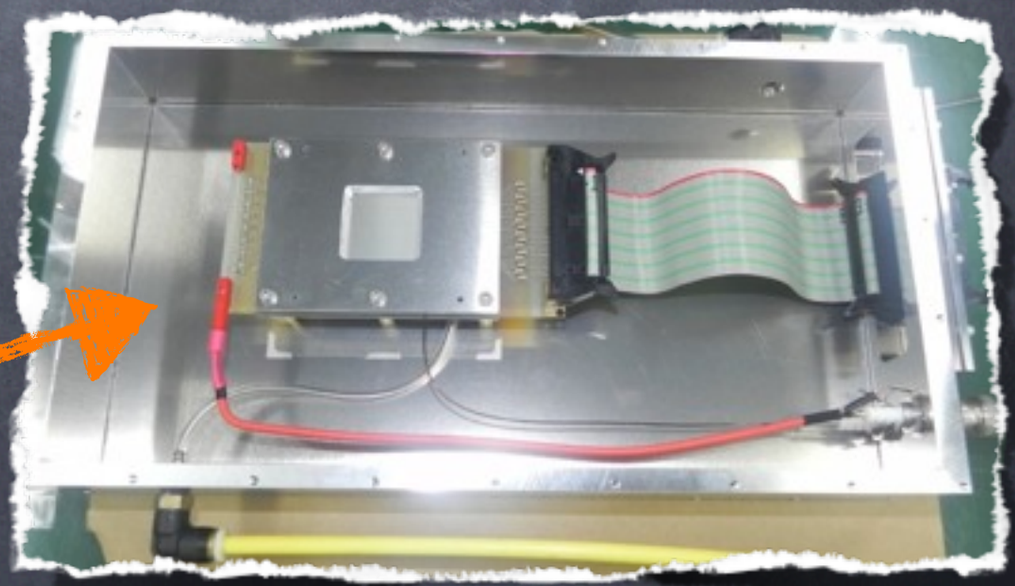
"after proton" measurement @ RCS

construction of coils for H-Line



gating PMT development

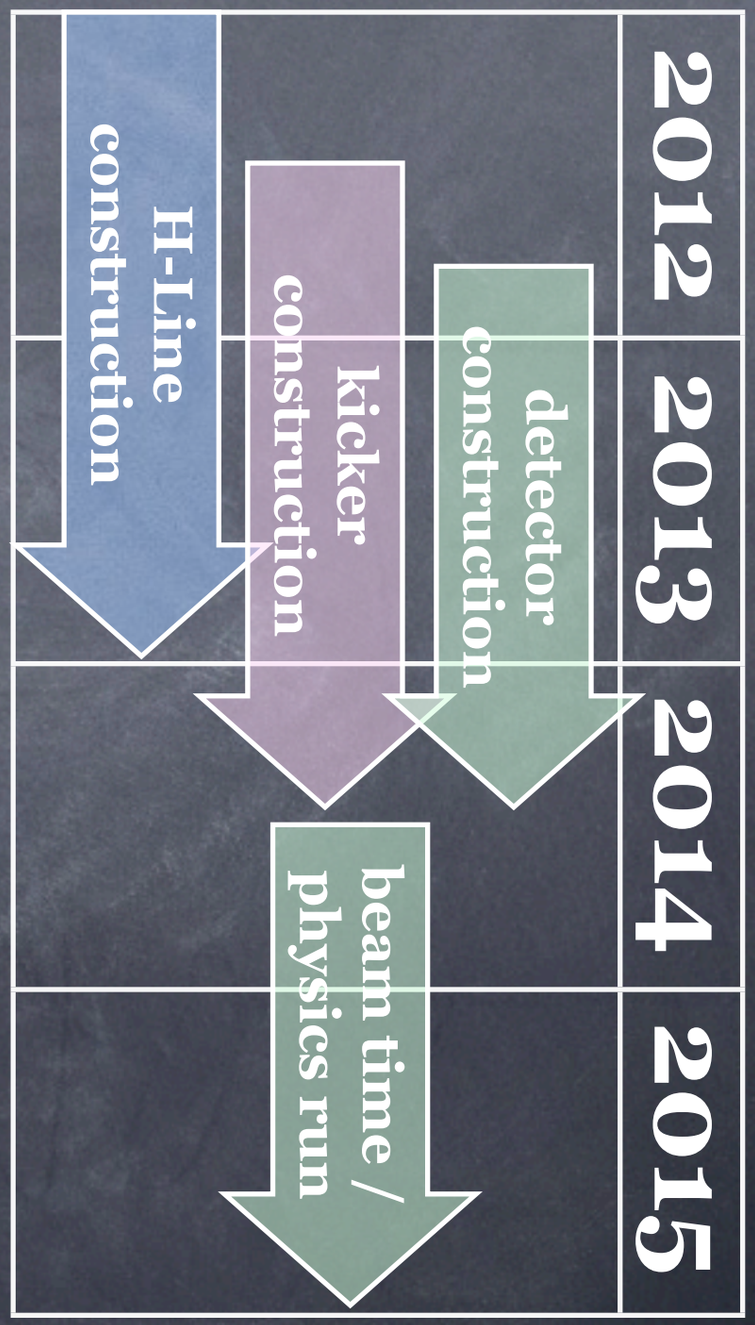
tracker development



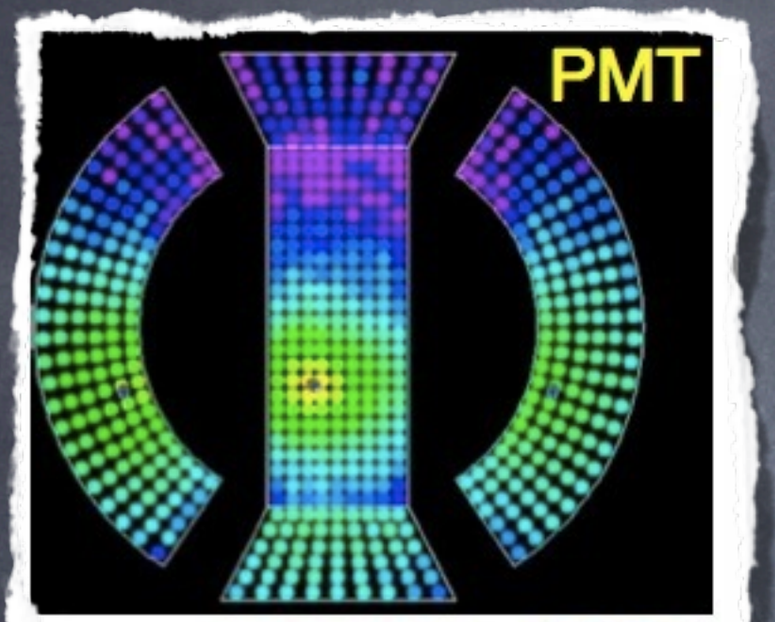
DeeMe : Cost & Schedule

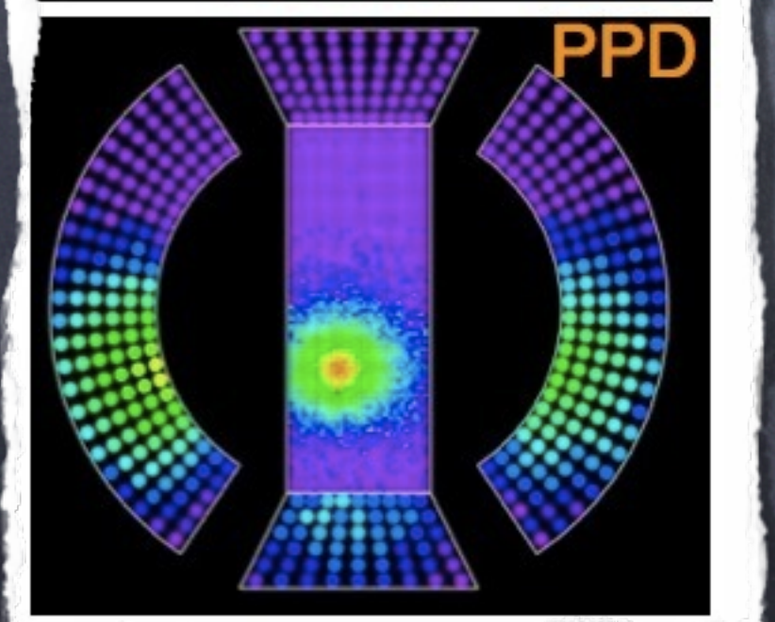
- DeeMe's most attractive advantage !!!

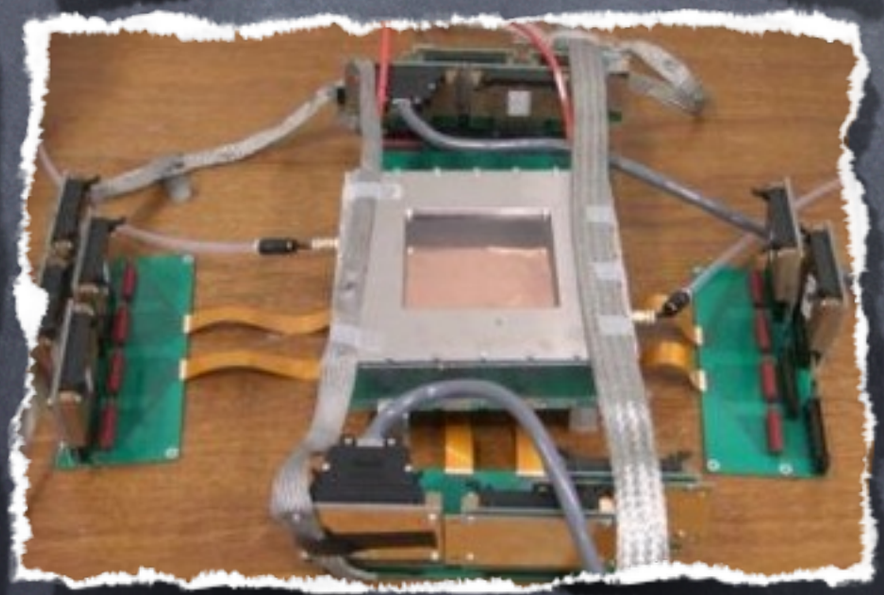
detector	subtotal : 1.03 M€	
	magnet	0.3 M€
	hodoscope	0.1 M€
	tracker (R&D)	0.03 M€
	tracker (prdct.)	0.5 M€
	electronics	0.1 M€
target	subtotal : 0.3 M€	
	SiC target	0.3 M€
Beam line (H-line)	require to the facility side	
kicker	subtotal : 2.2 M€	
	magnet	0.6 M€
	power	1.6 M€
PostDoc	subtotal : 0.75 M€ (for 3 posdocs)	
Grand Total	4.28 M€	



MEG : Upgrades

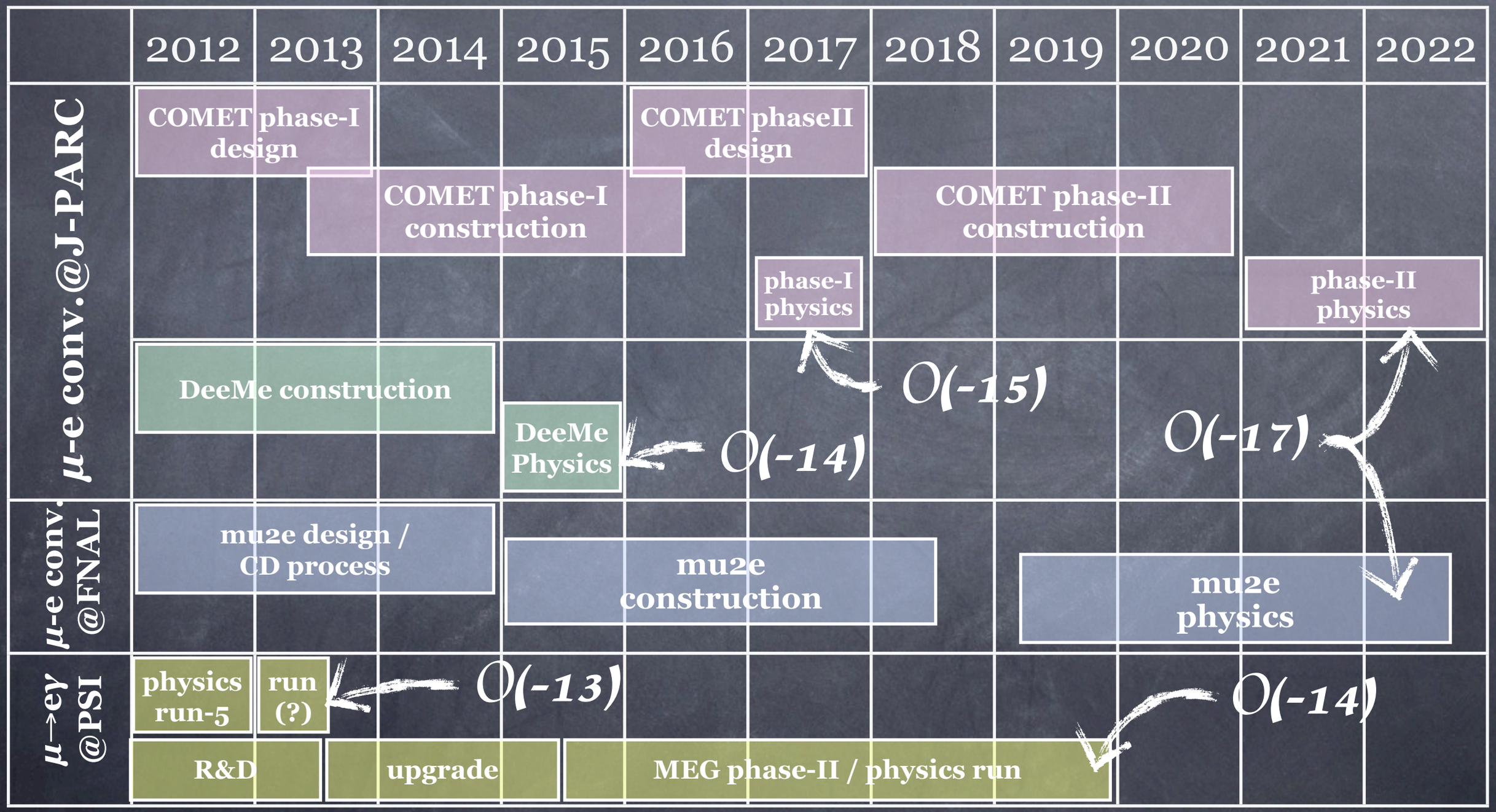






- MEG has recently started to consider the upgrade to perform experiment with three times higher beam intensity and better resolution for measurement.
- In parallel to the data-taking, several R&D is ongoing.
  - MPPC-base new γ detector
  - All-Stereo CDC
  - GEM-base radial TPC
  - MPPC-base new counter
  - Active target ... *etc.*
- We will finish the data-taking as "MEG phase-I" soon. At the end of 2012, we will submit the proposal to PSI for upgrade.

Grand Future Prospects



(!) For the MEG upgrade, nothing is decided yet, thus this timeline is my personal prospects (!)

References

- **MEG**
  - Latest Result : Phys. Rev. Lett. 107 (2011) 171801
    - http://prl.aps.org/abstract/PRL/v107/i17/e171801
  - Detector Paper & Up-to-date Result will be published soon
- **COMET (phase-I)**
  - Letter of Intent (Mar., 2011)
    - http://j-parc.jp/researcher/Hadron/en/pac_1203/pdf/COMET-PhaseI-LoI.pdf
  - Proposal is coming soon
- **COMET (full)**
  - Conceptual Design Report (Jun., 2009)
    - http://www.hep.ph.ic.ac.uk/muec/documents/comet-cdr-v1.0.pdf
- **DeeMe**
  - Proposal (Jan., 2011)
    - http://j-parc.jp/researcher/Hadron/en/pac_1101/pdf/KEK_J-PARC-PAC2010-13.pdf

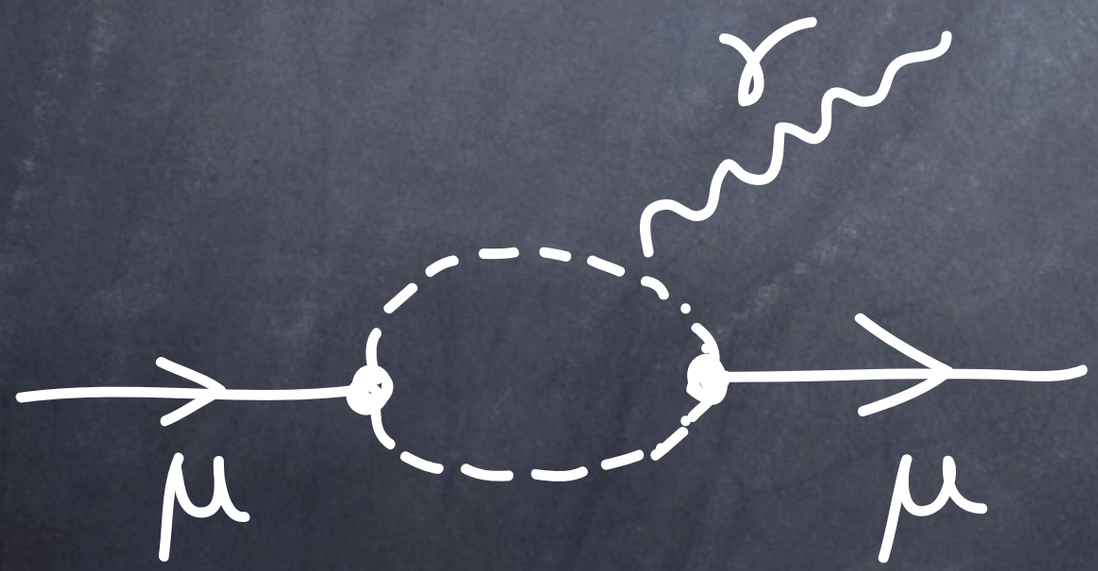
CONCLUSIONS

- In the Era of LHC,
  - "Muon Physics" ← complementary → "LHC"
- In the Muon Physics Experiments,
  - "Muon g-2/EDM" ← complementary → " Muon LFV"
- In the Muon LFV Experiments,
  - " $\mu \to e\gamma$ Search" ← complementary → " $\mu N \to eN$ Search"
    - MEG ⇔ COMET ⇔ DeeMe
    - COMET Stage-1

Again, Our Keyword is ...

- **Muon Physics** in the LHC Era
  - **Keyword** : "**COMPLEMENTARY**"

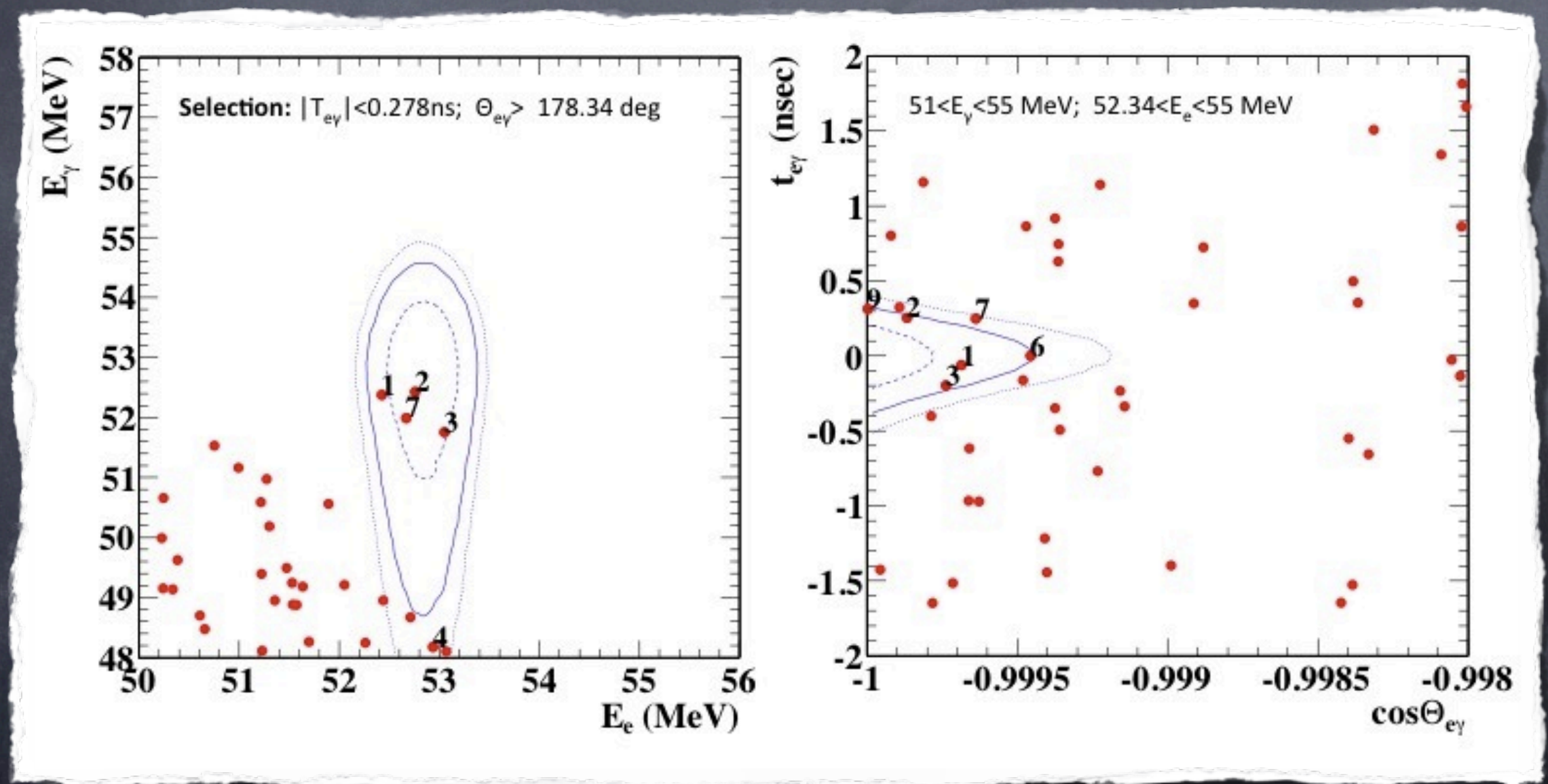
- Loop diagram for "**muon *g*-2**"



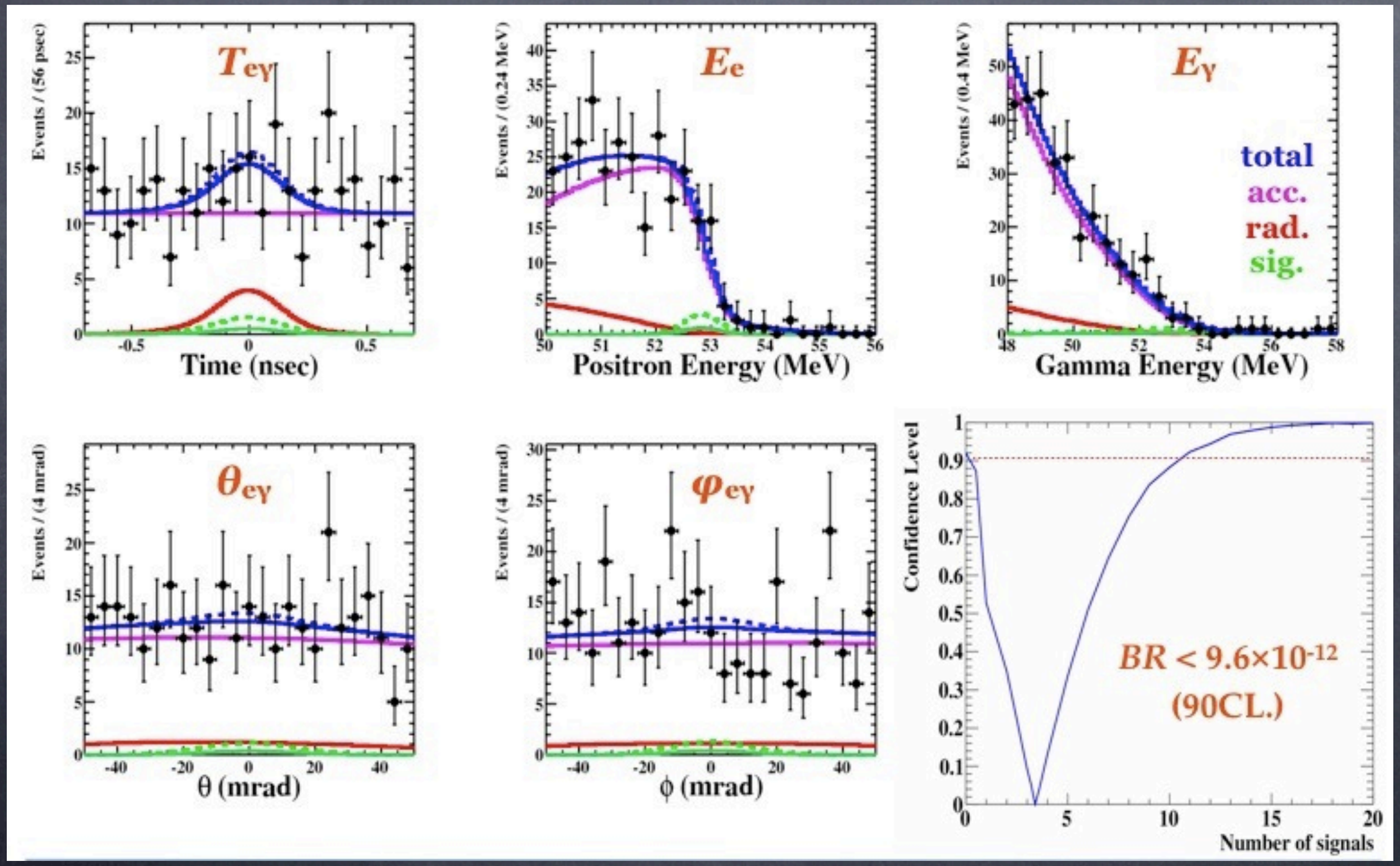
- Loop diagram for "$\mu \to e\gamma$"

Appendix

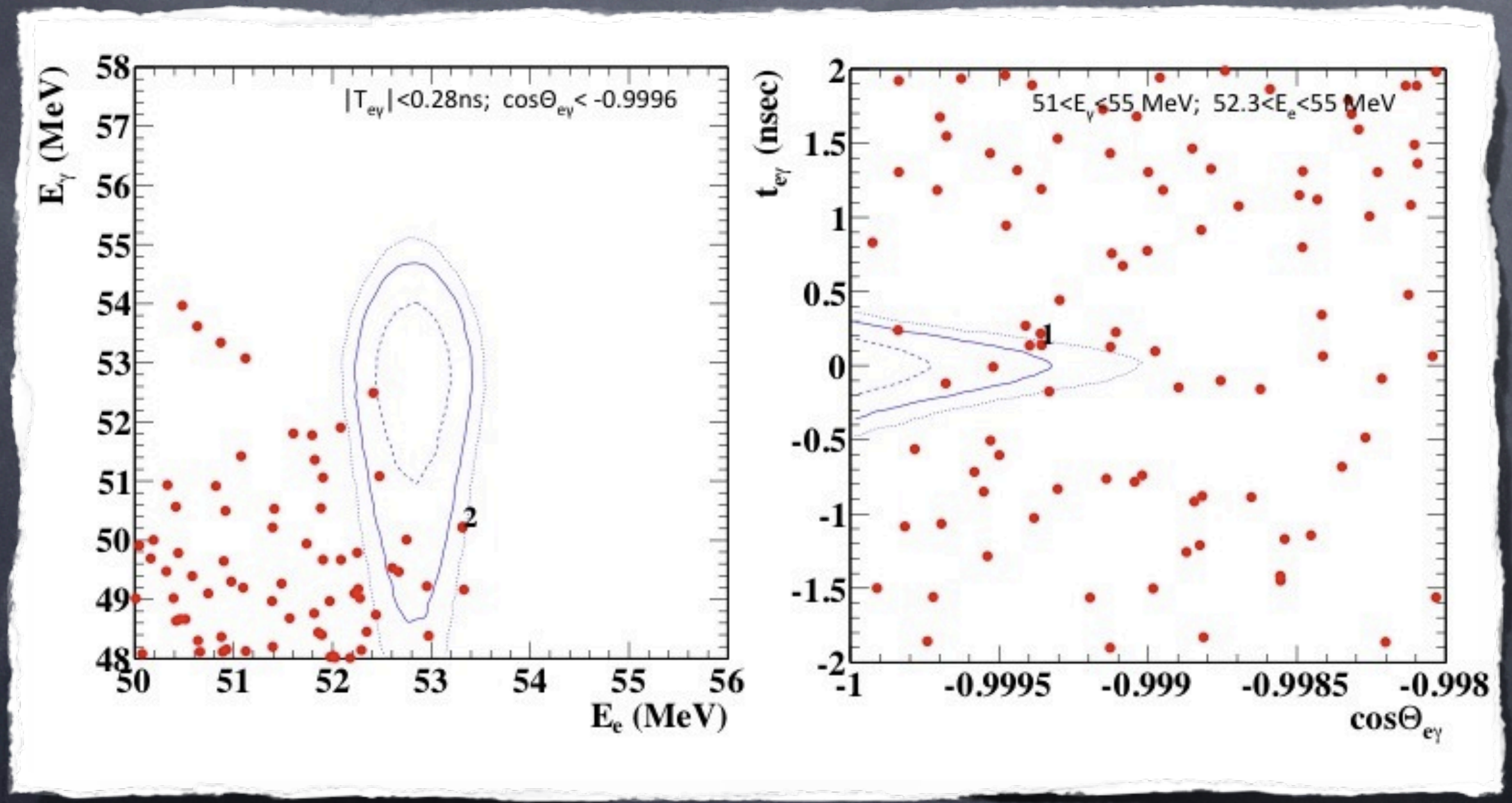
MEG - Run2009 (Event Distribution)



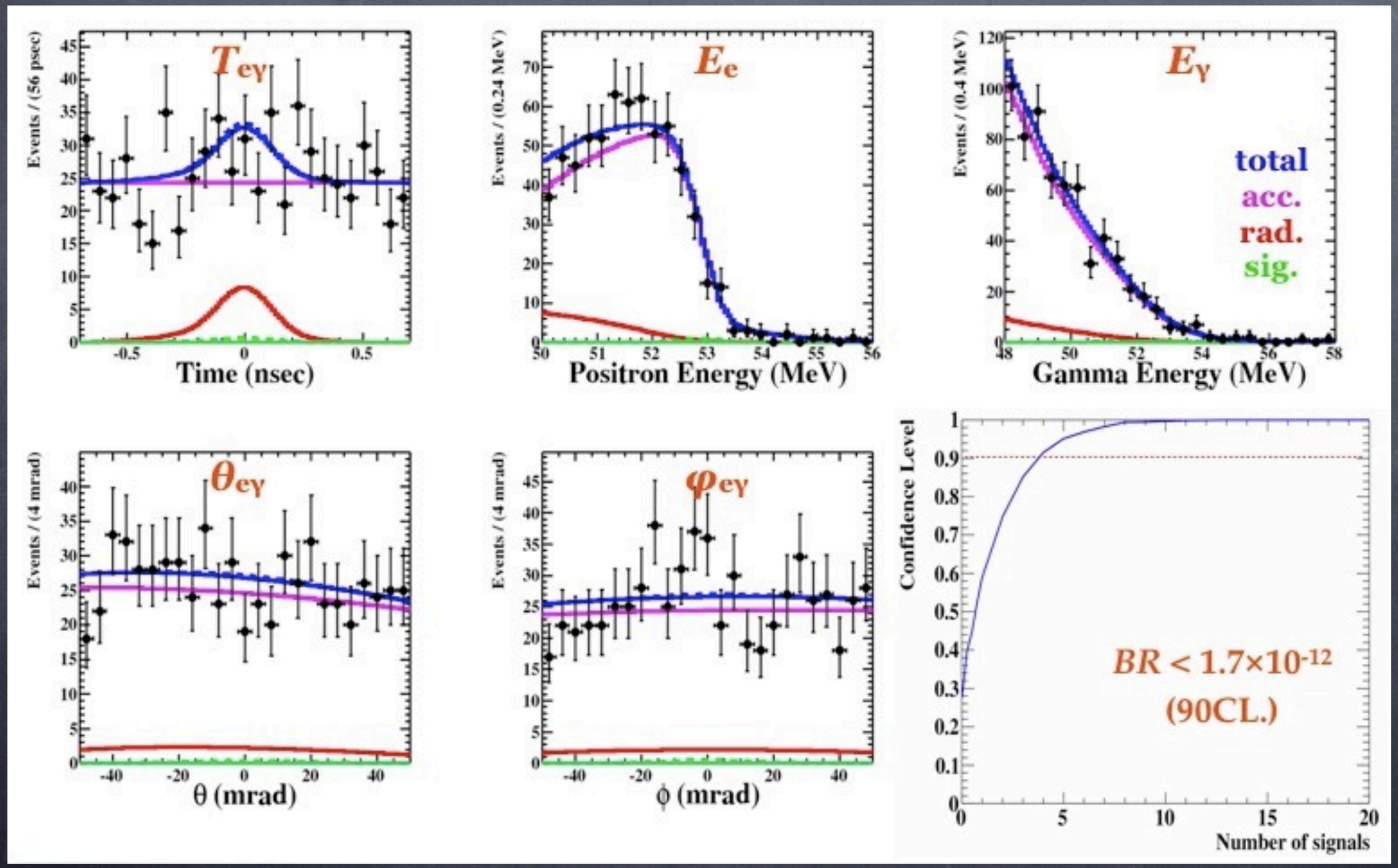
MEG - Run2009 (LH fit / CL curve)



MEG - Run2010 (Event Distribution)

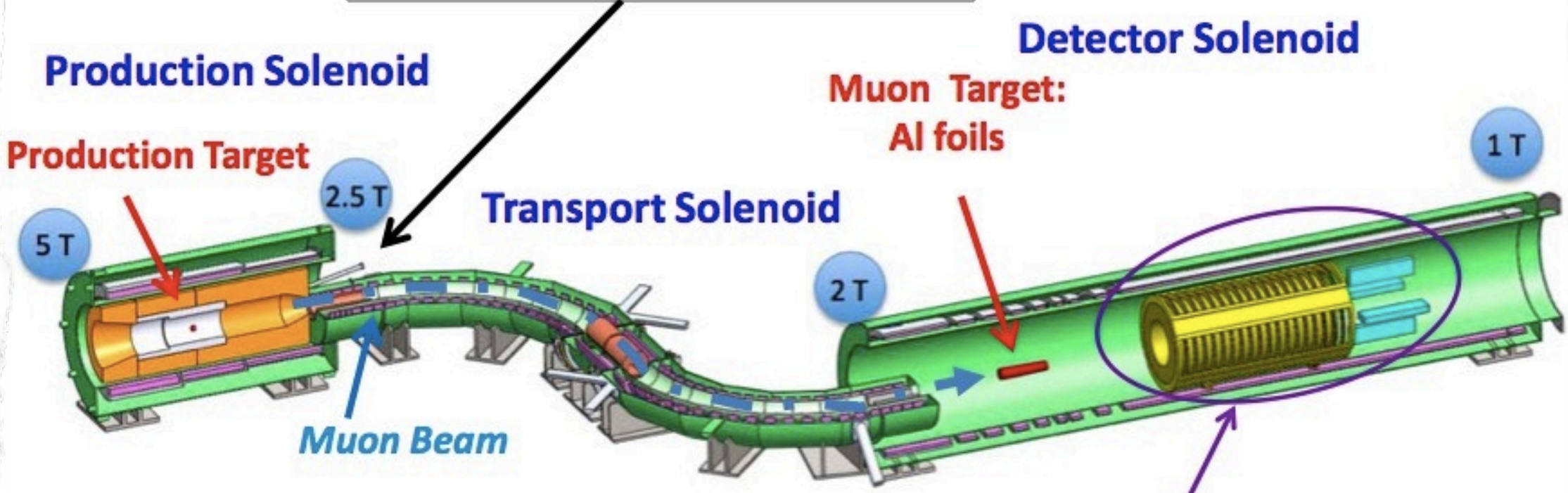


MEG - Run2010 (LH fit / CL curve)



mu2e : apparatus

Pulsed Proton Beam:
8 GeV protons produced by the Fermilab accelerator



DETECTORS:

- ▶ **Tracker** measures *e*- momentum with excellent intrinsic resolution (sigma core 115 keV/c , sigma tail 176 keV/c)
- ▶ **Calorimeter** after the tracker to confirm the signal