cLFV search with high intensity muon beams

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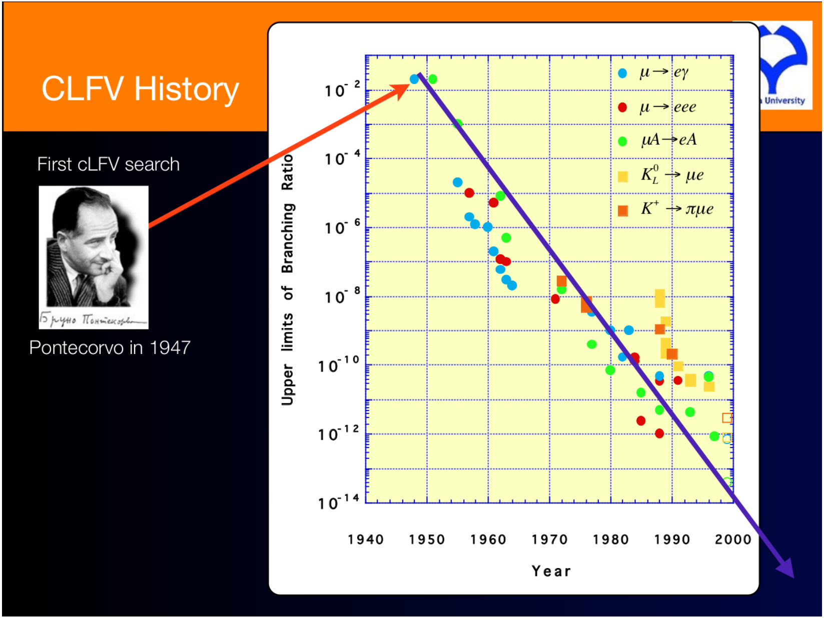
LPNHE Paris

G D R
neutrino

LPC Clermont,
9-10 june 2015

History (from Yoshitaka Kuno)

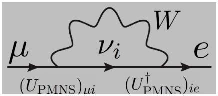


Physics Motivation : Beyond the Standard Model with muons

- We already know that LF is not conserved from neutrino oscillations.
- Direct search (Energy Frontier) LHC, ILC : higher energy for heavier new particle(s).

$$|A_{SM} + \varepsilon_{NP}|^2 \simeq |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP})$$

- Indirect search (Intensity Frontier): "slight" difference from SM prediction. cLFV in the SM (+m_ν) is negligibly small.



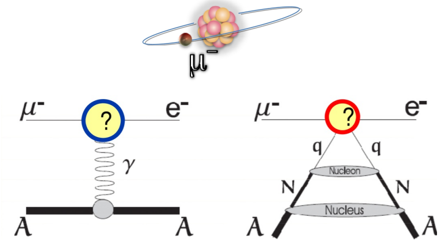
Adding some radiation for energy and momentum conservation.

μ-e transition results from the PMNS mixing.
Tiny neutrino mass suppresses the contribution.
Cheng and Li ('77,'80) Petcov('77).
$BR(\mu \to e\gamma) \simeq O(10^{-54})$.

$$|A_{SM} + \varepsilon_{NP}|^2 \simeq |\varepsilon_{NP}|^2 \Rightarrow \text{Rate} \simeq \frac{1}{\Lambda^4}$$

- Probe the PeV scale with cLFV.

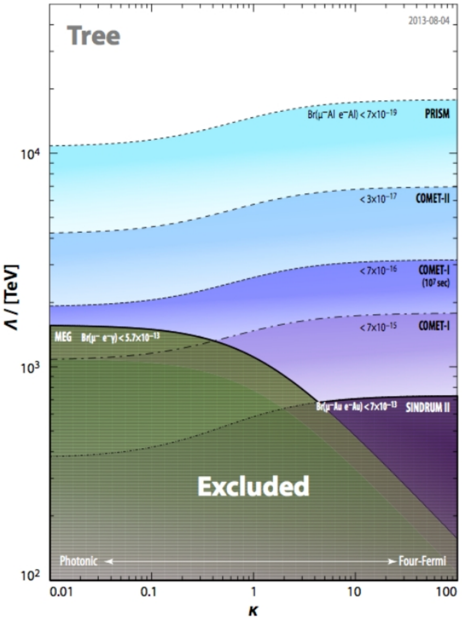
Exclusion diagrams



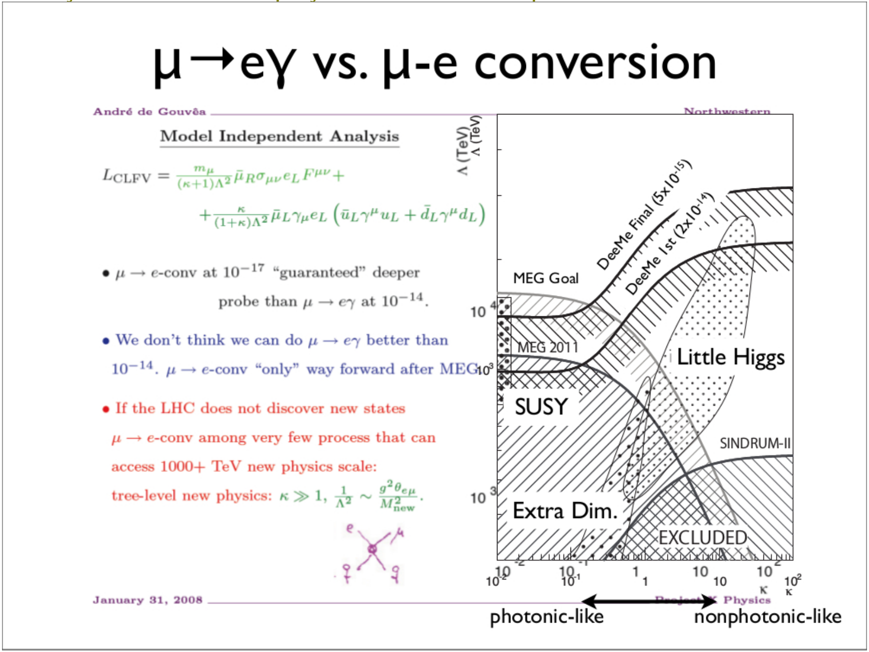
Dipole and 4-fermion couplings

$\mu^- N \to e^- N$ low energy effective lagrangian

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R \sigma^{\mu\nu} e_L \mathcal{F}_{\mu\nu}$$
$$+$$
$$\frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L) + h.c.$$



"Old Style" exclusion display with theoretical predictions



Experimental consequences

Rare decays searches require :

- Detectors with very good resolution and excellent background rejection.
- Background includes physical background, beam-related backgrounds, accidentals, cosmic rays and false tracking.
- As good as possible simulation and tracking are mandatory

Comparison between $\mu \to e\gamma$ and $\mu - e$ conversion :

	background	challenge	beam intensity
$\mu \to e\gamma$	accidentals	detector resolution	limited
$\mu - e$ conversion	beam	beam background	no limitation

- High intensity pulsed muon beams require strict proton beam extinction between pulses.
- Unlimited discussions on limits on BR or SES between experiments.

Current bounds and future sensitivities

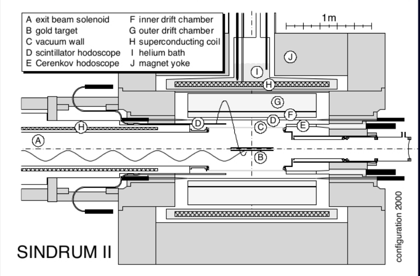
Process	Experiment	Limit
BR($\mu^+ \to e^+\gamma$)	MEG('13)	$5.7.10^{-13}$
	MEG-II($\geq$ '16) at PSI	4.10^{-14}
BR($\mu^+ \to eee$)	SINDRUM('88)	$1.0.10^{-12}$
	Mu3e($\geq$ '17) at PSI	$O(10^{-16})$
	MUSIC($\simeq$ '17)	$O(10^{-16})$
R($\mu \to e$:Au)	SINDRUM-II('06)	7.10^{-3}
R($\mu \to e$:Al)	COMET($\simeq$ '17)	$O(10^{-17})$
	Mu2e($\simeq$ '20)	$O(10^{-17})$
R($\mu \to e$:Ti)	PRISM($\simeq$ '20)	$O(10^{-18})$

PSI vs J-PARC : $10^8 \mu/s$ vs $10^{11} \mu/s$

Previous Measurements

Osaka University

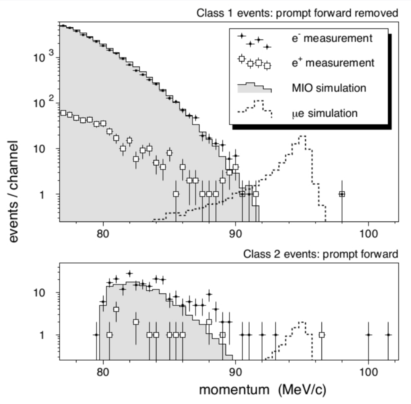
SINDRUM-II (PSI)



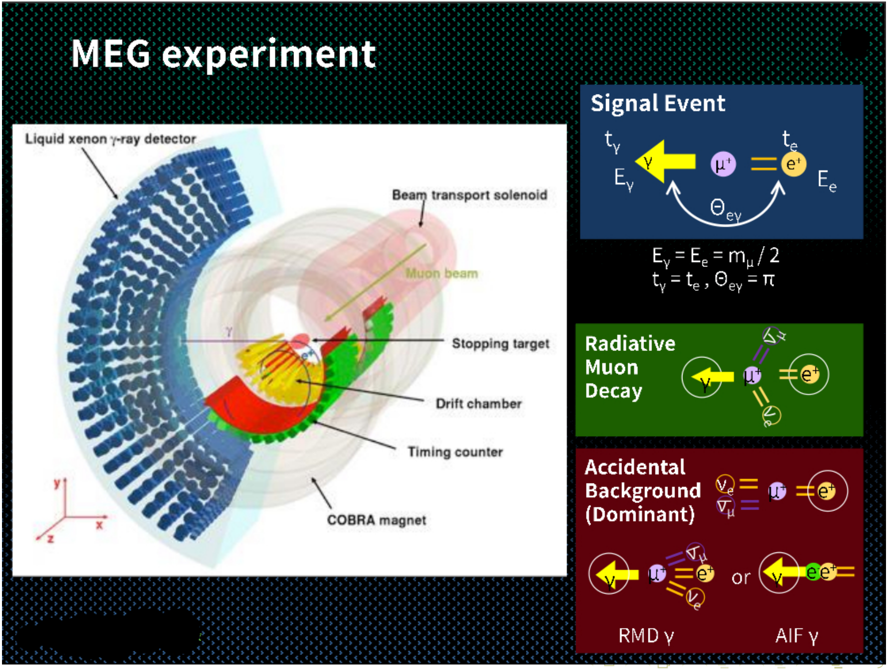
PSI muon beam intensity ~ 10^{7-8}/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results (2004)

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$

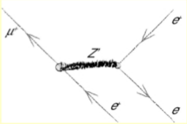


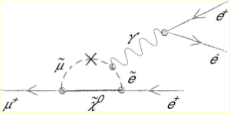
MEG

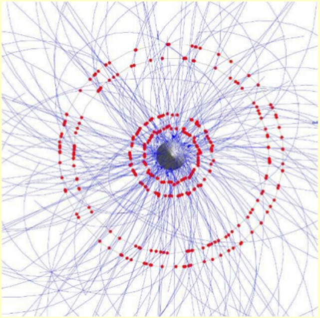

MEG experiment
Liquid xenon γ-ray detector
Beam transport solenoid
Muon beam
Stopping target
Drift chamber
Timing counter
COBRA magnet
y
x
z
Signal Event
t_γ
E_γ
t_e
E_e
$\Theta_{e\gamma}$
$E_\gamma = E_e = m_\mu / 2$
$t_\gamma = t_e$, $\Theta_{e\gamma} = \pi$
Radiative Muon Decay
Accidental Background (Dominant)
or
RMD γ
AIF γ

The Mu3e Experiment

- Search for LFV decay: **μ → eee**
- Single event sensitivity of
  - **10^{-15}** Phase I
  - **$<10^{-16}$** Phase II
- Muon rate **10^{8} ($>10^{9}$)** per second
- O(10) (O(100)) tracks within 50ns
- Sensitive to New Physics:



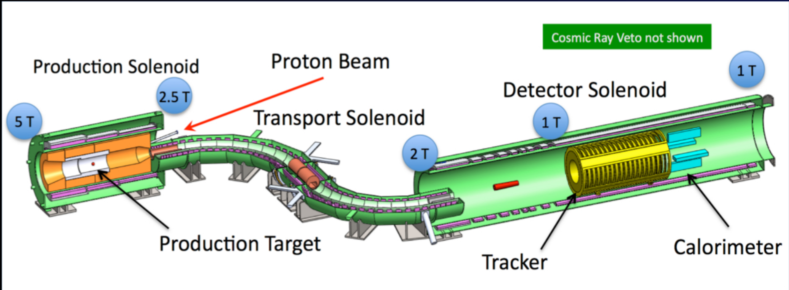




All silicon tracker
based on
HV-MAPS technology

Discussed in Research Proposal:
→ arXiv:1301.6113

μ-e conversion : Mu2e at Fermilab



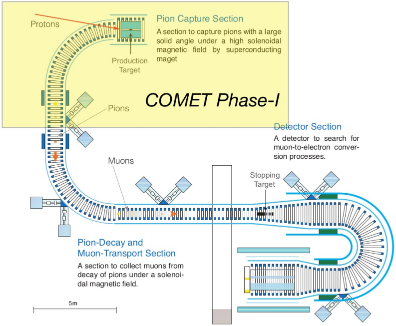
$$B(\mu^- + Al \to e^- + Al) = 5 \times 10^{-17} \quad \text{(S.E.)}$$
$$B(\mu^- + Al \to e^- + Al) < 10^{-16} \quad \text{(90\%C.L.)}$$

- Reincarnation of MECO at BNL.
- Antiproton buncher ring is used to produce a pulsed proton beam.
- Approved in 2009, and CD0 in 2009, and CD1 in 2011.
- Data taking starts in about 2019.

COMET

$\mu \to e$ conversion

- Staging approach
- Phase I to achieve 10^{-14} sensitivity and then Phase II



- Funding approved in JFY 2012 supplementary budget
- Annex of the current existing hall
- 8 GeV, pulsed proton beam to produce high-intensity muon beam
- COMET building finished and Muon Transport Solenoid installed

From Yoshitaka Kuno

From Yoshitaka Kuno

COMET Collaboration

Osaka University

164 collaborators
37 institutes, 13 countries

The COMET Collaboration

R. Akhmetshin[6,28], V. Anishchik[4], M. Aoki[29], R. B. Appleby[8,22], Y. Arimoto[15], Y. Bagaturia[33], Y. Ban[3], W. Bertsche[22], A. Bondar[6,28], S. Canfer[30], S. Chen[25], Y. E. Cheung[25], B. Chiladze[32], D. Clarke[30], M. Danilov[13,23], P. D. Dauncey[11], J. David[20], W. Da Silva[20], C. Densham[30], G. Devidze[32], P. Dornan[11], A. Drutskoy[13,23], V. Duginov[14], A. Edmonds[35], L. Epshteyn[6,27], P. Evtoukhovich[14], G. Fedotovich[6,28], M. Finger[7], M. Finger Jr[7], Y. Fujii[2], Y. Fukao[15], J-F. Genat[20], M. Gersabeck[22], E. Gillies[11], D. Grigoriev[6,27,28], K. Gritsay[14], R. Han[1], K. Hasegawa[15], I. H. Hasim[29], O. Hayashi[29], M. I. Hossain[16], Z. A. Ibrahim[21], Y. Igarashi[15], F. Ignatov[6,28], M. Iio[15], M. Ikeno[15], K. Ishibashi[19], S. Ishimoto[15], T. Itahashi[29], S. Ito[29], T. Iwami[29], Y. Iwashita[17], X. S. Jiang[2], P. Jonsson[11], V. Kalinnikov[14], F. Kapusta[20], H. Katayama[29], K. Kawagoe[19], V. Kazanin[6,28], B. Khazin[§6,28], A. Khvedelidze[14], M. Koike[36], G. A. Kozlov[14], B. Krikler[11], A. Kulikov[14], E. Kulish[14], Y. Kuno[29], Y. Kuriyama[18], Y. Kurochkin[5], A. Kurup[11], B. Lagrange[11,18], M. Lancaster[35], H. B. Li[2], W. G. Li[2], A. Liparteliani[32], R. P. Litchfield[35], P. Loveridge[30], G. Macharashvili[14], Y. Makida[15], Y. Mao[3], O. Markin[13], Y. Matsumoto[29], T. Mibe[15], S. Mihara[15], F. Mohamad Idris[21], K. A. Mohamed Kamal Azmi[21], A. Moiseenko[14], Y. Mori[18], N. Mosulishvili[32], E. Motuk[35], Y. Nakai[19], T. Nakamoto[15], Y. Nakazawa[29], J. Nash[11], M. Nioradze[32], H. Nishiguchi[15], T. Numao[34], J. O'Dell[30], T. Ogitsu[15], K. Oishi[19], K. Okamoto[29], C. Omori[15], T. Ota[31], H. Owen[22], C. Parkes[22], J. Pasternak[11], C. Plostinar[30], V. Ponariadov[4], A. Popov[6,28], V. Rusinov[13,23], A. Ryzhenenkov[6,28], B. Sabirov[14], N. Saito[15], H. Sakamoto[29], P. Sarin[10], K. Sasaki[15], A. Sato[29], J. Sato[31], D. Shemyakin[6,28], N. Shigyo[19], D. Shoukavy[5], M. Slunecka[7], M. Sugano[15], Y. Takubo[15], M. Tanaka[15], C. V. Tao[26], E. Tarkovsky[13,23], Y. Tevzadze[32], N. D. Thong[29], V. Thuan[12], J. Tojo[19], M. Tomasek[9], M. Tomizawa[15], N. H. Tran[29], I. Trek[32], N. M. Truong[29], Z. Tsamalaidze[14], N. Tsverava[14], S. Tygier[22], T. Uchida[15], Y. Uchida[11], K. Ueno[15], S. Umasankar[10], E. Velicheva[14], A. Volkov[14], V. Vrba[9], W. A. T. Wan Abdullah[21], M. Warren[35], M. Wing[35], T. S. Wong[29], C. Wu[2,25], G. Xia[22], H. Yamaguchi[19], A. Yamamoto[15], M. Yamanaka[24], Y. Yang[19], H. Yoshida[29], M. Yoshida[15], Y. Yoshii[15], T. Yoshioka[19], Y. Yuan[2], Y. Yudin[6,28], J. Zhang[2], Y. Zhang[2]

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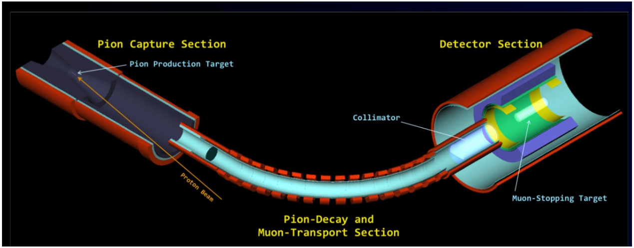
COMET (E21)

COMET Phase I (2016)

- Beam background study and achieve S.E.S. $\simeq 3.10^{-15}$ with 8 GeV - 3.2 kW proton beam, $\sim$ 3 months DAQ

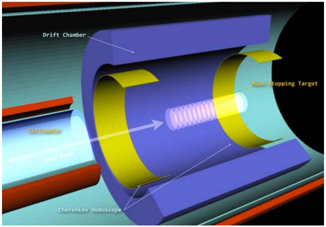


COMET Phase II (2020)

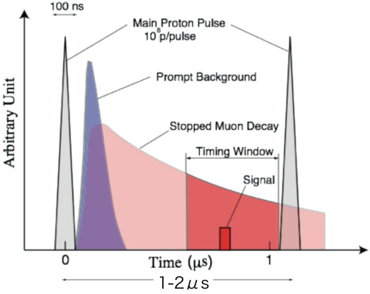
- 8 GeV - 56 kW proton beam , $\sim$ 1 year DAQ to achieve the COMET final goal of S.E.S $\simeq 3.10^{-17}$

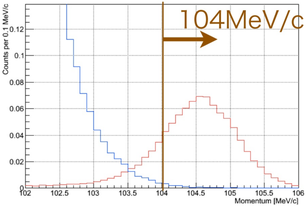
France-Japan collaboration in COMET

- CDC and Triggering counter surrounding a muon stopping target



- $\mu \to e$ conversion signal identified with an energetic electron of 105MeV emitted from a muonic atom with delayed timing.





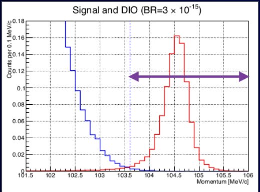
Signal Sensitivity for COMET Phase-I with CyDet

Osaka University

Signal Acceptance

Table 28: *Breakdown of the $\mu^- N \to e^- N$ conversion signal acceptance.*

Event selection	Value	Comments
Geometrical acceptance	0.37	
Track quality cuts	0.66	
Momentum selection	0.93	$103.6\ \mathrm{MeV}/c < P_e < 106.0\ \mathrm{MeV}/c$
Timing window	0.3	$700\ \mathrm{ns} < t < 1100\ \mathrm{ns}$
Trigger efficiency	0.8	
DAQ efficiency	0.8	
Track reconstruction efficiency	0.8	
Total	0.043	



Signal Sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

- $f_{cap} = 0.6$
- $A_e = 0.043$
- $N_\mu = 1.23 \times 10^{16}$ muons

$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-15}$$

$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

Muon intensity

about 0.00052 muons stopped/proton

With 0.4 μA, a running time of about 110 days is needed.

Background Estimate for COMET Phase-I with CyDet

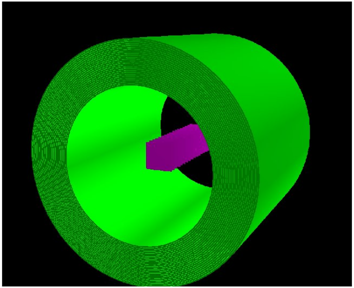
Osaka University

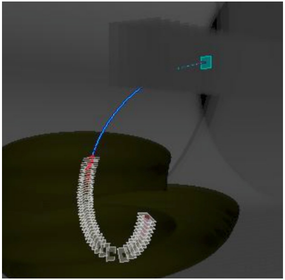
Table 30: *Summary of the estimated background events for a single-event sensitivity of* 3.1×10^{-15} *with a proton extinction factor of* 3×10^{-11}.

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
Physics	Radiative muon capture	5.6×10^{-4}
Physics	Neutron emission after muon capture	< 0.001
Physics	Charged particle emission after muon capture	< 0.001
Prompt Beam	Beam electrons (prompt)	8.3×10^{-4}
Prompt Beam	Muon decay in flight (prompt)	$\leq 2,0 \times 10^{-4}$
Prompt Beam	Pion decay in flight (prompt)	$\leq 2.3 \times 10^{-3}$
Prompt Beam	Other beam particles (prompt)	$\leq 2.8 \times 10^{-6}$
Prompt Beam	Radiative pion capture(prompt)	2.3×10^{-4}
Delayed Beam	Beam electrons (delayed)	~ 0
Delayed Beam	Muon decay in flight (delayed)	~ 0
Delayed Beam	Pion decay in flight (delayed)	~ 0
Delayed Beam	Radiative pion capture (delayed)	~ 0
Delayed Beam	Anti-proton induced backgrounds	0.007
Others	Electrons from cosmic ray muons	< 0.0001
Total		0.019

France-Japan collaboration in COMET

- LPNHE R&D for an active muon stopping target in order to get an additional point for the electron trajectory (CM11 - 2013)

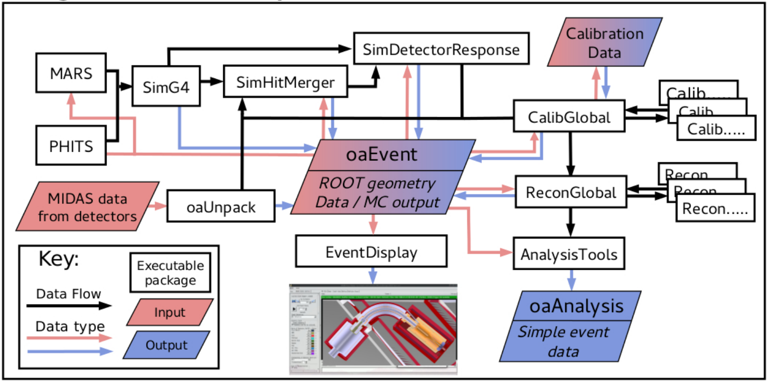




- Simulation and reconstruction with GENFIT within ICEDUST(Integrated Comet Experiment Data User Software Toolkit), the new COMET Software Framework rooted in T2K ND280.
- Discussion on the possibility of a beam test of ATLAS pixels at J-PARC with Kyushu University.
- MARS and ICEDUST installed at CCIN2P3 (thanks to Yonny Cardenas).

ICEDUST Overview

Integrated Comet Experiment Data User Software Toolkit



Recent history

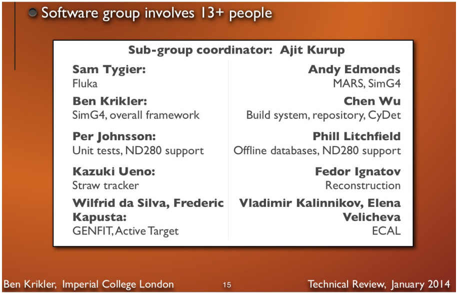
- COMET Software Framework: from ND280 to ICEDUST.
  Imperial College London lead : Ajit Kurup, Ben Krikler
- Common COMET g-2/EDM FJPPL Workshop (Paris, 20-21 february 2014)

- 3rd Workshop on Muon g-2, EDM and Flavour Violation in the LHC Era in december 2014

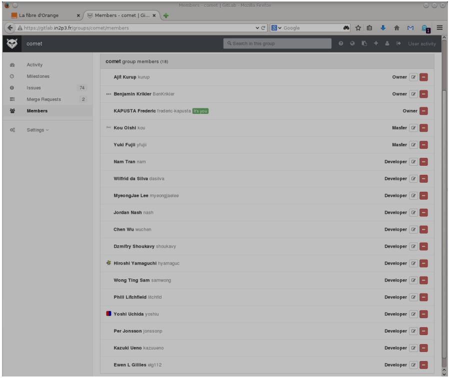
- It was the right time for a decision from CCIN2P3 director and IN2P3 Particle Scientific Deputy Director to create a comet group to allow "foreign collaborators" to register and use CCIN2P3 machines.

Software Activity

Software group structure, january 2014



GitLAB members, march 2015

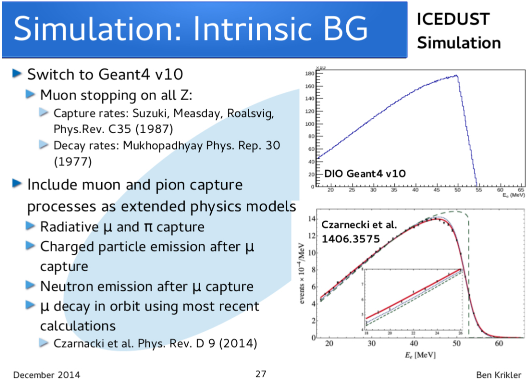


Recent events

- Accepted proposal from the french group to use the CCIN2P3 computing power and support in order to prepare a Grid computing at the COMET Collaboration level.
- Accepted proposal to have gitlab.in2p3.fr hosting the COMET software in order to ease the collaborative work.
- ICEDUST is running with MARS using a common 1 TB of semi-permanent space on /sps/hep/comet.
- SimMARS has been tested and optimized at CCIN2P3.
- A MySQL database is available for parameters storage.
- muon.in2p3.fr is a french website under construction to unify μ^+ (g-2/EDM) and μ^- (COMET) experiments for BSM physics, the official COMET website being comet.kek.jp
- AtCM16, CCIN2P3 was accepted as a COMET Member.
- Full Simulation is currently running at CCIN2P3 with 20 TB of data storage using iRODS for data sharing.

Questions and a proposal

- From the "3rd Workshop on Muon g-2, EDM and Flavour Violation ..." :
  - new idea of cLFV search $\mu^- e^- \to e^- e^-$ in muonic atom.
  - upgrade of the DIO spectrum using Czarnecki last computation...



- Expected contribution from french theorists : model predictions and "advertising plots".
- You are invited to give a talk at CM17 beginning of september in Paris and ... maybe join COMET.
- "4^{th} Workshop on Muon g-2, EDM and Flavour Violation in the LHC Era" in 2016 organized in Marseilles by Marc Knecht.