UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

Past and Plans

Fedor Ignatov
University of Liverpool

Leverhulme Retreat
Caer Beris Manor, Wales
19 September2025

An alternative evaluation of the $a_\mu^{LO\ had}$ with MUonE

Phys.Lett.B 848 (2024) 138344

Fedor Ignatov, Riccardo Pilato,
Thomas Teubner, Graziano Venanzoni

<u>Idea:</u> Replace kernel in a_μ integral with approx $K_1(s)$

→ evaluation via derivatives $\alpha'(0)$, $\alpha''(0)$, ..

$$a_\mu^{had} = -\frac{\alpha}{\pi}\int \frac{ds}{s} K(s) \frac{1}{\pi} \mathrm{Im}\, P(s)$$

MUonE $$= -\frac{\alpha}{\pi}\Big\{ a_1\,\alpha'(0) + \frac{a_2}{2}\alpha''(0) + \frac{a_3}{6}\alpha'''(0)$$ **~ 690x10^{-10}**

e+e- $$+\int_{s_{th}}^{s_0} \frac{ds}{s}\left(K(s)-K_1(s)\right)\frac{1}{\pi}\Im P(s)$$ **~ 2x10^{-10}**

pQCD $$-\frac{1}{2\pi i}\oint_{|s|=s_0} \frac{ds}{s} K_1^0 P(s) + \int_{s_0}^{inf} \frac{ds}{s}\left(K(s)-K_1^1(s)\right)\frac{1}{\pi}\Im P(s)$$ **~3x10^{-10}**

Phys. Lett. B 848 (2024) 138344

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Physics Letters B

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Letter

An alternative evaluation of the leading-order hadronic contribution to the muon $g-2$ with MUonE

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A R T I C L E I N F O

Editor: G.F. Giudice

A B S T R A C T

We propose an alternative method to extract the leading-order hadronic contribution to the muon $g-2$, a_μ^{HLO}, with the MUonE experiment. In contrast to the traditional method based on the integral of the hadronic contribution to the running of the electromagnetic coupling, $\Delta\alpha_{had}$, in the space-like region, our approach relies on the computation of the derivatives of $\Delta\alpha_{had}(t)$ at zero squared momentum transfer t. We show that this approach allows to extract $\sim 99\%$ of the total value of a_μ^{HLO} from the MUonE data, while the remaining $\sim 1\%$ can be computed combining perturbative QCD and data on e^+e^- annihilation to hadrons. This leads to a competitive evaluation of a_μ^{HLO} which is robust against the parameterization used to model $\Delta\alpha_{had}(t)$ in the MUonE kinematic region, thanks to the analyticity properties of $\Delta\alpha_{had}(t)$, which can be expanded as a polynomial at $t \sim 0$.

1. Introduction

The muon anomalous magnetic moment, also known as the muon $g-2$, where g is the muon gyromagnetic ratio, exhibits a discrepancy between theory and experiment which persists for more than 20 years. It has received renewed interest, following the first measurement of the muon anomaly $a_\mu = (g-2)/2$ by the Muon $g-2$ Experiment at Fermilab [1], subsequently confirmed by the new result with a twofold improved precision [2]. The comparison with the Standard Model (SM) prediction a_μ^{SM} [3] is currently limited by tensions in the evaluation of the leading-order hadronic contribution to the muon anomaly, a_μ^{HLO} [4]. This term represents the main source of uncertainty of the theory prediction, due to the non-perturbative nature of QCD at low energy. A recent computation of a_μ^{HLO} based on lattice QCD, performed by the BMW Collaboration [5], indeed shows a 2.1σ tension with the one used in the SM evaluation of a_μ [3], which is based on a data-driven approach involving data for $e^+e^- \to$ hadrons cross sections. Moreover, a new experimental measurement of $e^+e^- \to \pi^+\pi^-$ channel from the CMD-3 experiment disagrees with the previous measurements [6]. New calculations from other lattice QCD groups and new results from e^+e^- colliders are expected to shed light on these tensions in the next few years [4].
Recently a new approach has been proposed to compute a_μ^{HLO}, based on the measurement of the hadronic contribution to the running of the electromagnetic coupling, $\Delta\alpha_{had}$, in the space-like region [7]. The elastic scattering of high-energy muons on atomic electrons has been identified as an ideal process for this measurement and an experimental proposal, called MUonE, has been put forward at CERN to extract $\Delta\alpha_{had}$ from a precise measurement of the shape of the $\mu^+e^- \to \mu^+e^-$ elastic process [8]. The goal of MUonE is to determine a_μ^{HLO} with a $\sim 0.3\%$ statistical and a comparable systematic uncertainty, using the following integral [9]:

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)], \qquad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0, \tag{1}$$

where α is the fine structure constant, m_μ is the muon mass, and t is the space-like squared momentum transfer. The 160 GeV muon beam available at the M2 beamline at CERN allows to cover directly the momentum transfer range $-0.153\ \mathrm{GeV}^2 < t < -0.001\ \mathrm{GeV}^2$, which is equivalent to $0.258 < x < 0.936$. This corresponds to $\sim 86\%$ of the integral in Eq. (1), while the remaining fraction can be obtained by extrapolating $\Delta\alpha_{had}(t)$ outside the MUonE region by an appropriate analytical function or alternatively by using lattice data. In the first case the space-like integral of Eq. (1) is sensitive to the behaviour of the parameterization chosen to model $\Delta\alpha_{had}(t)$ in the whole t-region,

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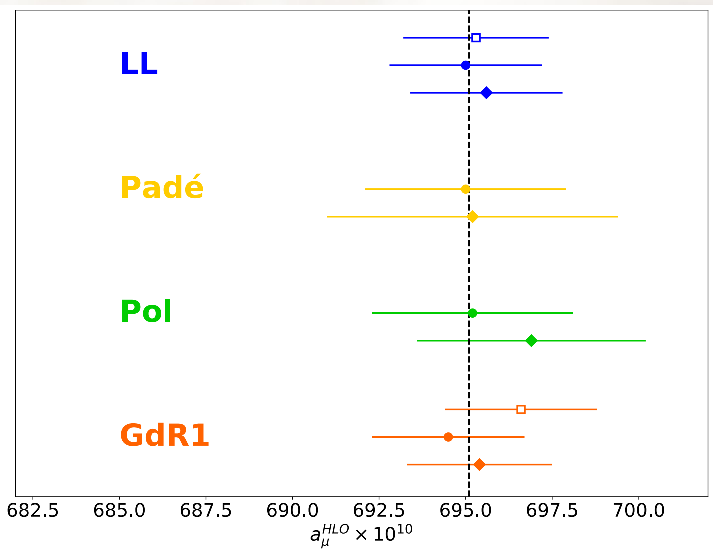
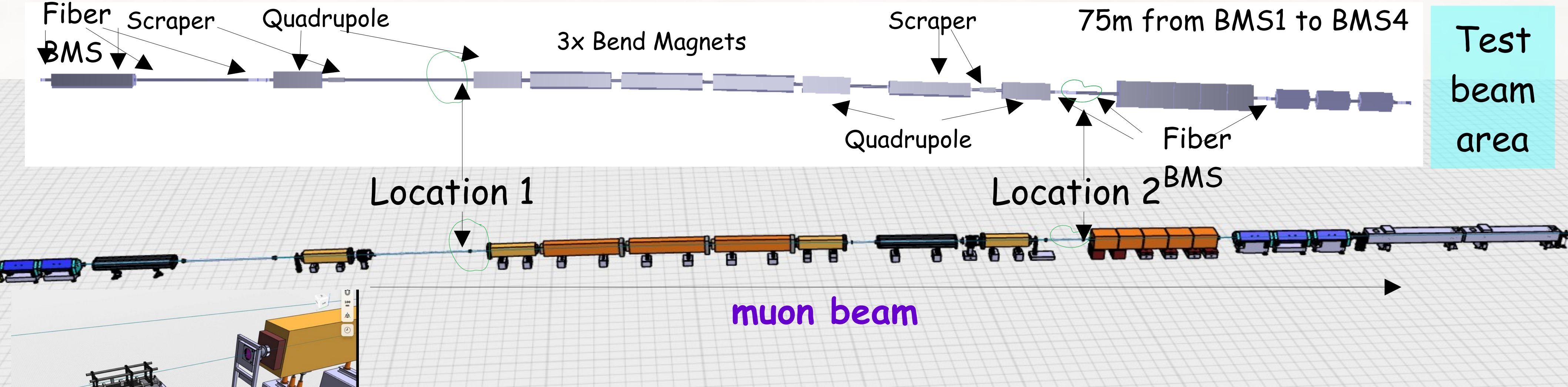
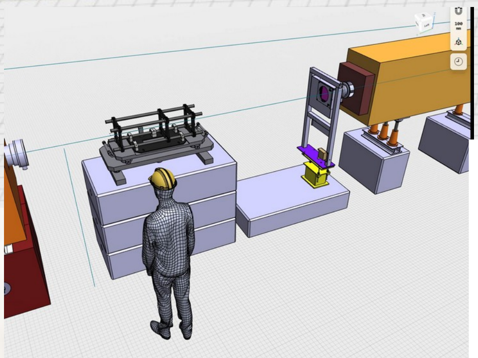


<u>Result:</u>
full a_μ integral
much more stable
regardless of different
$\alpha(t)$ parametrizations

Retreat, Wales

BMS simulation





BMS simulation (full GDML beamline model):
- standalone Geant4 MC and reconstruction
- simulation inside of FairMUonE framework

Muon beam is not monochromatic — RMS $E / E_{\mu\ beam}$ = 3.75% → Effect **22** x 10^{-5} on $d\sigma/d\theta_{e^-}$ spectra

BMS can provide $\sigma_E/E_{\mu\ beam}$ = 0.1% → Suppress the effect completely

Event-by-event BMS vs tracker sync → Will do μ-e scattering band twice narrower (S/N improved)

g-2 WP, RMCL efforts

SciPost Phys.Comm.Rep. (2025) 009

RMCLow

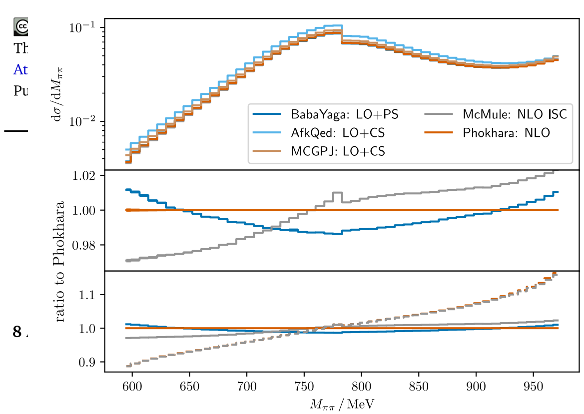
SciPost SciPost Phys. Comm. Rep. 9 (2025)

Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions

Riccardo Aliberti[1], Paolo Beltrame[2], Ettore Budassi[3,4], Carlo M. Carloni Calame[4], Gilberto Colangelo[5], Lorenzo Cotrozzi[2], Achim Denig[1], Anna Driutti[6,7], Tim Engel[8], Lois Flower[2,9], Andrea Gurgone[3,6,7], Martin Hoferichter[5], Fedor Ignatov[2], Sophie Kollatzsch[10,11], Bastian Kubis[12], Andrzej Kupść[13,14*], Fabian Lange[10,11], Alberto Lusiani[7,15], Stefan E. Müller[16], Jérémy Paltrinieri[2], Pau Petit Rosàs[2], Fulvio Piccinini[4], Alan Price[17], Lorenzo Punzi[7,15], Marco Rocco[10,18], Olga Shekhovtsova[19,20], Andrzej Siódmok[17], Adrian Signer[10,11*], Giovanni Stagnitto[21], Peter Stoffer[10,11], Thomas Teubner[2], William J. Torres Bobadilla[2], Francesco P. Ucci[3,4], Yannick Ulrich[2,5*] and Graziano Venanzoni[2,7*]
(RadioMonteCarLow 2 working group)

Abstract

We present the results of Phase I of an ongoing review of Monte Carlo tools relevant for low-energy hadronic cross sections. This includes a detailed comparison of Monte Carlo codes for electron–positron scattering into a muon pair, pion pair, and electron pair, for scan and radiative-return experiments. After discussing the various approaches that are used and effects that are included, we show differential cross sections obtained with AFKQED, BABAYAGA@NLO, KKMC, MCGPJ, MCMULE, PHOKHARA, and SHERPA, for scenarios that are inspired by experiments providing input for the dispersive evaluation of the hadronic vacuum polarisation.



White Paper 25

Physics Reports 1143 (2025) 1–158

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Phys.Rept. 1143 (2025) 1-158

Review article

The anomalous magnetic moment of the muon in the Standard Model: an update

R. Aliberti [1,2], T. Aoyama [3], E. Balzani [4,5], A. Bashir [6,7], G. B… V. Biloshytskyi [1,2], T. Blum [11,12], D. Boito [13], M. Bruno [14,15] … S. Burri [18], L. Cappiello [19], C.M. Carloni Calame [17], M. Cè … D.A. Clarke [22], G. Colangelo [18,*], L. Cotrozzi [23], M. Cottini … M. Davier [24,*], M. Della Morte [25], A. Denig [1,2,26,27], C. DeTa… G. Eichmann [29], A.X. El-Khadra [8,9,*], E. Estrada [30], X. Feng … R. Frezzotti [36], G. Gagliardi [37], A. Gérardin [38], M. Ghilardi … M. Golterman [41], S. Gonzàlez-Solís [42,43], S. Gottlieb [44], R. … V. Gülpers [47], A. Gurgone [48,49], F. Hagelstein [1,2], M. Hayal… N. Hermansson-Truedsson [10,47], A. Hoecker [52], M. Hoferi… S. Holz [18], R.J. Hudspith [53], F. Ignatov [23], L. Jin [11], N. Kalnt… A. Keshavarzi [54], J. Komijani [45], J. Koponen [1,2], S. Kubersk… A. Kupich [28], A. Kupść [57,58], S. Lahert [22], S. Laporta [4,5], C. L… M. Lellmann [1], L. Lellouch [38,*], T. Leplumey [59,60], J. Leutge… I. Logashenko [28], C.Y. London [13], G. López Castro [30], J. Lüc… A. Lutz [24], J. Mager [61], B. Malaescu [65], K. Maltman [66,67], M… J. Márquez [30], P. Masjuan [68,69], H.B. Meyer [1,2,26,27], T. Mibe… A. Miramontes [71,72], A. Miranda [68], G. Montagna [16,17], S.E… A.V. Nesterenko [28], O. Nicrosini [17], M. Nio [51,75], D. Nomu…

Formal Role:

Data-driven HVP

WG coordinator

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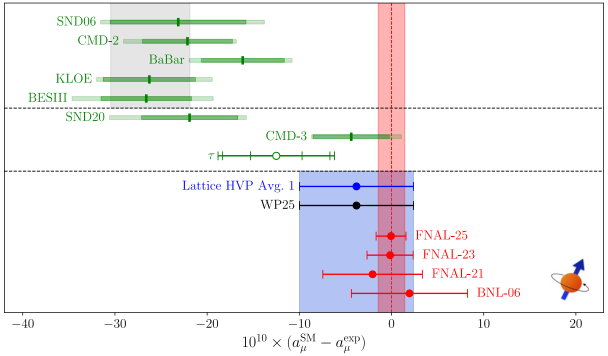
We dedicate this paper to the memory of Simon Eidelman.

Keywords:
Anomalous magnetic moment of the muon

ABSTRACT

We present the current Standard Model (SM) prediction for the muon anomalous magnetic moment, a_μ, updating the first White Paper (WP20) [1]. The pure QED and electroweak contributions have been further consolidated, while hadronic contributions continue to be responsible for the bulk of the uncertainty of the SM prediction. Significant progress has been achieved in the hadronic light-by-light scattering contribution using both the data-driven dispersive approach as well as lattice-QCD calculations, leading to a reduction of the uncertainty by almost a factor of two. The most important development since WP20 is the change in the estimate of the leading-order hadronic-vacuum-polarization (LO HVP) contribution. A new measurement of the $e^+e^- \to \pi^+\pi^-$ cross section by CMD-3 has increased the tensions among data-driven dispersive evaluations of the LO HVP contribution to a level that makes it impossible to combine the results in a meaningful way. At the same time, the attainable precision of lattice-QCD calculations has increased substantially and allows for a consolidated lattice-QCD average of the LO HVP contribution with a precision of about 0.9%. Adopting the latter in this update has resulted in a major upward shift of the total SM prediction, which now reads $a_\mu^{SM} = 116\,592\,033(62) \times 10^{-11}$ (530 ppb). When compared against the current experimental average based on the E821 experiment and runs 1–6 of E989 at Fermilab, one finds $a_\mu^{exp} - a_\mu^{SM} = 38(63) \times 10^{-11}$, which implies that there is no tension between the SM and experiment at the current level of precision. The final precision of E989 (127 ppb) is the target of future efforts by the Theory Initiative. The resolution of the tensions among data-driven dispersive evaluations of the LO HVP contribution will be a key element in this endeavor.



MEG experiment

2021 dataset: Eur.Phys.J.C 84 (2024) 3, 216

2021-22 dataset: E-Print: 2504.15711 (EPJC accepted)

Eur. Phys. J. C (2024) 84:216
https://doi.org/10.1140/epjc/s10052-024-12416-2

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

A search for $\mu^+ \to e^+\gamma$ with the first dataset of the MEG II experiment

MEG II Collaboration

K. Afanaciev[1], A. M. Baldini[2a], S. Ban[3], V. Baranov[1], H. Benmansour[2a,2b], M. Biasotti[4a], G. Boca[5a,5b], P. W. Cattaneo[5a,a], G. Cavoto[6a,6b], F. Cei[2a,2b], M. Chiappini[2a,2b], G. Chiarello[7a,18], A. Corvaglia[7a], F. Cuna[7a,7b,19], G. Dal Maso[8,9], A. De Bari[5a], M. De Gerone[4a], L. Ferrari Barusso[4a,4b], M. Francesconi[10], L. Galli[2a], G. Gallucci[4a], F. Gatti[4a,4b], L. Gerritzen[3], F. Grancagnolo[7a], E. G. Grandoni[2a,2b], M. Grassi[2a], D. N. Grigoriev[11,12,13], M. Hildebrandt[8], K. Ieki[3], F. Ignatov[14], F. Ikeda[3], T. Iwamoto[3], S. Karpov[11,13], P.-R. Kettle[8], N. Khomutov[1], S. Kobayashi[3], A. Kolesnikov[1], N. Kravchuk[1], V. Krylov[1], N. Kuchinskiy[1], W. Kyle[15], T. Libeiro[15], V. Malyshev[1], A. Matsushita[3], M. Meucci[6a,6b], S. Mihara[16], W. Molzon[15], Toshinori Mori[3], M. Nakao[3], D. Nicolò[2a,2b], H. Nishiguchi[16], A. Ochi[17], S. Ogawa[3], R. Onda[3], W. Ootani[3], A. Oya[3], D. Palo[15], M. Panareo[7a,7b], A. Papa[2a,2b,8], V. Pettinacci[6a], A. Popov[11,13], F. Renga[6a], S. Ritt[8] ... K. Shimada[3], G. Signorelli[2a], M. Takahashi[17], G ... A. Venturini[2a,2b], B. Vitali[2a,6b], C. Voena[6a,6b], K ... Yu. V. Yudin[11,13]

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[11] Budker Instit...
[12] Novosibirsk ...
[13] Novosibirsk ...
[14] Oliver Lodge...
[15] University of...
[16] KEK, High E...
[17] Kobe Univer...
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Received: 19 O...

~24 shifts/person
24hoursx7day – shifts coordination

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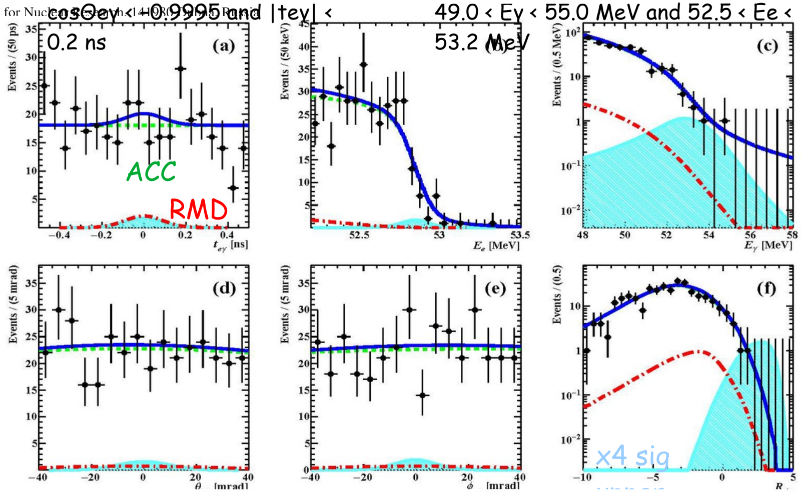

Upper limit reduced by 1./3 to the MEG-I result
Another factor 1./3 from full MEGII data

Eur.Phys.J.C 85 (2025) 7, 763

Eur. Phys. J. C (2025) 85:763
https://doi.org/10.1140/epjc/s10052-025-14345-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Search for the X17 particle in ^{7}Li(p, e^+e^-)^{8}Be processes with the MEG II detector

MEG II Collaboration*

K. Afanaciev[1], A. M. Baldini[2a], S. Ban[3], H. Benmansour[2a,2b], G. Boca[5a,5b], P. W. Cattaneo[5a], G. Cavoto[6a,6b,a], F. Cei[2a,2b], M. Chiappini[2a,2b], A. Corvaglia[7a], G. Dal Maso[8,9], A. De Bari[5a], M. De Gerone[4a], L. Ferrari Barusso[4a,4b], M. Francesconi[10], L. Galli[2a], G. Gallucci[2a], F. Gatti[4a,4b], L. Gerritzen[3], F. Grancagnolo[7a], E. G. Grandoni[2a,2b], M. Grassi[2a], D. N. Grigoriev[11,12], M. Hildebrandt[8], F. Ignatov[13], F. Ikeda[3], T. Iwamoto[3], S. Karpov[11], P. -R. Kettle[8], A. Kolesnikov[1], N. Khomutov[1], N. Kravchuk[1], V. Krylov[1], N. Kuchinskiy[1], F. Leonetti[2a,2b], W. Li[3], V. Malyshev[1], A. Matsushita[3], M. Meucci[6a,6b], S. Mihara[15], W. Molzon[14], T. Mori[3], D. N. Nicolò[2a,2b], H. Nishiguchi[15], A. Ochi[16], W. Ootani[3], A. Oya[3], D. Palo[14], M. Panareo[7a,7b], A. Papa[2a,2b,8], V. Pettinacci[6a], A. Popov[11], F. Renga[6a], S. Ritt[8], M. Rossella[5a], A. Rozhdestvensky[1], S. Scarpellini[6a,6b], P. Schwendimann[8,a], G. Signorelli[2a], M. Takahashi[16], Y. Uchiyama[15], A. Venturini[2a,2b], B. Vitali[2a,6b], C. Voena[6a,6b], K. Yamamoto[3], R. Yokota[3], T. Yonemoto[3]

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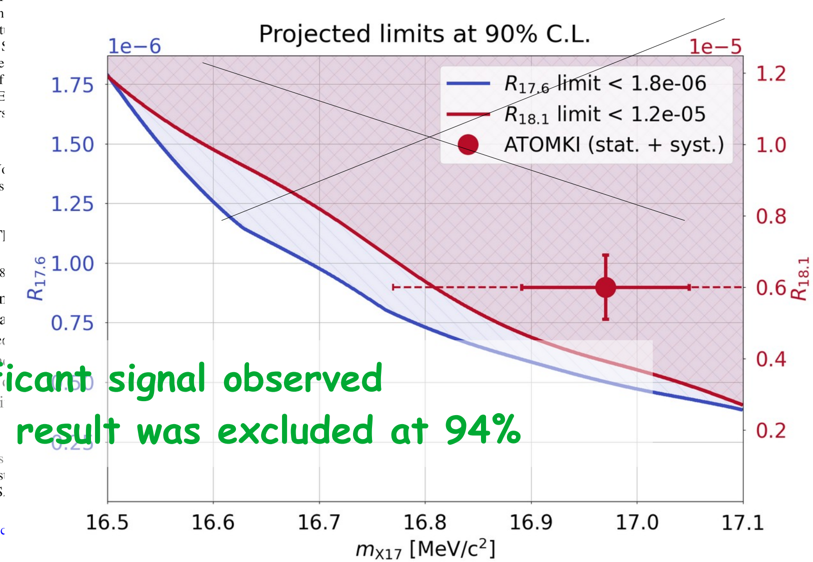
[13] Oliver Lodge...
[14] University of...
[15] KEK, High E...
[16] Kobe Univers...

Formal Role:
In review committee
for go/no-go unblinding

Received: 15 N...

Abstract T... the opening ... ^{7}Li(p,e^+e^-)^8... production an... (X17). Simila... later observe... with the sam... can be exploi...

[a] Present address: ... Physics and As... WA 98195, US...
[†] Deceased
[a] e-mail: gianluc...



No significant signal observed
ATOMKI result was excluded at 94%

Tracking in DCH of MEGII

Liverpool responsibility:

tracks pattern recognition algorithms

MEG DCH Operation under high hit rate

Hit rate up to 1.2 MHz per cell at $5{\times}10^{7}$ s^{-1} beam rate: 25% cell occupancy in 250ns.

Higher occupancy than in Alice TPC or Belle2 CDC

MEGII CDCH 9 layers vs 159 rows or 56 layers

MEG2 Track Finding is harder

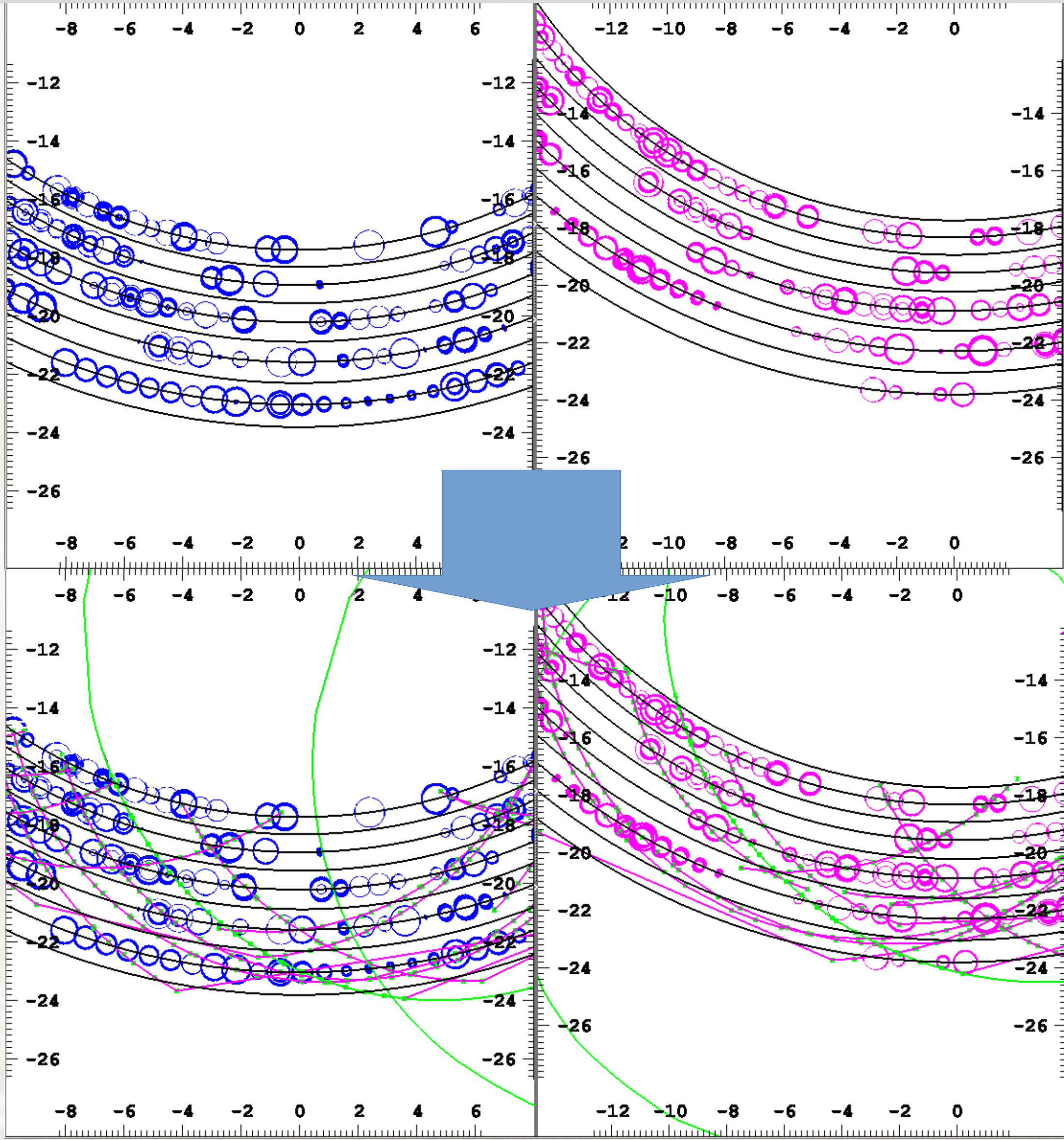
Needs stereo view + 4D reconstruction

(stereo DCH + t0 for each track)

PR based on conventional Kalman filter track following method

Further boost in a efficiency with:

ML: Transformer + GNN as additional prefilter are under development by collaboration



MEG counting room

August 2012

November 2024

Quiz: How many same objects are there in the two photos?

Since 2025 we have new counting room

In MEG collaboration since 2005
20 years….

KLOE

☐☑ Phase 0 – get data – see Lorenzo's slides

personal learning footpath

☑☐ Phase I – understand data

☑☐ Phase II – get MC/reco tools in hands

☐☐ Phase III – start to do analysis

Phase I

Cross checked:

prod2root sufficient to reproduce identically (up FP prec) everything in:

stentu,

F.Nguen's mmgeff/ppgeff/rpieff/cc2eff, …

VLAB

It was useful to understand how ntuples filled, cuts/streaming are applied

Phase II

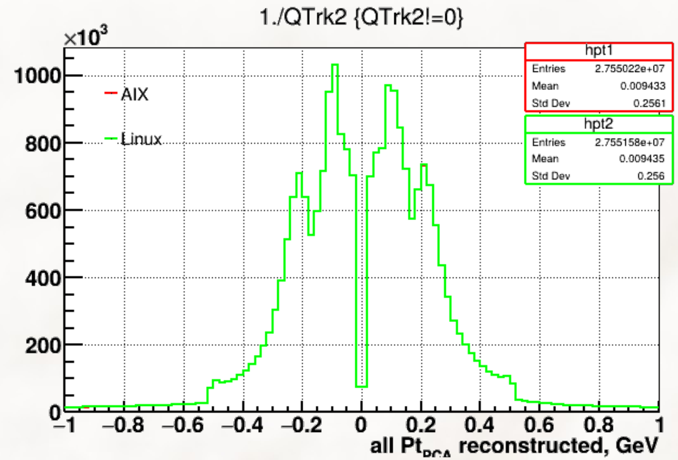
KLOE soft have been ported to Linux

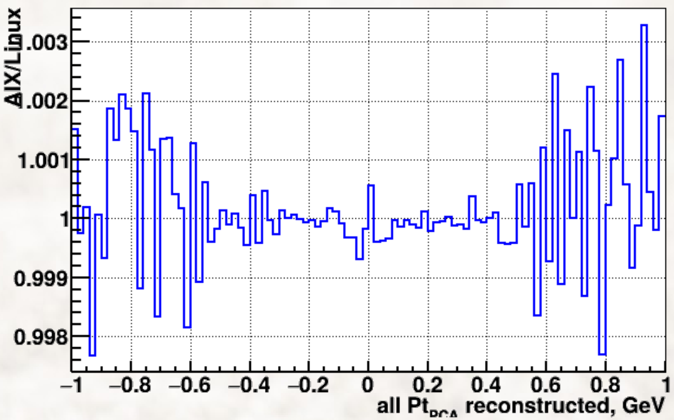
This gave an experience on geanfi, reconstructions, dataflow…

Runs:
24083,26758,41883

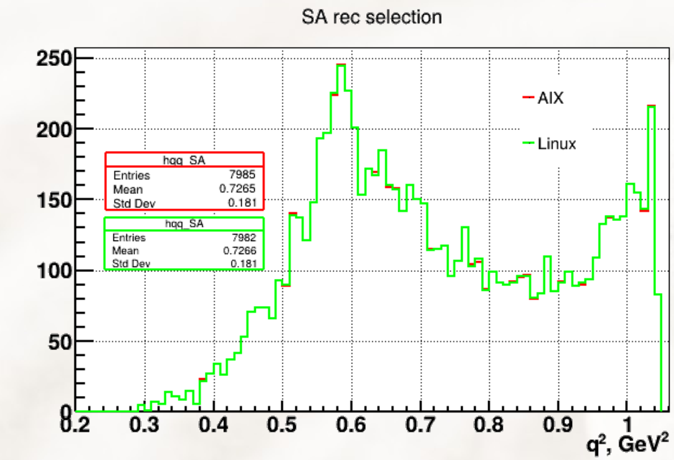
First reconstructed pions from raw data on Linux

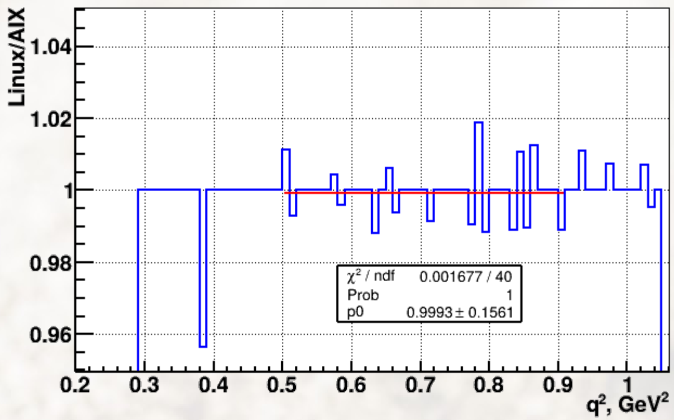
All reconstructed tracks



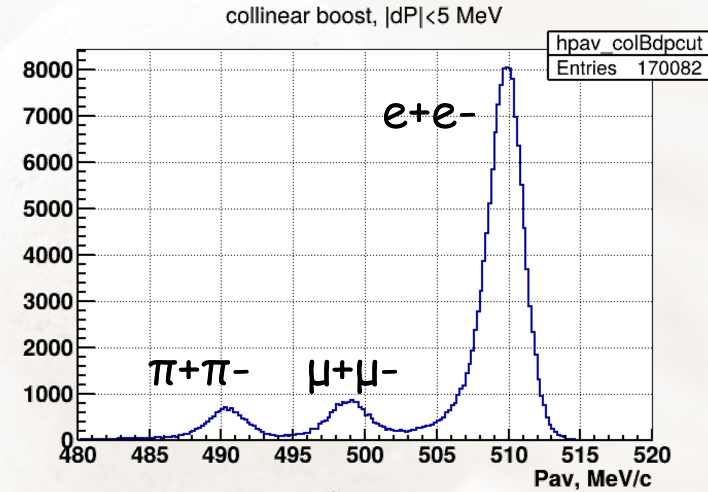


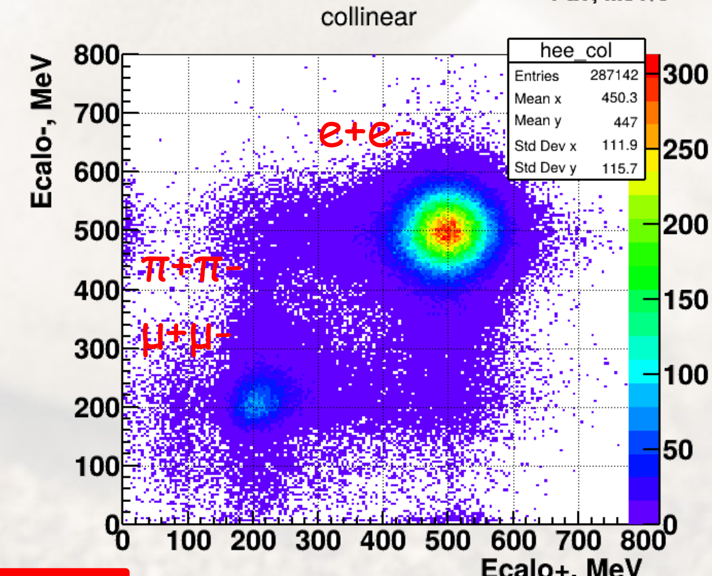
SA overall selection





Collinear events





AIX vs Linux are consistent < 0.1%

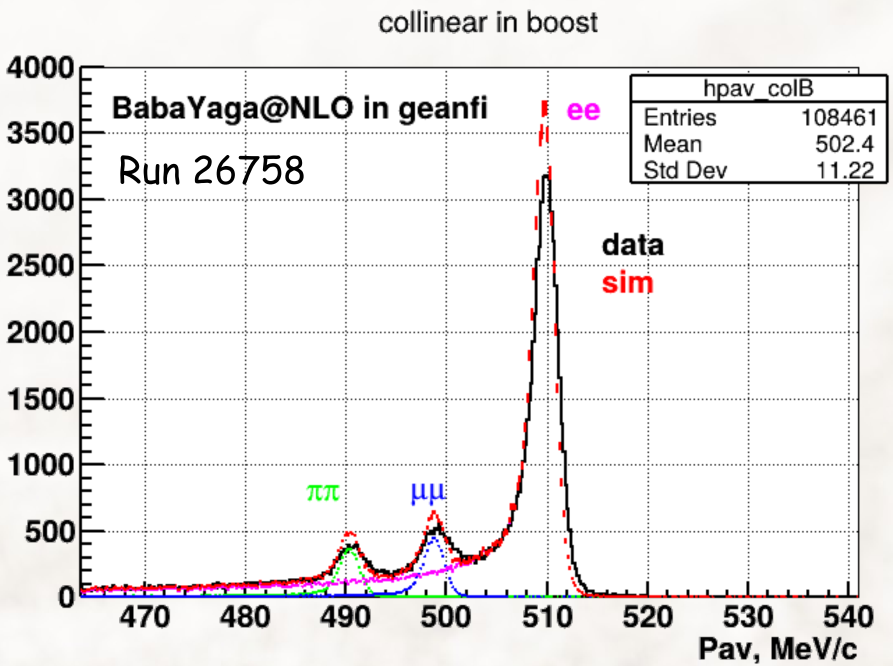
Needs more statistic to conclude

On hold for 2 months already, needs more efficient access to IBM batch system

Phase III (start to do physics)

New BabaYaga@NLO in geanfi

via general plugins interface
(any new generator will be easy to add)

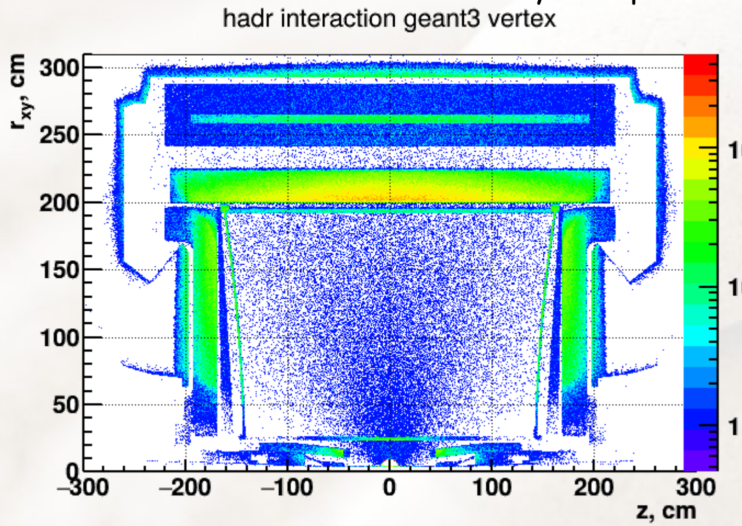


Simulation is normalized on
L= Nvlab/(428.8/1.007*1.005)

unstreamed/unfiltered data

Additional MC truth information from geanfi

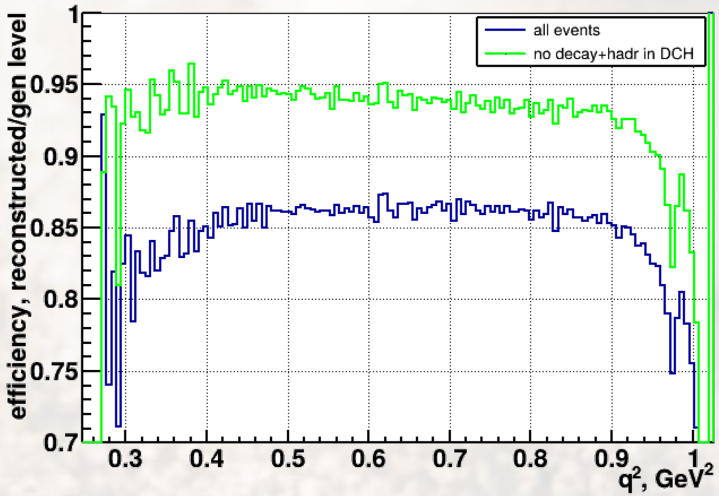
added all nuclear interactions/decays/stops/hard brem of primaries in DCH



This will help to split all sources of inefficiencies and to study them under close scrutiny.

Every cut to be studied
Topology of Hadronic/decay events seen differently by data efficiency procedure

ππγ SA selection (MC)



Total inefficiency ~15%
Decays ~ 10%
Hadr inter. ~ 1%

Decays eff depends on DCH reconstruction and details of MC/data description

Plans

- To boost forward KLOE analysis

  interest to look on collinear F_{π}, asymmetry

- MUonE

  support BMS development

- J-PARC g-2

  maybe tracking study in the detector for the high sensitivity effort?

- MEG-II

  2026 last data taking season + 1-2 years to finalize analysis

  → Future MEG experiment?

- μEDM PSI – consulting help with tracking

BMS simulation

12.02.2024

pre hardware stage

only virtual simulation in hands

→ Real implementation after ~1.5 years in Riccardo's slides

Bending magnets are here

Quiz: Where is the rabbit?

@Photos by GV

KLOE needs tools, data and simulation

Fedor Ignatov
KLOE weekly meetings
18 July 2025

KLOE on Linux

- ☑ YBOS files (dst) are fully compatible between AIX and Linux (can use prod2root or stentu on Linux)
- ☐ ☑ Simulation, reconstructions works on Linux (geanfi,datarec,prod2root):
  - ☑ checked on geanfi for ππγ generator
  - ☑ conditioning parameters with time for sim (beams, dead ch.)
  - ☐ ☑ mixing bgg/lsb pileup background
  - ☐ ☑ reconstruction of raw data

It seems works! needs to check on larger statistic

For MC mass productions
pileups bgg/lsb files are needed
downloaded from tapes fibm0a:
~ only half of bgg/lsb,
nothing for 2006

Stuck for 2 months already, Needs efficient access to IBM batch system

- ☐ ☑ No ported mass production/administrative/etc scripts (doesn't pretend to be a full IBM clone infrastructure)
  – needs to be rewritten (they will be much simpler without tape library logic, outdated stuffs, ...)

Nearest plans:

- ☑☐ 1) continue to refine software to make it as better tool
- ☐ 2) add KLOE1/2 modifications from DBV-42 development branch, will be it useful?

Todo physics:

- ☑ 1) interfacing geanfi with latest generators: BabaYaga@NLO, KKMC, etc
- ☑ 2) extend geanfi output with info on secondary vertices for efficiency studies
- ☐ **3) produce large dataset of collinear/ISR events: ee, μμ(γ), ππ(γ), 3π**

I would like to look on:
$|F_\pi|^2$ and asymmetries from collinears

AIX/Linux sim/reco cross checks

AIX vs Linux simulation (geanfi, datarec, prod2root, stentu)

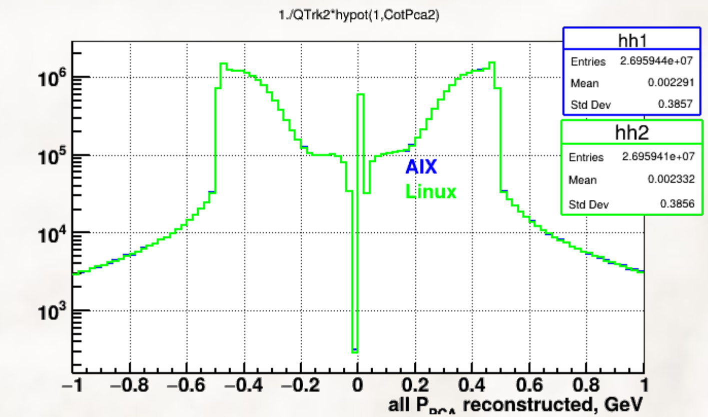
$\pi\pi\gamma$, 11.5m events, 115 runs 2002-2006

First tests were comparing text dumps of ROOT trees - OK

Full $\pi\pi\gamma$ selections cross-check:

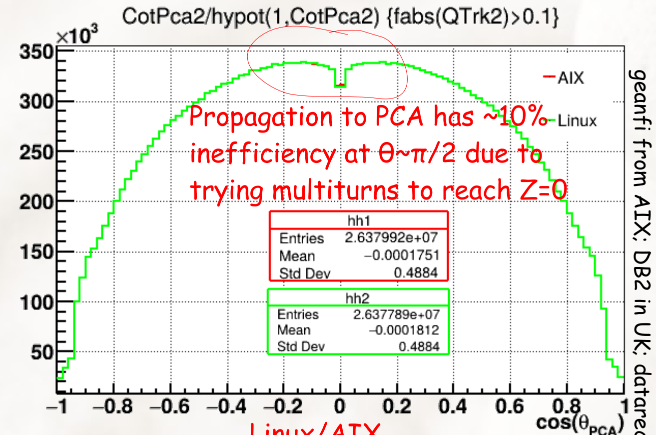
FILFO, PPG stream tag,
stentu selections,
final q2 hist selections

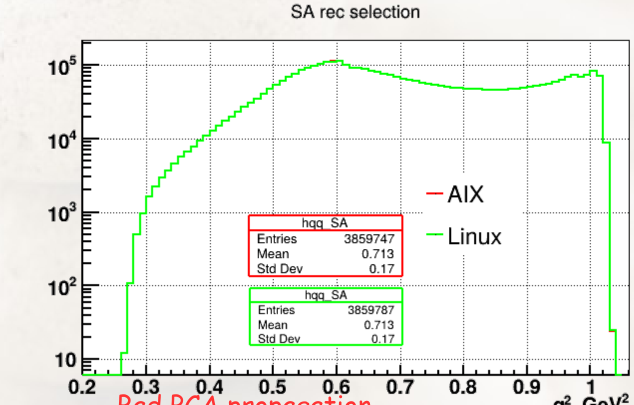
P_{PCA} all reconstructed tracks



$\cos(\theta_{PCA})$ all tracks

(datarec using same geanfi input from IBM)





geanfi from AIX; DB2 in UK; datarec/stentu AIX vs Linux

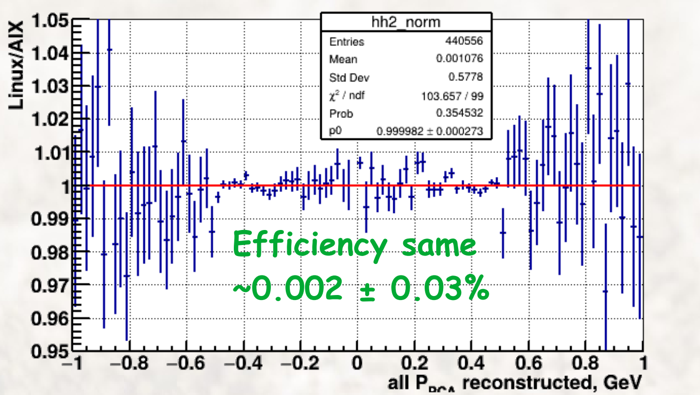
Linux/AIX

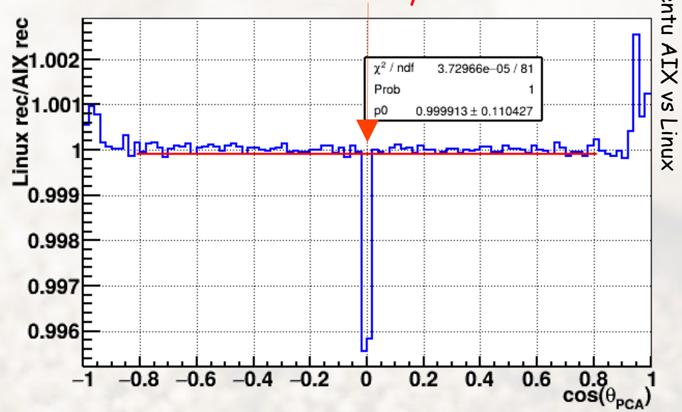
Numerically unstable

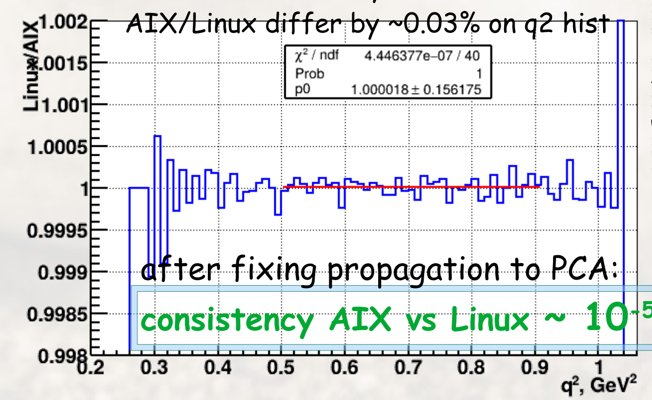
Bad PCA propagation

→ 0.25% inefficiency for $\pi\pi\gamma$ selections

AIX/Linux differ by ~0.03% on q2 hist







geanfi from AIX; DB2 in UK; datarec/stentu AIX vs Linux

Estifa'a have looked on more variables - statistically AIX/Linux seems same!

ybos files compatibility Linux/AIX

ybos files (dst) fully compatible on Linux, no problem to read DST produced on IBM

checked: prod2root either on AIX or on Linux
using ybos file input after reconstruction output on IBM (*.mcr)
100k geanfi events, $\pi\pi\gamma$

comparison of 1k events dumps:
56 MB text file (~8M numbers)
→ 250 numbers differ in last digits

Differences are only in variables related to tracks, full list:
PMod PModLa pModV Pxt PxtLa PxTv Pyt PytLa PyTv Pzt PztLa PzTv xQt yQt zQt
prod2root uses trigonometry functions to produce them
(from Phi, Cur, Cot variables saved in ybos banks)