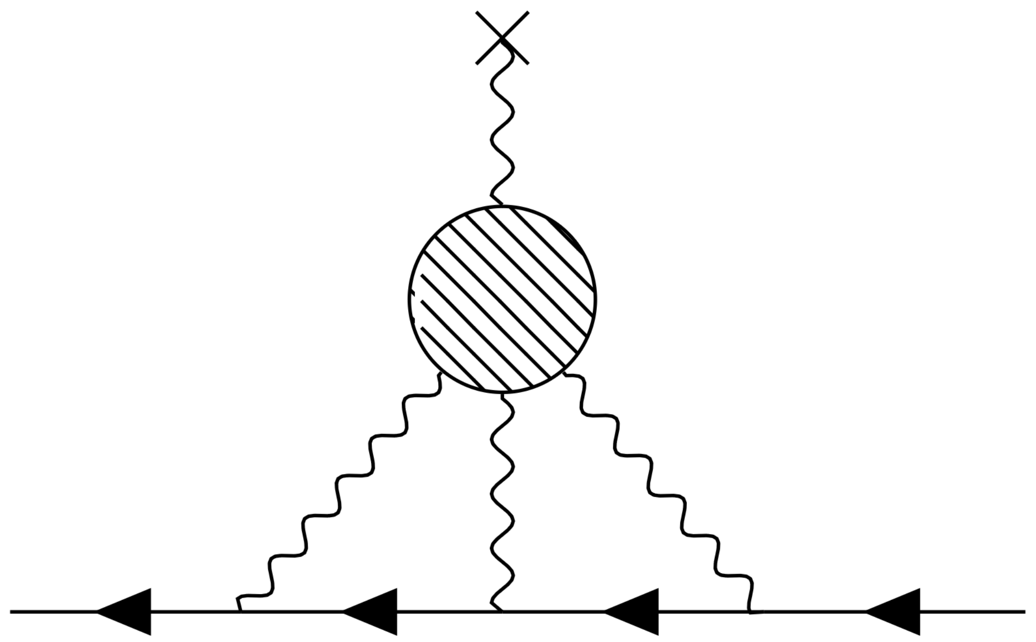
Status report on the hadronic light-by-light contribution to the muon g-2 using twisted-mass fermions



Nikolaos Kalntis
with
Gurtej Kanwar, Marcus Petschlies, Simone Romiti and Urs Wenger

on behalf of the ETM Collaboration

Nagoya, September 2nd, 2024

Extended Twisted Mass Collaboration
UNIVERSITÄT BERN
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- Presentation of preliminary results on the HLbL contribution to the muon g-2 from lattice QCD.

- Framework: **Twisted-mass fermions** on **2+1+1 gauge ensembles** at the **physical point**, generated by the Extended Twisted Mass Collaboration (ETMC).

- Mainz approach:

$$a_\mu^{\mathrm{HLbL}} = \frac{m e^6}{3} \int_{x,y} \bar{\mathcal{L}}_{[\rho,\sigma];\mu\nu\lambda}(x,y)\, i\widehat{\Pi}_{\rho;\mu\nu\lambda\sigma}(x,y)$$

- Focus on the connected and 2+2 contributions (as defined by Mainz).

- Presented preliminary results: Extrapolated results to the continuum for charm, strange connected; One-lattice-spacing results for light connected and light-light 2+2.

Poles, branching ratios and high precision lineshapes

L.A.Heuser, G.Chanturia, F.-K.Guo, C.Hanhart, M.Hoferichter, B.Kubis

- **resonances as main features of QCD spectrum**
- **first project: poles $\rightarrow$ lineshapes**
- **pions: largest hadronic contribution to $g_\mu - 2$**
  $\rightarrow$ need high precision vector form factor
- **formalism extended: more channels and resonances (inelasticities, see Gio's poster)**

September, 2024

NRW-FAIR Netzwerk

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HISKP

A multi-channel treatment for the pion vector form factor

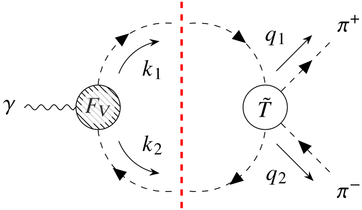
Definition: $\langle \pi^+(q_1)\pi^-(q_2)|\, j_\mu(0)\, |0\rangle = (q_1 - q_2)_\mu F_\pi^V(s)$, where $s = (q_1 + q_2)^2$.

Context: • The leading contribution to the HVP $\Longrightarrow$ relevant to $(g-2)_\mu$,
• Tension between theory and experiment $\Longrightarrow$ more precision needed,
• Tension between the experiments $\Longrightarrow$ inelastic channels are important.

Using dispersion relations,

$$F(s)_{ij} = \frac{1}{2\pi i}\int_{s_{\mathrm{thr}_1}}^{\infty} \mathrm{d}s' \frac{\mathrm{disc}\big(F(s')\big)_{ij}}{s' - s - i\epsilon}\,,$$

with $\mathrm{disc}\big(\mathcal{F}(s)\big) = 2iT^*(s)\rho(s)F(s)\,.$



We need a model that:
• preserves analyticity and unitarity, • maps to the Omnès–Muskhelishvili solution at low energies, • provides an accurate high-energy description, • includes contributions from coupled channels, • includes isospin-violating effects.

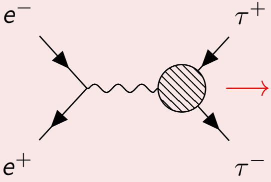
A two-potential model:

$$V_\mathrm{B}(s) = f_0/f(s) \quad \Longrightarrow \quad T_\mathrm{B} = (1 - V_\mathrm{B}\Pi)^{-1}\, V_\mathrm{B}\,;$$

$$V_\mathrm{R}(s) = -g^T G_\mathrm{R}(s) g\,, \quad G_\mathrm{R}^{kl}(s) = \frac{\delta_{kl}}{s - m_k^2} \quad \Longrightarrow \quad T_\mathrm{R} = \gamma_\mathrm{out}\,(1 - V_\mathrm{R}\Sigma)^{-1}\, V_\mathrm{R}\gamma_\mathrm{in}^\dagger\,.$$

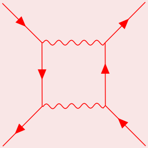
Extraction of Tau Magnetic Moment from $e^+e^- \to \tau^+\tau^-$

- Exception: $e^+e^- \to \Upsilon(nS) \to \tau^+\tau^-$

- Extract: 

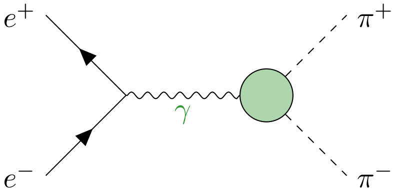
$\longrightarrow$ $F_2(s)$

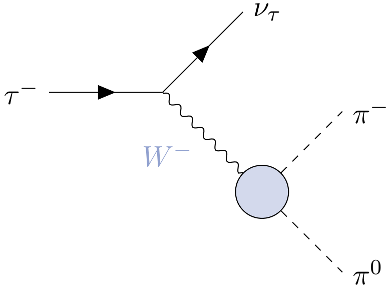
$\hookrightarrow a_\tau^{BSM} = F_2^{exp}(s) - F_2^{SM}(s), \quad s \ll \Lambda_{BSM}^2$

- Spoiled by box diagrams:  $+ \dots$

- Necessary: a_τ at $\sim 10^{-6} \implies$ 2-Loop accuracy of $A_T^\pm, A_L^\pm, A_N^\pm$

Isospin-breaking corrections to $\tau \to \pi\pi^0\nu_\tau$





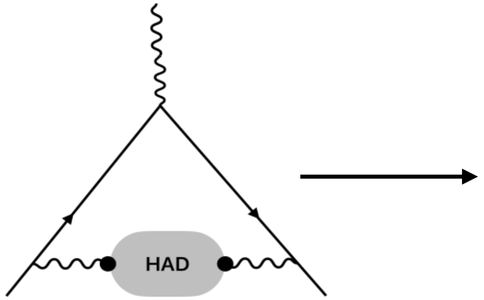
CVC between EM and weak form factors:

$$\sigma^{(0)}_{e^+e^-\to 2\pi}(s) = \frac{1}{\mathcal{N}(s)\Gamma_e^{(0)}} \frac{\mathrm{d}\Gamma(\tau^- \to \pi^-\pi^0\nu_\tau)}{\mathrm{d}s} \frac{R_{\mathrm{IB}}(s)}{S_{\mathrm{EW}}}$$

$\rightarrow$ Isospin-breaking corrections at $\mathcal{O}(e^2p^2)$ in a dispersive approach:

$$F_\pi^V(s) \to \frac{1}{\pi}\int_{s_{th}}^{\infty} \mathrm{d}s' \frac{\mathrm{Im}F_\pi^V(s')}{s'-s}$$

Isospin-breaking corrections to HVP with C* boundary conditions



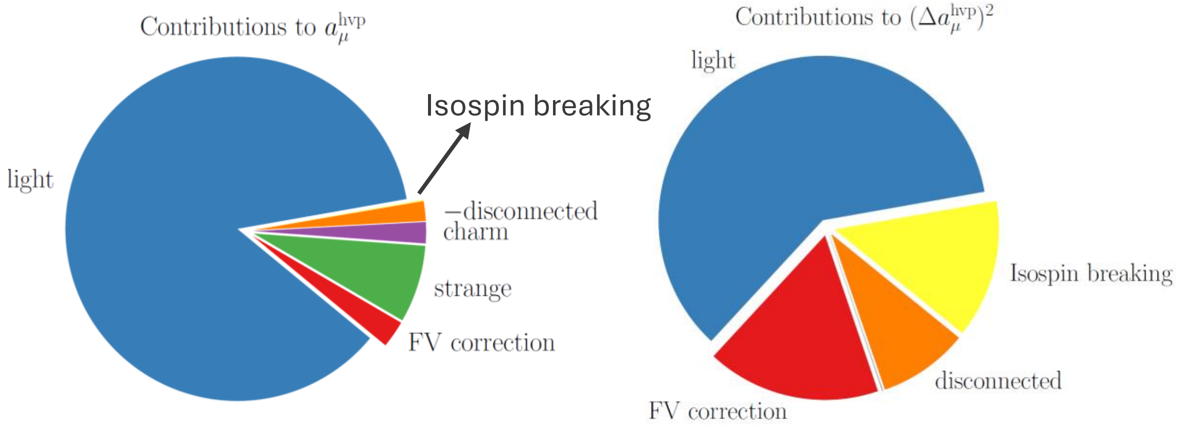
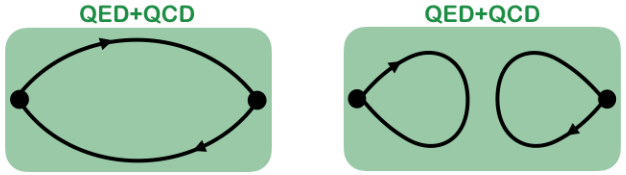
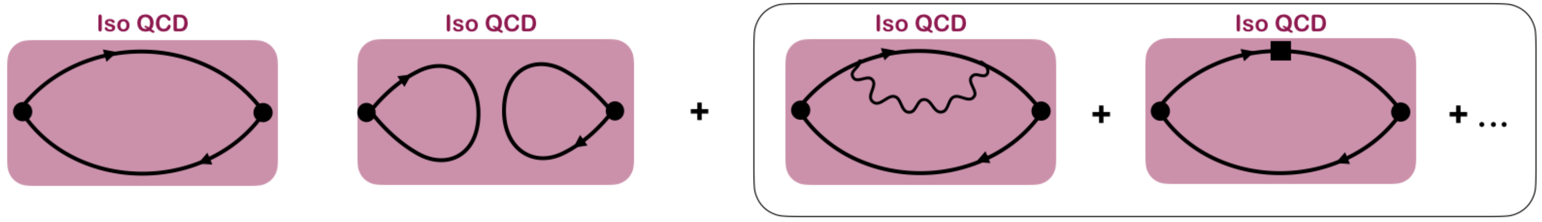


Figure from *PoS(LATTICE2023) 125*, based on calculation in *Nature 593 (2021) 51*

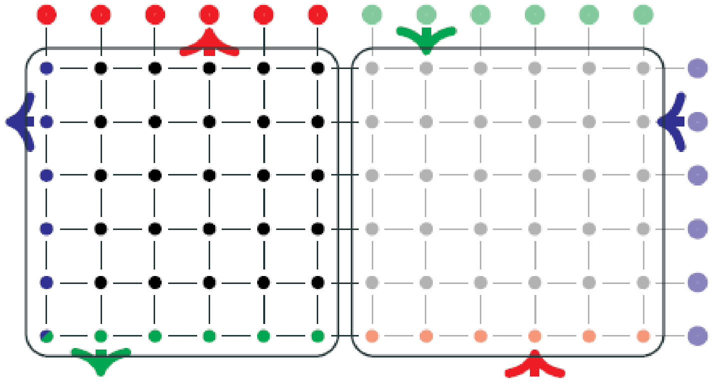
Method 1: dynamical QCD + QED simulations



Method 2: isoQCD simulations + perturbative expansion (RM123)



Setup with C-periodic (or C*) boundary conditions



Final goal: full cost comparison between the two methods including all sea-quark effects in Method 2

Development of the Data Acquisition System for the J-PARC muon g-2/EDM Experiment

- J-PARC muon g-2/EDM Experiment aims to measure the anomalous magnetic moment (g-2) and the electric dipole moment (EDM) of the muon.
- For this experiment, considering the following structure for the data acquisition system.
- Construct and demonstrate the DAQ system.

Conclusions

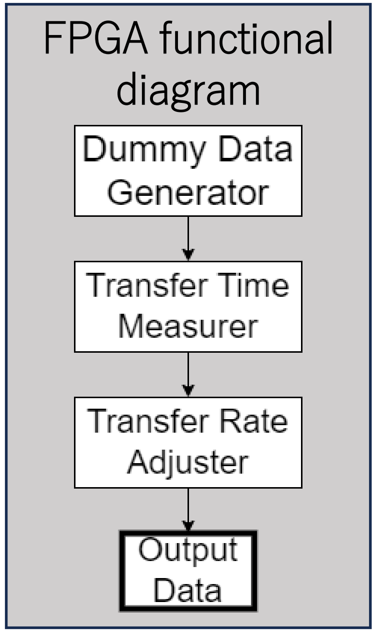
- Successful development of essential functions for demonstration DAQ system:

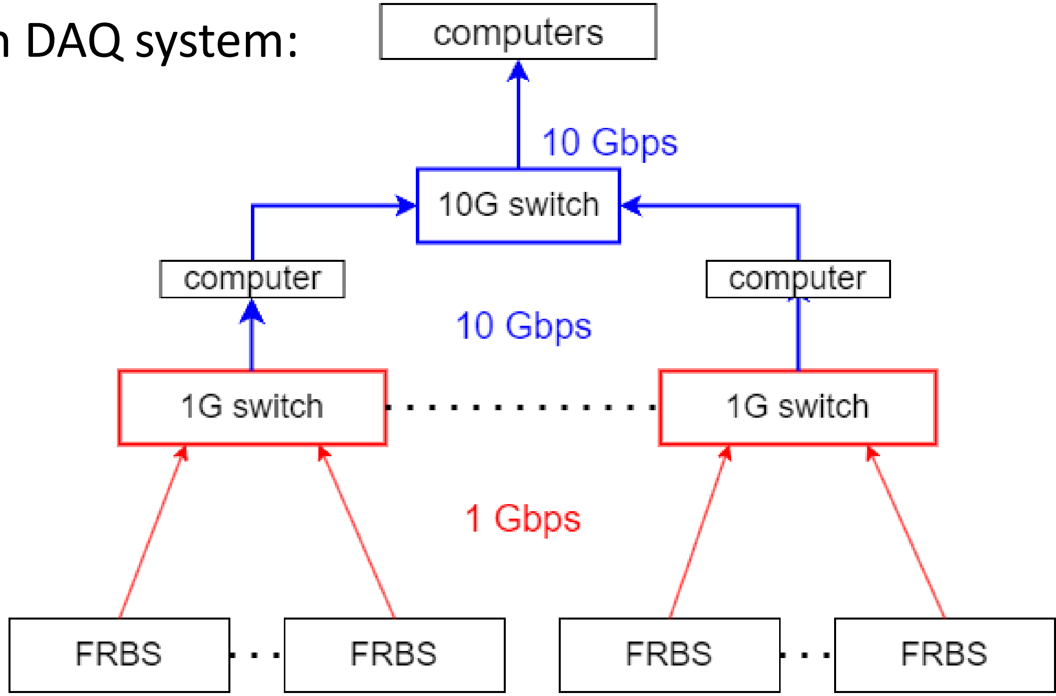
  - Dummy Data Generation
  - Time Measurement
  - Transfer Rate Adjustment

- Verified operation of a single readout board and network switch.

Plan

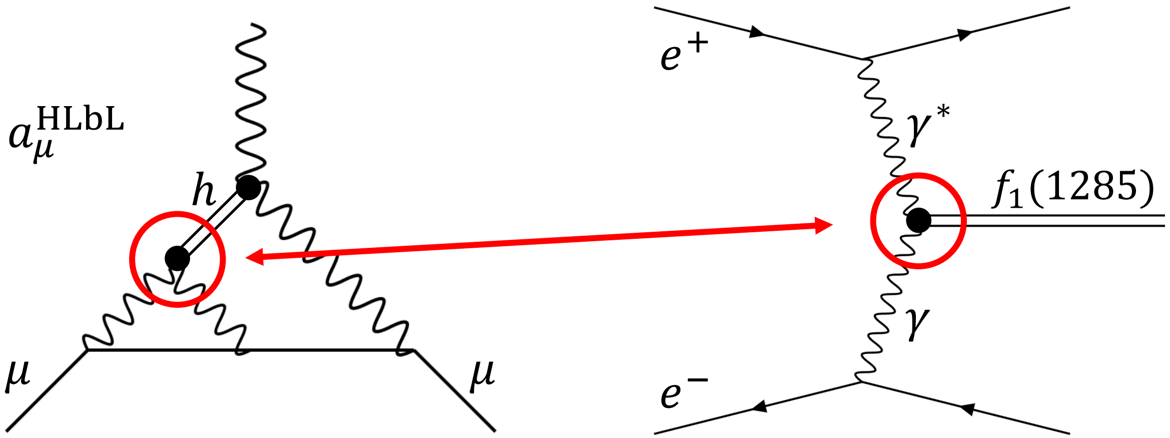
- Readout from multiple readout boards.
- Construct DAQ system based on DAQ-Middleware.





Measurement of the Process $\gamma\gamma^* \to f_1(1285)$ at BESIII

- Axial-vector mesons have the largest relative uncertainty in a_μ^{HLbL}
- Transition form factor measurements of two-photon coupling to hadrons needed
- Process $\gamma\gamma^* \to f_1(1285) \to \pi^+\pi^-\eta$ is investigated with largest BESIII data set



HLbL Contributions to a_μ^{SM}

Contribution	$a_\mu^{\mathrm{HLbL}} \times 10^{11}$
π^0, η, η'-poles	93.8 ± 4.0
π, K-loops/boxes	-16.4 ± 0.2
S-wave $\pi\pi$ rescattering	-8 ± 1
Scalars & tensors	-1 ± 3
Axial vectors	6 ± 6
u, d, s-loops / short distance	15 ± 10
c-loop	3 ± 1
Total	92 ± 19

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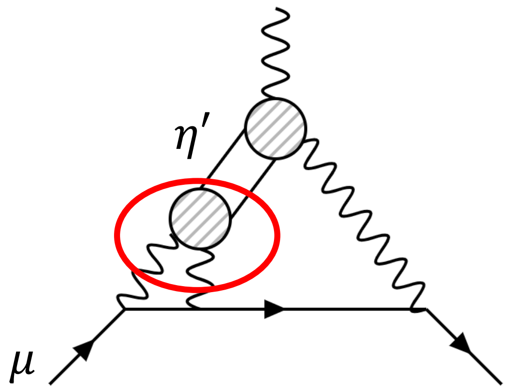
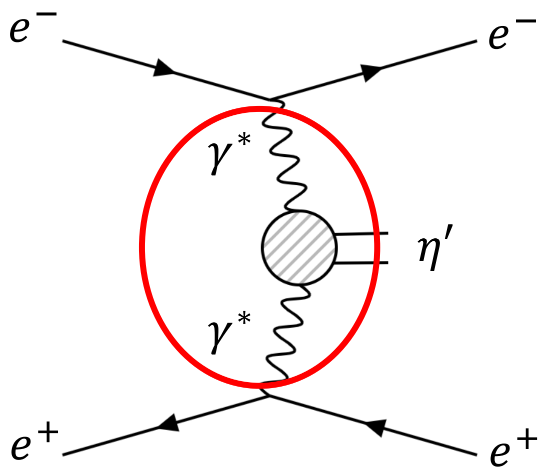
- Cross-section σ split into two terms due to polarization of the photons: Longitudinal (L) or Transversal (T)
- Use helicity angle to separate σ_{TL} and σ_{TT} in bins of momentum transfer Q^2

Investigation of $\gamma^*\gamma^* \to \eta'$ at the BESIII Experiment

- Double-virtual **Transition Form Factor** (TFF) $F_{\gamma^\star\gamma^\star\to\eta'}(Q_1^2, Q_2^2)$ of η'



Pseudoscalar meson contribution to a_μ^{HLbL}



Two-photon scattering in e^+e^- collisions

- Access momentum transfers Q_1^2, Q_2^2 by "double-tagging" scattered $e^\pm$
- **Beijing Spectrometer III** (**BESIII**) can measure $Q_1^2, Q_2^2 < 2\ \mathrm{GeV}^2$

➡ where $> 90\%$ of total η' contribution expected [*Phys.Rev.D* 94 (2016) 5, 053006]

- High-precision Lattice QCD predictions are extremely important.

$\Downarrow$

Quoting errors as reliably as possible.

- Given N correlated measurements O_i, we define the *autocorrelation function*

$$\Gamma(t) \equiv \langle (O_i - \langle O \rangle)(O_{i+t} - \langle O \rangle) \rangle \,, \quad \Longrightarrow \quad \sigma_O^2 = \frac{1}{N} \sum_{t=-\infty}^{\infty} \Gamma(t) \,,$$

In practice, the sum is approximated up to an (optimal) summation window.

- **Bounding Method**: exploiting Γ's properties, **strict** upper and lower bounds of Γ (and the error) can be introduced:

$\Downarrow$

Automatic windowing procedure by balancing the systematic error (from the bounds) and the statistical error of the error.

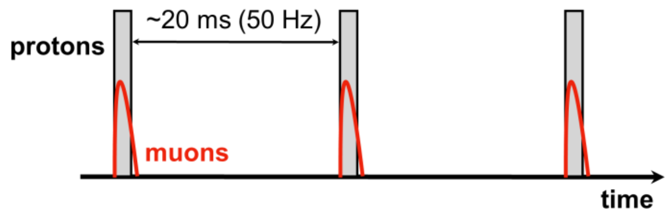
- Tested in traditional Monte Carlo simulations and in 1D Master-Field analysis, where actually finds its natural setting.

A High Repetition-Rate Pulsed Electron-Driven Surface Muon Beamline based on SHINE Facility

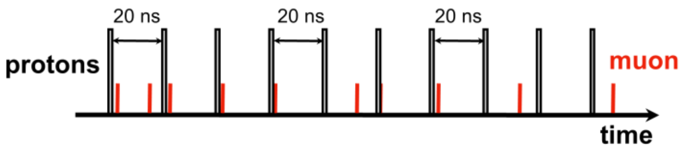
李政道研究所 TSUNG-DAO LEE INSTITUTE

Traditional vs. Ideal Muon Sources

ISIS Synchrotron, 50 Hz pulsed beam: all protons/muons in one bunch

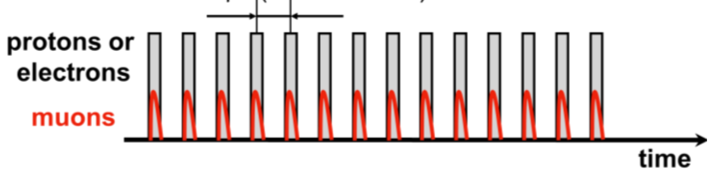


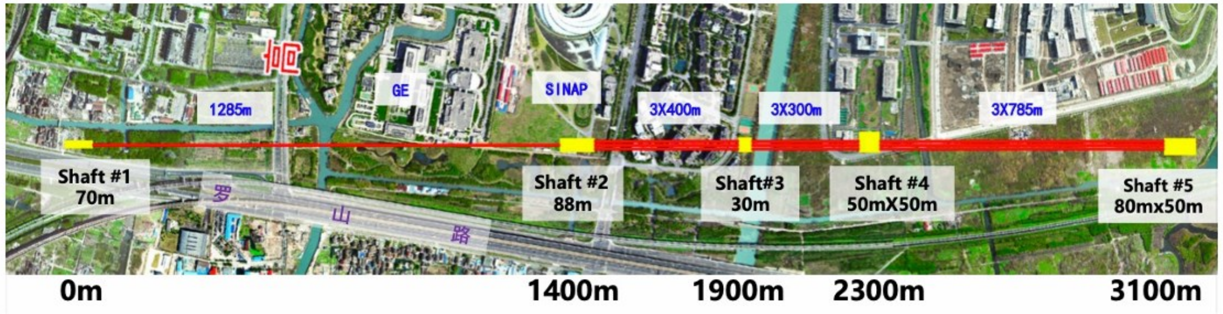
PSI 50 MHz Cyclotron, continuous beam: muons arrive randomly (time structure washed out by pion lifetime of 26 ns)



Ideal Muon Source : high repetition rate pulsed type

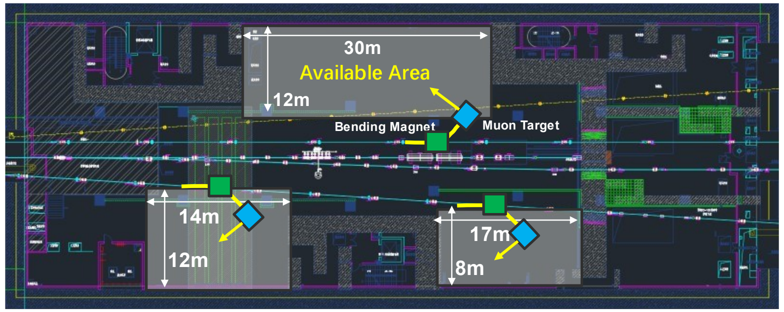
10 ~ 40 μs (25 ~ 100 kHz)



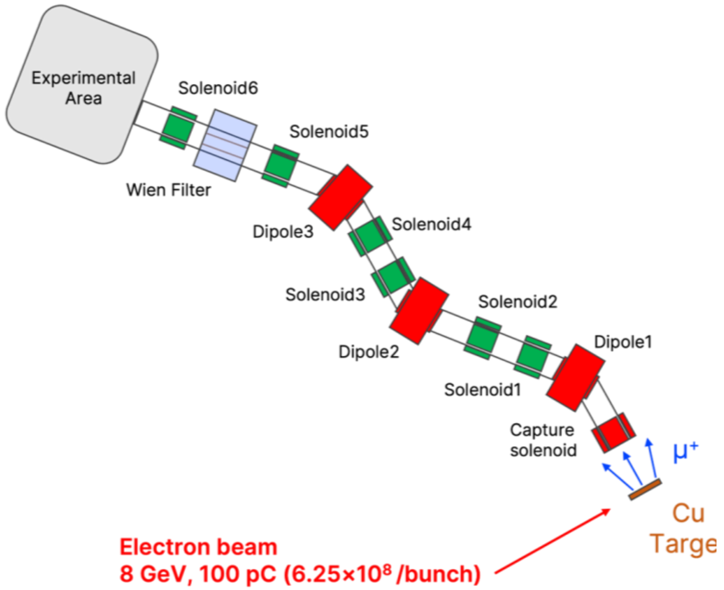


What SHINE Facility can offer?

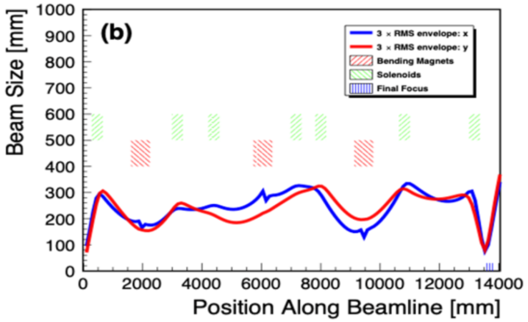
- Electron accelerator:
  - * 8 GeV energy
  - * 1 MHz bunch frequency
    (selecting 25 ~ 100 kHz using a kicker)
  - * 100 pC charge (6.25×10^8 electrons) per bunch
- Spaces in the Shaft #2:



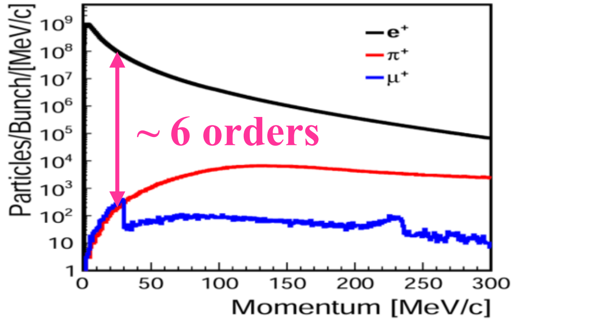
A surface Muon Beamline!



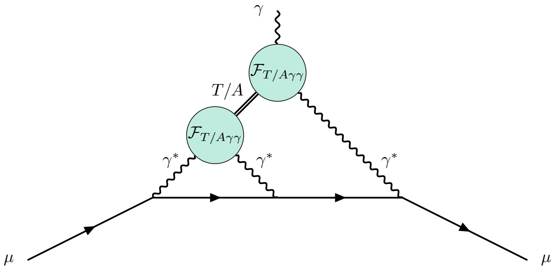
Muon+ beam size of SHINE SMS beamline

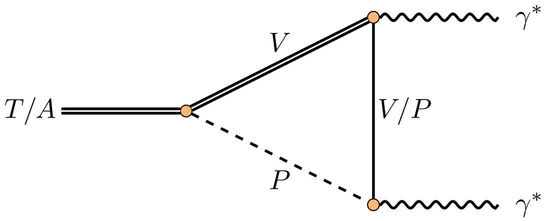


Momentum distribution of secondary particles (+)



Towards a new parametrization of tensor- and axial-vector-meson transition form factors





- better understand and estimate (uncertainty of) axial-vector and tensor poles in HLbL contribution to a_μ
- use gauge invariant representation and dispersive formalism
  $\rightarrow$ pole- and singularity-free basis for $\rho\pi \rightarrow \gamma^*\gamma^*$ needed
- connect $\mathcal{F}_{T/A\gamma\gamma}$ to phenomenological form factors F_π^V, $F_{\rho\pi}$, $F_i^{\rho\rho}$

Hannah Schäfer, Bastian Kubis, Eirini Lymperiadou, Pablo Sánchez-Puertas HISKP, University Bonn

Pion pair production in e^+e^- annihilation at next-to-leading order matched to Parton Shower

Francesco P. Ucci [1,2] on behalf of the BabaYaga@NLO collaboration

[1]Università di Pavia, Italy [2]INFN, Sezione di Pavia, Italy

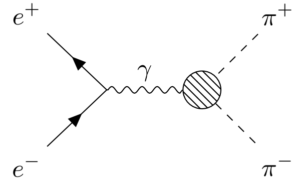
Calculation in sQED and F×sQED

Pion Vector Form Factor

$$\langle \pi^\pm(p')|j^\mu_{\rm em}(0)|\pi^\pm(p)\rangle = \pm(p'+p)^\mu F_\pi\left((p'-p)^2\right)$$

Born approximation

$$e^-(p_1)\, e^+(p_2) \to \gamma^* \to \pi^-(p_3)\, \pi^+(p_4)$$



$$\frac{d\sigma_{\rm LO}}{d\cos\vartheta} = \frac{\alpha^2\pi}{4s\beta_e}\beta_\pi^3(1-\beta_e^2\cos^2\vartheta)|F_\pi(s)|^2$$

NLO photonic corrections

$$\frac{d\sigma_{\rm NLO}}{d\cos\theta} = \frac{d\sigma_{\rm LO}}{d\cos\theta}\left(1+\delta^{\rm ISR}_{SV}+\delta^{\rm FSR}_{SV}+\delta^{\rm IFI}_{SV}\right) + \frac{d\sigma_H}{d\cos\theta}$$

Parton shower algorithm

$$\Pi(\varepsilon, Q^2) = \exp\left\{-\frac{\alpha}{2\pi}\int_0^{1-\varepsilon} dz\, P(z)\int d\Omega_k \mathcal{I}(k)\right\}.$$

$$I_+^{\rm QED}(\varepsilon) = \int_0^{1-\varepsilon} dz\, P_f(z) = -2\ln\varepsilon - \frac{3}{2} + 2\varepsilon - \frac{1}{2}\varepsilon^2,$$

$$I_+^{\rm sQED}(\varepsilon) = \int_0^{1-\varepsilon} dz\, P_s(z) = -2\ln\varepsilon - 2 + 2\varepsilon$$

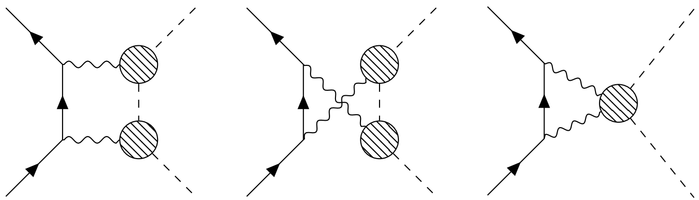
QED+sQED Parton Shower

$$d\sigma_{\rm NLOPS} = F_{SV}\,\Pi(\varepsilon,Q^2)\sum_{n=0}^{\infty}\frac{1}{n!}\left(\prod_{i=1}^{n}F_{H,i}\right)|\mathcal{M}_n^{\rm PS}|^2 d\Phi_n$$

Handling the pion composite structure in loops

$$\delta^{\rm IFI}_{V,\rm FF}(\lambda) = \frac{2\,{\rm Re}\left\{F_\pi(s)^*\mathcal{M}^\dagger_{\rm LO,0}\,\mathcal{M}^{\rm IFI}_V(\lambda)\right\}}{|F_\pi(s)|^2\,|\mathcal{M}_{\rm LO,0}|^2} = \frac{2\,{\rm Re}\left\{F_\pi(s)^*\bar\delta^i_V\right\}}{|F_\pi(s)|^2}$$

$$\rm FF = GVMD, FsQED$$



NLO calculation in the GVMD model

GVMD

$$F_\pi^{\rm BW}(q^2) = \sum_{v=1}^{n_r}F^{\rm BW}_{\pi,v}(q^2) = \frac{1}{c_t}\sum_{v=1}^{n_r}c_v\frac{\Lambda_v^2}{\Lambda_v^2-q^2}$$

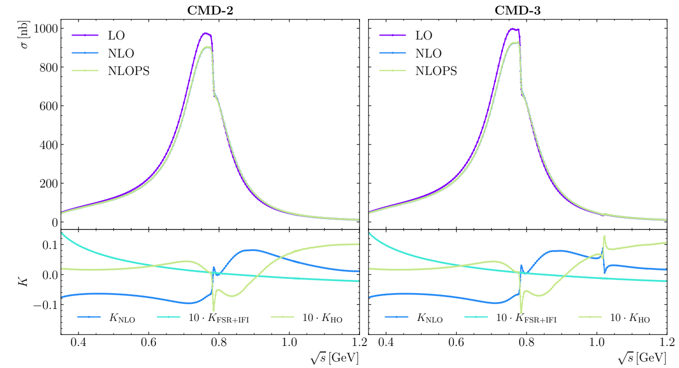
NLO calculation in the FsQED approach

Dispersion relation

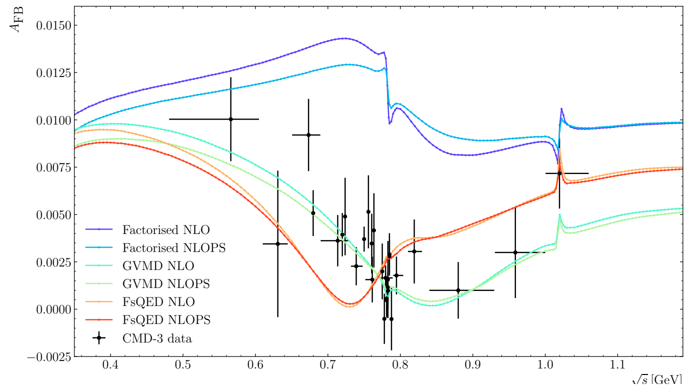
$$F_\pi(q^2) = 1 - \frac{q^2}{\pi}\int_{4m_\pi^2}^{\infty}\frac{ds'}{s'}\frac{{\rm Im}\,F_\pi(s')}{q^2-s'}$$

Numerical Results

Results for the integrated cross section



Results for the charge asymmetry



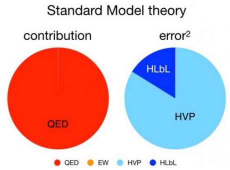
References

[1] G. Balossini, C. M. Carloni Calame, G. Montagna, O. Nicrosini, and F. Piccinini. Matching perturbative and parton shower corrections to Bhabha process at flavour factories. *Nucl. Phys.*, B758:227–253, 2006.

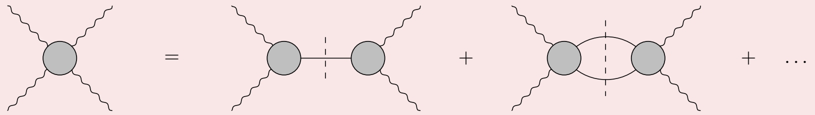
[2] Gilberto Colangelo, Martin Hoferichter, Joachim Monnard, and Jacobo Ruiz de Elvira. Radiative corrections to the forward-backward asymmetry in $e^+e^- \to \pi^+\pi^-$. *JHEP*, 08:295, 2022.

[3] Fedor Ignatov and Roman N. Lee. Charge asymmetry in $e^+e^- \to \pi^+\pi^-$ process. *Phys. Lett. B*, 833:137283, 2022.

New basis for dispersive approach to hadronic light-by-light



- $a_\mu^{\mathrm{Exp}} = 116\,592\,059(22) \times 10^{-11}$ (0.19 ppm)
  - Experimental goal: $\leq 0.14\,\mathrm{ppm}$
- $a_\mu^{\mathrm{HLbL}} = 92(18) \times 10^{-11}$
  - $\rightarrow$ Error of HLbL needs to be reduced by a factor of 2
- Largest uncertainties to HLbL: $a_\mu^{\mathrm{Axials}} = 6(6) \times 10^{-11}$, $a_\mu^{\mathrm{SDCs}} = 15(10) \times 10^{-11}$
- Dispersive Approach: Reconstruct HLbL in terms of hadronic intermediate states



- Problem: kinematic singularities for axial-vector states in old tensor basis
- Solution: New basis suited for evaluation of axial-vector states
- Goal: match axial-vector states to short-distance constraints

Improved information criteria for Bayesian model averaging in lattice field theory

University of Colorado Boulder

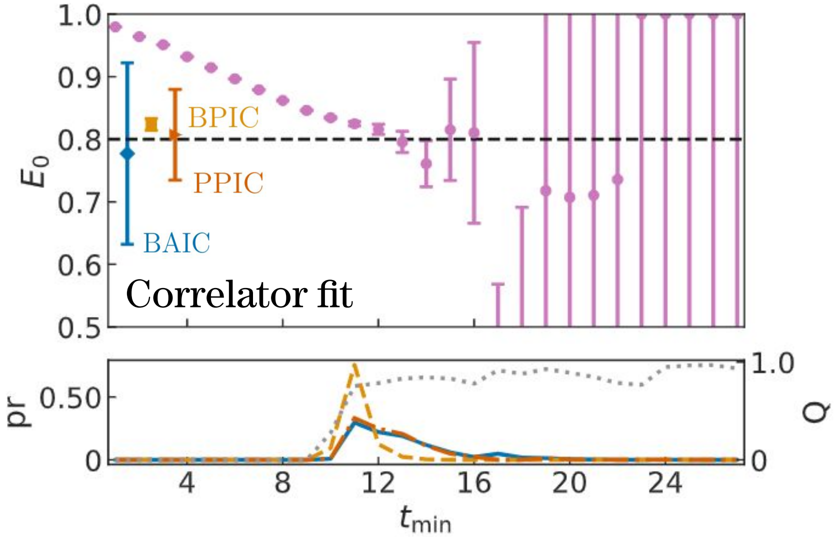
Jake Sitison and Ethan Neil

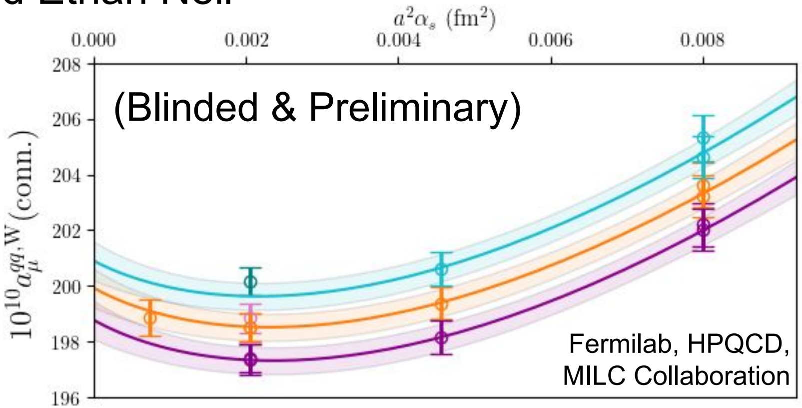
DOE Award No. DE-SC0010005

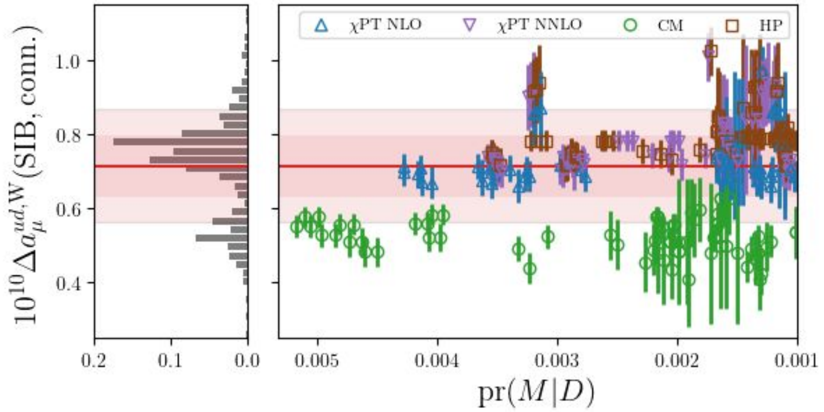
$$\langle f(\mathbf{a})\rangle = \sum_{\mu} \langle f(\mathbf{a}_\mu)\rangle \, \mathrm{pr}(M_\mu|\{y\})$$

$$\mathrm{KL}(M_\mu) = E_z[\log \mathrm{pr}(z|M_\mathrm{T})] - E_z[\log \mathrm{pr}(z|M_\mu)]$$

$$\mathrm{IC} \sim -2NE_z[\log \mathrm{pr}(\{y\}|M_\mu)]$$







GPU Based Track Finding for Muon g-2/EDM Experiment at *J-PARC*

Hridey Chetri[1], Saurabh Sandilya[1], Deepak Samuel[2], Tsutomu Mibe[3], Takashi Yamanaka[4], Taikan Suehara[5]

[1]Indian Institute of Technology Hyderabad, [2]Central University of Karnataka, [3]IPNS KEK, [4]Kyushu University, [5]ICEPP, University of Tokyo

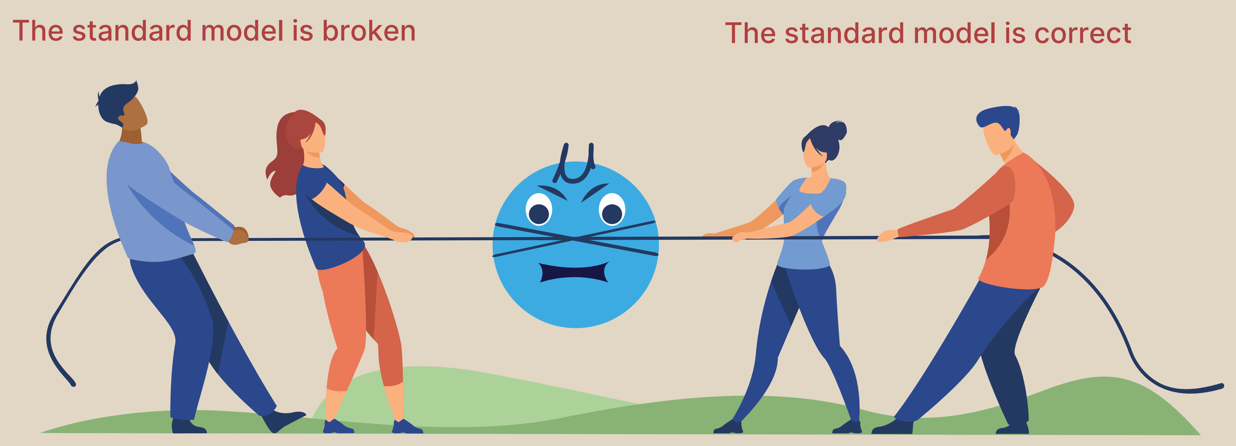
Introduction

Muon g-2/EDM experiment is dedicated to measuring the magnetic dipole moment and electric dipole moment of the muon to a very high precision[1].

$$\vec{\omega} = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2-1})\frac{\vec{\beta}\times\vec{B}}{c} + \frac{\eta}{2}(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c})\right]$$

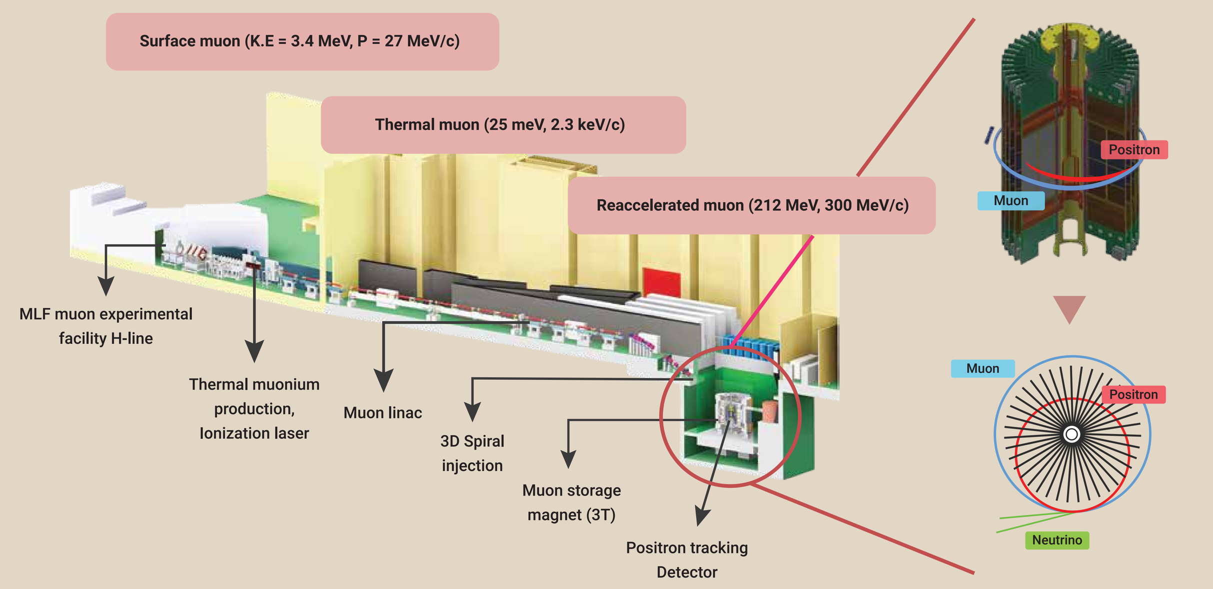
JPARC uses a very novel technique by using a 300 MeV/c reaccelerated thermal muon beam.

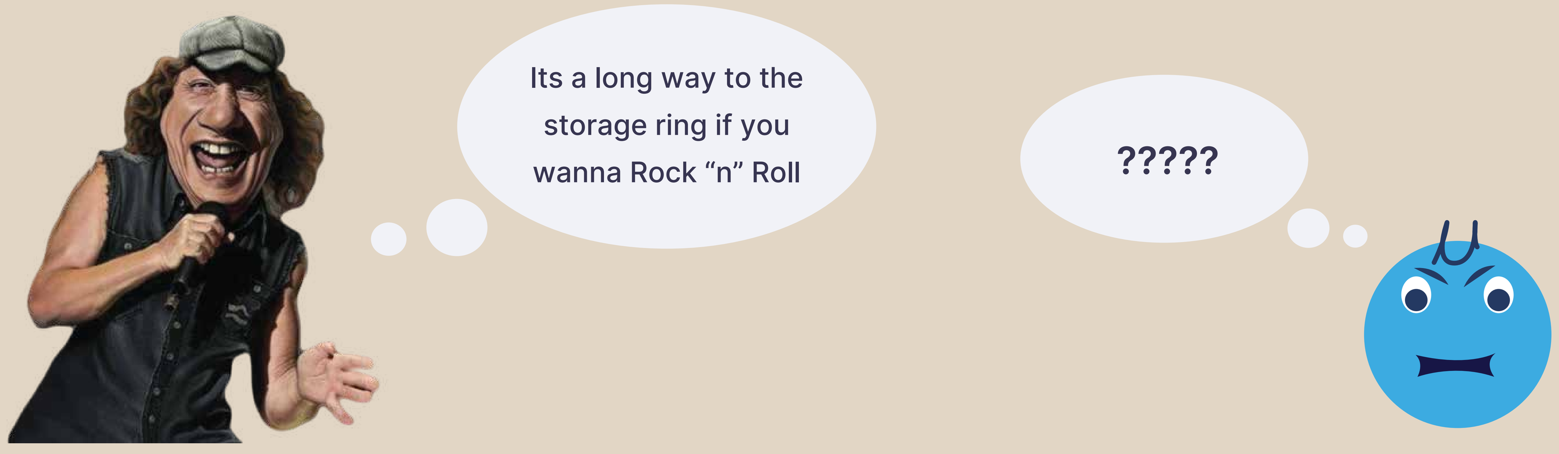
$$\vec{\omega} = -\frac{q}{m_\mu}\left[a_\mu \vec{B} + \frac{\eta}{2}(\vec{\beta}\times\vec{B})\right]$$



Experimental Setup

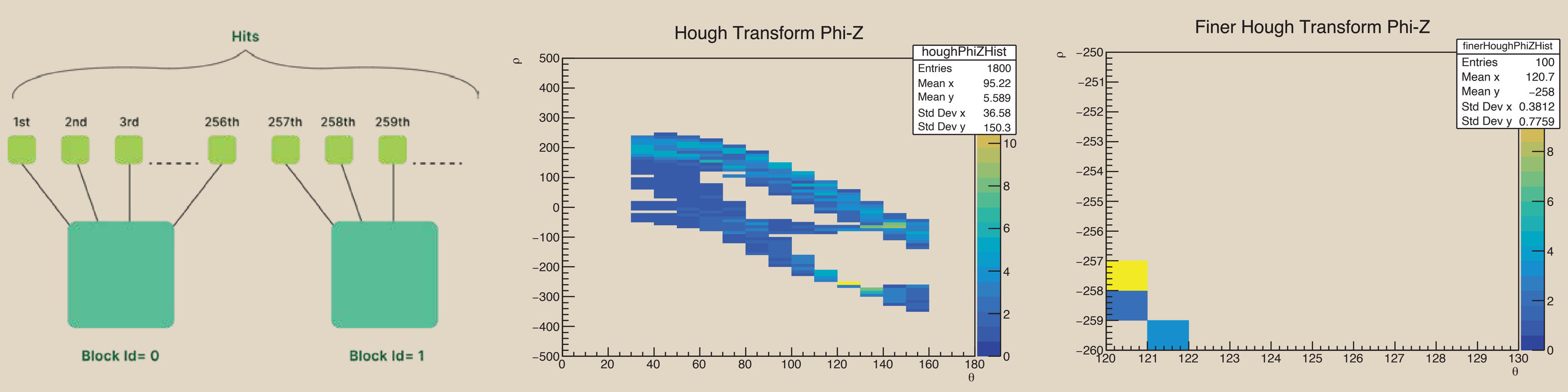
After the ionization of muon from muonium atom, they are accelerated using LINAC till the p reaches 300 MeV/c





Approach

Process 256 elements per block using shared memory. Each block handles hits in a 10 ns time window. Divide the Hough Histogram into coarse and fine bins to address shared memory constraints.



Challenges

Current Software

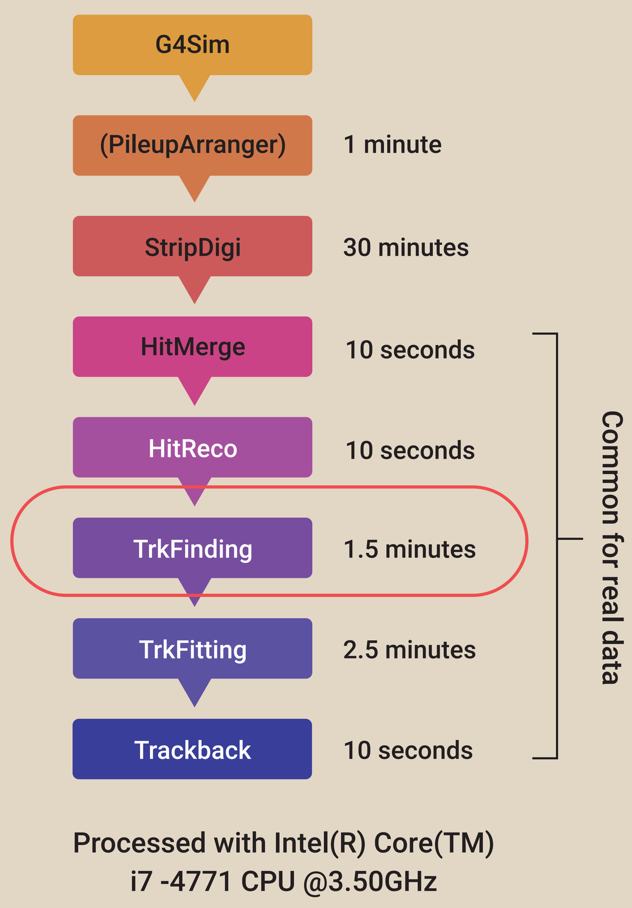
100 muons/sec/CPU

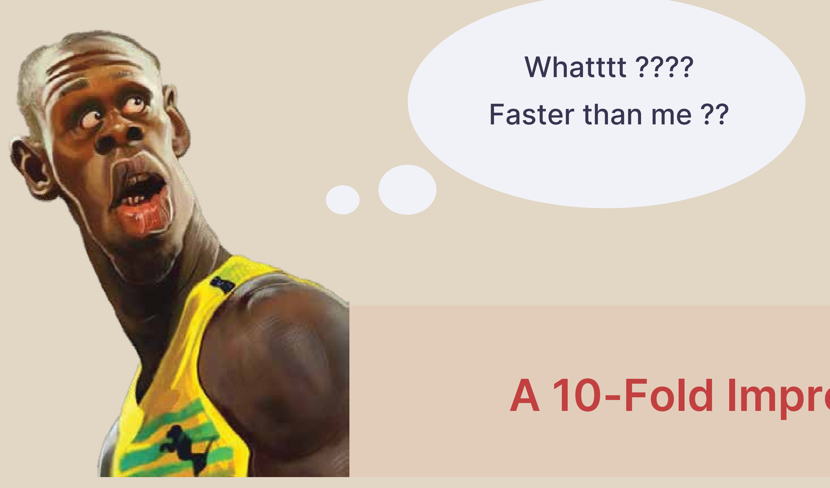
10^5 muons/sec (for 1000 CPUs)

Required Speed

~10^{13} muon decays Beam intensity~10^6 muons/sec

Speed required - O(10^6 muons/sec)



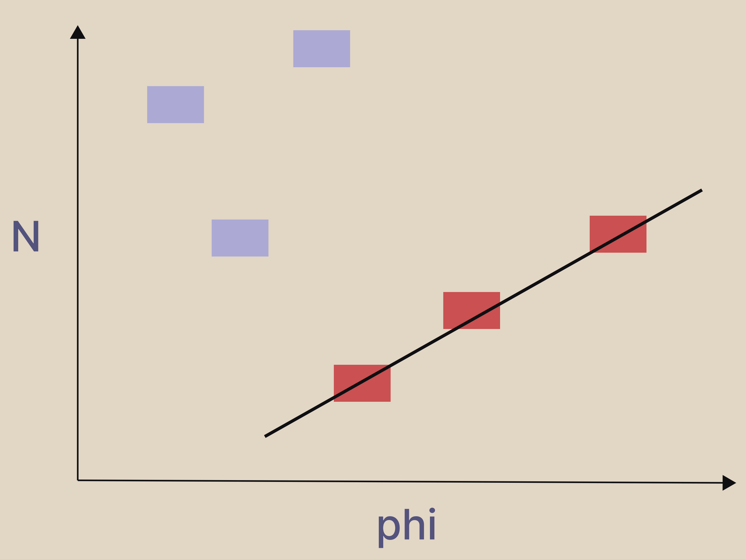


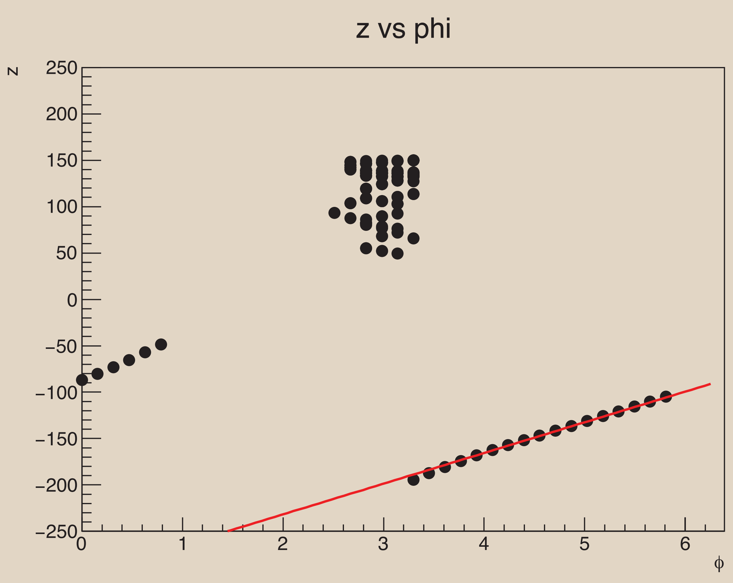
A 10-Fold Improvement in Speed is Required

Result

	Functions	Time
GPU Activities	Main Kernel	136.61 ms
	Memcpy HtD	5.45 ms
API Calls	Kernel Launch	288.90 ms
	Device Sync	144.08 ms
	Cuda Malloc	49.90 ms
	Memcpy	6.32 ms

GPU activity shows much acceleration in Hough Transformation





Summary and Outlook

- We have performed HT in GPU.
- We have seen good acceleration in the track finding process.
- Further refinement and clustering are needed to obtain a clean and complete track.

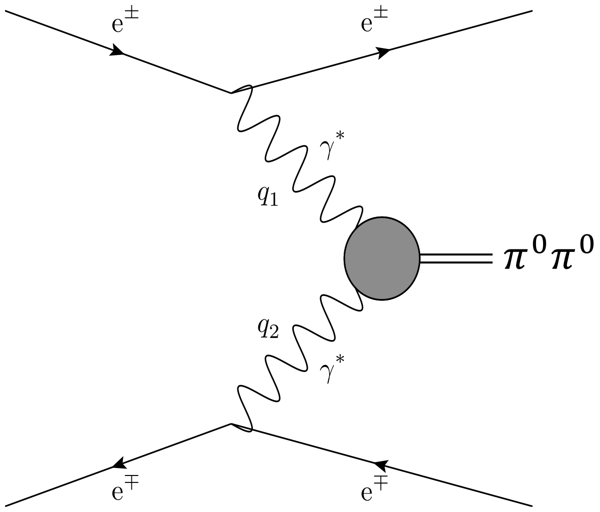
References

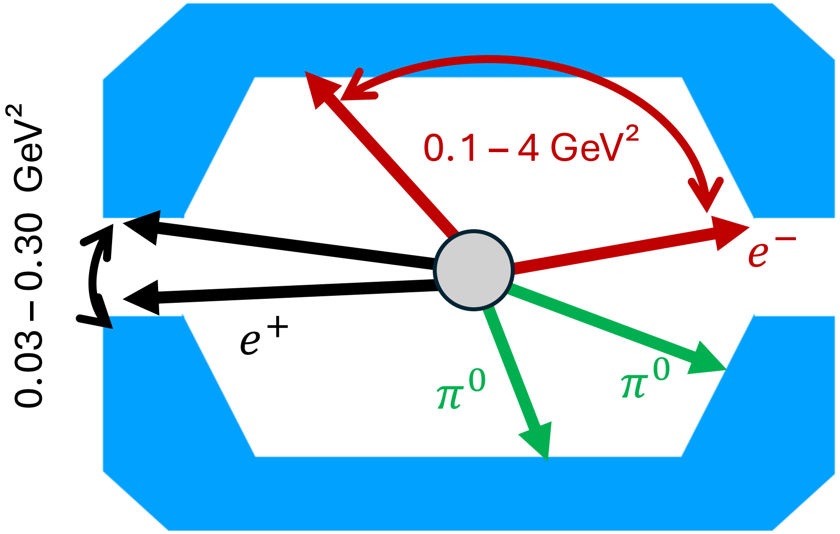
[1] M Abe et al. "A new approach for measuring the muon anomalous magnetic moment and electric dipole moment". In: Progress of Theoretical and Experimental Physics 2019.5 (May 2019), p. 053C02. ISSN: 2050-3911. DOI: 10.1093/ptep/ptz030.

Study of Neutral-Pion Pair Production in Two-Photon Scattering at BESIII

Max Lellmann, Achim Denig & Christoph F. Redmer

Studying the production of two-photon production $\pi^0\pi^0$ in single tagged two-photon scattering helps to understand the hadronic light-by-light contribution to a_μ!





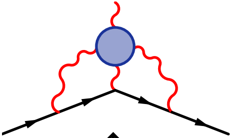
Restriction to single tagged events allows to study the process with reasonably high statistics!
They lack information on both momentum transfers.

Double tagged studies do not have this issue!
But there is very little statistics.

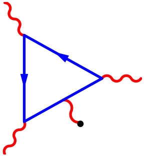
Is there a way around this?

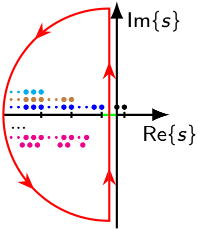
Short Distance Constraints on the HLbL contribution to the muon $g-2$

Daniel Melo-Porras, Edilson Reyes, Raffaele Fazio



$$\sum_i^{19} \Pi_i \, \partial^{\mu_5} \, T_i^{\mu_1\mu_2\mu_3\mu_4}\Big|_{q_4\to 0}$$



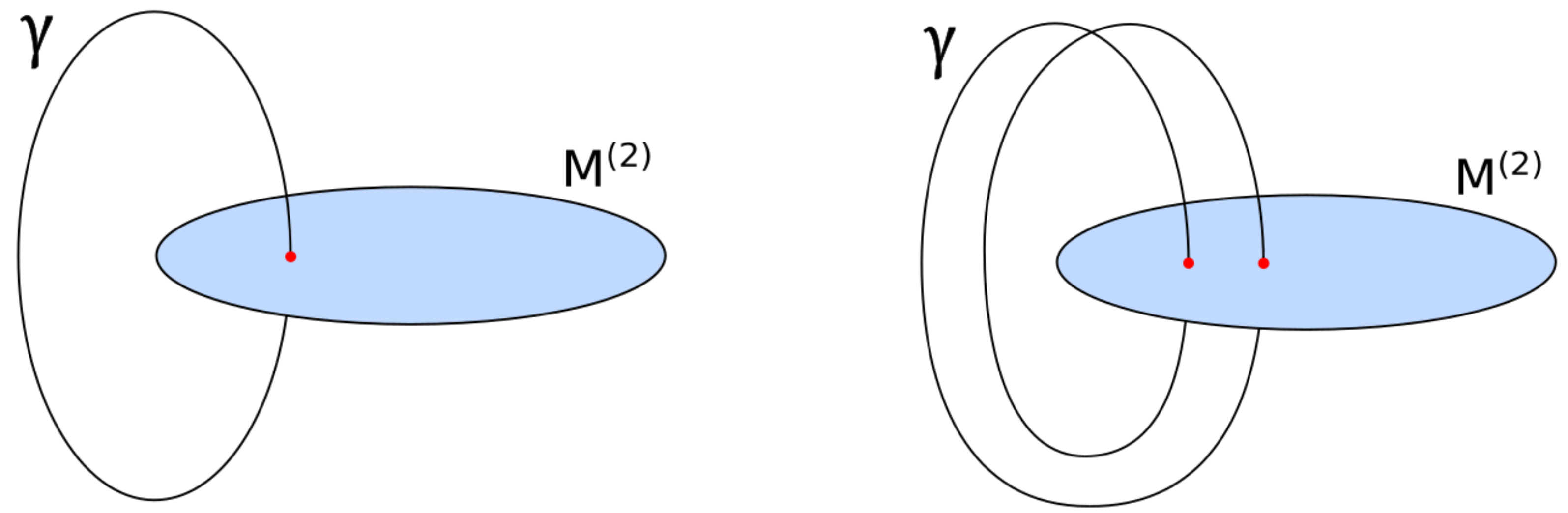


$$I^{(2)} \supset \left(\cdots\right)\times\sum_{l=0}^{\infty} \boxed{\left(-\frac{4m^2}{q^2}\right)^l} \frac{\Gamma(-2+2\nu+l)}{\Gamma(-\nu-l+\frac{5}{2})}\frac{1}{\Gamma(l+1)\Gamma(l+\nu-1)} \ln\left\{-\frac{q^2}{4m^2}\right\}$$

UPPSALA UNIVERSITET

Higher Form Symmetries in Maxwell Theory

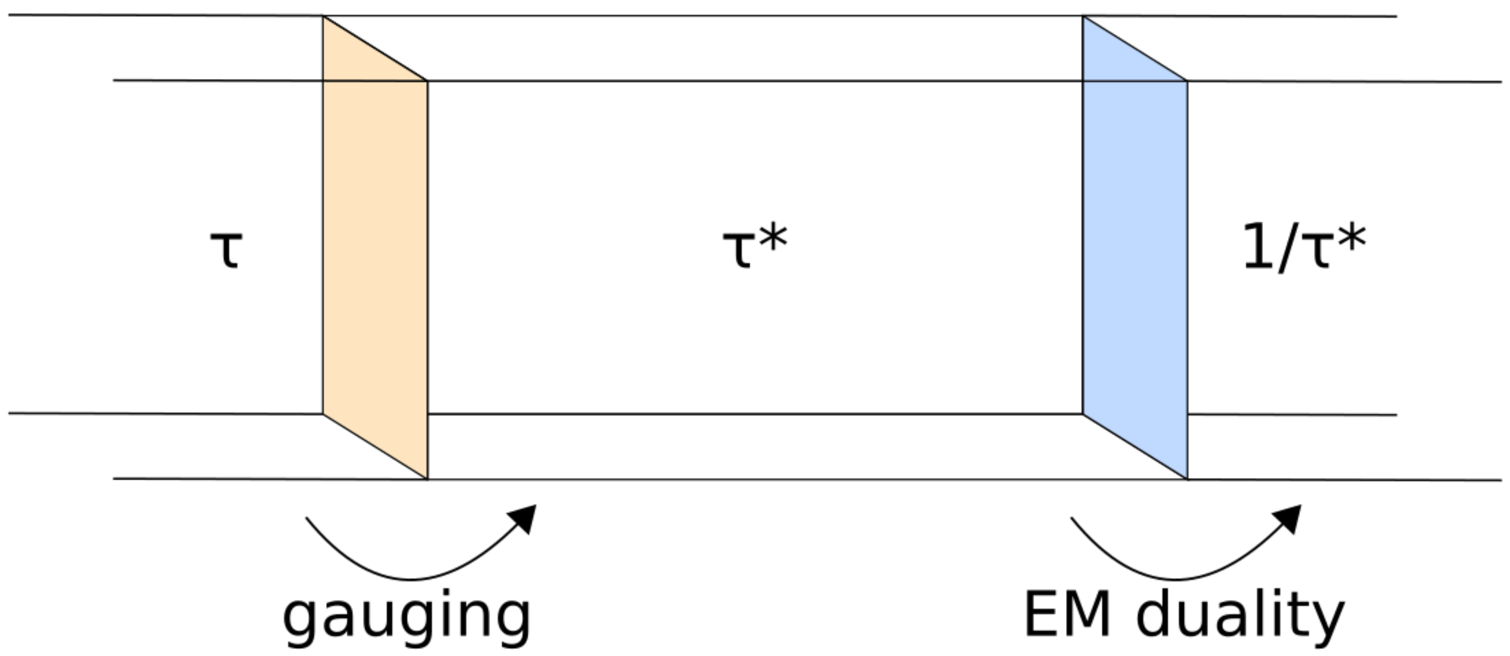
Borbála Farkas



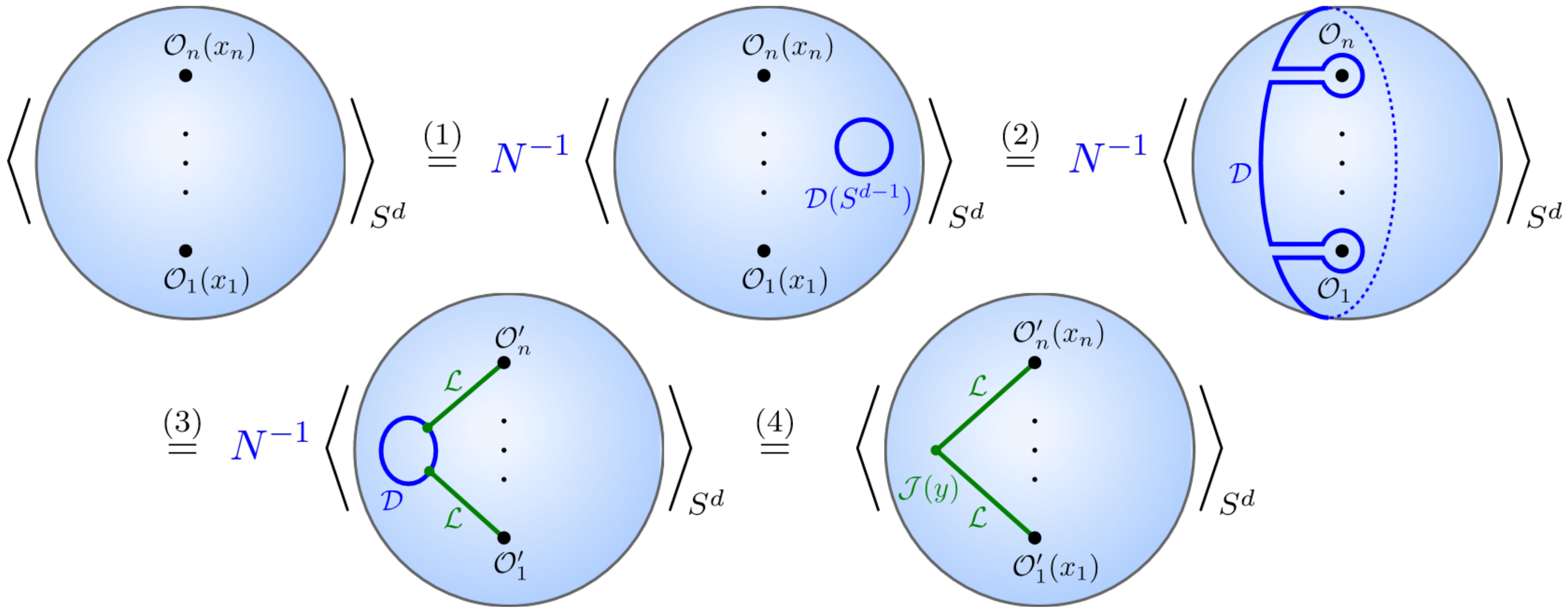
ordinary symmetries ⟷ higher p-form symmetries

linking action

Generalized Global Symmetries



topological defects

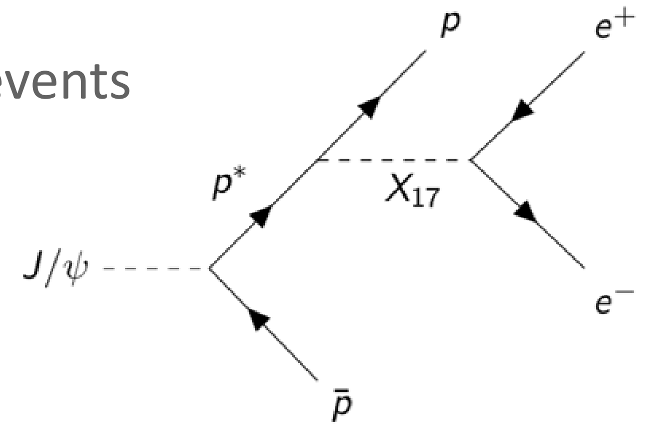


Ward-Takahashi identity

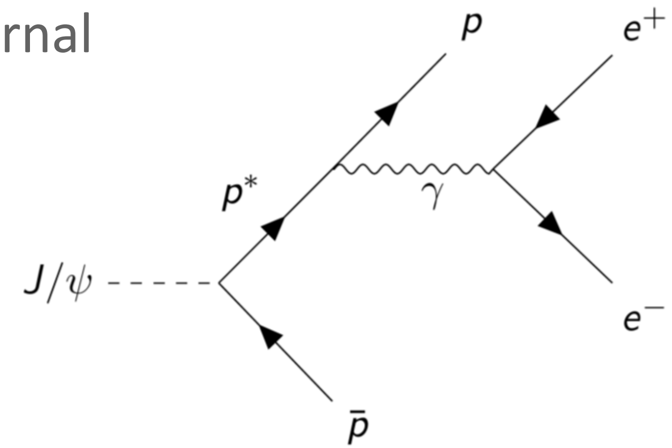
Search for $J/\psi \to p\bar{p}e^+e^-$ Decays with the BESIII Experiment

- BESIII holds **world's largest J/ψ dataset** on resonance with 10 billion events

➡ **Ideally suited for the search for rare decays!**



- $J/\psi \to p\bar{p}e^+e^-$ decays are **interesting in both BSM and SM contexts**
  - Search for the X17 Krasznahorkay, PRL 116 (2016), 1910.10459, 2209.10795
  - Measure the time-like proton form factor in the unphysical region Lin, Guo, Meißner, arXiv:2309.07850v2
  - Study the transition form factor of the X(1835) to evaluate its internal structure Jiang, 10.1016/j.nuclphysbps.2021.05.019

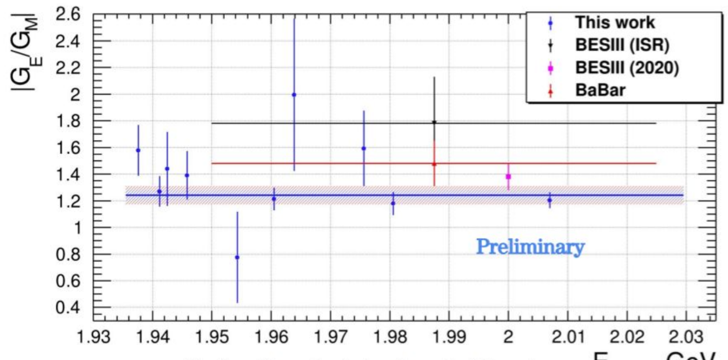


- **But:** decay has **not been measured yet!**

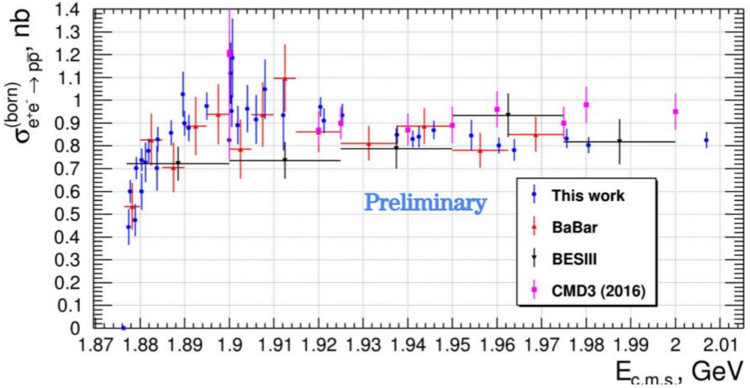
➡ **First study of $J/\psi \to p\bar{p}e^+e^-$!**

Study of the proto-antiproton production near the threshold

Experiment	BaBar	BES III	CMD-3 (2017)	**This work**
Events	2172	1386	2741	**43416**



Blue line with error bands show the result of this work.



available at arXiv:2405.13638

accepted by PRD

The use of Padé and D-Logs Padé approximants in the MUonE experiment

Diogo Boito, **Cristiane Yumi London**, Pere Masjuan, Camilo Rojas

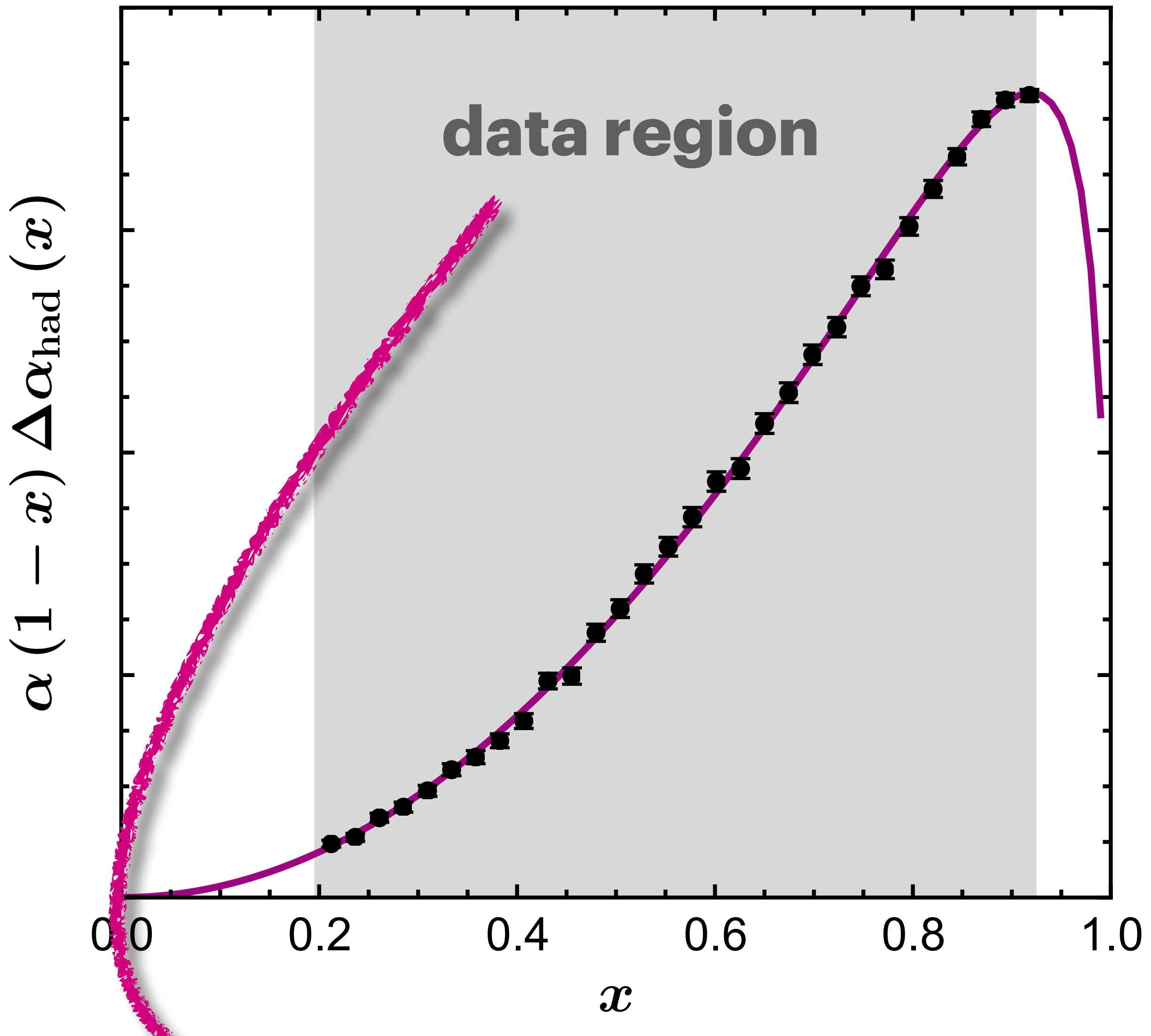
Simon Eidelman School on Muon Dipole Moments and Hadronic Effects

IFSC UNIVERSIDADE DE SÃO PAULO Instituto de Física de São Carlos

FAPESP SÃO PAULO RESEARCH FOUNDATION

MUonE Experiment

New experiment to measure $a_\mu^{\mathrm{HVP,LO}}$



86% of $a_\mu^{\mathrm{HVP,LO}}$

$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha^2}{\pi}\int_0^1 \mathrm{d}x\;(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

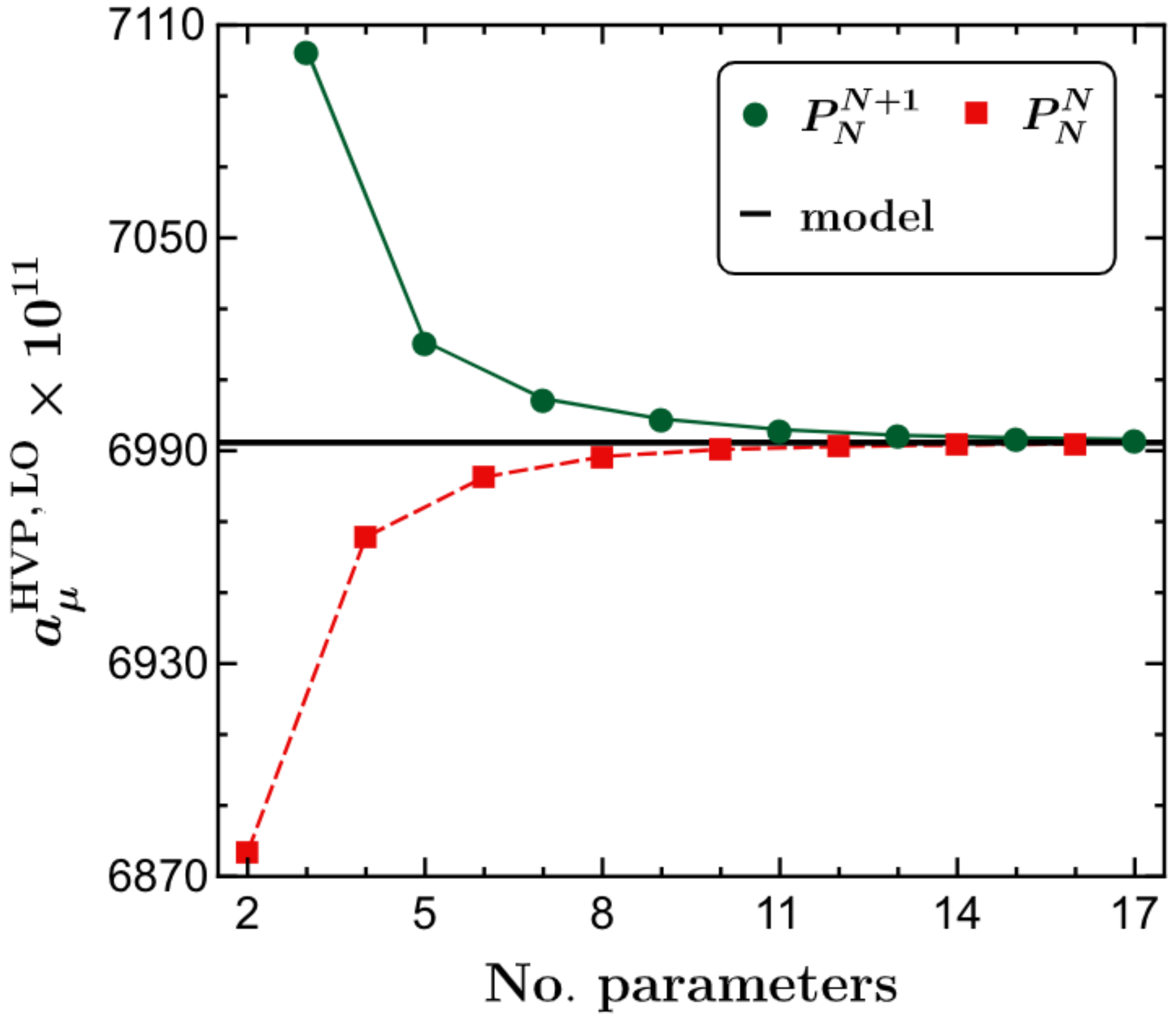
Stieltjes function

Stieltjes Functions

$$f(z) = \int_0^\infty \frac{\mathrm{d}\phi(u)}{1+zu}$$

Convergence theorems are present

PA sequences act as bounds to the Stieltjes function



Padé Approximants

$$P_M^N(z) = \frac{Q_N(z)}{R_M(z)} = \frac{q_0 + q_1\,z + \cdots + q_N\,z^N}{1 + r_1\,z + \cdots + r_M\,z^M}$$

model-independent fit function

bound the true value

P_N^N: lower bound

P_N^{N+1}: upper bound