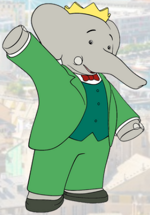
HADRON 2023

Recent Measurements of e^+e^- Annihilation into Hadrons at Low Energies with the *BABAR* Detector

Dexu Lin
(On behalf of *BABAR* Collaboration)

ORCID: 0000-0003-2943-9343
email: dxlin@impcas.ac.cn



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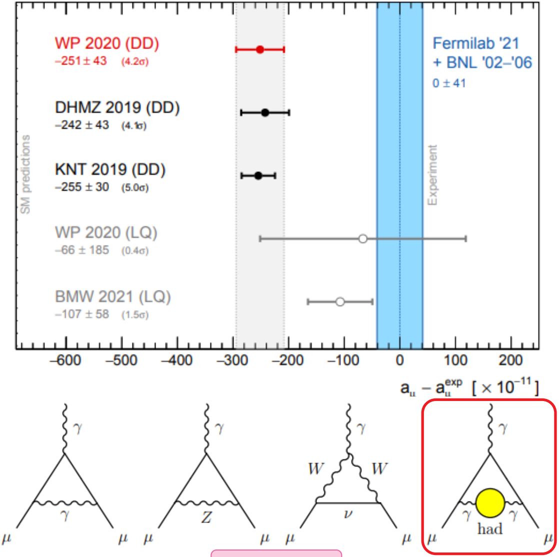
Outline

1. Motivation and Introduction
2. Introduction of *BABAR* Experiment
3. Hadronic Cross Section via ISR Process
   - $e^+e^- \longrightarrow 3\pi$ Process
   - $e^+e^- \longrightarrow 2K3\pi$ Processes
4. Summary

Motivation: The Muon g-2 Puzzle



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- Muon anomalous magnetic moment:

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

- Precise test of the Standard Model:

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

- Long-standing discrepancy (**4.2** σ) between theory and experiment for muon g-2,
- Main uncertainty of a_μ^{SM} rising from hadronic (quark and gluon) loop contributions a_μ^{Had}.

Motivation: Evaluating the Hadronic Contribution

source	contribution ($\times 10^{-11}$) value	error
a_μ^{QED}	116 584 718.93	±0.10
a_μ^{EW}	53.6	±1.0
a_μ^{Had}[LO]	**6931**	**±40**
a_μ^{Had}[NLO]	-98.3	±0.7
a_μ^{LBL}[NLO]	92	±18
a_μ^{SM}	116 591 810.1	±43.9
a_μ^{exp}	116 592 061	±41
a_μ^{exp} - a_μ^{SM}	**4.2σ** **251**	**±59**

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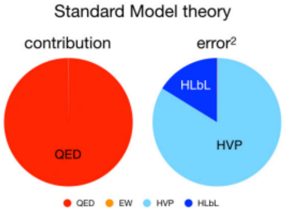

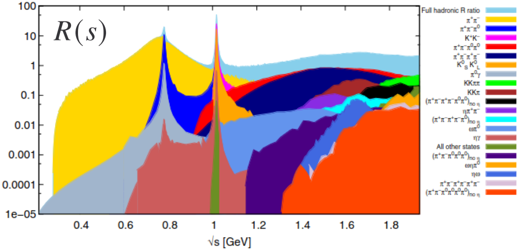

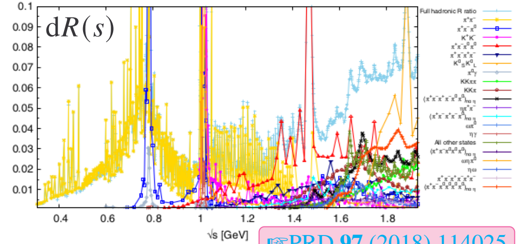

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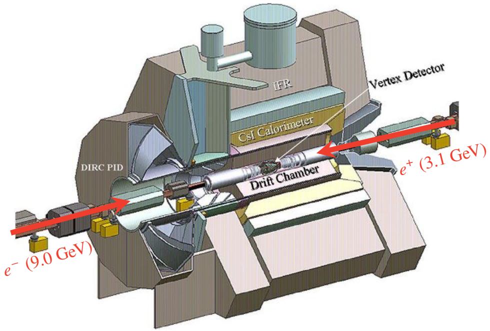
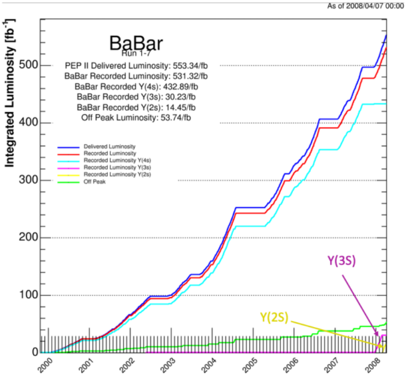
Theory calculations on a_μ^{Had} relying on the experiment inputs.

Introduction: The *BABAR* Experiment





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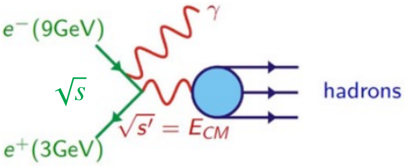
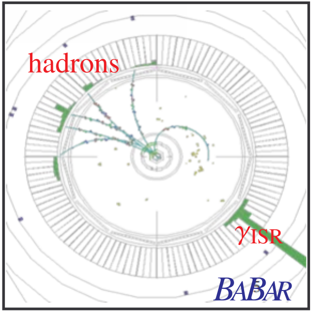
- Designed primarily for the research of CP-violation in B-meson decays,
- General-purpose design of detector and high quality of data suit for a large variety of studies,
- Ten years data taking to collect 531 fb^{-1} luminosity mainly at $\Upsilon(4S)$.

Introduction: Initial-State Radiation Technique





- High energy photon emitted via the initial-state radiation by the beam particle,
- To decrease the center-of-mass (c.m.) energy, $\sqrt{s'}$, allowing a distribution of energies for remaining system.

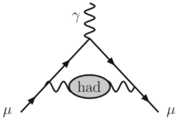
$$x \equiv 1 - \frac{s'}{s} = \frac{2E^*_\gamma}{\sqrt{s}}$$

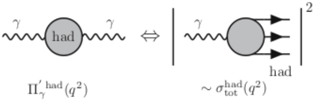
- Most ISR photons are emitted along the beam directions,
- Large luminosity needed due the suppression with a factor of π/α:

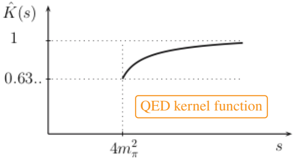
$$W(s,x) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2}\right)$$

- High acceptance, even at threshold,
- A large number of hadronic final states measured at *BABAR*.

Hadronic Cross Sections from *BABAR* ISR Contributions







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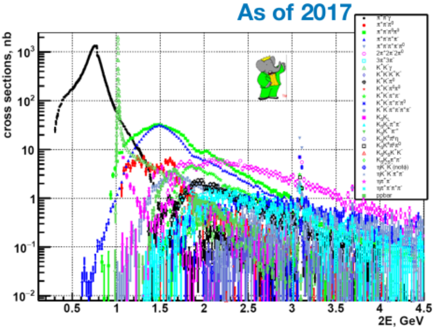
- The LO hadronic VP contribution calculated via dispersion relations from correspoding hadronic cross section measurements:

$$a_\mu^{\mathrm{Had}}[\mathrm{LO}] = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R_{\mathrm{Had}}(s)$$

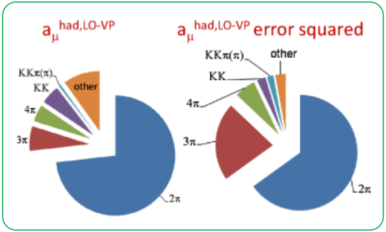
$$R_{\mathrm{Had}}(s) \equiv \frac{\sigma(e^+e^- \to \gamma^* \to \mathrm{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

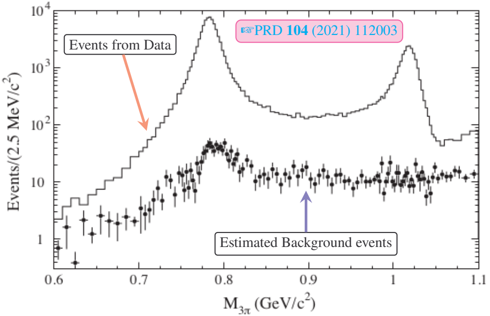
- Perturbative QCD (pQCD) can be used by theory for the energy region above ~2 GeV,
- Need experiment inputs for the energy region below that, and *BABAR* provides significant contributions.



picture from D. Brown's talk at "DIS2023"

The Process of $e^+e^- \to \pi^+\pi^-\pi^0$ at *BABAR*

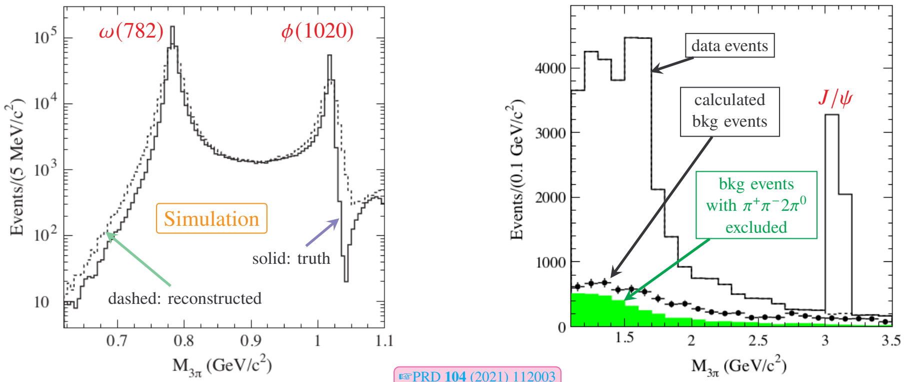




- The 2nd largest contribution mode, $e^+e^- \to 3\pi$, ~7% to $a_\mu^{\rm Had}$[LO] and ~19% to its uncertainty, ☞EPJ C80 (2020) 814
- The relative uncertainty on the 3π channel is over 3%, almost 5 times relative uncertainty on the 2π channel,
- Measuring $e^+e^- \to \pi^+\pi^-\pi^0$ to improve the precision is important for $a_\mu^{\rm Had}$[LO] calculation.

- The 3π channel was analyzed with the full *BABAR* dataset, 469 fb^{-1},
- ISR photon: with highest energy over 3 GeV,
- Require only 2 "good" tracks with opposite charge,
- At least 2 additional good photons, with $m_{\gamma\gamma} \in (0.10, 0.17)$ GeV/c^2,
- Kinematic fit, and further cuts to suppress background.

Expected Mass Spectrum for Resonances



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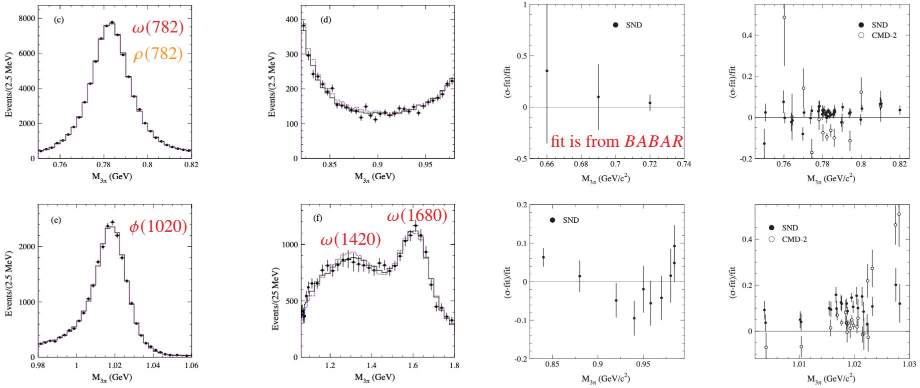
- Sharp structure of mass spectrum from resonances, over 4 orders of magnitude below 1.1 GeV,
- It is essential to unfold the detect efficiency effects,
- Fit to the 3π mass spectrum with four models, allowing or not for Lorentzian smearing and leaving the $\rho \to 3\pi$ branching fraction as a free parameter or forced to zero,
- To extract $P_V = \Gamma(V \to e^+e^-)\mathcal{B}(V \to \pi^+\pi^-\pi^0)$.

Mass Spectrum in Different Invariant Mass region



- In agreement with previous values,
- Rare decay $\rho \to \pi^+\pi^-\pi^0$ observed ($> 6\sigma$).

P_V	*BABAR*	Previous
P_ω	569.8±3.1±8.2 eV	557±11 eV (PDG)
P_ϕ	184.1±1.1±8.0 eV	192.5±4.3 eV (PDG)
$\mathcal{B}(\rho \to 3\pi)$	$(0.88\pm0.23\pm0.30)\times10^{-4}$	$(1.01^{+0.54}_{-0.34}\pm0.34)\times10^{-4}$ (SND)
ϕ_ρ	$-(99 \pm 9 \pm 15)^\circ$	$-(135^{+17}_{-13} \pm 9)^\circ$ (SND)

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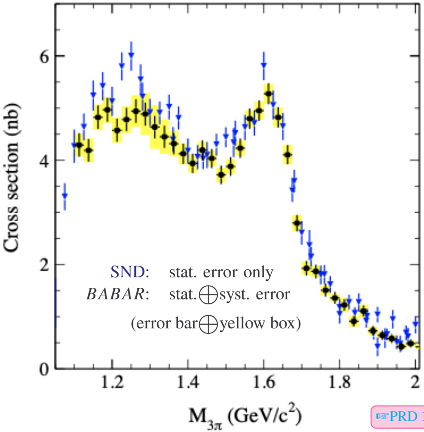
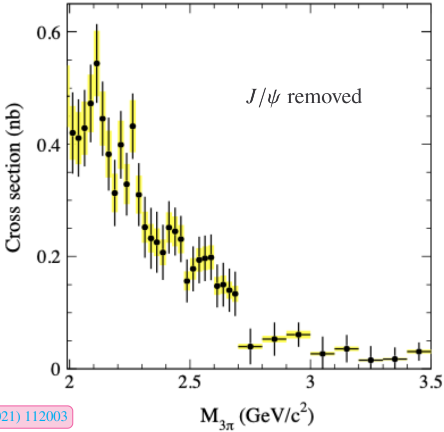
Cross Section for $e^+e^- \to \pi^+\pi^-\pi^0$ Measured at *BABAR*





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- Cross section for $e^+e^- \to \pi^+\pi^-\pi^0$ has been measured at *BABAR* from threshold up to 3.5 GeV,
- Systematic uncertainties are 1.3% and 4-15% for the region below and above 1.1 GeV, respectively,
- Reasonable agreement between SND (blue triangles) and *BABAR* (black points), except a sizable difference observed near 1.25 and 1.5 GeV/c^2.

Contribution to the Muon g-2

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TABLE VI. Values of $a_\mu^{3\pi}$ for different mass intervals. The first three rows represent the *BABAR* result, while the last three are the calculations [1,49–51] based on previous $e^+e^- \to \pi^+\pi^-\pi^0$ measurements.

$M_{3\pi}$ GeV/c^2	$a_\mu^{3\pi} \times 10^{10}$
0.62–1.10	$42.91 \pm 0.14 \pm 0.55 \pm 0.09$
1.10–2.00	$2.95 \pm 0.03 \pm 0.16$
<2.00	$45.86 \pm 0.14 \pm 0.58$
<1.8 [1]	$46.21 \pm 0.40 \pm 1.40$
<1.97 [49]	46.74 ± 0.94
<2 [50]	44.32 ± 1.48
<1.8 [51]	$46.2 \pm 0.6 \pm 0.6$

TABLE VII. Contributions to the systematic uncertainty in $a_\mu^{3\pi}(0.62 < M_{3\pi} < 1.1 \text{ GeV}/c^2)$ from different effects.

Effect	Uncertainty (%)
Luminosity	0.4
Radiative correction	0.5
Detection efficiency	1.1
MC statistics	0.15
Background subtraction	0.073
Gaussian smearing	0.0007
Lorentzian smearing	0.003
Unfolding procedure	0.045
Total	1.3

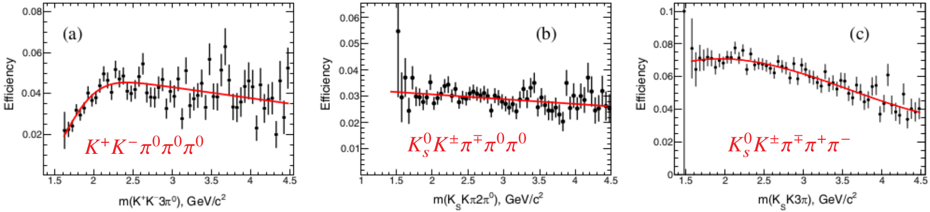
$$a_\mu^{3\pi} = (45.86 \pm 0.14 \pm 0.58) \times 10^{-10}$$

- LO hadronic contribution to muon anomaly magnetic moment is calculated with the measured cross section below 2.0 GeV,
- Agreement with calculation based on previous measurements, more precise by a factor of ~2,
- Previous relative uncertainty on the 3π mode is over 3%.

The Processes of $e^+e^- \to 2K3\pi$ at *BABAR*

- Three channels for the $2K3\pi$ mode measured at *BABAR* for the first time: $K^+K^-\pi^0\pi^0\pi^0$, $K_s^0K^\pm\pi^\mp\pi^0\pi^0$ and $K_s^0K^\pm\pi^\mp\pi^+\pi^-$,
- Only $K^+K^-\pi^+\pi^-\pi^0$ has been studied previously for the $2K3\pi$ mode,
- Similar technique used as $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{\text{ISR}}$,
- Total integrated luminosity used is 468.6 fb^{-1} (at $\Upsilon(4S)$: 424.7 fb^{-1}),
- Intermediate resonances (narrow), η, ρ and K^*, have been measured.

invariant-mass-dependent reconstruction efficiency



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Observed Intermediate Structures at *BABAR* (I)

$K^0_S K^{\pm}\pi^{\mp}\pi^0\pi^0$

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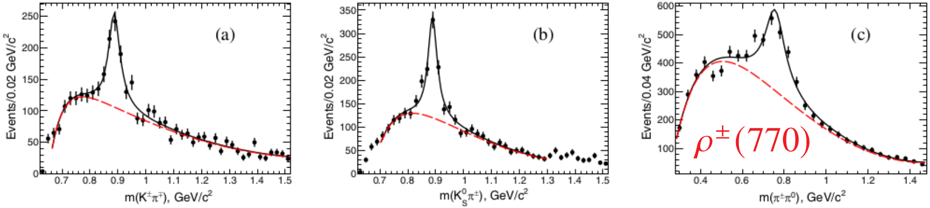
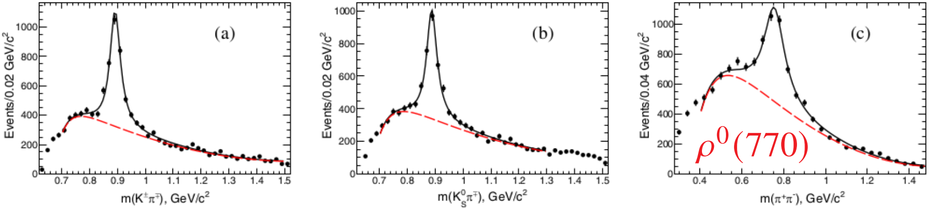
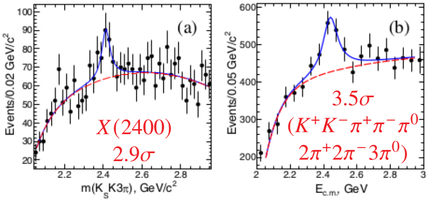


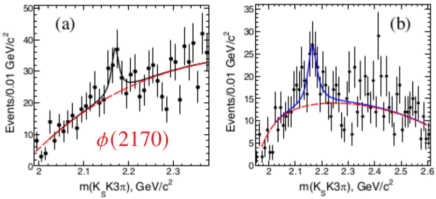
$K^*(892)^0$ $K^*(892)^{\pm}$

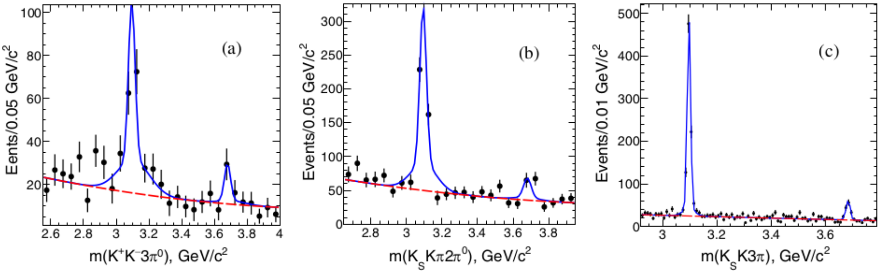


$K^0_S K^{\pm}\pi^{\mp}\pi^+\pi^-$

Observed Intermediate Structures at *BABAR* (II)







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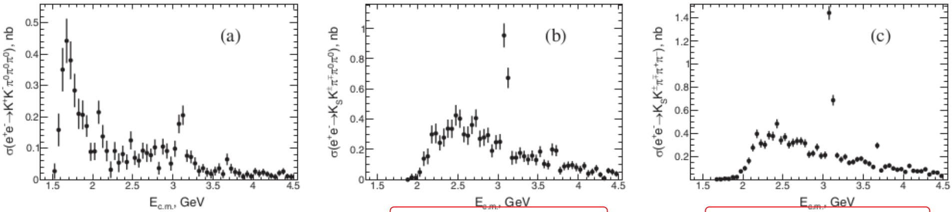
- $X(2400)$ and $\phi(2170)$ decays to $K_sK3\pi$ final states,
- Clear J/ψ and $\psi(2S)$ peaks in the $2K3\pi$ final states.

Cross Sections Measured for $e^+e^- \to 2K3\pi$



	$K^+K^-\pi^0\pi^0\pi^0$	$K_S^0K^\pm\pi^\mp\pi^0\pi^0$	$K_S^0K^\pm\pi^\mp\pi^+\pi^-$
signal events:	1230	2658	6582
uncertainty:	~10%	~10%	~8%

- Three channels of the $2K3\pi$ mode have been measured for the first time with ISR method at *BABAR*,
- The cross sections of $2K3\pi$ extracted in the invariant mass region below 4.5 GeV,
- The precision of the $2K3\pi$ cross section is around 10%.

Summary

- The muon g-2 puzzle is important for SM precise test, even a potential gateway to New Physics (NP),
- Precision studies of e^+e^- annihilation into hadrons in low energy at *BABAR* with ISR technique,
- These measurements provide important experimental input for a_μ^{Had} calculation,
- The new measurement of $e^+e^- \to \pi^+\pi^-\pi^0$ improved the precision of a_μ^{Had} calculation from this channel by a factor of ~2, ☞PRD **104** (2021) 112003
- Measurements of the cross section and substructure associated with $e^+e^- \to 2K3\pi$ modes help to improve knowledge of the hadronic contributions to a_μ^{Had}, ☞PRD **107** (2023) 072001.


thank you
gracias
danke
merci
obrigado
謝謝
teşekkür ederim
ngiyabonga
go raibh maith agat
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sukriya
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terima kasih
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arigatô
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Баярлалаа
рахмат
tapadh leat
хвала
asante
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mahalo
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dank je
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