Contribution of Hadronic Vacuum Polarization (HVP) in the anomalous magnetic moment of the muon

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- The hadronic vacuum polarization, theoretical approach and experimental technique.
- Advantage of working with Belle-II
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Introduction

- For a fundamental particle with intrinsic angular momentum $\vec{s}$ and charge Q, the intrinsic magnetic momenta is given by

$$\vec{\mu} = g\frac{Qe}{2m}\vec{s},$$

- The Dirac equation predicts $g = 2$. The value of g is adjusted by the Quantum fluctuation resulting non-zero value of the magnetic anomaly, defined as $a_\mu \equiv (g-2)/2$,

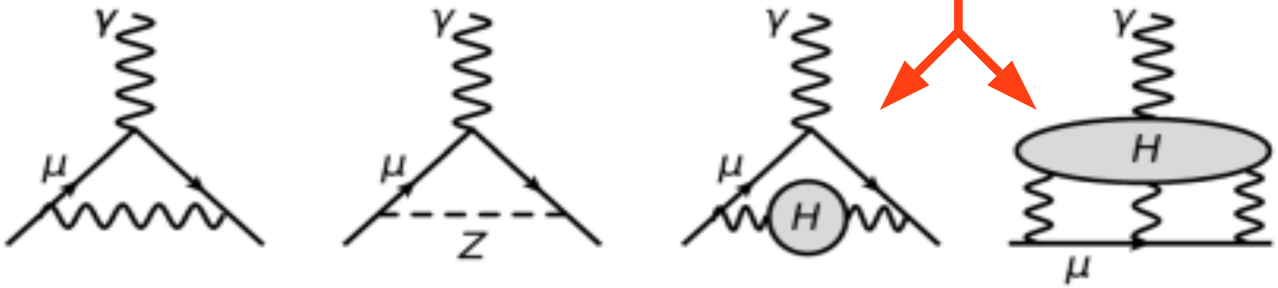

FIG. 1. Feynman diagrams of representative SM contributions to the muon anomaly. From left to right: first-order QED and weak processes, leading-order hadronic (H) vacuum polarization, and hadronic light-by-light contributions.

Motivation

- The tension between measurements and theoretical predictions of muon magnetic anomaly, $a_\mu \equiv (g_\mu - 2)/2$, provides the hint for new physics.
- The first results of Muon g-2 experiment at Fermilab (combined with BNL E821 result) strengthen the tension to 4.2 sigma.
- Discrepancy between KLOE (combined) and BABAR measurements

Belle II contribution is needed !!

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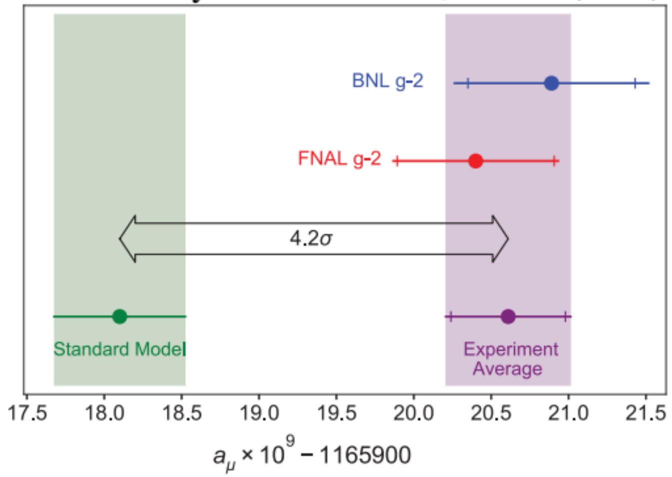


Fig. Theory vs experiment [1]

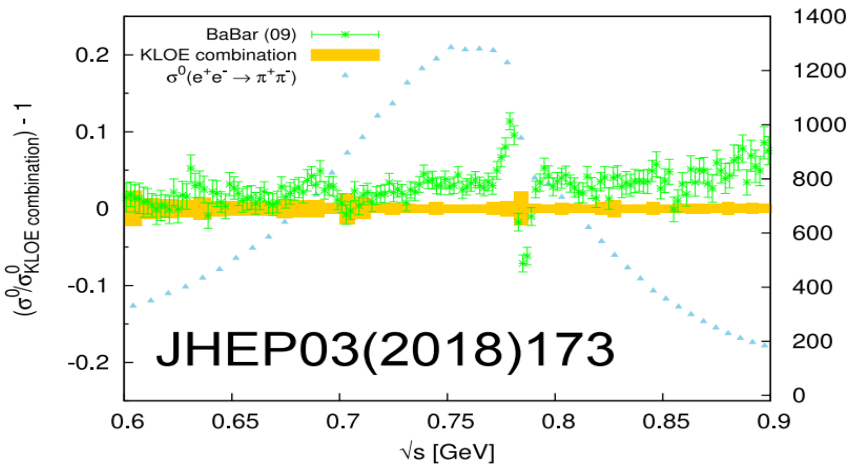


Fig. The KLOE combination compared to the BABAR [1]

The hadronic vacuum polarization (HVP) [1,4]

- The largest source of theoretical uncertainty in a_μ comes from the hadronic term.
- The perturbative QCD fails at a lower energy range.
- The leading order HVP corrections can be safely evaluated at low energy range with dispersion relation (DR).

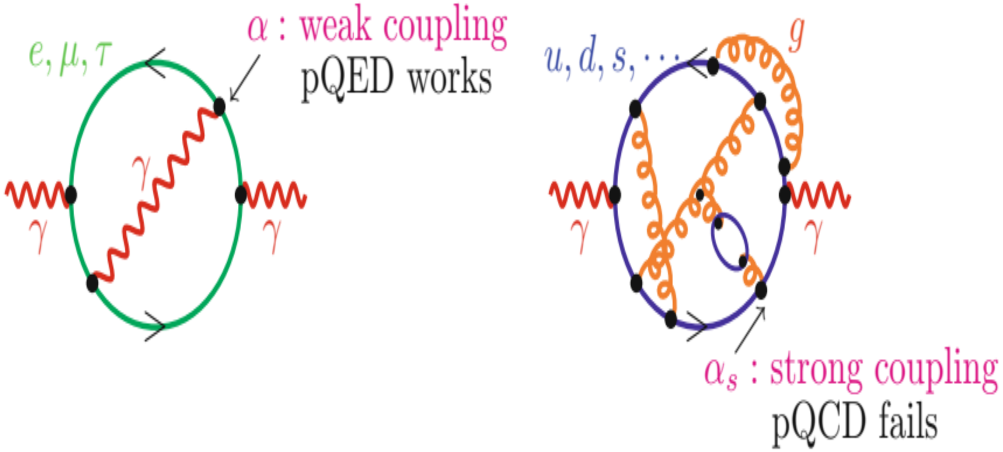
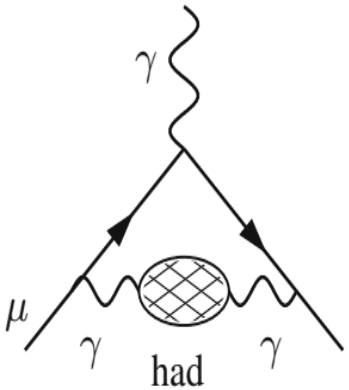


Fig. The hadronic analog of the lepton loop
[DOI 10.1007/978-3-319-63577]



Dispersion relation to calculate $a_\mu^{had,LO}$ at lower energy [1,2,5]

- At leading order (LO), i.e., $O(\alpha^2)$ The dispersion relation (DR) is given by,

$$a_\mu^{had,LO} = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

- When expressed in the form the kernel function $\hat{K}(s) = \frac{3s}{m_\pi^2} K(s)$, it rises from $\hat{K}(4M^2) \approx 0.63$ at the two pion threshold to its asymptotic value of 1 in the limit of large s.
- R(s) is the so-called (hadronic) R-ratio defined by,

$$R(s) = \frac{\sigma^0 \left(e^+ e^- \rightarrow \text{ hadrons } (+\gamma)\right)}{\sigma_{\rm pt}}, \quad \sigma_{\rm pt} = \frac{4\pi\alpha^2}{3s}$$

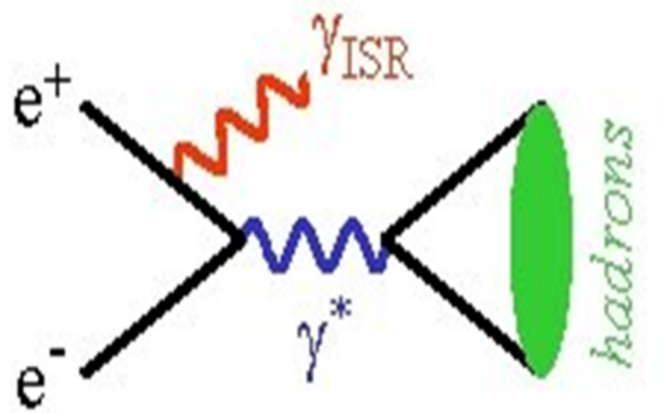
- The σ^0 is the total hadronic cross section in the dispersion integral must be the bare cross section, excluding effects from vacuum polarization (VP).

The ISR approach

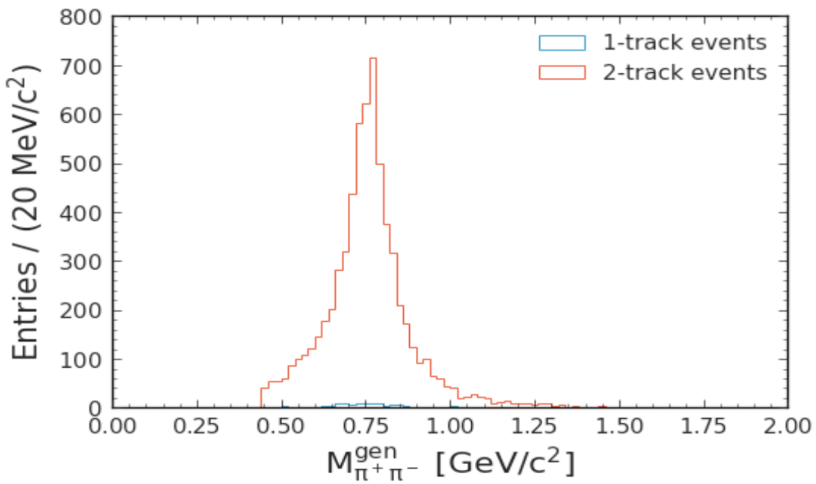
- The reduced collision energy, because of the ISR, s' is given by

$$s' = s\left(1 - \frac{2E_\gamma^*}{\sqrt{s}}\right),$$

where E_γ^* is the ISR photon energy.



- This is excellent way to get the final state mass spectrum allowing us to get the values from threshold to wider range in a single configuration of the e^+e^-storage rings.



Advantage of working with Belle-II

- The most important channel is the two-pion channel, which contributes more than 70 % of $a_{\mu}^{HVP,LO}$.
- Precision in the measurement is limited by the systematical uncertainty.
- With a new luminosity world record of $4.7 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ luminosity and a data sample of approximately $428\mathrm{fb}^{-1}$ already collected by Belle II, we have sufficient information to make measurements of $e^{+}e^{-} \to \pi^{+}\pi^{-}(\gamma)$ with systematic uncertainty down upto 0.5%.
- It will improve the theoretical calculation of the leading-order HVP contribution.

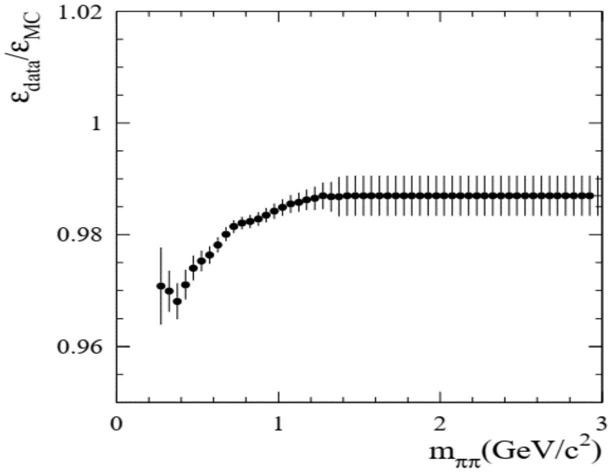
Sample and preselection

- MC:
  - SkimMC14rd_f: $\mu^+\mu^-, \pi^+\pi^-, \tau^+\tau^-$, qqbar
  - MC13a: $\pi^+\pi^-$ (signal, 1e7)

- Selection Criteria
  - ISR (highest E^* in case of multiple candidates),
    - $E^*_{ISR} > 2$ GeV,
    - In ECL inner barrel: [32.2+5 , 128.7-7] degree
  - 2 tracks:
    - dr < 2.0, abs(dz) < 5.0, p > 1.0
    - in KLM barrel : [47.0+5, 122.0-5] degree
  - $M_{\pi\pi} < 3.5 GeV$

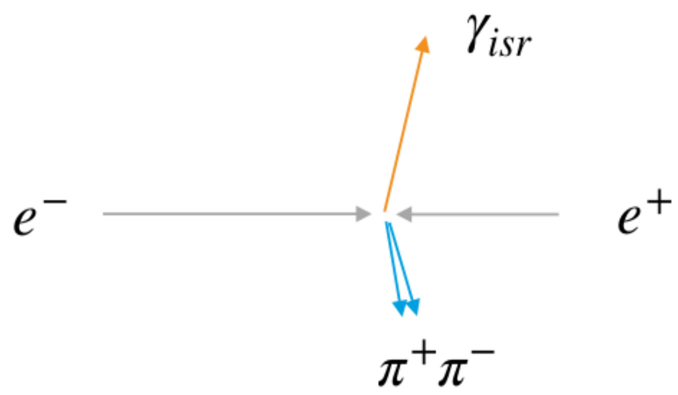
Tracking efficiency [7]

- The efficiency as a function of the di-pion mass is defined as



$$\varepsilon^{\text{data}} = \varepsilon^{MC}\left(\frac{\varepsilon^{\text{data}}_{\text{trigger}}}{\varepsilon^{MC}_{\text{trigger}}}\right)\left(\frac{\varepsilon^{\text{data}}_{\text{tracking}}}{\varepsilon^{MC}_{\text{tracking}}}\right)\left(\frac{\varepsilon^{\text{data}}_{PID}}{\varepsilon^{MC}_{PID}}\right)$$

- A 1C kinematic fit is used to select $\pi^+\pi^-\gamma$ events for tracking efficiency studies.



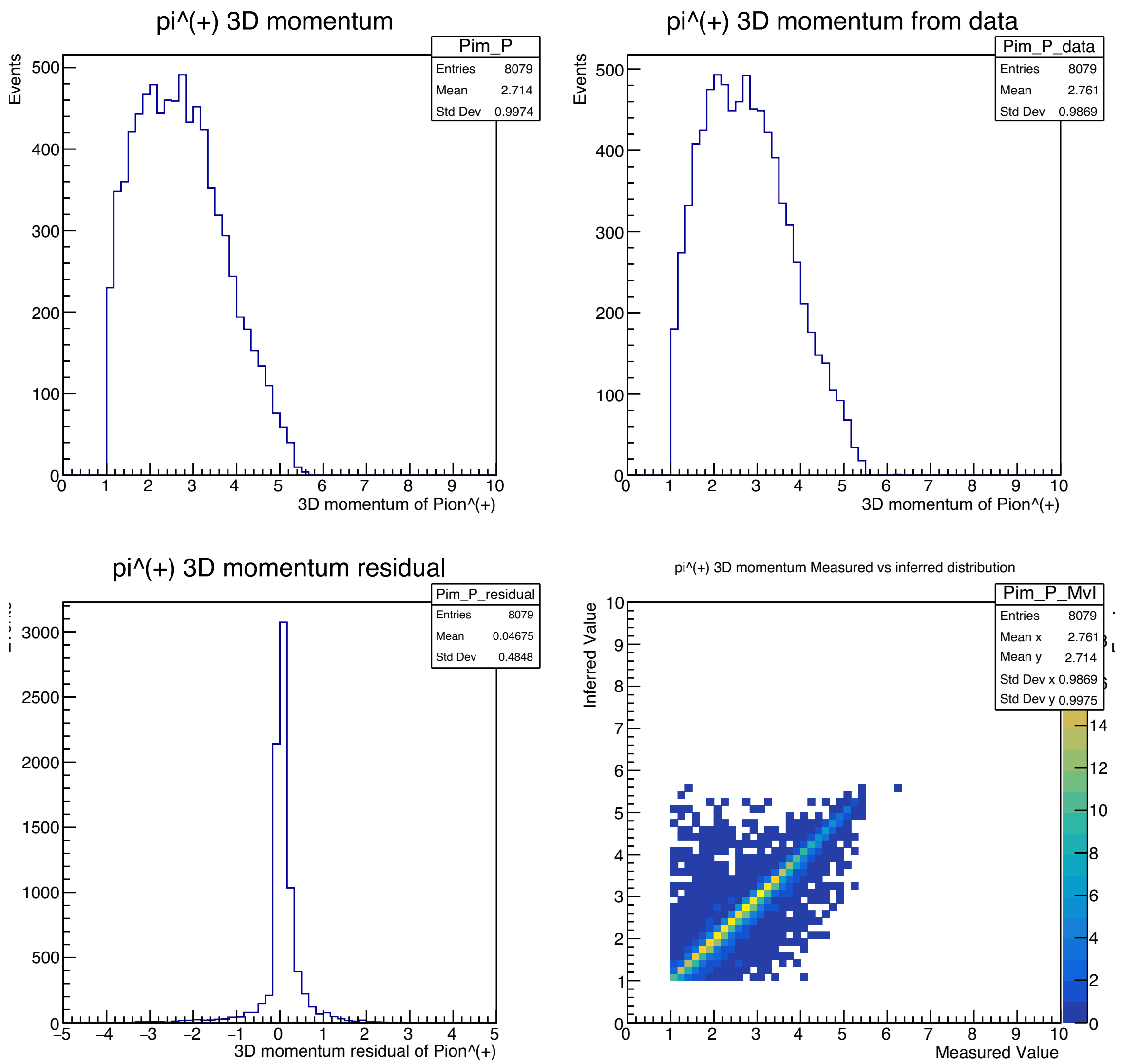
Work done so far:

- Used the basf2 software to extract the kinematic information of final state particles using simulated data set.
- Compared the generator level and reconstruction level information to check the detection efficiency of the detector.
- Applied the concept of 1C fit and cross checked with the data.

Plots for π^+ reconstruction using the π^- and ISR four-momentum and comparison with data

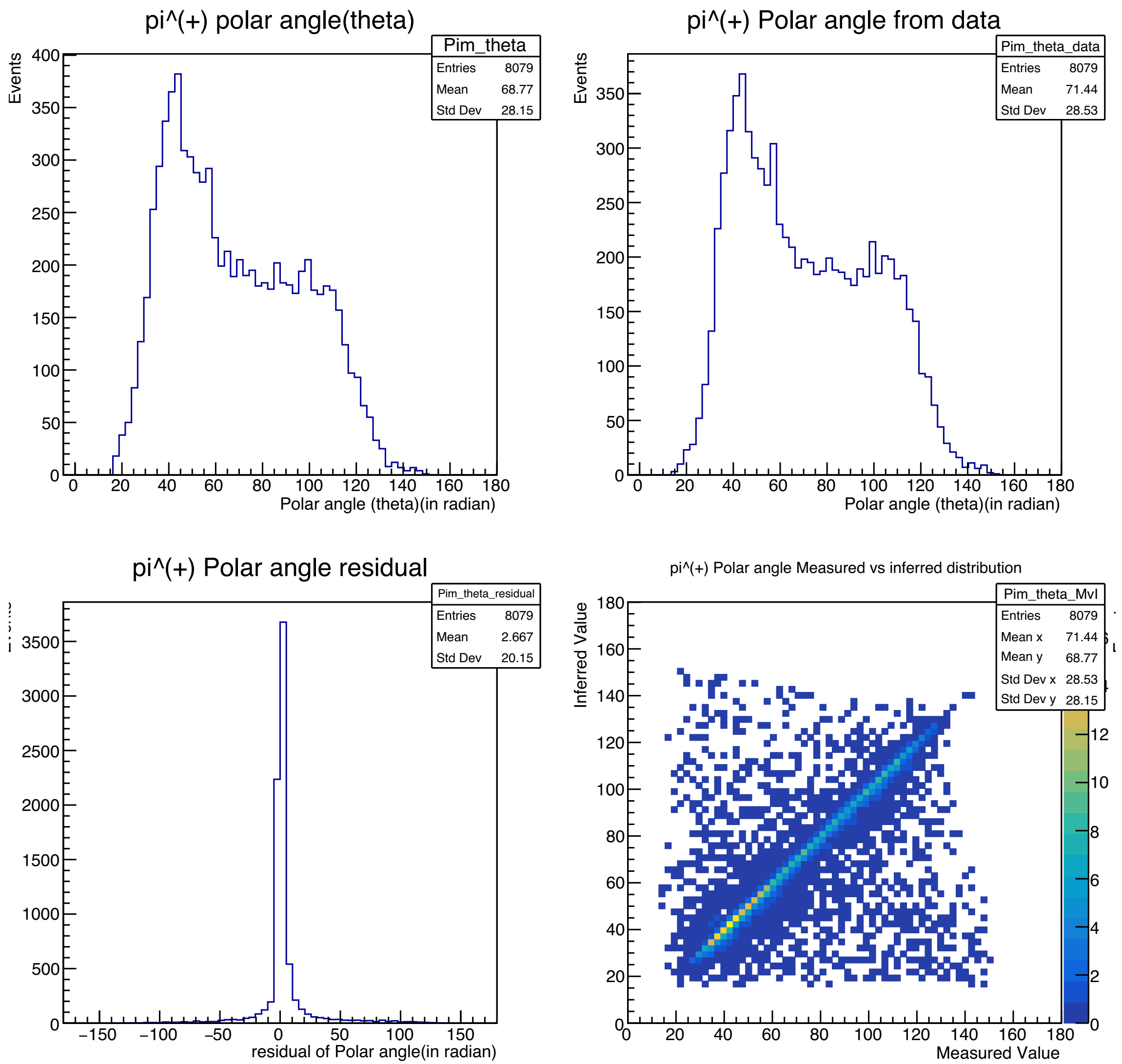
3D-momentum plots of π^+ assuming it is missing

- Gen-level data is used both for calculation as well as for comparing



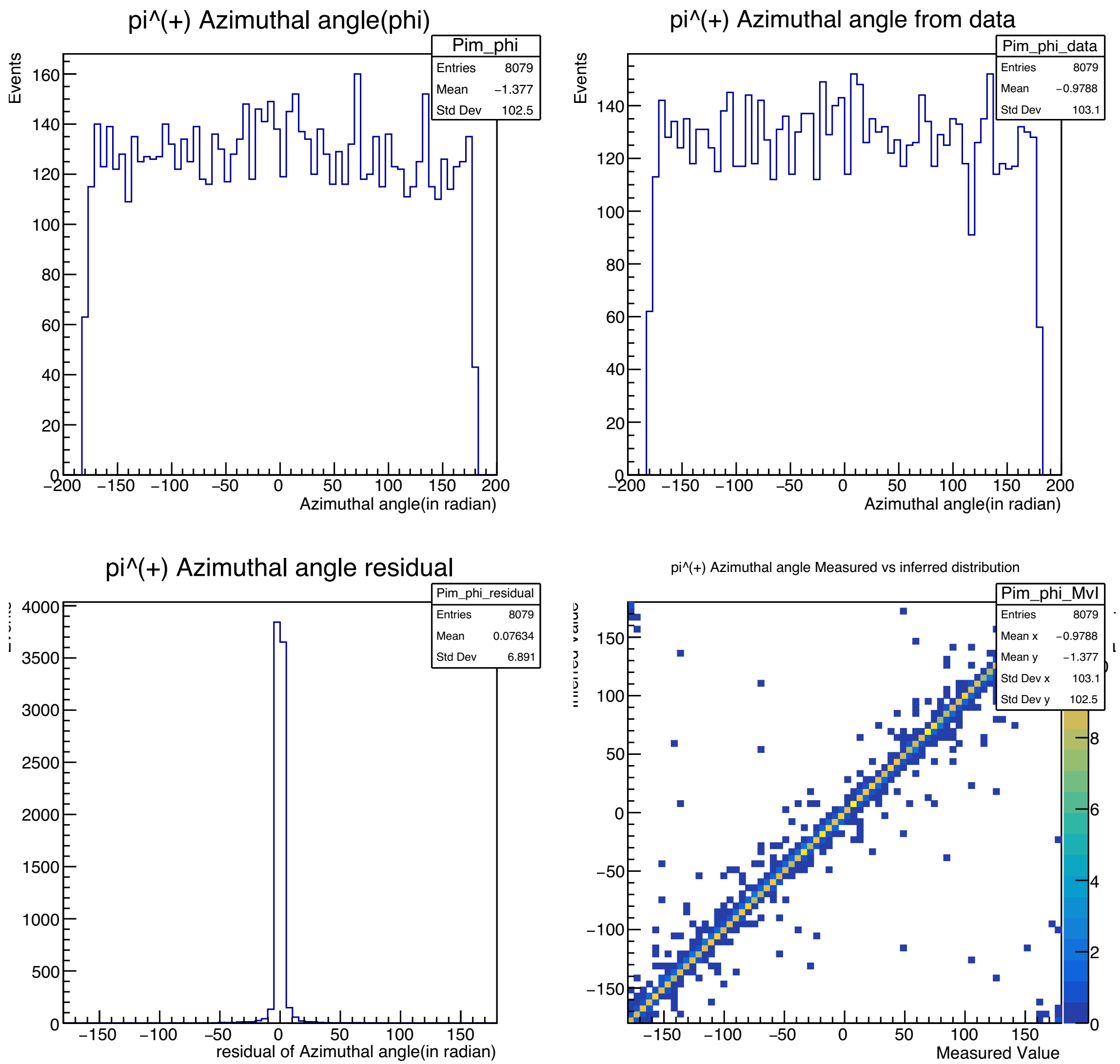
Polar angle (theta) plots of π^+ assuming it is missing

- Gen-level data is used both for calculation as well as for comparing



Azimuthal angle (phi) plots of π^+ assuming it is missing

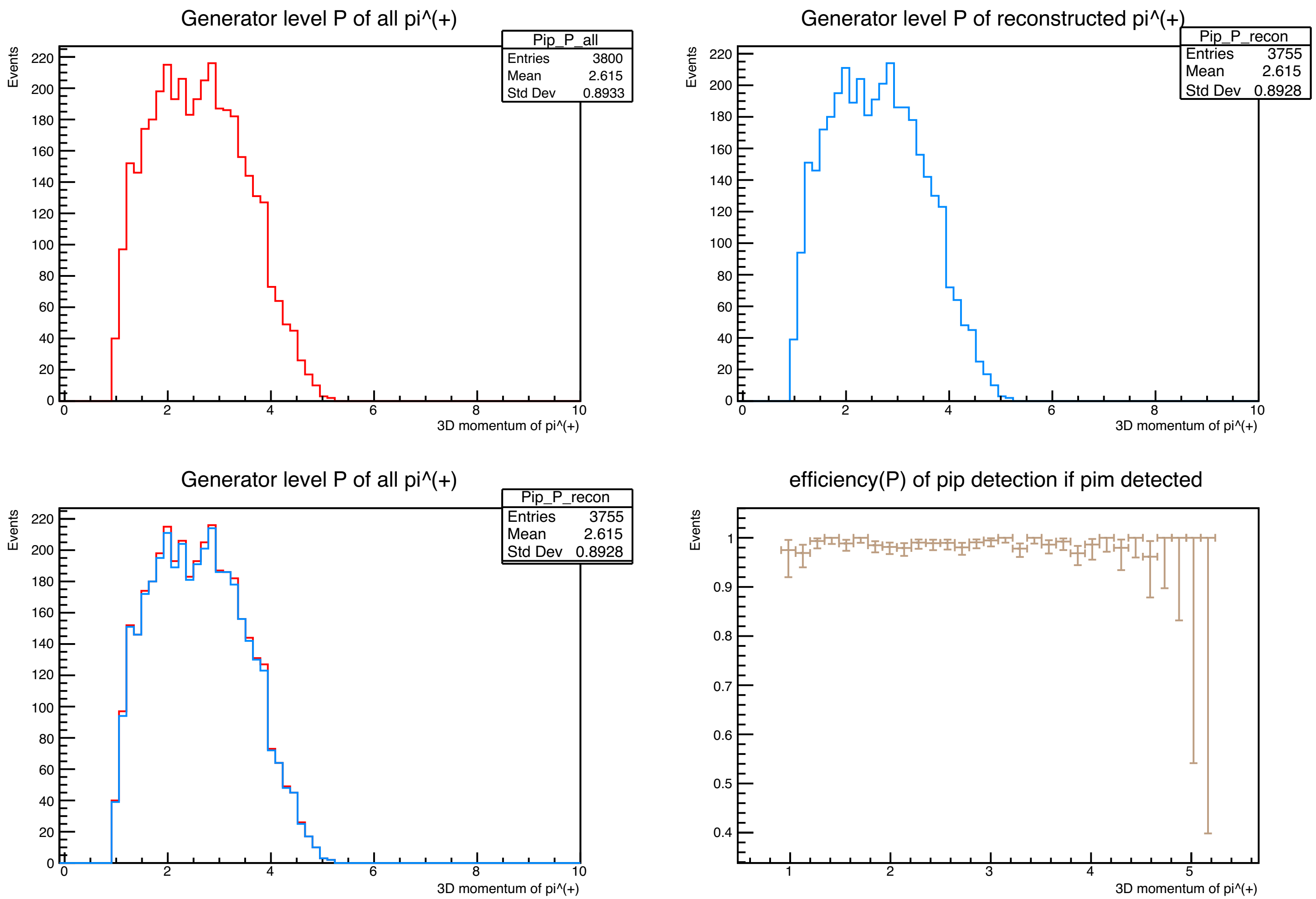
- Gen-level data is used both for calculation as well as for comparing



Plots for comparing reconstructed tracks with generator level information

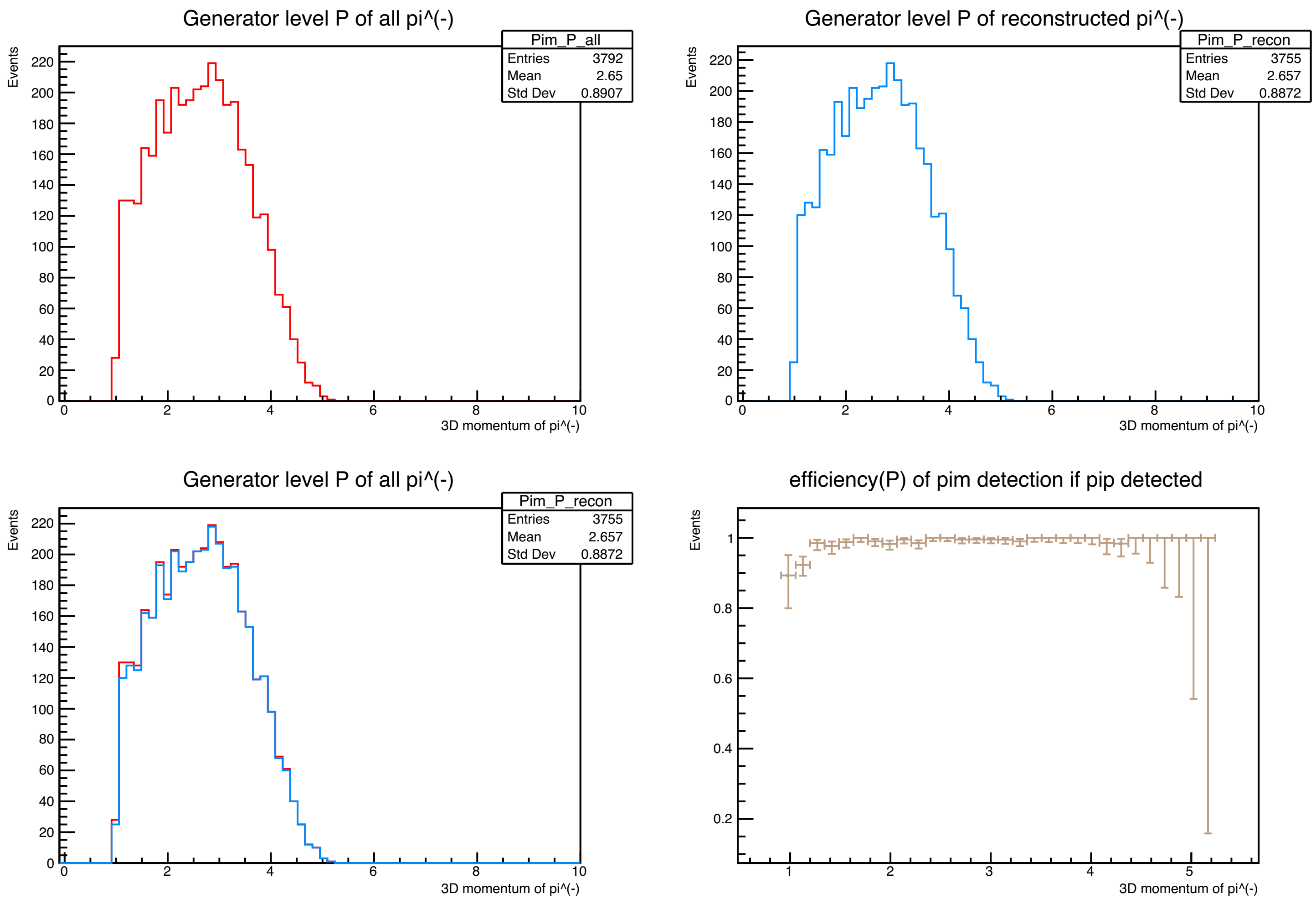
Comparing the π^+ data at reco level vs generator level

- Events with two tracks and one ISR photon using mc13a



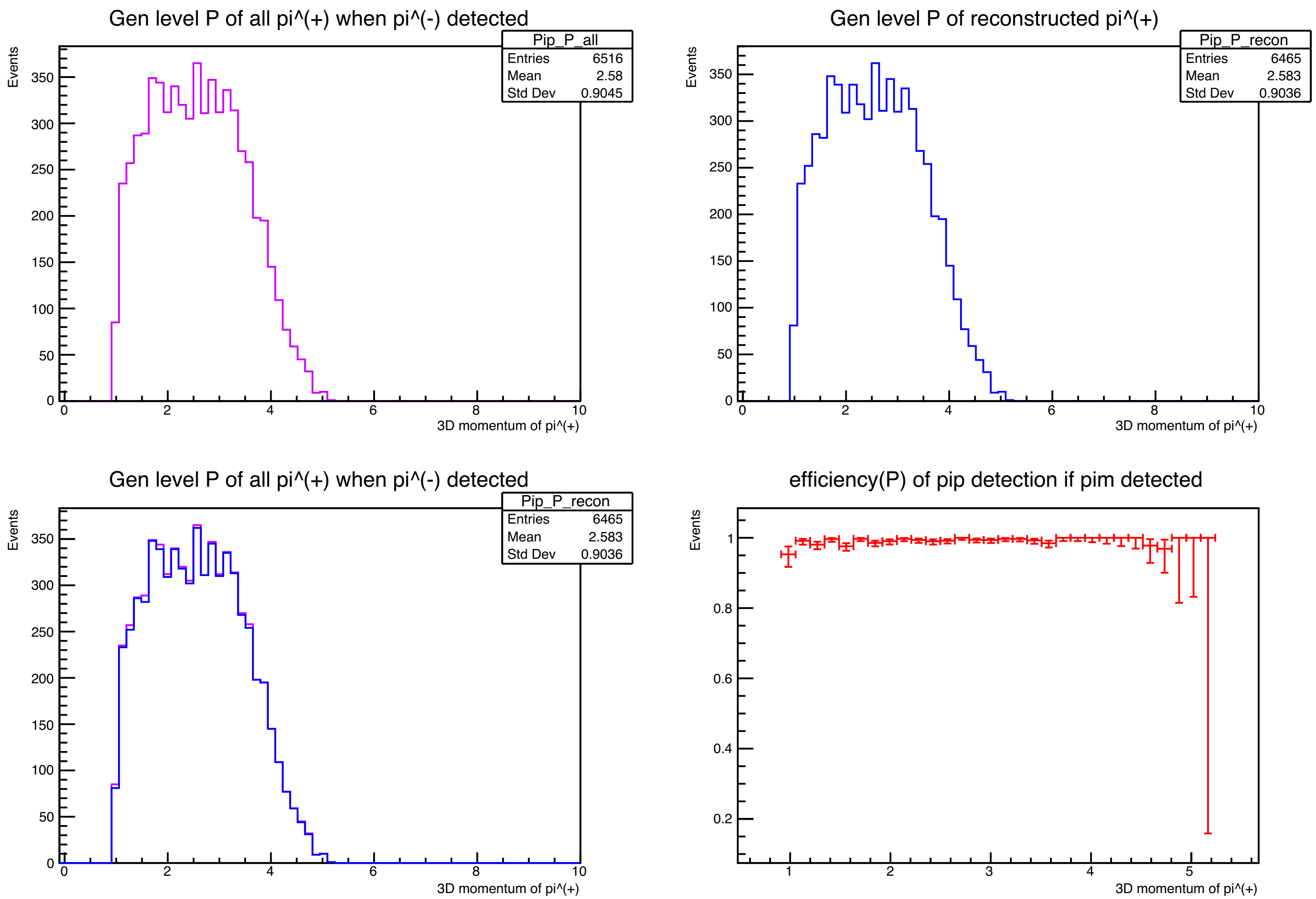
Comparing the π^- data at reco level vs generator level

- Events with two tracks and one ISR photon using mc13a



Comparing the π^+ data at reco level vs generator level

- Events with two tracks and one ISR photon using mc14rd_f



Comparing the π^- data at reco level vs generator level

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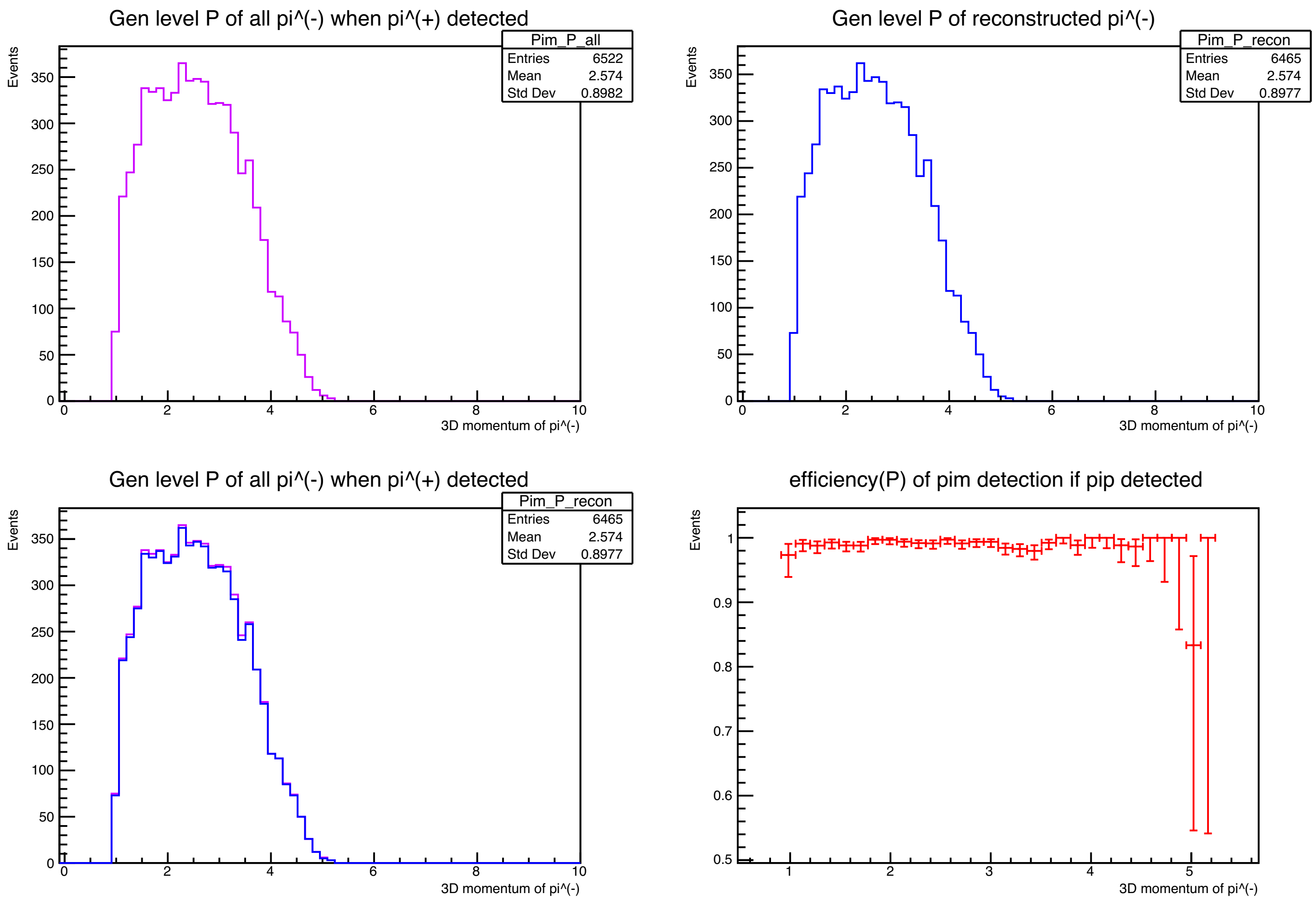

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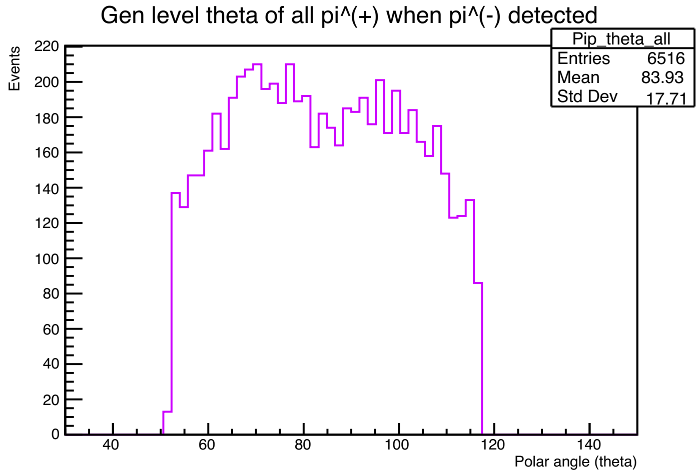

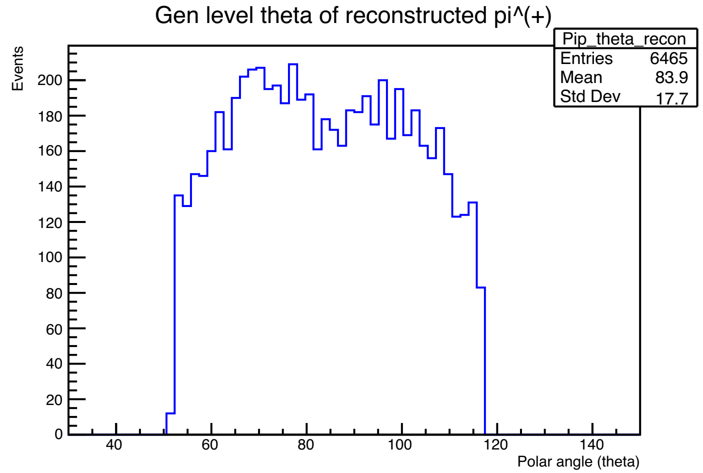

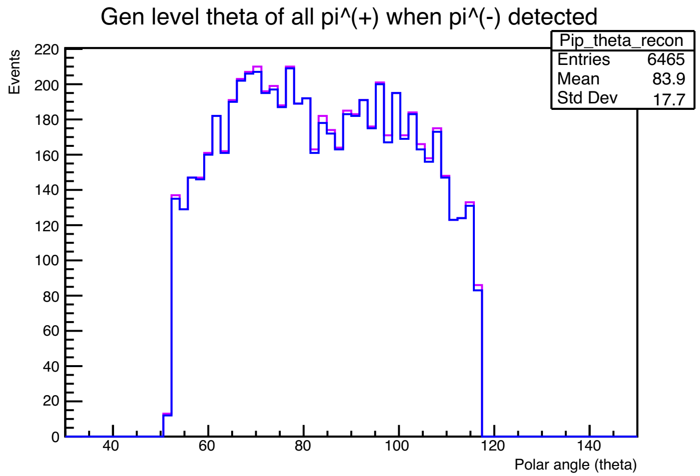

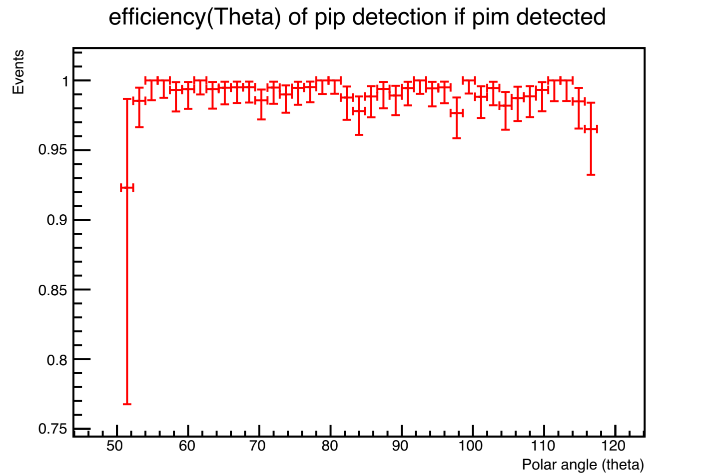

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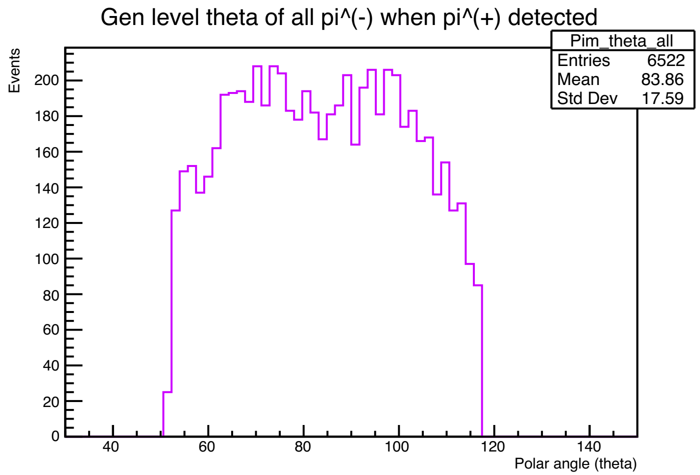

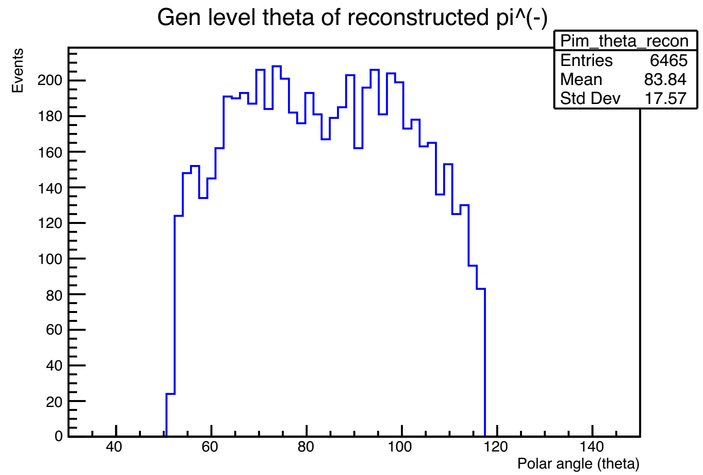

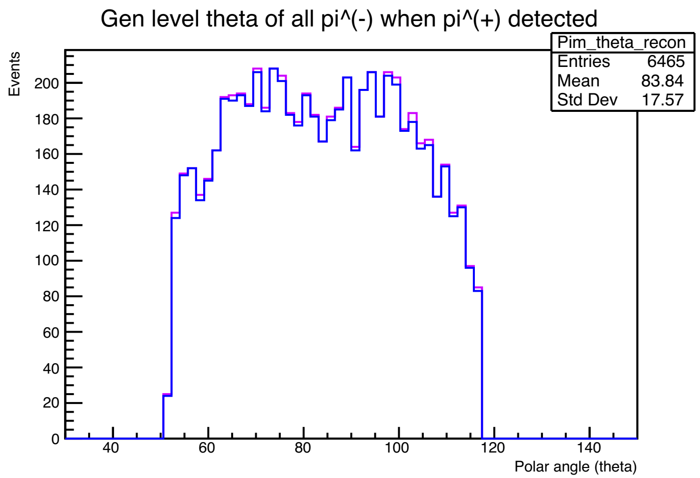

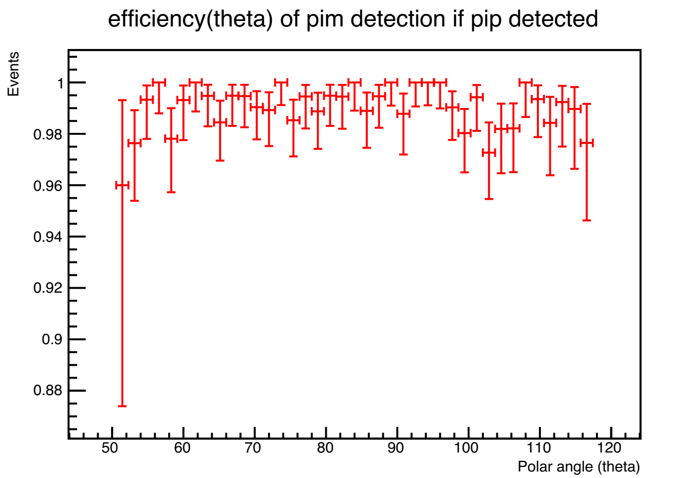

Comparing the π^+ data at reco level vs generator level

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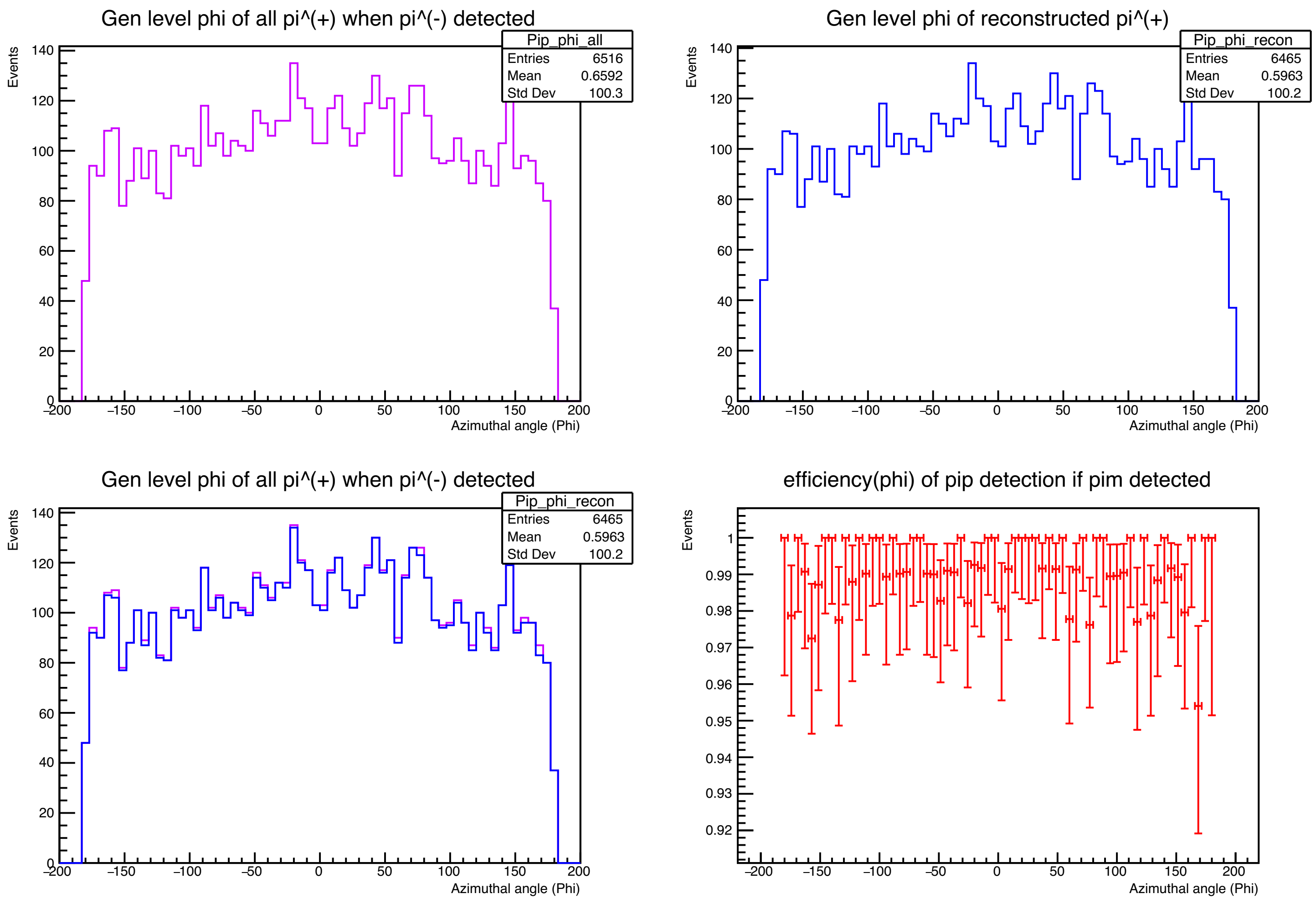
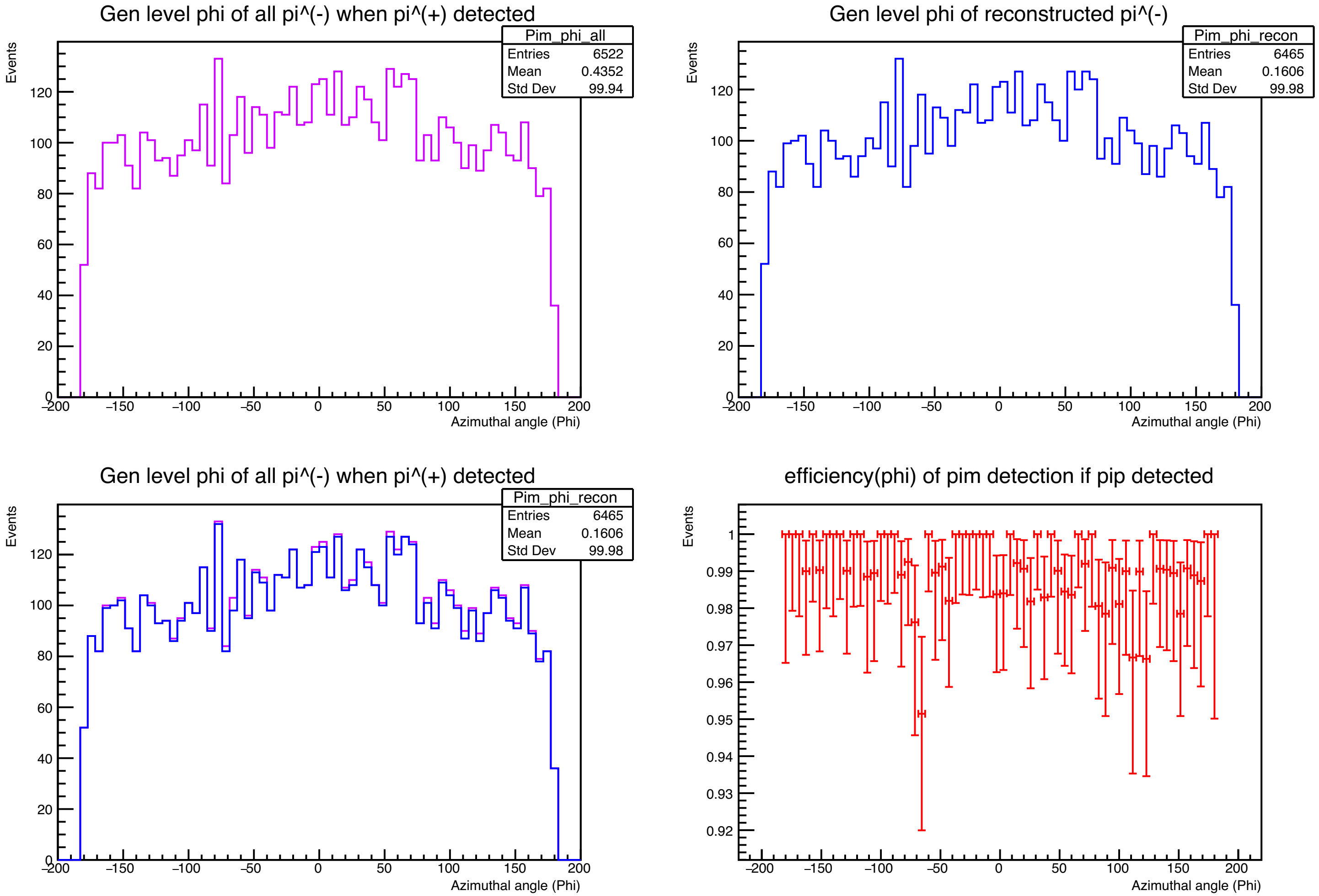


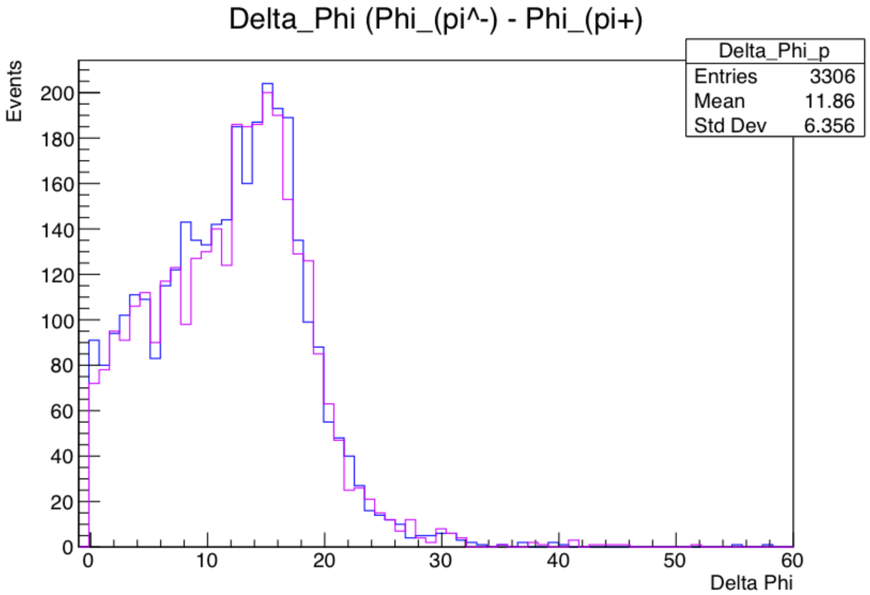
Comparing the π^- data at reco level vs generator level

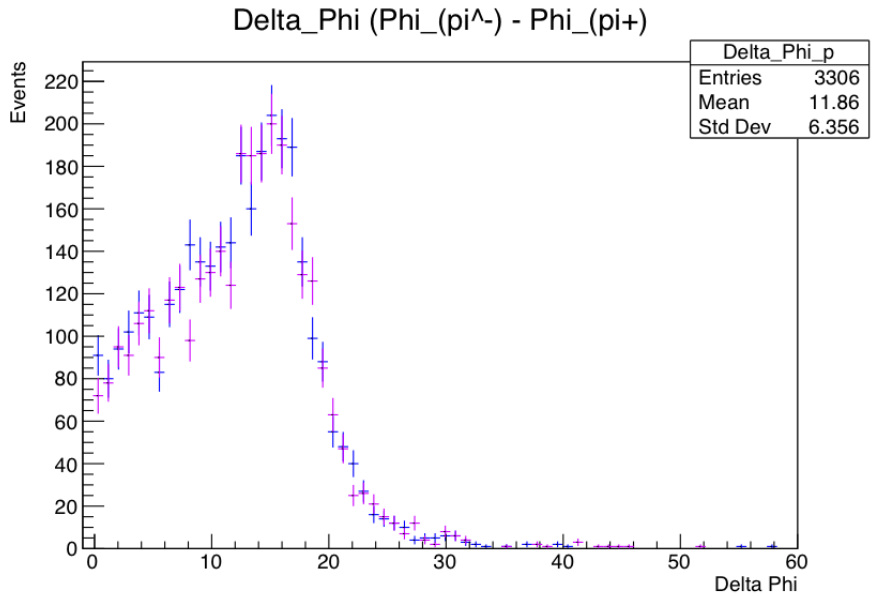
- Events with two tracks and one ISR photon using mc14rd_f



Delta Phi

- Events with two tracks and one ISR photon using mc14rd_f





Summary

- The anomalous magnetic moment of muon is an important number with a possibility of exploring the new physics.
- Currently we have $a_\mu^{exp} = 116592040(54) \times 10^{-11}$, and $a_\mu^{exp} = 116592061(41) \times 10^{-11}$ resulting $\Delta a_\mu = 251(59) \times 10^{(} - 14)$. [6]
- It is not only the most precisely measured quantity in particle physics, but theory and the experiment lie apart by 4.2 standard deviations.
- The $e^+e^- \to \pi^+\pi^-(\gamma)$ data from Belle-II will help in calculating more precise results.

Future plan

- Complete tracking efficiency study on MC then apply to the data.
- Apply similar technique to calculate particle identification corrections.
- Preliminary measurement of normalization mode $e^+e^- \rightarrow \mu^+\mu-(\gamma)$ by Summer 2023.
- First measurement of a_μ(HVP) by Summer 2024.

References

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7 J. P. Lees et al. "Precise measurement of the $e+e- \to \pi+\pi-(\gamma)$ cross section with the initial-state radiation method at BABAR.

Thank you

Backup slides

Relation between DR and data

- The cross section for the process $e^+e^- \to X$ is related to the $\sqrt{s'}$ spectrum of $e^+e^- \to X\gamma_{\mathrm{ISR}}$ events through

$$\frac{dN_{X\gamma_{\mathrm{ISR}}}}{d\sqrt{s'}} = \frac{dL^{\mathrm{eff}}_{\mathrm{ISR}}}{d\sqrt{s'}} \varepsilon_{X\gamma}\left(\sqrt{s'}\right) \sigma^0_X\left(\sqrt{s'}\right),$$

  where $dL^{\mathrm{eff}}_{\mathrm{ISR}}/d\sqrt{s'}$ is the effective ISR luminosity, $\varepsilon_{X\gamma}$ is the full acceptance for the event sample, and σ^0_X is the 'bare' cross section for the process $e^+e^- \to X$ (including additional FSR photons), in which the leptonic and hadronic vacuum polarization effects are removed.
- This eq applies equally to $X = \pi\pi(\gamma)$ and $X = \mu\mu(\gamma)$ final states, so that the ratio of cross sections is directly related to the ratio of the pion to muon spectra as a function of $\sqrt{s'}$. Specifically, the ratio $R_{\mathrm{exp}}\left(\sqrt{s'}\right)$ of the produced $\pi\pi(\gamma)\gamma_{\mathrm{ISR}}$ and $\mu\mu(\gamma)\gamma_{\mathrm{ISR}}$ spectra, obtained from the measured spectra corrected for full acceptance, can be expressed as:

$$\begin{aligned}
R_{\mathrm{exp}}\left(\sqrt{s'}\right) &= \frac{\frac{\frac{dN^{\mathrm{prod}}_{\pi\pi(\gamma)\gamma_{\mathrm{SR}}}}{ds^{\mathrm{S}}_{\mu}}}{\mathrm{prod}}}{d\sqrt{s'}\gamma_{\mathrm{ISR}}} \\
&= \frac{\sigma^0_{\pi\pi(\gamma)}\left(\sqrt{s'}\right)}{\left(1+\delta^{\mu\mu}_{\mathrm{FSR}}\right)\sigma^0_{\mu\mu(\gamma)}\left(\sqrt{s'}\right)} \\
&= \frac{R^0\left(\sqrt{s'}\right)}{\left(1+\delta^{\mu\mu}_{\mathrm{FSR}}\right)\left(1+\delta^{\mu\mu}_{\mathrm{add.FSR}}\right)}
\end{aligned}$$

- The 'bare' ratio R^0 (no vacuum polarization, but additional FSR included), which enters the VP dispersion integrals, is given by

$$R^0\left(\sqrt{s'}\right)=\frac{\sigma^0_{\pi\pi(\gamma)}\left(\sqrt{s'}\right)}{\sigma_{\mathrm{pt}}\left(\sqrt{s'}\right)}$$

where $\sigma_{\mathrm{pt}}=4\pi\alpha^2/3s'$ is the cross section for pointlike charged fermions.

- This way of proceeding considerably reduces the uncertainties related to the effective ISR luminosity function when determined through

$$\frac{dL^{\mathrm{eff}}_{\mathrm{ISR}}}{d\sqrt{s'}}=L_{ee}\frac{dW}{d\sqrt{s'}}\left(\frac{\alpha\left(s'\right)}{\alpha(0)}\right)^2\frac{\varepsilon_{\gamma_{\mathrm{ISR}}}\left(\sqrt{s'}\right)}{\varepsilon_{\gamma^{\mathrm{MC}}_{\mathrm{ISR}}}\left(\sqrt{s'}\right)}$$

Some equations

- Dirac eq. - $i\frac{\partial\psi}{\partial t} = \left(\frac{(-i\nabla - e\boldsymbol{A})^2}{2m} - 2\frac{e}{2m}\boldsymbol{S}.\boldsymbol{B} + e\varphi\right)\psi$