ISR-FSR Interference and the Initial State Radiation Method at *BABAR*

Lake Louise Winter Institute – Feb 13, 2016

Outline

BABAR Detector
a_{μ} and Charge Asymmetry
Results
Summary

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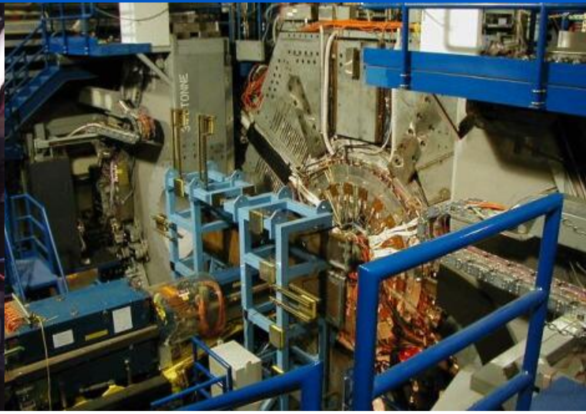
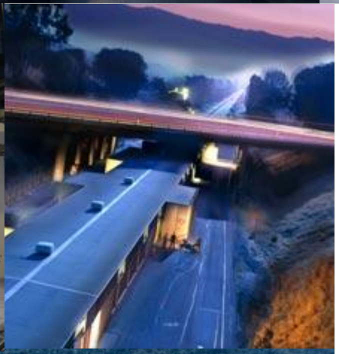
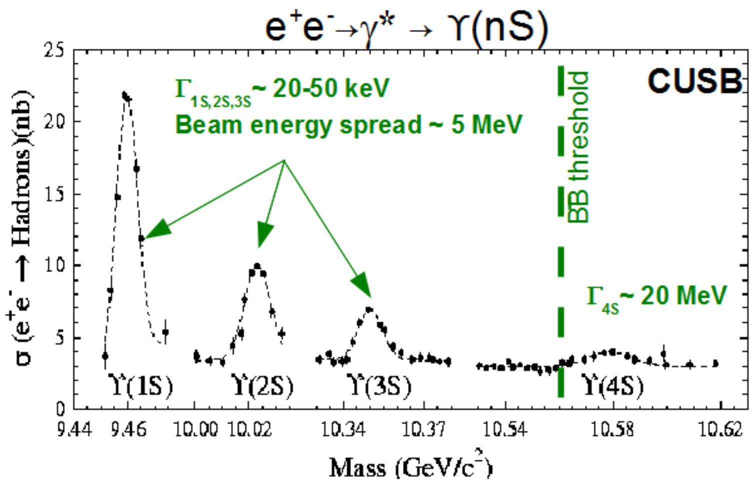
University of Victoria

SLAC and the *BABAR* Experiment





The *BABAR* Detector on the PEP II e^+e^- collider at SLAC, collected data from 1999-2008.

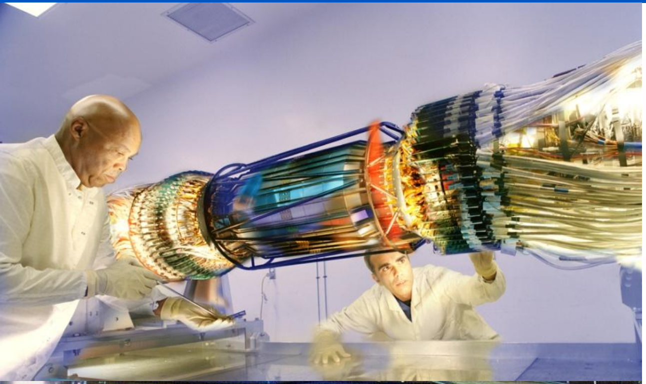


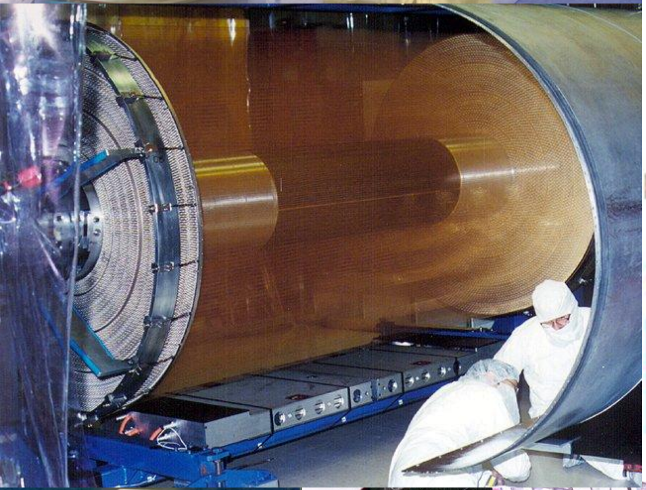
BABAR collected about 531 fb^{-1} of data

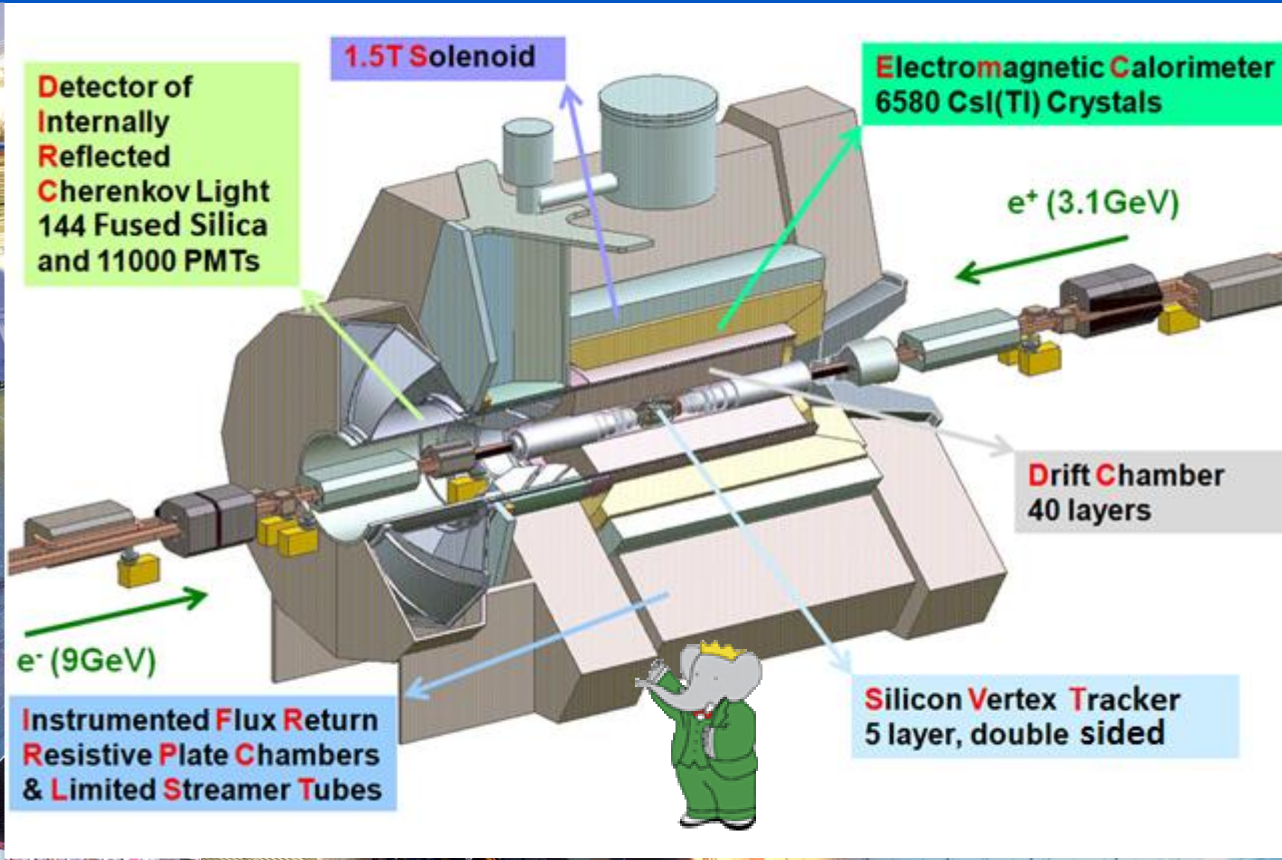
- ~470 x 10^6 events $\Upsilon(4S)$
- ~120 x 10^6 events $\Upsilon(3S)$ (10x Belle)
- ~100 x 10^6 events $\Upsilon(2S)$ (10x CLEO)
- ~ 18 x 10^6 events $\Upsilon(1S)$ from $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$

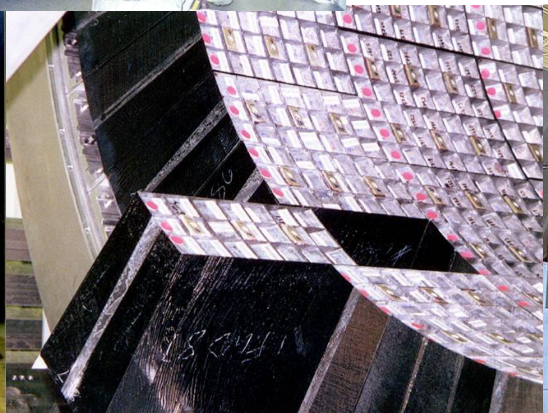
This work uses: 232fb^{-1} of data at 10.58GeV

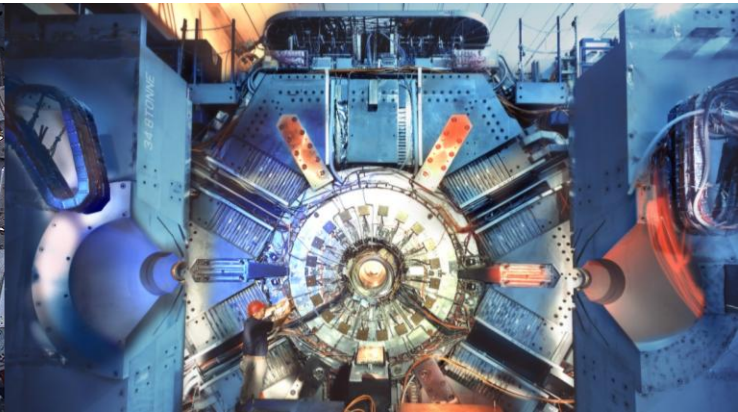
BABAR Detector











Anomalous Magnetic Moment: a_μ

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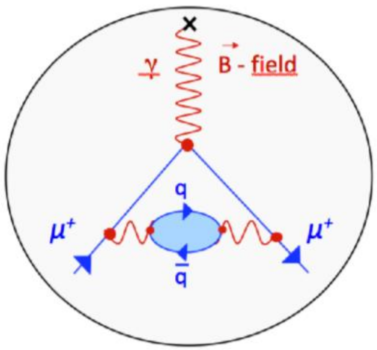
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had,LO} + a_\mu^{had,HO} + a_\mu^{had,LBL}$$



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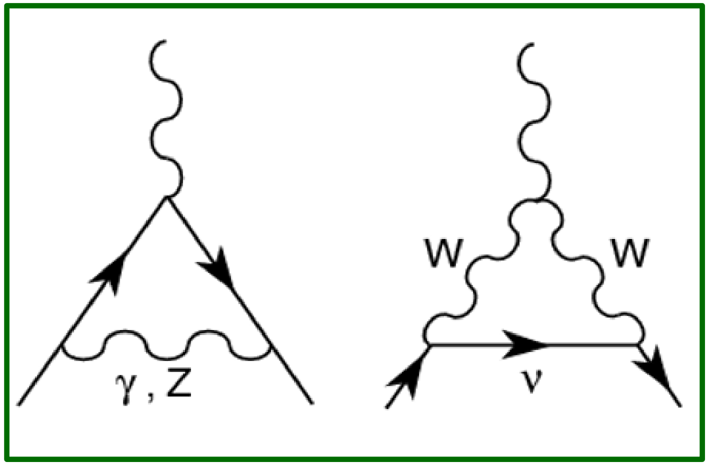

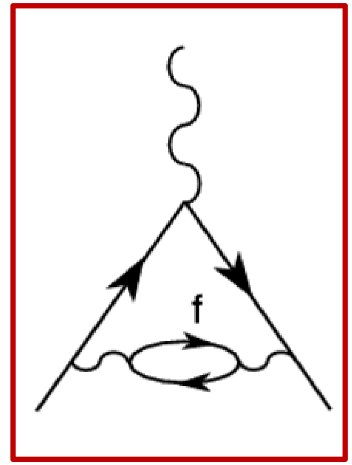

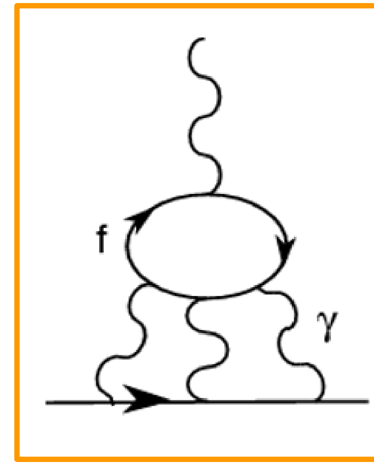

Calculated theoretical using Perturbative QED+EW

R Ratio: σ(e+e-→hadrons)

Meson transition form factors

Hadronic Vacuum Polarization

Hadronic Light-by-Light Contribution

a_μ^{SM}	=	$(116\,591\,773 \pm 53) \times 10^{-11}$
a_μ^{QED}	=	$(116\,584\,718.10 \pm 0.16) \times 10^{-11}$
a_μ^{weak}	=	$(154 \pm 1 \pm 2) \times 10^{-11}$
$a_\mu^{had,LO}$	=	$(6894 \pm 42 \pm 18) \times 10^{-11}$
$a_\mu^{had,HO}$	=	$(-98 \pm 1) \times 10^{-11}$
$a_\mu^{had,LBL}$	=	$(105 \pm 26) \times 10^{-11}$

Anomalous Magnetic Moment: $a_\mu^{LO,had}$

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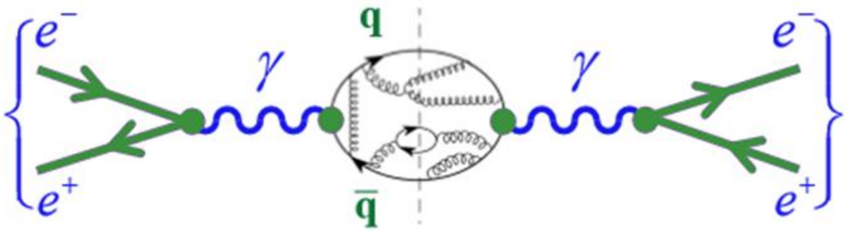
Hadronic vacuum polarization can be related at LO to experimental measurements through dispersion relations

$$\Pi^{\mu\nu}_{em}(q) = i\int d^4x e^{iqx}\langle 0|T[J^{\mu}_{em}(x)J^{\nu}_{em}(0)]|0\rangle = (-g^{\mu\nu}q^2 + q^\mu q^\nu)\Pi_{em}(q^2)$$

$\sigma \sim \mathrm{Im}$



$$\frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 12\pi \Im m \Pi_{em}(s)$$

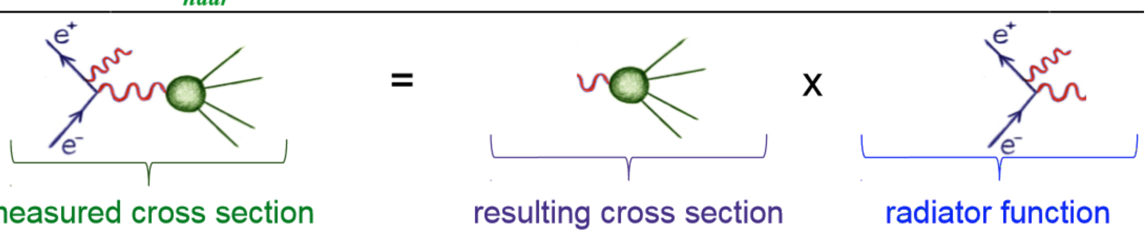
For a intermediate vector particle

$$a_\mu^{had,LO} = \frac{1}{\pi}\int_0^\infty \frac{ds}{s}\Im m\Pi^{(H)}(s)K(s) = \frac{1}{4\pi^2\alpha}\int_{4m_\pi^2}^{\infty} ds\,\sigma(e^+e^- \to \gamma^* \to hadrons)K(s) = \frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s}R(s)$$

Nucl Phys B10 (1969) 667, J Phys Radium 22 (1961) 121, Phys Rev 128 (1962) 441, Phys Rev 174 (1968) 1835, Phys Rev 168 (1968) 1620, Il Nuovo Cimento 11 (1954) 342

Experimentally the radiative return method is used to extract $\sigma(e^+e^- \to hadrons)$

$$\frac{d\sigma(e^+e^- \to hadrons + \gamma)}{dM^2_{hadr}} = \frac{\sigma(e^+e^- \to hadrons, M^2_{hadr})}{s} H(s, M^2_{hadr})$$



Charge Asymmetry

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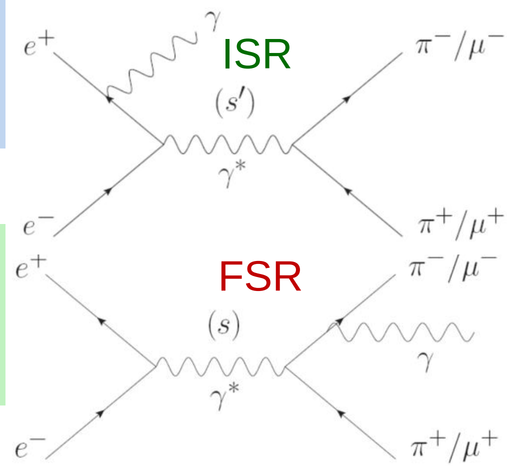
At *BABAR* the radiative return method is used to extract $\sigma(e^+e^-\rightarrow hadrons)$.
Radiation can be from initial state (ISR) or final state (FSR)

Cross section for $\sigma(e^+e^-\rightarrow x^+x^-\gamma)$ where $x=\mu,\pi$ [Phys. Lett. B 459, 279 (1999)]

$$\sigma \propto |M|^2 = |M_{ISR}|^2 + |M_{FSR}|^2 + 2\Re e(M_{ISR}M^*_{FSR})$$

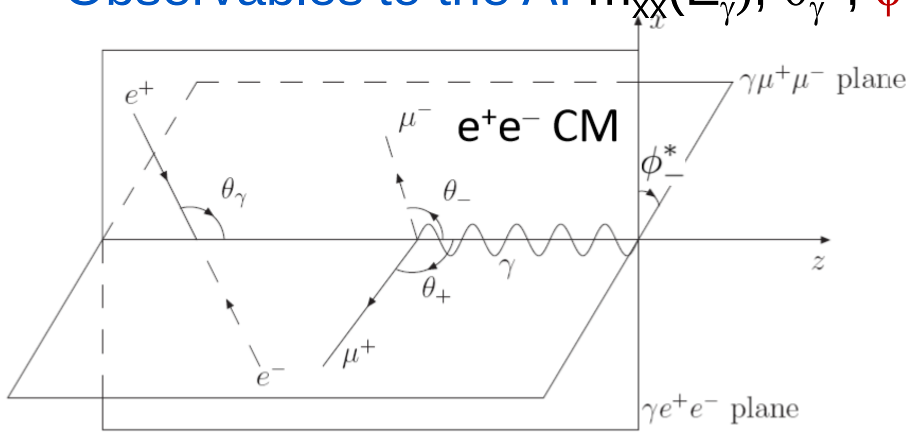
C=-1 C=+1 Changes sign under $x^+\leftrightarrow x^-$

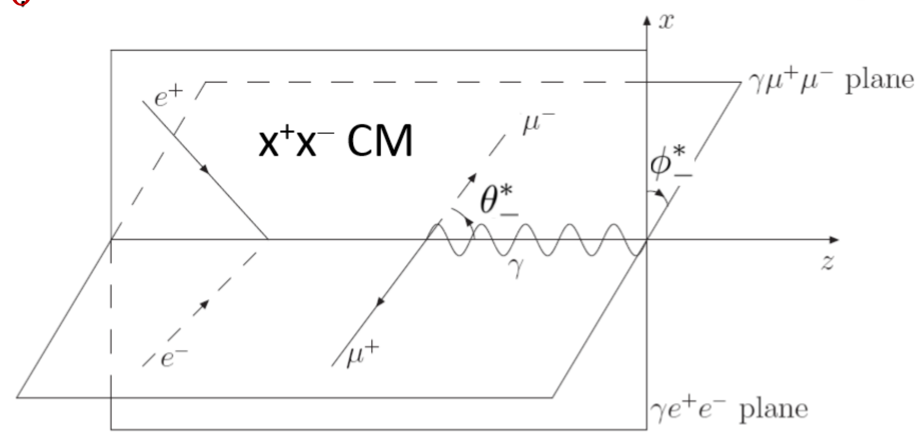


The charge asymmetry may then be expressed as:

$$A_0 = \frac{2\Re e(M_{ISR}M^*_{FSR})}{|M_{ISR}|^2 + |M_{FSR}|^2} = \frac{|M|^2 - |M_{x^+\leftrightarrow x^-}|^2}{|M|^2 + |M_{x^+\leftrightarrow x^-}|^2} = \frac{\sigma(\theta^*,\phi^*) - \sigma(\pi-\theta^*,\pi+\phi^*)}{\sigma(\theta^*,\phi^*) + \sigma(\pi-\theta^*,\pi+\phi^*)}$$

Observables to the A: $m_{xx}(E_\gamma)$, θ_γ^*, ϕ^*, θ^*



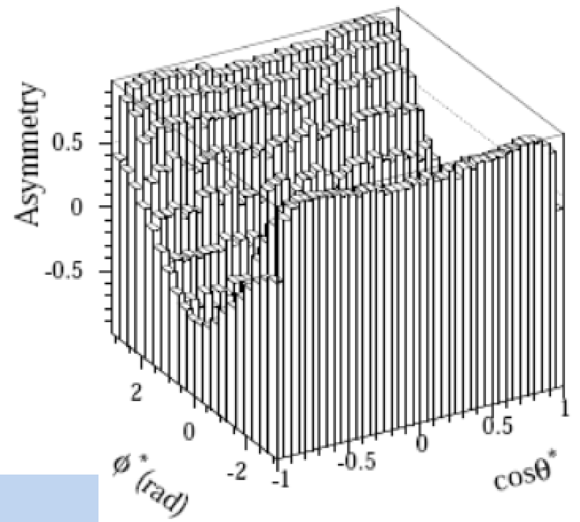


Charge Asymmetry: $e^+e^- \to \mu^+\mu^-\gamma$

In the massless limit the charge asymmetry is:

$$A_{e^+e^-\to\mu^+\mu^-\gamma}(m_{\mu\mu},\theta_\gamma^*,\theta^*,\phi^*) = -\frac{2\sqrt{s}m_{\mu\mu}\sin\theta_\gamma^*\sin\theta^*\cos\phi^*}{s\sin^2\theta^* + m_{\mu\mu}^2\sin^2\theta_\gamma^*}$$

R. Gastmans and T. T. Wu, 'The Ubiquitous Photon', Oxford (1990))



After integrating over θ^* (symmetric range) and θ_γ^* the asymmetry reduces to:

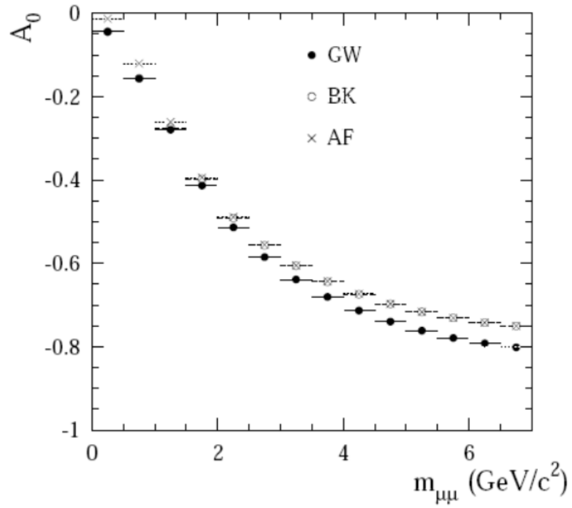
$$A_{e^+e^-\to\mu^+\mu^-\gamma}(m_{\mu\mu},\phi^*) = \int_{-a}^{a} d\theta^* \int d\theta_\gamma^* A_{e^+e^-\to\mu^+\mu^-\gamma}(m_{\mu\mu},\theta_\gamma^*,\theta^*,\phi^*) = A_0\cos\phi^*$$

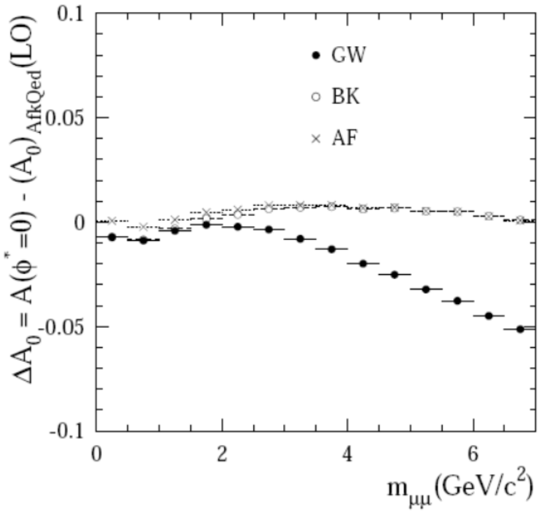
for $\phi^* \in [0,\pi)$

Gastmans and Wu (GW)
['The Ubiquitous Photon', Oxford (1990)]

AFKQED (AF)
[JHEP 9710, 001 (1997)]

Berends and R. Kleiss (BK)
[Nucl. Phys. B 177, 237(1981)]





Charge Asymmetry: $e^+e^-\to\pi^+\pi^-\gamma$

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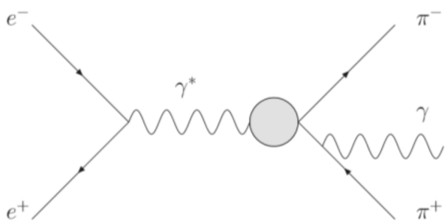
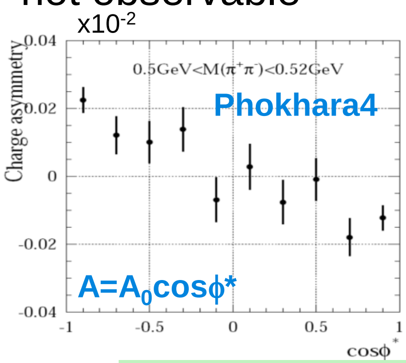
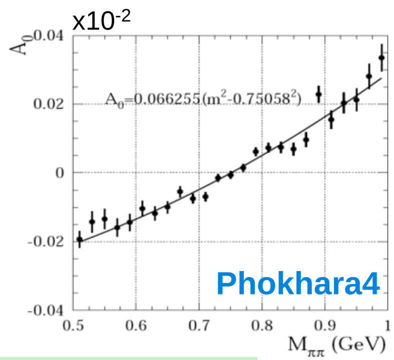
FSR Model 1: Point-like Particle



For $F_\pi(Q^2=(10.58\text{GeV})^2)$ the asymmetry is not observable

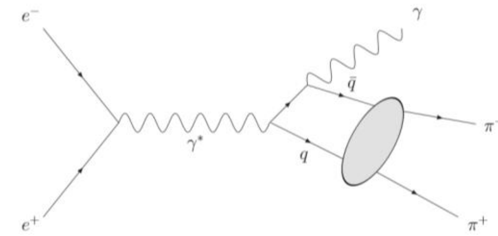




$$A(Q^2) = \frac{2\Re e(M_{ISR}M^*_{FSR})}{|M_{ISR}|^2+|M_{FSR}|^2} \propto \frac{\Re e(F_\pi(Q^2)F^*_\pi(s))}{|F_\pi(Q^2)|^2}$$

Model used by KLOE [Chin.Phys. C34 (2010) 686]
Model used in Phokhara [EPJ C 35, 527 (2004)] [EPJ C 39, 411 (2005)]

FSR Model 2: Radiation at Quark Level



Differential cross sections (modified for this work):
[PRD 73, 094021 (2006)]
[Erratum, PRD 75, 099902(E) (2007)]
C-even part 2-pion state described by amplitudes:
[PRD 62, 073014 (2000)]
Pion-pion phase shift
[Nucl. Phys. B 64, 134 (1973)]

$$\frac{d\sigma^{FSR}_{e^+e^-\to\pi^+\pi^-\gamma}}{dm^2_{\pi\pi}\,d\cos\theta^*_\gamma\,d\cos\theta^*\,d\phi^*} = \frac{\alpha^3\beta(s-m^2_{\pi\pi})}{64\pi s^3}(1+\cos^2\theta^*_\gamma)|V(m^2_{\pi\pi},\theta^*)|^2$$

$$\frac{d\sigma^{Interference}_{e^+e^-\to\pi^+\pi^-\gamma}}{dm^2_{\pi\pi}\,d\cos\theta^*_\gamma\,d\cos\theta^*\,d\phi^*} = \frac{\alpha^3\beta}{16\pi s^{5/2}m_{\pi\pi}}\Re e\{F^*_\pi(m^2_{\pi\pi})V(m^2_{\pi\pi},\theta^*)\}$$

$$\times\left\{-\sqrt{s}m_{\pi\pi}\cos\theta^*_\gamma\cos\theta^* + \left[(1+\cos\theta^*_\gamma)s + m^2_{\pi\pi}\sin^2\theta^*_\gamma\right]\frac{\sin\theta^*\cos\phi^*}{2\sin\theta^*_\gamma}\right\}$$

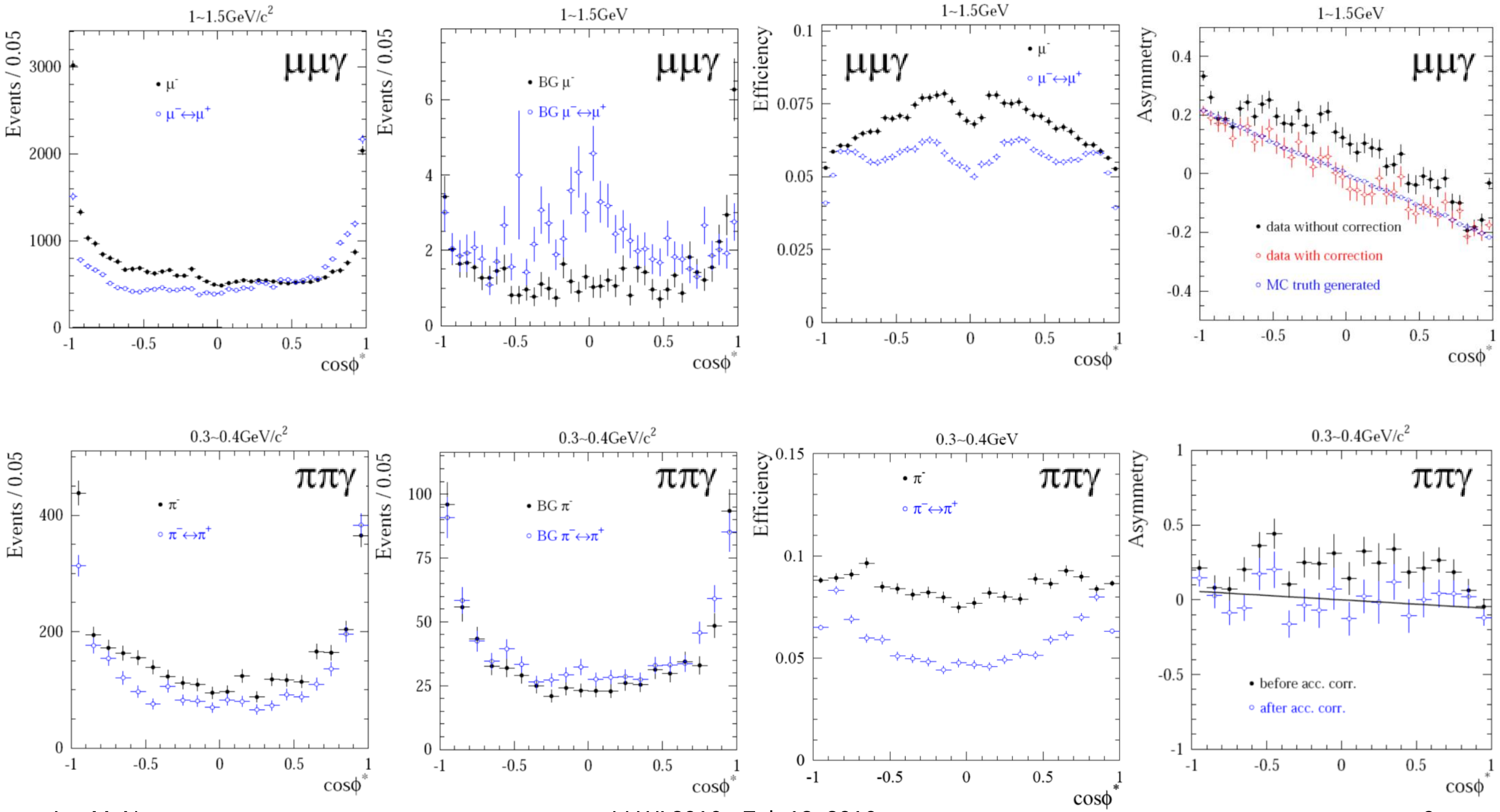
$$V(m^2_{\pi\pi},\cos\theta^*) = \sum_{q=u,d} e_q^2 V_q(m^2_{\pi\pi},\cos\theta^*) = \sum_{q=u,d} e_q^2\int_0^1 dz\,\frac{2z-1}{1-z}\Phi^+_q(z,m^2_{\pi\pi},\cos\theta^*)$$

$$\Phi^+_u(z,m^2_{\pi\pi},\cos\theta^*) = \Phi^+_d(z,m^2_{\pi\pi},\cos\theta^*)$$

$$=10z(1-z)(2z-1)\left[c_0\frac{3-\beta}{2}e^{i\delta_0(m_{\pi\pi})} + c_2\beta^2 BW(m_{\pi\pi})P_2(\cos\theta^*)\right]$$

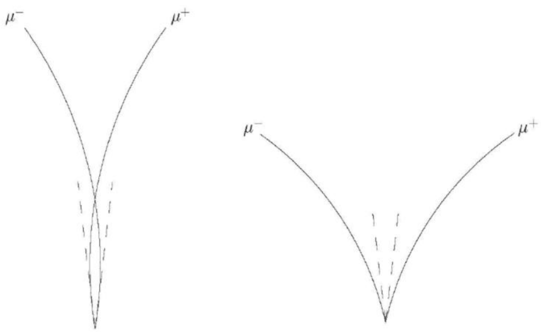
Measurement of Charge Asymmetry

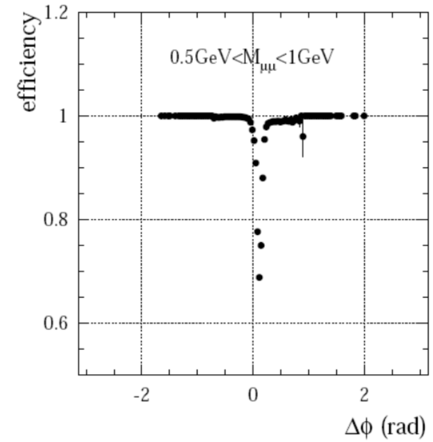
$N_{events}(\cos\phi^*)$	$N_{Bkg}(\cos\phi^*)$	Efficiency	Asymmetry Fit

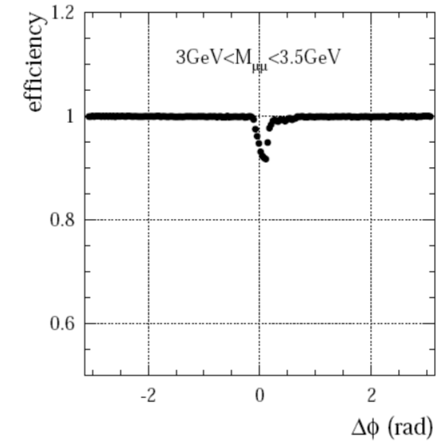


Asymmetries caused by detector effects are important in this analysis

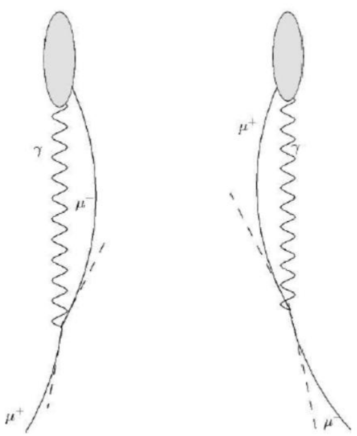
Charged tracks overlap in DCH (trigger, tracking)
⇒ Data/MC correction factors

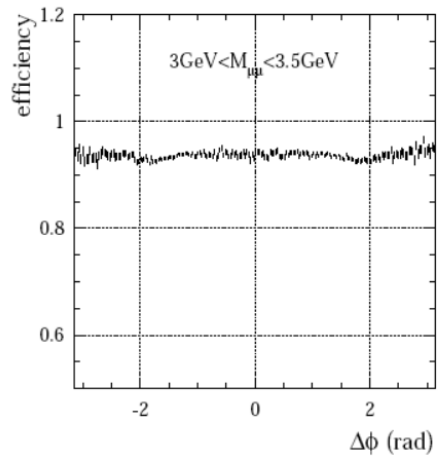


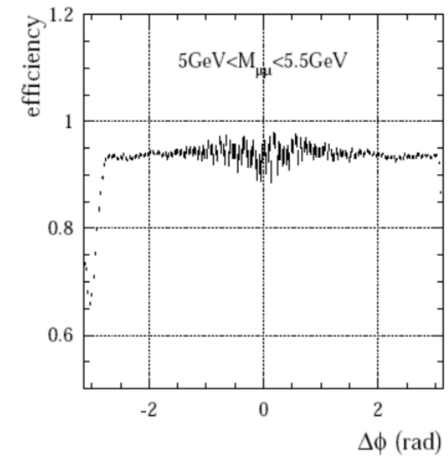




Track photon overlap in EMC (photon reconstruction and mu-ID)
⇒Remove events







The charge asymmetry is measured using the slope in A_0 because tends to be more robust against detector effects.

Charge Asymmetry: $e^+e^-\to\mu^+\mu^-\gamma$

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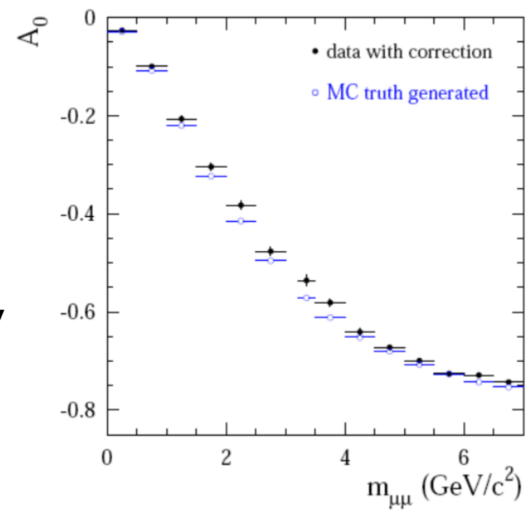
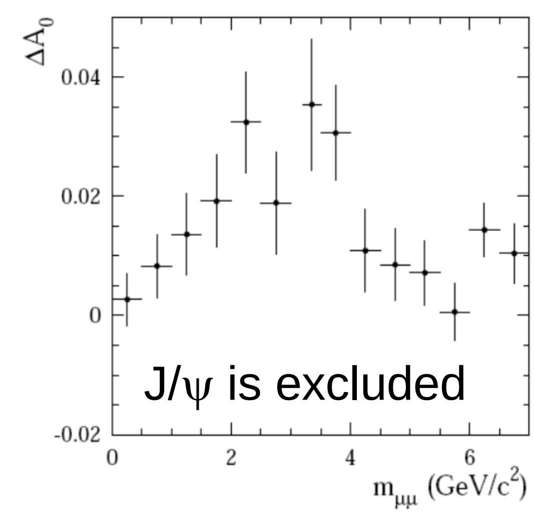
Results are in general agreement with LO QED within the 1.4% systematic uncertainty

- 1% theory (NLO and EW corrections)
- 0.7% acceptance effects
- 0.5% data/MC corrections

○ Excess of 1-2σ_{stat} above σ_{sys} in 2-4GeV

MC truth corresponds to AFKQED
[JHEP 9710, 001 (1997)]



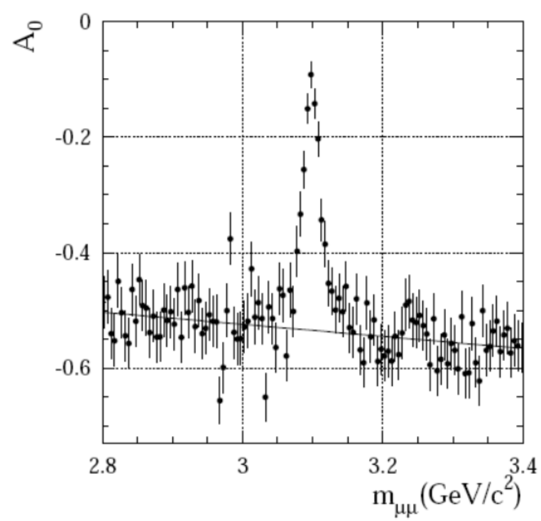


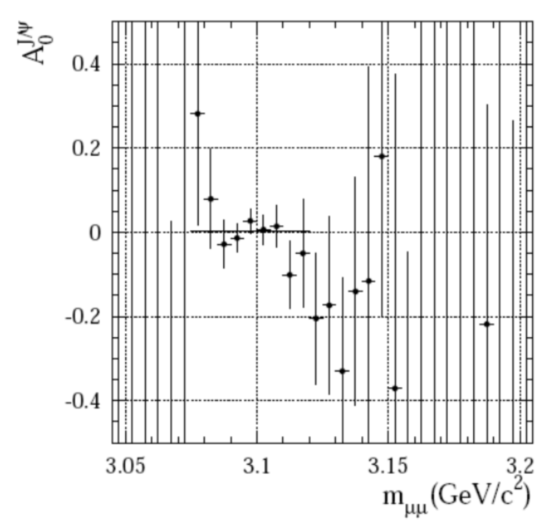
Pure ISR sample: $e^+e^-\to J/\psi\gamma\to\mu^+\mu^-\gamma$
Provides cross-check of this method and estimated fake asymmetry

$$A_0 = \frac{A_0^{J/\psi} N_{J/\psi} + A_0^{QED} N_{QED}}{N_{J/\psi} + N_{QED}}$$

Consistent with expected value:

$A_0=(0.3\pm1.6)$





$e^+e^- \to \pi^+\pi^-\gamma$ and $e^+e^- \to f_2(\pi\pi)\gamma$

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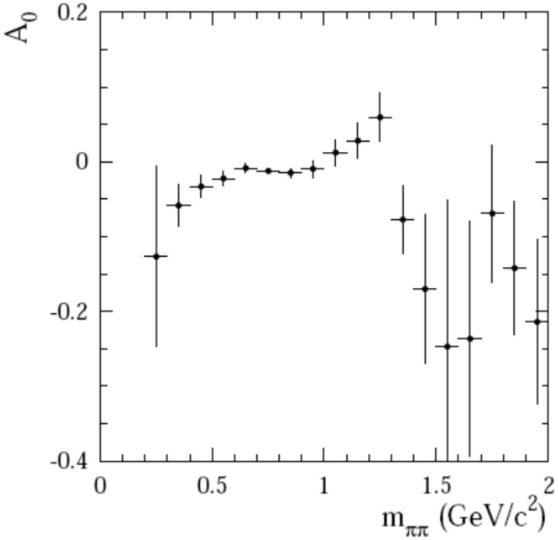
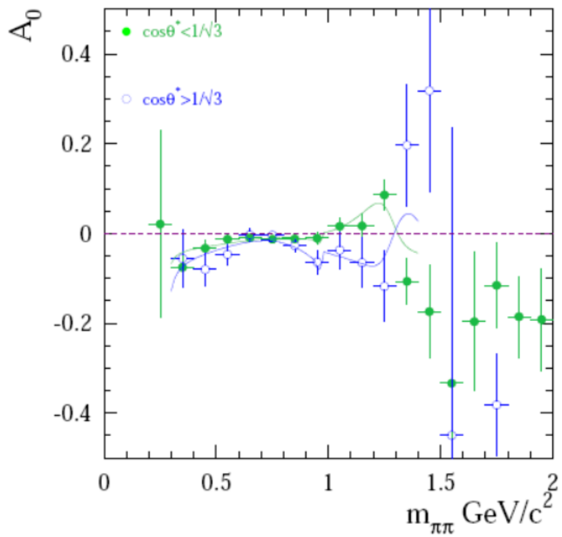




Qualitative agreement with model 2

- A clear interference pattern is observed at high mass
- Angular cut used to study interference between s-wave and d-wave (0 helicity) related to f_2

f_2 interference from C-even part 2-pion state described by amplitudes:

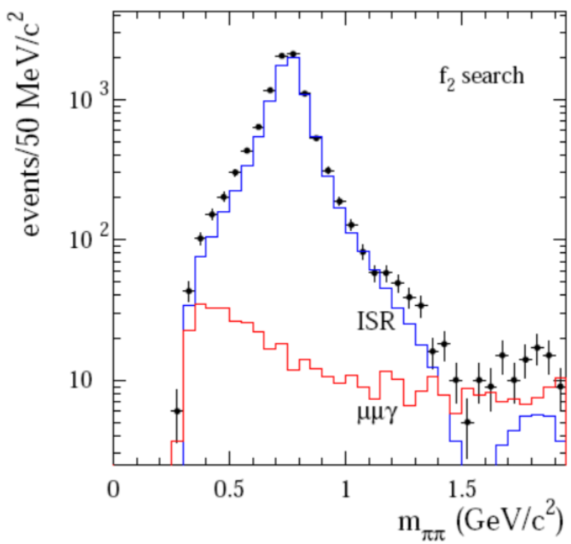
$$\Phi^{+}_{u/d}(z, m^2_{\pi\pi}, \cos\theta^*) =$$
$$10z(1-z)(2z-1)\left[c_0 \frac{3-\beta}{2} e^{i\delta_0(m_{\pi\pi})} + c_2\beta^2 BW(m_{\pi\pi})P_2(\cos\theta^*)\right]$$

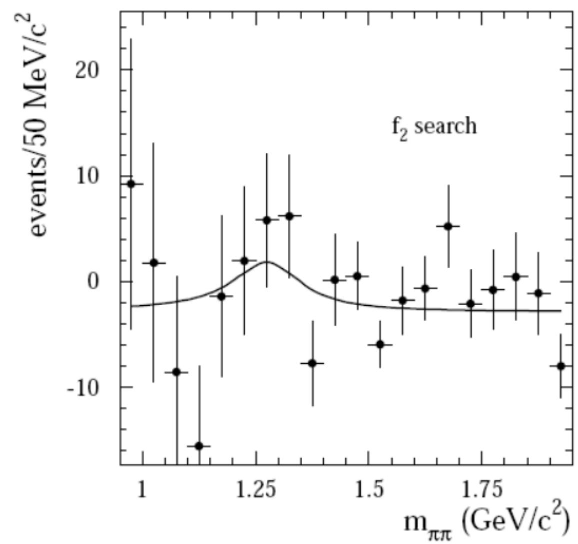
Direct search for f_2 using the high Angular region: $|\cos\theta^*|>0.85$

After efficiency correction

$\Rightarrow |f_2|^2/(|ISR|^2+|f_2|^2) = (0.22\pm0.15)$

	c_0 (f_0 s-wave)	c_2 (f_2 d-wave helicity 0)
This work	-0.93±0.20	-4.5±1.3
Diehl et al 2000	-0.5±0.5	0.5±0.5
Chernyak (private com.)		$\|c_2\|$=2.2±1.1





Summary

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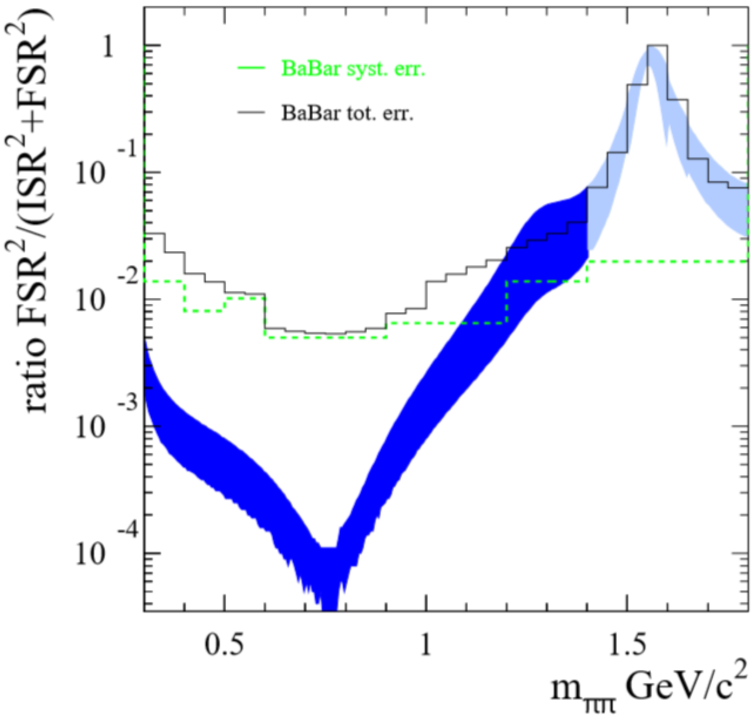
ISR and FSR has been studies, at *BABAR*, in $e^+e^-\to\mu^+\mu^-\gamma$ and $e^+e^-\to\pi^+\pi^-\gamma$ through measurements of the charge asymmetry $\Rightarrow$ FSR contribution



FSR uncertainty extrapolated using model 2

	$\pi\pi$ ($2m_\pi\to1.8$GeV)	$\pi\pi$ FSR ($2m_\pi\to1.8$GeV)
$a_\mu^{LO,had}(10^{-10})$	514.09± 2.22 ±3.11	0.26±0.12

Published in: [PRD 92 (2015) 7, 072015]

$e^+e^-\to\mu^+\mu^-\gamma$

- Results are consistent with LO QED within the 1.4% systematic uncertainty
  - 1% theory (NLO and EW corrections)
  - 0.7 acceptance effects
  - 0.5% data/MC corrections
- excess of 1-2σ_{stat} above σ_{sys} in 2-4GeV

$e^+e^-\to\pi^+\pi^-\gamma$

- FSR results are qualitatively consistent with model 2 (quark level radiation)
- Model 2 missing in MC (AfkQED, Phokhara)
- Measured relative FSR contribution using model 2
- Interesting structure around f_2 region fitted s-wave and d-wave parameters

$|M_{FSR}|^2$ contribution is negligible to cross section (except in f_2 region) and in the amplitude calculation