New developments
in PHOKHARA MC generator

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in collaboration with

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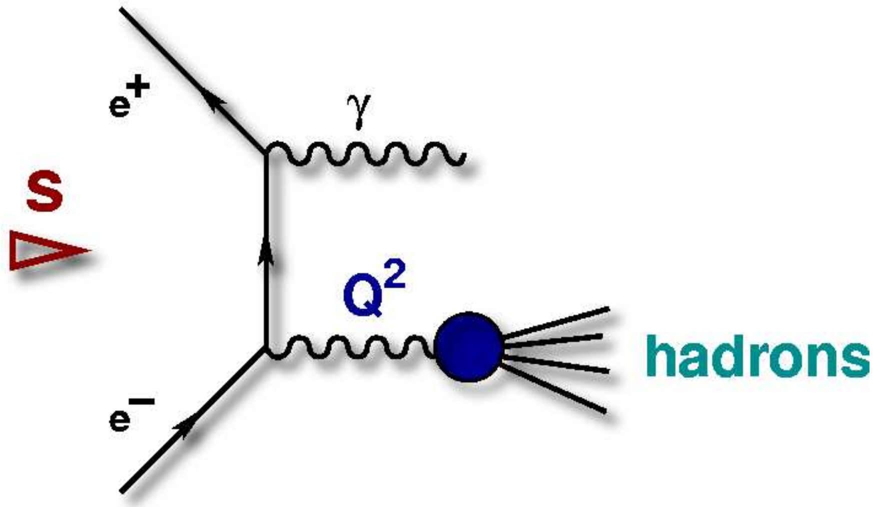
- Introduction to the radiative return
- Nucleon form factors
- PHOKHARA 6.0 - $\Lambda\bar{\Lambda}$
- PHOKHARA 7.0 - 4 $\pi, \cdots$

BASIC IDEA

$$d\sigma(e^+e^- \to \mathrm{hadrons} + \gamma(ISR)) =$$

$$H(Q^2, \theta_\gamma)\ d\sigma(e^+e^- \to \mathrm{hadrons})$$



- measurement of $R(s)$ over the full range of energies, from threshold up to $\sqrt{s}$
- large luminosities of factories compensate α/π from photon radiation
- radiative corrections essential (NLO)

High precision measurement of the hadronic cross-section at meson-factories

From EVA to PHOKHARA

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

- tagged photon ($\theta_\gamma > \theta_{cut}$)
- ISR at LO + Structure Function
- FSR: point-like pions

[Binner et al.]

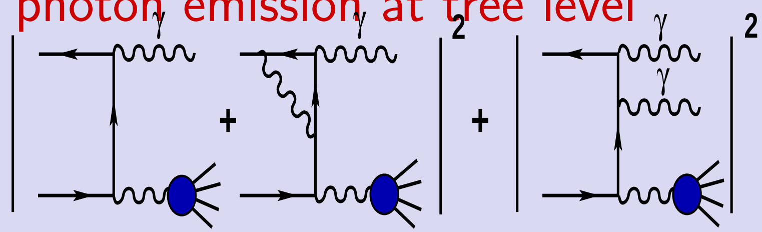
$e^+e^- \to 4\pi + \gamma$

- ISR at LO + Structure Function

[Czyż, Kühn,2000]

PHOKHARA 6.0: $\pi^+\pi^-$, $\mu^+\mu^-$, 4π, $\bar{N}N$, 3π, KK, $\Lambda(\to\cdots)\bar{\Lambda}(\to\cdots)$

- **ISR at NLO:** virtual corrections to one photon events and two photon emission at tree level

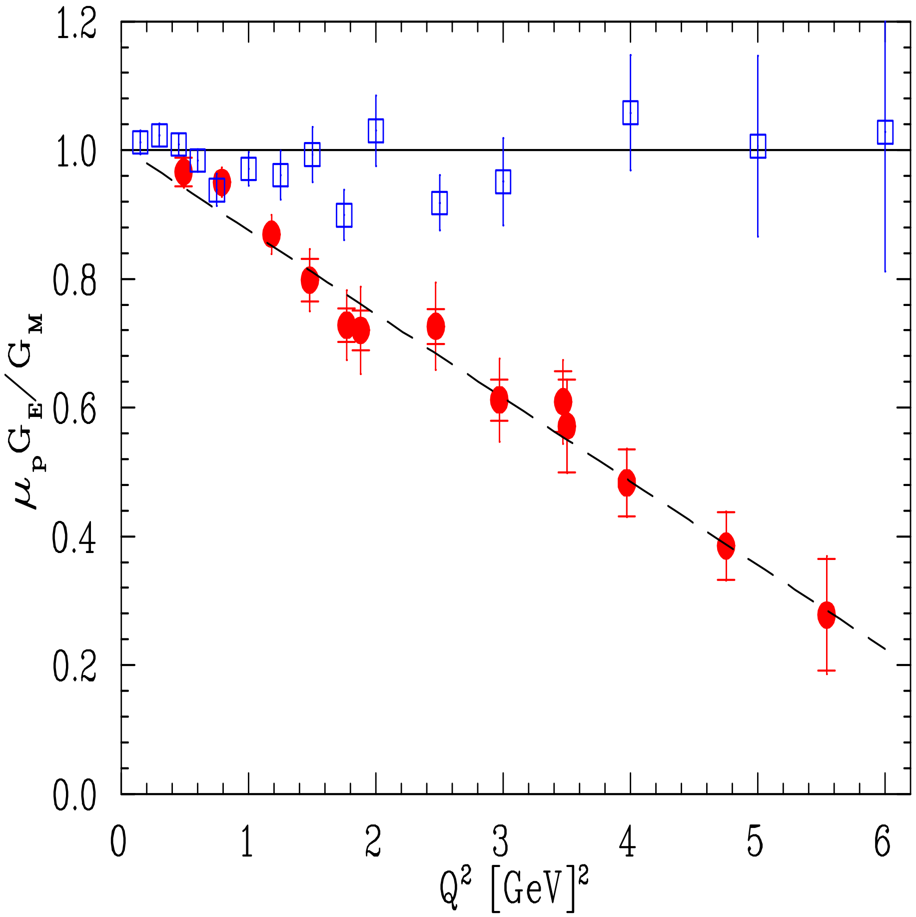


- FSR at NLO: $\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-
- tagged or untagged photons
- Modular structure

http://ific.uv.es/~rodrigo/phokhara/

FF separation at B-factories

H.C., J. H. Kühn, E. Nowak and G. Rodrigo, Eur.Phys.J.C35(2004)527



J. Arrington, Phys. Rev. **C 68** (2003) 034325

FF separation at B-factories

H.C., J. H. Kühn, E. Nowak and G. Rodrigo, Eur.Phys.J.C35(2004)527

Electromagnetic current describing production of baryon-antibaryon pair

$$J_\mu = -ie \cdot \bar{u}(q_2) \left(F_1^N(Q^2)\gamma_\mu - \frac{F_2^N(Q^2)}{4m_N} \left[\gamma_\mu, \not{Q}\,\right] \right) v(q_1) \ ,$$

$$G_M^N = F_1^N + F_2^N \ , \qquad G_E^N = F_1^N + \tau F_2^N \ ,$$

$\tau = Q^2/4m_N^2, \, Q = q_1 + q_2$

FF separation at B-factories

H.C., J. H. Kühn, E. Nowak and G. Rodrigo, Eur.Phys.J.C35(2004)527

AT LO ISR : $e^+ + e^- \to \bar{N} + N + \gamma.$

$$d\sigma = \frac{1}{2s} L_{\mu\nu} H^{\mu\nu} dLips(p_1 + p_2; q_1, q_2, k)$$

$$H_{\mu\nu} = 2|G_M^N|^2 (Q_\mu Q_\nu - g_{\mu\nu} Q^2)$$

$$- \frac{8\tau}{\tau - 1} \left(|G_M^N|^2 - \frac{1}{\tau} |G_E^N|^2 \right) q_\mu q_\nu$$

FF separation at B-factories

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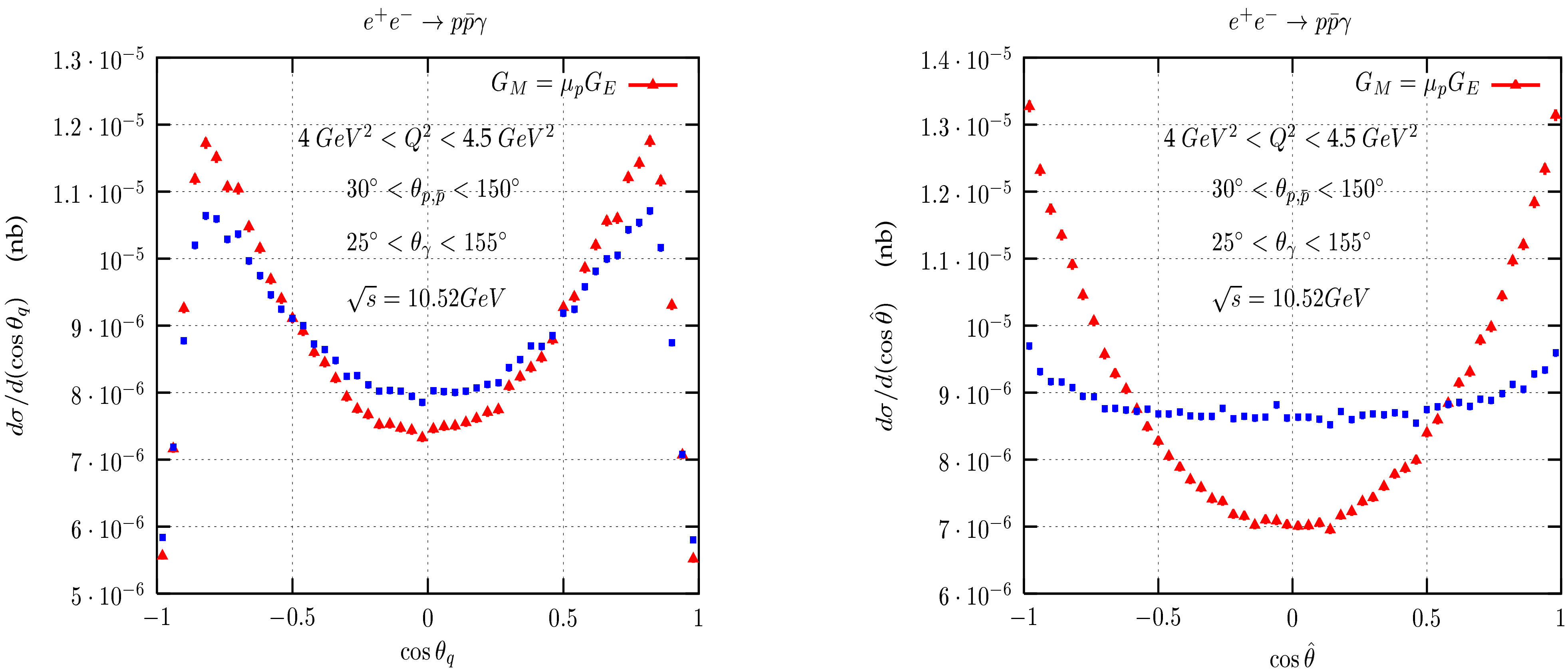
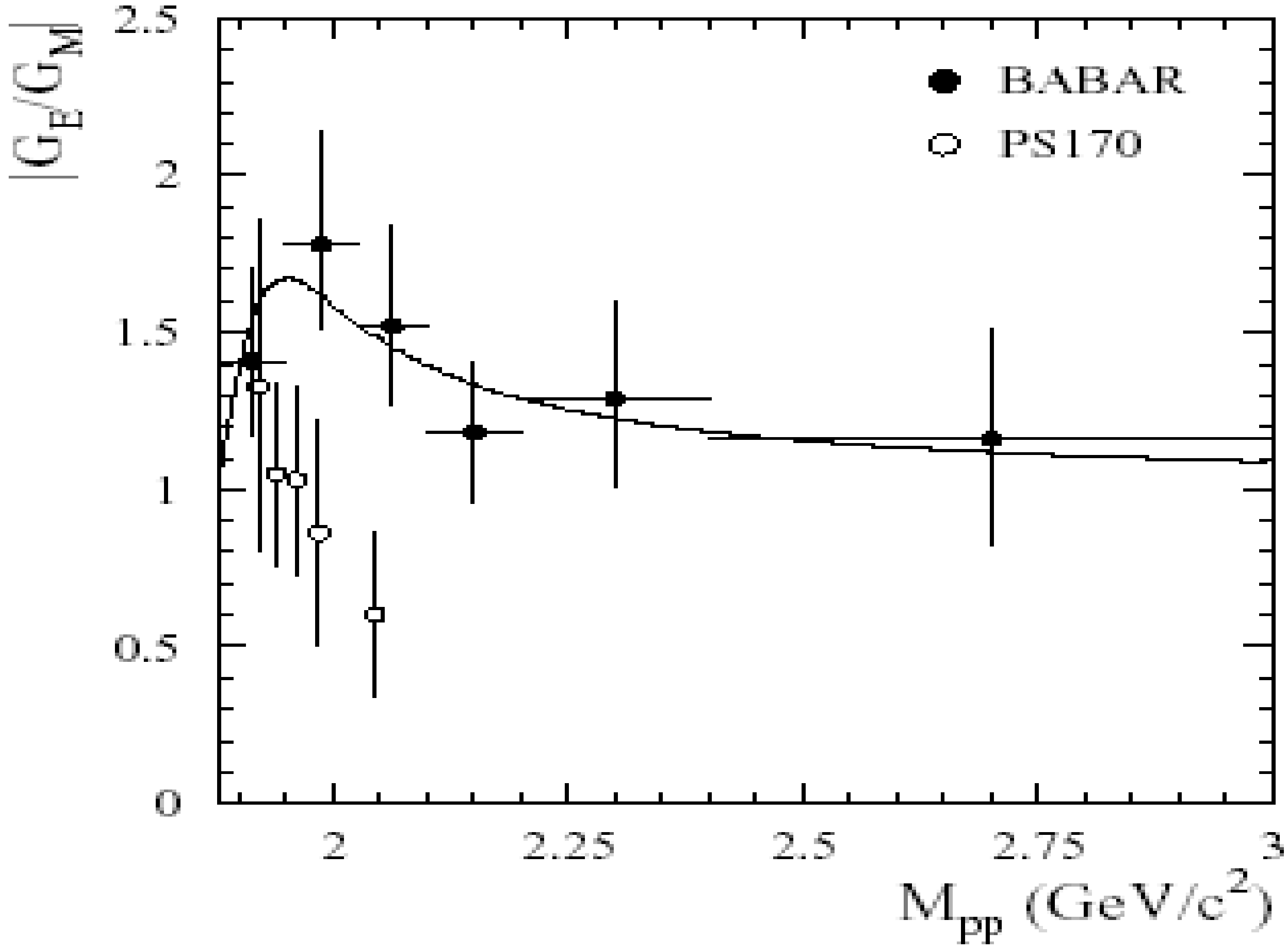


about 2000 events per 100 fb^{-1}

nucleon FF



BaBar: Phys.Rev.D73:012005,2006.

Λ formfactors

$$e^+e^- \to \Lambda(q_2, S_2)\bar{\Lambda}(q_1, S_1)$$

$$e^+e^- \to \Lambda(q_2, S_2)\bar{\Lambda}(q_1, S_1)\gamma_{ISR}$$

$$J_\mu = -ie \cdot \bar{u}(q_2, S_2)$$

$$\left(F_1^\Lambda(Q^2)\gamma_\mu - \frac{F_2^\Lambda(Q^2)}{4m_\Lambda}[\gamma_\mu, \not{Q}] \right) \; v(q_1, S_1)$$

The polarized cross section

$$d\sigma(e^+e^- \to \bar{\Lambda}\Lambda) \;=\; \frac{1}{2s}\, L^0_{\mu\nu}\, H^{\mu\nu} d\Phi_2(p_1+p_2; q_1, q_2)$$

$$L^0_{\mu\nu}\, H^{\mu\nu} =$$

$$4\pi^2\alpha^2 \Bigg\{ |G_M|^2 \left(1+\cos^2\theta_{\bar{\Lambda}}\right) + \frac{1}{\tau}|G_E|^2 \sin^2\theta_{\bar{\Lambda}}$$

$$+ \;\; Im(G_M G_E^*)/\sqrt{\tau}\;\sin(2\theta_{\bar{\Lambda}})\;\left(S^y_{\Lambda} + S^y_{\bar{\Lambda}}\right)$$

$$- \;\; Re(G_M G_E^*)/\sqrt{\tau}\;\;\sin(2\theta_{\bar{\Lambda}})\left(S^z_{\Lambda} S^x_{\bar{\Lambda}} + S^z_{\bar{\Lambda}} S^x_{\Lambda}\right)$$

$$+ \left(\frac{1}{\tau}|G_E|^2 + |G_M|^2\right)\sin^2\theta_{\bar{\Lambda}}\;\; S^x_{\bar{\Lambda}} S^x_{\Lambda}$$

$$+ \left(\frac{1}{\tau}|G_E|^2 - |G_M|^2\right)\sin^2\theta_{\bar{\Lambda}}\;\; S^y_{\bar{\Lambda}} S^y_{\Lambda}$$

$$- \left(\frac{1}{\tau}|G_E|^2 \sin^2\theta_{\bar{\Lambda}} - |G_M|^2 \left(1+\cos^2\theta_{\bar{\Lambda}}\right)\right)\;\; S^z_{\bar{\Lambda}} S^z_{\Lambda} \Bigg\}$$

$$Im(G_M G_E^*)/\sqrt{\tau}\ \sin(2\theta_{\bar\Lambda})\ \left(S^y_\Lambda + S^y_{\bar\Lambda}\right)$$

and

$$Re(G_M G_E^*)/\sqrt{\tau}\ \ \sin(2\theta_{\bar\Lambda})\left(S^z_\Lambda S^x_{\bar\Lambda} + S^z_{\bar\Lambda} S^x_\Lambda\right)$$

$$G_M = |G_M|\ e^{i\phi_M}$$

$$G_E\ = |G_E|\ \ e^{i\phi_E}$$

$$Re(G_M G_E^*) = |G_M|\ |G_E| \cos(\phi_M - \phi_E)$$

$$Im(G_M G_E^*) = |G_M|\ |G_E| \sin(\phi_M - \phi_E)$$

$$\boxed{\phi_M - \phi_E = \Delta\phi}$$

- relative phase between electric and magnetic form factors

The subsequent two body decays of Λs

The measurement of the subsequent two body decays:

$$\Lambda \to \pi^- p$$ and $$\bar{\Lambda} \to \pi^+ \bar{p}$$

allow for a spin analysis of the decaying Λs.

The decay distribution: $$R_\Lambda = 1 - \alpha_\Lambda \, \bar{S}_\Lambda \cdot \bar{n}_{\pi^-}$$

The spin vector is replaced by:

$$\bar{S}_\Lambda \to -\alpha_\Lambda \bar{n}_{\pi^-} \text{ and } \bar{S}_{\bar{\Lambda}} \to -\alpha_{\bar{\Lambda}} \bar{n}_{\pi^+}$$

$$e^+e^- \to \bar{\Lambda}(\to \pi^+\bar{p})\Lambda(\to \pi^- p)$$

using the narrow width approximation

$$d\sigma\left(e^+e^- \to \bar{\Lambda}(\to \pi^+\bar{p})\Lambda(\to \pi^- p)\right) =$$

$$d\sigma\left(e^+e^- \to \bar{\Lambda}\Lambda\right)\left(S_{\Lambda,\bar{\Lambda}} \to \mp\alpha_\Lambda n_{\pi^\mp}\right)$$

$$\times\ d\bar{\Phi}_2(q_1;p_{\pi^+},p_{\bar{p}})d\bar{\Phi}_2(q_2;p_{\pi^-},p_p)$$

$$\times\ \mathrm{Br}(\bar{\Lambda} \to \pi^+\bar{p})\mathrm{Br}(\Lambda \to \pi^- p)$$

$n_{\pi^+}(n_{\pi^-}) = (0,\bar{n}_{\pi^+})\ ((0,\bar{n}_{\pi^-}))$ in the $\bar{\Lambda}$ (Λ) rest frame

The cross section with ISR photon emision

$$L^{ij}H_{ij} \simeq \frac{(4\pi\alpha)^3}{4Q^2 y_1 y_2} \left(1+\cos^2\theta_\gamma\right) \left\{ |G_M|^2 \left(1+\cos^2\theta_{\bar{\Lambda}}\right) \right.$$

$$+\frac{1}{\tau}|G_E|^2 \sin^2\theta_{\bar{\Lambda}} - \alpha_\Lambda \frac{Im(G_M G_E^*)}{\sqrt{\tau}} \sin(2\theta_{\bar{\Lambda}}) \left(n^y_{\pi^-} - n^y_{\pi^+} \right)$$

$$+\alpha_\Lambda^2 \frac{Re(G_M G_E^*)}{\sqrt{\tau}} \sin(2\theta_{\bar{\Lambda}}) \left(n^z_{\pi^-} n^x_{\pi^+} + n^z_{\pi^+} n^x_{\pi^-} \right)$$

$$-\alpha_\Lambda^2 \left(\frac{1}{\tau}|G_E|^2 + |G_M|^2 \right) \sin^2\theta_{\bar{\Lambda}} \;\; n^x_{\pi^+} n^x_{\pi^-}$$

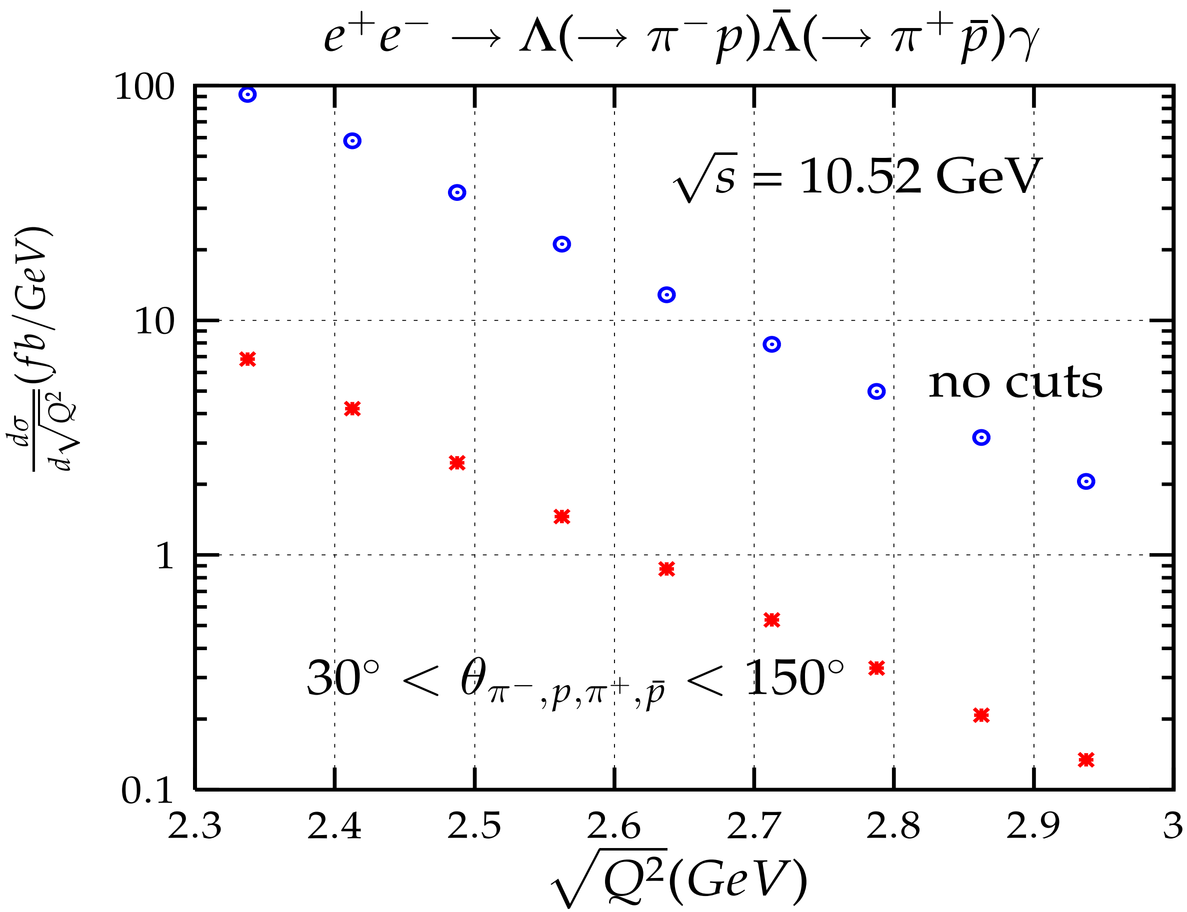
$$-\alpha_\Lambda^2 \left(\frac{1}{\tau}|G_E|^2 - |G_M|^2 \right) \sin^2\theta_{\bar{\Lambda}} \;\; n^y_{\pi^+} n^y_{\pi^-}$$

$$\left. +\alpha_\Lambda^2 \left(\frac{1}{\tau}|G_E|^2 \sin^2\theta_{\bar{\Lambda}} - |G_M|^2 \left(1+\cos^2\theta_{\bar{\Lambda}}\right) \right) \;\; n^z_{\pi^+} n^z_{\pi^-} \right\}$$

$\theta_{\bar{\Lambda}}$ - $\bar{Q}$ rest frame with the z-axis opposite to the photon direction

The cross section

FF from Körner et al. Phys. Rev. D 16 (1977) 2165



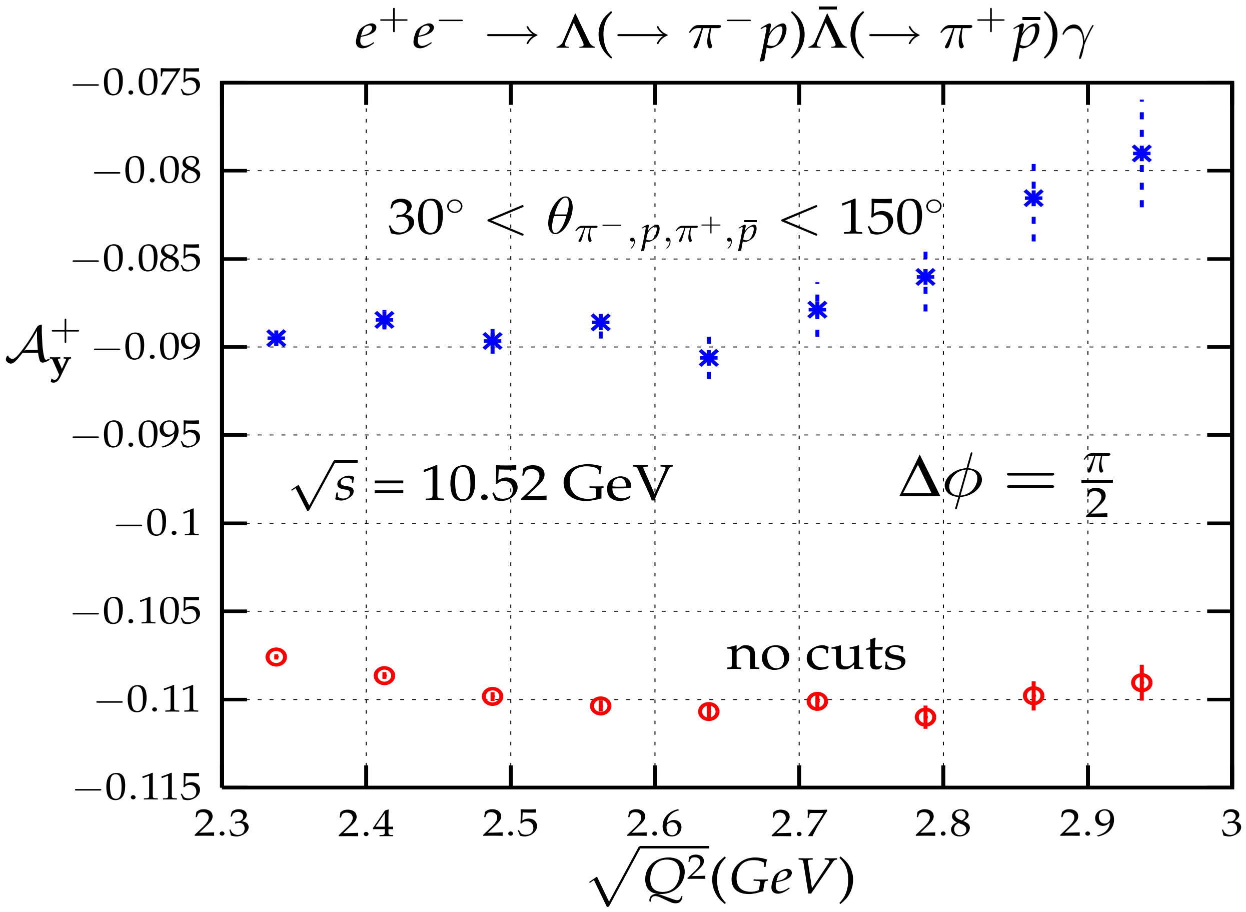
At B-factories we expect about 130 events per 100 fb^{-1}.

Asymmetry

$$\mathcal{A}_y^{\pm} = \frac{d\sigma(a^{\pm}>0) - d\sigma(a^{\pm}<0)}{d\sigma(a^{\pm}>0) + d\sigma(a^{\pm}<0)}$$

$$a^{+(-)} = \sin(2\theta_{\bar{\Lambda}})\; n^{y}_{\pi^{+}(\pi^{-})}$$

Asymmetry



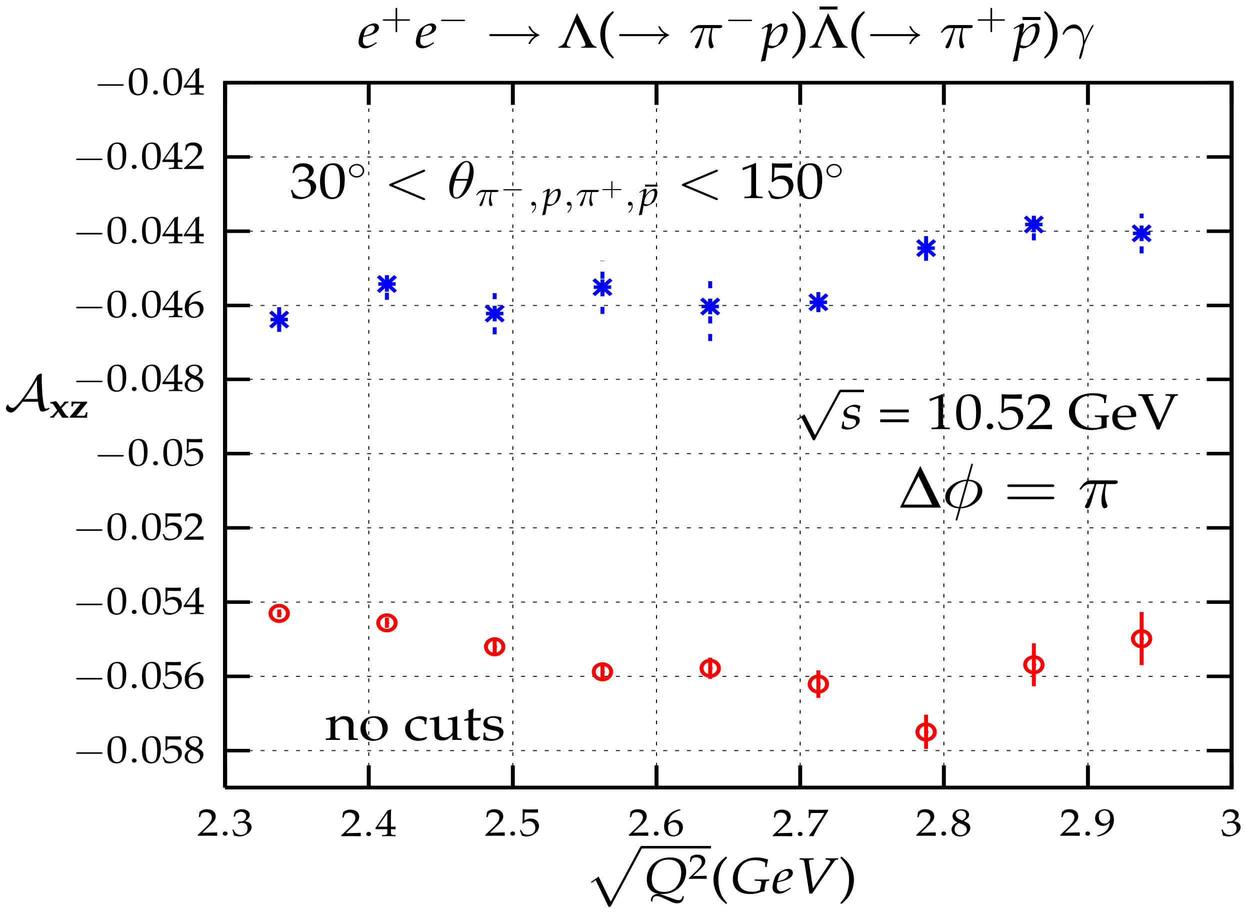
$e^+e^- \to \Lambda(\to \pi^- p)\bar{\Lambda}(\to \pi^+ \bar{p})\gamma$
$30^\circ < \theta_{\pi^-,p,\pi^+,\bar{p}} < 150^\circ$
$\sqrt{s} = 10.52$ GeV
$\Delta\phi = \frac{\pi}{2}$
no cuts
$\mathcal{A}_{\mathbf{y}}^{+}$
$\sqrt{Q^2}(GeV)$
−0.075
−0.08
−0.085
−0.09
−0.095
−0.1
−0.105
−0.11
−0.115
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3

Spin correlations

$$A_{xz} = \frac{d\sigma(\tilde{a}>0) - d\sigma(\tilde{a}<0)}{d\sigma(\tilde{a}>0) + d\sigma(\tilde{a}<0)}$$

$$\tilde{a} = \sin(2\theta_{\bar{\Lambda}}) \times \left(n^z_{\pi^-} n^x_{\pi^+} + n^z_{\pi^+} n^x_{\pi^-} \right)$$

Spin correlations



The cross section

BABAR Collaboration, arXiv:0709.1988

$|G_E/G_M| = 1.73^{+0.99}_{-0.57}$ for $\sqrt{Q^2}$: 2.23 - 2.40 GeV

$|G_E/G_M| = 0.71^{+0.66}_{-0.71}$ for $\sqrt{Q^2}$: 2.40 - 2.80 GeV

-0.76 $< \sin(\Delta\phi) <$ 0.98

PHOKHARA 7.0: near future developments

- 4π - revisited
- $J/\psi, \psi(2S)$ with the radiative return
- FSR for 3π and $\bar{N}N$

Final remark

Only investments in theoretical
and experimental analysis necessary
to obtain many valuable results
with the radiative return method