Theoretical aspects and status of MC generators for radiative return analysis

H. CZYŻ, IF, UŚ, Katowice GLASGOW 2007

Motivation - what is the radiative return

What do we have on the market

Tests - comparisons, which were performed

Plans

What do we like to measure and why:

WHAT : $\boldsymbol{\sigma}(\mathrm{e}^+\mathrm{e}^- \to \mathrm{hadrons})$

WHY:

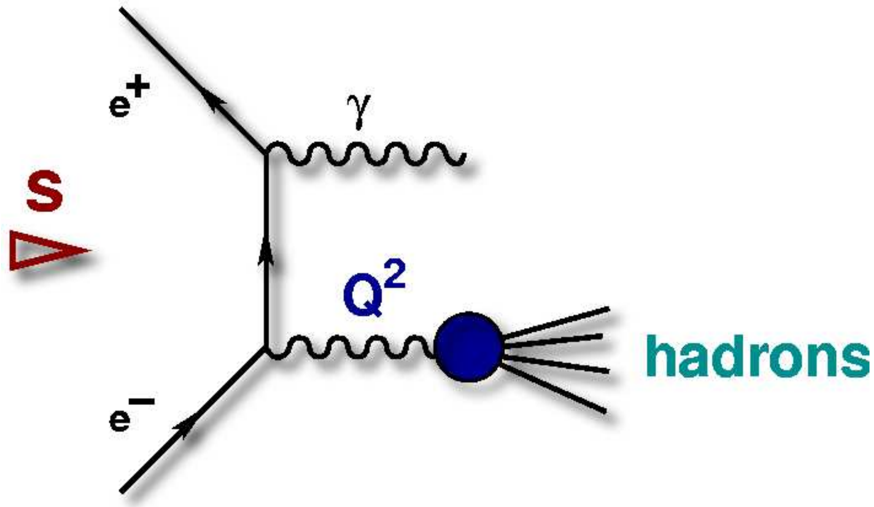
$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} \frac{ds}{s}\, K(s)\, R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma_{\mathrm{point}}}$$

THE RADIATIVE RETURN METHOD

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

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



- 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 and ...

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.]

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

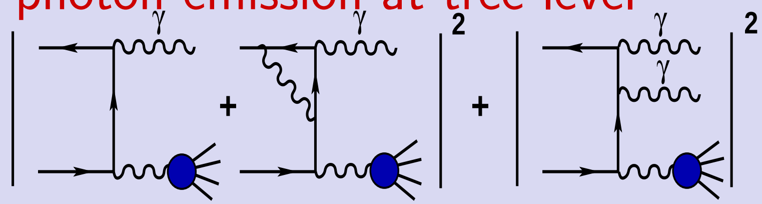
- ISR at LO + Structure Function

[Czyż, Kühn,2000]

H.C., A. Grzelińska,
J. H. Kühn, E. Nowak-Kubat,
G. Rodrigo, A. Wapienik

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/

From EVA to ...

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

- ISR at LO + Structure Function

[Czyż, Kühn]

→

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

- upgraded by BaBar - not public (?)
- PHOTOS [Barberio et al.] for FSR

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.]

→

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

- FSR studies

[Pancheri,Shekhovtsova,Venanzoni]

KKMC

S. Jadach, B. F. L. Ward and Z. Wąs

- YFS exponentation
- high accuracy only for muon pairs
- can we hope for: upgrades ???

S.Jadach: KKMC- Pisa 2003

Summary

- We found very good agreement of KKMC and PHOKHARA to within 0.2% for μ-pair final states for pure ISR
- Discrepancy of order 1-2% between KKMC and PHOKHARA or even larger at low mass, was found for π-pair final state.
- This is due to use of the inferior EEX matrix element in KKMC instead of CEEX.
- NB. We know how to upgrade ISR in KKMC to CEEX level for any hadronic final state...

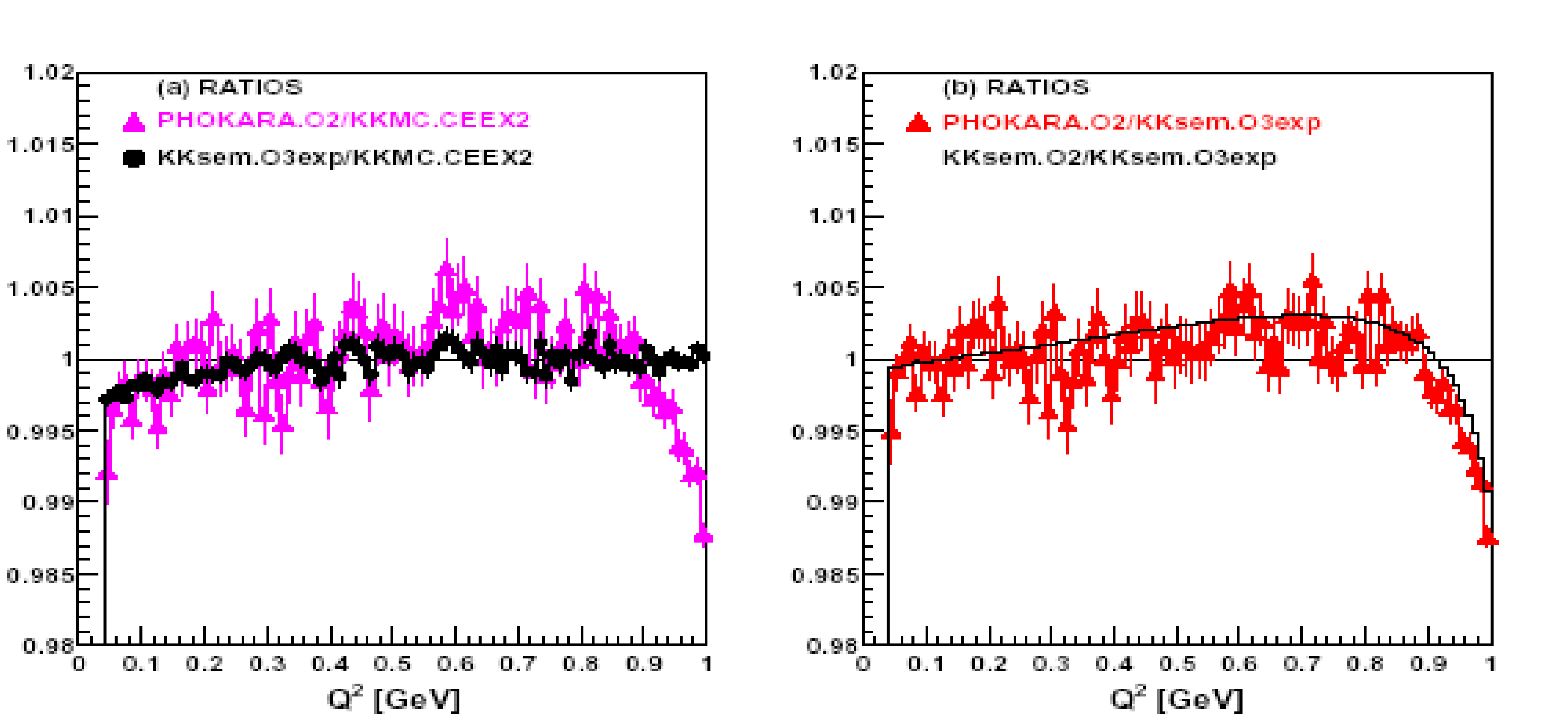
Dubna - Novosibirsk papers 2003

A. B. Arbuzov, E. Bartos (Bratislava), V. V. Bytev, E. A. Kuraev, Z. K. Silagadze

- muon and pion pairs
- analytic formulae based on RG - SF
- Comparisons with PHOKHARA planned
  first results in February 2008 ??

S.Jadach: KKMC

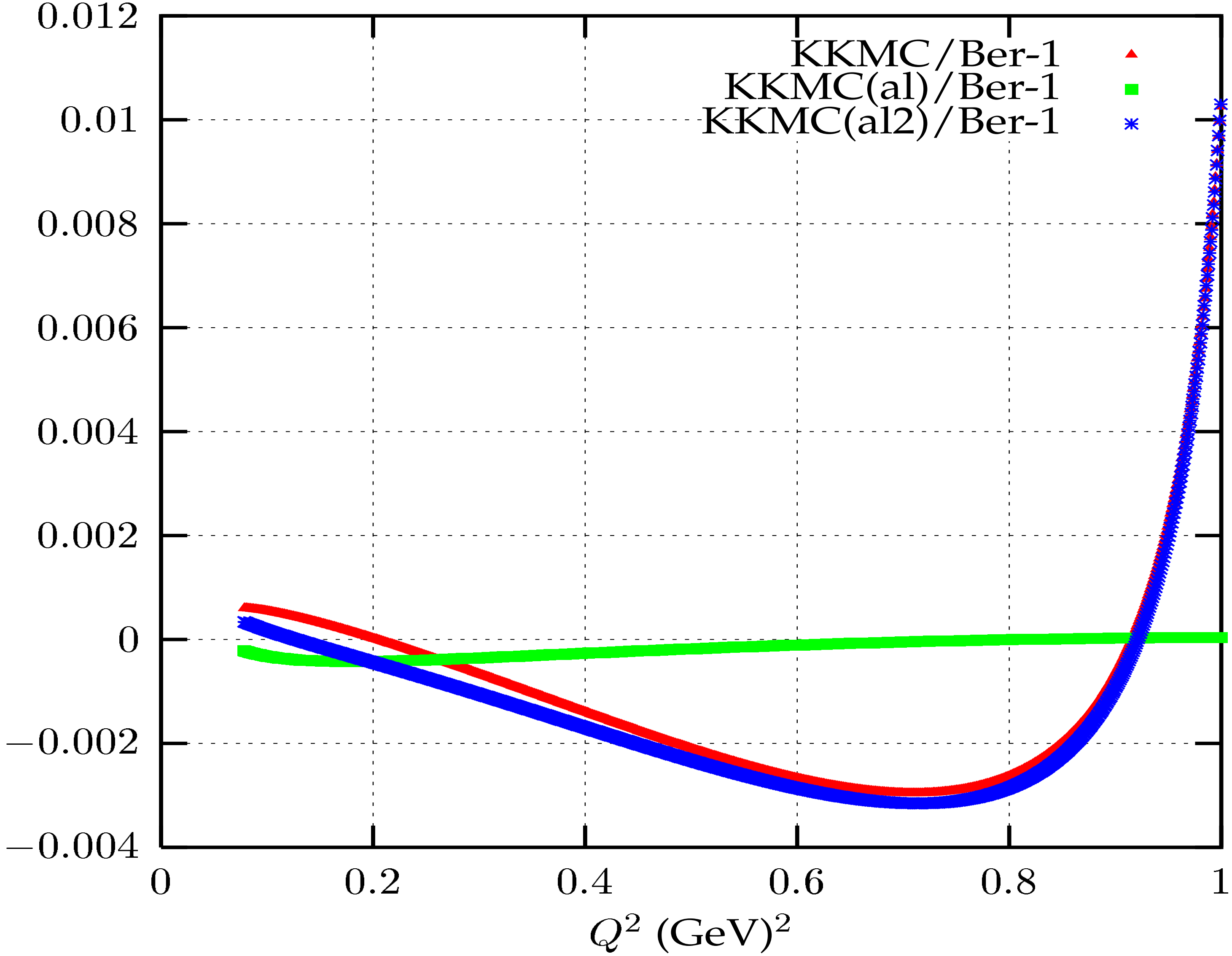
PHOKHARA included in the game, μ-pairs again



PHOKHARA agrees to within 0.3% with KKMC and KKsem.

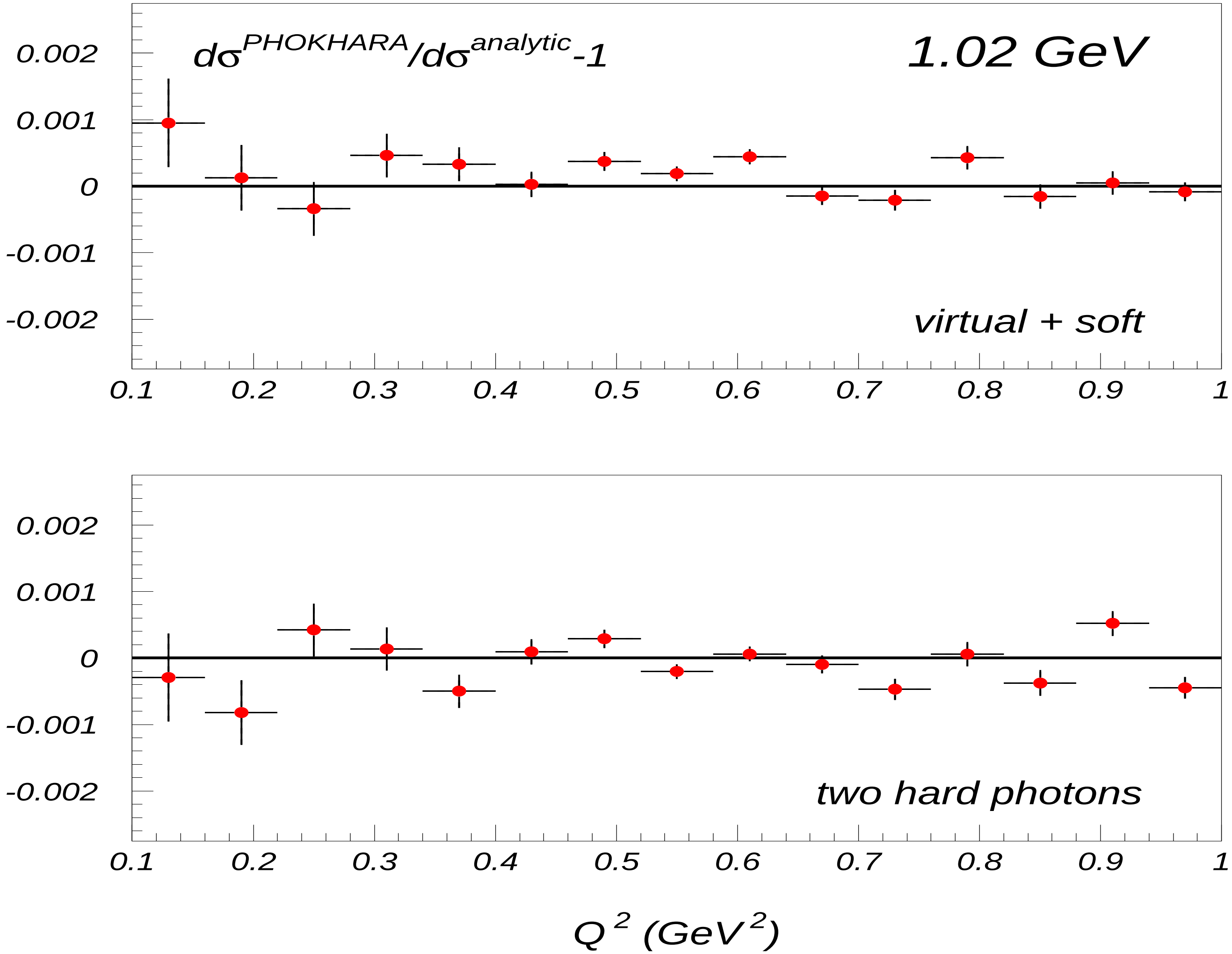
Discrepancy at high Q^2 reflects lack of exponentiation in PHOKHARA

PHOKHARA vs. KKMC cnd.



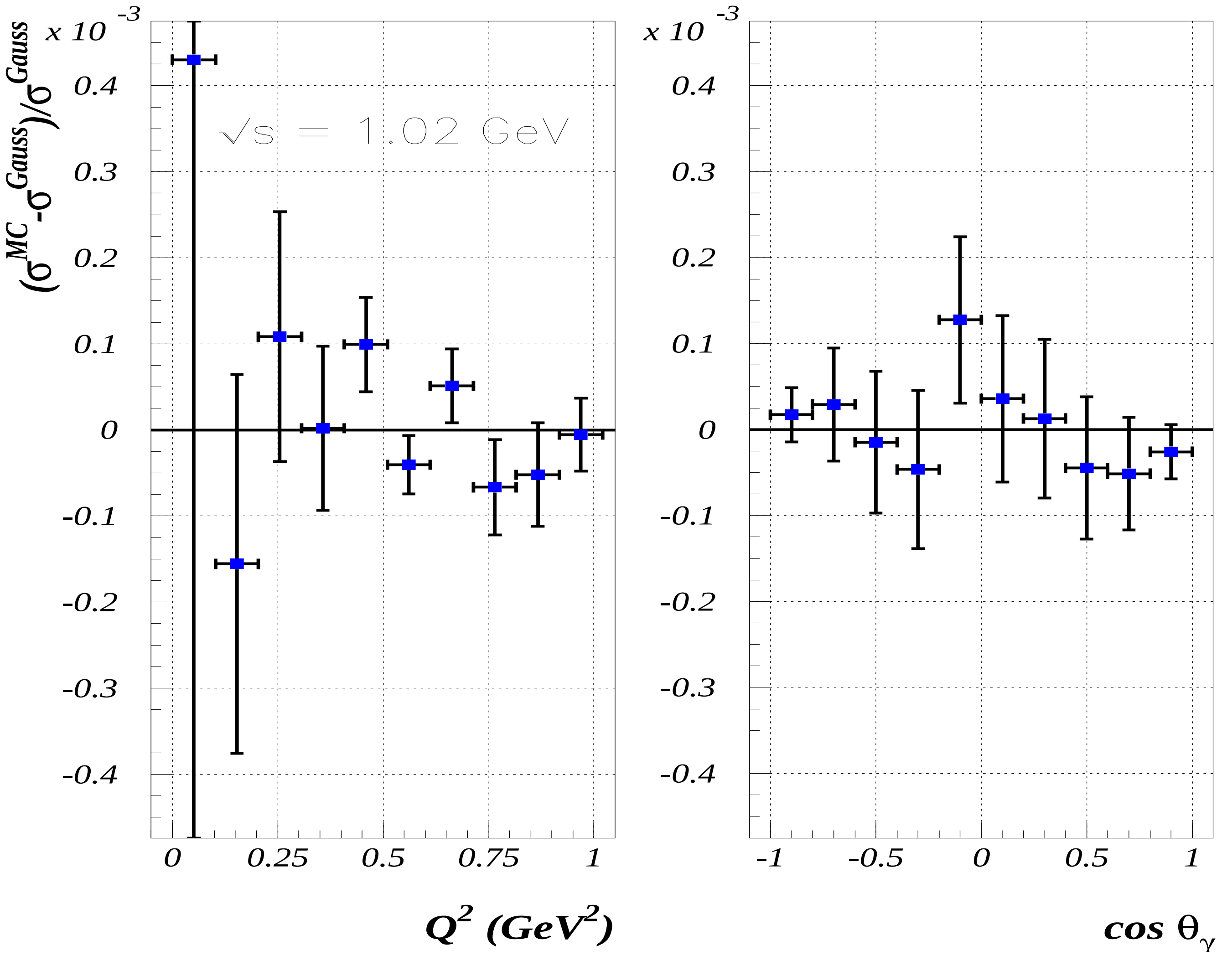
PHOKHARA generation tests

H. Czyż, A. Grzelińska, J.H. Kühn and G. Rodrigo EPJ C27 (2003)563



PHOKHARA generation tests

G. Rodrigo, H. Czyż, J.H. Kühn and M. Szopa, Eur.Phys.J.C24 (2002)71.



KKMC vs. PHOKHARA - ISR virt. corr.

C. Glosser, S. Jadach, B. F. L. Ward and S. A. Yost
Phys. Lett. B **605** (2005) 123;
Phys. Rev. D **73** (2006) 073001

- a precison $\mathbf{1.5 \cdot 10^{-5}}$

- not direct tests

PHOKHARA tests

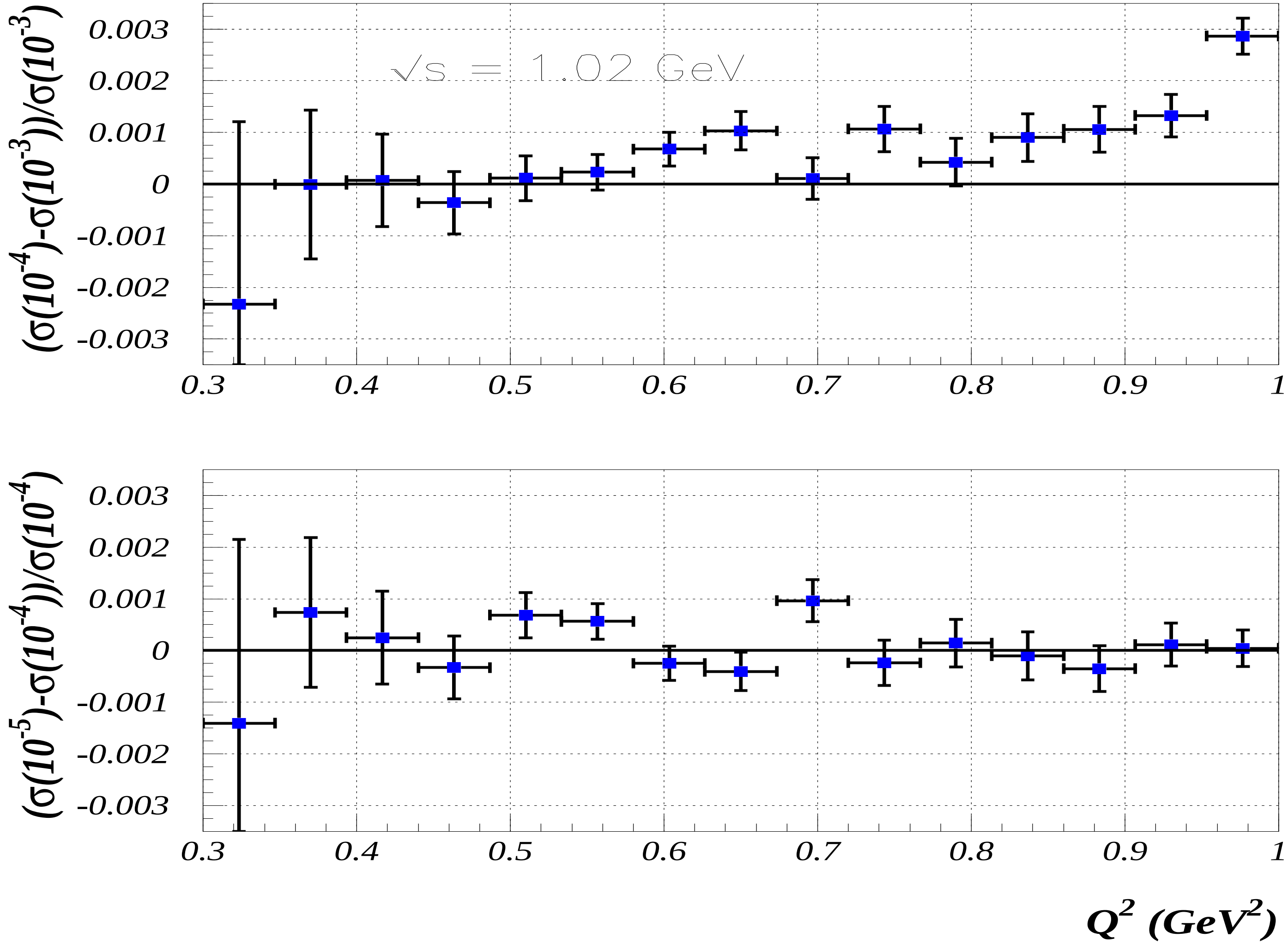
$\Rightarrow$ matrix elements tests

$\Rightarrow$ generation tests

$\Rightarrow$ KKMC comparison + ...

PHOKHARA generation tests

G. Rodrigo, H. Czyż, J.H. Kühn and M. Szopa, Eur.Phys.J.C24 (2002)71.



PHOKHARA: ISR tests summary

$\Rightarrow$ technical precision: few $\times 10^{-4}$

$\Rightarrow$ 'physical' precision: 0.5%

$\Rightarrow$ plans: accuracy $\sim$ 0.2%

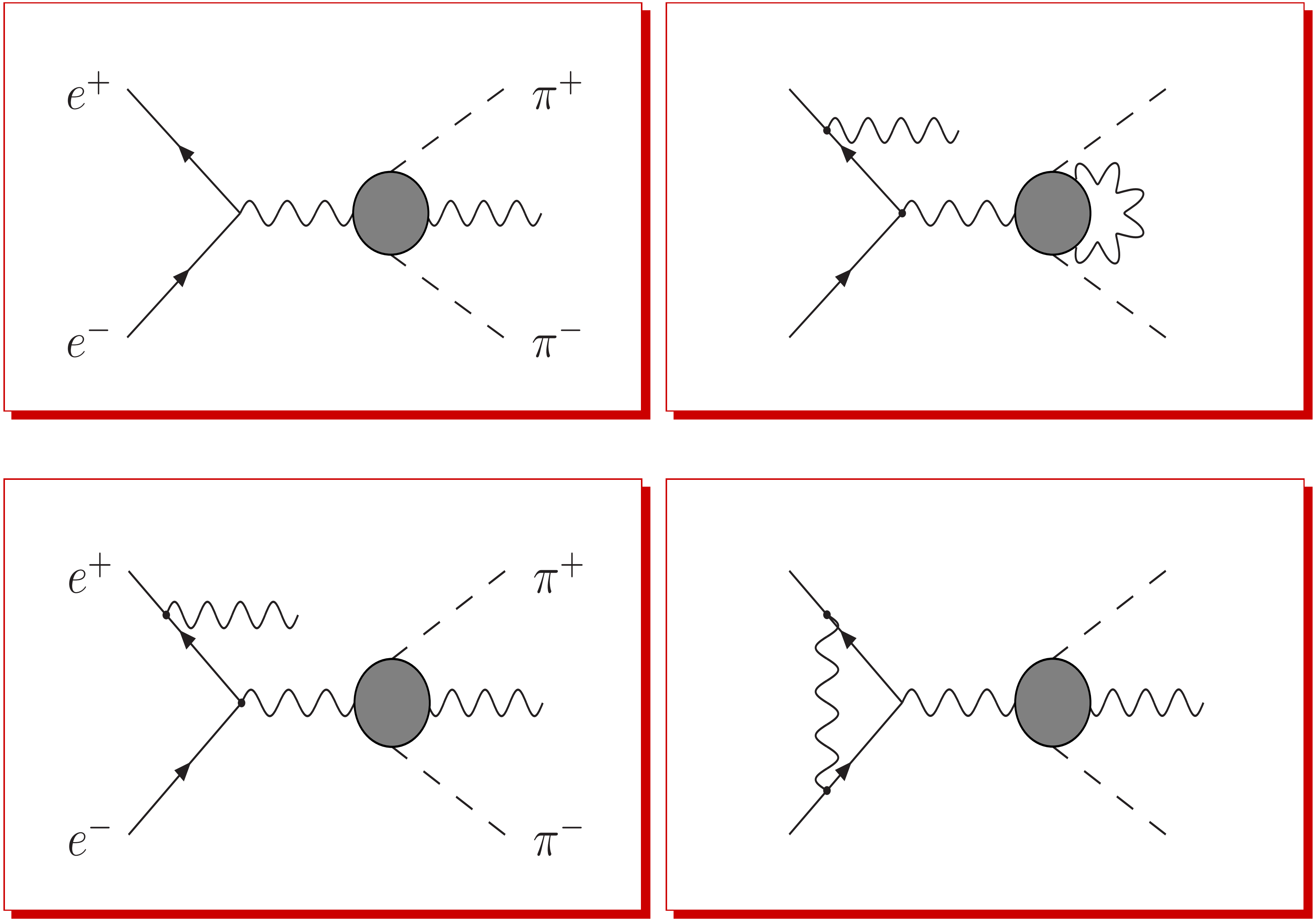
LA Bhabha luminosity: BabaYaga@NLO

G. Balossini, C. M. Carloni Calame, G. Montagna,
O. Nicrosini and F. Piccinini, Nucl. Phys. B **758** (2006) 227

- ►accuracy: 0.1%
- ►Comparisons with BHWIDE and MCGPJ:
  agreement within 0.1%

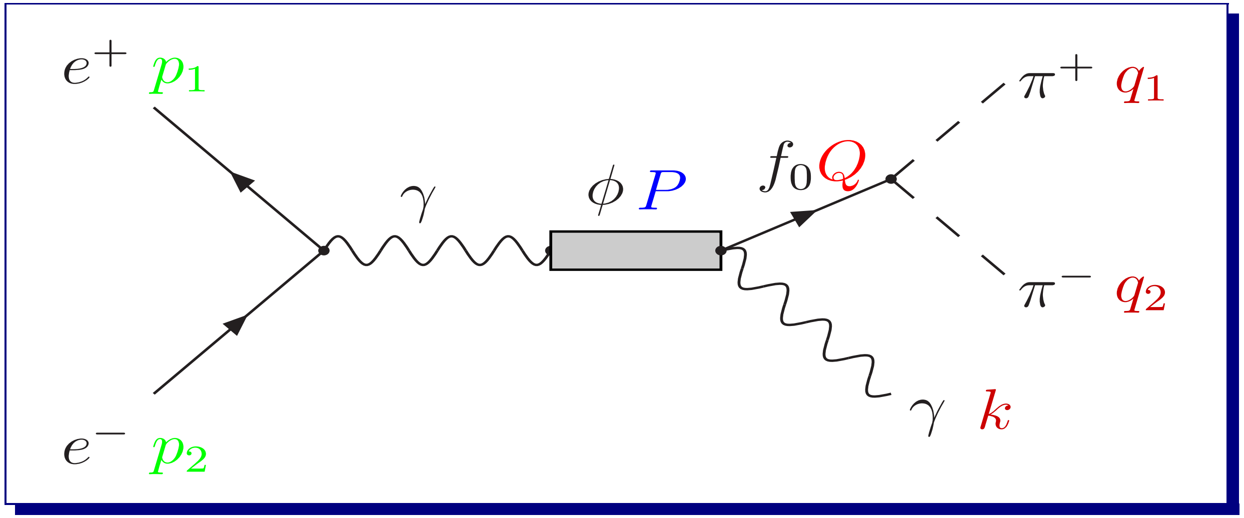
BHWIDE: S. Jadach, W. Placzek and B. F. L. Ward,
Phys. Lett. B **390** (1997) 298
MCGPJ: A. B. Arbuzov, G. V. Fedotovich, F. V. Ignatov, E. A. Kuraev
and A. L. Sibidanov, Eur. Phys. J. C **46** (2006) 689

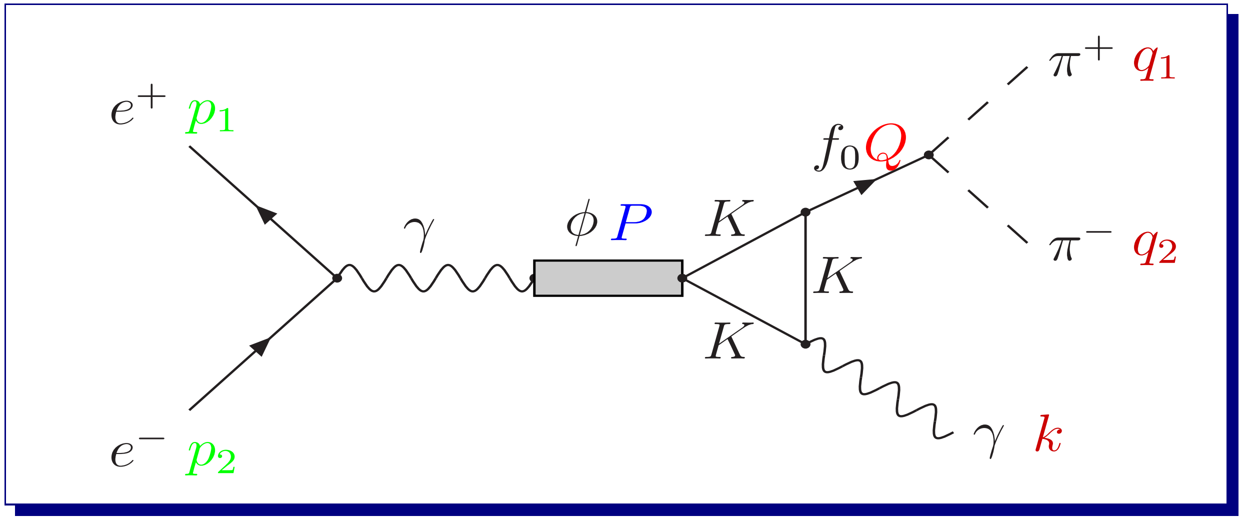
FSR in PHOKHARA



FSR at KLOE, additional contributions:

$$e^+e^- \to \phi^* \to (f_0(980)_{f_0} + f_0(600)_{\sigma})\gamma \to \pi\pi\gamma$$

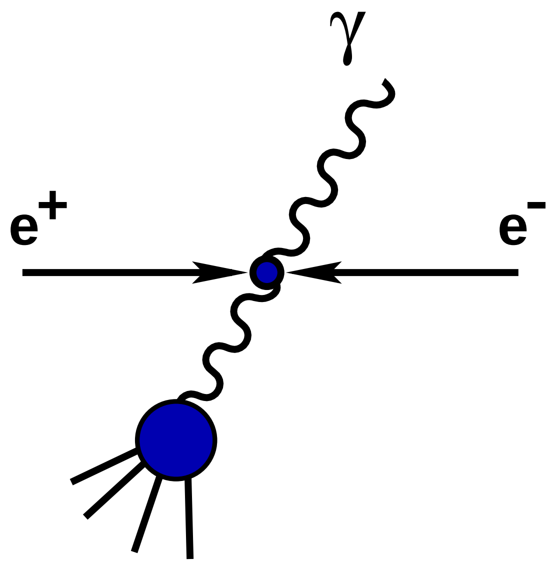




DAΦNE versus B-factories:

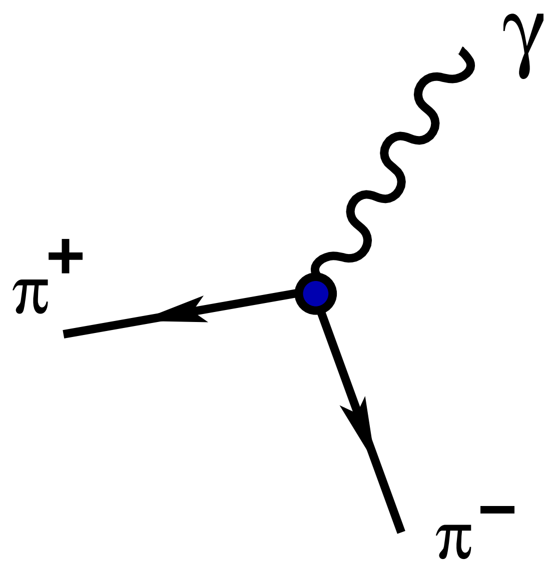
configurations in the cms - frame

10 GeV



very hard photon: clear kinematic separation between photon and hadrons

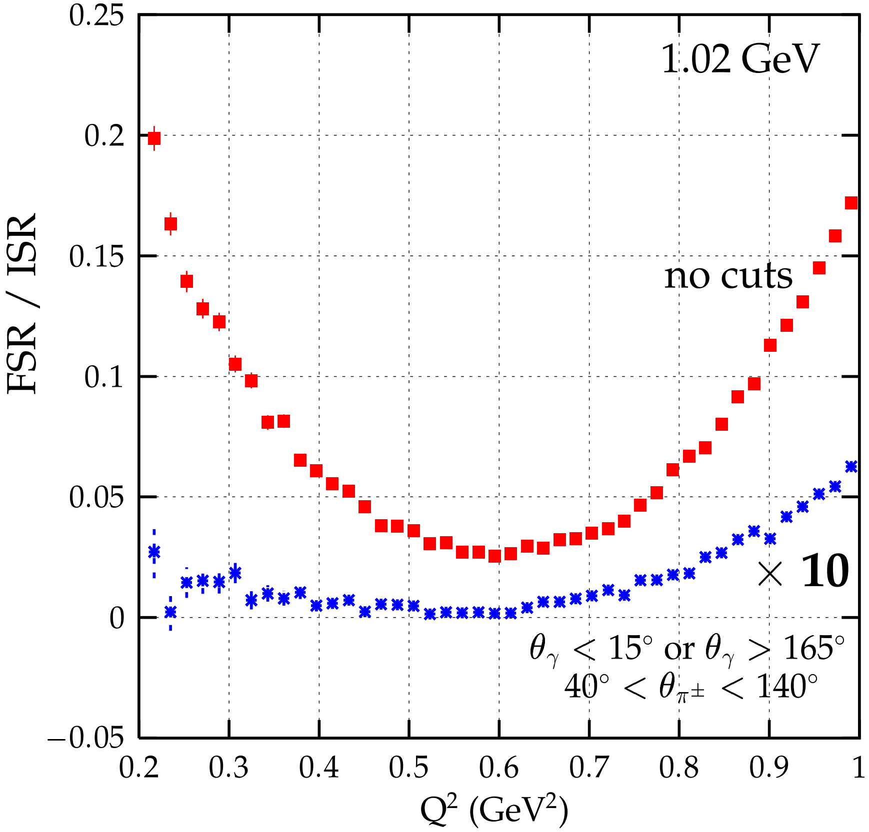
1 GeV

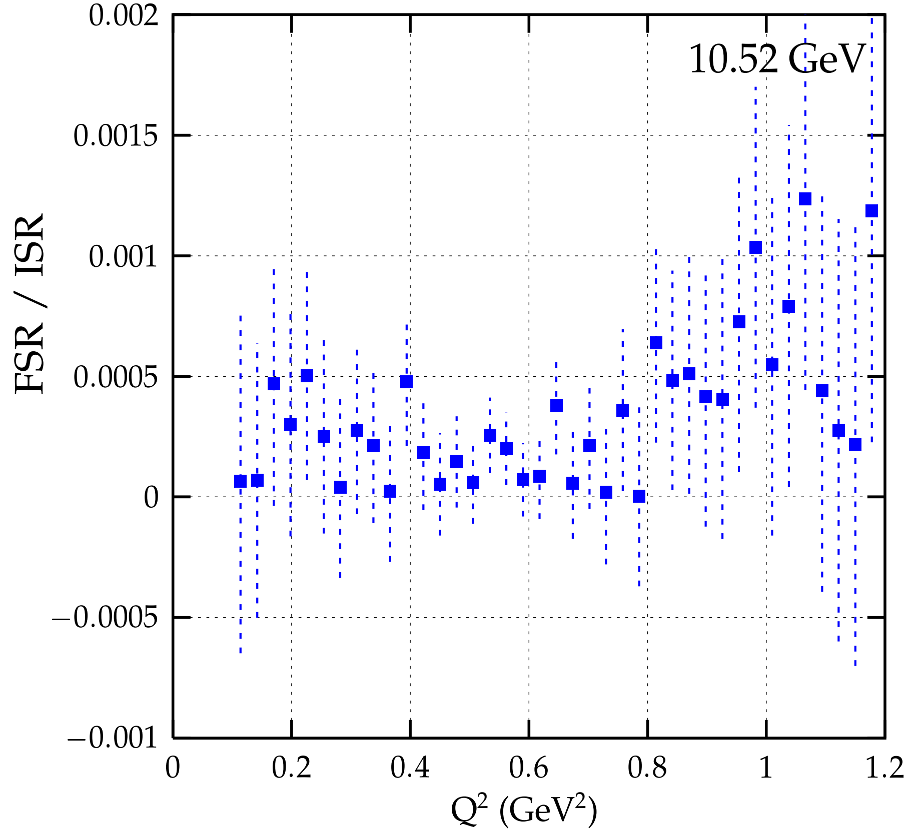


no natural kinematic separation

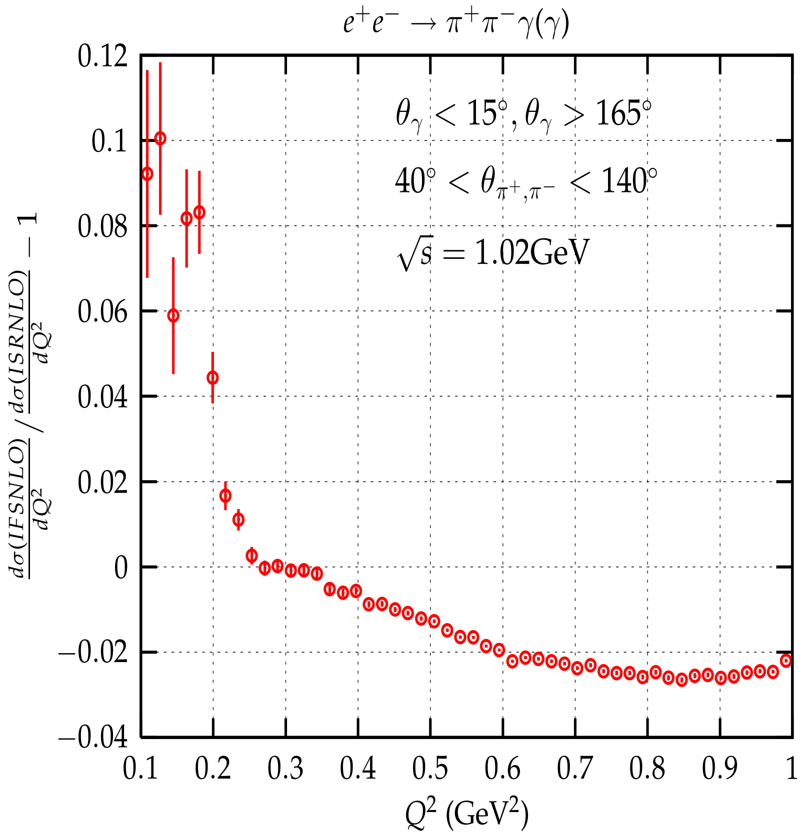
➪ cuts to control FSR versus ISR

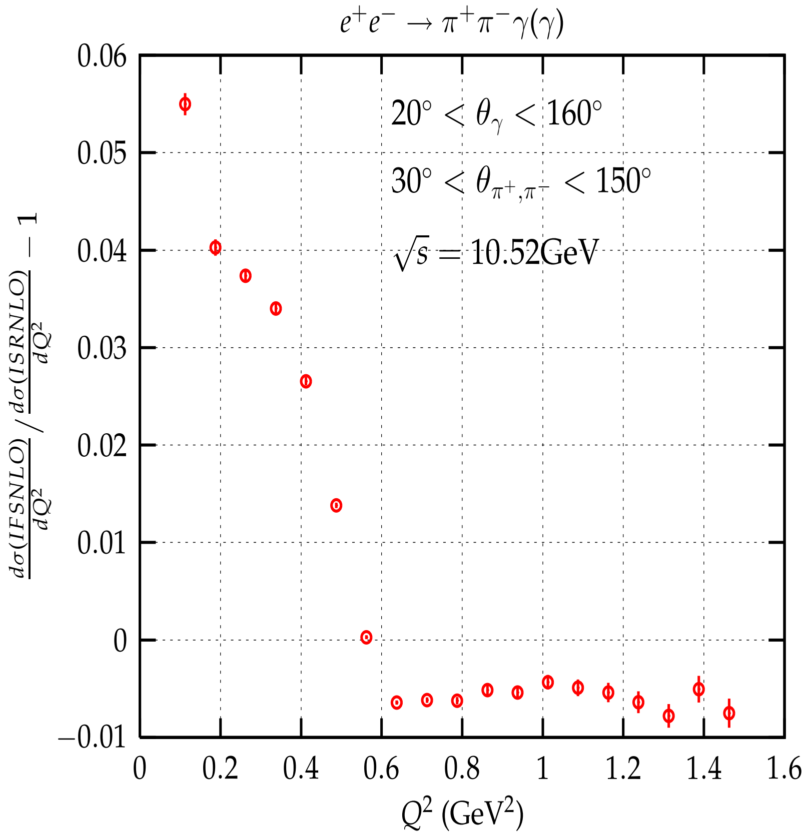
LO FSR DAΦNE versus B-factories:



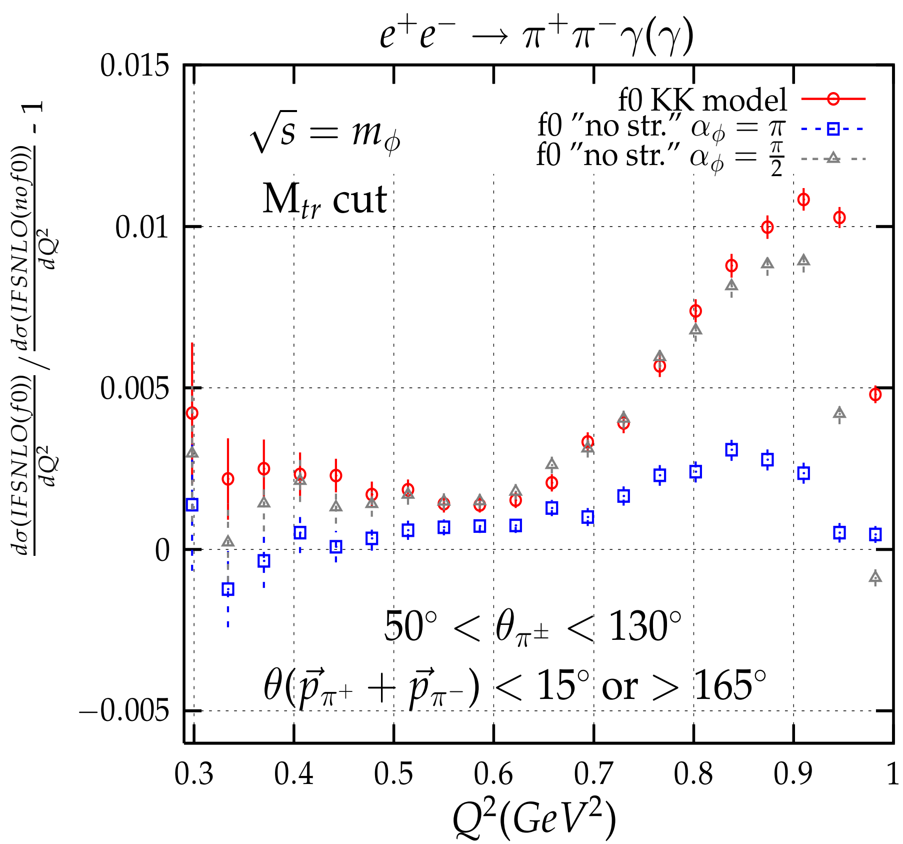


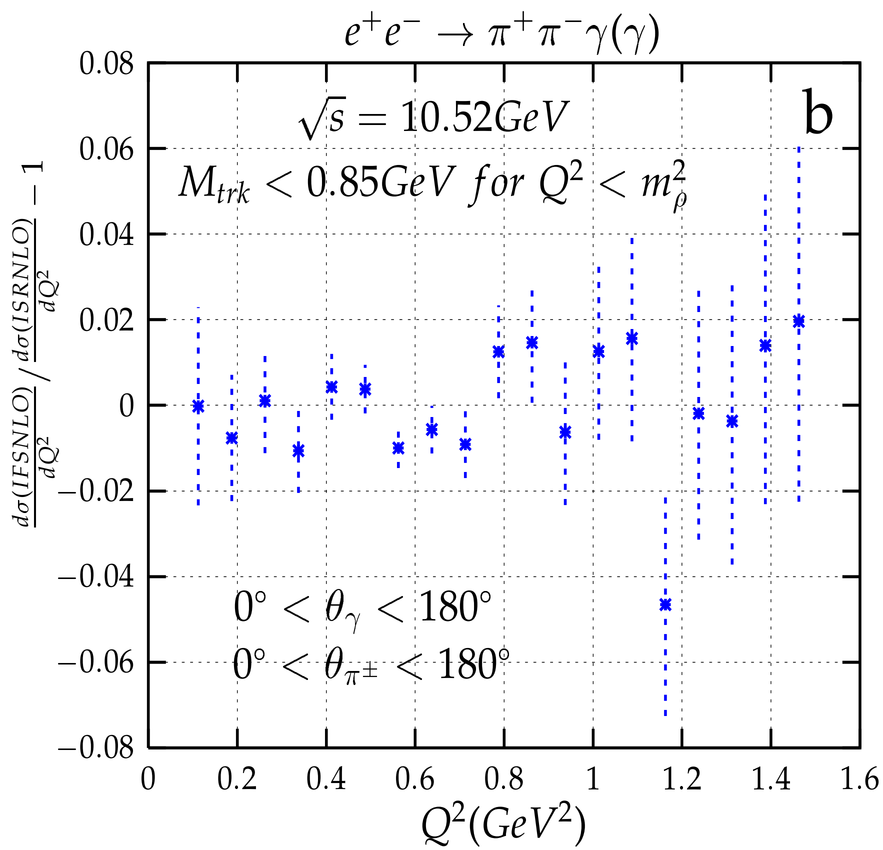
NLO FSR DAΦNE versus B-factories:





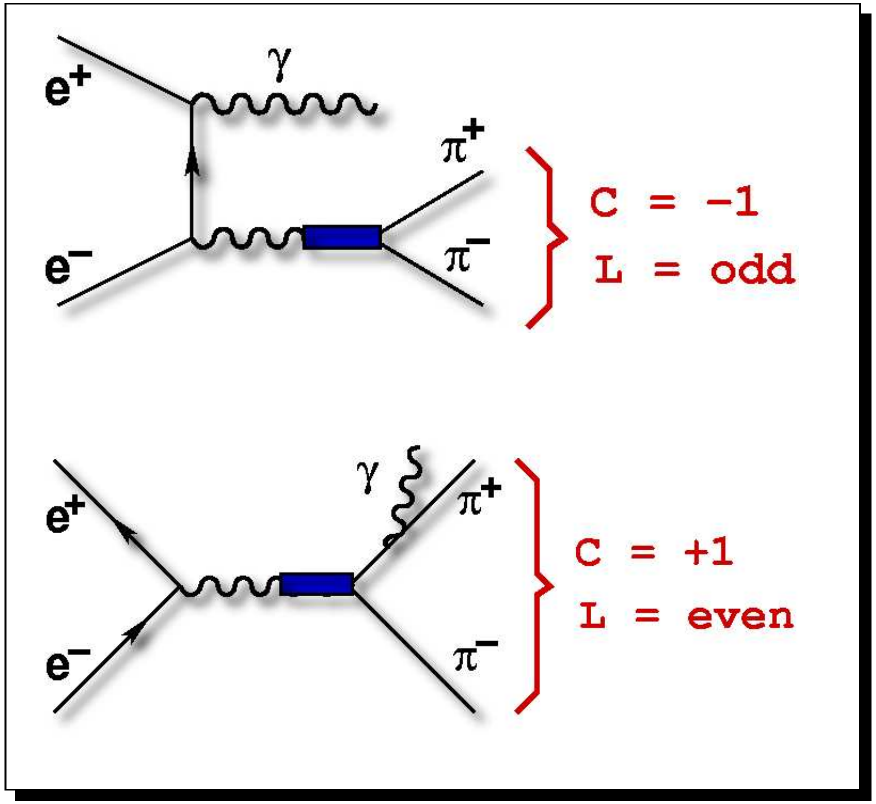
Controlling NLO FSR





Test of FSR model

interference:



- interference odd under $\pi^+ \leftrightarrow \pi^-$
- asymmetric differential distribution: $\int$ interf. $= 0$

$$A(\theta) = \frac{N^{\pi^+}(\theta) - N^{\pi^-}(\theta)}{N^{\pi^+}(\theta) + N^{\pi^-}(\theta)}$$

Charge asymmetries

⇒ F-B asymmetry defined for π^+

$$\mathcal{A}_{FB}(Q^2) = \frac{N(\theta_{\pi^+}>90^\circ) - N(\theta_{\pi^+}<90^\circ)}{N(\theta_{\pi^+}>90^\circ) + N(\theta_{\pi^+}<90^\circ)}(Q^2)$$

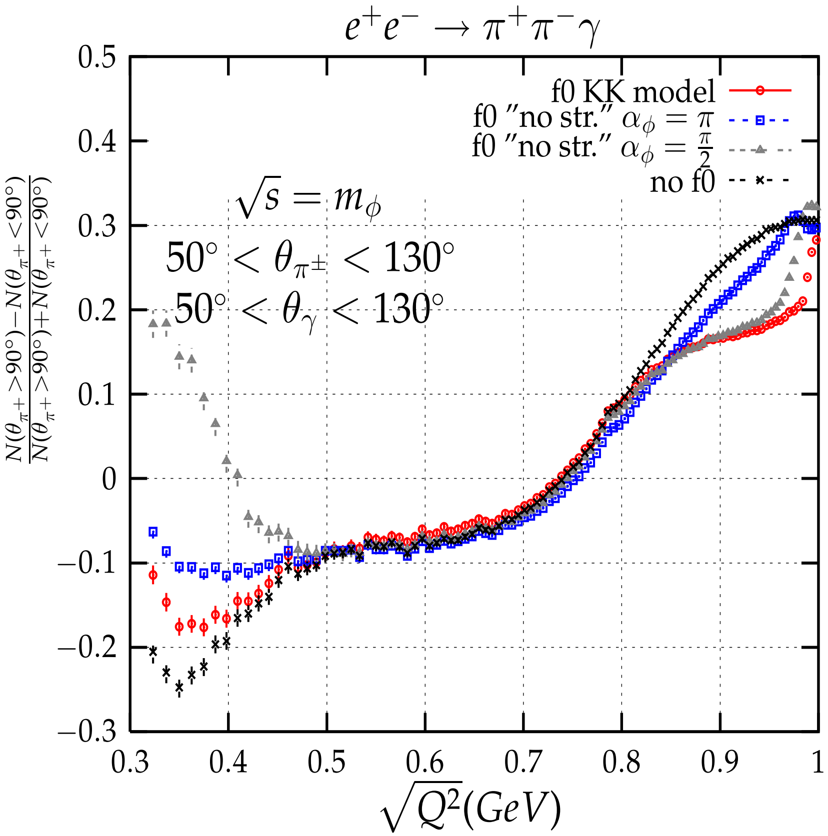
⇒ charge asymmetry

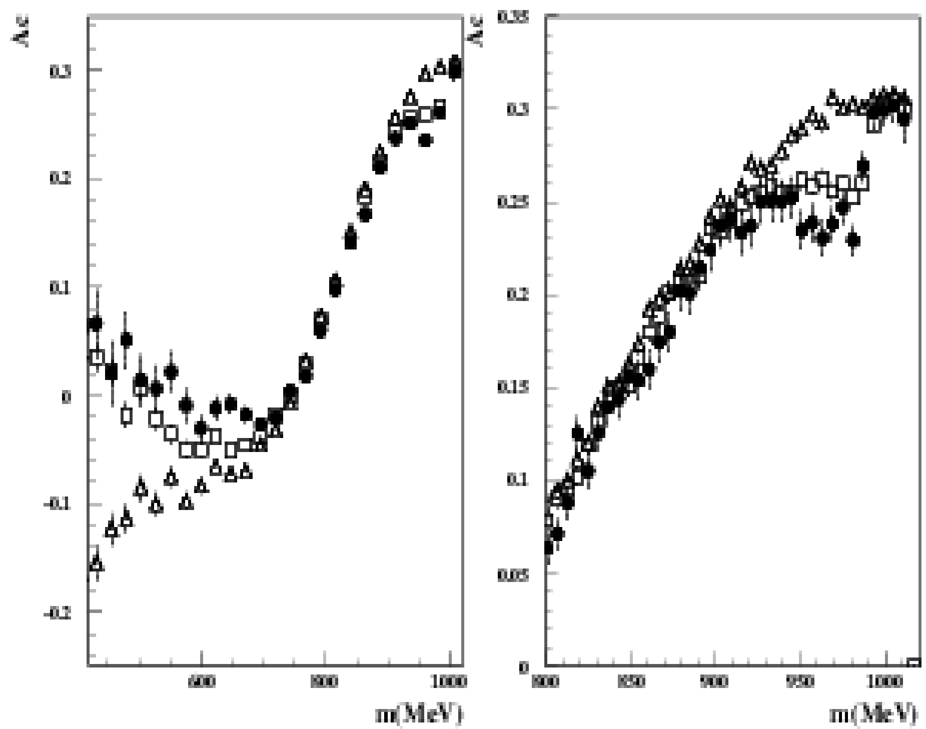
$$\mathcal{A}_{C}(\theta_\pi) = \frac{N(\pi^+) - N(\pi^-)}{N(\pi^+) + N(\pi^-)}(\theta_\pi)$$

F-B asymmetry

H. C., A. Grzelińska, J.H. Kühn, Phys. Lett. B **611** (2005) 116

KLOE: Phys.Lett.B634:148-154,2006





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

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

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

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

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

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

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

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

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

The subsequent two body decays of Λs

The measurement of the subsequent two body decays:

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

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

$$
\begin{aligned}
L^{ij}H_{ij} \simeq \frac{(4\pi\alpha)^3}{4Q^2y_1y_2}\left(1+\cos^2\theta_\gamma\right)\Bigg\{ & |G_M|^2\left(1+\cos^2\theta_{\bar\Lambda}\right) \\
& +\frac{1}{\tau}|G_E|^2\sin^2\theta_{\bar\Lambda} - \alpha_\Lambda\frac{Im(G_MG_E^*)}{\sqrt{\tau}}\sin(2\theta_{\bar\Lambda})\left(n^y_{\pi^-}-n^y_{\pi^+}\right) \\
& +\alpha_\Lambda^2\frac{Re(G_MG_E^*)}{\sqrt{\tau}}\sin(2\theta_{\bar\Lambda})\left(n^z_{\pi^-}n^x_{\pi^+}+n^z_{\pi^+}n^x_{\pi^-}\right) \\
& -\alpha_\Lambda^2\left(\frac{1}{\tau}|G_E|^2+|G_M|^2\right)\sin^2\theta_{\bar\Lambda}\;\; n^x_{\pi^+}n^x_{\pi^-} \\
& -\alpha_\Lambda^2\left(\frac{1}{\tau}|G_E|^2-|G_M|^2\right)\sin^2\theta_{\bar\Lambda}\;\; n^y_{\pi^+}n^y_{\pi^-} \\
& +\alpha_\Lambda^2\left(\frac{1}{\tau}|G_E|^2\sin^2\theta_{\bar\Lambda}-|G_M|^2\left(1+\cos^2\theta_{\bar\Lambda}\right)\right)\;\; n^z_{\pi^+}n^z_{\pi^-}\Bigg\}
\end{aligned}
$$

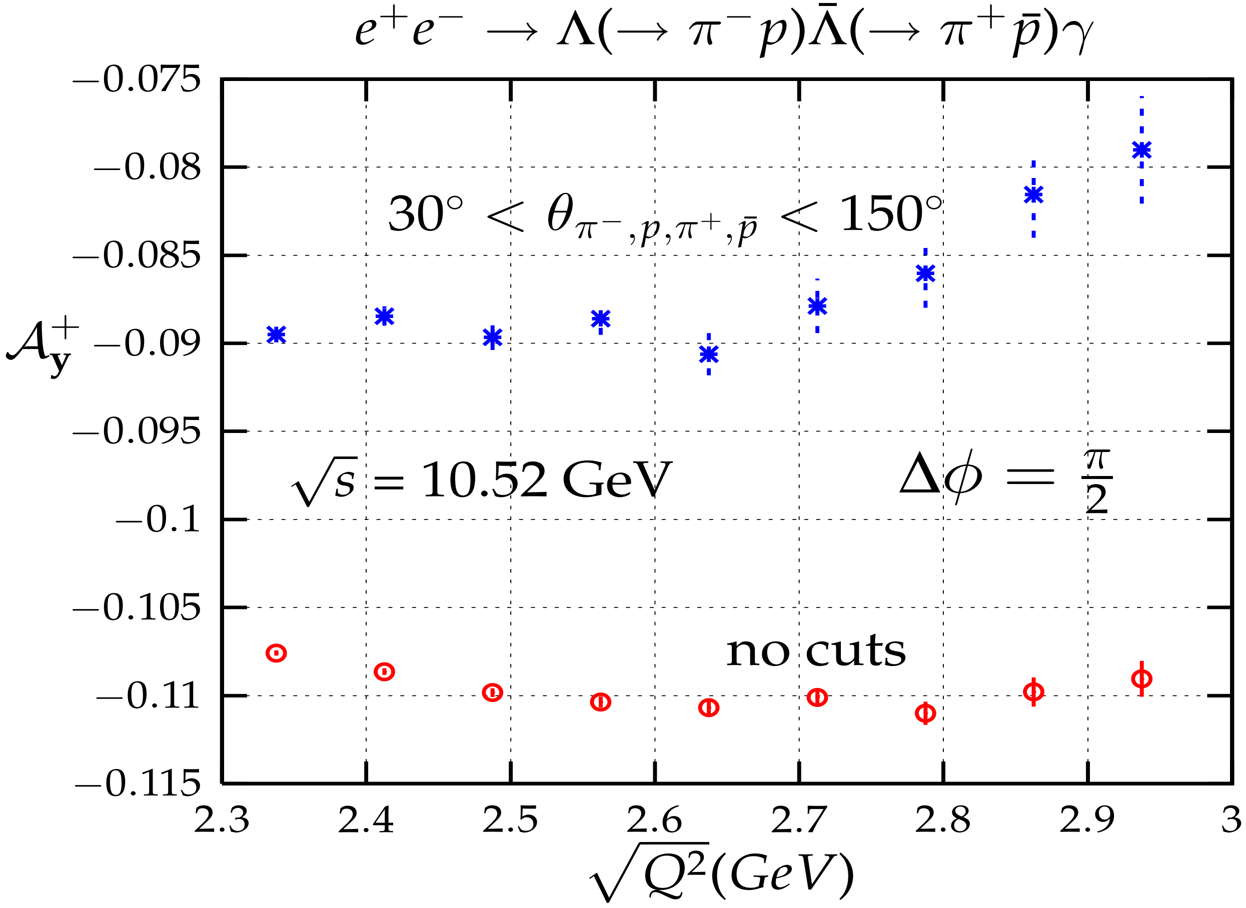
$\theta_{\bar\Lambda}$ - $\bar Q$ rest frame with the z-axis opposite to the photon direction

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
$\mathcal{A}_{\mathbf{y}}^{+}$
−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
$\sqrt{Q^2}(GeV)$

Summary and plans

- PHOKHARA: ISR accuracy 0.5%
  - need for ISR accuracy $\sim$0.2%
- carefull study of FSR necessary
  - tools for these studies are ready
- need for more codes comparisons
- the radiative return a tool in hadronic physics

Summary and plans

- soon J/ψ and $\psi(2S)$ in PHOKHARA
- 4π channels reanalysis