Monte Carlo generators for reactions $e^+e^- \to$ hadrons (+photons)

H. CZYŻ, IF, UŚ, Katowice,

Matter to the Deepest, Ustroń 2013

Outline of the talk

⇒ Motivation

⇒ Hadronic cross section from radiative return and scan

⇒ Available generators

⇒ PHOKHARA event generator

⇒ An outlook

Motivation: $(g-2)_\mu$

$$(g-2)_\mu^{SM} = 11659180.2 \pm 4.2(had) \pm 2.6(L-L) \pm 0.2$$

$$(g-2)_\mu^{exp} = 11659208.9 \pm 5.4 \pm 3.3$$

$$EXP\ -\ SM = 28.7 \pm 8.0$$

M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. **C71** (2011) 1515.

Muon g-2 Collaboration (G.W. Bennett et al.), Phys. Rev. D 73, 072003 (2006) [hep-ex/0602035].

$(g-2)_\mu$

E821

$$\left.\begin{array}{l}\sigma_{\rm stat} = \pm 0.46 \text{ ppm} \\ \sigma_{\rm syst} = \pm 0.28 \text{ ppm}\end{array}\right\} \sigma = \pm 0.54 \text{ ppm}$$

$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11}$$

$$a_\mu^{SM} = 116\ 591\ 793 \pm 51$$

E989

$$\left.\begin{array}{l}\sigma_{\rm stat} = \pm 0.1 \text{ ppm} \\ \sigma_{\rm syst} = \pm 0.1 \text{ ppm}\end{array}\right\} \sigma = \pm 0.14 \text{ ppm}$$

$$a_\mu^{exp} = 116\,59x\,xxx(16) \times 10^{-11}$$

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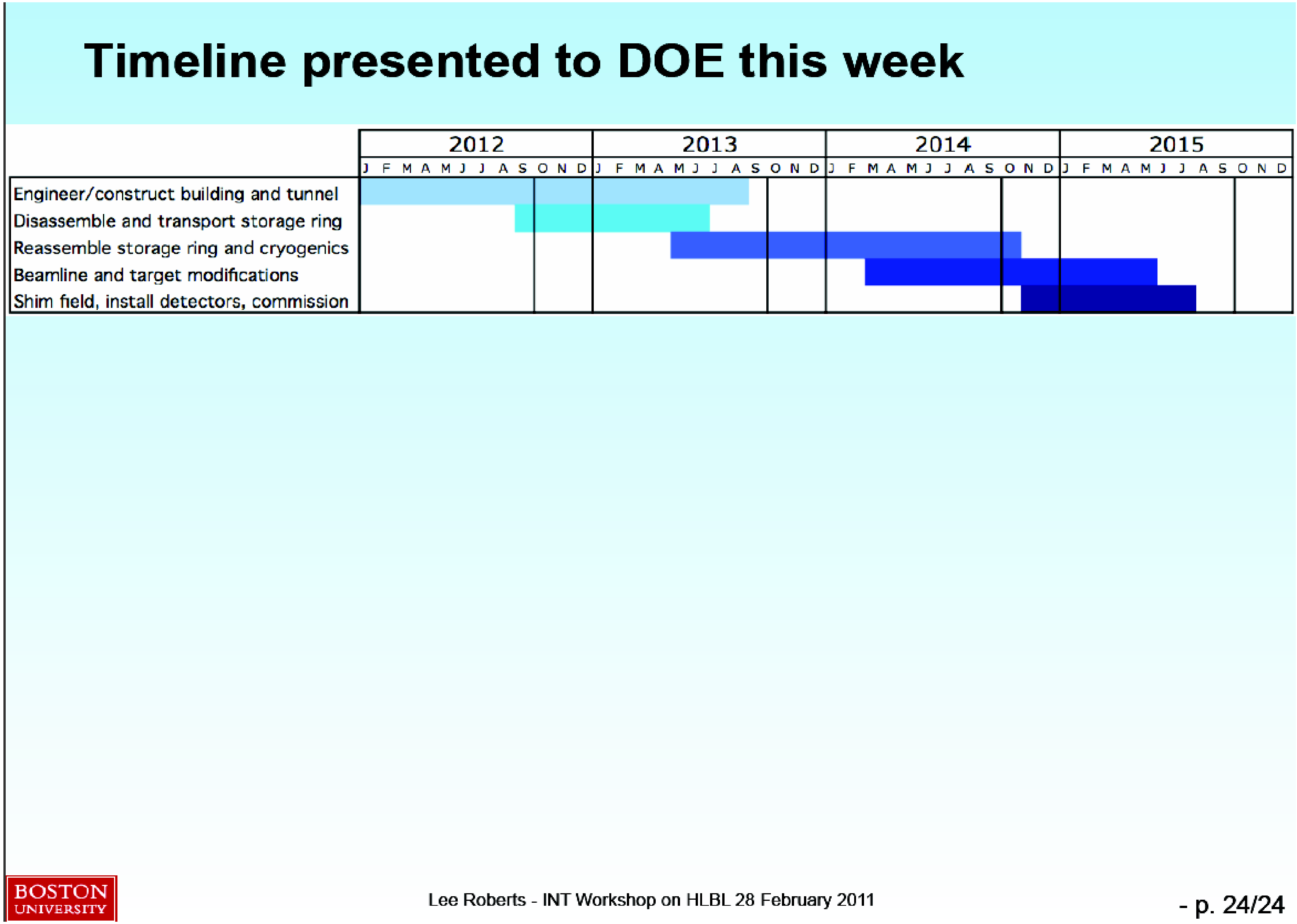
$(g-2)_\mu$


Timeline presented to DOE this week
2012
2013
2014
2015
J F M A M J J A S O N D
Engineer/construct building and tunnel
Disassemble and transport storage ring
Reassemble storage ring and cryogenics
Beamline and target modifications
Shim field, install detectors, commission
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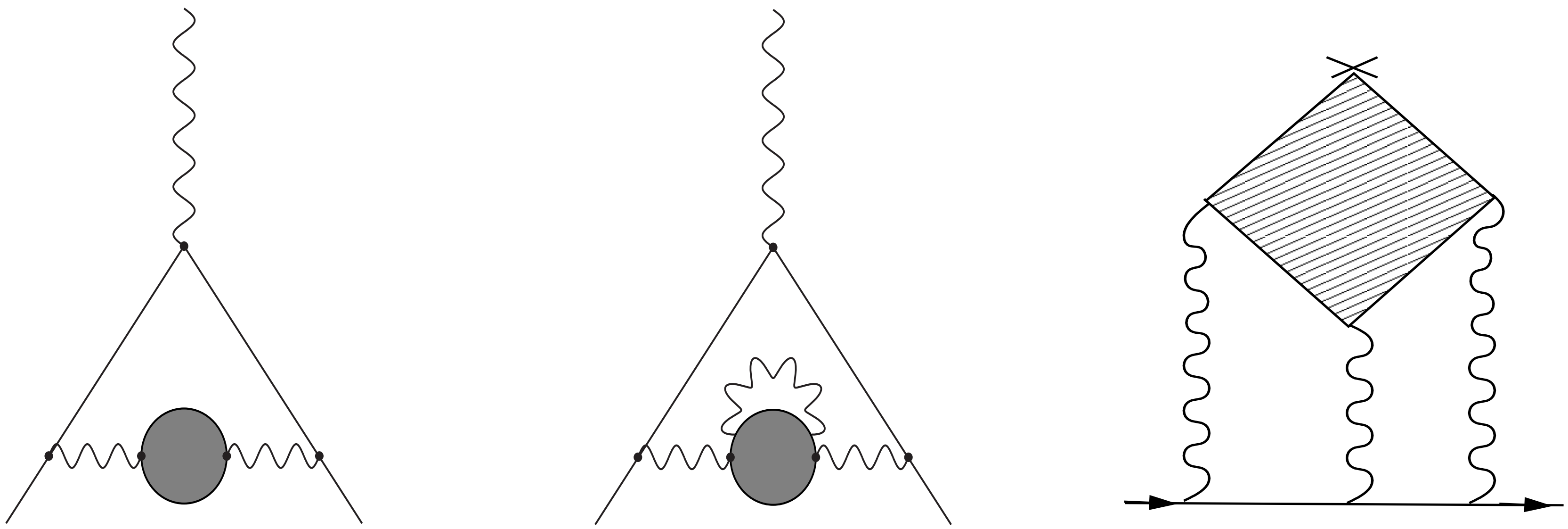
$(g-2)_\mu$

anatomy of $(g-2)_\mu$



$$a_\mu^{\mathrm{h}ad} = a_\mu^{\mathrm{h}ad,LO} + a_\mu^{\mathrm{h}ad,HO} + a_\mu^{\mathrm{h}ad,LBL}$$

anatomy of $(g-2)_\mu$

A. Höcker, Tau 2010, Manchester

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak}$$

$$a_\mu^{QED} = 116\,584\,718.09 \quad (0.14 + 0.04_\alpha) \times 10^{-11}$$

$$a_\mu^{weak} = 152 \quad (1 + 2) \times 10^{-11}$$

$$a_\mu^{had\ HO} = -98 \quad (1 + 0.3) \times 10^{-11}$$

$$a_\mu^{had\ LO} = 6\,914 \quad (42 + 14 + 7) \times 10^{-11}$$

$$a_\mu^{had\ LbL} = 105 \quad (26) \times 10^{-11}$$

$$a_\mu^{tot\ SM} = 116\,591\,793 \quad (51) \times 10^{-11}$$

The reason we need R(s)

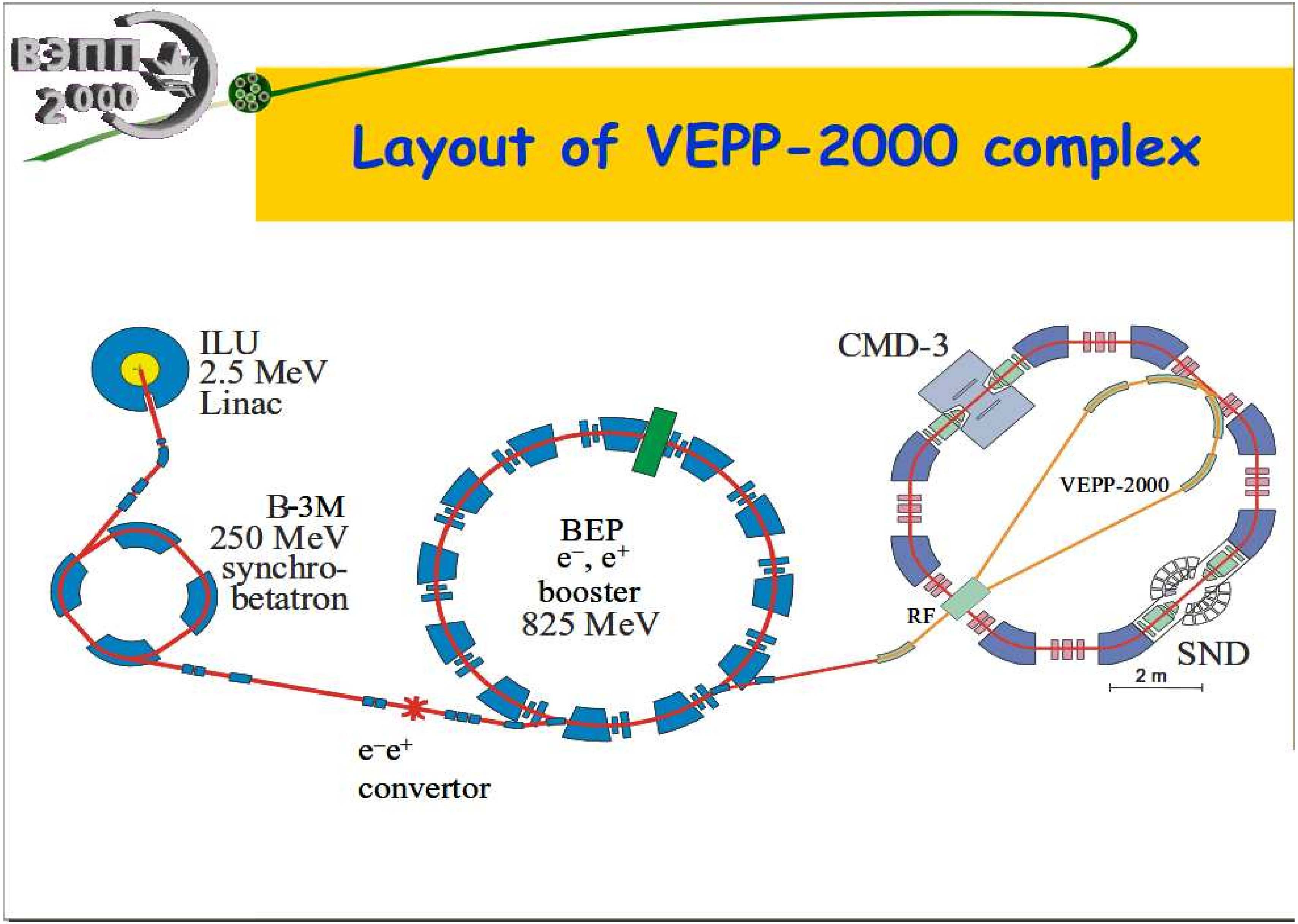
$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^{\infty} \frac{ds}{s} \, K(s) \; R(s)$$

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

One has to measure :

$$\sigma(e^+e^- \to hadrons)$$

R from scan

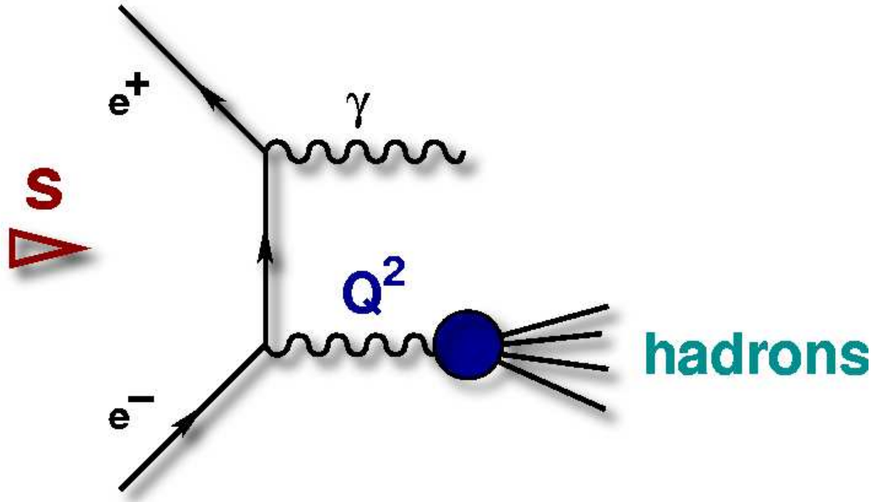


Layout of VEPP-2000 complex
ILU
2.5 MeV
Linac
B-3M
250 MeV
synchro-
betatron
BEP
e⁻, e⁺
booster
825 MeV
e⁻e⁺
convertor
CMD-3
VEPP-2000
RF
SND
2 m

THE RADIATIVE RETURN METHOD

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

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

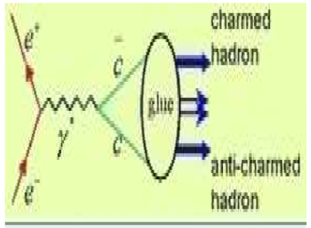


- measurement of $R(s)$ over the full range of energies, from threshold up to $\sqrt{s}$
- large luminosities of factories compensate α/π from photon radiation
- radiative corrections essential (NLO,...)

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

BES III

scan planned 2013 ...
see Trento WGM 10 April



$\sqrt{s} = 2 - 5$ GeV

MC generators needed

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]

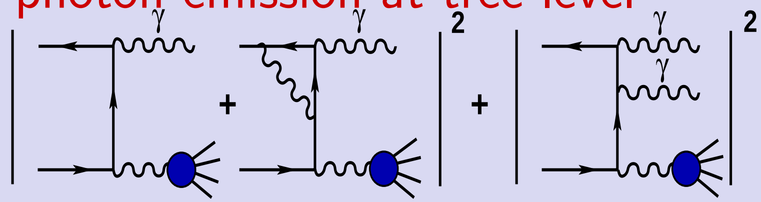
H.C., A. Grzelińska, M. Gunia,

J. H. Kühn, E. Nowak-Kubat,

G. Rodrigo, Sz. Tracz, A. Wapienik

PHOKHARA 8.0: $\pi^+\pi^-$, $\mu^+\mu^-$, 4π, $\bar{N}N$, 3π, KK, $\Lambda(\to\cdots)\bar{\Lambda}(\to\cdots)$, $J/\psi, \psi(2S)$

- **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^-, $\bar{p}p$
- tagged or untagged photons
- $e^+e^- \to hadrons\ (muons)$ ISR at NNLO
- Modular structure

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

MC and FSR studies

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

- ISR at LO + Structure Function

[Czyż, Kühn]

→

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

- upgraded by BaBar - AfkQED 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.]

→

$e^+e^- \to \pi^{+,0}\pi^{-,0} + \gamma$

- FASTERD: FSR studies

[Pancheri,Shekhovtsova,Venanzoni]

MC for $e^+e^- \to hadrons(muons)$

KKMC

- ISR,YFS exponentiation, muons, 'hadrons'

[S. Jadach, B. Ward and Z. Was]

Comp.Phys. Comm. 130 (2000) 260;Phys. Rev. D 63(2001)113009

MCGPJ

- ISR, structure functions, muons, $\pi^+\pi^-, K^+K^-, \bar{K}^0K^0$

[A. Arbuzov, G. Fedotovich, F. Ignatov, E. Kuraev and A. Sibidanov]

JHEP10(1997)006;JHEP10(1997)001

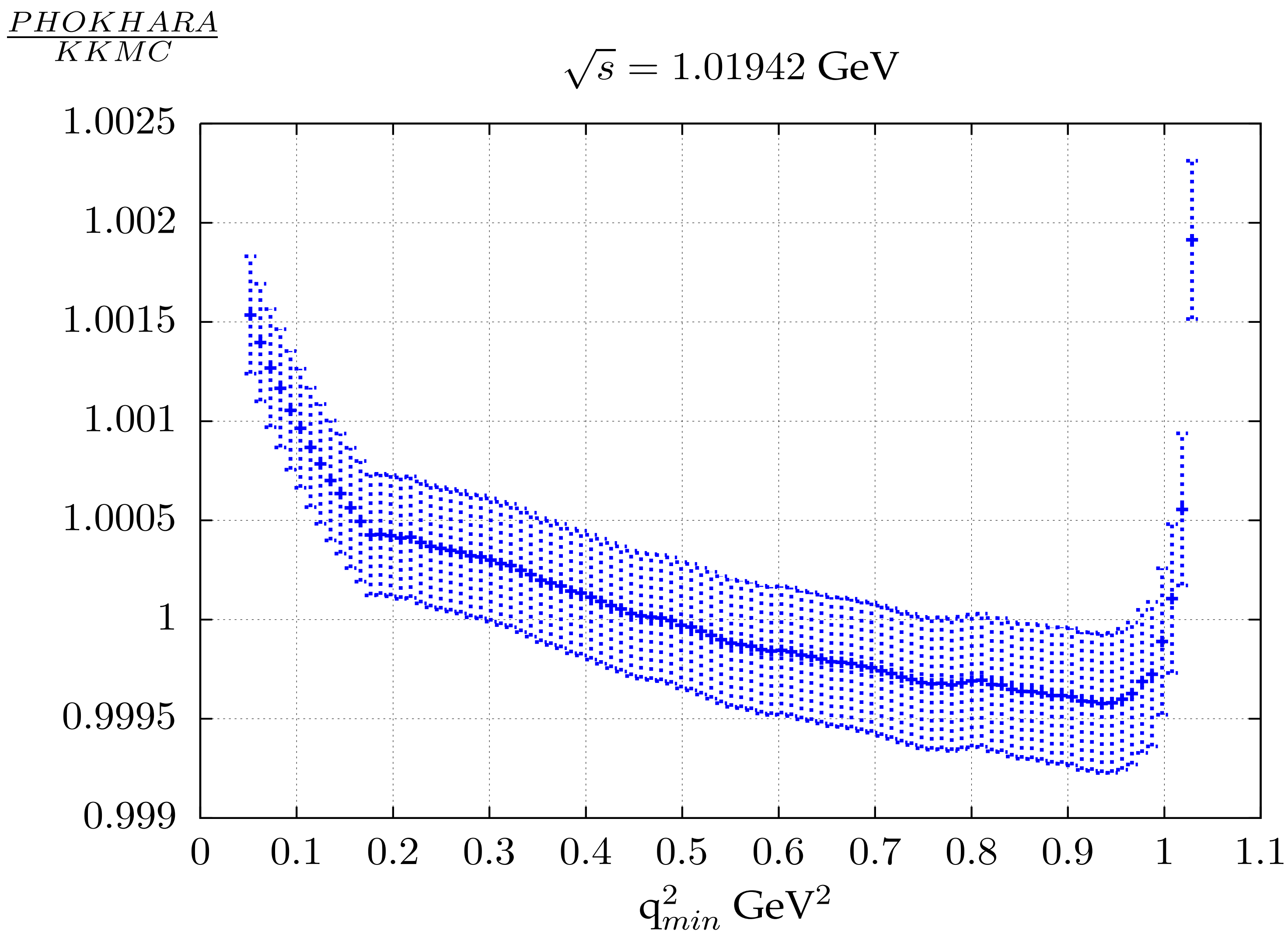
PHOKHARA 8.0

JHEP08(2013)110.

- ISR, fixed order (NNLO), muons, hadrons

[H.Czyz, M. Gunia, J.H. Kuhn]

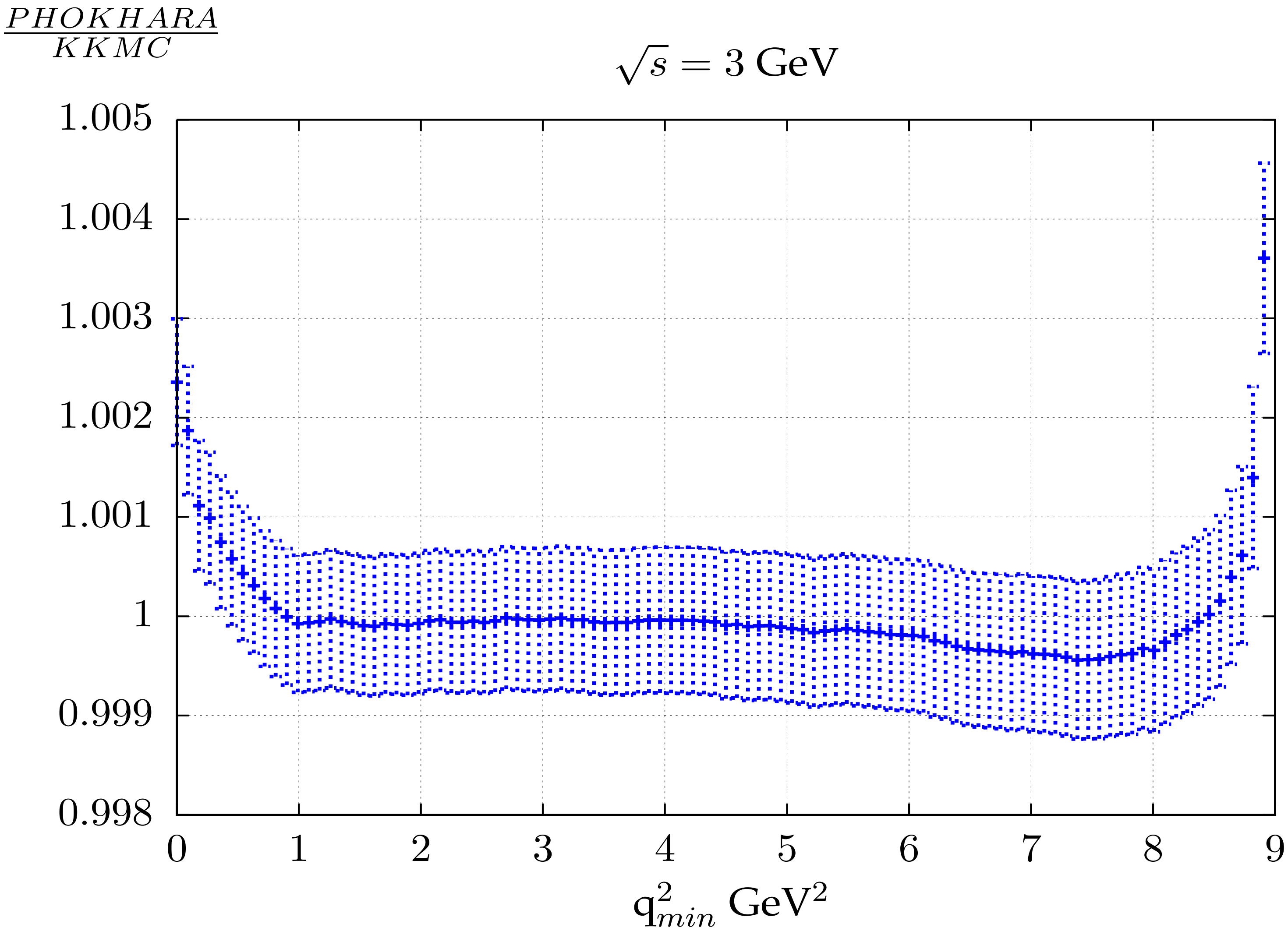
PHOKHARA 8.0 vs. KKMC 4.13



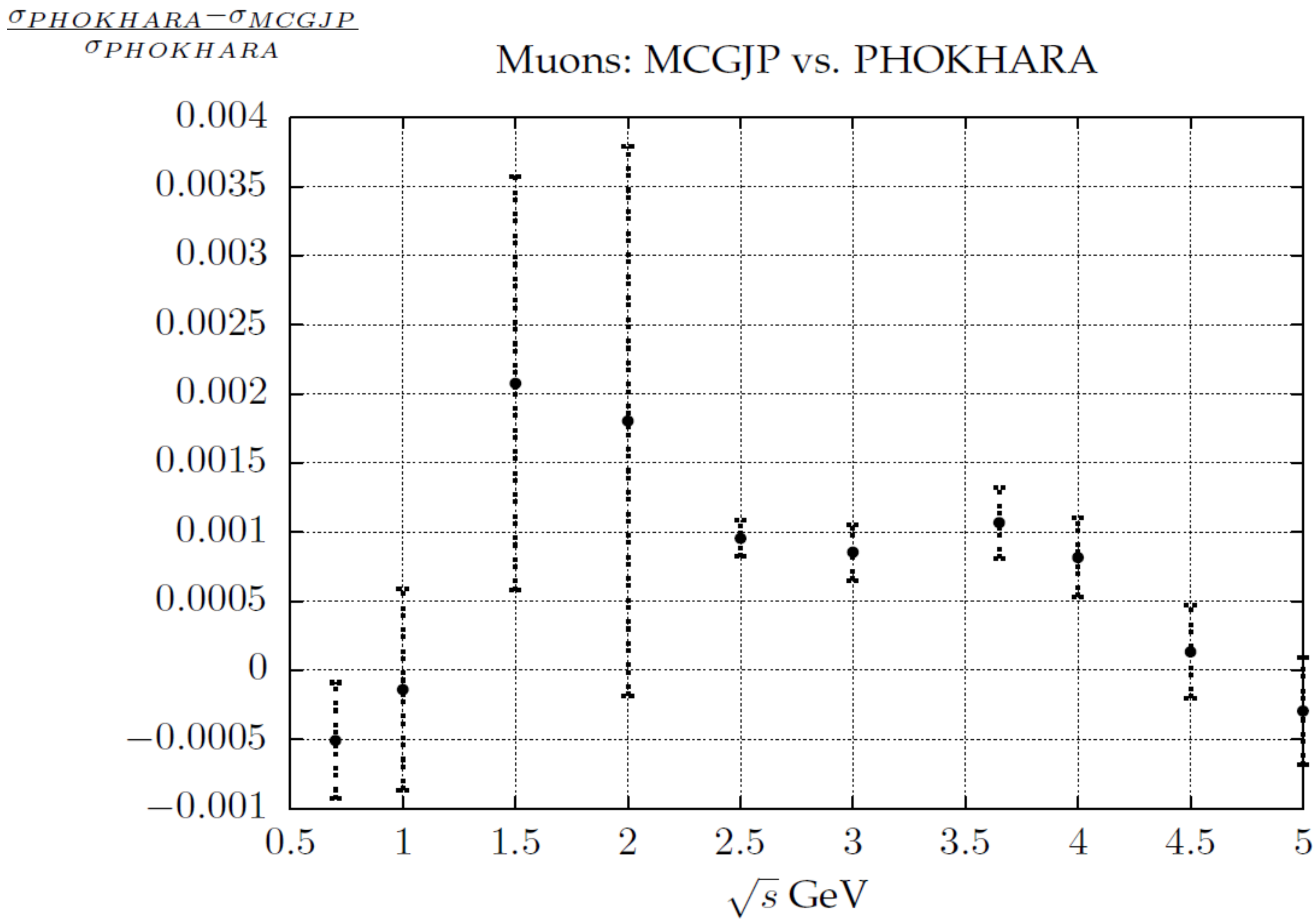
H. Czyz, M. Gunia and J.H. Kuhn, JHEP08(2013)110.

S. Jadach , Acta Phys. Polonica B36 (2005) 2387.

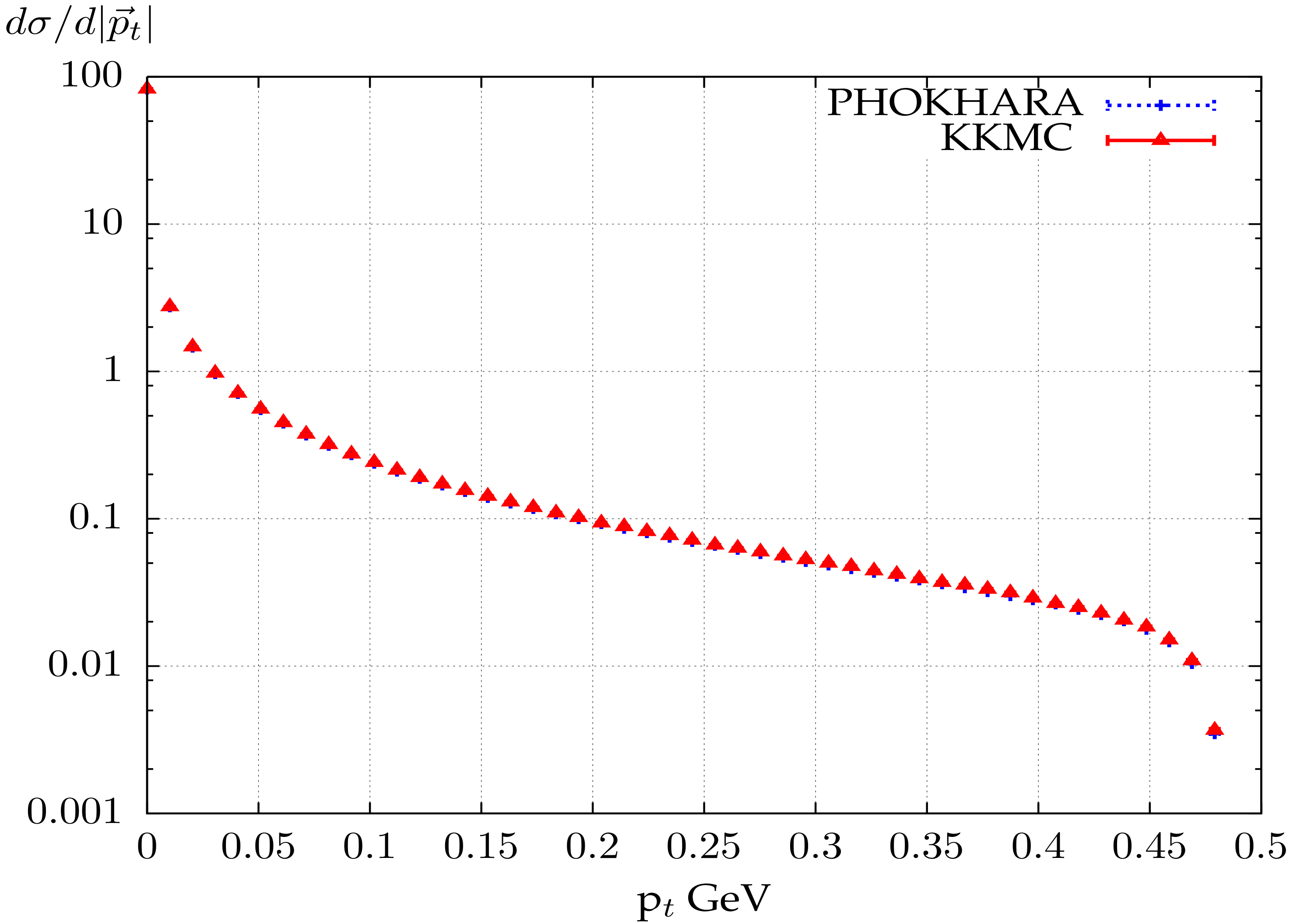
PHOKHARA 8.0 vs. KKMC 4.13



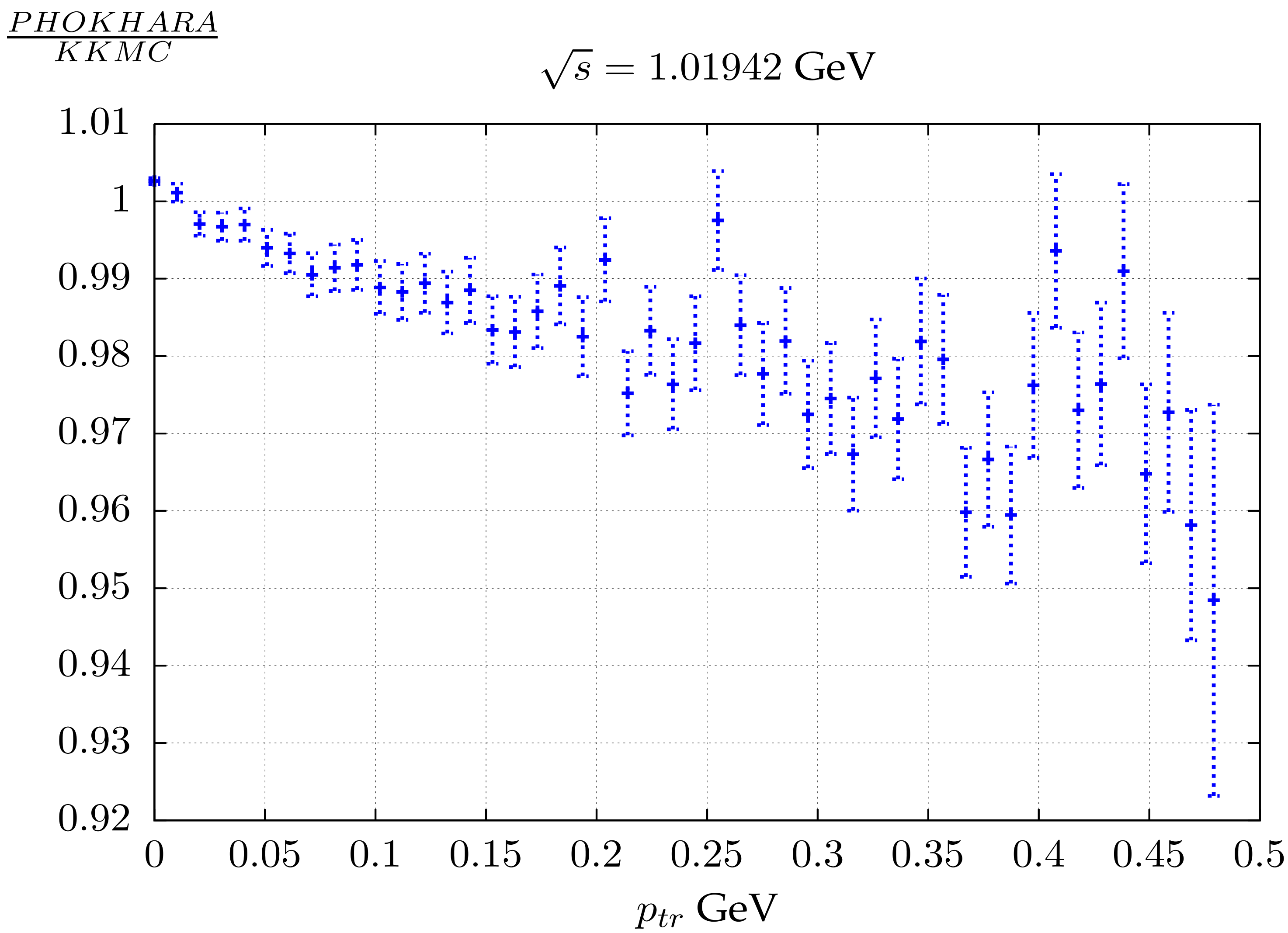
PHOKHARA 8.0 vs. MCGPJ



PHOKHARA 8.0 vs. KKMC 4.13



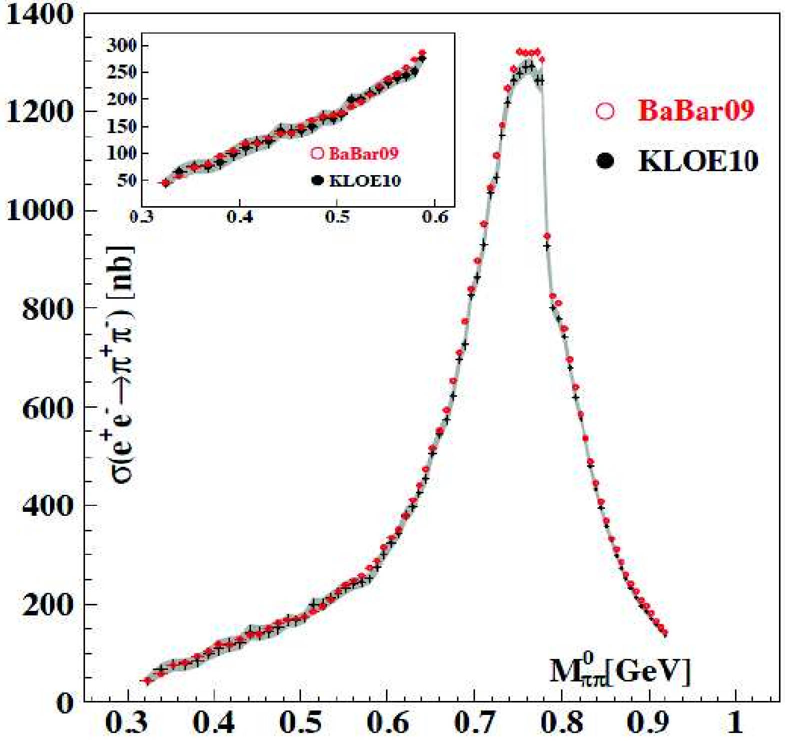
PHOKHARA 8.0 vs. KKMC 4.13

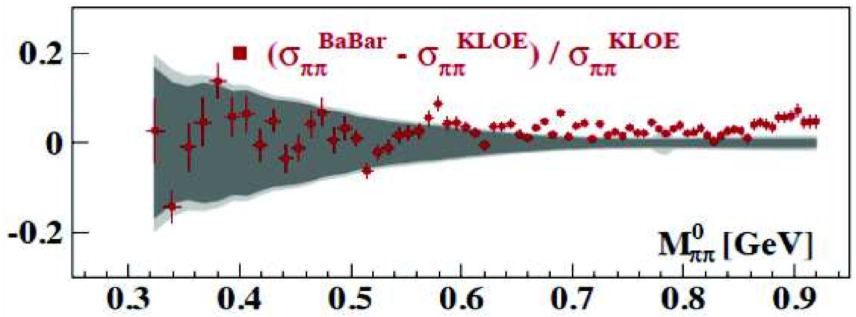


An outlook ...

Comparison of results: KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference

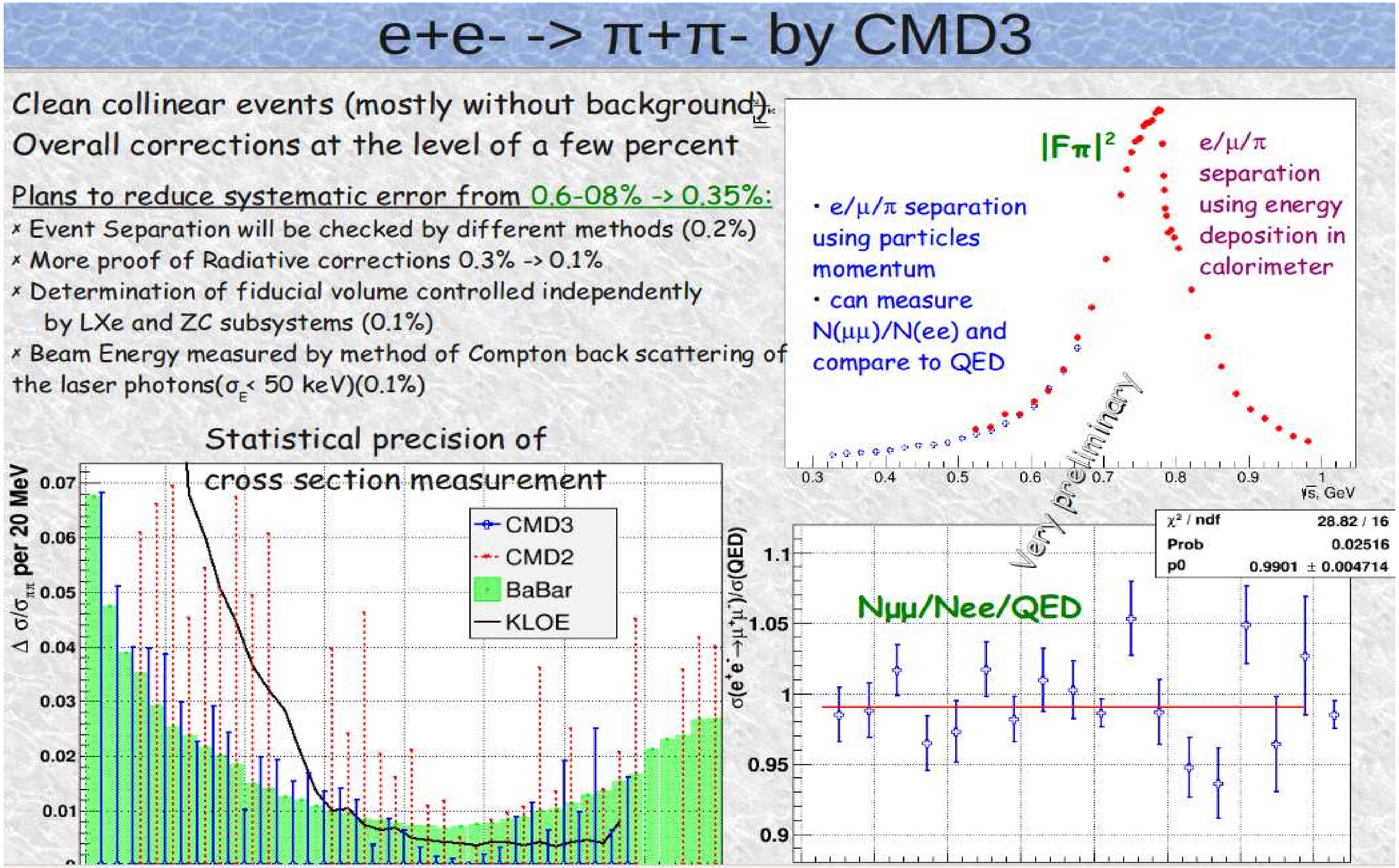




band: KLOE10 error

Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above

CMD-3 - F. Ignatov, EPS2013



BES-III - A. Denig, Trento 2013

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Run Planning

R measurement foreseen in 3 phases

Phase 1: **R in range 2 – 4.5 GeV**
~10^4 events per scan point, 3% systematic accuracy
→ improve $\alpha_{QED}(m_Z^2)$ by factor 2

Phase 2: **R in range 2 – 3 GeV, high statistics**
>10^5 events per scan point
→ Improve nucleon $|G_E|/|G_M|$ ratio, Nucleon FF

Phase 3: **Fine binning R ratio in charmonium region**
→ charmonium spectroscopy

An outlook

⇒ We also keep working

⇒ See talks by

Michał Gunia and Szymon Tracz