Towards a NNLO MC generator for low-energy e^+e^- to hadrons

LEVERHULME TRUST

STRONG 2020

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University of Liverpool and INFN-Pisa

European Physical Society
Conference on High Energy Physics
21-25 August 2023

Why we need Radiative Corrections

"Visible" cross section
$\sigma(e^+e^-(\gamma) \to X(\gamma))$

Here we correct for all detector effects

Adjust for radiative corrections (ISR, FSR)
$\sigma(e^+e^- \to X)$

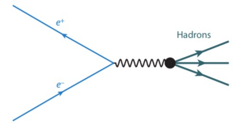
This one is used to get parameters of the resonances (mass, width,...)

Adjust for vacuum polarization and return back FSR
$\sigma^0(e^+e^- \to X(\gamma))$

This one is used in the a_μ integral

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

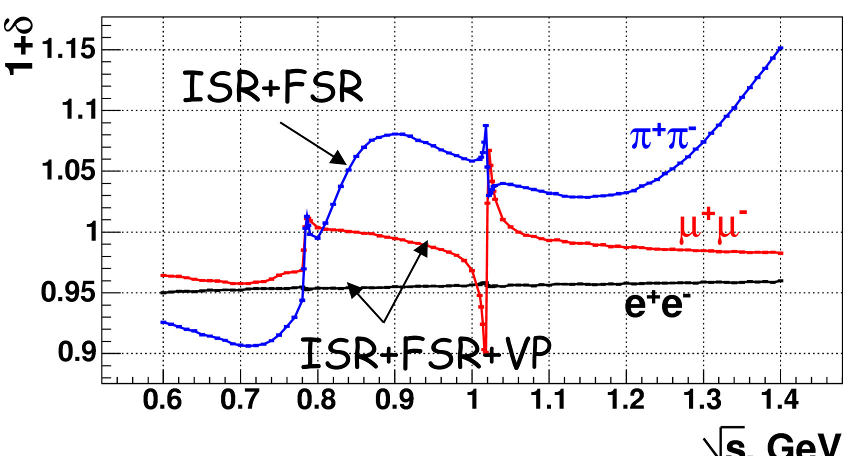
Radiative corrections for **energy scan**:



All modes except 2π

$$\sigma\left(e^+e^- \to H\right) = \frac{N_H - N_{bg}}{L \cdot \varepsilon \cdot (1+\delta)}$$

- Luminosity L is measured using Bhabha scattering at large angles
- Efficiency ε is calculated via Monte Carlo + corrections for imperfect detector
- Radiative correction δ accounts for ISR effects only



2π

$$|F_\pi|^2 = \frac{N_{2\pi}}{N_{ee}} \cdot \frac{\sigma_{ee} \cdot (1+\delta_{ee})}{\sigma_{2\pi}(\text{point-like } \pi) \cdot (1+\delta_{2\pi})}$$

- Ratio N(2π)/N(ee) is measured directly ⇒ detector inefficiencies are (partially) cancelled out
- Virtually no background
- Analysis does rely mostly on data
- Radiative corrections account for ISR and FSR effects
- Formfactor is measured to better precision than L (true VEPP2M; in VEPP2000 ~same precision)

Radiative corrections for ISR (KLOE)

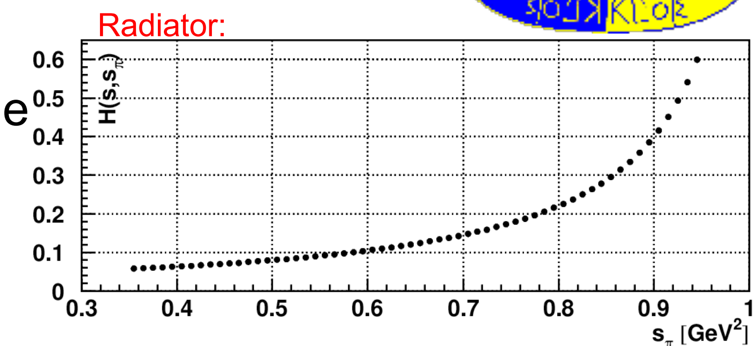
Radiator-Function $H(s,s_p)$ (ISR):

It cancels in the ratio to $\mu\mu\gamma$

- ISR-Process calculated at NLO-level *PHOKHARA* generator
  (H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

Precision: *0.5%*

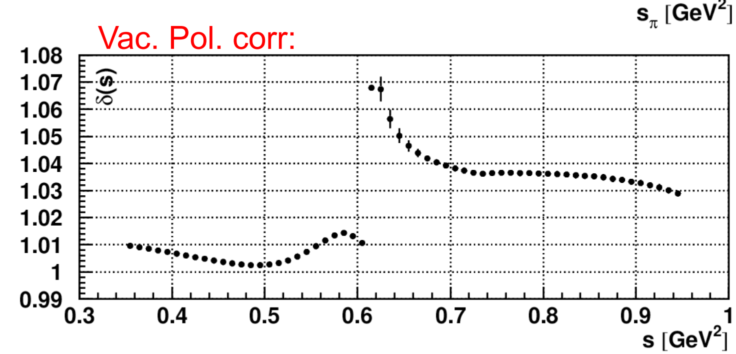
$$s \cdot \frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \times H(s,s_\pi)$$



Radiative Corrections:

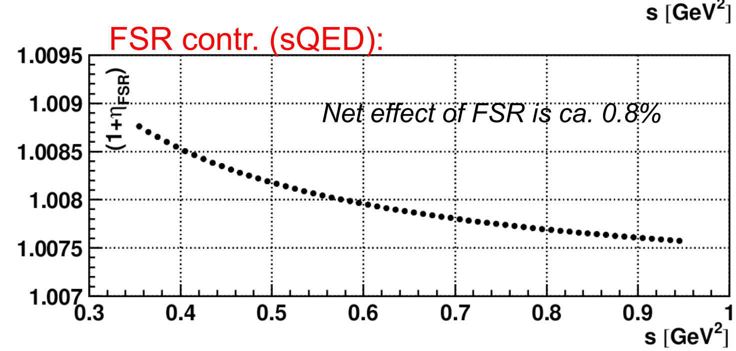
i) Bare Cross Section

divide by Vacuum Polarisation $d(s)=(a(s)/a(0))^2$



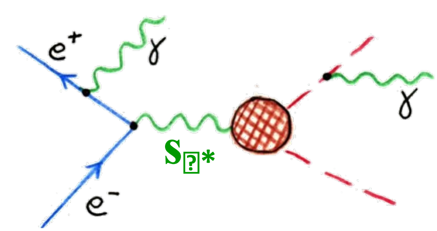
ii) FSR

Cross section s_{pp} must be incl. for FSR for use in the dispersion integral of a_m



FSR corrections have to be taken into account in the efficiency eval. (Acceptance, M_{Trk}) and in the mapping $s_\pi \rightarrow s_{\gamma*}$

(H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC33,2004)



$s_{?*} > s_p$

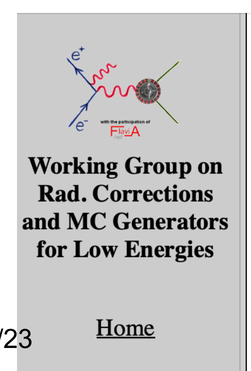
2006-2019:

Radio MonteCarLow: "Working Group on Radiative Corrections and MC Generators for Low Energies"

- An informal room and a valuable platform to exchange ideas
- Meetings with theorists and experimentalists sitting together.
- First meeting in Oct 2006. 20 meetings since then. More than 60 participants from more than 10 different countries. Last meeting on March 2019
- 2 WG coordinators (H. Czyz, G. Venanzoni)
- 7 Subgroups
- A first report in 2010.

http://www.lnf.infn.it/wg/sighad/

Web page:



Working Group on Rad. Corrections and MC Generators for Low Energies

The aim of this Working Group is to bring together theorists and experimentalists in order to discuss the current status of radiative corrections and Monte Carlo generators at low energies. These radiative corrections and MC generators are crucial for the measurement of the R-ratio (both with ISR and energy scan), as well as the determination of luminosity.

The Subjects covered:

- Monte Carlo generators for Luminosity
- Monte Carlo generators for e+e- into hadrons and leptons
- Monte Carlo generators for e+e- into hadrons and leptons plus photon (ISR)
- Monte Carlo generators for τ production and decays
- Hadronic Vacuum Polarization, $\Delta\alpha_{em}(Z0)$ and $(g-2)_{\mu}$
- Gamma-gamma physics
- FSR models and Transition Form Factors

Each of them has 2 convenors

UNIVERSITY OF LIVERPOOL

RADIO MONTECARLOW

Report from RMCWG: a common effort for RC and Monte Carlo tools

Eur. Phys. J. C (2010) 66: 585–686
DOI 10.1140/epjc/s10052-010-1251-4

THE EUROPEAN PHYSICAL JOURNAL C

Review

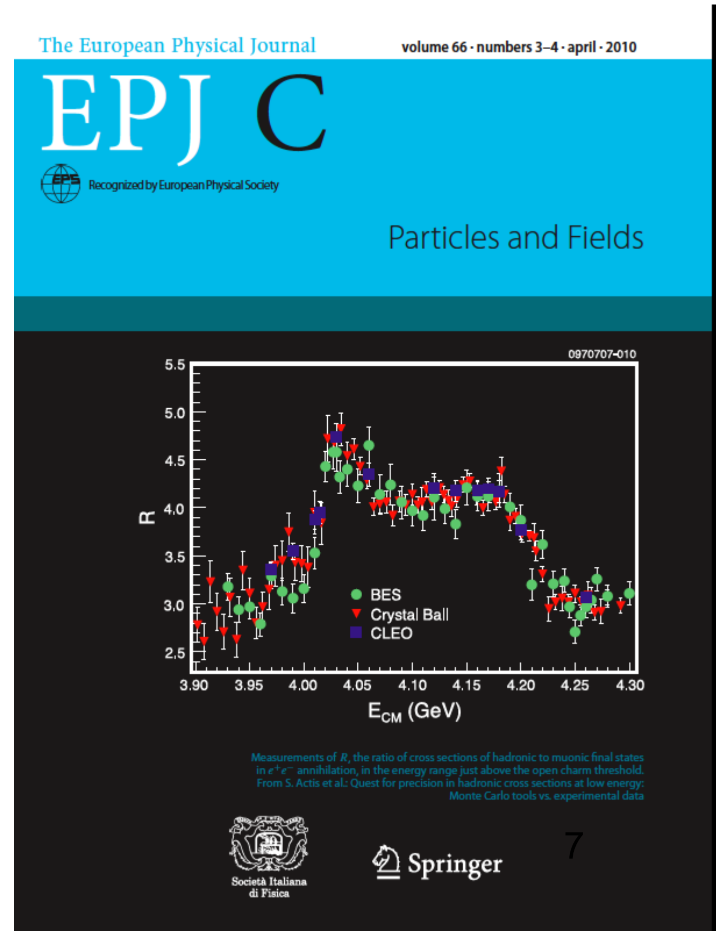
Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies

S. Actis[38], A. Arbuzov[9,e], G. Balossini[32,33], P. Beltrame[13], C. Bignamini[32,33], R. Bonciani[15], C.M. Carloni Calame[35], V. Cherepanov[25,26], M. Czakon[1], H. Czyż[19,a,f,i], A. Denig[22], S. Eidelman[25,26,g], G.V. Fedotovich[25,26,e], A. Ferroglia[23], J. Gluza[19], A. Grzelińska[8], M. Gunia[19], A. Hafner[22], F. Ignatov[25], S. Jadach[8], F. Jegerlehner[3,19,41], A. Kalinowski[29], W. Kluge[17], A. Korchin[20], J.H. Kühn[18], E.A. Kuraev[9], P. Lukin[25], P. Mastrolia[14], G. Montagna[32,33,b,d], S.E. Müller[22,f], F. Nguyen[34,d], O. Nicrosini[33], D. Nomura[36,h], G. Pakhlova[24], G. Pancheri[11], M. Passera[28], A. Penin[10], F. Piccinini[33], W. Płaczek[7], T. Przedzinski[6], E. Remiddi[4,5], T. Riemann[41], G. Rodrigo[37], P. Roig[27], O. Shekhovtsova[11], C.P. Shen[16], A.L. Sibidanov[25], T. Teubner[21,h], L. Trentadue[30,31], G. Venanzoni[11,c,i], J.J. van der Bij[12], P. Wang[2], B.F.L. Ward[39], Z. Was[8,g], M. Worek[40,19], C.Z. Yuan[2]

Eur. Phys. J. C. Volume 66, Issue 3 (2010), Page 585

(360 citations)



2020: Moving forward…

- New data/measurements from VEPP-2000, BaBar, Belle-II, BESIII with better quality and refined systematic errors
- New theoretical calculations and tools from LHC and MUonE* theory communities
- Discrepancy between lattice and dispersive approach for a_μ^{HLO}
- Discrepancy between CMD3 and previous measurements
- Radiative corrections and MC generators for e+e- → hadrons, leptons should aim at 0.1% uncertainty → **NNLO** calculation **needed**!
- Test of FSR model (BaBar using charge asymmetry; KLOE using FB asymmetry; FB asymmetry at CMD3)

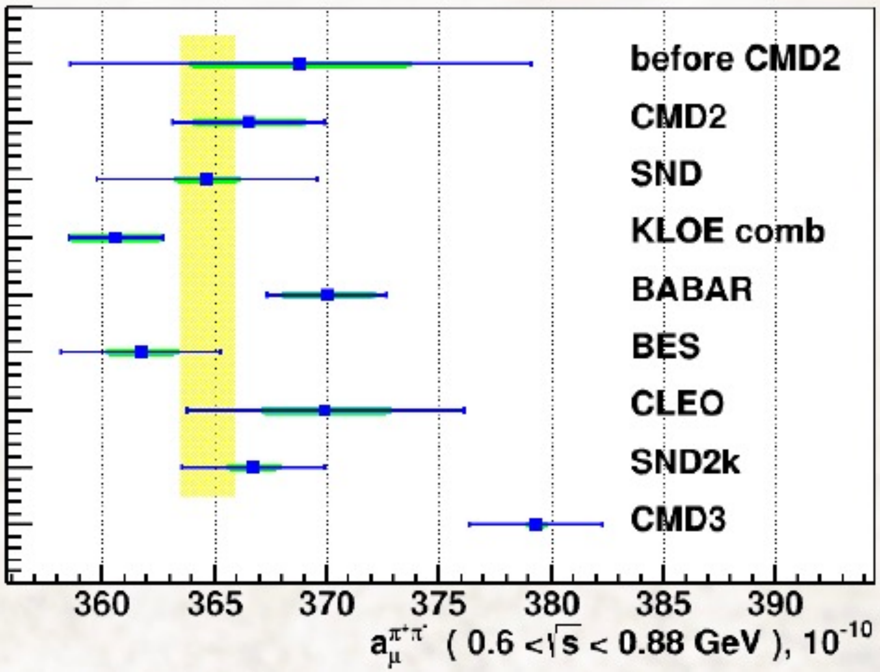
*see https://indico.desy.de/event/34916/contributions/147236, https://indico.desy.de/event/34916/contributions/147230

2020: Moving forward…

F. Ignatov et al. 2302.08834

$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty}\frac{\sigma_{e^+e^-\to\gamma^*\to hadrons}(s)K(s)}{s}ds$$

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



$0.6 < \sqrt{s} < 0.88$ GeV

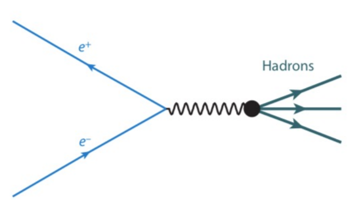
	$a_\mu^{\pi\pi,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0

RHO2013	380.06 ± 0.61 ± 3.64
RHO2018	379.30 ± 0.33 ± 2.62 $\times 10^{-10}$
Sum	379.35 ± 0.30 ± 2.95

Tensions between experiments could be (partly) due to approximate/missing RC's?

MC generators for exclusive channels (exact NLO + Higher Order terms in some approx)

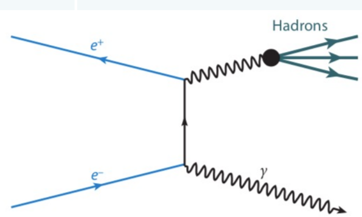
MC generator	Channel	Precision	Comment
MCGPJ (VEPP-2M, VEPP-2000)	$e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$	0.2%	photon jets along all particles (collinear Structure function) with exact NLO matrix elements
BabaYaga@NLO (KLOE, BaBar, BESIII)	$e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma$	0.1%	QED Parton Shower approach with exact NLO matrix elements
BHWIDE (LEP)	$e^+e^- \rightarrow e^+e^-$	(0.1%?)	Yennie-Frautschi-Suura (YFS) exponentiation method with exact NLO matrix elements
CARLOMAT	$e^+e^- \rightarrow$ hadrons	?	automatic computation of LO cross sections



MC generators for ISR

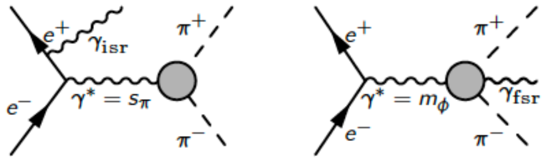
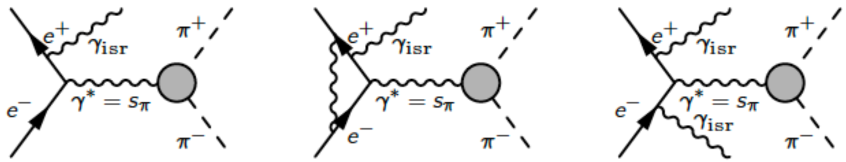
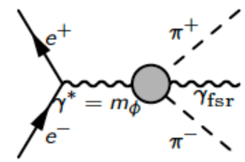
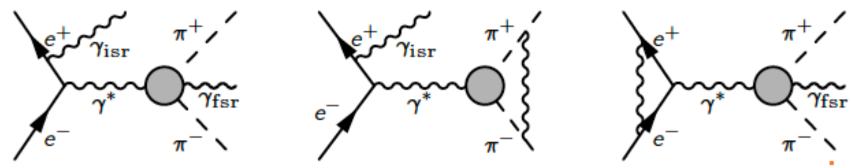
(from approximate to exact NLO)

MC generator	Channel	Precision	Comment
EVA (KLOE)	$e^+e^- \rightarrow \pi^+\pi^-\gamma$	O(%)	Tagged photon ISR at LO + Structure Function FSR: point-like pions
AFKQED (BaBar)	$e^+e^- \rightarrow \pi^+\pi^-\gamma$, …	depends on the event selection (can be as good as Phokhara)	ISR at LO +Structure Function
PHOKHARA (KLOE, BaBar BESIII)	$e^+e^- \rightarrow \pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$, $4\pi\gamma$, …	0.5%	ISR and FSR(sQED+Form Factor) at NLO
KKMC	$e^+e^- \rightarrow f^+f^-(n)\gamma$	High accuracy only for muon pairs	YFS exponentiation for soft photons + hard part and sub-leading terms in some approximation

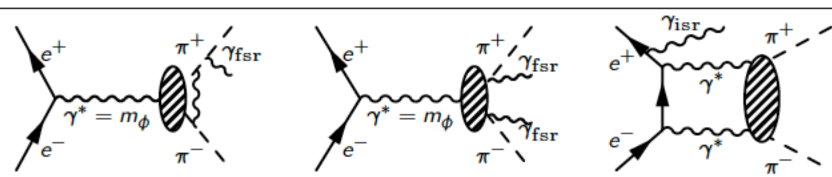


Development of PHOKHARA versions (2004-’19)

ISR and FSR contributions to $\pi\pi$ channel in PHOKHARA4

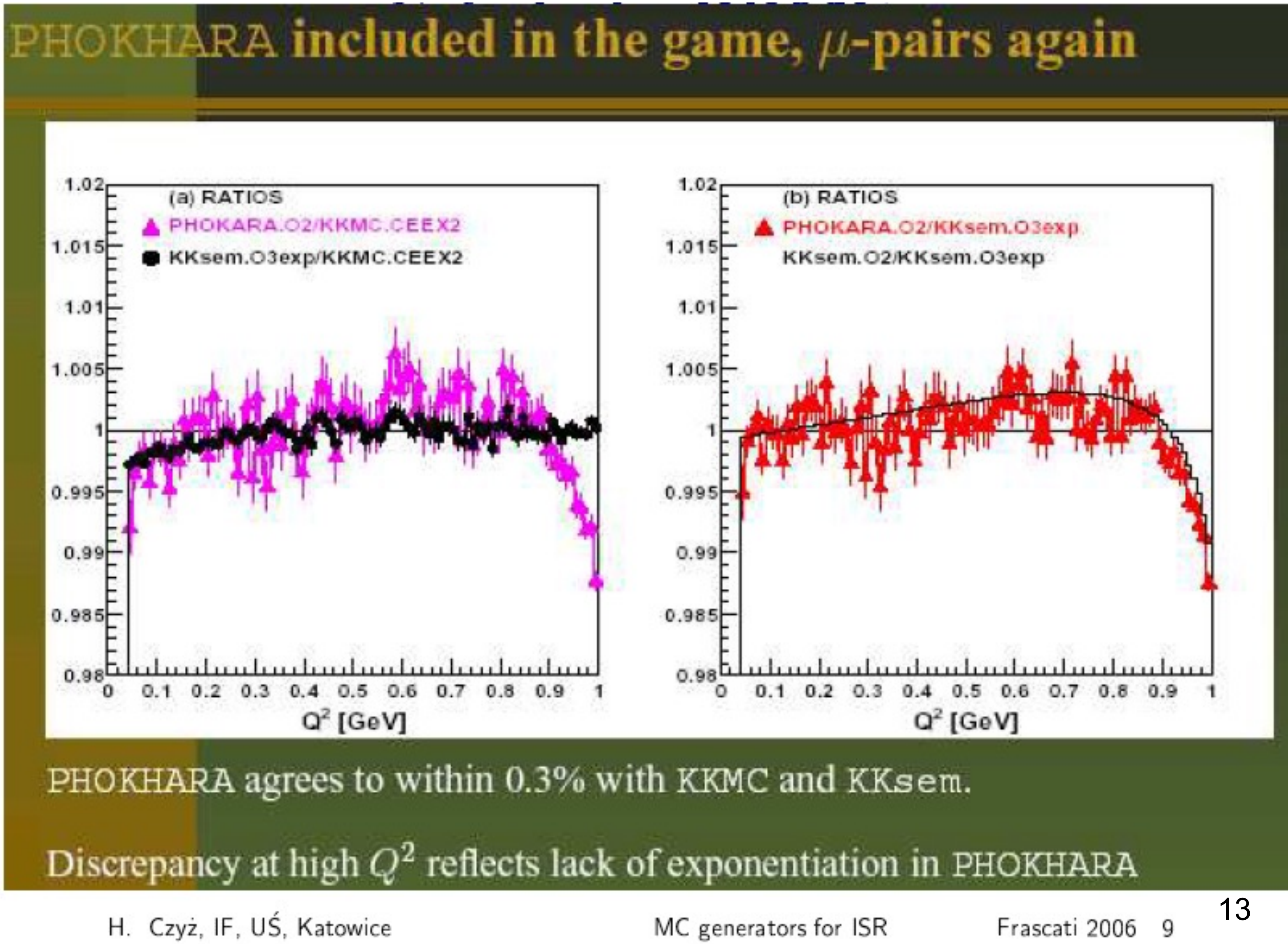
LO (fsr = 1, nlo = 0)		
ISRNLO (fsr = 0, nlo = 1)		
IFSLO (fsr = 1, nlo = 1)	ISRNLO +	
IFSNLO (fsr = 1, nlo = 1, fsrnlo = 1)	IFSLO +	

PHOKHARA10 contains complete NLO radiative corrections to the reaction $e^+e^- \to \pi^+\pi^-\gamma$ (see arXiv:1903.10197 [hep-ph])

compl. NLO (fsr=1, nlo=1 nlo2=1, fsrnlo=1)	

TUNED COMPARISON are important!

PHOKHARA vs KKMC $\mu\mu\gamma$



"Tuned" comparisons are essential!

Theoretical accuracies of these generators were estimated, whenever possible, by evaluating missing higher-order contributions. From this point of view, the great progress in the calculation of two-loop corrections to the Bhabha scattering cross section was essential to establish the high theoretical accuracy of the existing generators for the luminosity measurement. However, usually only analytical or semi-analytical estimates of missing terms exist which don't take into account realistic experimental cuts. In addition, MC event generators include different parameterisations for the VP which affect the prediction (and the precision) of the cross sections and also the RC are usually implemented differently.

Eur. Phys. J. C. Volume 66, Issue 3 (2010), Page 585

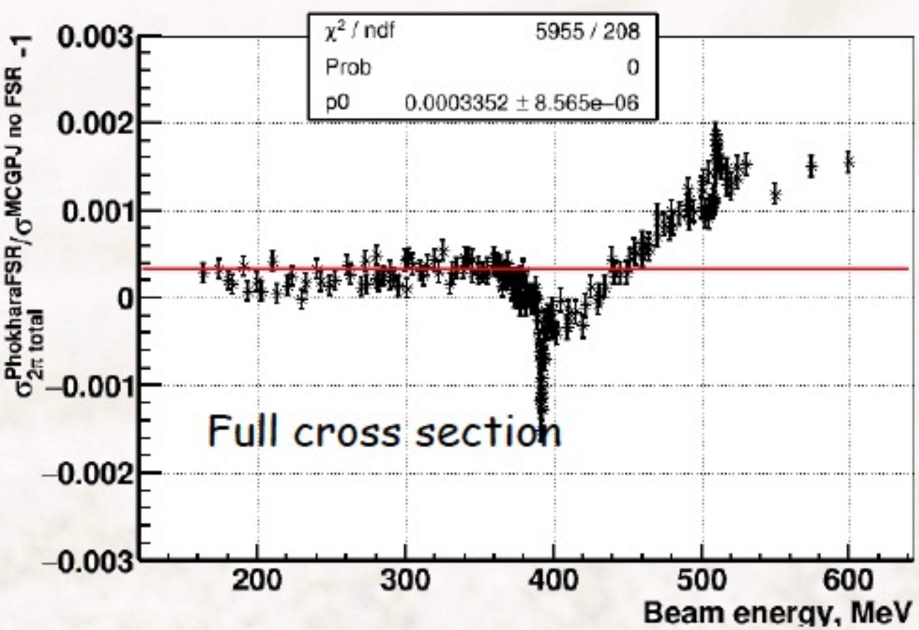
PHOKHARA vs MCGPJ

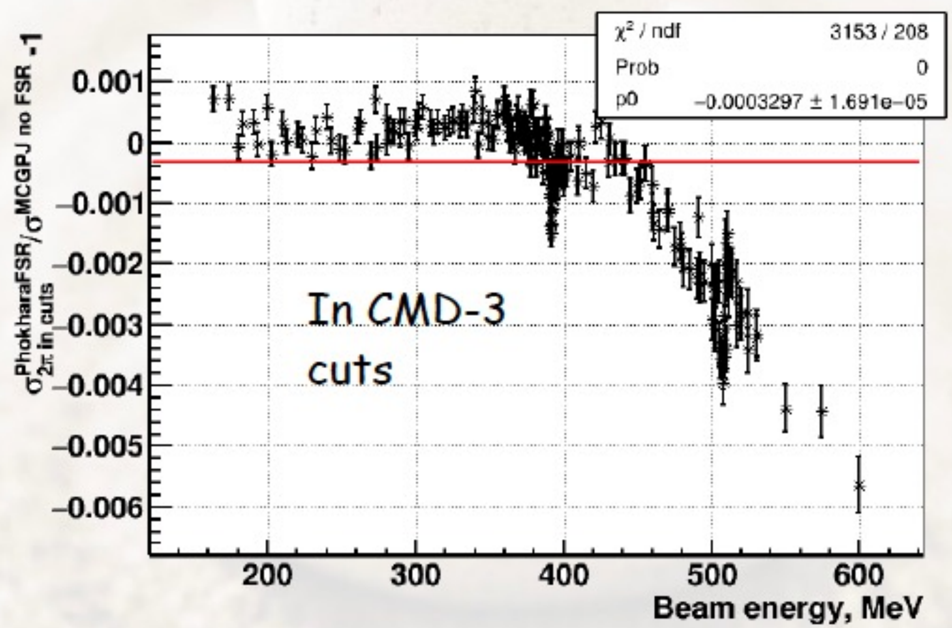
MCGPJ/Phokara

Phokara 10.0: For scan mode doesn't have FSR

CMD-3 cuts:
$|\Delta\varphi|<0.15$ rad, $|\Delta\theta|<0.25$ rad
$1<(\theta^{+} + \pi - \theta^{-})/2<\pi-1$ rad
$P^{+-} > 0.45\ E_{beam}$

ISR and Fπ cross check MCGPJ with FSR off,
Phokara 10 with same Fπ as in MCGPJ





Cross section is consistent at ~0.05% at ρ-peak
(at phi ~ 0.25%)

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TUNED COMPARISON

BabaYaga@NLO vs MCGPJ

$N_{\mu\mu}/N_{ee}$ $N_{\pi\pi}/N_{ee}$

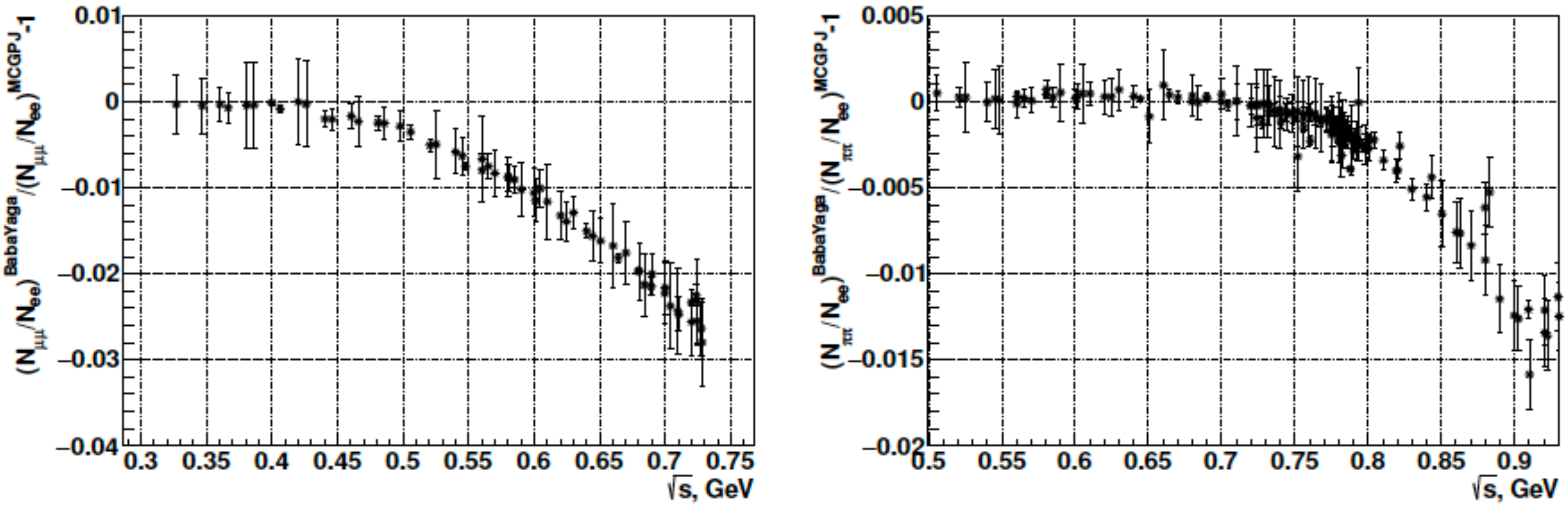
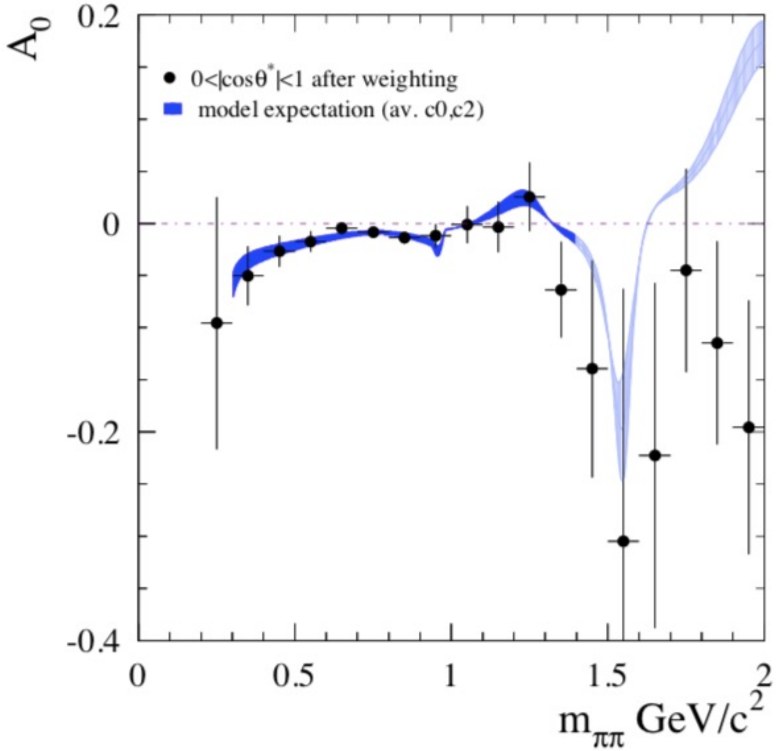


Figure 20: The relative effect on the $N_{\mu\mu}/N_{ee}$ (left) and on the $N_{\pi\pi}/N_{ee}$ (right) ratios from using the $\mu^+\mu^+$, e^+e^- momentum spectra from either the BaBaYaga@NLO or the MCGPJ generators as input for the event separation based on momentum information.

F. Ignatov et al. [2302.08834](2302.08834)

Test of FSR model for pions

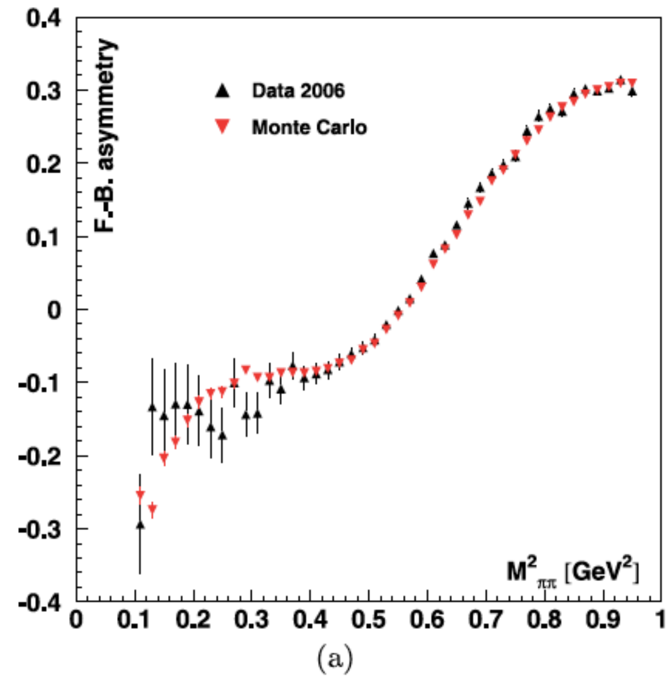
Charge asymmetry



BaBar vs AfkQed
PRD92 (2015) 7, 072015

Quark model for FSR by pions

F.B. asymmetry



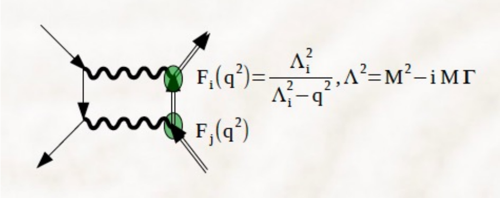
KLOE vs Phokhara
PLB634 (2006) 148
EPJC 66 (2010) 585

sQED model (pointlike pions) for FSR

Effect from FSR NLO can be as large as 5-10% at low $m_{\pi\pi}$ (EPJC33(2004) 333)

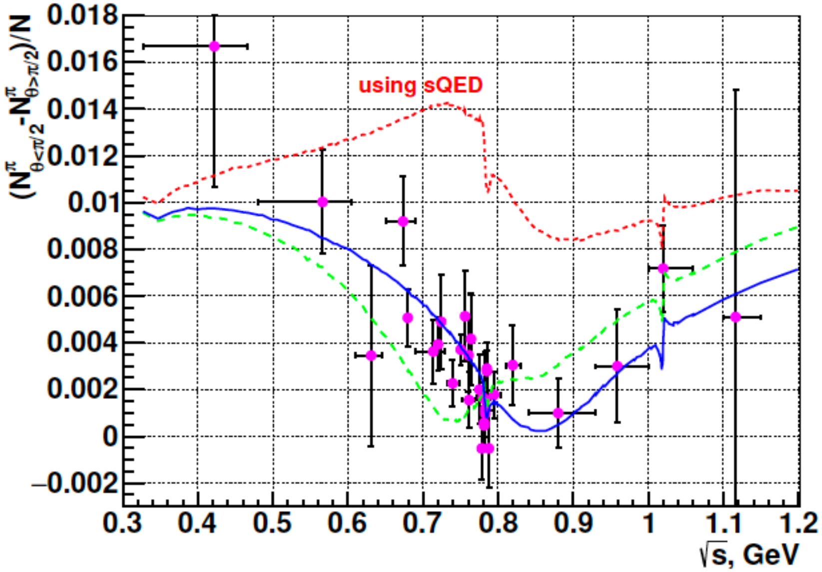
Test of FSR model for pions: CMD3

Inclusion of double Photon exchange

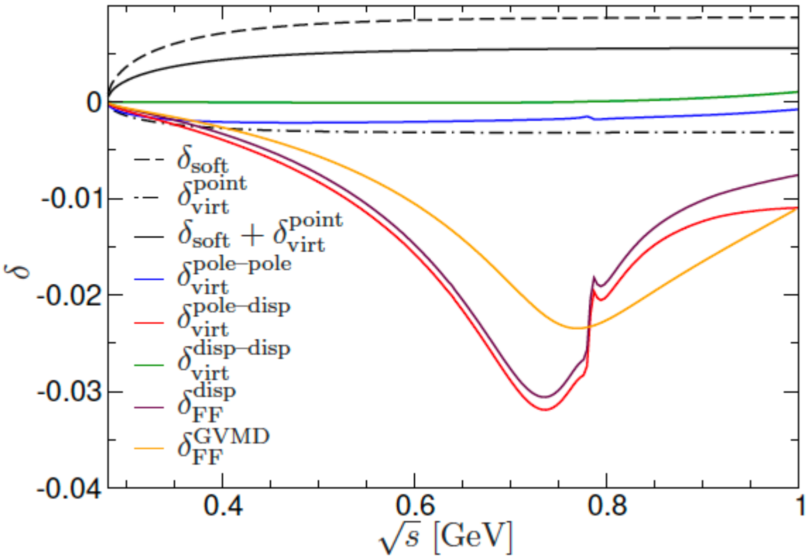


$$A = \frac{N_{\theta<\pi/2} - N_{\theta>\pi/2}}{N_{\theta<\pi/2} + N_{\theta>\pi/2}}.$$

GVMD model



Dispersive formalism



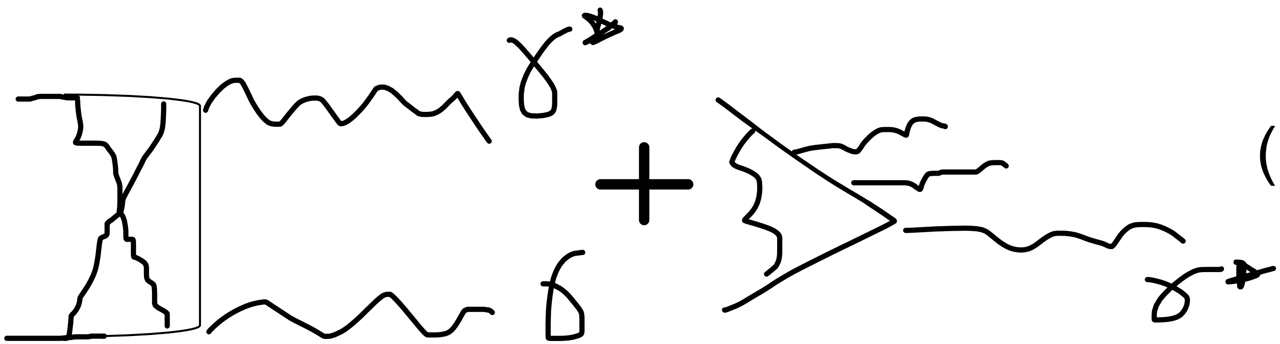
F. Ignatov, R. N. Lee

Phys. Lett. B 833 (2022) 137283

G. Colangelo *et al.*

JHEP 08 (2022) 295

Towards NNLO MC generator ….



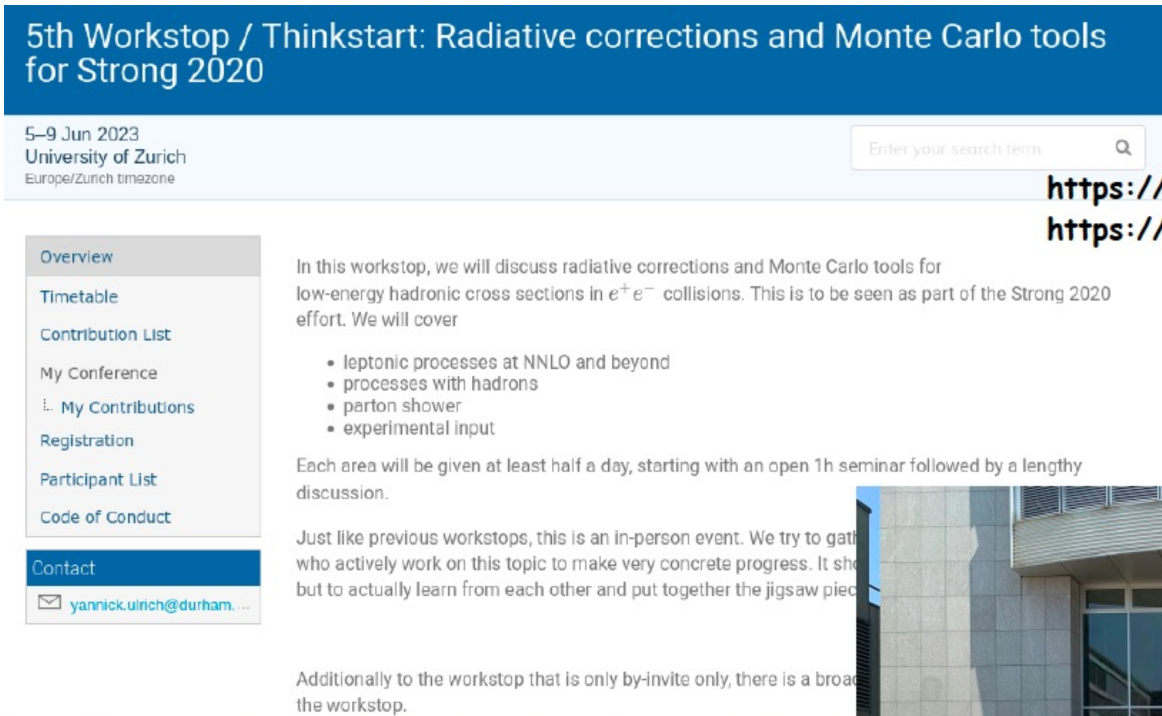
(+ others…)

- STRONG2020 (Virtual) meeting: 24-26 November 2021 (https://agenda.infn.it/event/28089/)
- N^3LO kick-off workstop/thinkstart 3-5 August 2022, IPPP Durham (https://conference.ippp.dur.ac.uk/event/1104/)
- WorkStop on "**Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collision**" on **05-09 June 2023** at the University of Zurich

(Strong interplay with MUonE theory activities)

Moving forward…

- **WorkStop** on "**Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collision**" **05-09 June 2023,** University of Zurich (LOC: A. Signer, G. Stagnitto, Y. Ulrich)



5th Workstop / Thinkstart: Radiative corrections and Monte Carlo tools for Strong 2020

5–9 Jun 2023
University of Zurich
Europe/Zurich timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- My Conference
  - My Contributions
- Registration
- Participant List
- Code of Conduct

Contact

yannick.ulrich@durham....

In this workstop, we will discuss radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions. This is to be seen as part of the Strong 2020 effort. We will cover

- leptonic processes at NNLO and beyond
- processes with hadrons
- parton shower
- experimental input

Each area will be given at least half a day, starting with an open 1h seminar followed by a lengthy discussion.

Just like previous workstops, this is an in-person event. We try to gat
who actively work on this topic to make very concrete progress. It sh
but to actually learn from each other and put together the jigsaw piec

Additionally to the workstop that is only by-invite only, there is a broa
the workstop.

https://indico.psi.ch/event/13707/
https://indico.psi.ch/event/13708/

The effort to bring forward MC tools precision!
Towards NNLO (and above) precision
Can help mitigate questions to theoretical parts of ISR & scan measurements

- Work packages:

- WP1: Leptonic processes at NNLO [T. Engel, W. Torres Bobadilla]
- WP2: Form factor contributions at N3LO [M. Fael, Y. Ulrich]
- WP3: Processes with hadrons [P. Stoffer, T. Teubner]
- WP4: Parton showers [C. M. Carloni Calame, M. Schonherr, A. Price]
- WP5: Experimental input [BaBar, BelleII, BESIII, KLOE, Novosibirsk]

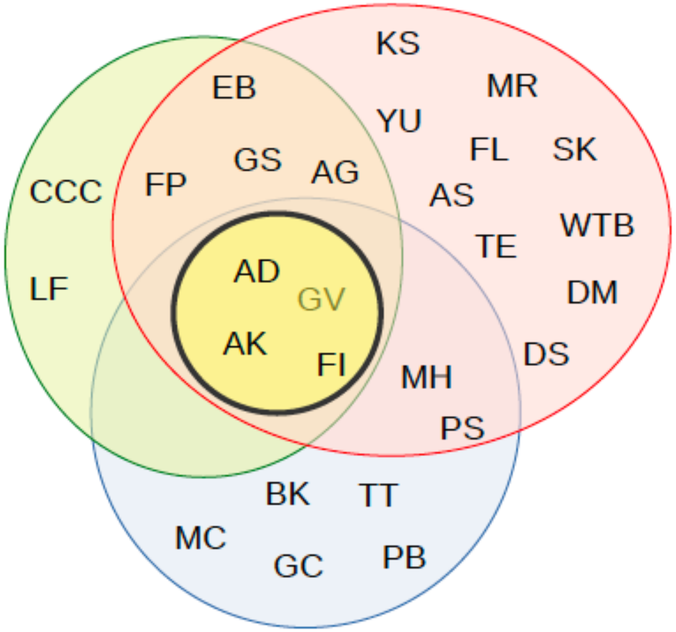
Teams started to work around October 2022, met three days in June in Zurich

Aim to write a report by Winter 2023 (authors not restricted to participants to the WorkStop)

5th WorkStop

Team: P. Beltrame, E. Budassi, C. Carloni Calame, G. Colangelo, M. Cottini, A. Driutti, T. Engel, L. Flower, A. Gurgone, M. Hoferichter, F. Ignatov, S. Kollatzsch, B. Kubis, A. Kupsc, F. Lange, D. Moreno, F. Piccinini, M. Rocco, K. Schönwald, A. Signer, G. Stagnitto, D. Stöckinger, P. Stoffer, T. Teubner, W. Torres Bobadilla, Y. Ulrich, G. Venanzoni

WP1:	QED for leptons at NNLO
WP2:	Form factor contributions at N^3LO
WP3:	Processes with hadrons
WP4:	Parton showers
WP5:	Experimental input



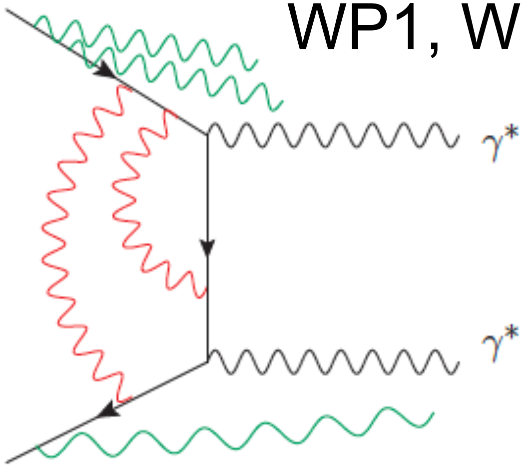
A. Signer, Jun 2023 – p.5/16

Workstop activities…

(drawings from A. Signer)

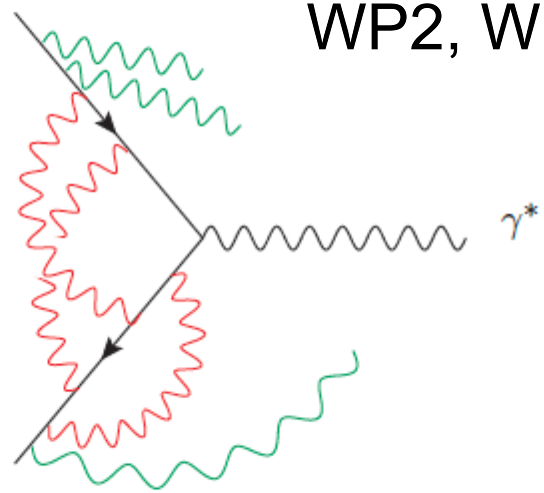
Buliding block $e^+ e^- \to \gamma^* \gamma^*$

WP1, WP4



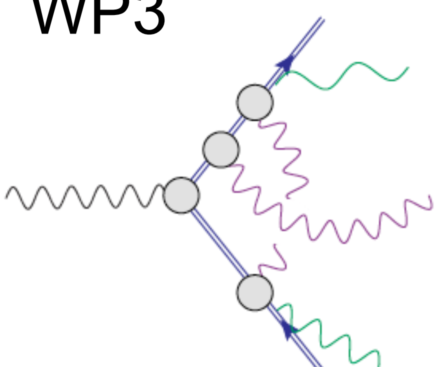
Buliding block $e^+ e^- \to \gamma^*$

WP2, WP4



Buliding block $\gamma^* \to \pi^+ \pi^-$

WP3



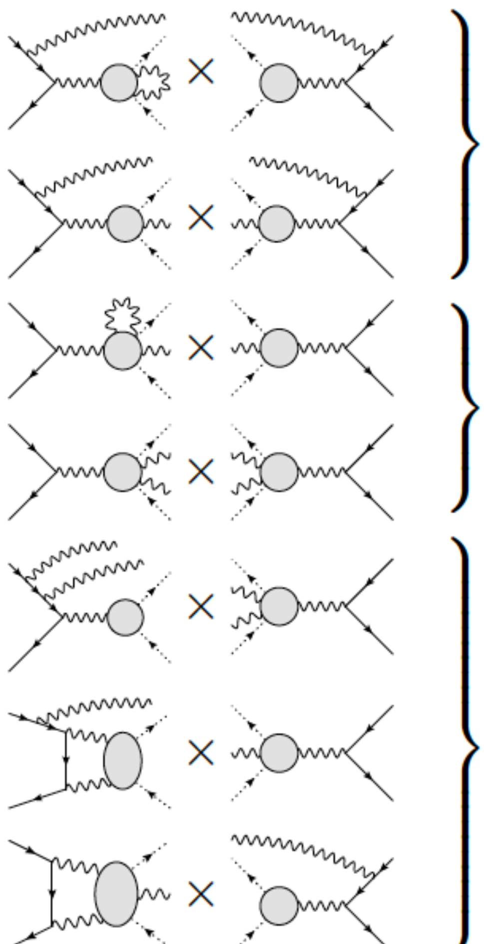
WP5:
Input from experiments

BABAR, KLOE, BESIII, Belle II

CMD3, SND, CMD2, CLEO,….

⑤ Relevant improvements to $e^+e^- \to$ hadrons?

ISR experiments: NLO (omitting pure QED corrections to LO)



PHOKHARA: sQED + resonance approximations
dispersive approach by Colangelo et al.

contained in PHOKHARA
pure FSR: sufficiently suppressed by experimental cuts?

???
PHOKHARA: sQED, multiplied by form factors *outside* loop
ISR–FSR interference
potential red flag identified during WorkStop

Status and plans for MCs

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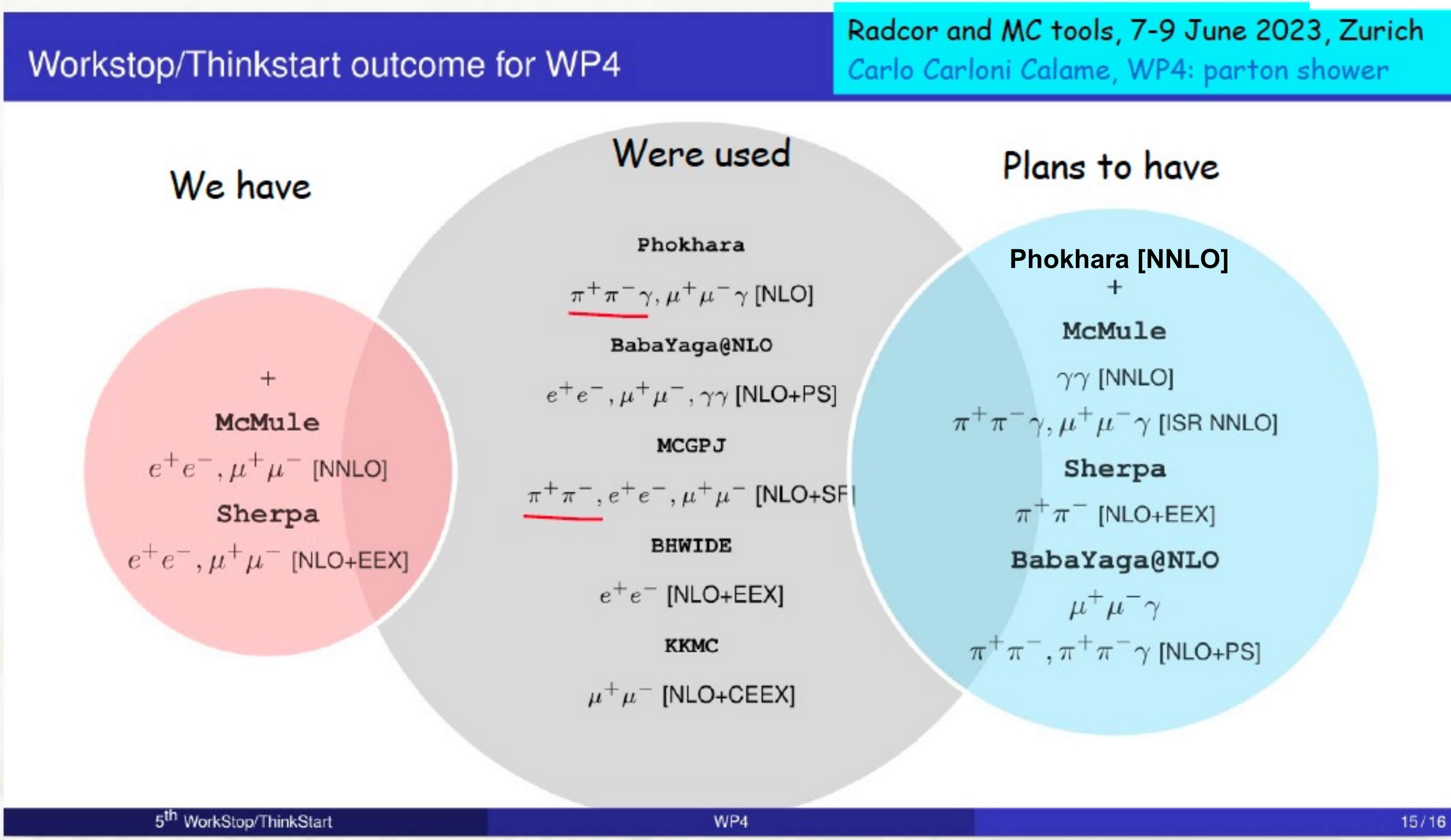
INFN Istituto Nazionale di Fisica Nucleare

Radcor and MC tools, 7-9 June 2023, Zurich
Carlo Carloni Calame, WP4: parton shower



Unfortunately until now, only single precise generators are available for e+e- → π+π-(γ) process:

For scan experiment: MCGPJ with declared 0.2% precision

For ISR: Phokhara with 0.5% precision

Conclusions

- A lot of effort in the last 20 years to improve MC generators and RC to e^+e^- into leptons/hadrons at low energy :
  - Accuracy between 0.2 and 0.5%
- New data and improved evaluation of a_μ^{HLO} requires improvement on MC generators at ~0.1% → **NNLO needed!**

- **WorkStop** on "**Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collision**" **05-09 June 2023**
  - ➢Aim to write a report by Winter 2023 (authors not restricted to participants to the WorkStop)
  - ➢Strong synergy with MuonE theoretical activity

- Goal: NNLO MC for exclusive channels (e^+e^-, $\mu^+\mu^-$, $\pi^+\pi$) and ISR ($\pi^+\pi\gamma$, $\mu^+\mu^-\gamma$) by 2024/25

If you are interested to contribute you are welcome!

END

Going forward: Strong2020: a database for e^+e^- into hadrons

- European project (http://www.strong-2020.eu)
- WP21 — JRA3 PrecisionSM: "*Hadron Physics for Precision Tests of the Standard Model*"
- Goal: combine theory and experiment for precision tests SM & BSM
- **Task 2: Hadronic Effects in Precision Tests of the electromagnetic sector of the Standard Model: Muon g-2:**
  - 2.1 Hadronic Vacuum Polarization from spacelike and timelike processes
  - 2.2 Hadronic Light-by-Light Scattering Contribution to $(g-2)\mu$
- Deliverable for Task 2.1:
  - Annotated database for low-energy hadronic cross sections in e+e- collisions. https://precision-sm.github.io

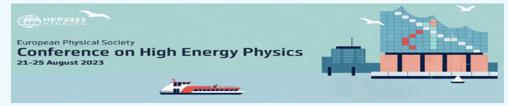
A. Driutti, L. Cotrozzi, F. Ignatov, A. Kupsc, A. Lusiani, S. Mueller, G.V.

See poster

PrecisionSM: an annotated database for low-energy $e^+e^- \to$ hadrons

Anna Driutti [a], Graziano Venanzoni [b]
on behalf of the Strong2020 group.

[a] University and INFN Pisa (Italy)
[b] University of Liverpool (UK) and INFN Pisa (Italy)



Abstract

PrecisionSM is an annotated database for low-energy e^+e^- into hadrons developed within the European Project STRONG2020 [1]. It relies on a custom web site (https://precision-sm.github.io) to list the measurements with links to their HEPData (https://www.hepdata.net/) location together with examples of tools to elaborate on them. The database contains information about the datasets, the systematic uncertainties and the treatment of Radiative Corrections. Such information is important for performing precision tests of the Standard Model, in the anomalous magnetic moment of the muon or in the electroweak sector where a limiting factor is the accuracy on the effective electromagnetic coupling at the Z boson mass.

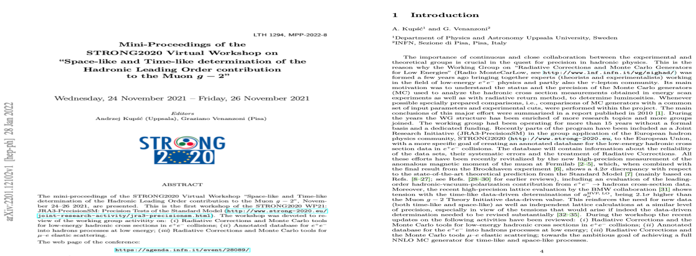
The Strong2020 Project

- EU project that aims to **study strong interactions** combining knowledge from many frontiers:

LOW ENERGY · HIGH ENERGY · INSTRUMENTATION · INFRASTRUCTURES

PrecisionSM: "Hadron Physics for Precision Tests of the Standard Model"

- Task within the Strong2020 project with the goal of:
  - combining theory and experiment for Standard Model and Beyond precision tests, **Recent Working Group Report** [2]



LTH 1294, MPP-2022-8

Mini-Proceedings of the STRONG2020 Virtual Workshop on "Space-like and Time-like determination of the Hadronic Leading Order contribution to the Muon $g-2$"

Wednesday, 24 November 2021 – Friday, 26 November 2021

Editors
Andrzej Kupść (Uppsala), Graziano Venanzoni (Pisa)

arXiv:2201.12102v1 [hep-ph] 28 Jan 2022

ABSTRACT

The mini-proceedings of the STRONG2020 Virtual Workshop "Space-like and Time-like determination of the Hadronic Leading Order contribution to the Muon $g-2$", November 24–26 2021, are presented. This is the first workshop of the STRONG2020 WP21: JRA3-PrecisionSM: Precision Tests of the Standard Model (http://www.strong-2020.eu/joint-research-activity/jra3-precisionsm.html). The workshop was devoted to review of the working group activitity on: (*i*) Radiative Corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions; (*ii*) Annotated database for e^+e^- into hadrons processes at low energy; (*iii*) Radiative Corrections and Monte Carlo tools for μ–e elastic scattering.

The web page of the conference:

https://agenda.infn.it/event/28089/

contains the presentations.

1 Introduction

A. Kupść[1] and G. Venanzoni[2]

[1] Department of Physics and Astronomy Uppsala University, Sweden
[2] INFN, Sezione di Pisa, Pisa, Italy

The importance of continuous and close collaboration between the experimental and theoretical groups is crucial in the quest for precision in hadronic physics. This is the reason why the Working Group on "Radiative Corrections and Monte Carlo Generators for Low Energies" (Radio MonteCarLow, see http://www.lnf.infn.it/wg/sighad/) was formed a few years ago bringing together experts (theorists and experimentalists) working in the field of low-energy e^+e^- physics and partly also the τ-lepton community. Its main motivation was to understand the status and the precision of the Monte Carlo generators (MC) used to analyze the hadronic cross section measurements obtained in energy scan experiments as well as with radiative return method, to determine luminosities. Whenever possible specially prepared comparisons, i.e., comparisons of MC generators with a common set of input parameters and experimental cuts, were performed within the project. The main conclusions of this major effort were summarized in a report published in 2010 [1]. During the years the WG structure has been enriched of more research topics and more groups joined. The working group had been operating for more than 15 years without a formal basis and a dedicated funding. Recently parts of the program have been included as a Joint Research Initiative (JRA3-PrecisionSM) in the group application of the European hadron physics community, STRONG2020 (http://www.strong-2020.eu), to the European Union, with a more specific goal of creating an annotated database for the low-energy hadronic cross section data in e^+e^- collisions. The database will contain information about the reliability of the data sets, their systematic errors and the treatment of Radiative Corrections. All these efforts have been recently revitalized by the new high-precision measurement of the anomalous magnetic moment of the muon at Fermilab [2–5], which, when combined with the final result from the Brookhaven experiment [6], shows a 4.2σ discrepancy with respect to the state-of-the-art theoretical prediction from the Standard Model [7] (mainly based on Refs. [8–27]; see Refs. [28–30] for earlier reviews), including an evaluation of the leading-order hadronic-vacuum-polarization contribution from $e^+e^- \to$ hadrons cross-section data. Moreover, the recent high-precision lattice evaluation by the BMW collaboration [31] shows tension with the time-like data-driven determinations of $a_\mu^{\mathrm{HVP,\,LO}}$, being 2.1$\sigma$ higher than the Muon $g-2$ Theory Initiative data-driven value. This reinforces the need for new data (both time-like and space-like) as well as independent lattice calculations at a similar level of precision, especially in view of the tensions that would arise if indeed the data-driven determination needed to be revised substantially [32–35]. During the workshop the recent updates on the following activities have been reviewed: (*i*) Radiative Corrections and the Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions; (*ii*) Annotated database for the e^+e^- into hadrons processes at low energy; (*iii*) Radiative Corrections and the Monte Carlo tools μ–e elastic scattering; towards the ambitious goal of achieving a full NNLO MC generator for time-like and space-like processes.

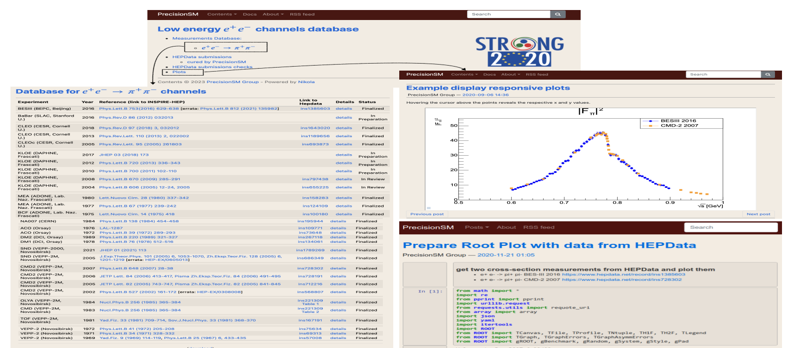
4

$\to$ Topics:

1. R measurement
2. Radiative Corrections and Monte Carlo generators for time-like processes
3. Radiative Corrections and Monte Carlo generators for space-like processes

  - constructing the annotated **Strong2020 Precision SM DataBase** for low-energy cross sections in $e^+e^- \to hadronic$, which includes:
    1. uploading in the public repository HEPData [3] all measurements from all experiments
    2. cataloguing the measurements in the **PrecisionDB Website** [https://precision-sm.github.io]
       - it contains also examples on how to read HEPData measurements and prepare responsive plots

$\to$ At present $e^+e^- \to \pi^+\pi^-$ measurements, important for the calculation of the Muon $g-2$ theoretical value, are catalogued.



Experiment	Year	Reference (link to INSPIRE-HEP)	Link to Hepdata	Details	Status
BESIII (BEPC, Beijing)	2016	Phys.Lett.B 753(2016) 629-638 [errata: Phys.Lett.B 812 (2021) 135982]	ins1385603	details	Finalized
BaBar (SLAC, Stanford U.)	2016	Phys.Rev.D 86 (2012) 032013		details	In Preparation
CLEO (CESR, Cornell U.)	2018	Phys.Rev.D 97 (2018) 3, 032012	ins1643020	details	Finalized
CLEO (CESR, Cornell U.)	2013	Phys.Rev.Lett. 110 (2013) 2, 022002	ins1189656	details	Finalized
CLEOc (CESR, Cornell U.)	2005	Phys.Rev.Lett. 95 (2005) 261803	ins693873	details	Finalized
KLOE (DAPHNE, Frascati)	2017	JHEP 03 (2018) 173		details	In Preparation
KLOE (DAPHNE, Frascati)	2012	Phys.Lett.B 720 (2013) 336-343		details	In Preparation
KLOE (DAPHNE, Frascati)	2010	Phys.Lett.B 700 (2011) 102-110		details	In Preparation
KLOE (DAPHNE, Frascati)	2008	Phys.Lett.B 670 (2009) 285-291	ins797438	details	In Review
KLOE (DAPHNE, Frascati)	2004	Phys.Lett.B 606 (2005) 12-24, 2005	ins655225	details	In Review
MEA (ADONE, Lab. Naz. Frascati)	1980	Lett.Nuovo Cim. 28 (1980) 337-342	ins158283	details	Finalized
MEA (ADONE, Lab. Naz. Frascati)	1977	Phys.Lett.B 67 (1977) 239-242	ins124109	details	Finalized
BCF (ADONE, Lab. Naz. Frascati)	1975	Lett.Nuovo Cim. 14 (1975) 418	ins100180	details	Finalized
NA007 (CERN)	1984	Phys.Lett.B 138 (1984) 454-458	ins195944	details	Finalized
ACO (Orsay)	1976	LAL-1287	ins109771	details	Finalized
ACO (Orsay)	1972	Phys.Lett.B 39 (1972) 289-293	ins73648	details	Finalized
DM2 (DCI, Orsay)	1989	Phys.Lett.B 220 (1989) 321-327	ins267118	details	Finalized
DM1 (DCI, Orsay)	1978	Phys.Lett.B 76 (1978) 512-516	ins134061	details	Finalized
SND (VEPP-2000, Novosibirsk)	2021	JHEP 01 (2021) 113	ins1789269	details	Finalized
SND (VEPP-2M, Novosibirsk)	2005	J.Exp.Theor.Phys. 101 (2005) 6, 1053-1070, Zh.Eksp.Teor.Fiz. 128 (2005) 6, 1201-1219 [errata: HEP-EX/0605013]	ins686349	details	Finalized
CMD2 (VEPP-2M, Novosibirsk)	2007	Phys.Lett.B 648 (2007) 28-38	ins728302	details	Finalized
CMD2 (VEPP-2M, Novosibirsk)	2006	JETP Lett. 84 (2006) 413-417, Pisma Zh.Eksp.Teor.Fiz. 84 (2006) 491-495	ins728191	details	Finalized
CMD2 (VEPP-2M, Novosibirsk)	2005	JETP Lett. 82 (2005) 743-747, Pisma Zh.Eksp.Teor.Fiz. 82 (2005) 841-845	ins712216	details	Finalized
CMD2 (VEPP-2M, Novosibirsk)	2002	Phys.Lett.B 527 (2002) 161-172 [errata: HEP-EX/0308008]	ins568807	details	Finalized
OLYA (VEPP-2M, Novosibirsk)	1984	Nucl.Phys.B 256 (1985) 365-384	ins221309 Table 1	details	Finalized
CMD (VEPP-2M, Novosibirsk)	1983	Nucl.Phys.B 256 (1985) 365-384	ins221309 Table 2	details	Finalized
TOF (VEPP-2M, Novosibirsk)	1981	Yad.Fiz. 33 (1981) 709-714, Sov.J.Nucl.Phys. 33 (1981) 368-370	ins167191	details	Finalized
VEPP-2 (Novosibirsk)	1972	Phys.Lett.B 41 (1972) 205-208	ins75634	details	Finalized
VEPP-2 (Novosibirsk)	1971	Phys.Lett.B 34 (1971) 328-332	ins69313	details	Finalized
VEPP-2 (Novosibirsk)	1969	Yad.Fiz. 9 (1969) 114-119, Phys.Lett.B 25 (1967) 6, 433-435	ins57008	details	Finalized

(download)

```
In [1]: from math import *
        import re
        from pprint import pprint
        import urllib.request
        from requests.utils import requote_uri
        from array import array
        import json
        import yaml
        import itertools
        import ROOT
        from ROOT import TCanvas, TFile, TProfile, TNtuple, TH1F, TH2F, TLegend
        from ROOT import TGraph, TGraphErrors, TGraphAsymmErrors
        from ROOT import gROOT, gBenchmark, gRandom, gSystem, gStyle, gPad
```

Conclusions

The Strong2020 Working Group has the goal of facilitating the collaboration between the experimental and theoretical groups with the goal of understanding the status of the Monte Carlo generators and the measurements in hadronic physics. All these efforts have been recently revitalized by the new high-precision measurement of the anomalous magnetic moment of the muon at Fermilab [4][5]. PrecisionSM provides an annotated database for low-energy $e^+e^- \to hadrons$ cross-section data, which is relevant for the updated comparison of the muon g-2 measurement with the Standard Model prediction based on the evaluation of the leading-order hadronic-vacuum-polarization contribution that uses the dispersive approach [6].

References

[1] http://www.strong-2020.eu
[2] https://arxiv.org/pdf/2201.12102.pdf
[3] https://www.hepdata.net
[4] Muon g-2 Collaboration, Phys. Rev. Lett. **126**, no.14, 141801 (2021)
[5] Muon g-2 Collaboration http://arxiv.org/abs/2308.06230 (2023)
[6] T. Aoyama, *et al.* Phys. Rept. **887**, 1-166 (2020) [https://muon-gm2-theory.illinois.edu]

Acknowledgements

This work was supported by the European Union STRONG 2020 project under Grant Agreement Number 824093.

PrecisionSM Contents Docs About RSS feed Search

Low energy e^+e^- channels database

- Measurements Database:
  - $e^+e^- \to \pi^+\pi^-$

Con

Database for $e^+e^- \to \pi^+\pi^-$ channels

Experiment	Year	Reference (link to INSPIRE-HEP)	Link to Hepdata	Details	Status
BESIII (BEPC, Beijing)	2016	Phys.Lett.B 753(2016) 629-638 [errata: Phys.Lett.B 812 (2021) 135982]	ins1385603	details	Finalized
BaBar (SLAC, Stanford U.)	2016	Phys.Rev.D 86 (2012) 032013		details	In Preparation
CLEO (CESR, Cornell U.)	2018	Phys.Rev.D 97 (2018) 3, 032012	ins1643020	details	Finalized
CLEO (CESR, Cornell U.)	2013	Phys.Rev.Lett. 110 (2013) 2, 022002	ins1189656	details	Finalized
CLEOc (CESR, Cornell U.)	2005	Phys.Rev.Lett. 95 (2005) 261803	ins693873	details	Finalized
KLOE (DAPHNE, Frascati)	2017	JHEP 03 (2018) 173			
KLOE (DAPHNE, Frascati)	2012	Phys.Lett.B 720 (2013) 336-343			
KLOE (DAPHNE, Frascati)	2010	Phys.Lett.B 700 (2011) 102-110			
KLOE (DAPHNE, Frascati)	2008	Phys.Lett.B 670 (2009) 285-291	ins7974		
KLOE (DAPHNE, Frascati)	2004	Phys.Lett.B 606 (2005) 12-24, 2005	ins6552		

PrecisionSM Contents Docs Abou

$\pi^+\pi^-$, BCF (ADONE, Frascati), 1975

- hepdata: ins100180
- method: Direct
- quotes: F_π
- energy [GeV]: 1.44 - 9
- rad_corr:
  - No Mention
- comment:
  - Errors not divided

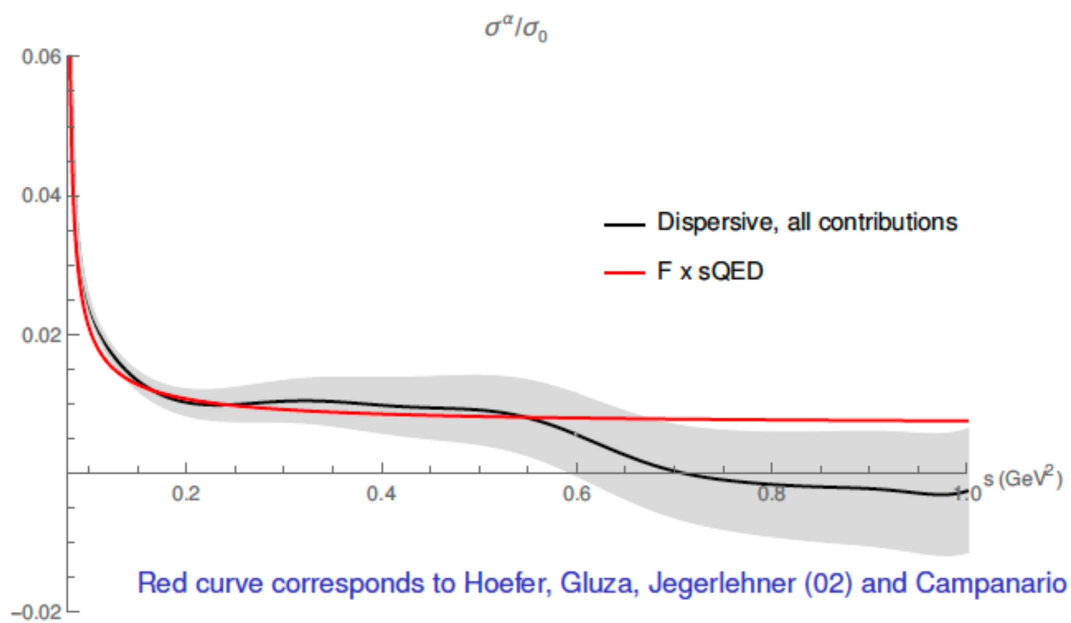
See poster at

Test of FSR model for pions

Dispersive treatment of FSR in $e^+e^- \to \pi^+\pi^-$

FSR correction

J. Monnard, PhD thesis 2021



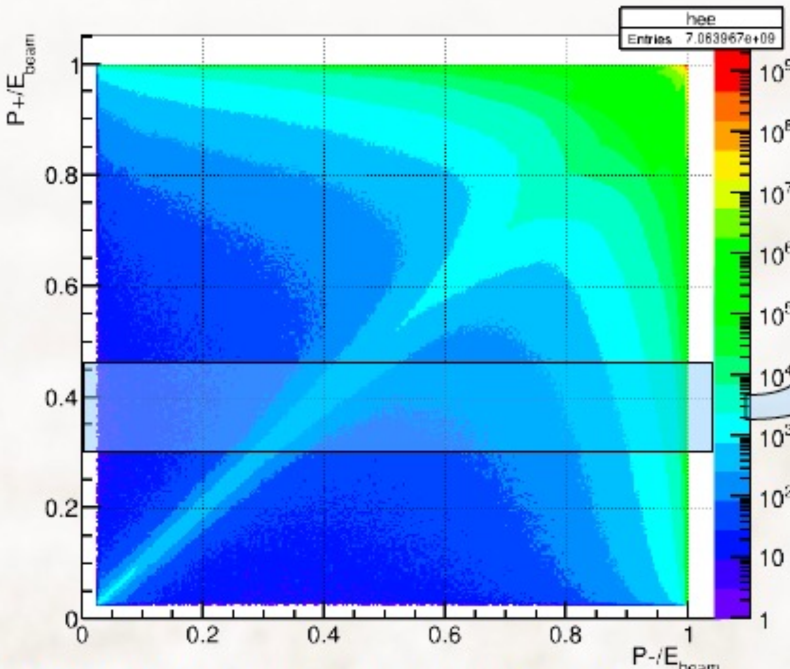
Red curve corresponds to Hoefer, Gluza, Jegerlehner (02) and Campanario et al. (19) (?)

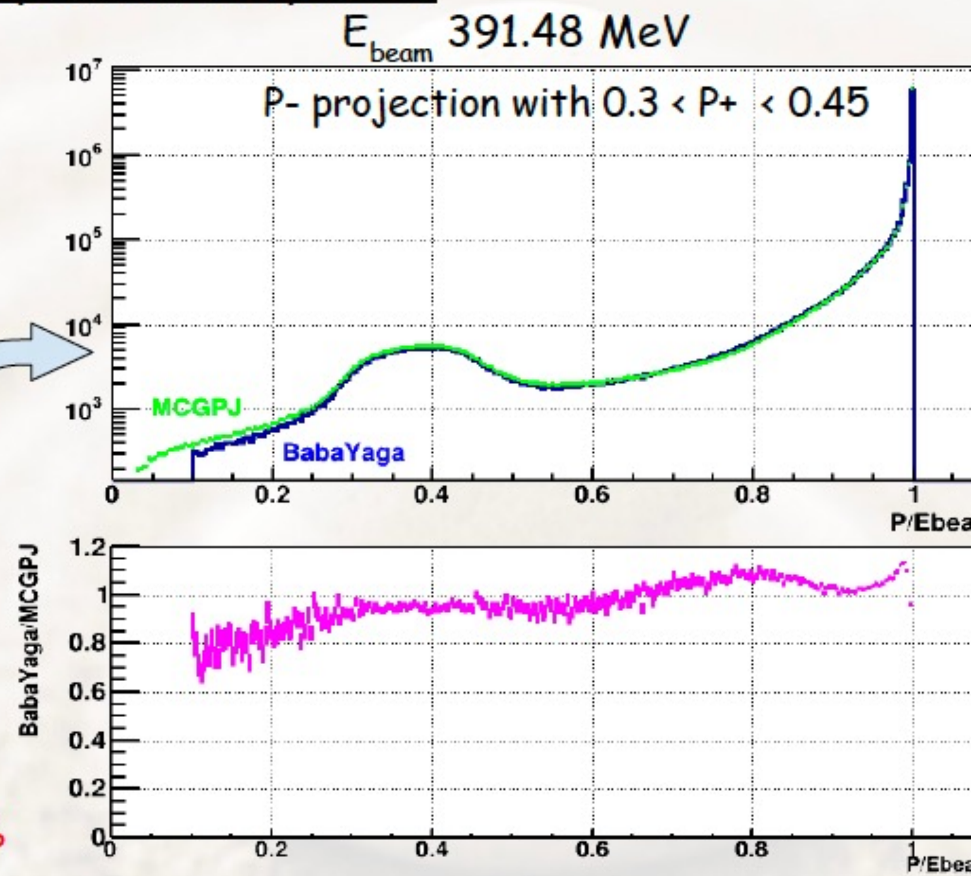
TUNED COMPARISON

BabaYaga@NLO vs MCGPJ

MCGPJ vs BabaYaga bhabha P+ vs P- spectrum

Differential over momentum spectrum comparison





MCGPJ last improvement with jets angles reduce discrepancy from x1.6-3 to x1.1

Momentum spectrum still disagree at level ~ 10%

Tails comes from e+e- → e+e- γγ , NNLO order

Very desirable to have more precise generators

Such discrepancy gives ~0.1-0.2% systematic for π+π- at ρ-peak using momentum analysis at CMD3

5^{th} WorkStop

- in the WorkStop, we 'just' want to take stock what is available and improve the theoretical description for $e^+ e^- \to$ hadrons
- main processes (input from WP5)

$$
\begin{aligned}
e^+ e^- &\to \pi^+ \pi^- \quad \gamma\{+\gamma\} \\
e^+ e^- &\to \mu^+ \mu^- \quad \gamma\{+\gamma\} \\
e^+ e^- &\to e^+ e^- \quad \gamma\{+\gamma\}
\end{aligned}
$$

- there are more processes and $(e + e-)$ in final state
- cross links with $\mu\, e^- \to \mu\, e^-$ and $\ell\, p \to \ell\, p$
- here: link WP1/2 – WP3 – WP4

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WP5: Experimental inputs

BES-III

1) which are the processes which need progress from the theory?

- ππ,ππg (QED and effects beyond sQED)
- μμ(g) (QED)
- ee(g) (add the generation of events where one or both tracks are emitted at small angles)
- 3π and 4π (FSR + new fit of FF to available data)

2) a set of "useful" observables to test the theory prediction (for example: FB asymmetry, charge asymmetry, etc…);

Effects to be included and tested:

- interference for ππ at NLO (2ISR with 1ISR+1FSR)
- radiative production and/or decay of hadrons

3) a minimum set of experimental conditions and cuts which apply to "your" experiment where to compare the theory prediction.

- angular acceptance: 21-159 degree for charged particles, 25-155 degree for photons
- momentum acceptance: > 200 MeV for charged particles, > 25 MeV for photons (50 MeV below 37 and above 143 deg)
- in untag analysis: missing momentum along the beam axis (< 5 deg)
- kinematic fit, roughly equivalent to requesting the mass recoiling against the hadronic system < 20 MeV

WP5: Experimental inputs CMD3/SND

List of crucial process for pi+pi- analysis are (listed in order of importance by my opinion):
1)e+e+ -> pi+pi-(gamma)
2)e+e+ -> e+e-(gamma)
3)e+e+ -> mu+mu-(gamma)

All of them looks like better to have in the NNLO order with proper matching to the next orders resummation of logarithmically enhanced corrections.
Also looks like the iterative generation of photons (as done in the BabaYaga@NLO) gives better result for some of differential cross sections.

Required predictions include (which affect analysis and part of measurable variables):
1) cross sections in used cuts,
2) differential cross section over polar angle of event and corresponding quantity as the forward backward charge asymmetry,
(in CMD-3 the polar angle is defined as average over charge particles (theta^+ + pi - theta^-)/2)
3) 2D differential cross section over momenta of charge particles, especially behavior separately in the soft photon region and in far tails.
…

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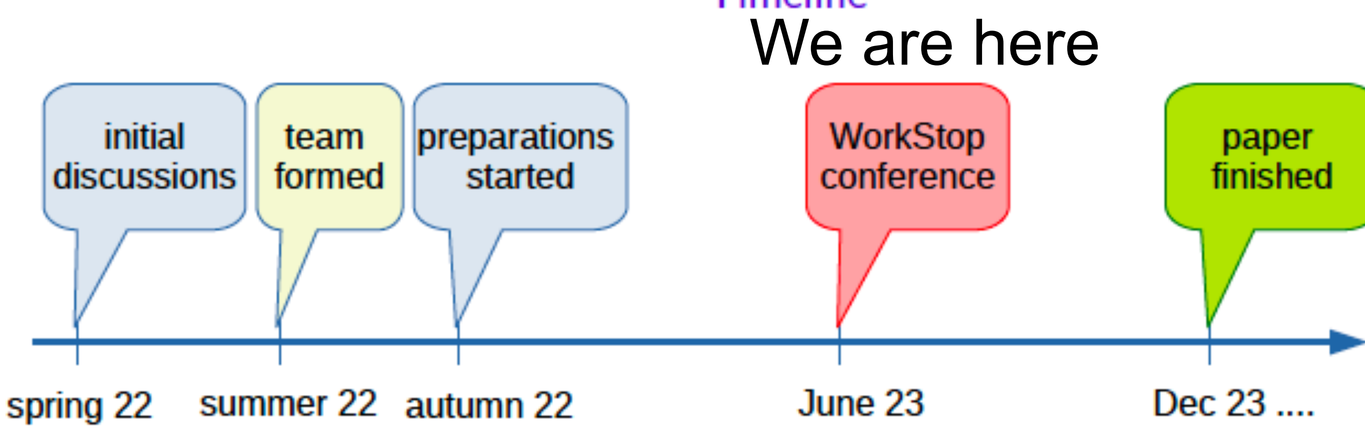
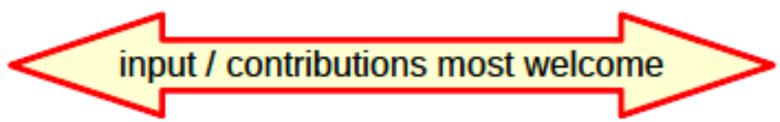
5^{th} WorkStop

Timeline





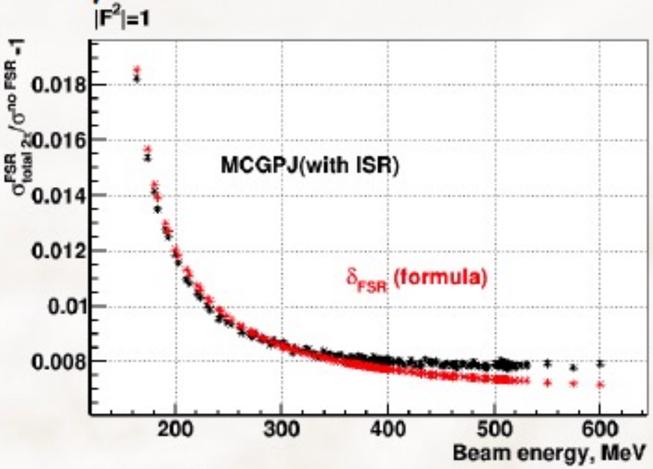
if you want to join (this means **work !**), please contact team members

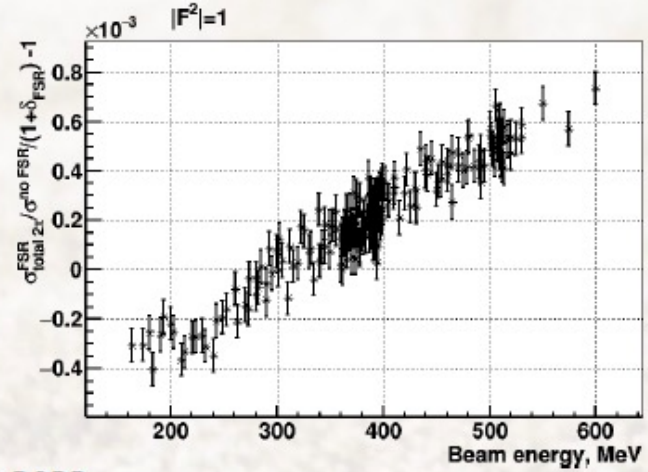
TUNED COMPARISON

PHOKHARA vs MCGPJ

MCGPJ FSR contribution

With Fpi=1 FSR is consistent with analytical formula at < 0.05%





$$\frac{\sigma^{FSR}}{\sigma^{no\,FSR}}-1$$

With full formfactor behaviour is different because of ISR return.

But looks reasonable