Measurement of hadronic cross sections via initial state radiation at BaBar

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on behalf of the *BaBar* collaboration

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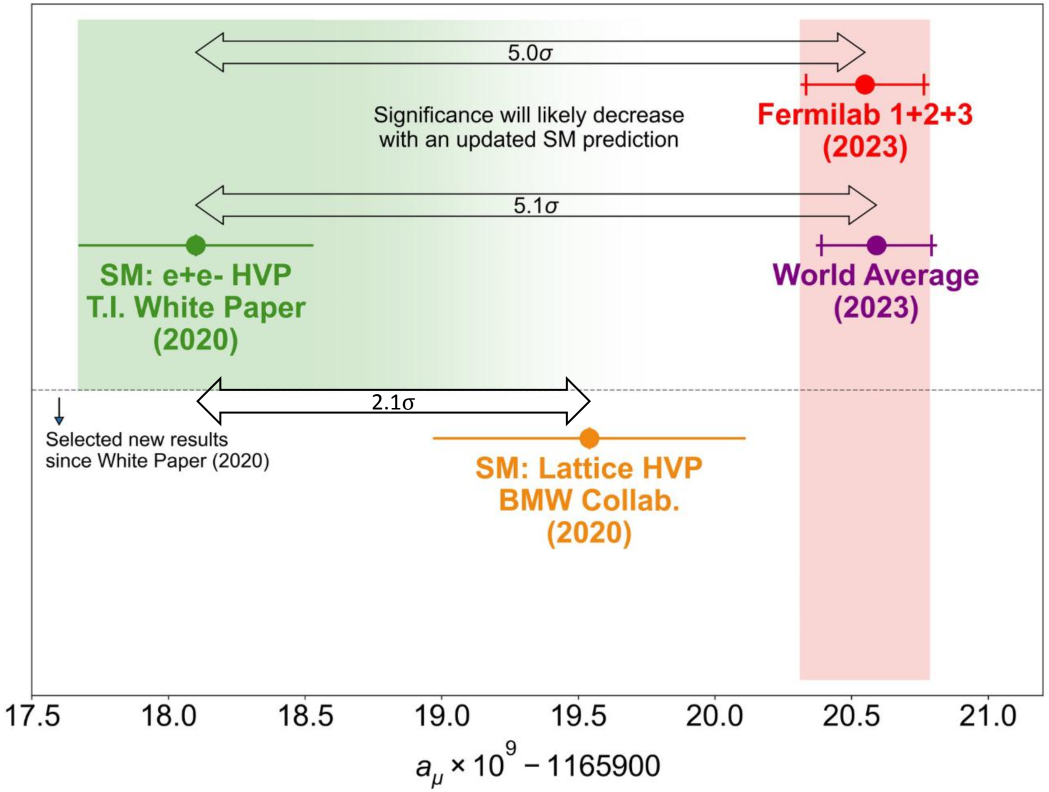
Rencontres de Moriond (Electroweak), 30/03/2024

Introduction

Hadronic vacuum polarization (HVP) contribution to the anomalous magnetic moment of the muon ($\boldsymbol{a_\mu}$) obtained by measuring cross section of $e^+e^- \rightarrow \text{hadrons}$ processes: largest input from $\boldsymbol{e^+e^- \rightarrow \pi^+\pi^-}$.

Current tensions between:

- predictions from **dispersion approach** and **direct measurement** (up to $\sim 5\sigma$),
- predictions from **dispersion approach** and **lattice QCD** (2.1σ),



EPS-HEP2023 & Sixth Plenary Workshop of the Muon g-2 Theory Initiative (2023)

Introduction

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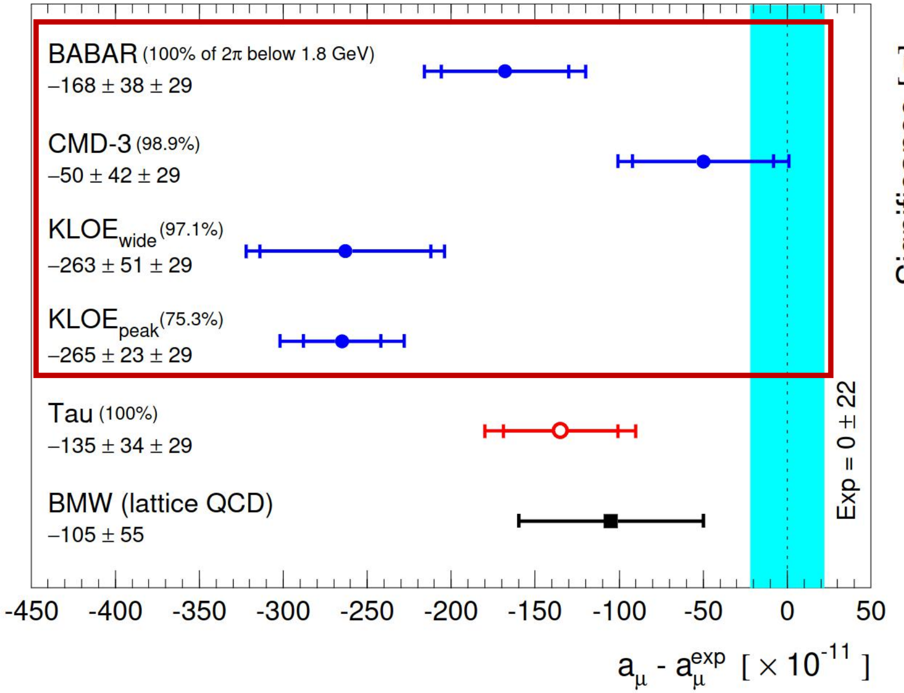
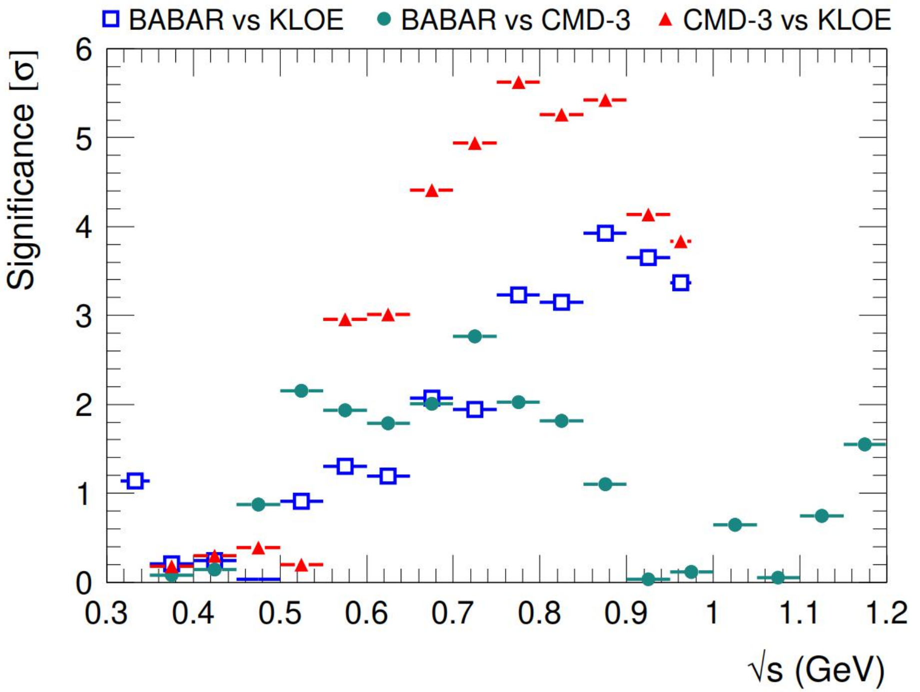
Current tensions between:

- measurements from **KLOE**, **BaBar** and **CMD-3**.

M. Davier, A. Hoecker, A.M. Lutz, B. Malaescu, Z. Zhang
Tensions in e+e−→π+π−(γ) measurements [...]
arXiv:2312.02053 (2023)





Last BaBar result 15 years ago.

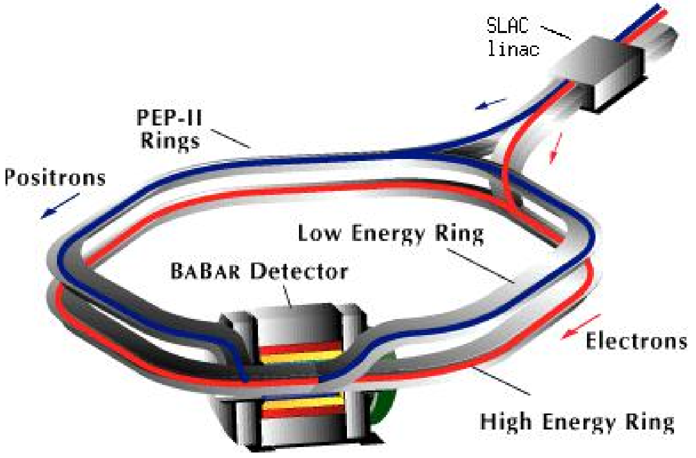
New upcoming BaBar analysis to measure the $e^+e^- \rightarrow \pi^+\pi^-(\gamma)/\mu^+\mu^-(\gamma)$ cross sections with: full data samples, improved precision, new measurement method.

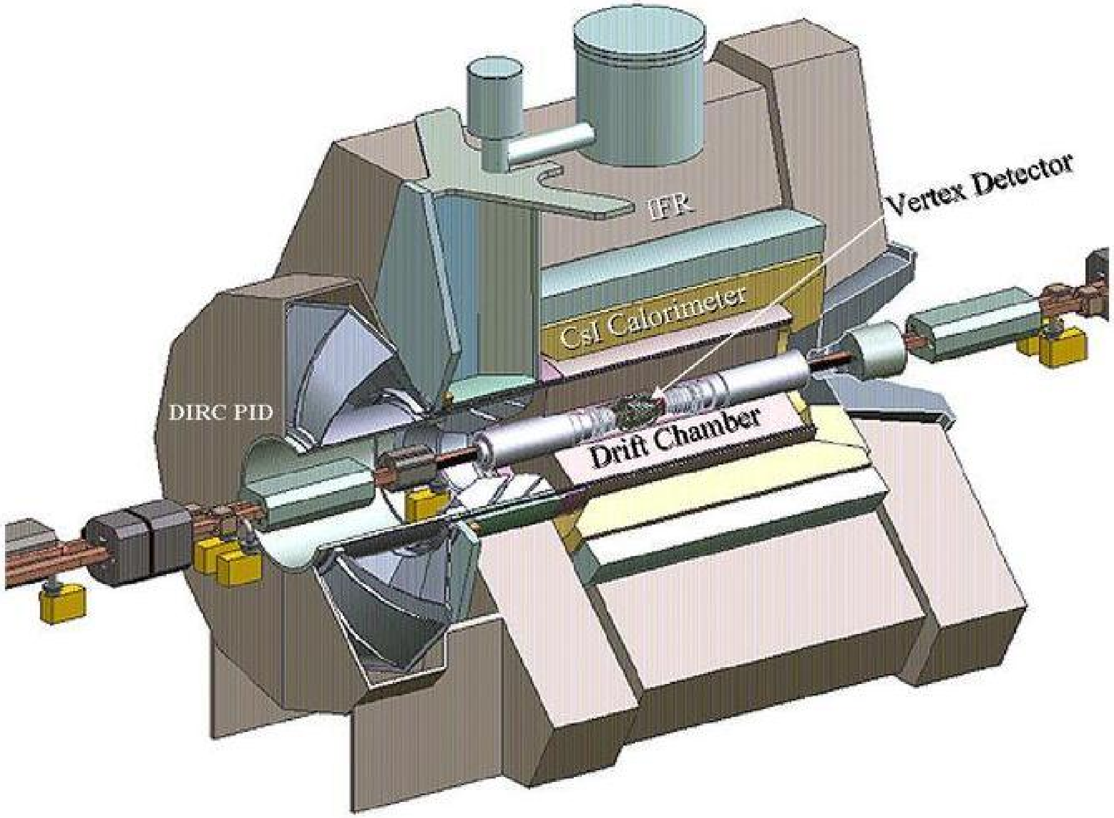
The BaBar experiment & Simulation samples

Asymmetric $\boldsymbol{e^+}$ **(3 GeV)** – $\boldsymbol{e^-}$ **(9 GeV) collider** located at SLAC (USA).

Operated from 1999 to 2008 at $\boldsymbol{\Upsilon(4S)}$ **resonance** energy ($\sqrt{s} = 10.58$ GeV/c²).

Collected **424.2 fb^{-1} at $\boldsymbol{\Upsilon(4S)}$** + 43.9 fb^{-1} off-resonance.





Monte Carlo (MC) signals: $\boldsymbol{\pi^+\pi^-\gamma_{\text{ISR}}}$, $\boldsymbol{\mu^+\mu^-\gamma_{\text{ISR}}}$

- ***Phokhara***: 10× data stat., **full NLO ISR**.
  (*full* = with large angle ISR & ISR-FSR interference)
- ***AfkQED***: smaller stat., **NLO+NNLO ISR**.

MC backgrounds:

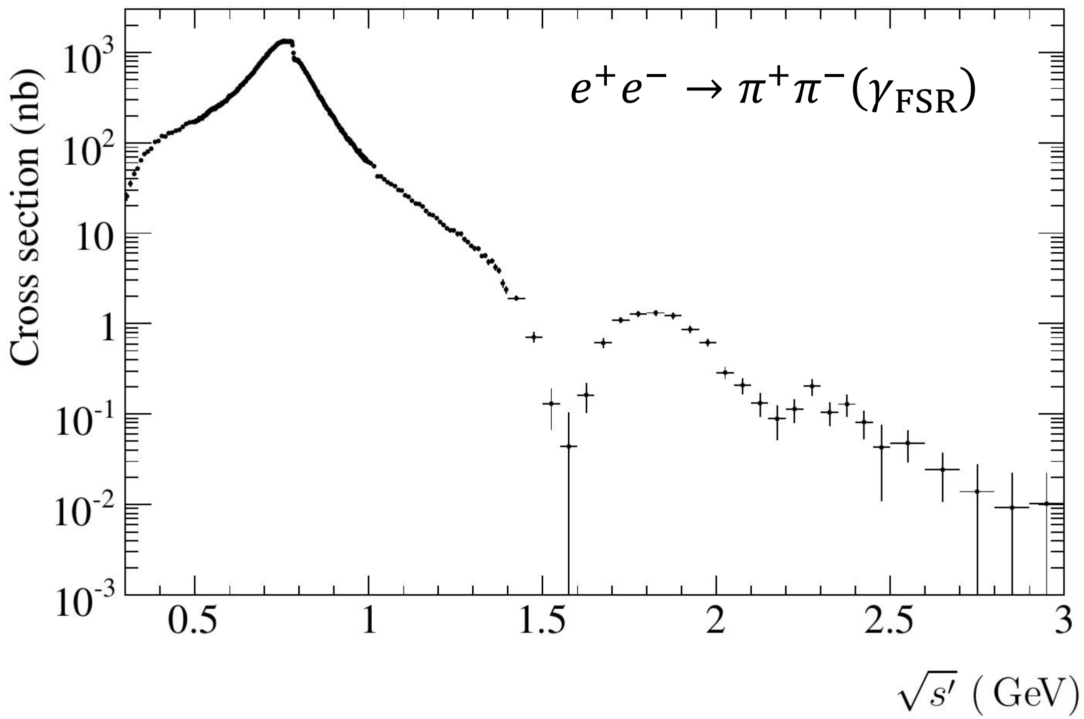
- Phokhara/AfkQED: $K^+K^-\gamma_{\text{ISR}}$
- JETSET: $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$,
- KK2f: $e^+e^- \to \tau^+\tau^-$,
- AfkQED: $e^+e^- \to X\gamma_{\text{ISR}}$ $(X = n\pi/K + m\pi^0, \ldots)$.

Reminder: Measurement of the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section

B. Aubert *et al.* (BABAR Collaboration)
Precise Measurement of the $e^+e^- \to \pi^+\pi^-(\gamma)$ Cross Section with the Initial State Radiation Method at BABAR
Phys. Rev. Lett. 103, 231801 – Published 3 December 2009

J. P. Lees *et al.* (BABAR Collaboration)
Precise measurement of the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section with the initial-state radiation method at BABAR
Phys. Rev. D 86, 032013 – Published 28 August 2012

Results of the 2009 / 2012 BaBar analysis



Relative systematic uncertainties (in 10^{-3}) on the $e^+e^- \to \pi^+\pi^-(\gamma_{FSR})$ cross section by $\sqrt{s'}$ intervals (in GeV)

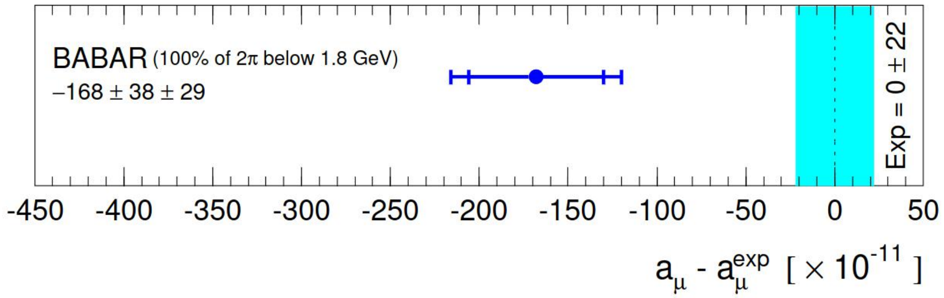
Sources	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.9	0.9-1.2	1.2-1.4	1.4-2.0	2.0-3.0
trigger/ filter	5.3	2.7	1.9	1.0	0.7	0.6	0.4	0.4
tracking	3.8	2.1	2.1	1.1	1.7	3.1	3.1	3.1
π-ID	10.1	2.5	6.2	2.4	4.2	10.1	10.1	10.1
background	3.5	4.3	5.2	1.0	3.0	7.0	12.0	50.0
acceptance	1.6	1.6	1.0	1.0	1.6	1.6	1.6	1.6
kinematic fit (χ^2)	0.9	0.9	0.3	0.3	0.9	0.9	0.9	0.9
correl $\mu\mu$ ID loss	3.0	2.0	3.0	1.3	2.0	3.0	10.0	10.0
$\pi\pi/\mu\mu$ non-cancel.	2.7	1.4	1.6	1.1	1.3	2.7	5.1	5.1
unfolding	1.0	2.7	2.7	1.0	1.3	1.0	1.0	1.0
ISR luminosity	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
sum (cross section)	13.8	8.1	10.2	5.0	6.5	13.9	19.8	52.4

Dispersion relation:

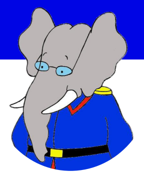
$$a_\mu^{\pi\pi(\gamma_{FSR}),\,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds' \, \overbrace{K(s')}^{\text{QED kernel}} \, \underbrace{\sigma^0_{\pi\pi(\gamma_{FSR})}(s')}_{\text{bare cross section (no VP)}}$$

$\sqrt{s'} = m_{\pi^+\pi^-(\gamma_{FSR})}$

$$a_\mu^{\pi\pi(\gamma_{FSR}),\,LO} = (514.09 \pm 2.22\,(stat) \pm 3.11\,(syst)) \times 10^{-10}$$



New features in the upcoming analysis



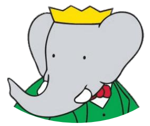
Previous analysis (2009 / 2012):

- Runs 1 to 4 (232 fb^{-1} at $\Upsilon(4S)$),
- π/μ separation using particle identification (PID), one of dominant systematics,
- Momentum selection on each track: $p > 1\ \mathrm{GeV}/c$ (more reliable μID),
- Total relative systematic uncertainty ($0.5 - 1\ \mathrm{GeV}/c^2$) = **0.50%**.

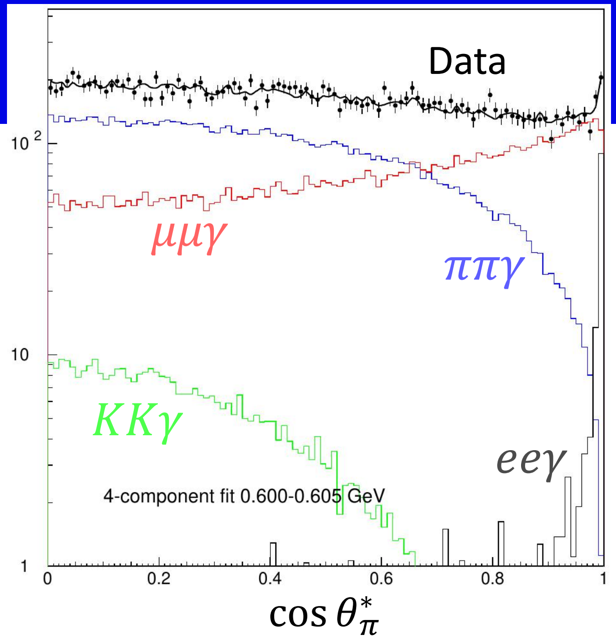
New analysis (202?):

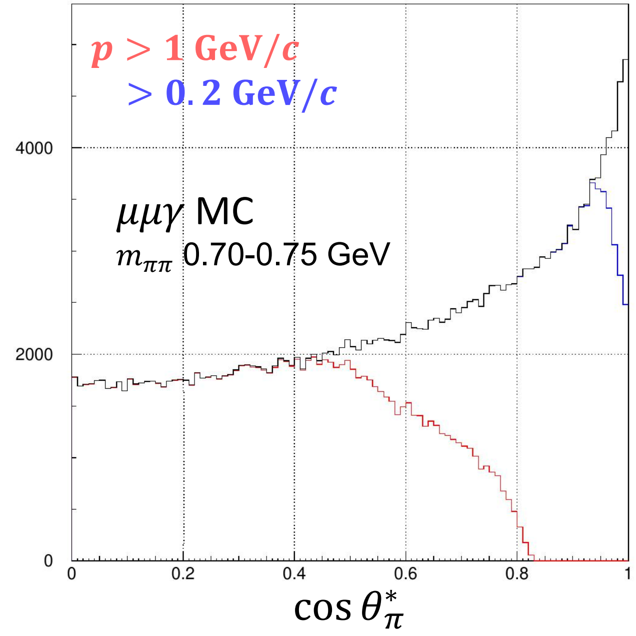
- Runs 1 to 6 (424.2 fb^{-1} + 43.9 fb^{-1} on/off $\Upsilon(4S)$ resonance) and no PID requirement: **larger statistics, smaller stat. & syst. uncertainties**,
- New method to separate all processes: fit of angular distributions in 2-particle CM frame → $\theta^*_\pi =$ angle between trk^- and γ_{ISR} in $\pi\pi$ CM frame,
- π/μ separation at large $\cos\theta^*_\pi$: release $p > 1\ \mathrm{GeV/c}$ cut → increase statistics.

→ **independent method** allowing to check the previous BaBar result + improve the precision.



2023: Measurement of add. radiation in $e^+e^- \to \pi^+\pi^-\gamma_{\mathrm{ISR}}(\gamma)/\mu^+\mu^-\gamma_{\mathrm{ISR}}(\gamma)$





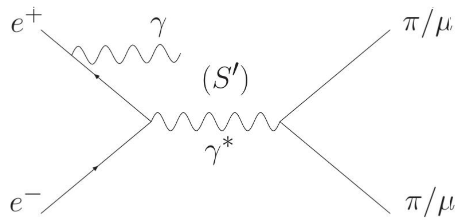
Measurement of additional radiation in ISR processes

J. P. Lees *et al.* (BABAR Collaboration)
Measurement of additional radiation in the initial-state-radiation processes $e^+e^-\to\mu^+\mu^-\gamma$ and $e^+e^-\to\pi^+\pi^-\gamma$ at BABAR
Phys. Rev. D 108, L111103 – Published 21 December 2023

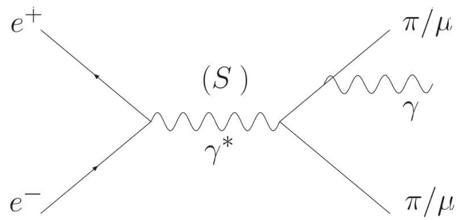
NLO fits

Study on data (full on/off $\Upsilon(4S)$) and **both Phokhara and AfkQED** using $\pi^+\pi^-(\gamma)/\mu^+\mu^-(\gamma)$ generated samples.

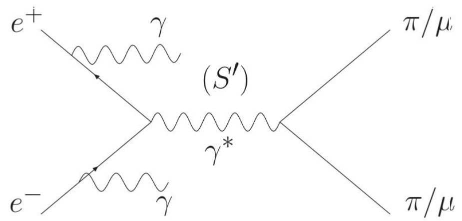
Lowest-order **(LO) ISR**



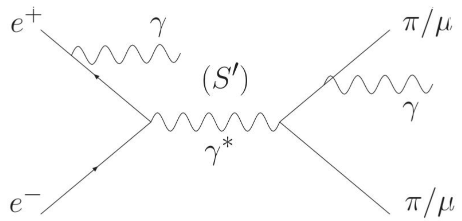
Lowest-order (LO) FSR



Next-to-leading-order **(NLO) ISR**



Next-to-leading-order **(NLO) FSR**



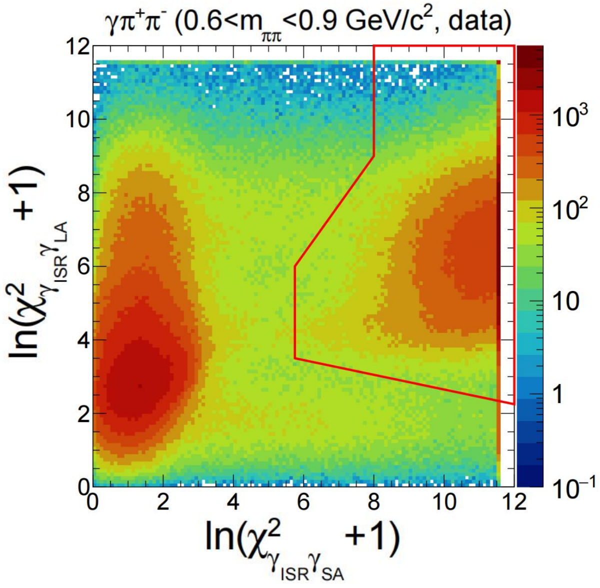
2 fits:

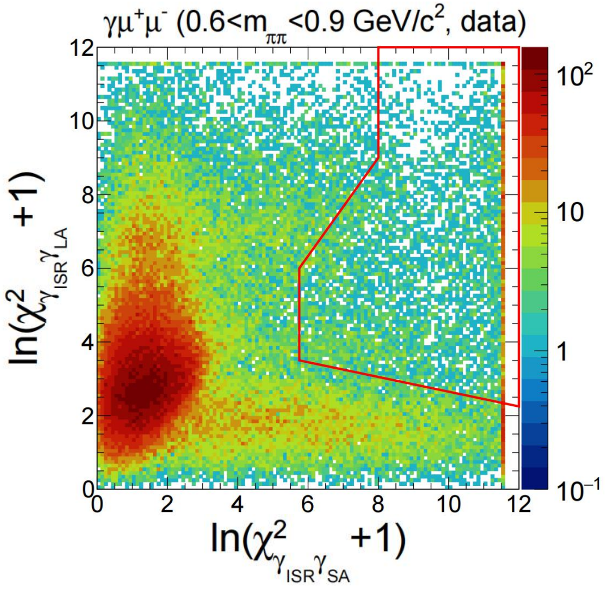
- $\gamma_{\mathrm{ISR}}\gamma_{\mathrm{LA}}$ **fit**: additional **large angle (LA)** γ $(0.35 - 2.45$ rad$)$.
- $\gamma_{\mathrm{ISR}}\gamma_{\mathrm{SA}}$ **fit**: additional **small angle (SA)** γ fitted, assumed collinear with one of the beams.

3 categories:

- **NLO LA sample**: $\chi^2_{\mathrm{LA}} < \chi^2_{\mathrm{SA}}$, $\mathrm{E}_{\gamma_{\mathrm{LA}}} > 200$ MeV.
- **NLO SA sample**: $\chi^2_{\mathrm{LA}} > \chi^2_{\mathrm{SA}}$, $\mathrm{E}^*_{\gamma_{\mathrm{SA}}} > 200$ MeV.
- **LO sample**: events below the thresholds.

Larger background in $\pi\pi\gamma$ process, suppressed with optimized BDT-based **2D-χ^2 selection** (98-99% signal efficiency).

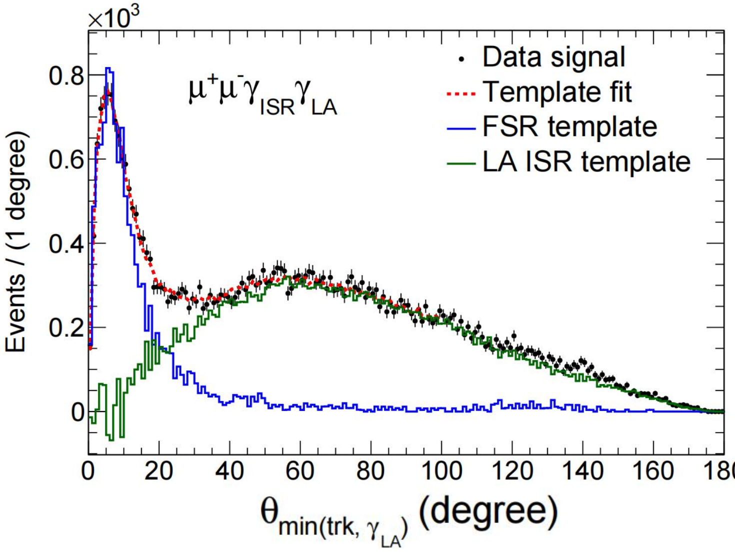


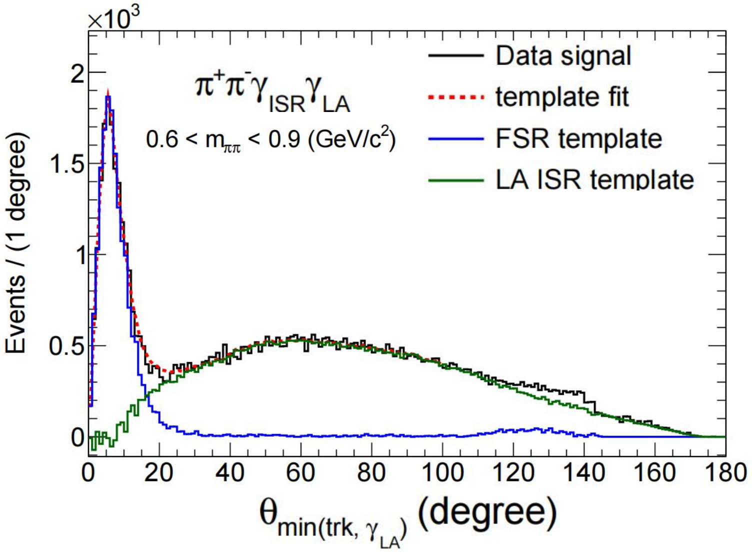


NLO LA fits

<u>FSR and LA ISR separation</u>:
→ minimum angle between additional γ_{LA} and charged tracks $\boldsymbol{\theta}_{\mathbf{min(trk,}\boldsymbol{\gamma}_{\mathbf{LA}}\mathbf{)}}$:

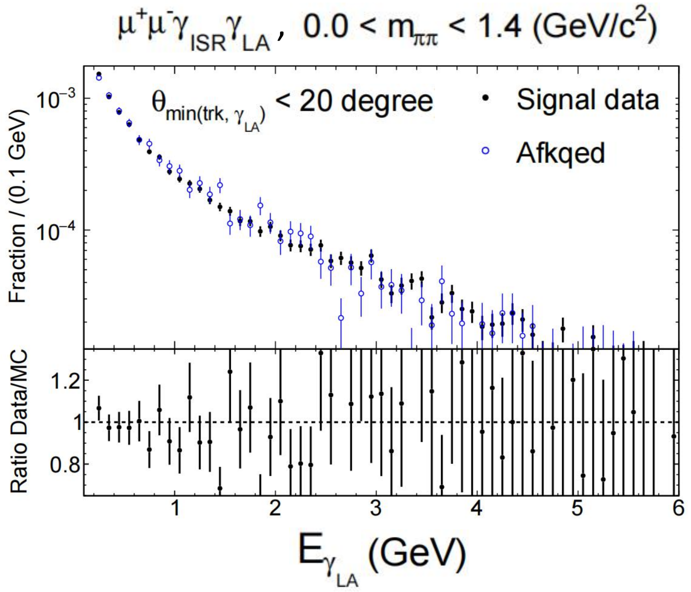
No LA ISR generated by AfkQED
⇒ fit to the data with FSR template (AfkQED) and LA ISR template (Phokhara - AfkQED).
FSR and LA ISR separation at 20 deg.

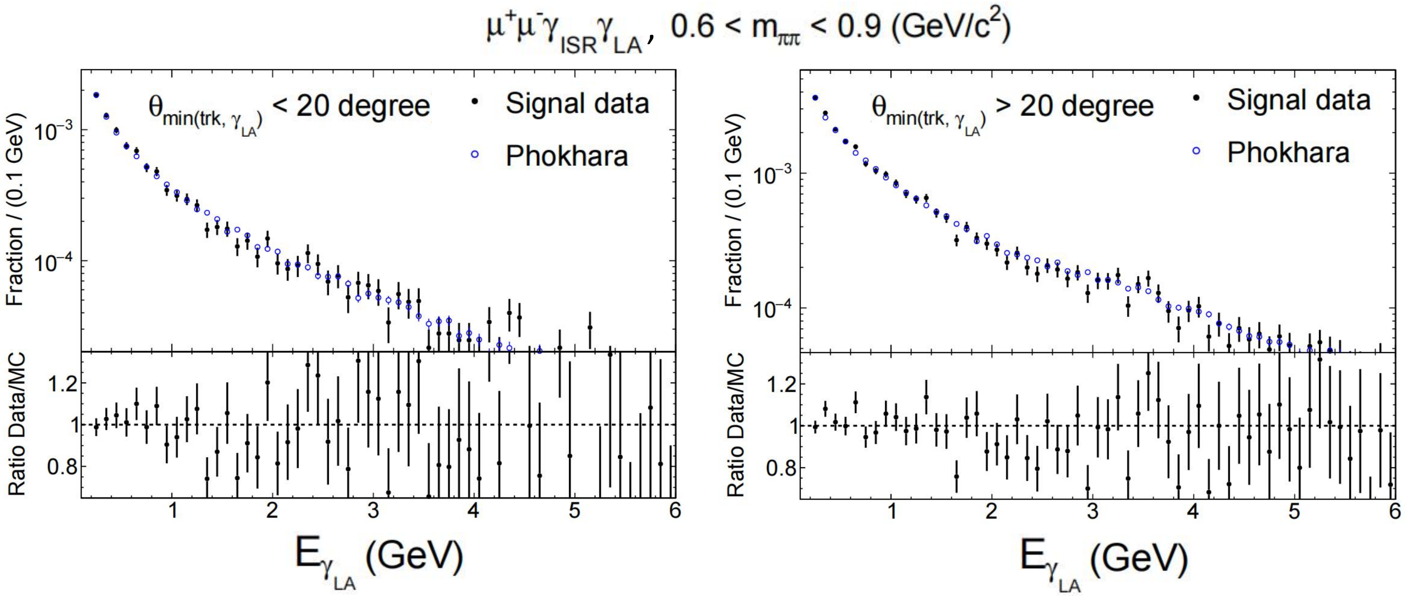




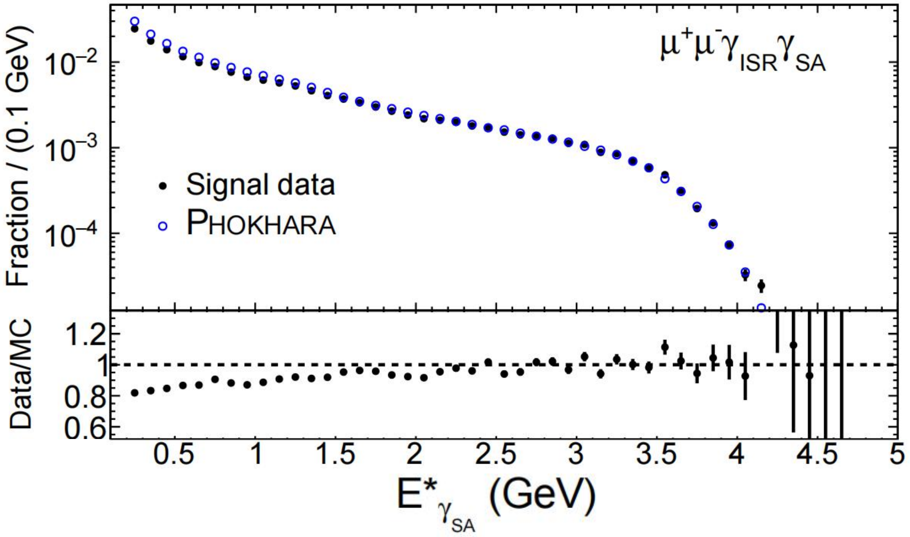
AfkQED: ✓

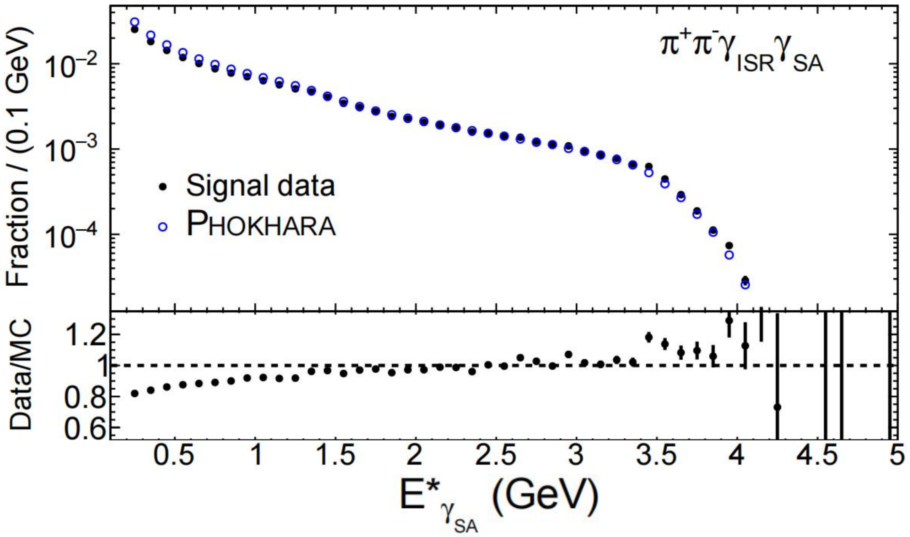
Phokhara: ✓





NLO SA fits



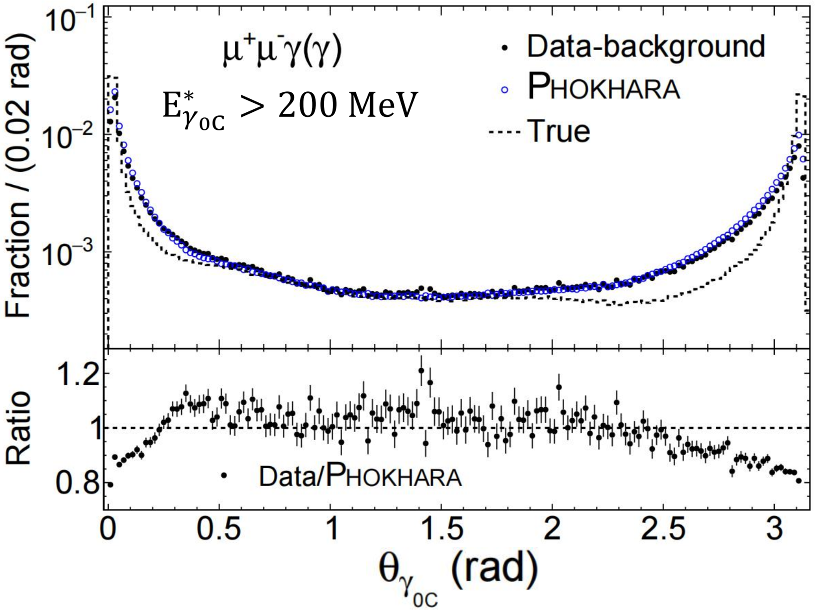


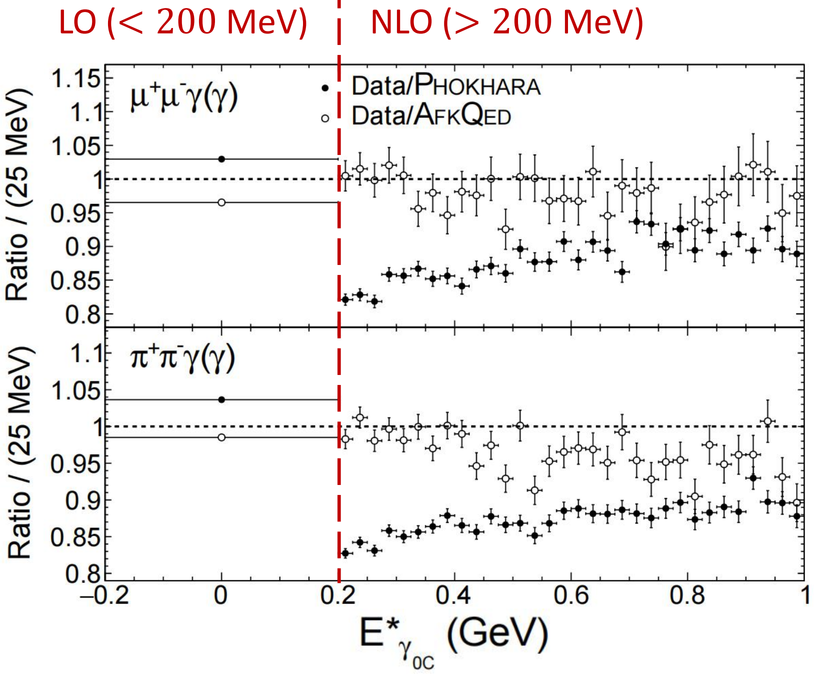
Excess of Phokhara SA events compared to data in energy distributions ($E^*_{\gamma_{SA}} > 200$ MeV).

Positive slope, better agreement at higher energies...

→ *collinear assumption of γ_{SA}?*

Zero-constraint (0C) calculation of **angle/energy** of add. photon γ_{0C}
→ no collinear assumption.



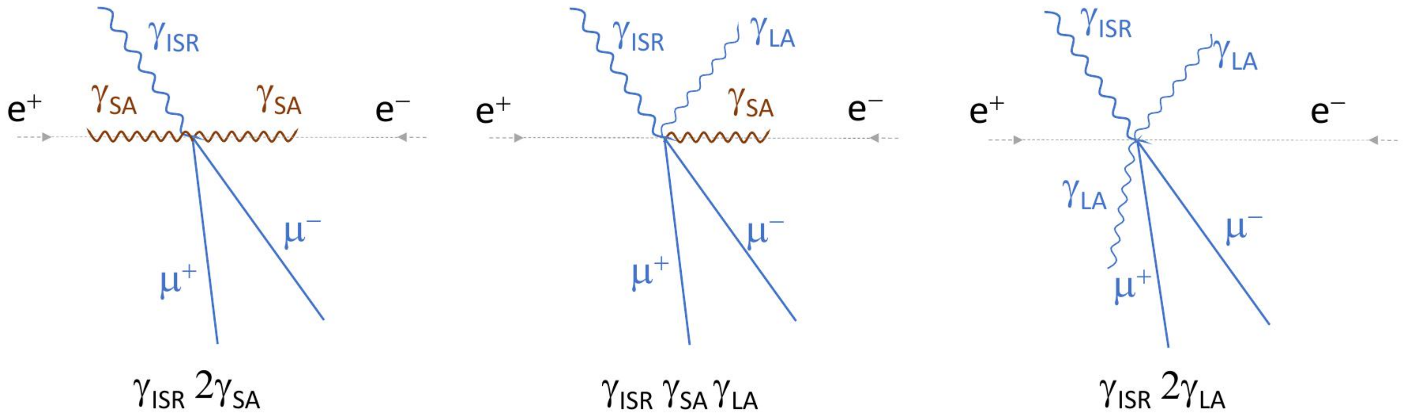


✅ **AfkQED consistent** with data and for LO-NLO.

❌ NLO SA overestimated in **Phokhara**. **Mismatch** between LO and NLO in data/Phokhara ratio, positive slope.
⇒ *not due to collinear assumption*.

NNLO fits

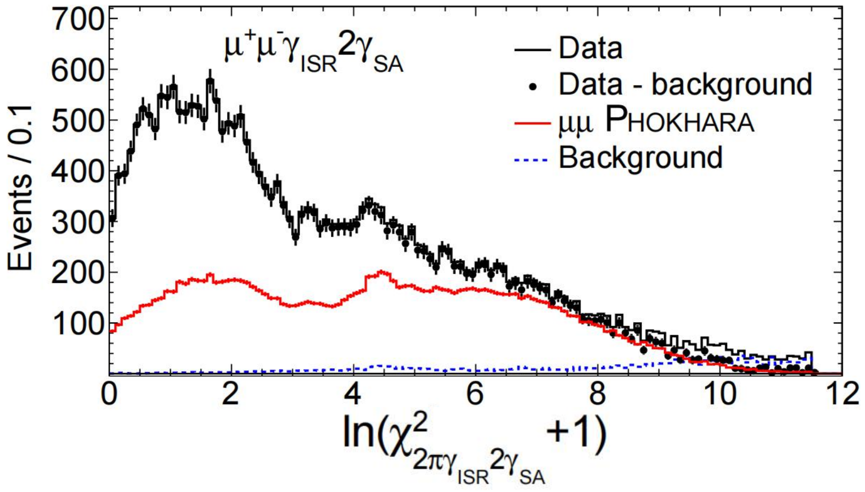
AfkQED events assigned to **NNLO 2SA**, **SA+LA** or **2LA** if χ^2 smaller than any other category, including NLO.

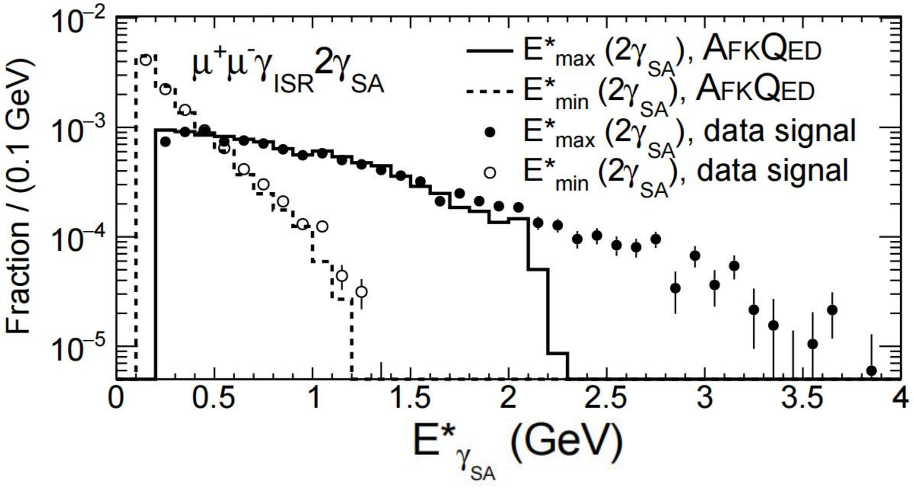


Category	$\mu\mu$ $m_{\pi\pi} < 1.4\,\mathrm{GeV}/c^2$	$\pi\pi$ $0.6 < m_{\pi\pi} < 0.9\,\mathrm{GeV}/c^2$
LO	0.7716(4)(14)	0.7839(5)(12)
NLO SA-ISR	0.1469(3)(36)	0.1401(2)(16)
NLO LA-ISR	0.0340(2)(9)	0.0338(2)(9)
NLO ISR	0.1809(4)(35)	0.1739(3)(20)
NLO FSR	0.0137(2)(7)	0.0100(1)(16)
NNLO ISR [a]	0.0309(2)(38)	0.0310(2)(39)
NNLO FSR [b]	0.00275(6)(9)	0.00194(12)(50)
NNLO 2LA [c]	0.00103(3)(1)	0.00066(4)(4)

[a] NNLO ISR = 2SA-ISR or SA-ISR + LA-ISR
[b] NNLO FSR = SA-ISR + LA-FSR
[c] NNLO 2LA = 2LA-ISR, LA-ISR + LA-FSR or 2LA-FSR

NNLO contribution obtained after NLO (Phokhara) subtraction from data.





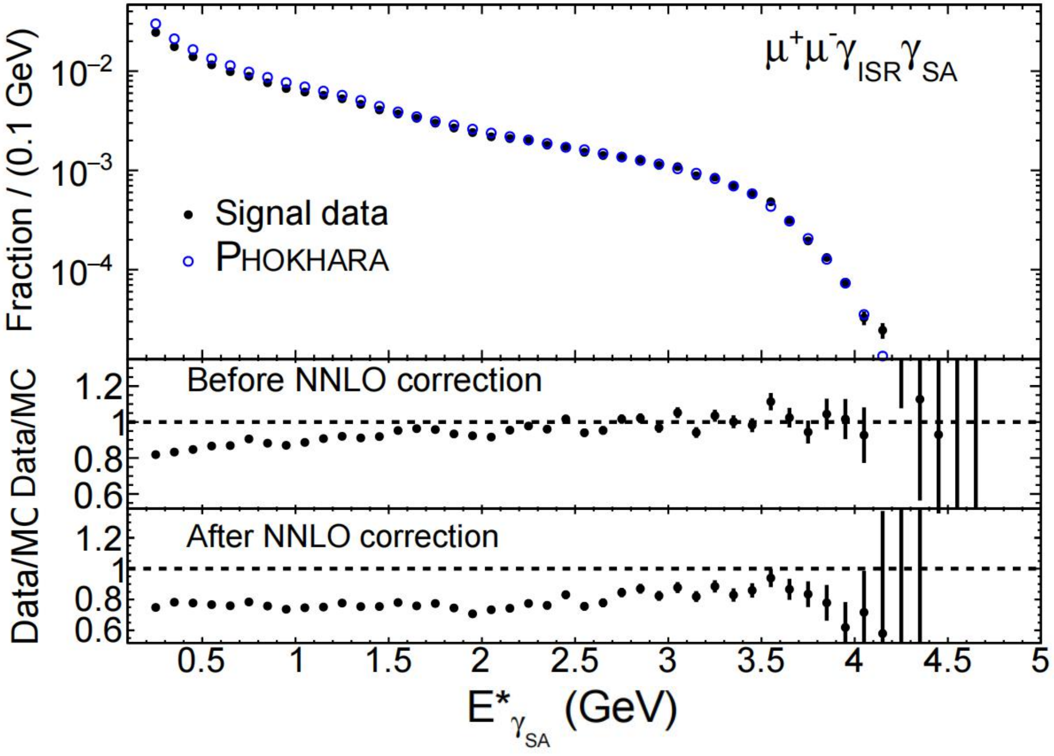
Significant NNLO signals found. 2SA dominant category.

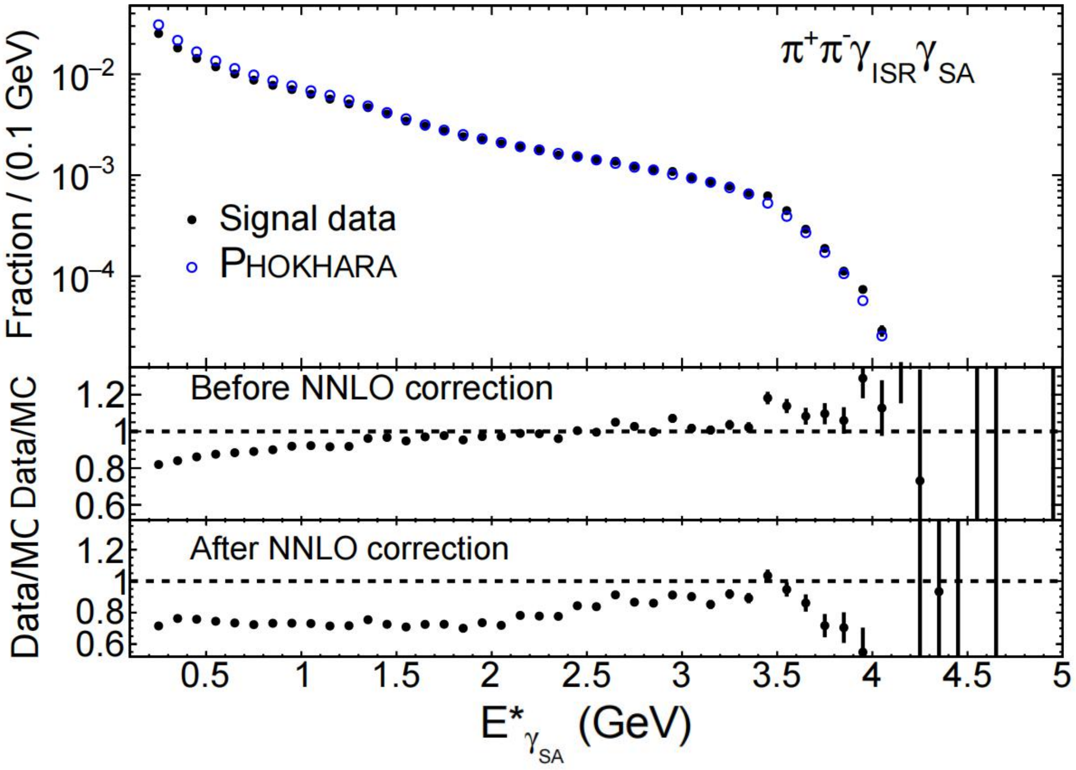
Good agreement with **AfkQED** up to 2.3 GeV.

NNLO correction to NLO SA results (Phokhara)

<u>NNLO 2SA feedthrough</u>: $2\gamma_{SA}$ from same beam not distinguished from single NLO γ_{SA}
→ correction to $\mathbf{E}^*_{\gamma_{SA}}$ **from NLO $\gamma_{ISR}\gamma_{SA}$ fit in Phokhara**.

Better agreement in shape but excess of ~20% in Phokhara. 🙁





Summary and consequences

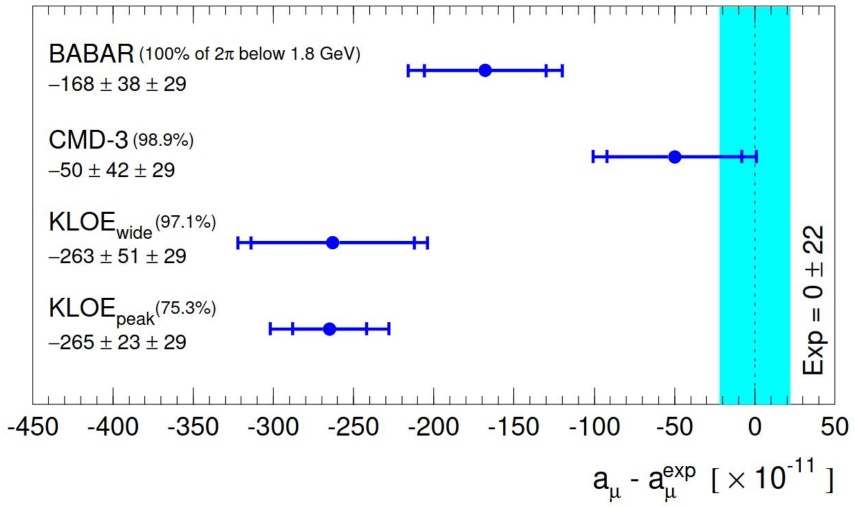
Results of the additional radiation study in ISR processes:

- Significant NNLO contribution: (3.47 ± 0.38)% for muons and (3.36 ± 0.39)% for pions.
- Large excess of NLO photons generated by Phokhara at small angles.
- Good performance from AfkQED in simulating data at NLO & NNLO. Slightly high data/MC ratios (1.061 ± 0.015 for muons and 1.043 ± 0.010 for pions) up to max. generated energy of additional photons.

Consequences for the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section measurement analyses:

(see also Z. Zhang talk on 05/04, Moriond QCD)

- BaBar analysis unaffected: NLO + higher orders already included. Correction of (0.3 ± 0.1) × 10^{-3} for acceptance, negligible compared to 0.5% systematic uncertainty on cross section.
- Other experiments relying on Phokhara for additional radiations and apply more stringent LO selection (KLOE, BESIII) might be affected → larger systematics?...
- **New BaBar analysis crucial to better understand the tensions between the different experiments.**



Backup

From $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section to a_μ

Cross section of $e^+e^- \to X$ at **reduced energy** $\sqrt{s'} = m_X$ (X = any final state) from measurement of $e^+e^- \to X\gamma_{\text{ISR}}$:

$$s' = s\left(1 - 2E^*_{\gamma_{\text{ISR}}}/\sqrt{s}\right),$$

$E^*_{\gamma_{\text{ISR}}} = \gamma_{\text{ISR}}$ energy in center of mass (CM) frame.

Measuring the yield $N_{X\gamma_{\text{ISR}}}$ gives the **bare cross section** $\boldsymbol{\sigma^0_X(\sqrt{s'})}$ **(excluding vacuum polarization)**:

$$\frac{dN_{X\gamma_{\text{ISR}}}}{d\sqrt{s'}} = \frac{dL^{eff}_{\text{ISR}}}{d\sqrt{s'}}\, \varepsilon_{X\gamma_{\text{ISR}}}(\sqrt{s'})\, \sigma^0_X(\sqrt{s'}) \qquad (1)$$

- $\varepsilon_{X\gamma_{\text{ISR}}}$ = detection efficiency in acceptance → from simulation with data corrections.
- L^{eff}_{ISR} = effective ISR luminosity → from $X = \mu\mu(\gamma_{\text{FSR}})$ in (1) and σ^0_X taken from QED computation.

Ratio of $\pi\pi$ and $\mu\mu$ mass spectra ⇒ cancellation of VP ⇒ ratio of (1) =

$$\frac{\sigma^0_{\pi\pi(\gamma_{\text{FSR}})}(\sqrt{s'})}{\sigma_{\text{pt}}(\sqrt{s'})(1+\delta^{\mu\mu}_{\text{FSR}})(1+\delta^{\mu\mu}_{\text{add. FSR}})}$$

- $\sigma_{\text{pt}} = 4\pi\alpha^2/3s'$ = cross section for pointlike charged fermions.
- $(1+\delta^{\mu\mu}_{\text{(add.) FSR}})$ = corrections for lowest-order (additional) FSR contributions.

Dispersion relation:

$$a_\mu^{\pi\pi(\gamma_{\text{FSR}}),\,\text{LO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds'\; K(s')\; \sigma^0_{\pi\pi(\gamma_{\text{FSR}})}(s')$$

where $K(s')$ is a QED kernel, relates the bare cross section to the lowest-order contribution of $\pi\pi(\gamma_{\text{FSR}})$ to a_μ.

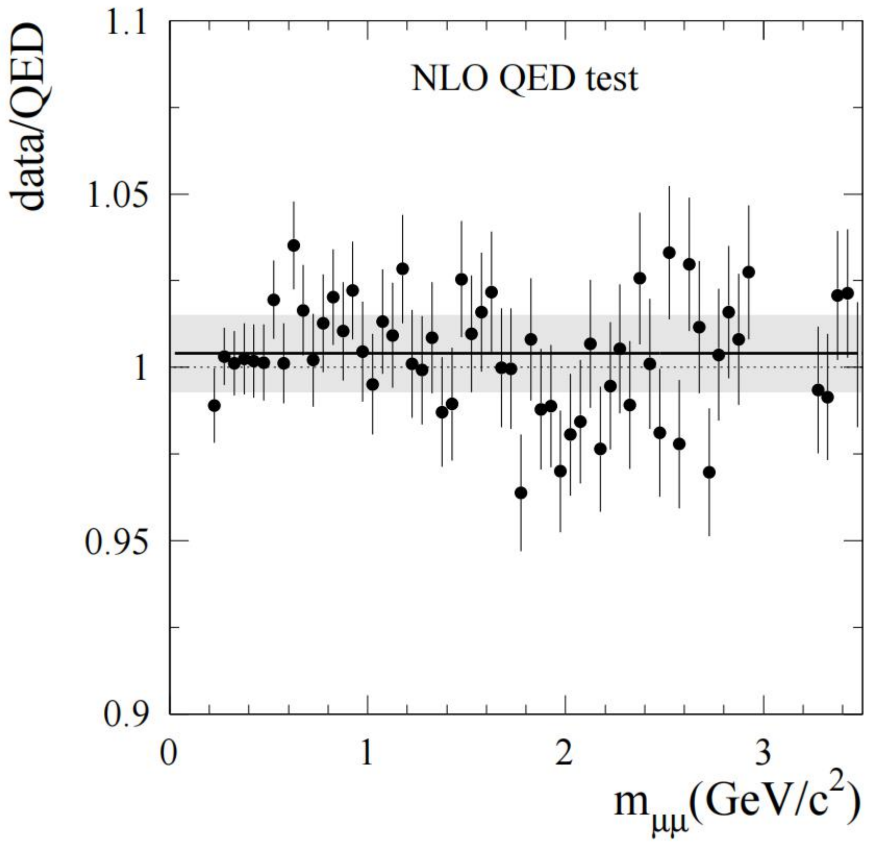
$$K(s) = x^2\left(1-\frac{x^2}{2}\right) + (1+x)^2\left(1+\frac{1}{x^2}\right)\left[\ln(1+x) - x + \frac{x^2}{2}\right] + x^2\ln x\frac{1+x}{1-x}, \quad x = (1-\beta_\mu)(1+\beta_\mu),\ \beta_\mu = \text{muon velocity}.$$

QED test with $\mu^+\mu^-(\gamma)\gamma_{\text{ISR}}$ events

Comparison of $\mu^+\mu^-(\gamma)\gamma_{\text{ISR}}$ cross section with QED: ratio of $m_{\mu\mu}$ in data and simulation.

- **Data**: background-subtracted.
- **Simulation**: AfkQED, normalized to data lumi., data/MC corrections (detector, reco.), corrections for NLO limitations (Phokhara/AfkQED comparison with fast simulation) ⇒ equivalent to NLO QED.

$$\frac{\sigma^{\text{data}}_{\mu\mu(\gamma)\gamma_{\text{ISR}}}}{\sigma^{\text{NLO QED}}_{\mu\mu(\gamma)\gamma_{\text{ISR}}}} = 1 + (4.0 \pm 1.9 \pm 5.5 \pm 9.4) \times 10^{-3}$$



QED prediction for $m_{\mu\mu}$:

$$\frac{dN_{\text{QED}}}{dm} = L_{ee}\, \sigma^{\text{NLO}}_{\text{Phokhara}} \left(\frac{1}{N_0}\frac{dN}{dm}\right)^{\text{AfkQed,M>8}}_{\text{fullsim}} \times \frac{\left(\frac{1}{N_0}\frac{dN}{dm}\right)^{\text{Phokhara}}_{\text{fastsim}}}{\left(\frac{1}{N_0}\frac{dN}{dm}\right)^{\text{AfkQed,M>8}}_{\text{fastsim}}} \times C_{\text{data/MC}}\ ,$$

- N_0: generated number of events,
- dN/dm: mass spectrum of events satisfying all criteria,
- $\text{M} > 8 \Leftrightarrow m_{X\gamma_{\text{ISR}}} > 8\ \text{GeV}/c^2$,
- $C_{\text{data/MC}}$: data/MC corrections for detector efficiencies.

Additional radiation study: track and γ_{ISR} selections

Two tracks of opposite charges, each with:

- θ: $0.4 - 2.45$ rad,
- $p_{\mathrm{T}} > 0.1\ \mathrm{GeV}/c^2$,
- at least 15 hits in drift chamber,
- $\mathrm{doca_{xy}} < 5\ \mathrm{mm}$ (distance of closest approach to collision point in transverse plane),
- $|\Delta \mathrm{z}| < 6\ \mathrm{cm}$ (distance along beam direction),
- $\left(\frac{E_{\mathrm{cal}}/p - 1}{0.15}\right)^2 + \left(\frac{dE/dx_{\mathrm{DCH}} - 690}{150}\right)^2 < 1$ (reduces electron contamination),
- No PID: consistent with cross section measurement analysis.

ISR photon candidate:

- $E_\gamma^* > 4\ \mathrm{GeV}$,
- largest E^* if multiple photons,
- θ: $0.35 - 2.40$ rad.

Any number of additional tracks and photons ($\mathrm{E}_\gamma > 50\ \mathrm{MeV}$) allowed.

NLO & NNLO fits description

- $\gamma_{\text{ISR}}\gamma_{\text{LA}}$ **fit**: additional **large angle (LA)** γ $(0.35 - 2.45$ rad) in EMC (threshold: energy > 50 MeV). Measured energy/angle of γ_{LA} used in fit.
- $\gamma_{\text{ISR}}\gamma_{\text{SA}}$ **fit**: additional **small angle (SA)** γ. No measured information: γ_{SA} assumed collinear with one of the beams. Additional photons in EMC ignored.

4-momentum conservation: use measured ISR energy/direction + momenta/angles of both tracks.
Tracks assumed to be pions: similar to cross section measurement analysis.

Asymmetry of EMC response when $E_\gamma < E_{\text{true}}$: ISR photon energy transformed to symmetric (gaussian) with Novosibirsk function → Z variable (3 parameters), initialized with measured E_γ.

χ^2 minimized according to 4-momentum conservation in terms of Z variable(s). Fitted energy obtained from returned Z values.

Same process in NNLO fits.

Optimization of 2D-χ^2 selection

BDT optimization with TMVA

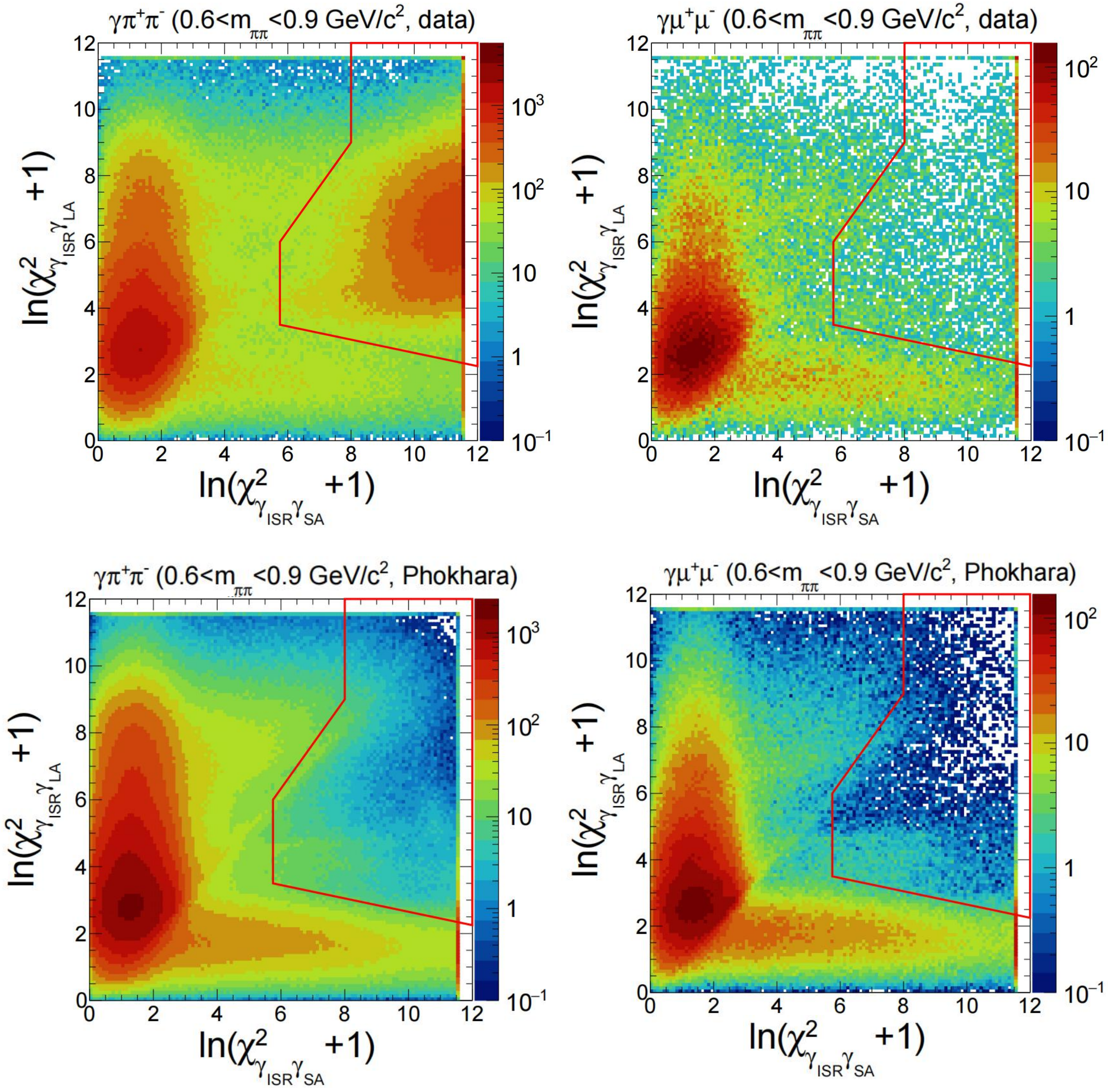
A. Hoecker *et al.*
TMVA - Toolkit for Multivariate Data Analysis
arXiv:physics/0703039 (2007)

Different optimization depending on mass range:
$< 0.6\ \mathrm{GeV}/c^2, \quad 0.6 - 0.9\ \mathrm{GeV}/c^2, \quad 0.9 - 1.4\ \mathrm{GeV}/c^2$

BDT features: $\chi^2_{\gamma_{\mathrm{ISR}}\gamma_{\mathrm{SA}}}$ and $\chi^2_{\gamma_{\mathrm{ISR}}\gamma_{\mathrm{LA}}}$.

Figure of merit: $\frac{S}{\sqrt{S+B}}$ (S (B) = integrated signal (background) to the right of the selection on BDT response).

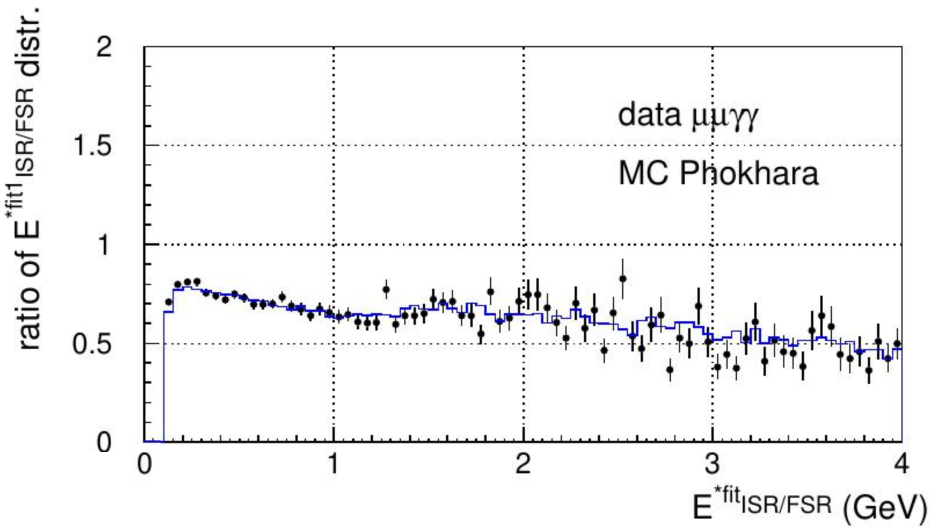
BDT selection translated to very close cut-based selection (red outline in figures = rejected by BDT).

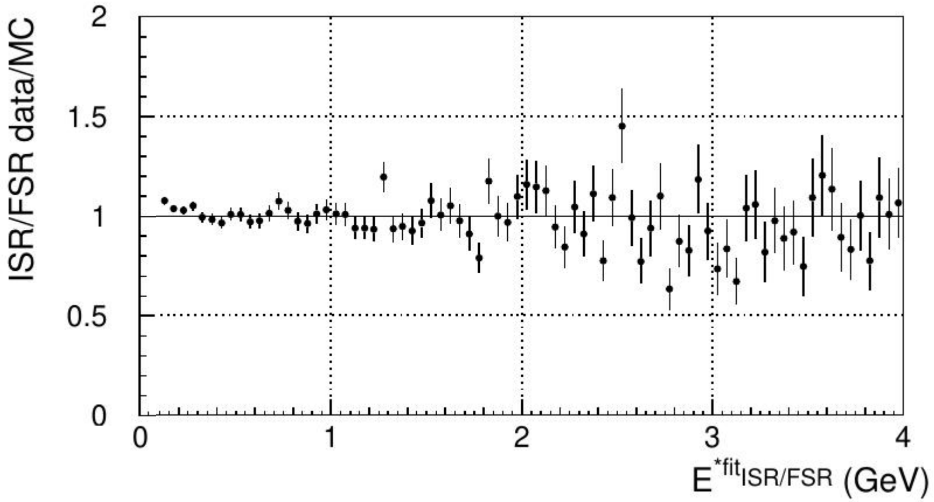


NLO SA fits: collinear assumption

Assumption that γ_{SA} is collinear to the beam in $\gamma_{\mathrm{ISR}}\gamma_{\mathrm{SA}}$ fit induces bias in fitted $\mathrm{E}^*_{\gamma_{\mathrm{SA}}}$ energy:
systematic shift $\mathrm{E}^*_{\gamma_{\mathrm{SA}}} <$ generated energy.

Shift increases with true angle to the beam and energy. Check with ratio of fitted energies in SA and LA fits (CM frame)
→ bias is actually well reproduced by simulation.





Data/Phokhara disagreement: 0C calculation

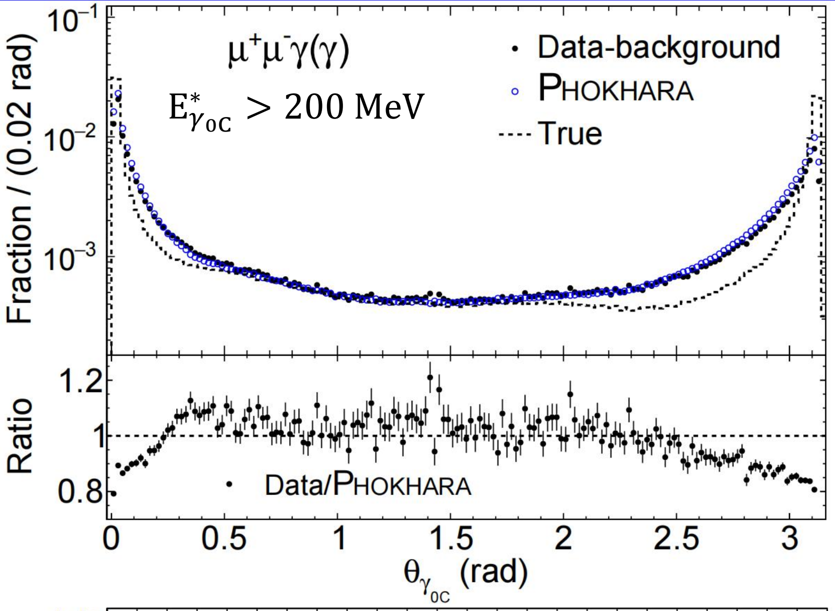
Zero-constraint (0C) calculation of **angle** and **energy** of additional photon (γ_{0C}):

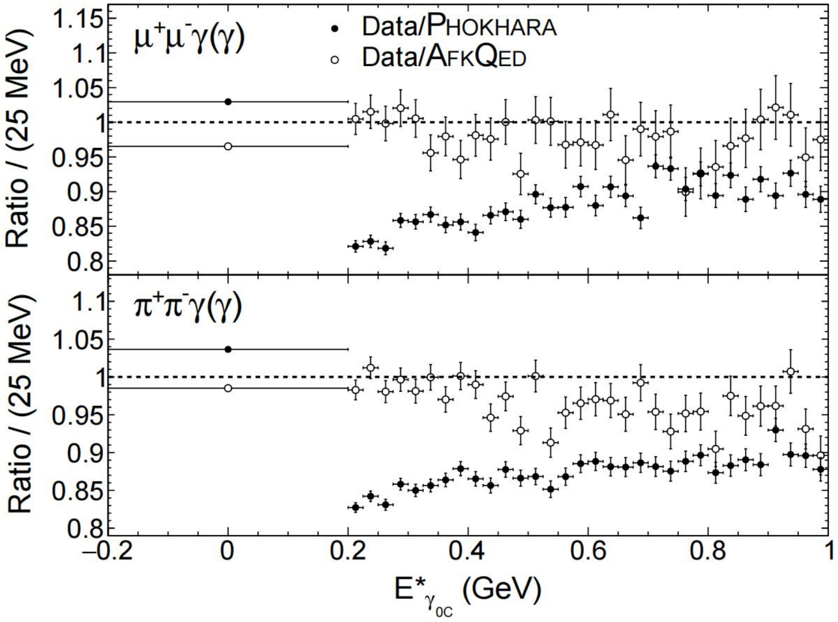
- 4-momentum conservation in $e^+e^- \rightarrow X\gamma_{ISR}\gamma_{0C}$,
- use momenta of both tracks + direction of γ_{ISR},
- $E_{\gamma_{ISR}}$ & γ_{0C} within 0.5 rad to γ_{ISR} direction ignored
  $\rightarrow$ avoid fake photons from shower fluctuations.

Independent of NLO SA fit, no collinear assumption.

- NLO SA in Phokhara overestimated compared to data.
- Similar rate of NLO LA in Phokhara and data.

- **Consistent results** between data and **AfkQED** for LO ($E^*_{\gamma_{0C}} < 200$ MeV) and NLO ($E^*_{\gamma_{0C}} > 200$ MeV).
- **Mismatch** between LO and NLO in data/**Phokhara** ratio, positive slope at $E^*_{\gamma_{0C}} > 200$ MeV.
  $\Rightarrow$ *not due to collinear assumption*.



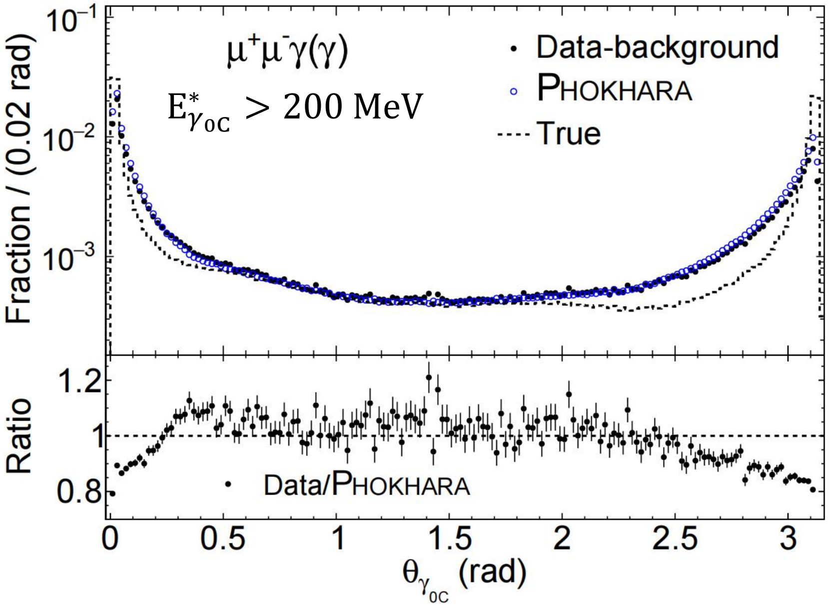


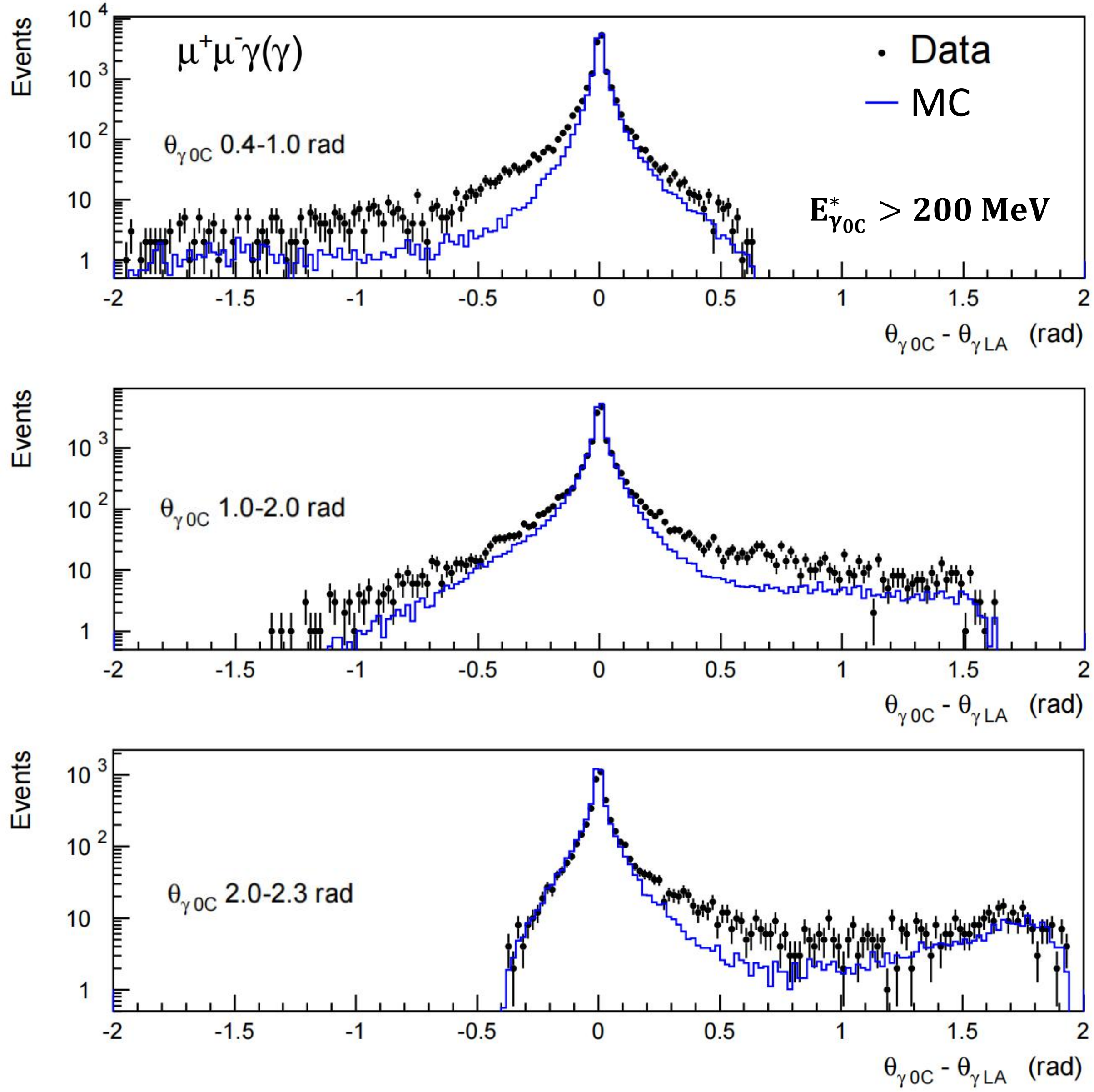
Angular resolution of the 0C calculation

Angular resolution in $\mu\mu\gamma(\gamma)$: comparison of calculated 0C polar angle $\theta_{\gamma_{0C}}$ with fitted LA angle $\theta_{\gamma_{LA}}$.

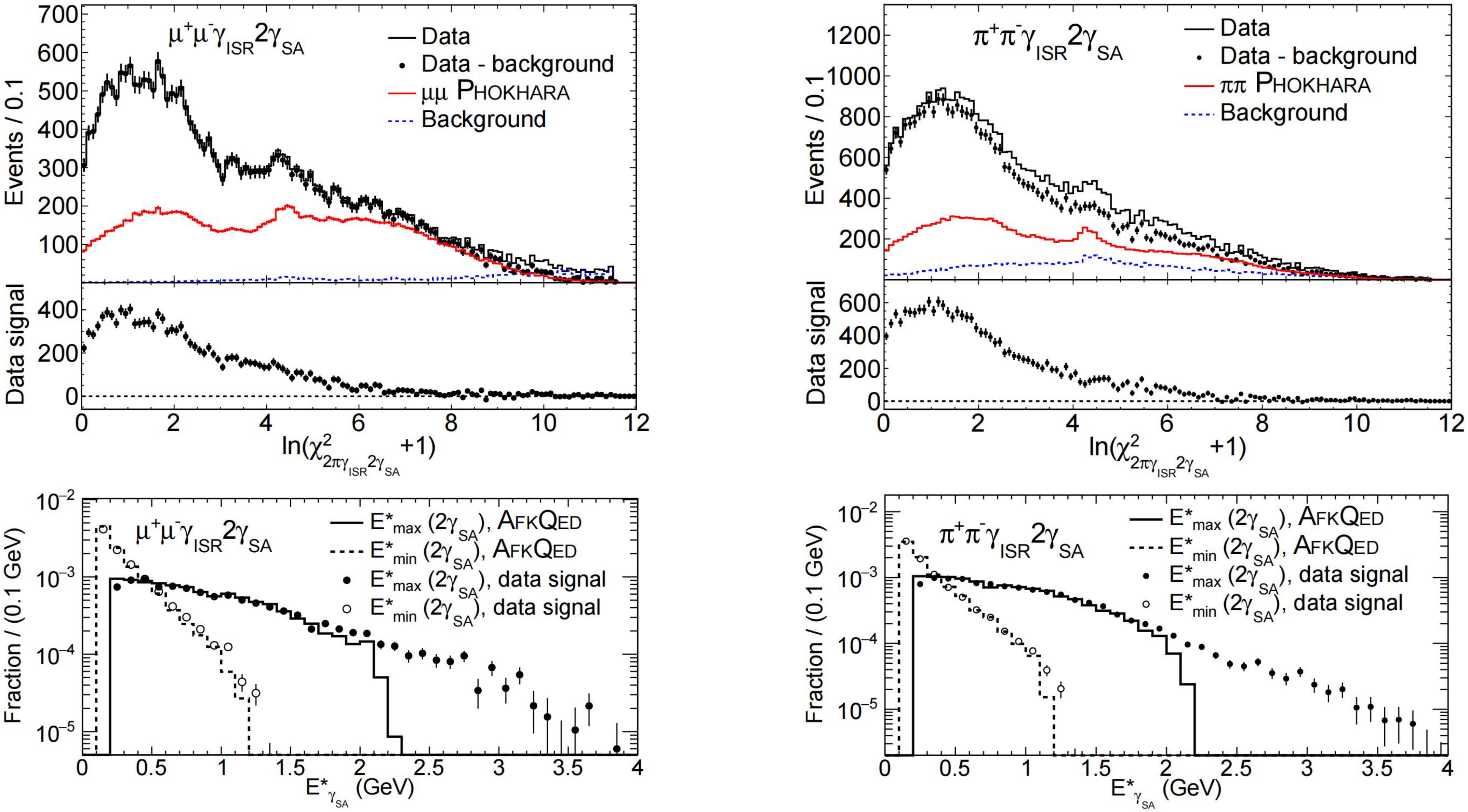
Good data/MC agreement in the core of $\theta_{\gamma_{0C}} - \theta_{\gamma_{LA}}$ $(\mathrm{rms} \approx 30\ \mathrm{mrad})$.

Data more important in the tails: transfer of photons from dominant sharp radiation peak (collinear with beam) towards large angles
→ data/MC ratio enhanced by 10% in central $\theta_{\gamma_{0C}}$ region.





NNLO 2SA fits



Acceptance correction in Phokhara

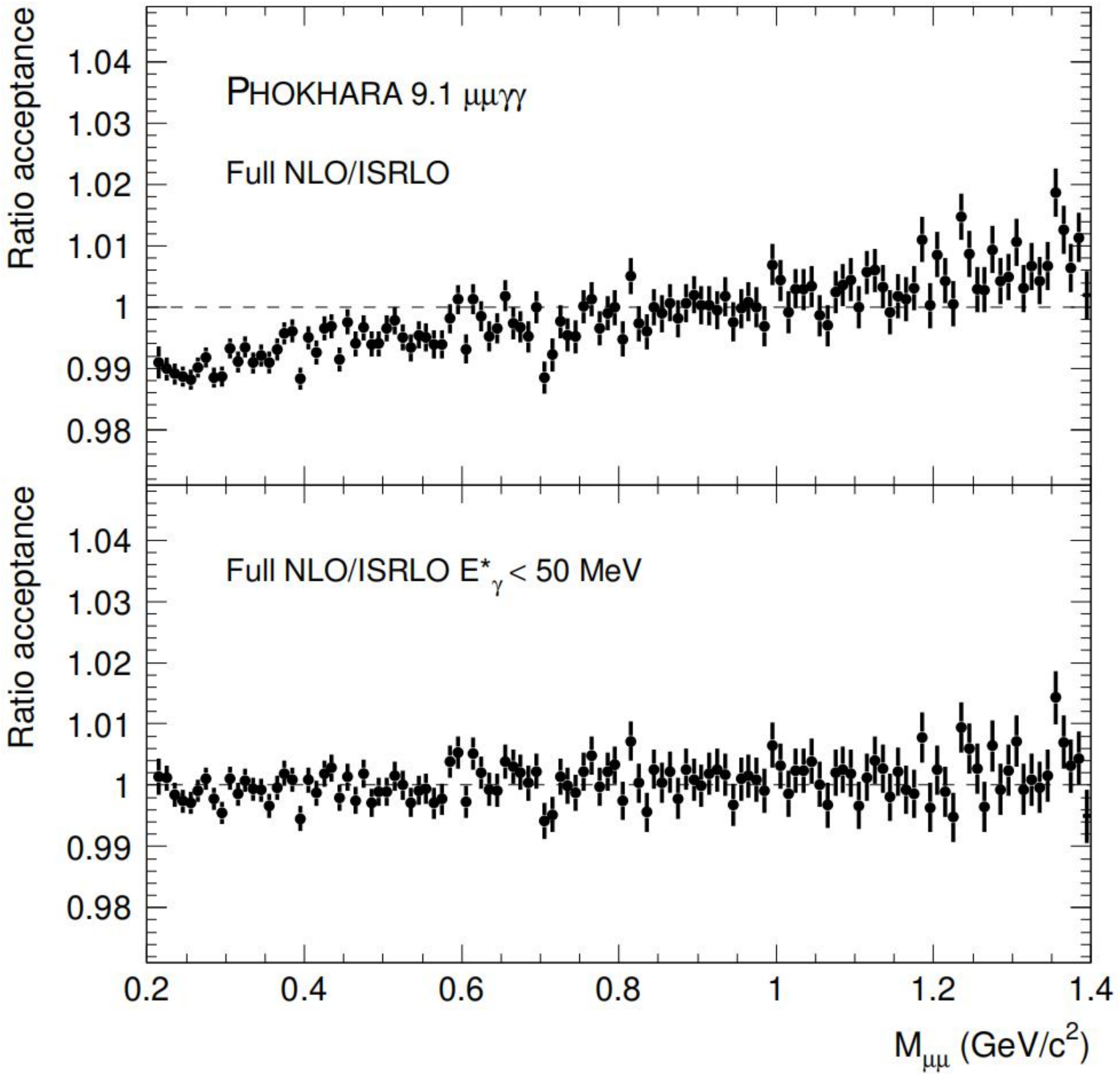
Effect of overestimated hard NLO ($E_{\gamma}^{*} > 50$ MeV) **in Phokhara**:

Ratio of NLO/LO acceptances computed as a function of mass in $\mu\mu\gamma_{\mathrm{ISR}}(\gamma)$ events.

- Bottom plot: *hard NLO excluded*. Same acceptance between final states at LO and virtual+soft NLO (better than 1 per mil).

- Top plot: *full NLO*. Acceptance affected, variations within ±1%.
  → Acceptance correction strongly correlated between $\mu\mu\gamma_{\mathrm{ISR}}(\gamma)$ and $\pi\pi\gamma_{\mathrm{ISR}}(\gamma)$ processes, thus largely reduced in $\pi\pi/\mu\mu$ ratio for cross section measurement (overall correction of 0.9981 ± 0.0004).

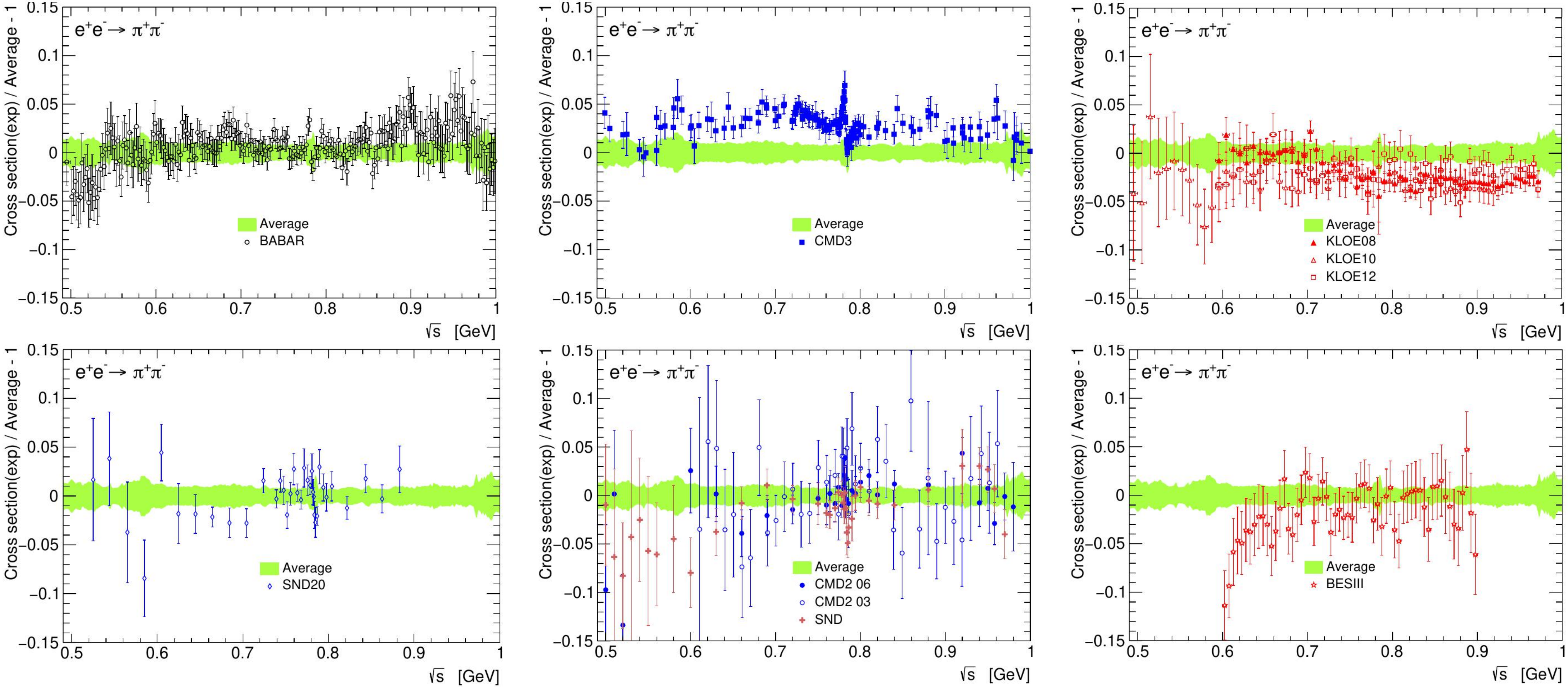
Induces negligible systematic bias of $(0.3 \pm 0.1) \times 10^{-3}$.



Comparison of $\pi^+\pi^-$ cross sections with HVPTools combination

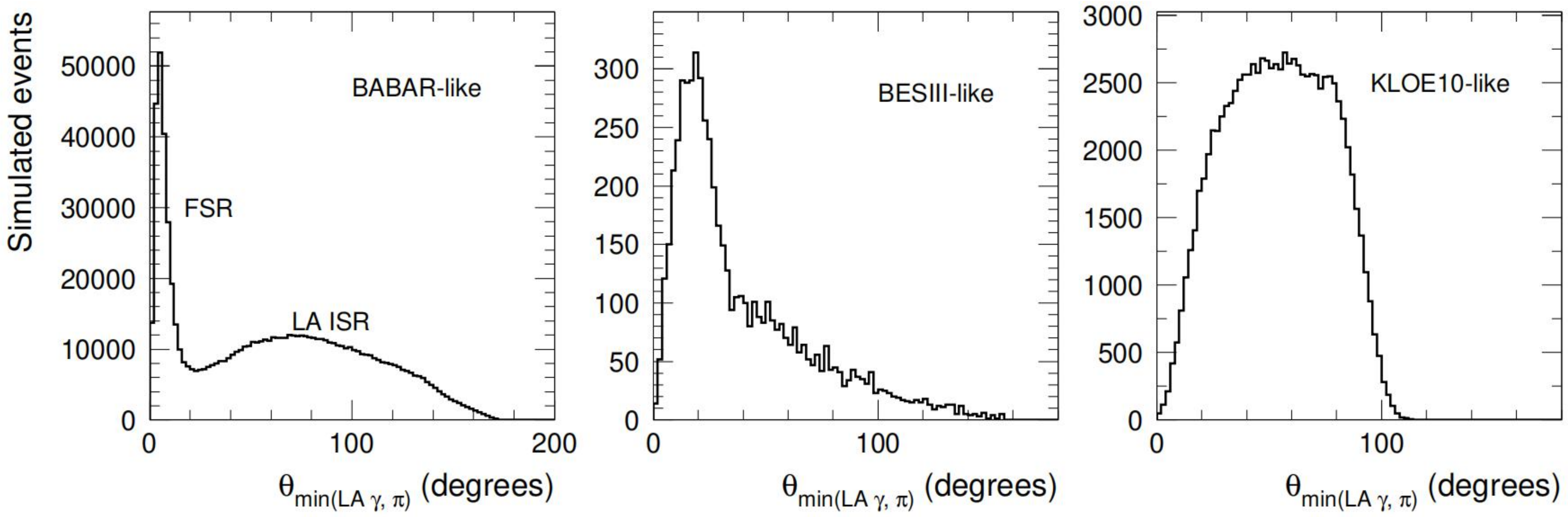
M. Davier, A. Hoecker, A.M. Lutz, B. Malaescu, Z. Zhang
Tensions in e+e−→π+π−(γ) measurements [...]
arXiv:2312.02053 (2023)

References on HVPTools:
Eur. Phys. J. C 66 (2010), 1-9,
Eur. Phys. J. C 66 (2010), 127-136



FSR - LA ISR separation in different experiments

$\boldsymbol{\theta}_{\mathbf{min(trk,}\boldsymbol{\gamma}_{\mathbf{LA}})}$ for simulated $e^+e^- \to \pi^+\pi^-\gamma_{\mathrm{ISR}}(\gamma_{\mathrm{add.}})$ events in the BaBar, BESIII and KLOE10 conditions (fast simulation).



M. Davier, A. Hoecker, A.M. Lutz, B. Malaescu, Z. Zhang
Tensions in e+e−→π+π−(γ) measurements [...]
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