BESIII Inputs to HVP: Status and Plans

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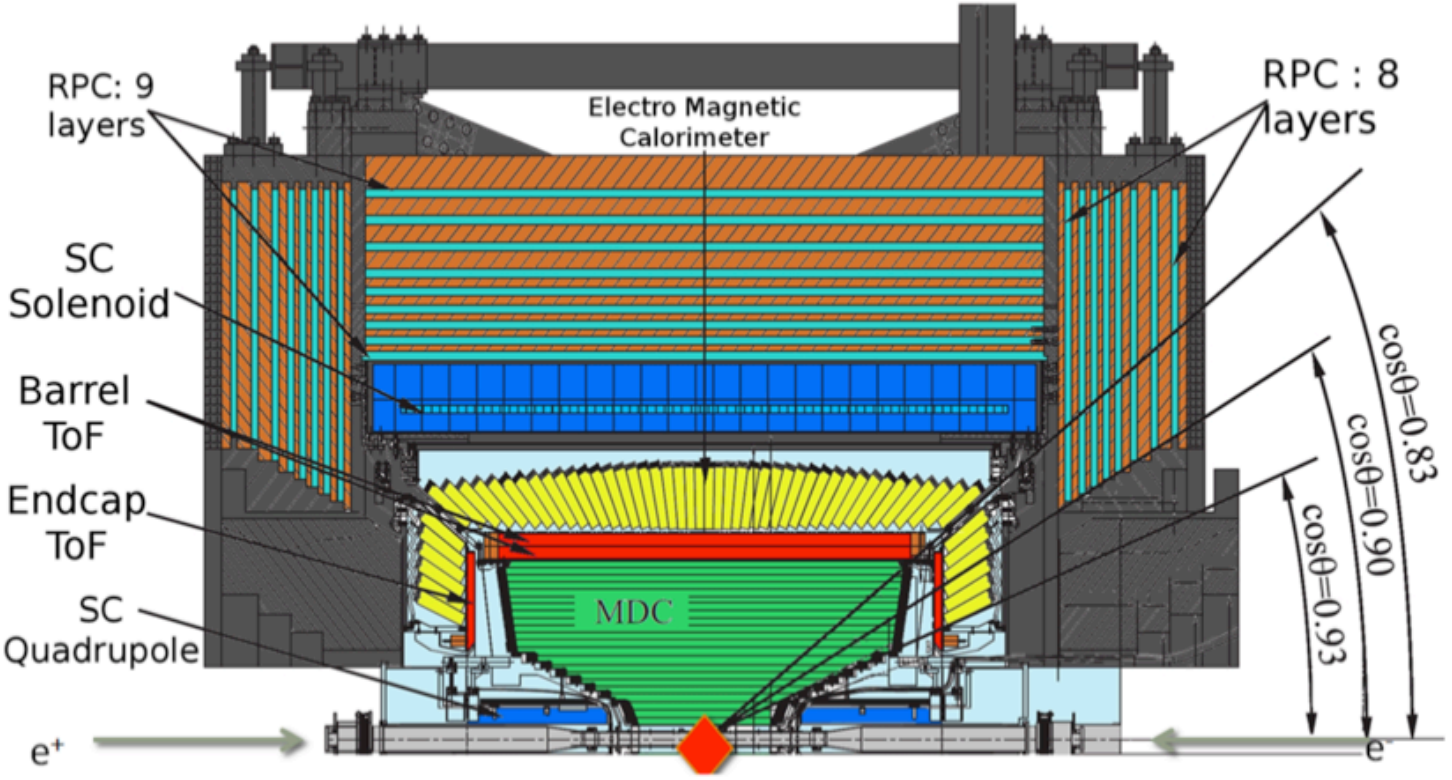
Eighth Plenary Workshop of the Muon g-2 Theory Initiative

Orsay, 08.09.2025

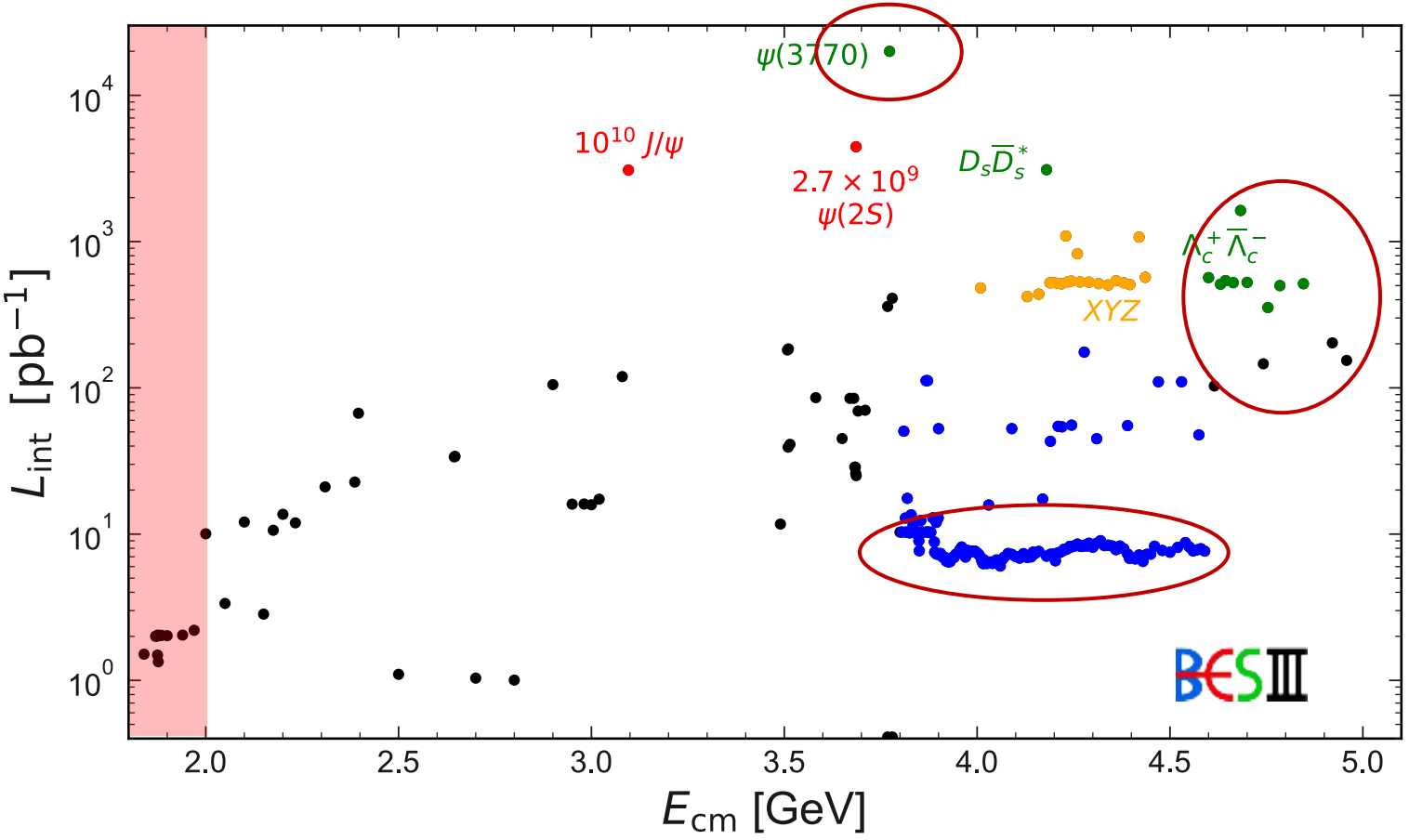
BESIII detector



- Symmetric electron-positron beams with c.m. energy between 1.84~4.95 GeV
- Maximum luminosity reaches 1.2×10^{33} cm^{-2}s^{-1}

- Multilayer drift chamber: $\sigma_{r\phi} \sim 130\ \mu$m (single wire), $\sigma_{p_t}/p_t \sim 0.5\%$@ 1 GeV/$c$
- Time-of-Flight system: $\sigma_t \sim 68$ ps (barrel), $\sigma_t \sim 110 \rightarrow 65$ ps (end-cap)
- Electromagnetic calorimeter: $\sigma_E/E < 2.5\%$ (barrel), $\sigma_E/E < 5.0\%$ (end-cap) at 1 GeV
- Resistive plate chamber Muon counter: $\Delta\Omega/4\pi = 93\%$

Data samples at BESIII



- 20 fb^{-1} at $\psi(3773)$, ISR returned $\pi^+\pi^-, \pi^+\pi^-\pi^0$, $K^+K^-, K_S^0K_L^0, 4\pi, \ldots$, and R
- 13 scan points in 1.84~2.00 GeV, an inclusive measurement of R
- More than 100 scan points in the open-charm region for R measurement

BESIII contribution to HVP

Published results:

- Time-like Pion Form Factor, 600 ~ 900 MeV, **Phys. Lett. B 753, 629 (2016)**
- R measurement, 2.23 ~ 3.67 GeV, **Phys. Rev. Lett., 128, 062004 (2022)**
- Several exclusive channels, 2.00 ~ 3.08 GeV, $\pi^+\pi^-\pi^0$, K^+K^-, $K_S^0K_L^0$, $\phi\pi^+\pi^-$, $\eta'\pi^+\pi^-$

Ongoing analysis:

- $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-$, 0.3 ~ 1.0 GeV, and $(\gamma_{\rm ISR})\pi^+\pi^-$, $m_{\pi\pi} > 1.0$ GeV
- $e^+e^- \to \gamma_{\rm ISR}K^+K^-/K_S^0K_L^0$, 1.0 ~ 3.0 GeV and $(\gamma_{\rm ISR})K^+K^-$, in 1.2 ~ 3.2 GeV
- $e^+e^- \to \gamma_{\rm ISR}q\bar{q}$, 0.3 ~ 2.0 GeV
- $e^+e^- \to q\bar{q}$ with scan points in 1.84 ~ 2.00 GeV and the open-charm region

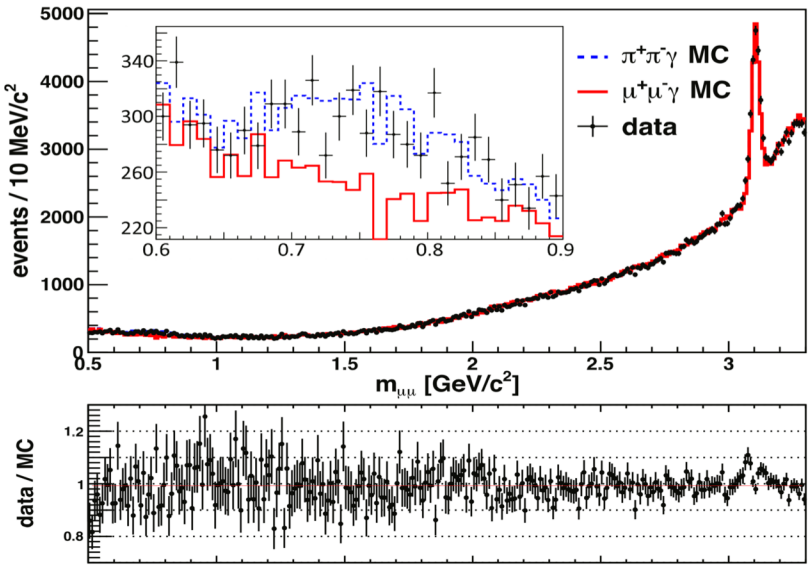
	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(0.83)(3.23)(0.55)	504.23(1.90)	3.62
$\pi^+\pi^-\pi^0$	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
K^+K^-	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
K_SK_L	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)(3.48)(1.47)	623.62(2.27)	2.46

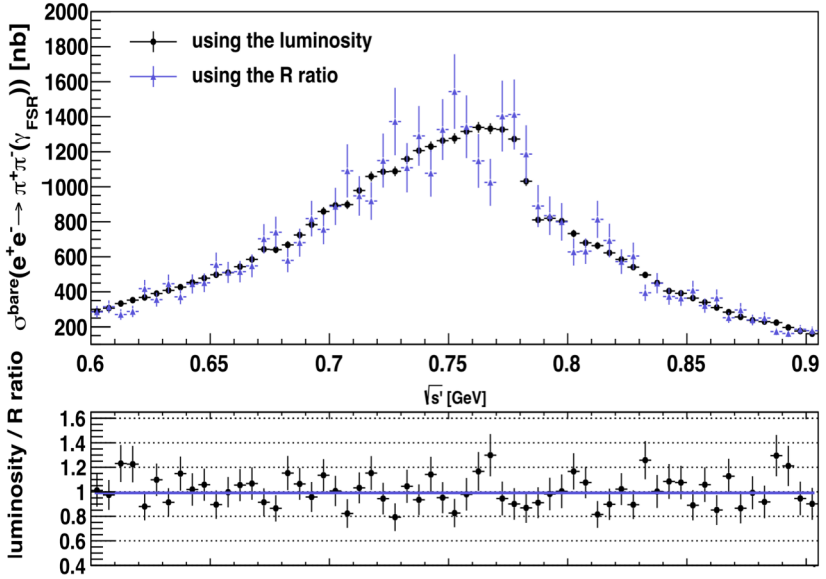
Pion form factor at BESIII

Tagged ISR analysis: $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-$ Phys. Lett. B 753, 629 (2016)

- 4C kinematic fit with the $\pi^+\pi^-\gamma$ hypothesis and $\chi^2_{\rm 4C} < 60$ is required
- dominant background is $\mu^+\mu^-\gamma$ events and a μ/π separation is realized with ANN

Validation and cross checks using $\mu^+\mu^-\gamma$ events

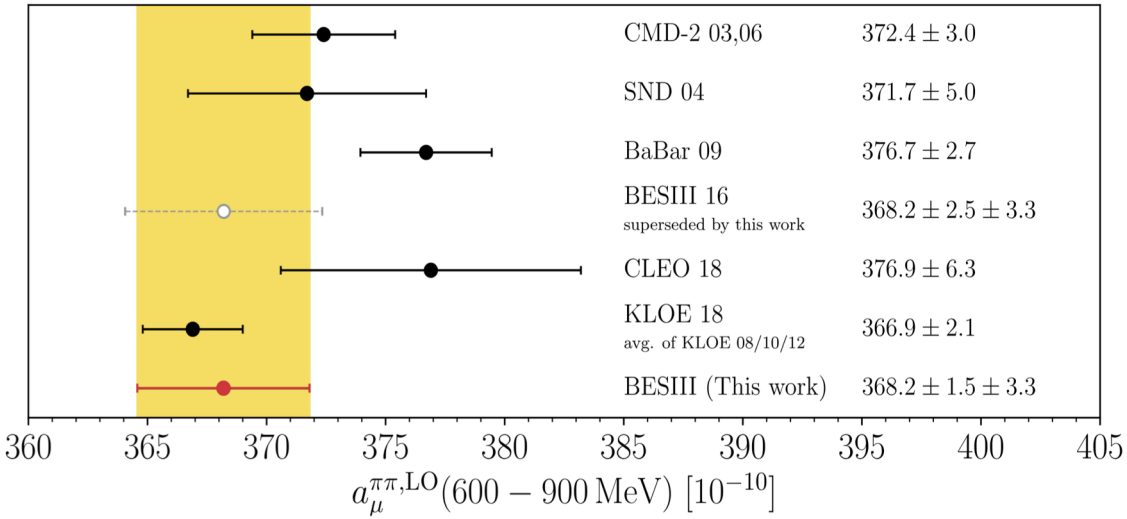




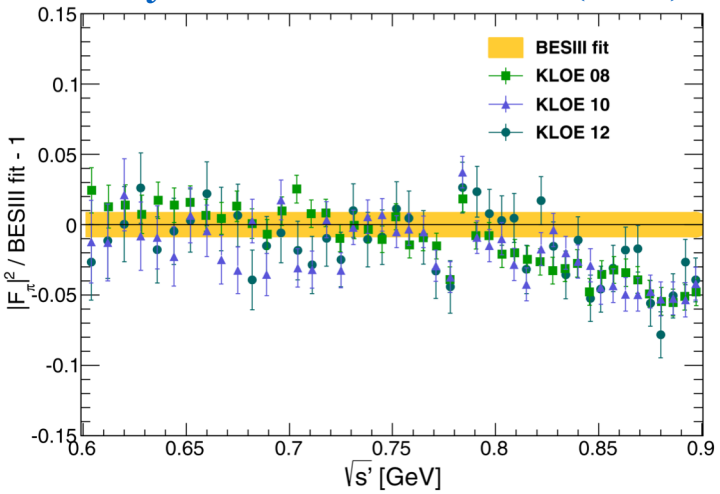
- Good MC-data agreement in $m_{\mu\mu}$ validates the corrections to signal efficiency
- Consistent bare cross sections within uncertainty are observed when normalizing the yields with luminosity and $\mu^+\mu^-\gamma$ events

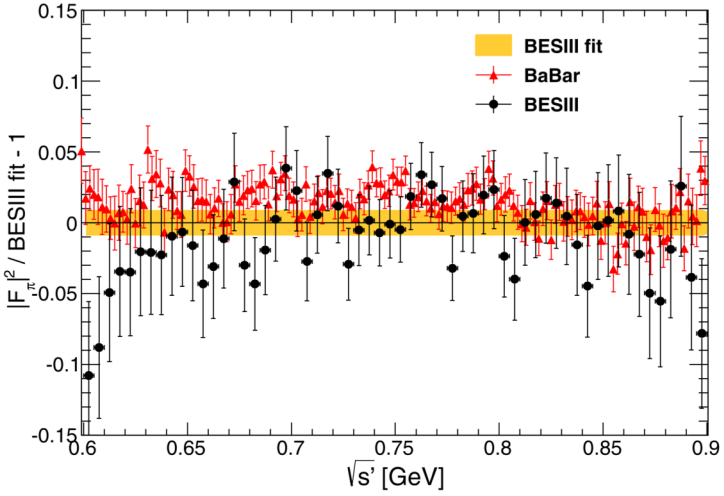
Pion form factor at BESIII

Contribution to a_μ:



Phys. Lett. B 753, 629 (2016)
Phys. Lett. B 812, 135982 (2021)





- Lower statistical uncertainty of a_μ is obtained after the covariance matrix being corrected
- Precision competitive with current best results:
  - BESIII: 1.0%
  - BaBar: 0.7% (2009) , 0.6% (2025)
  - KLOE: 0.6%
- Precision of 0.5% is expected at BESIII with 20 fb^{-1} data

Pion form factor at BESIII

New analysis on going: $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-$

First result with accuracy of 0.7%:

- Data sets at $\sqrt{s} = 3.773$ and 4.178 GeV
- Integrated luminosity ~6 $\rm fb^{-1}$
- 1C kinematic fit as nominal and 4C cross check
- Investigation of NLO radiative effects
- Normalization to integrated luminosity
- Blind analysis will be implemented

sources	Uncertainty (%)
Photon efficiency	0.2 → 0.0
Tracking efficiency	0.3 → 0.2
Pion ANN efficiency	0.2
Pion e-PID efficiency	0.2 → 0.0
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction $\delta_{\rm FSR}$	0.2
Vacuum polarization correction $\delta_{\rm vac}$	0.2
Radiator function	0.5
Luminosity $\mathcal{L}_{\rm int}$	0.5 → 0.3
Sum	**0.9 → 0.7**

Important cross checks:

- Perform previous measurement with different methods: 4C → 1C
- Apply same method at different c.m. energies: $\sqrt{s} = 3.773 \to 4.178$ GeV
- Measure the luminosity with a new method to reduce its uncertainty
- Compare the normalizations with the integrated luminosity and the $\mu^+\mu^-$ events

Pion form factor at BESIII

Current status:

- ✓ Blinding and unblinding strategies are defined and implemented

Three steps of blinding:

1. **Statistics**: use 5% of data sample, 2~5% accuracy achievable
2. **Form factor in MC**: scale by ±2% with $m_{\pi\pi}$-dependent function
3. **PID corrections**: scale elements of correction matrices by ±2%

Pion form factor at BESIII

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Main idea is preventing us from any bias!

Pion form factor at BESIII

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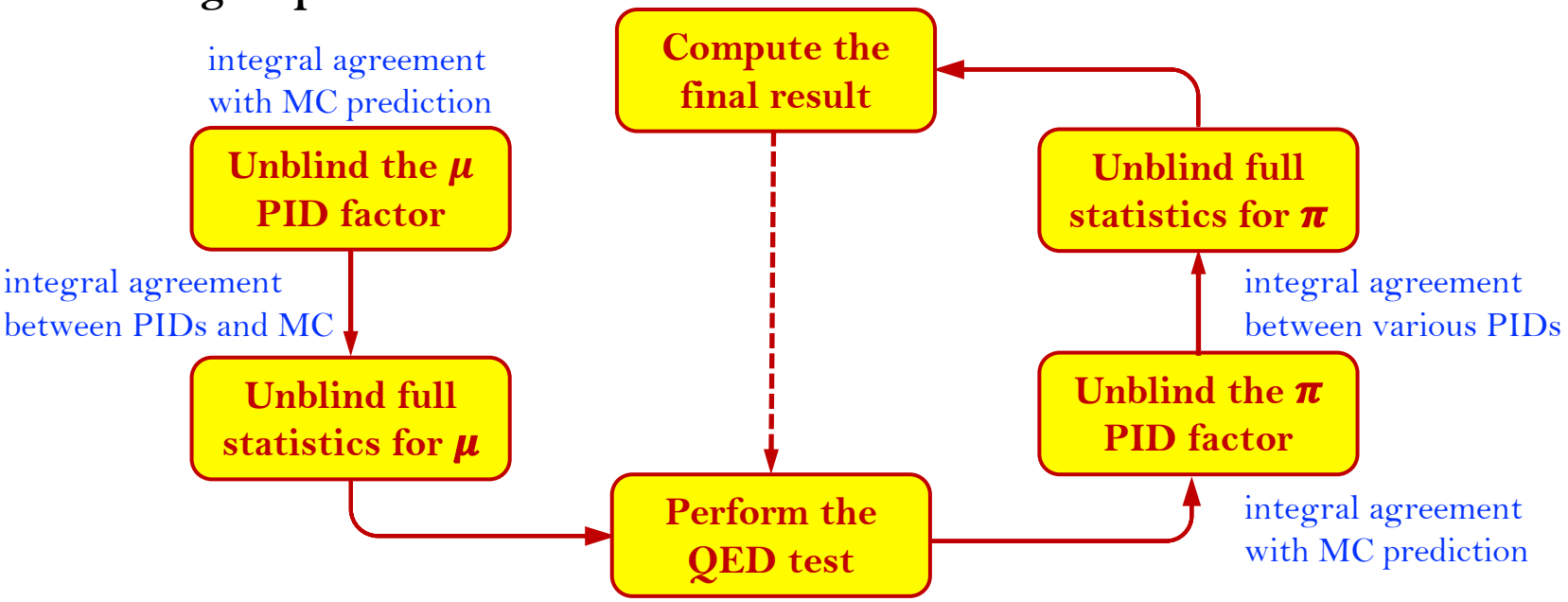
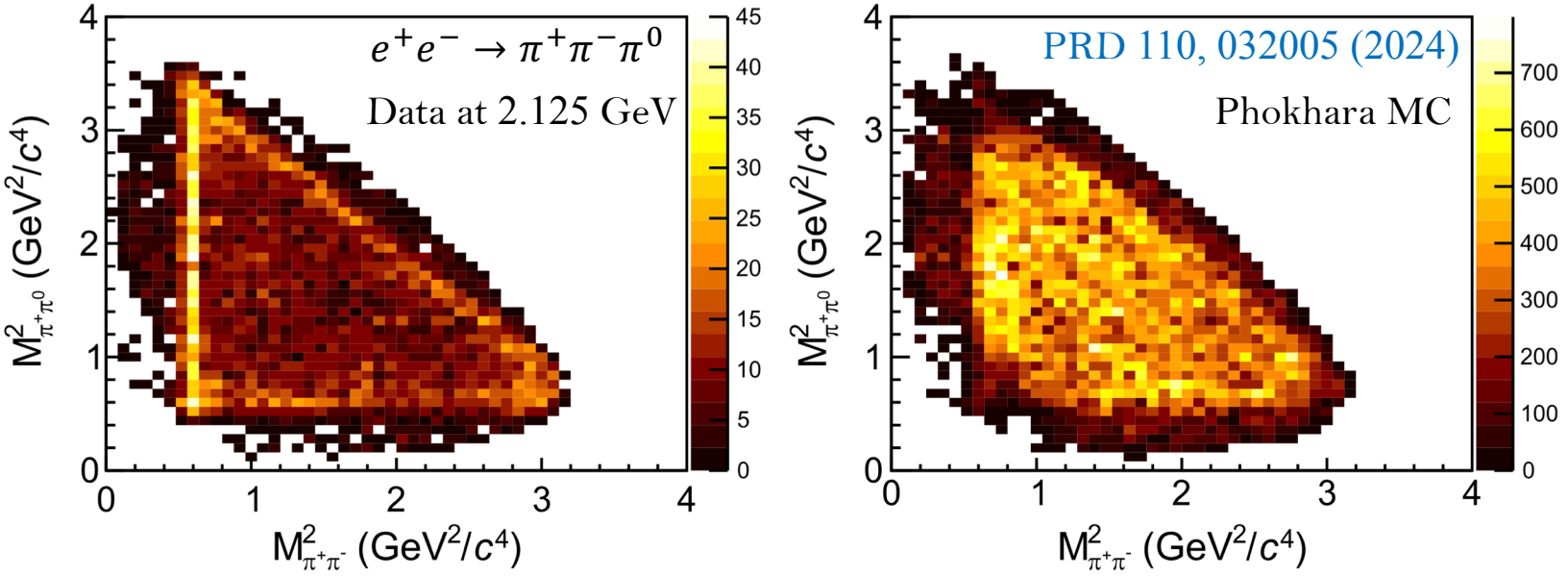
Unblinding steps:



Pion form factor at BESIII

Current status:

- ✓ Blinding and unblinding strategies are defined and implemented
- ✓ Event selection criteria are defined and frozen
- ✓ Dominant background is prompt $\pi^+\pi^-\pi^0$ event and evaluated via PWA
- ✓ Various corrections to efficiency are under finalization
- ✓ Systematic uncertainties under study
- ✓ Preparing documentation for internal review



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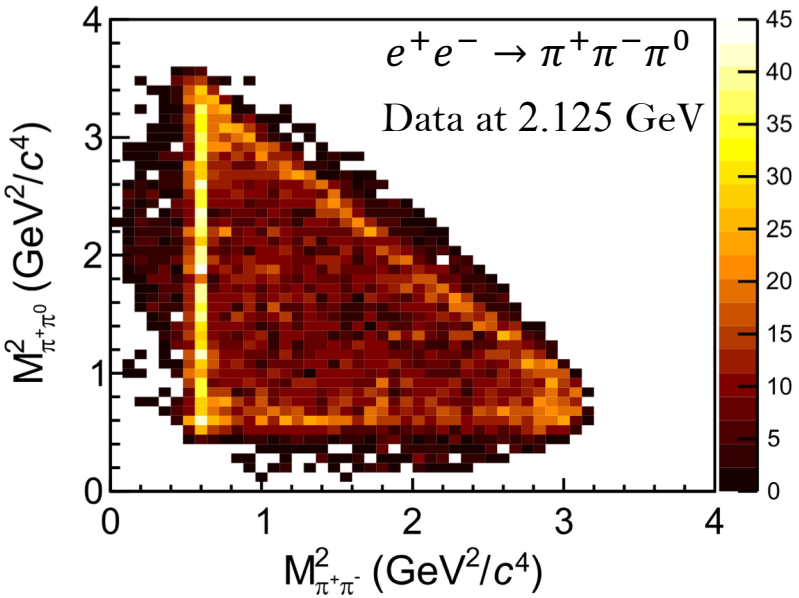
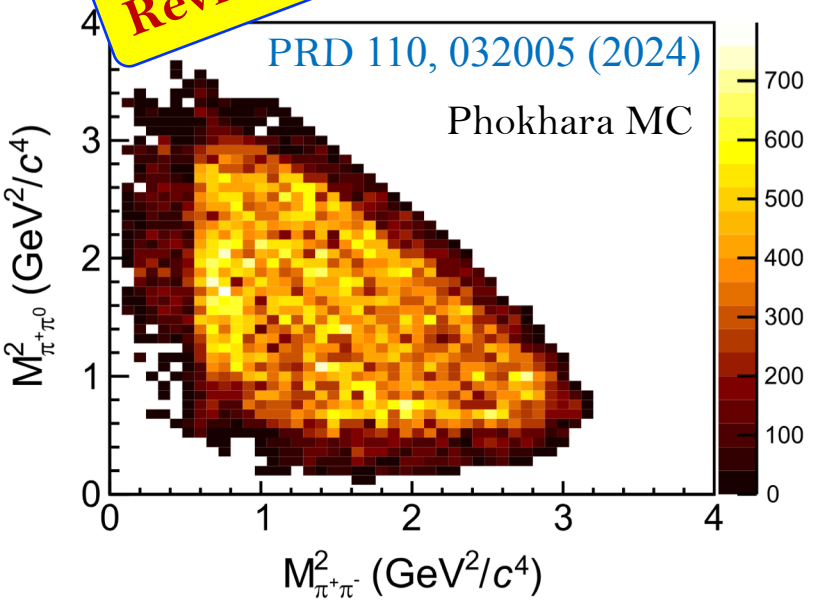
Review start expected in Fall 2025





Pion form factor at BESIII

Final result with accuracy of 0.5%:

- All the new data sets at $\sqrt{s} = 3.773$
- Integrated luminosity $\sim 17\ \mathrm{fb}^{-1}$
- 1C kinematic fit as nominal and 4C cross check
- Full PID and angular fit methods
- Investigation of NLO radiative effects
- Normalization to $\mu^+\mu^-$ events
- Blind analysis will be implemented

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Vacuum polarization correction δ_{vac}	0.2
Radiator function	0.5 → 0.0
Luminosity $\mathcal{L}_{\mathrm{int}}$	0.5 → 0.0
Sum	**0.9 → 0.5**

Important cross checks:

- Precise measurements with different methods: 4C and 1C kinematic fits
- Compare the $\boldsymbol{\mu/\pi}$ separation between ANN and fit on the angular distribution
- Compare the normalization with the $\mu^+\mu^-$ events and the integrated luminosity
- Compare results obtained with data sets taken in different rounds

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Two PhD students work on this respectively!

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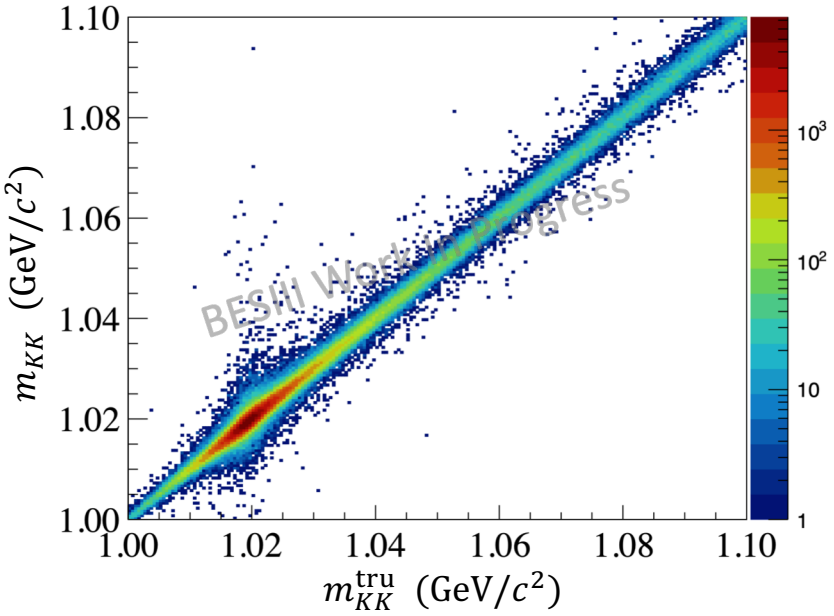
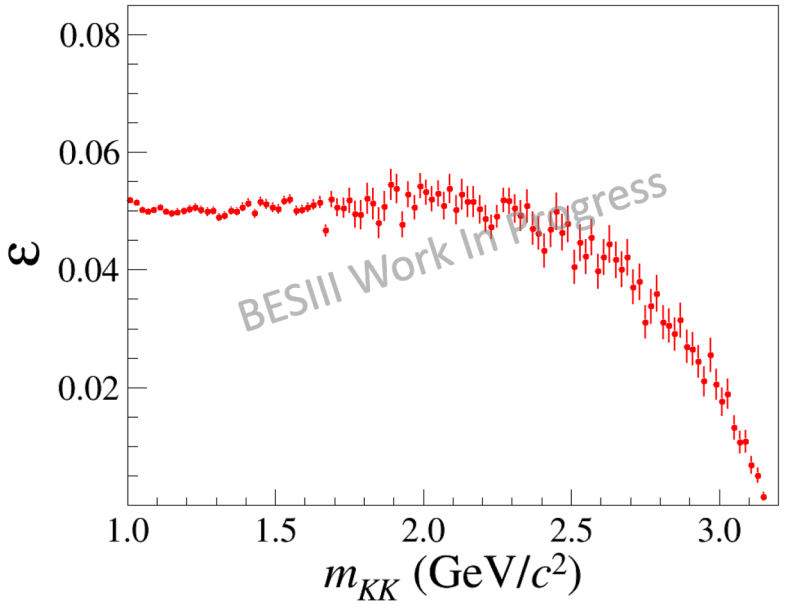
Kaon form factor at BESIII

Tagged ISR analysis: $e^+e^- \to \gamma_{\rm ISR}K^+K^-$

- Kaon identification based on energy loss ($\mathrm{d}E/\mathrm{d}x$) and TOF information
- 4C kinematic fit with the $K^+K^-\gamma$ hypothesis, $\chi^2_{\rm 4C} < 50$ and $\chi^2_{\rm 4C} < \chi^2_{\rm 4C,2\gamma}$ are required
- Data-driven method is used to estimate the remain background $K^+K^-\pi^0$ and $\pi^+\pi^-\pi^0$



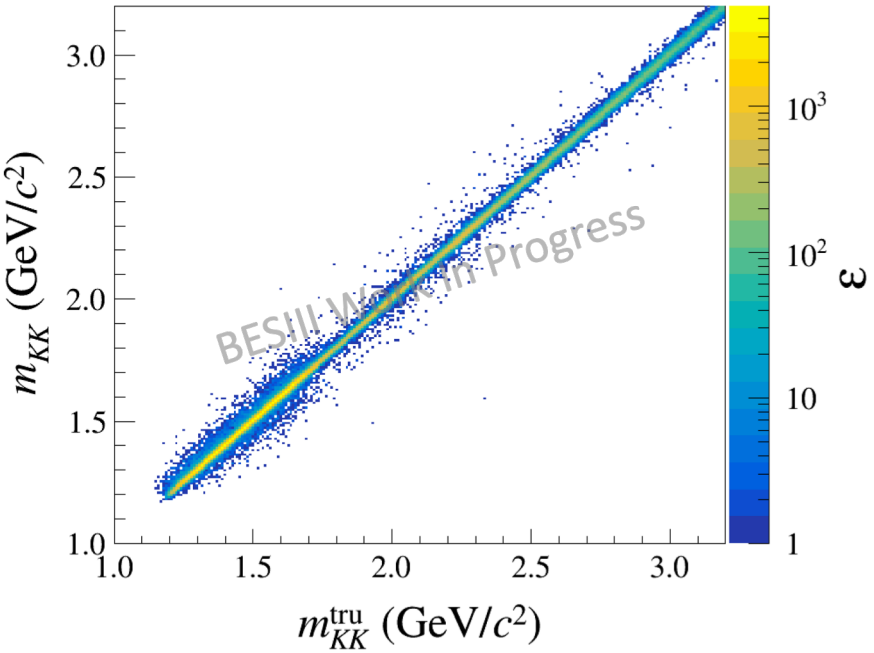


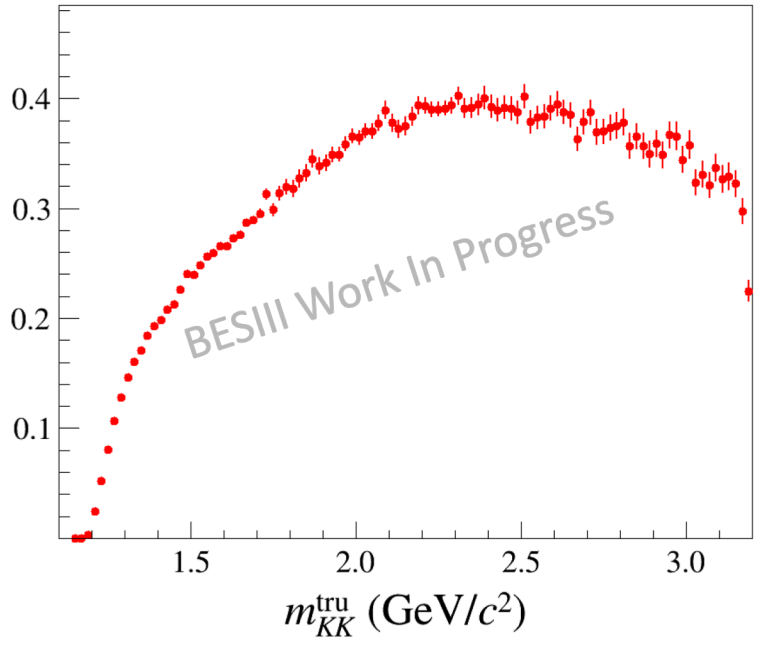
- Background ratios around the $\phi(1020)$ peak (mainly from $\pi^+\pi^-\pi^0$) is ~0.1%
- m_{KK}-independent detection efficiency (~5%) below 2.0 GeV/c^2
- With all the available data samples, a statistical uncertainty of 0.9% is expected

Kaon form factor at BESIII

Untagged ISR analysis: $e^+e^- \to (\gamma_{\rm ISR})K^+K^-$

- Kaon identification based on energy loss ($\mathrm{d}E/\mathrm{d}x$) and TOF information
- A missing ISR photon is implied by $|\cos\theta_{miss}| > 0.99$ where $P_{\rm miss} = P_{\rm c.m.} - P_{K^+} - P_{K^-}$
- Signal extracted by requiring $U_{\rm miss} = E_{\rm miss} - p_{\rm miss} \in [-0.1, 0.1]$ GeV



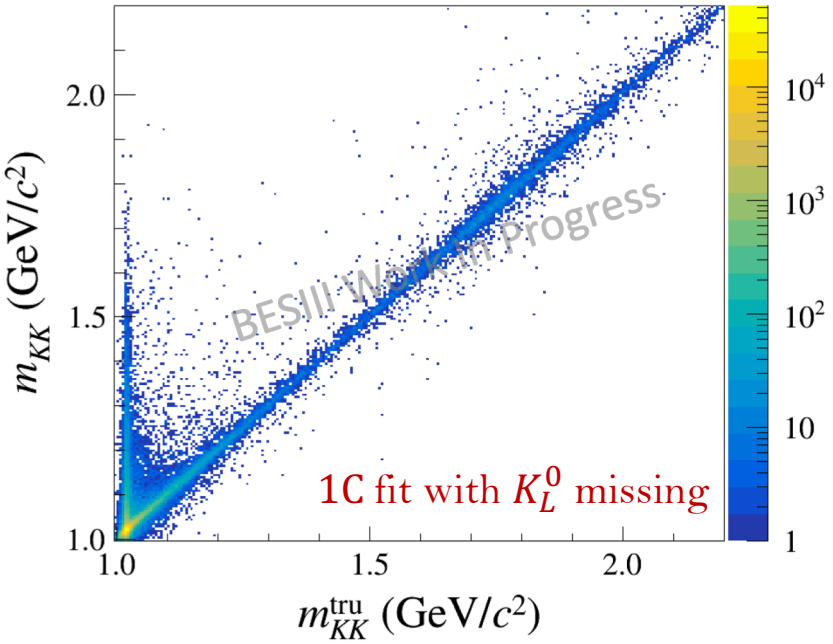


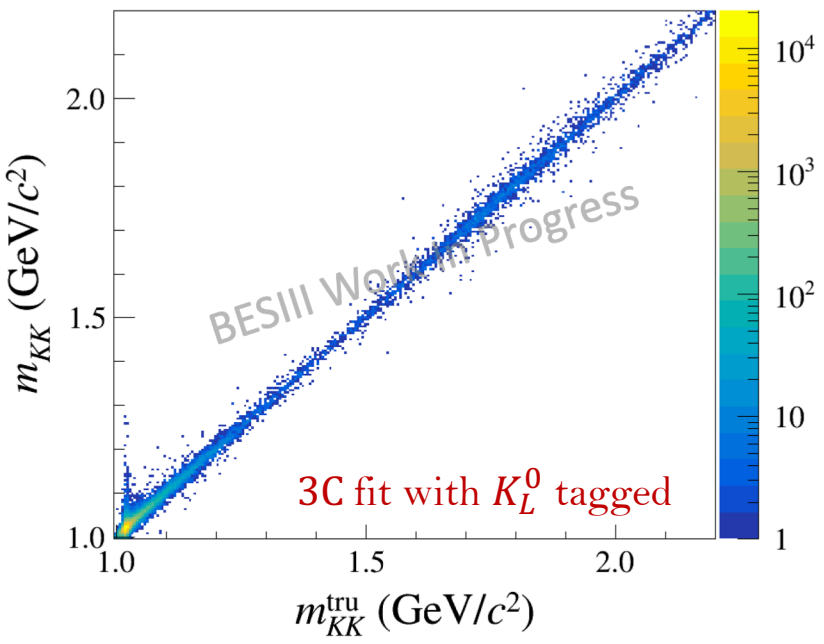
- The $\phi(1020)$ peak is no longer accessible and the response matrix is diagonal
- m_{KK}-dependent detection efficiency due to the boost effect of the missing ISR photon
- Dominant background is from $K^+K^-\pi^0$ (~2.5%) and estimated via a data-driven method

Kaon form factor at BESIII

Tagged ISR analysis: $e^+e^- \to \gamma_{\rm ISR} K_S^0 K_L^0$

- A good identification of K_S^0 is required to improve the resolution of m_{KK}
- 1C kinematic fit with the K_L^0 missing to reserve sufficient statistics around $\phi(1020)$
- 3C kinematic fit with direction of K_L^0 tagged to suppress background above $\phi(1020)$





- Roughly 50% signal events will be lost with tagging the K_L^0 direction in EMC
- A joint analysis strategy combining 1C around $\phi(1020)$ and 3C above is preferred

R measurement via ISR below 2 GeV

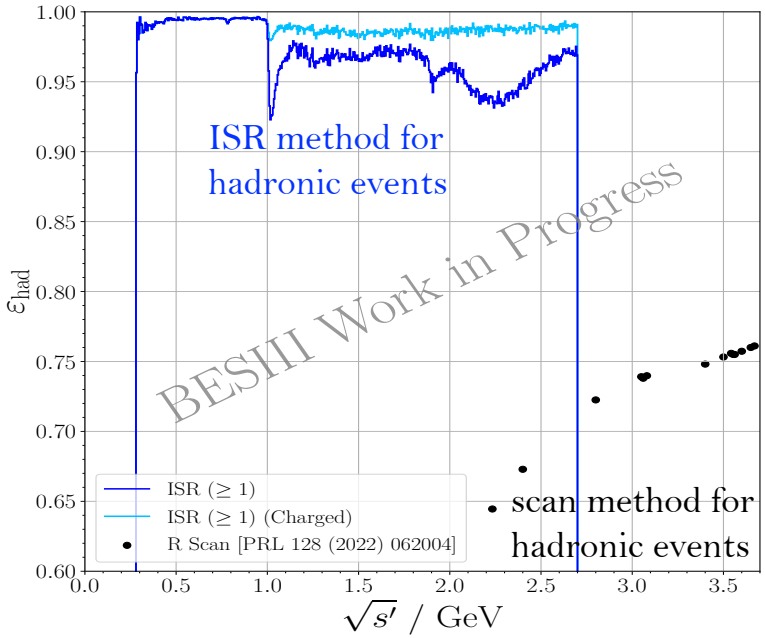
New idea: determine hadronic mass via energy of ISR photon only!

Simple events selection:

- 1 high-energetic photon at large polar angle: $E > 1.2$ GeV and $|\cos\theta| < 0.8$
- At least one charged track in each event

Advantages:

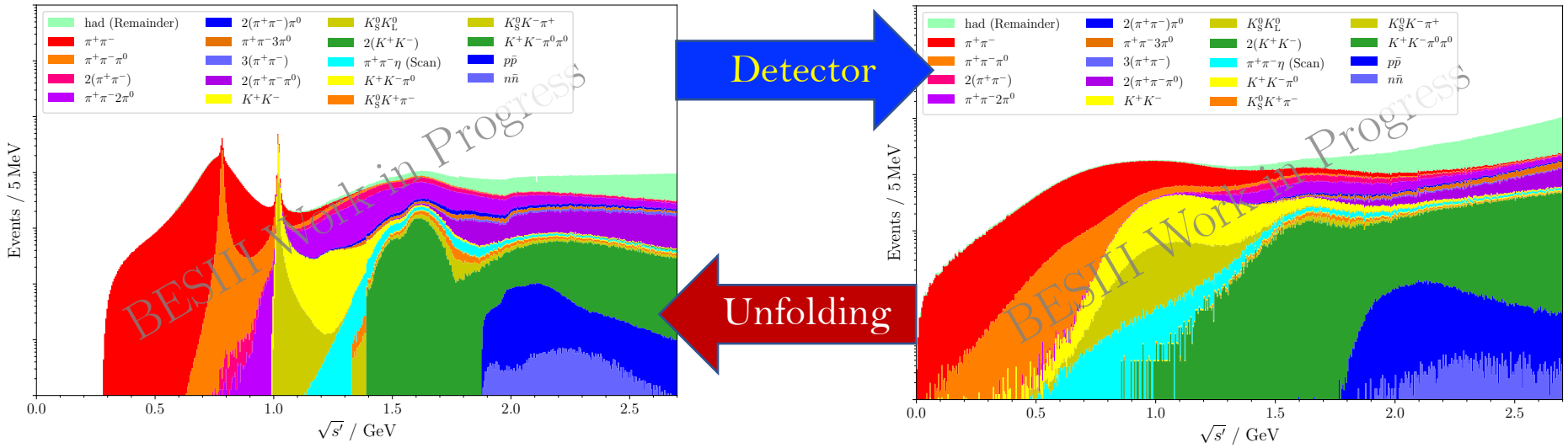
- Very high efficiency due to boost of ISR photon
- Less reliant on description of hadronic MC
- Single measured down to threshold
- Fully inclusive for FSR and higher order ISR



Challenges:

- Significant QED backgrounds due to their higher cross section: dedicated PID needed
- Background from non-ISR hadronic events containing π^0/η: dedicated vetoes
- Limited resolution due to high energy of ISR photon: unfolding of hadronic mass spectrum

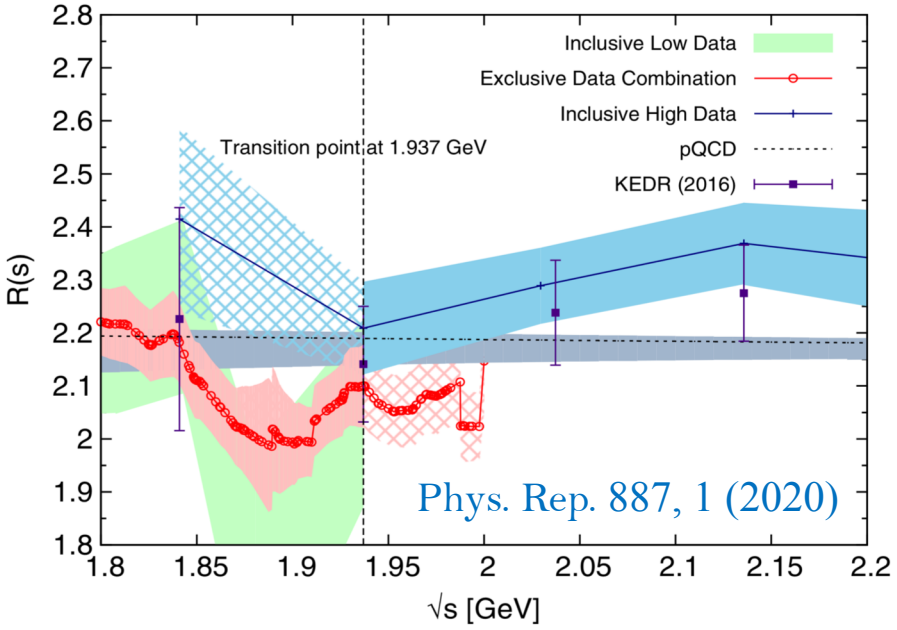
R measurement via ISR below 2 GeV

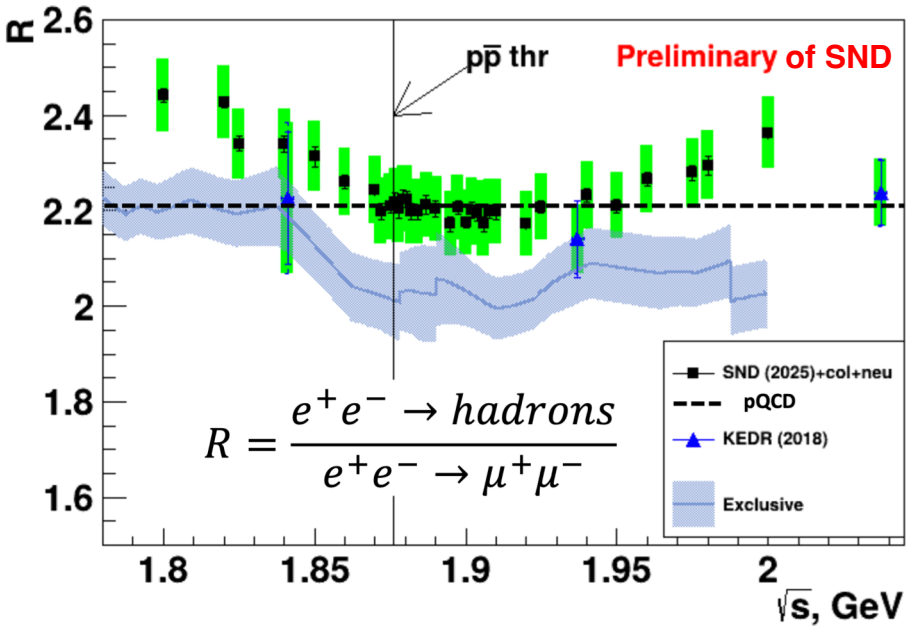


- Large smearing is caused by detector: track lost, photon energy leakage, …
- An un-biased unfolding is crucial to recover the true hadronic mass spectrum
- Fractions and shapes of $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ channels in the signal MC samples producing response matrix are modified to test the unfolding method
- Unfolded spectra keep unchanged within the corresponding standard deviation

R measurement at scan points below 2 GeV

Comparison of R between inclusive and exclusive sum is of particular interest:



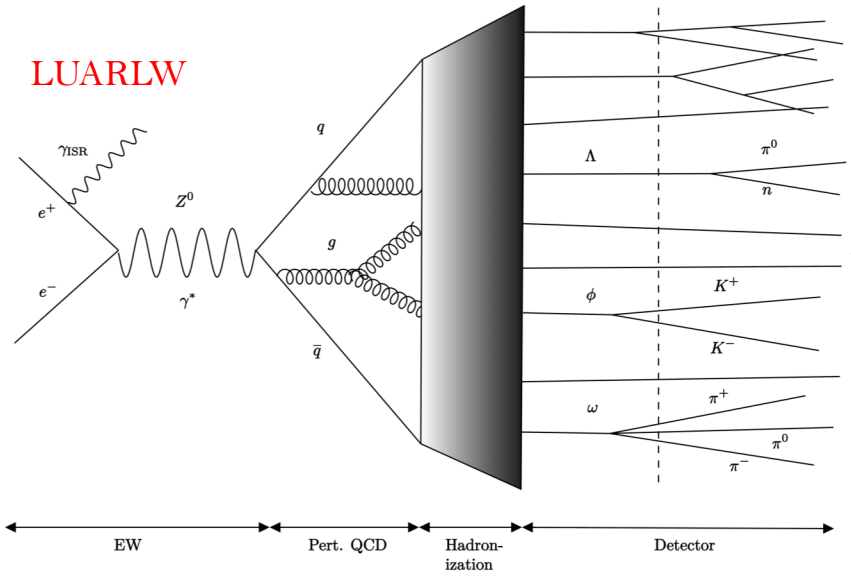


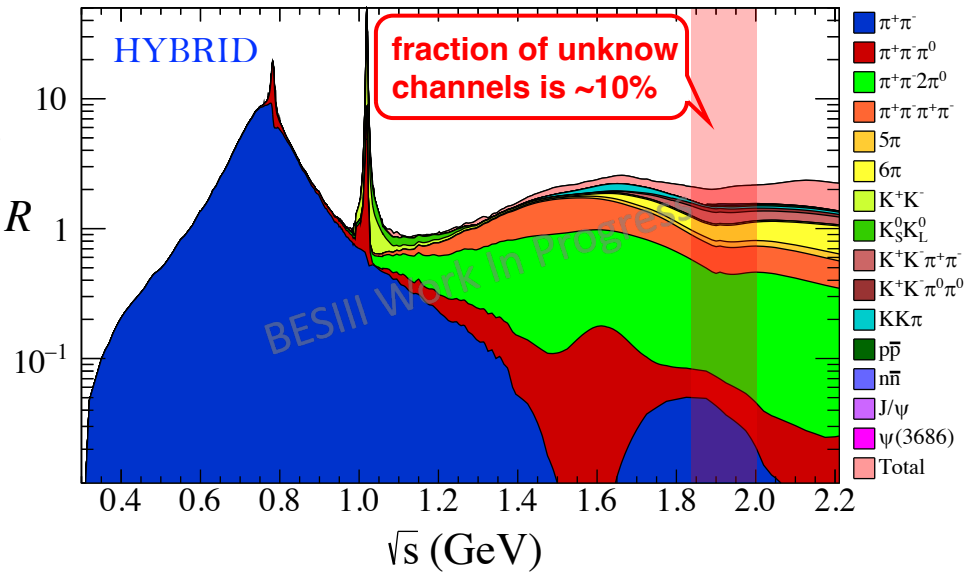
- KEDR results are consistent with exclusive sum within uncertainty
- Preliminary results of SND higher than exclusive sum by 10%
- SND results reproduce the trend of the exclusive sum around proton threshold
- BESIII has taken 13 scan points of which the statistic uncertainties are less than 0.5%

R measurement at scan points below 2 GeV

Great efforts have been made at BESIII to measure *R* inclusively:

completely inclusive measurement → larger QED background: ee, $\mu\mu$, $\gamma\gamma$ → **at least 2 tracks, not back-to-back** → $\pi\pi$, KK, $p\bar{p}$, $n\bar{n}$ fully removed, three-body events partially removed → **reliable simulation is crucial**

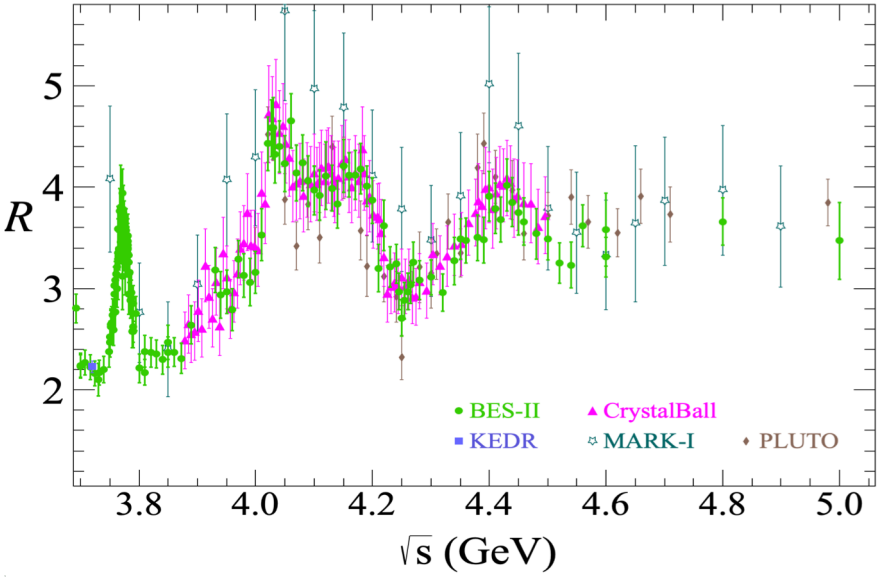


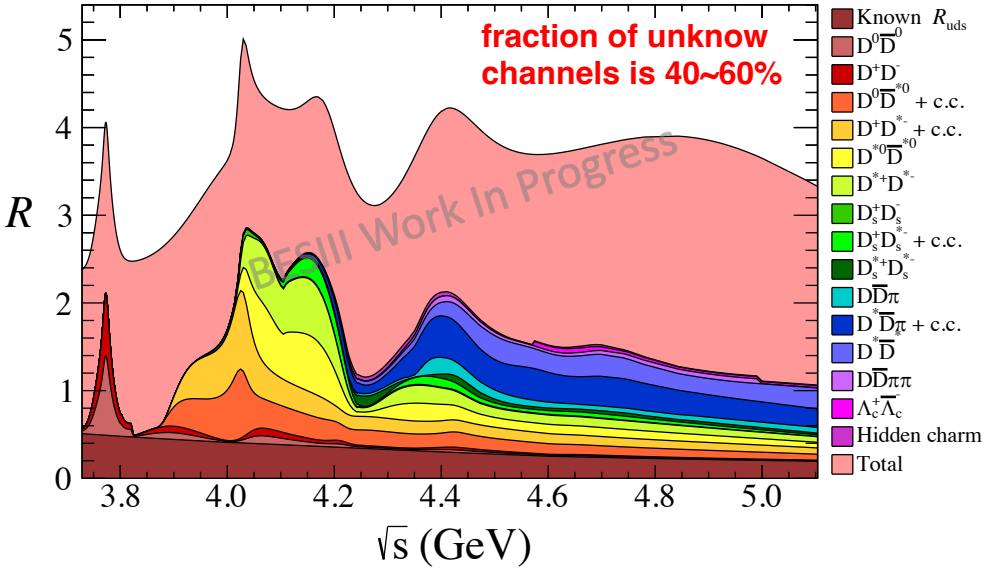


- Fractions and kinematics of few-body exclusive channels in MC is essential for efficiency
- Two relatively different simulation models are utilized to address the systematic uncertainty
- Final state radiations are included in the measured R values, which is evaluated as ~0.15%
- Internal review has already started and final result will come next year

R measurement in open-charm region

There is more possibility of inclusive *R* measurement at BESIII:





Why *R* measurement in open-charm region?

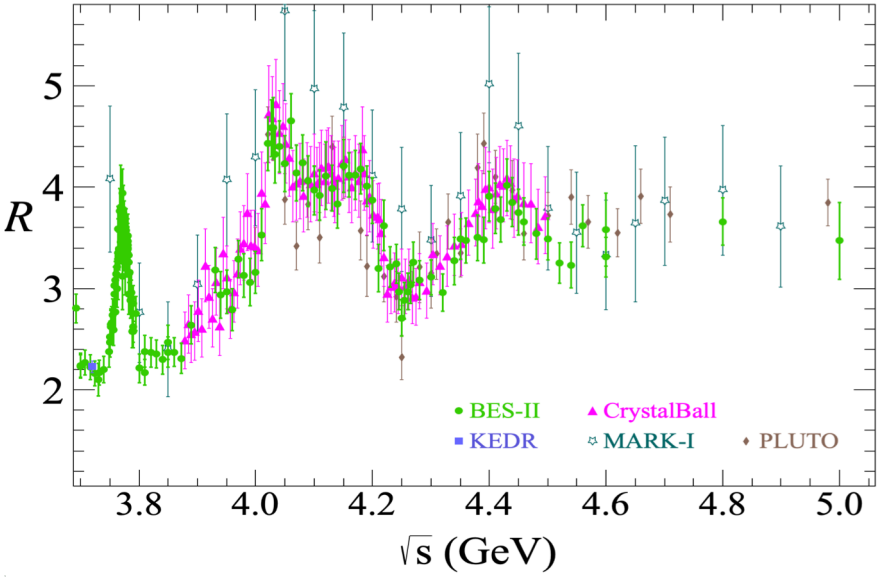
- pQCD could not describe the data due to the existence of excited charmonium resonances
- Significant uncertainty in current data: 6~7% for BES-II and 10% for CrystalBall

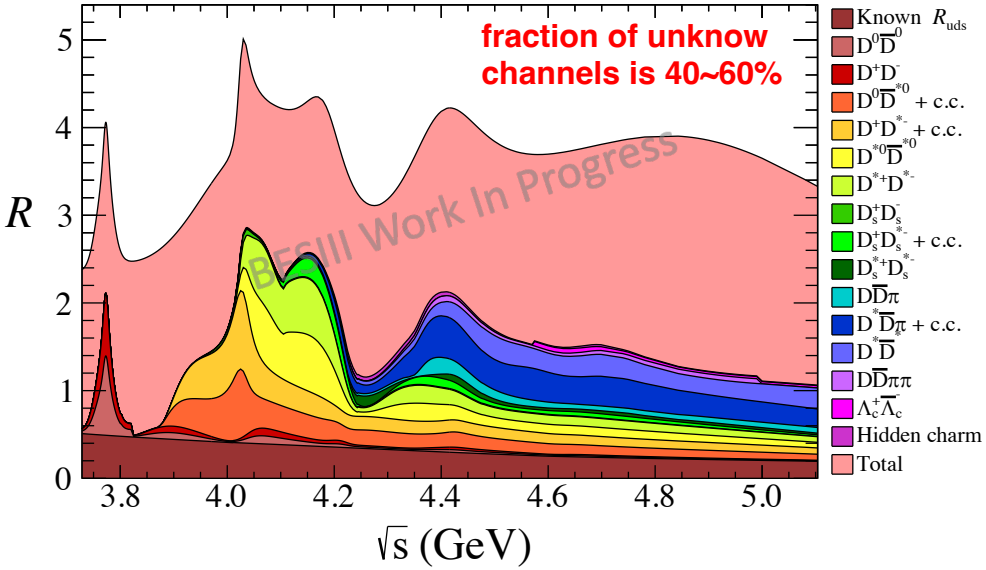
Why BESIII could do better?

- Data at more that 100 scan-points with high luminosity: statistical uncertainty less than 0.3%
- All the few-body open-charm channels are measured: more reliable signal simulation
- Two extensively investigated signal simulation models: better understanding of sys. uncertainty

R measurement in open-charm region

There is more possibility of inclusive *R* measurement at BESIII:





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Final result expected in next year!

Summary

BESIII strongly engaged in providing experimental inputs to HVP!

Published results:

- Pion form factor with sub-percent precision between $600 \sim 900$ MeV
- Most precise R measurement between $2.23 \sim 3.67$ GeV

The best is still to come:

- Pion form factor with $\mathcal{O}(0.7\%)$ precision
- Kaon form factor via tagged and untagged ISR methods
- Inclusive R measurement from threshold to 2.0 GeV via ISR
- Inclusive R measurement at 13 scan points from 1.84 to 2.0 GeV
- Inclusive R measurement in the open-charm region
- Pion form factor with $\mathcal{O}(0.5\%)$