Experimental Inputs to HVP at the BESIII Experiment

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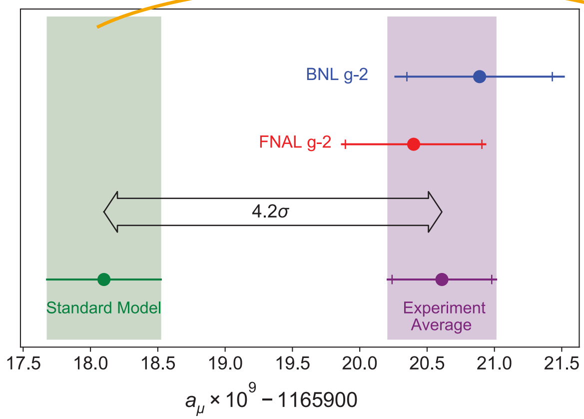
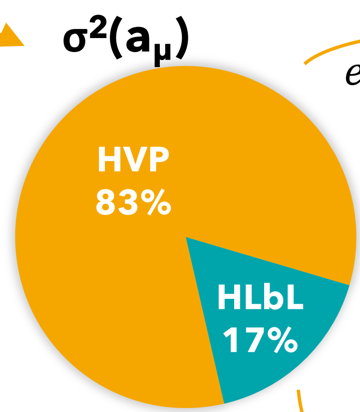
Muon g-2 Theory Initiative Workshop

Edinburgh, 5-9 September 2022

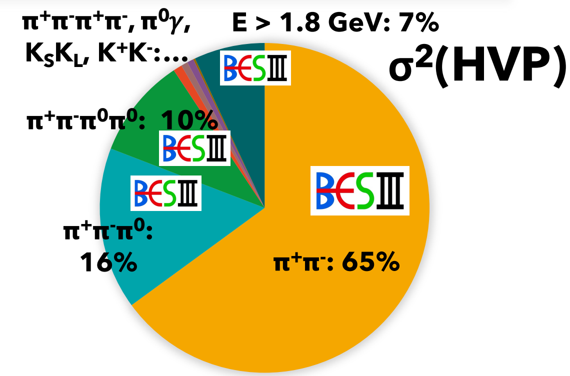
Muon (g-2): SM and Experiment



[Phys.Rev.Lett. 126 (2021) 141801]



$e^+e^- \rightarrow had$



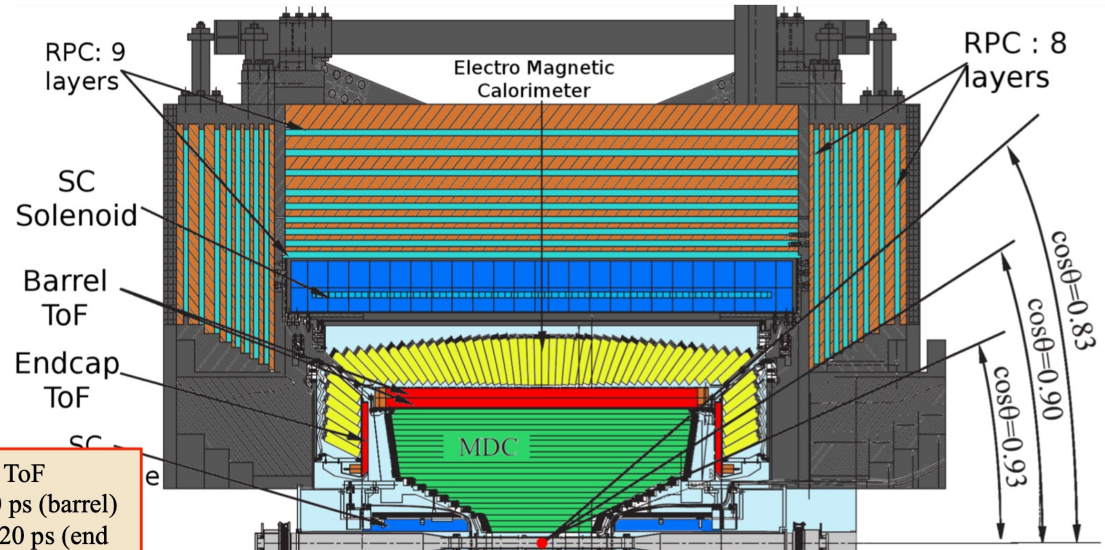
[Data from: Phys.Rep 887 (2020) 1-166]

$\gamma^{(*)}\gamma^{(*)} \rightarrow hadrons$

BESIII

- New result from FNAL confirms tension with SM (4.2σ!)
- Improvement of SM prediction highly desirable
- Uncertainty dominated by HVP and HLbL
- BESIII can provide important inputs to reduce the uncertainty!

The BESIII Experiment (1)



ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

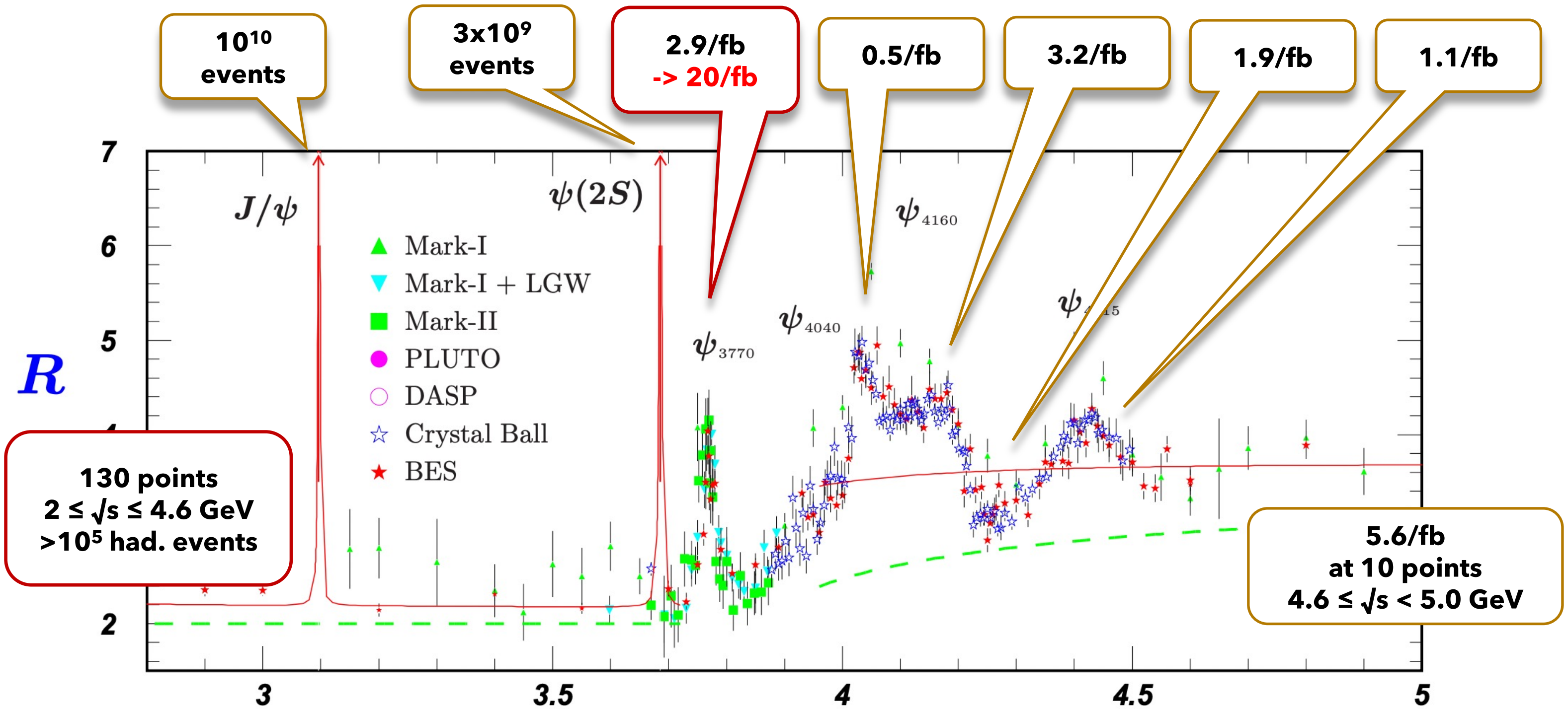
Drift Chamber
$\sigma_{r\phi} \sim 130$ μm (single wire)
$\sigma_{pt}/p_t \sim 0.5$ % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\ \text{mm})/E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi = 93\%$

- Located at the BEPCII collider (Beijing, China)
- Symmetric e^+e^- beams
- ECM between 2-5 GeV
- Maximum luminosity: 1 nb^{-1}/s
- 93% coverage of the solid angle

The BESIII Experiment (2)

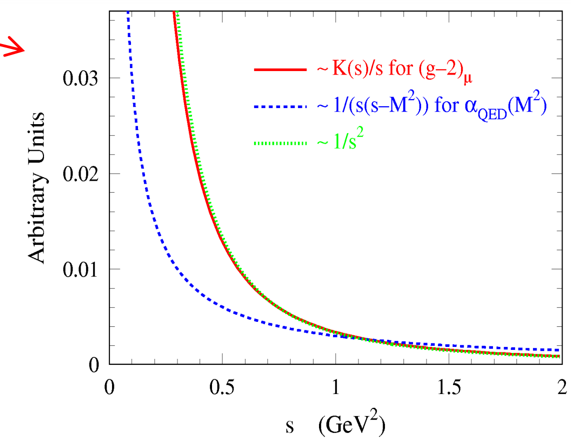


- World largest τ-charm dataset in e^+e^- annihilation
- Detailed studies in:
  - Charmonium spectroscopy and charm physics
  - Light hadron dynamics
  - τ-physics
  - R-scan

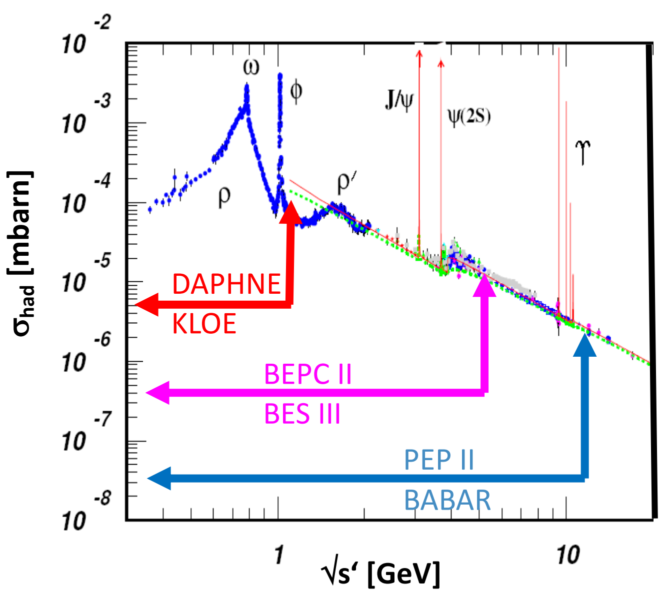
Initial State Radiation: Scan at Fixed Energy

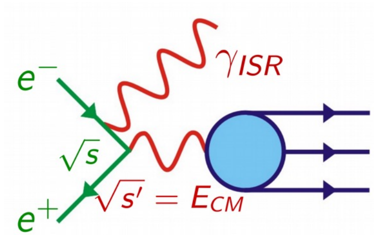
[Brodsky, de Rafael, 1988]

$$a_\mu^{HVP,LO} = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$



- Dominated by low energy region
- Not accessible in scan mode
- Initial State Radiation (ISR)





$$\sqrt{s'} = \sqrt{s - 2\sqrt{s}E_\gamma}$$

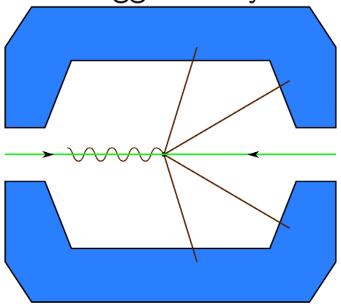
- Effectively reduces $\sqrt{s}$
- Emission suppressed by $\frac{\alpha}{\pi}$
- Radiator function relates ISR to non-radiative process

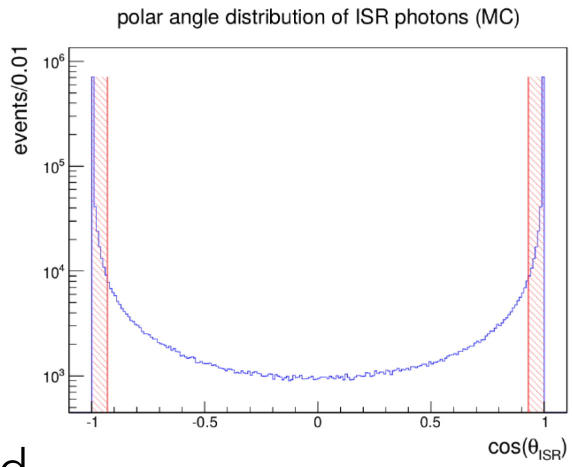
$$\frac{d\sigma_{ISR}(\sqrt{s'})}{d\sqrt{s'}} = \frac{2\sqrt{s'}}{s} W\left(s, E_\gamma, \theta_\gamma\right) \sigma(\sqrt{s'})$$

Initial State Radiation: Analysis Strategy

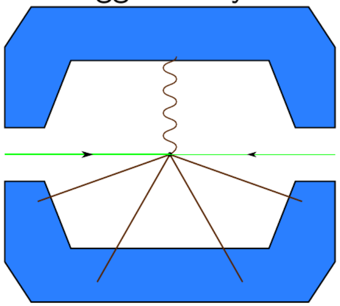
Detect full hadronic system

Untagged analysis





Tagged analysis



ISR photon undetected

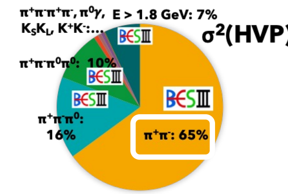
- High statistics
- Only high masses accessible (>900 MeV)
- Small background

ISR photon detected

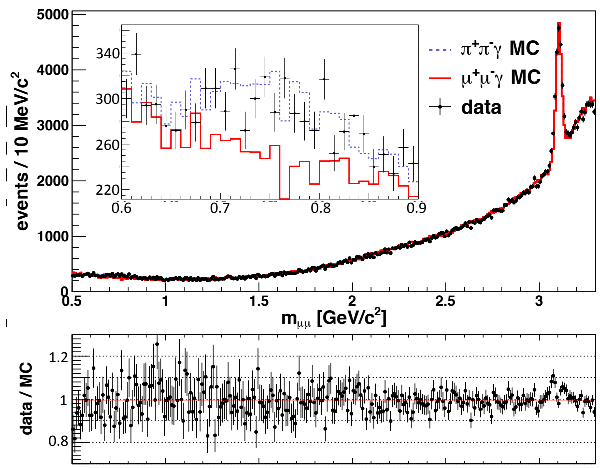
- Access to had. threshold region
- Large background at high masses

In the following results from 2.93 fb^{-1} at 3.773 GeV

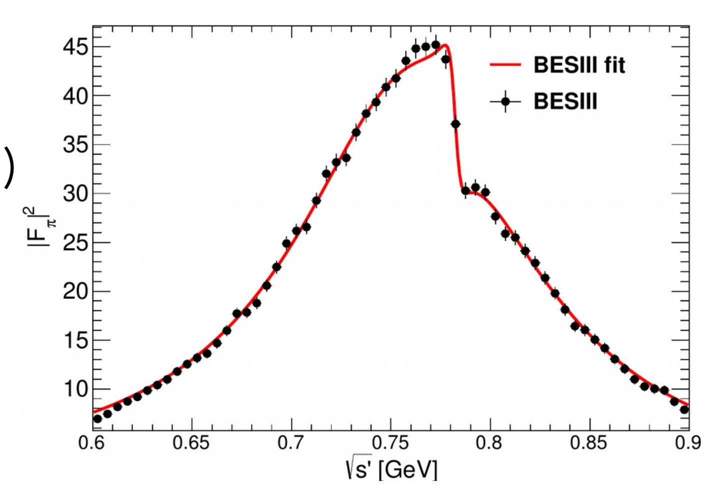
The Golden Channel: $e^+e^- \to \pi^+\pi^-$



- Tagged analysis
- Background only from μμ(γ) events
- π/μ separation based on neural network (ANN)



[Phys.Lett.B753 (2016) 629]



[Phys.Lett.B753 (2016) 629]

- Selecting muons using ANN
- Perfect agreement with QED prediction
- Measurement of J/ψ electronic width

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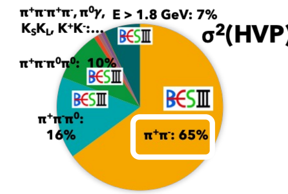
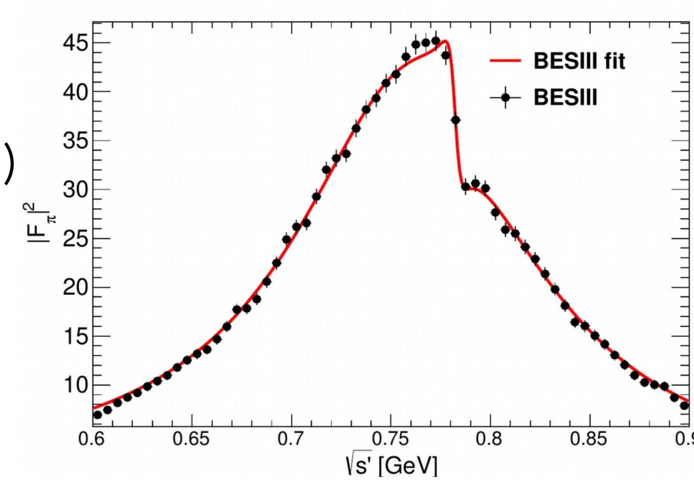


- Tagged analysis
- Background only from μμ(γ) events
- π/μ separation based on neural network (ANN)
- Careful evaluation of systematics

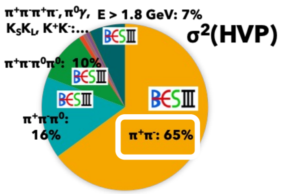
Source	Uncertainty (%)
Photon efficiency	0.2
Tracking efficiency	0.3
Pion ANN efficiency	0.2
Pion e-PID efficiency	0.2
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction δ_{FSR}	0.2
Vacuum polarization correction δ_{vac}	0.2
Radiator function	0.5
Luminosity $\mathcal{L}$	0.5
Sum	**0.9**



[Phys.Lett.B753 (2016) 629]

- Form factor evaluation for $0.6 \le m_{\pi\pi} \le 0.9$ GeV
  - 70% of total 2π contribution
  - 50% of a_μ^{HVP} contribution
  - Fit with Gounaris-Sakurai parameterization

The golden channel: $e^+e^- \rightarrow \pi^+\pi^-$



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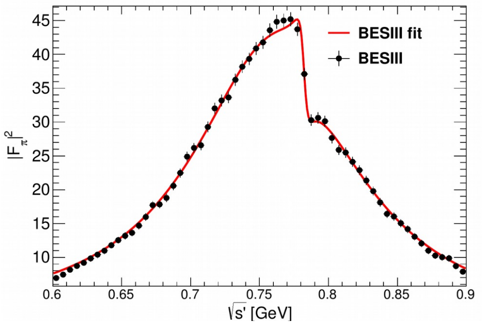

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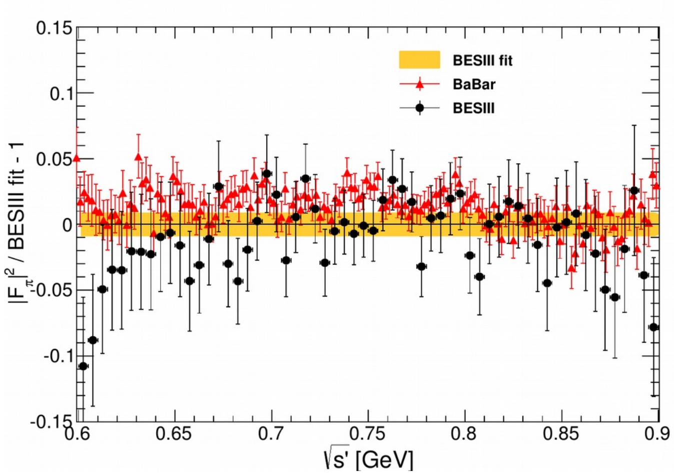
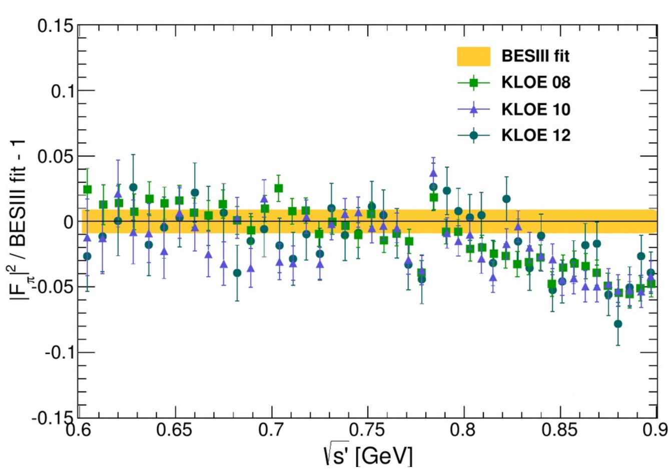
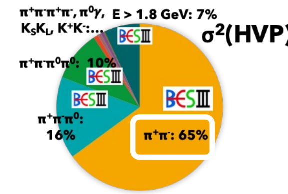
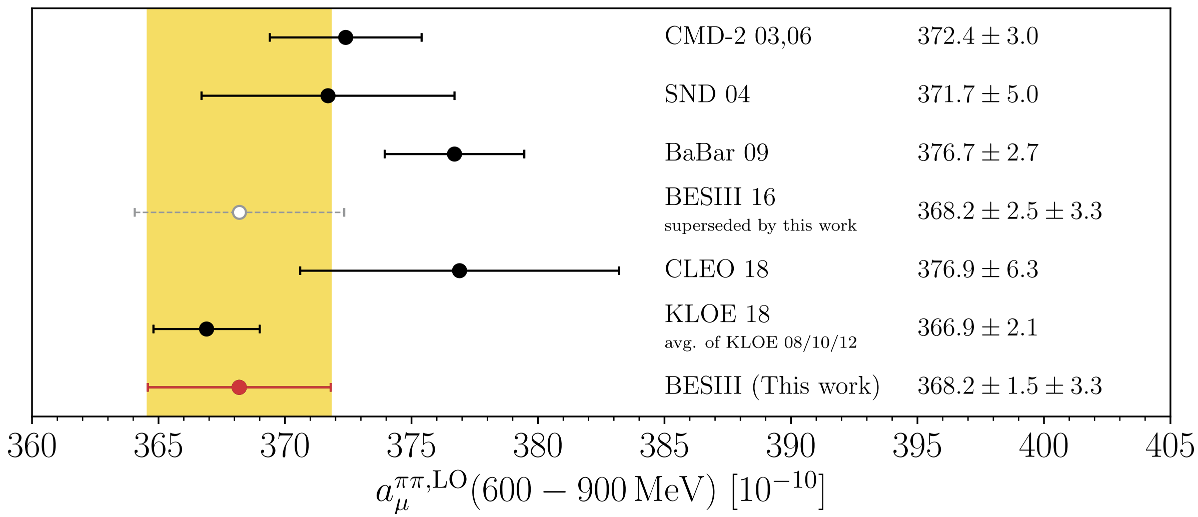




- Systematic shifts wrt previous (best) measurements
  - Below ρ/ω interference wrt BaBar
  - Above ρ/ω interference wrt KLOE

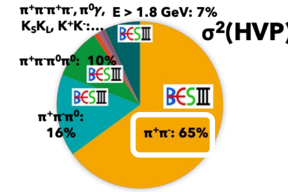
The Golden Channel: $e^+e^- \to \pi^+\pi^-$

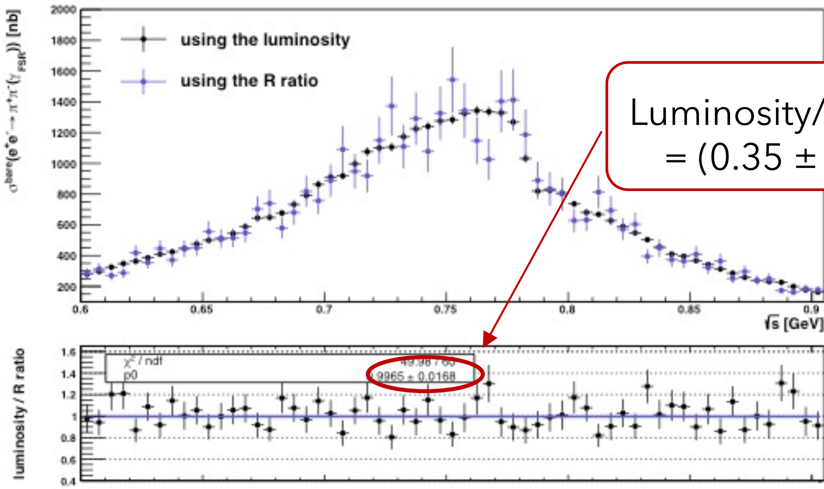




- Precision competitive with current best results:
  - BESIII: 1.0%
  - BaBar: 0.7%
  - KLOE: 0.6%
- Evaluation of covariance matrix corrected [Phys.Lett.B812 (2021) 135982]
  - Lower statistical uncertainty
- Work on going to resolve the "KLOE-BaBar puzzle"

The golden channel: $e^+e^- \to \pi^+\pi^-$





Luminosity/R-ratio -1 = (0.35 ± 1.68)%

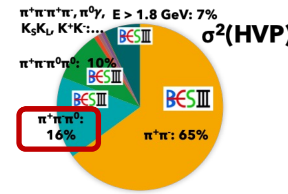
Source	Uncertainty (%)
Photon efficiency	0.2
Tracking efficiency	~~0.3~~ **0.2**
Pion ANN efficiency	0.2
~~Pion e-PID efficiency~~	~~0.2~~
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction δ_{FSR}	0.2
~~Vacuum polarization correction δ_{vac}~~	~~0.2~~
~~Radiator function~~	~~0.5~~
~~Luminosity $\mathcal{L}$~~	~~0.5~~
Sum	~~0.9~~ **0.5**

Aim to reach 0.5% precision with new analysis:

- **20 fb^{-1} of data at 3.773 GeV** (before only 2.9 fb^{-1})
- **Normalization to μμ (γ) events**
- Improved π/μ/e separation
- 2 independent analyses (Tagged and Untagged)
- Full $m_{\pi\pi}$ coverage up to 3 GeV
- Successful DFG funding request

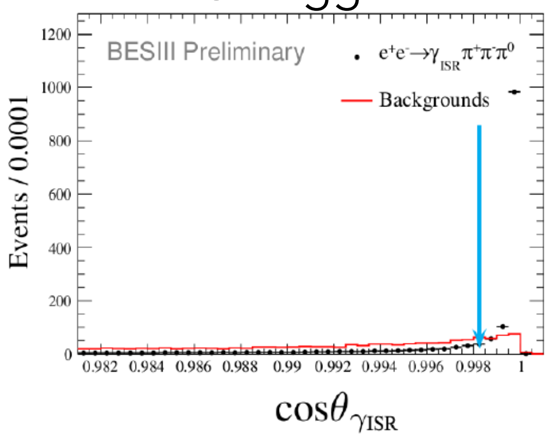
$$R = \frac{N_{2\pi\gamma}}{N_{2\mu\gamma}} \cdot \frac{\epsilon^{2\mu\gamma} \cdot \left(1 + \delta^{2\mu}_{FSR}\right)}{\epsilon^{2\pi\gamma} \cdot (1 + \delta^{2\pi}_{FSR})}$$

$e^+e^- \to \pi^+\pi^-\pi^0$ [arXiv:1912.11208]

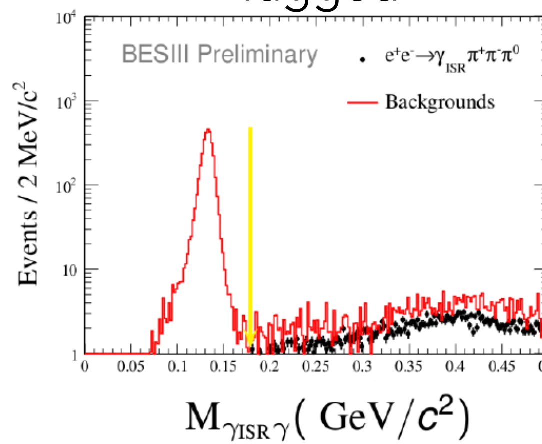


- Reconstructing events with $\pi^+\pi^- 2\gamma + \gamma_{ISR}$
- Kinematic Fit + constrain $m_{\gamma\gamma} = m_{\pi^0}$
- Both tagged and untagged configurations considered

Untagged



Tagged



γ_{ISR} polar angle

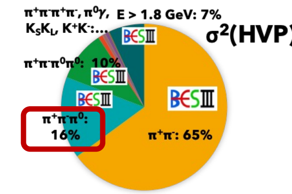
- Strong reduction of background

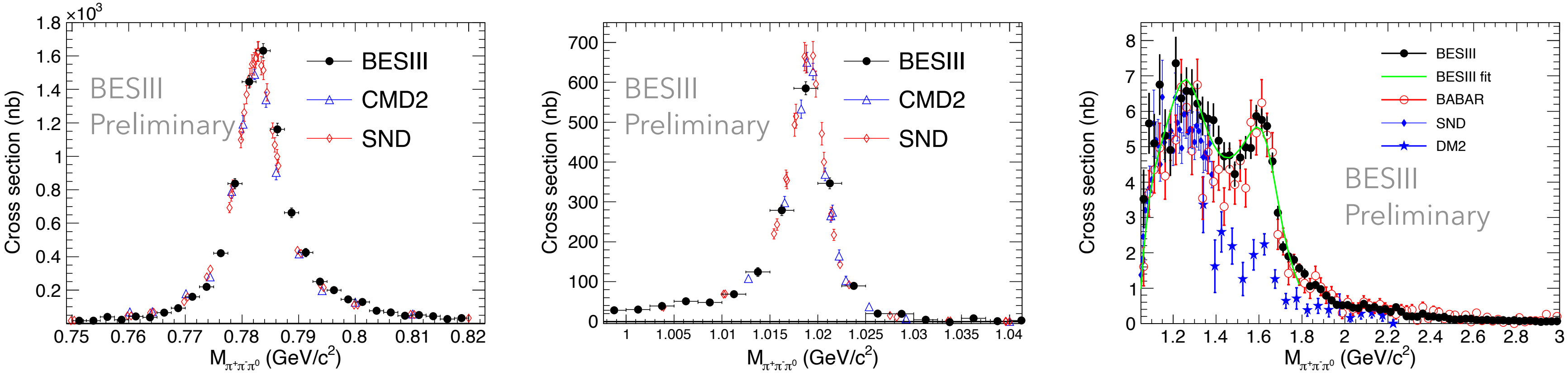
π^0 veto

- Check combination of γ_{ISR} with any other photon

- Measure $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ to correct background description

$e^+e^- \to \pi^+\pi^-\pi^0$ [arXiv:1912.11208]





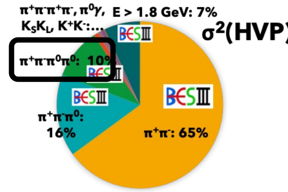
$$a_\mu^{3\pi}\,(0.7-3.0\,\mathrm{GeV}) = (49.15 \pm 0.56 \pm 0.58) \times 10^{-10}$$ BESIII Preliminary

$$a_\mu^{3\pi}\,(E<1.8\,\mathrm{GeV}) = \binom{46.63\pm0.94}{46.21\pm1.45} \times 10^{-10}$$ KNT19, DHMZ19

[Phys.Rep 887 (2020) 1-166]

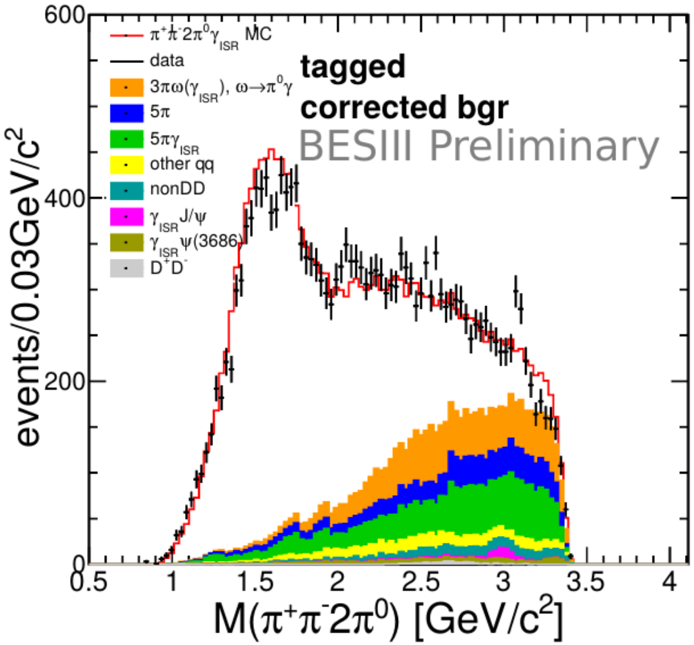
- Extraction of 3π contribution to a_μ in 0.7 to 3 GeV:
  - Precision comparable to latest calculations
  - Paper under journal review
  - Statistics limited
  - Improvement foreseen with the upcoming dataset at 3.773 GeV!

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

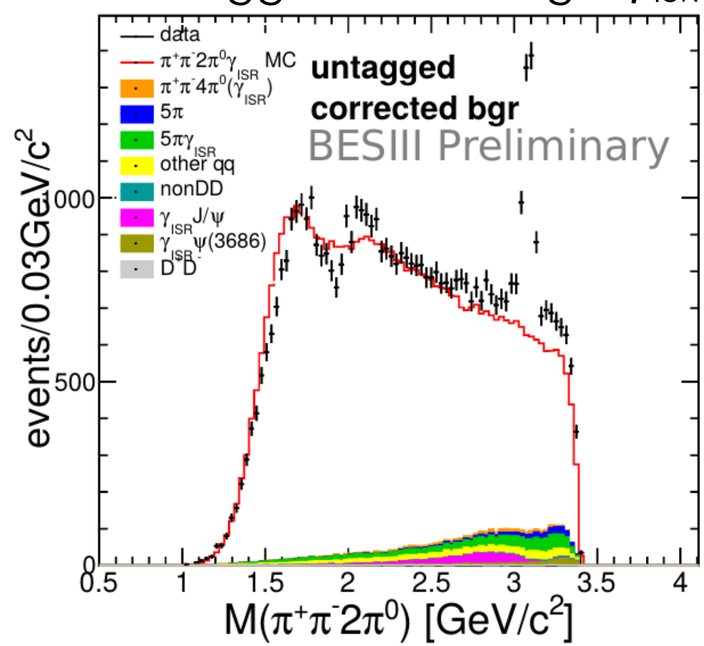


- Selection similar to $e^+e^- \to \pi^+\pi^-\pi^0$
  - Events with $\pi^+\pi^-$ $4\gamma + \gamma_{ISR}$
  - Kinematic Fit + constrain $m_{\gamma\gamma} = m_{\pi^0}$

Tagged: π^0 veto

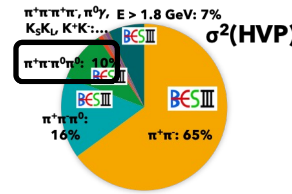


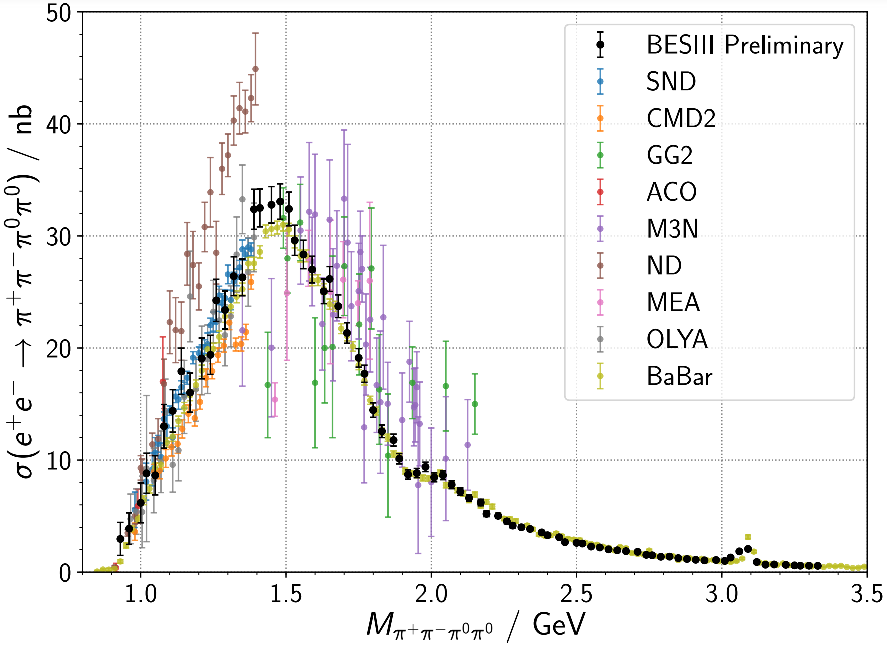
Untagged: Polar angle γ_{ISR}



➢ Measure $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$ to correct background description

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$





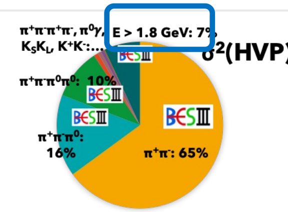
- Result from error weighted mean of tagged and untagged
- Strong improvement in precision
- a_μ compatible with BaBar result
- Room for improvement!

$$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}} = \frac{1}{4\pi^3}\int_{(4m_\pi)^2}^{(1.8\,\mathrm{GeV})^2} ds\, K(s)\sigma_{\pi^+\pi^-2\pi^0}(s)$$

	$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}}/10^{-10}$
BESIII (preliminary)	$18.63 \pm 0.27 \pm 0.57$
BABAR	$17.9 \pm 0.1 \pm 0.6$

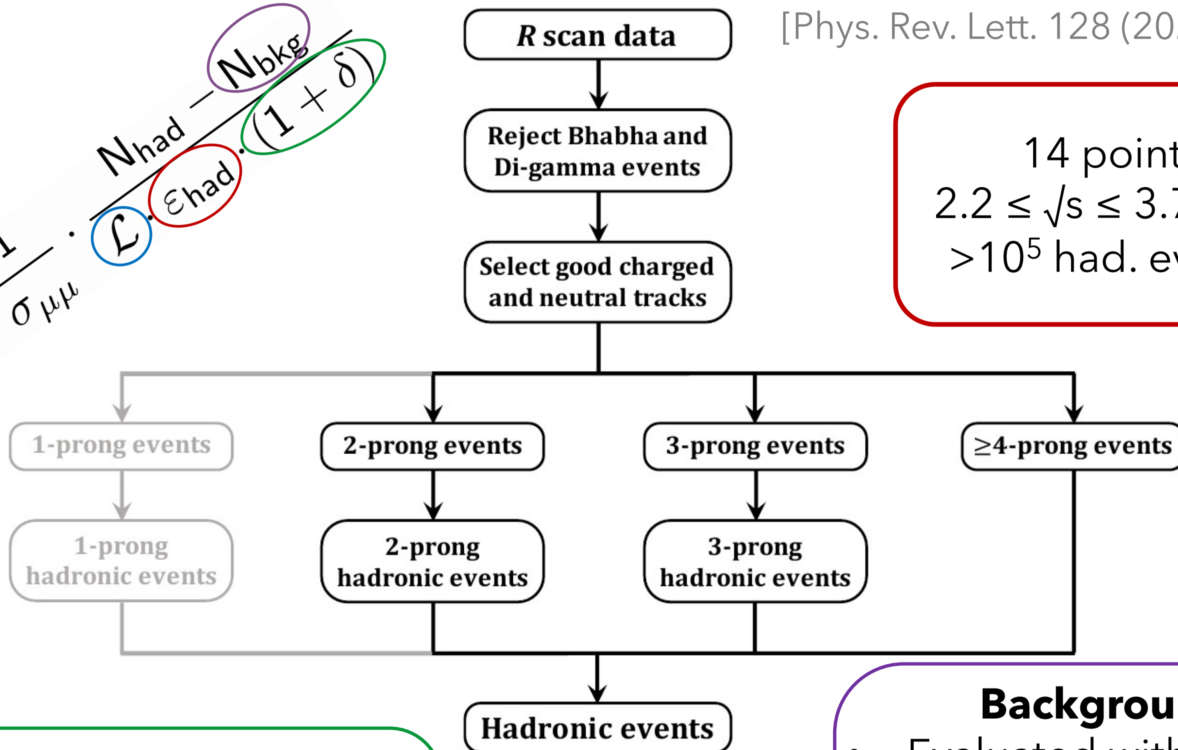
R Measurement

$$R \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)}$$



$$R = \frac{1}{\sigma_{\mu\mu}} \cdot \frac{N_{had} - N_{bkg}}{\mathcal{L} \cdot \varepsilon_{had} \cdot (1+\delta)}$$

[Phys. Rev. Lett. 128 (2022) 062004]



14 points
$2.2 \leq \sqrt{s} \leq 3.7$ GeV
$>10^5$ had. events

Luminosity
Large angle Bhabha

Radiative corrections
- Two schemes tested
  - Feynman diagram
  - Structure functions
- Agreement within 1.2%

Background contributions
- Evaluated with MC:
  - Babayaga, Phokhara, KKMC (ee,μμ,gg,tt)
  - BdkRC, Diag36, Galuga, Ekhara (ee -> ee + X)
- Beam related background

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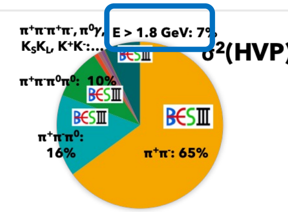

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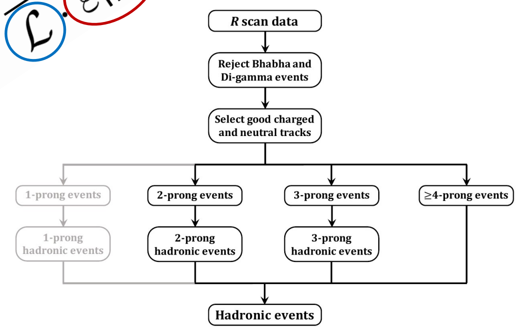

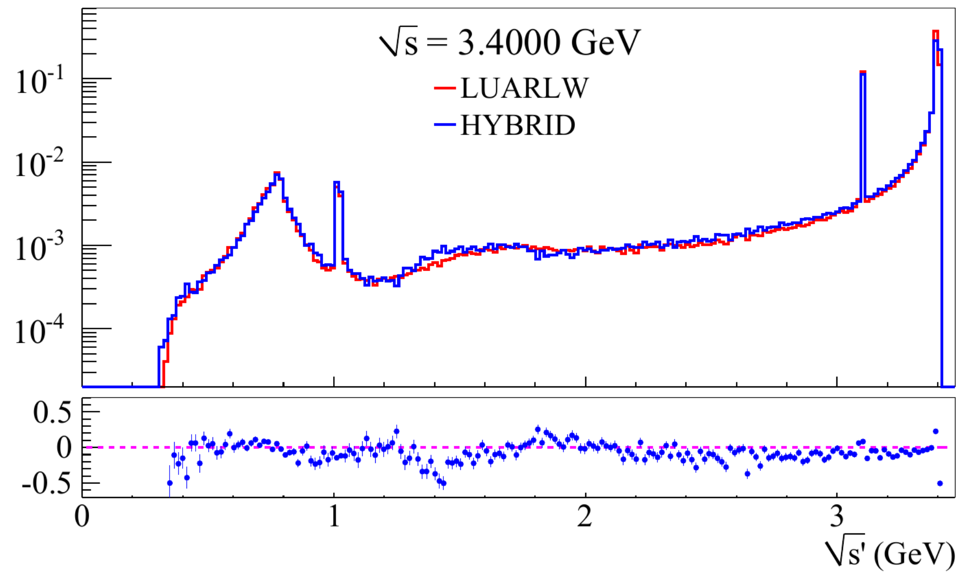

Efficiency

Ratio of generated and reconstructed events

Fully inclusive generator

- Lund Area Law
  - Low energy hadronization
  - Continuum, ISR, $J^{PC}=1^{--}$ resonances
  - Tuned to data

Hybrid generator

- Phokhara (10 excl. processes)
- ConExc (60 excl. proc. measured)
- Lund Area Law (unknown)

R Measurement

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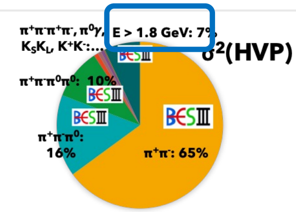

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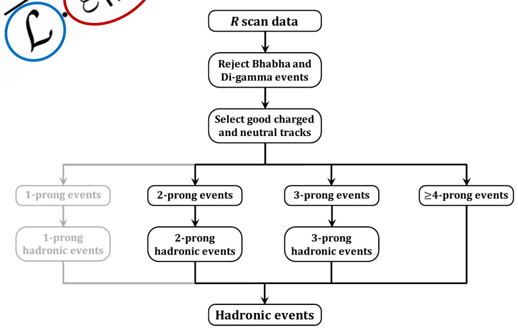

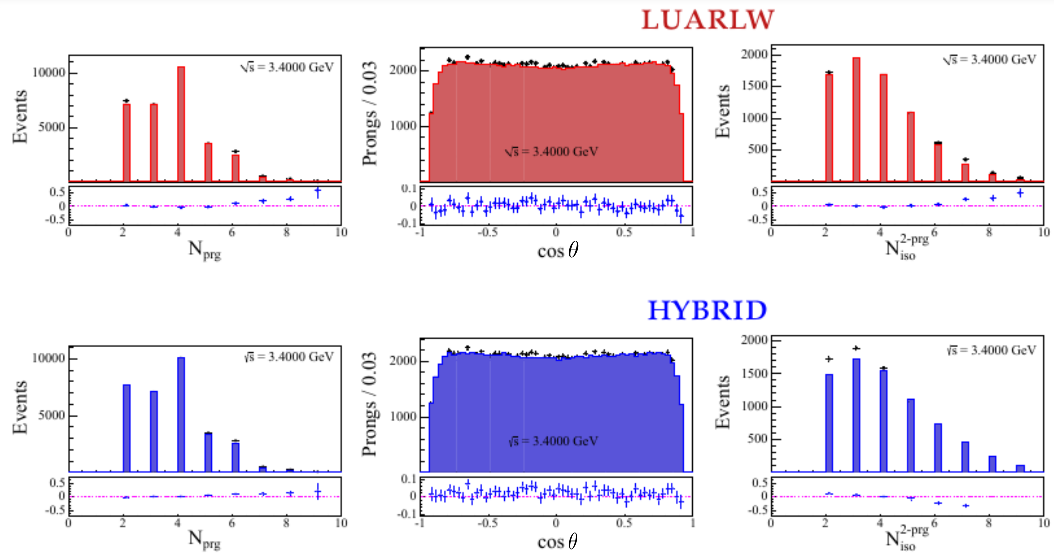

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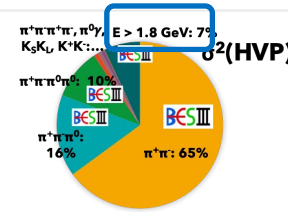
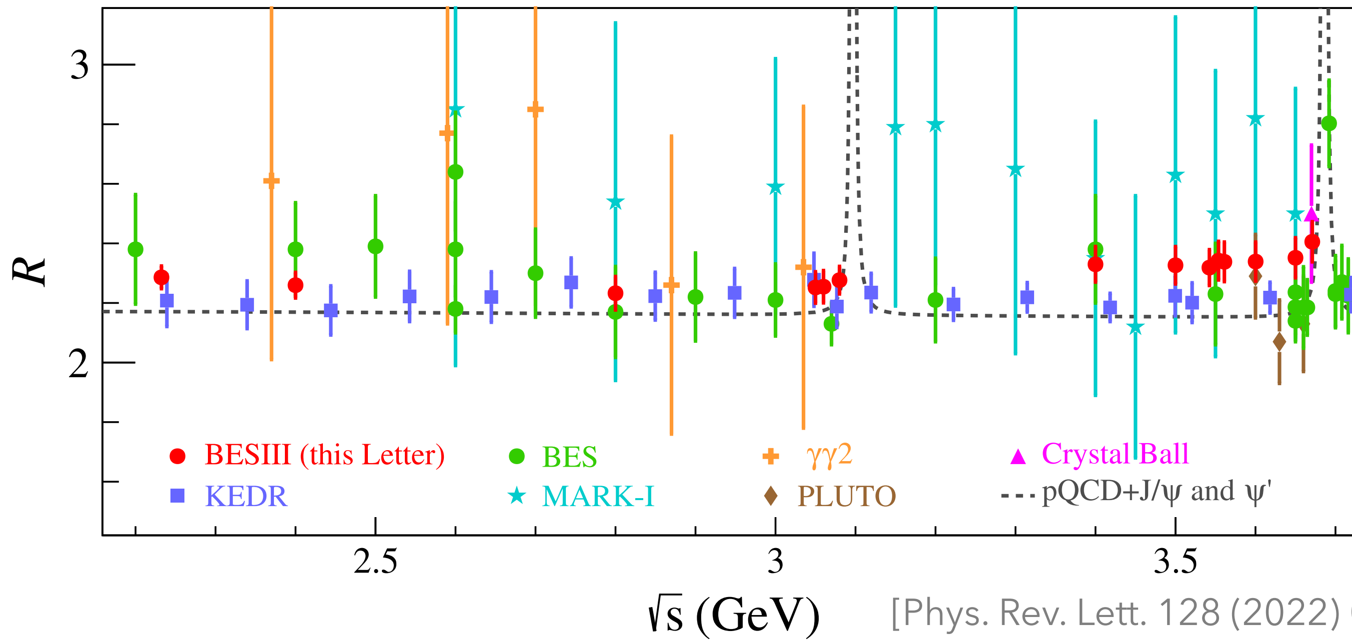




[Phys. Rev. Lett. 128 (2022) 062004]

- **Accuracy better than 2.6%** below 3.1 GeV and better than 3% above
- Exceeding pQCD predictions by 2.7σ above 3.4 GeV
- More to come in near future:
  - Result with **just 14 energy points out 130**
  - Feasibility studies for **low energy (<2 GeV) measurement via ISR**

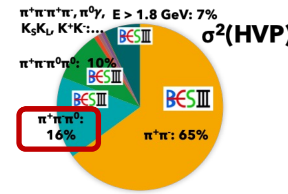
Conclusion

- SM uncertainty of a_μ dominated by hadronic processes
- BESIII plays an important role in the most important channels:
  - **$e^+e^- \to \pi^+\pi^-$**
    - Measurement with 1% uncertainty [Phys.Lett. B753 (2016) 629, B812 (2021) 135982]
    - Funding for new measurement granted
    - Aim to reach 0.5% precision → Resolution of the KLOE-BaBar puzzle!
  - **$e^+e^- \to \pi^+\pi^-\pi^0$**
    - Evaluation of a_μ with O(1%) precision achieved [arXiv:1912.11208]
    - Paper under journal review
  - **$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$**
    - Preliminary results with O(3%) precision in final review stage
  - **R measurement:** [Phys. Rev. Lett. 128 (2022) 062004]
    - Measurement with better than 2.6% accuracy below 3 GeV
    - More results to come: result based on 14 out of 130 energy points!

Great boost with upcoming 20fb^{-1} of data at 3.773 GeV

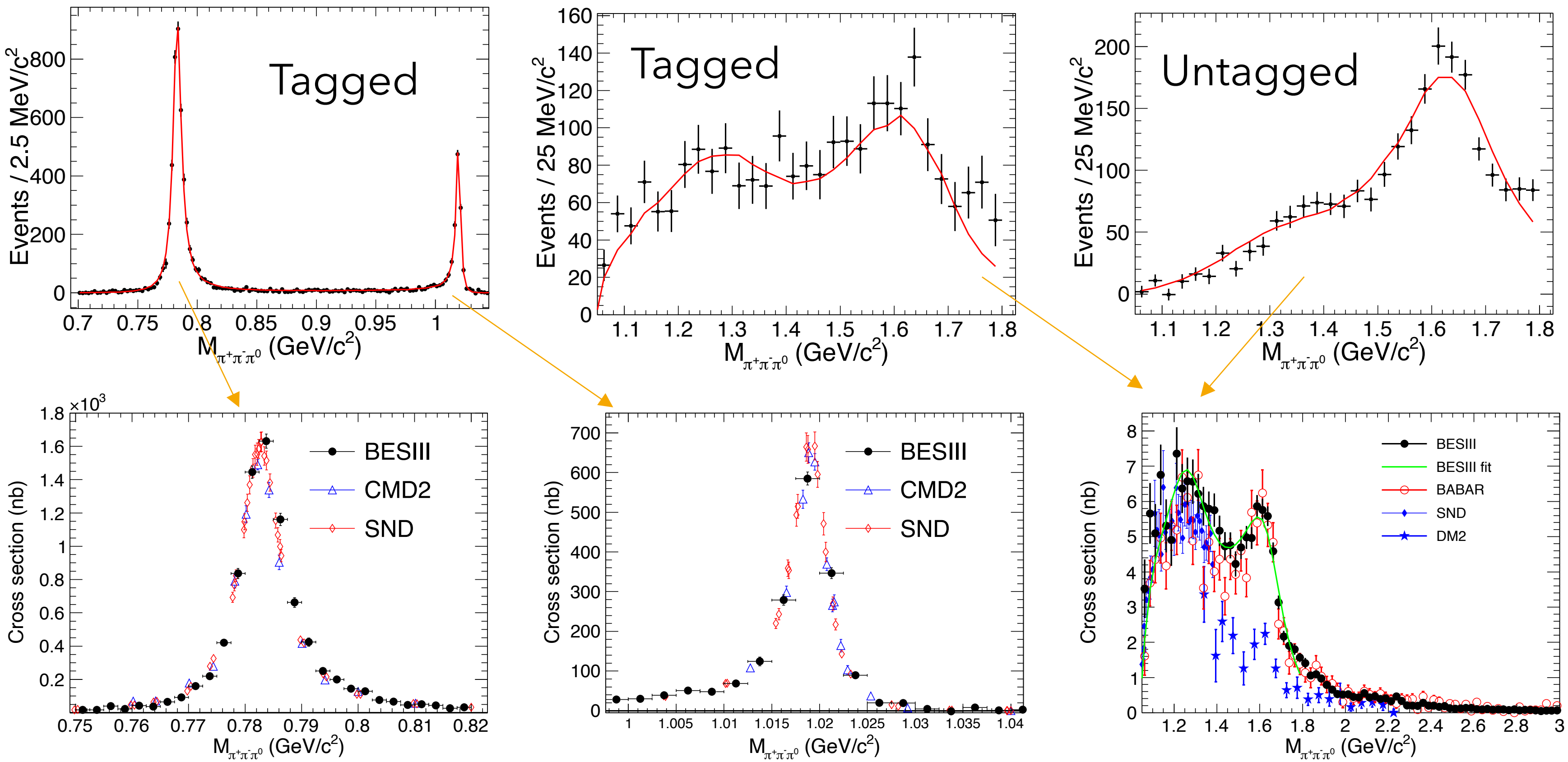
Backup

$e^+e^- \to \pi^+\pi^-\pi^0$ [arXiv:1912.11208]

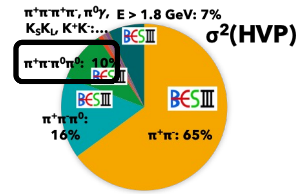


$$\sigma(m) = \frac{12\pi}{m^3} F_{\rho\pi}(m) \left| \sum_{V=\omega,\phi,\omega',\omega''} \frac{\Gamma_V m_V^{\frac{3}{2}} \sqrt{\Gamma_V^{ee} \mathcal{B}(V\to 3\pi)}}{D_V(m)} \frac{e^{i\varphi_V}}{\sqrt{F_{\rho\pi}(m_V)}} \right|^2$$

[Phys. Rev. D68 (2003) 052006]



$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$



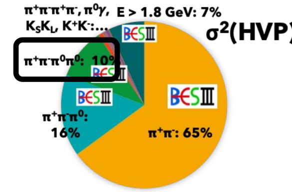
Region	Mass range [GeV]
R1	$0.5 < M(4\pi) < 1.5$
R2	$1.5 < M(4\pi) < 2.0$
R3	$2.0 < M(4\pi) < 3.0$
R4	$3.0 < M(4\pi) < 3.8$

Systematic Uncertainties

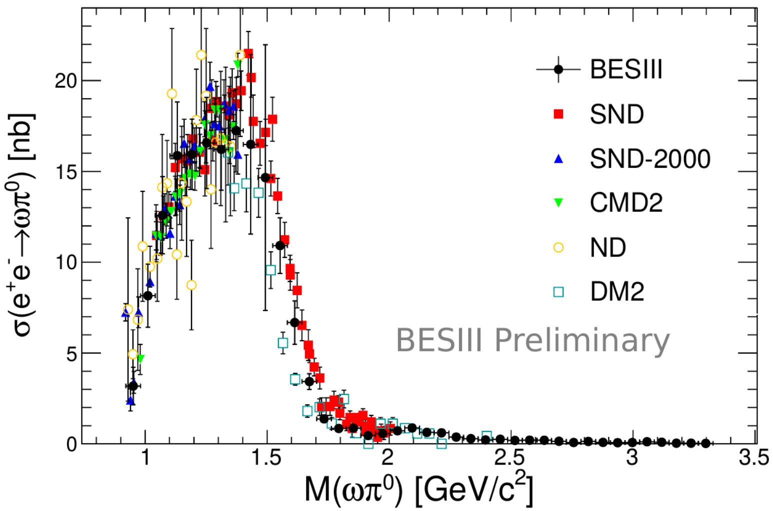
Source	Tagged [%]				Untagged [%]			
	R1	R2	R3	R4	R1	R2	R3	R4
Luminosity	0.50				0.50			
Tracking	0.60				0.60			
VP correction	0.05				0.05			
FSR correction	0.20				0.20			
Radiator Function	0.50				0.50			
ISR Photon Eff.	0.30				-			
π^0 Eff.	2.57				2.52			
Signal Eff.	0.58				0.61			
Kin. fit	0.42				0.45			
Event selection	0.60		1.46		0.64			
Bgr. Subtr. 5π	0.01	0.13	2.47	3.23	0.00	0.01	0.08	0.15
Bgr. Subtr. $5\pi\gamma_{ISR}$	0.48	0.47	7.77	10.27	0.59	0.25	0.65	0.71
Bgr. Subtr. $q\bar{q}$	0.50	0.98	12.68	21.05	0.58	0.22	0.82	0.76
Bgr. Subtr. other	0.05	0.14	2.31	5.34	0.01	0.02	0.30	0.32
ω fits (only for $\omega\pi^0$)	2.26				2.26			
$\pi^+\pi^-2\pi^0$ Total	2.97	3.09	15.58	24.45	2.95	2.85	3.04	3.04
$\omega\pi^0$ Total	3.80	4.84	7.71	3.73	3.91	3.70	4.48	3.68

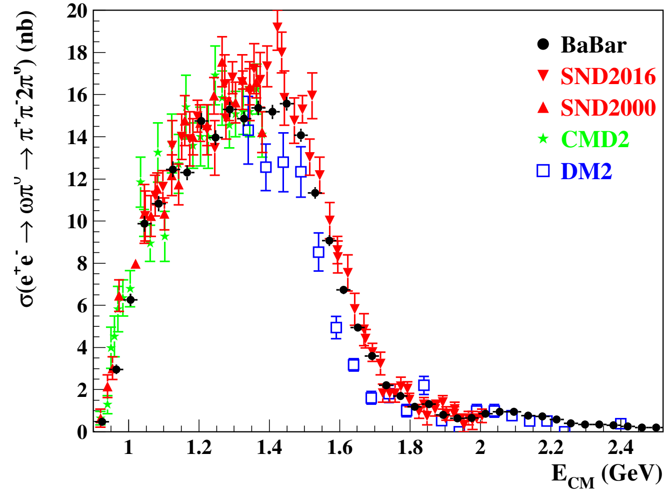
Limited by statistics! This can be reduced.

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ as $e^+e^- \to \omega\pi^0$



[Phys.Rev. D96 (2017) 092009]





- Fit the ω signal in every $m_{\pi^+\pi^-\pi^0\pi^0}$ bin
- Good agreement with previous results
- Extended measurement range wrt BaBar