Experimental Inputs to HVP and HLbL at the BESIII Experiment

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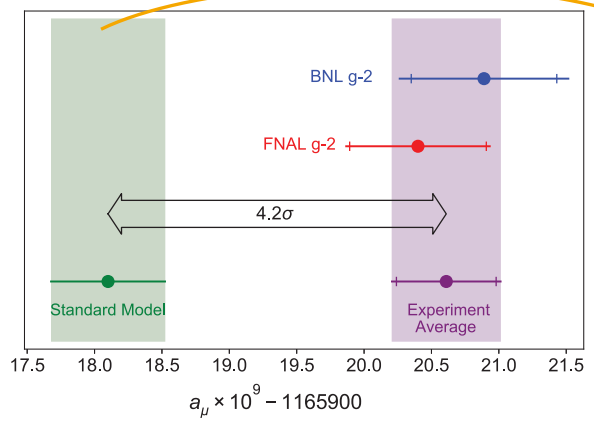
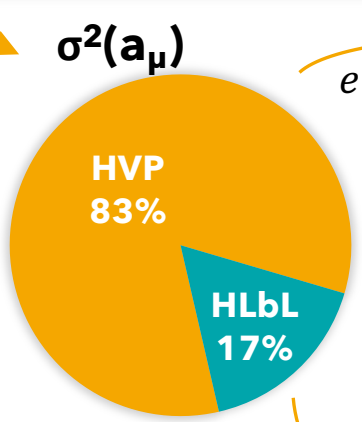
Muon g-2 Theory Initiative Workshop

KEK (online), 28 June 2021

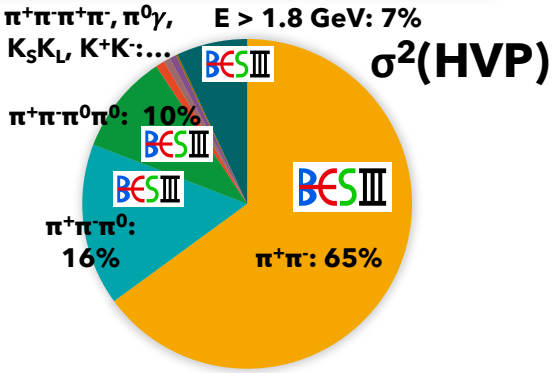
Muon (g-2): SM and Experiment



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



$e^+e^- \rightarrow had$



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

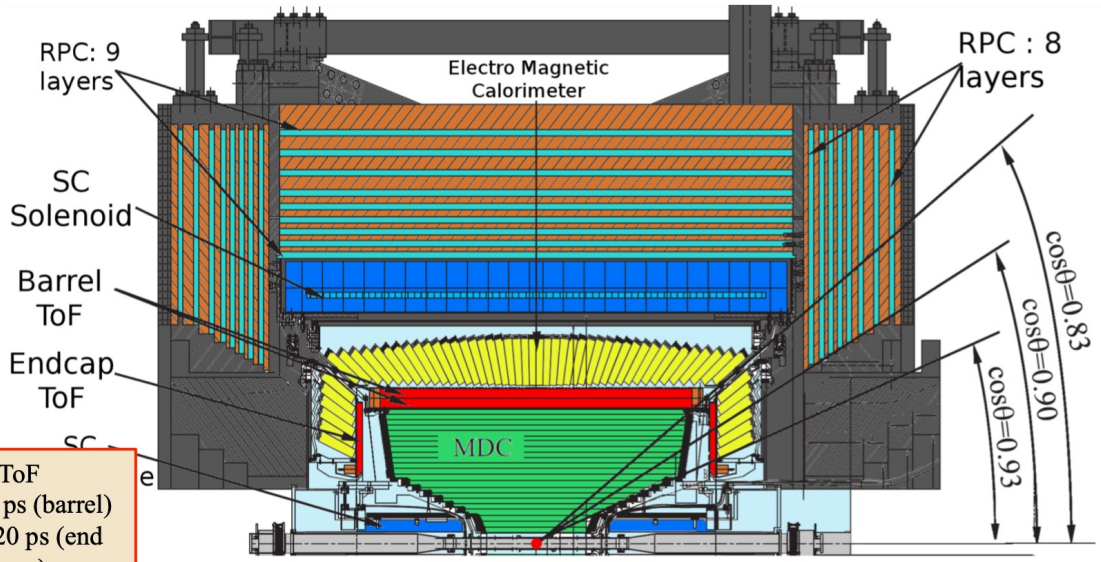
$\gamma^{(*)}\gamma^{(*)} \rightarrow hadrons$

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)

[NIM A614 (2010) 345]



- 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

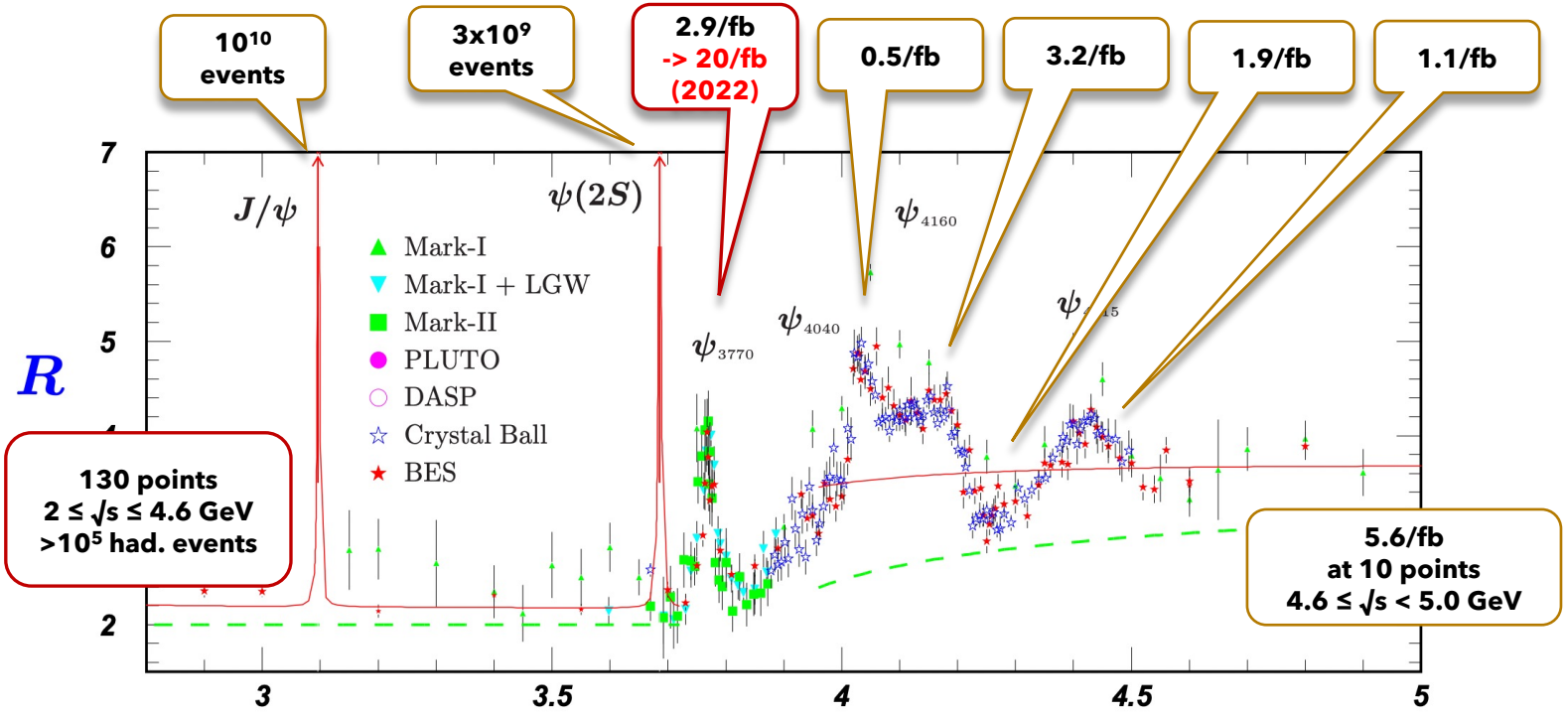
ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

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
$\Delta\Omega/4\pi = 93\%$

The BESIII Experiment (2)

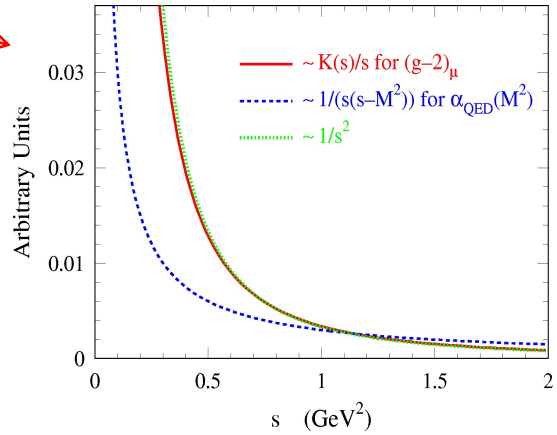


- World largest τ-charm dataset in e^+e^- annihilation
- Detailed studies in:
  - Charmonium spectroscopy and charm physics
  - Light hadron dynamics
  - τ-physics
  - R-scan

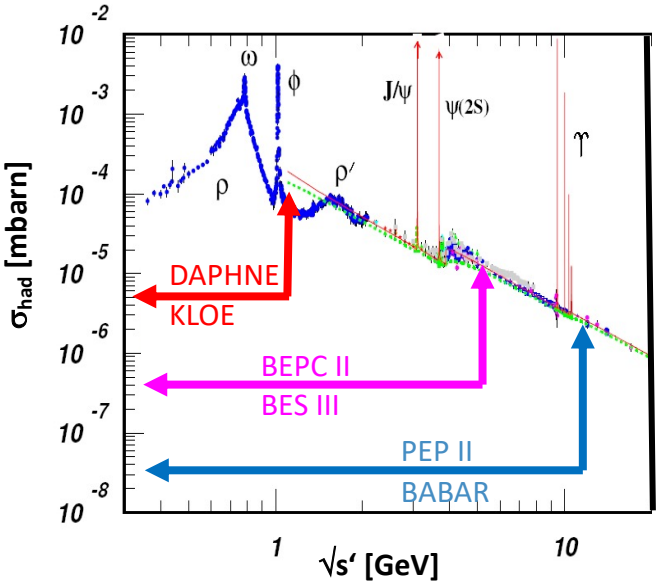
Initial State Radiation: Scan at Fixed Energy

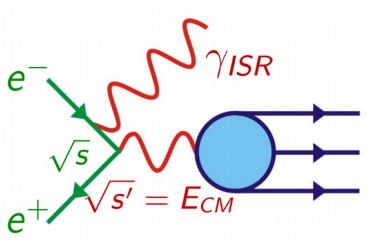
[Brodsky, de Rafael, 1988]

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



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





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

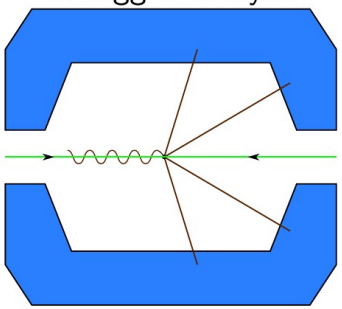
- Effectively reduces √s
- Emission suppressed by $\frac{\alpha}{\pi}$
- Radiator function relates ISR to non-radiative process

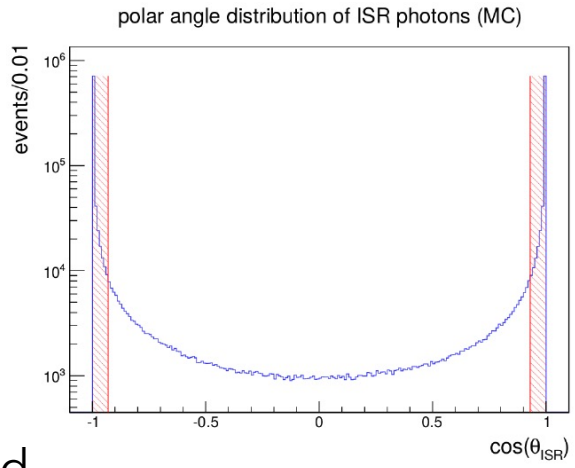
$$\frac{d\sigma_{ISR}(\sqrt{s'})}{d\sqrt{s'}} = \frac{2\sqrt{s'}}{s} W\left(s, E_\gamma, \theta_\gamma\right) \sigma(\sqrt{s'})$$

Initial State Radiation: Analysis Strategy

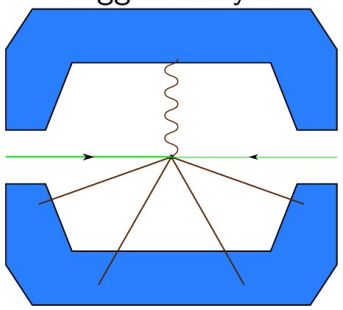
Detect full hadronic system

Untagged analysis





Tagged analysis



ISR photon undetected

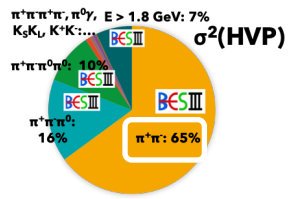
- High statistics
- Only high masses accessible (>900 MeV)
- Small background

ISR photon detected

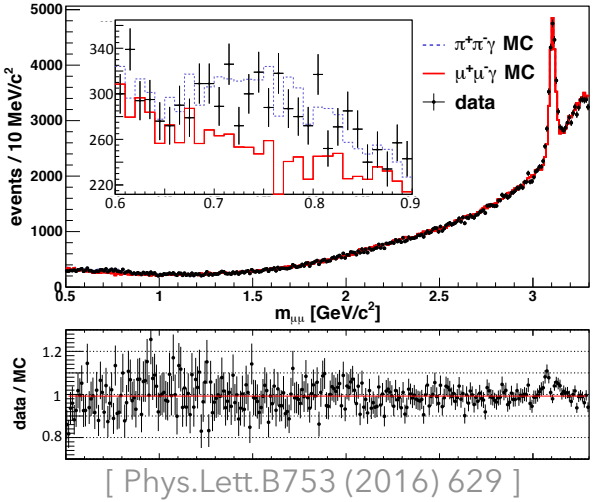
- Access to had. threshold region
- Large background at high masses

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

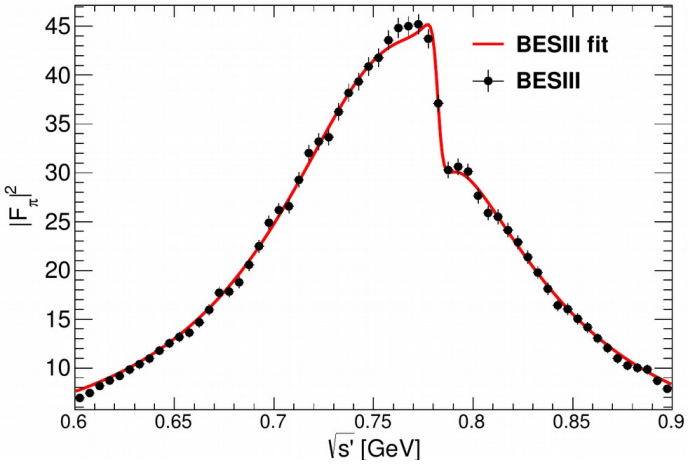
The Golden Channel: $e^+e^- \to \pi^+\pi^-$



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



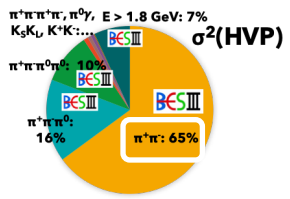
[Phys.Lett.B753 (2016) 629]



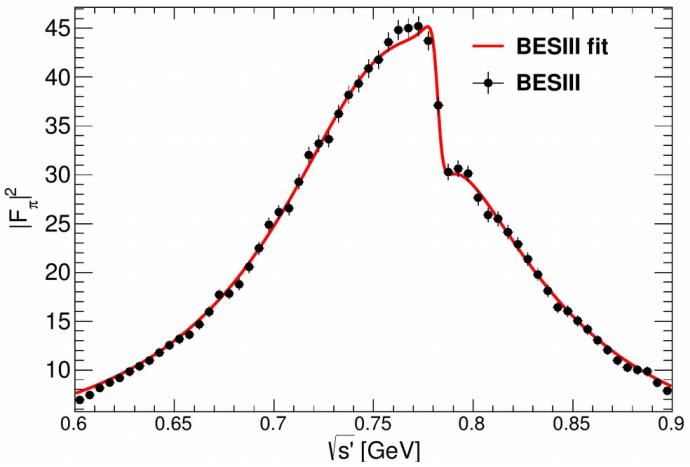
[Phys.Lett.B753 (2016) 629]

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

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



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

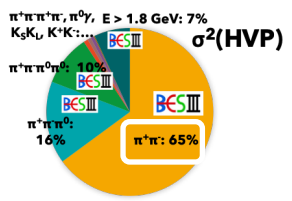


[Phys.Lett.B753 (2016) 629]

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**

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

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



- Tagged analysis
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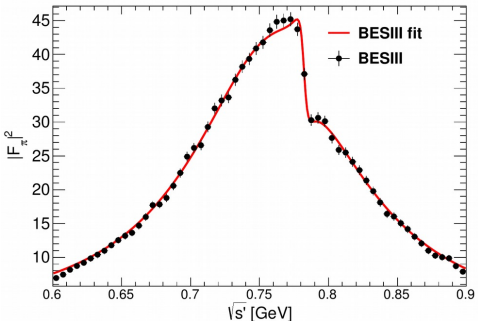
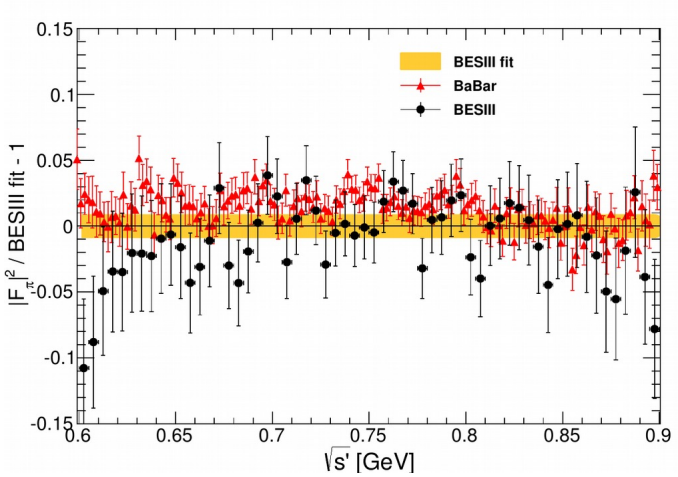
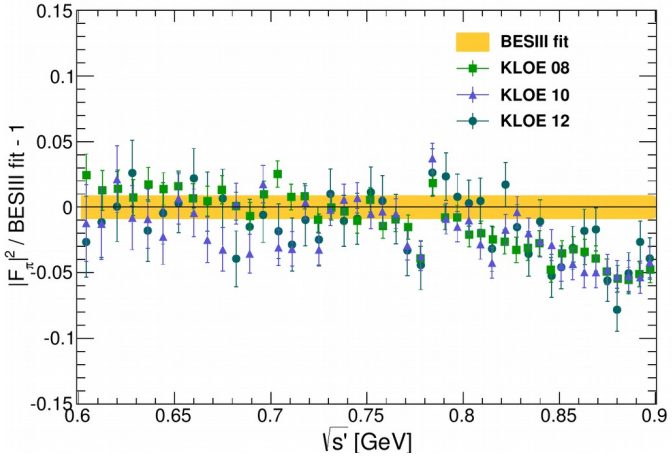


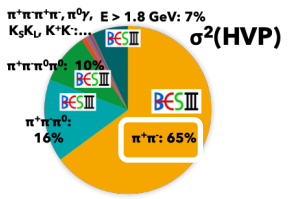
[Phys.Lett.B753 (2016) 629]

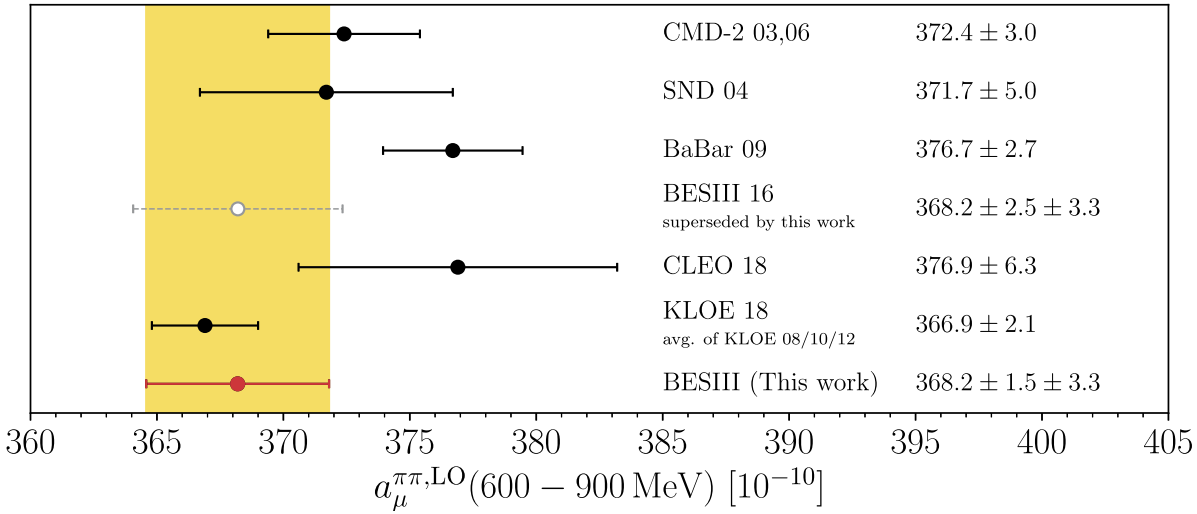




- Systematic shifts wrt previous (best) measurements
  - Below ρ/ω interference wrt BaBar
  - Above ρ/ω interference wrt KLOE

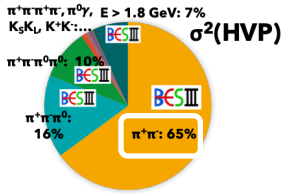
The Golden Channel: $e^+e^- \to \pi^+\pi^-$

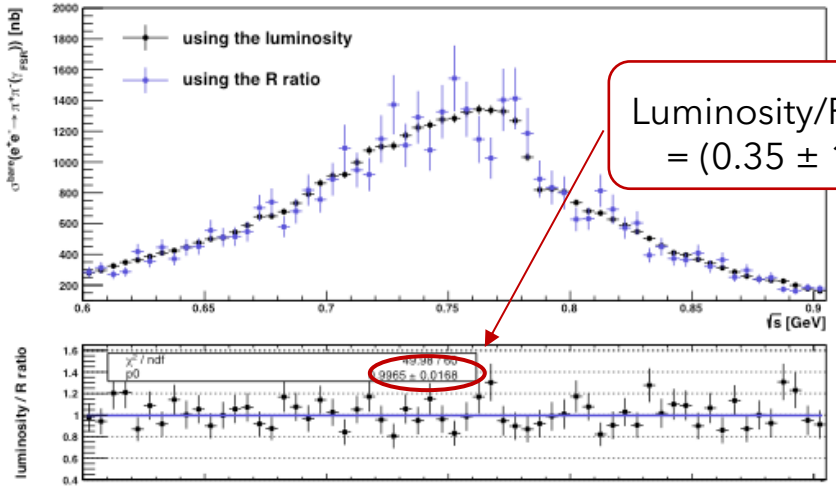




- Precision competitive with current best results:
  - BESIII: 1.0%
  - BaBar: 0.7%
  - KLOE: 0.6%
- Evaluation of covariance matrix corrected [Phys.Lett.B812 (2021) 135982]
  - Lower statistical uncertainty
- Work on going to resolve the "KLOE-BaBar puzzle"

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





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

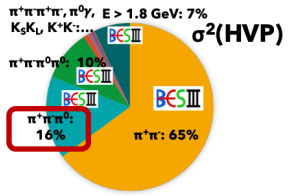
Source	Uncertainty (%)
Photon efficiency	0.2
Tracking efficiency	~~0.3~~ **0.2**
Pion ANN efficiency	0.2
~~Pion e PID efficiency~~	~~0.2~~
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction δ_{FSR}	0.2
Vacuum polarization correction δ_{vac}	0.2
~~Radiator function~~	~~0.5~~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

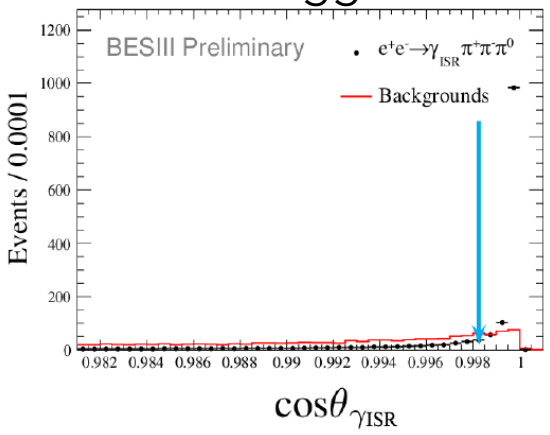
$$R = \frac{N_{2\pi\gamma}}{N_{2\mu\gamma}} \cdot \frac{\epsilon^{2\mu\gamma} \cdot \left(1 + \delta^{2\mu}_{FSR}\right)}{\epsilon^{2\pi\gamma} \cdot \left(1 + \delta^{2\pi}_{FSR}\right)}$$

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

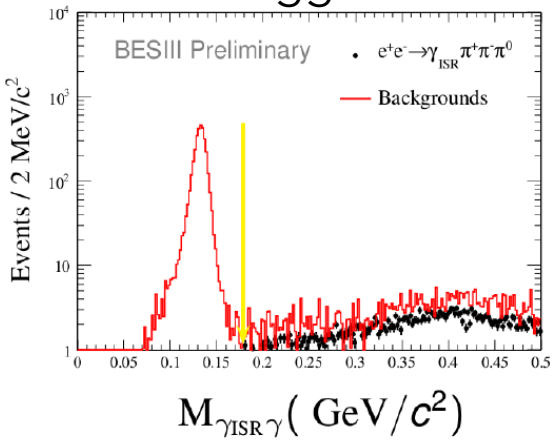


- Reconstructing events with $\pi^+\pi^- 2\gamma + \gamma_{ISR}$
- Kinematic Fit + constrain $m_{\gamma\gamma} = m_{\pi^0}$
- Both tagged and untagged configurations considered

Untagged



Tagged



γ_{ISR} polar angle

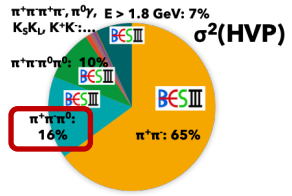
- Strong reduction of background

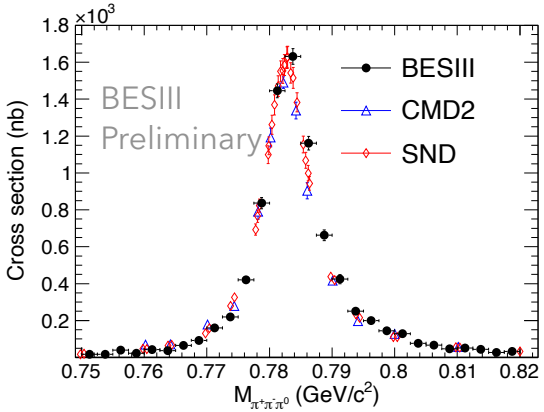
π^0 veto

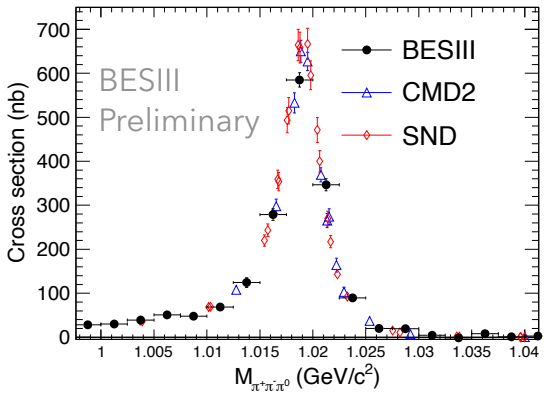
- Check combination of γ_{ISR} with any other photon

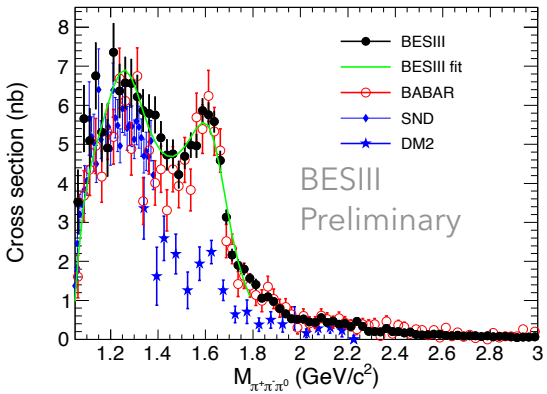
- Measure $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ to correct background description

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









$$a_\mu^{3\pi}\,(0.7-3.0\ \mathrm{GeV}) = (49.77 \pm 0.53 \pm 0.58) \times 10^{-10}$$

BESIII Preliminary

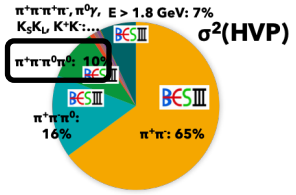
$$a_\mu^{3\pi}\,(E<1.8\ \mathrm{GeV}) = (46.63 \pm 0.94) \times 10^{-10}$$

KNT19

[Phys. Rev. D101, (2020) 014029]

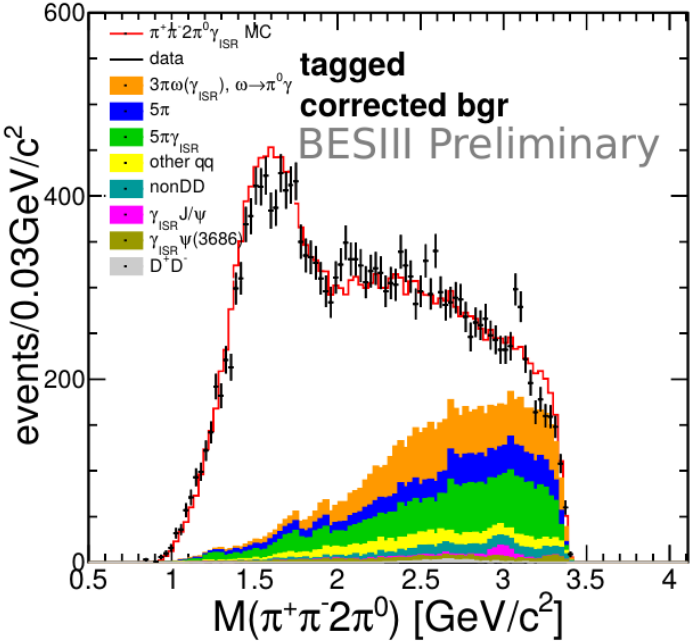
- Extraction of 3π contribution to a_μ in 0.7 to 3 GeV:
  - Precision comparable to latest calculations
  - Paper to be published soon
  - Statistics limited
  - Improvement foreseen with the upcoming dataset at 3.773 GeV!

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

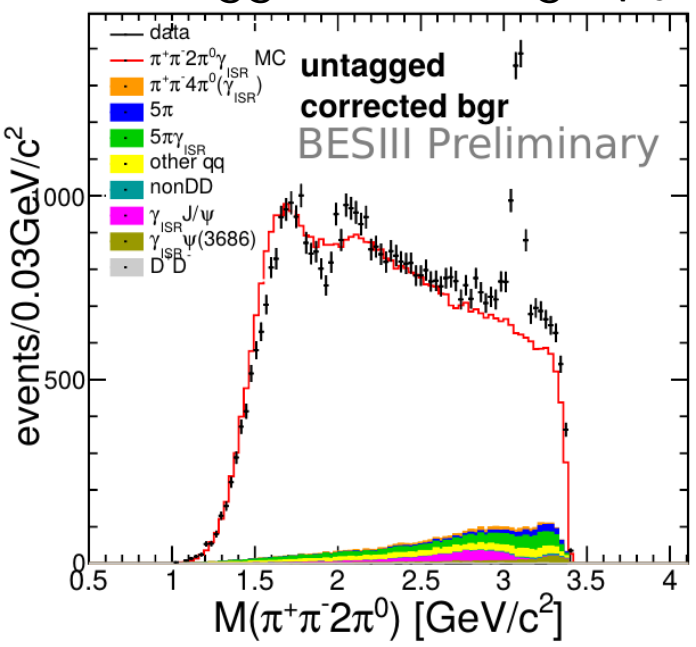


- Selection similar to $e^+e^- \to \pi^+\pi^-\pi^0$
  - Events with $\pi^+\pi^-$ $4\gamma + \gamma_{ISR}$
  - Kinematic Fit + constrain $m_{\gamma\gamma} = m_{\pi^0}$

Tagged: π^0 veto

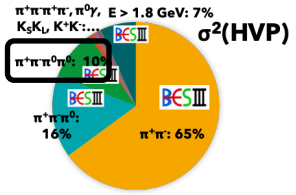


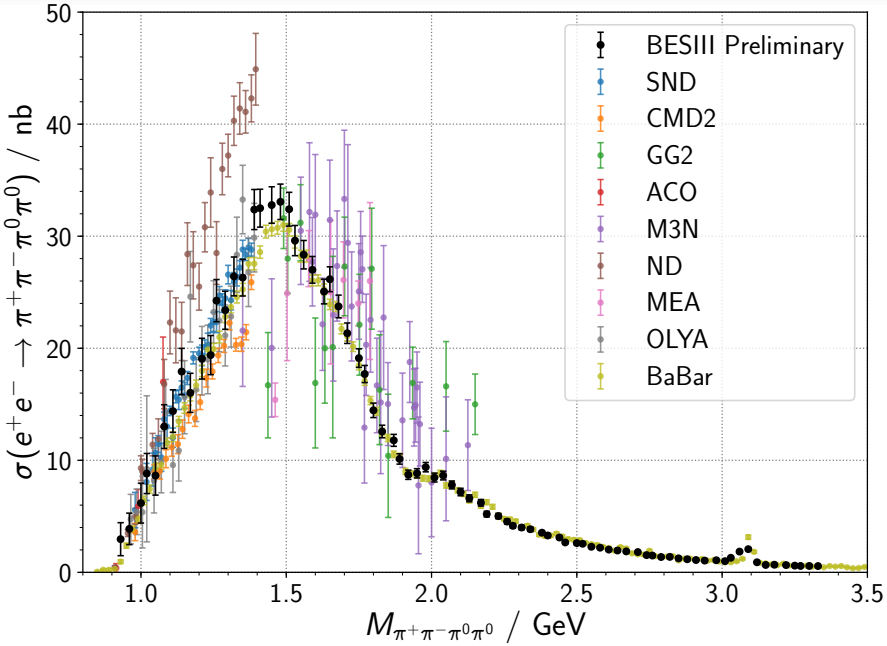
Untagged: Polar angle γ_{ISR}



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

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



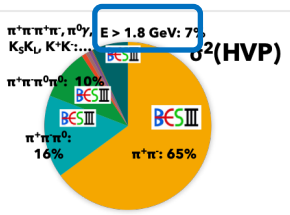


- Result from error weighted mean of tagged and untagged
- Strong improvement in precision
- a_μ compatible with BaBar result
- Room for improvement!

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

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

R Measurement



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

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

Luminosity
Large angle Bhabha

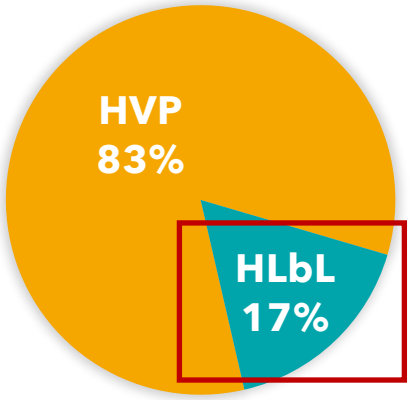
$$R = \frac{1}{\sigma_{\mu\mu}} \cdot \frac{N_{had} - N_{bkg}}{\mathcal{L} \cdot \varepsilon_{had} \cdot (1+\delta)}$$

Efficiency
Ratio of generated and reconstructed events

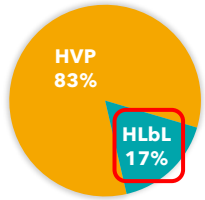
- Fully inclusive generator
  - Lund Area Law [hep-ph/9910285]
    - Low energy hadronisation
    - Continuum, ISR, $J^{PC}=1^{--}$ resonances
    - Tuned to data
- Hybrid generator
  - Phokhara (10 excl. processes) [JHEP 1402 (2014) 114]
  - ConExc (60 excl. proc. measured) [Chin.Phys. C40 (2016) 113002]
  - Lund Area Law (unknown)

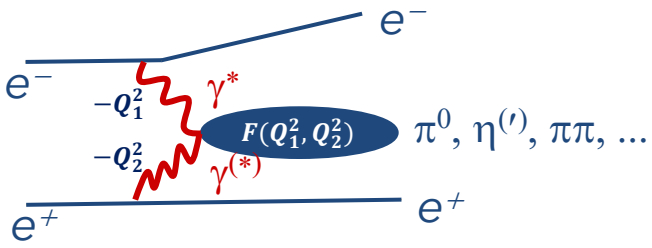
➢ **Aiming at < 3% uncertainty (BES measurement 6%)**

Inputs to Hadronic Light by Light

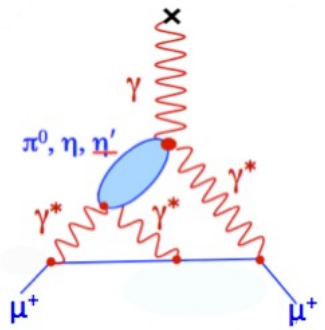


Two-Photon Collisions





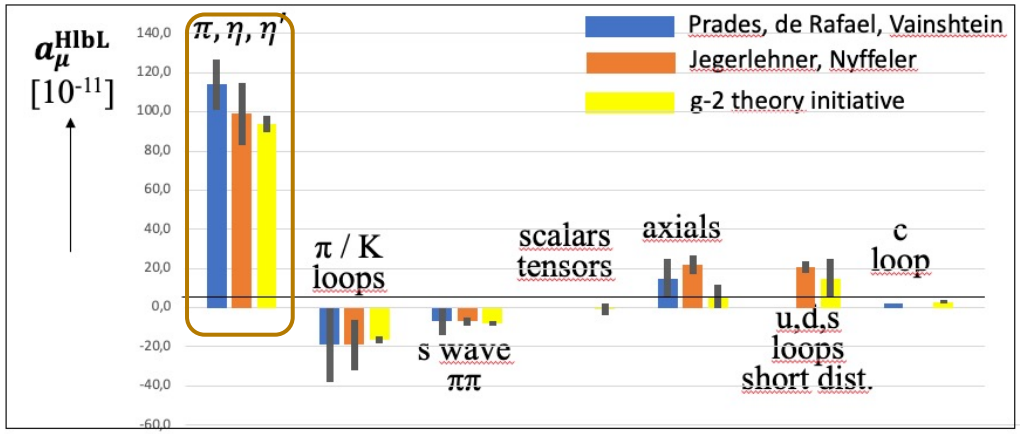
Data driven approach



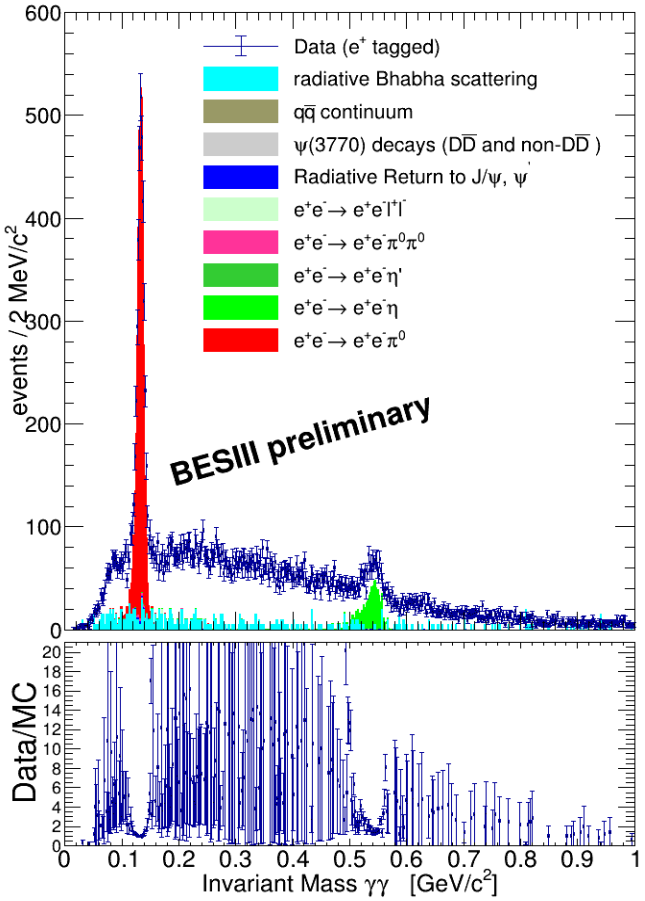
- Direct connection between HLbL and $\gamma\gamma$-collision events
- $\sigma \propto \alpha^2 \ln^2 E$ and $\sigma \propto F^2(Q_1^2, Q_2^2)$ (transition form factor)
- Forward peaking kinematics: experimentally challenging
  - Untagged measurement: quasi-real photons
  - **Single-tagged measurement: one photon offshell** ← **now**
  - Double-tagged measurement: both photons offshell ← future

BESIII

Spacelike π^0,η, and η' Transition Form Factor



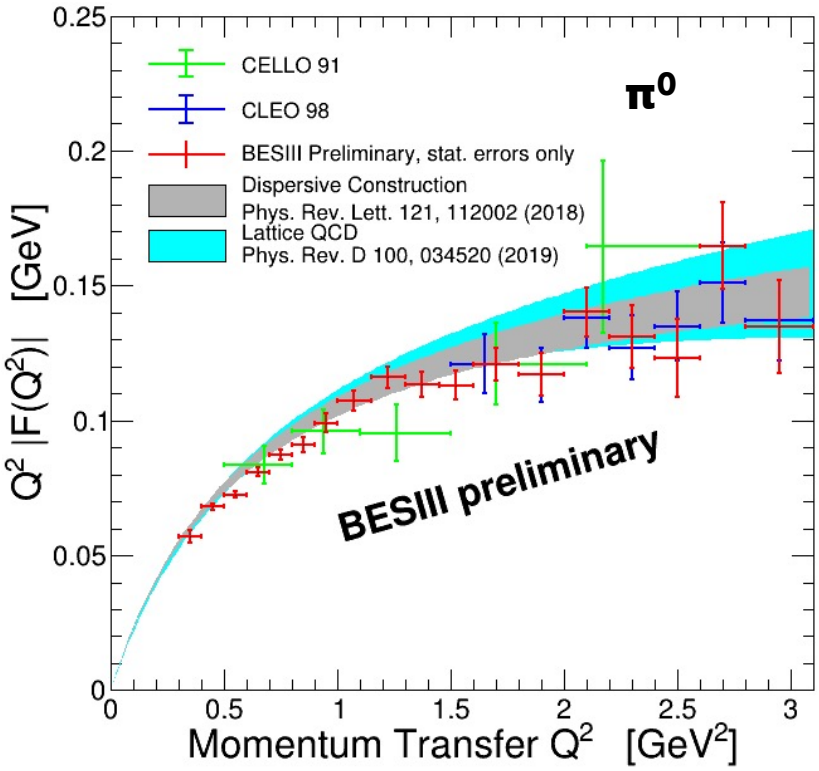
- Largest contribution to a_μ^{HLbL}
- Based on 2.9 fb^{-1} at 3.773 GeV
- Selecting event with:
  - Only 1 lepton (e^+/e^-)
  - At least 2 photons
  - Missing momentum in beam pipe
- Clear signals of π^0 and η



Spacelike π^0,η, and η' Transition Form Factor

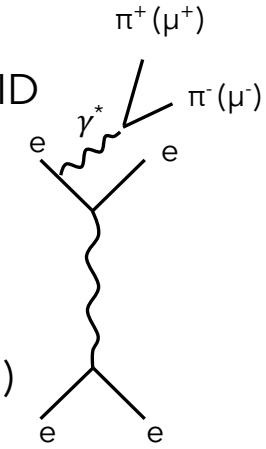
- Good agreement with previous results
- Unprecedented precision (Q^2<2 GeV^2)
- Data in the most relevant region for a_μ
- Paper draft in preparation
- Advanced analysis stage also for η and η' TFF
- Possibility to extend Q^2 range down to 0.1 GeV^2

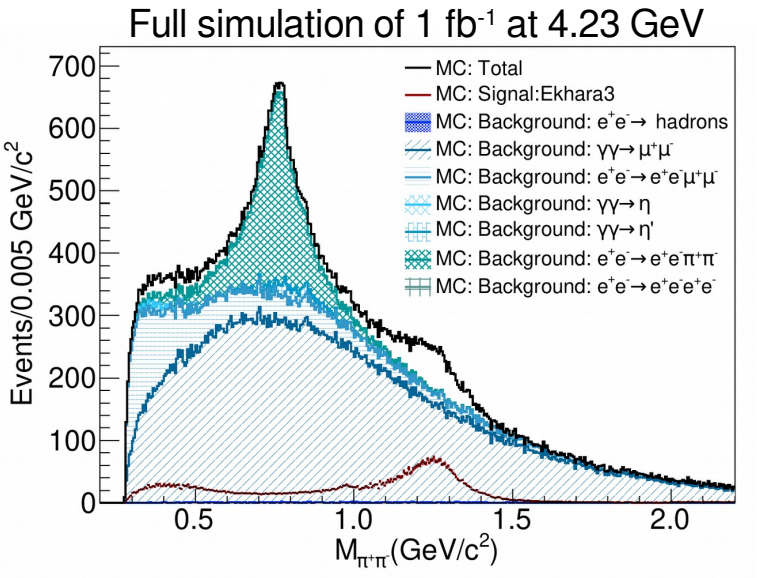
[Prog.Part.Nucl.Phys. 107 (2019) 20-68]



$\gamma\gamma^* \rightarrow \pi^+\pi^-$

- 7.5 fb^{-1} from 3.773 to 4.6 GeV
- Selecting events with:
  - 1 lepton (e^+/e^-)
  - 2 tracks (opposite charge) with π-ID
- Main backgrounds:
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ (PID)
  - $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ (parameterization)
- Machine learning for π/μ separation
- Full helicity angle coverage
- On the way to publication





First single-tagged measurement!

$\gamma^{(*)}\gamma^{*}$-Physics Outlook

Many promising studies currently on going:

- $\gamma\gamma^{*} \rightarrow \pi^0\pi^0$ and $\gamma\gamma^{*} \rightarrow \pi^0\eta$: will complement Belle results
- $\gamma\gamma^{*} \rightarrow \pi^+\pi^-\pi^0(\eta)$, $\gamma\gamma^{*} \rightarrow \pi^+\pi^-\ \pi^+\pi^-$: axial and tensor vector mesons ($f_1(1285)$)
- $\gamma^{*}\gamma^{*} \rightarrow \pi^0$: first double-tagged measurement!

Great improvement with upcoming 20fb^{-1} at 3.773 GeV

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 to be published soon
  - **$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$**
    - Preliminary results with O(3%) precision in final review stage
  - **R measurement:**
    - Aim for precision < 3%
    - Energy range 2.2 – 3.7 GeV
    - Draft paper under internal review

Conclusion

- Dispersive approach to HLbL evaluation: $\gamma^{(*)}\gamma^{*}$-collisions
- Unique opportunity for BESIII:
  - **Access to relevant Q^2 range (0.1 – 3 GeV^2)**
    - Complementary to KLOE and B-factory
    - Unprecedented precision
  - $\gamma\gamma^{*} \rightarrow \pi^0,\eta,\eta'$
    - First coverage for $Q^2<0.5$ GeV^2
    - Good agreement with latest theoretical evaluation
    - Draft in preparation (η and η' results next in line!)
  - $\gamma\gamma^{*} \rightarrow \pi^+\pi^-$
    - First measurement of single-tagged process
    - Final stage of internal review → Paper draft in preparation
  - **Production of axial and tensor vector mesons**
    - $\gamma\gamma^{*} \rightarrow \pi^+\pi^-\pi^0$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^+\pi^-$, …
    - Several analyses ongoing
  - **First studies for double-tagged measurement ($\gamma^{*}\gamma^{*} \rightarrow \pi^0$)**

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