Workshop on Flavour Changing and Conserving Processes (FCCP2022)
Anacapri, September 22, 2022

Status of R and gamma-gamma Measurements

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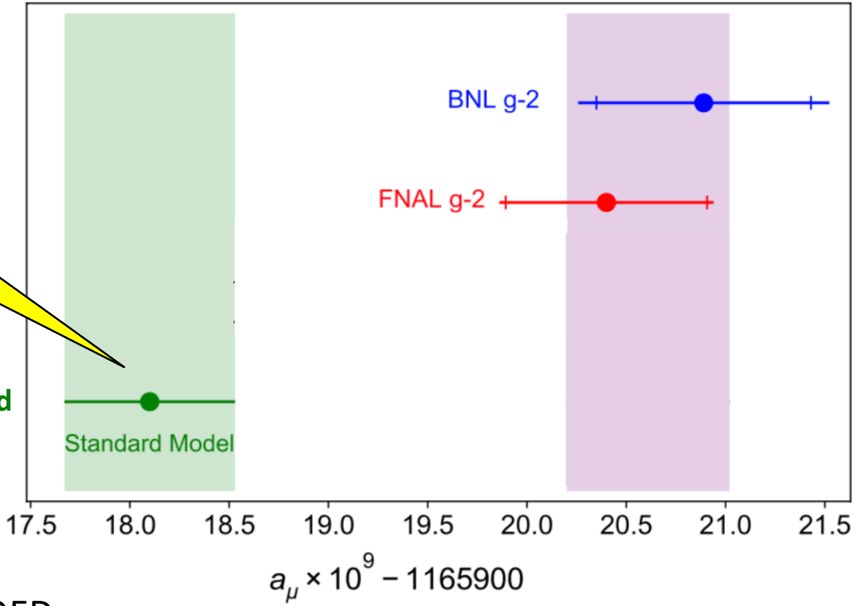
New direct $(g\text{-}2)_\mu$ Measurement FNAL

Data-driven reduction of SM uncertainty !
→ **This talk**!



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

Absolute contribution: dominated by QED

Uncertainty: dominated by **strong interactions**

- **Hadronic Vacuum Polarization** $(693.1 \pm 4.0 \cdot 10^{-10})$
- **Hadronic Light-by-Light** $(9.2 \pm 1.8 \cdot 10^{-10})$

Physics Reports 887 (2020) 1-166

Talks Winter Knecht

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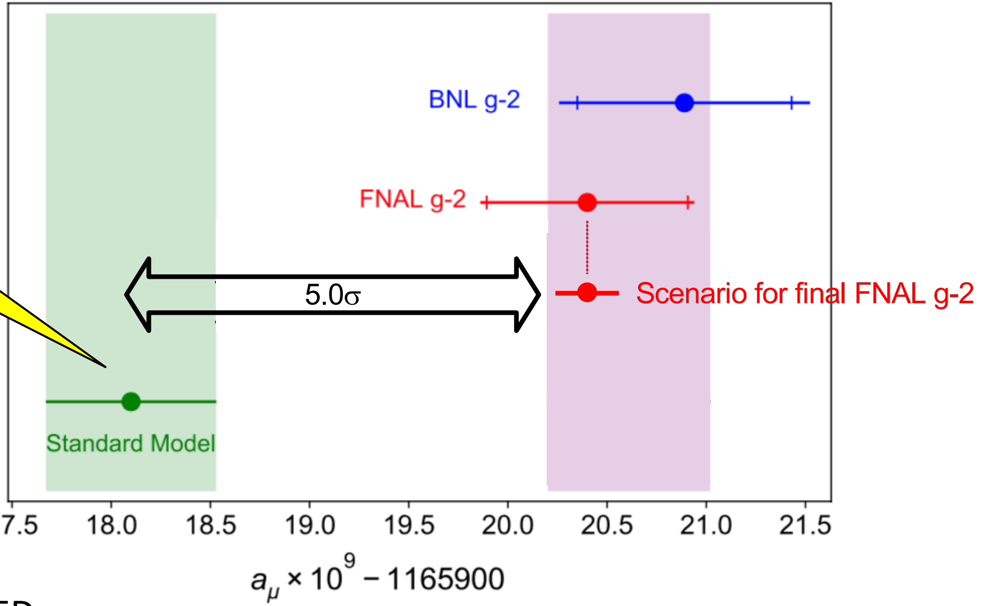

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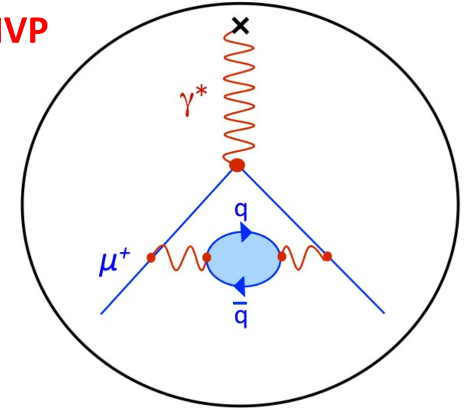
Talks Winter Knecht

Hadronic Vacuum Polarization (HVP)

HVP



Estimate of (g-2) Theory Initiative based on dispersive approach (including higher orders):

(**693.1** ± **4.0**) · 10^{-10}

was (≅ 687 ... 694 ± 2.4 ... 4.1) · 10^{-10}

Hadronic Vacuum Polarization Contrib. to $(g\text{-}2)_\mu$

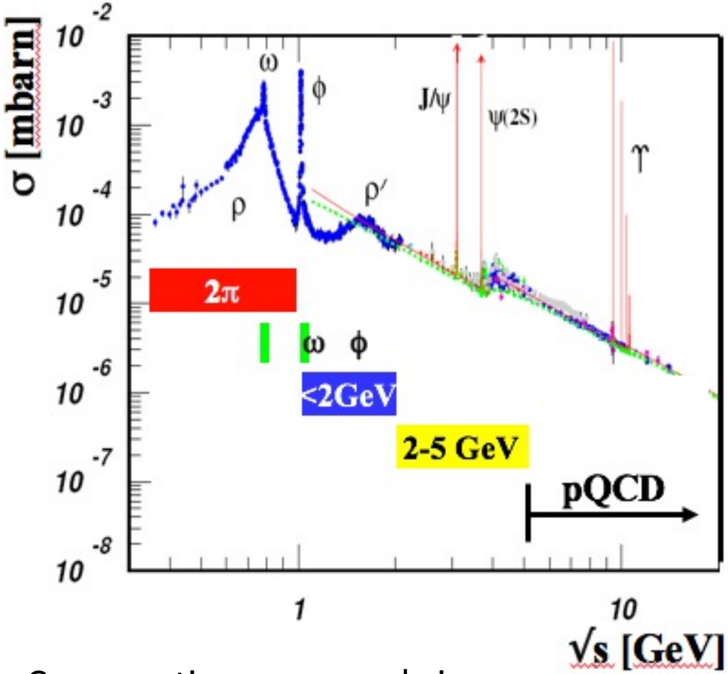
Optical theorem (unitarity) and analyticity:

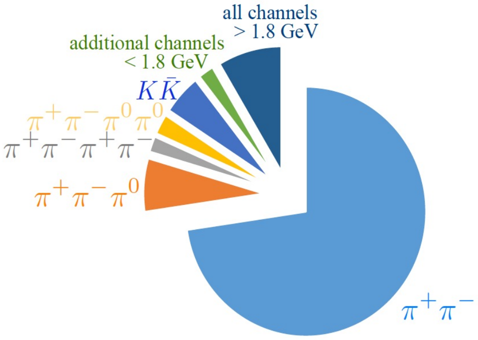
Data-driven approach: *K(s):* known kernel function
s: energy^2

$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \boldsymbol{\sigma_{\mathrm{had}}(s)}$$

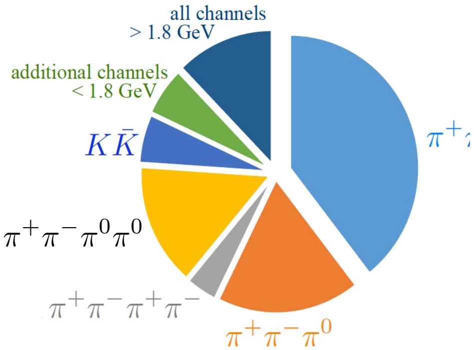
$$\boldsymbol{\sigma_{had}(s) = \sigma_{\mathrm{tot}}(e^+e^- \rightarrow \mathrm{Hadrons})}$$

low energy contributions especially important!





Contributions to HVP integral

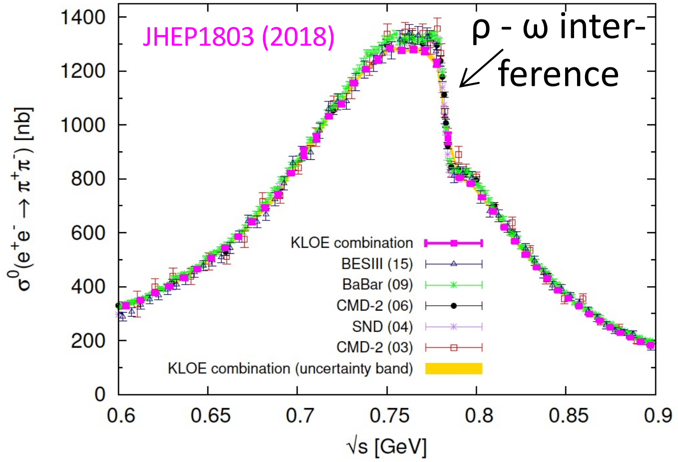


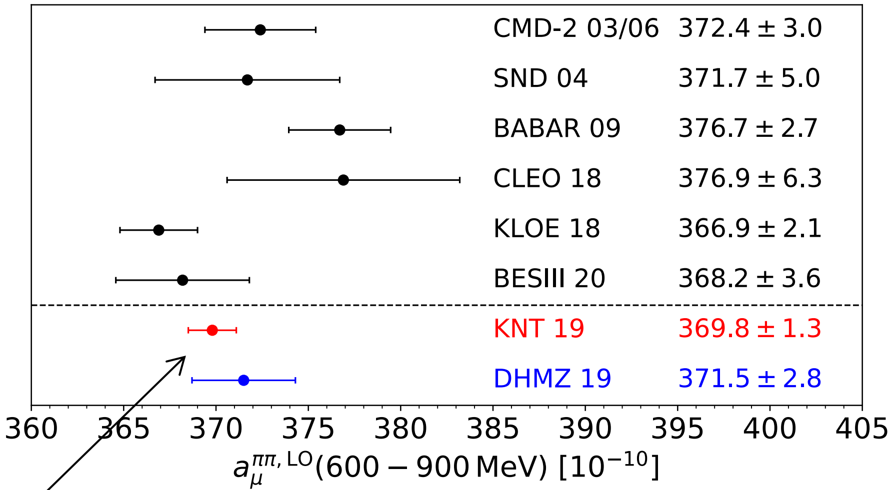
Contributions to HVP error

Cross section measured via:

- Energy scan (Novosibirsk, BESIII)
- Initial State Radiation (KLOE, BABAR, BESIII, ...)

Most relevant Channel: $e^+e^- \to \pi^+\pi^-$





Systematic Uncertainties on ρ(770) peak

- ISR BABAR 0.5%
- ISR KLOE 0.6%
- ISR BESIII 0.9%
- Energy Scan CMD2 0.8%*

  * limited in addition by statistics

Most recent evaluations of HVP:

- Davier, Höcker, Malaescu, Zhang (DHMZ)
  - averaging via 2nd ord. polynomial interpolation
  - systematic correlat. propagated via pseudo-data (MC)
- Keshavarzi, Nomura, Teubner (KNT)
  - data subjected to a clustering procedure
  - fit over all data sets taking into account correlations

Whitepaper Estimate of HVP

- Merging of KNT, DHMZ estimates + input from ChPT/dispersive fits: CHHKS for 2π, 3π channels; determinations from FJ17 and BDJ10 (assuming hadronic models in global fit) not considered

Talk Colangelo

	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
$K_S K_L$	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
[1.8, 3.7] GeV (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
J/ψ, $\psi(2S)$	7.76(12)	7.84(19)	−0.08
[3.7, ∞) GeV	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\text{HVP, LO}}$	$694.0(1.0)(3.5)(1.6)(0.1)_\psi(0.7)_{\text{DV+QCD}}$	692.8(2.4)	1.2

:-(

reasonable agreement

→ $a_\mu^{HVP,LO} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{syst}}(0.7)_{\text{pQCD}} = 693.1(4.0) \times 10^{-10}$ Whitepaper estimate

experimental uncertainties: domitated by 2π uncertainty

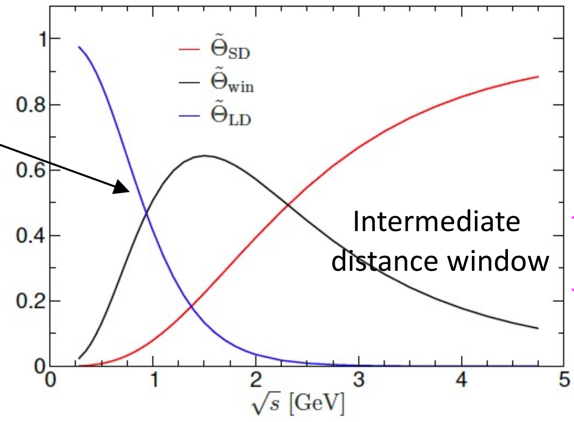
KLOE/BABR tension: leaving out KLOE or BABAR, respectively

energy region [1.8;3.7] GeV; usage of pQCD by DHMZ, while KNT follows data-driven approach

Discrepancy with Lattice QCD Windows Estimate

Serious deviation between data-driven evaluation of a_μ^{HVP} and intermediate-distance Lattice-QCD window

- weight function allows to relate Lattice-QCD window to total hadronic cross section
- weight function peaked at ~1.5 GeV
- ca. 1/3 of total a_μ^{HVP}, of which 60% given by $\pi^+\pi^-$
- selects ~28% of absolute $\pi^+\pi^-$ contribution
- need to explain deviation of 7 … 8×10^{-10}



PLB833 (2022) 137313

talk Blum

Explanation 1: Upscale π+π- data by >5% (flat), however this causes conflict with BMW result for full a_μ^{HVP}

Explanation 2: Underestimated contributions > 1 GeV (higher multipl.), however would need to be large effect; hadronic particle not being observed by experiment, e.g. Sexaquark? arxiv:2206.13460

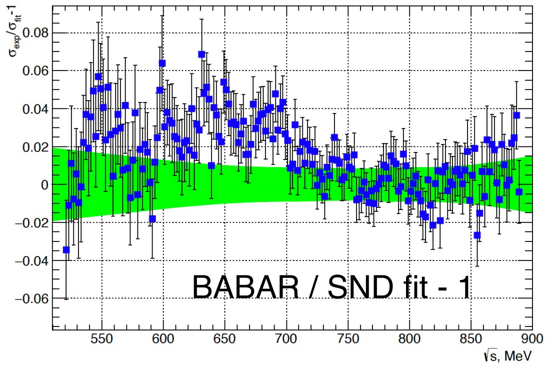
Explanation 3: Common systematic effect in Lattice-QCD and/or underestimated BMW21 result for full a_μ^{HVP}

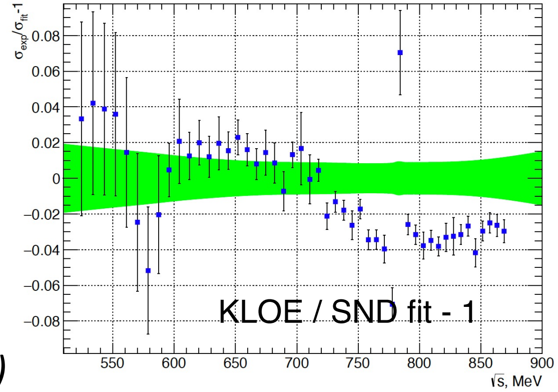
Hadronic Cross Section Data after Whitepaper

- BESIII $\pi^+\pi^-$, (600 < √s < 900) MeV, update of covariance matrix
  → central value unchanged, reduction of statistical error

- New SND analysis of $\pi^+\pi^-$ channel, (525 < √s < 883) MeV
  → systematic uncertainty > 600 MeV: 0.8%

Measurement	$a_\mu(\pi\pi) \times 10^{10}$
This work	$409.79 \pm 1.44 \pm 3.87$
SND06	$406.47 \pm 1.74 \pm 5.28$
BaBar	$413.58 \pm 2.04 \pm 2.29$
KLOE	$403.39 \pm 0.72 \pm 2.50$

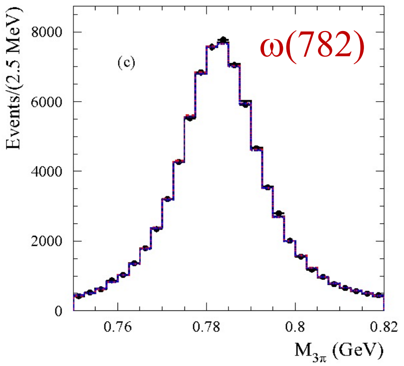


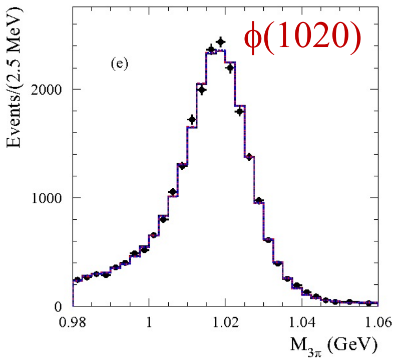


- New BABAR data on $\pi^+\pi^-4\pi^0$, $2(\pi^+\pi^-)3\pi^0$, $KK\pi\pi\pi$

- New BABAR analysis of $\pi^+\pi^-\pi^0$ channel, (0.62 < √s < 3.5) GeV
  → systematic uncertainty < 1.1 GeV: 1.3%
  → fit to $M_{3\pi}$ including $\omega(782)$, $\omega(1420)$, $\omega(1680)$, $\phi(1020)$, $\rho(770)$

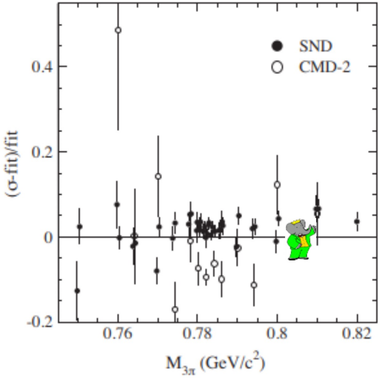
New BABAR-Analysis of $e^+e^- \to \pi^+\pi^-\pi^0$

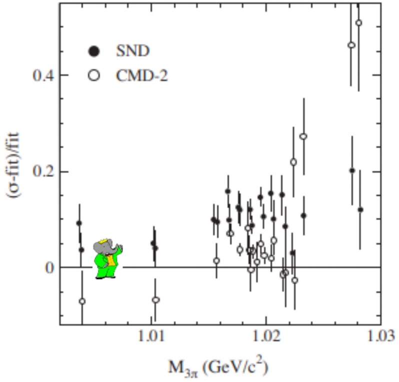




Δ(SND-BaBar) = 2%
Δ(CMD-2-BaBar) = 7%

Δ(SND-BaBar) = 11%
Δ(CMD-2-BaBar) = 3%





	$M_{3\pi}$ GeV/c^2	$a_\mu^{3\pi} \times 10^{10}$
	0.62–1.10	$42.91 \pm 0.14 \pm 0.55 \pm 0.09$
	1.10–2.00	$2.95 \pm 0.03 \pm 0.16$
	< 2.00	$45.86 \pm 0.14 \pm 0.58$
DHMZ 20	< 1.8	$46.21 \pm 0.40 \pm 1.40$
KNT 20	< 1.97	46.74 ± 0.94
FJ 17	< 2	44.32 ± 1.48
HHK 19	< 1.8	$46.2 \pm 0.6 \pm 0.6$

- Second largest contribution to HVP
- Good agreement with previous estimates
  → Reduction of uncertainty by factor of 2
- Precise measurement of M = ω, ϕ, and J/ψ values for $\Gamma(M \to e^+e^-) \cdot \mathcal{B}(M \to \pi^+\pi^-\pi^0)$
- Observation of $\rho(770) \to \pi^+\pi^-\pi^0$

NEW

Inclusive R Measurement

Phys. Rev. Lett. 128 (2022) 062004

Above cms energies of ~ 2 GeV inclusive measurement of R_{had}
(large QED background below, low multiplicities)

Master formula:

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

Background Contributions
- Evaluated with MC:
  - BabaYaga@NLO, Phokhara, KKMC
    $e^+e^- \to e^+e^-, \mu^+\mu^-, \gamma\gamma, \tau^+\tau^-$
  - BdkRC, Diag36, Galuga, Ekhara
    $e^+e^- \to e^+e^- X$
- Beam related background

CMS Energy
- 14 points
- 2.2 GeV to 3.7 GeV
- > 10^5 had. events

Luminosity
Determined with large angle Bhabha scattering

Efficiency
Ratio of generated and reconstructed events from Monte-Carlo

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

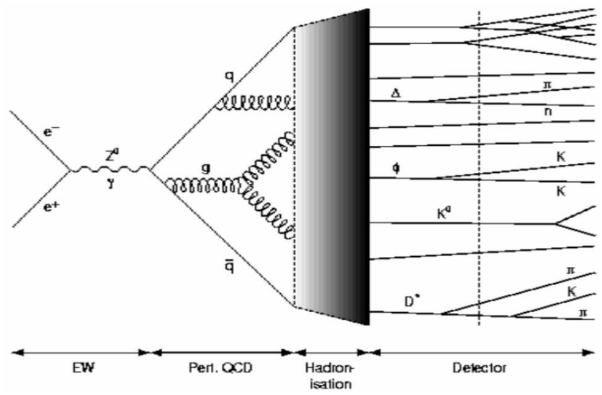
Analysis strategy: select all events with $\geq$ 2 tracks

- Reject back-to-back 2-prong events (Bhabha, Di-Muons)
- Remaining background from ISR and QED events ($e^+e^- \to e^+e^- / \mu^+\mu^-$) subtracted from MC

Two independent inclusive Monte-Carlo Generators

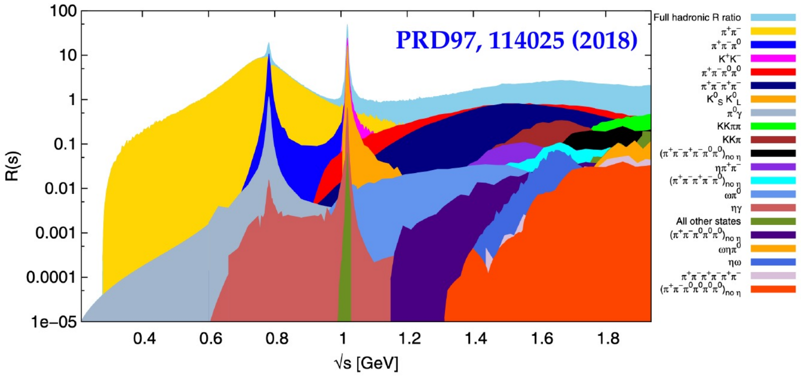
Fully theoretical MC production

- Development based on Jetset for low-energy experiments (LundAreaLaw)
- Simulation of resonances and continuum
- ISR and vacuum polarization implemented
- Kinematics of final hadrons tuned by experimental distributions (N_{trk}, N_γ, cosΘ, ...)



MC generator almost entirelybased on exptl. data

- PHOKHARA event generator (10 low-multiplicity channels 2π, 3π, 4π, $N\bar{N}$, ...) fitted to exptl. data
- CONEXC based purly on exptl. data (phase space), 47 channels



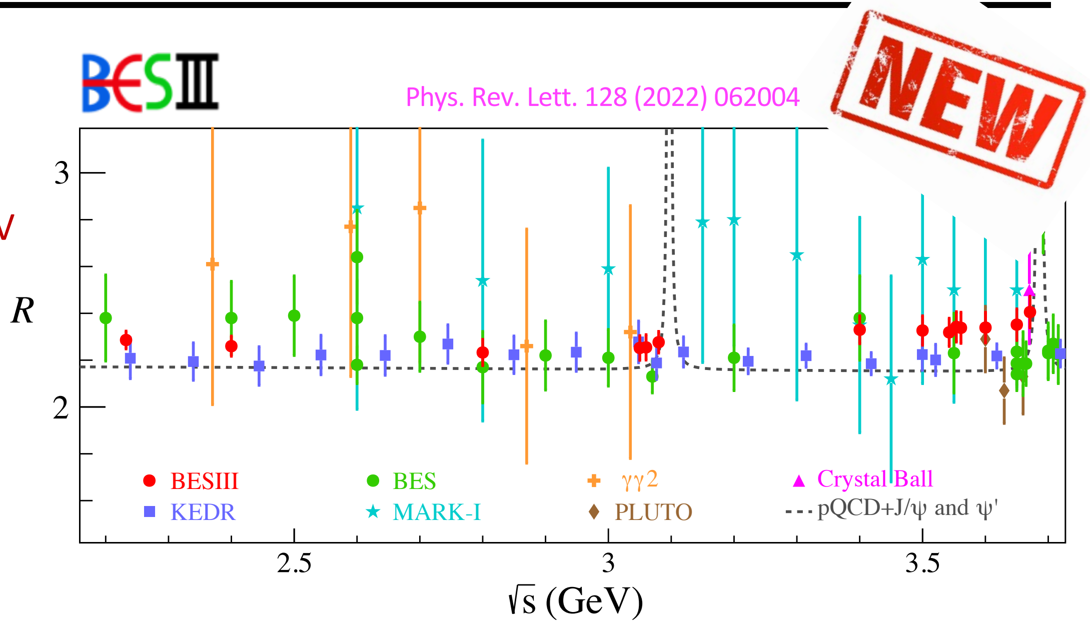
- Remaining channels simulated by LUARLW

After years of developments, tuning, and cross checks a deviation of better than 2.3% (including ISR) between the hybrid generator and LUARLW is found (major achievement)

New R_{incl} Measurement from BESIII

- Energy range covered: $2.2 < \sqrt{s} < 3.7$ GeV
- Statistical uncertainty <0.5%
  Systematic uncertainty <2.6% below 3.1 GeV
  ~3.0% above
- Above 3.4 GeV deviation observed with:
  - KEDR/Novosibirsk on the level of 1.9σ
  - pQCD theory on the level of 2.7σ

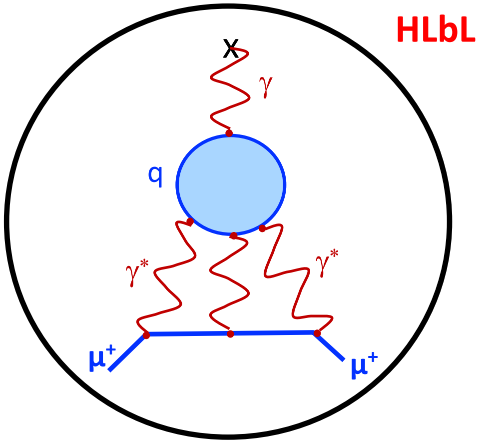
World's most precise R_{incl} measurement !
Some deviations from pQCD seen ?!



Next steps: 1) Analysis of high statistics energy scan in entire range 2.0 – 4.6 GeV

2) Attempt to measure R_{incl} using ISR with dramatically increased efficiency of MC generator (from ~65% to >90%) → reduced model dependence

Hadronic Light-by-Light Contribution (HLbL)

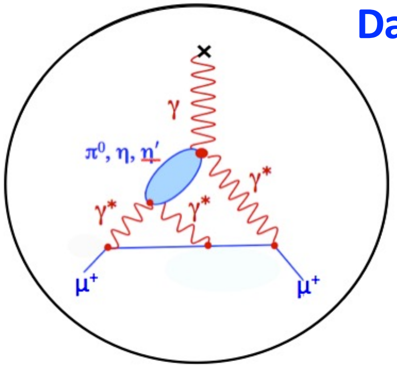


Estimate of (g-2) Theory Initiative:

(**9.2 ± 1.8**) · 10^{-10}

was (10.5 ± **2.6**) · 10^{-10}

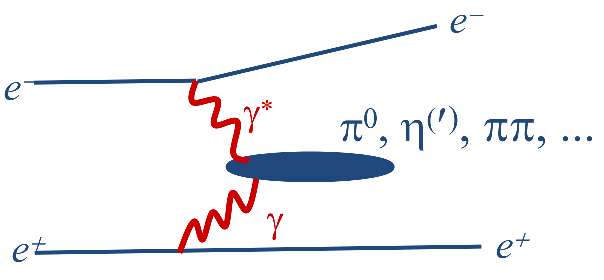
Meson Transition Form Factors and HLbL

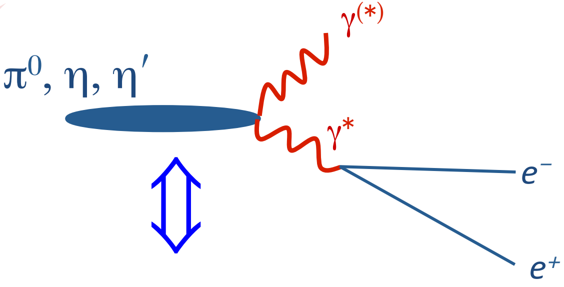


Data-driven approach!

⇔

Exp. Input !
Transition
Form Factors F(Q²)
below ~ 2 GeV²





⇕

Experimental challenges:

<u>Now</u>: measure single-virtual TFF and compare with theory assumption!

<u>Future</u>: provide measurements of double-virtual TFFs

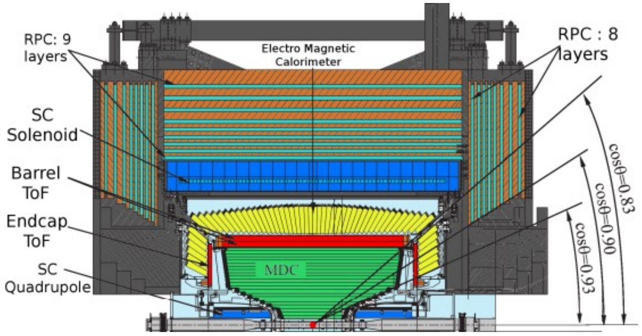
Problem: double-virtual TFFs needed, for which no measurements exist yet!

Way out: use theory calculations for double-virtual TFFs:
- Lattice QCD calculation
- Dispersive analyses

BESIII Experiment at the tau-charm Factory BEPC-II

World's by far largest τ-charm dataset in e^+e^- annihilation:

- Symmetric e^+e^- collider
- Located at the BEPCII collider (Beijing, China)
- CMS energy: 2 GeV to 5 GeV
- Maximum luminosity: $1 \times 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- 93% coverage of the solid angle



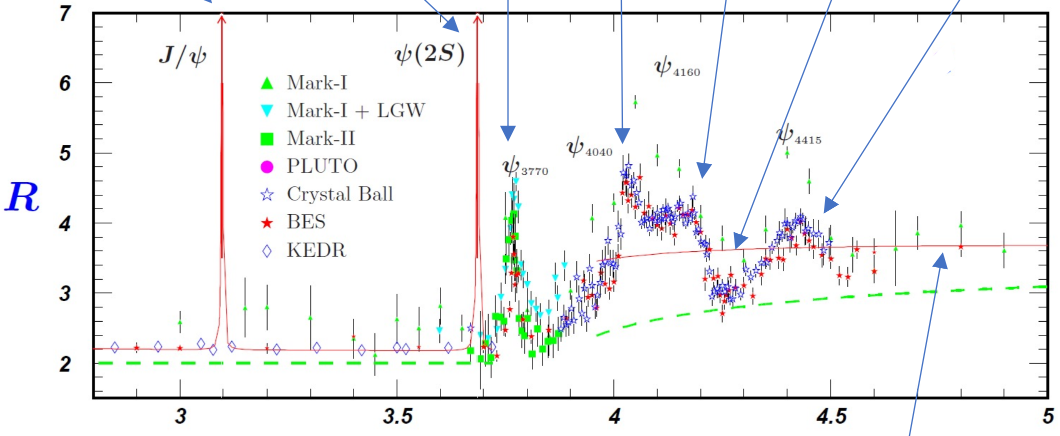
1×10^{10} Events

3×10^{9} Events

$2.9\ \mathrm{fb}^{-1}$

$20\ \mathrm{fb}^{-1}$ (2022)

$0.5\ \mathrm{fb}^{-1}$ $3.2\ \mathrm{fb}^{-1}$ $10.5\ \mathrm{fb}^{-1}$ $1.0\ \mathrm{fb}^{-1}$



130 points

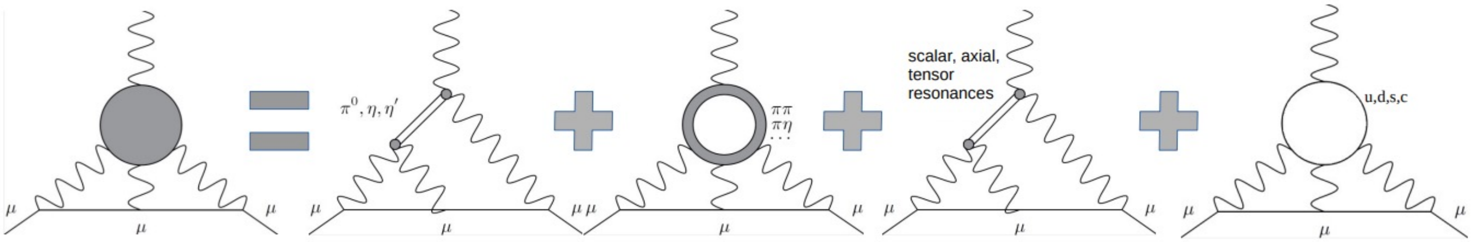
$2.0\ \mathrm{GeV} \leq \sqrt{s} \leq 4.6\ \mathrm{GeV}$

$\gg 1 \times 10^{5}$ had. Events each

$5.6\ \mathrm{fb}^{-1}$ at 10 points

$4.6\ \mathrm{GeV} \leq \sqrt{s} \leq 5.0\ \mathrm{GeV}$

HLbL and Impact of BESIII Data



- Uncertainties for pseudoscalar and π – box contributions significantly reduced
  → Validate theoretical TFFs with unique BESIII data set!

- Currently, axial vector, scalar, and tensor contributions together with short distance contributions limiting overall accuracy
  → BESIII measurements of axial vector, scalar, and tensor TFFs

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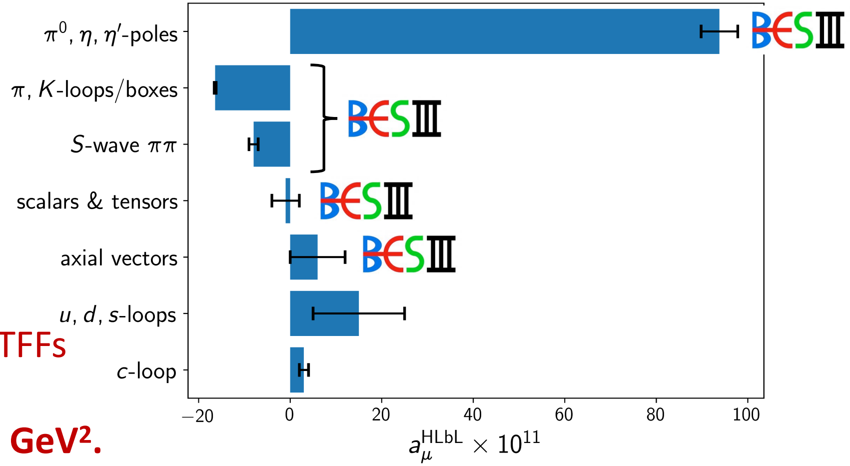


In very many cases no previous TFF measurements for $Q^2 < 2$ GeV².

Two-Photon Physics Programme at BESIII

Selection criteria

- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed

→ **cut on angle of missing momentum**

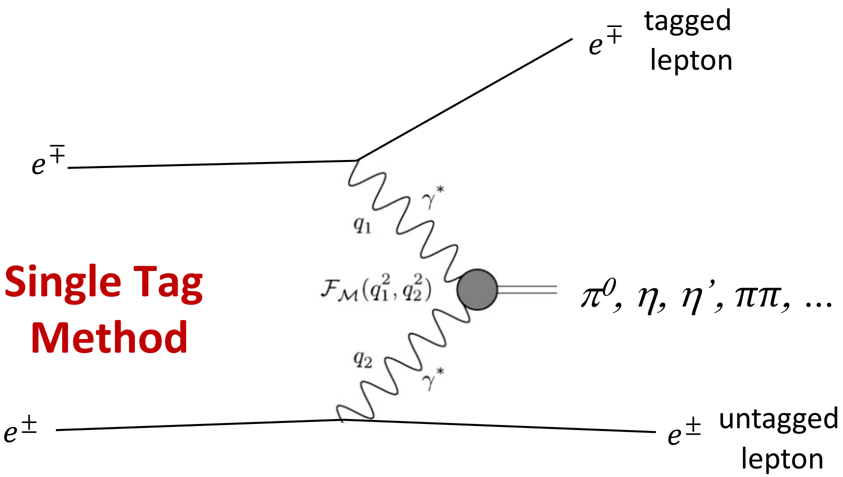
Momentum transfer

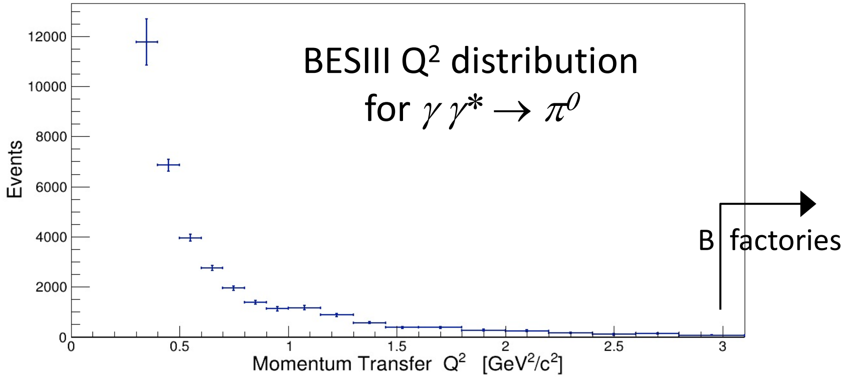
- tagged: $Q^2 = -q_1^2 = -(p - p')^2$
  $\rightarrow$ Highly virtual photon
- untagged: $q^2 = -q_2^2 \sim 0$ GeV^2
  $\rightarrow$ Quasi-real photon

EKHARA event generator

$$Q^2 = 4 \cdot E \cdot E' \cdot \sin^2(\theta/2)$$

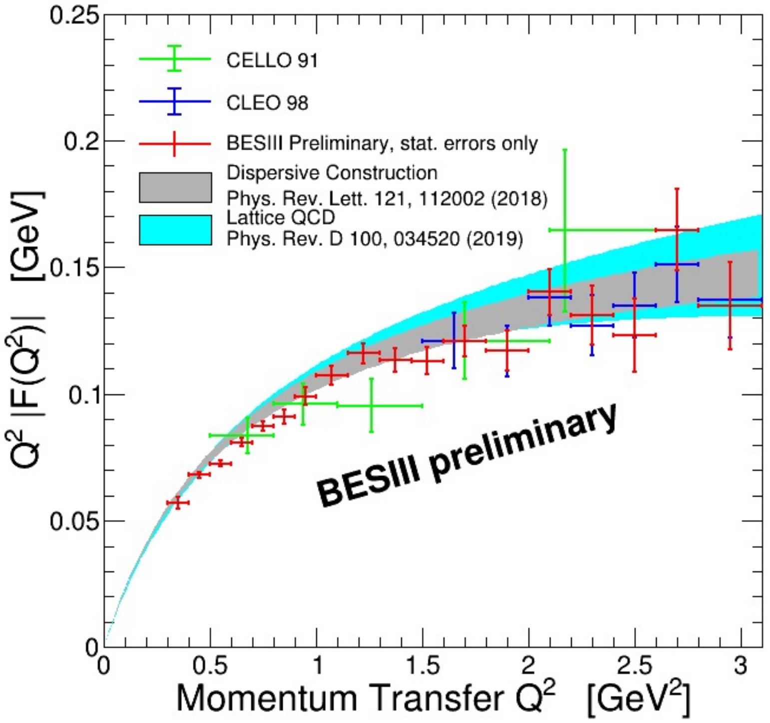
Single Tag Method





BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^0$

PPNP107 (2019) 20



- $\sqrt{s}_{\mathrm{BESIII}}$ = 3.77 GeV, L= 2.9/fb
- Unprecedented accuracy of BESIII
- Relevant Q^2 range for HLbL

→ **Very good agreement with recent dispersive analysis and of Lattice QCD calculation**

- Q^2 range below 0.3 GeV^2 accessible at BESIII with data from lower c.m. energy

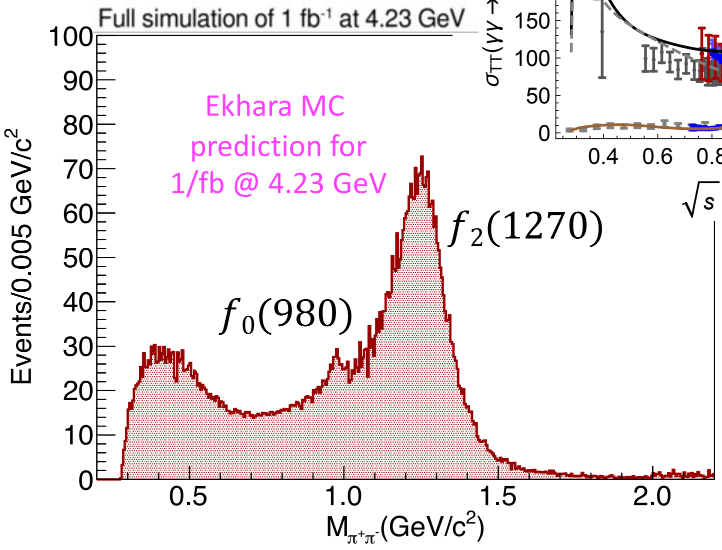
similar results for η and η' TFFs

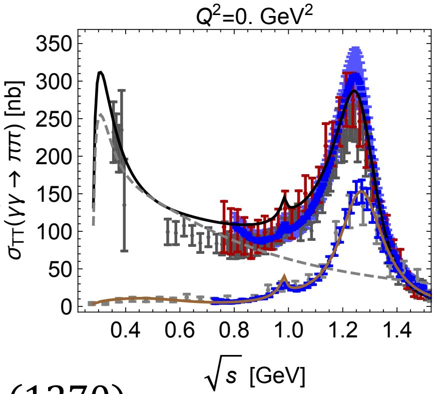
Upcoming BES III Analysis: $\gamma\gamma^* \rightarrow \pi^+\pi^-$

- Transition form factor for process $\gamma\gamma^* \rightarrow \pi^+\pi^-$ never measured before;
  only untagged measurements with Q^2=0 GeV^2 existing

- BESIII aims for:
  - first TFF measurement in Q^2 range 0.1 ... 3 GeV^2 in single-tag analysis
  - full coverage of the mass range up to 2 GeV
  - full coverage of the helicity angle

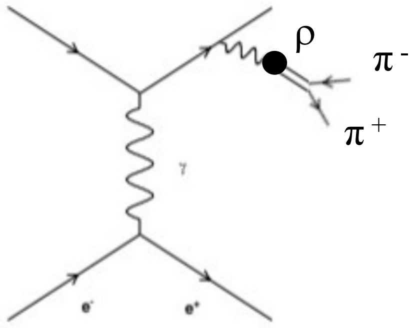
- Analysis in a very advanced state (7/fb):
  - 7/fb of data at cms energies $\geq$ 3.77 GeV
  - construction of MC generator Ekhara (H. Czyz)
  - detailed phenomenology program @ Mainz
  - subtraction of background channels !

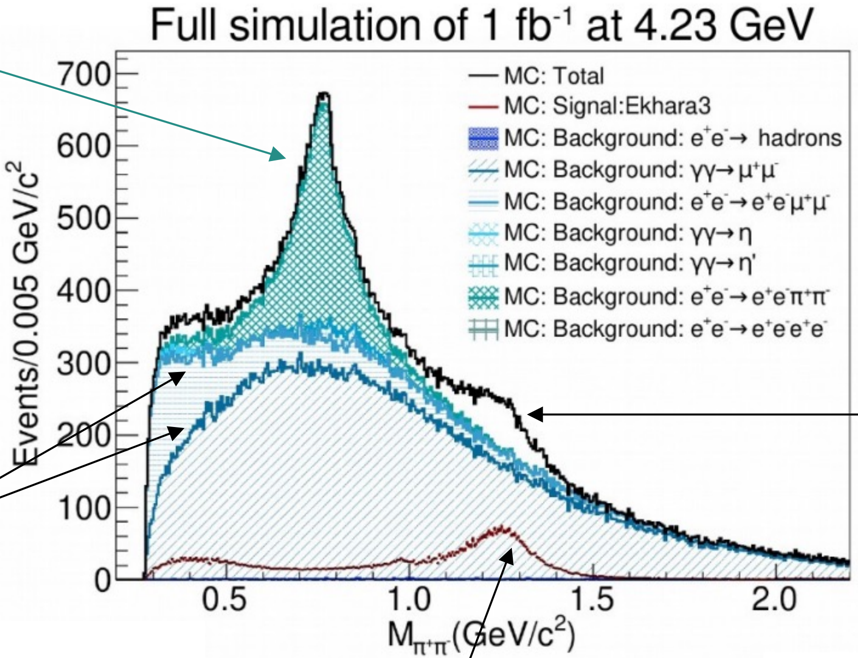




BES III Analysis: $\gamma\gamma^* \to \pi^+\pi^-$

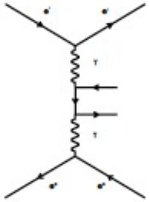
Radiative Bhabha scattering with production of rho meson

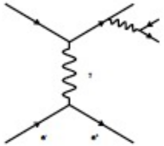


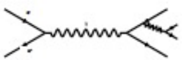


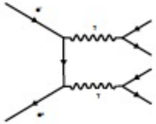
sum of all MC contributions

Process
$e^+e^- \to e^+e^-\ \mu^+\mu^-$









signal process
(see slide before)

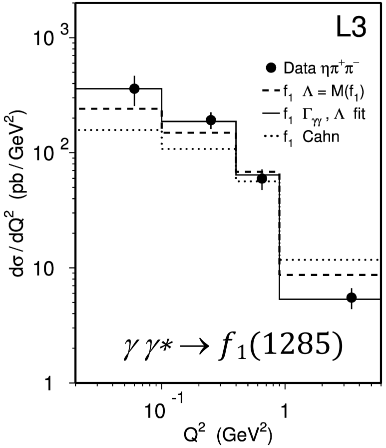
confident to publish $\pi^+\pi^-$ analysis shortly!

ongoing PhD project for $\pi^0\pi^0$ and $\pi^0\eta$ channels

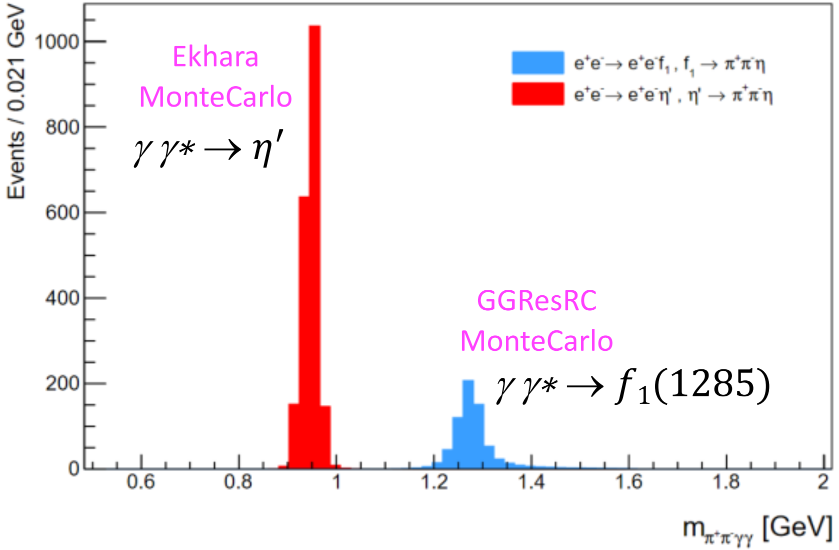
Upcoming BES III Analysis $\gamma\gamma^* \to f_1(1285) \to \pi^+\pi^-\eta$

- Design study recently completed
  - single-tag analysis
  - $f_1(1285) \to \pi^+\pi^-\eta$ ($\eta \to \gamma\gamma$)
  - 10/fb of data at cms energies > 4 GeV

- BESIII aims for:
  - TFF measurement in Q^2 range 0.24 ... 3 GeV^2
  - separation of LT and TT contribution by means of helicity angle
  - improved accuracy wrt. existing L3/LEP data below 6 GeV^2 (4 data points)



Simulation 10/fb, mass spectrum $\pi^+\pi^-\gamma$



- In addition investigations of higher lying states in preparation (different decay channels)

Conclusions

Conclusions

- Highly puzzling situation regarding discrepancy between L... ce QCD calculation and data-driven dispersive estimate of ...dronic Vac... arization (HVP)

- In data-driven appro... R puzzle), limiting SM uncertain... ... iation

- New data to b... ELLE-II
  → of ... y of HVP
  (0.6% ...

- Situati... ...ght-by-Light scattering (HLbL) contribution; good ... ent be... en data-driven dispersive approach and Lattice QCD, similar ... curacy; much room for further improvement

Next months going to be exciting,
both on the experimental side
as well as on theory/phenomenology side

Thank you !