Outlook on Precision Tests of Fundamental Physics with Light Mesons

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"*Prediction is very difficult, especially if it's about the future!*"
Niels Bohr

Outline

- general properties of the light mesons
- light meson spectroscopy (exotic states)
- decay width measurements (π^0 ,η, $\eta^/$)
- tests with rare decays
- precision form factor measurements
- search for physics BSM

Quark Structure of Light Mesons

- Mesons are the simplest (q, anti-q) strongly interacting particles in nature
- They are the lightest strongly interacting particles: $\pi^0, \pi^+, \pi^-, K^0, K^0, K^+, K^-, \eta, \rho, \omega, \ldots$
- They are all unstable
- π mesons as the lightest (q, anti-q) bound state plays the same role as the hydrogen in atomic physics

QCD Symmetries and their Partial Violations in Light Meson Sector

- Classical QCD Lagrangian in Chiral limit is invariant under:

$$SU_L(3)\times SU_R(3)\times U_A(1)\times U_B(1)$$

- Chiral $SU_L(3)xSU_R(3)$ spontaneously broken:

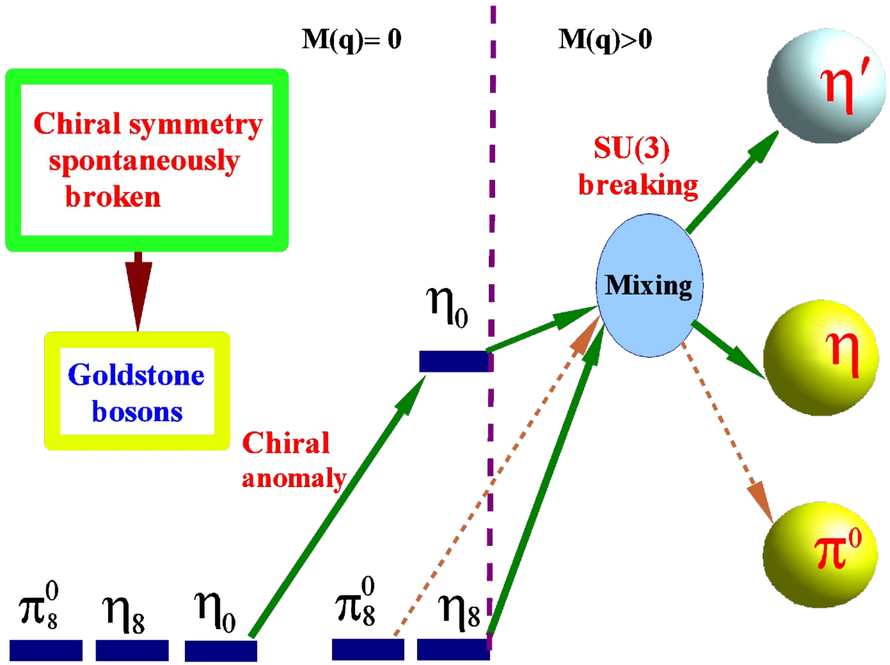
8 Goldstone bosons: $\pi^0, \pi^+, \pi^-, K^0, K^0, K^+, K, \eta, \eta'$

- $U_A(1)$ is explicitly broken:

  (axial or chiral anomaly)

  - $\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$
  - mass of η_0

- quarks are massive and different, SU(3) is broken:
  - Goldstone bosons are massive
  - mixing of π^0 η η'

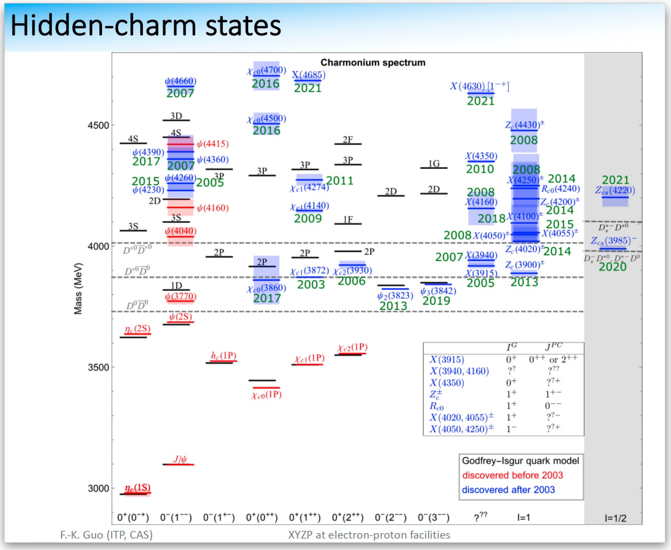


This system provides a rich laboratory to study the symmetry structure of QCD at low energies.

Meson Spectroscopy (light quark sector)

F-K Guo

- Direct production method:
  - ✓ moderate energies
  - ✓ high luminosity
  - ✓ high resolutions
  - ✓ large acceptance



- **The current status of the light meson spectroscopy** (with M. Battaglieri and A. Szczpaniak):
  - ✓ It is an important tool to study the strong force (QCD).
  - ✓ Several new multi-q states have been discovered that do not fit into the Quark Model.
  - ✓ Quark bound-states are genuine manifestation of non-perturbative regime of QCD.
  - ✓ The effort to un-reveal the internal structure of new states will be payed off by progressing our understanding of the strong force.

  - ✓ **It is still a long way to go but is an exciting journey!**

Meson Spectroscopy (light quark sector)

- **Future Perspective** (with M. Battaglieri and A. Szczpaniak):

  - ✓ Discoveries of XYZP phenomena show there is a large "hadronic landscape" yet to be discovered (also in the light flavor sector).
  - ✓ New high precision (both statistics and systematics) experiments are needed to pin down new states.
  - ✓ Compliment decay studies with "production".
  - ✓ Needs to distinguish "resonances" from "virtual states", "bound states" or "threshold rescattering" effects.
  - ✓ No single model accommodates all new states.
  - ✓ Modern hadron spectroscopy requires collaborations between experimentalist and theorists.
  - ✓ Properly constrained S-matrix amplitude analysis can determine if these "exotic" states are real.
  - ✓ Lattice is complementary to experiment. In spectroscopy it works as a digital scattering experiment rather than a "field theory solver". It should be used in coordination with phenomenological models.

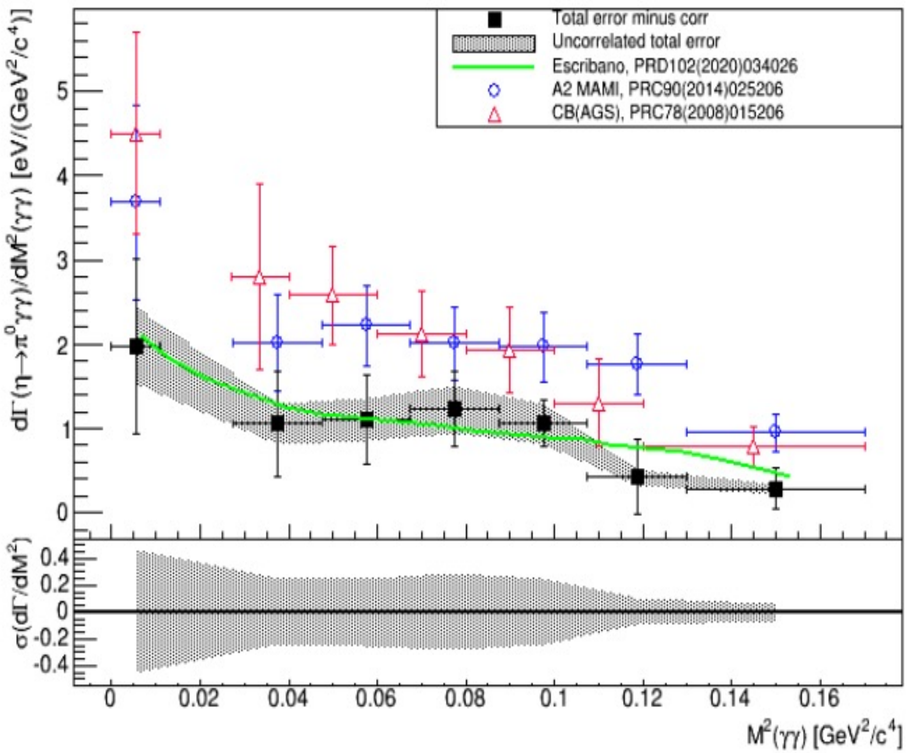
  - ✓ **Our expectation is that a decade from now we will have a very different view of hadrons compared to that proposed by Gell-Mann and Zweig.**

Tests With rare Decays ($\eta \rightarrow \pi^0\gamma\gamma$ ΚΛΟΕ–2 Results)

ChPT "golden mode": p^2 null, p^4 suppressed, p^6 dominates

S. Giovannella

KLOE prel. 2006, 450 pb^{-1} : 70 signal events, 4 s's discrepancy w.r.t. Crystal Ball measurement



~ 1200 signal events

same statistics as Crystal Ball

$$\mathbf{Br(\eta\rightarrow\pi^0\gamma\gamma) = (\,0.99 \pm 0.11_{stat} \pm 0.24_{syst}\,) \times 10^{-4}}$$

Confirmed:

- KLOE prel. central value
- **4 σ's difference with CB**

Rare Decays ($\eta \to \pi^0\gamma\gamma$ MAMI A2 Results)

Excellent χPT probe:

- $\mathcal{O}(p^2)$ and $\mathcal{O}(p^4)$ tree level terms vanish
- π and K loops at $\mathcal{O}(p^4)$ are heavily suppressed
- Major contribution to $d\Gamma(\eta \to \pi^0\gamma\gamma)$ comes from $\mathcal{O}(p^6)$ counter terms

Searches for possible new physics:

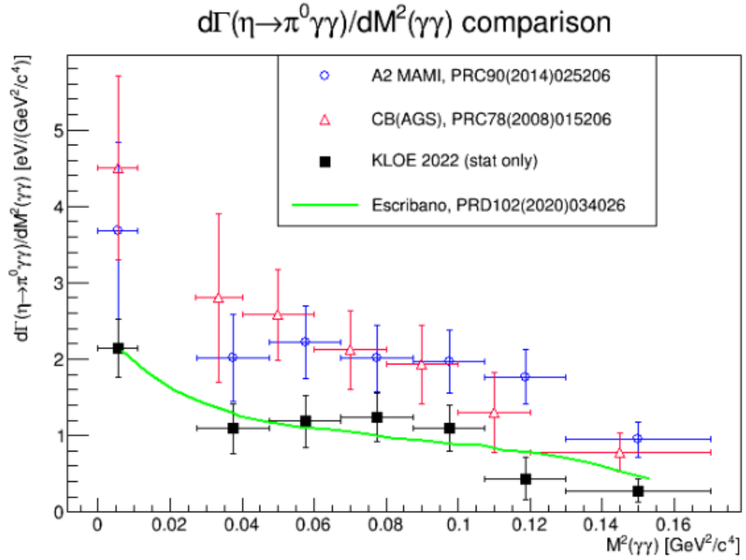
- Exclusion limit for Leptophobic $U(1)_B$-boson

$$\eta \to B\gamma \to \pi^0\gamma\gamma$$

Edoardo Mornacchi - JGU Mainz - Meson decay studies - A2@MAMI

R. Escribano, S. Gonzàlez-Solís, R. Jora and E. Royo, Phys. Rev. D 102, 034026 (2020)

Taken from: P. Gauzzi [KLOE-2], PoS **ICHEP2022**, 791 (2022)



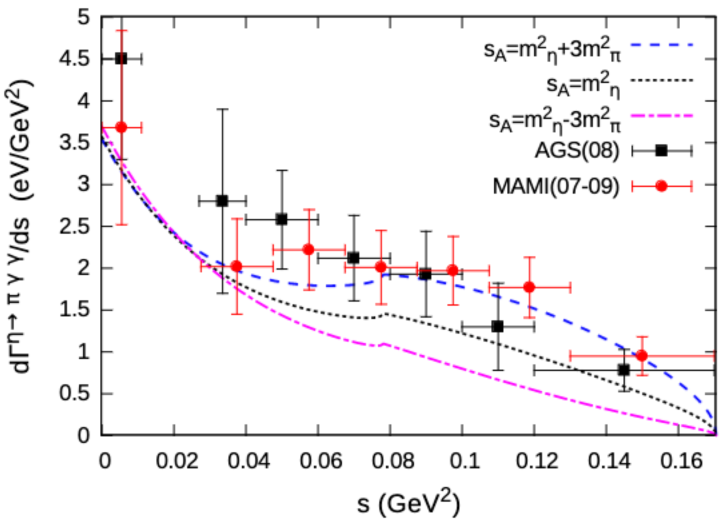
The experimental situation needs to be clarified (JEF, REDTOP, A2@MAMI)

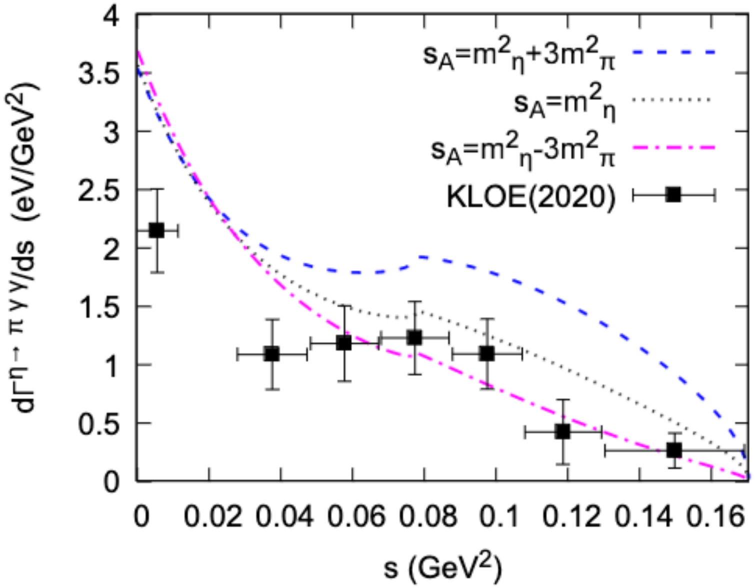
From E. Mornacchi

Theory Simulation ($\eta \to \pi^0\gamma\gamma$ Dispersive Approach, B. Moussallam)

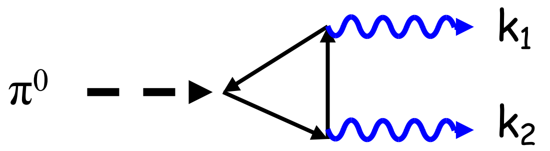
- Model for $\gamma\gamma \to \pi^0\eta$, $K_S K_S$, K^+K^- with analyticity/unitarity for the S-wave
- D-waves description more phenomenological
- Decay $\eta \to \pi^0\gamma\gamma$ predicted
  - ✓ Sensitive to Adler zero position
  - ✓ Sensitive to D-waves near s = 0

- Reasonable agreement with Crystal Ball@AGS and A2@MAMI but tension with new results by KLOE





$\pi^0 \to \gamma\gamma$ Decay Width



- Chiral anomaly defines the $\pi^0 \to \gamma\gamma$ decay width:
  O(P⁴) order Lagrangian (Wess, Zumino (1971) and Witten (1981))
  with anomalous term.
  - ✓ anomaly prediction is exact in massless quark limit (chiral limit):

$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.725\ eV$$

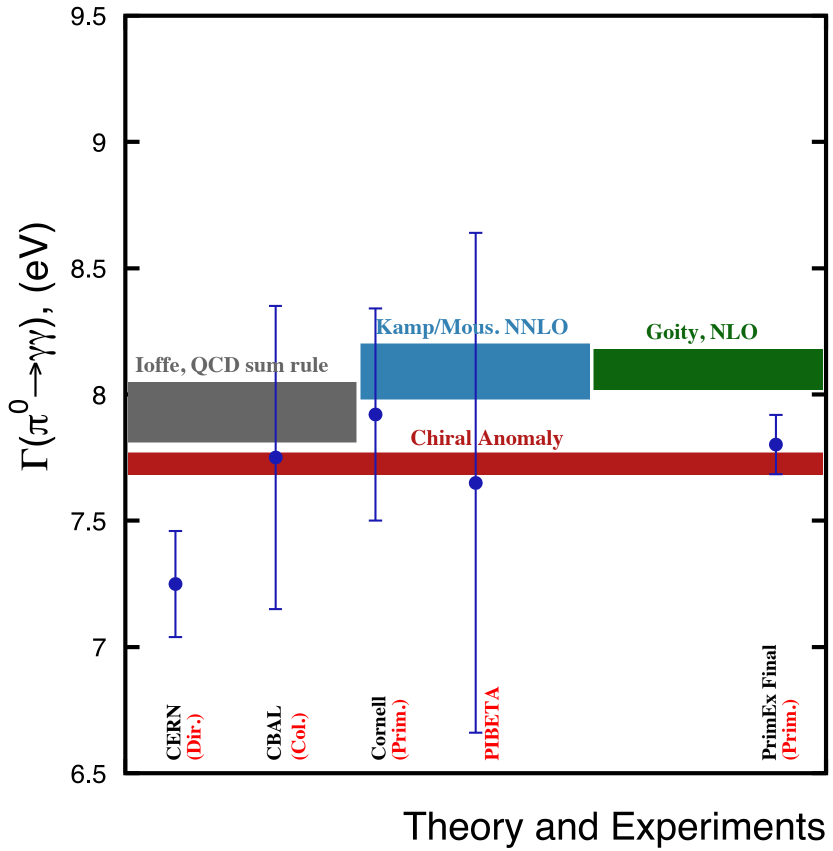
  - ✓ parameter free, no low-energy constants!

- Recent theory calculations give ≈ 4.5% increase with ≈1% uncertainty

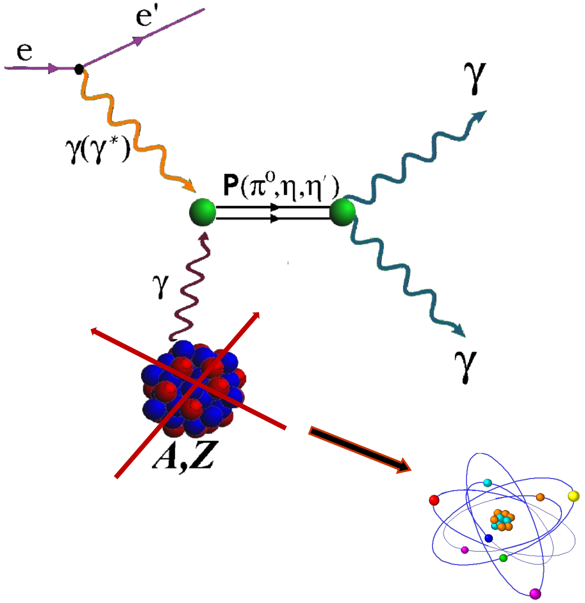
PrimEx final result:

$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.802 ±0.052(stat) ± 0.105(syst.) eV

(± 1.5%)



Primakoff Effect on Atomic electrons
($\pi^0 \to \gamma\gamma$ Decay Width High Precision Measurement)



- Use atomic electron as a target

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

  $\pi^0 \to \gamma\gamma$

- Requires threshold energy for γ^*

  $E_\gamma = ((m_{\pi 0} + m_{e-})^2 - m_{\gamma^*}^2 - m_{e-}^2)/(2\, m_{e-})$

  $E_\gamma \approx 18$ GeV

- Experimental method: detect all 3 final state particles:
  - ✓ recoil electrons
  - ✓ two photons from π^0 decay

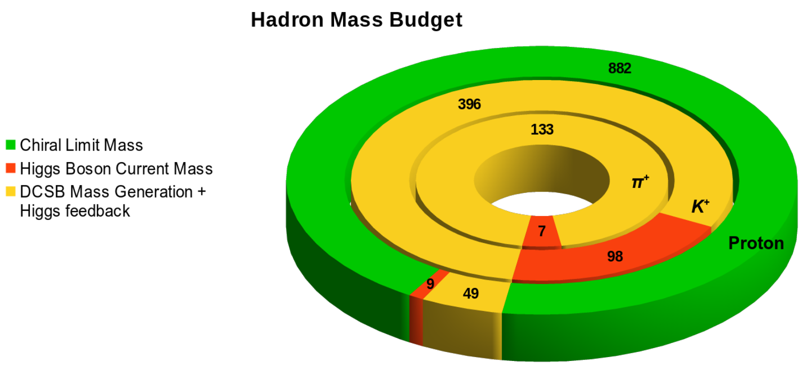
- Will provide full kinematical control:
  - ✓ reaction identification;
  - ✓ total energy conservation;
  - ✓ total 3-momentum conservation.

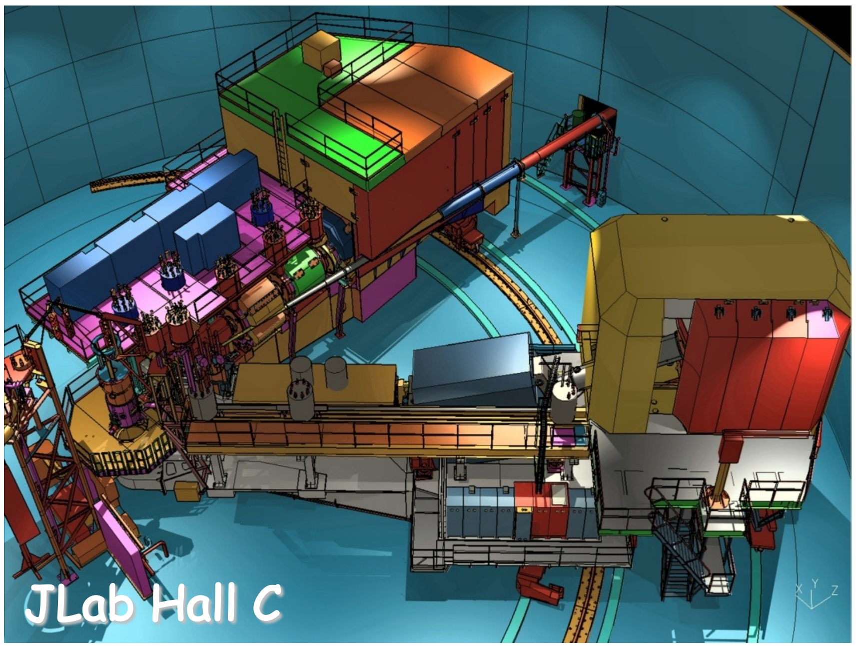
- It will provide a unique opportunity to measure the $\pi^0 \to \gamma\gamma$ decay width with a sub-percent accuracy. Experiment with the JLab 22+ energy upgrade.

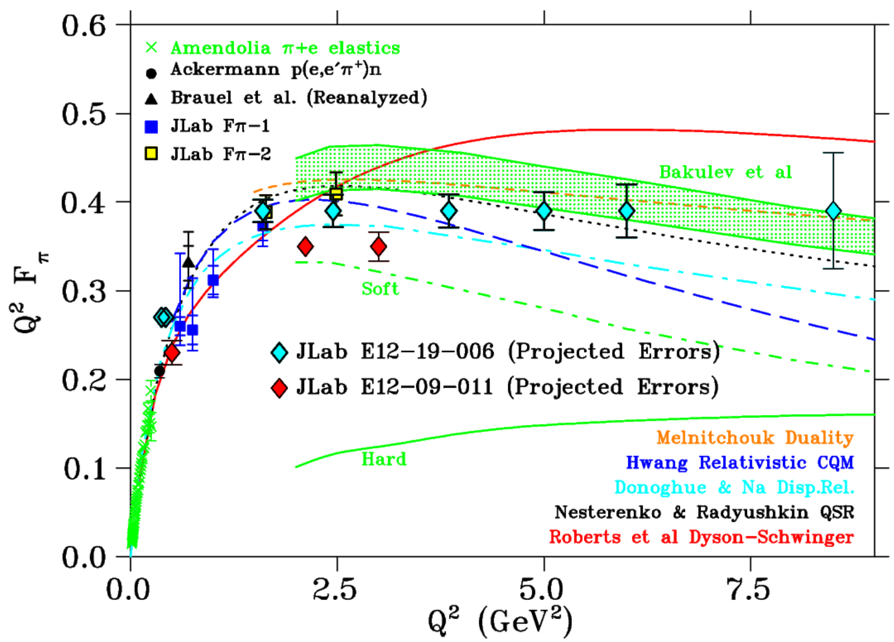
Charged Pion Form Factor Measurement to High Q^2

By G. Huber

- The pion is seen as key to confirm the mechanisms that dynamically generate almost all hadron mass and is central to the effort to understand hadron structure
- At empirically accessible Q^2, the π^+ form factor is sensitive to the emergent mass scale in QCD



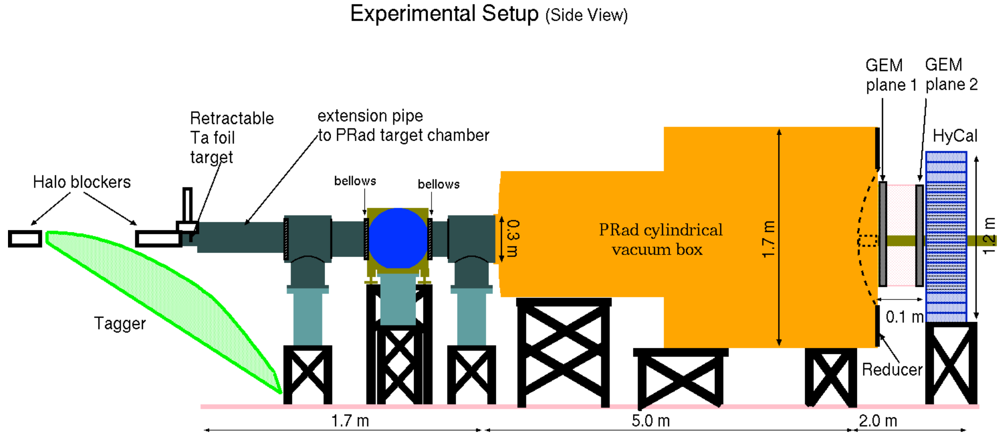


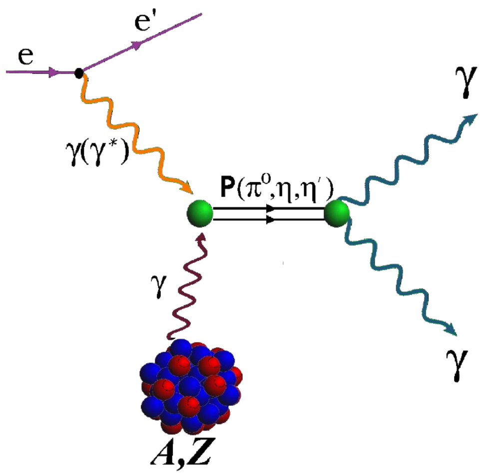


- Experiment is completed
- Results are expected in ~2025

$F(\gamma\gamma * \to \pi^0)$ Transition Form Factor Experiment
(Hall B at JLab)

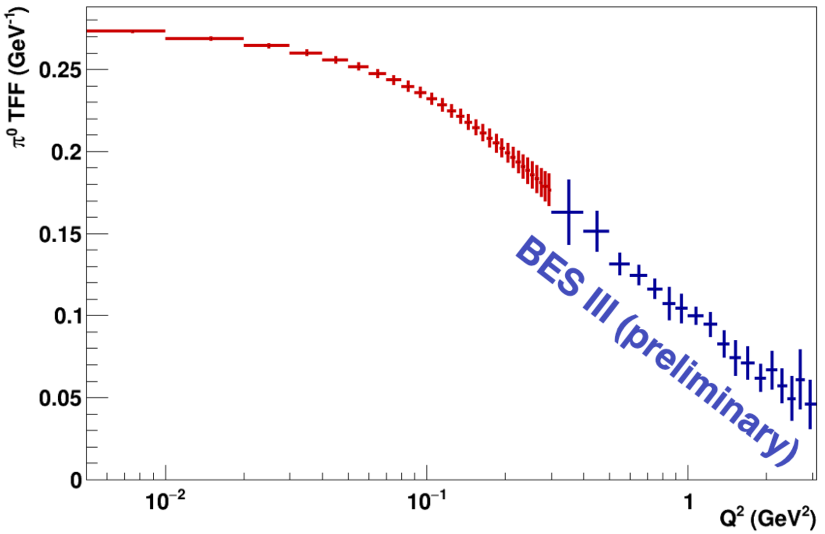
By R. Miskimen





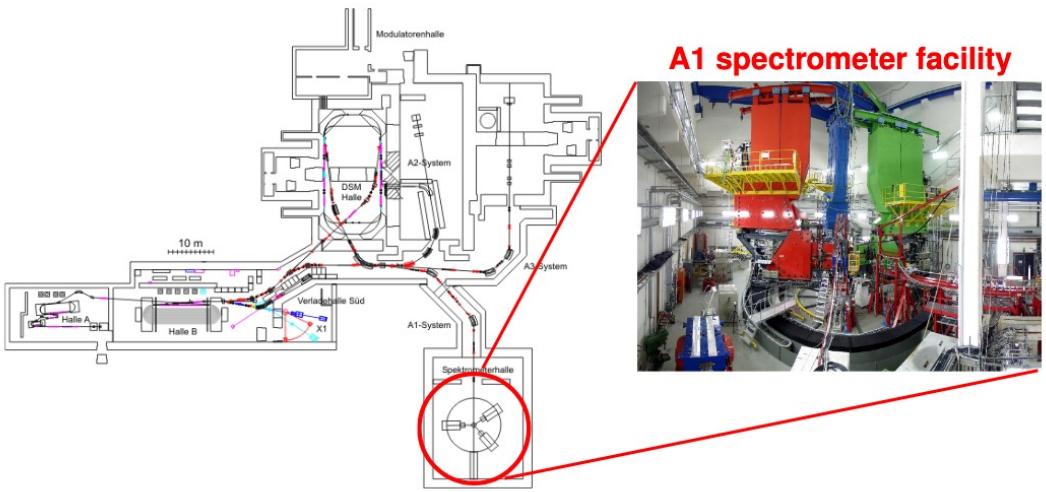
- PRad-II experimental setup will be used
- E_e = 10.5 GeV, I_e = 10 nA, Target ^{28}Si
- Q^2 = 0.003 – 0.3 GeV^2

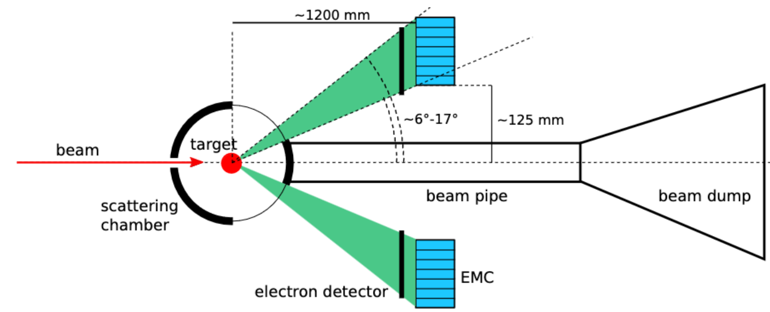
- Expected run time 2025

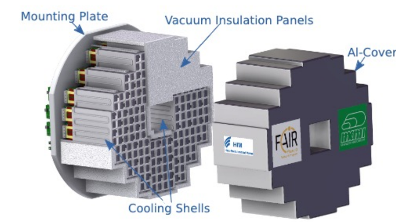


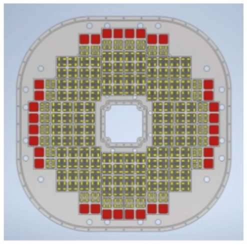
$F(\gamma\gamma* \to \pi^0)$ Transition Form Factor Experiment
(A1 at MAMI)

By Luigi. Capozza









- CW electron beam
- intensity up to 100 μA
  here: 100 nA needed
- beam energies up to 1.5 GeV

- 3 high-resolution magnetic spectrometers
  $\delta p/p \simeq 10^{-4}$, $\delta\theta < 3$ mrad
  $\rightarrow$ useful for alignment! ✓
- wide angular range (but $\theta_e \geq 15°$)
- limited acceptance } need for an EMC!

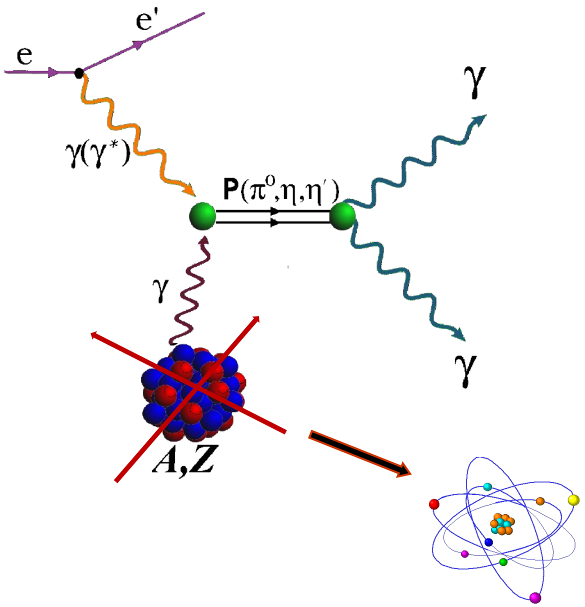
- Expected run time 2024-25

Outlook on $F(\gamma\gamma * \to \pi^0)$ Transition Form Factor Experiment
(Primakoff Effect on Atomic electrons)

- Use atomic electron as a target
  - ➢ requires threshold energy for γ (or γ^*)
    $E_{\gamma*} = ((m_{\pi 0} + m_{e-})^2 - m_{\gamma*}^2 - m_{e-}^2)/(2\, m_{e-})$
    for π^0 : $E_{\gamma*} \approx 18.1$ GeV

1) New high precision experiment for $\Gamma(\pi^0 \to \gamma\gamma)$
   $\gamma + e^- \to e^- + \pi^0$, with $\pi^0 \to \gamma\gamma$
   detection of: recoil e^- and $\gamma\gamma$

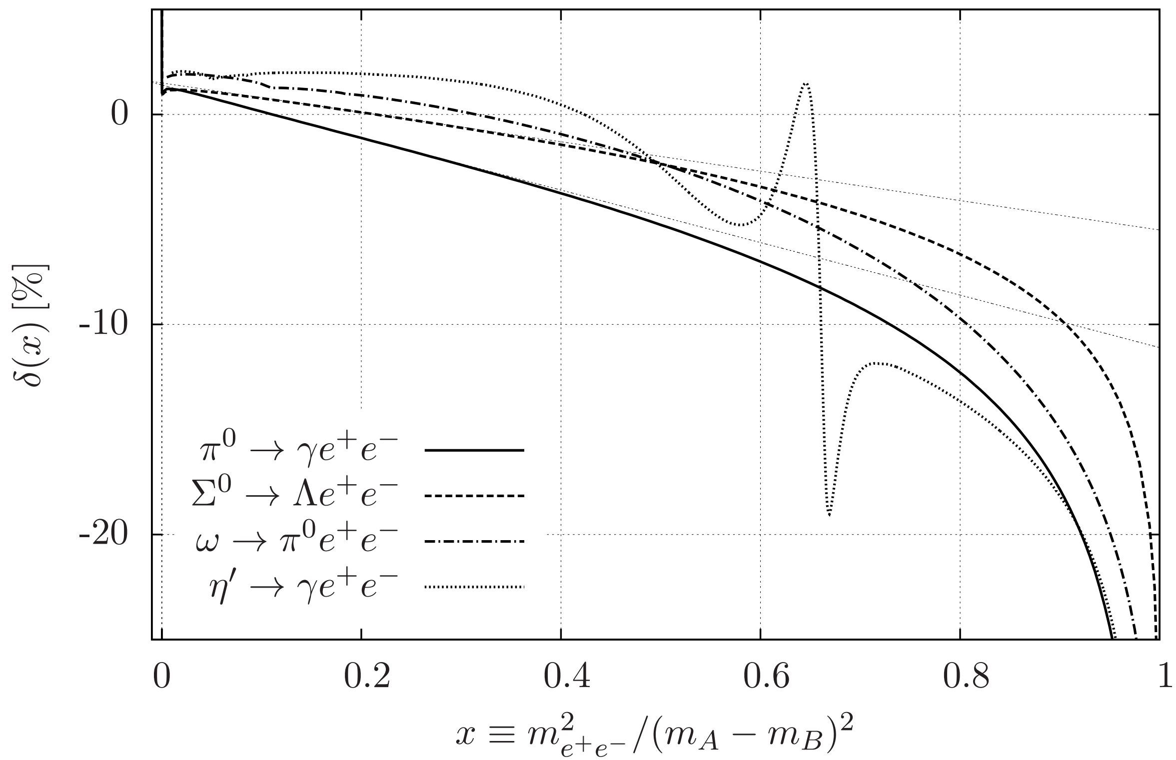
2) $F(\gamma * \gamma * \to \pi^0)$ transition form factor experiment at low Q^2 range
   - ➢ Experimental method: detect all 4 final state particles:
     - ✓ scattered electron
     - ✓ recoil electron
     - ✓ two photons from π^0 decay
   - ➢ Will provide full kinematical control:
     - ✓ reaction identification
     - ✓ total energy conservation
     - ✓ total 3-momentum conservation



- The sub-percent measurement of $F(\gamma\gamma * \to \pi^0)$ at low Q^2 range on the atomic electron will provide a critical input to the current $(g\text{-}2)_\mu$ anomaly.
- Requires JLab energy upgrade to 22+ GeV

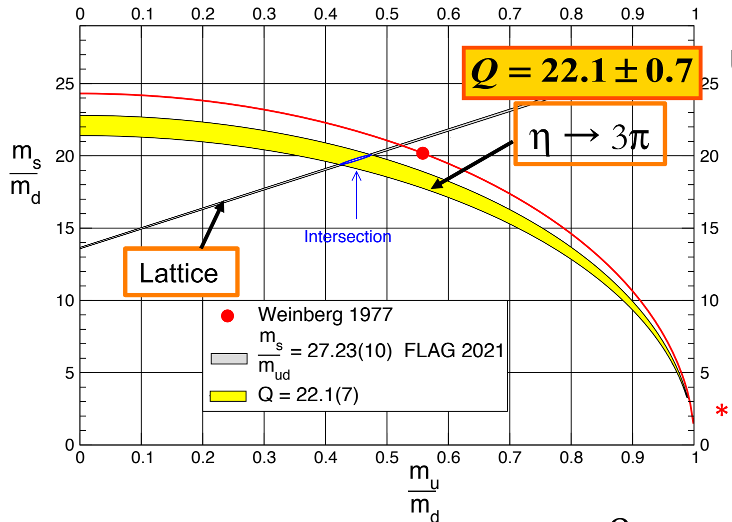
Radiative Corrections and Form Factors in Dalitz Decays of Lightest Mesons

- Tomas Husek "Radiative Corrections and Form Factors in Daltz Decays of Lightest Mesons"
- Question was: ".. is that really up to a 20% effect? "

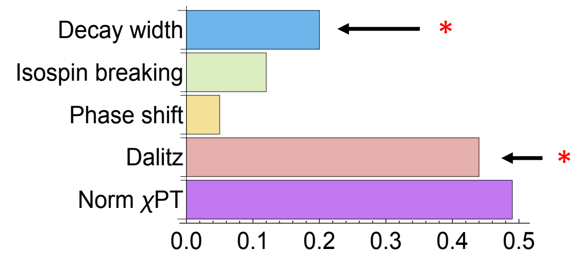


Last minute submission

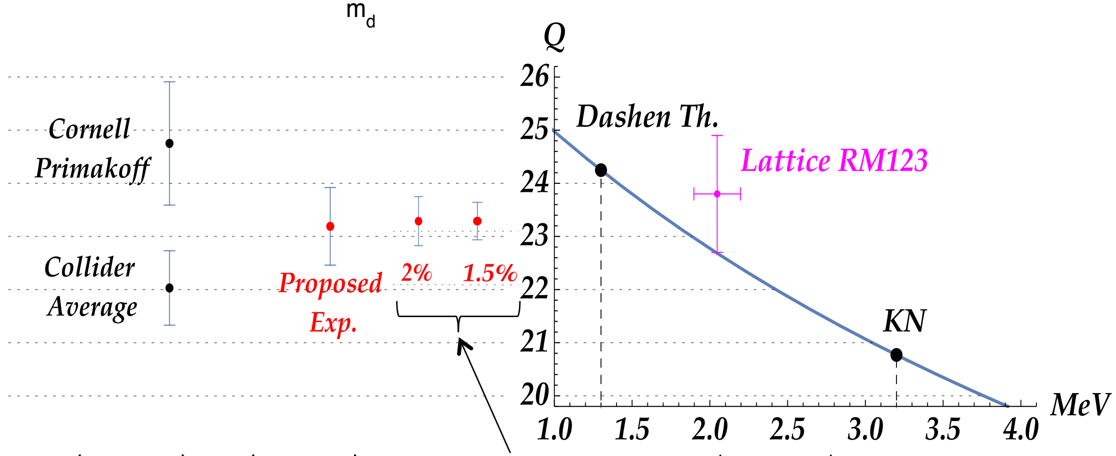
- Emilie Passemar



Uncertainties on the quark mass ratio:



* Can be investigated and reduced at *future facilities*



$\Gamma(\eta \rightarrow 3\pi) = \Gamma(\eta \rightarrow 2\gamma) \times BR$ **22 GeV upgrade** $(K^+ - K^0)_{EM\ Corr.}$

Prospects for studies of production, decays and structure of light mesons with HADES

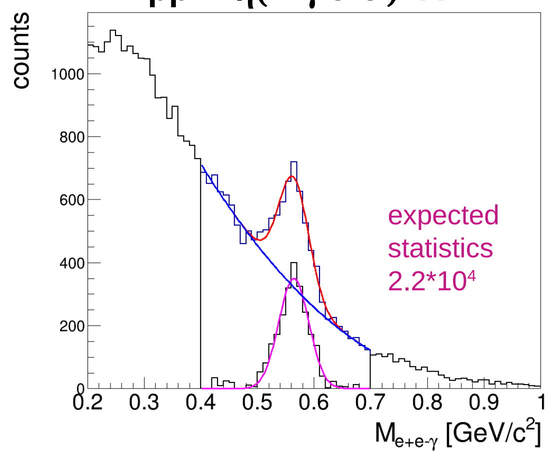
- Izabela Ciepal

Studies of neutral mesons production, structure and decays with HADES

- electromagnetic structure of $\eta(\rightarrow\gamma e+e-)$, $\omega(\rightarrow\pi^0 e+e-)$
- decay dynamics of $\eta/\omega\rightarrow\pi^+\pi^-\pi^0$
- production cross sections
- CP violation in $\eta\rightarrow\pi^+\pi^- e+e-$
- production mechanism of $f_1(1285)$

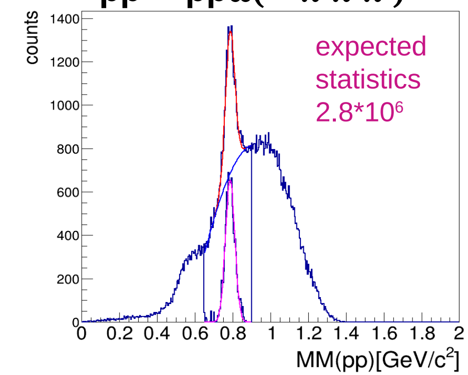
➢ inclusive analysis

$pp\rightarrow\ \eta(\rightarrow\gamma\, e^+e^-)+X$

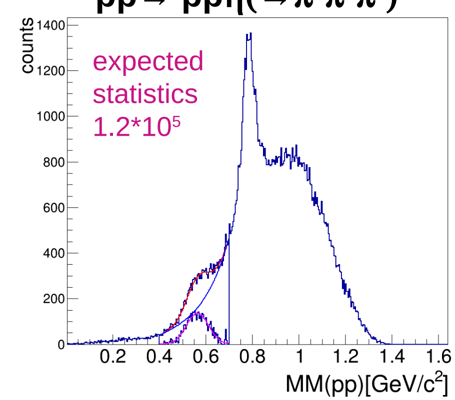


➢ exclusive analysis

$pp\rightarrow\ pp\omega(\rightarrow\pi^+\pi^-\pi^0)$

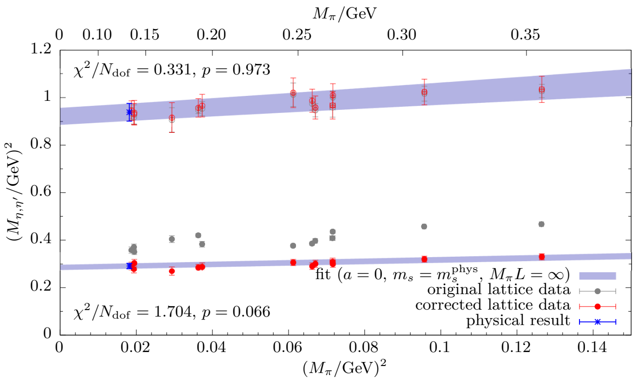


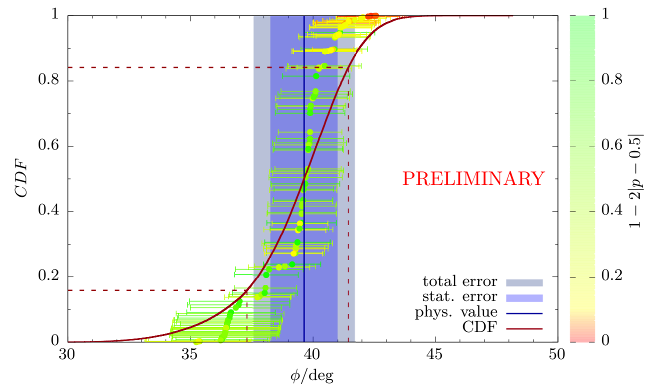
$pp\rightarrow\ pp\eta(\rightarrow\pi^+\pi^-\pi^0)$



Lattice Simulation ...

η,η' mixing from the lattice





LQCD calculation on ETMC ensembles with $N_f = 2+1+1$ flavors of Wilson Clover twisted-mass sea quarks:

- Three ensembles with physical quark mass, four lattice spacings.
- Improved control over systematic effects compared to our previous study; three times smaller stat error on e.g. M'_η.
- Controlled physical extrapolations for masses and mixing parameters in FKS scheme with stat. and sys. errors from model averages

$$M_\eta = 549(11)_{\rm stat}(11)_{\rm sys}\,\mathrm{MeV}, \quad M_{\eta'} = 971(19)_{\rm stat}(06)_{\rm sys}\,\mathrm{MeV}$$

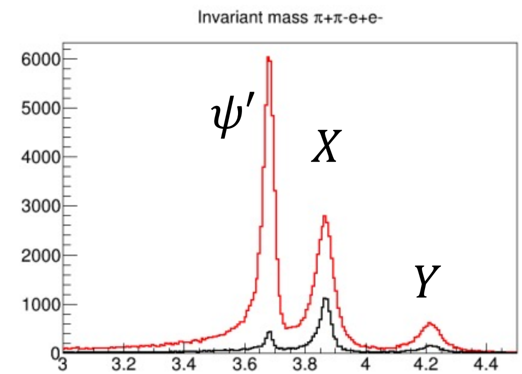
$$\phi = 39.6(1.4)_{\rm stat}(1.5)^\circ_{\rm sys}, \quad f_l = 138.3(4.0)_{\rm stat}(1.8)_{\rm sys}\,\mathrm{MeV}, \quad f_s = 170.7(3.2)_{\rm stat}(1.2)_{\rm sys}\,\mathrm{MeV}$$

Future prospects: Axialvector MEs + study of scale dependence of mixing parameters through $Z_A^0(\mu)$.

XYZ Spectroscopy at the EIC

By Pilloni

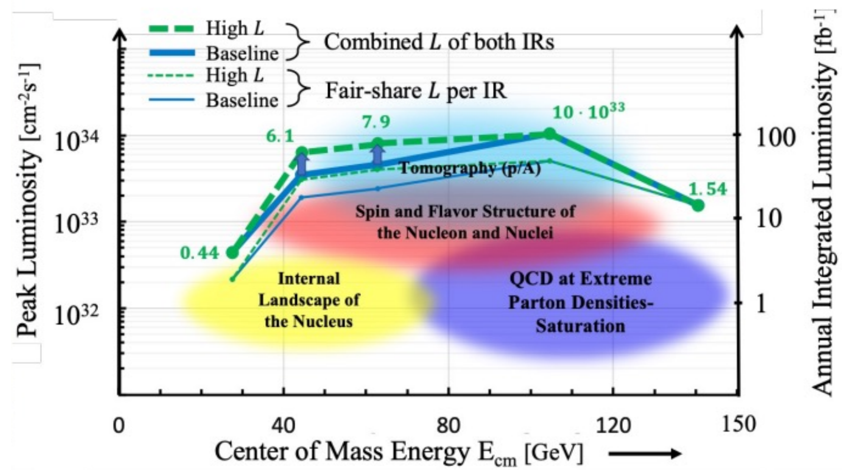
- It's new: no XYZ state has been uncontroversially seen so far
- Rescattering mechanisms that could mimic resonances in multibody decays can be controlled better (one can change the energy beam but not the B mass…)
- The framework is (relatively) clean from a theory point of view
- Radiative decays offer another way of discerning the nature of the states



Desiderata

- Low beam energies
- Low solenoidal field strength
- Require far forward and backward acceptance and resolution

Expected signal yields at the EIC competitive with BESIII if high-lumi scenario is realized



Future Facilities for Light Meson Physics

- Current JLab 12 GeV (GlueX, CLAS12):
  - ✓ Decay widths
  - ✓ Spectroscopy
  - ✓ Search for new physics
- JLab 22+ GeV beam upgrade (GlueX, CLAS22, SOLID …)
  - ✓ Precision decay widths
  - ✓ Spectrosopy
  - ✓ Search experiments
- EIC
  - ✓ Spectroscopy
  - ✓ Exotics …
- KLOE
  - ✓ Spectroscopy
  - ✓ Exotics
  - ✓ Decay widths
- MAMI
  - ✓ Spectroscopy
  - ✓ Exotics
  - ✓ Decay widths
- HADES:
  - ✓ spectroscopy
  - ✓ search for new physics
- ?
  - ✓ ?
- ?
- ?

Thanks to the Organizers for this scientifically Rich and very Intense Workshop