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The 16th International Conference on Meson-Nucleon Physics and the Structure of

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Yasemin Schelhaas
JGU Mainz

Small Angle Initial State Radiation Analysis of the Pion Form Factor at BESIII

MENU 2023 in Mainz

International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Yasemin Schelhaas

On behalf of the BESIII Collaboration

October 17, 2023

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence PRiSMA+ Precision Physics, Fundamental Interactions and Structure of Matter

DFG Deutsche Forschungsgemeinschaft

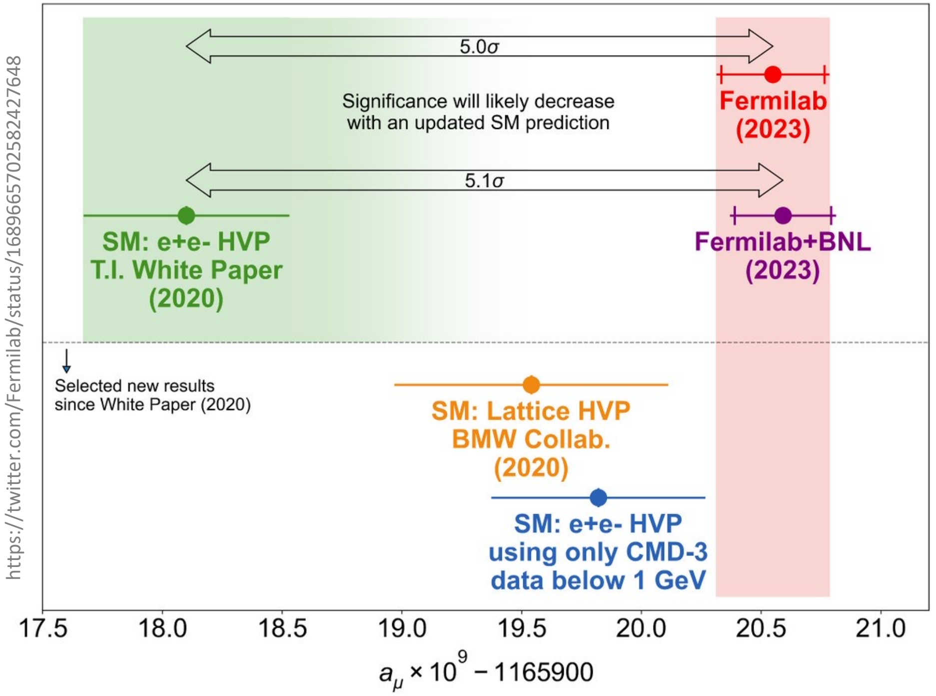
BESIII

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Anomalous Magnetic Moment of the Muon

- Muon g-2 puzzle: $\boxed{a_\mu = |g_\mu - 2|/2}$
- Standard Model (SM) prediction: $a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + \boldsymbol{a_\mu^{\mathrm{QCD}}} + a_\mu^{\mathrm{weak}}$
- Direct measurement: Experimental average of BNAL & FNAL



Discrepancy of 5.1σ!

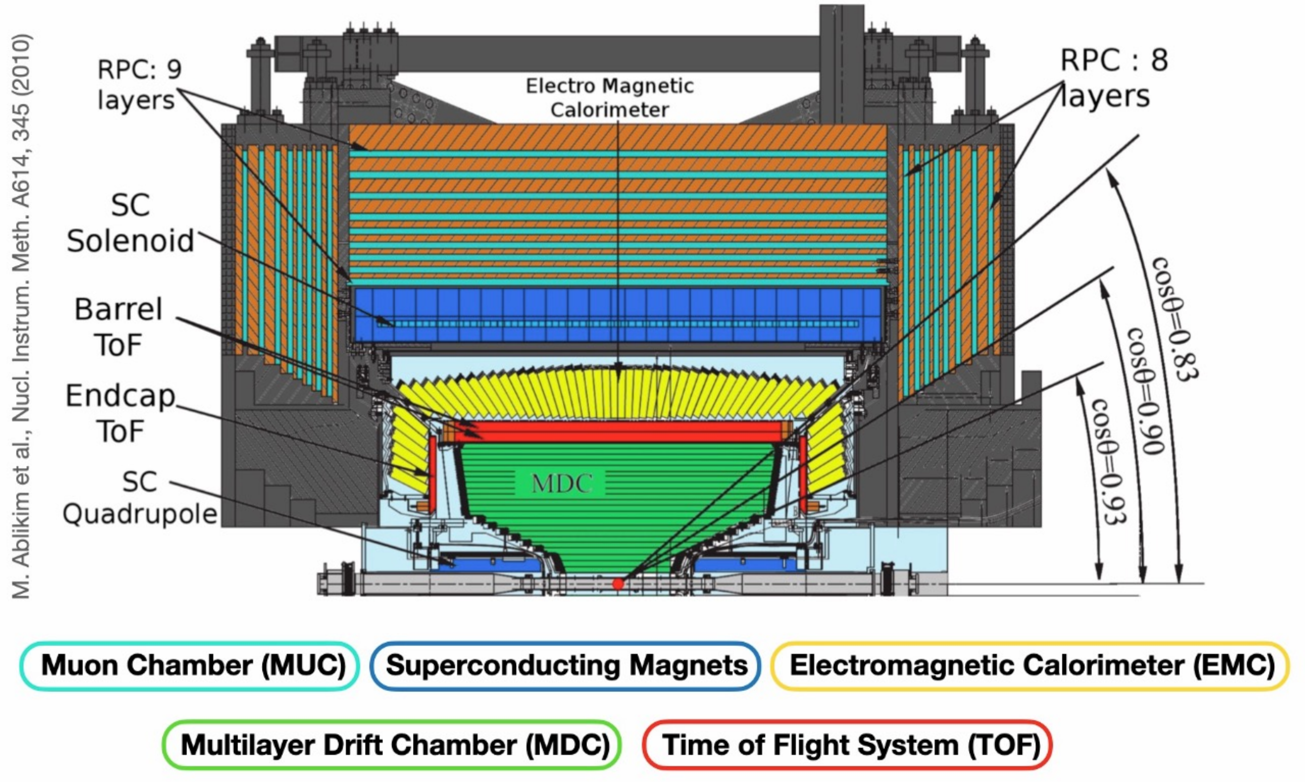
Hadronic contributions dominate uncertainty for a_μ^{SM}

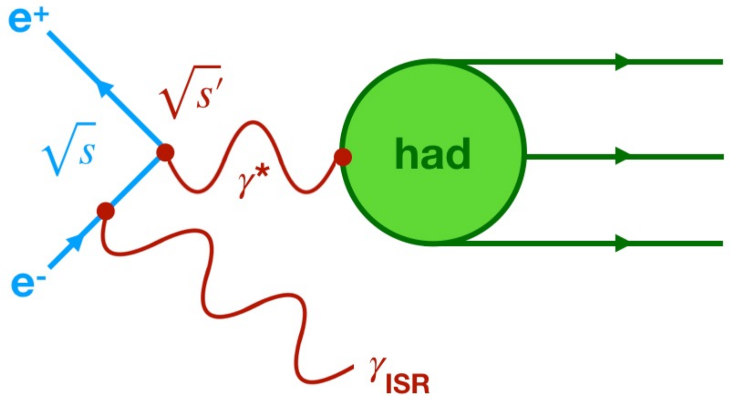
→ **Hadronic Vacuum Polarization (HVP)**

→ Most important channel: $\boldsymbol{\pi^+\pi^-}$

Reaction Channel $e^+e^- \to \pi^+\pi^-$ at BESIII

- BESIII: electron-positron collider with CM energies between 2.0 to 5.0 GeV
- Initial State Radiation technique to measure the pion FF above 0.8 GeV

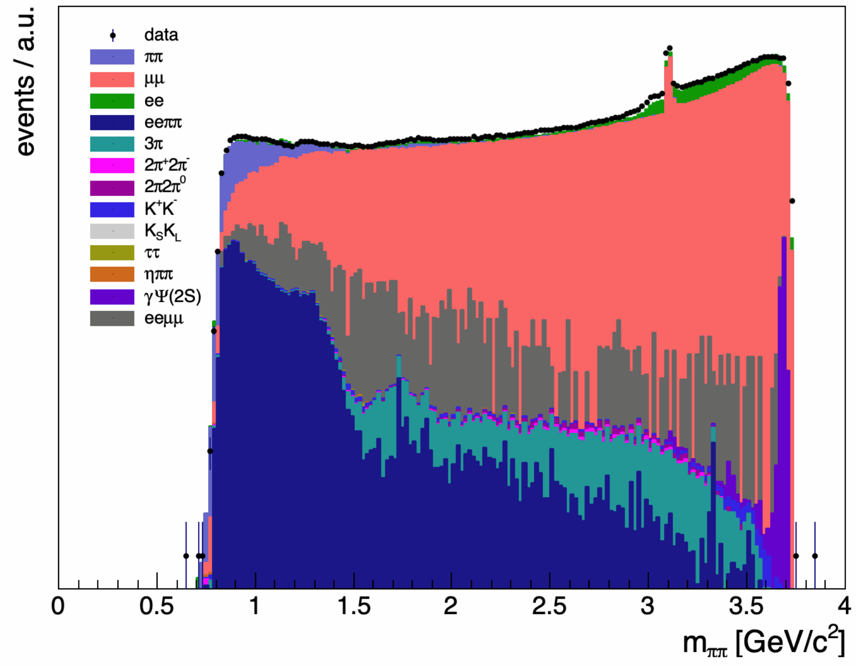


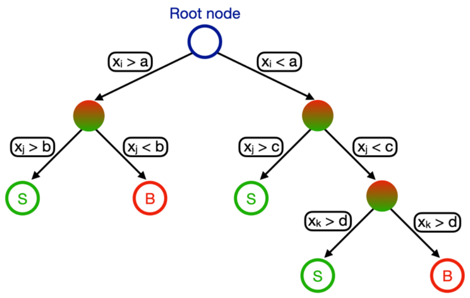


Data set: 1.9 fb^{-1} at 3.77 GeV
(Upcoming data set: 20 fb^{-1})

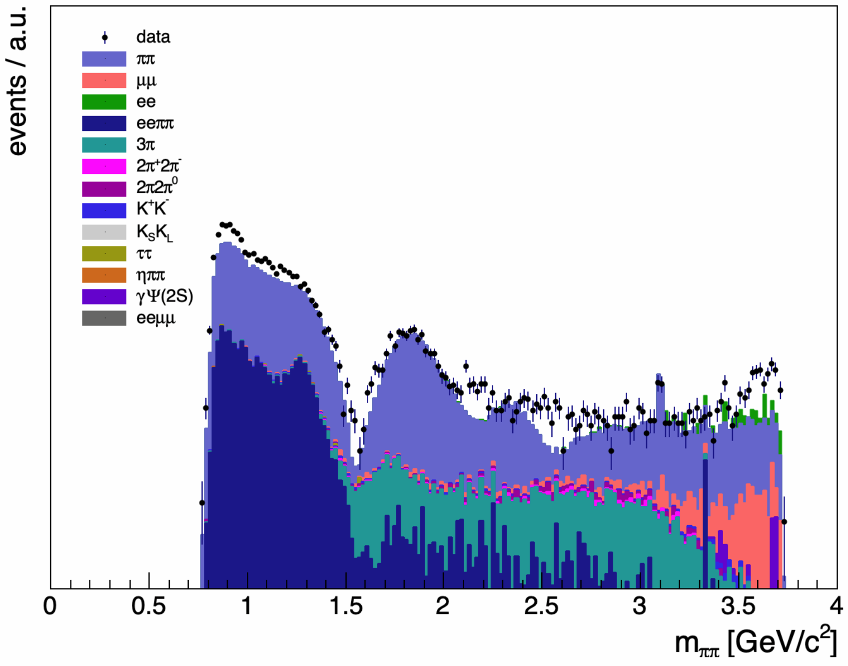
Main Challenge: Pion-Muon Separation

- Signal: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$ & main background: $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$
- Difficult to distinguish pions from muons at BESIII → Multivariate Analysis
- **Boosted Decision Tree with Gradient Boost (BDTG)**





Apply BDTG



Thomas Lenz
JGU Mainz

Feasibility Studies for an Inclusive R-Measurement using ISR with BESIII

Thomas Lenz, Achim Denig, Riccardo Aliberti on behalf of the BESIII Collaboration
Johannes Gutenberg University of Mainz, Germany

MENU2023
17.10.2023

Funded by
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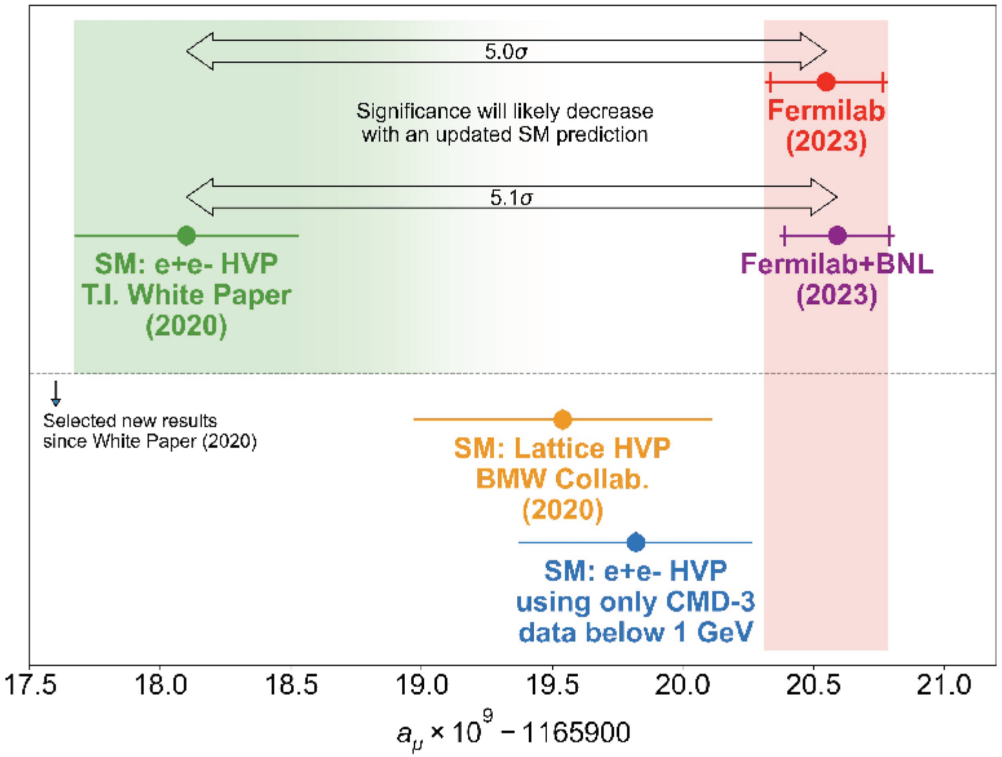
German Research Foundation

Anomalous Magnetic Moment of the Muon

- Deviation from $g = 2$: $a_\mu = \frac{(g-2)_\mu}{2}$
- Discrepancy of $5.1\ \sigma$ between
  - Experimental World Average
  - Standard Model prediction
- Uncertainties dominated by hadronic contribution
- Additional tensions between
  - Dispersive approach using e^+e^-
  - Lattice QCD evaluation

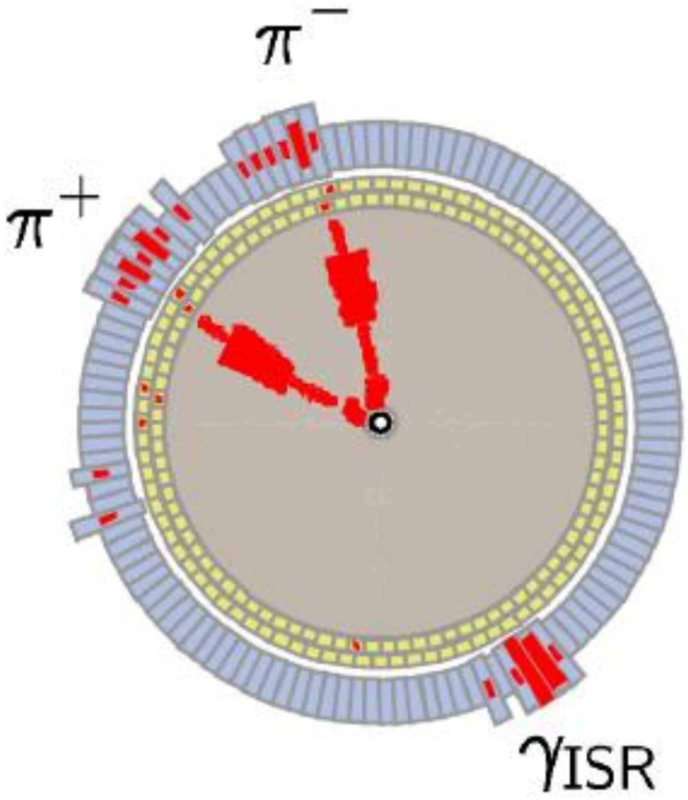
  and within e^+e^- cross section measurements

Taken from James Mott: https://indico.fnal.gov/event/60738/

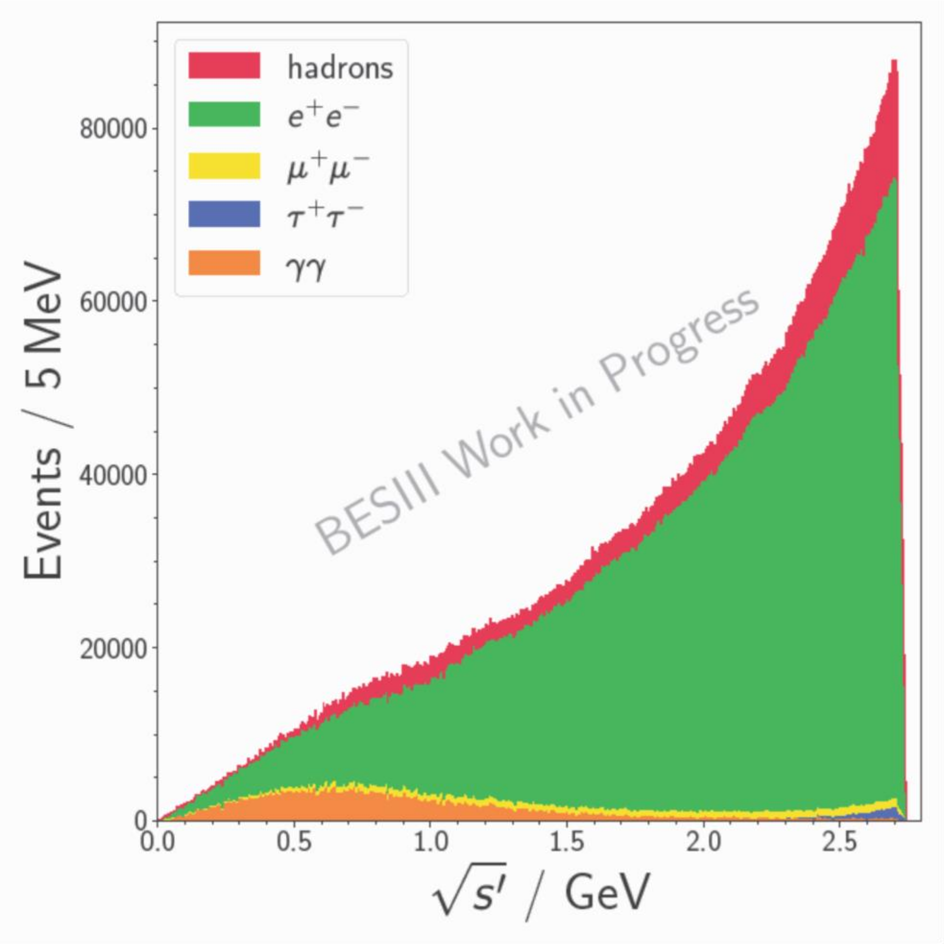


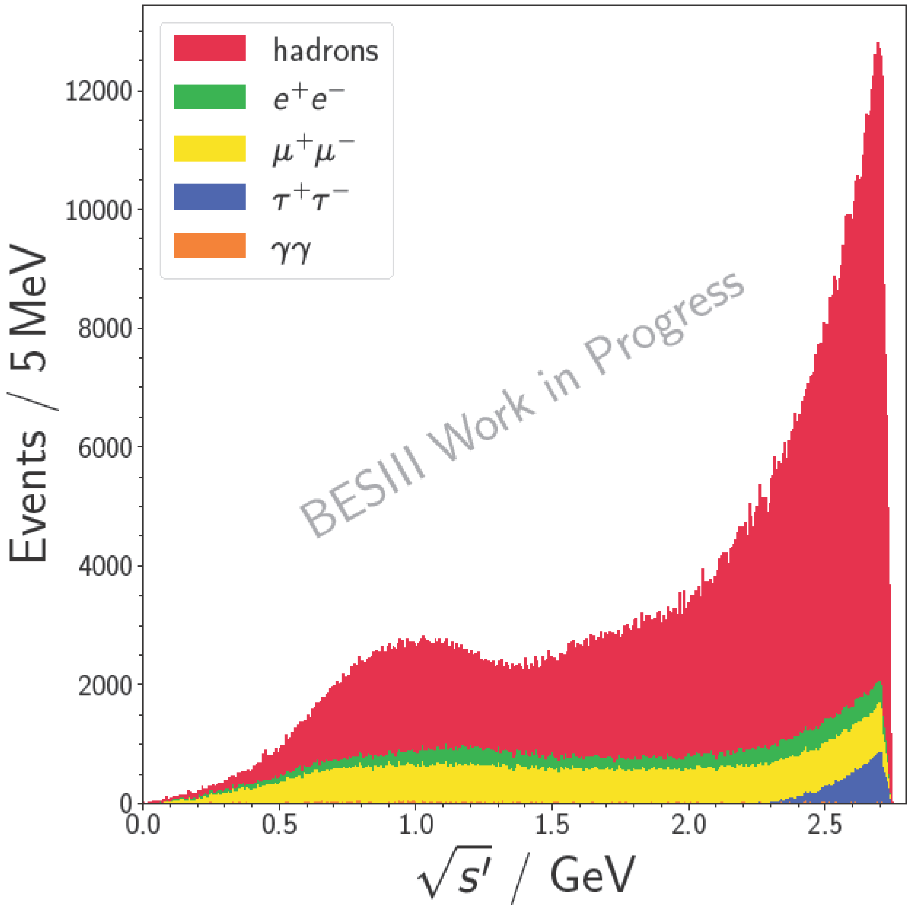
Analysis Strategy

- Detect ISR photon in barrel of calorimeter
- Look for charged tracks in the drift chamber
  - Very high efficiency to find tracks after tagging the ISR photon
- Reconstruct mass of hadronic final state from recoil of ISR photon
- Suppress background
  - QED
  - Hadronic

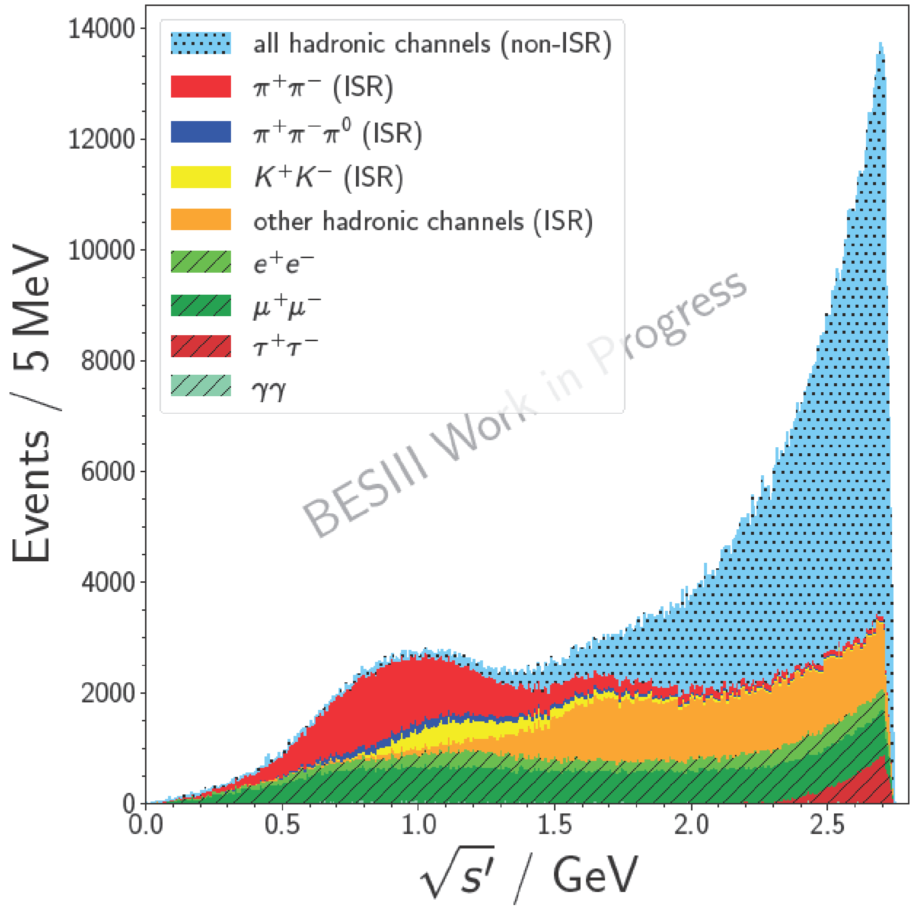


Electron Rejection

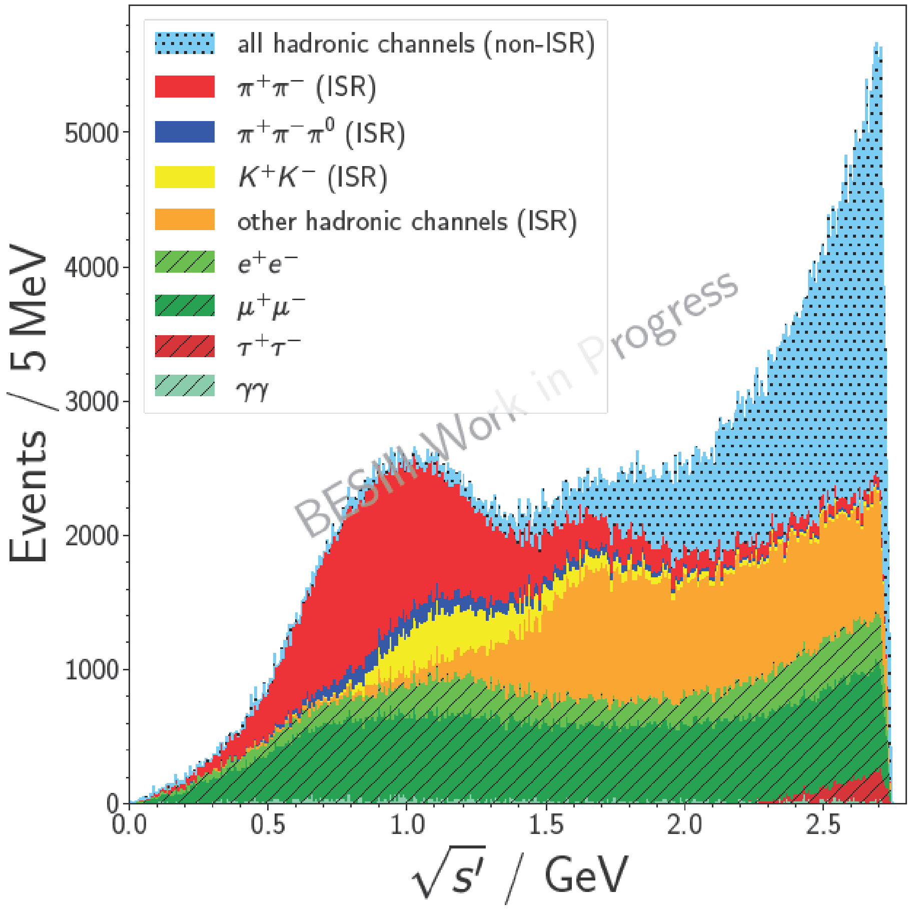




Meson Veto



all hadronic channels (non-ISR)
$\pi^+\pi^-$ (ISR)
$\pi^+\pi^-\pi^0$ (ISR)
K^+K^- (ISR)
other hadronic channels (ISR)
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$\gamma\gamma$
BESIII Work in Progress
Events / 5 MeV
$\sqrt{s'}$ / GeV
0
2000
4000
6000
8000
10000
12000
14000
0.0
0.5
1.0
1.5
2.0
2.5



all hadronic channels (non-ISR)
$\pi^+\pi^-$ (ISR)
$\pi^+\pi^-\pi^0$ (ISR)
K^+K^- (ISR)
other hadronic channels (ISR)
e^+e^-
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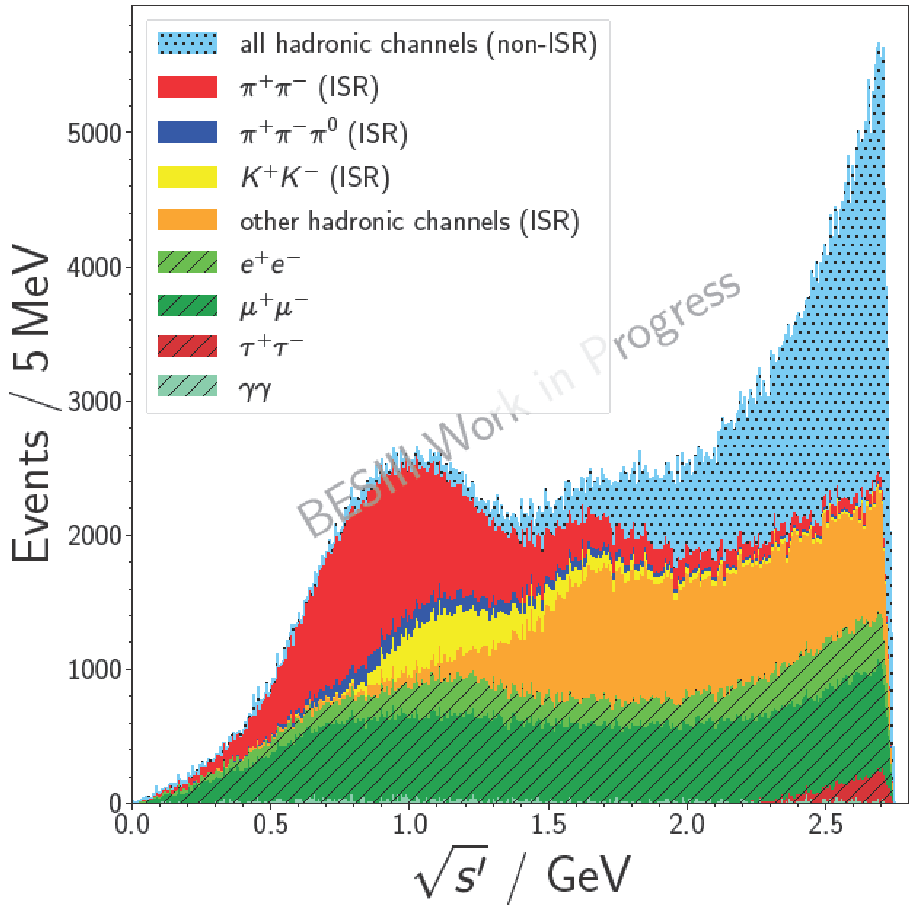
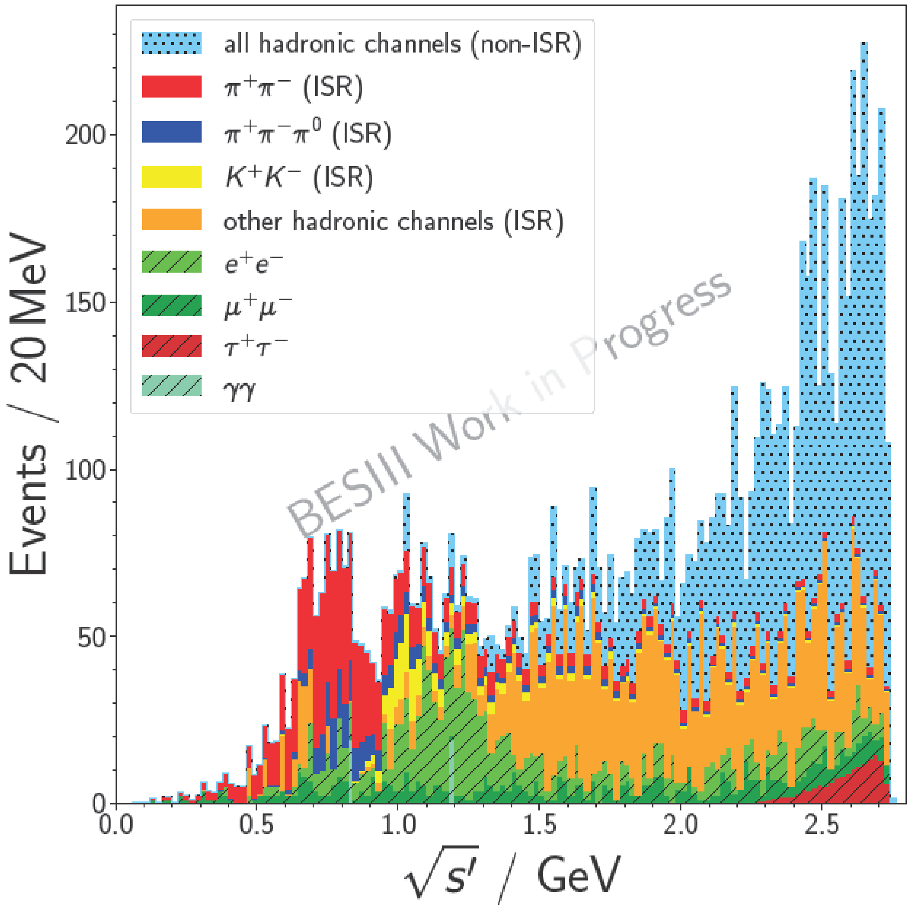
$\tau^+\tau^-$
$\gamma\gamma$
BESIII Work in Progress
Events / 5 MeV
$\sqrt{s'}$ / GeV
0
1000
2000
3000
4000
5000
0.0
0.5
1.0
1.5
2.0
2.5

Hadronic Mass Resolution

Measure ISR photon directly



Measure ISR photon via pair creation



Nikolai in der Wiesche

University of Münster

Universität
Münster

LIGHT MESON DECAYS AT BESIII

Nikolai in der Wiesche
On behalf of the BESIII Collaboration

Mainz, 17th October 2023

living.knowledge

NRW-FAIR Netzwerk

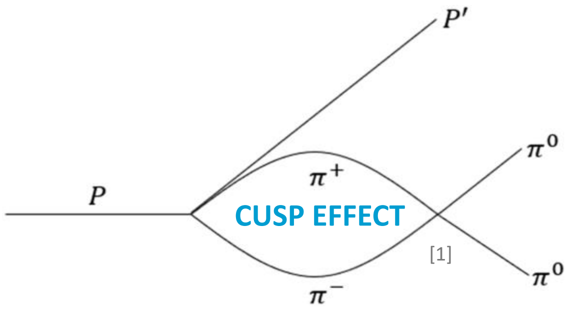
MENU 2023

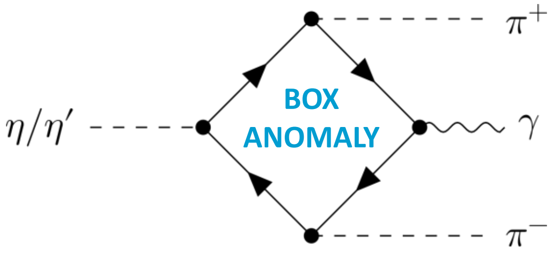
WHY YOU SHOULD BE INTERESTED IN LIGHT MESON DECAYS

Universität Münster

EXPLORE THE NON-PERTURBATIVE REGIME OF QCD
&
REACH THE LIMITS OF THE STANDARD MODEL

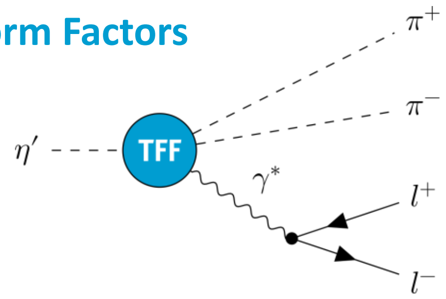
Test Effective Field Theory Predictions





Investigate the Meson Substructure

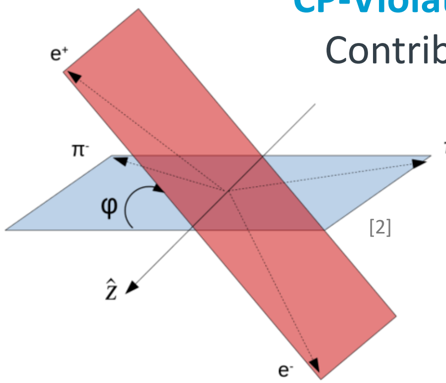
Probe **Transition Form Factors**



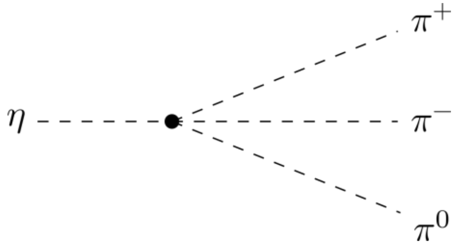
Hadronic Light-by-Light Contributions to the **Muon Anomalous Magnetic Moment**

Search for Symmetry Violations

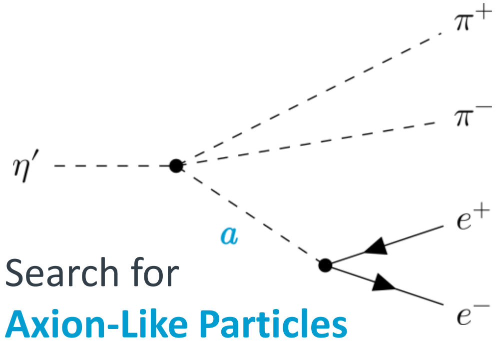
CP-Violating E1 Contributions



Rare **Isospin Violating** Decays



Discover New Particles & Rare Decays



Search for **Axion-Like Particles**

AND MUCH MORE!

[1] M. Ablikim et al., Phys. Rev. Lett. **130**, 81901 (2023) [2] M. Ablikim *et al.*, Phys. Rev. D **103**, 92005 (2021)

BESIII HIGHLIGHTS

Universität Münster

Over 1 decade of successful **LIGHT MESON DECAY** research with BESIII

> 5 First Observations

> Precision Measurements

> Upper limits

See you at the poster session!

Decay Channel	Physics	Publication
$\eta' \to \pi^+\pi^-\pi^+\pi^- / \pi^+\pi^-\pi^0\pi^0$	First Observation - BR	PRL112, 251801 (2014)
$\eta' \to \gamma e^+e^-$	First Observation - BR – TFF	PRD92, 012001 (2015)
$\eta \to \pi^+\pi^-\pi^0$ & $\eta/\eta' \to \pi^0\pi^0\pi^0$	Matrix Elements	PRD92, 012014 (2015)
$\eta' \to \omega e^+e^-$	First Observation - BR	PRD92, 051101 (2015)
$\eta' \to K\pi$	UL	PRD93, 072008 (2016)
$\eta' \to \rho\pi$	First Observation - BR	PRL118, 012001 (2017)
$\eta' \to \gamma\gamma\pi^0$	BR	PRD96, 012005 (2017)
$\eta' \to \gamma\pi^+\pi^-$	BR - Box Anomaly	PRL120, 242003 (2018)
$\eta' \to \pi^+\pi^-\eta / \pi^0\pi^0\eta$	Matrix Elements - Cusp Effect	PRD97, 012003 (2018)
$P \to \gamma\gamma$	BRs	PRD97, 072014 (2018)
$\omega \to \pi^+\pi^-\pi^0$	Dalitz Plot Analysis	PRD98, 112007 (2018)
Absolut BR of η' decays	BRs	PRL122, 142002 (2019)
$\eta' \to \gamma\gamma\eta$	UL	PRD100, 052015 (2019)
$\eta' \to \pi^0\pi^0\pi^0\pi^0$	UL	PRD101, 032001 (2020)
$\eta' \to \pi^+\pi^-\mu^+\mu^-$	First Observation - BR	PRD103, 072006 (2021)
Absolute BR of η decays	BRs	PRD104, 092004 (2021)

MORE EXCITING NEW BESIII RESULTS ON THE POSTER!

Viacheslav Tsaran

JGU Mainz

Second-order pion-nucleus potential for scattering and photoproduction

Viacheslav Tsaran

Institute of Nuclear Physics, University of Mainz

October 17, 2023

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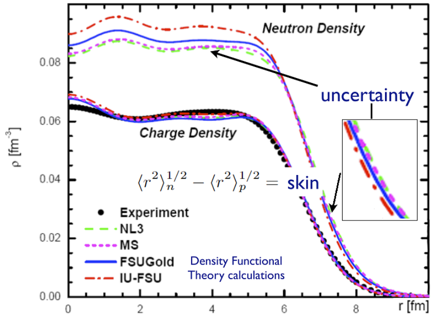
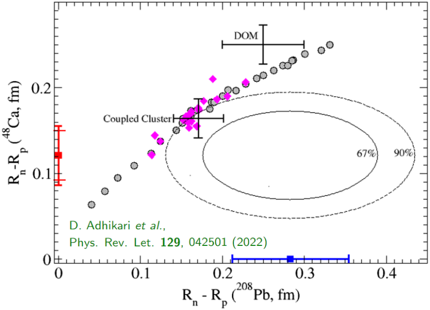
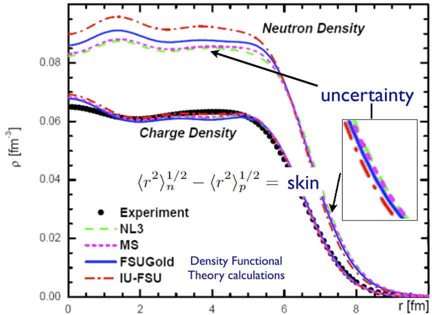
2023



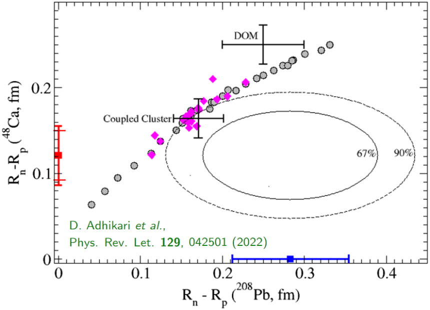
CREX and PREX-II data from JLab

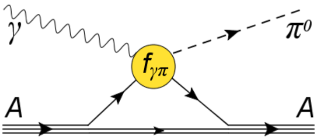


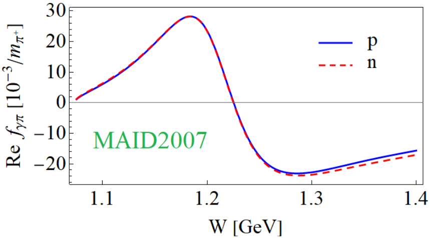
π^0 photoproduction – a tool for studying neutron distributions



CREX and PREX-II data from JLab







π^0 photoproduction provides nucleon FF:

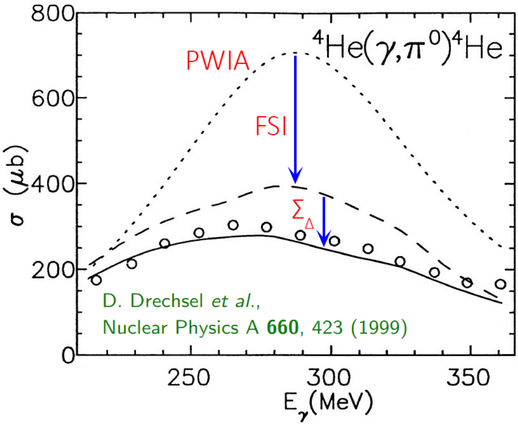
$$V_{\gamma\pi} \propto f_{\gamma\pi} F_N(q)$$

Neutron distribution can be extracted:

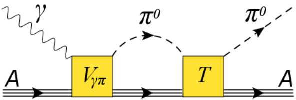
$$F_n(q) = F_N(q) - F_p(q)$$

Precise theoretical model for photoproduction on nuclei is required

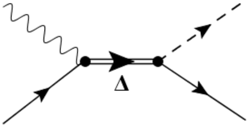
3 photoproduction components:



- $V_{\gamma\pi}$ for PWIA
- scattering amplitude T for FSI

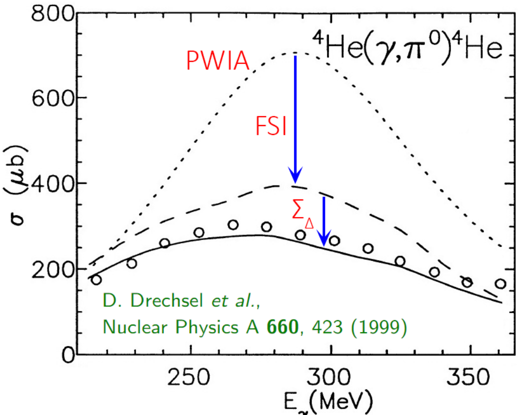


- Effective $\Delta(1232)$ self-energy Σ_Δ



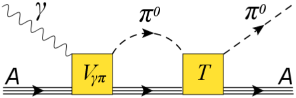
$$G_\Delta^{\text{bound}} = (W - m_\Delta + i\Gamma_\Delta/2 - \boldsymbol{\Sigma_\Delta})^{-1}$$

3 photoproduction components:



similar to π production in ν scattering

- $V_{\gamma\pi}$ for PWIA
- scattering amplitude T for FSI



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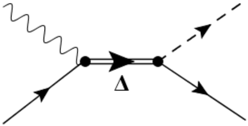


$$G_\Delta^{\text{bound}} = (W - m_\Delta + i\Gamma_\Delta/2 - \boldsymbol{\Sigma_\Delta})^{-1}$$

Outlook:

- Scattering: new potential fitted to $\pi^{\pm}$-^{12}C scattering data
- 3 energy-independent real parameters
- Inclusion of the intermediate charge exchange and spin-flip
- Application of our model to photoproduction

Chunjiang Shi

Institute of High Energy Physics,
Chinese Academy of Sciences, Beijing

Decays of 1^{-+} Charmoniumlike Hybrid

Poster presented by: Chunjiang Shi

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, PRC

Collaborate with Ying Chen, Ming Gong, Xiangyu Jiang, Zhaofeng Liu, Wei Sun.

Oct 17, 2023. Mainz, Germany.

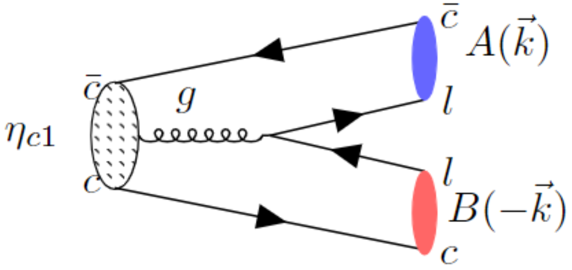
Based on: arXiv:hep-lat/2306.12884

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

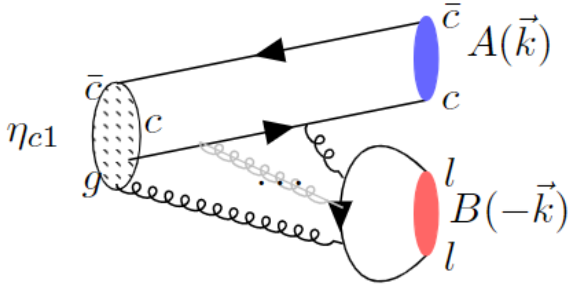
中国科学院大学
University of Chinese Academy of Sciences

η_{c1} decay

open-charm decay



close-charm decay



open-charm decay: $D\bar{D}_1(S\text{-wave})$, $D\bar{D}^*(P\text{-wave})$, $D^*\bar{D}^*(P\text{-wave})$.
close-charm decay: $\chi_{c1}\eta(S\text{-wave})$, $\eta_c\eta'(P\text{-wave})$, $J/\psi\omega(P\text{-wave})$.

Methodology: McNeile & Michael method

(C. McNeile, C.Michael, and P. Pennanen. 2002).

$$|\eta_{c1}\rangle = \begin{pmatrix}1\\0\end{pmatrix} \qquad |AB\rangle = \begin{pmatrix}0\\1\end{pmatrix}$$

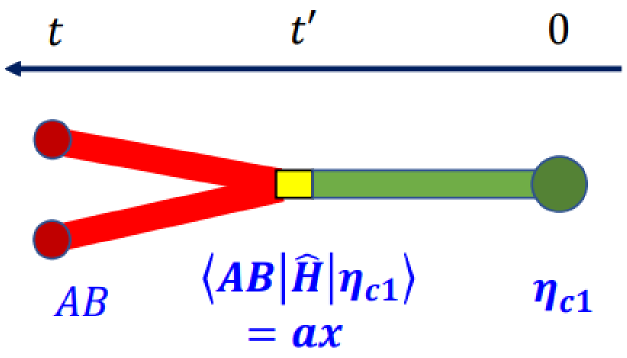
$$\hat{H} = \begin{pmatrix} m_{\eta_{c1}} & x \\ x & E_{AB}\end{pmatrix}$$

$$\Rightarrow$$

$$\hat{T}(a) = e^{-a\hat{H}} = e^{-a\bar{E}}\begin{pmatrix} e^{-a\Delta/2} & ax \\ ax & e^{a\Delta/2}\end{pmatrix}$$

$$\bar{E} = \frac{m_{\eta_{c1}} + E_{AB}}{2}, \qquad \Delta = m_{\eta_{c1}} - E_{AB}$$

$$\langle\Omega|\mathcal{O}_{AB}|\eta_{c1}\rangle \approx 0 \qquad \langle\Omega|\mathcal{O}_{\eta_{c1}}|AB\rangle \approx 0$$



The final results

Mode (AB)	$\hat{k}$(IE)	r_1 $(\times 10^{-3})$	g_{AB}	g_{AB} (ave.)	Γ_{AB} (MeV)
$D_1\bar{D}$	(0, 0, 0)(L16)	4.95(5)	4.27(5)	4.6(6)	258(133)
	(0, 0, 0)(L24)	3.10(26)	4.92(41)		
$D^*\bar{D}$	(1, 1, 1)(L16)	1.11(3)	8.35(21)	8.3(7)	88(18)
	(2, 2, 0)(L24)	0.78(7)	8.34(74)		
$D^*\bar{D}^*$	(1, 1, 1)(L16)	1.00(3)	3.44(12)	4.6(1.8)	150(118)
	(1, 1, 0)(L16)	1.15(4)	3.79(12)		
	(2, 0, 0)(L24)	1.05(9)	5.06(42)		
	(1, 1, 1)(L24)	0.67(7)	6.31(58)		
$\chi_{c1}\eta_{(2)}$	(0, 0, 0)(L16)	2.04(26)	1.31(2)	1.35(45)	–
	(0, 0, 0)(L24)	1.18(38)	1.39(45)		
$\eta_c\eta_{(2)}$	(1, 1, 1)(L16)	0.20(6)	0.62(18)	0.55(22)	–
	(2, 2, 0)(L24)	0.10(3)	0.47(12)		

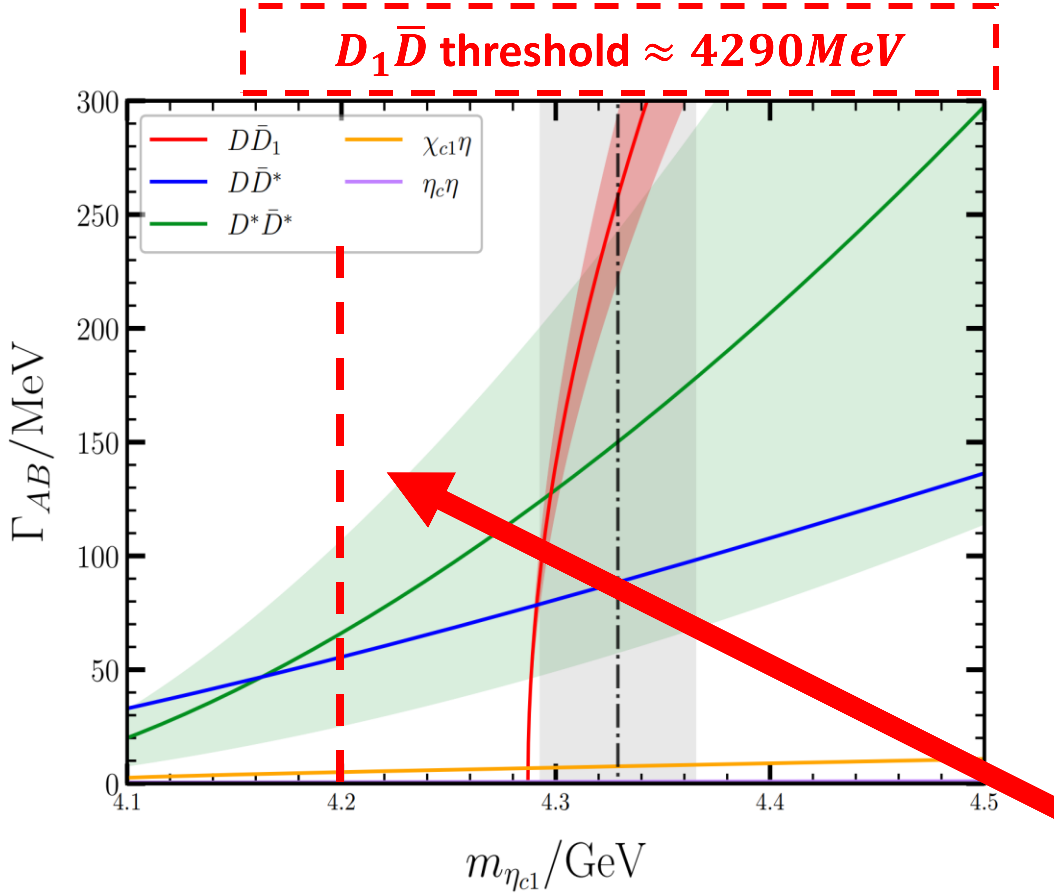
Due to $m_{\eta_{c1}} = 4.329(36)$ from our lattice

$$\overline{|\mathcal{M}(\eta_{c1} \to AP)|^2} = \frac{1}{3} g_{AP}^2 m_{\eta_{c1}} \left(3 + \frac{k_{\rm ex}^2}{m_A^2}\right),$$
$$\overline{|\mathcal{M}(\eta_{c1} \to PP)|^2} = \frac{4}{3} g_{PP}^2 k_{\rm ex}^2,$$
$$\overline{|\mathcal{M}(\eta_{c1} \to VP)|^2} = \frac{2}{3} g_{VP}^2 k_{\rm ex}^2,$$
$$\overline{|\mathcal{M}(\eta_{c1} \to D^*\bar{D}^*)|^2} = \frac{4}{3} g^2 k_{\rm ex}^2 \frac{m_{\eta_{c1}}^2}{m_{D^*}^2}.$$

$$\Gamma_{AB} = \frac{1}{8\pi} \frac{k_{\rm ex}}{m_{\eta_{c1}}^2} \overline{|\mathcal{M}(\eta_{c1} \to AB)|^2}$$

- $D_1\,\bar{D}$ dominates.
- $D^*\bar{D}$ and $D^*\bar{D}^*$ are important.

This observation is in striking contrast to the expectation of the flux-tube model.



The $m_{\eta_{c1}}$-dependence of partial decay widths

$$\left|D^*\bar{D}^*\right\rangle^{(I=0)}_{(C=+)} = \frac{1}{\sqrt{2}}\left(\left|D^{*+}D^{*-}\right\rangle + \left|D^{0*}\bar{D}^{0*}\right\rangle\right)^{(S=1)}_{(L=1)}$$

$\boxed{L + S = \text{even}}$

- For $m_{\eta_{c1}} = 4329(36)$ MeV, we have

$$\Gamma_{D_1\bar{D}} = 258(133)\ \text{MeV}$$
$$\Gamma_{D^*\bar{D}^*} = 150(118)\ \text{MeV}$$
$$\Gamma_{D\bar{D}^*} = 88(18)\ \text{MeV}$$

$$\Gamma_{\chi_{c1}\eta} = \sin^2\theta \cdot 44(29)\ \text{MeV}$$
$$\Gamma_{\eta_c\eta'} = \cos^2\theta \cdot 0.93(77)\ \text{MeV}$$

- Given the mass above, η_{c1} seems too wide to be identified easily in experiments.

- However, $\Gamma_{\eta_{c1}}$ is very sensitive to $m_{\eta_{c1}}$.
- If $m_{\eta_{c1}} \sim 4.2$ GeV, then $\Gamma_{\eta_{c1}} \sim 100$ MeV. The dominant decay channels are $D^*\bar{D}$ and $D^*\bar{D}^*$.
- Especially for $D^*\bar{D}^*$, the measurement of the polarization of D^* and $\bar{D}^*$ will help distinguish a 1^{-+} states from 1^{--} states.

- We suggest LHCb, BelleII and BESIII to search for η_{c1} in $D^*\bar{D}$ and $D^*\bar{D}^*$ systems !

Possible production in experiments

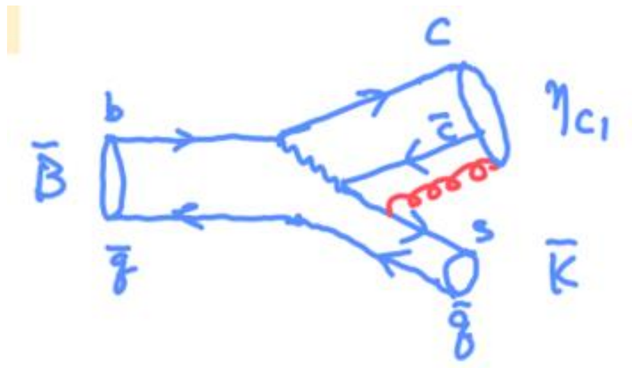
1) η_{c1} **production on** e^+e^- **collider experiments: (BESⅢ)**

$$e^+e^- \to \psi(nS) \to \gamma\eta_{c1}$$

2) η_{c1} **production from** ***B*** **meson weak decay**

$$B \to \eta_{c1}\bar{K}$$

(LHCb and Belle):



Summary

- ✓We give the first Lattice QCD prediction of the partial decay widths of the charmoniumlike η_{c1}.
- ✓Disfavor the results of the Flux-tube model.
- ✓We provide the theoretical information for the experimental search for charmoniumlike hybrid η_{c1}.

Thank You

Sungwook Choi

Korea University

Measurement of $K^*(892)$ production in the $^{12}C(K^-, p)$ reaction at 1.8 GeVc

Sungwook Choi, Jung Keun Ahn for the J-PARC E42 Collaboration

Why we measure $K^*(892)$?

Partial Chiral Symmetry Restoration at normal nuclear density

Would it modify hadronic properties?
(Mass, width, etc)

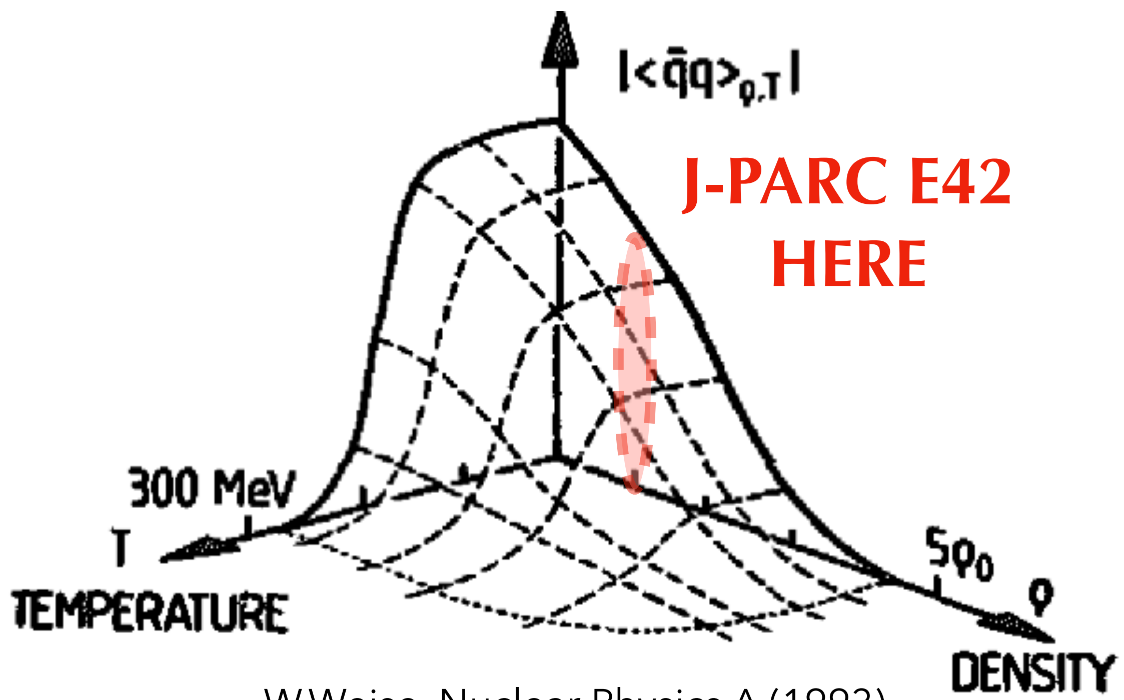
Light vector mesons are good probes..

Then, WHY $K^*(892)$?

Expected to "highly sensitive" to ChSB

Experimentally easy to measure

Its dominance in $K\pi$ system, especially in $K^- p \to p\bar{K}^0_S \pi^-$



W.Weise, Nuclear Physics A (1993)

J-PARC E42 has MILLIONS of $^{12}C(K^-, p)$ reaction events with large acceptance TPC.

Our results from high statistics can yield meaningful information

In-medium modification in ^{12}C

Production differential cross section

$K^*(892)$ measurement at J-PARC E42

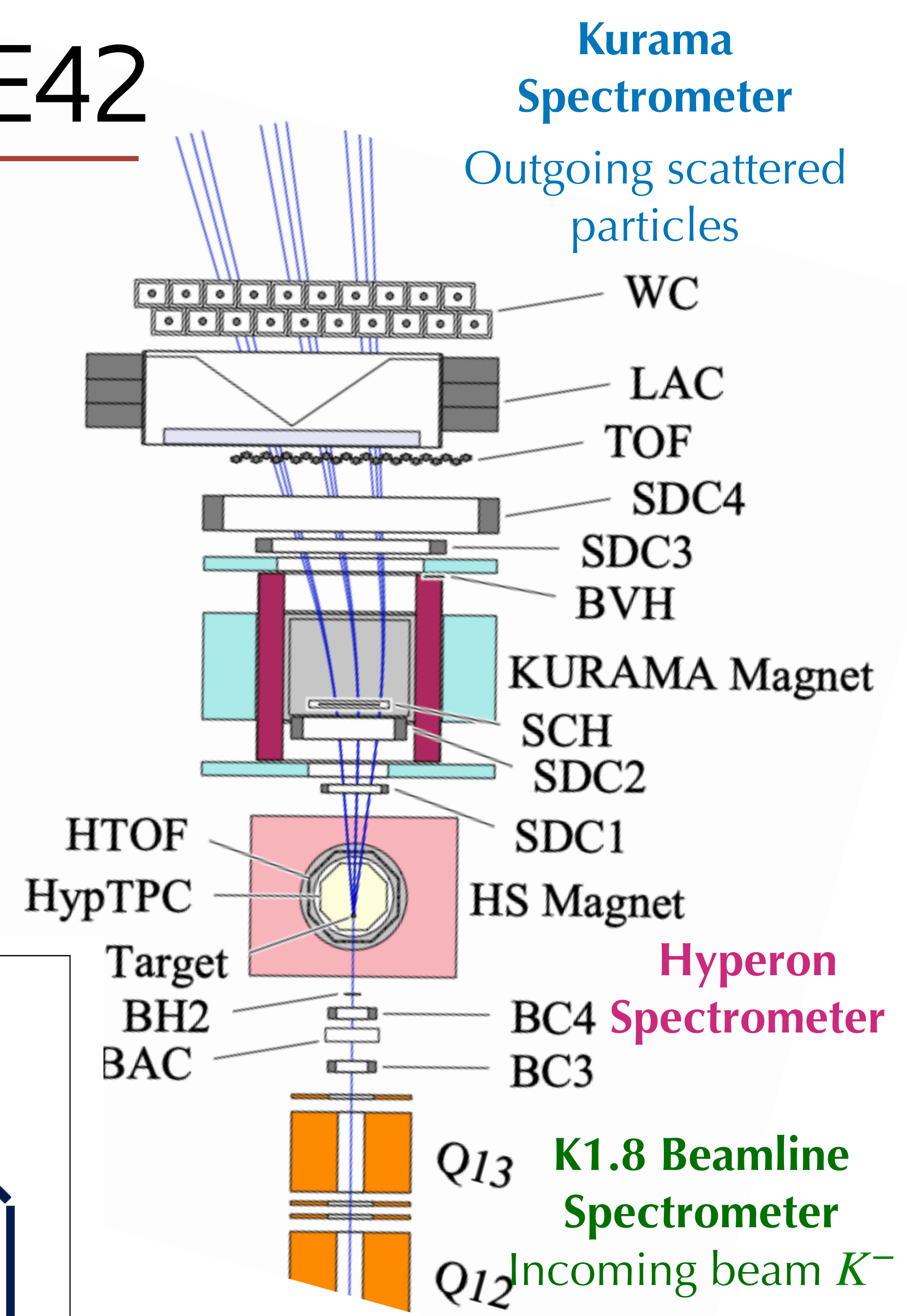
Measuring (K^-, p) reaction events

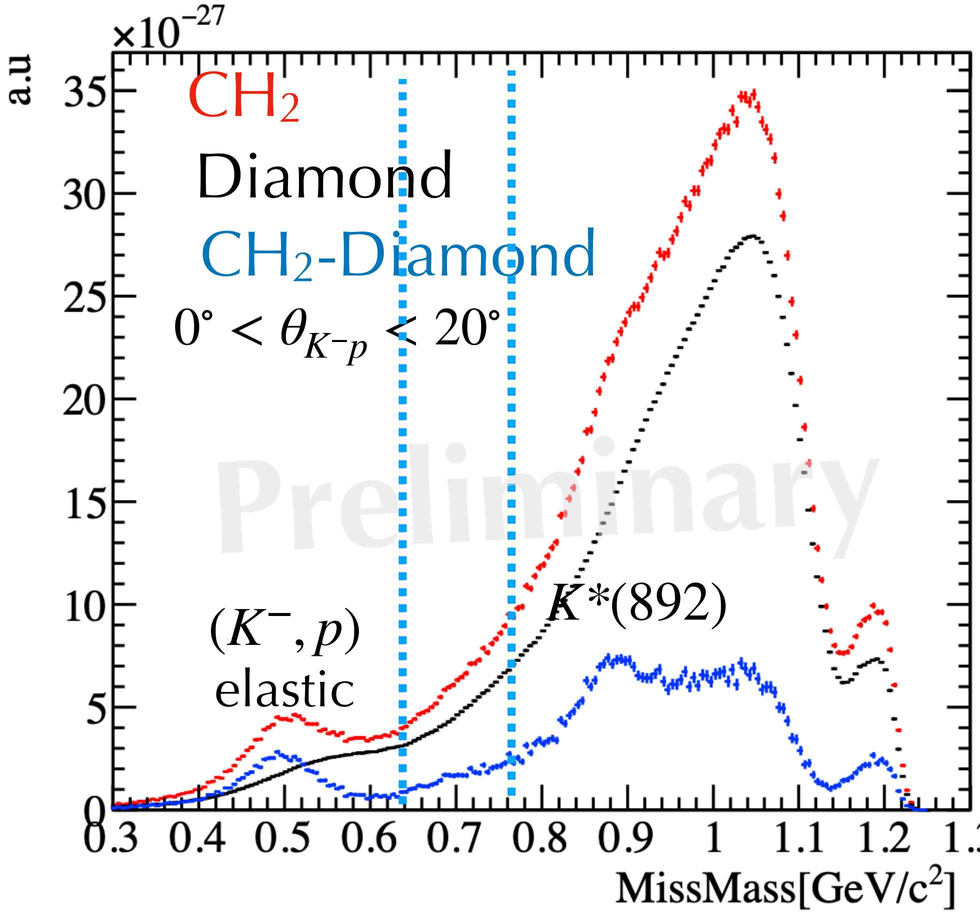
Missing-mass analysis $p(K^-, p)X$

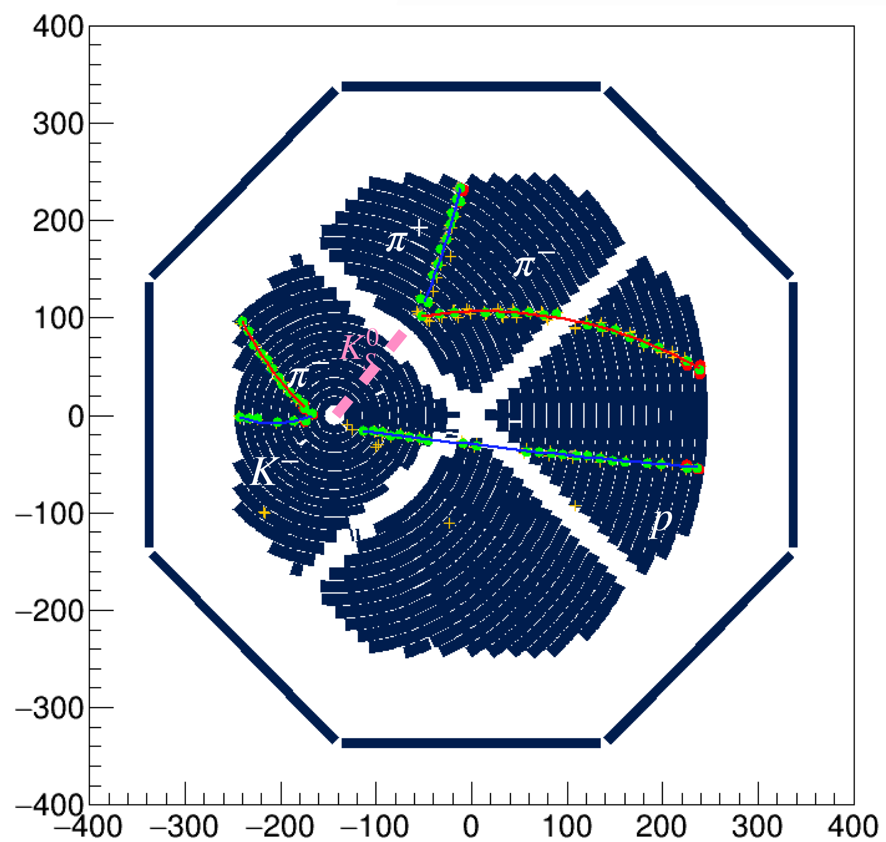
$$K^- p \rightarrow K^*(892) p$$

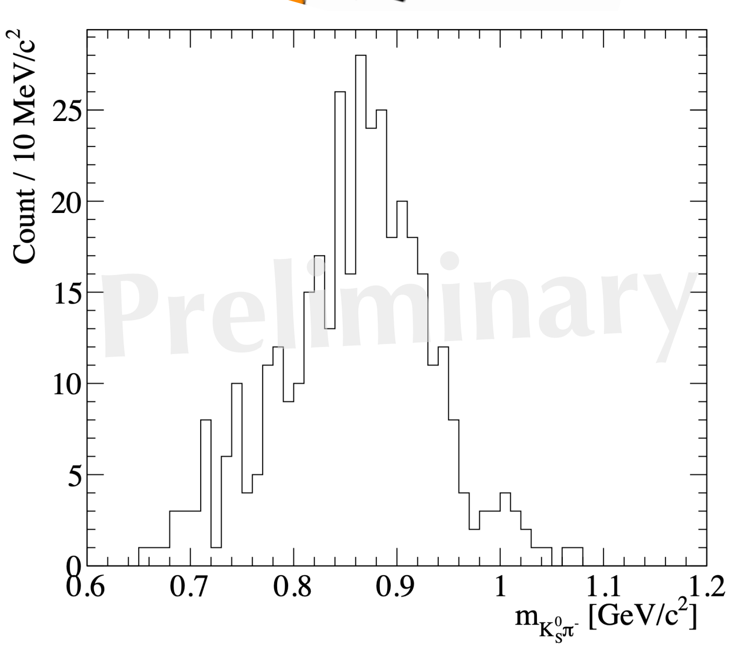
Observing $K^*(892)$ with Hyperon Spectrometer

$$K^*(892) \rightarrow K_S^0 \pi^- \rightarrow \pi^+ \pi^- \pi^-$$





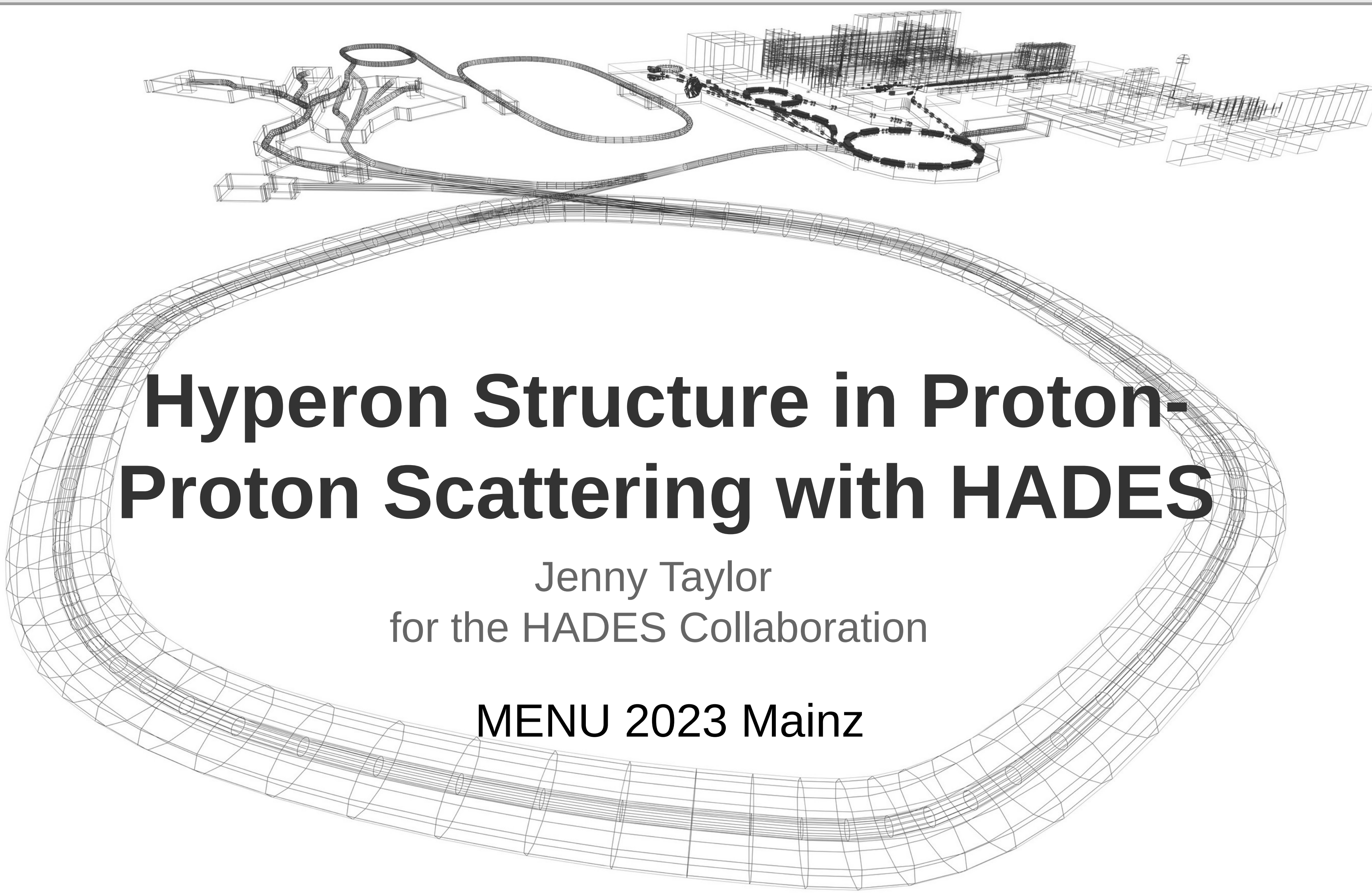




Check more details on poster!

Jenny Taylor

GSI



Hyperon Structure in Proton-Proton Scattering with HADES

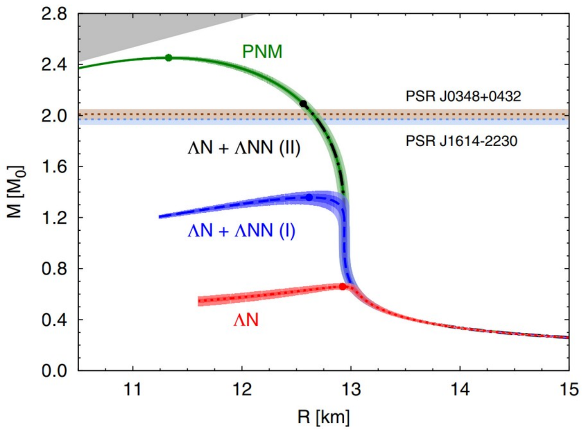
Jenny Taylor
for the HADES Collaboration

MENU 2023 Mainz

Why are hyperons interesting to study?

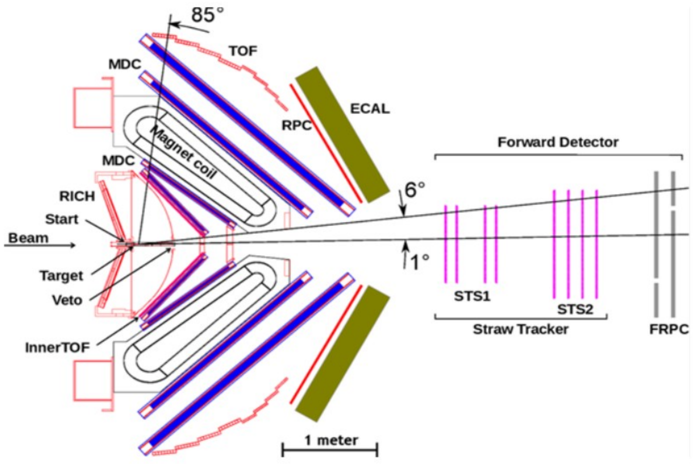
- Stydying the structure of baryons
- Understanding QCD by studying baryons with strangeness
- Hyperons energetically favorable to be created in neutron star cores
  - Reduction of Fermi pressure
  - Softer EOS
    - Allowed masses lower than those observed!
  - Ξ^--N interactions predicted to affect EOS

PRL114, 092301 (2015)

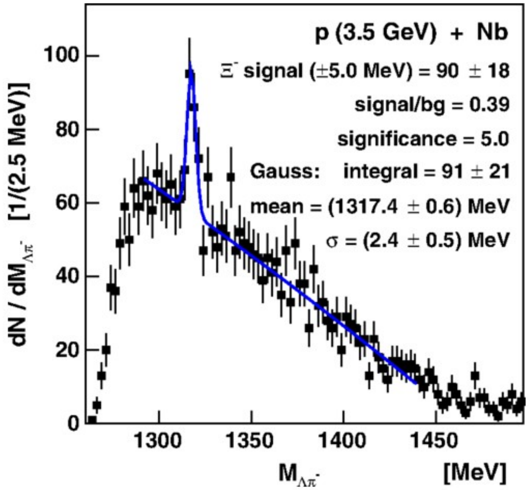


Ξ^- Reconstruction at HADES

- HADES (**H**igh **A**cceptance **D**i-**E**lectron **S**pectrometer) at GSI good for hyperon physics
  - Excellent e^+/e^- detection
  - Extended with forward spectrometer for detecting forward going particles
  - Ξ^- previously measured at HADES in *e.g.* p(3.5GeV)+Nb
    - Nice inclusive mass peak obtained
  - Successful pp data taken in 2022
    - **Exclusive** search for Ξ^- ongoing to explain how they are produced



Phys. Rev. Lett. 114, 212301



Can we find the Ξ^- in the pp data?

Looking forward to seeing you at the poster!

Thank you!

Saskia Plura
JGU Mainz

Search for Light Dark Matter with the DarkMESA Experiment

Saskia Plura

MENU 2023, Mainz
October 17, 2023

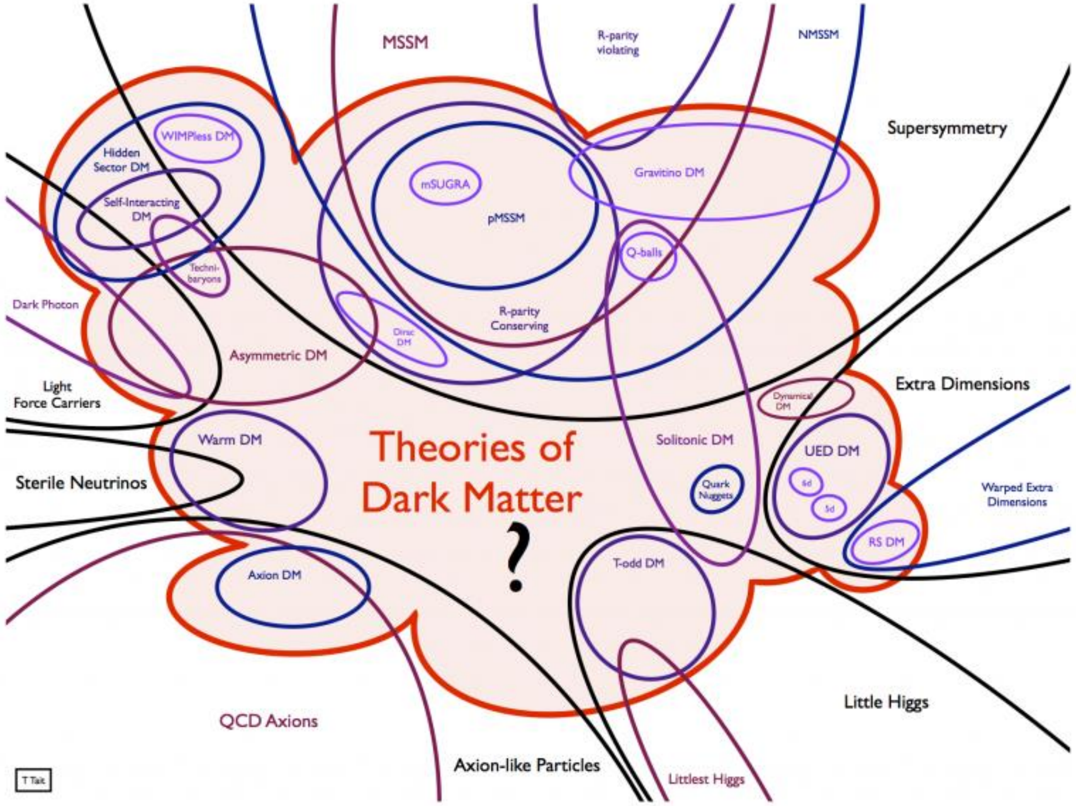
DARK MESA
MPA MAINZ PHYSICS ACADEMY
DFG Deutsche Forschungsgemeinschaft
PRISMA+

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Dark Matter Searches

- Dark Matter searches needed to extend the Standard Model
  - Especially interesting: Models with possible SM interactions

- Search for Dark Matter relies on large data sets due to rare processes
  - High intensity accelerator experiments needed!

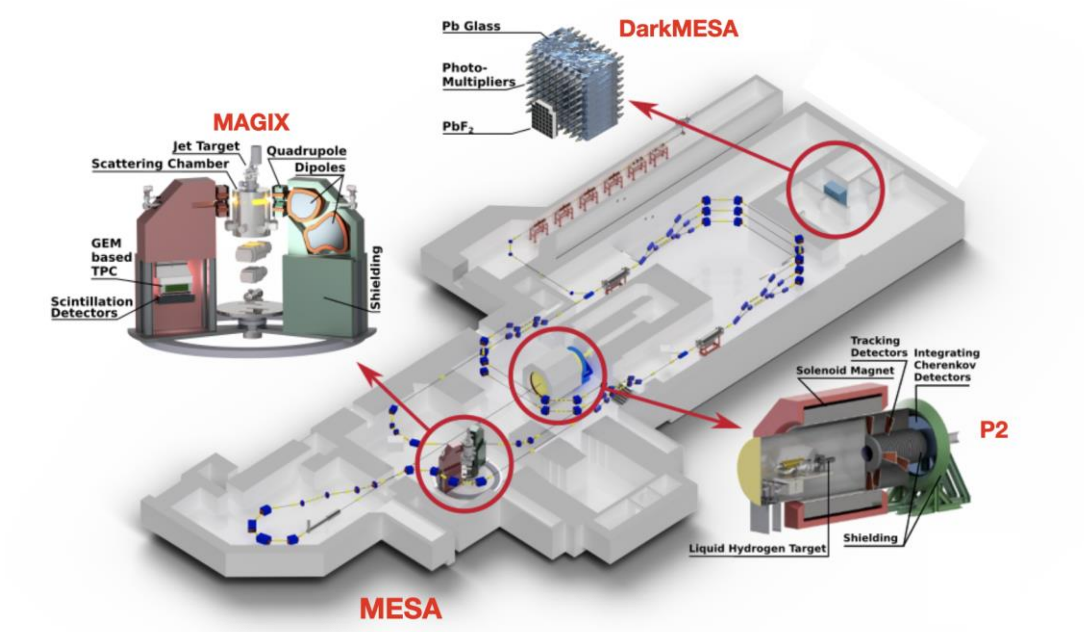


Tim Tait, https://physics.aps.org/articles/v11/48

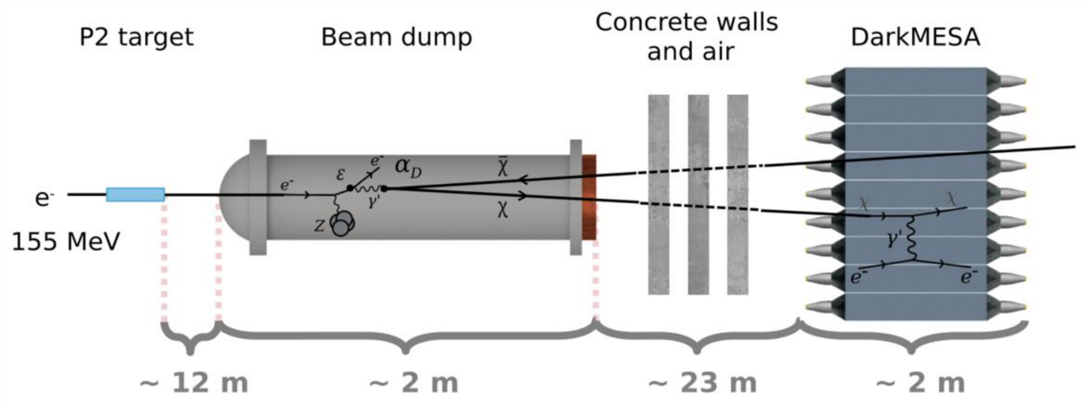
The DarkMESA Experiment

- Located at the upcoming MESA accelerator
  - Electron accelerator
  - Energy recovery mode: 105 MeV @ 1 mA for MAGIX
  - Extracted beam mode: 150 MeV @ 0.15 mA for P2 and DarkMESA

- DarkMESA
  - Parasitic beam dump experiment behind P2
  - Research objective: direct detection of Dark Matter



https://magix.uni-mainz.de/mesa.php

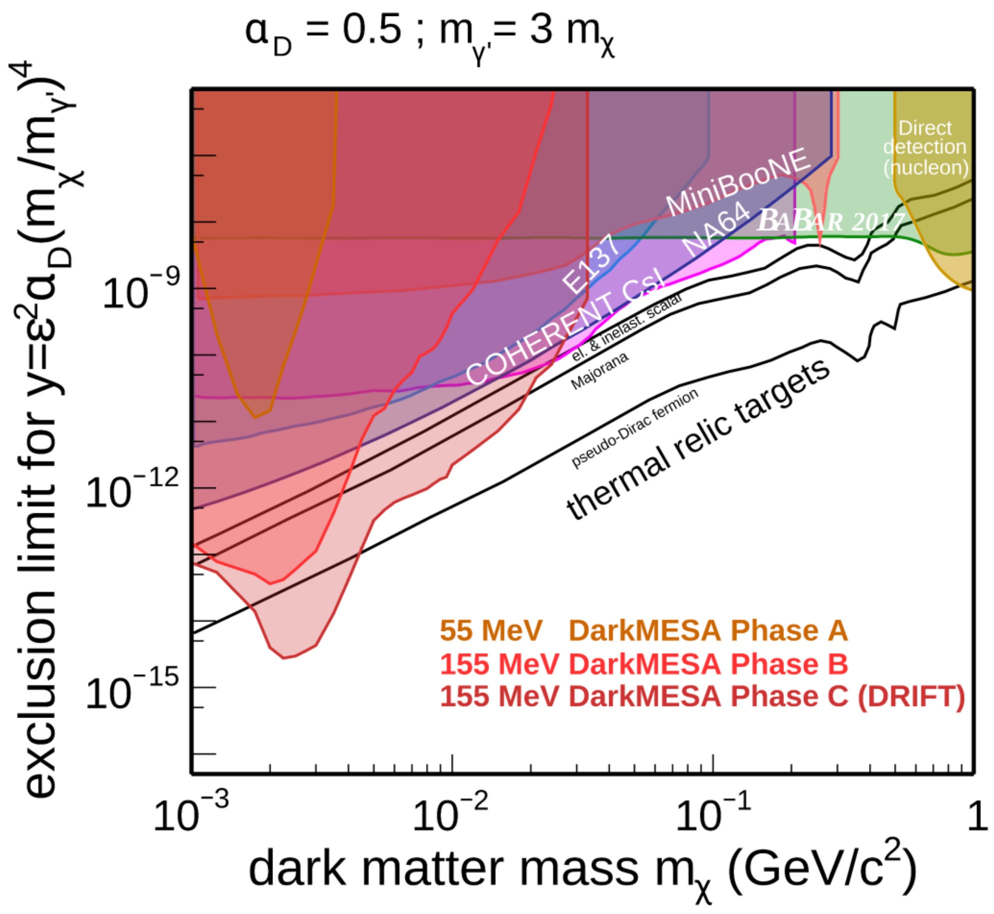


https://magix.uni-mainz.de/physics.php

Simulations of the Experimental Reach

- Evaluation of experimental range necessary before start
  - Modeling of the accessible parameter space
  - Comparison for data analyses in the future
  - Creation of a research programme

- Expand simulation to other Dark Matter models
  - Axions in the MeV range are well motivated
  - Utilise Primakoff processes for Axion production



Max Lellmann
JGU Mainz

Study of Neutral-Pion Pair Production in Two-Photon Scattering at BESIII

Max Lellmann on behalf of the BESIII collaboration

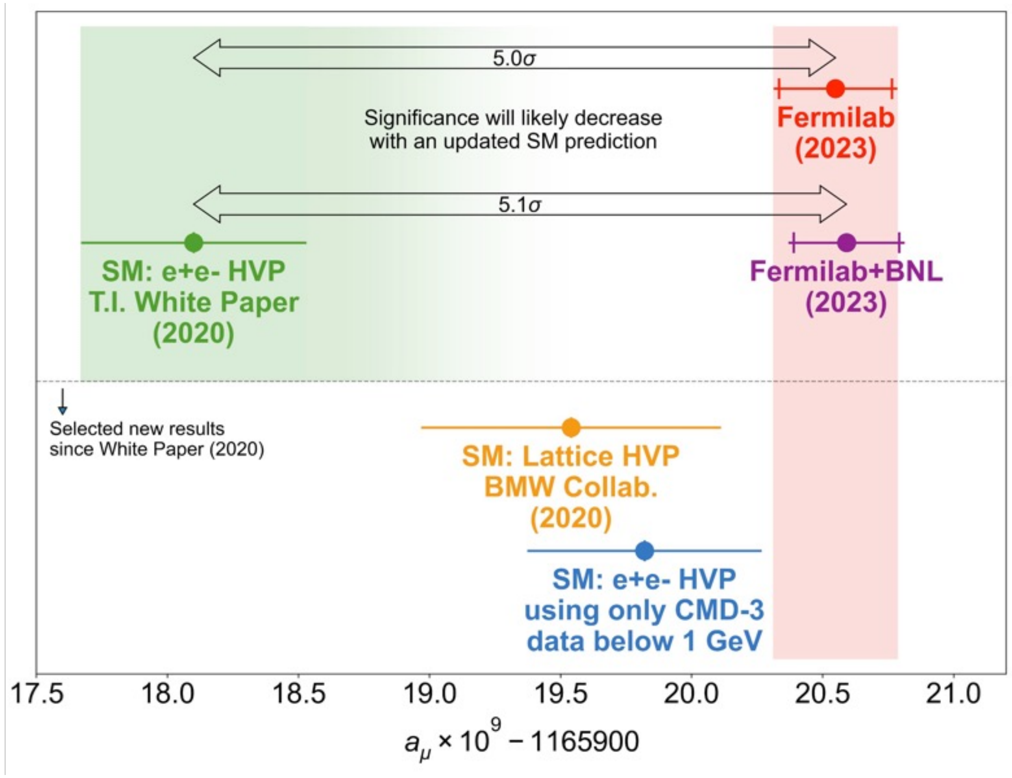
MENU23

17.10.2023

FOR5327 Photon-photon interactions in the Standard Model and beyond
Project TFF, Project XYZ, Project JRP, Project ALP, Project LBL
Cluster of Excellence PRISMA+
DFG
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

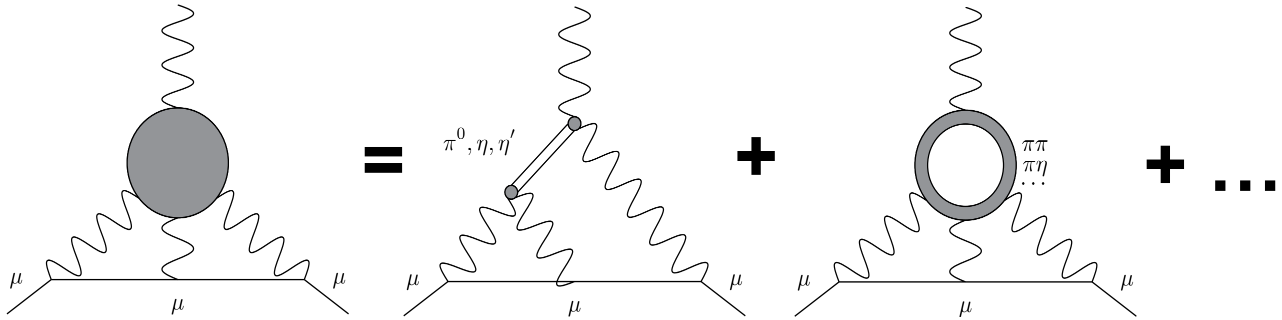
MUON ANOMALOUS MAGNETIC MOMENT

- Muon anomalous magnetic moment $a_\mu = \frac{g_\mu - 2}{2}$
- Better than 0.5 ppm accuracy in theory and experiment
  - Theory: $116\,591\,810(43) \times 10^{-11}$
    (Physics Reports 887 (2020) 1-166)
  - Measurement: $116\,592\,059(22) \times 10^{-11}$
    (arXiv:2308.06230)
- Discrepancy between direct measurement and SM prediction observed
- New direct measurements expected from J-PARC and Fermilab
- **SM prediction needs to be improved!**



https://twitter.com/Fermilab/status/1689665702582427648

THE HADRONIC LIGHT-BY-LIGHT CONTRIBUTION



- Next-to-leading order hadronic contribution
- Four photons coupling via hadronic intermediate state

Contribution	Value x 10^{-11}
π^0, η, η' poles	93.8(4.0)
π, K loops	−16.4(2)
S-wave $\pi\pi$ rescattering	−8(1)
Scalars & Tensors	−1(3)
Axials	6(6)
u, d, s loops / short distance	15(10)
c loop	3(1)

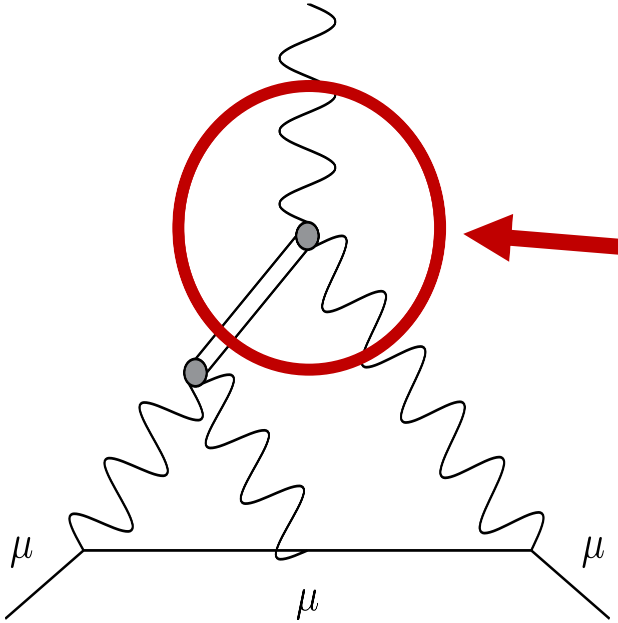
Physics Reports 887 (2020) 1-166

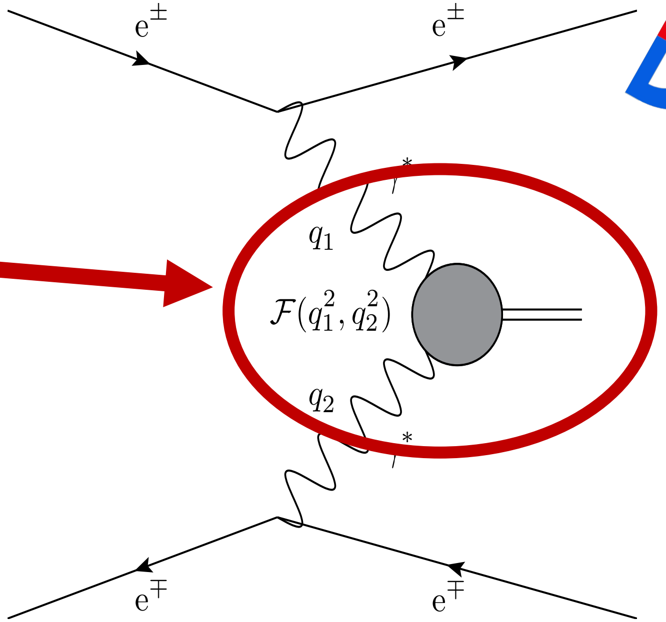
All of this sub-processes appear in the $\gamma^*\gamma^* \to \pi\pi \to \gamma^*\gamma^*$ process!

Information about the $\gamma^*\gamma^* \to \pi^0\pi^0$ dynamics int the relevant Q^2 range essential for a solid SM prediction!

STUDY OF TWO-PHOTON FUSION AT ELECTRON POSITRON COLLIDERS

Two-photon coupling can be directly accessed at electron positron colliders!





BESIII offers perfect conditions to study the relevant parameter ranges

Maurice Anderson

JGU Mainz

Investigation of $\gamma^{\star}\gamma^{\star} \to \eta'$ at the BESIII Experiment

Maurice Sylvester Anderson

MENU Poster Session
16 October 2023

Funded by DFG
FOR5327 Photon-photon interactions in the Standard Model and beyond

BESIII

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Search for η' TFF

Goal: double-virtual Transition Form Factor (TFF)

$F_{\gamma^\star\gamma^\star\to\eta'}(Q_1^2, Q_2^2)$ of η'

- Two-Photon Scattering in e^+e^- Collisions at BESIII
- $Q^2_{1,2}$ is the momentum transfer of $e^\pm$:

$$q^2 = (p - p')^2 = -Q^2 = -4EE' \sin\left(\frac{\theta}{2}\right)$$

- Access to Q^2 through "tagging"

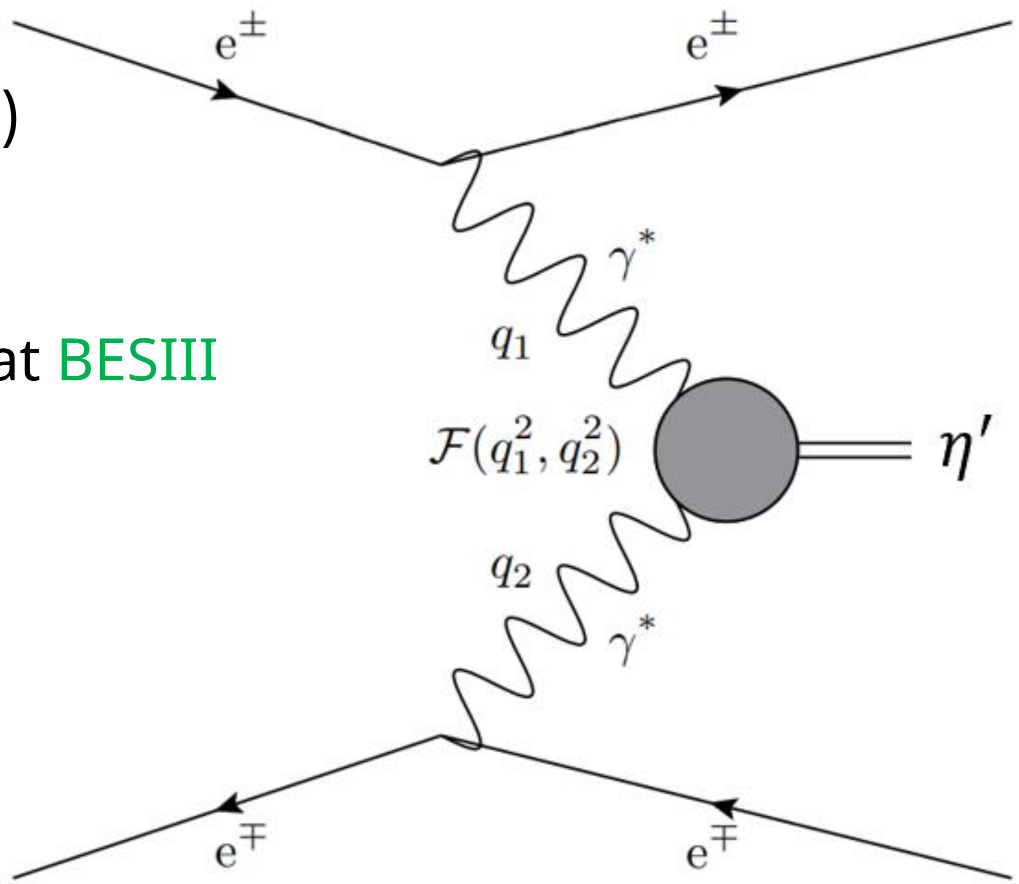


Image Credit: Max Lellmann

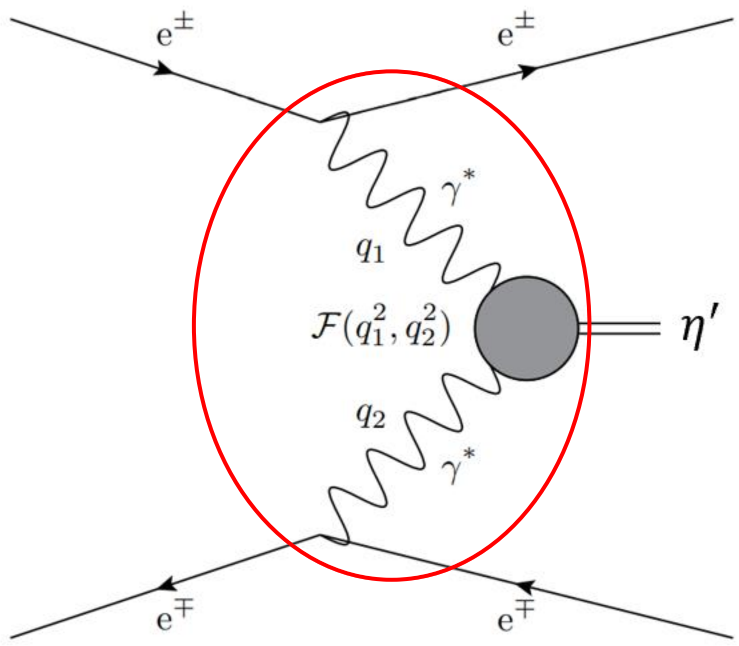
Double-Tagged Measurement

- Double-Tagged: measure both scattered $e^{\pm}$ in detector
  - ➢ study full momentum dependence of TFF
  - ➢ But very small cross section → rare process
- Only Published Double-Tagged Measurement: BABAR Phys. Rev. D 98, 112002 (2018)
  - ➢ found $46.2^{+8.3}_{-7.0}$ double-tagged η' events in full dataset for $2\ \mathrm{GeV}^2 < Q_1^2, Q_2^2 < 60\ \mathrm{GeV}^2$

→ At BESIII, TFF can be measured for $Q_1^2, Q_2^2 < 2\ \mathrm{GeV}^2$

Anomalous Magnetic Moment of the Muon

- Standard Model Prediction: $a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}}$
- a_μ^{HLbL} depends on Transition Form Factor (TFF) of pseudoscalar mesons such as η'



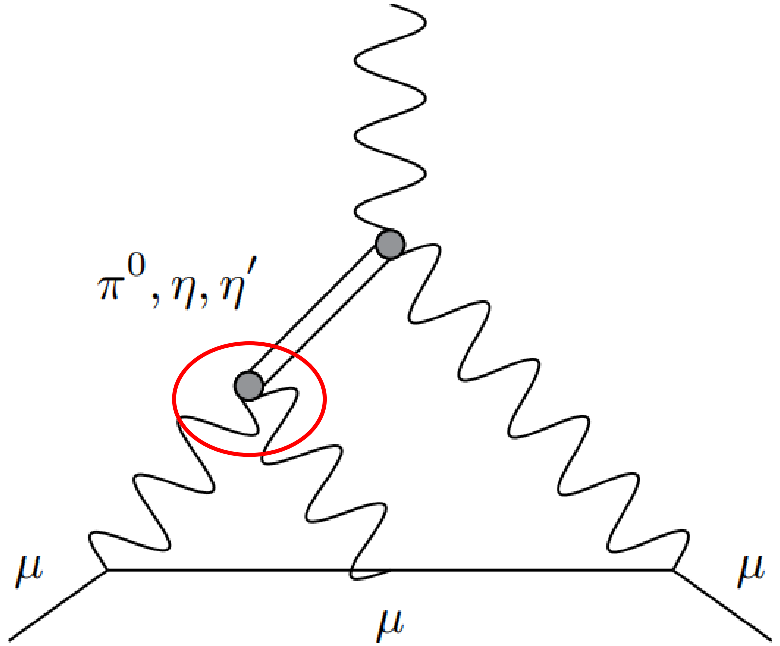


Image Credit: Max Lellmann

Xiaoxuan Ding

Peking University

Recent measurements of **charmonium** decay: $\psi(3686) \to \phi K_S^0 K_S^0$

PHYS. REV. D **108**, 052001(2023)

Xiaoxuan Ding (丁晓萱) on behalf of BESIII
Peking University
Mainz Oct 17, 2023

The 16th edition of the International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

What is charmonium ?

The Nobel Prize in Physics 1976

Psi J

Photo from the Nobel Foundation archive.
Burton Richter
Prize share: 1/2

Photo from the Nobel Foundation archive.
Samuel Chao Chung Ting

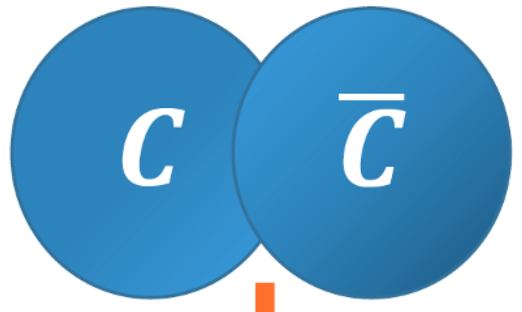
"for their pioneering work in the discovery of a heavy elementary particle of a new kind"

first charmonium state: J/ψ

Charm Quark Exist!

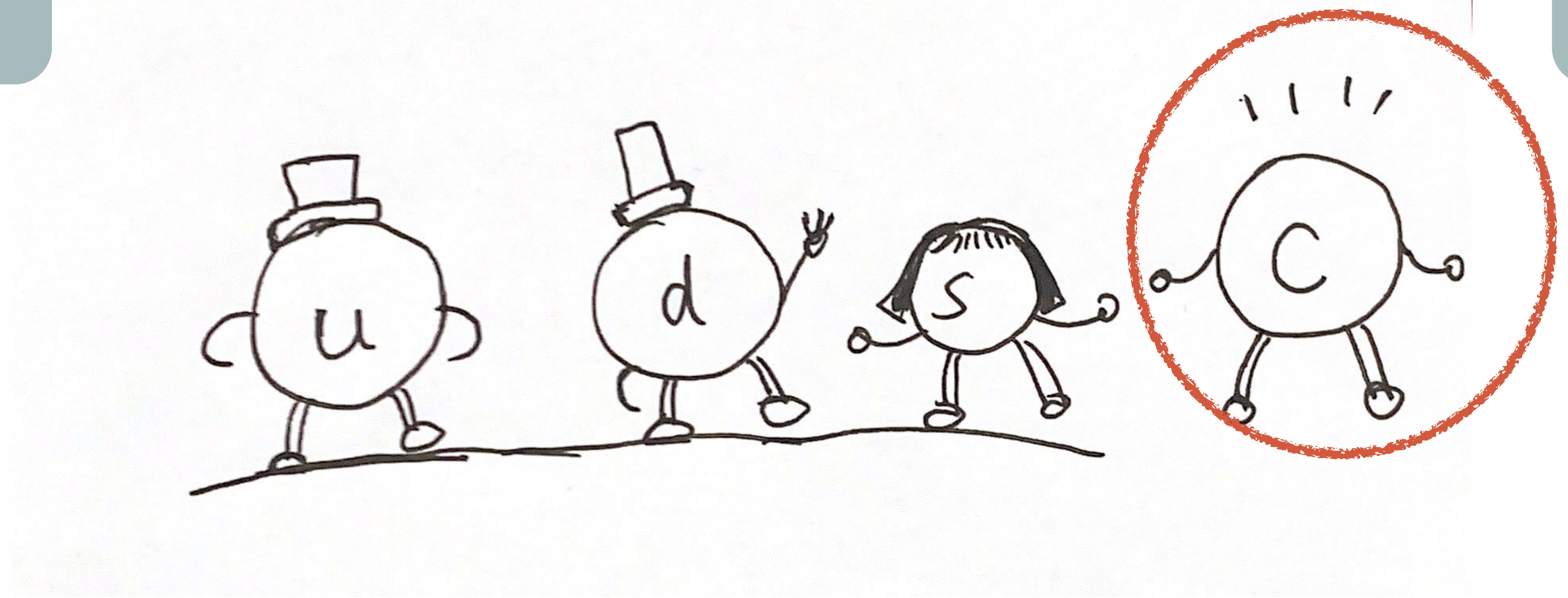
- ❖**Gell-mann quark model**
- ☐ The u, d, s quark model failed to describe J/ψ
- ❖**GIM mechanism**
- ☑ The fourth quark $\Rightarrow$ **Charm quark**

Study of the Charm onium



J/ψ

$\psi(3686)$



Hallo!

Why study this channel? $\psi(3686) \to \phi K_S^0 K_S^0$

❖**Charmonium decay**

✓Ideal place to

Validate models

Study the strong interactions

Test the quantum chromodynamics (QCD)

❖**12 % rule**

✓pQCD predict: The **relative ratio** of $J/\psi, \psi(3686)$ decays to the **same** final states is expected to be a **constant:**

$$\Rightarrow \mathscr{Q}_h = \frac{\mathscr{B}(\psi(3686) \to h)}{\mathscr{B}(J/\psi \to h)} \approx \underline{12\,\%}$$

Consistent well with many experimental result…
But!

✓$\rho - \pi$ **puzzles**

$\mathscr{Q}_{\rho\pi} < 0.6\,\%$

(suppressed 1/20)

Violation exists!

$\mathscr{B}(J/\psi \to \phi K_S^0 K_S^0) = (5.9 \pm 1.5) \times 10^{-4}$

$\mathscr{B}(\psi(3686) \to \phi K_S^0 K_S^0) =$?

We need more experimental results!

How to solve it?

Large charmonium data set are collected!

Clean environment with low backgrounds!

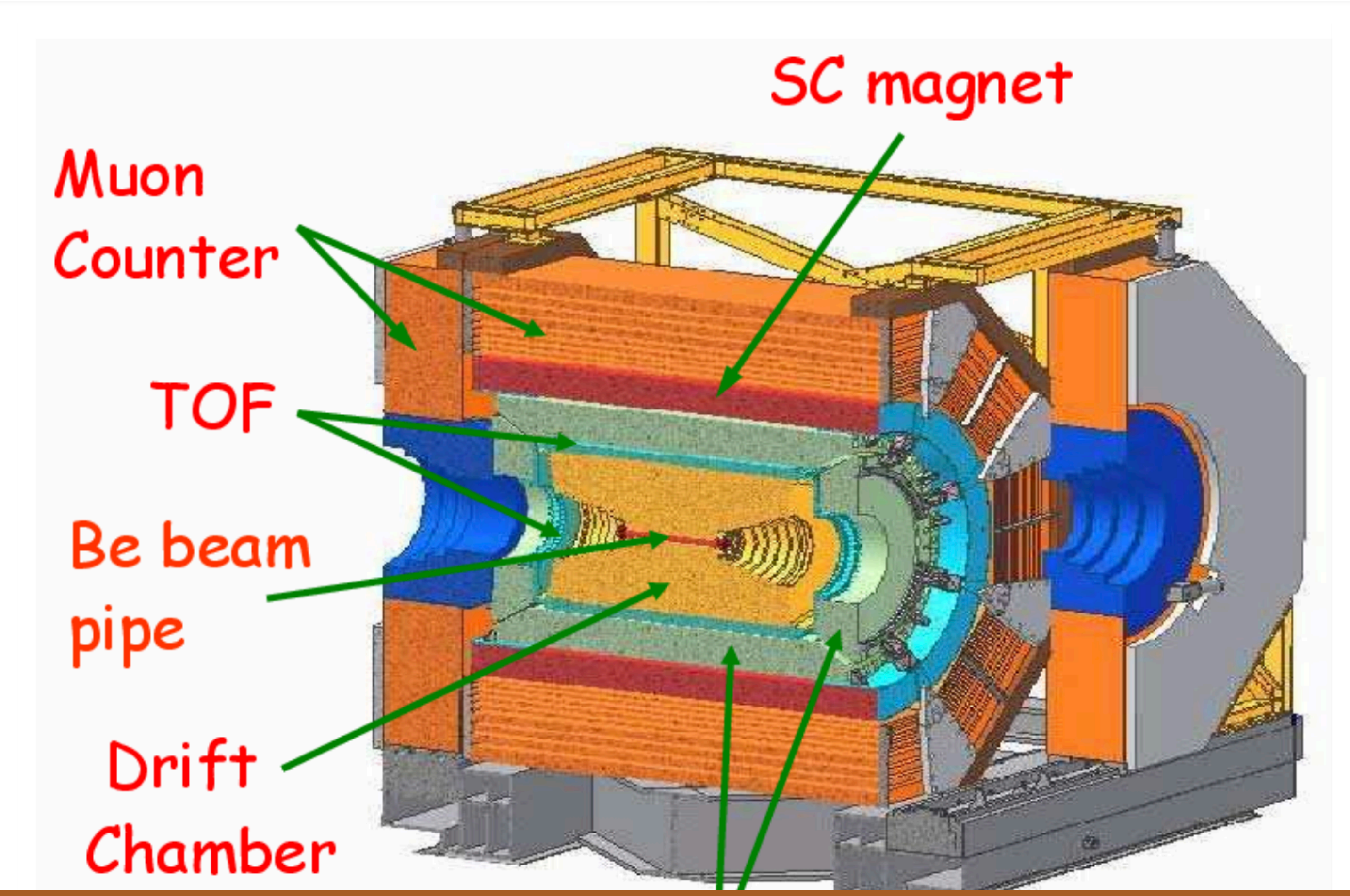
Fully reconstruct the cascade decay :

$$\psi(3686) \to \phi K_S^0 K_S^0,\ \ \phi \to K^+K^-, K_S^0 \to \pi^+\pi^-$$

allows us to search for processes with very low Branching fraction

≈ Half Billion $\psi(3686)$ events !

Large charmonium data set are collected!



Fully reconstruct the cascade decay

What's the result?

$\psi(3686) \rightarrow \phi K_S^0 K_S^0$ **First observation!**

The 12% rule is checked!

✓🥳Consistent? ✓🧐Violate?

Come to find the answer in the poster session!

Hong-Fei Shen

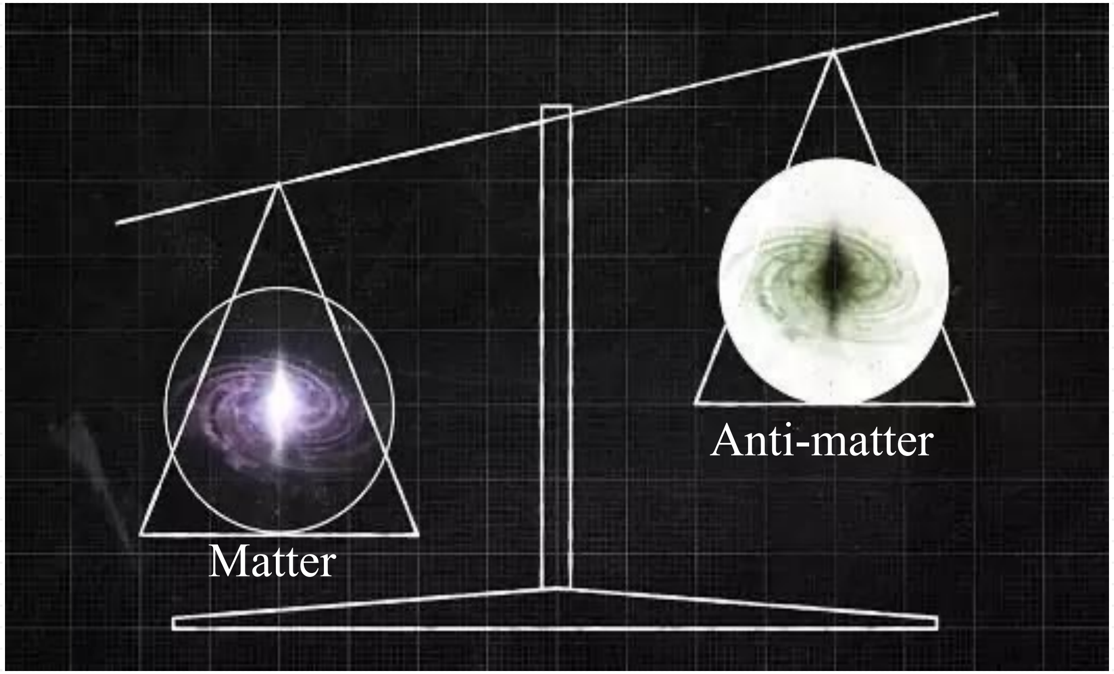
Institute of High Energy Physics,
Chinese Academy of Sciences, Beijing

Hyperon physics at BESIII

The 16th edition of the International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Hong-Fei Shen (On behalf of the BESIII Collaboration)
Institute of High Energy Physics

Mystery of matter-antimatter asymmetry



- According to the Big Bang theory:
  - Matter and anti-matter have the same amount
- The observed universe is matter dominant:

  $(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$

  New Journal of Physics 14 (2012) 095012

- The standard model predicted value：

  $(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$

- Why the anti-matter disappeared?
- Sakharov's three conditions :

  1. Baryon number violation
  2. C and CP violation
  3. Thermal non-equilibrium

Pisma Zh. Eksp. Teor. Fiz., 1967, 5: 32-35

CP violation （CPV）

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c \end{pmatrix}$$

$$\delta_{13} \rightarrow V_{CKM}^{*} \neq V_{CKM} \rightarrow CPV!$$

Chien-Shiung Wu

C.N. Yang

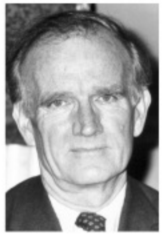
T.D. Lee

1.CPV has been founded at K, B, D meson systems, but not enough to explain matter dominant Universe;

2. No CPV is observed in baryon sector!

P violation	K meson CPV	B meson CPV	D meson CPV	Baryon?
1957	1964	2001	2019	

James Watson Cronin



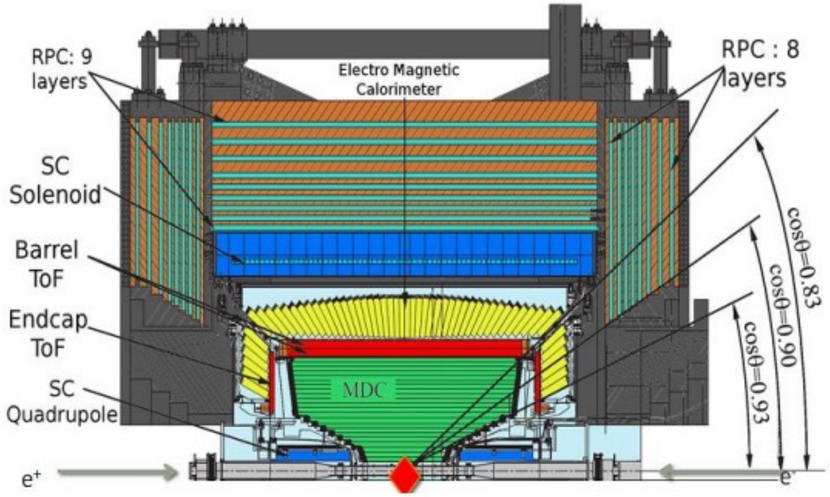
Val Logsdon Fitch

[1] Phys. Rev. 104 (1956) 254-258
[2] Phys. Rev. 105 (1957) 1413-1414
[3] Phys. Rev. Lett., 1964, 13: 138-140
[4] Phys. Rev. Lett., 2001, 87: 091801
[5] Phys. Rev. Lett., 2001, 87: 091802
[6] Phys. Rev. Lett., **122**, 211803 (2019)

Study hyperons at BESIII

Electromagnetic Calorimeter
CsI(Tl): L=28 cm
Barrel σ_E=2.5%
Endcap σ_E=5.0%

Muon Counter
RPC
Barrel: 9 layers
Endcap: 8 layers
σ_{spatial}=1.48 cm

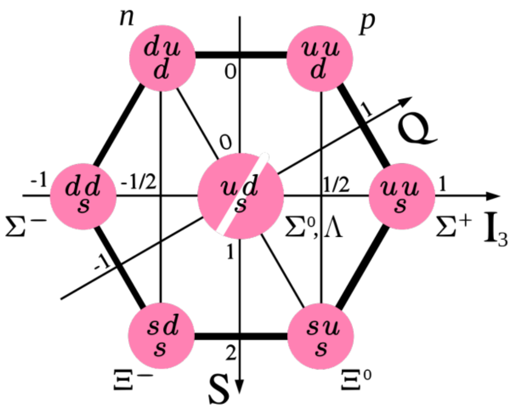


Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm
dE/dx~6%
σ_p/p= 0.5% at 1 GeV

Time Of Flight
Plastic scintillator
σ_T(barrel)=80 ps
σ_T(endcap)=110 ps
(update to 65 ps with MRPC)

With 10 billion J/ψ and 2.7 billion $\psi(3686)$ collected at BESIII.

$\sim 10^7$ entangled hyperon pairs can be produced, which enables precise studies of the hyperon physics.



$+\ \Omega^-(sss)$ spin-$\frac{3}{2}$

Front. Phys. 12(5), 121301 (2017)

Decay mode	$B(\times 10^{-3})$	$N_B(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	~ 18.9
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.172 ± 0.032	~ 11.7
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.07 ± 0.04	~ 10.7
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	~ 11.7
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.97 ± 0.08	~ 9.7
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.057 ± 0.003	~ 0.17

Come to see the interesting results of hyperon physics in the poster session!

Sebastian Ciupka
University of Bonn

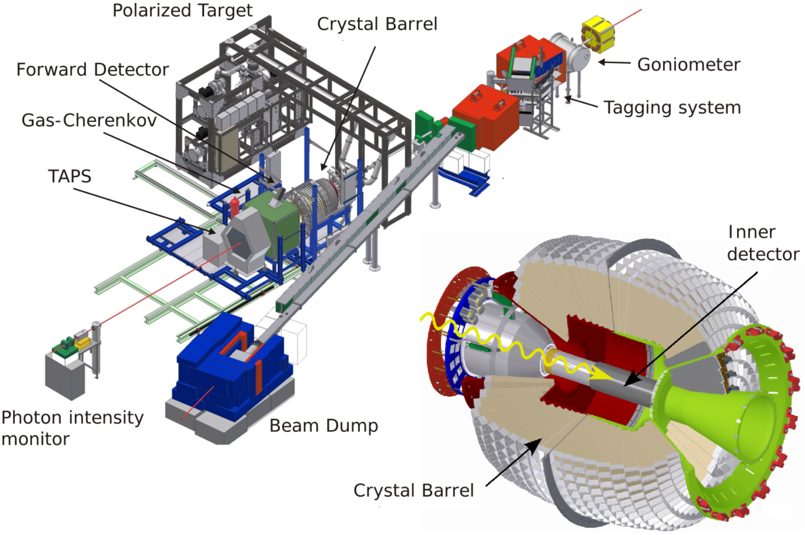
Determination of the polarization observables T, P and H in the reaction $\gamma p \rightarrow p\pi^0$

Sebastian Ciupka

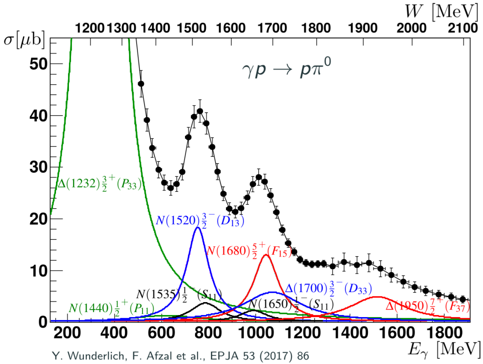
University of Bonn

17.10.23

The CBELSA/TAPS experiment

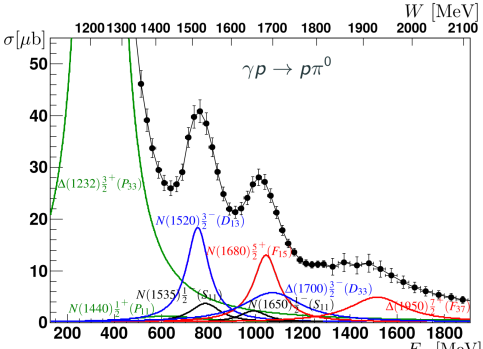


Baryon Spectroscopy



Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86

$$\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots$$



Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86

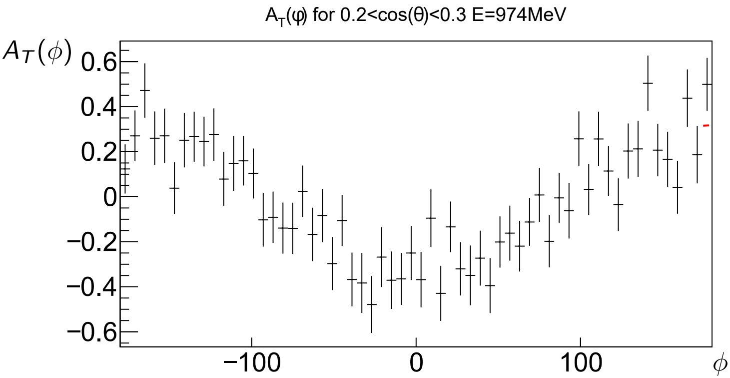
Photon polarization		Target polarization		
		X	Y	Z(beam)
unpolarized	σ	-	T	-
linear	$-\Sigma$	H	(-P)	-G
circular	-	F	-	-E

$$\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \dots$$

$$T \sim \underbrace{-2E_{0+}^* E_{1+} - 2E_{0+}^* M_{1+}}_{} + \dots$$

Interference $\Delta(1232)(P_{33})$ with N(1535)(S_{11})

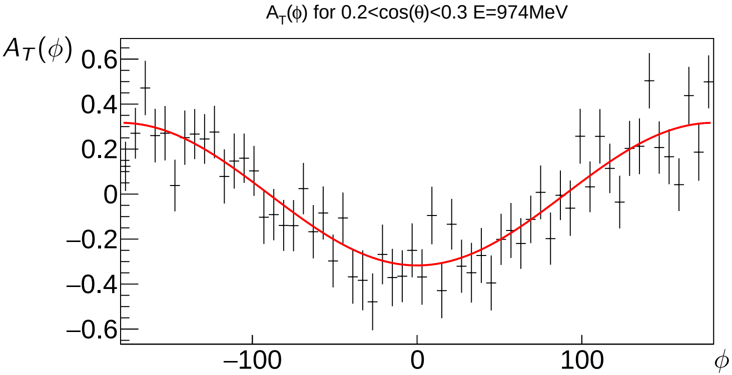
Extracting the Polarization Observables



$$A_T(\phi) = \frac{N_\uparrow - N_\downarrow}{\Lambda_\downarrow N_\uparrow + \Lambda_\uparrow N_\downarrow}$$

Λ: Target polarization

Extracting the Polarization Observables



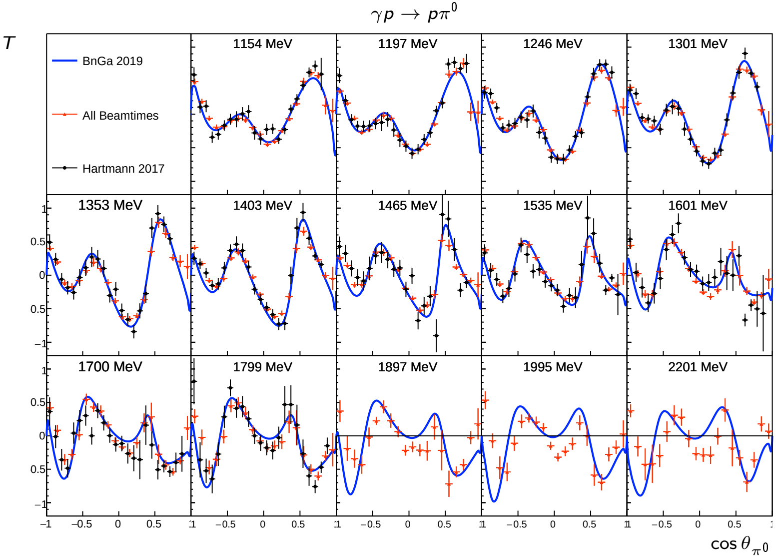
$$A_T(\phi) = \frac{N_\uparrow - N_\downarrow}{\Lambda_\downarrow N_\uparrow + \Lambda_\uparrow N_\downarrow} = d \cdot T \cdot sin(\beta - \phi)$$

Λ: Target polarization

β: Polarization angle

d: Dilution factor

Comparing the results - High energies



Photon polarization		Target polarization		
		X	Y	Z(beam)
unpolarized	σ	-	T	-
linear	-Σ	H	(-P)	-G
circular	-	F	-	-E

- Very good agreement with previous measurement
- Increased precision and better energy and angular coverage

[1] J. Hartmann et al., PLB 748, 212 (2015)

See you at the poster!

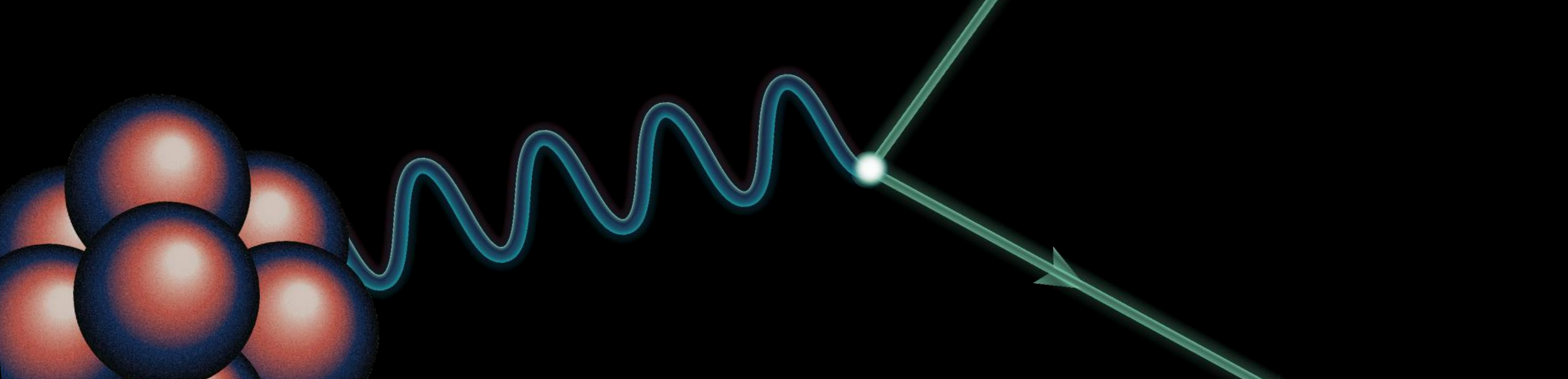
Cornelis Mommers

JGU Mainz

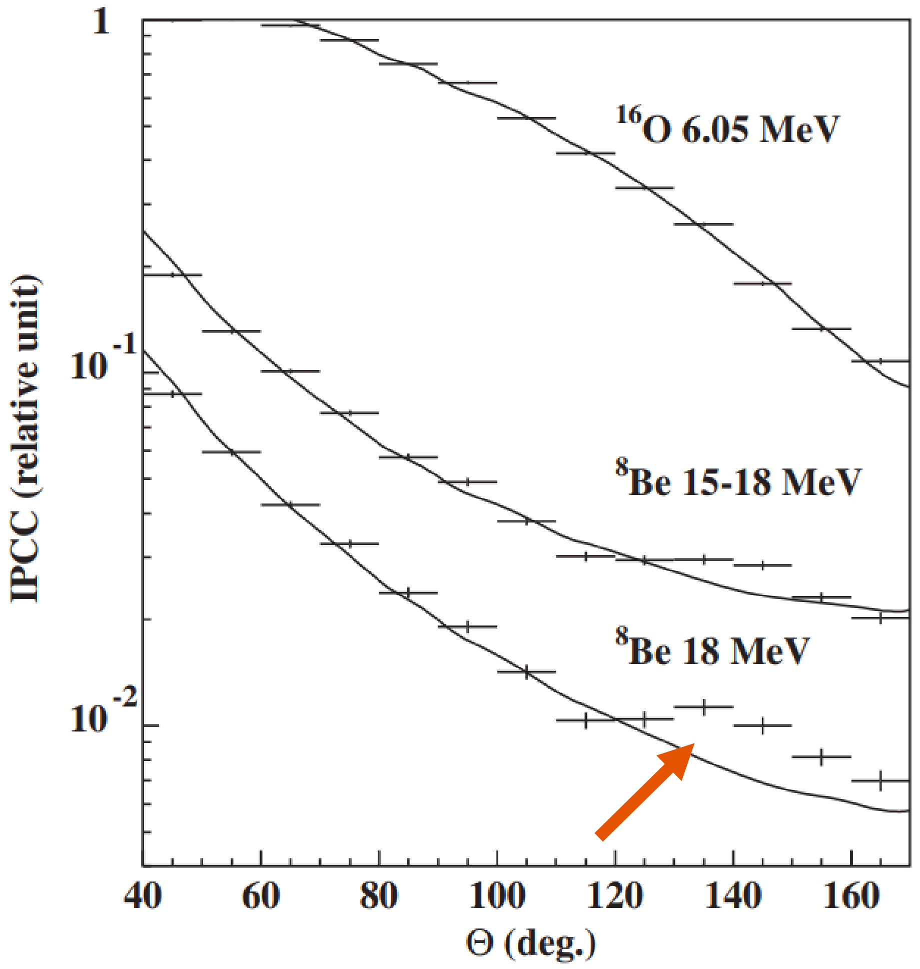
X17 discovery potential from $\gamma d \to e^+e^-pn$ with neutron tagging

Cornelis J.G. Mommers and Marc Vanderhaeghen,
JGU Mainz

arXiv:2307.02181 [hep-ph]



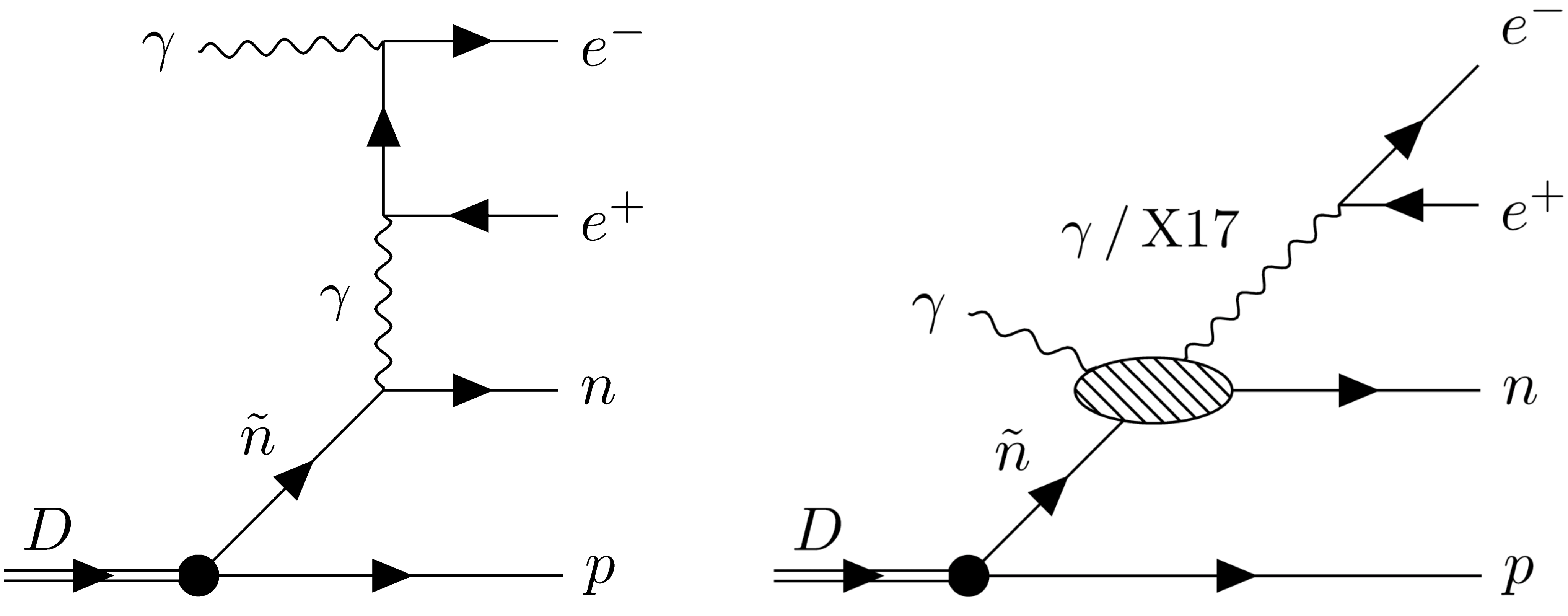
$\gamma d \to e^+e^- pn$ with neutron tagging



Phys. Rev. Lett. 116, 042501 (2016)

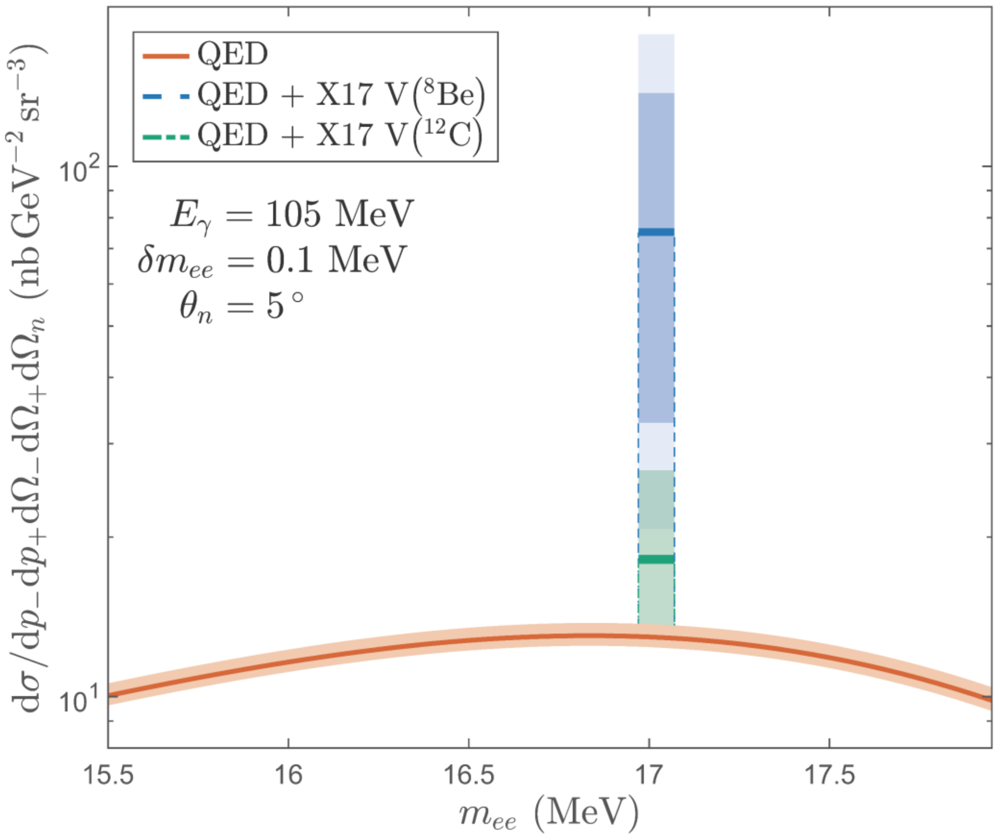
arXiv:2307.02181 [hep-ph]

$\gamma d \rightarrow e^+ e^- p n$ with neutron tagging



arXiv:2307.02181 [hep-ph]

$\gamma d \to e^+ e^- pn$ with neutron tagging



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X17 discovery potential from $\gamma d \rightarrow e^+e^-pn$ with neutron tagging

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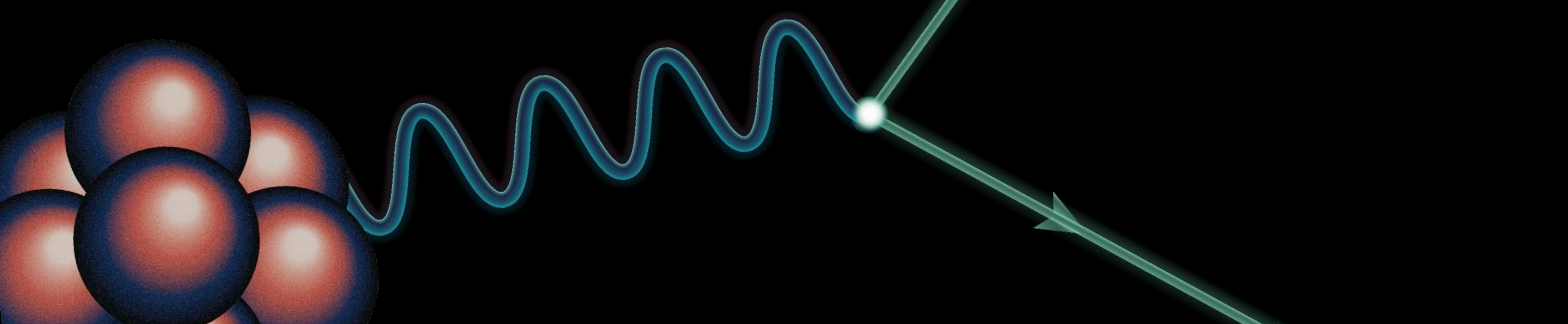


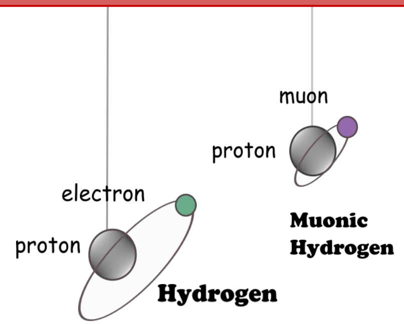
Vladyslava Sharkovska
Paul Scherrer Institute

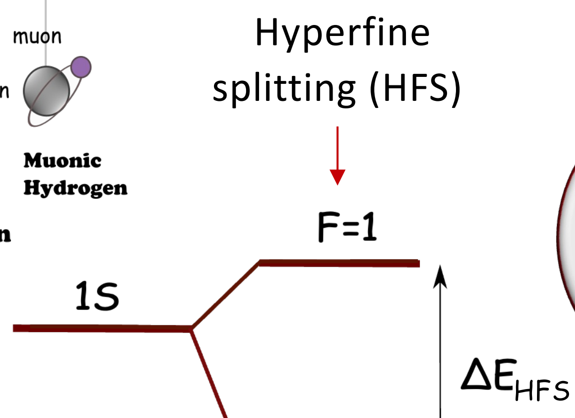
Vladyslava Sharkovska :: PhD student :: Paul Scherrer Institute

Proton Structure Corrections to Hyperfine Splitting in Muonic Hydrogen

MENU 2023 - The 16th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Oct 15-20, 2023

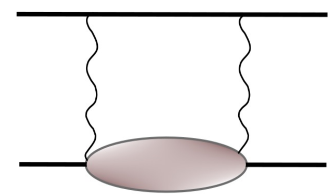


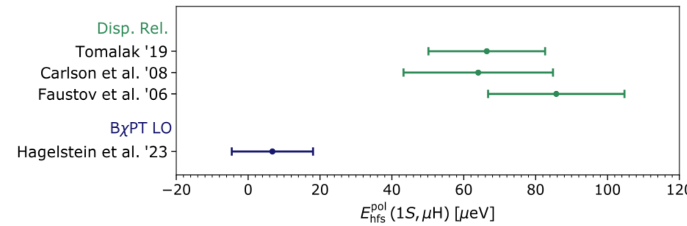


Muonic atoms are better!

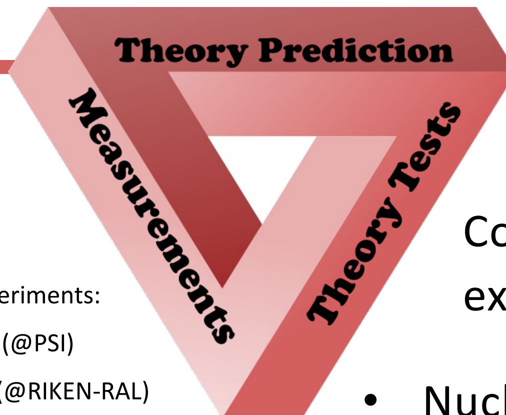
1. Atomic Spectro-scopy

TPE as the dominant uncertainty

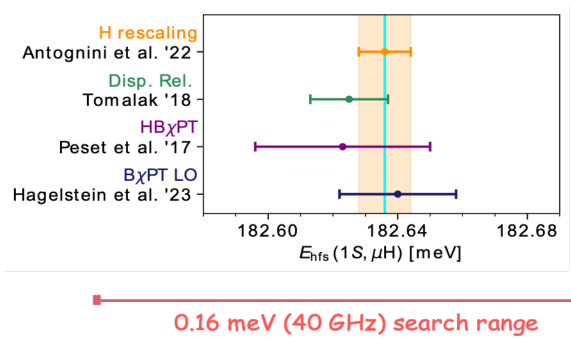




Why do we have a discrepancy?



2. Guiding the Experiment



Future experiments:

- CREMA (@PSI)
- FAMU (@RIKEN-RAL)

Theoretical prediction is needed to help finding the HFS transition

3. Checking the Theory

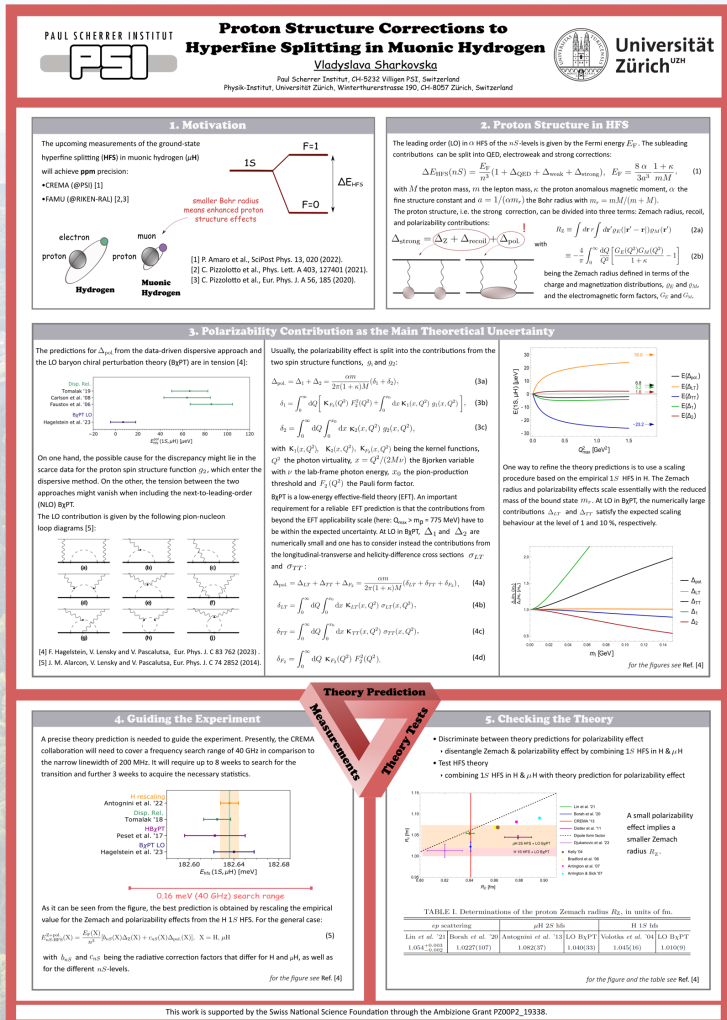
Combine with other exp. and/or theor. inputs for:

- Nuclear theory tests
- Fundamental constants refinement
- QED tests

… and also learn more about the proton spin-structure!

Thank you for your attention!

Would love to see you at my poster!



Tommaso Vittorini
Università di Genova

The A(i)DAPT program
AI for Data Analysis and Preservation

Tommaso Vittorini

on behalf of A(i)DAPT Working Group

A(i)DAPT
AI for Data Analysis and PreservaTion

- Data collected by NP/HEP experiments are (always) affected by the detector's effects
- Before starting physics analysis the detector's effect unfolding is required
- Traditional observables may not be adequate to extract physics in multidimensional space (multi-particles in the final state)
- At High-Intensity frontiers, data sets are large and difficult to manipulate/preserve

Should AI support NP/HEP experiments to extract physics from data in more efficient way?

A(i)DAPT
AI for Data Analysis and PreservaTion

Develop AI – supported procedures to:
- Accurately fit data in multiD space
- Unfold detector effects
- Compare synthetic (AI-generated) to experimental data
- Quantify the uncertainty (UQ)

Collaborative effort (regular meeting)
- ML experts (ODU, Jlab)
- Experimentalists (Jlab Hall-B)
- Theorists (JPAC, JAM)

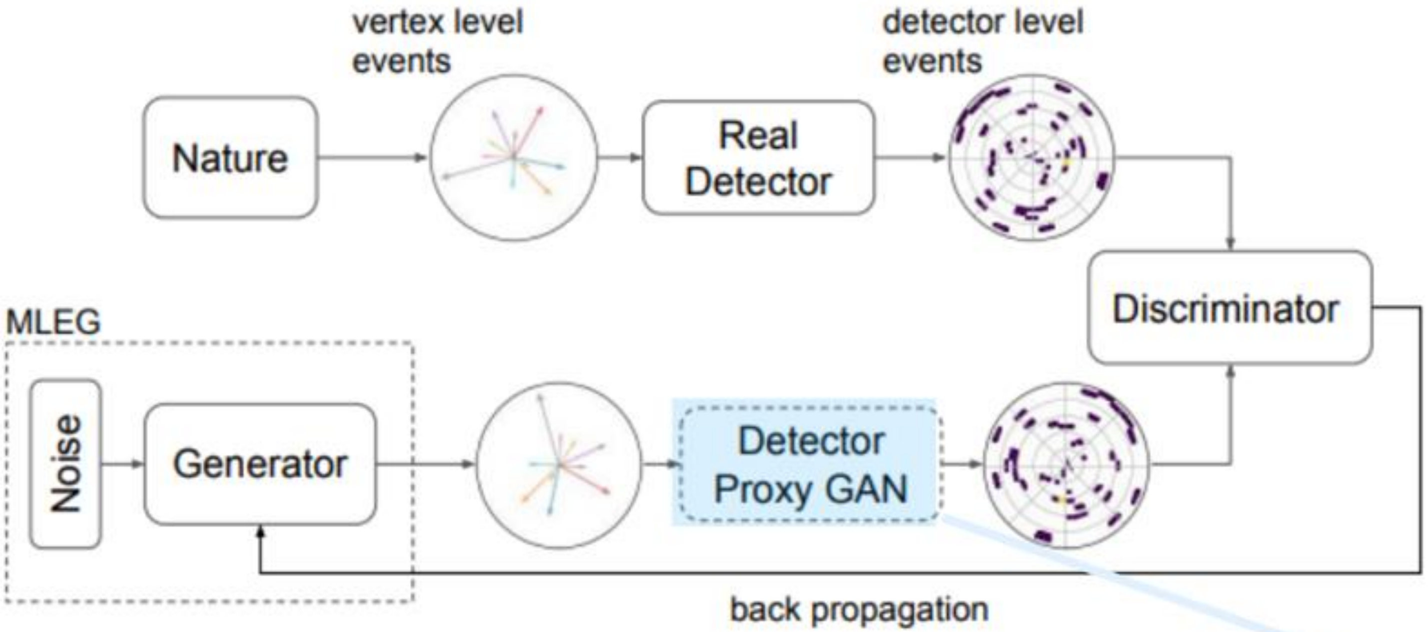
The A(i)DAPT road map

- Deploy an AI Generative Model to reproduce NP/HEP data
- Detector effects unfolding: smearning
- Detector effects unfolding: acceptance
- Extract few dimensions cross-section (PDF) (e.g. inclusive electron scattering – MC)
- Extend the closure test to cross-sections in a multiD phase-space (e.g. 2-π photoproduction – MC)
- Validate the analysis procedure extracting cross-section from data (e.g. high energy CLAS-g11 2-π data)
- Combinate data of the same final state taken in different kinematics (e.g. low energy CLAS-g11 2-π data)
- Combine data from different final states (e.g. CLAS-g11 3-π /ω data)
- Extract cross-section and amplitudes in a 2-body reaction (e.g. $\pi\pi$ scattering – MC)
- Extract amplitudes from a multi-particle exlusive channel (e.g. CLAS-g11 2-π data)
- Extract amplitudes in multi-coupled channel analysis (e.g. CLAS-g11 2-π + 3-π/ω data)
- Connect NN features to different physics processes (e.g. baryon and meson resonances in CLAS-g11 2-π data)
- ...
- Extract physics out of our data

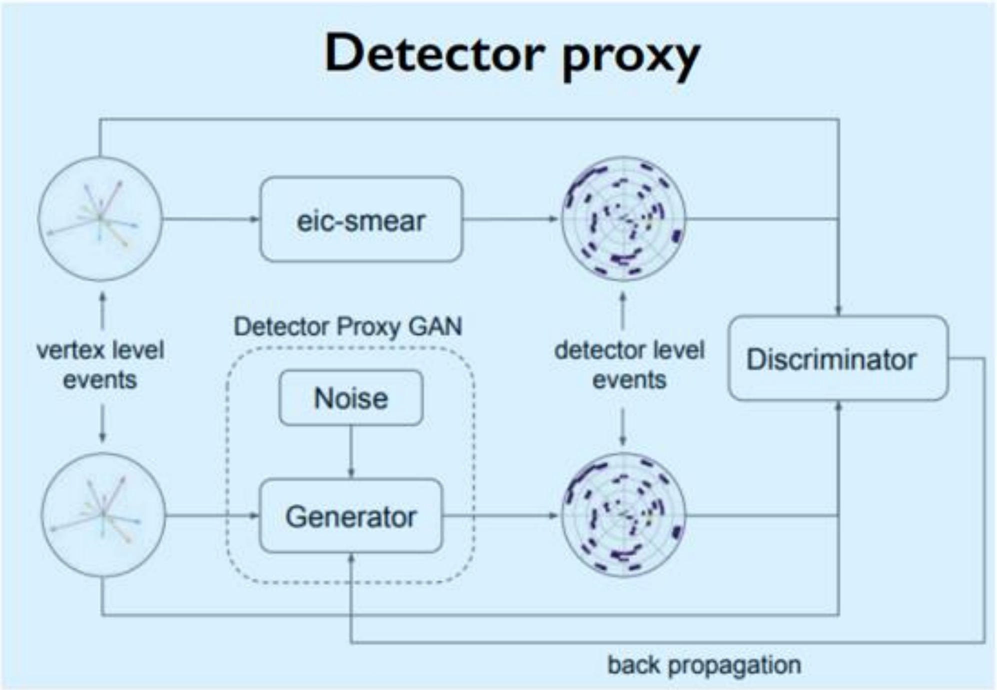
The A(i)DAPT road map

- Deploy an AI Generative Model to reproduce NP/HEP data ✓
- Detector effects unfolding: smearning ✓
- Detector effects unfolding: acceptance in progress
- Extract few dimensions cross-section (PDF) (e.g. inclusive electron scattering – MC) ✓
- Extend the closure test to cross-sections in a multiD phase-space (e.g. 2-π photoproduction – MC) ✓
- Validate the analysis procedure extracting cross-section from data (e.g. high energy CLAS-g11 2-π data)
- Combinate data of the same final state taken in different kinematics (e.g. low energy CLAS-g11 2-π data)
- Combine data from different final states (e.g. CLAS-g11 3-π /ω data)
- Extract cross-section and amplitudes in a 2-body reaction (e.g. $\pi\pi$ scattering – MC) in progress
- Extract amplitudes from a multi-particle exlusive channel (e.g. CLAS-g11 2-π data)
- Extract amplitudes in multi-coupled channel analysis (e.g. CLAS-g11 2-π + 3-π/ω data)
- Connect NN features to different physics processes (e.g. baryon and meson resonances in CLAS-g11 2-π data)
- ...
- Extract physics out of our data

ML Event Generator through a GAN (Generative Adversarial Network)



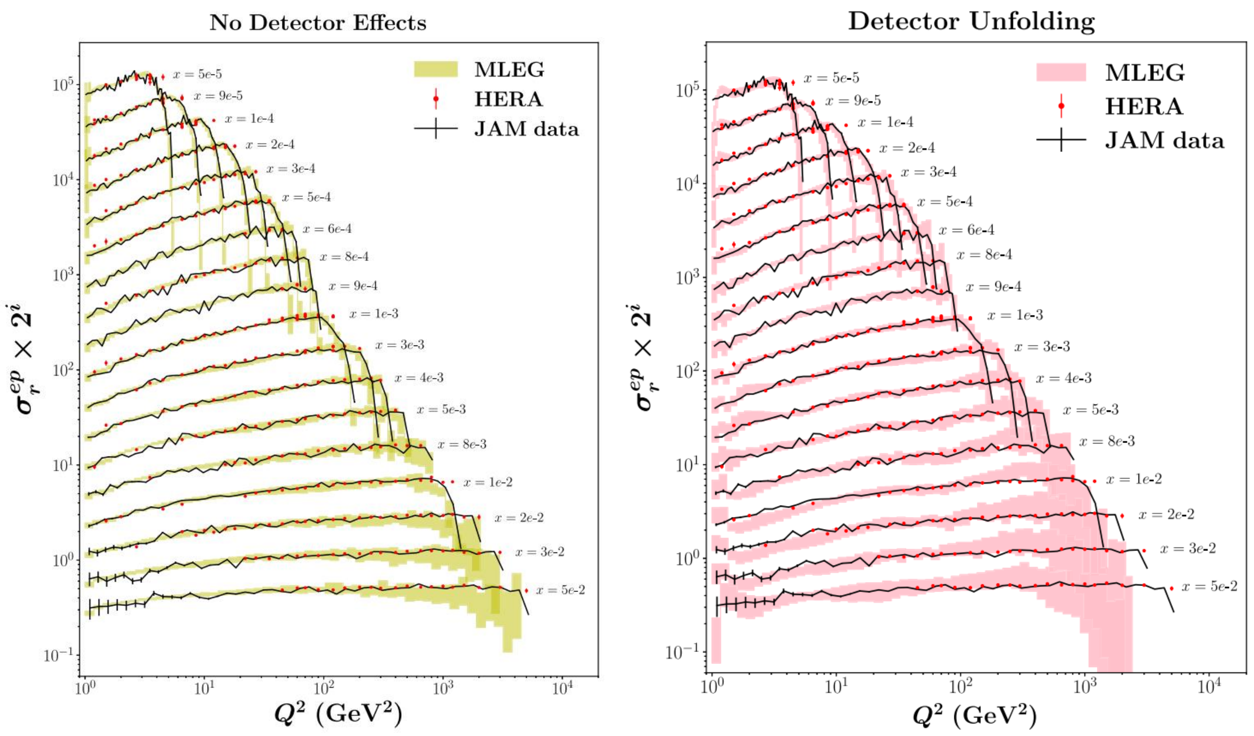
Trained indipendently on a different dataset



- Generative model based on the competition between two sub-models: Generator vs Discriminator
  - Generator produces synthetic data which progressively reproduce realistic data
  - Discriminator has to distinguish between synthetic and realistic data

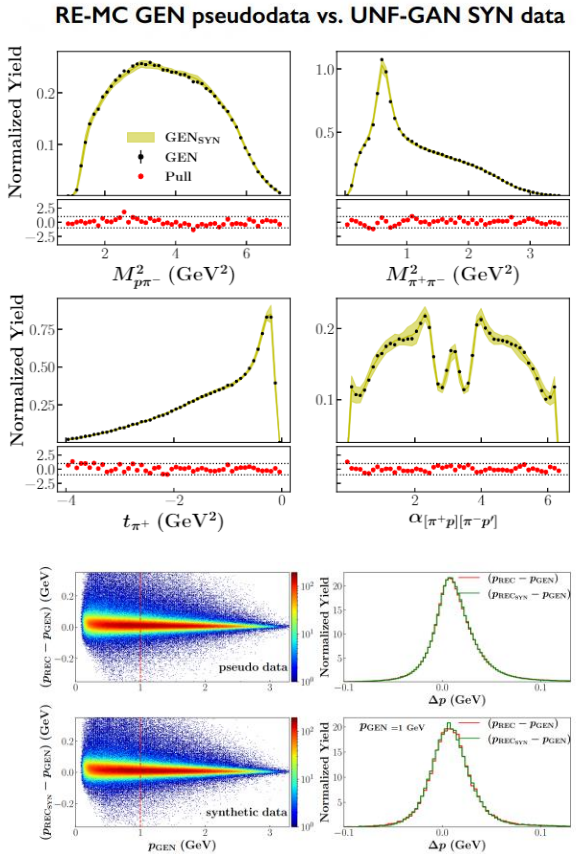
A(i)DAPT achievements

- Inclusive electron DIS generated at $E_\gamma = 318.2\ GeV$ (HERA kinematics)



GANs are able to reproduce, within the error bars, JAM pseudo-data in both cases: with and without detector smearing

- 2-π photoproduction at $E_\gamma = 3 - 4\ GeV$



GANs are able to reproduce with good agreement synthetic vertex-level variables used for the training and reproduce the CLAS detector smearing

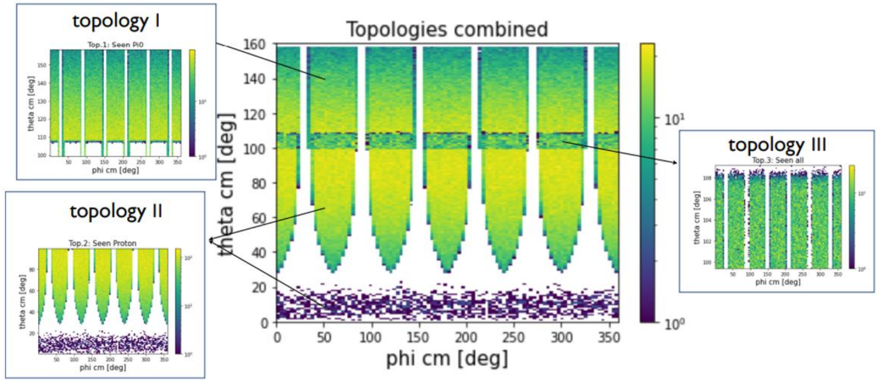
Work in progress

- Monte Carlo generated events from the two-body process $\gamma p \to \Delta^+(1232) \to \pi^0 p$ at fixed incoming energy:

$$\frac{d\sigma}{d\Omega} \propto \frac{p_f}{p_i\, s} \sum_{\lambda_\gamma \lambda_p \lambda_p'} \left| (-)^{\lambda_\gamma} H_{|\lambda_\gamma - \lambda_p|} \frac{d^{3/2}_{\lambda_\gamma - \lambda_p, -\lambda_p'}(\theta)}{m_\Delta^2 - s - i\Gamma_\Delta m_\Delta} \right|^2$$

$$\propto \frac{p_f}{p_i\, s} \frac{3\left|H_{3/2}\right|^2 + 5\left|H_{1/2}\right|^2 - 3\cos 2\theta \left(\left|H_{3/2}\right|^2 - \left|H_{1/2}\right|^2\right)}{(m_\Delta^2 - s)^2 + \Gamma_\Delta^2 m_\Delta^2}$$

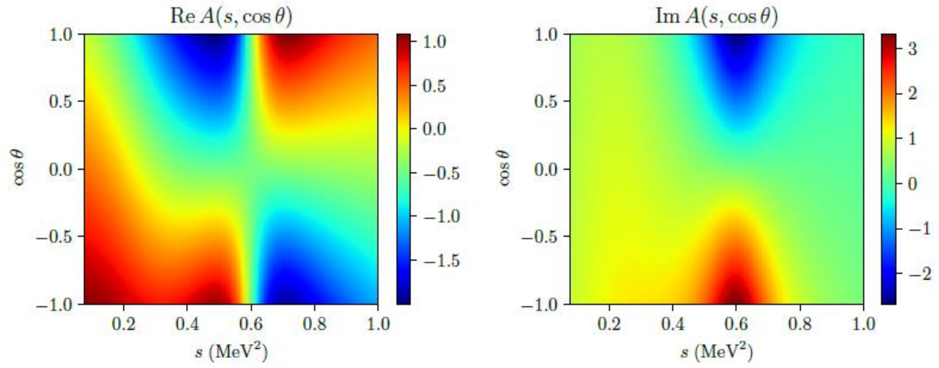
- Topologies definition through the detector (CLAS) acceptance implementation



- Train a single GAN which generates into all the different topologies to deal with the detector acceptance

- Monte Carlo generated events from the elastic scattering $\pi^+\pi^- \to \pi^+\pi^-$:

$$A(s, \cos\theta) = \sum_{\ell=0}^{n} (2\ell + 1) f_\ell(s) P_\ell(\cos\theta)$$



- Physics constraints on the partial waves $f_l(s)$

- Train a GAN to generate scattering amplitudes

Summary

AI can be used to:

- Unfold detector's effect to extract physics observables at vertex-level
- Embed (multiD) crossections informations (correlations) in a data-trained event generator
- Preserve data in alternative compact and efficient form
- Provide an alternative way to extract PDFs and amplitudes
- Extract NN features related to the underlying physics

A(I)DAPT program aims to demonstrate a novel way to extract and interpret physics observables

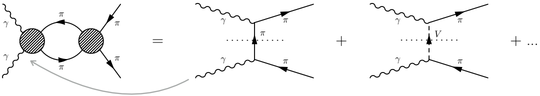
- Multi-step program
- We performed a positive closure test on inclusive electron scattering and 2pion photoproduction
- We demonstrated that GANs are a viable tool to unfold detector effects (smearing) to generate a synthetic copy of data
- We demonstrate that the original correlations are preserved
- We are currently working on quantifying the systematic error introduced by the detector acceptance
- The first attempt to use a model-indipendent procedure supervising at level of amplitudes is encouraging

There is still a long way to go to be able to use AI to extract physics from data in an efficient way, but we are moving towards the right direction!

Viktoriia Ermolina

JGU Mainz

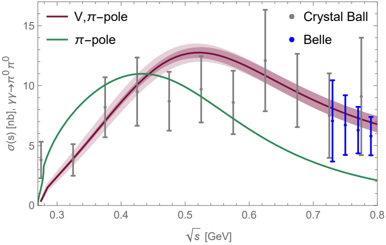
Pion polarizabilities from a dispersive analysis of the $\gamma\gamma \to \pi\pi$ process



▷ We present results for the charged and neutral pion polarizabilities, obtained through a dispersive analysis of the photon-photon fusion process, motivated by the current and future measurements at COMPASS and JLab

▷ Constructing partial wave helicity amplitudes using once subtracted dispersion relation, we fit the available $\gamma\gamma \to \pi^0\pi^0$ cross-section data

▷ Accounting for the influence of heavier than pion left cuts, primarily governed by vector mesons exchange, vastly affects the neutron pion dipole polarizability, narrowing the discrepancy with NNLO ChPT



Total $\gamma\gamma \to \pi^0\pi^0$ S-wave cross-section with and without vector pole left-hand cut contribution, $\chi^2 = 0.82$

	Dispersive			ChPT		Experiment
	Present work		Garcia-Martin et al 2010			
	π pole	π, V poles	π, V, A, T pole	NLO	NNLO	COMPASS
$(\alpha_1 - \beta_1)_{\pi^\pm}$ $[10^{-4}\mathrm{fm}^3]$	5.2	4.7(5)(1)	4.7	6.0	5.7 (1.0)	4.0 $(1.2)_{\mathrm{stat}}$ $(1.4)_{\mathrm{sys}}$
$(\alpha_1 - \beta_1)_{\pi^0}$ $[10^{-4}\mathrm{fm}^3]$	8.7	−1.4(0)(3)	−1.25 (17)	−1.0	−1.9 (2)	–

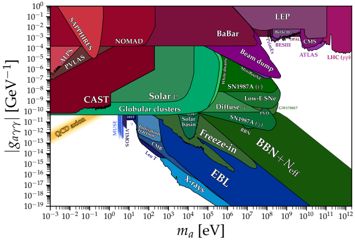
Aleksandr Pustyntsev

JGU Mainz

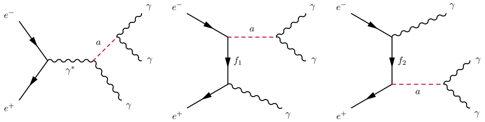
Improved constraints for axion-like particles from 3-photon events at e^+e^- colliders

▷ **QCD axion**: a proposed pseudoscalar particle with a linear relation between mass m_a and coupling $g_{a\gamma\gamma}$ aimed to solve the strong CP problem in QCD
▷ **Axion-like particle**: a generic pseudoscalar, free from mass/coupling constraints. Proposed as a possible dark matter candidate

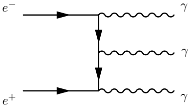
We aim to **improve** upon previous analyses by also including the ALP coupling to electrons and **show** that future analyses at e^+e^- colliders will allow to significantly extend the ALP search range and **impose** more stringent restrictions on their couplings



Existing limits for coupling $g_{a\gamma\gamma}$ versus mass m_a

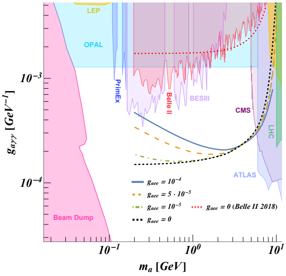


We then calculate the corresponding amplitudes analytically and apply them to the particular kinematics of the Belle II experiment, also taking into account QED background



The aimed sensitivity is then:

$$\frac{\sigma_{ALP}}{\sigma_{QED}} = \frac{N}{\sqrt{L \cdot \sigma_{QED}}} \Rightarrow$$



Julian Parrino
JGU Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The hadronic vacuum polarization contribution to $(g-2)_\mu$ from coordinate-space methods

En-Hung Chao, Harvey Meyer, Julian Parrino

MENU 2023, Mainz, Oktober 17, 2023

Hadronic contributions to $(g-2)_\mu$

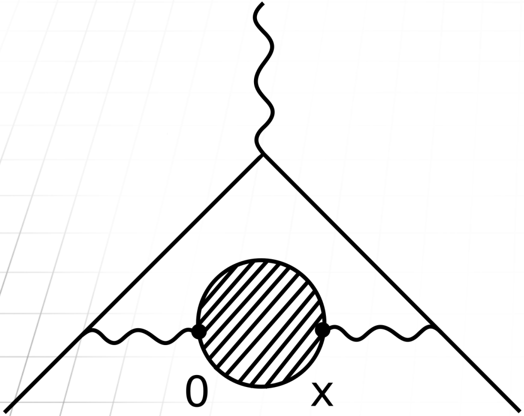


Fig. 1: Hadronic vacuum polarization (HVP) contribution

- Uncertainty of theory prediction is completely dominated by hadronic contributions
- $O(\alpha^2)$ contribution from hadronic vacuum polarization $\sim 700 \cdot 10^{-10}$, desirable accuracy $\sim 0.2\%$
- $O(\alpha^3)$ QED corrections become relevant
  - Understanding of tension between dispersive calculation of the HVP and lattice

The hadronic vacuum polarization HVP

2 branches of theoretical calculations:

- 1. Dispersive approach

$$a_\mu^{HVP} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^{\infty} \frac{K(s)}{s} R(s)\, ds \qquad R(s) : \text{ From experimental data}$$

The hadronic vacuum polarization HVP

2 branches of theoretical calculations:

- 1. Dispersive approach

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

$R(s)$: From experimental data

- 2. Lattice, Time-momentum representation (TMR)

$$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^{\infty} f(t, m_\mu) G(t)\, dt$$

$G(t)$: From lattice data

CCS representation

$$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty f(t, m_\mu) G(t)\, dt$$

CCS representation

$$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty f(t, m_\mu) G(t)\, dt \qquad a_\mu^{HVP} = \int H_{\mu\nu}(x) G_{\mu\nu}(x)\, d^4x$$

- with CCS kernel

$$H_{\mu\nu}(x) = -\delta_{\mu\nu}\mathcal{H}_1(|x|) + \frac{x_\mu x_\nu}{|x|^2}\mathcal{H}_2(|x|)$$

CCS representation

$$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty f(t, m_\mu) G(t)\, dt \qquad a_\mu^{HVP} = \int H_{\mu\nu}(x) G_{\mu\nu}(x)\, d^4x$$

- with CCS kernel

$$H_{\mu\nu}(x) = -\delta_{\mu\nu}\mathcal{H}_1(|x|) + \frac{x_\mu x_\nu}{|x|^2}\mathcal{H}_2(|x|)$$

- Integral is invariant under $H_{\mu\nu}(x) \to H_{\mu\nu}(x) + \partial_\mu \Big(x_\nu f(|x|)\Big)$
- Results for intermediate window observable $a_\mu^W \implies$ see poster

QED correction to the HVP

$$a_\mu^{HVP,NLO} = -\frac{e^2}{2}\int_{x,y,z} H_{\mu\sigma}(z)\delta_{\nu\rho}\Big[B(y-x)\Big]_\Lambda \langle j_\mu(z)j_\nu(y)j_\rho(x)j_\sigma(0)\rangle$$

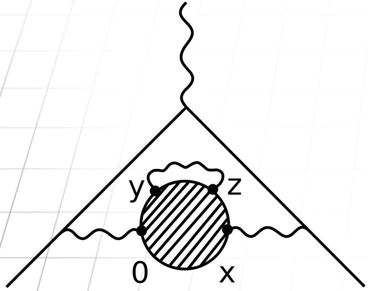


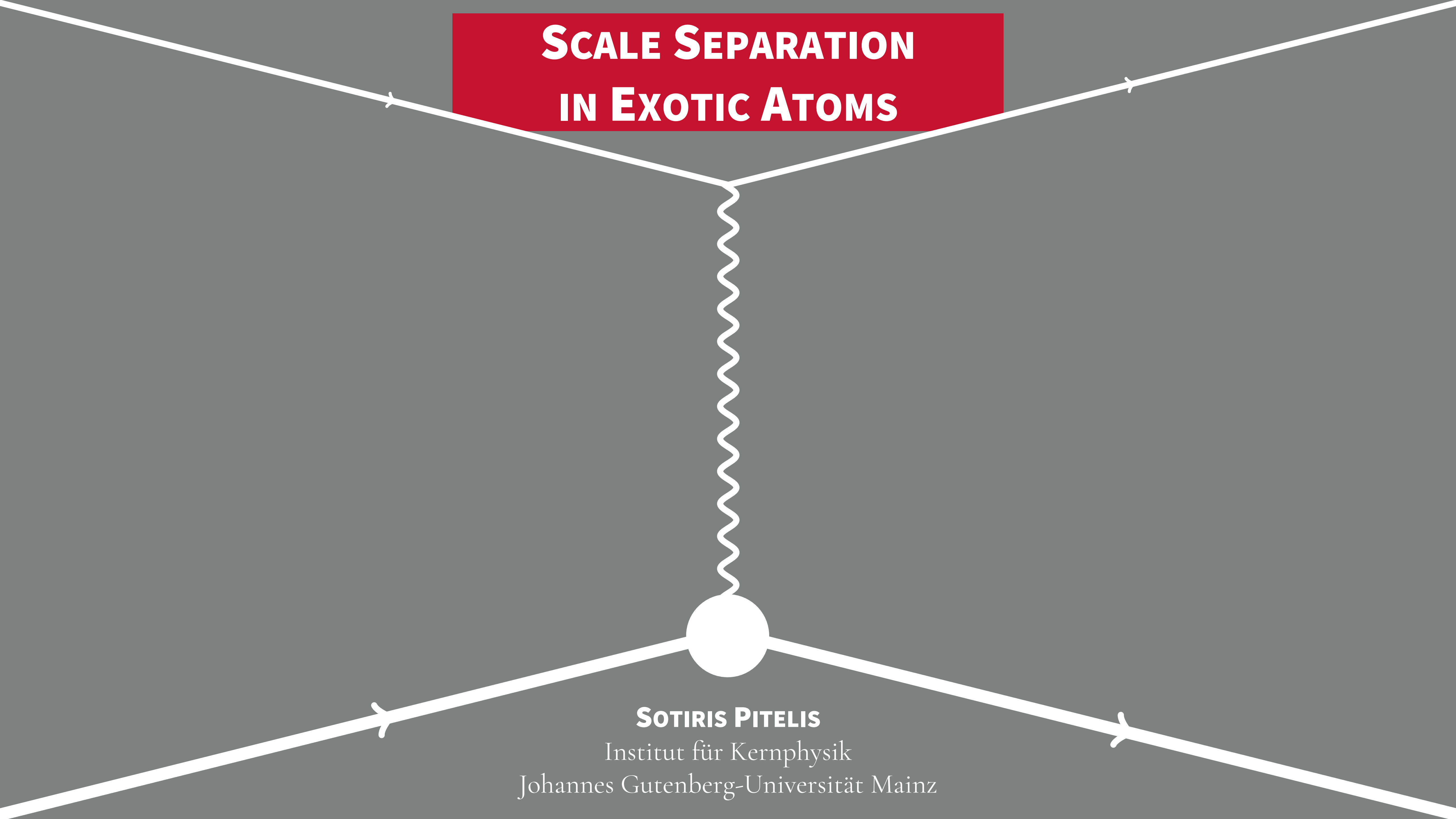
Fig. 2: HVP at NLO (lattice)

- Similarity to calculation of the hadronic light-by-light contribution
- Complicated four-point function
- Photon propagator with regulator $\Big[B(y-x)\Big]_\Lambda$

Sotiris Pitelis

JGU Mainz

Scale Separation in Exotic Atoms



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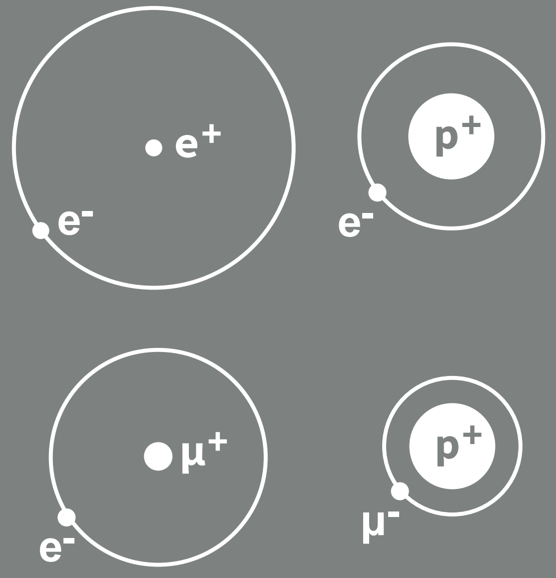
Institut für Kernphysik
Johannes Gutenberg-Universität Mainz

Scale Separation in Exotic Atoms

Precision Spectroscopy of (Exotic) Atoms



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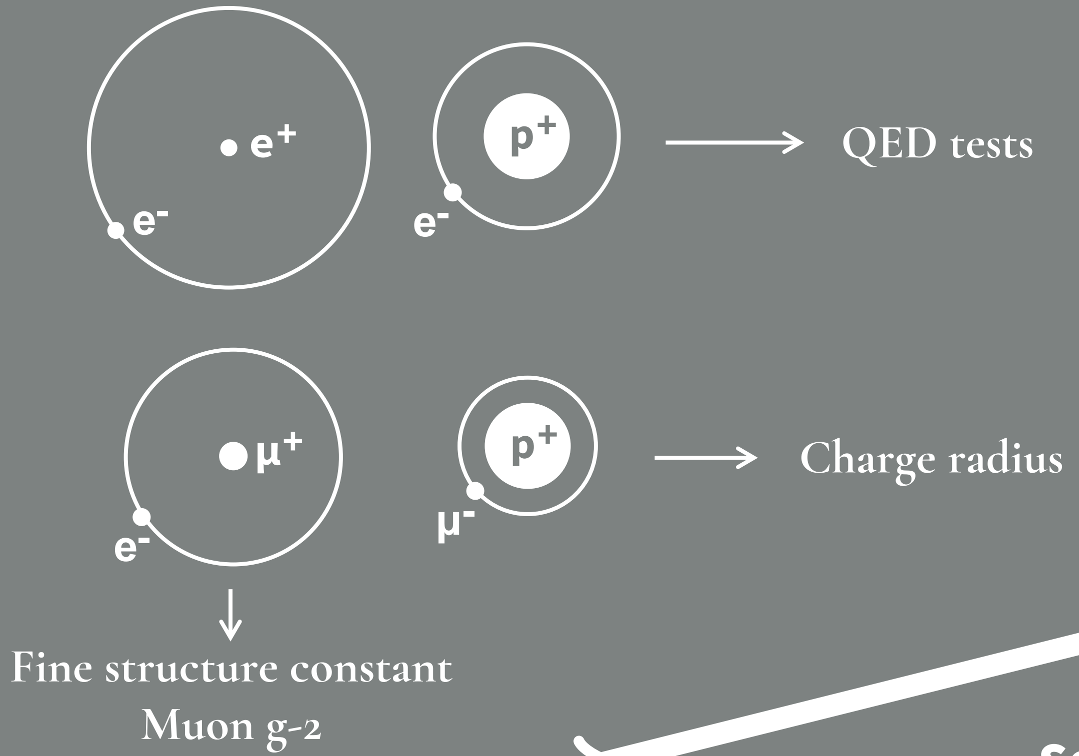
Scale Separation in Exotic Atoms

Precision Spectroscopy of (Exotic) Atoms



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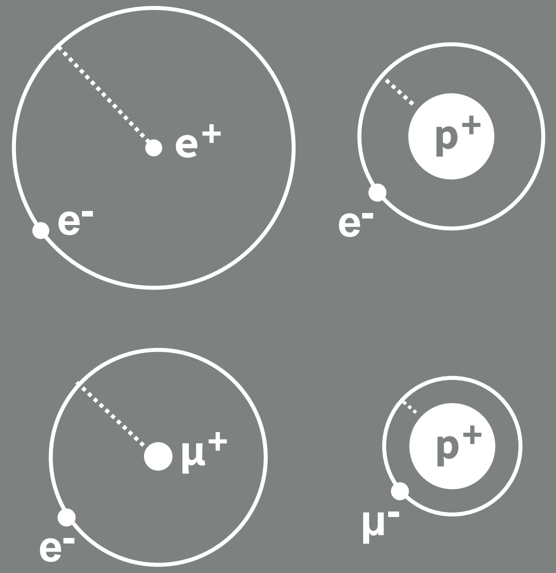
Scale Separation in Exotic Atoms

PRECISION SPECTROSCOPY OF (EXOTIC) ATOMS



→ QED tests

→ Charge radius

↓ Fine structure constant
Muon g-2

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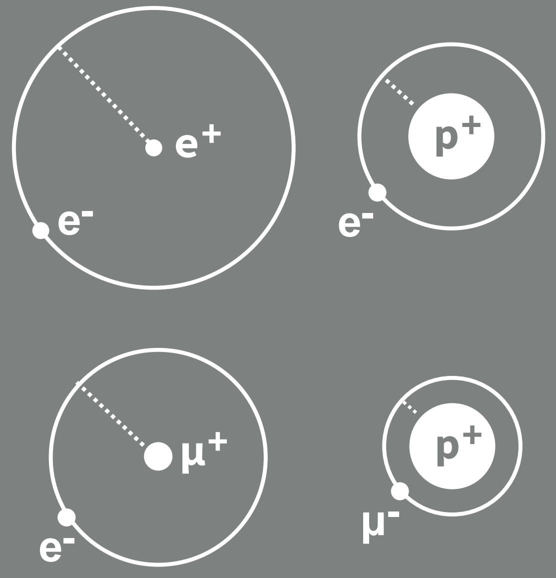
Johannes Gutenberg-Universität Mainz

Scale Separation in Exotic Atoms

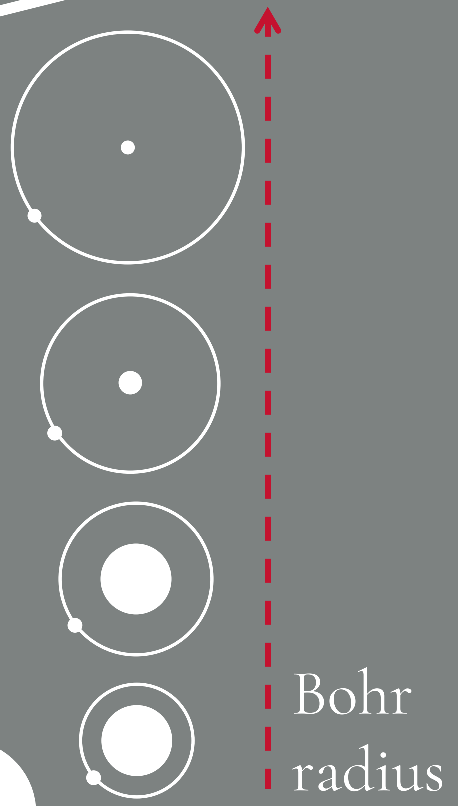
PRECISION SPECTROSCOPY OF (EXOTIC) ATOMS



→ QED tests

→ Charge radius

↓
Fine structure constant
Muon g-2



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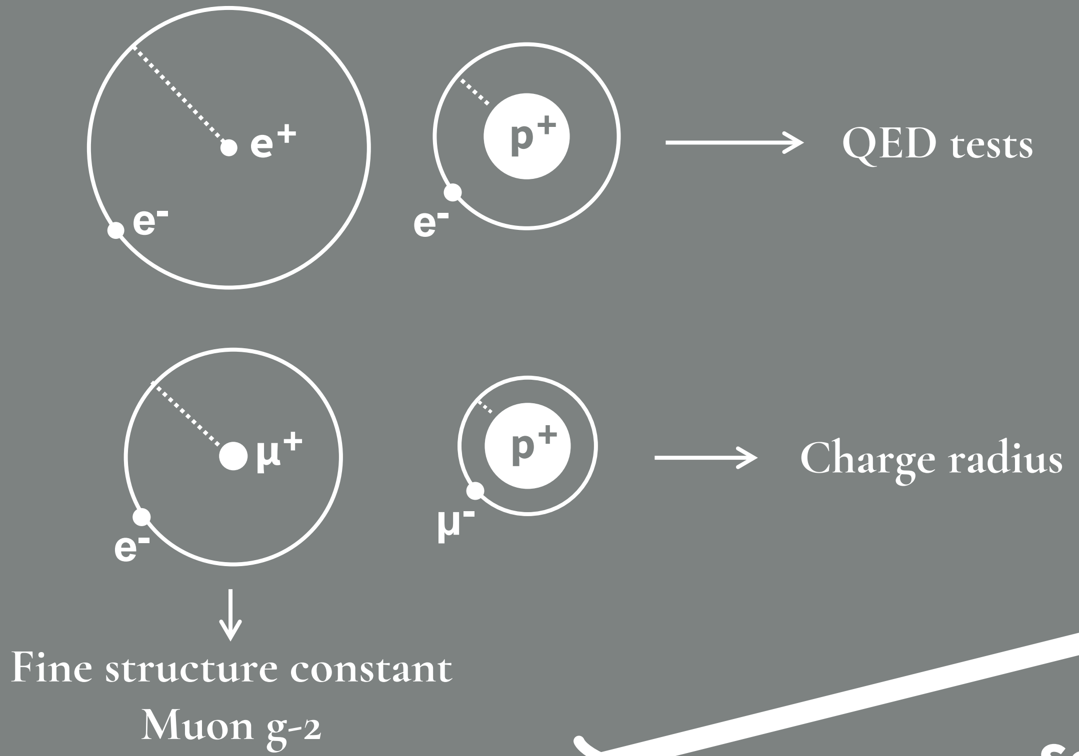
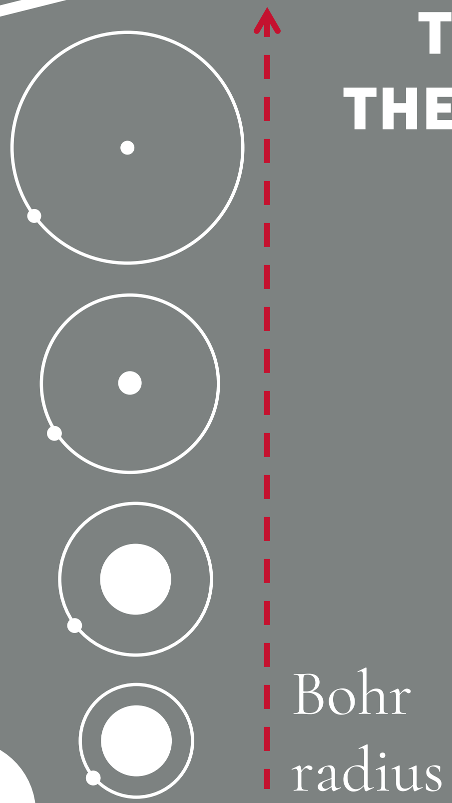
Scale Separation in Exotic Atoms

Precision spectroscopy of (exotic) atoms



Taking advantage of the separation of scales



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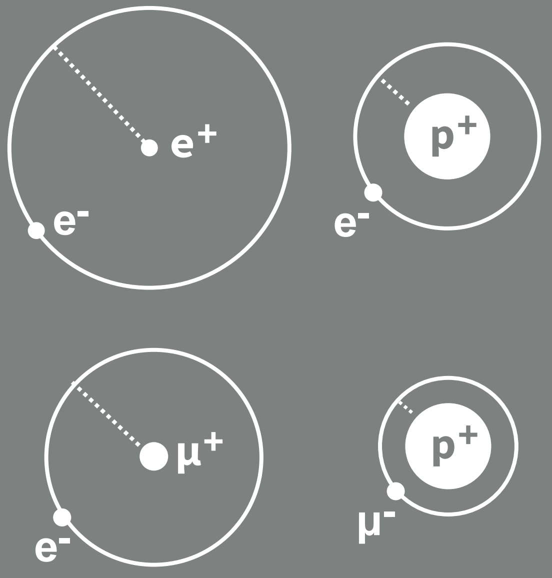
Scale Separation in Exotic Atoms

PRECISION SPECTROSCOPY OF (EXOTIC) ATOMS



→ QED tests

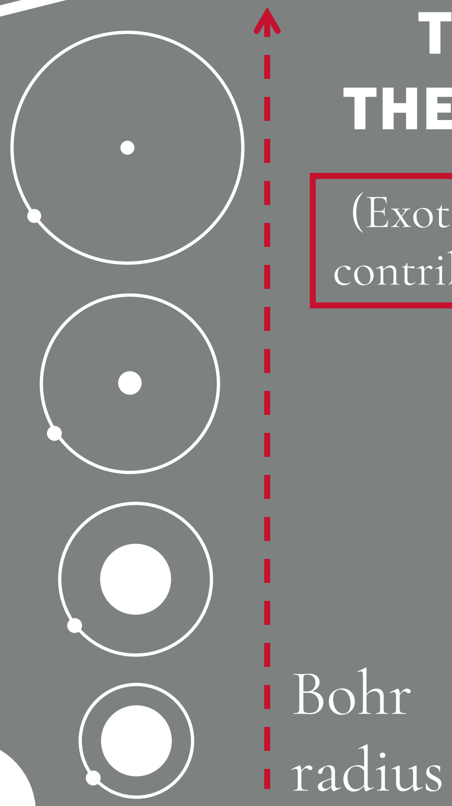
→ Charge radius

↓

Fine structure constant
Muon g-2

TAKING ADVANTAGE OF THE SEPARATION OF SCALES

(Exotic) atoms are sensitive to different soft contributions depending on their Bohr radius



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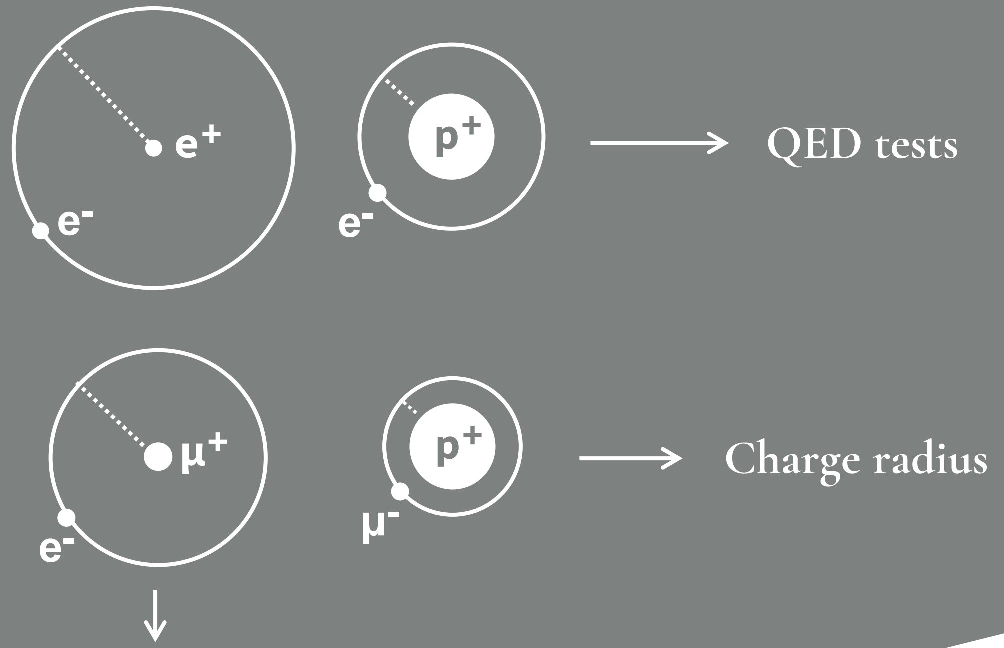

Fine structure constant
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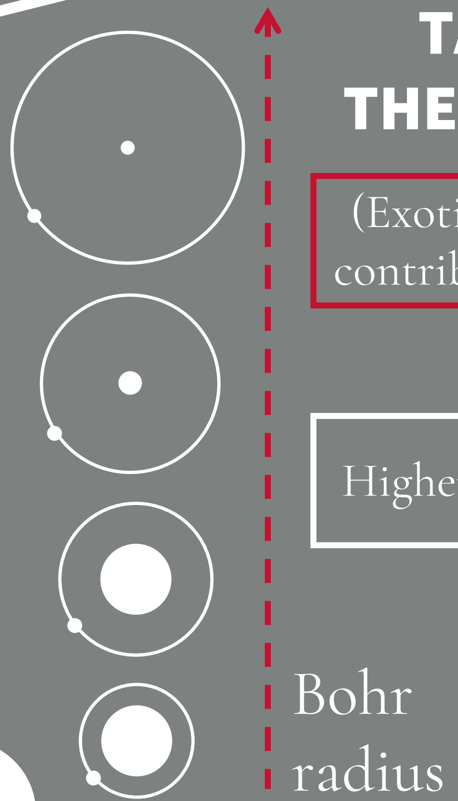

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Higher-order corrections might be enhanced

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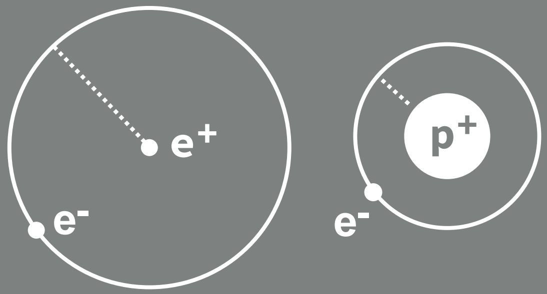
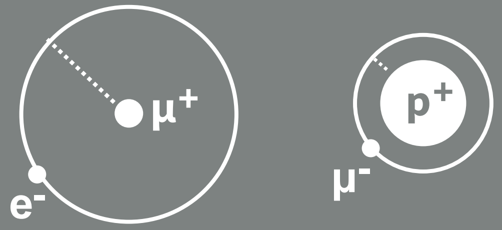


QED tests



Charge radius

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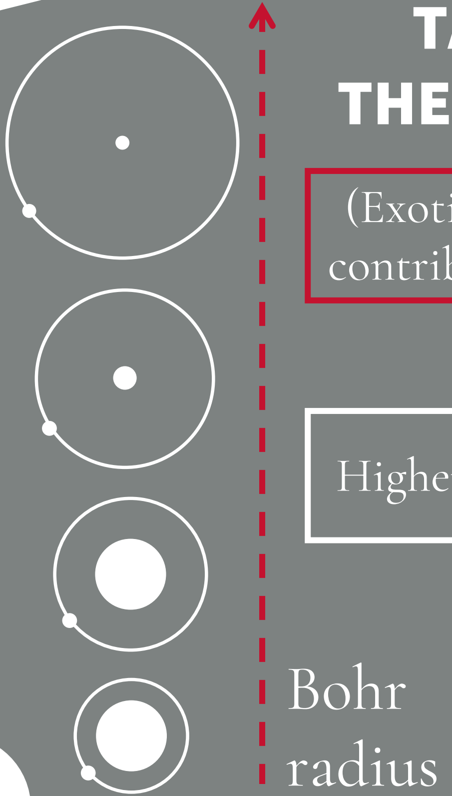
Taking advantage of the separation of scales



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BSM searches are sensitive to the light New Physics mass

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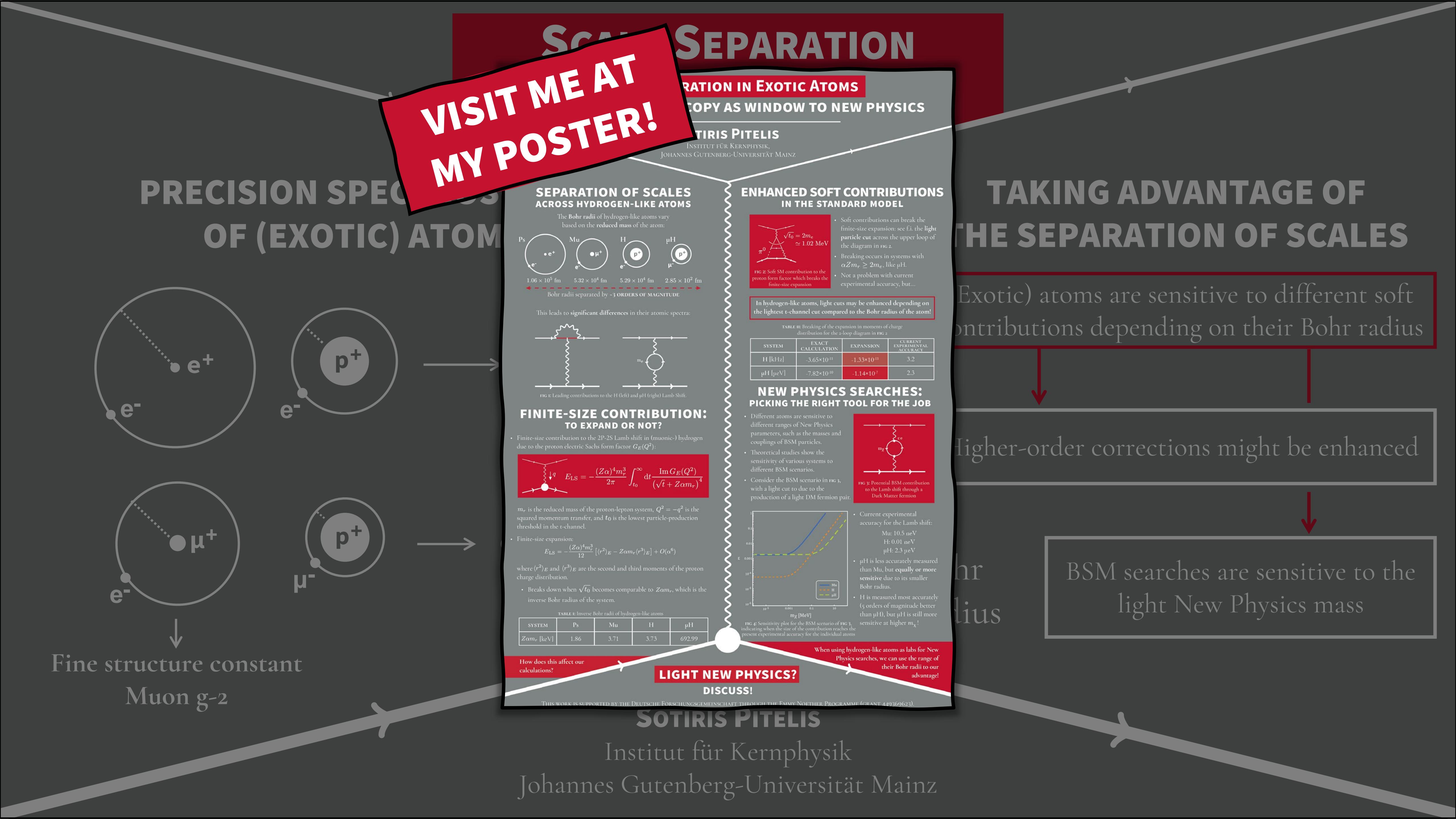

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SEPARATION
PRECISION SPEC
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RATION IN EXOTIC ATOMS
COPY AS WINDOW TO NEW PHYSICS
TIRIS PITELIS
INSTITUT FÜR KERNPHYSIK,
JOHANNES GUTENBERG-UNIVERSITÄT MAINZ
SEPARATION OF SCALES
ACROSS HYDROGEN-LIKE ATOMS
The Bohr radii of hydrogen-like atoms vary based on the reduced mass of the atom:
Ps Mu H μH
1.06×10^5 fm 5.32×10^4 fm 5.29×10^4 fm 2.85×10^2 fm
Bohr radii separated by ~3 ORDERS OF MAGNITUDE
This leads to significant differences in their atomic spectra:
FIG 1: Leading contributions to the H (left) and μH (right) Lamb Shift.
FINITE-SIZE CONTRIBUTION:
TO EXPAND OR NOT?
Finite-size contribution to the 2P-2S Lamb shift in (muonic-) hydrogen due to the proton electric Sachs form factor $G_E(Q^2)$:
$E_{LS} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{t_0}^{\infty} dt \frac{\operatorname{Im} G_E(Q^2)}{(\sqrt{t} + Z\alpha m_r)^4}$
m_r is the reduced mass of the proton-lepton system, $Q^2 = -q^2$ is the squared momentum transfer, and t_0 is the lowest particle-production threshold in the t-channel.
Finite-size expansion:
$E_{LS} = -\frac{(Z\alpha)^4 m_r^3}{12} \left[\langle r^2 \rangle_E - Z\alpha m_r \langle r^3 \rangle_E\right] + O(\alpha^6)$
where $\langle r^2 \rangle_E$ and $\langle r^3 \rangle_E$ are the second and third moments of the proton charge distribution.
Breaks down when $\sqrt{t_0}$ becomes comparable to $Z\alpha m_r$, which is the inverse Bohr radius of the system.
TABLE I: Inverse Bohr radii of hydrogen-like atoms
SYSTEM | Ps | Mu | H | μH
$Z\alpha m_r$ [keV] | 1.86 | 3.71 | 3.73 | 692.99
How does this affect our calculations?
ENHANCED SOFT CONTRIBUTIONS
IN THE STANDARD MODEL
$\sqrt{t_0} = 2m_e \simeq 1.02$ MeV
π^0
FIG 2: Soft SM contribution to the proton form factor which breaks the finite-size expansion
Soft contributions can break the finite-size expansion: see f.i. the light particle cut across the upper loop of the diagram in FIG 2.
Breaking occurs in systems with $\alpha Z m_r \geq 2m_e$, like μH.
Not a problem with current experimental accuracy, but...
In hydrogen-like atoms, light cuts may be enhanced depending on the lightest t-channel cut compared to the Bohr radius of the atom!
TABLE II: Breaking of the expansion in moments of charge distribution for the 2-loop diagram in FIG 2
SYSTEM | EXACT CALCULATION | EXPANSION | CURRENT EXPERIMENTAL ACCURACY
H [kHz] | -3.65×10^{-11} | -1.33×10^{-11} | 3.2
μH [μeV] | -7.82×10^{-10} | -1.14×10^{-7} | 2.3
NEW PHYSICS SEARCHES:
PICKING THE RIGHT TOOL FOR THE JOB
Different atoms are sensitive to different ranges of New Physics parameters, such as the masses and couplings of BSM particles.
Theoretical studies show the sensitivity of various systems to different BSM scenarios.
Consider the BSM scenario in FIG 3, with a light cut to due to the production of a light DM fermion pair.
εe
m_χ
FIG 3: Potential BSM contribution to the Lamb shift through a Dark Matter fermion
ε
m_χ [MeV]
Mu
H
μH
FIG 4: Sensitivity plot for the BSM scenario of FIG 3, indicating when the size of the contribution reaches the present experimental accuracy for the individual atoms
Current experimental accuracy for the Lamb shift:
Mu: 10.5 neV
H: 0.01 neV
μH: 2.3 μeV
μH is less accurately measured than Mu, but equally or more sensitive due to its smaller Bohr radius.
H is measured most accurately (5 orders of magnitude better than μH), but μH is still more sensitive at higher m_χ!
When using hydrogen-like atoms as labs for New Physics searches, we can use the range of their Bohr radii to our advantage!
LIGHT NEW PHYSICS?
DISCUSS!
THIS WORK IS SUPPORTED BY THE DEUTSCHE FORSCHUNGSGEMEINSCHAFT THROUGH THE EMMY NOETHER PROGRAMME (GRANT 449369623).
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Institut für Kernphysik
Johannes Gutenberg-Universität Mainz

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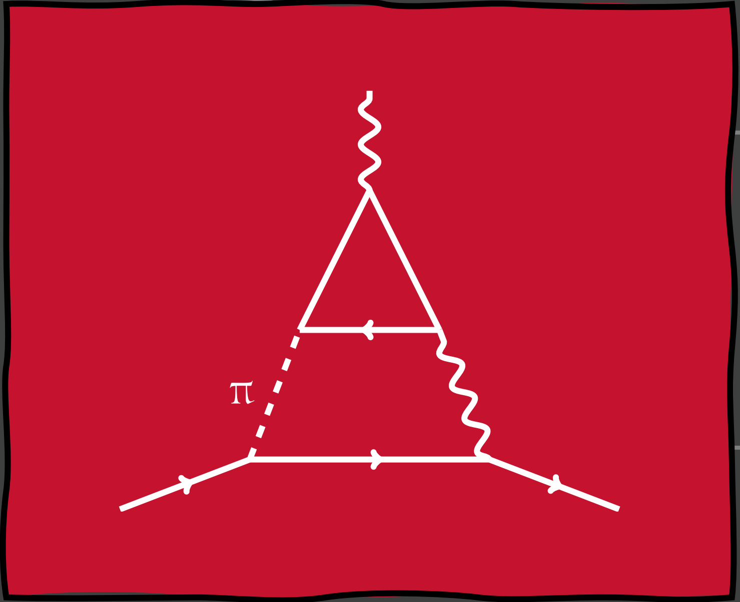
SCALE SEPARATION

PRECISION SPECTROSCOPY OF (EXOTIC) ATOMS



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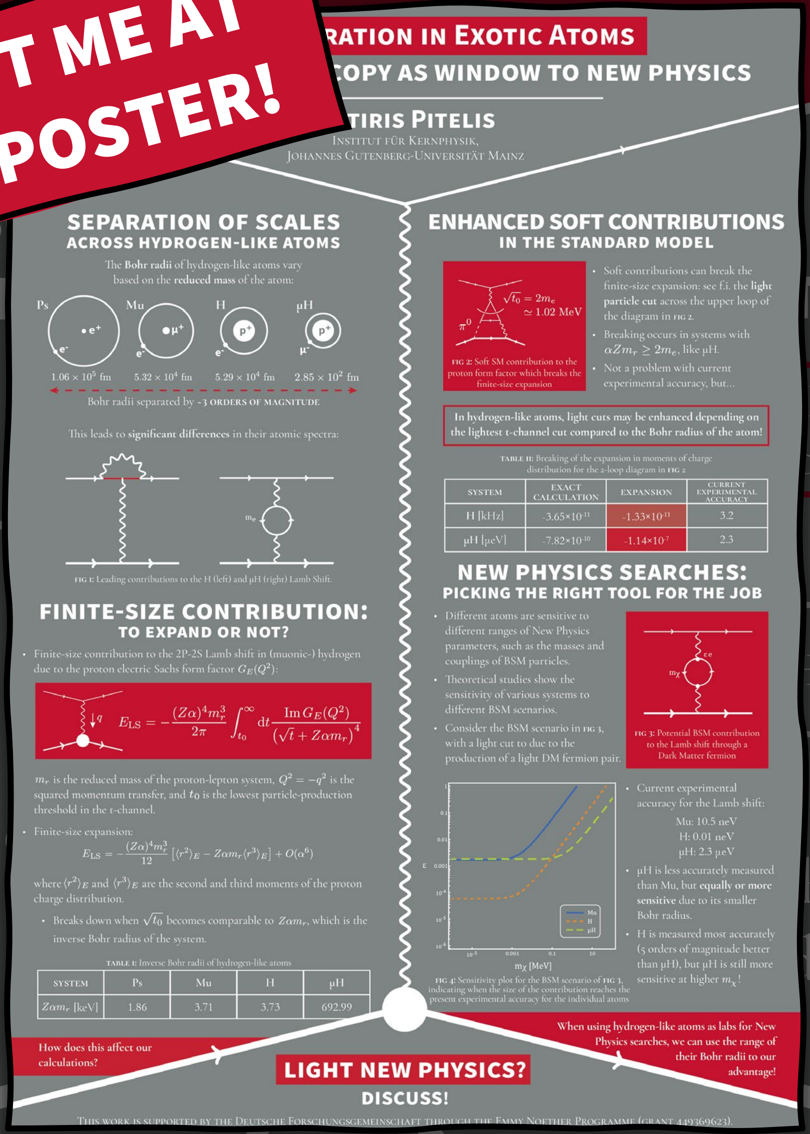

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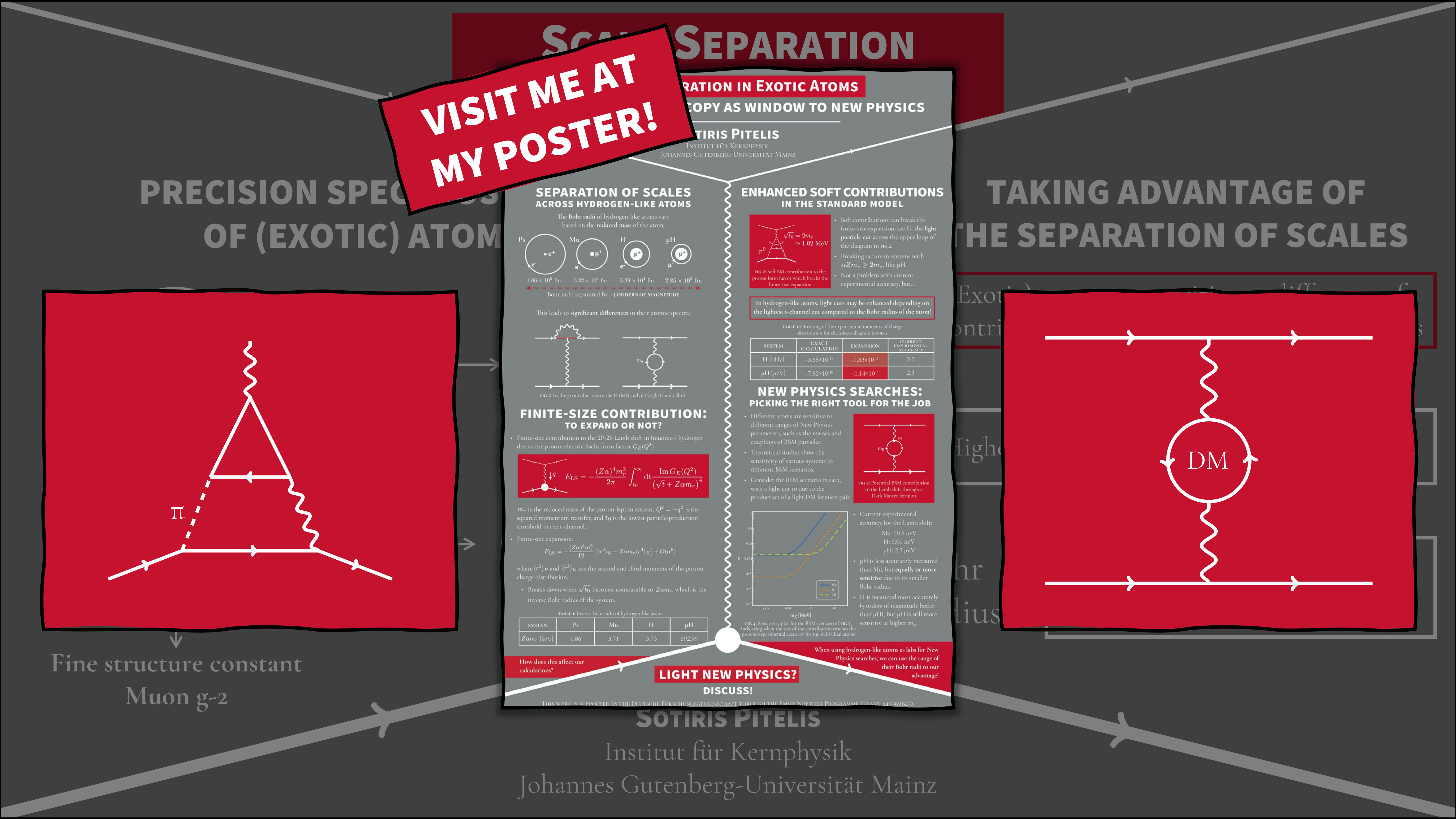
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