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JÜLICH FORSCHUNGSZENTRUM

Symmetries and the Emergence of Structure in QCD

– Introduction to the CRC 110 –

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Deutsche Forschungsgemeinschaft DFG

NSFC National Natural Science Foundation of China

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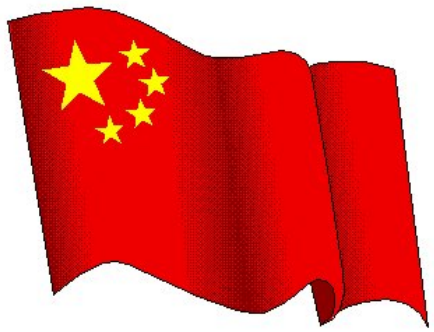
The CRC 110

What is a Colloborative Research Center?

Collaborative Research Centres (CRCs) are institutions established at universities for a period of up to 12 years that enable researchers to pursue an outstanding research programme, crossing the boundaries of disciplines, institutes, departments and faculties. They facilitate scientifically ambitious, complex, long-term research by concentrating and coordinating the resources available at a/up to three university/ties. Universities submitting a proposal are expected to provide appropriate core support. The CRC programme should, thus, contribute towards defining the profiles of participating universities. Gender equality and early career support are additional goals of a Collaborative Research Centre.
Collaborative Research Centres may also incorporate projects at neighbouring universities or non-university research institutions and collaboration with industry and business within the research programme, provided they serve to further the core research area. In addition, CRCs maintain scientific relations with universities and other research institutions outside of Germany. *Co-funding for international CRCs is also possible.*

http://www.dfg.de/en/research_funding/programmes/coordinated_programmes/collaborative_research_centres/index.html

The partners



Institute of High Energy Physics, CAS, Beijing

Peking University

Theoretical Center for Science Facilities, CAS

Rheinische-Friedrich-Wilhelms-Universität Bonn

Technische Universität München

Forschungszentrum Jülich

Rheinische Friedrich-Wilhelms-Universität Bonn

- Comprehensive university
  (Volluniversität)

- 7 faculties, about 30.000 students

- research foci: Mathematics (Cluster of Excellence)
  Physics and Astronomy (Bonn-Cologne Graduate School)
  Life sciences
  Economy

- 3 main research areas in physics:
  Particle & hadron physics, astrophysics, photonics and condensed matter

- physics high-lights:

  Nobel prize physics 1989 Wolfgang Paul

  Electron Stretcher Accelerator ELSA & CRC 16 “Subnuclear Structure of Matter”

  Bethe Center for Theoretical Physics & Bethe Forum (new)

Technische Universität München

- Technical university
  (*Exzellenz-Universität*)
- 13 faculties, about 26.000 students
- research foci: Mathematics & Informatics
  Physics
  Chemistry & Life Sciences
  Engineering
- 3 main research areas in physics:
  Nuclear, particle & astrophysics, condensed matter physics, biophysics
- Munich physics high-lights:

  Nobel prize physics 1961 R. Mößbauer (TUM), 1985 Klaus von Klitzing (TUM)

  Cluster of excellence "Origin and Structure of the Universe"

  Institute for Advanced Studies (TUM-IAS) and Leibniz Supercomputing Center

Forschungszentrum Jülich

- Large interdisciplenary research center
- 11 institutes, about 4500 employes
- research foci: Information technologies
  Energy and environment
  Health
- main research areas in physics:
  Hadron & nuclear physics, condensed matter physics, computational physics
- physics high-lights:

  Nobel prize physics 2007 Peter Grünberg

  Cooler Synchrotron COSY
  & construction of the HESR at FAIR

  Jülich Supercomputing Center

Institute of High-Energy Physics (IHEP)

- **Top institution in China for high-energy and hadron physics**

- hosts 3 big international experimental facilities

  → BEPC2 w/ BESIII collaboration
  → Daya Bay neutrino experiment
  → Tibet cosmic ray observatory

- 7 research divisions with about 750 researchers

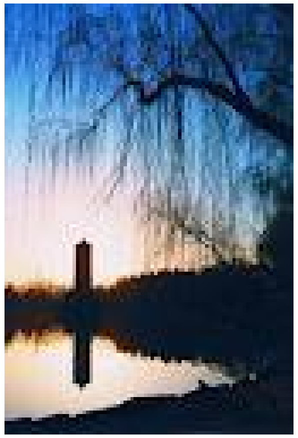
  Accelerator Center, Experimental Physics Center, Theory Division, Particle-Astroparticle Center, Computing Center, Technology R&D Center, Multi-disciplinary Center

- Host of the **Theoretical Center for Science Facilities**

  → improve the theory support of the chinese facilities

Peking University

- **Top comprehensive university in China**
  ranks 17th on the list of top universities



- 18 disciplines of PKU rank in the world top 1%
  $\rightarrow$ Mathematics, Physics, Chemistry, Materials Science, . . .

- 39 schools & departments, $\sim$30000 students

- School of Physics: 200 faculty and staff, $\sim$1400 students
  Inst. of Theoretical Physics (ITP),
  Inst. of Condensed Matter & Material Physics,
  Inst. of Heavy Ion Physics, . . .,
  + Dept. of Astronomy, . . .

- **NSFC fund for Innovative Research Groups**
  on Hadron Physics $\rightarrow$ ITP@PKU

Why this collaboration?

- Very challenging endeavour, requires complementary and overlapping expertise

$\Rightarrow$ this is available at the various institutions forming this CRC

- Large investment in facilities requires concentrated theory effort

$\Rightarrow$ strong focus on data from BEPC-II (now) and FAIR (future)

- Improving the bilateral scientific relations

$\Rightarrow$ best use of the science brain pool in both countries

- Builds on earlier and on-going collaborations by some of the PIs

$\Rightarrow$ [Brambilla, Vairo, Jia], [Guo, Hanhart, Meißner, Zhao], [Hanhart, Guo, Zou] [Kaiser, Meißner, Weise], [Rusetsky, Weise], [Dreiner, Hanhart], . . .

$\Rightarrow$ Potential for a long-term synergy and innovation very much desired by the partners

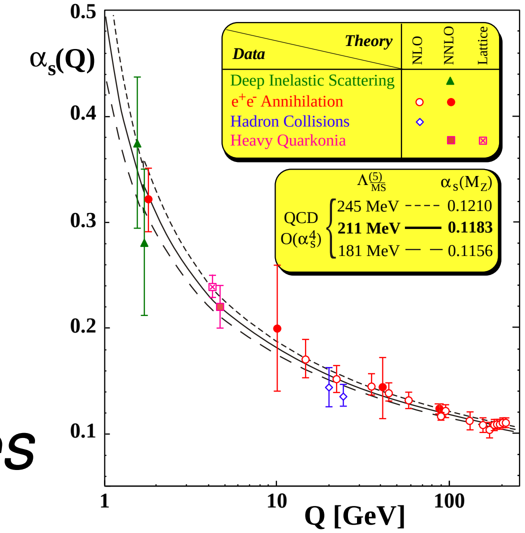
Principal Investigators (PIs)

- Principal investigators:

IHEP	Prof. Y. Chen, Prof. Y. Dong, Prof. M. Huang, Prof. Y. Jia, Prof. J.-X. Wang, Prof. P. Wang, Prof. Q. Zhao, Prof. B.-S. Zou [$\rightarrow$ ITP/CAS]
PKU	Prof. C. Liu, Prof. S.-L. Zhu
UB	Prof. H. Dreiner, Dr. F.-K. Guo, Prof. H.-W. Hammer, Prof. B. Kubis, Prof. U.-G. Meißner, PD A. Rusetsky, Prof. C. Urbach
FZJ	PD J. Haidenbauer, Prof. C. Hanhart, [Prof. U.-G. Meißner], Dr. A. Nogga, Prof. T. Luu [from 09/2013]
TUM	Prof. N. Brambilla, Prof. N. Kaiser, PD A. Vairo, Prof. W. Weise

Topics in Strong QCD

Facets of Quantum Chromodynamics



- perturbative QCD: quarks, gluons, . . .
- strong QCD: hadrons, nuclei, . . .
- a plethora of *structures* and *(broken) symmetries*

- Aspects of QCD in the **CRC 110**:
  - decays and interactions of hadrons (esp. charm sector)
  - how QCD generates structures: hadrons, nuclei, . . .
  - precision calculations to test physics beyond the SM

$\longrightarrow$ *interplay of lattice QCD, EFTs and models*

Role of CRC 110

- Two loose ends of the Standard Model:
  - the Higgs boson (EW symmetry breaking) [$\rightarrow$ just seen in 2012 at the LHC]
  - structure and dynamics of strong QCD

Unique contribution of CRC 110 to strong QCD:

Investigation of how QCD generates structures:
hadrons, nuclei, . . . and how symmetries
influence their structure and dynamics
based on a large international collaboration

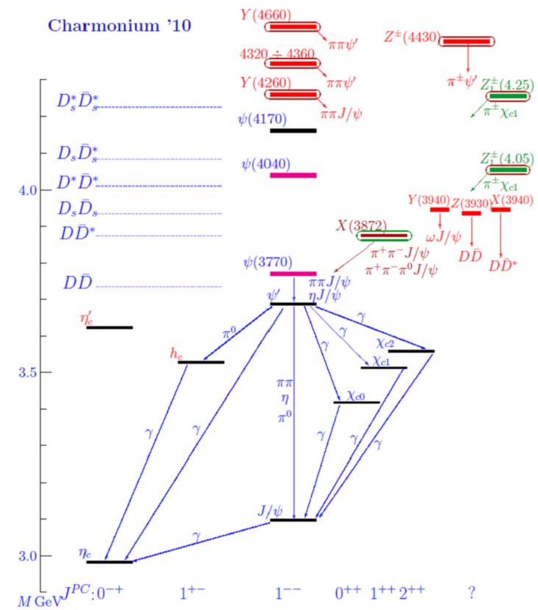
- For the first time, such a unified approach is attempted

FACETS of STRONG QCD

- quarks and gluons form hadrons

  $\Rightarrow$ **lattice QCD + EFT + models**

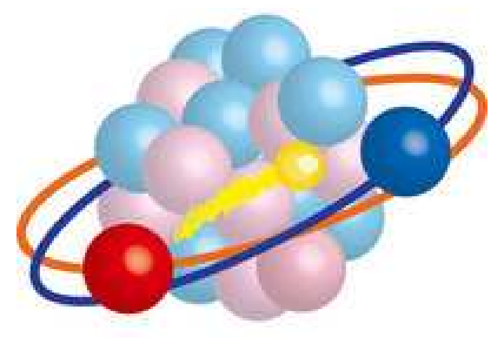
  $\Rightarrow$ exploring the strong color force



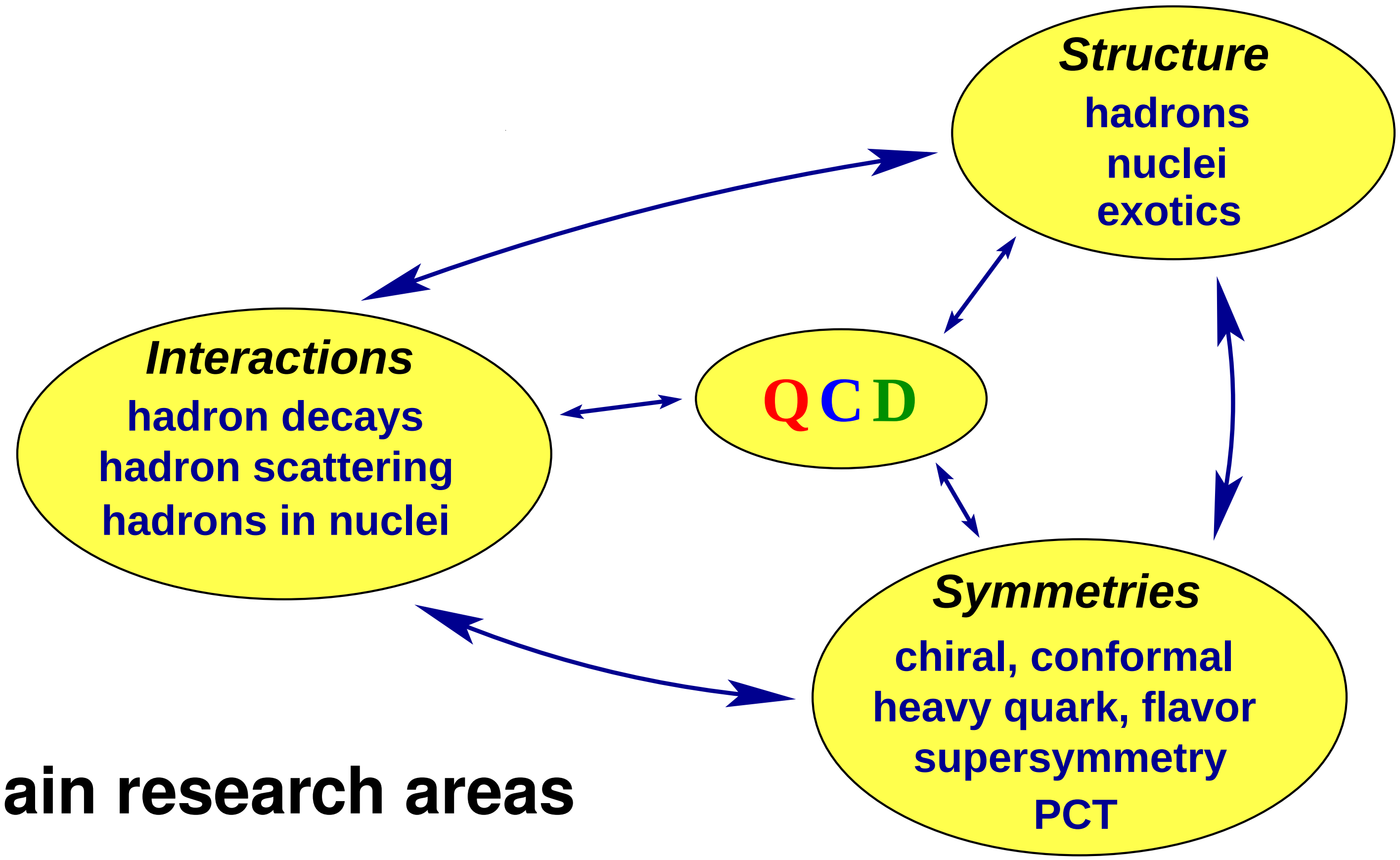
- nucleons and mesons form nuclei

  $\Rightarrow$ **nuclear physics (EFT, lattice, ...)**

  $\Rightarrow$ exploring the residual color force



QCD research in CRC 110



- **CRC 110: two main research areas**

  A – symmetries

  B – emergence of structure

- **strongly intertwined**

Project areas

- Project area A: **Symmetries**

A.1	Flavor symmetries and FSI in heavy hadron decays	Haidenbauer, Kubis, Zou
A.2	Hadron-hadron scattering in QCD	Liu, Urbach
A.3	Universality and EFT for threshold states	Brambilla, Hammer, Jia
A.4	Hadronic parity violation	Kaiser, Zhu
A.5	Quark mass dependence of heavy-light systems	Guo, Meißner, P. Wang

- Project area B: **Emergence of Structure**

B.1	Nucleon form factors	Dong, Hammer
B.2	Hadron spectroscopy	Huang, Zhu, Zou
B.3	Hadronic molecules with heavy meson loops	Hanhart, Guo, Zhao
B.4	Boxed exotica	Liu, Rusetsky
B.5	Exotic states from lattice QCD	Chen, Urbach
B.6	Hadronic systems with strange quarks	Rusetsky, Weise
B.7	Chiral dynamics of nuclei & hypernuclei	Meißner, Nogga, Kaiser
B.8	Quarkonium interactions in hadronic, nuclear and thermal matter	Jia, Vairo, J. Wang

$\Rightarrow$ 10 of 13 projects have chinese & german project leaders!

Scientific goals

- Symmetry tests in hadrons and nuclei & precision calculations

A.1,A.2,A.3,A.4,B.3,B.6

- Structure and dynamics of (heavy) hadrons

A.1,A.2,A.3,A.5,B.1,B.2,B.3,B.4,B.5,B.6

- QCD-based structure of nuclei, hypernuclei and nuclear matter

A.2,A.4,B.6,B.7,B.8

- *note: many further cross-links by use of common (non-perturbative) methods*

First steps & outlook

Making the CRC work

- Prerequisites: work towards a common aim, first step achieved

  $\hookrightarrow$ CRC 110 officially started July 1$^{\rm st}$, 2012

- Measures within the CRC for the next four years:

  ⋆ Annual CRC workshop alternating between the sites
  [first meeting organized at KITPC Beijing, July 2-6, 2012]

  ⋆ Bi-annual CRC lecture week or summer school

  ⋆ CRC focus workshops: recent developments/smaller groups
  [first meeting on Strangeness and Nuclear Physics, TUM, Oct. 2012]
  [second: Workshop on Threshold Phenomena; Beijing, April 27-28, 2013]
  [next: Workshop on Lattice QCD, Bonn, July 23-24, 2013]

  ⋆ Video-based exchanges using skype/EVO

  ⋆ Joint graduate (Ph.D.) students (one chinese and one german supervisor)

Excellent opportunities and perfect time
for Chinese-German STRONG-QCD-CRC

Outreach

- Special project on outreach - multiple activities
- Education of high-school students

  and high-school teachers

→ first program this year

→ topics include:

  Forces in nature
  Building blocks of matter
  Computer simulations
  Particle and hadron physics
  Nuclei, elements and stars
  Structures in the Universe

- Physik-Show

  http://physikshow.uni-bonn.de

Wish-list

- Making the first funding period a success

  $\hookrightarrow$ aim for over-achievement in all projects (lattice most difficult)

- Make better use of the infrastructures (HPC)

  $\hookrightarrow$ first step: CAS-HGF cooperation

  $\hookrightarrow$ next step: extend CAS-HGF cooperation to the CRC 110

- Set-up a common graduate program between CAS, PKU and german partners

  $\hookrightarrow$ first steps: meetings at CAS, PKU in September $\boxed{\rightarrow \text{signed MoUs}}$

- Include more colleagues from PKU (and also IHEP and ITP)

  $\hookrightarrow$ broaden the base to include chinese nuclear physicists!

- Include more partners? [second/third funding period]

  $\hookrightarrow$ must be strong / 3 university limit in Germany

First step: common graduate education

- research phase of the PhD (3 years)
- students have two supervisors
- students spend time at the home & the host institution
- MSc courses mutually accepted

Sept. 17, 2012

- similar MoU with the ITP of the CAS

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Rheinische Friedrich-Wilhelms-Universität Bonn

北京大學 PEKING UNIVERSITY

Memorandum of Understanding

between

**The Faculty of Mathematics and Natural Sciences,
University of Bonn, Bonn, Germany**

and

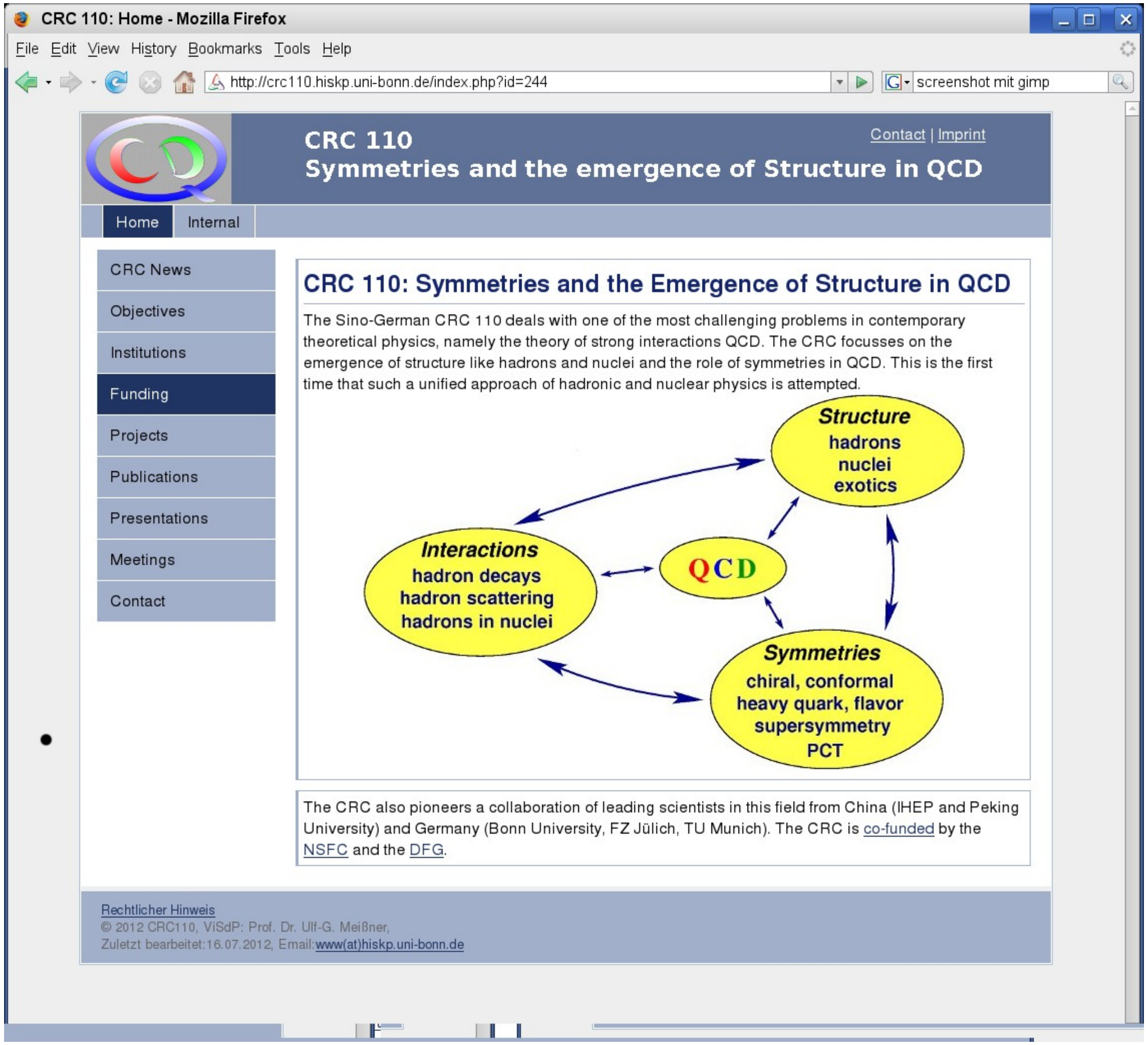
**The School of Physics,
Peking University, Beijing, China**

regarding a

Common Ph.D. program in Physics

Much more info

http://crc110.hiskp.uni-bonn.de



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Thank you for your attention !

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

北京大學 PEKING UNIVERSITY

TPCSF CAS

SPARES

Ex. 1: Isospin violation & light quark masses

ISOSPIN VIOLATION in the STANDARD MODEL

- Isospin violation has two sources (QCD + QED):

$$\mathcal{H}_{\rm QCD}(x) = \frac{1}{2}(m_d - m_u)(\bar{d}d - \bar{u}u)(x)$$

$$\mathcal{H}_{\rm QED}(x) = -\frac{1}{2}e^2 \int dy\, D^{\mu\nu}(x-y) T(j_\mu(x) j_\nu(y))$$

⇒ *unique window to quark masses for light quark and heavy-light quark systems*

- Both effects usually small *and* of the same size (e.g. $m_p - m_n$)

⇒ systematic machinery must cope with both these accurately

- Chiral perturbation theory w/ virtual photons is the tool to analyse the strictures of the spontaneously and explicitly broken chiral symmetry of **QCD**

- Lattice QCD: strong splittings, EM still not solved (first steps)

GENERAL REMARKS

- Can be probed in a phletora of Goldstone-boson N-point functions

$\Rightarrow$ requires high-precision calcs (e.g. GB masses) Gasser, Leutwyler, ...

- Isospin violation is enhanced in system with nucleons and (neutral) pions

Weinberg 1977

$$a(\pi^0 p) - a(\pi^0 n) = \frac{m_p c_5 B(m_d - m_u)}{\pi(m_p + M_\pi)F_\pi^2} = (-2.3 \pm 0.4) \cdot 10^{-3}/M_\pi$$

$\rightarrow$ precision data from hadronic atoms and threshold pion photoproduction

- further suppression in some processes involving two or more nucleons (CSB)

$\rightarrow$ pioneering data on $\boldsymbol{A_{fb}(np \rightarrow d\pi^0)}$ [TRIUMF] and $\boldsymbol{\sigma(dd \rightarrow \alpha\pi^0)}$ [IUCF]

- systems with **heavy** quarks can give additional information on $m_u - m_d$ through decays and mass differences

THE PUZZLE of m_u/m_d EXTRACTIONS

- Extract m_u/m_d from $\psi' \to J/\psi\pi^0(\eta)$

Ioffe, Shifman, 1980; Donoghue et al., 1982

$$R_{\pi^0/\eta} = \frac{\mathcal{B}(\psi' \to J/\psi\pi^0)}{\mathcal{B}(\psi' \to J/\psi\eta)} = 3\left(\frac{m_d - m_u}{m_d + m_u}\right)^2 \frac{F_\pi^2}{F_\eta^2}\frac{M_\pi^4}{M_\eta^4}\left|\frac{\vec{q}_\pi}{\vec{q}_\eta}\right|^3 (1+\Delta)$$

$\Rightarrow$ using CLEO data (2008): $\dfrac{m_u}{m_d} = 0.40 \pm 0.01$

- Extraction from the Goldstone bosons mass ratios:

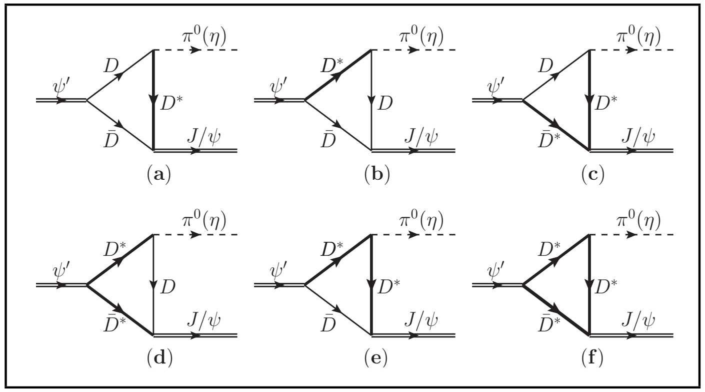
Weinberg, 1977; Gasser and Leutwyler, 1982; Leutwyler, 1996

$$\frac{m_u}{m_d} = \frac{M_{K^+}^2 - M_{K^0}^2 + 2M_{\pi^0}^2 - M_{\pi^+}^2}{M_{K^0}^2 - M_{K^+}^2 + M_{\pi^+}^2}(1 + \Delta^{\rm str} + \Delta^{\rm em}) = 0.553 \pm 0.043$$

$\Longrightarrow$ serious discrepancy

INCLUSION of CHARMED MESON LOOPS

Guo, Hanhart, UGM, Phys. Rev. Lett. **103** (2009) 082003



- consider intermediate charmed mesons
- HQEFT (velocity) expansion:

$$v \sim \sqrt{(2M_{\hat{D}} - M_{\hat{\psi}})/M_{\hat{D}}} \simeq 0.5$$

- direct versus charmed meson loop contribution:

$$\mathcal{M}(\psi' \to J/\psi\pi^0)_{\rm direct} \sim (m_d - m_u)\,|\vec{q}_\pi|$$

$$\mathcal{M}(\psi' \to J/\psi\pi^0)_{\rm D-loops} \sim (m_d - m_u)\frac{|\vec{q}_\pi|}{v} \quad \Leftarrow \text{ enhancement}$$

- charmed meson loop saturation: $R_{\pi^0/\eta} = 0.11 \pm 0.06$

$$R^{\rm exp}_{\pi^0/\eta} = 0.0388 \pm 0.023 \pm 0.005$$

$\Longrightarrow$ need an NLO calculation to see how accurately m_u/m_d can be extracted from these decays

BETTER NEWS: BOTTOMONIUM TRANSITIONS

Guo, Hanhart, UGM, Phys. Rev. Lett. **105** (2010) 162001

- Consider bottomonium transitions: $\Upsilon(4S) \to h_b \pi^0(\eta)$
- Loops are suppressed for two reasons:

$\star\ \vec{q}^{\,2}/(v^3 M_B^2) \simeq 0.6\ (0.2)$

$\star\ M_{B^0} - M_{B^+} = 0.33 \pm 0.06$ MeV $\ll m_d - m_u$

due to strong & em interference

Guo, Hanhart, UGM, JHEP **0809** (2008) 136

$\Rightarrow r = \dfrac{m_d - m_u}{m_d + m_u} \dfrac{m_s + \hat{m}}{m_s - \hat{m}}$ can be extracted with an accuracy of about 23 %

- by-product: $\Upsilon(4S) \to h_b \eta$ is a nice channel to search for the h_b (sizeable bf $\sim 10^{-3}$)

$\Rightarrow$ possible to measure at LHCb

FORWARD-BACKWARD ASYMMETRY in $np \to d\pi^0$

- CSB fb-asymmetry in $np \to d\pi^0$ @ 279.5 MeV measured at TRIUMF

Opper et al., 2003

$$A_{fb} = \frac{\int_0^{\pi/2}[\frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta)]d\cos\theta}{\int_0^{\pi/2}[\frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi-\theta)]d\cos\theta} = (17.2 \pm 8(\mathrm{stat}) \pm 5.5(\mathrm{sys})) \cdot 10^{-4}$$

- Goal: use the measured fb-asymmetry to extract the (strong) proton-neutron mass difference $\delta m_N \equiv m_n - m_p$

- best determination: use the Cottingham sum rule

Gasser, Leutwyler, 1982

$$\delta m_N^{\mathrm{str}} = 2.05 \pm 0.30\ \mathrm{MeV}$$
$$\delta m_N^{\mathrm{em}} = -0.76 \mp 0.30\ \mathrm{MeV}$$

- pioneering calculations for A_{fb}:

Niskanen 1999, van Kolck et al., 2000

THEORY of A_{fb} in $np \to d\pi^0$

- CSB fb-asymmetry through interference of IC and IV amplitudes:

$$\frac{d\sigma}{d\Omega} = A_0 + A_1 P_1(\cos\theta_\pi) + A_2 P_2(\cos\theta_\pi) + \ldots \Longrightarrow \boxed{A_{fb} \simeq \frac{A_1}{2A_0}}$$

- A_0 can be determined from pionic deuterium lifetime measured at PSI:

$$\sigma(np \to d\pi^0) = \tfrac{1}{2}\sigma(nn \to d\pi^-) = 252^{+5}_{-11}\,\eta\,[\mu\mathrm{b}] \to A_0 = 10.0^{+0.2}_{-0.4}\,\eta\,[\mu\mathrm{b}]$$

Hauser et al., 1998

- A_1 at LO in chiral EFT:

$$A_1 = \frac{1}{128\pi^2}\frac{\eta M_\pi}{p(M_\pi+m_d)^2}\mathrm{Re}\left[\underbrace{\left(M_{^1S_0\to{}^3S_{1,p}} + \frac{2}{3}M_{^1D_2\to{}^3S_{1,p}}\right)}_{\text{IC amplitude calculated at NLO}} M^*_{^1P_1\to{}^3S_{1,p}}\right]$$

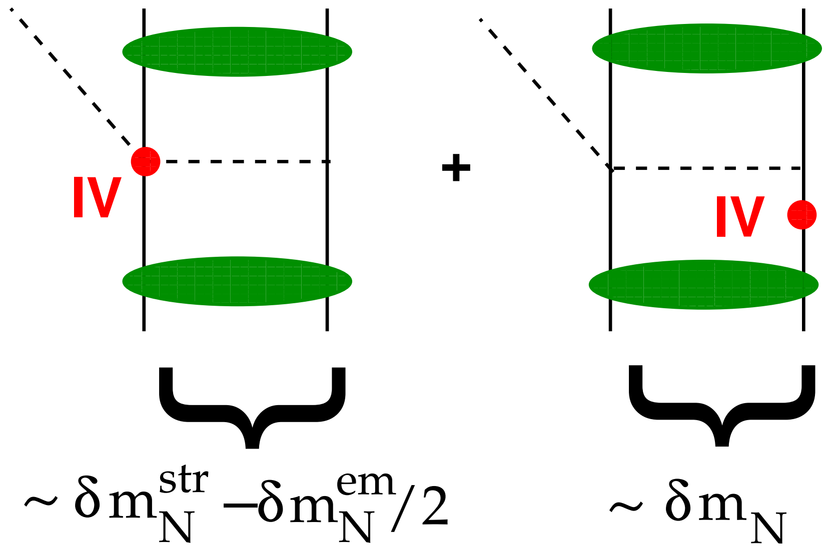
Hanhart et al., 2000

Baru et al., 2009

EXTRACTION of δm_N from $A_{fb}(np \to d\pi^0)$

- Both diagrams combine so that

  only $\delta m_N^{\rm str}$ survives



- so that we obtain

$$A_{fb}^{\rm LO} = (11.5 \pm 3.5) \cdot 10^{-4}\, \frac{\delta m_N^{\rm str}}{\rm MeV}$$

$$\Longrightarrow \quad \boxed{\delta m_N^{\rm str} = 1.5 \pm 0.8\,({\rm exp}) \pm 0.5\,({\rm th})\ \ {\rm MeV}}$$

– uncertainty of the expected size

– nice consistency with the earlier determination of $\delta m_N^{\rm str}$ & lattice

– crucial ingredient: A_0 from the precision PSI experiment

– can be improved systematically

Ex. 2: Hadronic molecules

What are HADRONIC MOLECULES ?

- Bound states of two hadrons in an S-wave just below a 2-particle threshold or between two close-by thresholds ⇒ particular decay patterns

- weak binding entails a large spatial extension

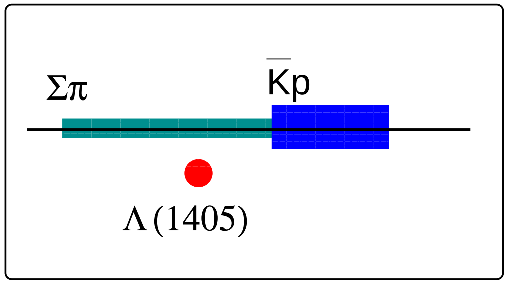
- classical examples:

⋆ the deuteron $m_p + m_n = 938.27 + 939.57$ MeV, $\varepsilon = 2.22$ MeV

⋆ the $\Lambda(1405)$ Dalitz et al., (1960)

$m_\Sigma + m_\pi = 1189.37 + 139.57 = 1328.94\,\text{MeV}$

$m_p + m_{\bar K} = 938.27 + 493.68 = 1431.96\,\text{MeV}$



⋆ the scalar mesons $f_0(980), \ldots$

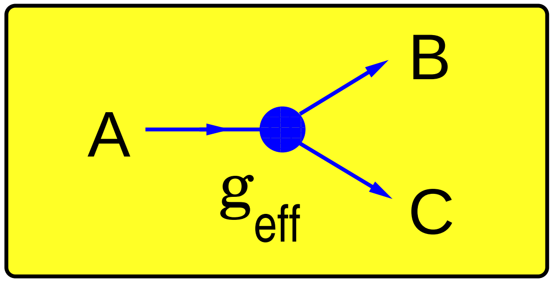
$m_K + m_{\bar K} = 2 \times 493.68 = 987.35\,\text{MeV},\ m(f_0) = 976.8$ MeV [KLOE 2007]

⇒ how to distinguish these from compact multi-quark states ?

COMPOSITENESS CRITERION

Weinberg (1963), . . ., Baru et al. (2003), . . .

- Consider S-wave decay $A \to BC$
  with a coupling constant g_{eff}
  and $m_A = m_B + m_C - \varepsilon$



$$\Rightarrow \quad \frac{g_{\text{eff}}^2}{4\pi} = 4(m_B + m_C)^{5/2}\,\lambda^2 \sqrt{\frac{2\varepsilon}{m_B m_C}}$$

$$\leq \quad 4(m_B + m_C)^{5/2} \sqrt{\frac{2\varepsilon}{m_B m_C}}$$

- λ^2 = probability to find the hadron pair in the physical state $|A\rangle$

$\Rightarrow$ the effective coupling g_{eff} encodes the **structure information** and can be extracted **model-independently** from experiment

PROPERTIES of the Y(4660)

- close to the $f_0\psi'$ threshold: Belle (2007)

$$m(Y(4660)) = 4664 \pm 11 \pm 5\,\text{MeV}, \quad m(f_0) + m(\psi') = 4666 \pm 10\,\text{MeV}$$

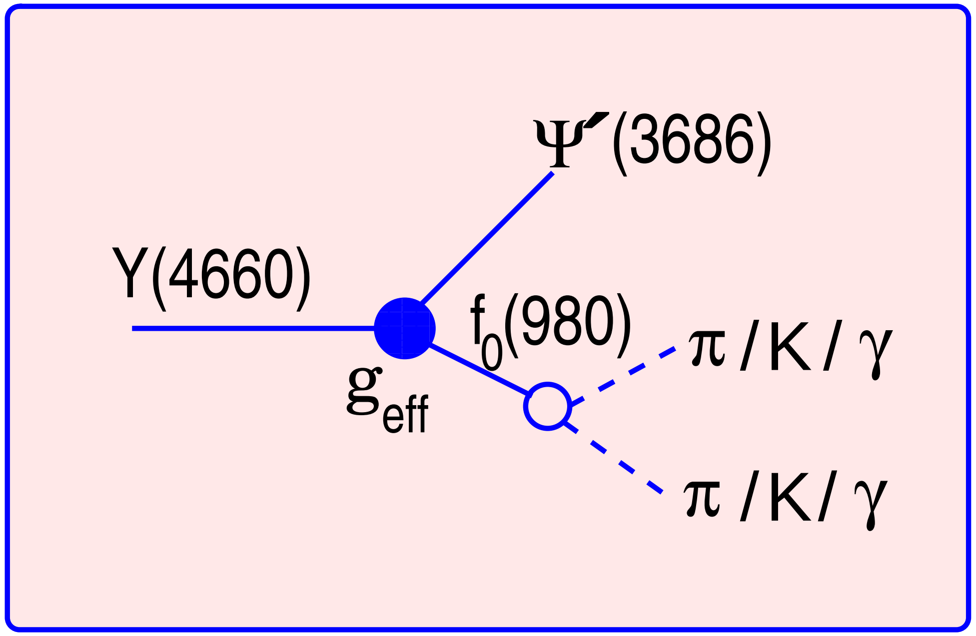
- seen only in $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi' \to J^{PC} = 1^{--}$
- $\pi^+\pi^-$ mass distribution strongly peaked around $m(f_0)$
- not seen in $e^+e^- \to \bar{D}^{(*)}D^{(*)}$ and $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$
- fit to the mass distr. $M(\psi'\pi\pi)$

  with two parameters:

  mass of the Y

  normalization

  note: $\lambda^2 = 1$



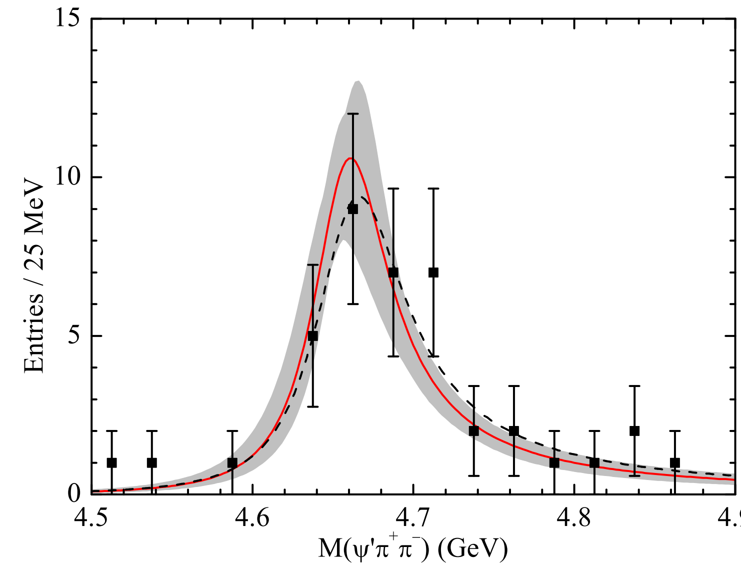
FITS and PREDICTIONS

Guo, Hanhart, UGM, Phys.Lett. B **665** (2008) 26

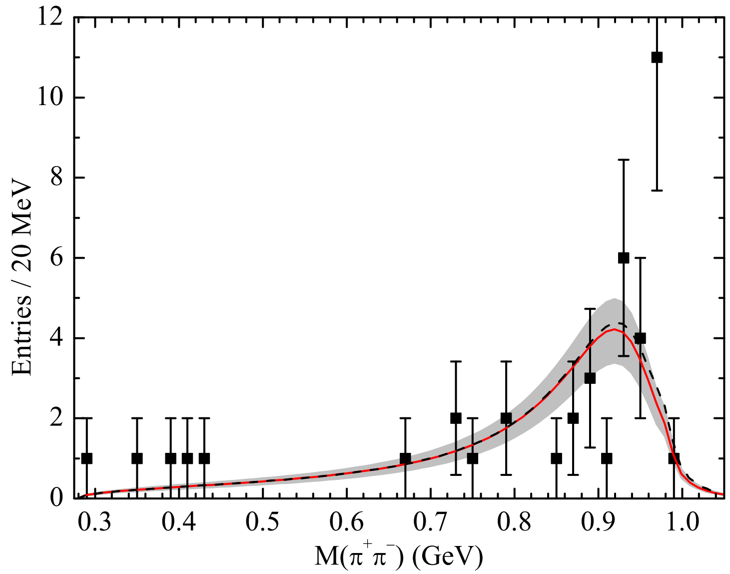
- fit to $M(\psi'\pi^+\pi^-)$: [Belle (2007)]

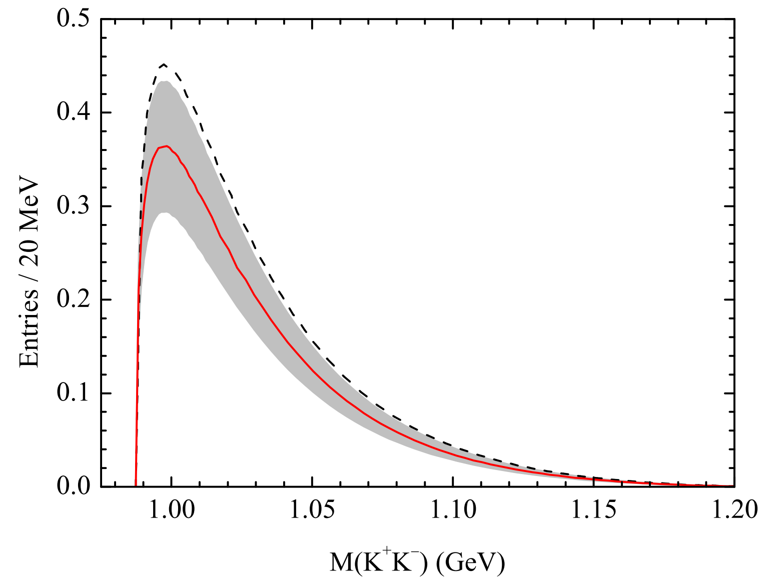
$$m_Y = (4665^{+3}_{-5})\ \text{MeV}$$

$$\rightarrow g_{\rm eff} = 11 \ldots 14\,\text{GeV}$$



- predictions for $\pi^+\pi^-$ and K^+K^- inv. mass distributions





TWO- versus THREE-BODY NATURE of the Y(4660)

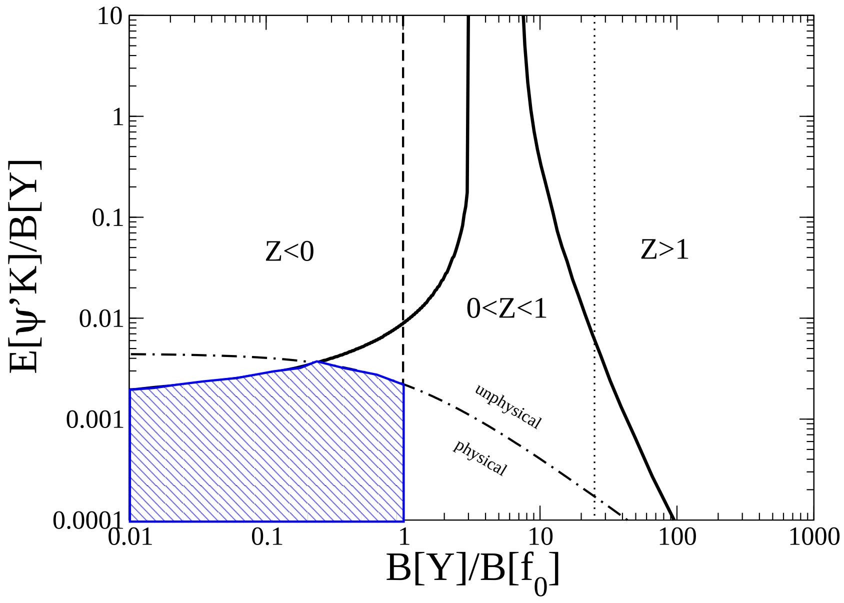
P. Hagen, H.-W. Hammer, C. Hanhart, Phys. Lett. B **696** (2011) 103

- investigate the role of the substructure of the $f_0(980)$

- relevant scales: $Y(4660)$ binding energy
  $f_0(980)$ binding energy
  $\psi' - K$ scattering length

- including compositeness criterion

$\Rightarrow$ determines parameter space, where
the two-particle b.s. picture applies



The SPIN PARTNER of the Y(4660)

Guo, Hanhart, UGM, Phys. Rev. Lett. **102** (2009) 242004

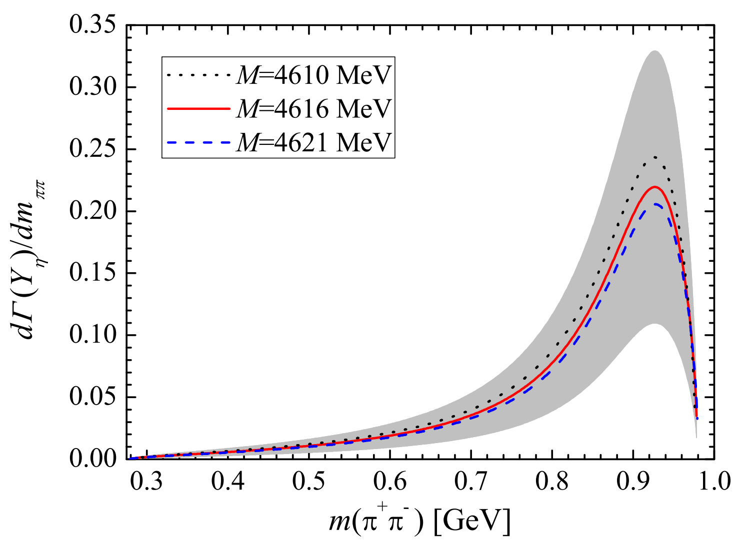
- all spin-dependent forces suppressed by powers of $1/m_Q$:

$\Rightarrow$ a spin partner of the $Y(4660)$, the $Y_\eta = |f_0\eta_c'\rangle$, with $J^P = 0^-$, must exist

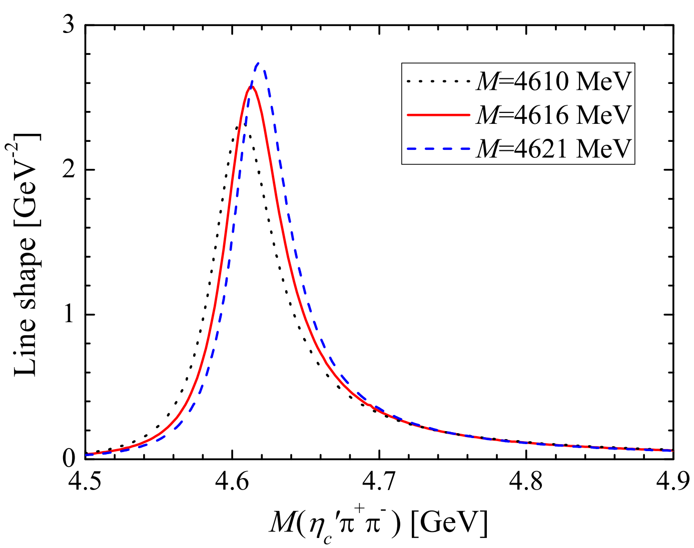
$$m(Y_\eta) = m(Y) + m(\eta_c') - m(\psi') = 4616^{+5}_{-6}\ \text{MeV}$$

- predictions

invariant mass spectrum



lineshape



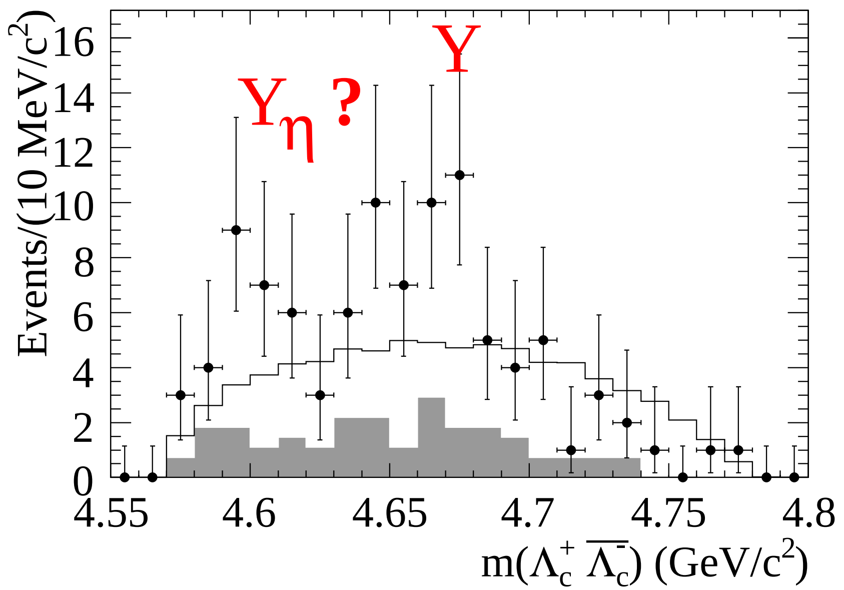
NEW TWISTS

- BaBaR observed a double-peak structure

  in $\bar{B} \to \bar{K}\Lambda_c^+\bar{\Lambda}_c^-$

  $\longrightarrow$ are these the Y and the Y_η ?

  Aubert et al., PRD77 (2008)



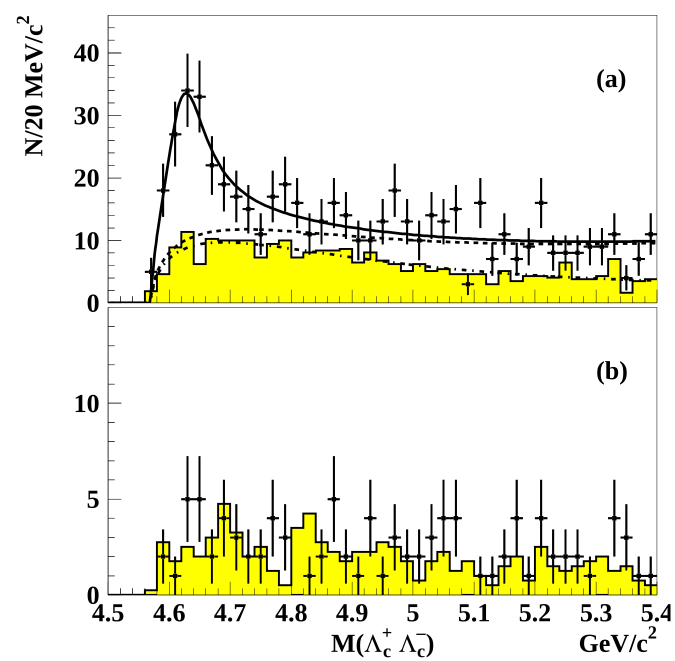
- Belle observed a threshold enhancement

  in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ with mass

  $m(X(4630)) = 4634^{+8+5}_{-7-8}$ MeV

  $\longrightarrow$ is this really a new state ?

  Pakhlov et al., PRL100 (2008)



RECONCILING the X(4630) with the Y(4660)

- include open charm channels (OCCs) in the analysis of the $Y(4660)$:
  - assume the $\Lambda_c^+\Lambda_c^-$ to be the dominant OCC
  - include $\Lambda_c^+\Lambda_c^-$ FSI from meson-exchange model Haidenbauer, Krein (2010)

$$\Rightarrow \Gamma^{\rm tot}(Y) = \tfrac{3}{2}\Gamma(Y \to \psi'\pi\pi) + \Gamma(Y \to \Lambda_c^+\Lambda_c^-)$$

$$\Gamma(Y \to \Lambda_c^+\Lambda_c^-) = \frac{g^2_{Y\Lambda_c\Lambda_c}}{|J(M)|^2}\frac{p}{6\pi}\left(1 + \frac{2M^2_{\Lambda_c}}{M^2}\right)\theta(M - 2M_{\Lambda_c})$$

- fit to Belle mass distributions with 3 parameters:

  normalization $\mathcal{N}$

  mass of the Y, $m(Y)$

  coupling constant $g_{Y\Lambda_c\Lambda_c}$

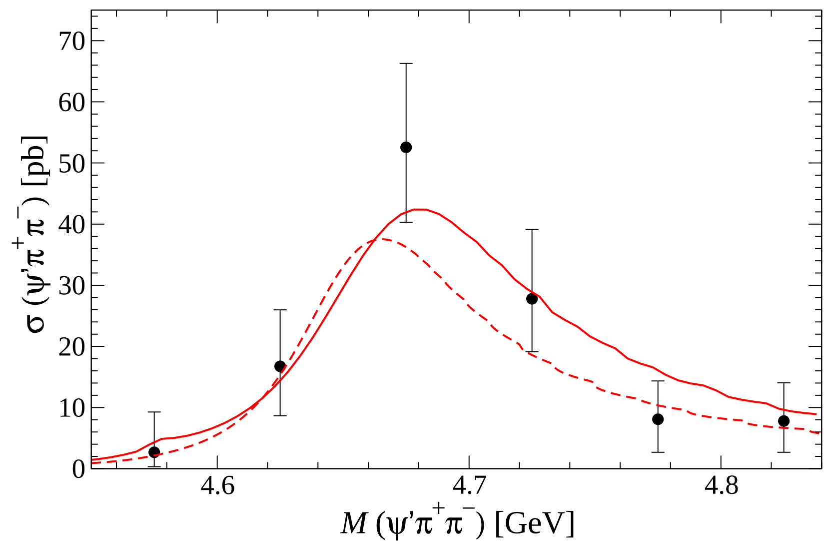
RECONCILING the X(4630) with the Y(4660) cont'd

- consistent w/ Belle data

$$m(Y) = 4662^{+0.1}_{-0.2}\text{ MeV},$$

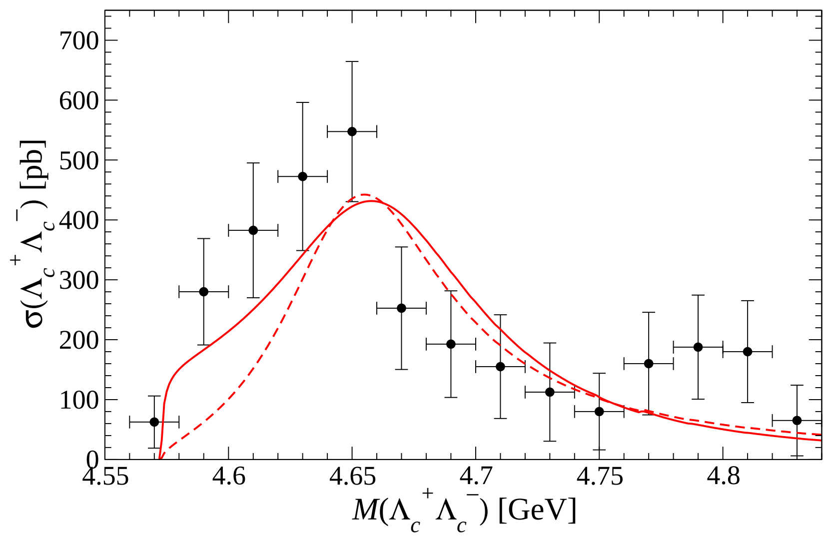
$$g_{Y\Lambda_c\Lambda_c} = 0.7 \pm 0.1$$

$$\frac{\Gamma(Y \to \Lambda_c^+\Lambda_c^-)}{\Gamma(Y \to \psi'\pi^+\pi^-)} = 11.5$$



- prediction for the spin partner:

$$\frac{\Gamma(Y_\eta \to \Lambda_c^+\Lambda_c^-)}{\Gamma(Y_\eta \to \psi'\pi^+\pi^-)} = 2.7$$



⇒ testable prediction

e.g. in $B^\pm \to K^\pm \eta_c' \pi^+\pi^-$

and $B^\pm \to K^\pm \Lambda_c^+\Lambda_c^-$