Prospect of hadron spectroscopy at future experiments

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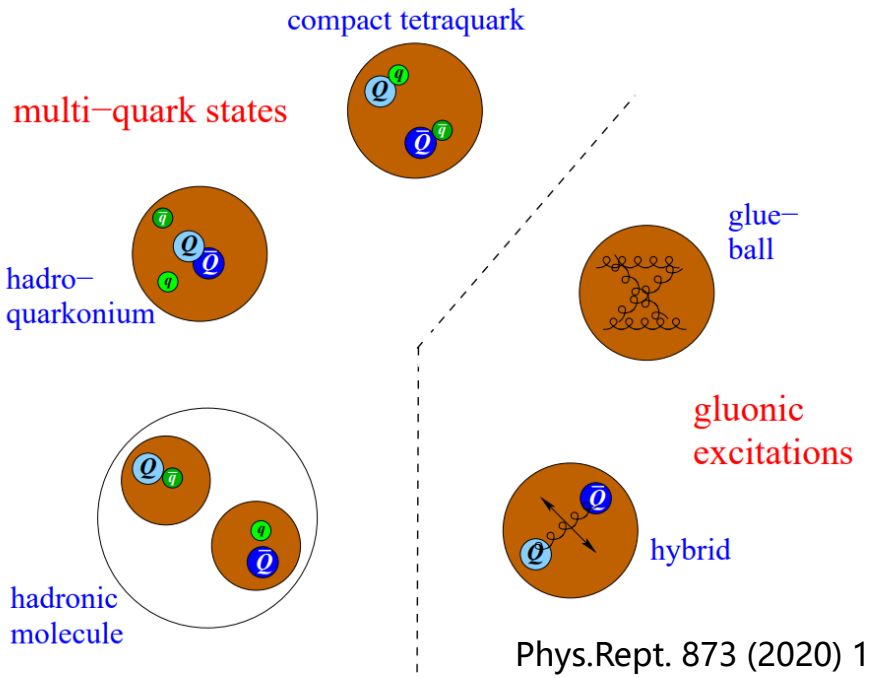
Hadron spectroscopy

- How do the rich and complex features of hadrons emerge from QCD?
  - Understanding hadron spectra in terms of the quark and gluon degrees of freedom
- Key things to search for: exotic forms of matter beyond quark model
  - Strong evidences for multi-quark in heavy quark sector *https://qwg.ph.nat.tum.de/exoticshub/*
  - Evidence for gluonic excitations remains sparse



Phys.Rept. 873 (2020) 1

Identification is challenging

Manifestly exotic: with forbidden QN

Flavor exotic: $Z_c, T_{cc}, T_{\psi\psi}$ ……

Spin exotic: $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$

Crypto exotic: with QN as $\mathbf{q\bar{q}}$

Supernumerary states

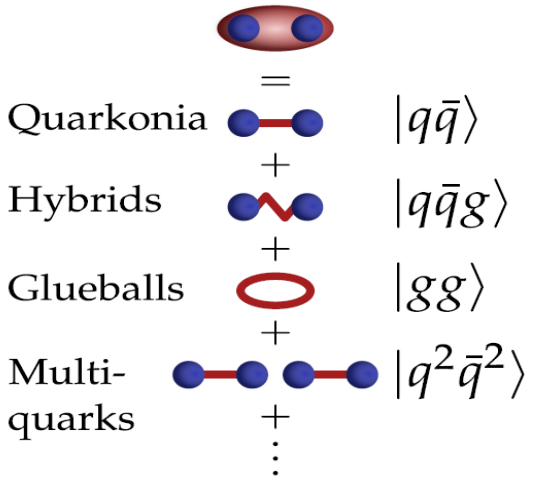
Abnormal properties

+ Kinematic effects

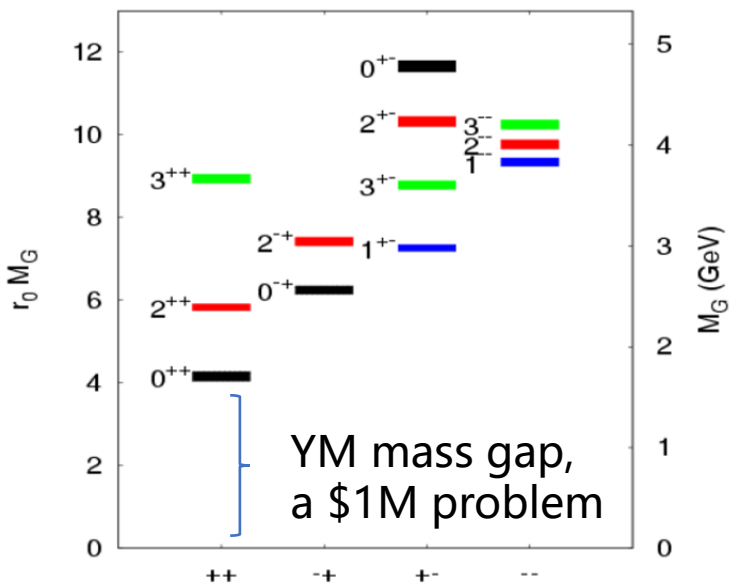
Glueballs

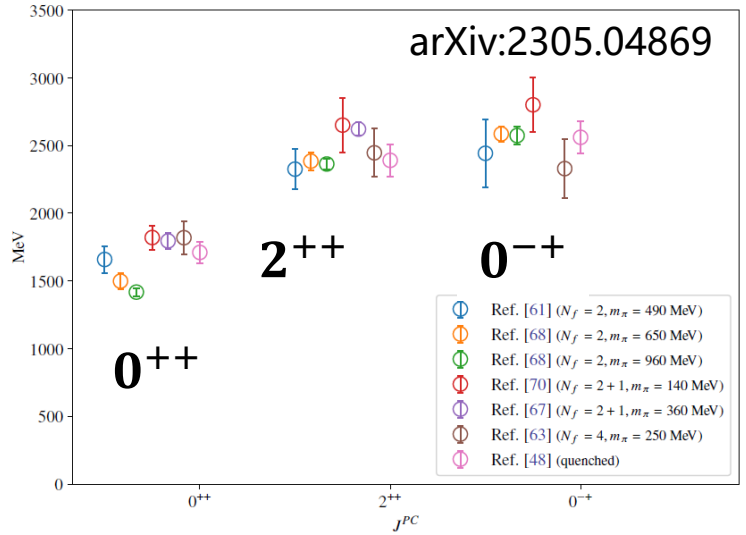
- Glueballs are the most direct prediction of QCD
  - Color singlets emerge as a consequence of the gluon self-interactions
  - Unique particles formed by gauge bosons (force)
- Essential for understanding of confinement and mass dynamical generation
- Theoretical predictions from lattice QCD and QCD-inspired models mostly consistent
  - Light-mass glueballs: $J^{PC} = 0^{++}, 2^{++}, 0^{-+}$

non-$\mathbf{q\bar{q}}$ nature with ordinary quantum numbers is difficult to establish



PRD 73 014516 (2006)



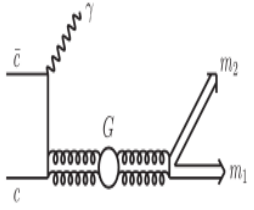


Yang-Mills glueballs on lattice (quenched and unquenched)

Glueball hunting for over 40 years

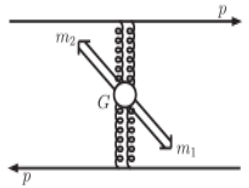
- **Supernumerary states** w.r.t. quark model
  - A priori, mixed with nearby $\mathbf{q\bar{q}}$
  - Assignment of some $q\bar{q}$ multiplets is difficult
- Detailed and accurate information about couplings to production and decay channels is required
- Strongly produced in **gluon-rich processes**
- Decay: **gluon is flavor-blind**
  - $SU(3)_{flavor}$ symmetry expected, but differing quark masses leads exceptions
  - No rigorous predictions on decay patterns
  - Could be analogy to **OZI suppressed** decays of charmonium, as they all decay via gluons [PLB 380 189(1996), Commu. Theor. Phys. 24.373(1995)]

gluon-rich processes [Phys. Rept. 454 1]



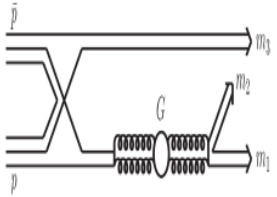
Charmonium decays:

BESIII, MRKIII…



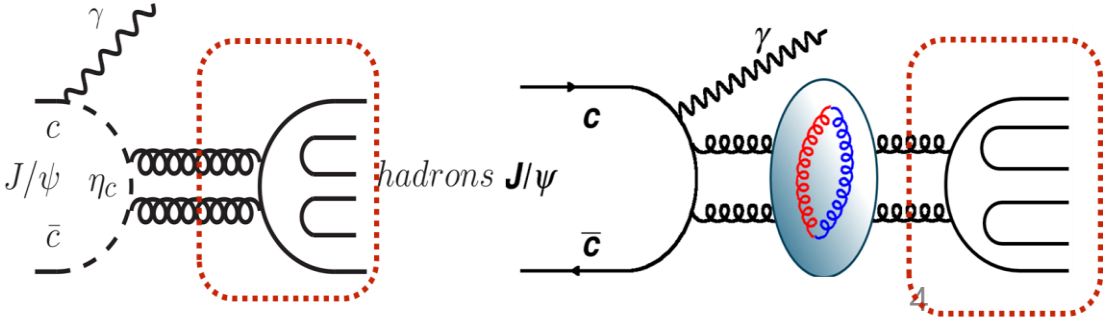
pp double-Pomeron exchange:

WA102, GAMS…



$p\bar{p}$ annihilation:

Crystal barrel, OBELIX…

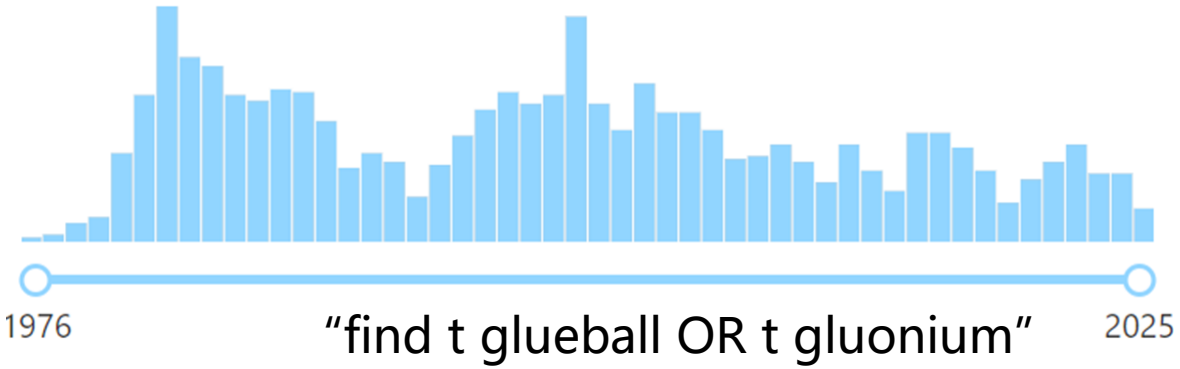


Some glueball candidates in the past

- The first glueball candidate, $\iota(1440)$, observed in J/ψ radiative decays in 1980s
- Scalar candidates $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ (MarkII in1980s, Crystal Barrel in 1990s)
- Narrow tensor glueball candidate $\xi(2230)$ (MarkIII in 1980s/BESI in 1990s)
  - Not confirmed by CLEO, BESII nor BESIII with much higher statistics

And,

- Odderon (odd C-parity) from D0 and TOTEM (2021)



"Update on Glueballs", C. Morningstar, Lattice 2024
"A review on glueball hunting", D. Vadacchino, Lattice 2022
"The Physics of Glueballs" Mathieu, Kochelev, and Vento, 2009
"The Status of Glueballs" Ochs, 2013
"Glueballs as the Ithaca of meson spectroscopy: From simple theory to challenging detection" Llanes-Estrada, 2021
"The Experimental Status of Glueballs" Crede and C. A.Meyer, 2009
...

Story thus far (with BESIII' s inputs)

Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: overpopulation

LQCD : ground state 0^+ glueball ~1.7 GeV;

$$\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$$

Tensor: 2 nonets($^3P_2$,$^3F_2$), complicated

Exp: large uncertainty

LQCD: 2^{++}(2.3~2.4 GeV);

$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{total} = 1.1(2) \times 10^{-2}$$

Pseudoscalar: η & η' , "simple"

Exp: lacking of info. above 2 GeV; puzzles $\eta(1295)$? $\eta(1405/1475)$?

LQCD: 0^{-+}(2.3~2.6 GeV)

$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$

✓**$B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$; suppression of $f_0(1710) \to \eta\eta'$**

➔ **Large gluonic component**

BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003, PRD 106 072012]

✓**Large production rate of $f_2(2340)$ in J/ψ radiative decays**

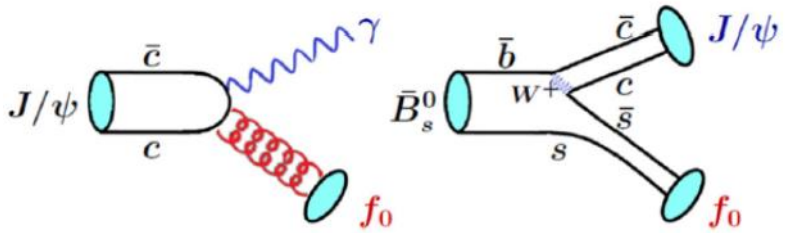
BESIII [PRD 87,092009, PRD 93, 112011, PRD 98,072003, PRD 105,072002]

✓**$X(2370)$: a good candidate with analogy decay pattern as η_c**

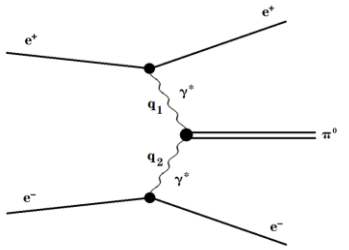
BESIII [PRL 106, 072002, PRL 117, 042002, EPJC 80 746, PRL 132, 181901, PoS ICHEP2024 490]

Next steps

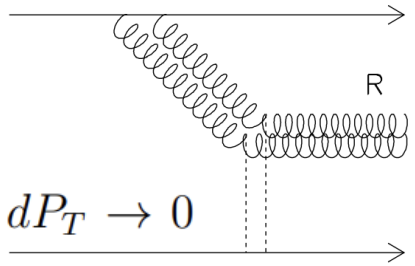
- Many channels to be explored in existing 10B J/ψ data at BESIII and STCF
  - More information on the properties of $X(2370), f_0(1710), \ldots$
- Complementary information
  - Two-photon process at Belle II and STCF, even CEPC and FCC-ee
  - Central Exclusive Production at LHC
  - B hadron decays
- Full spectrum of glueballs, especially oddballs, at PANDA



PLB 797 134789

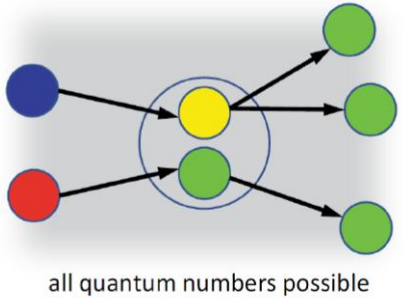


Glueball anti-filter?

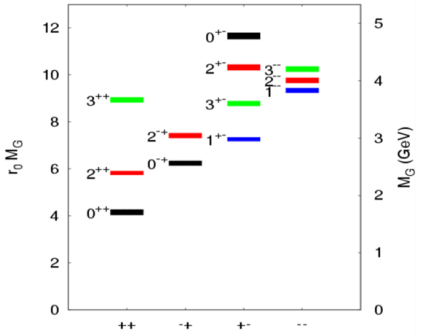


Glueball filter?

PLB397 333



all quantum numbers possible

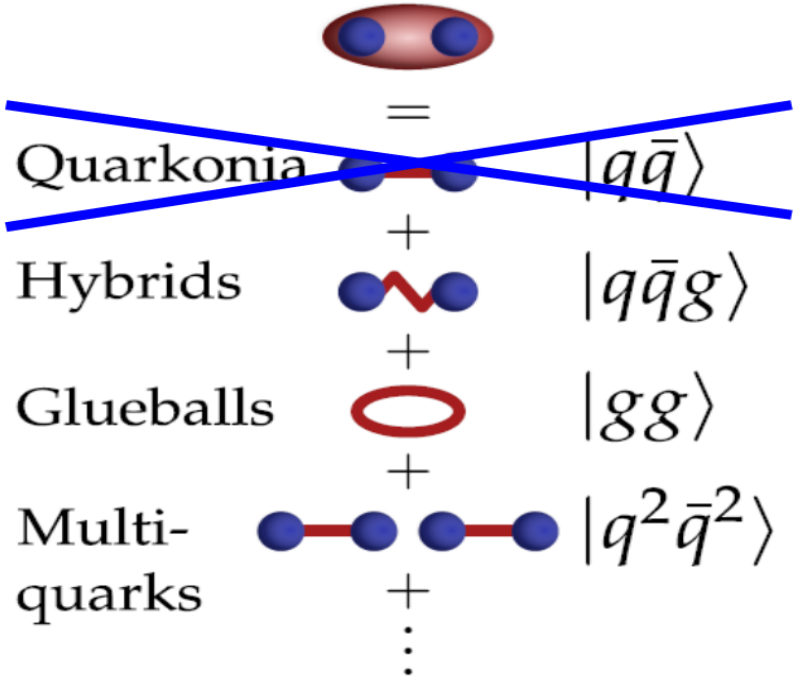


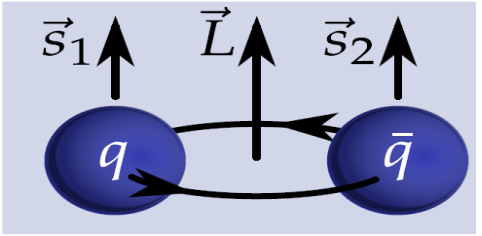
Light hadrons with exotic quantum numbers

- **Unambiguous signature for exotics**
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $q\bar{q}$:**
      $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$

Experiments:

- **Hadroproduction:** GAMS, VES, E852, COMPASS
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA(under construction)
- **Photoproduction:** GlueX(2017-), CLAS

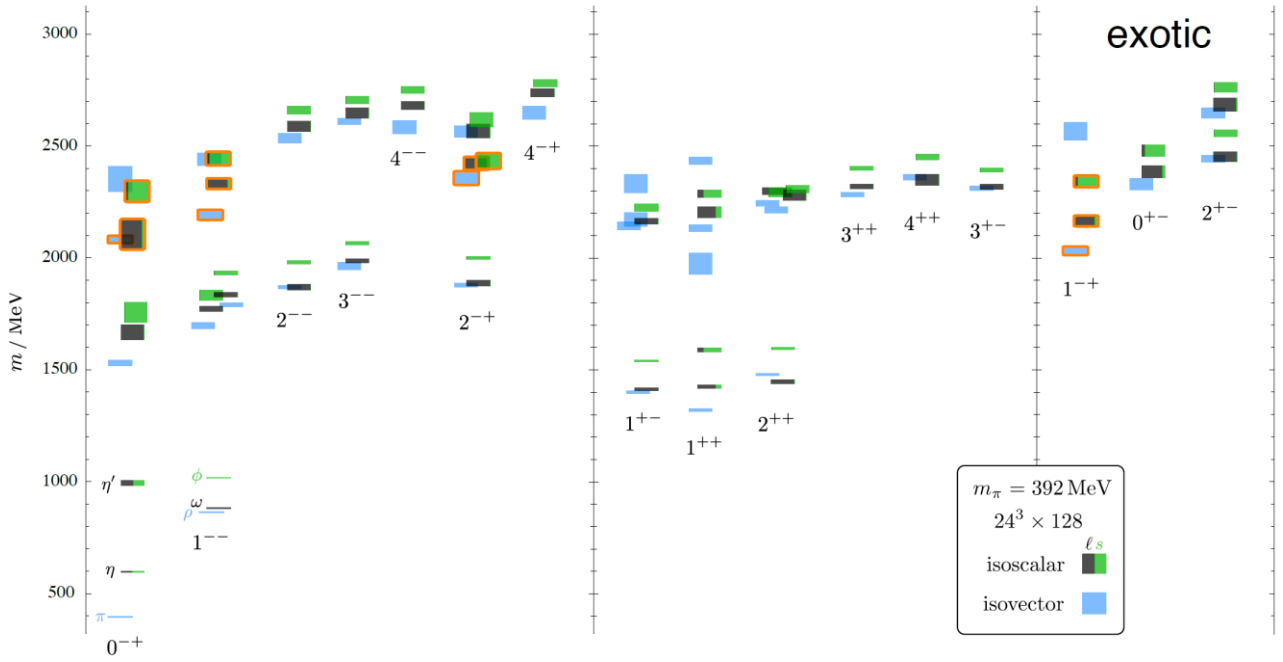




$\vec{\mathbf{J}} = \vec{\mathbf{L}} + \vec{\mathbf{S}}$ $\mathbf{P} = (-1)^{L+1}$ $\mathbf{C} = (-1)^{L+S}$

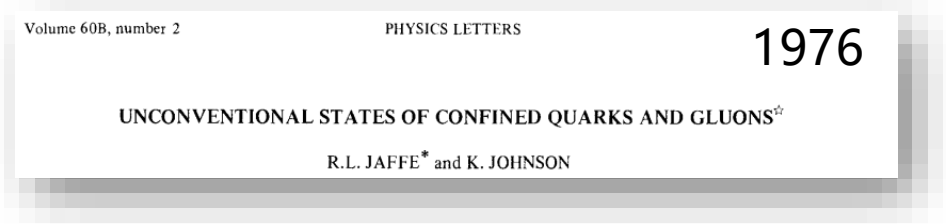
Allowed $\mathbf{J^{PC}}$: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Predictions



PRD 88 094505(2013)

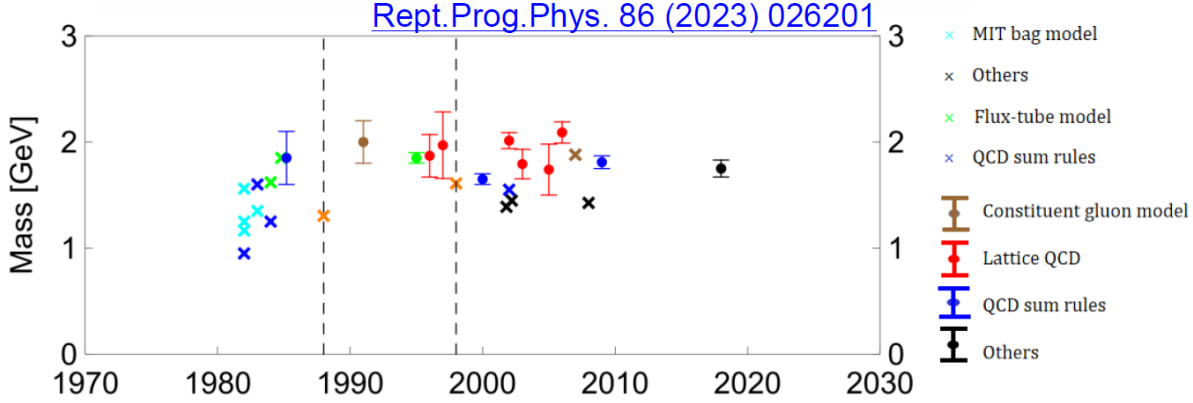
Lightest spin-exotic state in LQCD: $\mathbf{1^{-+}}$ hybrid


Volume 60B, number 2 PHYSICS LETTERS 1976

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

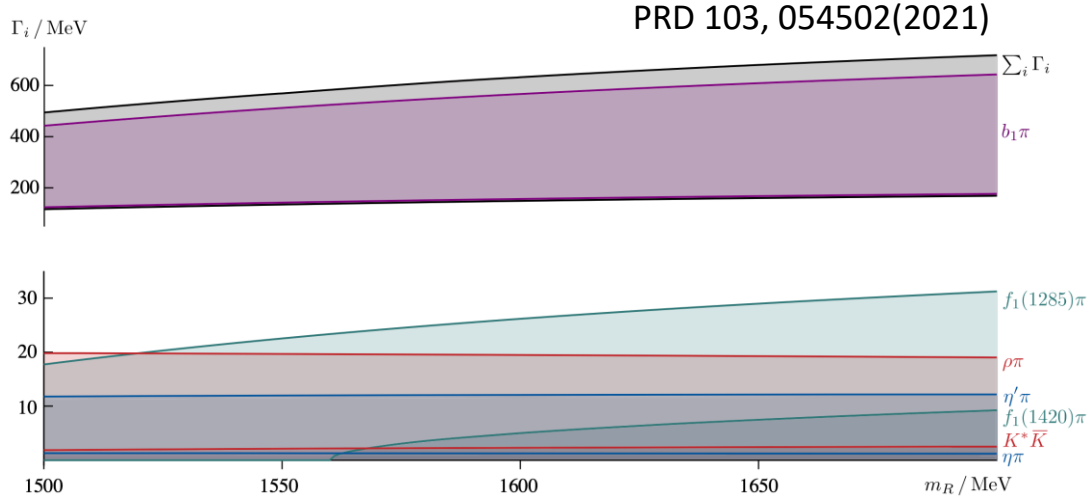
R.L. JAFFE* and K. JOHNSON

Rept.Prog.Phys. 86 (2023) 026201



Mass of $\mathbf{1^{-+}}$ hybrid

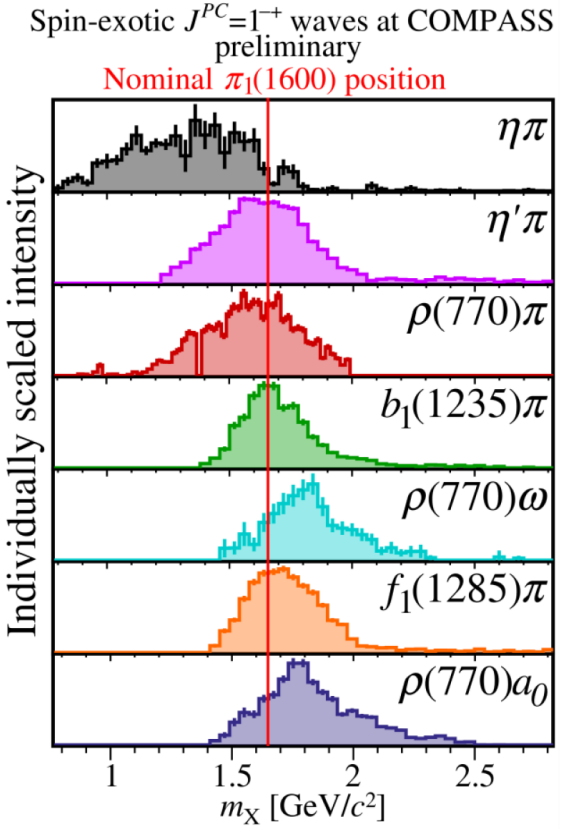
PRD 103, 054502(2021)

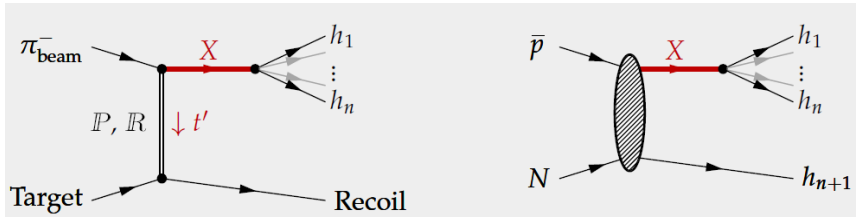


Decay width of $\mathbf{1^{-+}}$ hybrid π_1

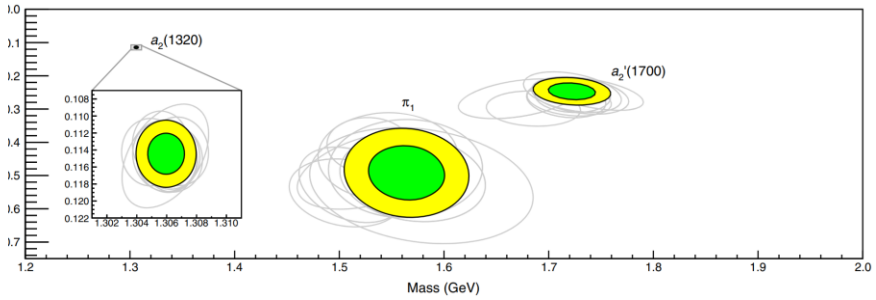
1^{-+} Hybrids

- Candidates over 3 decades
  - $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$ (needs confirmation), all isovetors





Review: PRC 82, 025208 (2010), PPNP 82, 21 (2015), EPJC 83 (2023) 1125

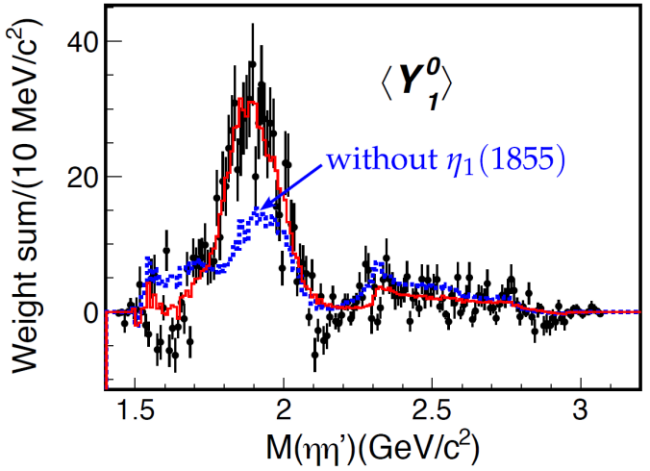


$\pi_1(1400)$ & $\pi_1(1600)$ can be one pole

[PRL 122, 042002 (2019), EPJ C 81, 1056 (2021])

- Observation of an exotic 1^{-+} isoscalar state $\eta_1(1855)$

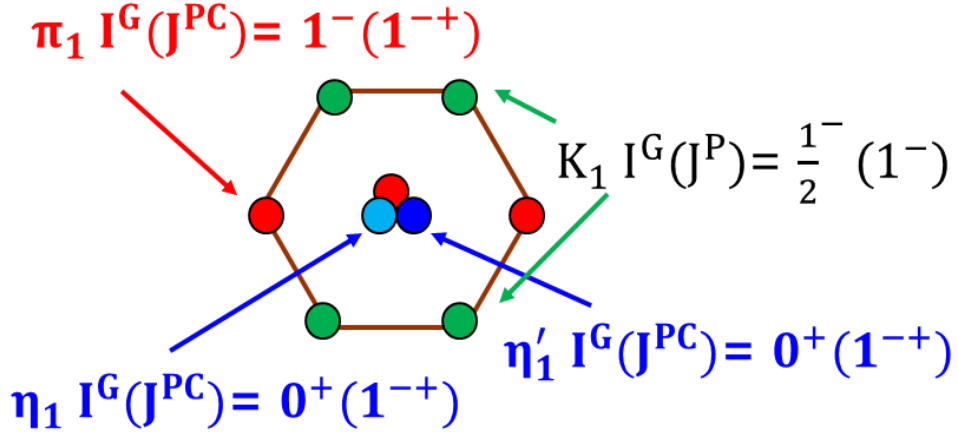
BESIII PRL 129 192002(2022) , PRD 106 072012(2022)



can be $\pi_1(1600)'$ s partner

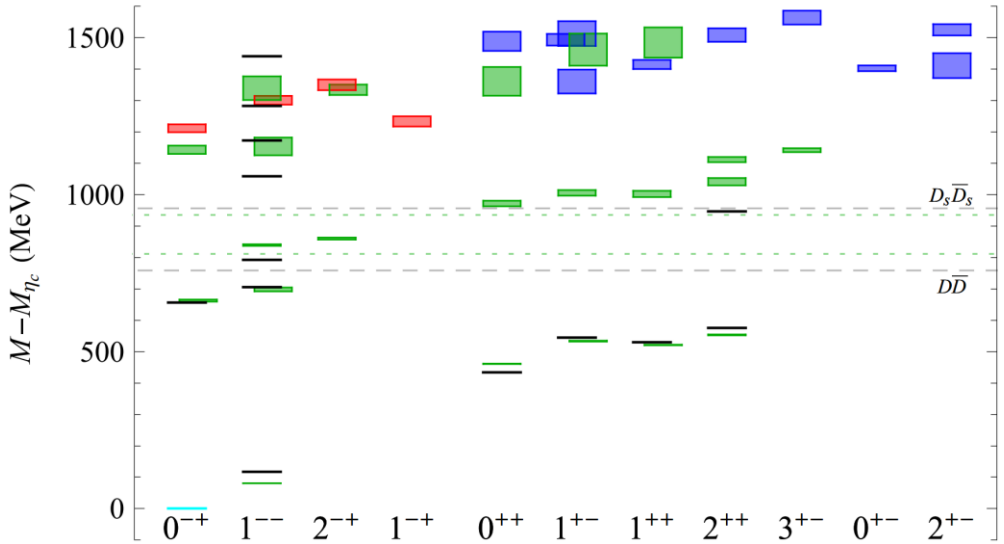
1^{-+} Hybrids

- What are the nature of $\pi_1(1600)$ and $\eta_1(1855)$?
  - Hybrid/$K\bar{K}_1$Molecule/Tetraquark?
    - Decay:$J/\psi \to \gamma + \eta f_1, K_1\bar{K}$
    - Production: $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$
- Where is the $\eta_1^{(\prime)}$?
- Does K_1 exist and how to identify it?
- Where are the other $J^{PC} = 0^{--}, \text{even}^{+-}, \text{odd}^{-+}$ states?
- New results from COMPASS, AMBER, BESIII, GlueX and PANDA are eagerly awaited



$\bar{c}cg$ hybrids

LQCD predicts similar supermultiplet as light hybrids

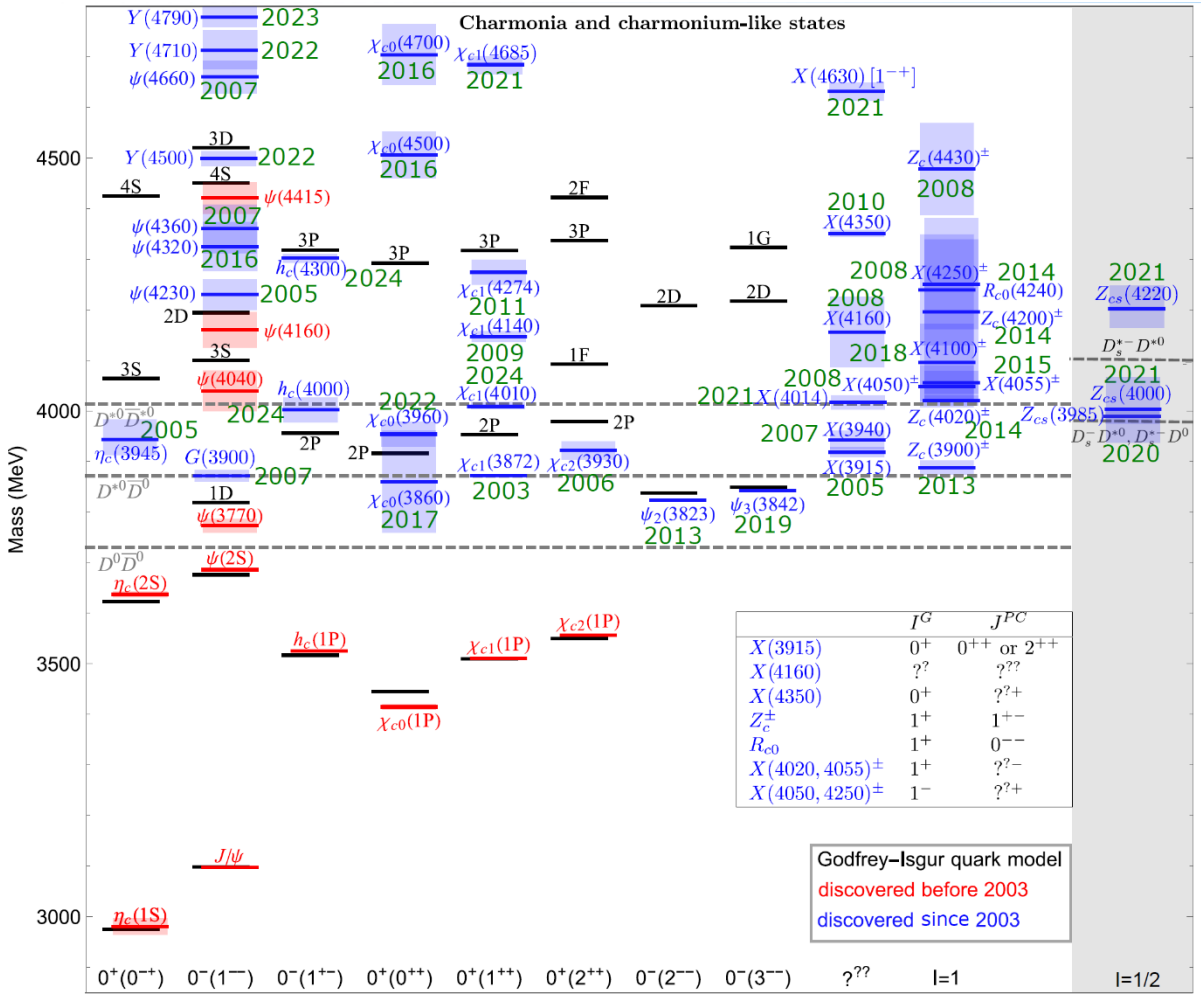


JHEP 07 (2012), 126

- Y(4230)? [see Prof. Zhao' s talk on Monday]
- Other vector?
- Transitions between 1^{--} and $\{0,1,2\}^{-+}$
- Molecule states of 1^{-+} and 1^{--} ?

Further studied at BESIII and Belle II

Heavy QCD exotics



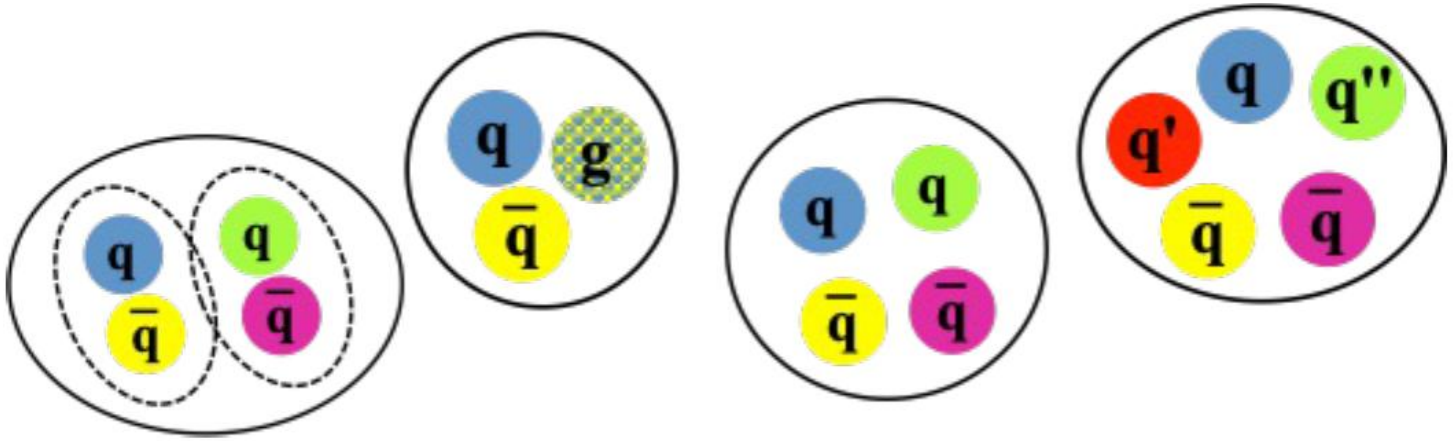
Courtesy to F.K. Guo

- Conventional $c\bar{c}$ meson fit well with potential model
- Abundance of new states with various probes
  - b-hadron decays
  - hadron/heavy-ion collisions
  - $\gamma\gamma$ processes
  - e^+e^- collisions

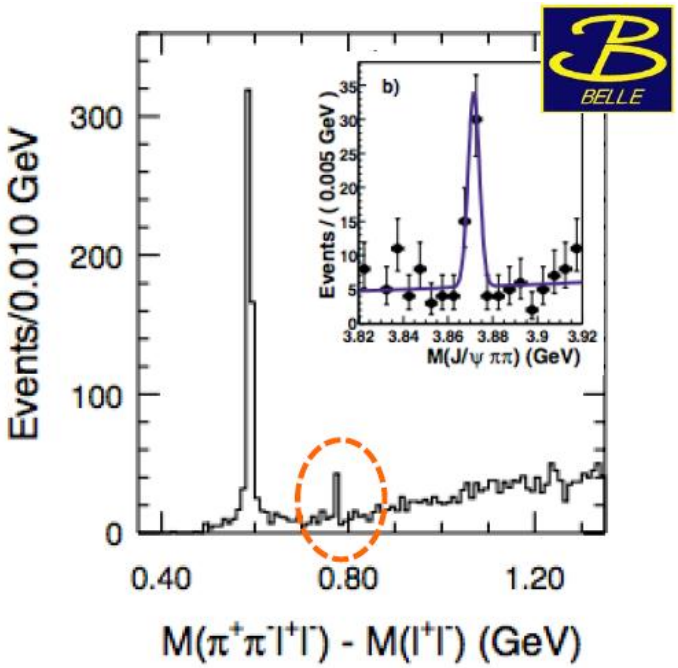
Heavy QCD exotics

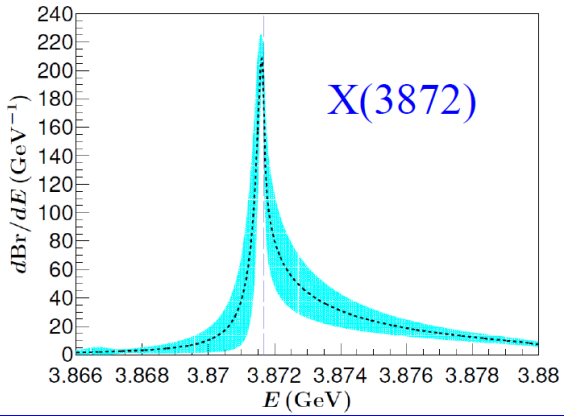
With tremendous progress of multiquark candidates, many puzzles remain

- Proximity to open thresholds
- With few exceptions, mostly observed in single production modes
- Binding mechanism(s) unclear

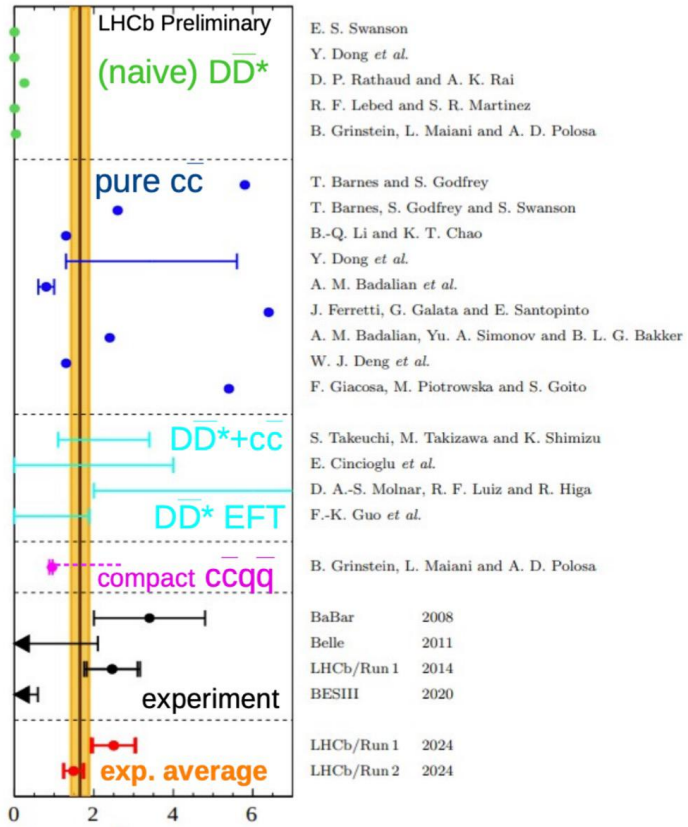


Further details
e.g. 22 yrs "young" X(3872)





	LHCb	Belle	BESIII
g	$0.108 \pm 0.003^{+0.005}_{-0.006}$	$0.29^{+2.69}_{-0.15}$	$0.16 \pm 0.10^{+1.12}_{-0.11}$
$Re[E_l]$ [MeV]	7.10	7.12	$7.04 \pm 0.15^{+0.07}_{-0.08}$
$Im[E_l]$ [MeV]	-0.13	-0.12	$-0.19 \pm 0.08^{+0.14}_{-0.19}$
$Re[k^+]$ [MeV]	-13.9	-15.3	$-12.6 \pm 5.5^{+6.6}_{-6.2}$
$Im[k^+]$ [MeV]	8.8	7.7	$12.3 \pm 6.8^{+6.0}_{-6.4}$
a (fm)	-27.1	-31.2	$-16.5^{+7.0\ +5.6}_{-27.6\ -27.7}$
r_e (fm)	-5.3	$-3.0^{+1.3}_{-1.5}$	$-4.1^{+0.9\ +2.8}_{-3.3\ -4.4}$
$\bar{Z}_A$	0.15 (0.33)	$0.08^{+0.04}_{-0.03}$	$0.18^{+0.06\ +0.19}_{-0.17\ -0.16}$



- More studies at BESIII, Belle II, LHCb
- Model-independent lineshape measurements via beam scan at PANDA

High precision measurements + Sophisticated models e.g., Y states

N. Husken, et al., arXiv:2404.03896

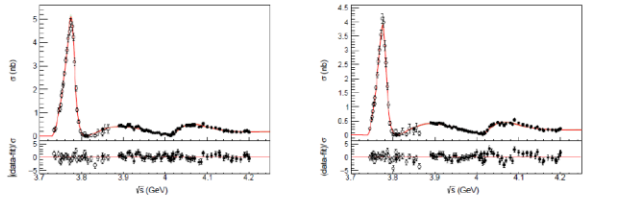


FIG. 2. Fit result for Model 1. Left: $e^+e^- \to D^0\bar{D}^0$. Right: $e^+e^- \to D^+D^-$. Open data points are the Born cross section values based on observed cross sections, as reported in Ref. [18]; closed data points are from Ref. [1].

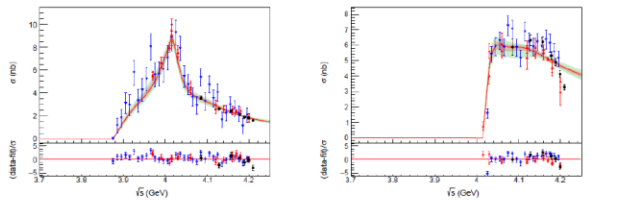


FIG. 3. Fit result for Model 1. Left: $e^+e^- \to D^*\bar{D}$. Right: $e^+e^- \to D^*\bar{D}^*$. The red region indicates the 68% confidence level, while green is the 90% confidence level. Black data points are from BESIII [21], red data is from CLEO-c [23, 24], blue data is from Belle [22].

S. G. Salnikov & A. I. Milstein, arXiv:2404.06160

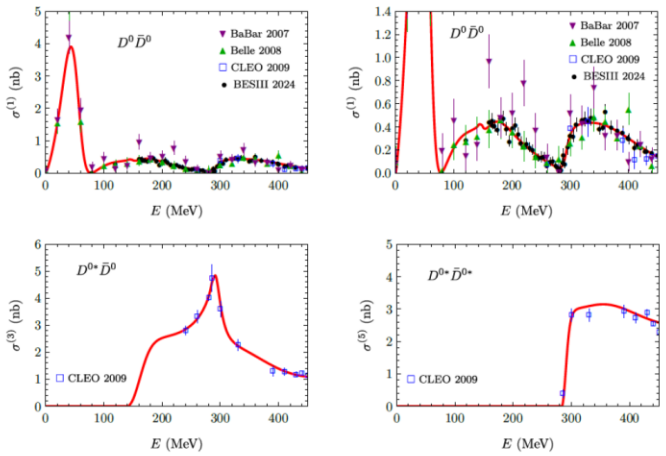


FIG. 1. Energy dependence of the cross sections for the production of neutral particles. Experimental data are taken from Refs. [32, 34–36, 39].

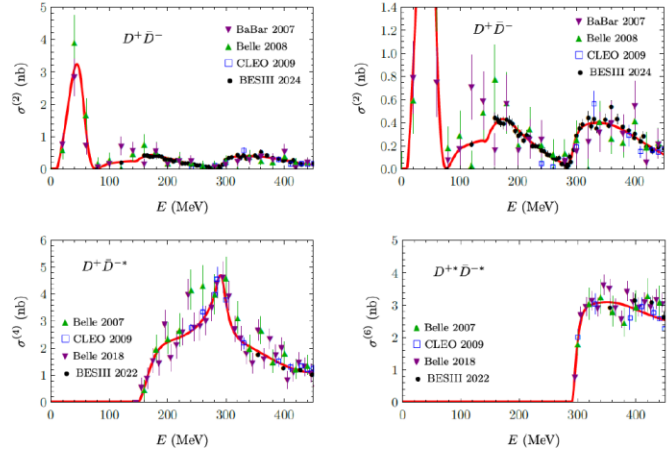
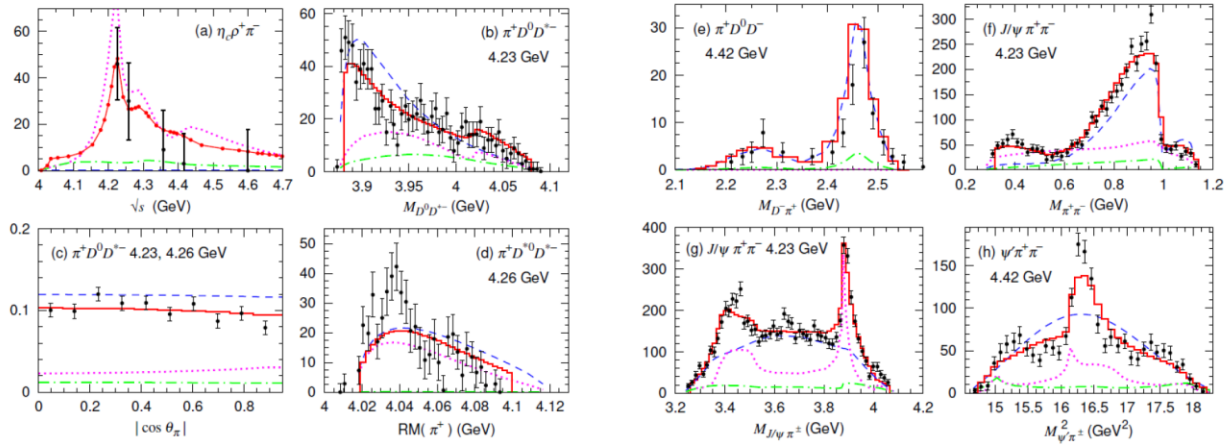
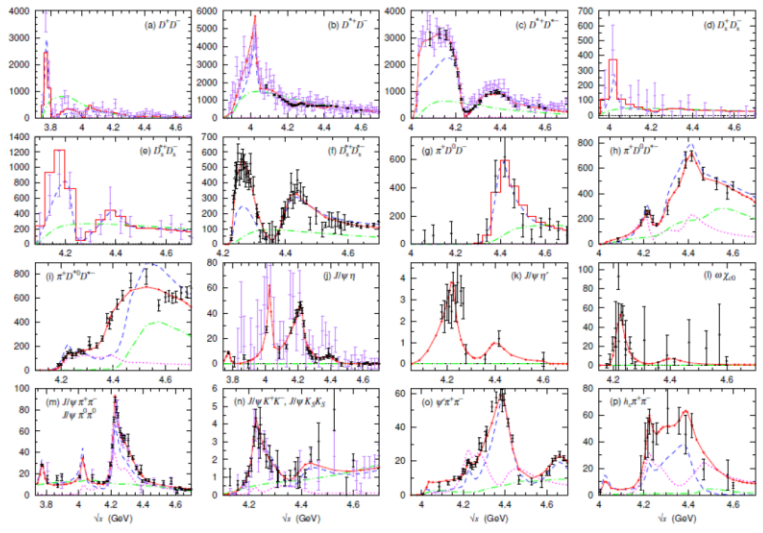


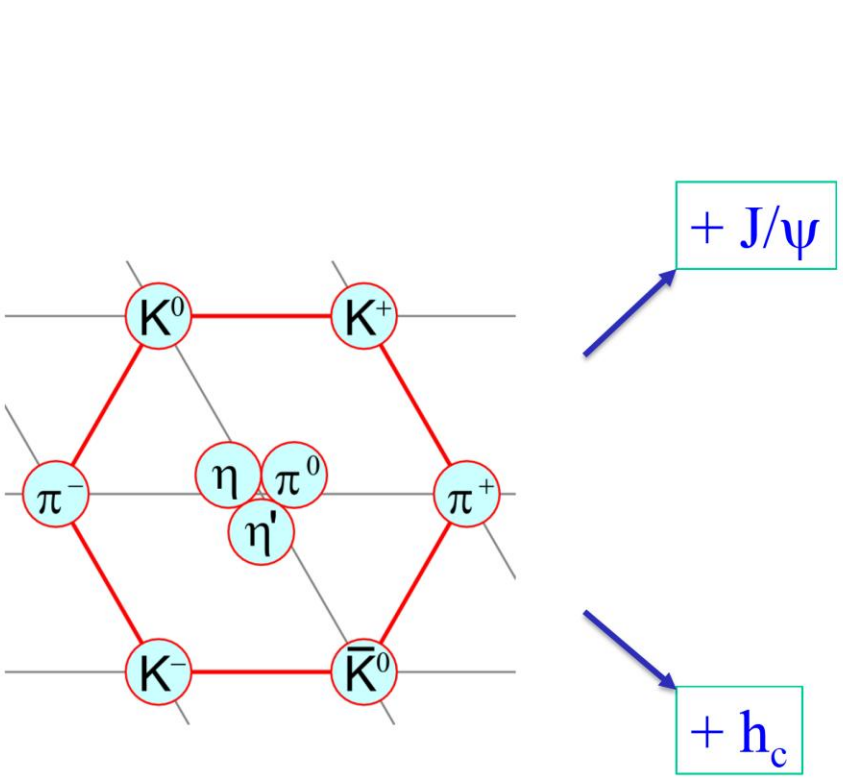
FIG. 2. Energy dependence of the cross sections for production of charged particles. Experimental data are taken from Refs. [32–39].

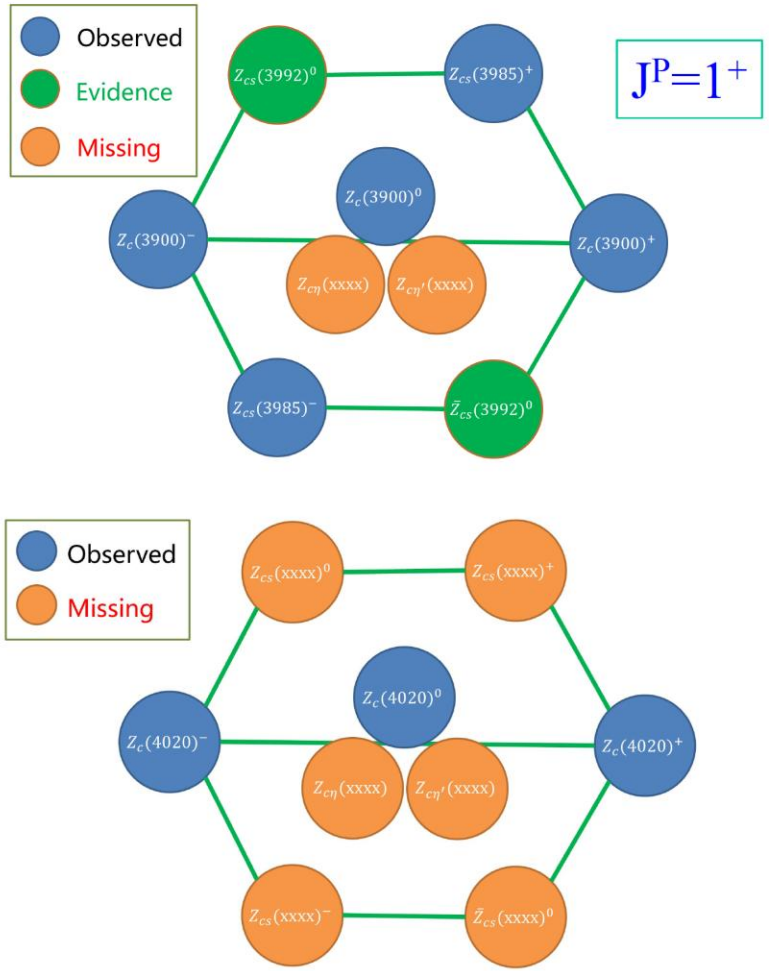
S. X. Nakamura, et al., arXiv:2312.17658





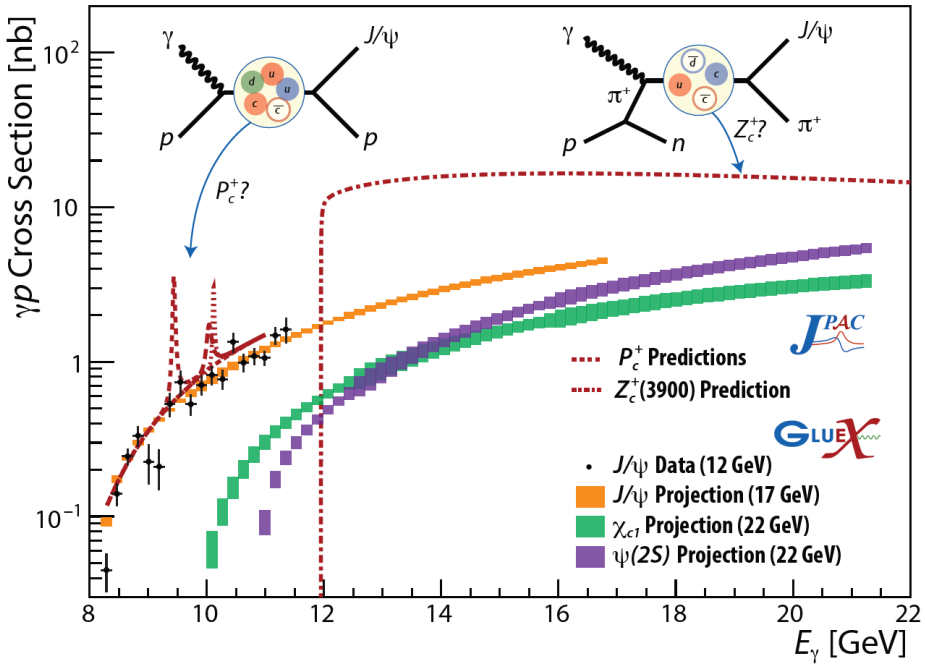
Symmetries governing the multiplets e.g. Z states

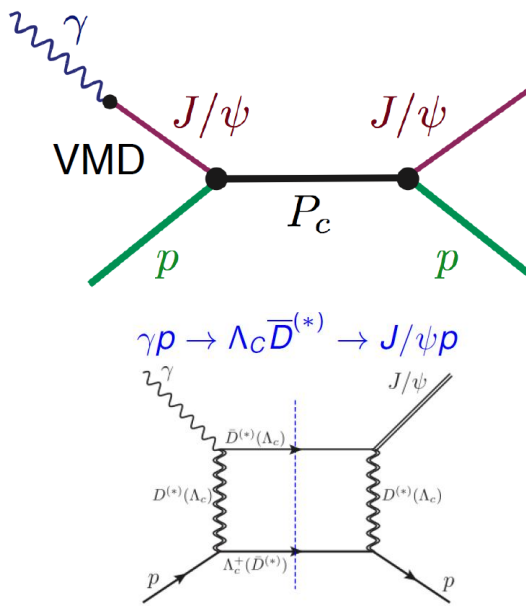


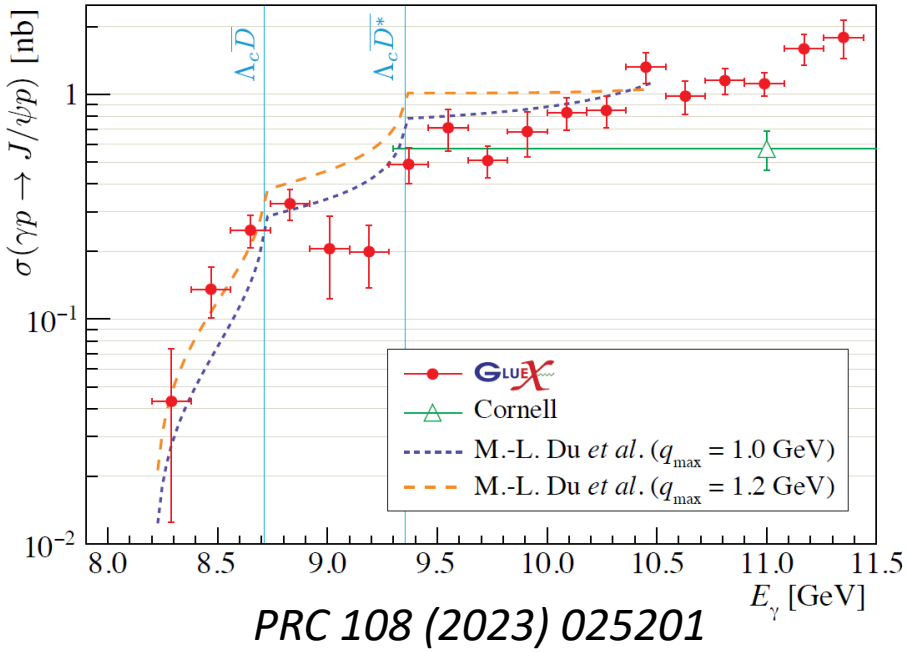


courtesy to C.Z. Yuan

More production mechanisms



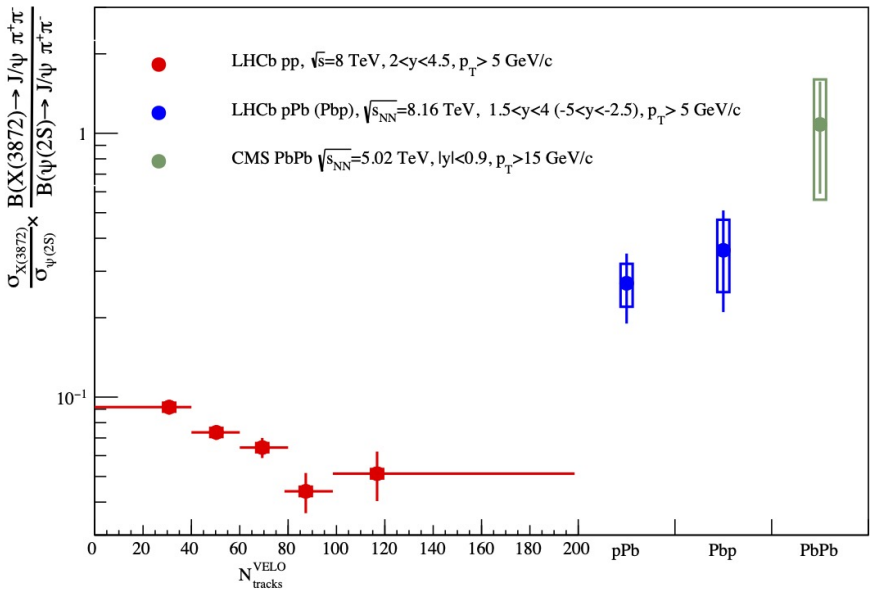


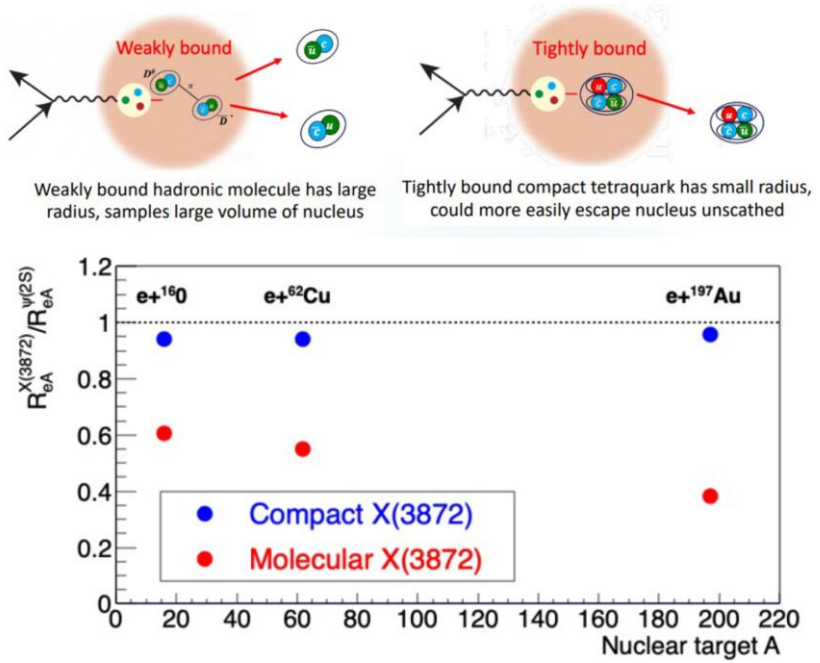


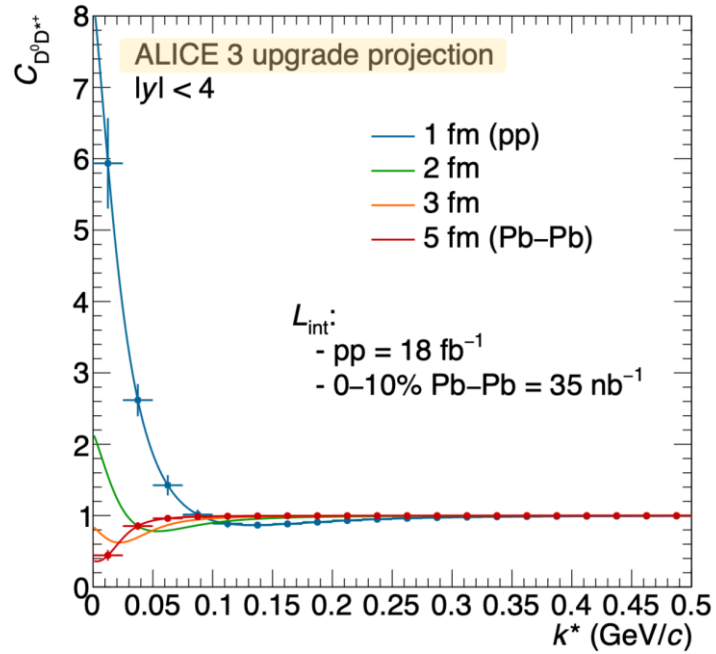
PRC 108 (2023) 025201

- photoproduction at GlueX
- quasi-real photoproduction at ePIC@EIC

Complementary insights:
in-medium effects, femtoscopic techniques, …





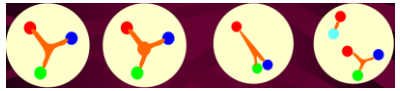


ALICE3 LOI, CERN-LHCC-2022-009

https://qwg.ph.nat.tum.de/exoticshub/

What I didn’ t cover

- Light baryons
  - Missing states



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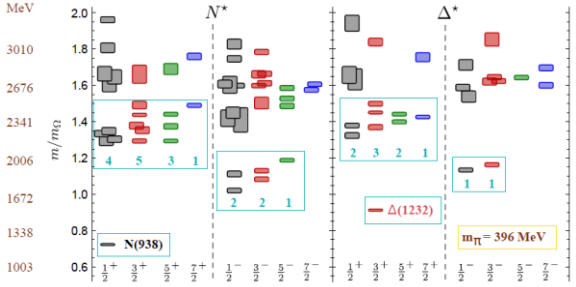

  - Various production mechanisms: $\pi N, \gamma^{(*)} N, charmonium\ decays, \mathrm{K}N$ …
  - Polarization observables
- Heavy baryons
  - Since the 2017 Ξ_{cc}^{++}, no other double heavies yet

- $t\bar{t}$ cross-section enhancement at threshold
  - Elusive NRQCD phenomena
  - Modelling of the threshold region is challenging
  - Spectrum of topped hadrons?

  Run3 and HL-LHC, FCC-ee, CEPC

Summary

- New generation of experiments
  - more measurements, more production/decay modes, more precision
- Advance analysis techniques
  - Amplitude analysis, ML, …
- Close exp-th collaboration

A comprehensive understanding of hadrons

Thank you for your attention