The search for exotic particles

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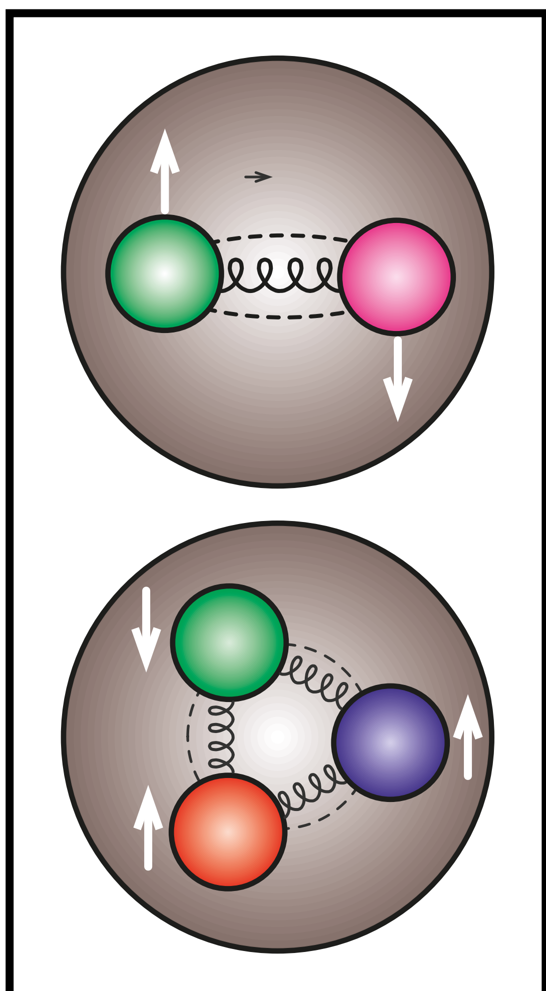
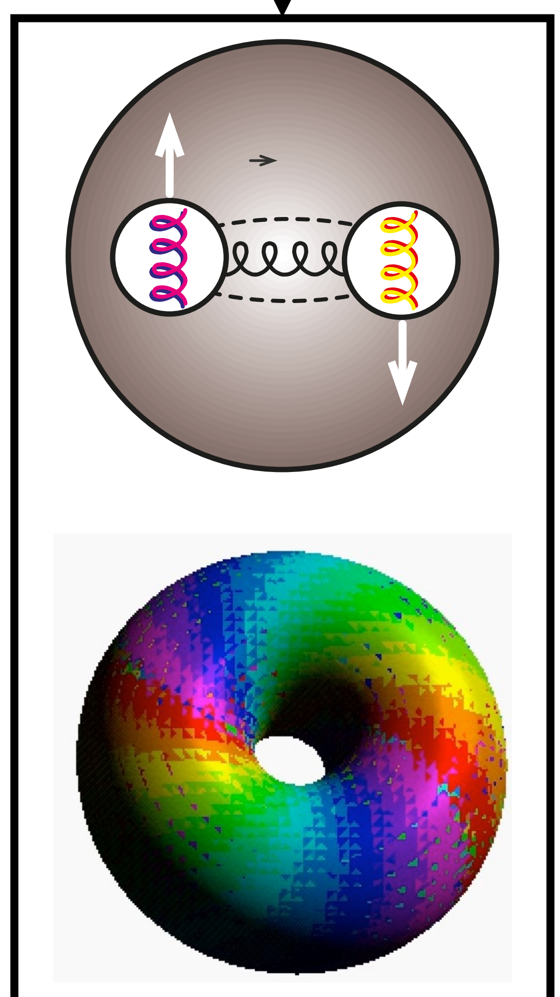
Ruhr-University Bochum

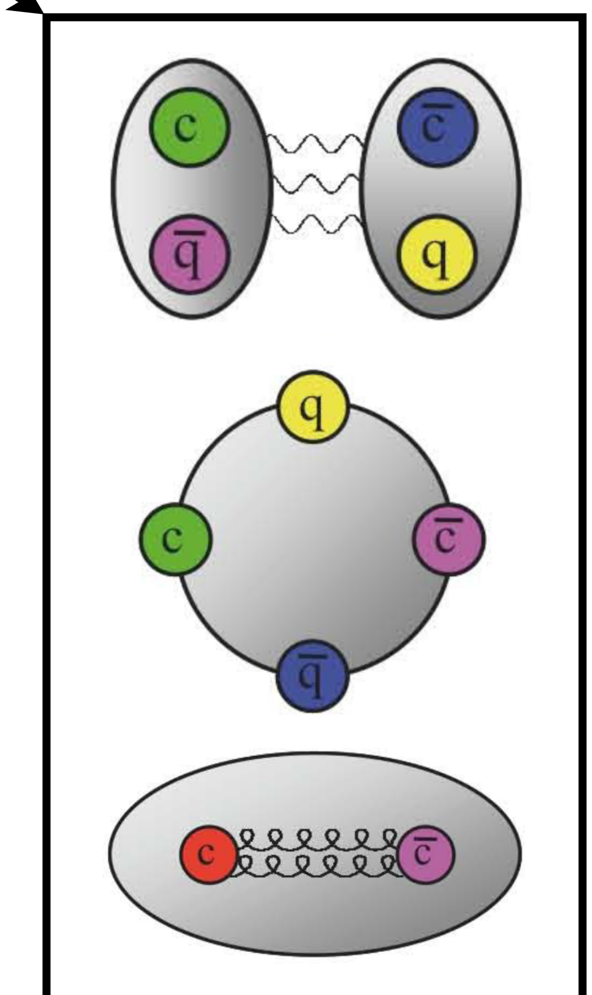
APCTP workshop on “Exotics and Exotic Phenomena in Heavy Ion Collision (ExHIC), September 30, 2022

Hadron physics and non-perturbative QCD are complex





Glueballs



X

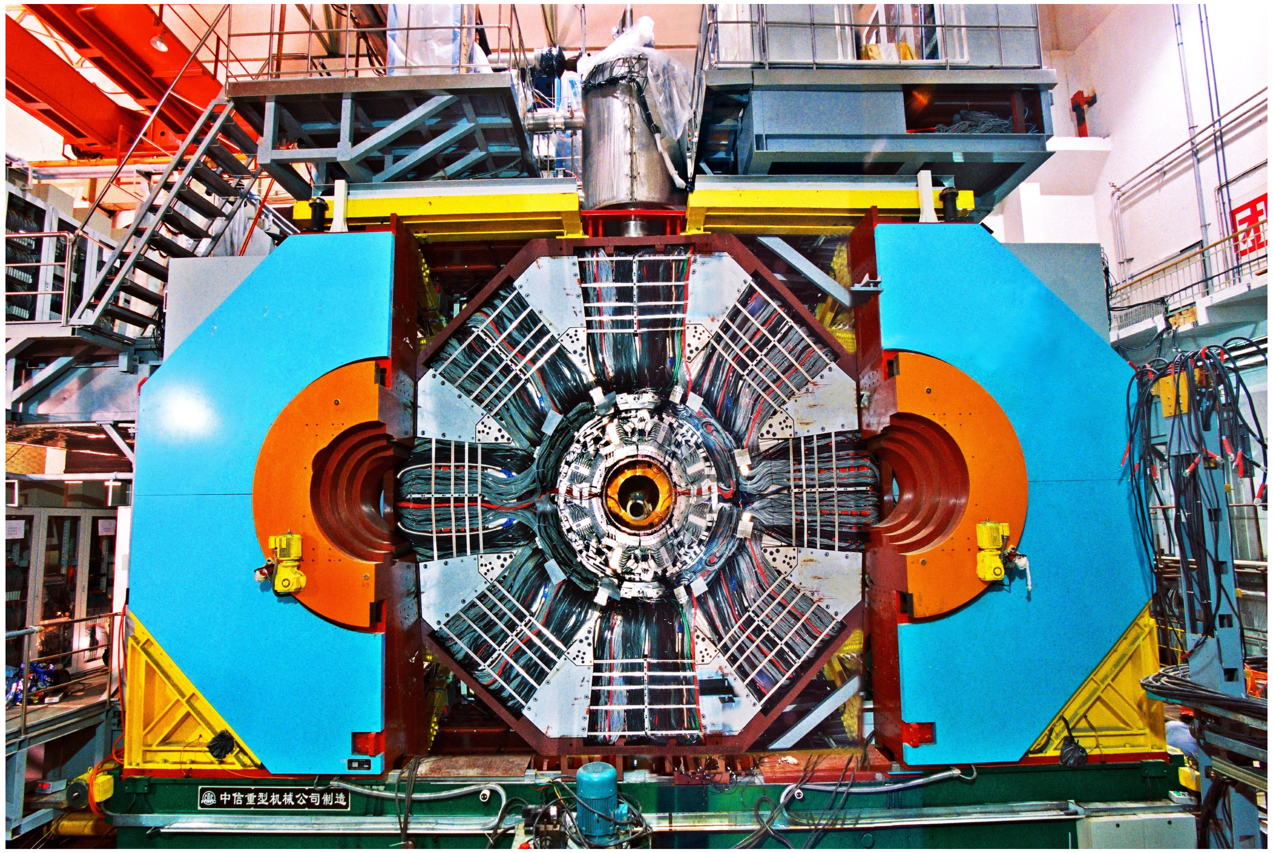
Y

Z

A typical hadron physics experiment nowadays

BESIII has produced beautiful new results and delivers many important papers.

(61 in high-ranking refereed journals from 2017 – now)



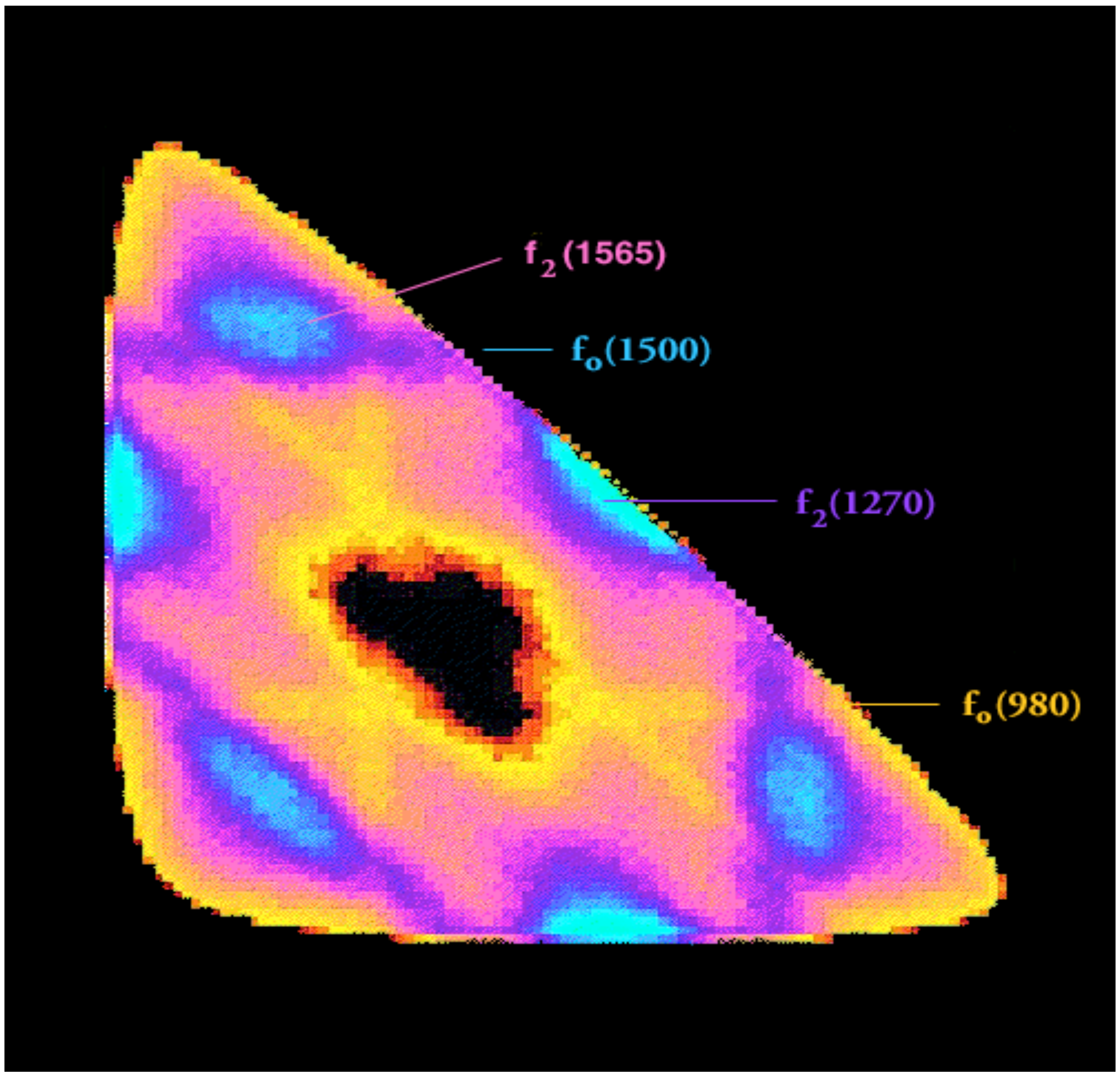
One lesson from the past:

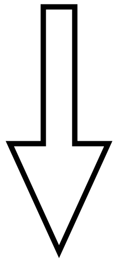
To determine nature of states: different production mechanisms and decay pattern necessary

$\Rightarrow$ combine results from as many as possible sources

Different analysis expertise in spectroscopy comes together

The analysis and interpretation of data is complex.



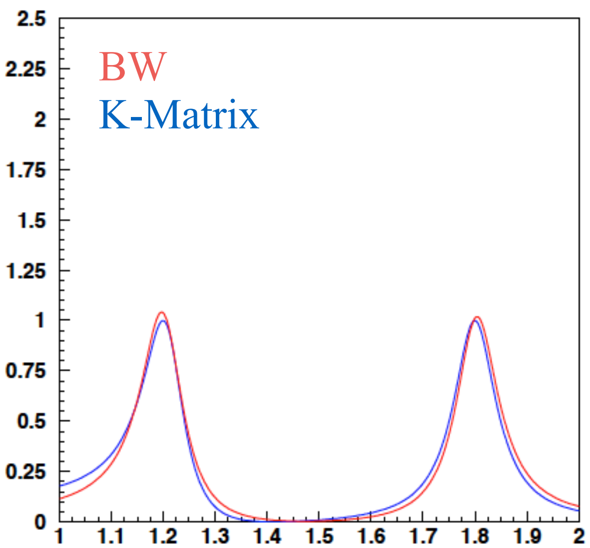


Amplitude Analysis

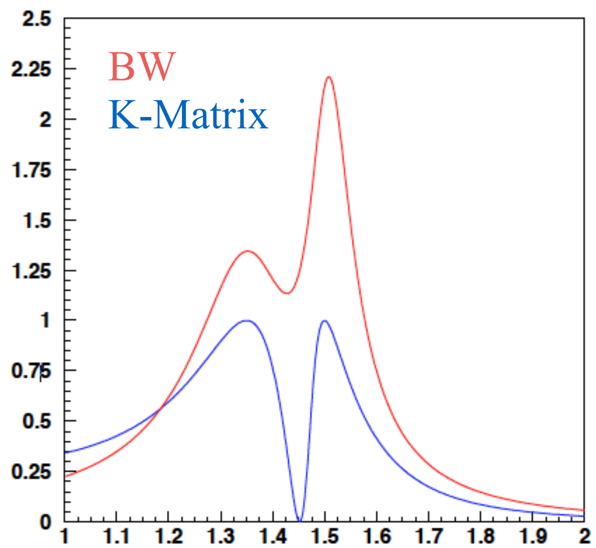
Amplitude analysis (PWA): Breit-Wigner and K-Matrix formalism

Breit-Wigner fitting might not be sufficient:

$J/\psi \rightarrow \gamma\omega\omega$ PAWIAN K-Matrix (Malte Albrecht)

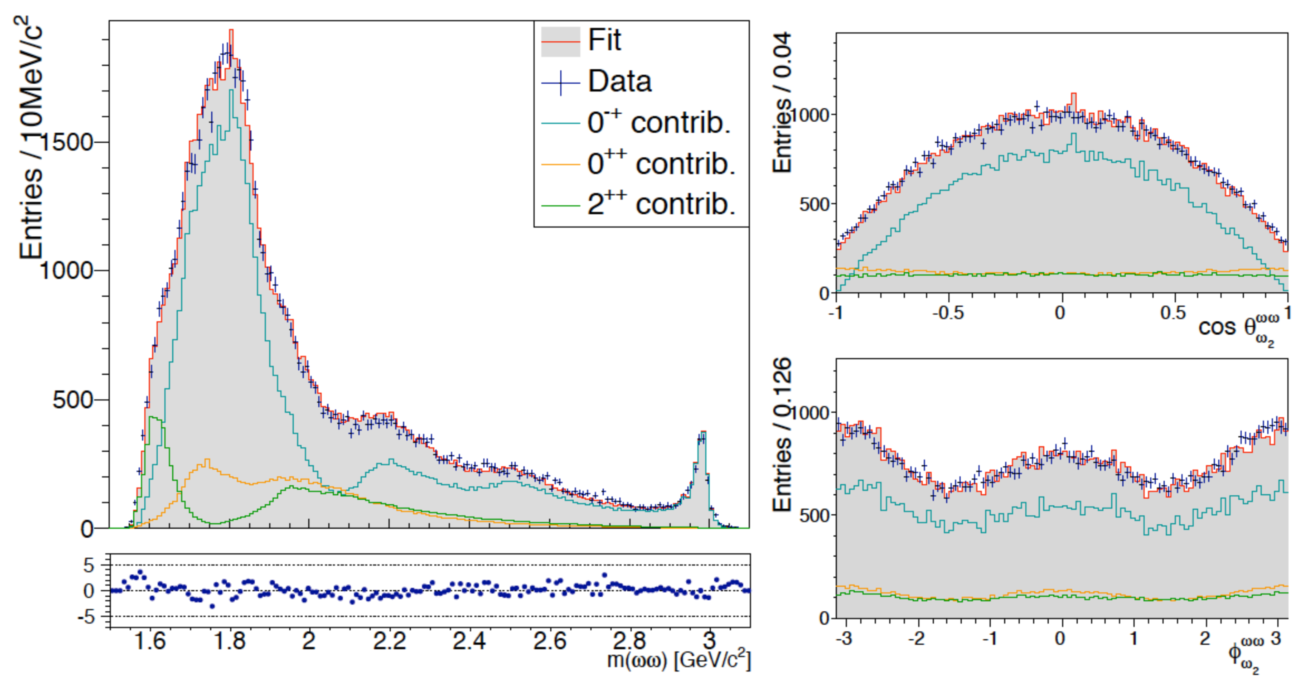


$f_0(1200)$, $\Gamma = 100$
$f_0(1800)$, $\Gamma = 100$

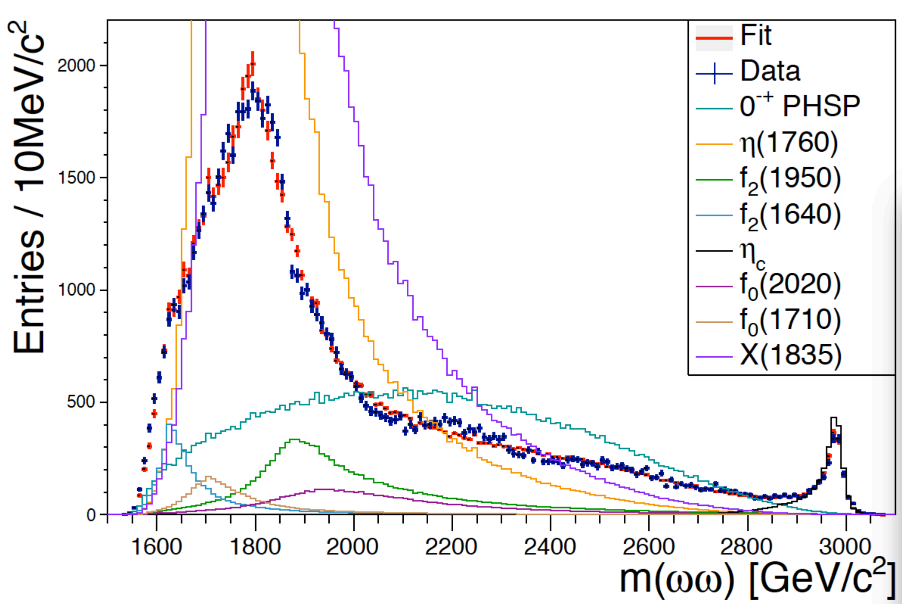


Plots: Curtis Meyer

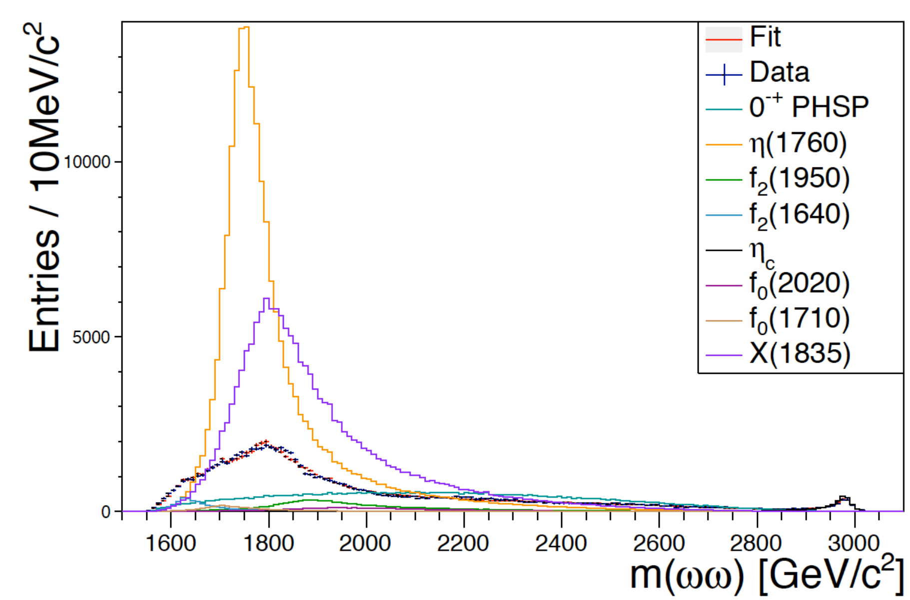
$f_0(1350)$, $\Gamma = 300$
$f_0(1500)$, $\Gamma = 100$



but still might give an equally good description:



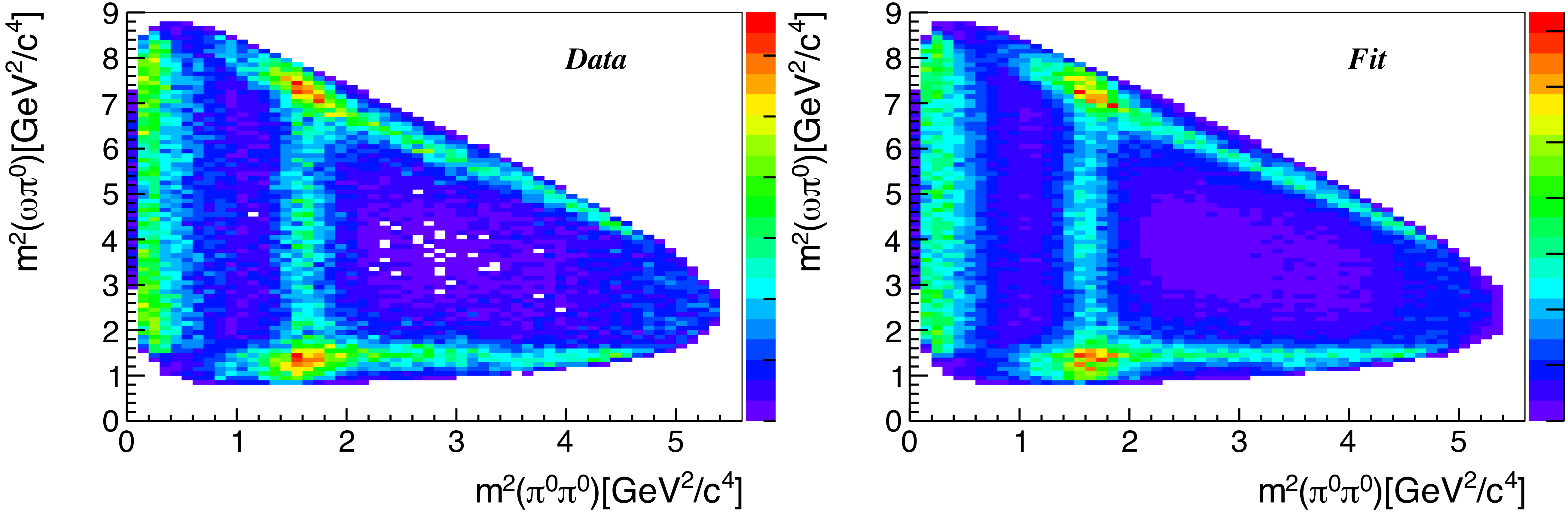
… unfortunately unphysical:



Coupled channel analysis

Baryon-antibaryon final states seem to play an important role in the description of data:

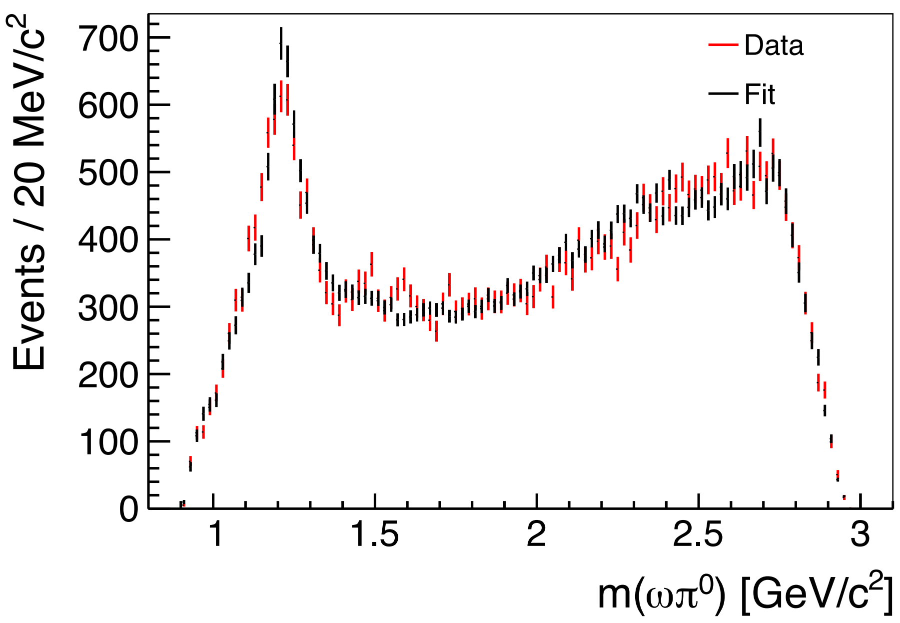
- PWA of final states become much more stable with coupled channel analysis of $\bar{p}p$



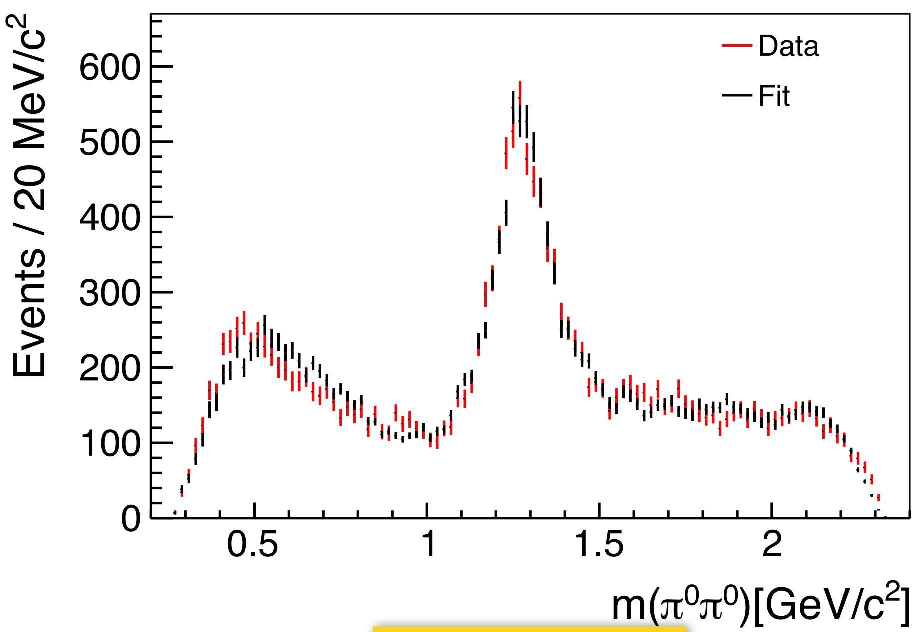
Analysis and coupled channel fit with PAWIAN: X. Qin (Bochum)

Coupled channel analysis

$J/\psi \to \omega\pi^0\pi^0$



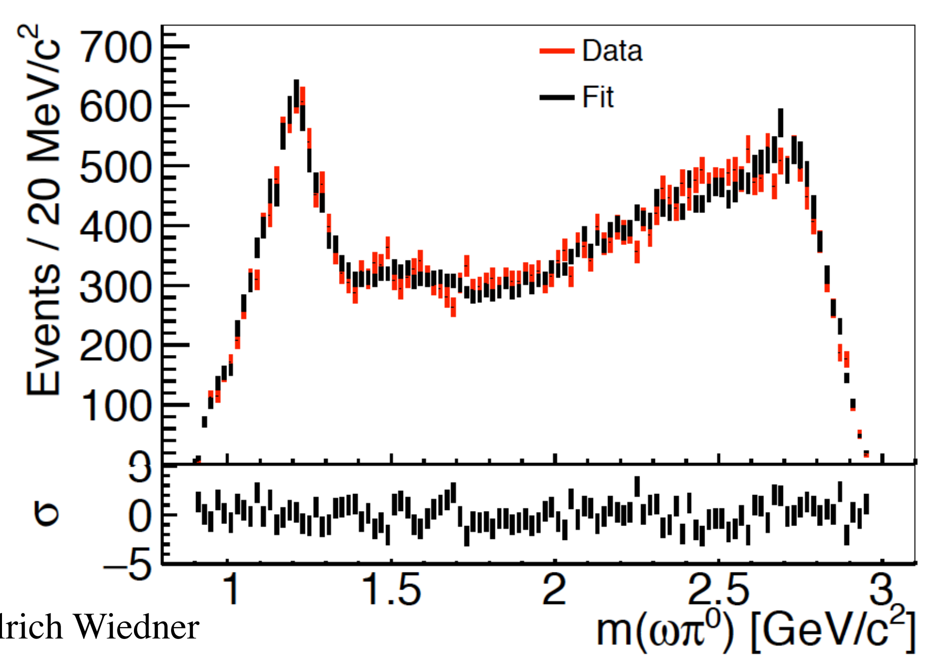
Fit not perfect in all regions



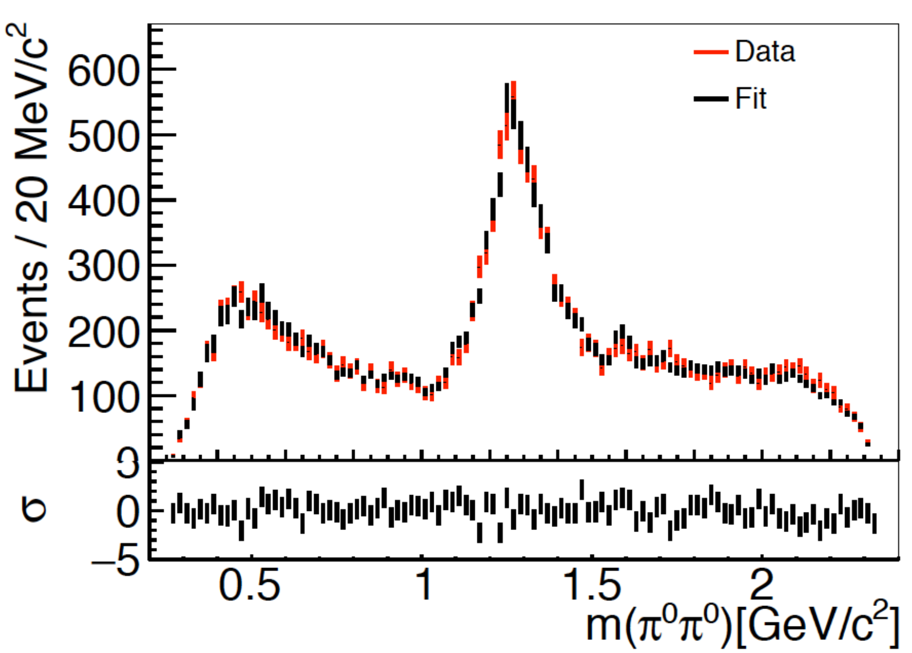
BESIII data: $J/\psi \to \omega\pi^0\pi^0$ and $J/\psi \to \omega p\bar{p}$

Coupled channel analysis including:

Scattering data:
- $\pi\pi \to \pi\pi,\ \bar{K}K,\ \eta\eta,\ \eta\eta'$ (I=0, S-wave)
- $\pi\pi \to \pi\pi,\ \bar{K}K,\ \eta\eta$ (I=0, D-wave)
- $\pi\pi \to \pi\pi$ (I=1, P-wave)



Much better description of data by fit



Data sets have to be analysed for different final states

Analysis of decay patterns necessary to reveal the nature of states:

Glueballs might decay into different final states than molecules, hybrids, four-quark states.

$\Rightarrow$ many different data sets need to be analyzed

$\Rightarrow$ many different decay channels need to be analyzed to establish a new resonance

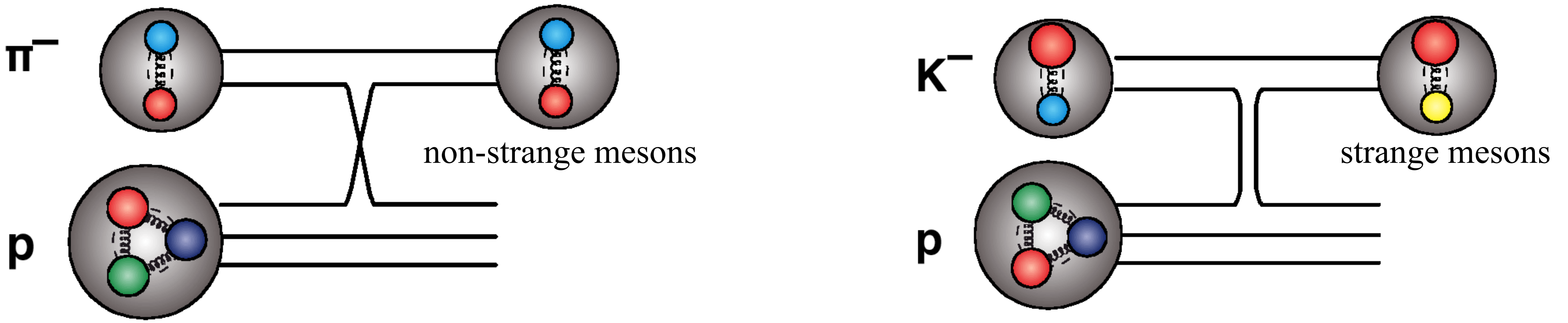
$\Rightarrow$ extensive background studies to be done

The combination of results is almost mandatory for a better understanding of states and observed patterns.

Broader theoretical expertise most welcome.

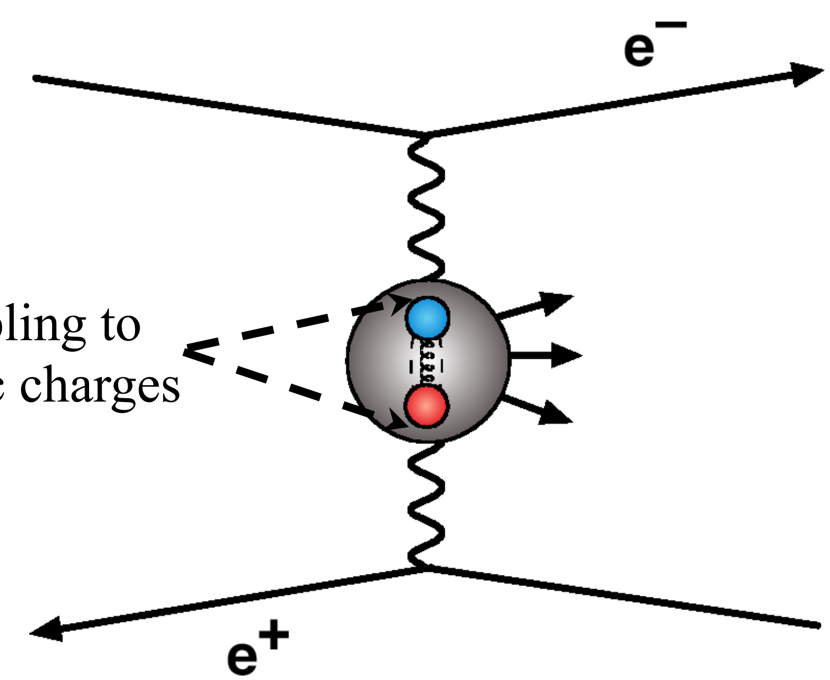
Particle production: “quark-rich” processes

Hadron beams



GAMS (CERN), LASS (SLAC), BNL experiments ...

γγ collisions

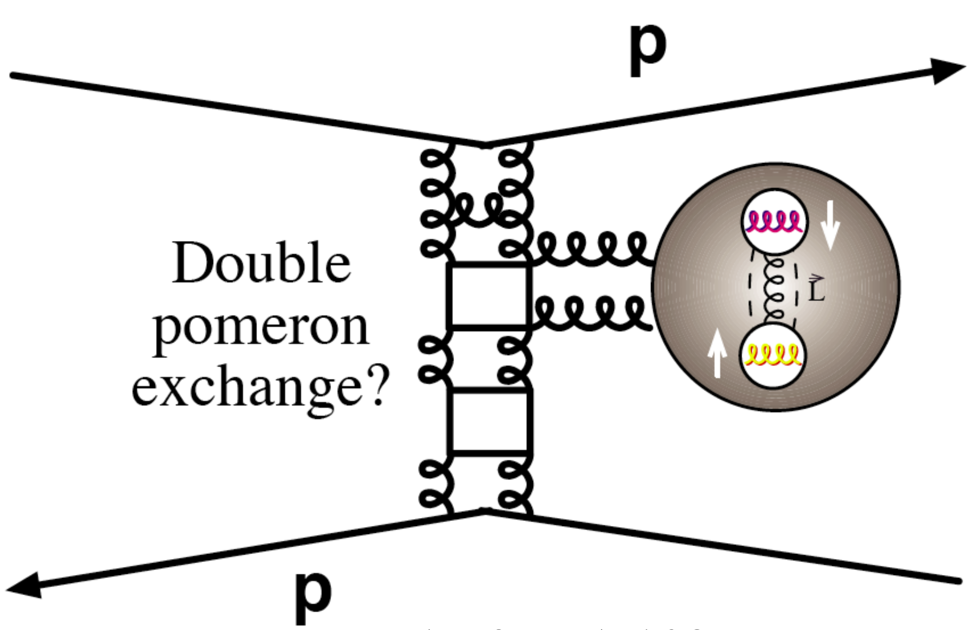


γγ collisions

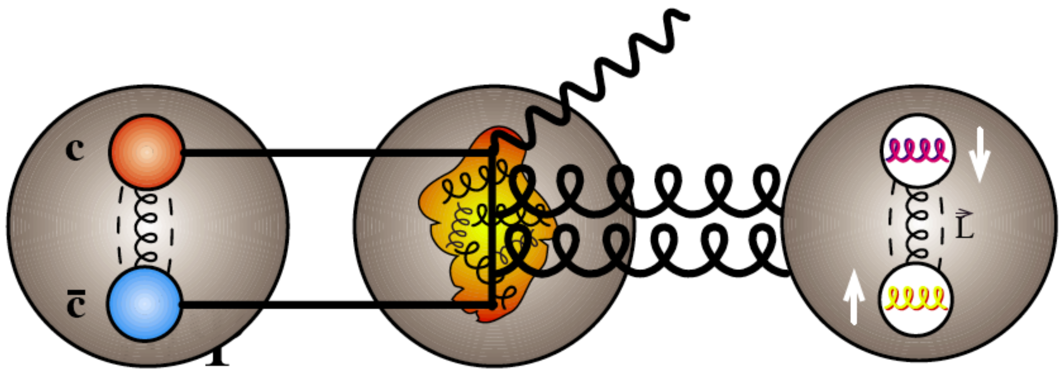
... act as anti-glueball filter

ARGUS, Crystal Ball, LEP experiments ...

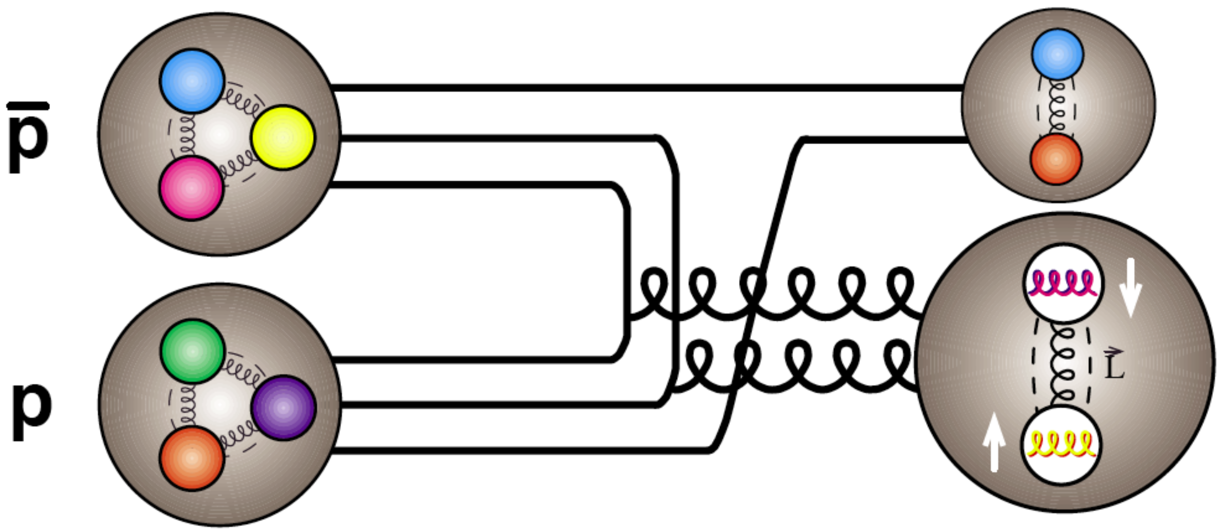
Particle production: “gluon-rich” processes



WA 79, WA 102



MARK III, DM2, BES

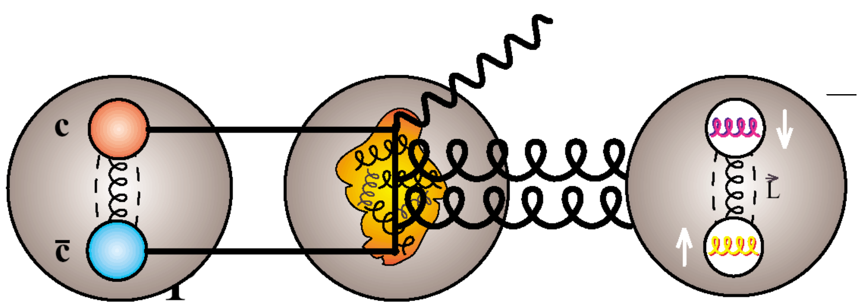


ASTERIX, Crystal Barrel, OBELIX, E835, PANDA

Glueballs are one of the most fascinating facets of QCD:

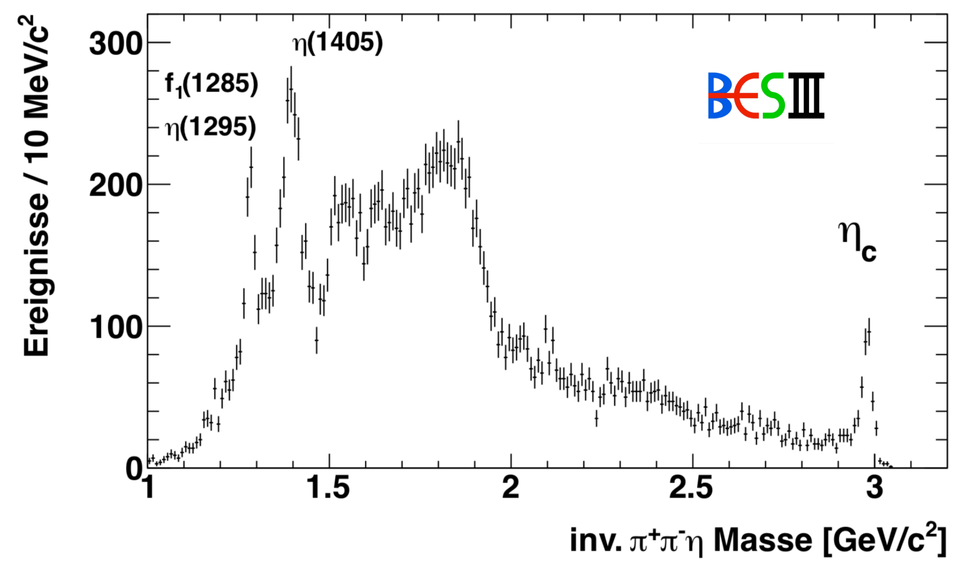
↳ massless gluons come together to form massive states

Many candidates are proposed and observed in gluon-rich processes:



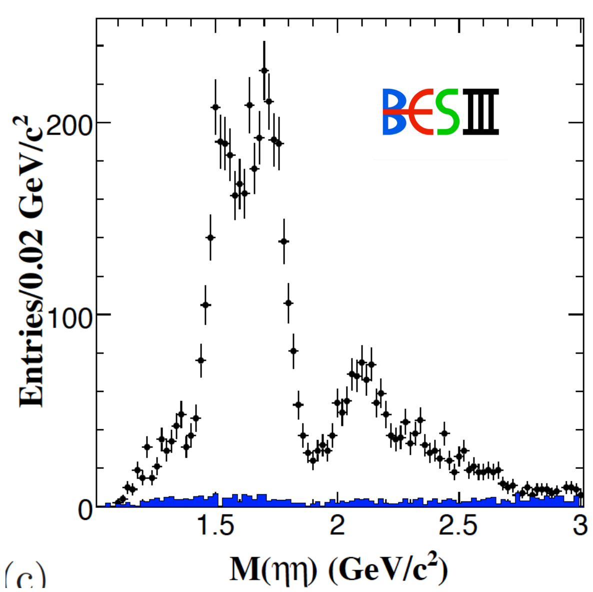
Radiative J/Ψ decays

η(1405)

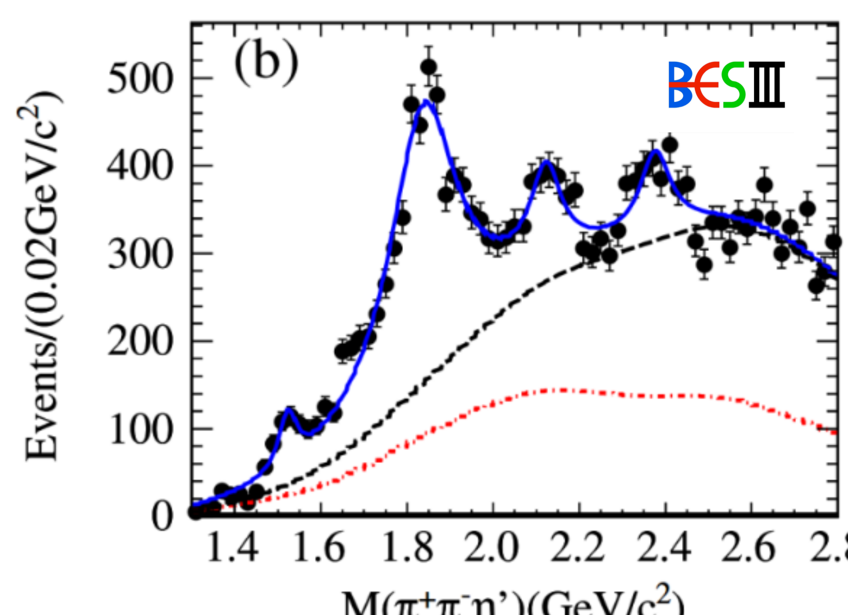


M. Leyhe (Thesis work)

f0(1500) and f0(1710)



X(1835)



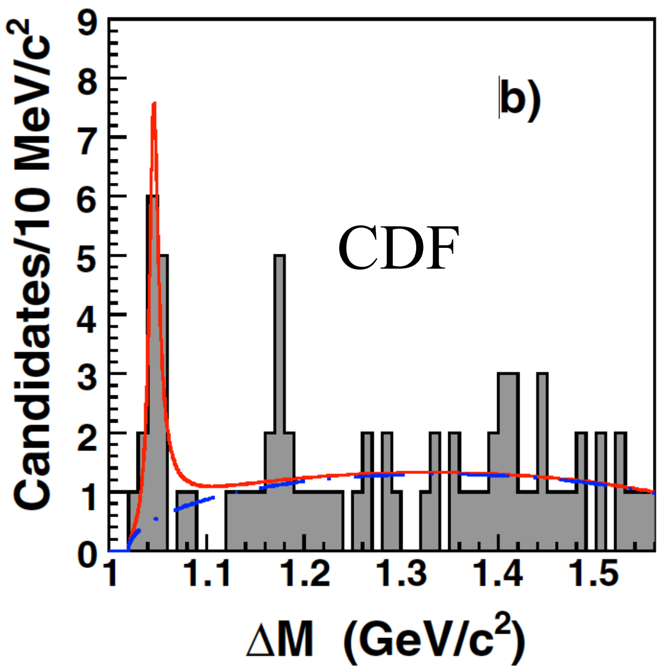
PRL 108, 112003 (2012)
PRL 115, 091803 (2015)

Glueballs

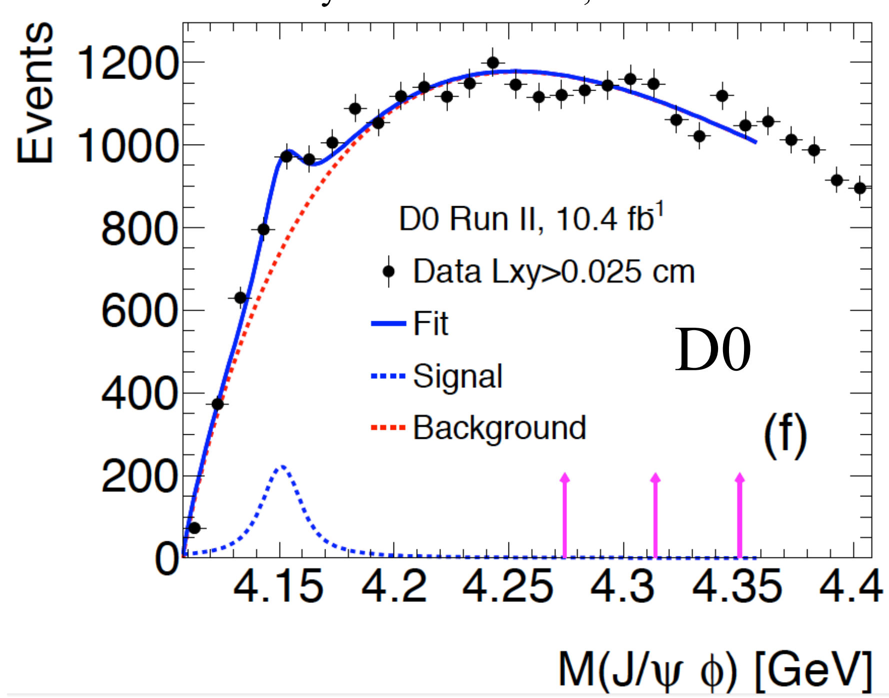
My personal glueball candidate for 1^{++} glueball: X(4140) M= 4147 MeV/c^2 , Γ = ~19 MeV

↳ decay mode $J/\psi\ \phi$ (flavour blind)

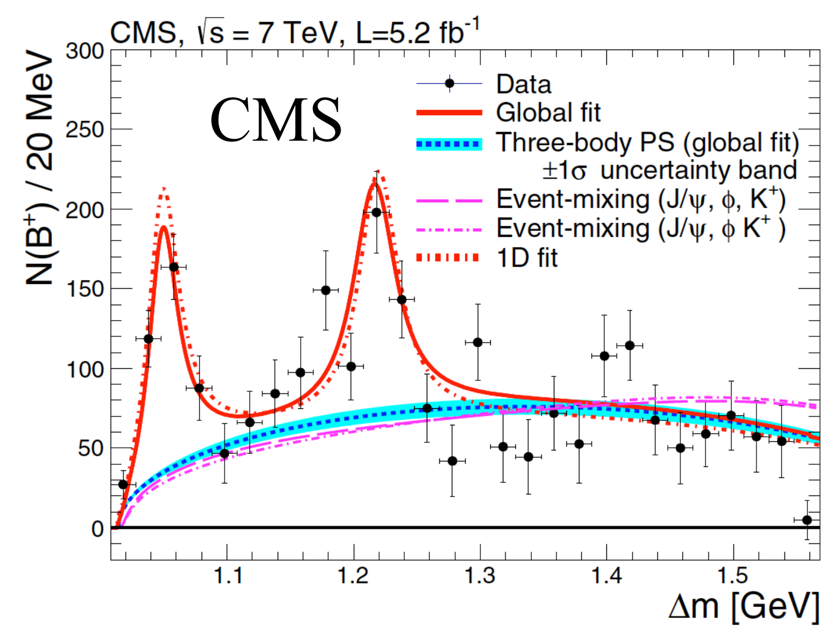
Phys.Rev.Lett. 102 (2009) 242002

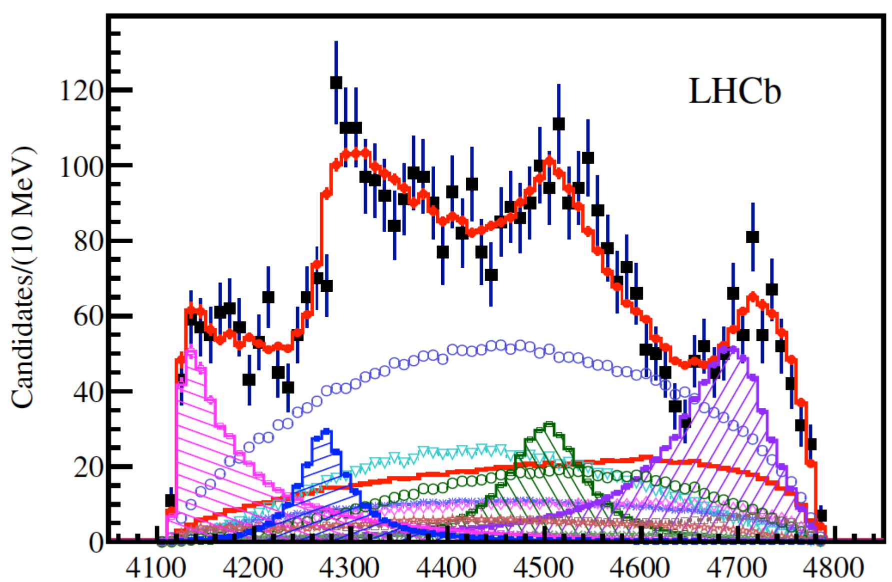


Phys. Rev. Lett. 115, 232001

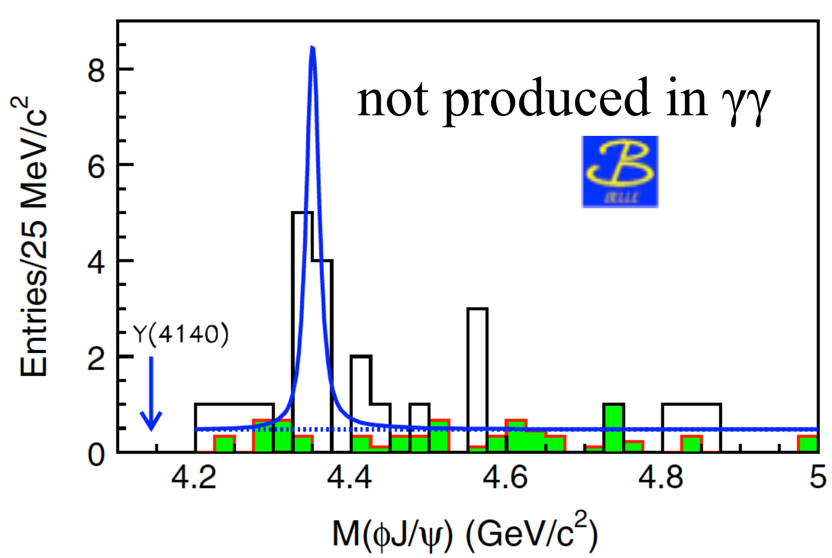


Phys.Lett. B734 (2014) 261-281

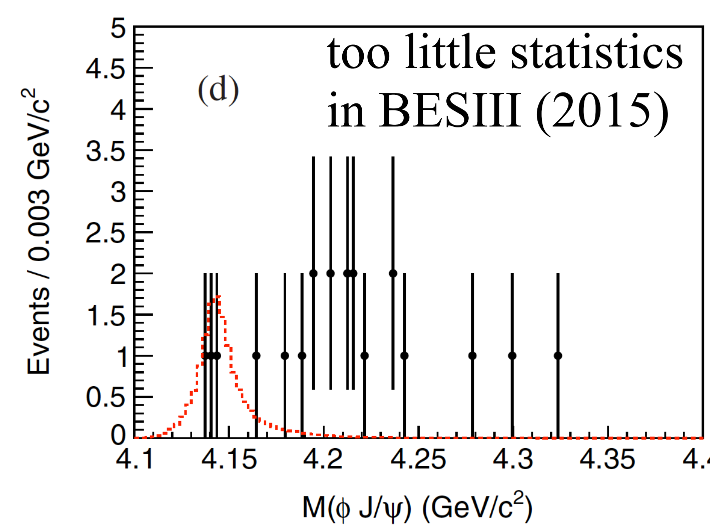




Phys.Rev.Lett. 118 (2017) no.2, 022003



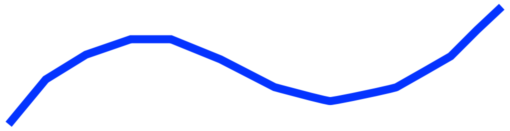
Phys.Rev.Lett. 104 (2010) 112004



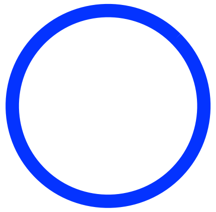
Phys.Rev. D91 (2015) no.3, 032002

Glueballs: connection to string theory?

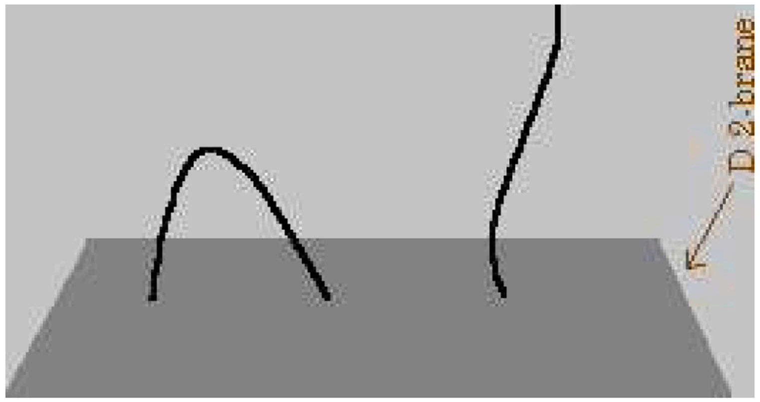
Open Strings



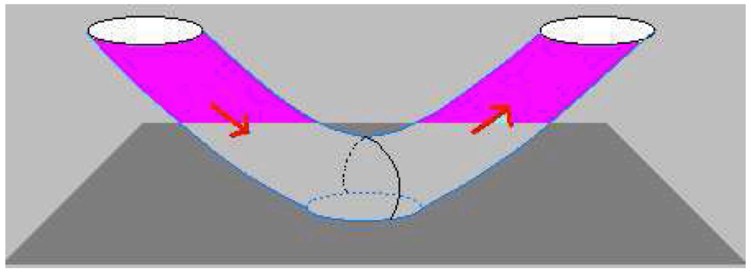
Closed Strings



String World

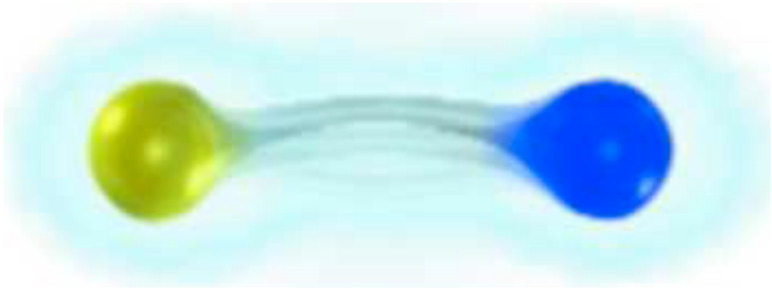


representing gauge theories

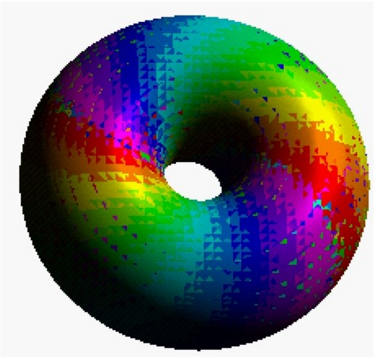


representing gravitation

Hadron World



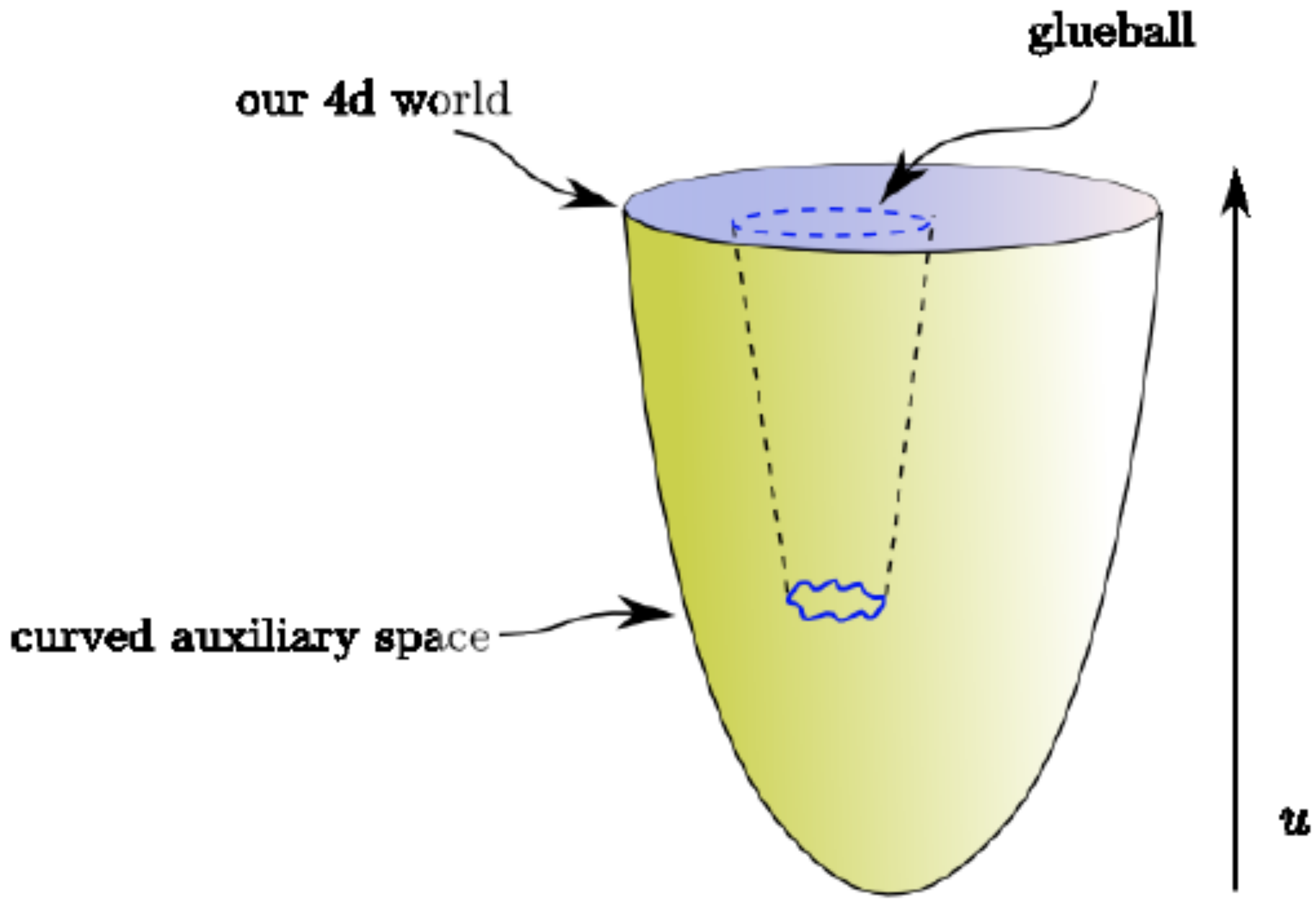
meson



glueball ?

Maldacena correspondence

- The string is ten-dimensional ! Maldacena 1997

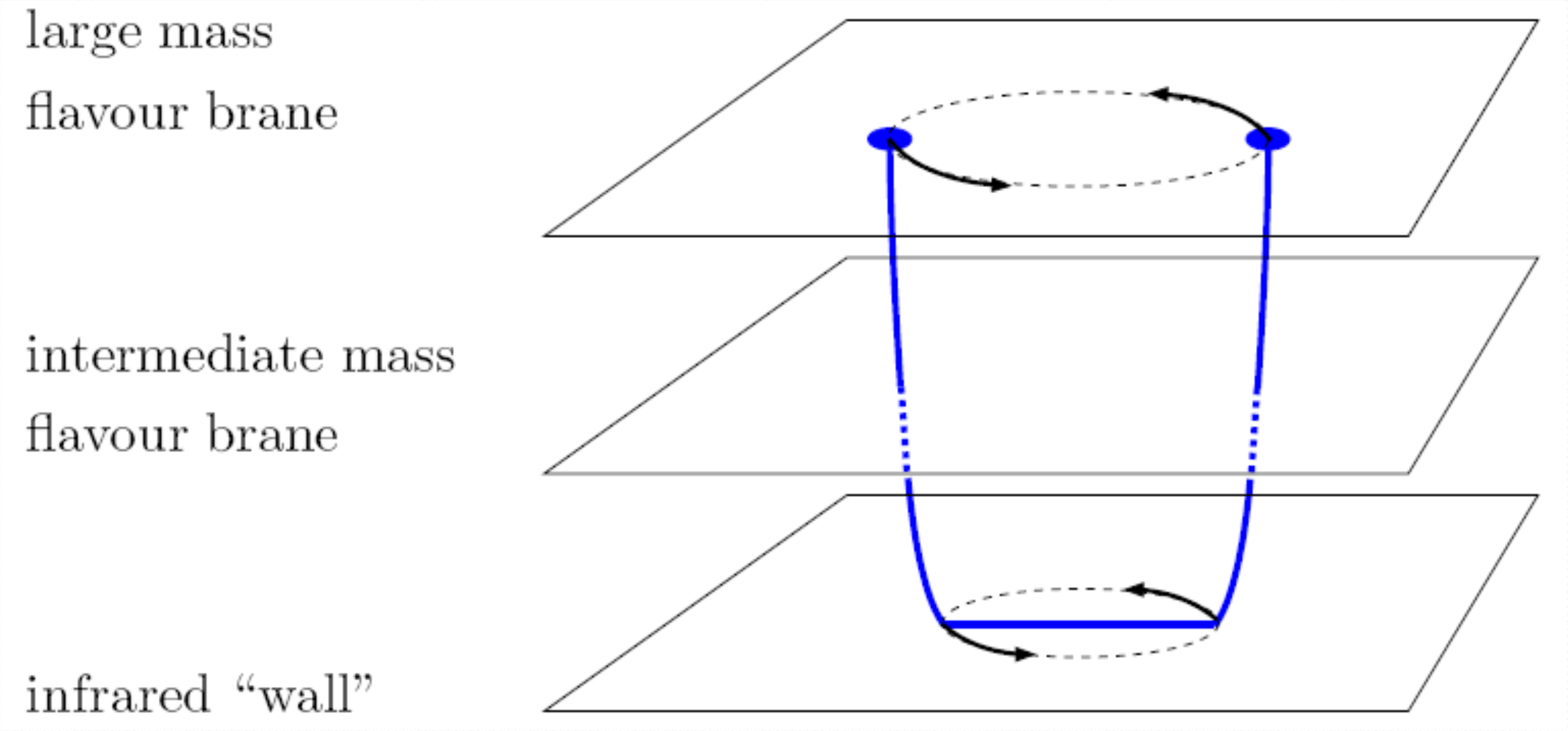


- The curvature in string-size units sets the 't Hooft coupling: $\lambda \sim \left(\frac{R}{l_{\text{string}}}\right)^4$.
- $R \gg l_{\text{string}}$: strings reduce to gravity: gauge/gravity correspondence.
- We will make this relation precise in a moment.

Jacob Sonnenschein: "Holographic Inspired Stringy Hadrons: arXiv:1602.00704

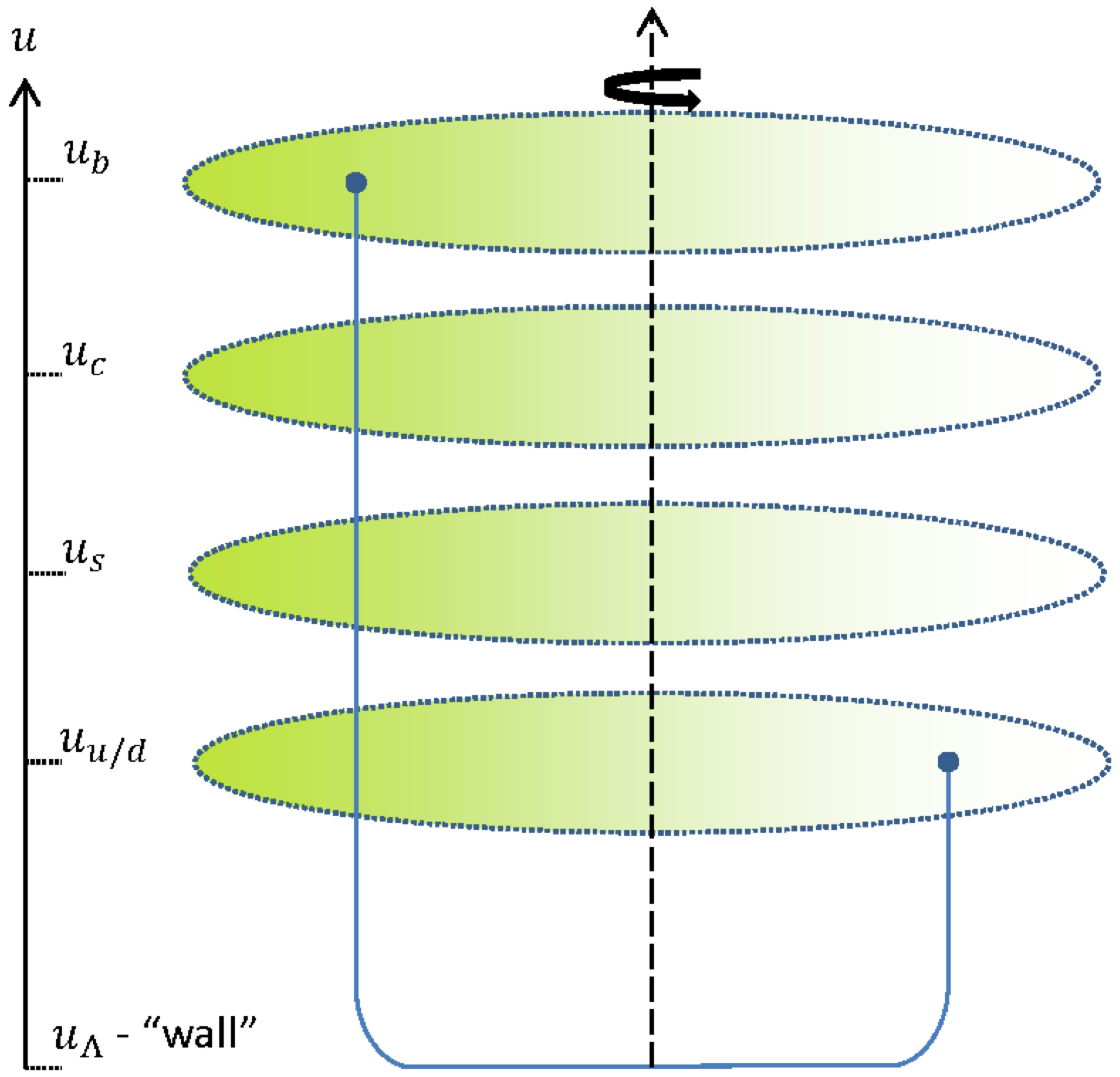
The structure of a rotating holographic string

- Thus the structure of a holographic meson connected to a large mass flavor brane



Jacob Sonnenschein: "Holographic Inspired Stringy Hadrons: arXiv:1602.00704

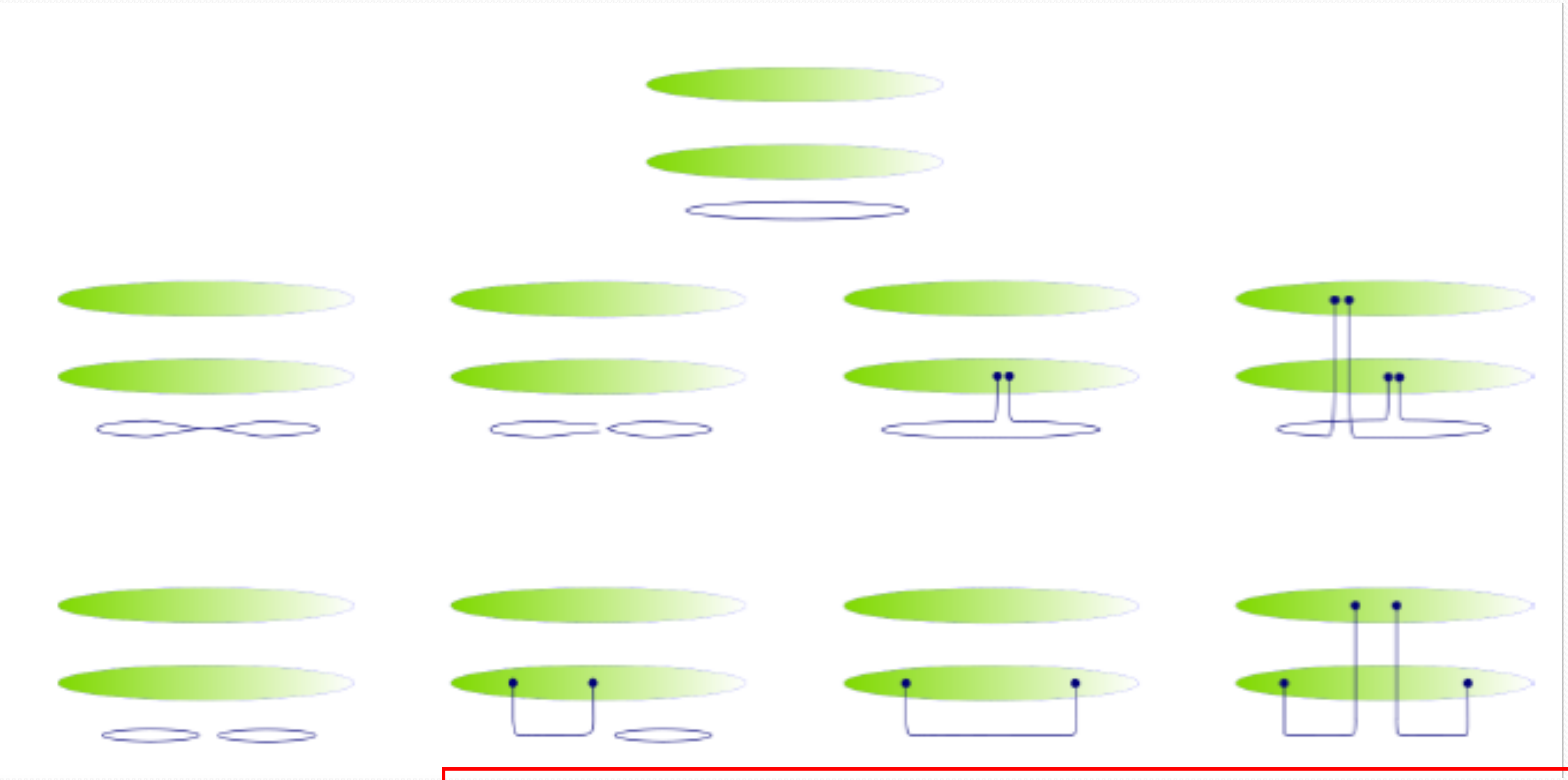
Example: The B meson



Jacob Sonnenschein: "Holographic Inspired Stringy Hadrons: arXiv:1602.00704

Decay of glueballs

- The glueball which is a folded rotating closed string can decay



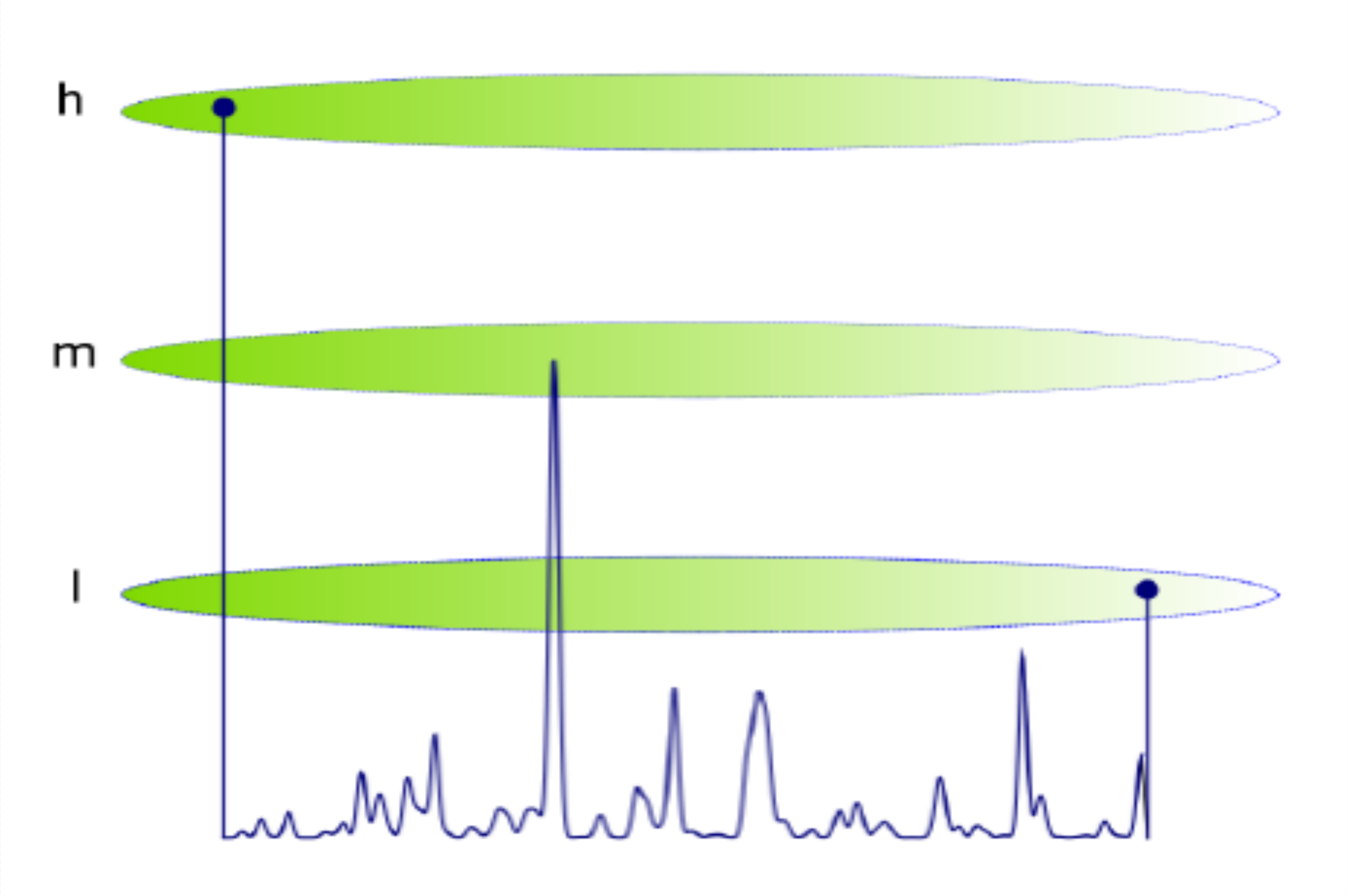
- The width

$$\Gamma_a \sim L\Gamma_{\text{cross}} \qquad \Gamma_b \sim L\Gamma_{\text{cross}} e^{-2\pi C m_{sep}^2/T}$$

$$\Gamma_c \sim L e^{-2\pi C m_{sep}^2/T} \qquad \Gamma_d \sim L^2 e^{-2\pi C m_{sep}^2/T} e^{-2\pi C m_{sep}'^2/T}$$

The suppression factor for stringy holographic hadrons

- The horizontal segment of the stringy hadron **fluctuates** and can reach flavor branes
- When this happens the string may **break up** , and the two new endpoints connect to a flavor brane



Jacob Sonnenschein: “Holographic Inspired Stringy Hadrons: arXiv:1602.00704

Decays of glueballs

- Recall that the width of the decay of a meson into two mesons is

$$\Gamma \propto L e^{-m_q^2/T}$$

- In a similar way the width for the decay of a glueball into two mesons is

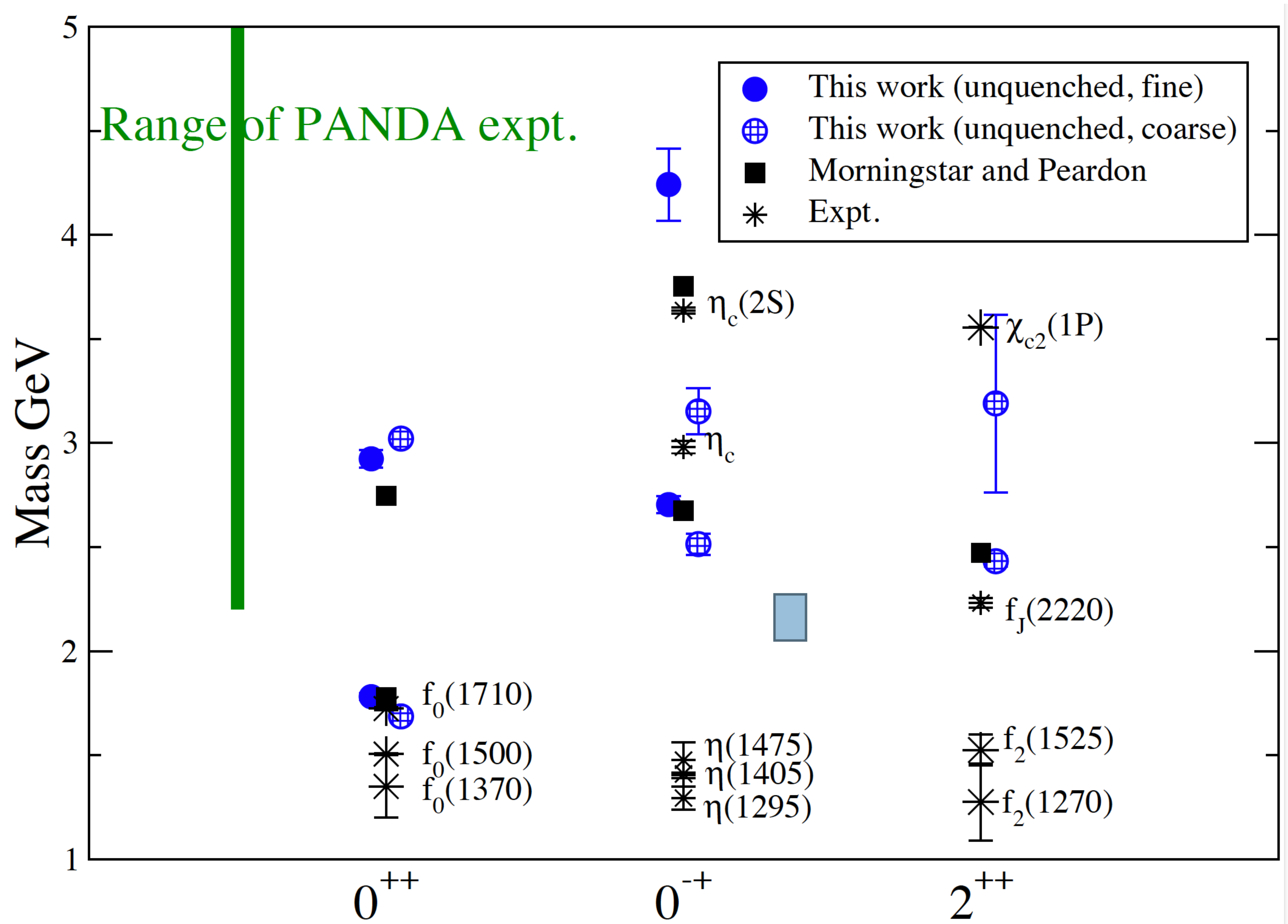
$$\Gamma \propto L \exp(-\frac{m_q^2}{T}) \exp(-\frac{m_{q'}^2}{T})$$

- Thus we get the following hierarchy for the decay of glueballs

$$\Gamma(Gb \to 2 \text{ light}) : \Gamma(Gb \to K\bar{K}) : \Gamma(Gb \to \phi\phi) = 1 \ : e^{-1} \ : e^{-2}$$

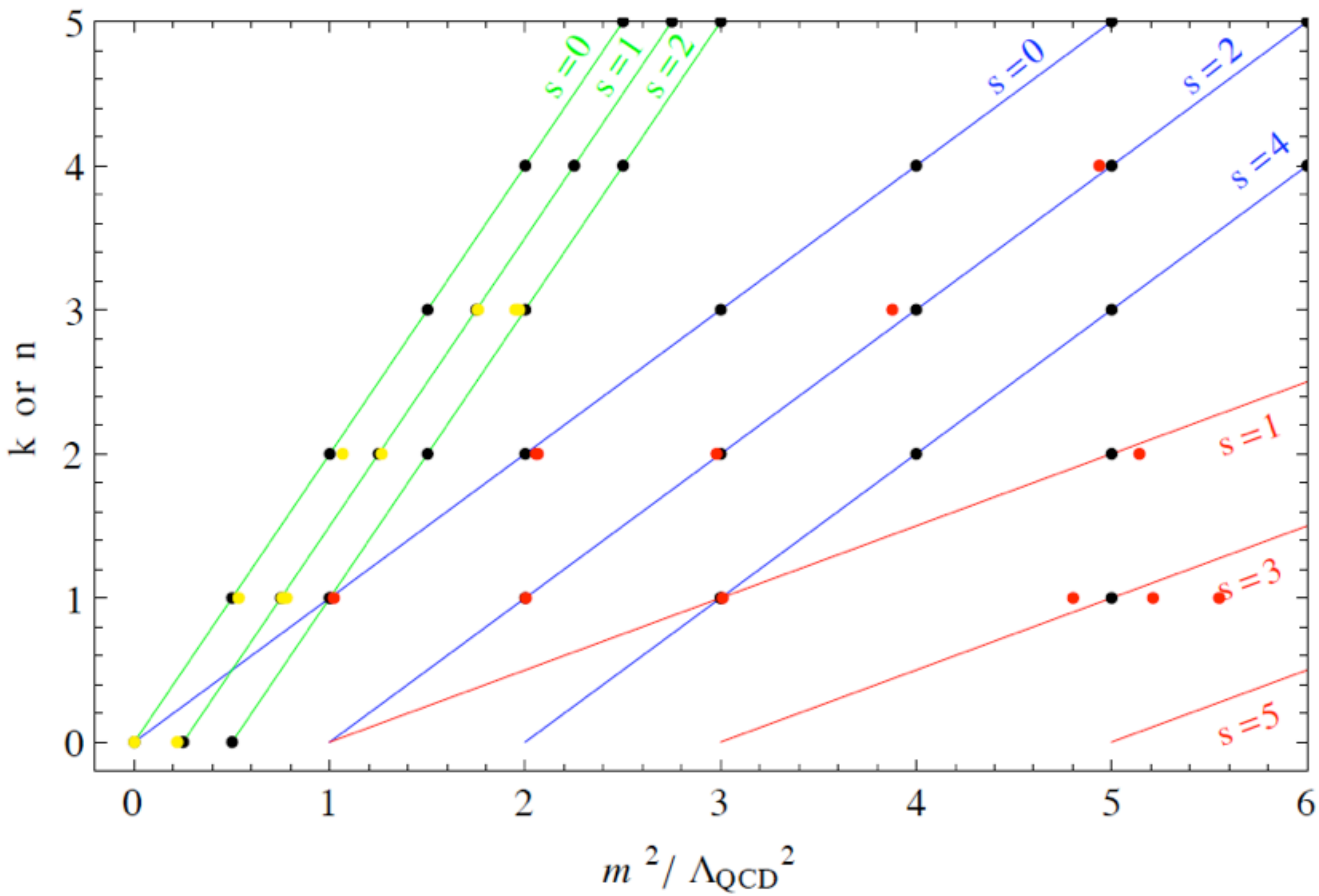
$$\Gamma(GB \to \omega\omega) : \Gamma(GB \to K^{*0}K^{*0}) : \Gamma(GB \to \phi\phi) = 1 : 0.30 : 0.07.$$

Glueballs on the lattice



UKQCD Collaboration, C. M. Richards, A. C. Irving, E. B. Gregory, and C. McNeile, Glueball mass measurements from improved staggered fermion simulations, Phys. Rev. D82 (2010) 034501, [arXiv:1005.2473].

Glueballs on Regge trajectories like mesons?

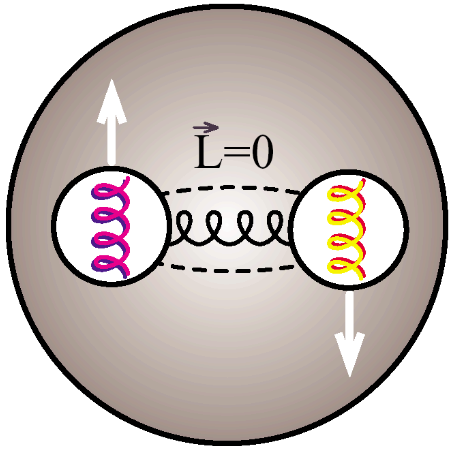


Marco Bochicchio; arXiv:1308.2925

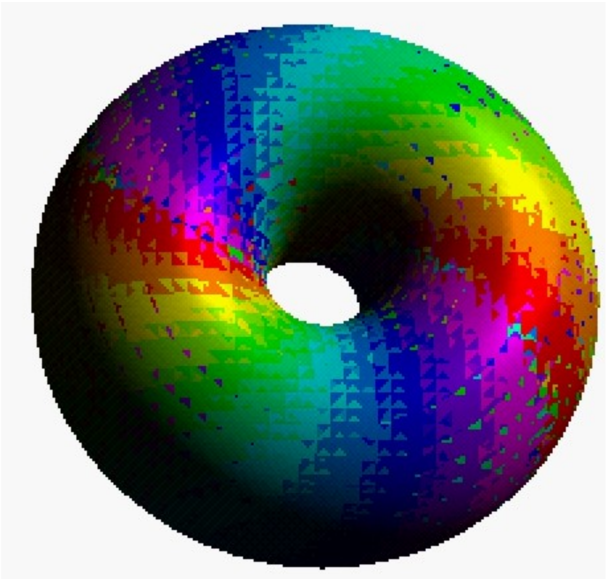
Harvey B. Meyer, Michael J. Teper; Phys.Lett. B605 (2005) 344-354

G. S. Bali et al.; arXiv:1302.1502

The structure of Glueballs

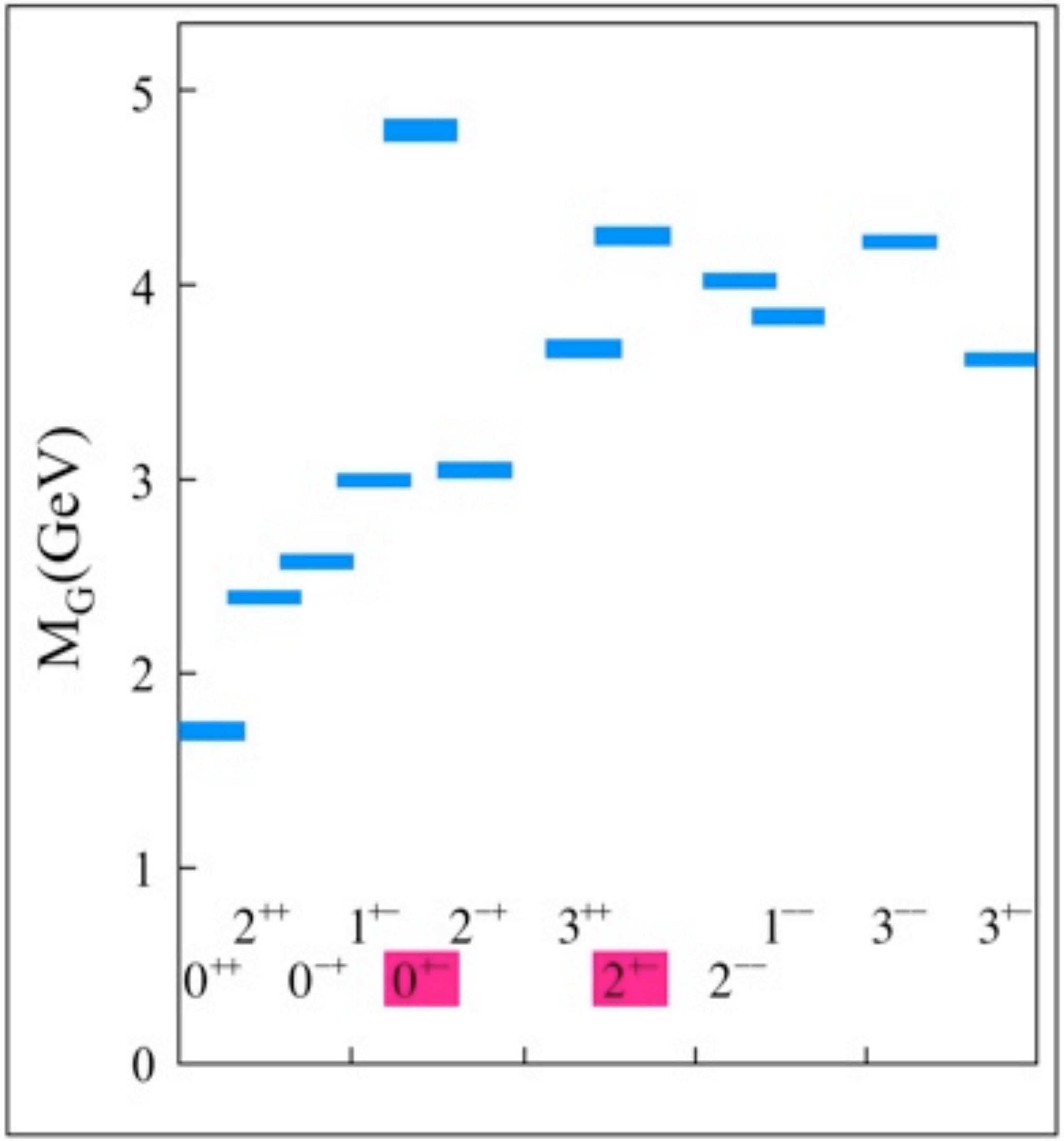


Glueball (gg)

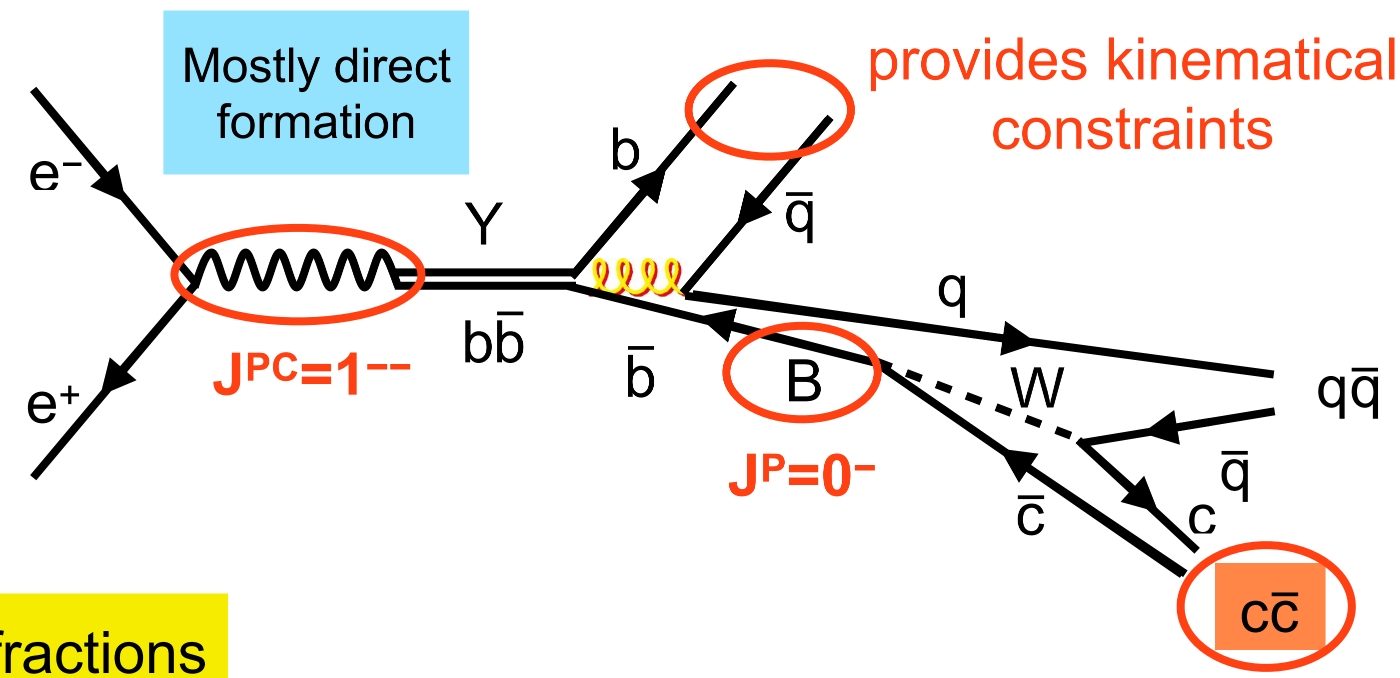


GLUEBALLS, FLUXTUBES AND η(1440).
L. Fadeev, A. Niemi and U. Wiedner Phys.Rev.D70:114033, 2004

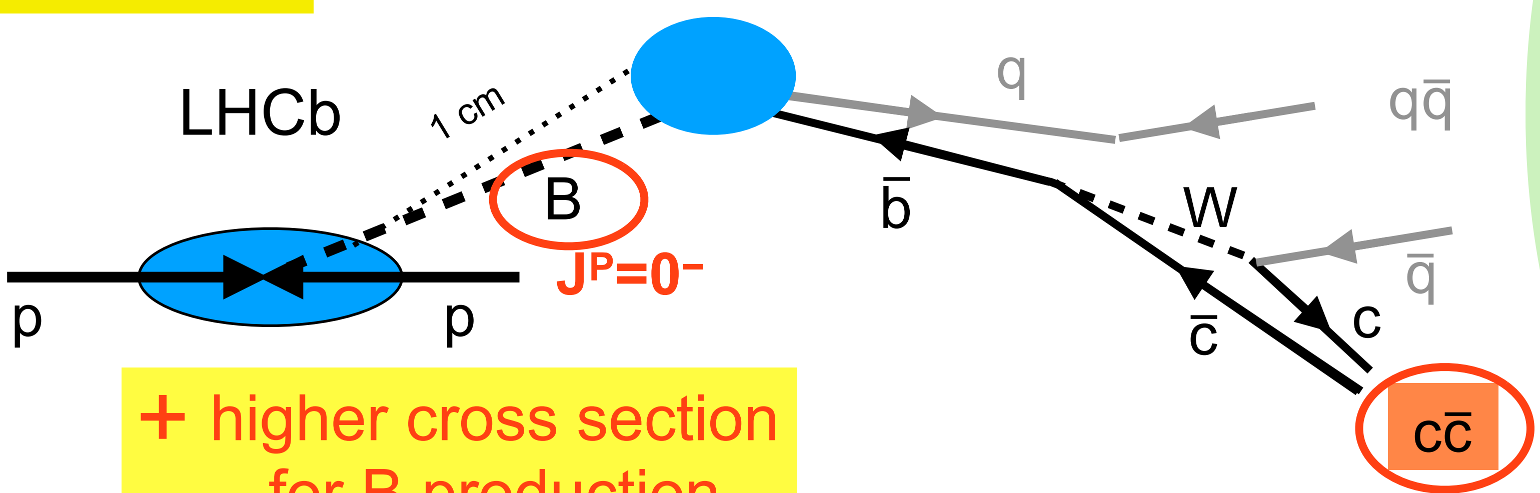
A possible Glueball spectrum predicted by lattice



$c\bar{c}$ production at e^+e^- colliders and at LHCb



Typical branching fractions for decays into charmonia $\leq 10^{-4}$



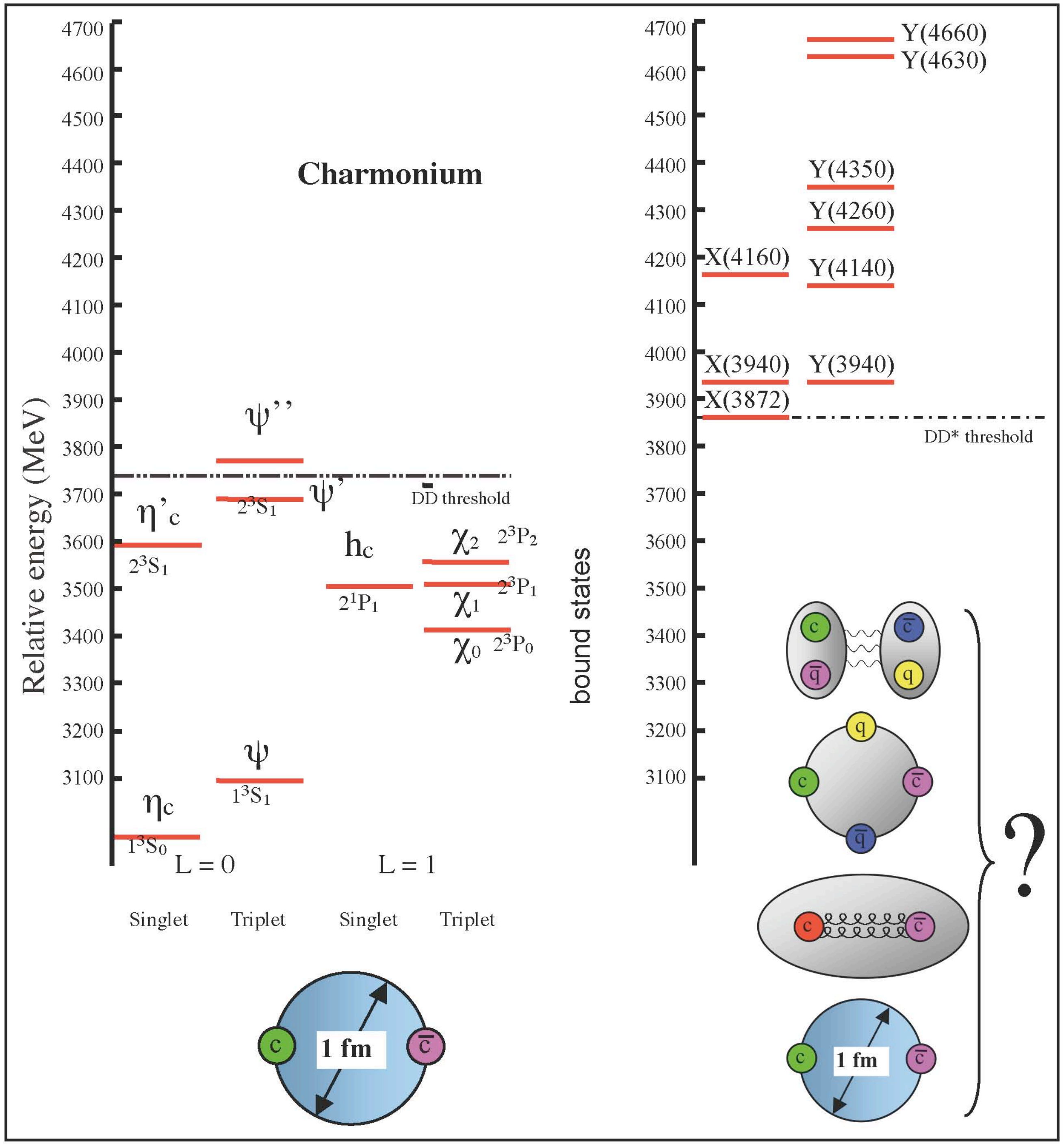
quantum numbers limited to low spins

quantum numbers limited to low spins

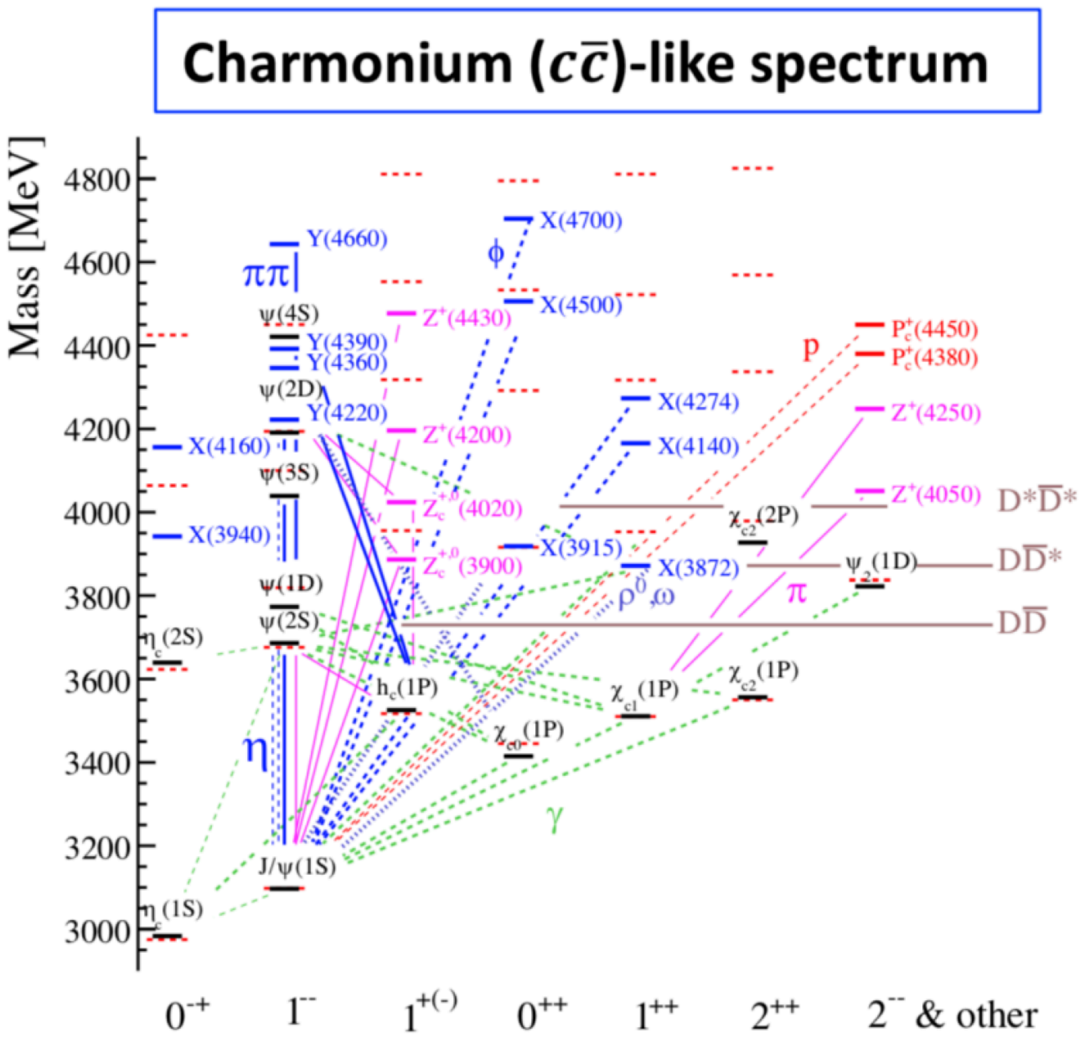
+ higher cross section for B production

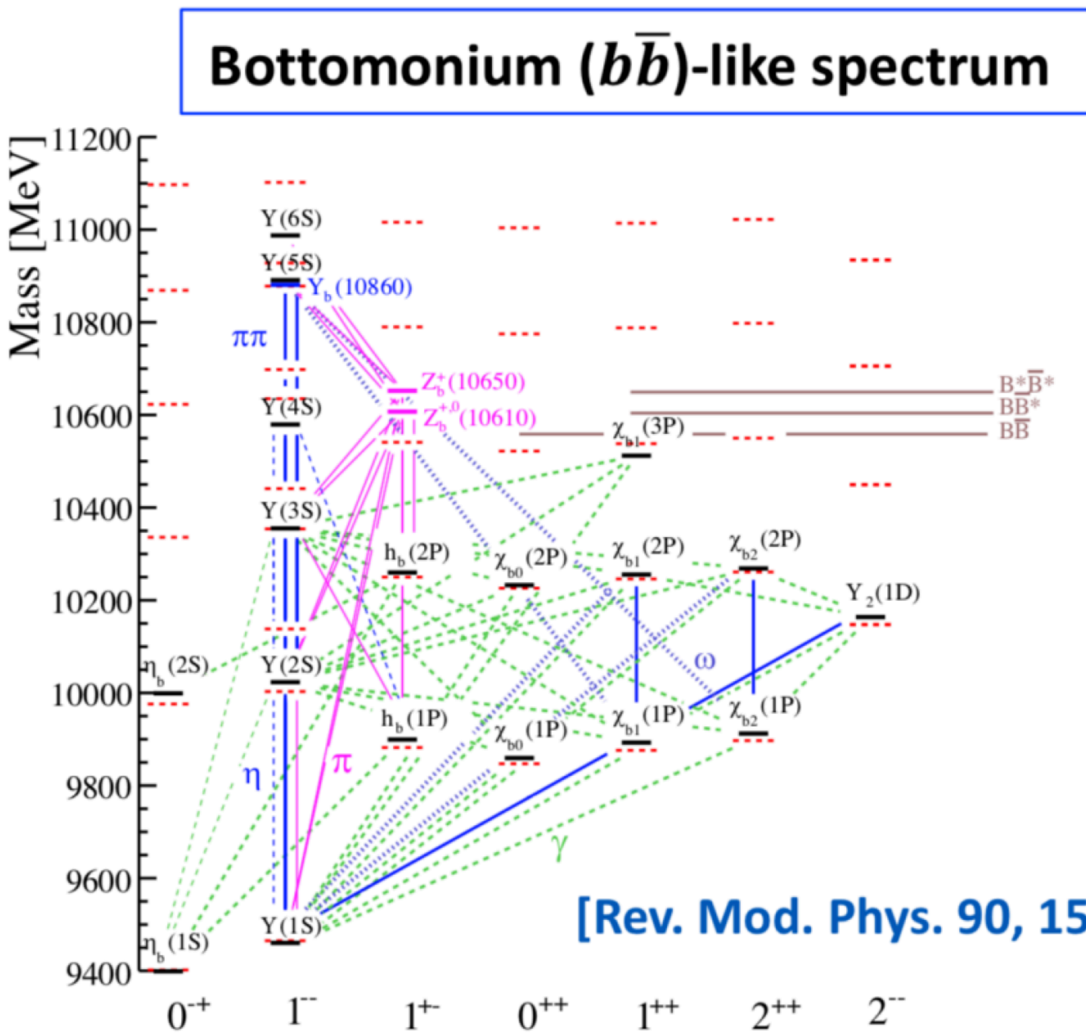
− missing kinematical constraints lead to reduced resolution

Particles not fitting conventional charmonium resonances: X, Y states



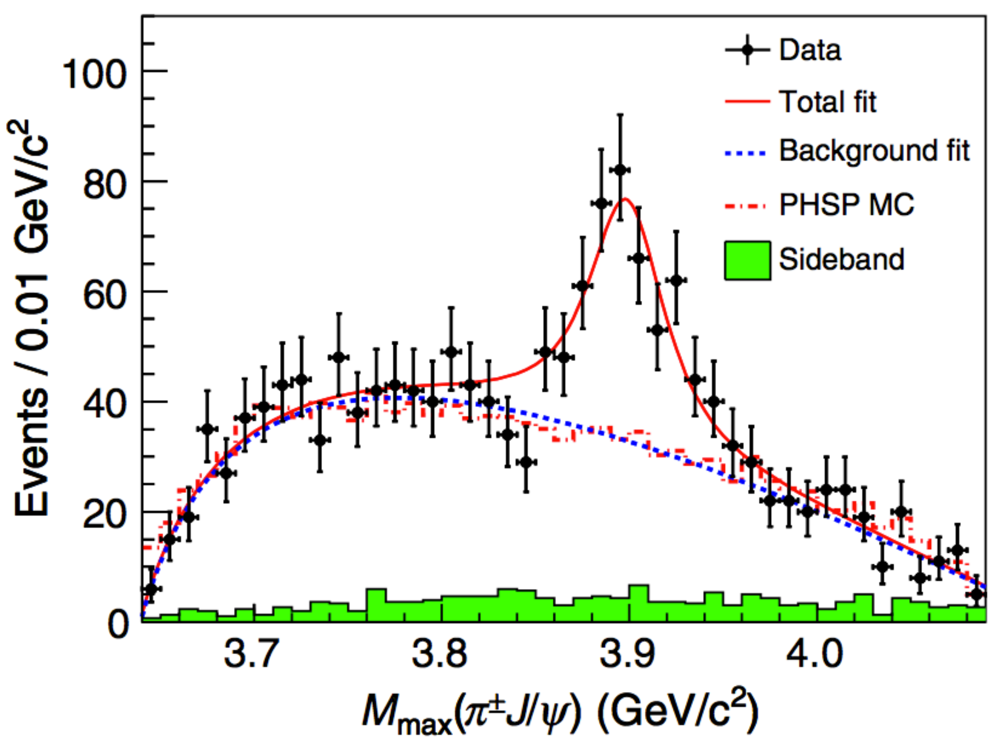
Particles not fitting conventional charmonium resonances: X, Y states



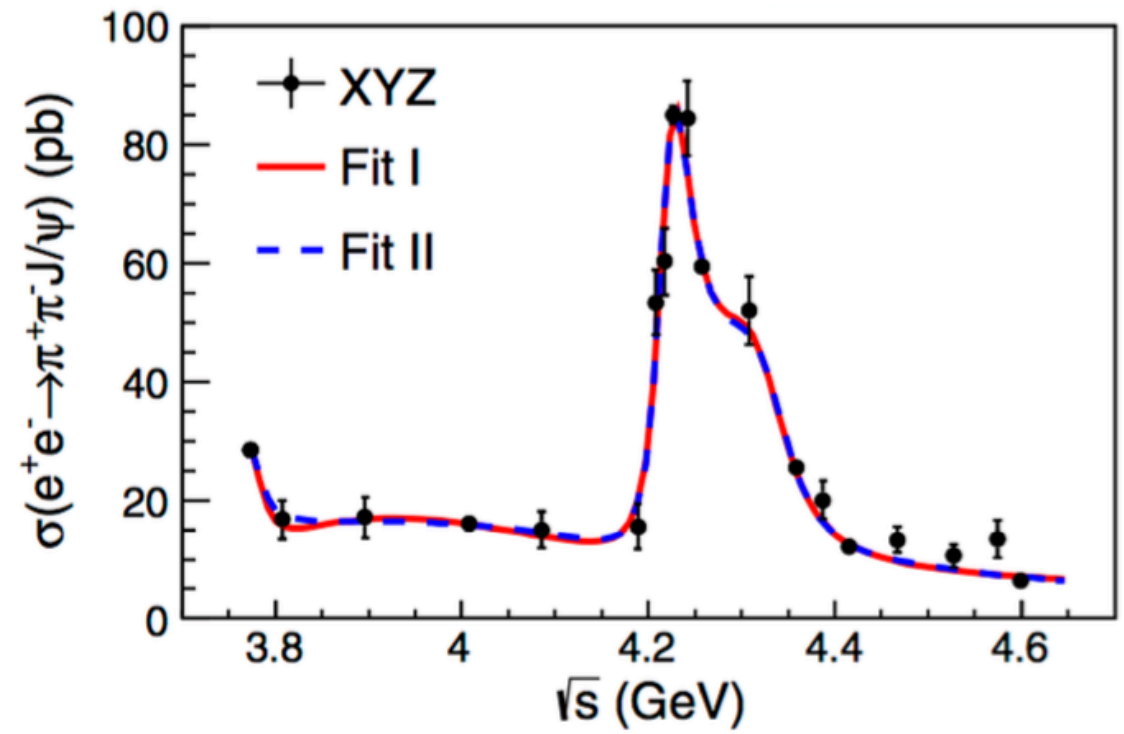


[Rev. Mod. Phys. 90, 15003 (2018)]

X, Y, Z exotics have been observed



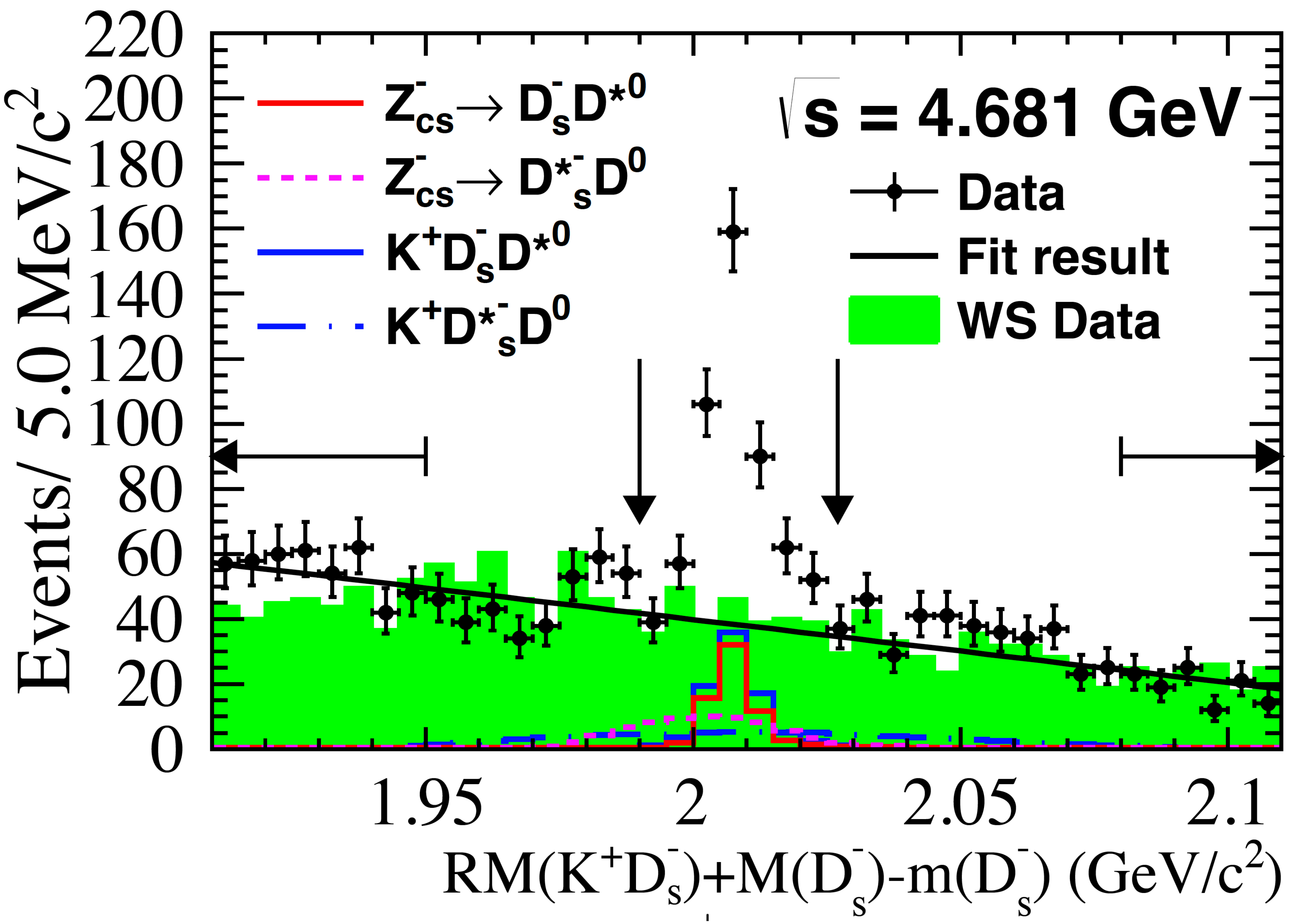
Discovery of $Z_c^{\pm}(3900) \to J/\psi\, \pi^{\pm}$
in the decay $Y(4260) \to J/\psi\, \pi^+\pi^-$



Precision cross section measurement
$e^+e^- \to Y(4260) \to J/\psi\, \pi^+\pi^-$
First observation: $\Psi(4360) \to J/\psi\, \pi^+\pi^-$

- Search for complementary final states
- Find isoscalar partners (if existent)
- Characterise X, Y, Z states

The most obvious exotic: Z_{cs}

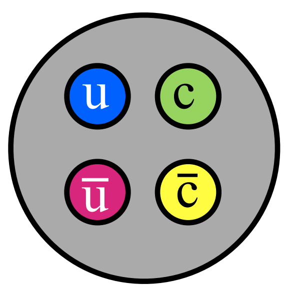


What are these new states?

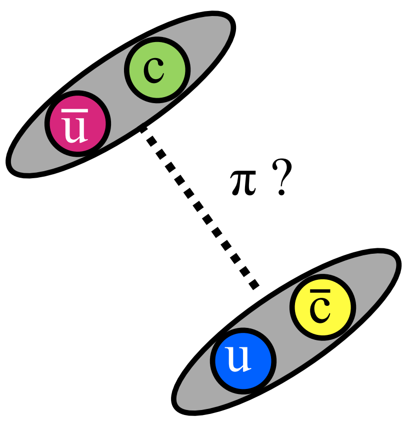
Colorful and colorless strong interaction

Compact objects
→ strong binding force

Other bound states
→ weaker binding force



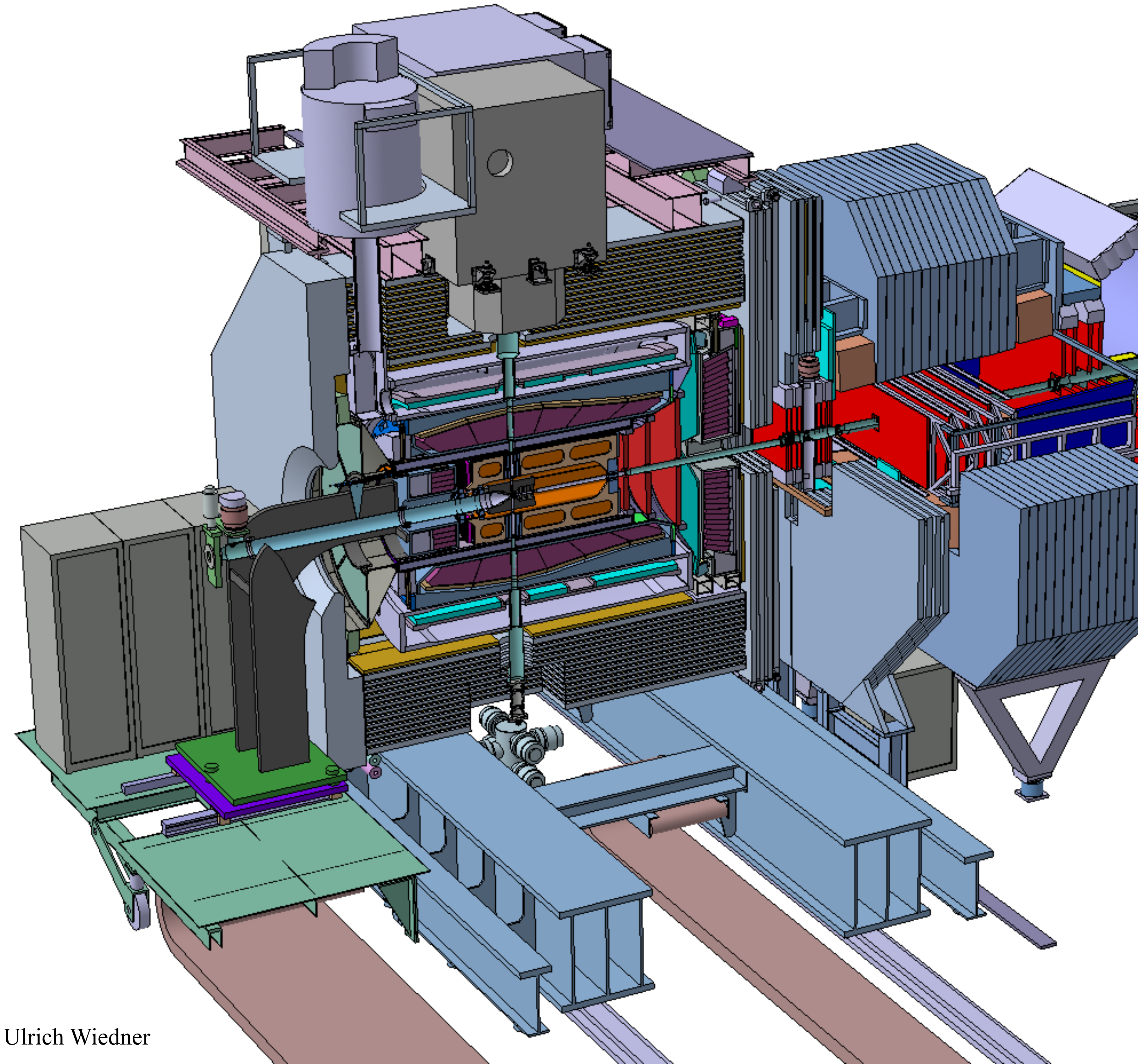
4-quark state



D-$\bar{D}$-“molecule”

How to distinguish? ☛ theory !

The $\overline{\text{P}}$ANDA detector at FAIR



Detector requirements:
4π acceptance

High rate capability:
$2\times10^{7}\ s^{-1}$ interactions

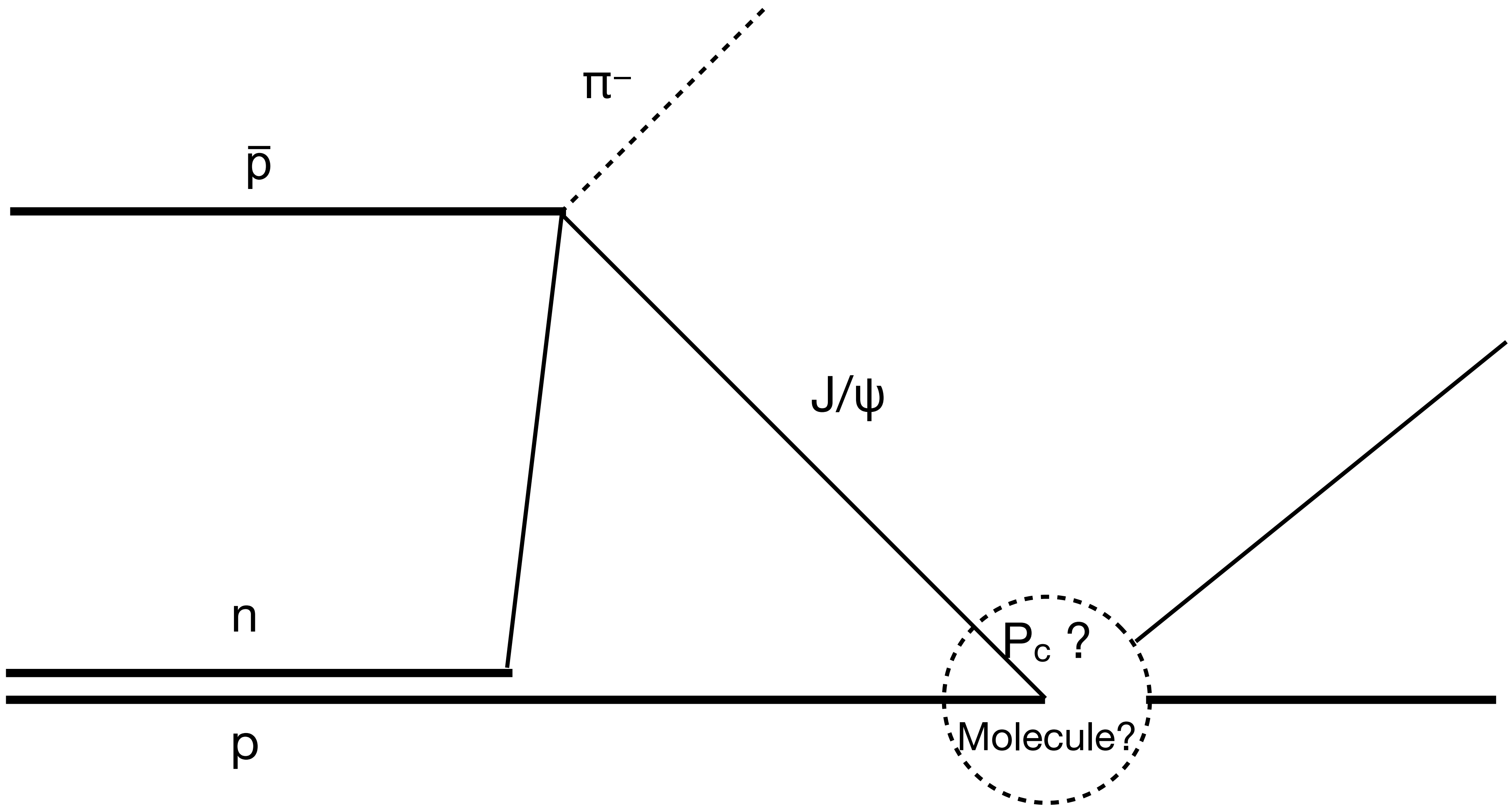
Efficient event selection
➔Continuous acquisition

Momentum resolution ~1%
Vertex info for D, K^0_s, Y
($c\tau$ = 317 μm for $D^{\pm}$)
➔Good tracking

Good PID (γ, e, μ, π, K, p)
➔Cherenkov, ToF, dE/dx

γ-detection 1 MeV – 10 GeV
➔Crystal Calorimeter

J/ψ - N interaction on fundamental level



$\Sigma_c^{++} + \bar{D}^-$

(exchange of d-quark)

$\Lambda_c^+ + \bar{D}^0$

(exchange of u-quark)

Thanks a lot!