Puzzles in Hadron Physics and their Experimental Investigations

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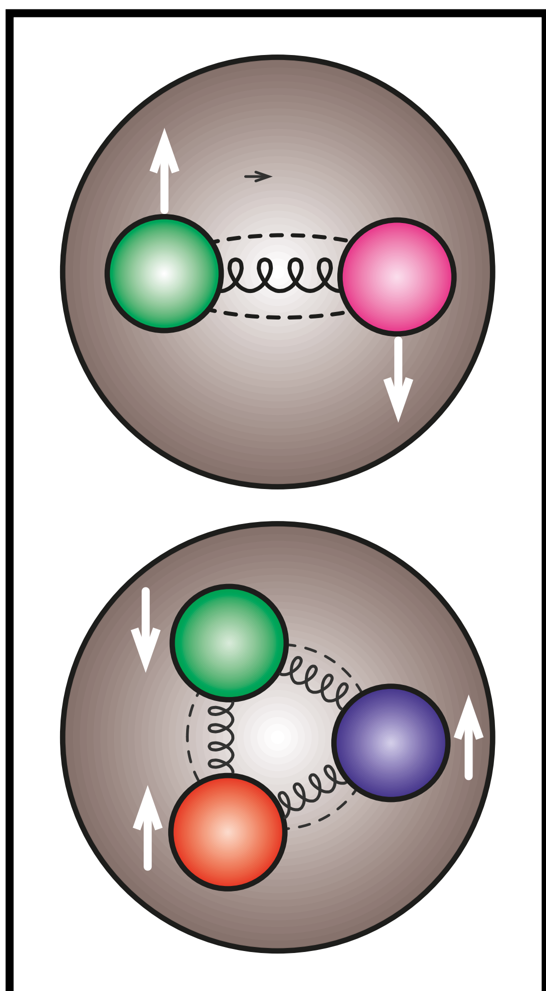
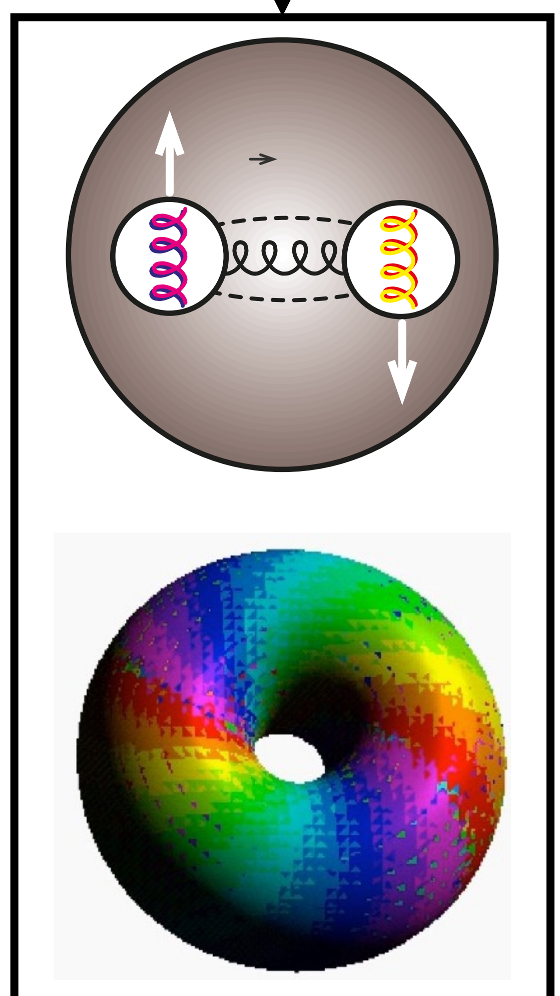
Ruhr-University Bochum

Camburi, May 1, 2018

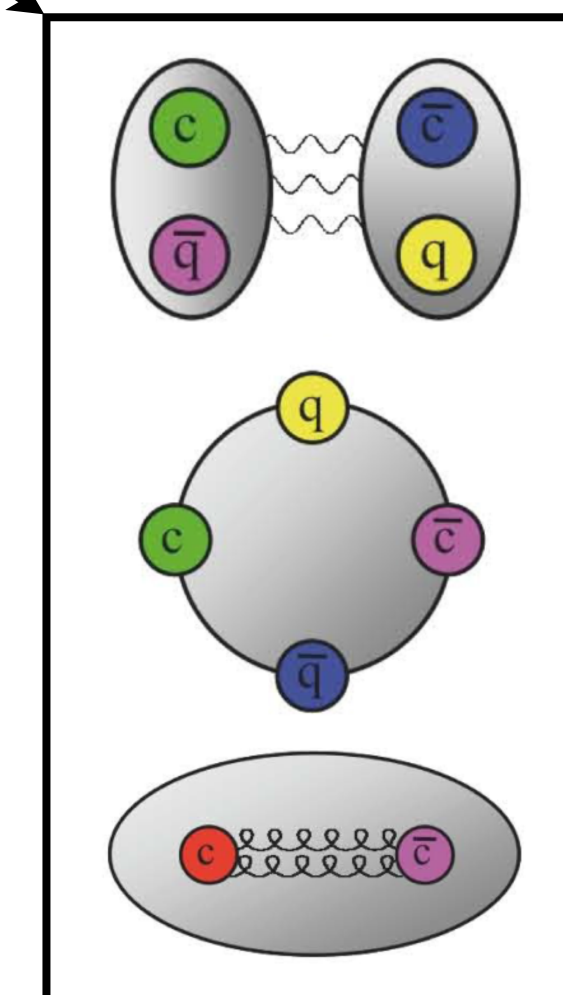
Hadron physics

Hadron physics and non-perturbative QCD are complex





Glueballs



X

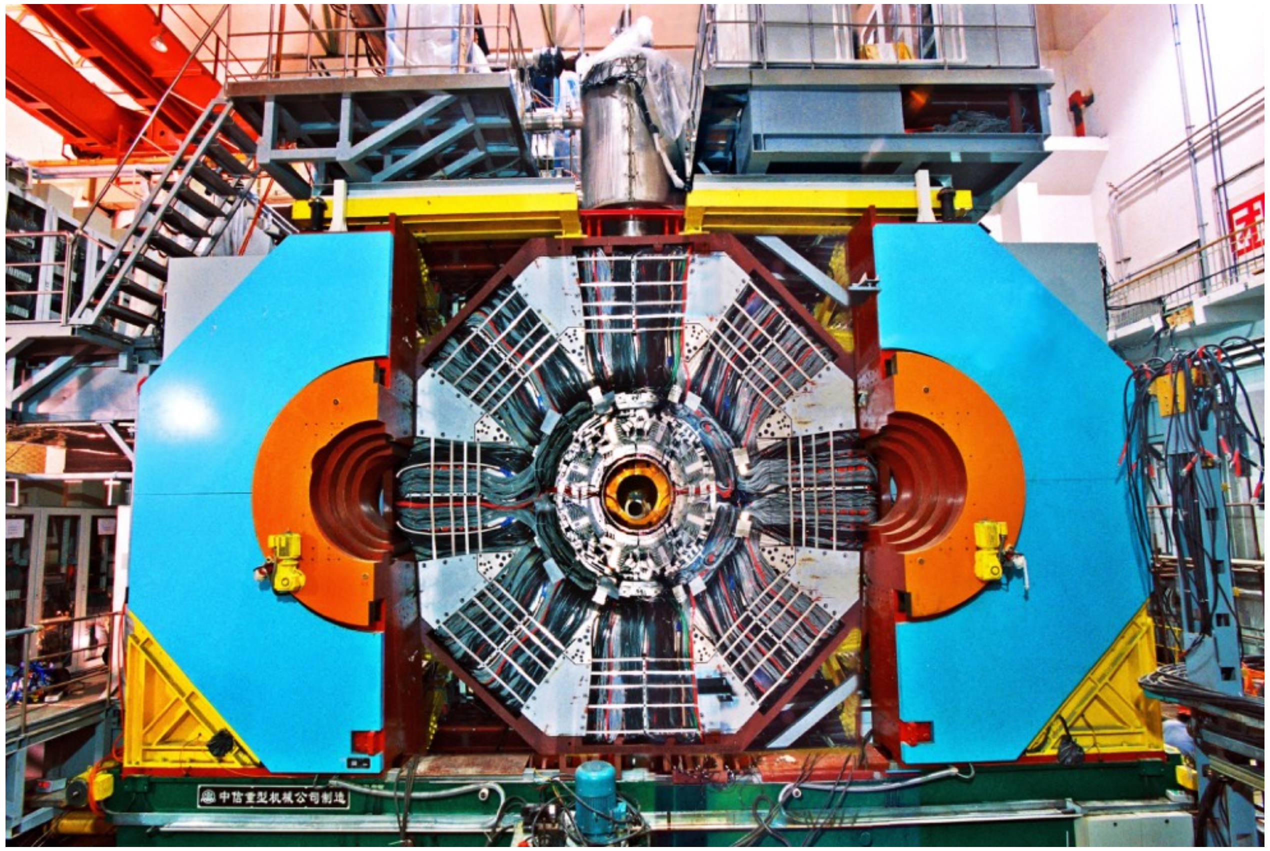
Y

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)

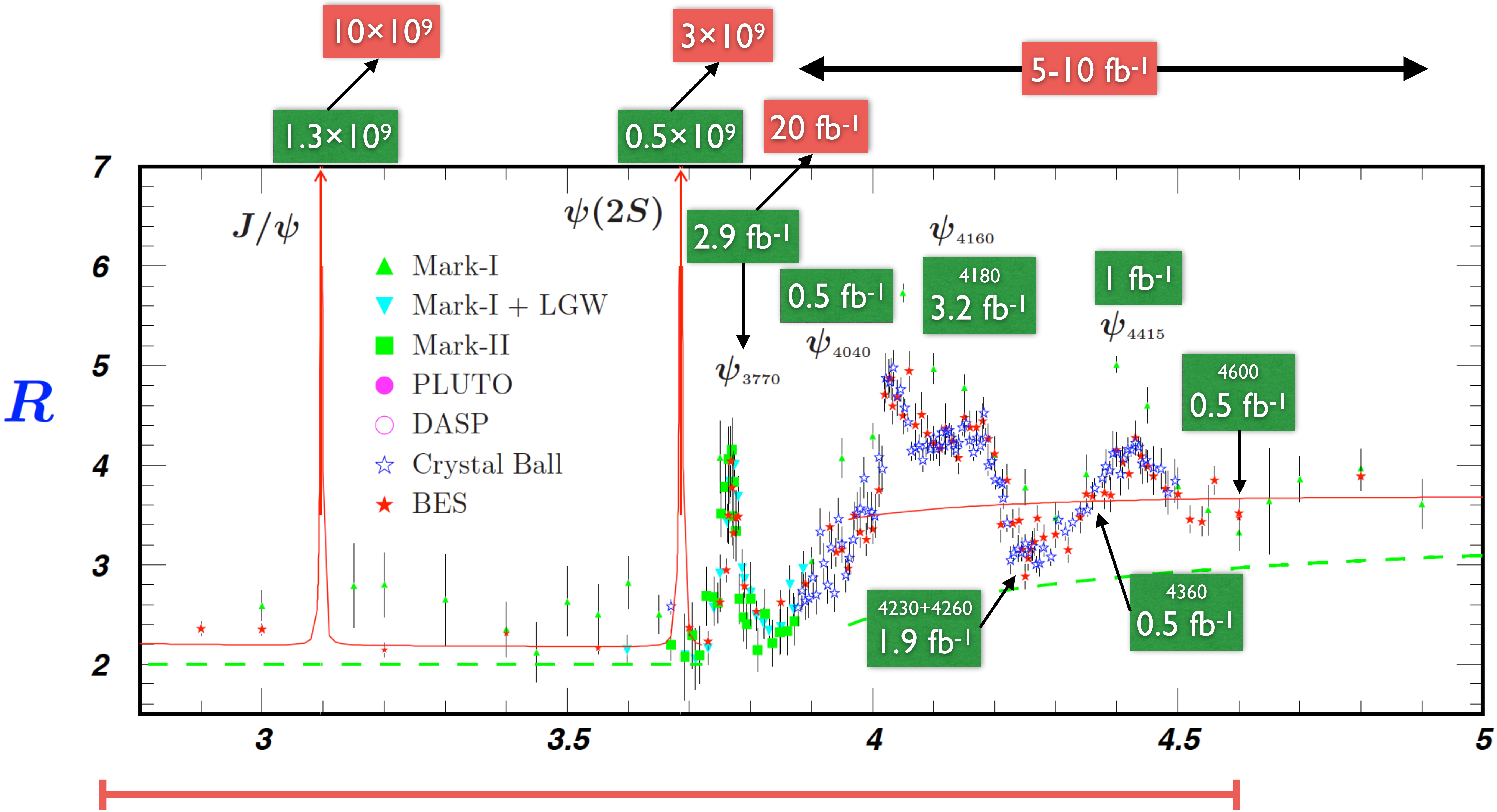


One lesson from the past:

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

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

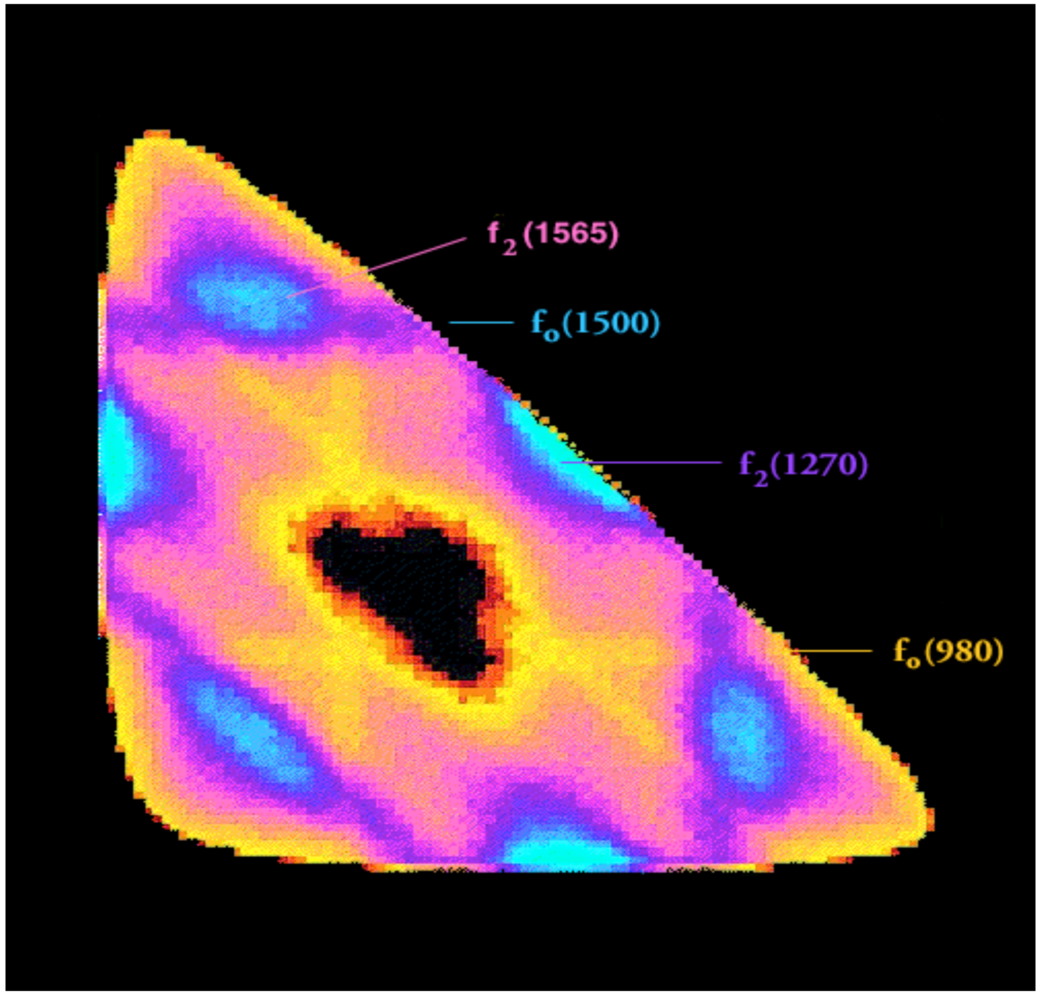
BESIII data sets



In total ~130 scan points between 2 – 4.6 GeV (~1.3 fb^{-1})

Different analysis expertise in spectroscopy comes together

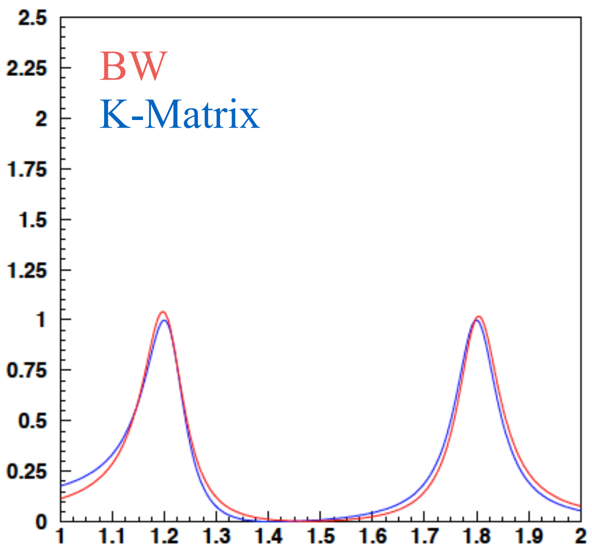
The analysis and interpretation of data is complex.



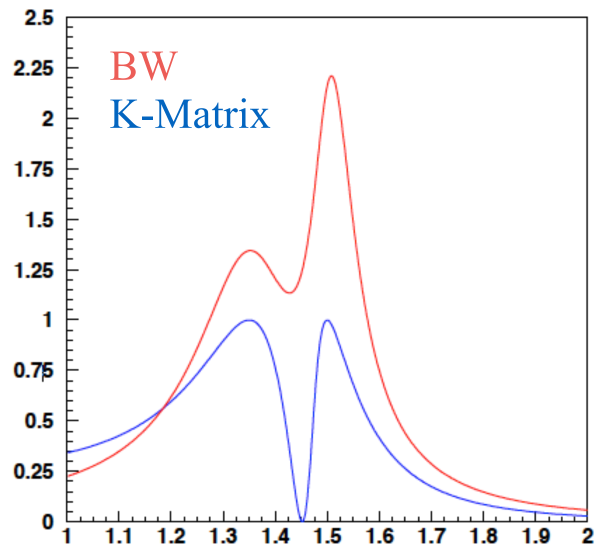
Common development of complex tools: Amplitude Analysis

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

Breit-Wigner fitting might not be sufficient:



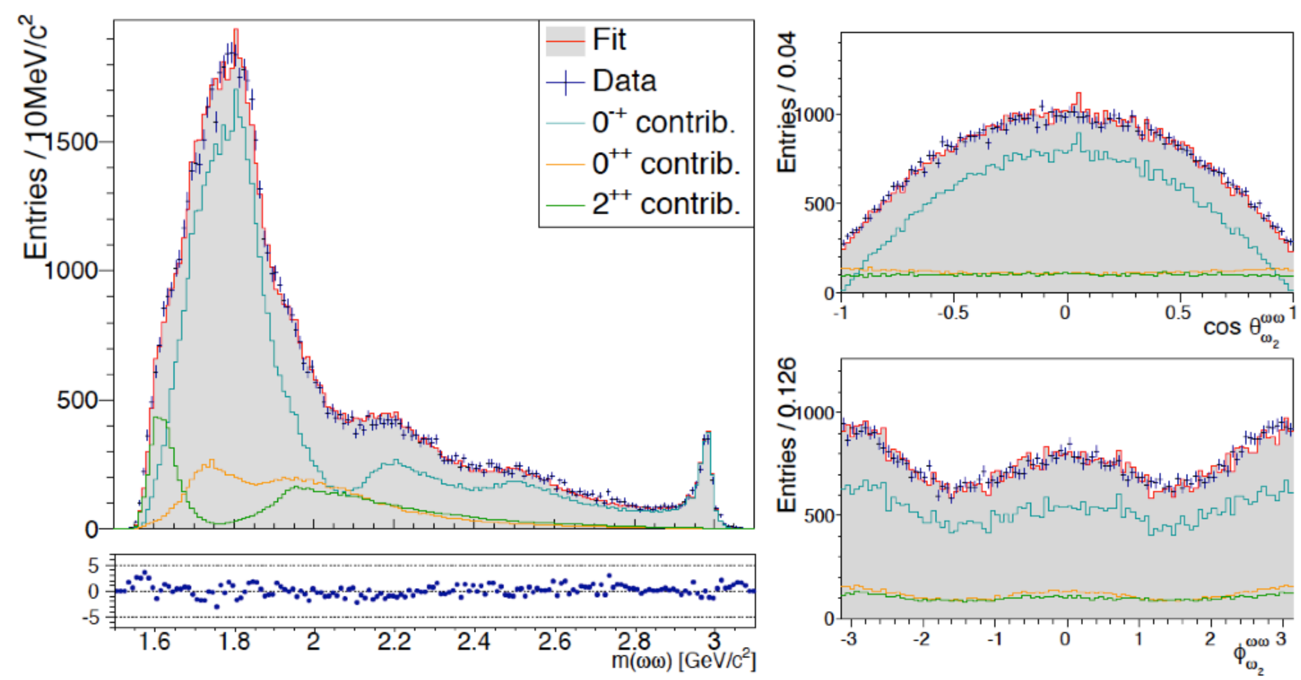
$f_0(1200)$, $\Gamma = 100$
$f_0(1800)$, $\Gamma = 100$



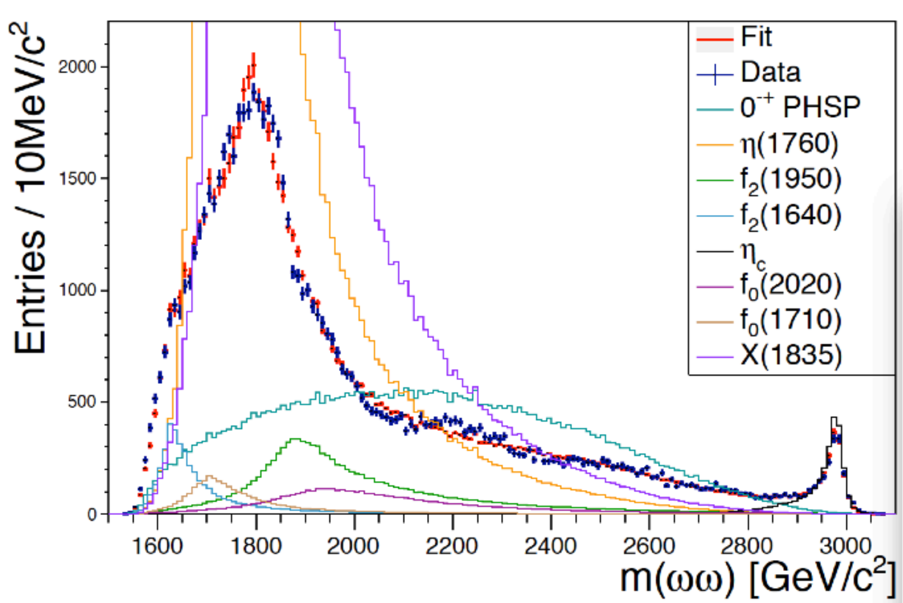
$f_0(1350)$, $\Gamma = 300$
$f_0(1500)$, $\Gamma = 100$

Plots: Curtis Meyer

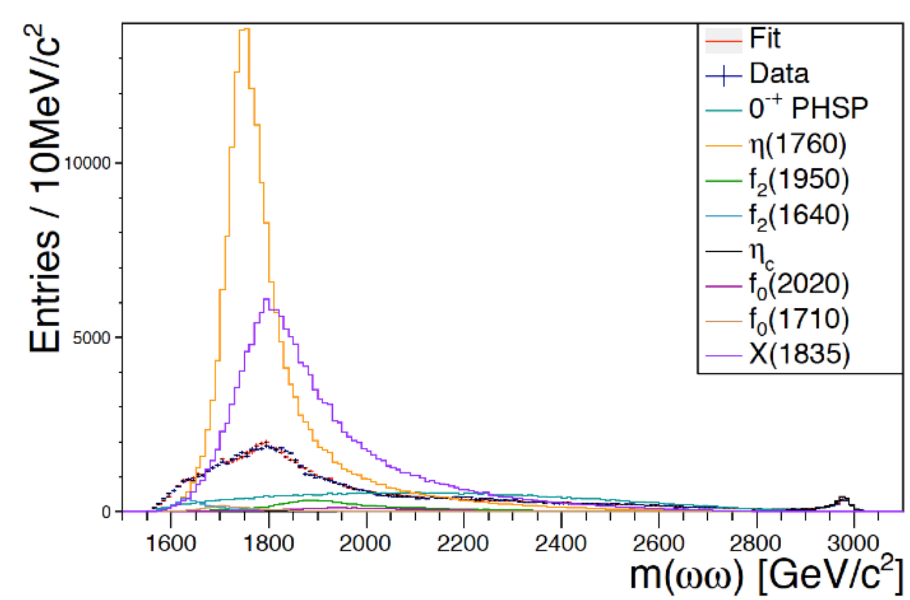
$J/\psi \rightarrow \gamma\omega\omega$ PAWIAN K-Matrix (Malte Albrecht)



but still might give an equally good description:



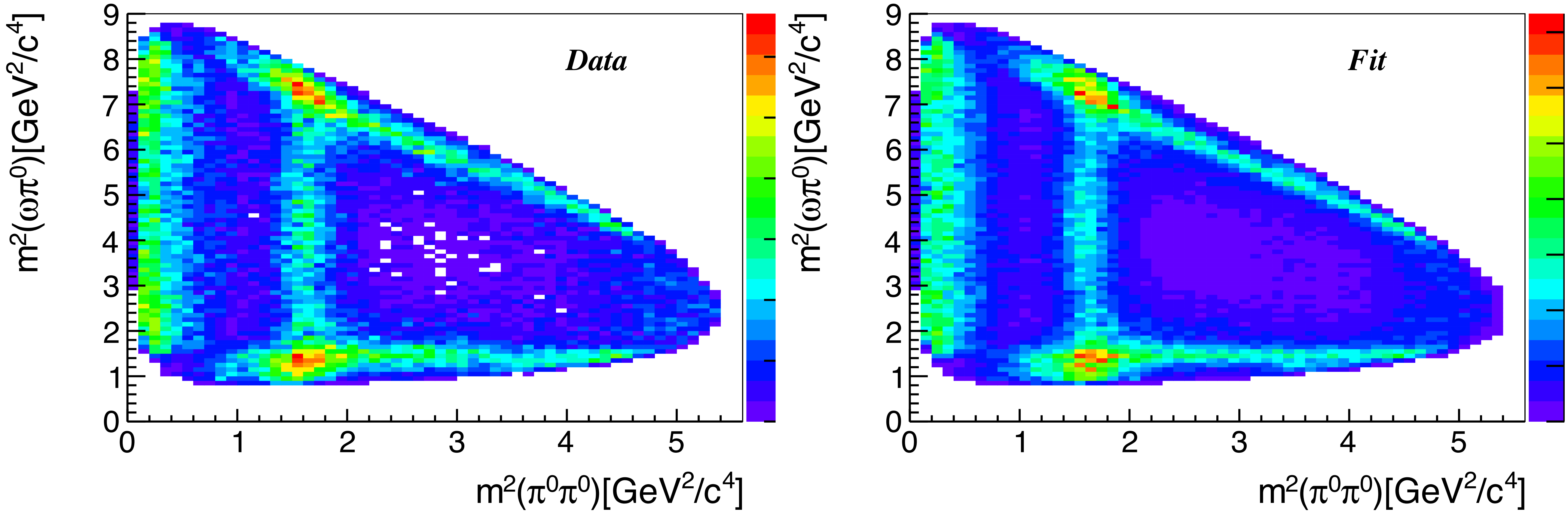
… unfortunately unphysical:



Coupled channel analysis

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

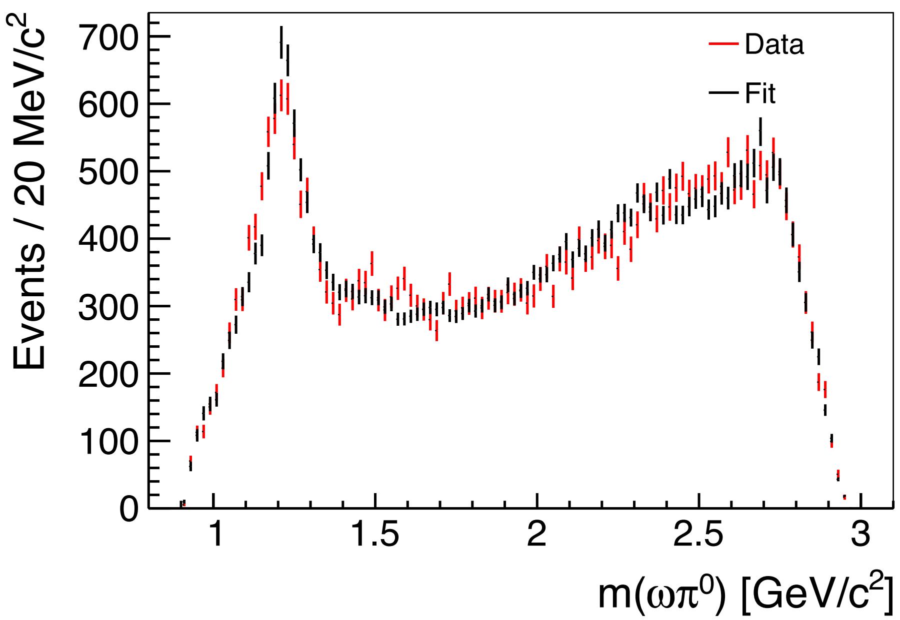
- PWA of final states become much more stable with coupled channel analysis of $\bar{p}p$



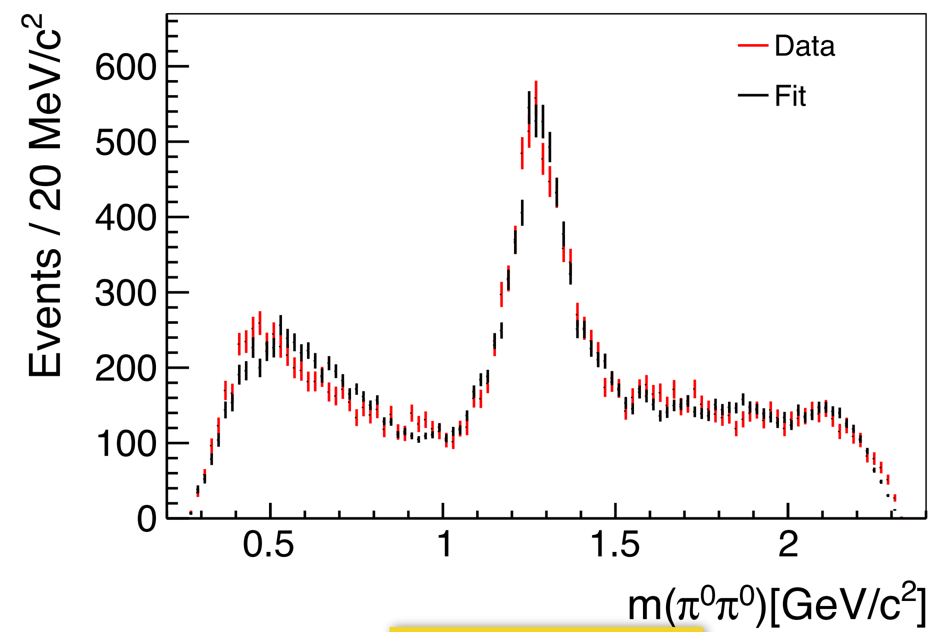
Analysis and coupled channel fit with PAWIAN: X. Qin (Bochum)

Coupled channel analysis

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



Fit not perfect in all regions

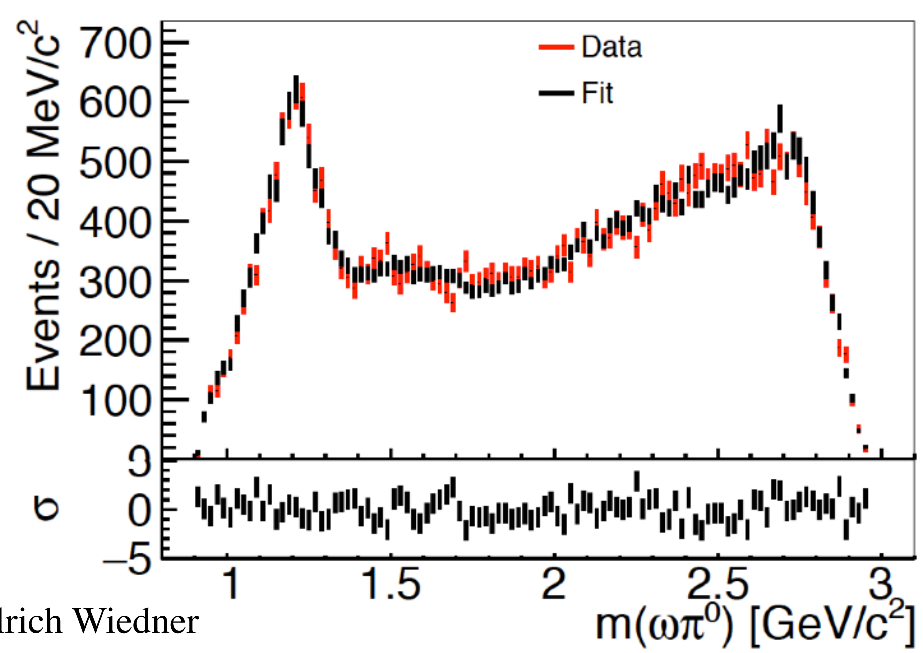


BESIII data: $J/\psi \to \omega\pi^0\pi^0$ and $J/\psi \to \omega p\bar{p}$

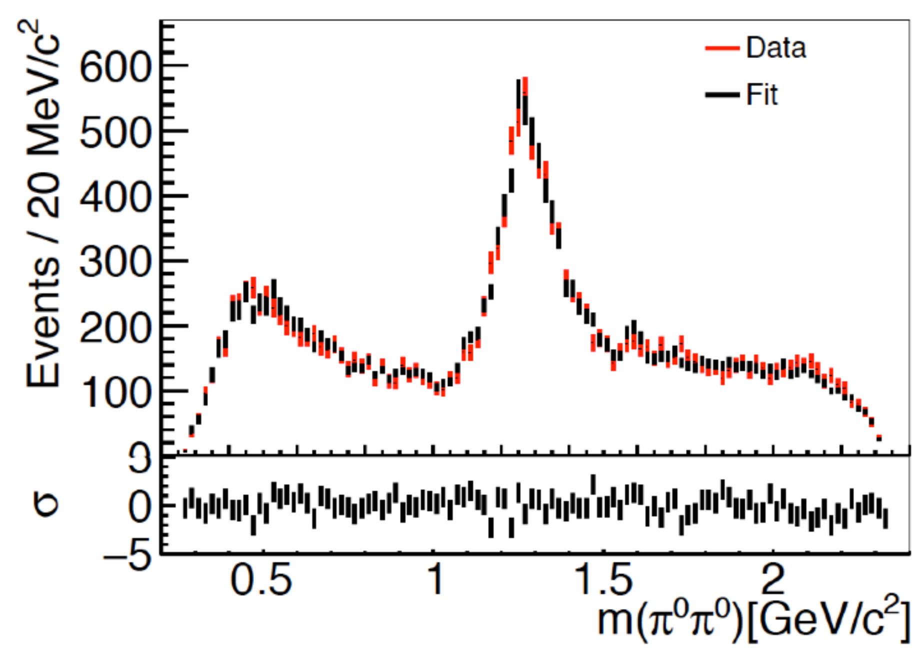
Coupled channel analysis including:

Scattering data:

$$\begin{cases} \pi\pi \to \pi\pi,\ \bar{K}K,\ \eta\eta,\ \eta\eta' & (I=0,\ S\text{-wave}) \\ \pi\pi \to \pi\pi,\ \bar{K}K,\ \eta\eta & (I=0,\ D\text{-wave}) \\ \pi\pi \to \pi\pi & (I=1,\ P\text{-wave}) \end{cases}$$



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 analysed

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

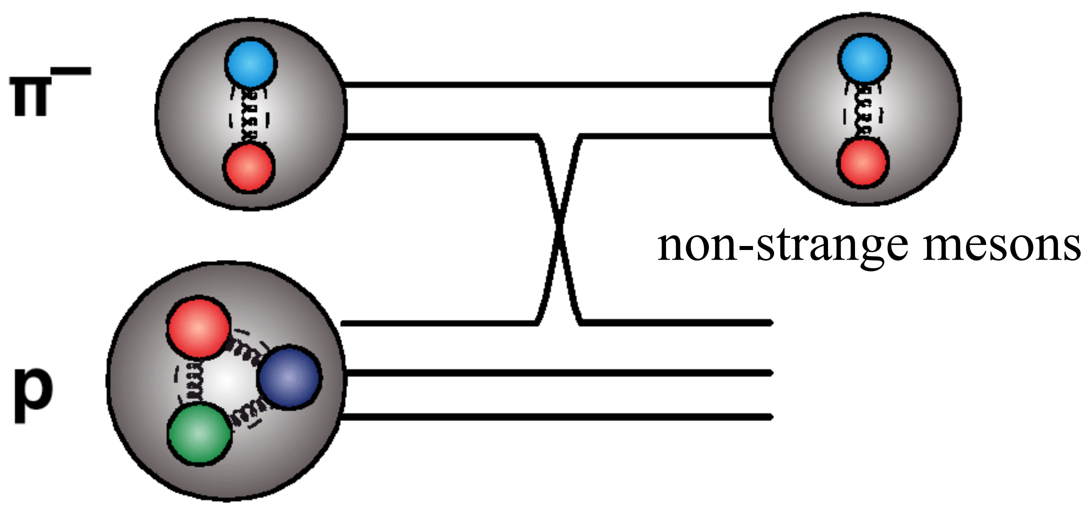
$\Rightarrow$ extensive background studies to be done

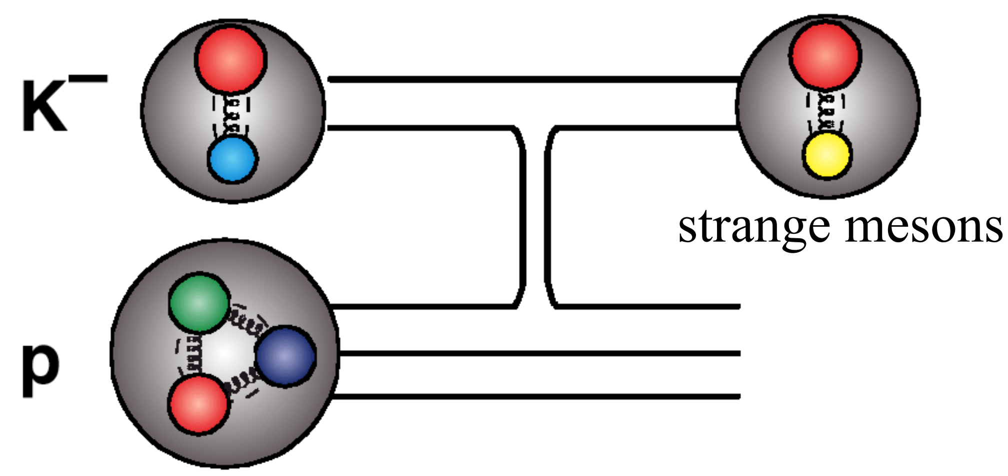
The combination of results is almost mandatory for a better understanding of states and observed patterns.

Broader theoretical expertise most welcome.

Particle production: "quark-rich" processes

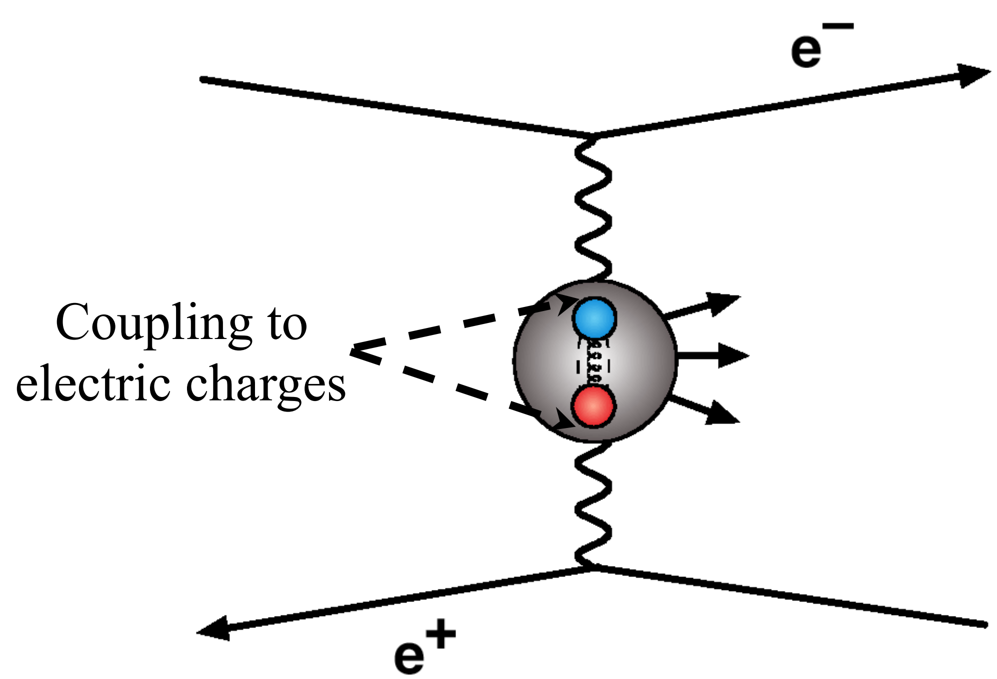
Hadron beams





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

γγ collisions

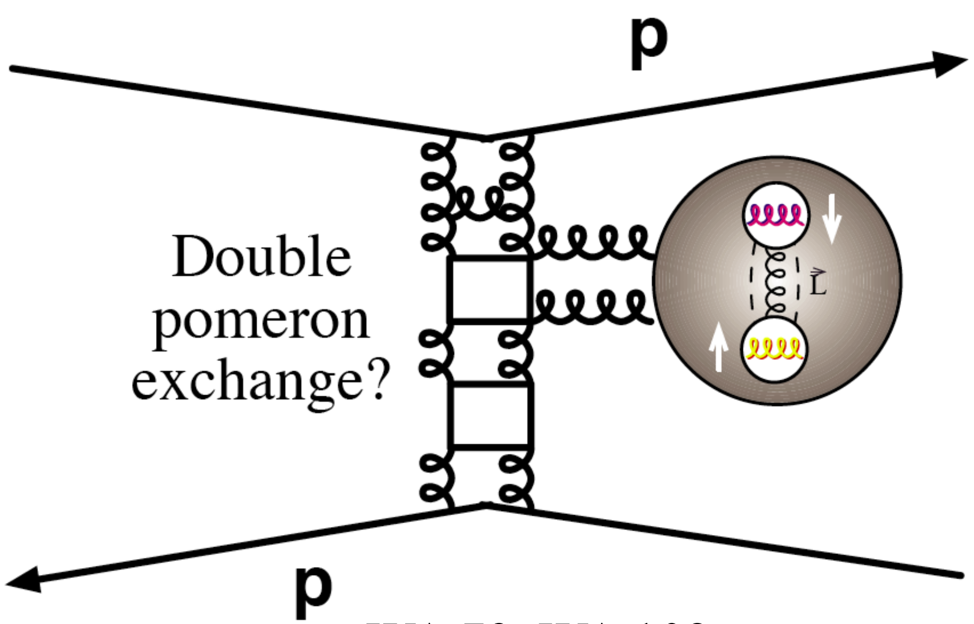


γγ collisions

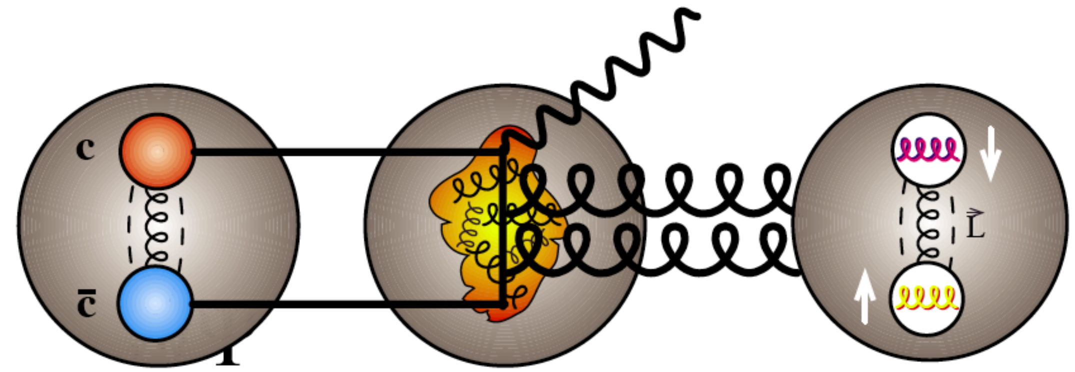
... act as anti-glueball filter

ARGUS, Crystal Ball, LEP experiments ...

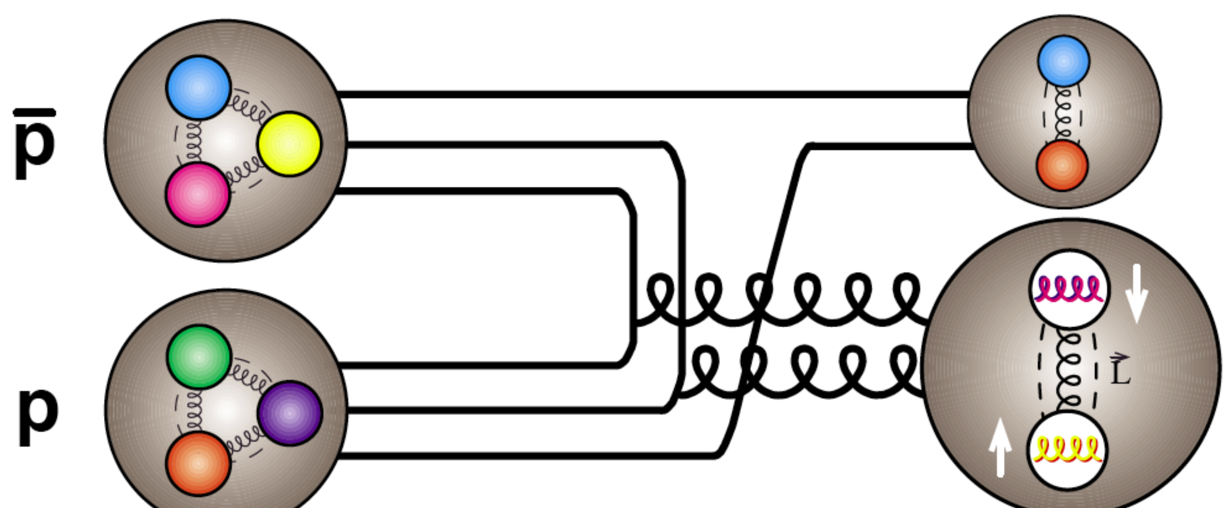
Particle production: “gluon-rich” processes



WA 79, WA 102



MARK III, DM2, BES



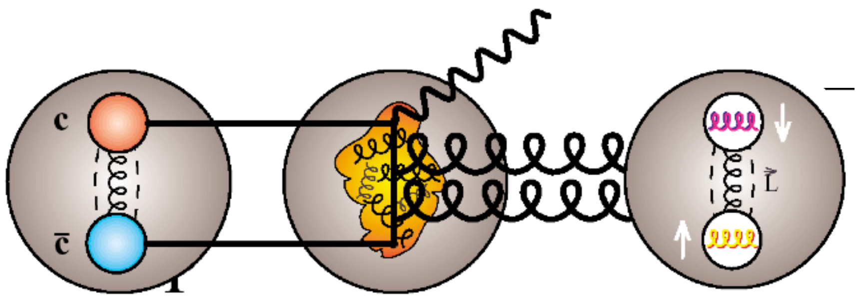
ASTERIX, Crystal Barrel, OBELIX, E835, PANDA

Glueballs

Glueballs are one of the most fascinating facets of QCD:

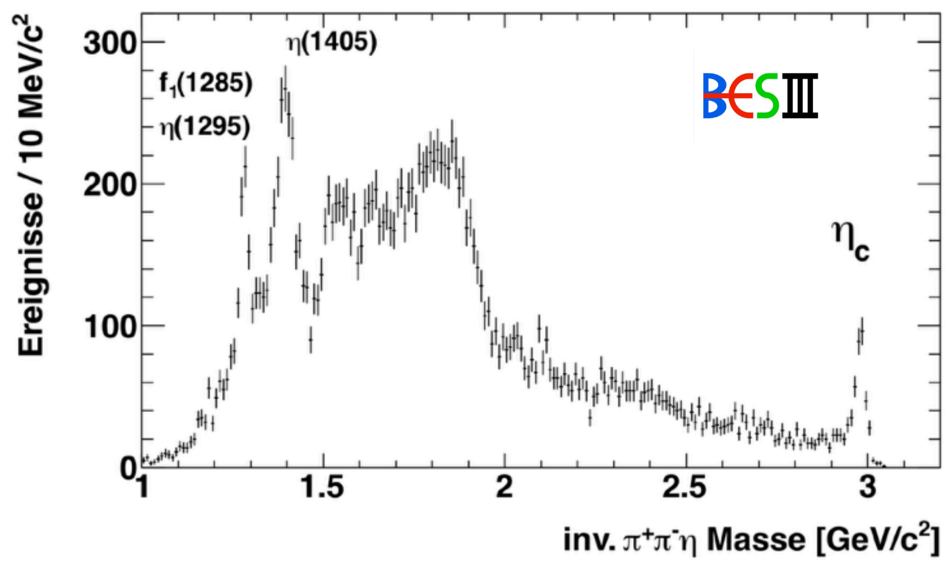
↳ massless gluons come together to form massive states

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



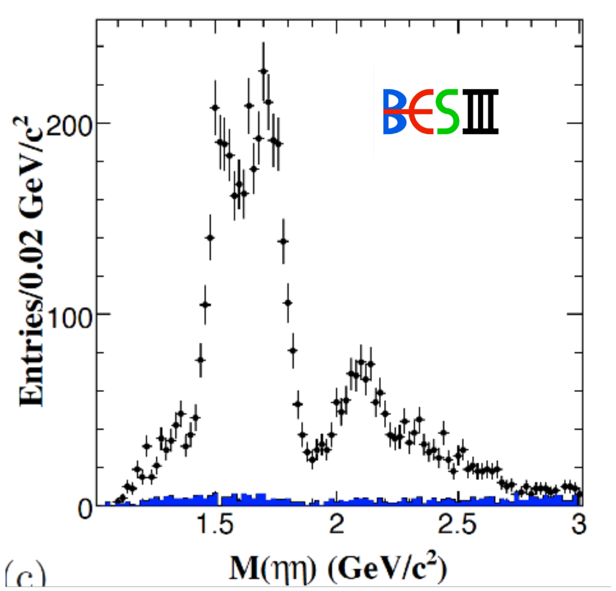
Radiative J/Ψ decays

η(1405)

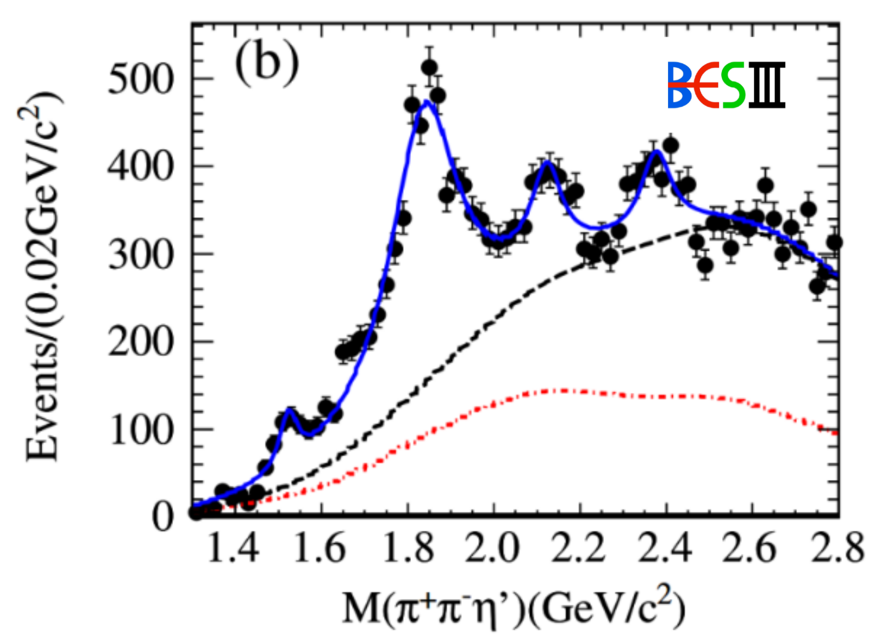


M. Leyhe (Thesis work)

f₀(1500) and f₀(1710)



X(1835)



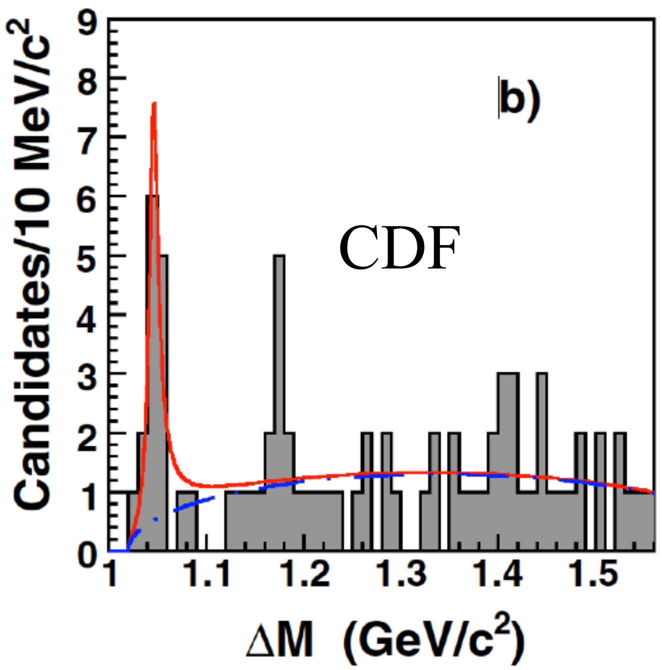
PRL 108, 112003 (2012)
PRL 115, 091803 (2015)

Glueballs

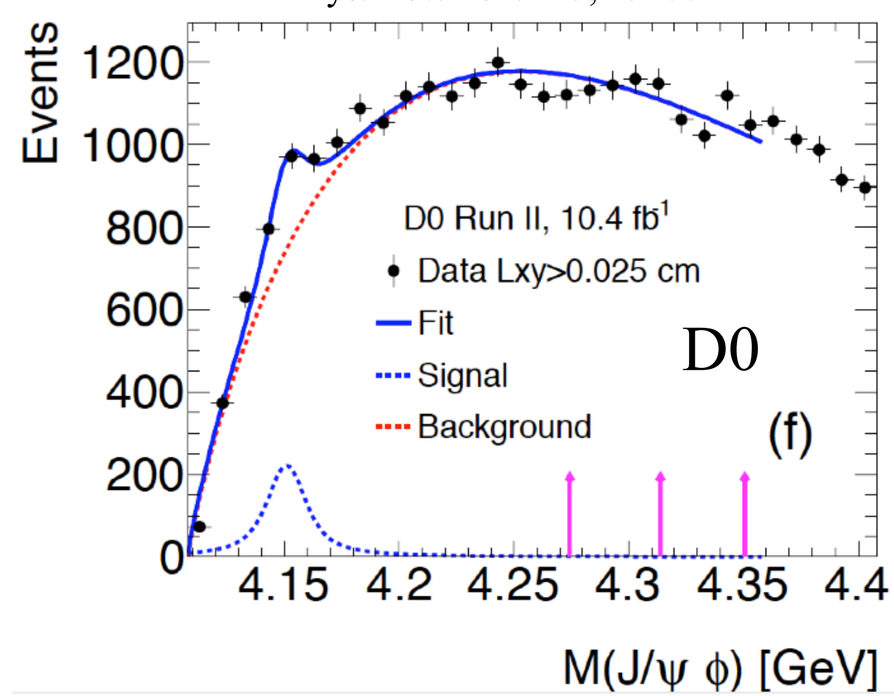
My personal glueball candidate for 1^{++} glueball: X(4140) M= 4147 MeV/c^2 , Γ = ~19 MeV

↳ decay mode J/ψ ϕ (flavour blind)

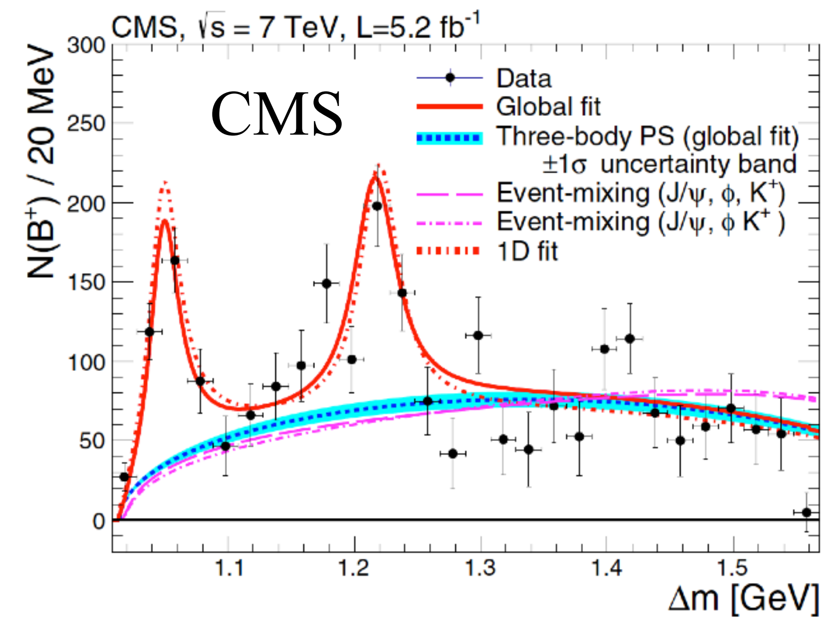
Phys.Rev.Lett. 102 (2009) 242002

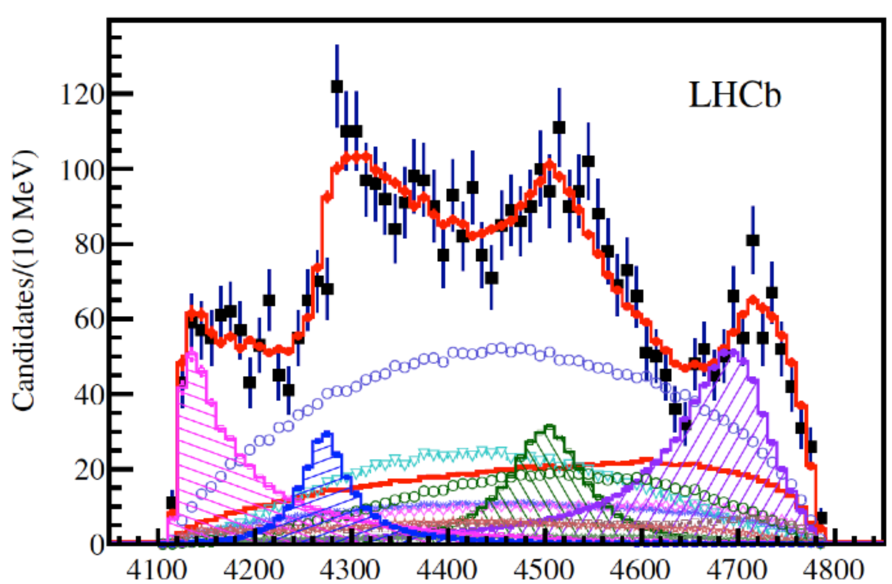


Phys. Rev. Lett. 115, 232001

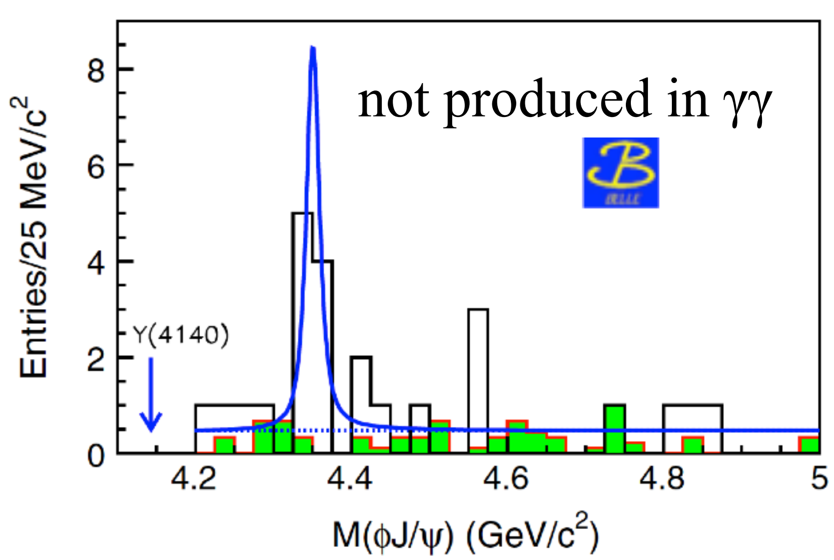


Phys.Lett. B734 (2014) 261-281

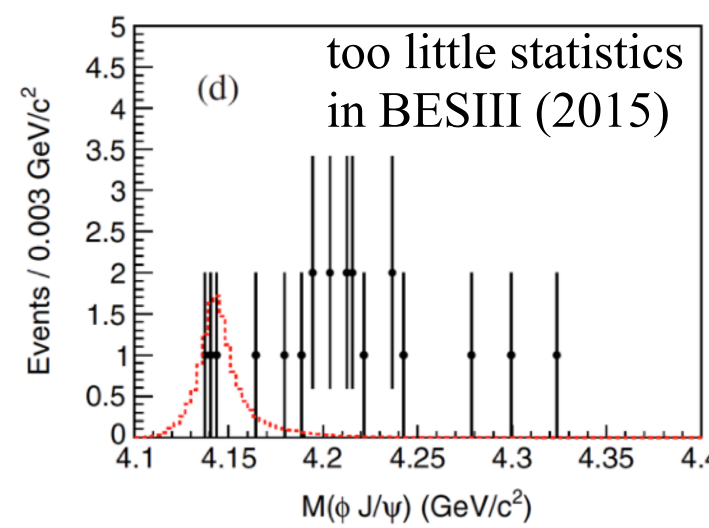




Phys.Rev.Lett. 118 (2017) no.2, 022003

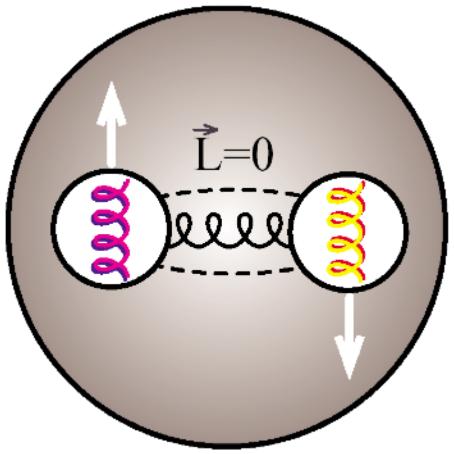


Phys.Rev.Lett. 104 (2010) 112004

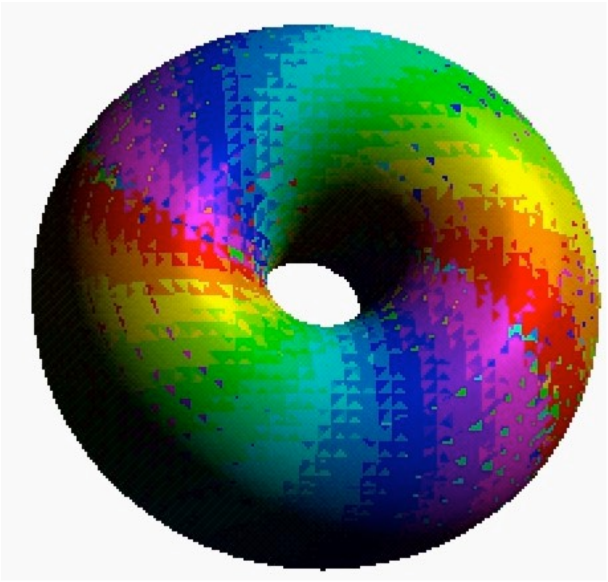


Phys.Rev. D91 (2015) no.3, 032002

The structure of Glueballs



Glueball (gg)

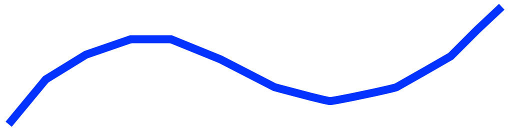


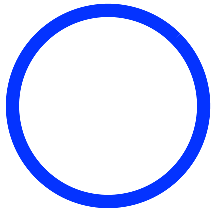
GLUEBALLS, FLUXTUBES AND η(1440).
L. Fadeev, A. Niemi and U. Wiedner Phys.Rev.D70:114033, 2004

Glueballs: connection to string theory?

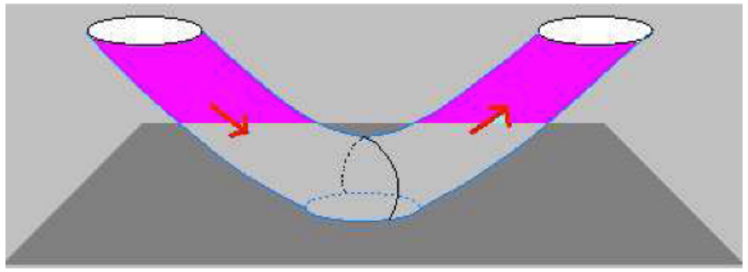
Open Strings

Closed Strings





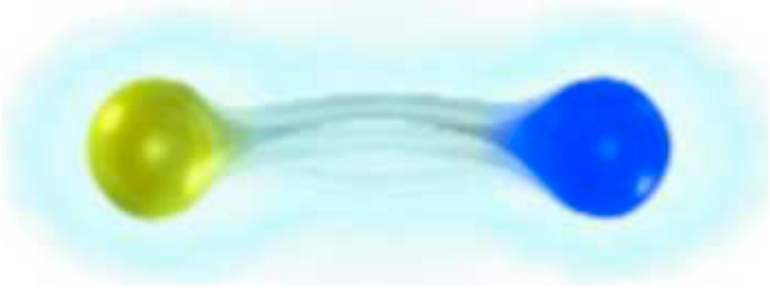
String World

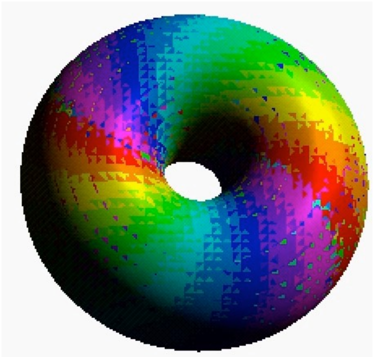


representing gauge theories

representing gravitation

Hadron World

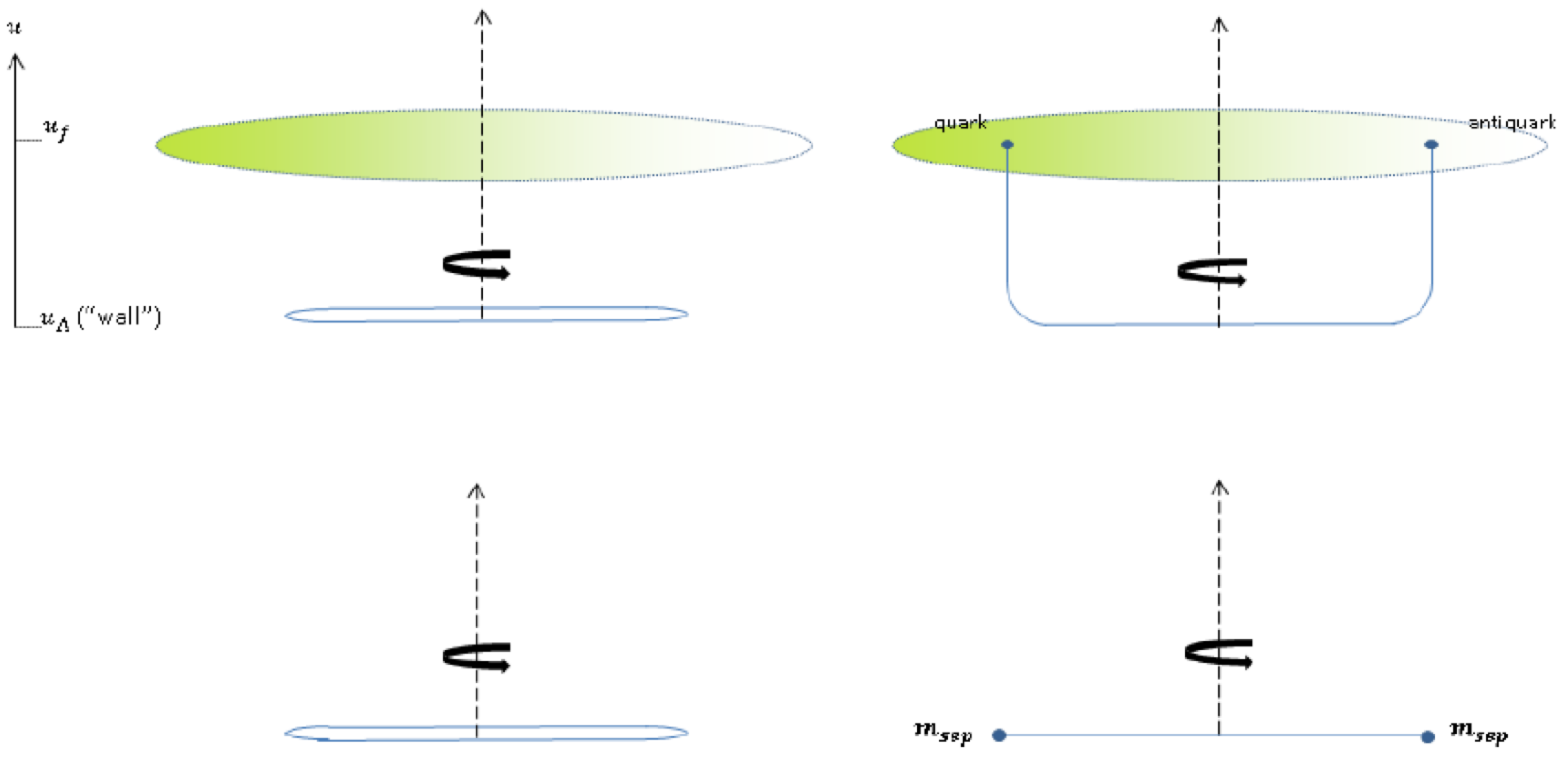




meson

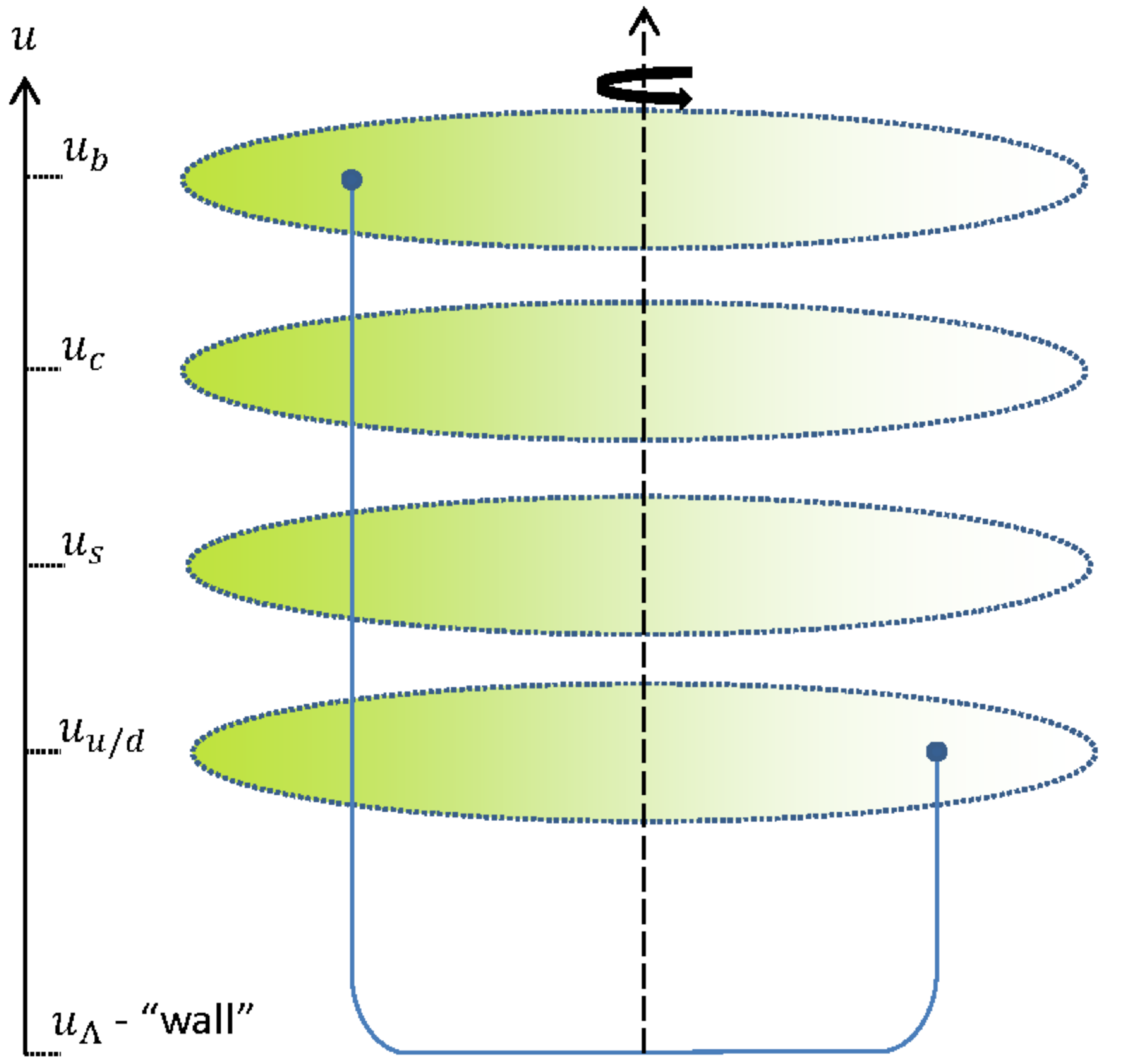
glueball ?

Holographic mesons and glueballs and their map



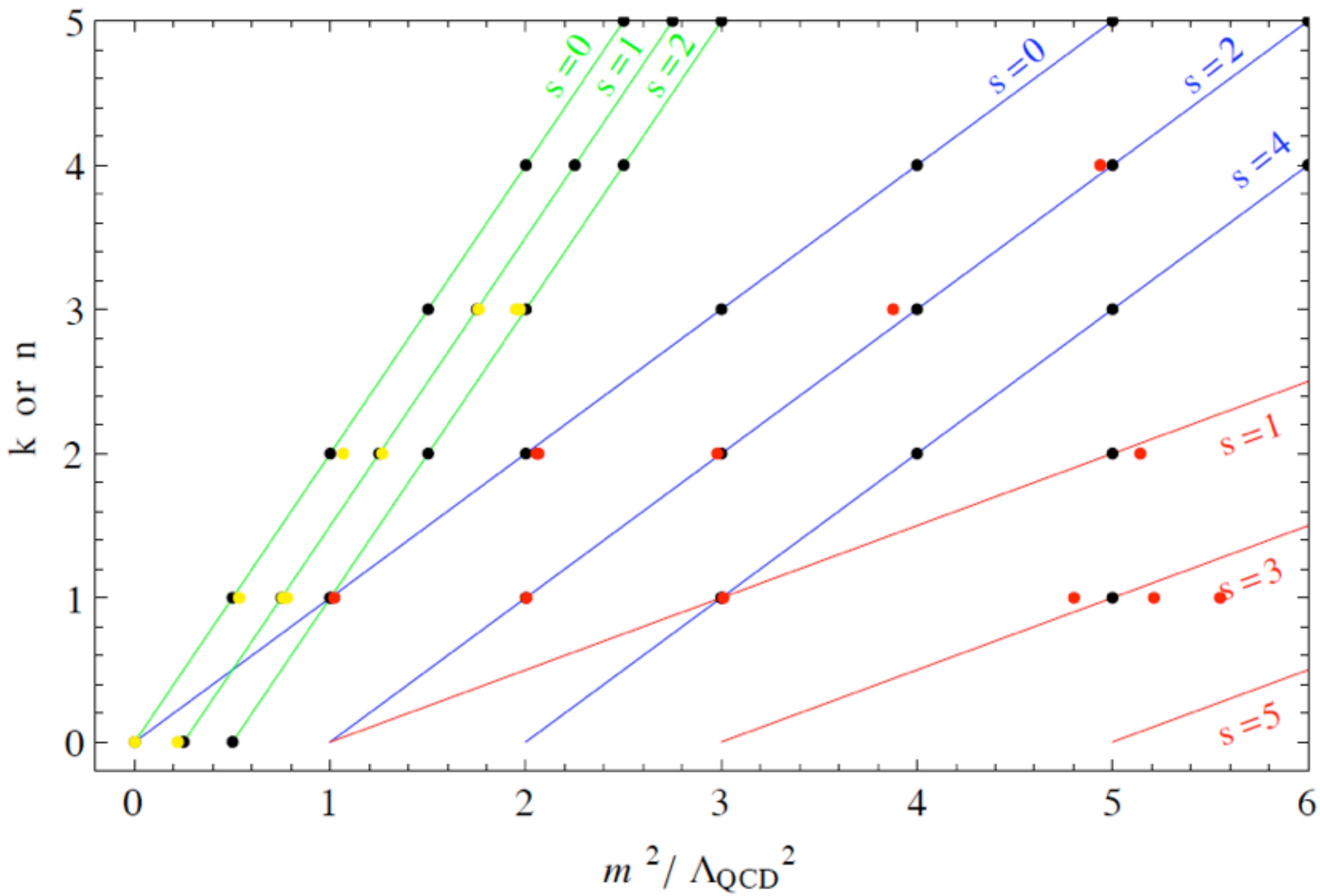
Jacob Sonnenschein: "Holographic Inspired Stringy Hadrons: arXiv:1602.00704

Example: The B meson



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

Glueballs on Regge trajectories like mesons?



Marco Bochicchio; arXiv:1308.2925

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

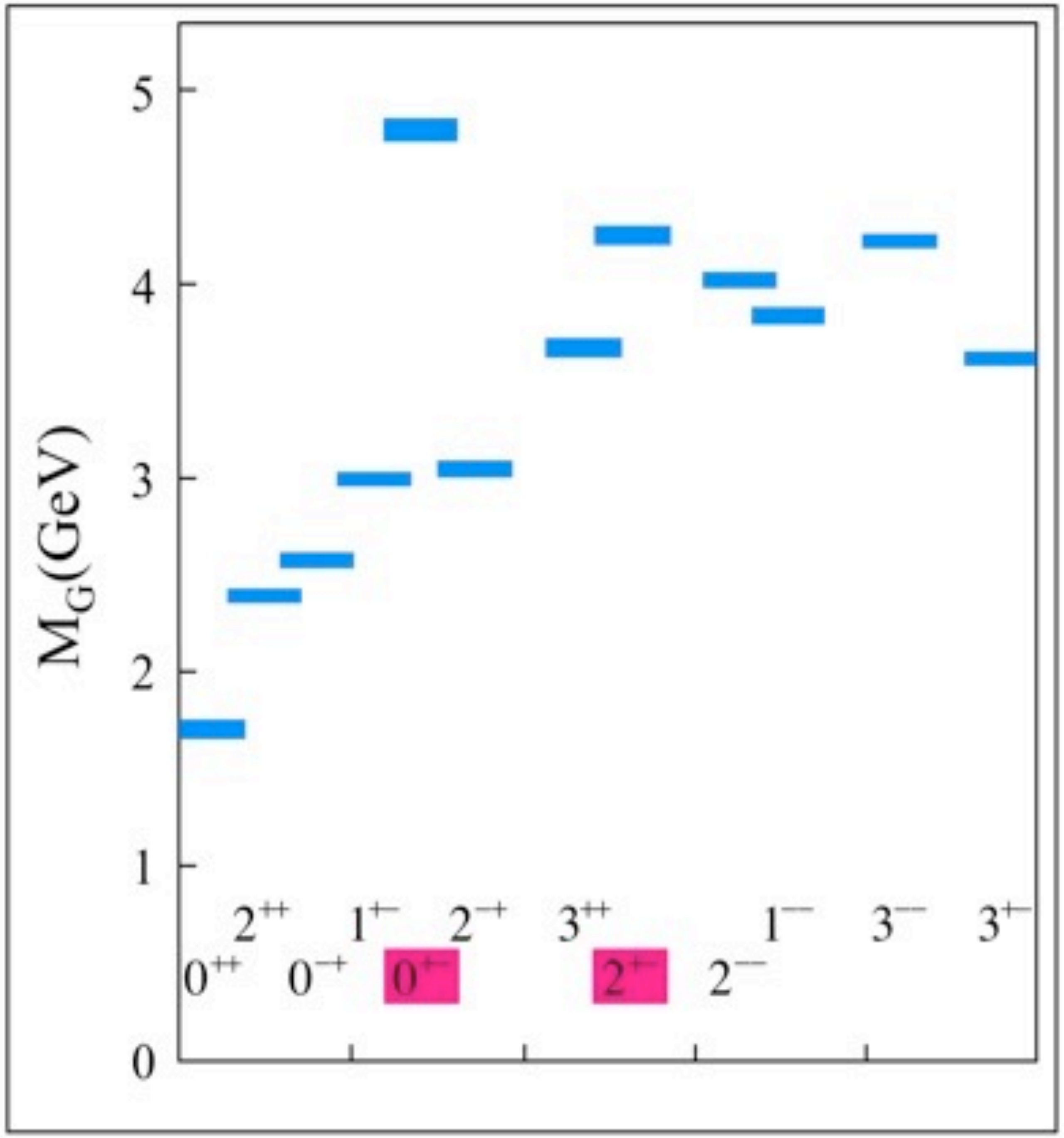
G. S. Bali et al.; arXiv:1302.1502

for glueball with fo(1500) ground state

n or J	Mass	Width
0	1505±6	109±7
2	2640±80	335±30
4	3415±100	560±50
6	4050±120	790±70
8	4590±135	1015±90

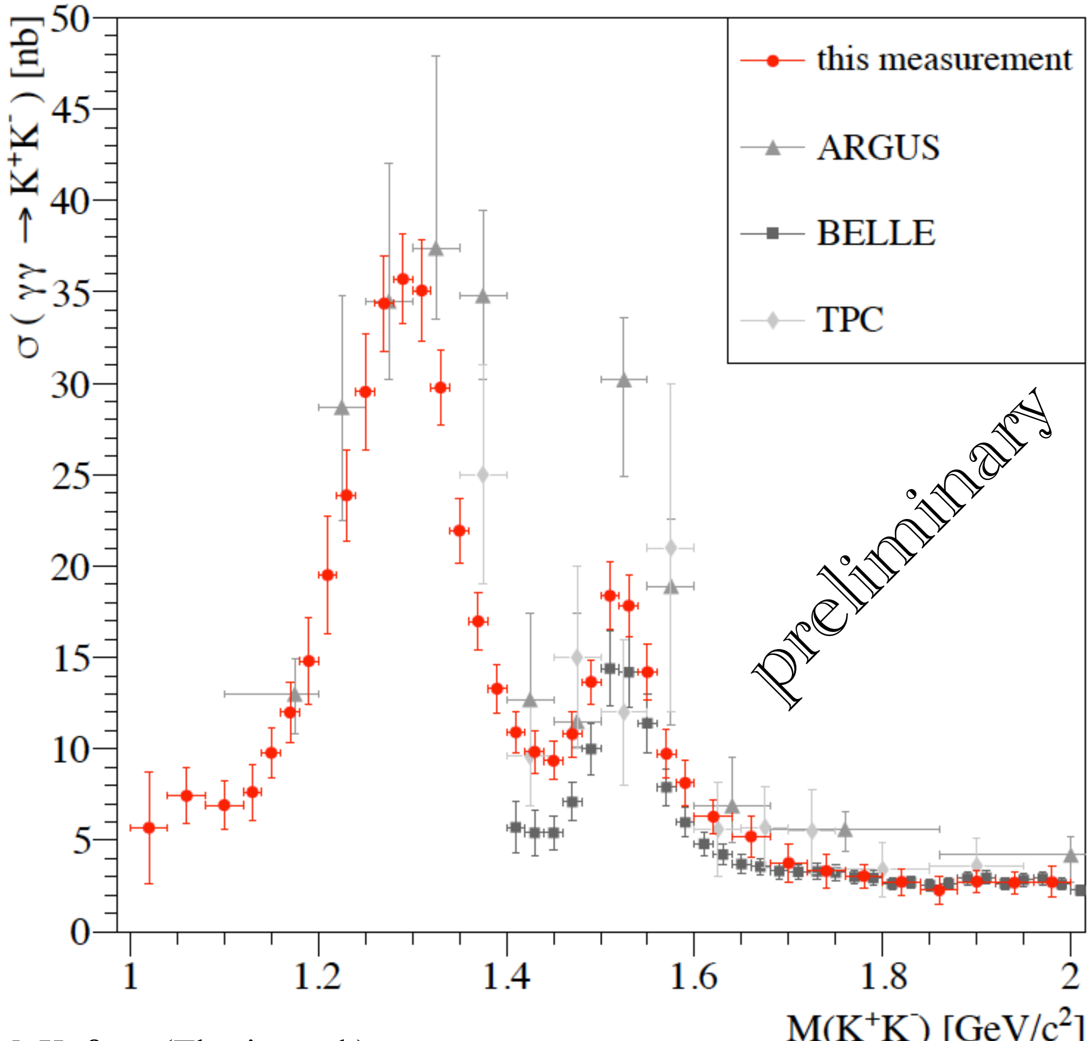
Jacob Sonnenschein, Dorin Weissman, JHEP 1512 (2015) 011, arXiv:1507.01604.

A possible Glueball spectrum predicted by lattice



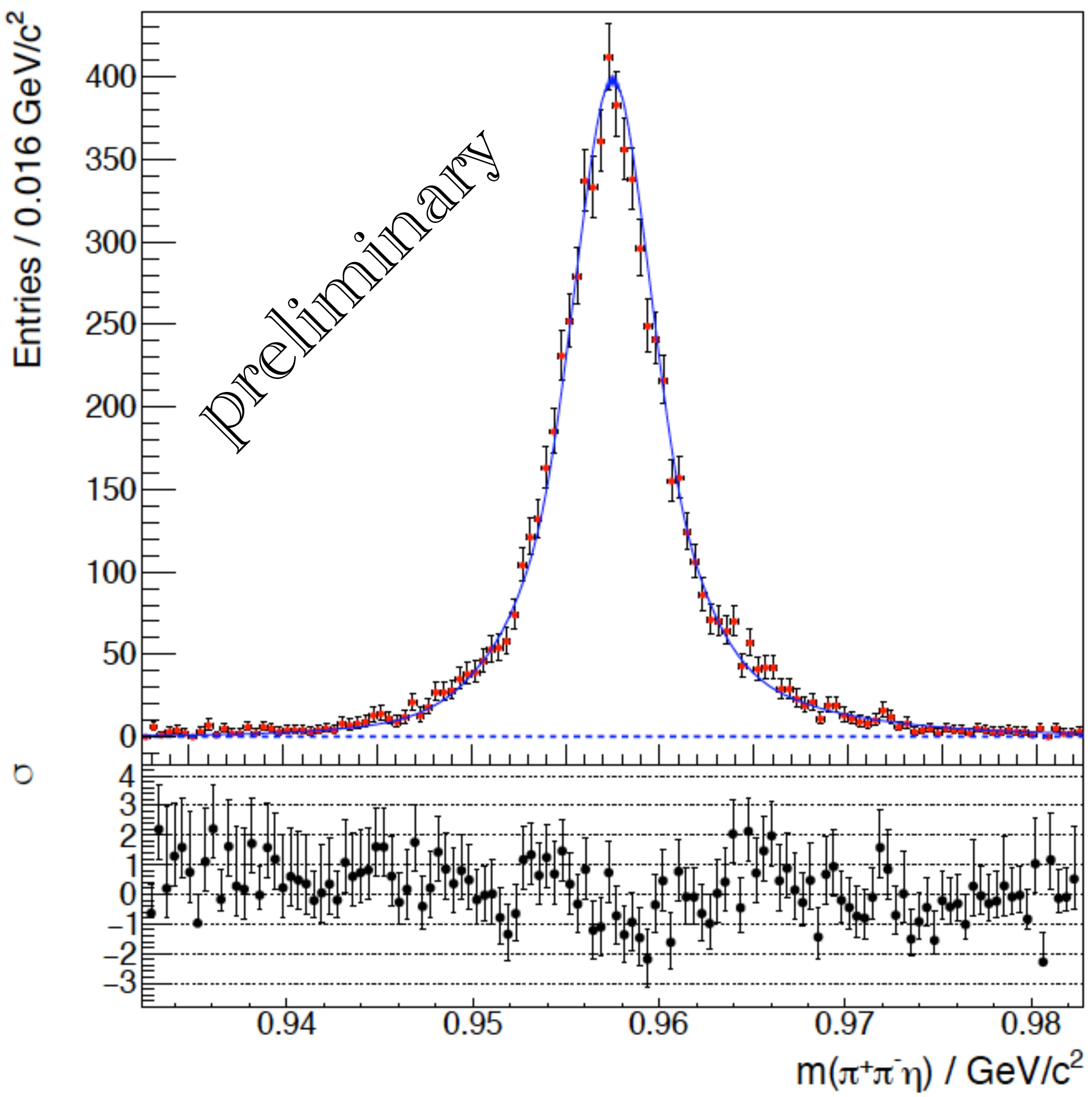
γγ physics

$\gamma\gamma \rightarrow K^+K^-$



M. Küßner (Thesis work)

$\gamma\gamma \rightarrow \eta\pi^+\pi^-$



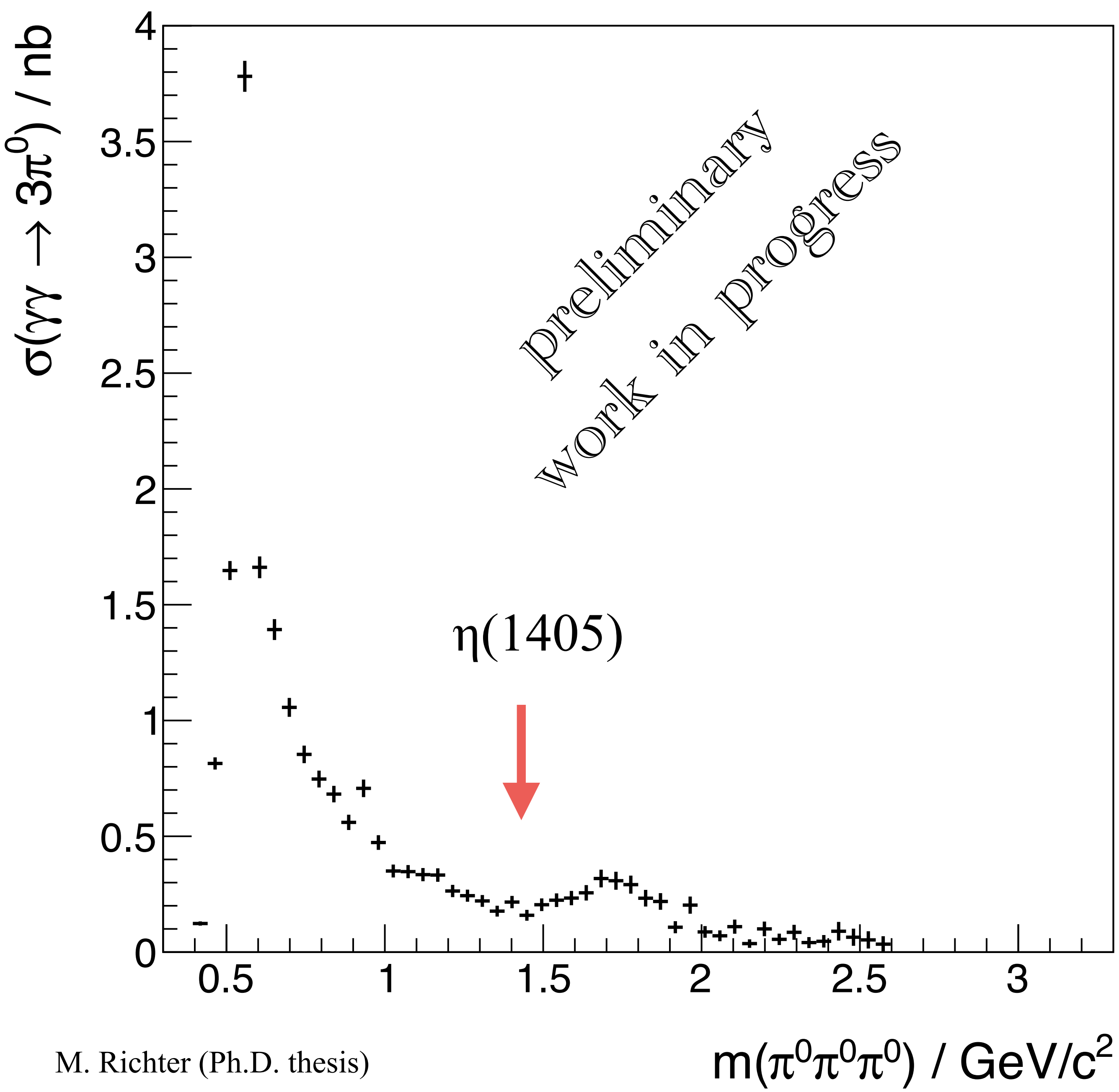
A. Mustafa (Thesis work)

Contributing resonances:

$f_2(1270)$, $a_2(1320)$, $f_2'(1525)$

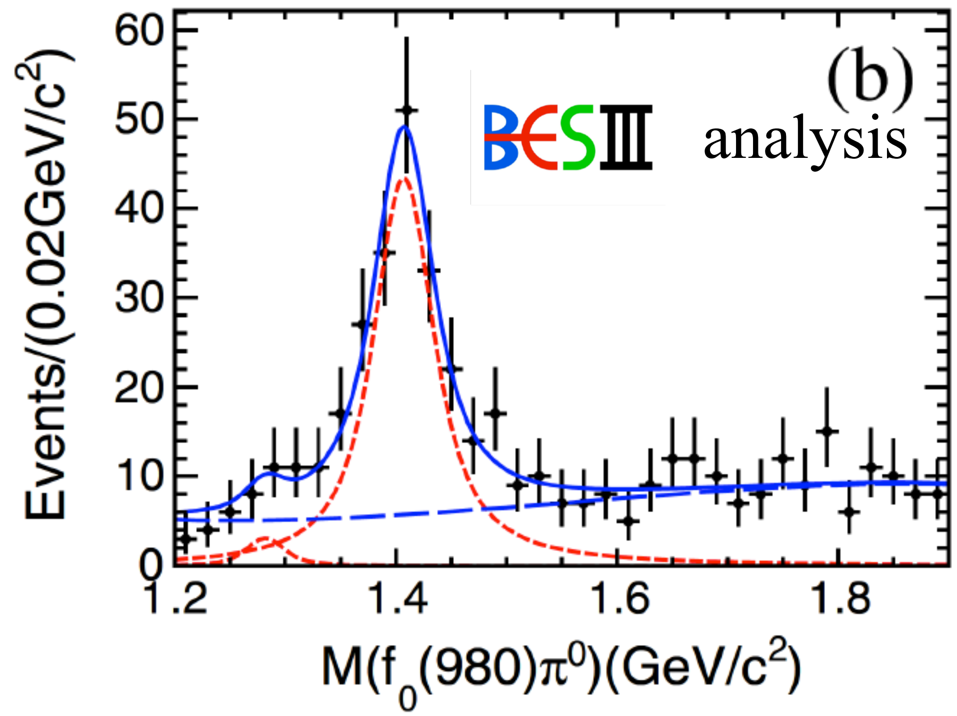
Comparison of γγ collisions with radiative J/ψ decays

$\gamma\,\gamma \rightarrow \pi^0\,\pi^0\,\pi^0$



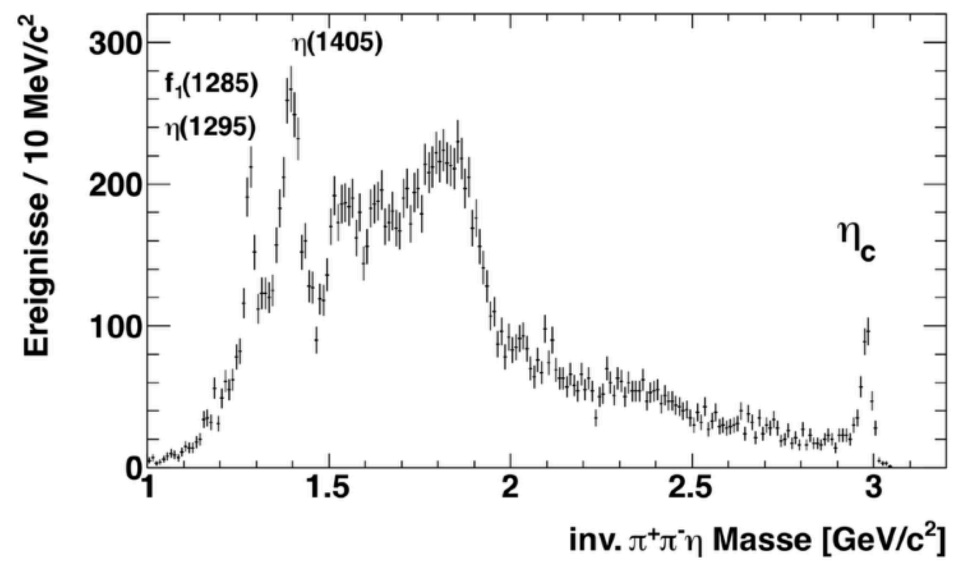
M. Richter (Ph.D. thesis)

$J/\psi \rightarrow \gamma\,\pi^0\,\pi^0\,\pi^0$



BES3, PRL108 (2012)182001

$J/\psi \rightarrow \gamma\,\pi^+\,\pi^-\,\eta$



M. Leyhe (Ph.D. thesis)

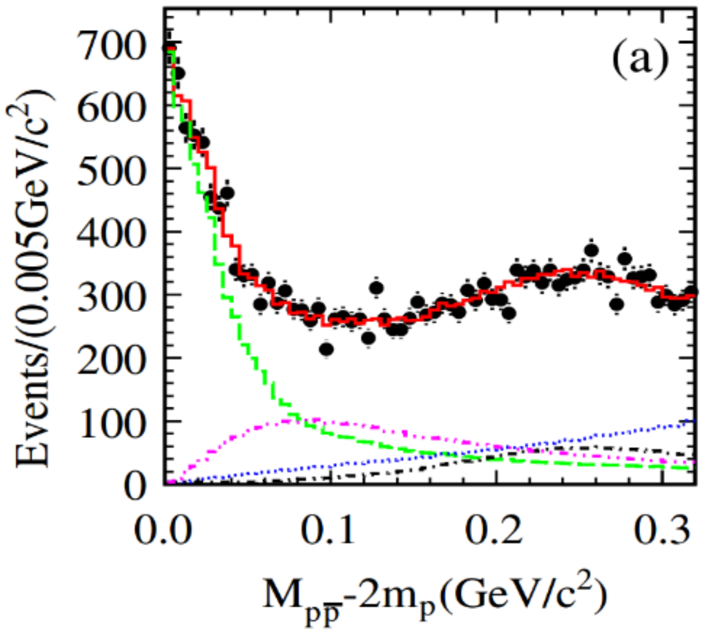
$\gamma\gamma$ physics at BESIII: plans for the future

$\gamma\gamma$ spectroscopy in BESIII

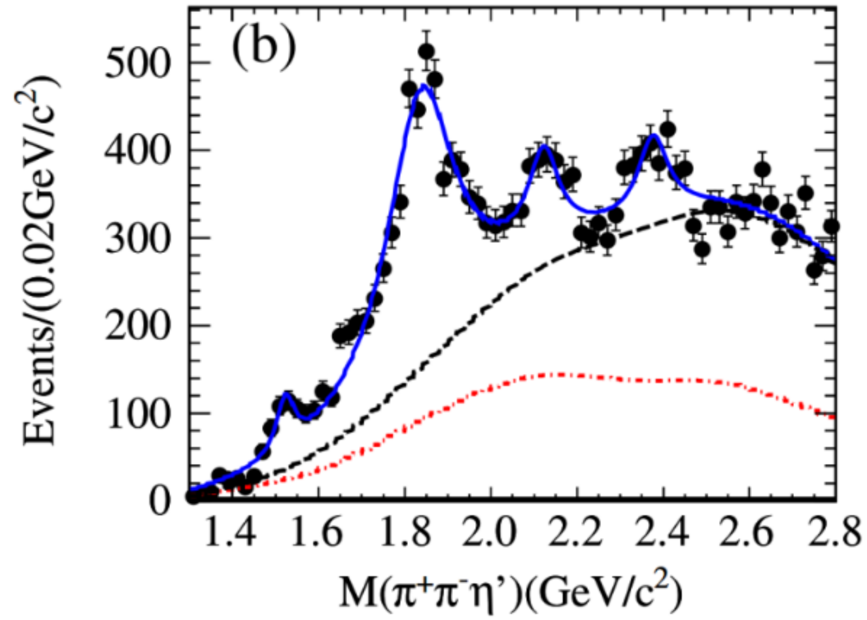
- Improving GamGam Monte Carlo and PWA software
- Take advantage of an installed cZDD → single and double tag analysis
- Analyses of further final states:
  - $\gamma\gamma \rightarrow \pi^0\eta$
  - $\gamma\gamma \rightarrow \eta\eta$
  - $\gamma\gamma \rightarrow \pi^+ \pi^- \pi^0$
  - $\gamma\gamma \rightarrow K^0_S K^0_S$
  - $\gamma\gamma \rightarrow K^+K^-\pi^0$
  - $\gamma\gamma \rightarrow K^0_S K^\pm \pi^\mp$
- Coupled channel analyses

The X(1835)

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



$\gamma\bar{p}p$ decays and X(1835)

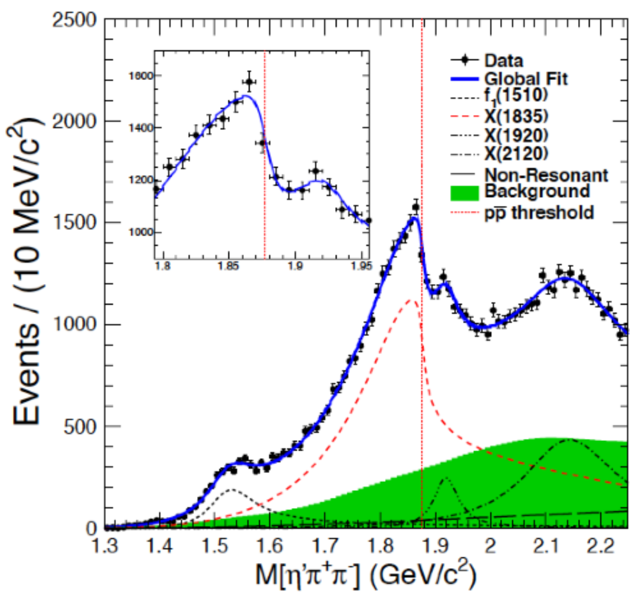


X($\bar{p}p$) $J^{PC} = 0^{-+}$ $M = 1832^{+19}_{-5}\,^{+18}_{-17}$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (<76 MeV/c^2 @ 90% C.L.)

PRL 106, 072002 (2011)

X(1835) $J^{PC} = 0^{-+}$ $M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20}_{-17}\,^{+62}_{-43}$ MeV/c^2

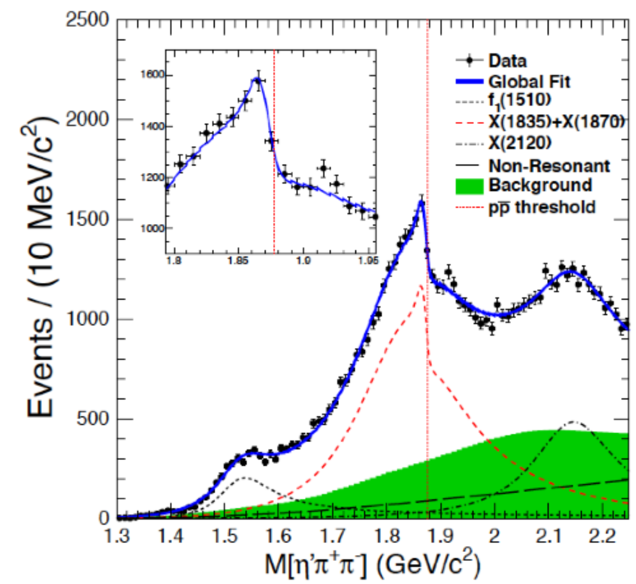
PRL 108, 112003 (2012)
PRL 115, 091803 (2015)



2 models with equally good description

Broad resonance with M=1909 MeV/c^2 and Γ=273 MeV/c^2 with strong coupling to $\bar{p}p$ (Flatté line shape and threshold opening causes distortion) + narrow BW @ 1920 MeV/c^2

X(1835) resonance + narrow sub-threshold resonance with M=1870 MeV/c^2 and Γ=13 MeV/c^2 with strong coupling to $\bar{p}p$



$\bar{p}p$ molecule-like state or $\bar{p}p$ bound state?

But coupling to $\bar{p}p$ seems obvious.

PRL 117, 042002 (2016)

Goals and work plan for glueballs

Search for glueballs

- Search for 1^{--} glueball by exploring the vector states in ISR reactions

  LQCD: Vector glueball at ~3.8 GeV/c^2
  Predicted decay pattern (F. Giacosa et al.)

  F. Giacosa, J. Sammet, S. Janowski
  Phys. Rev. D 95, 114004 (2017)

  $\rightarrow$ dominant decay modes: $\omega\pi\pi$ and $K^*\bar{K}\pi$

  Study of: $e^+e^- \rightarrow \gamma_{ISR} X$ at $\sqrt{s} > 4\ GeV$

- Search for 1^{+-}, 1^{++} glueballs by:

  $e^+e^- \rightarrow \pi\pi X,\ \pi^0 X,\ \eta X,\ \gamma X$ at $\sqrt{s} > 4.3\ GeV$

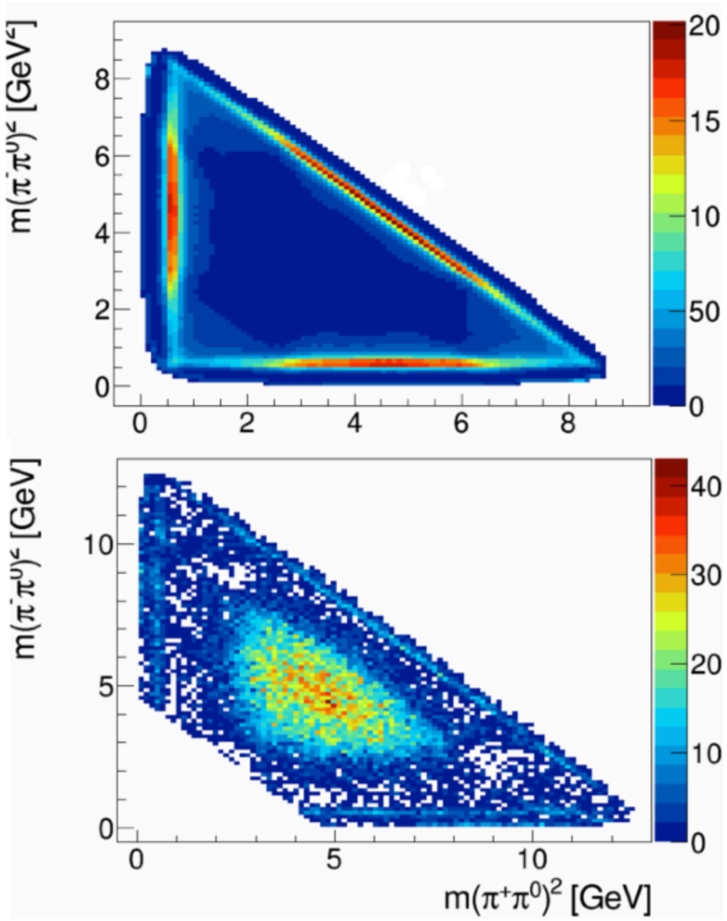
- Search for glueballs in h_c hadronic decays:

  Study $\psi' \rightarrow \pi^0 h_c$ and $e^+e^- \rightarrow h_c\pi\pi$ at $\sqrt{s} > 4\ GeV$
  Interesting modes $h_c \rightarrow V\pi\pi,\ VKK,\ V\eta\eta\ \ (V = \omega, \Phi)$

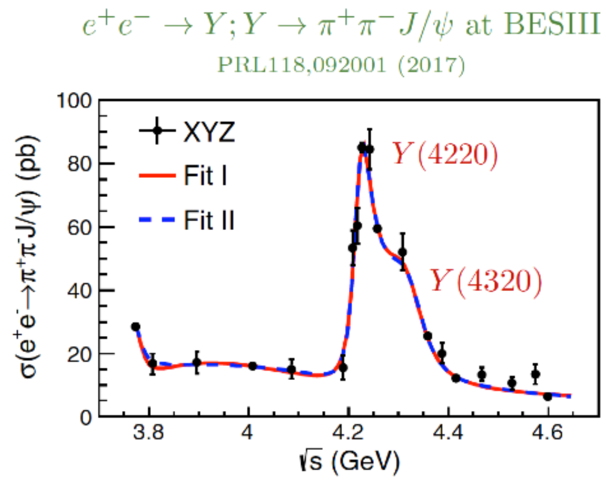
Puzzles in vector charmonia

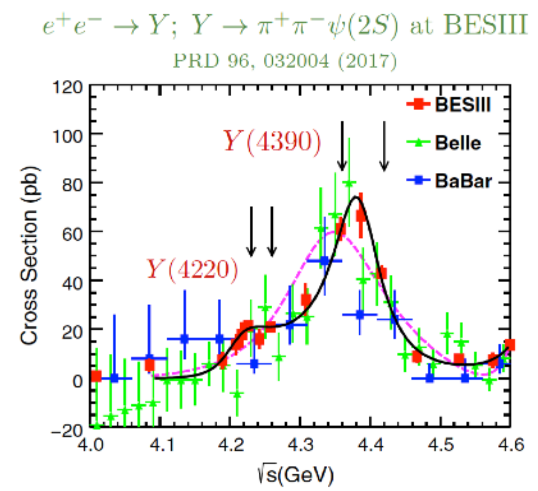
The puzzle(s) in the 1^{--} sector:

$J/\psi \to 3\pi^0$ and $\psi' \to 3\pi^0$



BESIII S. Fegan / Mainz



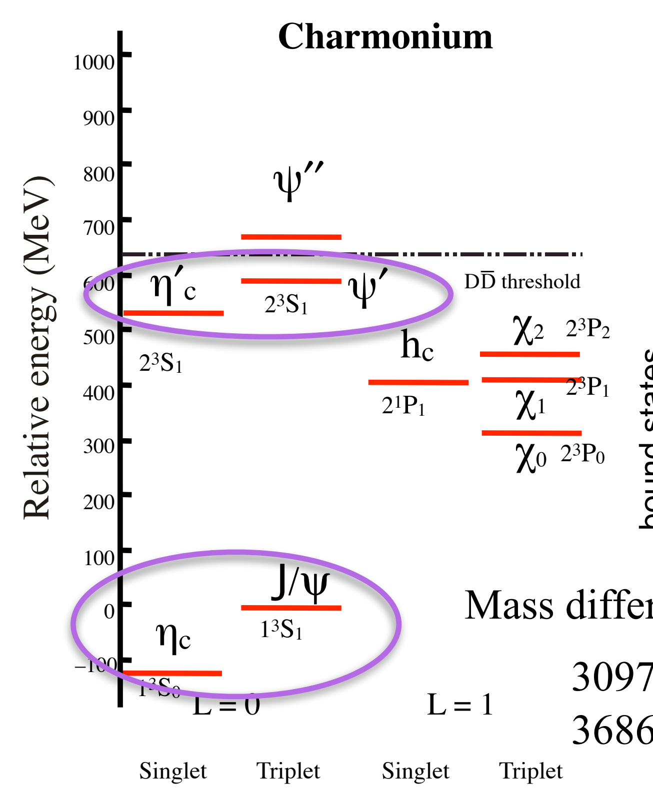


The "X(1835)"

CLEO: PRD 82, 092002

We do not find any evidence for a threshold enhancement in any of the three $\psi(2S)$ decay channels. For $\psi(2S) \to \gamma p\bar{p}$ we set a stringent upper limit for the threshold resonance $R_{\rm thr}$, $\mathcal{B}(\psi(2S) \to \gamma R_{\rm thr}) \times \mathcal{B}(R_{\rm thr} \to p\bar{p}) < 1.6 \times 10^{-6}$ at 90% CL.

With a limited sample of 8.6×10^6 J/ψ available to us from $\psi(2S) \to \pi^+\pi^- J/\psi$ we have searched for $J/\psi \to \gamma R_{\rm thr}$. We find a $p\bar{p}$ threshold enhancement. When it is analyzed taking into account an enhancement at $M(p\bar{p}) = 2100$ MeV$/c^2$, we obtain $M(R_{\rm thr}) = 1837^{+10+9}_{-12-7}MeV/c^2$, $\Gamma(R_{\rm thr}) = 0^{+44}_{-0}MeV/c^2$, and $\mathcal{B}(J/\psi \to \gamma R_{\rm thr}) \times \mathcal{B}(R_{\rm thr} \to p\bar{p}) = (11.4^{+4.3+4.2}_{-3.0-2.6}) \times 10^{-5}$.



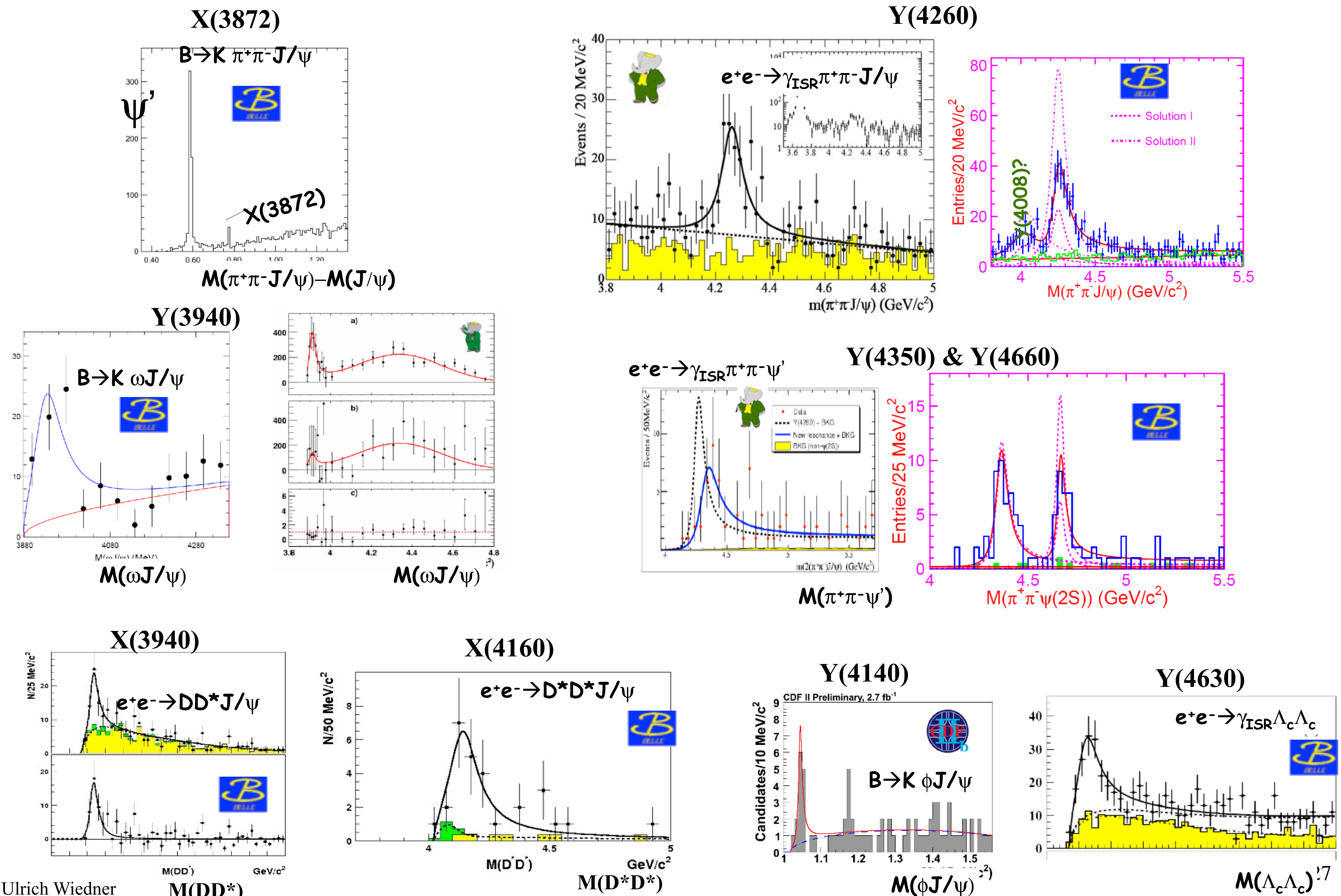
Mass differences in MeV/c²:

3097 − 2983 = 114

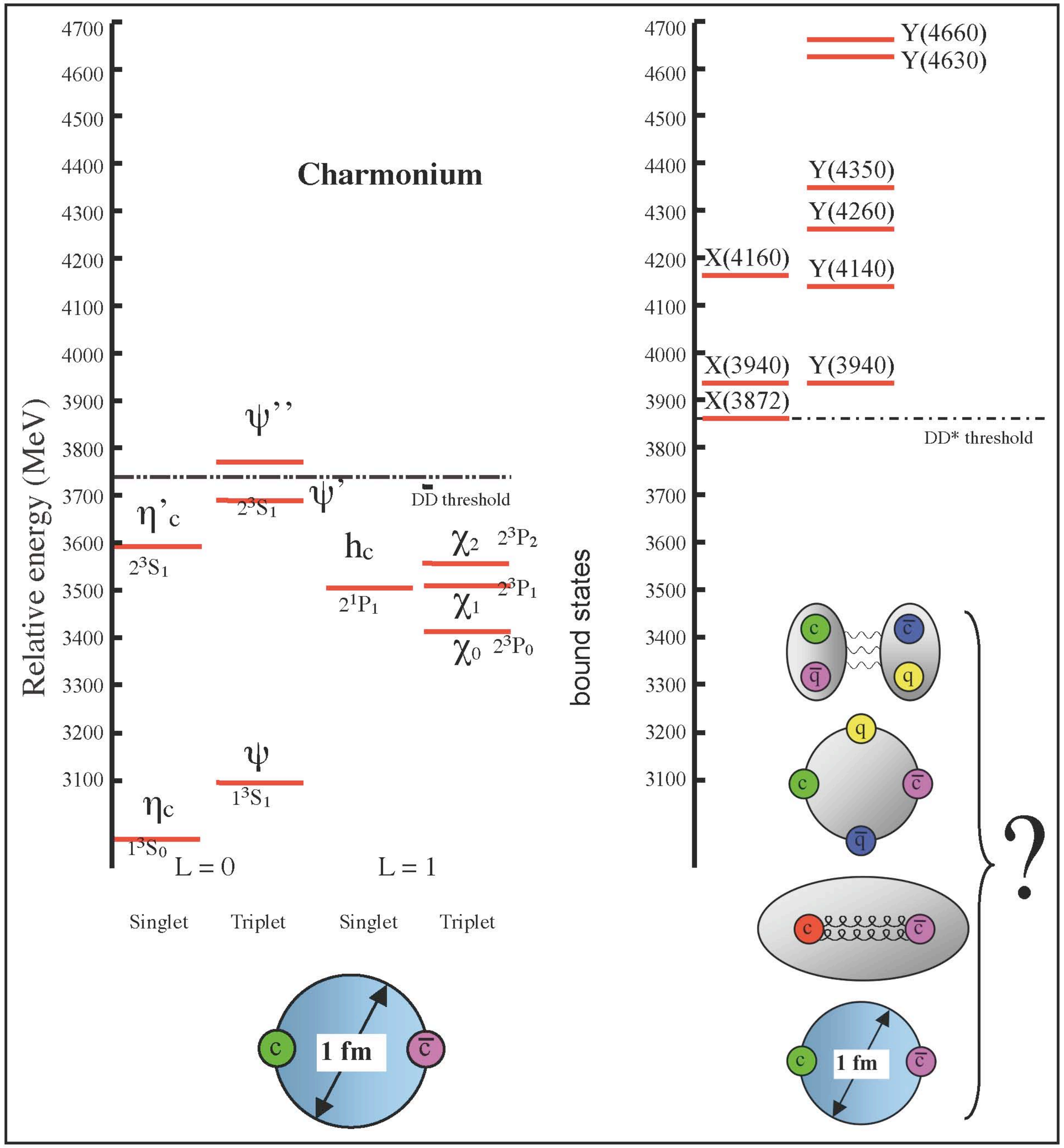
3686 − 3639 = 47

- Either J/ψ or ψ′ is not a proper 1S or 2S states ?
- A glueball disturbs the pattern ?
- … ?

Particles not fitting conventional charmonium resonances: X, Y states

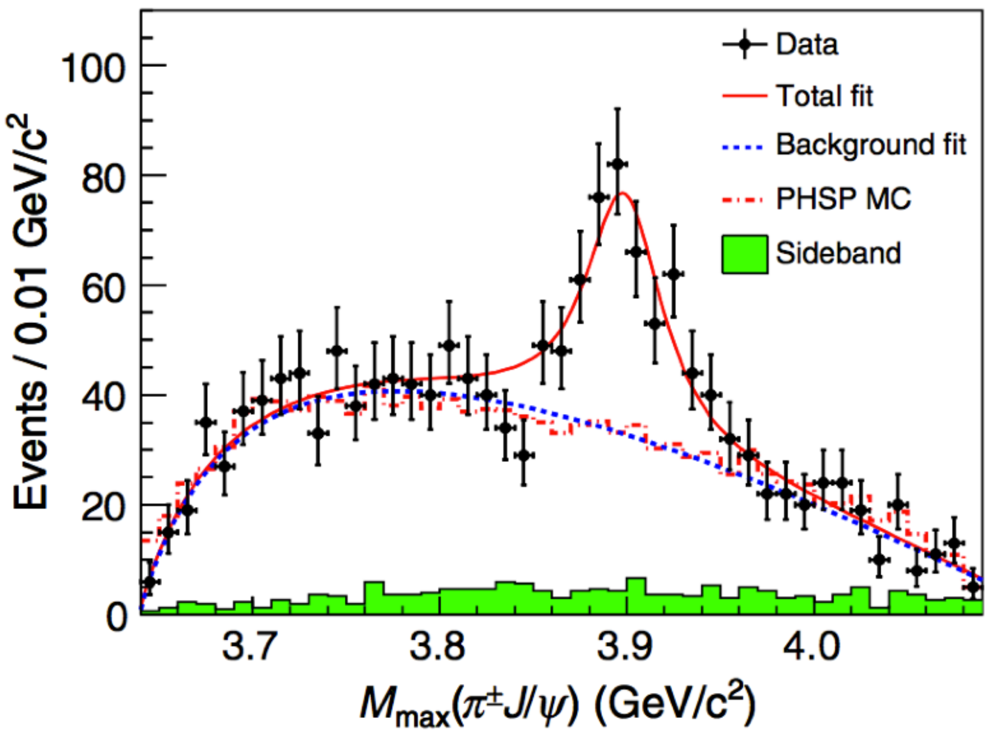


Particles not fitting conventional charmonium resonances: X, Y states

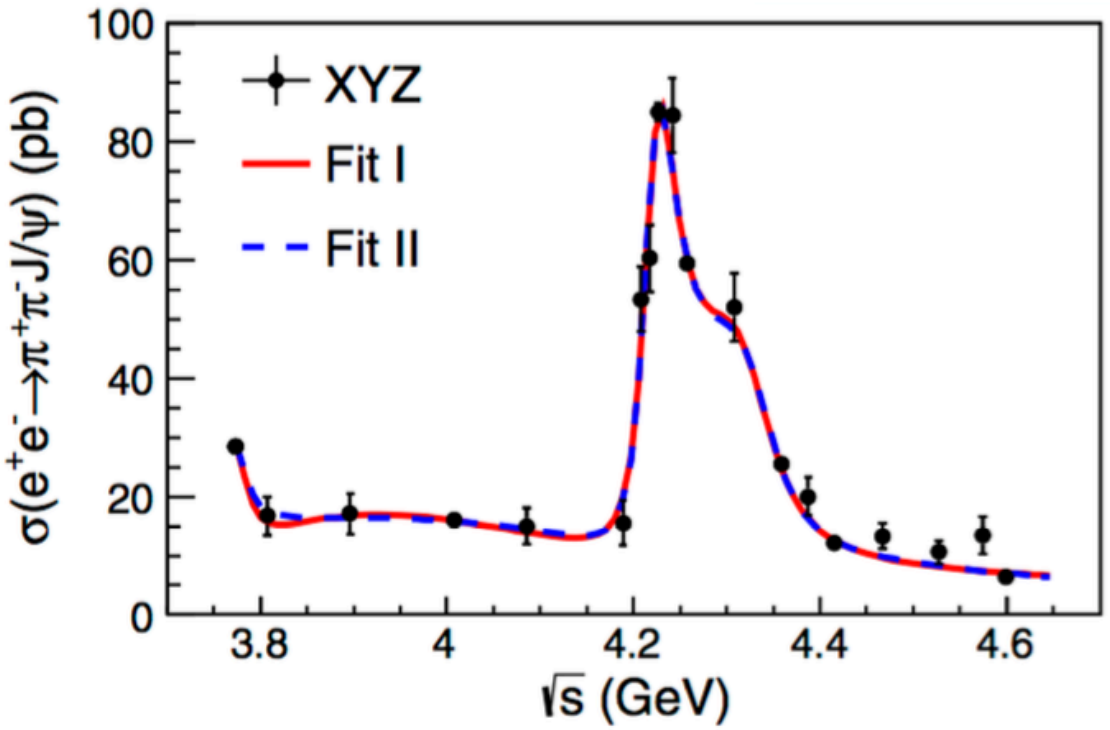


Even more exotic: $Z^{\pm}$

X, Y, Z exotics have been observed



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



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

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

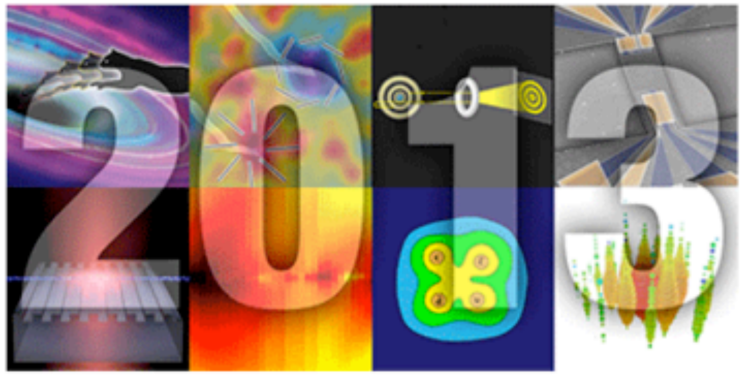
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas



Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

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New in Physics

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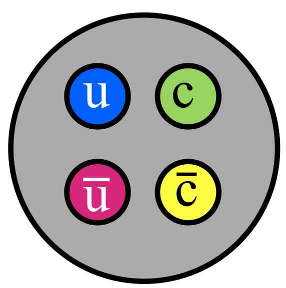
Electrons Not the Cause of Charged Grains
Focus | May 30, 2014
Seeing Just One Photon
Synopsis | May 29, 2014

What are these new states?

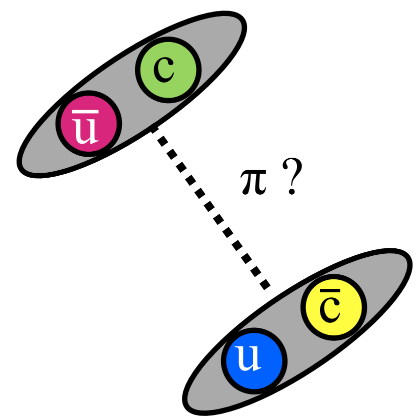
Colourful and colourless strong interaction

Compact objects
→ strong binding force



4-quark state

Other bound states
→ weaker binding force

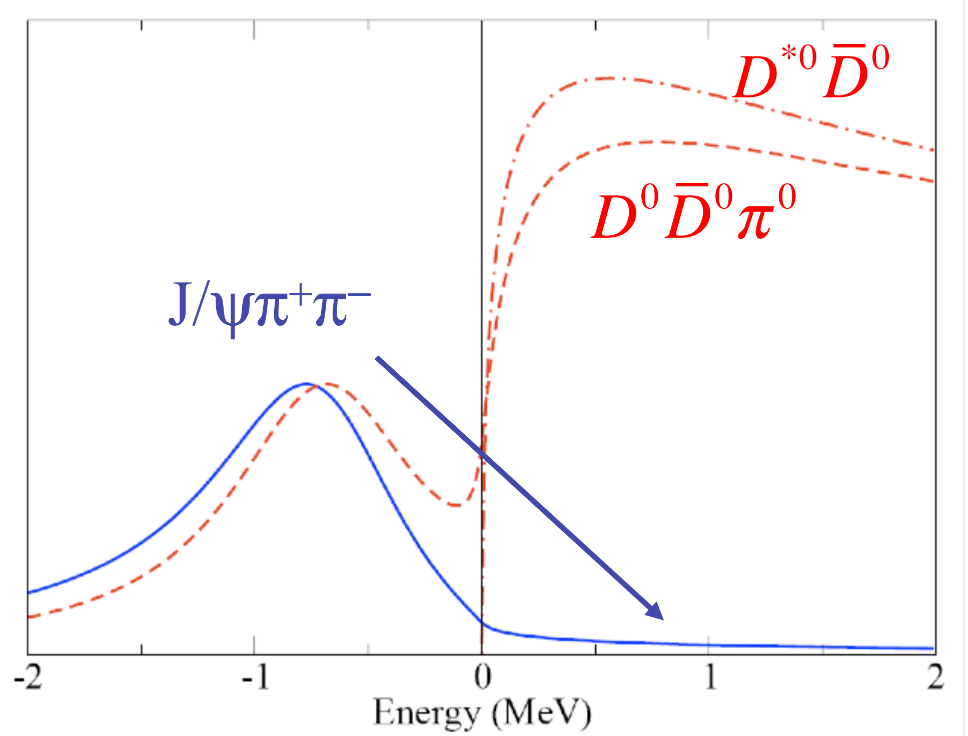


D-D̄-“molecule”

How to distinguish? ☛ theory !

How to classify these new states?

It is important to determine the resonance curve precisely ...



Above threshold 4-quark states and molecules are the same but dramatically different below threshold.

Analysis of $J/\psi\,\pi^+\pi^-$ and $D^0\bar{D}^0\pi^0$ Decays of the $X(3872)$

Eric Braaten and James Stapleton

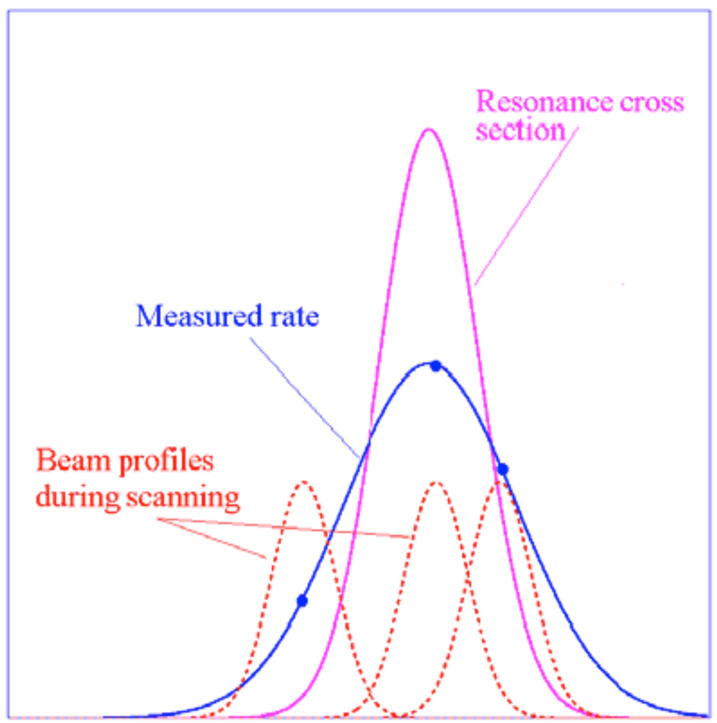
Physics Department, Ohio State University, Columbus, Ohio 43210, USA

(Dated: July 17, 2009)

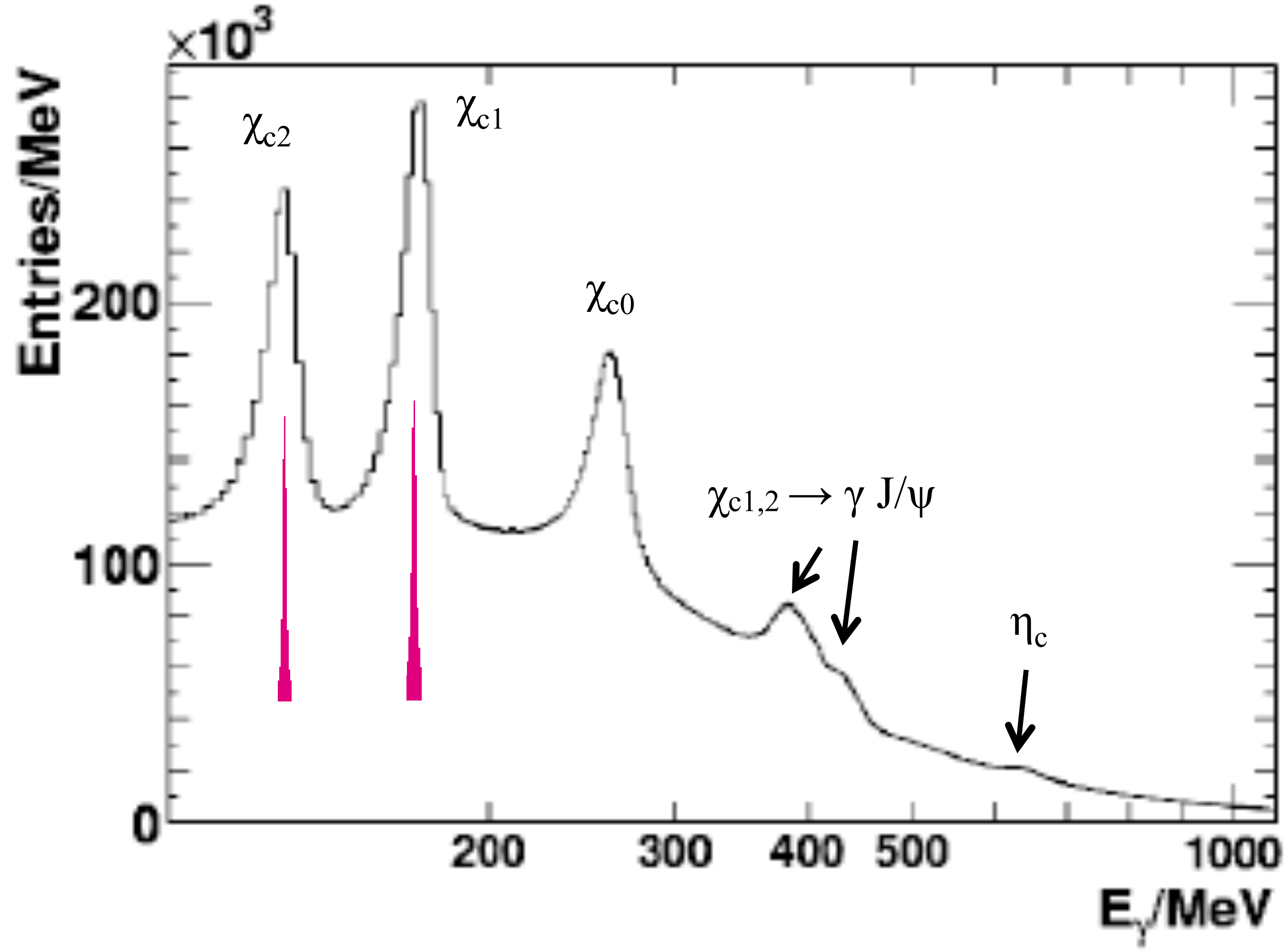
Phys.Rev. D81 (2010) 014019

Scanning resonance curves

Precise momenta at the HESR



BES III (e^+e^-: $\psi' \rightarrow \gamma X$)



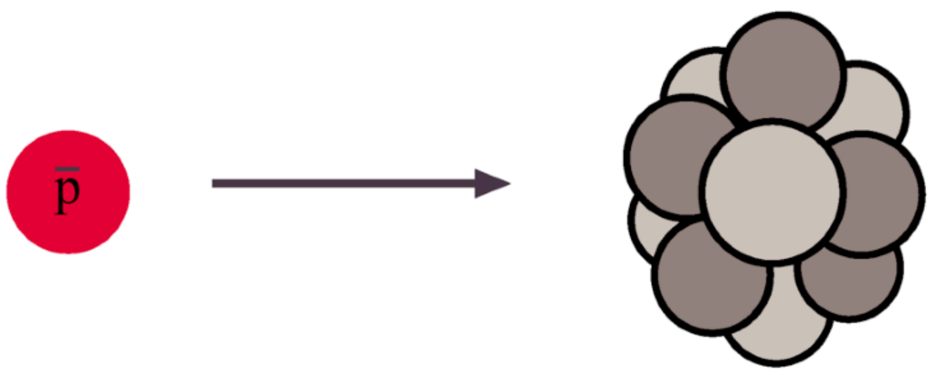
Just count:

$$R_i = L_0 \bullet \sigma(p_i) \bullet K\ (\Delta p/p,\ |p_i - p_R|)$$

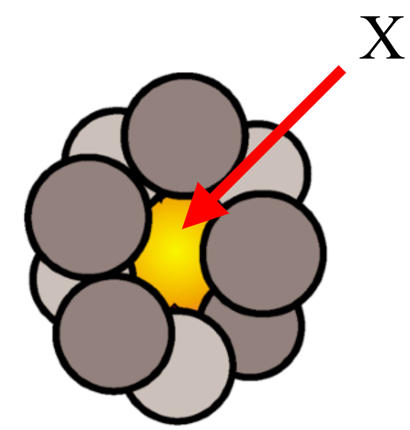
(K takes overlap between beam and resonance into account)

$\bar{p}$-formation (E760-experiment)

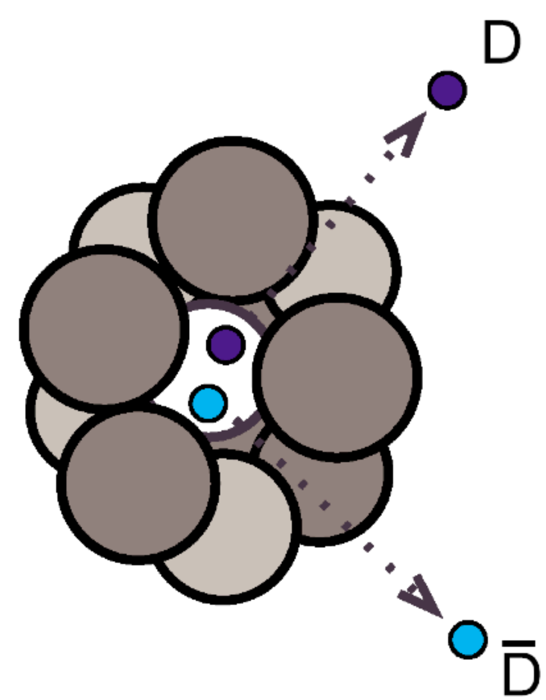
How to find molecules experimentally ?



$\bar{p}A \rightarrow X + (A\text{-}1)$



A weekly bound state
would be ripped apart by
the nuclear field

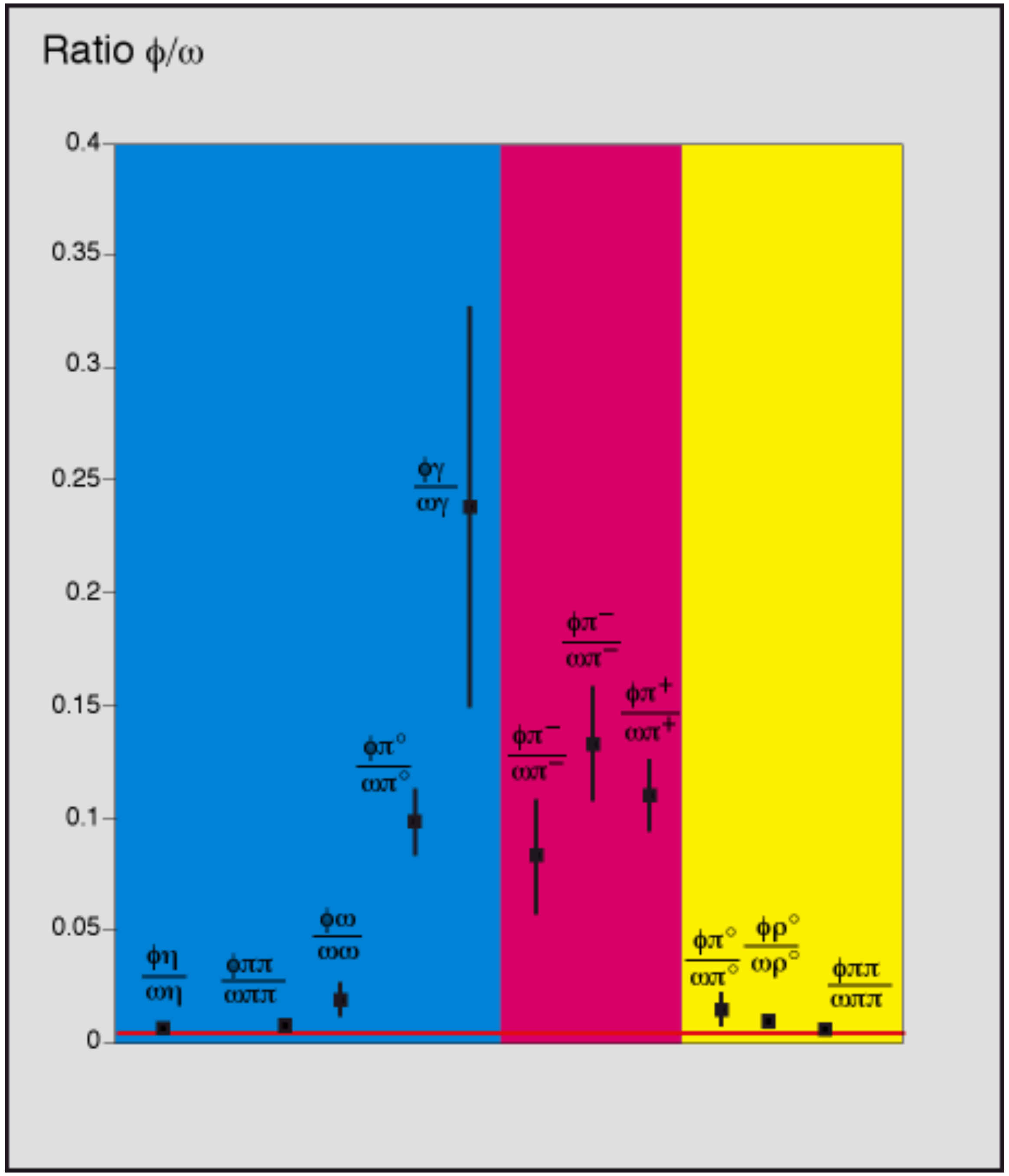


A change of decay patterns of X (or Y, or Z) in nuclei identifies molecules.

Only PANDA can do!

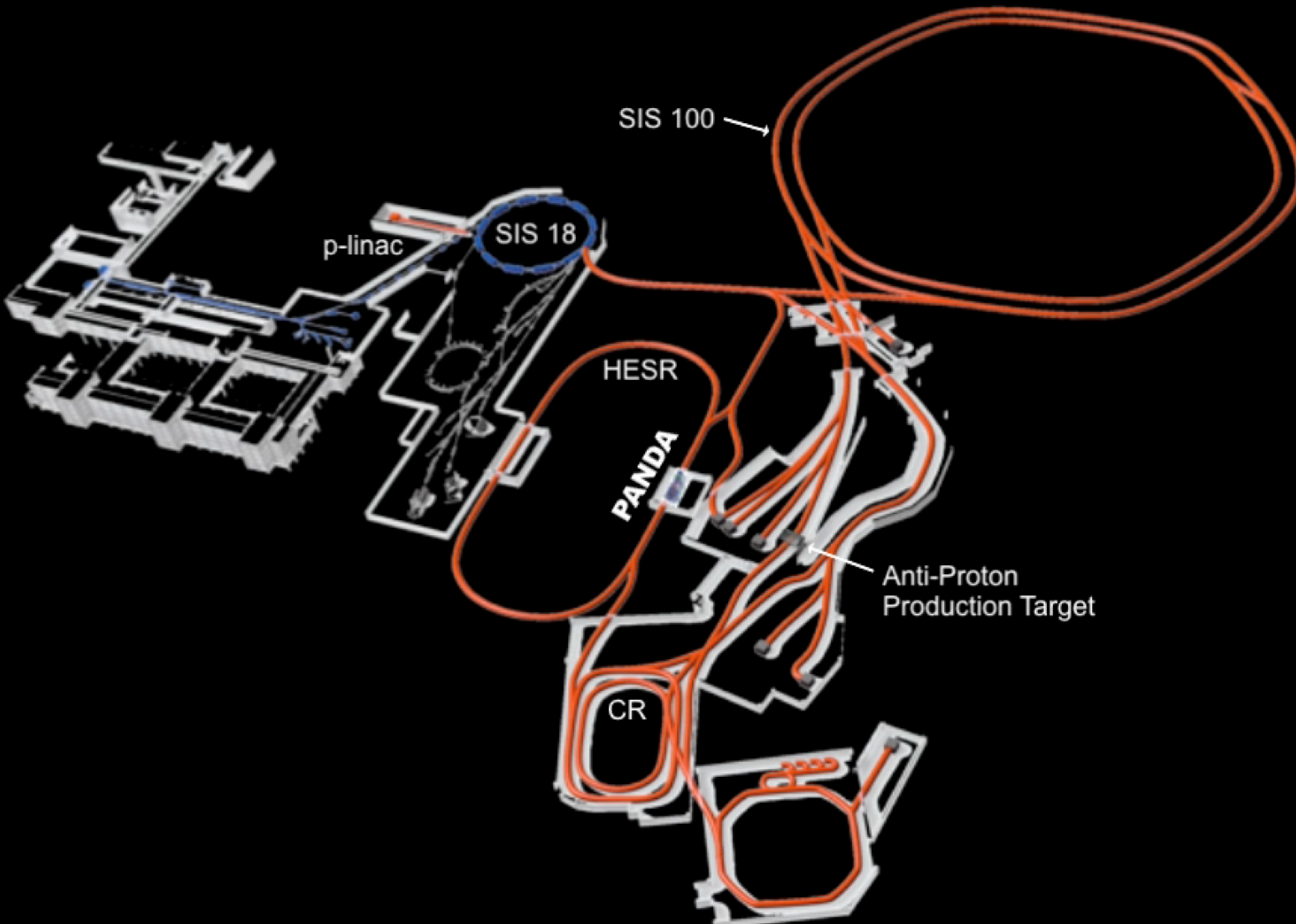
More puzzles in the strangeness sector

Strangeness-Produktion in $\bar{p}p$ (LEAR-data) : $\frac{\phi + X}{\omega + X}$

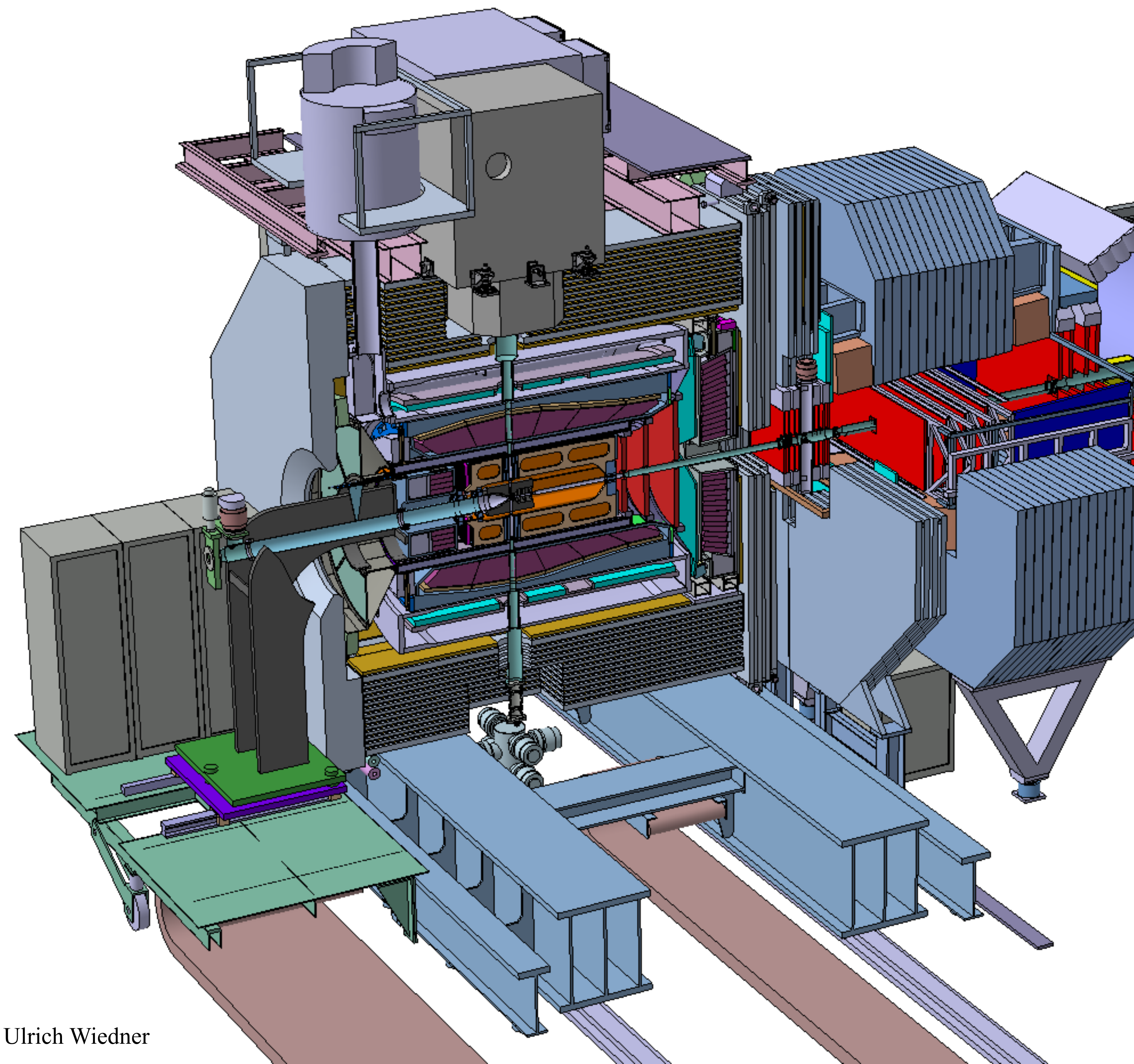


$\bar{p}p$ (S-wave) $\bar{p}n$ $\bar{p}p$ (P-wave)

OZI prediction


SIS 100
SIS 18
p-linac
HESR
PANDA
Anti-Proton
Production Target
CR

The $\bar{\text{P}}$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
(cτ = 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

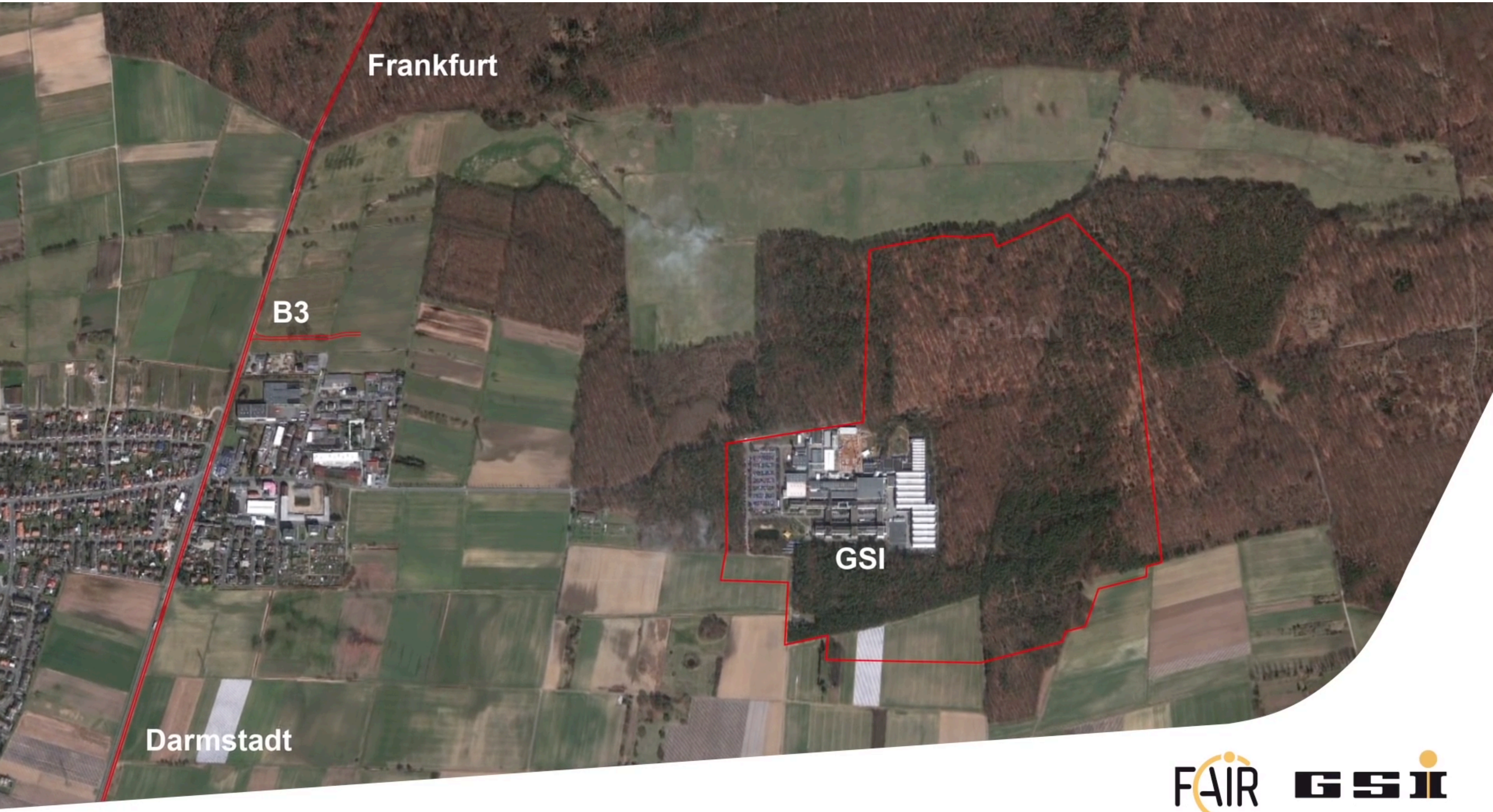
The FAIR construction side (Dec. 2017)

The FAIR construction side (as of yesterday)

Ulrich Wiedner

Thanks a lot!

Muito obrigado!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B3
GSI
Darmstadt