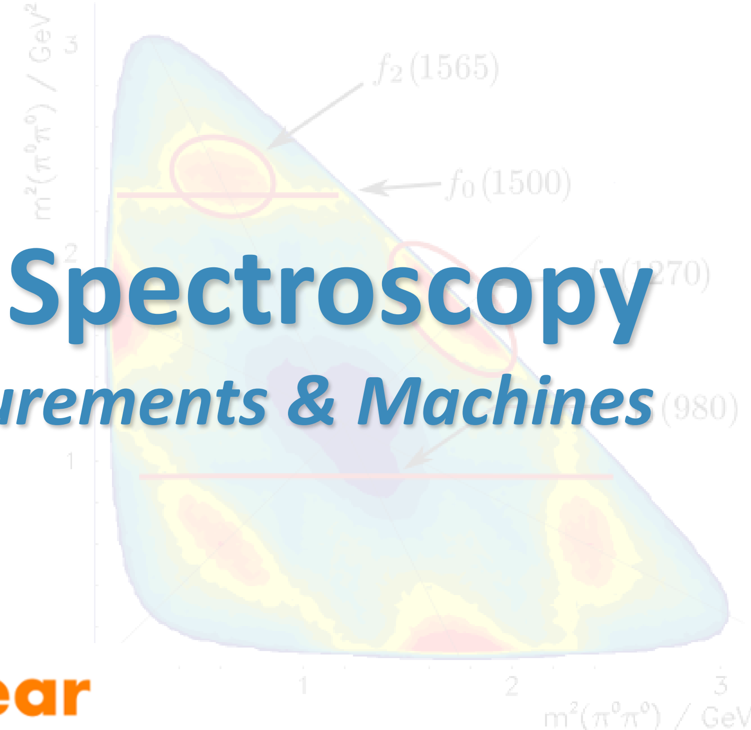
Meson Spectroscopy

Methods, Measurements & Machines



2015 European Nuclear Physics Conference

Aug. 31 – Sep. 4, Groningen

Klaus Götzen
GSI Darmstadt

Mesons – are they *really* interesting?

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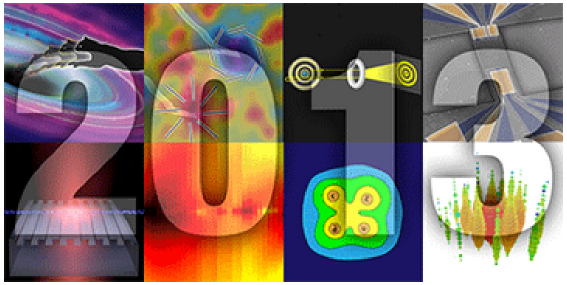
Notes from the Editors: Highlights of the Year

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.

... Three quarks for Muster Mark !?

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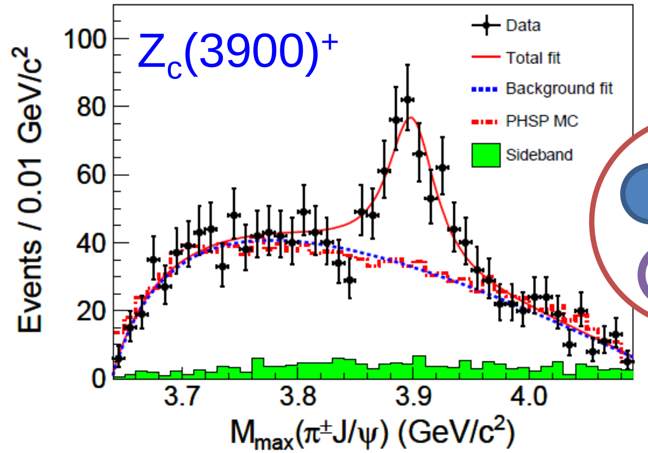

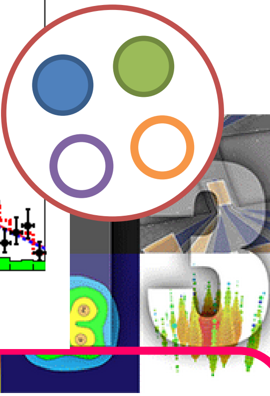

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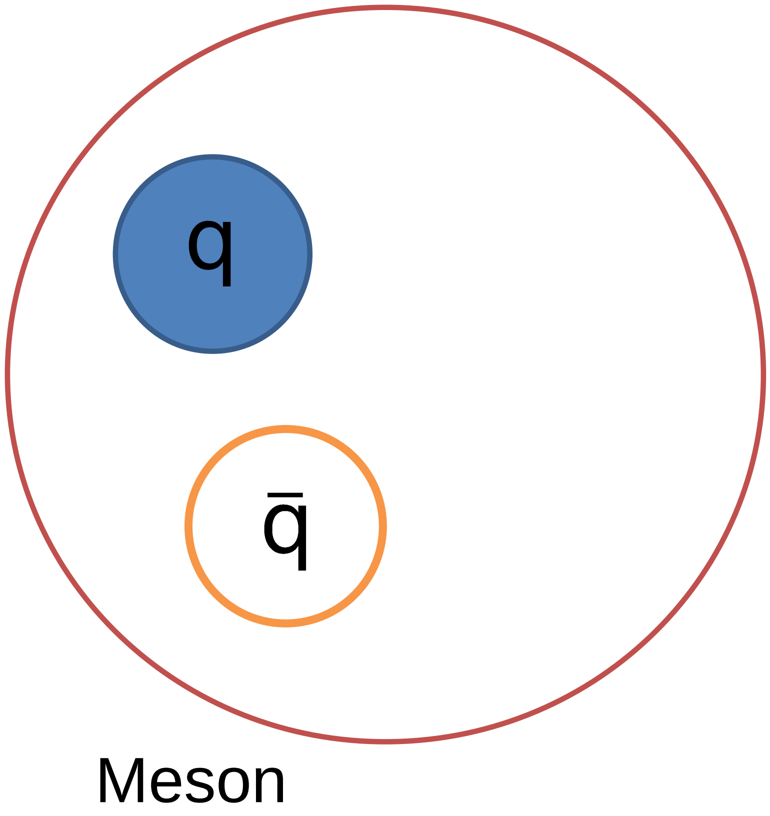
… ~~Three~~ quarks for Muster Mark !?
Four

What is a meson?

Definition: **Meson → Hadron with B = 0**

→ in contrast to simple quark anti-quark ($q\bar{q}$) allows a huge variety of states!



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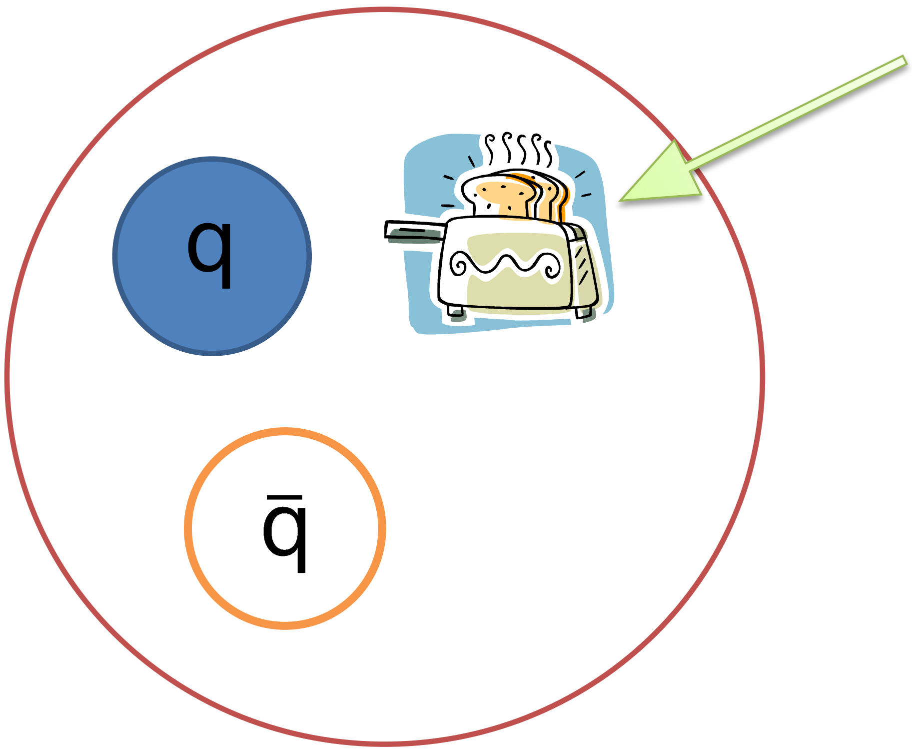

You can basically add whatever you want ...

Meson

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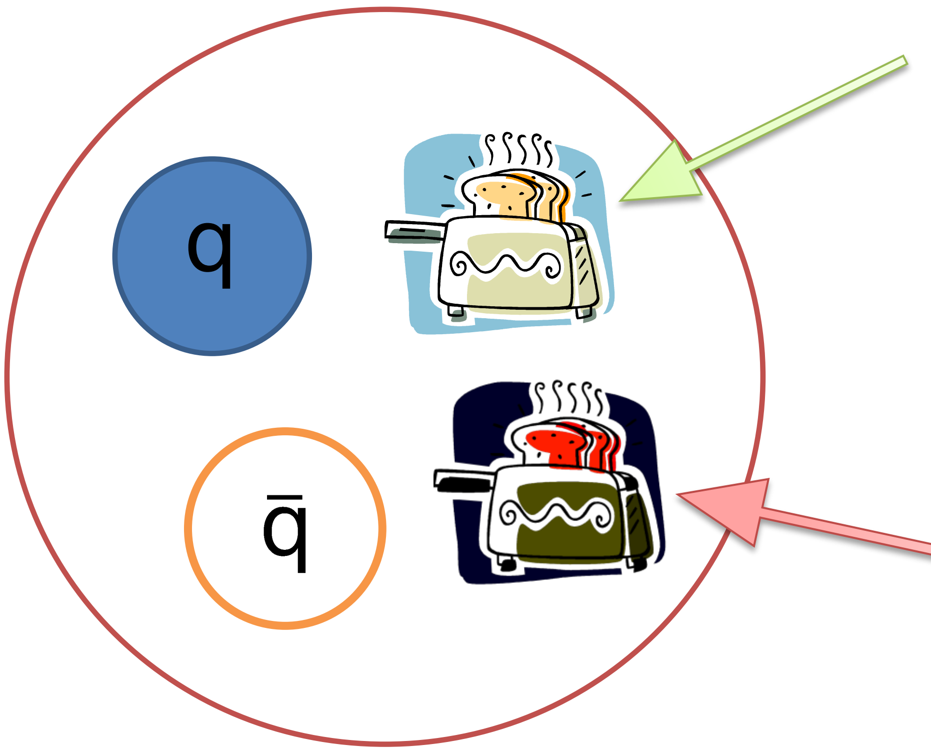


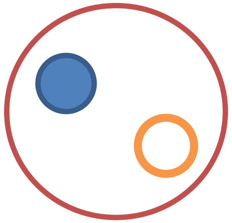
You can basically add whatever you want ...

... as long as you add something with the opposite baryon number

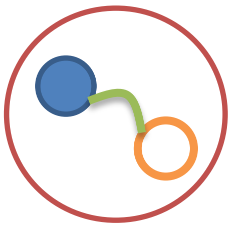
Meson

Meson Variations

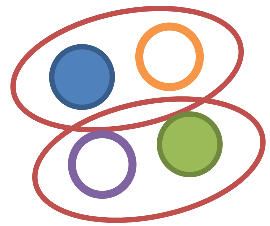
Commonly discussed:



Conventional $(q\bar{q})_1$

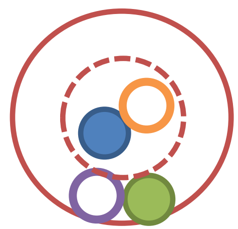


Hybrid $(q\bar{q})_8 g$

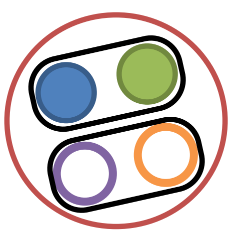


Molecule $(q\bar{q})_1(q\bar{q})_1$

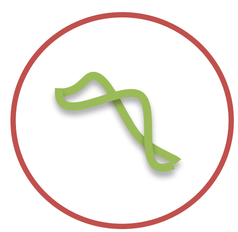
Tetraquark $(q\bar{q}q\bar{q})_1$



Hadro-quarkonium
$(Q\bar{Q})_1(q\bar{q})_1$



Diquarkonium
$(qq)_{\bar{3}}(\bar{q}\bar{q})_3$



Glueball $(gg)_1$ or $(ggg)_1$

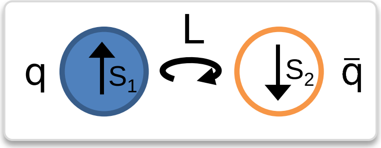
[e.g. Braaten, PRD90(2014)014044]

Identify Exotic Mesons

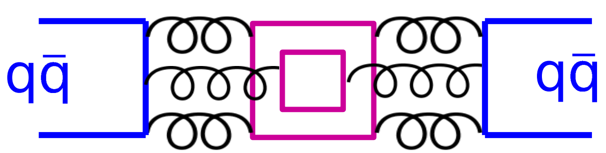
- **1st** order exotic
  - Simple to spot: QN invalid for $q\bar{q}$ states (e.g. |Q|, |S|, |C|>1...)

- **2nd** order exotic (spin exotic)
  - Special for $q\bar{q}$ states: some spin-parity values (J^{PC}) are forbidden

$\Rightarrow J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots \Rightarrow$ exotic meson

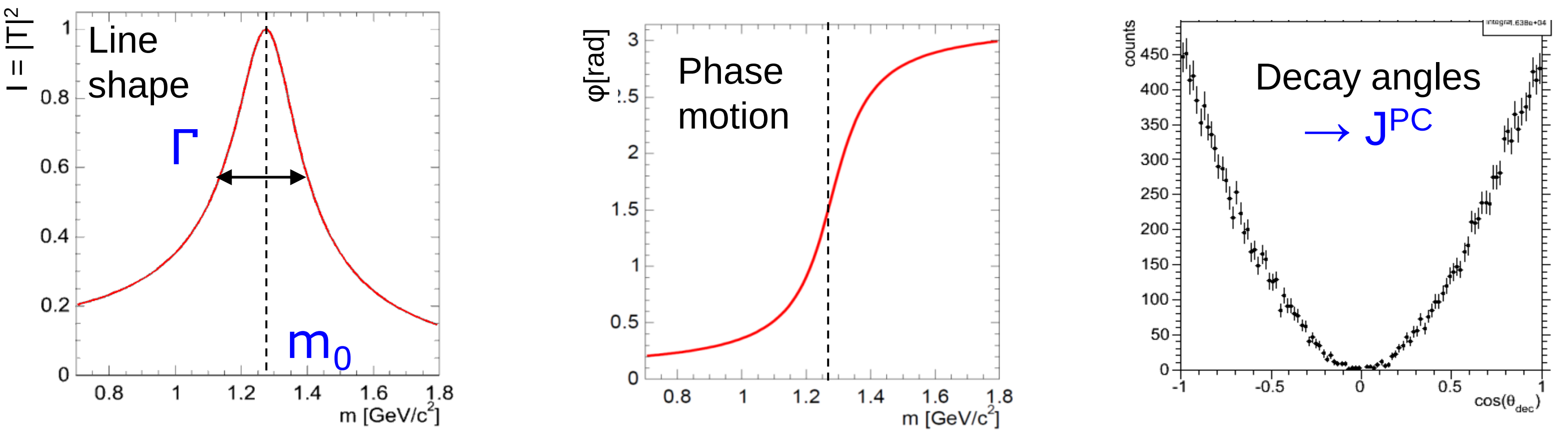


- **3rd** order exotic (crypto exotic)
  - No (obvious) difference to $q\bar{q}$ states $\rightarrow$ hard to identify!
  - Can mix with conventional states
  - Carefully study the decays & properties!



$$\Rightarrow \begin{pmatrix} M_1 \\ M_2 \end{pmatrix} = \begin{pmatrix} \cos & -\sin \\ \sin & \cos \end{pmatrix} \cdot \begin{pmatrix} q\bar{q} \\ \text{exotic} \end{pmatrix}$$

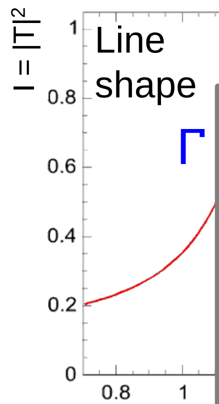
Properties and Dynamics of Mesons

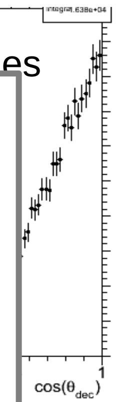


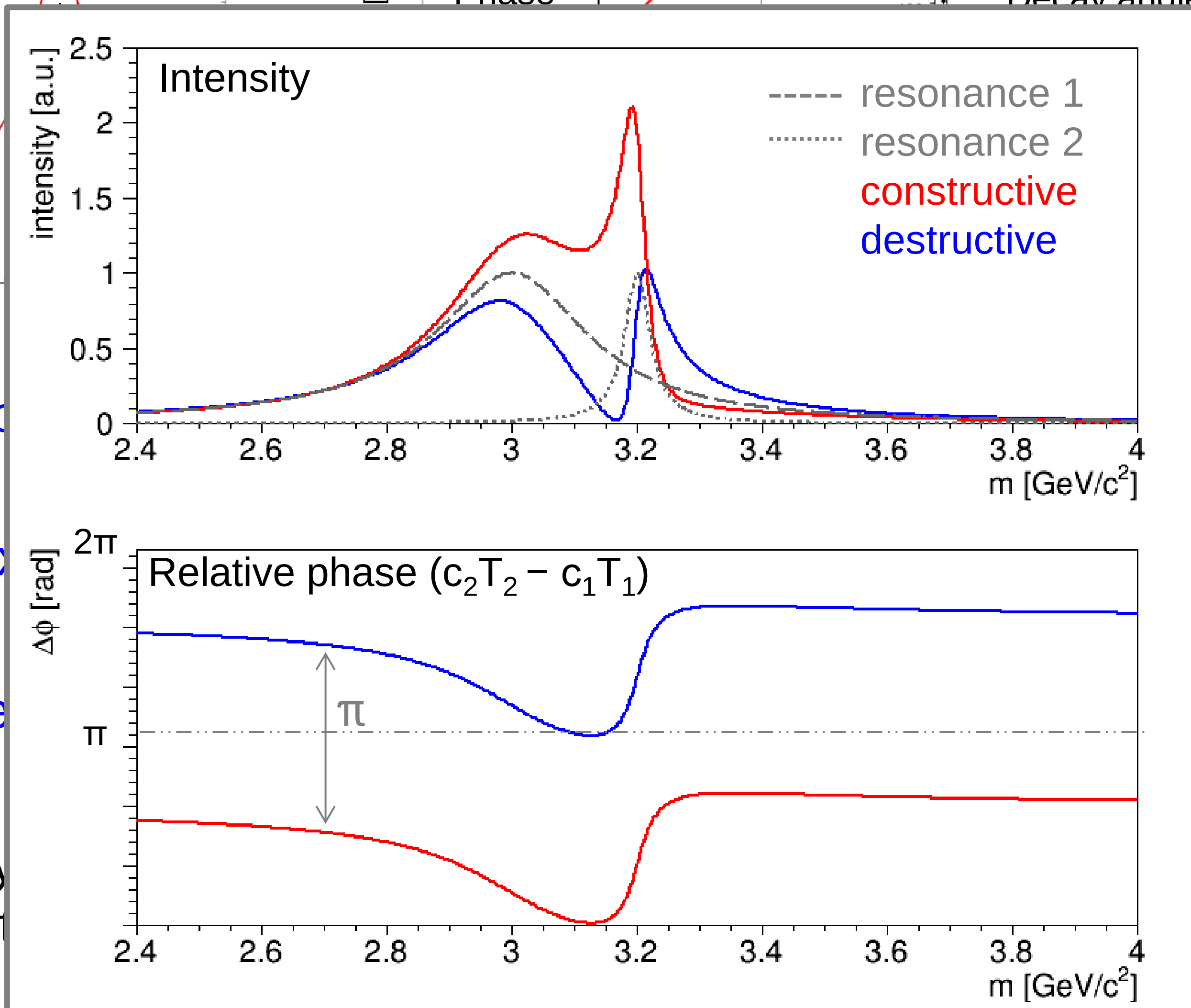
- Main properties: Mass m, width Γ, Spin-Parity J^{PC}, decays $\mathcal{B}(M \to f_i)$
- Complex dynamics, e.g. $T(m) = \dfrac{\frac{\Gamma}{2}}{m_0 - m - i\frac{\Gamma}{2}} = A \cdot e^{i\phi}$, $I = |T|^2$
- Interference of multiple resonances T_i ⇒ $I = |\Sigma c_i T_i|^2$ (strength c_i)

⇒ Typically: Amplitude Analysis (or Partial Wave Analysis) needed to disentangle signals and determine resonance properties

Properties and Dynamics of Mesons







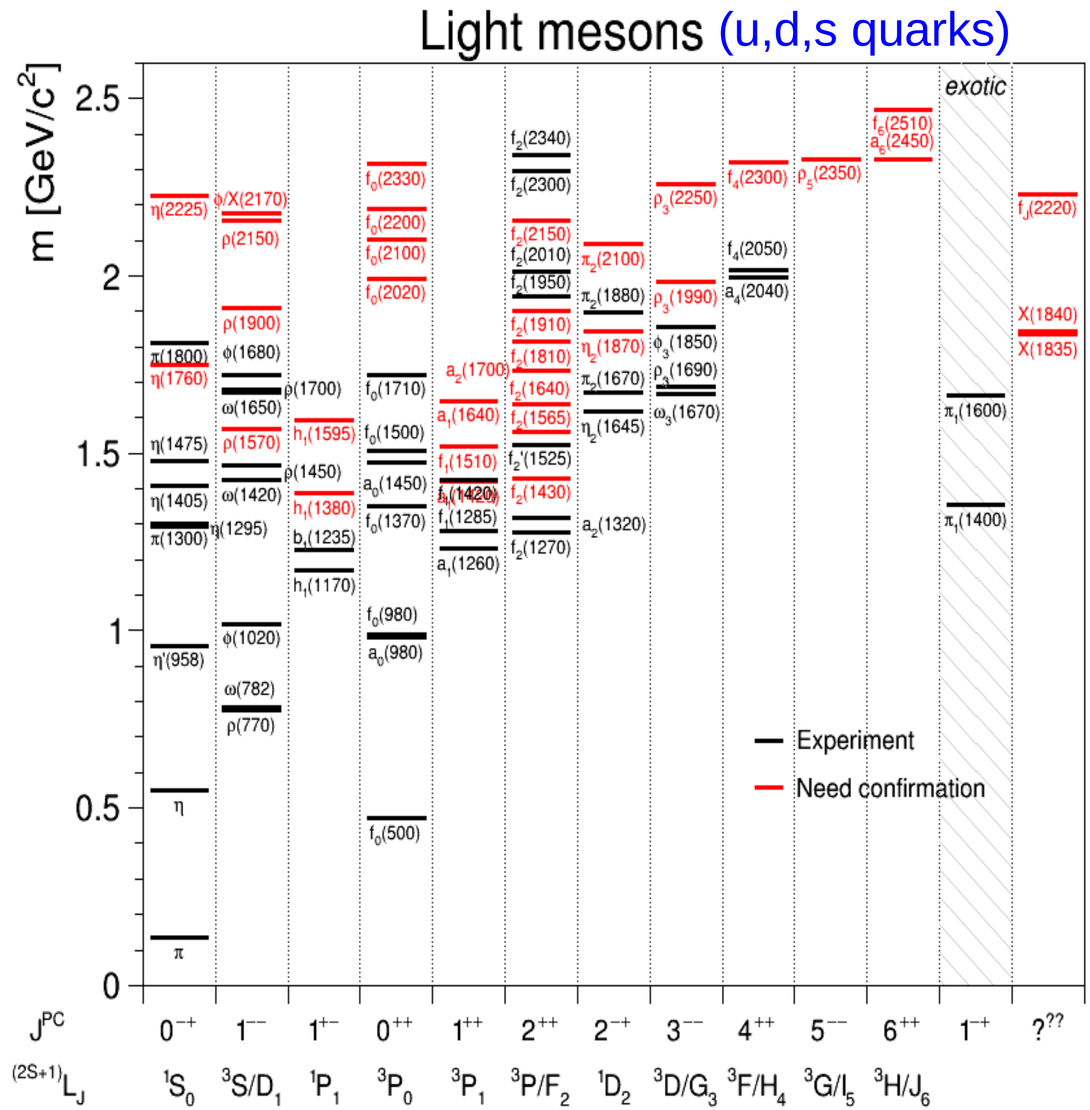
- Main pro … $M \rightarrow f_i$)
- Complex … $T|^2$
- Interfere … h c_i)

⇒ Typically … ed
to disent…

Light Quark Sector

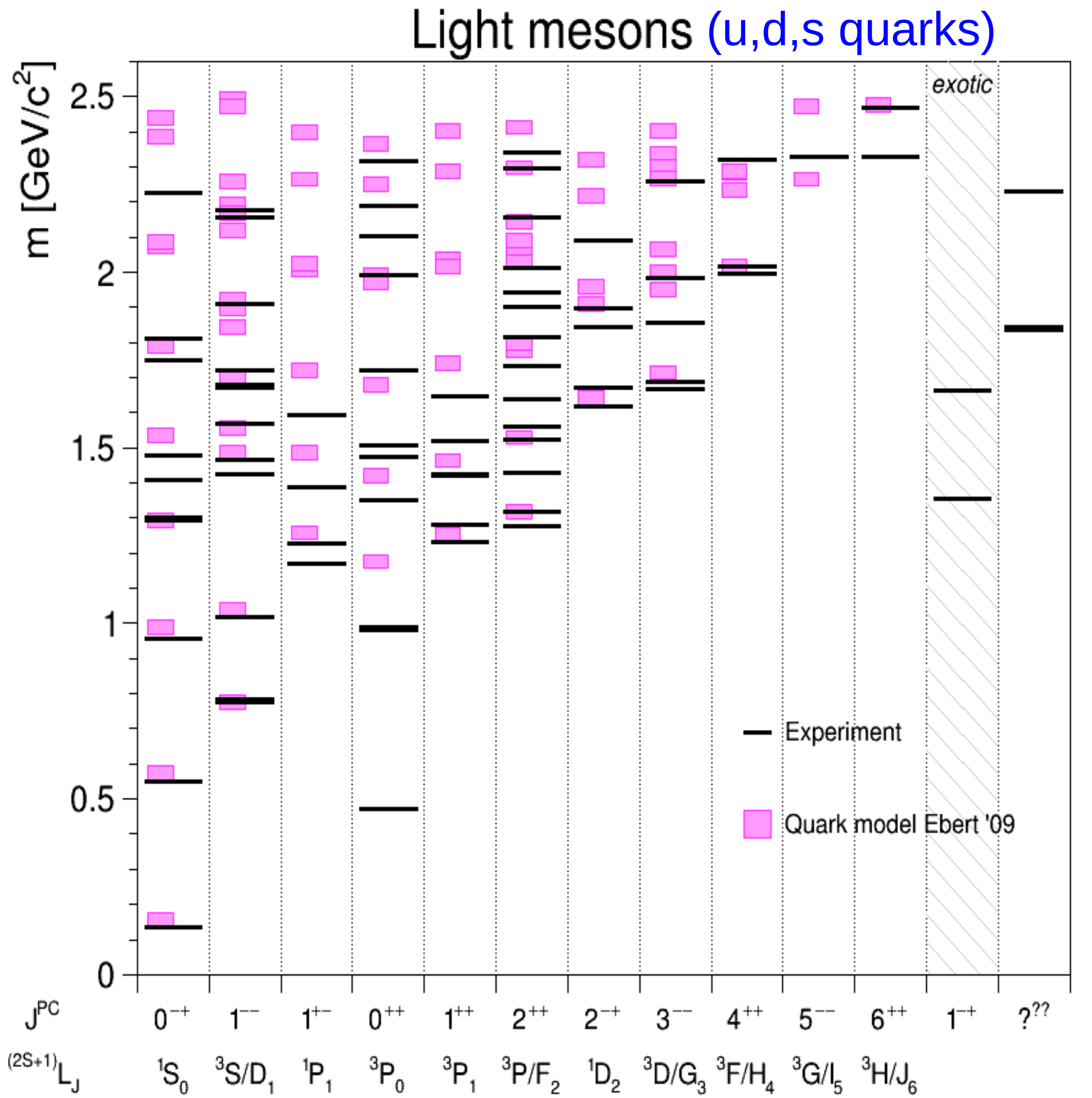
Light Meson Spectrum

- Many states found



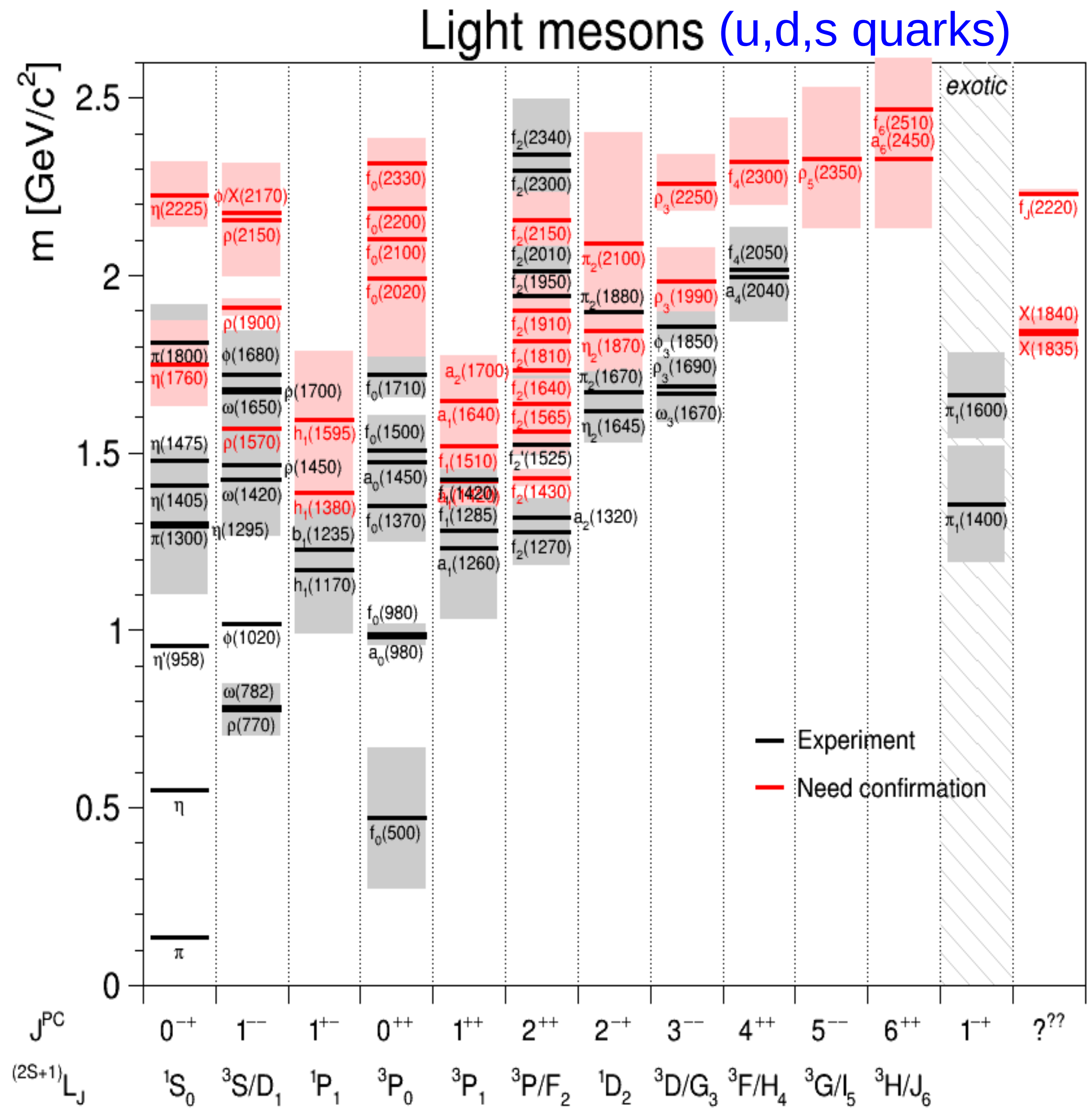
Light Meson Spectrum

- Many states found
- Predictions not perfect



Light Meson Spectrum

- Many states found
- Predictions not perfect
- Broad states
  ⇒ Strong overlap + mixing

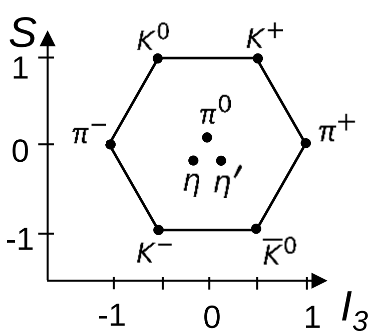


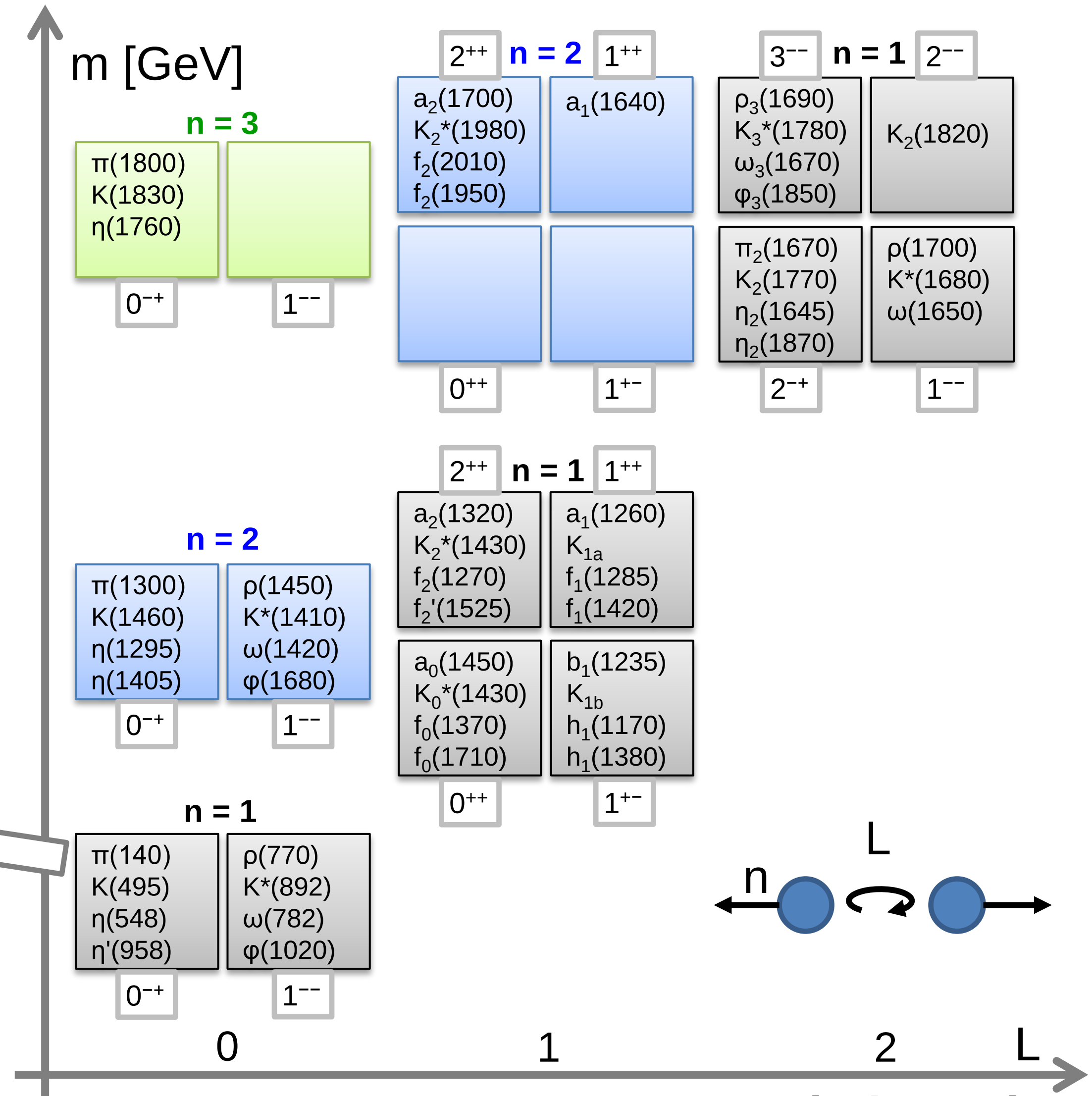
Light Meson Spectrum - Multiplets

- Many states found
- Predictions not perfect
- Broad states
  ⇒ Strong overlap + mixing

- Apply ordering to identify supernumerary states

→ J^{PC} Multiplets (Nonets)





[Amsler, 2007]

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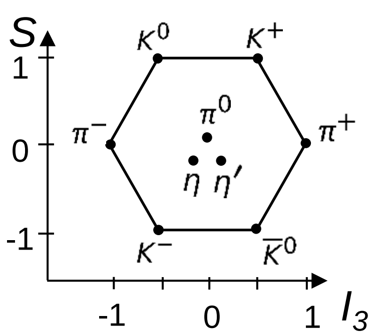
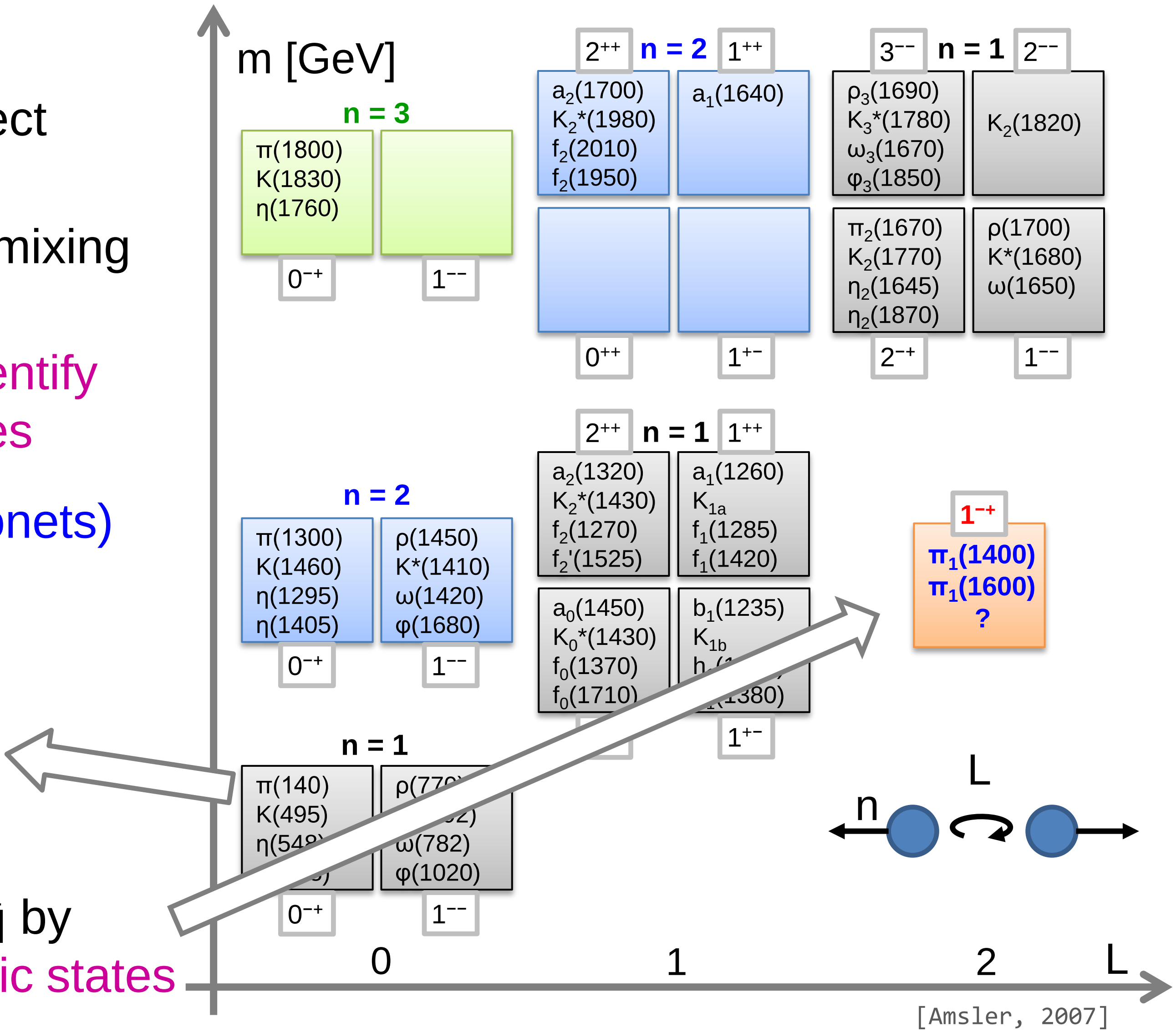


- Avoid mixing with $q\bar{q}$ by looking for spin-exotic states



Dalitz Plot Analysis $\pi_1(1400)$ (Crystal Barrel)

- Analyse 3-body reaction: $\bar{p}n \rightarrow \pi^- \pi^0 \eta$ @ rest

⇒ **Dalitz Plot Analysis**

  – 2D intensity study in 3 body reactions

  – 2 variables describe complete dynamics

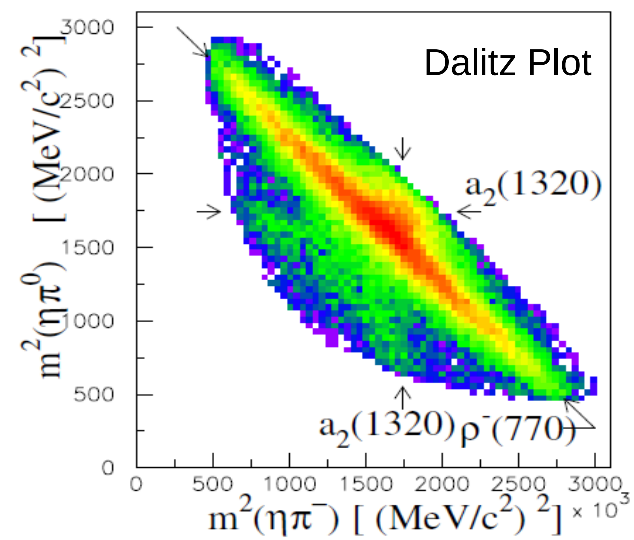
  – reveals 2-body resonances in the system

- Find set of resonances T_i and coefficients c_i , so that $I = |\Sigma c_i T_i|^2$ describes data

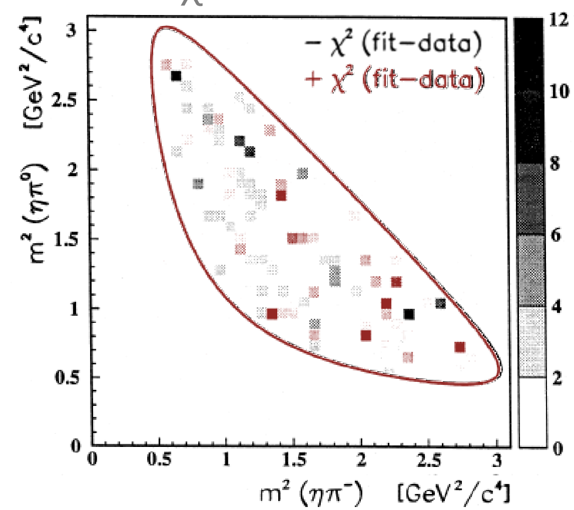
- Fit demands $X \rightarrow \eta\pi$ (both 0^{-+}) with $L=1$
  (m_X = 1400±30 MeV, Γ_X = 310±70 MeV)

⇒ $J^{PC}(X) = 1^{-+}$, X called $\pi_1(1400)$

[PL B423 (1998) 175]



Flat χ^2 distributions



GSI

Dalitz Plot Analysis $\pi_1(1400)$ (Crystal Barrel)

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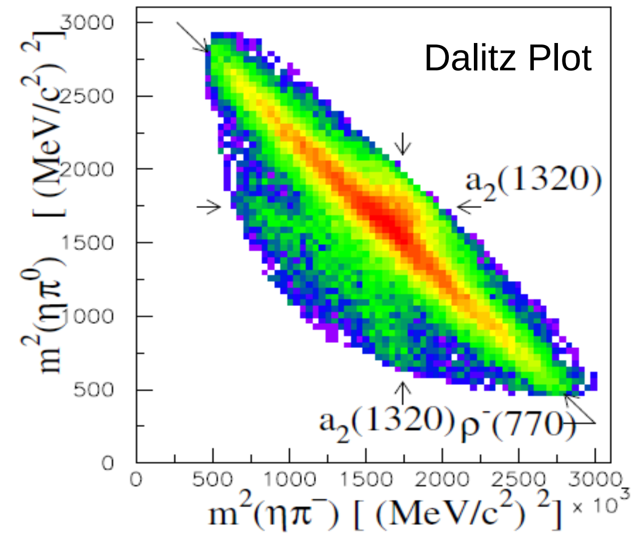

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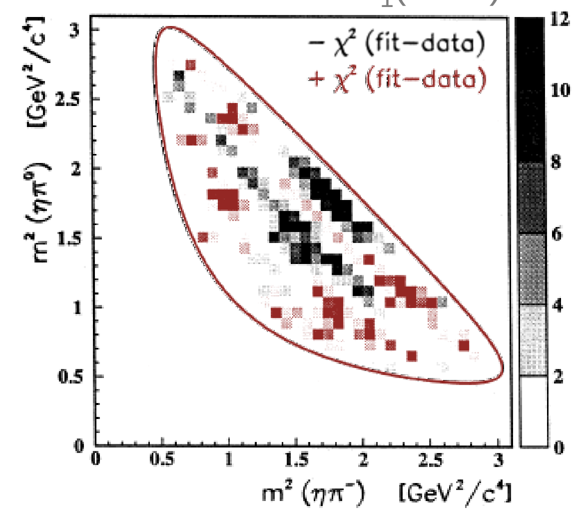
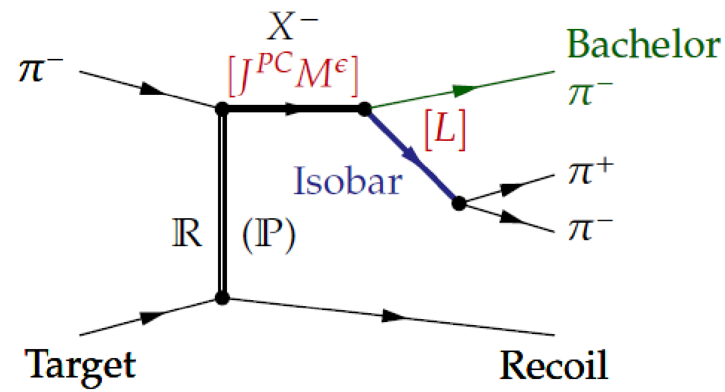
Bad fit without $\pi_1(1400)$



⇒ $J^{PC}(X) = 1^{-+}$, X called $\pi_1(1400)$

Partial Wave Analysis $\pi_1(1600)$ (COMPASS)

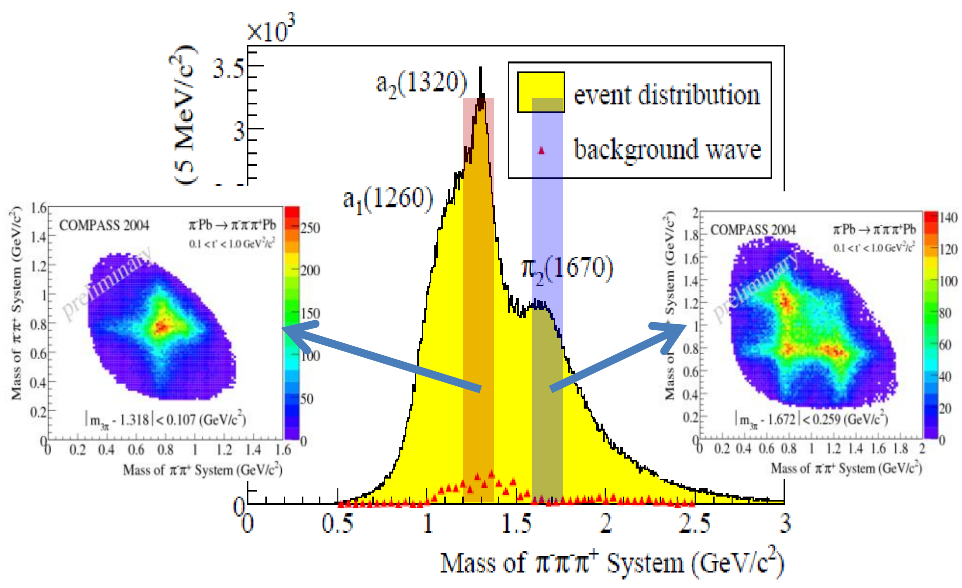
- Observation of hybrid candidate @ COMPASS: $\pi_1(1600)$
- Diffractive dissociation $\pi^- \to \pi^- \pi^- \pi^+$ with π^- beam (p=190 GeV/c) on Pb



⇒ **Partial Wave Analysis (PWA)** - 2 stages

1. Mass independent fit in $m_{3\pi}$ slices
   ⇒ Contributions & interferences
   of different $X^- \to (\pi^+\pi^-)_{ib}\,\pi^-$

2. Fit with model assumptions
   for the observed partial
   waves (resonances)



[PRL 104 (2010) 241803]

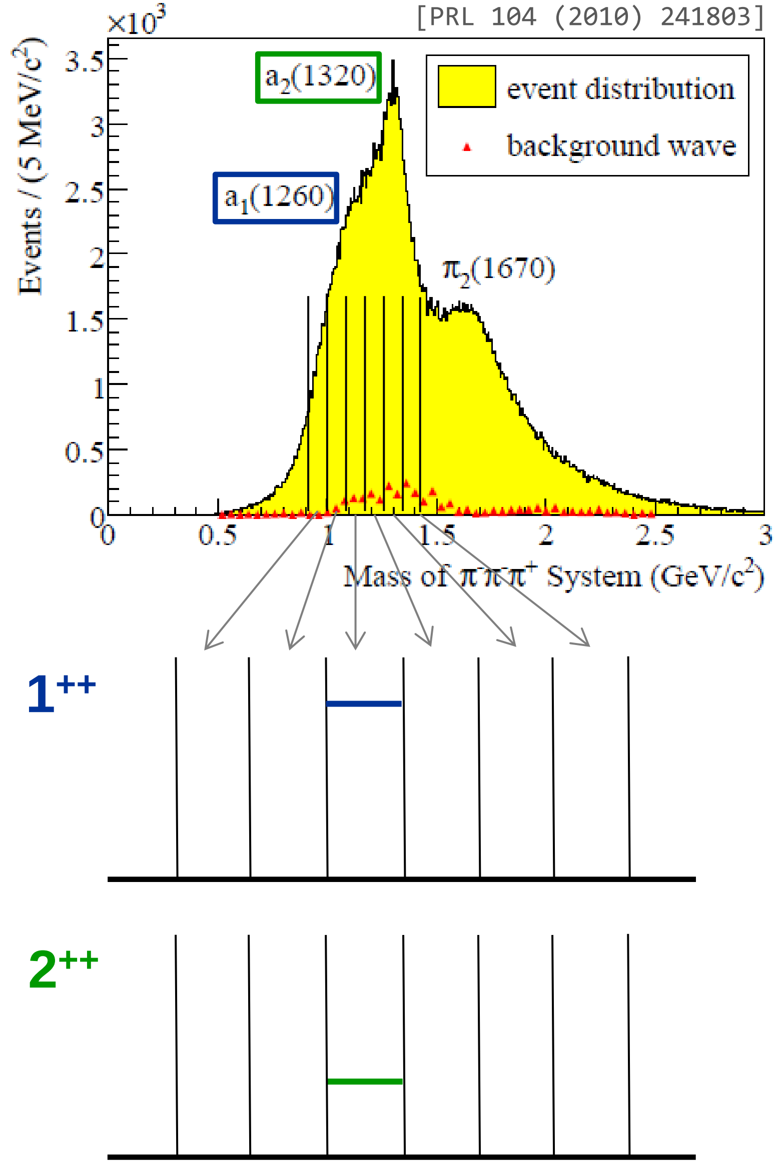
COMPASS PWA Fit

1. Mass independent fit
   - 5 observables τ (m_{isobar} + 4 angles)
   - Offer 42 partial waves to the fit
   - Fit production amplitudes to describe distributions of τ

→ Intensities of partial waves (PW)

→ Relative phases between PW

[PRL 104 (2010) 241803]



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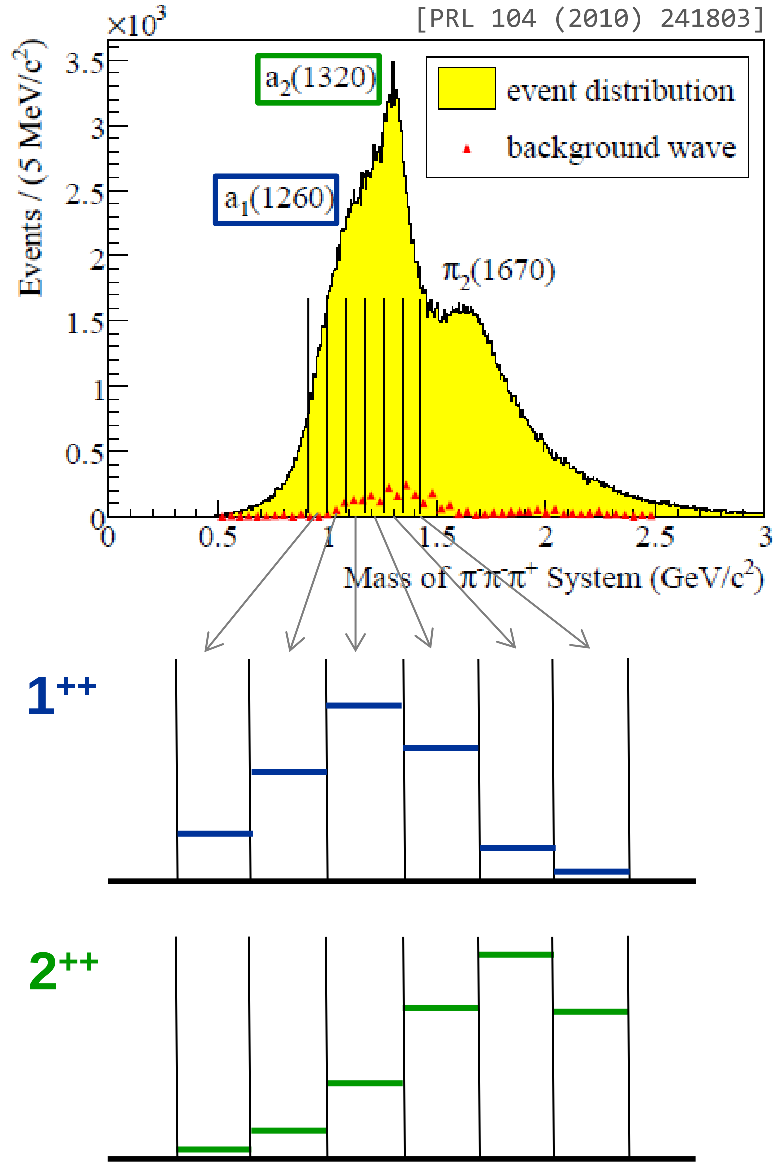

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1. Mass independent fit
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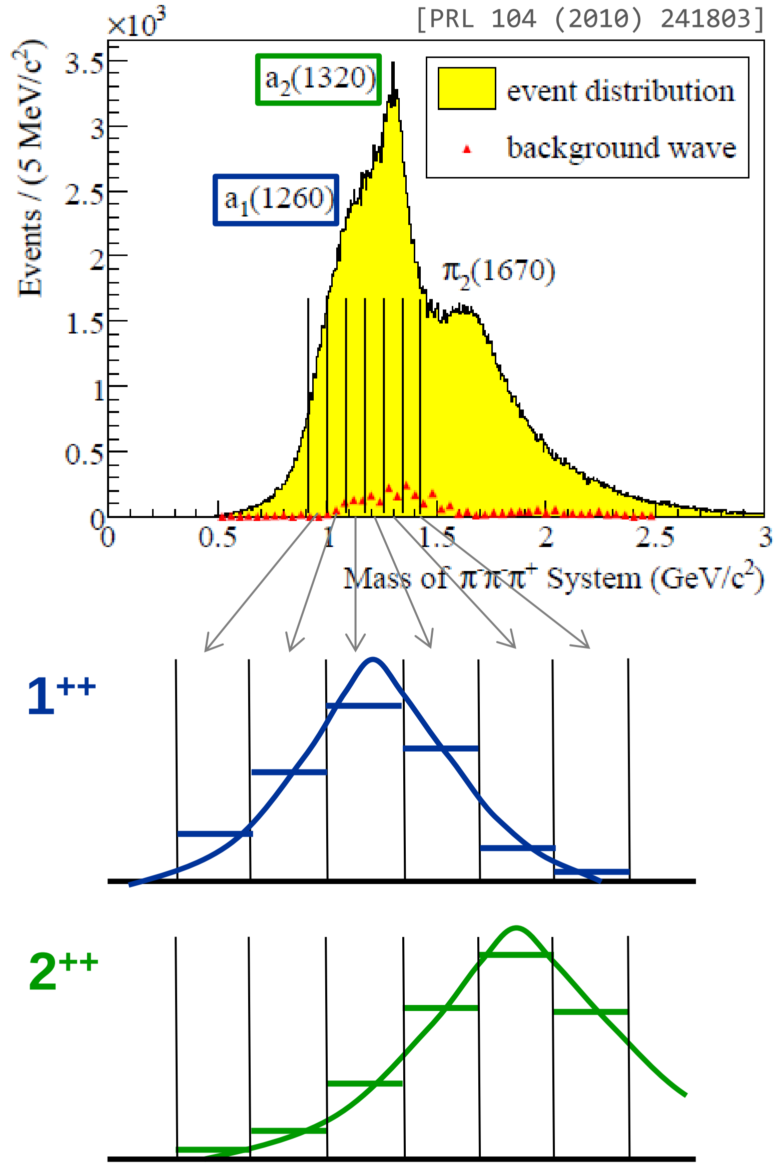
   – Offer 42 partial waves to the fit
   – Fit production amplitudes to describe distributions of τ

   → Intensities of partial waves (PW)
   → Relative phases between PW

2. Mass dependent fit
   – Select significant partial waves
   – Fit model amplitudes to these PW to extract parameters of resonances

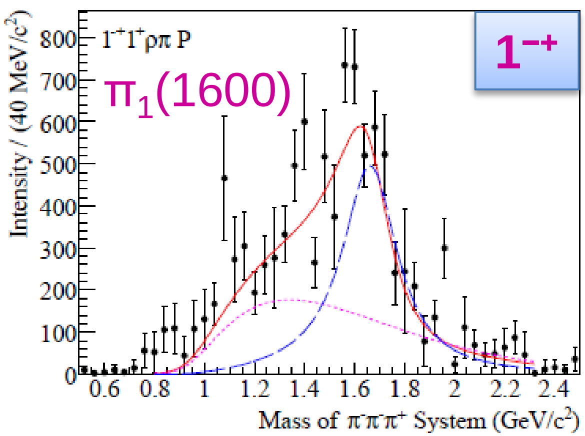


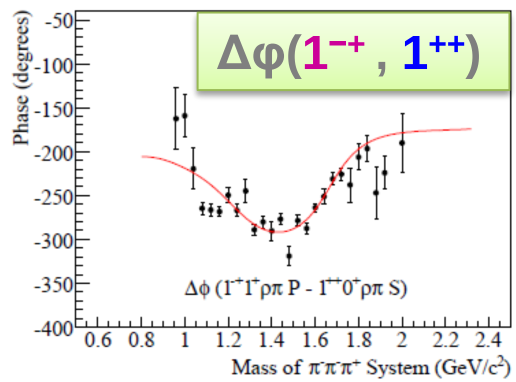
Fit Result

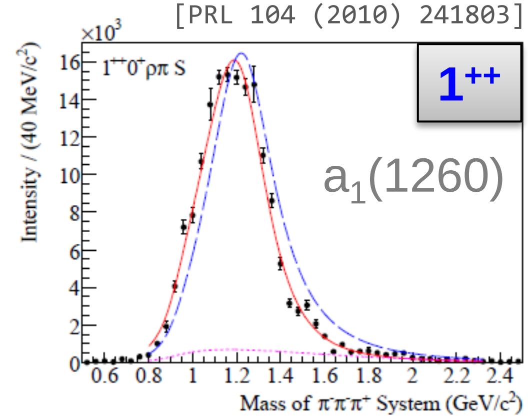
- Significant **intensity in 1^{-+} wave**
- **Physical motion of relative phase** to other resonances

→ **Exotic resonance $\pi_1(1600)$** ($m_X = 1660 \pm^{10}_{64}$ MeV, $\Gamma_X = 269 \pm^{47}_{67}$ MeV)

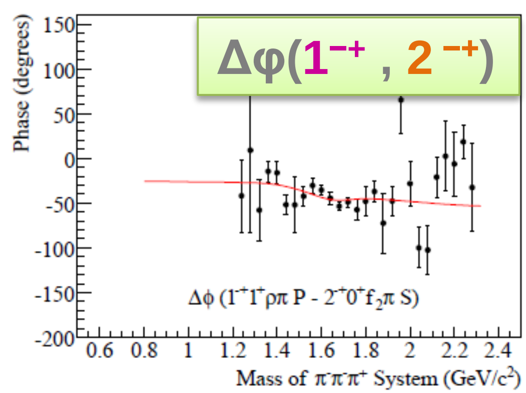
[PRL 104 (2010) 241803]

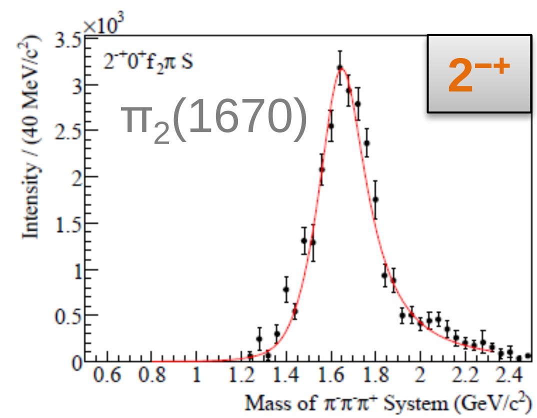






mass independent fit
mass dependent fit
resonances
non-resonant terms

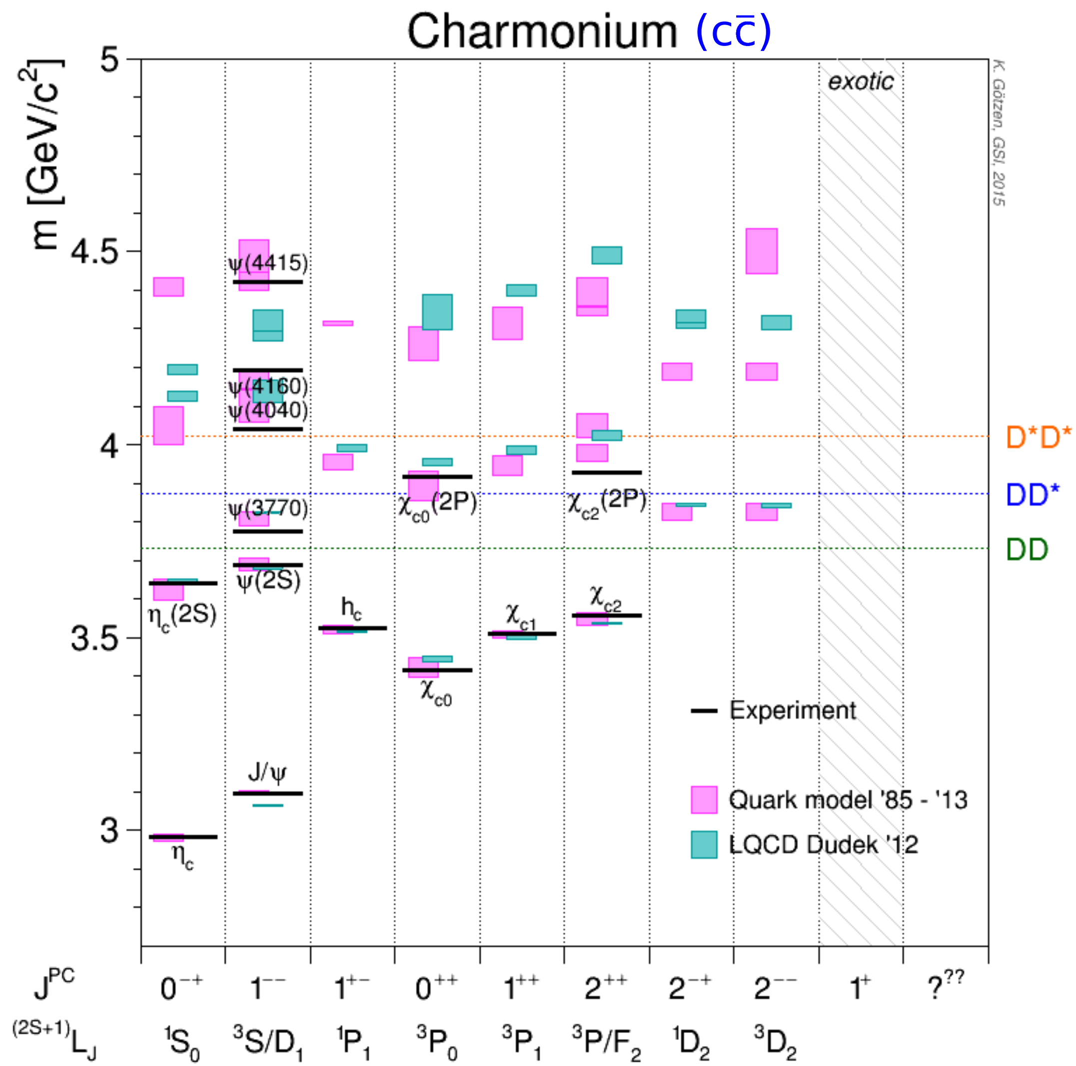




Heavy Quarks - Charmonium

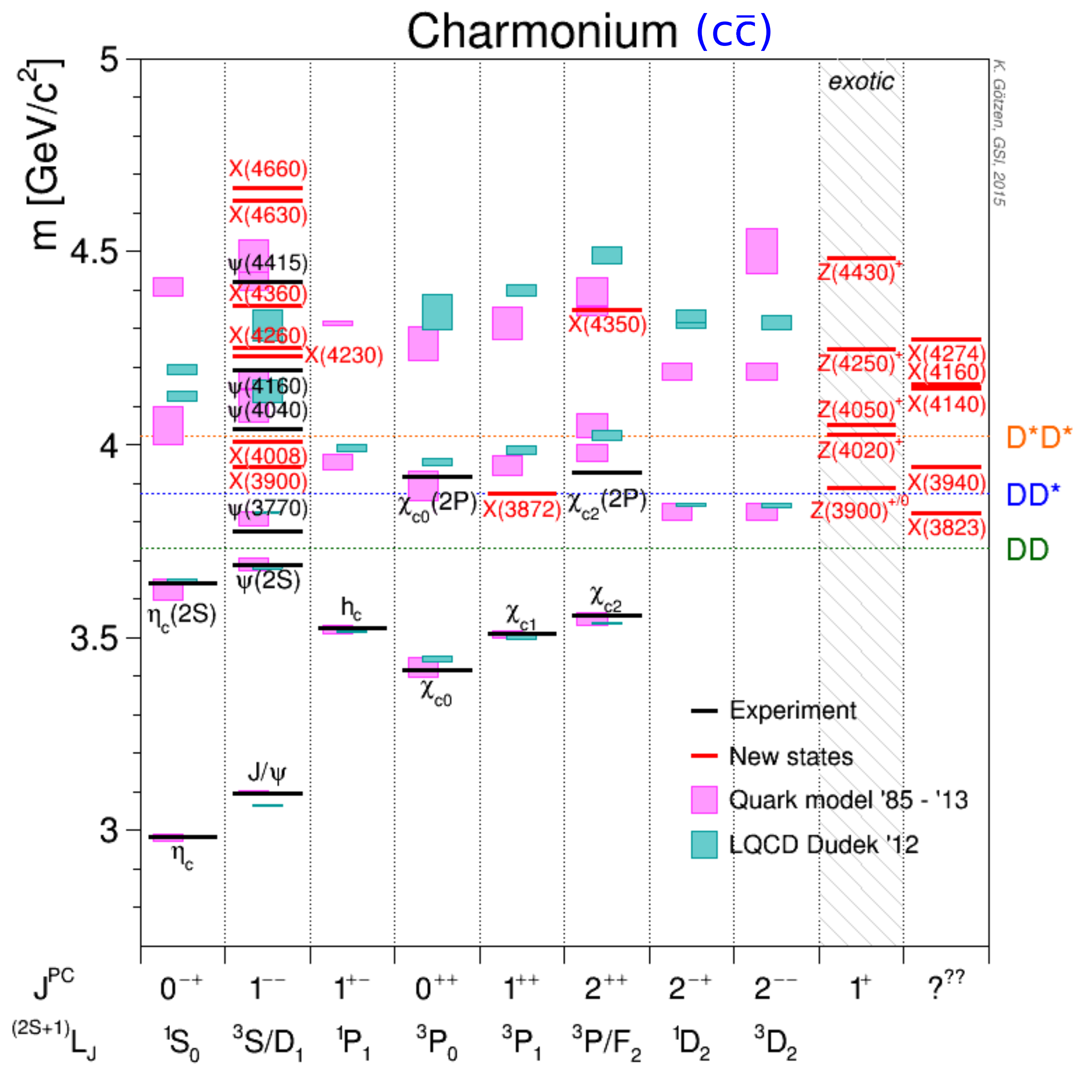
Charmonium

- Advantages:
  Lower level density
  Longer lifetime (small width)
- Charmonium predictions fitted well until 2003



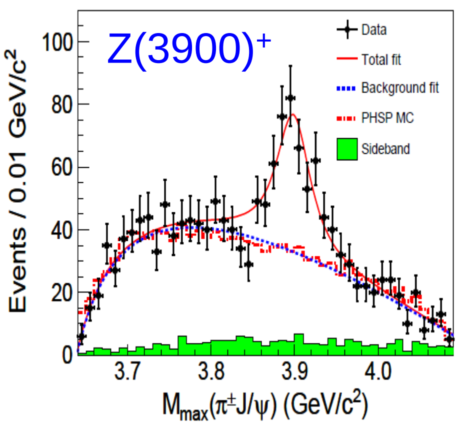
Charmonium

- Advantages:
  Lower level density
  Longer lifetime (small width)
- Charmonium predictions fitted well until 2003
- Since 2003: ≈ 20 new charmonium-like states not fitting well the predictions
- Five (almost) 1^{st} order exotics
  $Z(3900)^{+}$ ... $Z(4430)^{+}$
- Some very close to DD-like thresholds
  X(3872), Z(3900), Z(4020), ...

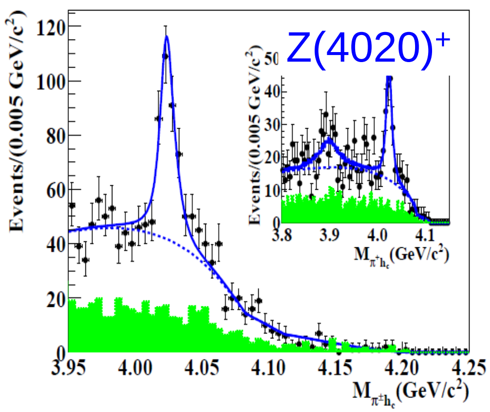


The charged Z^{+}'s

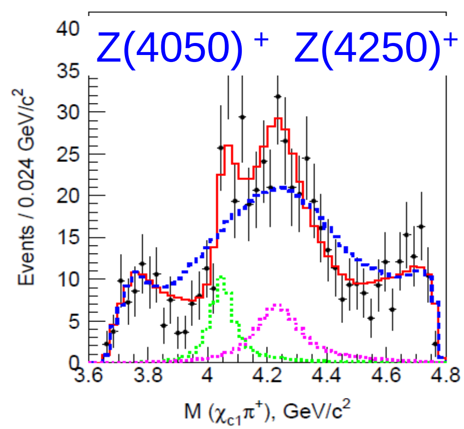
- Z^{+}'s all decay to $c\bar{c}\ \pi^{+}$
- Charged and too heavy for excited light meson
  - ⇒ Minimum quark content $c\bar{c}u\bar{d}$ (first time proof of exotic matter!!)



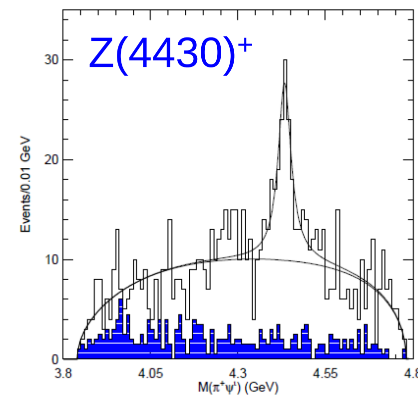
[PRL 110 (2013) 252001]



[PRL 111 (2013) 242001]



[PR D78 (2008) 072004]

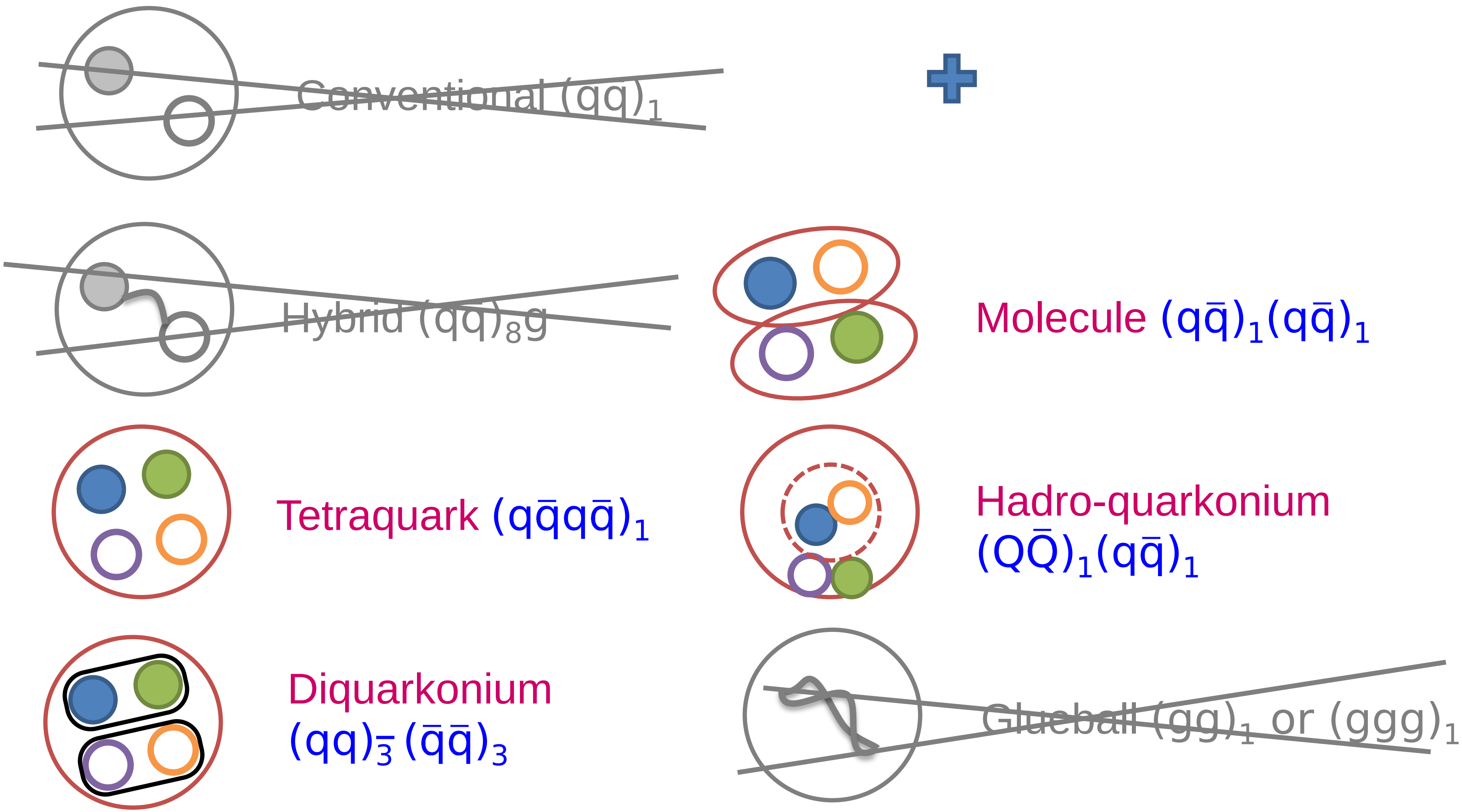


[PRL 100 (2008) 142001]

Name	Γ [MeV]	$c\bar{c}$ decay	open charm	closeby DD	Δm to DD [MeV]
Z(3900)$^{+}$	35 ± 7	$J/\psi\ \pi^{+}$	$(D\bar{D}^{*})^{+}$	$D^{0}\bar{D}^{*+}$	9.3 ± 3.4
Z(4020)$^{+}$	10 ± 6	$h_{c}\ \pi^{+}$	$(D^{*}\bar{D}^{*})^{+}$	$D^{*0}\bar{D}^{*+}$	6.7 ± 2.4
Z(4050)$^{+}$	82 ± 40	$\chi_{c}(1P)\ \pi^{+}$	?	$D^{0}\bar{D}^{*+}$	34 ± 2.4
Z(4250)$^{+}$	177 ± 100	$\chi_{c}(1P)\ \pi^{+}$	?	$D^{0}\bar{D}^{*+}$	-38 ± 50
Z(4430)$^{+}$	200 ± 50	$\psi(2S)\ \pi^{+}$	?	$D^{*+}\bar{D}_{1}$	12 ± 40

Nature of the Z's

Some of the possibilities ruled out, but many still possible



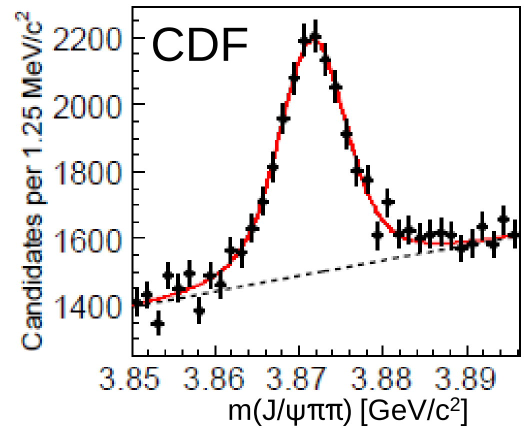
The *mysterious* X(3872)

- Seen by 7 experiments in 6 channels
  ($J/\psi\rho$, $J/\psi\omega$, $J/\psi\gamma$, $\psi'\gamma$, $D\bar{D}\pi^0$, $D^*\bar{D}$)
- $J^{PC} = 1^{++}$ → natural candidate for $\chi_{c1}(2P)$

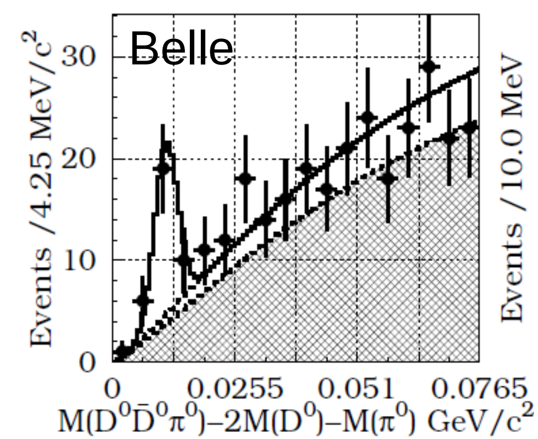
Oddities

- 50 - 100 MeV to light for $\chi_{c1}(2P)$
- Extremly narrow: Γ < 1.2 MeV
- Extremly close to $D^0\bar{D}^{0*}$ threshold:
  $m_X - m_{D\bar{D}^*}$ = 0.11 ± 0.21 MeV
  → Molecule?!
- If molecule → $d \approx 10$ fm
  - How to re-arrange quarks to form $c\bar{c}\,\rho$?
  - Why is this loosely bound state produced so abundantly @ CDF in TeV reactions?

[arXiv:0906.5218]

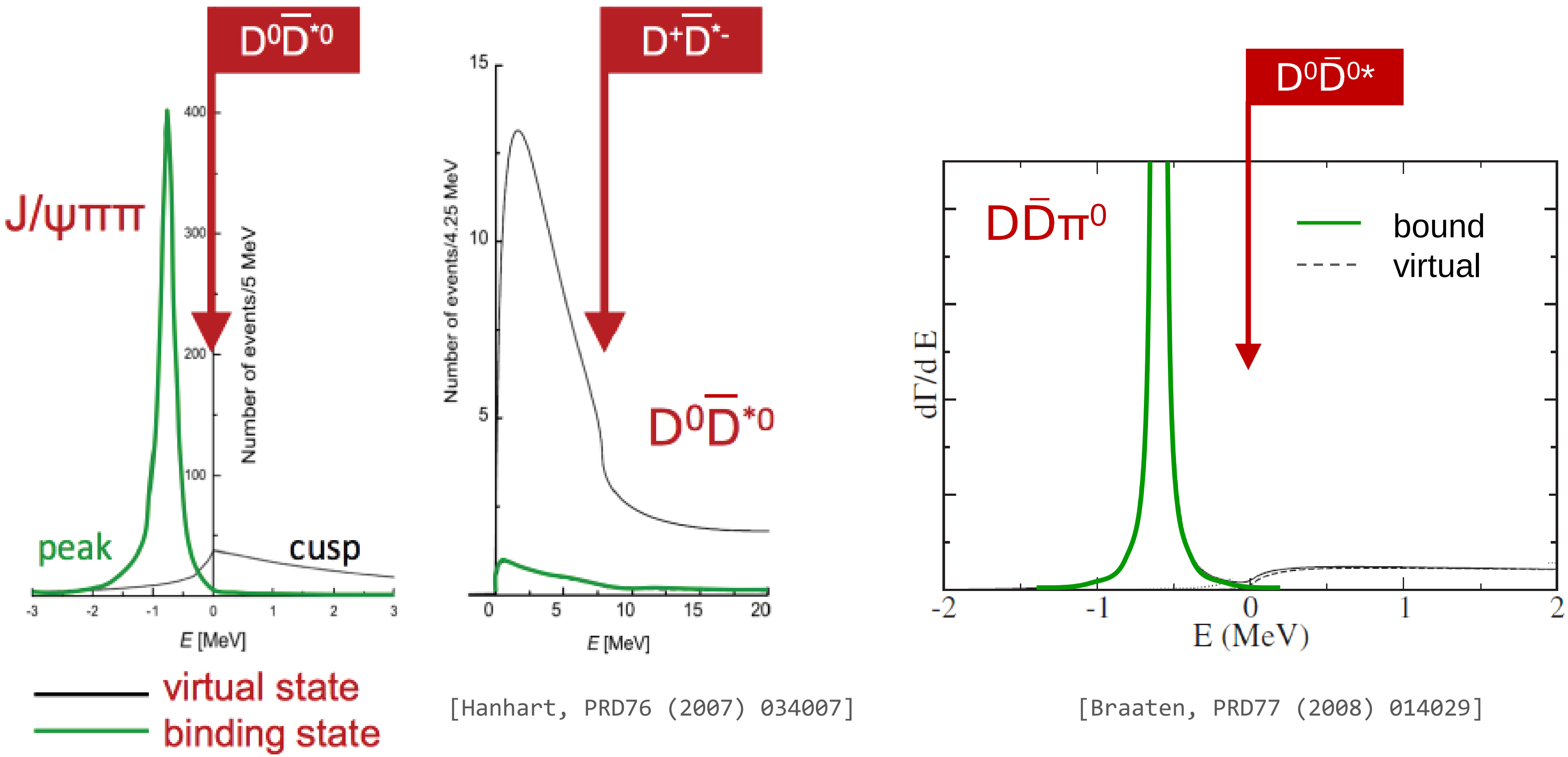


[arXiv:hep-ex/0606055]



Theory about X(3872)

- To clarify nature: line shape + width measurements essential



[Hanhart, PRD76 (2007) 034007]

[Braaten, PRD77 (2008) 014029]

→ Need p̄p scan experiment to get access to the line shape

Measure Multiplets to solve XYZ Puzzle

Different structure assumptions (models) ⇒ **Different multiplet patterns**

Diquarkonium

diquarks: cu, cd, cs

\+

di-antiquarks: c̄ū, c̄d̄, c̄s̄

Molecule

D⁺, D*⁺, D⁰, D₂, D₁, D_s^+ …

\+

D⁻, D*⁻, D̄⁰, D̄₂, D̄₁, D_s^- …

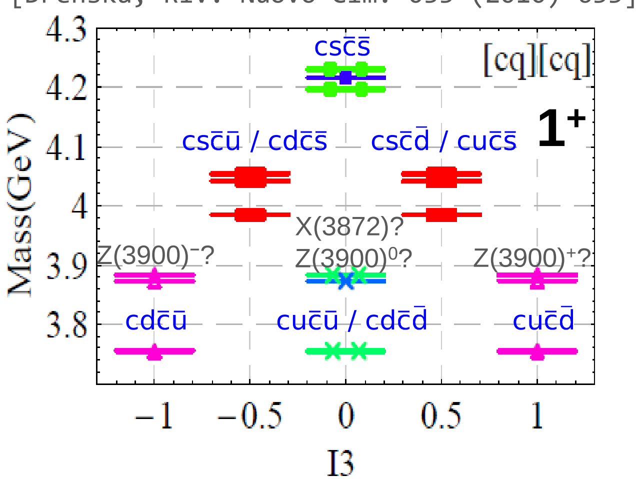
Hadro-charmonium

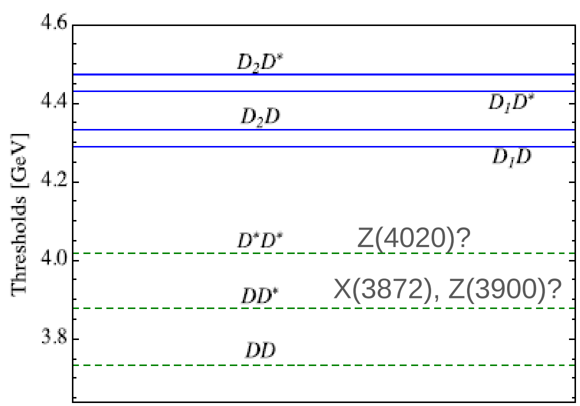
η_c, J/ψ, χ_c, h_c, ψ' …

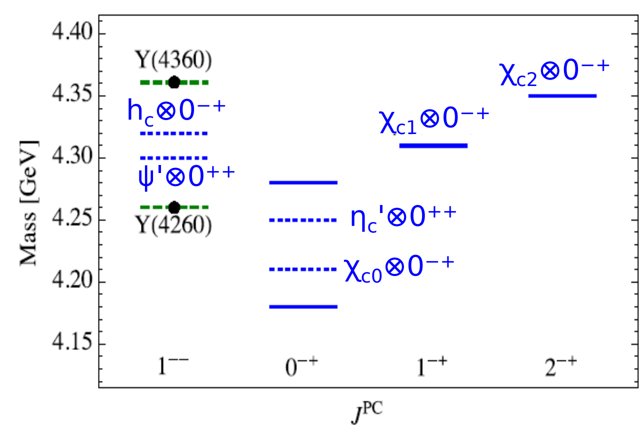
\+

π^0, π^-, K^+, K^0, ρ, φ, f_0, a_0 …

[Drenska, Riv. Nuovo Cim. 033 (2010) 633]







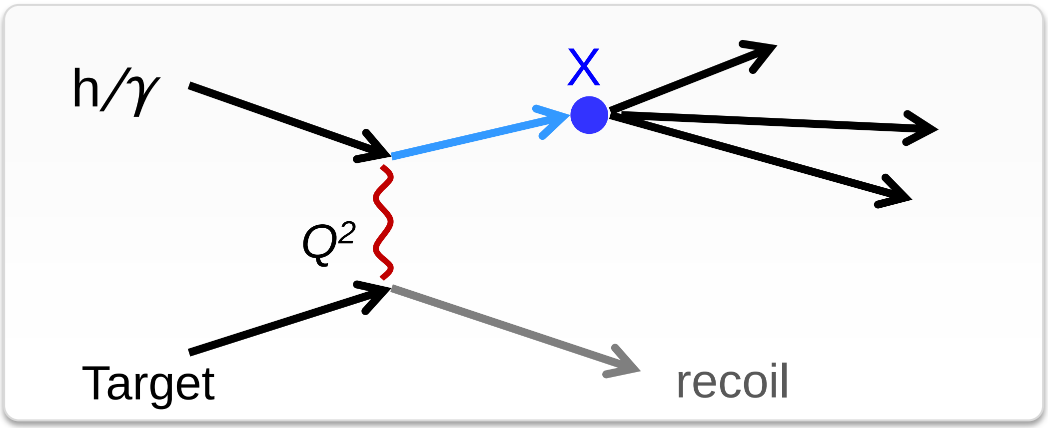
[Cleven et al., arXiv:1505.01771]

'Machines'
Present & Future Experiments

Meson Production (1)

➢ Hadron/gamma beam on fixed target

[GlueX: $\gamma \rightarrow p$ (9 GeV/c), COMPASS: π/K/p → p/nucl. (160 - 270 GeV/c)]



COMPASS — *running*

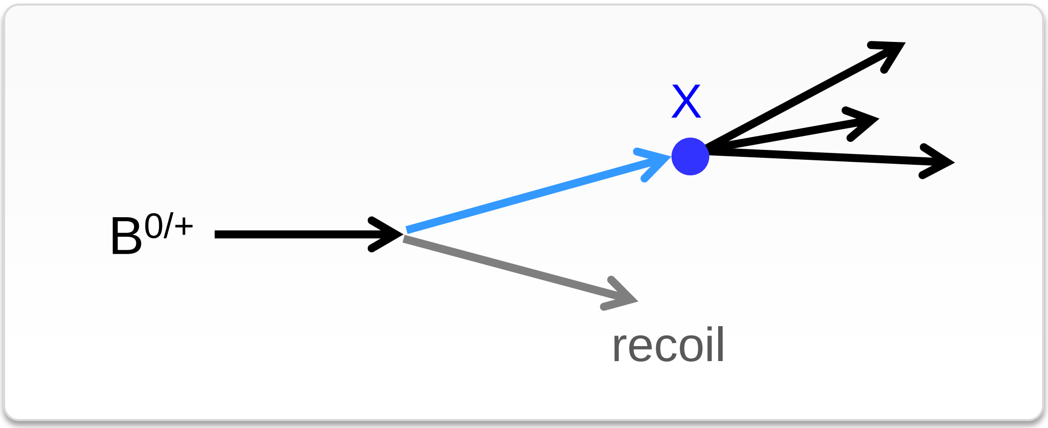
GlueX — *started*

- **Light sector only**

- Direct access to exotic QN ☺
- Always a recoil present (complicates analysis) ☹

Meson Production (2)

➢ B-meson decays



running (LHCb)

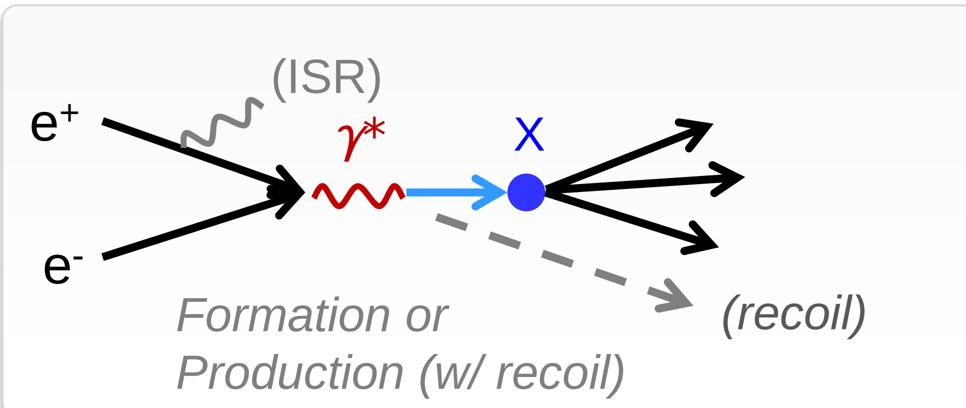
future (Belle II)

- **Light & charmonium sector**

- Exclusive systems for Dalitz plot analysis ☺
- Suppression of higher spins J ☹

Meson Production (3)

- **Formation/production in e^+e^-**
  [BESIII: E ≤ 4.6 GeV, Belle2: E ≤ 11 GeV]



BESIII *running*

Belle II *future*

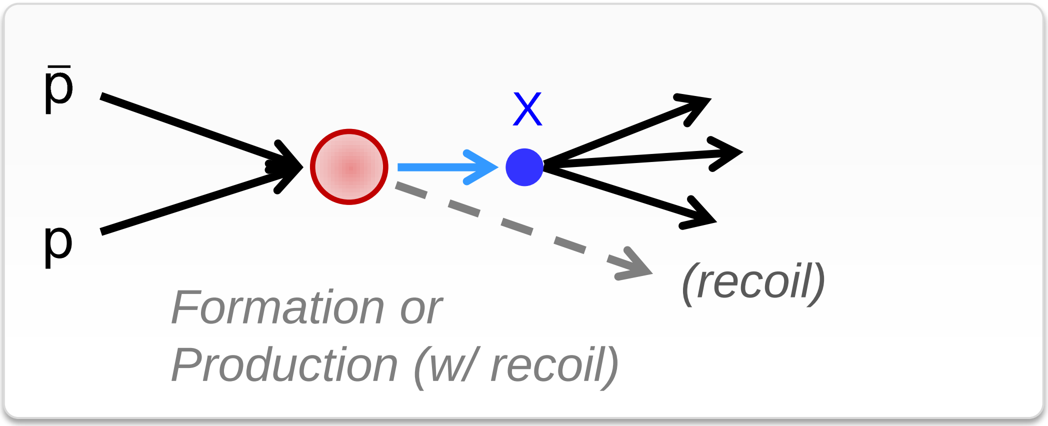
- **Light, charmonium & bottomonium sector**

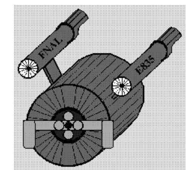
- High mass resolution by beam energy precision *(Formation)* ☺
- J^{PC} limited to 1^{--} *(Formation)* ☹
- Suppression of higher spins J

Meson Production (4)

➢ Formation/production in p̄p

[PANDA: E ≤ 5.5 GeV]





FermiLab E835 ***past***

p̄anda ***future***

- **Light & charmonium sector**

- High mass resolution with all (q̄q) J^{PC} possible ☺
- Currently no running experiment ☹

Summary and Prospects

- Meson spectroscopy
  → Tool to understand and quantify QCD binding
- Many new exotic states discovered in last decade
  - Proof validity of fundamental QCD principle
  - Great opportunity to refine and adapt models
- Many running and new experiments in planning
  - Understand conventional states binding
  - Complete the exotic multiplets
- Still some way to go ...

... stay tuned for more interesting discoveries!