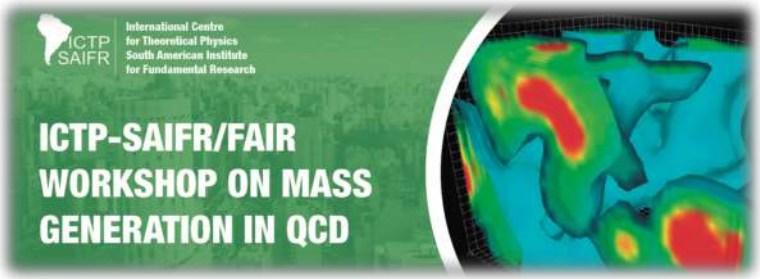
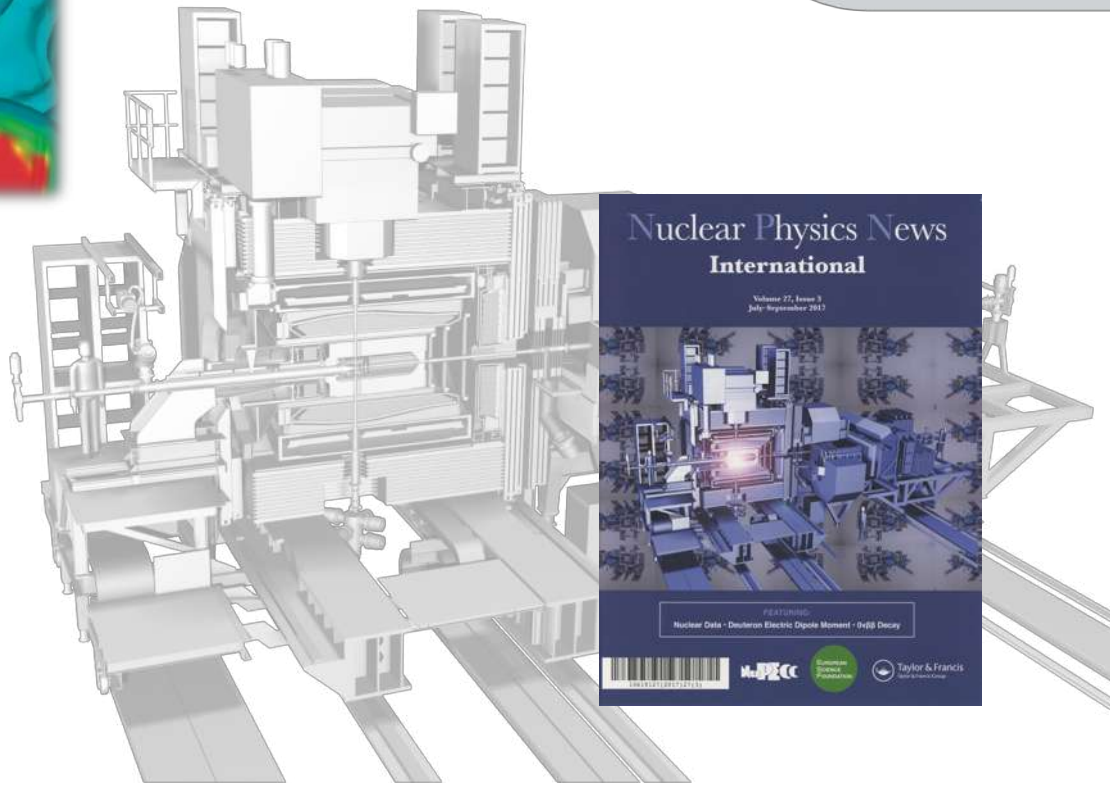
XYZ an exotic alphabet for PANDA



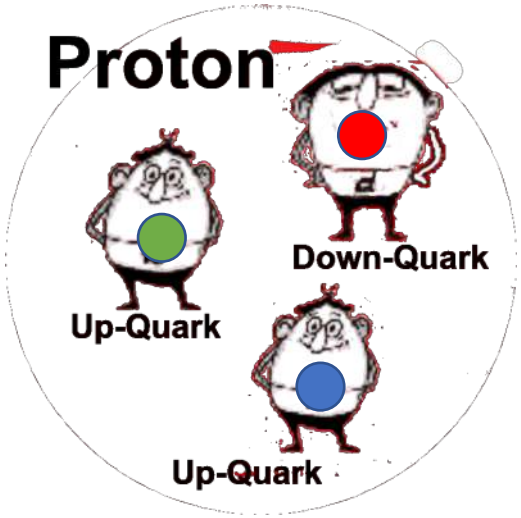
Sao Paolo, March 1, 2019



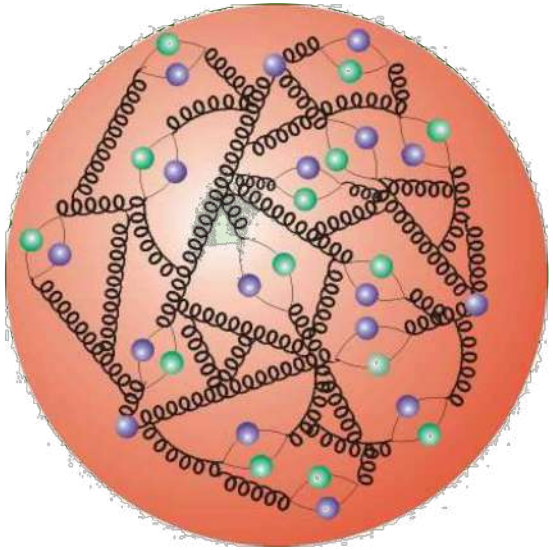
Klaus Peters - GSI/U Frankfurt

The Proton – and its mass

the usual picture is, that the **Proton** consists of a **few Quarks**



if you look **more closely**, things appear to be more **complicated**

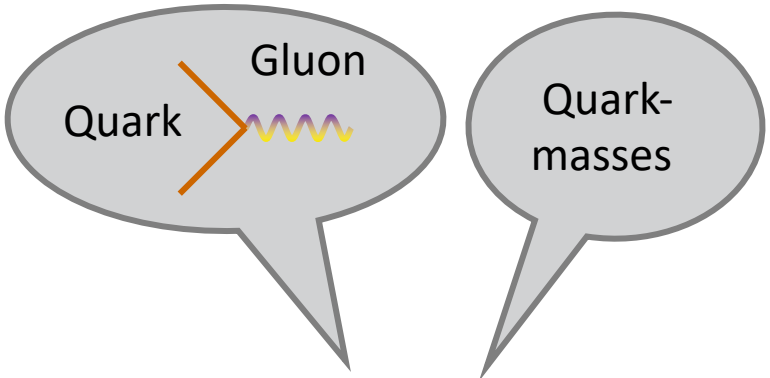


a **Proton** is one configuration
In general they are called **Hadron**
(from old-gr. ***ἀδρός hadrós*** ‚thick' ‚strong')

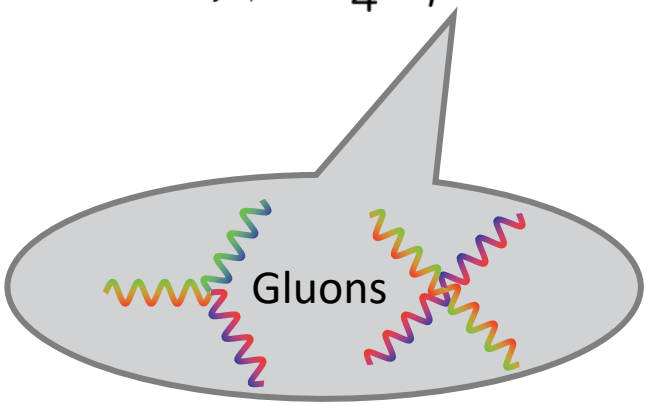
In addition there is glue → **Gluons**

QCD – Quantum Chromo Dynamics

Fritzsch, Gell-Mann, Leutwyler 1973



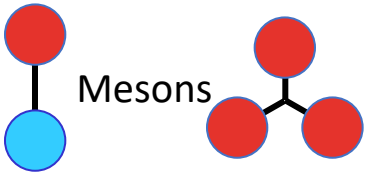
$$L_{QCD} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$

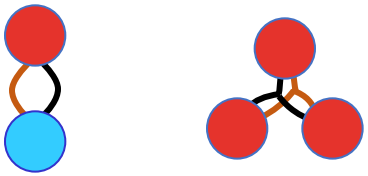


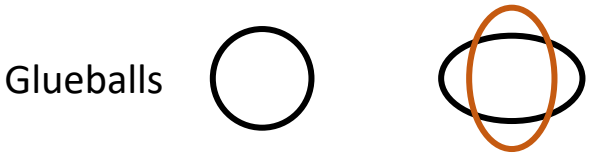
Quarks		spin=½	
Flavor		Approx. Mass GeV/c²	Charge
u	up	0.003	2/3
d	down	0.006	-1/3
c	charm	1.3	2/3
s	strange	0.1	-1/3
t	top	175	2/3
b	bottom	4.3	-1/3

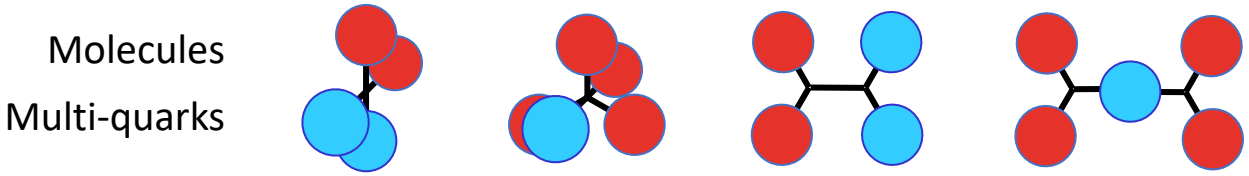
Gauge Boson		spin=1	
Name		Mass GeV/c²	Charge
g	gluon	0	0

Exotics

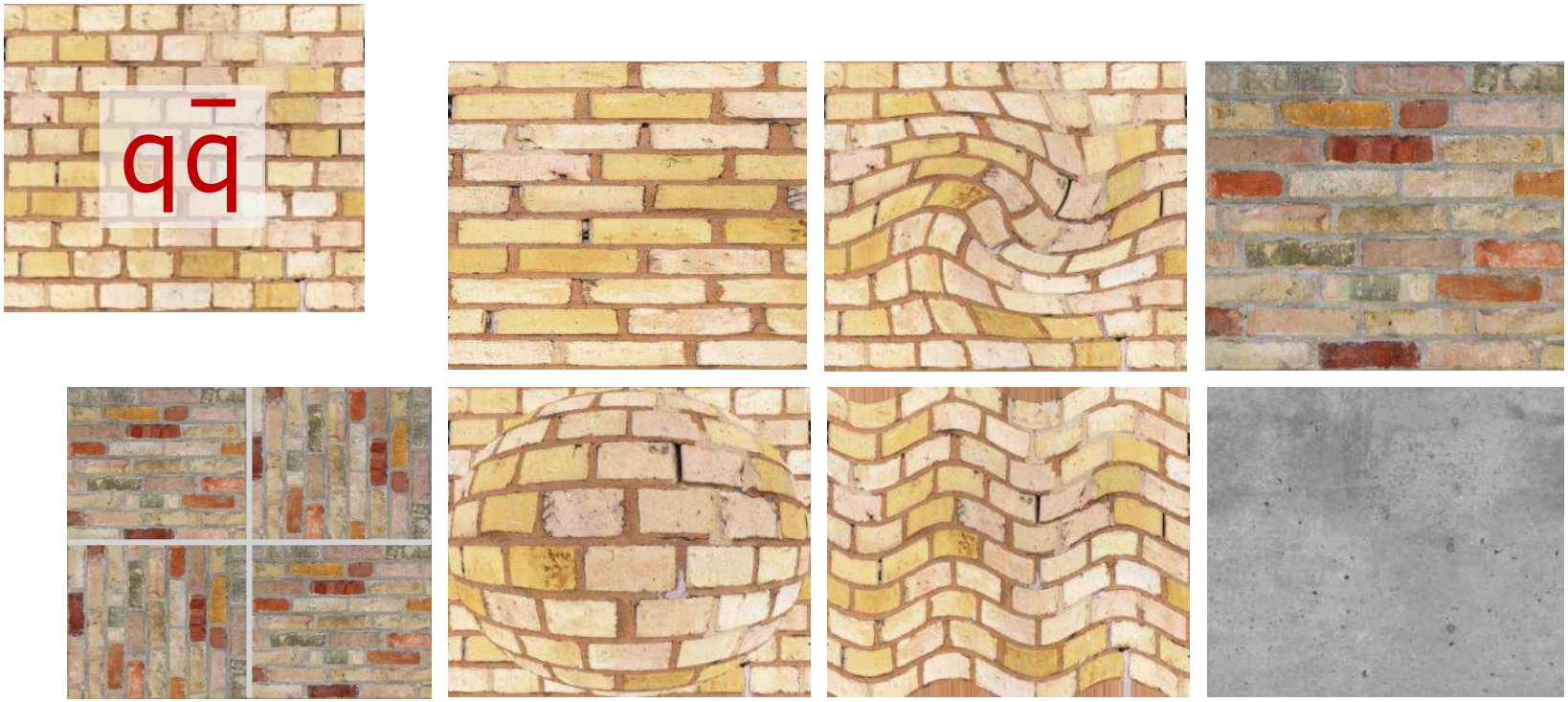






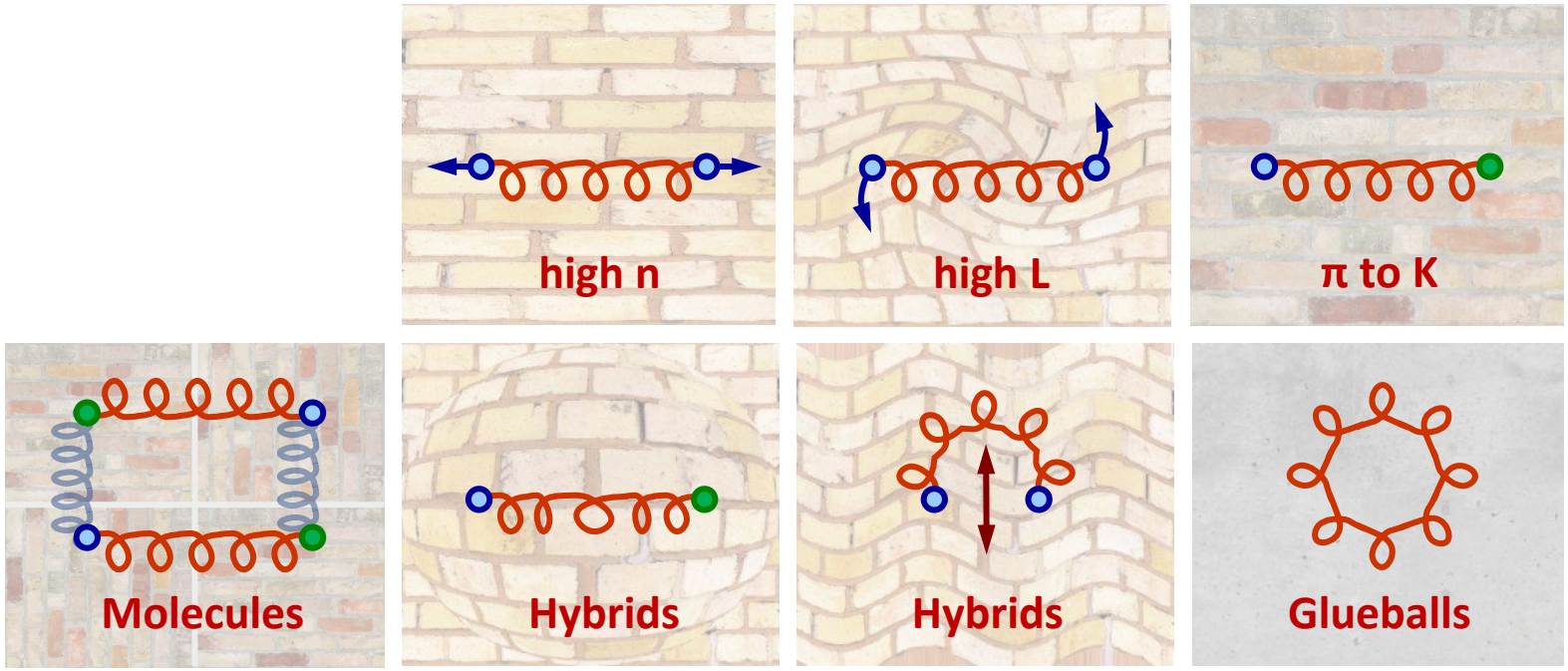


QCD „material science“



one may drag, bend, heat or resonate walls
one may exchange stones or use compound stones
one may remove the stones and has only grout

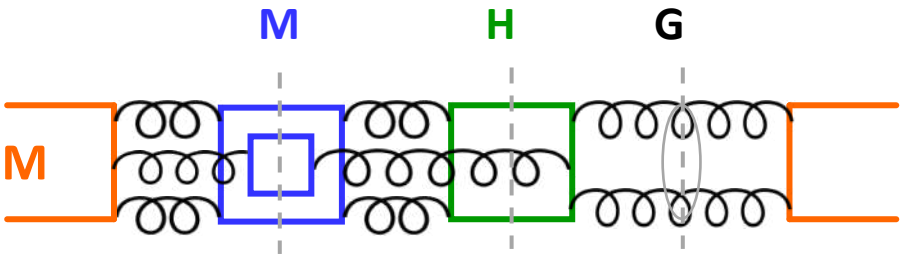
Translation to Hadrons



one may drag, bend, heat or resonate walls
one may exchange stones or use compound stones
one may remove the stones and has only grout

Fock-Expansion

Presence of mixing



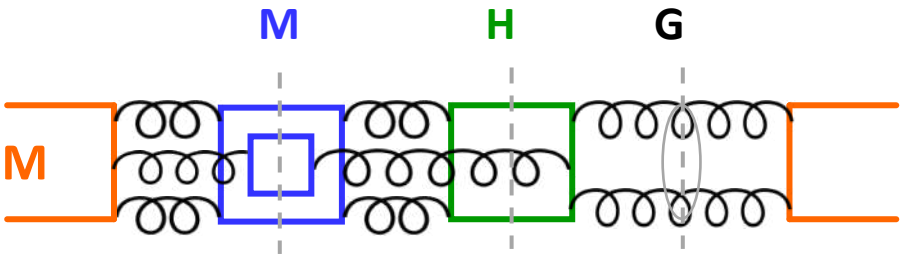
non-$q\bar{q}$ states expected
to contribute to the
meson wave function

exotics can (and will) mix
with conventional $q\bar{q}$ states for

identical quantum numbers

Fock-Expansion

Presence of mixing



non-$q\bar{q}$ states expected
to contribute to the
meson wave function

exotics can (and will) mix
with conventional $q\bar{q}$ states for
identical quantum numbers

$q\bar{q}$ +

$(q\bar{q})(q\bar{q})$ +

$(q\bar{q})g$ +

gg +

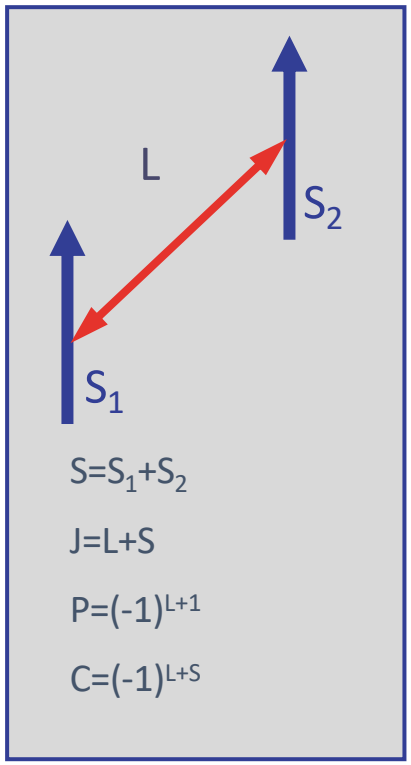
$\cdots\cdots$

$= \Sigma_i(q\bar{q})_i \Sigma_j g_j$

Fock-Expansion – solution to the problem?

remove the leading term
by selecting quantum numbers

e.g. for hybrids



impossible for $q\bar{q}$

J^{PC} exotic

Gluon	Magnetic	Electric
$^1S_0$, 0^{-+}	1^{++}	1^{--}
$^3S_1$, 1^{--}	0^{+-}	0^{-+}
	1^{+-}	1^{-+}
	2^{+-}	2^{-+}

$q\bar{q}$ +

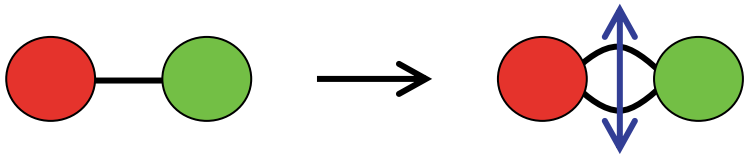
$(q\bar{q})(q\bar{q})$ +

$(q\bar{q})g$ +

+ ..

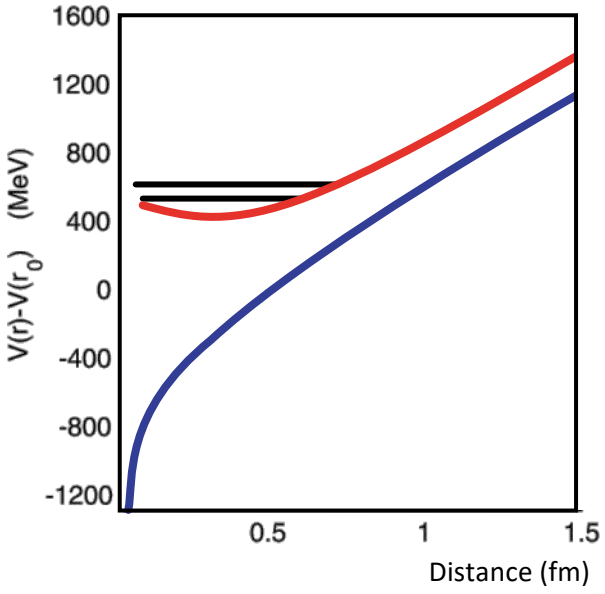
$= \Sigma_i(q\bar{q})_i \Sigma_j g_j$

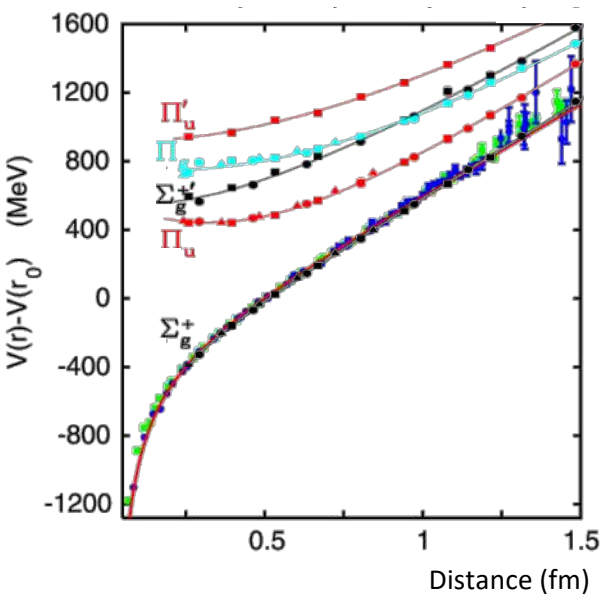
Charmonium – other degrees of freedom ?



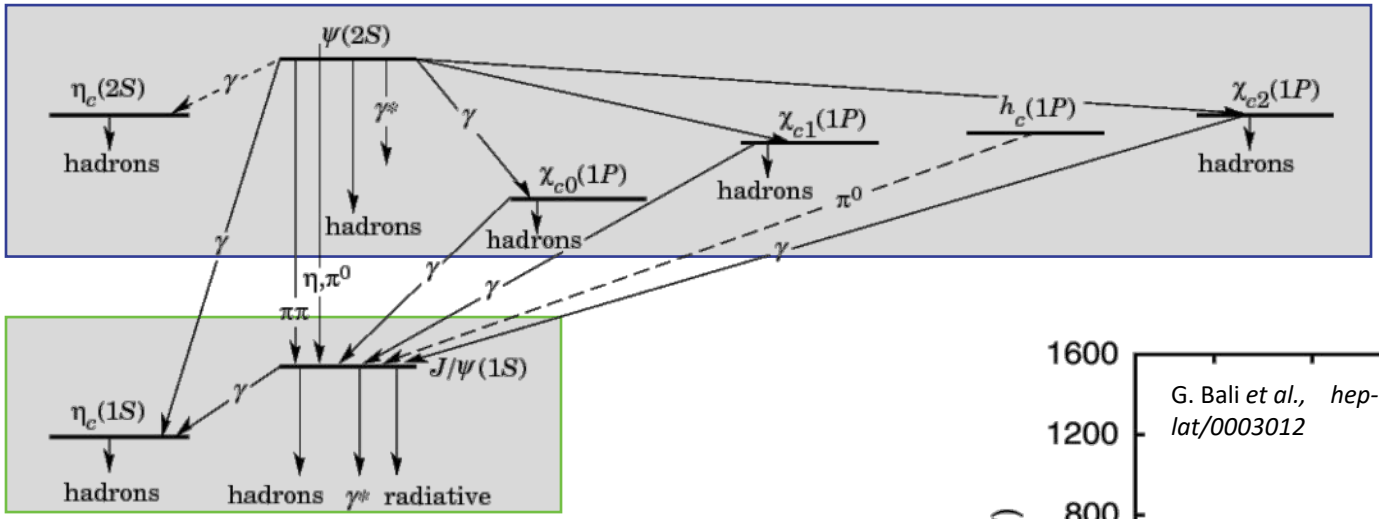
different "potential"

K.J. Juge, J. Kuti, C. Morningstar
hep/lat 9709131

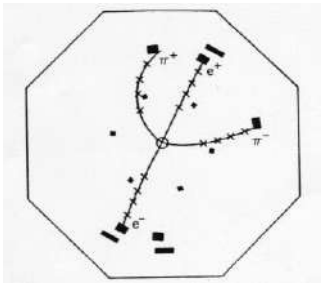


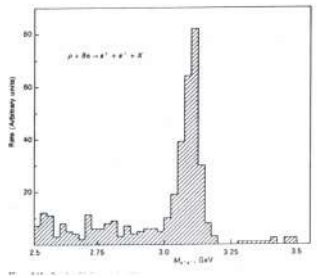


Charmonium

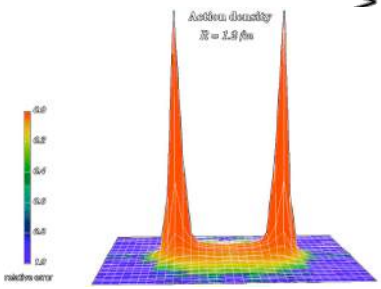


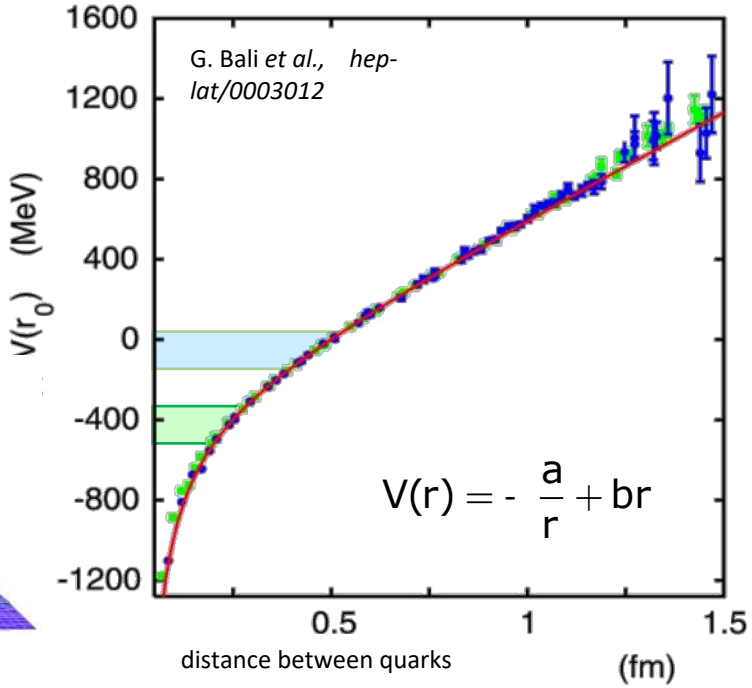
J^{PC} = 0^{-+} 1^{--} 0^{++} 1^{++}



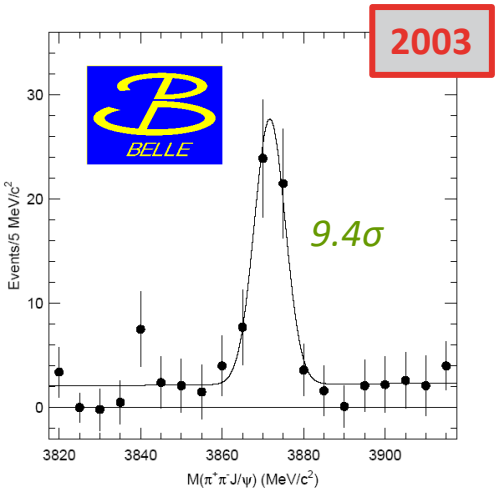


J.E. Augustin *et al.*, Mark I, Phys. Rev. Lett. 33, 1406–1408 (psi)
J.J. Aubert *et al.*, BNL, Phys. Rev. Lett. 33, 1404–1406 (J)

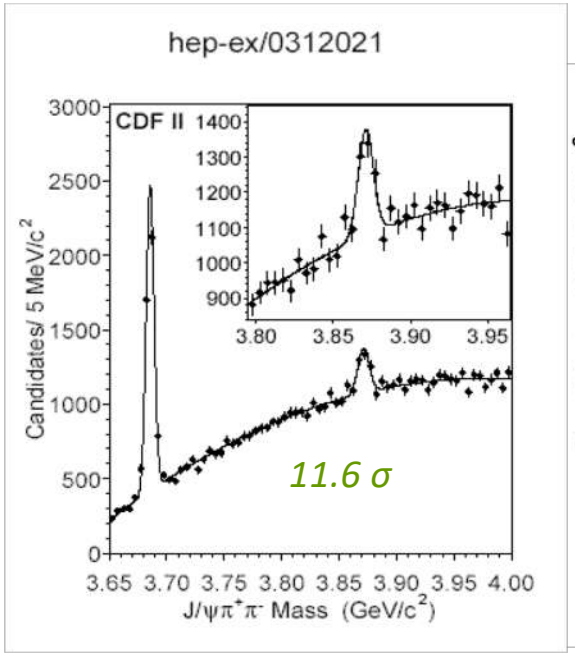


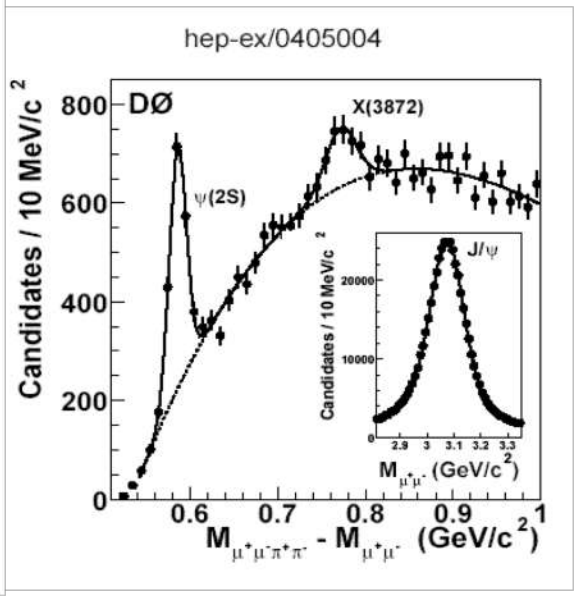


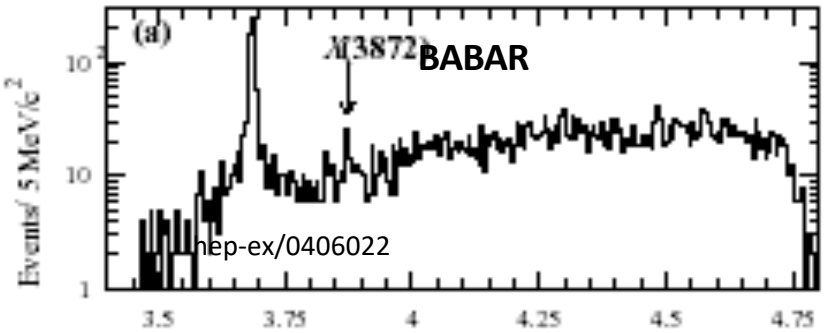
Discovery of the X(3872)



Phys. Rev. Lett. 91(2003)262001
152 Mill. BB

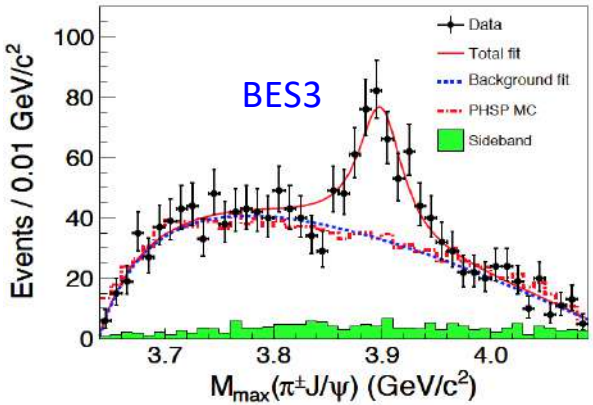




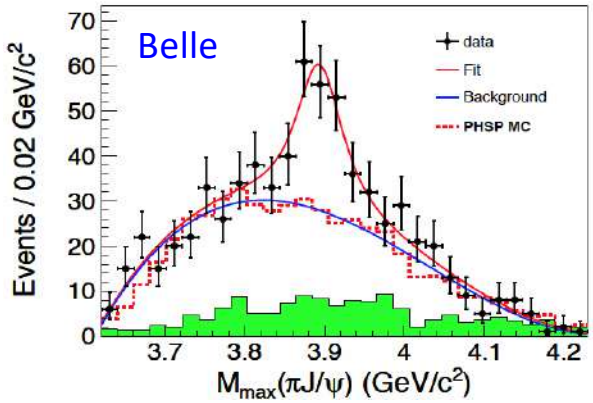


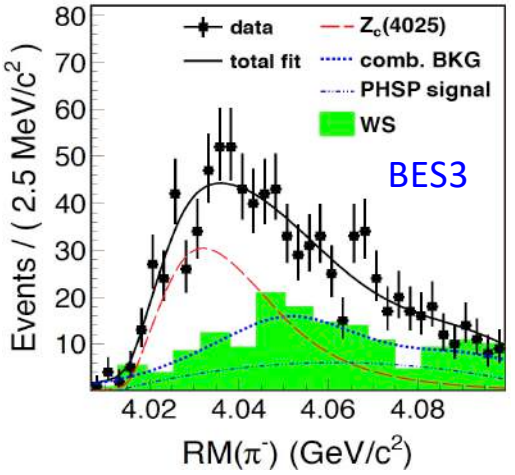
Discovery of the $Z^+(3900)$

2013

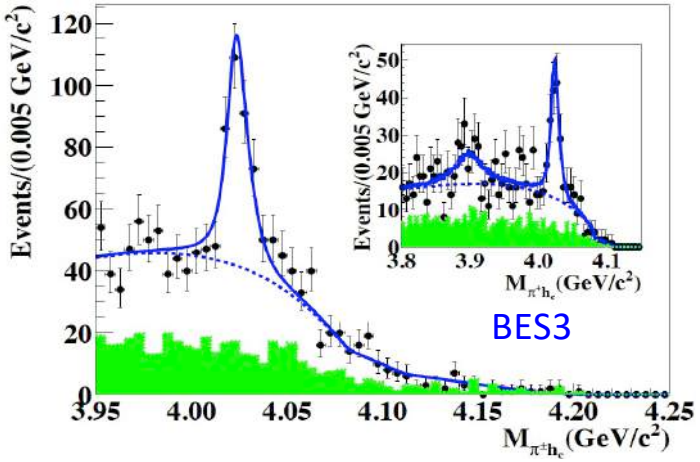


Discovery of the $Z_c^{+/-}(3900)$ in the $J/\psi\ \pi^{+/-}$ invariant mass spectrum in the decay $Y(4260) \rightarrow J/\psi\ \pi^+\pi^-$





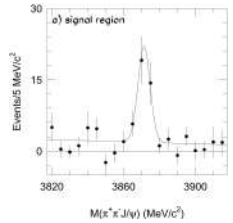
Observation of the $Z_c^{+/-}(4025)$ in the $h_c\pi^{+/-}$ and $\overline{D}^*D^*$ invariant spectrum in Y(4260/4360) decays



New Charmonium-like Discoveries

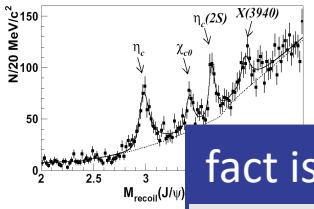
X(3872)

PRL 91,262001 (2003)



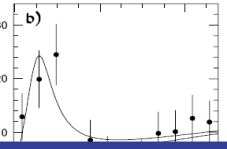
X(3940)

PRL 98,082001 (2007)



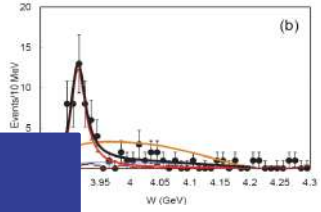
Y(3940)

PRL 94,182002 (2005)



X(3915)

PRL 104,092001 (2010)



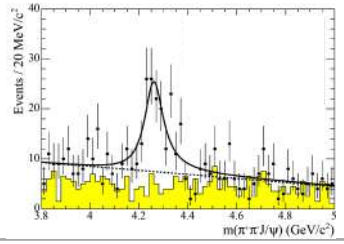
fact is

charmonium is very complicated

and guides us into a terra incognita

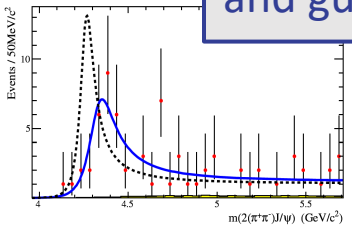
Y(4260)

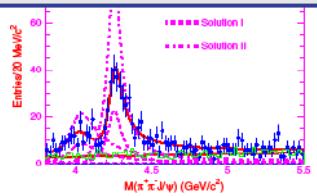
PRL 95,142001 (2005)



Y(43

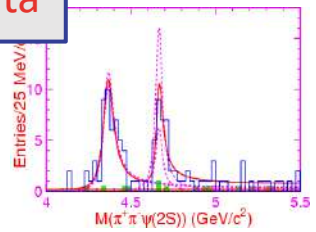
PRL 98,2120





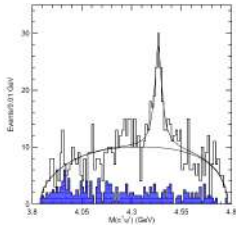
Y(4660)

99,142002 (2007)



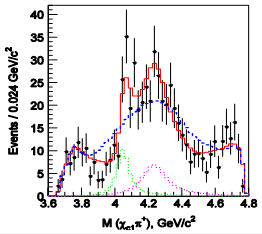
Z(4430)⁻

PRL 100,142001 (2008)



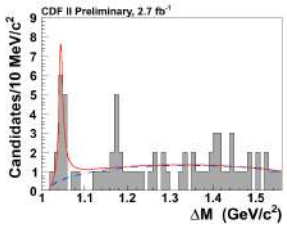
Z_1^- & Z_2^-

PRD 78,072004 (2008)



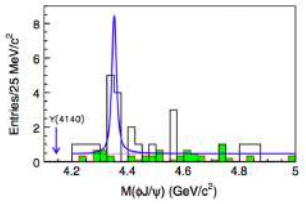
Y(4140)

PRL 102,242002 (2009)

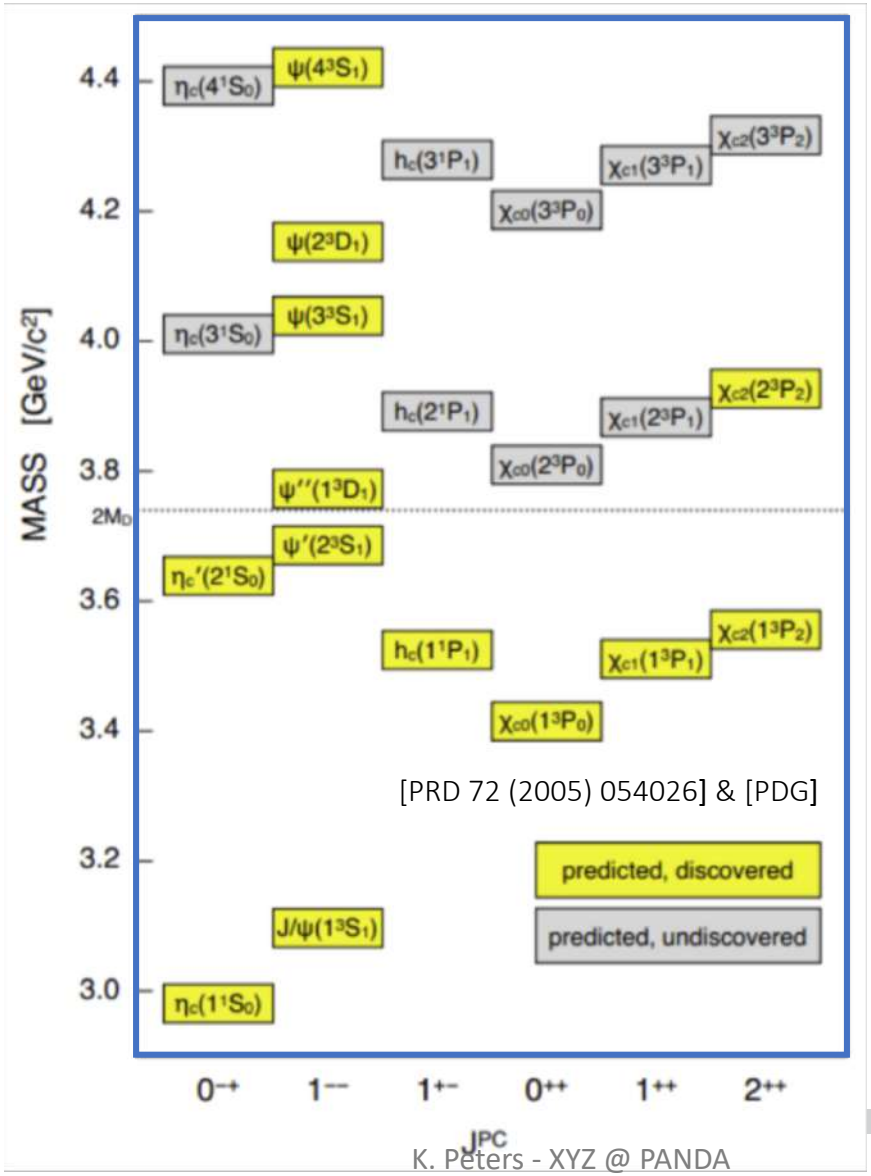


X(4350)

PRL 104,112004 (2010)



The puzzle of XYZ states



[PRD 72 (2005) 054026] & [PDG]

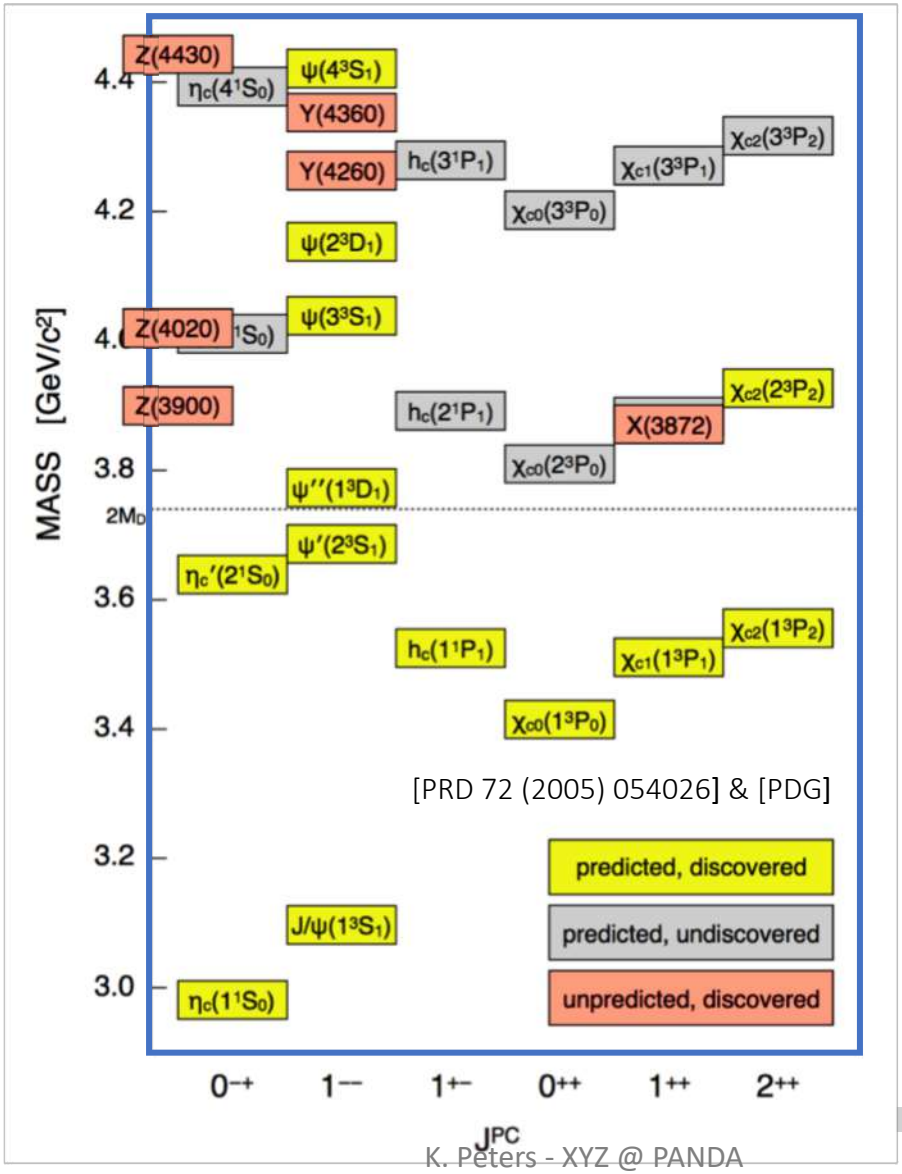
Below open charm threshold

- Good agreement theory vs. experiment

Above open charm threshold

- Many predicted states not discovered
- Many unexpected states observed

The puzzle of XYZ states



[PRD 72 (2005) 054026] & [PDG]

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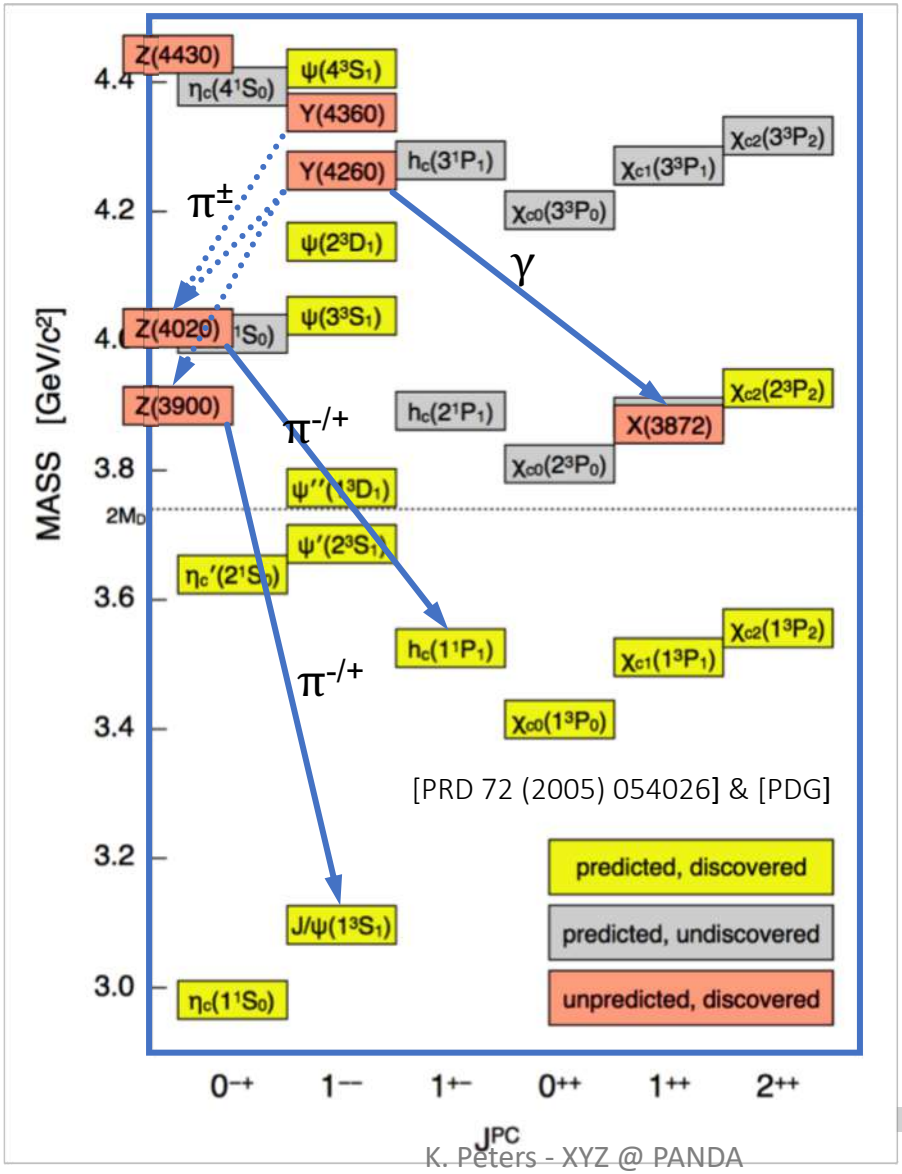
The puzzle of XYZ states



[PRD 72 (2005) 054026] & [PDG]

Below open charm threshold

- Good agreement theory vs. experiment

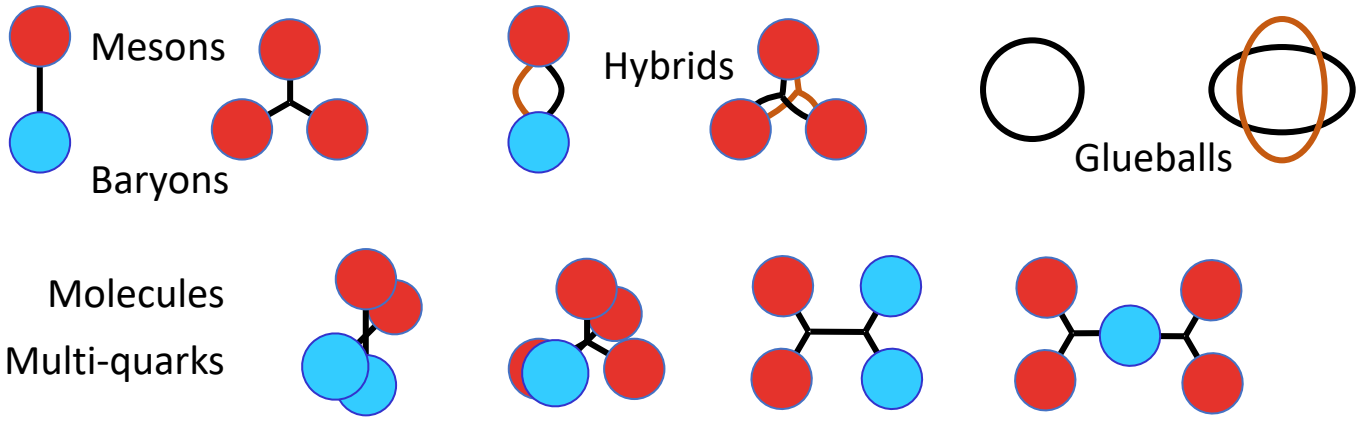
Above open charm threshold

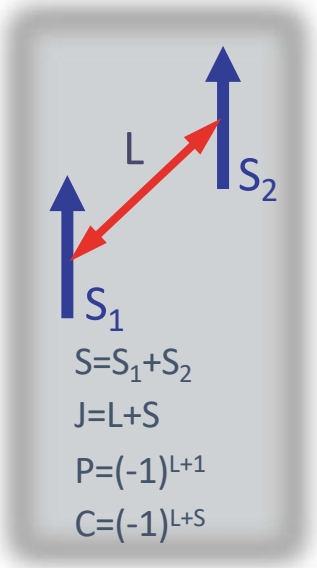
- Many predicted states not discovered
- Many unexpected states observed

What is missing?

- Precise Masses/Lineshapes for
  - Narrow states
  - Near threshold states
- Different Spin-Parities (not only 1^{--} and 1^{++})
  - Difficult in e+e- and B-physics
  - Angular Momentum Barrier
  - Preferred hadronic production like $\bar{p}p$

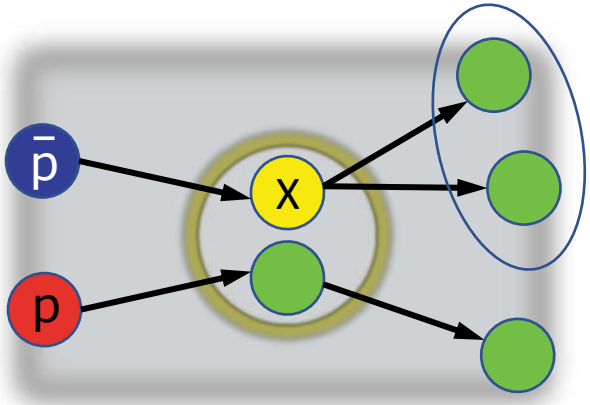
Production of Hadronic States





Production all exotic and non-exotic quantum numbers accessible with a recoil

- high discovery potential
- associated, access to all quantum numbers (exotic)



all quantum numbers possible

n-Particle Phase space, *n*=3

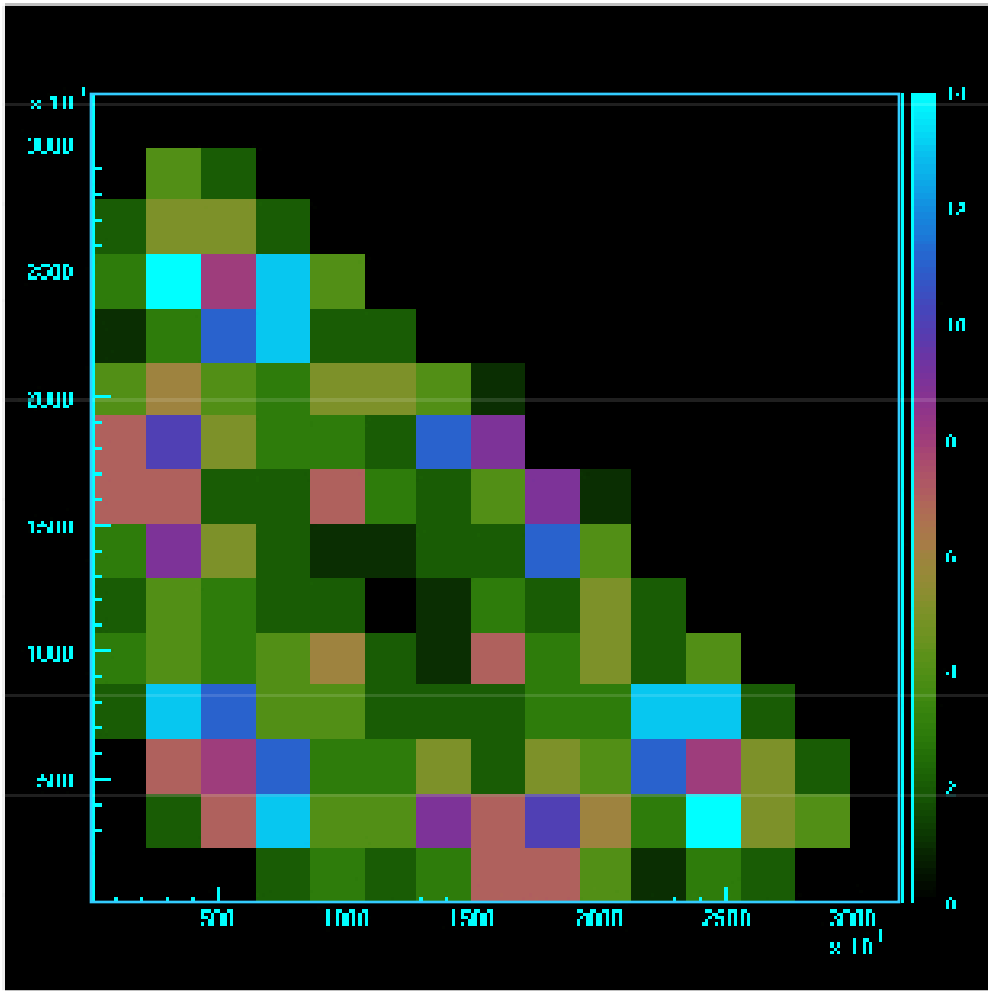
Dalitz plot

It's All a Question of Statistics ...

$p\bar{p} \rightarrow 3\pi^0$

with

100 events



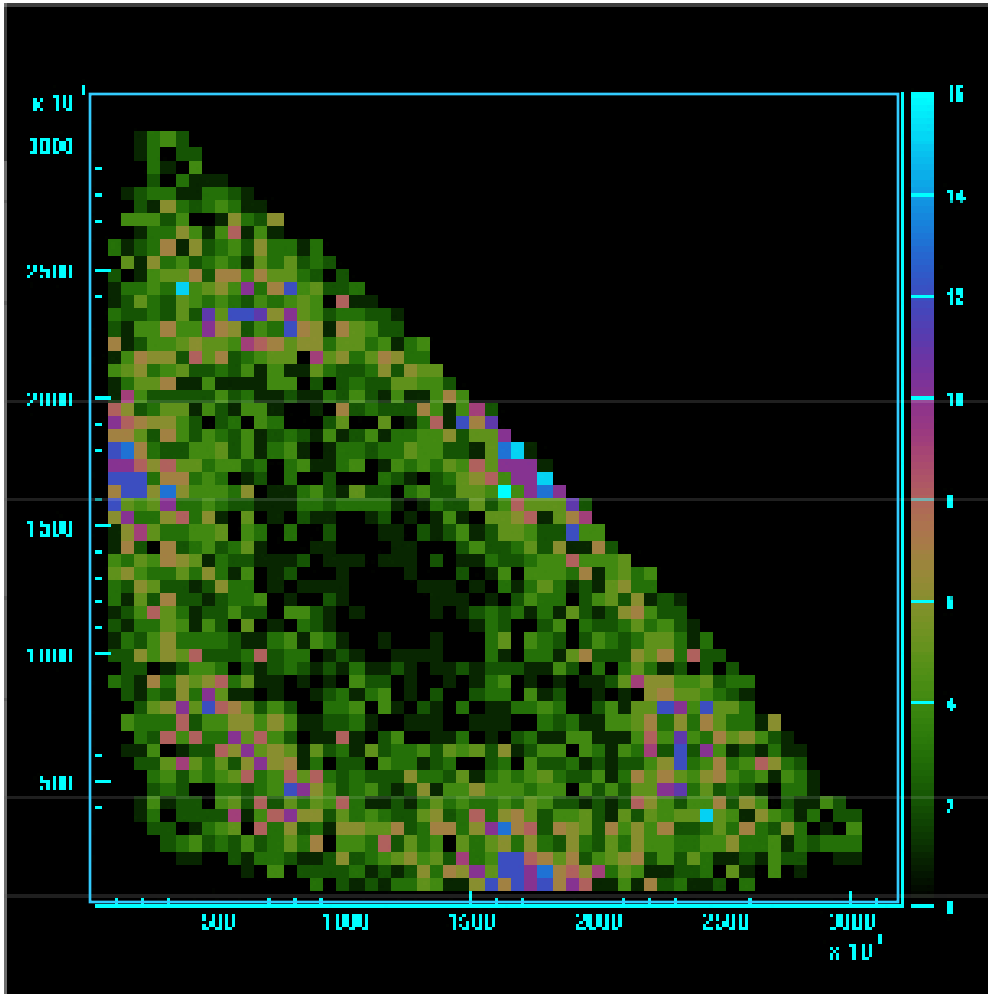
It's All a Question of Statistics … …

$p\bar{p} \rightarrow 3\pi^0$

with

~~100 events~~

1000 events



It's All a Question of Statistics … … …

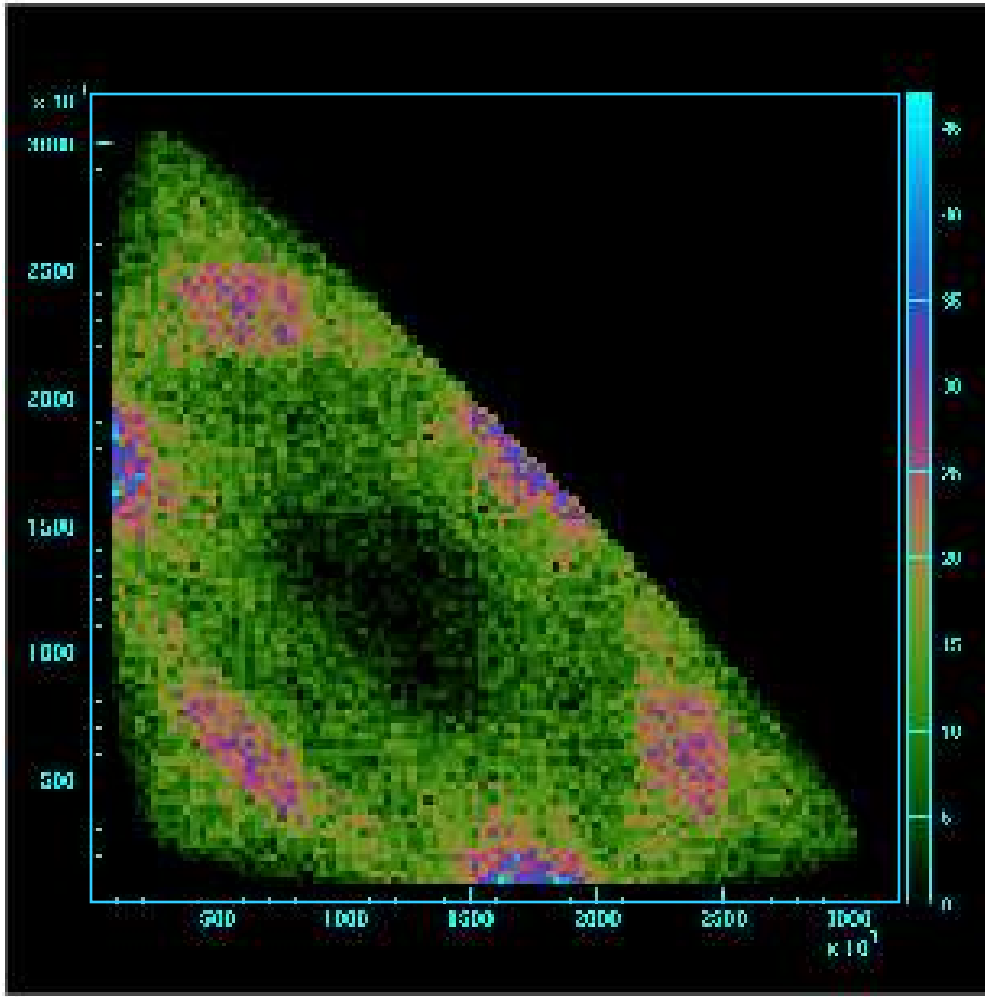
$p\bar{p} \rightarrow 3\pi^0$

with

~~100 events~~

~~1000 events~~

10000 events



It's All a Question of Statistics … … … …

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with

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~~1000 events~~

~~10000 events~~

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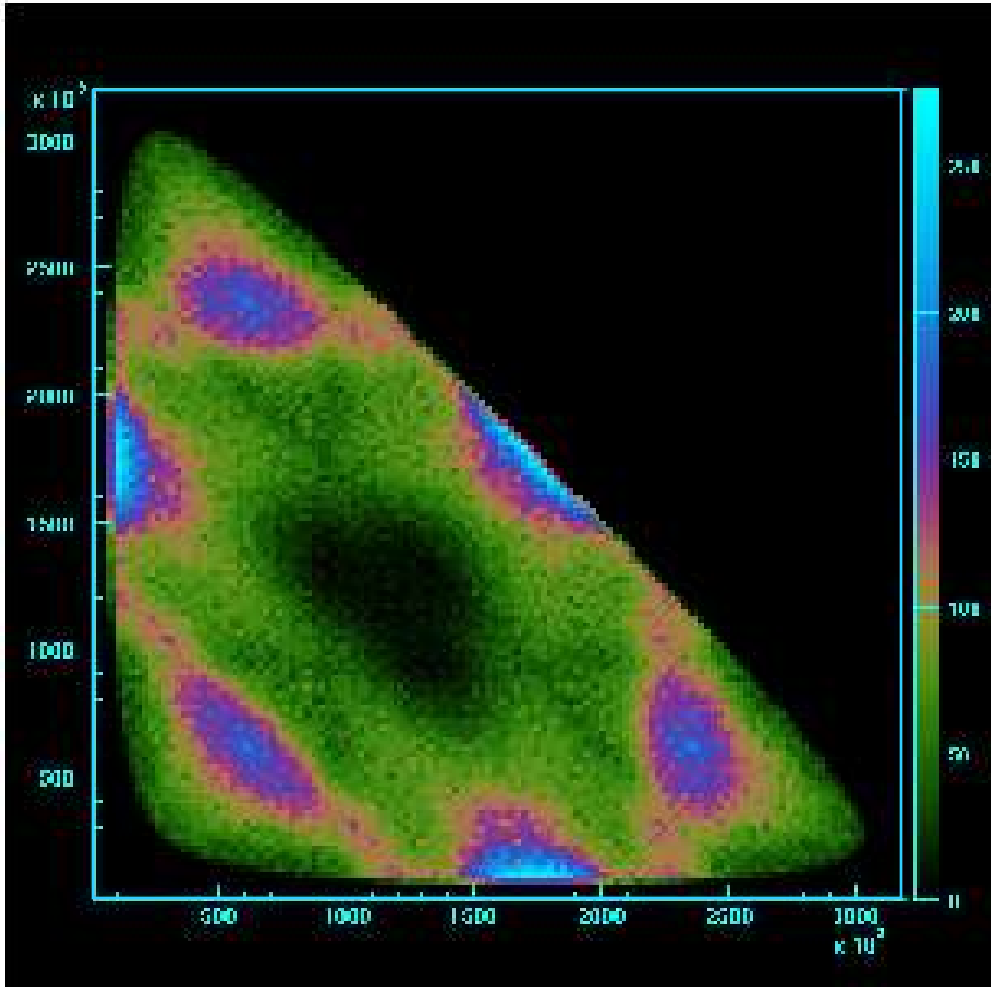
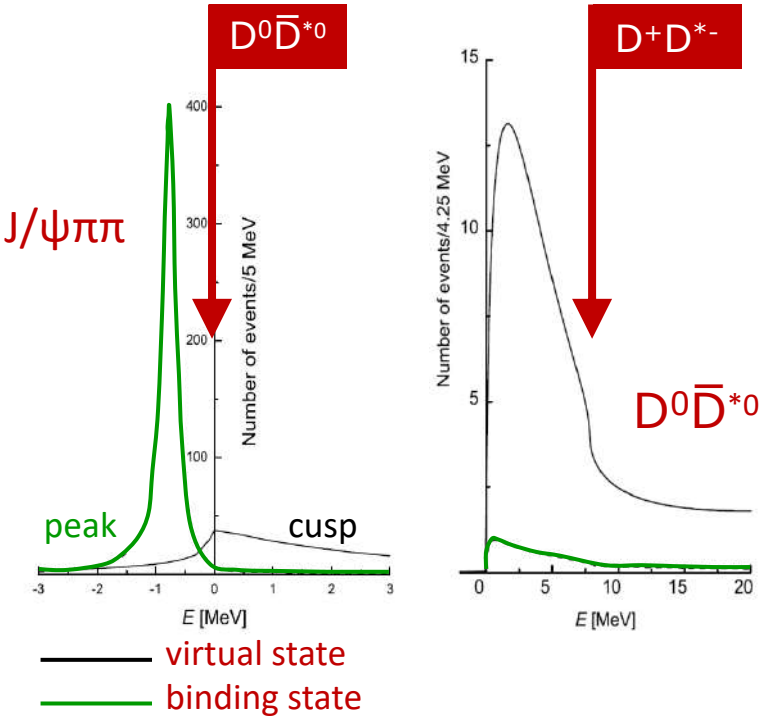
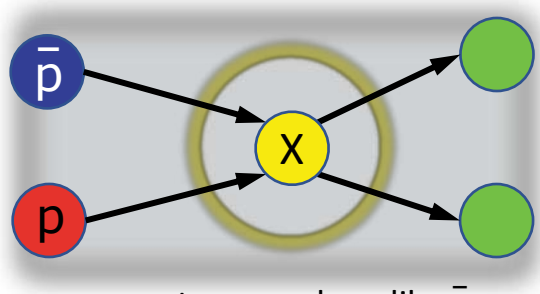


Formation: Line-shape Scans



needs a line-shape measurement



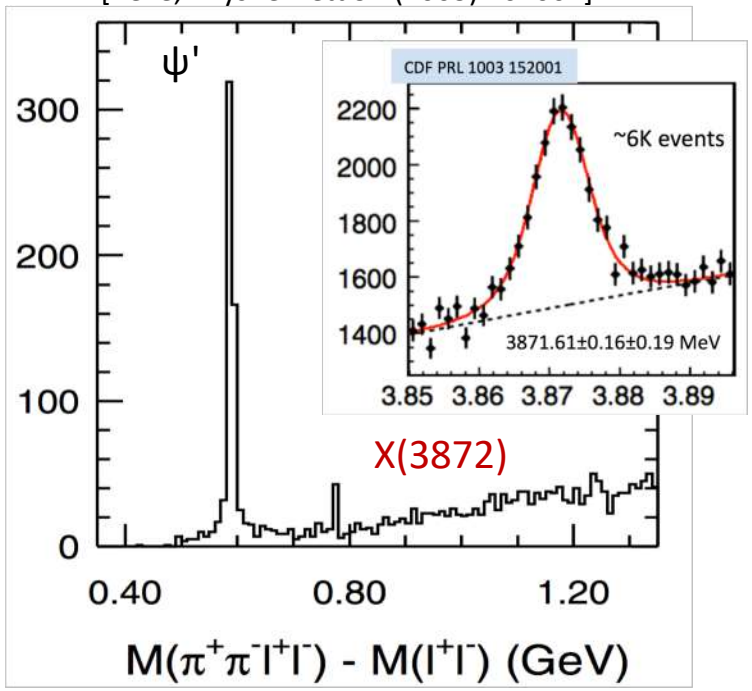
quantum numbers like $\bar{p}p$

Formation all non-exotic quantum numbers accessible

- not only limited to $J^{PC} = 1^{--}$ as e^+e^-
  precision physics of known states
- resonant, high statistics,
  extremely good precision
  in mass and width

Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]



The first unexpected states

- and the most intriguing one

First observed by Belle in 2003

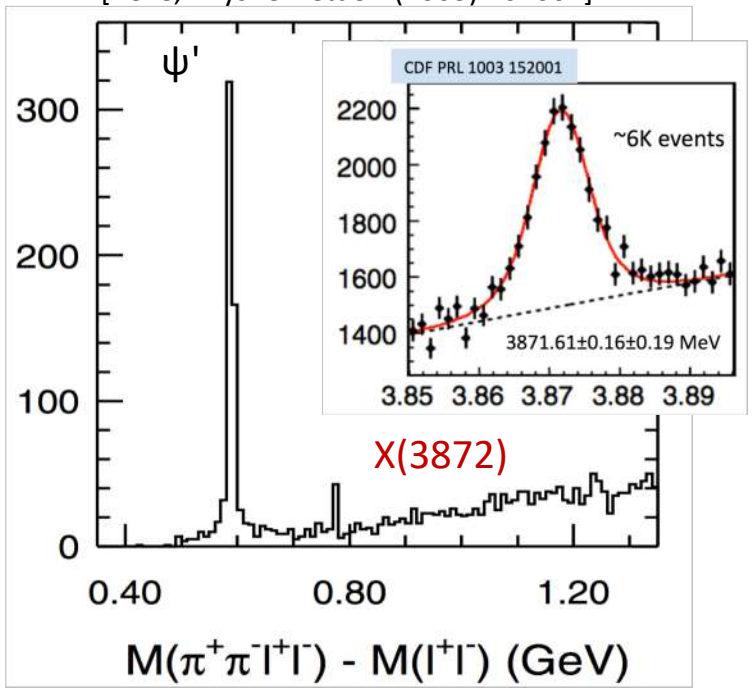
- X(3872) → J/ψ ππ
- very narrow state with $J^{PC} = 1^{++}$

Both, Belle & BaBar report signal in

- X(3872) → $D^0\bar{D}^{*0}$ ($D^0\bar{D}^0\pi^0$ and $D^0\bar{D}^0\gamma$) (+ cc impl.)

Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]



Mass: $m(X) - m(D^{*0}) - m(\bar{D}^0)$

$= -0.12 \pm 0.19$ MeV/c^2

Width: Upper limit by Belle

$\Gamma_{X(3872)} < 1.2$ MeV/c^2 (90% CL, 2011)

The first unexpected states

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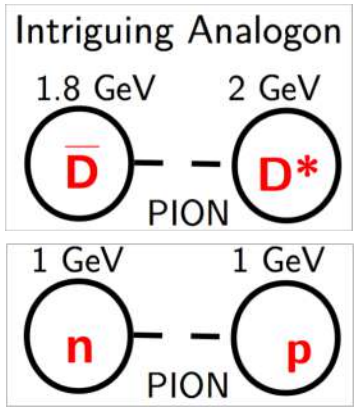
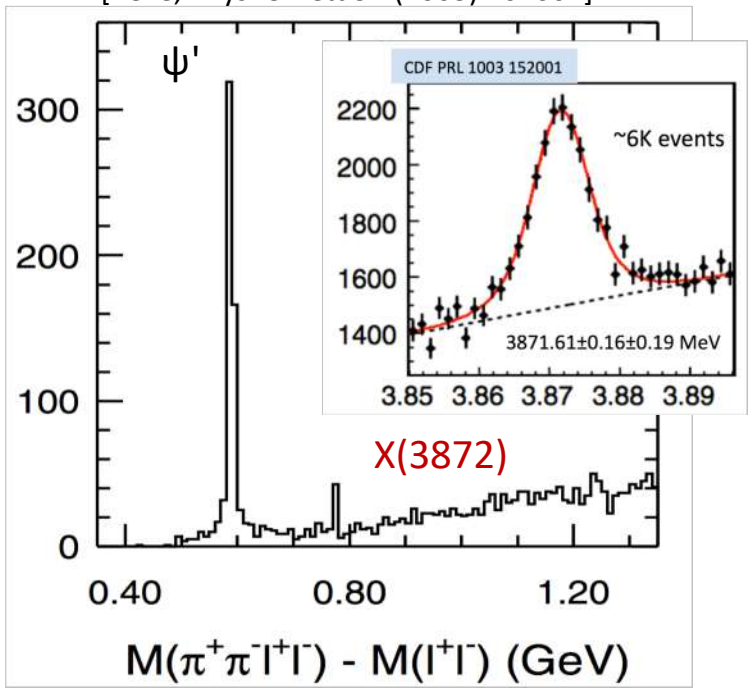
"binding energy" of -0.12±0.19 MeV ?



Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]



Mass: m(X) - m(D*⁰) - m($\bar{D}^0$)

= - 0.12 ± 0.19 MeV/c^2

Width: Upper limit by Belle

$\Gamma_{X(3872)}$ < 1.2 MeV/c^2 (90% CL, 2011)

For clarification: Precision measurement of $\Gamma_{X(3872)}$ in the sub-MeV range needed !

The first unexpected states

- and the most intriguing one

First observed by Belle in 2003

- X(3872) → J/ψ ππ
- very narrow state with J^{PC} = 1^{++}

Both, Belle & BaBar report signal in

- X(3872) → $D^0\bar{D}^{*0}$ ($D^0\bar{D}^0\pi^0$ and $D^0\bar{D}^0\gamma$) (+ cc impl.)

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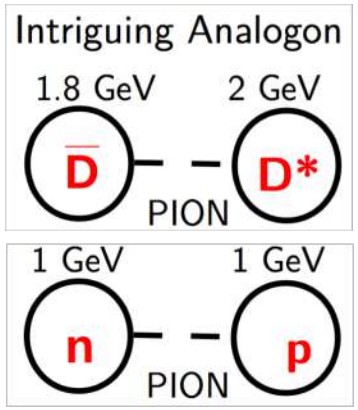


Molecular Picture

todo

Lineshapes from Kalashnikova et al. [Phys. Atom. Nucl. 73 (2010) 1592]
Here only interested in X(3872) → J/ψ ρ^0

$$\sigma(E) = C \cdot \frac{\Gamma_{\pi^+\pi^- J/\psi}(E)}{|D(E)|^2}$$

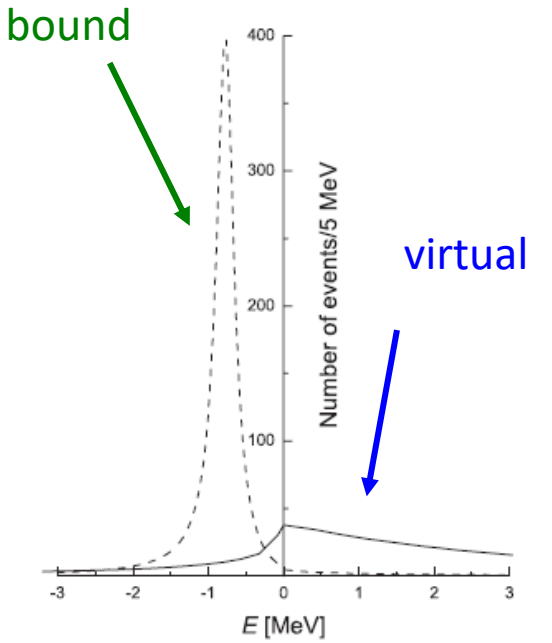
(assuming line-shape as in B decays)

$$D(E) = \begin{cases} E - E_f - \frac{g_1\kappa_1}{2} - \frac{g_2\kappa_2}{2} + i\frac{\Gamma(E)}{2}, & E < 0, \\ E - E_f - \frac{g_2\kappa_2}{2} + i\left(\frac{g_1 k_1}{2} + \frac{\Gamma(E)}{2}\right), & 0 < E < \delta, \\ E - E_f + i\left(\frac{g_1 k_1}{2} + \frac{g_2 k_2}{2} + \frac{\Gamma(E)}{2}\right), & E > \delta, \end{cases}$$

$$\Gamma(E) = \Gamma_{\pi^+\pi^- J/\psi}(E) + \Gamma_{\pi^+\pi^-\pi^0 J/\psi}(E)$$

$$\Gamma_{\pi^+\pi^- J/\psi}(E) = f_\rho \int_{2m_\pi}^{M - m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\rho}{(m - m_\rho)^2 + \Gamma_\rho^2/4} \Gamma_0$$

$$\Gamma_{\pi^+\pi^-\pi^0 J/\psi}(E) = f_\omega \int_{3m_\pi}^{M - m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\omega}{(m - m_\omega)^2 + \Gamma_\omega^2/4}$$



[Hanhardt et al., PRD 76 (2007) 034007]

Flatte energy E_f determines state to be bound or virtual

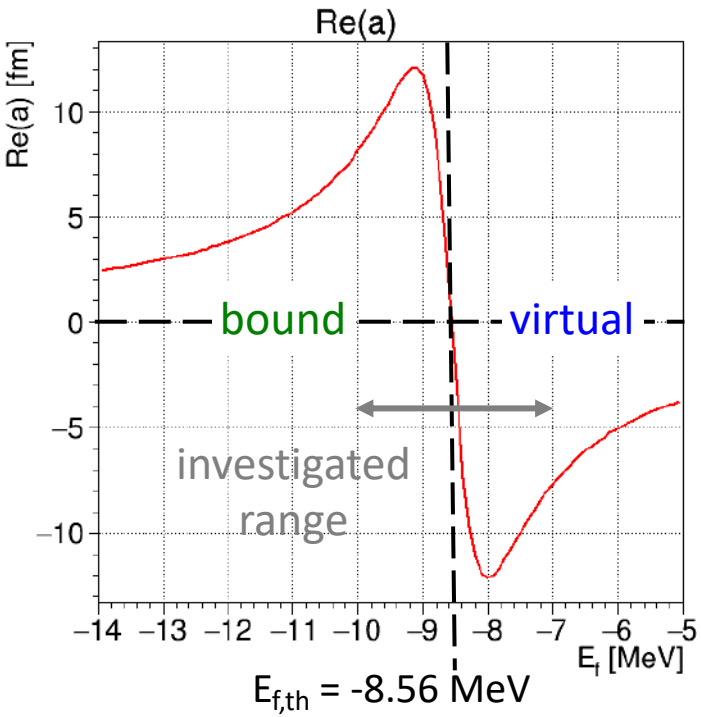
Line-shapes for different E_f

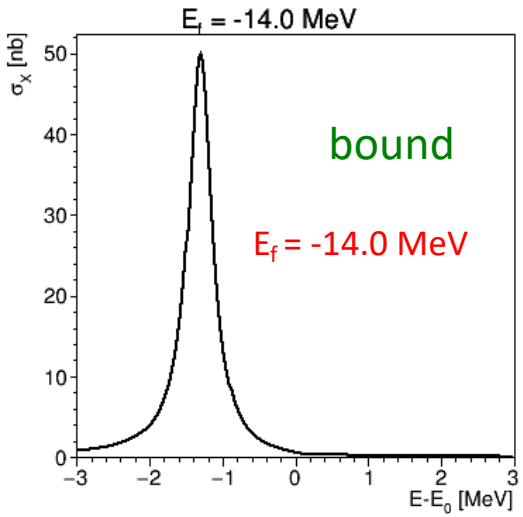
Scattering length $D^0\bar{D}^{0*}$ + cc.

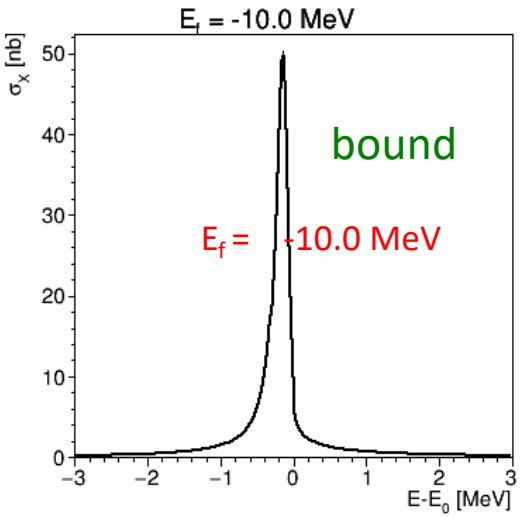
$$a = -\frac{\sqrt{2\mu_2\delta} + 2E_f/g + i\Gamma(0)/g}{(\sqrt{2\mu_2\delta} + 2E_f/g)^2 + \Gamma(0)^2/g^2}$$

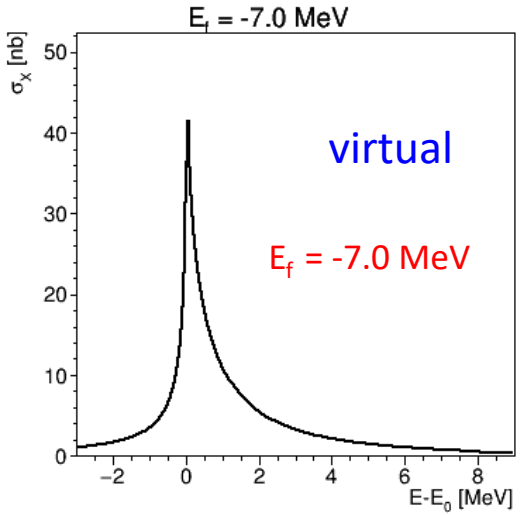
Re(a) > 0 : bound state

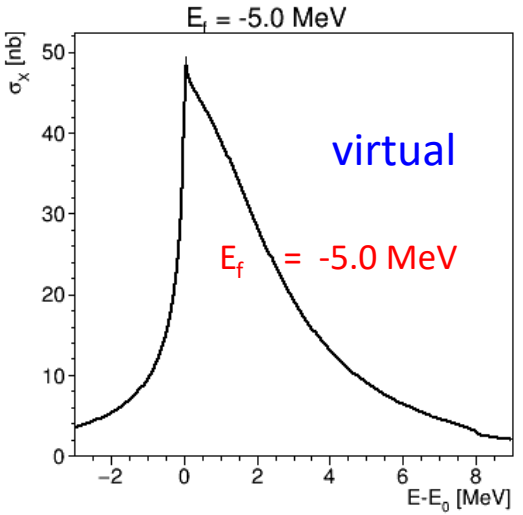
Re(a) < 0 : virtual state











Input Parameters

	Parameter	Value
Branching Fractions	BR($J/\psi \to e^+ e^-$)	5.97 %
	BR($J/\psi \to \mu^+ \mu^-$)	5.96 %
	BR($\rho^0 \to \pi^+ \pi^-$)	100%
	BR($X \to J/\psi\ \rho^0$)	5 % (UL: 6.6%)
Cross sections	$\sigma_{peak}(p\bar{p} \to X)$	[20,30,50,75,100,150] nb
	$\sigma(p\bar{p} \to J/\psi\ \pi^+\pi^-$ non-res)	1.2 nb [theory]
	$\sigma(p\bar{p} \to$ inelastic) @ 3.872 GeV	46 mb [CERN-HERA-84-01 (1984)]
Luminosities	L_{HL} (3.872 GeV)	13683 $(nb \cdot d)^{-1}$
	L_{HR} (3.872 GeV)	1368 $(nb \cdot d)^{-1}$
	L_{P1} (3.872 GeV)	1170 $(nb \cdot d)^{-1}$
Resolutions	ΔE_{abs} *(energy prec. w/ calibration)*	168 keV (dp/p = 10^{-4})
	ΔE_{rel} *(relative energy positioning)*	1.7 keV (dp/p = 10^{-6})
	ΔE_{mom} (HL)	168 keV (dp/p = 10^{-4})
	ΔE_{mom} (HR)	34 keV (dp/p = $2 \cdot 10^{-5}$)
	ΔE_{mom} (P1)	84 keV (dp/p = $5 \cdot 10^{-5}$)

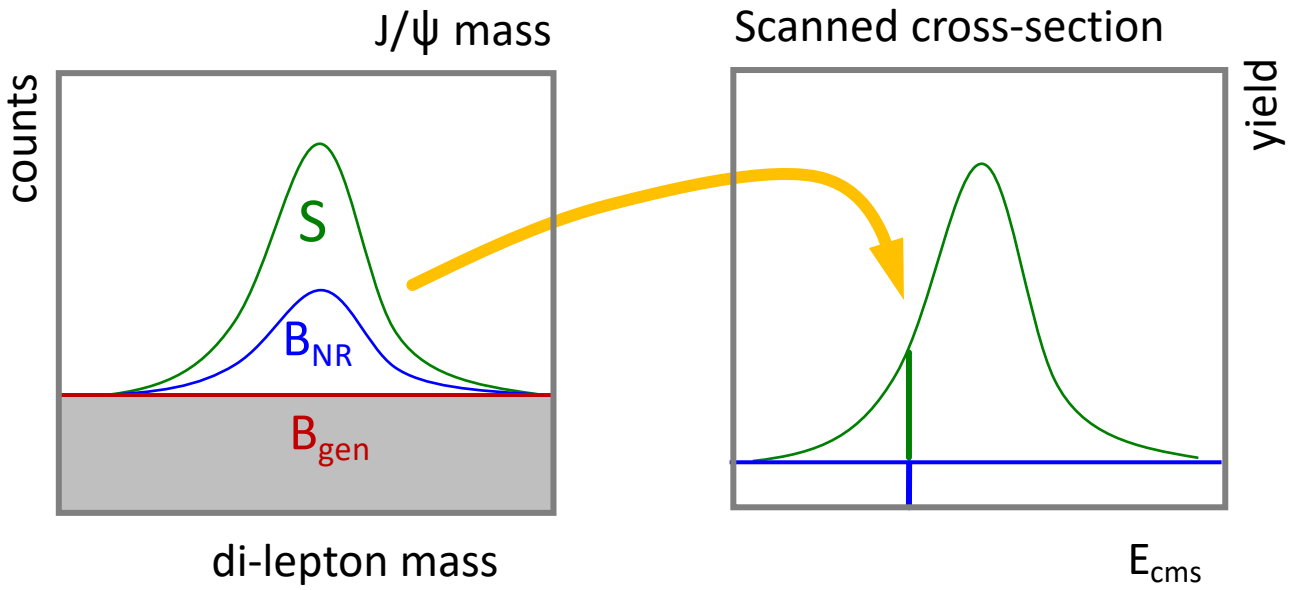
Yield Extraction

Simulated extraction of energy-dependent yield:

Fit signal in J/ψ mass

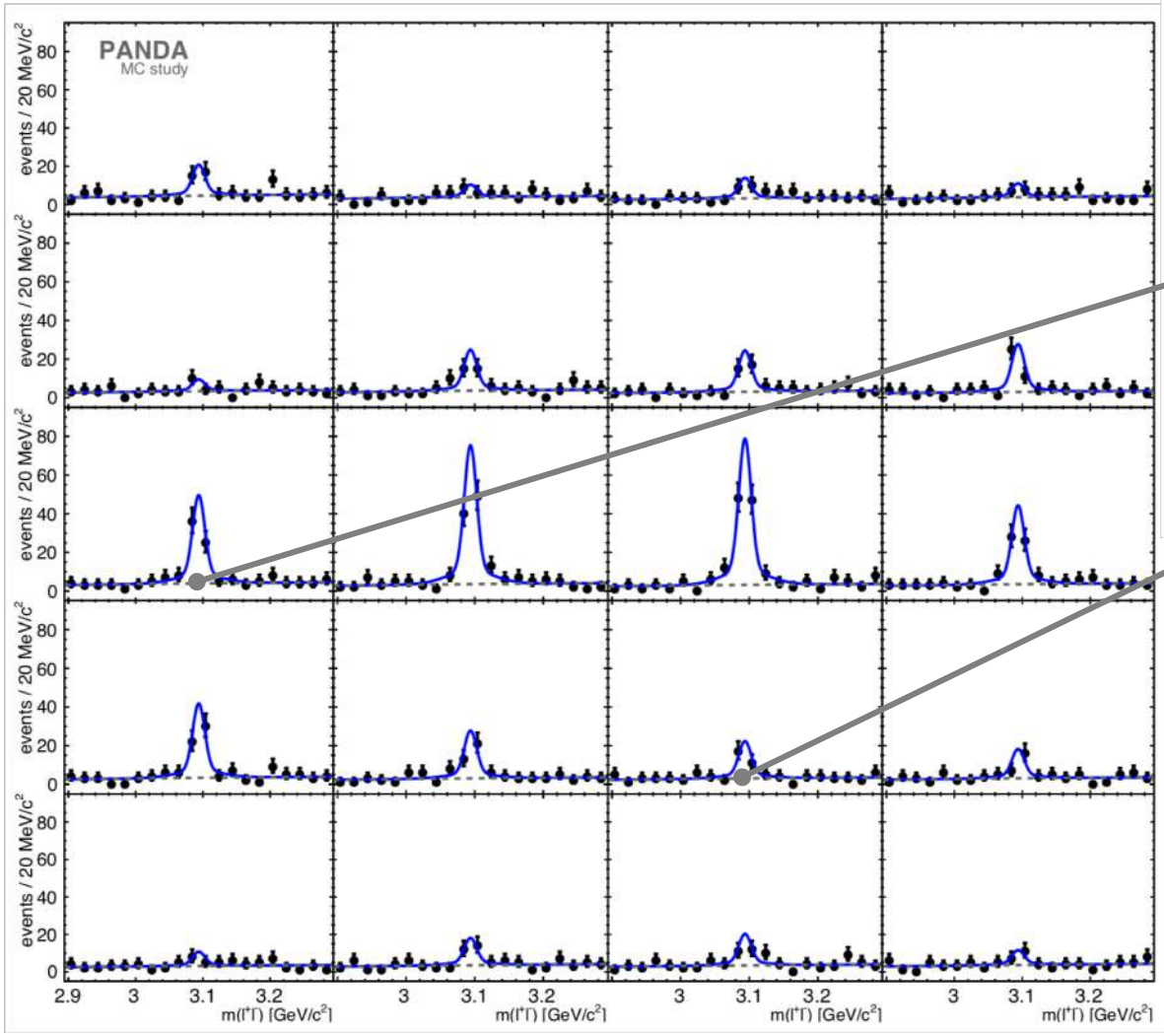
- Removes generic background
- NR background still present

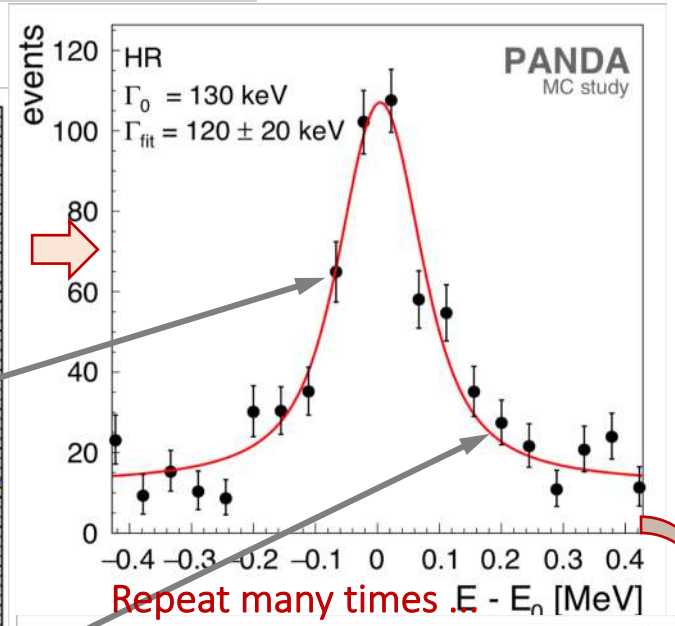
Requires sufficiently large J/ψ mass window



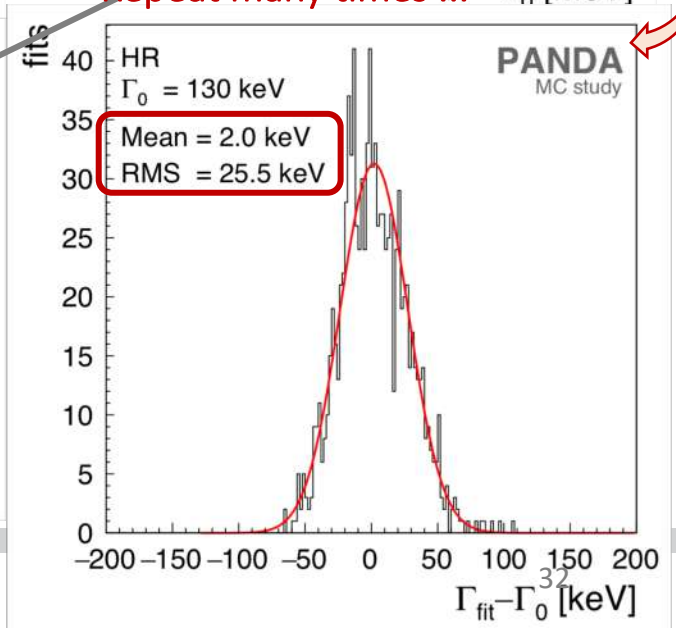
Scan Procedure Principle (Example)

20 E_{cms} scan point within ±0.4 MeV window around nominal mass





Repeat many times



Distinction of Lineshapes (40 x 2d)

Extract standard deviation from toy MC fits

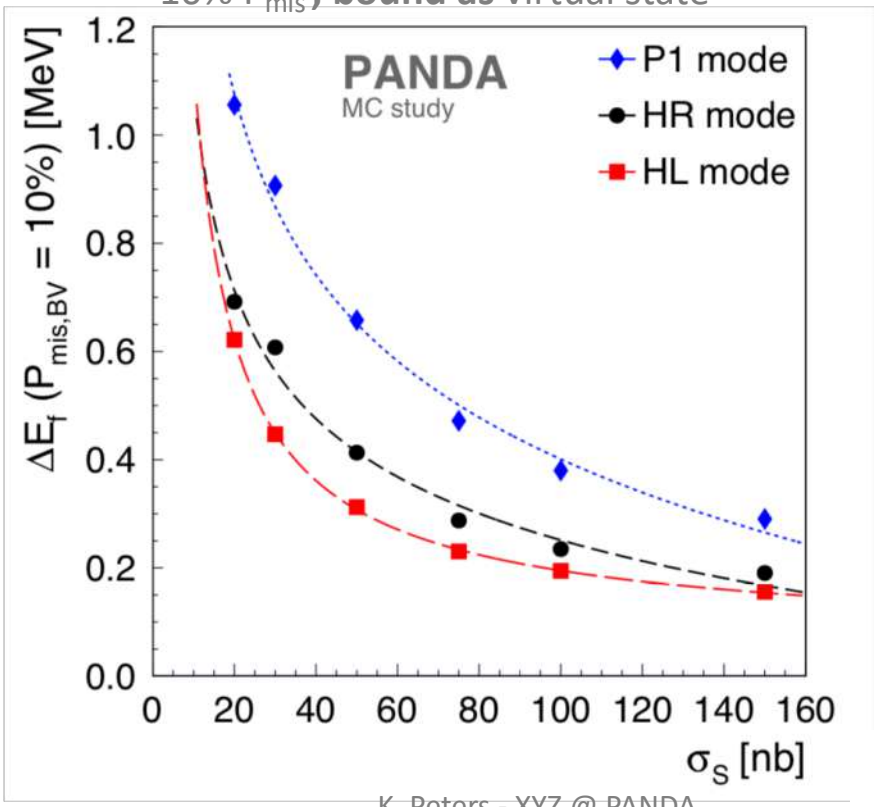
How well can virtual and bound state be distinguished?

→ integrate mismatch region

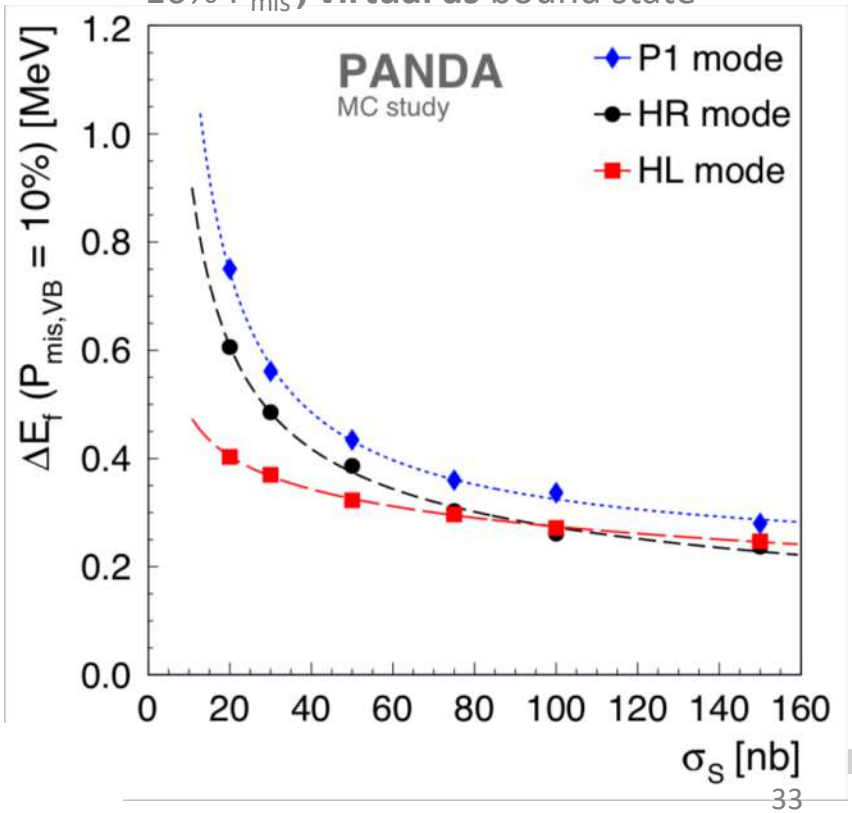
Sensitivity

$$P_{\mathrm{mis}} = N_{\mathrm{mis-id}}/N_{\mathrm{MC}} \quad \text{(Molecule case)}$$

10% P_{mis}, **bound as** virtual state



10% P_{mis}, **virtual as** bound state



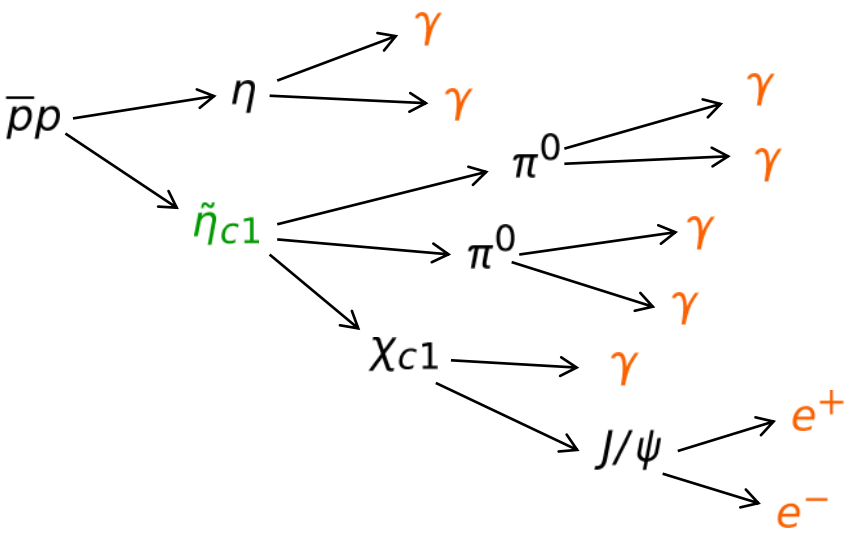
Charmonium Hybrid Candidate $\tilde{\eta}_{c1}$

From LQCD calculations

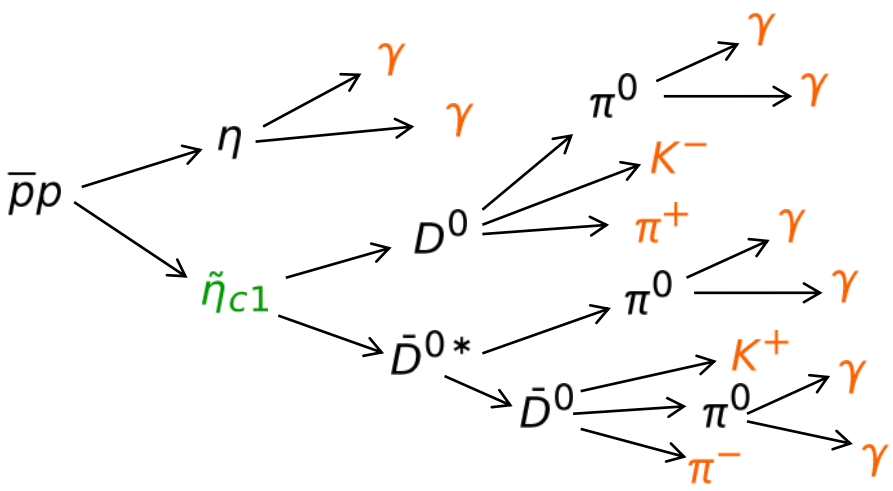
Spin-exotic hybrid candidate $\tilde{\eta}_{c1}$ with m ≈ 4.3 GeV/c^2 & $J^{PC} = 1^{-+}$

Exclusive reconstruction in two favoured channels:

$\bar{p}p \rightarrow \tilde{\eta}_{c1}\eta \rightarrow \chi_{c1}\pi^0\pi^0\eta$



$\bar{p}p \rightarrow \tilde{\eta}_{c1}\eta \rightarrow D^0\bar{D}^{0*}\eta$



Production X-section assumed similar to $\bar{p}p \rightarrow \psi(2S)\eta$ (33pb)

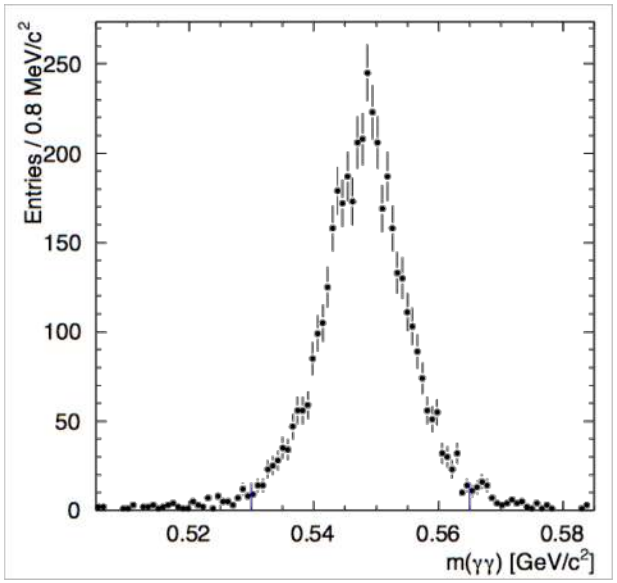
→ Need good calorimetry + good particle identification

$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta \rightarrow \chi_{c1}\pi^0\pi^0\eta$

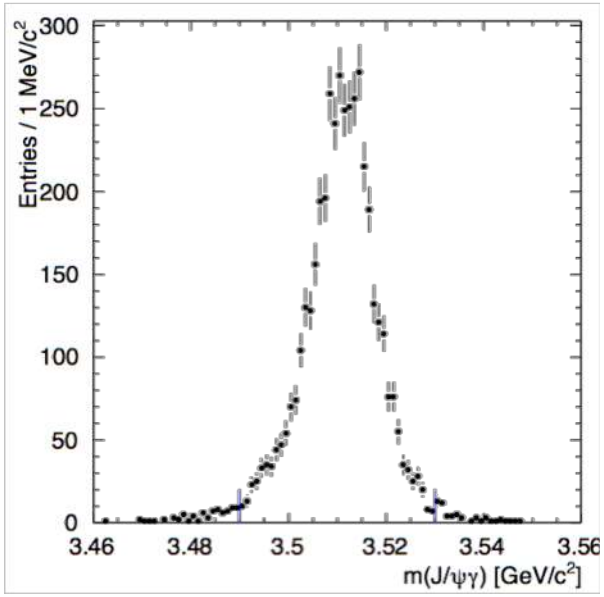
Simulation @ 15 GeV/c $\quad \bar{p}p \rightarrow J/\psi\,\pi^0\pi^0\pi^0\,\eta,\ \bar{p}p \rightarrow \chi_{c1}\pi^0\eta\eta$

- 80k signals + 80k each background, e.g.
- 9C kinematic fit (mass constraints & 4C energy momentum)

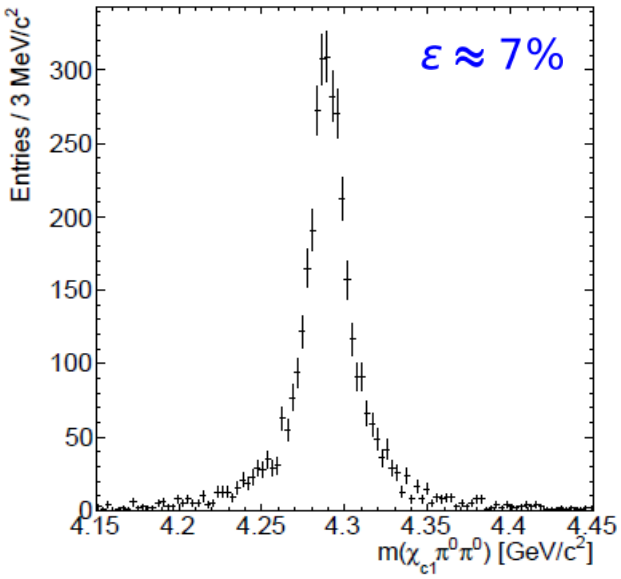
$\eta \rightarrow \gamma\gamma$



$\chi_{c1} \rightarrow J/\psi\gamma$



$\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0$



[arXiv:0903.3905, hep-ex]

$$\frac{S}{N} > 250 \cdot \frac{\sigma_S}{\sigma_B}$$

→ well feasible for $\sigma_B \lesssim 10\ \sigma_S$!

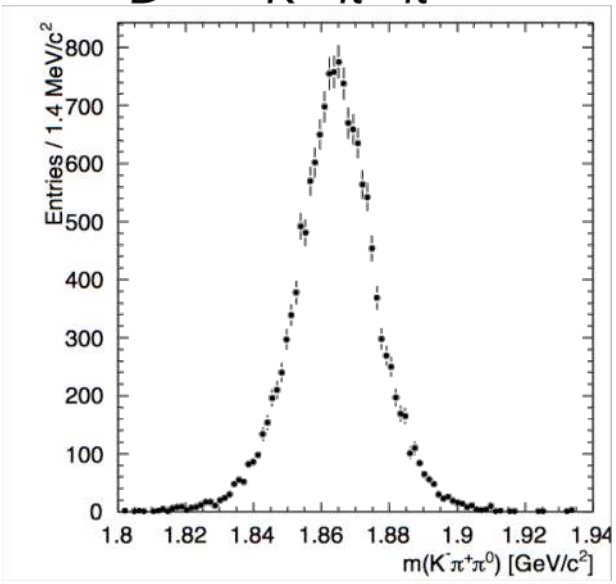
$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta \rightarrow D^0\bar{D}^{0*}\eta$

todo

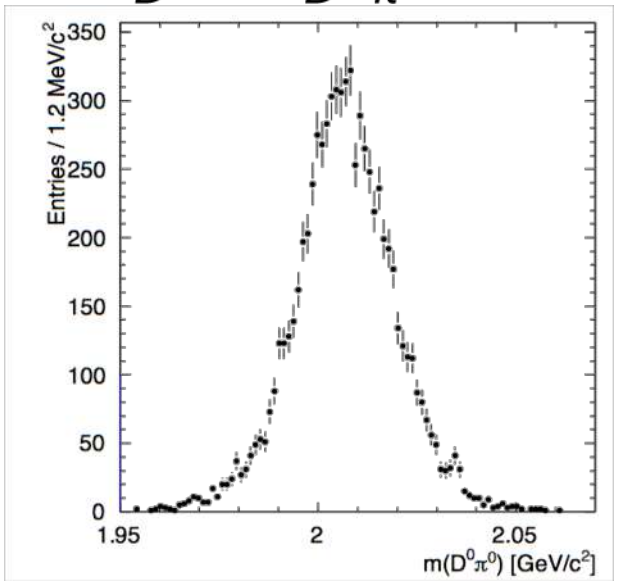
Simulation @ 15 GeV/c $\quad \bar{p}p \rightarrow D^0\bar{D}^{0*}\pi^0$

- 200k signals + background, e.g.
- 11C kinematic fit (mass constraints, 4C energy momentum)

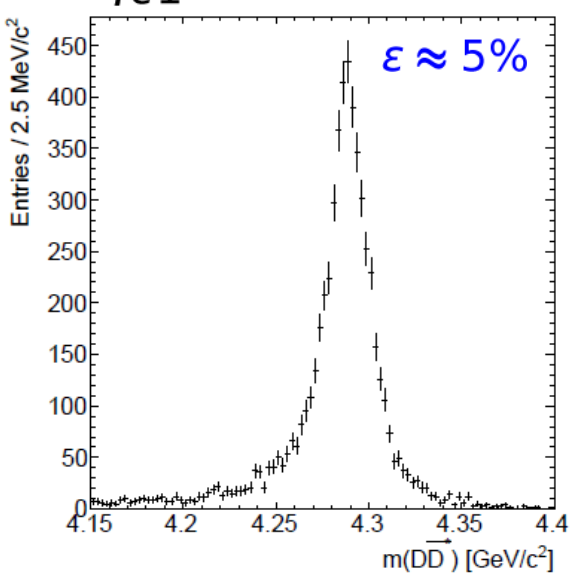
$D^0 \rightarrow K^-\pi^+\pi^0$



$D^{0*} \rightarrow D^0\pi^0$



$\tilde{\eta}_{c1} \rightarrow D^0\bar{D}^{0*}$



Signal to noise $\quad \frac{S}{N} > 2900 \cdot \mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\bar{D}^{0*})$ $\quad \rightarrow$ feasible for non-vanishing BR

[arXiv:0903.3905, hep-ex]

Width of $D_{s0}^*(2317)$

todo

Theoretical interpretations very sensitive for $\Gamma(D_{s0}^*(2317))$

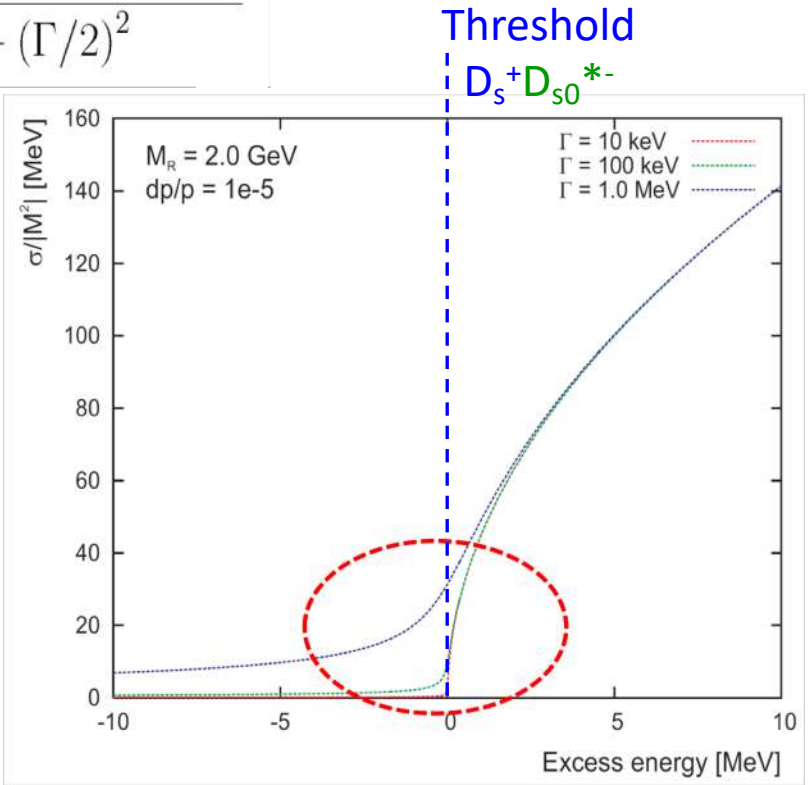
Formation reaction not possible $\bar{p}p \not\rightarrow D_{s0}^*(2317)$

$$\frac{\sigma(s)}{|M^2|} = \frac{\Gamma}{4\pi\sqrt{s}} \int_{-\infty}^{\sqrt{s}-m_{D_s}} \mathrm{d}m \frac{\sqrt{\left(s-(m+m_{D_s})^2\right)\left(s-(m-m_{D_s})^2\right)}}{\left(m-m_{D(2317)}\right)^2+(\Gamma/2)^2}$$

[C. Hanhart] $\bar{p}p \rightarrow D_s^+ D_{s0}^*(2317)^-$

➞ Energy-scan with recoil @ threshold

➞ Lineshape at threshold depends on $\Gamma(D_{s0}(2317)^*)$



Summary

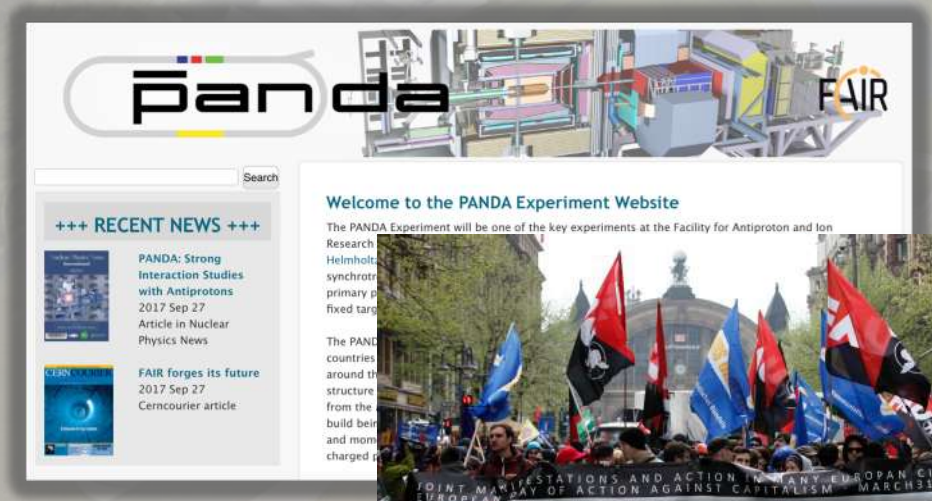
Excellent Opportunities for XYZ physics

- XYZ scans shown with the X(3872) as a published example
- Threshold scans can be made accordingly
- XYZ search, even broader and with higher spins and masses as in BES3 and others

PANDA Setup

- Perfectly suited for all possibilities

panda.gsi.de



Thank you

BACKUP

$\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$