Multiquark Resonances

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CHARGED EXOTIC RESONANCES

BES III
BELLE (2013)

$e^+e^- \to \gamma Y(4.26)$
$\hookrightarrow \pi^+ Z_c^-(3.9)$
$\hookrightarrow \pi^- J/\psi$

$I^G J^{PC} = 1^+ 1^{+-}$, $\Gamma \sim 50$ MeV

another decay modes of Y's

$Y(4.26) \to \gamma X(3.872)$
$\hookrightarrow DD^*$
$J/\psi\, \pi^+\pi^-$
$J/\psi\, \pi^+\pi^-\pi^0$

Z_c IS A 4-QUARK RESONANCE

$c\bar{c}\, d\bar{u}$

Charged $Z_c(3900)$

$$G = G_\pi C_{J/\psi} = \\ = -1(-1) = +1$$

$$P = +1 \ (S - \text{wave})$$

$$\Rightarrow Z_c^0 \text{ has } J^{PC} = 1^{+-}$$

$$I^G J^{PC} = 1^+ 1^{+-}$$

Found in $Y(4260) \to Z_c^\pm(3900)\,\pi^\mp \to J/\psi\,\pi^\pm\,\pi^\mp$

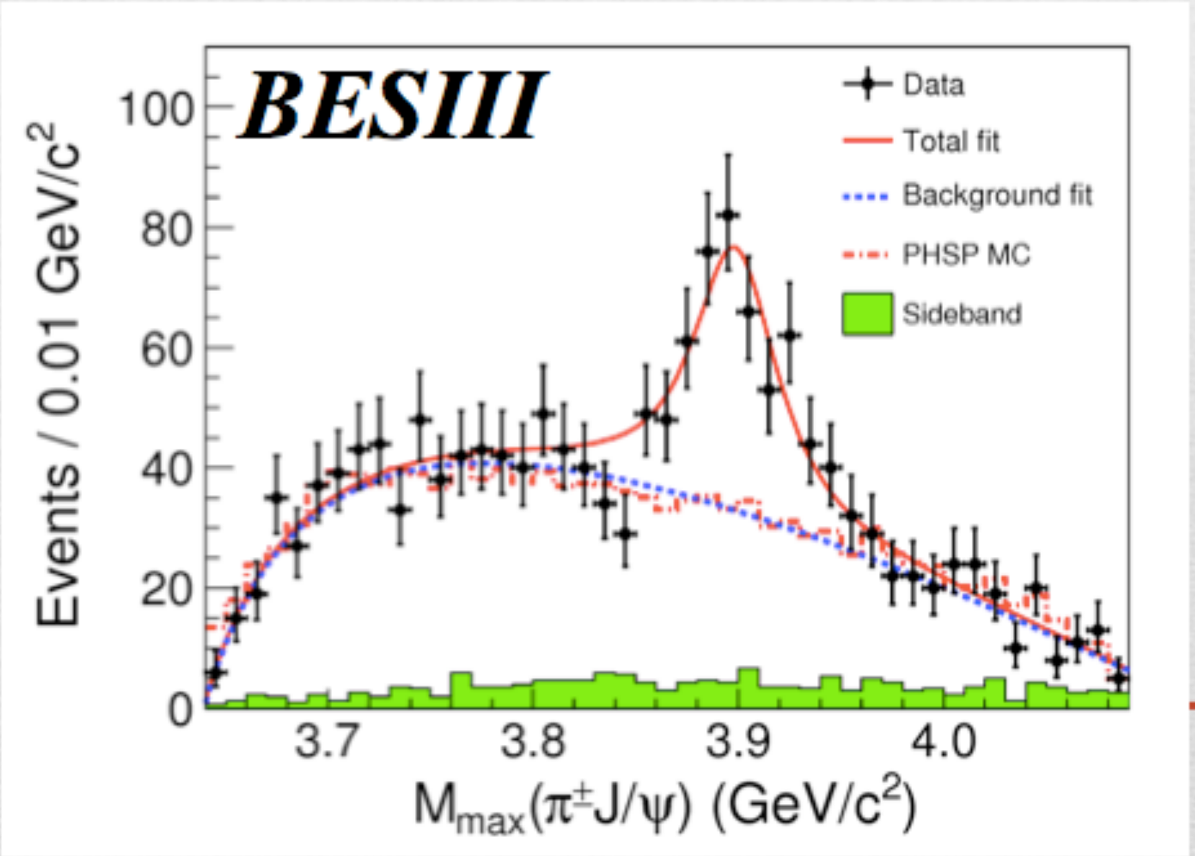
Exotic charged charmonium-like state!

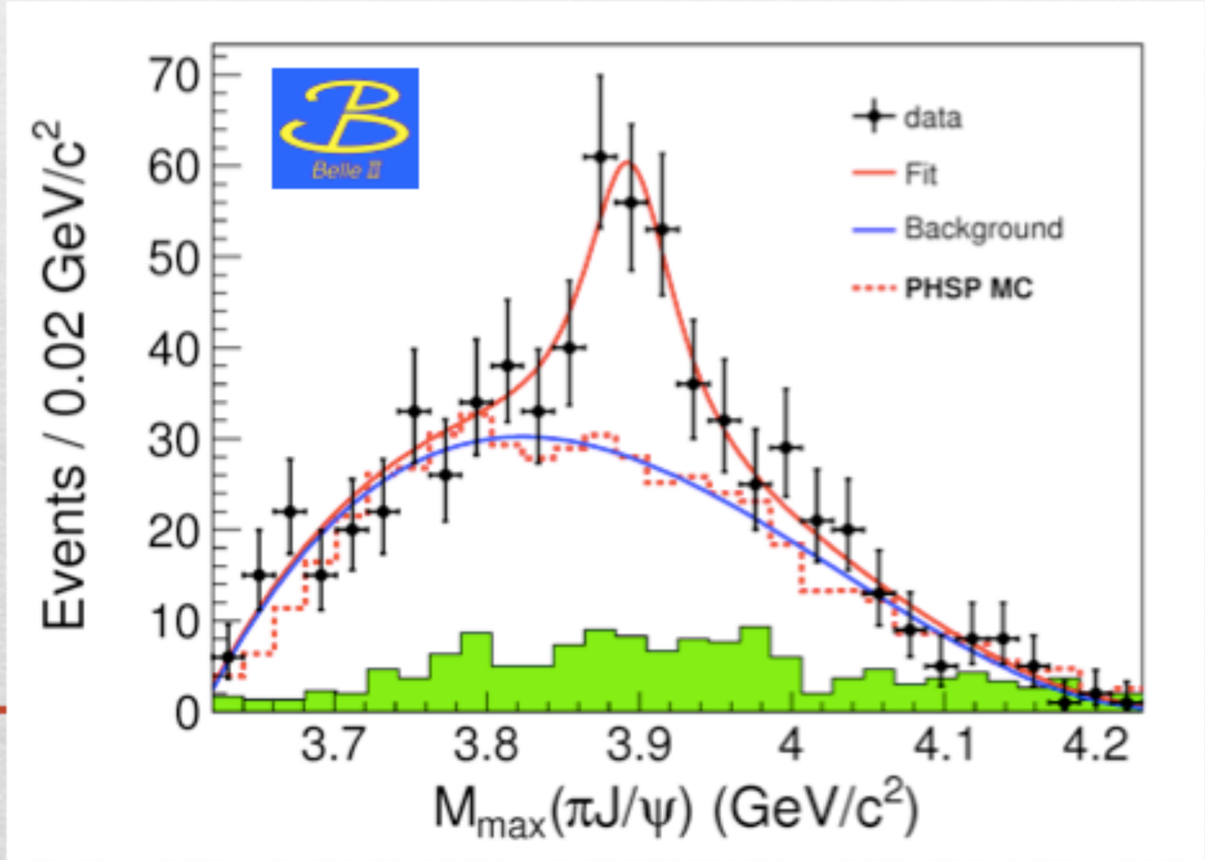
BESIII, arXiv:1303.5949

$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$
$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

Belle, arXiv:1304.0121

$$M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$$
$$\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$$





X(3872)

DISCOVERED BY BELLE IN 2003
CONFIRMED BY BaBar, DØ, CDF, CMS, LHCb & ATLAS!

4 $pp \to X(3872)$ @CMS

PROMPT PRODUCTION

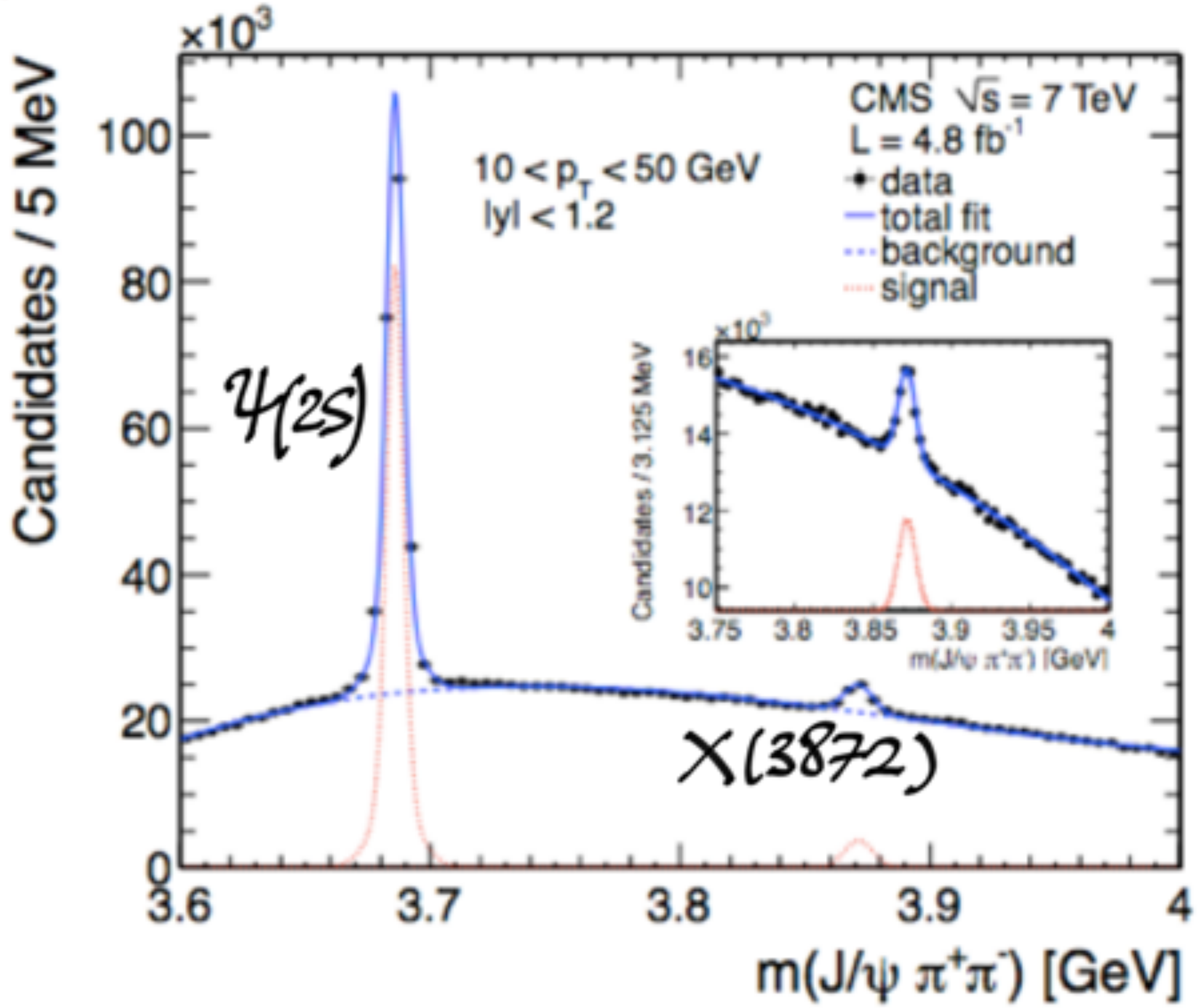


Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region.

INTERESTING FACTS ABOUT 'X'

1. $J^{PC} = 1^{++}$
2. The largest BR is

$$X \to \bar{D}^0 D^{*0}$$

and $M_X \equiv M_{D^0} + M_{D^{*0}}$!

3. ... but it was discovered in another channel

$$X \to J/\psi \rho^0$$

and $M_X \equiv M_{J/\psi} + M_{\rho^0}$!!

What about $X^\pm \to J/\psi \rho^\pm$? Never observed.

4. $X \to J/\psi \omega$

& $\frac{BR(X \to J/\psi \rho^0)}{BR(X \to J/\psi \omega)} \simeq 1$

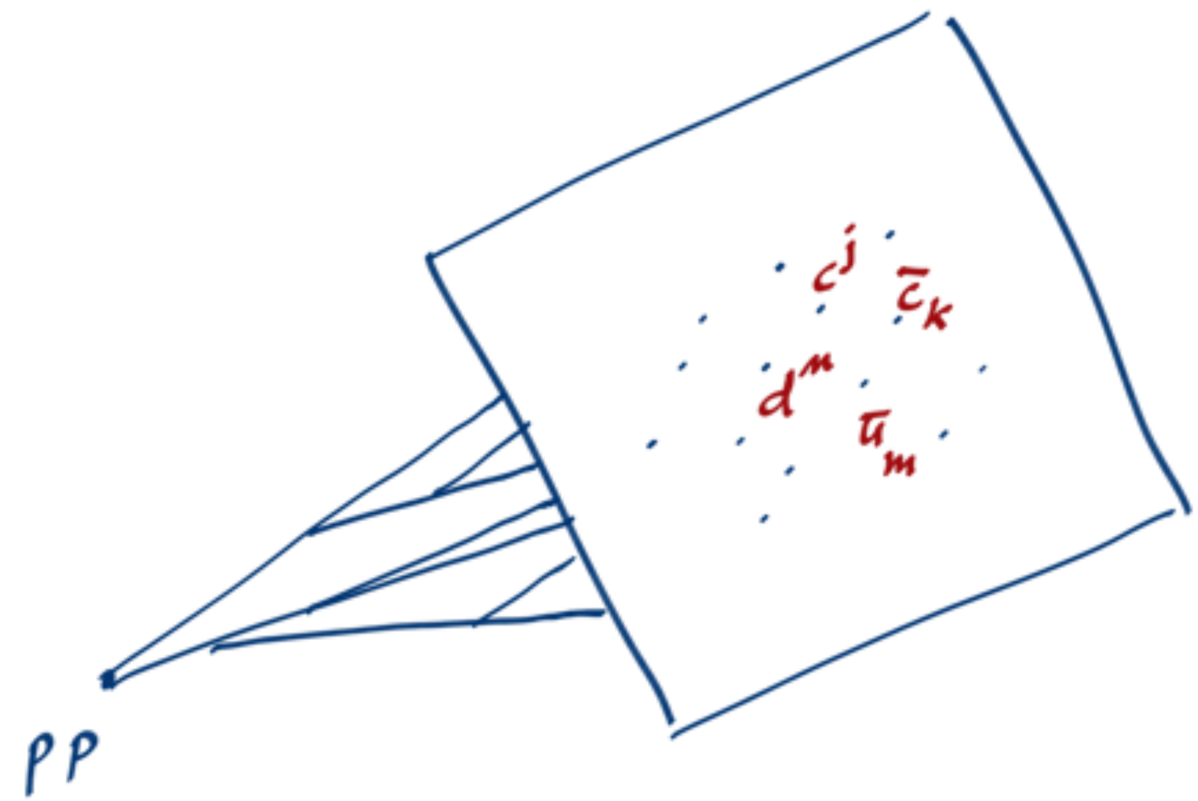
Is there any relation between $Z_C(3.9)$ and $X(3.872)$?

- X is neutral — no charged partner ever found
- Z_c appears in all three states of charge
- X and Z_c almost degenerate
- opposite G-parity

Both compact tetraquarks?… Where is X^+?
Both molecules?… One of the two has *positive* binding energy?!

CHARGED EXOTIC RESONANCES

It should be searched in prompt pp collisions at LHC



The relative motion must be compatible with the formation of a <u>compact tetraquark</u>

$$\epsilon_{ijn}\, c^j d^n\, \epsilon^{ikm}\, \bar{c}_k\, \bar{u}_m$$

CHARGED EXOTIC RESONANCES

According to the VIRIAL THEOREM

$$\bar{T}\ (= -\bar{E}) \simeq \frac{1}{2} m_c \alpha_c^2 (2m_c) \gtrsim 50\ \text{MeV}$$

However color might be neutralized also in two singlets

$$c^j \bar{u}_j \quad \bar{c}_k d^k$$

or

$$c^j \bar{c}_j \quad \bar{u}_k d^k$$

in all spin configurations preserving the spin of the heavy quark pair.

Bound states may not be formed (continuum spectrum) yet we may expect

$$E < E_{max} < |\bar{E}|$$

'HADRONIZATION STATE'

Superposition with unknown coefficients

$$\Psi = [cd][\bar{c}\bar{u}] + \psi\pi^- + \psi'\pi^- + \eta_c\rho + \bar{D}D^* + \bar{D}^*\bar{D}^*$$

$$= \Psi_d + \sum_i \Psi_{m_i}$$

$$\Psi = \Psi_Q + \Psi_P = \mathcal{Q}\Psi + \mathcal{P}\Psi$$

$$H\Psi = E\Psi$$

$$(E - H_{PP})\Psi_P = H_{PQ}\Psi_Q$$

$$(E - H_{QQ})\Psi_Q = H_{QP}\Psi_P$$

$$H_{PP} = H_0 + V_1$$

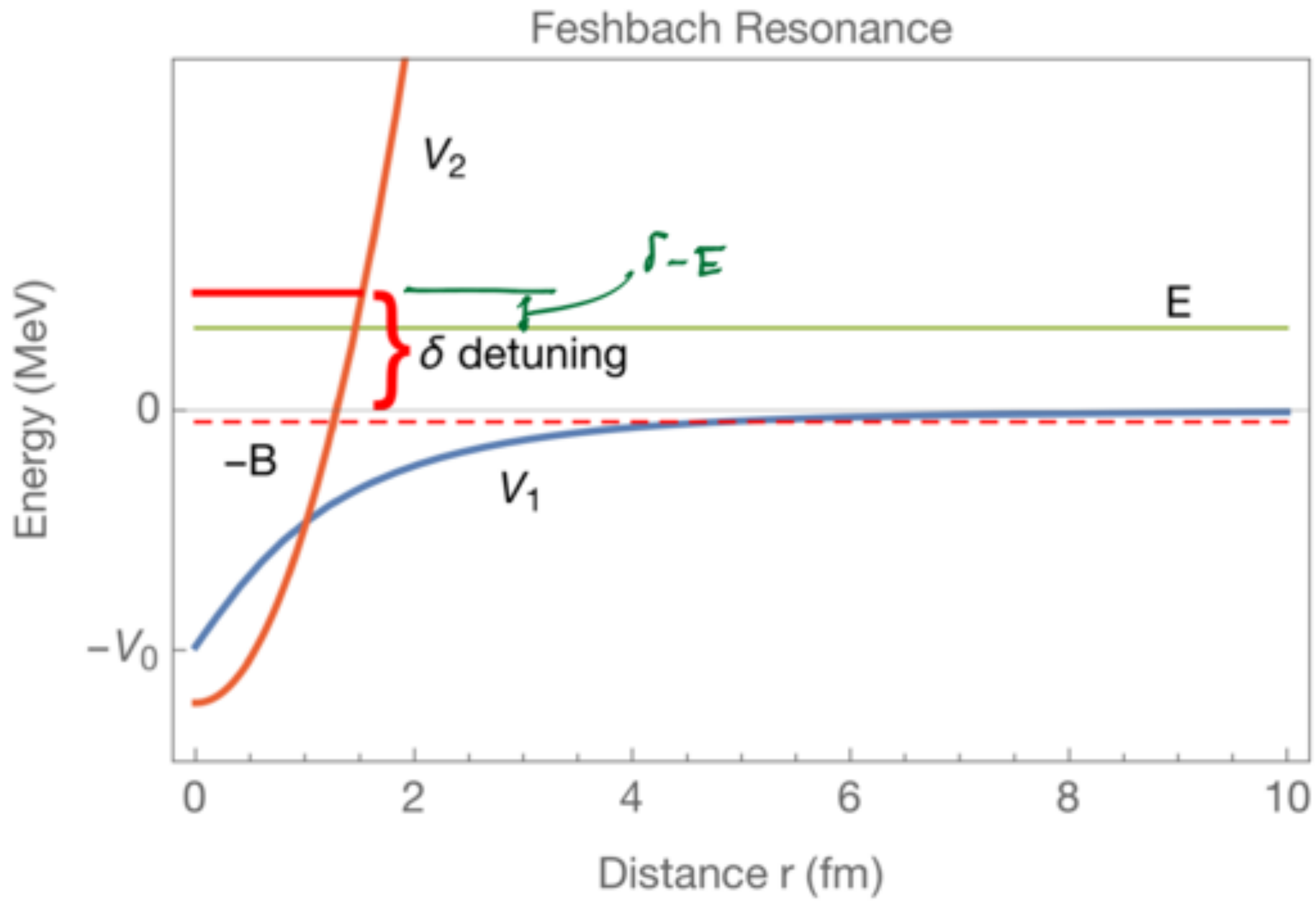
$$H_{QQ} = H_0 + V_2$$

& $\boxed{(E - H_{PP} - V_I)\Psi_P = 0}$

EFFECTIVE INT. IN THE P SPACE ($P \to Q \to P$)

$$V_I = H_{PQ} \frac{1}{E - H_{QQ} + i\epsilon} H_{QP}$$

OPEN & CLOSED CHANNELS



Because of V_I the scattering length in P is

$$a = a_p - c \frac{|\langle \Psi_m | H_{QP} \Psi_\alpha \rangle|^2}{E_m - E_\alpha + i\epsilon} \qquad (c>0)$$

$$\equiv \left(1 - \frac{x}{\delta - E + i\epsilon}\right) a_p$$

SCATTERING IN THE OPEN CHANNEL

Would-be hadron molecules in P, may momentarily rearrange their internal structure into compact tetraquarks: this happens w/ probability

$$\sigma \sim \frac{|\operatorname{Im} a|}{p} \sim \frac{1}{p}\,\frac{\epsilon}{(\delta-E)^2+\epsilon^2}$$

$$d\Gamma \sim \rho v \sigma \sim \delta(E-\delta)\,|\varkappa a_p|\,(2m)^{1/2}\sqrt{E}\,dE$$

$E < E_{max}$

If δ falls within E_{max}

$$\Gamma \sim (2m)^{1/2}\,|\varkappa a_p|\,\sqrt{\delta}$$

THIS MIGHT HAPPEN ONLY FOR ONE OF THE THRESHOLDS IN Ψ, the CLOSER (in energy) FROM BELOW TO $E_{\varkappa=0}$ -

CHARGED EXOTIC RESONANCES

The $Z_c(3.99)$ is not the only one.

$$Z'^{\mp}_c(4.025) \to \pi^{\mp} h_c$$

$$Z^{\mp}_b(10.61) \to \pi^{\mp} \Upsilon(nS)$$

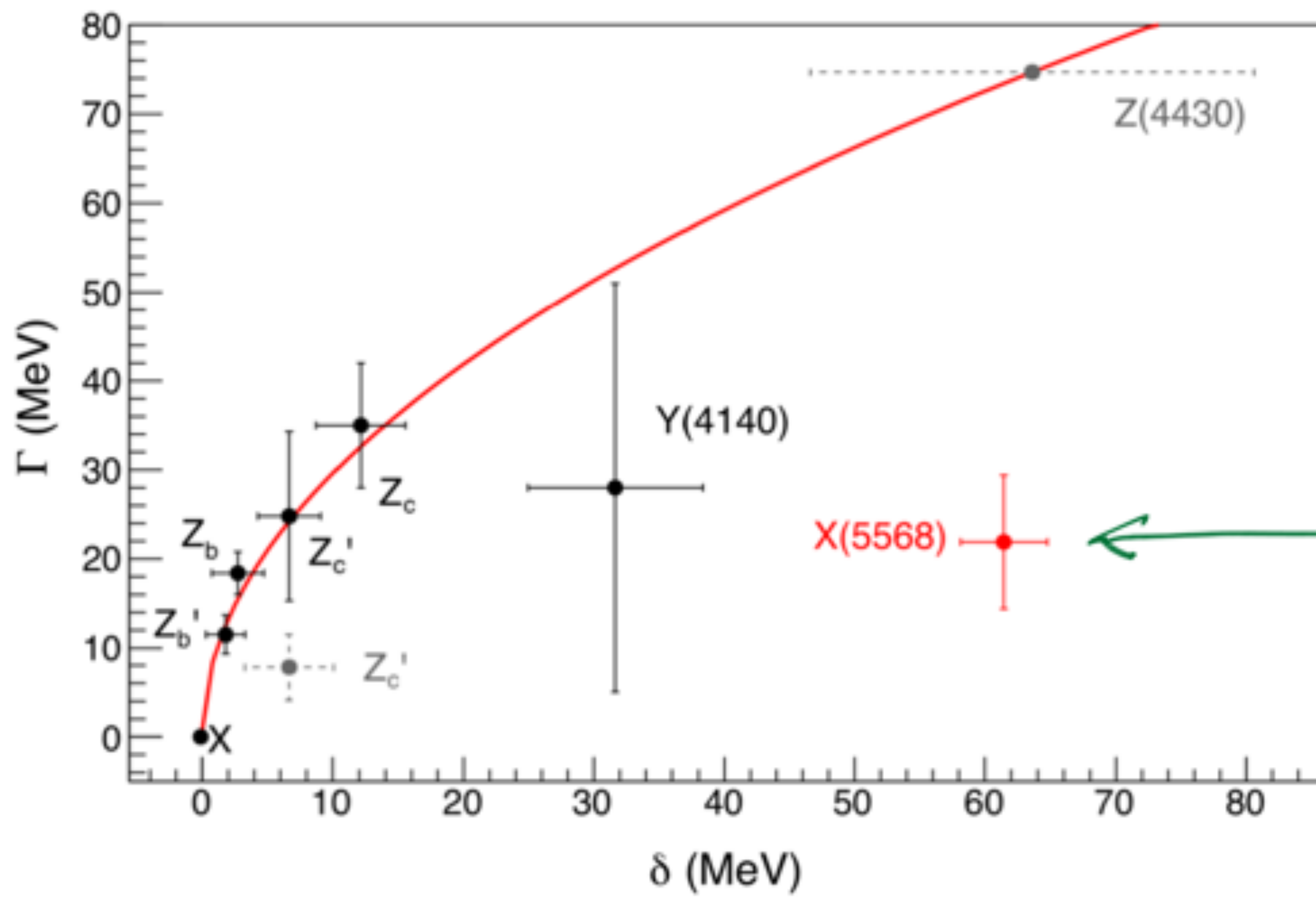
BELLE (2012)

$$Z'^{\mp}_b(10.65) \to \pi^{\mp} h_b(kP)$$

	MOL	δ
Z_c	DD^*	~24 MeV
Z'_c	D^*D^*	~8 MeV
Z_b	BB^*	~6 MeV
Z'_b	B^*B^*	≃1 MeV

'$\sqrt{\delta}$ - LAW'

A. ESPOSITO, A. PILLONI, ADP 1603.07667 (PLB)



← THE DIQUARK LEVEL E_0 CAN BE COMPUTED

X	$\bar{D}^0 D^{*0}$
Z_c	$\bar{D}^0 D^{*+}$
Z_c'	$\bar{D}^{*0} D^{*+}$
Y	$J/\psi\ \phi$
Z_b	$\bar{B}^0 B^{*+}$
Z_b'	$\bar{B}^{*0} B^{*+}$

$X(5.568)$ $B_s^0 \pi^+$

FEB 2016

A New $B^0_s\pi^\pm$ State Claimed by DØ

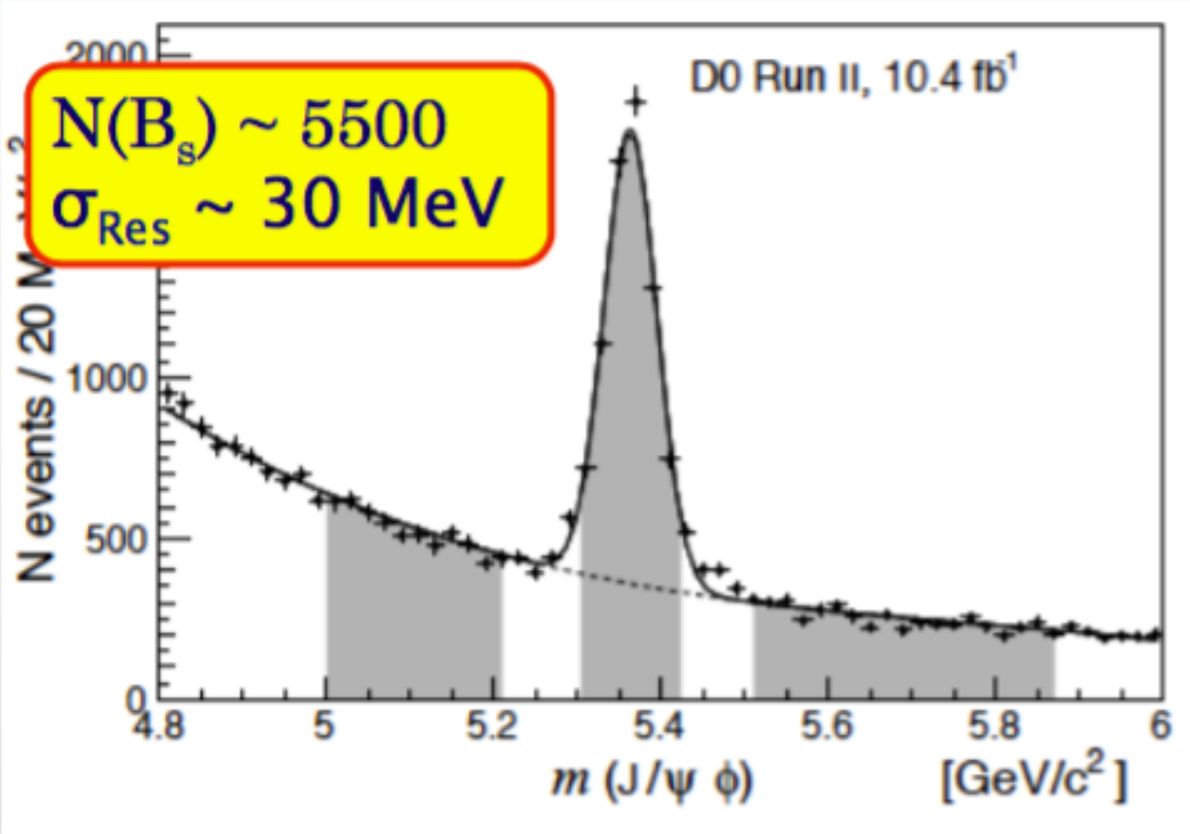
[DØ: arXiv:1602.07588]

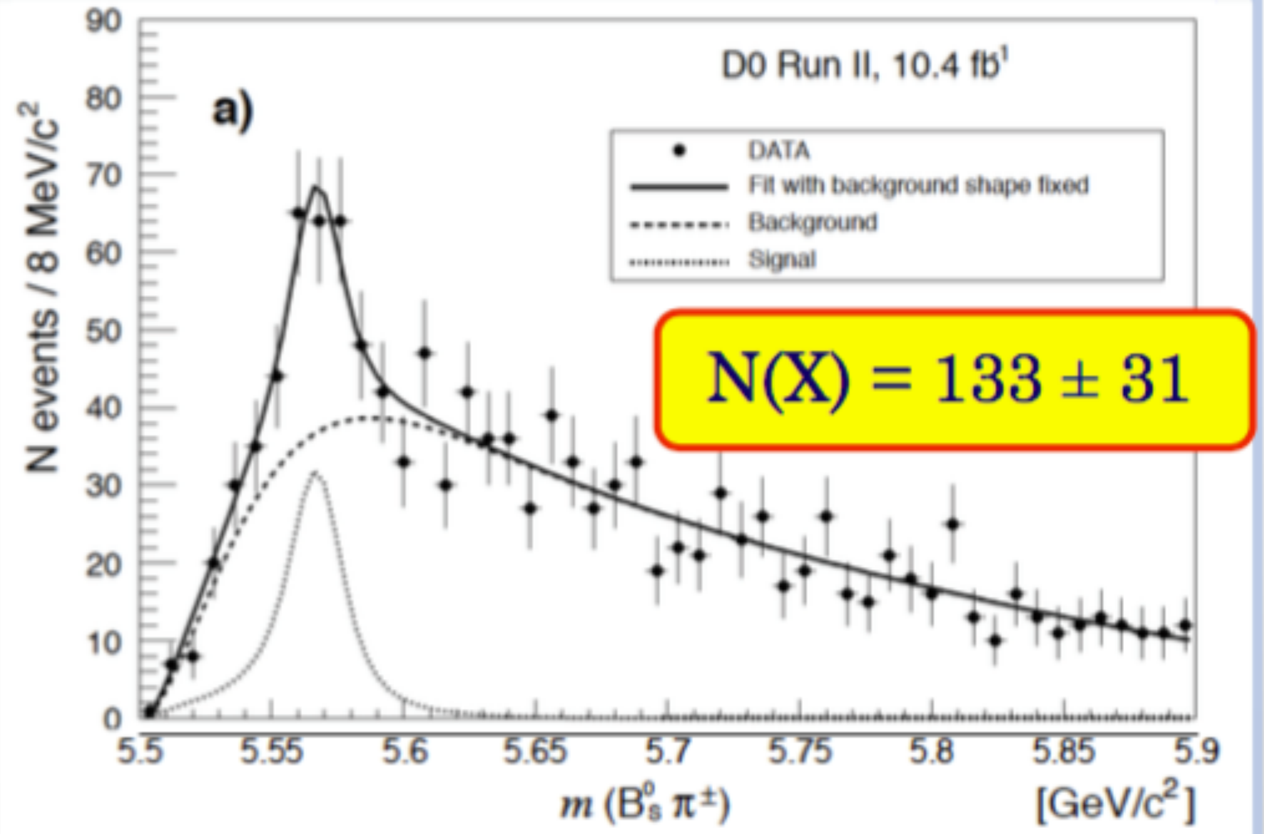
Claimed observation with 5.1 σ significance of an exotic state

✓ $X(5568)\to B_s^0\pi^\pm$, $B_s^0\to J/\psi\,\phi$, $J/\psi\to\mu^+\mu^-$, $\phi\to K^+K^-$

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV}/c^2$$

✓ Fraction of B_s^0 from X decay: $\rho_X^{D\O} = (8.6 \pm 1.9 \pm 1.4)$ %



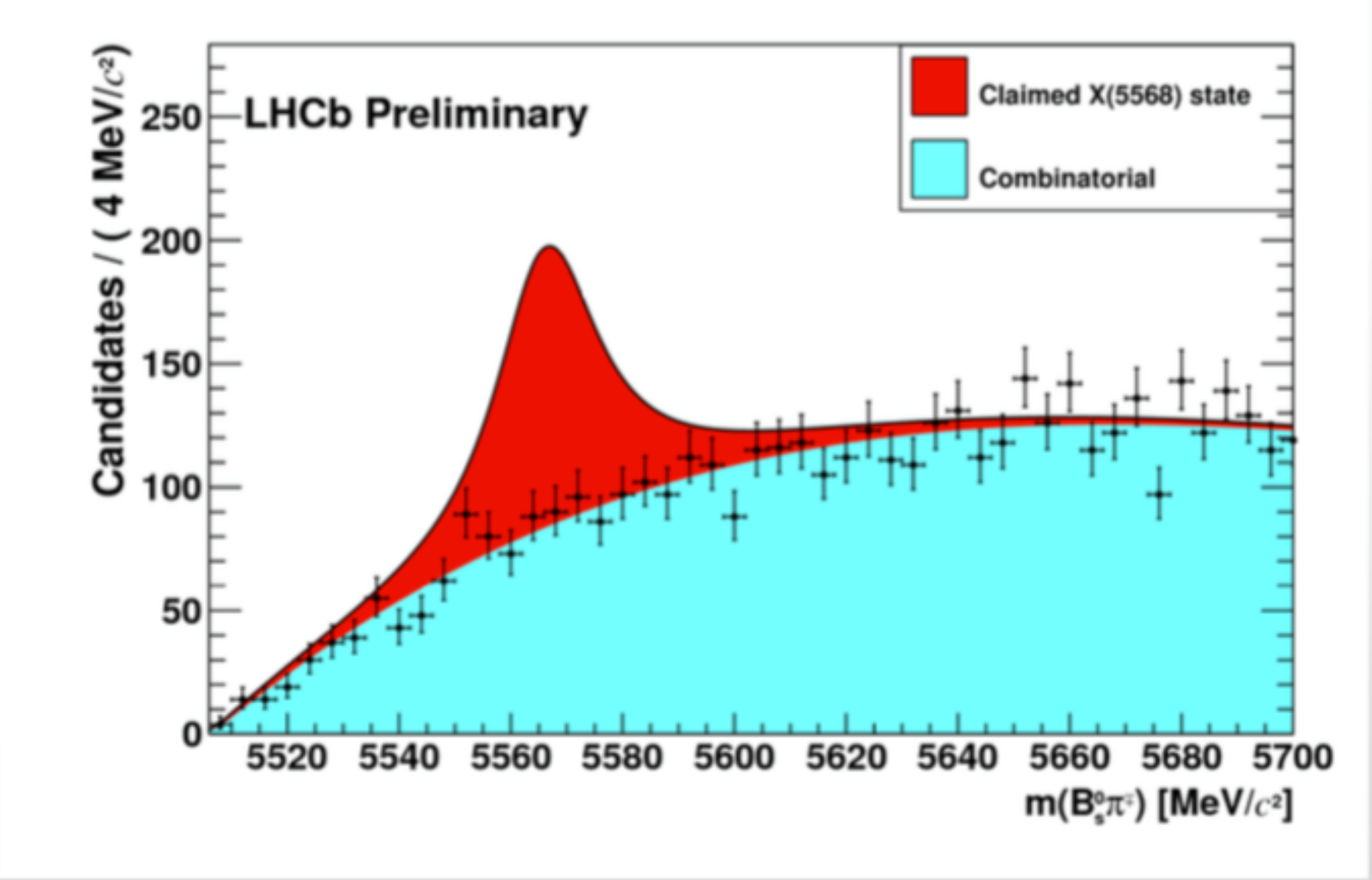


JUST FOR CURIOSITY…

LHCb-CONF-2016-004

If $\rho_X^{\mathrm{LHCb}} = \rho_X^{\mathrm{D\O}} = 8.6\%$, how would the X(5568) signal look like?

(Both modes combined: $p_T(B_s) > 10$ GeV/c)



STRONG INTERACTION FESHBACH PHENOMENON ?

1. Not all meson-meson thresholds correspond to a resonance (loosely bound molecules)

2. Not all 'diquarkonia' manifest in the spectrum.

A FAVOURABLE DETUNING MUST OCCUR

$$\delta \in [0, E_{max}]$$

This might explain why some observed isospin multiplets are incomplete.

- A pure diquarkonium theory predicts

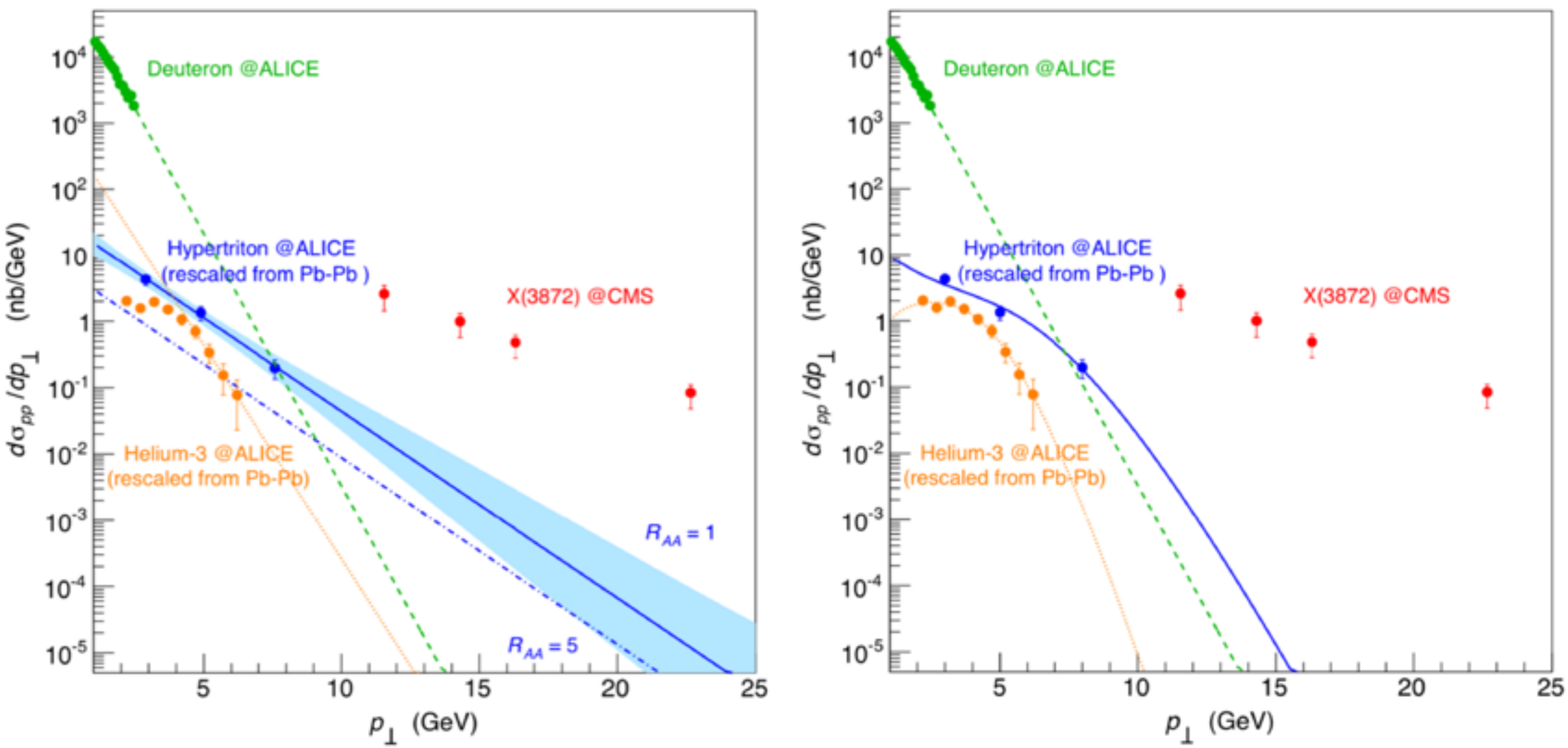
$$X^0, X^+, X^- \text{ @ } 3872 \text{ MeV}$$

(X^+, X^-:) NOT (YET??) SEEN.

- What about X_b?

DATA FROM ALICE

For those who think that we are observing real hadron molecules



Exponential fit — *'Blast wave' fit*

A Esposito et al. PRD 92 (2015) 034028

Diquarks and Exotic Hadrons

Jaffe and Wilczek hep-ph/0307341 (PRL)
Maiani, Piccinini, ADP, Riquer, hep-ph/0412098 (PRD)

DIQUARKS

$$d^{S,A} = q^{\alpha} \Gamma q'^{\beta} \pm q^{\beta} \Gamma q'^{\alpha}$$

BUILD NEW HADRONS WITH

$$S \begin{cases} q \mapsto \bar{d}^{A} \\ \bar{q} \mapsto d^{A} \end{cases}$$

$$\bar{q}\bar{q}\bar{q} \overset{S}{\longmapsto} d^{A}\bar{q}\bar{q} \longrightarrow \underbrace{d^{A}\bar{d}^{A}}$$

TETRAQUARK (charged & neutral!)

$$d^{A}\bar{q}\bar{q} \longrightarrow \underbrace{d^{A}d^{A}\bar{q}}$$

PENTAQUARK

$$d^{A}\bar{q}\bar{q} \longrightarrow \underbrace{d^{A}d^{A}d^{A}}$$

DIBARYON $(B=2)$

DIQUARKONIA

$$\begin{cases} H \simeq 2\, k_{Qq} \cdot \left(\vec{S}_q \cdot \vec{S}_Q + \vec{S}_{\bar{q}} \cdot \vec{S}_{\bar{Q}} \right) \\ \text{the spin of heavy-light diquarks can be 0, 1} \\ \quad \text{and is conserved in strong interactions.} \end{cases}$$

From phenomenology

$$|S_{c\bar{c}}, S_{q\bar{q}}\rangle \quad \begin{cases} Z = \frac{1}{\sqrt{2}} \left(|1,0\rangle - |0,1\rangle \right) \\ Z' = \frac{1}{\sqrt{2}} \left(|1,0\rangle + |0,1\rangle \right) \end{cases}$$

$$C = (-)^{L + S_{q\bar{q}} + S_{c\bar{c}}}$$

which in the diquarkonium basis

$$|S_{cq}, S_{\bar{c}\bar{q}}\rangle \quad \begin{cases} Z = \frac{1}{\sqrt{2}} \left(|1,0\rangle - |0,1\rangle \right) \\ Z' = |1,1\rangle_{1=J} \qquad C = (-)^J \end{cases}$$

$$X = \frac{1}{\sqrt{2}} \left(|1,0\rangle + |0,1\rangle \right) \qquad 1^{++}$$

DIQUARKONIA

$$(H)^{1+-} = \begin{vmatrix} -k & 0 \\ 0 & k \end{vmatrix} + 2m_{[Qq]}\mathbb{1} \rightarrow M_{Z'} - M_Z = 2k$$

$$M_Z + M_{Z'} = 4m_{[Qq]}$$

$$(H)^{1++} = -k + 2m_{[Qq]}\mathbb{1} \rightarrow M_Z \simeq M_X$$

Therefore

$$m_{[bq]} \simeq 5315 \text{ MeV}$$

$$\kappa_{bq} \simeq 22.5 \text{ MeV}$$

and for the DØ state $[\bar{b}\bar{q}][sq']$ in $B_s\pi$

$$M = m_{[bq]} + m_{[sq]} + 2\kappa_{bq}\vec{S}_{\bar{b}}\cdot\vec{S}_{\bar{q}} + 2\kappa_{sq}\vec{S}_s\cdot\vec{S}_{q'}$$

$$= m_{[bq]} + (m_{[sq]} - 3/2\,\kappa_{sq}) - 3/2\,\kappa_{bq}$$

$$\simeq 5771 \text{ MeV (vs 5568 observed)}$$

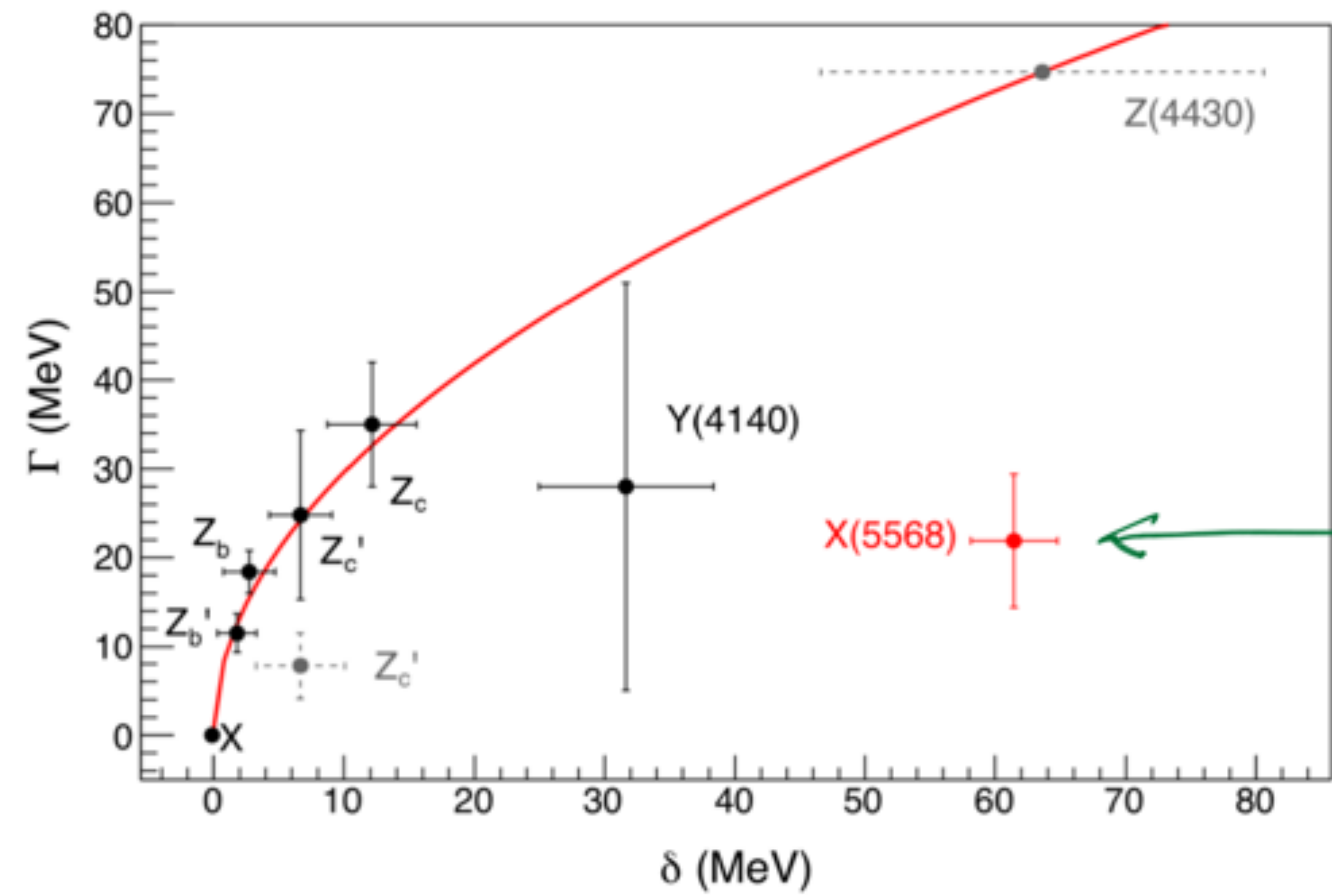
too large detuning δ wrt Γ_{exp}

16/05/16

4qggi

'$\sqrt{\delta}$ - LAW'

A. ESPOSITO, A. PILLONI, ADP 1603.07667 (PLB)



← THE DIQUARK. LEVEL E_0 CAN BE COMPUTED

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$X(5.568)$ $B_s^0 \pi^+$

FEB 2016

DIQUARKONIA

$$(H)^{1^{+-}} = \begin{vmatrix} -k & 0 \\ 0 & k \end{vmatrix} + 2m_{[Qq]}\mathbb{1} \rightarrow M_{Z'} - M_Z = 2k$$

$$M_Z + M_{Z'} = 4m_{[Qq]}$$

$$(H)^{1^{++}} = -k + 2m_{[Qq]}\mathbb{1} \rightarrow M_Z \simeq M_X$$

$$(H)^{2^{++}} = k$$

$$(H)^{0^{++}} = -3k$$

$$(H)^{0^{++\prime}} = k$$

more diquarkonia ... but no good matches in the 'P-channel'

Pentaquarks

based on 1507.04980 with L. Maiani and V. Riquer (Sapienza U.)

THE PENTAQUARK

Highly undesirable option for molecules (before discovery)
Perfect molecule (after discovery)

LHCb 2015

$$\Lambda_b(bud) \to K^- \mathbb{P}^+$$
$$\hookrightarrow J/\psi\, p$$

$$\mathbb{P}^+ = \bar{c}\, c\, u\, u\, d \Rightarrow \text{negative parity}$$

TWO STATES OBSERVED

$$J^P = 3/2^- \quad @ \quad 4380 \text{ MeV}$$

$$J^P = 5/2^+ \quad @ \quad 4550 \text{ MeV}$$

$L=0$ & $L=1$ Pentaquarks?

Note: Lower baryons have $P=+$ / pentaq. have $P=-$!
Lower mesons have $P=-$ / tetraq. have $P=+$

MASS DIFFERENCE

ISN'T $\Delta M = 170$ MeV too SMALL for one unit of L?

($\Delta M = 300$ MeV for $\Lambda(1405) - \Lambda(1116)$)

On the other hand, from $\Sigma_c - \Lambda_c$ we find

$$M_{[qq']_{S=1}} - M_{[qq']_{S=0}} \simeq 200\,\text{MeV}$$

So

$$\mathbb{P}(3/2^-) = \bar{c}\,[cq]_{S=1}\,[q'q'']_{S=1} \quad @\, L=0$$

$$\mathbb{P}(5/2^+) = \bar{c}\,[cq]_{S=1}\,[q'q'']_{S=0} \quad @\, L=1$$

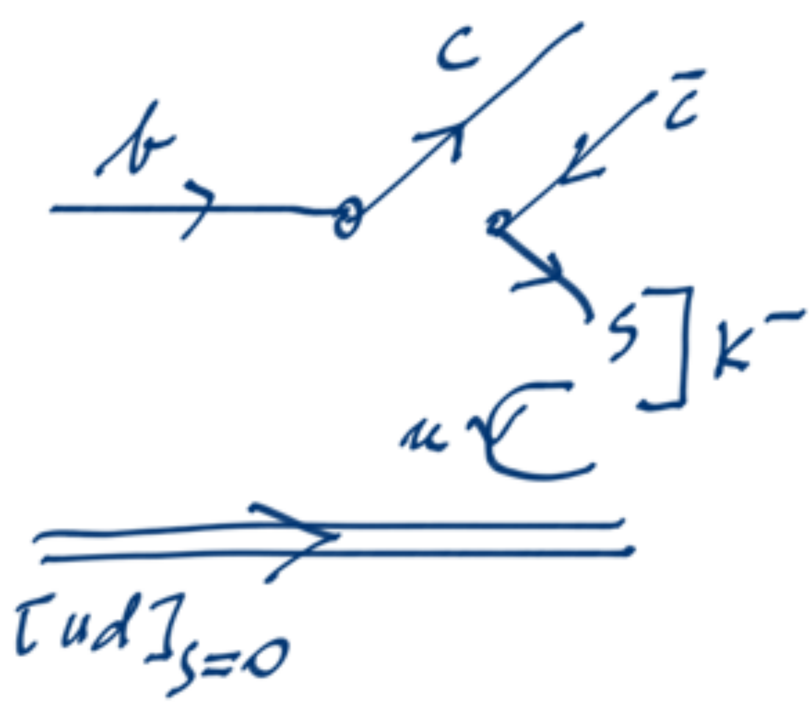
... combine diquark spin & orbital angular momentum -

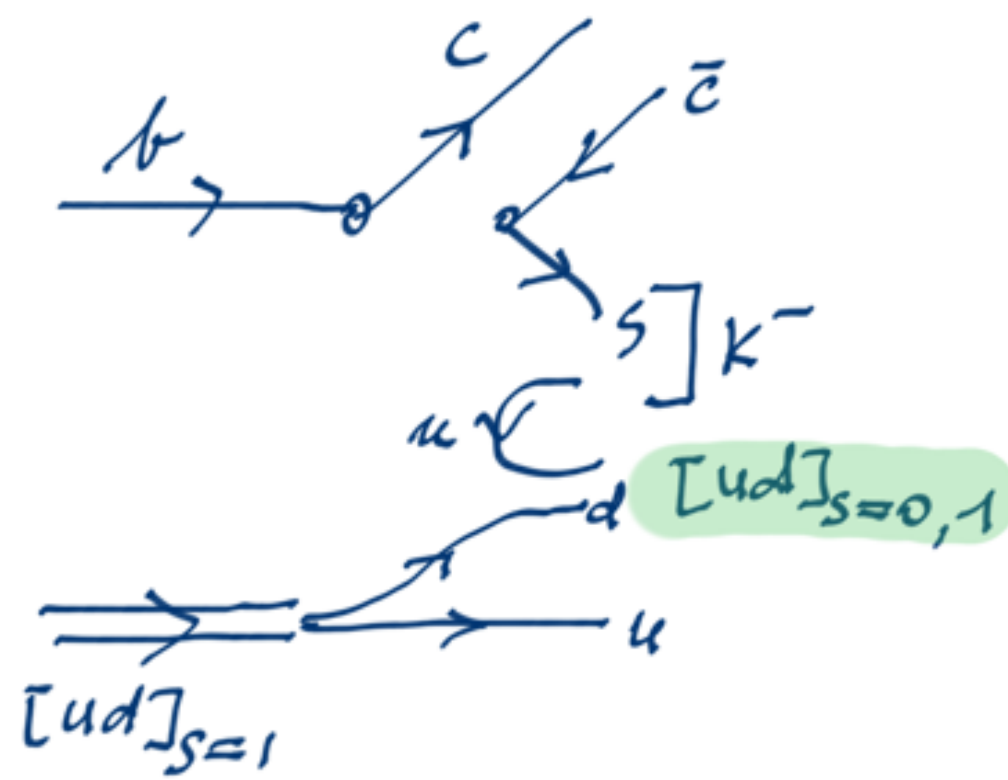
Other states?

L Maiani, ADP, V Riquer, PRD 749 (2015) 289; PLB 750 (2015) 37

$\Lambda \to K^- P^+$

Λ_b baryon might contain a $[ud]_{S=0}$, "good" diquark.
But $P(3/2^-)$ should contain $[ud]_{S=1}$, whereas $P(5/2^+)$ has $[ud]_{S=0}$.





One can show that both pentaquarks have $S_{c\bar{c}} = 1$ so that HQ spin cons. allows decay into J/ψ.

L Maiani, ADP, V Riquer, PRD 749 (2015) 289; PLB 750 (2015) 37

Flavor

$$\langle \mathbb{P}, M \,|\, H_w(\Delta I=0, \Delta S=-1) \,|\, \Lambda_b \rangle$$

$\mathbf{8}_f$ $\quad$ $\mathbf{3}_f$ (from s, d, u) $\quad$ $\bar{\mathbf{3}}_f$ (from [ud])

therefore $\mathbb{P}$ is either 8 or 10 (*)

We might expect

$$\Lambda_b \to \pi \, \mathbb{P}_{10}^{S=-1} \to \pi \, J/\psi \, \Sigma(1385)$$

$$\Lambda_b \to K \, \mathbb{P}_{10}^{S=-2} \to K \, J/\psi \, \Xi(1530)$$

or even

$$\Omega_b \to \phi \, \mathbb{P}_{10}^{S=-3} \to \phi \, J/\psi \, \Omega^-(1672)$$

(*) $\begin{cases} 8 \otimes 10 = 8 \oplus 10 \oplus 27 \oplus 35 \\ 8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus \overline{10} \oplus 27 \end{cases}$

Large N and tetraquarks

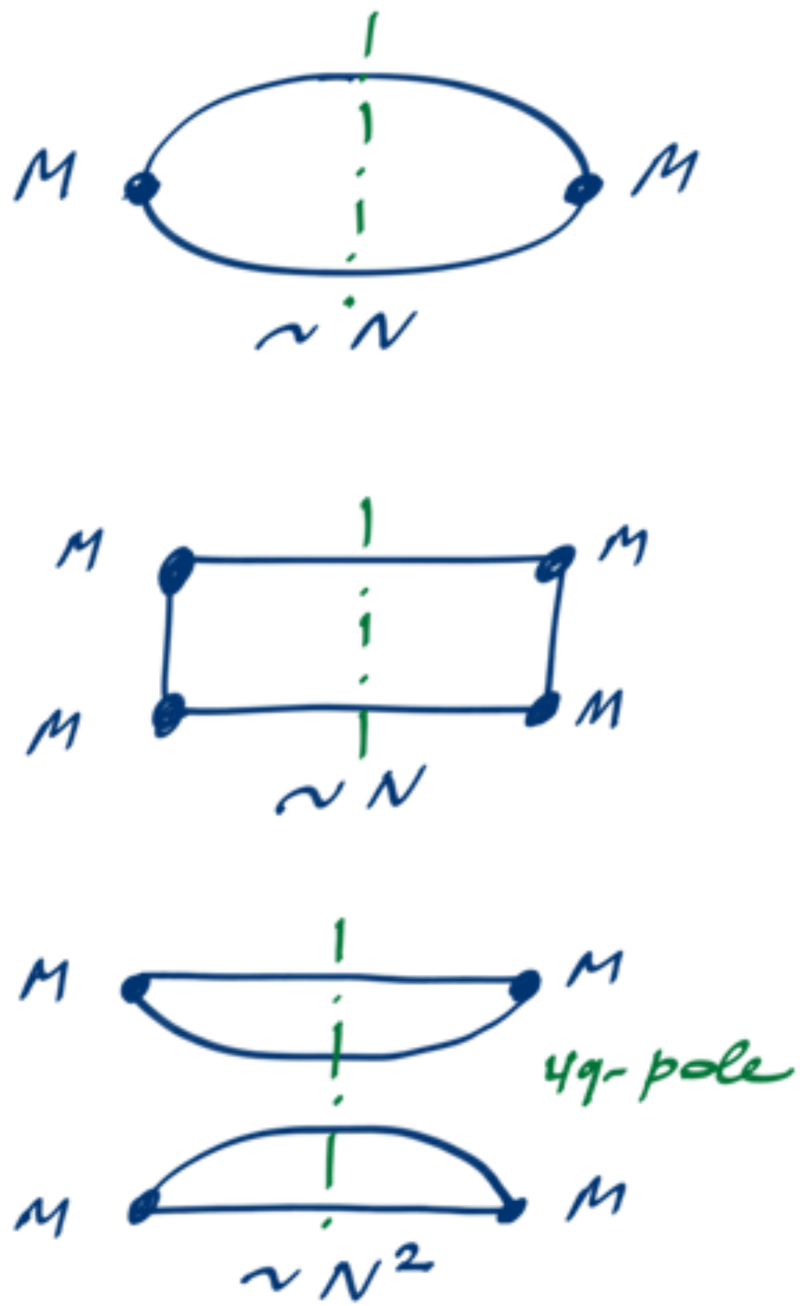
based on 1605.04839 with L. Maiani and V. Riquer

see G. Rossi and G. Veneziano 1605.04285 for an alternative approach

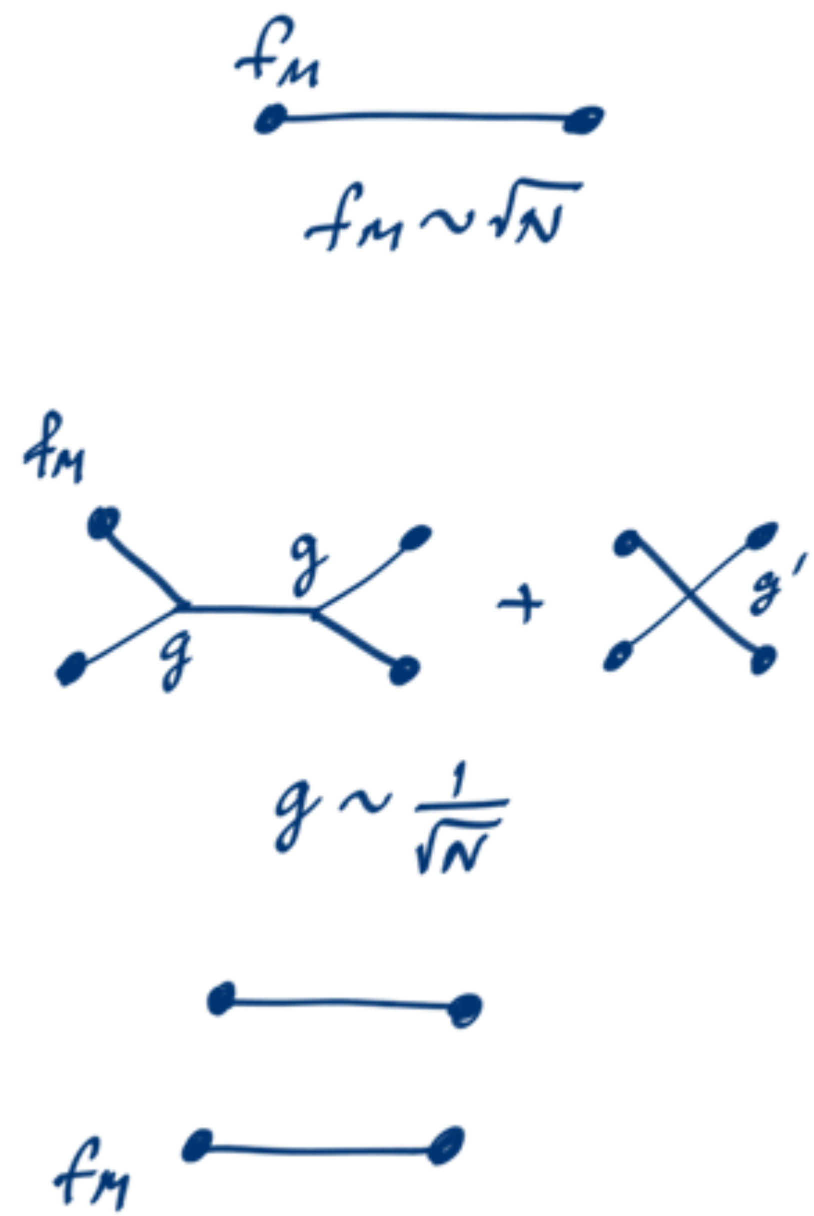
Large N - QCD & Tetraquarks

Reputation of tetraquarks obscured by some considerations by Witten and Coleman (Witten Nucl. Phys. B160 (1979))

Quark theory



Meson theory



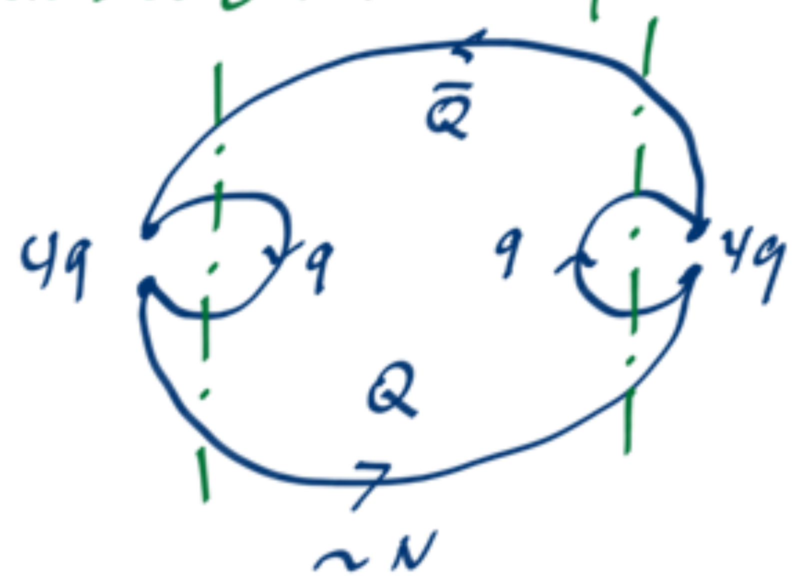
Large N - QCD & Tetraquarks

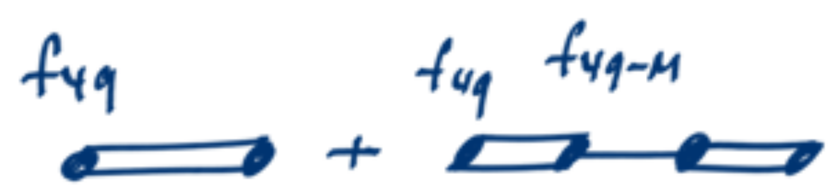
IF TETRAQUARKS DEVELOP A POLE, IT WILL BE IRRELEVANT IF THE RESIDUE IS OF ORDER $1/N$ WRT DISCONNECTED PARTS.

[S. Weinberg PRL 2013]

MOREOVER THE WIDTH $\Gamma_{4q} \sim 1/N$.

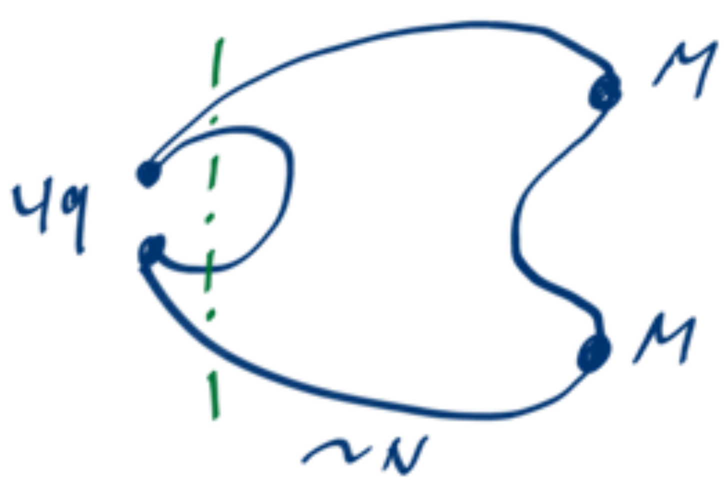
Consider the case of neutral tetraquarks

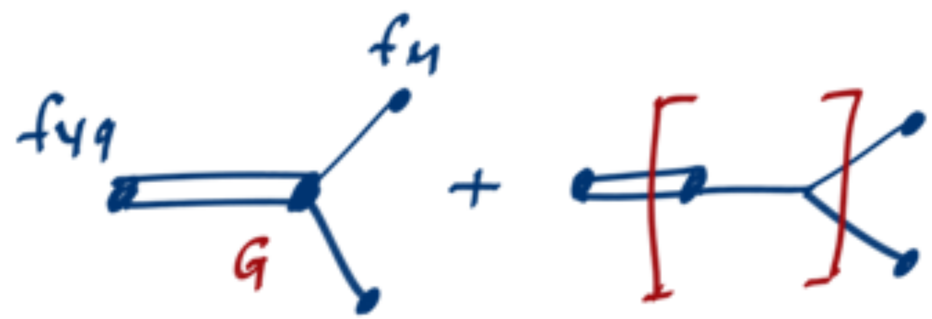




$f_{4q} \sim \sqrt{N}$

$f_{4q\text{-}M} \sim N^0$



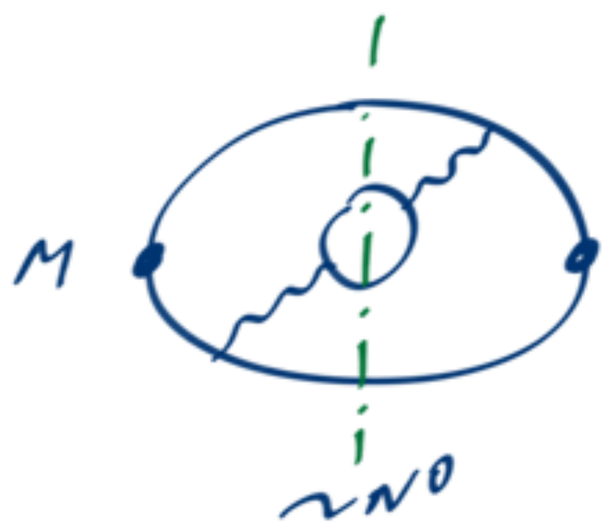


$G \sim \frac{1}{\sqrt{N}}$

$G \sim N^0 \cdot \frac{1}{\sqrt{N}}$

Large N - QCD & Tetraquarks

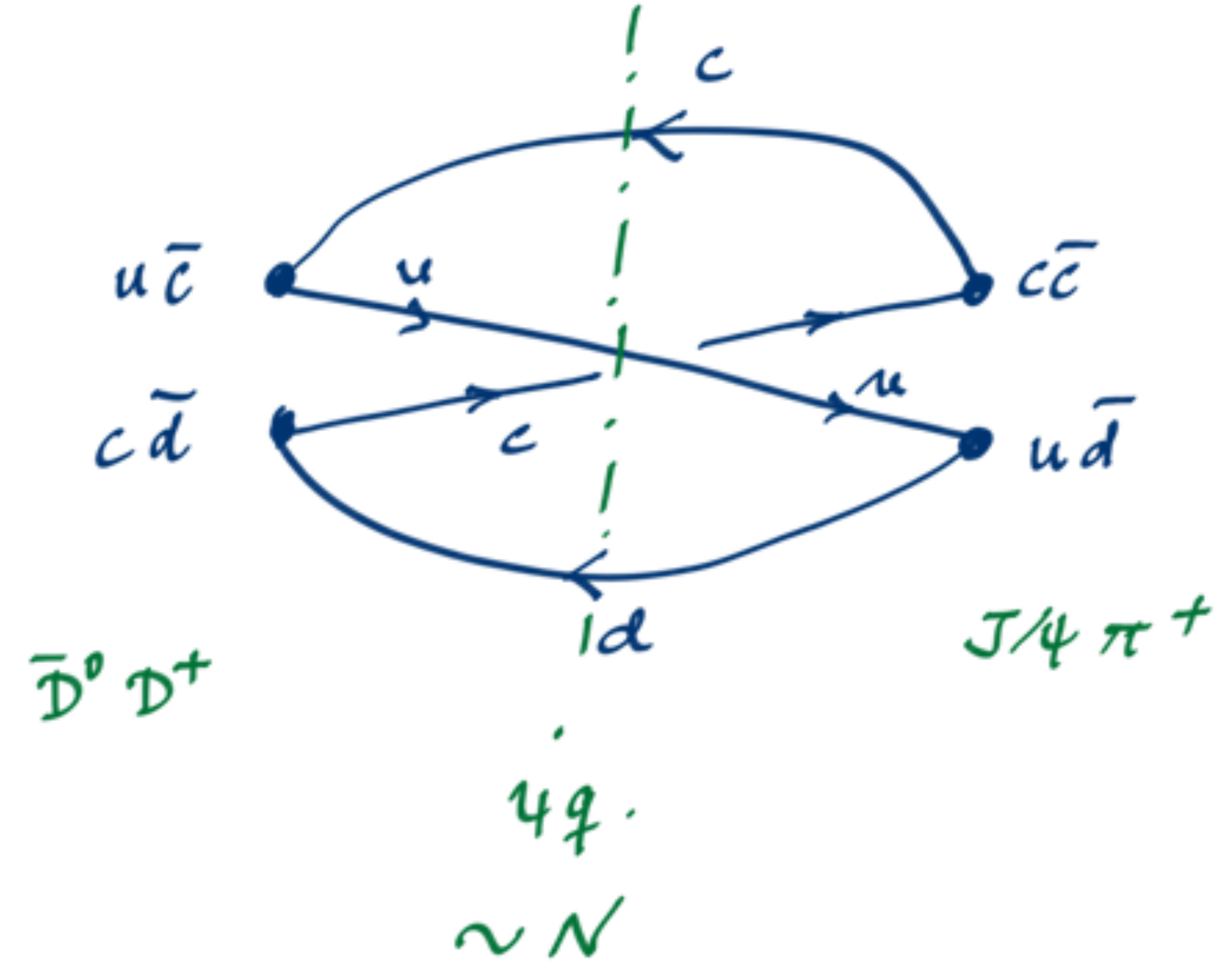
1. Aren't those cuts equivalently leading to Witten's argument?
2. Why the mixing should appear at a different N order in different diagrams?



$$f_{M-4q} \sim \frac{1}{\sqrt{N}}$$

Large N - QCD & Tetraquarks

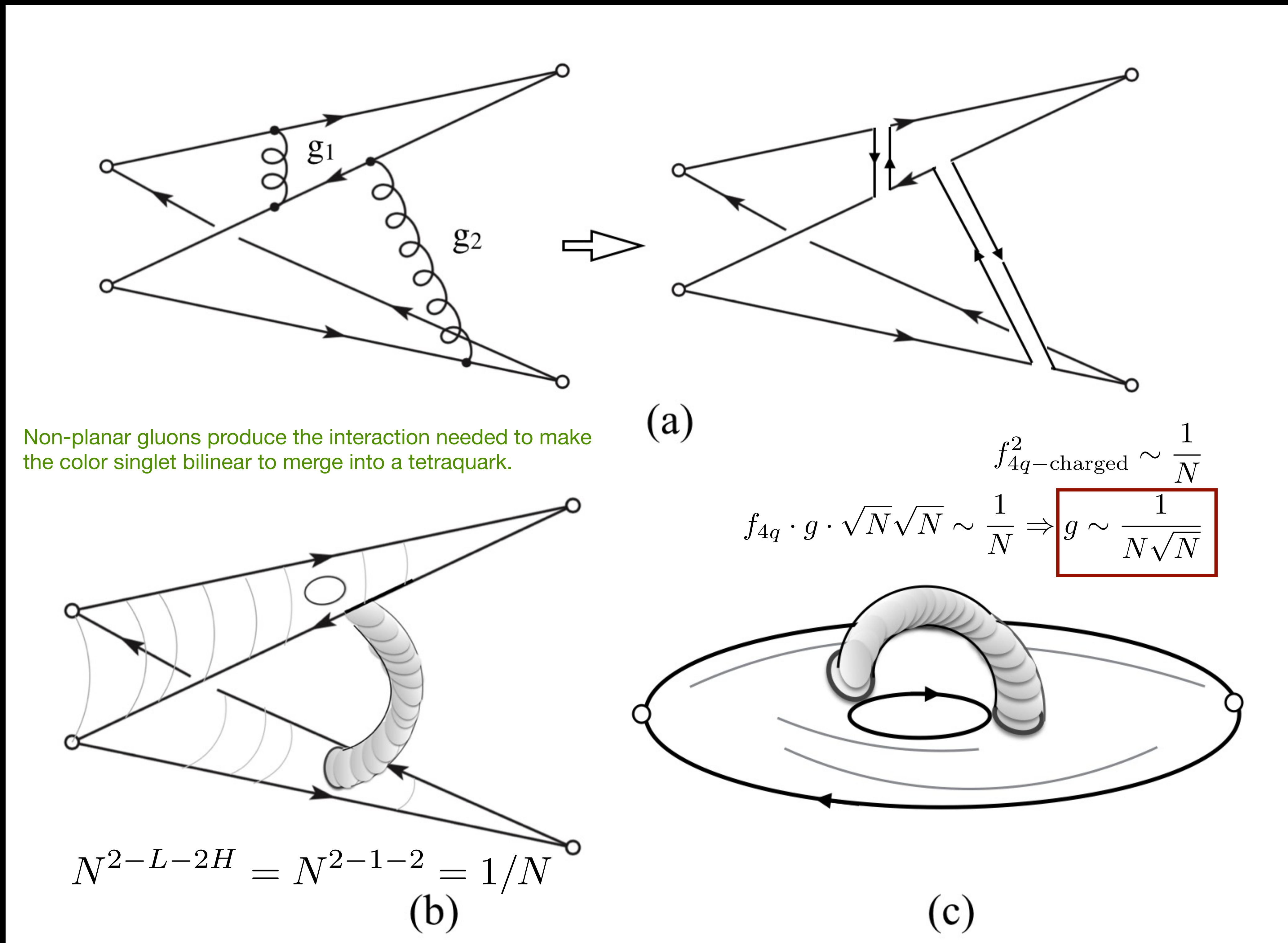
Consider a <u>charged</u> tetraquark corr. funct.



Can be 'untwisted': does it really contain a tetraquark pole?

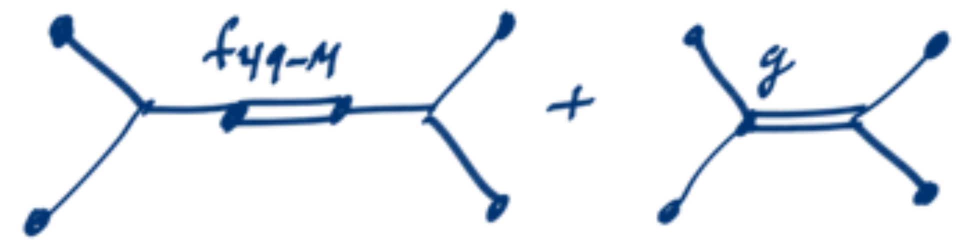
ONE CAN SHOW THAT DIQUARKONIA GIVE THE RIGHT DESCRIPTION OF THE INTERMEDIATE 4q-STATE!

Non-planar diagrams



Large N - QCD & Tetraquarks

$$\sim \frac{1}{N^2} \left(\equiv \frac{N}{(\sqrt{N})^6} \right)$$

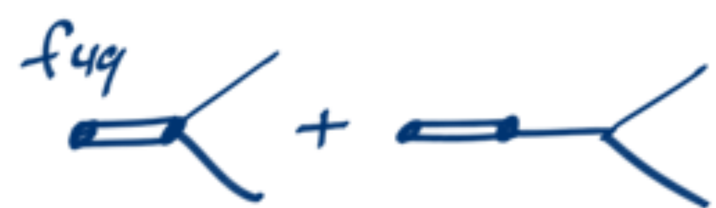


$$g \sim \frac{1}{N^2}$$

$$f_{4q-M} \sim \frac{1}{N\sqrt{N}}$$

$$\sim \frac{1}{N^2}$$

$$\sim \frac{1}{N} \left(\equiv \frac{N}{(\sqrt{N})^4} \right)$$



$$f_{4q} \sim N^0$$

SUMMARY

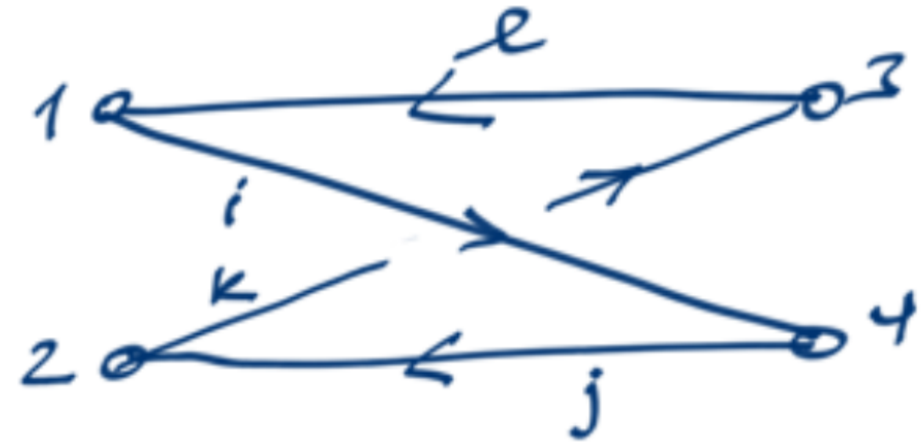
About 20 (exotic) resonances have been discovered

1. Some have complete I-multiplets, some do not
2. Most of them close to M-M thresholds (above!)
3. Diquarks predict charged states & pentaquarks –
   But need complete I-multiplets.
   Several quantum numbers predicted $0^{--}, 2^{++}$...
4. Very similar problems with loosely bound molecules.

– A FESHBACH PHENOMENON AT WORK IN STRONG INTERACTIONS?

Combining diquarkonia predictions and threshold positions, a new picture might emerge –

Backup



$$(\Gamma_1)_{il}\,(\Gamma_4^+)_{ji}\,(\Gamma_2)_{kj}\,(\Gamma_3^+)_{lk} = \langle \Gamma_1 \Gamma_3^+ \Gamma_2 \Gamma_4^+ \rangle$$

(spin matrices : $\sigma^2, \sigma^2\sigma^a$)

	$\bar{D}^0 (D^{*+})^b$	$D^+ (\bar{D}^{*0})^b$	$(\bar{D}^{*0} \wedge D^{*+})^b$
$\eta_c (\rho^+)^a$	1	1	1
$\psi^a \pi^+$	1	1	−1
$(\psi \wedge \rho^+)^a$	1	−1	0

$\cdot \frac{1}{2} \delta^{ab}$

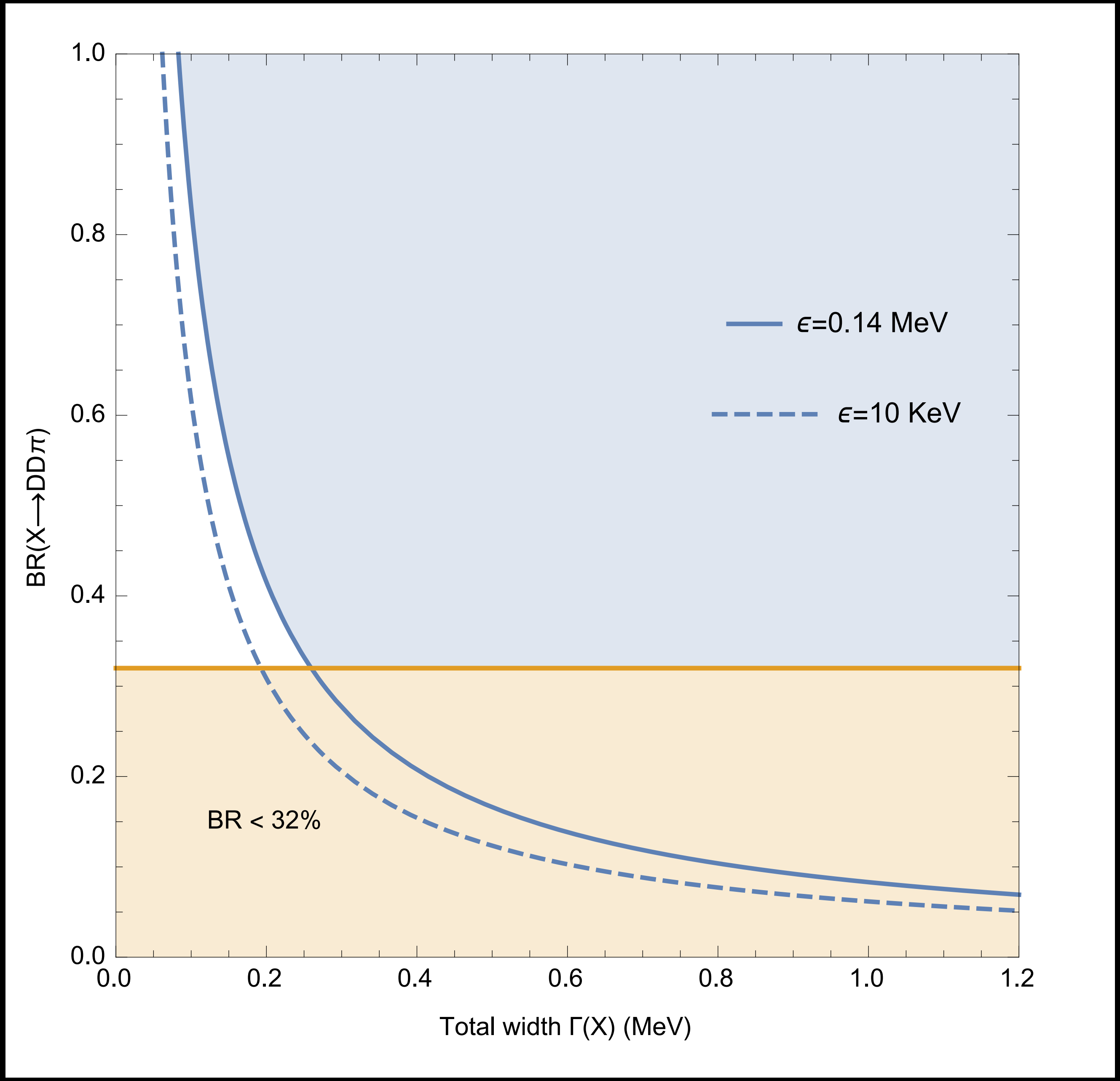
The $J^P = 1^+$, $G = -1$ state corresponds to

$$i\,\frac{(\psi \wedge \rho^+)}{\sqrt{2}} \pm \frac{\bar{D}^0 D^{*+} - D^+ \bar{D}^{*0}}{\sqrt{2}} \qquad (*)$$

Binding energy and decay rates

$$B \simeq \frac{G^4}{512\,\pi^2}\frac{m^5}{(m_a m_b)^4}$$

$$\mathcal{B}(X \to DD\pi)\cdot\Gamma(X) \sim G^2 \sim \sqrt{B}$$



ADP
1505.03083 PLB

CHARGED RESONANCES

LHCb 2014 confirms BELLE 2007 (& disproves Babar 2007)

$$B \longrightarrow K^+ Z^-(4430)$$
$$\hookrightarrow \psi(2S)\pi^-$$

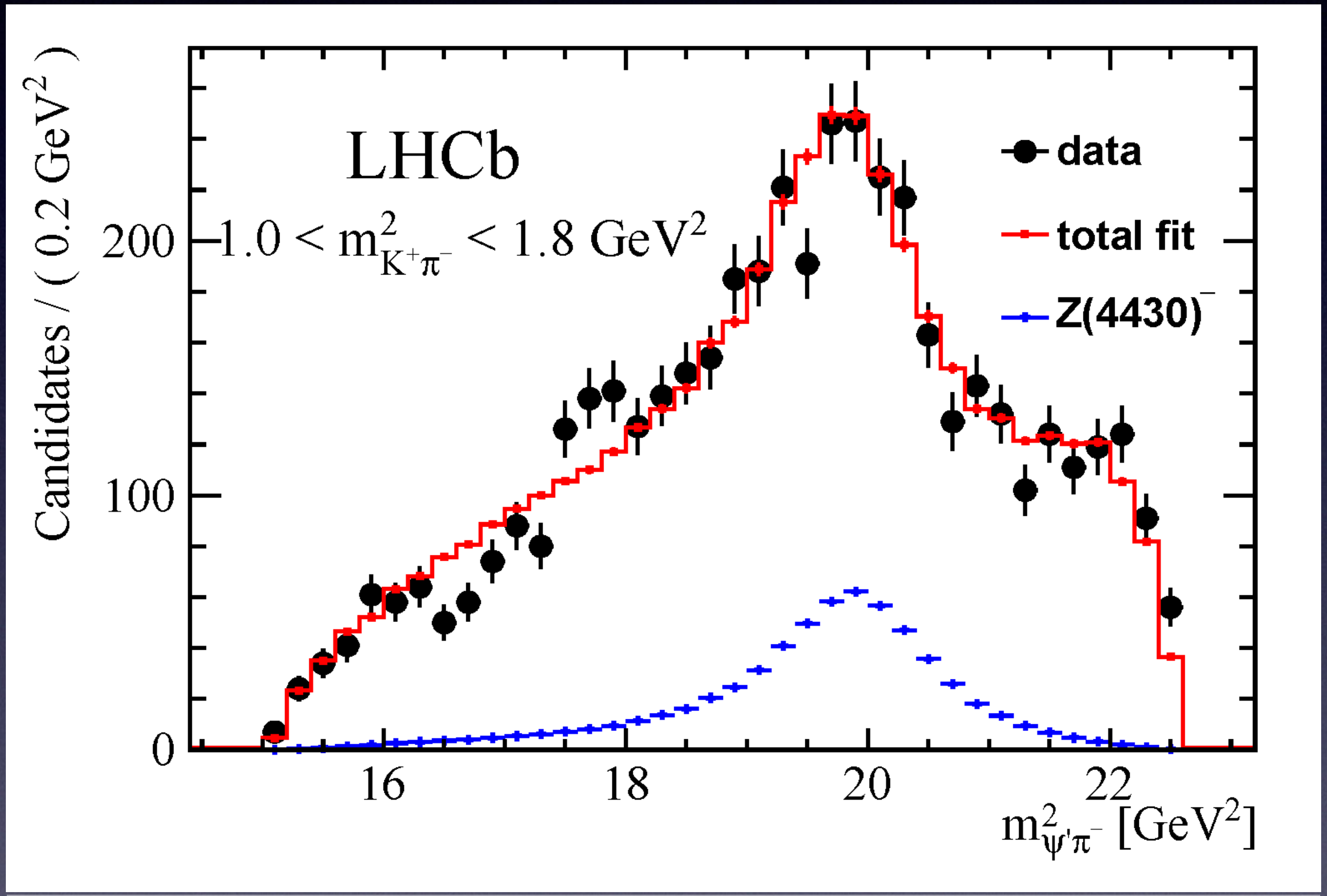
0708.3997 "A CRUCIAL CONSEQUENCE OF Z^- IS A CHARGED STATE IN $J/\psi\,\pi^\pm$ AT 3880 MeV" (Z^- is its radial excitation)

$$M(\psi(2S)) - M(\psi) \simeq M(Z(4430)) - M(Z(3880))$$

BES III FOUND $Z_c(3900)$ IN 2013.

CHARGED RESONANCES HAVE NOT (YET?) BEEN SEARCHED/OBSERVED IN PP PROMPT COLLISIONS.

Z(4430)$^-$ at LHCb | April 2014



$$B \to K^+(\psi(2S)\pi^-)_{J^{PG}=1^{++}}$$

Signal: 13.9 σ

Other assignments ruled out at 9.7σ

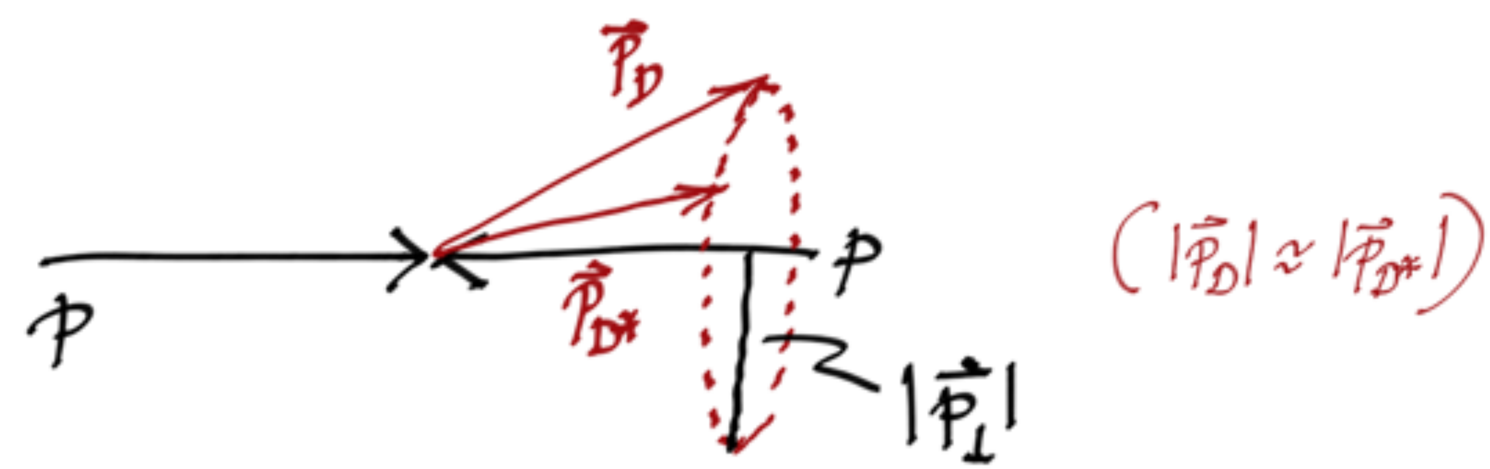
First observed by BELLE in 2007 and not confirmed by BaBar at that time

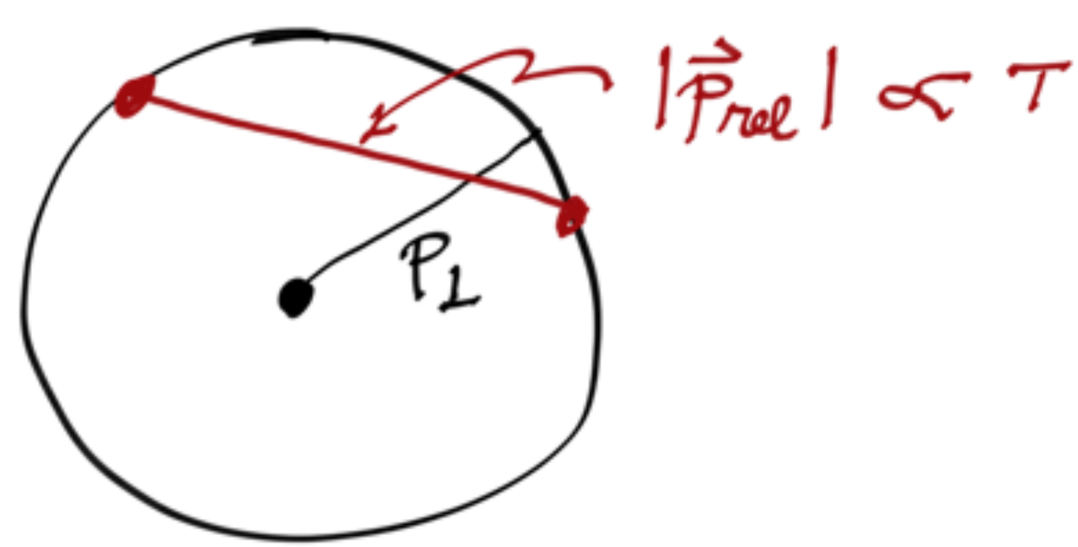
A $D^0 D^{*0}$ MOLECULE?

The previous arguments rely on $T \simeq 0$

What is T (barycentric energy of DD^* after subtraction of rest masses)

in pp collisions at LHC with HIGH $P_\perp$ CUTS?





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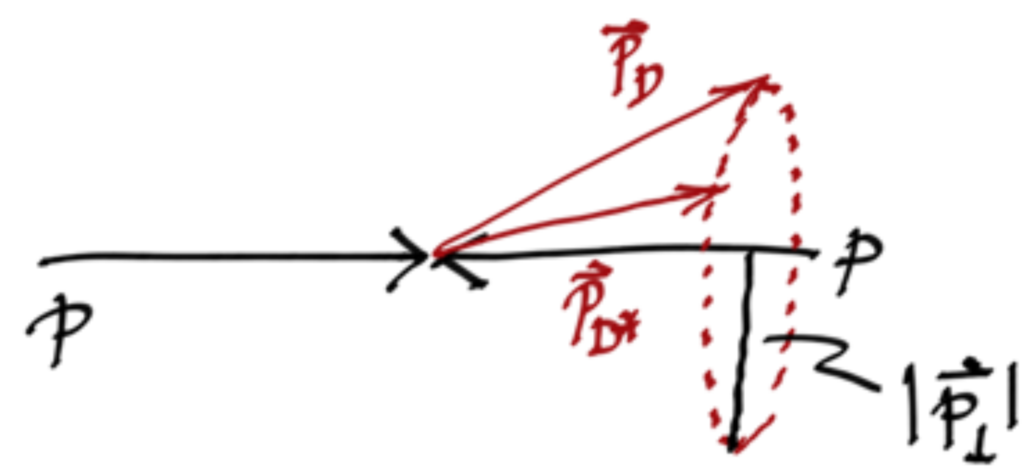
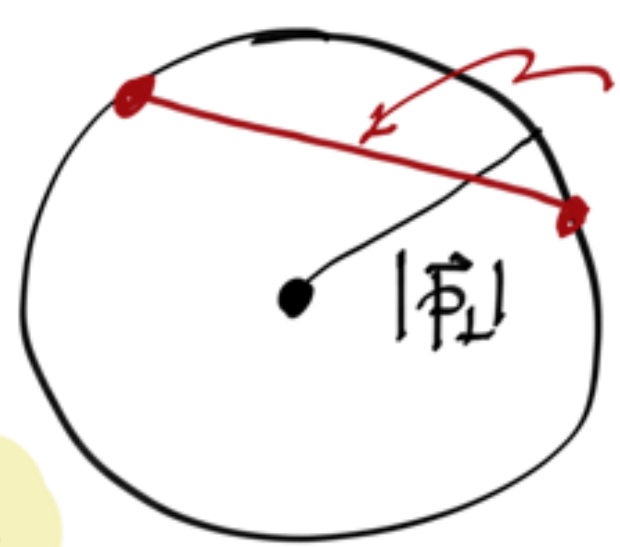


$(|\vec{p}_D| \simeq |\vec{p}_{D^*}|)$

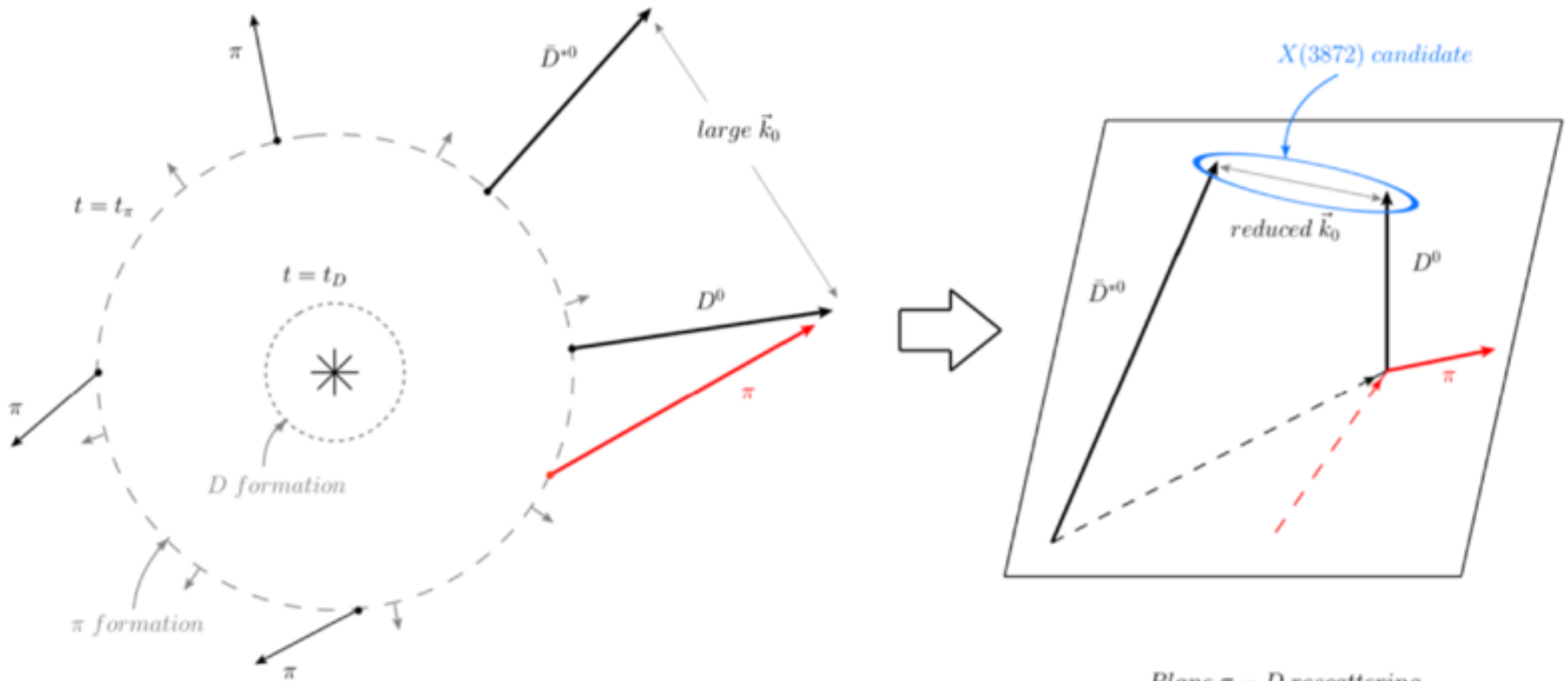
$$\overline{|\vec{p}_{rel}|} = 1.27\, |\vec{p}_\perp|$$



$$P(|\vec{p}_{rel}|) = \frac{1/\pi}{\sqrt{|\vec{p}_\perp|^2 - (|\vec{p}_{rel}|/2)^2}}$$

$$P(\overline{|\vec{p}_{rel}|}) \sim 40\%$$

RESCATTERINGS ?



Expanding hadronization sphere

(a)

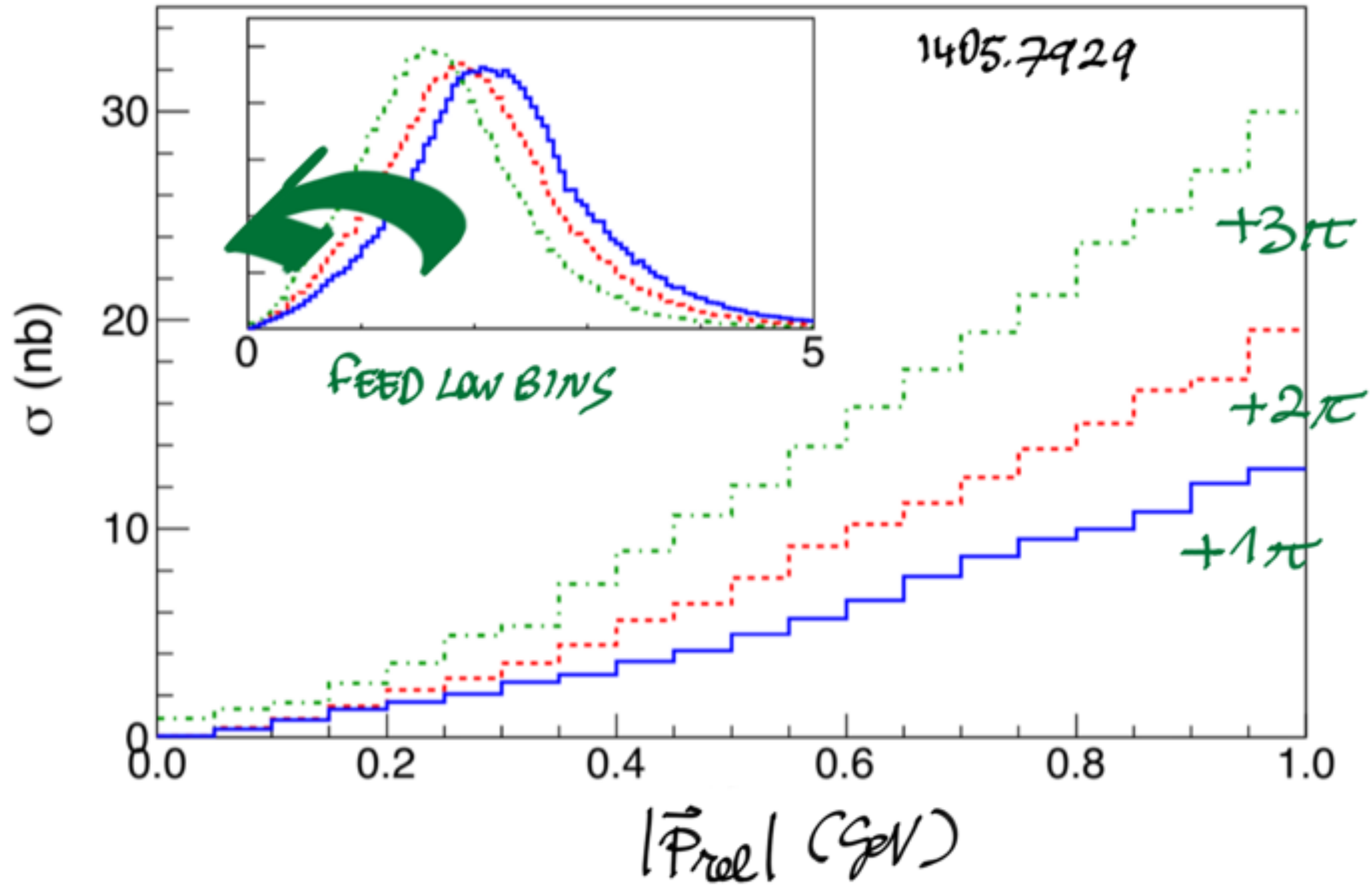
Plane $\pi - D$ rescattering

(b)

RESCATTERINGS WITH HADRONS (π) MIGHT HELP TO DECREASE $|\vec{p}_{rel}|$ IN THE DD^* PAIR

A Esposito et al. J.Mod.Phys. 4 (2013) 1569
A Guerrieri et al. PRD 90 (2014) 034003
C Bignamini et al PRL 103 (2009) 162001

RESCATTERINGS ?



- THE MOST PROBABLE DD^* CONFIGURATIONS HAVE HIGH |$\vec{P}_{rel}$|
- THIS IS MORE AND MORE VISIBLE INCREASING THE CUT IN |$\vec{P}_\perp$|
- THE FEED-DOWN OBTAINED BY RESCATTERING ON 1,2,3 π IS NEGLIGIBLE.