Round Table Discussion on Exotics

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What we understand and what needs to be measured at current and future experiments?

XVIII International Conference on
Hadron Spectroscopy and StructureTheory and Experiment
HADRON 2019
Guilin, China
16-21 August, 2019

The Panel

Theory

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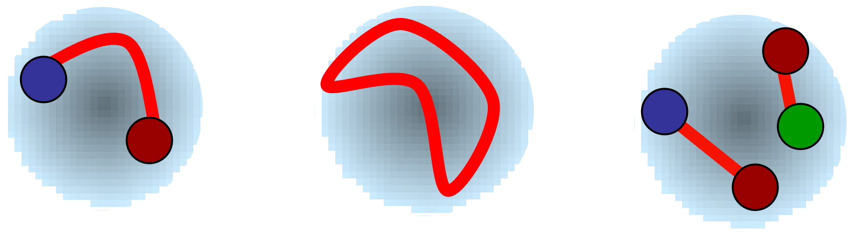
Hadrons beyond the conventional quark model and their signatures

Exotics of Type-I:

J^{PC} are not allowed by $Q\bar{Q}$ configurations, e.g. $0^{--}, 1^{-+}$

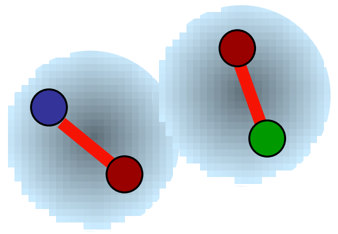
- **Direct observations**



Exotics of Type-II:

J^{PC} are the same as $Q\bar{Q}$ configurations

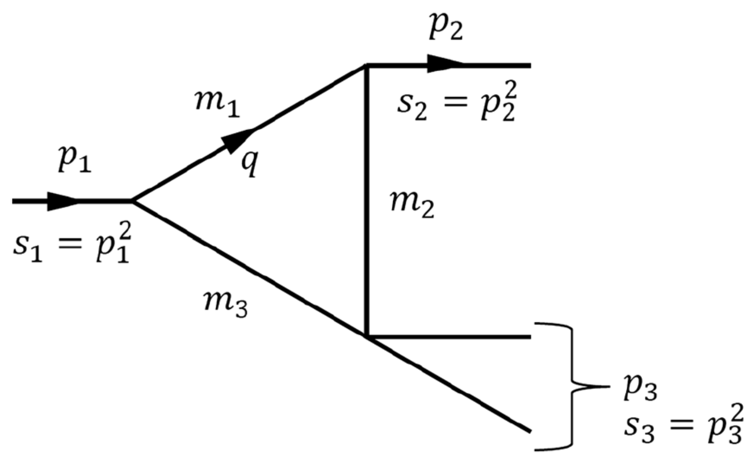
- **Outnumbering of conventional QM states?**
- **Peculiar properties?**



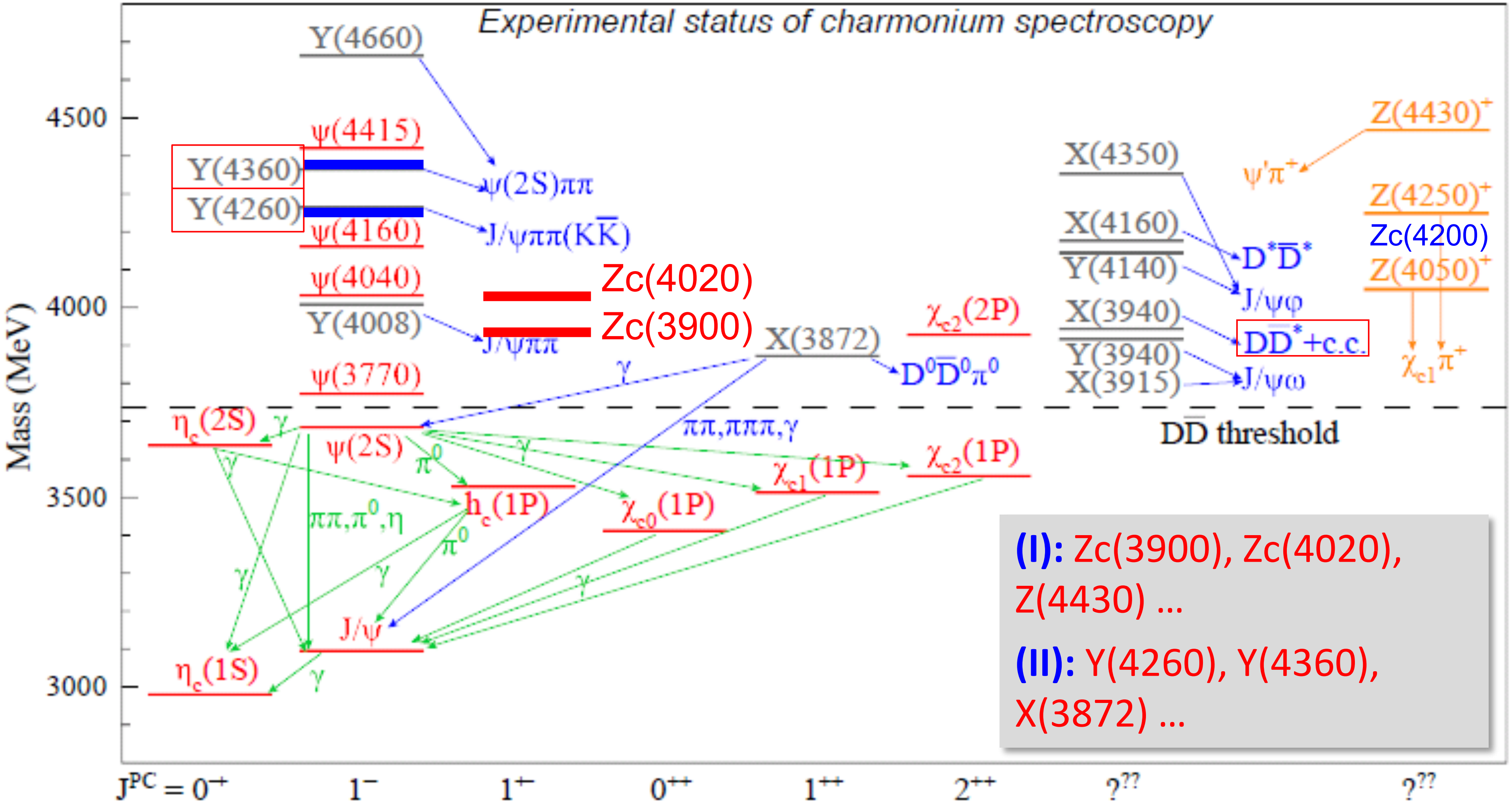
"Exotics" of Type-III:

Leading kinematic singularity can cause measurable effects, e.g. the triangle singularity.

- **What's the impact?**
- **How to distinguish a genuine state from kinematic effects?**



Heavy flavor states: Charmonia and charmonium-like states, i.e. X, Y, Z's.

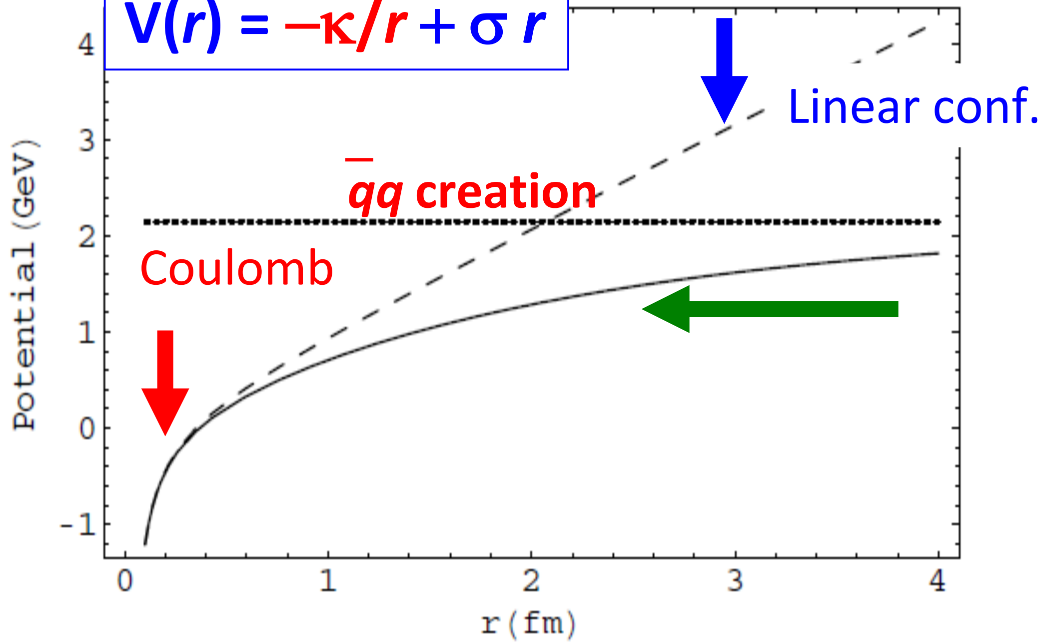


(I): Zc(3900), Zc(4020), Z(4430) …

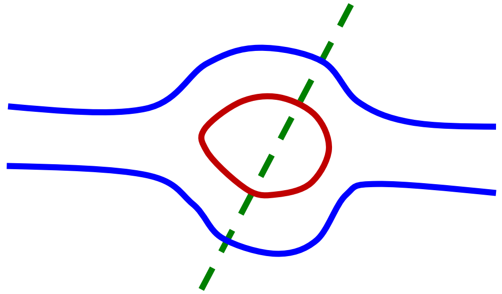
(II): Y(4260), Y(4360), X(3872) …

The minimum input which breaks down the potential QM

$V(r) = -\kappa/r + \sigma r$



- Color screening effects? String breaking effects?



- **The effect of vacuum polarization due to dynamical quark pair creation may be manifested by the strong coupling to open thresholds and compensated by that of the hadron loops, i.e. coupled-channel effects.**

E. Eichten et al., PRD17, 3090 (1987)
E. J. Eichten, K. Lane, and C. Quigg, Phys. Rev. D 69, 094019 (2004)
B.-Q. Li and K.-T. Chao, Phys. Rev. D79, 094004 (2009);
T. Barnes and E. Swanson, Phys.Rev. C77, 055206 (2008)

Features with the charmonium spectrum and some general questions to ask:

1) The states below the open charm thresholds are well described by the potential quark model.

2) There exist apparent deviations of the energy levels from the experimental observations above the open charm thresholds.

-- What causes such a change?

-- If there is a mechanism accounting for such a phenomenon, should it also have impact on the states below thresholds?

-- Which observables could be sensitive to such a mechanism?

3) The signals for charged charmonium states definitely indicate novel phenomena beyond the potential quark model.

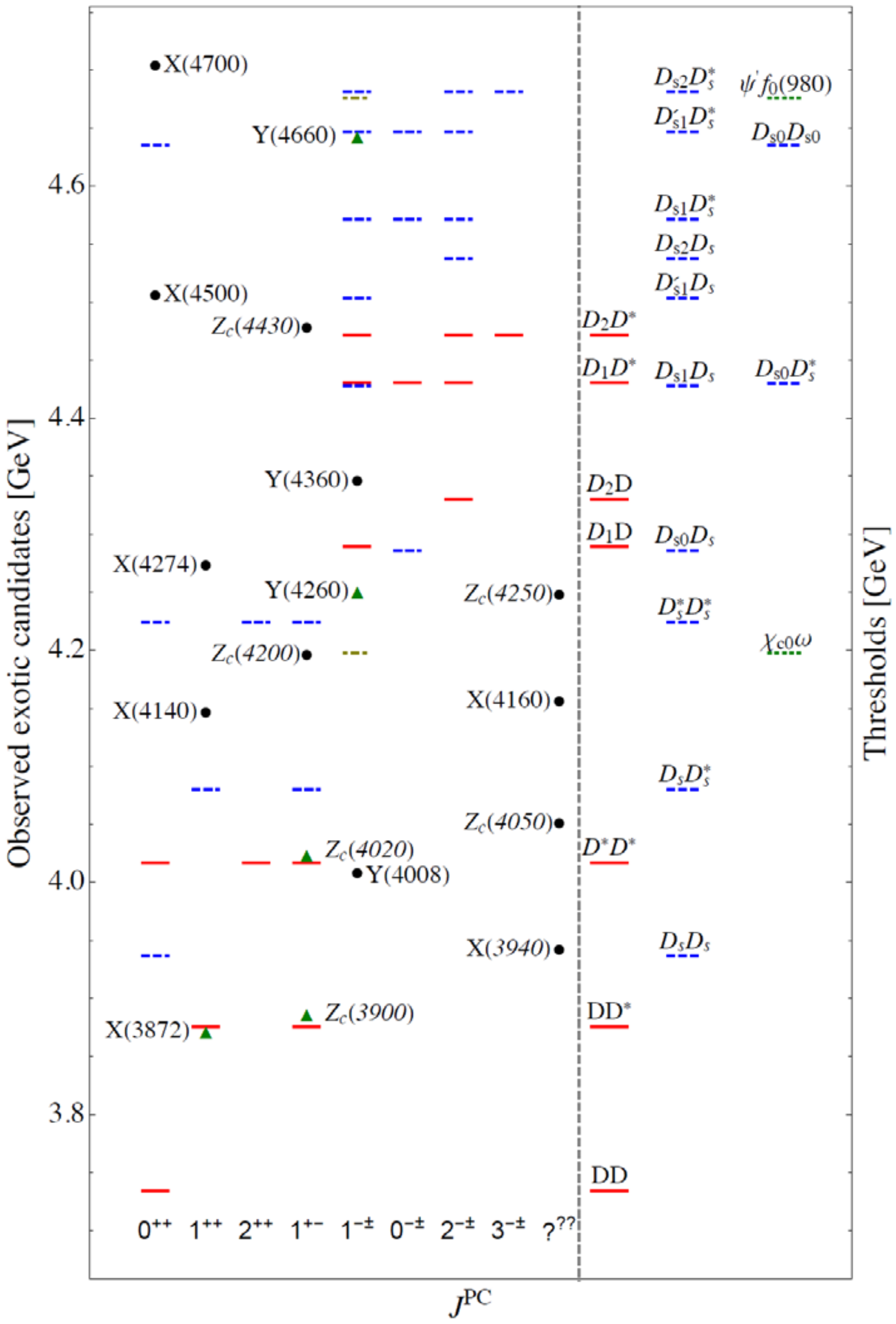
-- What are they?

-- What are the reliable criteria?

Systematic scan over energy regions covering the narrow two-body open thresholds

	$S-wave(L=0)$	$P-wave(L=1)$
PP	$0^{+(\pm)}$	$1^{-(\pm)}$
PV	$1^{+(\pm)}$	$0^{-(\pm)},\ 1^{-(\mp)},\ 2^{-(\pm)}$
VV	$0^{+(+)},\ 1^{+(-)},\ 2^{+(+)}$	$1^{-(+)};$ $0^{-(-)},\ 1^{-(-)},\ 2^{-(-)};$ $1^{-(+)},\ 2^{-(+)},\ 3^{-(+)}$
PA	$1^{-(-)}$	……
VA	$0^{-(\pm)},\ 1^{-(\mp)},\ 2^{-(\pm)}$	……

- The number of states would depend on the interactions between the threshold hadrons.
- So far, the S-wave phenomena is evidence.
- Model-building is required.



Unanswered questions:

- What are the proper effective degrees of freedom for hadron internal structures?
- What are the possible color-singlet hadrons apart from the simplest conventional mesons ($q\bar{q}$) and baryons (qqq)? (e.g. multiquarks, hadronic molecules, hadroquarkonia …)
- What are the proper observables for determining the internal structures for hadrons ?
- What’s happening in between “perturbative” and “non-perturbative”?
- … …

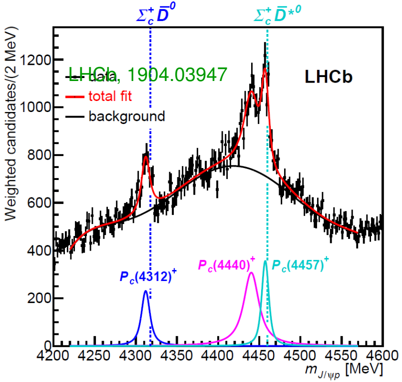
Round table discussion on exotic hadrons

Feng-Kun Guo

Institute of Theoretical Physics, Chinese Academy of Sciences

XIII International Conference on Hadron Spectroscopy and Structure,
Guilin, China, Aug. 16-21, 2019

Issue 1: P_c structures



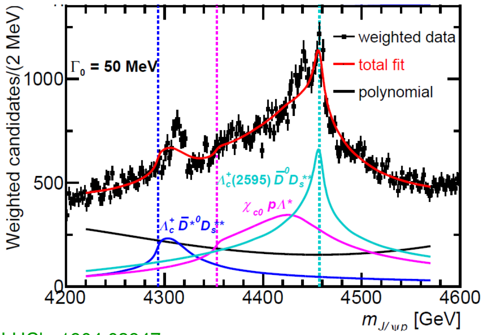
- Lots of XYZ structures (pattern?), whatever they are, likely analogues in the baryon sector
- LHCb discovery: $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$; what are they?
- If $\Sigma_c\bar{D}$ ($J^P = \frac{1}{2}^-$) and $\Sigma_c\bar{D}^*$ ($\frac{1}{2}^-, \frac{3}{2}^-$) molecules, then why are the others not seen? [Generally 7 states were predicted]

  Xiao, Nieves, Oset, 1304.5368; Liu et al., 1903.11560; Sakai et al., 1907.03414; . . .

- Were $P_c(4457)$ due to $\Lambda_c(2595)\bar{D}$ ($\frac{1}{2}^+$) [Burns, Swanson, 1908.03528], should there be $\Lambda_c(2595)\bar{D}^*$ ($\frac{1}{2}^+, \frac{3}{2}^+$) states? Why not seen?
- One way to distinguish the two models for $P_c(4457)$, isospin breaking decays into $J/\psi\Delta$: huge for $\Sigma_c\bar{D}^*$ [FKG et al., 1903.11503; Burns, 1509.02460];

  tiny for $\Lambda_c(2595)\bar{D}$ [Burns, Swanson, 1908.03528]

Issue 2: proper and practical amplitude analysis tools



LHCb, 1904.03947

- Final states contain three or more strongly interacting hadrons, triangle singularities and threshold cusps are around
- Producing peaks in the P_c region,
  FKG et al. (2015); X.-H. Liu et al. (2015); appendix of LHCb, 1904.03947
- and for many other near-threshold structures many related talks in Session 5

- How can one build up a practical amplitude analysis toolbox with such kinematical singularities properly taken into account?
- Essential to establish the hadronic resonance spectrum

Issue 3: the $X(3872)$ mass

PDG2018 average from the $J/\psi\pi\pi$ and $J/\psi\pi\pi\pi$ modes

$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE

INSPIRE search

VALUE (MeV)	EVTS		DOCUMENT ID		TECN	COMMENT
3871.69 ± 0.17	**OUR AVERAGE**					
$3871.9 \pm 0.7 \pm 0.2$	20 ± 5		ABLIKIM	2014	BES3	$e^+ e^- \to J/\psi\pi^+\pi^-\gamma$
$3871.95 \pm 0.48 \pm 0.12$	0.6k		AAIJ	2012H	LHCB	$p\,p \to J/\psi\pi^+\pi^- X$
$3871.85 \pm 0.27 \pm 0.19$	~ 170	1	CHOI	2011	BELL	$B \to K\pi^+\pi^- J/\psi$
$3873\,^{+1.8}_{-1.6} \pm 1.3$	27 ± 8	2	DEL-AMO-SANCH..	2010B	BABR	$B \to \omega J/\psi K$
$3871.61 \pm 0.16 \pm 0.19$	6k	3, 2	AALTONEN	2009AU	CDF2	$p\,\overline{p} \to J/\psi\pi^+\pi^- X$
$3871.4 \pm 0.6 \pm 0.1$	93.4		AUBERT	2008Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
$3868.7 \pm 1.5 \pm 0.4$	9.4		AUBERT	2008Y	BABR	$B^0 \to K^0_S\, J/\psi\pi^+\pi^-$
$3871.8 \pm 3.1 \pm 3.0$	522	4, 2	ABAZOV	2004F	D0	$p\,\overline{p} \to J/\psi\pi^+\pi^- X$

PDG AVERAGE: $M_{D^0} = (1864.834 \pm 0.05)$ MeV, $M_{D^{*0}} = (2006.85 \pm 0.05)$ MeV

The most near-threshold hadron: $M_{D^0} + M_{D^{*0}} - M_{X(3872)} = (0.00 \pm 0.18)$ MeV

Why is that??? Is the $X(3872)$ below, above or exactly at the $D^0\bar{D}^{*0}$ threshold?

Issue 3: the $X(3872)$ mass

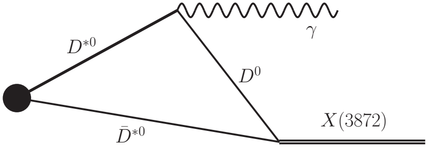
$\delta \equiv M_{D^0} + M_{D^{*0}} - M_{X(3872)}$ measurable via a triangle singularity (TS) FKG, arXiv:1902.11221

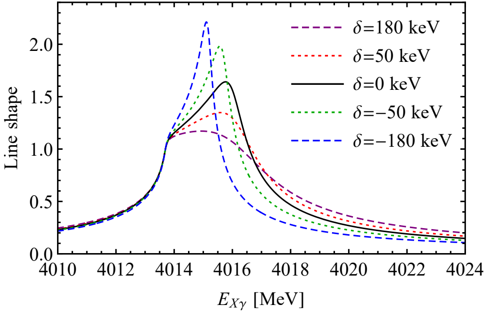
- Short-distance $D^{*0}\bar{D}^{*0}$ source with $J^{PC} = 1^{+-}$
- TS for the $X\gamma$ invariant mass:

$$E_{X\gamma}^{\text{TS}} \simeq 2M_{D^{*0}} + \frac{\left(M_{D^{*0}} - M_{D^0} - 2\sqrt{-M_{D^0}\delta} + \delta\right)^2}{2M_{D^0}}$$

$\Rightarrow$ TS in $E_{X\gamma}$ at around the $D^{*0}\bar{D}^{*0}$ threshold

- To measure the $X(3872)\gamma$ line shape
- Precision may be improved by one order of magnitude
- Experiments:
  $\overline{\text{P}}$ANDA [$p\bar{p} \to D^{*0}\bar{D}^{*0} \to X\gamma$],
  STCF [$e^+e^- \to D^{*0}\bar{D}^{*0}\pi^0 \to X\gamma\pi^0$],
  LHCb, Belle-II





THANK YOU FOR YOUR ATTENTION!

Backup slides

Sensitivity study (1)

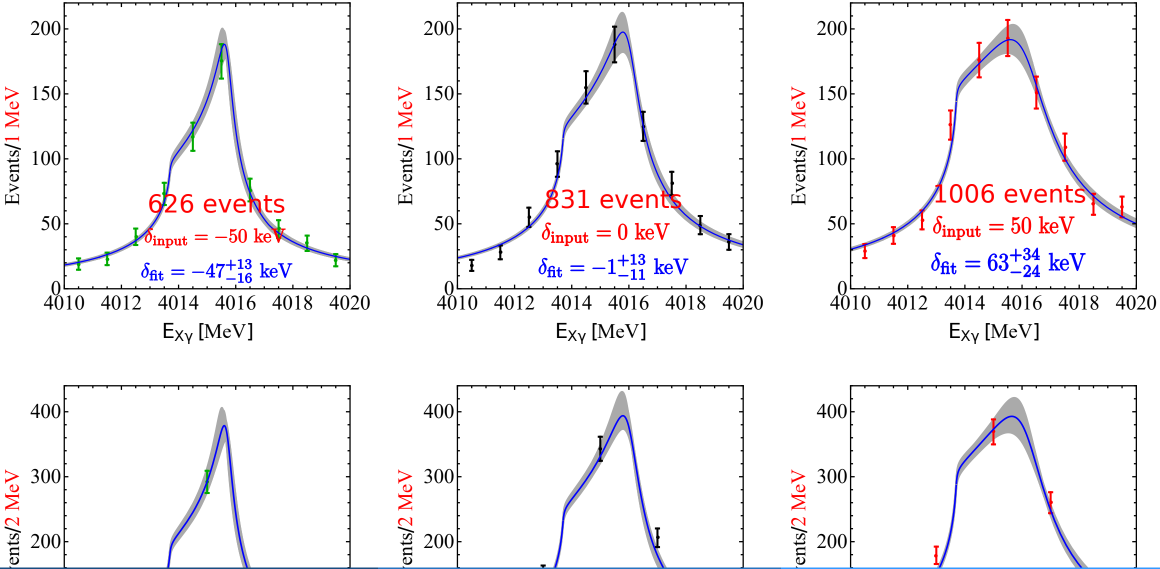
Sensitivity study from a simple Monte Carlo simulation:

(1) Generate synthetic events following the distribution

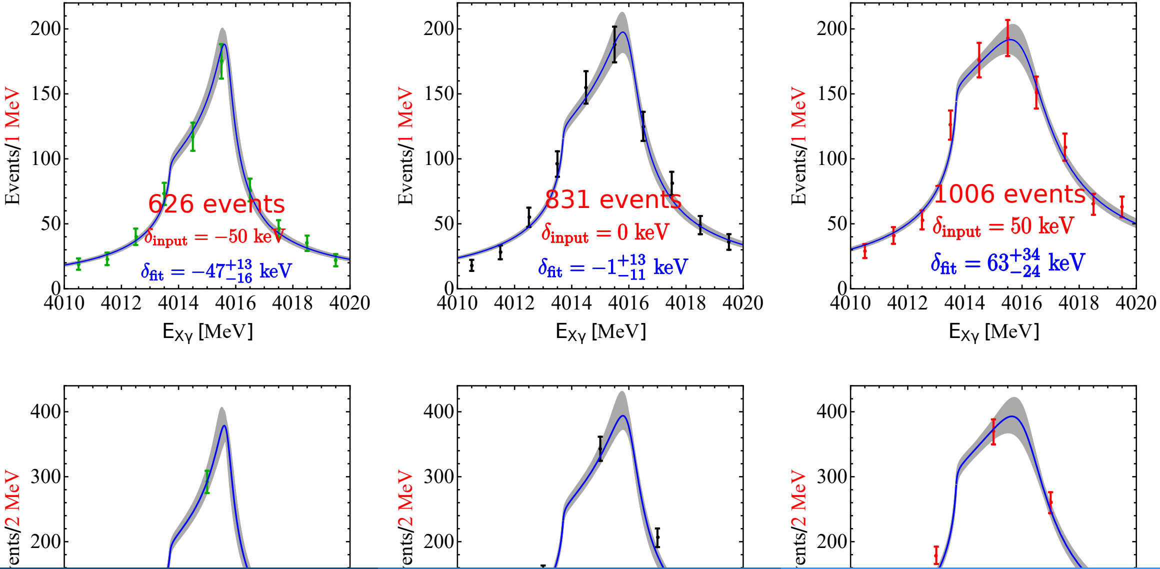
$$F(E_{X\gamma}) = \frac{|I(E_{X\gamma})|^2}{|I(2m_*)|^2} \frac{E_\gamma^3}{\left[(4m_*^2 - m_X^2)/(4m_*)\right]^3}$$

(2) Fit to the synthetic data treating δ as a free parameter

Sensitivity study (2)



Sensitivity study (2)



Sensitivity study (3)

A	$\delta_{\text{in}} = -50$ keV (127 events)	$\delta_{\text{in}} = 0$ (164 events)	$\delta_{\text{in}} = 50$ keV (192 events)
10 bins	-24^{+24}_{-28}	11^{+31}_{-20}	22^{+41}_{-23}
5 bins	-17^{+24}_{-27}	30^{+64}_{-29}	40^{+67}_{-31}
B	$\delta_{\text{in}} = -50$ keV (626 events)	$\delta_{\text{in}} = 0$ (831 events)	$\delta_{\text{in}} = 50$ keV (1006 events)
10 bins	-47^{+13}_{-16}	-1^{+13}_{-11}	63^{+34}_{-24}
5 bins	-48^{+15}_{-19}	-4^{+11}_{-10}	53^{+38}_{-25}
C	$\delta_{\text{in}} = -50$ keV (3133 events)	$\delta_{\text{in}} = 0$ (4027 events)	$\delta_{\text{in}} = 50$ keV (5015 events)
10 bins	-53^{+7}_{-8}	-2 ± 5	55^{+13}_{-11}
5 bins	-52^{+7}_{-8}	-2^{+7}_{-6}	61^{+17}_{-14}

10 bins: 1 MeV/bin

5 bins: 2 MeV/bin

Jozef Dudek

exotics from lattice QCD — executive summary

glueballs

definitely exist in pure Yang-Mills (QCD without quarks) mostly as stable states

properties as excited isoscalar resonances in QCD basically unknown

hybrids

very likely exist as isovector, isoscalar and hidden charm mesons in QCD

exotic q.n. $1^{-+}, 0^{+-}, 2^{+-}$ and many non-exotic q.n. also likely to be hybrid baryons

decay properties basically unknown currently

'tetraquarks'

most likely candidate, a stable $bb\overline{ud}$ state, about 150 MeV below ***BB****

so far no evidence for Z_c as a narrow resonance

molecules, other stuff

??????

what observable tells us the internal structure of a hadron … ?

lattice QCD — rigorously

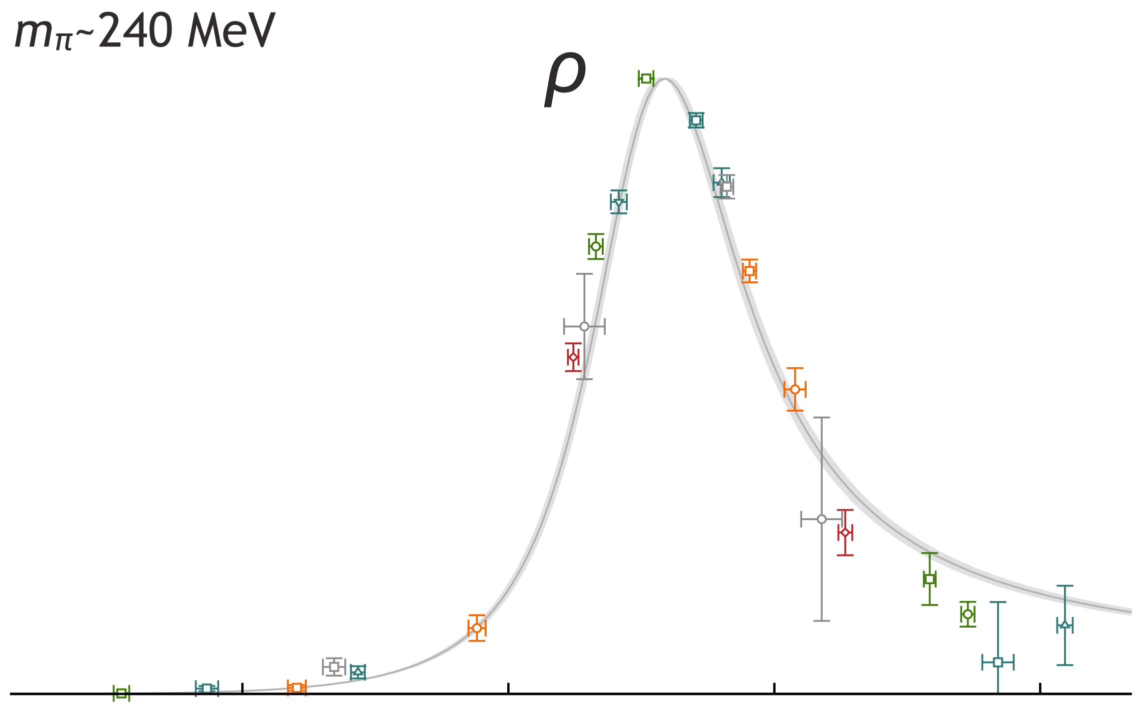
rigorous calculation in QCD → the full complexity of the real world

(minus stuff we can turn off:
isospin violation, QED …)

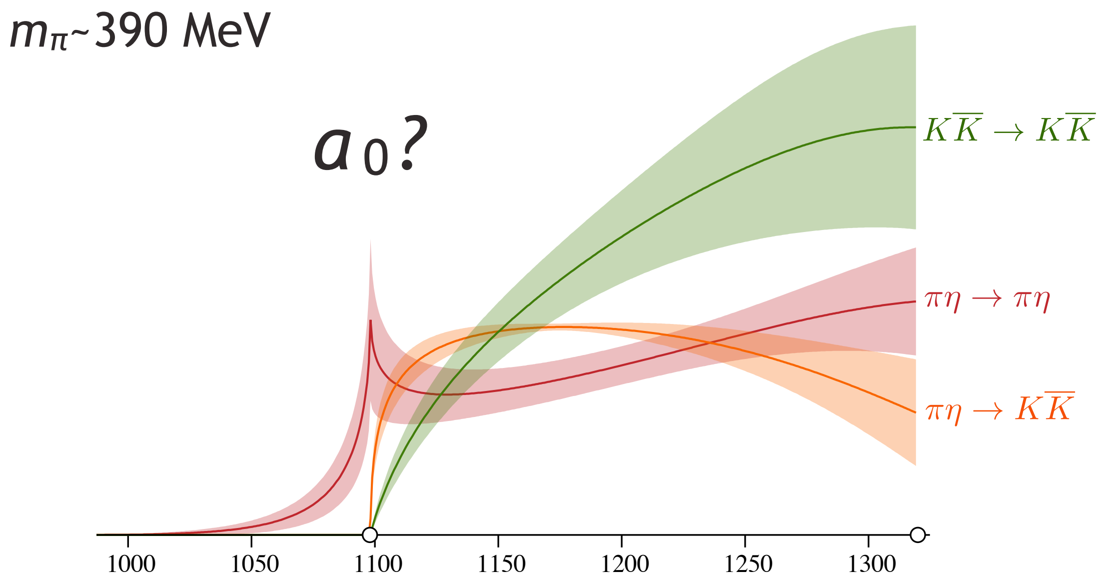
unstable resonances in coupled-channels

can this be done? yes, so far for relatively simple cases, e.g.

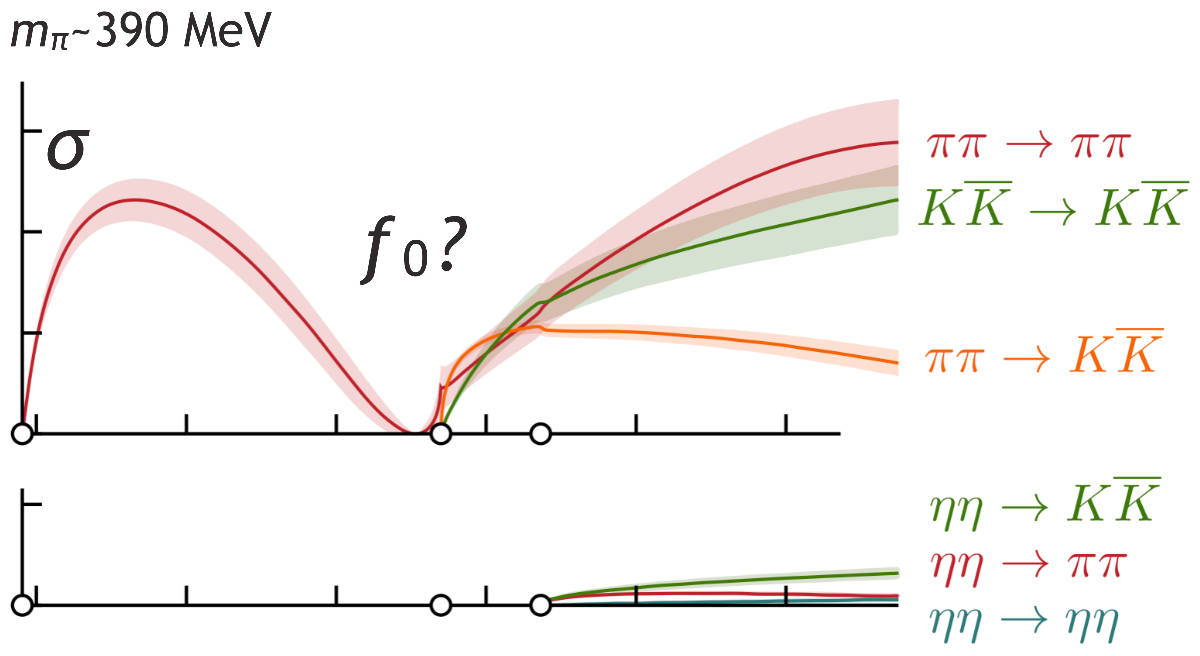
$\pi\pi \to \pi\pi$ $I=1$ $J^P=1^-$



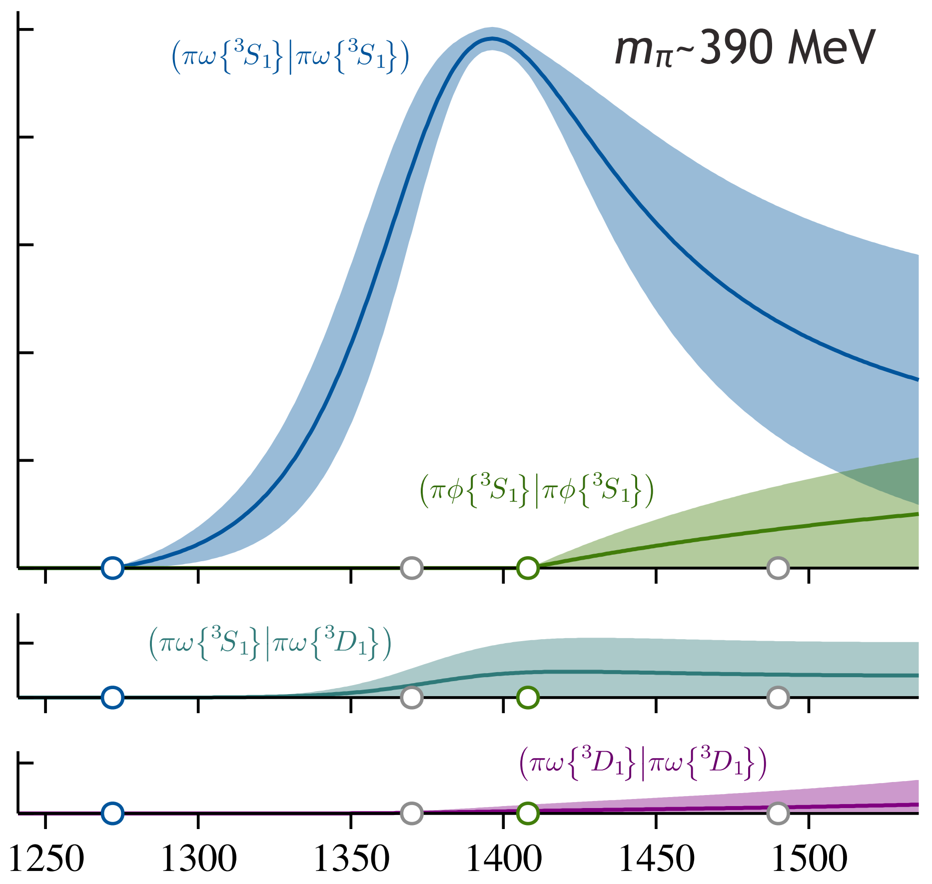
$\pi\eta$, $K\bar{K}$ $I=1$ $J^P=0^+$



$\pi\pi$, $K\bar{K}$, $\eta\eta$ $I=0$ $J^P=0^+$



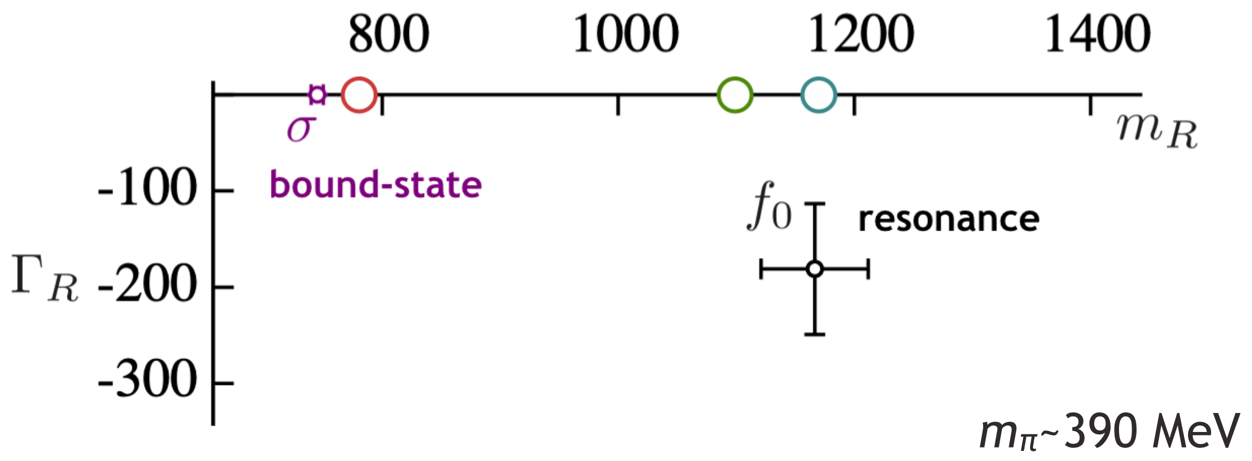
$\pi\omega$, $\pi\varphi$ $I=1$ $J^P=1^+$



compute matrix of correlation functions
extract discrete spectrum in finite volume
use f.v. formalism to infer coupled t-matrix

extract **pole singularities** of amplitudes

e.g.



not restricted by available production mechanisms

e.g. $e^+e^- \to \pi\,\underline{\pi\,J/\psi}$ three-body environment complicates matters

Z_c

additional singularities, rescattering …
however you want to phrase it

lattice can 'directly' study π J/ψ scattering without the third hadron

a disadvantage is that the finite-volume spectrum is influenced by **all kinematically accessible channels**

can't look channel by channel like experiment, get it all at once

means high lying resonances become increasingly challenging

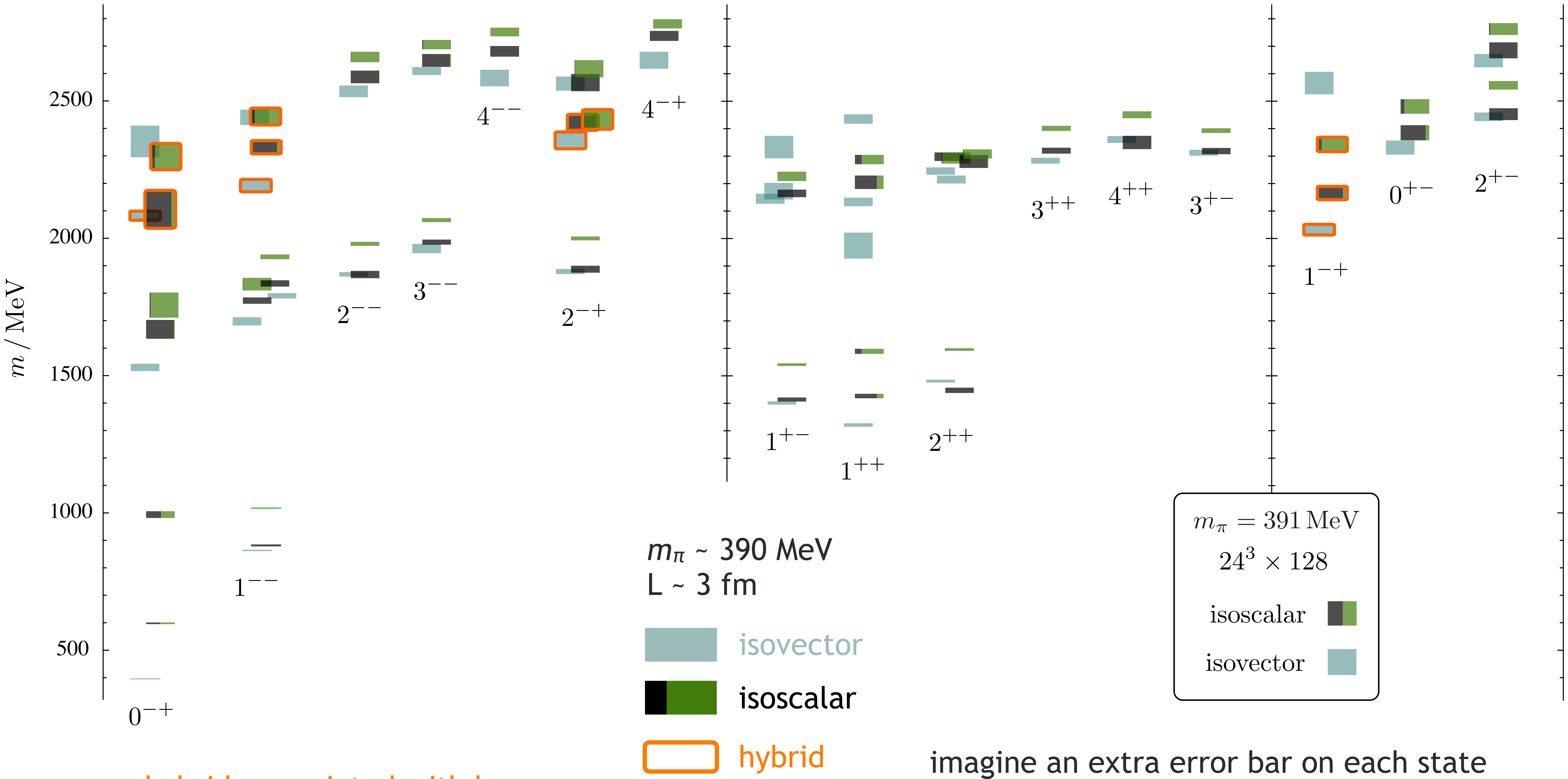
unphysically heavy pion masses still common for spectroscopy calculations

this is to push up three-body thresholds
(formalism to determine such amplitudes is not yet 'ripe')

lattice QCD at a lower level of rigour

large basis of $q\bar{q}$-like operators $\bar{\psi}\Gamma\overleftrightarrow{D}\ldots\overleftrightarrow{D}\psi$

an uncontrolled approximation,
should only be used as a guide to which
states likely manifest as narrow resonances



hybrids associated with large overlap with $\bar{\psi}\Gamma t^a \psi\, B^a$

— certainly a model

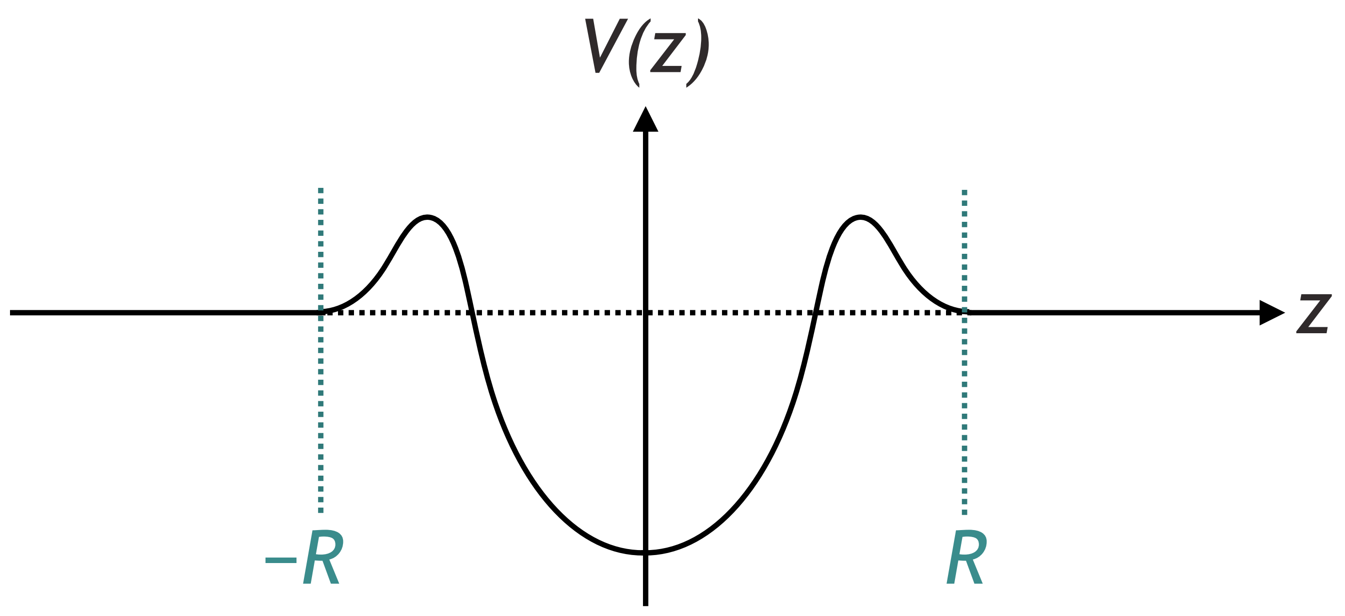
imagine an extra error bar on each state the size of the decay width

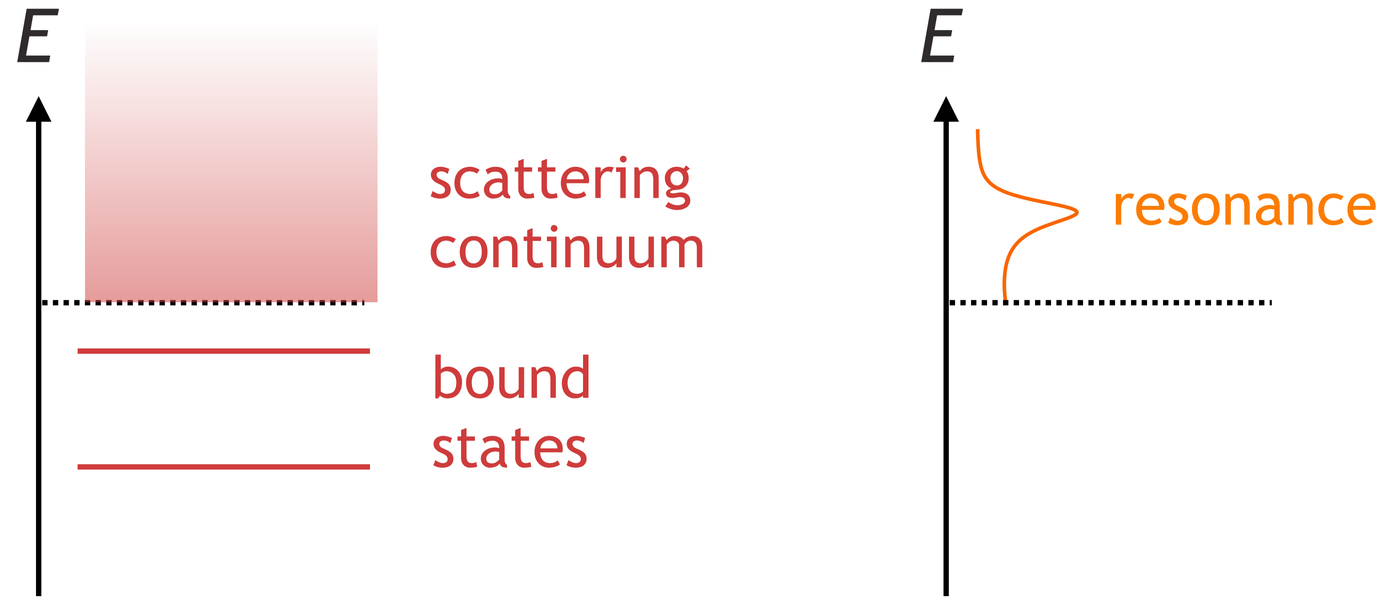
and some objects could be missing

resonances in a finite volume ?

the approach can be illustrated within **one-dimensional quantum mechanics**

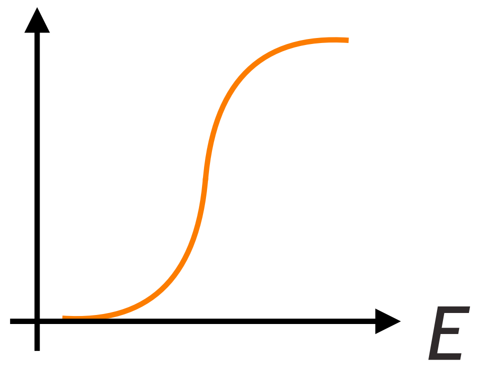
imagine two identical bosons separated by a distance *z*
interacting through a finite-range potential *V(z)*





$$\psi(|z|>R) \sim \cos\left(p\,|z| + \boxed{\delta(p)}\right)$$

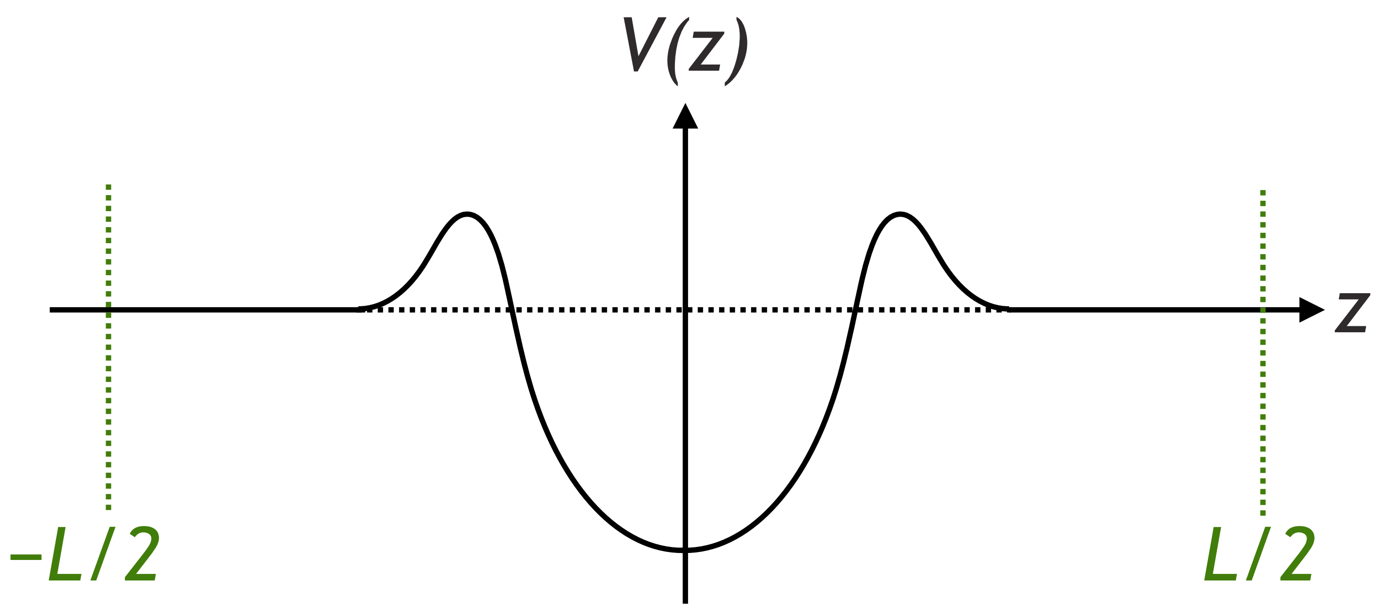
phase-shift



'scattering' in a finite-volume

now put the system in a 'box'

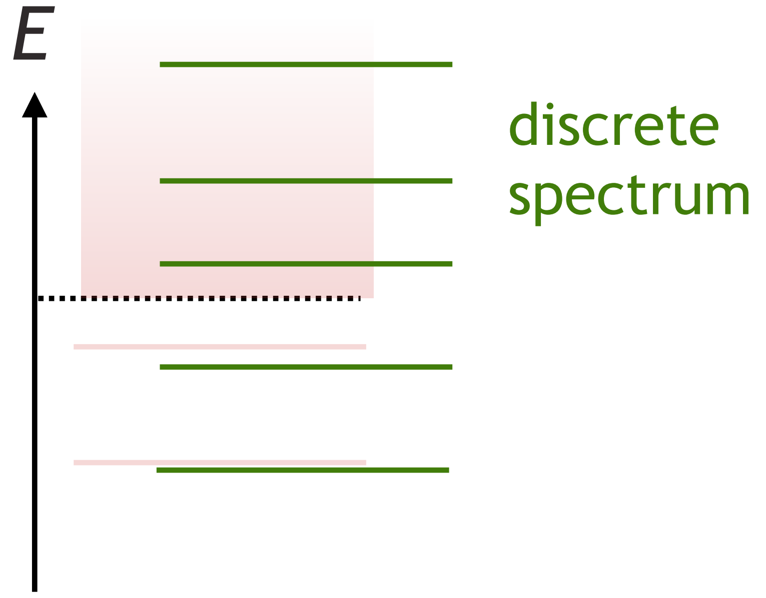
— periodic boundary condition at $z = \pm L/2$



$$\psi(|z| > R) \sim \cos\big(\, p\,|z| + \delta(p)\,\big)$$

$$\psi(L/2) = \psi(-L/2)$$
$$\frac{d\psi}{dz}(L/2) = \frac{d\psi}{dz}(-L/2)$$

momentum quantization condition $$p = \frac{2\pi}{L} n - \frac{2}{L}\delta(p)$$



reversing the logic:

if you can compute the **discrete finite-volume spectrum** in a quantum theory, you can find the **scattering amplitude**

$$E_n(L) \longrightarrow \delta(E)$$

3dim QFT result conceptually similar ...

determining the *t*-matrix

one approach:

– **parameterize** the energy dependence of $\boldsymbol{t}(E; \{a_i\})$

– solve $0 = \det\left[\mathbf{1} + i\boldsymbol{\rho}(E)\cdot\mathbf{t}(E)\cdot\big(\mathbf{1} + i\boldsymbol{\mathcal{M}}(E,L)\big)\right]$ for E_n^{par}

– compare 'model' spectrum to lattice spectrum …

$$\chi^2(\{a_i\}) = \sum_{n,n'}\Big(E_n^{\mathrm{lat}} - E_n^{\mathrm{par}}(\{a_i\})\Big)\left[\mathbb{C}^{-1}\right]_{nn'}\Big(E_{n'}^{\mathrm{lat}} - E_{n'}^{\mathrm{par}}(\{a_i\})\Big)$$

lattice energy level
data covariance

ensure important features are independent of parameterization details by varying parameterization …

e.g. can ensure unitarity with *K*-matrix approach

$$\left[t^{-1}\right]_{ab} = \left[K^{-1}\right]_{ab} + I_a\delta_{ab} \qquad \mathrm{Im}\, I_a = -\rho_a$$

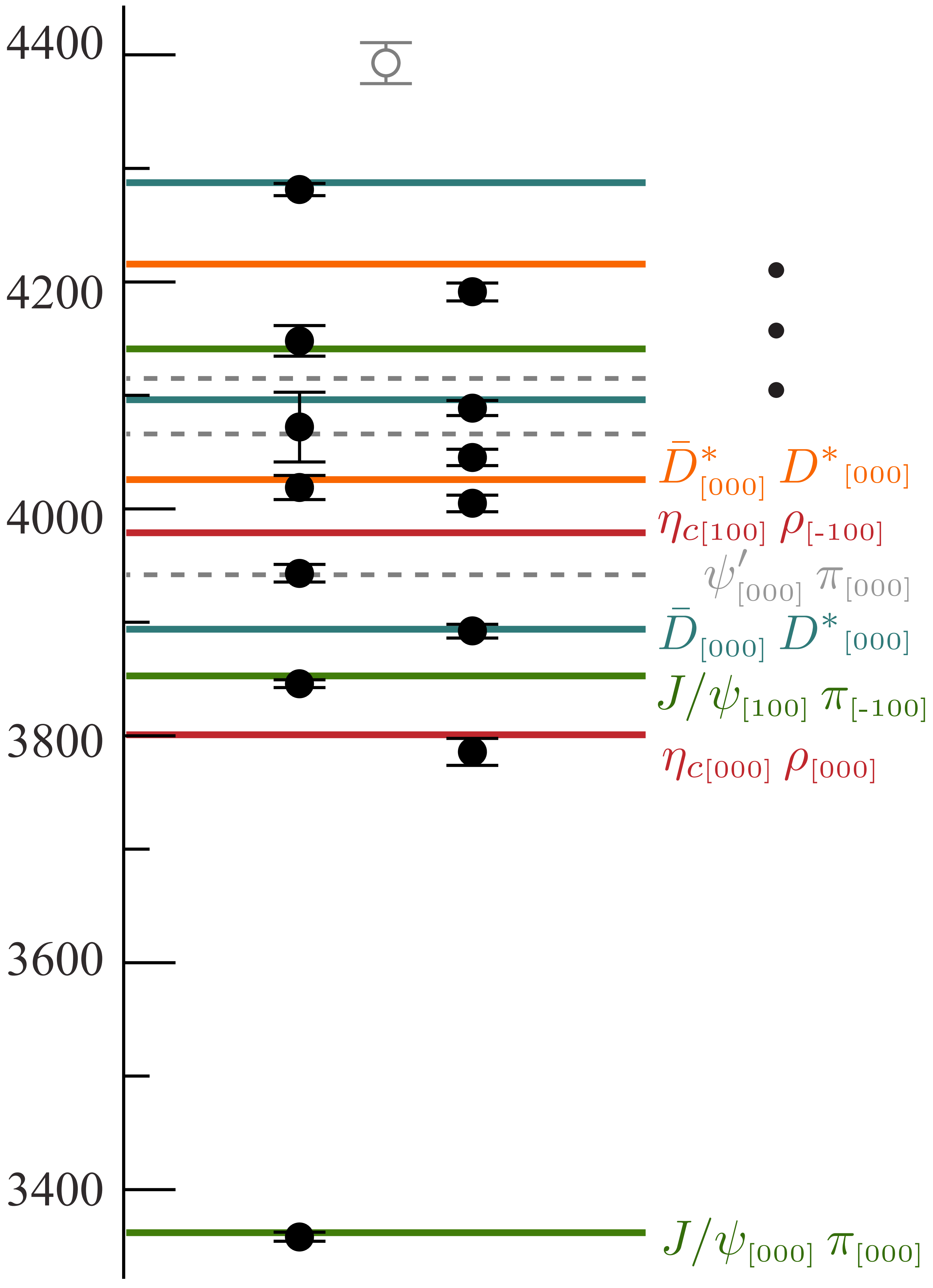
e.g. Chew-Mandelstam phase-space

$$I(s) = -\frac{\rho(s)}{\pi}\log\left[\frac{\rho(s)-1}{\rho(s)+1}\right]$$

consider many parameterizations of ***K*** …

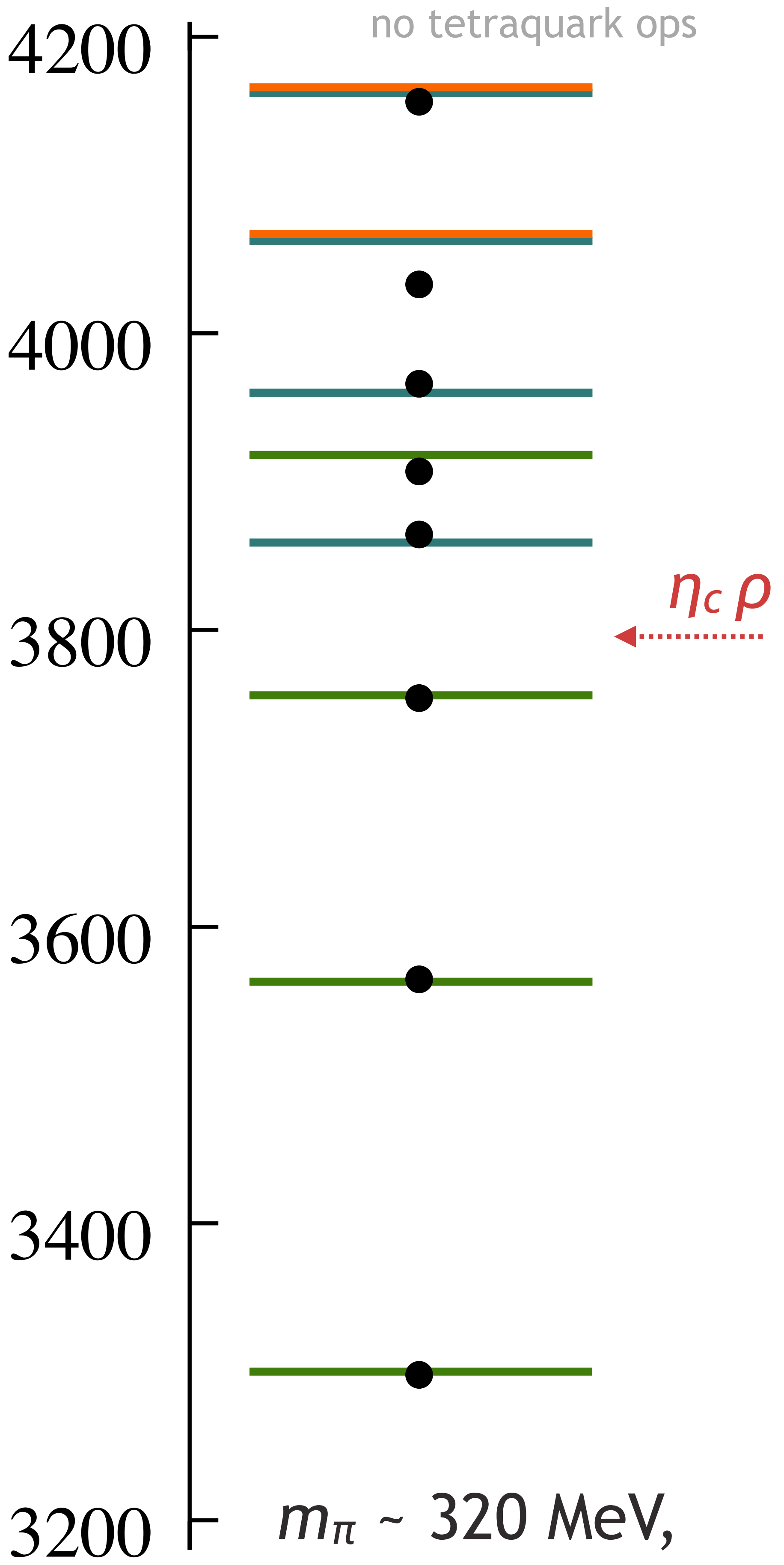
‘$Z_c(3900)$’ channel — $J^P=1^+$

Prelovsek et al (2015)



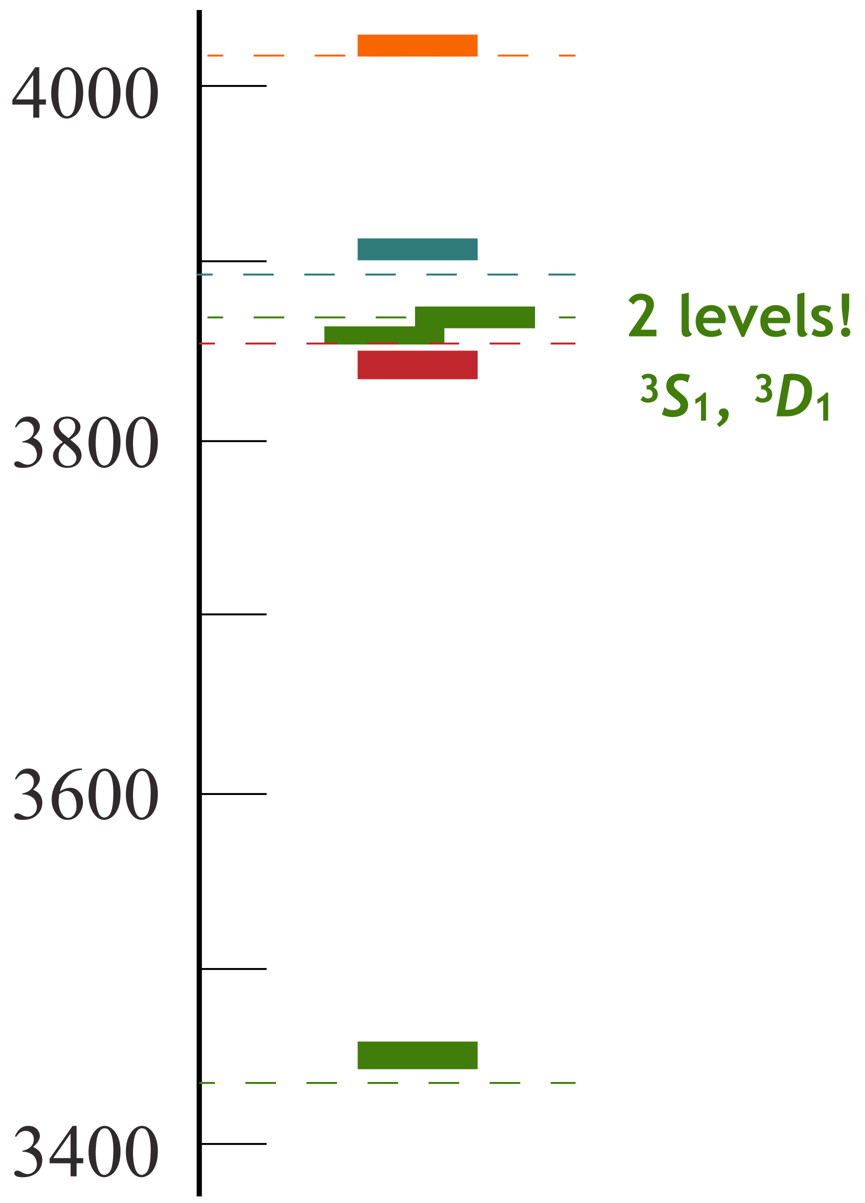
m_π ~ 270 MeV, L ~ 2 fm

Chen et al (2019)



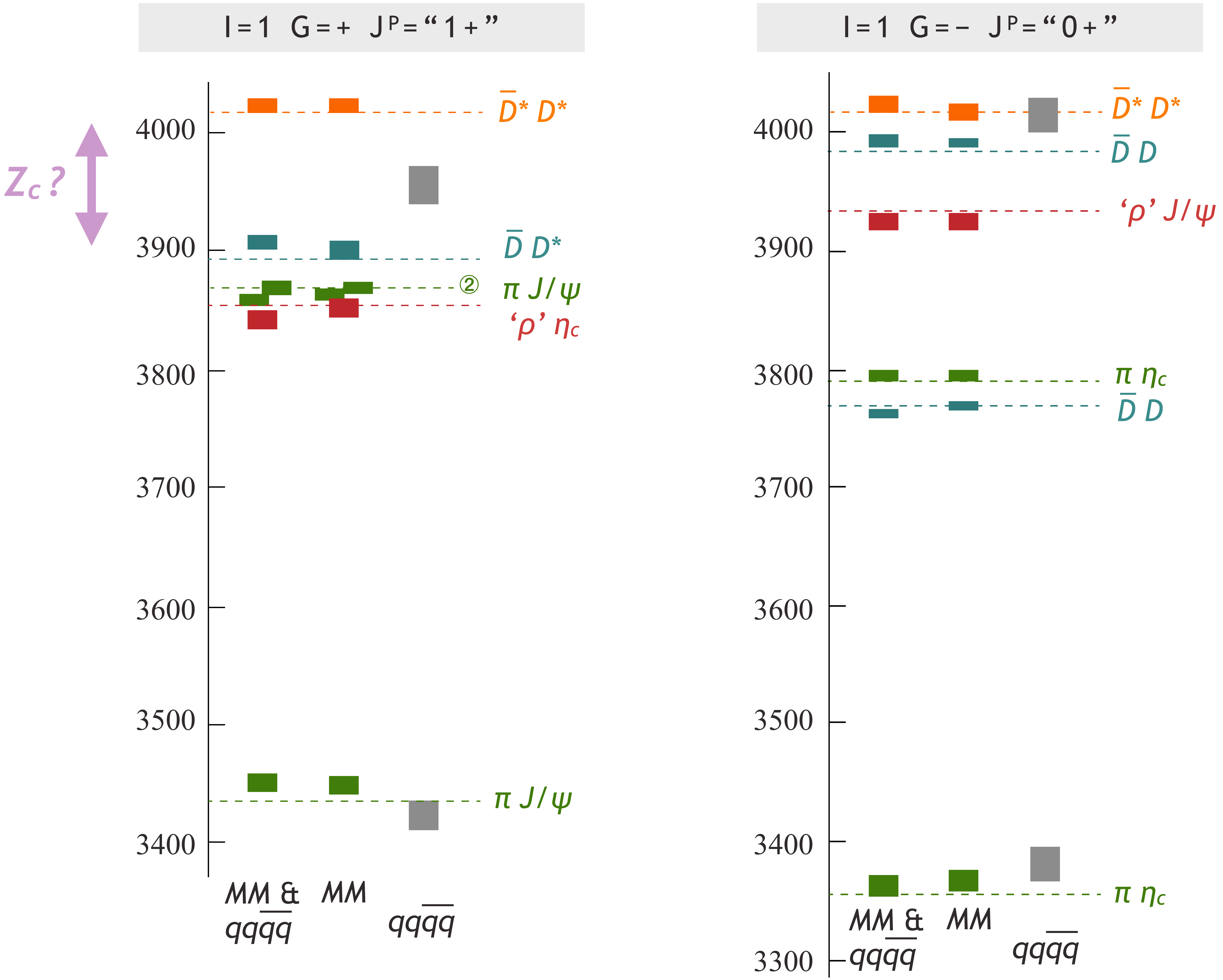
m_π ~ 320 MeV,
L ~ 2.8 fm

hadspec (2017)



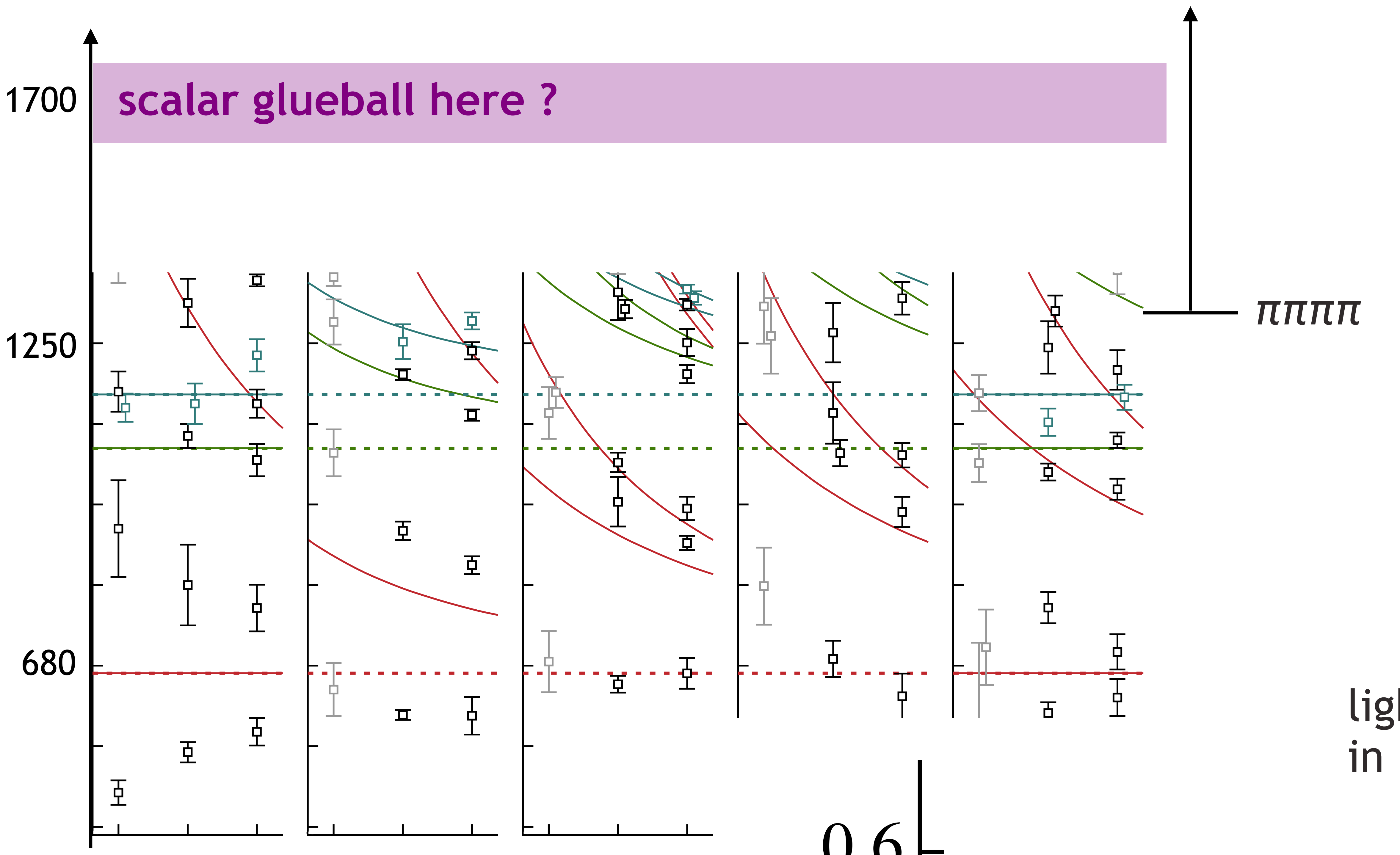
m_π ~ 390 MeV,
L ~ 2 fm

see also HALQCD approach …

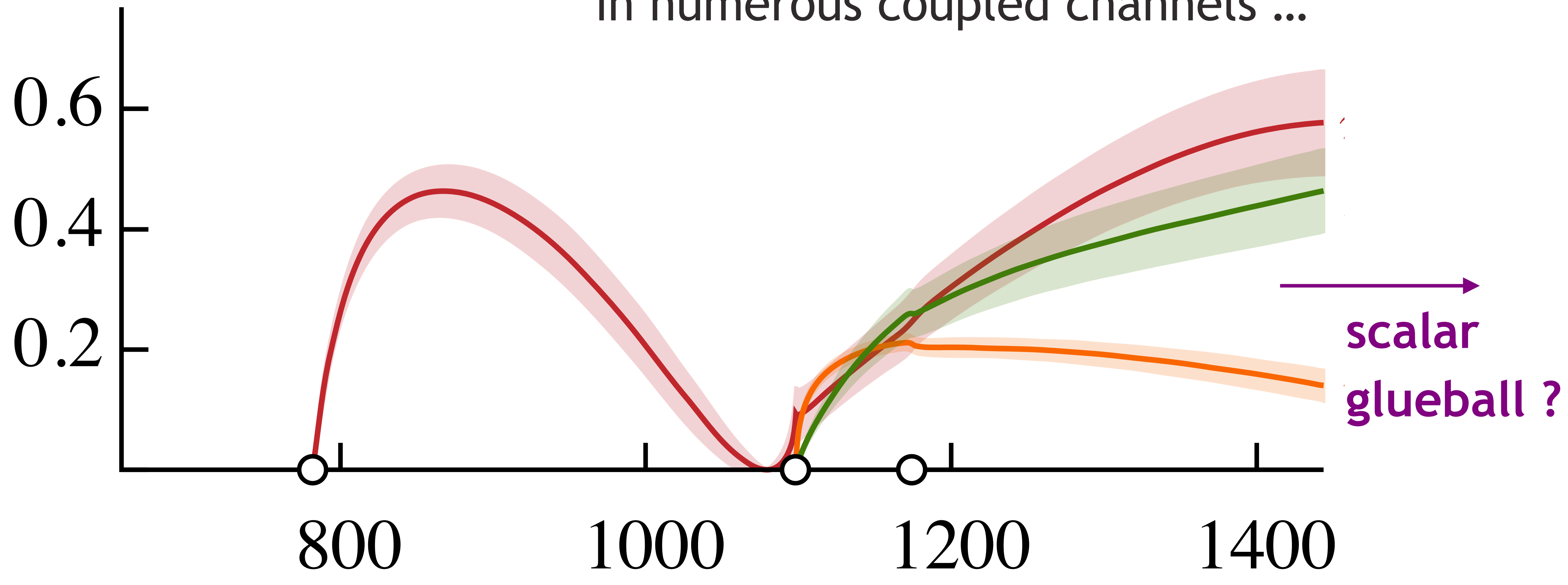

I = 1 G = + J P = "1 +"
I = 1 G = − J P = "0 +"
Zc ?
4000
3900
3800
3700
3600
3500
3400
3300
D̄* D*
D̄ D*
π J/ψ
'ρ' ηc
D̄ D
'ρ' J/ψ
π ηc
MM & qq̄qq̄
MM
qq̄qq̄

glueballs are excited isoscalar meson resonances

glueballs in **QCD** are much more complicated beasts …

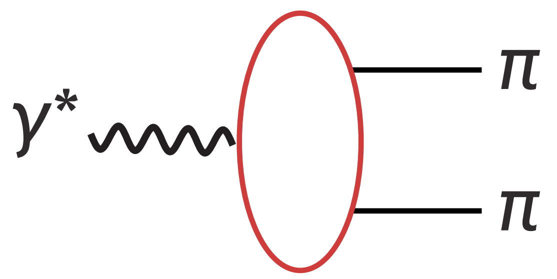


lightest glueball will be the n^{th} resonance in numerous coupled channels …

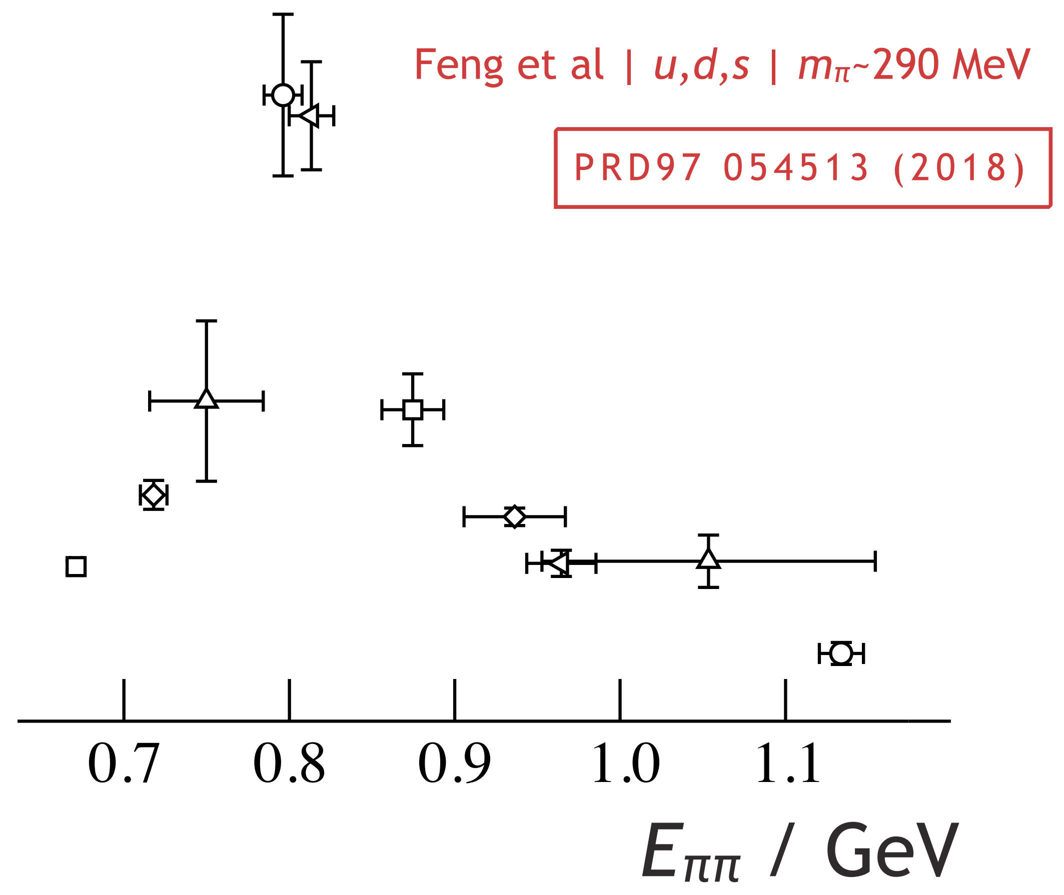


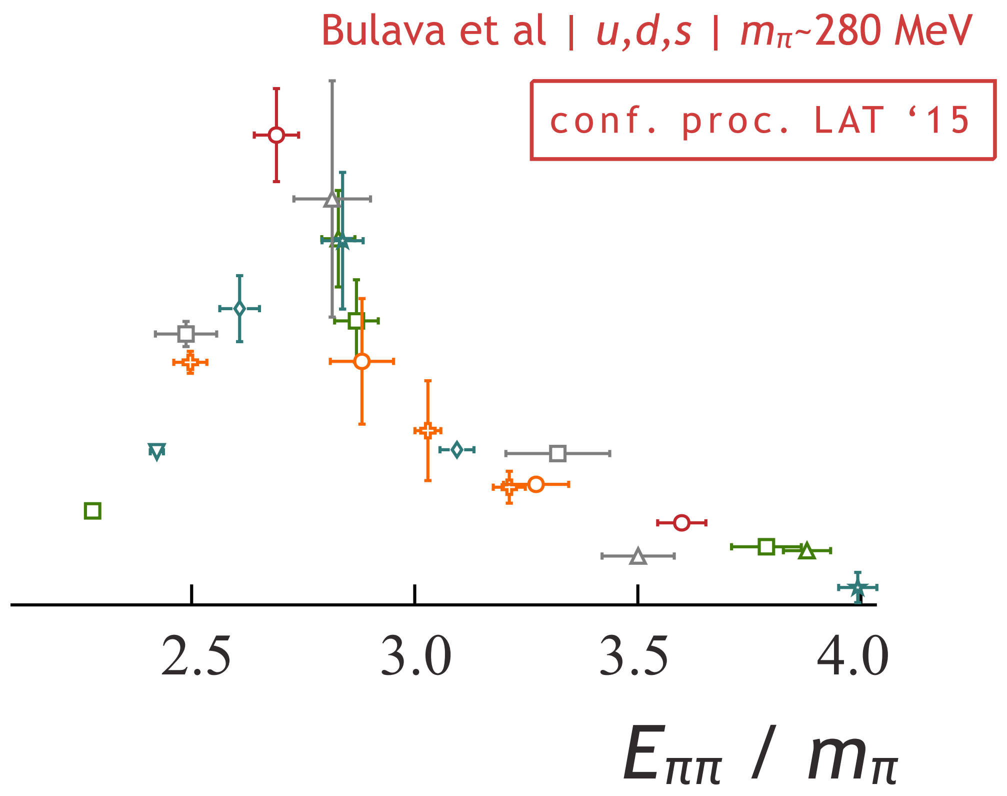
transition form-factors of unstable $\rho \to \pi\pi$

$\gamma^* \to \pi\pi$

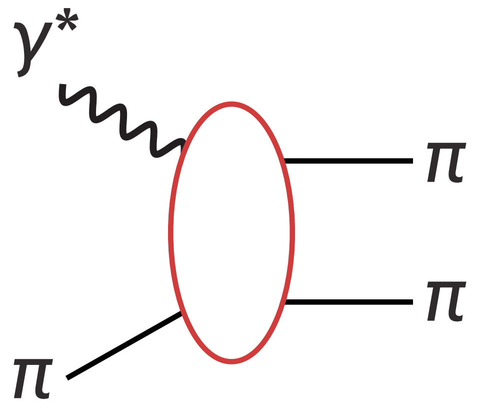


$F_\pi(E_{\pi\pi})$





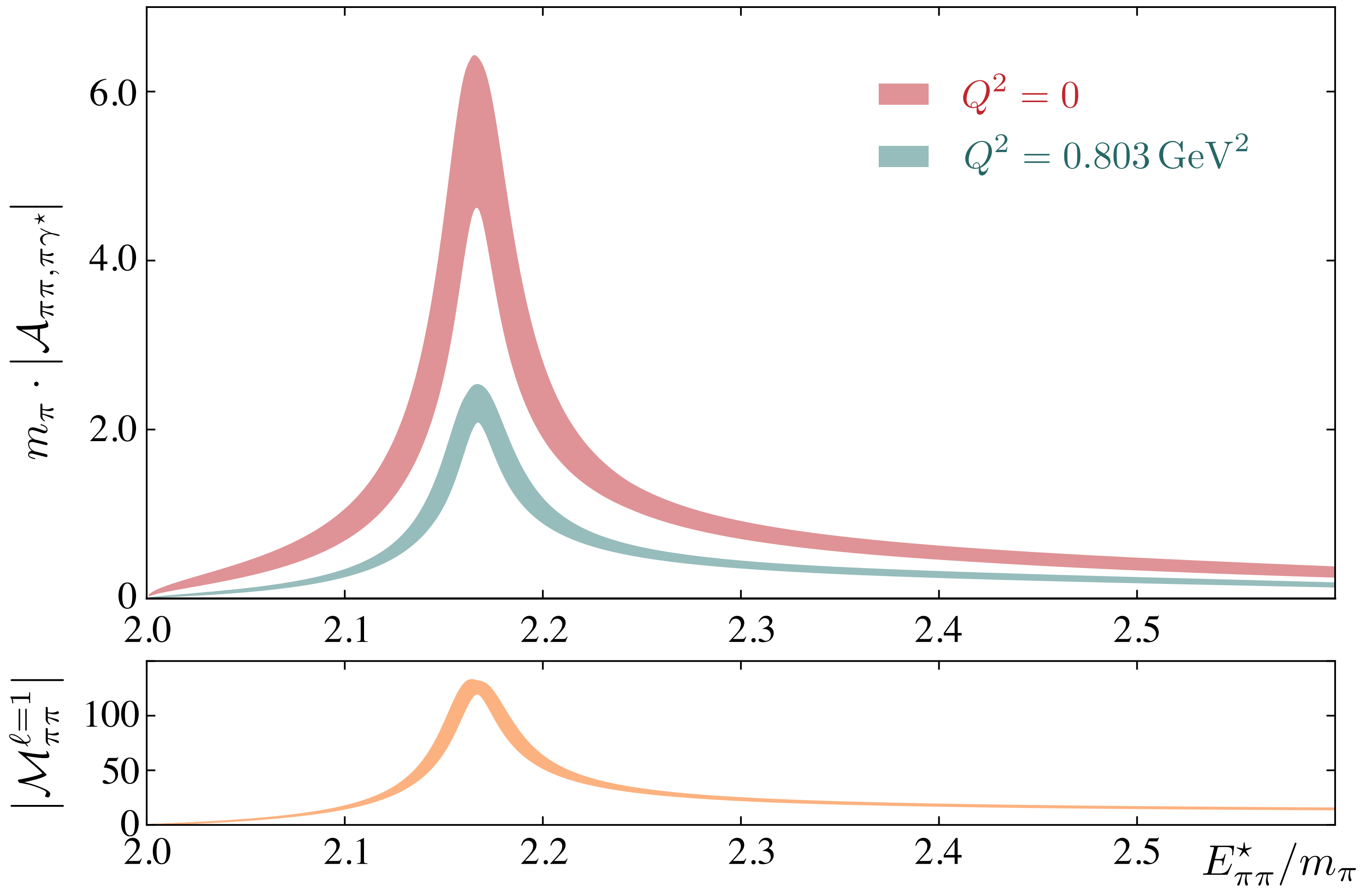
$\gamma^*\pi \to \pi\pi$

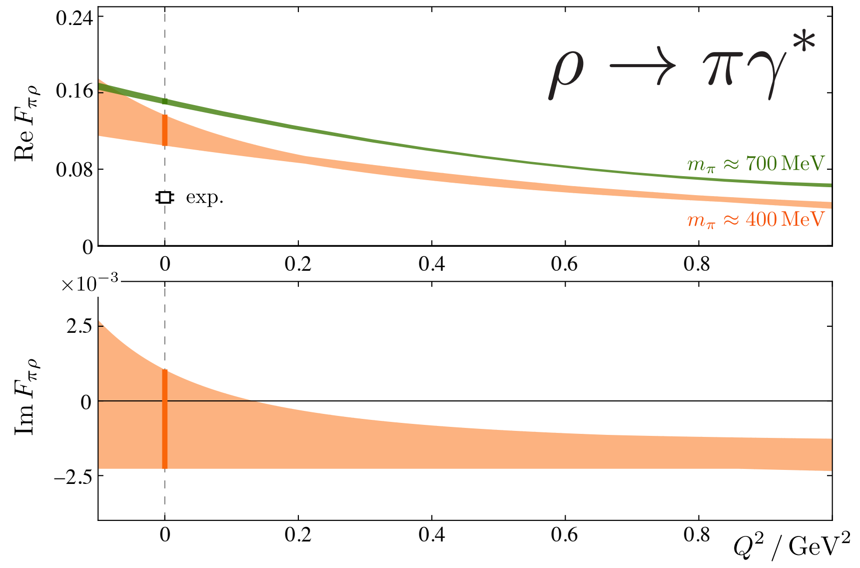


$\mathcal{A}(E_{\pi\pi}, Q^2)$

Briceno et al | u,d,s | mπ~391 MeV

PRL115 242001 (2015)



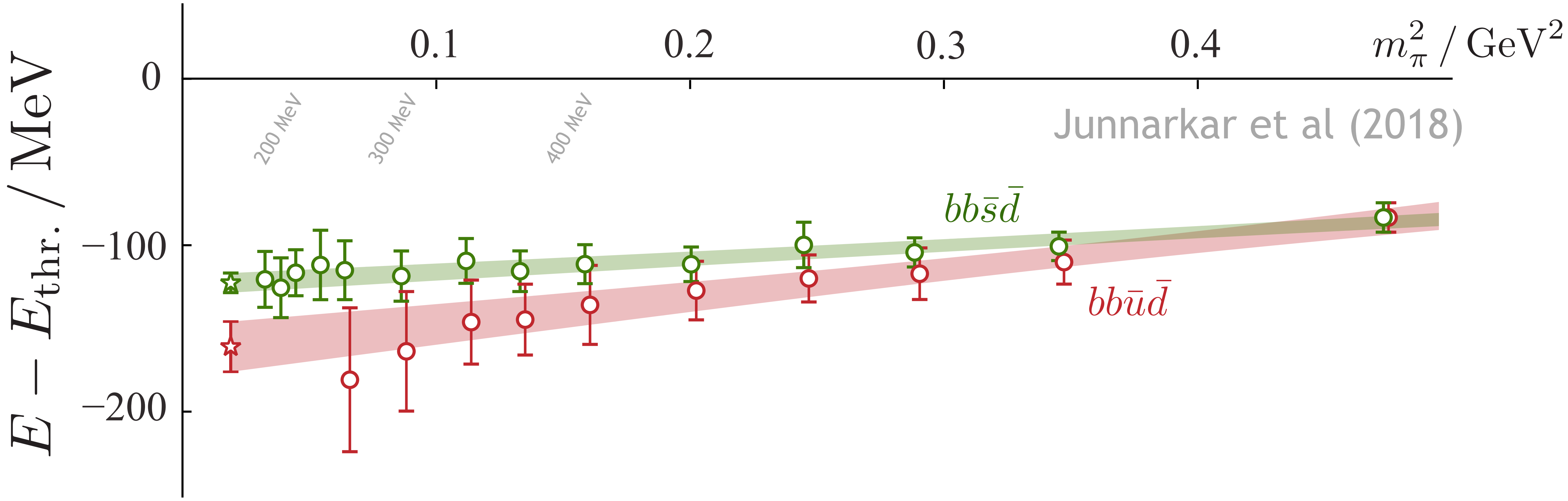


truly flavor-exotic hadrons

one recent observation in lattice QCD that has a good chance of being robust:

a double-bottom bound-state $bb\bar{u}\bar{d}$ (I=0, J^P=1$^+$, lying well below $B\,B^*$ threshold)

and probably a strange partner



Francis et al (2017)
Junnarkar et al (2018)
Leskovec et al (2018)

$|\Delta E(bb\bar{u}\bar{d})| \sim 100 - 200\,\mathrm{MeV}$

$|\Delta E(bb\bar{s}\bar{d})| \sim 90 - 120\,\mathrm{MeV}$

see Eichten & Quigg (2017) for heavy quark symmetry argument

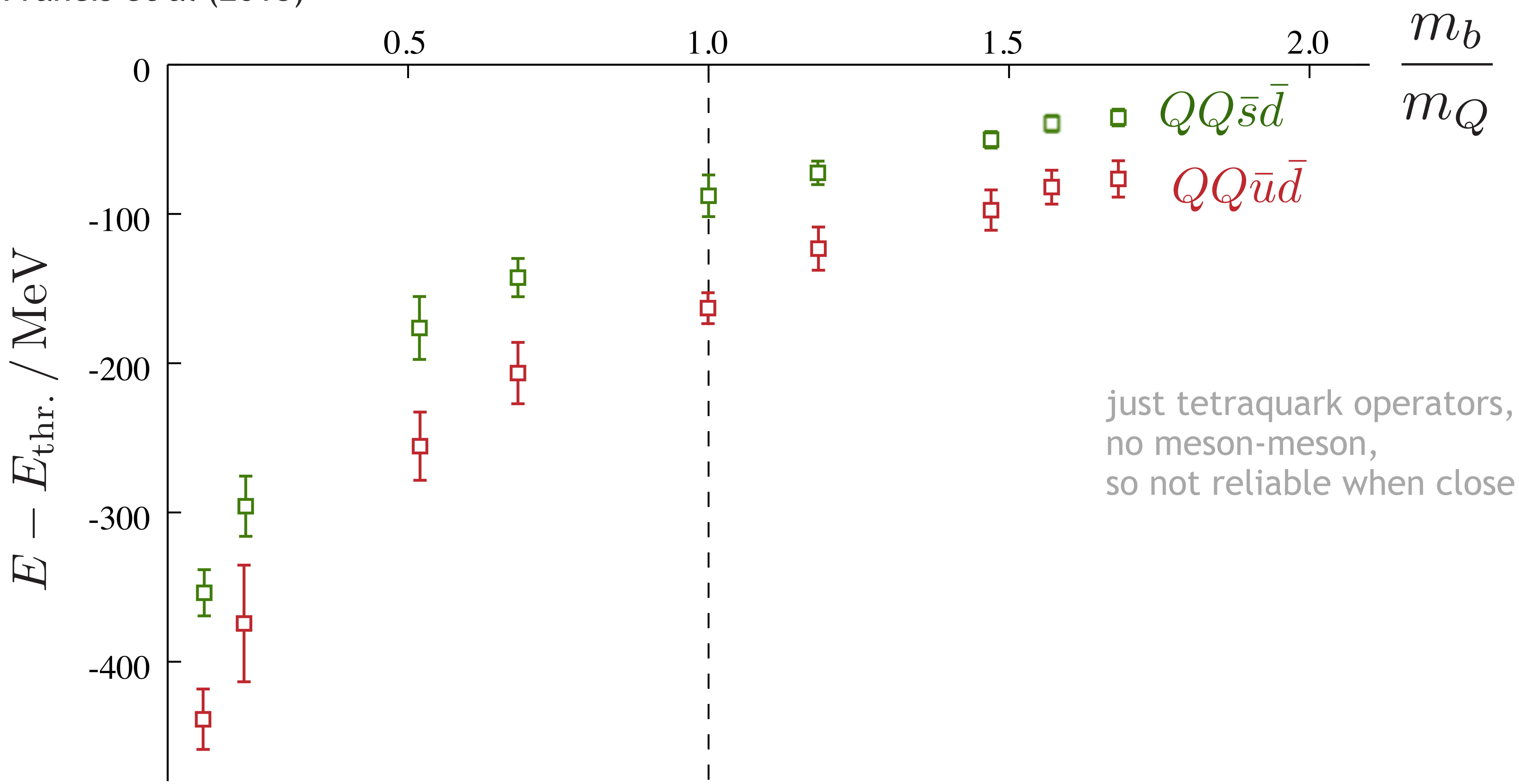
binding energy with changing heavy quark mass

Francis et al (2018)

heavier than bottom

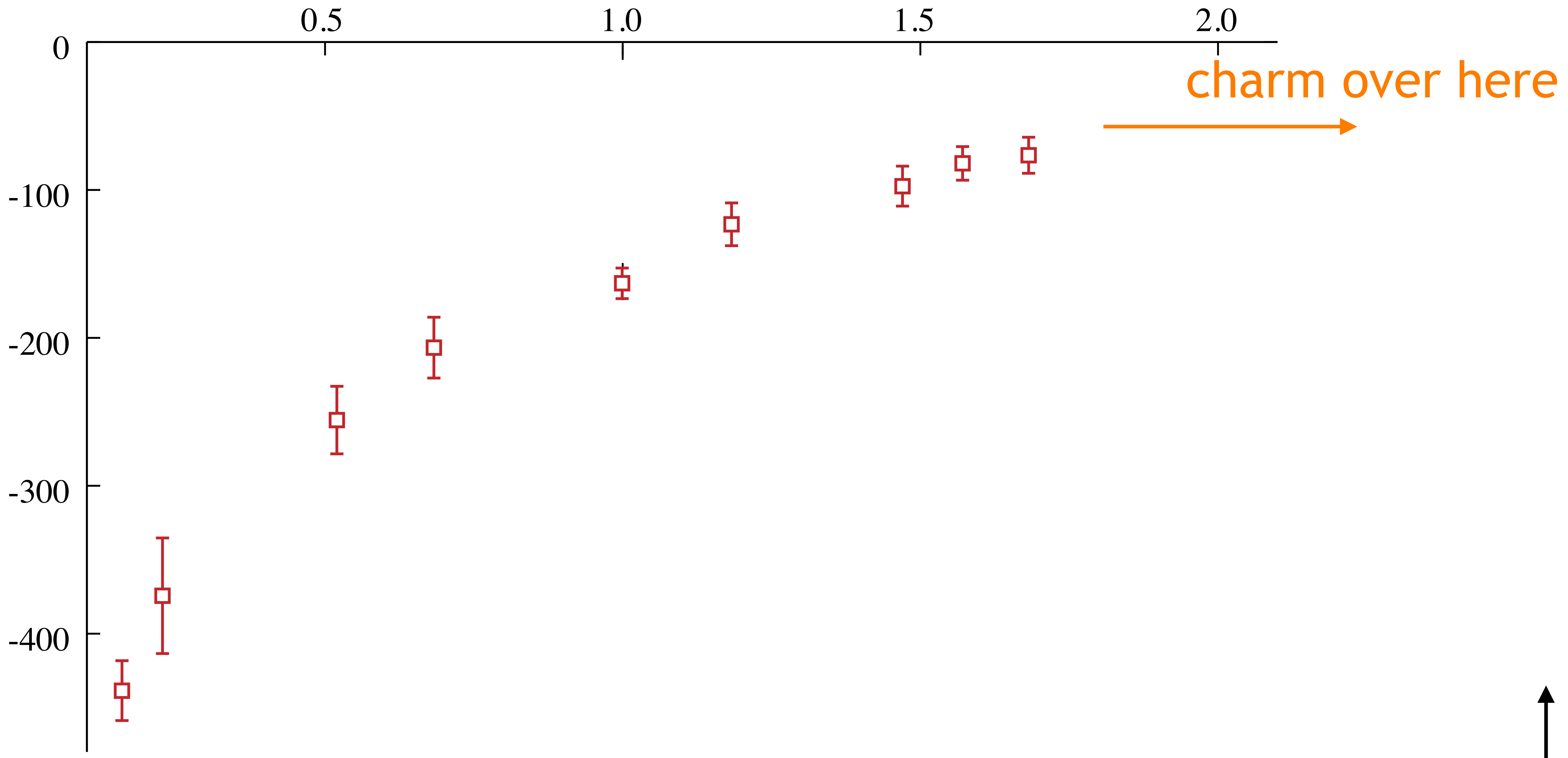
lighter than bottom

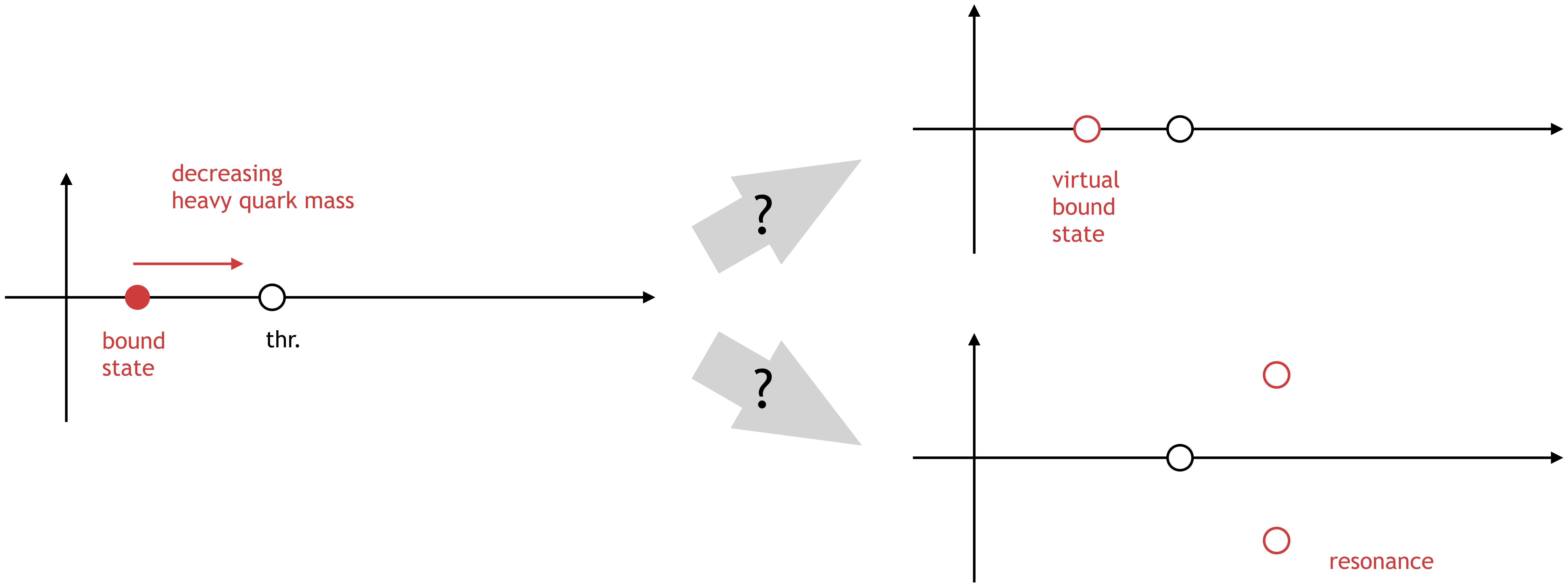
charm over here



just tetraquark operators,
no meson-meson,
so not reliable when close to threshold

what happens for $cc\bar{u}\bar{d}$?

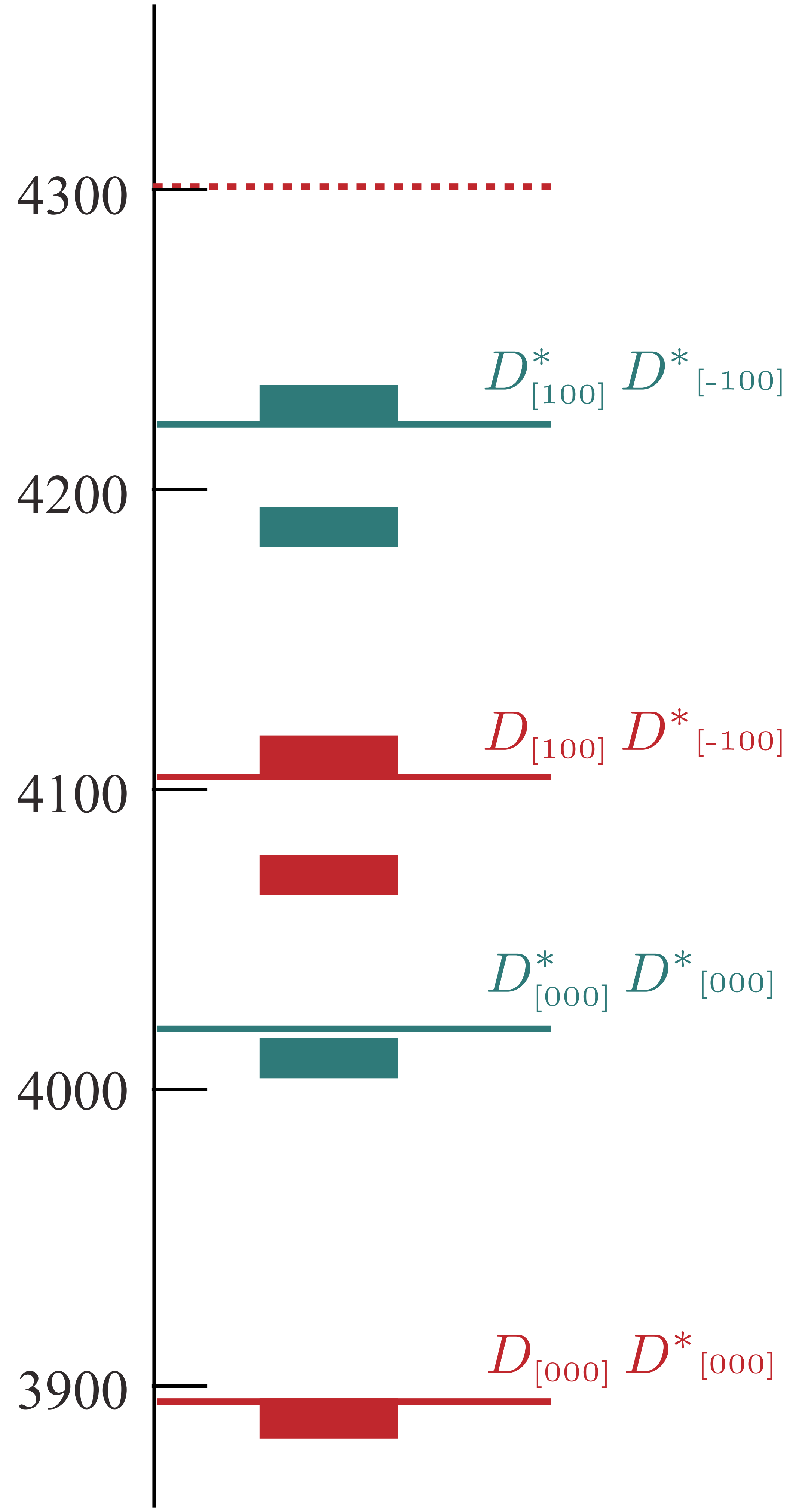




direct calculation of $cc\bar{u}\bar{d}$

tetraquark operators
& meson-meson operators

m_π ~ 390 MeV,
L ~ 2 fm

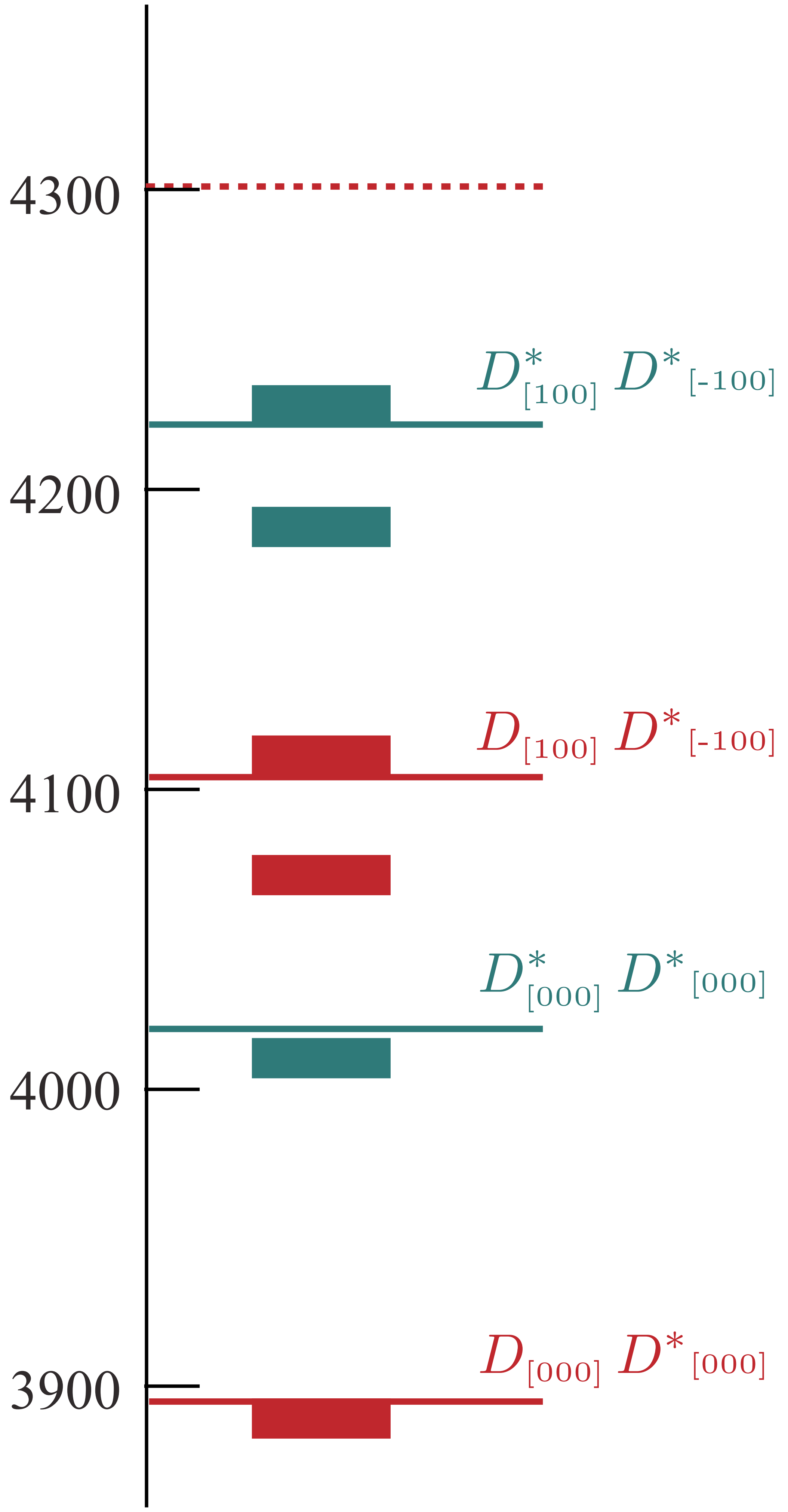


no obvious sign of a narrow resonance …

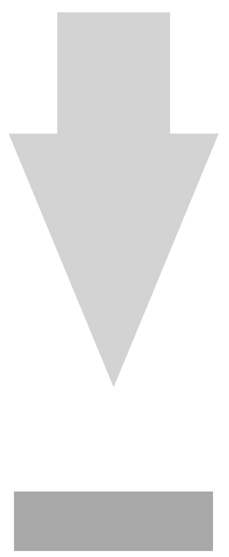
direct calculation of $cc\bar{u}\bar{d}$

tetraquark operators
& meson-meson operators

m_π ~ 390 MeV,
L ~ 2 fm



just tetraquark ops

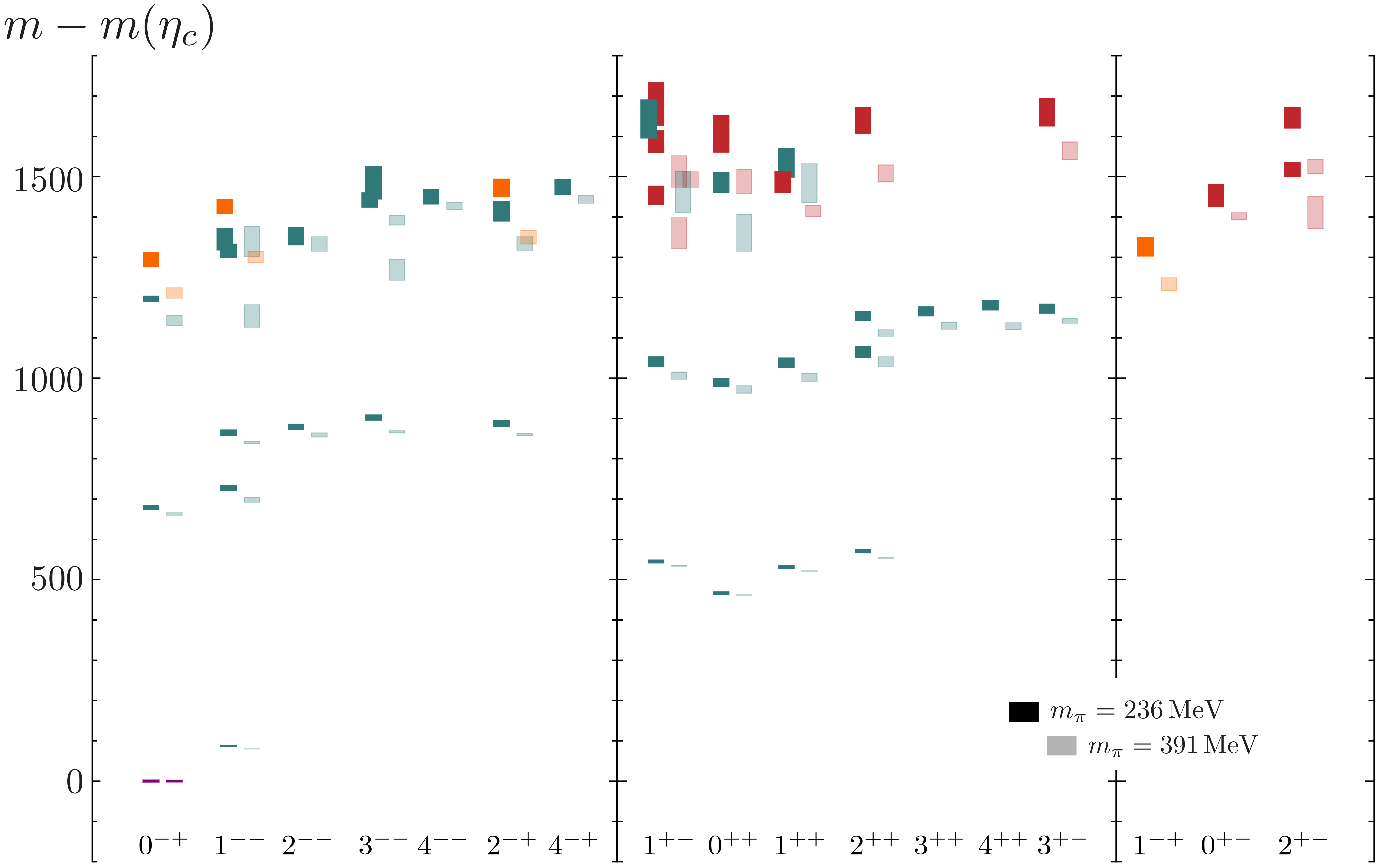


completely misleading spectrum

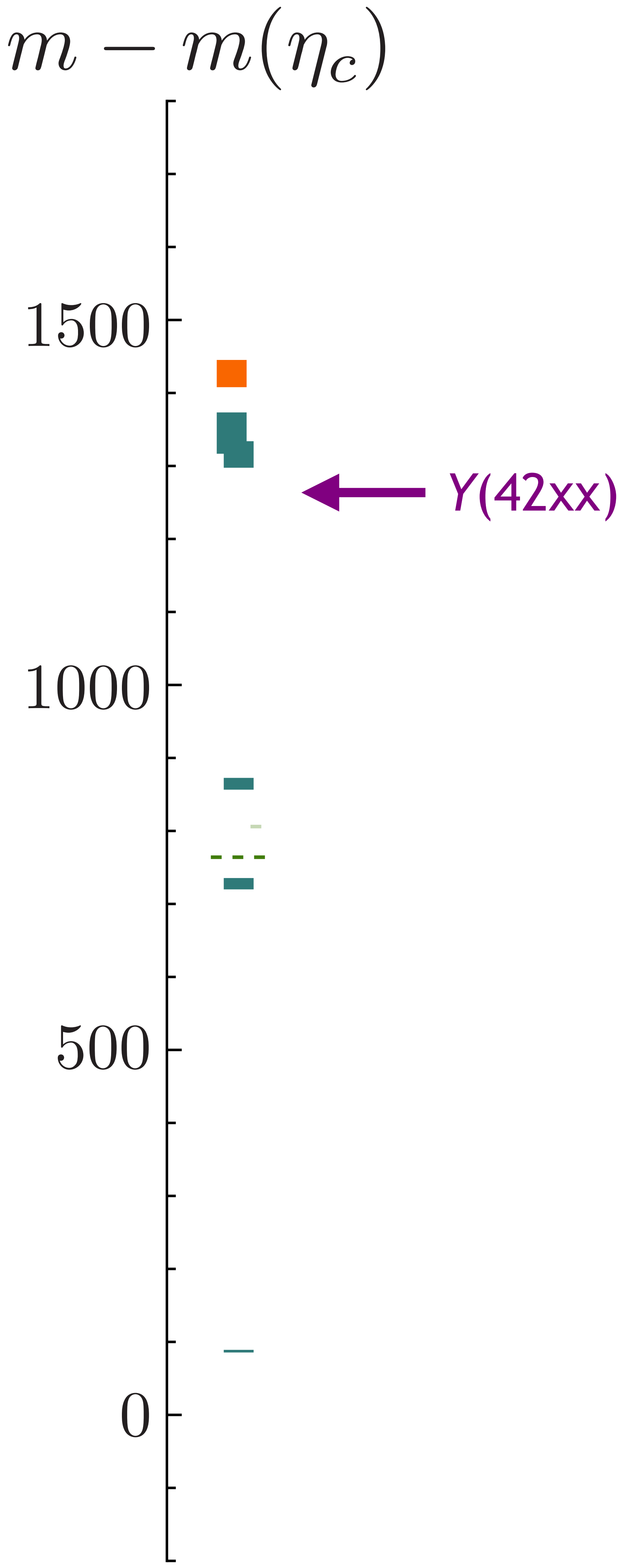
BE CAREFUL WITH SMALL OPERATOR BASES !

'qualitative' picture of the charmonium spectrum

JHEP 1612 089 (2016)



‘qualitative’ picture of the charmonium spectrum



chromo-magnetic gluonic excitation

- lightest set of hybrid mesons appear to contain a *1*⁺⁻ gluonic excitation

quarks in an *S*-wave

$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^1S_0\right] G^\star_{\mathbf{8_c}} \left[B\right] \right]_{\mathbf{1_c}} \to 1^{--}_{\mathrm{hyb.}}$$

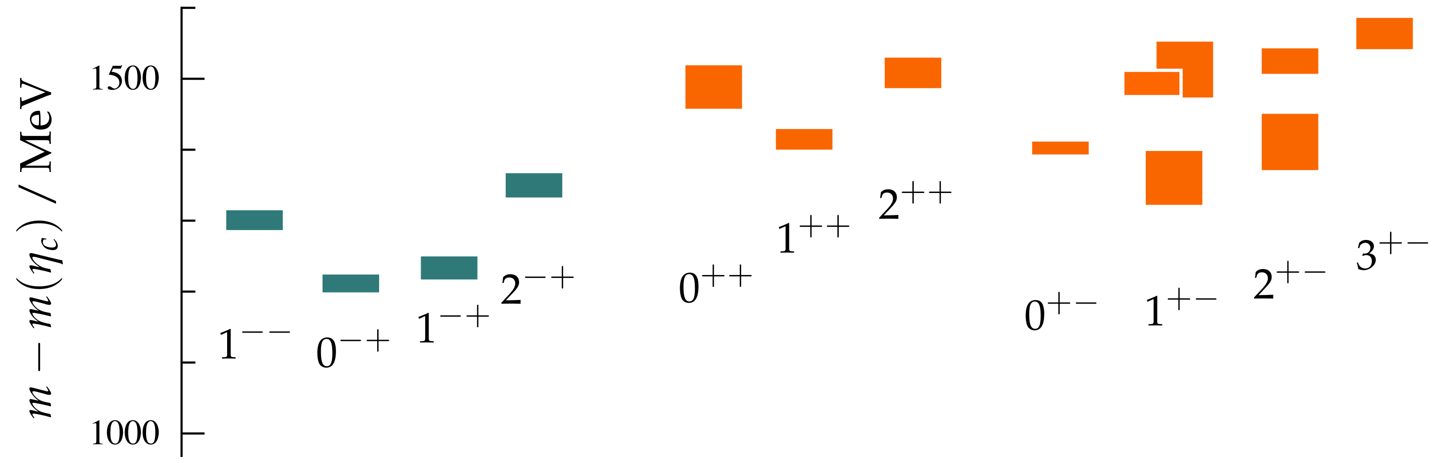
$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^3S_1\right] G^\star_{\mathbf{8_c}} \left[B\right] \right]_{\mathbf{1_c}} \to (0,1,2)^{-+}_{\mathrm{hyb.}}$$

quarks in a *P*-wave

$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^1P_1\right] G^\star_{\mathbf{8_c}} \left[B\right] \right]_{\mathbf{1_c}} \to (0,1,2)^{++}_{\mathrm{hyb.}}$$

$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^3P_{0,1,2}\right] G^\star_{\mathbf{8_c}} \left[B\right] \right]_{\mathbf{1_c}} \to (0,1^3,2^2,3)^{+-}_{\mathrm{hyb.}}$$

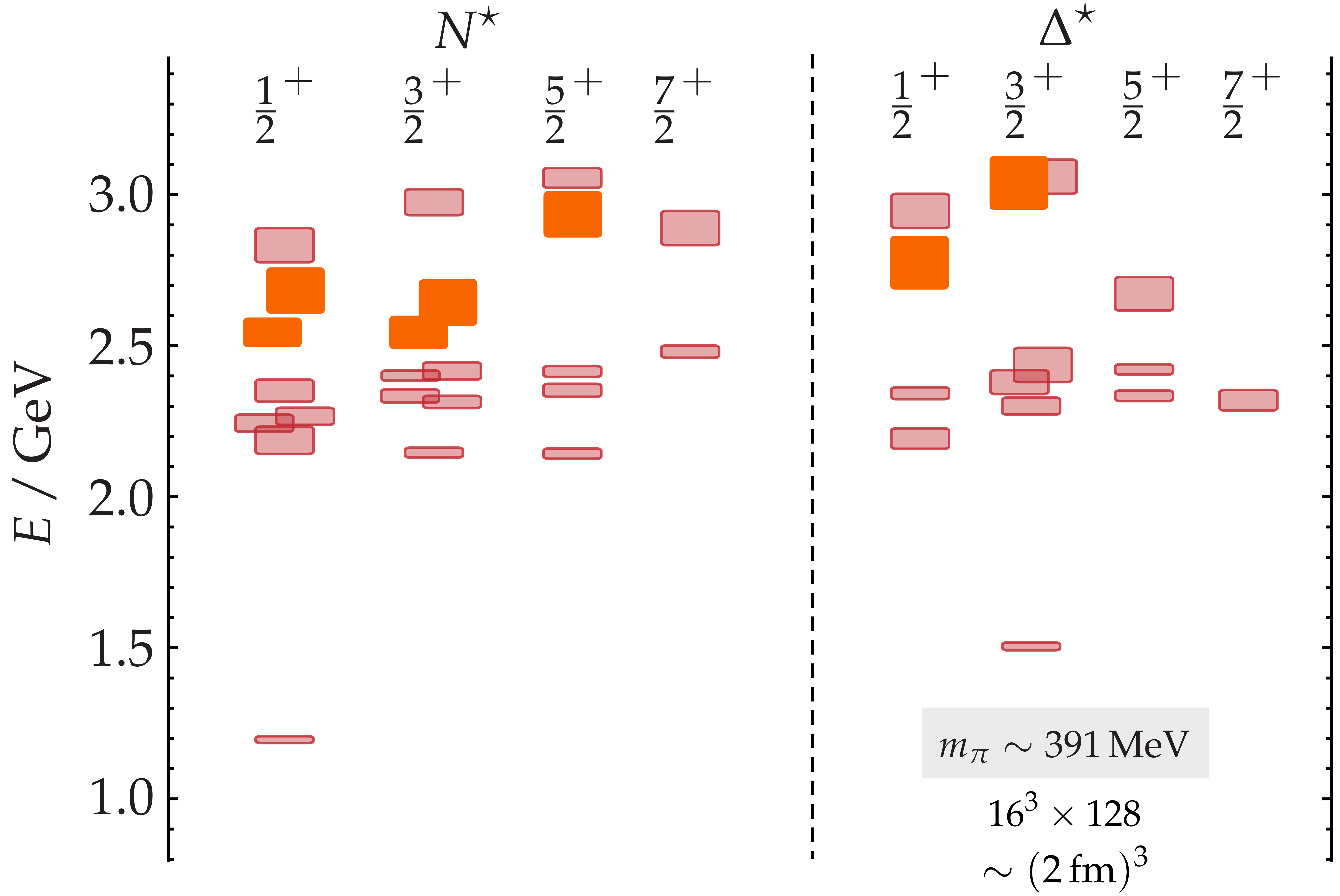
CHARMONIUM HYBRIDS



- some models have similar systematics
  - bag model also has *1*⁺⁻ lowest in energy
  - *1*⁺⁻ in a Coulomb-gauge approach

excited baryons

- a ‘super’-multiplet of **hybrid baryons**



spectrum from large basis of baryon operators

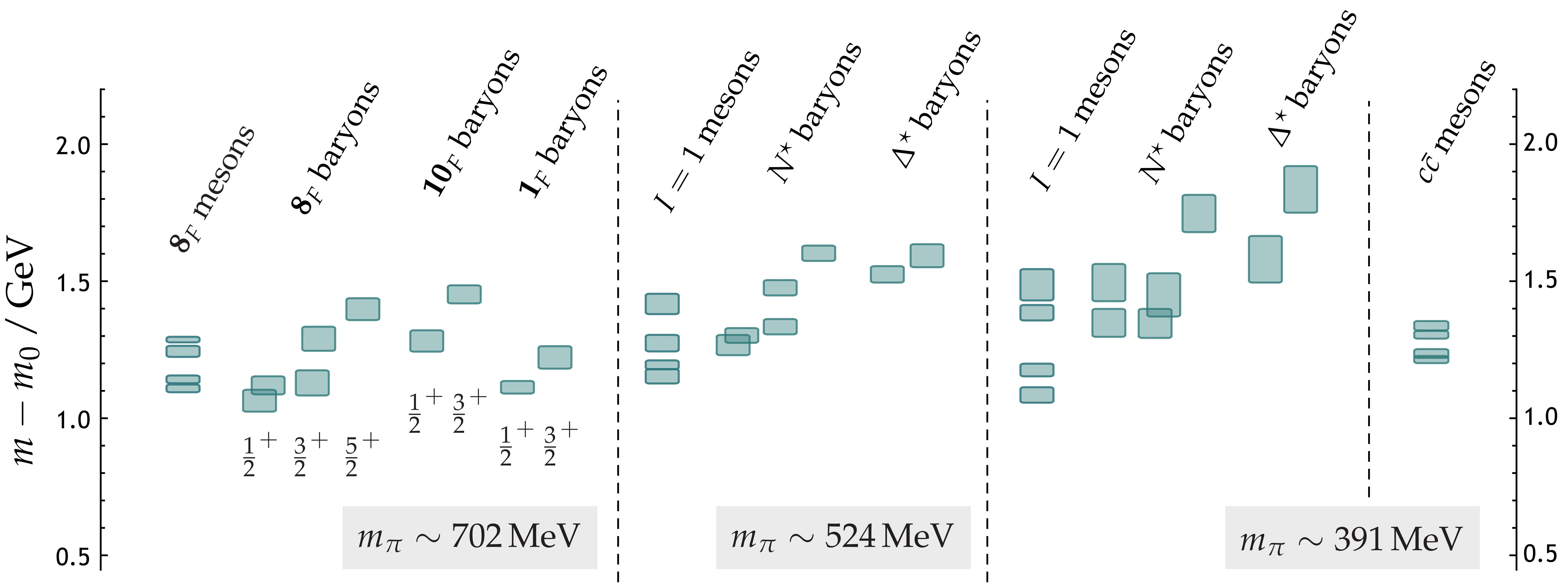
$$\epsilon_{abc}\left(D^{n_1}\tfrac{1}{2}(1\pm\gamma_0)\psi\right)^a\left(D^{n_2}\tfrac{1}{2}(1\pm\gamma_0)\psi\right)^b\left(D^{n_3}\tfrac{1}{2}(1\pm\gamma_0)\psi\right)^c$$

PRD84 074508 (2011)
PRD85 054016 (2012)

chromo-magnetic excitation

- subtract the ‘quark mass’ contribution

$$m_0^{\text{mes}} = m_\rho$$
$$m_0^{\text{bar}} = m_N$$
$$m_0^{c\bar{c}} = m_{\eta_c}$$



SU(3)$_F$ point

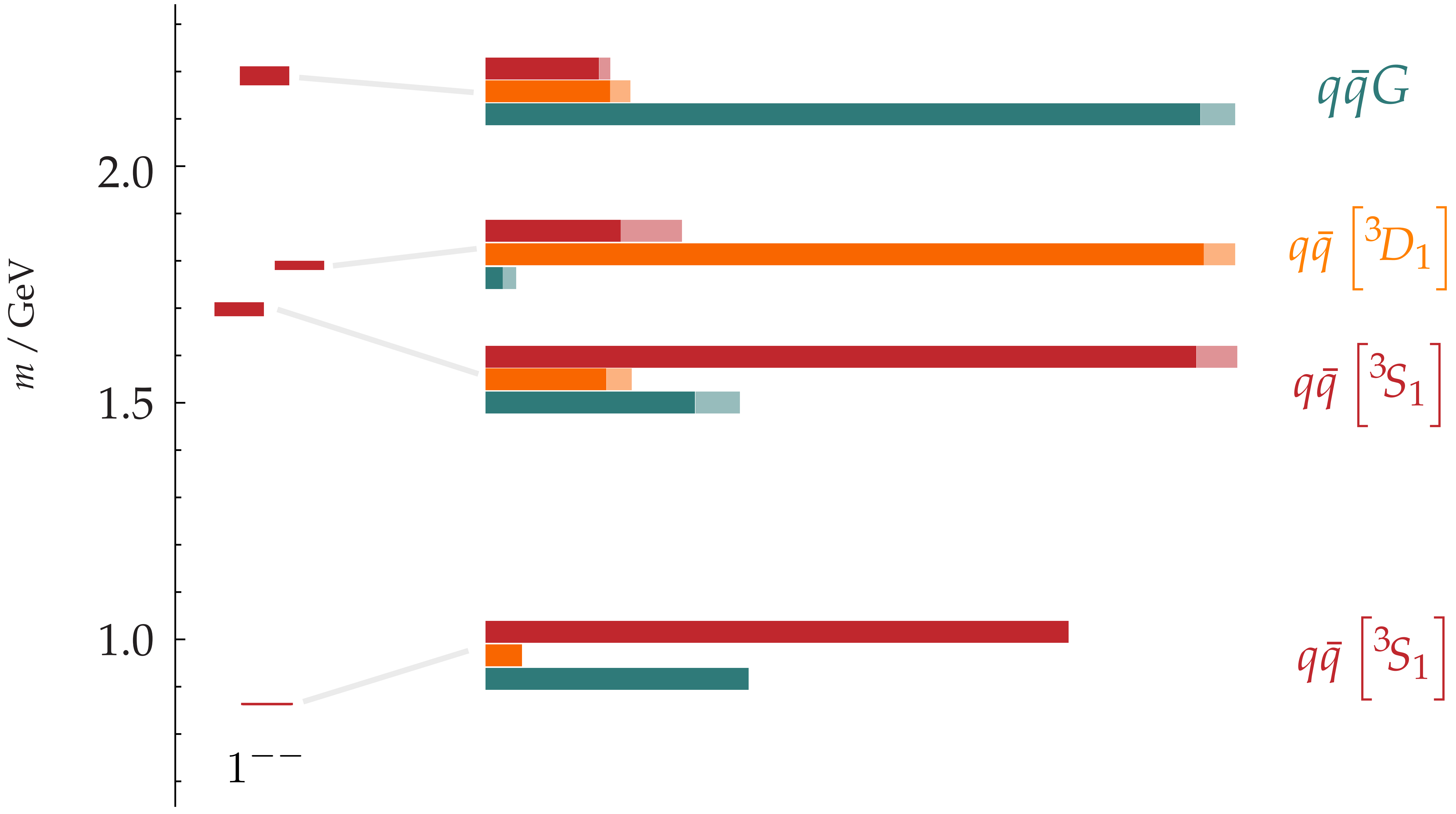
common energy scale of chromomagnetic gluonic excitation $\sim 1.3\,\text{GeV}$

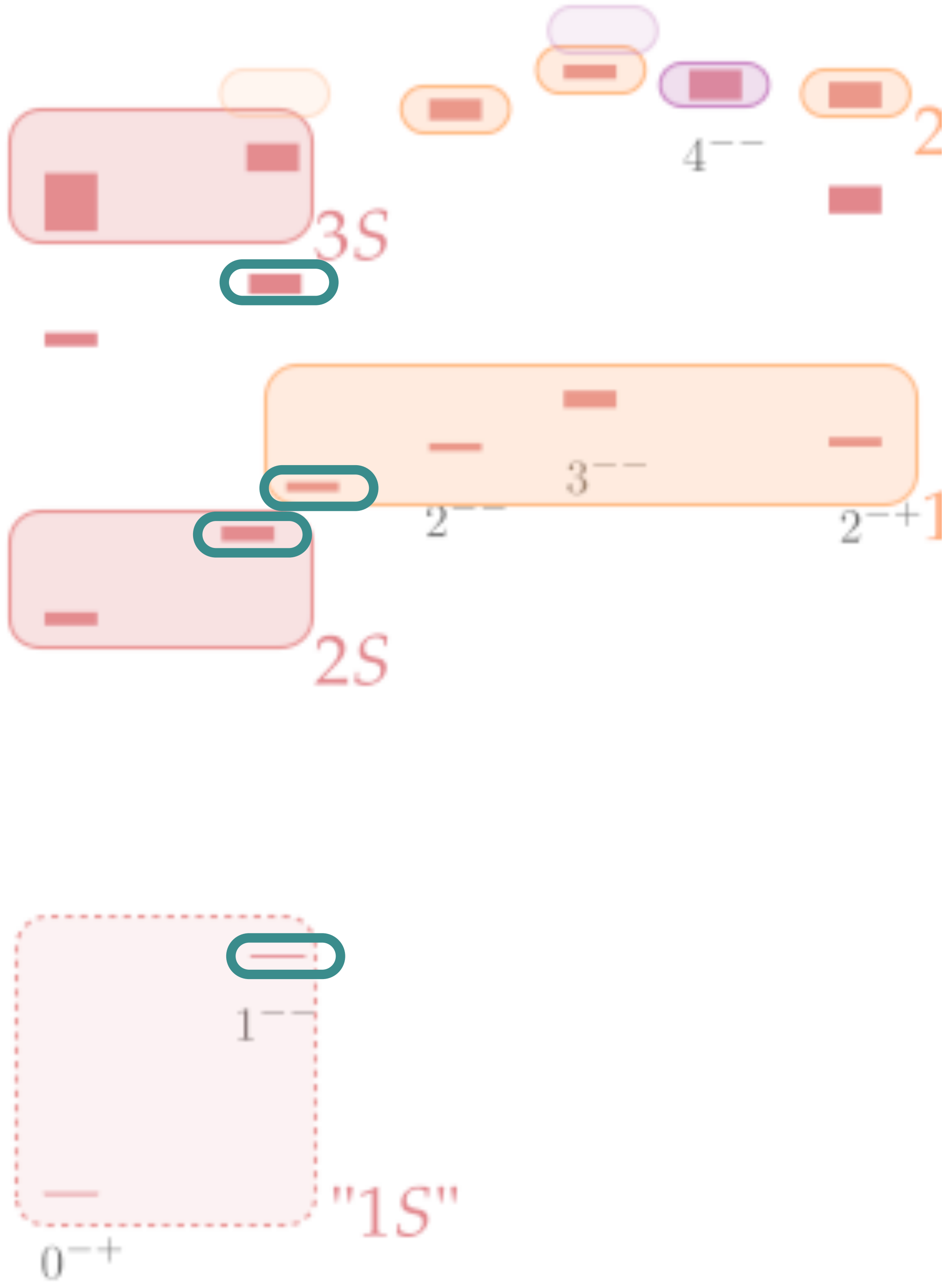
lowest gluonic excitation in QCD now determined ?

1^{--} operator overlaps

- consider the relative size of operator overlaps

$$\langle \mathfrak{n} | \mathcal{O}_i^\dagger | \varnothing \rangle$$



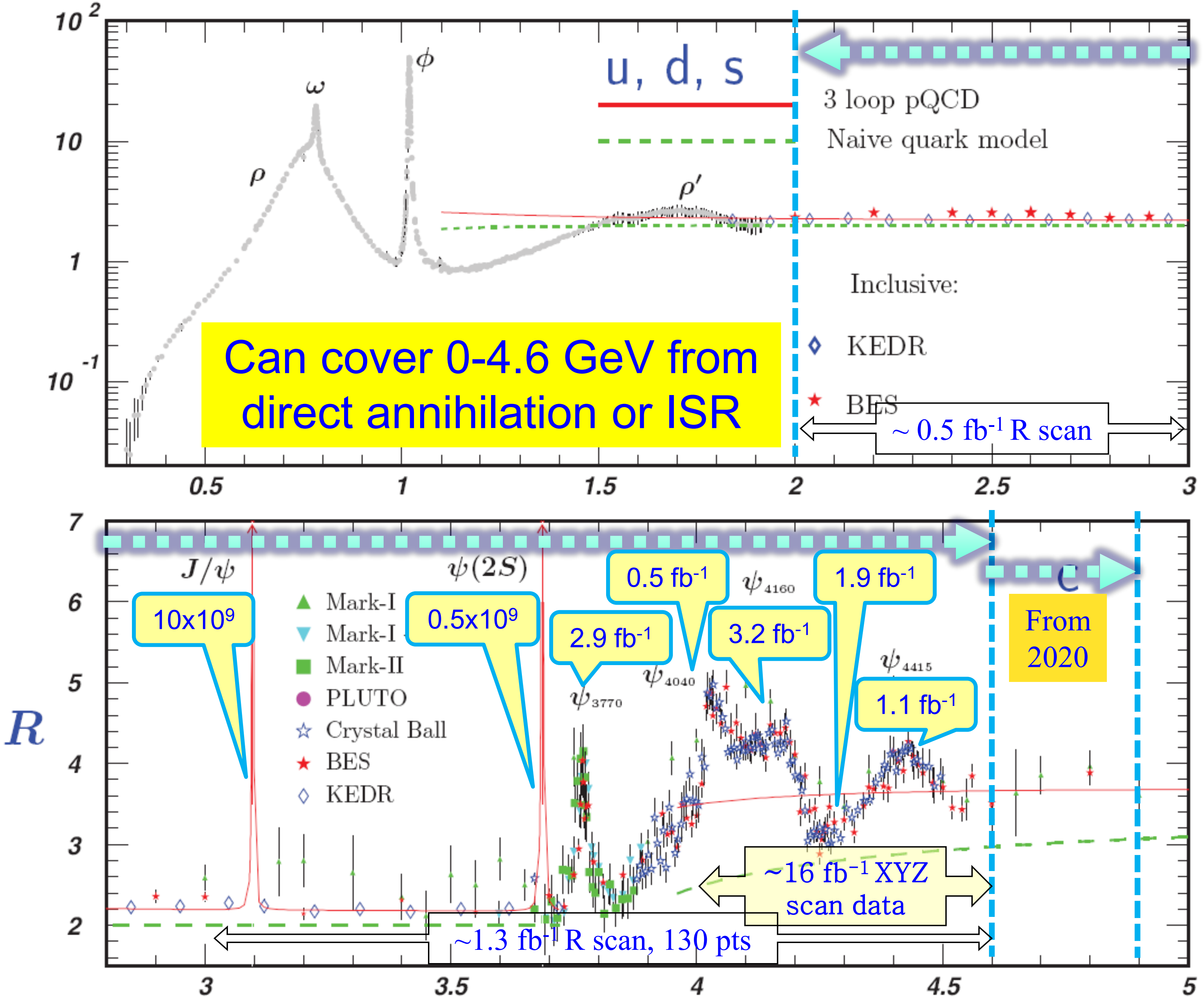


BESIII, Belle II & XYZ states

Changzheng Yuan

IHEP, Beijing

Hadron2019, Aug. 19, 2019

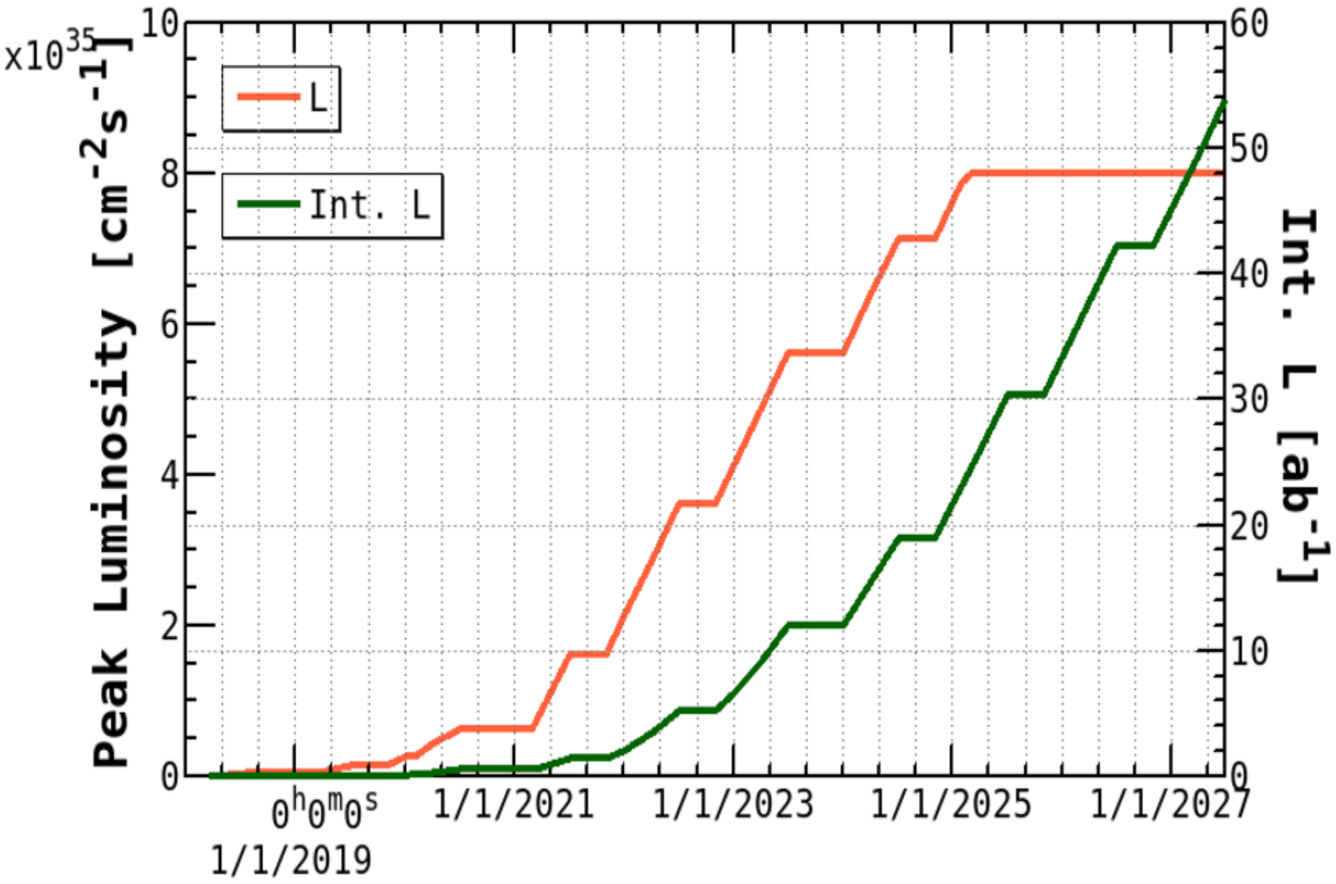


u, d, s
3 loop pQCD
Naive quark model
Inclusive:
KEDR
BES
~ 0.5 fb-1 R scan
Can cover 0-4.6 GeV from direct annihilation or ISR
ω
φ
ρ
ρ′
R
J/ψ
ψ(2S)
10x10⁹
0.5x10⁹
2.9 fb-1
0.5 fb-1
3.2 fb-1
1.9 fb-1
1.1 fb-1
ψ3770
ψ4040
ψ4160
ψ4415
Mark-I
Mark-I
Mark-II
PLUTO
Crystal Ball
BES
KEDR
From 2020
~16 fb-1 XYZ scan data
~1.3 fb-1 R scan, 130 pts

Belle II luminosity

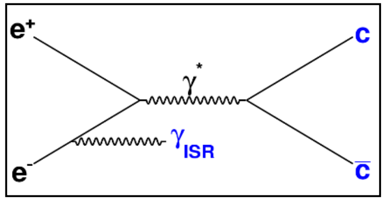
4.4-4.9 GeV
Peak Lum.
($\times 10^{33}$)

2.5
2.0
1.5
1.0
0.5
0.0

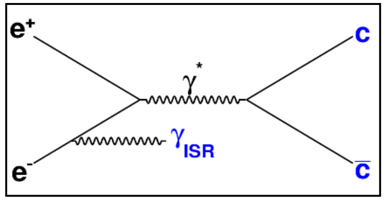


4.4-4.9 GeV
Int. Lum.
(fb^{-1})

150
125
100
75
50
25
0



$\varepsilon_{\mathrm{Belle\ II}} \sim \frac{1}{4}\, \varepsilon_{\mathrm{BESIII}}$ **for** $e^+e^- \rightarrow \pi^+\pi^- J/\psi$



5.2. Issues and opportunities in experiments

In X sector:

- X(3872) line shape
- X(3872) BR
- Inclusive B→KX(3872)
- Search for X_b [the bottomonium analog of the X(3872)]
- Search for states with exotic J^{PC}

In Y sector:

- Study Y(4630)/Y(4660)
- Line shapes of more final states in e^+e^- annihilation
- Coupled-channel analysis
- Search for the Y/ψ states above 4.7 GeV
- Y_b states?

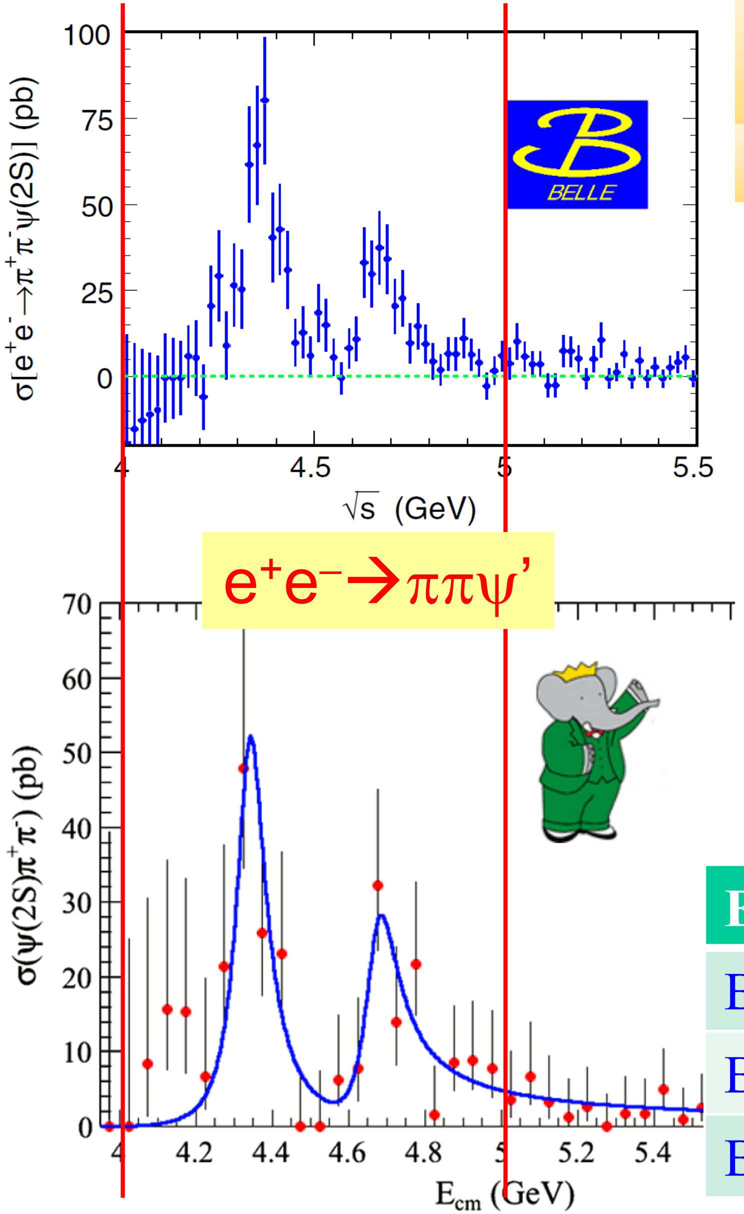
In Z sector:

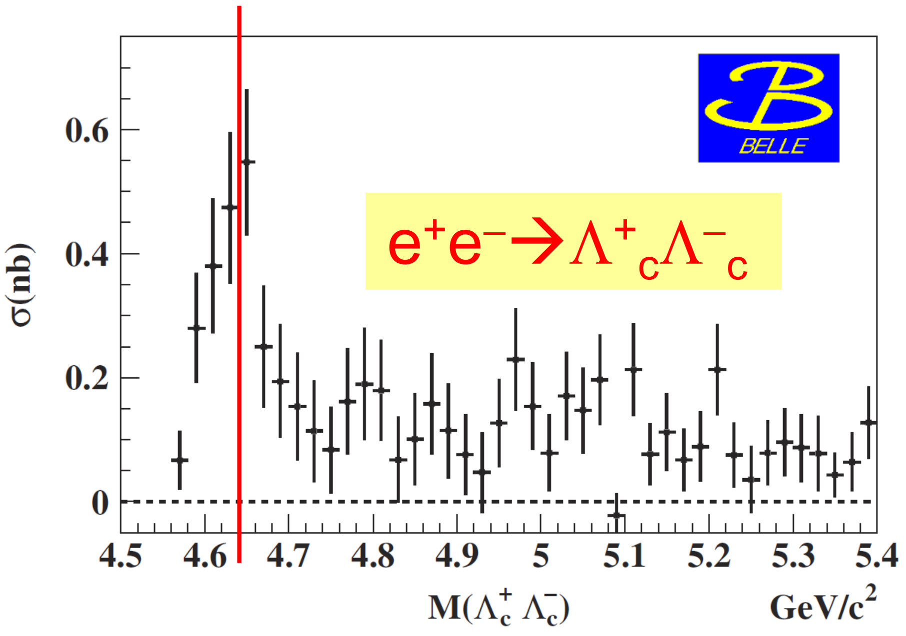
- Z_c production in e^+e^- annihilation, in B or other particle decays
- Spin-parity, Argand plot of the resonant amplitude
- Search for more Z_c states, search for Z_{cs} and Z_s states
- More decay modes
- Z_b production & properties
- Search for quantum number partners of the Z states

Y(4630)=Y(4660)? $Z_c(4430)$ in $e^+e^- \to \pi^+\pi^-\psi'$? Z_{cs} exists?

Belle: PRD91, 112007 (2015), 980/fb
BaBar: PRD89, 111103 (2014), 520/fb

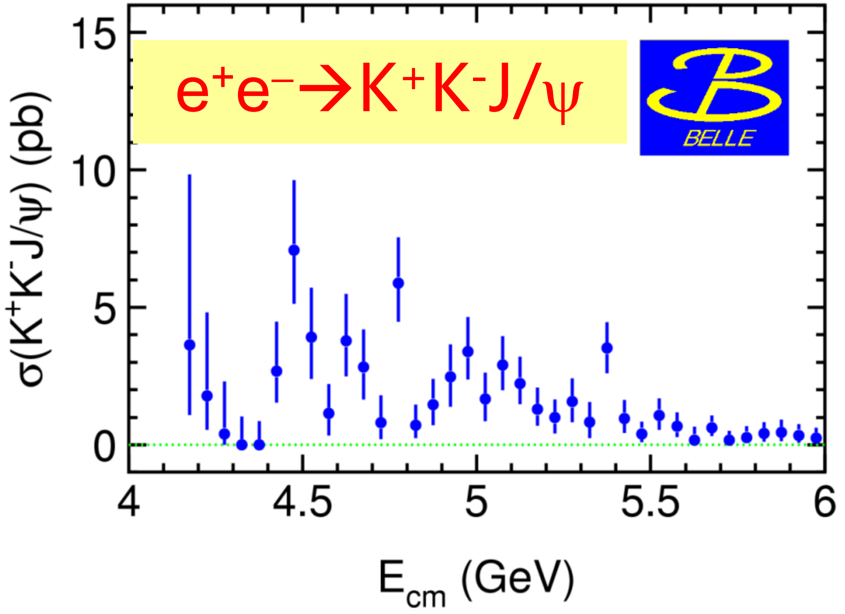
Belle: PRL101, 172001 (2008), 695/fb





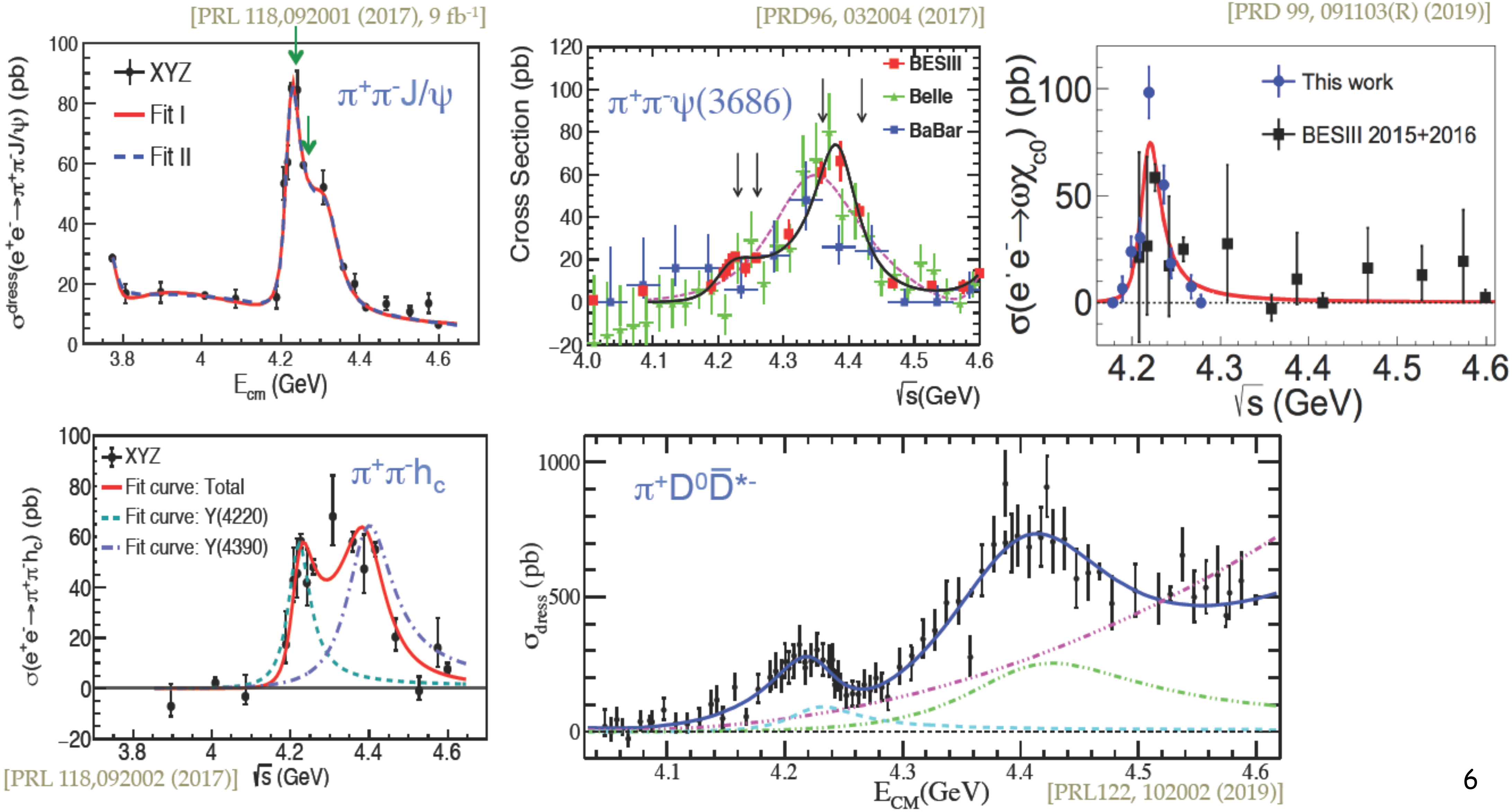
Experiment	Mass (MeV)	Width (MeV)
Belle, Y(4630)	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, Y(4660)	4652±10±8	68±11±1
Babar, Y(4660)	4669±21±3	104±48±10

Z_{cs} related to $D_sD^*/D_s^*D/D_s^*D^*$ thresholds?

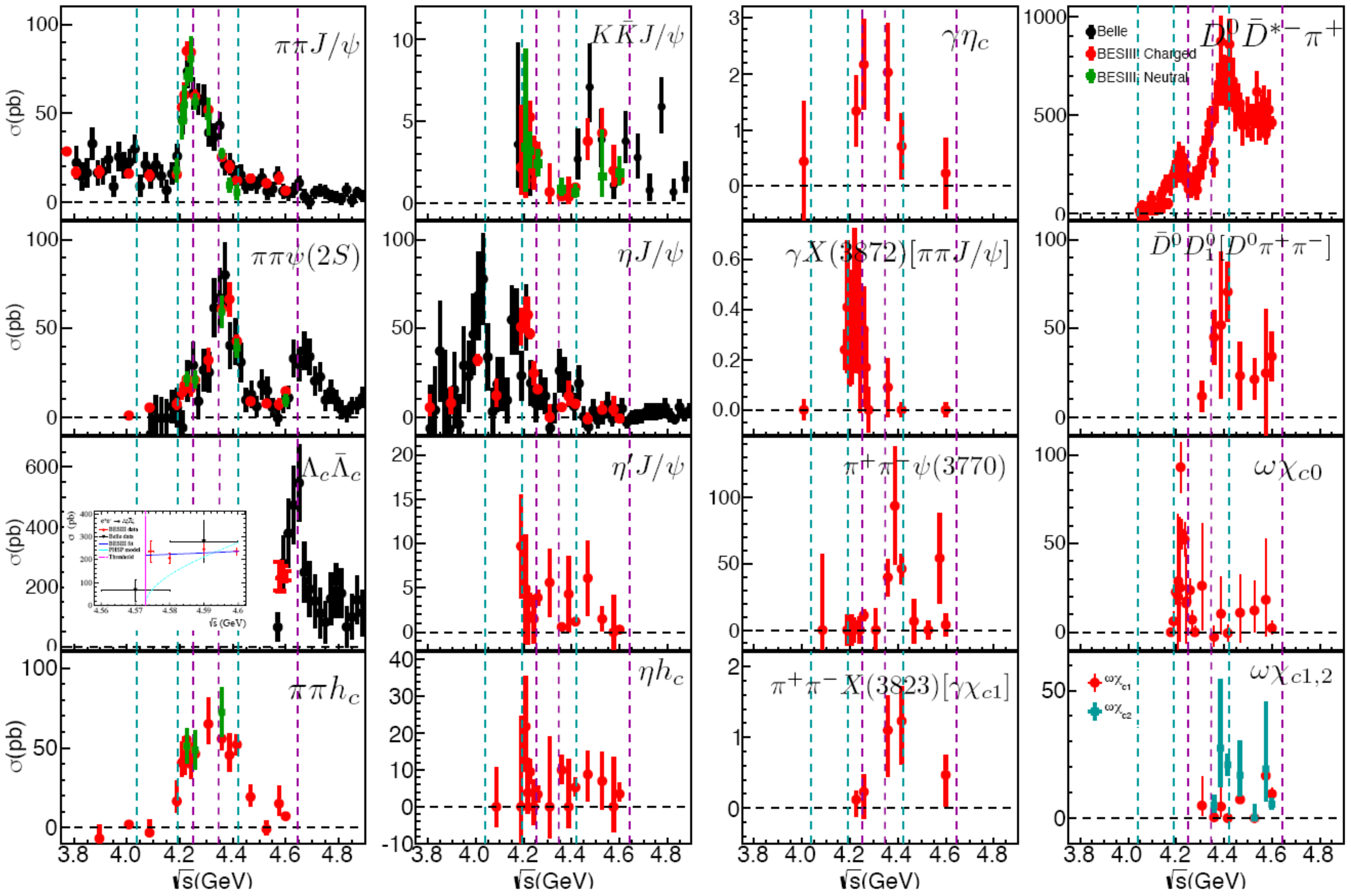


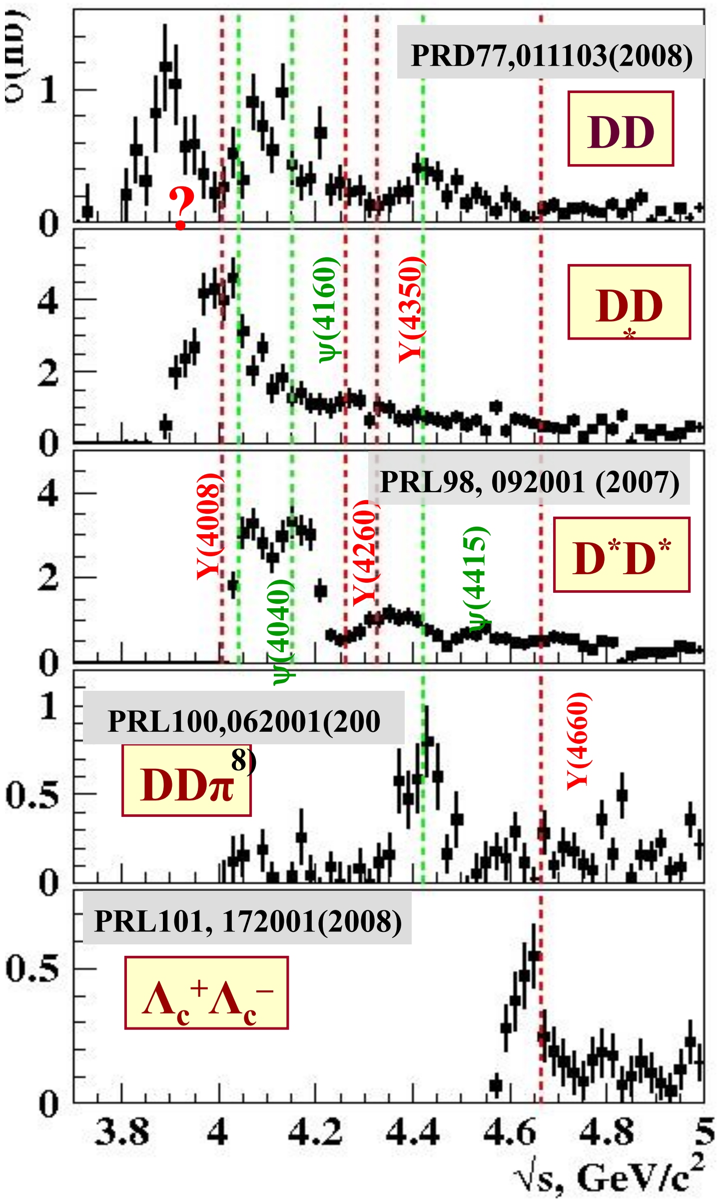
Search for Z_{cs} ($c\bar{c}u\bar{s}$) in K^+K^-J/ψ, $K^+D_s^-D^*$, $K^+D_s^{*-}D$, and $K^+D_s^{*-}D^*$ final states.

From Y. P. Guo's talk: **Y states with high precision data**

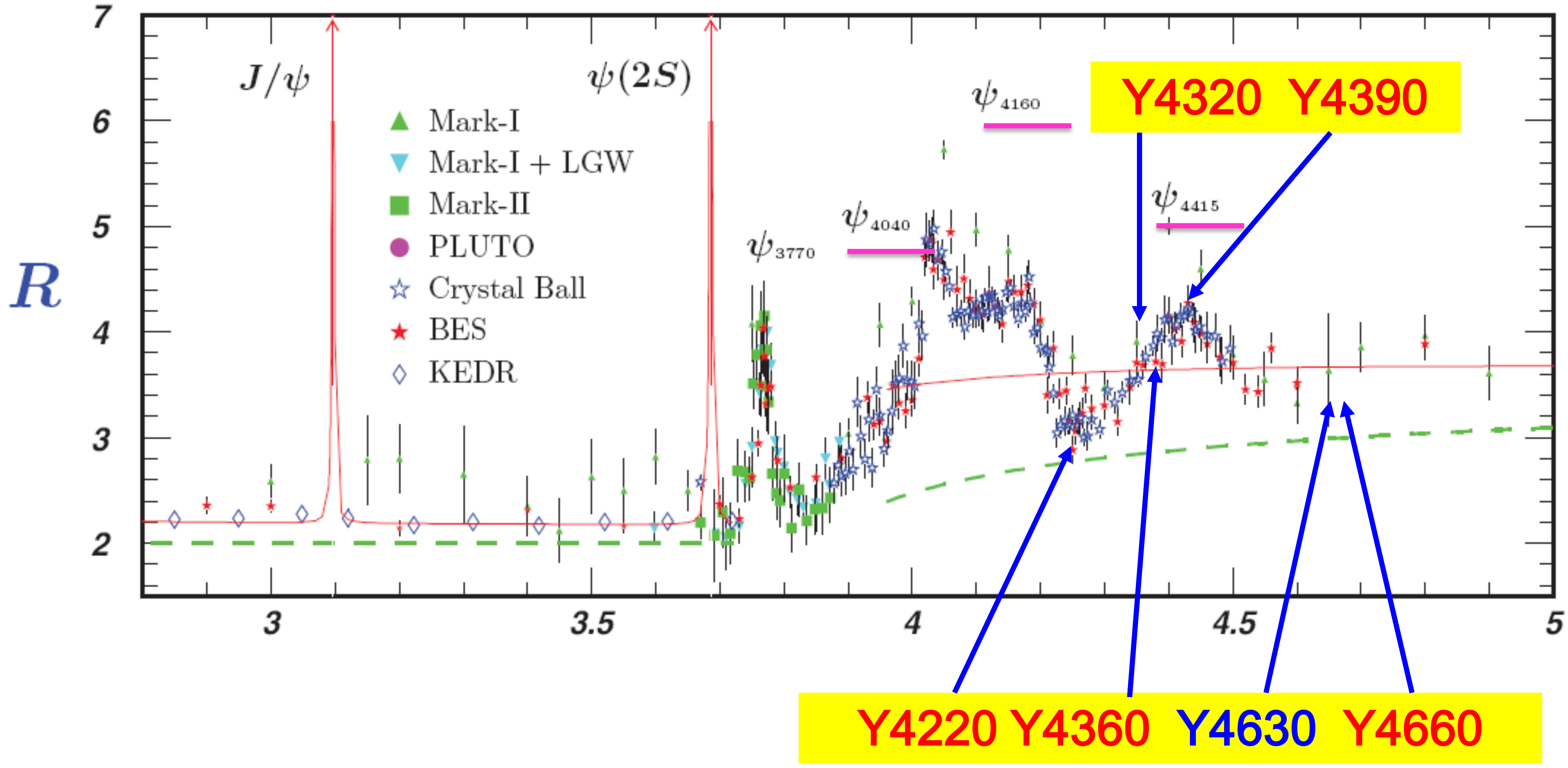


After we have measured all the e^+e^- annihilation cross sections, what do we do to get the resonant parameters of the vector charmonium(-like) states?





Are they charmonium states?



backup

Belle II vs. BESIII in XYZ study

Full Belle II data sample (50 ab^{-1} at 10.58 GeV, ISR events in 10 MeV) compared with 0.5 fb^{-1} at BESIII

ISR mode	$L_{BESIII}/L_{Belle\ II}$	$\varepsilon_{BESIII}/\varepsilon_{Belle\ II}$	$N_{BESIII}/N_{Belle\ II}$
$\pi^+\pi^- J/\psi$ @ 4.26 GeV	0.5 fb^{-1} / 2.2 fb^{-1}	46% / 10%	1.07
$\pi^+\pi^-\psi'$ @ 4.36 GeV	0.5 fb^{-1} / 2.3 fb^{-1}	41% / 5%	1.82
@ 4.66 GeV	0.5 fb^{-1} / 2.5 fb^{-1}	35% / 6%	1.19
$\pi^+\pi^- h_c$ @ 4.26 GeV @ 4.36 GeV	0.5 fb^{-1} / 2.2 fb^{-1}	2.7% / —	> 5
$K^+K^- J/\psi$ @ 4.6 GeV	0.5 fb^{-1} / 2.4 fb^{-1}	29% / 7.5%	0.81
@ 4.9 GeV	0.5 fb^{-1} / 2.7 fb^{-1}	~29% / 10%	0.54
$\Lambda^+_c\Lambda^-_c$ @ 4.6 GeV	0.5 fb^{-1} / 2.4 fb^{-1}	51% / 7.5%	1.42
@ 4.9 GeV	0.5 fb^{-1} / 2.7 fb^{-1}	~37% / 7.5%	0.91

Liming Zhang

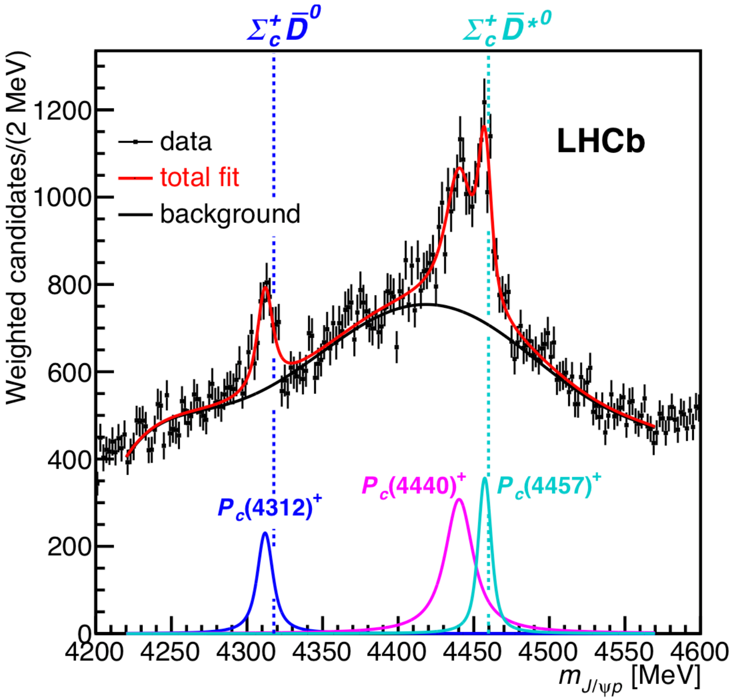
Exotic hadrons

- A large amount of studies are under way and/or prospected to understand the nature of exotic hadrons, e.g.
  - Establishing multiplets of observed tetraquarks and pentaquarks
  - Prompt production of exotic hadrons
  - Tetraquarks with open heavy flavour(s): $(bb)(\bar{q}\bar{q}')$, $(cc)(\bar{q}\bar{q}')$, $(bs)(\bar{q}\bar{q}')$, $(cs)(\bar{q}\bar{q}')$
  - Search for analogs in the beauty sector

Most of them might need a much lager sample

Pentaquarks

- Three narrow P_c^+ states observed in $\Lambda_b^0 \to J/\psi p K^-$ decays
- A lot of open questions:
  - J^P, mode decay modes,…?
  - SU(3) partners, hidden-bottom pentaquarks?
- An incomplete list of decays for pentaquark studies



PRL 122 (2019) 222001

- ✓ $B_c^+ \to J/\psi p\bar{p}\pi^+$
- ✓ $\Upsilon(1S) \to J/\psi p\bar{p}$
- ✓ $B_s^0 \to J/\psi p\bar{p}$
- ✓ $B^+ \to J/\psi p\bar{\Lambda}$
- ✓ Prompt $J/\psi p$, $J/\psi\Lambda$, Υp
- ✓ $\Lambda_b^0 \to \eta_c p K^-$
- ✓ $\Lambda_b^0 \to \chi_{c1} p K^-$
- ✓ $\Xi_b^- \to J/\psi \Lambda K^-$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ D^- K^*$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ D_s^- \phi$
- ✓ $\Lambda_b^0 \to J/\psi p\pi^+\pi^- K^-$
- ✓ $\Lambda_b^0 \to \Sigma_c^{++} D^- K^-$
- ✓ $\Lambda_b^0 \to J/\psi \Lambda\phi$
- ✓ $\Lambda_b^0 \to J/\psi \Lambda\eta^{(\prime)}$

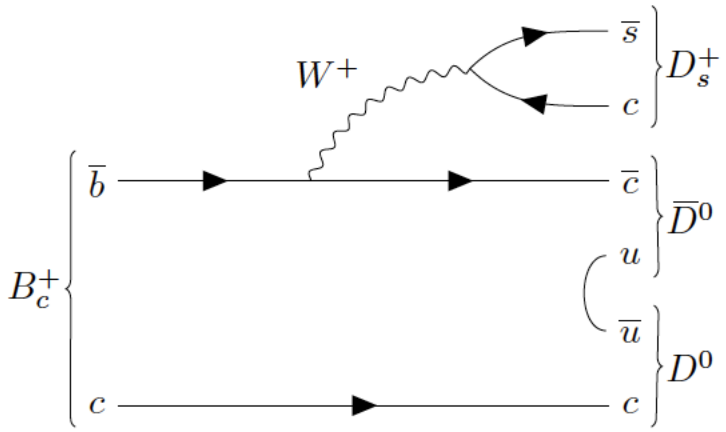
Similar strategy for tetraquarks

Searches for $(cc)(\bar{q}\bar{q}')$

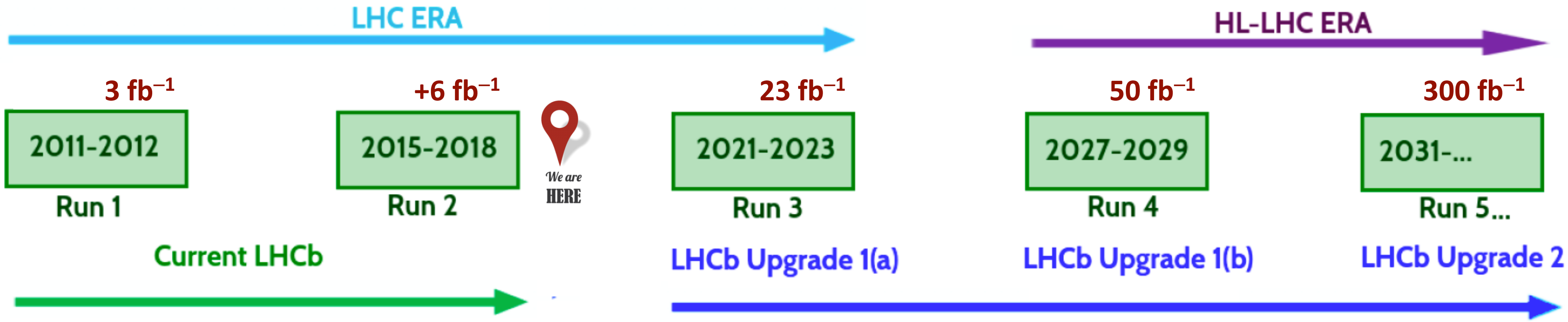
- Mesons with double charm or beauty flavours, such as $(bb)(\bar{q}\bar{q}')$, $(cc)(\bar{q}\bar{q}')$, would unambiguously be states with four quarks
- If $(cc)(\bar{q}\bar{q}')$, which decay into D^+D^+ or $D^+D_s^+$, are narrow states, they could be easily observed in prompt production
  - Associate production of D^+D^+ or $D^+D_s^+$ with 0.3fb^{-1} data
  - Expected yields $N(D^+D^+) \approx$ 100k $N(D^+D_s^+) \approx$ 20k with 50fb^{-1}
- Can be also searched for in B_c^+ decays with 300fb^{-1}

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]
D^+D^+	$80 \pm 10 \pm 10$	9.6 ± 1.6
D^+D^-	$780 \pm 40 \pm 130$	
$D^+D_s^+$	$70 \pm 15 \pm 10$	12.1 ± 3.3
$D^+D_s^-$	$550 \pm 60 \pm 90$	

LHCb, JHEP 06 (2012) 141



LHCb upgrade schedule



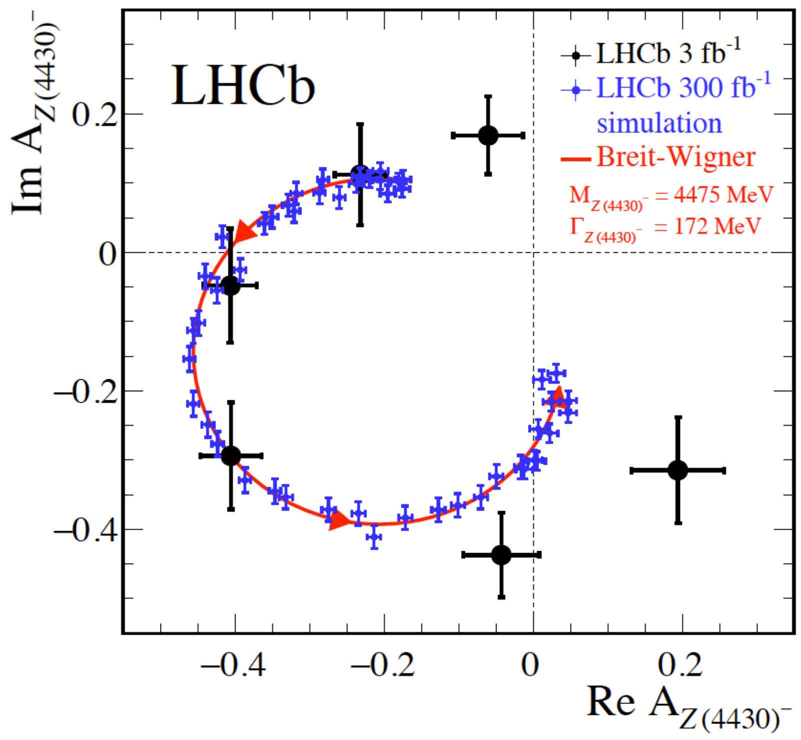
- LHCb is now boosting the data to a new level
  - Most of LHCb results are still finalizing with full Run 1-2 data
  - Expect to **7x** more data (**14x** more hadronic events) by 2029 than current data
  - Could have another factor of **6** increase from Upgrade II

CERN-LHCC-2018-027
arXiv:1808.08865

Summary

- A good review of open questions and many interesting ideas for physics at LHCb upgrade from theorist and experimentalists [arXiv:1812.07638]

Decay mode	LHCb 23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi \pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$	680k	1.4M	8M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600



Before getting the new data, from theoretical point view, what're the most priority questions you want experiment to do with the current data?

Round-Table Discussion on Exotic Hadrons

The Light-Meson Sector

Boris Grube

Institute for Hadronic Structure and Fundamental Symmetries
Technische Universität München
Garching, Germany

XVIII International Conference
on Hadron Spectroscopy and Structure
Guilin, 18. August 2019

Huge data sets for multitude of decay and production channels

- $\mathcal{O}(10^7 \text{ to } 10^8)$ events

Light-meson exotics

- Broad states
- Often large branchings to multi-particle final states
- Often small signals: $\mathcal{O}(1\,\% \text{ to } 0.1\,\%)$ of total intensity
- Partial-wave analysis necessary

Example: COMPASS
$\pi_1(1600) \to \pi^-\pi^-\pi^+$

0.8 % of total intensity

COMPASS, PRD **98** (2018) 092003

Analyses limited by systematics

Need to understand, quantify, and reduce systematic uncertainties

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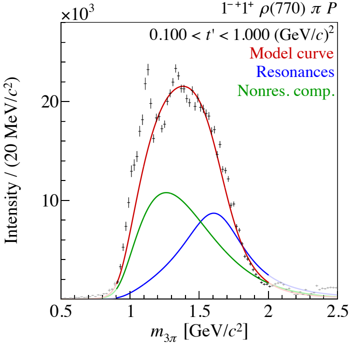

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COMPASS, PRD **98** (2018) 092003

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Example: COMPASS

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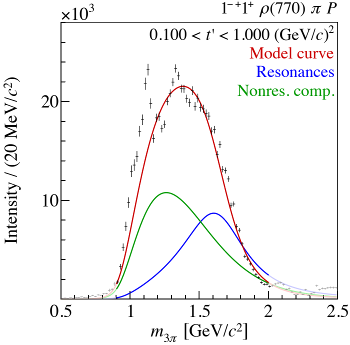

0.8 % of total intensity

COMPASS, PRD **98** (2018) 092003

Analyses limited by systematics

Need to understand, quantify, and reduce systematic uncertainties

Partial-wave decomposition

- Where to truncate the partial-wave expansion?
  - Model comparison/selection
- Need to improve models for multi-particle decay amplitudes
  - How to correctly include knowledge about subsystems?
  - How to take into account final-state interactions?
  - Model-independent methods ("freed-isobar PWA") provide testing ground

Example: COMPASS

$\pi(1800) \to [\pi^- \pi^+]_{0^{++}} + \pi^- \; S$

COMPASS, PRD **95** (2017) 032004

The Light-Meson Sector

Multifaceted and Intertwined Challenges

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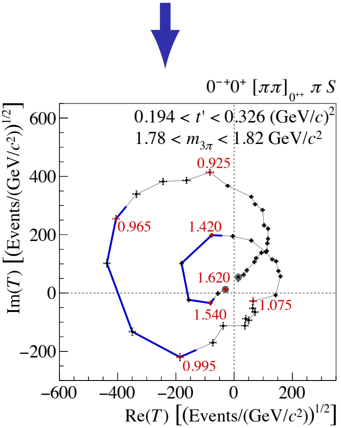

COMPASS, PRD **95** (2017) 032004

The Light-Meson Sector

Multifaceted and Intertwined Challenges

Resonance-model fits

- *Goal:* extract pole parameters of resonances
  - Requires amplitudes that fulfill S-matrix principles: analyticity, unitarity, and crossing
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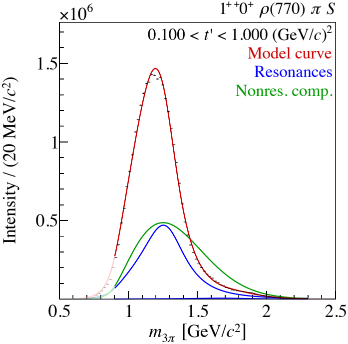
Example: COMPASS

$a_1(1260) \to \rho(770) + \pi^- \; S$



32.7 % of total intensity

COMPASS, PRD **98** (2018) 092003

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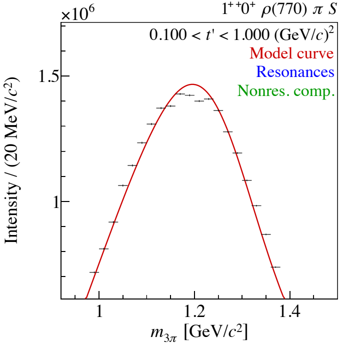

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COMPASS, PRD **98** (2018) 092003

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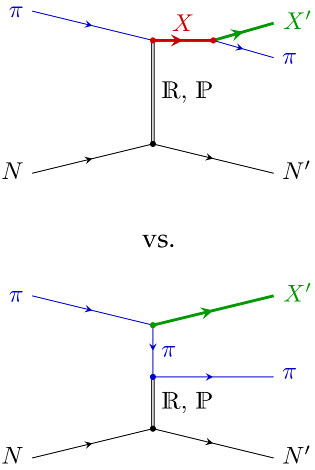

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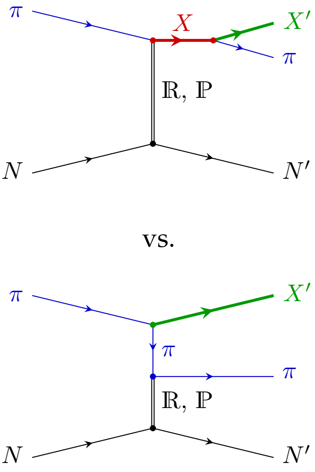


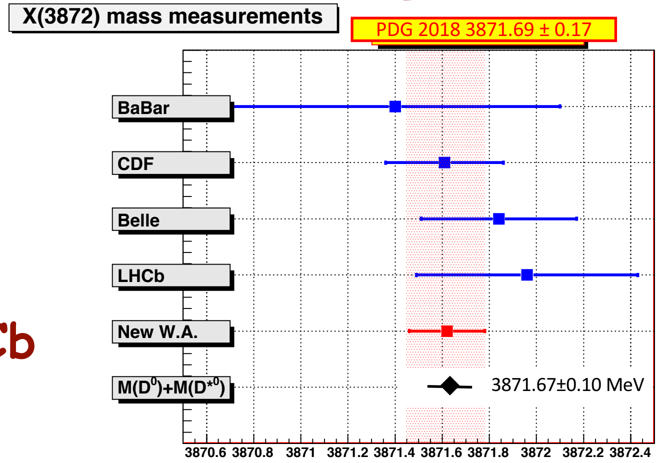
questions about the X(3872)

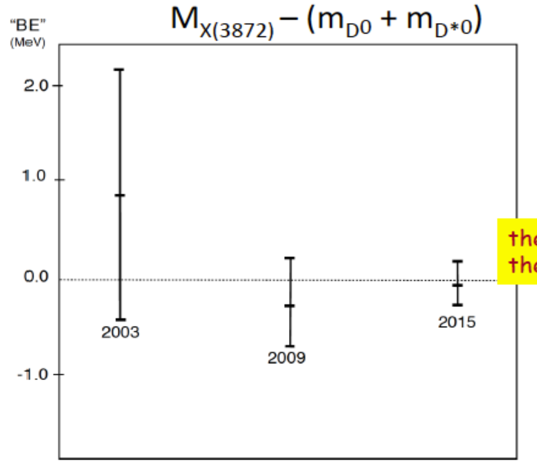
-- S. Olsen (UCAS) --

1) What is its mass relative to $m_{D^0}+m_{D^{0*}}$?

still no precision result from LHCb

"B.E."=-2 ± 148 keV

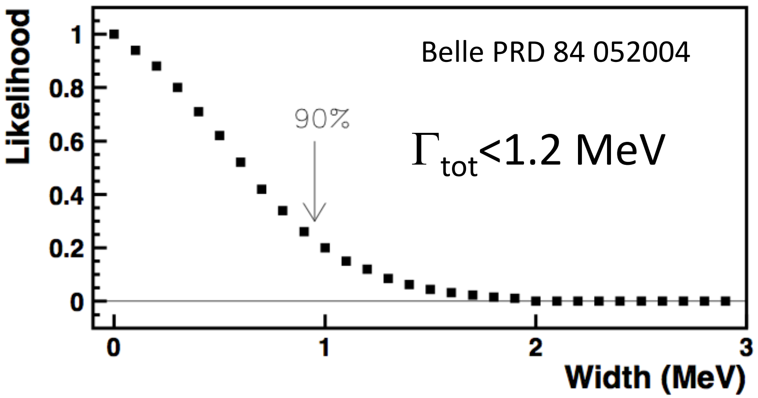




the better it is measured, the closer it is to zero

2) What is its total width?

are the rumors that LHCb has a result true?



For comparison:

$\Gamma_{\chi_{c1}}$ = 840 + 40 keV

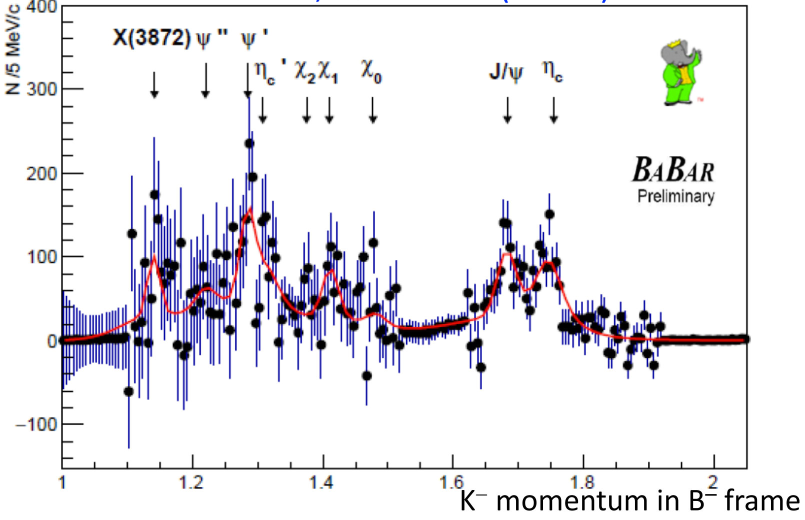
$\Gamma_{\psi'}$ = 294 + 8 keV

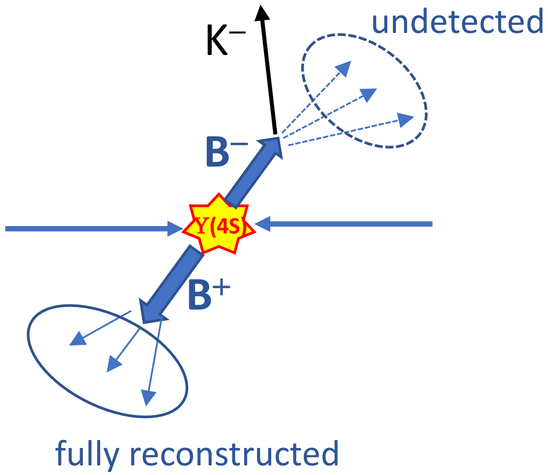
$\Gamma_{D^{*0}} \approx$ 50 keV

3) What is $Bf(B^- \to K^- X(3872))$?

needed to determine absolute X(3872) *Bf*s

G. Wormser, QWG2019 (BaBar)





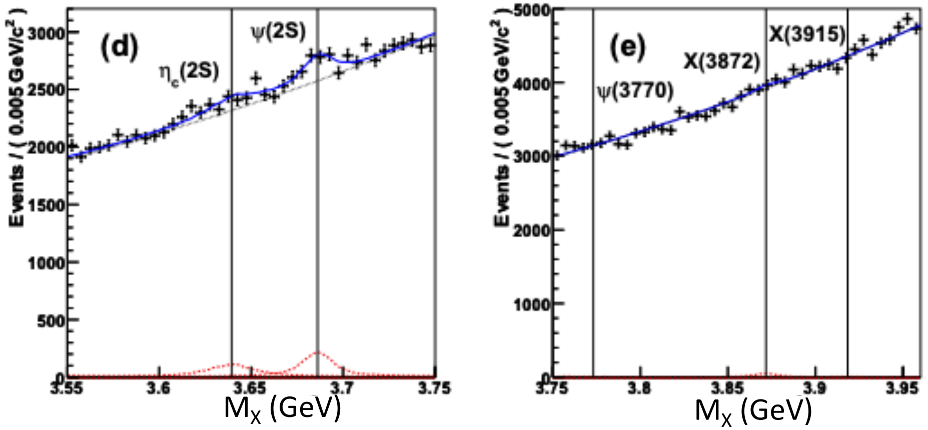
$Bf(B^- \to K^- X(3872)) = (2.1 + 0.6 + 0.3) \times 10^{-4}$

C.Z. Yuan's average:

$$B(B^- \to K^- X(3872)) = (1.8 \pm 0.6) \times 10^{-4}$$

good subject for a joint BaBar-Belle analysis?

Belle PRD 97, 012005



$Bf(B^- \to K^- X(3872)) = (1.2 + 1.1 + 0.1) \times 10^{-4}$

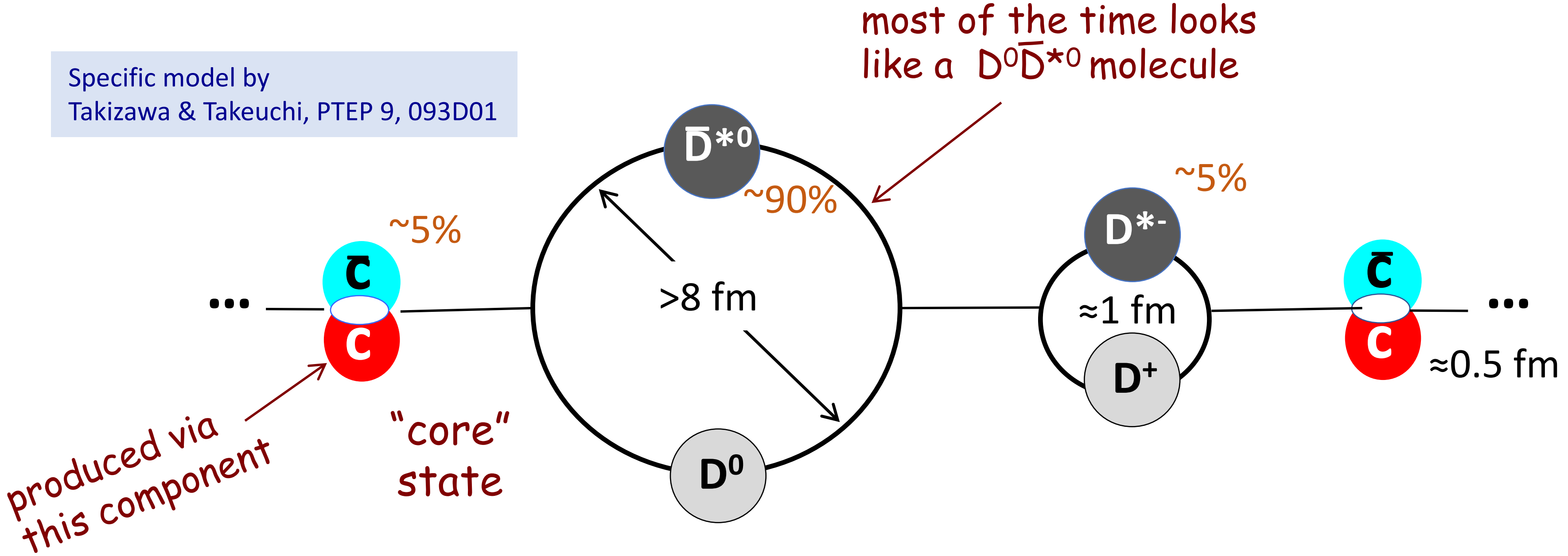
My scorecard for my favorite XYZ mesons. (Charm 2018)

state	molecule?	tetraquark?	charmonium hybrid?	kinematic effect?	hadro-charmonium?
$X(3872)$	coupled-channel system; not a deuson	partner states not found	m≈500 MeV too low	width too narrow	decays to $\gamma J/\psi$ & $\gamma\chi_{c1}$
$X(3915)$	π-exchange forbidden	$\eta\eta_c$ decay not seen	m≈500 MeV too low	no nearby threshold	???
$Y(4220)$	$D\bar{D}_1(2420)$ BE≈65 MeV -too high-	???	possible	no nearby threshold	decays to $\pi^+\pi^- J/\psi$ & $\pi^+\pi^- h_c$
$Z_C(3900)$	$D\bar{D}^*$ virtual state?	???	Isospin=1	possible?	???
$Z_c(4020)$	$D^*\bar{D}^*$ virtual state?	???	Isospin=1	possible?	???
$Z(4430)$	too wide for a $D\bar{D}^*(2P)$ molecule?	???	Isospin=1	too wide	???

X(3872) as a $D\bar{D}^*$ molecule + a $c\bar{c}$-"core" mixture?

-- "consensus" opinion (?) --

Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



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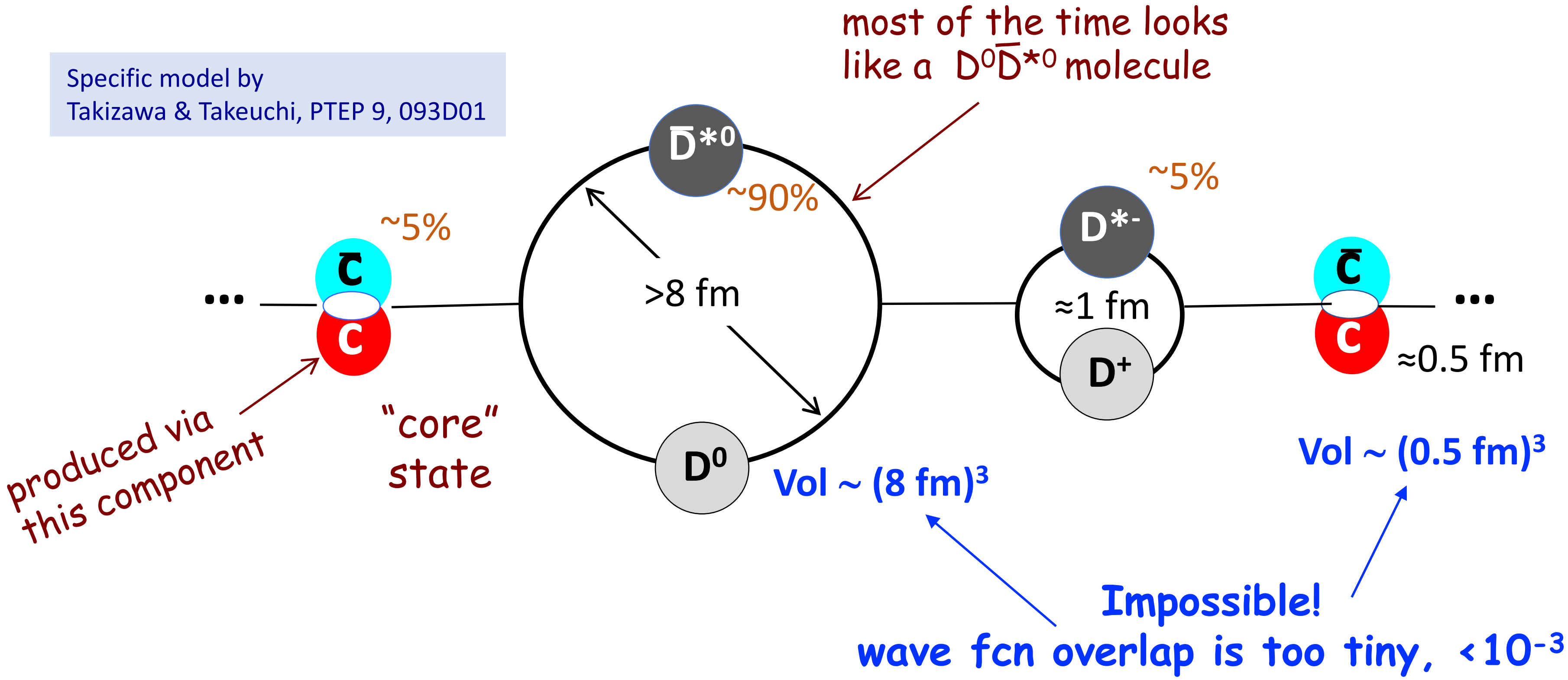
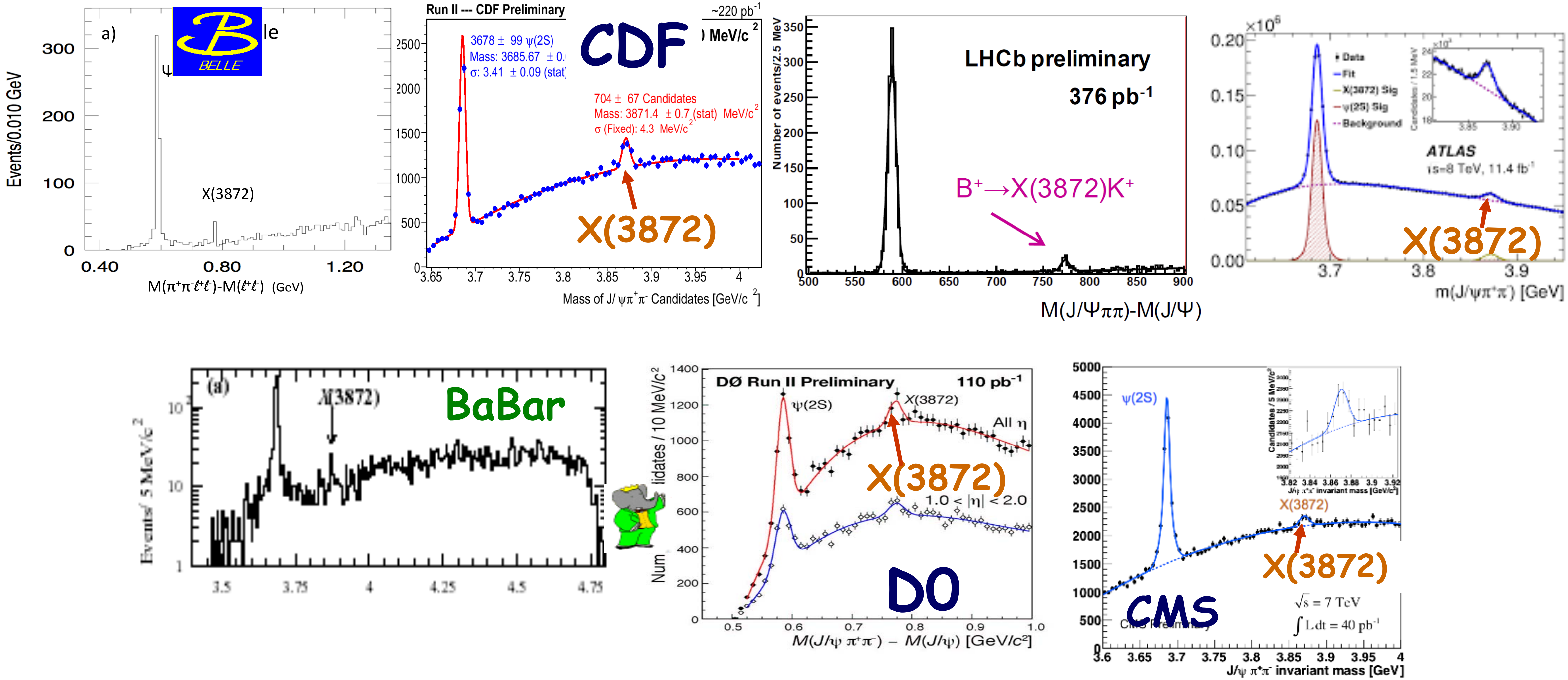


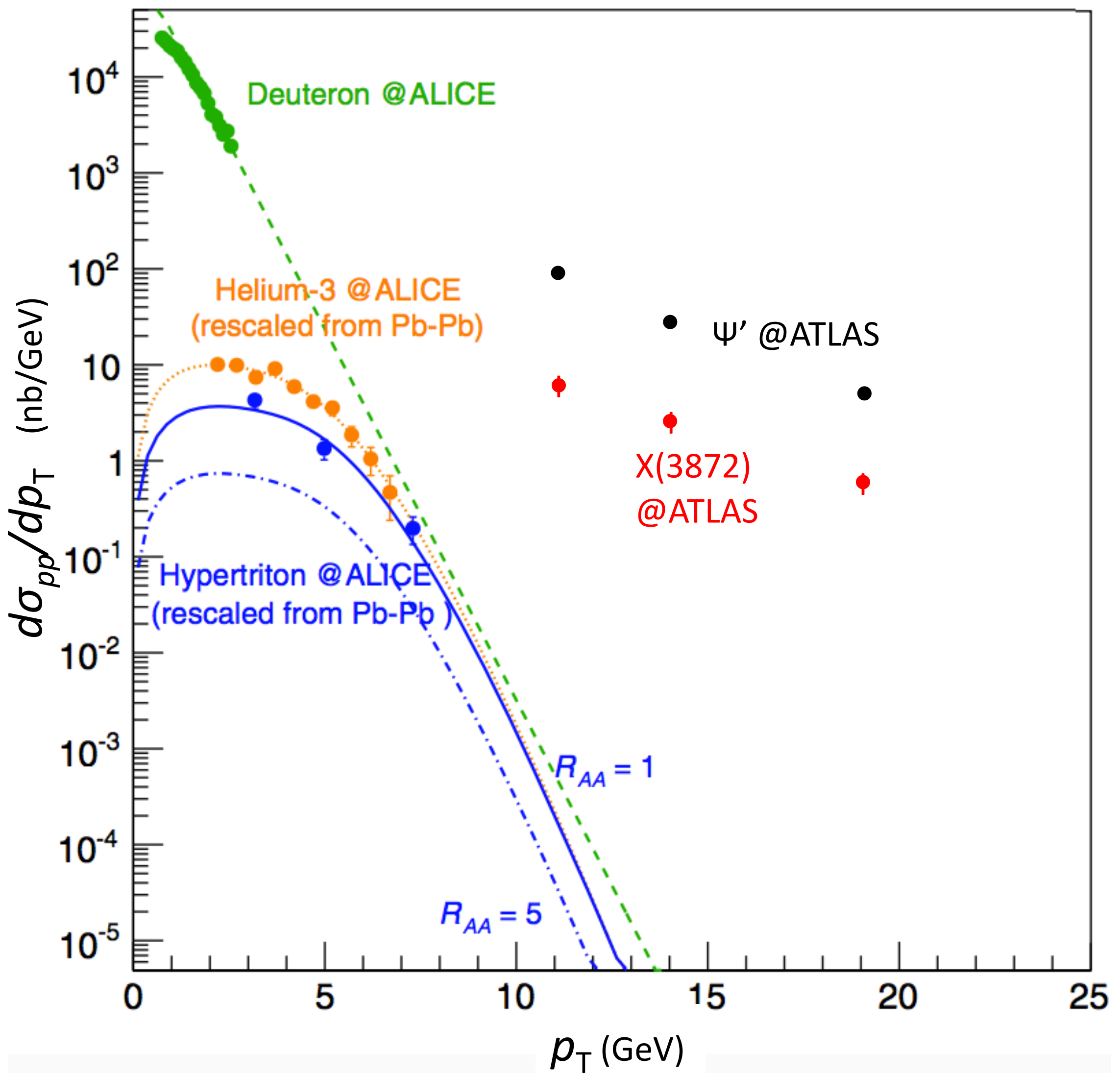
Polosa: "Multiquark Hadrons," pg 56
Achasov: MPLA 30, 1550181 (2015)

Q4) proposal to test this (LHCb? NICA? Panda?)

$X(3872) \rightarrow \pi^+\pi^- J/\psi \approx 5\%$ of $\psi' \rightarrow \pi^+\pi^- J/\psi \Leftarrow$ all production modes

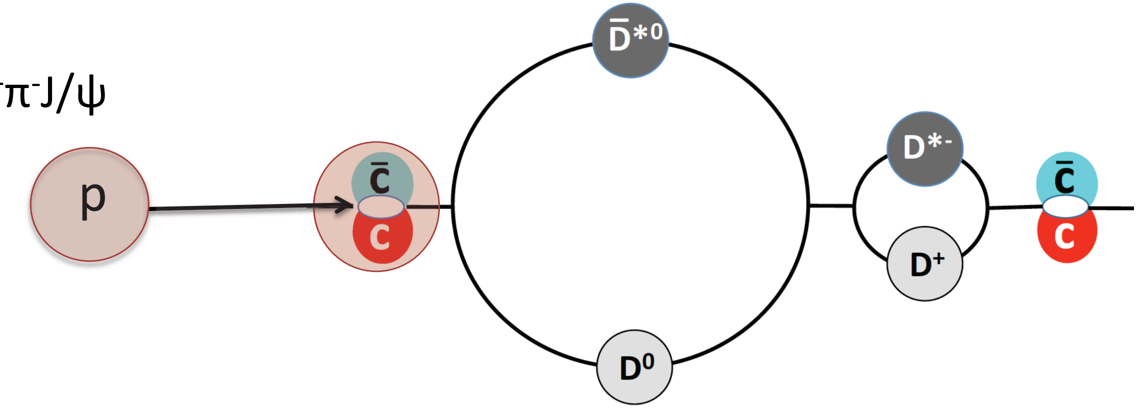


even at very high p_T



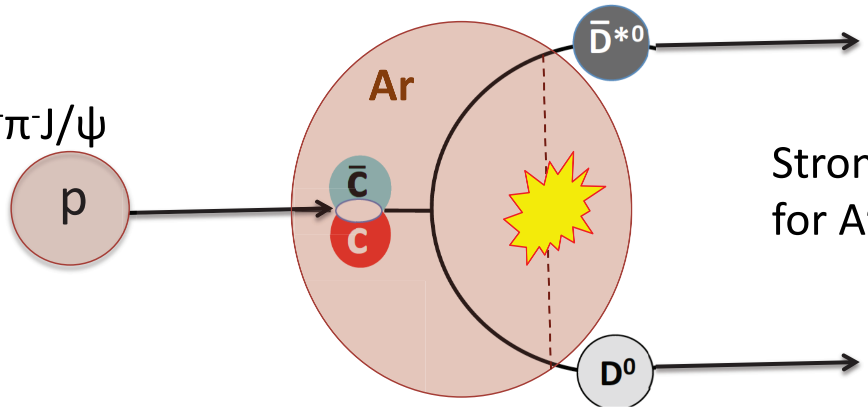
compare production ratio for pp with that for pA

pp→X(3872)→$\pi^+\pi^-$J/ψ



$$\frac{X(3872) \to \pi^+\pi^- J/\psi}{\psi' \to \pi^+\pi^- J/\psi} \approx 5\%$$

pAr→X(3872)→$\pi^+\pi^-$J/ψ



Strong quenching for A~40 nuclei??

$$\frac{X(3872) \to \pi^+\pi^- J/\psi}{\psi' \to \pi^+\pi^- J/\psi} = ???$$