Institute of Theoretical Physics
Chinese Academy of Sciences

Effective Field Theories and XYZ states at LHC and BES

Jorgivan M. Dias

What are Exotic States ?

Quark Model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

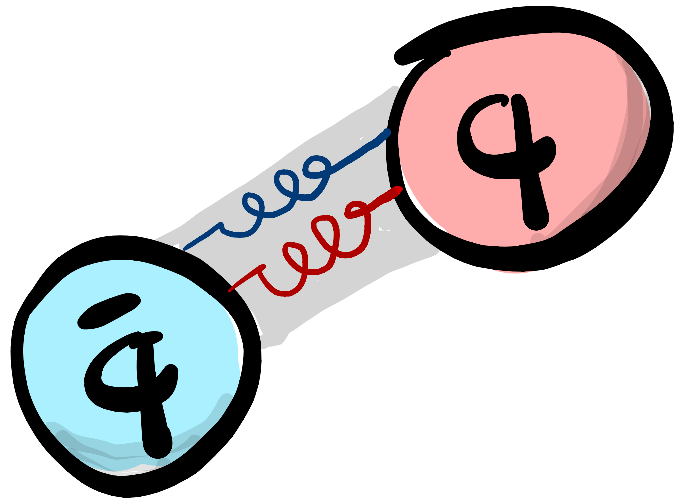
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

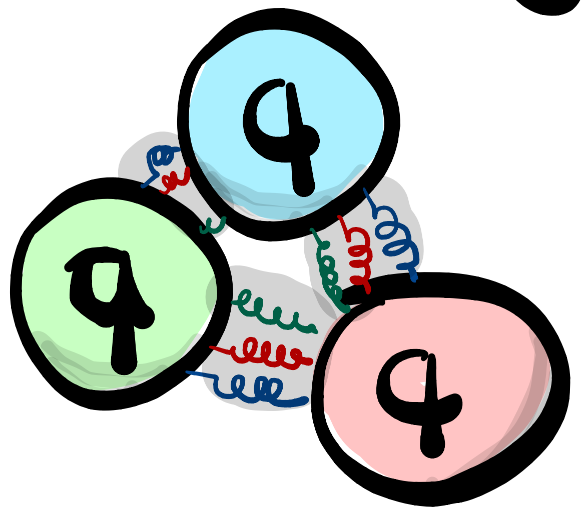
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

Exotic

Meson

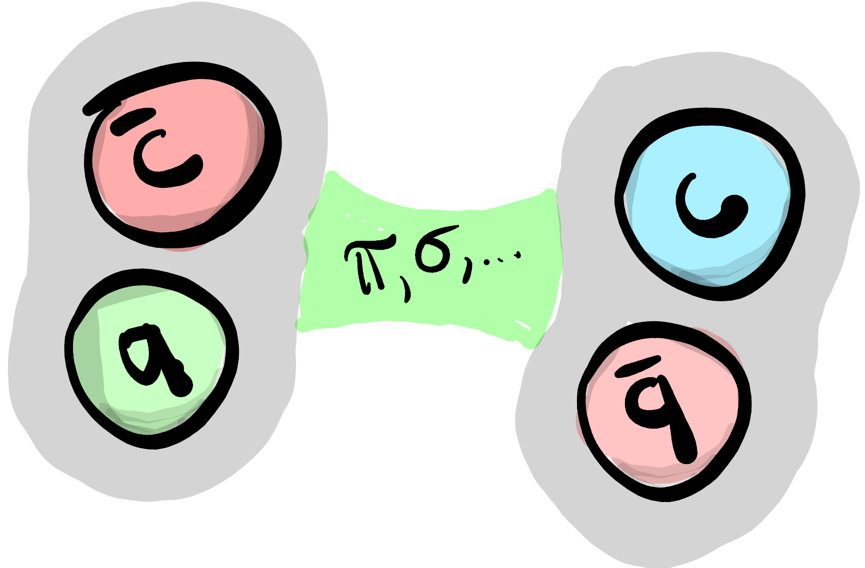


Baryon

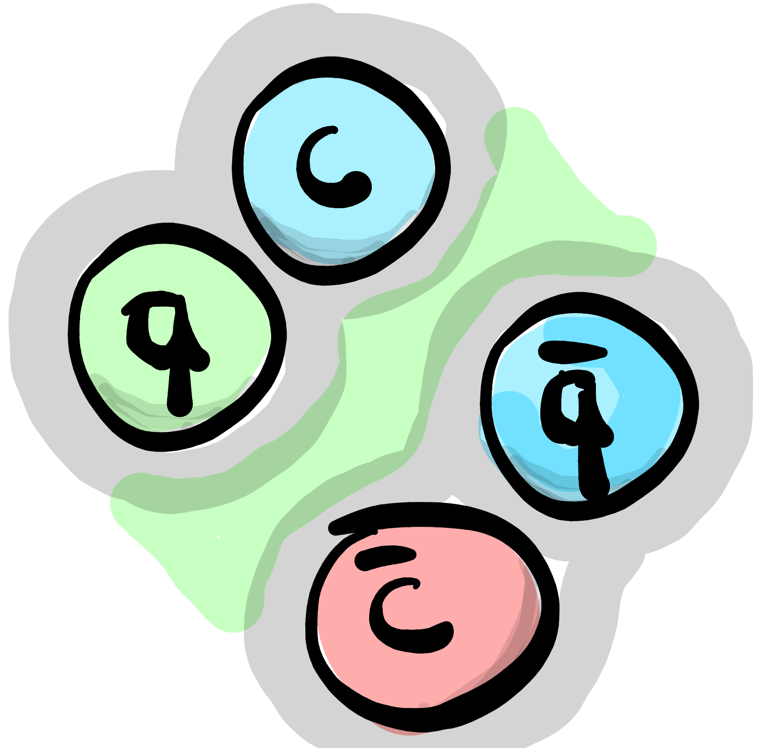


Other configurations

Molecule



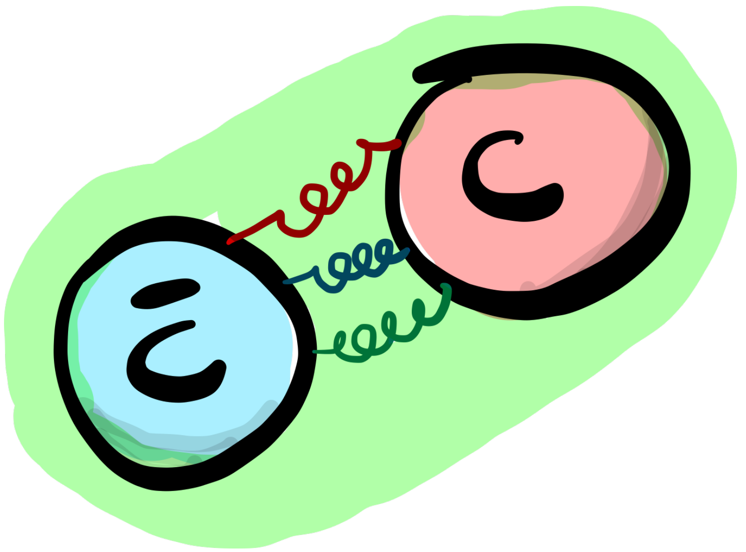
Tetraquark



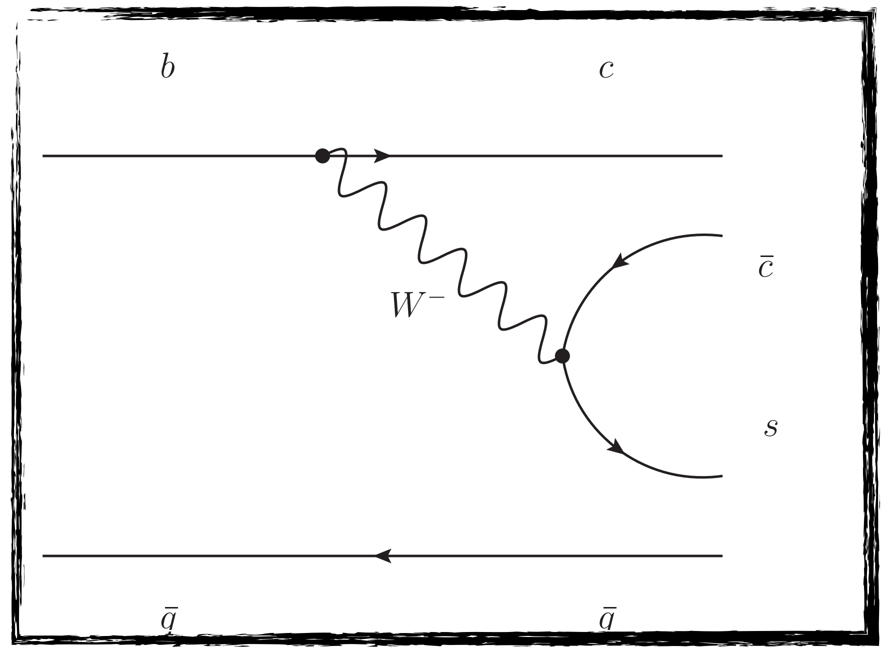
Where do we find evidence ?

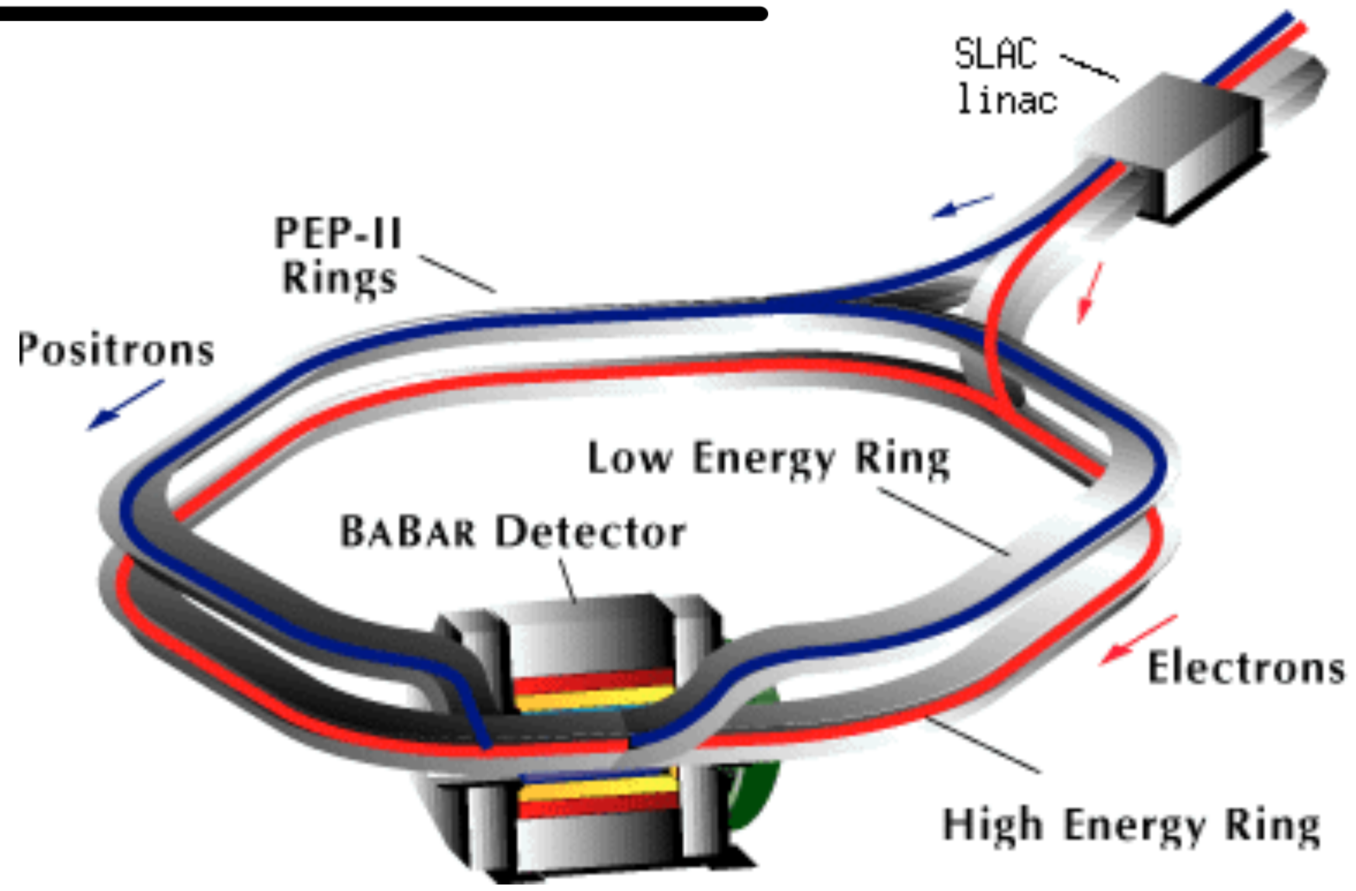
CHARMONIUM AND THE B-FACTORIES

charmonium



electron - positron collider

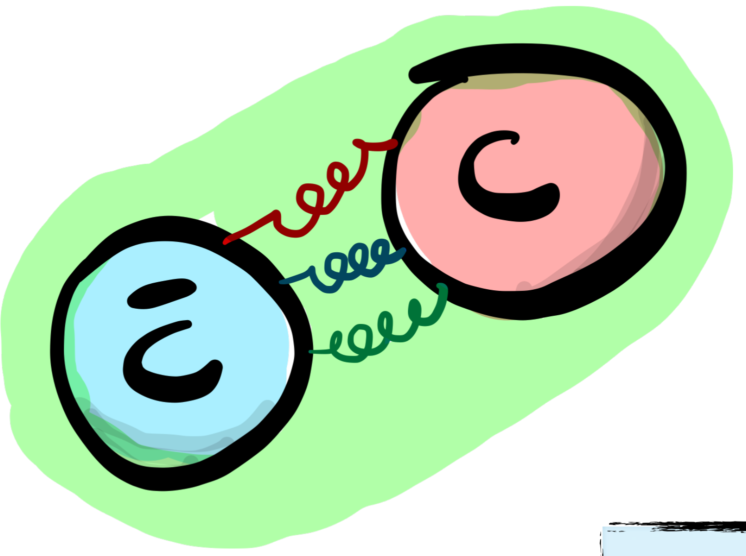




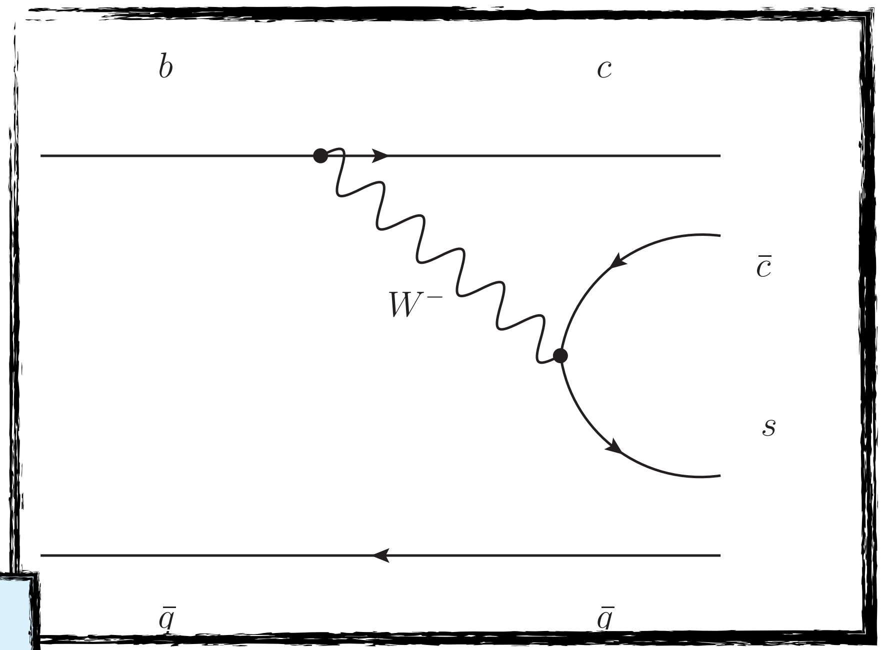
B-factories

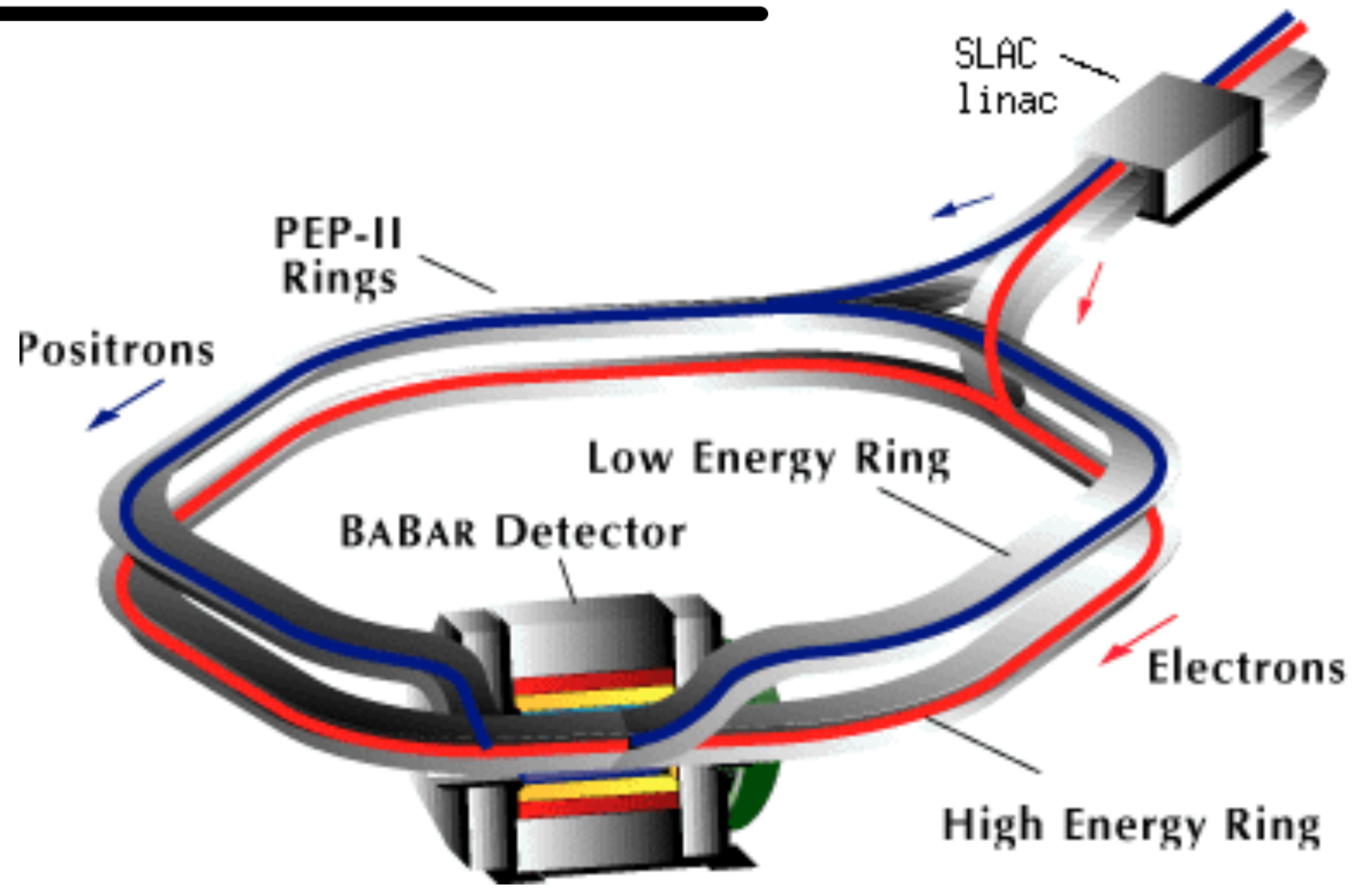
CHARMONIUM AND THE B-FACTORIES

charmonium

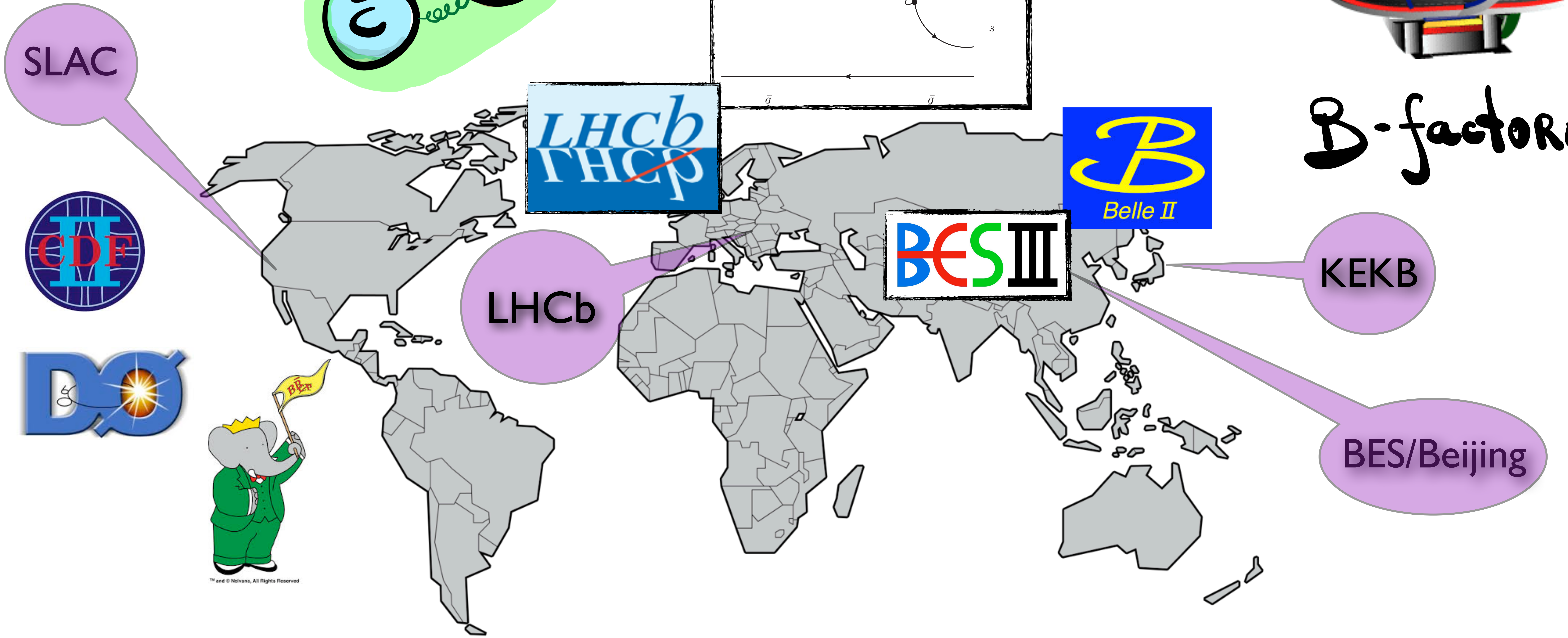


electron - positron collider



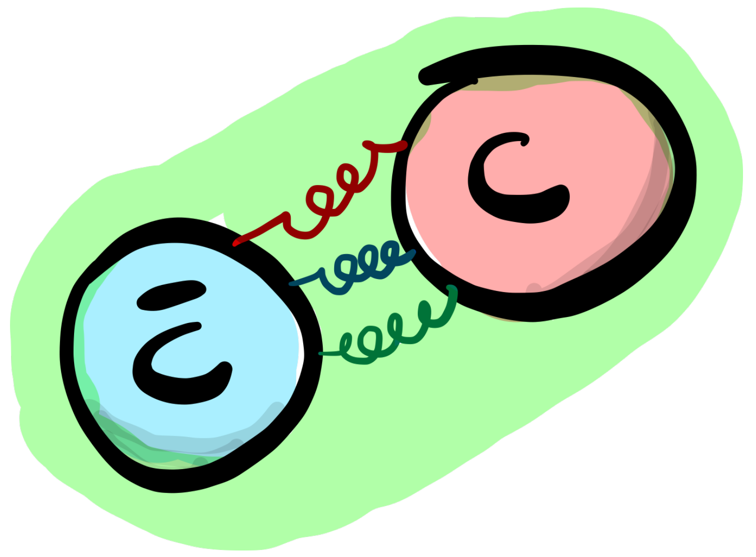


B-factories



CHARMONIUM SPECTRUM

charmonium

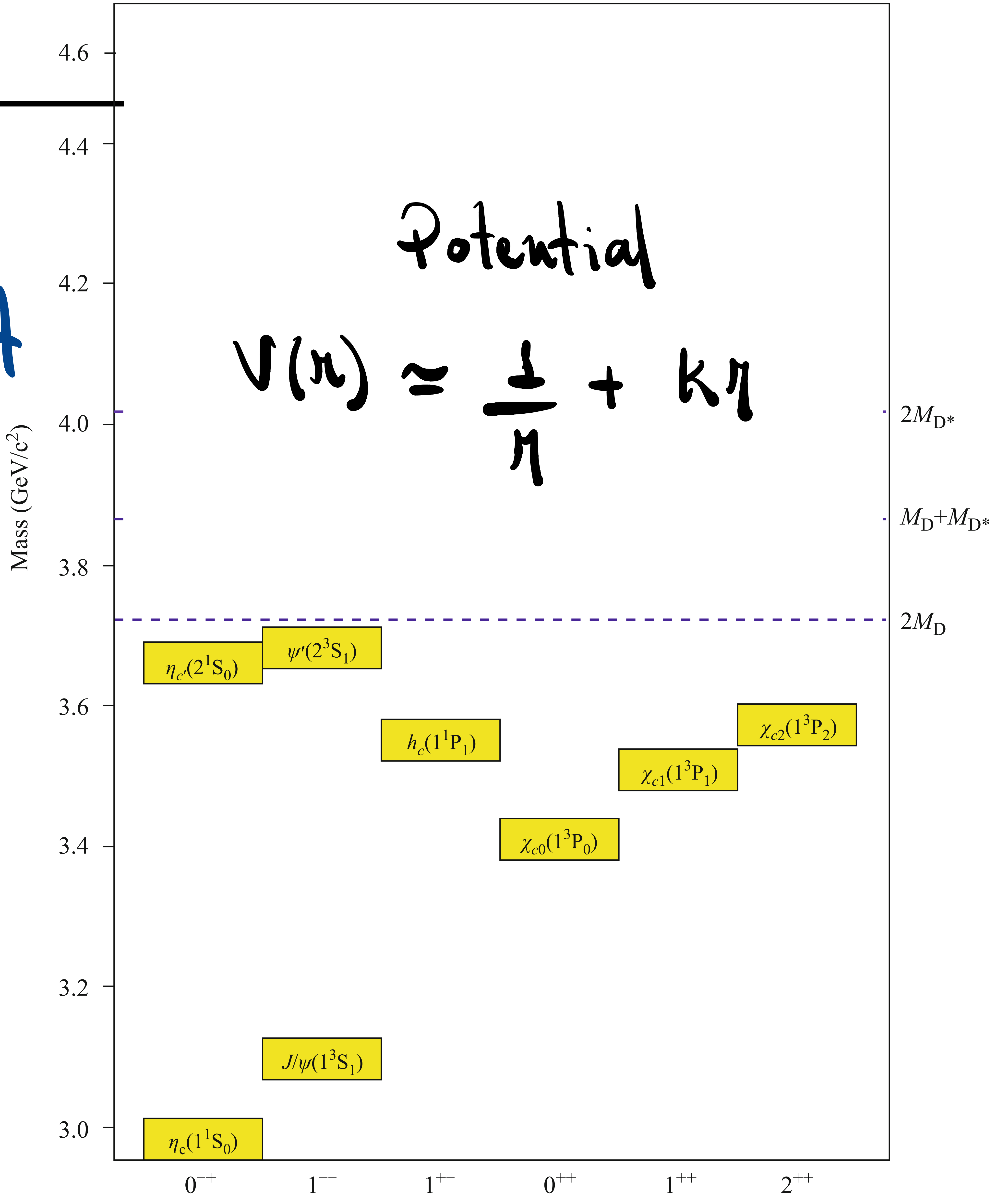


Good agreement with experiment

They were established by 1975!

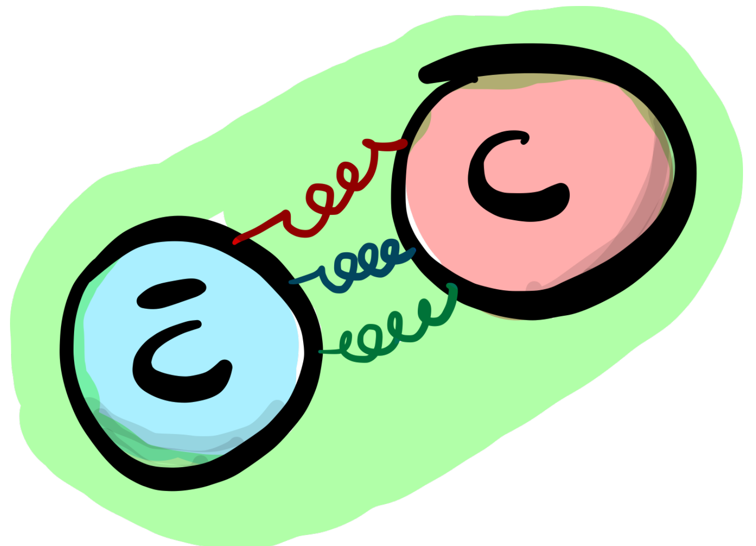
Potential

$$V(r) \simeq \frac{1}{r} + kr$$

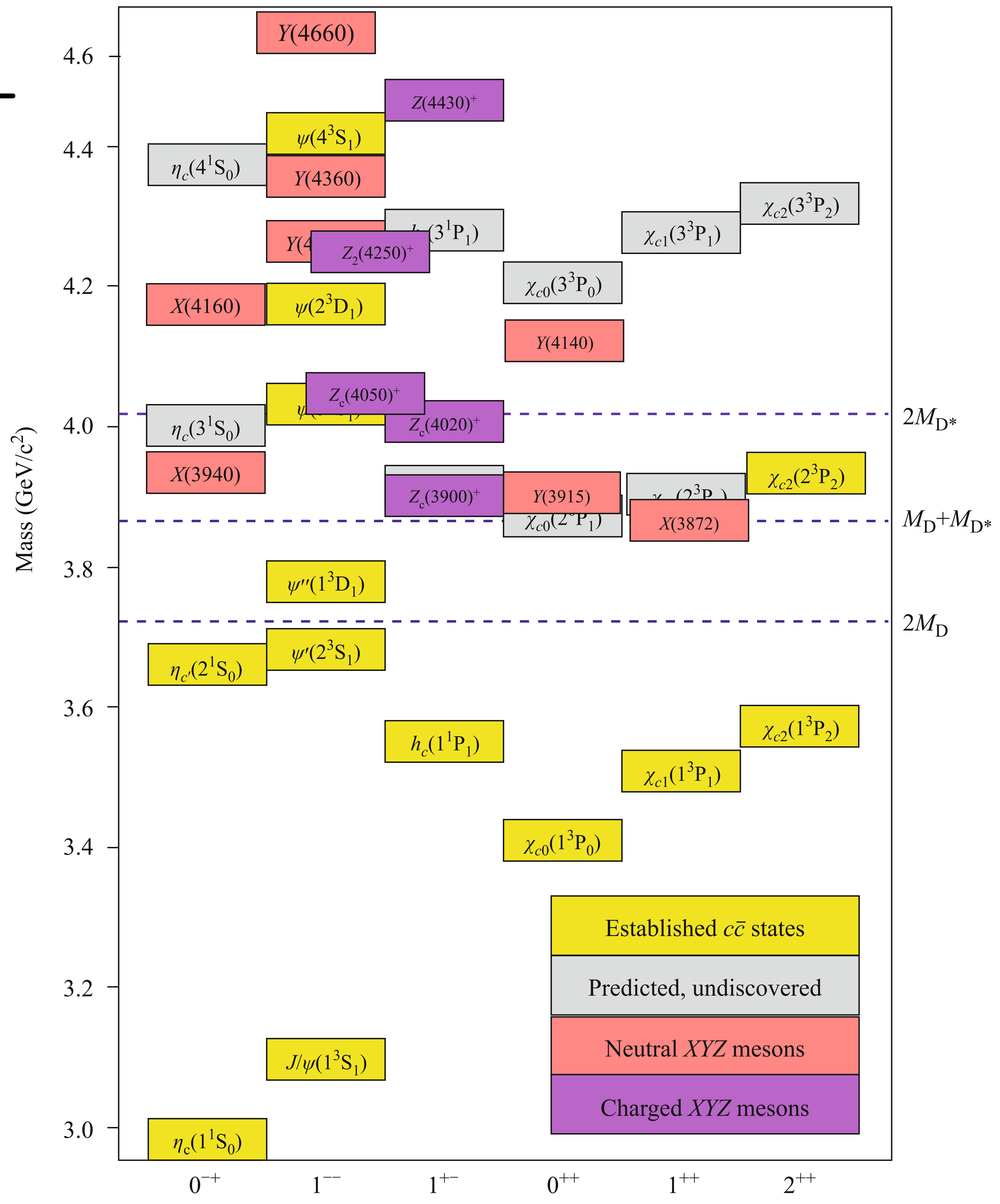


CHARMONIUM SPECTRUM

charmonium



Challenging!

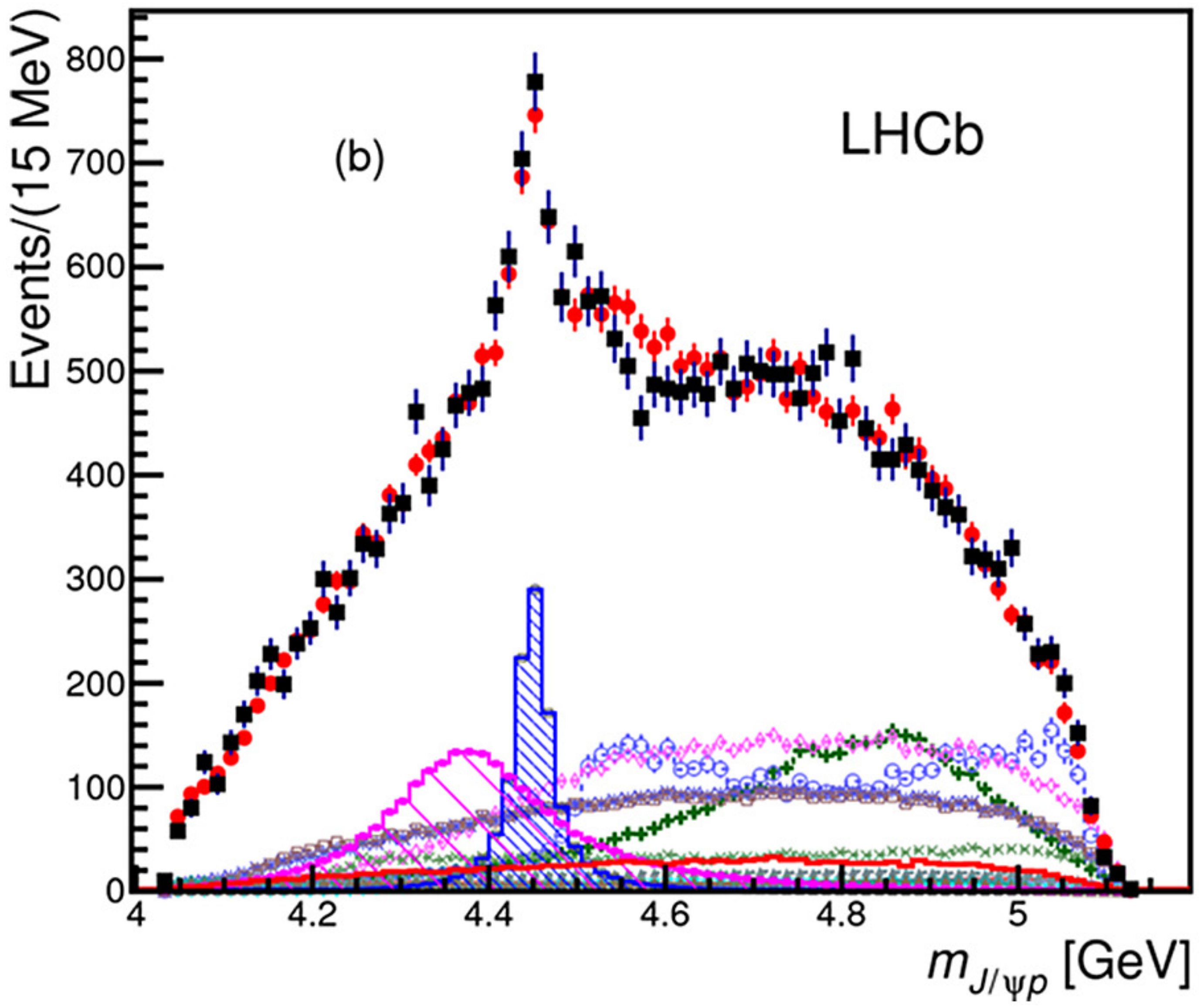


In baryon sector...

Pentaquarks →

$P_c^+(4380)$ and

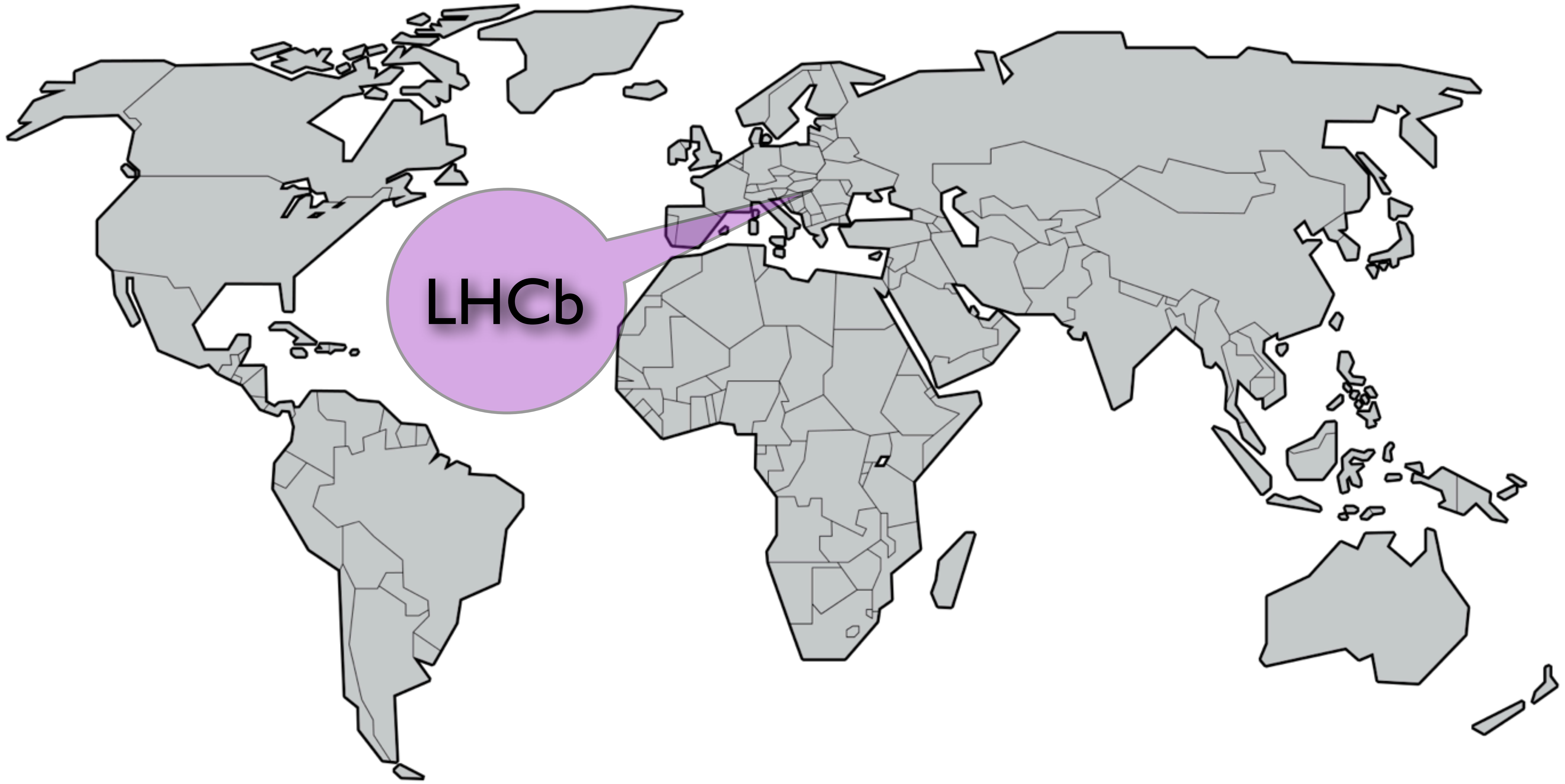
$P_c^+(4450)$



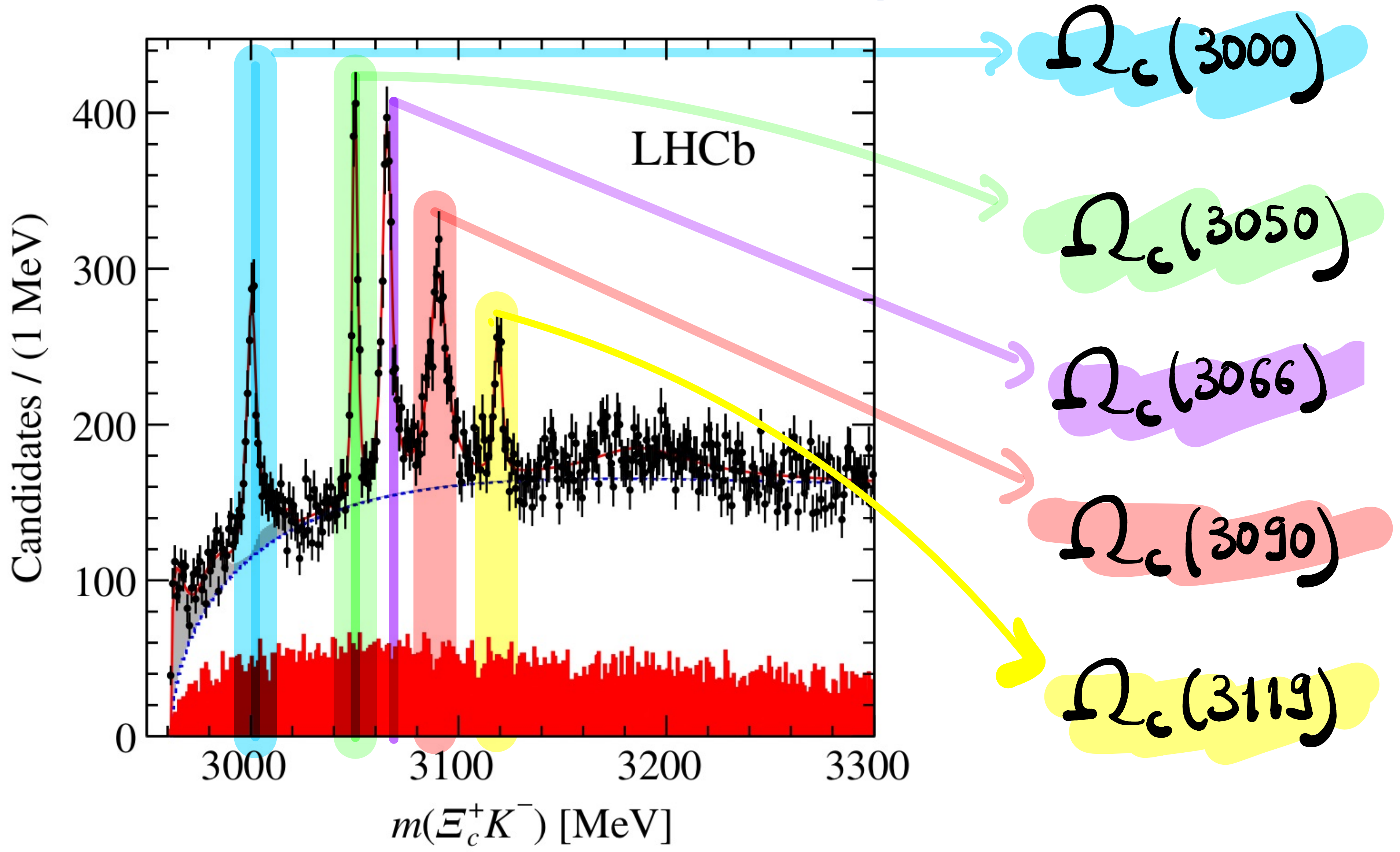
$\Lambda_b^0 \to J/\psi p \bar{K}$

Phys. Rev. Lett 115, 072001 (2015)

Phys. Rev. Lett 117, 082002 (2016)



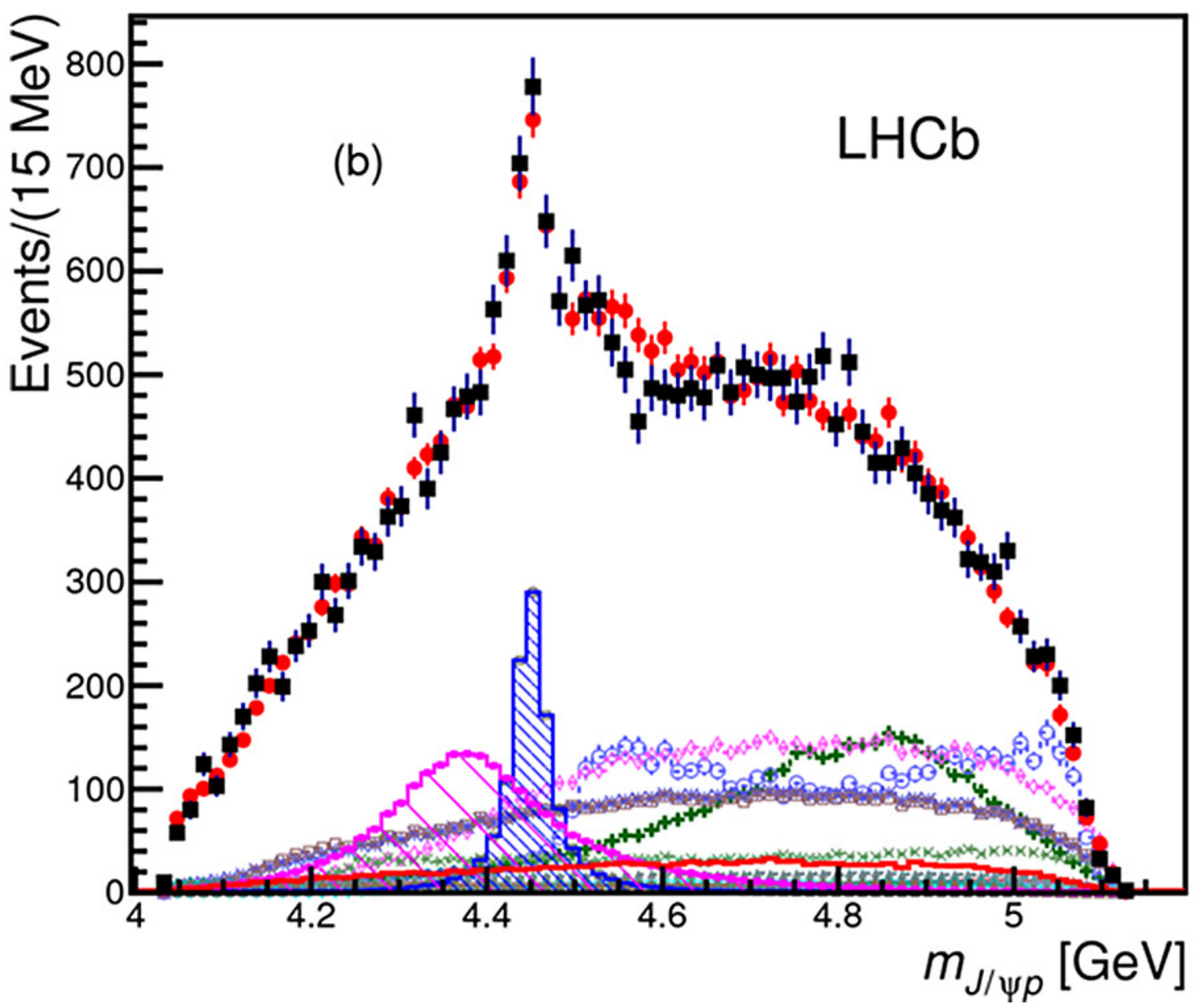
Phys. Rev. Lett. 118, 182001 (2017)



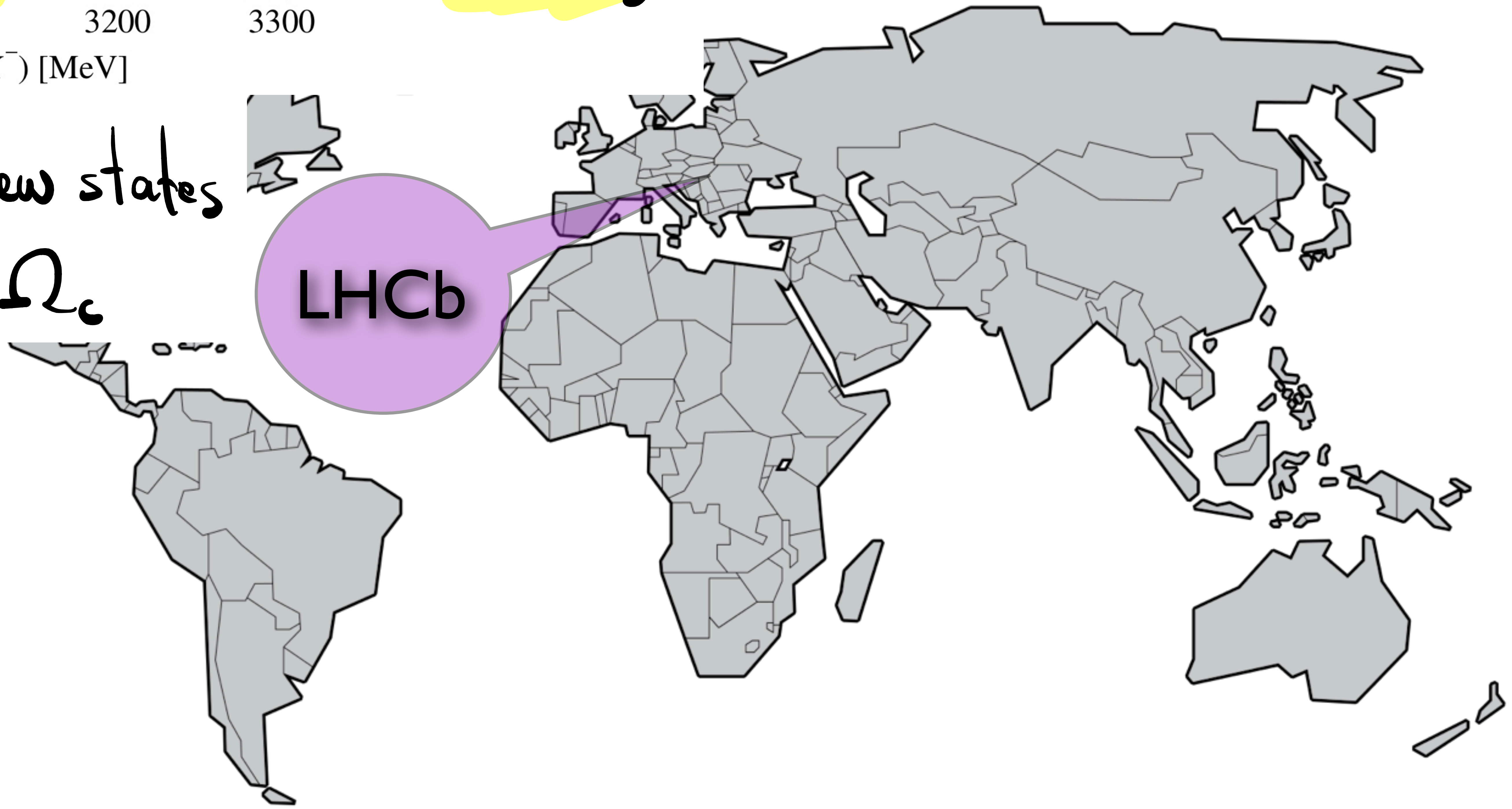
Pentaquarks

$P_c^+(4380)$ and

$P_c^+(4450)$



Five new states called Ω_c



$\Lambda_b^0 \to J/\psi p \bar{K}$

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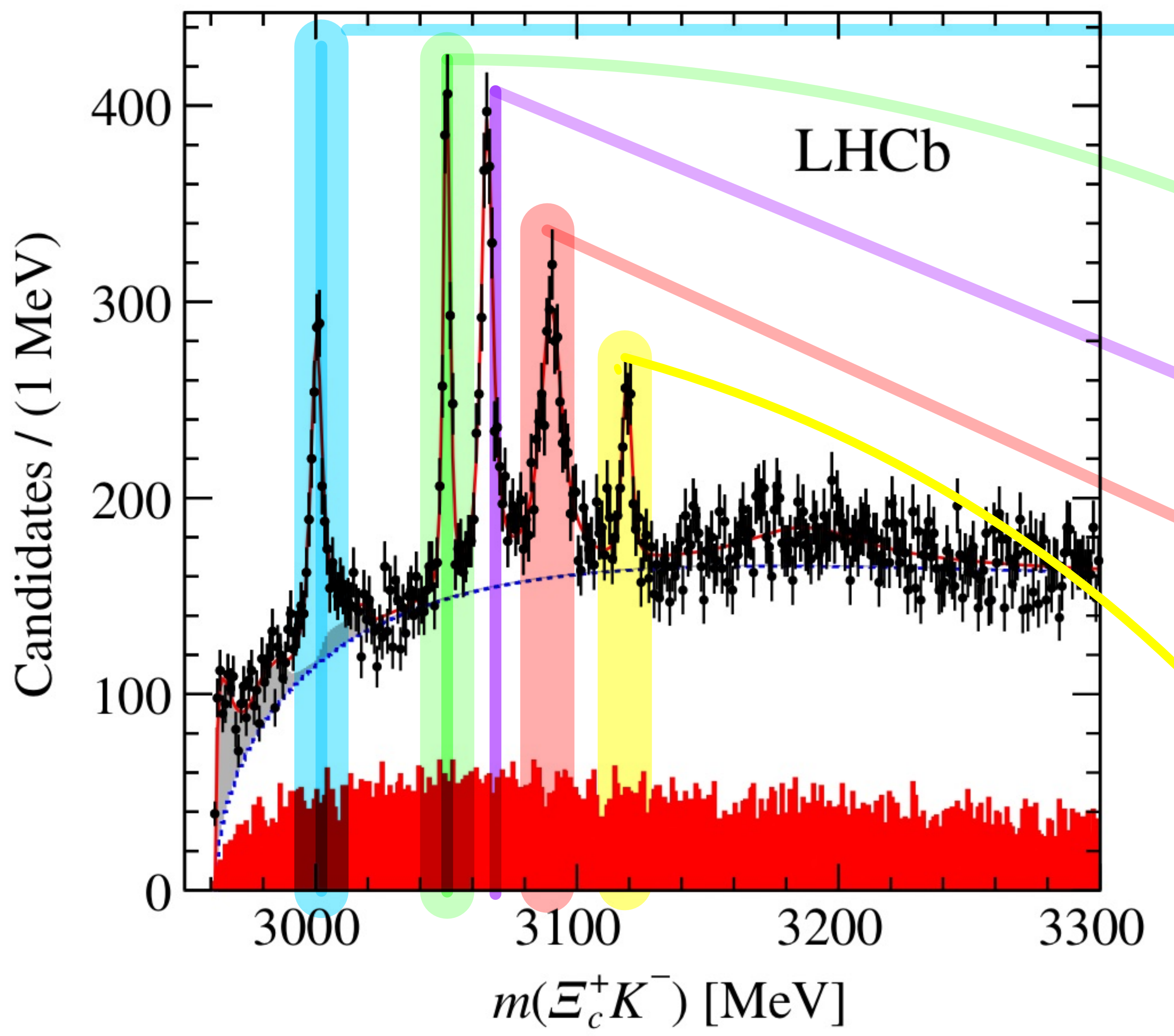


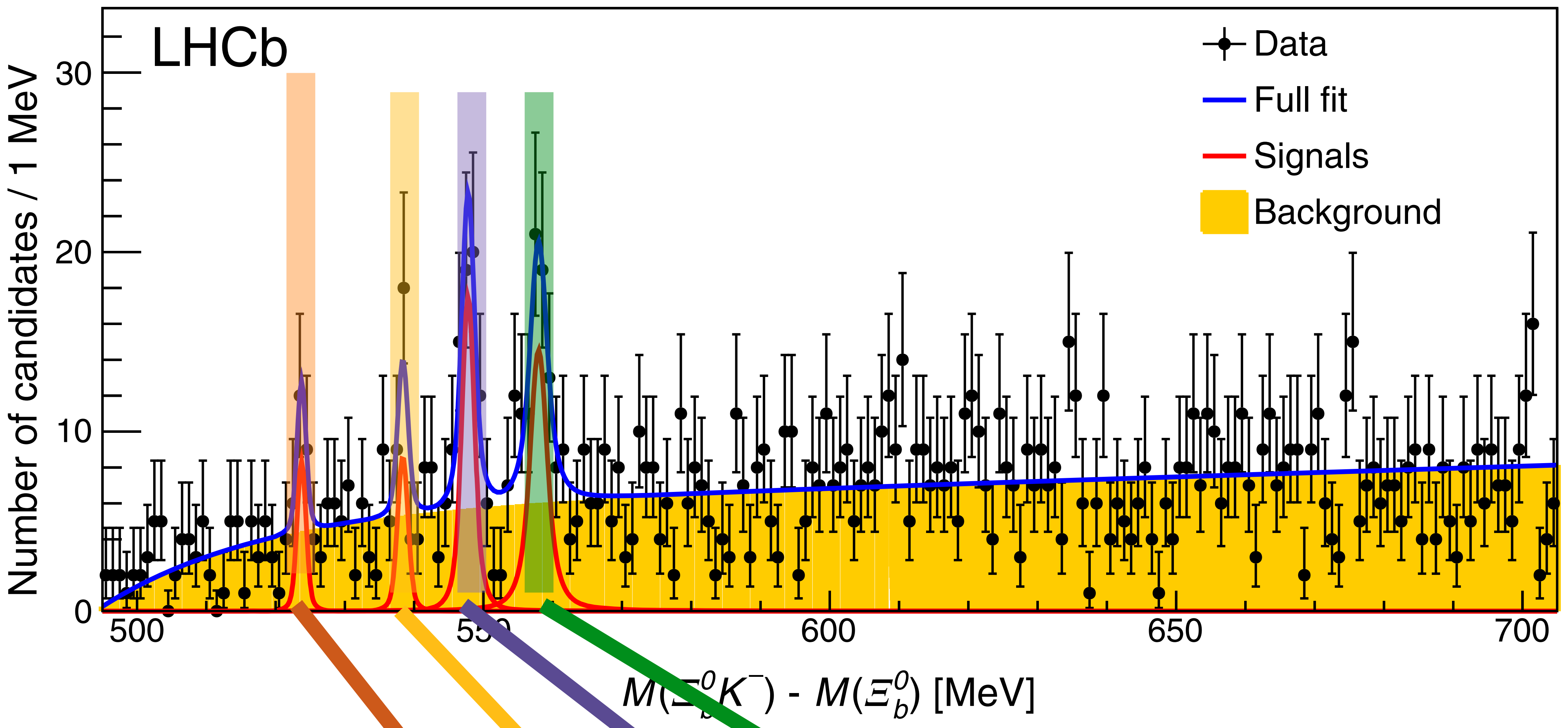
$\Omega_c(3000)$

$\Omega_c(3050)$

$\Omega_c(3066)$

$\Omega_c(3090)$

$\Omega_c(3119)$



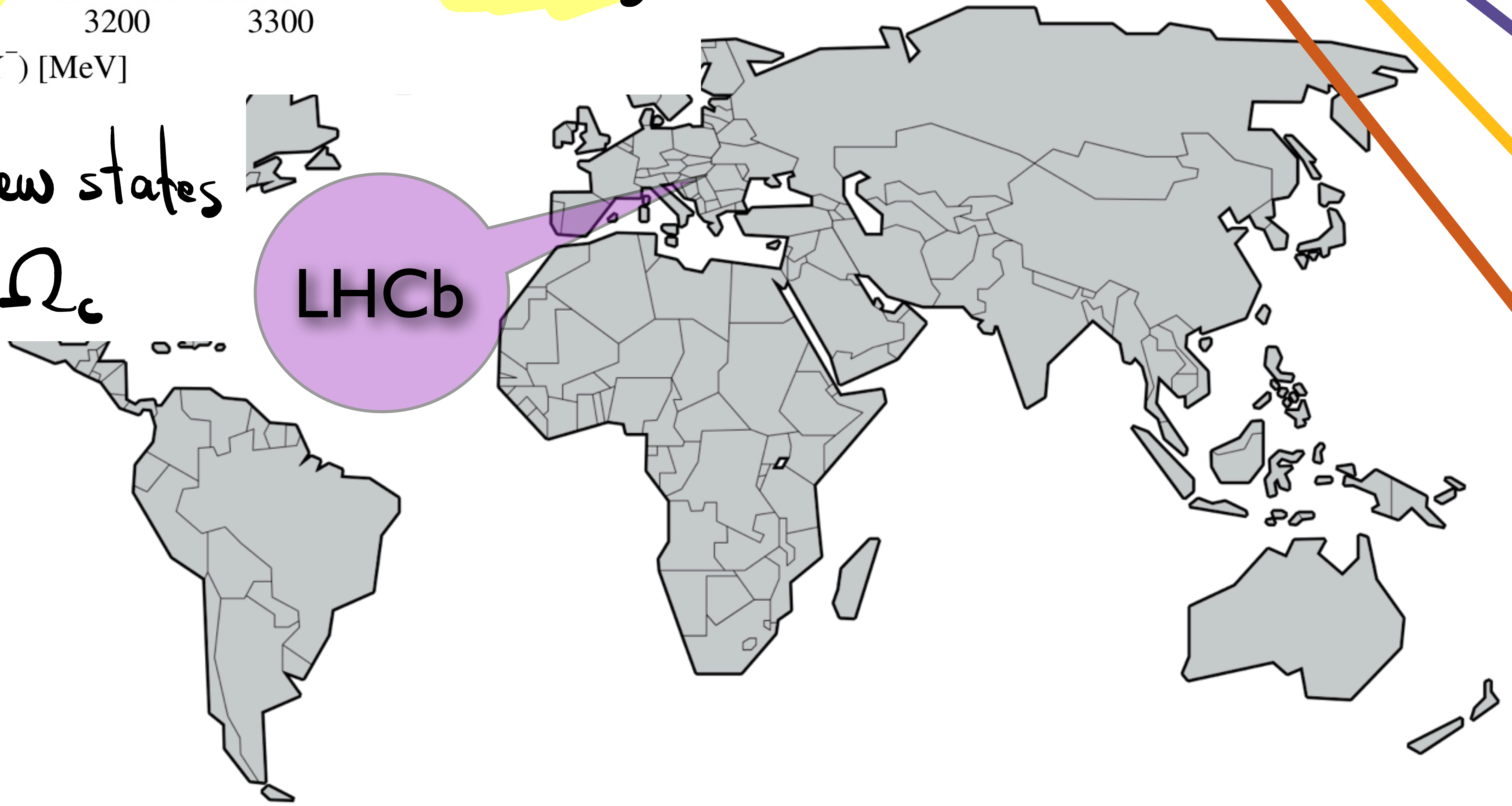
$\Omega_b(6315)$

$\Omega_b(6330)$

$\Omega_b(6339)$

$\Omega_b(6349)$

Five new states called Ω_c



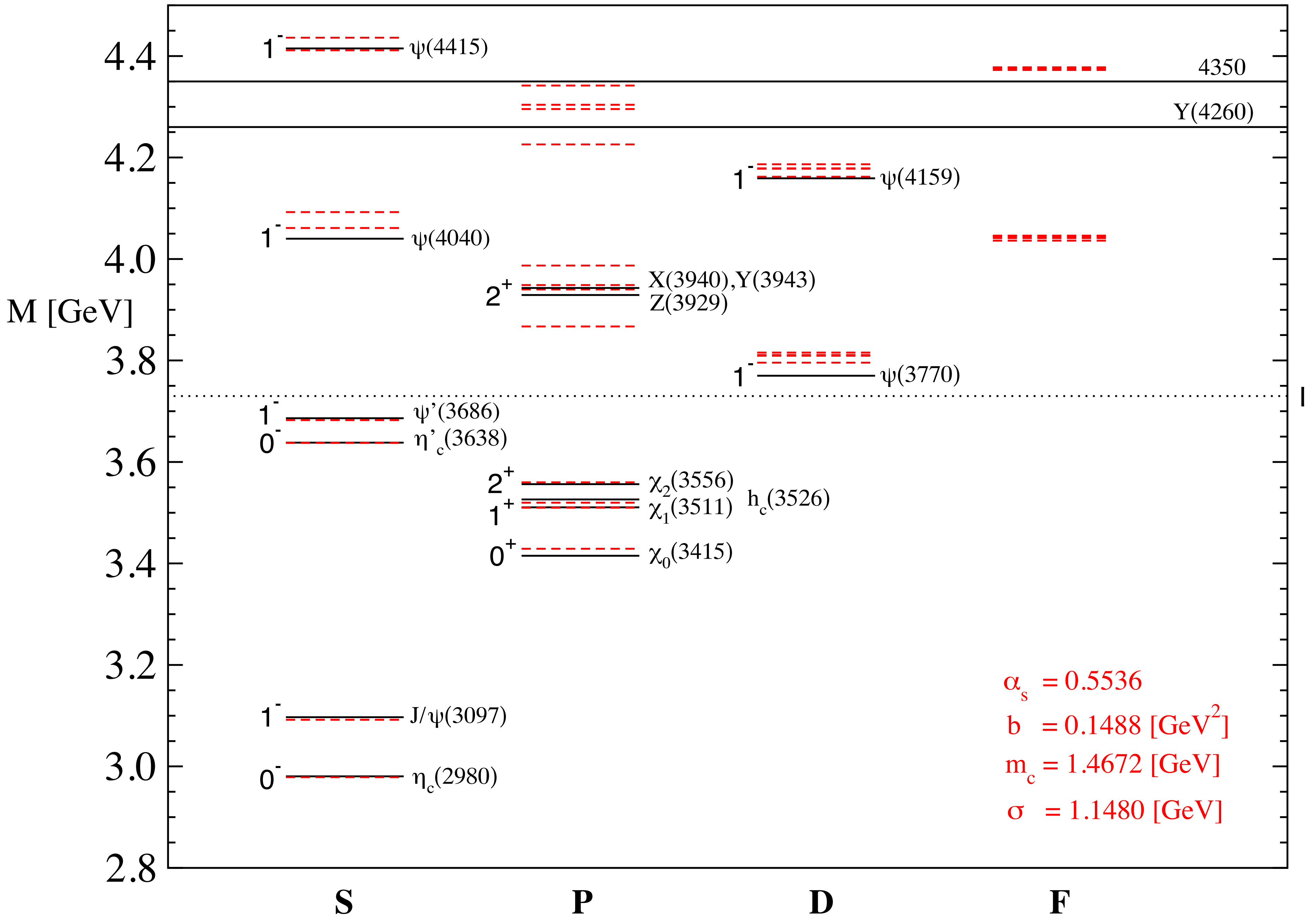
Phys. Rev. Lett. 124, 082002 (2020)

Why are they considered to be Exotic States ?

① → Predictions from Potential Models

$$V(r) \sim \cancel{\frac{a}{r}} + br$$

Ted Barnes, Int. J. Mod. Phys. A21 (2006)



① → Predictions from Potential Models

$$V(r) \sim \cancel{\frac{a}{r}} + br \quad \Longrightarrow$$

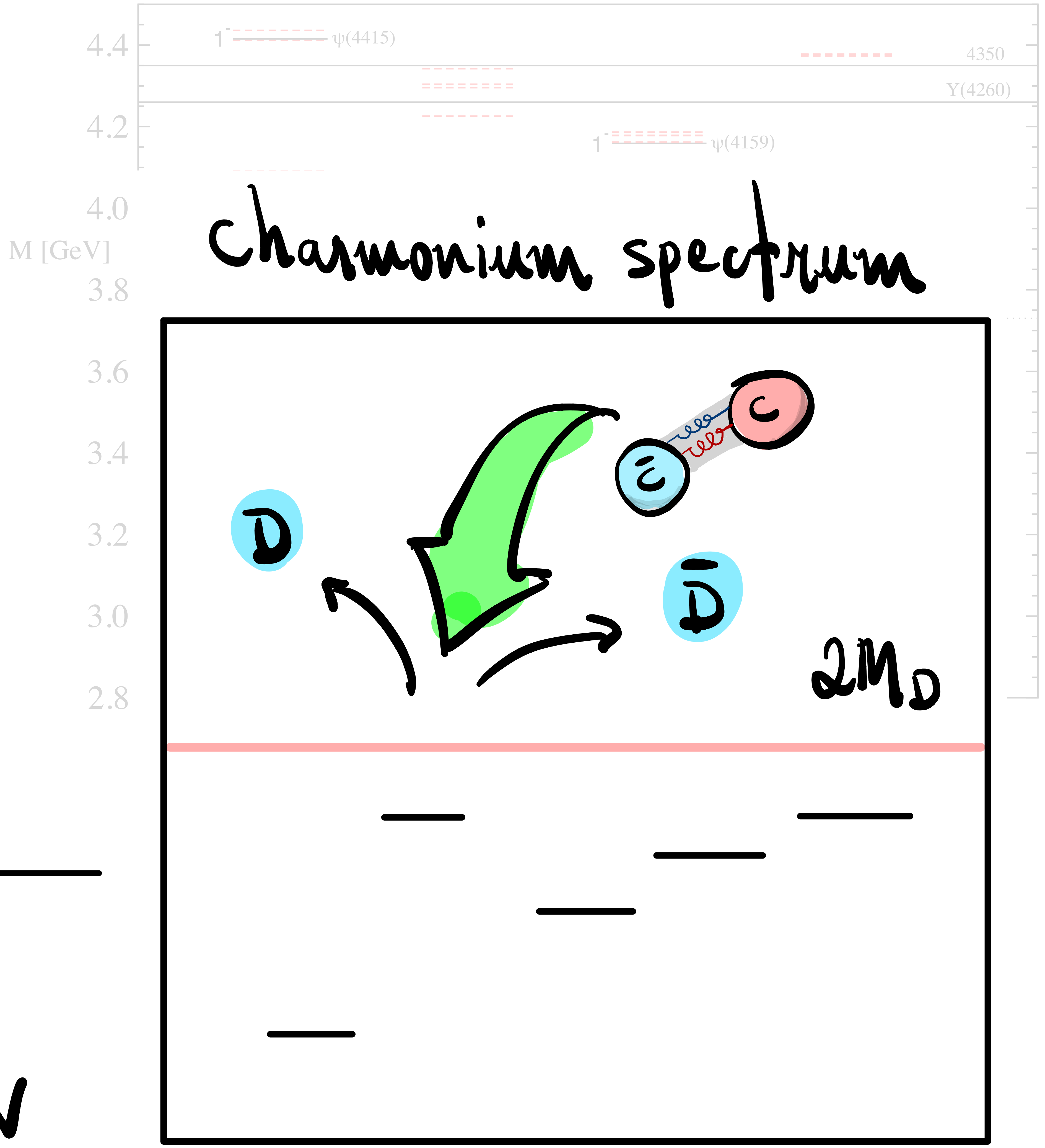
② → Most of them are "Narrow"

- Large phase space
- Decay into J/ψ and π's

$$\Gamma_{X(3872)} < 1.2 \text{ MeV}$$

$$\Gamma_{Z_c(3900)} \sim 27.9 \text{ MeV}$$

Ted Barnes, Int. J. Mod. Phys. A21 (2006)



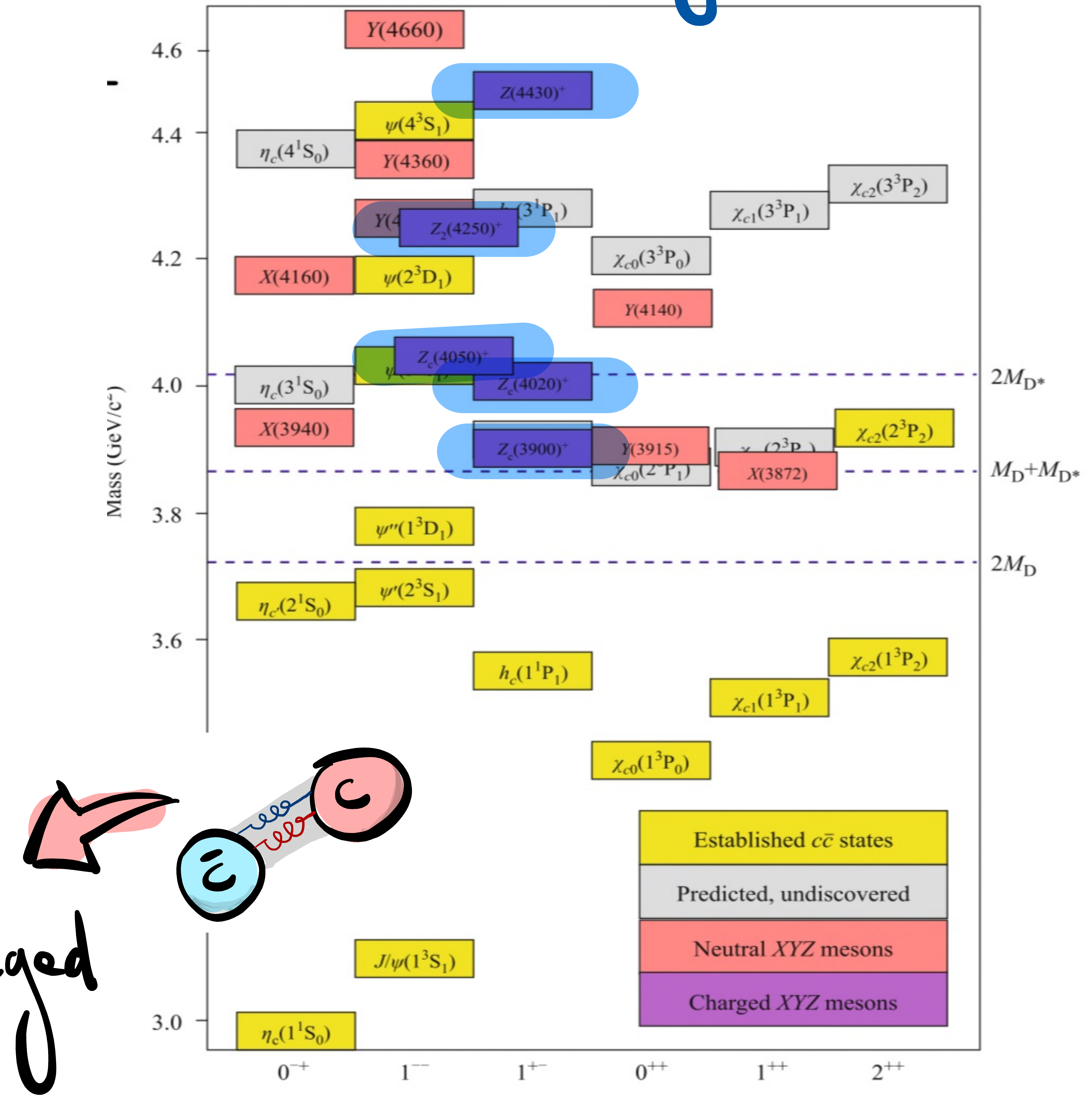
① → Predictions from Potential Models

$$V(r) \sim \cancel{\frac{a}{r} + br}$$

② → Most of them are "Narrow"

- Large phase space
- Decay into J/ψ and π's
- Charged States

All charged!



not charged

3 → Isospin violation ?

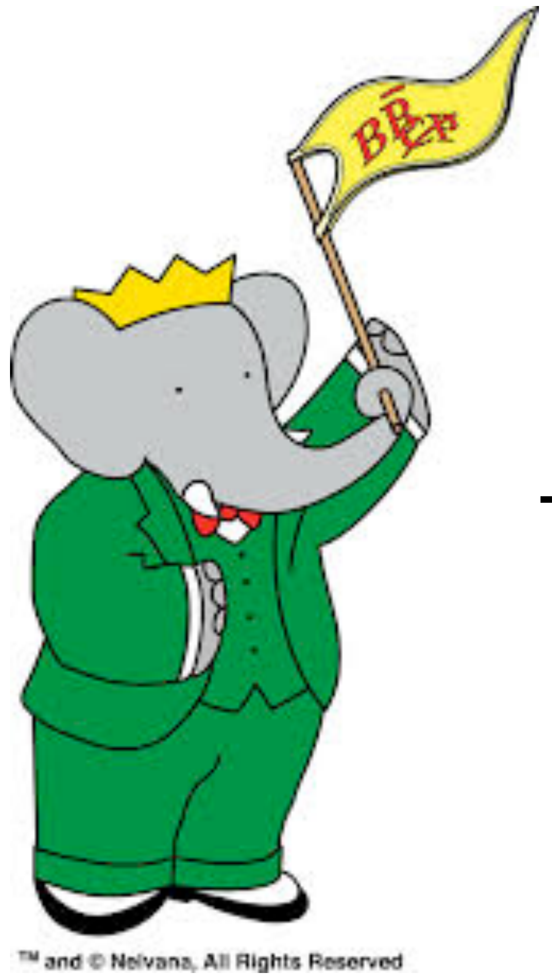
22nd International Symposium on Lepton-Photon Interactions at High Energy (LP 2005)}

Striking feature!

$\chi_{c1}(3872)$ aka $X(3872)$

$$\frac{\mathcal{B}(X \to J/\psi\ \pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

It violates isospin!

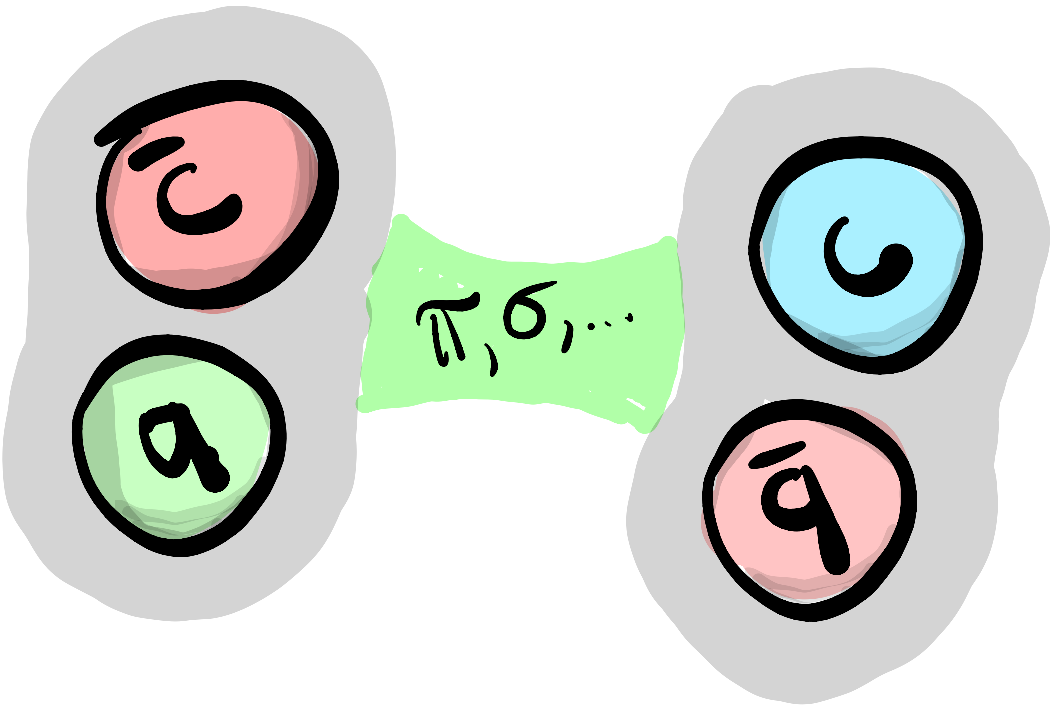


$$\frac{\mathcal{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 0.8 \pm 0.3$$

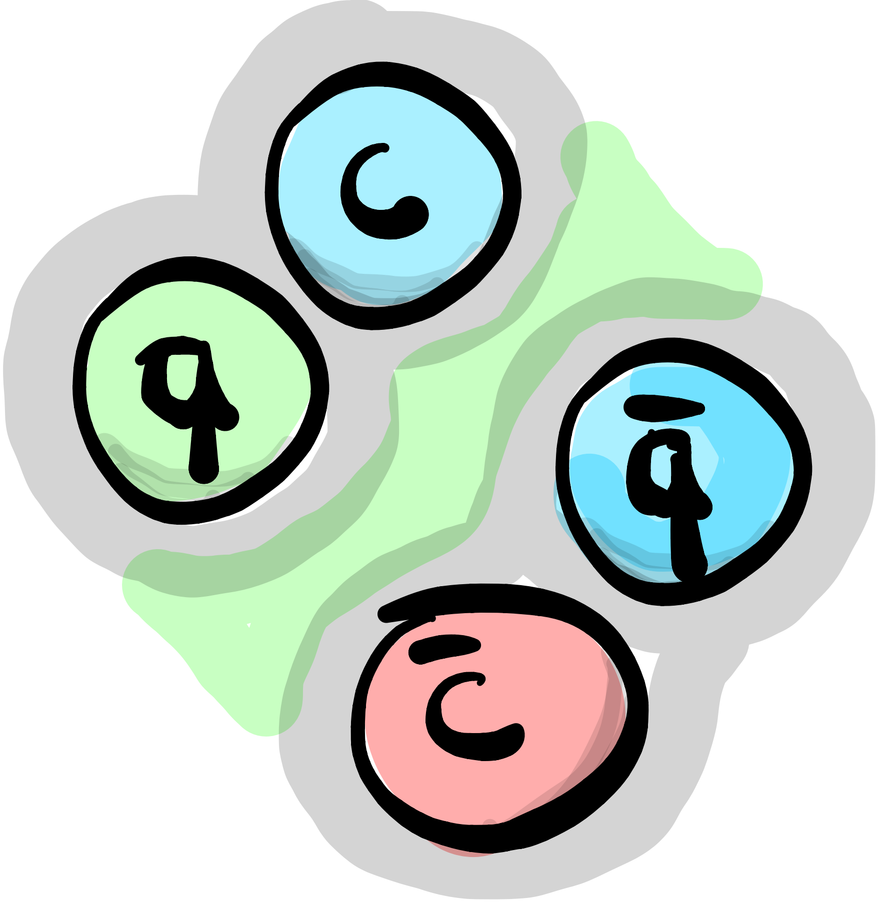
Phys. Rev. D 82, 011101 (2010)

OTHER POSSIBLE CONFIGURATIONS

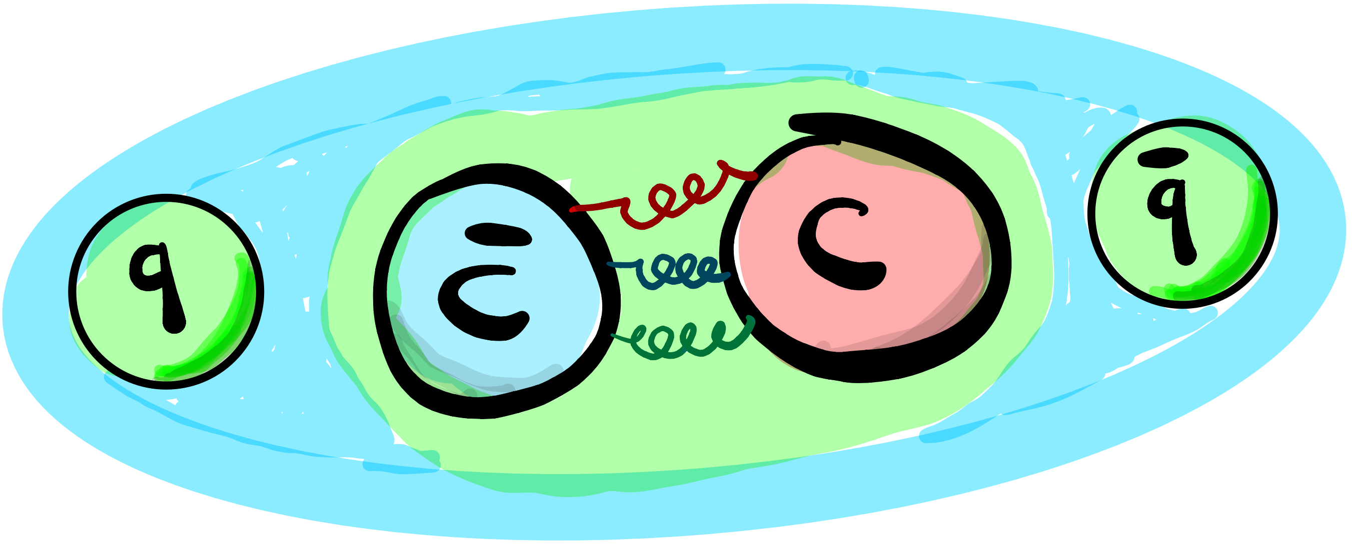
Molecule



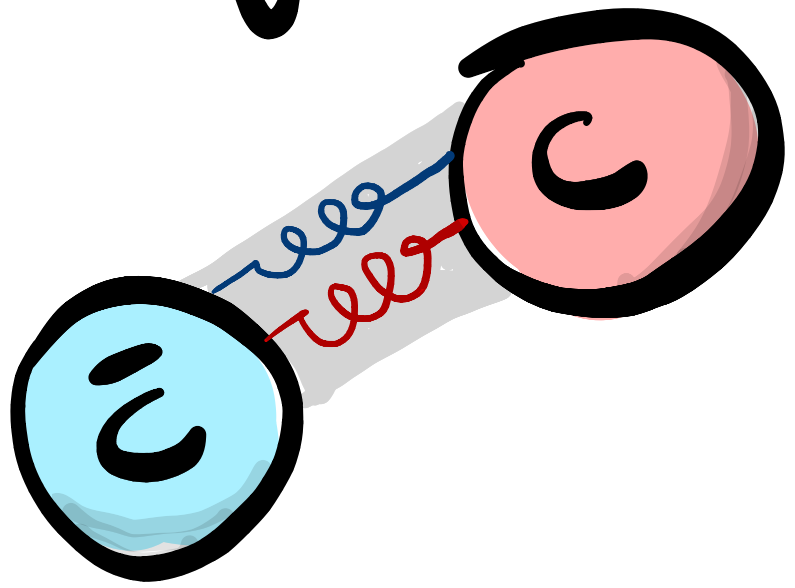
Tetraquark



Hadro-Charmonium



Hybrid



How do we study them ?

How do we study them?

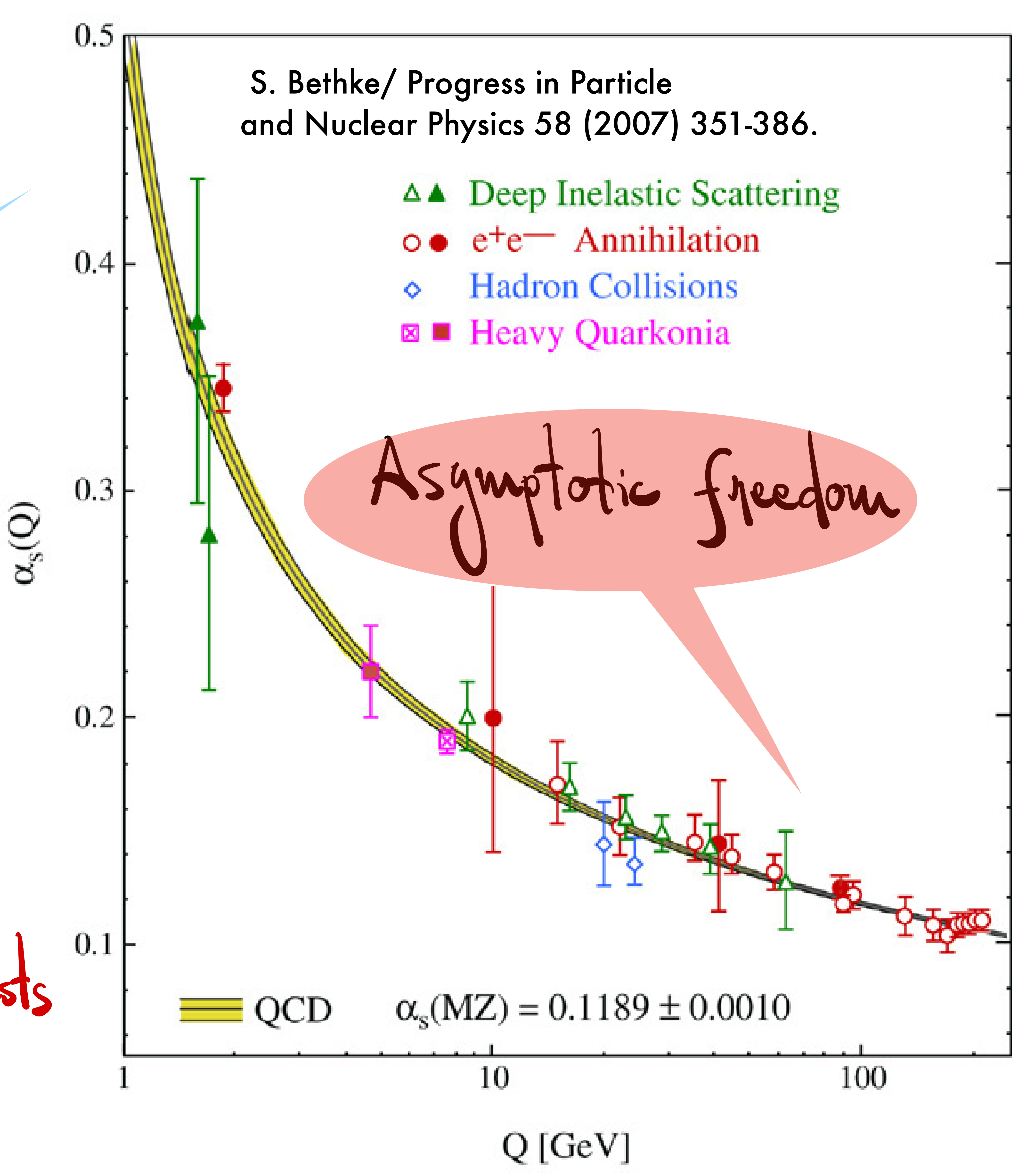
- $\alpha_s(\mu^2)$ decreases as the scale increase
- For a particular scale Λ_{QCD}, $\alpha_s(\mu^2) \sim 1$!

Confinement

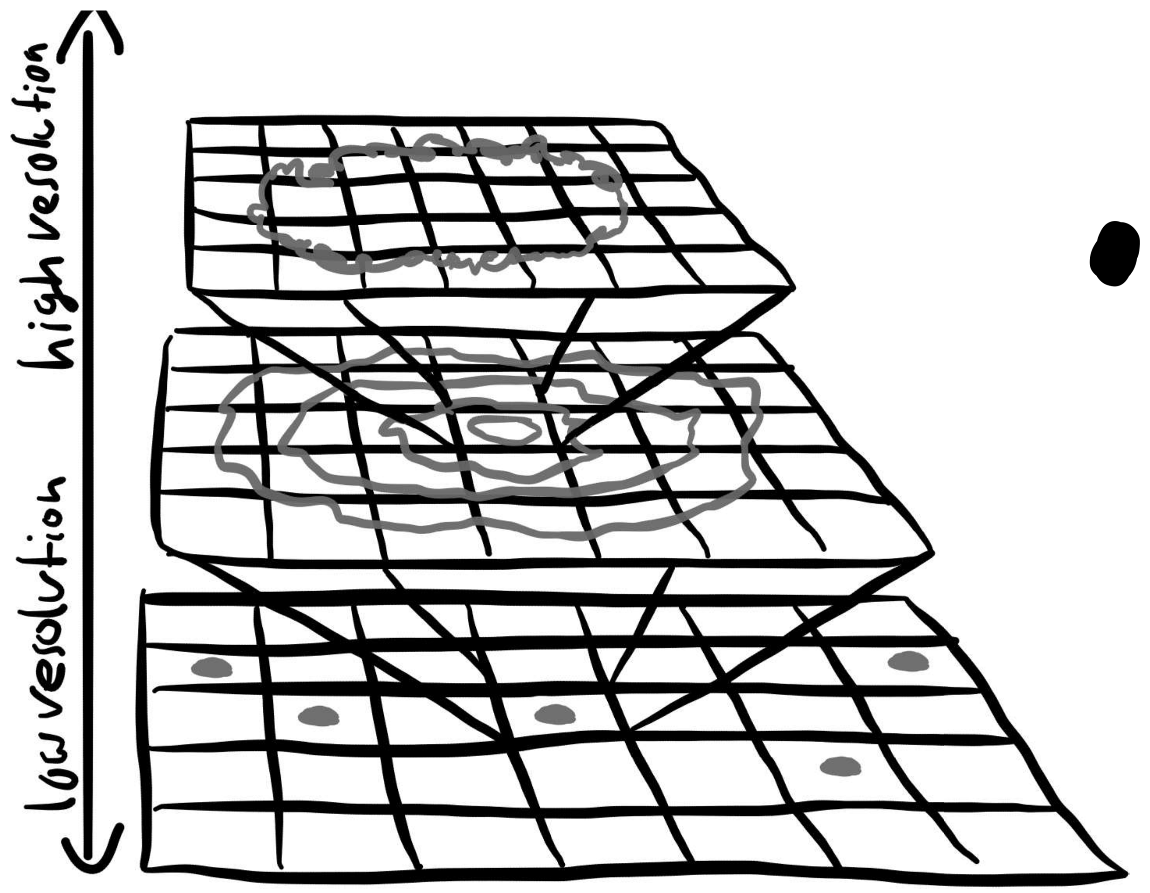
- Λ_{QCD} is a fundamental parameter in QCD:

  $\alpha_s \to \Lambda_{QCD}$ via dim. transmutation

Study QCD at Λ_{QCD} scale ($q^2 \sim \Lambda_{QCD}$) requests non-perturbative methods



How do we study them?

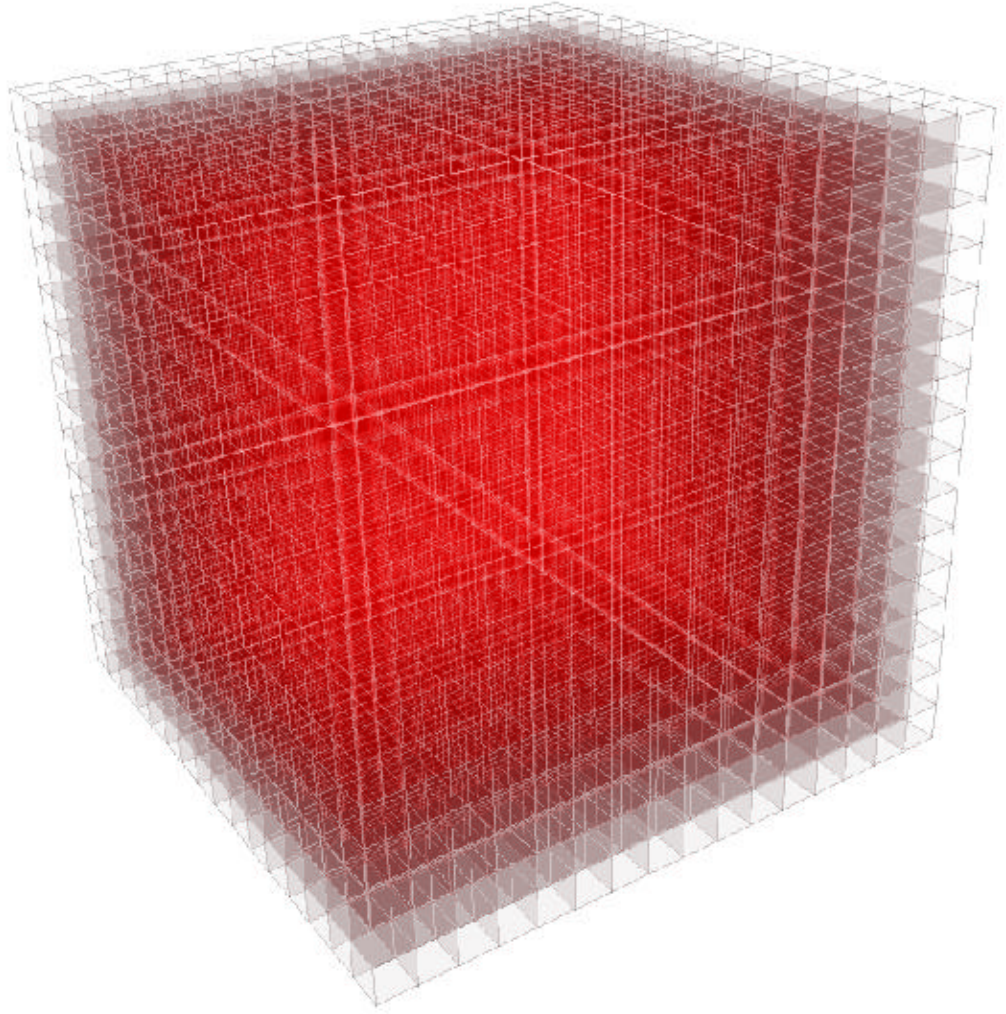


J. Schwichtenberg, ISBN10 - 3948763011

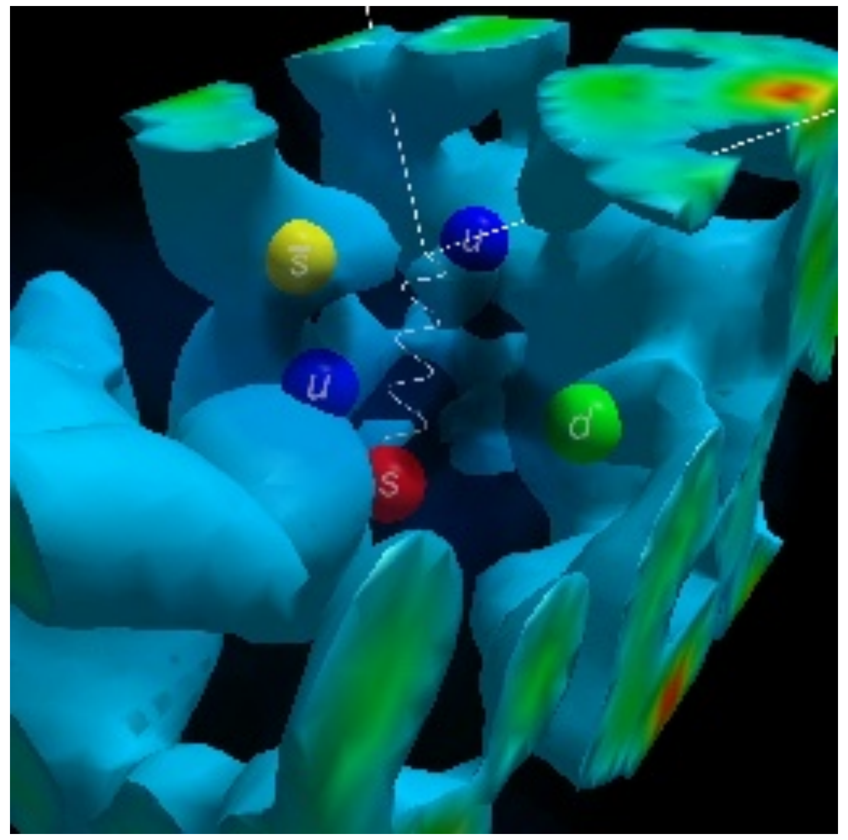
- Effective Field Theories

https://www.physi.uni-heidelberg.de/~fschney/2008SS-Preseminar/Lattice.pdf

- Lattice QCD



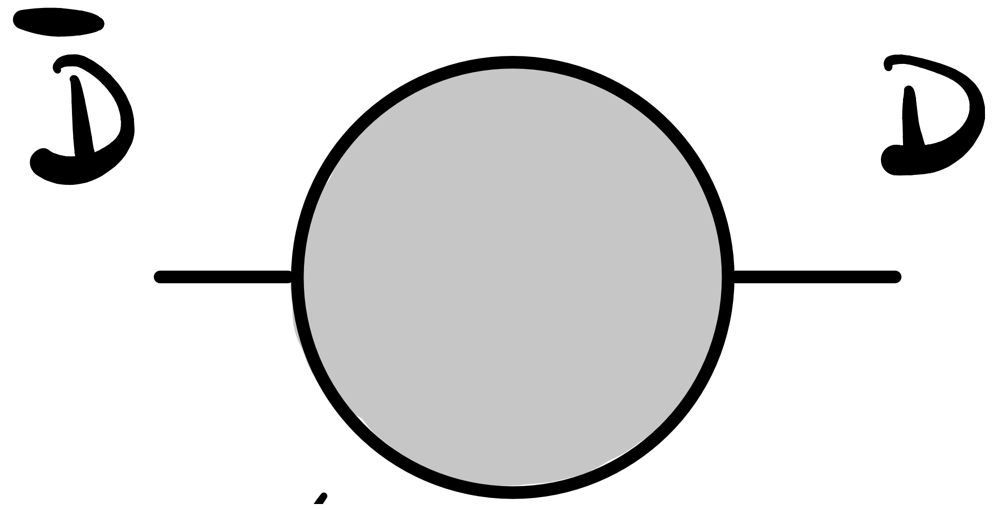
- QCD Sum Rules

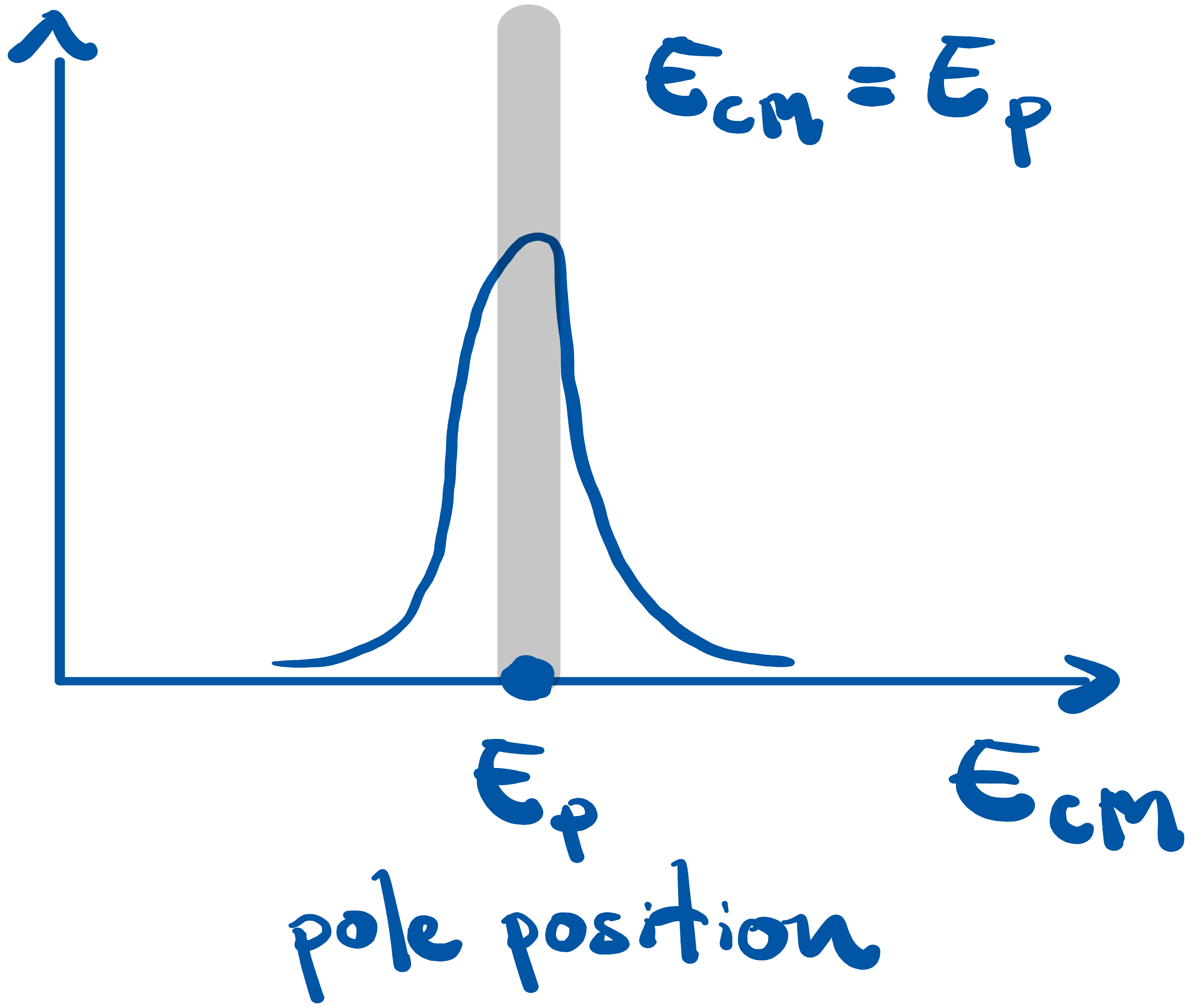


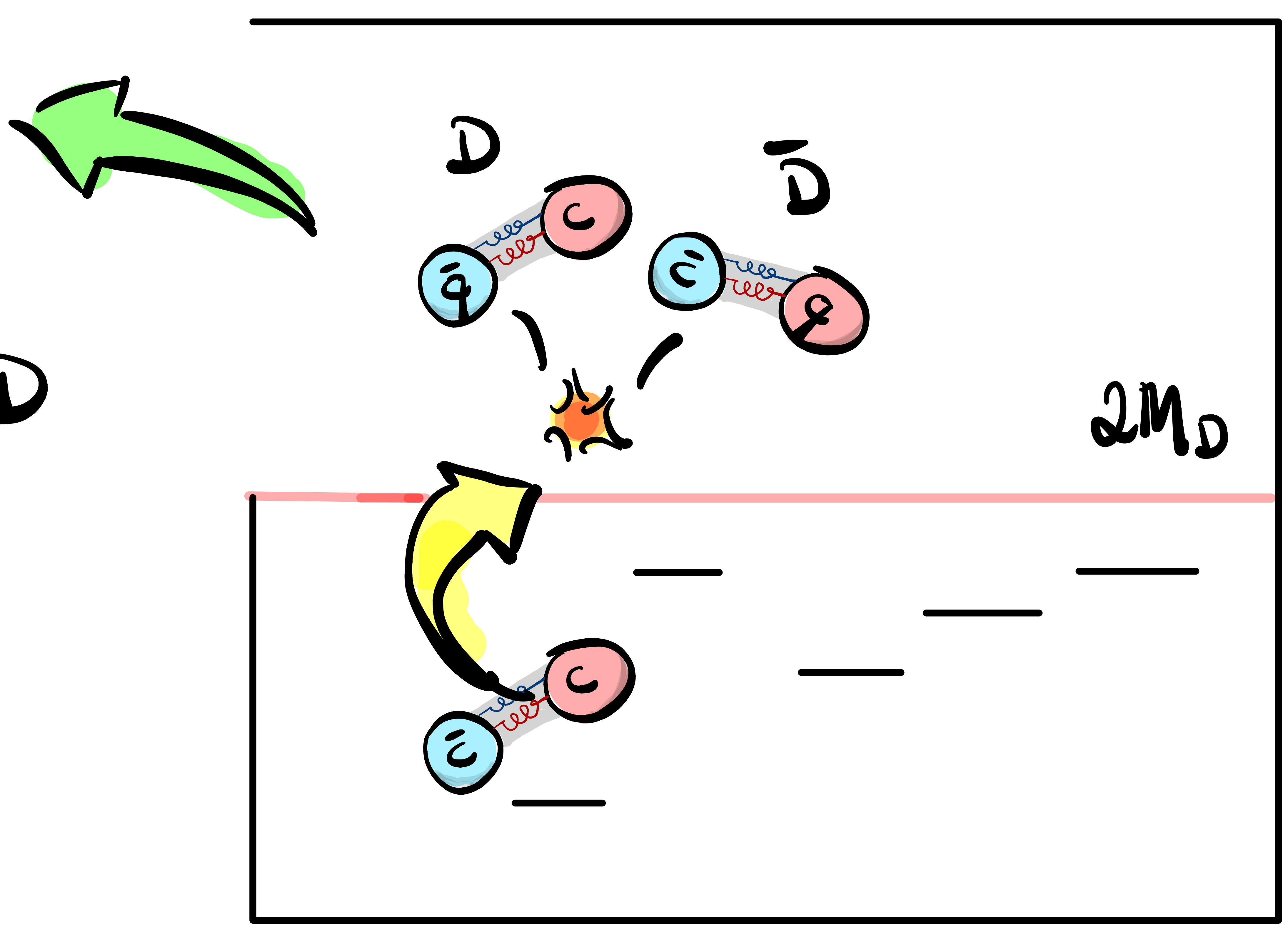
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

Chiral Unitary Approach

• They might interact



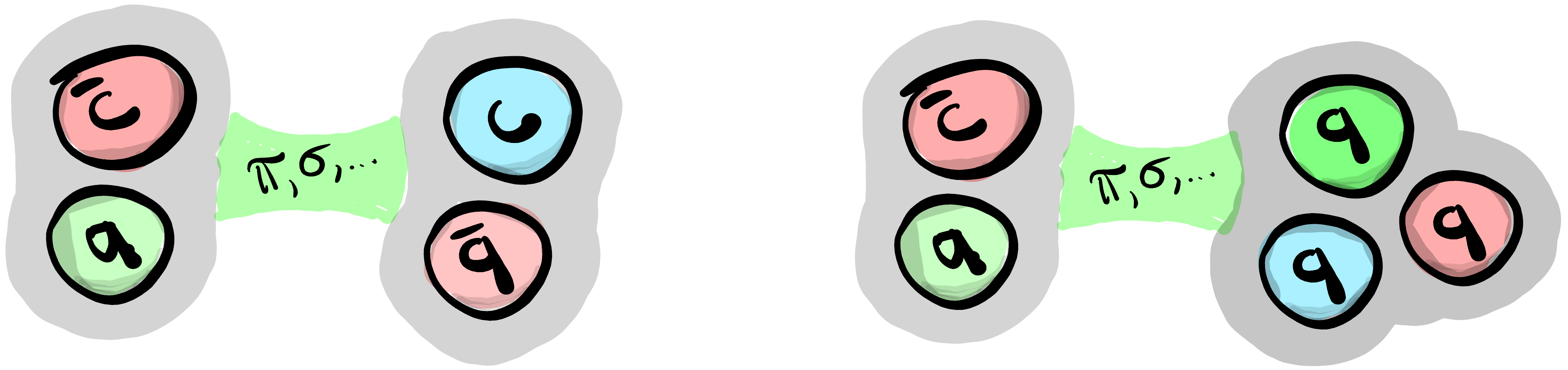




• Dinamically generated through the meson-meson interaction!

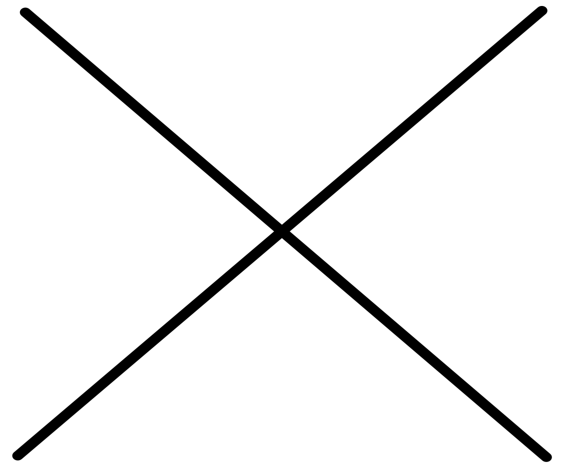
CHIRAL UNITARY FORMULATION

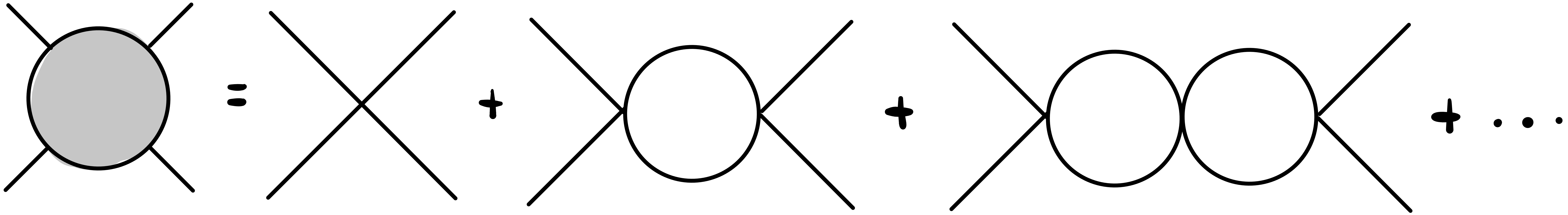
- Good for meson-meson and meson-baryon interactions

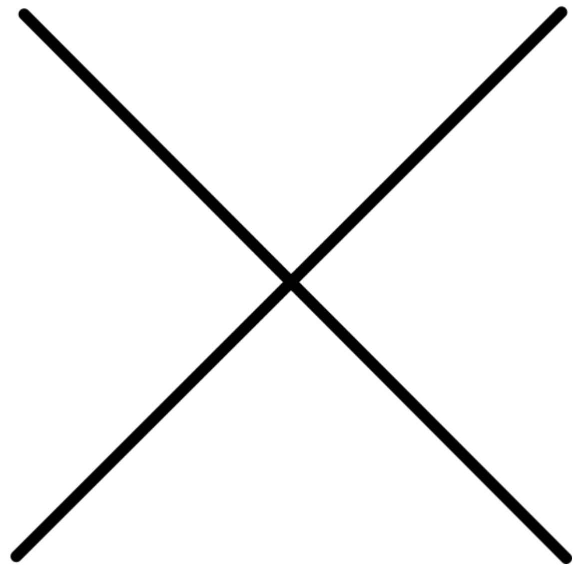


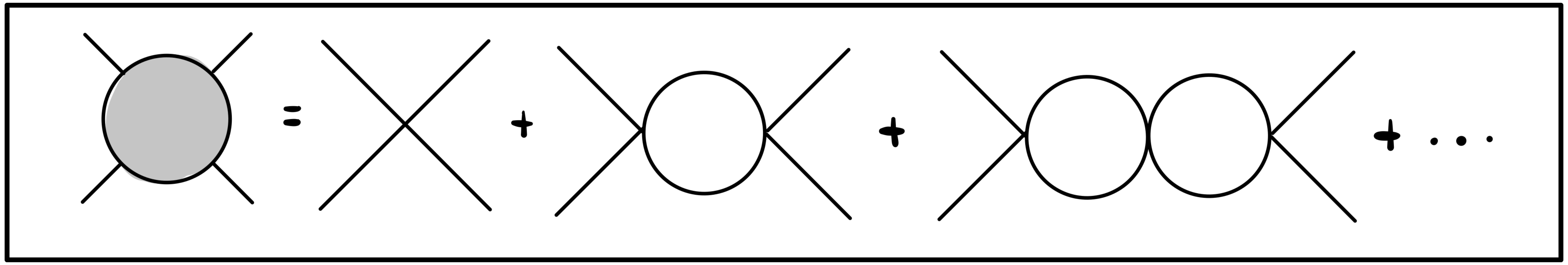
Molecular states

- The interaction is described at lowest order in χPT → V ~



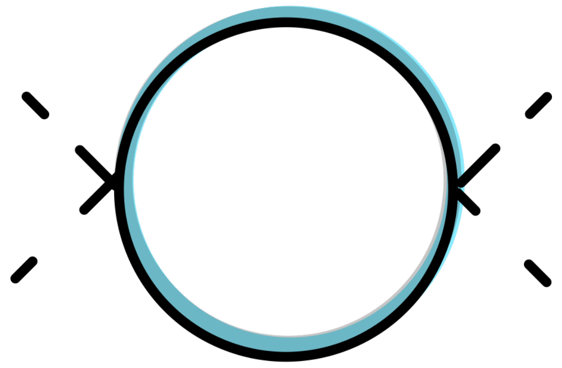


- The interaction is described at lowest order in χPT $\rightarrow$ $V \sim$ 



$$T = \frac{V}{(1 - VG)}$$

Unitarization implies

$G \rightarrow$ Loop-function $\sim$ 

It must be regularized either by a cut-off or by dim. reg. !

Singly and doubly heavy baryon states as meson-baryon interactions

PHYSICAL REVIEW D **97,** 094035 (2018)

Molecular Ω_c states generated from coupled meson-baryon channels

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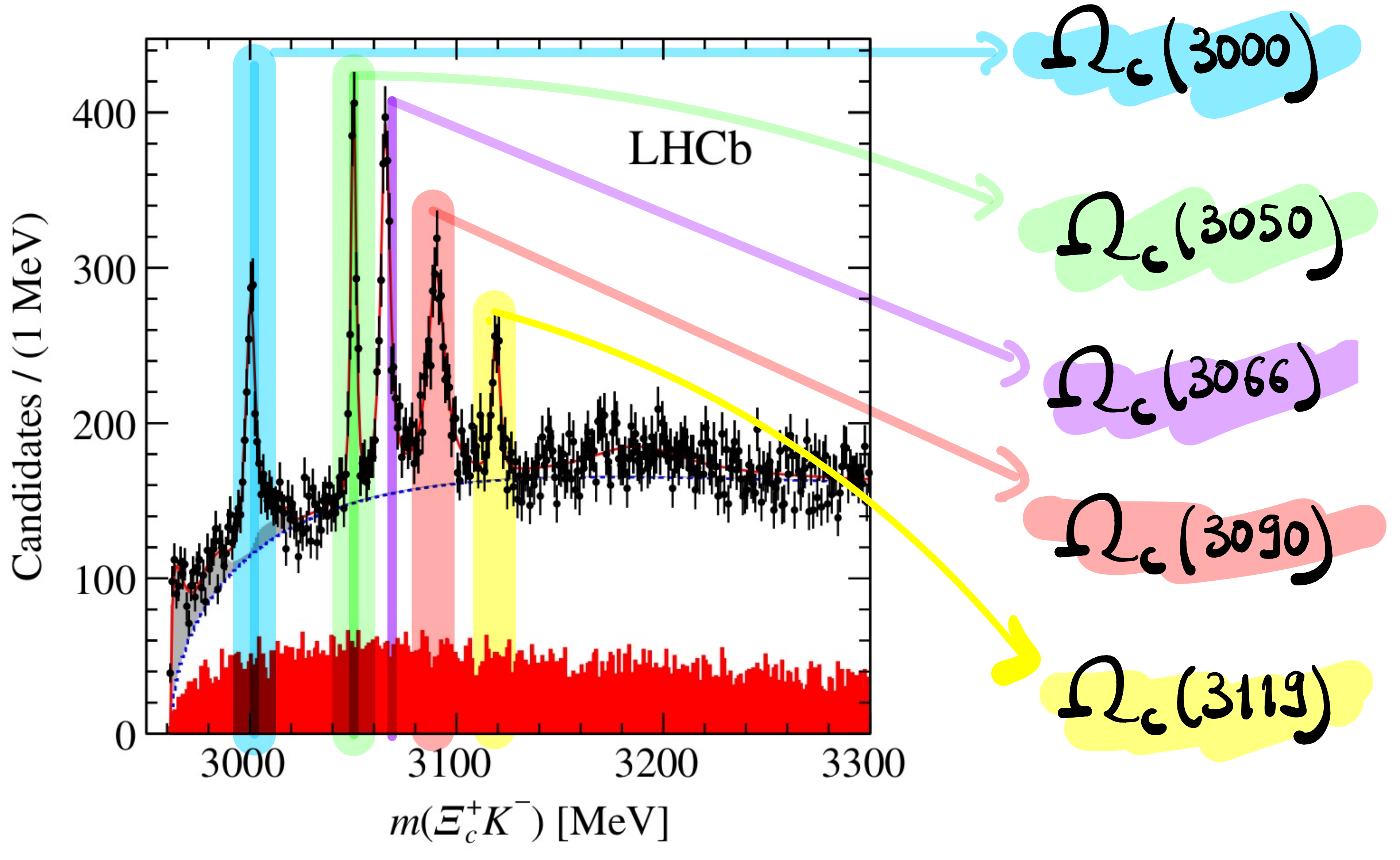
[3]*Department of Physics, Guangxi Normal University, Guilin 541004, China*

Phys. Rev. Lett. 118, 182001 (2017)



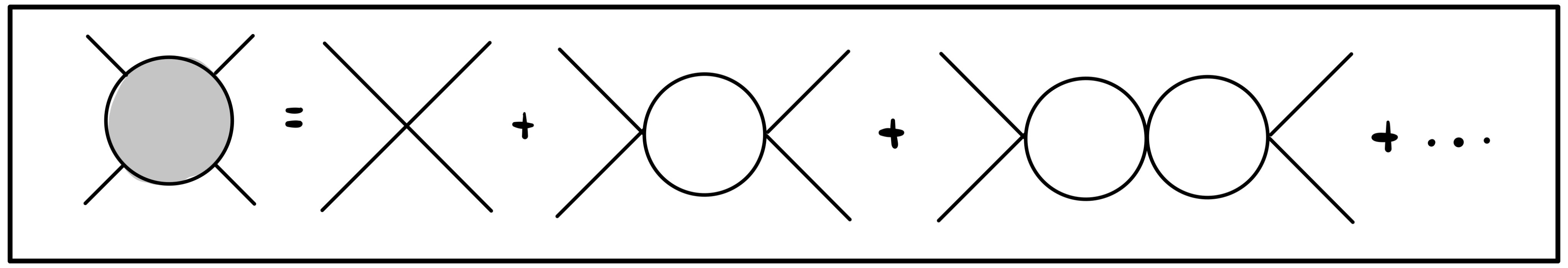
Channels

TABLE I. $J = 1/2$ states chosen and threshold mass in MeV.

States	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
Threshold	2965	3074	3185	3243	3327	3363	3472

TABLE II. $J = 3/2$ states chosen and threshold mass in MeV.

States	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
Threshold	3142	3314	3327	3363	3401	3472



$$V_{ij} = D_{ij} \frac{2\sqrt{s} - M_{B_i} - M_{B_j}}{4 f_\pi^2} \sqrt{\frac{M_{B_i} + E_{B_i}}{2M_{B_i}}} \sqrt{\frac{M_{B_j} + E_{B_j}}{2M_{B_j}}}$$

$$T = \frac{V}{(1 - VG)}$$

$\Omega_c(3050)$

$\Gamma \sim (0.88 \pm 0.2 \pm 0.1)$ MeV

$\Omega_c(3090)$

$\Gamma \sim (8.7 \pm 1.0 \pm 0.8)$ MeV

$\Omega_c(3119)$

$\Gamma \sim (1.1 \pm 0.8 \pm 0.4)$ MeV

Pseudoscalar meson - Baryon (1/2)

Pole position [MeV], couplings g_i [dimensionless], and wave functions at the origin $g_i G_i^{II}$ [MeV] from pseudoscalar(0^-)-baryon($1/2^+$) interaction describing the $\Omega_c(3050)$ and $\Omega_c(3090)$.

3054.05 + i0.44	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$
g_i	$-0.06 + i0.14$	$\mathbf{1.94 + i0.01}$	$-2.14 + i0.26$	$1.98 + i0.01$
$g_i G_i^{II}$	$-1.40 - i3.85$	$\mathbf{-34.41 - i0.30}$	$9.33 - i1.10$	$-16.81 - i0.11$
3091.28 + i5.12	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$
g_i	$0.18 - i0.37$	$0.31 + i0.25$	$\mathbf{5.83 - i0.20}$	$0.38 + i0.23$
$g_i G_i^{II}$	$5.05 + i10.19$	$-9.97 - i3.67$	$\mathbf{-29.82 + i0.31}$	$-3.59 - i2.23$

Pseudoscalar meson - Baryon (3/2)

The coupling constants to various channels for the poles in the $J^P = 3/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_i G_i^{II}$ in MeV.

3124.84	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
g_i	1.95	1.98	0	0	–0.65	0
$g_i G_i^{II}$	–35.65	–16.83	0	0	1.93	0
3290.31 + i0.03	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
g_i	$0.01 + i0.02$	$0.31 + i0.01$	0	0	$6.22 - i0.04$	0
$g_i G_i^{II}$	$-0.62 - i0.18$	$-5.25 - i0.18$	0	0	$-31.08 + i0.20$	0

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B 930 (2018) 524–532
www.elsevier.com/locate/nuclphysb

Molecular Ω_b states

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[c] Instituto de Física, Universidade de São Paulo, Rua do Matão, 1371, Butantã, CEP 05508-090, São Paulo, São Paulo, Brazil

Channels

The pseudoscalar–baryon states with $J^P = \frac{1}{2}^-$ and their threshold masses in MeV.

States	$\Xi_b \bar{K}$	$\Xi'_b \bar{K}$	$\Omega_b \eta$	$\Xi \bar{B}$
Threshold	6289	6431	6594	6598

The pseudoscalar–baryon states with $J^P = \frac{3}{2}^-$ and their threshold masses in MeV.

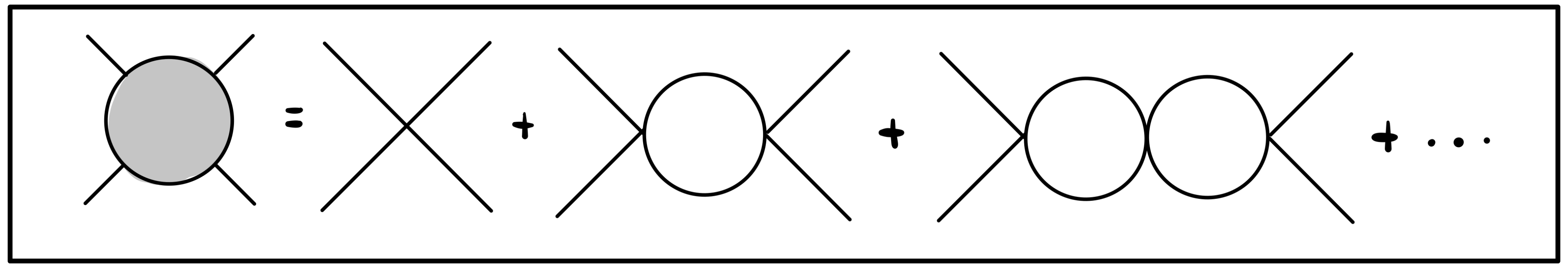
States	$\Xi^*_b \bar{K}$	$\Omega^*_b \eta$	$\Xi^* \bar{B}$
Threshold	6451	6619	6813

The vector–baryon states with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ and their threshold masses in MeV.

States	$\Xi \bar{B}^*$	$\Xi_b \bar{K}^*$	$\Xi'_b \bar{K}^*$
Threshold	6643	6687	6829

Channels

$$V_{ij} = D_{ij} \frac{2\sqrt{s} - M_{B_i} - M_{B_j}}{4 f_\pi^2} \sqrt{\frac{M_{B_i} + E_{B_i}}{2M_{B_i}}} \sqrt{\frac{M_{B_j} + E_{B_j}}{2M_{B_j}}}$$



$$T = \frac{V}{(1 - VG)}$$

The poles, and coupling constants of the poles to various channels in the PB sector with $J^P = 1/2^-$, taking $q_{max} = 650$ MeV. g_i has no dimension and $g_i\, G_i^{II}$ has dimension of MeV.

6405.2	$\Xi_b \bar{K}$	$\Xi'_b \bar{K}$	$\Xi \bar{B}$	$\Omega_b \eta$
g_i	$-0.01 + i0.02$	$\mathbf{2.04 + i0.01}$	$-1.62 + i0.02$	$\mathbf{2.08 + i0.01}$
$g_i\, G_i^{II}$	$-0.34 - i0.47$	$\mathbf{-37.31 - i0.18}$	$2.27 - i0.02$	$\mathbf{-18.28 - i0.09}$

$\mathbf{6465.3 + i1.2}$	$\Xi_b \bar{K}$	$\Xi'_b \bar{K}$	$\Xi \bar{B}$	$\Omega_b \eta$
g_i	$0.07 - i0.15$	$0.11 + i0.125$	$\mathbf{10.70 - i0.10}$	$0.15 + i0.11$
$g_i\, G_i^{II}$	$3.92 + i3.91$	$-4.53 - i1.66$	$\mathbf{-18.89 + i0.08}$	$-1.55 - i1.14$

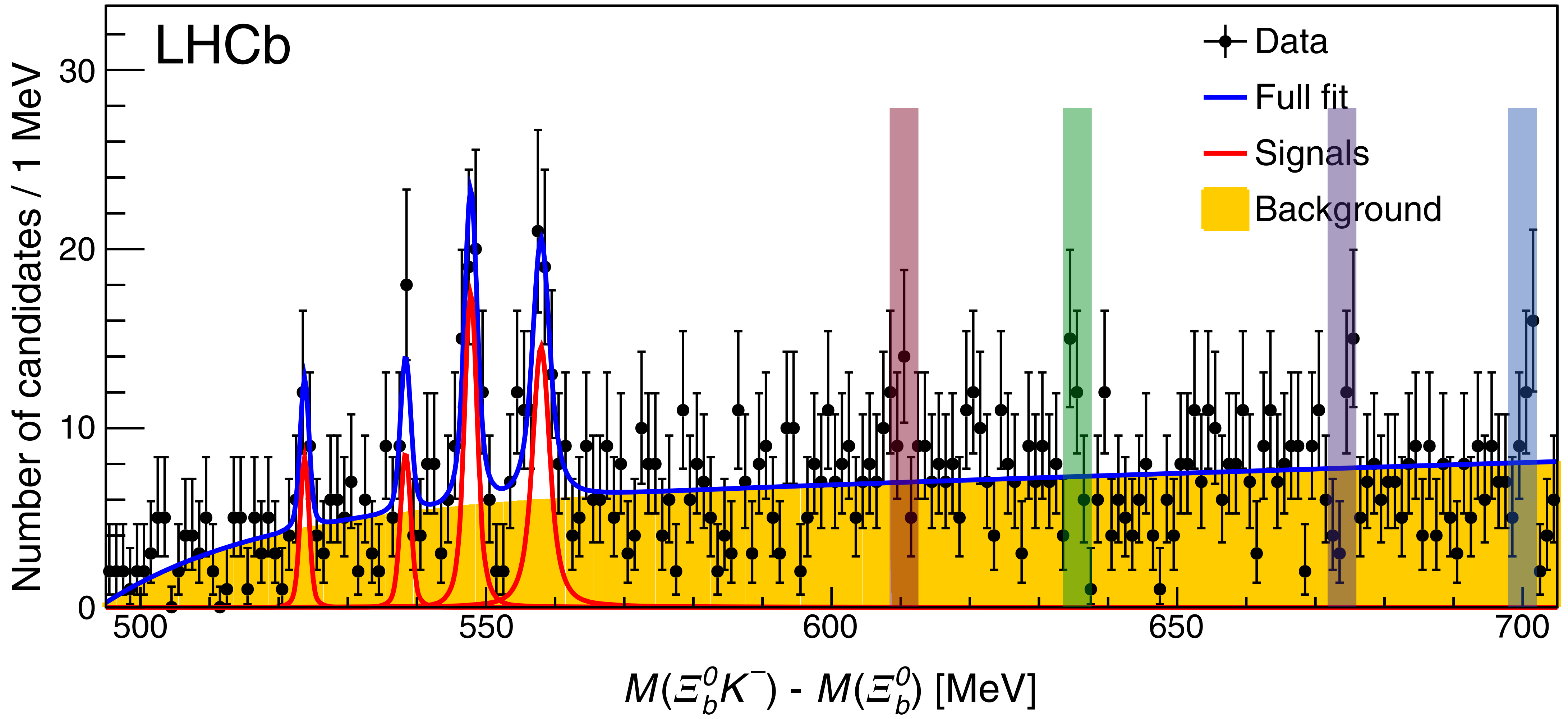
The poles, and coupling constants of the poles to various channels in the PB sector with $J^P = 3/2^-$, taking $q_{max} = 650$ MeV. g_i has no dimension and $g_i\, G_i^{II}$ has dimension of MeV.

6427.1	$\Xi_b^* \bar{K}$	$\Omega_b^* \eta$	$\Xi^* \bar{B}$
g_i	**2.01**	**2.05**	-0.60
$g_i\, G_i^{II}$	**−37.17**	**−17.86**	0.53

The poles, and coupling constants of the poles to various channels in the VB sector with $J^P = 1/2^-, 3/2^-$, taking $q_{max} = 650$ MeV. g_i has no dimension and $g_i\, G_i^{II}$ has dimension of MeV.

6508.0	$\Xi \bar{B}^*$	$\Xi_b \bar{K}^*$	$\Xi'_b \bar{K}^*$
g_i	**10.88**	0.32	-0.15
$g_i\, G_i^{II}$	**−18.86**	-2.37	0.77

Phys. Rev. Lett. 124, 082002 (2020)

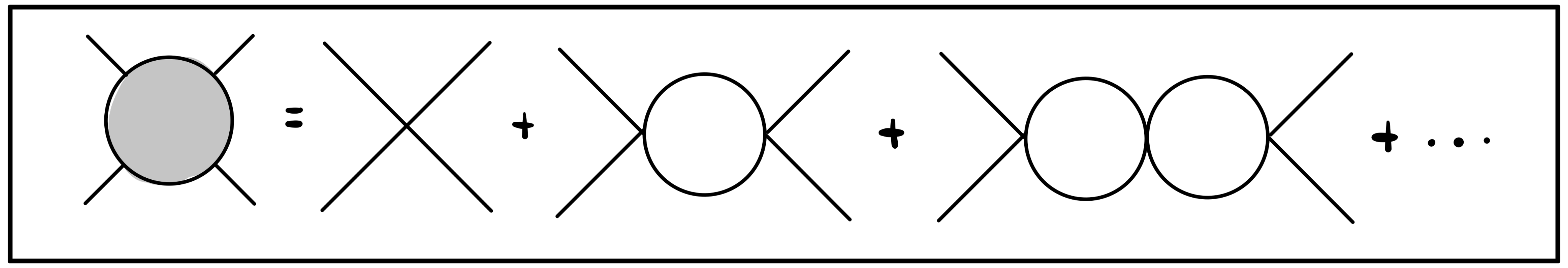


~ 6402 MeV

~ 6495 MeV

~ 6427 MeV

~ 6468 MeV



$$T = \frac{V}{(1 - VG)}$$

PHYSICAL REVIEW D **98,** 094022 (2018)

$\Omega_b^- \to (\Xi_c^+ K^-)\pi^-$ decay and the Ω_c states

V. R. Debastiani,[1,*] J. M. Dias,[1,2,†] Wei-Hong Liang,[3,‡] and E. Oset[1,§]
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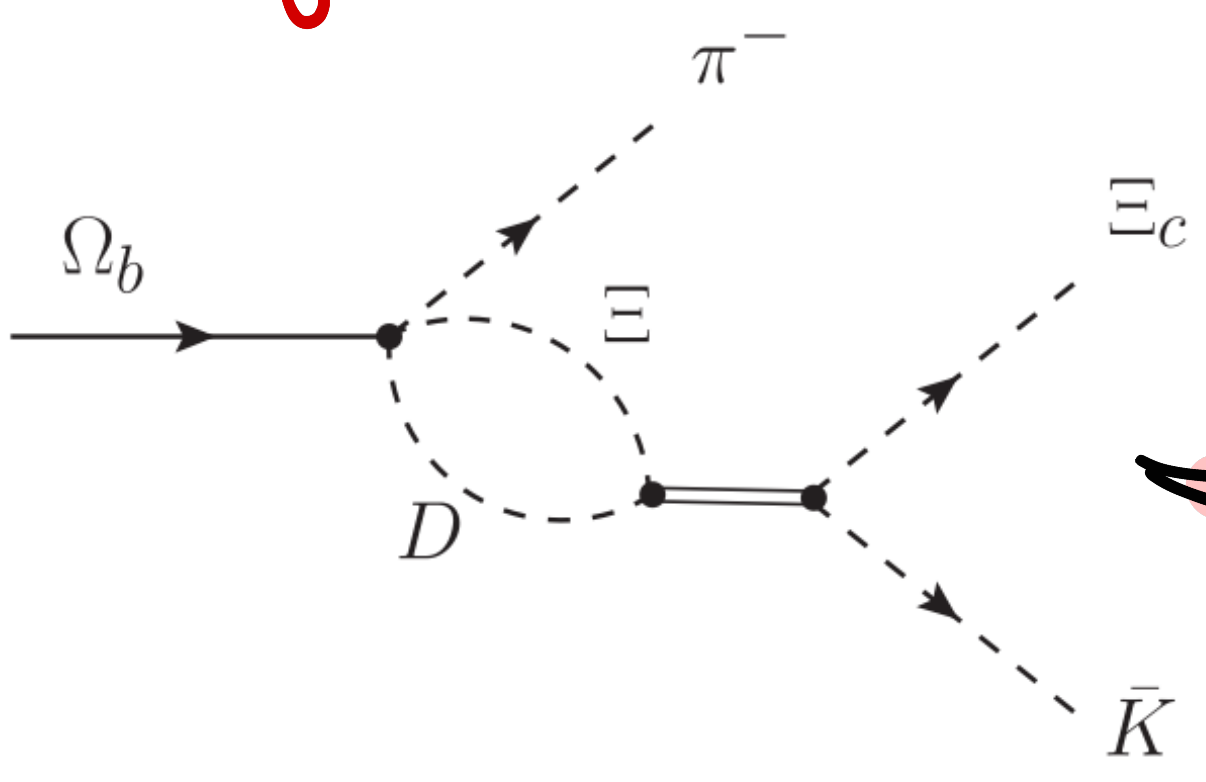
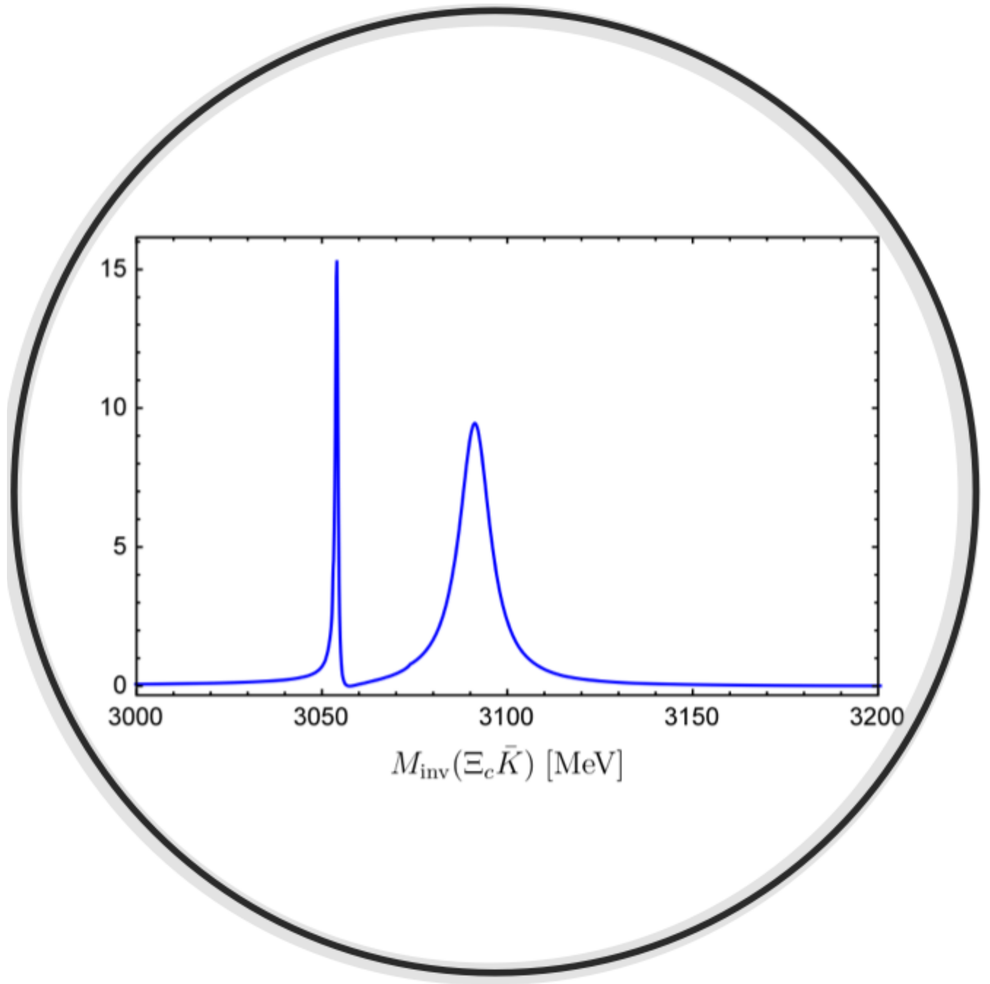
[2]*Instituto de Física, Universidade de São Paulo, Rua do Matão, 1371, Butantã, CEP 05508-090, São Paulo, São Paulo, Brazil*
[3]*Department of Physics, Guangxi Normal University, Guilin 541004, China*

Searching for Ω_c at Ω_b decays





Channels

TABLE I. $J = 1/2$ states chosen and threshold mass in MeV.

States	$\Xi_c\bar{K}$	$\Xi'_c\bar{K}$	ΞD	$\Omega_c\eta$	ΞD^*	$\Xi_c\bar{K}^*$	$\Xi'_c\bar{K}^*$
Threshold	2965	3074	3185	3243	3327	3363	3472

TABLE II. $J = 3/2$ states chosen and threshold mass in MeV.

States	$\Xi_c^*\bar{K}$	$\Omega_c^*\eta$	ΞD^*	$\Xi_c\bar{K}^*$	$\Xi^* D$	$\Xi'_c\bar{K}^*$
Threshold	3142	3314	3327	3363	3401	3472

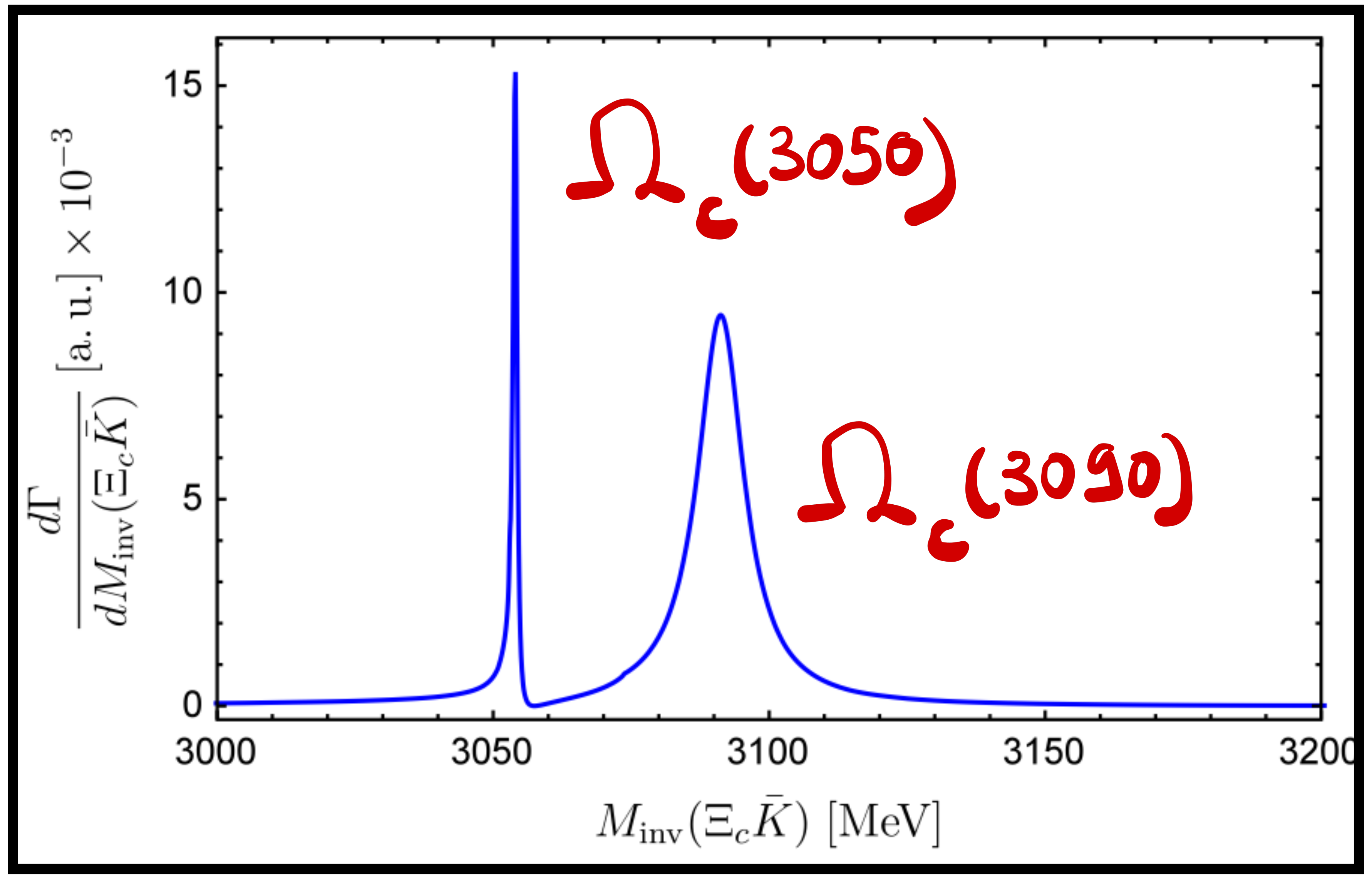
$$\frac{d\Gamma}{dM_{inv}} = \frac{1}{(2\pi)^3}\frac{M_{\Xi_c}}{M_{\Omega_b}} p_\pi \tilde{p}_K \left| T_{\Omega_b \to \pi \Xi_c \bar{K}} \right|^2$$

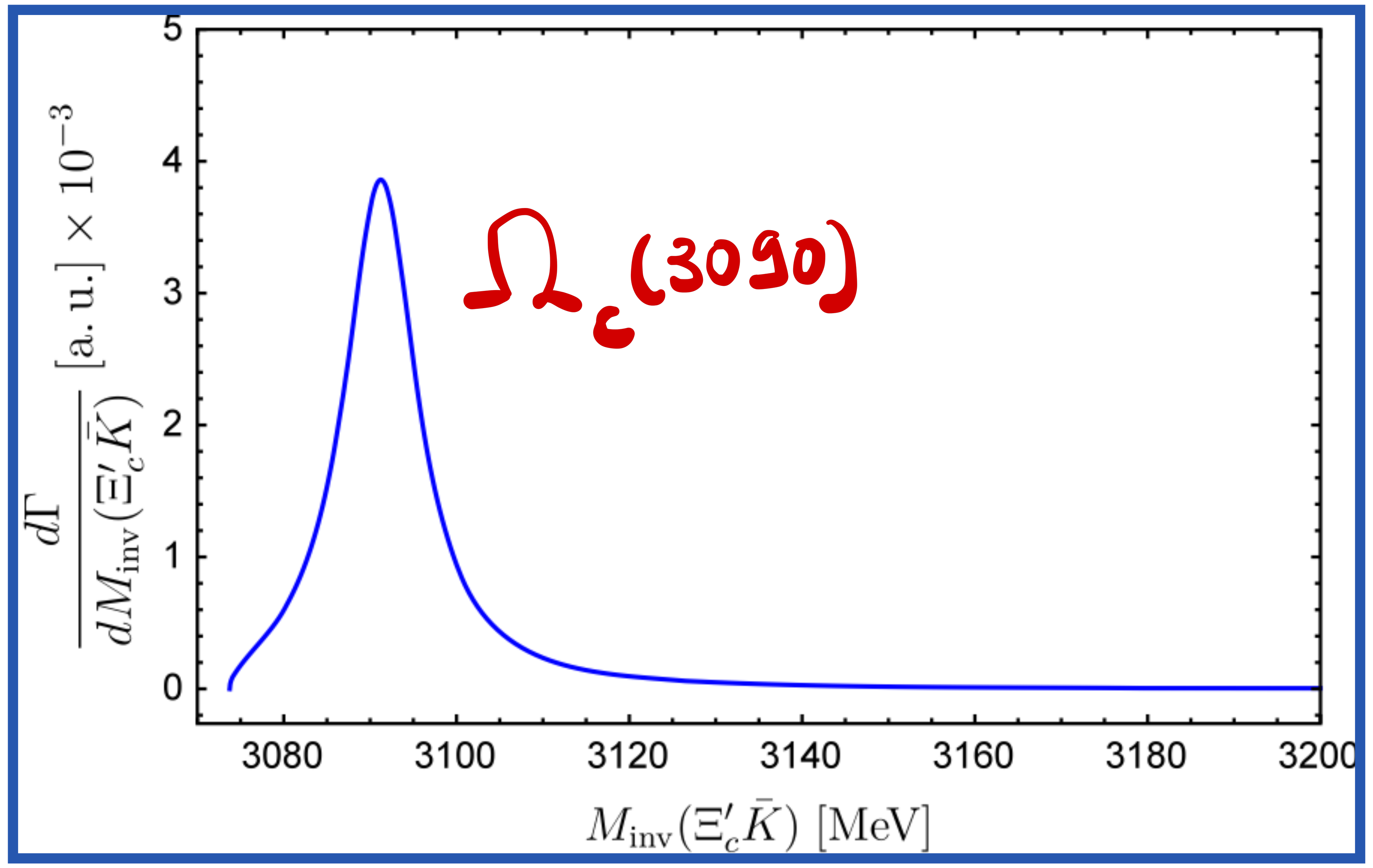
$$V_p G_{\Xi D} t_{\Xi D \to \Xi_c \bar{K}}$$

Phys. Rev. D 97, 094035 (2018)

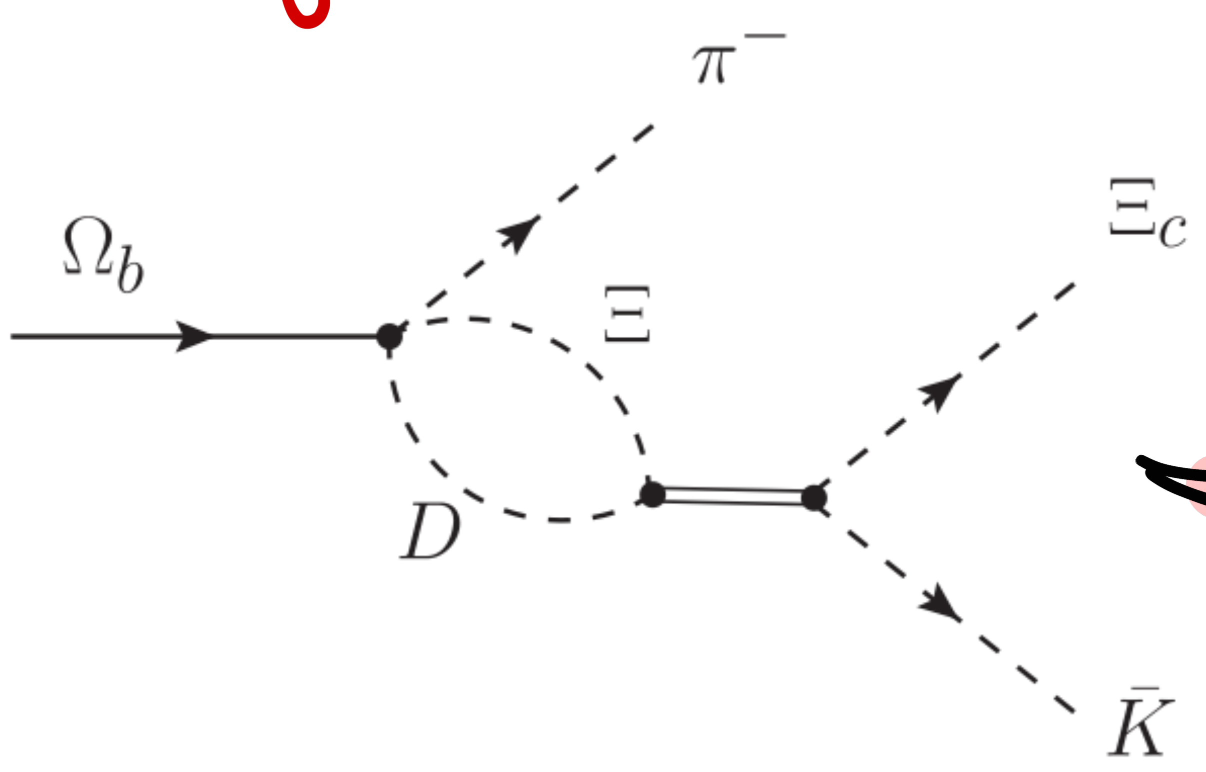
Solved in coupled channels

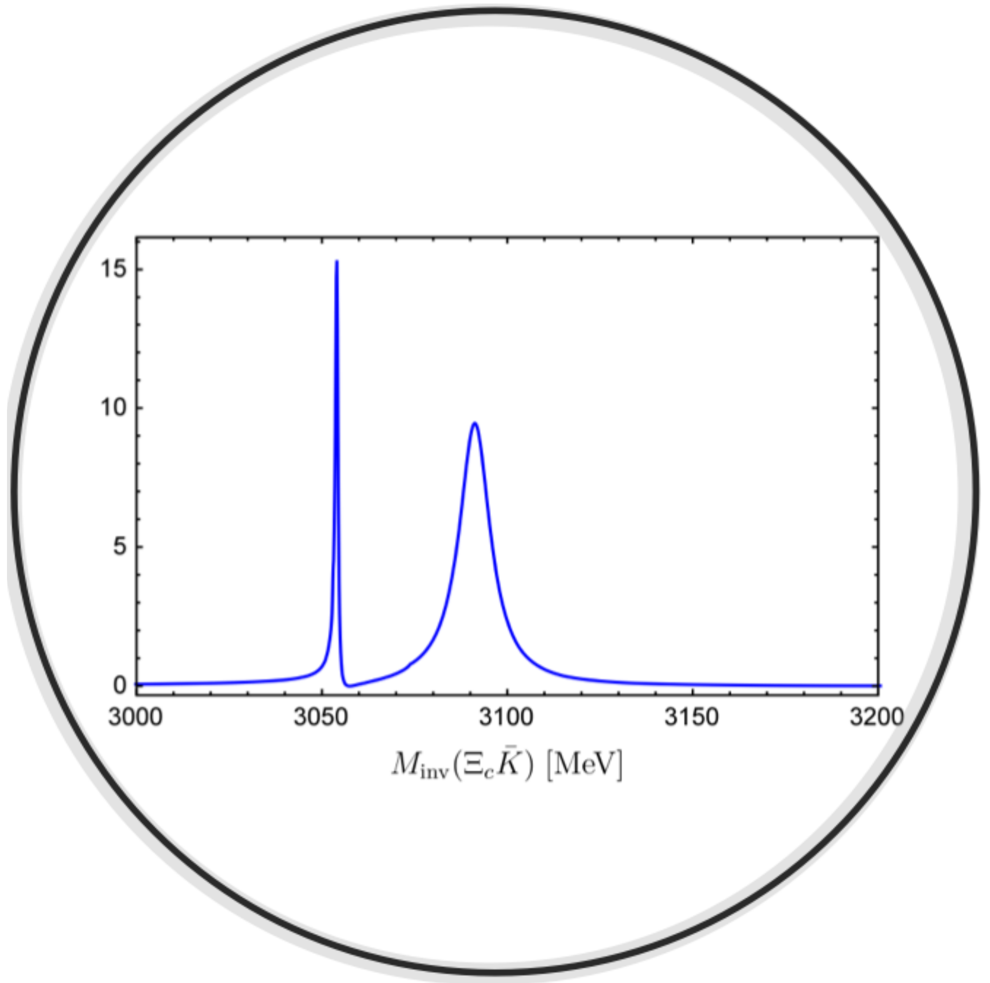
Results obtained





Searching for Ω_c at Ω_b decays





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$$V_p G_{\Xi D} t_{\Xi D \to \Xi_c \bar{K}}$$

Phys. Rev. D 97, 094035 (2018)

Solved in coupled channels

QCD Sum Rules Approach

QCD SUM RULES

Shifman

Nuclear Phys. B 147 (1979).

Vanishtein

Zakharov

SVZ (QCD) sum Rules

$K, \pi, \rho \ldots$

Pheno Side

Hadron

Λ scale

Duality Principle

u d c s

t b

g

QCD SIDE

QCD SUM RULES

The two point-function: $\Pi(q) = i\int d^4x\, e^{iq\cdot x}\langle 0|T(j(x)j^\dagger(0))|0\rangle$

given quark content

Example: $j_n(x) = \bar{q}_a \Gamma_n q_a$, with

Tensorial structure

$\Gamma_n = 1, \gamma_\mu, \gamma_\mu\gamma_\nu, \ldots$

- $\Gamma_0 \Rightarrow j(x) = \bar{q}_a(x) q_a(x) \Rightarrow J^P = 0^+$ (Scalar)
- $\Gamma_\mu \Rightarrow j_\mu(x) = \bar{q}_a(x)\gamma_\mu q_a(x) \Rightarrow J^P = 1^-$ (Vector)

$\vdots$

QCD SUM RULES

The two point-function: $\Pi(q) = i\int d^4x\, e^{iq\cdot x}\langle 0|T(j(x)j^\dagger(0))|0\rangle$

$$\Pi(q) = \sum_d C_d(q^2)\langle \hat{O}_d\rangle$$

Wilson Operator Expansion

Perturbative part

Encodes the non-trivial structure of QCD-vaccum: condensates

We have a clean separation of scales!

QCD SUM RULES

The two point-function: $\Pi(q) = i\int d^4x\, e^{iq\cdot x}\langle 0|T(j(x)j^\dagger(0))|0\rangle$

$$\Pi(q) = \sum_d C_d(q^2)\langle \hat{O}_d\rangle = C_0(q^2)\,\mathbb{1} + C_3(q^2)\langle \bar{q}q\rangle + \dots$$

Series of Feynman diagrams

quark condensate

$\hat{O}_3 = :\bar{q}(0)q(0): \equiv \bar{q}q$

QCD SUM RULES

The two point-function: $\Pi(q) = i\int d^4x\, e^{iq\cdot x}\langle 0|T(j(x)j^\dagger(0))|0\rangle$

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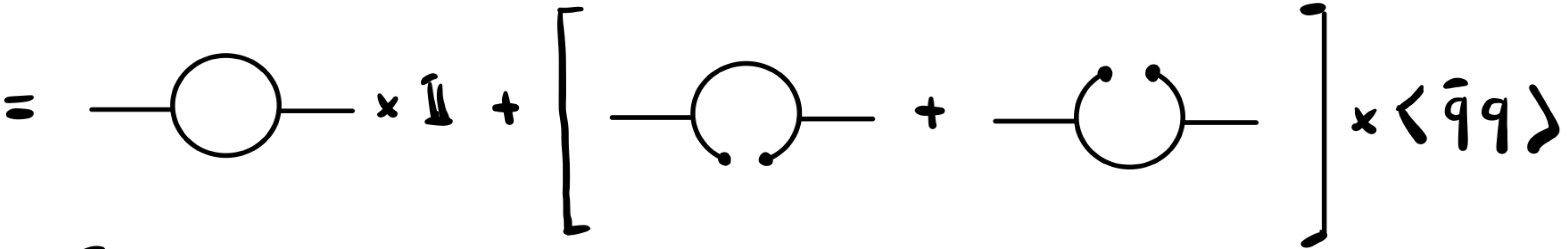

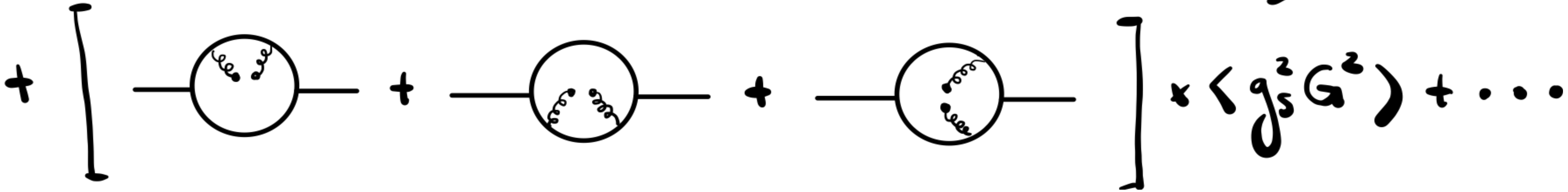

QCD SUM RULES

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Nuclear Phys. B 147 (1979).

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$K, \pi, \rho \ldots$

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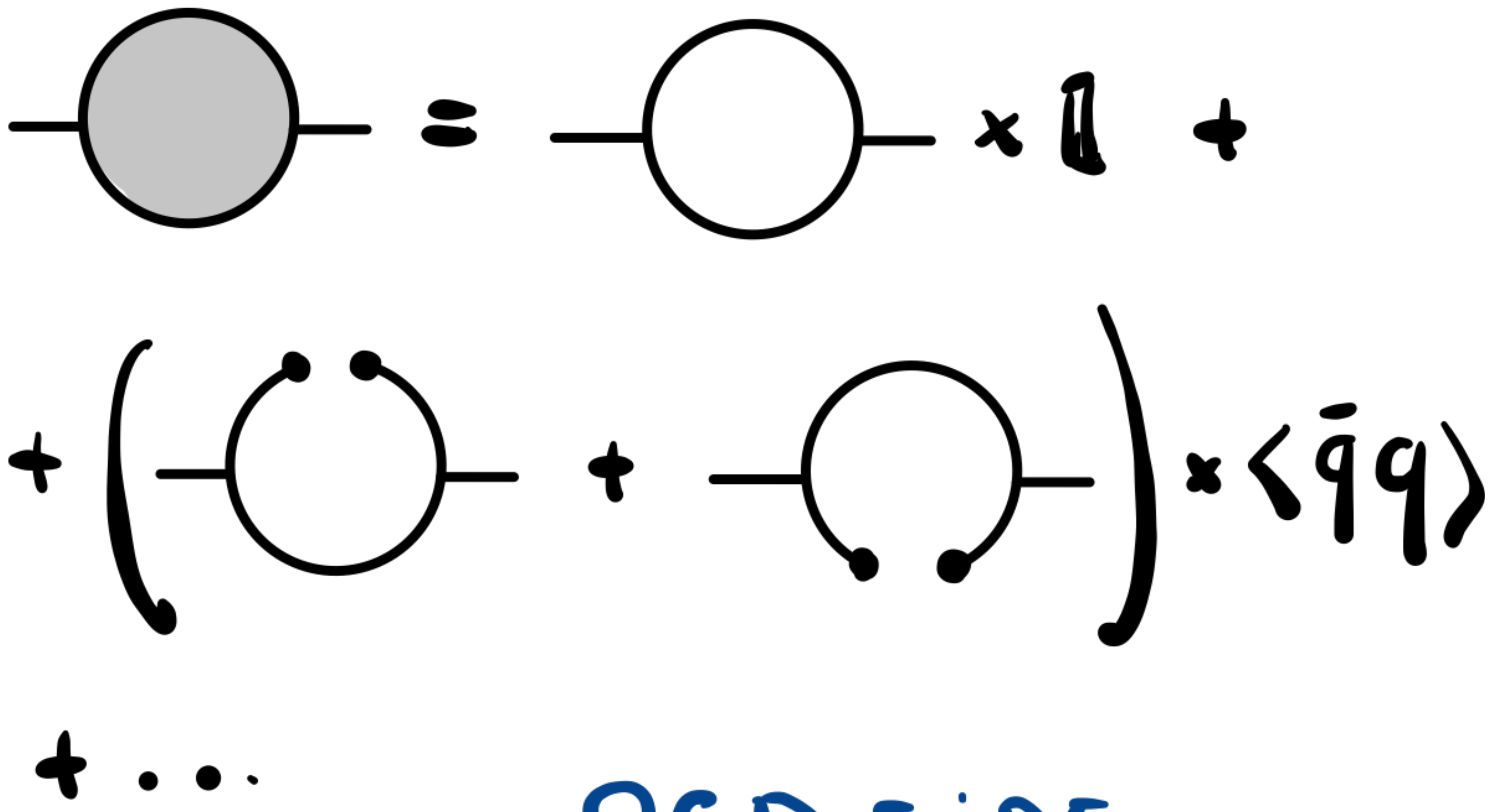

QCD SIDE

QCD SUM RULES

The two point-function: $\Pi(q) = i\int d^4x\, e^{iq\cdot x}\langle 0|T(j(x)j^\dagger(0))|0\rangle$

$$\Pi(q) = \langle 0|T\{j(q)j^\dagger(0)\}|0\rangle = \underbrace{\langle 0|j(q)|H(q)\rangle}_{\approx \lambda}\frac{i}{q^2-M_H^2}\underbrace{\langle H(q)|j^\dagger(0)|0\rangle}_{\lambda^*}$$

$$|H(q)\rangle\frac{i}{q^2-M_H^2}\langle H(q)| = \mathbb{1}$$

complete set

Hadronic Observable!

$$\Pi(q) = \frac{\lambda M_H}{q^2-M_H^2} + \cdots$$

Other parametrizations:

- $\langle 0|j_\mu|V\rangle = M_V f_V \varepsilon_\mu$
- $\langle 0|j_s|P\rangle = f_P\frac{M_P^2}{m_q}$
- $\langle 0|j_\mu|A\rangle = i f_P P_\mu$

QCD SUM RULES

Shifman

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Zakharov

SVZ (QCD) sum Rules

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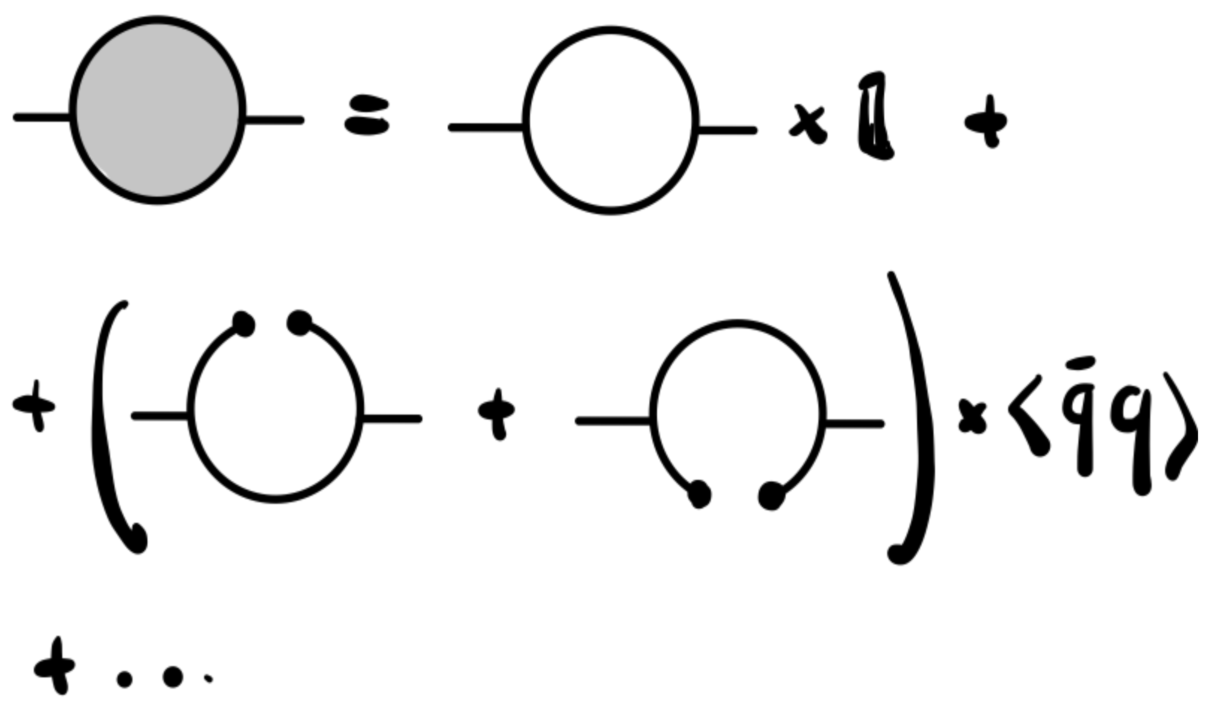


Borel Transform - M_B

$$\Pi^{pheno}(s, M_B^2) = \lambda^2 e^{-s/M_B^2} + \int ds\, \rho(s) e^{-s/M_B^2}$$

$$\Pi^{OPE}(s, M_B^2) = \int_{s_{min}}^{\infty} ds\, \rho^{OPE}(s) e^{-s/M_B^2}$$

$$\rho^{OPE}(s) = \frac{1}{\pi} \mathrm{Im}\left[\Pi(s, M_B^2)\right]$$

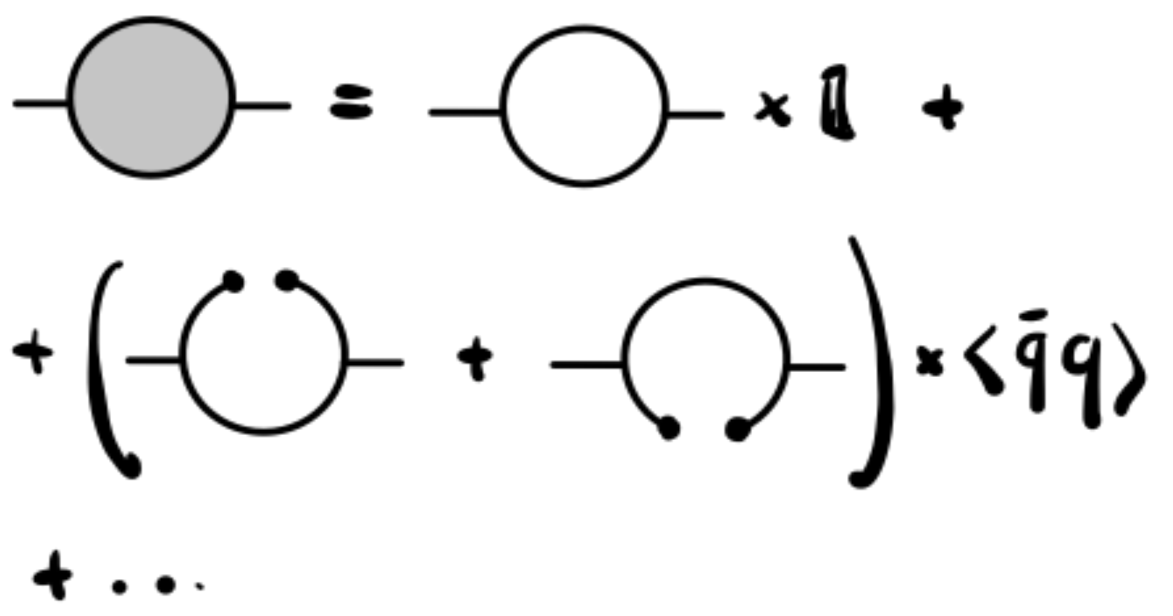
SVZ (QCD) sum Rules

QCD SIDE

$$\Pi(q) = \frac{\lambda M_H}{q^2 - M_H^2} + \dots$$

Hadron

Λ scale



Pheno Side

Duality Principle

Borel Transform - M_B

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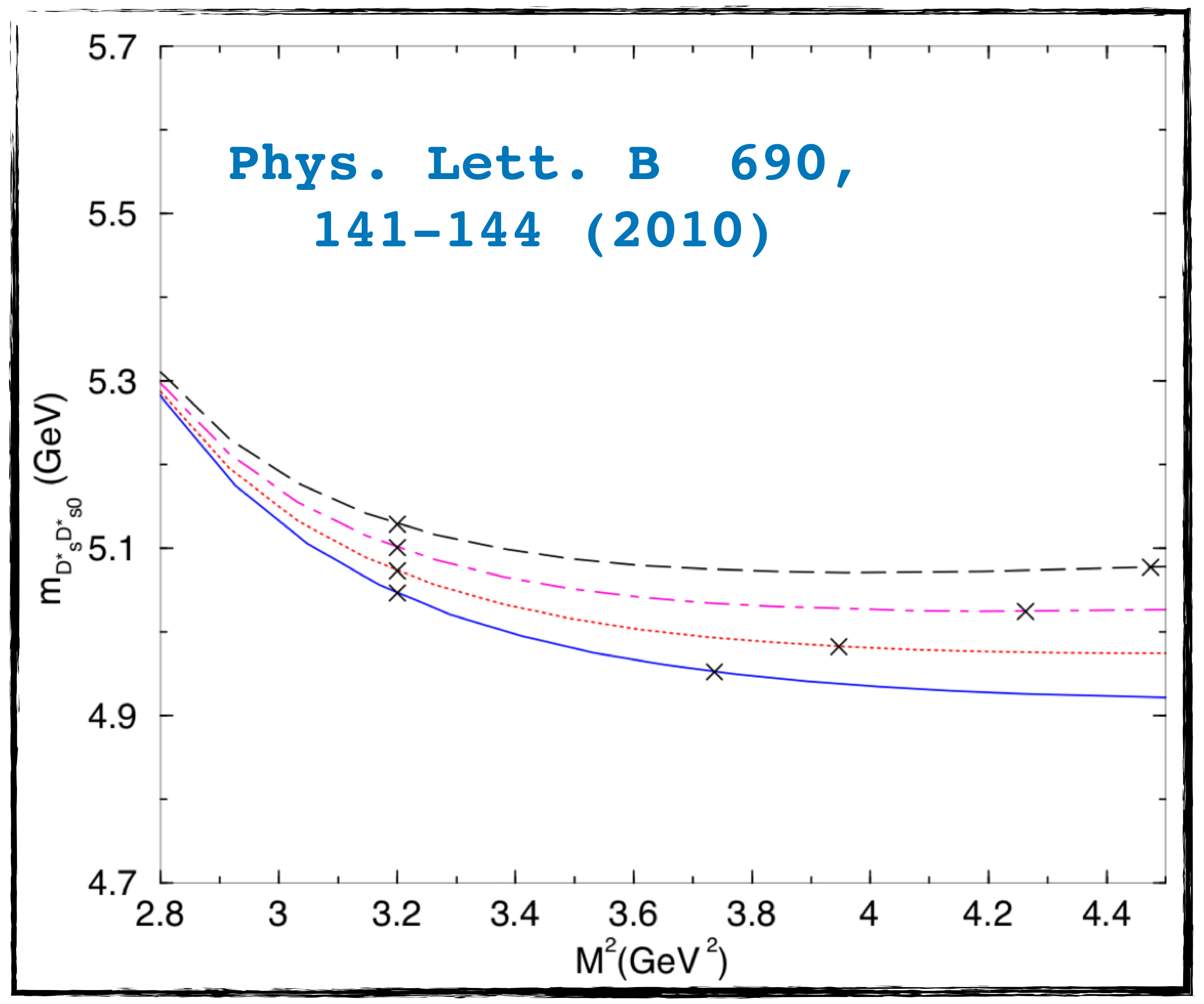
$$\Pi^{OPE}(s, M_B^2) = \int_{s_{min}}^{\infty} ds\, \rho^{OPE}(s) e^{-s/M_B^2}$$

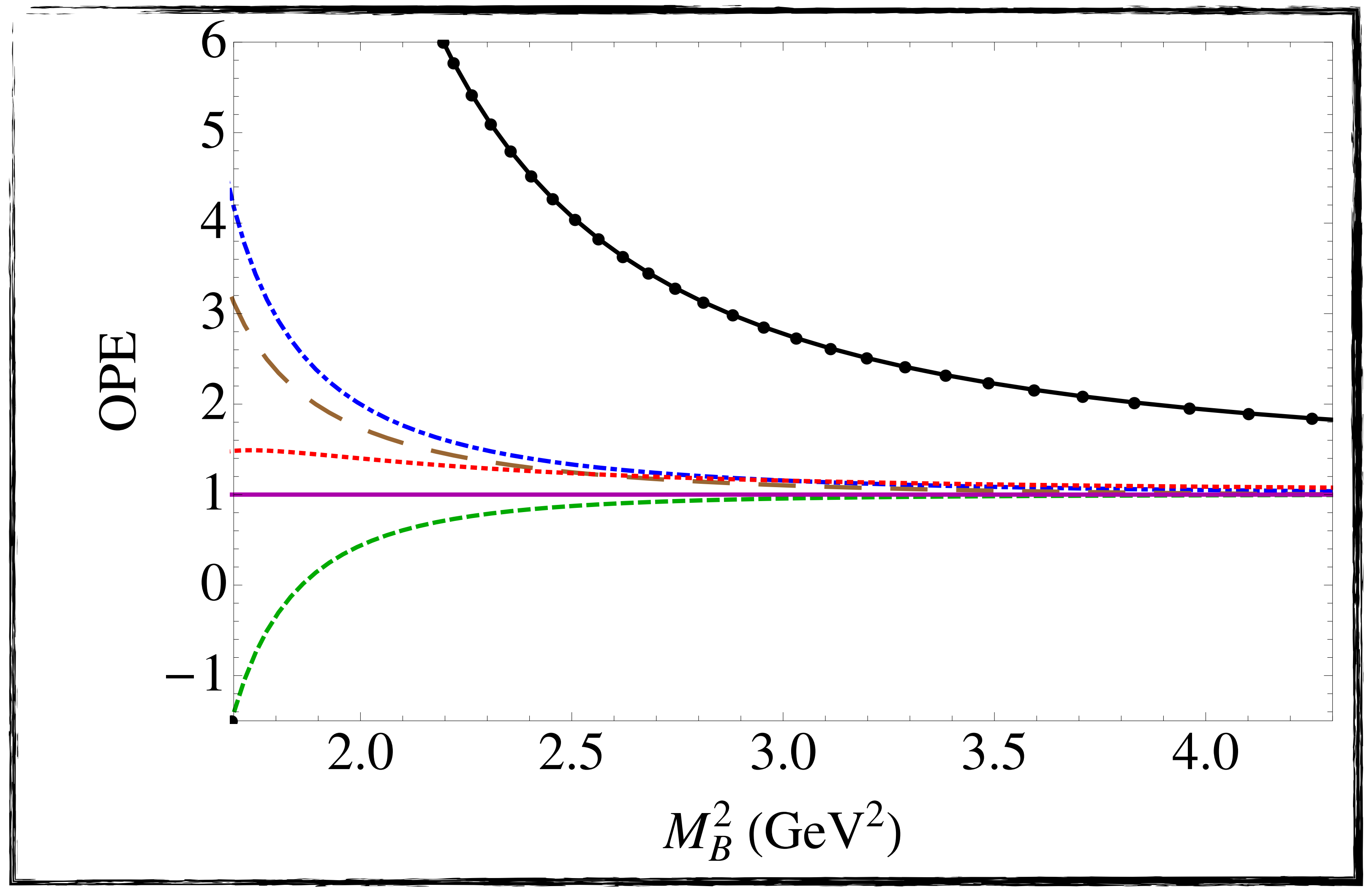
$$\rho^{OPE}(s) = \frac{1}{\pi} Im[\Pi(s, M_B^2)]$$

OPE series must be convergent !

$$M_H^2 = \frac{\int_{s_{min}}^{s_0} ds\, s\, \rho^{OPE}(s) e^{-s/M_B^2}}{\int_{s_{min}}^{s_0} ds\, \rho^{OPE}(s) e^{-s/M_B^2}}$$

Must be stable with M_B^2





PHYSICAL REVIEW D **88,** 016004 (2013)

$Z_c^+(3900)$ decay width in QCD sum rules

J. M. Dias,* F. S. Navarra,† and M. Nielsen‡

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Faculdade de Tecnologia, Universidade do Estado do Rio de Janeiro, Rodovia Presidente Dutra Km 298, Pólo Industrial, 27537-000 Resende, Rio de Janeiro, Brazil

(Received 13 May 2013; published 3 July 2013)

We identify the recently observed charmoniumlike structure $Z_c^\pm(3900)$ as the charged partner of the $X(3872)$ state. Using standard techniques of QCD sum rules, we evaluate the three-point function and extract the coupling constants of the $Z_c^+ J/\psi \pi^+$, $Z_c^+ \eta_c \rho^+$ and $Z_c^+ D^+ \bar{D}^{*0}$ vertices and the corresponding decay widths in these channels. The good agreement with the experimental data gives support to the tetraquark picture of this state.

DOI: 10.1103/PhysRevD.88.016004 PACS numbers: 11.55.Hx, 12.38.Lg, 12.39.−x

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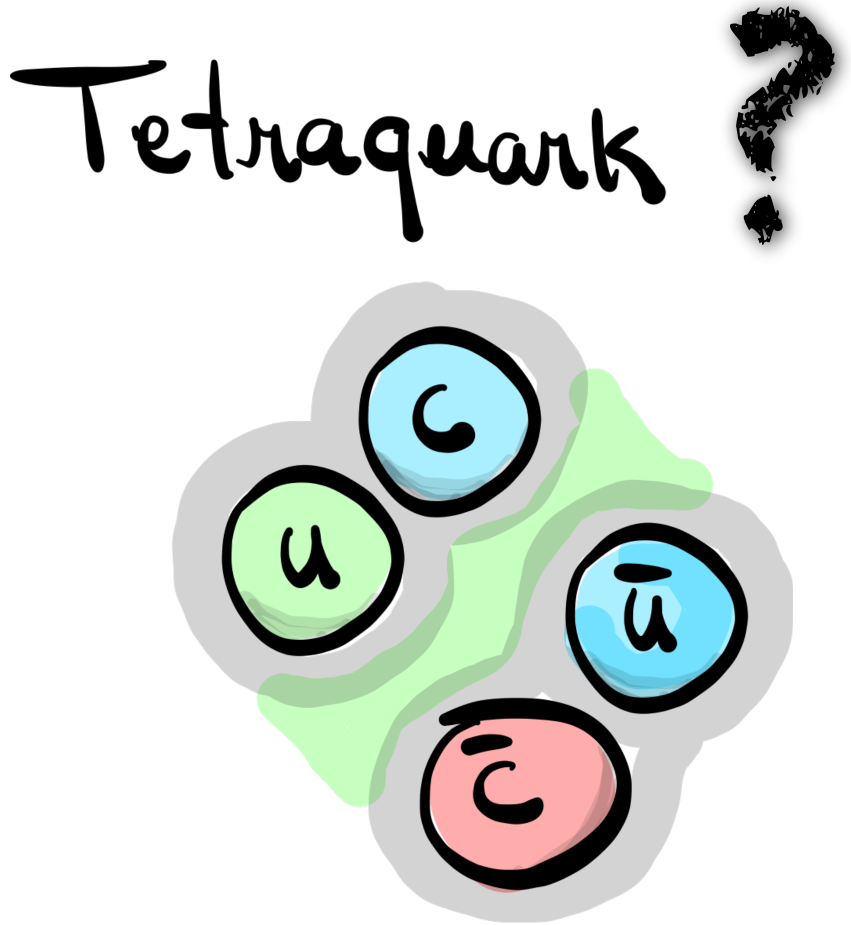

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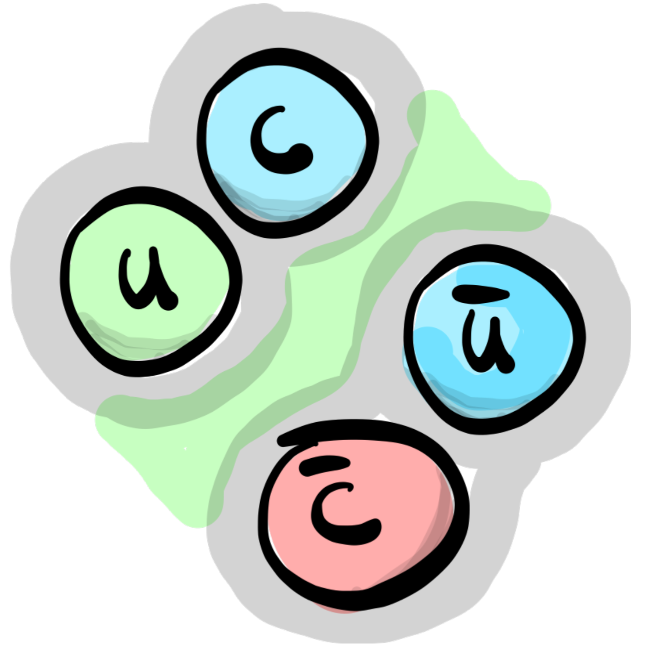
$$Y(4260) \to J/\psi\, \pi^+ \pi^-$$

Tetraquark ?



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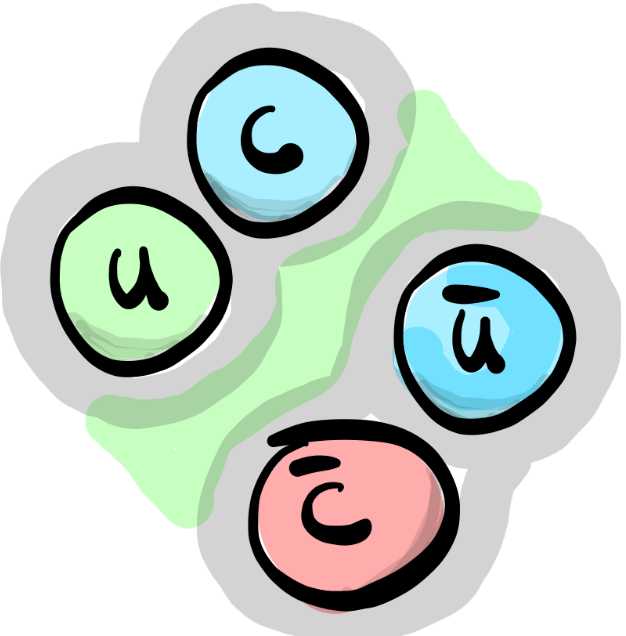
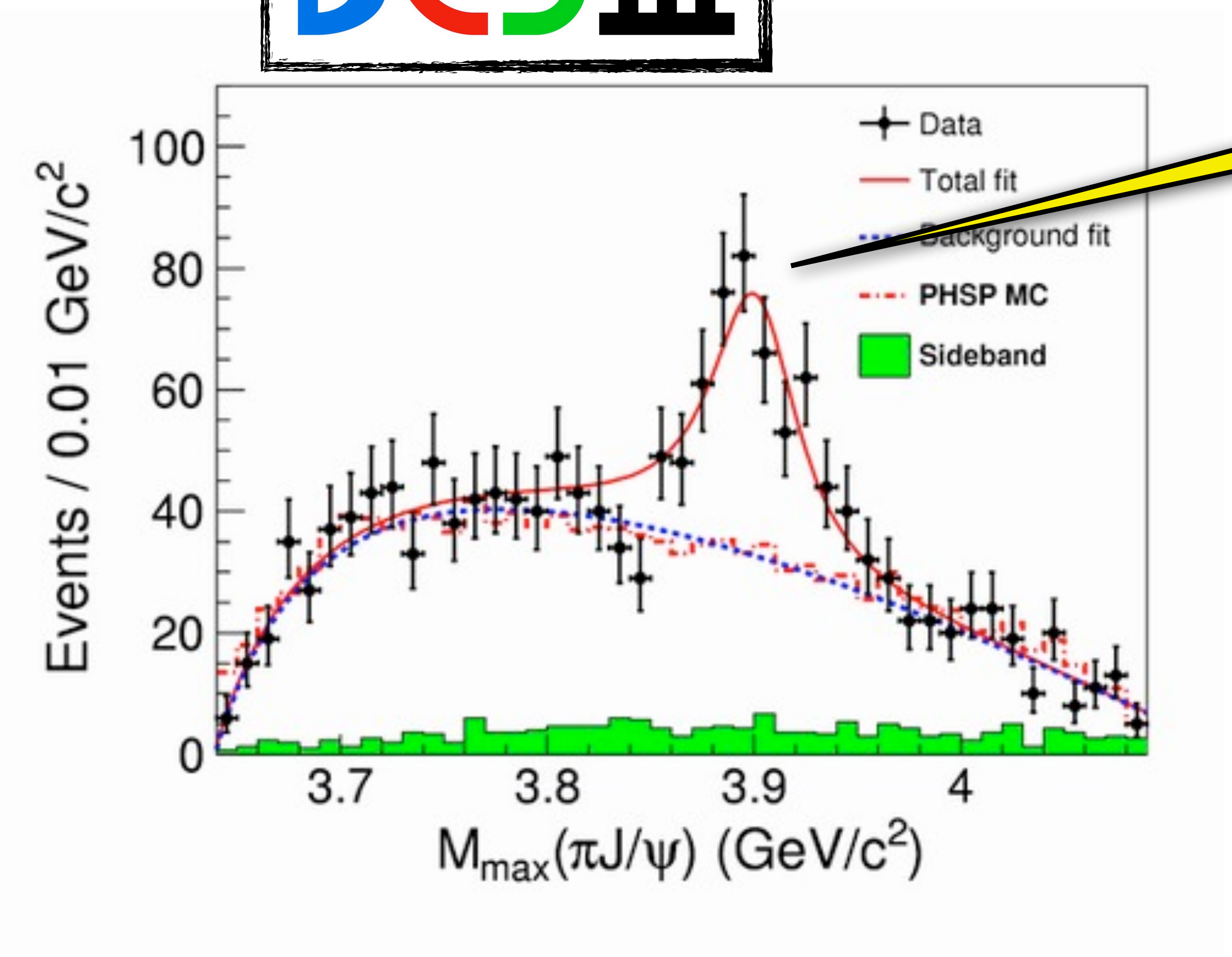
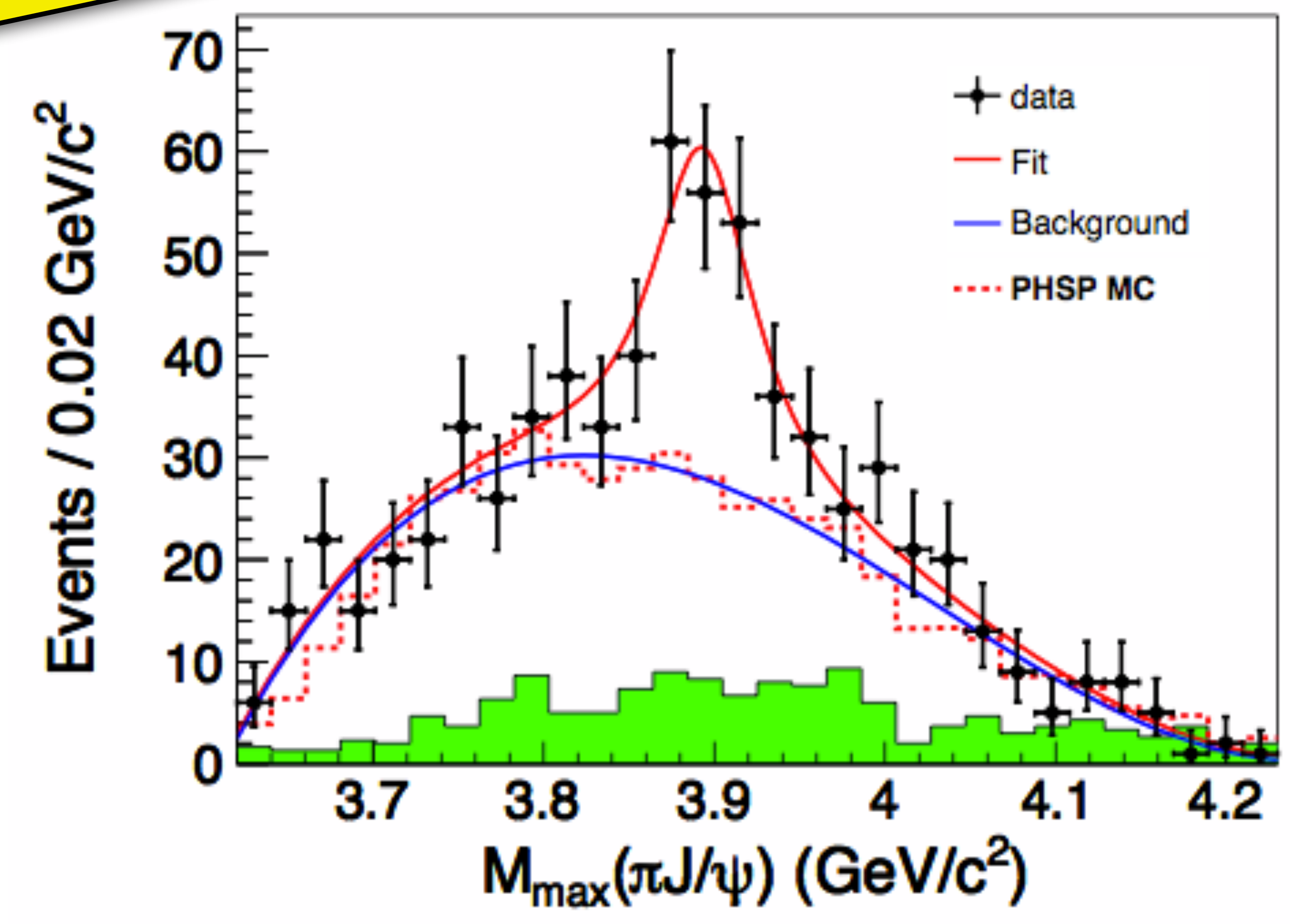
Tetraquark ?



$$Y(4260) \to J/\psi\,\pi^+\pi^-$$





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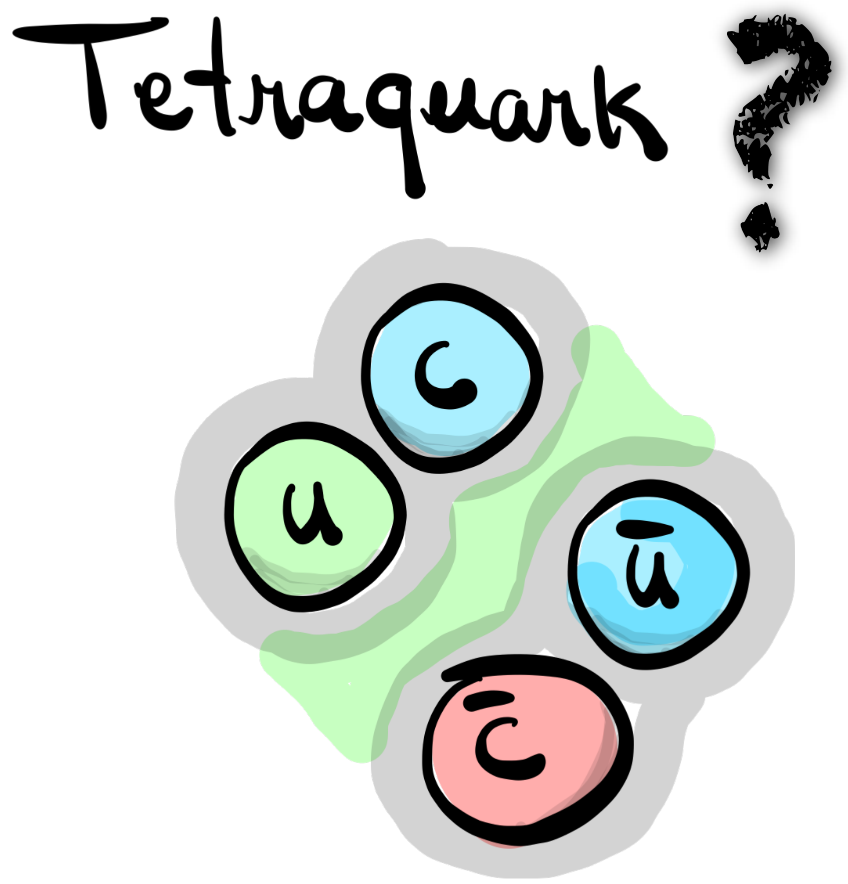

$Z_c^+(3900) \to J/\psi\pi^+$ DECAY WIDTH

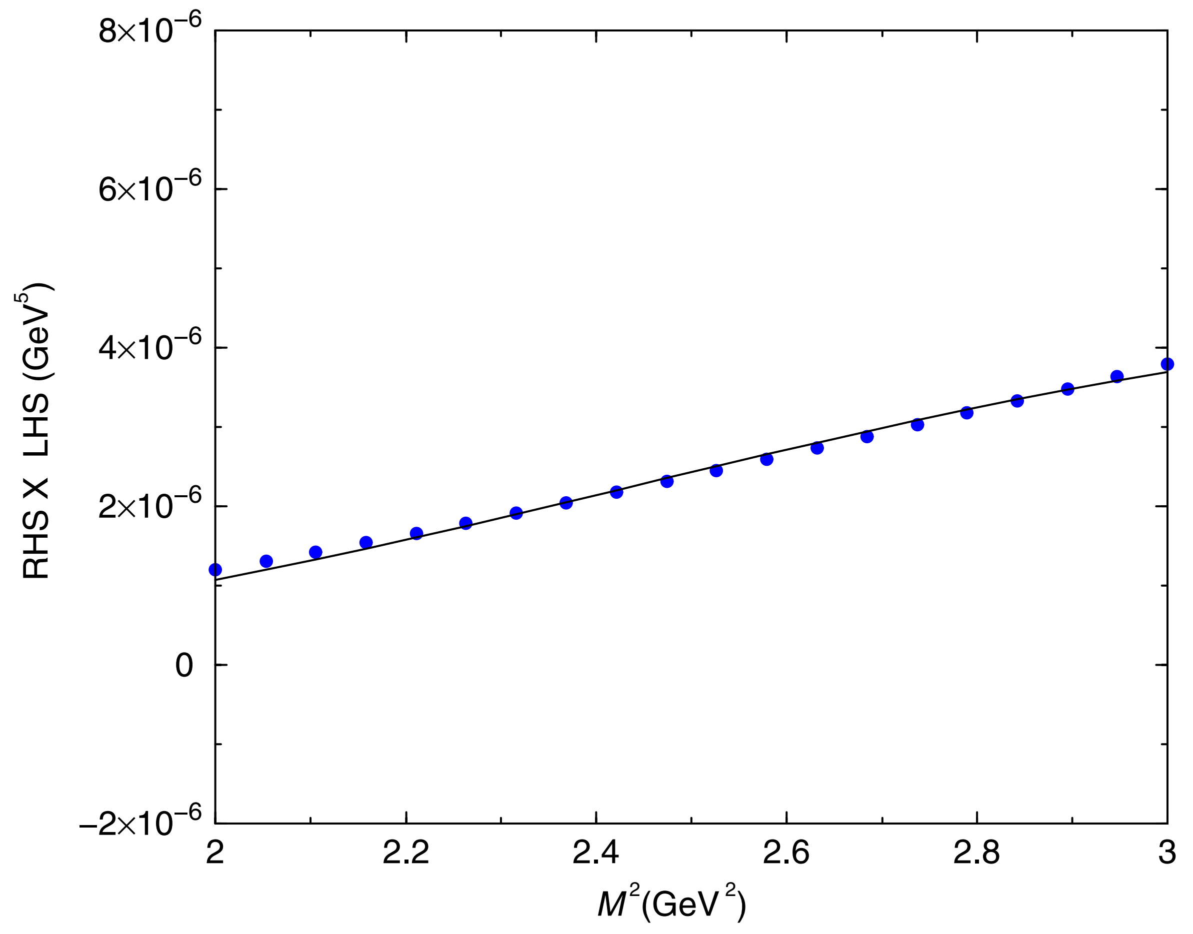

FIG. 3 (color online). Dots: the rhs of Eq. (9), as a function of the Borel mass for $\Delta s_0 = 0.5$ GeV. The solid line gives the fit of the QCDSRs results through the lhs of Eq. (9).

$Z_c^+(3900) \to \eta_c\rho^+$ DECAY WIDTH

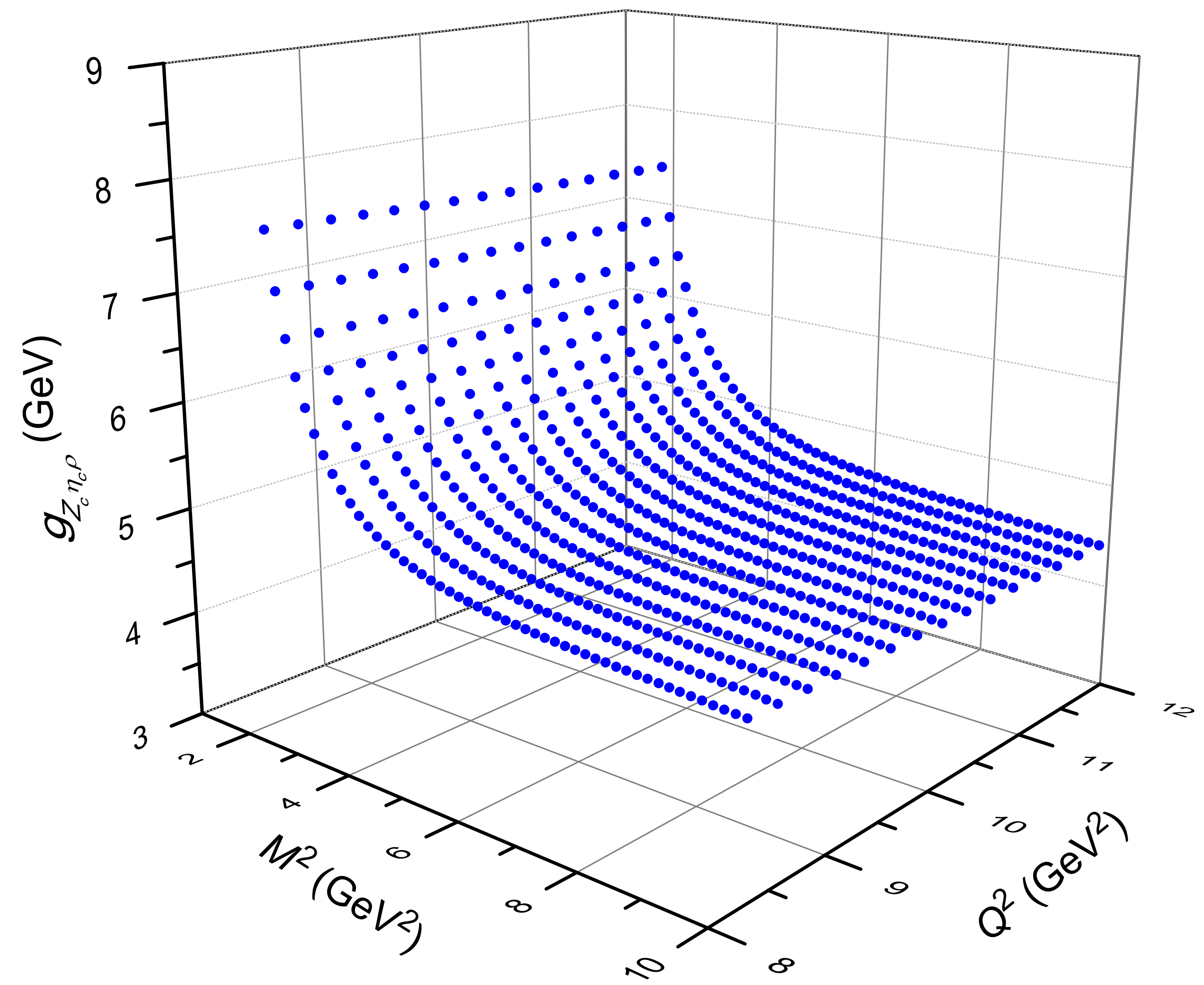

FIG. 4 (color online). QCDSRs results for the form factor $gZ_c\eta_c\rho(Q^2)$ as a function of Q^2 and M^2 for $\Delta s_0 = 0.5$ GeV.

$Z_c^+(3900) \to D^+\bar{D}^{*0}$ DECAY WIDTH

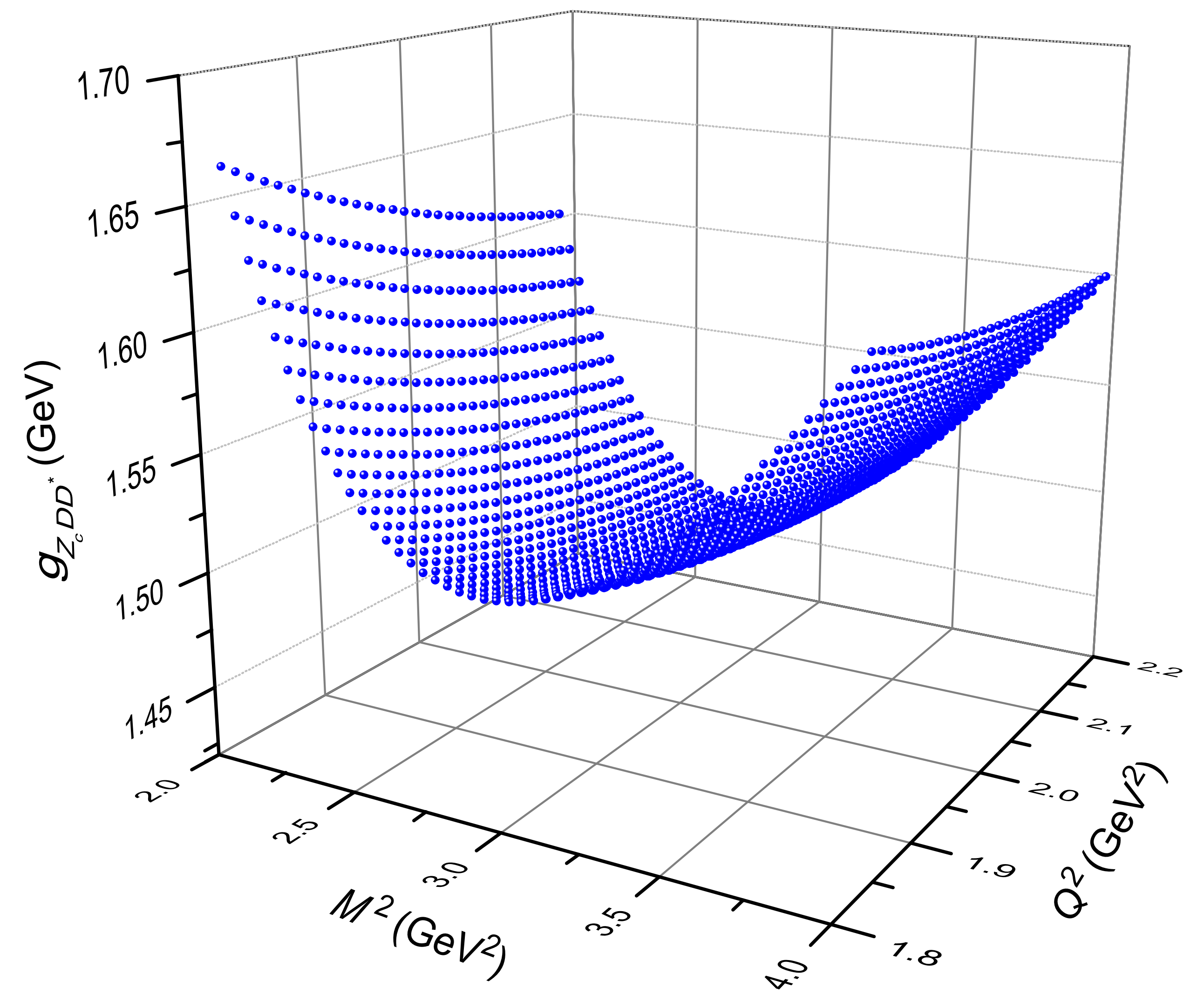

FIG. 6 (color online). QCDSRs results for the form factor $g_{Z_cDD^*}(Q^2)$ as a function of Q^2 and M^2 for $\Delta s_0 = 0.5$ GeV.

PHYSICAL REVIEW D **88,** 016004 (2013)

$Z_c^+(3900)$ decay width in QCD sum rules

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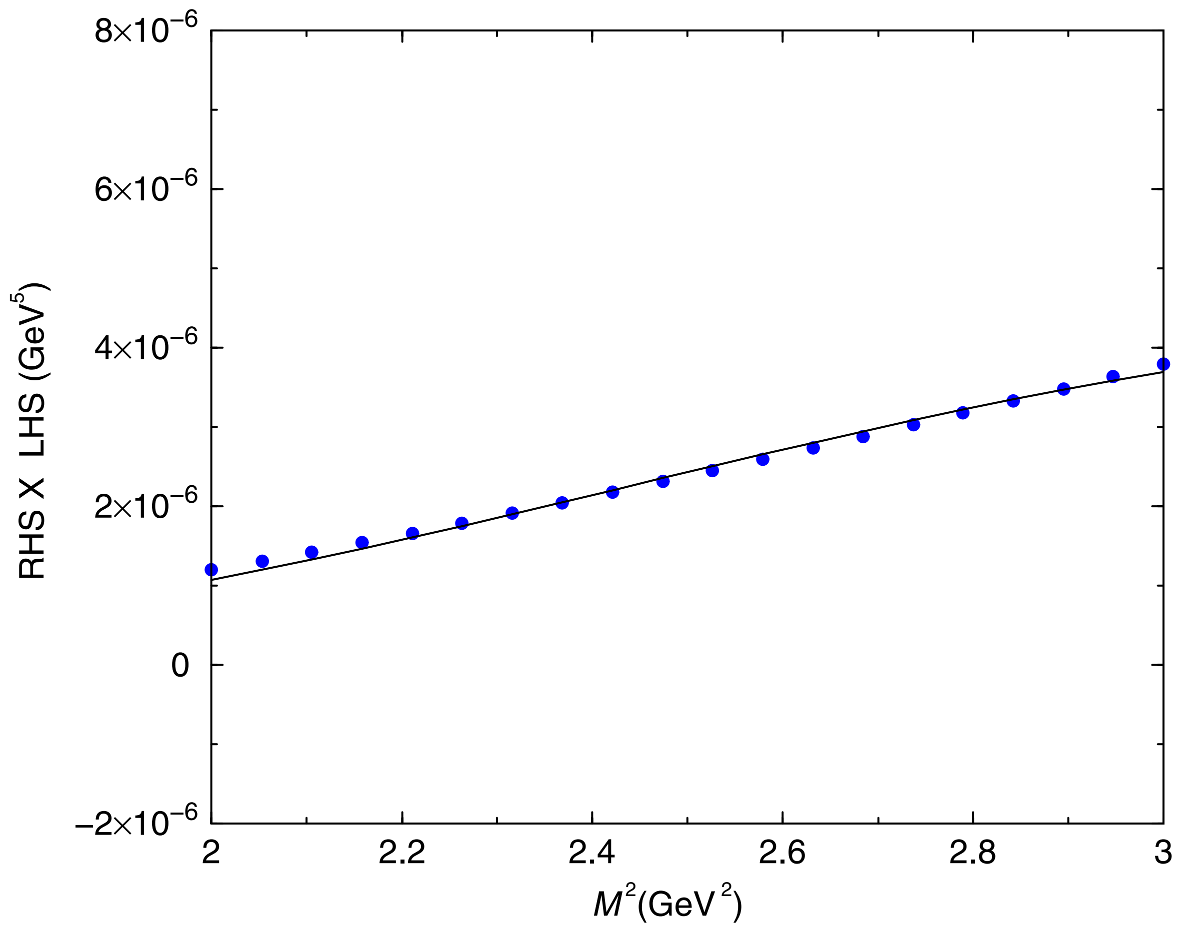
TABLE I. Coupling constants and decay widths in different channels.

Vertex	Coupling constant (GeV)	Decay width (MeV)
$Z_c^+(3900)J/\psi\pi^+$	3.89 ± 0.56	29.1 ± 8.2
$Z_c^+(3900)\eta_c\rho^+$	4.85 ± 0.81	27.5 ± 8.5
$Z_c^+(3900)D^+\bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7
$Z_c^+(3900)\bar{D}^0D^{*+}$	2.5 ± 0.3	3.2 ± 0.7

$Z_c^+(3900) \to J/\psi\pi^+$ DECAY WIDTH



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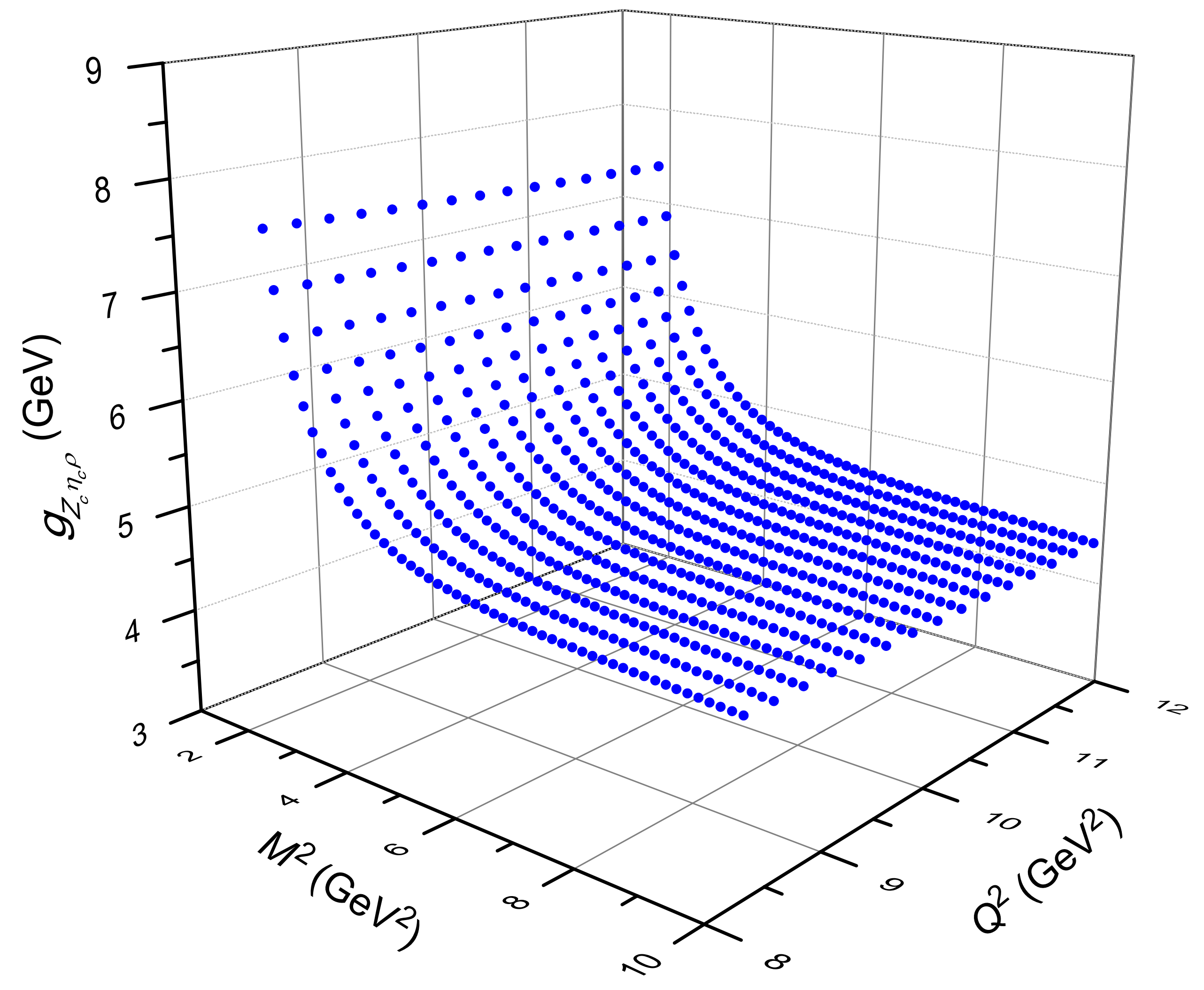
$Z_c^+(3900) \to \eta_c\rho^+$ DECAY WIDTH



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$Z_c^+(3900) \to D^+\bar{D}^{*0}$ DECAY WIDTH

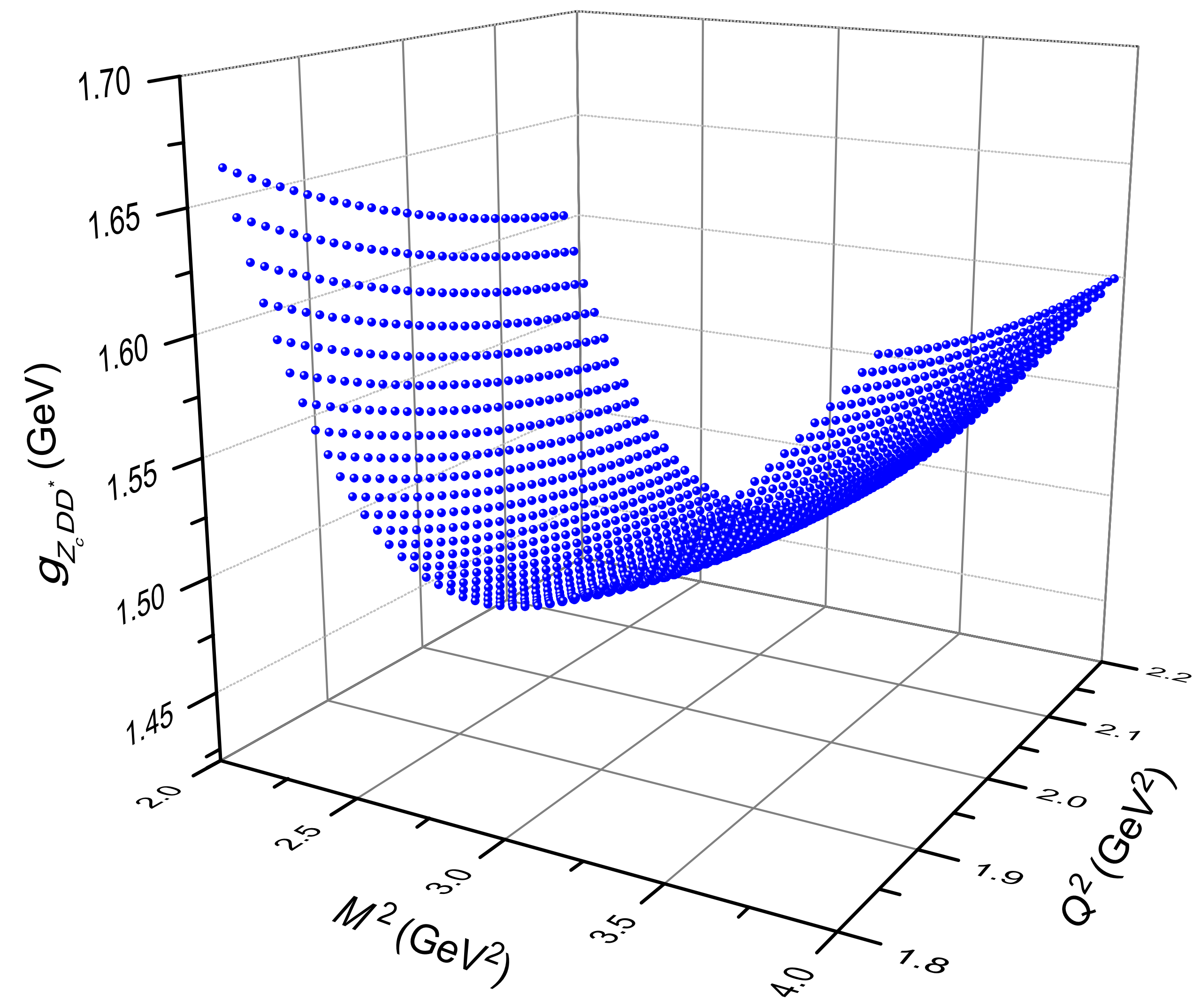

FIG. 6 (color online). QCDSRs results for the form factor $g_{Z_cDD^*}(Q^2)$ as a function of Q^2 and M^2 for $\Delta s_0 = 0.5$ GeV.

PHYSICAL REVIEW D **88,** 016004 (2013)

$Z_c^+(3900)$ decay width in QCD sum rules

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(Received 13 May 2013; published 3 July 2013)

TABLE I. Coupling constants and decay widths in different channels.

Vertex	Coupling constant (GeV)	Decay width (MeV)
$Z_c^+(3900)J/\psi\pi^+$	3.89 ± 0.56	29.1 ± 8.2
$Z_c^+(3900)\eta_c\rho^+$	4.85 ± 0.81	27.5 ± 8.5
$Z_c^+(3900)D^+\bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7
$Z_c^+(3900)\bar{D}^0 D^{*+}$	2.5 ± 0.3	3.2 ± 0.7

$$\Gamma_{Z_c^+} = (63 \pm 18)\ \text{MeV}$$

Vertex	coupling constant (GeV)	decay width (MeV)	Maiani (2013)
$Z_c^+(3900)J/\psi\pi^+$	3.89 ± 0.56	29.1 ± 8.2	29
$Z_c^+(3900)\eta_c\rho^+$	4.85 ± 0.81	27.5 ± 8.5	19
$Z_c^+(3900)D^+\bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7	4
$Z_c^+(3900)\bar{D}^0 D^{*+}$	2.5 ± 0.3	3.2 ± 0.7	4

$$\Gamma_{Z_c^+}^{BELLE} = (63 \pm 35)\text{MeV}$$

$$\Gamma_{Z_c^+}^{BES} = (46 \pm 22)\text{MeV}$$

PHYSICAL REVIEW D **88,** 096014 (2013)

Prediction for the decay width of a charged state near the $D_s\bar{D}^*/D_s^*\bar{D}$ threshold

Jorgivan M. Dias,[1,*] Xiang Liu,[2,3,†] and Marina Nielsen[1,‡]

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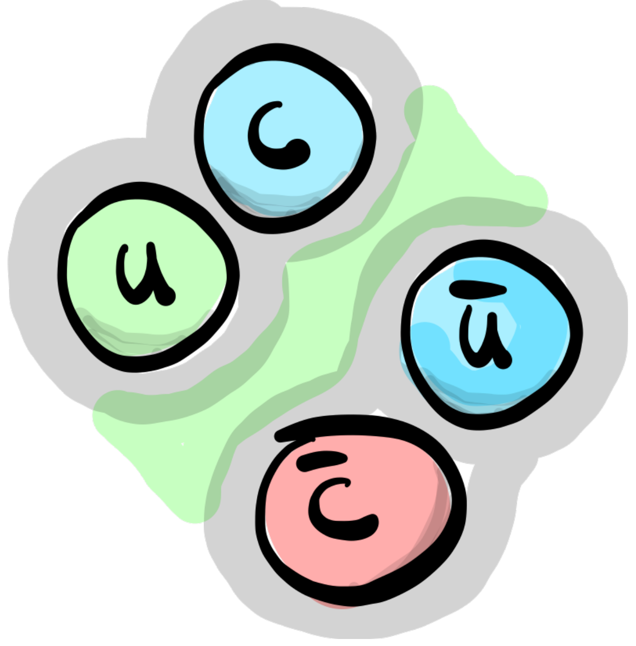
(Received 2 August 2013; published 27 November 2013)

Tetraquark



- $Z_{cs}^+ \to J/\psi K^+$
- $Z_{cs}^+ \to \eta_c K^{*+}$
- $Z_{cs}^+ \to \bar{D}^{*0} D_s^+$
- $Z_{cs}^+ \to \bar{D}^0 D_s^{*+}$

$$\Gamma = (24.9 \pm 12.6)\ \text{MeV}$$

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_{cs}^+ J/\psi K^+$	2.58 ± 0.30	11.2 ± 3.5
$Z_{cs}^+ \eta_c K^{*+}$	3.4 ± 0.3	10.8 ± 6.2
$Z_{cs}^+ D_s^+ \bar{D}^{*0}$	1.4 ± 0.3	1.5 ± 1.5
$Z_{cs}^+ \bar{D}^0 D_s^{*+}$	1.4 ± 0.4	1.4 ± 1.4

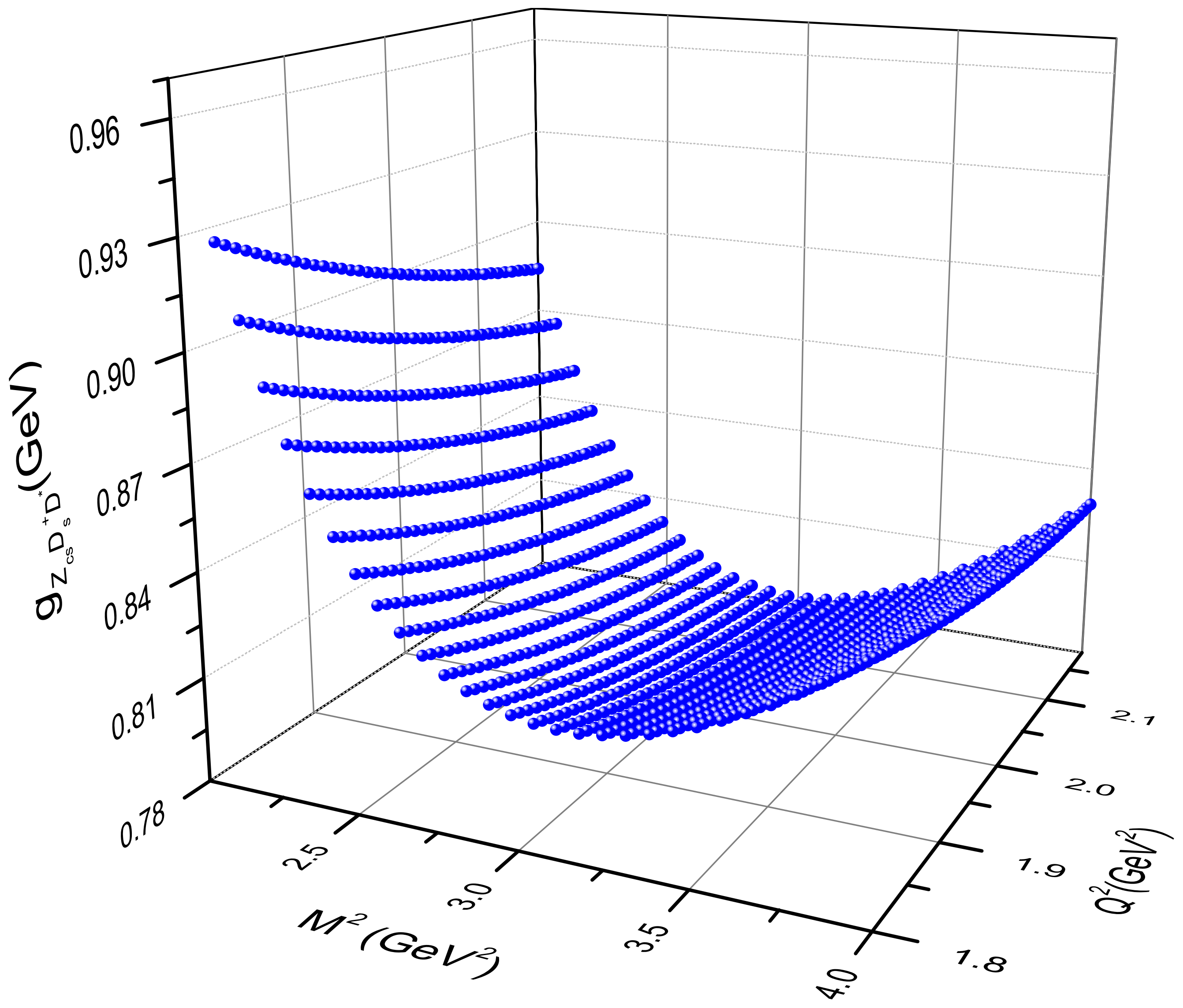
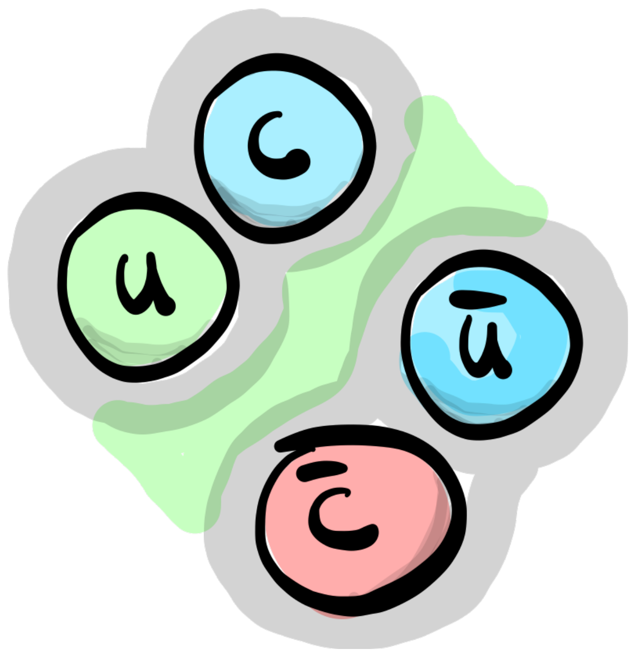


FIG. 6 (color online). QCDSR results for the form factor $g_{Z_{cs}D^*D_s}(Q^2)$ as a function of Q^2 and M^2 for $\sqrt{s_0} = 4.5$ GeV.

10 years later…

Tetraquark



PHYSICAL REVIEW LETTERS **126,** 102001 (2021)

Editors' Suggestion | Featured in Physics

Observation of a Near-Threshold Structure in the K^+ Recoil-Mass Spectra in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

- $Z_{cs}^+ \to J/\psi K^+$
- $Z_{cs}^+ \to \eta_c K^{*+}$
- $Z_{cs}^+ \to \bar{D}^{*0} D_s^+$
- $Z_{cs}^+ \to \bar{D}^0 D_s^{*+}$

$$\Gamma = (24.9 \pm 12.6)\ \mathrm{MeV}$$

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_{cs}^+ J/\psi K^+$	2.58 ± 0.30	11.2 ± 3.5
$Z_{cs}^+ \eta_c K^{*+}$	3.4 ± 0.3	10.8 ± 6.2
$Z_{cs}^+ D_s^+ \bar{D}^{*0}$	1.4 ± 0.3	1.5 ± 1.5
$Z_{cs}^+ \bar{D}^0 D_s^{*+}$	1.4 ± 0.4	1.4 ± 1.4

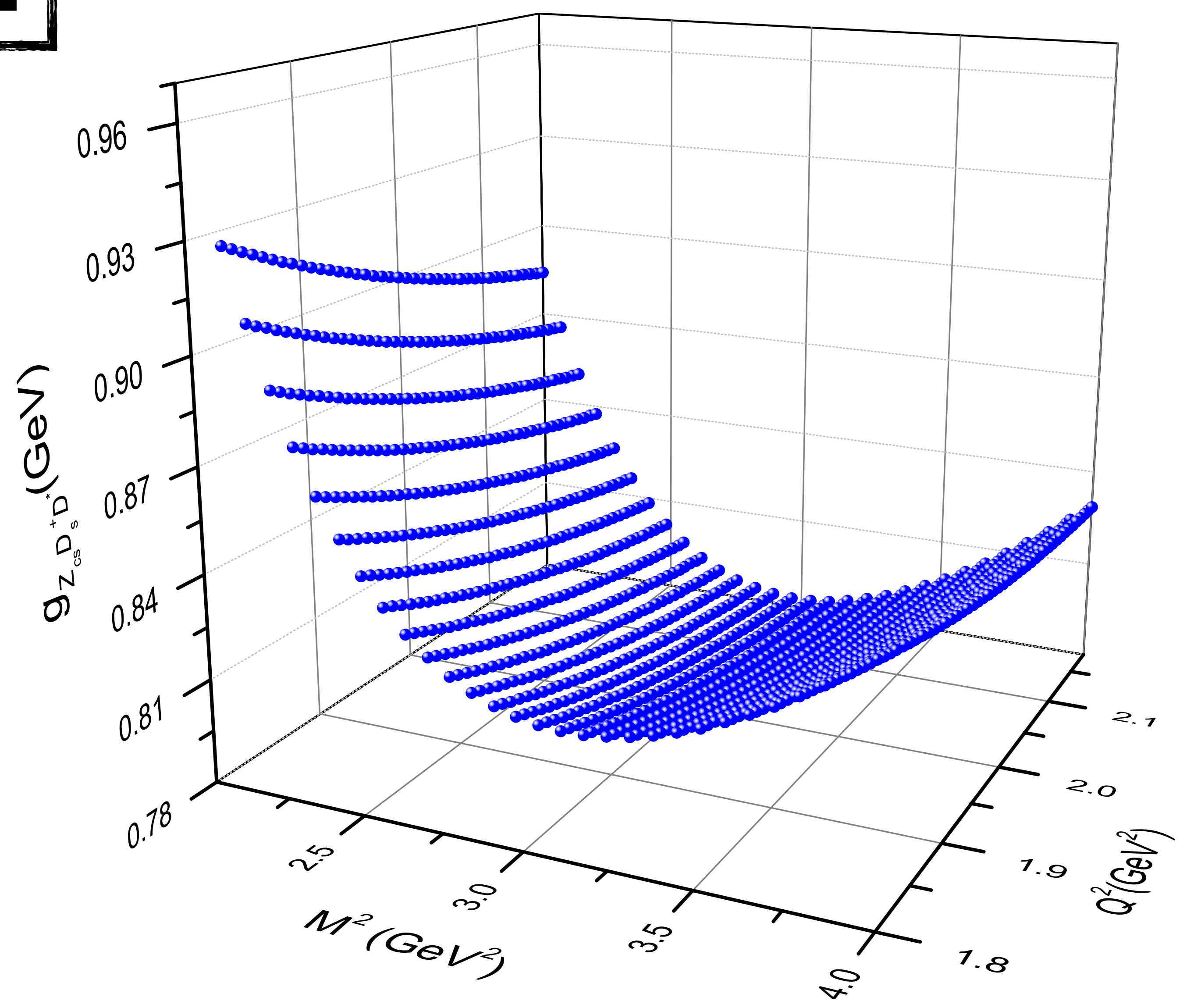


FIG. 6 (color online). QCDSR results for the form factor $g_{Z_{cs}D^*D_s}(Q^2)$ as a function of Q^2 and M^2 for $\sqrt{s_0} = 4.5$ GeV.

Conclusions

- The new hadronic states have been challenging our comprehension of the QCD dynamics at low-energies;
- It seems that there might be different dynamics involved. It is hard to believe that just one is enough to explain what we have seen up to now;
- The Chiral Unitary approach has been proving a successfull non-perturbative tool to describe these new states at the heavy sector;
- It is a suitable tool to describe them as hadronic molecules;
- Tetraquarks are suitably described by the QCD sum rules approach, athough the method provide large uncertainties.

Backup Slides

CHIRAL UNITARY FORMULATION

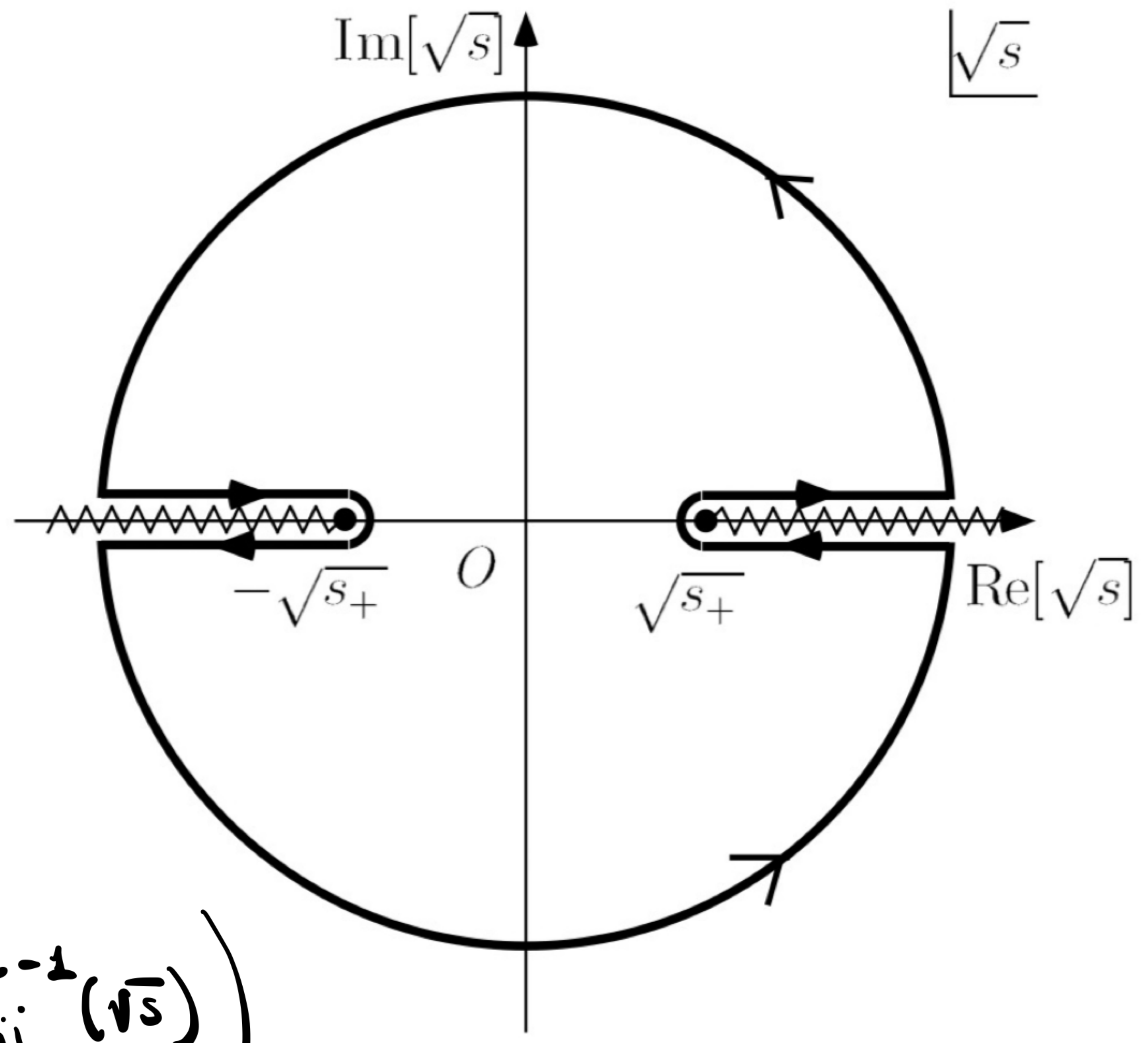
① N/D method

$$T(s) = \frac{N(s)}{D(s)}$$

"unitary cut" $\mathrm{Im}\,(T)^{-1} = -\rho$

$$T^{-1}_{ij}(\sqrt{s}) = \delta_{ij}\Big(\underbrace{\tilde{a}_i(s_0) + \frac{s-s_0}{2\pi}\int_{s_0}^{\infty} ds' \frac{\rho_i(s')}{(s'-s)(s'-s_0)}}_{\equiv\, -G} + \tau^{-1}_{ij}(\sqrt{s})\Big)$$

Loop-function !



CHIRAL UNITARY FORMULATION

① N/D method

$$T(s) = \frac{N(s)}{D(s)}$$

"unitary cut" $\mathrm{Im}\,(T)^{-1} = -\rho$

② $T^{-1}_{ij} \to V^{-1}$ at lowest order in χPT!

What about this term?

$$T^{-1}_{ij}(\sqrt{s}) = \delta_{ij}\Big(\underbrace{\tilde{a}_i(s_0) + \frac{s-s_0}{2\pi}\int_{s_0}^{\infty} ds' \frac{\rho_i(s')}{(s'-s)(s'-s_0)}}_{\equiv -G} + \tau^{-1}_{ij}(\sqrt{s})\Big)$$

Loop-function!

CHIRAL UNITARY FORMULATION

1 N/D method

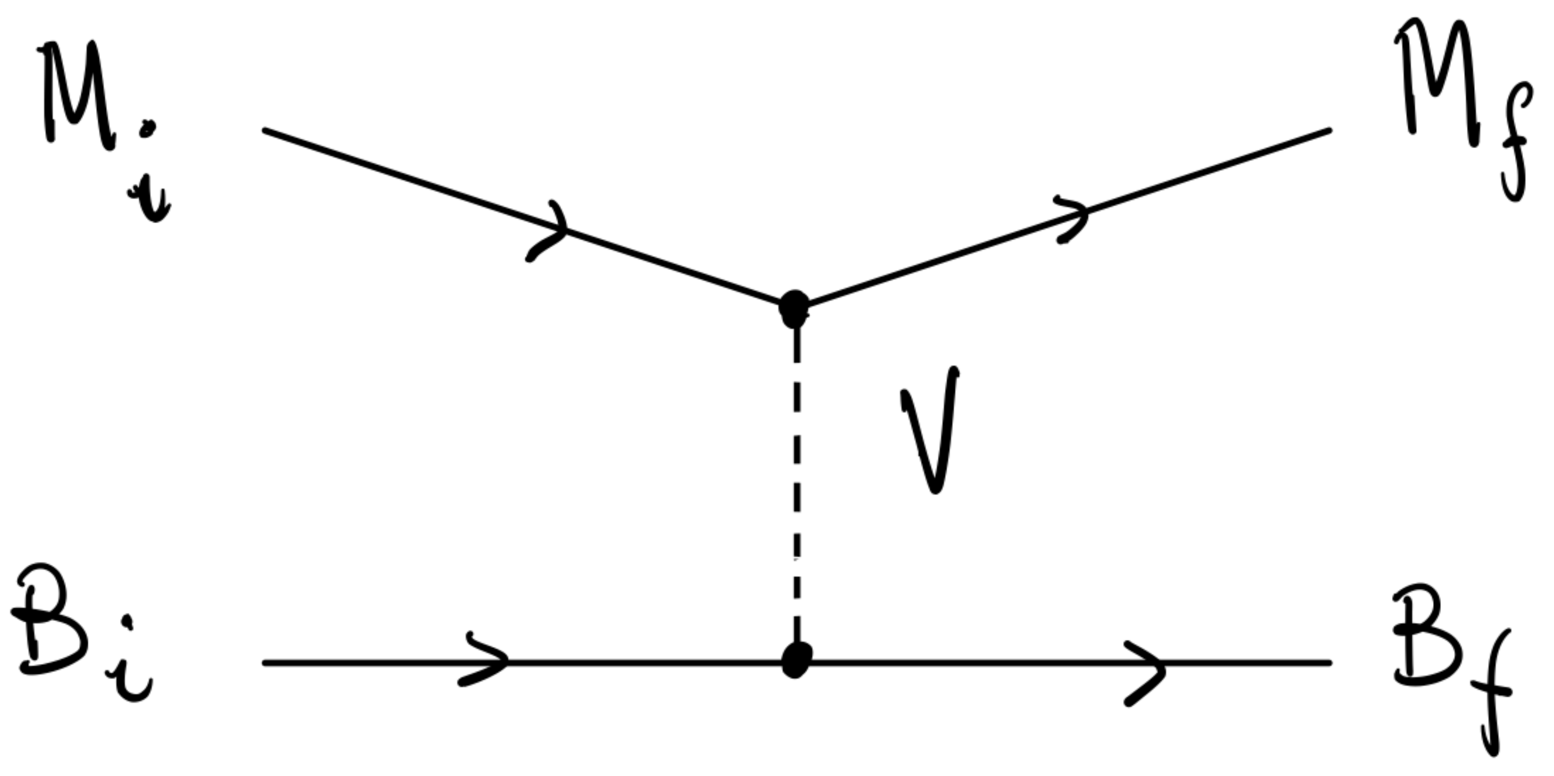
$$T(s) = \frac{N(s)}{D(s)}$$

"unitary cut" $\mathrm{Im}\,(T)^{-1} = -\rho$

2 $T_{ij}^{-1} \to V^{-1}$ at lowest order in χPT!

$$T^{-1} = V^{-1} - G$$ or $$T = (1 - VG)^{-1} V$$

TRANSITION AMPLITUDES

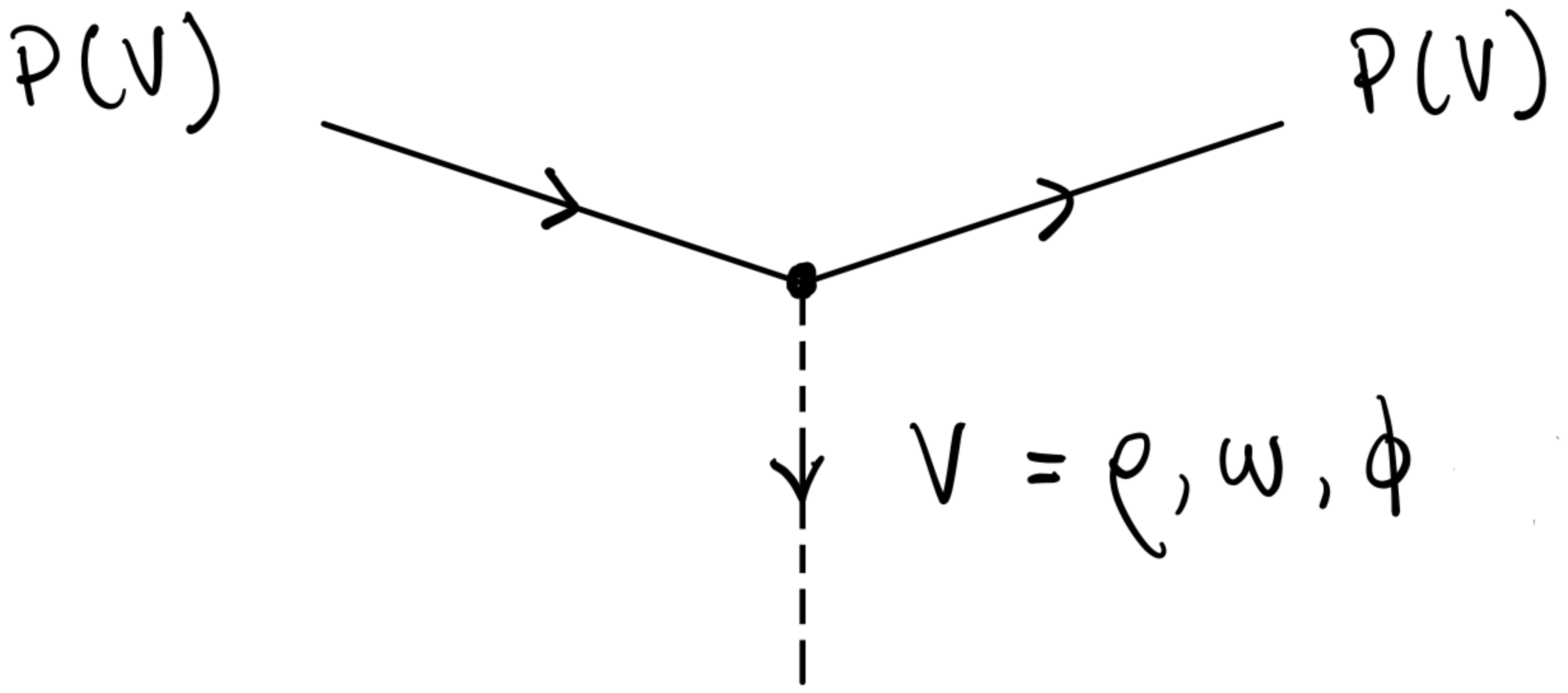


Is not possible through Chiral Lagrangians!

$$\mathcal{L}_{PPV} = -ig\langle [\phi, \partial_\mu \phi] V^\mu \rangle$$

$$\mathcal{L}_{VVV} = ig\langle (V^\mu \partial_\nu V_\mu - \partial_\nu V^\mu V_\mu) V^\nu \rangle$$

However, we can use the Lagrangians from Hidden Gauge Symmetry!

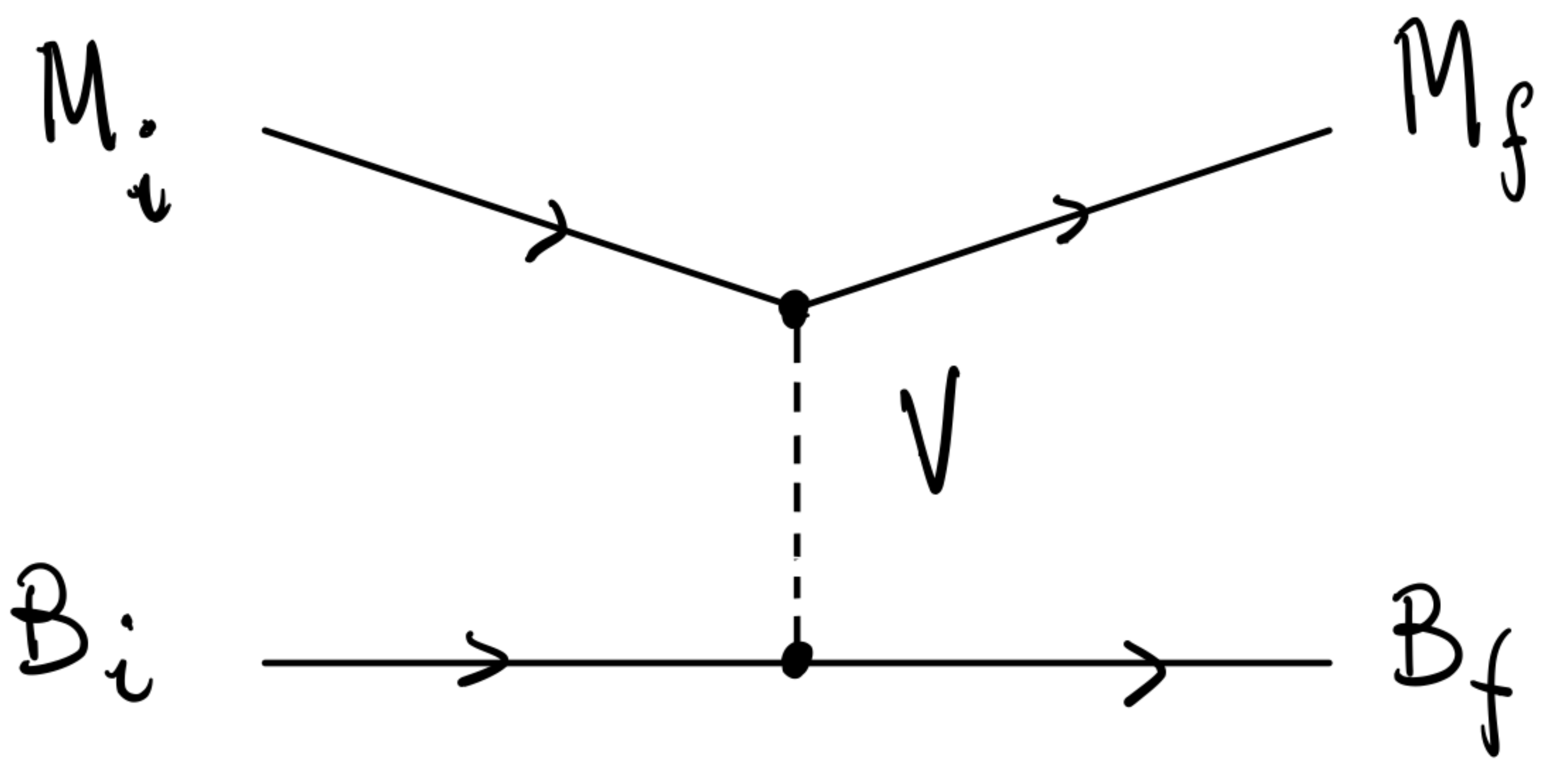


Phys. Rep. 381, 1 (2003).

Phys. Rep. 161, 213 (1988).

Phys. Rep. 164, 217 (1988)

TRANSITION AMPLITUDES



Is not possible through Chiral Lagrangians!

$$\begin{cases} \mathcal{L}_{PPV} = -ig\langle [\phi, \partial_\mu \phi] V^\mu \rangle \\ \mathcal{L}_{VVV} = ig\langle (V^\mu \partial_\nu V_\mu - \partial_\nu V^\mu V_\mu) V^\nu \rangle \end{cases}$$

$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu$$

SU(3)

TRANSITION AMPLITUDES

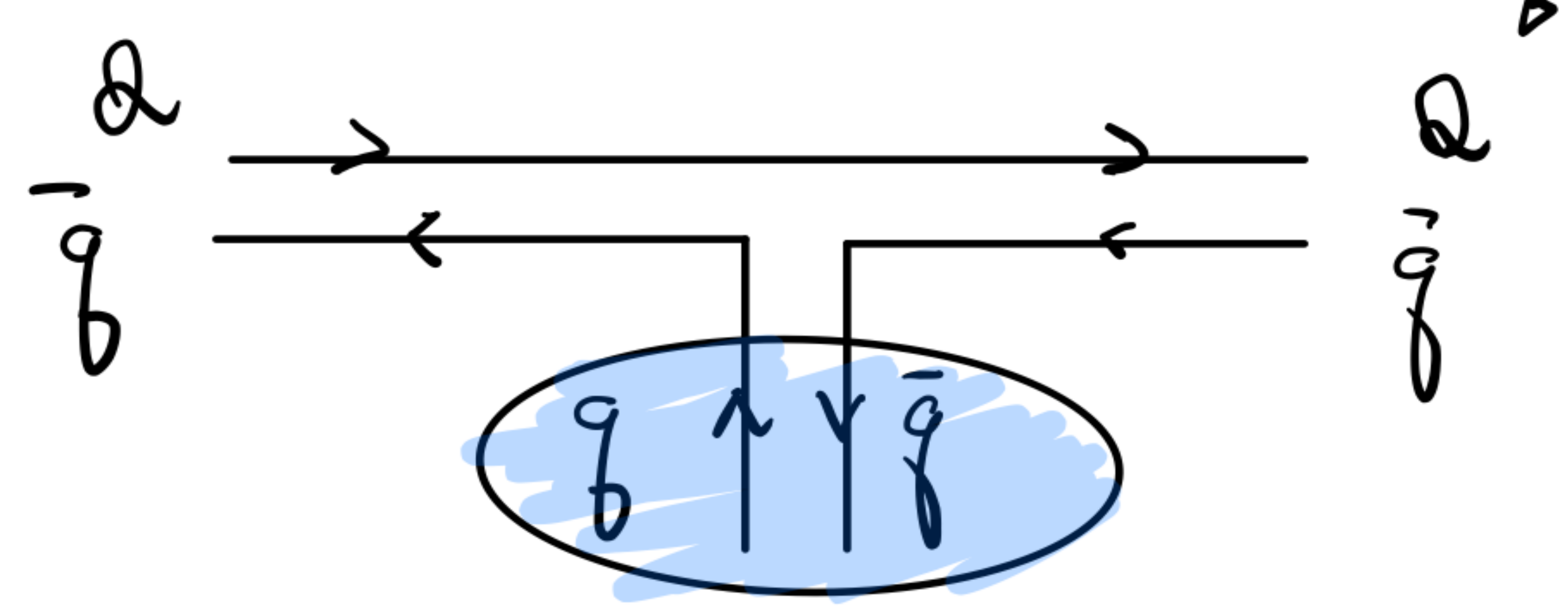
For Meson-Baryon interactions with charm $\longrightarrow$ ~~SU(4)~~

$\downarrow$

It is not a good symmetry!

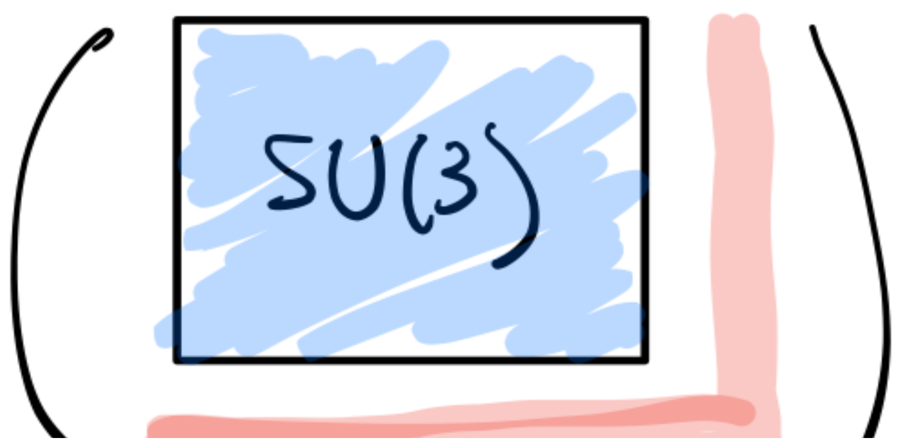
However, ...

spectator!



So, just light flavors are involved!

SU(4) Matrix

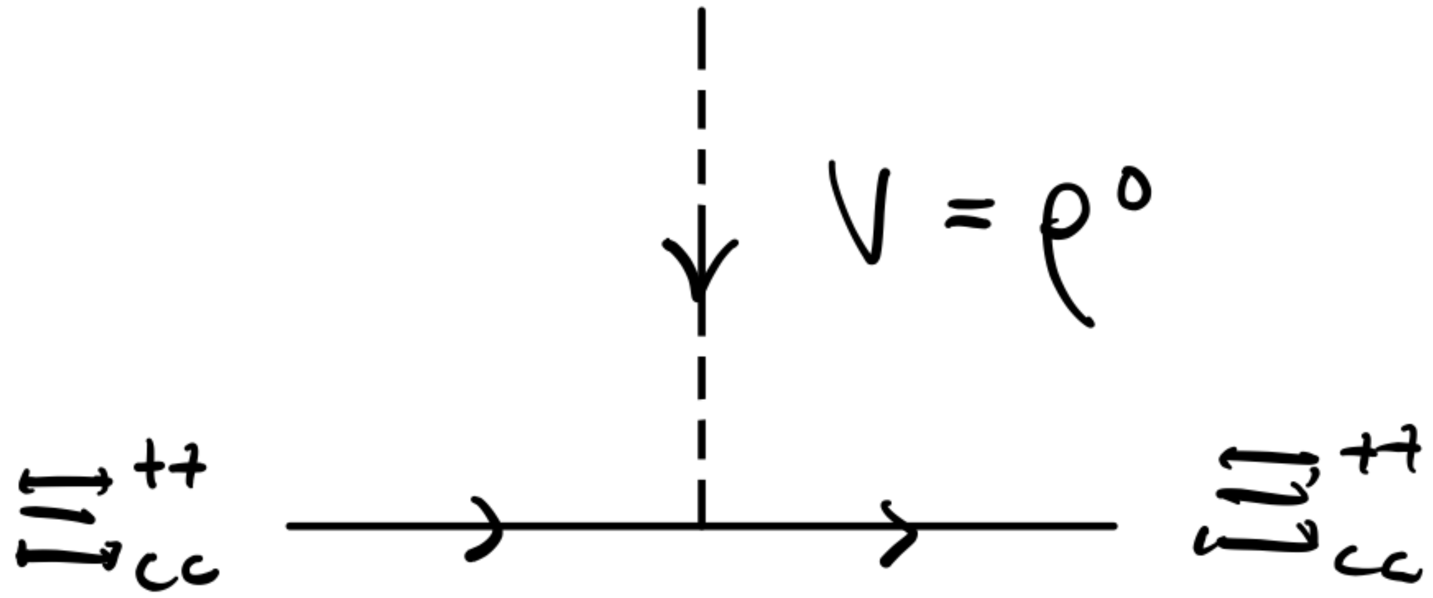


$\Longrightarrow$ $\boxed{\text{SU(3) content of SU(4)!}}$

In fact, we are not using SU(4) explicitly, but the SU(3)!

TRANSITION AMPLITUDES

How does this work in practice?



$$\sim \langle \Xi_{cc}^{++} | g \rho^0 | \Xi_{cc}^{++} \rangle$$

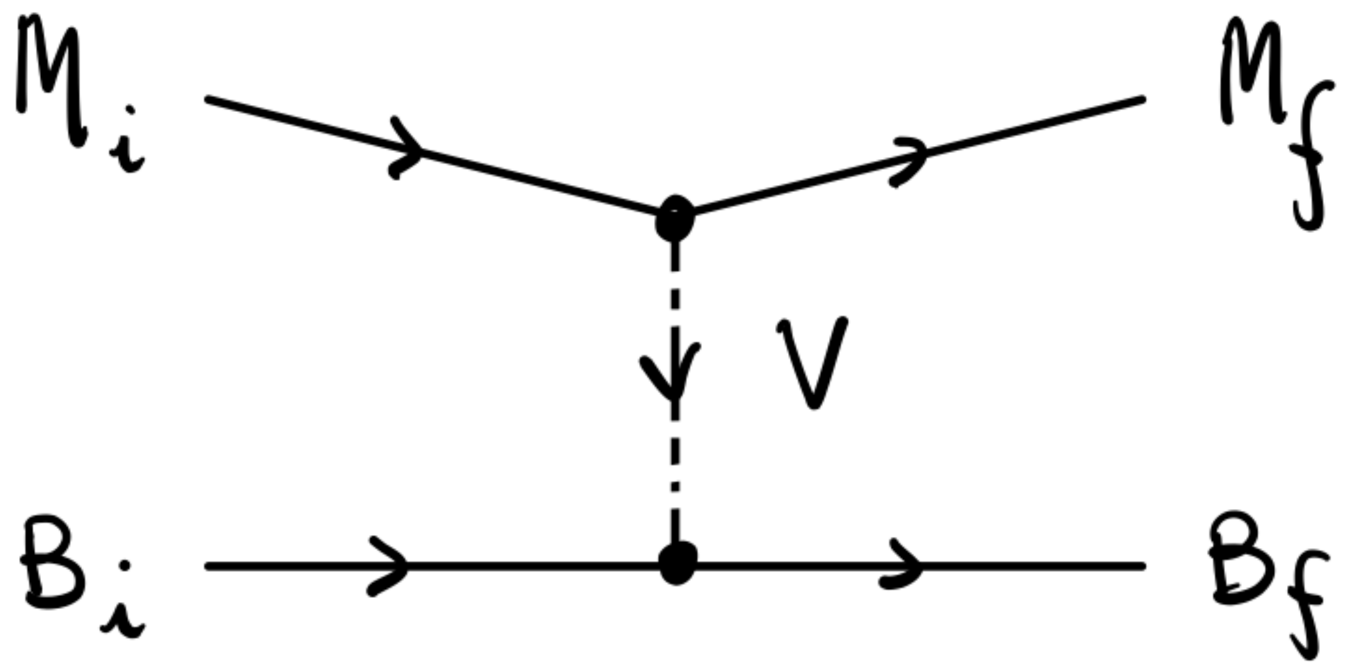
act like an operator!

Therefore,

$$\langle \Xi_{cc}^{++} | g \rho^0 | \Xi_{cc}^{++} \rangle \sim g \langle \chi_{MS} | \otimes \langle cuu | \frac{1}{\sqrt{2}} \left(u\bar{u} - \cancel{d\bar{d}} \right) | cuu \rangle \otimes | \chi_{MS} \rangle$$

does not contribute!

$$\sim g \frac{1}{\sqrt{2}}$$



$\sim$

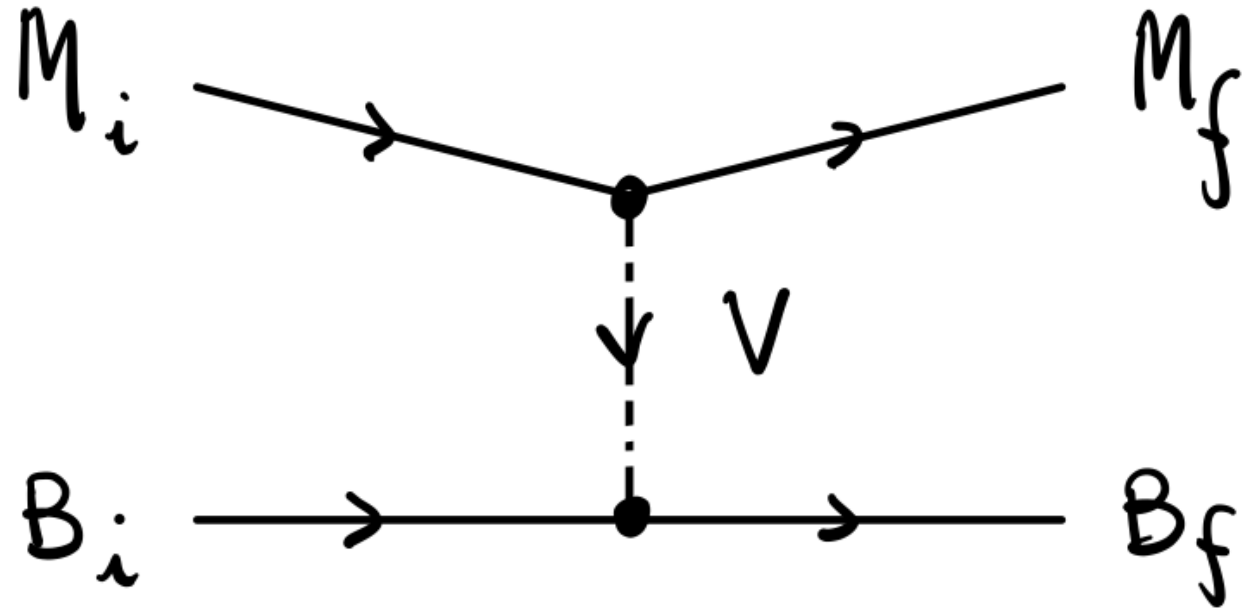
$$\boxed{V_{ij} = C_{ij} \frac{1}{4f^2} \left(p^0 + p'^0 \right)}$$

Transition amplitudes

C_{ij} coefficients of Eq. (12) for the pseudoscalar meson-baryon states coupling to $J^P = 1/2^-$ in S-wave.

$PB_{1/2}$	$\Xi_{cc}\pi$	$\Lambda_c D$	$\Xi_{cc}\eta$	$\Omega_{cc}K$	$\Sigma_c D$	$\Xi_c D_s$	$\Xi'_c D_s$
$\Xi_{cc}\pi$	-2	0	$-\frac{\sqrt{2}}{3}$	$-\sqrt{\frac{3}{2}}$	0	0	0
$\Lambda_c D$		-1	0	0	0	-1	0
$\Xi_{cc}\eta$			0	$-\frac{1}{\sqrt{3}}$	0	0	0
$\Omega_{cc}K$				-1	0	0	0
$\Sigma_c D$					-3	0	$-\frac{1}{\sqrt{3}}$
$\Xi_c D_s$						-1	0
$\Xi'_c D_s$							-1

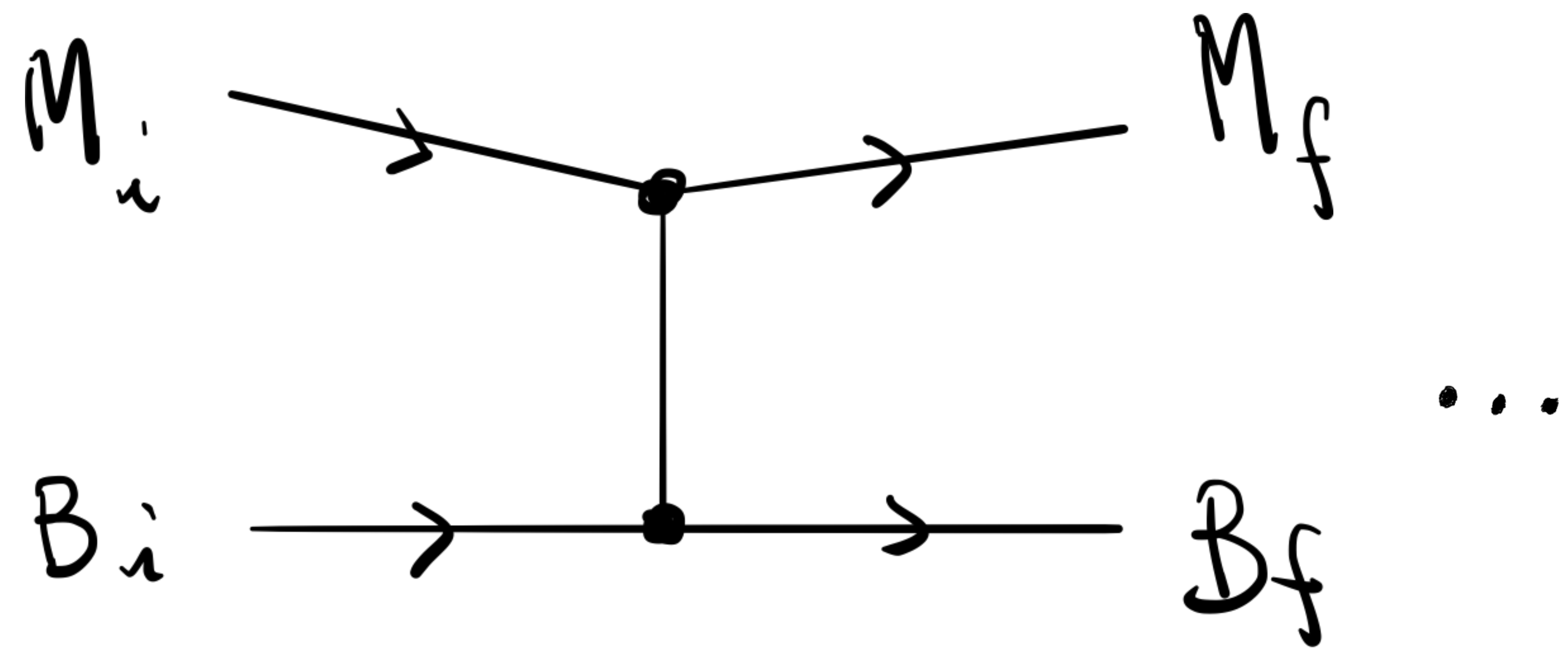
Therefore,



$\sim$

$$\boxed{V_{ij} = C_{ij}\,\frac{1}{4f^2}\left(p^0 + p'^0\right)}$$

TRANSITION AMPLITUDES



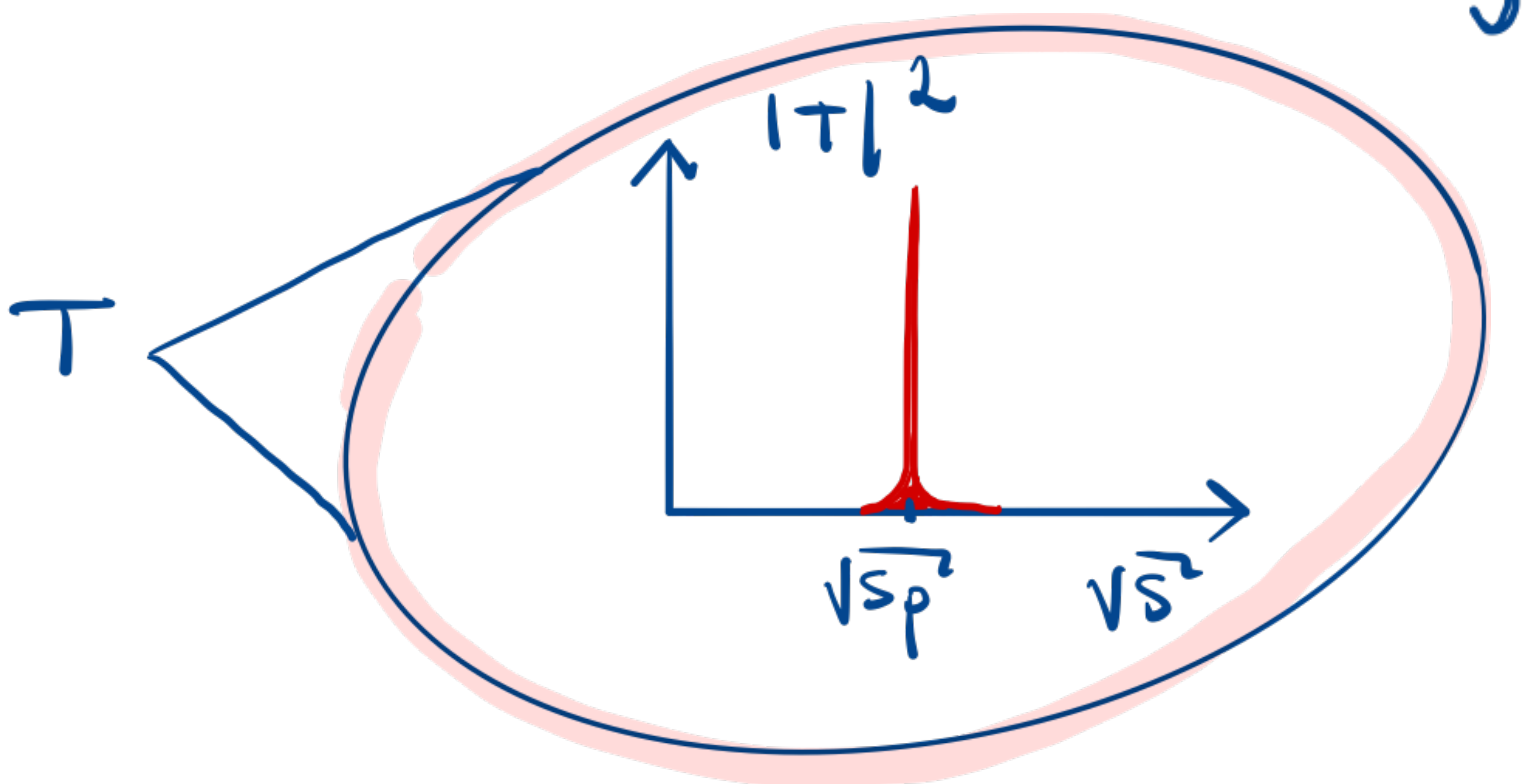
are unitarized through the Bethe-Salpeter equation

Loop function

$$T = (1 - VG)V$$

cutoff

$$G_\ell = \int^{q_{max}} \frac{d^3\vec{q}}{(2\pi)^3} \frac{1}{2\omega_\ell(\vec{q})} \frac{M_\ell}{2E_\ell(\vec{q})} \frac{1}{\underbrace{k^0 + p^0}_{\sqrt{s}} - \omega_\ell(\vec{q}) - E_\ell(\vec{q}) + i\varepsilon}$$



Resonances / Bound States emerge as poles

Backup Slides:

Predictions for the Xi_cc states from meson-baryon interactions

Doubly charmed Ξ_{cc} molecular states from meson-baryon interaction

J. M. Dias,[1,2,3,*] V. R. Debastiani,[1,2,†] Ju-Jun Xie,[1,‡] and E. Oset[1,2,§]
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[2]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain*
[3]*Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970 São Paulo, SP, Brazil*

Charm = 2,
Strangeness =0,
and Isospin =1/2

Channels

TABLE I. Baryon-pseudoscalar states ($J^P = 1/2^-$) chosen and threshold mass in MeV.

Channel	$\Xi_{cc}\pi$	$\Lambda_c D$	$\Xi_{cc}\eta$	$\Omega_{cc}K$	$\Sigma_c D$	$\Xi_c D_s$	$\Xi'_c D_s$
Threshold	3759	4154	4169	4208	4321	4438	4545

TABLE II. Baryon-pseudoscalar states ($J^P = 3/2^-$) chosen and threshold mass in MeV.

Channel	$\Xi^*_{cc}\pi$	$\Xi^*_{cc}\eta$	$\Omega^*_{cc}K$	$\Sigma^*_c D$	$\Xi^*_c D_s$
Threshold	3840	4250	4291	4385	4615

TABLE III. Baryon-vector meson states ($J^P = 1/2^-, 3/2^-$) chosen and threshold mass in MeV.

Channel	$\Lambda_c D^*$	$\Xi_{cc}\rho$	$\Xi_{cc}\omega$	$\Sigma_c D^*$	$\Xi_c D_s^*$	$\Omega_{cc}K^*$	$\Xi_{cc}\phi$	$\Xi'_c D_s^*$
Threshold	4295	4397	4404	4462	4582	4606	4641	4689

TABLE IV. Baryon-vector meson states ($J^P = 1/2^-, 3/2^-, 5/2^-$) chosen and threshold mass in MeV.

Channel	$\Xi^*_{cc}\rho$	$\Xi^*_{cc}\omega$	$\Sigma^*_c D^*$	$\Omega^*_{cc}K^*$	$\Xi^*_{cc}\phi$	$\Xi^*_c D_s^*$
Threshold	4478	4485	4526	4689	4722	4759

RESULTS

We get three states:

TABLE XI. Poles and couplings in the $PB_{1/2}$, $J^P = 1/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_l G_l^{\mathrm{II}}$ in MeV.

3837.26 + *i*100.48	$\Xi_{cc}\pi$	$\Lambda_c D$	$\Xi_{cc}\eta$	$\Omega_{cc}K$	$\Sigma_c D$	$\Xi_c D_s$	$\Xi'_c D_s$
g_l	**1.72 + *i*1.30**	0	$0.41 + i0.32$	$0.80 + i0.77$	0	0	0
$g_l G_l^{II}$	**−74.27 − *i*12.89**	0	$-2.11 - i2.41$	$-4.03 - i5.35$	0	0	0
4082.79	$\Xi_{cc}\pi$	$\Lambda_c D$	$\Xi_{cc}\eta$	$\Omega_{cc}K$	$\Sigma_c D$	$\Xi_c D_s$	$\Xi'_c D_s$
g_l	0	0	0	0	**8.86**	0	1.93
$g_l G_l^{\mathrm{II}}$	0	0	0	0	**−31.29**	0	−4.04
4092.20	$\Xi_{cc}\pi$	$\Lambda_c D$	$\Xi_{cc}\eta$	$\Omega_{cc}K$	$\Sigma_c D$	$\Xi_c D_s$	$\Xi'_c D_s$
g_l	0	**4.01**	0	0	0	3.75	0
$g_l G_l^{\mathrm{II}}$	0	**−29.49**	0	0	0	−9.76	0

RESULTS

Two states were obtained in this case:

TABLE XII. Poles and couplings in the $PB_{3/2}$, $J^P = 3/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_l G_l^{\mathrm{II}}$ in MeV.

$\mathbf{3918.15 + i100.32}$	$\Xi_{cc}^* \pi$	$\Xi_{cc}^* \eta$	$\Omega_{cc}^* K$	$\Sigma_c^* D$	$\Xi_c^* D_s$
g_l	$\mathbf{1.72 + i1.30}$	0	$0.41 + i0.32$	$0.80 + i0.76$	0
$g_l G_l^{II}$	$\mathbf{-74.27 - i12.91}$	0	$-2.10 - i2.41$	$-3.99 - i5.30$	0
4149.67	$\Xi_{cc}^* \pi$	$\Xi_{cc}^* \eta$	$\Omega_{cc}^* K$	$\Sigma_c^* D$	$\Xi_c^* D_s$
g_l	0	0	0	**8.82**	1.30
$g_l G_l^{\mathrm{II}}$	0	0	0	**−31.46**	−2.71

RESULTS

Results for meson-baryon: 1/2 and 3/2

For vector mesons, we have a degenerate case: 1/2 and 3/2:
4 bound states!

Poles and couplings in the $VB_{1/2}$, $J^P = 1/2^-, 3/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_l G_l^{\mathrm{II}}$ in MeV.

4217.21	$\Lambda_c D^*$	$\Xi_{cc}\rho$	$\Xi_{cc}\omega$	$\Sigma_c D^*$	$\Xi_c D_s^*$	$\Omega_{cc} K^*$	$\Xi_{cc}\phi$	$\Xi_c' D_s^*$
g_l	0	0	0	**9.31**	0	0	0	2.03
$g_l G_l^{\mathrm{II}}$	0	0	0	**−30.40**	0	0	0	−3.94
4229.19	$\Lambda_c D^*$	$\Xi_{cc}\rho$	$\Xi_{cc}\omega$	$\Sigma_c D^*$	$\Xi_c D_s^*$	$\Omega_{cc} K^*$	$\Xi_{cc}\phi$	$\Xi_c' D_s^*$
g_l	**4.21**	0	0	0	3.98	0	0	0
$g_l G_l^{\mathrm{II}}$	**−28.70**	0	0	0	−9.59	0	0	0
4293.12	$\Lambda_c D^*$	$\Xi_{cc}\rho$	$\Xi_{cc}\omega$	$\Sigma_c D^*$	$\Xi_c D_s^*$	$\Omega_{cc} K^*$	$\Xi_{cc}\phi$	$\Xi_c' D_s^*$
g_l	0	**3.71**	1.16	0	0	2.42	−0.45	0
$g_l G_l^{\mathrm{II}}$	0	**−37.49**	−11.30	0	0	−12.42	1.96	0

RESULTS

Results for meson-baryon: 1/2 and 3/2

For vector mesons and baryons with 3/2, we have: 1/2, 3/2 and 5/2: 2 bound states!

Poles and couplings in the $VB_{3/2}$, $J^P = 1/2^-, 3/2^-, 5/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_l G_l^{II}$ in MeV.

4280.43	$\Xi^*_{cc}\rho$	$\Xi^*_{cc}\omega$	$\Sigma^*_c D^*$	$\Omega^*_{cc} K^*$	$\Xi^*_{cc}\phi$	$\Xi^*_c D^*_s$
g_l	0	0	**9.31**	0	0	2.03
$g_l G_l^{II}$	0	0	**–30.42**	0	0	–3.90
4374.00	$\Xi^*_{cc}\rho$	$\Xi^*_{cc}\omega$	$\Sigma^*_c D^*$	$\Omega^*_{cc} K^*$	$\Xi^*_{cc}\phi$	$\Xi^*_c D^*_s$
g_l	**3.70**	1.15	0	2.42	–0.44	0
$g_l G_l^{II}$	**–37.53**	–11.30	0	–12.35	1.94	0

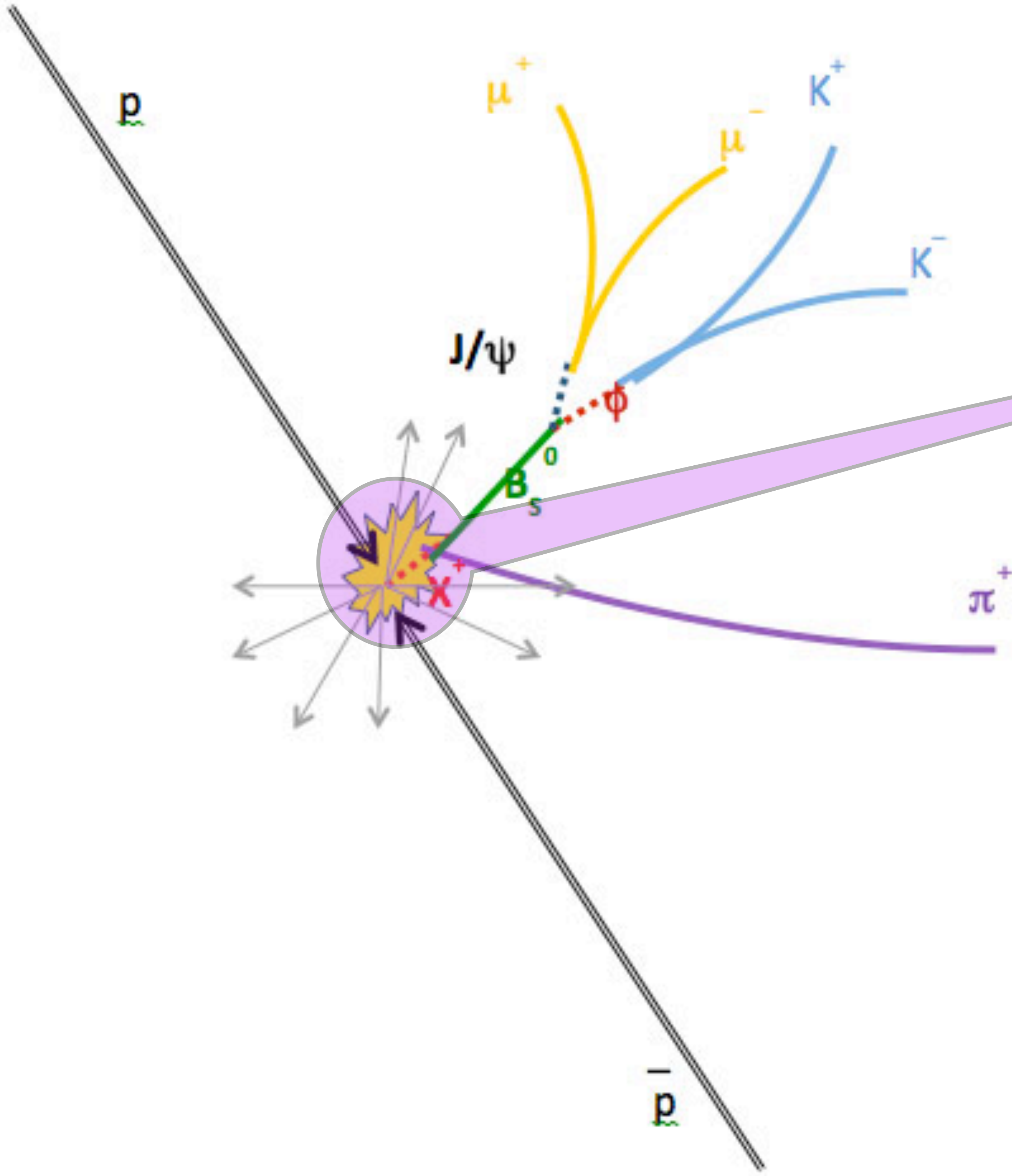
Backup Slides:

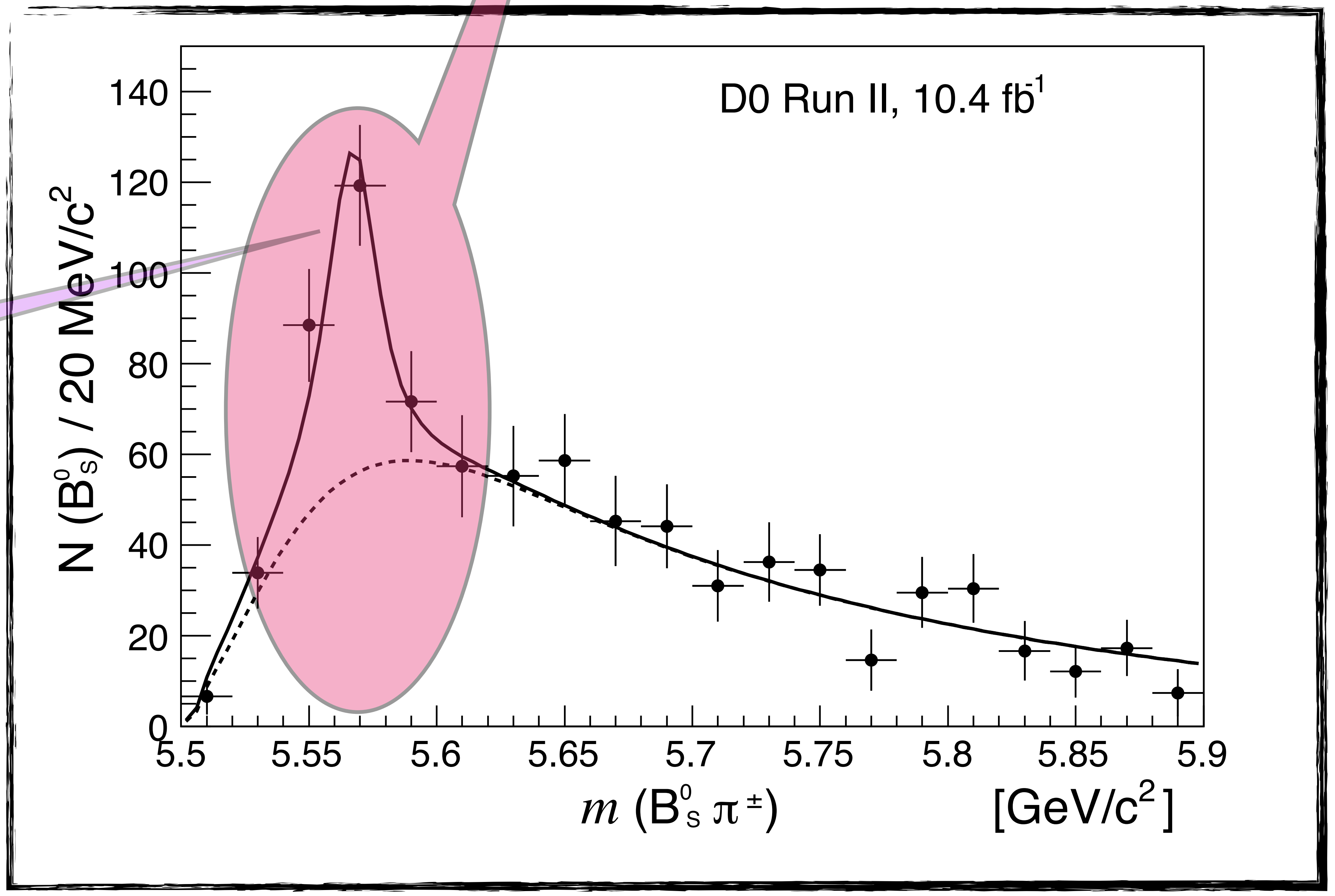
The X(5568) and the OPE convergence issue

January 2016...

X(5568)

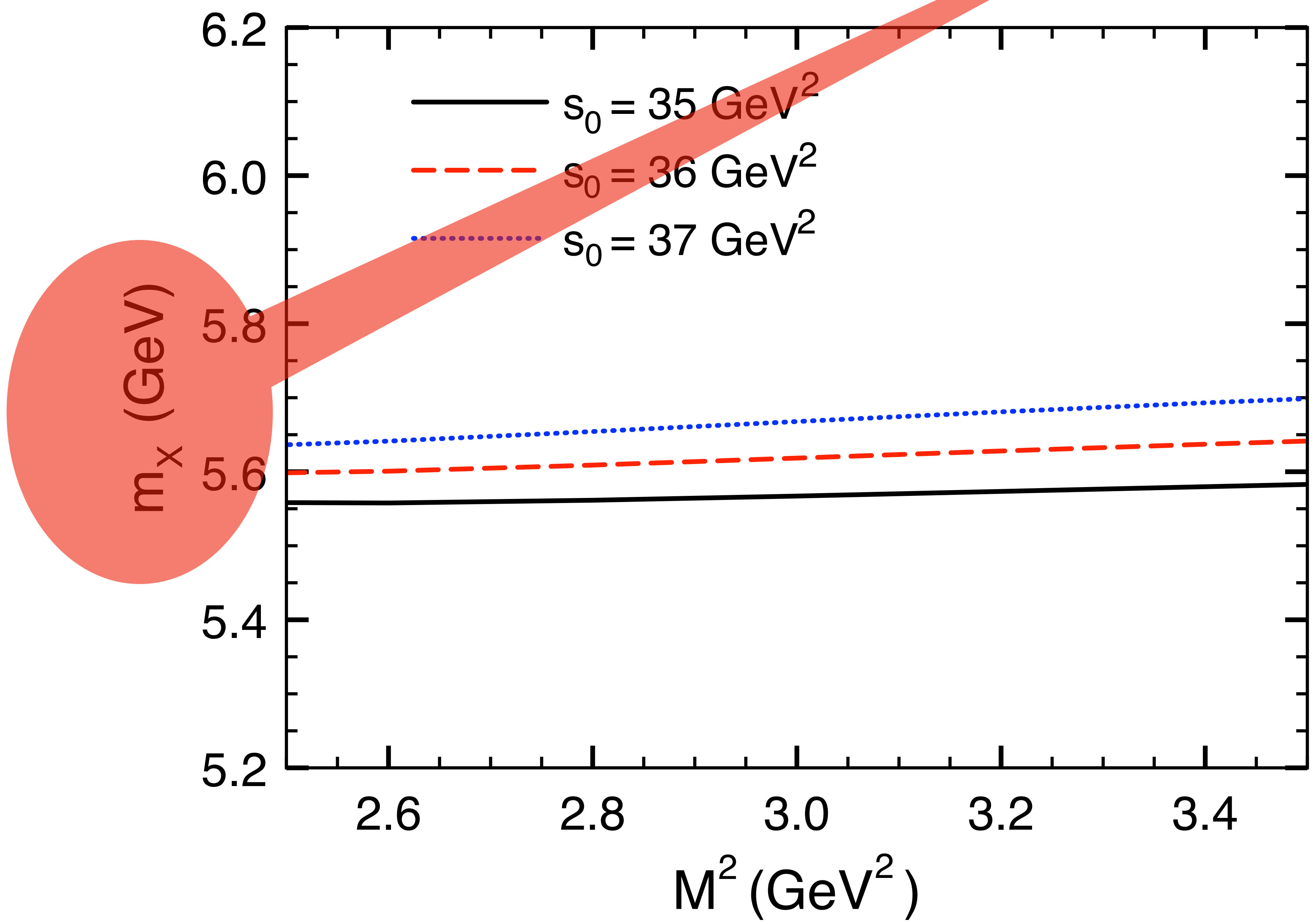
$$X \to B_s^0\,\pi^+$$

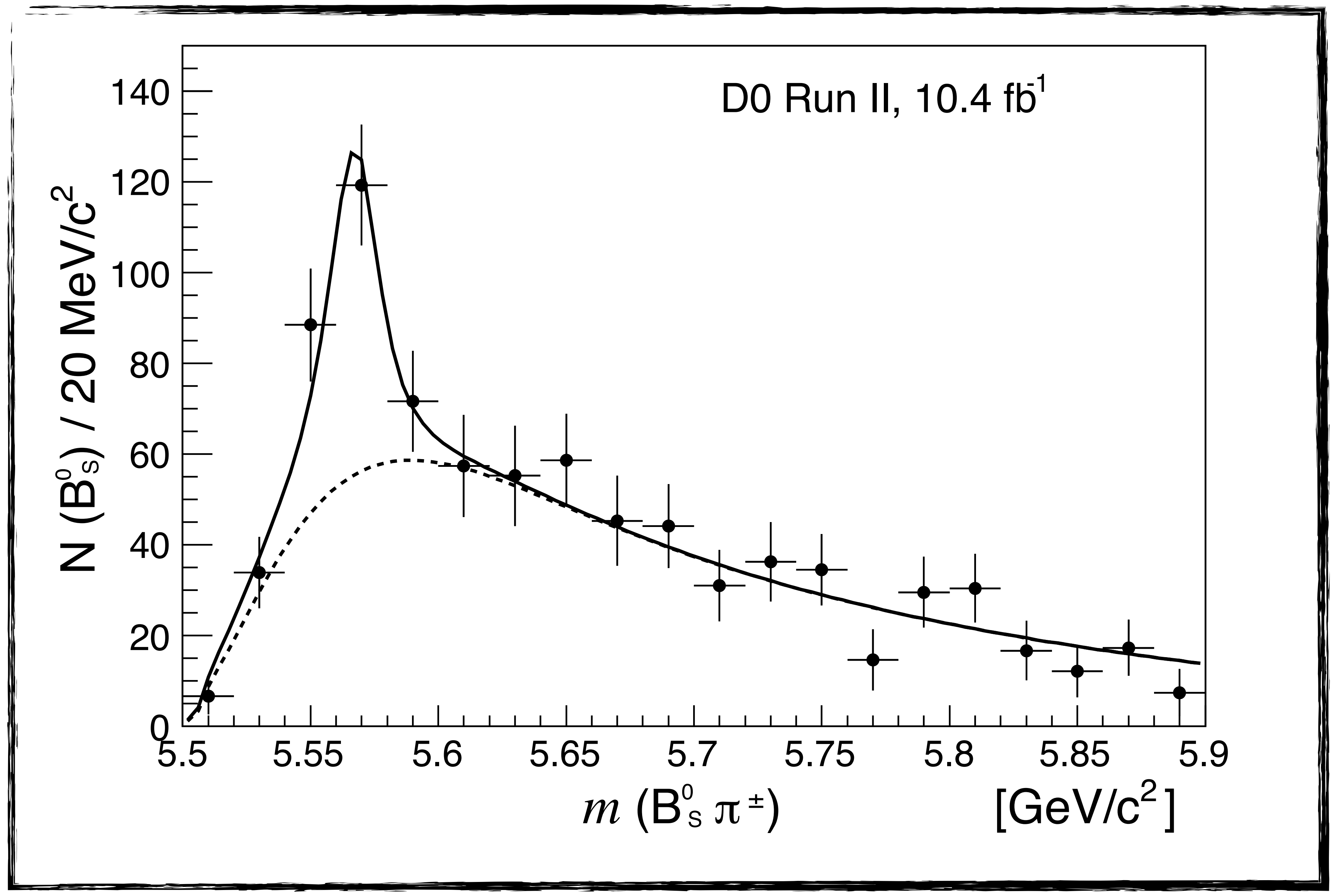




Phys. Rev. 93, 096011 (2016)

$$M_{X(5568)} = (5.58 \pm 0.17)\ \text{GeV}$$





Physics Letters B 758 (2016) 235–238

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ELSEVIER

A QCD sum rule calculation of the $X^{\pm}(5568) \to B_s^0 \pi^{\pm}$ decay width

CrossMark

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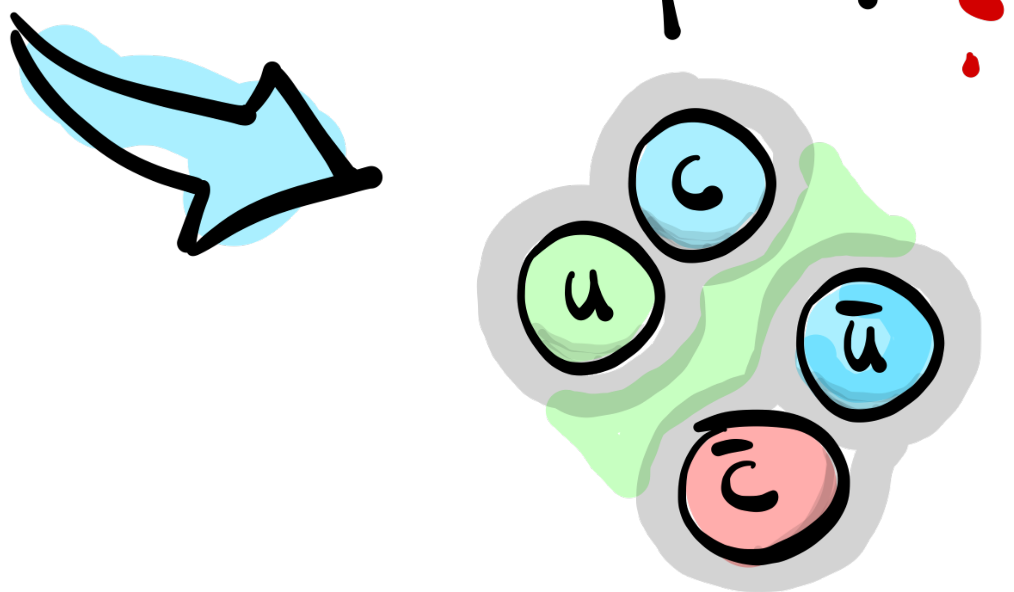
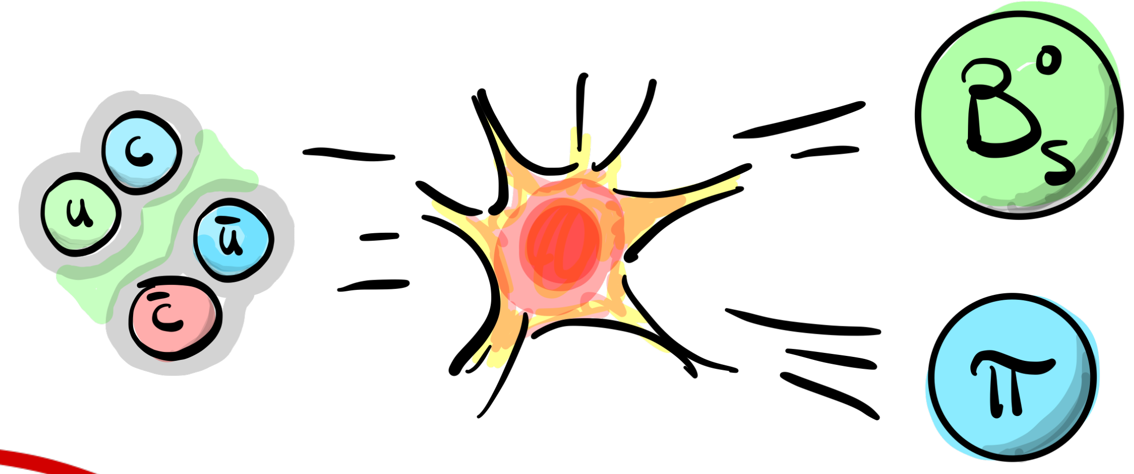
Our assumption

Tetraquark ?



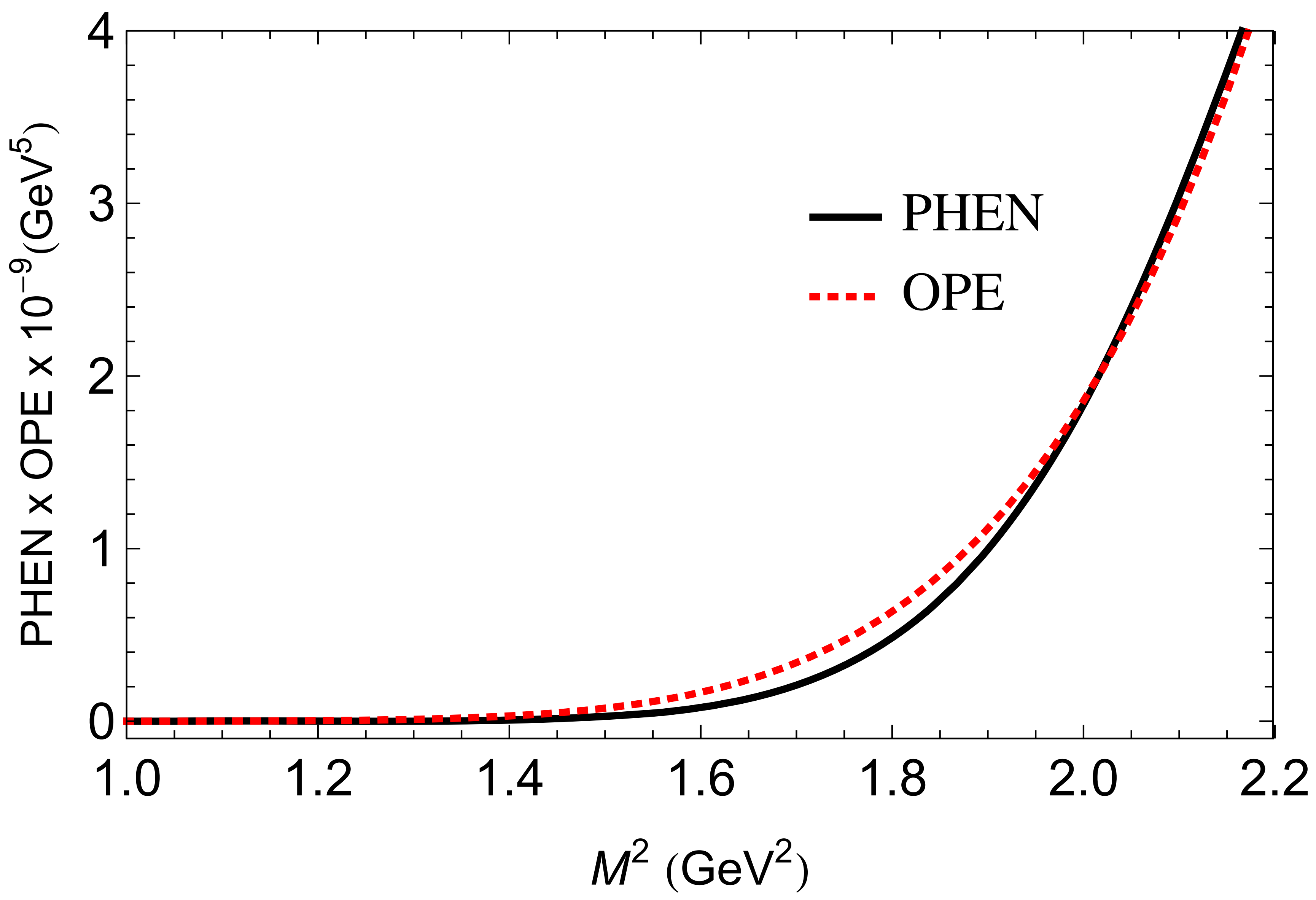
$X^+ \to B_s^0 \pi^+$



Results

$$\boxed{\Gamma_{X \to B\pi} \sim (20.4 \pm 8.7)\ \text{MeV}}$$

Experimentally $\Rightarrow$ $21.9 \pm 6.4(\text{sta})^{+5.0}_{-2.5}$ MeV



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A QCD sum rule calculation of the $X^{\pm}(5568) \to B_s^0\pi^{\pm}$ decay width

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However, ...

Let's have a look at the OPE convergence:

$$\Gamma_{X \to B\pi} \sim (30.1 \pm 8.6)\ \text{MeV}$$

- It is bigger than the previous one!
- But, the errors make the result still compatible with the experimental one

But, since the QCD sum rule mass for this state is about ~ 6.39 GeV, it cannot be assign to the X(5568)!