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Fundamental approaches to hadron spectroscopy

Andreas Krassnigg

FAIRNESS 2017

30.5.2017

@akrassnigg

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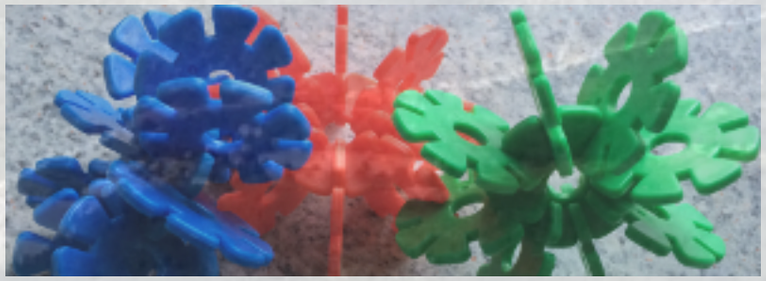

Outline

- What? What?
- Definitions and how to bend them
- Hadrons
- Approaches

- The most beautiful, only relevant, bestest ever approach
- Spectroscopy - bound states
- Hadron decays
- Are you ready to rumble?

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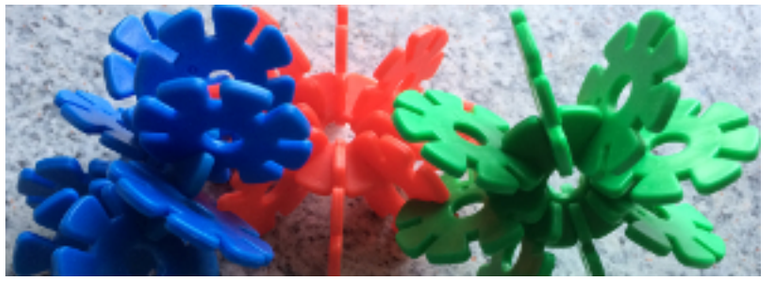

Meta-Data

Work done at:

University of Graz, Inst. f. Physik, NAWI Graz

Research group “Covariant Models of Hadrons”

http://Covariant.ModelsofHadrons.com

Collaborators:

M. Blank, M. Gomez-Rocha, T. Hilger, C. Popovici,

G. Eichmann, V. Mader

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Project P25121-N27

and HEPHY, Vienna

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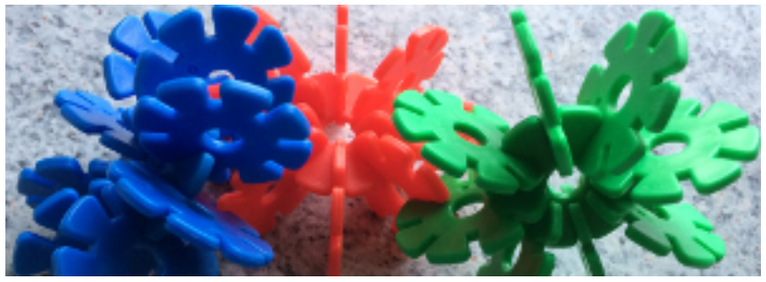

Meta-Questions

Fundamental approaches to hadron spectroscopy

What does **fundamental** actually mean?

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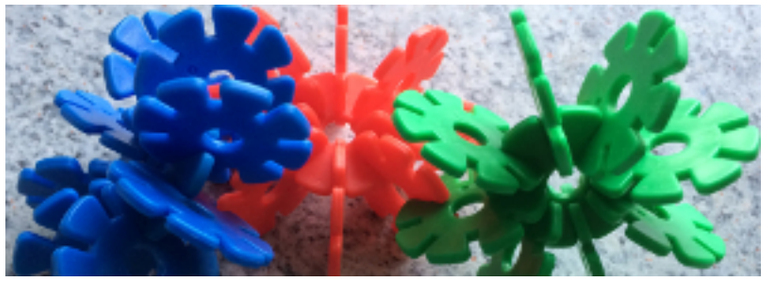

Meta-Questions

Fundamental approaches to **hadron spectroscopy**

What does **hadron spectroscopy** actually imply?

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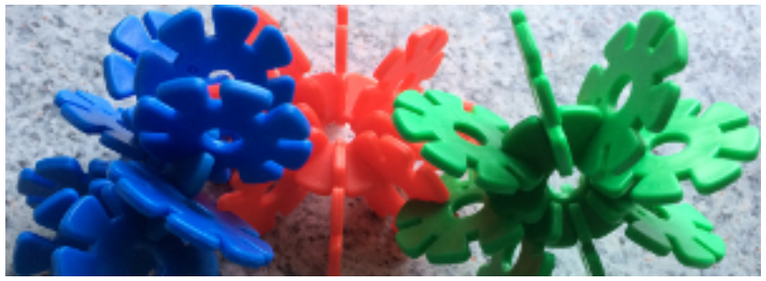
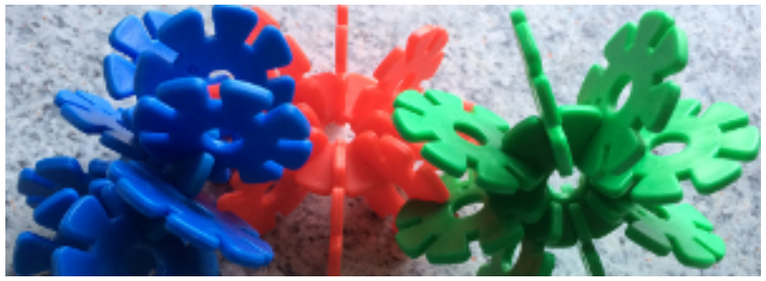
Fundamental



- What is the meaning of **fundamental**?

  Let's ask Webster's Encyclopedic Unabridged Dictionary:
  fun|da|men|tal:

1. serving as, or being an essential part of, a foundation or basis; basic; underlying
2. of, pertaining to, or affecting the foundation or basis
3. being an original or primary source
4. a basic principle, rule, law, or the like, that serves as the groundwork of a system; essential part



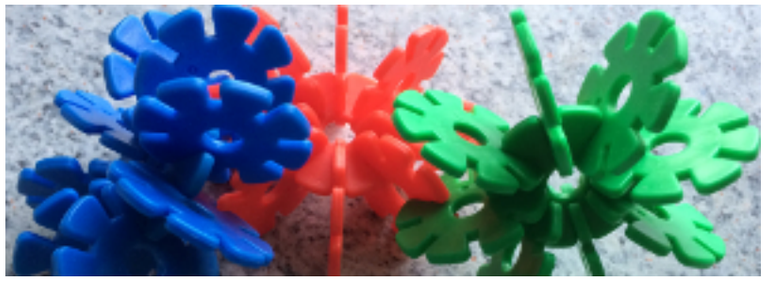
Hadron

- What is a **hadron**?

  Let’s ask Webster’s Encyclopedic Unabridged Dictionary (again):
  had|ron:

any elementary particle that is subject to the strong interaction. Hadrons are subdivided into baryons and mesons.

- We also know why:
  There is something called baryon number



Elementary particle

- What is an **elementary particle**?

  Let’s ask Webster’s Encyclopedic Unabridged Dictionary (again):
  el|e|men|ta|ry par|ti|cle:

any lepton, hadron, photon, or graviton, the particles once thought to be the indivisible components of all matter or radiation.

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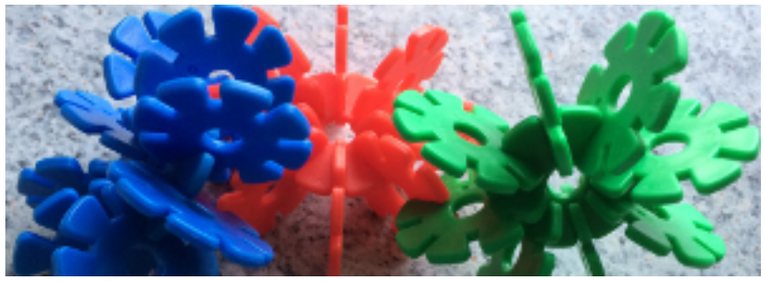

Spectroscopy

- What is **spectroscopy**?

  Let’s ask Webster’s Encyclopedic Unabridged Dictionary (again):
  spec|tros|co|py:

the science that deals with the use of the spectroscope and with spectrum analysis.

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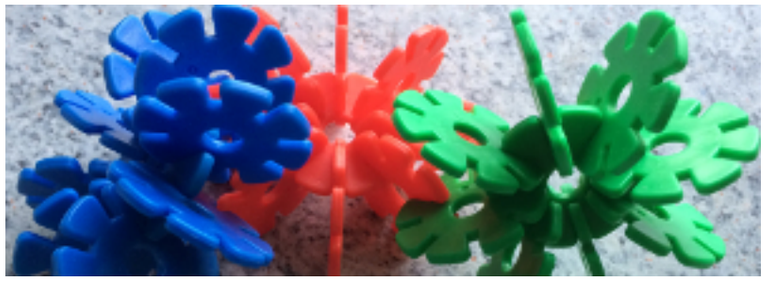
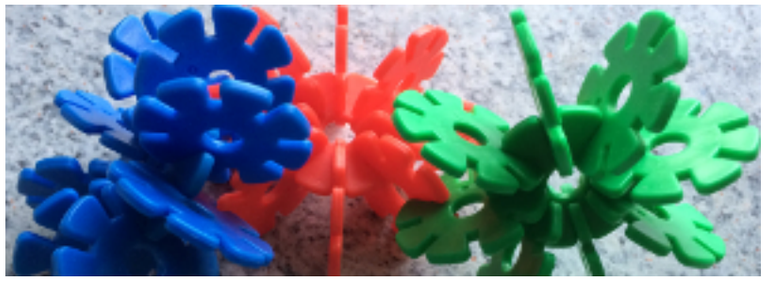


Spectrum

- What is a **spectrum**?

  Let’s ask Webster’s Encyclopedic Unabridged Dictionary (again):
  spec|trum:

an array of entities, as light waves or particles, ordered in accordance with the magnitudes of a common physical property, as wavelength or mass …

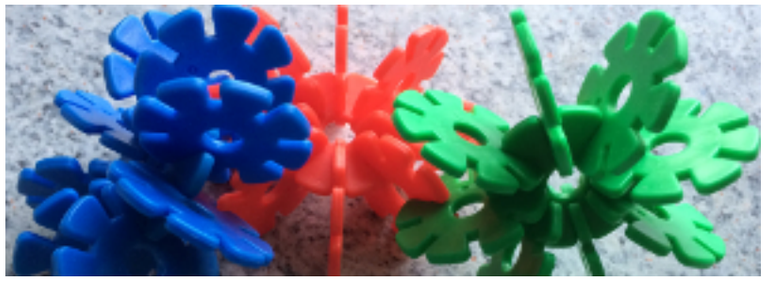


Fundamental

- What is the meaning of **fundamental**?

  Let’s check also at www.urbandictionary.com:
  fundamental:

The very basic or more simplistic form/version that can make up something of a larger and more complex structure/format/ design/ect.



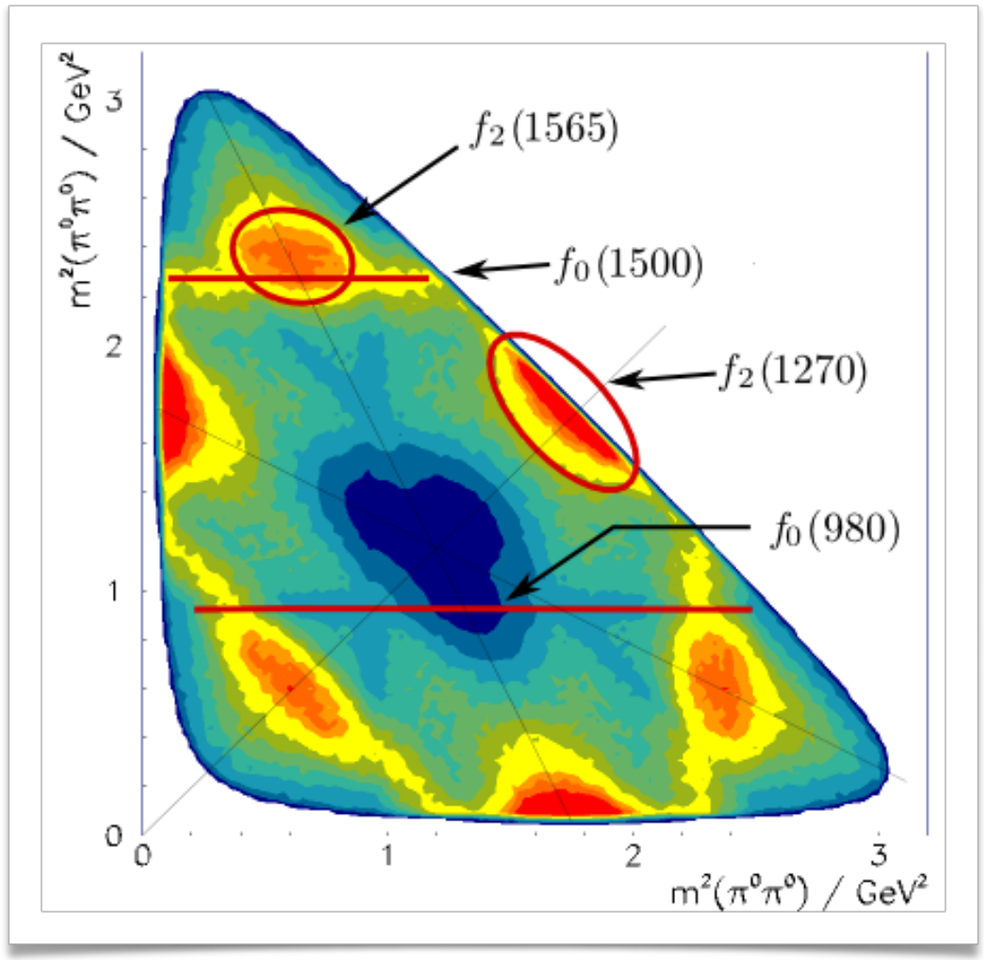
Hadron Spectrum

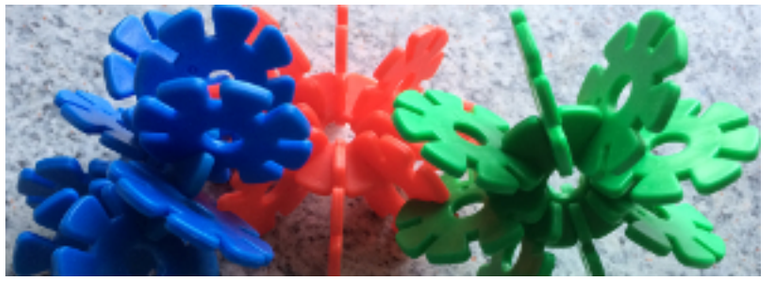
- Collect experimental information about hadrons

  → our experimentalist friends

- Various techniques
  (image stolen from PANDA webpage)
- Mass and width
- Widths goes to branching ratios
  - hadronic: MeV
  - electromagnetic & weak: eV - keV

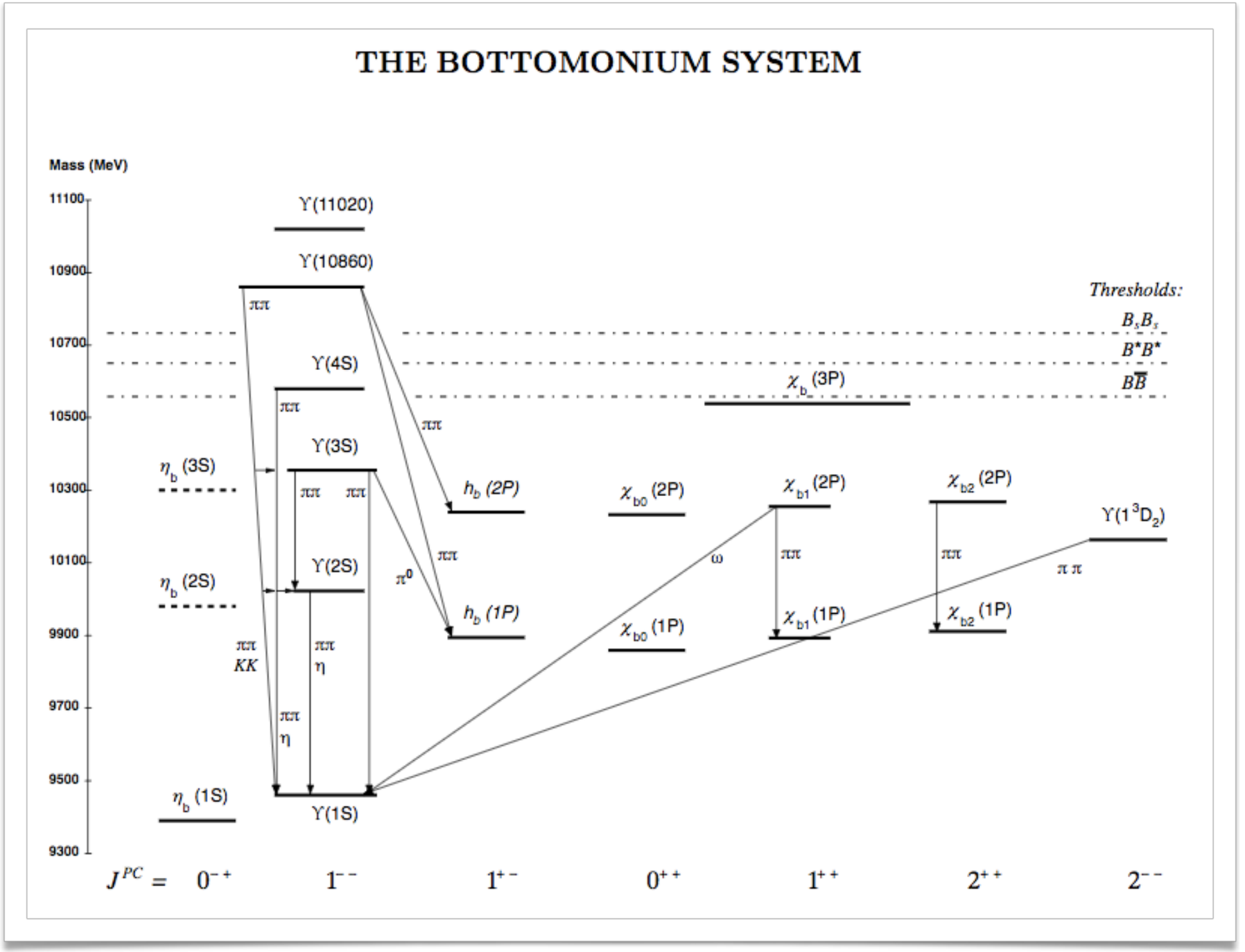
- This means: Hadrons are resonances!
  - different processes
  - observe (strong decay) thresholds

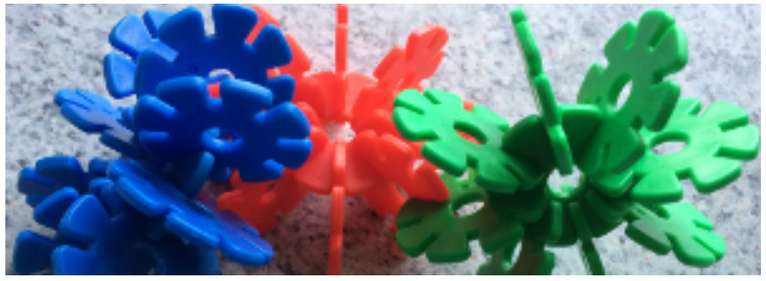




Meson Spectrum

From the PDG:
http://pdglive.lbl.gov





Meson Spectrum

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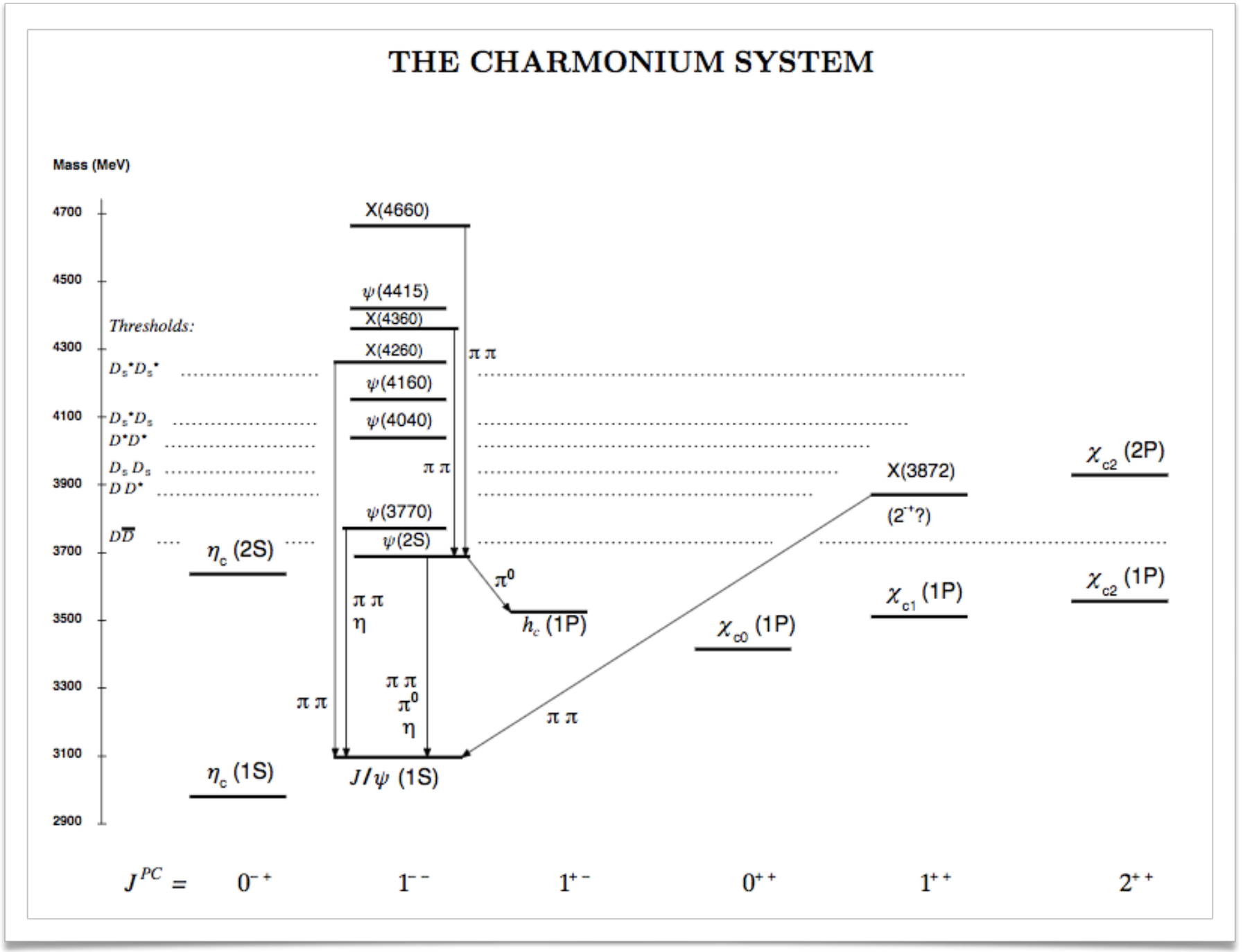

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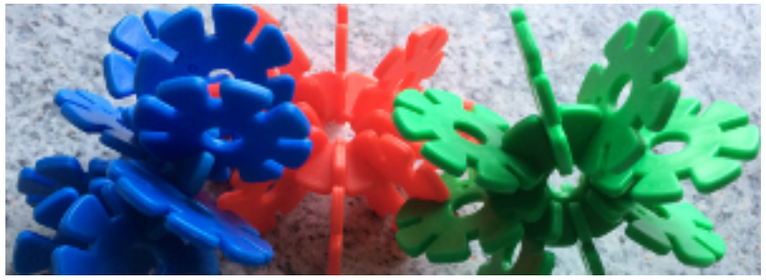

Hadron Spectrum

- For light mesons and baryons, everyone's a resonance
- Many, many states
- Many, many thresholds
- System? Order?
- Need someone to keep order!

- Need something, rather …
  - Spin J
  - Parity P
  - Charge-conjugation parity C (sometimes)
  - Additional quantum numbers: strangeness, charm, …

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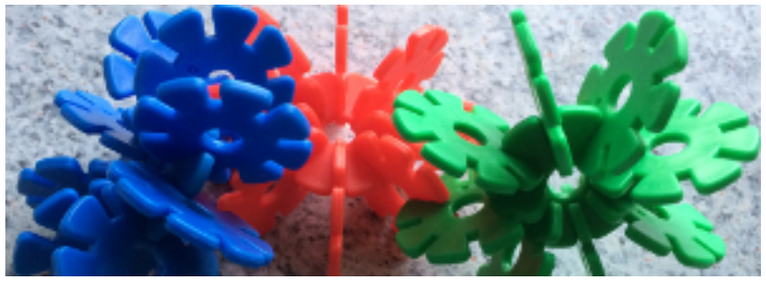
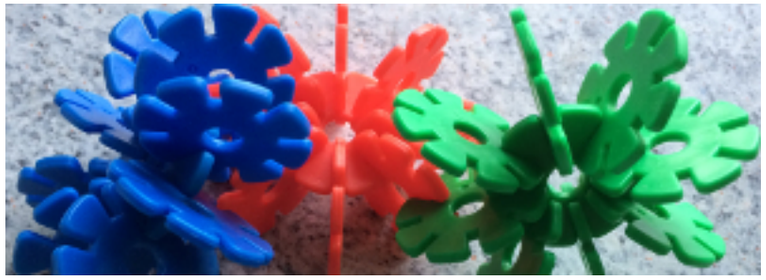


Fundamental Approach

"All approaches to hadron spectroscopy are fundamental, but some approaches are more fundamental than others ..."

- Yes, indeed, all depends on scales and assumptions
- But how do we deal with this mess in a systematic way?

- Effective field theories with meson degrees of freedom
- Build, e.g. meson tower from the bottom up and couple channels $\rightarrow$ Albert, Martin, Pedro
- Dispersion Relations
- Chiral perturbation theory



Composite Hadrons

Study hadrons as composites of quarks and gluons

That solves a lot of problems:

- Reduce crazy mess of states
- Flavors of quarks → create needed combinations and quantum numbers
- Concepts of color and fractional baryon number → explain mesons and baryons
- Do simple calculations → get comprehensive results and phenomenology

http://www.particlezoo.net/

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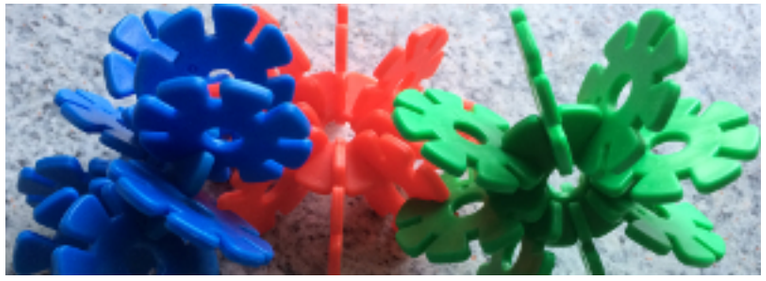
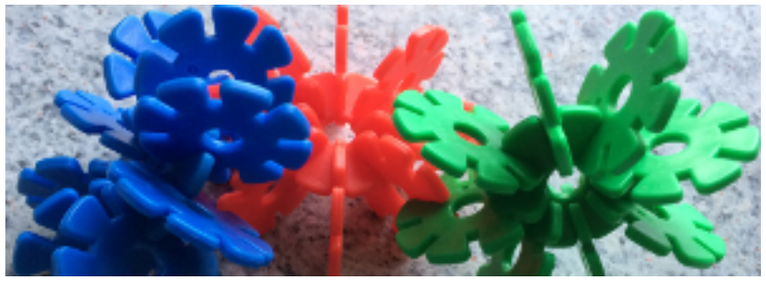


Composite Hadrons

Study hadrons as composites of quarks and gluons

Problems/Challenges/Features:

- STRONG INTERACTION!!!
- GLUONS SELF-INTERACT!!!
- chiral symmetry and $D\chi SB$
- high-energy perturbative limit
- quark and gluon confinement
- Poincare covariance/relativity
- bound-state/resonance problem is non-perturbative
- need to push really hard …



Fundamental Approach

"All approaches to hadron spectroscopy are fundamental, but some approaches are more fundamental than others ..."

Approaches to theory of quarks and gluons

- QCDSR
- EFTs with (heavy) quarks and gluons → Sungmin
- Quark model (relativised) → Paolo
- (p)NRQCD → Jorge
- AdS/QCD models → Rico
- Lattice → Attila
- FRG → Jordi
- DSBSE → Esther, Paul
- 3D-reduced equations (Salpeter, CIA, CST, CSI, NCIS, ...)

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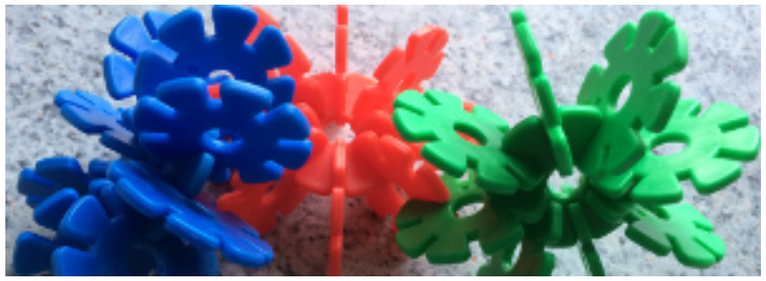
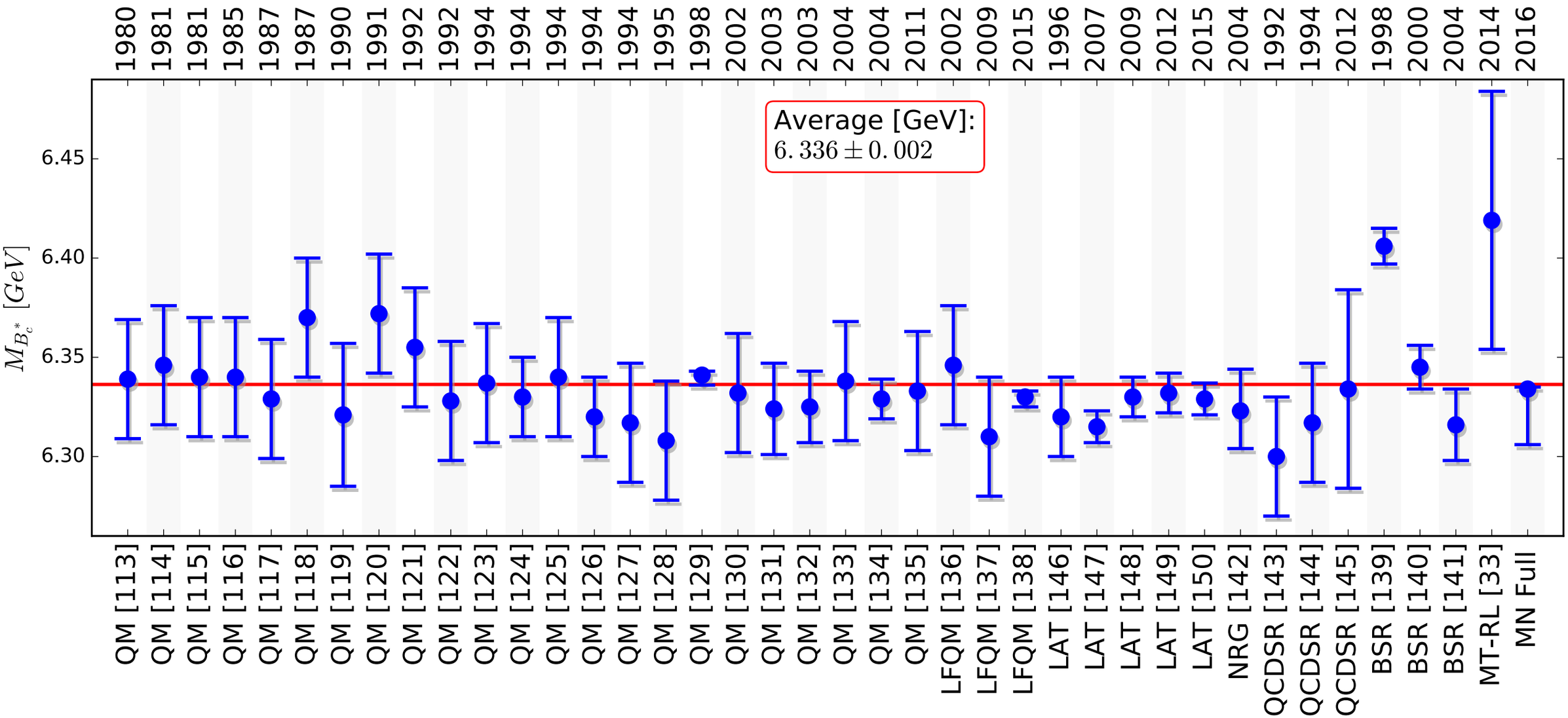


Hadron Theory: Open Questions, e.g.



M. Gomez-Rocha, T. Hilger, A.K., PRD 93 (2016) 074010

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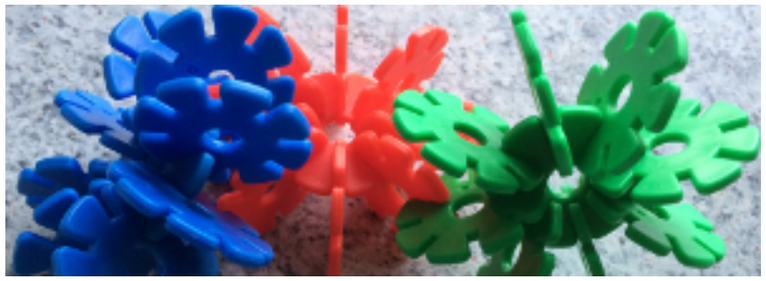
Hadron Theory: Expected from $\bar{\text{P}}$ANDA

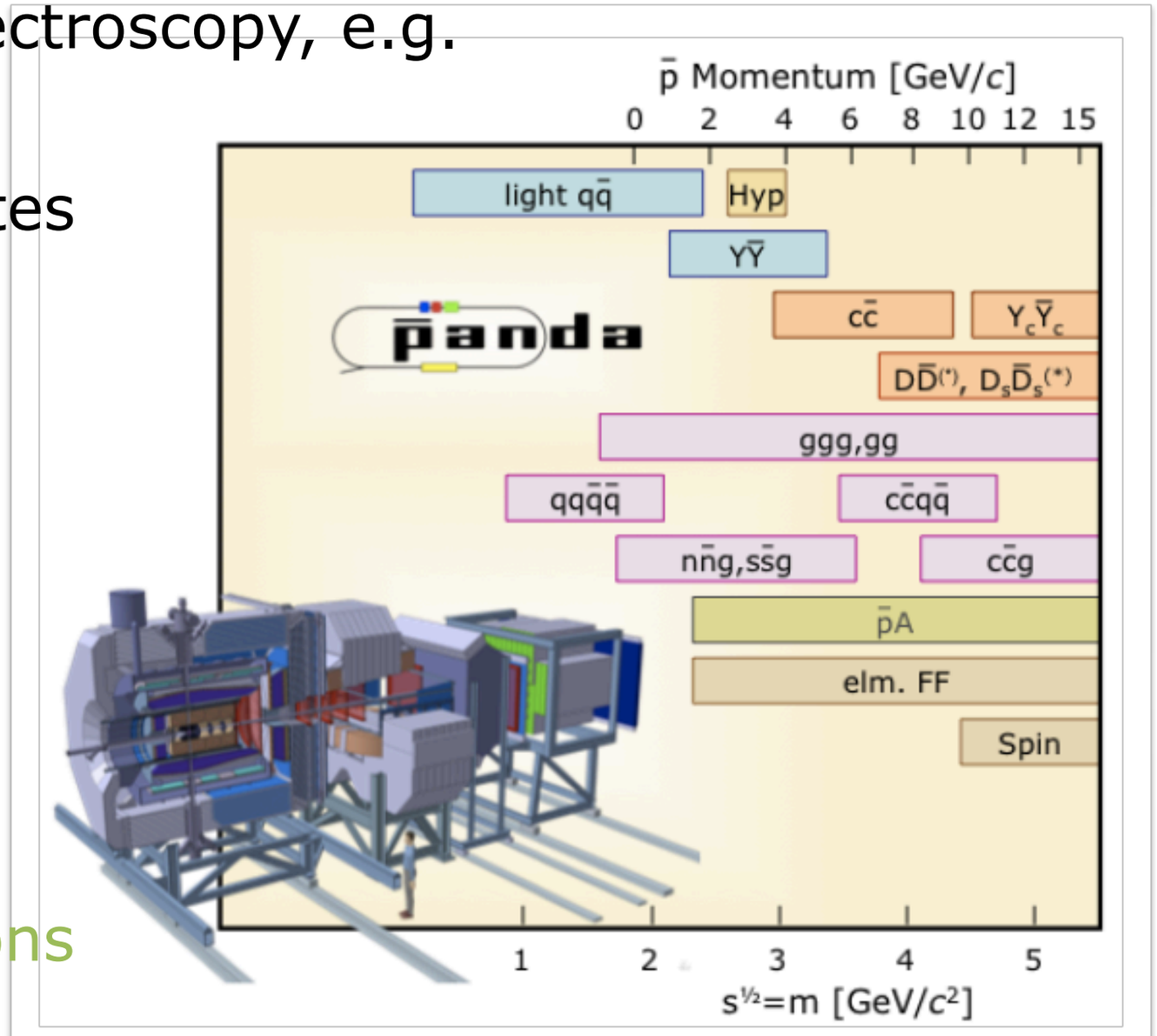


→ Elisabetta

Learn more about hadron spectroscopy, e.g.

- Exotic mesons
  - Gluonic excitations of states
  - AKA Hybrids
  - Charmonium hybrids
- Focus on XYZ states
- Glueballs
- Multiquark states

- Heavy-light mesons
- Strange and charmed baryons
- Decay channels



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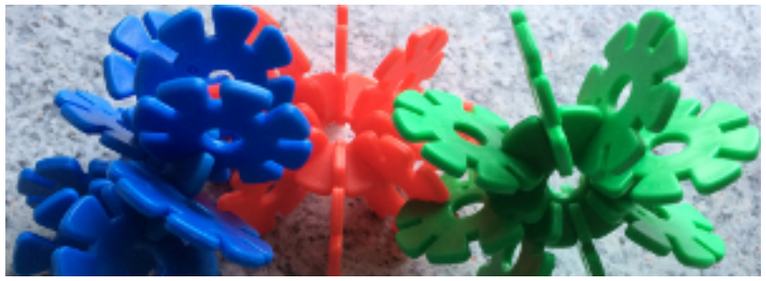

Department of Shameless Self-Promotion

- Dyson-Schwinger equations can be used to solve QCD
- Bethe-Salpeter and Faddeev-type equations allow covariant and symmetry-preserving study of bound-state problems
- Infinite set of coupled (and nonlinear) integral equations
- Numerical studies: Truncation $\leftrightarrow$ numerical effort
- Make the truncation respect symmetries
- Construct sophisticated models
- Perform reliable calculations of hadron properties
- Reviews:
  - C.D. Roberts, M. S. Bhagwat, A. Holl, S. V. Wright, Eur. Phys. J. Special Topics 140 (2007) 53
  - G. Eichmann, H. Sanchis-Alepuz, R. Williams, R. Alkofer, C. S. Fischer, Prog. Part. Nucl. Phys. 91 (2016) 1

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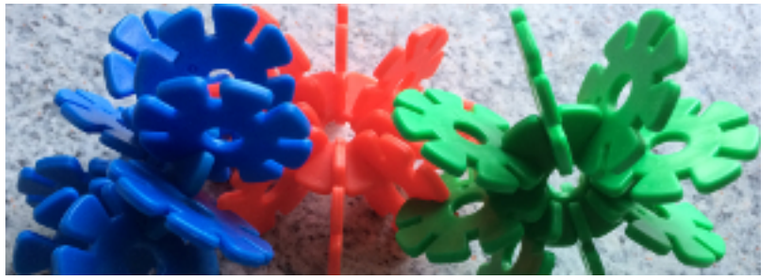
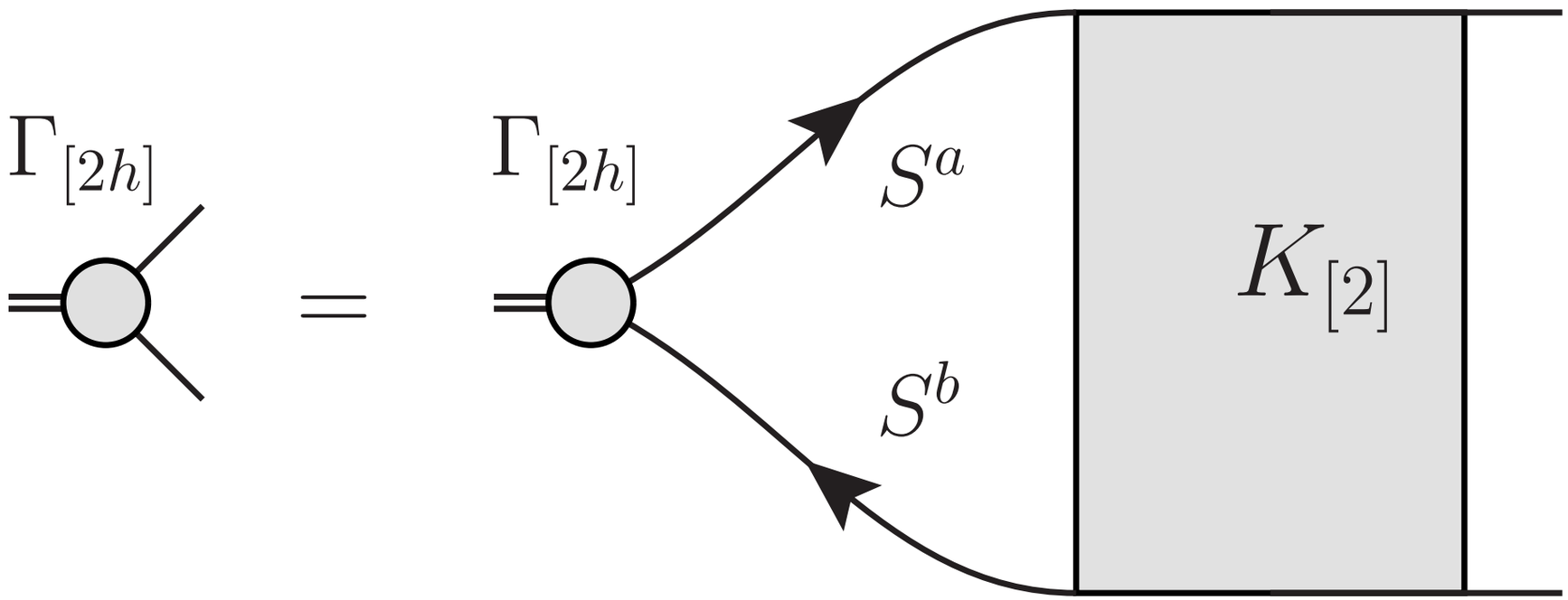
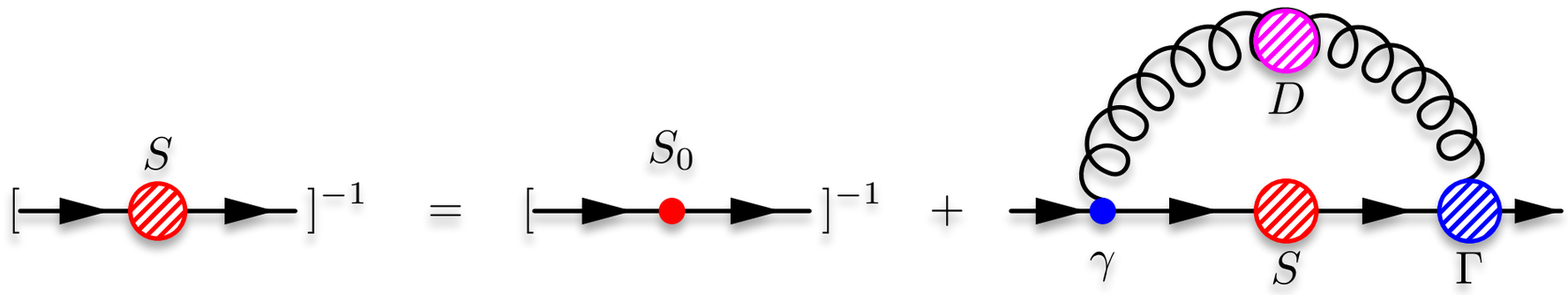


The DSBSE system

meson BSE



quark DSE



FWF Der Wis

M. Blank, A.K., Comput. Phys. Commun. 182 (2011) 1391

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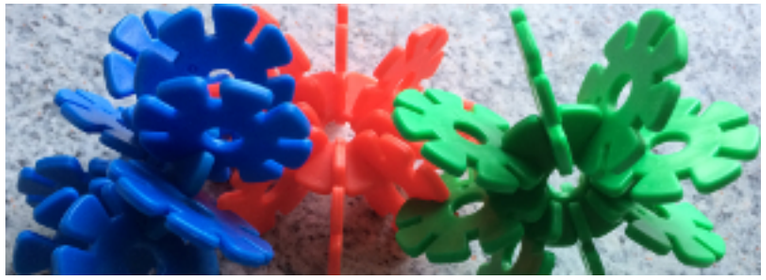
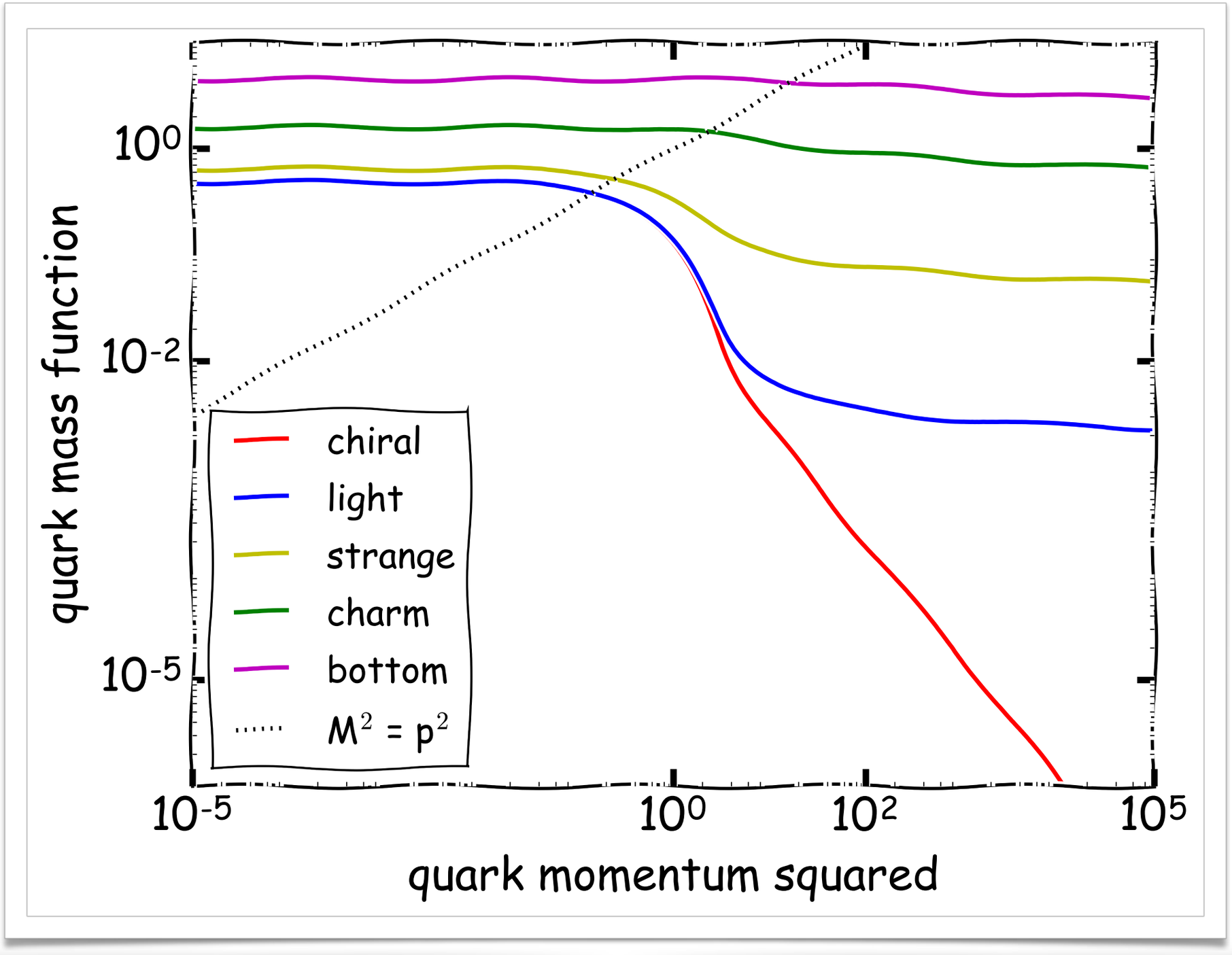
Solutions to the quark DSE





FWF e.g., A.K., M. Gomez-Rocha, T. Hilger, J.Phys.Conf.Ser. 742 (2016) 012032

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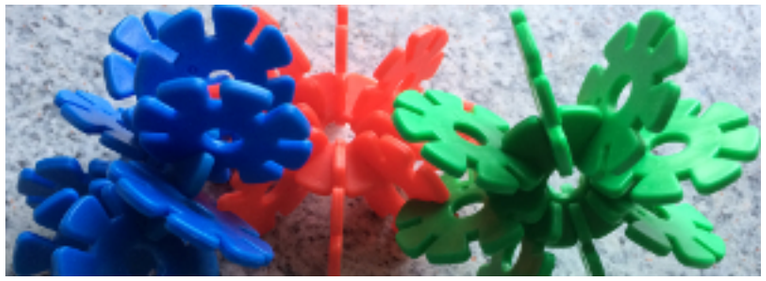
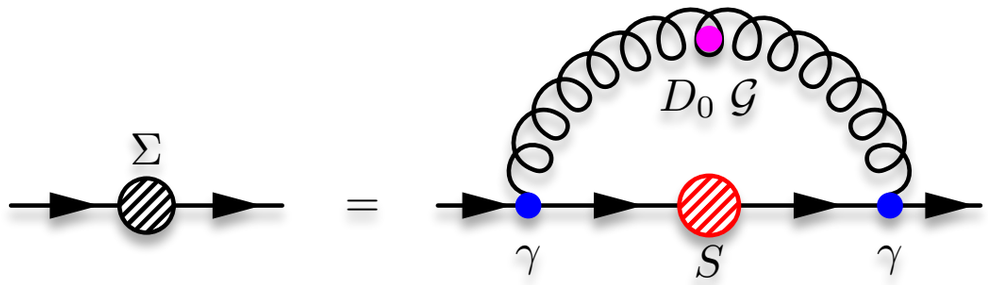
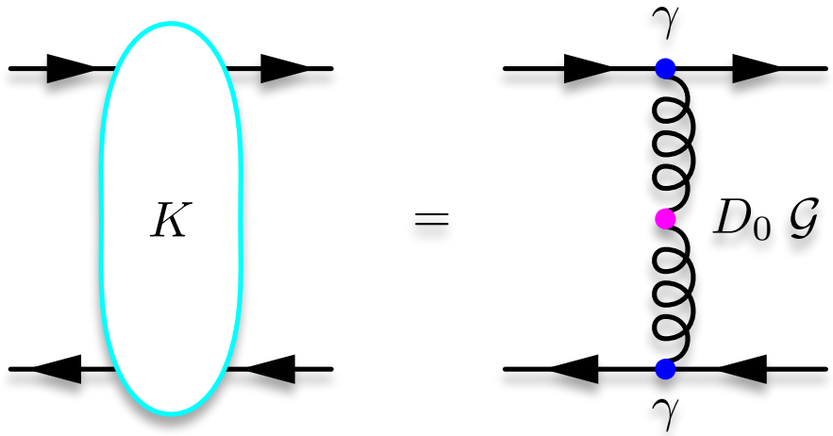


Rainbow-Ladder Truncation

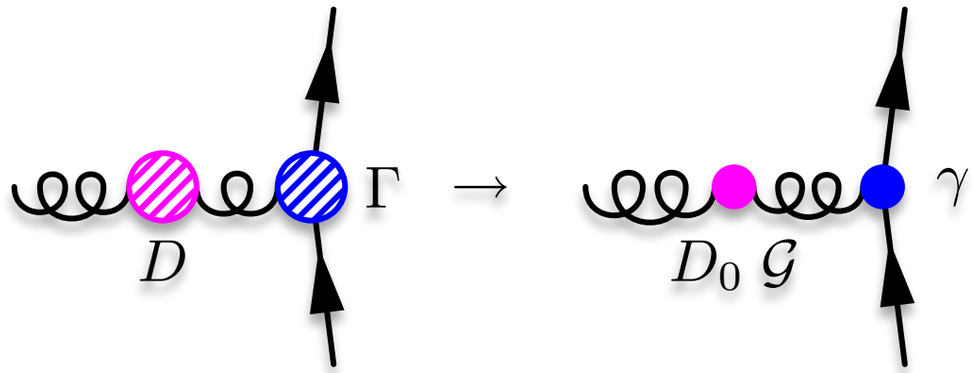
Gap equation / quark self-energy:



BSE:



Interaction:



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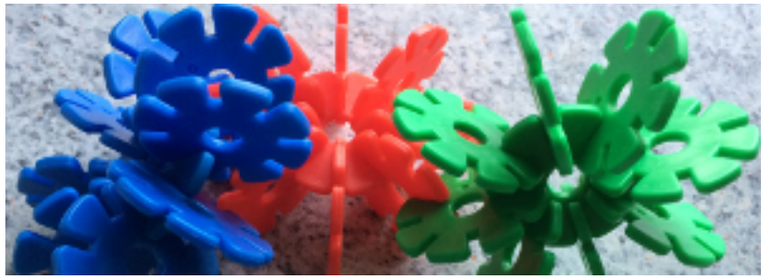
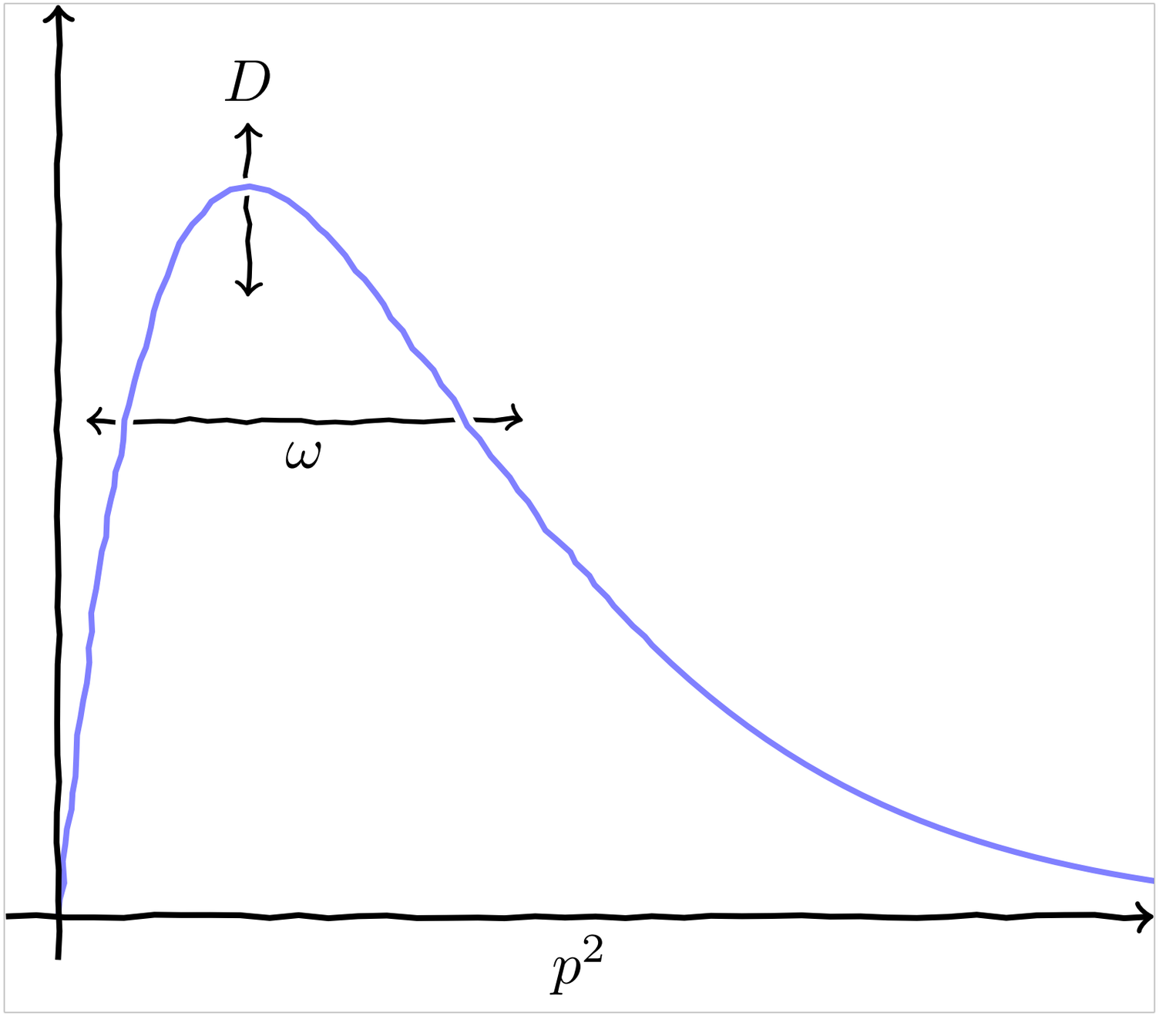
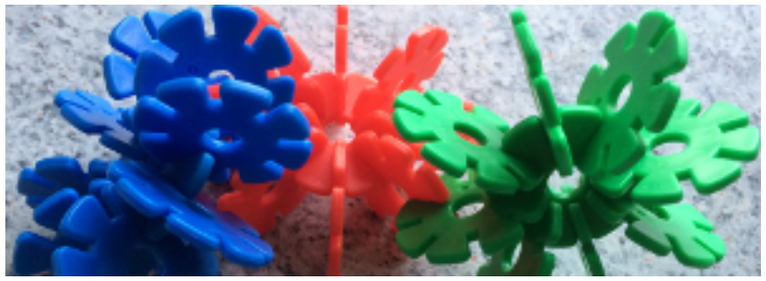


Effective Interaction

Parameters determine curve characteristics

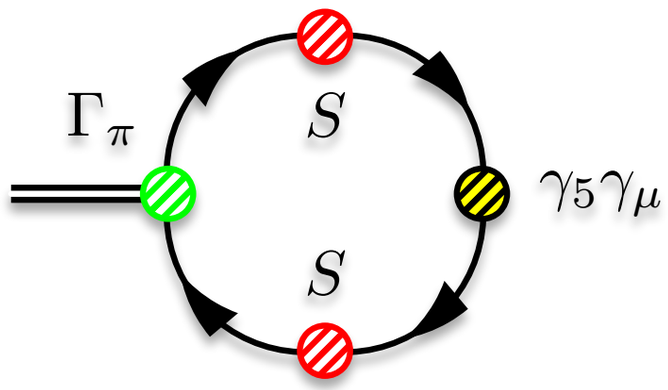


e.g., A.K., M. Gomez-Rocha, T. Hilger, J.Phys.Conf.Ser. 742 (2016) 012032

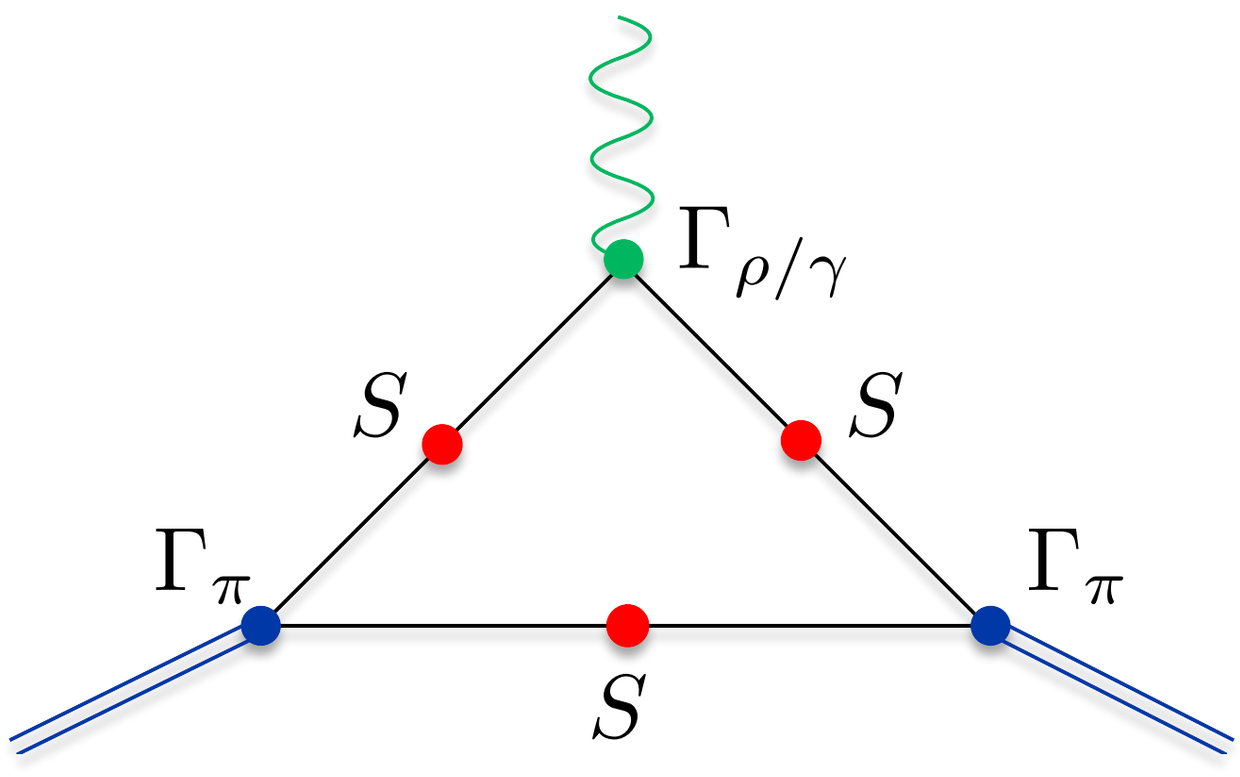


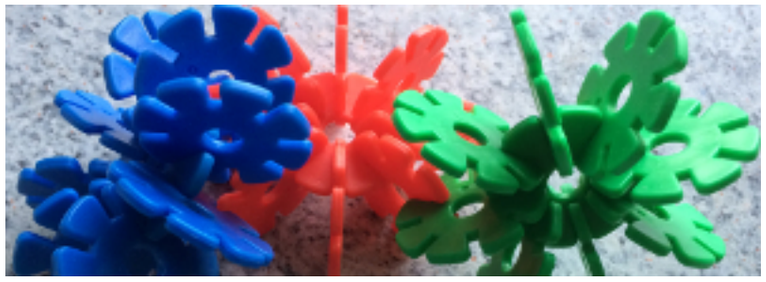
Beyond Spectroscopy

Leptonic decay:



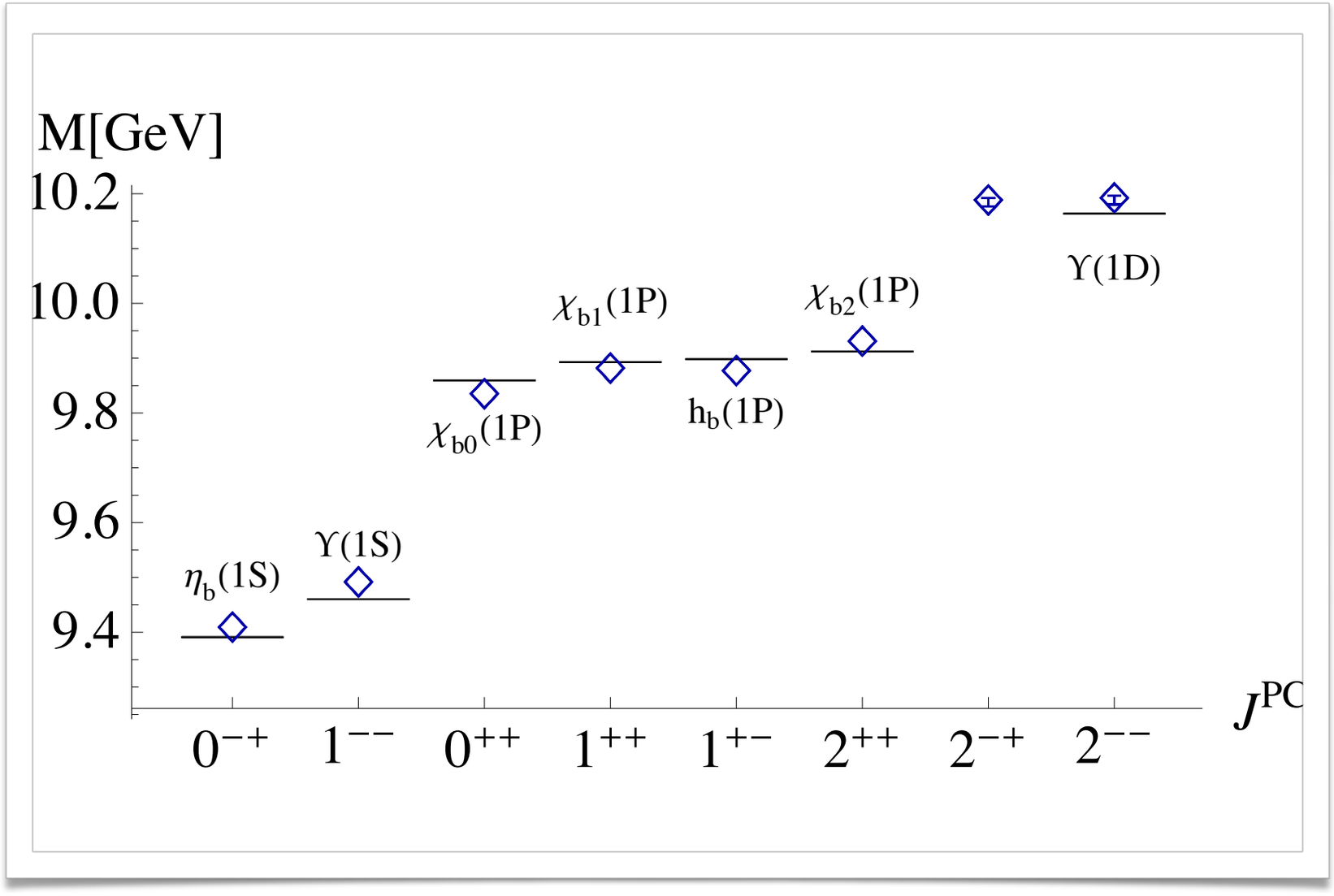
Hadronic decay
& Form factor:





Spectroscopy

- Use RL truncation for simplicity on comprehensive scale
- apply it to systems where corrections beyond RL are expected least important
- First attempt: Bottomonium ground states:



M. Blank, A.K., PRD 84 (2011) 096014

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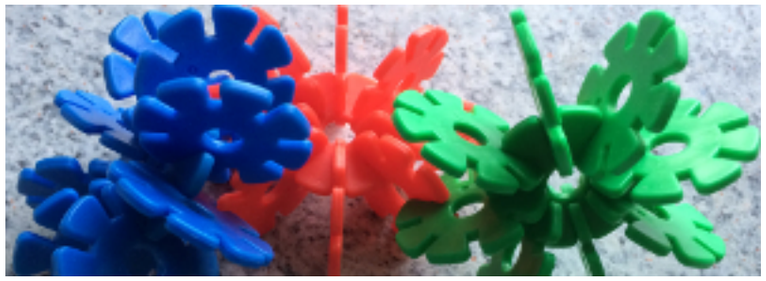
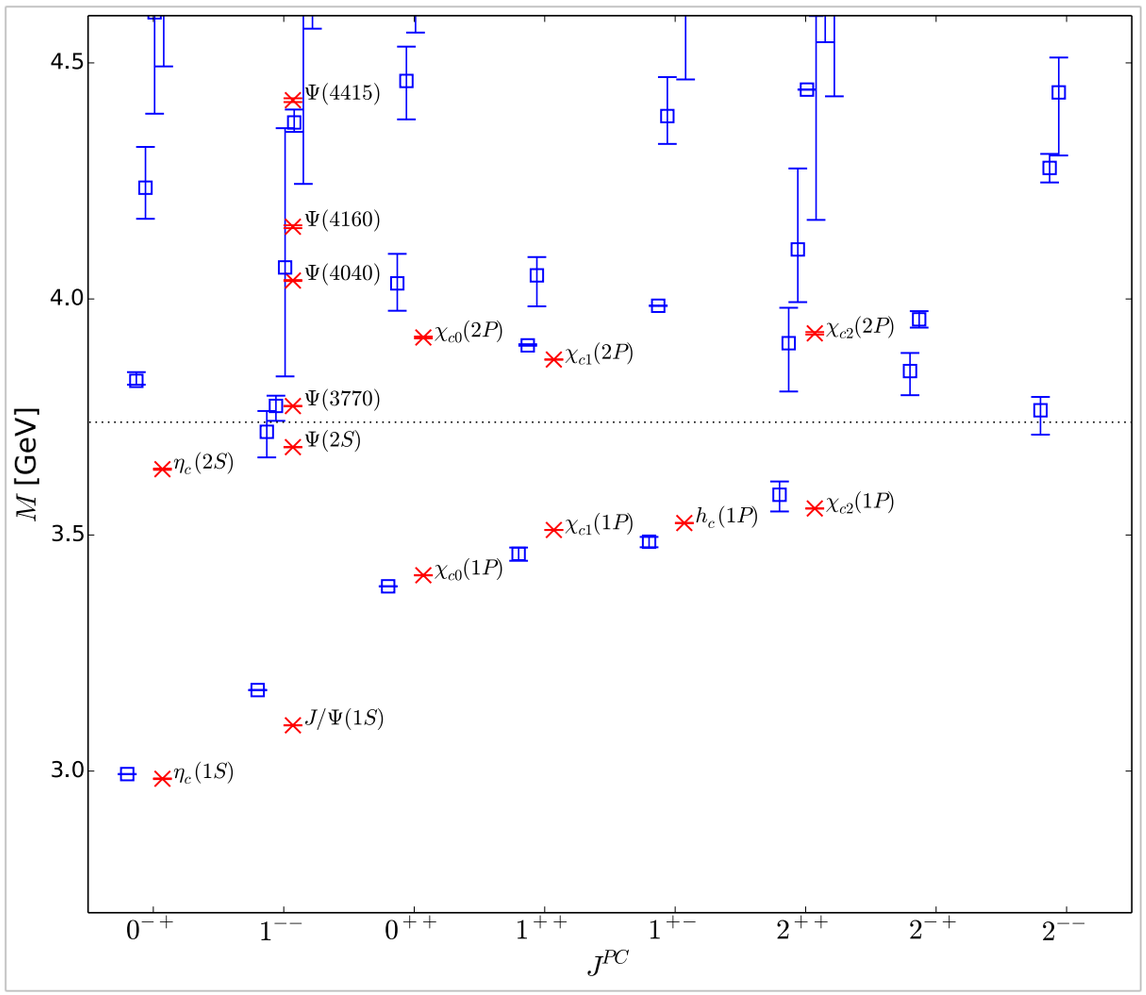
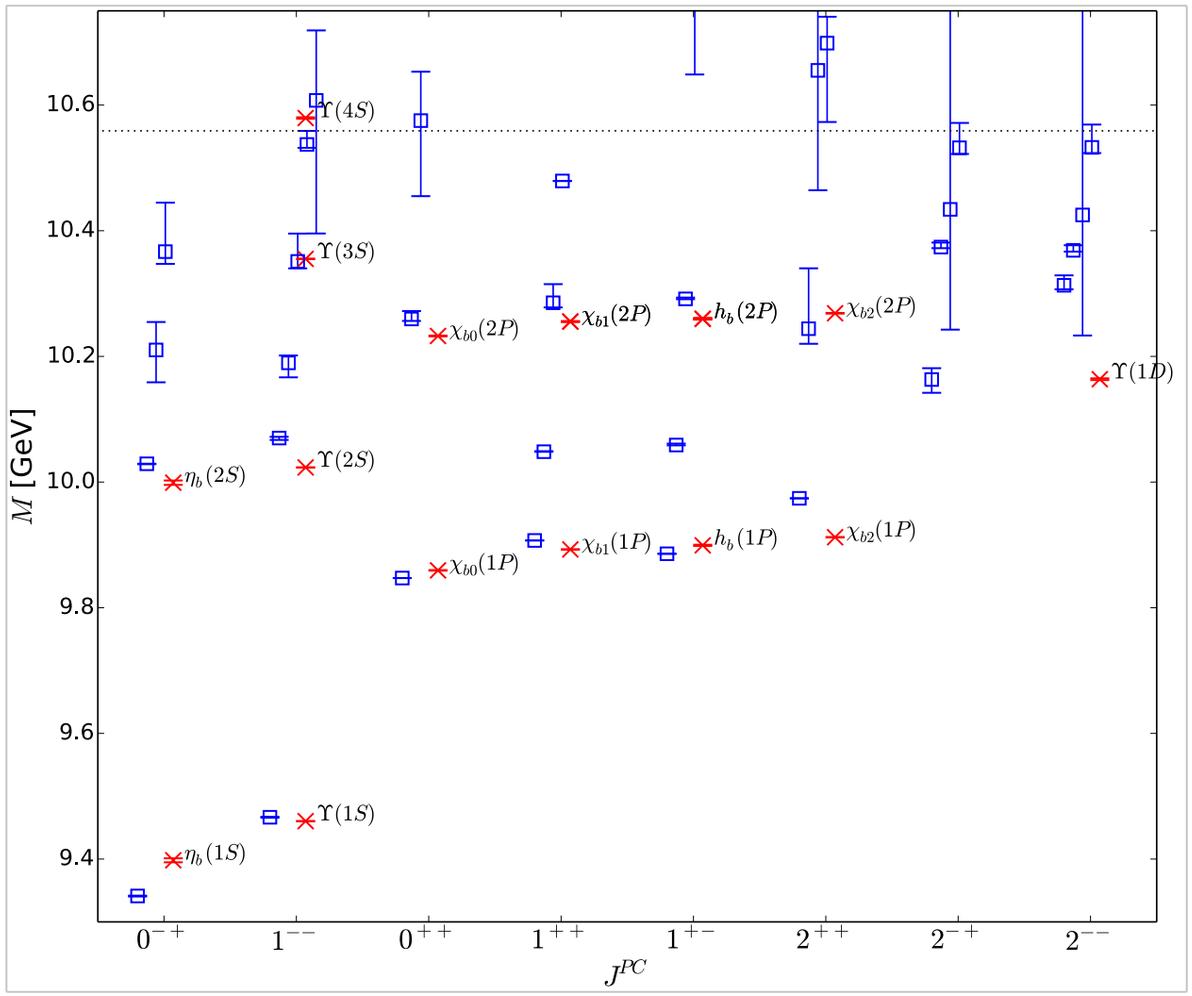


Spectroscopy

- Next step: more freedom in effective interaction: $b\bar{b}$ and $c\bar{c}$





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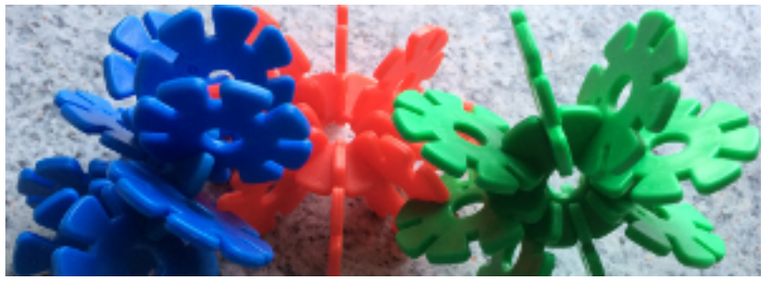

Leptonic Decays

Heavy quarkonia, S vs. D wave in 1^{--} channel, judge by f

State	J^{PC}	Calc. I	II	Exp.
Pseudoscalar				
η_c	0^{-+}	401	378	339(14)
$\eta_c(2S)$	0^{-+}	244(12)	82	189(50)
$\eta_c(3S)$	0^{-+}	145(145)	206	–
$\eta_c(4S)$	0^{-+}	–	87	–
Vector				
J/Ψ	1^{--}	450	411	416(5)
$\Psi(2S)$	1^{--}	30(3)	155	294(4)
$\Psi(3770)$	1^{--}	118(91)	45	99(3)
$\Psi(4040)$	1^{--}	–	188	187(8)
$\Psi(4160)$	1^{--}	–	1	142(34)
$\Psi(4415)$	1^{--}	–	262	161(10)

State	J^{PC}	Calc. I	II	Exp.
Pseudoscalar				
η_b	0^{-+}	773	756	–
$\eta_b(2S)$	0^{-+}	419(8)	285	–
$\eta_b(3S)$	0^{-+}	534(57)	333	–
$\eta_b(4S)$	0^{-+}	–	40(15)	–
Vector				
Υ	1^{--}	768	707	715(5)
$\Upsilon(2S)$	1^{--}	467(17)	393	497(4)
$\Upsilon(1^3D_1)$	1^{--}	41(7)	371(2)	–
$\Upsilon(3S)$	1^{--}	–	9(5)	430(4)
$\Upsilon(2^3D_1)$	1^{--}	–	165(50)	–
$\Upsilon(4S)$	1^{--}	–	20(15)	341(18)

A.K., M. Gomez-Rocha, T. Hilger, J.Phys.Conf.Ser. 742 (2016) 012032

FWF Der Wissenschaftsfonds.

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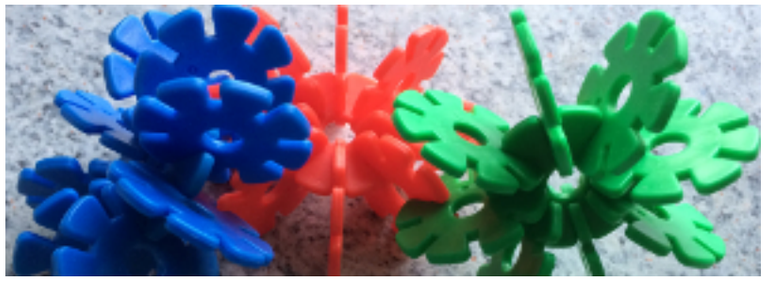
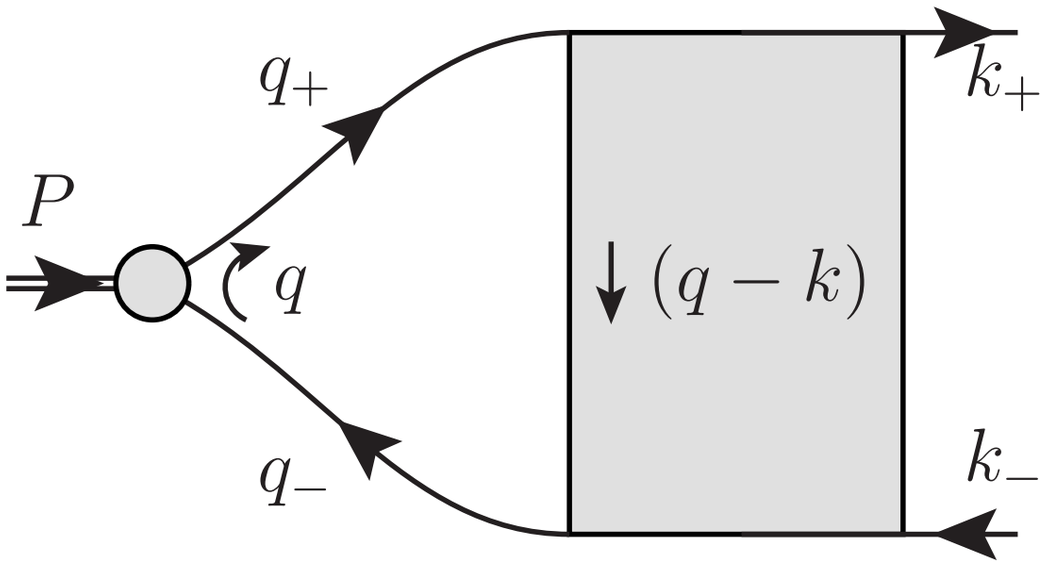
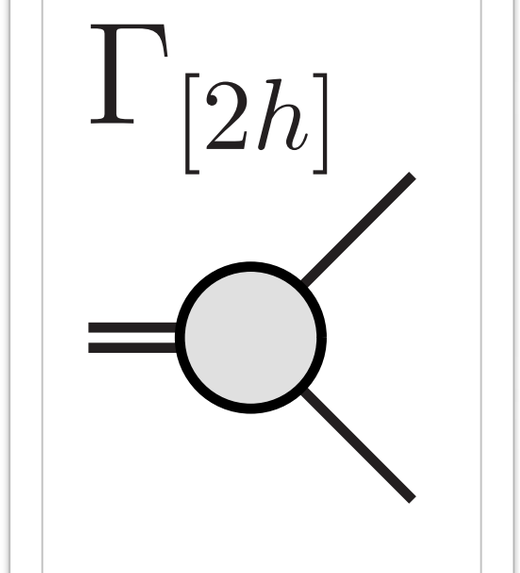


Orbital Angular Momentum Decomposition

Bethe-Salpeter Amplitude: Total momentum *P*, relative momentum *q*





$$\Gamma_{[2]}(\gamma; q; P) = \sum_{i=1}^{N} T_i(\gamma; q; P)\ F^i(P^2, q^2, q \cdot P)$$

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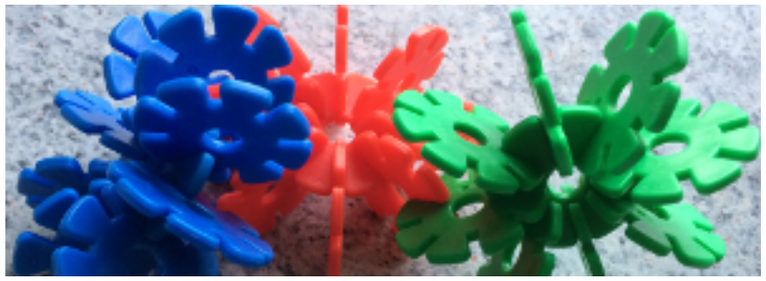

Orbital Angular Momentum Decomposition

Example Covariants:

pseudoscalar meson $\longrightarrow$

vector meson $\downarrow$

i	T_i	l	$\mathcal{C}$
1	γ_5	0	+
2	$\gamma_5\ \gamma\cdot\hat{P}$	0	+
3	$\gamma_5\ \gamma\cdot q^{(T)}$	1	−
4	$\gamma_5\ [\gamma\cdot q, \gamma\cdot\hat{P}]$	1	+

i	T_i	l	$\mathcal{C}$
1	$\gamma^{\mu(T)}$	0	−
2	$\gamma^{\mu(T)}\ \gamma\cdot\hat{P}$	0	−
3	$[\gamma^{\mu(T)}, \gamma\cdot q^{(T)}]$	1	+
4	$\gamma^{\mu(T)}\ [\gamma\cdot q, \gamma\cdot\hat{P}] - 2\,q^{\mu(T)}\ \gamma\cdot\hat{P}$	1	−
5	$q^{\mu(T)}\ \mathbf{1}$	1	−
6	$q^{\mu(T)}\ \gamma\cdot\hat{P}$	1	+
7	$q^{\mu(T)}\ \gamma\cdot q^{(T)} - \frac{1}{3}q^{(T)2}\ \gamma^{\mu(T)}$	2	−
8	$q^{\mu(T)}\ [\gamma\cdot q, \gamma\cdot\hat{P}] - \frac{1}{3}q^{(T)2}\ [\gamma^{\mu(T)}, \gamma\cdot\hat{P}]$	2	−

FWF Der Wissenscha

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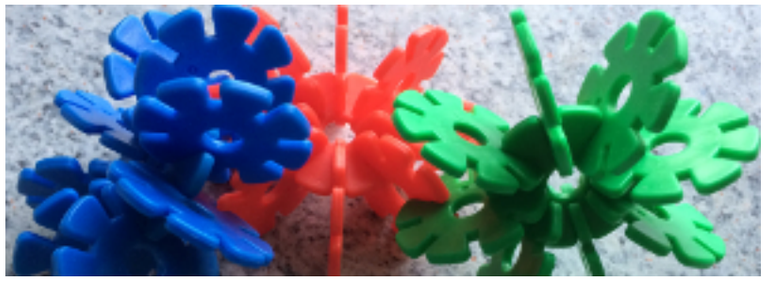
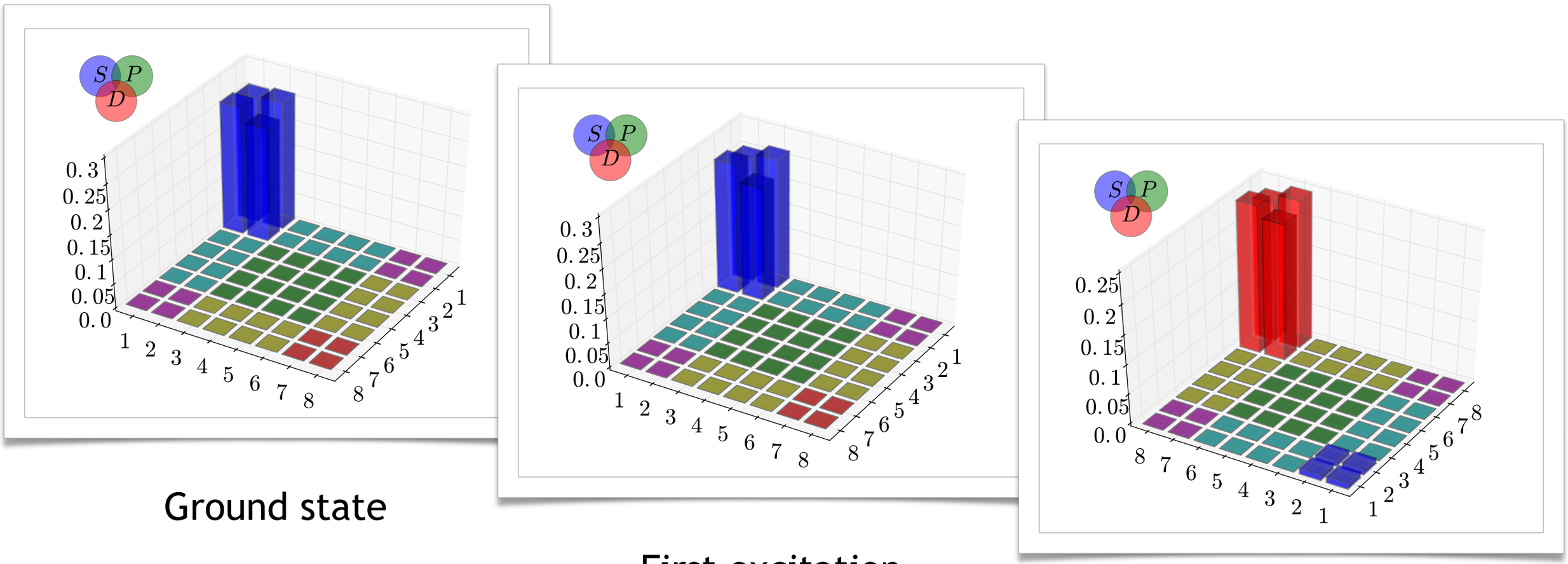


Orbital Angular Momentum Decomposition

Bottomonium, S vs. D wave in 1^{--} channel, judge by OAMD



Ground state

First excitation

Second excitation

A.K., T. Hilger, in preparation

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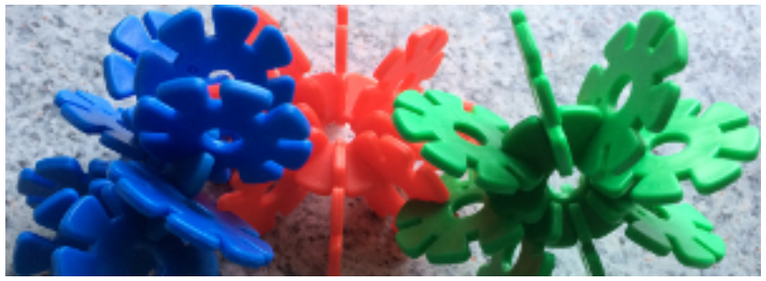
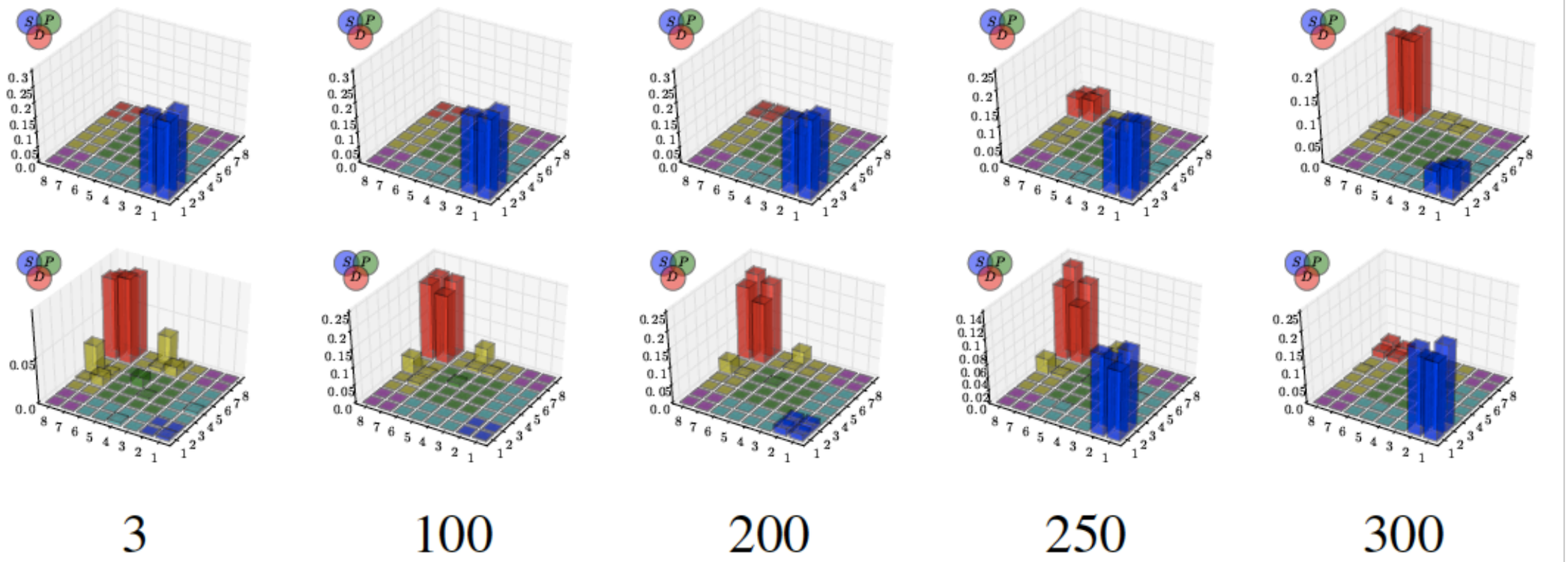
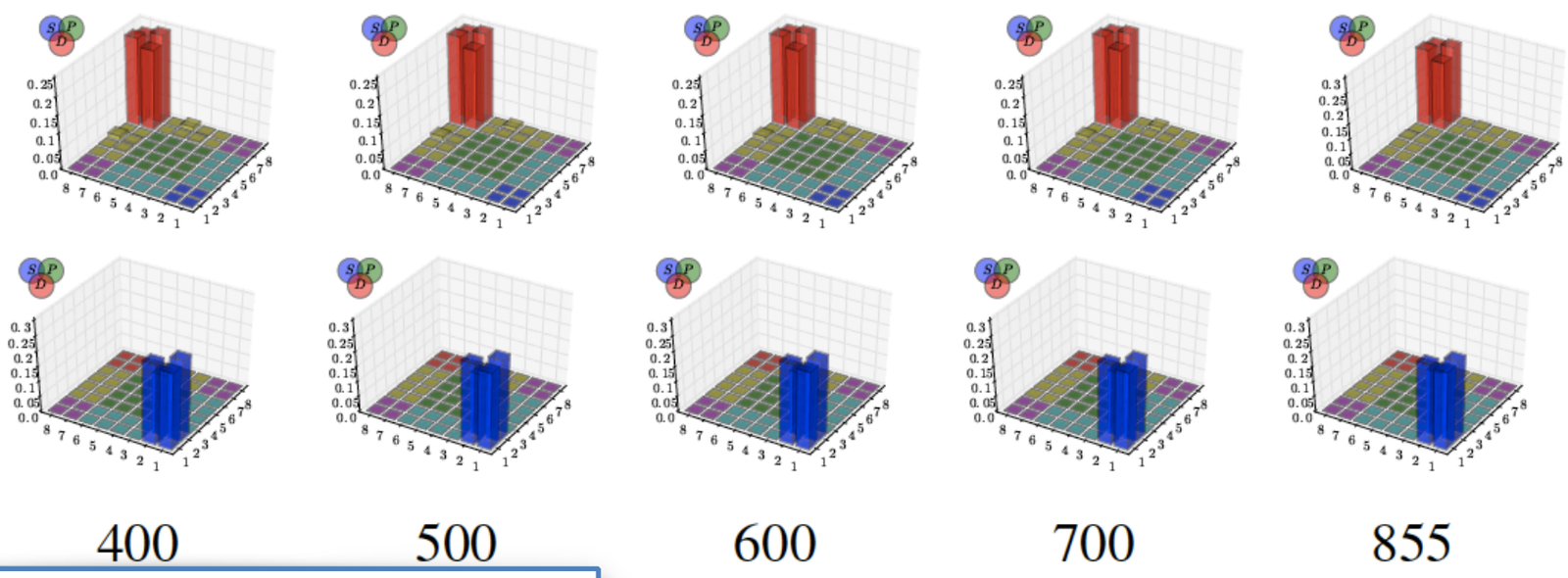


OAMD: a function of m_q



OAMD in 1^{--} channel for excitations



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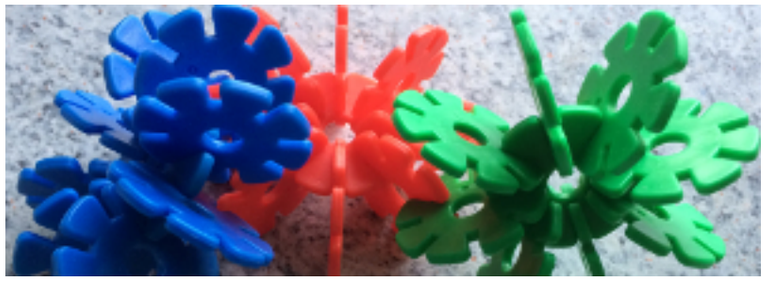
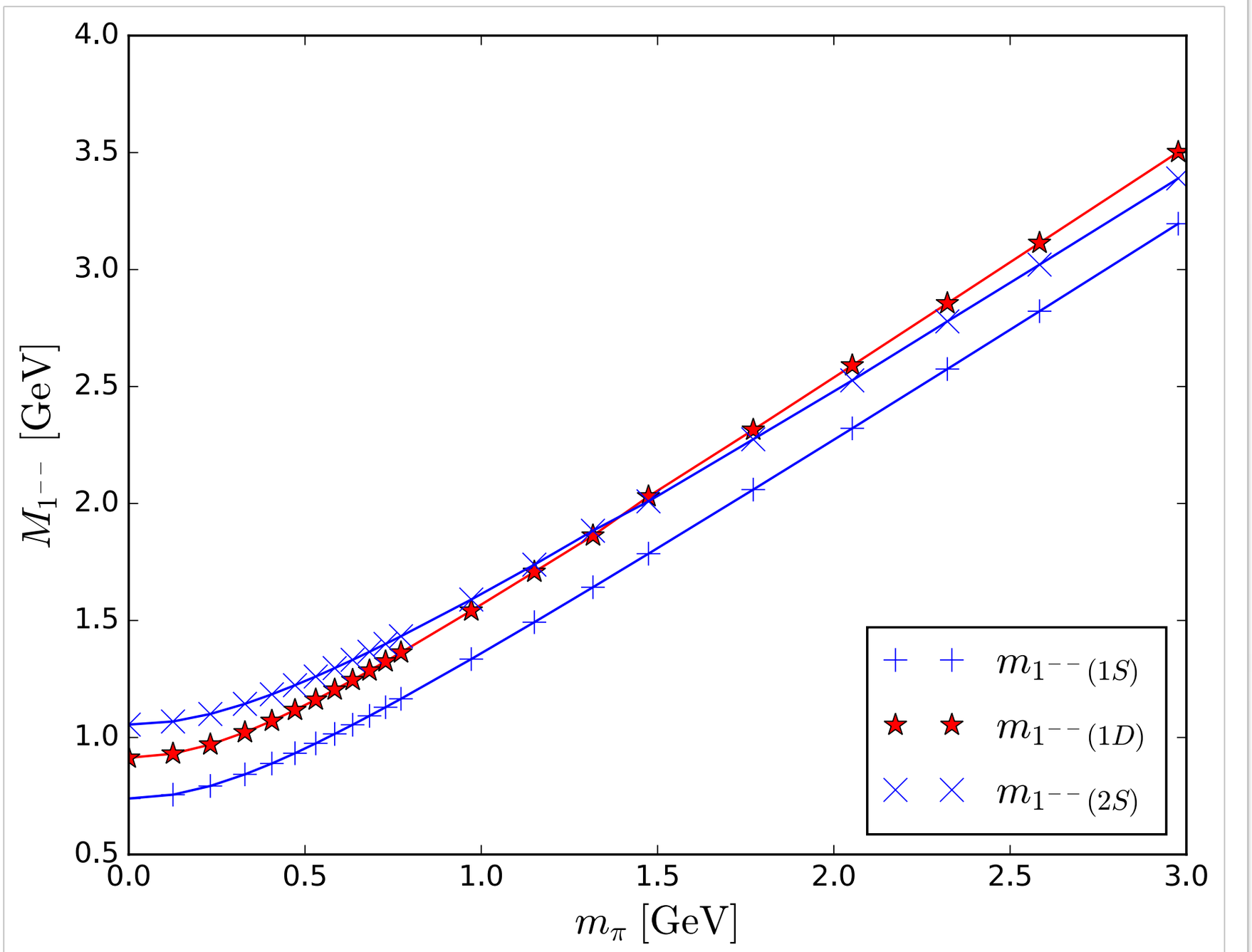
OAMD: a function of m_q



OAMD in 1^{--} channel for excitations

Roles of S and D waves change among first and second excited states



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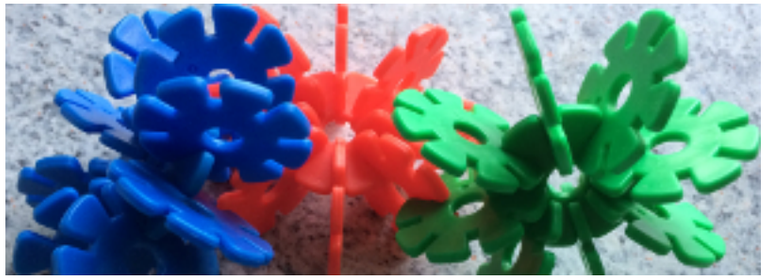
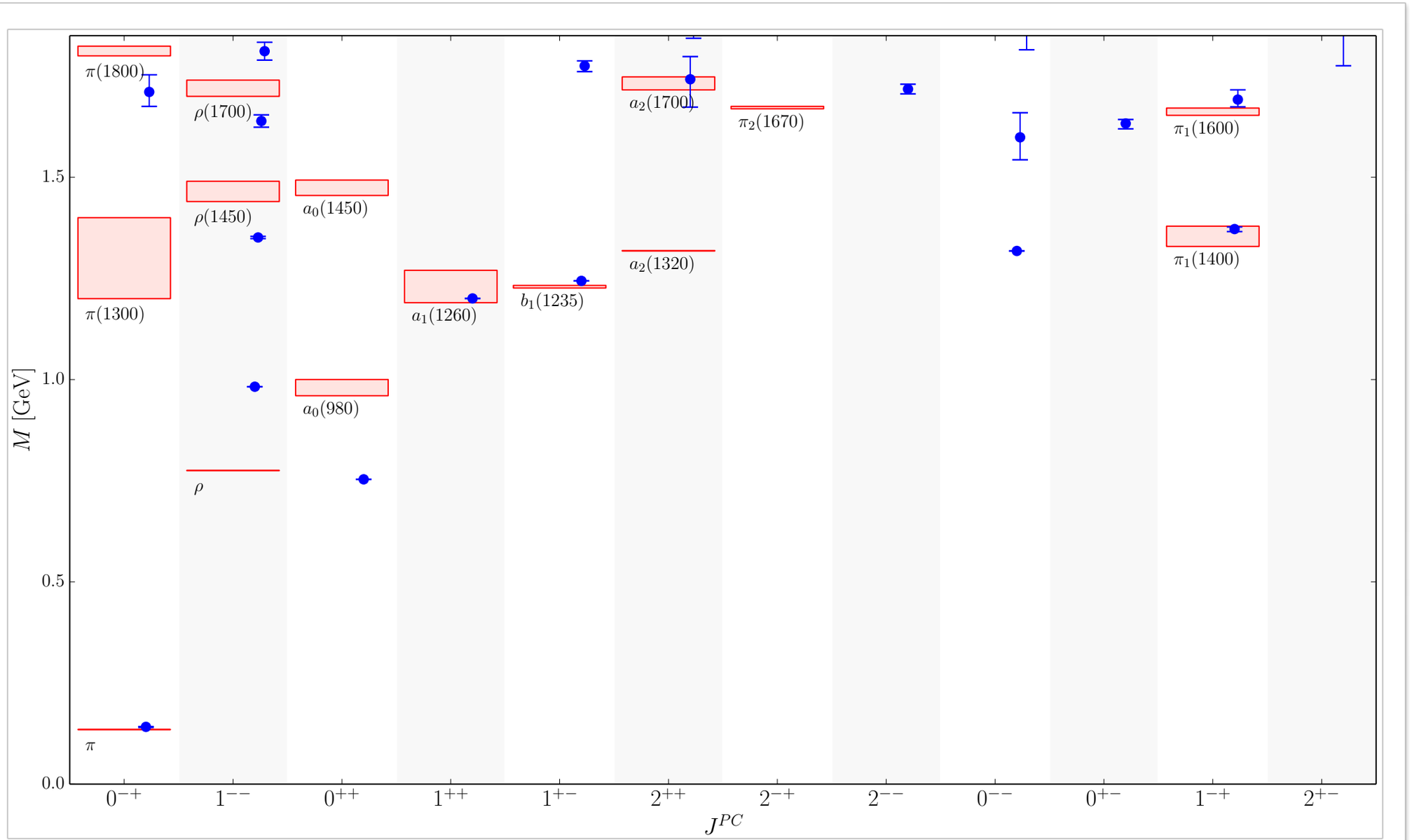


For the record:
Exotic quantum numbers

No Problemo in DSBSE approach. Examples: π_1



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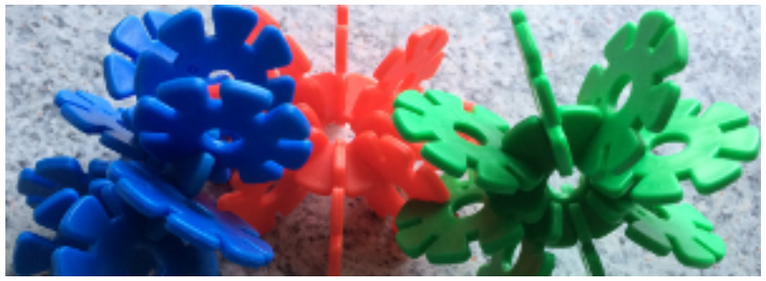
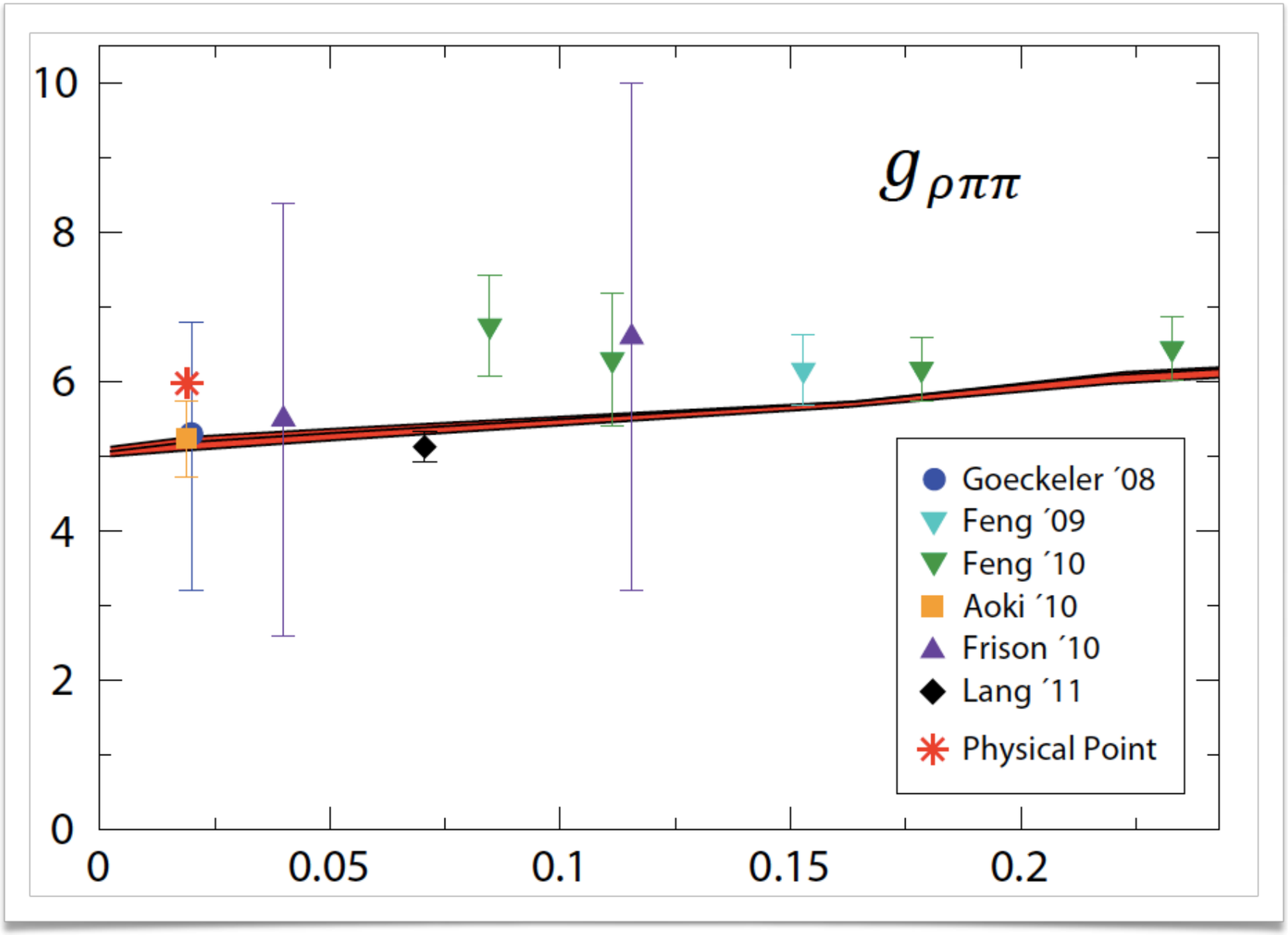


Hadronic Decays Examples

- Hadronic decay
- $\rho \longrightarrow \pi\pi$
- Compare:
  - ✳ Experiment
  - ✳ Lattice QCD
- Analogously for baryon case

  $\Delta \rightarrow N\pi$



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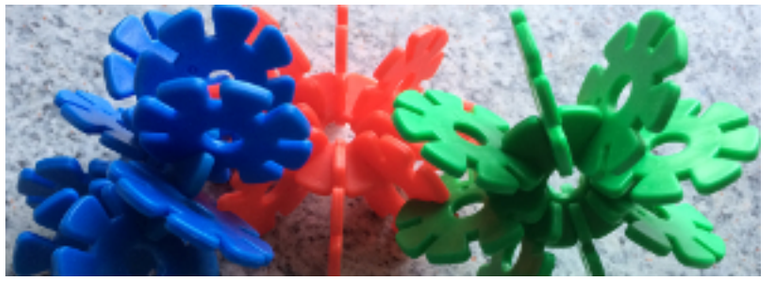

Summary

- We must/should/try to:
  - work around it or solve QCD, but that's hard
  - various fundamental approaches to the problem
  - attack hadron spectroscopy
  - don't forget: hadrons are resonances (of various kinds)
  - think beyond masses and widths
- Many speakers here cover such approaches
  - ask them about their approaches' details
- Many interesting open questions …

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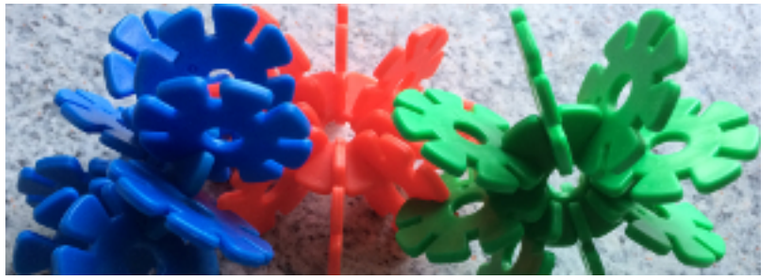

Thank you very much for your attention!

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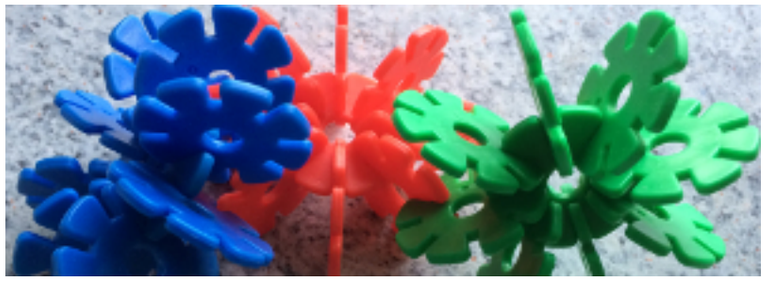
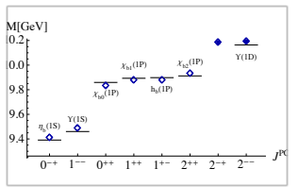
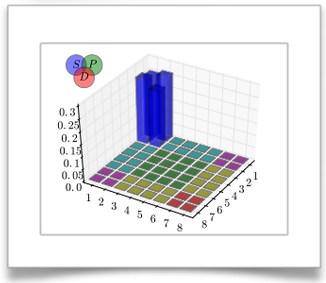
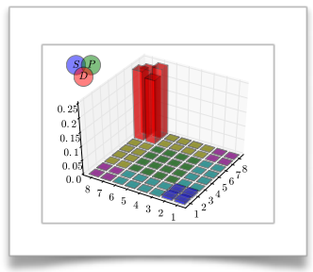


Reminder

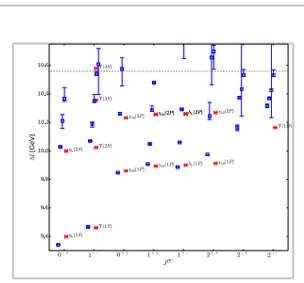


M. Blank, A.K., PRD 84 (2011) 096014





T. Hilger, M. Gomez-Rocha, A.K., arXiv:1508.07183



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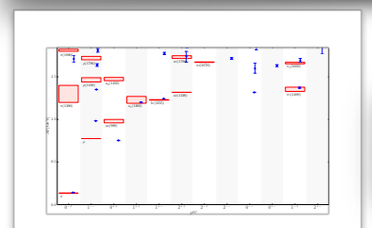

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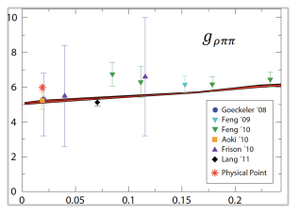

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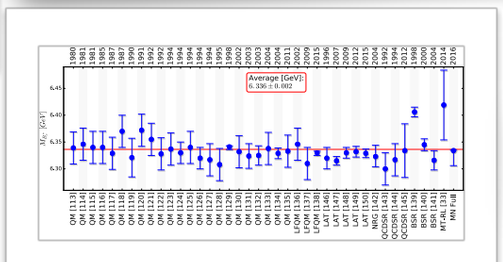
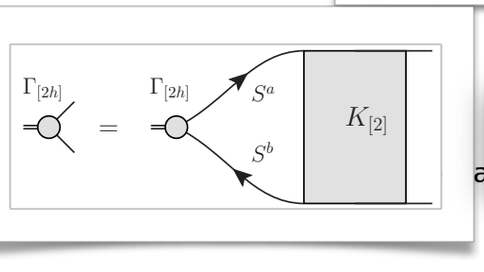


M. Gomez-Rocha, T. Hilger, A.K., PRD 93 (2016) 074010



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