Light and strange baryon spectrum from functional methods

Christian S. Fischer

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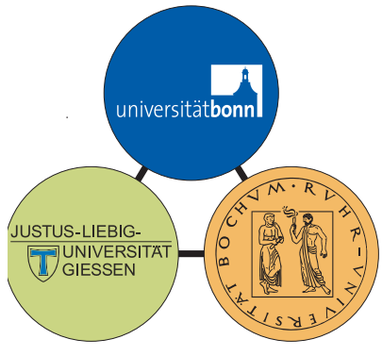
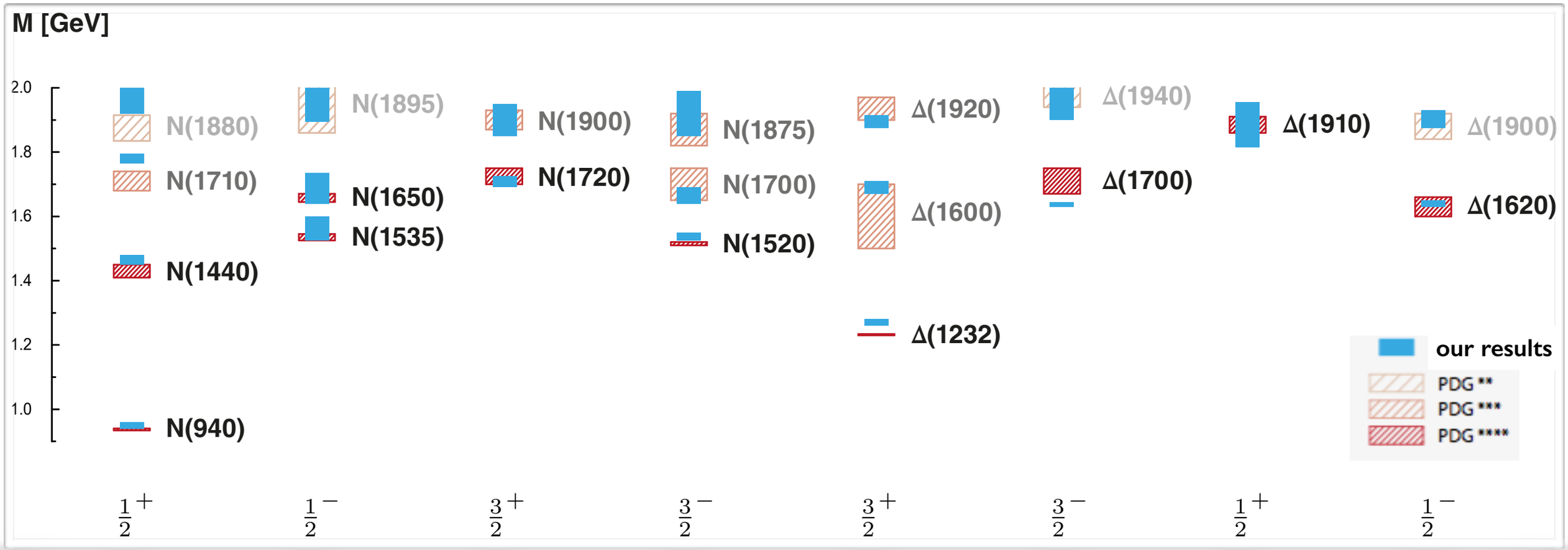
Review: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]



Overview - Take home messages

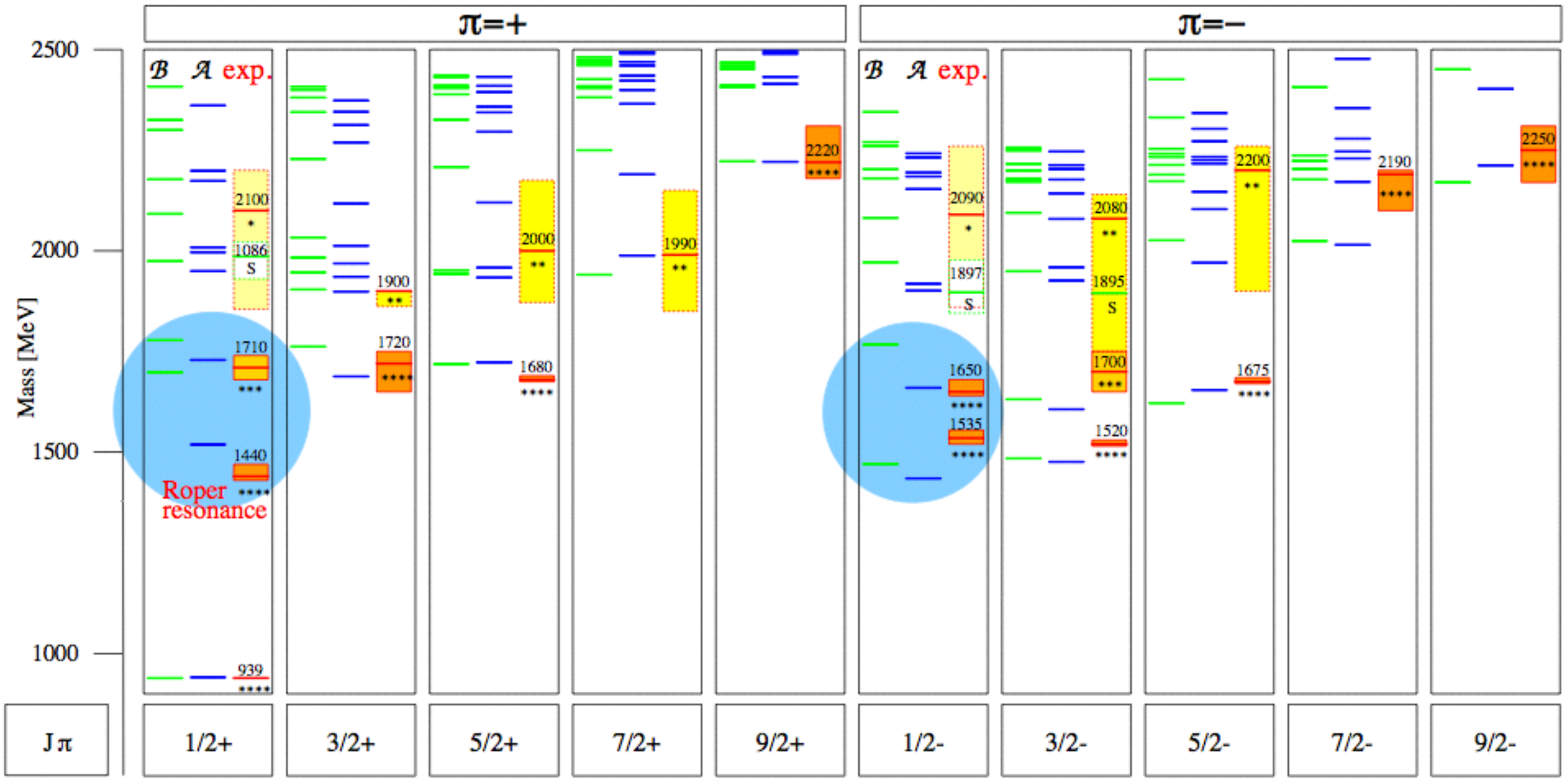
Light baryon spectrum



Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]

- relativistic effects are mandatory
- two body forces dominant inside baryons

Light baryon spectrum - quark model



Loring, Metsch, Petry, EPJA 10 (2001) 395

- 'missing resonances': three-body vs. quark-diquark
- level ordering: $N_{\frac{1}{2}+}$ vs. $N_{\frac{1}{2}-}$

Baryon spectroscopy from QCD

- Underlying QCD forces
  - two-body vs. three-body → Δ vs Y - configuration
  - confinement → Regge trajectories ?!
  - spin structure → (Hyper)-Fine structure
  - meson cloud effects → GB-exchange vs QCD
  - heavy/heavy-light systems → Flavor dependence
- 'Missing resonances' → 3-quark vs. quark-diquark
- Coupled-channel effects

Strategies to deal with this situation:

Nonperturbative QCD: Lattice, Functional methods

Effective theories with hadronic dof

Klemt, Richard, Rev.Mod.Phys. 82 (2010) 1095

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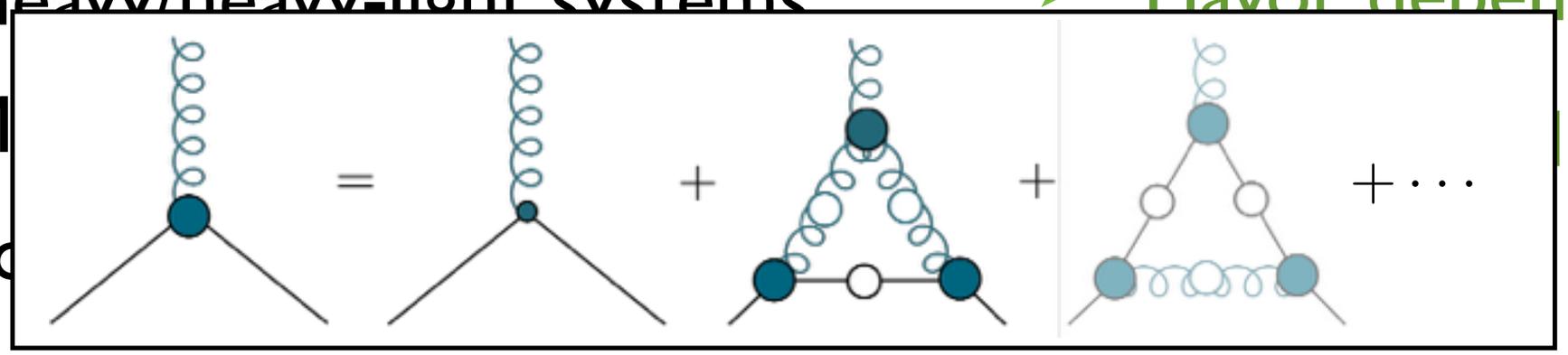

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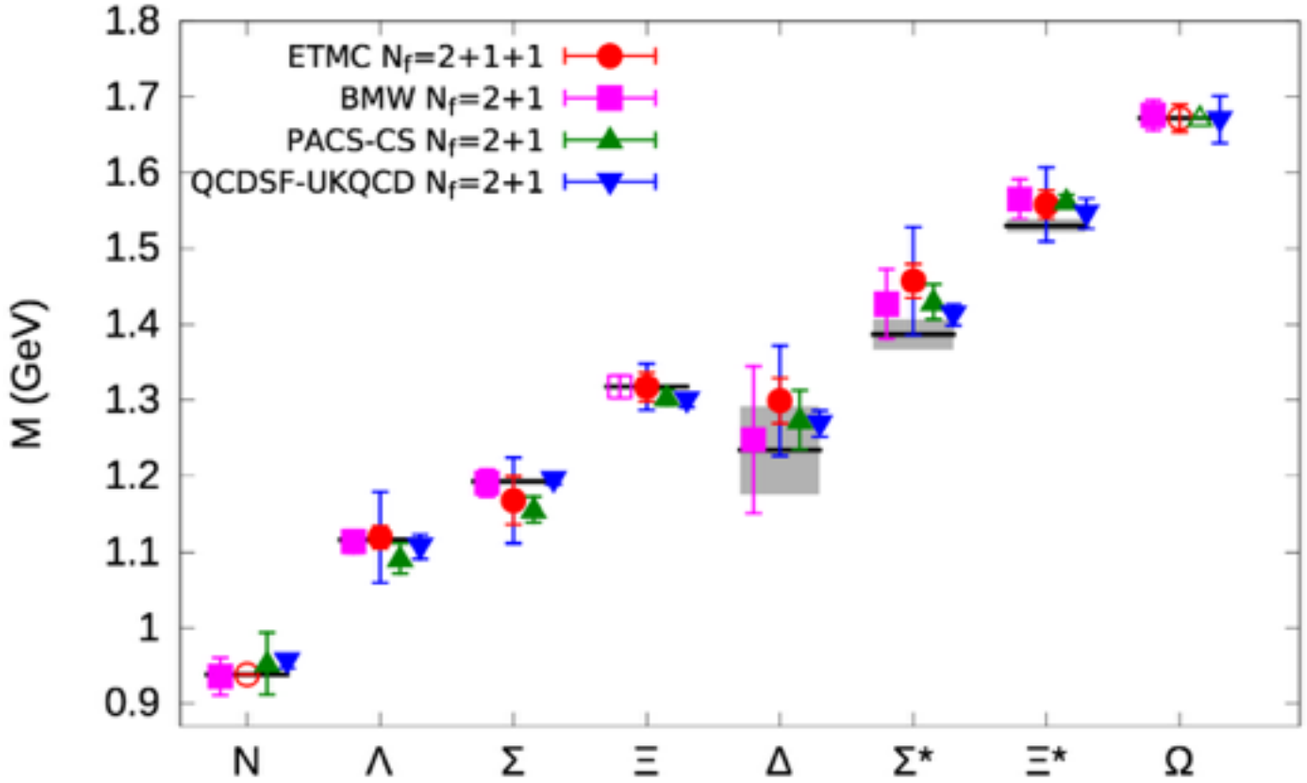
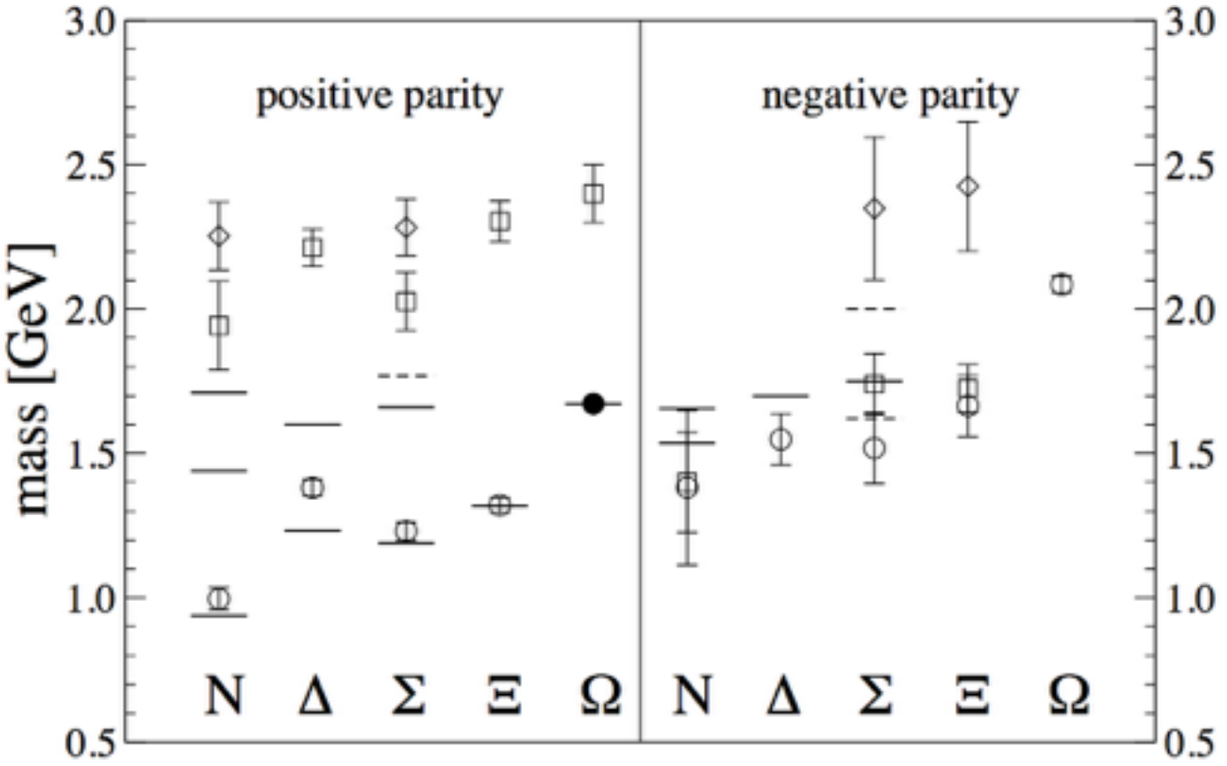
Klemt, Richard, Rev.Mod.Phys. 82 (2010) 1095

Lattice QCD



Alexandrou et al. (ETMC), PRD 90 (2014) 7

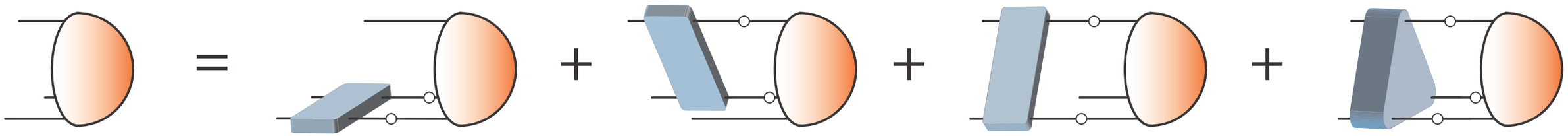


Engel et al. (BGR), PRD82 (2010) 034505

- baryon ground states well under control
- baryon excited states: very tough problem

Three-body vs. Diquark-quark approximation

Bethe-Salpeter equation for baryons:



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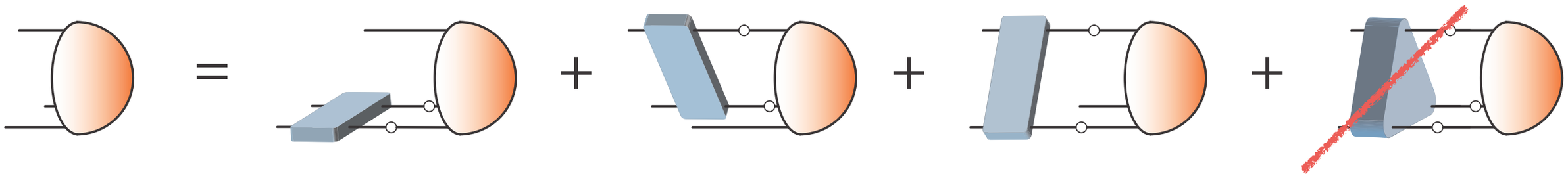

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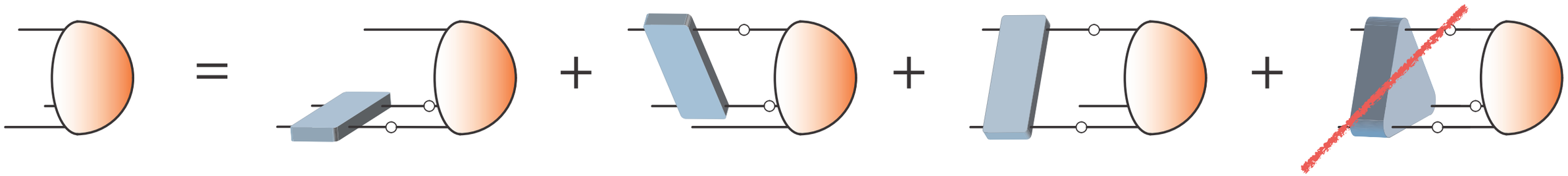
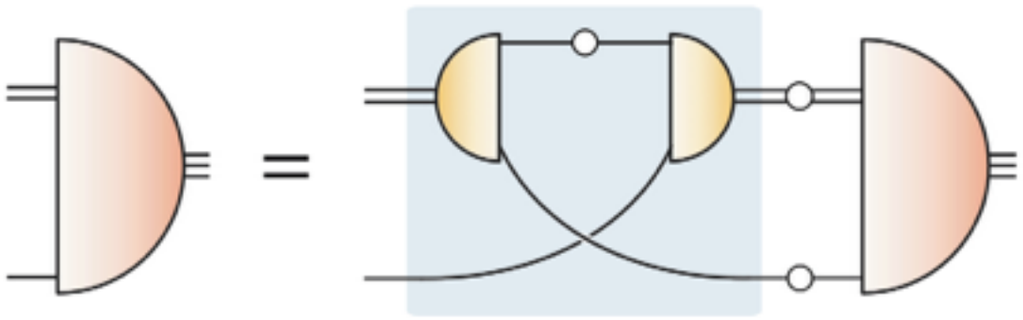
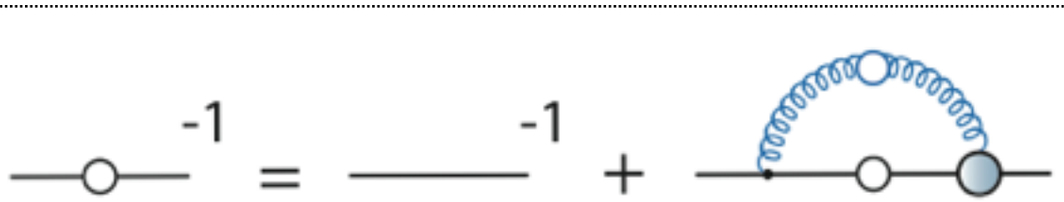
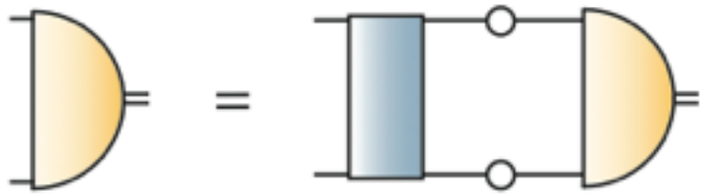


Diquark-quark approximation:







- Input: quark-gluon interaction
- Diquarks are NOT point like

Quantum numbers: non-relativistic vs relativistic

non-relativistic $q\bar{q}$

S	L	J^{PC}
0	0	0^{-+}
1	0	1^{--}
0	1	1^{+-}

$$P : (-1)^{L+1}$$

relativistic $q\bar{q}$

$$\Gamma_\pi(P,p) = \gamma_5 \left[F_1(P,p) \right. \qquad \text{s-wave}$$
$$+ F_2(P,p) i\not{P}$$
$$+ F_3(P,p) pP i\not{p} \qquad \text{p-wave}$$
$$\left. + F_4(P,p)[\not{p}, \not{P}]\right]$$

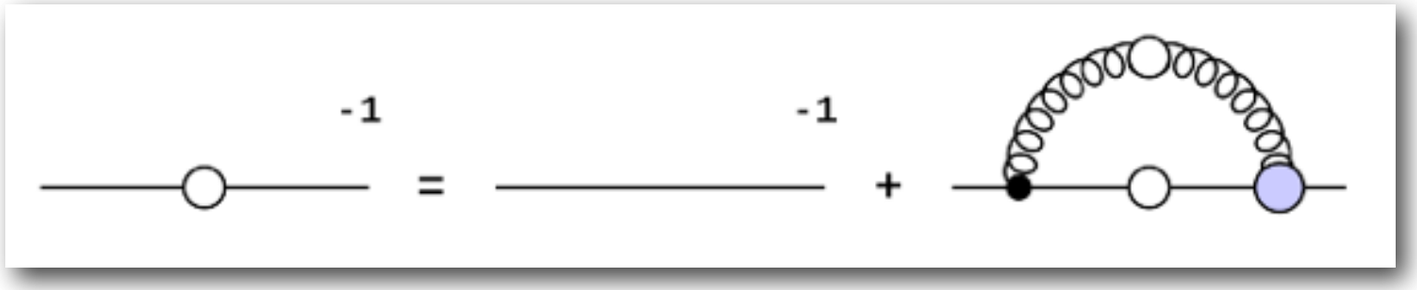
(rest frame of π)

$$P : (-1)^{L+1}$$

Bethe,Salpeter, Llewelyn-Smith 1950ies

- baryon states more complicated
  - octet: 64 tensors with s,p,d wave
  - decuplet: 128 tensors with s,pd,f wave
- mesons: 'exotic' quantum numbers possible: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \ldots$

The DSE for the quark propagator



Approximations:

I) NJL/contact model:

II) Quark-diquark model: *ansatz for quark (and diquark wave function)*

III) Rainbow-ladder (RL):

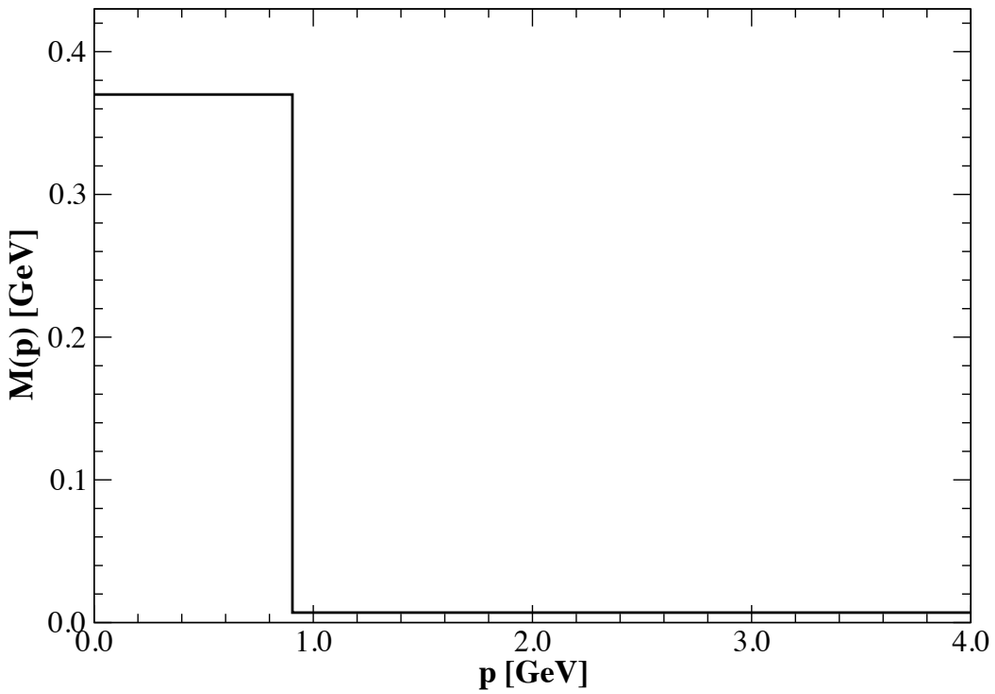
IV) Beyond rainbow-ladder (bRL): *solve DSEs for quark, gluon, vertex*

Sanchis-Alepuz, Williams, PLB 749 (2015) 592
Williams, CF, Heupel, PRD93 (2016) 034026, and refs. therein
Binosi, Chang, Papavassiliou, Qin, Roberts PRD95 (2017) 031501 and refs. therein

Quark mass

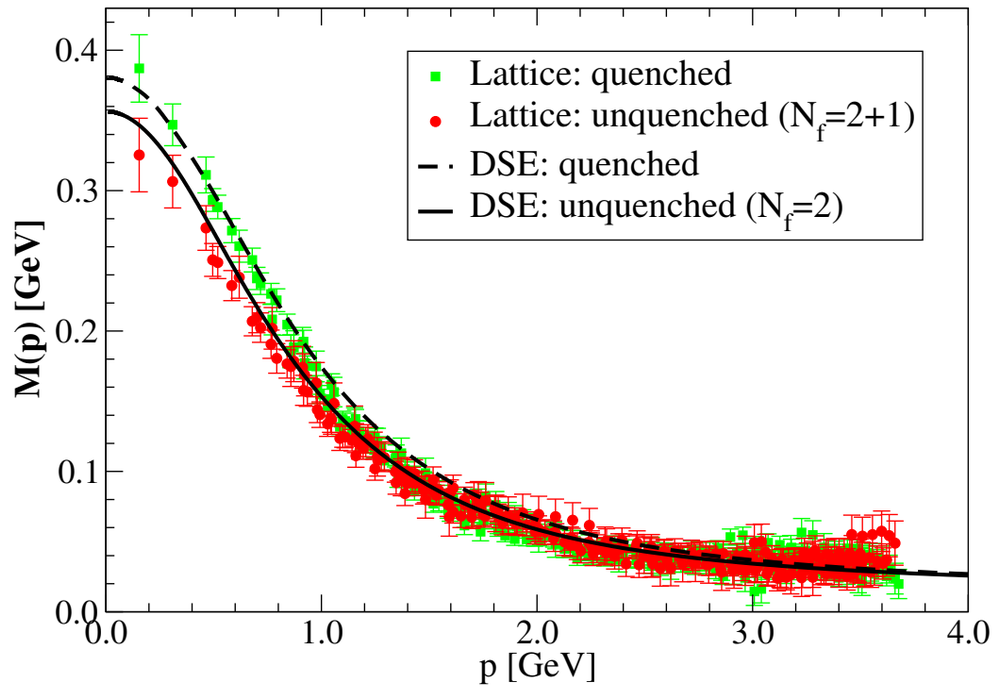
$$[S(p)]^{-1} = [-i\not{p} + M(p^2)]/Z_f(p^2)$$

NJL/contact model



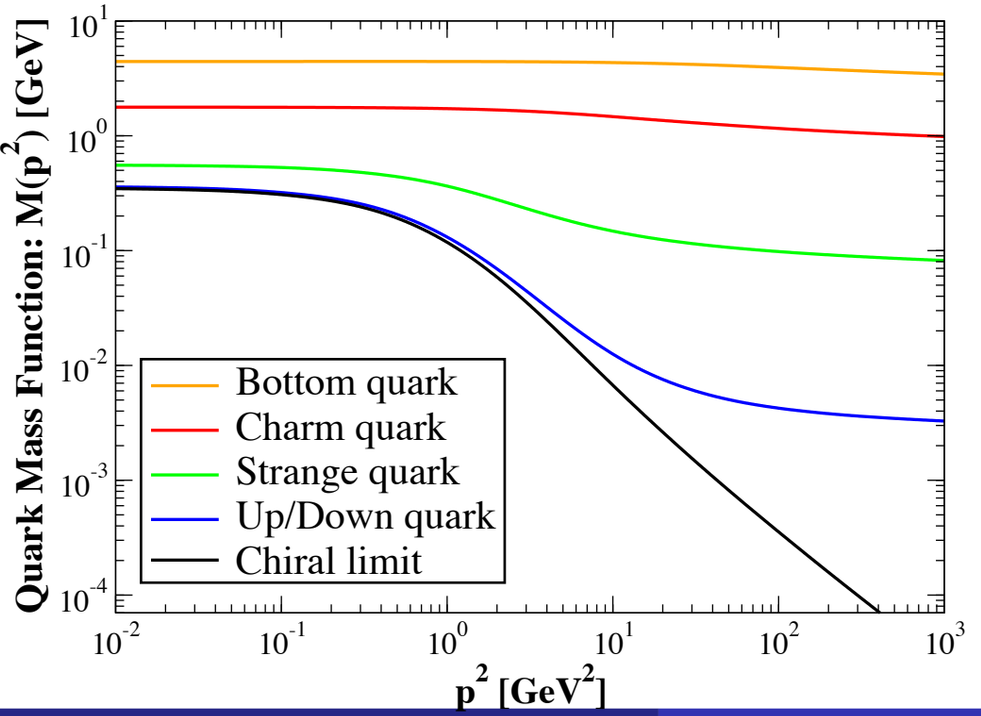
Lu, Chen, Roberts et al., PRC 96 (2017) 015208

DSE (RL/bRL)



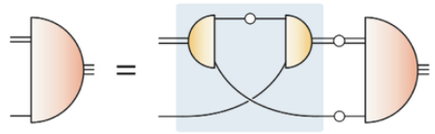
DSE: CF, Nickel, Williams, EPJ C 60 (2009) 47
Lattice: P. O. Bowman, et al PRD 71 (2005) 054507

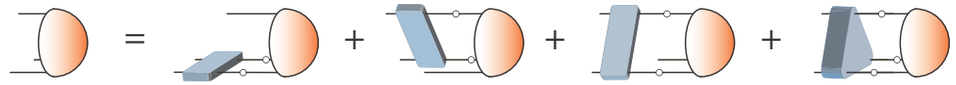
- Quark mass dynamically generated
- running important for wave functions, FFs etc.



DSE/BSE/Faddeev landscape (2015)

level of sophistication





	I) NJL/contact interaction	II) Quark-diquark model	III) DSE (RL)	III) DSE (RL)	IV) DSE (bRL)
N, Δ masses	✓	✓	✓	✓	✓
N, Δ em. FFs	✓	✓	✓	✓	
$N \to \Delta\gamma$	✓	✓	✓		
Roper,...	✓	✓			
$N \to N^*\gamma$	✓	✓			
$N^*(1535), \ldots$		✓			
$N \to N^*\gamma$					
Σ, Ξ, Ω excited strange		✓			
Σ, Ξ, Ω em. FFs					
	Cloet, Thomas, Roberts, Segovia et al.	Oettel, Alkofer, Roberts, Bloch, Segovia et al.	Eichmann, Alkofer, Krassnigg, Nicmorus, Sanchis-Alepuz, CF	Eichmann, Alkofer, Sanchis-Alepuz, CF	Sanchis-Alepuz, Williams, CF

Eichmann, N*-Workshop, Trento 2015

DSE/BSE/Faddeev landscape

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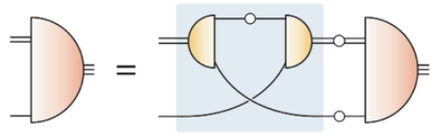

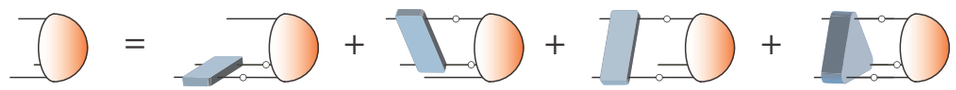

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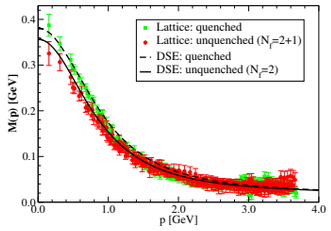
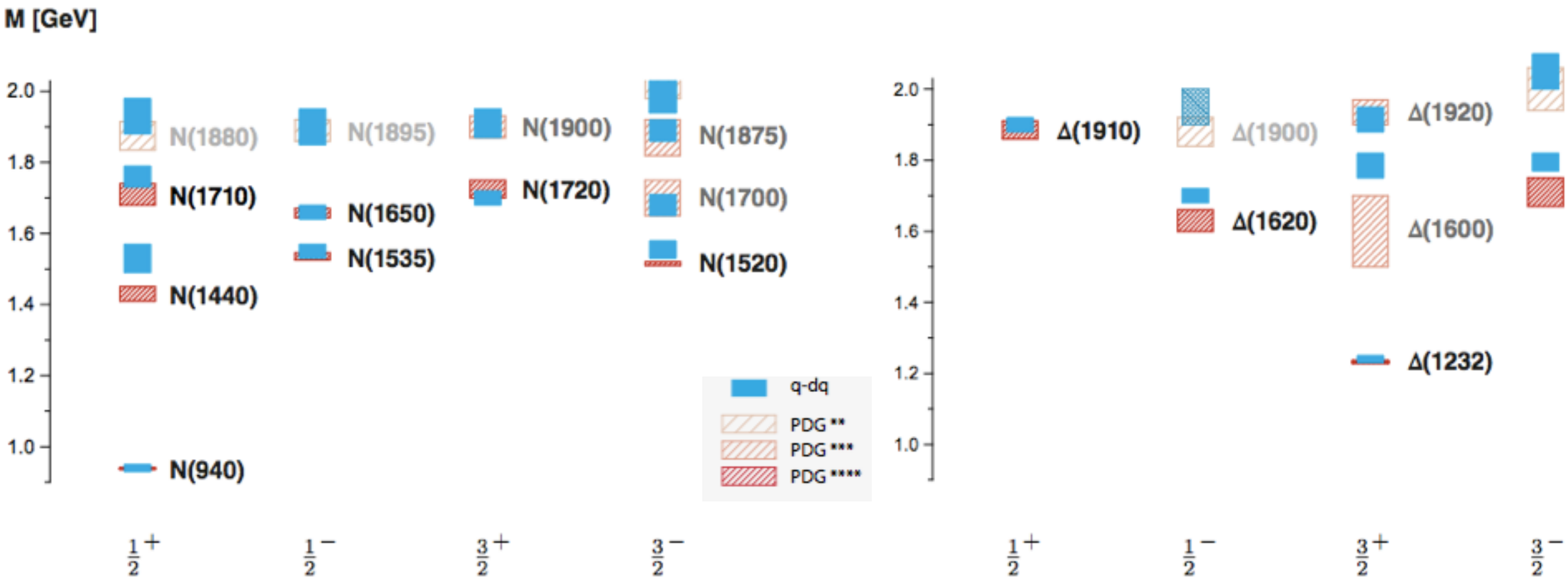
Light baryon spectrum: DSE-RL





sc+av ps+v

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, in preparation

- spectrum in one to one agreement with experiment
- correct level ordering (without coupled channel effects…)

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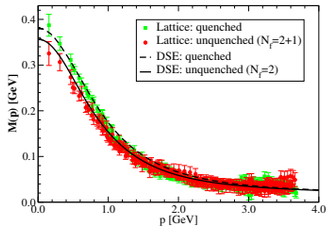

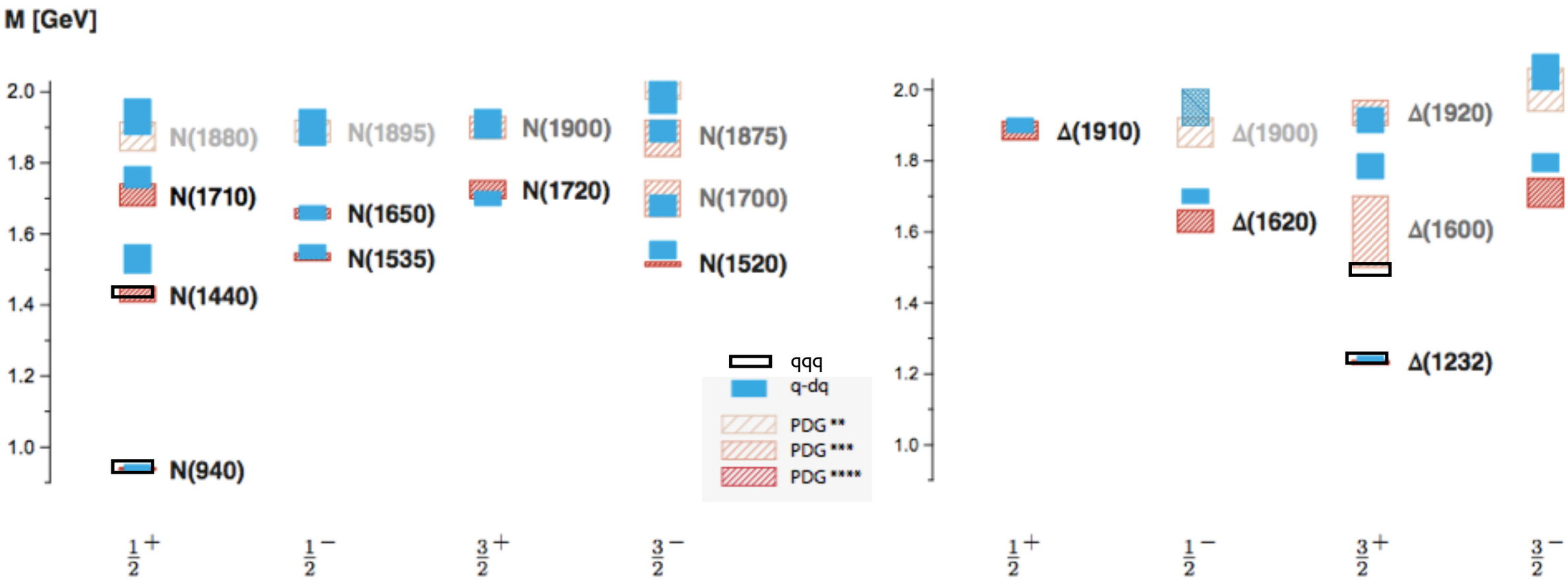

sc+av ps+v

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Eichmann, CF, in preparation

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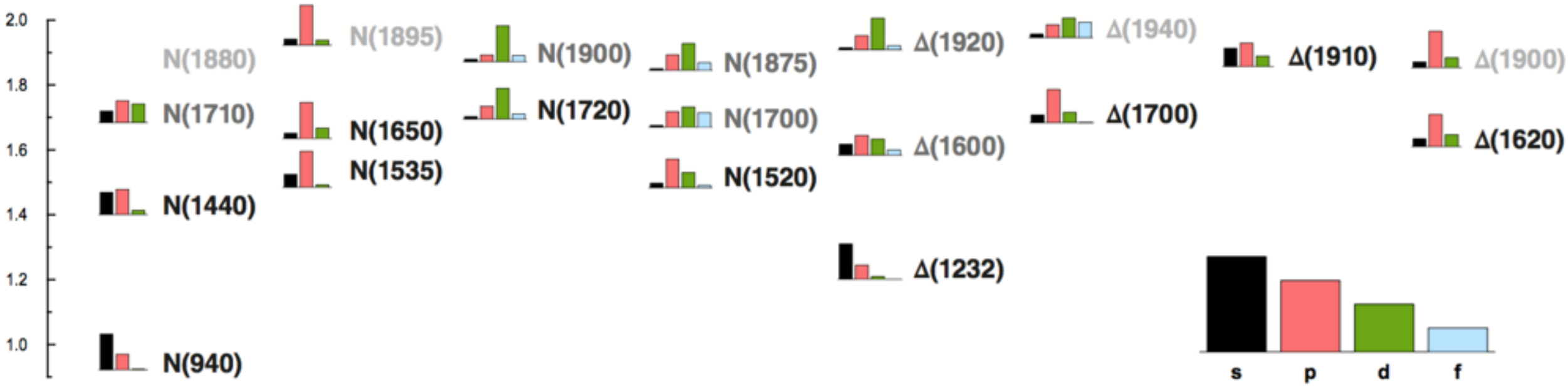
- correct level ordering (without coupled channel effects…)
- three-body agrees with diquark-quark where applicable

Angular momentum



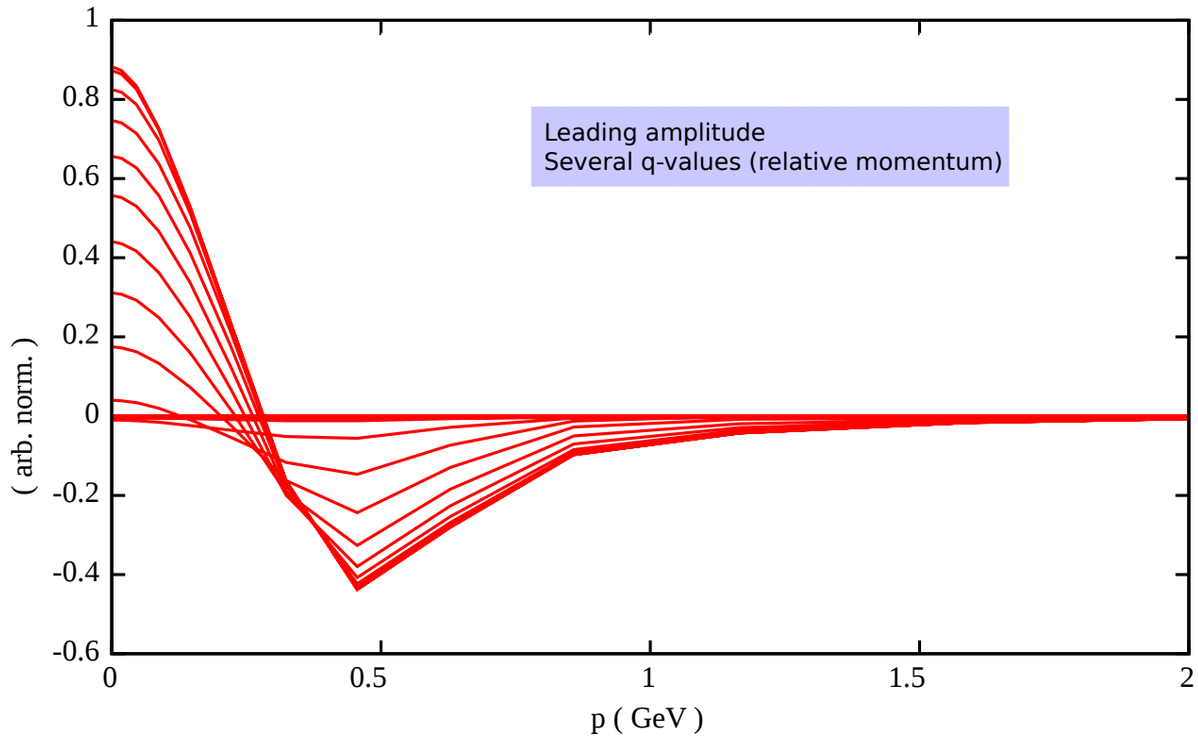
$$J^P = \tfrac{1}{2}^+ \quad \tfrac{1}{2}^- \quad \tfrac{3}{2}^+ \quad \tfrac{3}{2}^- \quad \tfrac{3}{2}^+ \quad \tfrac{3}{2}^- \quad \tfrac{1}{2}^+ \quad \tfrac{1}{2}^-$$

- non-relativistic quark model: restriction to certain ang. mom.
- here: quark-model forbidden contributions always present

Properties of the Roper

angular mom. decomposition

%	N	$N^*(1440)$	Δ	$\Delta^*(1600)$
s wave	66	15	56	10
p wave	33	61	40	33
d wave	1	24	3	41
f wave	–	–	< 0.5	16

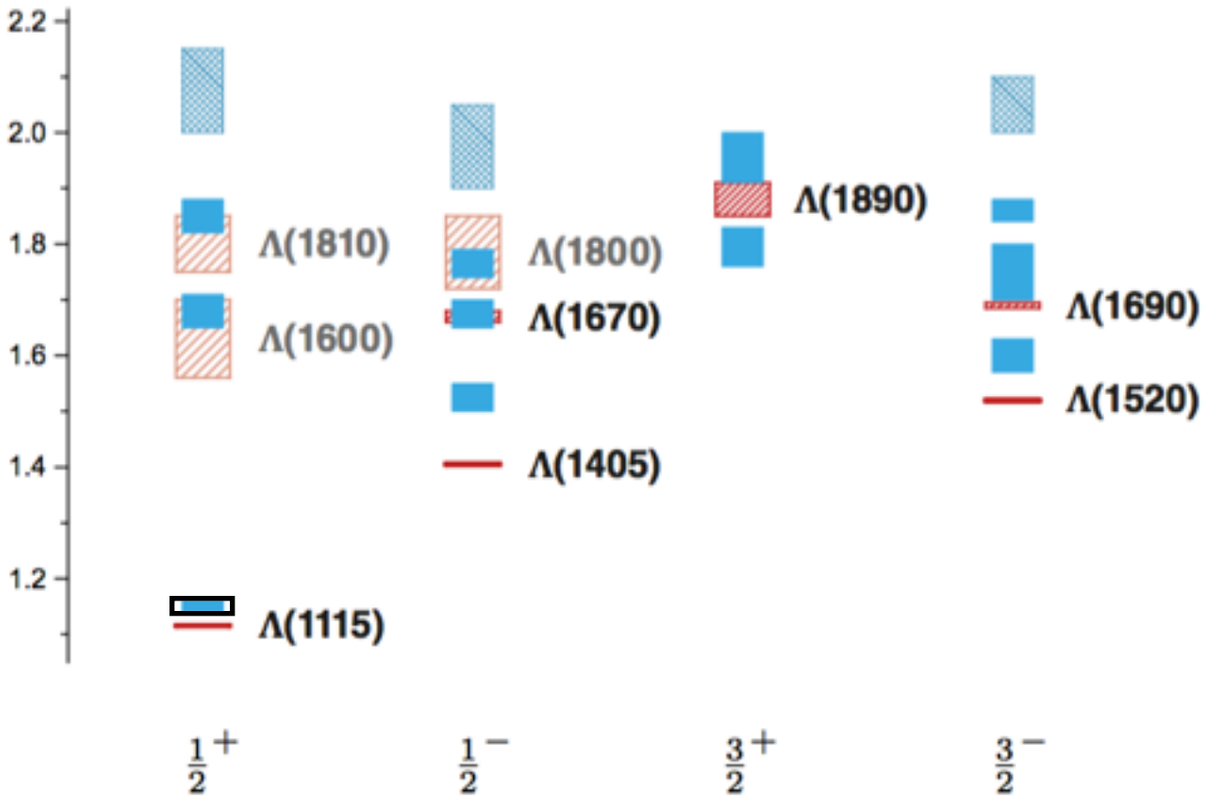


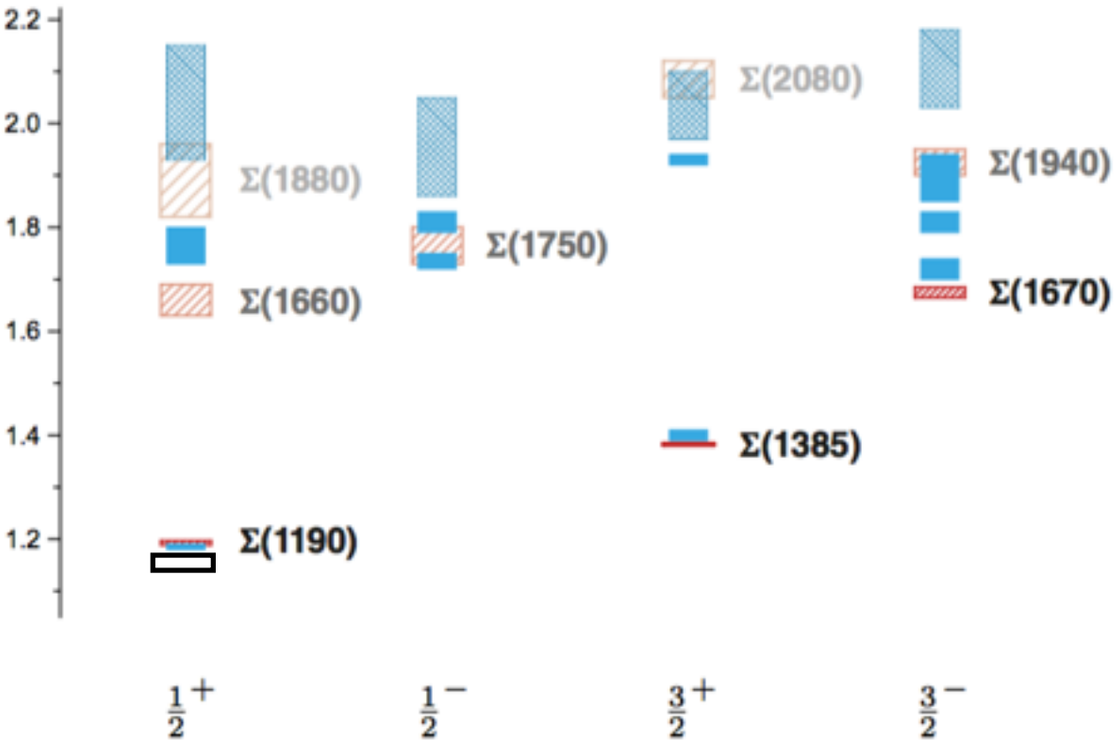
Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016)

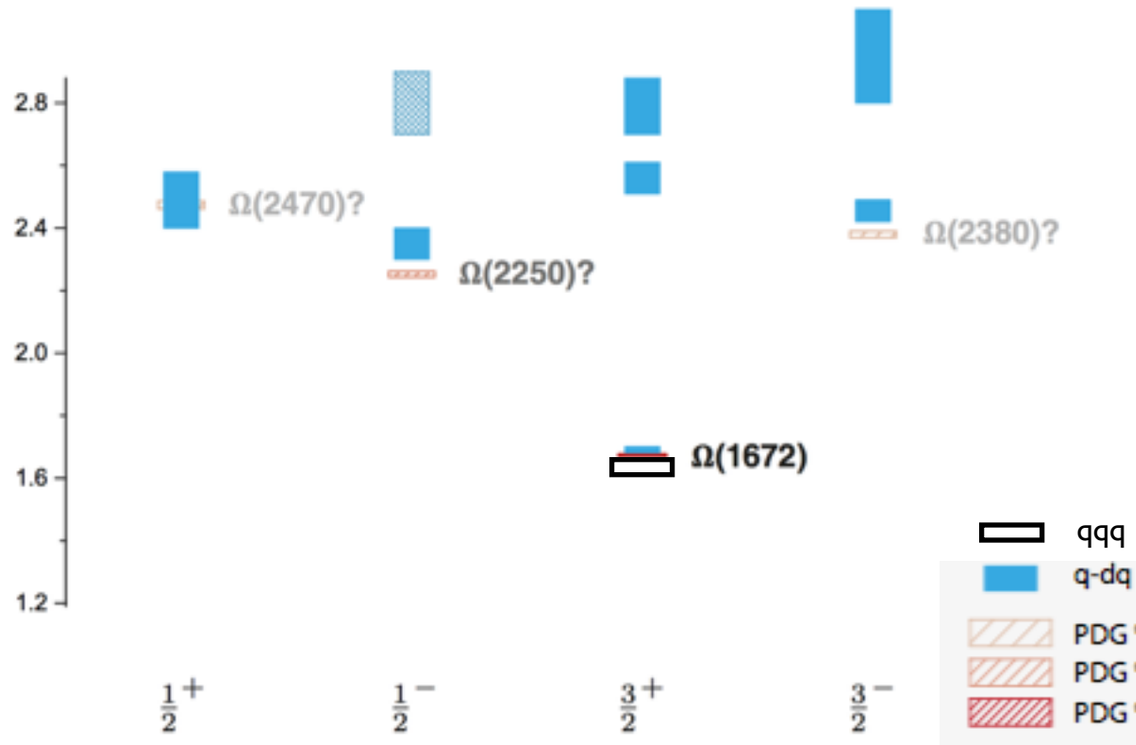
- zero crossing of wave function: 2s-state
- every state is mixture of several partial waves !
- different internal structure of radial excitations

tension with simpler calculations ('contact interaction', 'QCD based model'):
Wilson, Cloet, Chang and Roberts, PRC 85 (2012) 025205,
Segovia, El-Bennich, Rojas, Cloet, Roberts, Xu and Zong, PRL 115 (2015) 17
Lu, Chen, Roberts et al., PRC 96 (2017) 015208

Strange baryon spectrum: DSE-RL (preliminary !)







Eichmann, CF, in preparation
Sanchis-Alepuz, CF, PRD 90 (2014) 096001

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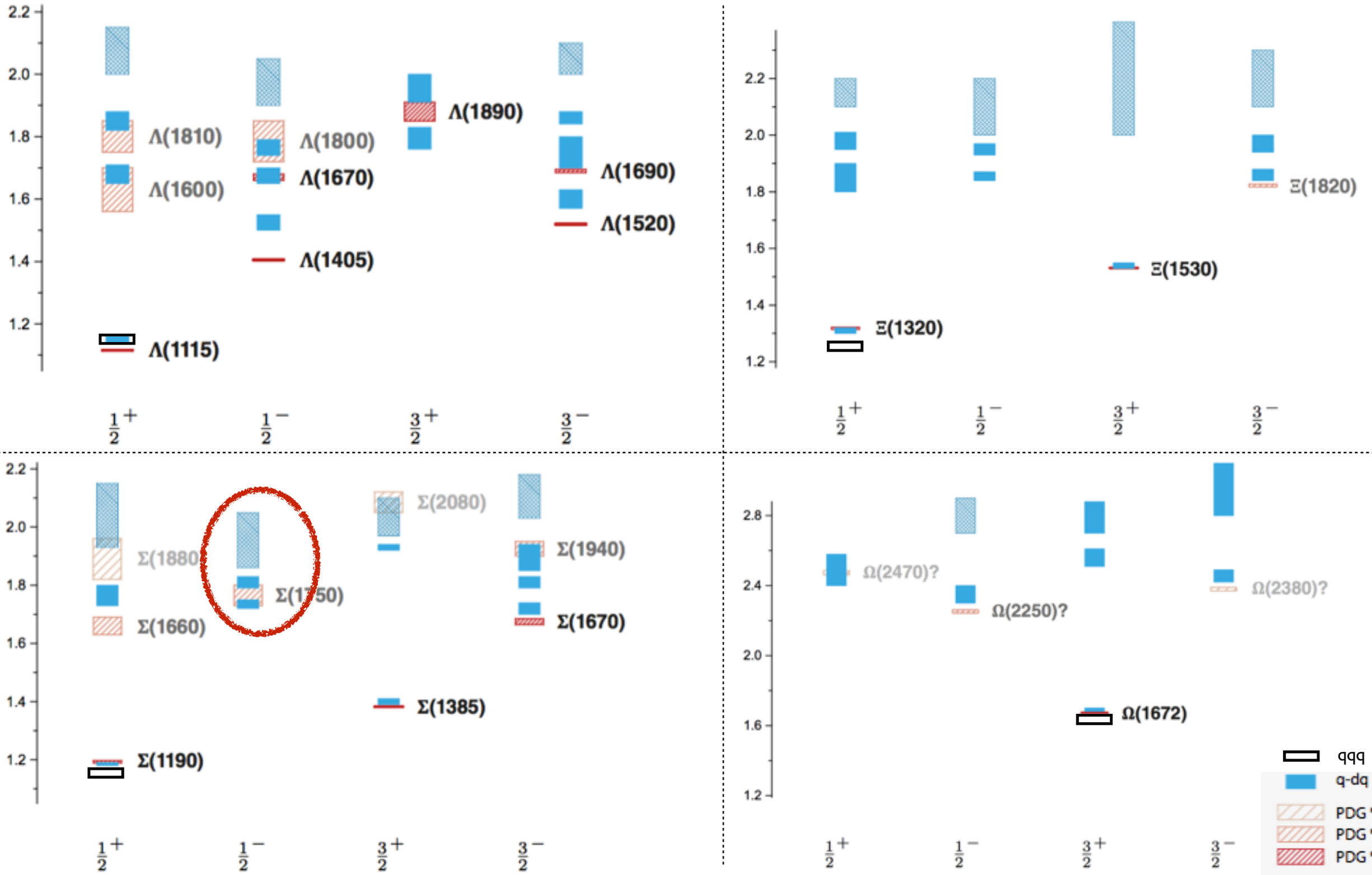

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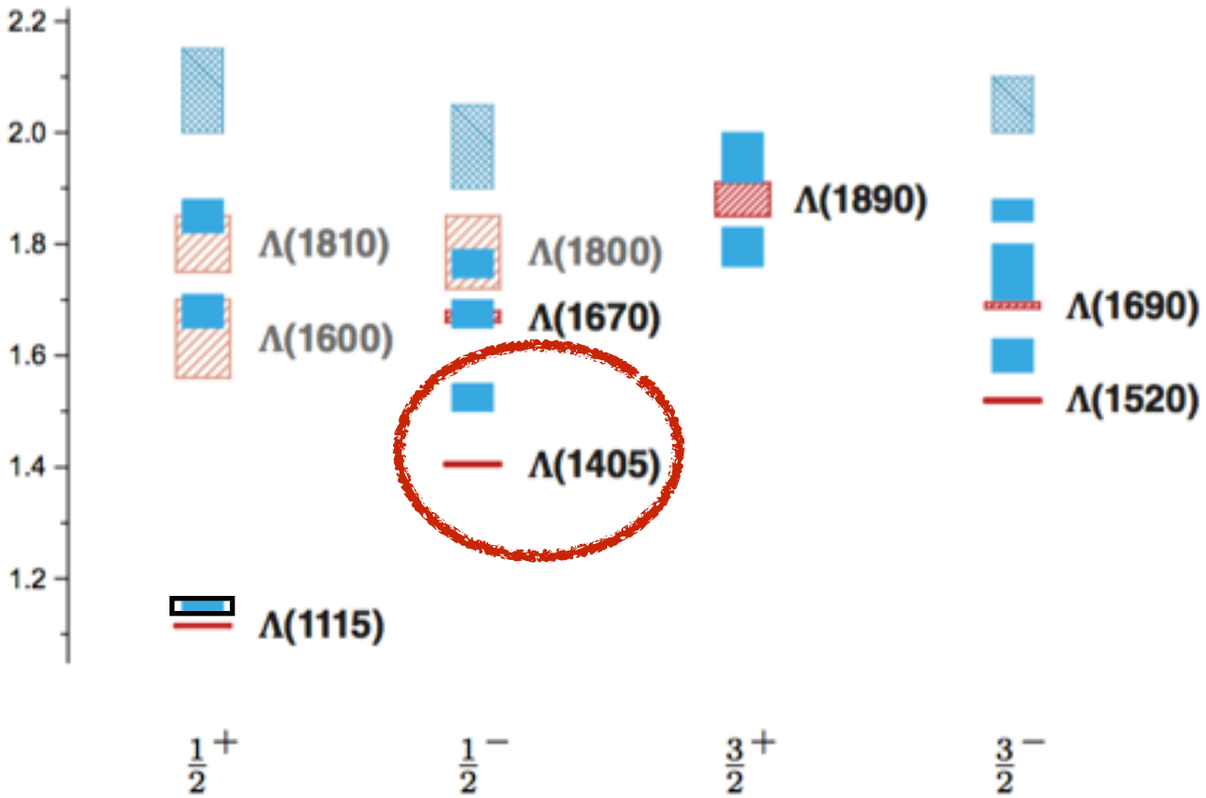
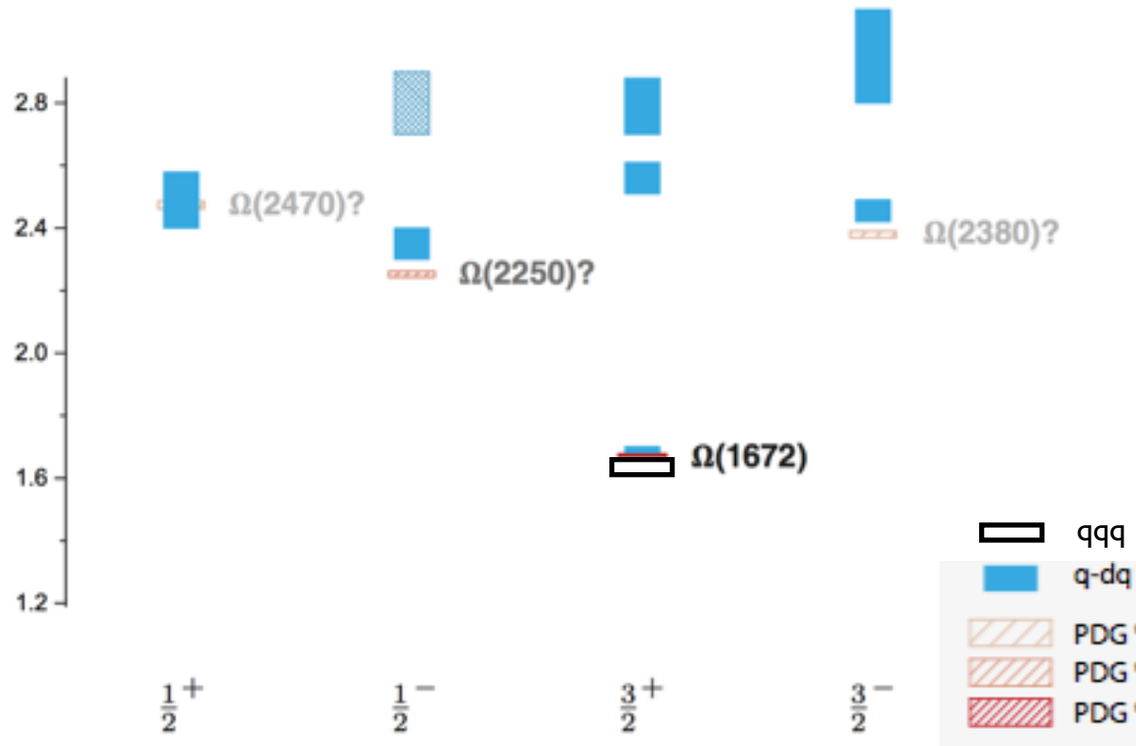




Eichmann, CF, in preparation
Sanchis-Alepuz, CF, PRD 90 (2014) 096001

Summary and outlook

Summary

- Baryon spectrum: good agreement with experiment!
- Three-body vs diquark-quark: fair agreement
- ‘forbidden’ angular momenta always present
- prediction for strange baryons

Further results:

- Baryons: form factors

Review: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

- Tetraquarks: light scalar nonet done
  explore heavy-light systems

Heupel, Eichmann, CF, PLB 718 (2012) 545-549
Eichmann, CF, Heupel, PLB 753 (2016) 282-287

- Glueballs: $M(0^{++}) = 1.64\ \mathrm{GeV}$

Sanchis-Alepuz, CF, Kellermann and von Smekal, PRD 92 (2015) 3, 034001
(see also Meyers, Swanson, PRD 87 (2013) 3, 036009)

Backup

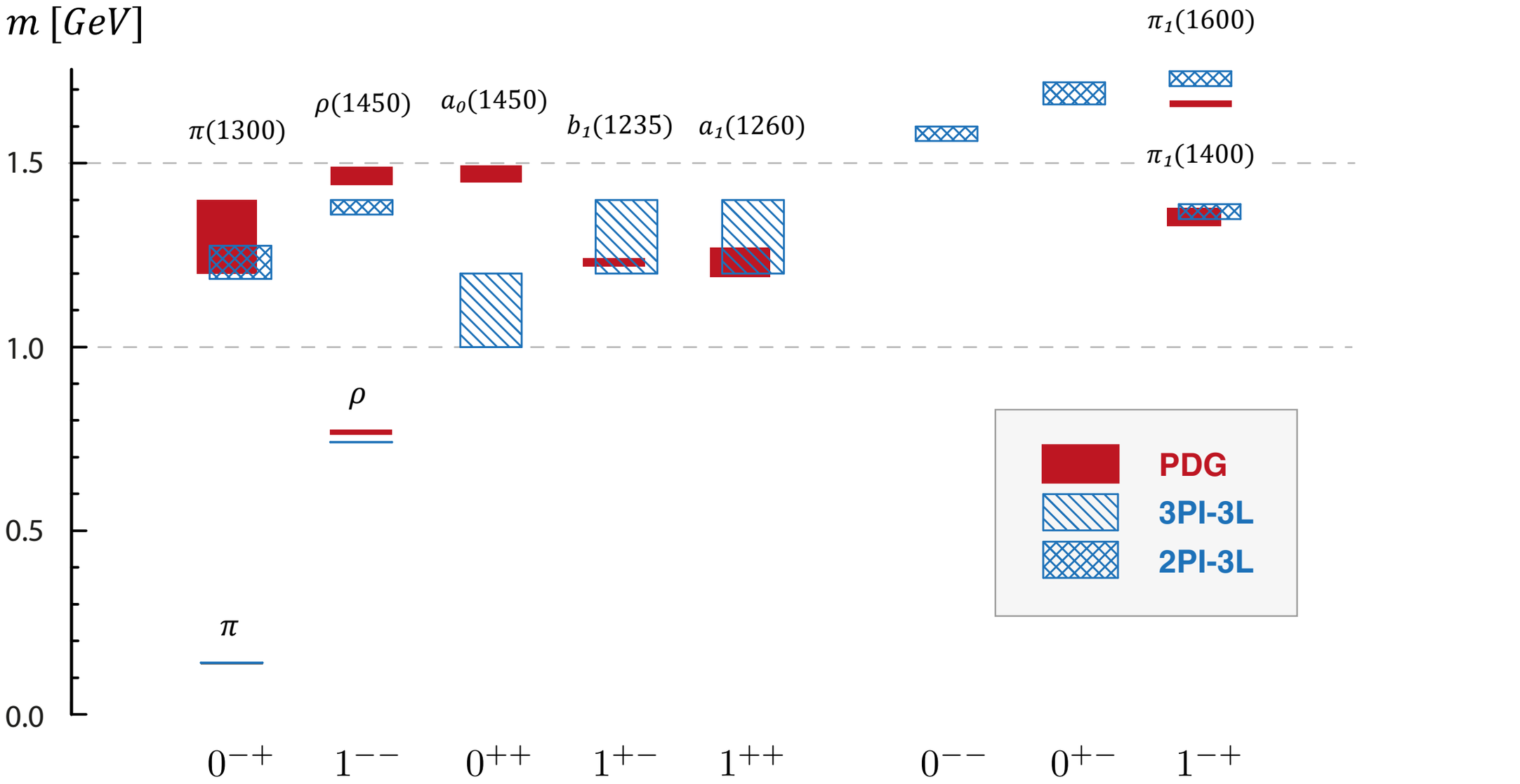
Light meson spectrum (bRL)

CF, Kubrak, Williams, EPJA 50 (2014) 126

Williams, CF, Heupel, PRD93 (2016) 034026

- nice agreement with experiment (up to scalar)
- exotics as relativistic quark-antiquark states
- drastic improvement beyond rainbow-ladder !

Light meson spectrum (bRL)



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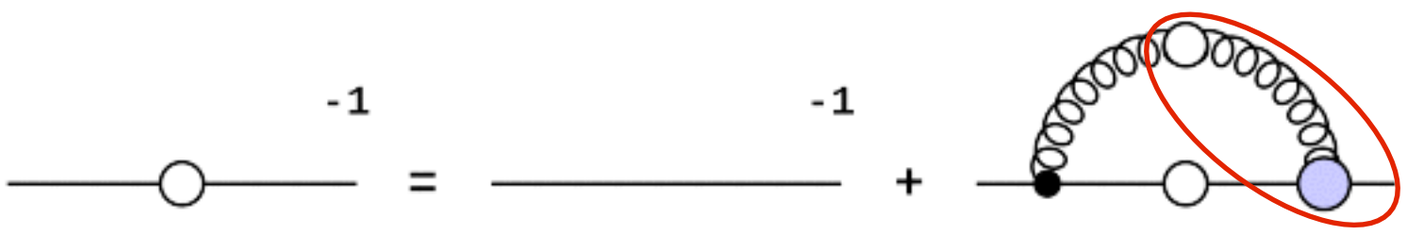
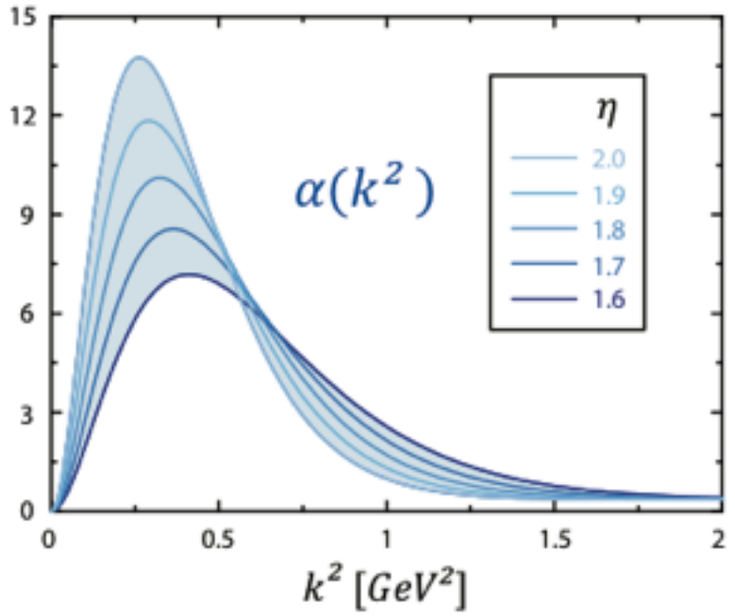
Rainbow-ladder model for quark-gluon interaction





Maris, Roberts, Tandy, PRC 56 (1997), PRC 60 (1999)

Combine gluon with quark-gluon vertex:

effective coupling

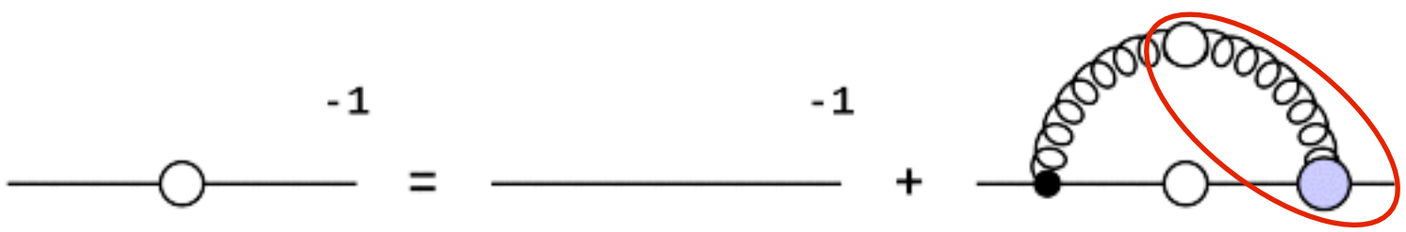
$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

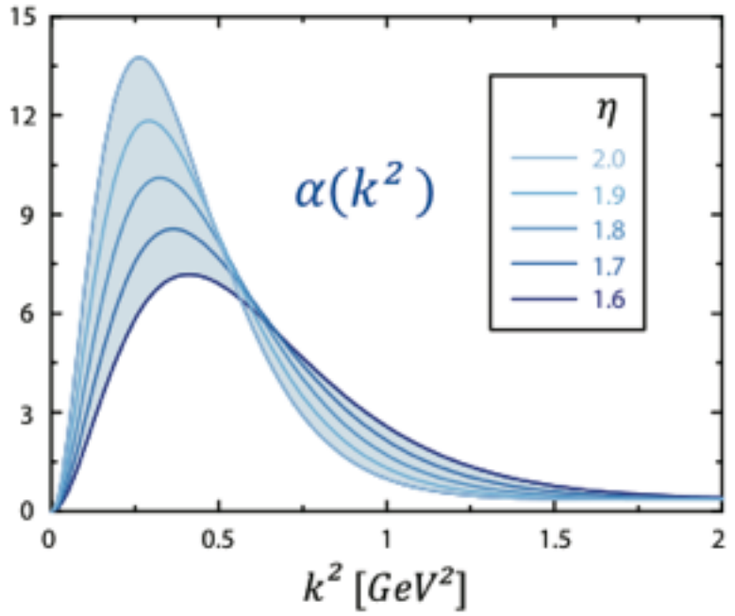
- scale Λ from f_π, masses m_u=m_d, m_s from m_π, m_K
- α_{UV} from perturbation theory
- parameter η : band of results

Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

Rainbow-ladder model for quark-gluon interaction





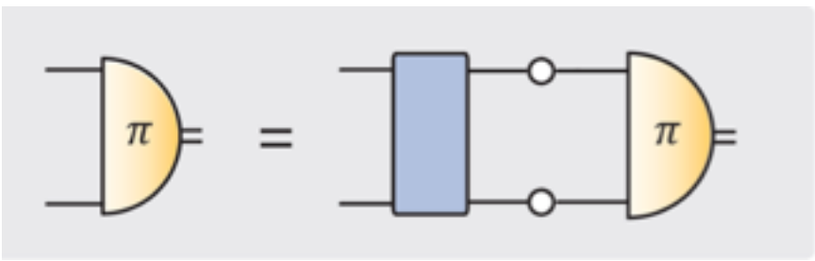
Maris, Roberts, Tandy, PRC 56 (1997), PRC 60 (1999)

Combine gluon with quark-gluon vertex:

effective coupling

$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

- scale Λ from f_π, masses m_u=m_d, m_s from m_π, m_K
- α_{UV} from perturbation theory
- parameter η : band of results



Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

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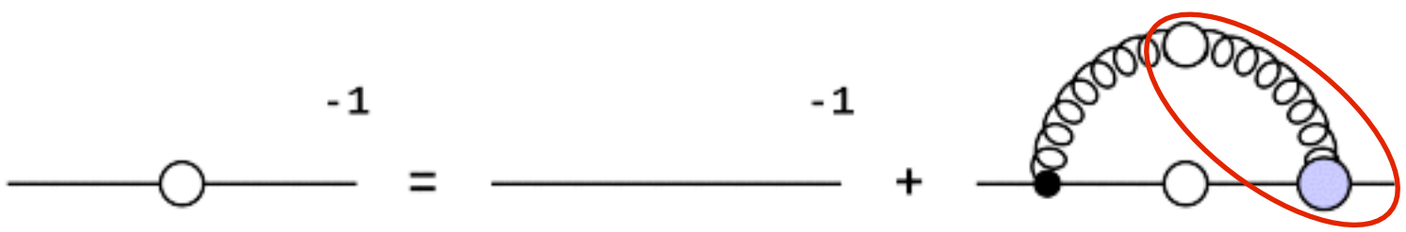

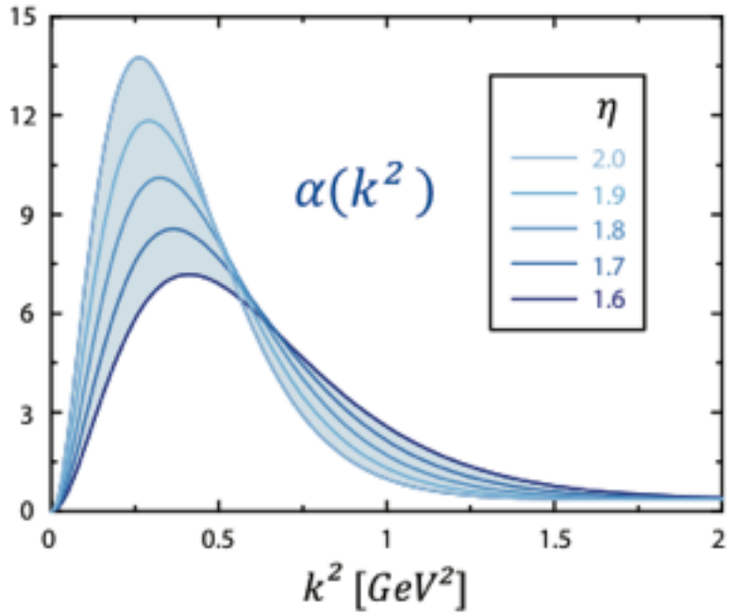

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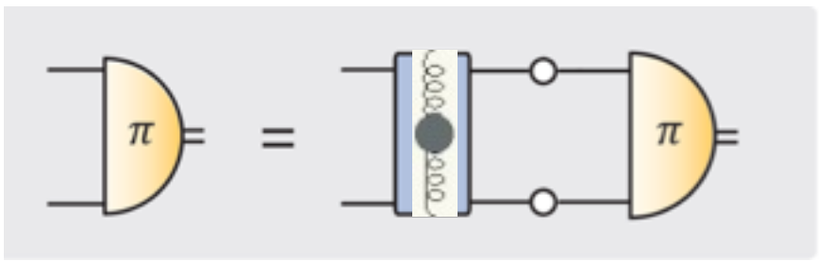
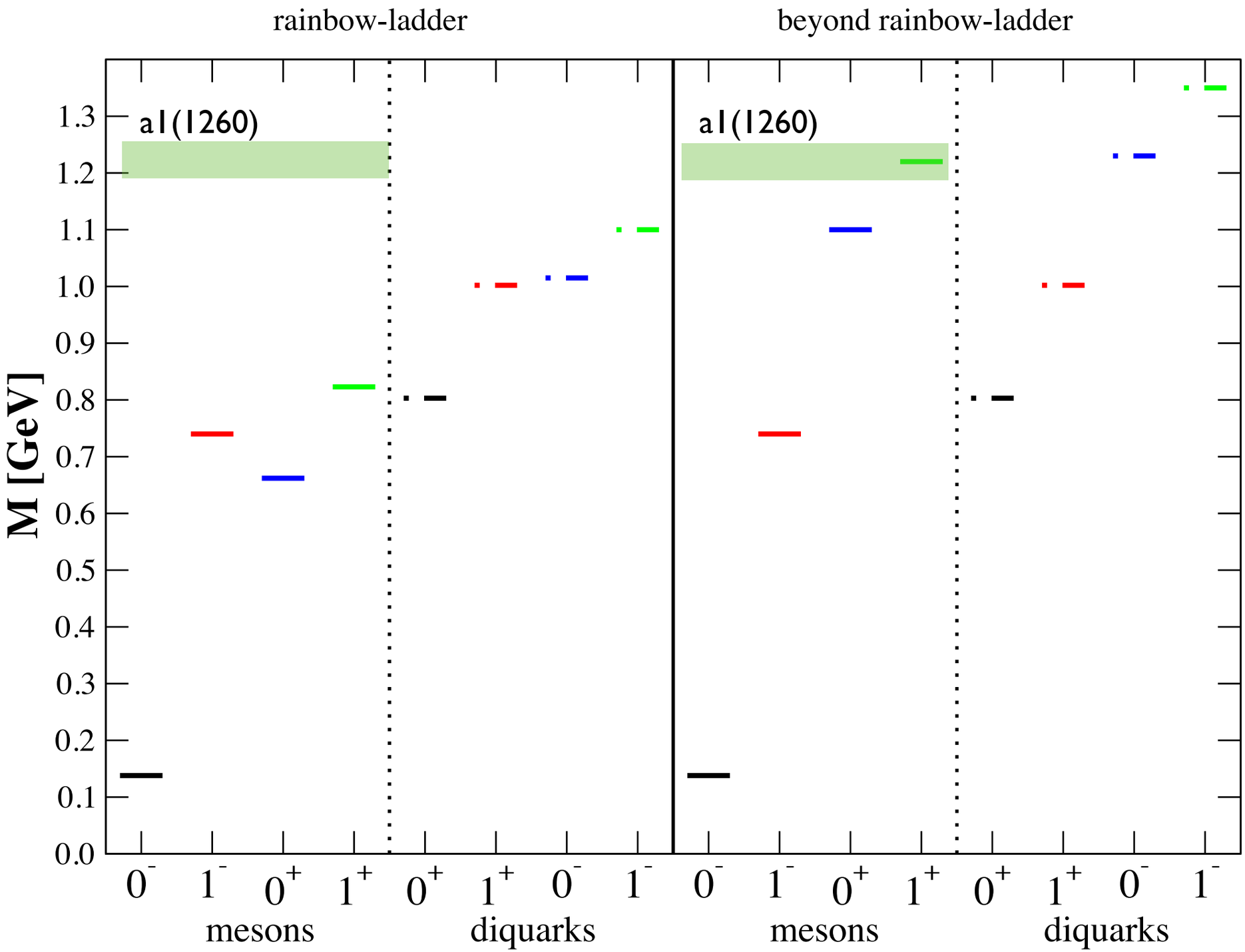


Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

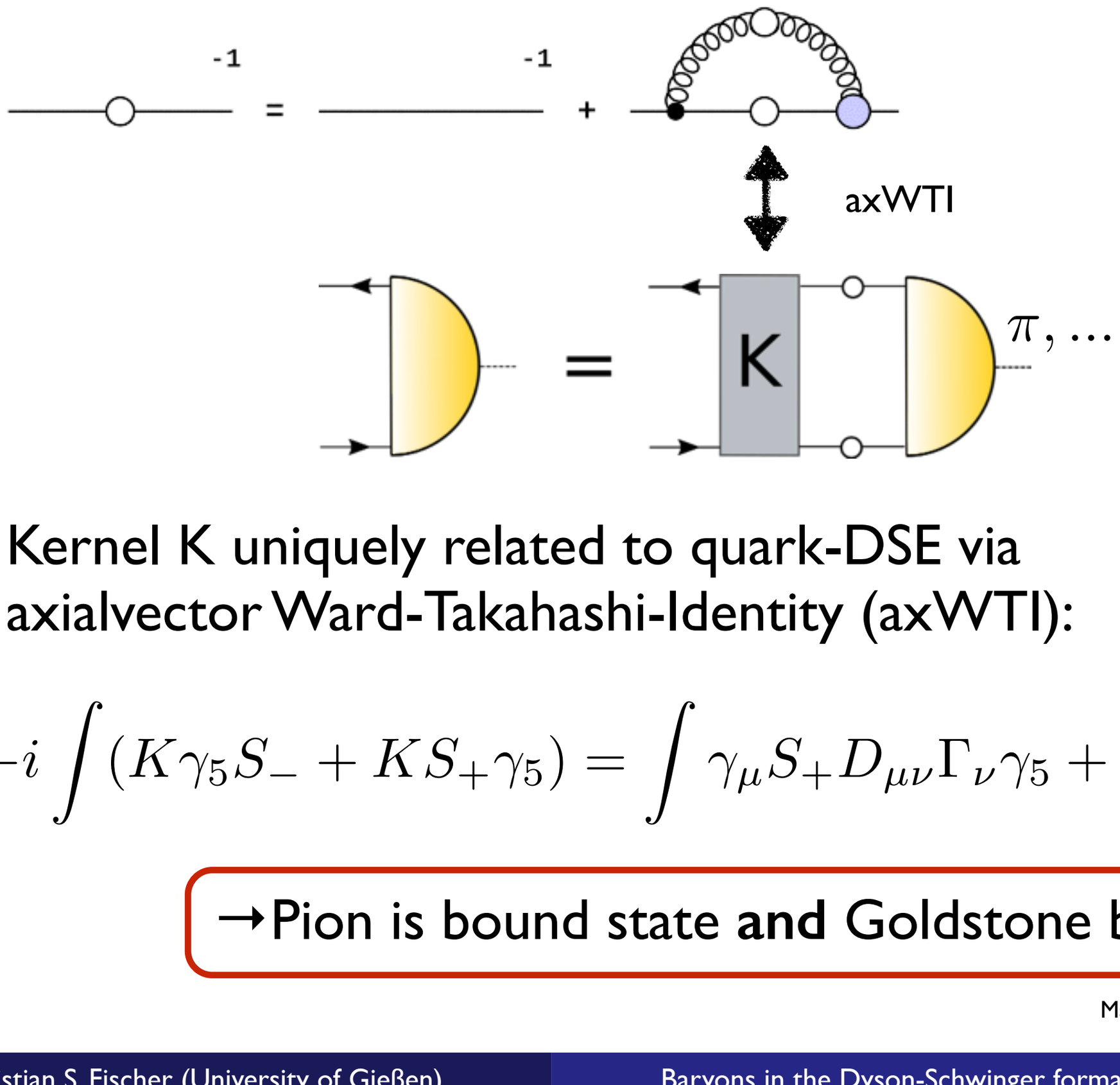
Diquarks with modified rainbow-ladder



- α multiplied with 0.35 in 'bad' channels

see also: Williams, CF, Heupel, PRD93 (2016) 034026

DSEs and Bethe-Salpeter equation



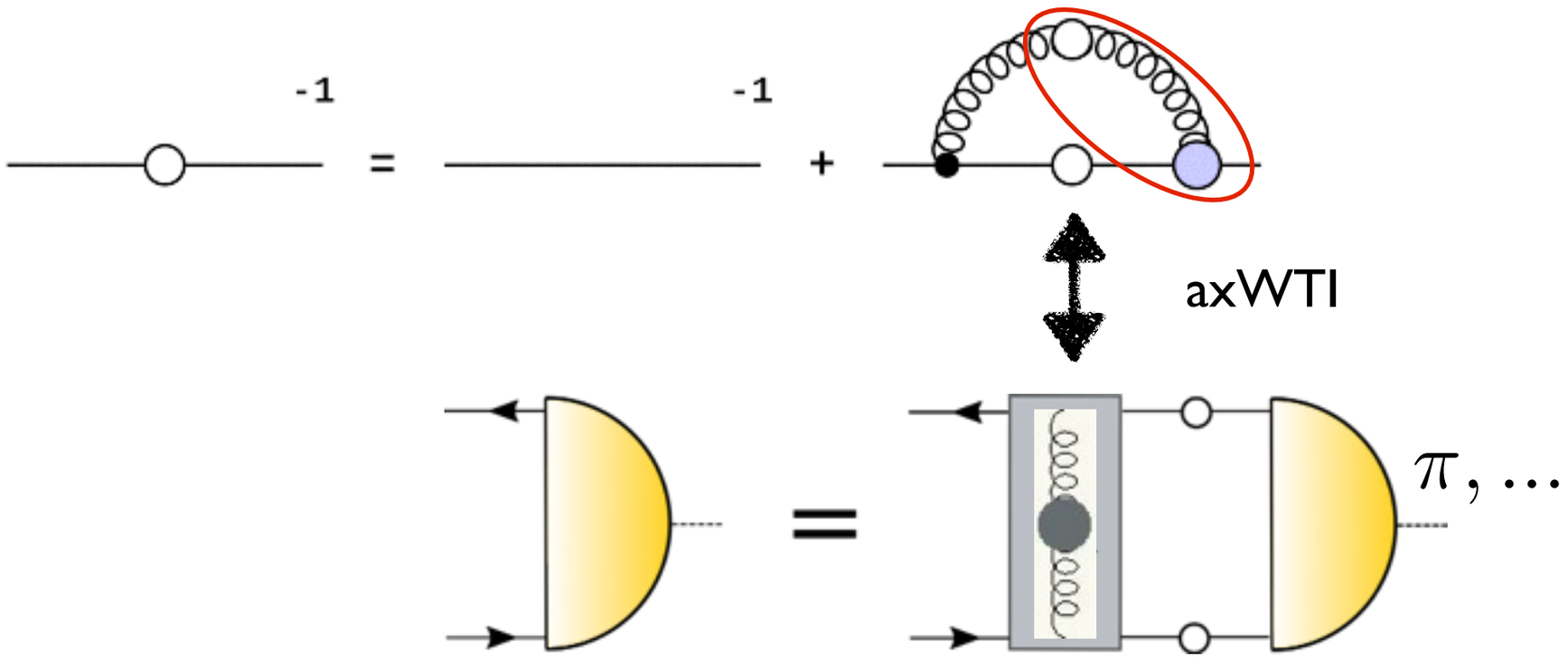
Kernel K uniquely related to quark-DSE via axialvector Ward-Takahashi-Identity (axWTI):

$$-i\int(K\gamma_5 S_- + K S_+\gamma_5) = \int \gamma_\mu S_+ D_{\mu\nu}\Gamma_\nu\gamma_5 + \int \gamma_5\gamma_\mu S_- D_{\mu\nu}\Gamma_\nu$$

→Pion is bound state **and** Goldstone boson

Maris, Roberts, Tandy, PLB 420 (1998) 267

DSEs and Bethe-Salpeter equation



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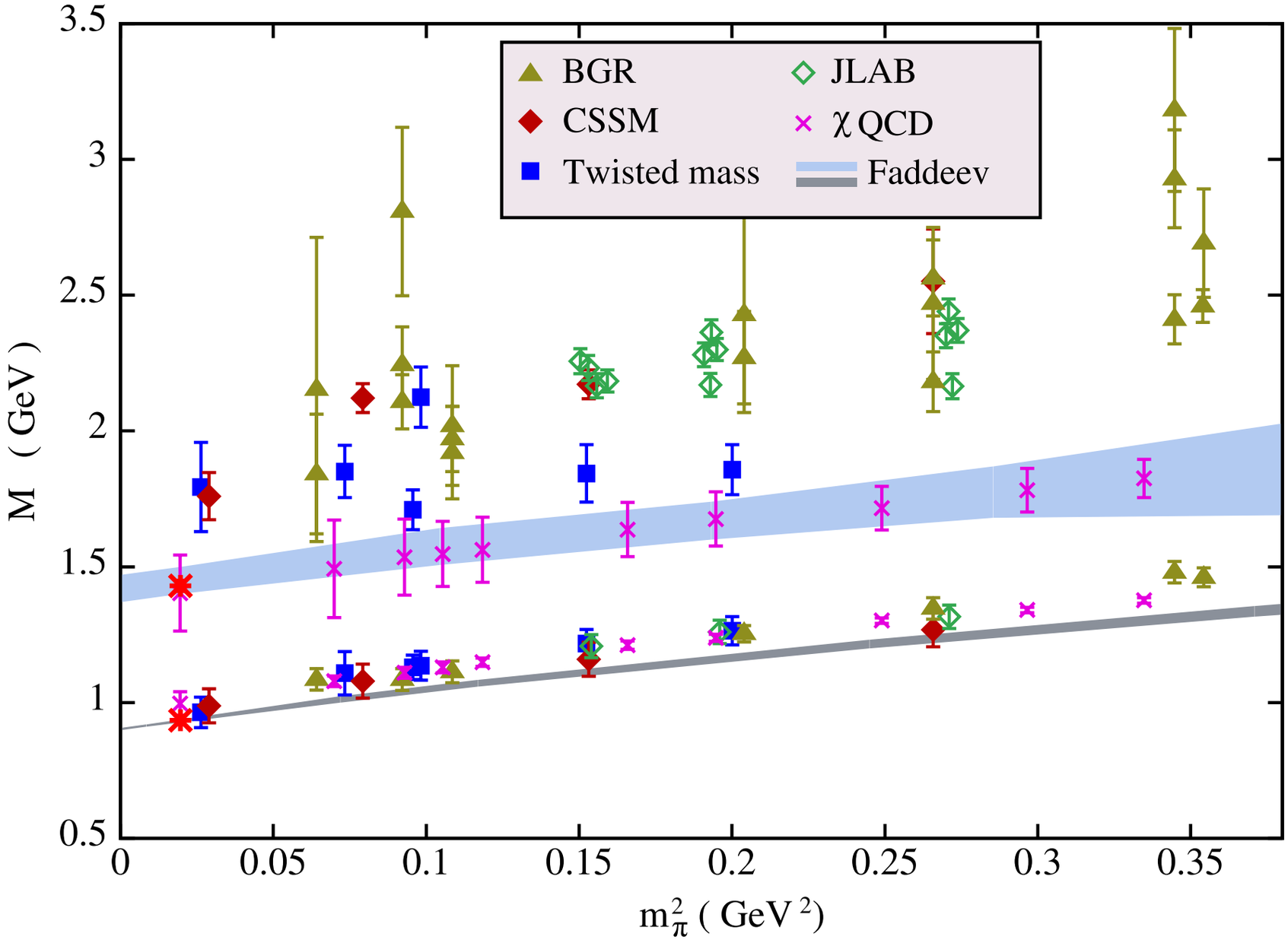
Maris, Roberts, Tandy, PLB 420 (1998) 267

Mass evolution

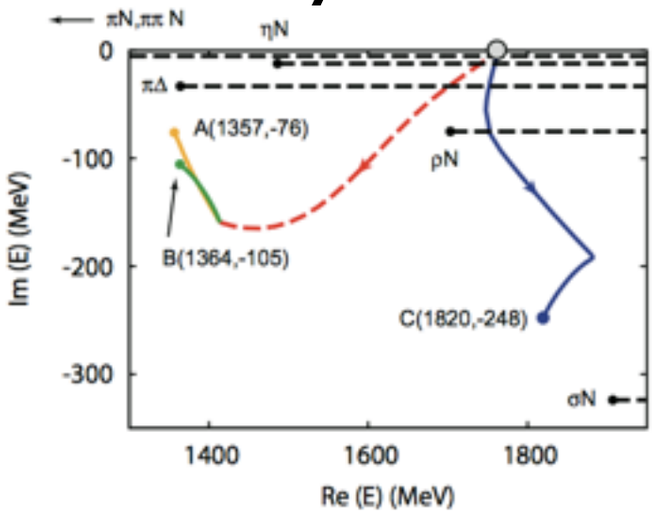


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]

- Mass evolution as expected for three-body state…

Explaining the Roper

- Quark model: p(2S), but generically too large mass
  e.g. Loring, Metsch, Petry, EPJA 10 (2001) 395 and many others…
- Hybrid ? Evidence from lattice to the contrary
  Dudek, Edwards, PRD 85 (2012) 054016
- Dynamically generated by coupled channels (no 'bare' state)
  Krehl, Hanhart, Krewald and Speth, PRC C 62 (2000) 025207
  Doring, Hanhart, Huang, Krewald and Meissner, NPA 829 (2009) 170
- Dynamically modified by coupled channels



Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama and Sato, PRL 104 (2010) 042302

- 'bare' state via DSE/Faddeev (NJL, QCD inspired model)
  Wilson, Cloet, Chang and Roberts, PRC 85 (2012) 025205,
  Segovia, El-Bennich, Rojas, Cloet, Roberts, Xu and Zong, PRL 115 (2015) 17