$Z_c(3900)/Z_c(3885)$: what have we really seen?

[M. A., F. K. Guo, C. Hidalgo-Duque, J. Nieves, arXiv:1512.03638. Phys. Lett. B (to appear)]

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Outline

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Light sector before the heavy...

Take three examples from the light sector:

1. Scalar−isoscalar sector in 1 − 2 GeV: $f_0(1370), f_0(1500), f_0(1710)$ (and $f_0(1790)$)
2. Pseudoscalar sector 1 − 2 GeV
3. Light scalar sector: $f_0(500), f_0(980), a_0(980), \kappa$

Scalar−isoscalar in 1 − 2 GeV

- Three candidates for the two isoscalars in the nonet: $f_0(1370), f_0(1500)$, $f_0(1710)$
- Again, they can be dynamically generated within the Unitary Chiral Approach (*PP* interactions + unitarity)
- One extra member makes it a candidate to be a glueball ($f_0(1500)$ and $f_0(1710)$)
- (See the note of the PDG about the scalar sector)

Light sector before the heavy...

Take three examples from the light sector:

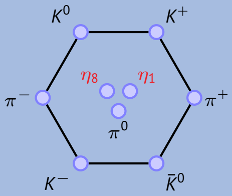
1. Scalar−isoscalar sector in $1-2$ GeV: $f_0(1370), f_0(1500), f_0(1710)$ (and $f_0(1790)$)
2. Pseudoscalar sector $1-2$ GeV
3. Light scalar sector: $f_0(500), f_0(980), a_0(980), \kappa$

Excited Pseudoscalars above 1 GeV

- $I=1$ $\pi(1300), \pi(1800)$
- $I=1/2$ $K(1460), K(1630)$
- $I=0$

  $\eta(1295), \underbrace{\eta(1405), \eta(1475)}_{\eta(1440)?}$

  [Masoni *et al.*,JPG,32('06)]
  [Klempt,Zaitsev,PR,454('07)]
  [Wu *et al.*,PRL,108('11)]
- $I=0$ $X(1835)$?
- Exotic quantum numbers? Glueballs?
  [Chanowitz,PRL,46,981('81)][Ishikawa,PRL,46,978('81)][Close,PRD,55,5749('97)]



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Take three examples from the light sector:

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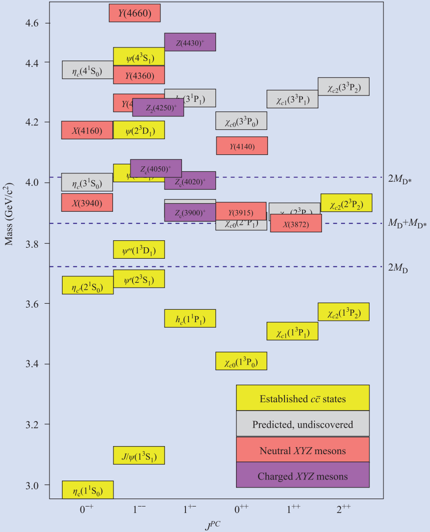
Light scalar sector

- A full nonet (no extra members): $\sigma \equiv f_0(500), f_0(980), a_0(980), \kappa$
- They can be dynamically generated within the Unitary Chiral Approach (*PP* interactions + unitarity)
- Still, what are they?
  - MIT Bag Model predicts tetraquark 0^{++} nonet, with masses $m_\sigma \simeq 600$ MeV
  - For the σ meson, $\sqrt{\langle r^2 \rangle_s^\sigma} = 0.44$ fm, compare with $\sqrt{\langle r^2 \rangle_s^\pi} = 0.65$ fm. [M.A., J.A. Oller, Phys.Rev. **D** 86,034003(2012)]
  - The σ meson is very compact. Tetraquark?

General

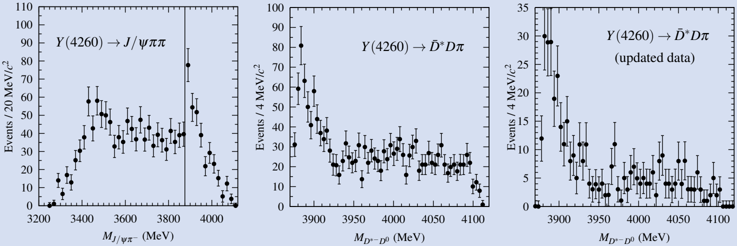


(Taken from: [Olsen, Front. Phys. **10**, 101401])

- Two recent reviews (2015):
  - [Olsen, Front. Phys. **10**, 101401]
  - [Chen *et al.*,arXiv:1601.02092]
- All the $c\bar{c}$ states predicted by QM below $D\bar{D}$ threshold have been found
- In 2003, $X(3872)$ is discovered [Belle Collab., PRL,91,262001]
  - Very close to $D^0\bar{D}^0$ threshold.
  - Close to (but lower) $\chi_{c1}(2^3P_1)$.
- **Lattice QCD**: [Prelovsek, Leskovec, PRL,111,192001] candidate for $X(3872)$ only if $c\bar{c}$ + $D\bar{D}^*$ components are considered **together**

Introduction: experimental information on $Z_c(3885)/Z_c(3900)$

- **$Z_c(3900)$** first seen by **BESIII** and **Belle** Collabs. in $J/\psi\pi^{\pm}$ invariant mass spectrum in $e^+e^- \to Y(4260) \to J/\psi\pi^+\pi^-$
  [Phys. Rev. Lett. **110**, 252001 (2013),Phys. Rev. Lett. **110**, 252002 (2013)]
- Later on, **CLEO-c** data confirmed **$Z_c(3900)$** in $e^+e^- \to \psi(4160) \to J/\psi\pi^+\pi^-$
  [Phys. Lett. B **727**, 366 (2013)]
- **BESIII** analyses $e^+e^- \to Y(4260) \to \bar{D}^*D\pi$, and sees **$Z_c(3885)$** in $\bar{D}^*D$ invariant mass spectrum. $J^P = 1^+$ favoured. [Phys. Rev. Lett. **112**, 022001 (2014)]
- **BESIII** confirms **$Z_c(3885)$** in $\bar{D}^*D$ spectrum at different e^+e^- c.m. energies
  [Phys. Rev. D **92**, 092006 (2015)]
- If they are the same object, **Ratio:** $\frac{\Gamma(Z_c\to D\bar{D}^*)}{\Gamma(Z_c\to J/\psi\pi)} = 6.2 \pm 2.9$



Introduction: theoretical speculation

- "One of the most interesting resonances": couples strongly to charmonium ($\sim \bar{c}c$) and yet it has charge ($\sim \bar{u}d$). Minimal quark constituent is **four** [$\bar{c}c\bar{u}d$].
- Many different interpretations have been given:
  [Olsen, Front. Phys. **10**, 101401][Chen *et al.*,arXiv:1601.02092]
  - Tetraquark
  - $\bar{D}^* D$ molecular state
  - Simply a kinematical effect
  - Hadrocharmonium
  - It has also been searched for in lattice QCD

What is still missing?

A **joint study of both reactions** in which the Z_c structure has been seen

Introduction: theoretical speculation

- "One of the most interesting resonances": couples strongly to charmonium ($\sim \bar{c}c$) and yet it has charge ($\sim \bar{u}d$). Minimal quark constituent is **four** [$\bar{c}c\bar{u}d$].
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What is still missing?

A **joint study of both reactions** in which the Z_c structure has been seen

Outline

Coupling $\bar{D}^* D$ and $J/\psi\pi$ channels

Coupled channel formalism is needed, because $Z_c(3900)$:

- is expected to be dynamically generated in $\bar{D}^* D$ channel (#2),
- but it is also seen in $J/\psi\pi$ channel (#1).

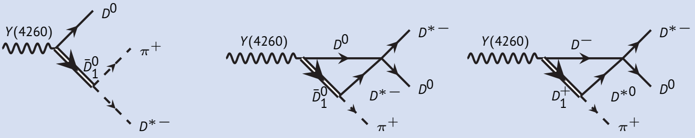
$$T = (\mathbb{I} - V \cdot G)^{-1} \cdot V \,,$$

$$V_{ij} = 4\sqrt{m_{i1} m_{i2}}\sqrt{m_{j1} m_{j2}}\, e^{-q_i^2/\Lambda_i^2} e^{-q_j^2/\Lambda^2} C_{ij} \,,$$

- $G(E)$ are loop functions (Regularized with standard gaussian regulator)
- **$J/\psi\pi \to J/\psi\pi$:** known to be tiny, $C_{11} = 0$.
- **$\bar{D}^* D \to J/\psi\pi$:** we make the simplest possible assumption, $C_{12} \equiv \widetilde{C}$ (constant)
- **$\bar{D}^* D \to \bar{D}^* D$:** In a momentum expansion (HQSS), simply a constant, $C_{22} \equiv C_{1Z}$.
- **Problem:** no resonance in the complex plane above threshold with only constant potentials (even with coupled channels).
- We introduce some energy dependence,

$$C_{22}(E) = C_{1Z} + b\,(E - m_D - m_{D^*}) \,.$$

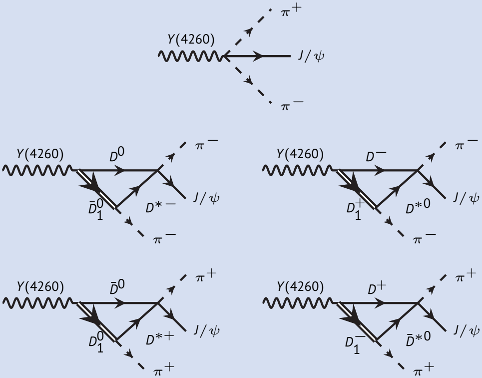
Amplitudes: $Y(4260) \to (J/\psi\pi^-)\pi^+, (D^{*-}D^0)\pi^+$



$$\left|\overline{\mathcal{M}_2}(s,t)\right|^2 = \left|\frac{1}{t - m_{D_1}^2} + I_3(s)T_{22}(s)\right|^2 q_\pi^4(s) + \left|\beta\left(1 + T_{22}(s)G_{22}(s)\right)\right|^2$$

- s (Mandelstam) $\bar{D}^* D$ invariant mass squared
- $I_3(s)$: three meson loop propagator
- $\bar{D}^* D$ rescattering enters through $T_{22}(s)$
- ${q_\pi}^2(s) = \lambda(M_Y^2, s, m_\pi^2)/(4M_Y^2)$

Amplitudes: $Y(4260) \to (J/\psi\pi^-)\pi^+, (D^{*-}D^0)\pi^+$



- The decay proceeds mainly through $[T_{12}(s)]$ $Y \to (\bar{D}^* D)\pi \to (J/\psi\pi)\pi$
- Some direct production included through α
- s, t (Mandelstam) $J/\psi\pi^-, J/\psi\pi^+$ invariant mass squared

$$\left|\overline{\mathcal{M}_1}(s,t)\right|^2 = |\tau(s)|^2 q_\pi^4(s) + |\tau(t)|^2 q_\pi^4(t) + \frac{3\cos^2\theta - 1}{4}\Big(\tau(s)\tau(t)^* + \tau(s)^*\tau(t)\Big) q_\pi^2(s) q_\pi^2(t)\,,$$

$$\tau(s) = \sqrt{2} I_3(s) T_{12}(s) + \alpha$$

Events distributions and Experimental data

- Events distributions $\mathcal{N}_i$:

$$\mathcal{N}_i(s) = K_i \left(\mathcal{A}_i(s) + \mathcal{B}_i(s)\right)$$

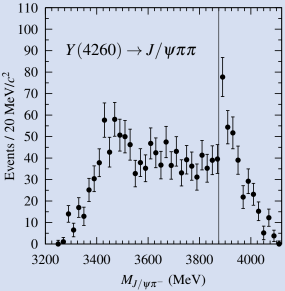
$$\mathcal{A}_i(s) = \int_{t_{i,-}}^{t_{i,+}} dt \left|\overline{\mathcal{M}}_i(s,t)\right|^2$$

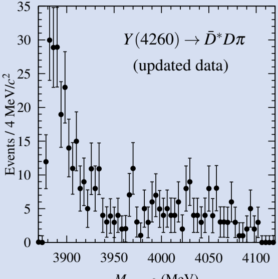
- K_i (unknown) global normalization constants
- B_i are background functions (parametrized as in the experimental analyses)
- "Branching ratio":

$$R_{\text{exp}} = \frac{\Gamma\left(Z_c \to D\bar{D}^*\right)}{\Gamma\left(Z_c \to J/\psi\pi\right)} = 6.2 \pm 2.9$$

- Theoretically estimated as the (physical) ratio of areas around $Z_c(3900)$ mass

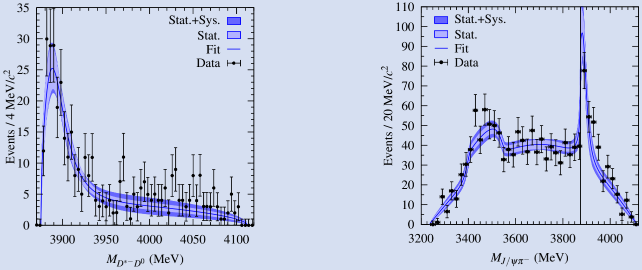
$$R_{\text{th}} = \frac{\int ds \mathcal{A}_2(s)}{\int ds \mathcal{A}_1(s)}$$





Outline

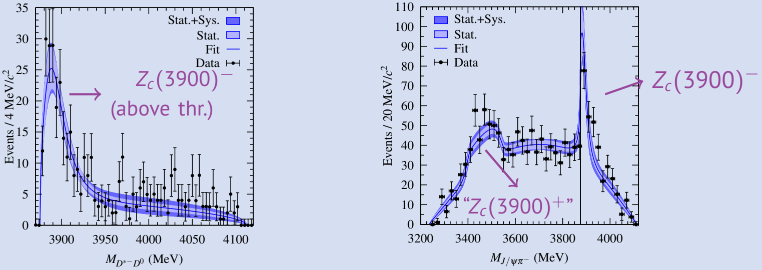
Results: comparison with experiment(s)



Λ_2 (GeV)	C_{1Z} (fm^2)	b (fm^3)	$\widetilde{C}$ (fm^2)	χ^2/dof	R_{th}
1.0	$-0.19 \pm 0.08 \pm 0.01$	$-2.0 \pm 0.7 \pm 0.4$	$0.39 \pm 0.10 \pm 0.02$	1.02	$6.0 \pm 3.5 \pm 0.5$
0.5	$+0.01 \pm 0.21 \pm 0.03$	$-7.0 \pm 0.4 \pm 1.4$	$0.64 \pm 0.16 \pm 0.02$	1.09	$6.5 \pm 3.6 \pm 0.2$
1.0	$-0.27 \pm 0.08 \pm 0.07$	0 (fixed)	$0.34 \pm 0.14 \pm 0.01$	1.31	$10.3 \pm 9.0 \pm 1.1$
0.5	$-0.27 \pm 0.16 \pm 0.13$	0 (fixed)	$0.54 \pm 0.16 \pm 0.02$	1.36	$10.9 \pm 9.0 \pm 2.5$

- Four different fits: $b = \{\text{free}, 0\}, \Lambda_2 = \{0.5, 1.0\}$ GeV
- Only the T-matrix parameters are shown (not shown: normalization, ...)
- All fits have $\hat{\chi}^2 \simeq 1$ ($\simeq 1.4$ for $b = 0$), and are within the error band of the best one
- Reproduction of the data is **excellent**

Results: comparison with experiment(s)



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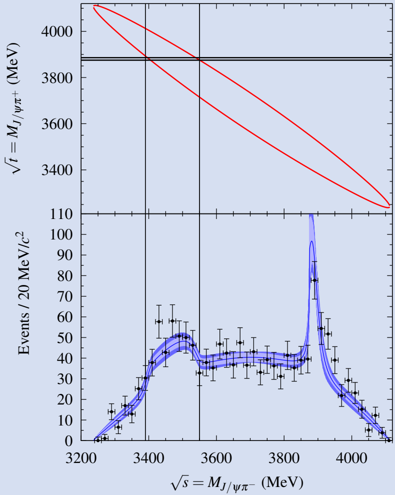
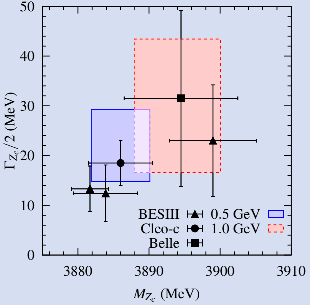
Reflection of threshold and $Z_c(3900)$



Results: Spectroscopy



M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	▲(BESIII)	$J/\psi\ \pi$
3895 ± 8	32 ± 18	■(Belle)	$J/\psi\ \pi$
3886 ± 5	19 ± 5	●(CLEO-c)	$J/\psi\ \pi$
3884 ± 5	12 ± 6	▲(BESIII)	$\bar{D}^* D$
3882 ± 3	13 ± 5	▲(BESIII)	$\bar{D}^* D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	($\Lambda = 1.0$ GeV)	both
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	($\Lambda = 0.5$ GeV)	both
$3831 \pm 26^{+7}_{-28}$	virtual state	($\Lambda = 1.0$ GeV)	both
$3844 \pm 19^{+12}_{-21}$	virtual state	($\Lambda = 0.5$ GeV)	both

Two different scenarios:

1. ($b \neq 0$) Z_c is a $\bar{D}^* D$ **resonance** very close to threshold
   (Differences with experiments are related to Breit-Wigner parametrizations)
2. ($b = 0$) Z_c is a **virtual state**

In both scenarios,

- Data are very well reproduced
- A single structure (not two) $Z_c(3885)/Z_c(3900)$ is needed

Bound state, resonance, virtual ...

Well known example: *NN* scattering and the deuteron

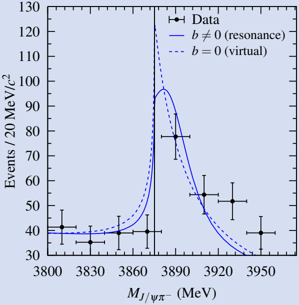
Triplet ($^3S_1$–$^3D_1$):

- $a_t \simeq 5$ fm.
- In this wave there is a **bound state**. The deuteron is a well known, really physical particle.

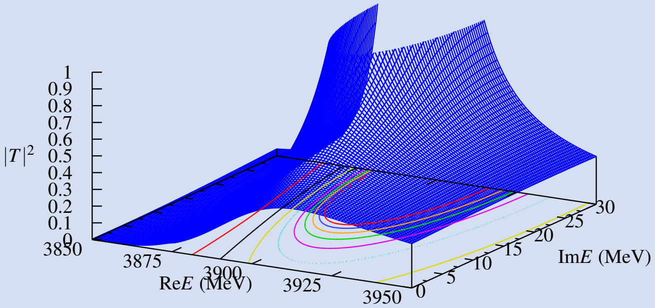
Singlet ($^1S_0$):

- $a_s \simeq -24$ fm.
- In this wave there is a **virtual state**.

- A **virtual state** does not correspond to a real particle. (Wavefunction not localized.)
- It produces effects at the threshold similar to those of a bound state or a nearby resonance.



Complex plane & poles: First scenario (resonance)



- Pole located at $3894 - i30$ MeV
- Plot: unphysical Riemann sheet connected to the physical one above $D^*\bar{D}$
- Shift of the pole towards higher energies (interference!)

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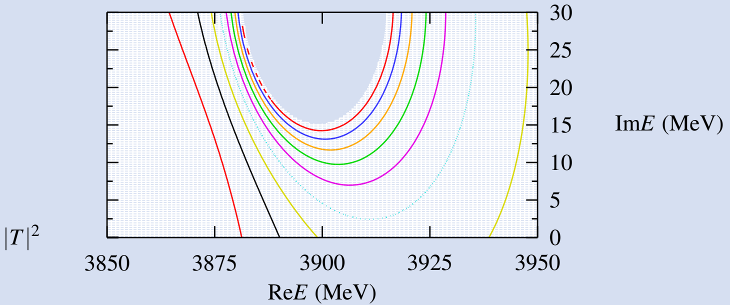

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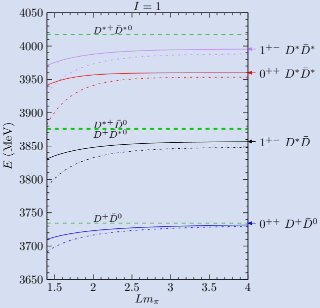
Outline

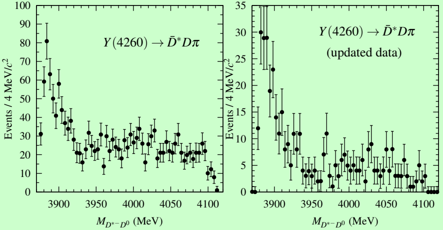
$Z_c(3900)$ on the lattice

- Two recent works:
  - [Prelovsek *et al*, Phys.Rev.**D**91,014504(2015)] ($m_\pi = 266$ MeV)
    "no additional candidate"
  - [HAL QCD, arXiv:1602.03465] ($m_\pi \gtrsim 410$ MeV)
    Virtual poles with very low masses and deep in the complex plane.
- Results are not conclusive (large pion masses, etc...)
- We can predict energy levels in a finite box. It might be helpful to understand these (and future) lattice simulations



Experimental improvements for $Z_c(3900)$

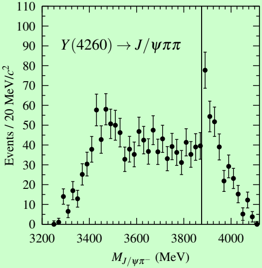
New data on $\bar{D}^* D$ from BESIII



- Better statistics
- Lower "background"
- double D-tag

New data on $J/\psi\pi$

The spectrum of $J/\psi\pi$ with **narrower bins** is highly desirable in order to better elaborate on the nature of $Z_c(3900)$



Outline

Conclusions (this work)

- $Z_c(3900)$ is a most-interesting, exotic, structure. A candidate for "tetraquark"
- We have presented the first simultaneous study of the two decays ($Y(4260) \to J/\psi\pi\pi, \bar{D}^* D\pi$) in which $Z_c(3900)$ is seen
- Data are well reproduced in all fits ($\hat{\chi}^2 \simeq 1$)
- Two different scenarios are found:
  1. ($b \neq 0$) $Z_c(3900)$ is a $\bar{D}^* D$ resonance
  2. ($b = 0$) $Z_c(3900)$ is a virtual state
- In any case, a single structure for $Z_c(3885)/Z_c(3900)$ is needed.
- Improved data on $J/\psi\pi$ invariant mass spectrum are necessary

Conclusions (general)

- Charmonium spectrum, well known below $D\bar{D}$ threshold.
- Since 2003, the charmonium(-like) spectrum increases continuously ($\simeq 1$ state/year), but we do not fully understand: there are $c\bar{c}$, there are meson-meson **molecules**, there are **tetraquarks**, and many others.
- They must be **mixing**, specially around thresholds.
- Lattice still must go down to physical masses.
- We shall all be studying **Heavy Quark Physics**...

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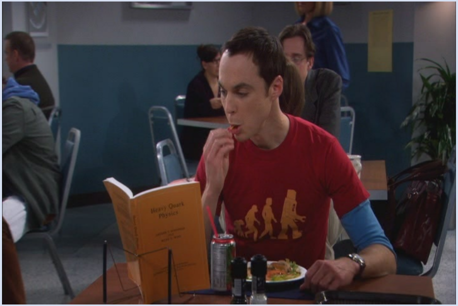

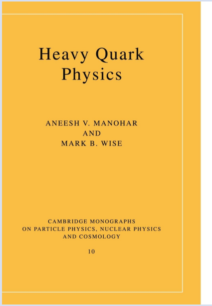

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[M. A., F. K. Guo, C. Hidalgo-Duque, J. Nieves, arXiv:1512.03638. Phys. Lett. B (to appear)]

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FAIRNESS 2016
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Thanks for your attention

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