SUMMARY TALK

XVII INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE

September 25th-29th 2017

Salamanca, Spain

Salamanca

HADRON 2017

XVII International Conference on Hadron Spectroscopy and Structure

Fitting and selecting scattering data

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XVII International Conference on Hadron Spectroscopy and Structure
September 25th-29th, 2017
Salamanca (Spain)

Rodrigo Navarro Pérez (Athens, Ohio)
José Enrique Amaro Soriano (Granada),

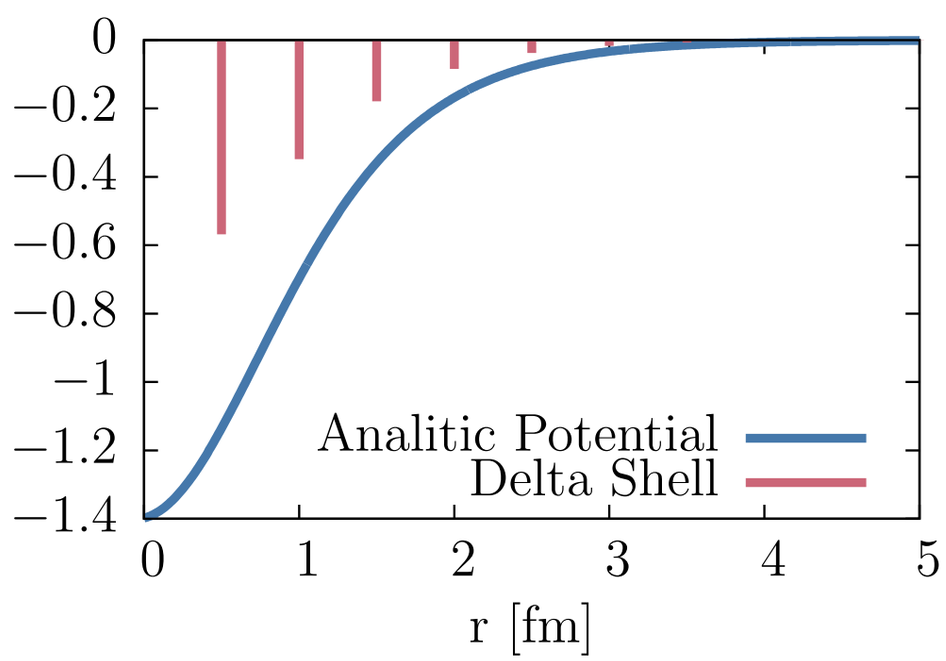
Delta Shell Potential

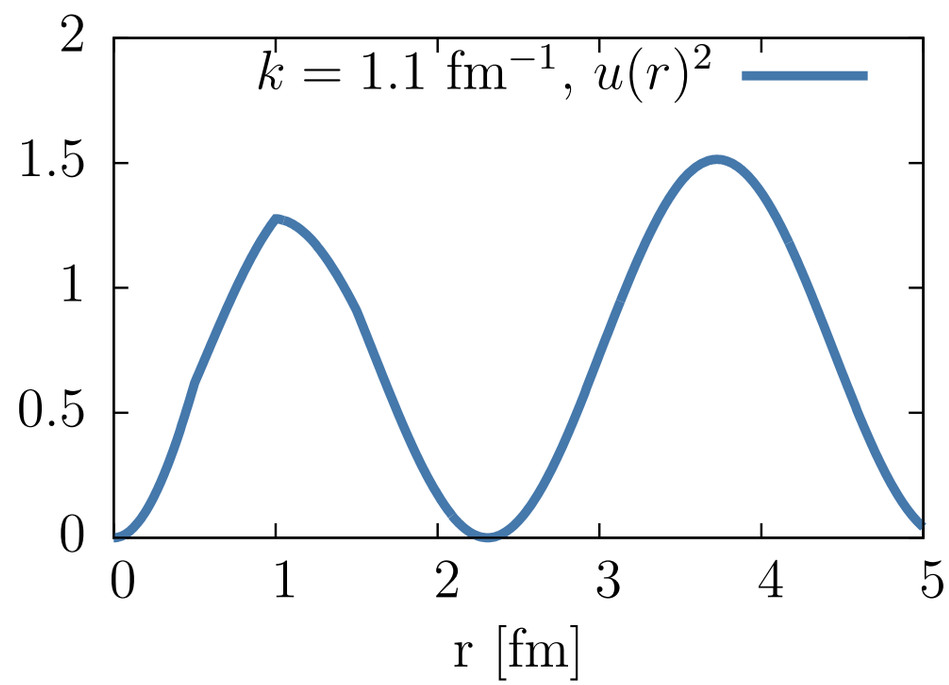
- A sum of delta functions

$$V(r) = \sum_i \frac{\lambda_i}{2\mu} \delta(r - r_i)$$

[Aviles, Phys.Rev. C6 (1972) 1467]

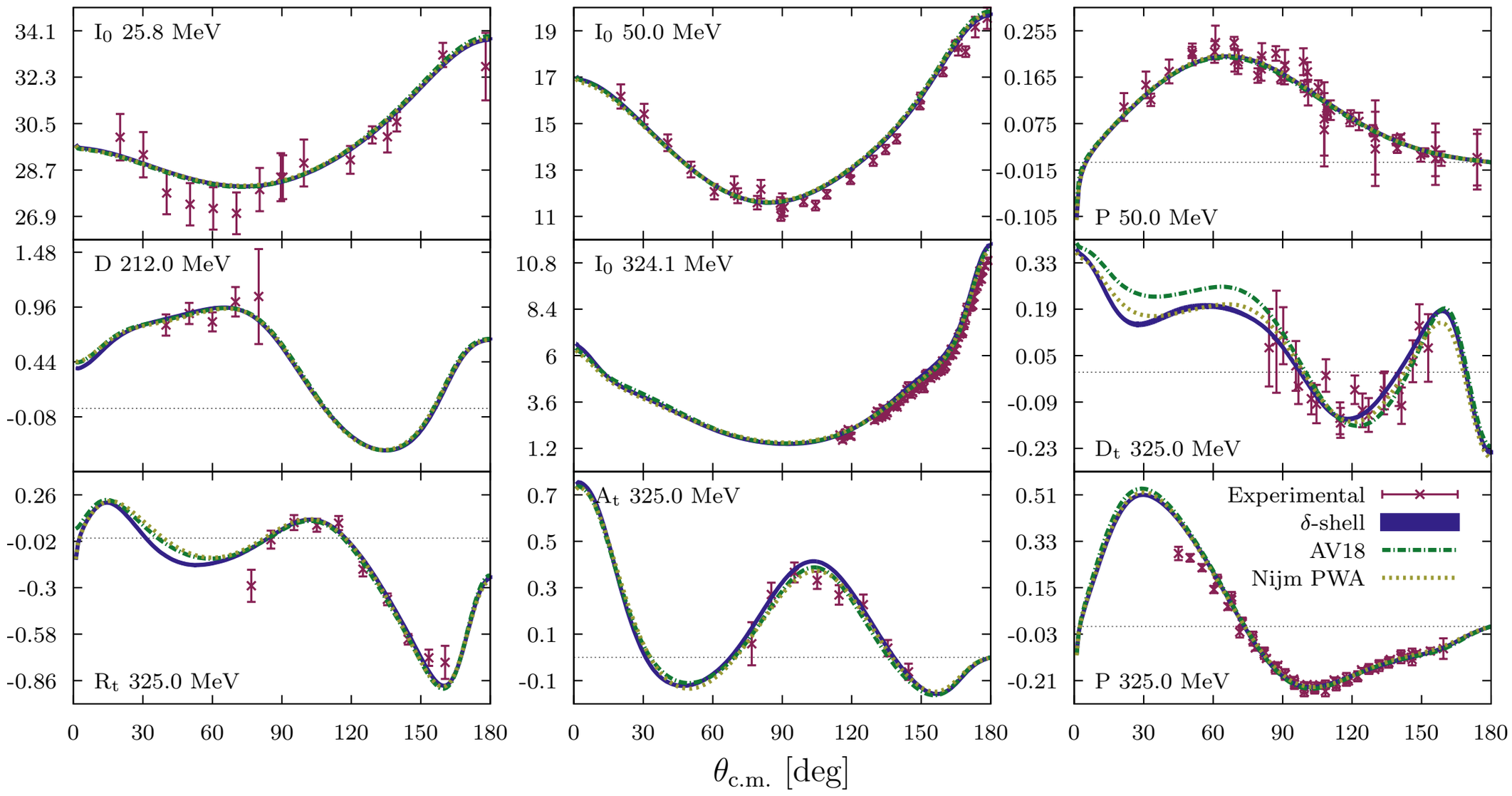
- Optimal and minimal sampling of the nuclear interaction
- Pion production threshold $\Delta k \sim 2$ fm^{-1}
- Optimal sampling, $\Delta r \sim 0.5$fm





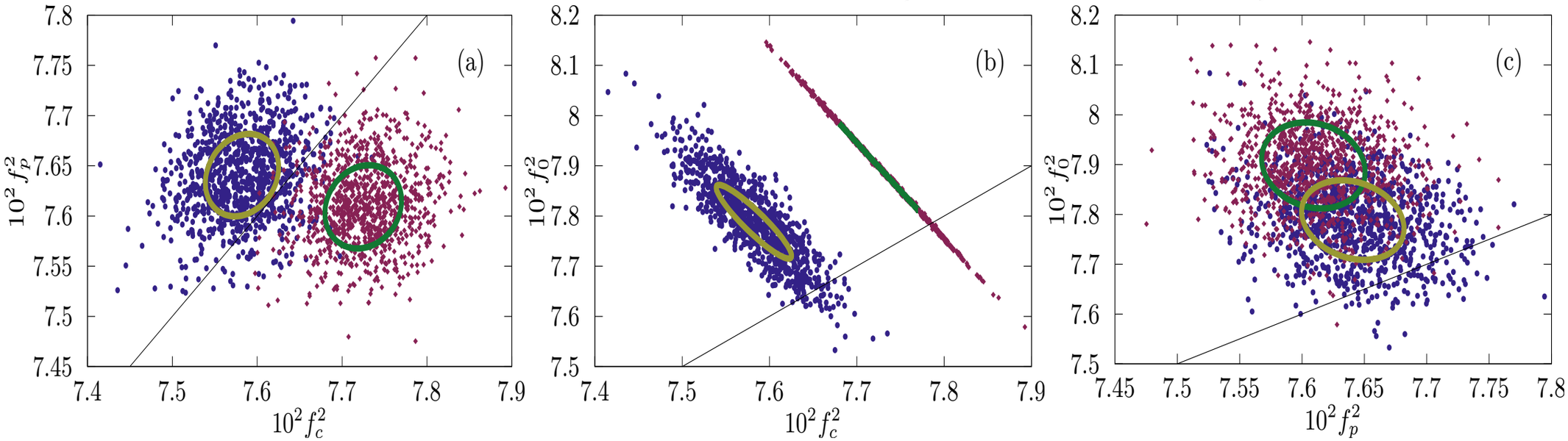
Scattering Observables

- Comparing with Potentials and Experimental data
- np data



Coupling constants

Bootstrapping 6713 np+pp data (benchmark $\sim 0.5\%$)

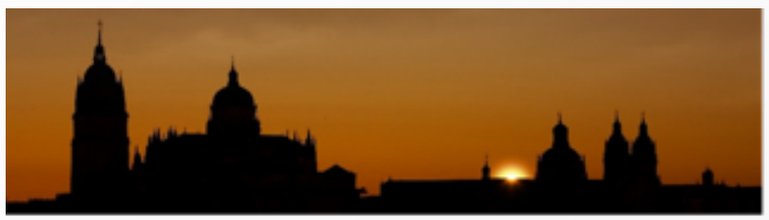


Fits to the Granada-2013 database.

f^2	f_0^2	f_c^2	CD-waves	χ^2_{pp}	χ^2_{np}	$N_{\rm Dat}$	$N_{\rm Par}$	χ^2/ν
0.075	idem	idem	${}^1S_0$	3051	3951	6713	46	1.051
0.0761(3)	idem	idem	${}^1S_0$	3051	3951	6713	46+1	1.051
-	-	-	${}^1S_0, P$	2999	3951.40	6713	46+3	1.043
0.0759(4)	0.079(1)	0.0763(6)	${}^1S_0, P$	3045	3870	6713	46+3+9	1.039

Quarkonium production to explore hadron 3D structure

Miguel G. Echevarría



Salamanca

HADRON 2017

XVII International Conference on Hadron Spectroscopy and Structure

Salamanca, 25-29 Sep 2017

INFN Istituto Nazionale di Fisica Nucleare

HasQCD HADRONICS STRUCTURE AND QCD

3DSPIN MAPPING THE PROTON IN 3D

erc European Research Council

In collaboration with

[T. Kasemets, J.-P. Lansberg, C. Pisano & A. Signori]

1. *Introduction*
2. *TMD factorization: gluon TMDs*
3. *Pheno: Matching TMD & Collinear frameworks*

Conclusions & Outlook

- *There is not yet any phenomenological extraction of gluon TMDs*
- *Quarkonium production is the best way to access/constrain gluon TMDs*
- *Quarkonium production is tricky: multi-scale, formation of bound-states*
- *TMDs are much more complicated than ordinary PDFs!! Perturbative and non-perturbative contributions are entangled in an intricate way*
- *We have devised a new method to match Resummed and Fixed-Order results: the Weighted Average*

★ *We need more data!! To better constrain the non-perturbative part of gluon TMDs*

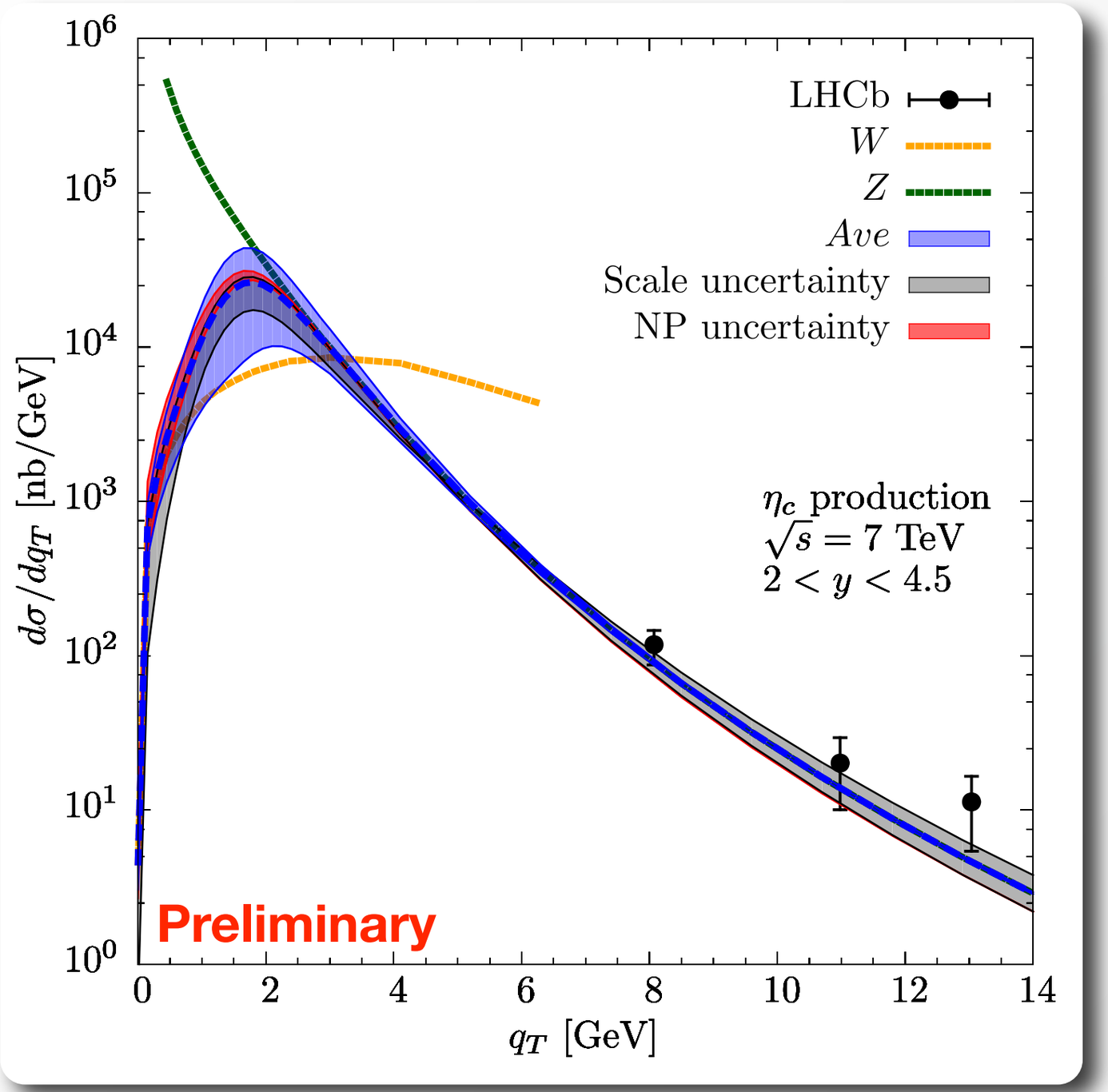
★ *Future facilities: fixed target @ LHC (AFTER@LHC & LHCb proposal), EIC*

★ *Open issues: soft entanglement in quarkonium production, factorization breaking*

★ *Increase theoretical precision: resummation, matching TMD&Col,…*

Thank you!

η_c production at the LHC: full q_T spectrum



[LHCb data: 1409.3612]

Fixed-order Z *result at LO from:*

[Kuhn, Mirkes hep-ph/9301204]

Resummed W *result at NNLL*

- *Matching uncertainty*
- *Scale uncertainty*
- *Non-perturbative uncertainty*

Formalism is ready!
We need more data!

Effective-particle approach to bound states of quarks and gluons in QCD

María Gómez-Rocha
Trento ECT*

in collaboration with
S.D. Głazek (U. Warsaw & Yale U.), K. Serafin (U. Warsaw)
& J. More (IIT Bombay).

Phys. Lett. B 773 (2017) 172-178

HADRON 2017, Salamanca, September 25, 2017

The method of calculation

Start from the Lagrangian density $\mathcal{L}_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{2}\mathrm{tr}F^{\mu\nu}F_{\mu\nu}$

1. **Canonical Hamiltonian** Use front-form dynamics:

   - $\mathcal{L}_{QCD} \to \mathcal{T}^{\mu\nu}_{QCD} \to H_{QCD} = \int_{\mathrm{x}^+=0} \mathcal{H}_{QCD}(\mathrm{x})d\mathrm{x}, \quad A^+ = 0$

     $k^+ = k^0 + k^3, \quad k^- = k^0 - k^3, \quad \vec{k}^\perp = (k^1, k^2)\ ; \quad x = k^+/P^+$

2. **Regularization** Introduce regulating functions at vertices

   - UV and small-x cutoff $\int dx d^2\kappa^\perp \to \int dx d^2\kappa^\perp r_\delta(x) r_\Delta(\kappa^\perp)$

     $\lim_{\delta\to 0} r_\delta(x) = 1, \ \lim_{\Delta\to\infty} r_\Delta(\kappa^\perp) = 1$

3. **Renormalization**

   $q_0^\dagger|0\rangle = |q\rangle \quad \to \quad q_s^\dagger|0\rangle = |q_s\rangle \qquad q_s^\dagger = \mathcal{U}_s\, q_0^\dagger\, \mathcal{U}_s^\dagger$

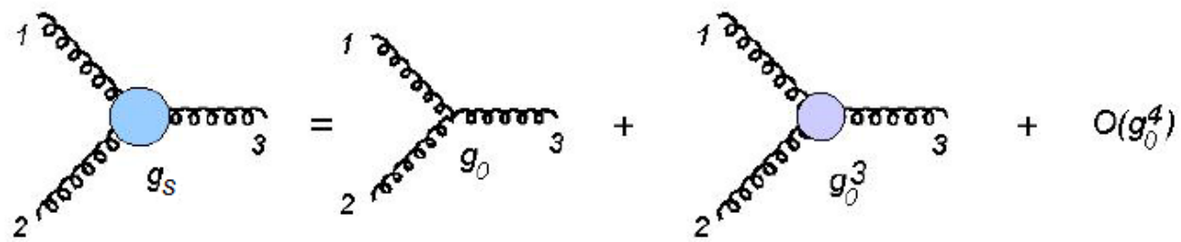
   Effective particles of size $s = 1/\lambda$ introduced by RGPEP

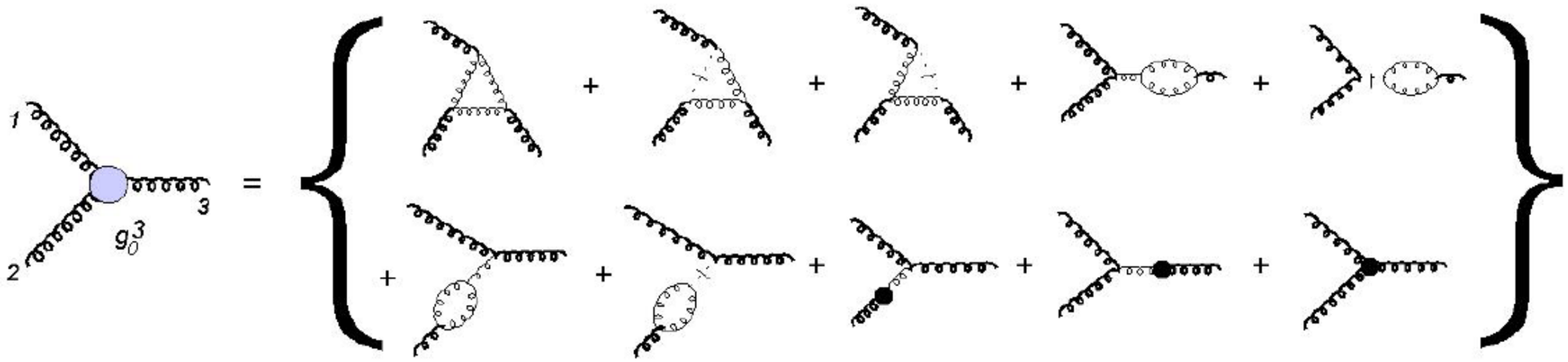
$$\frac{d}{ds^4} H_s \quad = \quad [\mathcal{G}_s, H_s]$$

Example of 3rd-order calculation:

→ **The three-gluon vertex:**

$$Y_\lambda \quad = \quad gH_{1\lambda} + g^3 H_{3\lambda}$$





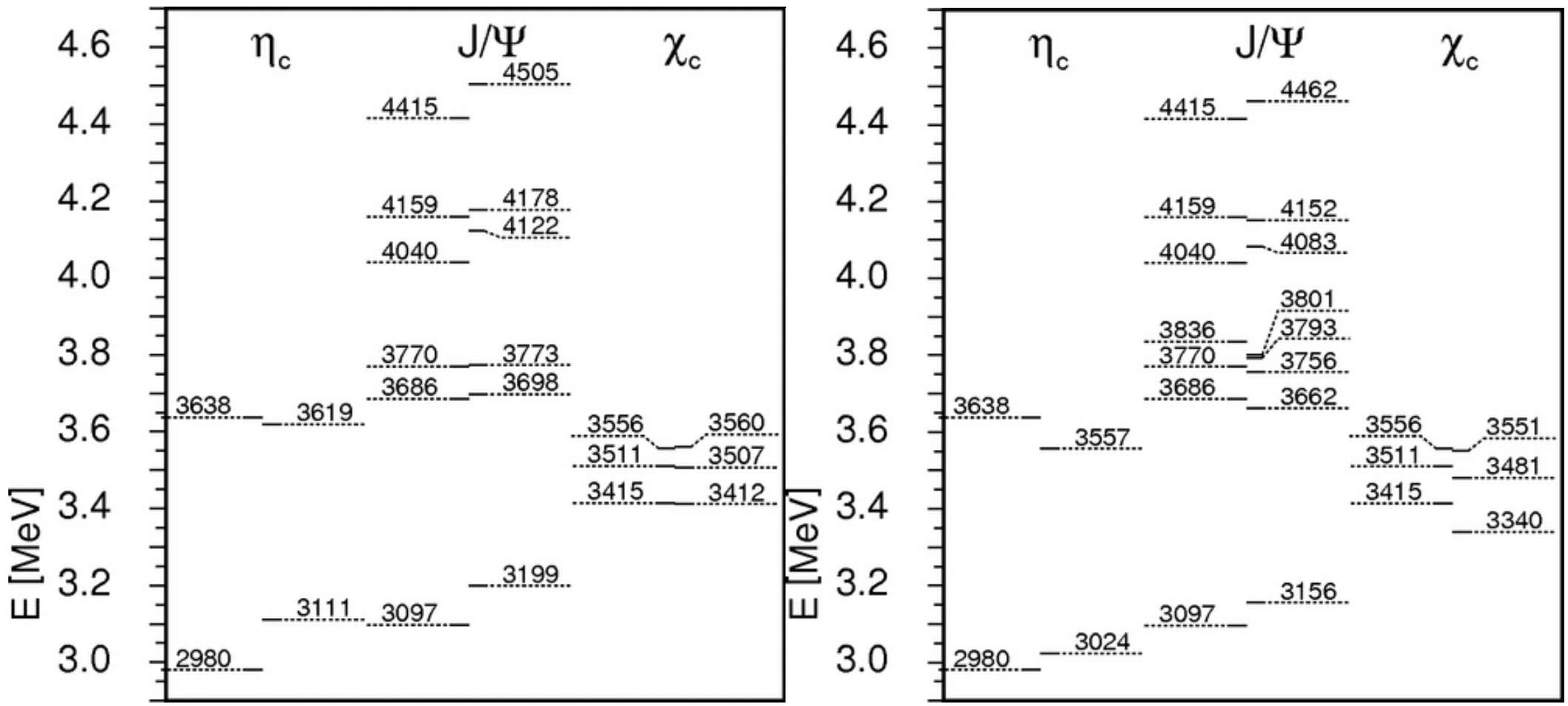
$$Y_\lambda \quad = \quad \sum_{123} \int [123]\, \tilde{Y}_\lambda(\kappa_{12}^\perp, \sigma)\, a^\dagger_{1,\lambda} a^\dagger_{2,\lambda} a_{3,\lambda} + H.c.$$

→ **We obtain the running coupling with the correct AF behavior in** $\kappa_{12}^\perp \to 0$**:**

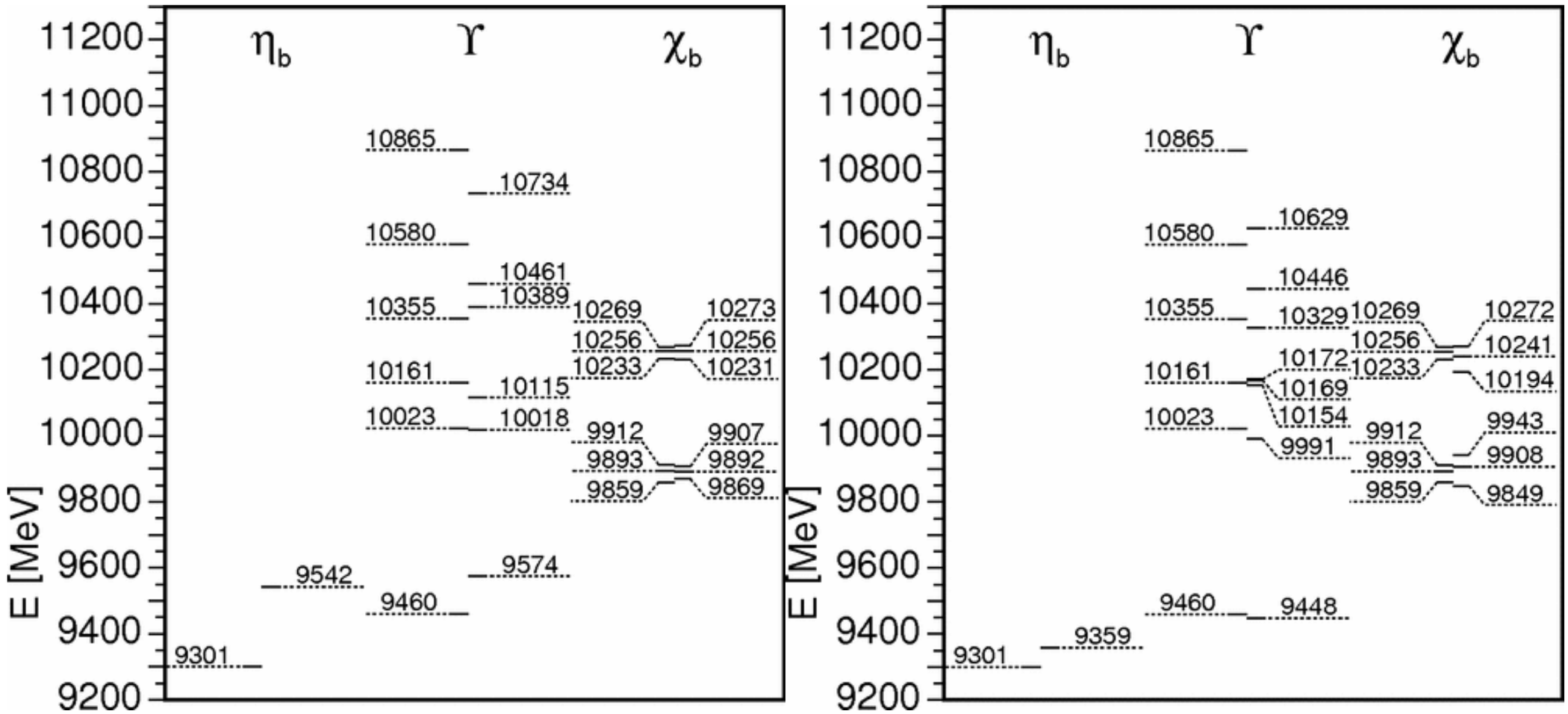
$$\Rightarrow g_\lambda \quad = \quad g_0 - \frac{g_0^3}{48\pi^2} N_c\, 11\, \ln \frac{\lambda}{\lambda_0} \ ,$$

[MGR, Głazek, PRD **92** (2015)]

Phenomenological fit of parameters IV



Phenomenological fit of parameters II



$\eta \to 3\pi$ in coupled-channels Khuri-Treimann formalism

Based on: Eur. Phys. J. C**77**, 508 (2017)
[arXiv:1702.04931]

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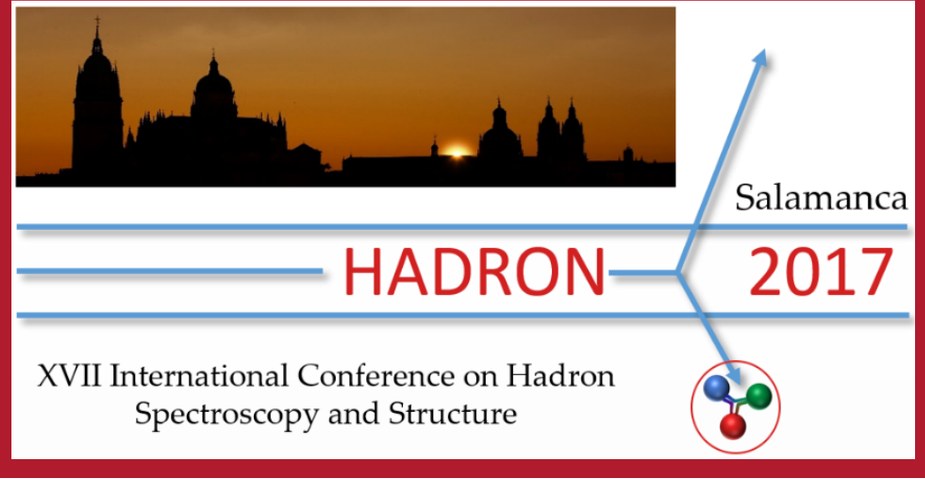
Miguel Albaladejo (U. Murcia)

In collaboration with:
B. Moussallam (IPN, Orsay)



Results: Dalitz plot parameters

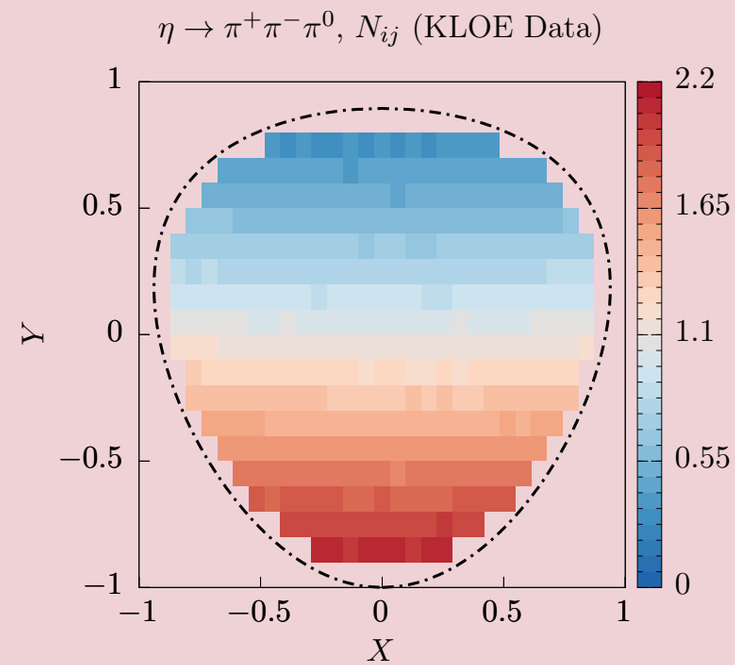
- DP variables X,Y: $X = \frac{\sqrt{3}}{2m_\eta\, Q_c}(u-t),\ Y = \frac{3}{2m_\eta\, Q_c}\left((m_\eta - m_{\pi^0})^2 - s\right) - 1$

- Charged mode amplitude written as:

$$\frac{|M_c(X,Y)|^2}{|M_c(0,0)|^2} = \boxed{1 + a\,Y + b\,Y^2 + d\,X^2 + f\,Y^3 + g\,X^2 Y} + \cdots$$

- Neutral decay mode amplitude $[Q_c \to Q_n]$:

$$\frac{|M_n(X,Y)|^2}{|M_n(0,0)|^2} = \boxed{1 + 2\alpha\,|z|^2 + 2\beta\,\mathrm{Im}(z^3)} + \cdots$$



		$O(p^4)$	elastic	coupled	KLOE	BESIII
charged	a	-1.328	-1.156	-1.142(45)	-1.095(4)	-1.128(15)
	b	0.429	0.200	0.172(16)	0.145(6)	0.153(17)
	d	0.090	0.095	0.097(13)	0.081(7)	0.085(16)
	f	0.017	0.109	0.122(16)	0.141(10)	0.173(28)
	g	-0.081	-0.088	-0.089(10)	-0.044(16)	–
neutral					PDG	
	α	+0.0142	-0.0268	-0.0319(34)	-0.0318(15)	
	β	-0.0007	-0.0046	-0.0056	–	

BESIII Collab., Phys. Rev. D**92**,012014 (2015)
KLOE-2 Collab., JHEP **1605**, 019 (2016)

- (Theory) **uncertainty estimation**:
  1. $\eta\pi$ interaction put to zero or to "large"
  2. $10^3 L_3^r = -3.82 \to -2.65$
- General trend: **improve agreement** $[\mathcal{O}(p^4) \to \text{elastic} \to \text{coupled}]$
- Particularly relevant: α.

Results. Quark mass ratio Q

From the amplitudes $M_l(s)$ one can compute the width up to the unknown factor Q^2:

$$\Gamma = \epsilon_L^2 \int_{4m_\pi^2}^{m_-^2} \mathrm{d}s \int_{t_-(s)}^{t_+(s)} \mathrm{d}t \, |M_0(s) + \cdots|^2$$

$$\epsilon_L = Q^{-2} \frac{m_K^2 - m_\pi^2}{3\sqrt{3} f_\pi^2} \frac{m_K^2}{m_\pi^2} \,, \quad Q^{-2} = \frac{m_d^2 - m_u^2}{m_s^2 - \hat{m}^2}$$

$\Gamma(\eta \to 3\pi^0)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$	
PDG (fit)	1.426(26)
PDG (average)	1.48(5)
CLEO	1.496(43)(35)
chiral $\mathcal{O}(p^4)$	1.425
elastic	1.449
coupled	1.451

Decay	Q elastic	Q coupled
$\Gamma^{(\mathrm{exp})}_{(\mathrm{neu.})} = 299(11)$ eV	21.9(2)	21.7(2)
$\Gamma^{(\mathrm{exp})}_{(\mathrm{cha.})} = 427(15)$ eV	21.8(2)	21.6(2)

- Effect of inelastic channels $\sim 1\%$ (decreasing)
- Theoretical error on Q:
  - Phase shifts [$s \leqslant 1$ GeV^2]: $\sim 1\%$
  - $\mathcal{O}(p^4)$ ampl. [L_3]: $\sim 1\%$
  - NNLO ampl.: $\Delta Q_{\mathrm{th.}} = \pm 2.2$

$$Q = 21.6 \pm 0.2 \pm 2.2$$

- Fitted (not matched) polynomial parameters:

$$Q_{\mathrm{fit}} = 21.50 \pm 0.67 \pm 0.70$$

PATTERNS AND PARTNERS FOR CHIRAL SYMMETRY RESTORATION

Angel Gómez Nicola

Universidad Complutense Madrid, Spain

OUTLINE:

- $U(3)$ **Ward Identities:** $O(4)$ **vs** $O(4) \times U(1)_A$**, chiral partners**
- **WI and scaling of meson screening masses**
- **Hadron realization: ChPT, role of thermal** $\sigma/f_0(500)$ **pole**

AGN, R.Torres Andrés, J.Ruiz de Elvira, PRD88, 076007 (2013)
AGN, J.Ruiz de Elvira, JHEP 1603 (2016) 186, arXiv:1704.05036

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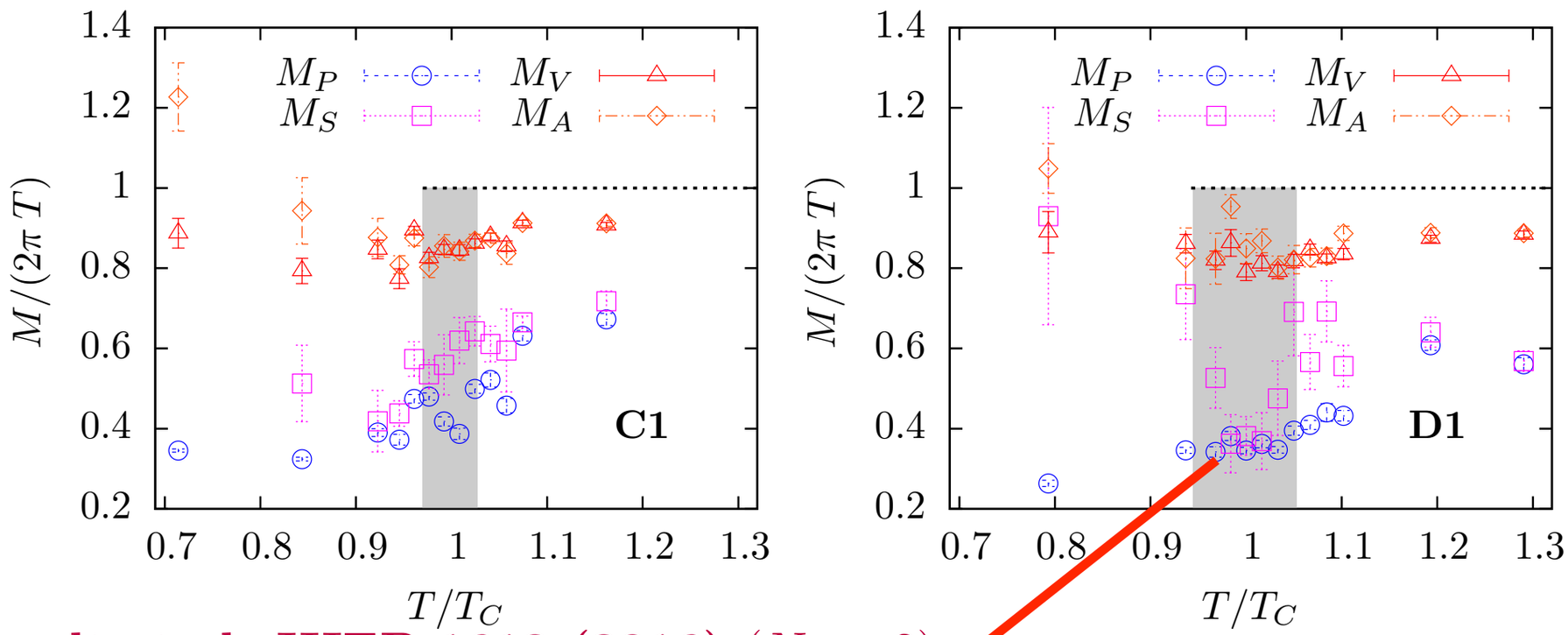
Chiral Patterns and Partners



Brandt et al, JHEP 1612 (2016) $(N_f = 2)$

$U_A(1)$ **restored at** $T_c \Longrightarrow O(4) \times U_A(1)$ **pattern**

$$\begin{array}{ccc} \pi^a = \bar{\psi}_l \gamma_5 \tau^a \psi_l & \overset{SU_A(2)}{\longleftrightarrow} & \sigma = \bar{\psi}_l \psi_l \\ \updownarrow U_A(1) & & \updownarrow U_A(1) \\ \delta^a = \bar{\psi}_l \tau^a \psi_l & \overset{SU_A(2)}{\longleftrightarrow} & \eta_l = \bar{\psi}_l \gamma_5 \psi_l \end{array}$$

About the structure of the proton at very low momentum

Antonio Pineda

Universitat Autònoma de Barcelona & IFAE

HADRON 2017, Salamanca, September 25-29 2017

	$\mathcal{O}(m_r\alpha^3)$	$V_{\rm VP}^{(0)}$	205. 00737
	$\mathcal{O}(m_r\alpha^4)$	$V_{\rm VP}^{(0)}$	1. 50795
	$\mathcal{O}(m_r\alpha^4)$	$V_{\rm VP}^{(0)}$	0. 15090
	$\mathcal{O}(m_r\alpha^5)$	$V_{\rm VP}^{(0)}$	0. 00752
	$\mathcal{O}(m_r\alpha^5)$	$V_{\rm LbL}^{(0)}$	−0. 00089(2)
	$\mathcal{O}(m_r\alpha^4 \times \frac{m_\mu^2}{m_p^2})$	$V^{(2,1)} + V^{(3,0)}$	0. 05747
	$\mathcal{O}(m_r\alpha^5)$	$V_{\rm VP}^{(2,2)} + V^{(2,1)} \times V_{\rm VP}^{(0,2)}$	0. 01876
	$\mathcal{O}(m_r\alpha^5)$	$V_{\rm no-VP}^{(2,2)} + \text{ultrasoft}$	−0. 71896
	$\mathcal{O}(m_r\alpha^6 \times \ln(\frac{m_\mu}{m_e}))$	$V^{(2,3)}; c_D^{(\mu)}$	−0. 00127
	$\mathcal{O}(m_r\alpha^6 \times \ln\alpha)$	$V_{\rm VP}^{(2,3)}; c_D^{(\mu)}$	−0. 00454
	$\mathcal{O}(m_r\alpha^4 \times m_r^2 r_p^2)$	$V^{(2,1)}; c_D^{(p)}$	$-5.\ 1975\,\frac{r_p^2}{\rm fm^2}$
	$\mathcal{O}(m_r\alpha^5 \times m_r^2 r_p^2)$	$V_{\rm VP}^{(2,2)} + V^{(2,1)} \times V_{\rm VP}^{(0,2)}; c_D^{(p)}$	$-0.\ 0282\,\frac{r_p^2}{\rm fm^2}$
	$\mathcal{O}(m_r\alpha^6 \ln\alpha \times m_r^2 r_p^2)$	$V^{(2,3)}; c_D^{(p)}$	$-0.\ 0014\,\frac{r_p^2}{\rm fm^2}$
	$\mathcal{O}(m_r\alpha^5 \times \frac{m_r^2}{m_\rho^2})$	$V_{\rm VP_{had}}^{(2)}; d_2^{\rm had}$	0. 0111(2)
	$\mathcal{O}(m_r\alpha^5 \times \frac{m_r^2}{m_\rho^2}\frac{m_\mu}{m_\pi})$	$V^{(2)}; c_3^{\rm had}$	0. 0344(125)

$$\Delta E_L^{\rm th} = \left[206.0243(30) - 5.2270(7)\frac{r_p^2}{\rm fm^2} + 0.0455(125)\right] \,{\rm meV}\,.$$

This expression includes the leading logarithmic $\mathcal{O}(m_\mu \alpha^6)$ terms, as well as the leading $\mathcal{O}\left(m_\mu \alpha^5 \frac{m_\mu^2}{m_\rho^2}\right)$ hadronic effects. The accuracy of our result is limited by uncomputed terms of $\mathcal{O}(m_\mu \alpha^5 \frac{m_\mu^3}{m_\rho^3}, m_\mu \alpha^6)$.
Using

$$\Delta E_L^{\rm exp} \equiv E(2P_{3/2}) - E(2S_{1/2}) = 202.3706(23)\,{\rm meV} \quad \text{Antognini et al.}$$

$$r_p = 0.8413(15)\,{\rm fm}.$$

At 6.8σ variance with respect the CODATA value.

r_p = 0.8335(95) fm **Beyer et al. 2017**

Roy-Steiner-equation analysis of pion-nucleon scattering

J. Ruiz de Elvira

Institute for Theoretical Physics, University of Bern

In collaboration with:

M. Hoferichter, B. Kubis, U.-G. Meißner.

PRL 115 (2015) 092301, PRL 115 (2015) 192301 , Phys.Rept. 625 (2016), Phys.Lett. B760 (2016) 74-78, Eur. Phys. J. A52 (2016), 331, Phys. Lett. B770, (2017), arXiv:1706.01465

HADRON 2017, Salamanca, September 26th, 2017

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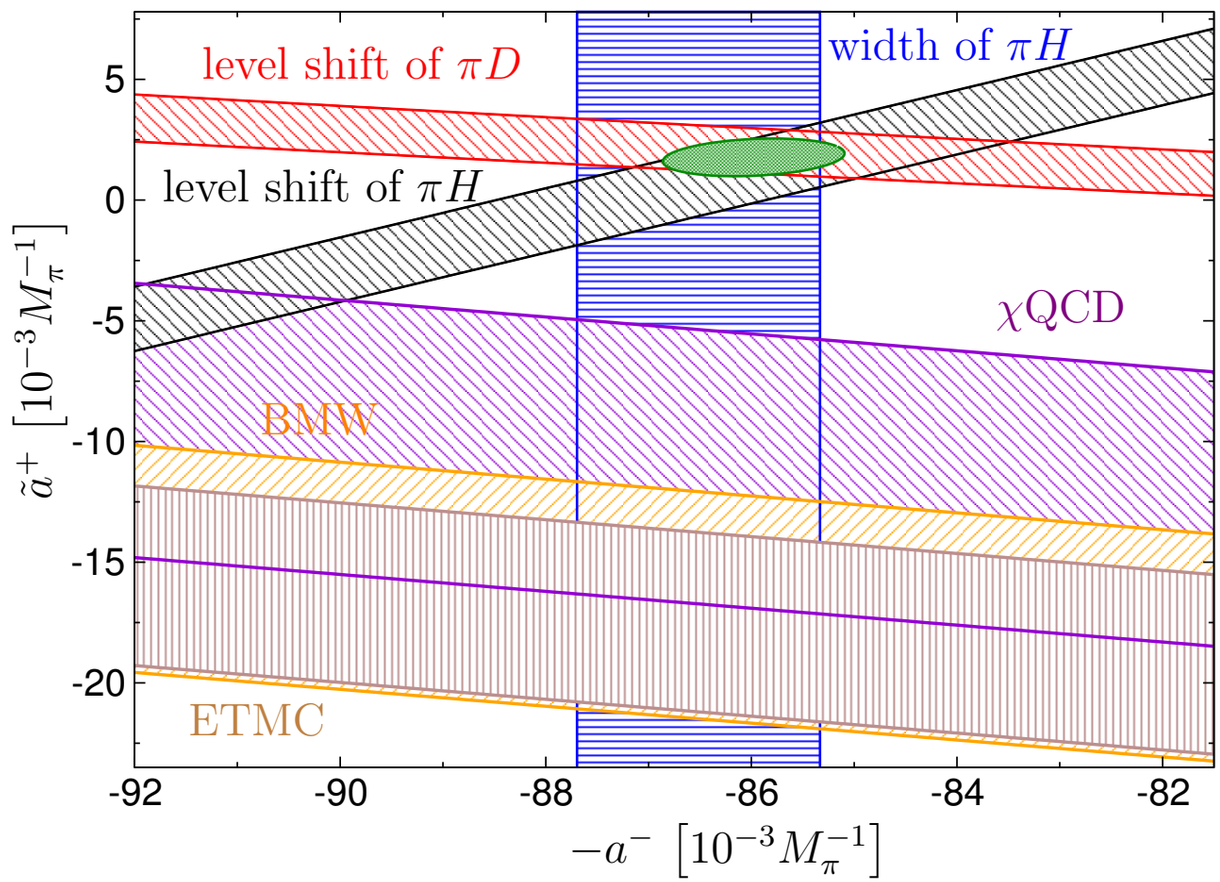
FOR FUNDAMENTAL PHYSICS

Comparison with lattice $\sigma_{\pi N}$ results

- Recent lattice determination of $\sigma_{\pi N}$ at (almost) the physical point
  - ▷ BMW $\sigma_{\pi N} = 38(3)(3)$MeV [Durr et al. 2015]
  - ▷ χQCD $\sigma_{\pi N} = 44.4(3.2)(4.5)$MeV [Yang et al. 2015]
  - ▷ ETMC $\sigma_{\pi N} = 37.22(2.57)(1)$MeV [Abdel-Rehim et al. 2015]
  - ▷ RQCD $\sigma_{\pi N} = 35(6)$MeV [Bali et al. 2016]

Phenomenology: $\sigma_{\pi N} = 59(7)\ \mathrm{MeV}$ **[Alarcón et al. 2011]** $\sigma_{\pi N} = 59.1(3.5)\ \mathrm{MeV}$ **[Hoferichter et al. 2015]**

- The linear dependence of $\sigma_{\pi N}$ on the scattering lengths introduces an additional constraint



- Inconsistent with the hadronic atom phenomenology

$\hookrightarrow$ determine the πN scattering lengths in the lattice

Extracting the σ-term from experimental cross-section data

- Linearized version of RS $d\sigma/d\Omega$ around the HA scattering lengths
- Unbiased fit to the pion-nucleon data base $\Rightarrow$ normalizations constants as fit parameters
- minimize the χ^2-like as a function of a_{0+}^{I} and ζ

$$\chi^2(a, a_0, \zeta, \zeta_0, \Delta\zeta_0) = \sum_{k=1}^{N} \chi_k^2(a, a_0, \zeta, \zeta_0, \Delta\zeta_0),$$

$$\chi_k^2(a, a_0, \zeta, \zeta_0, \Delta\zeta_0) = \sum_{i,j=1}^{N_k} \left(\zeta_k^{-1}\sigma(W_i^k, a) - \sigma_i^k\right)\left(C_k^{-1}(a_0, \zeta_0, \Delta\zeta_0)\right)_{ij}\left(\zeta_k^{-1}\sigma(W_j^k, a) - \sigma_j^k\right),$$

$$\left(C_k(a_0, \zeta_0, \Delta\zeta_0)\right)_{ij} = \delta_{ij}\left(\Delta\sigma_i^k\right)^2 + \sigma(W_i^k, a_0)\sigma(W_j^k, a_0)\left(\frac{\Delta\zeta_{0,k}}{\zeta_{0,k}^2}\right)^2, \tag{1}$$

channel	SL combination	result	HA SL	KH80 SL
$\pi^+p \to \pi^+p$	$a_{0+}^{3/2}$	-84.4 ± 1.5	-86.3 ± 1.8	-101 ± 4
$\pi^-p \to \pi^-p$	$(2a_{0+}^{1/2} + a_{0+}^{3/2})/3$	82.5 ± 1.5	84.4 ± 1.7	81.6 ± 2.4
$\pi^-p \to \pi^0n$	$-\sqrt{2}(a_{0+}^{1/2} - a_{0+}^{3/2})/3$	-122.3 ± 3.4	-120.7 ± 1.3	-129.2 ± 2.4

A non-comprehensive and subjective summary of HADRON 2017

Vincent MATHIEU

Jefferson Lab
-
Joint Physics Analysis Center

JLab 'cake seminar'
Jefferson Lab - October 2017

INDIANA UNIVERSITY

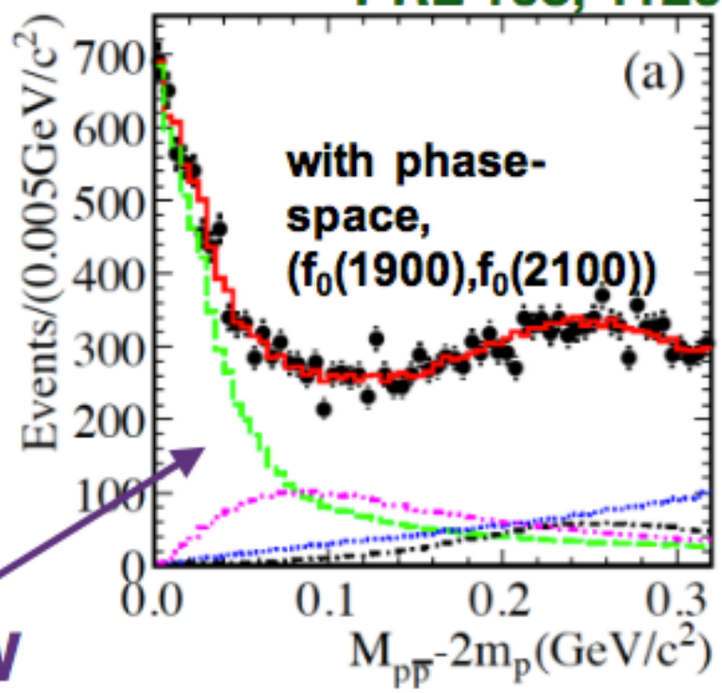
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Light Quarks Meson Spectroscopy
BESIII, COMPASS, GlueX

BES III: States In 1.8 — 1.9 GeV Mass Region

PWA of $J/\psi \to \gamma\, p\bar{p}$

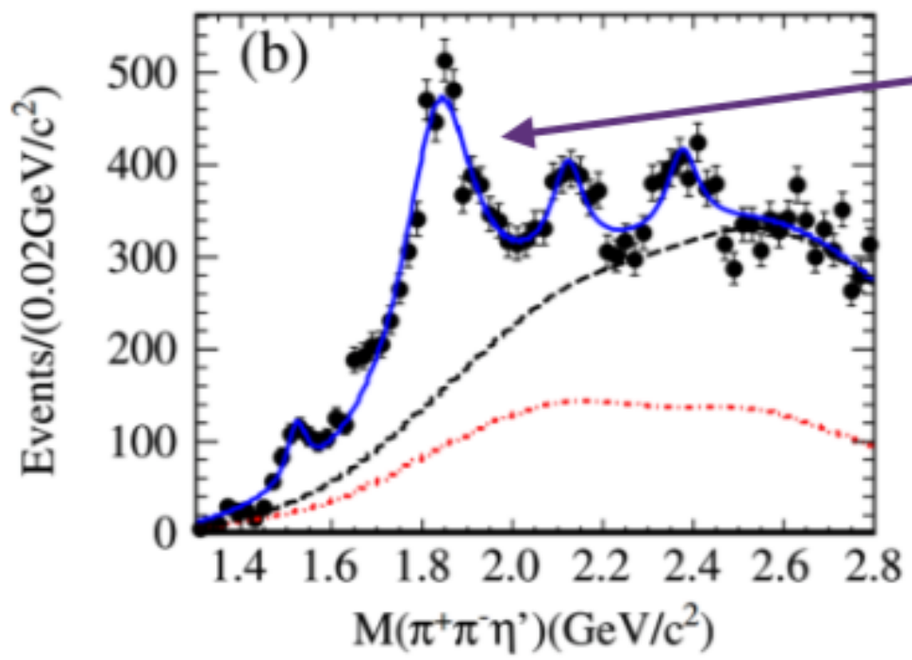
PRL 108, 112003 (2012)



$p\bar{p}$ BW
$J^{PC} = 0^{-+}$

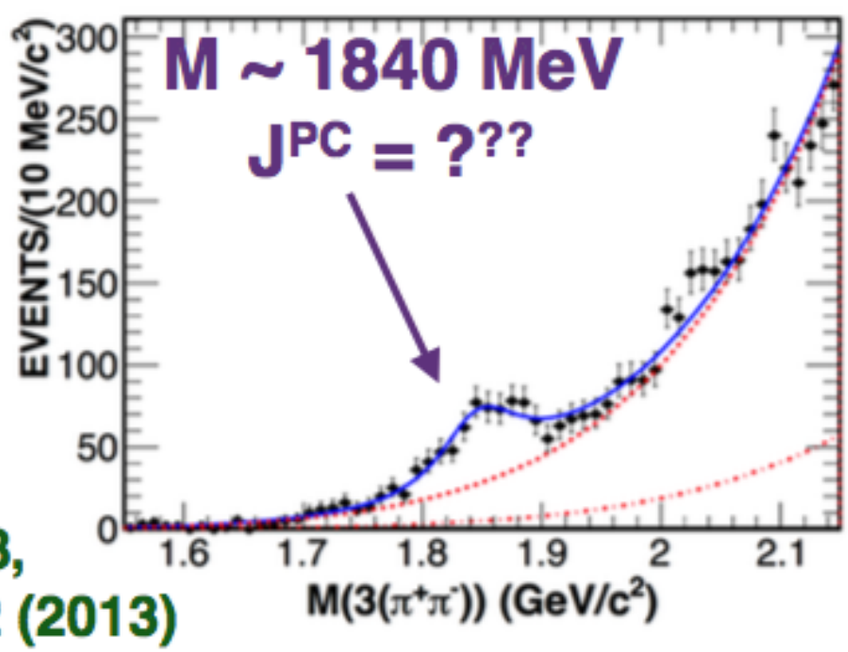
$J/\psi \to \gamma\, \eta'\pi^+\pi^-$

PRL 106, 072002 (2011)



X(1835)
$J^{PC} = 0^{-+}$

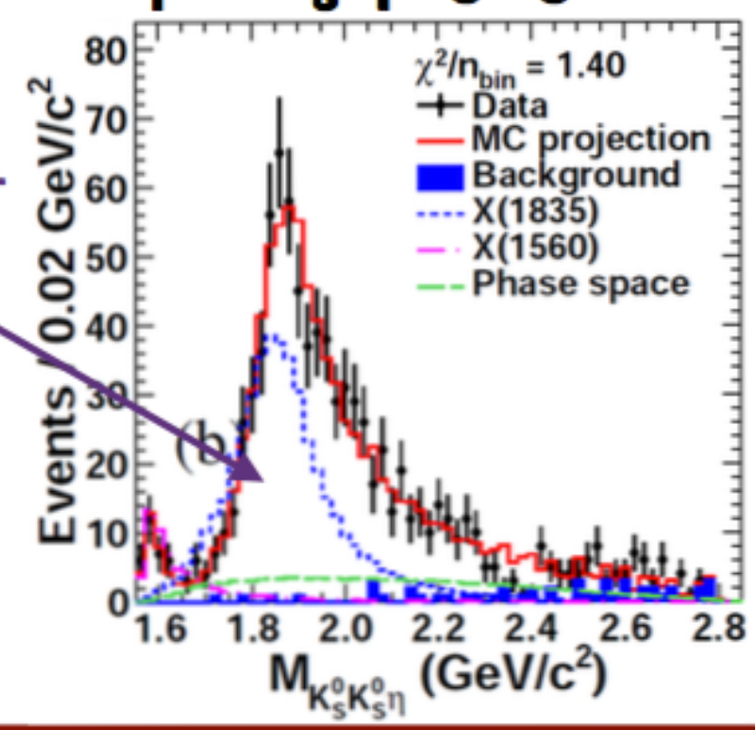
$J/\psi \to \gamma\, 3(\pi^+\pi^-)$



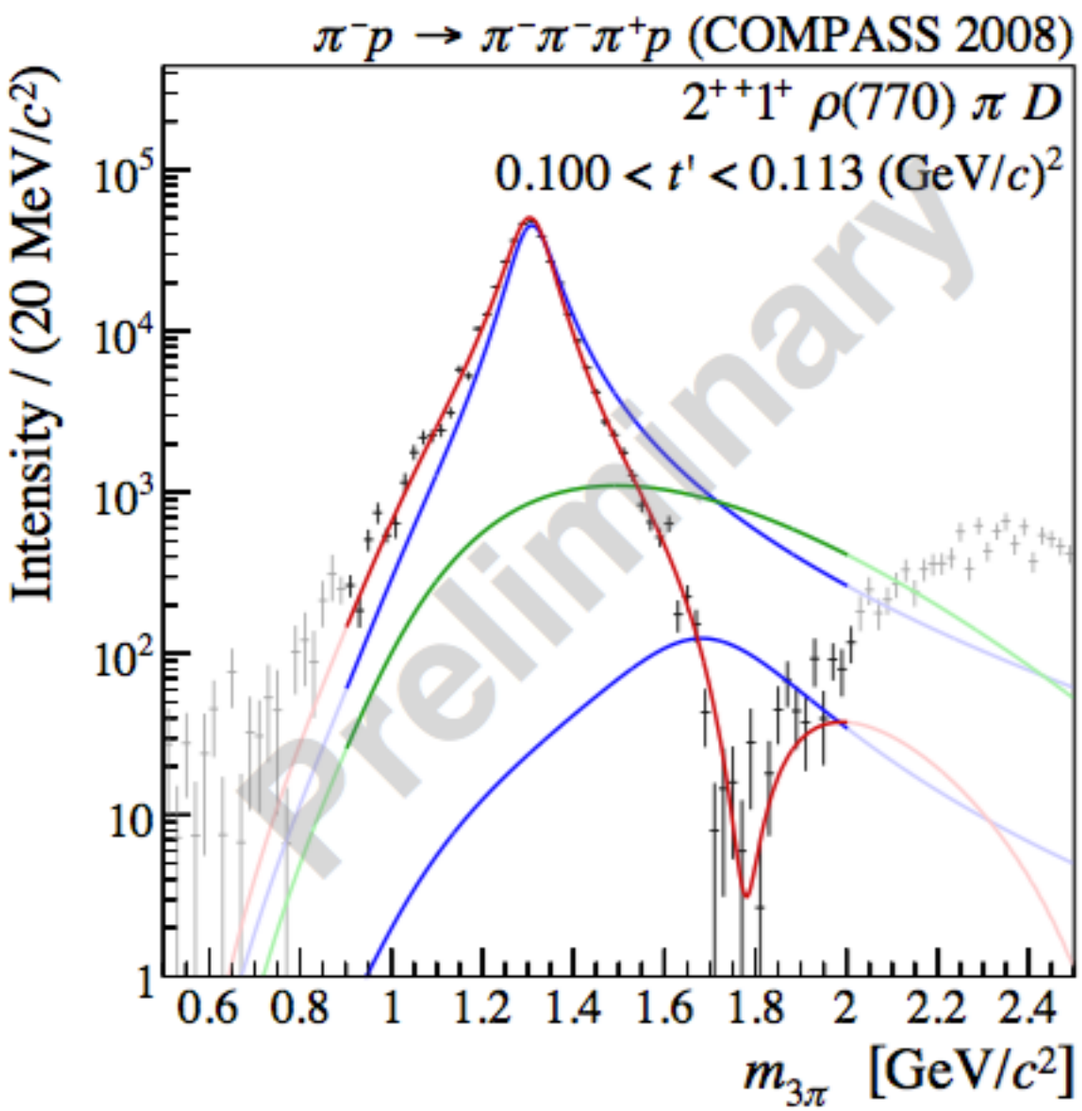
PRD 88, 091502 (2013)

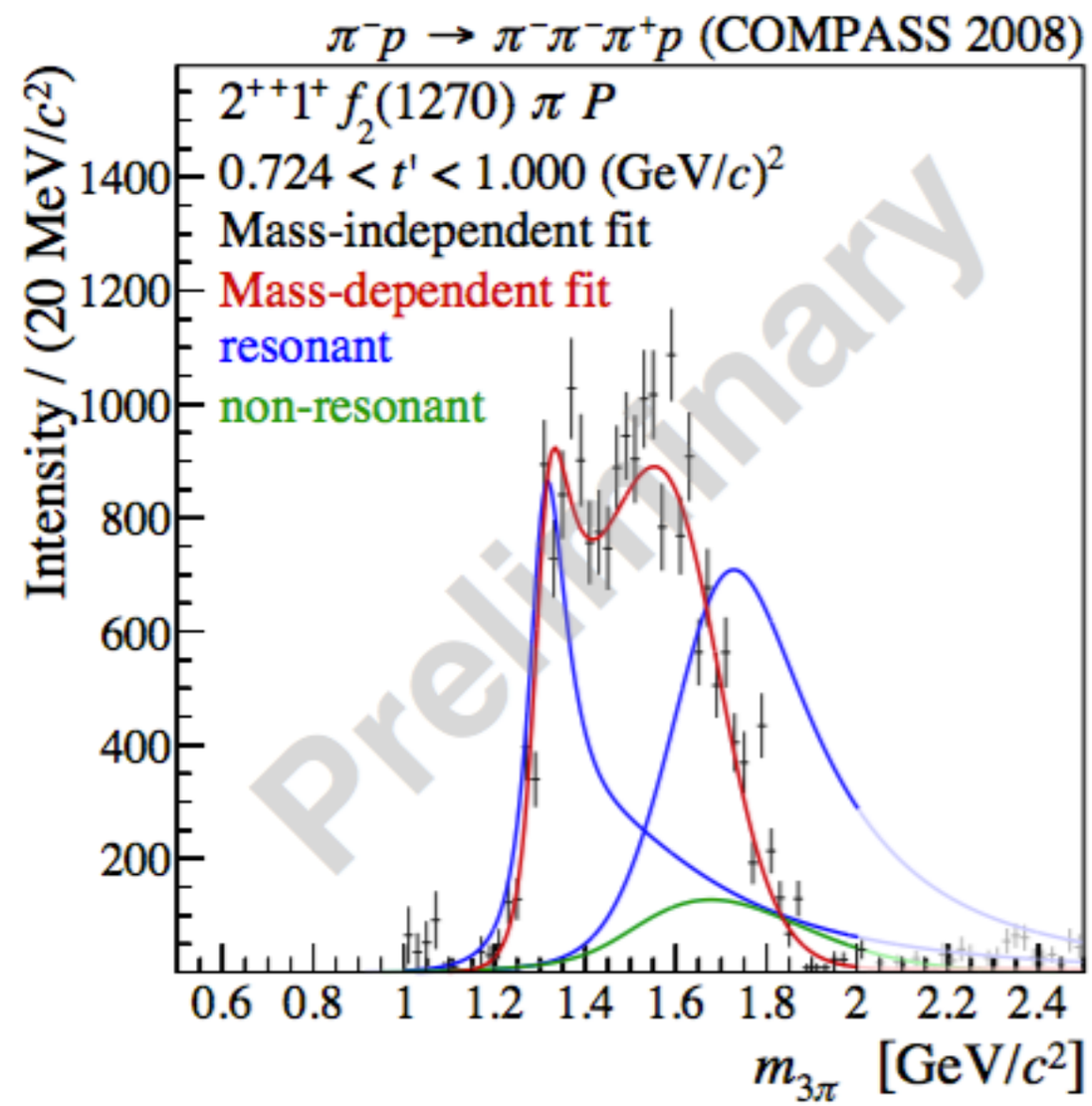
$J/\psi \to \gamma\eta K_S K_S$

X(1835)
$J^{PC} = 0^{-+}$



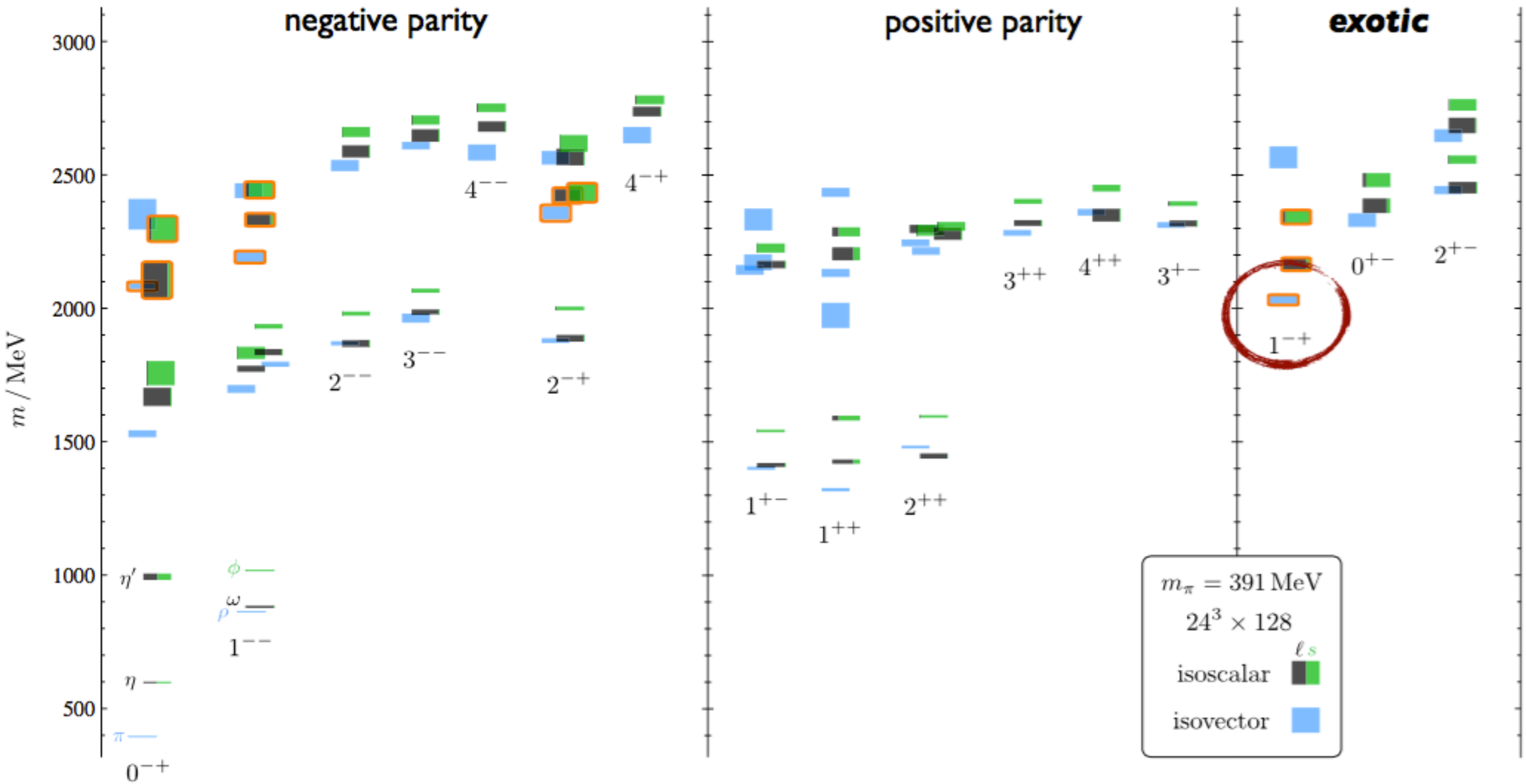
PRL 115, 091803 (2015)


$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)
$2^{++}1^+$ $\rho(770)$ π D
$0.100 < t' < 0.113$ (GeV/c)^2
Intensity / (20 MeV/c^2)
$m_{3\pi}$ [GeV/c^2]
Preliminary


$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)
$2^{++}1^+$ $f_2(1270)$ π P
$0.724 < t' < 1.000$ (GeV/c)^2
Mass-independent fit
Mass-dependent fit
resonant
non-resonant
Intensity / (20 MeV/c^2)
$m_{3\pi}$ [GeV/c^2]
Preliminary

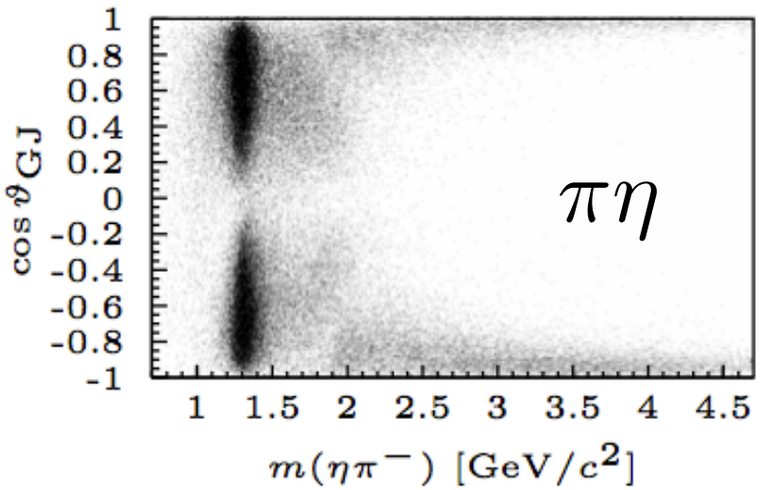
Exotic J^{PC} Candidates

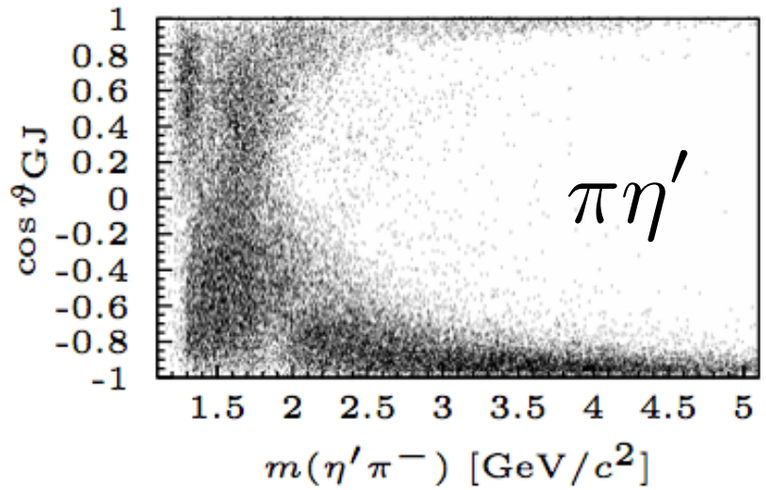
Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)

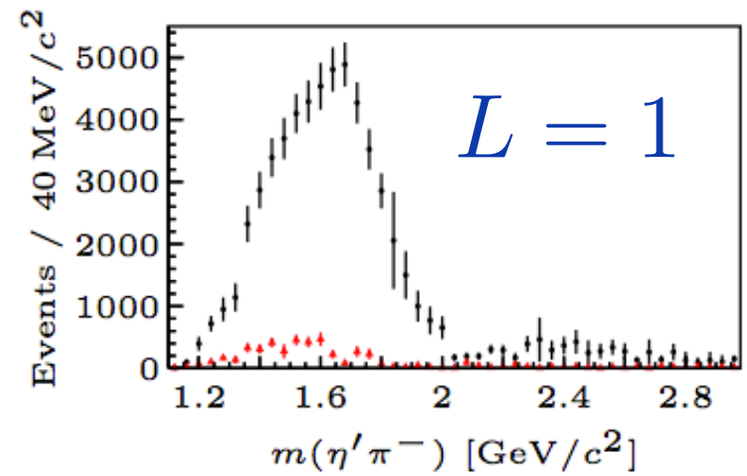


Eta-Pi @COMPASS

COMPASS Phys. Lett. B740 (2015)



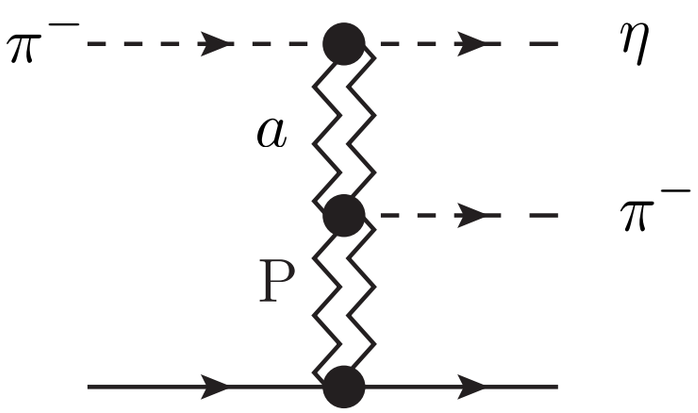




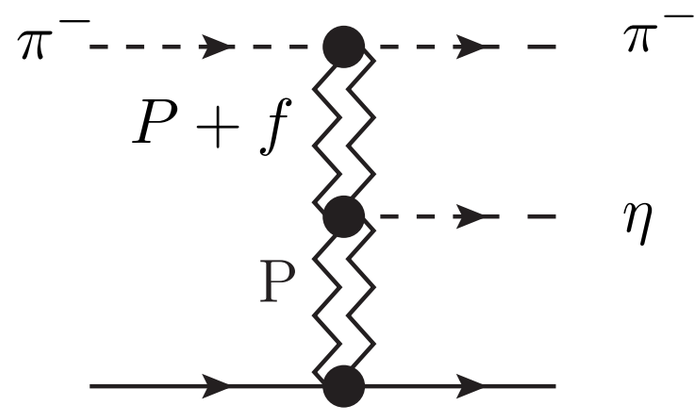
black: $\pi\eta'$

red: $\pi\eta$ **(scaled)**

Resonance in L = 1 ?
JPC = 1-+



$\cos\theta_{GF} \sim 1 \rightarrow \eta$ forward



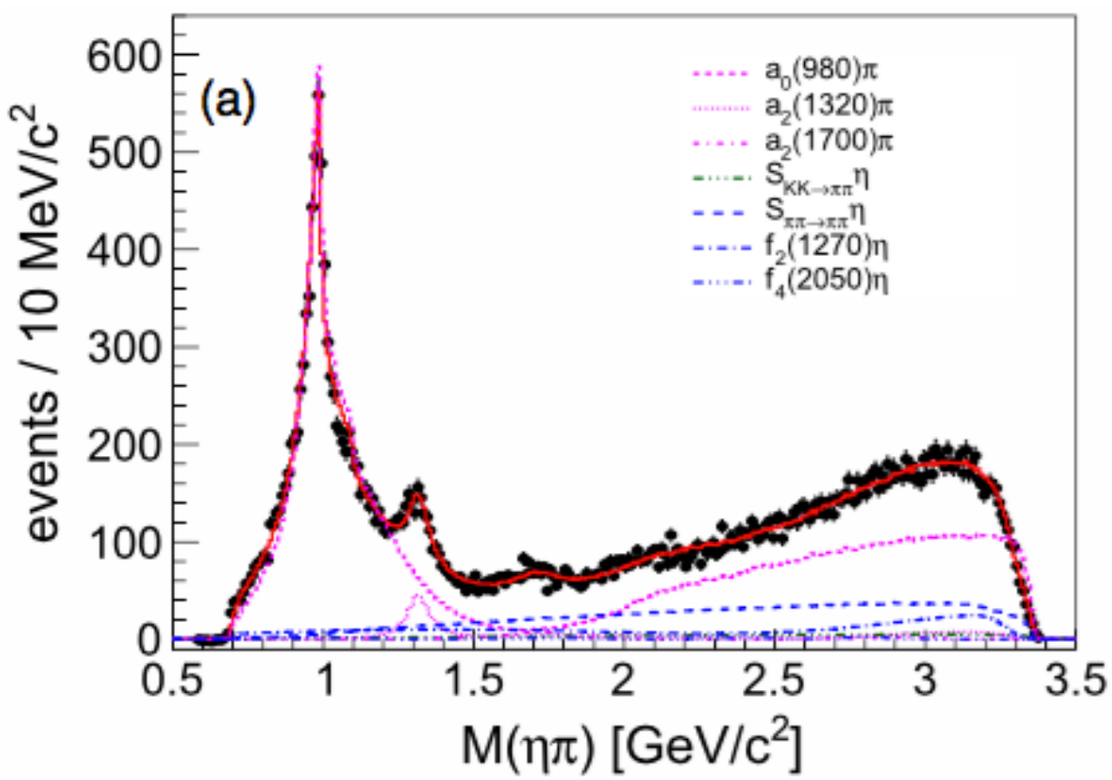
$\cos\theta_{GF} \sim -1 \rightarrow \eta$ backward

Hypothesis: exchanges $a \sim f$

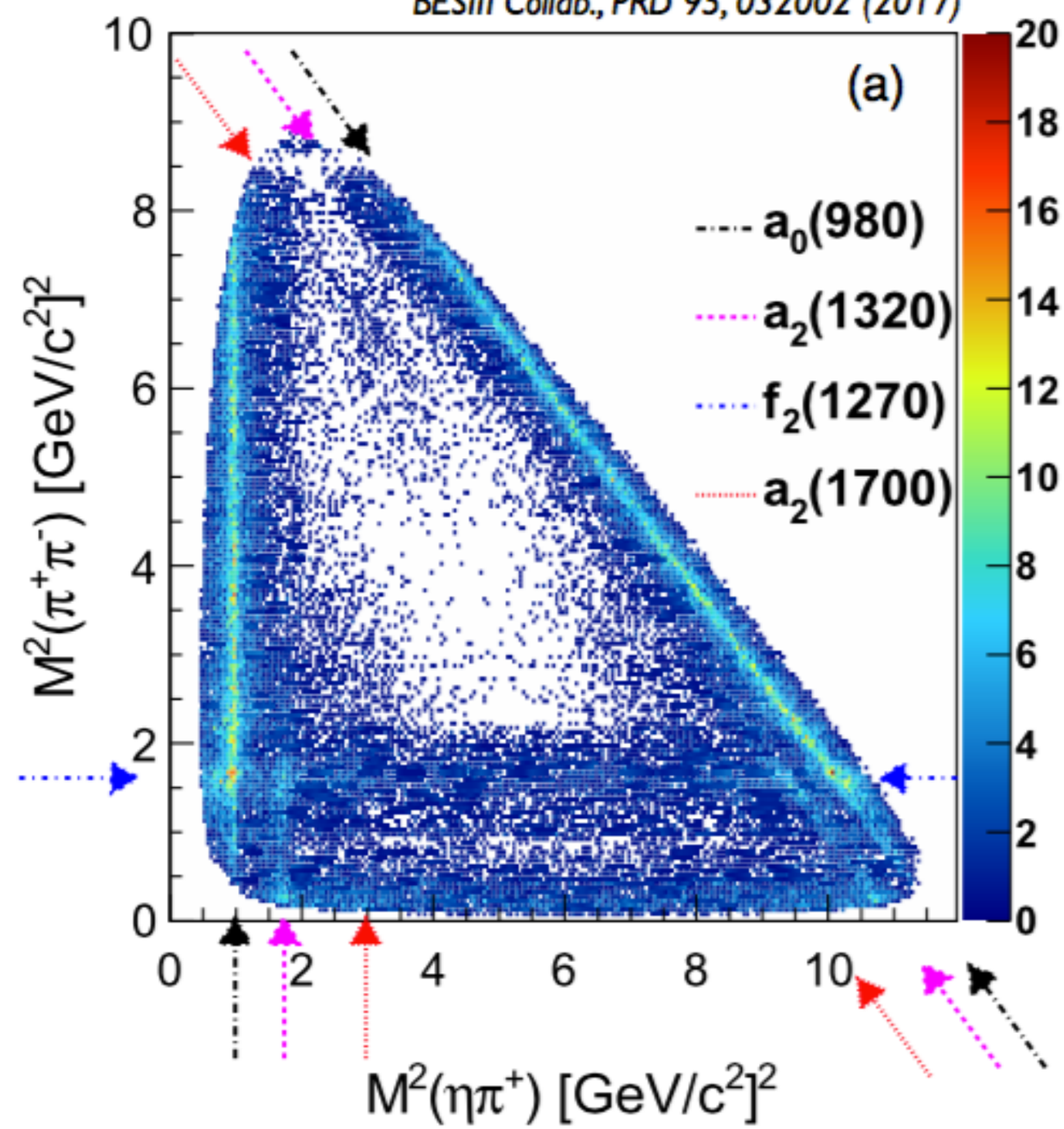
eta' couples more to Pomeron than eta

Complementary Production: $\chi_{c1} \to \eta\pi\pi$

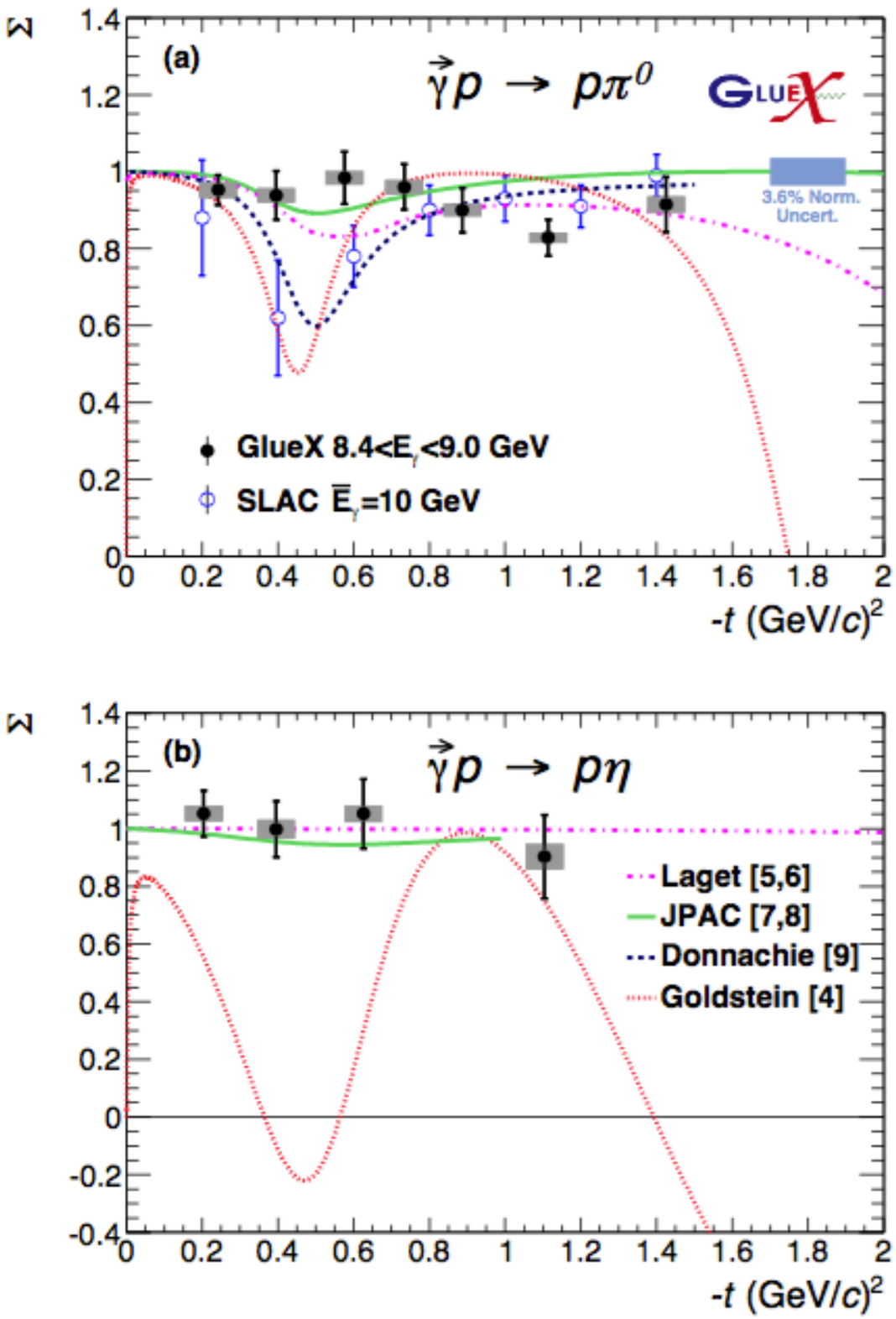
- Additional evidence for the of a_2'
- No evidence for $\pi_1 \to \eta\pi$
- CLEO reported *P*-wave $\eta'\pi$ in $\chi_{c1} \to \eta'\pi\pi$ [*CLEO Collab., PRD 84, 112009 (2011)*]
  - can be explored at BESIII with better statistical precision



BESIII Collab., PRD 95, 032002 (2017)

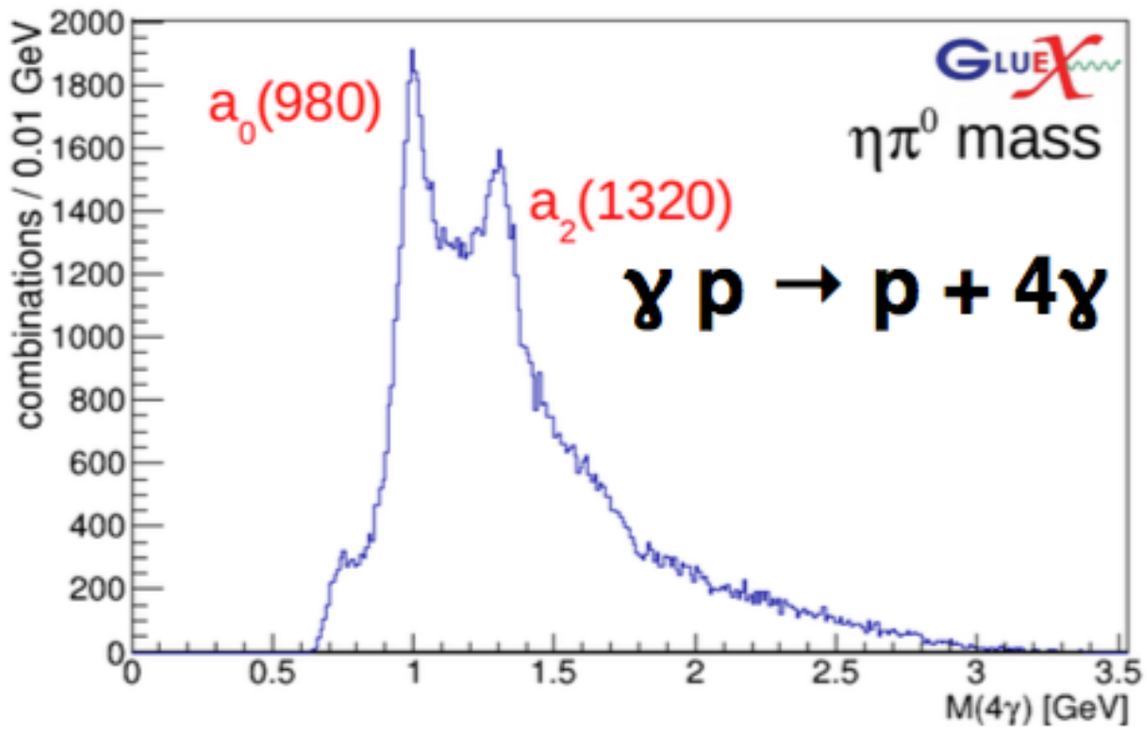


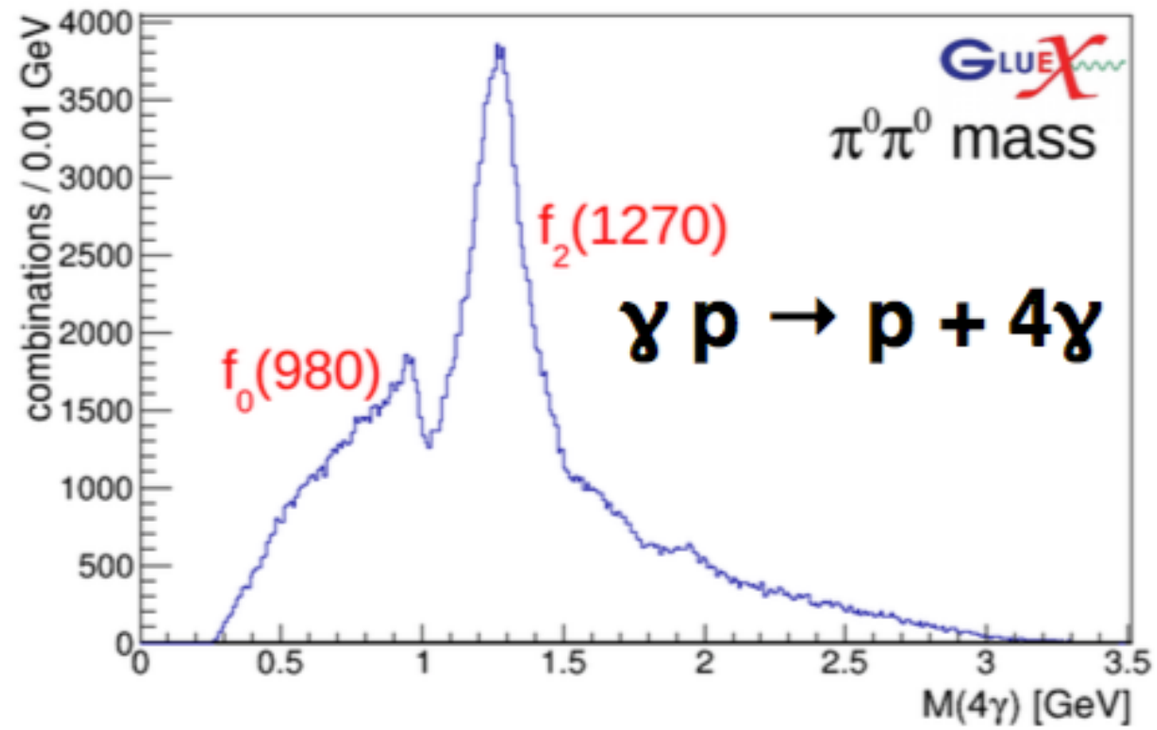
GlueX: Beam Asymmetries in $\gamma p \rightarrow p + \pi^0 / \eta$

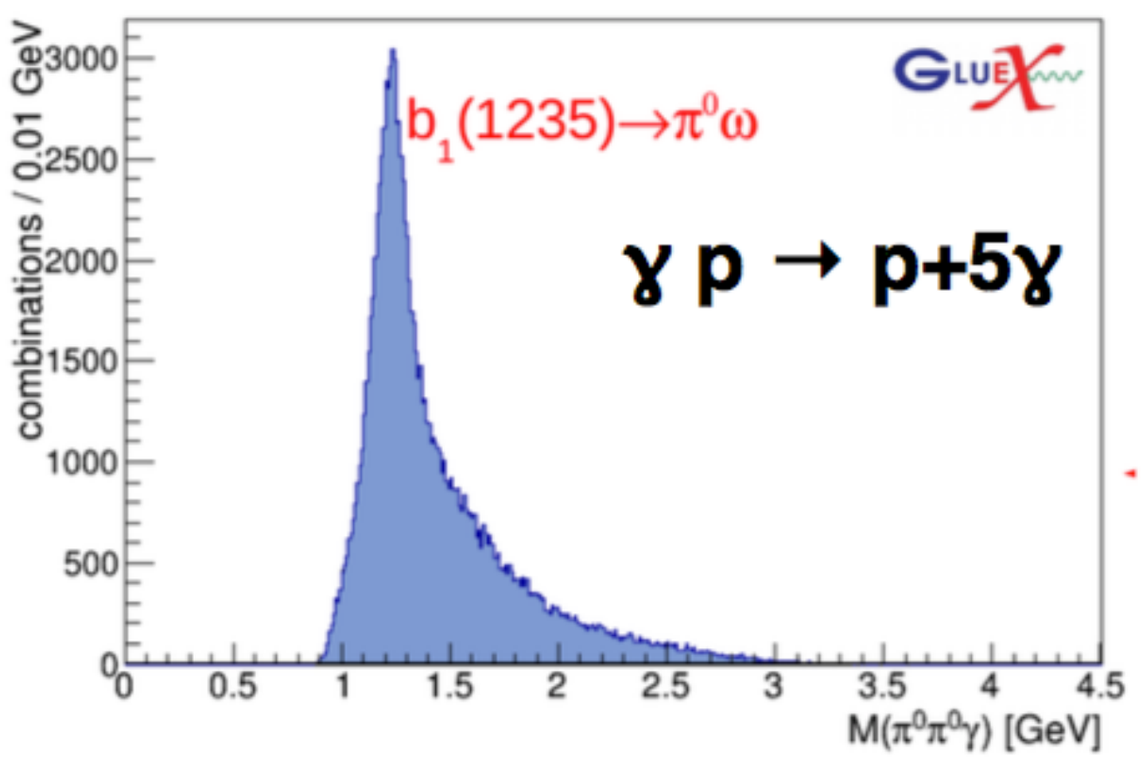


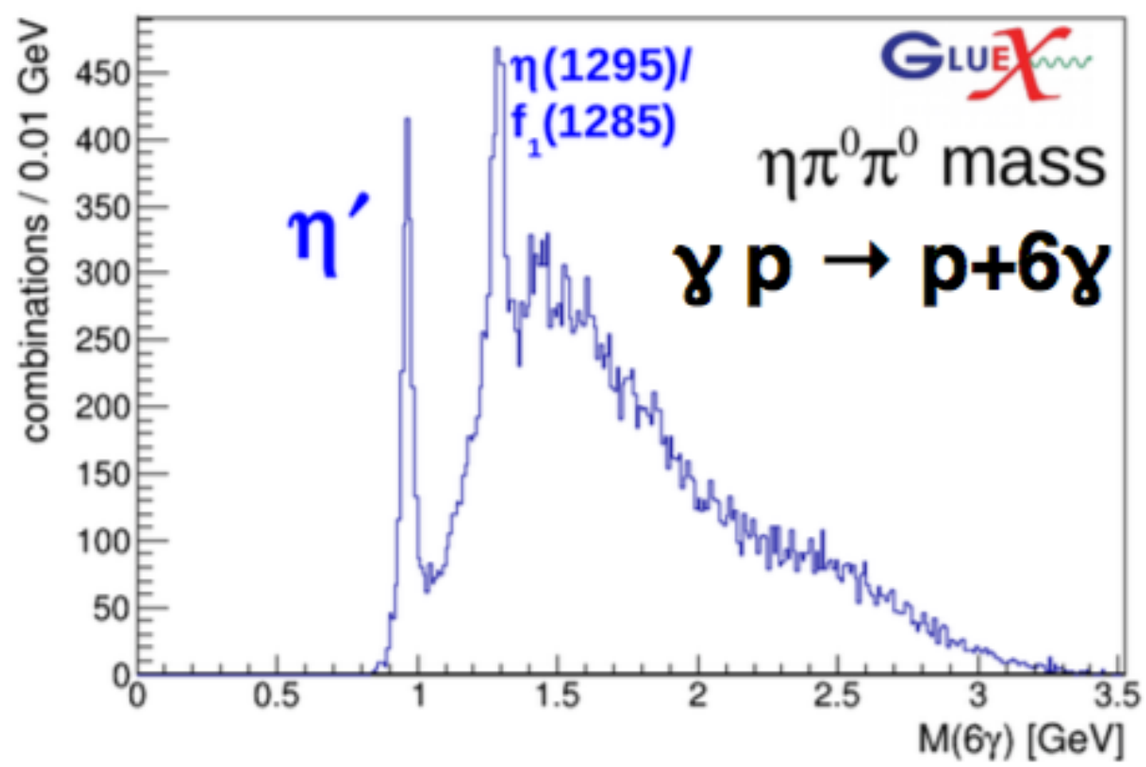
- Study of beam asymmetry Σ variation with t provides information on production mechanism
- **First GlueX paper!**
  H. Al Ghoul et al, PRC 95, 042201
- First η measurement at this energy
  - Expect other asymmetries with current data
  - On way towards detailed understanding of production mechanism

GlueX: Meson Spectroscopy Prospects: γ p → p + (4,5,6)γ



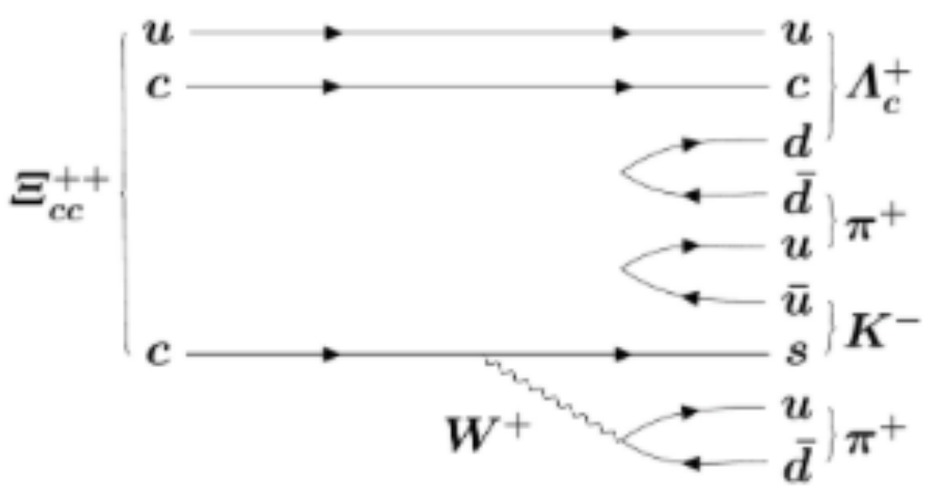


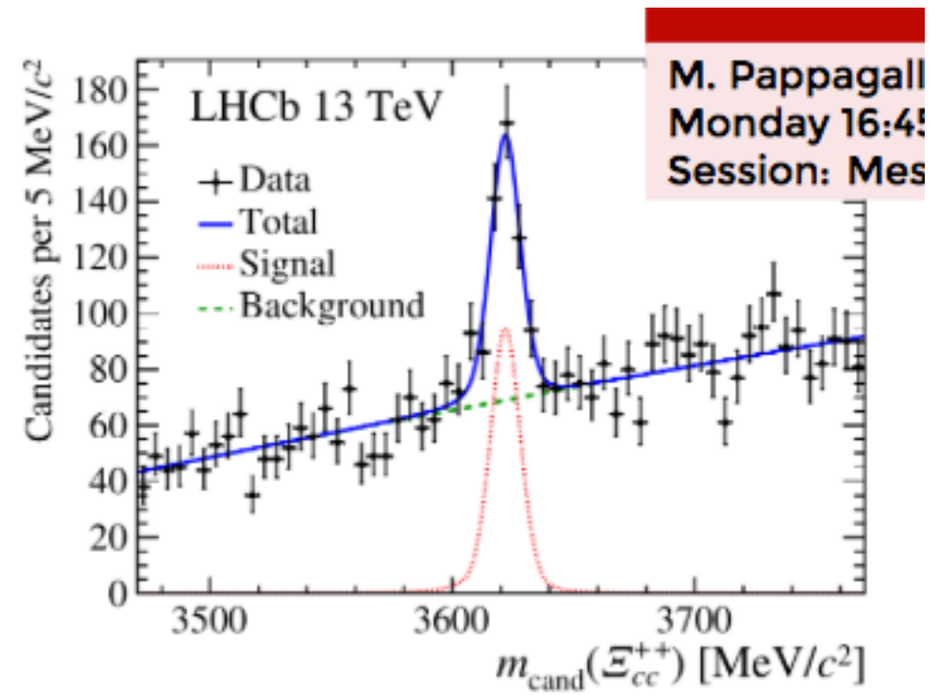




Heavy Quarks Baryon Spectroscopy

S. Neubert: Heavy Baryons@LHCb





with $\Lambda_c^+ \to pK^-\pi^+$

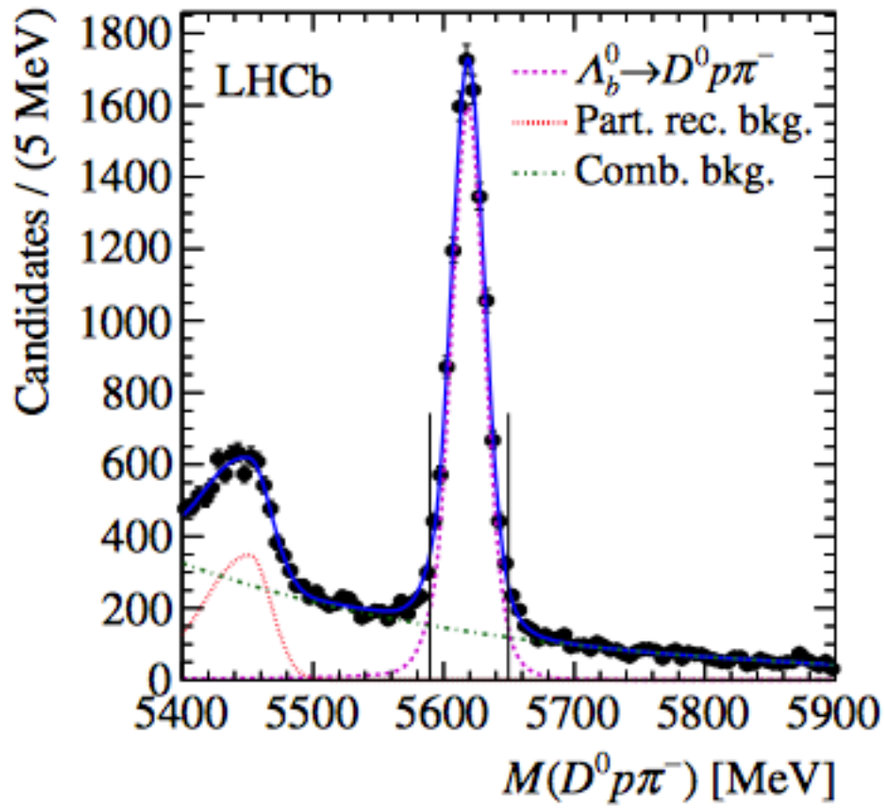
Method	$m_{\Xi_{cc}^{++}}$ [MeV/c^2]	Reference
Experiment	$3621.40 \pm 0.72 \pm 0.27 \pm 0.14$	[PRL119(2017)112001]
Effective potential	3627 ± 12	[PRD90(2014)094007]
Relativized Quark Model	3613	arXiv:1708.04468
Relativistic Quark Model	3620	[PRD66(2002)014008]
Lattice QCD	$3610 \pm 23 \pm 22$	[PRD90(2014)094507]
HQ effective theory	3610	[Pr. Part. Nucl. Phys. 33(1994)787]

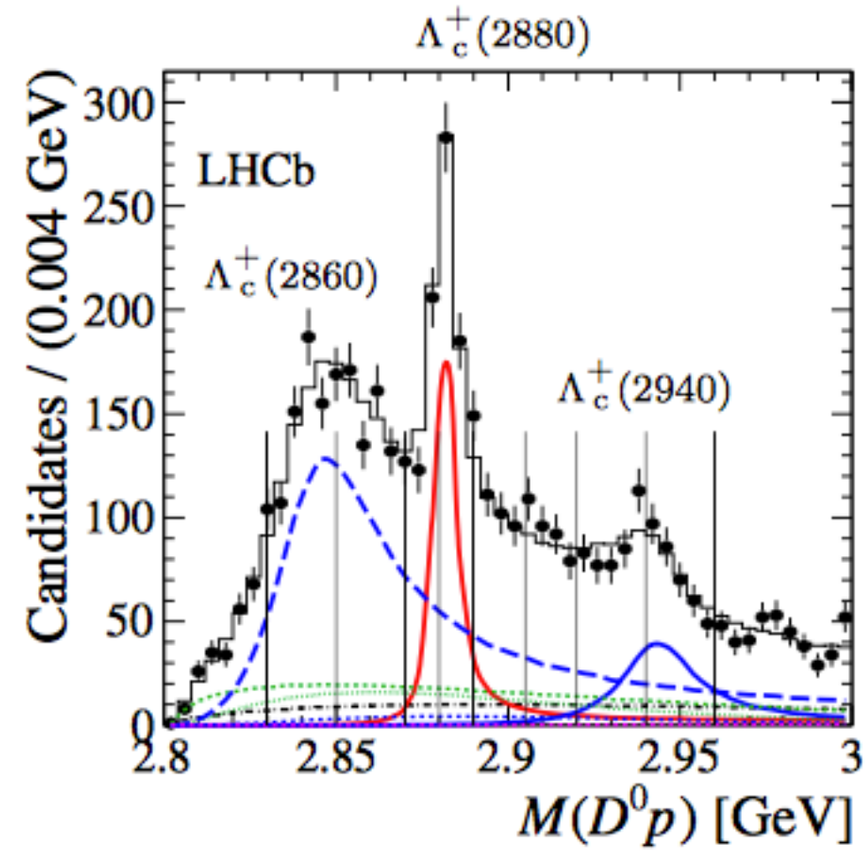
S. Neubert: Heavy Baryons@LHCb

$\Lambda_c^+(2880)$

in the decay chain

$\Lambda_b \to D^0 p \pi^-$

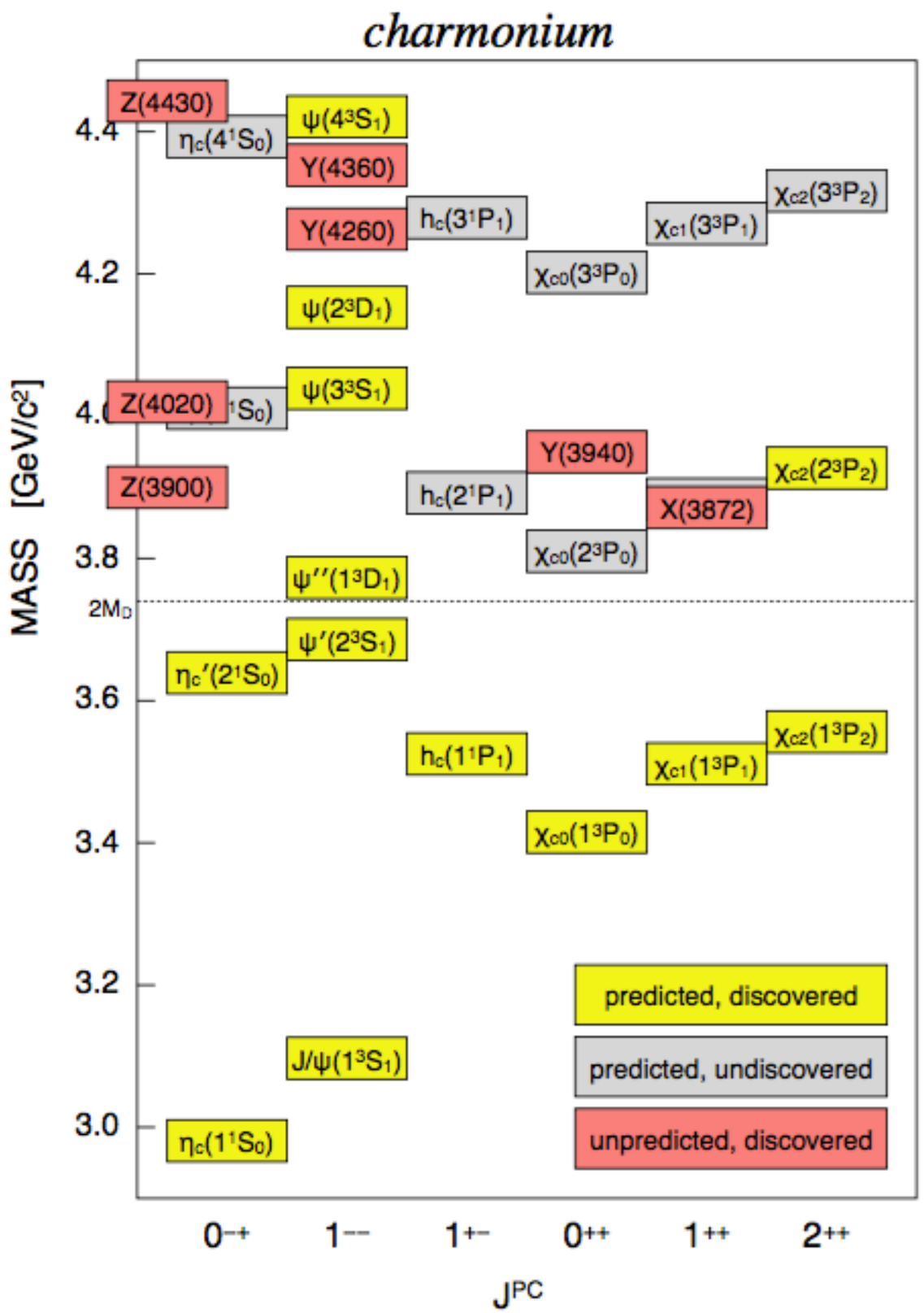




- LHC is a heavy quark baryon factory
- Discovery of 5 new Ω_c states and
- Doubly charmed Ξ_{cc}^{++} this year's highlight
- Impressive success for theory
- More puzzles to solve – which role do multiquark states play in the baryon spectrum?

Heavy Quarks Meson Spectroscopy

Introduction to Heavy Quark Exotica



Q: What are heavy quark exotica?

A: Phenomena in the heavy quark sector that do not easily fit into the naive quark model picture of mesons and baryons.

Q: Why are they interesting?

A: They can be used to explore novel phenomena in QCD:

hybrid mesons, tetraquarks, pentaquarks, molecules, hadroquarkonium, thresholds

Q: Why are they called XYZ?

A: Mostly historical reasons.

But now there are patterns:

Z: electrically charged (I = 1).

Y: $J^{PC} = 1^{--}$, made directly in e^+e^-.

X: whatever is leftover.

But there are many exceptions!

[The PDG will soon name them by IJ^{PC}.]

Q: How many have been found?

A: Many.

[OUTLINE] A Tour through the XYZ

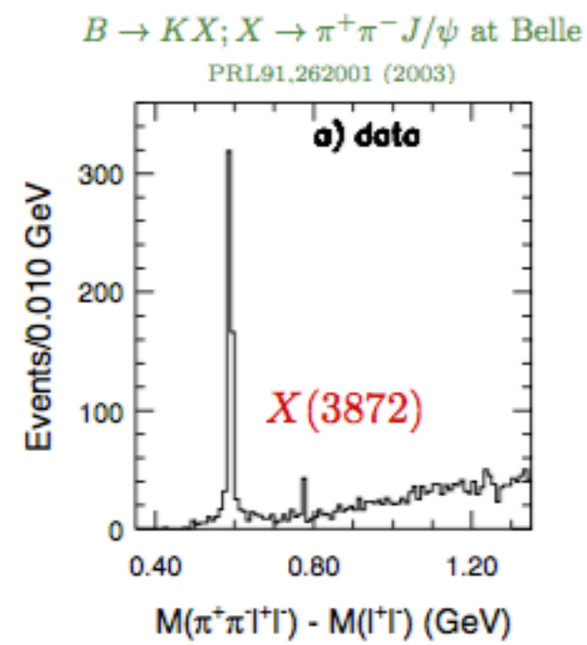
[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

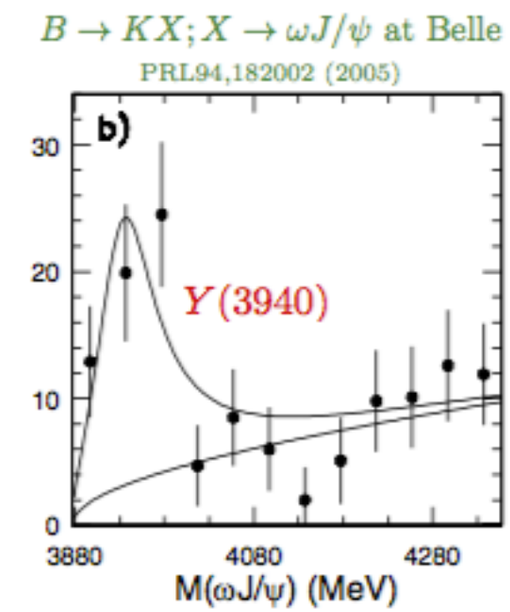
[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

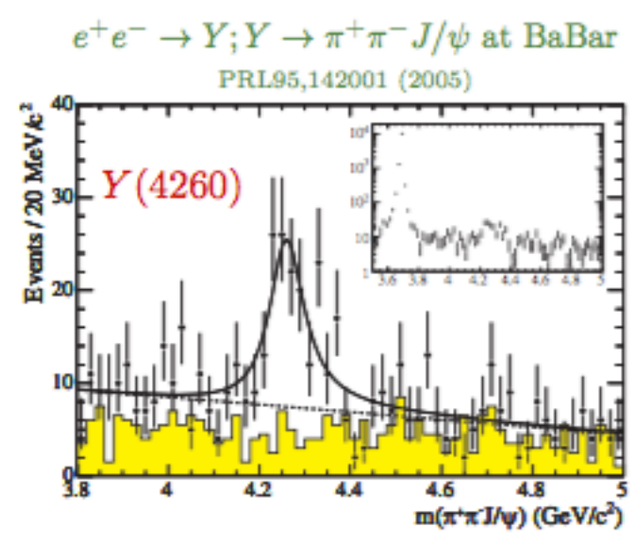
[Part II: Y(3940)]
What happened to the Y(3940)?
The ongoing search for the χ_{c0}(2P).

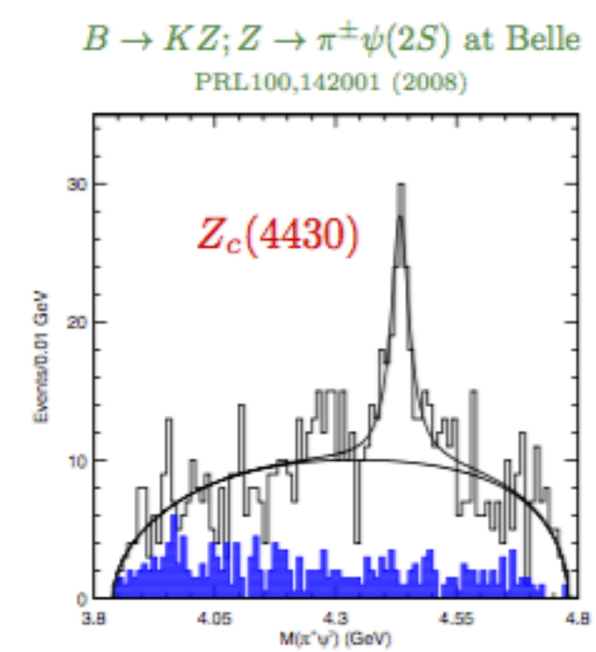
[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections ("Y states").
Peaks in their decays ("Z states").

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in Λ_b decays.









Closing Thoughts on the Future of Heavy Quark Exotica

(1) The field is characterized by:

* experimental results that are unexpected but robust.
* theoretical developments that are unsettled but productive.
* many avenues left to explore.

(2) The flow of experimental results has no end in sight:

BESIII and LHC experiments will continue…
Belle II will soon be online…

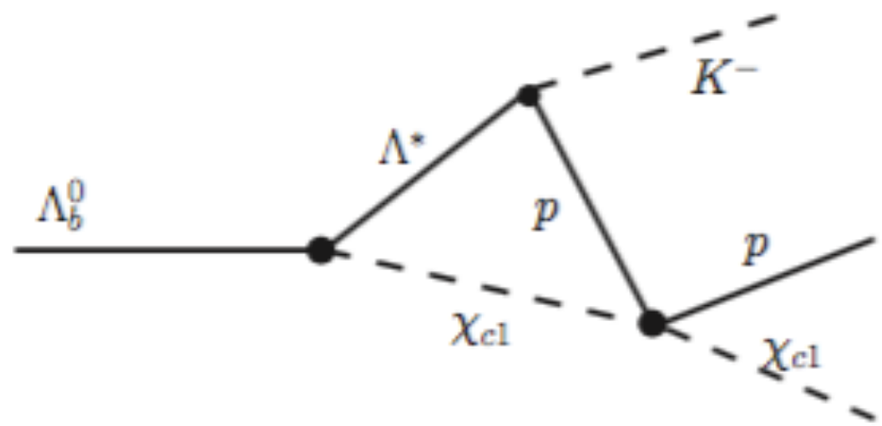
(3) Further progress will require more interchange between experiment and theory.

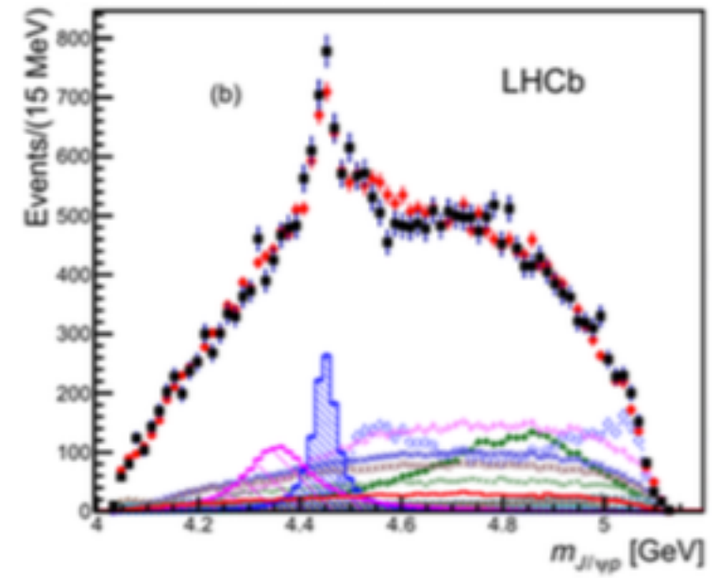
(4) New production mechanisms need to be explored
(e.g. PANDA, COMPASS).

(5) We should also test ideas beyond charmonium and bottomonium
(e.g. GlueX, LHC).

We are making progress!

Triangle singularity





- Conditions (Coleman, Norton (1965); Bronzan (1964)):
  - ☞ all three intermediate particles can go on shell simultaneously
  - ☞ $\vec{p}_2 \parallel \vec{p}_3$, particle-3 can catch up with particle-2 (as a classical process)
- requires very special kinematics
  $\Rightarrow$ process dependent!
- S-wave TS can produce a narrow peak mimicking a resonance
- old knowledge, many recent applications:
  $\eta(1405/1475), a_1(1420), f_1(1420), Z_c, Z_b, P_c, \ldots$


THIS IS JUST
A STUPID TRIANGLE.

The End

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 $q\bar{q}$

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

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

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