N* Resonances from (mostly) low to (sometimes) high virtualities

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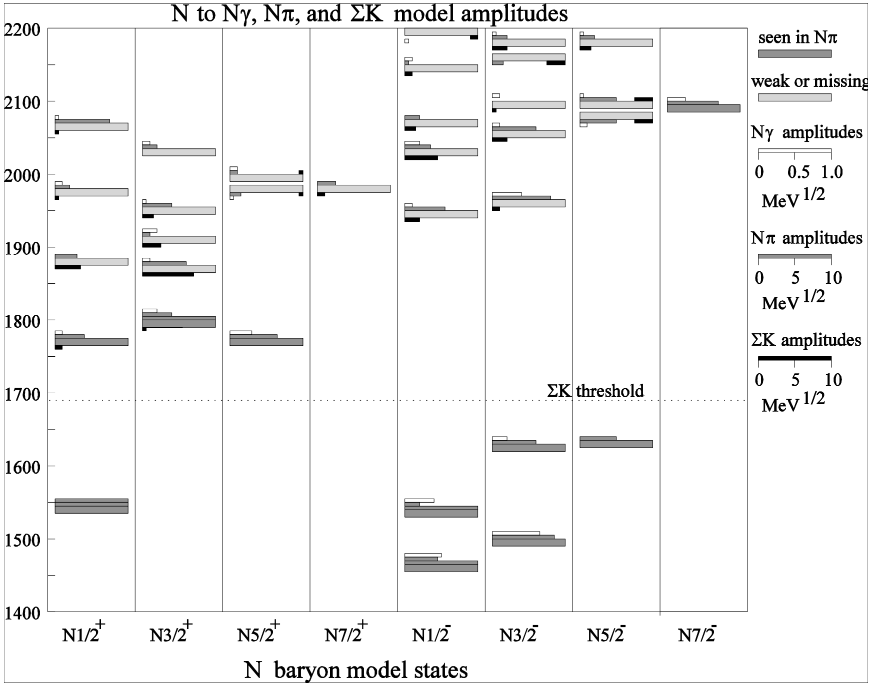
ECT*, Trento, Oct. 2015

Outline

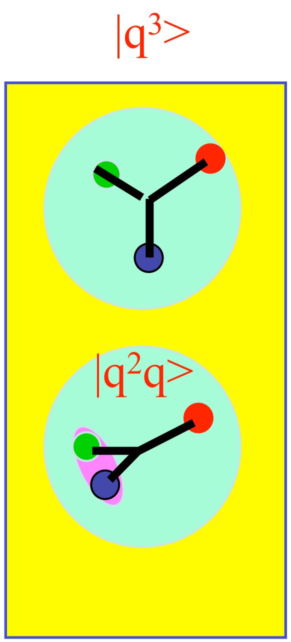
- Spectroscopy: theory and experiment
- Quantum Chromodynamics on the lattice
- Recent Highlights
- Resonances
  - phenomenology
  - strong decays
  - Form factors and Matrix Elements
- Summary and prospects

Baryon Spectroscopy

- No baryon **"exotics"**, ie quantum numbers not accessible with simple quark model; but may be **hybrids**!
- Nucleon Spectroscopy: Quark model masses and amplitudes – states classified by isospin, parity and **spin**.



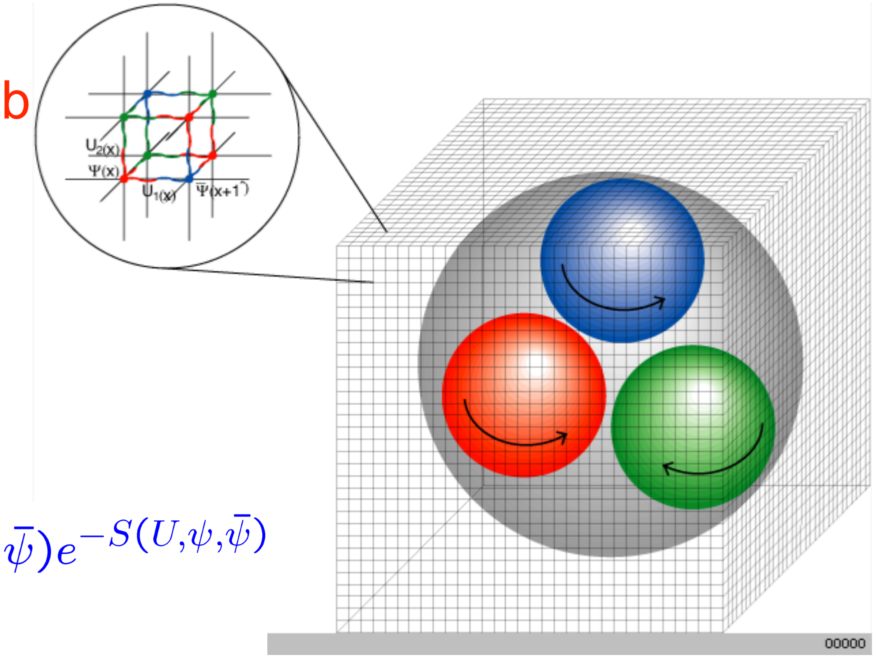
- Missing, because our pictures do not capture correct degrees of freedom?
- Do they just not couple to probes?



Capstick and Roberts, PRD58 (1998) 074011

Lattice QCD - I

- Lattice QCD enables us to undertake ab initio computations of many of the low-energy properties of QCD
- Continuum Euclidean space time replaced by four-dimensional lattice



$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \prod_{x,\mu} dU_\mu(x) \prod_x d\psi(x) \prod_x d\bar{\psi}(x) \mathcal{O}(U,\psi,\bar{\psi}) e^{-S(U,\psi,\bar{\psi})}$$

where

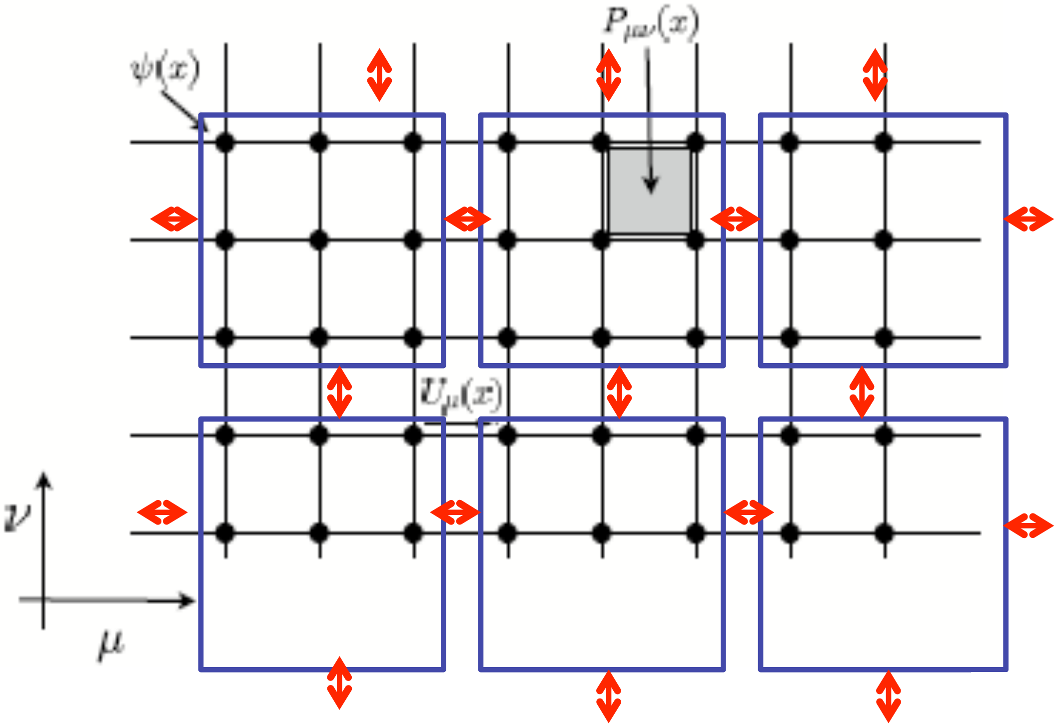
$$S(U,\psi,\bar{\psi}) = -\frac{6}{g^2} \sum_x \mathrm{Tr} U_{Pl} + \sum_x \bar{\psi} M(U) \psi$$

ψ, ψ are Grassmann Variables

Importance Sampling

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \prod_{x,\mu} dU_\mu(x) \mathcal{O}(U) \det M(U) e^{-S_g(U)}$$

Hierarchy of Computations



Capability Computing -
Gauge Generation

Capacity Computing -
Observable Calculation

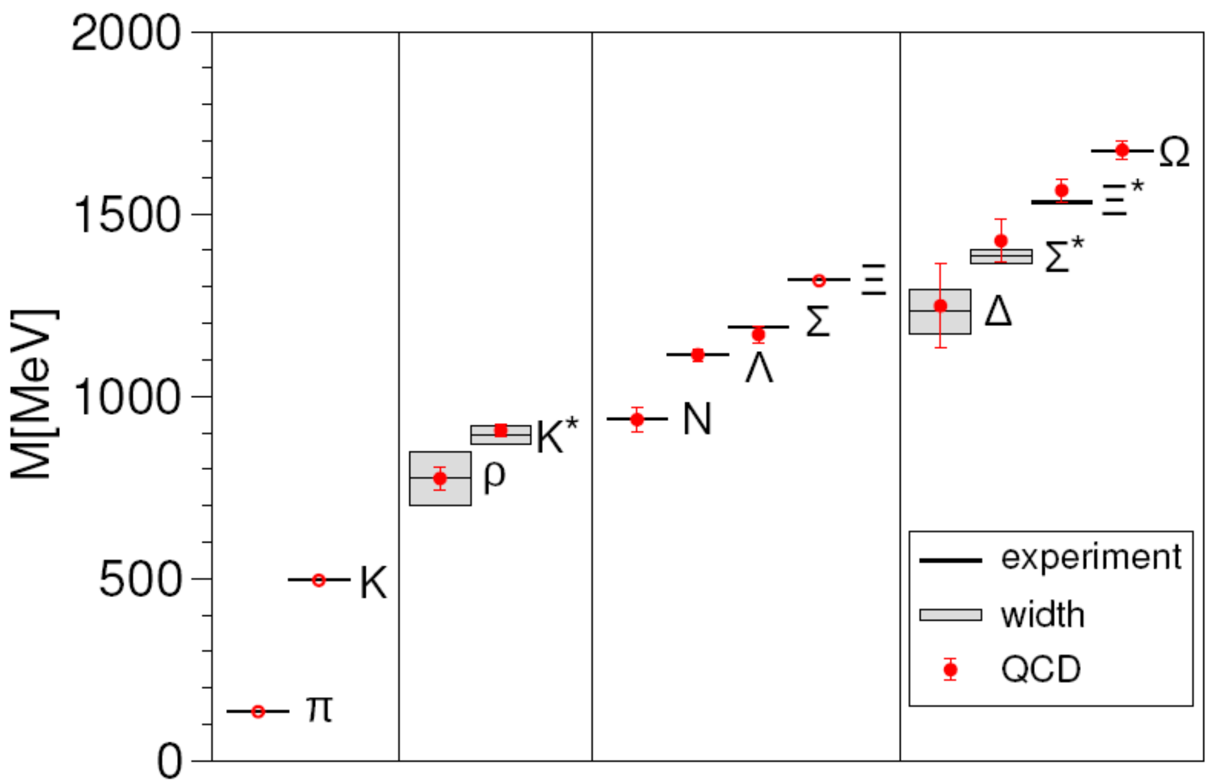
Highly regular problem, with simple boundary conditions – *very efficient use of massively parallel computers using data-parallel programming.*

Low-lying Hadron Spectrum

Benchmark of LQCD

$$C(t) = \sum_{\vec{x}} \langle 0 \mid N(\vec{x},t)\bar{N}(0) \mid 0 \rangle \;=\; \sum_{n,\vec{x}} \langle 0 \mid e^{ip\cdot x} N(0) e^{-ip\cdot x} \mid n \rangle \langle n \mid \bar{N}(0) \mid 0 \rangle$$

$$= \;\mid \langle n \mid N(0) \mid 0 \rangle \mid^2 e^{-E_n t} = \sum_n A_n e^{-E_n t}$$



Durr et al., BMW Collaboration

Science 2008

Control over:

- ***Quark-mass dependence***
- ***Continuum extrapolation***
- ***finite-volume effects (pions, resonances)***

Nucleon EM Form Factors

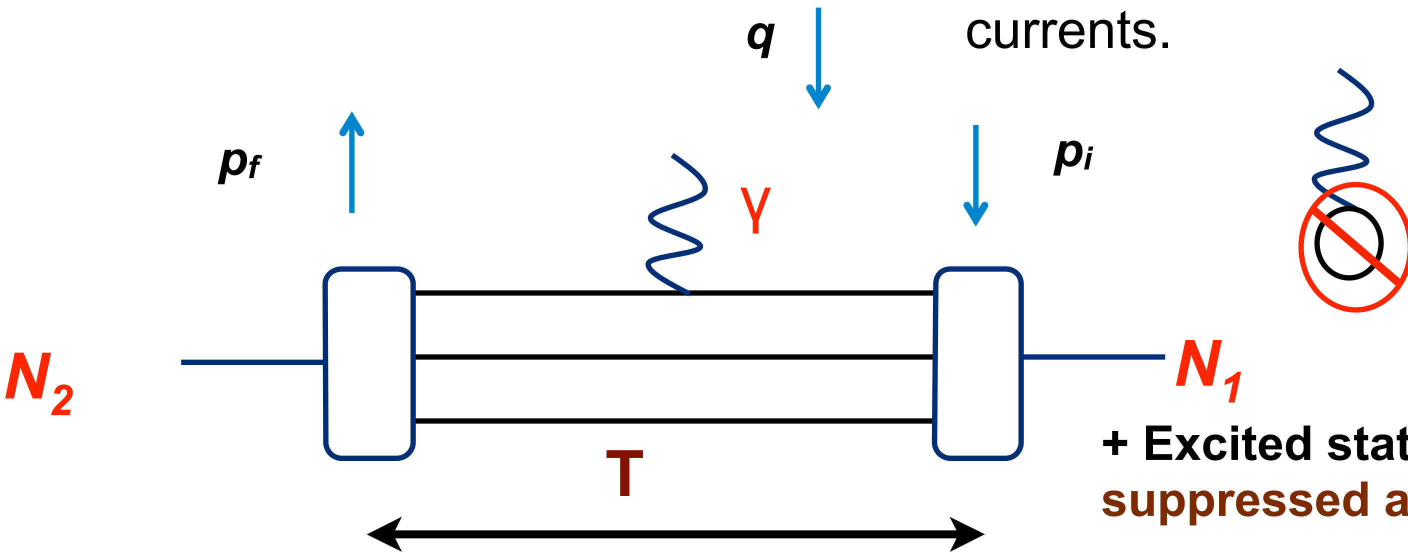
Two form factors

$$\langle p_f \mid V_\mu \mid p_i \rangle = \bar{u}(p_f)\left[\gamma_\mu \underbrace{F_1(q^2)}_{\text{Dirac}} + i q_\nu \frac{\sigma_{\mu\nu}}{2m_N} \underbrace{F_2(q^2)}_{\text{Pauli}}\right] u(p_i)$$

Related to familiar Sach's electromagnetic form factors through

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \frac{Q^2}{(2m_N)^2} F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

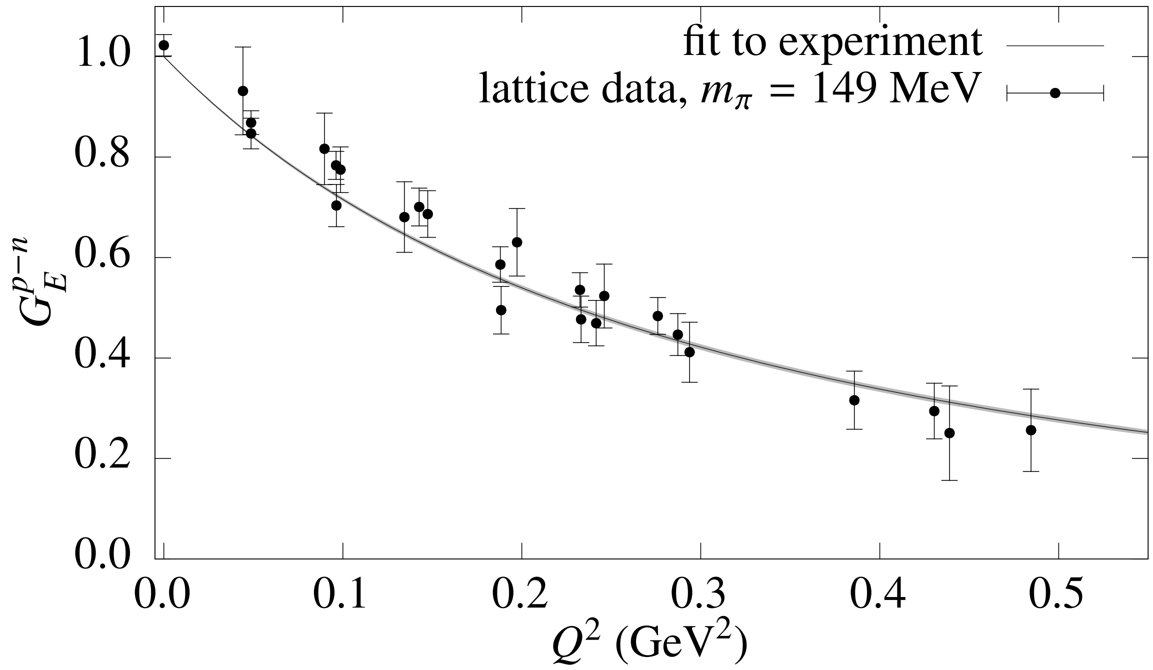
Isovector: difference between p and n or difference between u and d currents.



+ Excited states - suppressed at large T

Electromagnetic Form Factors

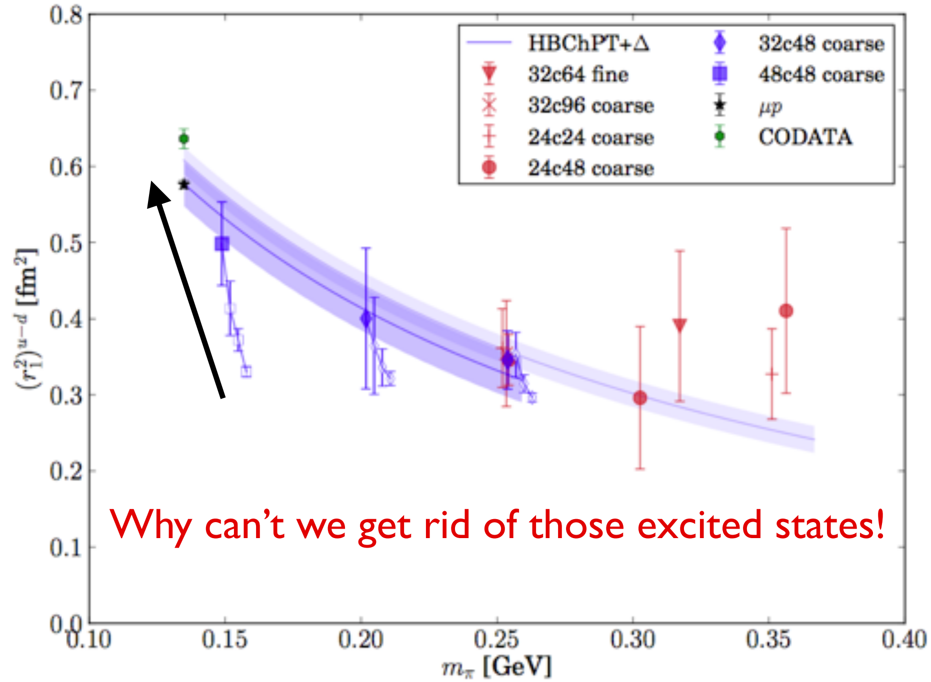
Wilson-clover lattices from BMW



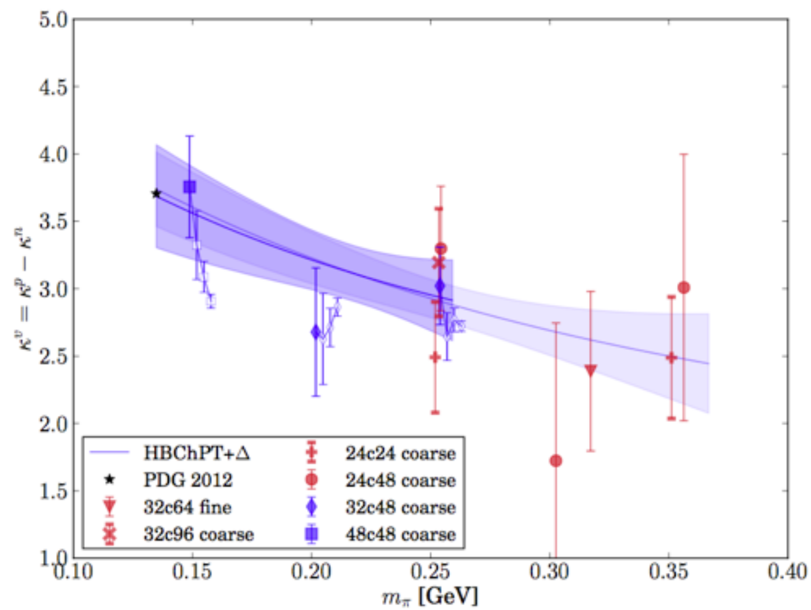
Hadron structure at nearly-physical quark masses

Green et al (LHPC), Phys. Rev. D 90, 074507 (2014)

Isovector Charge Radius



Precision Calculations of the Fundamental Quantities in Nuclear Physics - **at physical quark masses**



Green et al, arXiv:1404.40

Variational Method

Subleading terms → *Excited states*

Construct matrix of correlators with *judicious choice of operators*

$$\begin{aligned} C_{\alpha\beta}(t,t_0) &= \langle 0 \mid \mathcal{O}_\alpha(t)\mathcal{O}^\dagger_\beta(t_0) \mid 0\rangle \\ &\longrightarrow \sum_n Z^n_\alpha Z^{n\dagger}_\beta e^{-M_n(t-t_0)} \end{aligned}$$

Delineate contributions using variational method: solve

$$C(t)u(t,t_0) = \lambda(t,t_0)C(t_0)u(t,t_0)$$

$$\lambda_i(t,t_0) \rightarrow e^{-E_i(t-t_0)}\left(1 + O(e^{-\Delta E(t-t_0)})\right)$$

Eigenvectors, with metric $C(t_0)$, are orthonormal and project onto the respective states

➡ Resolve energy dependence - *anisotropic lattice*

➡ Judicious construction of interpolating operators - *cubic symmetry*

Baryon Operators

Aim: interpolating operators of *definite* (continuum) JM: O^{JM}

- **Lattice does not respect symmetries of continuum: *cubic symmetry for states at rest***

$$\langle 0 \mid O^{JM} \mid J', M' \rangle = Z^J \delta_{J,J'} \delta_{M,M'}$$

Starting point
$$B = \left(\mathcal{F}_{\Sigma_F} \otimes \mathcal{S}_{\Sigma_S} \otimes \mathcal{D}_{\Sigma_D}\right)\{\psi_1 \psi_2 \psi_3\}$$

Introduce circular basis:
$$\overleftrightarrow{D}_{m=-1} = \frac{i}{\sqrt{2}}\left(\overleftrightarrow{D}_x - i\overleftrightarrow{D}_y\right)$$
$$\overleftrightarrow{D}_{m=0} = i\overleftrightarrow{D}_z$$
$$\overleftrightarrow{D}_{m=+1} = -\frac{i}{\sqrt{2}}\left(\overleftrightarrow{D}_x + i\overleftrightarrow{D}_y\right).$$

Straighforward to project to definite spin: *J = 1/2, 3/2, 5/2*

$$\big|\,[J,M]\big\rangle = \sum_{m_1,m_2} \big|\,[J_1,m_1]\big\rangle \otimes \big|\,[J_2,m_2]\big\rangle \big\langle J_1 m_1; J_2 m_2 \big| JM \big\rangle$$

Use projection formula to find subduction under irrep. of cubic group - operators are closed under rotation!

$$O^{[J]}_{\Lambda\lambda}(t,\vec{x}) = \frac{d_\Lambda}{g_{O_h^D}} \sum_{R \in O_h^D} D^{(\Lambda)*}_{\lambda\lambda}(R) U_R O^{J,M}(t,\vec{x}) U_R^\dagger$$
$$= \sum_M S^{J,M}_{\Lambda,\lambda} O^{J,M}$$

Irrep, Row **Irrep of R in Λ** **Action of R**

Efficient Correlation fns:

- Use the new "distillation" method.
- Observe $$L^{(J)} \equiv (1 - \frac{\kappa}{n}\Delta)^n = \sum_{i=1} f(\lambda_i) v^{(i)} \otimes v^{*(i)}$$

Eigenvectors of Laplacian

- Truncate sum at sufficient i to capture relevant physics modes – we use 64: set "weights" f to be unity
- *Baryon* correlation function

$$C_{ij}(t) = \Phi^{i,(p,q,r)}_{\alpha\beta\gamma}(t) \Phi^{j,(\bar{p},\bar{q},\bar{r})\dagger}_{\bar{\alpha}\bar{\beta}\bar{\gamma}}(0) \times \Big[\tau^{p\bar{p}}_{\alpha\bar{\alpha}}(t,0) \tau^{q\bar{q}}_{\beta\bar{\beta}}(t,0) \tau^{r\bar{r}}_{\gamma\bar{\gamma}}(t,0) - \tau^{p\bar{p}}_{\alpha\bar{\alpha}}(t,0) \tau^{q\bar{r}}_{\beta\bar{\gamma}}(t,0) \tau^{r\bar{q}}_{\gamma\bar{\beta}}(t,0) \Big]$$

M. Peardon *et al.*, PRD80,0 (2009)

where

$$\Phi^{i,(p,q,r)}_{\alpha\beta\gamma} = \epsilon^{abc} S^i_{\alpha\beta\gamma} (\mathbf{\Gamma}_1 \xi^{(p)})^a (\mathbf{\Gamma}_2 \xi^{(q)})^b (\mathbf{\Gamma}_3 \xi^{(r)})^c$$

$$\tau^{p\bar{p}}_{\alpha\bar{\alpha}}(t,0) = \xi^{\dagger(p)}(t) M^{-1}_{\alpha\bar{\alpha}}(t,0) \xi^{(\bar{p})}(0)$$

Perambulators

Excited Baryon Spectrum - I

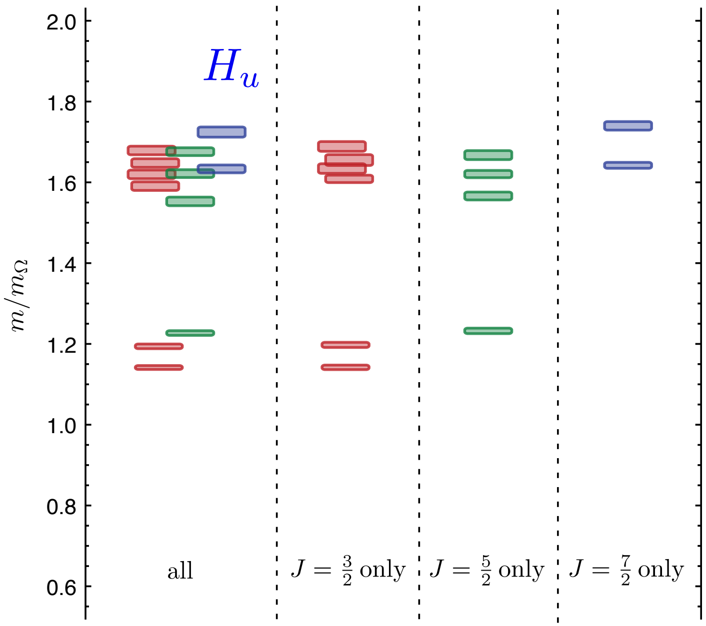
Construct basis of 3-quark interpolating operators in the continuum:

$$\left(N_{\mathsf{M}} \otimes \left(\tfrac{3}{2}^{-}\right)^{1}_{\mathsf{M}} \otimes D^{[2]}_{L=2,\mathsf{S}}\right)^{J=\frac{7}{2}}$$

"Flavor" x Spin x Orbital

Subduce to lattice irreps:

$$\mathcal{O}^{[J]}_{n\Lambda,r} = \sum_{M} \mathcal{S}^{J,M}_{n\Lambda,r}\,\mathcal{O}^{[J,M]} \;:\; \Lambda = G_{1g/u}, H_{g/u}, G_{2g/u}$$



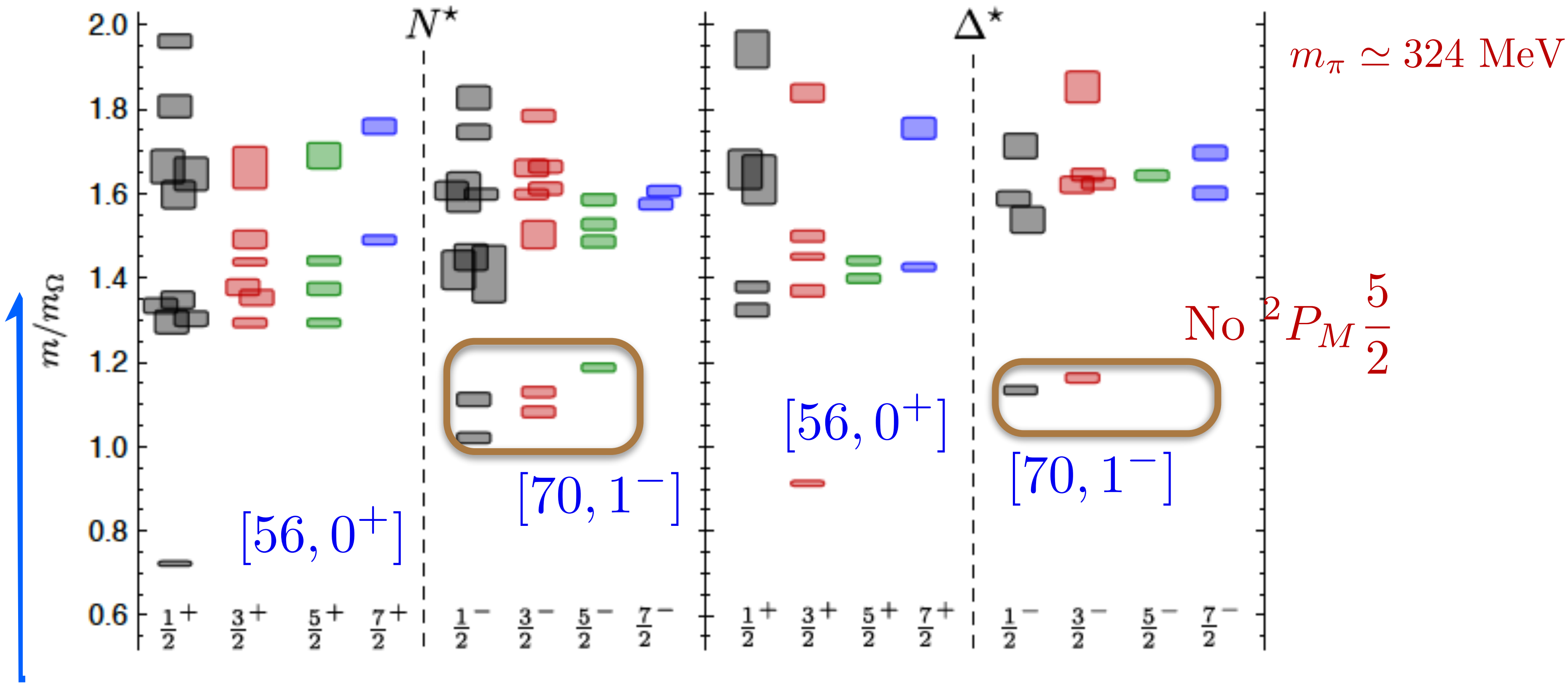
Continuum antecedents

R.G.Edwards et al., arXiv:1104.5152

$16^3 \times 128$ lattices $m_\pi = 524, 444$ and 396 MeV

Observe remarkable realization of rotational symmetry at hadronic scale: *reliably determine spins up to 7/2, for the first time in a lattice calculation*

Excited Baryon Spectrum - II



$[70, 0^+], [56, 2^+], [70, 2^+], [20, 1^+]$

N $^{1/2+}$ sector: need for complete basis to faithfully extract states

Broad features of SU(6)xO(3) symmetry.

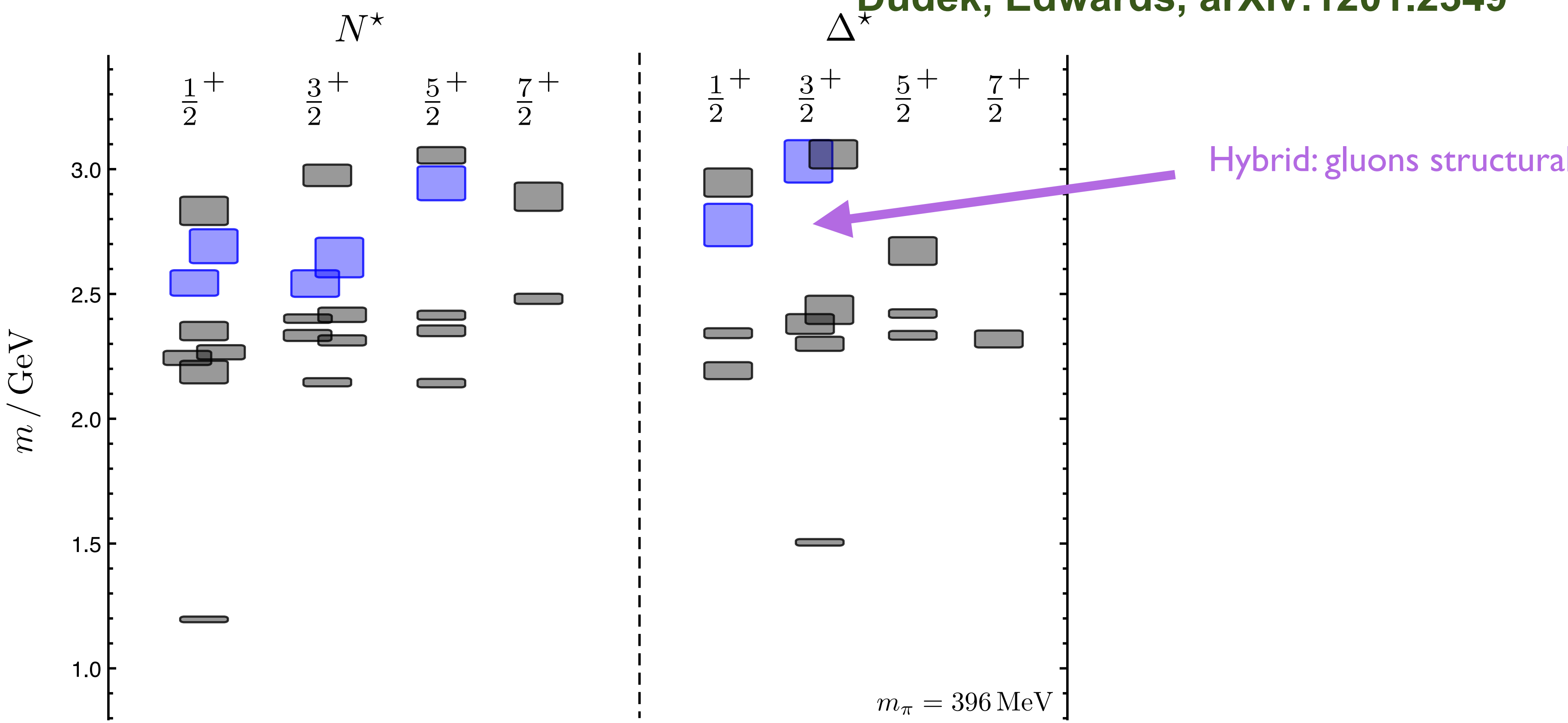
Counting of states consistent with NR quark model.

Inconsistent with quark-diquark picture or parity doubling.

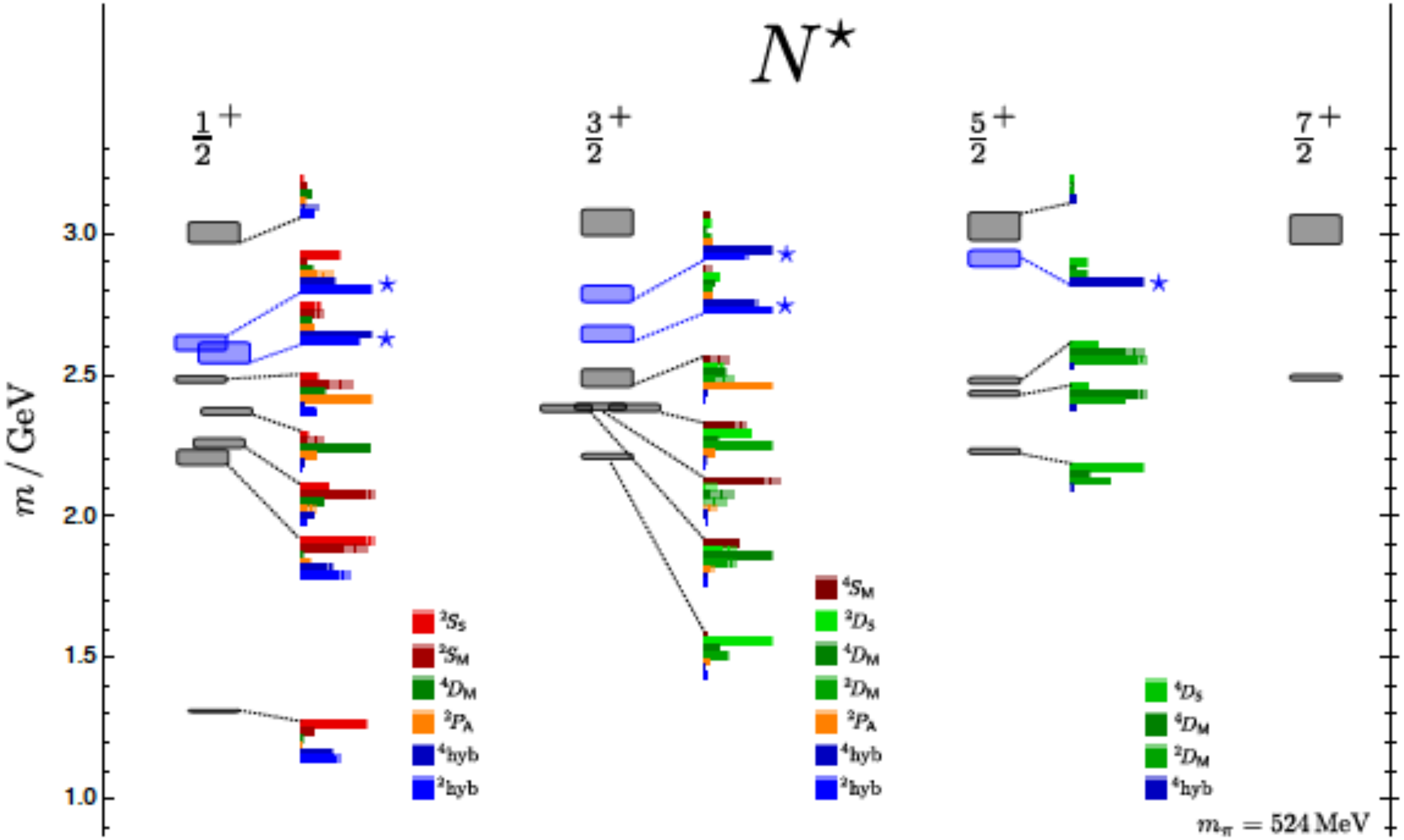
Hybrid Baryon Spectrum

Original analysis ignore hybrid operators of form $D^{[2]}_{l=1,M}$

Dudek, Edwards, arXiv:1201.2349

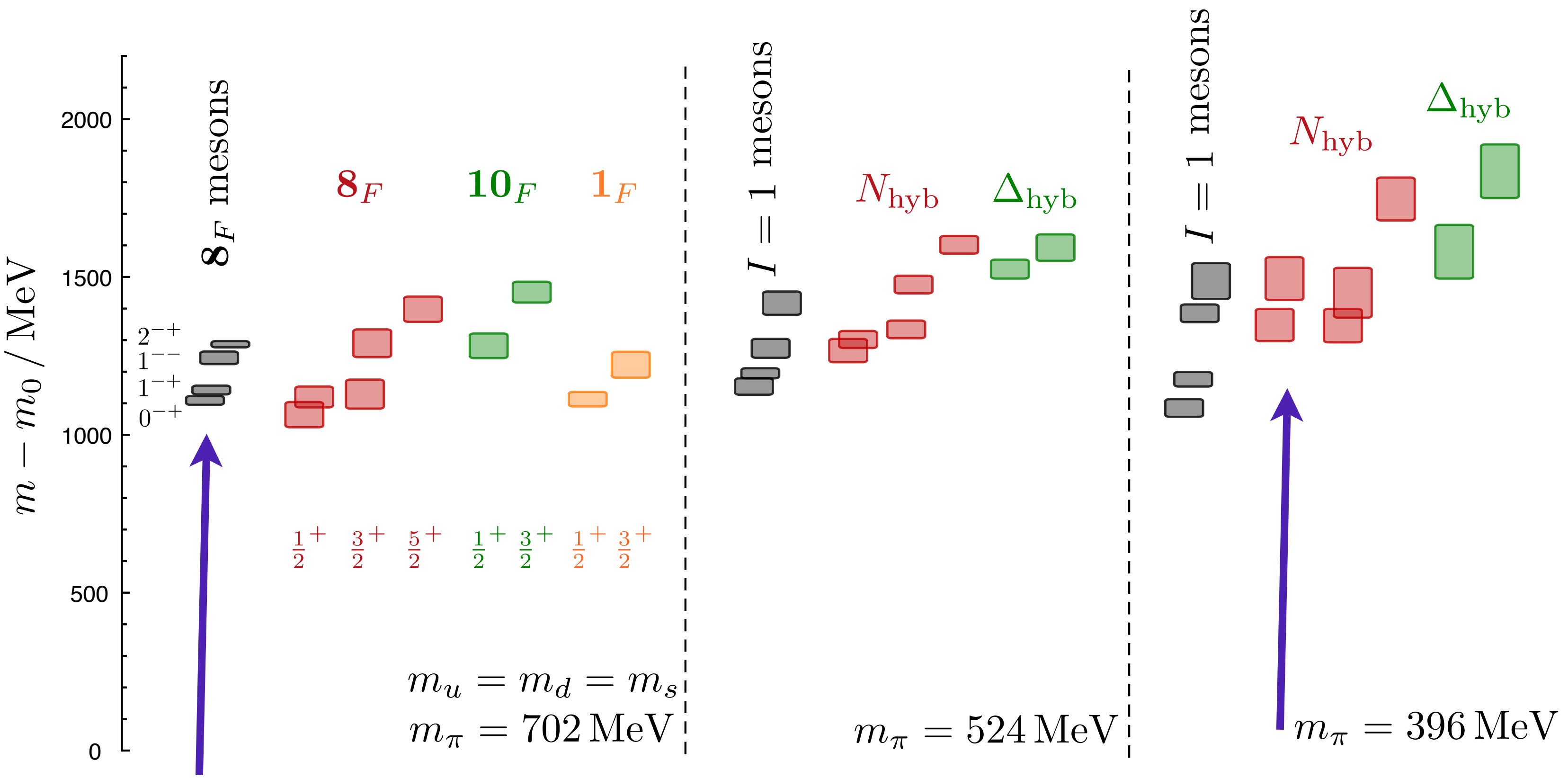


Interpolating Operators



Examine overlaps onto different NR operators, i.e. containing upper components of spinors: *ground state has substantial hybrid component*

Putting it Together



Subtract ρ ***Subtract N***

Common mechanism in meson and baryon hybrids: chromomagnetic field with *E_g ~ 1.2 - 1.3 GeV*

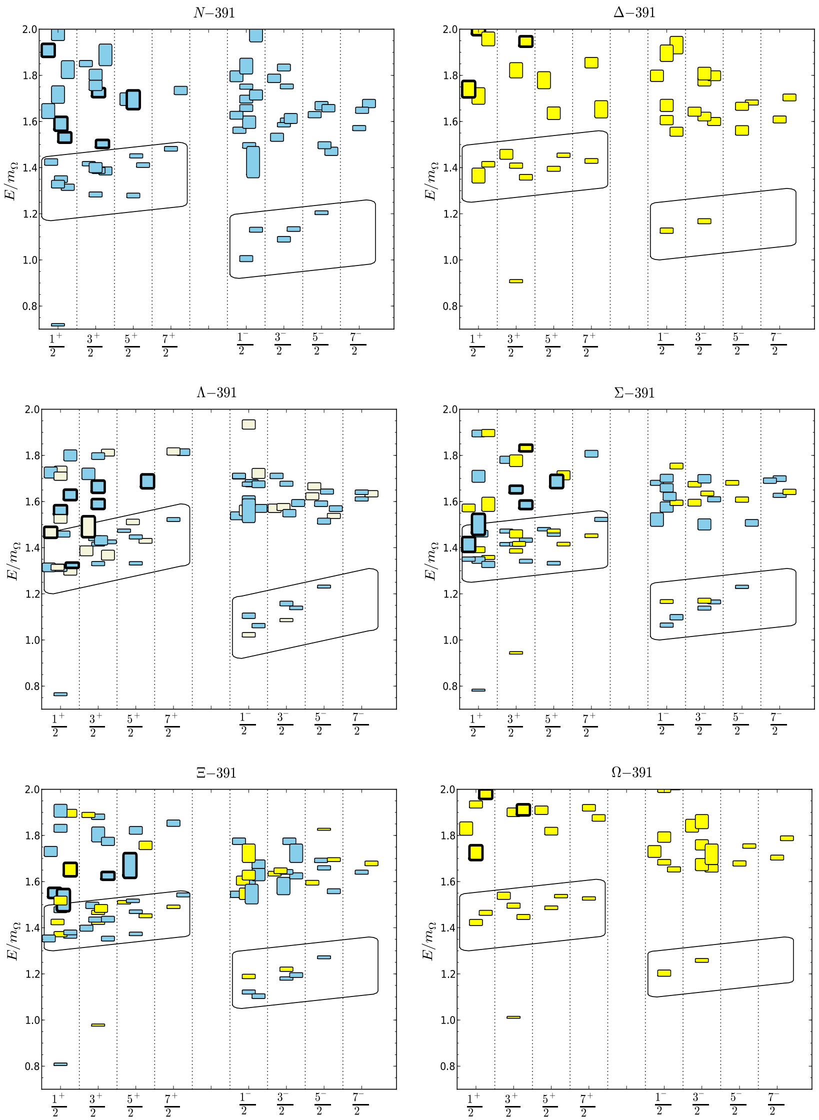
Flavor Structure

$SU(3)_F$	S	L	J^P		
$\mathbf{8_F}$	$\frac{1}{2}$	1	$\frac{1}{2}^-$	$\frac{3}{2}^-$	
	$\frac{3}{2}$	1	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$N_8(J)$			**2**	**2**	**1**
$\mathbf{10_F}$	$\frac{1}{2}$	1	$\frac{1}{2}^-$	$\frac{3}{2}^-$	
$N_{10}(J)$			**1**	**1**	**0**
$\mathbf{1_F}$	$\frac{1}{2}$	1	$\frac{1}{2}^-$	$\frac{3}{2}^-$	
$N_1(J)$			**1**	**1**	**0**

One derivative

$SU(3)_F$	S	L	J^P			
$\mathbf{8_F}$	$\frac{1}{2}$	0	$\frac{1}{2}^+$			
	$\frac{1}{2}$	0	$\frac{1}{2}^+$			
	$\frac{1}{2}$	1	$\frac{1}{2}^+$	$\frac{3}{2}^+$		
	$\frac{1}{2}$	2		$\frac{3}{2}^+$	$\frac{5}{2}^+$	
	$\frac{1}{2}$	2		$\frac{3}{2}^+$	$\frac{5}{2}^+$	
	$\frac{3}{2}$	0		$\frac{3}{2}^+$		
	$\frac{3}{2}$	2	$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$	$\frac{7}{2}^+$
$N_8(J)$			**4**	**5**	**3**	**1**
$\mathbf{10_F}$	$\frac{1}{2}$	0	$\frac{1}{2}^+$			
	$\frac{1}{2}$	2		$\frac{3}{2}^+$	$\frac{5}{2}^+$	
	$\frac{3}{2}$	0		$\frac{3}{2}^+$		
	$\frac{3}{2}$	2	$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$	$\frac{7}{2}^+$
$N_{10}(J)$			**2**	**3**	**2**	**1**
$\mathbf{1_F}$	$\frac{1}{2}$	0	$\frac{1}{2}^+$			
	$\frac{1}{2}$	2		$\frac{3}{2}^+$	$\frac{5}{2}^+$	
	$\frac{3}{2}$	1	$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$	
$N_1(J)$			**2**	**2**	**2**	**0**

Two derivative



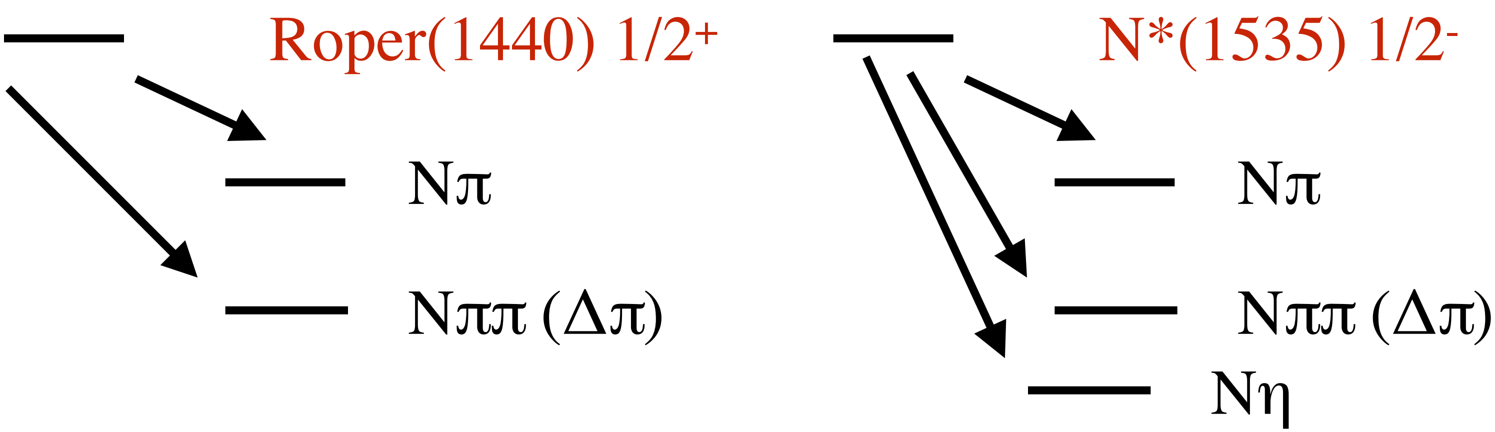
Examine Flavor structure of baryons constructed from u, d s quarks.

- Can identify predominant flavor for each state: Yellow (10F), Blue (8F), Beige (1F).
- SU(6) x O(3) Counting
- Presence of “hybrids” characteristic across all *+ve parity* channels: **BOLD Outline**

R. Edwards et al., Phys. Rev. D87 (2013) 054506

Some of our states are missing…

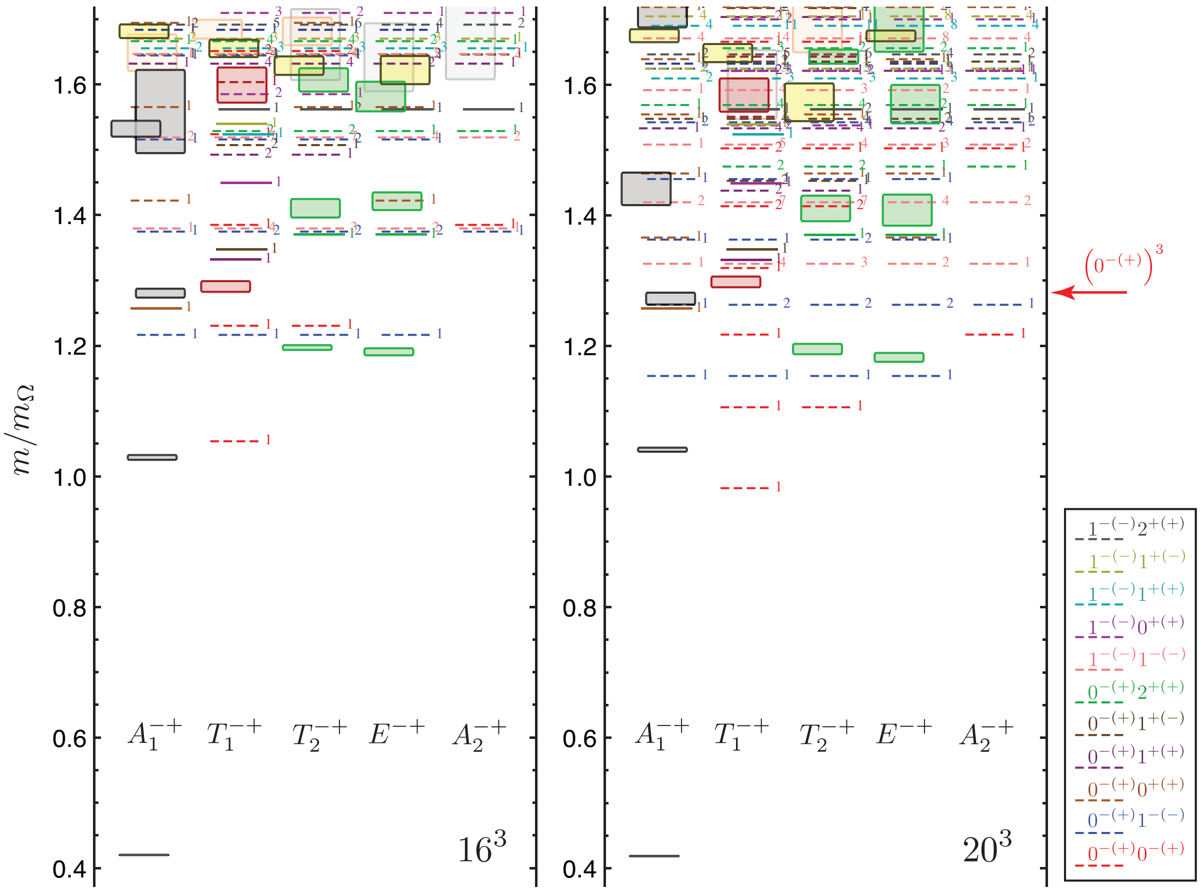
Partial decay widths



Momenta are quantised → discrete spectrum of energies. *Even above threshold at our quark masses we should see (close-to?) these energies in spectrum*

Isovector meson spectrum

States unstable under strong interactions



Meson spectrum on two volumes: dashed lines denote expected (non-interacting) multi-particle energies.

Allowed two-particle contributions - momenta - governed by cubic symmetry of volume

Calculation is incomplete.

Momentum-dependent I = 2 ππ Phase Shift

Dudek *et al.*, Phys Rev D83, 071504 (2011)

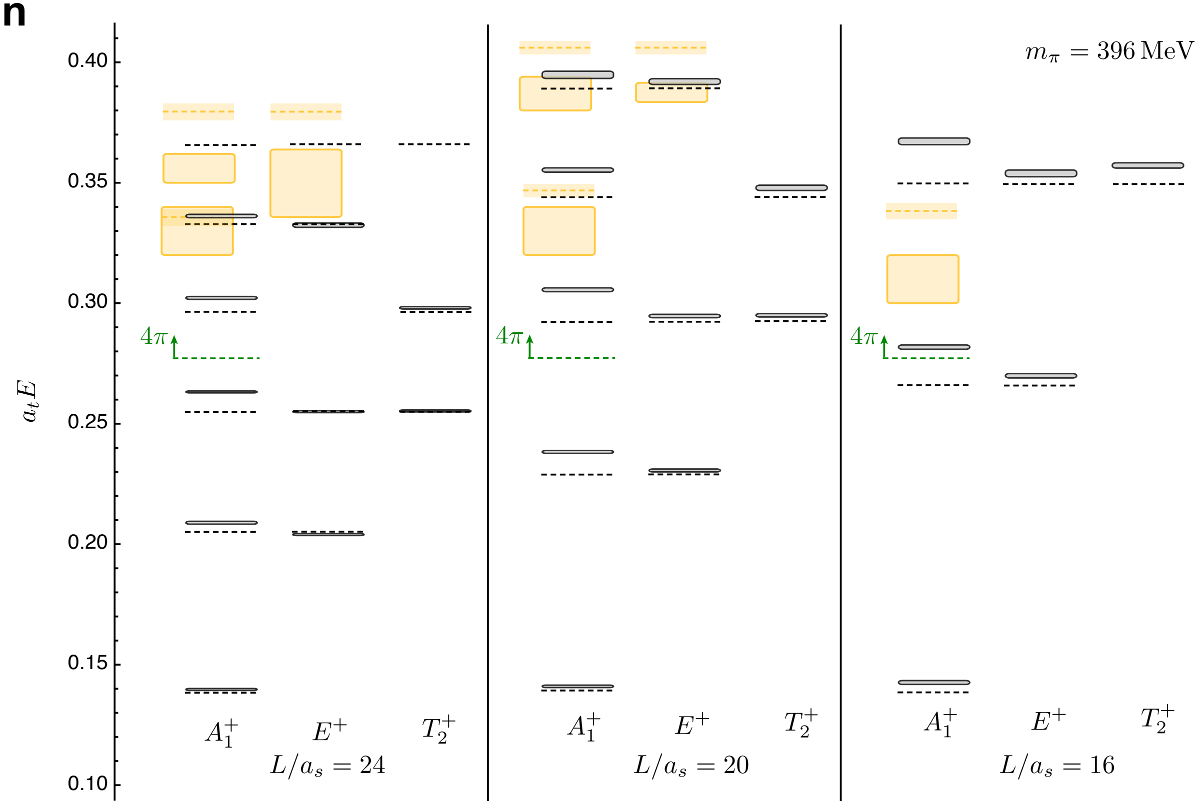
Include two-body operators

Operator basis

$$\mathcal{O}^{\Gamma,\gamma}_{\pi\pi}(|\vec{p}|) = \sum_m \mathcal{S}^{\ell,m}_{\Gamma,\gamma} \sum_{\hat{p}} Y^m_\ell(\hat{p})\, \mathcal{O}_\pi(\vec{p})\mathcal{O}_\pi(-\vec{p})$$

Total momentum zero - pion momentum ±*p*

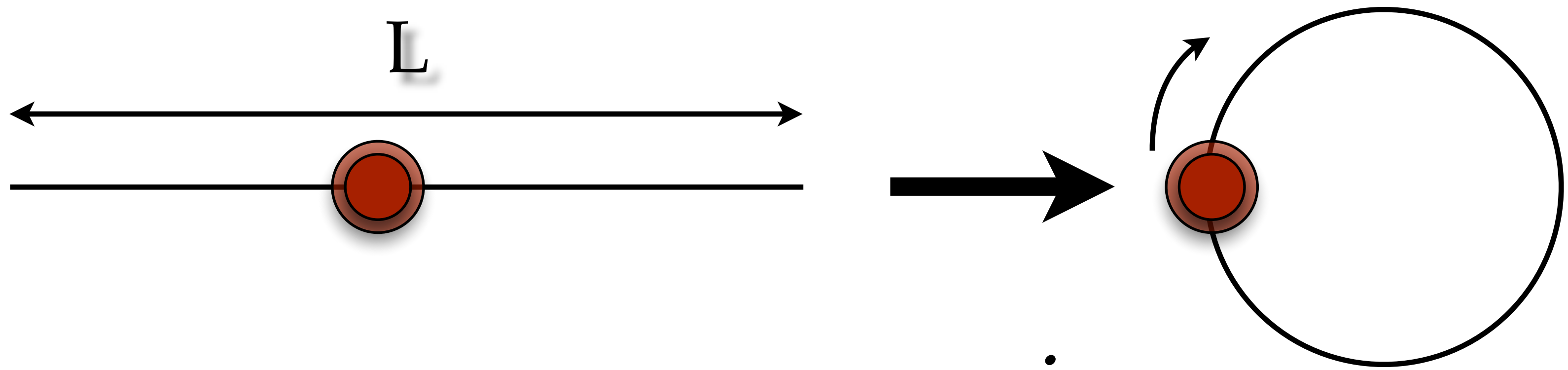
Luescher: energy levels at finite volume ↔ phase shift at corresponding *k*



Reinventing the *quantum-mechanical* wheel

Thanks to Raul Briceno

(in 1+1 dimensions)

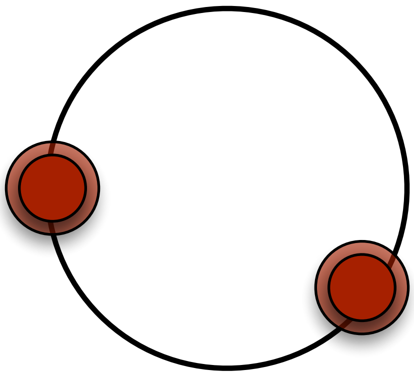


$$\phi(x) \sim e^{ipx}$$

Periodicity: $\boxed{L\, p_n = 2\pi n}$

Reinventing the *quantum-mechanical* wheel

Two particles:



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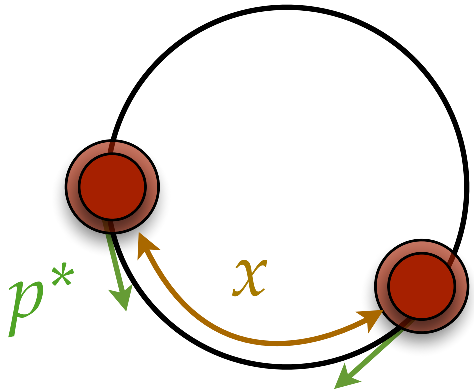

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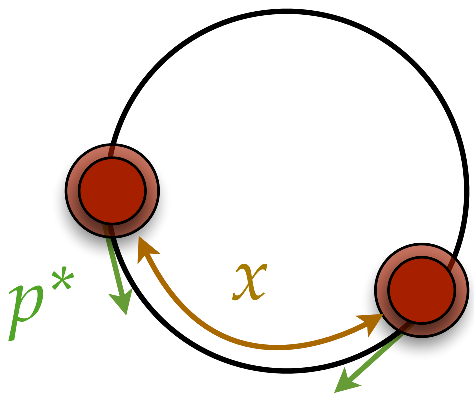

infinite volume scattering phase shift

$$\psi(x) \sim e^{ip^*|x| + i2\delta(p^*)}$$

Asymptotic wavefunction

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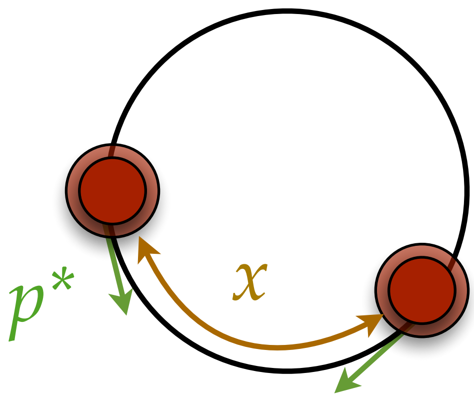
Two particles:



infinite volume scattering phase shift

$$\psi(x) \sim e^{ip^*|x| + i2\delta(p^*)}$$

Asymptotic wavefunction

Periodicity: $$L\, p_n^* + 2\delta(p_n^*) = 2\pi n$$

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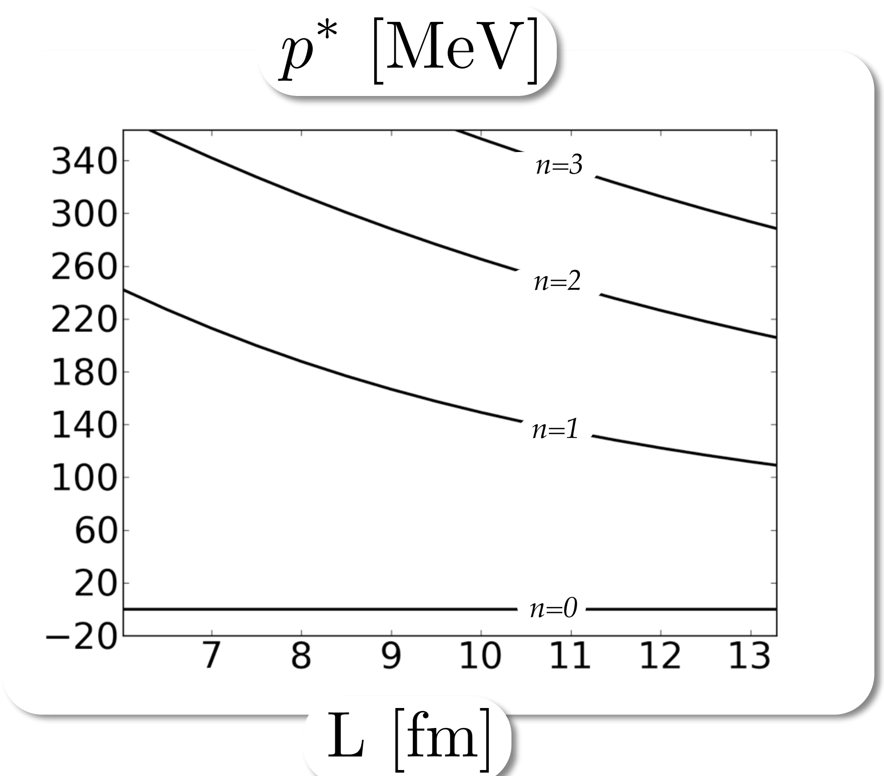

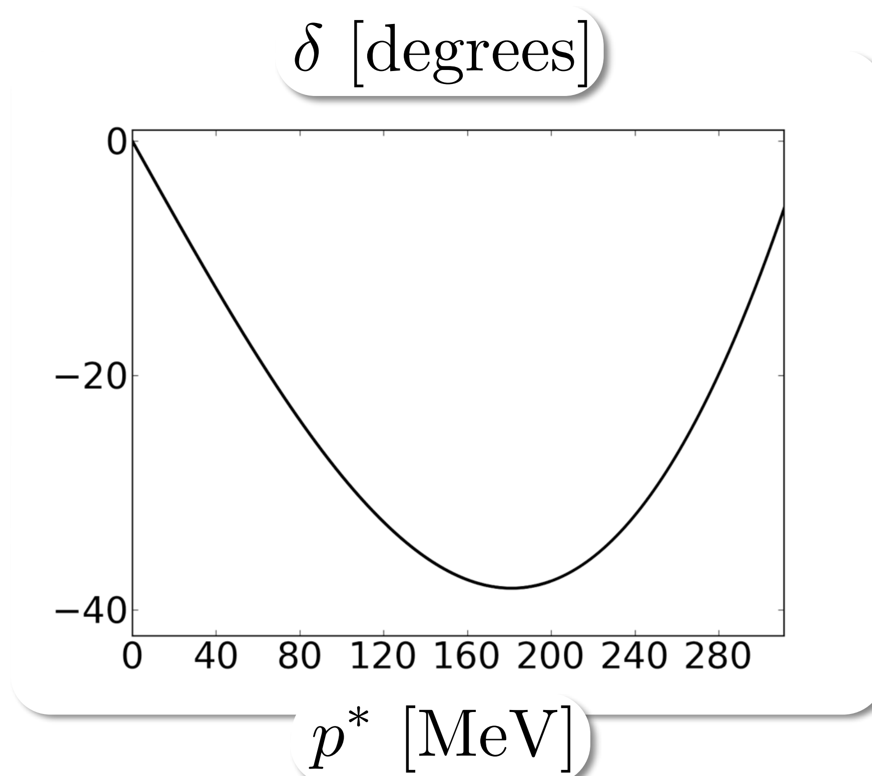

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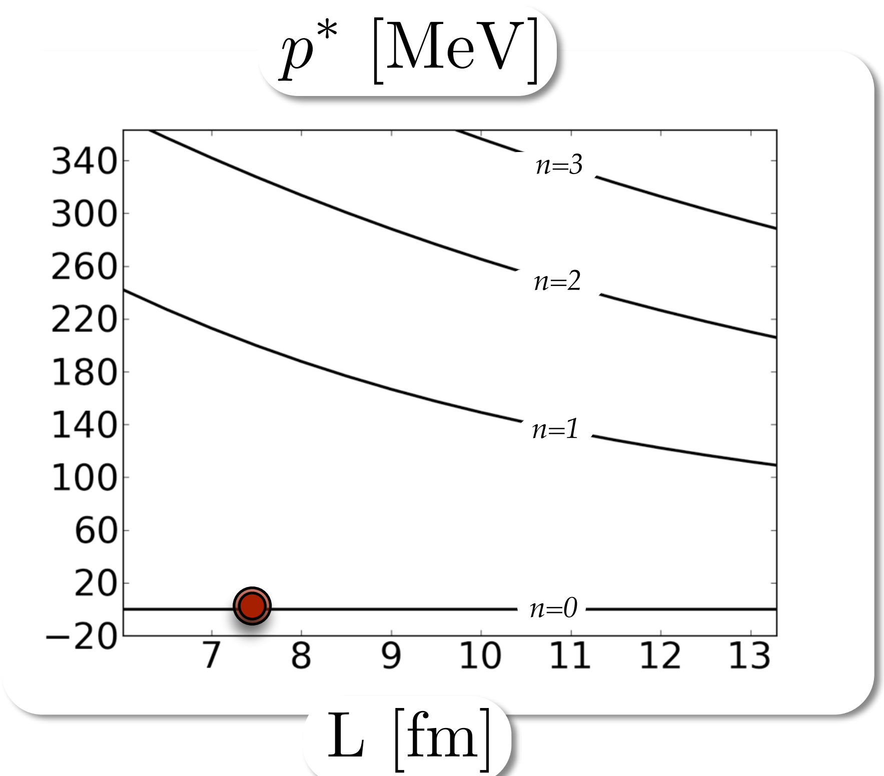

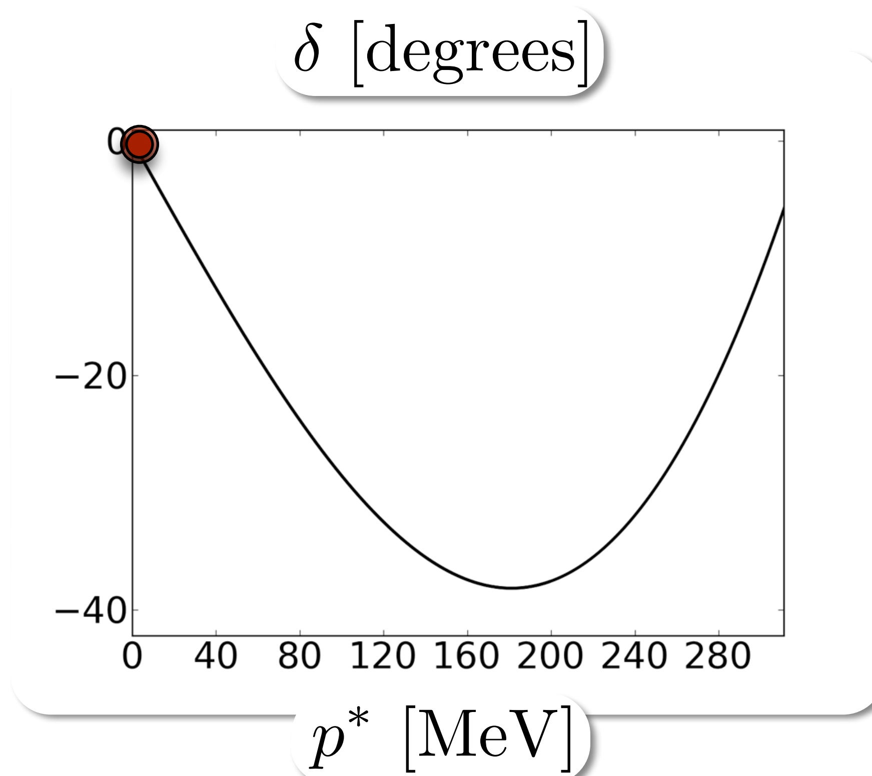

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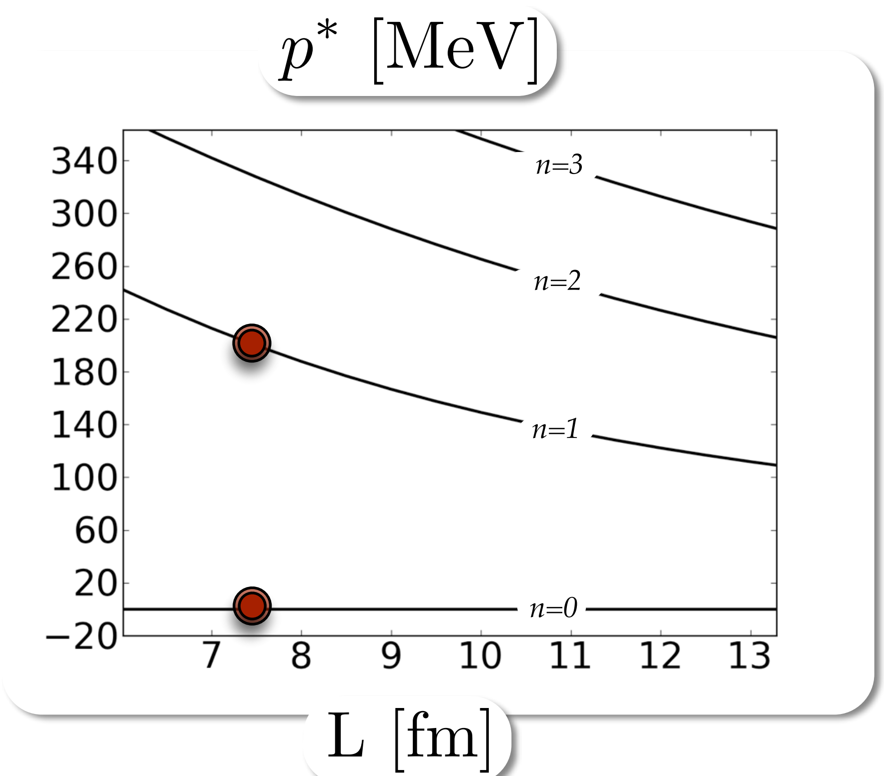

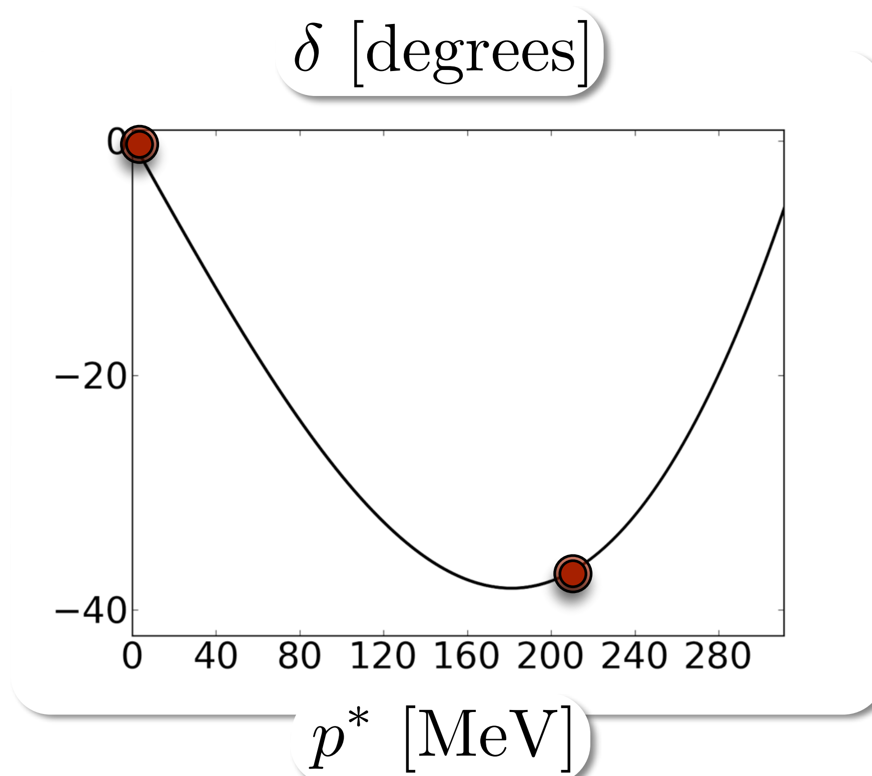

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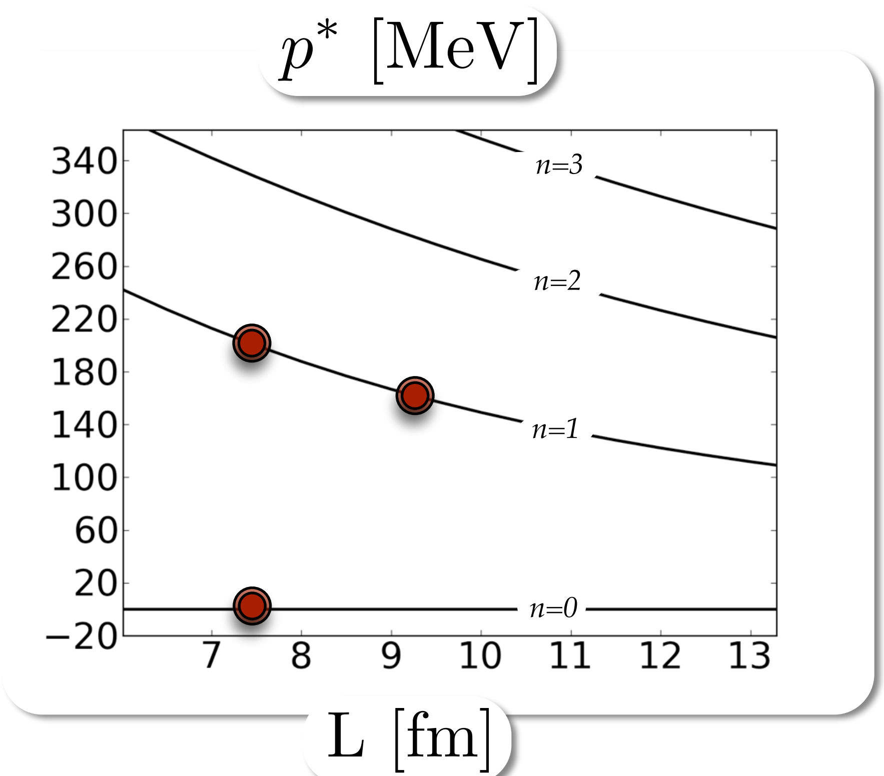

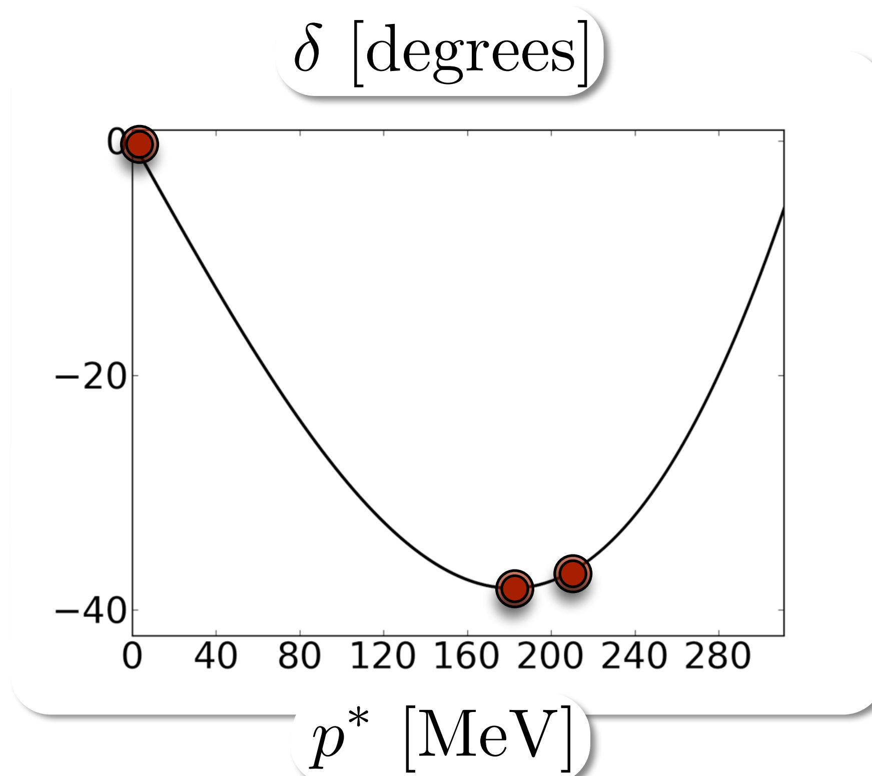

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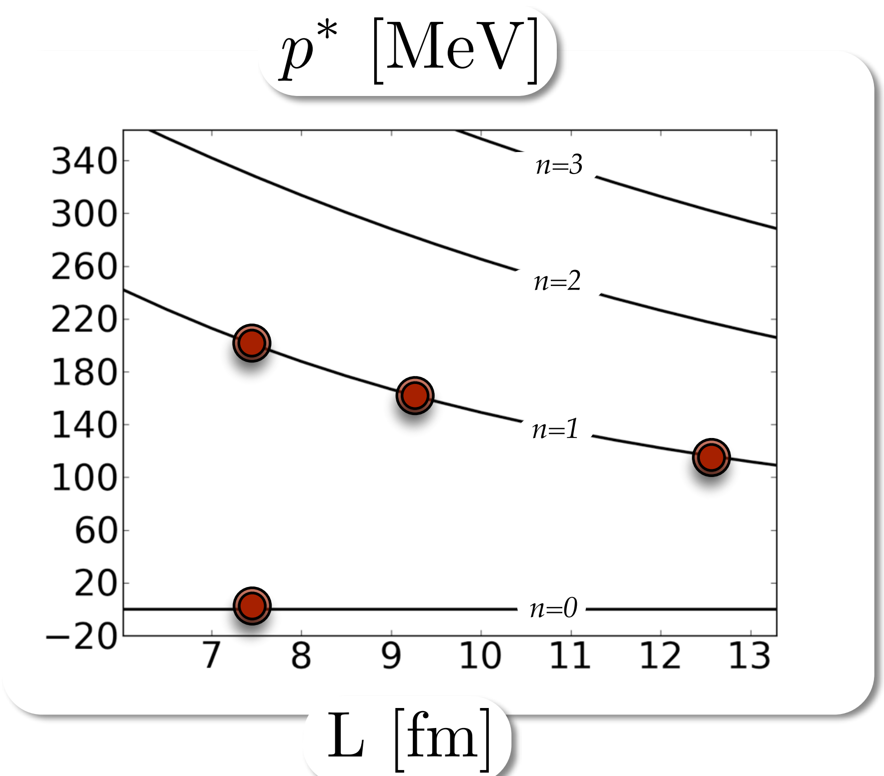
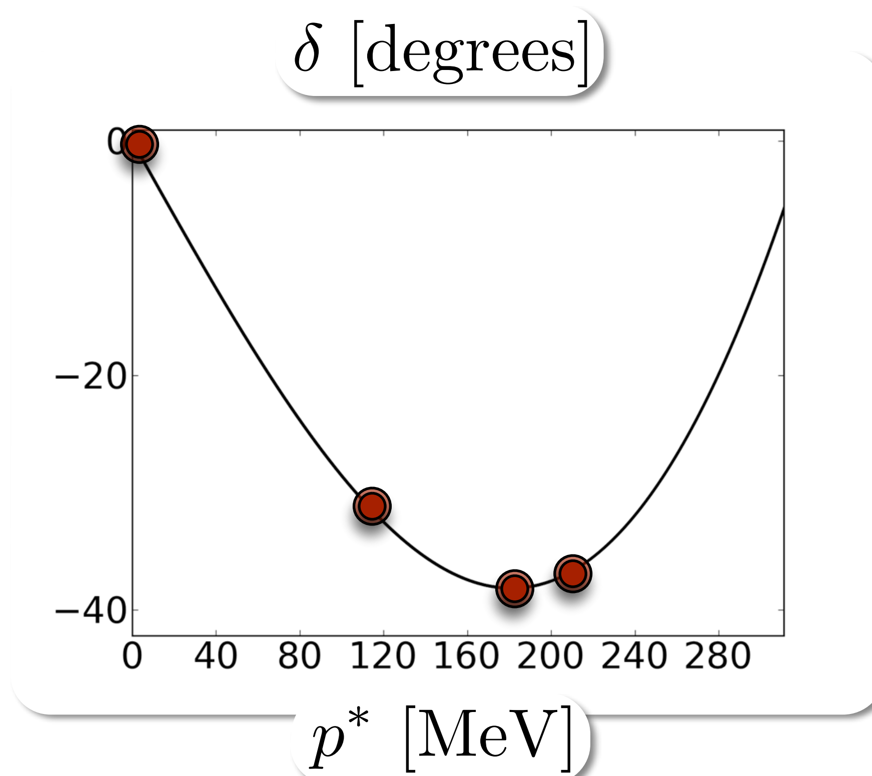


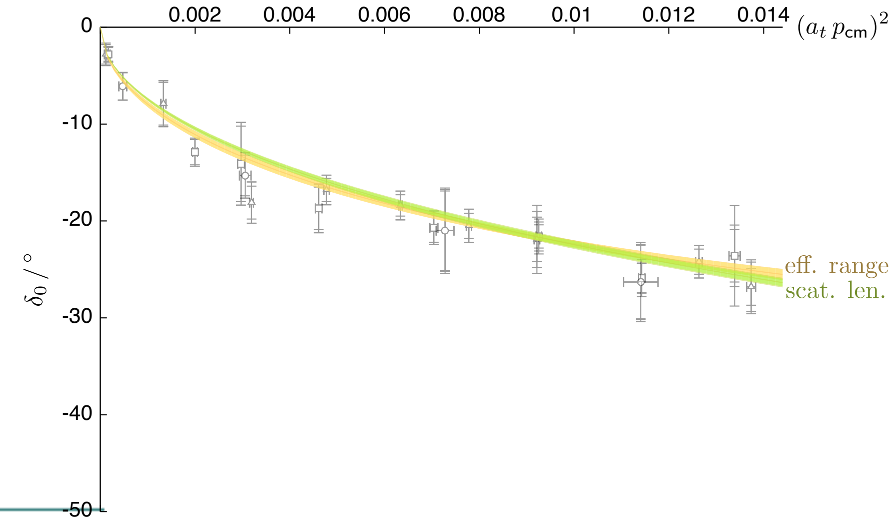


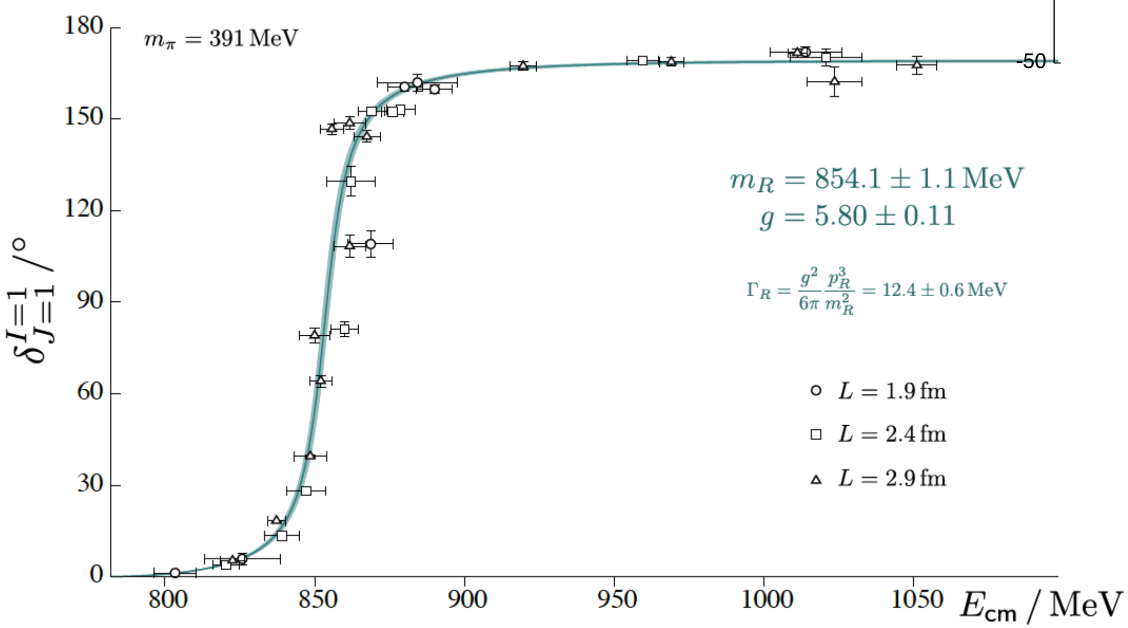
I=2 and Resonant I = 1 ππ Phase Shift

$$\det\left[e^{2i\boldsymbol{\delta}(k)} - \mathbf{U}_\Gamma\left(k\frac{L}{2\pi}\right)\right] = 0$$

Matrix in l **lattice irrep**

Dudek *et al.*, Phys Rev D83, 071504 (2011); arXiv:1203.6041





Feng, Renner, Jansen, PRD83, 094505

PACS-CS, PRD84, 094505

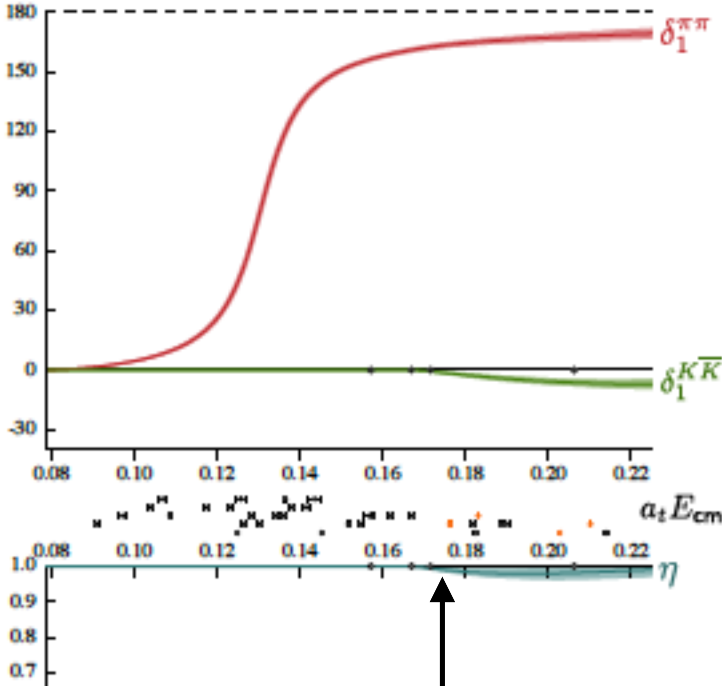
Alexandru et al

Lang et al., PRD84, 054503

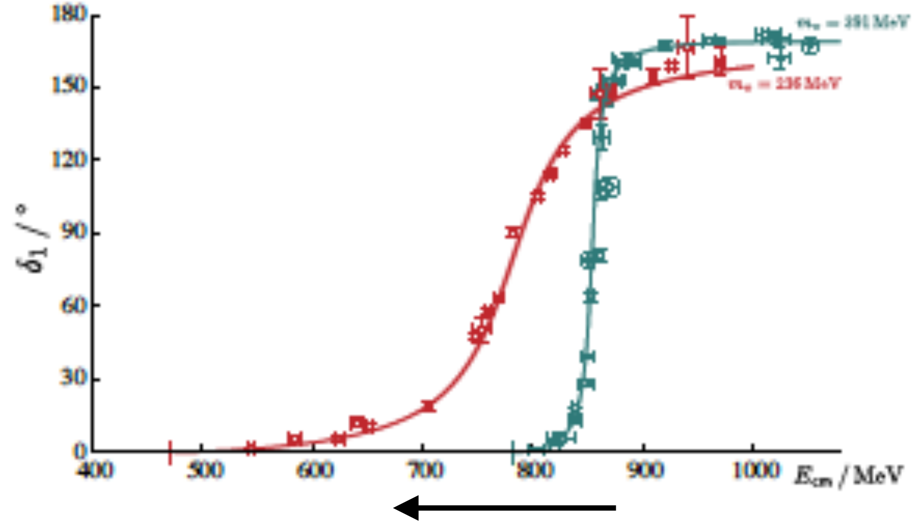
Dudek, Edwards, Thomas, Phys. Rev. D 87, 034505 (2013)

Inelastic in ππ KK channel

Wilson, Briceno, Dudek, Edwards, Thomas, arXiv:1507.02599



Inelastic Threshold



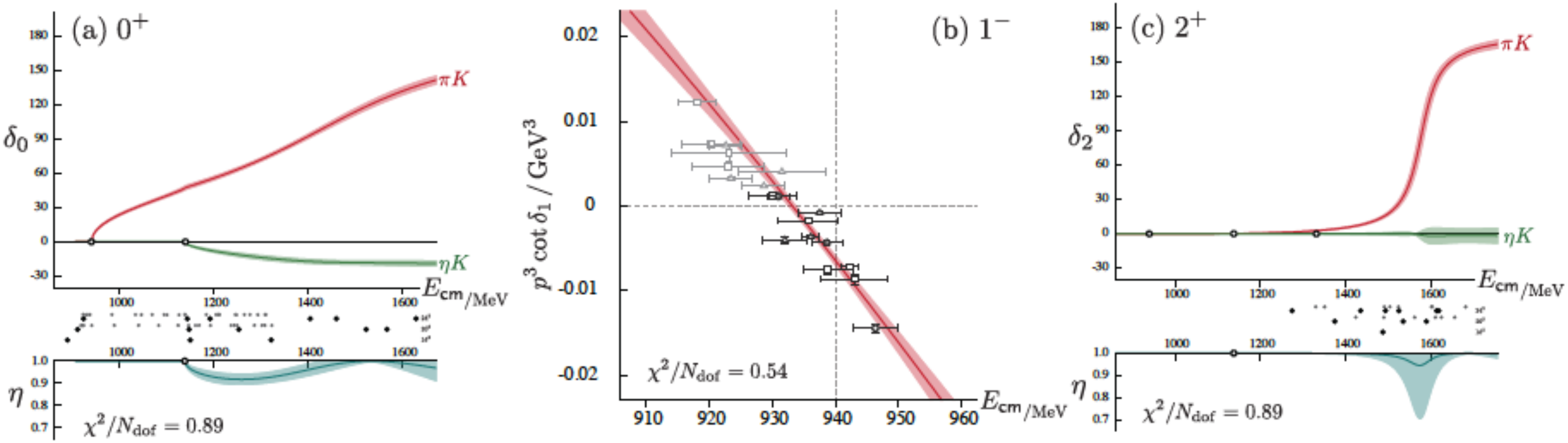
Decreasing Pion Mass

First - and Successful - inelastic

$$\det\left[\delta_{ij}\delta_{JJ'} + i\rho_i\, t_{ij}^{(J)}(E_{\mathsf{cm}})\left(\delta_{JJ'} + i\mathcal{M}_{JJ'}^{\vec{P}\Lambda}(p_i L)\right)\right] = 0$$

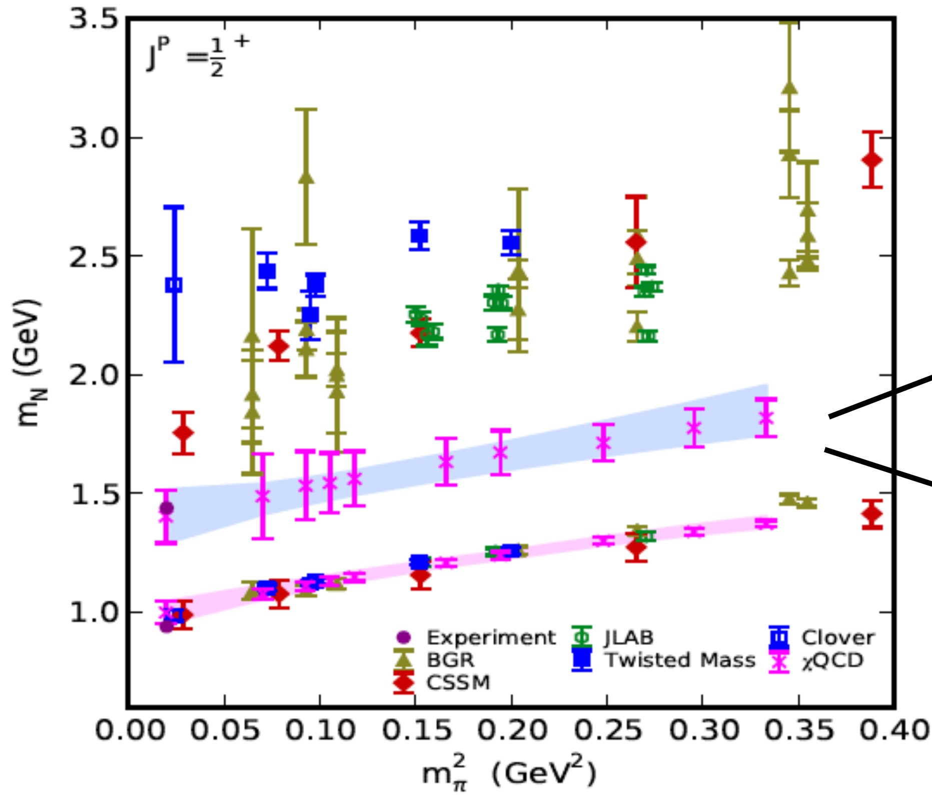
Parametrized as phase shift + inelasticity

$$t_{ii} = \frac{(\eta e^{2i\delta_i} - 1)}{2i\rho_i}, t_{ij} = \frac{\sqrt{1-\eta^2}\, e^{i(\delta_i+\delta_j)}}{2\sqrt{\rho_i\,\rho_j}}$$



Dudek, Edwards, Thomas, Wilson, PRL, PRD

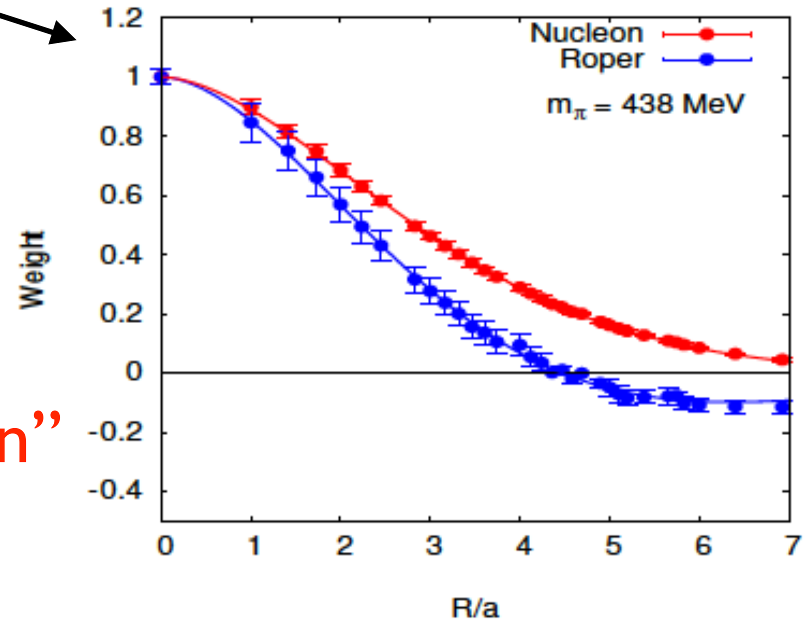
Roper Resonance



Compendium of Roper results

χQCD, arXiv:1403.6847

Overlap Fermions,
Sequential Bayesian Method



"radial wave function"

Electromagnetic (Weak) Properties

e.g.
$$\langle 0 \mid J_\mu \mid \text{"1"} \rangle$$
$$\langle 0 \mid A_\mu \mid \pi \rangle$$
$$\langle 0 \mid uud \mid N \rangle$$

e.g.
$$\langle \text{"1"} \mid J_\mu \mid \text{"1"} \rangle$$
$$\langle N \mid V_\mu \mid N \rangle$$

e.g.
$$\langle 0 \mid J_\mu \mid \text{"2"} \rangle$$
$$\langle 0 \mid A_\mu \mid \pi' \rangle$$
$$\langle 0 \mid uud \mid N* \rangle$$

e.g.
$$\langle \text{"2"} \mid J_\mu \mid \text{"2"} \rangle$$
$$\langle N* \mid V_\mu \mid N* \rangle$$

e.g.
$$\langle \text{"1"} \mid J_\mu \mid \text{"2"} \rangle$$
$$\langle \pi \mid V_\mu \mid \pi\pi \rangle$$
$$\langle N \mid V_\mu \mid N* \rangle$$

Briceno and Hansen - arXiv:1502.04314, arXiv:1509.08507

See **Raul Briceno**, this session

Pseudoscalar Decay Constants

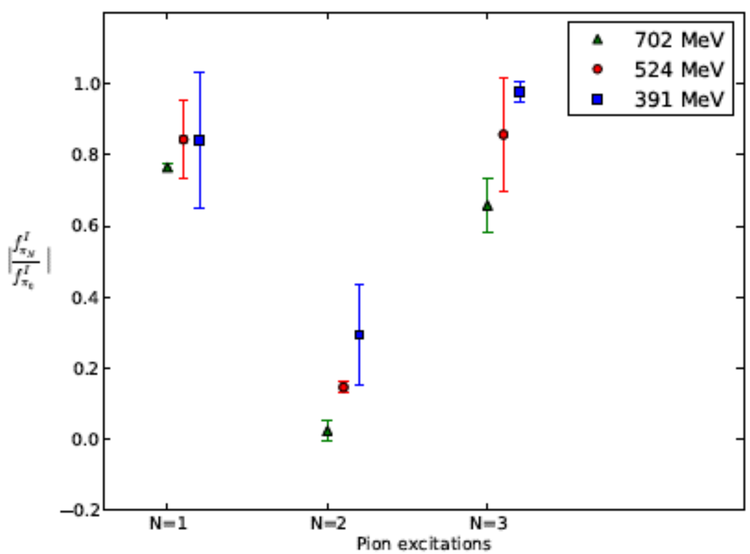
e.g. Chang, Roberts, Tandy, arXiv:1107.4003

- Expectation from WT identity $f_{\pi_N} \equiv 0, N \geq 0$
- Compute in LQCD

$$C_{A_4,N}(t) = \frac{1}{V_3} \sum_{\vec{x},\vec{y}} \langle 0 \mid A_4(\vec{x},t)\Omega_N^\dagger(\vec{y},0) \mid 0 \rangle \longrightarrow e^{-m_N t} m_N \tilde{f}_{\pi_N}$$

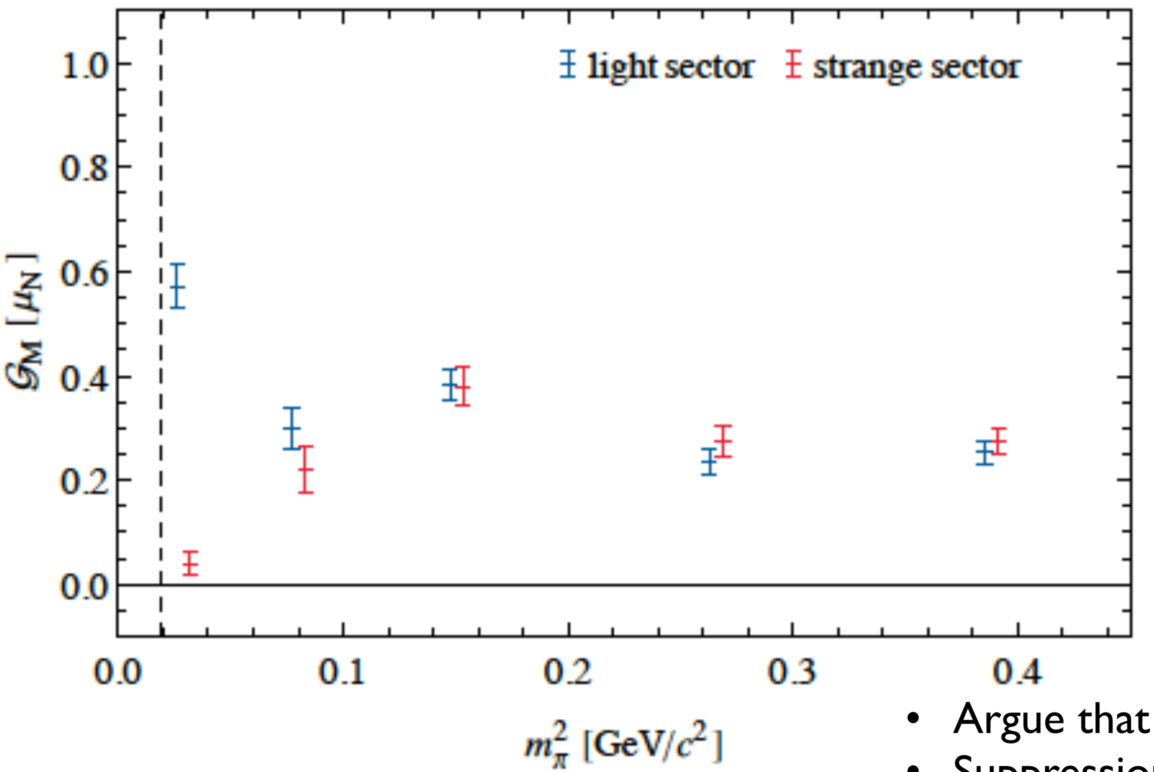
where $\Omega_N = \sqrt{2m_N} e^{-m_N t_0/2} v_i^{(N)} \mathcal{O}_i$

E. Mastropas, DGR, arXiv:1403.5575



Infinite-volume matrix elements: need vacuum to two-body matrix elements and energy-dependent amplitudes

Lambda (1405)



Hall et al, arXiv;1411.3402, PRL

- Argue that is molecular state
- Suppression of strangeness contribution to magnetic moment consistent with KN molecule
- Strong caveat - *interpretation in terms of infinite-volume matrix element requires two-body analysis at finite volume*

Lattices for Hadron Physics

- Calculations at physical light-quark masses: *direct comparison with experiment*
- Several fine lattice spacings: *controlled extrapolation to continuum, and to reach high Q2*
- Hypercube symmetry: *simplified operator mixing*
- *Variational method, to control and extract excited states*

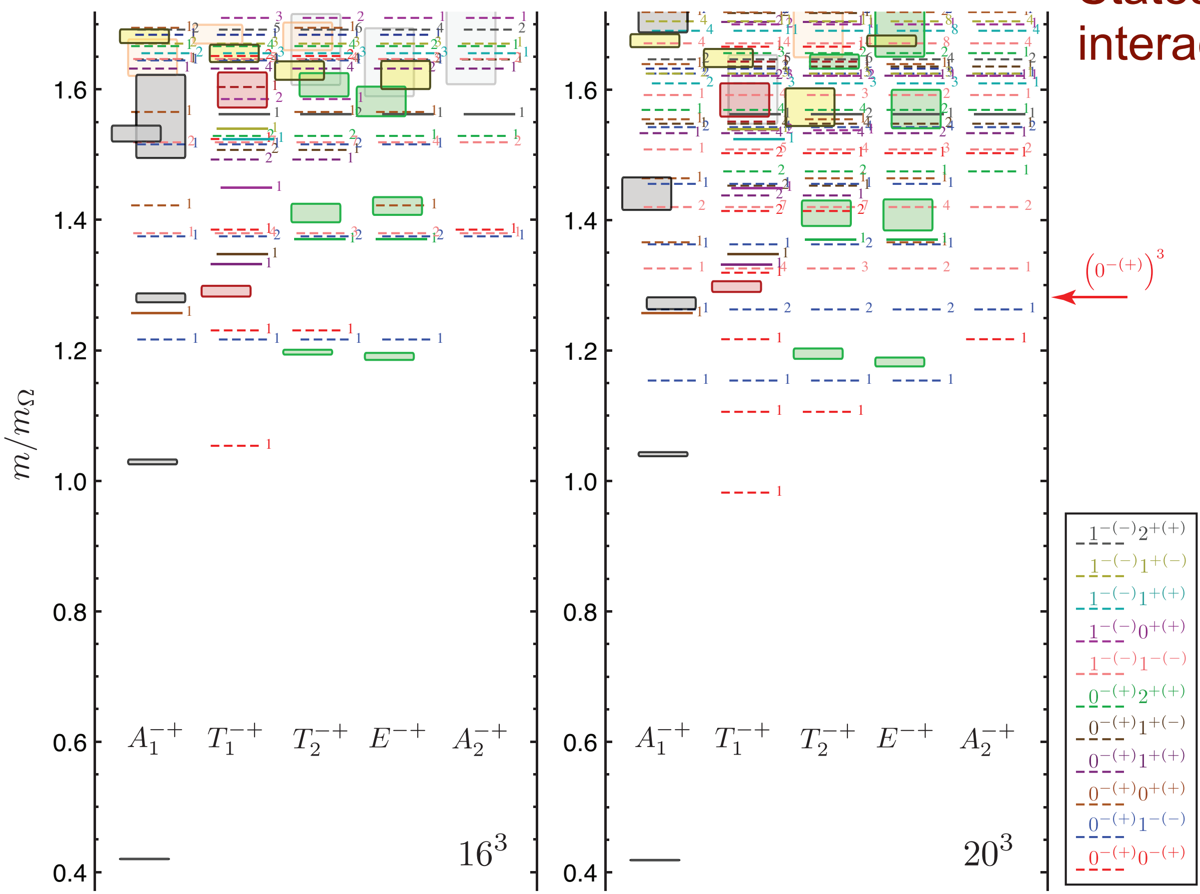
$$\mathrm{Cost}_{\mathrm{traj}} = C\xi^{1.25}\left(\frac{\mathrm{fm}}{a_s}\right)^6 \cdot \left[\left(\frac{L_s}{\mathrm{fm}}\right)^3\left(\frac{L_t}{\mathrm{fm}}\right)\right]^{5/4}$$

Major Effort by USQCD

Summary

- Determining the quantum numbers and the study of the “single-hadron” states a solved problem
- Lattice calculations used to construct new “phenomenology” of QCD
  – Quark-model like spectrum, *common mechanism for gluonic excitations in mesons and baryons. LOW ENERGY GLUONIC DOF*
- **Prediction** *- Additional states in baryon spectrum associated with hybrid dof.*
- Formalism for extracting scattering amplitudes, including inelastic channels, developed - applied for first time to meson sector
- COUPLED-CHANNEL METHODS ARE KEY
- Formalism for extracting infinite-volume matrix elements from calculations at finite volume developed - *Next Talk*
- Next step for lattice QCD:
  – Baryons more challenging…. *…New improved methods in progress…*
  – Calculations at closer-to-physical pion masses - isotropic lattices

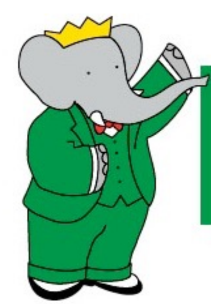
The elephant in the room...



States unstable under strong interactions

Meson spectrum on two volumes: dashed lines denote expected (non-interacting) multi-particle energies.

Allowed two-particle contributions governed by cubic symmetry of volume



Calculation is incomplete.