GLUEBALLS AND QCD: FROM THE LATTICE TO THE EXPERIMENT

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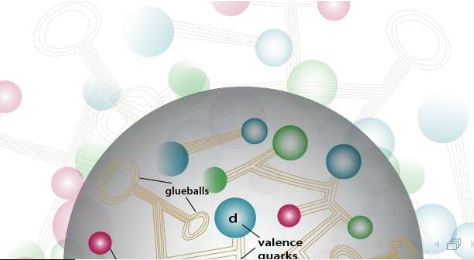
UAM

June, 29th 2010



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- Recently works on AdS/CFT correspondence suggests holographic confinement mechanisms!This models qualitatively reproduce lattice results (more or less)And finally...
- Glueballs (and hybrids/exotics) are sexy and exciting (themes for researching and Ph.D.)!

EXTRA BONUS: THE YM GAP-MASS CLAY MILLENIUM'S PROBLEM

Understanding glueball masses is an equivalent formulation of a celebrated Millenium's problem: the Yang-Mills mass-gap!

Extra credit: understanding this glueball spectrum worth $ 1 million!

To celebrate mathematics in the new millennium, The Clay Mathematics Institute (CMI) identified seven old and important mathematics questions that resisted all past attempts to solve them. The CMI designated the $7 million prize fund for their solution, with $1 million allocated to each Millennium Prize Problem.

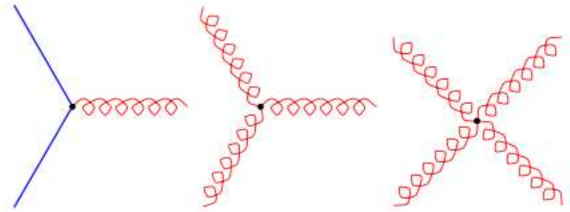
QCD in a nutshell: lagrangian and fields

The QCD lagrangian, as everyone knows, is ($q_i = \Psi_i$)

$$\mathcal{L}_{QCD} = \overline{\Psi}_i \left(i\partial_\mu \gamma^\mu \delta_{ij} + g \frac{\lambda^a_{ij}}{2} A^a_\mu \gamma^\mu - m_f \delta_{ij} \right) \Psi_j - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

where

$$G^a_{\mu\nu} = \partial \mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$



Symmetries in QCD

- $SU(N_c)$ gauge symmetry (SM has $N_c = 3$)
- Massless fermions enlarge symmetry:
  $U(N_f)_A \times U(N_f)_V = SU(N_f)_V \times SU(N_f)_A \times U(1)_V \times U_1(A)$
- $SU(N_f)_A$ suffers SSB, $U(1)_V$ is an actual symmetry, $U(1)_A$ carries the axial anomaly.

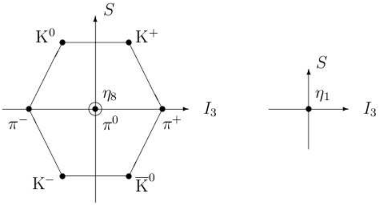
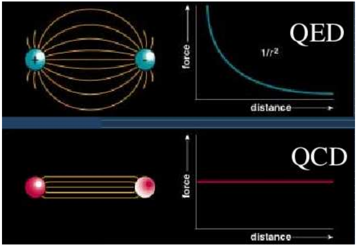


Figure 1: $\mathrm{SU}(3)_{flavor}$ nonet of the lightest pseudoscalar mesons ($J^{PC} = 0^{-+}$). The light u, d and s quarks and their corresponding antiquarks $\bar{u}$, $\bar{d}$ and $\bar{s}$ form the basis for $9 = 3 \otimes 3$ mesons. These are the illustrated octet (left) and the η_1 singlet (right).

Key qualitative QCD features

- Fundamental degrees of freedom (quarks and gluons) cannot be observed in isolation
- Attractive force between quark-antiquark is constant with separation
- It suggests that gluon field forms a string-like object between quark-antiquark

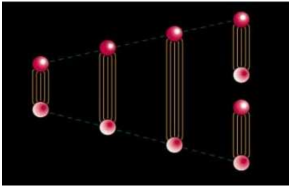


Constituent quark model

- Much of our understanding of hadron formation comes from the so-called **constituent quark model**
  - Motivated by QCD
  - Valence quarks interacting via Coulomb + linear potential
  - Gluonic degrees of freedom: source of the potential, dynamics ignored
  $P = (-1)^{L+1}$ $L = 0, 1, 2, ...$ and
  $C = (-1)^{L+S} qquad$ $S = 0, 1$
- Mesons: only certain J^{PC} values are allowed: $0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, 4^{+-}, ...$ forbidden
- Most of observed low-lying hadron spectrum described reasonably well by quark model (agreement is amazing given the crudeness of the model experimental)
- Results now need input beyond the quark model(over-abundance of states, forbidden 1^{-+} states)

Quark confinement

- Quarks can never be isolated (confinement)!
- Linearly rising potential $V \sim \sigma r$
- Result (I): separation of quark from antiquark takes an infinite amount of energy
- Result (II): gluon flux breaks, new quark-antiquark pair produced



Quark model of hadrons

- Mesons are $|\Psi\rangle = q\overline{q}$ states. Group theory gives

$$q \otimes \overline{q} = 3 \otimes 3 = 8 \oplus 1$$

- Baryons are $|\Psi\rangle = qqq$ states. Group theory gives

$$q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$

However QCD predicts the so-called exotics and glueball states.

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However QCD predicts the so-called exotics and glueball states.

$$q \otimes \overline{q} \otimes q = 15 \otimes 6 \otimes 3 \otimes 3 \to \text{It does not work, no color singlet!}$$

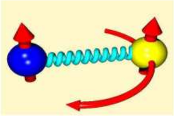
Color singlets are required in $SU(3)_c$ gauge theory!!! We need a multiple $(q \otimes \overline{q})^n$ or $(q \otimes q \otimes q)^n$. As well,

- $g \otimes g = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1 \Longrightarrow$ **GLUEBALLS**
- $q \otimes \overline{q} \otimes g = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus 1 \Longrightarrow$ **HYBRIDS**

Ordinary Mesons

$J^{PC} \equiv {}^{2S+1}L_J$

- Parity $P = (-1)^{L+1}$
- Charge Conjugation (defined for neutral mesons) $C = (-1)^{L+S}$
- G parity $G = C(-1)^I$

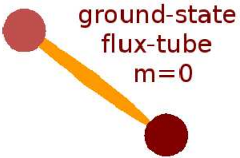


$L = 0,\ S = 1:$

$\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$L = 0,\ S = 0:$

e.g. $\pi\ (J^{PC} = 0^{-+})$



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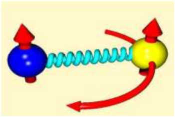

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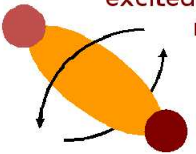
12 GeV CEBAF upgrade has high priority
(DOE Office of Science, Long Range Plan)
"[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."



excited flux-tube
m=1

Forbidden States (Exotics):
$J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, \cdots$

Mesons: Quantum numbers (I)

		J^{PC}	$^{2S+1}L_J$	$I=1$	$I=0\ (n\bar{n})$	$I=0\ (s\bar{s})$	Strange
$L=0$	$S=0$	0^{-+}	$^1S_0$	π	η	η'	K
	$S=1$	1^{--}	$^3S_1$	ρ	ω	ϕ	K^*
$L=1$	$S=0$	1^{+-}	$^1P_1$	b_1	h_1	h'_1	K_1
	$S=1$	0^{++}	$^3P_0$	a_0	f_0	f'_0	K^*_0
	$S=1$	1^{++}	$^3P_1$	a_1	f_1	f'_1	K_1
	$S=1$	2^{++}	$^3P_2$	a_2	f_2	f'_2	K^*_2

Notation

1. J^{PC} s are measured quantities.
2. $^{2S+1}L_J$ s are internal quantum numbers in a non-relativistic quark model.

Mesons: Quantum numbers (II)

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Why lattice gauge theory?

1. Calculational tools of QED generally use small coupling expansions: work well for deep inelastic scattering in QCD!(Due to asymptotic freedom)
2. Perturbative methods utterly fail for hadron formation: bound state problem $\propto e^{-1/g^2}$
3. Ken Wilson (1974) suggests novel approach
   - Formulate QCD using a discrete space-time lattice
   - Lattice acts as ultraviolet regulator (nonperturbative renormalization of gauge theories)
   - Wilson formulation preserves exact local gauge invariance!
4. Main advantages of this approach
   - Easy computer simulations of quarks and gluons
   - Theoretical ability to explore small-coupling expansions!

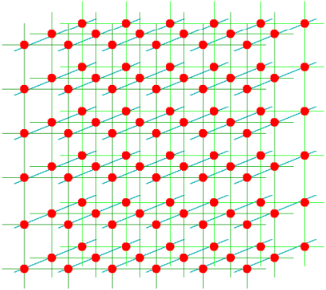
Lattice basis (I)

- Useful for brute force calculations of strong interaction observables (e.g.: spectra, decay constants f_B , structure functions, quantities needed to go beyond the standard model,. . .)
- Useful tool to help understand QCD (examples: testing mechanisms of confinement, answering why the naive quark model works as well as it does, answering the question "do certain field configurations dominate path integral?", developing better tools for nonperturbative aspects of gauge theories, lattice repercussions go beyond QCD and, beyond SM?)
- Lattice simulations have told us much about QCD! Yet much more to learn!

Lattice basis (II)

- hypercubic space-time lattice
- quarks reside on sites, gluons reside on links between sites
- for gluons, 8 dimensional integral on each link

- path integral has dimension $32 N_x N_y N_z N_t$
  - 10.6 million for 24^4 lattice
- more sophisticated updating algorithms
- systematic errors
  - discretization
  - finite volume



Lattice basis (III): MonteCarlo calculations in the lattice

- The vacuum expectation value (VEVs) can be calculated in terms of path integrals, and the masses are proportional to correlators in this way: $C(t) = \langle \Phi(t)\Phi^*(0) \rangle \propto e^{-Mt}$

$$\langle \Phi(t)\Phi^*(0) \rangle = \frac{\int D\Phi\Phi(t)\Phi^*(0)e^{-S[\Phi]}}{\int D\Phi e^{-S[\Phi]}}$$

- $S[\Phi]$ is the Euclidean Space Action, Φ^* creates interesting states
- Evaluation methods of path integrals:
  - Markov-chain Monte Carlo methods (Metropolis, heatbath, overrelaxation, hybrid methods)
  - No expansions in a small parameter
  - Statistical errors are important!
- MonteCarlo provides a first principles approach, "universal" with present computer technology

Lattice QCD advanced technology

- Quantum Chromodynamics (QCD) can be defined non-perturbatively as the continuum limit of a Lattice gauge theory.
- This approach provides both an ultraviolet regulator of the continuum field theory and admits numerical evaluation of the functional integrals required for calculating physical observables.
- In the continuum, the QCD path integral is

$$\mathcal{Z} = \int \mathcal{D}A_\mu \mathcal{D}\overline{\Psi}\mathcal{D}\Psi e^{\int d^4x\left(-\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \sum_f \overline{\Psi_f}[D_\mu\gamma_\mu + m_f]\Psi_f\right)}$$

- Observables (physical quantities) in this theory can be calculated from correlation functions of operators $\hat{O}$ that are functions of the quantum fields (quarks and gluons):

$$\left\langle \hat{O} \right\rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}A_\mu \mathcal{D}\overline{\Psi}\mathcal{D}\Psi \hat{O} e^{\int d^4x\left(-\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \sum_f \overline{\Psi_f}[D_\mu\gamma_\mu + m_f]\Psi_f\right)}$$

Lattice QCD advanced technology(II): Links and plaquettes

The discrete gauge action is the sum over all plaquettes $P_{\mu\nu}(X)$ which are the product of the links $U_\mu(x)$ around the elementary plaquettes of the lattice($\beta = \frac{2N_c}{g^2}$):

$$P_{\mu\nu} = U_\mu(x) U_\nu(x+\mu) U_\mu(x+\nu)^\dagger U_\mu(x)^\dagger$$

$$S_{g,Wilson-plaquette}^{lat,discrete} = \beta \sum_{x,\mu\nu} \left(1 - \frac{1}{3} Tr P_{\mu\nu}\right)$$

Link variables are Wilson-line operators: $U_\mu(x) = \mathcal{P} \int_x^{x+a\mu} dz^\mu A_\mu(z)$

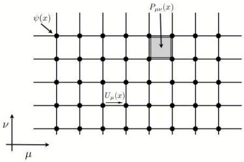


Figure 1: A two dimensional slice of the four dimensional space-time lattice. μ and ν denote unit-vectors in the indicated directions. $\psi(x)$ denotes a fermion-field at the lattice-site x, $U_\mu(x)$ denotes the gauge-link from the lattice-site x to the site $x + b\mu$, and $P_{\mu\nu}(x)$ denotes the 1×1 Wilson plaquette centered at $x + b\mu/2 + b\nu/2$.

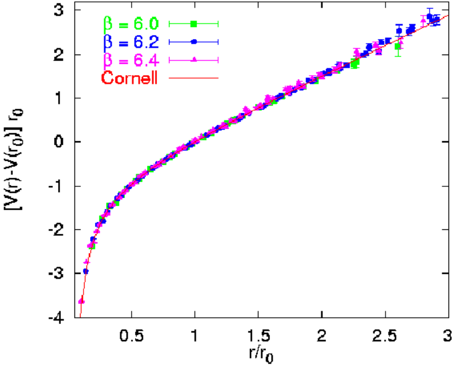
Lattice theory status

1. Significant advances in simulation techniques during 1990's:
   - Improved actions (quantum corrections to couplings, tadpoles)
   - Excited states using variational techniques with correlator matrices
   - Anisotropic lattices
   - Chiral fermions (domain wall, overlap)
2. Computers today: vastly improved performance, lower costs
3. Accurate calculations of many quantities for the first time (Yang-Mills glueball spectrum , quenched light hadron spectrum, quenched f_B, etc.)
4. Full incorporation of virtual quark-antiquark pairs still a problem (very active subject of current research)

Lattice results(I): linear potential

- Lattice simulations confirm linearly rising potential from gluon exchange

Fig.1. From Bali et. al. we get the following plot ($r_0 = 0.5fm$):



Lattice results(II): the glueball spectrum

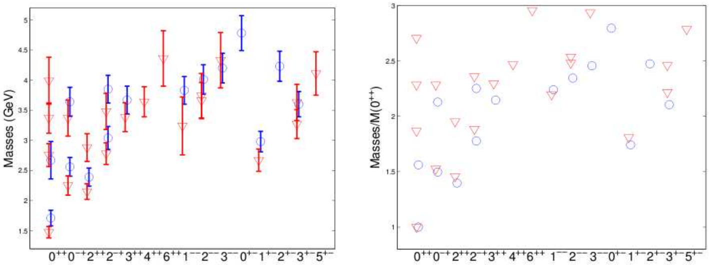


FIG. 2: Comparison between Morningstar and Peardon (circles) and Meyer and Teper (triangles) of the mass spectrum of glueballs in pure $SU_C(3)$ gauge theory. Absolute masses (left) and mass ratios with respect the scalar glueballs (right).

Recently, Meyer updated masses of the scalar and the tensor using his technique.[22] In this latter reference, he used the lattice scale r_0 allowing to compare with the other studies. The new masses are closer the Morningstar and Peardon's ones and read

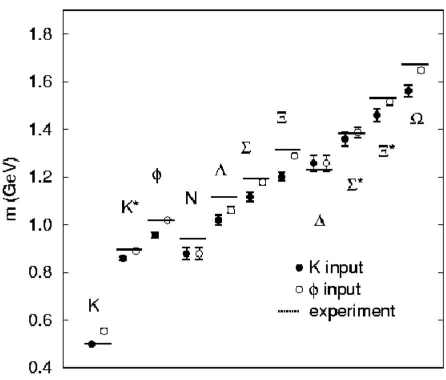
$$r_0 M_{0^{++}} = 3.958(47), \qquad r_0 M_{2^{++}} = 5.878(77). \tag{6}$$

All lattice calculations are now consistent and shown that, in pure gauge theory, the masses of the lowest states are

$$M_{0^{++}} \sim 1.6 - 1.7 \text{ GeV}, \qquad M_{2^{++}} \sim 2.4 \text{ GeV} . \tag{7}$$

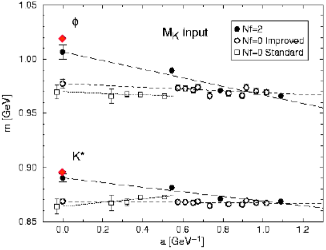
Lattice results (III): the QCD light hadron spectrum

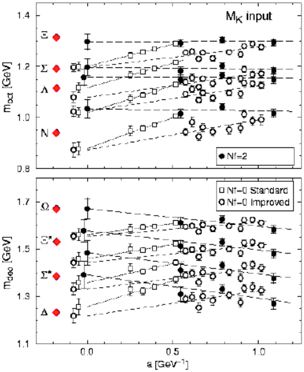
The CP-PACS collaboration (Japan) Phys Rev Lett 84, 238 (2000) obtains



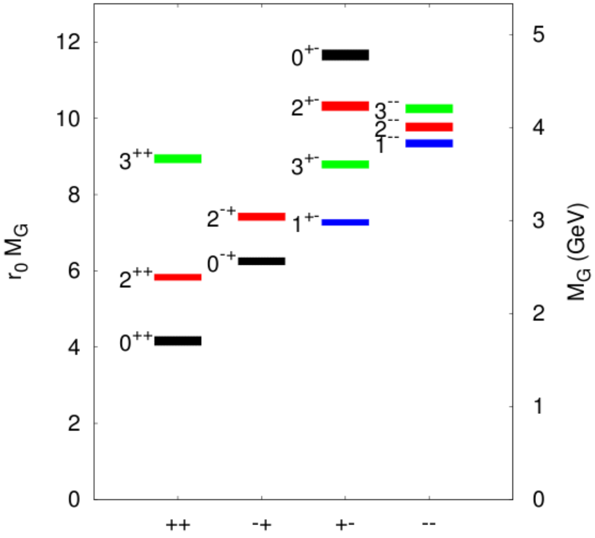
Lattice results (IV): the QCD light hadron spectrum $N_f = 2$

CP-PACS collaboration hep-lat/0010078: consider baryons, finite volume effects and try to fit experimental values

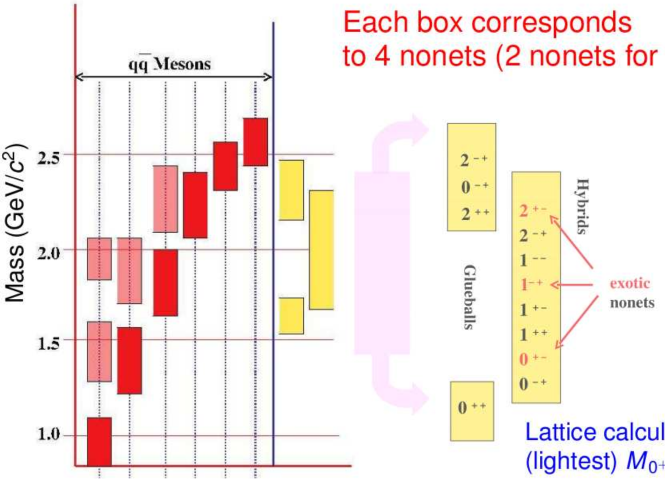




The gluonic excitations in lattice QCD(I)



The gluonic excitations in lattice QCD(II)



Each box corresponds to 4 nonets (2 nonets for $L = 0$)

Lattice calculations:
(lightest) $M_{0^{++}} \approx 1.55$ GeV/c^2

THE PROBLEMS WITH GLUEBALLS

Why is difficult to identify the Glueballs?

1. There are several mesons which have same charges and roughly same mass as the glueballs:The branching ratio *are needed* to distinguish them! Very difficult experimental task...
2. Experimentally we do not know much about the branching ratio of the glueball candidates: We expect that LHC, and other accelerators, will give us a huge amounts of hadoronic data and improve the experimental situation drastically!
3. On the theoretical side, it is very difficult to compute reliably couplings of glueballs to ordinary mesons in QCD. Actually, no reliable computations ever have done.

THE SERIOUS ISSUE WITH GLUEBALLS: We need a way to compute the glueball decay reliably!

GLUEBALL DECAY PROBLEMS

Known issues for existing methods to compute glueball decay:

- **Chiral Lagrangian approach**: The glueballs have relatively heavy (heavier than 1500 MeV). Thus no control by the derivative expansion. Moreover, glueballs are singlets of the flavor symmetry.
- **Lattice QCD**: Spectrum is easy. To compute the decay rate is possible, but very difficult because Lattice QCD is defined on the Euclidean space-time.
- **Usual large N expansion**: Weak t'Hooft coupling is needed to compute explicitly the decay rate. But confinement can not be seen by the weak coupling expansion. Recent developments in this area involve holography. Holographic QCD will be useful computational framework as an alternative check to lattice calculations (present work is very preliminar and not so reliable as lattice calculations now).

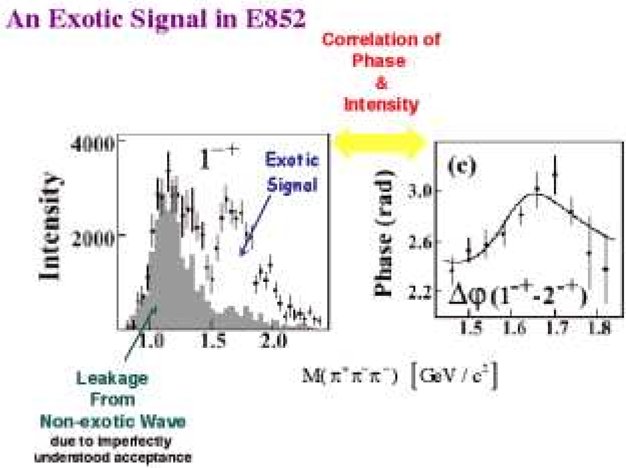
ACTUAL GLUEBALL CANDIDATES

THE OBELIX, CRYSTAL-BARREL, BES-II, VES AT PROTVINO, WA102, WA76,WA91, E852 BROOKHAVEN NAT.LAB. experiments have nominated some glueball candidates:

- **The scalar glueball**: $f_0(1500)$ or $f_J(1710)$ (due to possible mixing between states, complicated measurements)
- **The tensor glueball**: $\xi(2230)$ or $f_2(1980)$
- 1^{-+} hybrid mesons found (E852 BNL 1997)
  - 1.4 GeV (controversial)
  - 1.6 GeV (lattice predicts 1.9 GeV)
- higher $c\bar{c}$ and $b\bar{b}$ states
- hybrid baryon $P_{11}(1710)$
- Others (no conclusive evidence till now: subtle experimental problem to identify states)

RESULTS FROM THE EXPERIMENTS: other candidates

Some exotics

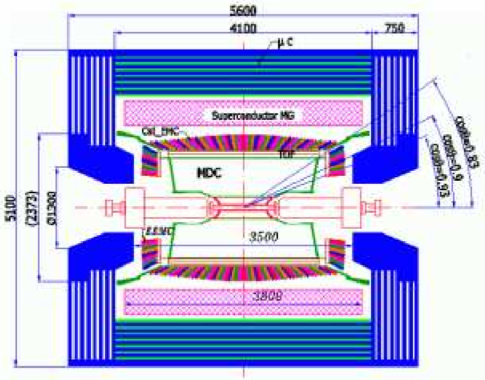


BES-III

- The BES-III experiment at BEPCII in Beijing started operation in summer of 2008.
- The amount of expected J/Ψ data is nearly 200 times as large as the BES-II.
- Large data sets will make it possible to study hadron spectroscopy in the decays of the charmonium states and the charmed mesons.
- Particularly interesting: glueball searches since J/Ψ decays have always been viewed as one of the best places to look for glueballs.
- Tensor glueball candidate pursued $2^{++} = f_J(2220)$
- The authors point out that a partial wave analysis will be needed to resolve ambiguities.

BES-III (continuation)

The BES-III detector facility (“cheap” chinese technology):

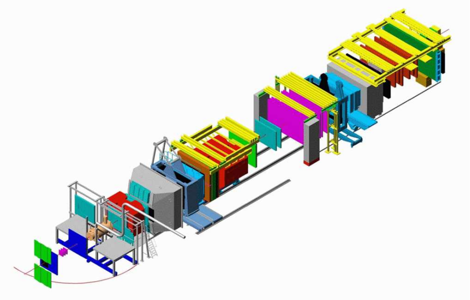


COMPASS

- COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) is a fixed-target experiment approved by CERN in February 1997, which started data taking in 2002.
- The detector is a two-stage magnetic spectrometer with a flexible setup to allow for physics programs with different beams.
- The spectrometer is equipped with tracking systems based on silicon detectors for high-precision tracking in the target region, micromega and GEM detectors for small area and wire/drift chambers as well as straw tubes for large area tracking.
- Particle identification is provided by a large-acceptance ring imaging Cerenkov detector and by hadronic (HCAL) and electromagnetic (ECAL) calorimeters.
- The goal of the COMPASS experiment is the investigation of hadron structure and hadron spectroscopy, both manifestations of non-perturbative QCD.

COMPASS(continuation)

- Key scientific issues addressed at COMPASS are nuclear spin structure and hadron spectroscopy. 2004 initial run with diffractive mesons through lead nuclei seeking excited pions...
- A dedicated spectroscopy run using liquid hydrogen has been planned for 2008. The experiment may also focus on the glue-rich environment produced in central production.

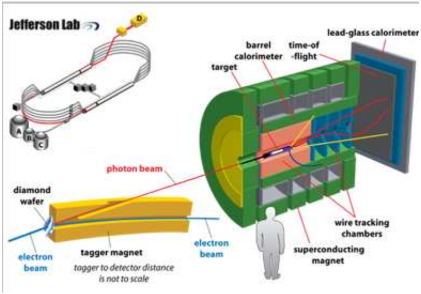


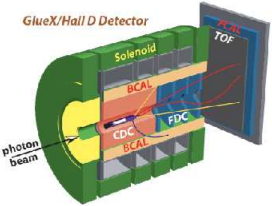
GlueX (at JLab)

- The main physics program of GlueX will be to search for light-quark hybrid mesons and to map out the spectrum of the exotic-quantum-number states.
- Necessary to reconstruct final states with several charged particles and photons.
- The GlueX experiment has been designed to have nearly full solid angle coverage for these particles with sufficient energy and momentum resolution to exclusively identify the desired final states.
- While the primary physics of GlueX will be the search for light-quark hybrids, this will imply a fairly significant program in the spectroscopy of light-quark mesons as well. Specially, glueball (to erase some controversial glueball claims).

GlueX(continuation)

The glueX facility is impressive:





PANDA (at GSI)

- The PANDA (antiProton ANnihilation at DArmstadt) research program will be conducted at the Facility for Antiproton and Ion Research (FAIR), localized at GSI near Frankfurt in Germany.
- The heart of the new accelerator complex is a super-conducting High-Energy Storage Ring (HESR) for antiprotons with a circumference of about 1,100 meters.
- A system of cooler-storage rings for effective beam cooling at high energies and various experimental halls will be connected to the facility.
- Beams will allow high-precision hadron physics using the small energy spread available with antiproton beams (cooled to p/p 105).
- The energy range has been chosen to allow detailed studies of hadronic systems up to charmonium states.
- The use of antiprotons allows to directly form all states with non-exotic quantum numbers in formation experiments.

PANDA (continuation)

- Main goals(exotic physics: charmonium spectroscopy, the search for gluonic excitations, open and hidden charm in nuclei, and also *gamma*-ray spectroscopy of hypernuclei.
- If heavier glueballs exist, then proton-antiproton annihilation may be a good place to look for them. The collaboration will specially study final states including $\phi\phi$ or $\phi\eta$ for states below 3.6 GeV and $J/\psi\eta$ and $J/\psi\phi$ for more massive states.

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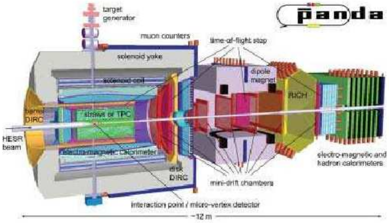

Future and forthcoming works

- Glueball mixing with scalar quarkonium
- Tests of confinement scenarios with glueball spectrum
- flux tube profiles (energy, angular momentum)
- Identify the glueball between candidates(existence almost demonstrated)
- Strings for potentials in other representations (adjoint,...)
- Much more,. . . Waiting surprises to advance in confinement and spectrum understanding of QCD

More future directions

- Final goal: to wring out hadron spectrum from QCD Lagrangian using Monte Carlo and gauge field methods on a space-time lattice baryons, mesons (and glueballs, hybrids, tetraquarks, ...)
- Extraction of excited states in Monte Carlo calculations
- Multihadron operators, relative momenta, more exotics states identification
- Nonperturbative consistent and definitive regularization of gauge theories (possible?)
- Holographic QCD
- New experiments and new surprises (glueballs with exotic quantum numbers?)

CONCLUSIONS: WHAT PHYSICISTS HAVE DONE WITH GLUEBALLS?WHY DO WE WORRY ABOUT IT?

- Identify possible experimental glueball (and exotics) candidates.
- Consistent calculations about glueball spectrum in the lattice. Solidly and consistently established!
- Previously calculated glueball masses consistent with experiments! Definitive check of QCD and lattice methods!
- Some recent work: Now using the holographic Gauge/Gravity corresponde to understand confinement and alternative spectrum calculation to the lattice (qualitative results matching).

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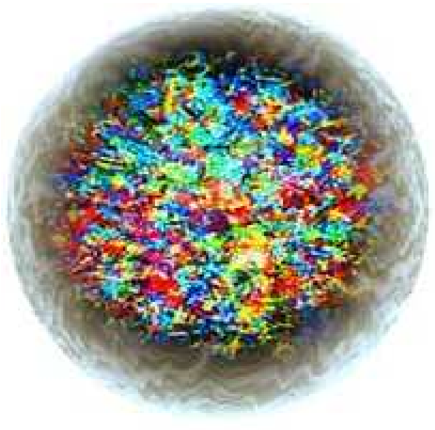
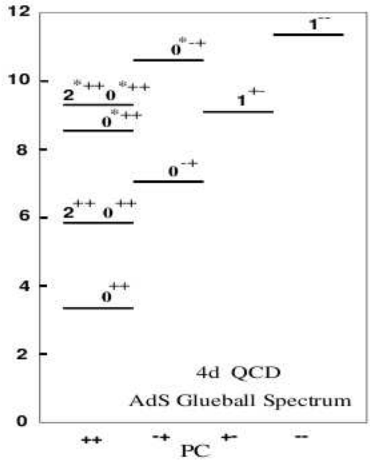
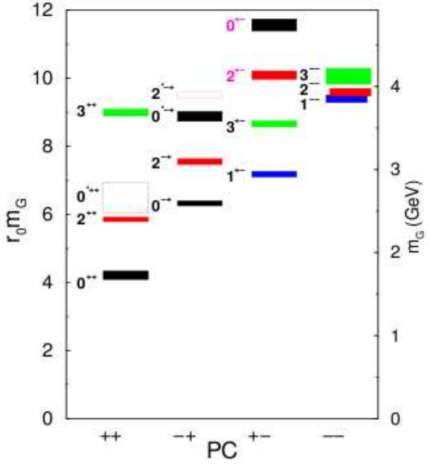
The End...

THANK YOU!

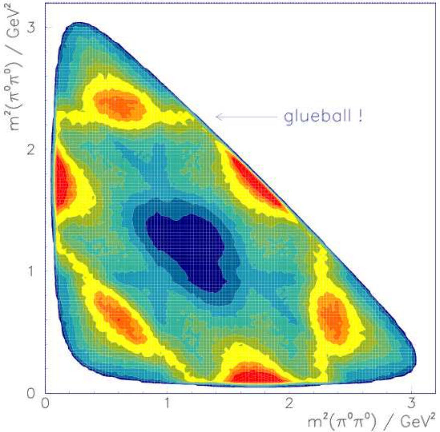


Extra Slide (I): AdS/CFT calculations in QCD

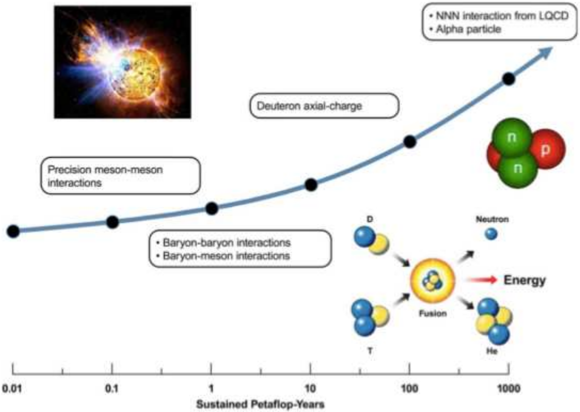




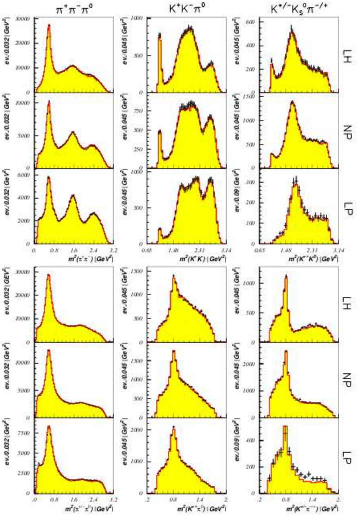
Extra Slide (II): Dalitz plot



Extra Slide (III): Energy resources for lattice theories



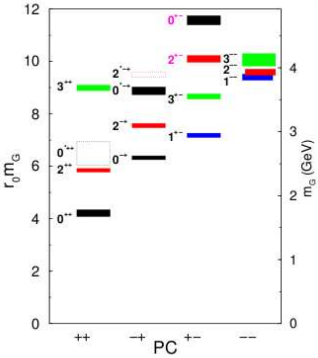
Extra Slide (IV): OBELIX DATA



Extra Slide (V): BAG MODEL GLUEBALL SPECTRUM

Gluons	J^{PC} Quantum Numbers	Mass
$(TE)^2$	0^{++}, 2^{++}	0.96 GeV/c^2
$(TE)(TM)$	0^{-+}, 1^{-+}, 2^{-+}	1.29 GeV/c^2
$(TE)^3$	0^{+-}, 1^{++}, 2^{+-}, 3^{++}	1.46 GeV/c^2
$(TM)^2$	0^{++}, 2^{++}	1.59 GeV/c^2

Extra Slide (VI): THE MORNINGSTAR ET AL. SPECTRUM



J^{PC}	Other J	$r_0 m_G$	m_G (MeV/c^2)
0^{++}		4.21 (11)(4)	1730 (50) (80)
2^{++}		5.85 (2) (6)	2400 (25) (120)
0^{-+}		6.33 (7) (6)	2590 (40) (130)
0^{*++}		6.50 (44)(7)†	2670 (180)(130)
1^{+-}		7.18 (4) (7)	2940 (30) (140)
2^{-+}		7.55 (3) (8)	3100 (30) (150)
3^{+-}		8.66 (4) (9)	3550 (40) (170)
0^{*-+}		8.88 (11)(9)	3640 (60) (180)
3^{++}	6, 7, 9, ...	8.99 (4) (9)	3690 (40) (180)
1^{--}	3, 5, 7, ...	9.40 (6) (9)	3850 (50) (190)
2^{*-+}	4, 5, 8, ...	9.50 (4) (9)†	3890 (40) (190)
2^{--}	3, 5, 7, ...	9.59 (4) (10)	3930 (40) (190)
3^{--}	6, 7, 9, ...	10.06 (21)(10)	4130 (90) (200)
2^{+-}	5, 7, 11, ...	10.10 (7) (10)	4140 (50) (200)
0^{+-}	4, 6, 8, ...	11.57 (12)(12)	4740 (70) (230)

Fig. 12. The mass spectrum of glueballs in pure $SU_C(3)$ gauge theory [145]. The masses are given in units of the hadronic scale r_0 along the left vertical axis and in GeV/c^2 along the right vertical axis. The mass uncertainties indicated by the vertical extents of the boxes do *not* include the uncertainty in r_0. Numerical results are listed in tabular form. In some cases, the spin-parity assignment for a state is not unique. The figure shows the smallest J value, the other possibilities are indicated in the second column of the table. In column 3, the first error is the statistical uncertainty from the continuum-limit extrapolation and the second is the estimated uncertainty from the anisotropy. In the final column, the first error comes from the combined uncertainties in $r_0 m_G$, the second from the uncertainty in $r_0^{-1} = 410(20)$ MeV/c^2. The dagger indicates states for which the authors of [145] suggest further studies before interpreting them.