Outlook

• inlook
• outlook (i)
  › experiment
  › lattice
  › theory
• outlook(ii)
inlook
<table>
<thead>
<tr>
<th>Year</th>
<th>Region</th>
<th>States</th>
</tr>
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<tbody>
<tr>
<td>1993</td>
<td>Como</td>
<td>$\xi(2220)$</td>
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<tr>
<td>1995</td>
<td>Manchester</td>
<td>$f_0(1500)$</td>
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<tr>
<td>1997</td>
<td>BNL</td>
<td>$\pi_1(1400)$</td>
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<td>1999</td>
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<td>$\pi_1(1600)$</td>
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<td>2001</td>
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<td>2003</td>
<td>Aschaffenburg</td>
<td>$X(3872)$, $D_s(2317)$, $\Theta(1540)$, $\eta_c'$, $D_s(2630)$, $\pi_1(1900)$</td>
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<td>2005</td>
<td>Rio</td>
<td>$Y(4260)$, $h_c$, $X(1835)$, $D_s(2860)$</td>
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<td>2007</td>
<td>Frascati</td>
<td>$Z(4430)$, $Y(4660)$, $\eta_b$</td>
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<td>2009</td>
<td>Tallahassee</td>
<td>$X(1500)$</td>
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</table>

- lattice hybrids
- flux tube model
- unitarised chiral models
- NRQCD IR SDEs
- pNRQCD
- lattice glueballs
- DCC models
- tetraquarks
- $\sigma$ resolution
- unquenched lattice
Play the match-it-up game!

\( \xi(2220) \)
\( \pi_1(1400) \)
\( \Theta(1540) \)
\( D_s(2630) \)
\( Z(4430) \)
\( \iota(1400) \)
outlook(i)

experiment
# Future Facilities and Experimental Effort at Hadron09

<table>
<thead>
<tr>
<th>[glueballs!]</th>
<th>RHIC</th>
<th>J.H. Lee</th>
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<tr>
<td></td>
<td>COMPASS</td>
<td>S. Paul</td>
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<tr>
<td></td>
<td>Tevatron</td>
<td>K. Yi &amp; R. van Kooten</td>
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<td>[&gt;CLAS12]</td>
<td>CLAS</td>
<td>R. Schumacher &amp; E. Pasyuk</td>
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<td>PANDA</td>
<td>C. Sfienti</td>
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<td>GLUEX</td>
<td>B. Zihlmann</td>
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<td></td>
<td>J-PARC</td>
<td>S. Sawada</td>
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<td></td>
<td>Super-Bs</td>
<td>R. de Sangro</td>
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<td>[five more years]</td>
<td>ELSA &amp; MAMI</td>
<td>B. Krusche, U. Thoma, S. Schumann</td>
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<td>BES</td>
<td>Y. Mao</td>
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<tr>
<td></td>
<td>Belle &amp; BaBar</td>
<td>S. Uehara &amp; C. Heartly</td>
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<td>[new analyses]</td>
<td>CLEO</td>
<td>A. Tomaradze</td>
</tr>
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<td></td>
<td>LHC</td>
<td>A. Askew</td>
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<tr>
<td>[pre-PANDA]</td>
<td>COSY</td>
<td>F. Goldenbaum</td>
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</table>
Central production for searching for glueballs in Double Pomeron Exchange (DPE) processes.
Experimental Tools

Deep Inelastic Lepton Scattering and related hard e.m. processes

Nucleon Structure
- Helicity
- Transversity
- GPDs

Spectroscopy

QCD Bound States
- Mass spectrum
- Gluonic excitations
- Multi-quark systems

Processes at low $Q^2$

Hadron Structure at Low Energies
- Polarizabilities
- Chiral anomaly

$\lambda = 1 / \sqrt{Q^2}$

[muons for two years, then apply for more hadrons]
Hadron Spectroscopy
Search for exotic particles and measurement of hadron properties

Nucleon Structure
Generalized parton distribution, Drell-Yan processes and time-like form factor of the proton

Hadrons in Matter
Study in-medium effects of hadronic particles

Hypernuclei
Measurement of nuclear properties with an additional strangeness degree of freedom

[1.3B€, ready for 2016]
J-PARC Facility

Materials and Life Science Experimental Facility

Hadron Experimental Facility

Nuclear Transmutation (Phase 2)

Linac (330m)

3 GeV Synchrotron (25 Hz, 1 MW)

50 GeV Synchrotron (0.75 MW)

Neutrino to Kamiokande

5.00 m

J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA
Directions of hadron physics at J-PARC

- Hypernuclear Spectroscopy
  - A major direction.
  - Precise $S=-1$ measurement
  - 1$^{st}$ measurement for $S=-2$

- Chiral Phase Transition and Origin of Hadron Mass
  - Vector meson in nuclear medium

- Exotic Hadrons, Spectroscopy, Hadron Structure
  - Tetraquark, pentaquark, molecular resonance, …
  - K-nucleus

- Hard Processes
  - Nucleon structure
  - Short range correlation
  - Others?
Main Physics Topics

• Light hadron spectroscopy
  – Full spectra: normal & exotic hadrons QCD
  – How quarks form a hadron? non-pQCD

• Charm physics
  – CKM matrix elements $\rightarrow$ SM and beyond
  – $D\bar{D}$ mixing and CPV $\rightarrow$ SM and beyond

• Charmonium physics
  – Spectroscopy and transition $\rightarrow$ pQCD & non-pQCD
  – New states above open charm thresholds $\rightarrow$ exotic hadrons?
  – pQCD: $\rho\pi$ puzzle $\rightarrow$ a probe to non-pQCD or?

• Tau physics and QCD
  – Precision measurement of the tau mass and R value

• Search for rare and forbidden decays
Heavy Flavour Physics at CMS and ATLAS

Moriond 2023 Interactions

Measurement

- Quarkonia
- $b\bar{b}$ production
- Lifetime and properties of $b$ Hadrons: $B^+, B_d, B_s, B_c, \ldots$
- $B_s$ oscillations and CP violation
- Rare decays: $B_s \rightarrow \mu\mu, \ldots$

$\mathcal{L}_{int}$

lowest order SM contributions
russian "ГНС"??
Contents

1 Introduction
   1 Tasks of WG1 ...........................................
   2 The ATLAS and CMS experiments ....................

2 Flavour phenomena in top quark physics
   1 Introduction ...........................................
   2 Wtb vertex .............................................
      2.1 Wtb anomalous couplings .........................
      2.2 Measurement of Vtb in single top production ...
   3 FCNC interactions of the top quark .........
      3.1 Top quark production in the effective lagrangian approach
      3.2 Higgs boson FCNC decays into top quark in a general two-Higgs doublet model
      3.3 Single top production by direct SUSY FCNC interactions 
      3.4 ATLAS and CMS sensitivity to FCNC top decays ...
   4 New physics corrections to top quark production
      4.1 Potential complementary MSSM test in single top production
      4.2 Anomalous single-top production in warped extra dimensions
      4.3 Non-standard contributions to t̅t̅ production

3 Flavour violation in supersymmetric models
   1 Introduction ..........................................
   1.1 The MSSM with R-parity conservation ...........
   1.2 The MSSM with broken R-parity ....................
   1.3 Spontaneous R-parity violation ....................
   1.4 Study of supersymmetry at the LHC ..............
   1.5 Inclusive searches ..................................
   1.6 Mass measurement ..................................

http://arxiv.org/pdf/0801.1800v1

[currently uninterested in hadrons ... but they will be!]
[$300M, ready for 2014]
summary

- many B’s, B_s’s, Υ’s, D’s, charmonia will be produced
- two-pronged attack on hybrids
- glueballs are orphaned? [plan to study them at RHIC in double pomeron production. J.H. Lee]
- heavy baryons orphaned?
- baryon spectroscopy continues at CLAS, MAMI, COSY, ELSA
- era of nucleon holography starts
outlook(i)
lattice
BMW
LHC
**Petascale Computing**

**Blue Waters Petascale Computing System**

<table>
<thead>
<tr>
<th>System Attribute</th>
<th>Typical Cluster (NCSA Abe)</th>
<th>Blue Waters*</th>
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<tbody>
<tr>
<td>Vendor</td>
<td>Dell</td>
<td>IBM</td>
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<td>Processor</td>
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<td>Peak Performance (PF)</td>
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<td>Number of Cores/Chip</td>
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<td>Number of Processor Cores</td>
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<td>External Bandwidth (Gbps)</td>
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* Reference petascale computing system (no accelerators).

The road to exascale for Spectroscopy

Photocouplings in charmonium
Cascade Spectrum
Precise computations of ground-states
Meson and baryon spectrum with $m_\pi \sim 180$ MeV
N-N* transition form factors
N* Spectrum
Spectrum and photoproduction of isovector mesons
Spectrum and properties of mesons, in particular with exotic quantum number

GlueX

Forefront Questions in Nuclear Science and the Role of High Performance Computing
January 26-28, 2009 · Washington, D.C.
The road to exascale for Hadron Structure

Contribution of gluons to the nucleon mass and spin; low moments of the gluon distributions $g(x)$ and $\Delta g(x)$.

Flavor-separated contn. to FF, moments of PDFs and GPDs

Precision calculations of the flavor-non-singlet form factors, moments of PDF, and moments of GPDs

EIC
The road to exascale for Nuclear Forces

Baryon-baryon interactions

Deuteron axial-charge

NNN interaction from LQCD

Alpha particle

EFTs and LQCD

10x tera 100x tera peta 10x peta 100x peta exa-flop year sustained
SCIDAC 2008 Meeting, Michael Strayer

good news

2008: 1/4 billion processor-hours allocated
2009: 1/2 billion processor-hours to be allocated

a warning!

“we can see that the gigaflops and teraflops era was a regime where we were following Moore’s law through advances in clock speed. In the current regime, we’re introducing massive parallelism... in order to reach [the] exascale [regime], extrapolations talk about machines that require 100 megawatts of power.”
outlook(i)

theory
- effective field theory → beyond threshold physics
- potential models → coupled channel effects
- gluonic models → data-driven improvements
- Schwinger-Dyson equations → beyond two-point functions; beyond rainbow-ladder; incorporate gluonics
- lattice → multiparticle operators; resonances; hairpin correlators; coupled channel Luescher formalism; the end of Moore’s Law?
- full coupled channel analysis of $\pi N, \gamma N$
- long range/short range factorisation
Nathan: “QCD is the perfect theory!”

outlook(ii)
**mass hierarchy problem**

<table>
<thead>
<tr>
<th>Nu</th>
<th>e</th>
<th>u</th>
<th>d</th>
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</thead>
<tbody>
<tr>
<td>ν</td>
<td>μ</td>
<td>τ</td>
<td>μ</td>
</tr>
</tbody>
</table>

Perhaps different mass scales can be generated dynamically? Ex: massless QCD3, where $g^2$ provides the scale, with dynamical chiral symmetry breaking.

T. Appelquist and R. Pisarski, PRD23, 2308 (81)

P. Maris, PRD54, 4049, (96)
EW symmetry breaking

(Higgs mass fine tuning problem)

Hypercolour

Dynamical EWSB: scale QCD up to the TeV range, break chiral symmetry, GBs are eaten by the W and Z which become massive.

\[ \langle H \rangle = v \sim f_{\pi T} \]

v = 246 GeV

S. Weinberg, PRD13, 974, (76).
EW symmetry breaking

Other GBs are light. And what about fermion masses?

Extended Technicolour

Introduce extra gauge interactions to raise the GB and fermion masses.

The ETC gauge symmetry is broken at the ETC scale, giving rise to effective four-fermion operators at the EW scale:

S. Dimopoulos and L. Susskind, NPB155, 237 (79)
\[
\frac{(\bar{Q}Q)(\bar{Q}Q)}{\Lambda^2_{\text{ETC}}} \quad \text{raise ETC GB masses}
\]
\[
\frac{(\bar{Q}Q)(\bar{q}q)}{\Lambda^2_{\text{ETC}}} \quad \text{get fermion masses}
\]
\[
\frac{(\bar{q}q)(\bar{q}q)}{\Lambda^2_{\text{ETC}}} \quad \text{get FCNC (oops!)}
\]

Assume SXSB so \((\bar{Q}Q) \rightarrow \langle \bar{Q}Q \rangle\)

Thus one requires \(\Lambda_{\text{ETC}} \approx 1TeV\)
But this means that fermion masses are too small.

\[ m_q \sim \frac{\langle \bar{Q}Q \rangle}{\Lambda_{\text{ETC}}^2} \quad \frac{\langle \bar{q}q \rangle}{f_\pi^2} \sim 25 \quad m_q \sim 0.4 \text{ MeV} \]

A possible finesse: if the coupling runs slowly then the ETC condensate will be enhanced.

Walking Technicolour

B. Holdom, PRD24, 1441 (81).
The Conformal Window
defn: the range of $N_f$ for which the theory is asymptotically free and has an IRFP (no confinement or SXSB: the nonAbelian Coulomb phase). For $N_c = 3$, $N_f \in (7.75:16.5)$ at 2-loop.

For walking TC we want to sit just below the conformal window.
Thus constructing viable DEWSB models requires (at minimum) finding the conformal window for a variety of QCD-like theories.

Lattice gauge theory:

IRFP for $N_c=3$, $N_f=12$.
No IRFP for $N_c=3$, $N_f=8$
other constraints

Parametrise NP corrections to the SM with S,T,U.

\[ S \sim \frac{d}{dq^2}(\Pi_{VV}(q) - \Pi_{AA})\bigg|_{q^2=0} \]

S is related to \( \rho \) and \( a_1 \)
spectral densities!

Experimentally, S,T are very small and ETC models need to obey this

M. Peskin and T. Takeuchi, PRL65, 964 (90)
B. Holdom and J. Terning, PLB247, 88 (90)
Dark Matter Problems

1. Why should $\rho_{DM} = 5\rho_B$?

Generate DM abundance with the same SM mechanism that generates the baryon matter asymmetry.

S. Nussinov, PLB165, 55 (85)
2. WIMP interactions with the SM must be ‘sub-weak’, how, then, are their masses generated?

Consider a technibaryon that is charge and EW neutral, thereby suppressing SM interactions.

Or: ‘quirky DM’. Scalar baryon bound state with $N_C=2$, $N_f=2$; nonAbelian force becomes strong below the EW scale; masses generated by Higgs.
3. Quirky glueball decays can inject too many photons into nucleosynthesis!

QCD-like theories:

- condensates and symmetry breaking
- value of Peskin-Takeuchi parameters
- lightest baryon properties
- glueball decays
conclusions

- many advances
- much to look forward to!
- NP and BSM problems? QCD to the rescue!