QCD theory in Canada

prepared using input from
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QCD in perspective

- *QCD is required for essentially all practical calculations in particle physics.*
  Topics that at first glance have nothing to do with QCD can actually have QCD effects as the limiting factor.

  Today's brief discussion will include
  $(g-2)_{\rm muon}$, CKM matrix elements, determination of α_s, dark matter production, dark matter detection.

- *QCD has an important role in theoretical physics.*
  confinement, connections to computation, connections to string theory, the strong CP problem, topology.

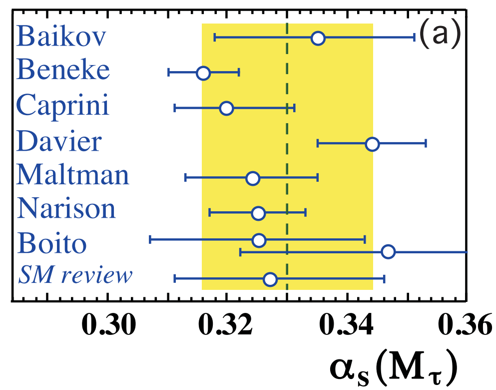
- *QCD itself has intriguing unanswered questions.*
  quark-gluon plasma, heavy quark transitions and masses, tetraquarks.

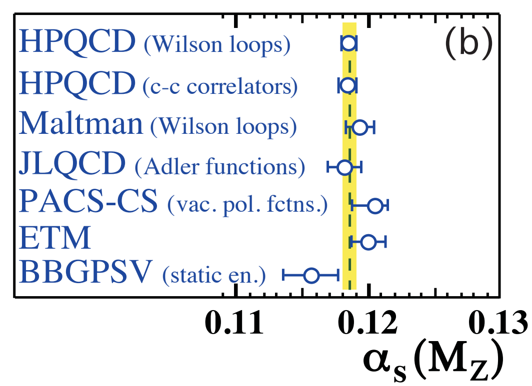
Some recent lattice and continuum work on QCD at York:

- α_s determinations from sum rule analyses of hadronic τ decay data (first with a PhD student at York, then further work with collaborators at San Francisco State University, University Autonoma Barcelona, TU Munich, and University of Wisconsin)
- Work on duality violating effects in current-current two-point functions with collaborators at San Francisco State University, University Autonoma Barcelona, TU Munich, and University of Wisconsin
- Combined lattice and continuum analysis of the light quark V-A correlator with the RBC/UKQCD lattice collaboration, and collaborators (including postdocs) at York, San Francisco State University and University Autonoma Barcelona
- Work on flavor-breaking sum rules and conventional attempts at determinating V_{us} from inclusive hadronic τ decay distributions with an RA at York
- Work on lattice input to the inclusive flavor-breaking τ $V_u s$ determination puzzle, first with a subset of the RBC/UKQCD lattice collaboration and more recently (including what looks like a probable resolution of this long-standing problem) with collaborators (including postdocs) at York and University of Adelaide
- World-best determinations of a number of NLO and NNLO chiral low-energy constants from combined lattice and continuum analyses, including of a number of flavor-breaking inverse moment (chiral) finite-energy sum rules using B-factory strange exclusive mode hadronic τ decay distributions, with collaborators (including post-docs) at York, San Francisco State University, TU Munich and University Autonoma Barcelona
- Identification of crucial systematic issues in previous lattice determinations of the leading order hadronic contribution to $(g-2)_\mu$ and development of a strategy for overcoming this problem, now being used by many lattice collaborations, with collaborators from San Francisco State University and University Autonoma Barcelona
- Ongoing work with the RBC/UKQCD latttice collaboration and collaborators (including postdocs) at York on the lattice determination of the leading order hadronic contribution to $(g-2)_\mu$ using RBC/UKQCD data from the new physical point domain wall fermion ensembles
- Ongoing lattice work with collaborators (including postdocs) at York aimed at identifying, and determining the expected masses of, certain exotic multi-quark states expected to be strong-interaction stable
- Ongoing work with collaborators (including postdocs) at York on determining α_s using data for current-current two-point functions measured on the lattice, expected to be competitive with, and have certain systematic advantages over, the continuum determination using hadronic τ decay data

Thanks to Kim Maltman for preparing this list. There is a lot of QCD activity at York, including faculty, postdocs, students and external collaborators.

Reminder: Kim's work is prominent in the PDG:





QCD for dark matter

Frederick S. Sage and Rainer Dick, Journal of Physics G 41 (2014) 105007.

The Higgs-portal singlet model adds just one scalar field to the Standard Model.

Gluon-gluon fusion and CTEQ gluon distribution functions were used.

Dark matter
production cross sections
in pp collisions

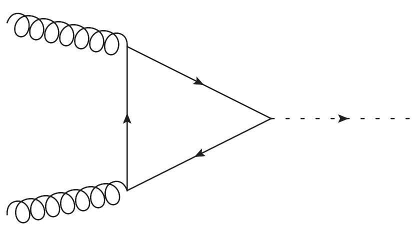


Figure 2. Higgs production by gluon fusion.

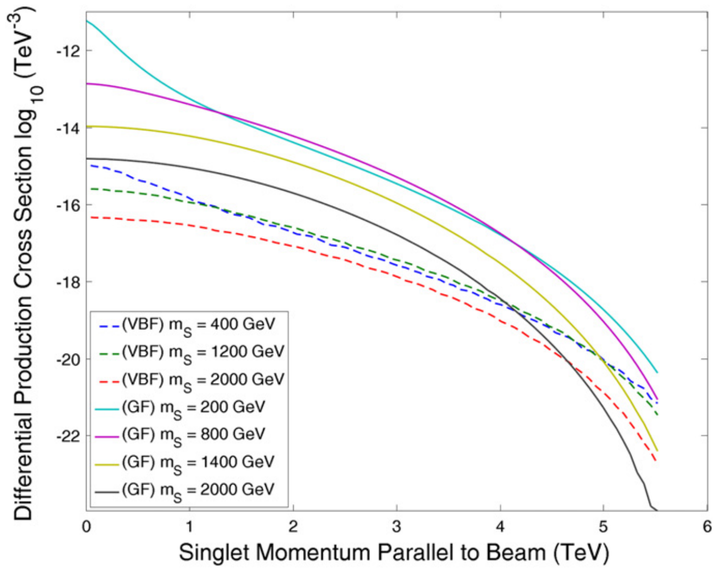


Figure 4. Differential cross section for singlet production $\mathrm{d}\sigma/\mathrm{d}p_{S\parallel}$ ($k_p = 6.5$ TeV).

GF = gluon-gluon fusion

VBF = vector boson fusion

k_p = proton momentum

Frederick S. Sage and Rainer Dick, Astroparticle Physics (2015) 31.

Nuclear recoil cross sections for perturbative Higgs portal dark matter models will be probed by DEAP-3600 and XENON1T within two years of observations.

Crucial input from lattice QCD calculations of $$y_N = \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u+\bar{d}d|N\rangle}$$

Conformality or confinement?

Erich Poppitz and Mithat Ünsal,
JHEP 0909 (2009) 050,
JHEP 0912 (2009) 011.

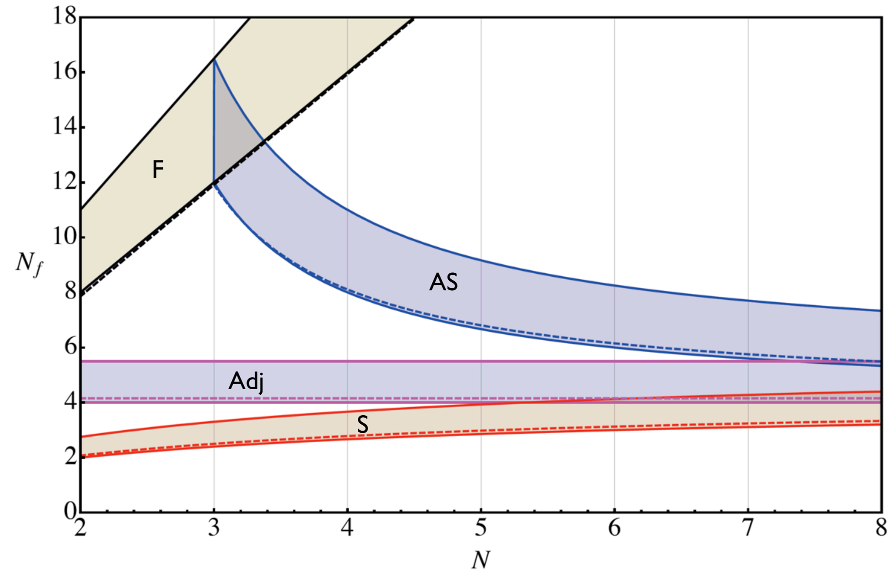


Figure 2. Conformal window estimates for QCD(F/AS/Adj/S) by using deformation theory and the mass gap criterion of this paper (solid lines, upper limits on the lower boundary) and the truncated Schwinger-Dyson approximation (dashed-lines). In order to not overcrowd the figure, we do not plot the estimates of other approaches; see table 2.

The work of Erich Poppitz and collaborators continues to provide a deep understanding for QCD and many related quantum field theories:

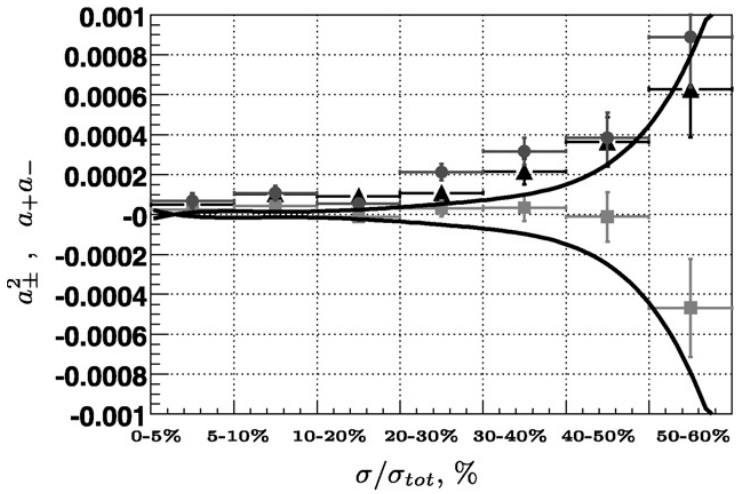
- semiclassical methods in QCD-like theories in a calculable domain
  - confinement
  - properties of confining strings
  - relations to lattice data and string theory
- path integrals in QFT in various dimensions using Lefshetz thimbles
  - complexification
- relations between supersymmetric and nonsupersymmetric dynamics
  - continuity between thermal deconfinement and (softly broken) super Yang-Mills
  - suggestive comparisons to lattice studies

Dmitri Kharzeev and Ariel Zhitnitsky, Nuclear Physics A 797 (2007) 67.

This famous paper shows that quantum anomalies in QCD produce surprising effects.

It has led to theoretical developments for non-vanishing θ, T, and chemical potential.

It has also led to testable consequences for heavy ion collisions at RHIC and LHC.



$$a_i a_j = \left\langle \sum_{k,l} \sin(\phi_i^k - \psi_{\mathrm{RP}}) \sin(\phi_j^l - \psi_{\mathrm{RP}}) \right\rangle$$

where RP = reaction plane

Fig. 1. Preliminary STAR data from [27]. Charged particle asymmetry parameters as a function of centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are a_+a_-, see text for details. Black lines are theoretical prediction [25] corresponding to the topological charge $|Q| = 1$.

Ongoing work has many applications at the intersection of
particle physics, nuclear physics, astrophysics and cosmology.
Recent examples include

The topological long range order in QCD. Applications to heavy ion collisions and cosmology.
Ariel R. Zhitnitsky, EPJ Web of Conferences 95 (2015) 03041.

Inflaton as an auxiliary topological field in a QCD-like system.
Ariel R. Zhitnitsky, Phys Rev D89 (2014) 063529.

QCD under extreme conditions

Quark-gluon plasma is a strongly-coupled many-body system.

Its bulk properties are close to those of an ideal fluid.

The McGill group is producing state-of-the-art theory for relativistic collisions.

The importance of the bulk viscosity of QCD in ultravelativistic heavy-ion collisions
Ryu, Paquet, Shen, Denicol, Schenke, Jeon and Gale, arXiv:1502.01675

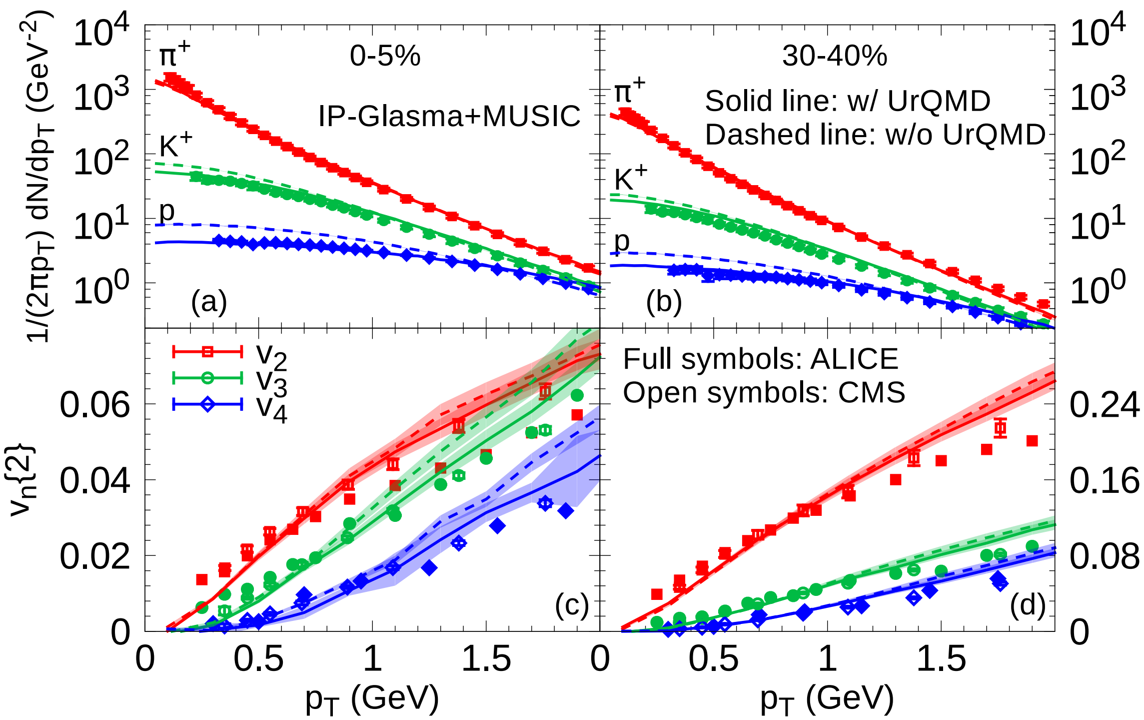
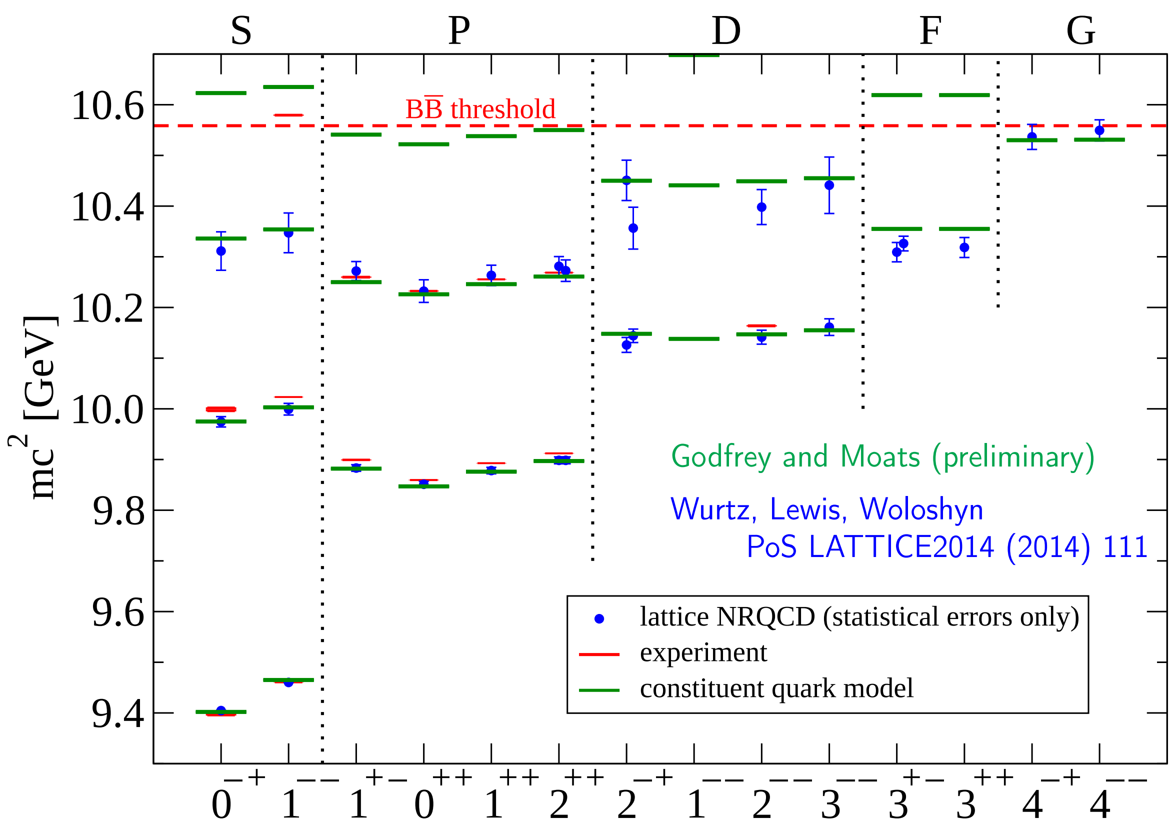


FIG. 3: (Color online) Transverse momentum spectra (upper panels) of pions, kaons, and protons and harmonic flow coefficients (lower panels) as a function of the transverse momentum. Two centrality classes are considered: 0–5% (left panels) and 30–40% (right panels). The bands denote the statistical uncertainty of the calculation. The full and open symbols correspond to measurements by the ALICE [49] and CMS [53, 54] collaboration respectively, with bars denoting the experimental uncertainty.

hadrons from a quark model



Steve Godfrey et al are working on properties of hadrons relevant to BES-III, Belle-II, LHCb and GlueX.

⇐ EXAMPLE
bottomonium spectrum

Parent	Decay chain	Combined BR	Events pp	Events e^+e^-
3^3S_1	$\xrightarrow{13.6\%} 2^3P_2\ (86.2) \xrightarrow{1.1\%} 1^3D_3\gamma\ (96.5) \xrightarrow{91.0\%} 1^3P_2\gamma\ (256.0) \xrightarrow{19.1\%} 1^3S_1\gamma\ (441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	6.4×10^{-6}	2003	6400
	$\xrightarrow{13.6\%} 2^3P_2\ (86.2) \xrightarrow{0.2\%} 1^3D_2\gamma\ (104.4) \xrightarrow{19.0\%} 1^3P_2\gamma\ (248.4) \xrightarrow{19.1\%} 1^3S_1\gamma\ (441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.4×10^{-7}	75	240
	$\xrightarrow{13.6\%} 2^3P_2\ (86.2) \xrightarrow{0.2\%} 1^3D_2\gamma\ (104.4) \xrightarrow{78.0\%} 1^3P_1\gamma\ (267.3) \xrightarrow{33.9\%} 1^3S_1\gamma\ (423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.8×10^{-6}	563	1800
	$\xrightarrow{13.6\%} 2^3P_2\ (86.2) \xrightarrow{0.02\%} 1^3D_1\gamma\ (78.0) \xrightarrow{1.6\%} 1^3P_2\gamma\ (239.1) \xrightarrow{19.1\%} 1^3S_1\gamma\ (441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.1×10^{-9}	0.7	2
	$\xrightarrow{13.6\%} 2^3P_2\ (86.2) \xrightarrow{0.02\%} 1^3D_1\gamma\ (78.0) \xrightarrow{28.0\%} 1^3P_1\gamma\ (258.0) \xrightarrow{33.9\%} 1^3S_1\gamma\ (423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	6.4×10^{-8}	20	64
	$\xrightarrow{13.6\%} 2^3P_2\ (86.2) \xrightarrow{0.02\%} 1^3D_1\gamma\ (78.0) \xrightarrow{47.0\%} 1^3P_0\gamma\ (290.5) \xrightarrow{1.76\%} 1^3S_1\gamma\ (391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	5.6×10^{-9}	2	6
	$\xrightarrow{13.6\%} 2^3P_2\ (86.2) \xrightarrow{0.02\%} 1^3D_1\gamma\ (78.0) \xrightarrow{0.0039\%} \mu^+\mu^-$	7.8×10^{-9}	2	8
	$\xrightarrow{12.6\%} 2^3P_1\ (99.3) \xrightarrow{2.1\%} 1^3D_2\gamma\ (91.3) \xrightarrow{19.0\%} 1^3P_2\gamma\ (248.4) \xrightarrow{19.1\%} 1^3S_1\gamma\ (441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	2.4×10^{-6}	751	2400
	$\xrightarrow{12.6\%} 2^3P_1\ (99.3) \xrightarrow{2.1\%} 1^3D_2\gamma\ (91.3) \xrightarrow{78.0\%} 1^3P_1\gamma\ (267.3) \xrightarrow{33.9\%} 1^3S_1\gamma\ (423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	1.7×10^{-5}	5321	17,000
	$\xrightarrow{12.6\%} 2^3P_1\ (99.3) \xrightarrow{0.88\%} 1^3D_1\gamma\ (100.8) \xrightarrow{1.6\%} 1^3P_2\gamma\ (239.1) \xrightarrow{19.1\%} 1^3S_1\gamma\ (441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	8.4×10^{-8}	26	84
	$\xrightarrow{12.6\%} 2^3P_1\ (99.3) \xrightarrow{0.88\%} 1^3D_1\gamma\ (100.8) \xrightarrow{28.0\%} 1^3P_1\gamma\ (258.0) \xrightarrow{33.9\%} 1^3S_1\gamma\ (423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	2.6×10^{-6}	814	2600
	$\xrightarrow{12.6\%} 2^3P_1\ (99.3) \xrightarrow{0.88\%} 1^3D_1\gamma\ (100.8) \xrightarrow{47.0\%} 1^3P_0\gamma\ (290.5) \xrightarrow{1.76\%} 1^3S_1\gamma\ (391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	2.3×10^{-7}	72	230
	$\xrightarrow{5.9\%} 2^3P_0\ (122.0) \xrightarrow{0.2\%} 1^3D_1\gamma\ (78.0) \xrightarrow{1.6\%} 1^3P_2\gamma\ (239.1) \xrightarrow{19.1\%} 1^3S_1\gamma\ (441.6) \xrightarrow{2.48\%} \mu^+\mu^-$	8.9×10^{-9}	3	9
	$\xrightarrow{5.9\%} 2^3P_0\ (122.0) \xrightarrow{0.2\%} 1^3D_1\gamma\ (78.0) \xrightarrow{28.0\%} 1^3P_1\gamma\ (258.0) \xrightarrow{33.9\%} 1^3S_1\gamma\ (423.0) \xrightarrow{2.48\%} \mu^+\mu^-$	2.8×10^{-7}	88	280
	$\xrightarrow{5.9\%} 2^3P_0\ (122.0) \xrightarrow{0.2\%} 1^3D_1\gamma\ (78.0) \xrightarrow{47.0\%} 1^3P_0\gamma\ (290.5) \xrightarrow{1.76\%} 1^3S_1\gamma\ (391.1) \xrightarrow{2.48\%} \mu^+\mu^-$	2.4×10^{-8}	8	24

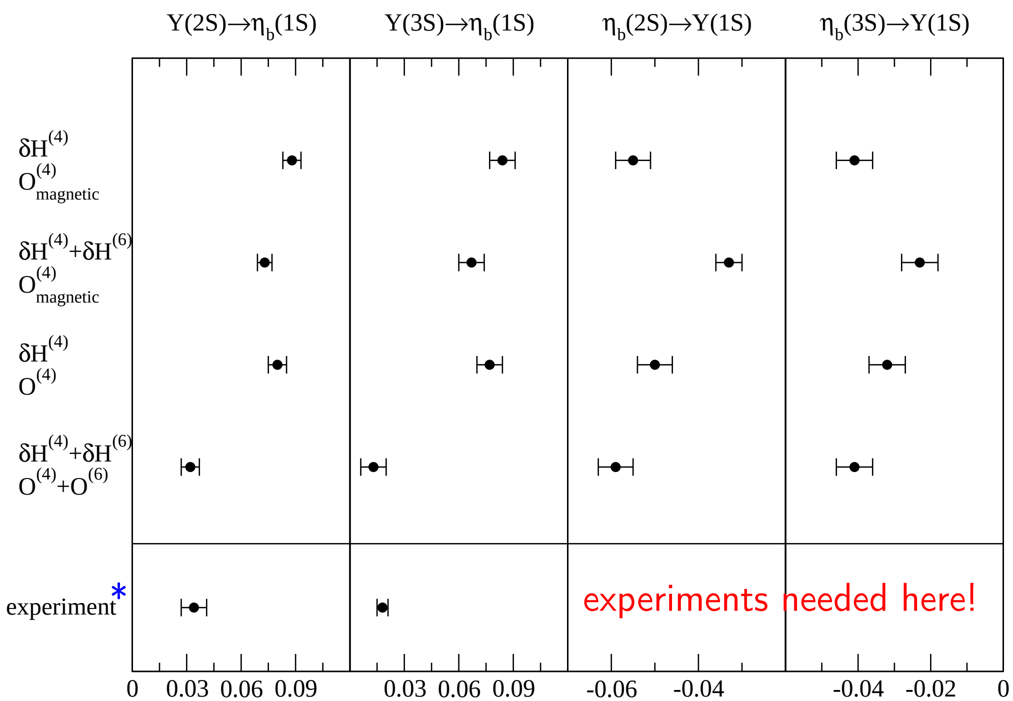
They can also calculate production rates.

⇐ EXAMPLE
These are for Belle-Babar at 250 fb^{-1}.

Lattice QCD and BaBar

transition matrix elements

Lewis, Woloshyn, PRD84, 094501 (2011)
and PRD85, 114509 (2012)

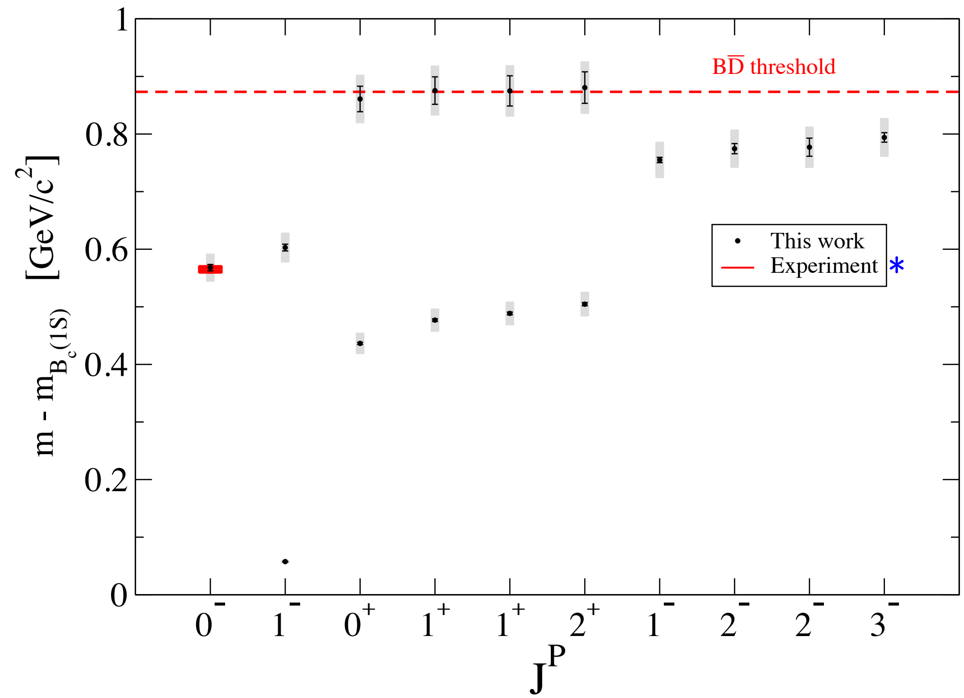


*BaBar, PRL101, 071801 (2008) and PRL103, 161801 (2009).

Lattice QCD and ATLAS

spectrum of B_c masses

Wurtz, Lewis, Woloshyn, arXiv:1505:04410



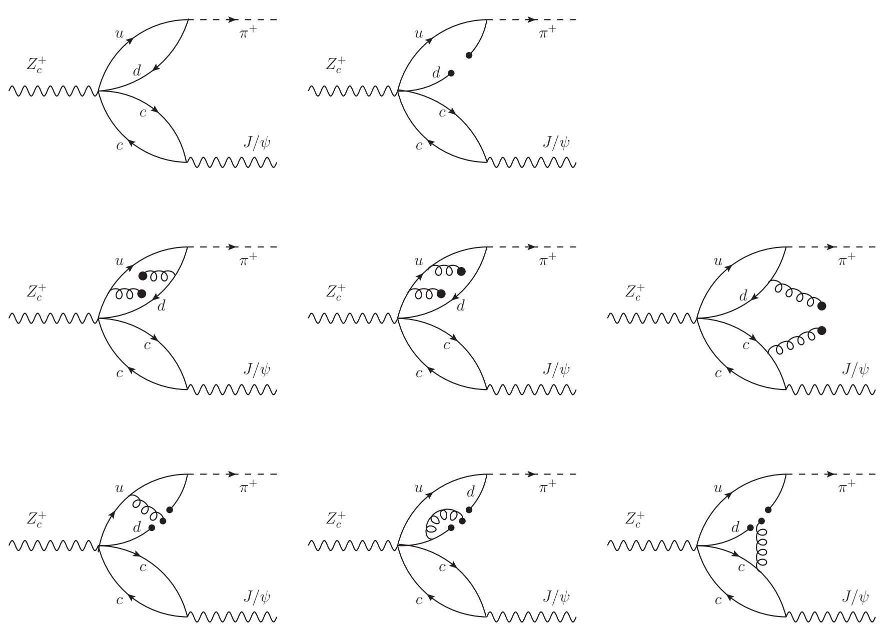
*ATLAS, PRL113, 212004 (2014).

Only one experimental measurement so far!

tetraquarks and other exotics from QCD sum rules

Many charmonium-like resonances have been observed by Belle, Babar, CLEO and BESIII.
They are difficult to interpret as conventional quark-antiquark mesons.
Tom Steele and collaborators use QCD sum rules to study them.

For example: Chen, Steele, Chen and Zhu, arXiv:1501.03863



The $Z_c(4200)^+$ is treated as a hidden-charm tetraquark state.
The full decay width agrees with experiment.
Predictions are given for the branching ratios into $J/\psi\pi^+$, $\eta_c\rho^+$, $D^+\bar{D}^{*0}$ and $\bar{D}^0 D^{*+}$.

summary

- *QCD is required for essentially all practical calculations in particle physics.*
- *QCD has an important role in theoretical physics.*
- *QCD itself has intriguing unanswered questions.*

QCD does not exist in isolation.

It is closely connected to many aspects of subatomic physics,
theoretical physics and beyond.

Canadian researchers are making internationally recognized contributions
but Canadian researchers are relatively few in number.

Strengthening QCD research in Canada would be of benefit to everyone.