QCD
Experimental and theoretical context

Markus Diehl, Jan Pawlowski, Gunar Schnell

PBC Working Group Meeting
CERN, 1-2 March 2017
Scope of this talk

• starting from slides of PBC Kickoff Meeting (Sept. 2016) we have tried to situate the different proposals within a global QCD context

• we will ask critical questions, make suggestions please consider us as friendly critics/critical friends

★ others will ask tough questions later (review panels, management, the broader community), so better be prepared for those

• this is the beginning of a process we are not making final assessments now

• will now go through the various proposals one by one
QCD experiment landscape (selection)
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This talk: status and recent results; no projections or plans
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→ talks by E. Aschenauer, V. Burkert
QCD experiment landscape (selection)

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future EIC: either BNL or JLab
Electron-positron annihilation

• mainly charm and B factories, but also useful for QCD studies, e.g.
  ★ fragmentation functions
  ★ spectroscopy

• BaBar@PEP-II (SLAC): $\sqrt{s} = 10.58$ GeV; until 2008

• Belle(2)@KEKB: $\sqrt{s} = 10.58$ GeV;
  Belle until 2010 accumulated $\sim 1$ ab$^{-1}$
  Belle2 2017++ to accumulate $\sim 50$ ab$^{-1}$

• BESIII@BEPC II: up to $\sqrt{s} = 4.6$ GeV with a design luminosity of $10^{33}$ cm$^{-2}$·s$^{-1}$ (ongoing); acceptance $|\cos\theta|<0.8$
Lepton-nucleon/nucleus scattering

- HERA (until 2007): longitudinally pol. e± (27.6 GeV) unpolarized protons (460/575/820/920 GeV)
  - H1, ZEUS: e±p (√s = 225/251/300/320 GeV)
  - HERMES: HERA e± on long. pol. H, D, ³He; transv. pol. H; unpolarized nuclei (H, D, He, … Kr, Xe)

- Jefferson Lab: longitudinally pol. e⁻ (6 GeV; upgraded to 12 GeV)
  - various experimental halls w/ diff. focus
  - unpol. and polarized nuclear targets
  - hadron structure via exclusive and (semi-)inclusive reactions
  - dedicated hall for spectroscopy
lepton-nucleon scattering @ JLab12

Hall-C
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-B
CLAS12 H,D polarized targets up to $10^{35}$ cm$^{-2}$ s$^{-1}$
“complete” acceptance, hadron ID

Hall-A
Spectrometer Pair, polarized $^3$He target
up to to $10^{38}$ cm$^{-2}$ s$^{-1}$ hadron ID

SOLID $^3$He, NH$_3$ polarized targets
up to $10^{36}$ cm$^{-2}$ s$^{-1}$ large acceptance, pion ID

from: M. Contalbrigo @ QCD-N'16
A future Electron-Ion Collider (EIC) - 2025++

- high-luminosity, versatile, polarized (e⁻ and p, d, ³He)
- Peak luminosity $2 \times 10^{34}$ cm⁻²s⁻¹ for $\sqrt{s} \sim 70$-105 GeV (250 GeV p↑)
- “Low-risk” luminosity $\sim 5$-9×$10^{32}$ cm⁻²s⁻¹ (BNL)
- 5-10×$10^{33}$ cm⁻²s⁻¹ (JLab)
- 20-~100 (140) GeV variable CoM energy
- large and complementary kinematic coverage
- unpolarized nuclei from ²H to Pb / U
• lumi strongly increases with beam energy
• lumi strongly increases with beam energy
• large kinematic coverage for a wide range of observables
Hadron structure: AFTER and COMPASS++

- understanding structure and dynamics of hadrons at level of quarks and gluons
  - fundamental Lagrangian \(\rightarrow\) physical states
  - remains very active field, many open questions
- many possibilities sketched in presentations at kickoff workshop. Suggestion:
  - identify a few measurements that can support a strong physics case and that may drive the experimental setup
  - for these, make detailed feasibility/performance studies
  - this requires some choices, but will provide focus and considerably ease the task of any review panel
  - further possibilities can always be pointed out (but beware of "laundry lists")
AFTER: possible highlights (1)

- Parton densities at high $x$
  - current uncertainties very large
  - important input for LHC! (heavy particle production)
  - very little competition:
    JLAB: lower scale $Q^2$; higher $Q^2$ accessible at EIC, but potential not yet quantified, even then AFTER might have edge for gluons

- possible measurements: Drell-Yan for quarks? for gluons? open charm?

- intrinsic charm in proton (expected to reside at large $x$) measurement again open charm?

- for simulations beware: at high $x$ expect soft-gluon resummation to be essential (should increase rates)
AFTER: possible highlights (2)

• nuclear parton densities?
  ★ intrinsic interest: how does nucleus modify partonic structure of nucleon? collective effects?
  ★ important input for heavy-ion collisions
  ★ nuclear targets: reach large x in nucleus; with Pb beam would get low x in nucleus
  ★ measurements? quantitative impact? possible competition from LHC? from EIC?
Drell-Yan: target spin asymmetry

- transverse momentum distribution of partons is shifted in transversely polarised proton (Sivers effect)
  - spin-orbit coupling, sensitive to orbital angular mom.
- effect comes from soft gluon exchange in physical process

\[
\gamma^* \rightarrow \pi \\
\text{SIDIS} \\
\text{Drell-Yan} \\
p \rightarrow p
\]

- definite change of distribution between SIDIS and DY:
  \[ f_{\text{Sivers, SIDIS}}(x, k_T) = - f_{\text{Sivers, DY}}(x, k_T) \]
- fundamentally tests our understanding of soft gluon effects on hadron structure

- related: Boer-Mulders shift for transv. quark pol. in unpolar. p
AFTER: possible highlights (3)

★ measurement: Drell-Yan on transversely polarised target

★ detailed recent study arXiv:1702.01546

★ for LHCb setup find wide coverage in $x$ comfortable rates, e.g., with HERMES-like target
HERMES polarized target

- storage cell with atomic-beam source internal to (HERA-e) ring
HERMES polarized target

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- both long./transv. polarization, as well as diff. target gases

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<td>0.845±0.028</td>
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<tr>
<td>$t$</td>
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<td>($10^{14}$ nucl./cm$^2$)</td>
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HERMES polarized target

- storage cell with atomic-beam source internal to (HERA-e) ring
  - both long./transv. polarization, as well as diff. target gases
  - various unpolarized gases, e.g. high-density end-of-fill runs
Present/future polarized Drell-Yan experiments

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two main fixed-target polarized-DY programs with 120 GeV proton beam of main injector

E-1039 polarized target:

kinematic range $4 < M < 9$ GeV @ $\sqrt{s} = 15$ GeV
luminosity: $3 \cdot 10^{35}$ /cm$^2$/s (NH$_3$)
dilution factor: 0.176 (NH$_3$), 0.3 (ND$_3$)
Polarization <$80\%$, <$32\%$>

$L_{\text{int}} = 1.82 \times 10^{42}$/cm$^2$ NH$_3$ and
$2.11 \times 10^{42}$/cm$^2$ ND$_3$ for 2 years
mainly sensitive to sea quark Sivers function
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Polarized Drell-Yan @ FNAL

- Two main fixed-target polarized-DY programs with 120 GeV proton beam of main injector

★ **E-1027 polarized beam:**

- Kinematic range $4 < M < 9$ GeV @ $\sqrt{s} = 15$ GeV
- Luminosity: $2 \cdot 10^{35} / \text{cm}^2/\text{s} \ (\text{NH}_3)$
- Polarization $<60\%$ no dilution!

- Probes valence-quark Sivers function in DY at high precision
polarized Drell-Yan @FNAL

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- \textbf{E-1027 polarized beam:}

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- luminosity: $2 \cdot 10^{35}$ /cm$^2$/s (NH$_3$)
- polarization $< 60\%$ no dilution!

- probes valence-quark Sivers function in DY at high precision
Drell-Yan @ COMPASS

- 2 years of pion-induced polarized-target DY data by LS2
- substantial increase of precision possible with much more running time or substantial improve in target (can’t really improve polarization, but dilution - currently factor 4-6), → how?
- new beam possibilities discussed: RF-separated hadron beam (1yr data taking)

→ 1% (?) precision on K/π induced DY (integrated over acceptance)
COMPASS++: kaon beams

- Drell-Yan: $K + p \rightarrow \mu^+\mu^- + X$
  - compared with $\pi + p$: parton densities in kaon
  - kaon and pion distributions related by SU(3) flavour symmetry $\rightarrow$ study SU(3) breaking (influence of strange mass)
  - measurement without competition
  - expected size of effects vs. experimental accuracy?
  - strong enough as physics driver?

Estimate in NJL model, arXiv:1604.02853
COMPASS++: antiproton beams

- Drell-Yan with $\bar{p} + p(\text{pol})$
  
  ★ **strong physics** motivation: see earlier slide

  ★ possible advantage for rates compared with $p+p$:

  
  \[ x_1 x_2 s = Q^2 \text{ gives } x_1 x_2 > 0.01 \]

  \[ \rightarrow \text{(anti)quarks in valence region in beam and target} \]

  ★ but: **tough competition** with $p+p$ Drell-Yan proposals
  \[ \rightarrow \text{to be worked out quantitatively} \]
selected further Drell-Yan activities

- J-Parc: polarized DY program “in stasis” (30 or even 50 GeV proton beam) “near-term” (2020~), 20 GeV pi- beam fixed-target program possibility for <10 GeV pion/kaon/(anti-)proton beam

- PANDA@FAIR (under construction); 2025++ √s = 5.5 GeV; valence quarks because of anti-proton beam

- SPASCHARM @ IHEP 20xx ? 40-70 (100?) GeV proton beam on (pol.) fixed-target secondary hadron beams & tertiary polarized (anti)protons

- NICA (under construction); 2023++ √s = 26 GeV, but polarized beam uncertain

- fsPHENIX@RHIC (under consideration); 2021++ √s = 200/500 GeV doubly polarized DY possible

Reminder: DY cross section ~1/s ; BG processes increase with s
COMPASS++

RF separated kaon beam $\sim 8 \times 10^6 / s$, beam momentum $\sim 100$ GeV

What can we contribute as COMPASS?

- State-of-the-art high-resolution spectrometer with full PID
- Advanced analysis techniques being developed in the light-quark sector

Method to be used: Kaon beam diffraction scattering on LH$_2$ and thin nuclear targets

- Goal: $\sim 10$ larger data sample than existing worldwide
- what would make possible to have similar to pion diffraction
- wave set: 88 waves in 11 t`bins;

- COMPASS could rewrite PDG tables for strange mesons
- Extend studies of chiral dynamics to strange sector

No real competitors

JParc - $\sim 10^5 / s$, low momenta kaons
JLab - $\sim 10^4 / s$, $K^0$ long beam, lower momenta

- quantitative comparison with competition?
  is high energy essential?

- strange spectroscopy at PANDA?
COMPASS++

RF separated antiproton beam, beam momentum ~ 20 GeV

Method: antiproton-proton annihilation

Goal: charmed hybrids and exotics study in the mass range higher than reachable in PANDA

Complementary to LHCb (p-pbar annihilation – gluon rich environment and it allows high spin states)

Otherwise no competitors for the next at least 10 years

- gain compared with PANDA large enough?
- comparison with LHCb? what is advantage of p+pbar over p+p for producing these states?
• possible extension of muon programme: DVCS
  Deeply Virtual Compton Scattering (μp → μpγ)

• two interfering mechanisms:

• $p_T$ of scattered proton → spatial distributions of quarks/glueons inside proton
  femtometer analogue of Bragg refraction

• under investigation: transverse target polarisation
  ★ related with sum rule for orbital angular momentum
  ★ technically demanding (pol. target with proton recoil det.)
  ★ severe competition from EIC
$\mu-e$

- idea: measurement of $\mu-e$ elastic scattering 
  $\rightarrow$ hadronic vacuum pol. contribution to $(g-2)_\mu$

\[ \alpha(t) \quad t=q^2<0 \]

- physics motivation:

\[ a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8) \times 10^{-10} \]

Current discrepancy limited by:
- Experimental uncertainty $\rightarrow$ New experiments at FNAL and J-PARC ×4 accuracy
- Theoretical uncertainty $\rightarrow$ limited by hadronic effects

\[ a_\mu^{SM} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} \]

Hadronic Vacuum polarization (HLO)

\[ a_\mu^{HLO} = (692.3 \pm 4.2) \times 10^{-10} \]

\[ \delta a_\mu / a_\mu \sim 0.6\% \]
determination would be "more direct" than via $e^+e^-$ annihilation data and dispersion relation and complementary to efforts to compute in lattice QCD

- need $O(10^{-5})$ accuracy on $s$ for target precision of 0.3% on $a_\mu$
- uncertainty from unmeasured $t$ region?
- competition? scattering at BES? other muon beams worldwide?
- could this be done with COMPASS?

integral under curve $\rightarrow a_{\text{had}\mu}^{\mu}$


- CERN-SPS: wide range of $\mu_B$ coverage & interaction rate

★ complementary to existing/planned experiments: SIS & HADES, BES RHIC

★ High interaction rate (higher than NICA; plot would have to be provided)

★ very interesting proposal: sharpen physics case!
**NA60++**

- Dilepton thermometer as probe of confinement-deconfinement temperature

\[ \propto M^{3/2} e^{-M/T} \]

- Charmonium & open charm

  ★ J/psi anomalous suppression, refined analysis

- Sharpen case for NA60++: (New) physics impact!
NA61++

- **Experimental competition?**

- **Physics case:**
  - Statistical Model vs. dynamical approaches (strong enough?)

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**QCD Context**

PBC Working Group Meeting, March 2017
• DIRAC: pioneering experiment at CERN PS producing $\pi\pi$ and $\pi K$ atoms and measuring their lifetimes $\rightarrow$ compute $\pi\pi$ and $\pi K$ scattering lengths

• physics: chiral symmetry breaking in QCD $\rightarrow$ low-energy interactions between $\pi$’s and $K$’s predicted $\rightarrow$ chiral perturbation theory (ChPT)

• lattice computation of low-energy constants: very active field, significant progress

compilation of results in arXiv:1607.00299
DIRAC++

- DIRAC: pioneering experiment at CERN PS producing $\pi\pi$ and $\pi K$ atoms and measuring their lifetimes $\rightarrow$ compute $\pi\pi$ and $\pi K$ scattering lengths
- physics: chiral symmetry breaking in QCD $\rightarrow$ low-energy interactions between $\pi$'s and $K$'s predicted $\rightarrow$ chiral perturbation theory (ChPT)
- DIRAC++ at SPS: would have significantly higher yield for $\pi K$ atoms $\rightarrow$ measure $|a_{1/2} - a_{3/2}|$ with accuracy below 5%
  ⭐ quantity computed using ChPT/lattice techniques

which impact would this measurement have on the field?
DIRAC++

- in pp sector: could improve existing accuracy on $|a_0 - a_2|$ from $\sim 4\%$ to $\sim 2\%$

- possibility to measure $|2a_0 + a_2|$ with long-lived pp atoms? (observed by DIRAC)

★ quantitative estimates? would probably require different expt'l setup than πK programme

★ expected physics impact?
Baryon magnetic moments

- idea: measure magnetic moments of short-lived baryons $\Lambda_c$ (udc), possibly also $X_c$ (usc) or $X_{cb}$ (ubc) via spin precession using bent crystal at LHC
  - possibly extend technique to $\tau$ lepton?
- physics motivation (for baryons): probe anomalous magnetic moment of c (or b) quark
- physics questions (QCD):
  - how reliably can connect magn. moments of baryon and heavy quark?

<table>
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<th>Baryons</th>
<th>Bag</th>
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<th>[15]</th>
<th>[16]</th>
<th>[17]</th>
<th>[20]</th>
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<tr>
<td>$\Lambda_c^+$</td>
<td>0.411</td>
<td>0.39</td>
<td>0.40</td>
<td>0.341</td>
<td>0.42</td>
<td>0.37</td>
<td>0.39</td>
<td>0.37</td>
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<tr>
<td>$\Sigma^0_c$</td>
<td>-1.043</td>
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<td>0.41</td>
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★ possibly extend technique to $\tau$ lepton?

- physics motivation (for baryons): probe anomalous magnetic moment of c (or b) quark

- physics questions (BSM):
  ★ existing constraints on $(g-2)_c$ or $(g-2)_b$ or $(g-2)_\tau$? e.g. from $e^+e^-$ annihilation?
  ★ estimates on their size from BSM models?
  ➡ achievable experimental precision adequate?