Precision Timing at the Electron Ion Collider

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Michael Murray, University of Kansas

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Abstract

One of the most powerful tools tools for understanding the three dimensional structure of the nucleus is Deeply Virtual Compton Scattering. In such events an electron radiates a virtual photon which scatters off the nucleus. If all the final particles can be reconstructed the initial kinematics are fixed and the distributions of the scattered electrons, photons and protons reveals the internal structure of the protons. A generic feature of any EIC detector is that it must be compact, work at very high rates and include both central and far forward detectors. Given these constraints precision timing offers a way to maximize the effectiveness of the forward detectors were space is extremely limited. We propose to leverage our work on fast timing for the CMS-TOTEM Precision Proton Spectrometer to maximize the physics reach of the forward spectrometers for EIC. For this year we will focus on simulations of the very forward region at the EIC while continuing our electronic and radiation studies of fast tracking detectors.

1 Introduction

One of the major physics topics for the EIC is 3D-imaging of nucleon structure through Generalized Parton Distributions (GPDs). The GPDs are new structure functions generalizing the concept of form factors and parton distributions. GPDs encode more information than the standard parton distributions since they contain the correlations between space and momentum of the partons. GPDs can be accessed by measuring exclusive reactions, the simplest of which is Deeply Virtual Compton Scattering (DVCS) where a real photon is produced in the final state, [1, 2].

The DVCS process was studied at HERA on the H1, ZEUS and HERMES experiments [3]. Jefferson Laboratory is currently making a major study of DVCS in the high X region [4]. This work is illuminating GPDs of the valence quarks in the protons. The polarized beams and the high luminosity of EIC will allow to extensively study the GPDs in the low x region which is dominated by gluons.

A typical DVCS $ep \to ep\gamma$ produces an electron in the Deeply Inelastic regime. This electron has a large scattering angle and will be detected in the central detector. Ideally we all 3 particles are measured. However if the resolution of the detectors is sufficient, for those events with only two particles in the acceptance, the momentum of the third one can be deduced using the missing mass technique. This ability can greatly improve the acceptance of a given experiment.

2 Measuring Forward Protons

A great challenge for studying DVCS events is detecting the outgoing proton or ion which are scattered at very small angles. Fig. 1 from the EIC TDR shows the distribution of forward protons from DVCS events for various sets of electron and proton beam energies. Such particles have to be measured in dedicated detectors, hosted in Roman pots, located close to the beam and far away from the main central detector.

Figure 2 shows two proposed forward detectors for the JLEIC and eRHIC colliders. Both spectrometers have a series of Roman Pots extending up to 40m from the interaction point. The CT-PPS project at the LHC is measuring diffractive protons using the worlds most sophisticated set of Roman Pots. These contain tracking and timing detectors with very high resolution and so allow the resolution of the missing mass of diffractive events to unprecedented precision [5, 6, 7]. A side view of the detector is shown in Fig. 3. We plan to leverage this work and our expertise in fast timing electronics to develop forward

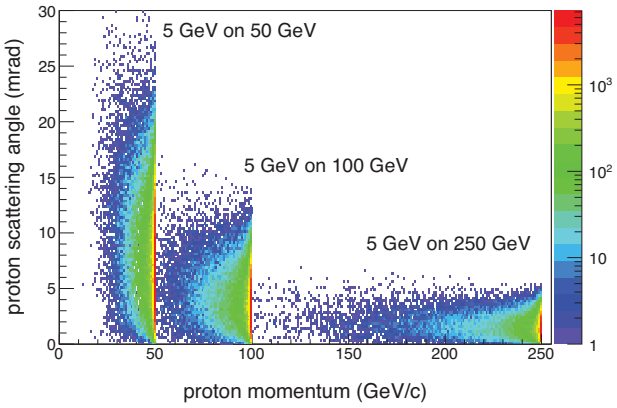

Figure 1: The scattering angle of protons versus the proton momentum for DVCS events with different beam energy combinations, EIC white paper [1].

tracking detectors for high luminosity running at the EIC.

The complete EIC physics program requires luminosities in the range 10^{33} to $10^{34}\mathrm{cm}^{-2}s^{-1}$ [1]. To achieve this goal, either the accelerator will have to go to very frequent bunch crossings, say 5 ns, or else produce multiple interactions per bunch crossing. Measuring the proton time-of-flight with a precision of 20 ps constrains the origin of the proton to be within 4.2 mm. Such precision allows one to tag exactly which collision produced the diffracted proton. Knowing the flight time to such precision also provides a very effective veto against background that may scatter into the acceptance of the forward detect. This can lead to a significant reductions in backgrounds since any particle that does travel along the fiducial flight path will have a time of flight several tens of ps away from the signal. Precision timing allows one to track in 4 dimensions, X, Y, Z and flight time T. For a particle of mass m, momentum p measured over a flight path of length L the rate of change of time with mass is given by

$$\frac{dT}{dm} = \frac{L}{c} \cdot \frac{m\beta}{p^2} \tag{1}$$

For a 40m path length and a 50 GeV proton this implies that $\frac{dT}{dm} = 50$ ps/GeV. Thus a timing resolution of 20ps would give precise enough mass resolution to significantly improve the tracking. Recently the SAMPIC chip has provided an affordable means to reach such precision [8, 9, 10].

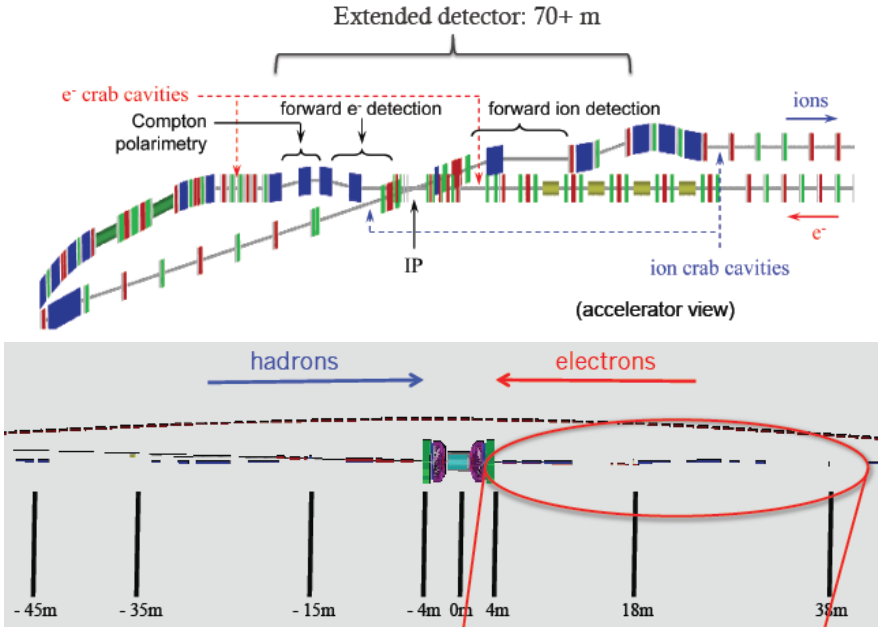

Figure 2: Accelerator views of a proposed forward detectors for the JLEIC (top) and eRHIC (bottom) machines.

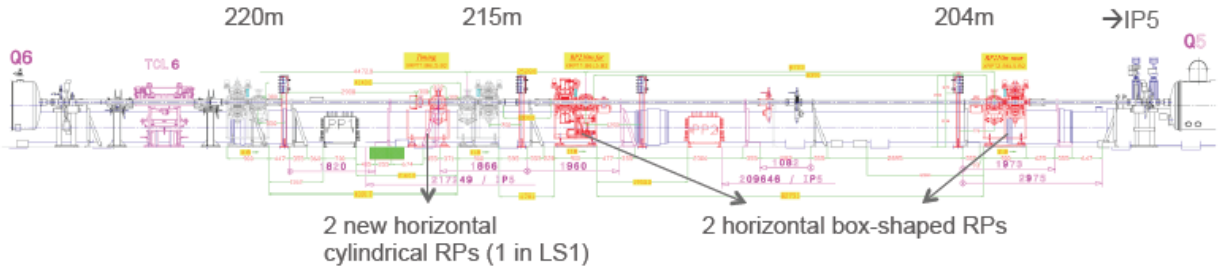

Figure 3: Layout of the Precision Proton Spectrometer, CT-PPS, in the LHC tunnel. There is an identical spectrometer on each side of the interaction region.

3 SAMPIC: A Waveform TDC

Before SAMPIC, the best Time to Digit Converters (TDCs) used digital counters and Delay Line Loops (DLLs). In such a system the timing resolution is limited by the DLL step. This results in a resolution of about 20 ps. Unfortunately such TDCs need a digital input signal: the analog input signal has to be transformed into a digital one with a discriminator. The final timing resolution is then the quadratic sum of the discriminator and TDC timing resolutions. Even if a constant fraction discriminator is used the system uses only part of the information available and thus the timing resolution is not optimal.

The SAMPIC approach is to make finely grained samples of the complete waveform. Precise time information results from the use of three steps:

- Coarse: 6ns time stamp using a Gray-code counter
- Medium: 100ps DLL locked on the clock to define the region of interest
- Fine: 5ps by interpolating samples of the waveform

Since the full waveform information is kept in SAMPIC it is possible to use offline signal processing algorithms in order to improve the timing resolution. It can also be used to obtain other signal characteristics such as the total charge.

Each channel includes an analog memory (64 cells) and recording is triggered by a discriminator. A Gray

counter connected to DLLs assigns a time to the different samples and an ADC converts each sample into a digital signal [11]. The input signal range has to be between 0.1 and 1V with a fast rising time up to 1ns in order to get the best possible performance of SAMPIC. The present version of the chip holds 16 channels (50 Ω terminated) with independent dead time. The chip can be externally triggered or run in self triggering mode. A schematic of the SAMPIC chip is shown in Fig. 4 and a picture of a full test stand in Kansas is shown in Fig. 5.

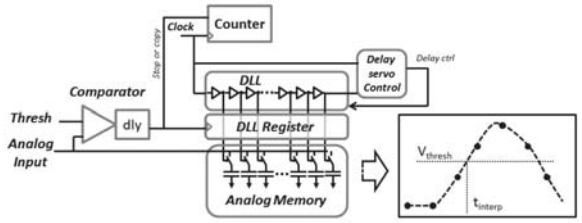

Figure 4: Schematic of the SAMPIC chip.

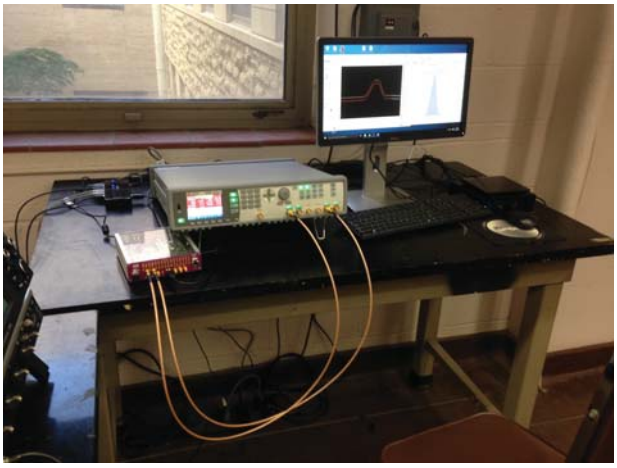

Figure 5: Picture of the SAMPIC test stand at Kansas.

SAMPIC is quite cheap (about $11 per channel) with respect to about $1000/channel for alternative systems. The average noise is quite low, ≈ 1 mV RMS. This gives a dynamic range of 1000. Cross talk was measured by sending a signal of 800 mV with a 300 ps rise time on one channel and reading out the neighbouring channels. The cross talk was found to be less than 1%. The timing resolution was studied by sending the same signal to two channels but delaying one with a cable. The pulse had an amplitude of about 1.2 V, and we used the 6.4 Gigasamples per second configuration. The RMS of the time difference between the two signals as a function of delay is given in Fig. 6 using two different offline algorithms to reconstruct the time difference (CDF as constant fraction discriminator and CC as cross correlation using a linear or a spline interpolation between the different points measured by SAMPIC). The time resolution is quite flat as a function of the delay between the two signals and is about 5 ps, implying a time resolution per channel of about 4 ps.

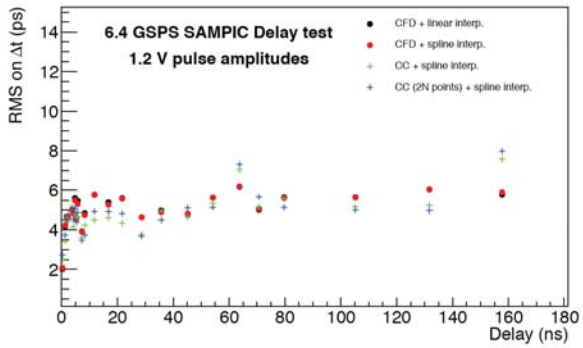

Figure 6: RMS on the time difference between two signals, one being delayed with respect to the other using two offline algorithms (Constant Fraction Discriminator (CFD) and cross correlation (CC)) using a linear or a spline interpolation.

4 Ultra Fast Silicon Detectors

Currently the best timing resolution from solid state detectors is on the order of 100 ps. Such results has been obtained using diamond detectors designed by several collaborations, such as HADES [12] and TOTEM [13]. To reach its timing goals the CT-PPS group is working on new types of ultra fast silicon detectors. Low Gain Avalanche Diodes (LGAD) are a novel type of silicon detectors that combines the advantages of internal gain, as in avalanche photodiodes (APDs), with the properties of standard silicon detectors. Since the devices run at low gain they do not generate the dark counts and excessive leakage current that are typical for APDs. Starting from this idea, Ultra-Fast Silicon detectors have been developed [14, 15, 16]. If the time walk can be corrected and the time drift is negligible, the time resolution σ_t is the given by $\sigma_t = \tau/S_{NR}$ where, is the rise time of the signal and S_{NR} is the signal-to-noise ratio [17]. A measurement and simulation of such a signal is shown in Fig. 7. Such detectors have very fast rise times, 3ns and preliminary studies have already shown that a time resolution below 50ps is possible. These detectors also a total signal duration of order

10ns which makes them ideal for high rate applications. However they do require the development of custom front-end electronics, designed to provide the best compromise between signal-to-noise ratio and bandwidth. The Kansas group, in collaboration with Torino and Santa Cruz, is developing an appropriate preamplifier for these detectors. We are also planning to test the degradation of their performance as a function of neutron dose up to $\sim 10^{16}$ n/cm^2.

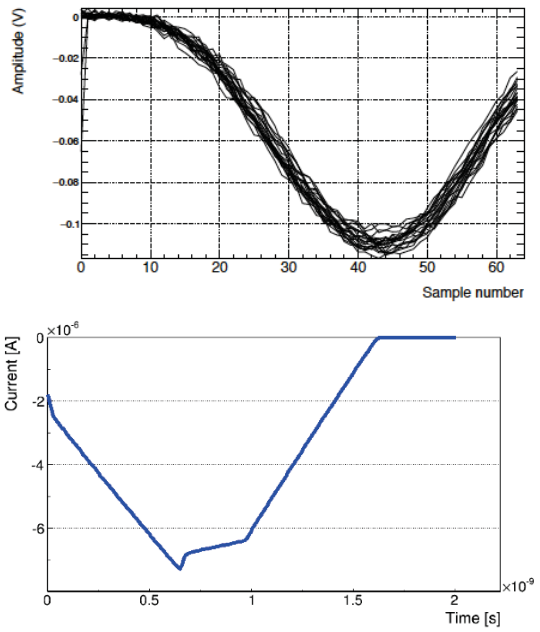

Figure 7: (Top) Signals generated by a USFD amplied with a CIVIDEC C2-BDA amplifier and acquired by a SAMPIC chip sampling at 6.4 GS/s. (Bottom)Simulated signal produced by a MIP passing through a 50 μm UFSi produced using the Weightfield2 package [18].

5 Simulation

In order to leverage the TOTEM expertise in high resolution timing detectors in the Roman Pots, we are proposing to do extensive simulation work to determine the requirements for timing and its potential for improving physics measurements. In a first step we are planning to setup the different simulation frameworks for EIC to be able to have the current planned detector configurations and work conjointly with the simulation teams to study the physics background and the effect of the combination of high resolution timing in Romans pots in coincidence with the main detector.

For processes such as Deeply Virtual Compton Scattering, a detailed simulation is needed to determine the contamination by inelastic events, and contribution from accidentals. We expect that a tight timing cut will significantly improve the signal to background ratio. Also the acceptance of detection of DVCS events could be enhanced if the resolution for two particles is sufficient to allow missing mass techniques to be used. So good timing and position resolution in the Roman pots could allow us to accurately reconstruct the photon where EM calorimetry is poorer or non existent. Acceptance and background have to be studied to determine the ideal position and granularity of the detector and evaluate the improvement on the measurements of such a detector.

6 Workplan and milestones

In order to understand the potential for fast timing to contribute to EIC physics we propose to make a series of detailed simulations of the proposed forward detectors shown in Figure 2. In parallel we continue our electronics development of fast silicon detectors, their associated preamps and radiation hardness. We propose to devote 50% FTE of one of our existing postdocs to GEANT simulations for this work. For this funding period, we are planning to start with JLEIC GEMC framework but will expand to the EIC Root framework used for eRHIC as time permits. The goal of this work is to map out a realistic option for deploying fast timing detectors in Roman Pots in the very forward interaction region at the EIC. The milestones for this work are shown in Table 1.

7 Personnel

The nuclear physics group at the University of Kansas currently consists of four faculty, Steve Sanders, Michael Murray, Daniel Takaki and Christophe Royon, four postdocs and 8 graduate students. The group has a strong interest in exclusive processes and low x physics as well as significant expertise in flow studies. The KU group is currently making a significant effort in the deployment of fast for CT-PPS and has one faculty, 3 postdocs and 3 graduate students working on this. We have recently built a test stand for testing LGAD silicon detectors readout by SAMPIC. We are also taking responsibility for the radiation tests of these detectors. This work is in close collaboration with groups at Torino and Santa Cruz. On CMS the KU group is also responsible for the CMS Zero Degree

Period	Task
Oct - Nov	Setting GEMC on local machines
Nov - May	Study x,y and time distributions in Roman Pots
Oct - Jan	Radiation tests for ultra-fast silicon detectors
Jan - May	Test of new pre-amplifiers for ultra-fast silicon
May - Oct	Study of proton identification in Roman Pots
May - Oct	Timing tests on KU test stand

Table 1: Workplan for simulations and tests of fast silicon detectors.

Calorimeters and luminosity determination for heavy ion runs. For CVs of key personnel see Appendix 1.

8 Budget

The budget is shown in Appendix 2. The main cost is for 50% time for one postdoc. This salary is based on typical rates at Kansas. The travel costs are to allow the postdoc to visit either Jefferson or Brookhaven labs. . Indirect costs are based on the standard rate at the University of Kansas.

9 Budget Justification

Senior Personnel: Dr. Christophe Royon, Principal Investigator (0.09 summer month), the PI has requested the minimum salary required by the university. The PI will oversee the work, guide the postdoctoral associate and serve as liaison with other groups working on far forward detectors.

Other Personnel: Postdoctoral Associate (6 calendar months). The postdoc will be responsible for setting up the EIC simulation framework at Kansas, studying the acceptance and background for exclusive events as well as detector tests.

Fringe Benefits: Benefits are calculated at a rate of 35% for faculty and postdoctoral researchers and at a rate of 7% for graduate and undergraduate students working less than 75% FTE.

Travel: Domestic Travel $2,000 has been requested to cover travel costs of the postdoc to visit either Jefferson or Brookhaven Lab. This should cover airfare and perfume.

Indirect Costs: Indirect costs are calculated @ 51.5% of modified total direct costs (MTDC), where MTDC equals total direct costs excluding equipment, tuition and subcontracts in excess of $25,000. This rate was determined by the indirect cost rate agreement negotiated with DHHS for The University of Kansas Center for Research, dated March 22, 2016.

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[18] F. Cenna, *et al.*, Nucl Inst Meth A, **796** 149 (2015).

Appendix 1

CV - Christophe Royon

Education

- 1998: Habilitation to lead researchers at University of Orsay (FR)
  1994: PhD in Physics obtained with highest distinction («Felicitations du jury») University of Orsay - Paris XI/CEA Saclay (FR)
- 1991: Master in Quantum Physics at Ecole Normale Superieure (FR)
- 1990: «Agregation» of Physics at Ecole Normale Superieure (FR)
- 1987-1991: Ecole Normale Superieure (FR)

Research career

- 2016-present **Foundation Distinguished Professor**, Kansas University, Lawrence, USA
- 2015-present: Science Advisor for Brazil (science without borders programme)
- 2015-present: Member of the TOTEM and CMS experiments
- 2012-present: Development of a fast timing readout chip with applications in PET medical detectors and drones
- 2012-present : **Co-convener** of the LHC Forward Physics Working Group coordinating forward physics between all LHC experiments (ATLAS, CMS, ALICE, LHCB, TOTEM)
- 2011-2013 : **Spokesperson** of the ATLAS Forward Physics project to install forward proton detectors in the ATLAS experiment at the LHC (worldwide collaboration of 150 physicists from 28 institutes and 11 countries)
- 2007 – 2015: **Research director** at CEA-Saclay, IRFU-SPP. Member of the ATLAS and D0 collaboration.
- 2005-2015: Member of the ATLAS experiment
- 2002-present : Member of the international organising committee of the « Diffraction » workshops
- 2000-present : Co-chairman of the international organising committee of the « Small x » conferences, Fermilab, Chicago, USA
- 2000-present : Collaboration with the Theory Division of Saclay (QCD and diffraction, beyond standard model physics such as extra-dimensions, anomalous couplings)
- 1994 – 2015: **Permanent position of Research Associate at CEA-Saclay**. Member of the H1 collaboration
- 1992-present : Chairman of the organising committee of the « low x » workshops

- 2009-2011 : Responsible of **Calorimeter group** (D0)
- 2002-2006 : Member of the D0 speakers' bureau which decides the speakers of the collaboration in international conferences
- 2004-2006: Responsible of the **D0 Jet Energy Scale group**
- 2002-2004 : Responsible of the **D0 QCD group**, one of the six physics groups of the D0 collaboration
- 2000-2002 : Responsible of the **Muon group** of the D0 collaboration
- 2000-2002; 2004-2006: Fermilab guest scientist of the University of Chicago, permanently based at Fermilab, different convenership (muon, QCD, jet energt scale groups)

Teaching career

- 2016-present: Distinguished Professor, University of Kansas
- 2014 (November): Organisation of a Summer School on LHC physics, Natal, Brazil
- 2007 (July): Organization of a Summer School on diffraction and QCD, Copanello, Italy, July 2007, in collaboration with A. Papa and R. Fiore – Editor of the book containing the write up of the lectures;
- 2005, 2007: Lectures given at the Zakopane Summer School on Physics about QCD and diffraction at HERA, Tevatron, LHC.

Supervision of PhD Dissertations

- 2013 – present: Supervisor of PhD Dissertation by Matthias Saimpert (Paris XI) – *Measurement of diphoton cross section in ATLAS and search for photon quartic anomalous couplings"*
- 2011 – 2014: Supervisor of PhD Dissertation by Martin Zeman (university of Prague/Paris XI) - "*Diffraction in ATLAS*" – ATLAS (Coleadership with Czech Republic);
- 2010 – 2013: Supervisor of PhD Dissertation by Herve Grabas (university of (Paris XI) – "*Fast timing electronics and search for anomalous couplings at the LHC*" – ATLAS/electronics (timing detectors);
- 2010 – 2013: Supervisor of PhD Dissertation by Emilien Chapon (university of {Paris VII) – "*Search for the Higgs boson at high mass in D0 and for anomalous couplings between photon and W boson in ATLAS*" – D0/ATLAS;
- 2009 – 2012: Supervisor of PhD Dissertation by Maciej Trzebinski (university of {Cracow/Paris XI) – "*Jet gap jet event and diffractive studies "* – ATLAS (Coleadership with Poland)
- 2008 – 2012: Supervisor of PhD Dissertation by Rafal Staszewski (university of (Cracow/Paris XI) – "*Study of W asymmetries in diffractive events in ATLAS*" – ATLAS (Coleadership with Poland)
- 2007 – 2010: Supervisor of PhD Dissertation by David Salek (university of (Prague/Paris XI) – "*Diffraction in H1 and ATLAS"* – ATLAS (Coleadership with Czech Republic)
- 2006 – 2009: Supervisor of PhD Dissertation by Oldrich Kepka (university of (Prague/Paris XI) – "*Study of QCD and diffraction in ATLAS*" – ATLAS (Coleadership with Czech Republic)
- 2005 – 2008: Supervisor of PhD Dissertation by Murilo Rangel (university of (Rio de Janeiro/Paris XI) – "*Diffraction in D0*" – D0 (Coleadership with Brazil)
- 2004 – 2008: Supervisor of PhD Dissertation by Mikko Voutilainen (university of (Helsinki/Paris XI) – "*Inclusive jet cross section measurement and jet energy scale in D0*" - D0 (Coleadership with Finland);
- 2003 – 2005: Supervisor of PhD Dissertation by Jean-Laurent Agram (university of (Strasbourg/Mulhouse) – "*Inclusive jet cross section measurement in D0*" –D0;
- 2000 – 2003: Supervisor of PhD Dissertation by Alexander Kupco (university of (Prague) – "*Inclusive jet cross section measurement in D0*" –D0;
- 1999 – 2002: Supervisor of PhD Dissertation by Frédéric Déliot (university of (Paris VII) – "*Search for resonant SUSY production at D0*" – D0.

Funding ID: Participation in Successful Project Writing and Management

- 2015-present: Responsible with Prof. Amir Reizaian of an ECO-SUD project for collaboration between Valparaiso, Chile, and Saclay
- 2015-present: Responsible with Prof. Michal Przalowicz of a POLONIUM project for collaboration between Cracow, Poland, and Saclay
- 2015-present: Responsible with Prof. Alexander Kupco of a BARRANDE project for collaboration between Prague, Czech Republic, and Saclay
- 2012-present: Responsible with Prof. Victor Goncalves of a CAPES/COFECUB project for collaboration between France and Brazil
- 2011-2012: Responsible with Prof. Janusz Chwastowski of a POLONIUM project for collaboration between Cracow, Poland, and Saclay
- 2011-2012: Responsible with Prof. Alexander Kupco of a BARRANDE project for collaboration between Prague, Czech Republic, and Saclay
- Major past funding: responsible for ECONET project from 2006-2010; with Prof. Yoshitaka Hatta for SAKURA project
- 2007-present: Collaboration with the University of Chicago about timing detector electronics (Memorandum of Understanding)

Memberships to Editorials Boards of International Journals

- Editor of the review about exclusive diffraction with M. Albrow and V. Khoze, Int. J. Mod. Phys., 2014
- Editor of the review about diffraction, Int. J. Mod. Phys., 2015
- Editor of the Proceedings of the Workshop on fast timing detectors and medical applications, Clermont-Ferrand, March 2014
- Editor of the Proceedings of the Summer School on diffraction and QCD, Copanello, Italy, July 2007

- Editor of the Proceedings of the Workshop on timing detectors, Cracow, Poland, November 2010
- Referee for different International Publications: Phys. Lett., Phys. Rev. Lett., Phys. Rev. D, Eur. Phys. J, Nucl. Inst. Meth. (in average, 1 paper per month to referee)

Collaboration with theorists
CR has published 50 papers in collaboration with theorists on QCD and new phenomena phenomenology (J. Bartels, A. Bialas, G. von Gersdorff, K. Golec-Biernat, S. Lavignac, C. Marquet, R. Peschanski, G. Soyez, S. Wallon…)

Overview past scientific achievements with references to major paper
CR has published in total 193 papers in Phys. Rev. Lett. and one in Nature. CR has contributed to more than 928 publications with more than 60,000 citations (h-index: 107).

10-Year track-record

Christophe Royon (CR) has contributed to more than 928 publications with more than 60,000 citations (h-index: 107). These publications are mainly from the D0/ATLAS collaborations in which CR gave an important contribution or publications on phenomenology with a small number of authors. In the period 2005-2014 CR has published 785 publications with more than 40,000 citations (H-index: 91), In this period he had 162 Phys. Rev. Lett., 2 Nature and 26 papers in collaboration with theorists on QCD and new phenomena phenomenology (J. Bartels, A. Bialas, G. von Gersdorff, K. Golec-Biernat, S. Lavignac, C. Marquet, R. Peschanski, G. Soyez,…) .

Top 10 publications

- Obervation of a new particle for the SM Higgs boson with the ATLAS detector at the LHC, ATLAS Coll., Phys. Lett. B 716 (2012) 1, 3748 citations
- Combined search for the SM Higgs boson using up to 4.9 fb-1 of pp collisions at 7 TeV with the ATLAS detector at the LHC, Phys. Lett. B 710 (2012) 49, 521 citations
- Jet energy measurement with the ATLAS detector in pp collisions at 7 TeV, Eur. Phys. J. C73 (2013) 3, 501 citations
- "The upgraded D0 detector", D0 Coll., Nucl. Inst. Meth. A565 (2006) 463, 895 citations
- "A precision measurement of the mass of the top quark", D0 Coll., Nature 429 (2004) 638-642, 314 citations
- "Observation of Single Top Quark production", D0 Coll., Phys.Rev.Lett. 103 (2009) 092001, 339 citations
- "First direct two-sided bound on the Bs0 oscillation frequency", D0 Coll., Phys. Rev. Lett. 97 (2006) 021802, 337 citations
- "Measurement of the inclusive jet cross-section in p anti-p collisions at s**1/2 =1.96-TeV", D0 Coll., Phys. Rev. Lett. 101 062001, 2008, 211 citations
- "Measurement of inclusive and dijet cross sections in pp collisions at 7 TeV with the ATLAS detector", ATLAS Coll., 196 citations
- "Measurement of the dijet azimuthal decorrelations at central rapidities in p pbar collisions at s**1/2=1.96 TeV", D0 Coll., Phys. Rev. Lett. 94 (2005) 221801, 123 citations.

Additional publications with theorists (only a few examples)

- "Probing new physics in diphoton production with proton tagging at the LHC", S. Fichet, G, von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys. Rev. D89 (2014) 11, 114004, 11 citations
- "Popping out the Higgs boson off vacuum at Tevatron and LHC", M. Boonekamp, R. Peschanski, C. Royon, Nucl. Phys. B669, (2003) 277, 59 citations
- "Azimuthal decorrelation of Mueller-Navelet jets at the Tevatron and the LHC", C. Marquet, C. Royon, Phys. Rev. D79 (2009) 034028, 79 citations
- "Anomalous WWgamma coupling in photon-induced processes using forward detectors at the LHC",

Phys. Rev. D 78 (2008) 073005, O. Kepka, C. Royon, 74 citations

- "Diffractive SUSY particle production at the LHC", M. Boonekamp, J. Cammin, S. Lavignac, R. Peschanski, C. Royon, Phys. Rev. D73 (2006) 115011, 38 citations
- "Anomalous quartic WWgamma gamma, ZZ gamma gamma and trilinear WWgamma couplings in two-photon processes at high luminosity at the LHC", E. Chapon, O. Kepka, C. Royon, Phys. Rev. D81 (2010) 074003, 71 citations
- "Towards an unified description of total and diffractive structure funtions at HERA in the QCD dipole picture", A. Bialas, R. Peschanski, C. Royon. Phys. Rev. D57 (1998) 6899, 57 citations
- "Inclusive Higgs boson and dijet production vis double pomeron exchange", M. Boonekamp, R. Peschanski, C. Royon, Phys. Rev. Lett. 87 (2001) 251806, 84 citations
- "Proton structure function in the dipole picture of NFKL dynamics", H. Navelet, R. Peschanski, C. Royon, S. Wallon, Phys. Lett. B385 (1996) 357, 105 citations

Research monographs, chapters in collective volumes and any translations thereof

- Understanding the structure of the proton: From HERA and Tevatron to LHC. M. Boonekamp, F. Chevallier, C. Royon, L. Schoeffel, arXiv:0902.1678, Acta Phys.Polon.B40:2239-2321,2009.
- Frontiers of QCD at hadron colliders, C. Royon, Published in Europhys.News 41N1:19-22, 2010.

Invited presentations (in total 52 in the last 10 years)

- Invited colloquium about the Higgs boson discovery for the 50th birthday of particle physics at the UFRJ, Rio de Janeiro, Brazil
- Invited presentation about the Higgs boson discovery, Gramow Conference, Odessa, Ukraine, August 2014
- Invited review talk about Forward Physics at the LHC at the conference "Physics in the LHC Era", Vina Del Mar, Chile, December 2013
- Invited review talk about diffraction at the LHC and the AFP project, Kruger 2012 conference, Kruger Park, South Africa, December 2013
- Invited review talk about diffraction at LHC, LISHEP 2012 conference, Rio de Janeiro, Brazil, March 2012
- "Review about Tevatron Results ", January 2012: Invited review, Workshop on High Energy Physics in the LHC Era, Vina Del Mar, Chile
- Summary talk of the "Photon 2011" conference, Spa, Belgium
- Review about D0 results in QCD, July 2010: Invited talk, ICHEP 2010, Paris, France
- Review about jet physics, August 2010, Invited review, HESI2010, Kyoto, Japan
- QCD at Tevatron and LHC, November 2009, Invited talk, Workshop on QCD in honor of Alfred Mueller, University of Columbia, New York
- QCD at Tevatron and LHC, January 2009, Invited review, « Epiphany 2009 » conference in honour of Jan Kwiecinski, Cracow
- Jet physics at Tevatron and LHC, June 2008, Invited review, PIC 2008, Perugia, Italy
- Jet Physics, August 2007, Invited review, John Hopkins Workshop, Heidelberg, Germany
- Recent results from the D0 and CDF experiments, April 2006, Invited plenary talk, DIS 2006, Tsukuba, Japan
- Diffractive Higgs boson production, August 2004, Invited talk, ICHEP 2004, Beijing, China
- Experimental tests of QCD, August 2004, Invited review, Rencontres du Vietnam, Hanoi, Vietnam
- Diffractive production of Higgs boson at the LHC, July 2003, Invited talk, EPS 2003, Aachen, Germany
- Results in R-partity violated SUSY from the D0 and CDF experiments, July 2002, Invited talk, SUSY 2002, Hamburg, Germany
- Diffraction at Tevatron, July 2011, Invited talk, EPS 2011, Budapest, Hungary

Organisation of International conferences (in total 24 in the last 10 years)

- Member of the organizing committee of the series of workshop "Diffraction", Cracow

- Responsibility of the "Diffraction" session, Multi-particle ISMD 2014 conference, Bologna, September 2014
- Chair of the organizing committee of the workshop about "Forward Physics at the LHC", Trento, Italy, March 2014
- Member of the organizing committee of the workshop about "Forward detectors:, Elba Island, Italy, June 2014
- Member of the organizing committee of the workshop about "Forward physics and heavy ions", Lawrence, USA, September 2014
- Responsibility of the "Low x" session at the EDS 2013 conference, Ivalo, Finaland, September 2013
- Member of the organizing committee of the "Photon 2013" conference, May 2013, Paris, France
- Member of the Organizing Committee of the 6th International Conference on Quarks and Nuclear Physics, QNP 2012, Ecole Polytechnique, Palaiseau, France, April 16-20 2012
- Organizer of the diffraction session, Rencontres du Vietnam, 15-21 December 2011, Quy Nhon, Vietnam
- Member of the Organizing Committee of the International Conference on High Energy Physics, ICHEP 2010, Paris, France
- Co-Chairman with Patrick Le Du (Lyon) and Henry Frisch (Chicago) of the annual "Workshop on Timing Detectors"
- Co-organizer of the ECFA session on photon photon physics, CLIC-ILC project (2010)
- Organizer of different sessions at the series of conferences "DIS": Diffraction (2009, Madrid), Diffraction (2002, Cracow)
- Organizer of the diffractive session, Blois Conference, Hamburg, 2007
- Organizer of the QCD session, ICHEP conference, Moscow, 2006
- Organizer of the QCD and jet session, ISMD, Kromericz, Czech Republic, 2005
- Organizer of the Diffraction session, Baryons 2004, Ecole Polytechnique, France, 2004
- Organizer with of a workshop about the "Future of Fermilab", Batavia, USA, 2004

Management and Committee memberships

- Chairman of the International Committee of the annual series of conferences "Low x" on QCD and diffraction since 1994 (held in DESY, Saclay, Cambridge, Durham, Madrid, Berlin, Tel Aviv, Oxford, Cracow, Antwerp, Nafplio, Prague, Sinaia, Lisbon, Helsinki, Crete, Ischia, Kavala, Santiago de Compostela, Cyprus
- Co-Chairman of the series of conferences "Small x" on diffraction, Fermilab, USA
- Member of the International Advisory Committee of the "Diffraction" conferences
- Member of the International Advisory Committee of the "Blois" series of conferences

Memberships to Editorials Boards of International Journals

- Editor of the Proceedings of the Summer School on diffraction and QCD, Copanello, Italy, July 2007
- Editor of the Proceedings of the Workshop on timing detectors, Cracow, Poland, November 2010, and Clermont-Ferrand, October 2014
- Editor of the Proceedings of the Summer School of LHC physics, Natal, Brazil, November 2014
- Referee for different International Publications: Phys. Lett., Phys. Rev. D, Eur. Phys. J Nucl. Inst. Meth. (in average, 1 paper per month to referee)

Major contributions to early-career of excellent researchers

CR lead 14 PhD students during his career (9 since 2005, 1 ongoing). 8 obtained permanent academic positions directly after PhD or after a post-doc (2 in CEA, 1 in at French university, 5 in universities abroad). 1 student obtained the prize for the best PhD at Fermilab (Mikko Voutilainen) for his outstanding results on QCD and jet energy scales, two (Alexander Kupco and Oldrich Kepka) the price for the best young Czech physicist for major accomplishment in early stage research career.

Michael Murray
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University of Kansas,
Lawrence KS 660495
785 550 8835, 785 864 394
mjmurray@ku.edu

Professional Preparation:
University of Manchester, UK, B.Sc. Joint Honors in Mathematics & Physics 1982
University of Pittsburgh, Pennsylvania, Ph. D in Experimental High Energy Physics, 1989
Los Alamos National Laboratory, New Mexico, Post doctorate in Nuclear Physics, 1989-92

Appointments:
2013 – Present Full Professor, University of Kansas Dept. of Physics & Astronomy
2009 – 2013 Associate Professor, University of Kansas Dept. of Physics & Astronomy
2003 – 2009 Assistant Professor, University of Kansas Dept. of Physics & Astronomy
1995 – 2003 Cyclotron Institute, Texas A&M University, Research Scientist
1992 – 1995 Cyclotron Institute, Texas A&M University, Research Associate

Awards:
NSF Career Award, KU Physics and Astronomy Undergraduate Research Mentor, Graduate Teaching Award.

Research Support:
2003 – Present DOE Research Contract (co PI)
2005 – 2010 NSF Career Award
2004 – 2007 DOE EPSCoR

Professional Societies:
American Physical Society, National Society of Black Physicists

Research Focus:
I am trying to understand how the vacuum affects the fundamental particles. To do this I study collisions of high-energy heavy ions such as lead using the CMS experiment at the Large Hadron Collider. For CMS I am the head of the Zero Degree Calorimeter project, https://twiki.cern.ch/twiki/bin/view/CMS/ZDCWikiHome and was past convener of the Forward Physics group. I am also interested in how life on earth has been influenced radiation from cosmic events in the distant past.

Graduate Advisor: Julia Thompson (University of Pittsburgh)
Postdoctoral Advisor(s): Barbara Jacak (Los Alamos National Laboratory)
Recent Collaborators: BRAHMS and CMS Collaborations, Kansas Astrobiology Group
Postdoctoral Advisees: Quan Wang, Christopher Bruner, Eun-Joo Kim, (Currently: Faculty Chunbok University, Korea), Dipali Pal (Currently: National Association of Insurance Commisioners), Oleg Grachov, currently Yale

Graduate Student Advisees: Jeffery Wood (Pacific Northwest National Laboratory), Patrick Kenny (Analysis at Rex Animal Health), Christopher Bruner (Postdoc at University of Kansas). Ayhman Al-Bataineh and James Bowen are still working on their Ph Ds. Three of my students have won NSF LHC fellowships, one a CMS Achievement Award and one a DOD SMART Fellowship.

Recent Conference Talks

"Bottomonium Production in pPb and PbPb Collisions with CMS", QWG2016: 11th International Workshop on Heavy Quarkonium, 6-10 Jun 2016, Richland, WA

"Centrality and pseudorapidity dependence of transverse energy flow in pPb collisions at 5.02 TeV with CMS", Quark Matter 2015, XXV INTERNATIONAL CONFERENCE ON ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS, 27 Sep-3 Oct 2015, Kobe (Japan)

"Ultra peripheral vector meson production from PbPb Collisions at 2.76 TeV

DIS2015: XXIII International Workshop on Deep-inelastic scattering and related subjects, 27 Apr-1 May 2015, Dallas, TX"

"Identified particles, soft and forwards physics with CMS

Plenary given at WWND 2014: 30th Winter Workshop on Nuclear Dynamics, 6-12 Apr 2014, Galveston, TX"

"CMS Heavy Ion Results, International Workshop on Nuclear Dynamics and Thermodynamics", 21st August 2013, College Station, Tx

"ZDC and CASTOR et al. in CMS", GCOE International Workshop on High-Energy Scattering at Zero Degrees, Nagoya University, Japan 3rd March 2013

"Low x Physics with CMS", seminar at Ecole Polytechnique, Paris, June 15 2012

Related Publications:

"Coherent J/Psi photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the CMS experiment", CMS Collaboration, http://arxiv.org/abs/1605.06966 submitted to PhysLett B

"Multiplicity and rapidity dependence of strange hadron production in pp, pPb, and PbPb collisions at the LHC", CMS Collaboration, http://arxiv.org/abs/1605.06699 submitted to PhysLett B

"Study of Z boson production in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV", CMS Collaboartion, Phys Lett B **759**, 10 36–57

"Event activity dependence of Y(nS) production in $\sqrt{s_{NN}}$ = 5.02 TeV pPb and $\sqrt{s_{NN}}$ = 2.76 TeV pp collisions", CMS Collaboration, arXiv:1312.6300, Submitted to JHEP

"Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV" CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1312.1845 [nucl-ex].

"Observation of long-range near-side angular correlations in proton-lead collisions at the LHC", CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1210.5482 [nucl-ex], 10.1016/j.physletb.2012.11.025, Phys.Lett. B718 (2013) 795-814.

"Observation of sequential Upsilon suppression in PbPb collisions", CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1208.2826 [nucl-ex], Phys.Rev. Lett. 109 (2012) 222301.

"Measurement of higher-order harmonic azimuthal anisotropy in PbPb collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV", CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1310.8651 [nucl-ex].

"Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions", CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1305.0609 [nucl-ex], 10.1016/j.physletb.2013.06.028, Phys.Lett. B724 (2013) 213-240.

"Azimuthal anisotropy of charged particles at high transverse momenta in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1204.1850 [nucl-ex], 10.1103/PhysRevLett.109.022301, Phys.Rev. Lett. 109 (2012) 022301.

"Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1201.3158 [nucl-ex], 10.1140/epjc/s10052-012-2012-3, Eur.Phys.J. C72 (2012) 2012.

"Long-range and short-range dihadron angular correlations in central PbPb collisions at a nucleon-nucleon center of mass energy of 2.76 TeV", CMS Collaboration (Serguei Chatrchyan et al.), arXiv:1105.2438 [nucl-ex],10.1007/JHEP07(2011)076, JHEP 1107 (2011) 076.

"Measurement of the pseudorapidity and centrality dependence of the transverse energy density in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", CMS Collaboration, Phys. Rev. Lett., 109 (2012) 152303

"Atmospheric Consequences of Cosmic Ray Variability in the Extragalactic Shock Model: II Revised ionization levels and their consequences" (Adrian L. Melott, Dimitra Atri, Brian C. Thomas, Mikhail V. Medvedev, Graham W. Wilson, and Michael J. Murray) Journal of Geophysical Research-Planets 115, E08002 (2010)

"Measurement of jet fragmentation into charged particles in pp and PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", CMS Collaboration, JHEP 10 (2012) 087

"Indications of Suppression of Excited Y States in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV"CMS Collaboration, Phys. Rev. Lett. 107 (2011) 052302

"Study of Z boson production in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV"
CMS Collaboration, Phys. Rev. Lett. 106 (2011) 212301

Synergistic Activities:
"A Place for Boys" $42,080 grant from Kritz foundation for refurbishing scout cabin

"Nuclear Science Boy Scout Merit Badge", June 2014.

"Integrating the Spencer Museum into the Curriculum", Faculty Workshop, Spencer Museum of Art, Lawrence, KS, September, 2014

"Using Light to Bring Science and Art to Children", Workshop for Kansas grade school teachers, Spencer Museum of Art, Lawrence, KS, May 2014

"Black Holes, Extra Dimensions, and all that",
University of Kansas Mini College, Lawrence KS, June 2010

Appendix 2

PROPOSED BUDGET

Year 1: 10/01/16 to 09/30/17

SALARIES AND WAGES							
Senior Personnel	P-Months	% time	Months	Rate			
Christophe Royon, PI summer	0.09	3.000%	3	8,889	800		
Michael Murray, Co-I							
Total senior personnel						800	
Other Personnel	Persons	% time	Months	Rate			
Post Doctoral Associate calendar	1.00	50.00%	12	4,000	24,000		
Total other personnel						24,000	
Total salaries and wages						24,800	
FRINGE BENEFITS							
35% faculty and staff					8,680		
Total fringe benefits						8,680	
Total salaries, wages & fringe benefits							33,480
TRAVEL							
Domestic						2,000	
Total travel							2,000
TOTAL DIRECT COSTS							35,480
INDIRECT COSTS - 51.5% excluding equipment, participant support, tuition and subs in excess of $25k							18,272
TOTAL PROPOSED COSTS - YEAR 1							**$ 53,752**