Mapping Proton Quark Structure using Petabytes of COMPASS data

BLUE WATERS
Symposium 2019

April Futch, Robert Heitz, Riccardo Longo[4], Marco Meyer, Matthias Perdekamp[2], Caroline Riedl[1,3] (UIUC)

ILLINOIS

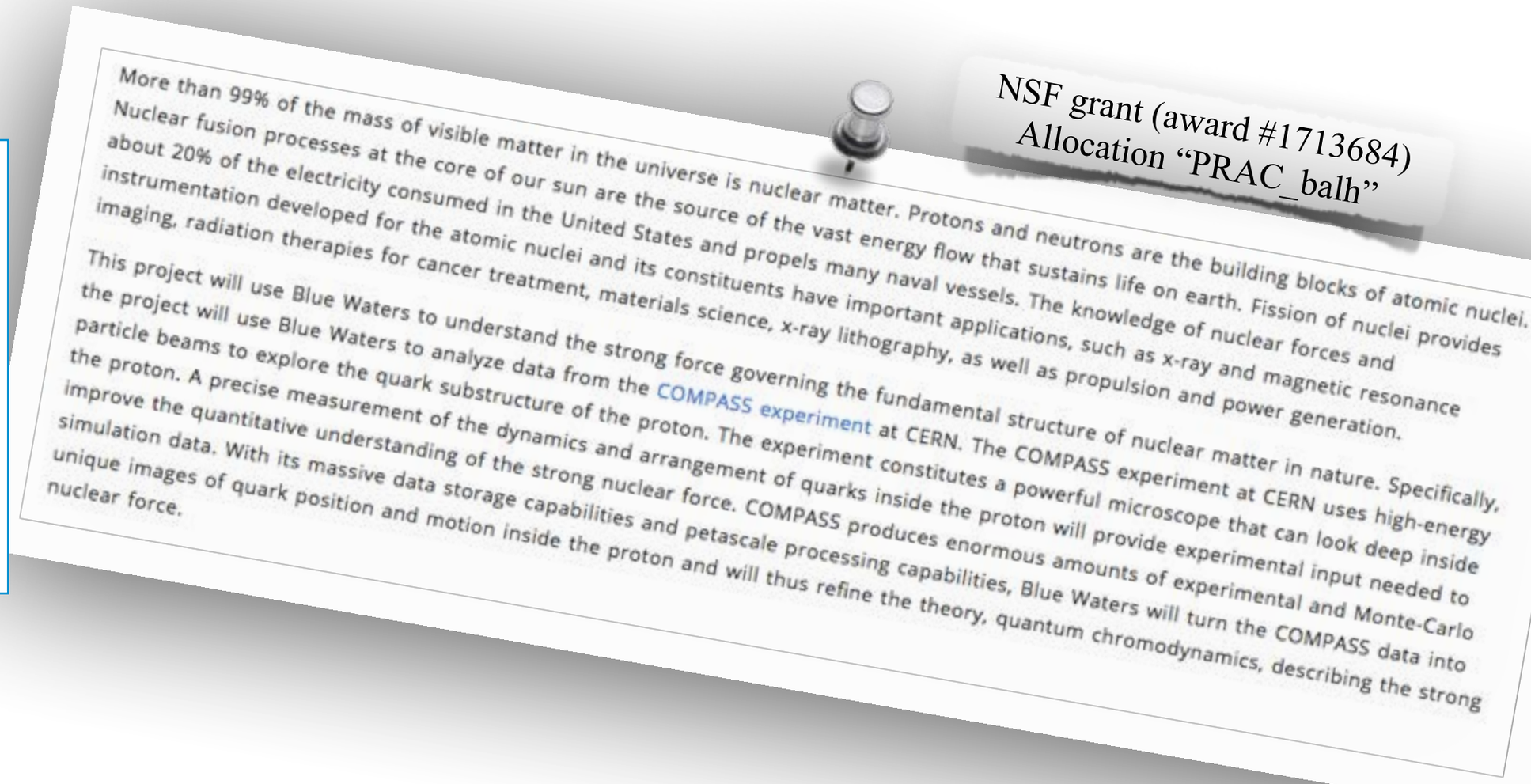
NSF

[1] PI and contact
[2] co-PI
[3] speaker
[4] co-contact and production manager

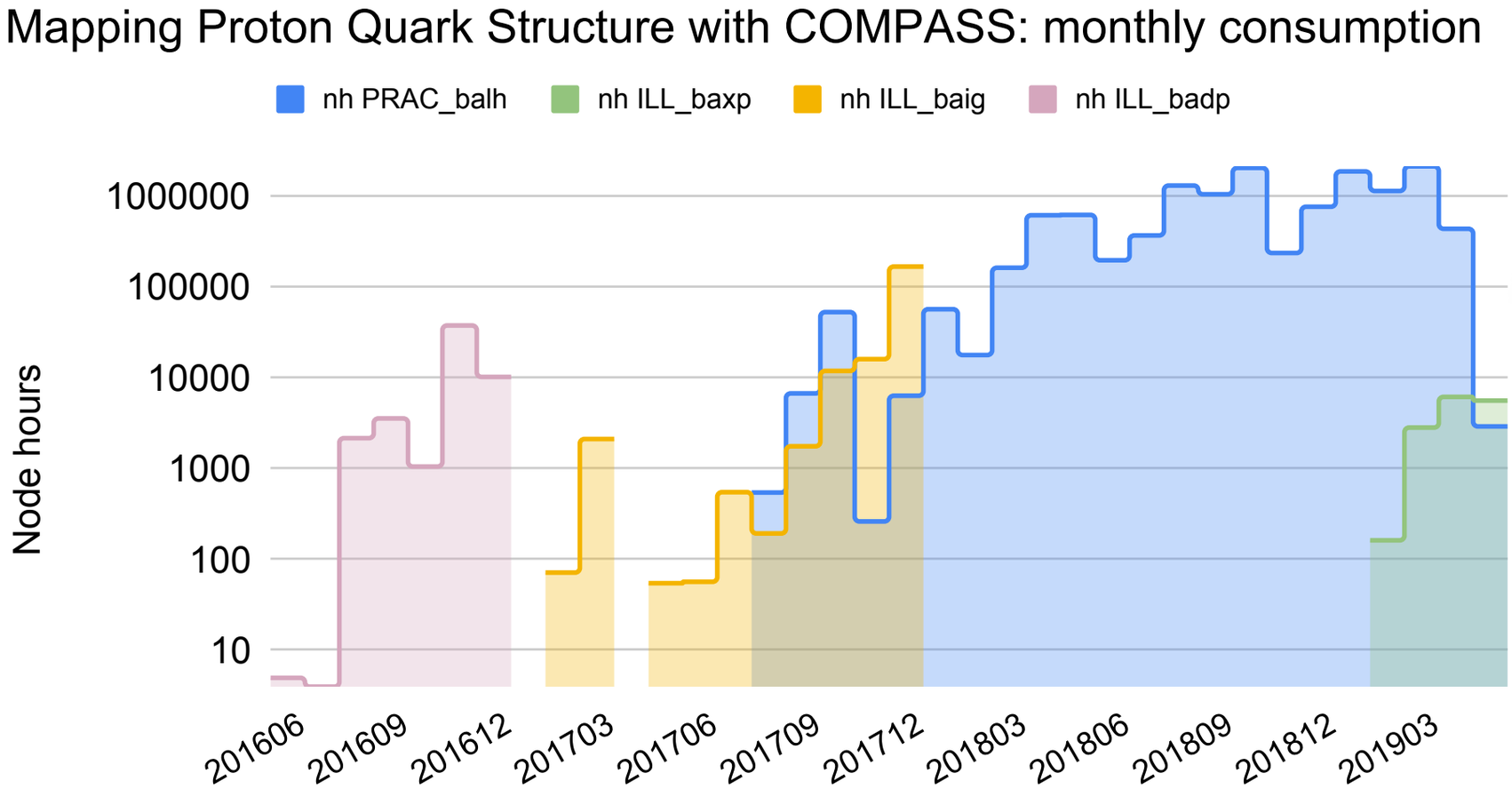
Key Challenges

We use Blue Waters to…

- Investigate **how quarks spin inside the proton** and advance our understanding in **nuclear physics**
- Convert raw data to a format that can be used for physics analysis
- Simulate data
- Analyze the produced data to extract physics observables



3 years of “Mapping Proton Quark Structure” on Blue Waters



77,700 xe jobs submitted
13,344,000 node hours used
222 <node hours / job>
213 min <job duration>
58 <nodes / job>

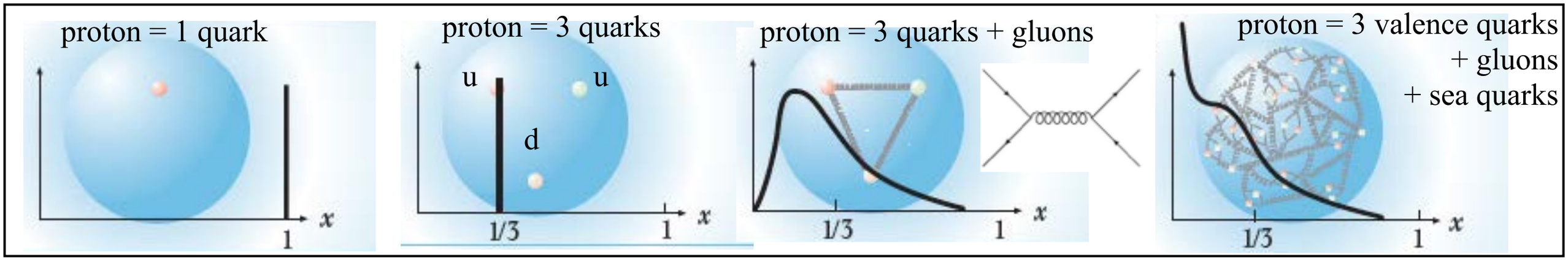
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
2016			✎						✎		✎	
2017												
2018										✎		
2019												

	allocated node hours	proposal submission ✎
exploratory	40k	Mar 2016
campus 17	200k	Sep 2016
PRAC-A	9,440k	Nov 2016
PRAC-B	9,440k	(together with PRAC-A)
campus 19	600k	Oct 2018

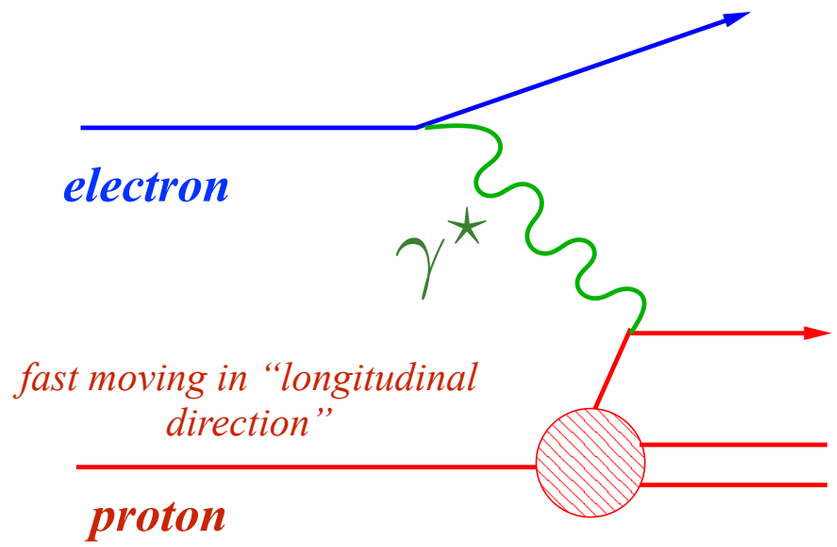
Why it matters

The proton: the closer you look

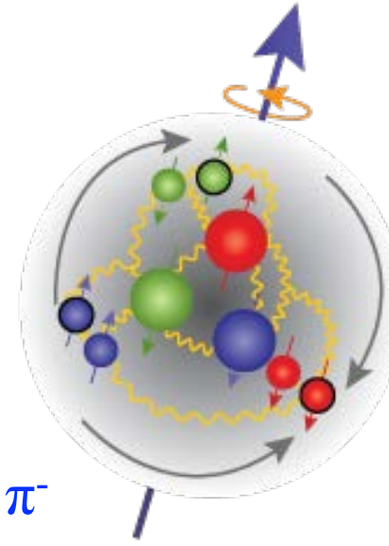
Parton Distribution Function = number density ("parton" = quark or gluon):

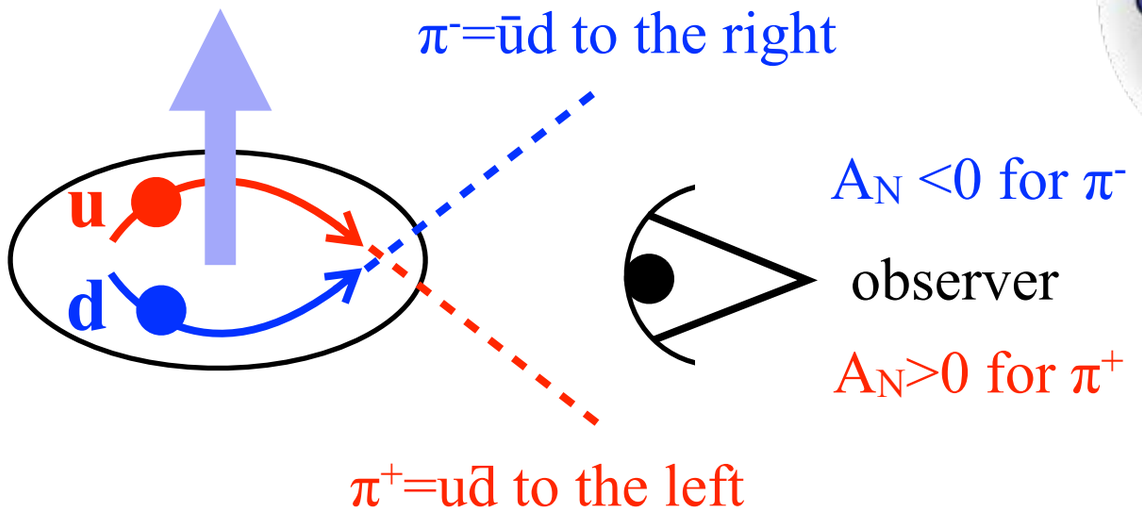


probed in deep-inelastic **electron**-proton scattering (for example):



Now add proton / quark spin & transverse momentum!

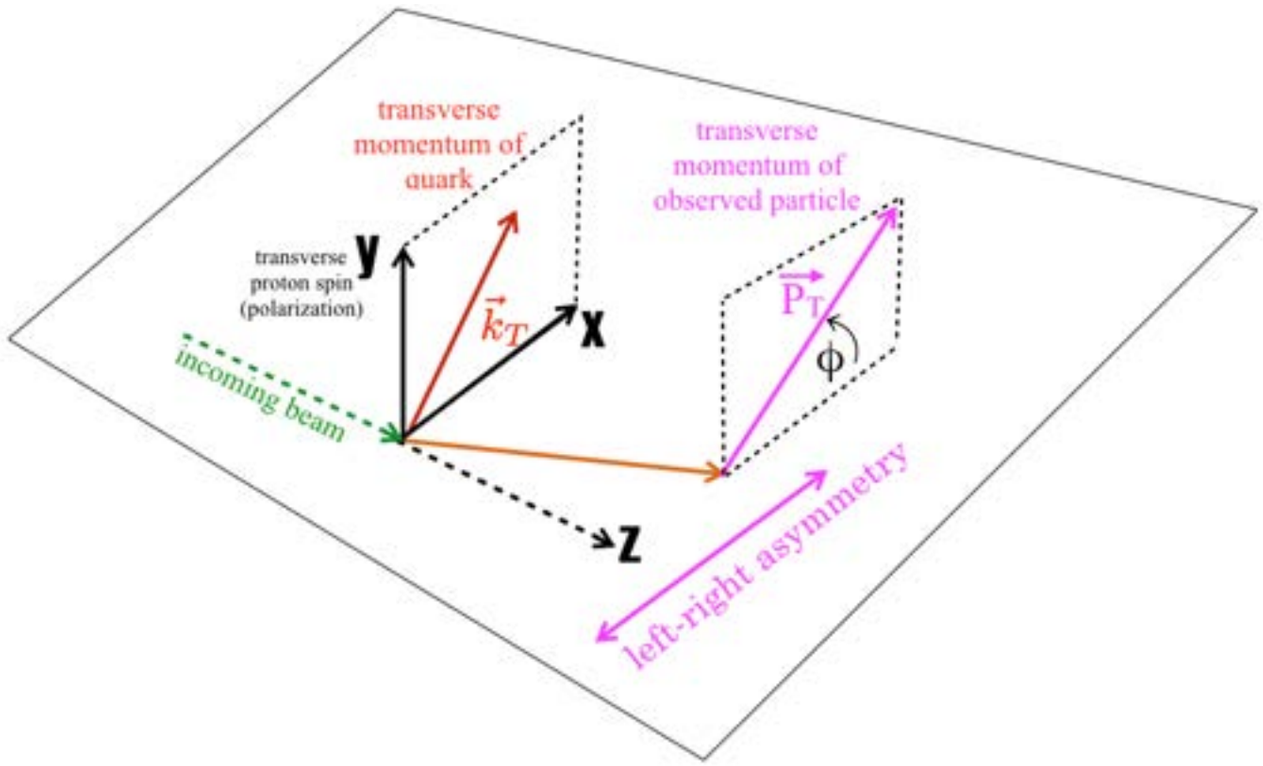


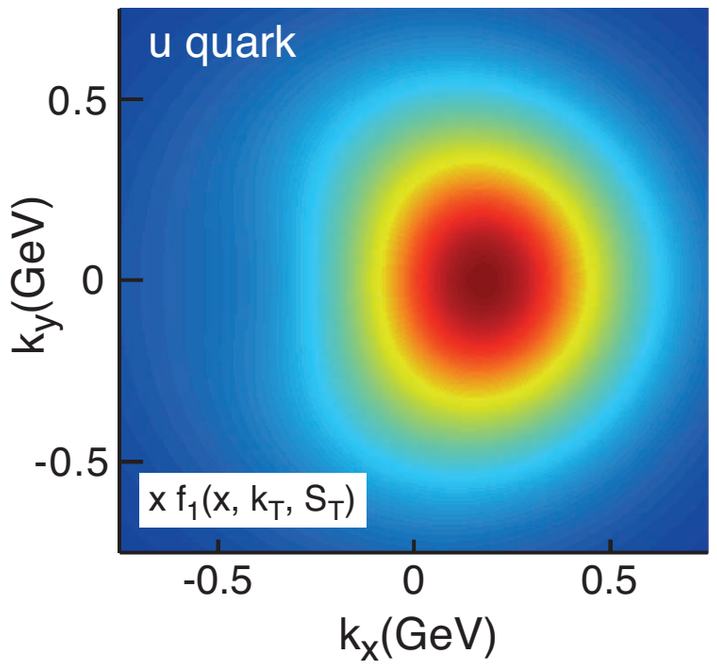


quarks' orbital movement inside the proton creates left-right asymmetry

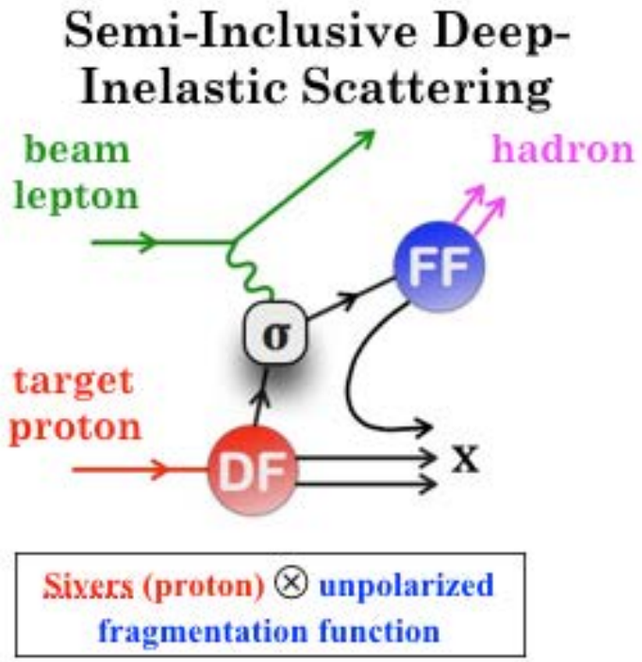
Why it matters

Sivers effect: distortion of quark distribution in transversely polarized proton

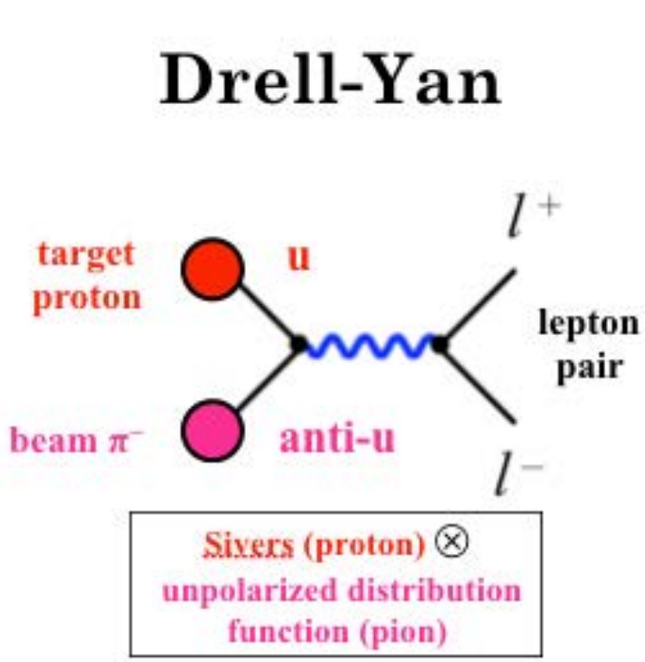




EIC "White Paper" arXiv:1212.1701, based on M. Anselmino et al., J. Phys. Conf. Ser. 295, 012062 (2011), arXiv:1012.3565



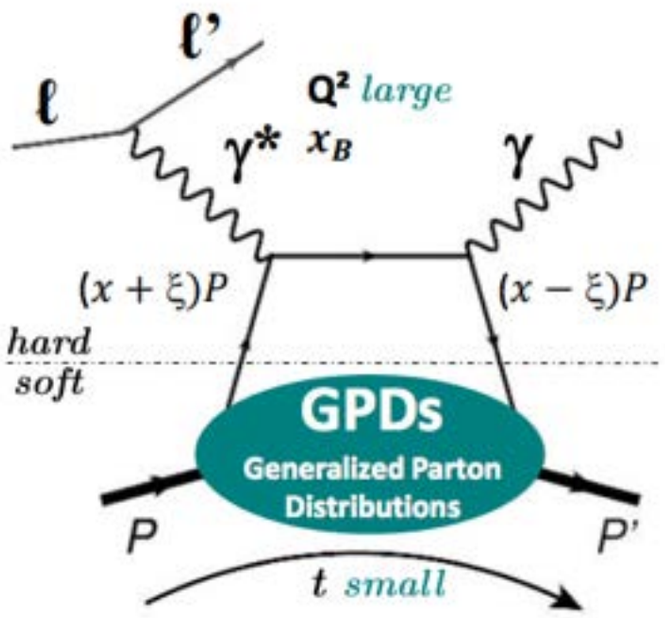
The Sivers function is expected to have the **same magnitude** but **opposite sign** in SIDIS vs. Drell-Yan



Why it matters

Exclusive reactions, hadron multiplicities and spectroscopy

(‘exclusive’ means all particles are detected. Particles made of quarks are called hadrons)

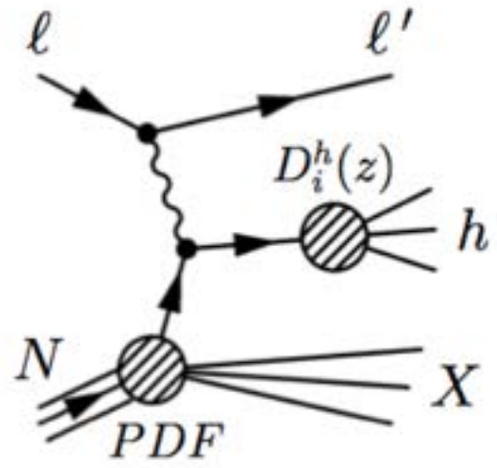


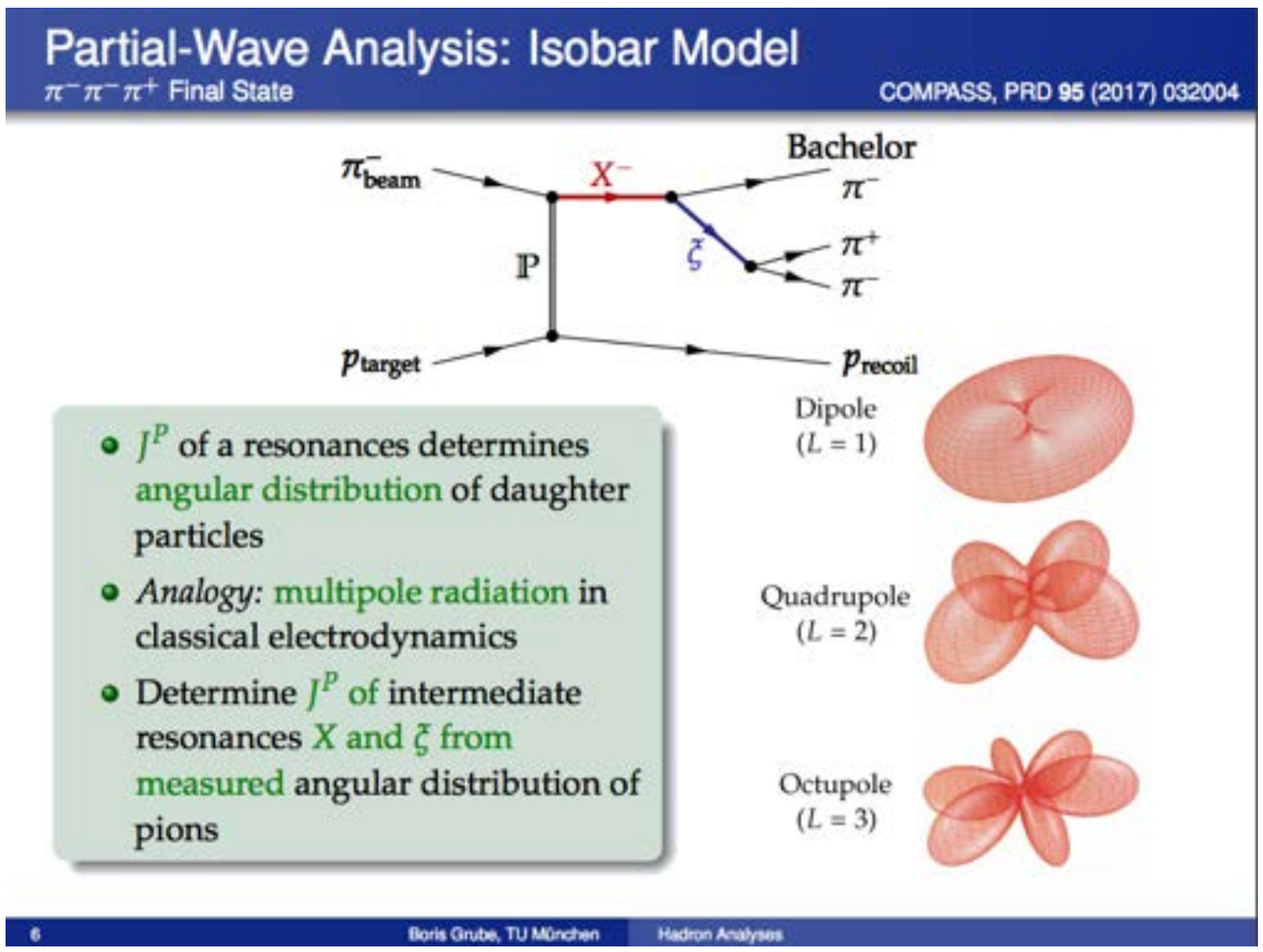
Fragmentation Functions (FFs) :

$$\frac{dM^h(x,Q^2,z)}{dz} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

quark to hadron FFs

quark PDFs

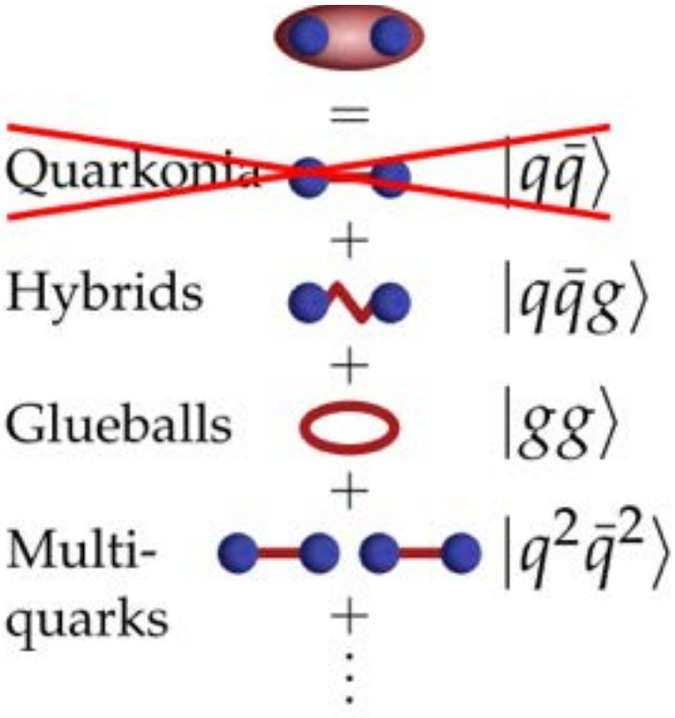




Courtesy A. Vidon/N. D’Hose, N. Pierre, B. Grube

QCD permits color-neutral configurations beyond $q\bar{q}$

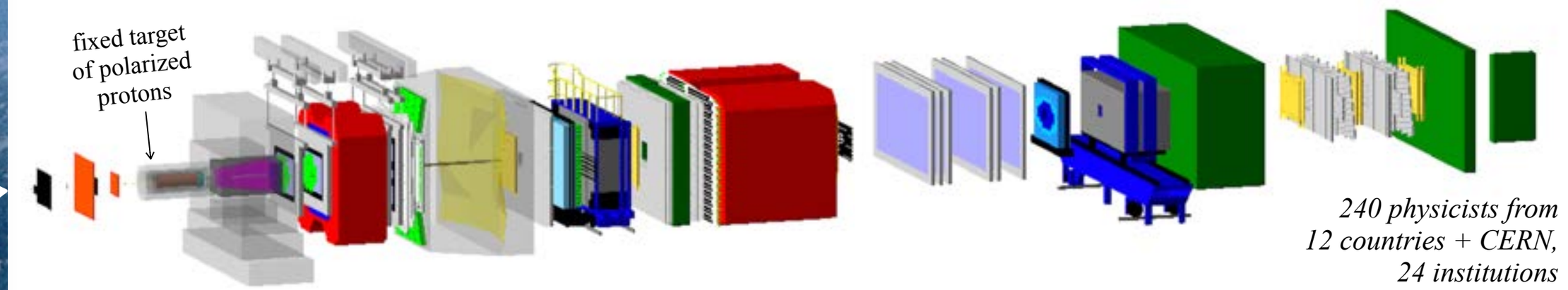
“Exotic” mesons



Why it matters

COMPASS @ CERN

CERN = European Center for Nuclear Research
COMPASS = COmmon Muon Proton Apparatus for Structure and Spectroscopy



240 physicists from
12 countries + CERN,
24 institutions

particle beam

Lake Geneva

COMPASS

France

CERN North Area

Switzerland

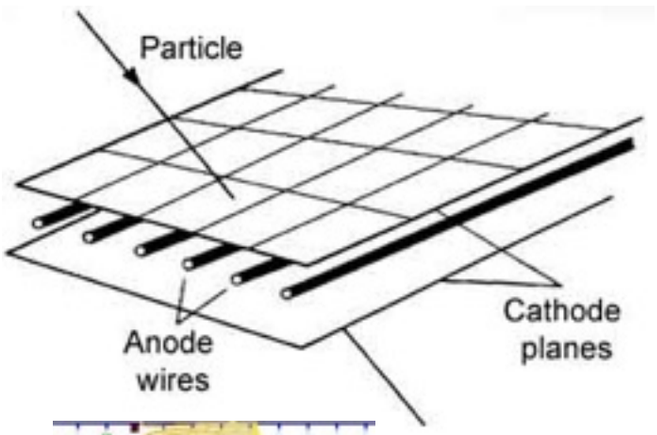
Geneva airport

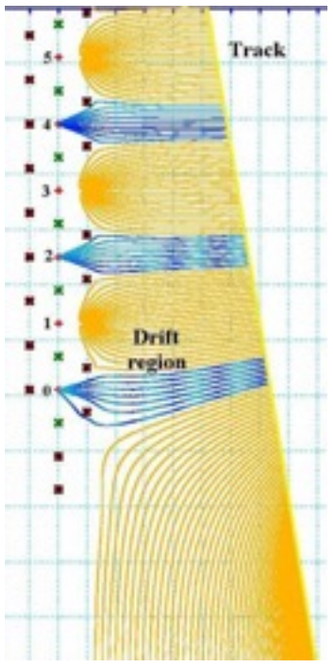
LHC

SPS

Why it matters

Tracking of high-energetic charged particles





Analog signal is amplified & digitized.

~40kilo events recorded per second.

~ 50kilo events written online in
1 file of ~ 1 GB (~ 20 kB / event).

~ 1 petabyte of raw data / year

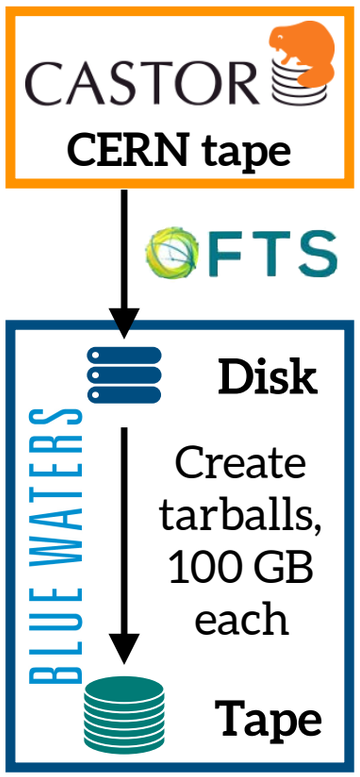
Example: 2015 DY	real data	simulated data
alignment periods	9	2
number of events [all M]	38,500 M	12,800 M
number of events [M>2GeV]	**41 M**	**12,800 M**
file size	1 GB	5 GB
total volume	750 TB	165 TB
files	770,000	33,000
file type	raw	GEANT

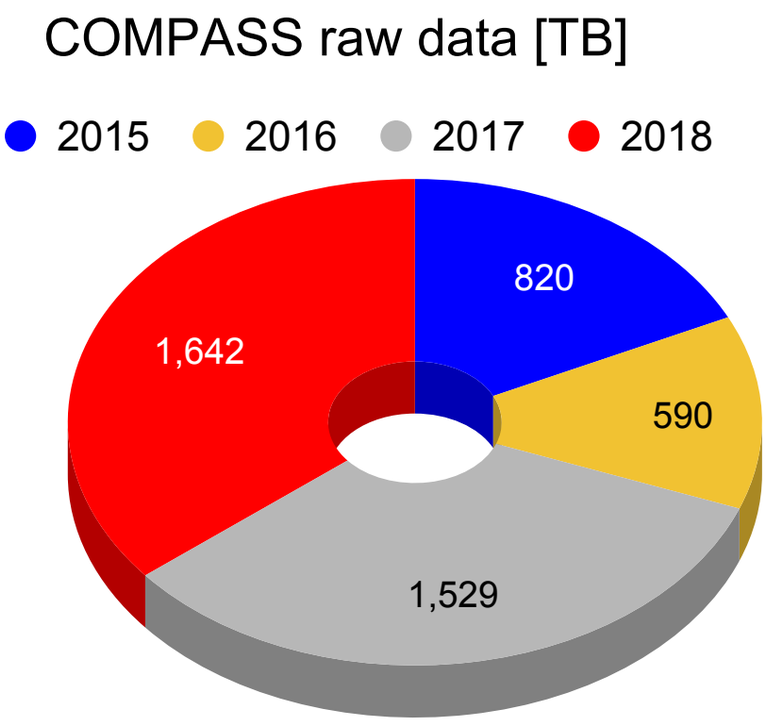
Accomplishments

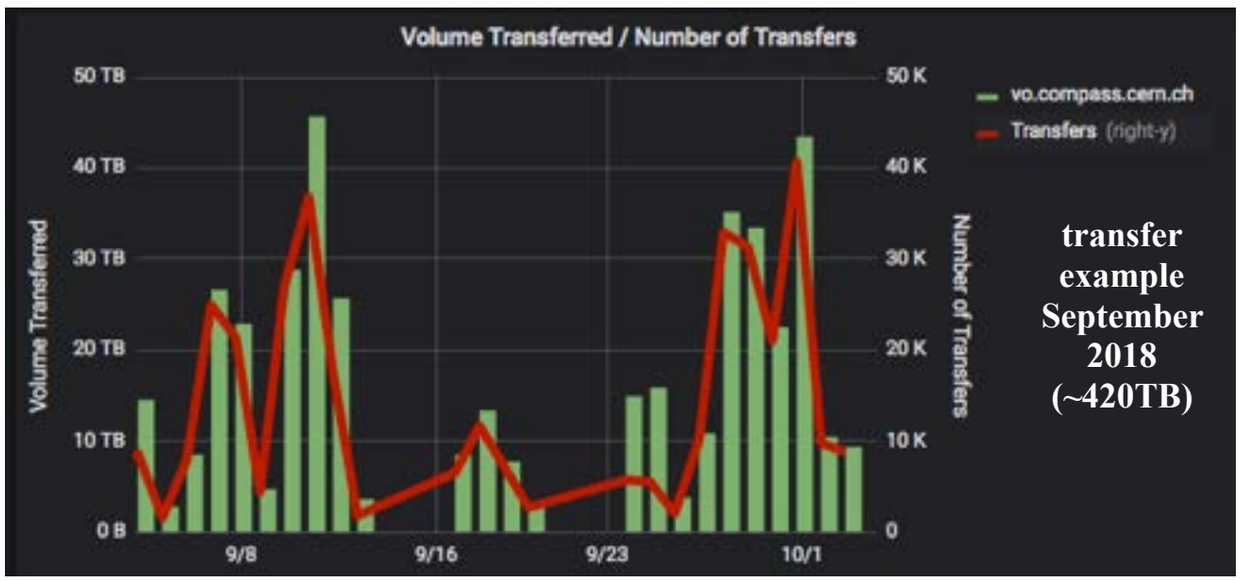
COMPASS data transfer to Blue Waters

C. Riedl

- Transferred ~ 3 petabytes of raw COMPASS data from CERN to BW, ~ 3 million files of ~ 1GB
- Transferred BW-produced DSTs (~1/10 reduction factor) back to CERN
- Using FTS3 **(File Transfer System)**: bulk data mover created to globally distribute LHC data. FTS3 effectively uses globus-url-copy.







transfer example September 2018 (~420TB)

1 data period = 2 weeks of data taking

raw dy15	[TB]	chunks
W07	104	97,766
W08	104	98,067
W09	112	105,450
W10	85	80,188
W11	138	129,467
W12	96	89,995
W13	84	78,970
W14	57	53,978
W15	40	37,234

raw dvcs2016	[TB]	chunks
W06 (P01)	28	27,332
W07 (P02)	57	53,711
W08 (P03)	60	57,467
W09 (P04)	60	57,661
W10 (P05)	55	51,919
W11 (P06)	57	54,473
W12 (P07)	70	66,080
W13 (P08)	77	72,444
W14 (P09)	62	58,533
W15 (P10)	64	60,608
W16 (P11)	14	13,652

raw dy18		[TB]	chunks
dy18W01	P0	214	200,312
dy18W02	P0	116	108,693
dy18W03	P1	65	60,931
dy18W04	P1	62	58,422
dy18W05	P2	49	45,533
dy18W06	P2	71	66,655
dy18W07	P2	79	73,675
dy18W08	P2	55	51,807
dy18W09	P3	100	93,428
dy18W10	P3	78	72,869
dy18W11	P4	53	49,305
dy18W12	P4	48	45,398
dy18W13	P4	82	77,048
dy18W14	P5	64	60,146
dy18W15	P5	47	43,748
dy18W16	P6	59	55,418
dy18W17	P6	65	60,551
dy18W18	P7	71	67,077
dy18W19	P7	77	72,380
dy18W20	P7	52	48,401
dy18W21	P7	51	48,084
dy18W22	P8	55	50,951
dy18W23	P8	29	27,248

Sketches courtesy R. Longo (poster at this symposium)

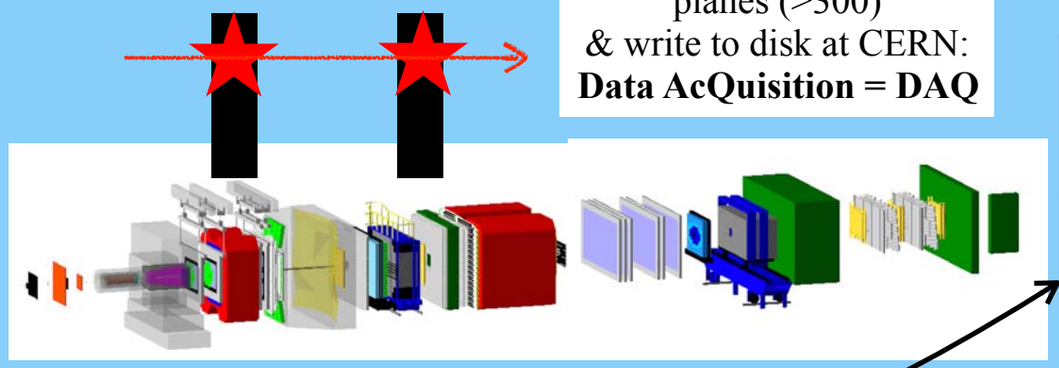
Why it matters

COMPASS data productions on Blue Waters

R. Longo,
M. Meyer

RD (Real Data)

If coincident signal in trigger detectors: Read out all detector planes (>300) & write to disk at CERN: **Data AcQuisition = DAQ**

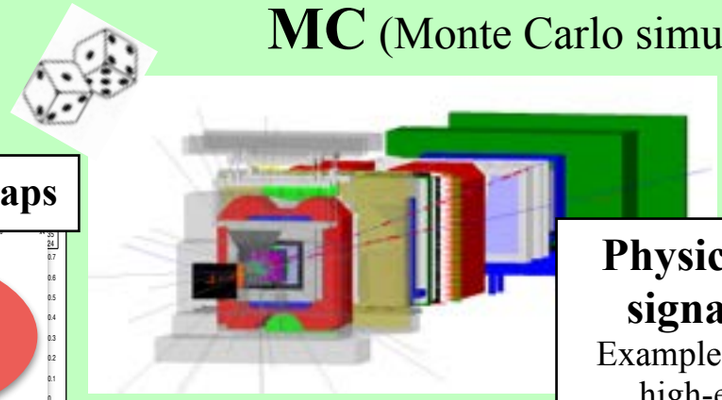


raw data

Calibration: physical energy deposits in detectors

mySQL DB

MC (Monte Carlo simulation)

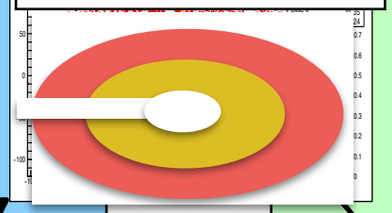


Physics event generator signal & background
Example PYTHIA: generation of high-energy physics events
http://home.thep.lu.se/Pythia

GEANT4
Toolkit for the simulation of the passage of particles through matter
http://geant4.web.cern.ch

CPU intensive part

2D efficiency maps

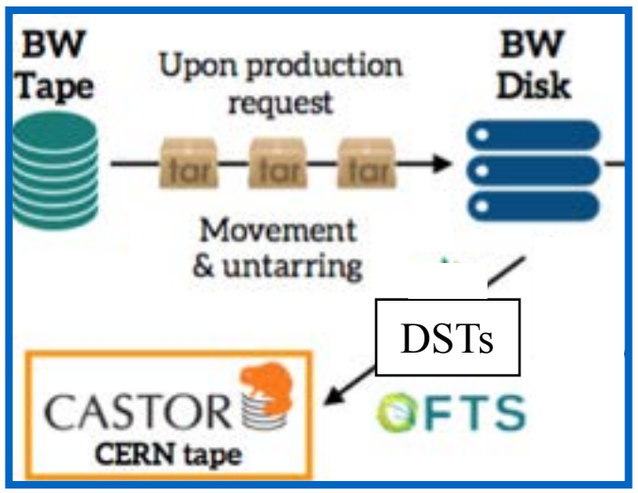


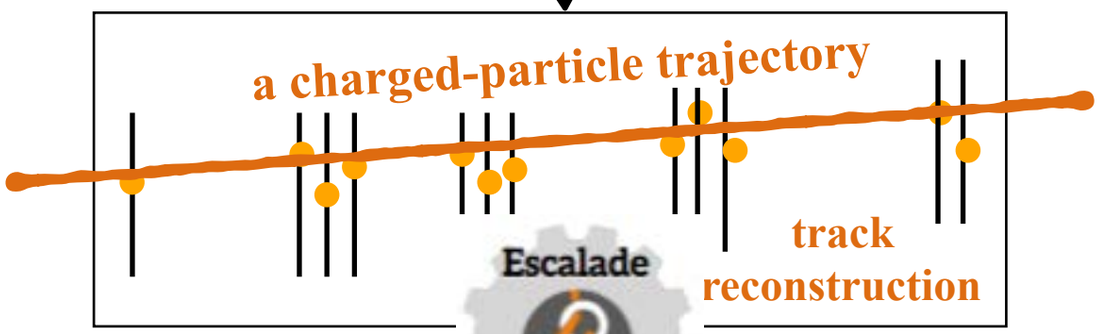
Alignment: spatial hits in detectors

CORAL = COmpass Reconstruction Analysis Library

if RD

if MC





Escalade
Production System

DSTs
(skimmed Data Summary Trees)
factor 5-10 reduction

User analysis

Simulations of the detectors play a central role in understanding subtle detector effects and removing background events from the data sample.

Submissions to BW grid: real data

R. Longo

- Calibration data base (Db) is copied to one dedicated node, from where the tasks are dispatched and terminated (MPI-based code)
- Then do not need connected nodes:
  `#PBS -l flags=commtransparent`

A. Copy only MySQL calibrations (data folder) to the node.
B. Start database on **Rank 0** with the local calibrations. Wait buffer time (2 min) for Db for run.
C. **Rank 0** dispatches up to 31 executions (fed via a command list, as for pcp) to remaining **31 Ranks (1 - 31).**
D. Each Rank **(1 - 31)** sends back a **termination signal** to Rank 0 once execution is finished.
E. Once **Rank 0** has collected all **termination signals**, the Db is shut down and execution on the node is terminated.

1 **node** = 32 CPUs:
•1 **Db;**
•31 **chunks processed;**

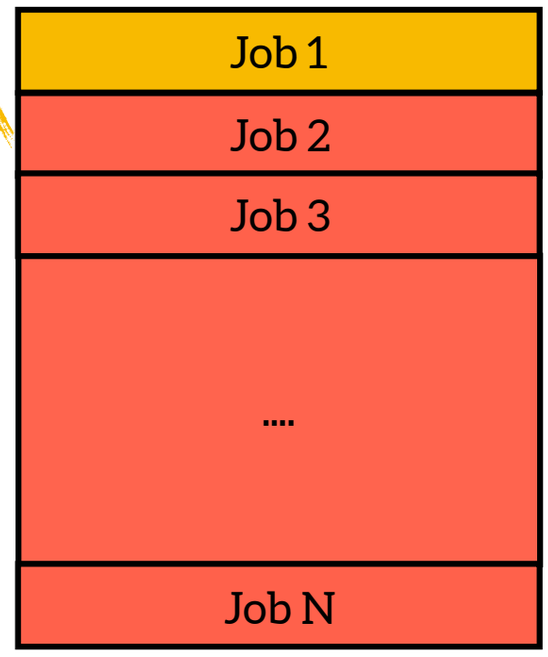
1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16
17	18	19	20
21	22	23	24
25	26	27	28
29	30	31	32

1 **job** =
100 **nodes** =
3100 chunks

1	2	3	…
….			
…	98	99	100

#PBS -l flag=commtransparent

1 **period**:
•N ~25 jobs (2015);
•N ~50 jobs (2018);



Sketches courtesy R. Longo (poster at this symposium)

Accomplishments

Mapping Proton Quark Structure: projects 2018/19

student
postdoc
senior

Drell-Yan

R. Longo (UIUC)
- Analysis of transverse-target-spin asymmetry Drell-Yan for DIS2019

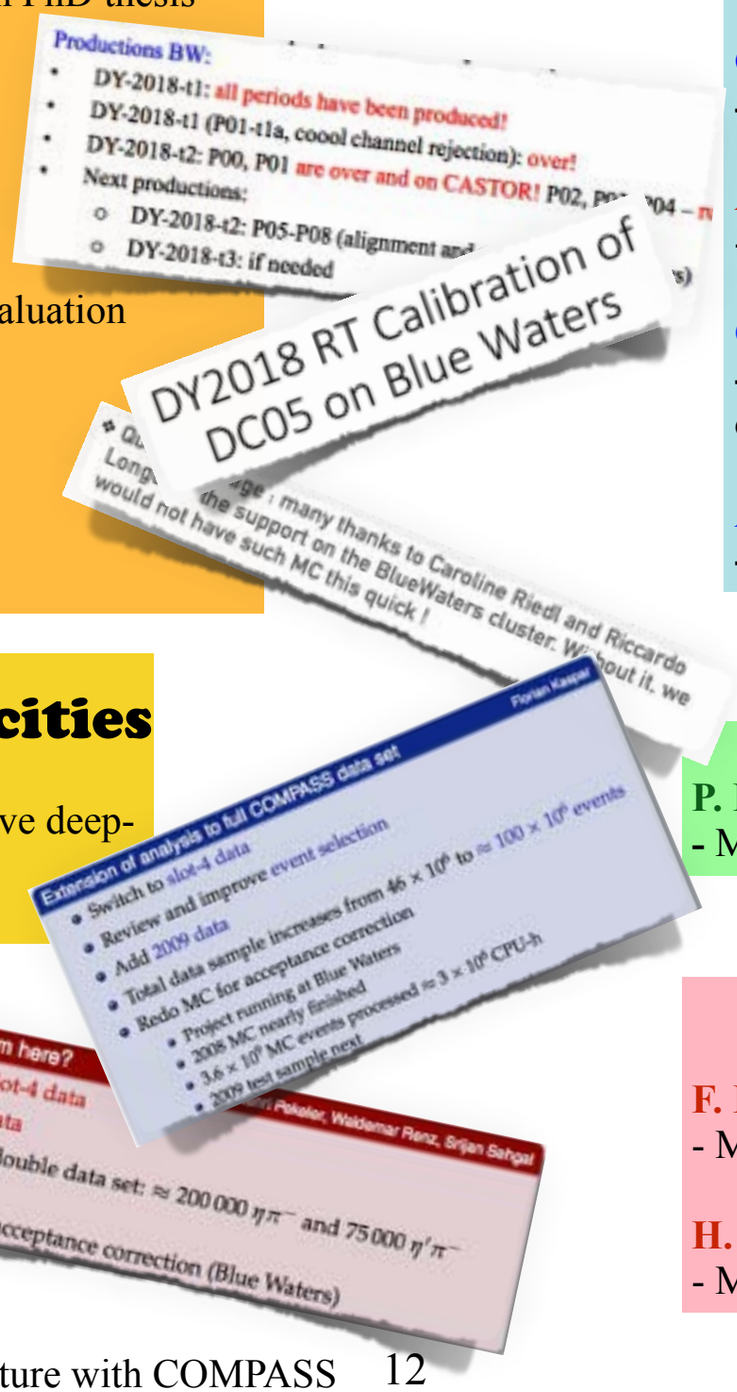
R. Heitz (UIUC)
- Analysis of left-right asymmetry in Drell-Yan with PhD thesis May 2019

C. Naim, M. Meyer (CEA-Saclay, France)
- MC simulation for Drell-Yan

C. Naim (CEA-Saclay, France)
- Tuning of Drell-Yan/JPsi MC for cross-section evaluation

M. Meyer (UIUC and CEA-Saclay, France)
- Analysis of Drell-Yan cross section

A. Gridin (JINR Dubna, Russia)
- Analysis of double J/psi production



Technical

R. Longo (UIUC)
- Real data productions of 2018 and 2015 data
- 2-dimensional detector efficiency maps 2015/18 data

A. Koval (University of Warsaw, Poland)
- 2-dimensional detector efficiency maps (2016 data)

C. Franco (LIP, Portugal)
- Machine learning techniques to tag Drell-Yan events

A. Futch (UIUC)
- Illinois drift chamber calibration & resolution

C. Riedl (UIUC)
- Raw data transfer from CERN and taring for storage on BW Nearline

A. Maggiora (INFN Torino, Italy)
- Radio Protection simulations for 2018 Drell-Yan run

Hadron Multiplicities

N. Pierre (CEA-Saclay, France)
- MC simulation of radiative effects in semi-inclusive deep-inelastic scattering (acceptance correction for multiplicities)

Exclusive

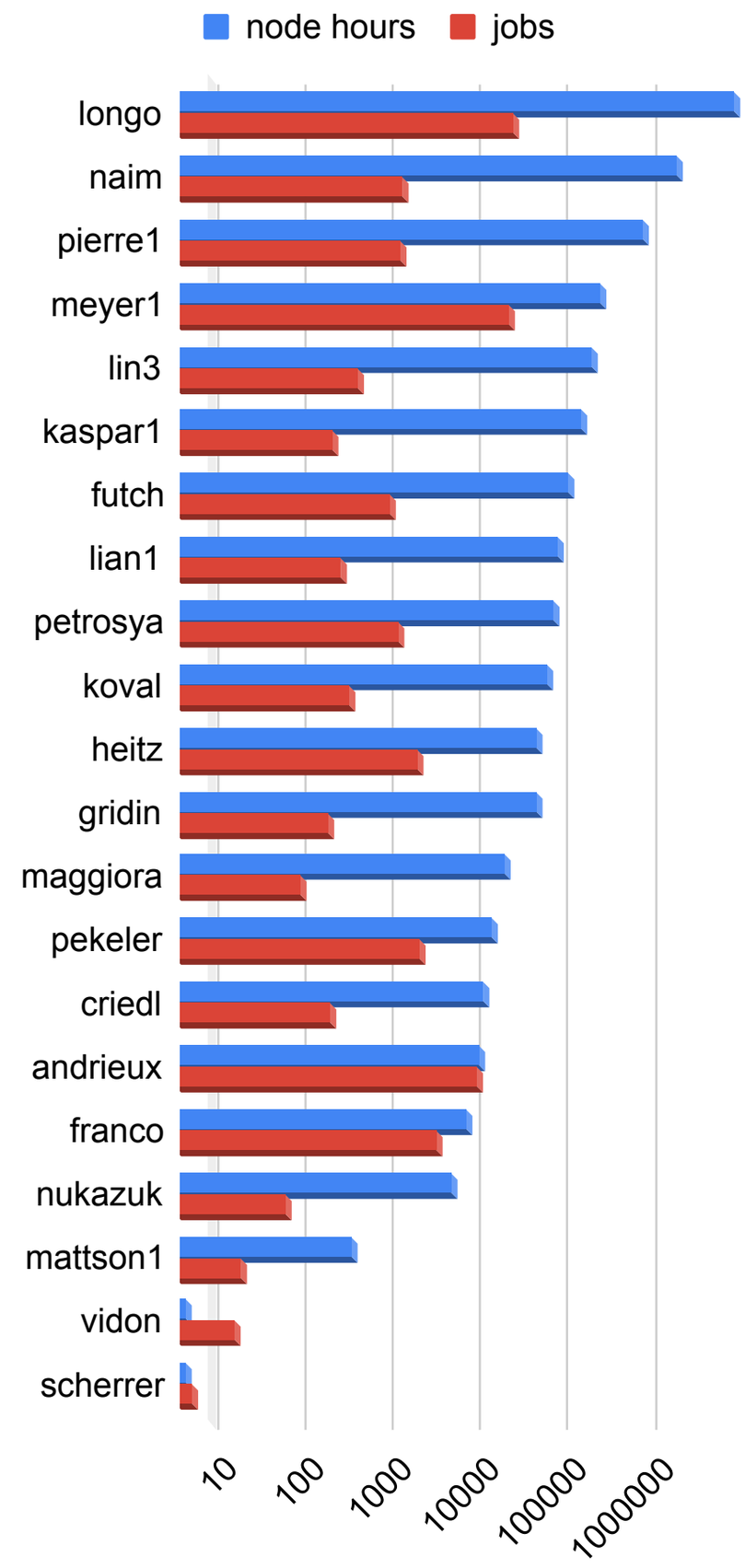
P. Lin (CEA-Saclay, France)
- MC simulation for hard exclusive processes, DVCS/GPD

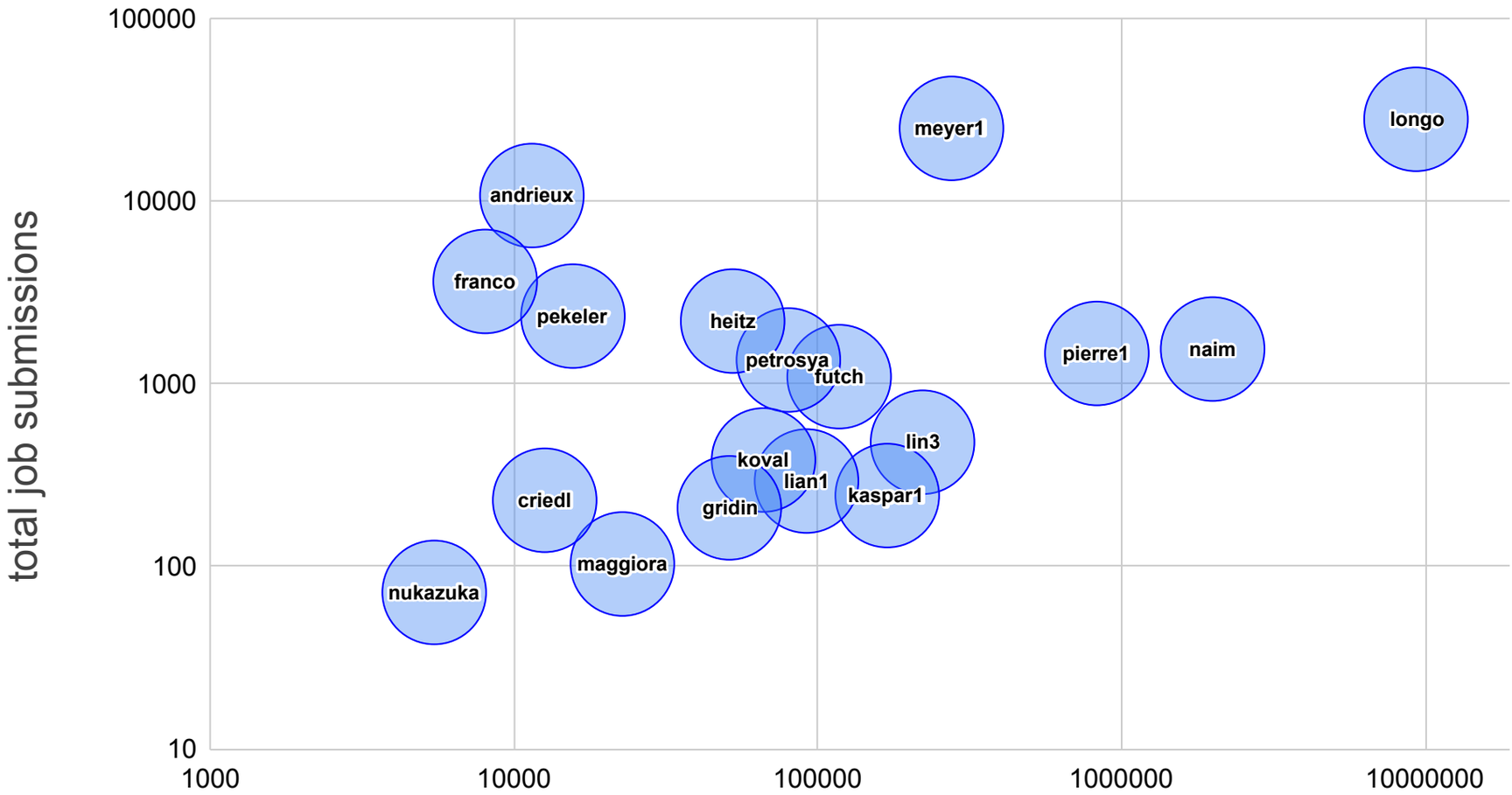
Hadron Spectroscopy

F. Kaspar (University of Munich, Germany)
- MC simulation for hadron spectroscopy $\pi p \rightarrow \pi\pi\pi p$

H. Pekeler (University of Bonn, Germany)
- MC simulation for hadron spectroscopy $\rightarrow \pi\eta$

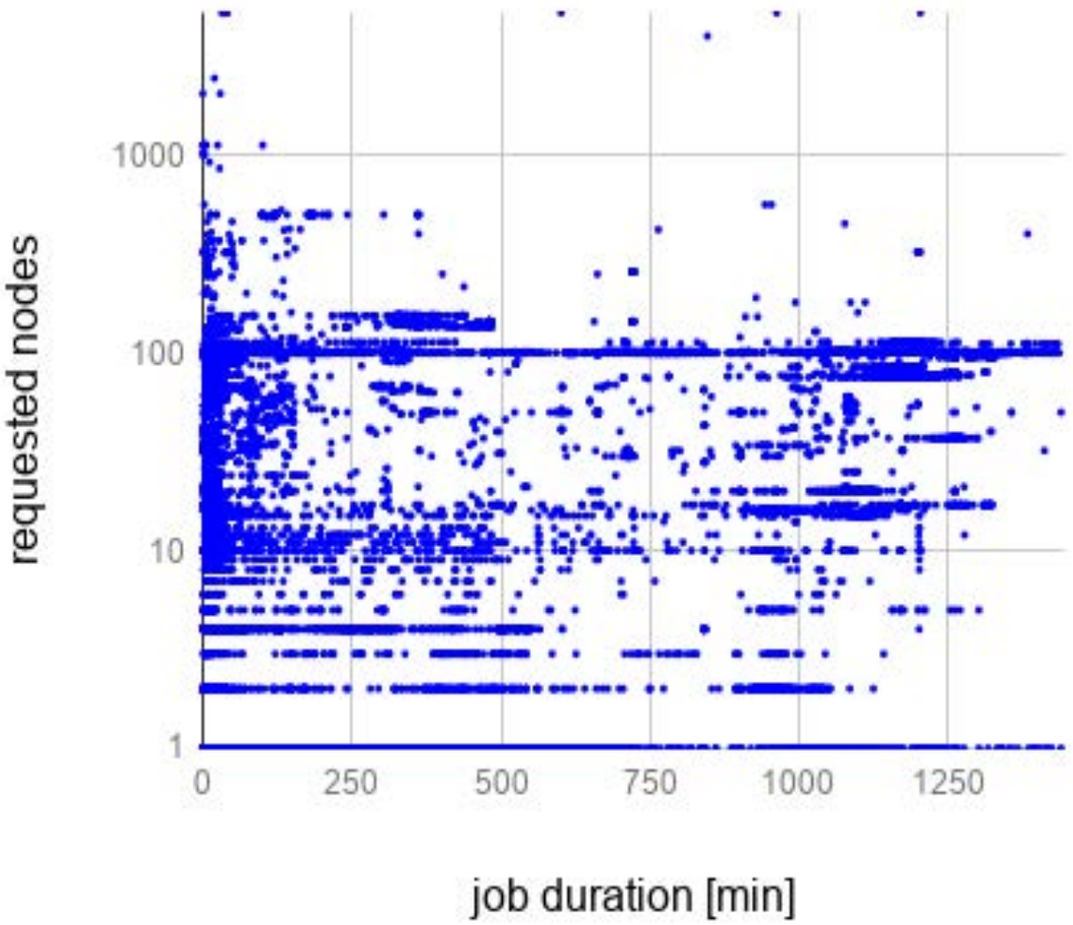
Mapping Proton Quark Structure: users

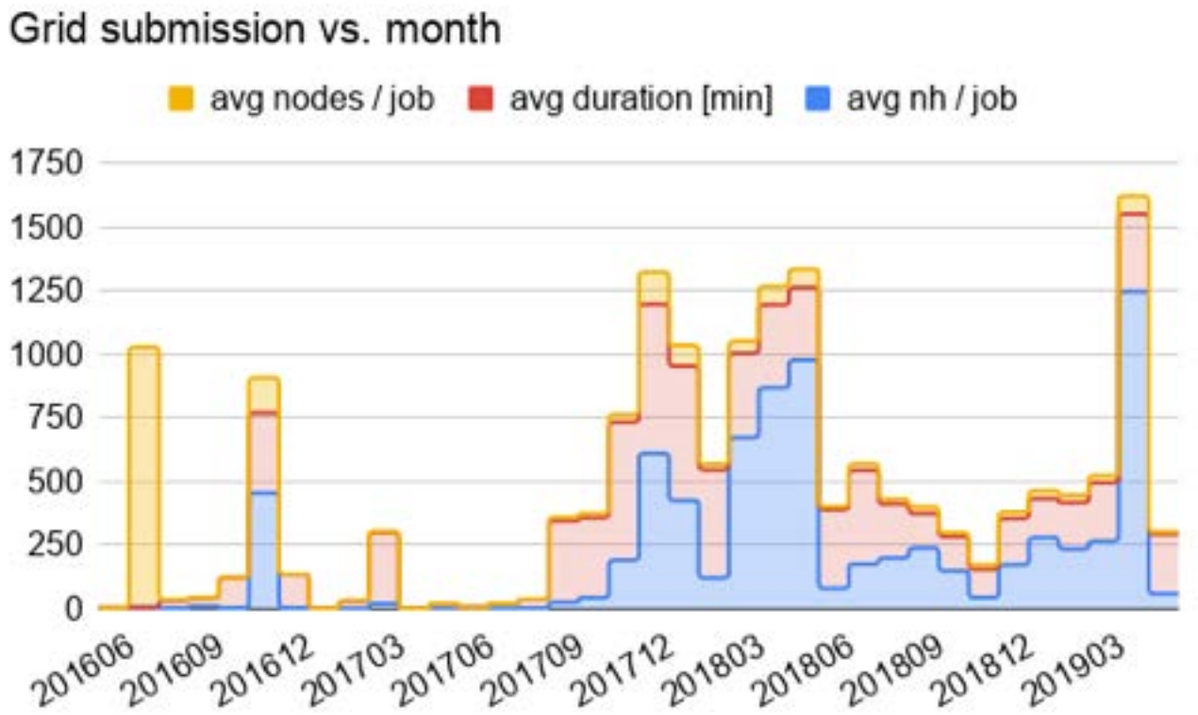


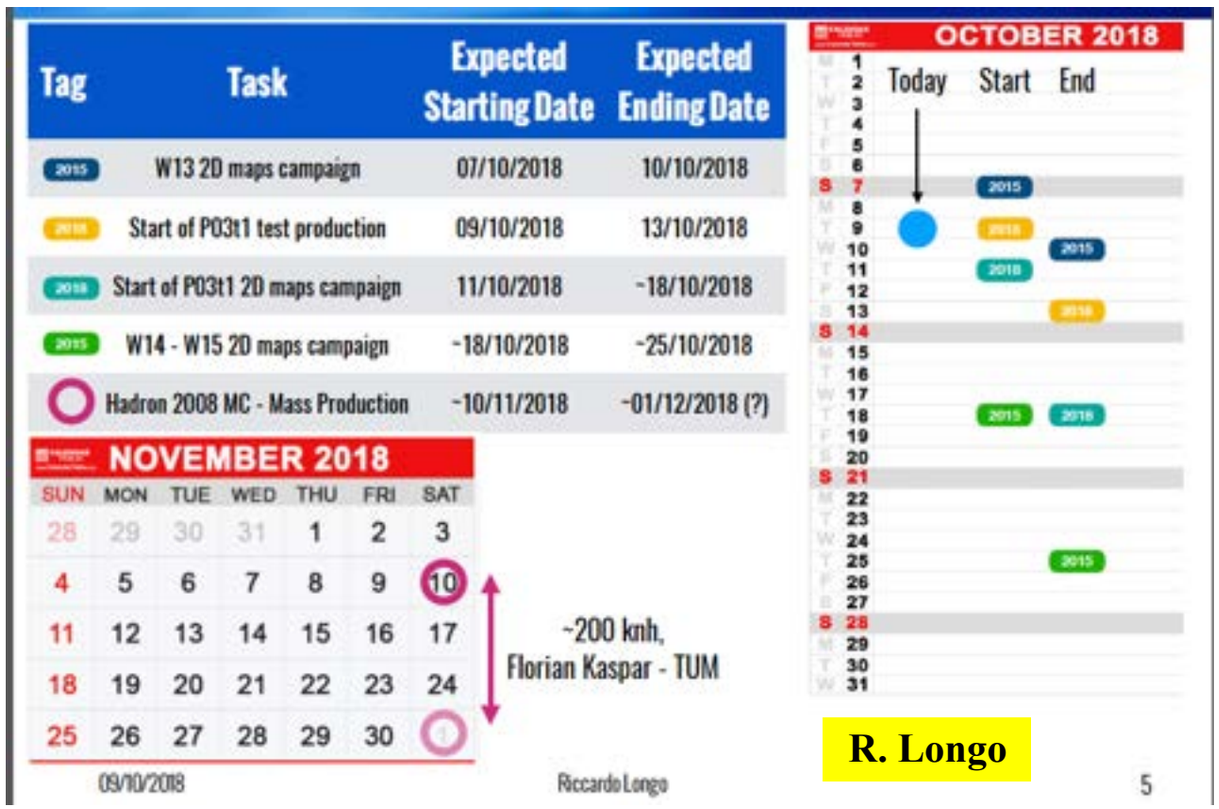


node hours per data year	data production	detector efficiency maps
2018	9x 75k	3x 450k
2015	5x 40k	9x 300k
2016	-	1x 220k

Mapping Proton Quark Structure - grid submission & planning







R. Longo

Products

Products from this Blue-Waters project

- **Software and coordination:**
  - Adaption of COMPASS software (R. Longo, M. Meyer).
  - COMPASS-specific job framework (escalade) and job templates (M. Meyer).
  - Coordination of computing project with ~ 25 accounts (C. Riedl, R. Longo).
    - Dedicated mailing list for COMPASS users @ BW
    - Detailed documentation on University-of-Illinois Twiki
    - Working meeting and tutorials

- **Effective changes**
  - Improvement of radiation shielding for COMPASS 2018 run, and consequently enabling higher beam intensity and higher statistical precision of real data at the end of the day (A. Maggiora & CERN radio protection).

- **Public results**
  - Preparation and post-production of **2018 COMPASS run:**

Maggiora RP simulations,
Riedl COMPASS technical coordinator & data transfer to BW,
Andrieux COMPASS run coordinator,
Futch calibration and resolution of Illinois-built drift chamber,
Longo production manager and physics analyzer,
Meyer production system ‘escalade’.

“All-round care package” for COMPASS 2018 DY run from synergetic energy of Blue Waters and our team

- Unprecedentedly fast release of physics result after end of 2018 data taking campaign (~ half year)
- Data production and analysis on Blue Waters (R. Longo)
- 8 talks given at international conferences or workshops, 1 PhD thesis

Products

Public results from this project

- COMPASS Status Report at the June 2018 SPSC meeting, COMPASS spokespersons, CERN, Switzerland. https://indico.cern.ch/event/730078/contributions/3008244/attachments/1663286/2665890/COMPASS_SPSC_20180607.pdf

- Pion-induced Drell-Yan scattering at COMPASS, C. Riedl, talk given at the 23rd international Spin symposium 2018, Ferrara, Italy, 9-14 September 2018. https://agenda.infn.it/event/12464/contributions/14197/

- HPC at COMPASS: The Blue-Waters project, R. Longo, CERN PRACE workshop, Switzerland, October 22, 2018. https://indico.cern.ch/event/760705/contributions/3156790/attachments/1738511/2812780/COMPASS_HPC_BlueWaters.pdf

- Transversely polarized Drell-Yan measurement, B. Parsamyan, talk given at the XXVII International Workshop on Deep Inelastic Scattering and Related Topics (DIS 2019), April 8-12, 2019, Torino, Italy. https://indico.cern.ch/event/749003/contributions/3336232/

- Measurement of qT-weighted transverse-spin-dependent azimuthal asymmetries at COMPASS, R. Longo, talk given at the XXVII International Workshop on Deep Inelastic Scattering and Related Topics (DIS 2019), April 8-12, 2019, Torino, Italy. https://indico.cern.ch/event/749003/contributions/3336279/

- Kaon multiplicities in SIDIS from COMPASS, N. Pierre, talk given at the XXVII International Workshop on Deep Inelastic Scattering and Related Topics (DIS 2019), April 8-12, 2019, Torino, Italy. https://indico.cern.ch/event/749003/contributions/3336221/

- Exclusive single-photon muonproduction at COMPASS, A. Vidon, talk given at the XXVII International Workshop on Deep Inelastic Scattering and Related Topics (DIS 2019), April 8-12, 2019, Torino, Italy. https://indico.cern.ch/event/749003/contributions/3336219/

- GPDs with COMPASS at CERN, N. D'Hose, talk given at the 8th workshop of the APS topical group on Hadron Physics, April 10-12, 2019, Denver. https://www.jlab.org/indico/event/282/session/20/contribution/132/material/slides/0.pdf

- Transverse momentum dependent nucleon structure from pions impinged on a transversely polarized proton target, R. Heitz, PhD Dissertation, University of Illinois at Urbana-Champaign, May 2019.

This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work is also part of the "Mapping Proton Quark Structure using Petabytes of COMPASS Data" PRAC allocation supported by the National Science Foundation (award number **OCI 1713684**).

DIS 2019 TORINO 8-12 April

BW @ DIS

CORRECTIONS TO DATA : ACCEPTANCE AND SMEARING

Correction for the limited geometrical acceptance, reconstruction and detector inefficiencies as well as resolutions.

Reconstructed multiplicities

Kinematic bin determined using reconstructed values

$$A(x,y,z) = \frac{M^h_{rec}}{M^h_{gen}} = \frac{N^h_{rec}(x_{rec},y_{rec},z_{rec})/N^{DIS}_{rec}(x_{rec},y_{rec})}{N^h_{gen}(x_{gen},y_{gen},z_{gen})/N^{DIS}_{gen}(x_{gen},y_{gen})}$$

Generated multiplicities

Kinematic bin determined using generated values

MC technical features :

- Events are generated with the DJANGOH generator (LEPTO + radiative events, SOPHIA for low energy hadronic final state, LUND MODEL, ARIADNE for parton cascade. http://www.thep.physik.uni-mainz.de/~hspiesb/djangoh/djangoh.html)
- JETSET package for parton hadronization with COMPASS high-pT tuning
- Spectrometer simulated using TGEANT based on GEANT4.

This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work is also part of the "Mapping Proton Quark Structure using Prototype of COMPASS Data" PRAC allocation supported by the National Science Foundation (award number OCI 1713684).

N. Pierre - DIS 2019 — April 9, 2019

Conclusions

- COMPASS is investigating the TMD PDFs in SIDIS and DY also using weighted asymmetries;
- q_T-weighted asymmetries in Drell-Yan have been extracted from the full 2015 dataset and from ~50% of 2018 data;
- 2018 analysis is ongoing, final results are expected to be released by autumn;

Thank you for your attention!

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Riccardo Longo — 25 — 5/04/2019

COMPASS 2018 data production and analysis

- About 1.8 PB data was collected during ~5 months of data taking
- A special care was taken to ensure stable detector conditions during the data-taking
- Already during the run the data started to be transferred to the Blue Waters supercomputer storage system (NCSA, US)
- Between December 2018 and March 2019 two full mass data-productions were performed at Blue Waters
- About ~50% of data was considered to be ready for the physics analyses
- For the remaining 50% some further alignment and calibration fixes are needed

BLUE WATERS

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COMPASS 2016 insight

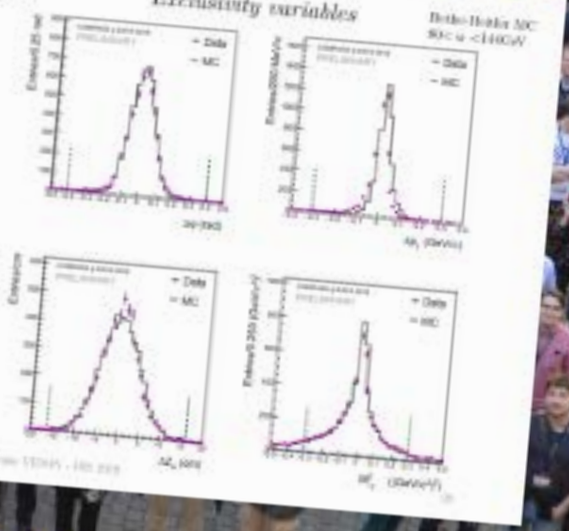
$$\Delta p_T = p_T^{rec} - p_T^{gen}$$

$$\Delta\varphi = \varphi^{rec} - \varphi^{gen}$$

$$\Delta z_\Lambda = z_\Lambda^{rec} - z_\Lambda^{gen}$$ and vertex

$$M^2_{\Lambda\to p} = (p_{\mu_{in}} + p_{\mu_{out}} - p_{\gamma_{out}} - p_p)^2$$

Exclusivity variables



BLUE WATERS

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Conclusions

- During phase I COMPASS has measured all possible SIDIS azimuthal LSAs and TSAs.
  - The Sivers and Collins SIDIS-TSAs were measured to be non-zero in particular at the Q^2-interval corresponding to the Drell-Yan "high-mass range": PLB 770 (2017) 138
- In 2017 COMPASS has published the results for the first polarized DY measurements: PRL 119, 112002 (2017)
- The second year of polarized DY data-taking was performed in 2018
- The analysis of 2018 data is ongoing (~50% of the data has already been analyzed)
- Final results are expected to be out for autumn conferences

Thank you!

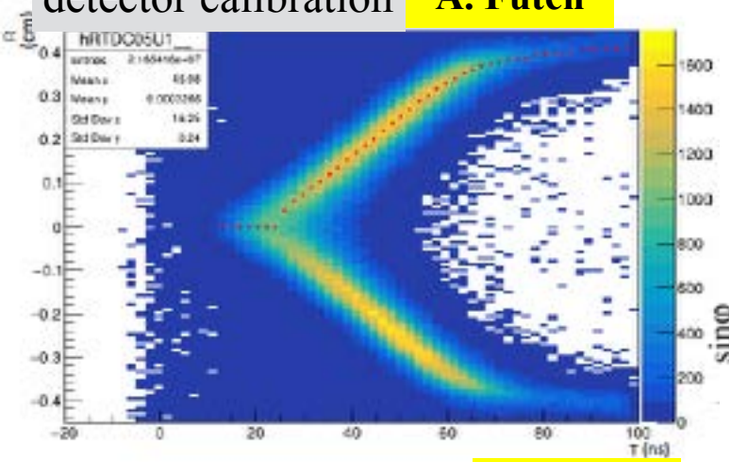
BLUE WATERS

4 COMPASS talks with BW acknowledgements

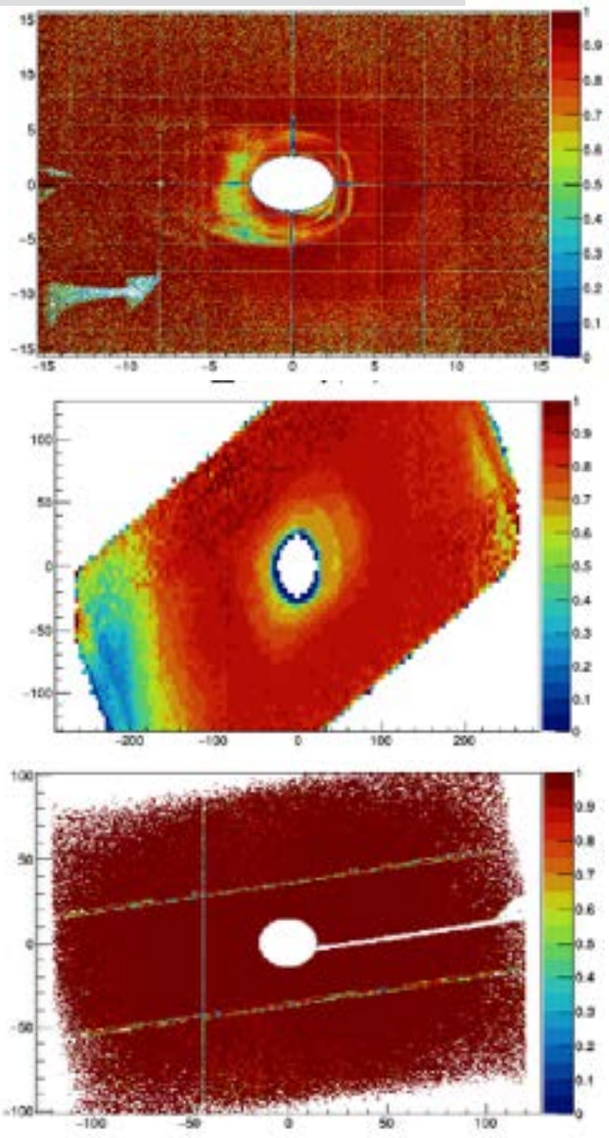
Products

Selected results from Blue Waters

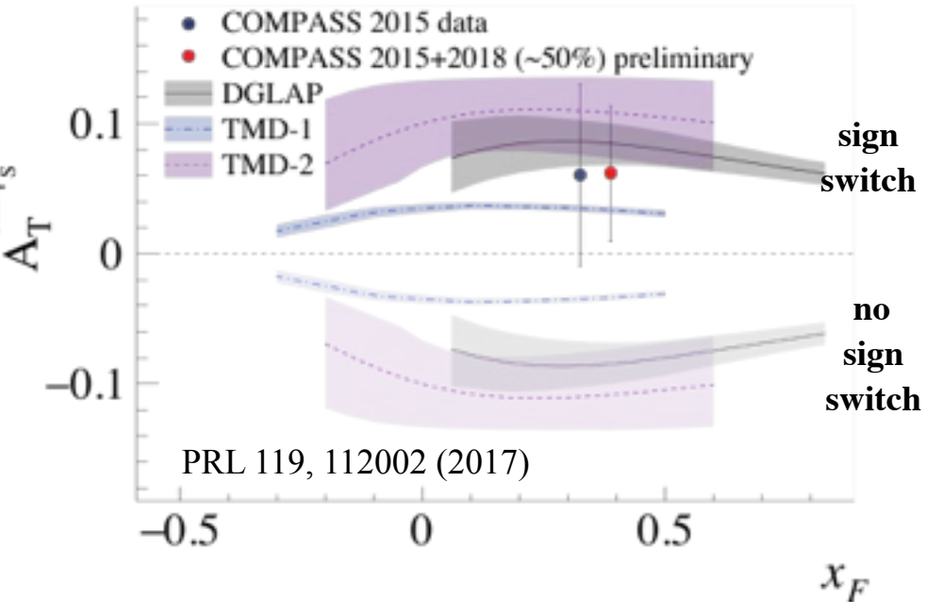
detector calibration **A. Futch**



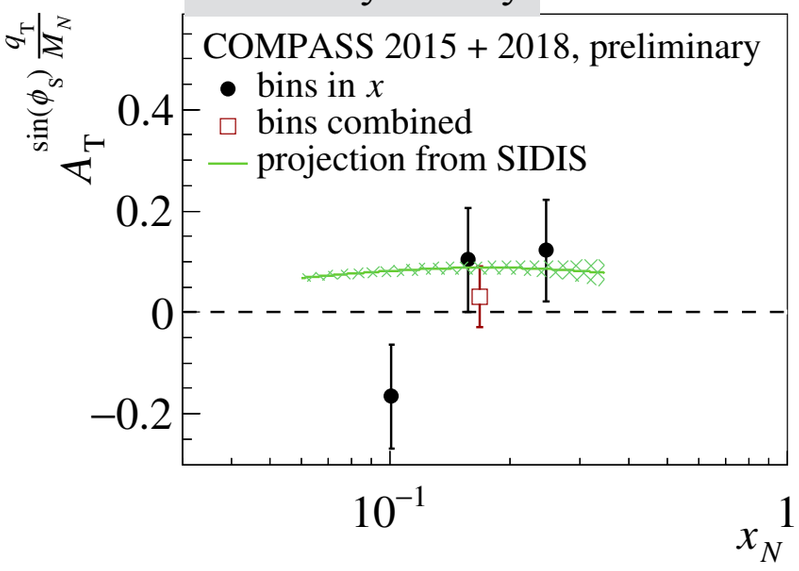
detector efficiency maps **R. Longo**



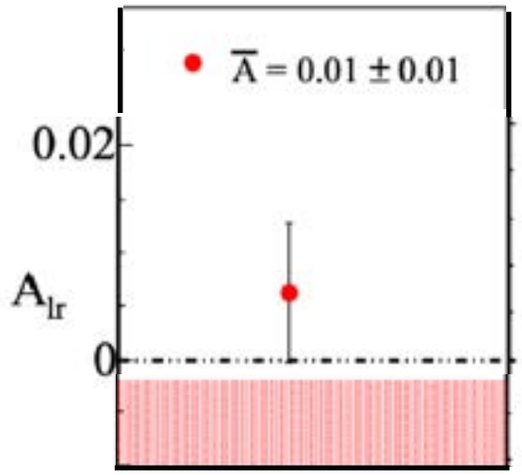
Drell-Yan Sivers asymmetry **R. Longo et al.**

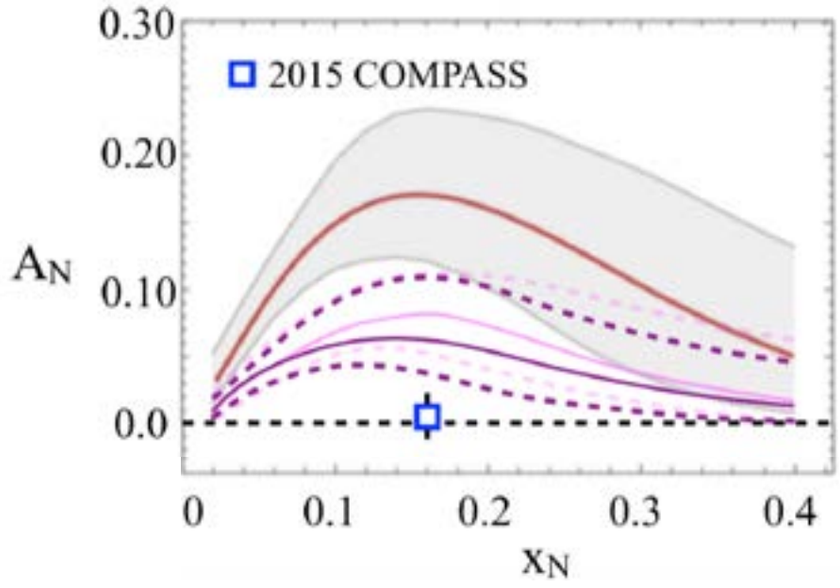


qT weighted Sivers asymmetry **R. Longo**

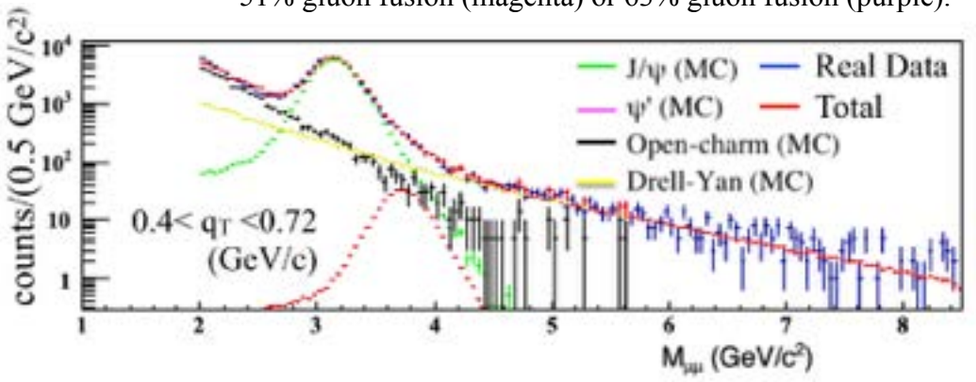


Left-right asymmetry in J/Psi production **R. Heitz**





Theory curves from Anselmino, Barone, Boglione, PLB770:302, 2017 assuming no gluon contamination (gray), 51% gluon fusion (magenta) or 63% gluon fusion (purple).



Why Blue Waters?

- Preparation of 2018 COMPASS result for spring 2019 conference

- Simulation of realistic pile-up (~100ns) - *increases CPU time by factor of 3*
- Radio protection studies for 2018 COMPASS run

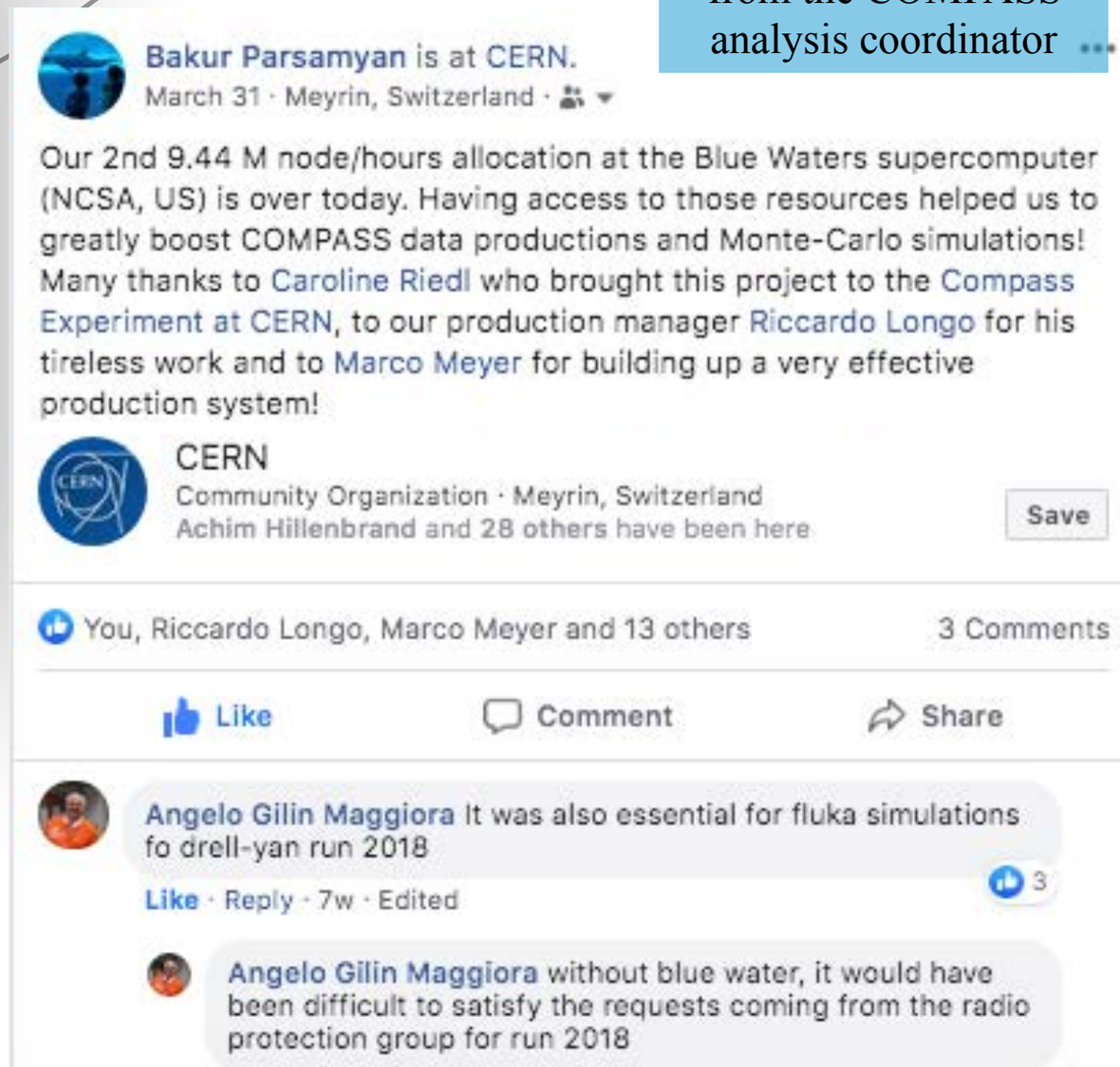
☑ **Unprecedented speed**: allows to complete physics analyses in a timely manner
- PhD theses with well-defined time frames
- Before the end of the collaboration's "Memorandum of Understanding"

☑ **Unprecedented precision**: allows to simulate larger MC samples to keep systematic uncertainties at smallest possible level.

☑ **Novel exploration**: certain studies could not be done at all.

- Detector efficiency maps
- Detector resolutions over time

At the end of the PRAC allocation: a message from the COMPASS analysis coordinator



Broader Impact & Shared Data

Broader Impact and Sharing of Data

- **Broader Impact**

  - ***Outstanding educational potential*** for a significant number of students and postdocs towards building a community capable of using petascale computing.

  - ***NSAC milestone***: the Nuclear Science Advisory Committee has designated a measurement of the process dependence of the Sivers functions as one of its few performance milestones for DOE- and NSF-funded research in nuclear physics.

    The Frontiers of Nuclear Science: A Long-Range Plan, The DOE/NSF Nuclear Science Advisory Committee Working Group, December 2007, arXiv:0809.3137.

- **Sharing of Data**

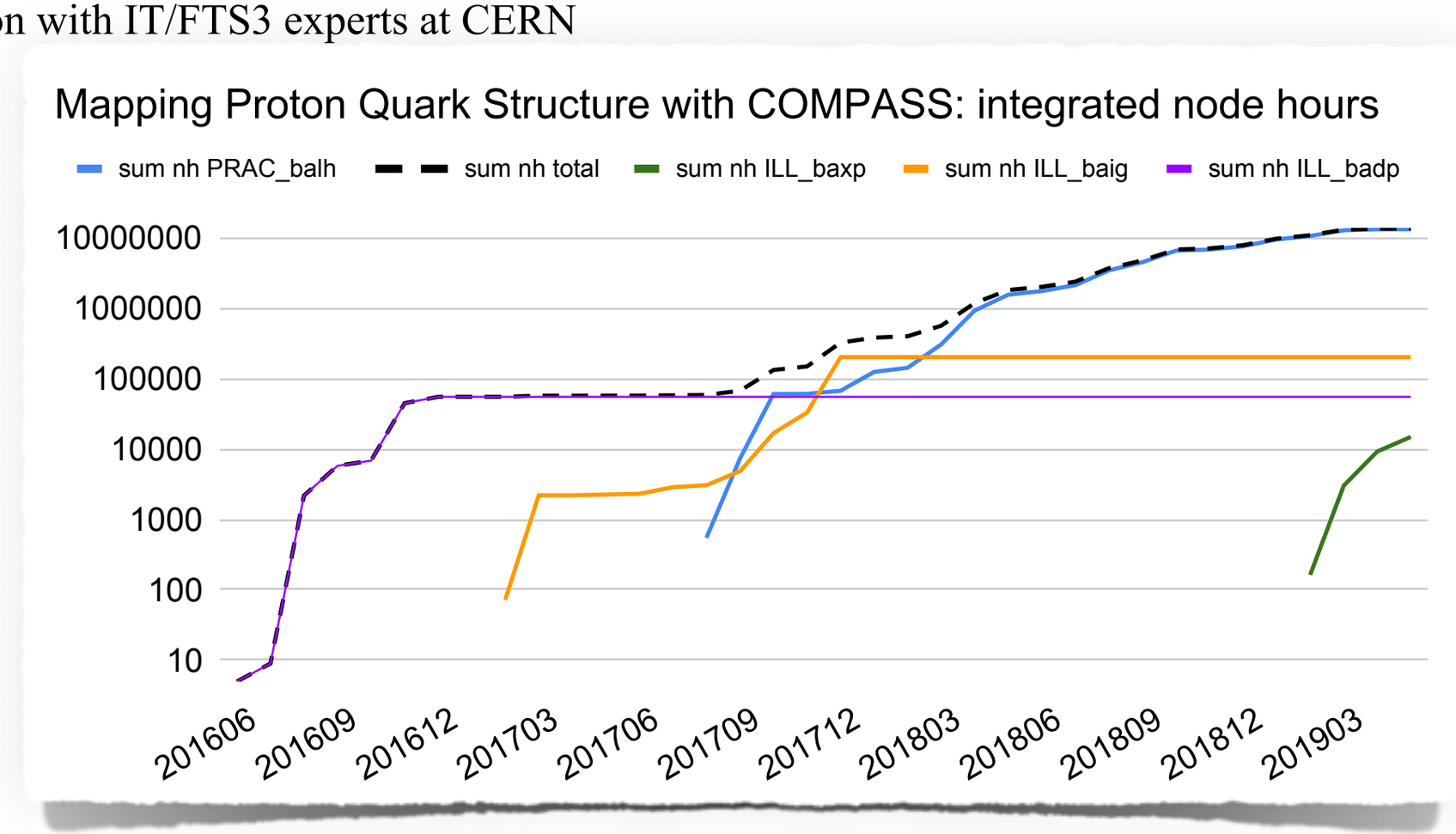
  - Mass productions of RD and MC data are transferred to CERN and collaborating COMPASS institutions.

  - The productions are the reference data to be used by every COMPASS analyzer, in particular for analyses resulting in presentations at international workshops and conferences, and publications in peer-reviewed journals.

Blue Waters team contributions

Thank you to the BW team!

- Very generous in Nearline and Online quota
- Data movement to and from BW-tape (Nearline):
  - Advice to tar archive large number of files
  - Help with stuck files
  - Help with moving old data with the start of a new allocation
- Data transfers from CERN:
  - Solution to gridftp issues on BW side
  - Discussion with IT/FTS3 experts at CERN
- Advice in how to transfer data to TACC (Ranch)
- User support (lost token, login difficulties, wrong e-mail address, etc…)
- COMPASS calibration mySQL data base: how to run it without exceeding login-node CPU limit
- COMPASS data work flow: optimization of load distribution, usage of commtransparent feature



PRAC allocation: wrapping up

- Cleaning up tape, /project, /scratch

- Transferring raw COMPASS data to Ranch @ TACC.

  - Use TACC Mig2 Ranch node reserved for NCSA users
  - Typical: 3 streams with each 250 MB/s, 100 GB files
  - 1 stream with 500 files or more works fine

Mapping Proton Quark Structure using Petabytes of COMPASS data

Don't miss R. Longo's poster!

Why it matters

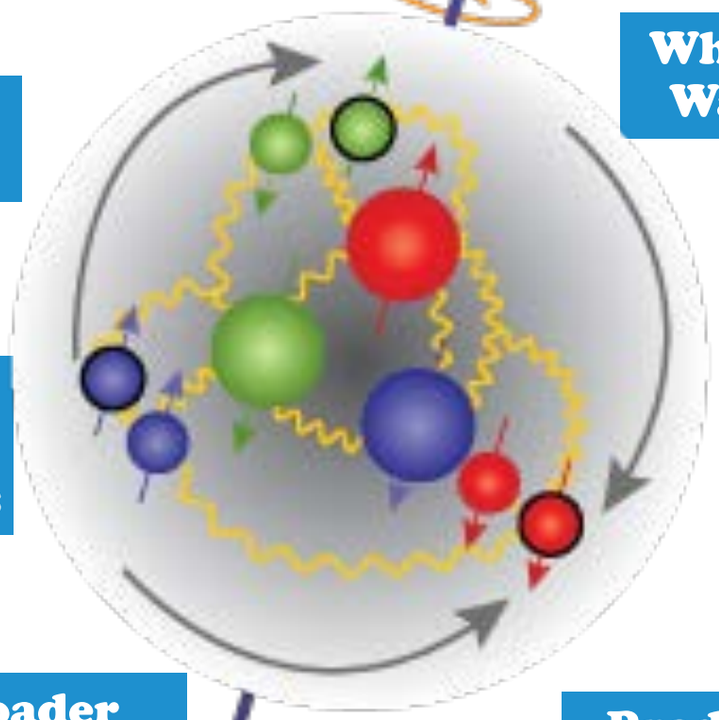
Transverse-momentum and -spin degrees of freedom cause novel proton behavior

Key Challenges

Timely production of Real Data and high-statistics Monte-Carlo data

Why Blue Waters?

Blue Waters is **faster**, allows for **high-precision** analysis and allows for **novel studies** otherwise too CPU intensive.



Blue Waters team contributions

Amazing support and advice

Broader Impact & Shared Data

Education of students and young postdocs in petascale computing. Creation of reference data productions shared with ~250 researchers.

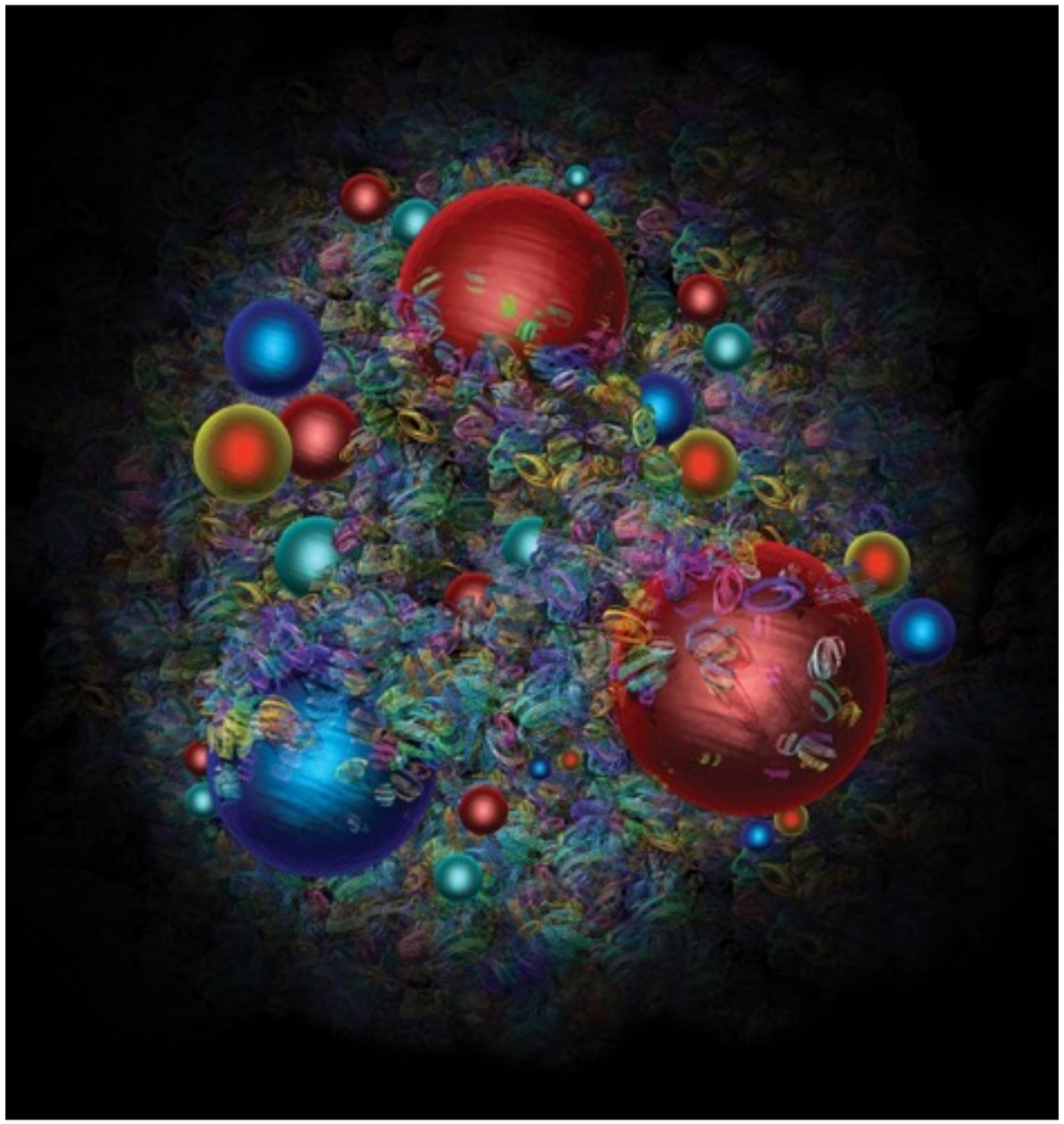
Accomplishments

Products

Mass productions of real data at **unprecedented speed** and Monte-Carlo simulations

Public talks in particular at recent DIS2019 conference

Backup

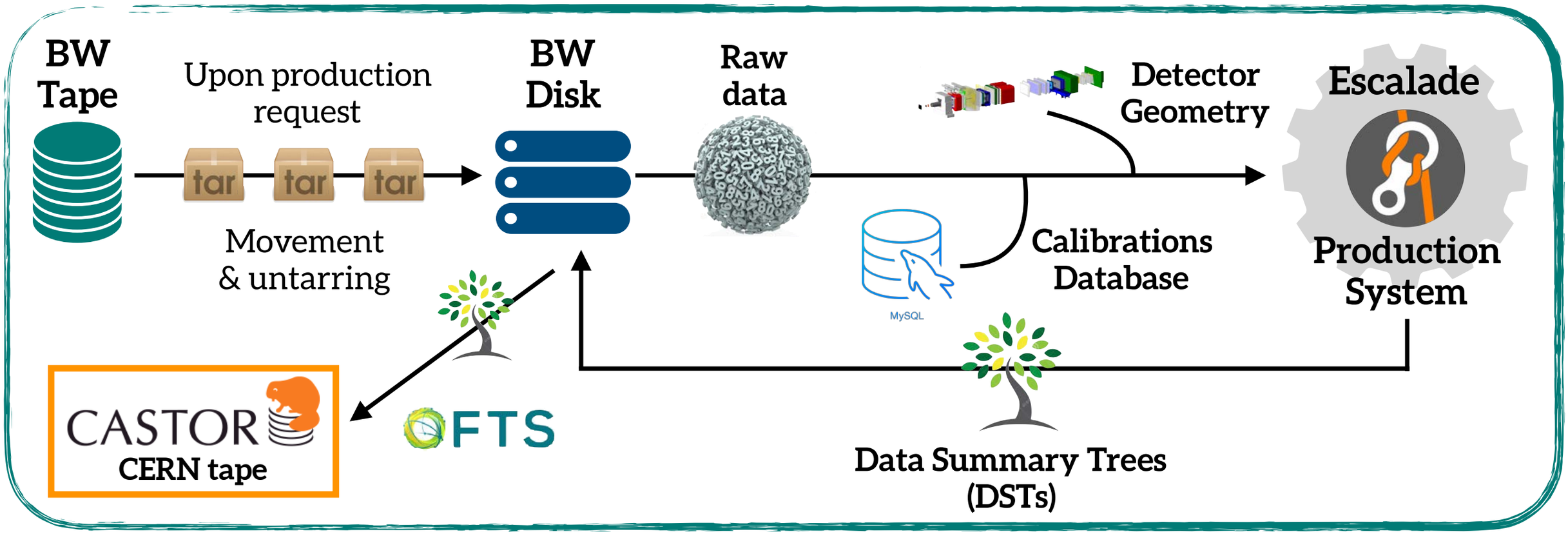


D. Dominguez, CERN courier May/June 2019
"The proton laid bare"

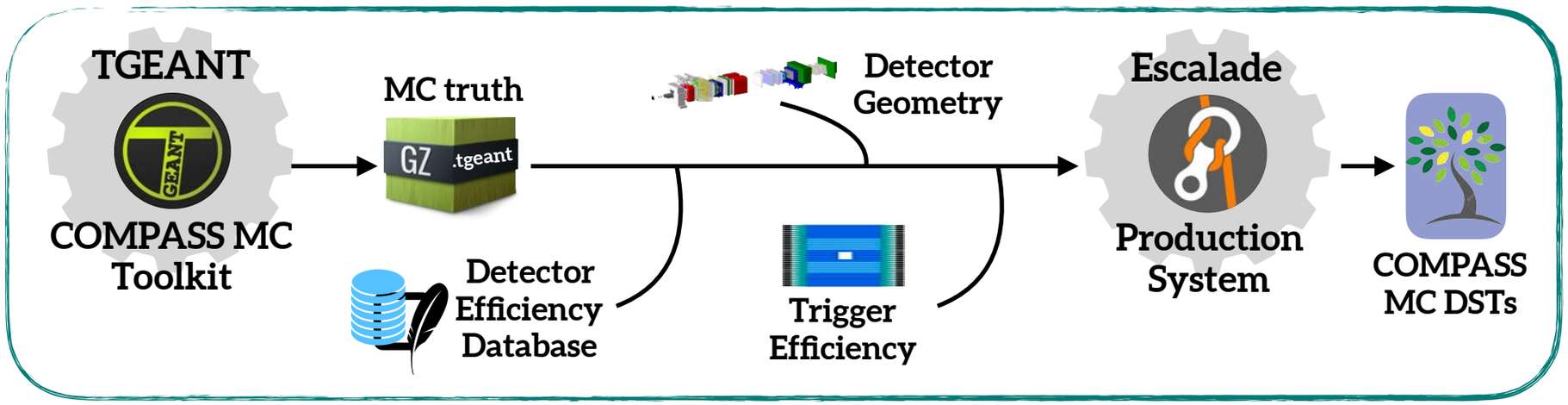
Accomplishments

COMPASS data productions on Blue Waters

R. Longo,
M. Meyer



Montecarlo Chain



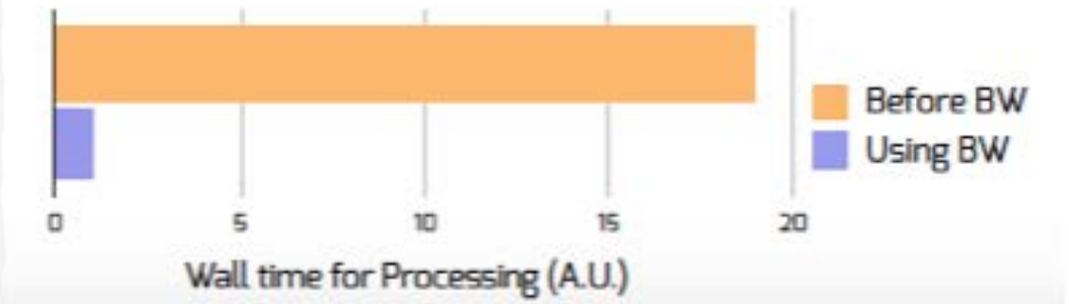
Sketches courtesy R. Longo (poster at this symposium)

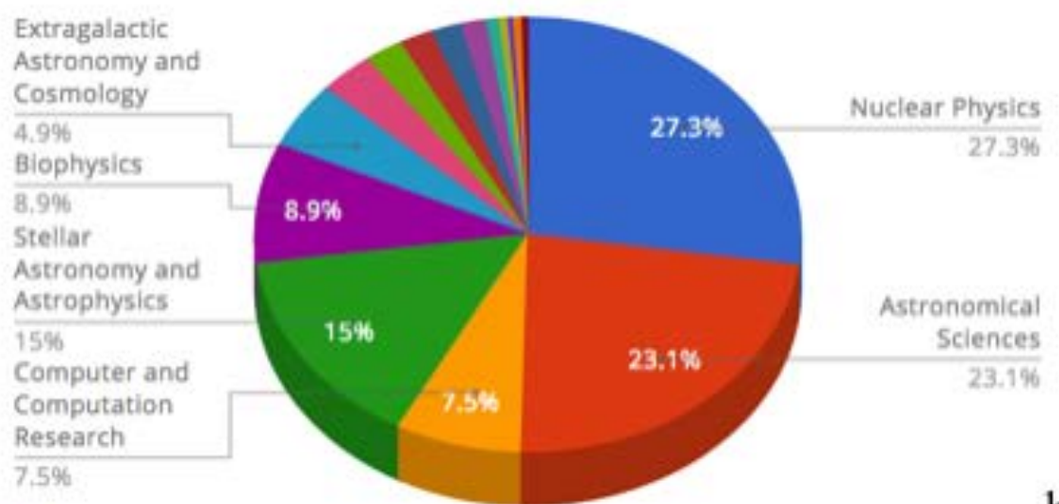
Using a supercomputer in experimental nuclear physics

The scope of the project:

NSF grant (award #1713684)
Allocation "PRAC_balh"

- Monte Carlo productions
- Real data productions
- 2D efficiency maps
- Physics analysis





The advantages, compared to the standard computing clusters:

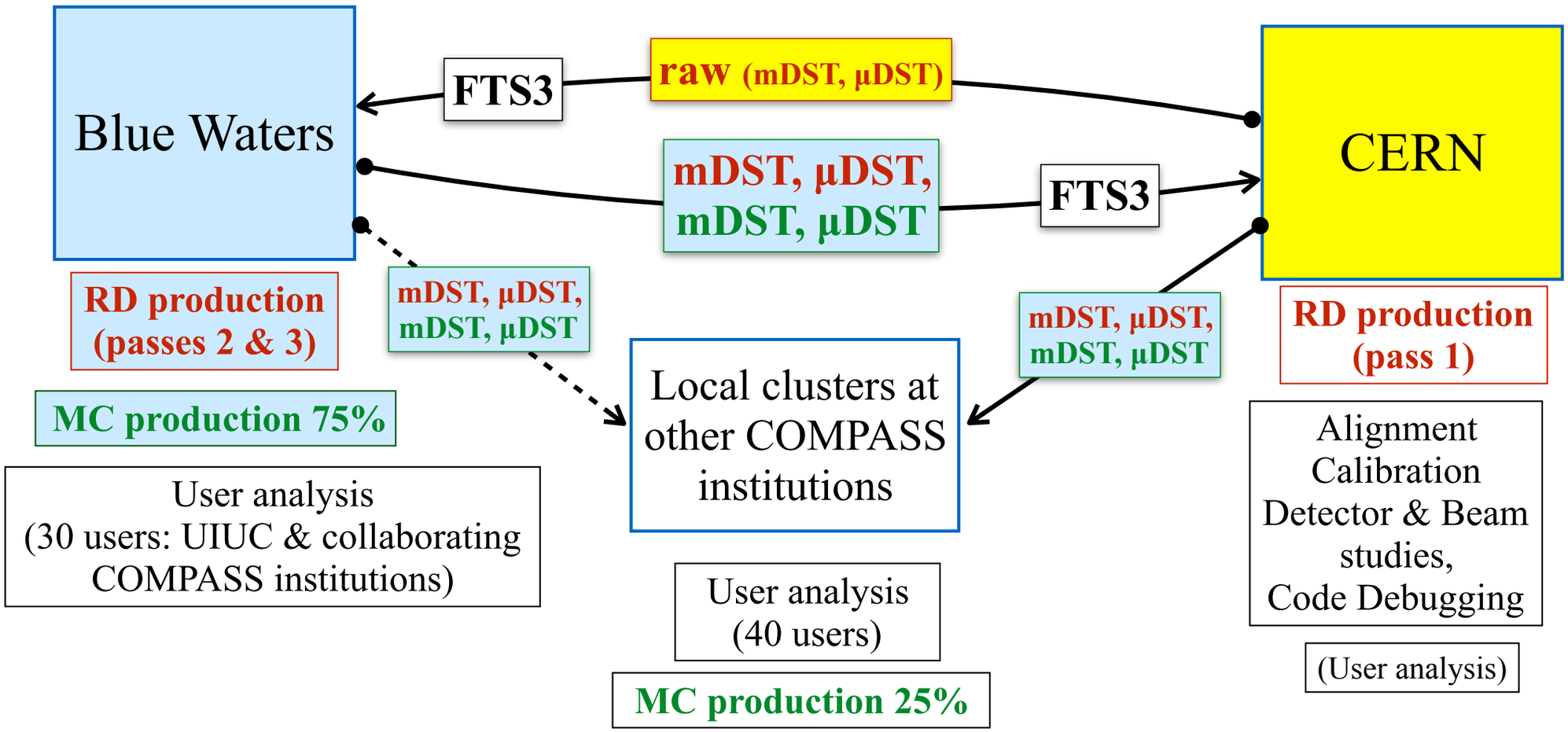
- (Much) faster data production due to parallel processing
- Minimization of systematic uncertainties due to possibility of
  - applying multi-dimensional acceptance corrections;
  - simulating high realistic pile-up;
  - generating with minimum-bias trigger.
- Unprecedented precision determination of detector efficiencies
- More disk space for fast access available (in general)

These are examples.
They might not apply in general.

BLUE WATERS

https://bluewaters.ncsa.illinois.edu/usage-project-details?project=balh

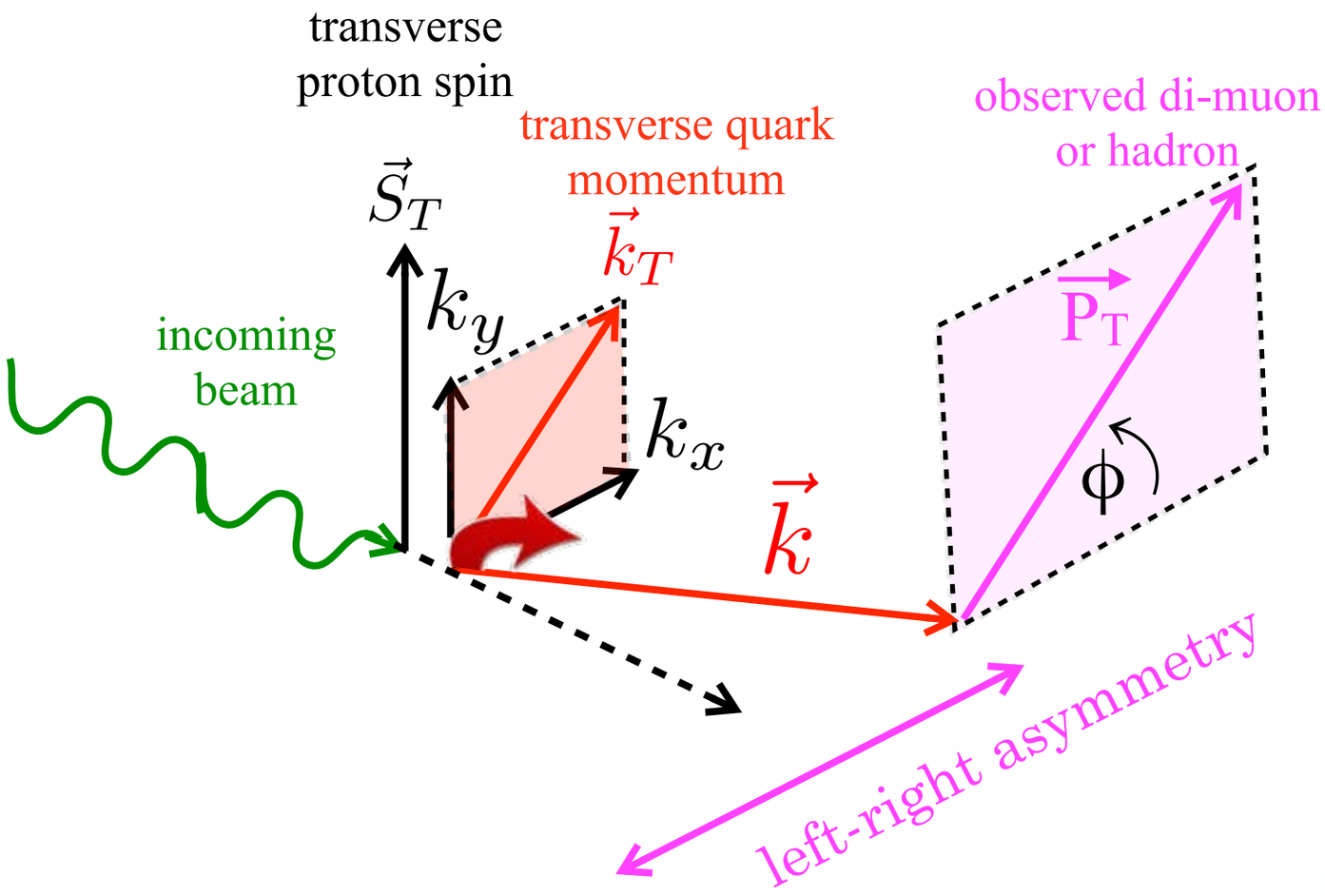
COMPASS computing model with Blue Waters (from the PRAC proposal)

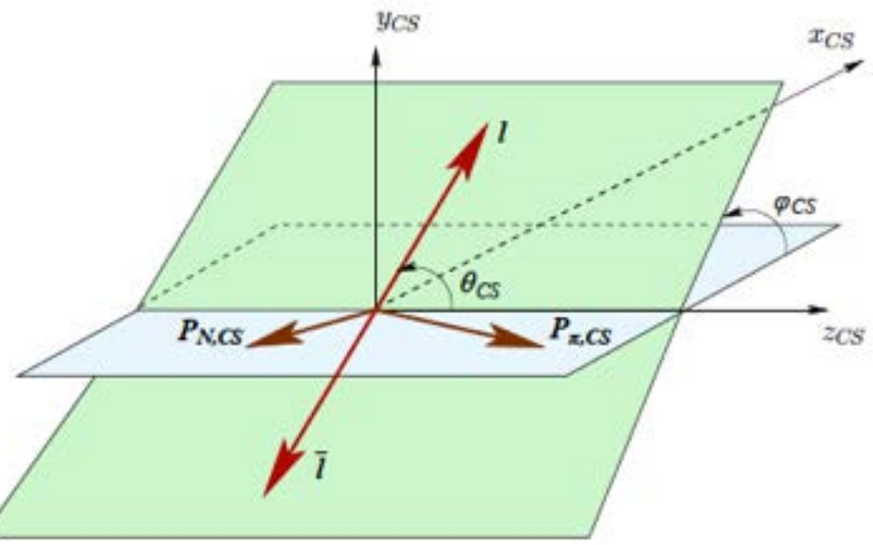


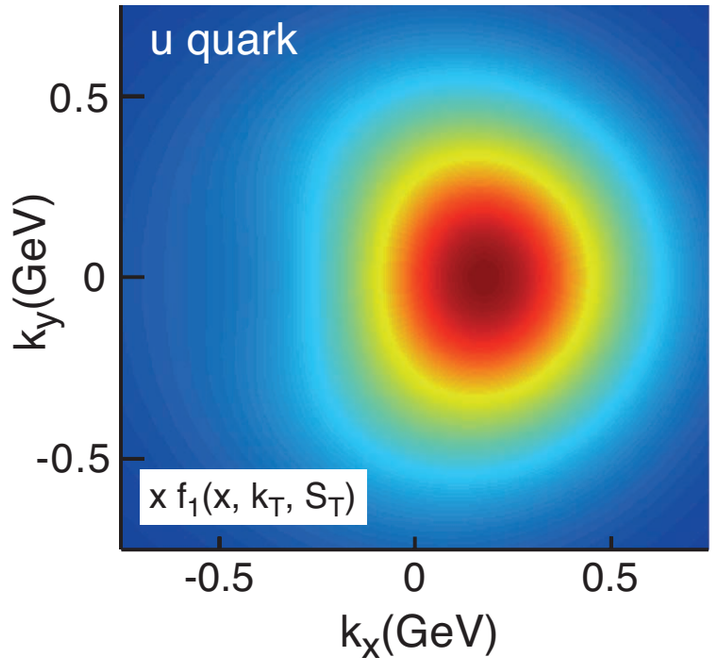
19% experimental data production.
76% Monte-Carlo data production.
5% physics data analysis.

FTS3: bulk data mover created to globally distribute LHC data.

The Sivers effect

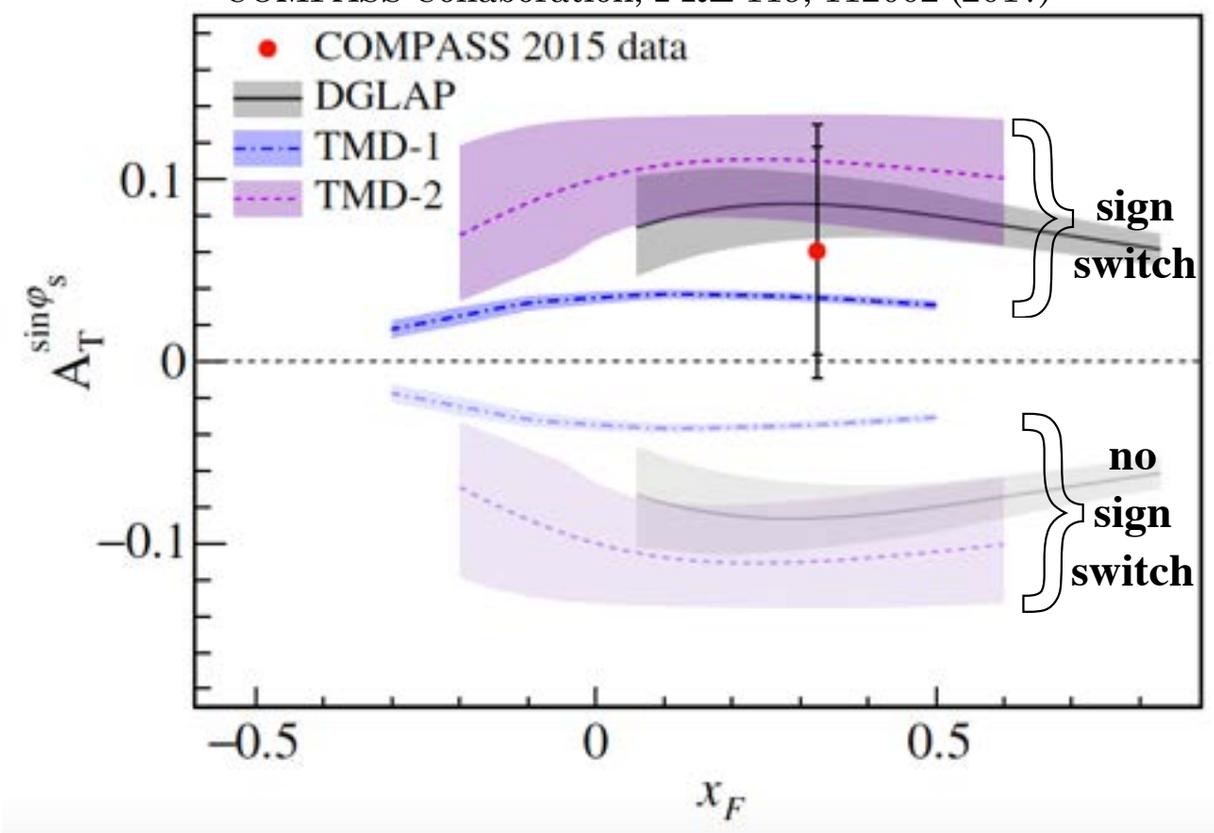


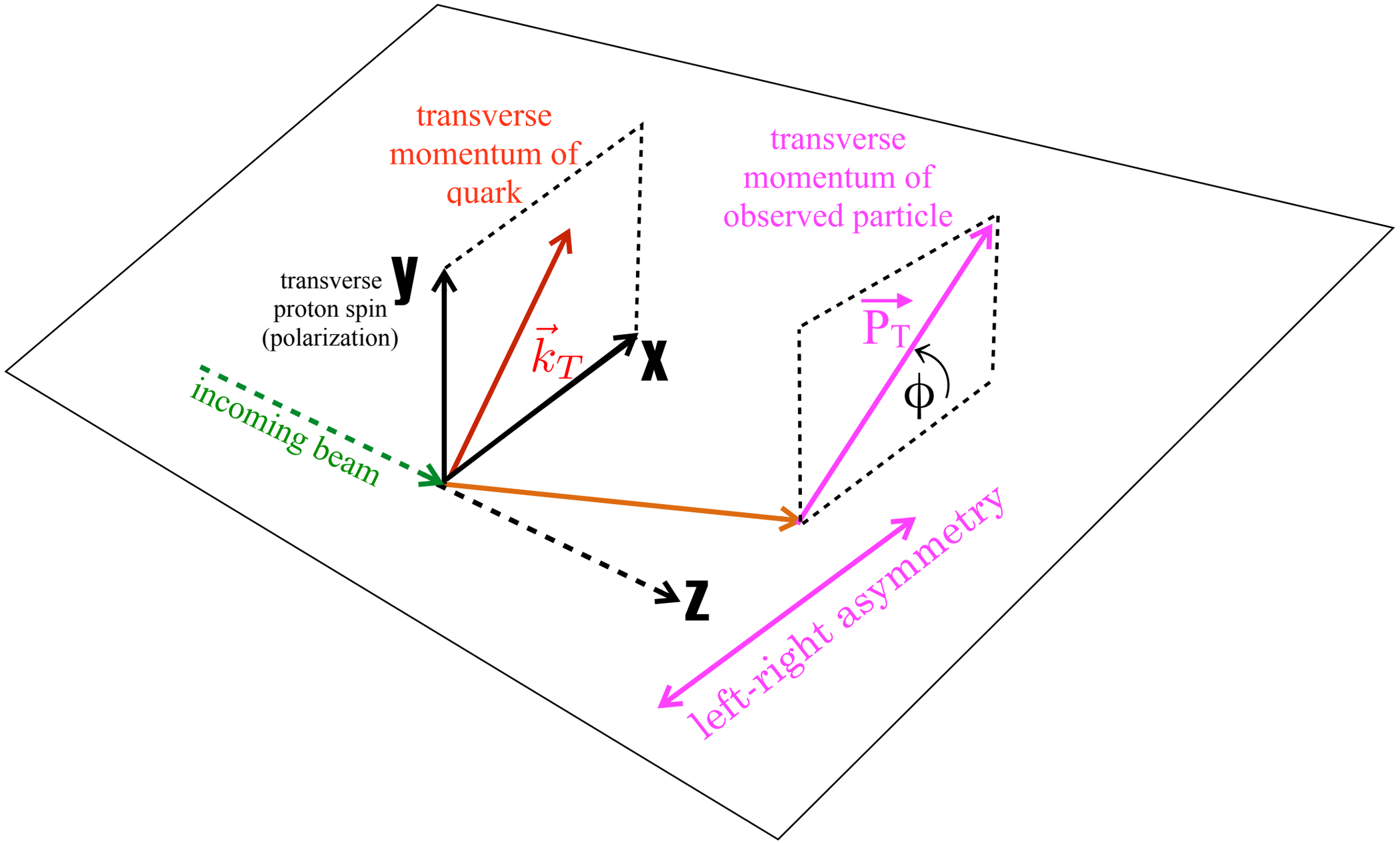




EIC "White Paper" arXiv:1212.1701, based on M. Anselmino et al., J. Phys. Conf. Ser. 295, 012062 (2011), arXiv:1012.3565

COMPASS Collaboration, **PRL** 119, 112002 (2017)



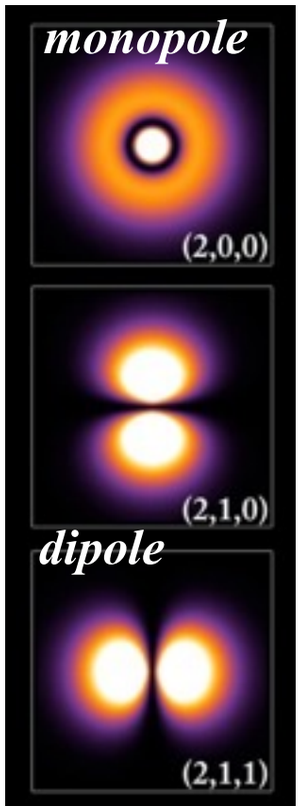

transverse
momentum of
quark
transverse
momentum of
observed particle
transverse
proton spin
(polarization)
y
x
z
$\vec{k}_T$
$\vec{P}_T$
ϕ
incoming beam
left-right asymmetry

Why it matters

Proton "orbitals": from QED to QCD

~ 1930's: Quantum Electro Dynamics QED
(the theory of the electromagnetic force between charged particles)

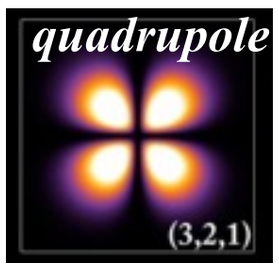
Hydrogen atom - "wave function"



$$\psi_{\mathrm{nlm}}(r,\theta,\phi)$$

orbital angular momentum

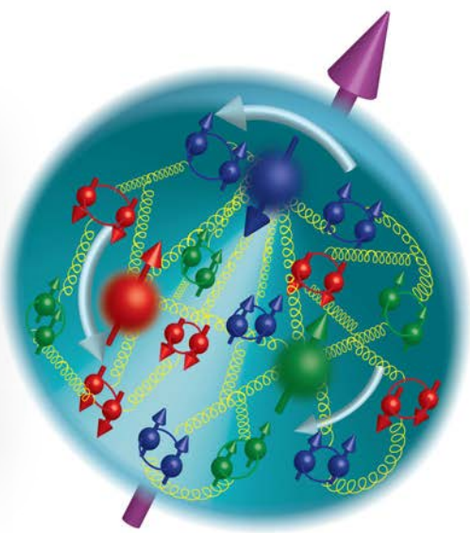
spin



~ 2010's: Quantum Chromo Dynamics QCD
(the theory of the **strong nuclear force between quarks**)
with transverse degrees of freedom

nucleon \ quark	unpolarized U	long. polarized L →	trans. polarized T ↑
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Correlation between **transverse spin** of proton and **transverse momentum of quarks** is indicative of **orbital angular momentum of quarks** in the proton

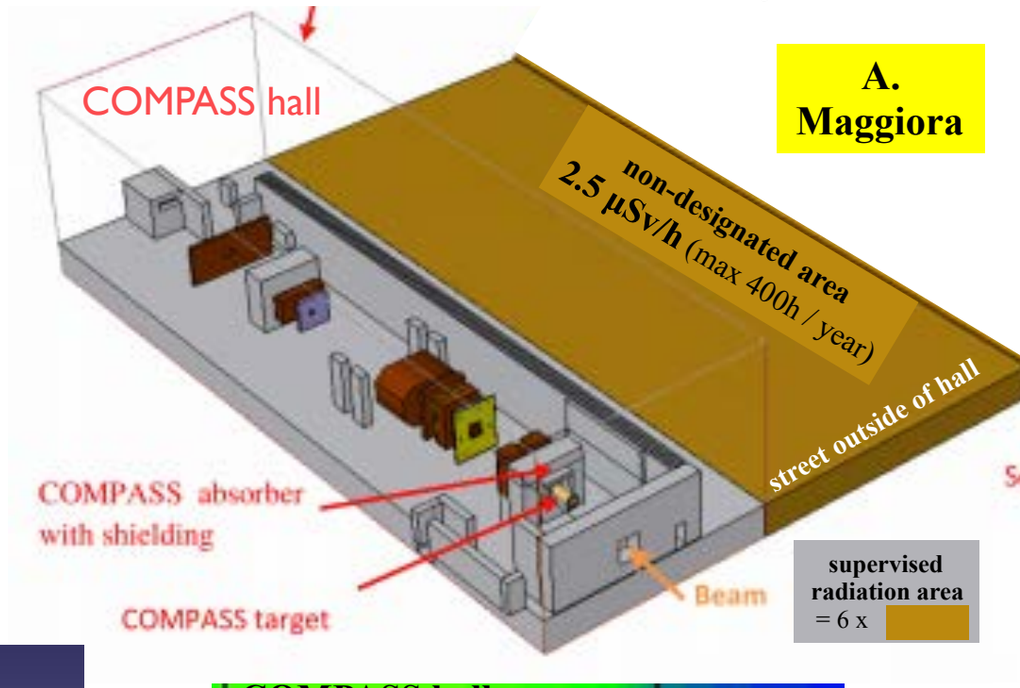


Products

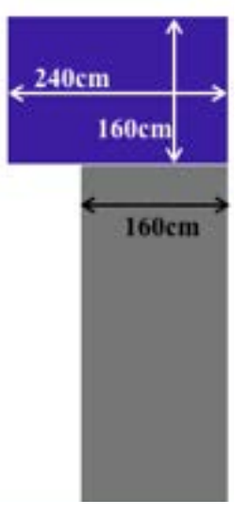
Radio Protection Simulations for COMPASS 2018

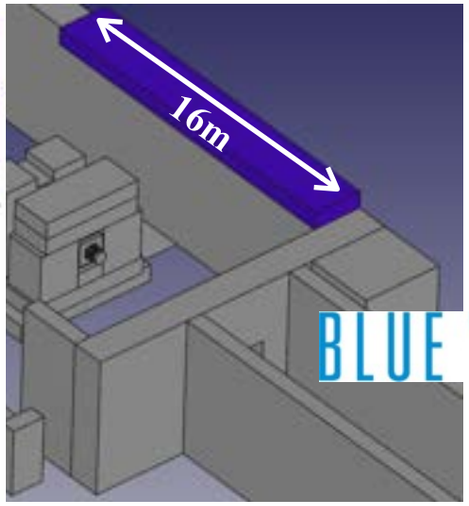
- **Improvement of shielding for better radio protection**
  at intensity 100 million pions per second on the COMPASS target.

- Simulation with **FLUKA**, a general-purpose tool for calculations of particle transport and interactions with matter.
  http://www.fluka.org/fluka.php

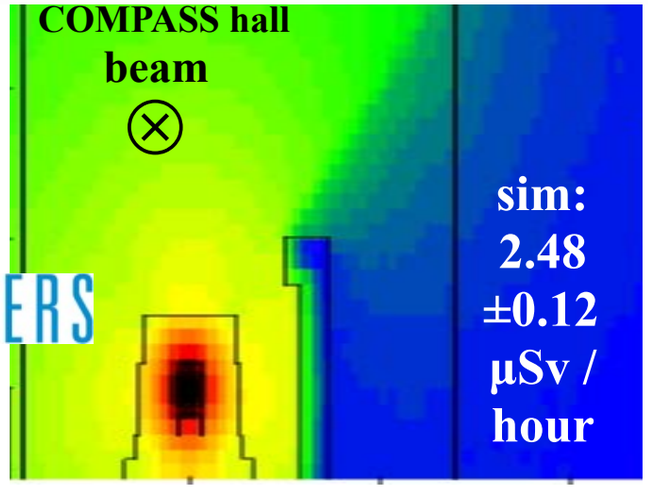


New "balcony" concrete shielding installed at COMPASS based off simulations on Blue Waters





BLUE WATERS



- 3M of primary particles reconstructed vs. 0.04M with previously available computing resources **- factor of 75 more**

- This statistical power results in sufficiently small error bars to reveal also small differences between the different configurations of radiation shielding with concrete and polyethylene.