QCD Theory (Nuclear Beams)

13.05.2019

Urs Achim Wiedemann, CERN TH

QCD theory - main message

QCD theory is fundamental for any future collider project:

1. Advances in QCD enable advances in electroweak precision measurements and BSM searches. (talks by Salam and Gehrmann)
2. **Open fundamental questions in QCD** are accessible at current and future colliders. (this talk)
   Further developments in QCD theory
   - are required to fully exploit the experimental opportunities of the 2020's and 2030's.
   - anchor current and future collider projects on the widemost scientific community.

It is important to communicate both points on equal par.

see input 163 *QCD TH*, input 48 *HI Town meeting*

Fundamental questions in QCD

1. **How do collective phenomena and macroscopic properties of matter arise from the fundamental interaction of QCD?**
   - Phase transitions of fundamental quantum fields have shaped our Early Universe.
   - QCD is the only non-abelian QFT whose high-temperature phase is experimentally accessible. Nuclear beams at current and future hadron colliders provide the unique access.
   - In AA, collective dynamics reveals QGP transport properties that are calculable from 1st principles in QCD at extreme temperatures/densities.

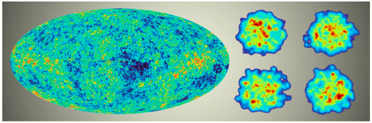
Main goals of nuclear beams programs @ HL-LHC

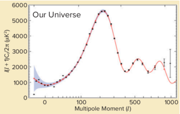
(as defined in HL-LHC WG5 report: arXiv:1812.06772)

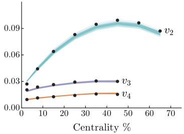
1. **Characterizing the long-wavelength QGP properties** with unprecedented precision.
2. **Probing the inner workings of the QGP:** investigating microscopic parton dynamics in hot and dense QCD matter.
3. **System size dependence:** developing a unified picture of particle production and QCD dynamics from pp to AA.
4. **Exploring nuclear parton densities** in a broad (x, Q^2) range and searching for onset of parton saturation.

1. Long Wavelength properties

1. In Little Bangs as in the Big Bang, material properties are accessed via fluctuations. (v_n, EbyE distributions of multi-particle correlations.)







2. The measured one-to-one correspondence between initial spatial gradients and azimuthal momentum anisotropies v_n gives strong evidence of **fluid-like response**.
3. **Relativistic viscous fluid dynamics**
   - accounts for collective dynamics in terms of QGP properties (EOS, transport coefficients) that are calculable from first principles in QFT.
   - simulations indicate minimally dissipative, close-to-perfect fluid: $\Longrightarrow$ QGP may be the only known material free of quasi-particle excitations. **"Perfect fluid paradigm"**

1. Long Wavelength properties - TH challenges

1. In QFT, any self-interacting matter carries both fluid-dynamic and non-fluid dynamic excitations.
   - fluid excitations are universal and constrained experimentally.
   - **nature of non-fluid excitations not yet established.**

     Candidates: quasi-particles (appear in weakly coupled theories),

     Matsubara modes (indicate quantum nature and de Broglie wavelength of quasi-particles),

     quasi-normal holes (appear in strongly coupled QFTs with gravity duals)
2. Access to the microscropic structure of the QGP requires **QCD-based descriptions beyond fluid dynamics.**

   (e.g. QCD-based effective kinetic theory, understanding of hydrodynamization, thermalization)
3. Further **progress in calculating fluid dynamic response functions** for weak, strong and realistic coupling required.

1. Long Wavelength properties - EXP status

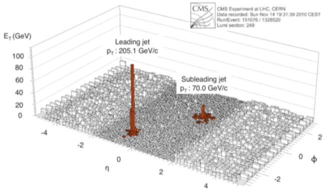
well-advanced but still incomplete (p.111, arXiv:1812.06772).

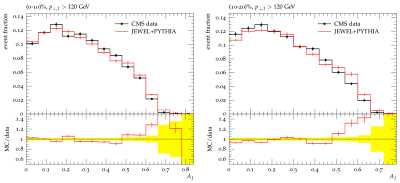
Table 8: Summary of bulk observables or effects in Pb–Pb collisions, as well as in high multiplicity p–Pb and pp collisions at the LHC. References to key measurements for the various observables and systems are given. See text for details. Table adapted from Ref. [666].

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[47, 71, 317, 318, 654, 657, 663, 664, 667, 668]
Intermediate p_T ("recombination")	yes	yes	yes	[317, 657–663]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[318, 638, 664, 665]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	MB: $\gamma_s^{C} < 1$, 20–40%	[318, 638, 669]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[670–677]
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4	[48, 312–314, 632, 633, 652, 678–688]
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2	[48, 315, 326, 683, 686, 689–691]
Directed flow (from spectators)	yes	no	no	[692]
Charge-dependent correlations	yes	yes	yes	[249, 253, 254, 693–696]
Higher-order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"	[316, 683, 688, 697–708]
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)	[227, 687, 709–712]
Non-linear flow modes	up to v_6	not measured	not measured	[713]
Weak η dependence	yes	yes	not measured	[685, 707, 714–719]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[682, 684, 720–722]
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured	[723–725]
Direct photons at low p_T	yes	not measured	not observed	[544, 726]
Jet quenching through dijet asymmetry	yes	not observed	not observed	[348, 360, 374, 727–729]
Jet quenching through R_{AA}	yes	not observed	not observed	[323, 344, 346, 347, 352, 730–737]
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured	[354, 357, 375, 376, 380, 388, 733, 738–740]
Heavy flavor anisotropy	yes	yes	not measured	[262, 326, 460–464, 497, 741–745]
Quarkonia production	suppressed†	suppressed	not measured	[262, 454, 456, 459, 478, 479, 491, 492, 494, 495, 497, 579, 746–755]

2. Probing the inner workings of the QGP

1 QGP properties accessible via quenching of hard probes





- constraints on opacity and path-length dependence identified
- indication of scale-dependent isotropization exist
- effects of Rutherford-type scattering on QGP constituents **predicted but not yet identified unambiguously.**

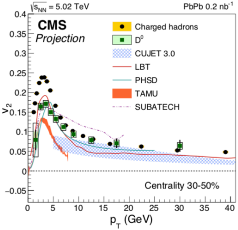
$\Longrightarrow$ drives the $\mathcal{L}_{\rm int} = 13\, nb^{-1}$ request for run 3/4

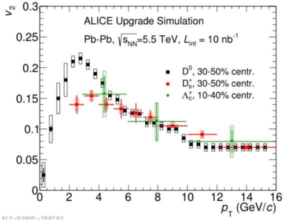
$\Longrightarrow$ need improvements in TH/EXP analysis of jet substructure (out-of-cone radiation, jet deflection, Z-jet, b-jet correlations)

see NSAC 2015 Long Range Plan; HL-LHC WG5 report 1812.06772; HI Town Mtg.

2. ... quarkonia and open heavy flavor

1. Charm/Beauty: **unique tools to test transport and hadronization of conserved color charges in the QGP.**

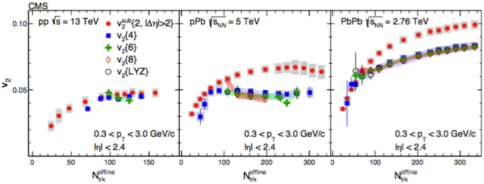


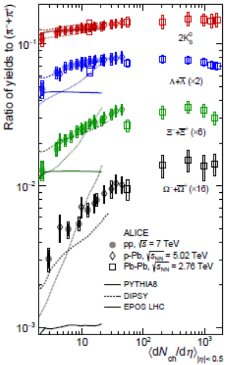


2. different TH challenges on different $p_\perp$-scales
   - test mass/color charge hierarchy of parton energy loss
   - Do heavy flavors flow like light flavors?
   - Hadronization models: fragmentation vs. recombination.

3. Emergence of collectivity in small systems

“Heavy-ion like behavior in pp indicates that more physics effects are at work than originally thought.”
T. Sjostrand





1. **Are liquid droplets produced in pp and pPb or do non-fluid excitations build up collectivity?**
$\Longrightarrow$ system size can test inner workings of QGP

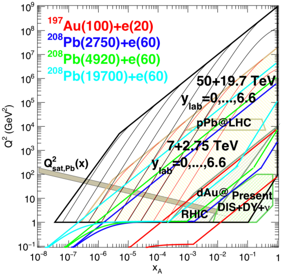
3. Collectivity in small systems - cont'd

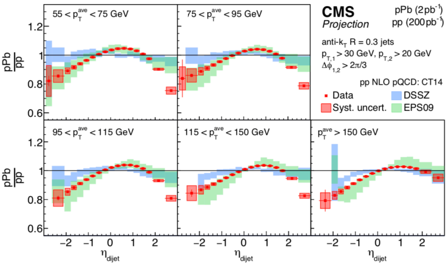
1. TH/EXP interplay in run 3 & 4 required in search for
   - thermal photon & dilepton radiation in pp, pPb
   - heavy quark transport in pp, pPb
   - parton energy loss in pPb & pp
2. TH challenge to calculate these observables in systems of small opacity for which thermalized scenarios cannot be assumed.

4. nPDF's partonic structure of initial conditions

1. nPDF's: precision physics with nuclear beams
   - prerequisite for controlling initial conditions in AA
   - TH challenge to identify and scrutinize **signatures for onset of non-linear QCD evolution**.
   - Open question: how to use data from UPCs in global fits?
2. data from pPb@HL-LHC can improve global nPDF-fits

(high-precision W, Z and dijet in pPb, constrain A-dependence of nPDFs with light AA.)

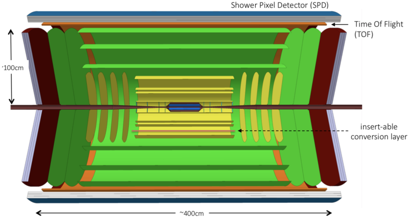




QCD TH beyond guaranteed HL-LHC deliverables

1. due to the chiral anomaly, **the hydrodynamics of QED+QCD is anomalous**: $j_\mu \propto B_\mu$, $j_\mu \propto \omega_\mu$. Can this be tested in AA?
2. **QGP in ultra-strong magnetic fields**. AA collisions realize transient elmag. fields $eB > m_\pi^2$. Questions of astrophysical relevance.
3. **Physics at very low $p_T < 50 MeV$**. E.g. is quantum statistics of thermal distributions visible in identified hadron spectra?

- QCD TH contributes to the physics case for a next generation HI experiment @ HL-LHC. (see input 110)



Resources to enable the next TH generation

Fully exploiting the physics opportunities offered by ultrarelativistic heavy ion collisions requires

1. long-term investment in tools and specialized researchers in
   - MCs for jet quenching, their interface with multi-purpose event generators and models of underlying event
   - parton cascades, transport codes and fluid dynamic simulations
   - global nPDF fits
2. sustained support of finite-T lattice QCD (see talk of H. Wittig)
3. funding aimed at enriching the intellectual interplay between HI physics and neighboring fields, e.g.
   - strengthening the exchange with HEP theory (e.g. jet finding, underlying event simulation)
   - AdS/CFT: non-abelian plasmas of QFTs with gravity duals
   - synergies with studies of high-density QCD in neutron stars
   - overlap with techniques and concepts in astroparticle physics and cosmology.

QCD theory - main message

QCD theory is fundamental for any future collider project:

1. Advances in QCD enable advances in electroweak precision measurements and BSM searches. (talks by Salam and Gehrmann)
2. **Open fundamental questions in QCD** are accessible at current and future colliders. (this talk)
   Further developments in QCD theory
   - are required to fully exploit the experimental opportunities of the 2020's and 2030's.
   - anchor current and future collider projects on the widemost scientific community.

It is important to communicate both points on equal par.

see input 163 *QCD TH*, input 48 *HI Town meeting*

The End