Fixed-target physics at the LHC

Focus on opportunities for Aladdin

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TWOCRYST & ALADDIN Workshop

Idea of this talk

Why fixed-target kinematics@LHC interesting beyond the dipole moments measurements and spectroscopy in decays?

I) Generic considerations

2) Focus

- Strong interaction physics
- Unpolarised proton-nucleus collisions
  - No TMD/Spin physics, no classic QGP physics covered
- complementary to collider mode & LHCb fixed-target + without additional subsystems

No attempt to be comprehensive, biased towards my exposure

Generic considerations: kinematics & hadron structure

Hard scale Q: factorisation of cross section

soft (initial) x Hard (perturbative QCD) [x soft (final)]

used to extract hadron structure: ‘soft (initial) ‘

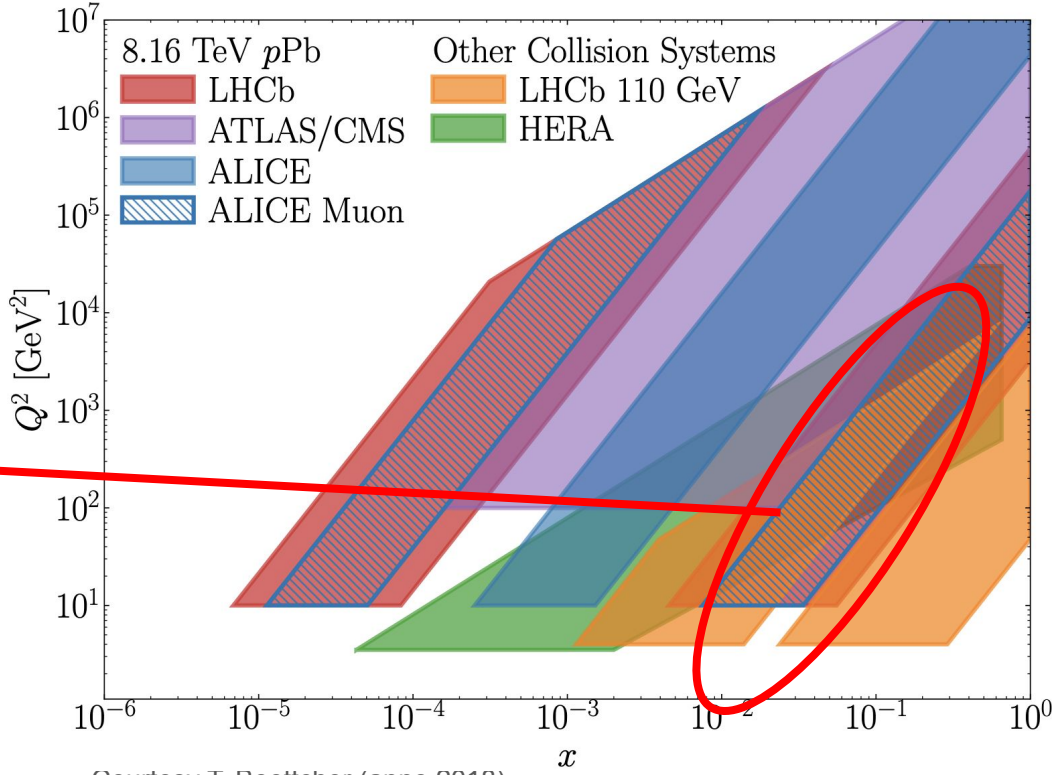
- Final state particle kinematics mapped to:
  fractional longitudinal momentum x & other variables (kT, bt)

Fixed-target LHC:

- Complementary x - Q values w.r.t. past/current/future facilities
  - Highly boosted: high-x (close to target fragmentation) simple to access
  - lower Q than typical collider observables used for parton distribution constraints

Generic considerations: kinematics for hadron structure

ALADDIN



Courtesy T. Boettcher (anno 2018)

Caveat:

- No Relativistic heavy-ion collider (RHIC) here

Generic considerations: Aladdin kinematics

- Midrapidity detector in nucleon-nucleon centre-of-mass frame $\sqrt{s_{NN}}$
  - Low-pt charm production samples Bjorken-x: mass/sqrt(s) for both target & projectile

$$x \approx 3\ \text{GeV} / 115\ \text{GeV} = 0.026$$

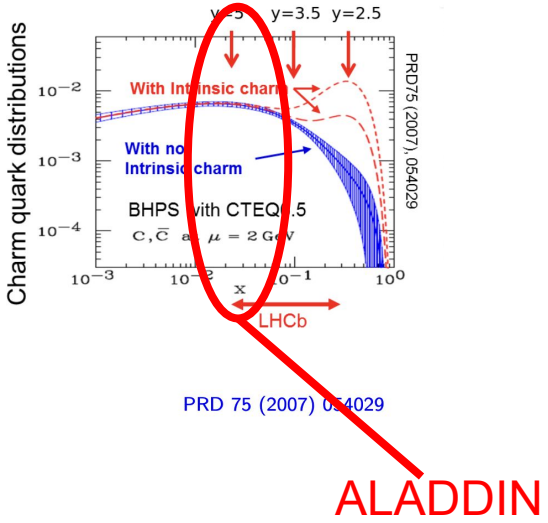
- Kinematics similar to STAR/PHENIX@RHIC d-Au data
  - $\sqrt{s}$ at RHIC predominantly 200 GeV
  - For charm/UPC@RHIC: most results on Au-Au and/or limited precision in d/p-Au

Generic considerations: kinematics for hadron structure

Main cases:

Intrinsic charm at high-x

nuclear modification



Intrinsic charm: Aladdin not well placed or need to go to high-pT kinematic edge : large luminosity

Generic considerations: kinematics for hadron structure

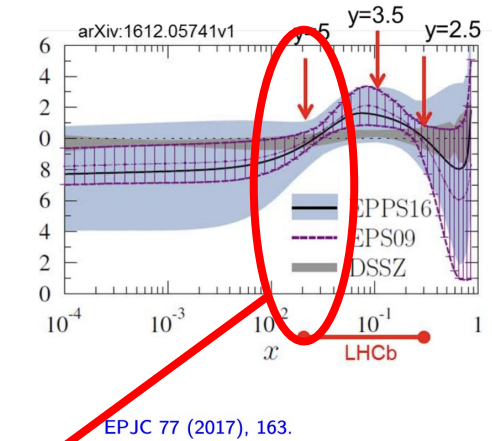
Main cases:

Intrinsic charm at high-x

nuclear modification

Observables:

- Cross section as function of rapidity and pt
- Cross section ratios between different nuclear targets



ALADDIN

- Nuclear modification factor range interesting for a heavy-target
  - Transition between antishadowing and shadowing
- Require 2nd target for exploitation: normalisation, absolute cross section uncertainties very large in theory
- Significant rapidity range to vary x highly beneficial

PDFs in plot outdated : now constraints from LHC (Dijets for gluons in particular) in Aladdin x-range

See for a recent nuclear PDF review: https://arxiv.org/abs/2311.00450

Aladdin: Does pQCD DGLAP as function of Q works for nuclear PDF? slight complication W (ALADDIN) is not Pb (LHC)

Generic considerations: charm for hadron structure

Inclusive charm/beauty @ fixed-target: in principle hard, BUT

- Factorisation may be broken by:
  - w.r.t. the initial state factorisation in pA: energy-loss [1]
  - w.r.t. the final state in any hadron-hadron collision: hadronization modification [2]
- Debate on use of charm/beauty for hadron structure
- Interesting physics on its own

[1] Coherent energy-loss as scenario for nuclear modifications in pA: **Heavy quarkonium suppression in p-A collisions from parton energy loss in cold QCD matter,** Arleo, Peigné, https://inspirehep.net/literature/1205150, competing effect with gluon suppression in nuclei, publication for heavy-quark mesons https://inspirehep.net/literature/1883006

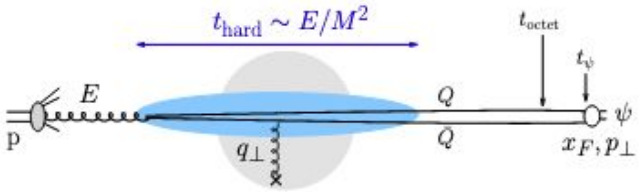
[2] Hadronisation modification charm : pp collider ALICE: more charm baryons than mesons in pp vs. ee:

https://inspirehep.net/literature/1863128

pA fixed-target LHCb: effect of beam remnants on hadronisation:

https://inspirehep.net/literature/2673124

Generic considerations: kinematics energy-loss



At large energy in target rest-frame: coherent gluon energy loss emission of gluons

- Effect might be accidentially absorbed in nuclear PDFs based on LHC hadro production data
- Ideally measure process not affected (Drell-Yan) and one affected (charm/hadrons) to verify importance of effect

Observables:

- Cross section as function of rapidity and pt
- Cross section ratios between different nuclear targets

- Aladdin not ideal (only charm), but effect relevant for acceptance: up to O(20%) effect proton-proton vs. proton-lead:

  Significant rapidity range to vary x highly beneficial

- A second, lighter target would be needed
- Precision is key

Publication for fixed-target kinematics quarkonium to be taken as first order proxy for open-heavy flavour : https://arxiv.org/pdf/1504.07428

Charm hadronization: kinematics

- Hadronisation changes between ee and hadronic collisions

- Collider@LHC: charged particle density as scaling variable for hadronisation
  - Combined with correlation measurements: main finding of QGP physics at the LHC
    - Observations associated with QGP found also in pp: smooth transition

Fixed-target :

- Charged-particle density only scaling variable ?
- Impact of beam remnants ?
  - modification of hadronisation via conserved quantum numbers from beam particles

Observables:

- Measure charge asymmetries
- Measure Meson/Baryon ratios and Baryon-to-baryon ratios

- ALADDIN complementary w.r.t. LHCb and completely in line with core Aladdin programme
  - Midrapidity detector, minimise impact of beam remnants
  - Large nuclear-mass-number target
  - Can check in pA: effects different on p-going or A-going side
- A second, lighter target would certainly be beneficial : check target dependence

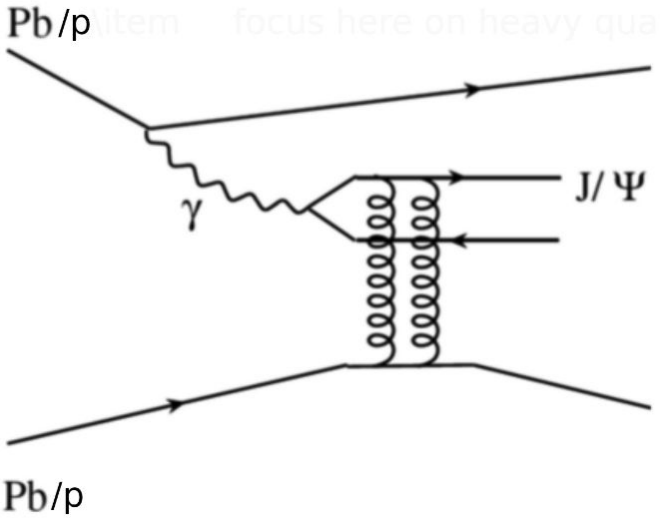
Exclusive photoproduction

- Hadron-hadron collisions at high-energy: Sizeable photoproduction cross sections
  - Ultra-peripheral collisions (UPC)

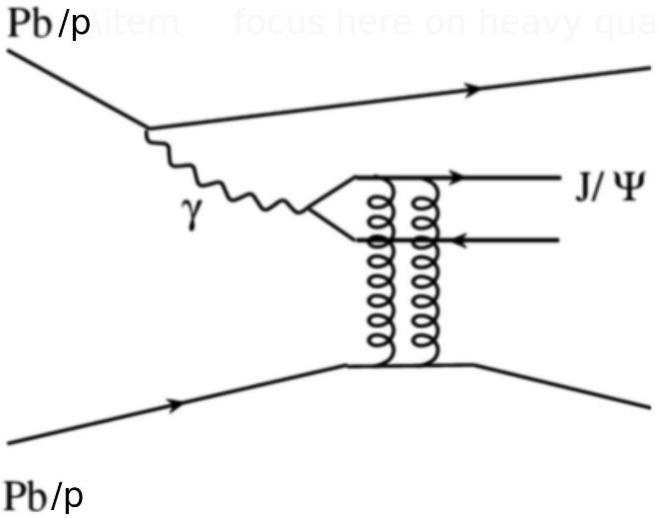
- Experimentally:

  Exclusive production easiest in hadronic collisions

  - Bonus: certain channels available with little/no PID (e.g. Jpsi to dileptons)
  - Most measured process: meson production



Exclusive photoproduction



Near- Threshold production

1) Pentaquark or other exotica searches as function of $W_{gammaproton}$

2) Gluonic contribution to gravitational form factor
   - What is the size/spatial distribution of the gluon contribution to the proton mass ?
   - See e.g. https://arxiv.org/abs/2207.05212
   - Just a starting point: transfer from experimental data model-dependent

Exclusive photoproduction: kinematics proton-nucleus

In symmetric collision system (p+p/nucleus+nucleus): you don't know the photon emitter, both kinematic contributions

Proton+large-A-nucleus (ALADDIN)

the nucleus is typically the photon emitter and the proton is the target: probe proton structure

Considering one data point at average rapidity y in lab-frame =5 and J/jpsi, p_proton = 7000 GeV

- **Wgammap = 17 GeV corresponding to Bjorken-x of 0.03**

- Would need to more forward at y = 6: W = 10.2 GeV for j/psi
- Calls for very high-statistics + forward acceptance

Estimate based on high-energy approximations, get more crude approaching threshold, see formulae in A. Glaenzer's thesis: https://theses.hal.science/tel-03850896

STAR/PHENIX in similar acceptance range, but mostly focus on gamma-nucleus, see e.g. today on arxiv:

https://arxiv.org/pdf/2311.13632 , W about 25 GeV

Exclusive production: kinematics proton-nucleus

World data compilation in: https://arxiv.org/pdf/2304.12403 without new JLAB data

Aladdin at low-energy edge of LHC collider data

@Jefferson Lab, e.g. Glue-x

8.56 - 11.8 GeV

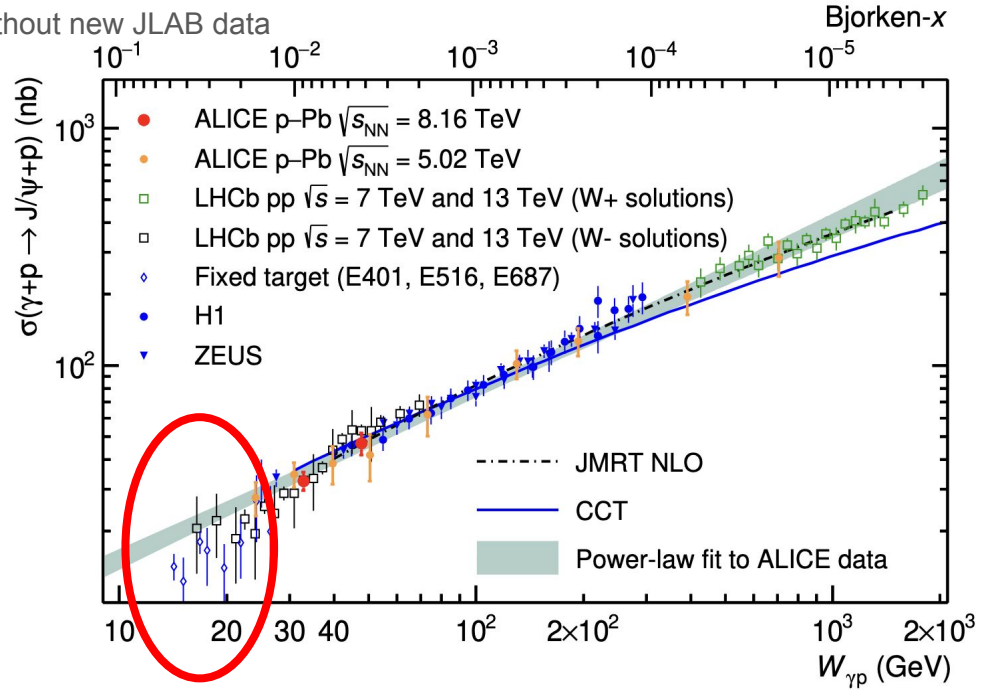
10 points in W_{gammap}

Hall-C@Jlab differential in t

https://arxiv.org/pdf/2207.05212

- difficult to compete near threshold

  for J/psi: several players at JLAB



- Exclusive open charm production: S/B + statistics to be studied: could use J/psi as normalisation to judge what can be done
  - At JLAB large acceptance CLAS12 could do as well
  - requires dedicated feasibility study and comparison
    - Exclusivity control to be studied

Strong interaction at very low momenta: why fixed-target ?

Low-momentum physics:

- It does not matter to first approximation whether I look at 100 GeV or 10 TeV collisions for physics at the 1-100 MeV scale

- It is simpler to go to low-pt while going forward: can do low-pt with minimum ionizing particles

Aladdin interesting?

- need eta-pt plane for tracking + pion-PID

- If good reconstruction below 200 MeV (50 MeV ?) even if it is a narrow window in eta:

  very interesting !

Strong interaction at very low momenta

Pythia and other event generators of inelastic hadron-hadron collisions:

100 GeV and more: collection of scatterings at semi-hard scales, i.e. ‘pQCD’

- a conjecture in a certain sense

- Interesting phenomena not yet fully explored due to difficulty to get to very low transverse momentum in collider mode (below 100-200 MeV)

Two identified physics cases

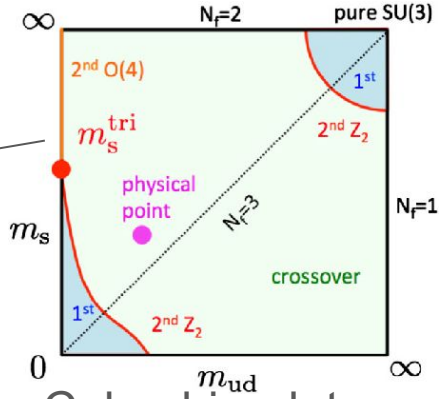
- Low momentum pion condensates
- Very low-momentum photon emission
  - More complicated experimentally, no time to cover, see ALICE LOI https://arxiv.org/abs/2211.02491 & this theory publication: https://arxiv.org/abs/2307.13291v3

Strong interaction at very low momenta: pion condensate

Hadron-to-Quark-Gluon Plasma transition

two transitions : deconfinement + chiral restoration

Real QCD QGP-hadron transition close to chiral phase transition



Columbia-plot
Lattice-QCD

Paradigm for nucleus-nucleus collisions, also applied to proton-nucleus:

- Thermodynamic system created
- consequences of phase transition ignored since ‘only’ cross-over

However Chiral transition may induce enhanced production of soft pions

- ‘Tension’ between hydrodynamic output & Low-pt pions from ALICE in PbPb sometimes put in this context

Observable:

- Pion cross section/pion yield as function of pt

Running in nucleus-nucleus collisions (reconstructing most central collisions with soft pions) would certainly have a big impact

Theory reference: https://arxiv.org/pdf/2306.06887

Summary

- QCD physics in fixed-target@LHC: A rich programme
- Aladdin different from LHCb:
  - around midrapidity
  - pA collisions where A heavy: LHCb Xenon heaviest, only at the end of a data-taking year
  - 2nd light target ‘built-in’: Silicon/Germanium, lighter target would be more convenient

- Physics cases to be explored & an educated guess of relevance
  - Charm: inclusive production in view of hadron structure, energy loss and hadronization
    - Hadronization studies interesting & nearly for ‘free’ given charm baryon focus
    - Hadron structure & E-loss: 2nd light target, rapidity range, precision
  - Exclusive: photoproduction in view of hadron structure & spectroscopy
    - doable for vector meson provided luminosity, difficult to compete with Jlab photo/electro-production, open-charm production require careful study of S/B, luminosity, rapidity range requirements
  - Ultra-low momentum: bulk and electromagnetic particle production
    - Require single-track acceptance to judge, nucleus-nucleus collisions would be a major motivation
- Factors for impact
  - Precision: first measurements exist or will exist, apart from hadronisation percent-level precision required
  - Luminosity (Charm+Exclusive)
  - Rapidity extent (all cases except ultra-low momentum)
  - Other targets (Charm(pA(light)), Ultra-low momentum (nucleus-nucleus))
  - Track-pT acceptance (ultra-low momentum)

Physics cases not covered

Collection of ‘classic’ physics cases (hadron structure/QGP): **A fixed-target programme at the LHC, Hadjidakis et al. (2018)**
https://inspirehep.net/literature/1680452

New development: Nuclear structure from correlation measurements in nucleus-nucleus

- Aladdin: solid target bring more options in the game
- See for introduction: PhD thesis of Giuliano Giacalone: A matter of shape: seeing the deformation of atomic nuclei at high-energy colliders: https://inspirehep.net/literature/1839199
- Workshop on the topic at CERN: https://indico.cern.ch/event/1436085/