Event Generators for Heavy Ion Collisions

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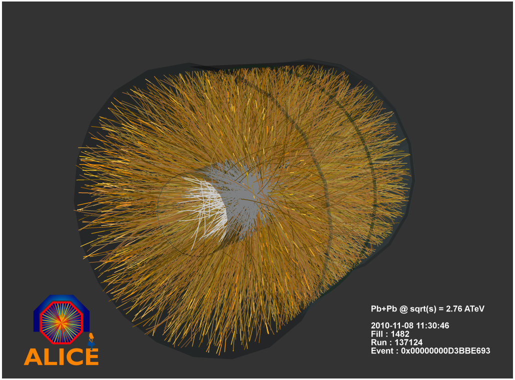
MCnet Summer School 2024

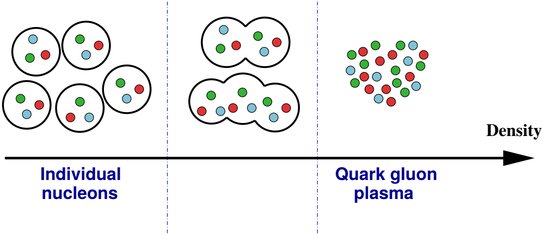
A heavy ion collision



- $\sim$ 1600 primary charged hadrons per unit rapidity
- system with high energy density $\rightarrow$ final state re-scattering

What is this stuff we're producing? – qualitative arguments

- QCD is asymptotically free → becomes weakly coupled at high temperature and/or density



S. Flörchinger, ESHEP 2015

- formation of a quark-gluon plasma (QGP)
  - (anti-)quarks and gluons become deconfined
  - chiral symmetry is restored
- in heavy ion collisions at collider energies: nuclei are largely transparent → central rapidity region essentially baryon-free

Why do we care?

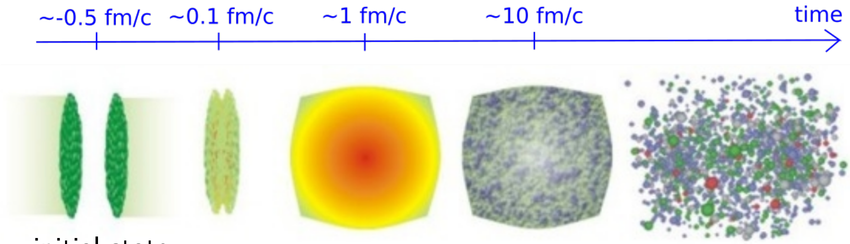
Differences between p+p and A+A collisions

- high multiplicities & extreme densities
- strong final state re-scattering
- geometry plays important role

Why are heavy ion collisions interesting?

- QGP: only strongly coupled system of Standard Model microscopic degrees of freedom
  - How do heavy ion collisions equilibrate?
  - How does collectivity arise in asymptotically free theory?
- QGP: "simplest form of complex quantum matter"
  - How does multitude of complex materials arise from simple underlying theory?

Timeline of heavy ion collisions



initial state

pre-equilibrium dynamics

hydrodynamic expansion

hadronisation

hadronic re-scattering

picture from https://phy.duke.edu/modeling-relativistic-heavy-ion-collisions

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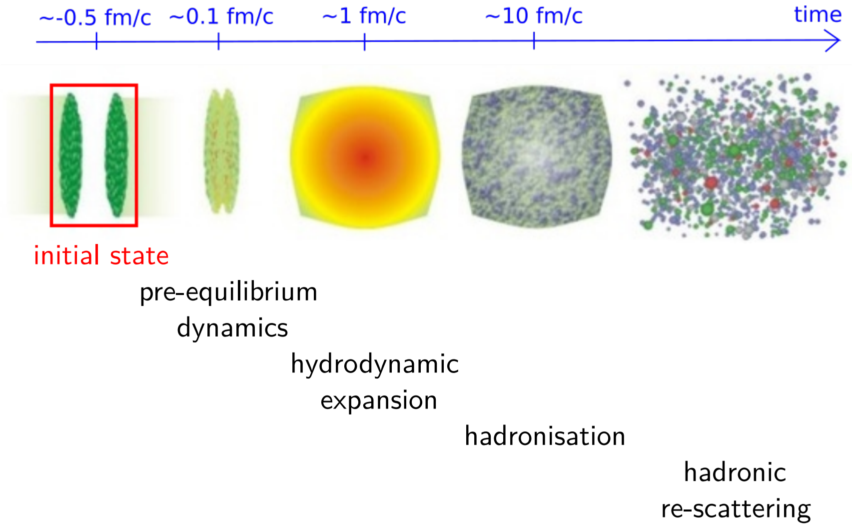


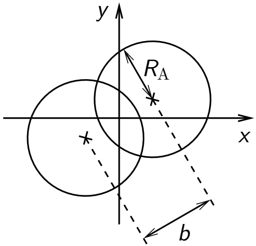
Centrality

impact parameter b: transverse distance between centres of colliding nuclei

centrality: fraction of geometric cross section

N_{part}: number of nucleons involved in collision

N_{coll}: number of binary nucleon–nucleon collisions

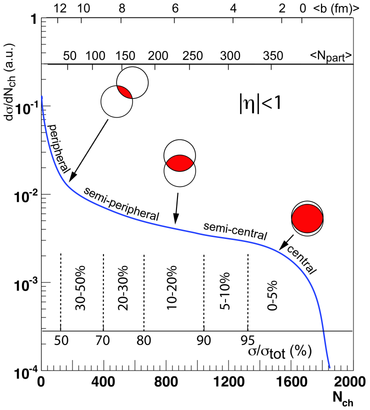


Particle production

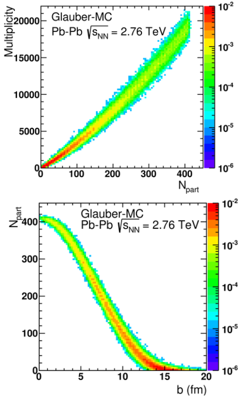
- soft particle production: scales with N_{part}
- hard particle production: scales with N_{coll}

Measuring centrality

- one option: forward multiplicity
- relation to b or N_{part} relies on models



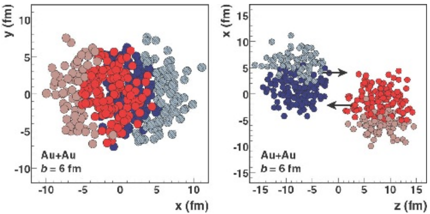
Sarkar, Satz, Sinha, "The physics of the quark-gluon plasma", Lect. Notes Phys. **785** (2010) pp.1



ALICE, Phys. Rev. C **91** (2015) no.6, 064905 [arXiv:1412.6828]

Monte Carlo Glauber model

- simple way of dealing with event-by-event fluctuations
- distribute nucleons in nucleus according to nuclear potential
- for each nucleon in one nucleus calculate number of nucleons in other nucleus with transverse distance $< \sqrt{\sigma_{\text{inel}}^{\text{NN}}/\pi}$
- from this compute N_{part} and N_{coll}
- some allow for fluctuations in cross section → Good-Walker states

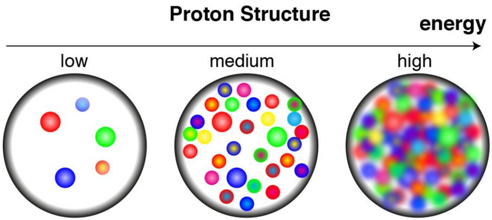


Miller, Reygers, Sanders, Steinberg, Ann. Rev. Nucl. Part. Sci. **57** (2007) 205 [nucl-ex/0701025]

Gluon saturation

- soft particle production probes low-x gluons
- rapid rise of gluon density due to scale evolution
- at high gluon densities recombination becomes important

  slows down evolution and leads to gluon saturation
- saturation scale Q_s: typical $p_\perp$ of saturated gluons
- or: saturated gluons have size $1/Q_s$
- for RHIC and LHC energies Q_s is of order a few GeV



https://www.uu.nl/en/research/institute-for-subatomic-physics/research/color-glass-condensate

The Colour Glass Condensate (CGC)

CGC in a nutshell

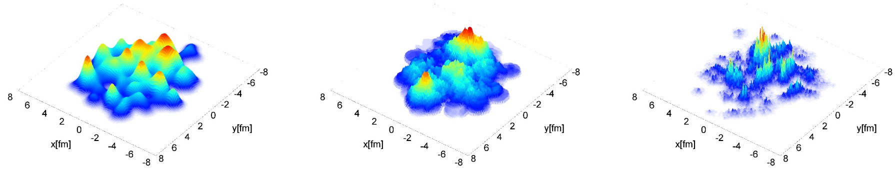
- hard valence partons: "frozen" by time dilation, colour sources for
- saturated gluons with typical momenta Q_s
- saturated gluons have occupation number $1/\alpha_s \rightarrow$ over-occupied
- strong fields but weakly coupled $(\alpha_s(Q_s) \ll 1)$
- can be described using classical field theory

MC models

- use MC method to sample distribution of colour charges
- solve classical Yang-Mills equations to get gluon fields
- IP-Glasma — Schenke, Tribedy, Venugopalan, Phys. Rev. Lett. **108** (2012), 252301
- MC-KLN — Hirano, Heinz, Kharzeev, Lacey, Nara, Phys. Lett. B **636** (2006), 299-304

Comparing different models

- compute distribution of energy density ϵ in different models
- Glauber model doesn't predict ϵ
  $\rightarrow$ have to make assumptions & tune to data
- here: for each participant add Gaussian with width 0.4 fm
- in contrast: length scale for fluctuations in IP-Glasma is $1/Q_s$



Glauber-MC MC-KLN IP-Glasma

Schenke, Tribedy, Venugopalan, Phys. Rev. Lett. **108** (2012) 252301 [arXiv:1202.6646]

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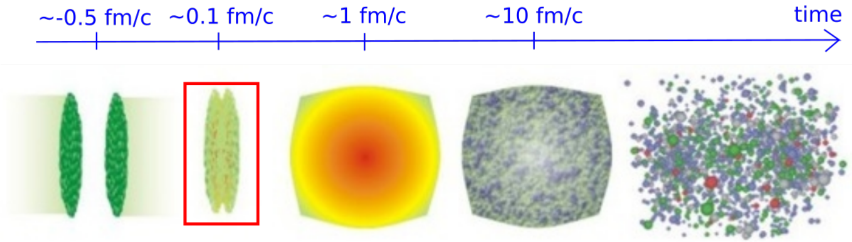

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Kinetic theory

- assumptions: system consisting of (quasi-)particles with local binary interactions
- Boltzmann equation:

$$-(\partial_t + \mathbf{v} \cdot \nabla_x) f(\mathbf{x}, \mathbf{p}, t) = \mathcal{C}[f]$$

- evolution of phase space density $f(\mathbf{x}, \mathbf{p}, t)$ in presence of scattering
- dynamics encoded in collision kernel $\mathcal{C}[f]$
- applicable in- and out-of-equilibrium

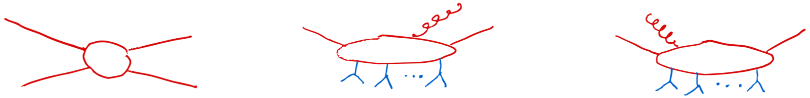
Kinetic theory and QCD

- AMY effective kinetic theory of QCD at high temperature

  Arnold, Moore, Yaffe, JHEP **01** (2003), 030 [hep-ph/0209353]

  - $\mathcal{C}_{\text{“}1\leftrightarrow 2\text{”}}$: splitting/merging rate in presence of multiple scattering

    coherent multiple scattering suppresses rate $\rightarrow$ LPM effect
  - $\mathcal{C}_{2\leftrightarrow 2}$: elastic scattering rate



$2 \leftrightarrow 2$ "$1 \rightarrow 2$" "$2 \rightarrow 1$"

- dynamical colour screening
- equilibration on timescales $\lesssim 1\,\text{fm/c}$

Parton cascades

- solve Boltzmann equation by explicit simulation
- way of treating fluctuations
- partons interact when they are closer than $\sqrt{\sigma/\pi}$
- potential problems with causality violation
- large number of codes, a few examples:
  - ZPC: only elastic scattering regulated by screening mass

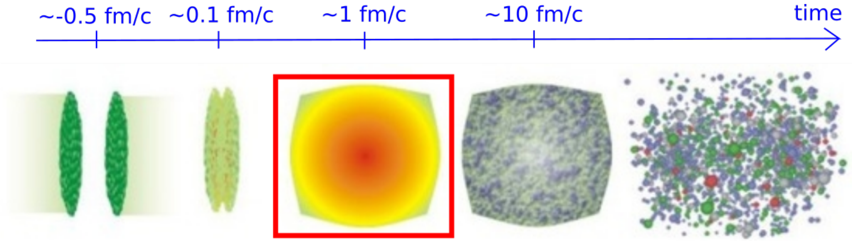
    Zhang, Comput. Phys. Commun. **109** (1998), 193-206 [nucl-th/9709009]
  - PCPC: elastic scattering, first Lorentz invariant parton cascade

    Borchers, Meyer, Gieseke, Martens, Noack, Phys. Rev. C **62** (2000), 064903 [hep-ph/0006038]
  - BAMPS: $2 \leftrightarrow 2$ and $2 \leftrightarrow 3$ scattering regulated by screening mass

    Xu, Greiner, Phys. Rev. C **71** (2005), 064901 [hep-ph/0406278]
  - ALPACA: implementation of AMY effective kinetic theory

    Kurkela, Törnkvist, Zapp, Eur. Phys. J. C **84** (2024) no.1, 74 [2211.15454]

Timeline of heavy ion collisions



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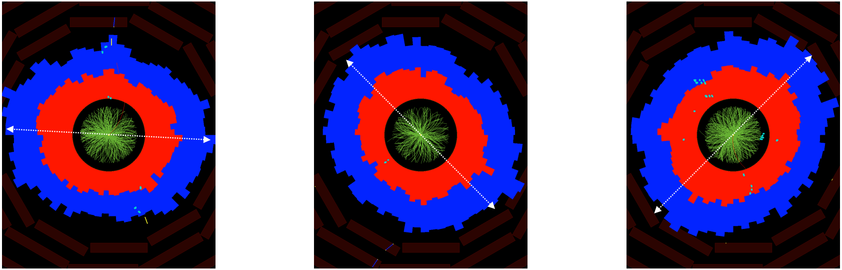
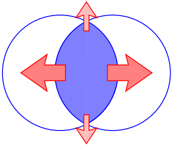
First main discovery of heavy ion physics



event displays from G. Roland, CMS



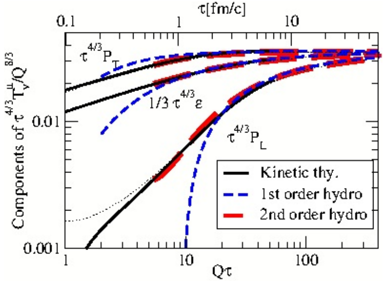
- anisotropy due to different pressure gradients

→ collective flow

- sensitive to fluctuations in geometry

Event generators for hydrodynamic phase

- most commonly modelled by hydrodynamics
- parton cascades can also do this if the system supports a description in terms of quasi-particles

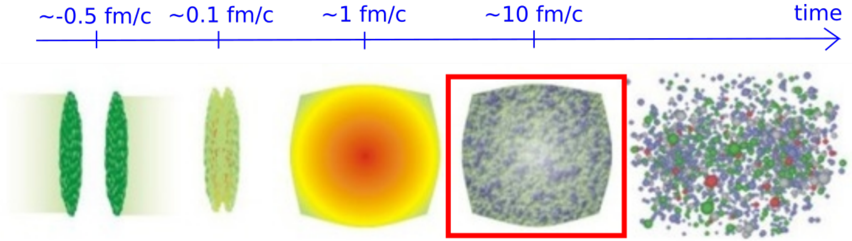


Kurkela, Zhu, Phys. Rev. Lett. **115** (2015) no.18, 182301

- alternative: DQPM (off-shell partons with spectral function)

Peshier, Cassing, Phys. Rev. Lett. **94** (2005), 172301 [hep-ph/0502138]

Timeline of heavy ion collisions



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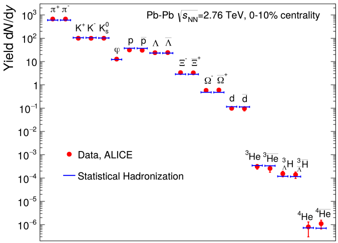
Hadronisation models

- statistical hadronisation
  - assume system in thermal & chemical equilibrium
  - hadron abundances determined by temperature and baryon chemical potential
  - naturally explains strangeness enhancement
  - e.g. THERMINATOR

Andronic, Braun-Munzinger, Redlich, Stachel, Nature **561** (2018) no.7723, 321



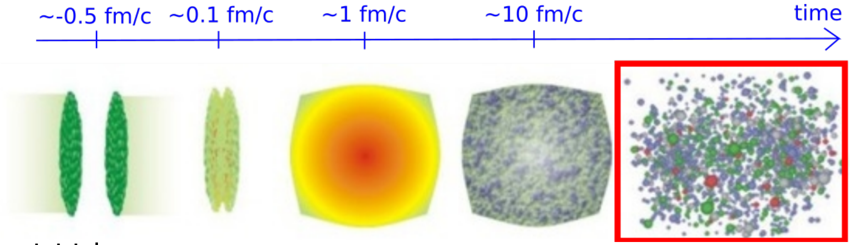
Chojnacki, Kisiel, Florkowski, Broniowski, Comput. Phys. Commun. **183** (2012), 746-773

- quark coalescence — Greco, Ko, Levai, Phys. Rev. C **68** (2003), 034904
  - similar to cluster model, but including space-time information
- string fragmentation (→ PYTHIA)
- beyond standard strings: colour ropes

Bierlich, Gustafson, Lönnblad, Tarasov, JHEP **03** (2015), 148 [1412.6259]

  - overlapping strings combine to ropes of higher colour

Timeline of heavy ion collisions



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Re-scattering in hadronic phase

Transport codes

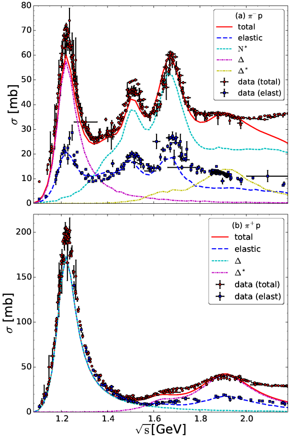
- explicit simulation with transport codes
- based on Boltzmann equation
- need to include large number of resonances & cross sections
- UrQMD & SMASH

Petersen, Bleicher, Bass, Stocker, [arXiv:0805.0567]

Weil *et al.*, Phys. Rev. C **94** (2016) no.5, 054905

- both can simulate entire HIC

important at lower beam energies

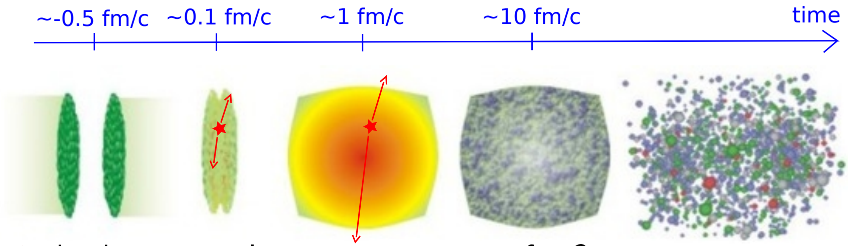


PYTHIA

- now also has a model for hadronic re-scattering

Bierlich, Sjöstrand, Utheim, Eur. Phys. J. A **57** (2021) no.7, 227 [arXiv:2103.09665]

Hard processes: timescale



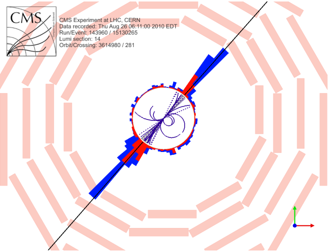
- hard processes: large momentum transfer Q
- corresponds to short time scales $\Delta t \sim 1/Q$

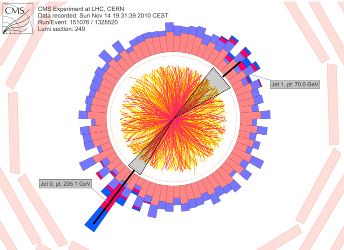
  due to uncertainty principle

- first processes to happen in heavy ion collision
- time/length scales of production processes too short to feel nuclear environment
- produced hard particles traverse QGP

Second main discovery of heavy ion physics

Jet quenching: Hard jets are suppressed and their structure modified.





- p+p collisions: 2 jets with balancing transverse momentum
- in heavy ion collisions: significant softening of jets

→ thermalisation of a far-from-equilibrium system

→ jet quenching informs us about equilibration in QCD

Factorisation in nuclear environment

- production cross section for hard particles:

$$\sigma(P_1, P_2) = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}_{ij}(x_1 P_1, x_2 P_2, \alpha_s, Q^2)$$

  - $\hat{\sigma}_{ij}$: short distance physics: insensitive to nature of incoming hadrons — i.e. no nuclear modifications
  - $f_i(x, Q^2)$: nuclear pdf fits available — at best moderate effects
- observed cross section may be lower due to final state interactions
  - electroweak gauge bosons: escape without final state interaction
  - jets: strong final state re-scattering → jet quenching
  - quarkonia: interesting story, but no time

What happens to jets in medium?

Scenario I: hard partons don't resolve quasi-particles

- interactions between jet & medium at large coupling
- AdS/CFT techniques

Scenario II: hard partons do resolve quasi-particles

- jet – medium interactions at weak(ish) coupling
- perturbative techniques
- thermalisation through elastic re-scattering (slow)
- parton energy loss through QCD bremsstrahlung
- destructive interference in multiple scattering LPM effect

relevant scale: momentum transfer q between hard parton and medium

Jet quenching MCs

- Q-PYTHIA/Q-HERWIG: standard parton shower with modified splitting function $P_{\text{tot}} = P_{\text{vac}} + P_{\text{BDMPS}}$

  Armesto, Cunqueiro, Salgado, Eur. Phys. J. C **63** (2009), 679-690 [arXiv:0907.1014]
- MARTINI: based on AMY transition rates (elastic & inelastic)

  Schenke, Gale, Jeon, Phys. Rev. C **80** (2009), 054913 [0909.2037]
- Hybrid: PYTHIA 8 parton shower + strong coupling (AdS/CFT) energy loss

  Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, JHEP **10** (2014), 019 [erratum: JHEP **09** (2015), 175]
- LBT: regularised pQCD elastic scattering + additional gluon radiation from higher twist formalism

  Wang, Zhu, Phys. Rev. Lett. **111** (2013) no.6, 062301 [1302.5874]
- JetMed: DLA treatment of vacuum & medium induced emissions

  Caucal, Iancu, Soyez, JHEP **10** (2019), 273 [1907.04866]
- JETSCAPE: modular framework for combining different jet and background models

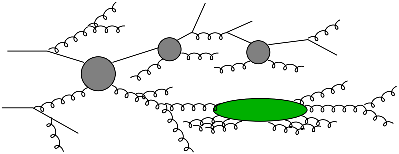
  Putschke *et al.* [1903.07706]

JEWEL in a nutshell

Zapp, Krauss & Wiedemann, JHEP **1303** (2013) 080

Assumptions

1. medium as seen by jet: collection of quasi-free partons
2. use perturbation theory to describe interactions between hard partons and QGP



- radiation and re-scattering interleaved
- re-scatterings within emission's formation time are coherent

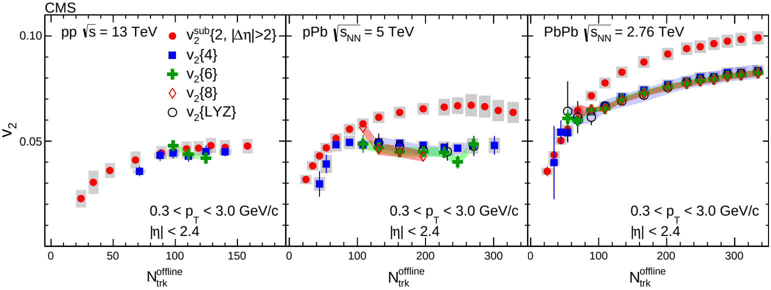
$\rightarrow$ LPM effect

Third main discovery of heavy ion physics

- (partial) equilibration of final state in A+A
  - expectation: p+p qualitatively different from A+A

    p+p collisions too dilute to develop collectivity
  - observed:

Soft particle production in high-multiplicity p+p and p+A closely resembles A+A, but so far no jet quenching is observed.

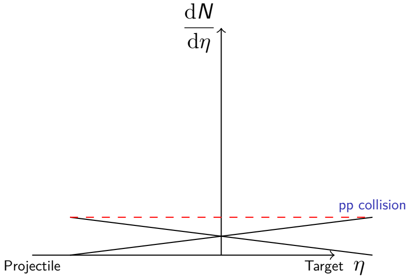


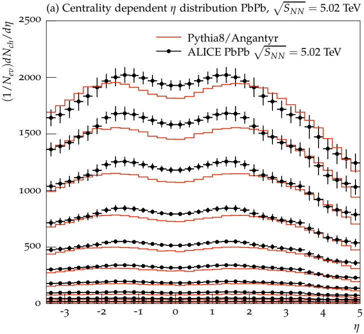
CMS, Phys. Lett. B **765** (2017) 193

ANGANTYR

Bierlich, Gustafson, Lönnblad, Shah, JHEP **10** (2018), 134 [arXiv:1806.10820]

- baseline without final state interactions
- wounded nucleon model
- stack nucleon–nucleon collisions with advanced Glauber model
- event generation with diffractive event generation in PYTHIA





- can add string interactions (ropes & shoving) on top

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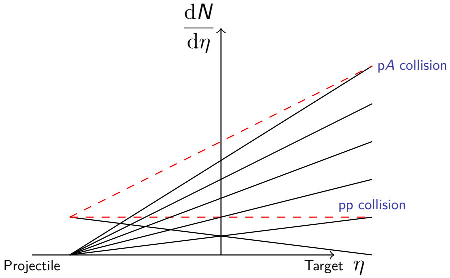

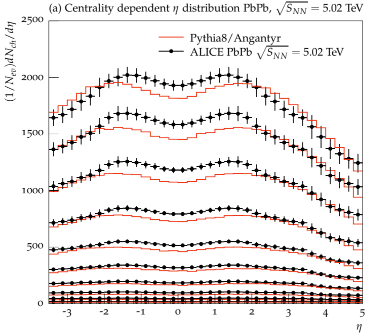

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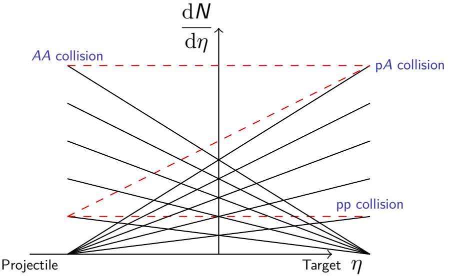
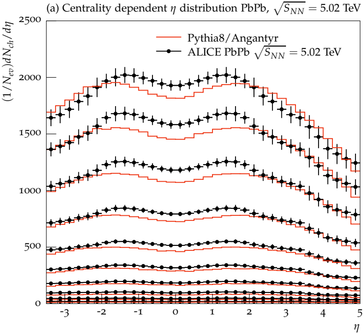




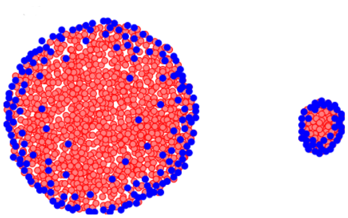
- can add string interactions (ropes & shoving) on top

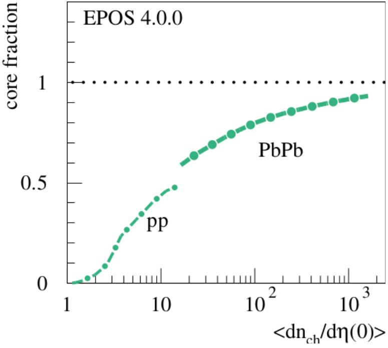
EPOS

Werner, Phys. Rev. C **108** (2023) no.6, 064903 [arXiv:2301.12517]

- pomeron exchange
- string hadronisation
- high density regions: hydrodynamics + statistical hadronisation

→ core–corona picture





Other event generators

- HIJING
  Deng, Wang, Xu, Phys. Rev. C **83** (2011), 014915 [1008.1841]
  - eikonal model for soft and hard scattering
  - individual nucleon-nucleon interactions generated with PYTHIA
  - model for impact parameter dependent nuclear PDFs
  - simple model for induced gluon radiation
- HYDJET
  Lokhtin, Malinina, Petrushanko, Snigirev, Arsene, Tywoniuk, Comput. Phys. Commun. **180** (2009), 779-799
  - soft event: parametrised hydro + statistical hadronisation
  - hard event: Glauber model + PYTHIA + induced gluon emission (BDMPS) and elastic energy loss
- AMPT
  Lin, Ko, Li, Zhang, Pal, Phys. Rev. C **72** (2005), 064901 [nucl-th/0411110]
  - HIJING: hadrons are dissolved into their valence quarks
  - ZPC
  - hadronisation: simple coalescence model
  - hadronic re-scattering (ART)

Conclusions

- heavy ion physicists use event generators to
  - make a very complex problem tractable
  - be able to compare to data
  - deal with fluctuations
- no consensus about relevant physics
- fluctuations are important
- no general purpose event generators, but many specialised codes
- different use cases for event generators:

  parametrisation of data vs. predictive theory tool
- signs for collective behaviour in small collision systems bring heavy ion and particle community into closer contact