Heavy Ion Physics

part II

Korinna Zapp

Lund University

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First lecture: summary

- heavy ion collisions: unique opportunity to study matter at extreme conditions (temperature and pressure)
- formation of new phase of QCD matter: quark-gluon plasma

  $\rightarrow$ deconfinement, chiral symmetry restoration
- QGP: only strongly coupled system of Standard Model microscopic degrees of freedom
- what we have learned so far
  - QGP created in heavy ion collisions at RHIC and LHC
  - “rapid hydrodynamisation”
  - QGP is a strongly coupled liquid

Summary: stages of a heavy ion collision

- initial state:
  - geometry ($\rightarrow$ Glauber model)
  - gluon saturation ($\rightarrow$ colour glass condensate)
- pre-equilibirium dynamics:
  - successful descriptions at weak (kinetic theory) and strong coupling (AdS/CFT)
  - leads to hydrodynamic regime on timescales $\mathcal{O}(1\,\mathrm{fm/c})$
- hydrodynamic expansion:
  - the QGP flows $\rightarrow$ collective behaviour
  - least dissipative system known ($\eta/s \gtrsim 1/4\pi$)
- hadronisation: phenomenological modeling
- hadronic re-scattering: hydrodynamics or transport theory

more important at lower beam energies

Outline of today's lecture

Hard processes
- Factorisation and nuclear PDFs
- Quarkonia
- Elecroweak bosons
- Jets

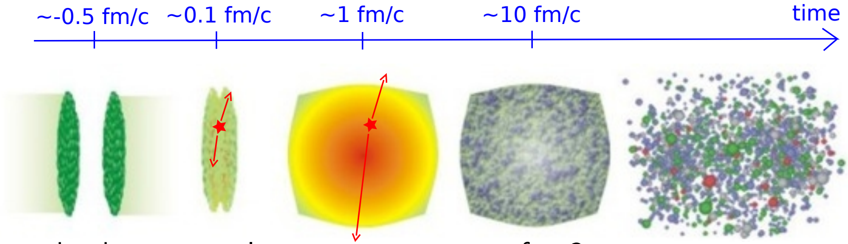
Small collision systems

Ultra-peripheral collisions

Summary

Outline

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

Factorisation of the cross section

- factorisation of the cross section:

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

- $\hat{\sigma}_{ij}$: partonic cross section
  - has perturbative expansion in α_s
    known: NNLO for di-jets, NLO for up to ~ 5 jets
  - short distance physics: insensitive to nature of incoming hadrons
    i.e. no nuclear modifications
- $f_i(x, Q^2)$: parton distribution function
  nuclear pdf fits available

Nuclear PDFs: EPPS16

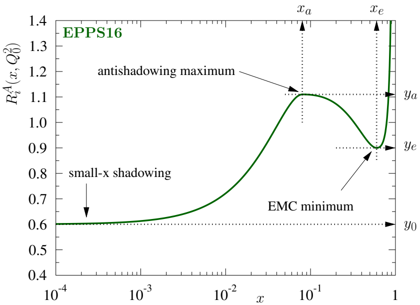
Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C **77** (2017) no.3, 163

- bound proton PDF defined as

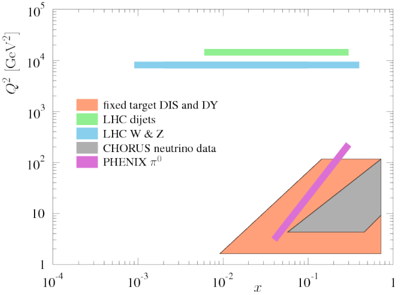
$$f_i^{\mathrm{p}/\mathrm{A}}(x, Q^2) = R_i^A(x, Q^2) f_i^{\mathrm{p}}(x, Q^2)$$

- bound neutron PDF from isospin symmetry

- Q^2 dependence: DGLAP with 2-loop splitting functions
- parametrise R_i^A and fit for chosen free proton PDF (in this case CT14NLO)
- other nPDF sets: nCTEQ15, DSSZ



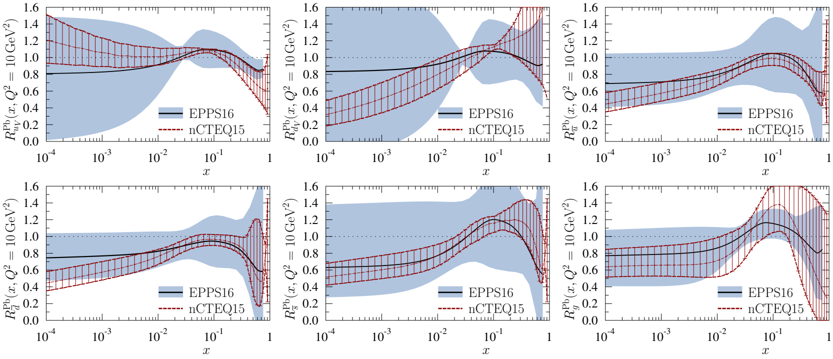
Nuclear PDFs



Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C **77** (2017) no.3, 163

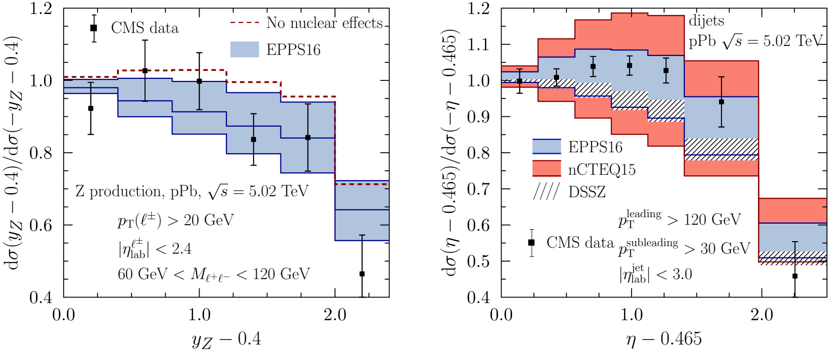
- consistent fit to all available data
- constraining data sparse $\rightarrow$ sizeable uncertainties
- modifications less important at higher momentum scales

Nuclear PDFs



Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C **77** (2017) no.3, 163

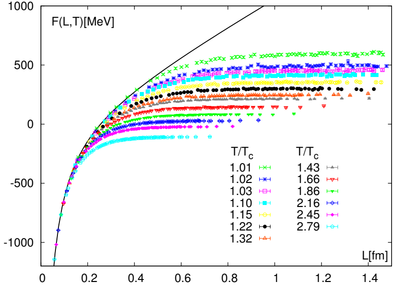
Nuclear PDFs



Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C **77** (2017) no.3, 163

Quarkonium suppression: idea

- in deconfined medium: colour screening
- attractive force between quark and anti-quark screened

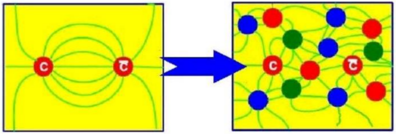


Ewerz, Kaczmarek, Samberg, JHEP **1803** (2018) 088 [arXiv:1605.07181]

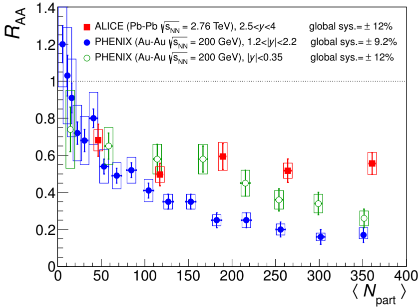
- should lead to dissociation of bound states
- suitable states to observe this: charmonium & bottomonium

Matsui & Satz, 1986

J/Ψ suppression



Cartoon: T. Tveter

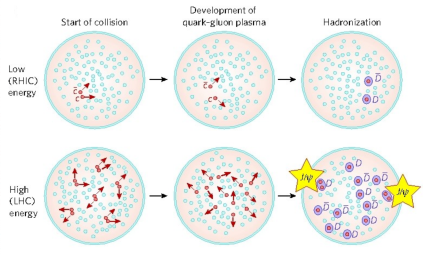


ALICE, Phys. Rev. Lett. **109** (2012) 072301 [arXiv:1202.1383]

- ✓ clear suppression of J/Ψ
- ✗ weaker suppression at higher cms energy

J/Ψ regeneration

- charm quarks produced early in a hard processes
  too heavy for thermal production
- quark move quasi-freely in QGP phase



picture: J. Stachel

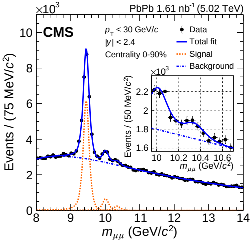
- at phase boundary J/Ψ production by combinatorics
- J/Ψ production rate depends sensitively on charm cross section
- effect increases rapidly with cms energy

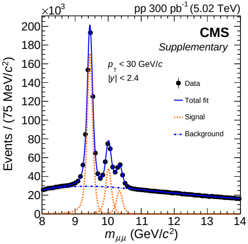
Sequential suppression

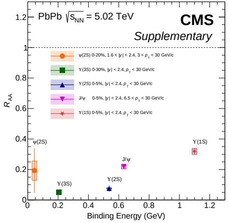
state	J/Ψ	Ψ'	Υ	Υ'	Υ''
mass [GeV]	3.10	3.68	9.46	10.02	10.36
ΔE [GeV]	0.64	0.05	1.10	0.54	0.20
r [fm]	0.25	0.45	0.14	0.28	0.39

- expect dissociation at different temperatures
- "QGP thermometer"

Sequential suppression







CMS, arXiv:2303.17026

- there is an indication of sequential suppression
- the story is actually much more complicated

static potential over-simplified, quarkonia not produced at rest, . . .

Nuclear modification factors

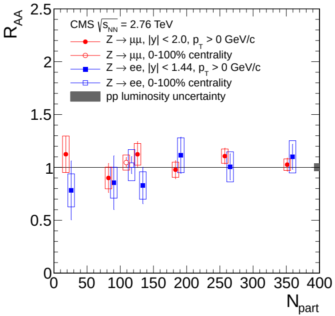
- standard procedure for quantifying QGP effects: divide by result from p+p
- but: have to scale p+p result by number of N-N collisions

hard processes scale like N_{coll}

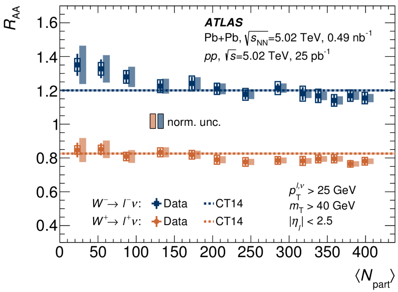
$$R_{AA}(\{\cdot\}) = \frac{\left.\frac{\mathrm{d}\sigma_X}{\mathrm{d}\{\cdot\}}\right|_{AA}}{\langle N_{\mathrm{coll}}\rangle \left.\frac{\mathrm{d}\sigma_X}{\mathrm{d}\{\cdot\}}\right|_{pp}}$$

- deviations from unity signal effects beyond incoherent superposition of nucleon-nucleon collisions
- in case of electroweak processes: have to take different isospin composition into account

W & Z production



CMS, JHEP **1503** (2015) 022 [arXiv:1410.4825]

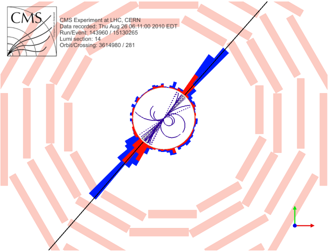


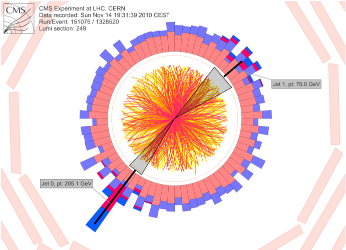
ATLAS arXiv:1907.10414

- no significant deviation from unity
- W and Z don't interact strongly → leave dense interaction region without re-scattering
- important confirmation of N_{coll} scaling and nPDFs

Second main discovery of heavy ion physics

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



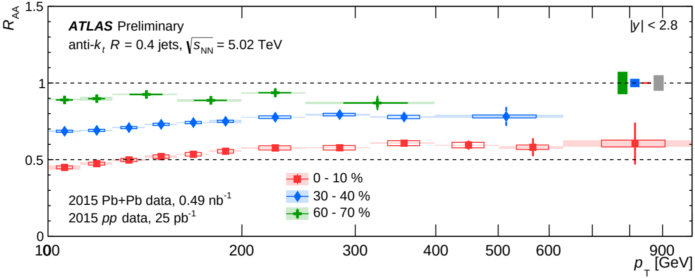


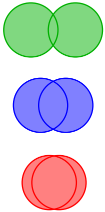
- proton-proton collisions: 2 jets with balancing transverse momentum
- in heavy ion collisions: significant softening of jets

→ thermalisation of a far-from-equilibrium system

→ jet quenching informs us about equilibration in QCD

Suppression of single-inclusive jets



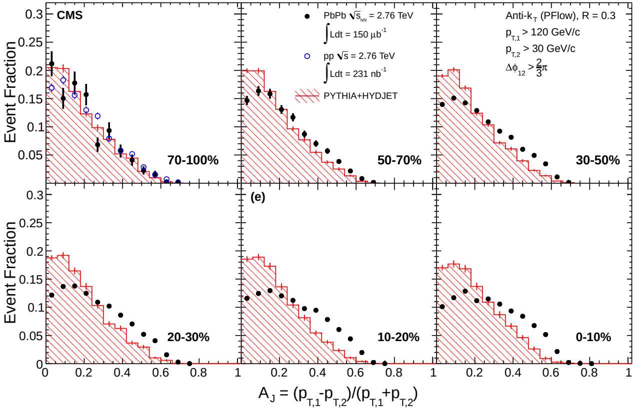


ATLAS-CONF-2017-009

- suppression of jets by factor 2 relative to expectation from p+p

  need to scale p+p reference by number of hard N+N collisions

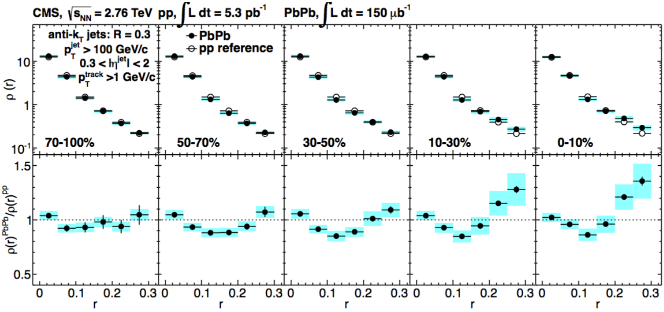
Di-jet momentum asymmetry

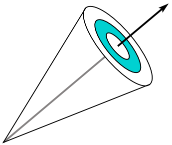


CMS, Phys. Lett. B **712** (2012) 176

- enhancement of asymmetric configurations

Intra-jet energy distribution: Jet profile



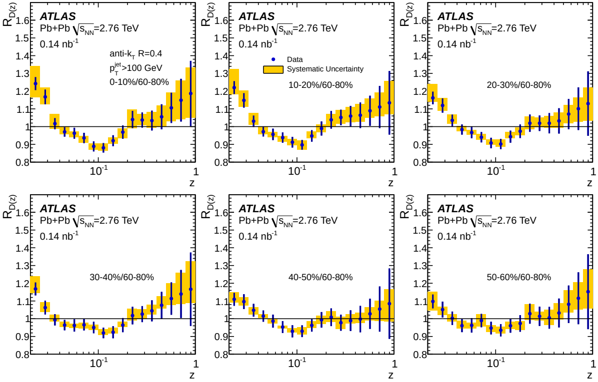


CMS, Phys. Lett. B **730** (2014) 243

- suppression of activity at intermediate r
- increase near the edge of the jet

Intra-jet energy distribution: fragmentation function

$$z = \frac{p_{\perp,h}}{p_{\perp,J}} \cos(\Delta R_{hJ})$$



ATLAS, Phys. Lett. B **739** (2014) 320

- distribution of hadrons inside jets
- suppression at intermediate & enhancement of soft momenta

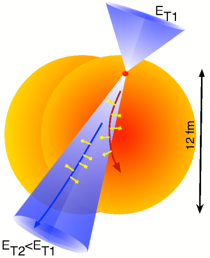
A first lesson

Summary of experimental results

- jet production suppressed by factor ~ 2 up to $p_\perp$'s of 1 TeV
- hard structures inside jets survive largely unmodified
- enhancement of soft activity far away from jet axis

A first lesson to be learned

- energy loss from jets driven by peeling off of soft gluons
- rare, semi-hard emissions not an important effect
- both were equivalent in early calculations

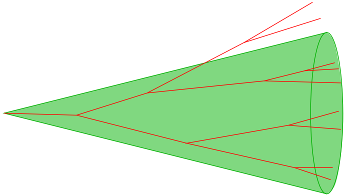


Casalderrey-Solana, Milhano, Wiedemann, J. Phys. G 38 (2011) 035006 [arXiv:1012.0745]

What is unique about jet quenching

- "calibrated" probe: well understood in p+p

  fixed order matrix elements + resummation (parton showers)



- jet quenching allows to observe *process* of equilibration

  soft observables see *result* of equilibration

- jets give access to scale dependence of medium properties

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 at strong coupling

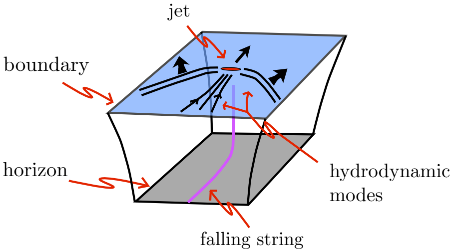
Advantages:

1. exact solution of gauge theory at strong coupling
2. no uncertainty in jet-medium interaction

Fundamental problems:

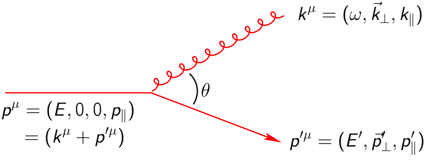
1. jets are a weak-coupling phenomenon
2. QCD is not $\mathcal{N} = 4$ SYM

"holographic jet":
$q\bar{q}$ pair in QGP dual to classical string in black hole geometry



Chesler, Jensen, Karch, Yaffe, Phys. Rev. D **79** (2009) 125015
Chesler & Rajagopal, JHEP **1605** (2016) 098

How long does it take to radiate a gluon?



assume: massless quark

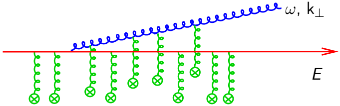
- virtual state: $p^2 = E^2 - \mathrm{p}^2 \neq 0 \quad \rightarrow \quad m_{\text{virt}}^2 = p^2$
- uncertainty principle: $1 = \Delta t \, \Delta E = \Delta t \;\, m_{\text{virt}}$
- gluon formation time: $t_{\text{form}} = \Delta t \times (\text{boost factor})$

$$t_{\text{form}} = \frac{1}{m_{\text{virt}}} \frac{E}{m_{\text{virt}}} = \frac{E}{2 p_\mu k^\mu} \simeq \frac{E}{\omega E \theta^2} \simeq \frac{\omega}{k_\perp^2}$$

- time for entire jet evolution: $\mathcal{O}((1-10)\,\text{fm})$
- (transverse) size of medium: $\mathcal{O}((1-10)\,\text{fm})$

Bremsstrahlung in medium: heuristic discussion

Baier, Dokshitzer, Mueller, Peigne, Schiff, Nucl. Phys. B **483** (1997) 291
Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. **50** (2000) 37



$$E \gg \omega \gg k_\perp, q_\perp$$

Brownian motion of the gluon: $\langle k_\perp^2 \rangle = \hat{q} L$

formation time of the radiated gluon:

$$t_\mathrm{f} \simeq \frac{\omega}{k_\perp^2} \simeq \frac{\omega}{\hat{q} t_\mathrm{f}} \quad \Rightarrow \quad t_\mathrm{f} = \sqrt{\frac{\omega}{\hat{q}}} \quad \text{and} \quad N_\mathrm{coh} = \frac{t_\mathrm{f}}{\lambda}$$

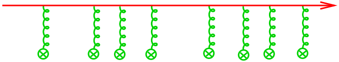
gluon energy spectrum:

$$\frac{\mathrm{d}^2 I^\mathrm{coh}}{\mathrm{d}\omega \mathrm{d}y} \simeq \frac{1}{N_\mathrm{coh}} \frac{\mathrm{d}^2 I^\mathrm{incoh}}{\mathrm{d}\omega \mathrm{d}y} \propto \frac{\alpha_\mathrm{s}}{\omega \lambda} \lambda \sqrt{\frac{\hat{q}}{\omega}} = \alpha_\mathrm{s} \sqrt{\hat{q}}\, \omega^{-3/2}$$

radiative energy loss: $\Delta E = \int_0^L \mathrm{d}y \int_0^{\omega_\mathrm{c}} \mathrm{d}\omega\, \omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}y} \propto \alpha_\mathrm{s} \hat{q} L^2$

Beyond parametric estimates

Eikonal (straight line) propagation



- interactions result in colour phase rotation
- in-medium propagator: Wilson line

$$W(x_{f+}, x_{i+}; \mathbf{x}_\perp) = \mathcal{P} \exp\left\{ ig \int_{x_{i+}}^{x_{f+}} d\xi \, A_-(\xi, \mathbf{x}_\perp) \right\}$$

path ordering ($\mathcal{P}$)

medium colour field ($A_-(\xi, \mathbf{x}_\perp)$)

Further developments

- non-eikonal propagation
- 2-gluon emission
- resummation of incoherent emissions
- ...

From partons to jets: antennae

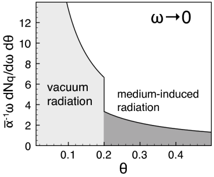
- consider colour singlet dipole in medium
- in vacuum colour coherence leads to angular ordering of radiation
- re-scattering in medium introduces new scale: $q_\perp$
- medium modifications depend on whether dipole is resolved

- in particular: unresolved structures remain unperturbed

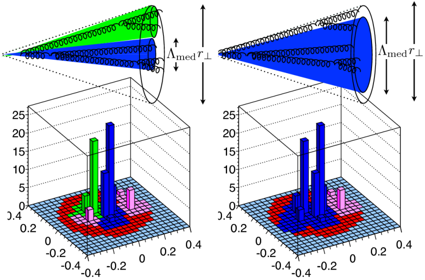
Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, Phys. Lett. B **725** (2013) 357

From partons to jets: antennae

- decoherence time scale: $\tau_{\mathrm{d}} \sim \left(\frac{1}{\hat{q}\theta^2_{q\bar{q}}}\right)^{1/3}$
- decoherence opens up phase space
- in soft limit: geometric separation



Mehtar-Tani, Salgado, Tywoniuk, JHEP **1204** (2012) 064 doi:10.1007/JHEP04(2012)064 [arXiv:1112.5031]

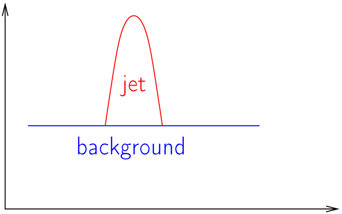


- can be generalised to jets

Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, Phys. Lett. B **725** (2013) 357 [arXiv:1210.7765]

Medium response

- medium response: medium's reaction to energy & momentum deposited by jet
- gives rise to additional soft activity
- momentum conservation $\rightarrow$ additional particles follow jet direction
- correlated background



- correlated background cannot and should not be subtracted
- rather, it is part of jet
- fluctuations matter

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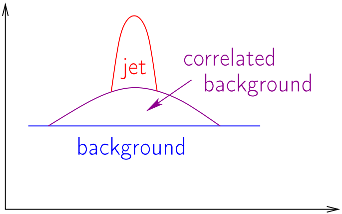

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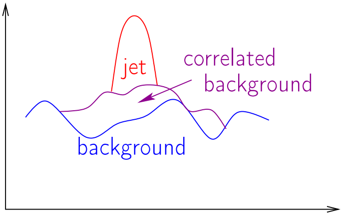

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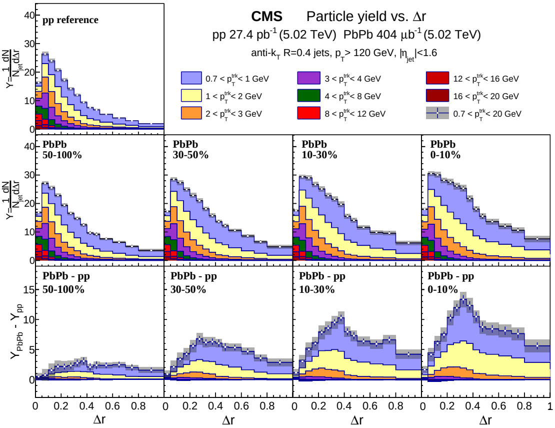
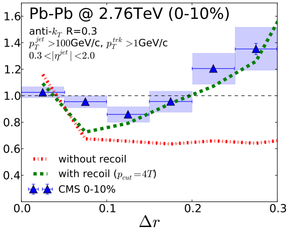
Particle distribution outside jets



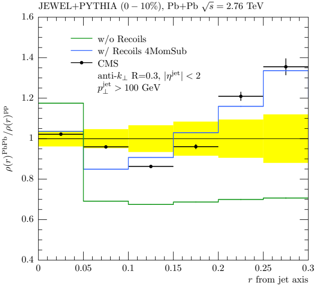
CMS, CMS-HIN-16-020, arXiv:1803.00042

- enhancement of soft particles far away from jet

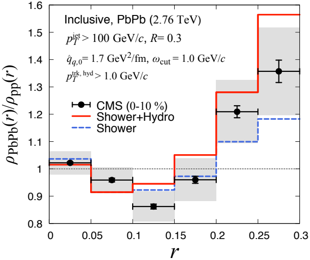
Some theory results



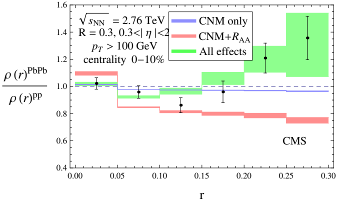
Park, Jeon, Gale, arXiv:1807.06550



Kunnawalkam Elayavalli, Zapp, JHEP 1707 (2017) 141

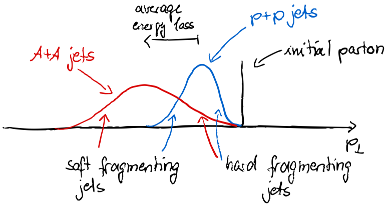


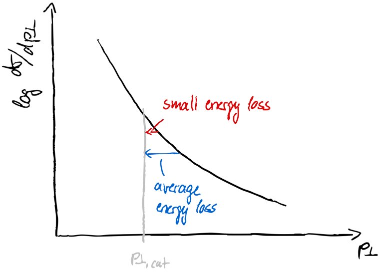
Tachibana, Chang, Qin, Phys. Rev. C 95 (2017) no.4, 044909



Chien, Vitev, JHEP 1605 (2016) 023

Selection bias





- jet spectrum steeply falling

→ selecting on final jet $p_\perp$ favors jets with small energy loss

- these are predominantly hard fragmenting, narrow jets
- bias stronger in A+A than in p+p
- complicates interpretation of jet shapes and sub-structure of quenched jets

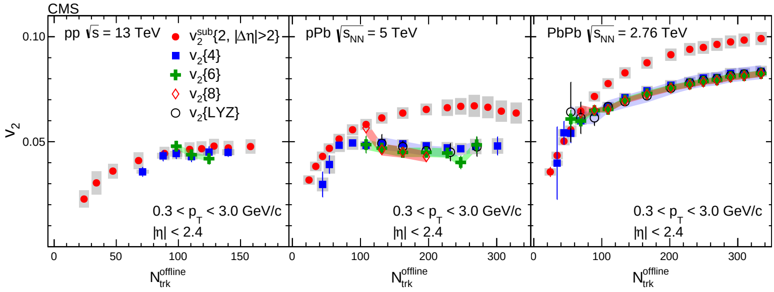
Outline

Third main discovery of heavy ion physics

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

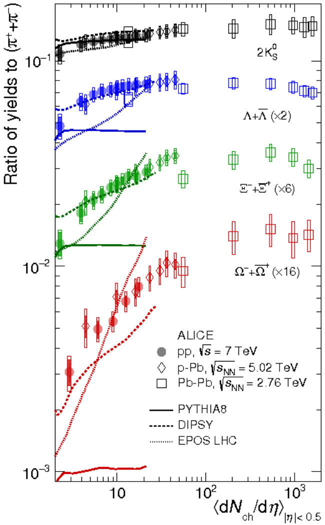
    p+p collisions too dilute to develop collectivity
  - observed:

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

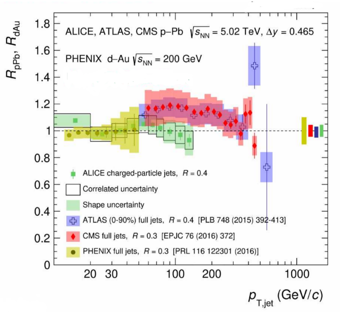
Strangeness enhancement



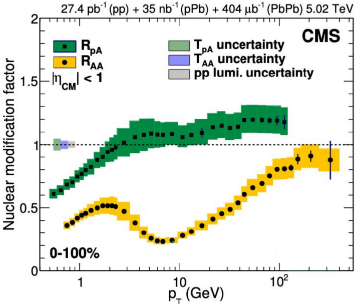
- strong increase of strange particle production with multiplicity
- traditional view: strangeness production in p+p suppressed due to *s* quark mass
- strangeness practically equilibrated in Pb+Pb collisions at LHC
- strangeness enhancement counted as signal for formation of hot system

ALICE, Nature Phys. 13 (2017) 535

Jet quenching



ALICE, arXiv:2307.10860



CMS, JHEP 04 (2017) 039

- no suppression of jets and leading hadrons in p+Pb
- large suppression in Pb+Pb collisions

Possible explanations for v_n's in p+p

Final state interactions

azimuthal anisotropies due to response to initial geometry

- hydrodynamics — Weller, Romatschke, Phys. Lett. B **774** (2017) 351
- kinetic theory — Kurkela, Wiedemann, Wu, Phys. Lett. B **783** (2018) 274

Initial state correlations

initial state correlations imprinted on final state

- color-glass condensate — Schenke, Schlichting, Venugopalan, Phys. Lett. B **747** (2015) 76

Alternative explanations

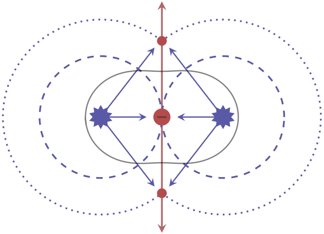
models inspired by p+p physics

- string shoving — Bierlich, Gustafson, Lönnblad, Phys. Lett. B **779** (2018) 58 [arXiv:1710.09725]

at hadronisation densely packed strings repel each other

The escape mechanism

Kurkela, Wiedemann, Wu, Phys. Lett. B **783** (2018) 274



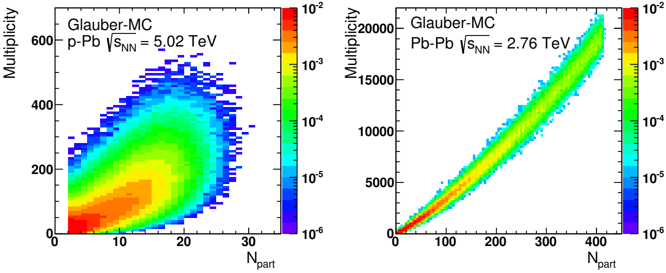
- initially isotropic particle distribution with spatial anisotropy
- local anisotropy where scatterings happen
- local isotropisation due to scattering induces global anisotropy

- requires only $\mathcal{O}(1)$ scattering per particle
- also observed in transport code AMPT

He, Edmonds, Lin, Liu, Molnar, Wang, Phys. Lett. B **753** (2016) 506

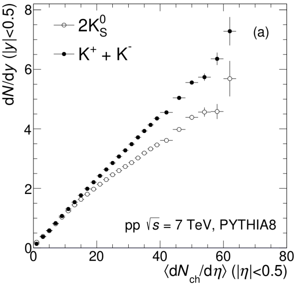
Important differences between small and large systems

- multiplicity generated in different ways:
  - Pb+Pb: requiring high multiplicity biases towards central events
  - p+p/Pb: requiring high multiplicity biases towards jetty events
- not clear what multi-particle correlations measure in jetty events
- no strong correlation between centrality and multiplicity



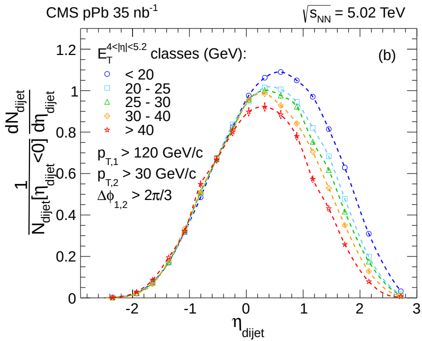
ALICE, Phys. Rev. C 91 (2015) no.6, 064905

Auto-correlations in small collision systems



O. Matonoha, PhD thesis

- autocorrelation with charged particle multiplicity at mid-rapidity
- improves when measuring $N_{\rm ch}$ at forward rapidity



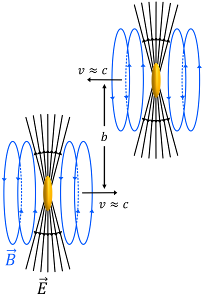
CMS, Eur. Phys. J. C **74** (2014) no.7, 2951

- but: rapidity shift of di-jets due to energy conservation

Armesto, Gülhan, Milhano, Phys. Lett. B **747** (2015) 441

Outline

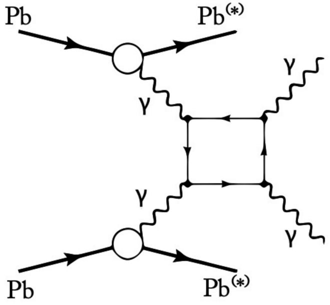
Ultra-peripheral collisions

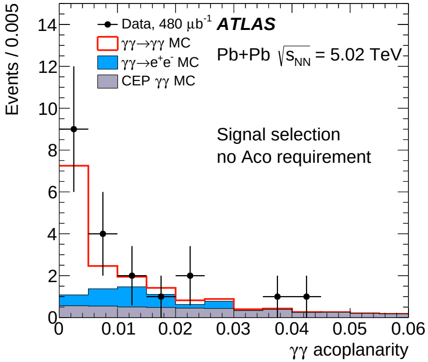


- relativistic ions are sources of strong EM fields
- $E_{\max} \approx 10^{16} - 10^{18}\text{V/m}$
  $B_{\max} \approx 10^{14} - 10^{16}\text{T}$
- strongest EM fields in universe
- very short-lived
- twp types of interactions: photon-photon scattering and photo-nuclear reactions

Light-by-light scattering

- first evidence for $\gamma\gamma \to \gamma\gamma$ scattering

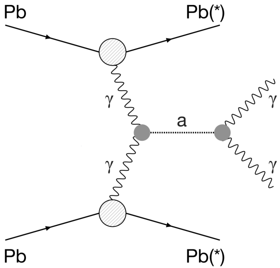


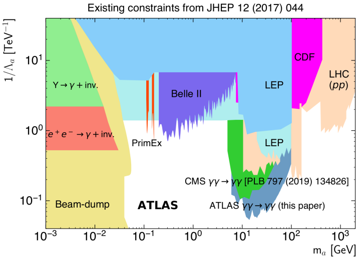


ATLAS, Nature Phys. 13 (2017) no.9, 852 [arXiv:1702.01625]

Light-by-light scattering

- sensitive to axion-like particles



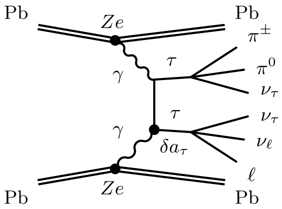


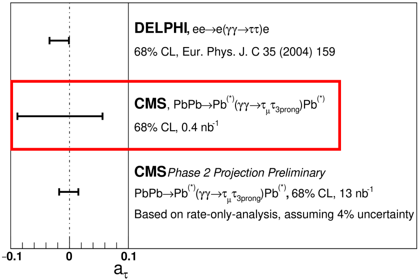
ATLAS, JHEP **03** (2021), 243 [erratum: JHEP **11** (2021), 050]

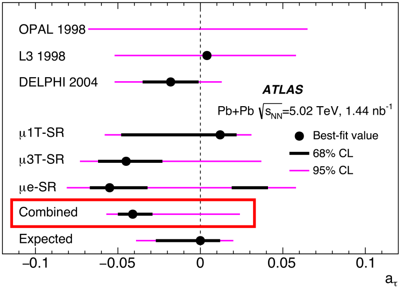
τ pair production

- sensitive to τ anomalous magnetic moment a_τ
- BSM sensitivity $\delta a_l \propto m_l^2$

$\rightarrow$ 280 $\times$ larger than for muon

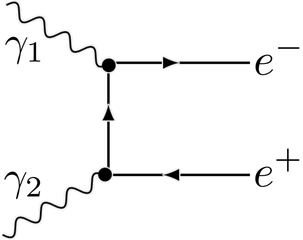






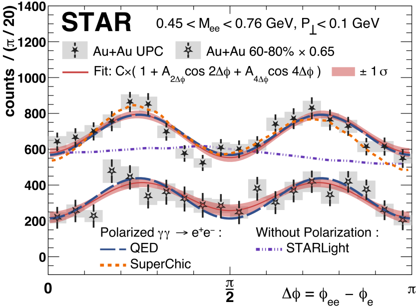
CMS, arXiv:2206.05192 & ATLAS, arXiv:2204.13478

Breit-Wheeler process and photon spin



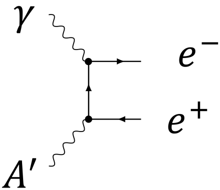
- real photons: only transverse polarisation
- imprinted on leptons as angular orbital momentum

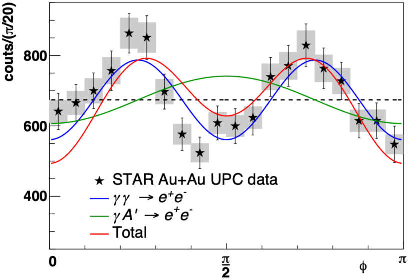
→ angular asymmetry

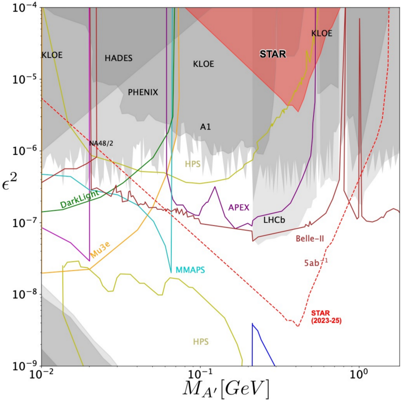


STAR, Phys. Rev. Lett. **127** (2021) no.5, 052302

Breit-Wheeler process and dark photons

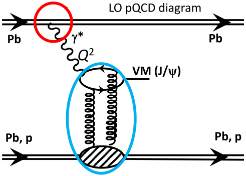


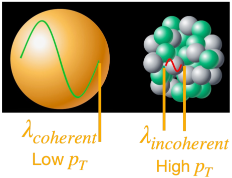


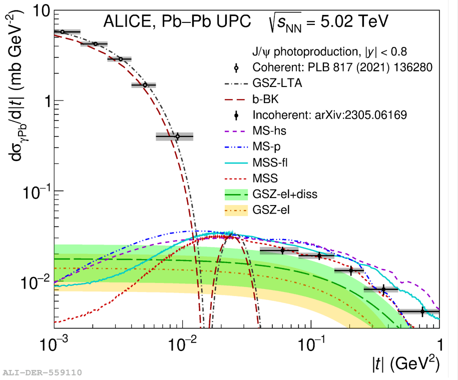


Xu, Lewis, Wang, Brandenburg, Ruan, arXiv:2211.02132

Photonuclear J/Ψ production







ALICE, Phys. Lett. B **817** (2021), 136280

ALICE, arXiv:2305.06169

- sensitive to nuclear and sub-nucleonic structure

Outline

Wrap-up

- heavy ion collisions allow to study fundamental questions in strong interaction physics
- three main discoveries of heavy ion physics:
  1. hydrodynamic behaviour
     - QGP behaves as an almost perfect liquid
     - lowest η/s observed, close to theoretical lower bound of $1/4\pi$
  2. jet quenching
     - partial thermalisation of a far-from-equilibrium system
     - informs us about how the QGP came into being
     - gives access to scale dependence of QGP properties
  3. similarity between p+p/p+A and A+A collisions
     - exciting, but no firm conclusions yet
- many more exciting phenomena

some of which I discussed, others I had to leave out

Wrap-up

- heavy ion physics is new physics
- rich and diverse phenomenology
- have to develop new theoretical tools using
  - classical field theory
  - AdS/CFT
  - thermal field theory
  - kinetic theory/transport theory
  - relativistic hydrodynamics
  - effective field theories
  - zero-temperature field theory (in particular perturbation theory)
  - phenomenological models
- also new experimental techniques needed

e.g. variety of correlations, background subtraction for jets, . . .

Wrap-up

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Wrap-up

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  e.g. variety of correlations, background subtraction for jets, . . .
- heavy ion physics is a broad, multifaceted and exciting field