High energy heavy-ion collisions - hot QCD in a lab

Mateusz Ploskon
Berkeley Lab

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Until now...

- Phases of HI collision
- How to measure centrality of a collision
- ... energy density
- ... temperature
- ... freeze-out volume (and time)
- QGP: hot, short-lived system with rapid dynamical evolution
Today (2/3)

- particle abundance's at hadronization
- QGP properties / transport coefficients:
  - flow
  - jet-medium interactions
Collision timeline

- a) without QGP
- b) with QGP

... to follow-up: chemical & kinetic freeze-out
Freeze-out:

- chemical freeze out $\implies$ hadron composition fixed
- kinetic freeze-out $\implies$ hadron momenta fixed (interactions stop)
- overall: $T_{ch} > T_{kin}$ (system cools down - follow the time axis)
Thermal equilibrium...
Chemical and kinetic freeze-out

Chemical equilibrium:
- correct relative particle abundances?
- large system \(\rightarrow\) Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
- small system \(\rightarrow\) conservation laws \(E\)-by-\(E\) \(\rightarrow\) "canonical suppression" (strangeness)

\[
n_i^0 = \frac{g_i}{2\pi^2} \int \frac{p^2 dp}{e^{(E-\mu_B B_i-\mu_S S_i-\mu_3 l^3)/T} \pm 1}
\]

The ratios of produced particle yields between various species can be fitted to determine \(T, \mu\).

Kinetic equilibrium - radial flow:
- for any interacting system of particles expanding into vacuum, radial flow is a natural consequence.

During the cascade process, an ordering of particles with the highest common underlying velocity at the outer edge develops naturally.

Hadrons are released in the final stage and therefore measure “FREEZE-OUT” Temp. -

instructive simple parametrization - radially boosted source with velocity \(\beta\) and at \(y=0\):

\[
d^3N \propto e^{-E/T}; E \frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T dp dy} \propto E e^{-E/T} = m_T \cosh(y) e^{-m_T \cosh(y)/T}
\]

Simple assumption: uniform sphere of radius \(R\) and boost velocity varies linearly with \(r\):

\[
\rho = \tanh^{-1}(\beta_{\text{boost}})
\]

Blast Wave model \(\Rightarrow\) common \(T\) and \(\beta\)
Thermal equilibrium...

Chemical and kinetic freeze-out

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\]

\[
    \frac{1}{m_T} \frac{dN}{dm_T} \propto m_T I_0 \left( \frac{p_T \sinh(\rho)}{T} \right) K_1 \left( \frac{m_T \cosh(\rho)}{T} \right)
\]

\[\rho = \tanh^{-1}(\beta_{boost})\]

Simple assumption: uniform sphere of radius \(R\) and boost velocity varies linearly w/ \(r\):

\[
    \frac{1}{m_T} \frac{dN}{dm_T} \propto \int_0^R r^2 dr m_T I_0 \left( \frac{p_T \sinh(\rho)}{T} \right) K_1 \left( \frac{m_T \cosh(\rho)}{T} \right)
\]

\[\rho(r) = \tanh^{-1} \left( \beta_{T MAX} \frac{r}{R} \right)\]

Blast Wave model => common \(T\) and \(\beta\)
**Hadron abundances**

Assumption: Multiplicities are determined by statistical weights (chemical equilibrium)

Grand-canonical ensemble:

$$\langle n_j \rangle = \frac{(2J_j + 1)V}{(2\pi)^2} \int d^3 p \left[ e^{(\sqrt{p^2 + m_j^2} + \mu_i)/T} \pm 1 \right]^{-1}$$

Parameters: $V$, $T$, $\mu_B$, $(\gamma_s)$

Results in excellent fits to measured multiplicities of hadron for ALL energies (even $d$, $^3$He, $^3$ΛHe ... ) - statistical harmonization of a thermal system...

**Fig. 6.** Energy dependence of the rapidity density for identified hadrons produced in central nucleus–nucleus collisions. Figure taken from [112, 116]. The colliding systems are either Pb–Pb or Au–Au and central collisions are selected by the requirement of at least 350 participating nucleons in each collision.

**Fig. 7.** Measured hadron abundances in comparison with thermal model calculations for the best fit to ALICE data [127] for central Pb–Pb collisions at the LHC. Plotted are the ''total'' thermal model yields, including all contributions from strong decays of high-mass resonances (for the $\Lambda^*$ hyperon, the contribution from the electromagnetic decay $\Xi^0 \rightarrow \Lambda^*$, which cannot be resolved experimentally, is also included).

Source: Figure taken from [128].

Assumed to be driven by rapid changes in energy and entropy density near the phase boundary [118]. The fireball formed in the collision is assumed to be in chemical equilibrium when the dramatic changes in density near the phase boundary lead to (nearly) simultaneous freeze-out of all hadrons at the chemical freeze-out temperature $T$ and baryo-chemical potential $\mu_B$. The energy dependence of $T$ and $\mu_B$ and of the rapidity density of charged pions determine the thermal parameters $T$, $\mu_B$, and $V$, and, hence, the rapidity density of all hadron species. In general, the precision of this description is on the order of 10%. Due to the data sets available, the energy dependence of the thermal parameters is measured at discrete energies and interpolated in between, see below.

This approach provides a phenomenological link between the data and the QCD phase diagram shown in Fig. 1, a link surmised a long time ago [5, 119] but explored and discussed in quantitative detail only more recently [120–122, 118, 114, 123, 124]. In this review we use the most recent data and the latest update of the model as described in [125].

We note that, for the first time, the data obtained by the ALICE collaboration at the LHC are corrected in hardware for feed-down from weakly decaying resonances via the use of the excellent ALICE inner tracking detector, see [126]. Consequently, for a description of ALICE data no feed-down correction is applied to the thermal model calculations. For analysis of the data from the RHIC, SPS and AGS accelerators, feeding from weak decays needs to be taken into account. For details of this procedure see, e.g., [112, 114]. The uncertainties resulting from this correction lead to significantly increased uncertainties in the data from RHIC and the lower energy accelerators compared to those from the LHC.

Good fits of the measurements are achieved with the thermal model [117] with 3 parameters: Temperature $T$, baryochemical potential $\mu_B$, and volume $V$, as shown in Fig. 7 for the fit of data at the LHC [125, 127]. Remarkably, multiply-strange hyperons and light nuclei and (hyper)nuclei are well described by the model. At LHC energy, the baryochemical potential turns out be zero within uncertainties, implying [129] equal production of matter and antimatter at the LHC [130].

Note that also loosely bound systems such as the deuteron (with binding energy $E_b = 2\times(23 \text{ MeV})$) and hypertriton (binding
Chemical freeze out systematics

Provides rough idea which region in T, µ are probed
Thermal equilibrium...

Chemical and kinetic freeze-out

Chemical equilibrium:
- correct relative particle abundances?
- large system $\rightarrow$ Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
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Kinetic equilibrium - radial flow:
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Hadrons are released in the final stage and therefore measure "FREEZE-OUT" Temp. - instructive simple parametrization - radially boosted source with velocity $\beta$ and at $y=0$:

$$
\frac{d^3N}{d^3p} \propto e^{-E/T} \cdot E \frac{d^3N}{dm_anl} \propto E e^{-E/T} = m_r \cosh(y) e^{-m_r \cosh(y)/T} \\
1 \frac{dN}{m_T \, dm_T} \propto m_T I_0 \left( \frac{p_T \sinh(\rho)}{T} \right) K_1 \left( \frac{m_T \cosh(\rho)}{T} \right)
$$

Simple assumption: uniform sphere of radius $R$ and boost velocity varies linearly with $r$:

$$
\rho(r) = \tanh \left( \beta_T^{\text{MAX}} \frac{r}{R} \right)
$$
Identified particles & expansion of the system

Stronger radial flow at the LHC. “Blast wave” fits to spectra indicate an increase of the average radial boost velocity up to (2/3)c and a decrease in the kinetic freezeout temperature to just below 100 MeV relative to RHIC.

LHC: Large kinematic reach to explore
ALICE: excellent particle identification capabilities at the LHC
Impact of expansion on hadron $p_T$-spectra in heavy-ion collisions

A quick analysis of particle spectra...

**RHIC vs LHC**
(LHC: higher mean $p_T$ – more flow)

Much more baryons than mesons in central collisions as compared to proton-proton (coalescence/recombination? bulk+jet?)

LHC similar to RHIC
Maximum at slightly higher-$p_T$
bulk, jets, medium and $p_T$:

arbtrary regions

and INFORMAL Language

Fig. 5 (left panel) for different centralities in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and for pp at $\sqrt{s} = 0.9$ and 7 TeV.

The $\Lambda/K_0^0$ ratio in peripheral Pb–Pb collisions is slightly larger than that for pp interactions at $\sqrt{s} = 7$ TeV where $\Lambda/K_0^0 \sim 0.5$.

For more central collisions, the $\Lambda/K_0^0$ ratio increases and develops a maximum, reaching a ratio $\Lambda/K_0^0 \sim 1.5$ for $p_T \sim 3-3.5$ GeV/c in 0–5% central collisions.

A comparison with results from RHIC for 0–5% central and 60–80% peripheral Au–Au collisions in Fig. 5 (right panel) shows only slightly larger ratios at the LHC, but perhaps a persistence of ratios larger than those of pp out to higher $p_T$.

FIGURE 5. Left panel: $\Lambda/K_0^0$ ratios at midrapidity as a function of transverse momentum for various centralities in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Ratios are also presented for minimum bias pp events at 0.9 and 7 TeV. Right panel: Comparison of central and peripheral collision ratios from the left panel with ratios in similar Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV. See text for details.

COLLECTIVE FLOW

Charged Particle Elliptic Flow

Elliptic flow ($v_2$) measurements at RHIC indicate that multiple interactions within a very short timescale create a strongly-interacting medium of low viscosity in these collisions, more precisely a low value of the ratio shear viscosity ($\eta/s$).

Furthermore, since the temperature dependence of $\eta/s$ of this medium is unknown, a measurement of the elliptic flow at the LHC and determination of $\eta/s$ are needed. In Fig. 6 (left panel) is the “world’s data” on the elliptic flow $v_2$ integrated over $p_T$ as a function of $\sqrt{s_{NN}}$.[8] The integrated elliptic flow of charged particles at the LHC increases by ~30% over that of the top energy at RHIC. Thus, the hot medium created in Pb–Pb collisions at the LHC behaves very much like that at RHIC and should provide constraints on the temperature dependence of $\eta/s$.

Differential elliptic flow measurements are sensitive to the dynamical evolution and freezeout conditions of the system. Displayed in Fig. 6 (right panel) is the elliptic flow $v_2(4)$ determined from the 4-particle cumulant as a function of $p_T$ for ALICE data[8] at $\sqrt{s_{NN}} = 2.76$ TeV and STAR data at $\sqrt{s_{NN}} = 200$ GeV, 62.4 GeV and 39 GeV[9].

The $p_T$ dependence of $v_2(4)$ appears essentially identical for 20–30% centrality Pb–Pb collisions at the LHC and Au–Au collisions at RHIC from $\sqrt{s_{NN}} = 2.76$ TeV down to a...
Novel effects: hadronization of a mix bulk & hard - parton coalescence

Recombination of thermal (‘bulk’) partons produces baryons at larger $p_T$

Recombination enhances baryon/meson ratio

Note also: $v_2$ scaling

- Fragmenting parton: $p_h = z p$, $z < 1$
- Recombining partons: $p_1 + p_2 = p_h$

Meson $p_T = 2p_{T, parton}$
Baryon $p_T = 3p_{T, parton}$
Properties of QGP with particle correlations
Expanding "fireball"

Initial transverse energy density profile and its time dependence in coordinate space for a non-central heavy-ion collision.

Expanding "fireball"

Initial transverse energy density profile and its time dependence in coordinate space for a non-central heavy-ion collision

Azimuthal angular asymmetry in particle production

Initial spatial anisotropy

\[ \varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \]

Final momentum anisotropy

\[ \nu_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle} \]

Reaction plane defined by “soft” (low \( p_T \)) particles

\[ \Delta \varphi = \varphi - \varphi^\text{Reaction Plane} \]

Elliptic flow

\[ \frac{dN}{d\Delta \varphi} \propto 1 + 2\nu_2 \cos(2\Delta \varphi) \]

INTERATIONS (hydrodynamics?)
Experimental signature

measurement: azimuthal angular distribution of particles with respect to event plane

$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos [2(\phi - \Psi_R)] + \ldots$$

Sizeable effect!
Azimuthal anisotropy

Energy dependence of $v2$

APS Viewpoint: A “Little Bang” arrives at the LHC (E. Shuryak)

1. Collective behavior observed in Pb-Pb collisions at LHC (integrated: +0.3 $v2^{RHIC}$ – consequence of larger $<p_T>$) -> $v2(p_T)$ similar to RHIC – almost ideal fluid at LHC? Similar observation down to 39GeV!

2. New input to the energy dependence of collective flow

3. Additional constraints on Eq-Of-State and transport properties
Relativistic (ideal) hydrodynamics

Mass hierarchy vs momentum is characteristic of common velocity distribution.

Ideal hydro: qualitative agreement but missing the details

\[ \partial_\mu T^{\mu\nu} = 0 \]

shear viscosity \( \eta = 0 \)

Heinz ‘04

Anisotropy Parameter \( V_2 \)

Transverse Momentum \( p_T \) (GeV/c)
Hydrodynamics crash course

Energy-momentum conservation (local)

\[ \partial_t T_{00} = -\partial_x T_{0x} - \partial_y T_{0y} + \partial_z T_{0z} \]

\[ \partial_t T_{0x} = \partial_x T_{xx} + \partial_y T_{yx} + \partial_z T_{zx} \]

Ideal hydrodynamics: \( T_{i\neq j} = 0 \)

Navier-Stokes equation: \( T_{ij} = P\delta_{ij} - \eta(\partial_i v_j + \partial_j v_i) - \zeta \nabla \cdot \vec{v} \)

where \( \eta \) is shear viscosity: friction between layers of fluid

\[
\frac{d}{dt} P_x = A_y \eta \partial_y v_x
\]

and \( \zeta \) is bulk viscosity: dissipation of divergent flow

\[
\delta E = -P\delta V + \zeta \nabla \cdot \vec{v} \delta V
\]
Shear viscosity in fluids...

\[ \frac{F}{A} = \eta \frac{v}{L}; \quad \eta \sim \rho \langle v \rangle \lambda_{mfp} \]

Properties are counter-intuitive:

**Weak coupling**
- small cross section, long mean free path
  \( \Rightarrow \) large viscosity

**Strong coupling**
- large cross section, small mean free path
  \( \Rightarrow \) small viscosity

\( \eta \rightarrow 0 \): strongly coupled (perfect) fluid
\( \eta \rightarrow \infty \): weakly coupled (ideal) gas
QGP liquid - how perfect is perfect?

Shear viscosity – lower limit:

\[ \frac{\eta}{s} > \frac{1}{4\pi} \]

rather recent: in principle can go to zero

Hot, deconfined QCD matter flows as an almost perfect fluid
Comparison QGP to other fluids near $T_c$

Green-Cubo relations:
transport coefficients in terms of integrals of time correlation functions
- correlations of particles x relaxation time

\[ \eta = \frac{\tau_\eta}{T} \int d^3r \langle T_{xy}(0,0)T_{xy}(\vec{r},t=0) \rangle \]
\[ = \frac{\tau_\eta}{T} \sum_\alpha (2S_\alpha + 1) \int \frac{d^3p}{(2\pi)^3} e^{-E/T} \frac{p_x^2 p_y^2}{E^2} \]

\[ \eta/s \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{Comparison of $\eta/s$ for different systems.}
\end{figure}

\begin{itemize}
\item Kubo (\(\sigma=22\) mb, \(\tau_\eta=1.9\tau_{\text{coll}}\))
\item Anybody’s guess
\item Perturbative QCD
\end{itemize}

Similar behavior near $T_c$
Improved (multiparticle) $v_2 \{4\}$:
very weak energy dependence of $v_2(p_t)$ -
from 2.76 TeV down to 39 GeV (!)
Same phase for different initial collision energies !?
Understanding correlations & $v_2$ - the so-called non-flow

Figure 9. Examples of particle distributions in the transverse plane, where for a) $v_2 > 0$, $v_2\{2\} > 0$, b) $v_2 = 0$, $v_2\{2\} = 0$, and c) $v_2 = 0$, $v_2\{2\} > 0$. 
Reaction plane (RP)
Participants plane (PP)

Genuine 2,4-particle correlations

\[ c_2\{2\} \equiv \langle e^{i2(\varphi_1-\varphi_2)} \rangle = \langle v_2^2 + \delta_2 \rangle, \]
\[ c_2\{4\} \equiv \langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \rangle - 2 \langle e^{i2(\varphi_1-\varphi_2)} \rangle^2, \]
\[ = \langle v_2^4 + \delta_4 + 4v_2^2\delta_2 + 2\delta_2^2 \rangle - 2 \langle v_2^2 + \delta_2 \rangle^2, \]
\[ = \langle -v_2^4 + \delta_4 \rangle. \quad \delta_2 \propto \frac{1}{M_c} \quad \text{and} \quad \delta_4 \propto \frac{1}{M_c^3} \]

[AMPT] calculation using Glauber initial conditions
\[ v_2: \text{RP, EP } v_2\{2\} \quad v_2\{4\} \]
Two particle correlations

\[ \Delta \varphi - \text{azimuthal angle difference} \]
\[ \text{angle in the transverse plane} \]

\[ \Delta \eta - \text{longitudinal - pseudo-rapidity distance} \]
Sensitivity of particle correlations to the underlying/initial conditions

Two-particle correlations
- conditional [per-trigger] yields

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{assoc}}}{d\Delta \varphi} \quad \text{and} \quad \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc}}}{d\Delta \varphi d\Delta \eta}
\]

At Low-$p_T$:
- Ridge
- Hydrodynamics, flow

At High-$p_T$:
- Quenching/suppression, broadening

$I_{\text{CP}}$: Yields in central v.s. peripheral collisions

$I_{\text{AA}}$: Yields in A-A compared to p-p
"Beyond" v2
higher moments -> fluctuations / hotspots

\[ \frac{dN}{d\varphi} \sim 1 + 2v_2 \cos(2\Delta\varphi) + \ldots \]

Non-zero!
Two-particle correlations - Fourier decomposition

Integration of the correlation function in $0.8 < |\Delta \eta| < 1.8$ (long) and Fourier decomposition

Collective flow: the coefficients factorize $V_{n\Delta} = v_n(p_T^A) v_n(p_T^T)$

$$C(\Delta \phi) = \frac{1}{\Delta \eta_{\text{max}} - \Delta \eta_{\text{min}}} \int_{\Delta \eta_{\text{min}}}^{\Delta \eta_{\text{max}}} C(\Delta \eta, \Delta \phi) \sim 1 + 2 \sum_{n=1} V_{n\Delta} \cos(n \Delta \phi)$$

Few components describe the low-p$_T$ correlations

⇒ Strong near side ridge and double-peak on the away
⇒ Also recoil jet up to p$_T^{\text{trig}}$ > 8 & p$_T^{\text{assoc}}$ 6-8 in central
Long range correlations – collective flow: the coefficients must factorize such that:

\[ V_{n\Delta} = \langle \cos \left[ n (\phi_{\text{trig}} - \phi_{\text{assoc}}) \right] \rangle = \langle \cos \left[ n (\phi_{\text{trig}} - \Psi_n) \right] \rangle \langle \cos \left[ n (\phi_{\text{assoc}} - \Psi_n) \right] \rangle = v_n(p_t^{\text{trig}}) \cdot v_n(p_t^{\text{assoc}}) \]

Global fits show:
- Collective flow dominates to about 3-4 GeV/c for all \( n > 1 \)
- Description breaks for high \( p_T \) or peripheral collisions
- For low \( p_T \): double peak and ridge structures seen in two particle correlations are naturally explained by measured anisotropic flow coefficients

\[ C(\Delta \Phi) \sim 1 + \sum v_n^2 \cos (\Delta \Phi) \]
Higher harmonic flow

\[ \psi_3 \psi_{RP} \psi_2 \]

PRL, 107, 032301 (2011)

- Fluctuations in initial state lead to e-by-e fluctuating symmetry planes
- Odd harmonics are not zero
- Triangular flow (\( v_3 \) harmonic)
- Weak centrality dependence
- Vanishes as expected when measured w.r.t. reaction plane
- Similar \( p_T \) dependence for all \( v_n \)
- Higher harmonics provide additional constraints on \( \eta/s \)

\( \eta/s \) small, similar as at RHIC

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**Higher harmonics w.r.t. to event plane**

\( v_3 \) - triangular flow:
- weak centrality dependence
- vanishes as expected when measured w.r.t. reaction plane

Similar \( p_T \) dependence for all \( v_n \)

Higher harmonics - additional constraints on \( \eta/s \)

\( \eta/s \) small, similar as at RHIC

\[ \psi_3 = \epsilon_2 + \epsilon_3 + \epsilon_4 + \epsilon_5 \]
(viscous) fluid dynamics works!

Small shear viscosity over entropy ratio:

\[ \frac{\eta}{s} \leq 0.25 \]
Jet-medium-flow coupling via two particle correlations?

Motivation (II)

- Broadening in a static medium
- Longitudinal flow results in deformation of the conical jet shape
- Different $\Delta \phi$ and $\Delta \eta$ widths (eccentric jets)
- Interest to study modifications of the jet shape
- Increase of width (radiation)
- Increase of eccentricity (longitudinal flow)
- In particular at low parton $p_T$ where quenching effects are strongest.


$\Rightarrow$ LHC? - more jets + somewhat more flow...
Jet-peak shape evolution - intermediate $p_T$

- Wider peak in central collisions
- Peripheral and $p$-$p$ similar shape
- Strong $p_T$ dependence

$2 < p_{T,\text{trig}} < 3$ GeV
$1 < p_{T,\text{assoc}} < 2$ GeV

$4 < p_{T,\text{trig}} < 8$ GeV
$2 < p_{T,\text{assoc}} < 3$ GeV

=> Characterize the peak
Measuring widths of the correlations in azimuth and pseudo-rapidity

- Greater longitudinal than azimuthal broadening
- Suggestive of "medium drag" of radiation
- Caution: physics evolves rapidly with $p_T$

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Comparison with AMPT MC

- AMPT (A MultiPhase Transport Code)
  - Initial conditions simulated using HIJING
  - Parton scattering
  - Hadronization: Lund model + coalescence
  - Hadron scattering
- AMPT describes the main features of the near-side shape evolution observed in data

Measure of jets interactions with longitudinal flow (?)
Probing an unknown medium...
Probing the unknown medium...

Jet suppression (quenching)

Charm/bottom dynamics

$J/\psi$ & $\Upsilon$

Color-less particles
How to probe a patient that comes for only $O(\text{micro sec.})$?
How to probe a medium that lasts only $O(\text{micro sec.})$?
... to probe the short lived medium

=> use "auto-generated probes" - heavy-ion collisions at high-energies produce internally high-energy partons (fragment into jets of particles)...

<= critical input from pp (vacuum) measurements - pQCD
Jets in collider experiments

LEP: Opal

CMS is using a Particle Flow Technique to reconstruct Jets and Missing Transverse Energy. They use the best measurement for each component:

- Tracker for charged hadrons
- ECAL for electrons & photons
- HCAL for neutral hadrons

Tevatron: CDF

RHIC: Star

STAR TPC Event Display

LHC: CMS

Jet 1 $p_T = 22$ GeV/c
Jet 2 $p_T = 42$ GeV/c
Jet 3 $p_T = 38$ GeV/c

MET 1.9 GeV

xy plane
What is a jet?

A spray of collimated showers/particles
- Hardly ever better defined...

Jet = Parton AND its radiation

Note: experiment measures spray of particles (~hadrons)

Jets (unlike single hadrons) are objects which are “better” understood/calculable within pQCD

Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...
Jets in collider experiments

Jets are fairly well known by now... and well described by theory and MC => attractive tool for heavy-ions

---

CDF Run II Preliminary \( (L=1.13 \text{ fb}^{-1}) \)

- Data corrected to the hadron level
- Systematic uncertainty
- NLOJET++ CTEQ 6.6M \( \mu_F=2.7, R_{\text{part}}=1.3 \)
- Midpoint: \( R=0.7, f_{\text{merge}}=0.75 \)

\[
\frac{d^2\sigma}{d\eta dP_T} \; \text{(GeV/c)}
\]

Cone Algorithm

---

LHC: 7 TeV

- ATLAS
- \( \int L = 2 \mu \text{b}^{-1} \)
- \( N_{\text{jet}} = 1, P_T > 200 \text{ GeV} \)
- \( \eta = \text{anti-} k_T, R=1.0 \) jets
- Pythia
- Herwig++

---

LHC: 7 TeV

- ATLAS
- \( N_{\text{jet}} = 7 \text{ TeV} \)
- \( \int L = 17 \text{ nb}^{-1} \)
- \( N_{\text{jet}} = 7 \text{ TeV} \)
- NLO pQCD (CTEQ 6.6) × Non-pert. corr.
- \( |\eta| < 2.8 \)

---

STAR
- \( p+p \rightarrow \text{jet} + X \)
- \( \sqrt{s} = 200 \text{ GeV} \)
- Midpoint-cone
- \( \epsilon_{\text{cone}}=0.4 \)
- \( 0.2<|\eta|<0.8 \)

- Combined MB
- Combined HT
- NLO QCD (Vogelsang)

- Systematic Uncertainty
- Theory Scale Uncertainty
Hadronic collisions: pQCD and jets

\[ E \frac{d^3 \sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab \rightarrow cd}}{dt} \otimes D_{h/c}(z_c, Q^2) \]

Jets are defined via rigorous (collinear and infrared safe) clustering algorithms.

Same clustering definitions in experiment and theory – integration over hadronic/parton showers.

pQCD factorization:
- parton distribution fn \( f_{a/A} \)
- partonic cross section
- fragmentation fn \( D_{h/c} \)

\( D(z, m_F) \) is the fragmentation function.
Jets are fairly well known by now... and well described by theory and MC => attractive tool for heavy-ions

Inclusive jet production: pQCD & data

Jets are fairly well known by now... and well described by theory and MC => attractive tool for heavy-ions

Inclusive jet production in hadron-induced processes

\( \sqrt{s} = 200 \text{ GeV} \)
- STAR: \( 0.2 < \frac{y}{y_T} < 0.8 \)

\( \sqrt{s} = 300 \text{ GeV} \)
- (x 100)

\( \sqrt{s} = 318 \text{ GeV} \)
- DIS

\( \sqrt{s} = 546 \text{ GeV} \)
- (x 16)

\( \sqrt{s} = 630 \text{ GeV} \)
- DØ: \( \frac{y}{y_T} < 0.5 \)

\( \sqrt{s} = 1800 \text{ GeV} \)
- (x 6)

\( \sqrt{s} = 1960 \text{ GeV} \)
- (x 1)

LHC: 7 TeV
- ATLAS

\( y_T < 0.9 \)
- Systematic Uncertainties
- NLO pQCD (CTEQ6.6): Non-pert. corr.
- + jet, jets, \( y_T > 0.9 \)

\( 1 < y_T < 1.7 \) (6.7 TeV)

Data/Theory

\( p_T \) (GeV/c)

All pQCD calculations using NLOJET++ with fastNLO:
- \( \alpha_s(M_Z) = 0.118 \)
- CTEQ6.1M PDFs
- \( \mu_F = \mu_R = p_T^{\text{jet}} \)

NLO plus non-perturbative corrections
- \( \text{pp, p\bar{p}, inc. threshold corrections (2-loop)} \)

Collision energy: \( \sqrt{s} \)
Probing the unknown medium...

jet suppression (quenching)
charm/bottom dynamics
$J/\psi$ & $\Upsilon$

color-less particles
QED: Passage of electrically charged particle through

\[ \langle dE/dx \rangle \]

What is the equivalent in QCD?
Bremsstrahlung in QCD:
Formation time $\rightarrow$ coherence effects

Formation time physics

- $\tau_f < \lambda < L$ Incoherent multiple collisions
- $\lambda < \tau_f < L$ LPM effect (radiation suppressed by multiple scatterings within one coherence length)
- $\lambda < L < \tau_f$ Factorization limit (acts as one single scatterer)

Landau-Pomeranchuk-Migdal effect
Formation time important

$\lambda_g$

Radiation sees length $\sim \tau_f$ at once

$\vec{q} \rightarrow \vec{q} \vec{g}$
Bremsstrahlung in QCD

High energy **color charged probe**
propagating **through color charged medium**
(LPM effect; multiple soft radiations)

Define a transport coefficient:
\[ \hat{q} \sim \frac{\mu^2}{\lambda} \]

Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ∼ linear)
- to density of the medium

⇒ energy flow (parton+radiation) modified as compared to jet in vacuum
⇒ jet “quenched” (“softened” fragmentation)

\[ q \rightarrow qg \quad \tau_{\text{form}} = \frac{2\omega}{k_T^2} \]

\[ \lambda < \tau : \text{multiple scatterings add coherently} \]

\[ t_{\text{formation}} < L \Leftrightarrow \omega < \omega_c \]
Jets in heavy-ion collisions

- an idealization

Factorization in heavy-ion collisions?

\[ \sigma \propto f_a^{PDF} \otimes f_b^{PDF} \otimes \sigma^{hard} \]

\[ \text{production vertex: high } Q^2 \]

\[ \Rightarrow \text{pQCD} \]

\[ \text{Propagation in strongly coupled Quark Gluon Plasma} \]

\[ \Rightarrow \text{pQCD-based jet quenching} \]

\[ \Rightarrow \text{hydrodynamics} \]

\[ \Rightarrow \text{AdS/CFT} \]

\[ \Rightarrow \ldots \]

Vacuum fragmentation into hadrons

\[ \Rightarrow \text{non-pert. QCD} \]
Jets in heavy-ion collisions
RhIC & LHC

STAR: Au+Au at 0.2 TeV

CMS: Pb+Pb at 2.76 TeV

back-to-back jets
~220 GeV

LHC + RHIC: QCD evolution of jet quenching?

Vary energy of the jet:
LHC: Vary the scale with which QGP is probed (a la DIS)

Compare and contrast RHIC and LHC
Jets in $\chi^{+}\chi^{-}$ collisions & Experimental difficulties: Vacuum jet vs jet on top of the $\chi^{+}\chi^{-}$ background...

Vacuum
Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Heavy-ion collision @ LHC
Probing the unknown medium...

jet suppression (quenching)
charm/bottom dynamics
J/ψ & Υ

color-less particles
Jet quenching - RHIC

\[
\text{Ratio} = \frac{\text{(#(particles observed in AA collision per binary collision)}}{\text{(#(particles observed per p-p collision)}}
\]

High-pT particles - proxy for jets

No “effect”:
- R < 1 at small momenta
- R = 1 at higher momenta where hard processes dominate

Photon - color neutral probe => No suppression

Hadrons from color charged jets => Suppression
"Soft", large cross-section processes expected to scale with $N_{\text{part}}$

"Hard", low cross-section processes expected to scale with $N_{\text{bin}}$

$N_{\text{part}}$ (or $N_{\text{wound}}$) = 7 “participants”

$N_{\text{bin}}$ (or $N_{\text{coll}}$) = 12 “binary collisions”
"Easier" (than full jet reconstruction) exercise: Jet-quenching via leading hadrons

Di-hadron correlations

Inclusive hadron production
Measured as a function of collision centrality

Note on correlations: interesting tool to study the "intermediate" - pt region - jets vs flow and recombination

Rates of recoil ("away-side") hadrons suppressed

Note on correlations: interesting tool to study the "intermediate" - pt region - jets vs flow and recombination
Hadron suppression

Nuclear modification factor:

\[ R_{AA} = \frac{\# \text{particles observed in AA collision per } N-N \text{ (binary) collision}}{\# \text{particles observed per } p-p \text{ collision}} \]

\[ R_{AA} = \frac{1/N_{AA}(dN_{ch}/d\eta)}{1/N_{pp}(dN/d\eta)} \]

Loss of measured yield in central A-A

"No effect" case is for \( R_{AA} = 1 \) at high \( p_T \) where hard processes dominate.
Energy-loss - QGP state effect!

Color charged probes suppressed
Color neutral probe production scales with $N_{\text{bin}}$ collisions
$pA$ collisions: suppression is an effect of QGP

$$R_{AA} = \frac{1}{<N_{\text{coll}}>\frac{dN_{AA}}{dp_T}}$$

Throughout the talk: $R_{AA} = \text{QCD in medium} / \text{QCD in vacuum}$

Note: only colored probes quenched; $pA$: jet quenching is an in-medium effect
Extraction of QGP transport coefficients

\[ -dE/dx \sim \alpha_s \hat{q} L^2 \]

JET theory collaboration 2013

Systematic data-model(s) study

\[ \Rightarrow \text{extract transport coefficient} \]

Use of RHIC & LHC data

Temperature dependence (?)

\[ \hat{q} \sim \mu^2 / \lambda \]

\[ \lambda \propto \frac{1}{\rho} \]

RHIC : \( \hat{q} \approx 1.2 \pm 0.3 \text{ GeV}^2/\text{fm} \)

LHC : \( \hat{q} \approx 1.9 \pm 0.7 \text{ GeV}^2/\text{fm} \)

Cold matter (HERMES DIS) : \( \hat{q} \approx 0.02 \text{ GeV}^2/\text{fm} \)
High energy heavy-ion collisions:

- hot medium; thermal \{statistical hadronization\} particle emission

- QGP flows as almost perfect fluid - well described by viscous hydrodynamics - transport coefficient constrained

- slow evolution with energy - similar medium over large span of energies (?) - role of mean free path vs. medium size...

- QGP is opaque to high energy jets (dense medium) - transport coefficient constrained (first syst. results)