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Summarizing a conference

... is worse than herding a hundred cats
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Jet parallel talks
Advances in Jet Theory

- Escobedo [Sat.Jet.1]: Fluctuations in E-loss
- var der Schee [Sat.Jet.1]: Jet E-loss and cone-angle in AdS/CFT
- Nonaka [Sat.Jet.2]: The $\hat{q}$ from Lattice
- Apolinarío [Sat.Jet.2], Dominguez [Sun.Jet.3]: Factorization beyond eikonal approximation
- Ringer [Sat.Jet.2]: Jet production from SCET
- Pablos [Sat.Jet.3]: Angular jet structure in a hybrid model
- Ayala [Sun.Jet.3], Transport coeff. from e-loss in linearized hydro
- Horowitz [Sun.Jet.3]: Wobbly limp noodle (Time dep. $\hat{q}$ from AdS/CFT)
- Majumder [Sun.High $p_T$.2]: PDF of QGP partons
- Rasonaivoa [Sun.High $p_T$.2], $N$-gluon emission amplitude
Event Generators for Jets

- Kordell [Sat.Sim.1], MATTER
- Branafoldi [Sat.Sim.1], HIJING++
- BierLich [Sat.Sim.1], General Purpose Event Generator
- PETRUSHANKO [Sat.Sim.1], HYDJET++
- Luo [Sat.RT.1], LBT
- Apolonario [Sat.RT.1], QPYTHIA
- Pablos [Sat.RT.1], Hybrid
- Kordell [Sat.RT.1], MATTER
- Jeon [Sat.RT.1], MARTINI
Advances in Jet parameter extractions

- Andres Casas [Sat.Jet.1]: QPYTHIA, New $\hat{q}$ puzzle
- Chang [Sun.Jet.6]: Jet shape using Boltzmann + Hydro
- Zhang [Sun.High $p_T$.1]: New fit for $\hat{q}$ and $\lambda_0$
- Chen [Sun.High $p_T$.2]: Jet charge using PYQUEN
Advances in Jet data descriptions

- Ma [Sat.Jet.3]: Jet reconstruction, Dijet asymmetry using AMPT
- Lapidus [Sat.Jet.3]: $z_g$ discriminates JEWEL and YaJEM
- Kunnawalkam Elayavalli [Sat.Jet.3], JEWEL with recoil can do $z_g$ distributions
- Dai [Sun.High $p_T$.1]: High $p_T$ $\eta$’s are mostly from quark jets
- Tachibana [Sun.Jet.6]: Jet-medium interaction can do jet shape functions
High $p_T$ correlations parallel talks
Advances in high $p_T$ correlations

**Adv. in QGP param. extractions with the High $p_T$ correlations**
- Wei [Sun.Corr.3]: Sudakov resummation. Jet broadening through di-hadron ad hadron-jet corr. can measure $\hat{q}_L$.

**Advances in the High $p_T$ correlations data descriptions**
- Chen W. [Sat.Corr.1]: Linear Boltzmann Transport (LBT) can do gamma-jet
- Luo [Sat.Corr.2]: LBT can do gamma-jet and dijet
Electromagnetic Probes
parallel talks
• Hauksson [Sat.EM.2]: Bulk viscosity $\delta f$ corrections
• Greif [Sat.EM.2]: BAMP with LO photons
• Ru [Sat.EM.3]: Kulagin-Petti nPDF are better for W and Z
• Benic [Sat.EM.3]: LO CGC pA photons
• Ruggieri [Sat.EM.3]: Early stage photons from CGC is bright around $p_T \approx 2$ GeV
Bulk viscosity extraction

- Vujanovic [Sat.EM.1]: Bulk viscosity effect opposite in $l\bar{l}$ $v_2$ and $h$ $v_2$

Photon $v_2$ puzzle

- Yang [Sat.EM.2]: Holographic models make both spectra and flow at high $p_T$ go up
Heavy Flavor parallel talks
Advances in the HF Theory

- Hambrock [Sat.HF.2]: AdS/CFT inspired model
- Salgado [Sat.HF.2]: Use top for early time dynamics
- D’Enterria [Sat.HF.2]: Higgs and tops in HIC
- Hattori [Sat.HF.4]: Quark diffusion with strong B field
- Gossiaux [Sun.Quarko.2]: Schrödinger-Langevin approach
- Chen [Sun.HQ-Quarko.1]: Light front Hamiltonian
Adv. in QGP param. extractions with the HF probes & Data descriptions

Adv. in QGP param. extractions with the HF probes

- Xu [Sat.HF.3]: Data driven analysis of T dependent HF transport coefficient

Advances in the HF data descriptions

- Cao [Sat.HF.1]: $R_{AA}$ and $v_2$ with LBT
- Noronha [Sat.HF.1]: $R_{AA}$ and $v_n$ with visc. hydro
- Xu [Sat.HF.1]: BAMP. Jet shape functions for b-tagged jets
- Greco [Sat.HF.3]: Fokker-Planck. Drag $D \sim T^{0-1}$
- He [Sat.HF.4]: T-matrix approach. $R_{AA}$ and $v_2$.
- Lansberg [Sun.Quarko.2]: Understanding feed-down patterns with co-mover approach
Small systems parallel talks
Advances in the Small Systems Study

- Vogt [Sat.pp-pA.1]: Predictions for pA
- Levai [Sat.pp-pA.1]: Anisotropic gluon brem in GLVB
- Park [Sat.pp-pA.1]: Jets in MARTINI with $L$-dep and $\alpha(k)$
- Shen [Sat.EM.1]: Systematic study of small system EM probes
- Zhu [Sat.pp-pA.2]: NLO hadron cross-section with a rapidity (UV) cut-off
- Lappi [Sat.pp-pA.2]: NLO BK might spoil geometric scaling
Initial States parallel talks
Advances in the Initial State studies

- Fries [Sun.Init.1]: Small $\tau$ expansion of Glasma evolution
- Mantysaari [Sun.Init.1]: Fluctuating proton in pA
- McDonald [Sun.Init.1]: New IP-Glasma implementation
- Csernai [Sun.Init.1]: New skewed IS model for peripheral collisions
Plenary talks
Friday Plenary talks

- Armesto: Theory overview
- Kaczmarek: Hard probes on the Lattice
- Venugopalan: IS of Heavy-Ion collisions and Hard Probes
- Cacciari: Jet substructure
- Jets in strong coupling: Casalderry-Solana
Monday Plenary talks

- Tywoniuk: Parton energy loss in QCD matter
- Qin: Modification of jet rate, shape and structure model and phenomenology
- Vitev: SCET for jet physics in the vacuum and the medium
- Verweij: Monte Carlo simulations of hard probes
- Noronha-Hostler: Resolving $R_{AA}$ and $v_n$ puzzle
- Arleo: Hard processes in p+A collisions
- Gonzalez Ferreiro: Quarkonium production in pp and pA
- Evolution equations and factorization in pA collisions
Tuesday Plenary talks

- Nahrgang: Heavy Flavor Theory
- Strickland: Quarknoia production
- Paquet: Photons and dileptons production
Plenary speakers did amazing job in summarizing the state of each field.

That frees me to talk about what I want to talk about. I will mainly talk about parallel session talks. Again with apologies to those I won’t be able to mention directly.
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What do we really want to know about?
QCD properties

Hard probes are tools to study Many-body QCD.

- In particular, QGP properties
  - Thermalization
  - Equation of state
  - $\alpha_s(T)$
  - Transport coefficients – $\eta/s, \zeta/s, \hat{q}, \hat{e}, \ldots$

- Also how they are being modified – We want to understand the underlying physics

- Caveat: Modifications in hard probes are both means and ends of theory
To learn: QGP property – $\frac{\zeta}{s}$
Vujanovic [Sat.EM.1]: Dileptons and hadrons behave oppositely

Viscous hydrodynamics & bulk pressure

- Dissipative hydrodynamic equations including coupling between bulk and shear viscous terms:
  
  $\partial_\mu T^{\mu\nu} = 0$
  
  $T^{\mu\nu} = -\Pi^{\mu\nu} - \Pi^\Delta\delta^{\mu\nu} + \Pi_0^{\mu\nu}$
  
  $T_0^{\mu\nu} = \epsilon u^{\mu} u^{\nu} - P(\Delta^{\mu\nu})$
  
  $\tau_\Pi^\Pi + P = -\zeta \Pi + \Pi_0 = -\lambda_\Pi_0 \Pi^\mu \Pi_{\mu} + \lambda_\Pi_0 \Pi^{\mu\nu} \Pi_{\mu\nu}$
  
  $\tau_\Pi^\Pi + P = -2\eta \Pi^{\mu\nu} \Pi_{\mu\nu} - 2\lambda_\Pi_0 \Pi^\mu \Pi_{\mu} + \phi_2 (\Pi^{\mu\nu} \Pi_{\mu\nu} - \Pi^\Pi)$
  
  $\tau_\Pi^\Pi + P = -2\eta \Pi^{\mu\nu} \Pi_{\mu\nu} - 2\lambda_\Pi_0 \Pi^\mu \Pi_{\mu} + \phi_2 (\Pi^{\mu\nu} \Pi_{\mu\nu} - \Pi^\Pi) + \lambda_\Pi_0 \Pi^{\mu\nu} \Pi_{\mu\nu}$

$\eta/s = \text{constant}$

- Other than $\zeta$ and $\eta$, all transport coefficients are in PRD 85 114047, PRC 90 024912.

$P(e)$: Lattice QCD EoS [Huovinen & Petreczky, NPA 837, 26]. (s95p-v1)

Bulk viscosity and dileptons at RHIC

- Bulk viscosity causes an increase in anisotropic flow build-up in both the QGP and the hadronic sector which translates into an $\uparrow$ $v_2$($M$) of thermal dileptons.

- $v_2$($M$) behaves in the opposite direction, as they are emitted at later times.

- This anti-correlation is a key feature of bulk viscosity at fixed $\eta/s$. 

Jeon (McGill)
QGP Property – Bulk Viscosity

- McDonald [Sun.Init.1]: With the same $\zeta$ and new implementation of IP-Glasma

Testing the Model and Making Predictions

- **Identified Particle $\langle p_T \rangle$**
  - Effects of hadronic re-scatterings and bulk viscosity
  - Prediction for 5.02 TeV shows slight increase over 2.76 TeV

- **Identified Particle $dN/dy$**
  - Particle sampling is able to reproduce particle multiplicities.

*McDonald, et. al. (arXiv:1609.02958)*
The conformal anomaly $\theta = T^\mu_\mu$ also has a peak near $T_c$.

In FTFT: $\zeta \propto \theta^2$

In AdS/(broken CFT): $\zeta \propto \theta$

One of very few ways to get at the conformal anomaly

More observables sensitive to $\zeta/s$ desirable

**Lattice QCD**

To learn: QGP property – $\hat{q}$
QGP Property – $\hat{q}$

- $\hat{q}$ through jet-medium interactions

Ayala [Sun.Jet.3]: Medium excitation is sensitive to $dE/dx$

$\hat{q}$ vs $\eta/s$ (trigger particle)
**QGP Property – \( \hat{q} \)**

- \( \hat{q}_L \) through jet-medium interactions

**Wei [Sun.Corr.3]: Di-hadron and hadron jet angular correlation sensitive to \( \hat{q}_L \)**

**Dihadron & hadron-jet correlations**

\[
S_{AA}(Q, b) = S_{pp}(Q, b) + \langle \hat{q}_L \rangle b^2 \frac{4}{4}
\]

\[
\langle \hat{q}_L \rangle_{\text{tot}} = 14^{+42}_{-14} \text{ GeV}^2
\]

- Larger than the value, \( \hat{q} = 1.2 \pm 0.3 \text{ GeV}^2/\text{fm} \)
- Extracted from single hadron \( R_{AA} \) by JET Collaboration
- Radiative correction
- Effective length

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Shu-yi Wei (CCNU)  Hard Probes - 2016 @ Wuhan

Jeon (McGill)  Jets
QGP Property – $\hat{q}$

- Zhang [Sun.High $p_T$.1]: Bracketing $\hat{q}$

### Extracting parameters $\hat{q}_0$ and $\lambda_0$ at RHIC/LHC

With simultaneous $\chi^2$/d.o.f. fits for $R_{AA}(p_T)$ in central A+A collisions

A couple of inputs: $\hat{q}_0$, $\lambda_0$

- $\chi^2$/d.o.f. for $R_{AA}$ in 0-5% Au+Au at 200 GeV
  
- $\chi^2$/d.o.f. for $R_{AA}$ in 0-5% Pb+Pb at 2.75 TeV

**RHIC**

$\hat{q}_0 = 1.1 \pm 0.2 \text{GeV}^2 / f n$

$\lambda_0 = 0.4 \pm 0.03 f n$

**LHC**

$\hat{q}_0 = 1.7 \pm 0.3 \text{GeV}^2 / f n$

$\lambda_0 = 0.5 \pm 0.05 f n$

Chang [Sun.Jet.6]: With Boltzmann + Hydro

\[ \hat{q}_{30-40} = (1.8 - 1.6 \text{ GeV}^2/\text{fm}) \frac{T_{30-40}^3}{T_{0-10}^3} \]

Sensitivity to the value of \( q \hat{q} \)

Every mechanism has sensitivity to \( q \hat{q} \), but the sensitivity become modest when all of them exist.
Xu Y. [Sat.HF.3]: Bayesian revolution is coming

\[ D_s = \frac{T^2}{\hat{q}}, \quad \hat{q} = \hat{q}_{pQCD} \text{preK} \left( 1 + K_T e^{-\frac{(T-T_c)^2}{2\sigma_T^2}} \right) \]
With that \( \hat{q} \) ...

- Cao [Sat.HF.1]: With LBT

Possible Solutions to the \( R_{AA} \) vs. \( \nu_2 \) Puzzle

1. Near \( T_c \) enhancement of transport coefficient (arXiv: 1605.06447)

- While \( R_{AA} \) is fixed, the enhancement of transport coefficient near \( T_c \) increases \( D \) meson \( \nu_2 \)
- Consistent with findings presented in
- The detailed microscopic mechanism is still an open question
Andres Casas [Sat.Jet.1]: A puzzle?

\[ \hat{q} \approx 2.2 \varepsilon^{3/4} \]

Why is \( K = \hat{q}/2\varepsilon^{3/4} \) (almost) independent of centrality but sharply dependent upon \( \varepsilon \tau_0 \)?
Mini Summary – QGP property extractions

- $\hat{q}(T)$
  
  Majumder [Sun.High $p_T.2$]: “What you may think this means!”

If this is true, must effect the centrality dependence of $R_{AA}$, $v_2$, and its centrality dependence at a given collision energy.
To learn: Fluctuations are everywhere and they are important
Fluctuations are everywhere

- Fluctuations
  - Geometrical fluctuations – Initial condition
  - Branching number fluctuations – Nature is probabilistic
  - Thermal fluctuations – Langevin noise
  - Vacuum fluctuations – Virtual parton cloud of a thermal parton
  - ...

They have *all* become important

Caveat: If you do not have a good reason and theory behind it, it may end up being just another knob to turn
Majumder [Sun.High $p_T$2]: “Consistent $Q$ evolution of $\hat{q}$ ...  
May solve the JET puzzle”
Lappi [Sat.pp-pA.2]: Resummed NLO BK might spoil geometric scaling

Recall initial condition: \( N(r) = 1 - e^{-\frac{1}{4} \ln \left( \frac{r_{QCD}^{-1}}{r_Q} + \alpha \right)} \).

Define

\[ \gamma(r) \equiv -\frac{d \ln N(r)}{d \ln r^2} \]

Geometric scaling?

- LO: fast to \( \gamma \sim 0.8 \)
- NLO: stay at initial \( \gamma \)

LO \( y = 0 \) to \( y = 5 \)

- Solid: initial condition
- Dotted: \( y = 5 \) NLO
- Dot-dashed: \( y = 5 \) LO (rc)
Branching number fluctuations

- Escobedo [Sat.Jet.1]: $\langle \Delta E^2 \rangle \neq 0$

Fluctuations in energy and fluctuations in size

Average of all back-to-back jets created in a heavy-ion collision with initial energy $E$ taking into account both fluctuations in energy and in size:

$$\langle E_1 - E_2 \rangle^2 = (N_c \alpha_s \hat{q})^2 (\langle L_1^2 \rangle - \langle L_2^2 \rangle)^2$$

$$\sigma_{E_1-E_2}^2 = \langle (E_1-E_2)^2 \rangle - \langle E_1-E_2 \rangle^2 = (N_c \alpha_s \hat{q})^2 \left[ \frac{1}{3} (\langle L_1^4 \rangle + \langle L_2^4 \rangle) + \sigma_{L_1}^2 + \sigma_{L_2}^2 \right]$$

The dijet asymmetry is produced:

- Asymmetry between the path lengths of the 2 jets in the medium.
- Fluctuations of the energy loss that are present even if the size is fixed.
- Fluctuations in the size of the medium seen by the jet.
- Fluctuations dominate over average whenever $L_1 \sim L_2$.

Leads to KNO type scaling
Thermal fluctuations

- Gossiaux [Sun.Quarko.2]: Schrödinger-Langevin approach to the bottomoniums

**Final suppression (3): vs** $N_{\text{part}}$

![Graph showing suppression vs $N_{\text{part}}$]

We miss some suppression in most central events (under investigation; CNM?)
Geometrical fluctuations

- Mantysaari [Sun.Init.1]: Proton is round *only* on average. Actual shape fluctuates

Adding color charge fluctuations: IP-Glasma

- Obtain saturation scale $Q_s(b_T)$ from IPsat (with constituent quarks)
- Sample color charges $\rho(b_T) \sim Q_s(b_T)$
- Solve Yang-Mills equations to obtain the Wilson lines
  
  \[ V(x_T) = P \exp \left( -ig \int dx^+ \frac{\rho(x^-, x_T)}{\nabla^2 + m^2} \right) \]

- Dipole amplitude: $N(x_T, y_T) = 1 - \text{Tr}(V(x_T)V^\dagger(y_T))/N_c$
- Fix parameters $B_{qc}, B_q$ and $m$ with HERA data

Example configurations: $1 - \text{Re}(\text{Tr}(V(x_T)))/N_c$

Fluctuating protons in pA collisions

Preliminary hydro calculations with proton fluctuations from HERA

- Hydro numbers
  - $\tau_0 = 1$ fm
  - $T_{fo} = 160$ MeV
  - Viscosity as in arXiv:1512.01538

Large $v_2$ and $v_3$ at largest centrality bins reproduced well.

Work in progress (centrality dependence, initial $\pi^{\mu\nu}, ...$)
Pre-equilibrium flow fluctuations

- McDonald [Sun.Init.1]: Even in the boost invariant case (IP-Glasma) $|u^\eta| \sim |u_\perp|$

**How we think about initial flow**

**How we should think about initial flow**

On average, $\langle u_\|^n \rangle \approx 0.5 \langle u_\perp \rangle$

\[
\langle u_\rangle = \sqrt{\frac{\int (u_\|^n \epsilon d^2 x)}{\int \epsilon d^2 x}}
\]
Nature reminds us that she is quantum mechanical

To understand physics and distinguish models, one needs at least the first and the second moment

Challenge: Include vacuum fluctuations in Glasma based models

Fluctuations crucial in small systems
To learn: QGP droplets in small systems
**Small systems**

- Shen [Sat.EM.1]: QGP flows in dA and shines in pA (with MC-Glauber IC)

- The interplay between radial and elliptic flow in the hydrodynamic simulations can reproduce the mass splitting of pid $v_2(p_T)$ in small collision systems

**Indication of a strongly coupled QCD matter?**

**Signature of a nearly thermalized medium in small systems**
Vogt [Sat.pp-pA.1]: “The $J/\psi$ and $\nu$ results are compatible with both shadowing only and energy loss only but not really with CGC+CEM”

Figure 9: (Left) The $R_{pPb}$ ratio for $J/\psi$ as a function of $y$. The dashed red histogram shows the EPS09 NLO CEM uncertainties. The EPS09 LO CSM calculation by Lansberg et al. is shown in cyan. The energy loss calculation of Arleo and Peigne is shown in magenta. The upper and lower limits of the CGC calculation by Fujii et al. are in blue at forward rapidity. (Right) The $R_{pPb}$ ratio for $\gamma$ as a function of $y$. The dashed red histogram shows the EPS09 NLO CEM uncertainties. The EPS09 LO CSM calculation by Lansberg et al. is shown in cyan. The energy loss calculation of Arleo and Peigne is shown in magenta. The upper and lower limits of the CGC calculation by Fujii et al. are in blue at forward rapidity.
Small systems

- Park [Sat.pp-pA.1]: Prediction of QGP droplets in pA

Rapidity dependent energy loss
- Net QGP medium energy loss related to temperature and energy
  - a clear signature of QGP droplet in central collisions is predicted

Charged hadron $v_2$ at high $p_T$
- Scalar product method; reference flow integrated from 0.3 - 3GeV
- 1~3% $v_2$ in central p-Pb collisions
- Medium induced energy loss dependency on integrated $v_2$
Do we have QGP in small systems?
- Yes, maybe.
- Will Horowitz: “[We] are faced with a need to reassess the applicability of the large formation time assumption in any description of energy loss.” [1511.09313]
- Also need other signs of collective motion such as $c_2\{4\}$
- If not QGP droplet, what are alternatives?
AdS/CFT modelling comes of age

To learn: Strong $g_S$ dynamics
\( \hat{q} \) from AdS/CFT

- Horowitz [Sat.Jet.3]: Wobbly limp noodle

\[ s^2 \approx 2Dt = 8\left( T^2 / v \hat{q} \right)t \]
van der Schee [Sat.Jet.1]: Tracking both energy and angle

RESULTS

Shooting about 50,000 jets through plasma

Naïve QCD: \( a \sim 1.7, \ b \sim 0.78 \)
Pablos [Sat.Jet.3]: Energy loss by AdS/CFT

\[
\frac{1}{E_{\text{in}}} \frac{dE}{dx} = -\frac{4}{\pi} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}
\]

where

\[
x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}} \left( \frac{E_{\text{in}}^{1/3}}{T_{4/3}^4} \right)
\]
Pablos [Sat.Jet.3]: Energy loss by AdS/CFT

\[ \frac{1}{E_{\text{in}}} \frac{dE}{dx} = -\frac{4}{\pi} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}} \]

where

\[ x_{\text{stop}} = \frac{1}{2\kappa_{sc}} \frac{E_{\text{in}}^{1/3}}{E_{T}^{4/3}} \]

Monte Carlo Implementation

Jet production and evolution in PYTHIA
Assign spacetime description to parton shower (formation time argument) \( \tau_f = \frac{2E}{Q^2} \)
Embed the system into a hydrodynamic background (2+1 hydro code from Heinz and Shen)
Between splittings, partons in the shower interact with QGP, lose energy
Turn off energy loss below a \( T_c \) that we vary over \( 145 < T_c < 170 \) MeV
Extract jet observables from parton shower

Small sensitivity of jet shapes to broadening:
- strong quenching removes soft fragments that appear early
- remaining soft tracks fragment late
Holography helps resolving the photon $\nu_2$ puzzle

- Yang [Sat.EM.2]: – Holographic models make both yield and $\nu_2$ go up

**Emission Rates**

**Direct-Photon Flow in LHC**

Similar to the case in RHIC, the flow from holographic models is increased in high pT but reduced at low pT.
In Finite temperature field theory, expansion parameter is $g_s$

not $\alpha_S = g_s^2 / 4\pi$

At $Q = M_Z$, $g_s \approx 1$

At $Q = T_{QGP}$, $g_s \approx 2$

In principle, perturbation theory expressions are not really applicable

$g_s$ is not $\infty$, either – Phenomenology looks close to it, though.

Reality is somewhere in between – How do we get at it?

Eventually, we need to construct $AdS/QCD$ models
SCET comes of age

To learn: The right way to separate scales (and factorize)
Ringer [Sat.Jet.2]: Jets and HF in SCET

\( \mathcal{L}_{SCET} = \mathcal{L}_{SCET_{M,G}} \)

\[ \mathcal{L}_{SCET_{M,G}} = \mathcal{L}_{SCET_{M}} + \mathcal{L}_{G}(\xi_n, A_n, A_G) \]

Kang, FR, Vitev '16

\[ \mathcal{L}_{SCET_{M}} = \frac{1}{2} \mathcal{L}_{SP} + \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{coll}} \]

Leibovich, Ligeti, Wise '03

\[ \mathcal{L}_{G}(\xi_n, A_n, A_G) = \sum_{p, p'} e^{-m_{p'}^2 p'^2} \left( e_{\mu\nu} x_{\mu\nu} \right) A_{\mu\nu} \]

Ovanesyan, Vitev '12

Feynman rules for interaction with the medium do not depend on the mass to leading-power!

Bauer, Fleming, Luke, Pirjol, Rothstein, Stewart '00-02

Idilbi, Majumder '08, D’Eramo, Liu, Rajagopal '10

Comparison to LHC data
The $z_g$ power

or “I’ll harangue anyone who uses the term.” – Brian Cole on modified splitting function
Lapidus [Sat.Jet.3]: $z_g$ has discrimination power

**Hard Jet Splitting probed with Soft Drop**

A. J. Larkoski, S. Marzani, J. Thaler PRD 81, 111501(R)

- $z_g = \min \left( \frac{p_T1, p_T2}{p_T1 + p_T2} \right) > z_{cut}
- \text{groomed momentum fraction}
- p(z_g) = \int \frac{dz}{z} P_1(z)
- z_g$ recursively removes soft subjets, until a hard splitting is identified

$p(z_g)$ is approx. independent of:
- jet $p_t$ and radius
- $\alpha_S$
- collision energy

What MC including jet quenching effects predicts?

**z_g: Data vs. Models**

- Good discriminating potential of the $z_g$ observable
- Momentum dependence is not described well
- Both models (YaJEM-DE and JEWEL) incorporate unmodified splitting functions

Is $z_g$ sensitive to a modified $P(z)$?


Kirill Lapidus, Yale
The $z_g$ power

- Kunnawalkam Elayavalli [Sat.Jet.3]: – JEWEL with medium recoil can do $z_g$

Comparing with Data
CMS-PAS-HIN-16-006

- Good description!
- The PbPb jets prefer to be more asymmetric as compared to pp (and general qcd) which features harder splitting
Mini Summary – \( z_g \) power

- New tool that's sensitive to the first branching
- Sensitive to the details of branching and soft \( p_T \) stripping
- When refined, this can provide a good way to select more refined way of selecting jet classes
Direct photon puzzle
It’s still a good puzzle

- Greif [Sat.EM.2]: – BAMP with LO photons

- Also Yang [Sat.EM.2]: – Holographic models make both yield and $v_2$ go up
Mini Summary – Direct photon puzzle

- It’s still a good puzzle but what don’t we understand?
- Pre-hydro?
- Post-hydro?
- Jet-medium photons?
- Opportunity abounds!
Heroic feats of calculations
Rasonaivoa [Sun.High \( p_T .2 \): Resumming N-gluon emission amplitudes

Two pillars of MHV amplitudes
- Color decomposition
  \[ \mathcal{M} = \sum_{\text{perm}} C_{\alpha_1, \ldots, \alpha_n} A(1, 2, \ldots, n) \]
- Spinor helicity formalism
  \[ \begin{align*}
  & p^\alpha \quad \rightarrow \quad p'^\alpha = \lambda^\alpha \lambda'^\alpha \\
  & k_1, k_2 \quad \rightarrow \quad (12) = \epsilon_{ab} \lambda_i^a \lambda_j^b \quad \text{and} \quad [12] = \epsilon_{ab} \lambda_i^b \lambda_j^a
  \end{align*} \]

Partial amplitude for \( n \) gluon emissions

The probability distribution \( P_n \) of \( n \) gluon emissions is given by
\[ P_n \sim \sum_{i=0}^{n} \int |J_i(1, \ldots, n)|^2 \]

Resummation decoupled into a sum over different symmetry
\[ \sum_{i=0}^{n} \int |J_i|^2 = \sum_{i=0}^{n} N_c^i \int |J_i|^2 + \sum_{i=0}^{n} \text{tr}(C_i^a |p^a|^2) \int |J_i|^2 + \sum_{i=0}^{n} \int |\text{Mixed}|^2 \]

The purely symmetric, QED like factor, can be exponentiate
\[ \sum_{i=0}^{n} N_c^i \int |J_i|^2 \rightarrow \exp \left( N_c \int |J_i(k_1)|^2 \right) \]

\( J_n^a \) computed with no exponentiation pattern (Week ago).

Now! working on the mixed symmetry case for general \( n \).
By students

- Hauksson [Sat.EM.2]: Out-of equilibrium calculation of the photon AMY rate

### Out-of-equilibrium case

Without using the KMS condition we derived that out of equilibrium

\[
P+K \frac{1}{P} = \frac{\Sigma^<}{\Sigma^< - \Sigma^>} \left(1 + \frac{\Sigma^<}{\Sigma^> - \Sigma^<} \right) P \quad \text{Re} \quad \frac{r}{r}
\]

where

\[
\begin{align*}
\frac{r}{r}^a &= \frac{r}{r}^a + \frac{r}{r}^a + \frac{r}{r}^a + \ldots
\end{align*}
\]

Exactly the same diagrams contribute in and out of equilibrium.

Need the quark and gluon self energies.

The diagrams can be summed up giving an integral equation that needs to be solved numerically.

### Out-of-equilibrium case

Need to check that we have the same power counting scheme out of equilibrium.

Calculations so far show that the power counting scheme is still valid for \( \delta f \sim f_{\text{eq}} \).

We can always write

\[
\begin{array}{c}
\begin{array}{c}
1 \quad 2 \\
\sim
\end{array}
\end{array}
\]

aa quark lines vanish and ra and ar lines are simple.
These two beasts still surprising us after all these years

- Theory community vibrant and strong
- Entering the precision measurement era – Eyes on the prize!
Thank you organizers and volunteers for a great conference!