LBNL Nuclear Science Division Staff Meeting

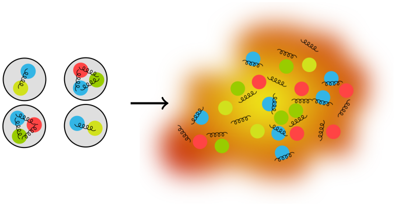
Jet modifications in a quark-gluon plasma

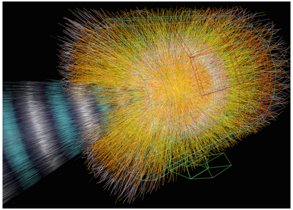
Weiyao Ke, in collaboration with Xin-Nian Wang

This work is supported in part by NSFC Nos. 11935007, 11221504, and 11890714, by DOE No. DE-AC02-05CH11231, by NSF No. ACI-1550228, and by the UCB-CCNU Collaboration Grant.

Creating and probing the properties of the quark-gluon plasma

Quarks & gluons are confined in hadrons in ordinary matter. Heavy-ion collisions deposit huge energy in a finite region, creating quark-gluon plasma (QGP) medium for $\Delta x, \Delta\tau \sim 10$ fm.





ALICE event

↗ Only see final state.

↓

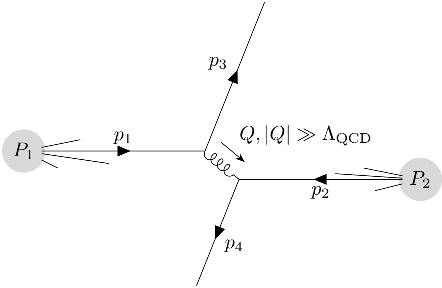
What are medium's properties?

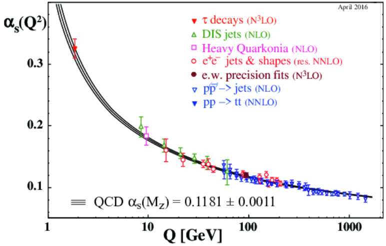
- The created QGP demonstrates hydrodynamic and near-equilibrium behaviors $\rightarrow$ we can learned a lot long-wave length properties $\eta/s, \zeta/s, \cdots$
- **We still need additional probes to test its microscopic structures.**

Self-generated probes at short distances in QCD: hard collisions

On high energy colliders, occasionally, a hard QCD collision happens with $Q \sim p_T \gg \Lambda_{QCD}$.
Asymptotic freedom of QCD: coupling $\alpha_s = g^2/(4\pi)$ decreases with energy scale.

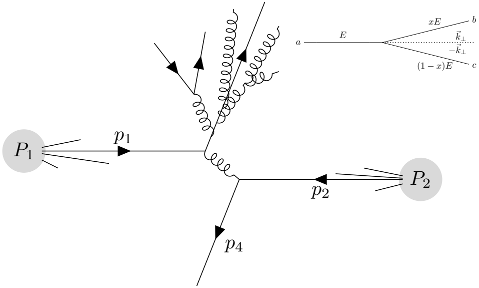
A perturbatively understanding of the scattering in terms of partons (quarks and gluons).





Self-generated probes at short distances in QCD: hard collisions

On high energy colliders, occasionally, a hard QCD collision happens with $Q \sim p_T \gg \Lambda_{QCD}$.
Asymptotic freedom of QCD: coupling $\alpha_s = g^2/(4\pi)$ decreases with energy scale.



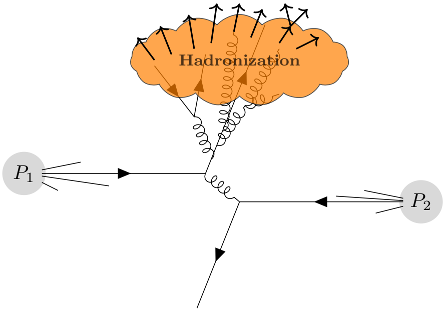
- Highly off-shell parton tends to radiate. Enhanced soft and collinear radiation,

$$\frac{dP^q_{qg}}{dxdk_\perp^2}, \frac{dP^g_{gg}}{dxdk_\perp^2} \sim \alpha_s C_R \frac{1}{x}\frac{1}{k_\perp^2}$$

- DGLAP-type equations describe the system's evolution towards smaller scale (reducing off-shellness).
- Hard parton evolves into a parton shower.

The hard process evolved to large distances

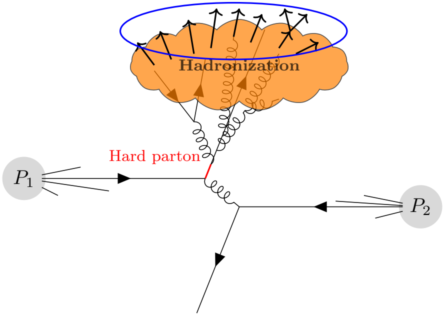
The scale evolution (decreasing Q) eventually drives the system towards the non-perturbative region $Q \gtrsim \Lambda_{QCD}$. Parton picture is not validate $\rightarrow$ hadronization, requires lots of modeling.



- Hadronization + decay. Final states are collimated hadrons and decay products.

The hard process evolved to large distances

The scale evolution (decreasing Q) eventually drives the system towards the non-perturbative region $Q \gtrsim \Lambda_{QCD}$. Parton picture is not validate $\rightarrow$ hadronization, requires lots of modeling.

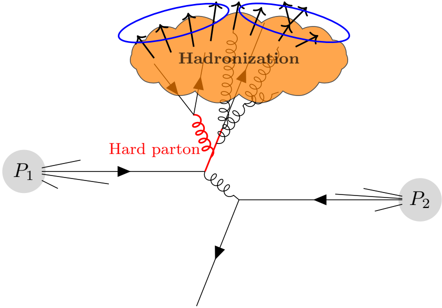


- Hadronization + decay. Final states are collimated hadrons and decay products.
- Jet is defined by grouping[1] the four-momentum of final state particles with in a radius of $\sqrt{(\eta-\eta^{\mathrm{jet}})^2+(\phi-\phi^{\mathrm{jet}})^2} < R$ (jet radius).

[1]Experimentally, jet has an operational definition to iteratively group final state particles. These algorithms are guaranteed to be insensitive to QCD soft and collinear splittings.

The hard process evolved to large distances

The scale evolution (decreasing Q) eventually drives the system towards the non-perturbative region $Q \gtrsim \Lambda_{QCD}$. Parton picture is not validate → hadronization, requires lots of modeling.



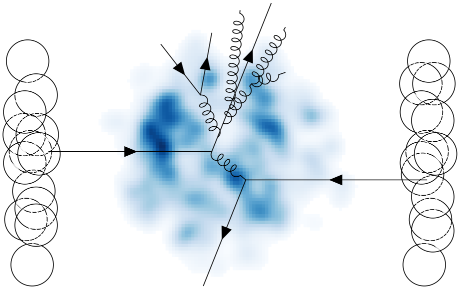
- Hadronization + decay. Final states are collimated hadrons and decay products.
- Jet is defined by grouping[1] the four-momentum of final state particles with in a radius of $\sqrt{(\eta-\eta^{\rm jet})^2+(\phi-\phi^{\rm jet})^2} < R$ (jet radius).
- An analog, but not precise correspondence, of the hard partonic process.

[1]Experimentally, jet has an operational definition to iteratively group final state particles. These algorithms are guaranteed to be insensitive to QCD soft and collinear splittings.

Hard QCD process in hot nuclear environment

Jets in relativistic heavy-ion collisions are surrounded by hot & dense medium.

- $\frac{dN_{ch}}{d\eta} \sim 500$ in central Au-Au @$\sqrt{s} = 200$ GeV, 2000 in central Pb-Pb @$\sqrt{s} = 5.02$ TeV[2].
- Mostly soft particles, $\langle p_T \rangle \sim 0.5$ to 0.7 GeV.

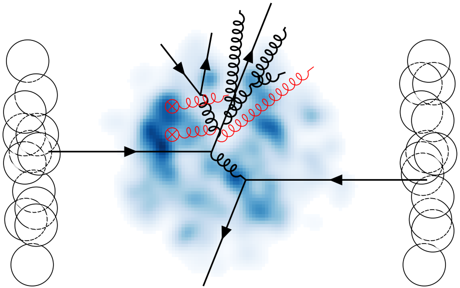


[2] These are final-state charged hadron multiplicities measured at RHIC and LHC, the medium parton densities are even higher.

Hard QCD process in hot nuclear environment

Jets in relativistic heavy-ion collisions are surrounded by hot & dense medium.

- $\frac{dN_{ch}}{d\eta} \sim 500$ in central Au-Au @$\sqrt{s} = 200$ GeV, 2000 in central Pb-Pb @$\sqrt{s} = 5.02$ TeV[2].
- Mostly soft particles, $\langle p_T \rangle \sim 0.5$ to 0.7 GeV.



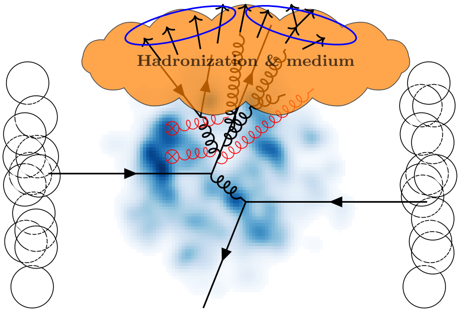
- Hard partons interact with colorful medium:

[2]These are final-state charged hadron multiplicities measured at RHIC and LHC, the medium parton densities are even higher.

Hard QCD process in hot nuclear environment

Jets in relativistic heavy-ion collisions are surrounded by hot & dense medium.

- $\frac{dN_{ch}}{d\eta} \sim 500$ in central Au-Au @$\sqrt{s} = 200$ GeV, 2000 in central Pb-Pb @$\sqrt{s} = 5.02$ TeV[2].
- Mostly soft particles, $\langle p_T \rangle \sim 0.5$ to 0.7 GeV.



- Hard partons interact with colorful medium:
- Hadronization in/out medium, hadronic interactions.

[2] These are final-state charged hadron multiplicities measured at RHIC and LHC, the medium parton densities are even higher.

Jet as probes of the medium

Interaction between hard partons & medium modifies the jet compared to the baseline.

- Jet quenching: suppression of production yield of hard process in nuclear collisions[3].

$$R_{AA} = \frac{d\sigma_{AA\rightarrow(h,j)+X}}{\langle N_{\mathrm{Ncoll}}\rangle d\sigma_{pp\rightarrow(h,j)+X}},$$

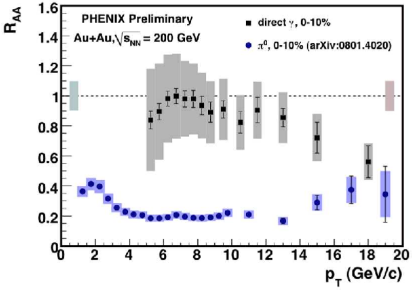
  $\langle N_{\mathrm{Ncoll}}\rangle$: effective number of nucleon-nucleon collisions in nuclear collisions.

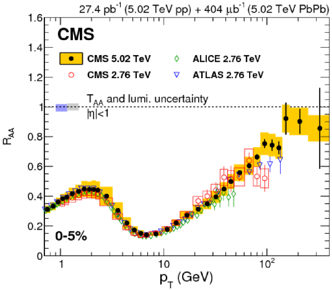
- Di-jet, γ-jet, Z-jet momentum imbalance.
- Modification to the internal structures of jets[4].

[3] Early proposal from J. D. Bjorken (1982), and M. Gyulassy and M. Plumer, X.N. Wang and M. Gyulassy.

[4] For applications in relativistic heavy-ion collisions J. Phys. G 47, no.6, 065102 (2020)

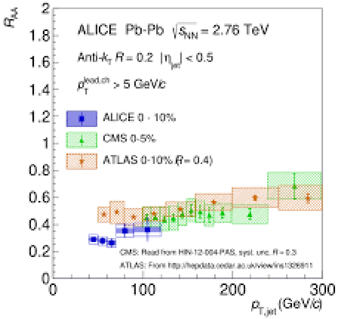
Jet quenching: what do we see?

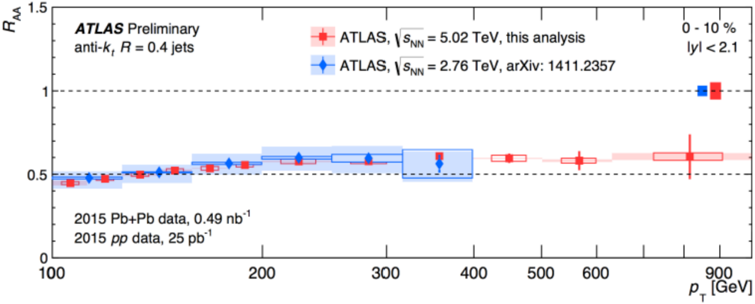




- Inclusive hadron suppression: $AA \to h(p_T) + X$.
- Factor of 5 suppression around p_T = 7-10 GeV at both RHIC and LHC energy.
- Fast rising to unity with increasing ln p_T at the LHC.
- What are the mechanism that transfers initial high-p_T partons to lower p_T regions?

Jet quenching: what do we see?

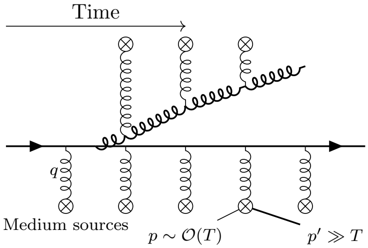




- Inclusive jet suppression: $AA \to j(p_T) + X$.
- Much weaker p_T dependence than inclusive hadron suppression.
- Hundreds GeV jets are suppressed by factor of 2 in central Pb-Pb collisions!
- How are particles / energy-momentum flowing in/out the jet cone due to medium effects.

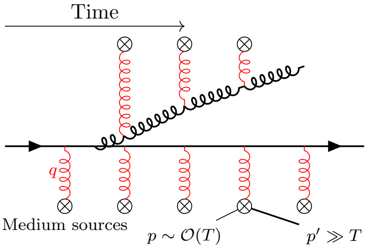
Traveling of a single energetic parton in a hot medium

A formidable task, what is shown is already a **much simplified** picture.



Traveling of a single energetic parton in a hot medium

A formidable task, what is shown is already a **much simplified** picture.



Collisional: energy-momentum exchange with medium.

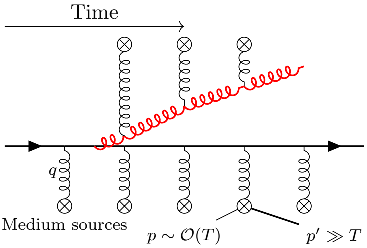
- Medium properties packed into jet transport parameter (leading order):

$$\hat{q} = \frac{d\langle \Delta p_\perp^2 \rangle}{dt} = \underbrace{\alpha_s C_R T}_{\text{“(mean-free-path)}^{-1}\text{”}} \underbrace{m_D^2 \ln Q^2/m_D^2}_{\text{“avg. } q_\perp^2\text{”}}$$

- m_D: plasma screening (Debye) mass. $m_D^2 \sim \alpha_s T^2$
- Q^2: hard cut-off of momentum transfer.

Traveling of a single energetic parton in a hot medium

A formidable task, what is shown is already a **much simplified** picture.



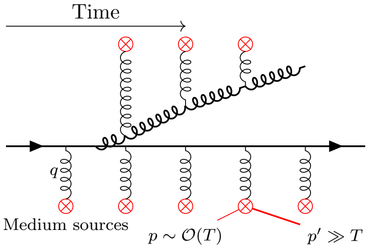
Induced radiations triggered by collisional processes[5].

$$\frac{dP}{dxdk_\perp^2} = \frac{dP^{\mathrm{vac}}(Q)}{dxdk_\perp^2} + \frac{dP^{\mathrm{med}}(\hat{q}(L), \cdots)}{dxdk_\perp^2}$$

[5] Theory of medium-induced radiations of QCD are developed in B. G. Zakharov, JETP Lett. 63, 952 (1996),] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, and D. Schiff, Nucl. Phys. B484, 265 (1997).

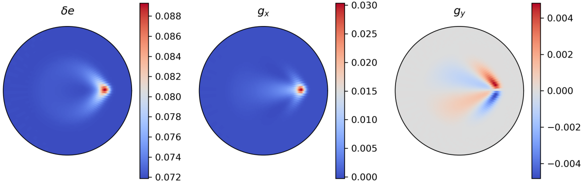
Traveling of a single energetic parton in a hot medium

A formidable task, what is shown is already a **much simplified** picture.



"Recoil": final state of elastic process can become energetic. Interpolate between elastic and radiation.

"Medium excitation": response of medium dynamics to the energy-momentum exchange.



Sum multiple interactions

Modified QCD evolution equation[6]: medium effects as perturbation.

- Apply DGLAP-type evolution equation $\frac{\partial D(z,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dy}{y}[P_{\rm vac}(y) + P_{\rm med}(y)]D(\frac{z}{y}, Q^2)$.

Transport equation approach: medium effect dominates (the method that we took[7]).

- Define interaction rate $R = dP/dt$,

$$(\partial_t + \mathbf{v}\cdot\nabla)f(t,x,p) = \int_p [R_{\rm coll}(E+p,p;T)f(E+p) - f(E;T)R_{\rm coll}(E,p)] + \text{[Radiation, corrected for coherence effect]}$$

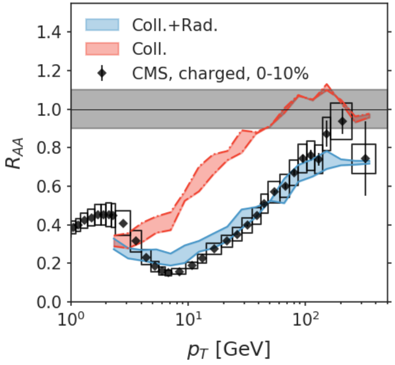
  medium information (T, u^μ) from hydrodynamic simulation.

- Soft partons $E < 4T$ are redistributed with a hydro-motivated ansatz to guarantee energy-momentum conservation $\rightarrow$ mimic jet-induced medium excitation.

---

[6] For example, Y.T. Chien, et al PRD 93 074030 (2016)
[7] W. Ke, Y. Xu, S. A. Bass, PRC 100 064911 (2019).

Inclusive hadron suppression in a transport model

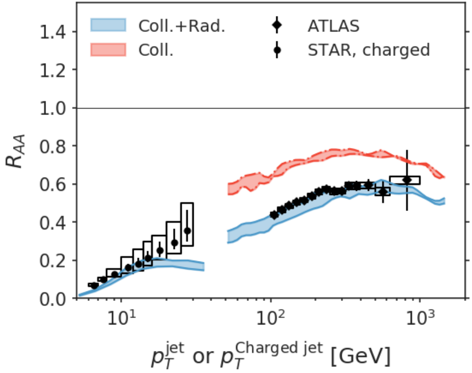


CMS JHEP04(2017)039

- Inclusive charged particle R_{AA}
  - Data: CMS Pb-Pb @ 5.02 TeV, 0-10%.
  - Bands: transport model with variation of coupling[8].
- Elastic: frequent, but only changes momentum by $O(T)$ per collisions .
- Induced radiation: rare, but efficient in changing parton's momentum $p \to xp, (1-x)p$.
- Elastic process dominates at low-p_T. Radiation increasing important at high-p_T.

[8] $\alpha_s(Q^2) = \frac{12\pi}{(11N_c - 2N_f)\ln(\max\{Q^2, \mu_{\min}\})}$. The running α_s is truncated at $\mu_{\min}$ in a QGP medium with temperature T. Here, $\mu_{\min}$ is varied from $1.5\pi T$ to $2\pi T$

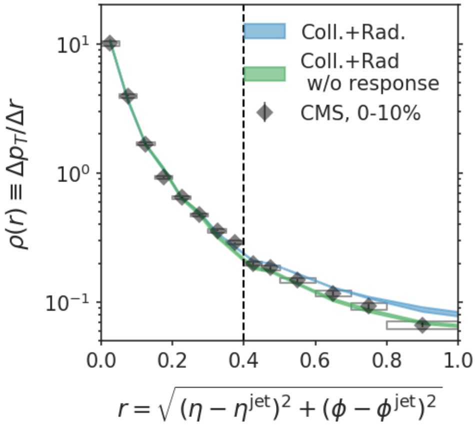
Inclusive jet suppression in a transport model



- Inclusive jet R_{AA} with radius $R = 0.4$
  ATLAS Pb+Pb @ 5.02 TeV, 0-10% (PLB 790 108-128)
  STAR Au+Au @ 200 GeV, 0-10% (arXiv:2006.00582)
- Collisional: efficient in transfer momentum to large-angle[9] outside jet cone R, $\tan(\theta) \sim 1/g$.
- Induced radiation: collinear splittings stay in jet cone, large angle radiations go out of cone.
- Comparable effect of coll. & rad. for $R = 0.4$.

[9] In CoM frame of collisions: $\sqrt{s} \sim ET$, $q_\perp \sim m_D, q_z \sim q_\perp^2/\sqrt{s}$. Boost it back to the medium frame $q_z' \sim q_\perp^2/T$, $\tan(\theta) = q_\perp/q_z \sim T/m_D \sim 1/g$

Where is the medium excitation?



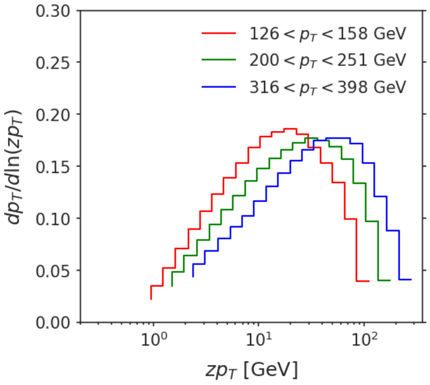
CMS Pb-Pb @ 5.02 TeV, JHEP05(2018)006

Looking at jet shape, radial r distribution of jet p_T.

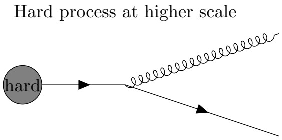
$$\rho(r) = \frac{1}{\sum_{r<1} \Delta p_T} \frac{\Delta p_T}{\Delta r}$$

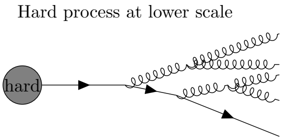
- Comparing calculations w/ and w/o energy momentum carried by medium excitation.
- Medium excitation only carries a tiny fraction of p_T produced by the hard process.
- Medium excitation / energy-momentum conservation becomes important at large radial distances.

Why are hundreds GeV to TeV jets also suppressed?



- Jet is not a single parton. At the scale resolved by medium, it consists of a spectrum of partons.
- Even TeV jets have large share of energy carried by $p_T \sim \mathcal{O}(10)$ GeV partons.
- Medium interaction happens at a particular resolution scale $Q^2_{\rm med} \sim \int \hat{q} dt$.

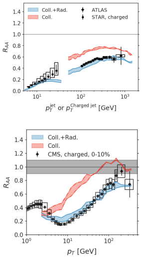




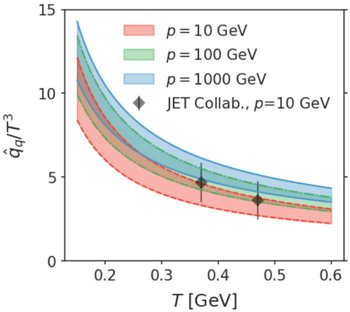
But what have we learned about the medium?

Tuning the coupling strength in the model to fit inclusive hadron and jet suppression pin down the jet transport parameter (on-going work to achieve a systematic Bayesian tuning).

$$\hat{q}_R = \alpha_s C_R T m_D^2 \ln \frac{Q^2}{m_D^2}, Q^2 = 6ET$$



→



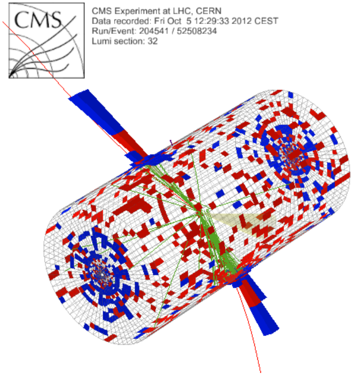
- Coupling is large $g(T \sim 2T_c) \sim 2$.
- Jet suppression can be explained by hot medium effect assuming it has a near-thermal color density.

[10]Symbols in figure: earlier extraction from the JET collaboration PRC 90, 014909 (2014).

Summary

- Jets, high-p_T hadrons are produced in short distance hard QCD processes.
- Production and evolution of hard processes are pertrubatively understandable.
  $\rightarrow$ Controlled probes to study medium effects.
- Hot medium effects explains the large suppression of hard process in nuclear collisions
  $\rightarrow$ the medium contains color charges expected from a thermal QGP.
- In the future,the use of more differential jet measurement to characterize scale dependent QGP properties.

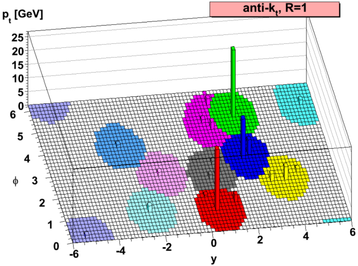
Jets in vacuum and definition



Event display from CMS

- Experimentally, one needs to identify jets from a list of "particles" (p^μ).
- Operational definition with jet finding algorithms.
  - Angular distance $\Delta r_{ij} = \sqrt{\Delta\phi^2 + \Delta\eta^2}$.
  - Define new distances $d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p})\frac{\Delta r_{ij}}{R}$.
  - Iteratively group the four momentum of "nearest" "particles" into jets.
  - "R" is the jet distance parameter (radius).
- Insensitive to a soft or collinear splitting.

Jets in vacuum and definition



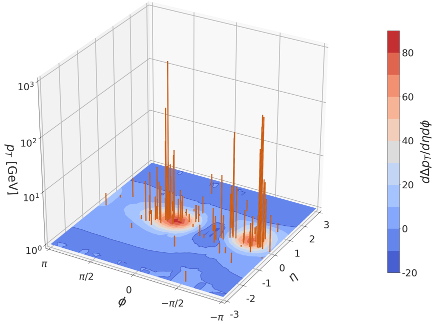
M. Cacciari et al JHEP04(2008)063

- Experimentally, one needs to identify jets from a list of "particles" (p^μ).
- Operational definition with jet finding algorithms.
  - Angular distance $\Delta r_{ij} = \sqrt{\Delta\phi^2 + \Delta\eta^2}$.
  - Define new distances $d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p})\frac{\Delta r_{ij}}{R}$.
  - Iteratively group the four momentum of "nearest" "particles" into jets.
  - "R" is the jet distance parameter (radius).
- Insensitive to a soft or collinear splitting.

Jet definition in heavy-ion collisions

In our model: compute transverse energy towers in each $\Delta\eta$-$\Delta\phi$ bin, summing both hard particle and medium excitation contribution:

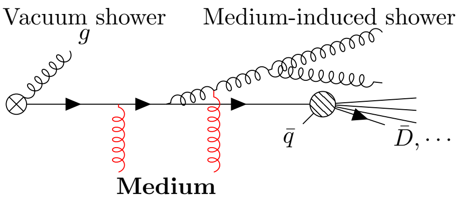
$$P_{ij}^{\mu} = \underbrace{\sum_{\Delta\eta\Delta\phi} p_{\mathrm{hard}}^{\mu}}_{\text{Hard particles}} + \underbrace{\frac{d\Delta p^{\mu}}{d\phi d\eta}\Delta\eta\Delta\phi}_{\text{Medium excitation}}$$



- Define jets using the grid P_{ij}^{μ} with anti-k_T algorithm as implemented in `FastJet`[1]
- The background is implicitly considered as the "unperturbed" medium.

[1] Cacciari and Salam, PLB 641 (2006) 57.

Single parton interacts with medium (in a weakly coupled picture)



Equilibrium distribution $f(p) \sim e^{-p\cdot u/T}$

Screening mass $m_D^2 = \left(\frac{N_c}{3} + \frac{N_f}{6}\right) g^2 T^2$.

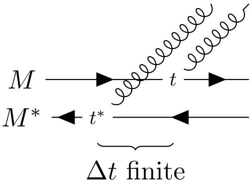
- **Hard**: $p \gg T$. **Elastic collisions**: direct momentum exchange between hard parton and medium constituents.
- Rate: number of collision per unit time,

$$\frac{dP}{dtdq_\perp^2} \propto T^3 \frac{\alpha_s^2}{q_\perp^2(q_\perp^2 + m_D^2)}$$

- A more physical quantity than rate is the so-called jet transport parameter $\hat{q}$, which measures the momentum broadening per unit time, directly related to medium properties.

$$\hat{q}_R = \frac{d\langle(\Delta p_\perp)^2\rangle}{dt} = \int q_\perp^2 \frac{dP}{dtdq_\perp^2} dq_\perp^2 = \alpha_s C_R T m_D^2 \ln \frac{Q_{\max}^2}{m_D^2}$$

Single parton interacts with medium (in a weakly coupled picture)



Medium-induced radiation

- Radiates of another parton due to collision with medium.
- Inelastic: energy is shared among two hard daughter partons.

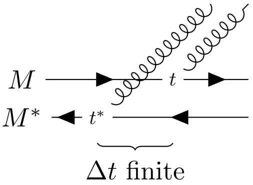
Single radiation probability for a parton moving in a medium of length L[1].

$$M_{gg}^{g} = \int_0^L dt' dk_\perp^2 \overbrace{\langle xp, (1-x)p, k_\perp^2 | e^{i\int_{t'}^{L} \hat{H}_{xp} + \hat{H}_{(1-x)p} dt}}^{\text{Evolution of 2-particle state to } t=L} \overbrace{\sqrt{P_{gg}^{g}(x)} \frac{k_\perp \cdot \epsilon}{k_\perp^2}}^{\text{splits into two}} \overbrace{e^{i\int_0^{t'} H_p dt} | p\rangle}^{\text{1 particle at t'}}$$

$$\frac{dP}{dx} = \langle M_{bc}^{a*} M_{bc}^{a} \rangle_{\text{ensemble avg.}}$$

[1] Zakharov JETP 63 952 and 65 615; Caron-Huot, Gale, PRC 82 064902; Arnold, Iqbal, JHEP04(2015)070

Single parton interacts with medium (in a weakly coupled picture)



Medium-induced radiation

- Radiates of another parton due to collision with medium.
- Inelastic: energy is shared among two hard daughter partons.

Single radiation probability breaks into two pieces $dP = dP_{\rm vac} + dP_{\rm med}$,

$$\frac{dP_{\rm med}}{dtdx} = \frac{P_{gg}^{g}(x)}{2x(1-x)E}\int_0^t dt' dk_\perp^2 dq_\perp^2 \langle k_\perp | iV_3 e^{iH_3 t'} | q_\perp \rangle, \quad |k_\perp\rangle = \frac{\vec{k}_\perp}{k_\perp^2}$$

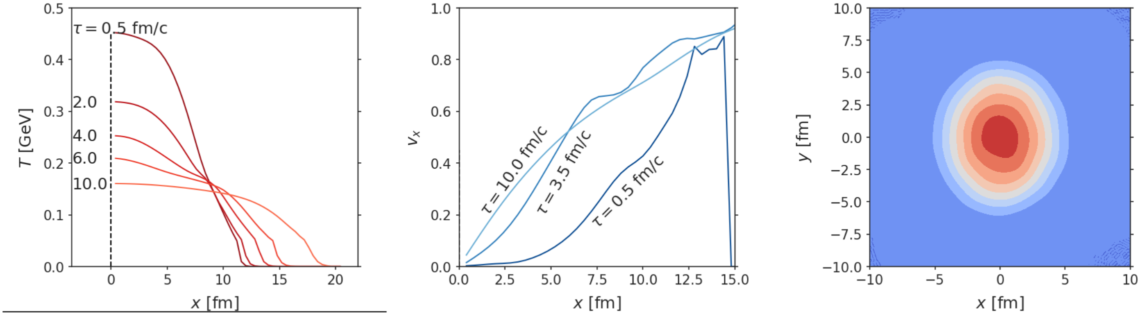
Radiation is not localized, $\Delta t^{-1} \sim$ average formation time in the medium $\langle \tau_f^{-1} \rangle$

$$H_3 \approx \frac{p_\perp^2}{2x(1-x)E} + i\frac{1}{2}\hat{q}_{\rm eff} b^2 + \cdots, \quad \begin{cases} H_3 = \Omega a^\dagger a + \cdots \\ \Omega = \sqrt{i2x(1-x)E\hat{q}_{\rm eff}} = \sqrt{i}\langle \tau_f^{-1} \rangle \end{cases}$$

Medium evolution

A hydrodynamic based medium simulation[10] provides space-time information of medium temperature (T) and flow velocity (v).

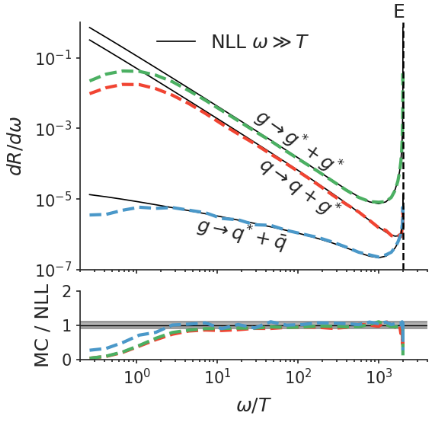
- Event-averaged initial condition + free-stream + (2+1) D viscous hydrodynamics.
- Hard production vertices sampled according binary collision density.
- Below: 0-10% central event for Pb+Pb @ 5.02 TeV.



[10] hic-eventgen, Bernhard arXiv:1804.06469

Single radiation rate: simulation compared to theory in special cases

Infinite static medium:
simulation from transport equation compared to next-to-leading-log solution of the rate in infinite limit.



Finite size effect:
path-length dependence of the radiation rate, simulation compared to numerical solution of the rate in finite medium