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Combined constraints from jet and hadron quenching to $\hat{q}$

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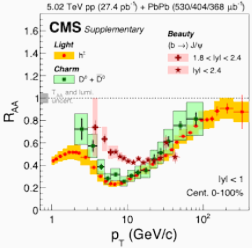
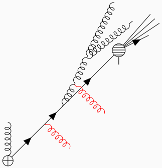
Based on W Ke, X-N Wang JHEP 05, 041 (2021)

Hadron & jet probe different aspects of parton dynamics in the QGP

Single hadron suppression at high-p_T

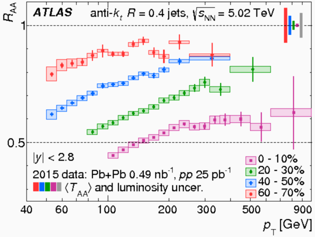


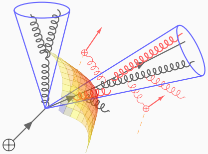


Probe modification/eloss of large-z partons

- Induced radiations that modify $D(z)$ at $zE \gg T$.
- Energy loss from soft rad. & collisions, $\omega \sim T$.

Single jet suppression





Sensitive to redistribution of "lost energy" by

- Collisions, induced radiations.
- Collective excitations.

This work: - study hadron & jet within the LIDO parton transport model.

- a consistent transport parameter for jet and hadron from Bayesian analysis.
- basis for predicting other jet modifications: R-dependence, fragmentation, shape.

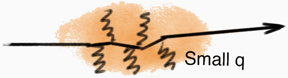
& many other predictions for, *dijet T. Rinn ATLAS* ↗, *b-jet, γ-jet S. Araya, ATLAS* ↗ *Y. Go, ATLAS* ↗

Method: LIDO transport model approach for hadron and jet

Hard parton transport $f_H = f(t,x,p)\Theta(p\cdot u > 4T)$, $f_s = e^{-p\cdot u/T}$

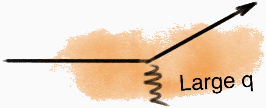
$$\begin{aligned}\frac{df_H}{dt} \quad = \quad & \Theta(p\cdot u > 4T)\left\{\mathcal{D}f_H + \mathcal{D}_{12}f_H \longrightarrow \text{ small-}q\text{ diffusion \& diff.-induced rad.}\right.\\ & \left.\qquad\qquad\qquad \mathcal{C}_{22}f_H + \mathcal{C}_{23}f_H\right\} \longrightarrow \text{ large-}q\text{ collision \& coll.-induced rad.}\end{aligned}$$

1. Soft diffusion[1]: $\mathcal{D} = -\eta\nabla_p - \frac{\hat{q}_s}{2}\nabla_p^2$



2. Large-q collision: $\frac{d\sigma}{d^2\mathbf{q}_\perp} \propto \frac{\alpha_s^2(\mathbf{q}_\perp)}{\mathbf{q}_\perp^4}\Theta(\mathbf{q}_\perp^2 - Q_c^2)$

   $\mathcal{C}_{22}f_H = \int_{\mathbf{k},\mathbf{q}}[\frac{d\sigma}{d^2\mathbf{q}}f_s(\mathbf{k})f_H(\mathbf{p}-\mathbf{q}) + \ldots$



▷ Combine to the jet transport parameter

$$\hat{q}_F = \underbrace{\alpha_s C_F T m_D^2 \ln\frac{Q_c^2}{m_D^2}}_{\hat{q}_s} + \int_{Q_c^2} \mathbf{q}_\perp^2 \frac{d\sigma}{d^2\mathbf{q}_\perp} d^2\mathbf{q}_\perp$$

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[1] In J. Ghiglieri, G. D. Moore, D. Teaney JHEP 03, 095(2016), separation requires $m_D \ll Q_c \ll T$. we take $Q_c = 2m_D$

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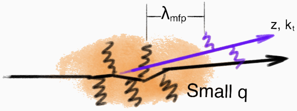
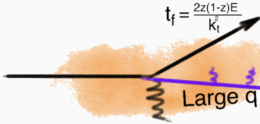


3. Diffusion-induced 1 *to* 2 radiation:

$$\mathcal{D}_{12} f(x) = \int \frac{dz}{1-z} z d^2\mathbf{k}_\perp \frac{\alpha_s P_{ij}(z)}{2\pi^2 \mathbf{k}_\perp^2} \frac{\hat{q}_s}{\mathbf{k}_\perp^2} f\left(\frac{x}{1-z}\right) + \ldots$$

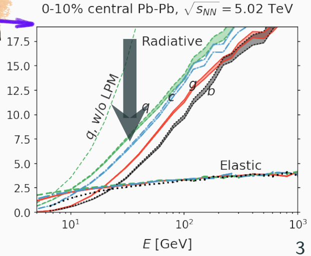


4. Large-q collision-induced 2 *to* 3 radiation.

$$\mathcal{C}_{23}(x) = \int_{\mathbf{k},\mathbf{q}} \frac{dz}{1-z} \frac{d\sigma_{23}}{dz d^2\mathbf{k}_\perp d^2\mathbf{q}} f_s(\mathbf{k}) f_H\left(\frac{x}{1-z}, \mathbf{p} - \mathbf{q}\right) + \ldots$$

▷ Landau-Pomeranchuk-Midgal effect implemented. Radiation suppressed by $\#\lambda_{\mathrm{mfp}}/\tau_f$.

[WK, Y Xu, S Bass, PRC100 064911 (2019)].



Method: A model for collective excitation induced by energy loss

- Energy-momentum deposition to soft sector:

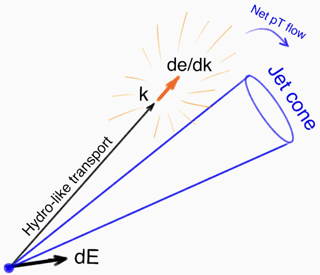
$$\frac{d\delta p^\mu}{dt}(t,x) = \int_{\mathbf{p}} \Theta(p\cdot u < 4T) p^\mu \frac{d}{dt} f_H(t,x,p)$$

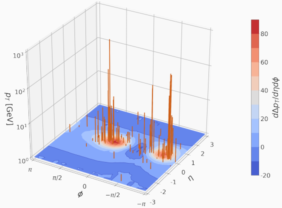
- An ideal-hydro response:

$$\frac{de}{d\Omega_{k'}} = \frac{\delta p^0 + \hat{k}'\cdot\delta\vec{p}/c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega_{k'}} = \frac{3(c_s\delta p^0 + \hat{k}'\cdot\delta\vec{p})\hat{k}'}{4\pi}$$

- Freeze-out to massless particles w/ radial flow $v_\perp$ $\Rightarrow$ corrections to momentum density in the cone:

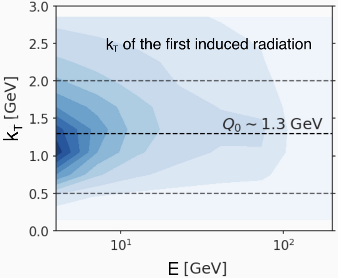
$$\begin{aligned} \frac{d\Delta p_T}{d\phi d\eta} &= \int \frac{3}{4\pi}\frac{\frac{4}{3}\sigma u_\mu - \hat{p}_\mu}{\sigma^4}\delta p^\mu(\hat{k})\frac{d\Omega_{\hat{k}}}{4\pi} \\ \sigma &= \gamma_\perp\left[\cosh(\eta-\eta_s-\eta_{\hat{k}}) - v_\perp\cos(\phi-\phi_{\hat{k}})\right] \end{aligned}$$





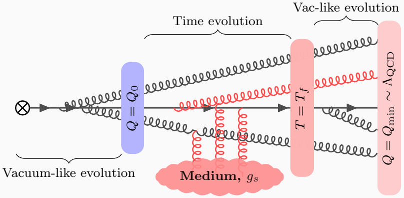
Method: Merging vacuum-like evolution and transport equation

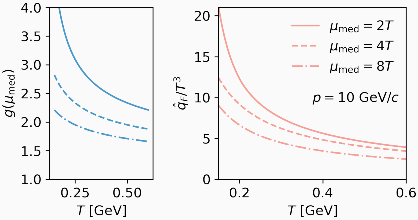
- Medium effects take place in a more restricted $\mathbf{k}_\perp$ region:
  - Collisions $|\mathbf{k}_\perp| \sim m_D = 0.4 ... 1.2$ GeV.
  - Induced radiation $|\mathbf{k}_\perp| \sim 1$ GeV.
- A "sudden" transition from DGLAP to transport at Q_0.
  - A reasonable $Q_0^2 \approx \langle \mathbf{k}_\perp^2 \rangle = \int_{t_0}^{\tau_f} \hat{q}(t) dt \propto t_0 T_0^3$ in fast-expanding medium.
  - Q_0: wealy energy dependnce; change in different medium.



Systems	Pb-Pb 5 TeV		Au-Au 0.2 TeV	Xe-Xe 5.44 TeV
	0-5%	40-50%	0-5%	0-5%
$5 t_0 T_0^3$ [GeV^2]	1.1	0.55	0.46	0.96

Uncertainties: two separation scales affect the extraction of g_s, $\hat{q}$





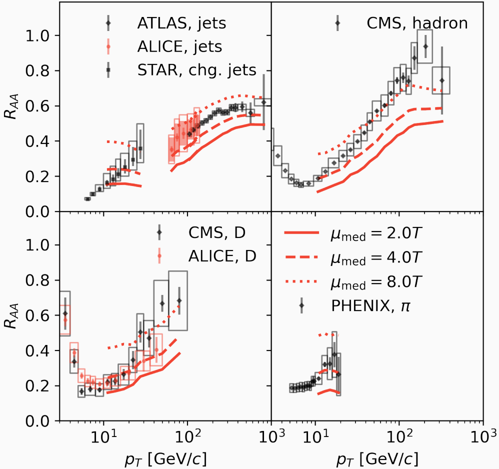
Objective: determine "jet-medium coupling g_s"
or "jet transport parameter $\hat{q}$".

Uncertainties:

- $0.5 < Q_0 < 2.0$ GeV: separates vacuum-like and transport evolution.
- $0.15 < T_f < 0.17$ GeV: color source $= 0$ for $T < T_f$.
- $0.7\pi T < \mu_{\rm med} < 4\pi T$: controls in-medium g_s:

$$\frac{g_s^2(\mathbf{k}_\perp)}{4\pi} = \frac{4\pi}{9} \ln^{-1}\left[\frac{\max\{\mathbf{k}_\perp^2, \mu_{\rm med}^2\}}{\Lambda^2}\right]$$

Uncertainties: μ_{med} or $g_s(\max\{k_T, \mu_{\text{med}}\})$



Experimental data:

[STAR charged jet: PRC 102, 054913(2020)]

[ALICE jet: PRC 101 034911(2020)]

[ATLAS jet: PLB 790 108-128(2019)]

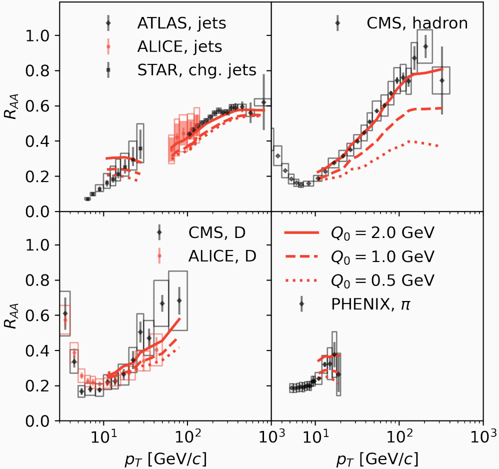
[CMS D: PLB 287 474-496(2018)]

[CMS h: JHEP 04, 039(2017)]

[PHENIX π: PRC 87, 034911(2013)]

Changing the coupling strength by varying $\mu_{\text{med}} = 2T, 4T, 8T$ GeV

Uncertainties of Q_0: advantage of using jet R_{AA} to calibrate $\hat{q}$



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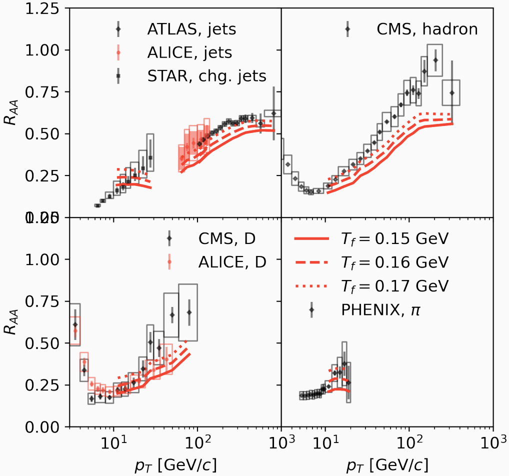
[CMS h: JHEP 04, 039(2017)]

[PHENIX π: PRC 87, 034911(2013)]

Test the variation of $Q_0 = 0.5, 1.0, 2.0$ GeV.

- Light hadron R_{AA} are very sensitive to Q_0.
- Jet and heavy-flavor R_{AA} at the LHC energy are the least sensitive.

Uncertainties: the QGP termination temperature T_f



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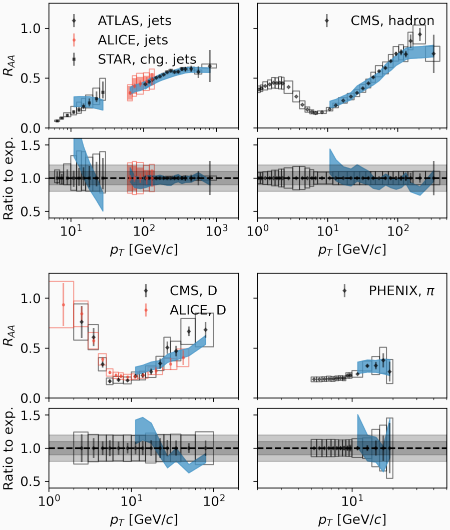
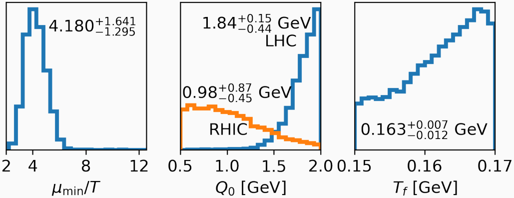
[PHENIX π: PRC 87, 034911(2013)]

Change $T_f = 0.15, 0.16, 0.17$ GeV. $\Leftrightarrow$ effectly change color density near T_c.

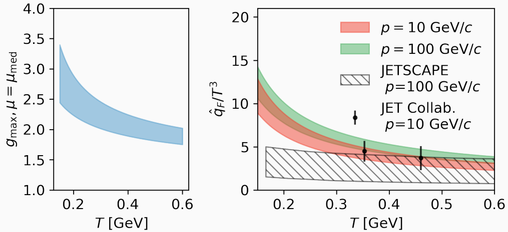
Results: Bayesian analysis of μ_{med}, Q_0^{LHC}, Q_0^{RHIC}, T_f





- Q_0^{LHC} varies independently from Q_0^{RHIC}. $Q_0^{\mathrm{LHC}} > Q_0^{\mathrm{RHIC}}$ is consistent with the expectation from $T_0^{\mathrm{LHC}} > T_0^{\mathrm{RHIC}}$.
- Favors higher T_f than the pseudo-critical T_c.
- Running of g_s in medium saturates around $\mathbf{k}_\perp > \mu_{\mathrm{med}} \approx 4.2T$ (or $1.3\pi T$).

Results: jet-medium coupling g and jet transport parameter $\hat{q}$



Left: maximum coupling at different temperature $g_s(\mu_{\rm med})$
Right: $\hat{q}$ at $p = 10$ and 100 GeV for a quark.

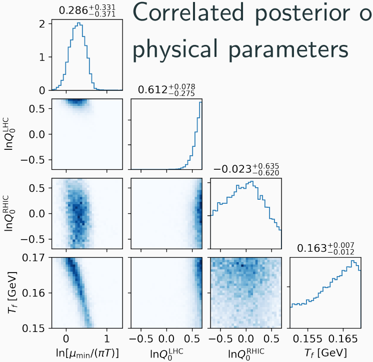
Compared to [JET Collab: PhysRevC.90.014909 (2014), JETSCAPE : PRC 104, 024905 (2021)] using inclusive hadrons.

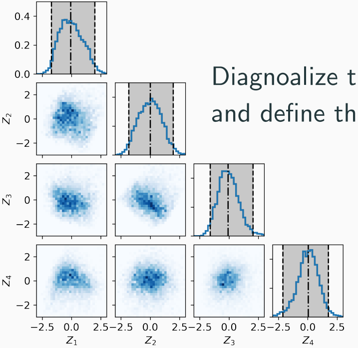
- Results consistent with JET collaboration at high p.
- Higher than the recent JETSCAPE Collaboration analysis.
  Possible reason: JETSCAPE include medium corrections to the DGLAP stage ($\mathbf{k}_\perp^2 > Q_0^2$)

”Representative parameter sets” for the study of other observables

To make “quick” predictions: we defined central + error parameter sets

Correlated posterior of physical parameters



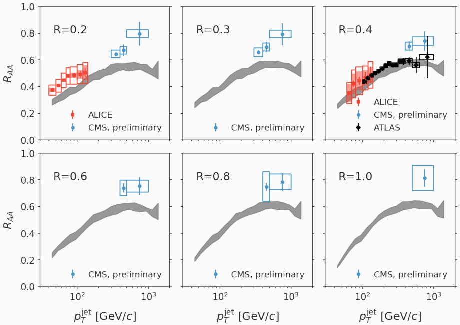


Diagnoalize the covariance matrix and define the $50^{+47.5}_{-47.5}$% bands.

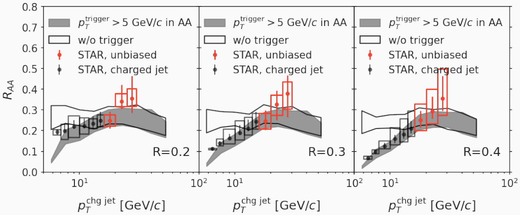
Transform the median and $^{+47.5}_{-47.5}$% edges back to physical parameters ▽

#	μ_{med}	Q_0^{LHC}[GeV]	Q_0^{RHIC}[GeV]	T_f [GeV]
0	1.32	1.81	0.97	0.16
1	1.90	1.64	0.83	0.153
...	...	...	...	...

Test the transport of energy: cone-size dependence of jet R_{AA}



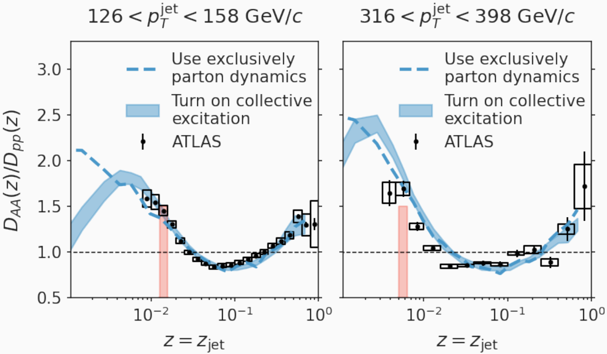
[CMS: JHEP 05, 284(2021)]



△ Unbiased region (red) are in sensitive to the high-p_T hadron trigger. The triggering bias is also understood from the simulation. [STAR: PRC 102, 054913(2020)]

- LHC: LIDO predicts R_{AA} inreased by 10% from $R = 0.2$ to $R = 1.0$ at $p_T^{\text{jet}} = 500$ GeV.
- RHIC: Weak R-dependence in the unbiased region.
  Triggering bias well understood from simulation.

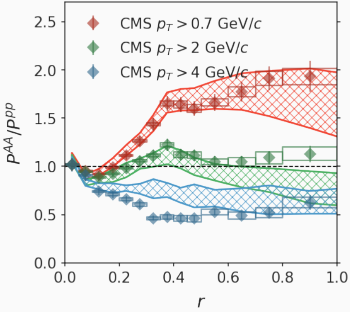
Test the transport of energy: fragmentation function



[ATLAS: PRC 98, 024908(2018)]

- Calcualtions that *treats everything with partonic dynamics* well describes the fragmentation at $zp_T^{\text{jet}} > 2$ GeV (red bands).
- *Use collective excitations to redistribution soft particles* improves at $p_T \lesssim 2$ GeV.

Test the transport of energy: a detailed look at low-p_T particles



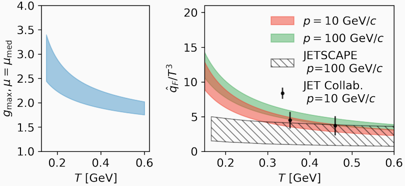
[CMS: JHEP05, 006(2018)]

◁ Jet shape with different minimum hadron p_T

- Energy is shifted to particles at lower p_T and larger r.
- Discrepancy appears wihtin the cone for $p_{T,cut} = 4$ GeV
  - Can this be fixed by fine-tuning of parameters?
  - Suggest missing physics? Such as coalescence shifting intermediate-p_T hadrons to higher p_T.

Summary and outlook

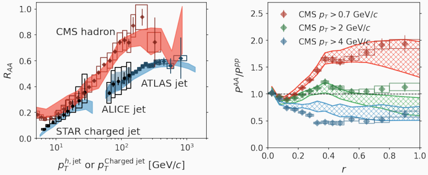
- Jet and hadron quenching are sensitive to different aspects of parton dynamics.
    - Hadron: total energy loss.
    - Jet: redistribution of the lost energy. Require a modeling of collective excitation.
    - Jet R_{AA}: less dependent on the separation scale between vacuum-like evolution & transport equation.



- Extract $g_s/\hat{q}$ from jet ($R = 0.4$) and hadron (h/D) R_{AA} at RHIC and LHC central AA collisions. ⇒

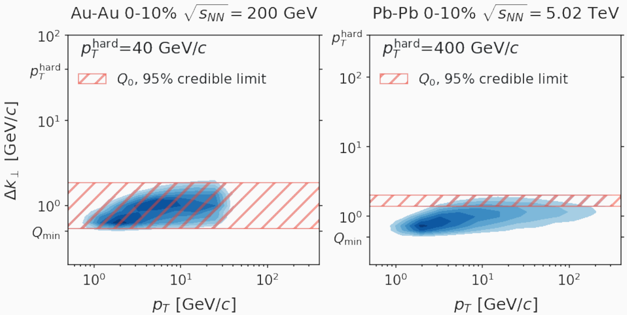
- The resulting jet cone-size dependence is weak. Undershoot CMS data; consistent with STAR data.

- The redistribution of low momentum particles around the jet tested with fragmentation fucntion and jet shape.



Questions?

A consistency check: compare Q_0^{RHIC} and Q_0^{LHC} to the medium $\mathbf{k}_\perp$



- Compare the radiative $\mathbf{k}_\perp$ distribution with the separation scale Q_0.
- At LHC: most in-medium activity happens below Q_0^{LHC}.
- At the RHIC, Q_0^{RHIC} is comparable to typical $\mathbf{k}_\perp$.