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Comparative multi-probe study of jet energy-loss in QGP

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Rouzbeh Yazdi[1], Shuzhe Shi[1,2], Charles Gale[1], Sangyong Jeon[1]

[1]McGill University, Montreal, QC, Canada

[2]Stony Brook University, Stony Brook, NY, USA

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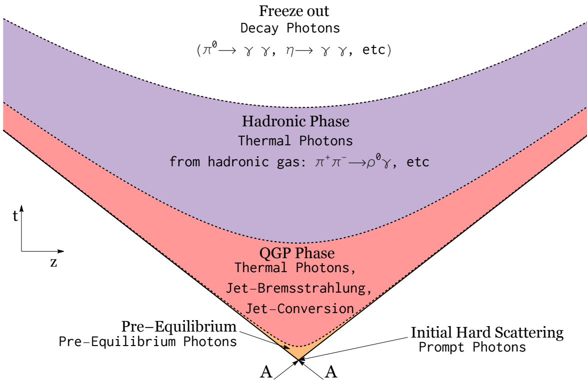
2023 HARD PROBES Aschaffenburg

Introduction

- Jet energy loss: important signal of QGP creation
- Our interest: CUJET-DGLV vs. MARTINI-AMY in a multi-probe, multi-stage analysis
- Aim: jet-medium photons as well as strong probes
- JETSCAPE framework: faithful comparison of diff. models, with all else held fixed



Radiative Energy-Loss: Gluon Emission

CUJET: Leading order DGLV

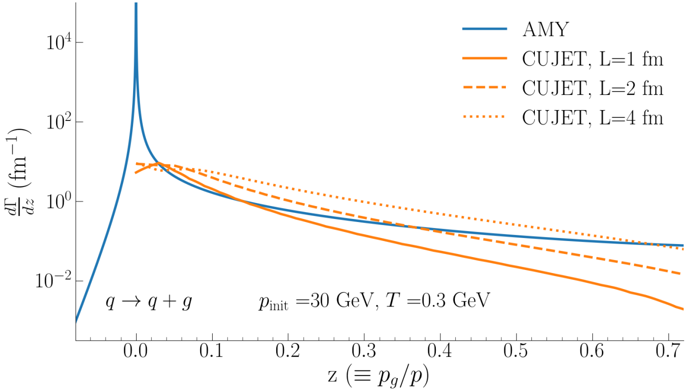
- LO in opacity (thin medium)
- Dynamic scattering centers, $\rho(T)$ via EOS

MARTINI: AMY

- All orders of opacity (thick medium)
- Dynamic QGP, equilibrium dists.

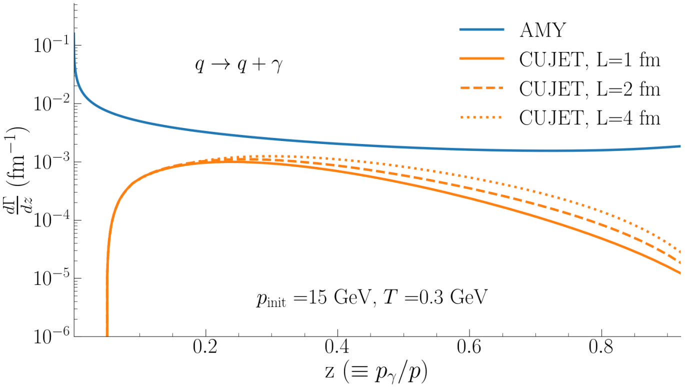
Both Models:

- LPM effect
- Running coupling



Radiative Energy-Loss: Photon Emission

- LO-DGLV photons previously calculated by Zhang et al. in EPJ. C67(2010) for static centers & a Gaussian profile ansatz for their density
- We extend it to dynamic centers with the same $\rho(T)$ as gluon emission channel

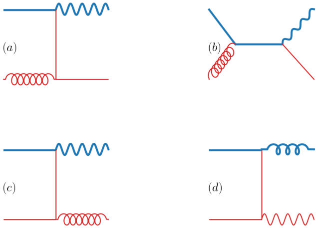


Conversion Photons

- Proposed by Fries et al. in PRL 90 (2003)
- Identity changing process: hard $q(\bar{q})$ is converted to a photon via fermion exchange with a medium particle
- No energy loss in the process

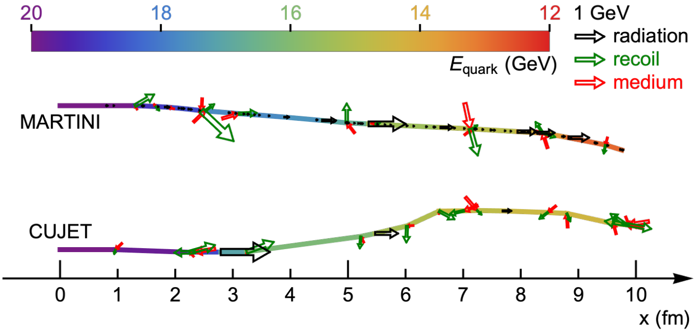
$$\frac{d\Gamma}{d\omega}(E,T) = \frac{2\pi}{3}\alpha\alpha_s\frac{T^2}{E}\left(\frac{1}{2}\log\left(\frac{2ET}{m_\infty^2}\right) + C_{2\to 2}(E/T)\right)\delta(\omega - E)$$

- For both CUJET and MARTINI we fix $\alpha_s = 0.3$ (Conversion only)



CUJET vs MARTINI: Model Comparison

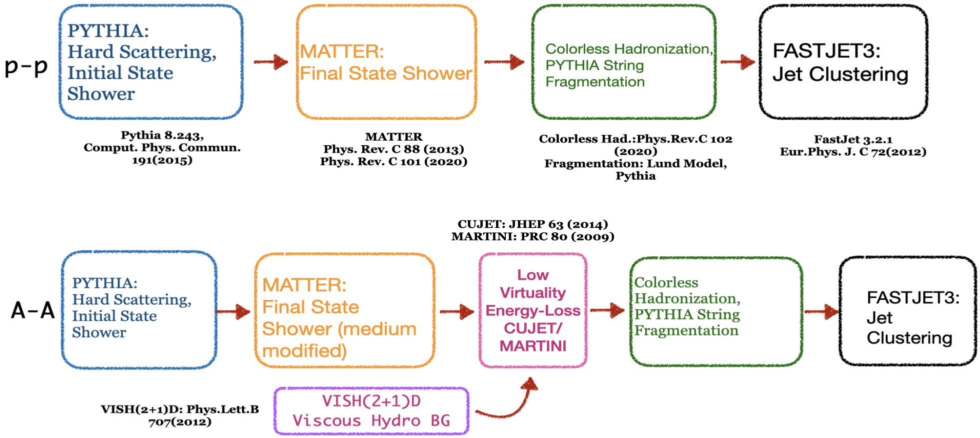
- Radiative:
  - CUJET: LO-DGLV
  - MARTINI: AMY, include $g \to q\bar{q}$
- Collisional: LO t-channel diagrams
  - CUJET: regulation via Debye mass
  - MARTINI: HTL gluon propagator
- Conversion Channels:
  - Photons: both
  - $q \to g$, $g \to q$: MARTINI only
- Both have medium response via recoil partons



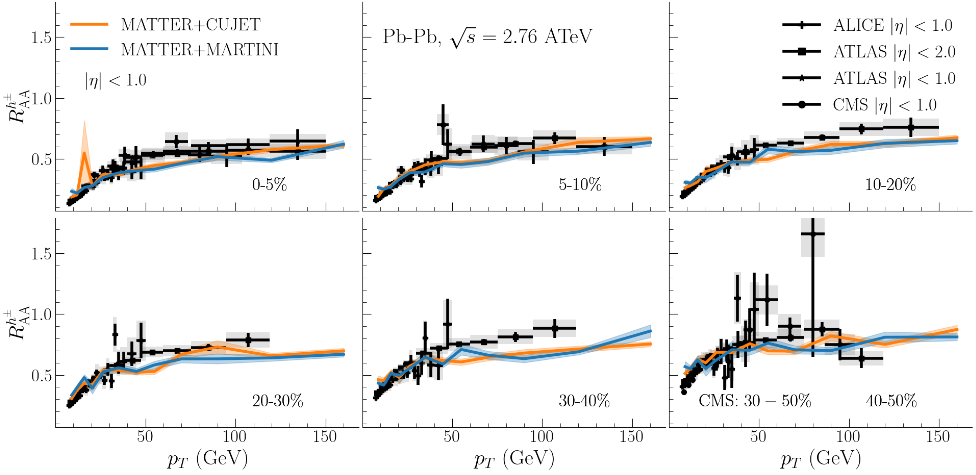
Brick temperature: T $= 0.3$ GeV

Workflow

- We use a JETSCAPE multi-stage workflow(PRC 102 (2020) 5) for both pp and AA simulations

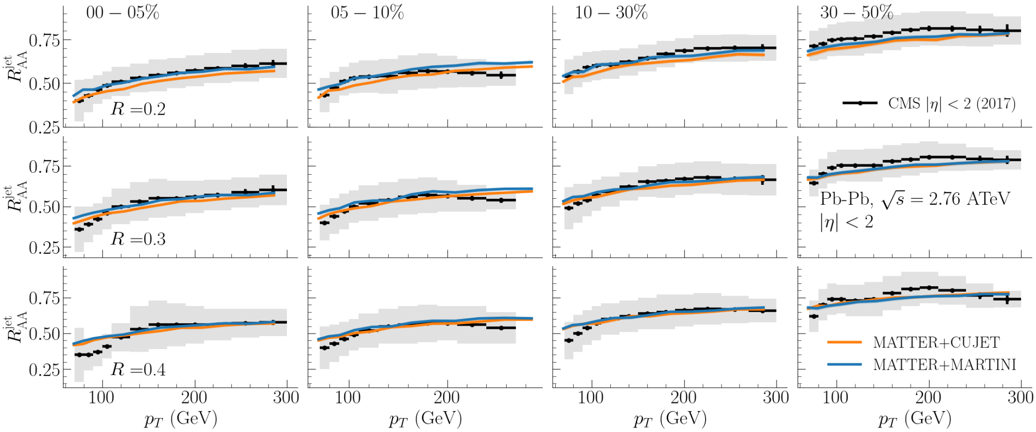


Results: Charged Hadron R_{AA}



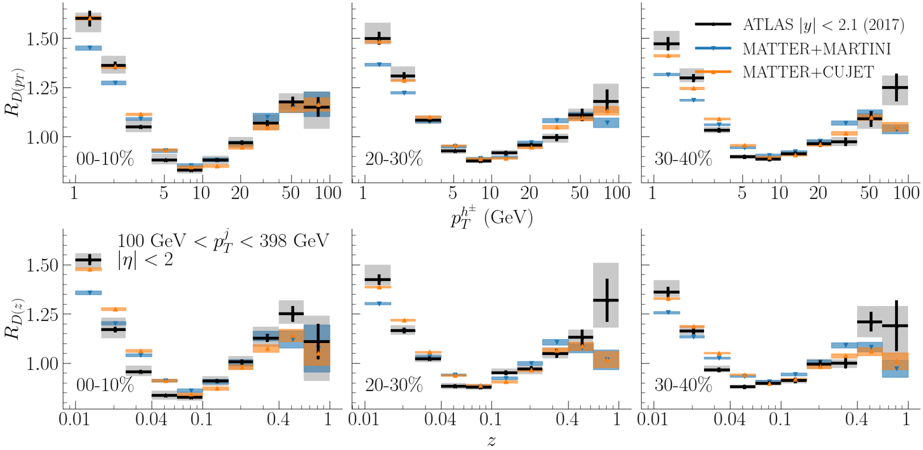
(0-5% centrality: used to fit CUJET and MARTINI.)

Results: Jet R_{AA}



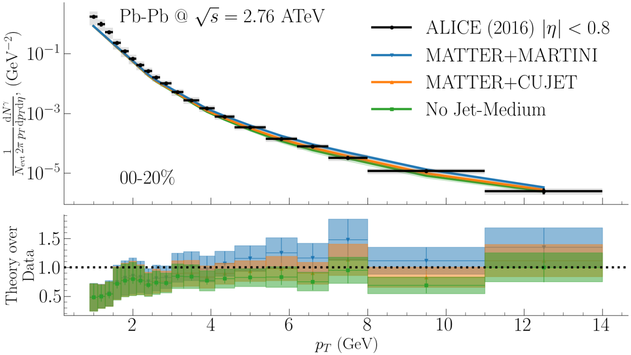
Good Agreement! (Notice the relative movement...)

Jet Fragmentation Function Ratios



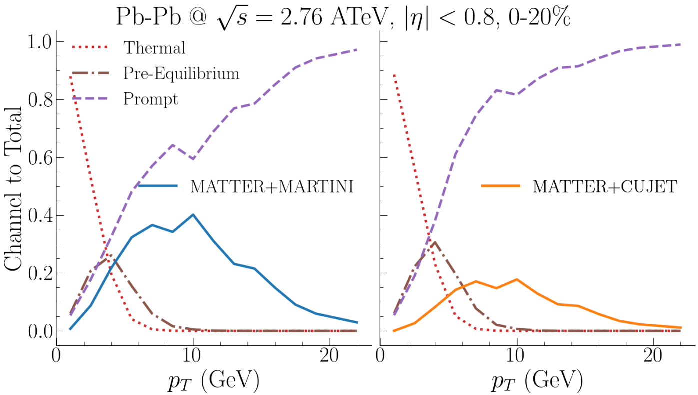
- $\left(z \equiv \frac{\mathbf{p}_{jet} \cdot \mathbf{p}_{trk}}{\mathbf{p}_{jet} \cdot \mathbf{p}_{jet}}\right)$

Photons: Pb-Pb at 2.76 ATeV



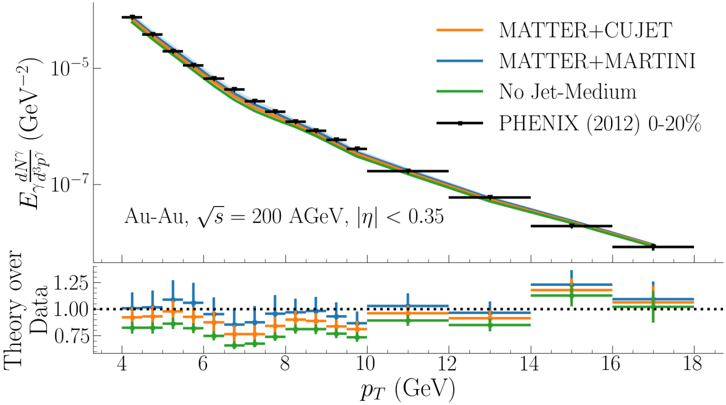
- Non-Jet Medium $\gamma \rightarrow$ [Prompt γ(PYTHIA:NNPDF2.3LO + EPOS09) + Pre-Eq. γ(KøMPøST) +Thermal γ]
- Prompt : kFactor to match the highest p_T bin: 1.65
- Thermal and Pre-Eq. taken from Phys.Rev.C 105 (2022) 1, 014909

Photon Spectrum Composition: Pb-Pb at 2.76 ATeV



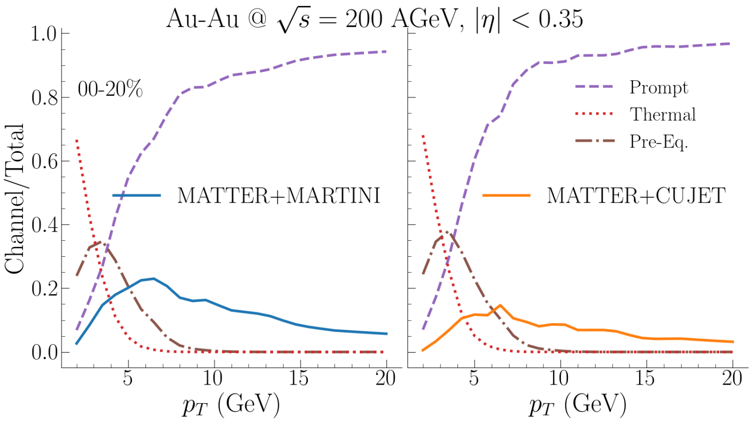
- Low and high p_T parts dominated by thermal and pQCD photons respectively
- Important contribution at intermediate p_T (40% of γ yield for $p_T \in [5, 10]$ GeV for MARTINI)

Photons: Au-Au at 200 AGeV



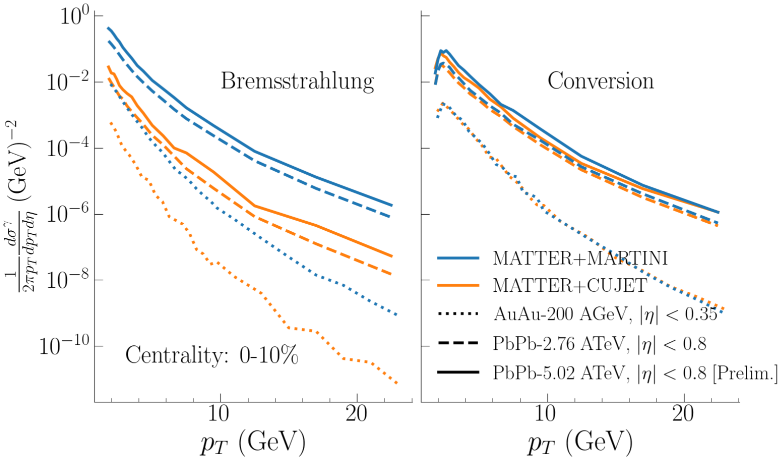
- Prompt : kFactor to match the highest p_T bin: 1.12
- Inclusion of jet-medium photons improves agreement.
- Smaller effect than in Pb-Pb @ 2.76 ATeV.

Photon Spectrum Composition: Au-Au at 200 AGeV



- Still significant but contribute less than in `Pb−Pb` at 2.76 ATeV: jet population, temperature

Jet-Medium Photons: System Dependence



- Significant difference in the brem. channel (rates) , system dependence in conversion

Summary

- First multi-probe, multi-stage comparative study of CUJET & MARTINI in a realistic simulation
- Similar performance in $R_{AA}^{h^{\pm}}$, R_{AA}^{jet}
- Observed differences in jet fragmentation function ratios
- Different expectation of jet-medium photon spectra:
  - Major source of γ's in Pb-Pb at 2.76 ATeV ($\approx 40\%$ of yield according to MARTINI, $p_T \in [5, 10]$ GeV)
- Going forward:
  - Photon spec. for Pb−Pb at 5.02 ATeV,
  - Photon v_2,
  - γ-hadron correlations...
- Precision studies of jet-quenching: jet-medium photons have a major role to play!

BACKUPS

Backup Slides

α_s on a run: I

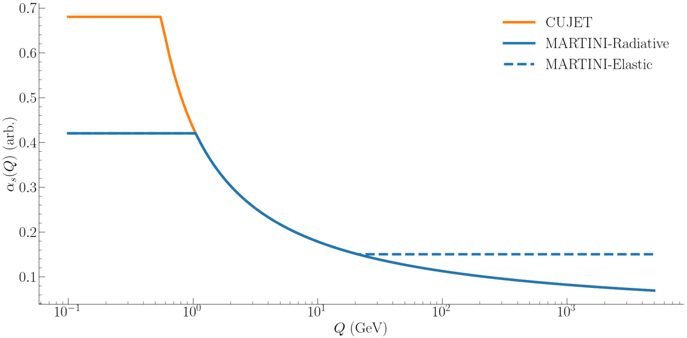
- Both models: α_s runs according to LO pQCD expression

$$\alpha_s(Q) = \frac{4\pi}{9\ln\left(\frac{Q^2}{\Lambda_{QCD}^2}\right)}$$

where $\Lambda_{QCD} = 0.2$ GeV

- MARTINI:

$$Q = \begin{cases} \kappa_r \sqrt[4]{\hat{q}p^0} & \text{Radiative} \\ \kappa_e \sqrt{\hat{q}\lambda_{mfp}} & \text{Elastic} \end{cases}$$



α_s on a run: II

$$\hat{q} = C^R \alpha_{s,0} m_D^2 T \ln(1 + q_{\text{max}}^2/m_D^2)\,,$$

$$\lambda_{\text{mfp}} = \left(C^R \alpha_{s,0} T \ln \frac{1 + m_D^2/q_{\text{max}}^2}{1 + m_D^2/q_{\text{min}}^2} \right)^{-1}\,.$$

Parameters Used

Model	Parameter	Value
Both	N_c	3
	Λ_{QCD}	0.2 GeV
MARTINI	N_f	3
	$\alpha_{s,0}$	0.3
	κ_r	1.5
	κ_e	4.5
CUJET	N_f	2.5
	$\alpha_{s,\mathrm{max}}$	0.68
MATTER	α_s	0.234

Rates: 1

LO-DGLV:

$$\frac{d\Gamma^{\text{DGLV}}_{i\to gi}}{dz}(p,z,\tau) = \frac{18C_i^R}{\pi^2}\frac{4+N_f}{16+9N_f}\rho(T)\int d^2\mathbf{k}_\perp\left\{\frac{1}{z_+}\left|\frac{dz_+}{dz}\right|\alpha_s\left(\frac{\mathbf{k}_\perp^2}{z_+-z_+^2}\right)\right.$$
$$\times\int\frac{d^2\mathbf{q}_\perp}{\mathbf{q}_\perp^2}\left[\frac{\alpha_s^2(\mathbf{q}_\perp^2)}{\mathbf{q}_\perp^2+m_D^2}\frac{-2}{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+\chi^2}\left(\frac{\mathbf{k}_\perp\cdot(\mathbf{k}_\perp-\mathbf{q}_\perp)}{\mathbf{k}_\perp^2+\chi^2}-\frac{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2}{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+\chi^2}\right)\right.$$
$$\left.\left.\times\left(1-\cos\left(\frac{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+\chi^2}{2z_+p}\tau\right)\right)\right]\right\},$$

where

$$m_g(T) = m_D(T)/\sqrt{2}, \qquad \text{g} - \text{plasmon mass}$$
$$\chi^2(T) = M^2z_+^2 + m_g^2(1-z_+)$$

Rates: 2

$$\frac{d\Gamma^{\text{DGLV}}_{q\to q\gamma}}{dz}(p,z,\tau) = \frac{e_f^2\alpha_{\text{em}}}{\pi^2}\frac{32+8N_f}{16+9N_f}\rho(T)\int d^2\mathbf{k}_\perp \frac{(1-z_+)^2}{z_+}\left|\frac{dz_+}{dz}\right|\int\frac{d^2\mathbf{q}_\perp}{\mathbf{q}_\perp^2}\frac{\alpha_s^2(\mathbf{q}_\perp^2)}{\mathbf{q}_\perp^2+\mu^2}\times$$

$$\left[\left(\frac{\mathbf{k}'_\perp}{\mathbf{k}'^{\,2}_\perp+\chi^2}-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2+\chi^2}\right)^2 + 2\left(\frac{\mathbf{k}_\perp\cdot\mathbf{k}'_\perp}{(\mathbf{k}'^{\,2}_\perp+\chi^2)(\mathbf{k}_\perp^2+\chi^2)}-\frac{\mathbf{k}_\perp^2}{(\mathbf{k}_\perp^2+\chi^2)^2}\right)\right.$$

$$\left.\times\cos\left(\frac{\mathbf{k}_\perp^2+\chi^2}{2z_+p}\tau\right)\right],$$

$$\mathbf{k}'_\perp \equiv \mathbf{k}_\perp - z_+\mathbf{q}_\perp$$

$$\rho_g = \frac{16\,\rho}{16+9N_f},\quad \rho_q = \frac{9N_f\,\rho}{16+9N_f}$$

$$\rho = s/4$$

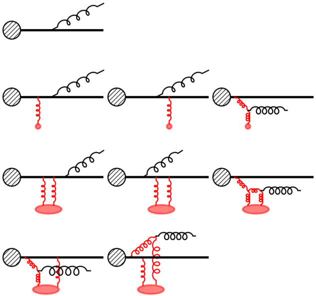
Rates: 3

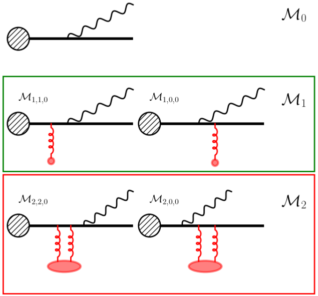
AMY:

$$\frac{d\Gamma^{\text{AMY}}_{i\to jk}}{dz}(p,z) = \frac{\alpha_s P_{i\to jk}(z)}{[2p\,z(1-z)]^2}\bar{f}_j(z\,p)\,\bar{f}_k((1-z)p)\int\frac{d^2\mathbf{h}_\perp}{(2\pi)^2}\,\text{Re}\left[2\mathbf{h}_\perp\cdot\mathbf{g}_{(z,p)}(\mathbf{h}_\perp)\right]\ ,$$

$$\begin{aligned}2\mathbf{h}_\perp = i\delta E(z,p,\mathbf{h}_\perp)\mathbf{g}_{(z,p)}(\mathbf{h}_\perp) + \int\frac{d^2\mathbf{q}_\perp}{(2\pi)^2}\,\bar{C}(q_\perp)\Big\{&C_1\left[\mathbf{g}_{(z,p)}(\mathbf{h}_\perp)-\mathbf{g}_{(z,p)}(\mathbf{h}_\perp-\mathbf{q}_\perp)\right]\\ &+C_z\left[\mathbf{g}_{(z,p)}(\mathbf{h}_\perp)-\mathbf{g}_{(z,p)}(\mathbf{h}_\perp-z\mathbf{q}_\perp)\right]\\ &+C_{1-z}\left[\mathbf{g}_{(z,p)}(\mathbf{h}_\perp)-\mathbf{g}_{(z,p)}(\mathbf{h}_\perp-(1-z)\mathbf{q}_\perp)\right]\Big\}\end{aligned}$$

Diagrams





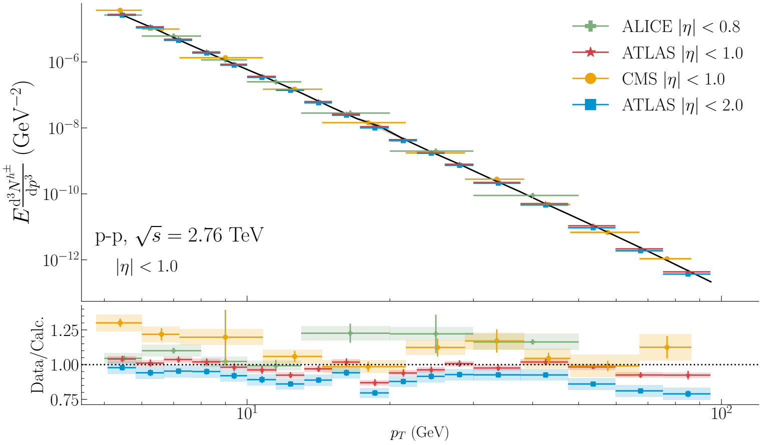
Diagrams used in our LO-DGLV rates.

Hydro

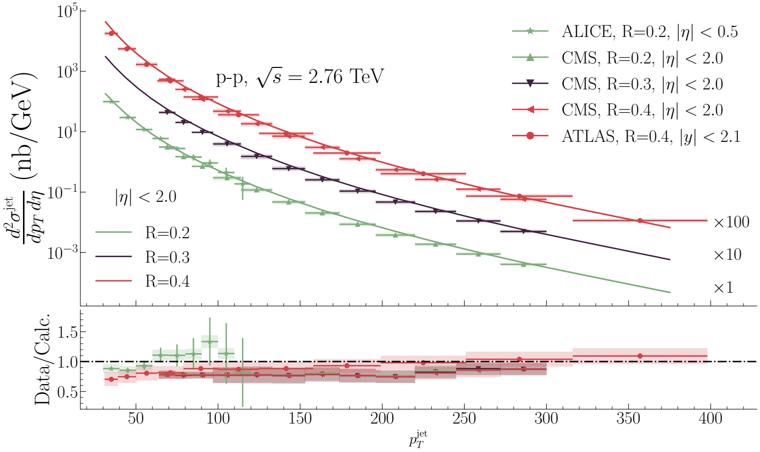
- EOS : HOTQCD (2014) matched to hadronic gas, matching Lattice at high T to a hadron gas at low T
- Chemical freeze out at $T = 165$ MeV
- TRENTO+ Free-Streaming + VISH(2+1)-dimensional hydro simulation

EOS for LO-DGLV rates: `s95p-PCE`

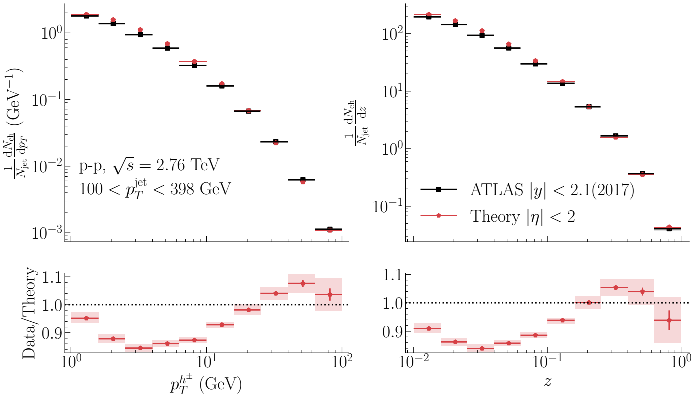
p-p @ 2.76 TeV: Charged Hadrons



p-p @ 2.76 TeV: Jets



p-p @ 2.76 TeV: Jet FF's



Au-Au @ 200 AGeV: hadrons