UNIVERSITY OF BERGEN

Constraining jet quenching models in heavy-ion collisions using Bayesian Inference

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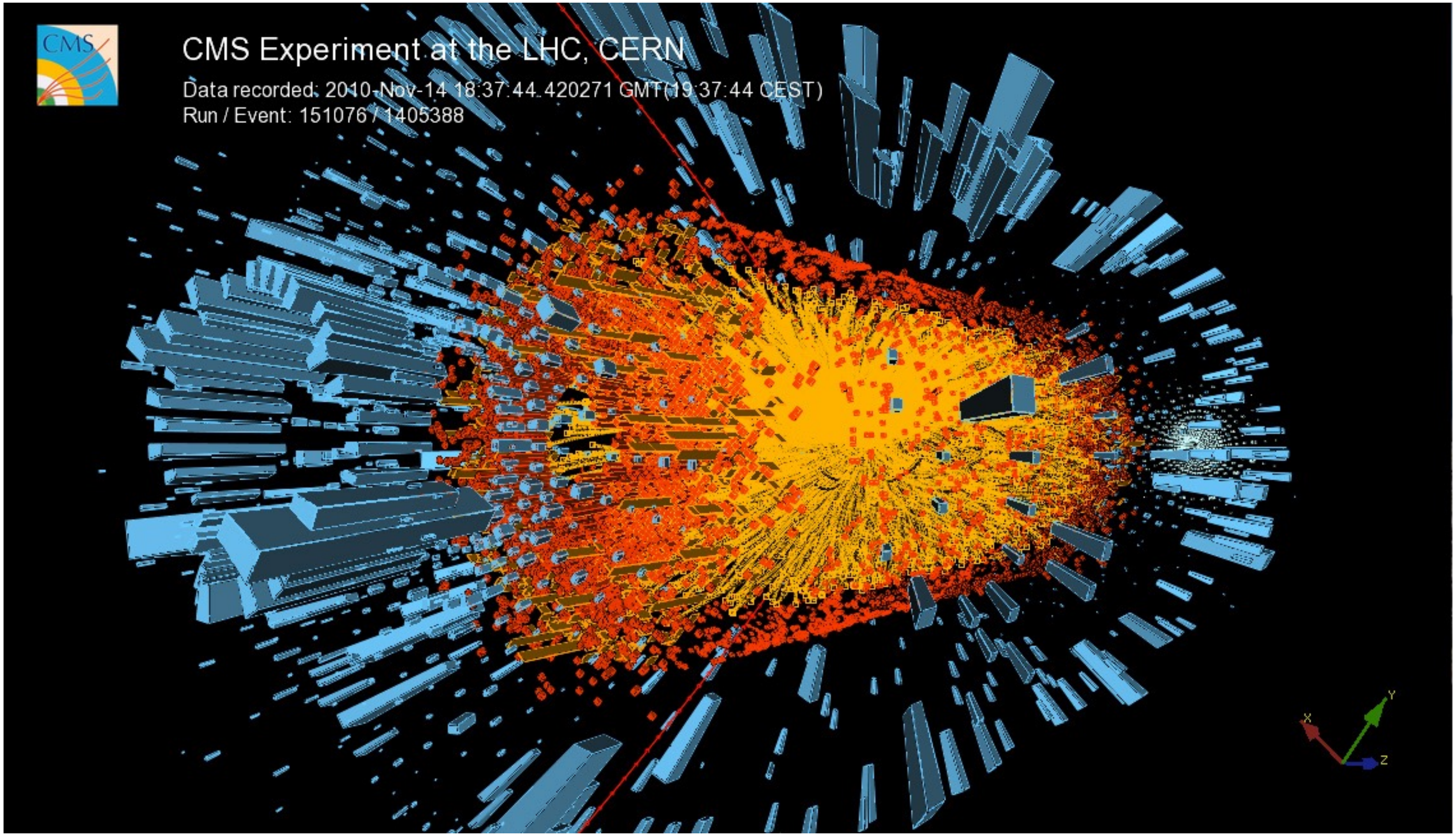
Outline

- **Jet quenching in heavy-ion collisions**
  - Heavy-ion collisions and QGP
  - Jets
  - Jet quenching in heavy-ion collisions
- **Theory of one parton going through the medium**
  - One parton through the medium
  - A jet through the medium
  - Factorization in jet quenching
- **Modelling the energy loss in Bayesian inference**
- **Results**

Heavy-ion collisions

Pb ⟶ ⟵ **Pb**

Heavy-ion collisions



Heavy-ion collisions

τ_0

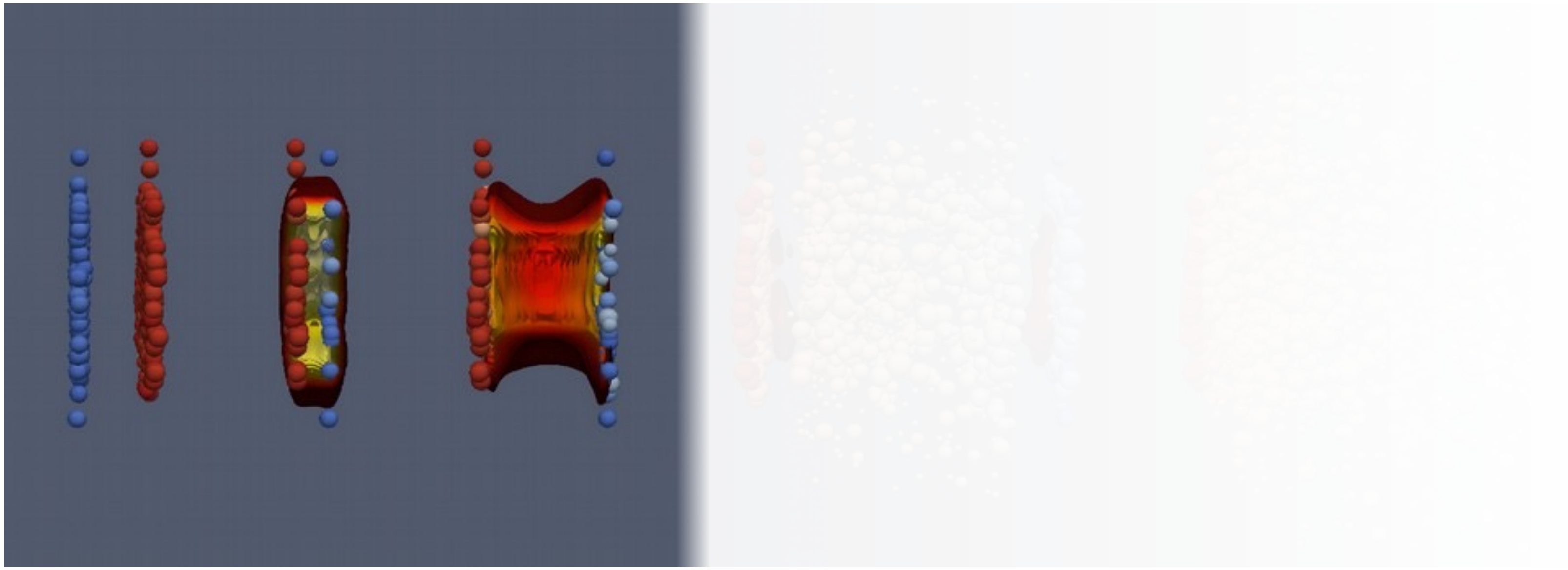
$\ll 1$ fm

~ 1 fm

~ 10 fm

The highly Lorentz-contracted nuclei collide

Heavy-ion collisions



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$\ll 1$ fm　　~ 1 fm　　~ 10 fm

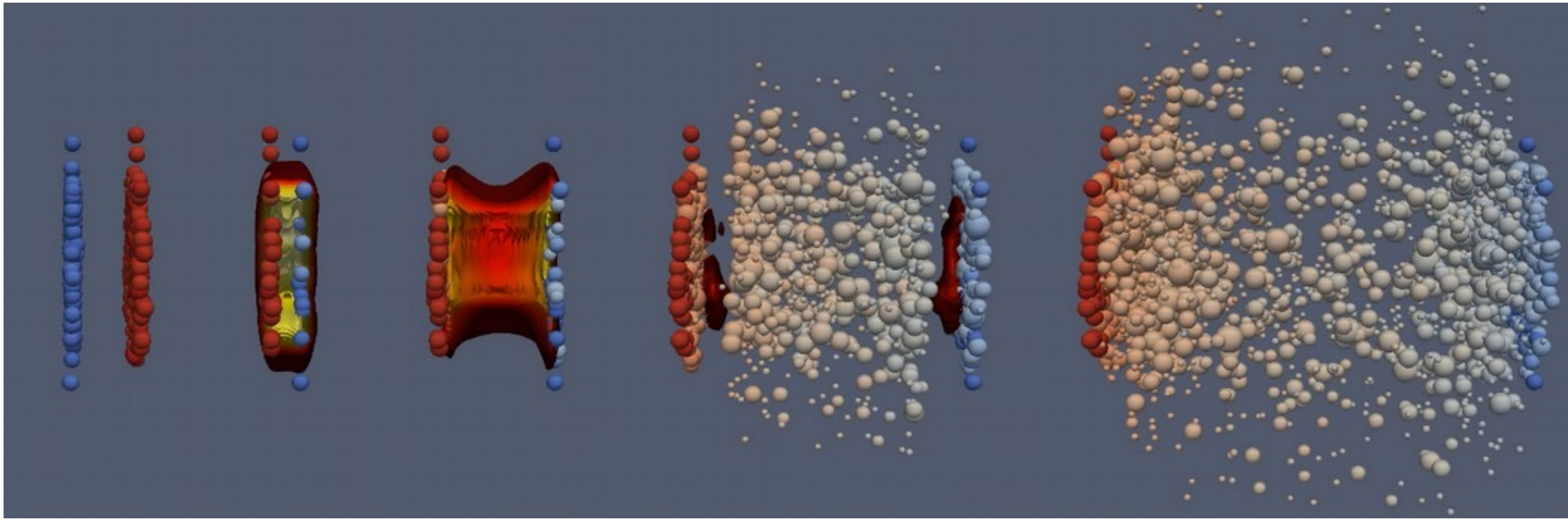
The highly Lorentz-contracted nuclei collide

Out of equilibrium quark-gluon plasma forms and evolves hydrodynamically

$T \sim 500$ MeV
$\sim 5{\times}10^{12}$ K !!

$\eta/s \sim 1/4\pi \rightarrow$ near perfect fluid

Heavy-ion collisions



from MADAI collaboration, Hannah Petersen and Jonah Bernhard

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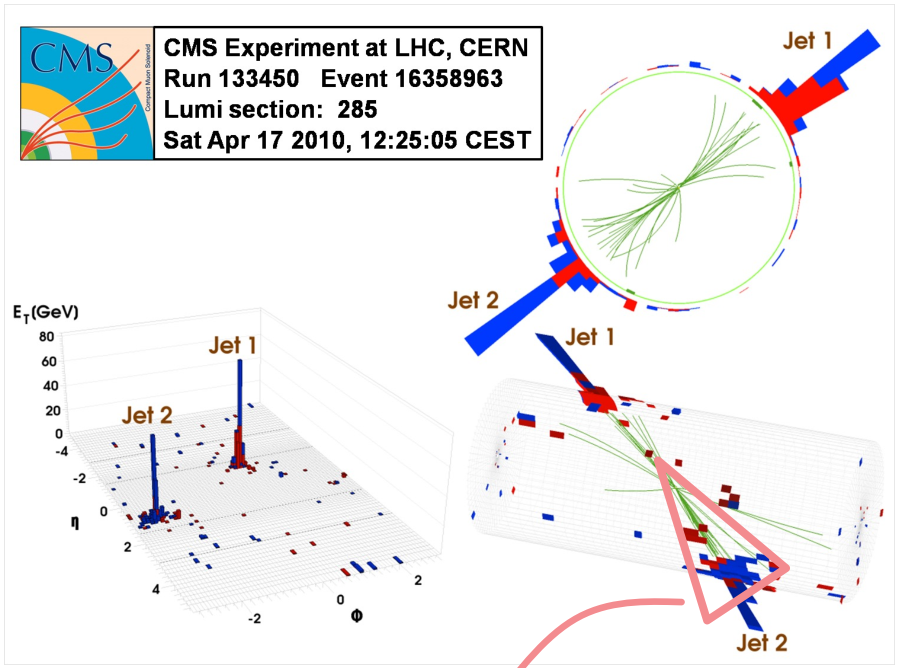
QGP cross over transition $\Rightarrow$ hadronization
followed by chemical and then kinetic freeze-out

$T \approx 170$ MeV

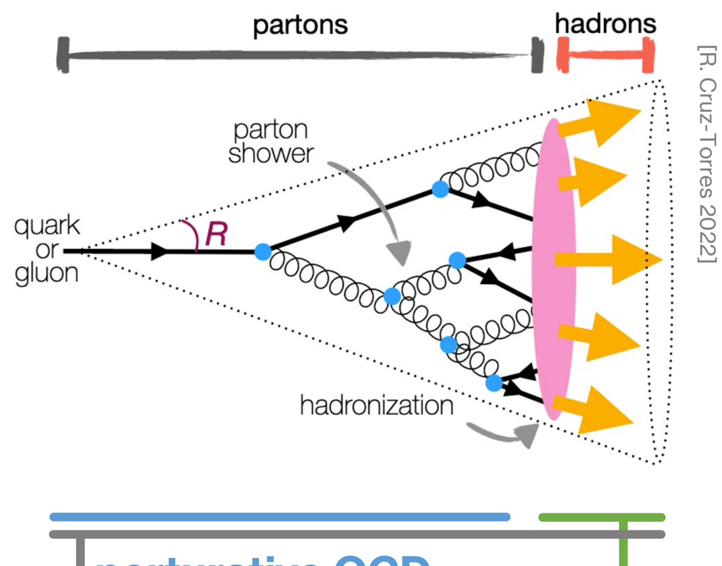
Jets

Experiment



collimated spray of hadrons = jet

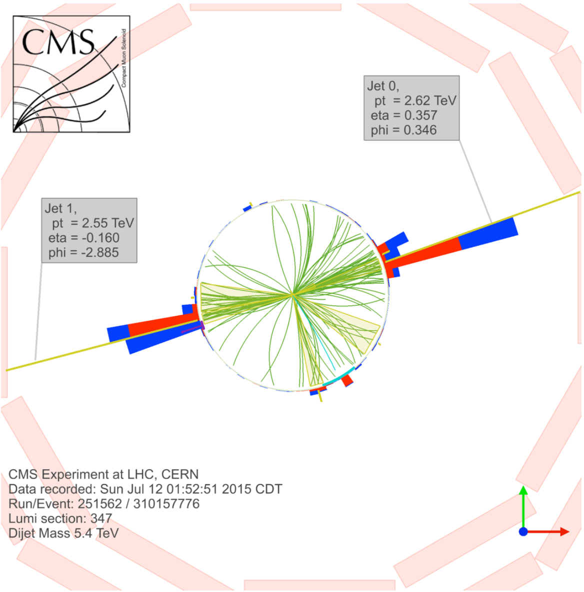
Theory



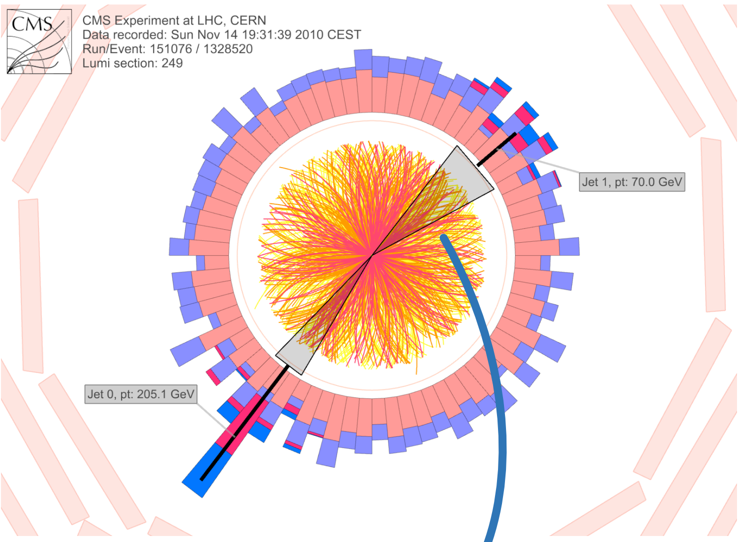
Monte Carlo simulations

Jet quenching in heavy-ion collisions

pp event



AA event



$$\left(\begin{array}{c}\textbf{AA}\\ \textbf{collision}\end{array}\right) \neq \mathbf{A} \times \left(\begin{array}{c}\textbf{pp}\\ \textbf{collision}\end{array}\right)$$

Quenched jet:

- modification of the transverse energy balance
- modification of jet internal structure
- suppression of the jet yields

Jet quenching in heavy-ion collisions

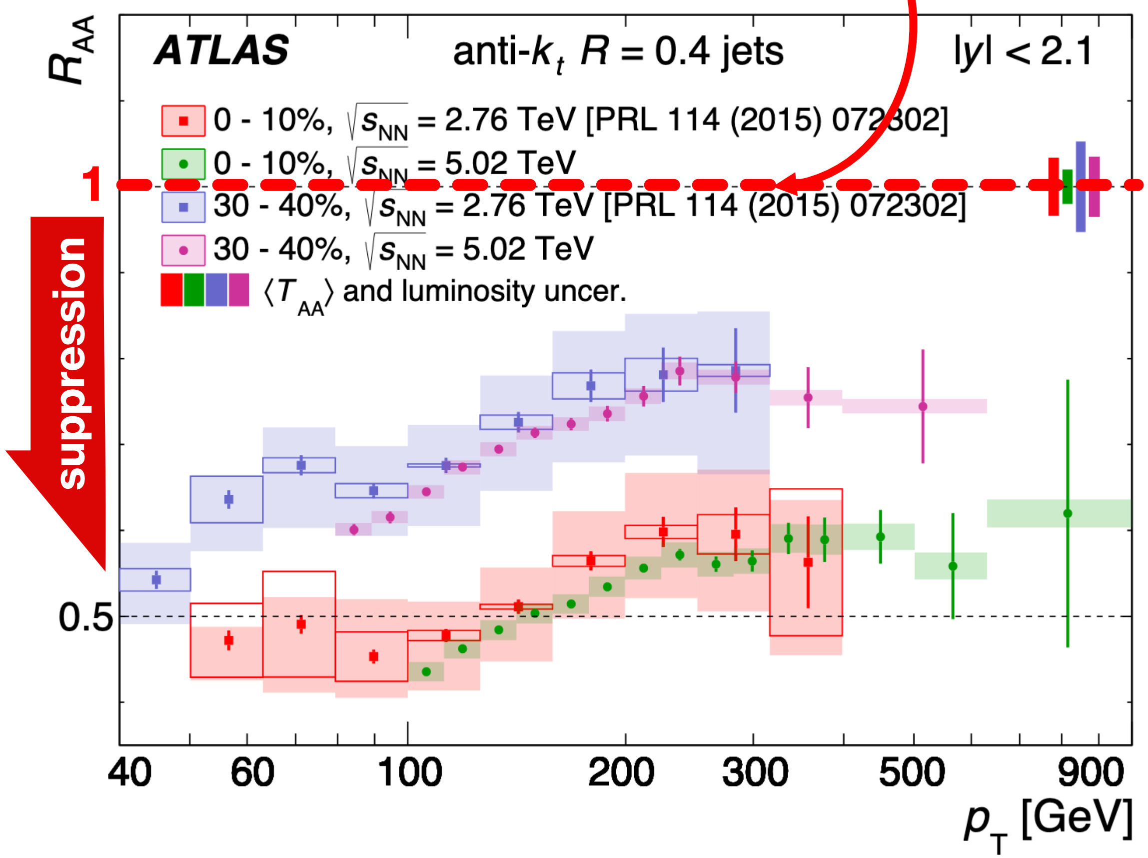
Jet supression

nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{evt}} \frac{d^2 N_{jet}}{dp_T dy}\bigg|_{cent}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{jet}}{dp_T dy}\bigg|_{pp}},$$

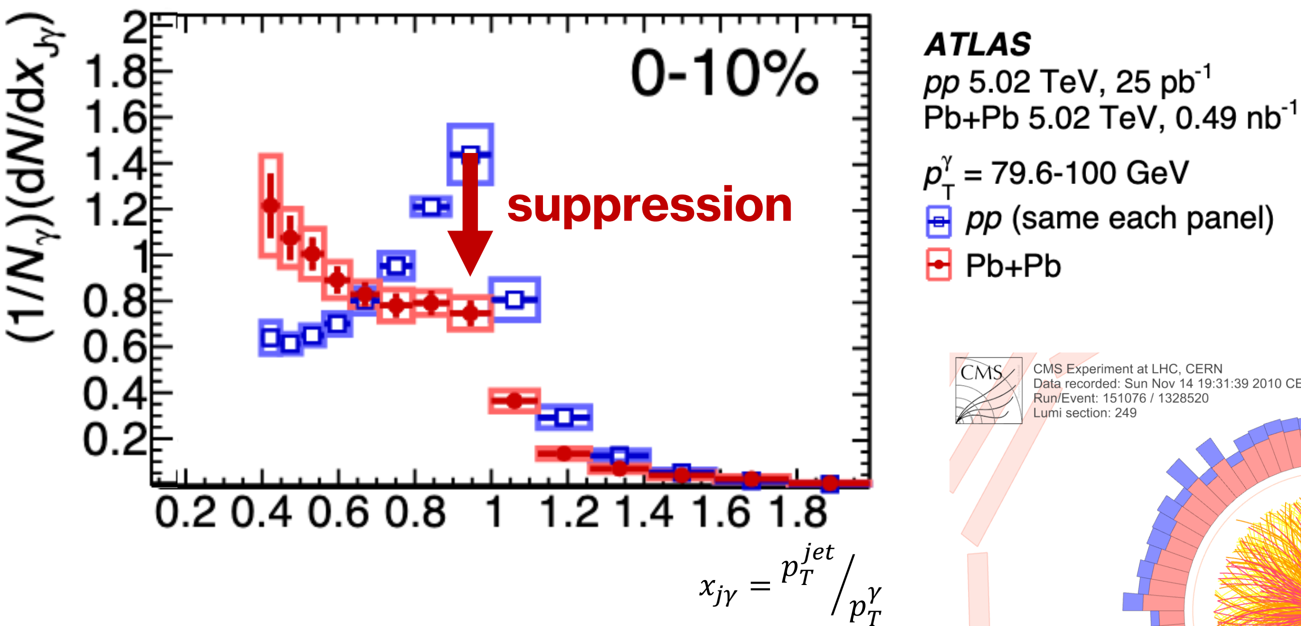
$$= \left(\frac{d\sigma^{AA}}{dp_T}\right) \Big/ \left(\frac{d\sigma^{pp}}{dp_T}\right)$$

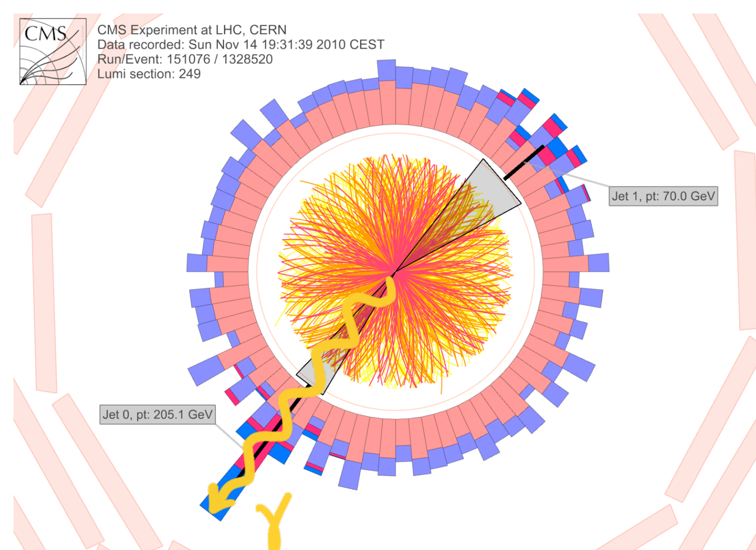
if $\left(\begin{smallmatrix}\text{AA}\\\text{collision}\end{smallmatrix}\right) = A \times \left(\begin{smallmatrix}\text{pp}\\\text{collision}\end{smallmatrix}\right)$



Coincidence measurements

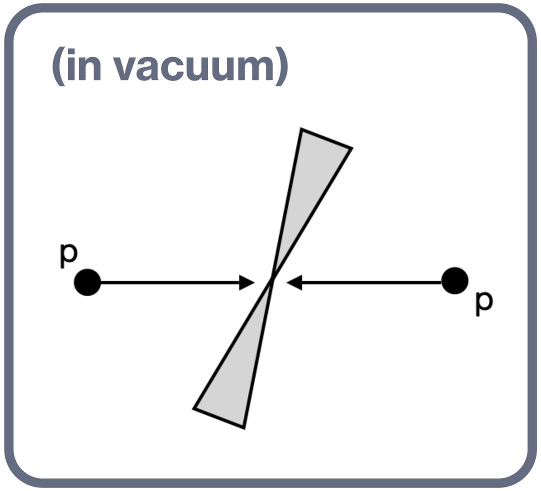
photon-tagged jet events

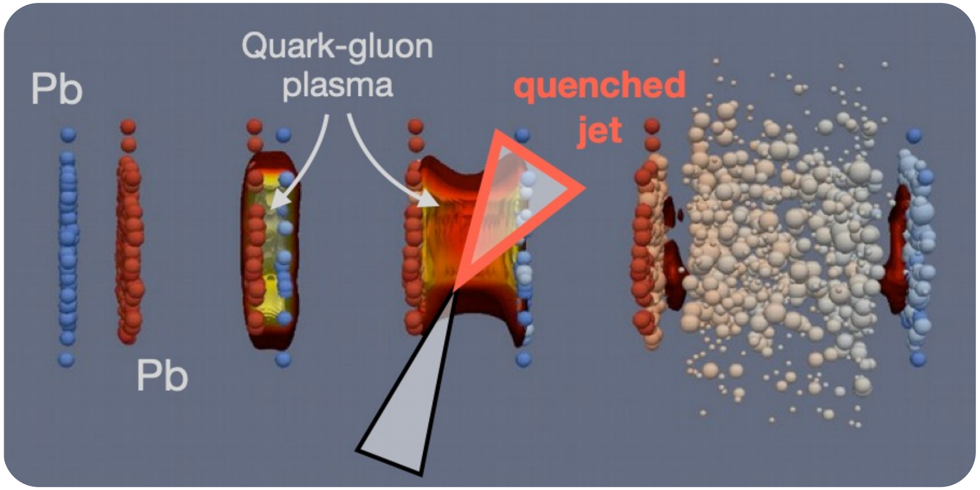




different hard processes involved

Jet energy loss distribution

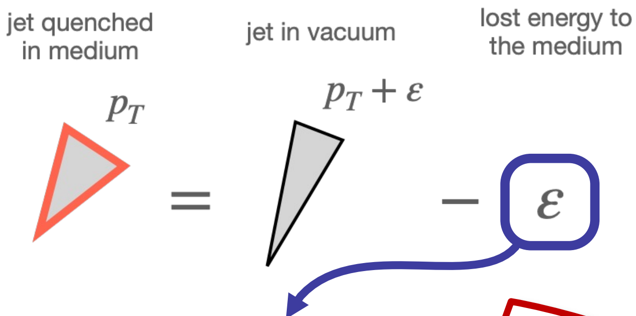




from MADAI collaboration, Hannah Petersen and Jonah Bernhard

Jets in medium:

- **Quark gluon plasma (QGP)** is created in the heavy-ion collision
- Jet created by hard process within QGP probes the medium
- Medium properties can be retrieved by studying jet quenching



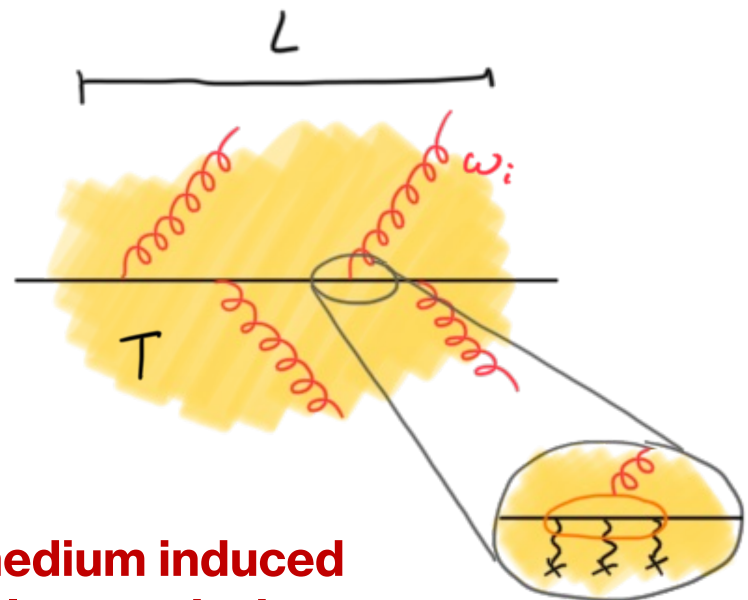
given by $D(\varepsilon)$

jet energy loss distribution

WHAT WE ARE INTERESTED IN

One parton through the medium

The energy loss distribution via medium induced gluon emissions of a hard parton can be computed from the theory side [Arleo 2002, Baier 2001]



medium induced gluon emission

$$\langle \varepsilon \rangle \sim \alpha_s \hat{q}(T) L^2 C_R$$

In the one parton through the medium, it depends on:

- n **number of radiated gluons**
- ω_i **energy of emitted gluon i**
- $\frac{\mathrm{d}I}{\mathrm{d}\omega}$ **medium-induced gluon spectrum**

Depends on:

- medium length: L
- transport coefficient: $\hat{q}(T) \sim T^3$
- parton color: C_R

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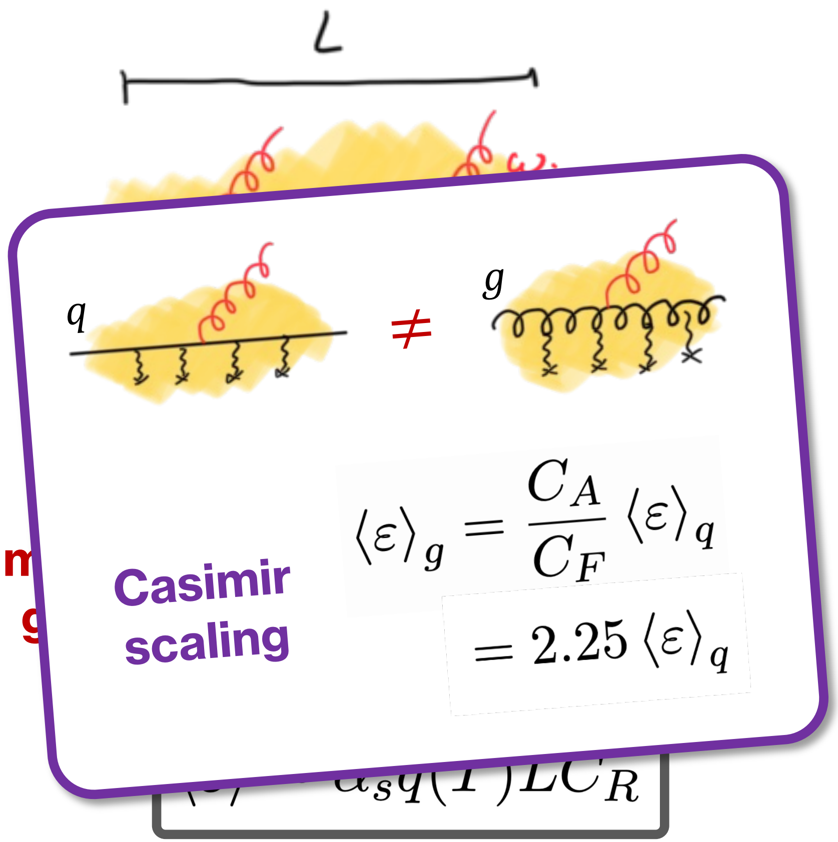

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Depends on:

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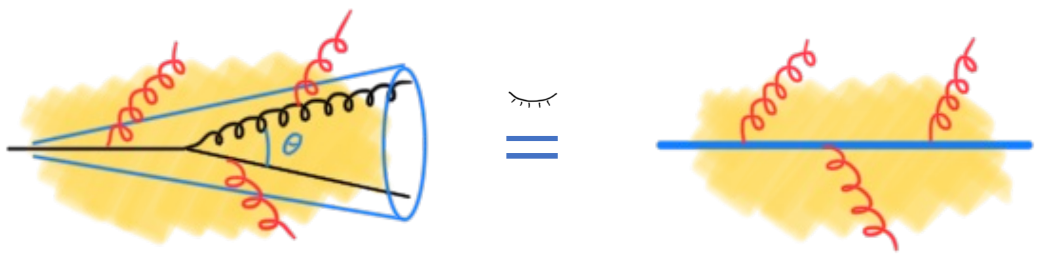
A jet through the medium

When a ”vacuum” splitting happens:

- If splitting anlge is smaller than medium resolution angle



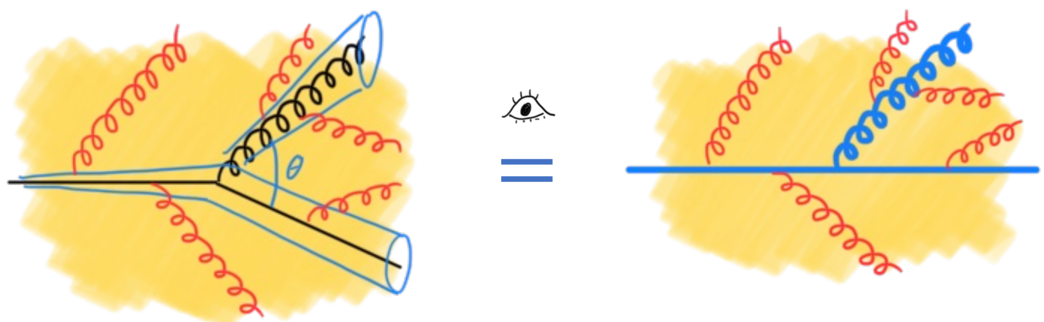
splitting is not resolved

(medium does not see the splitting)

$$D_{\text{jet}}(\varepsilon) = D_q(\varepsilon) \otimes D_{\text{MR}}$$

medium response

- If splitting angle is greater than medium resolution angle



splitting is resolved

$$D_{\text{jet}}(\varepsilon) = D_q(\varepsilon_q) \otimes D_g(\varepsilon_g) \otimes D_{\text{MR}}$$

with $\varepsilon = \varepsilon_q + \varepsilon_g$

$D(\varepsilon)$ is sensitive to the jet substructure (parton energy loss $\neq$ jet energy loss)

Jet energy loss universality and factorization

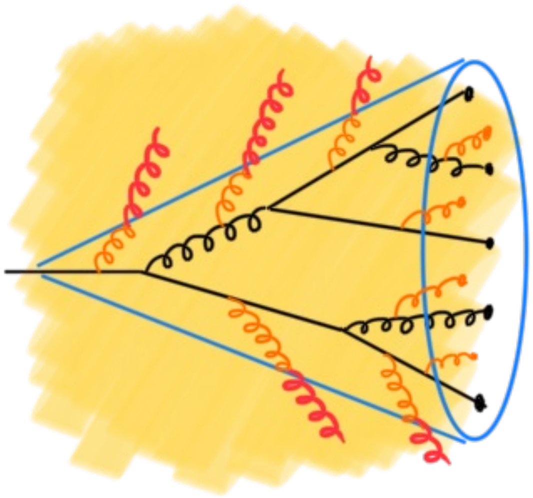
What to keep in D(ε) to achieve universality?

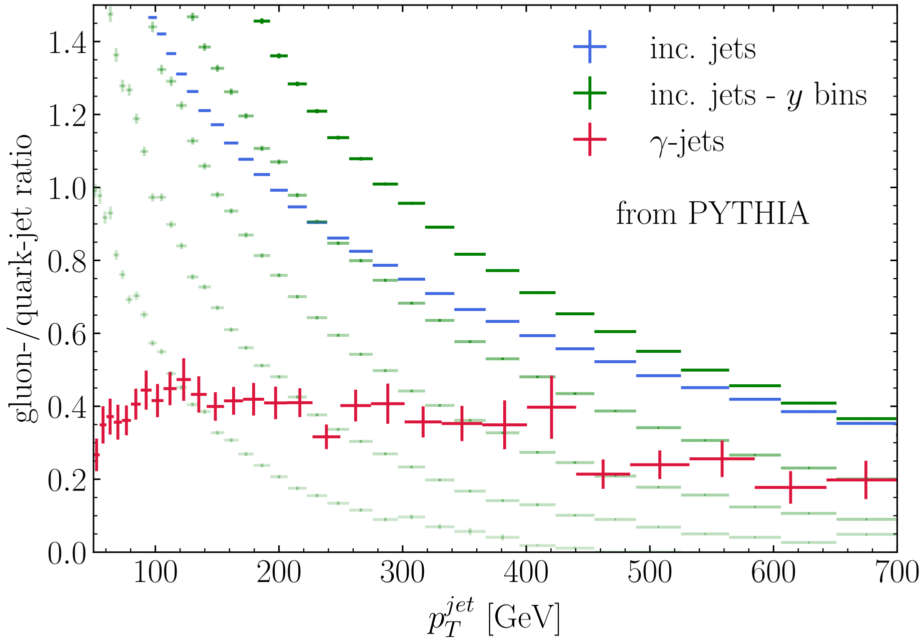
- has been done [arXiv:1808.05310]:

$$D(\varepsilon|p_T, C_R, \hat{q}(T), L, R) = D(\varepsilon)$$

- now we explore color dependence:

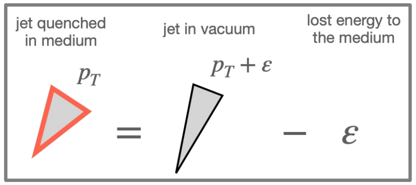
$$D_i(\varepsilon|p_T, C_R, \hat{q}(T), L, R), \quad i = q, g$$





quark- and gluon-jets ratio varies for different processes, and for different kinematical cuts

Jet energy loss universality and factorization



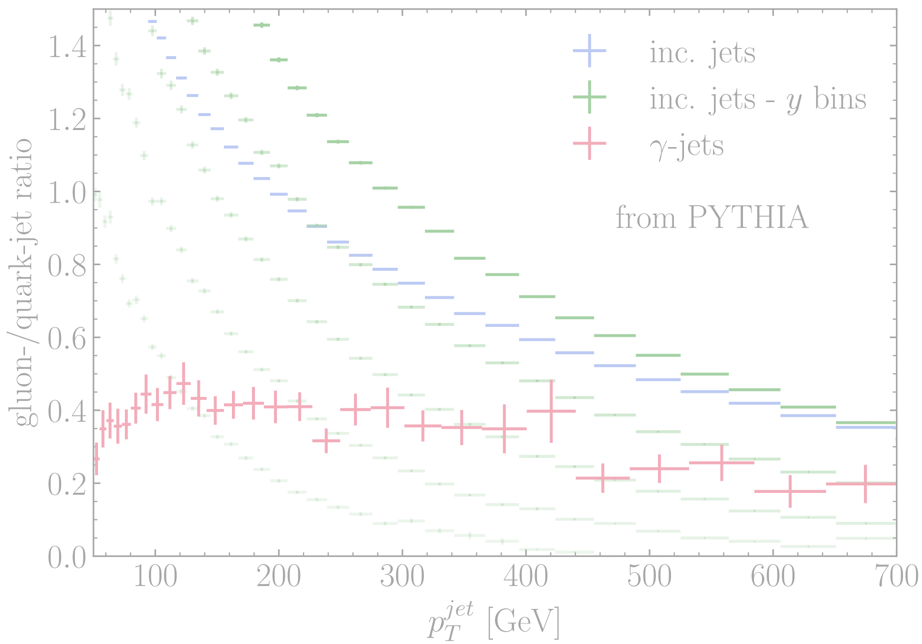
factorization

$$\left.\frac{\mathrm{d}\sigma^{AA}}{\mathrm{d}p_T}\right|_{p_T} = \int_0^\infty \mathrm{d}\varepsilon \sum_{i=q,g} D_i(\varepsilon) \left.\frac{\mathrm{d}\sigma_i^{vac}}{\mathrm{d}p_T}\right|_{p_T+\varepsilon}$$

experimental data

theory (simulation) ((PYTHIA))

our resource



quark- and gluon-jets ratio varies for different processes, and for different kinematical cuts

FINAL GOAL:

Does the factorization hold for different processes with only the information about the jet-initiating parton?

Bayesian inference

ILUSTRATIVE ANALYSIS

experimental measurement

model parameters

likelihood

$$\mathcal{L}\left(R_{AA}^{\text{data}}(p_T)\middle|\theta,\delta\right) = \mathcal{N}\left(R_{AA}^{\text{data}}(p_T)\middle|\mu = R_{AA}^{\text{model}}(\theta, p_T), \sigma = \delta \cdot \sigma_{R_{AA}}\right)$$

extra parameter for extra constaining power

BAYESIAN INFERENCE

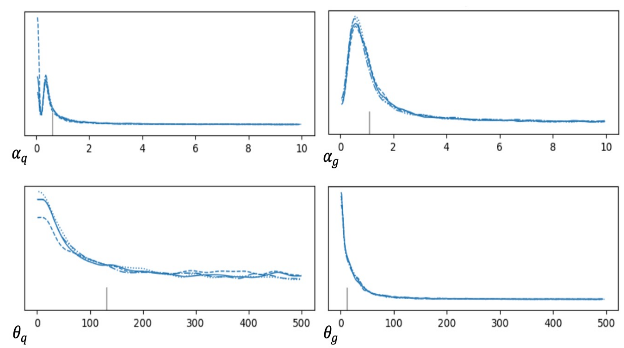
priors

$$\alpha_{q,g} \sim \text{Uniform}[0, 10]$$

$$\theta_{q,g} \sim \text{Uniform}[0, 500] \text{ (GeV)}$$

$$\delta_{q,g} \sim \text{Uniform}[0, 1]$$

posterior distributions



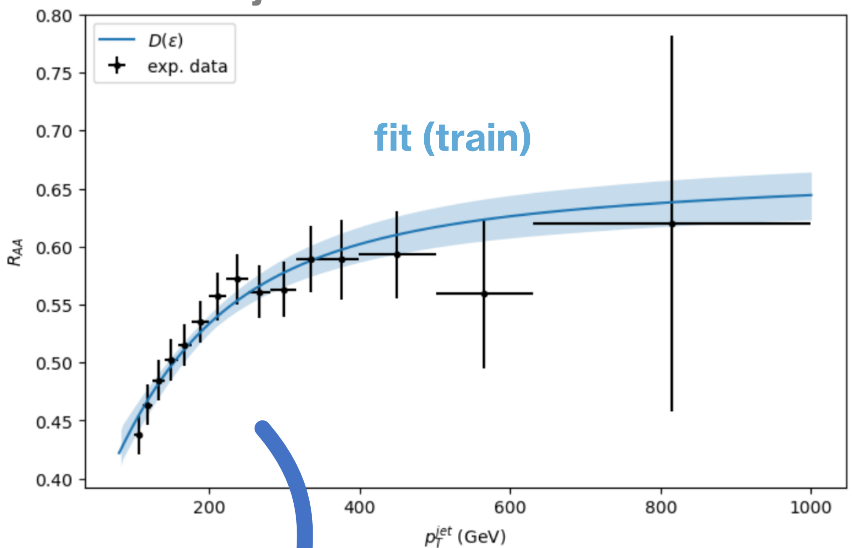
Markov Chain Monte Carlo (MCMC)

Bayesian inference

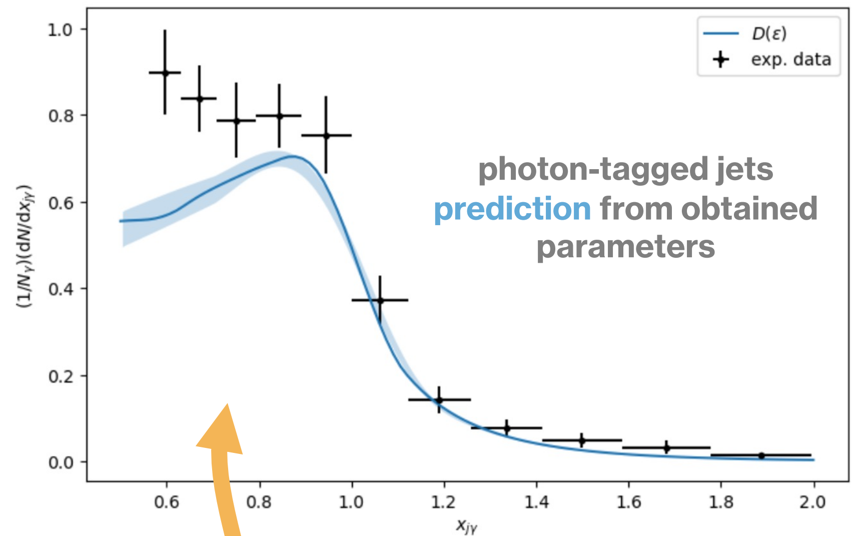
ILUSTRATIVE ANALYSIS

From the posterior distributions for the parameters, we can resconstruct the R_{AA} as well as predict other observables.

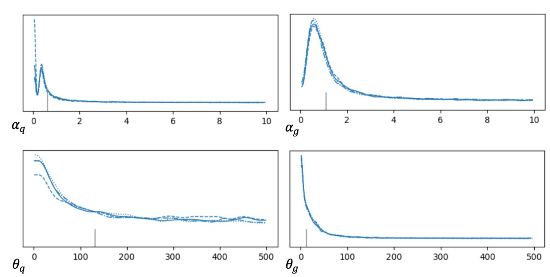
inclusive jet observable



photon-tagged jet observable



posterior distributions

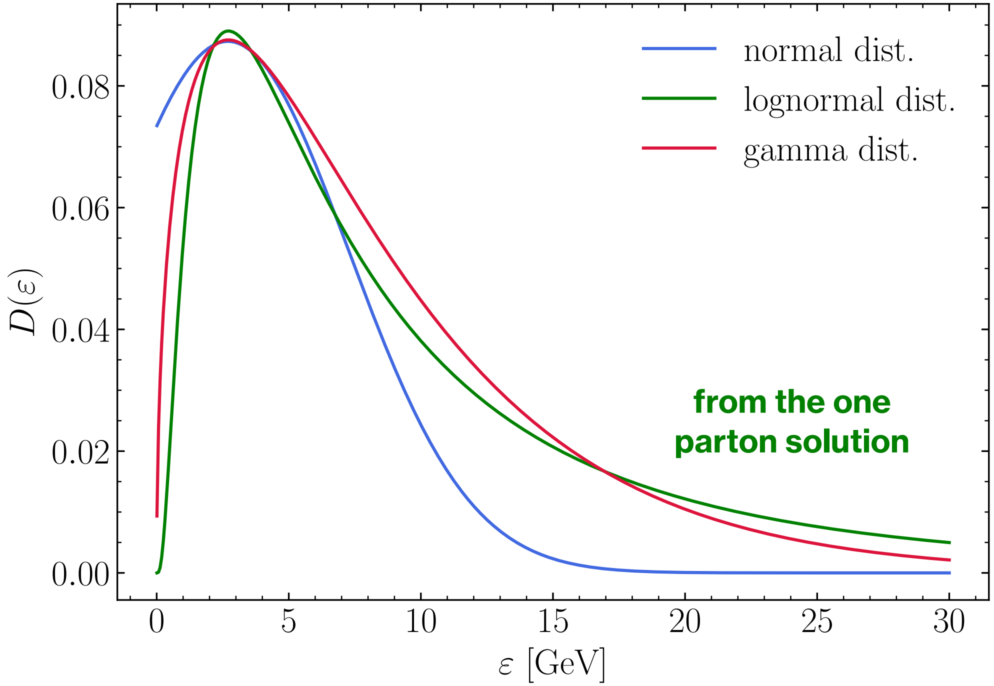


plug them into new observable

(which was not fitted)

Modelling the jet energy loss

We consider three parameterizations for $D(\varepsilon)$:



Normal distribution

$$D(\varepsilon) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{\varepsilon-\mu}{\sigma}\right)^2\right\}$$

Lognormal distribution

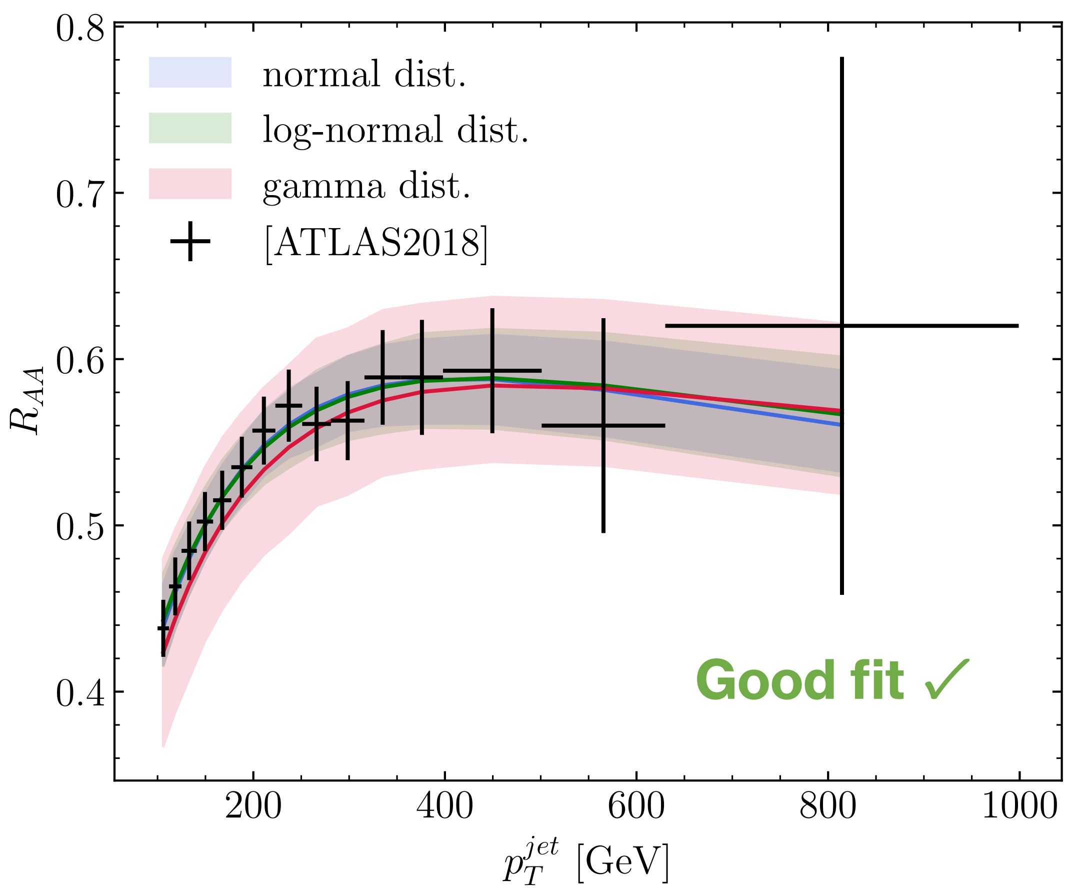
$$D(\varepsilon) = \frac{1}{\varepsilon\sigma\sqrt{2\pi}} \exp\left\{-\frac{(\ln\varepsilon-\mu)^2}{2\sigma^2}\right\}$$

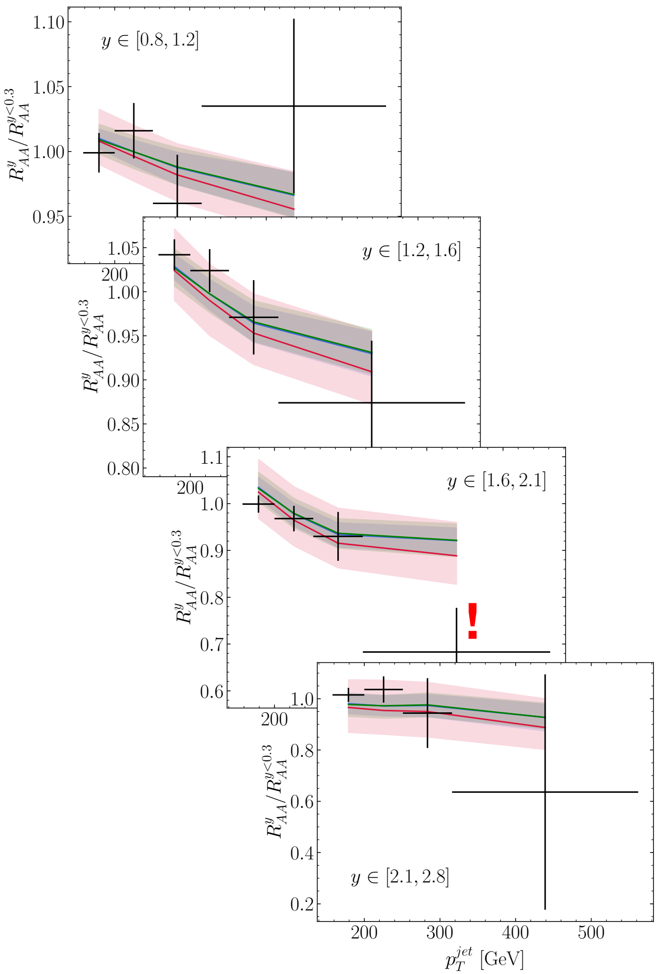
Gamma distribution

$$D(\varepsilon) = \frac{\theta^{-\alpha}\varepsilon^{\alpha-1}e^{-\varepsilon/\theta}}{\Gamma(\alpha)}$$

Results: the fit

Inclusive jets are fitted:



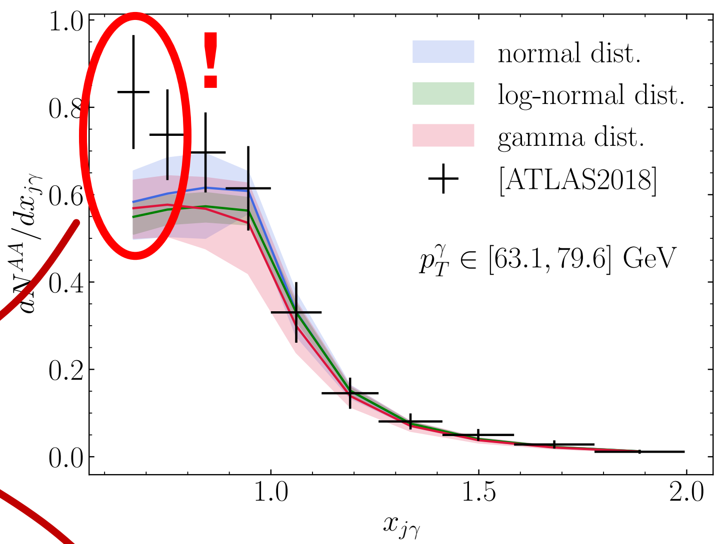


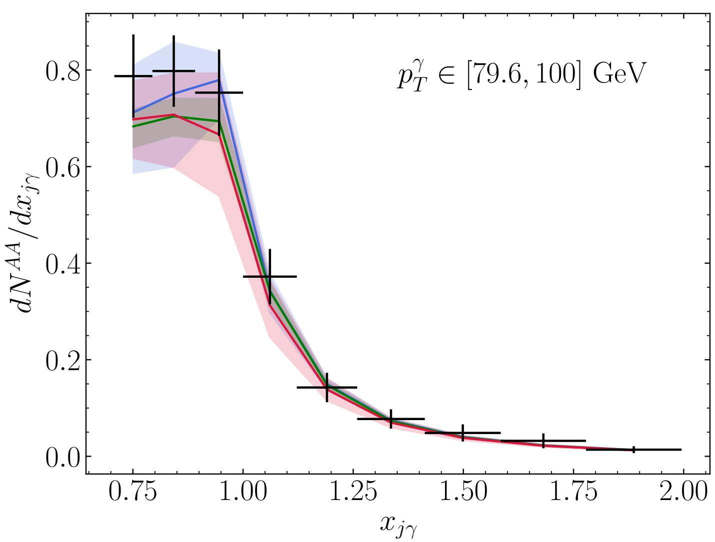
Results: the prediction

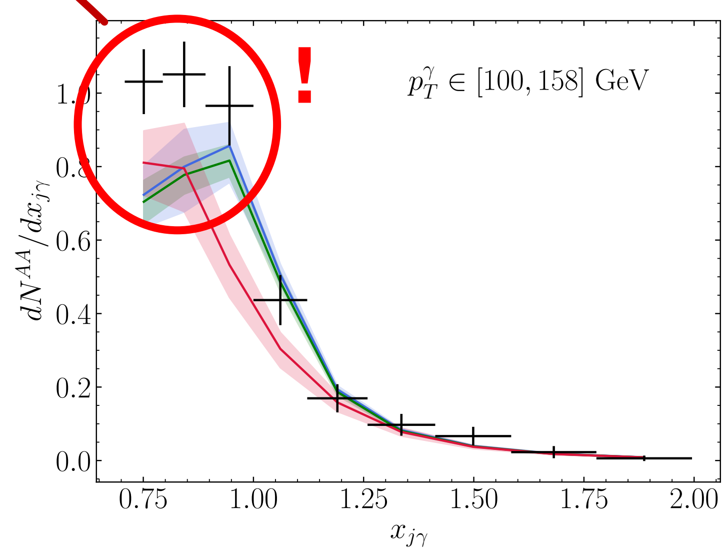
Photon-tagged jets are used for prediction/validation:

Good predictions ✓
independent of $D(\varepsilon)$ parameterization choice!

deviations for $p_T^{jet} < p_T^{\gamma}$ might show lack of information in the model

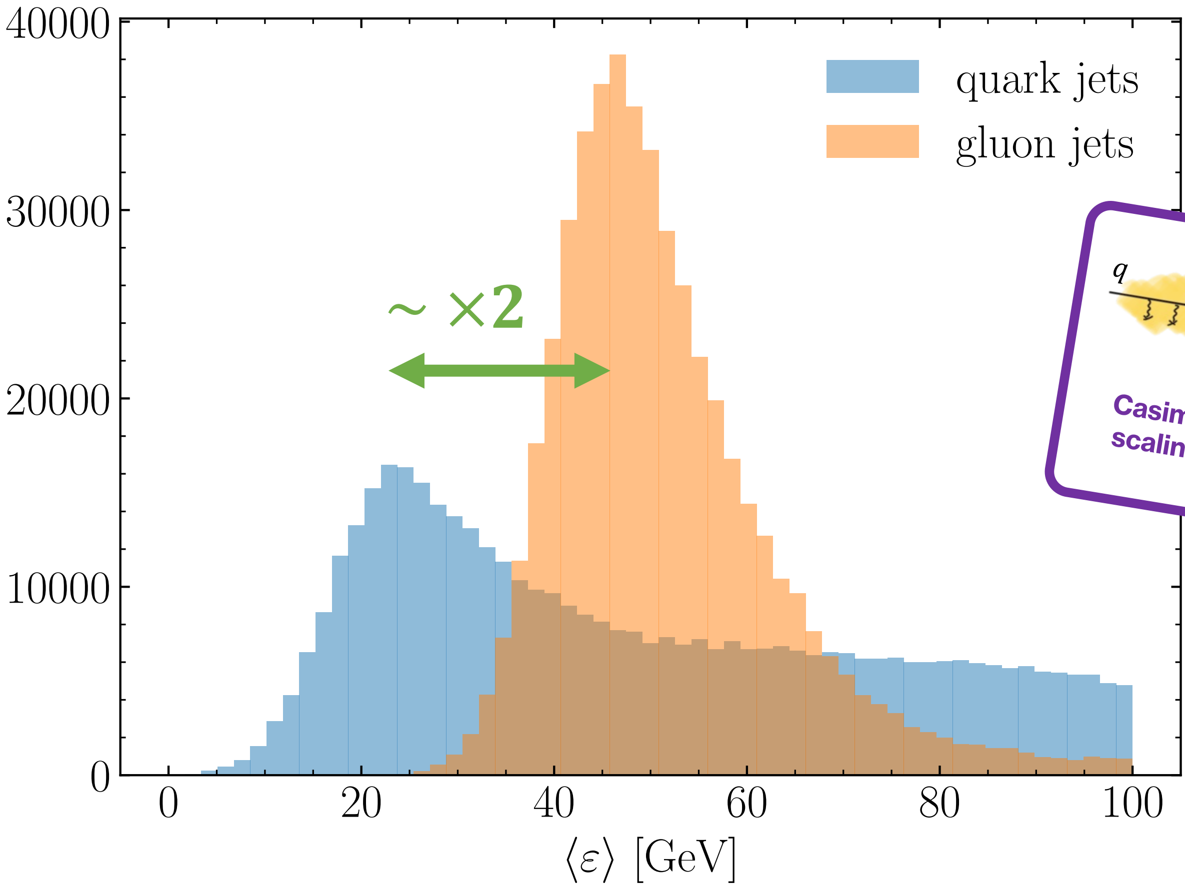


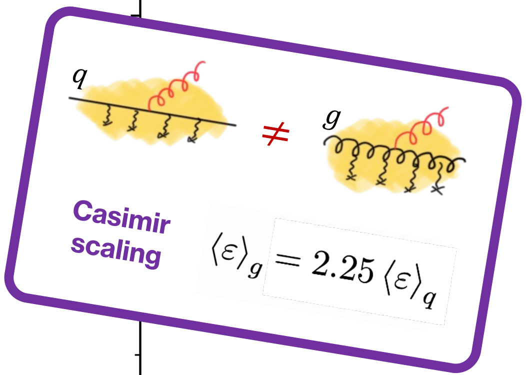




Results: quark- Vs. gluon-jet energy loss

From the posterior distributions, we can access the distribution for the mean energy loss of the quark- and gluon-jets:





Summary and next steps

- From the theory, we expect that quark- and gluon-jets lose energy differently in the medium;
- Our goal is then to show if the factorization holds for different observables, with only the information about the jet-initiating parton, in a data driven way;
- For this, we rely on Bayesian analysis;
- We concluded that by only considering inclusive jet data, we can successfully describe the data;
- The factorization pictures holds when used to predict photon-tagged jet spectra;
- Furthermore, the model is able to distinguish between the energy loss of quark- and gluon-jets in the expected way.

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- The factorization pictures holds when used to predict photon-tagged jet spectra;
- Furthermore, the model is able to distinguish between the energy loss of quark- and gluon-jets in the expected way.

Next steps:

- Add different measurements to better learn and validate the model;
- Test the model generalization by using the extracted energy loss distributions to predict other kind of jet observables;
- Incorporate information about the jet substructure.