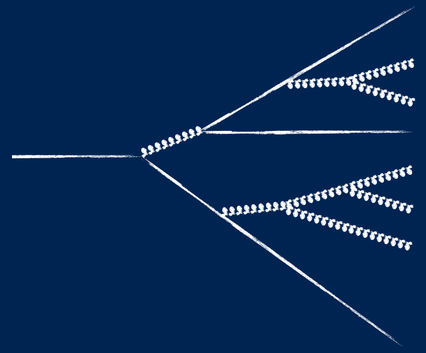
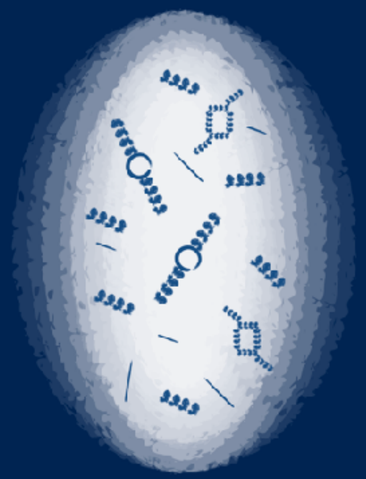
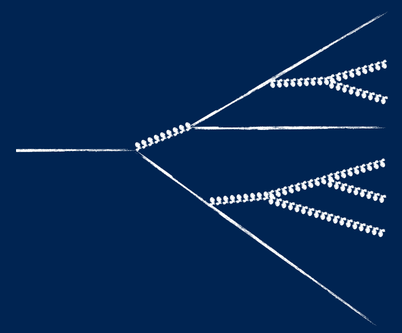
Overview:
Experimental Nuclear Physics



James Mulligan
UC Berkeley and LBNL

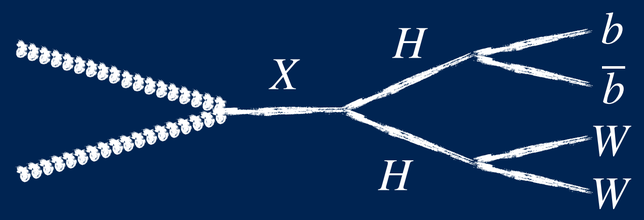


BOOST 2023
Lawrence Berkeley National Lab
July 31, 2023

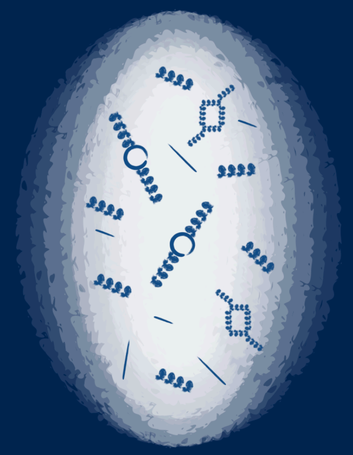


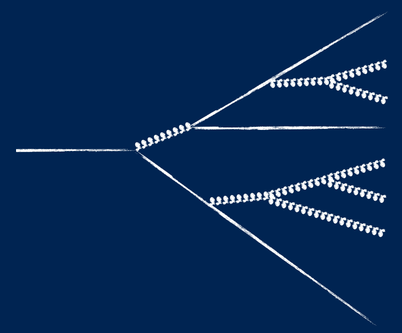
QCD in vacuum

BSM searches



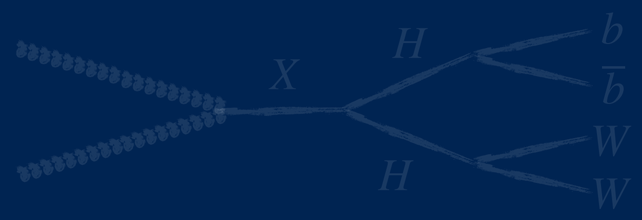
Deconfined QCD



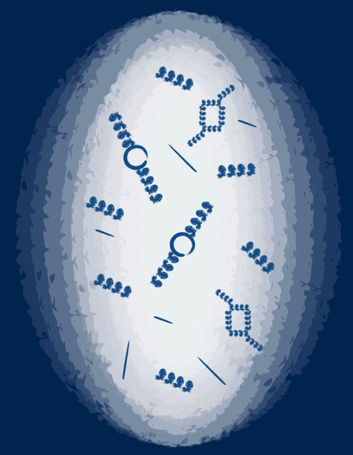


QCD in vacuum

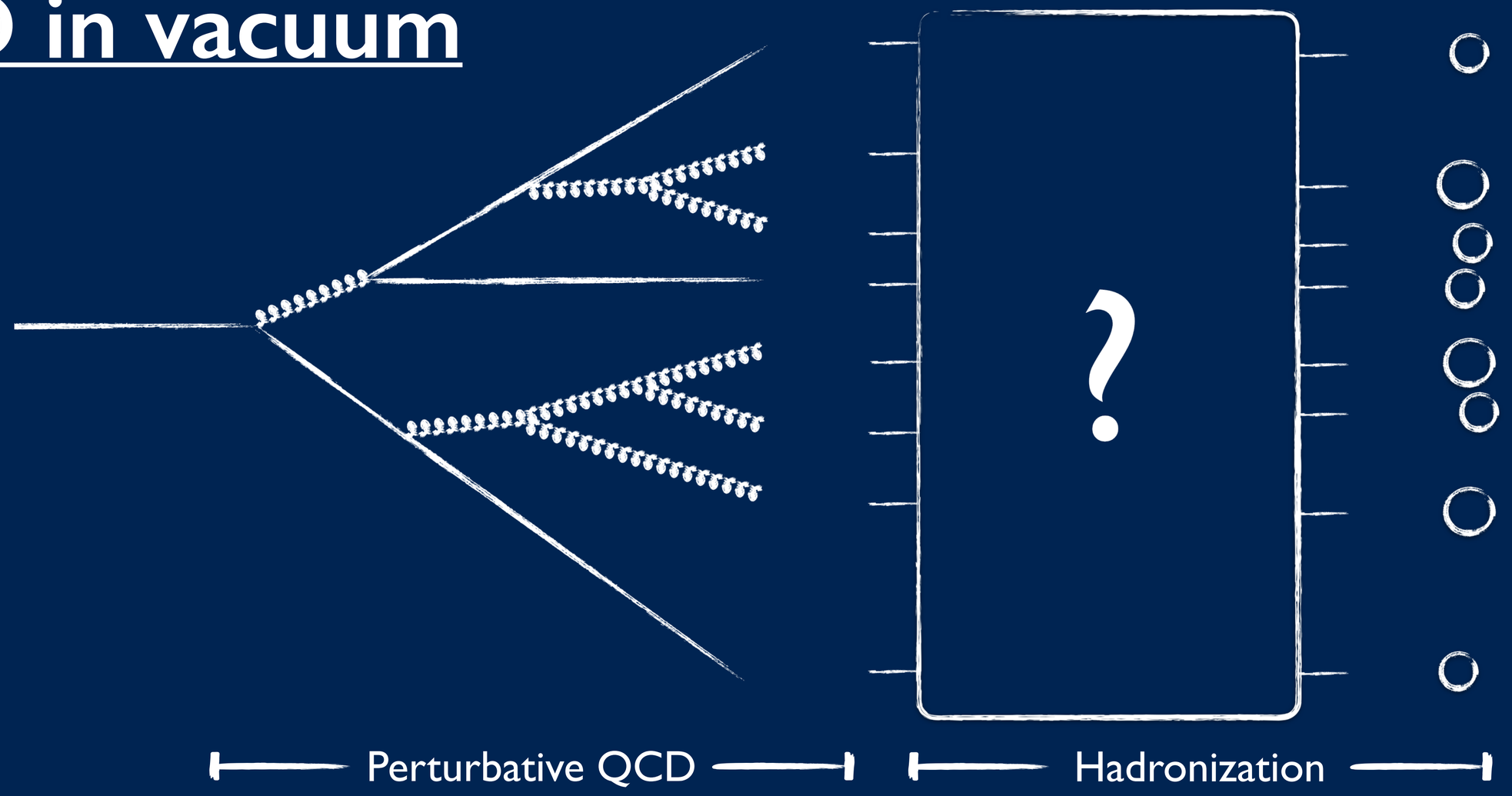
BSM searches



Deconfined QCD



QCD in vacuum

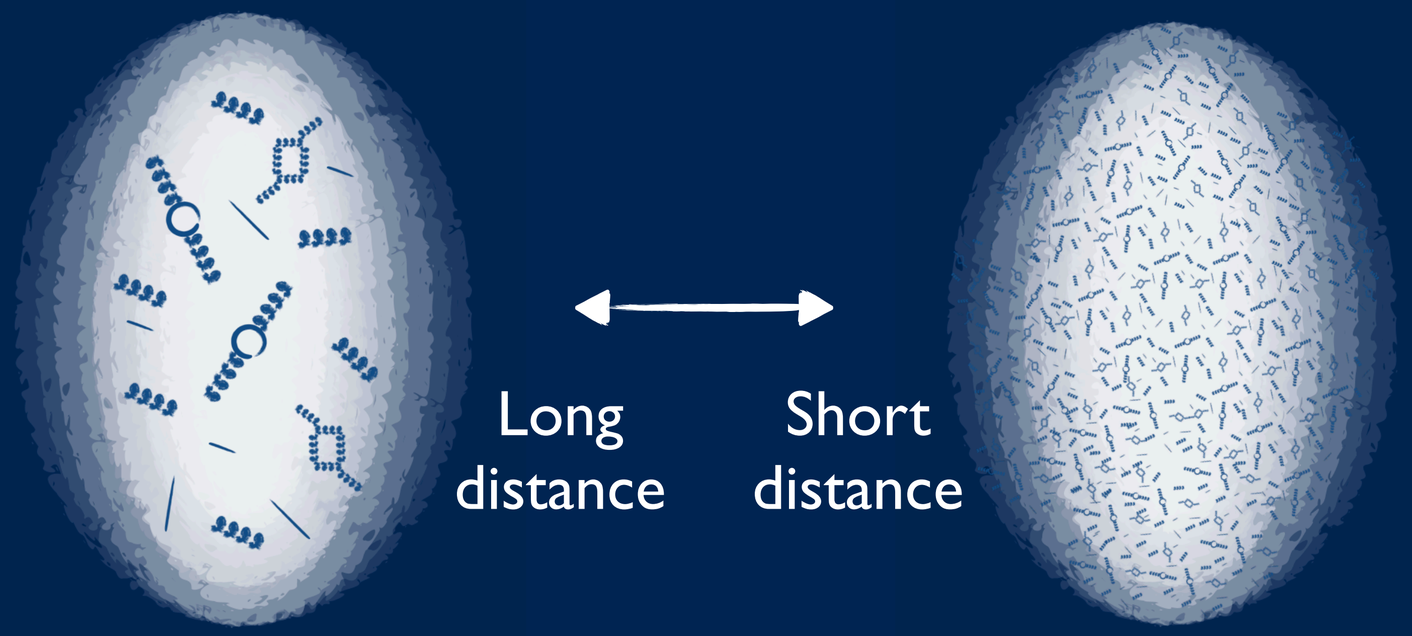


How much of the fragmentation process is perturbatively calculable?

Can experiment guide our understanding of the hadronization process?

Deconfined QCD: quark-gluon plasma

High-temperature / high-density QCD



What are the relevant degrees of freedom of deconfined QCD matter?

Can experiment guide our understanding of the confinement transition?

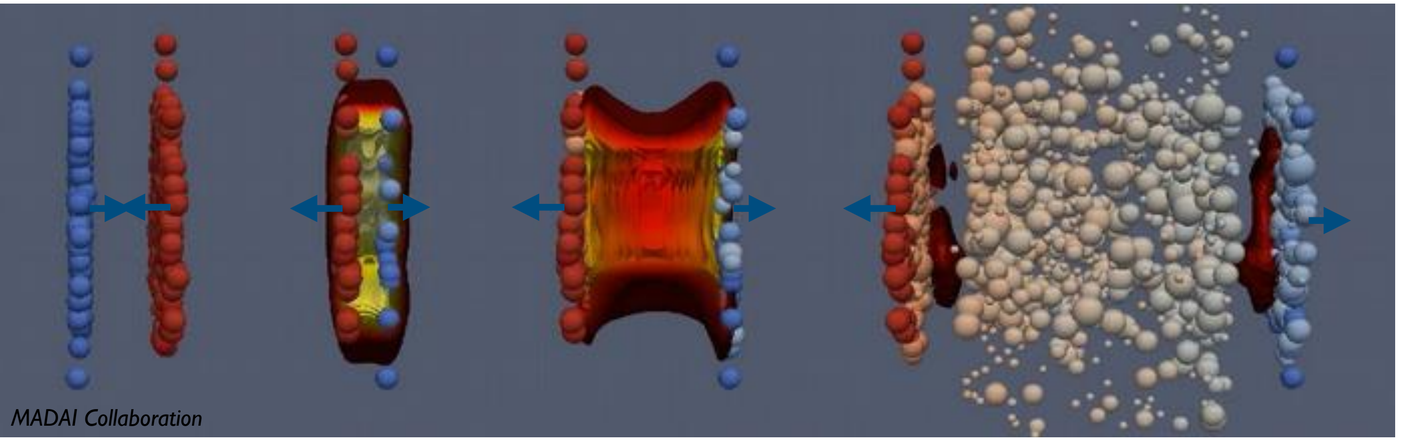
Heavy-ion collisions

We collide nuclei together at the

Large Hadron Collider (LHC)

Relativistic Heavy Ion Collider (RHIC)

to produce droplets of hot, dense quark-gluon plasma



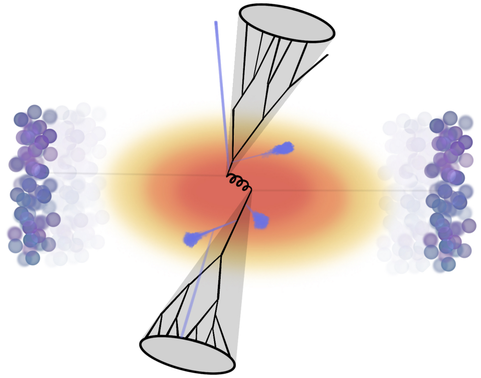
Soft collisions transform kinetic energy of nuclei into region of large energy density

$T \approx 150\text{-}500$ MeV $\quad t \sim \mathcal{O}\left(10\ \mathrm{fm}/c\right)$

Jet quenching in the quark-gluon plasma

The QGP is too small and short-lived to be probed by traditional scattering beams

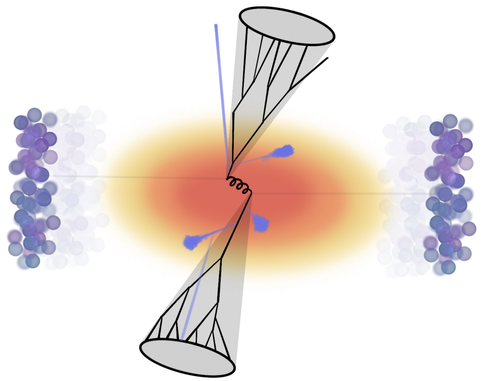
→ **Use jets as probes**



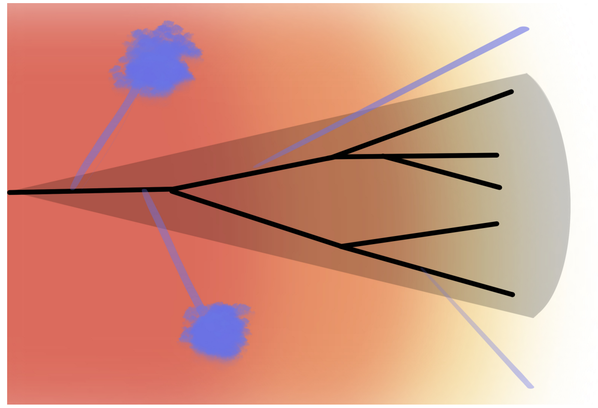
Jet quenching in the quark-gluon plasma

The QGP is too small and short-lived to be probed by traditional scattering beams

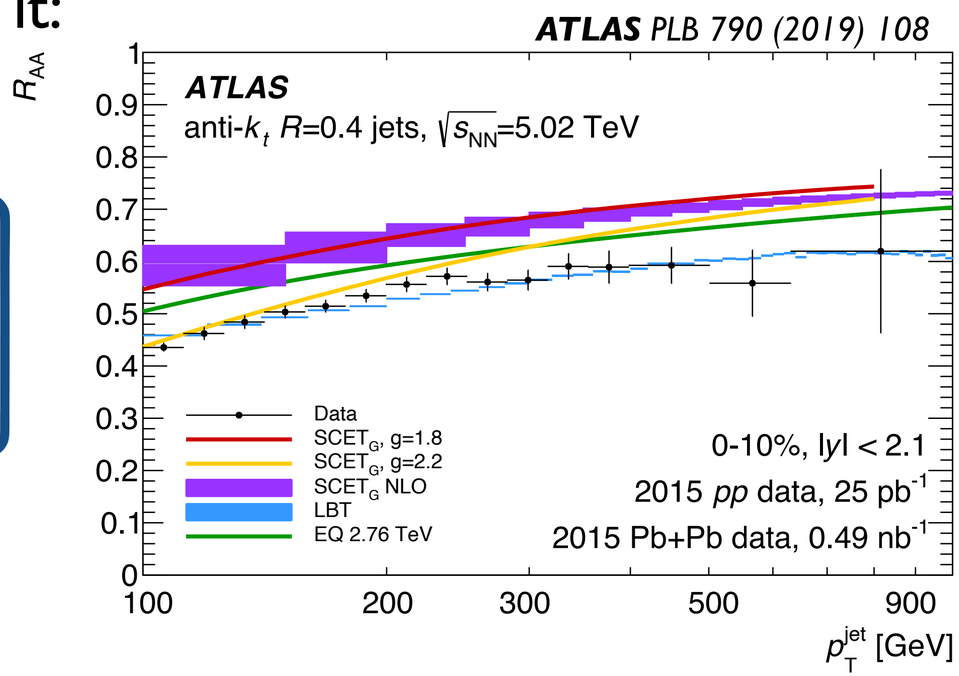
→ **Use jets as probes**



Jets interact with the quark-gluon plasma as they traverse it:

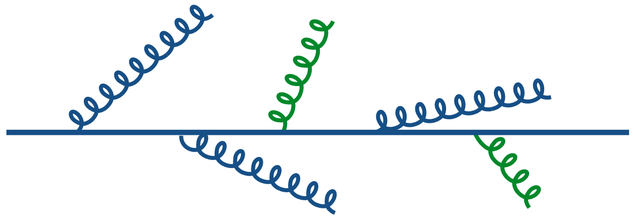


$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

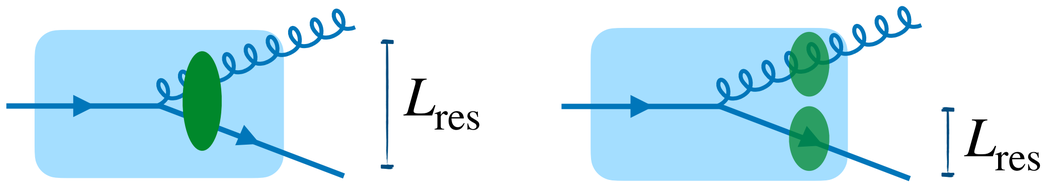


Jet quenching in the quark-gluon plasma

What is the microscopic picture of jet-medium interactions?

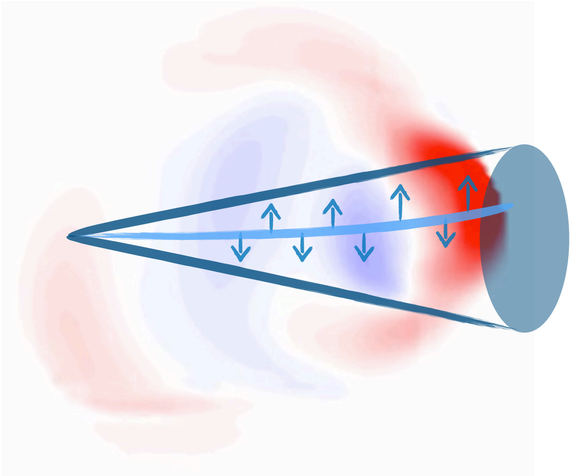


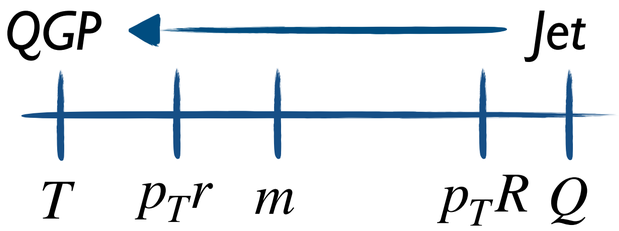
How to modify vacuum parton showers?



How does jet quenching depend on the properties of the QGP?

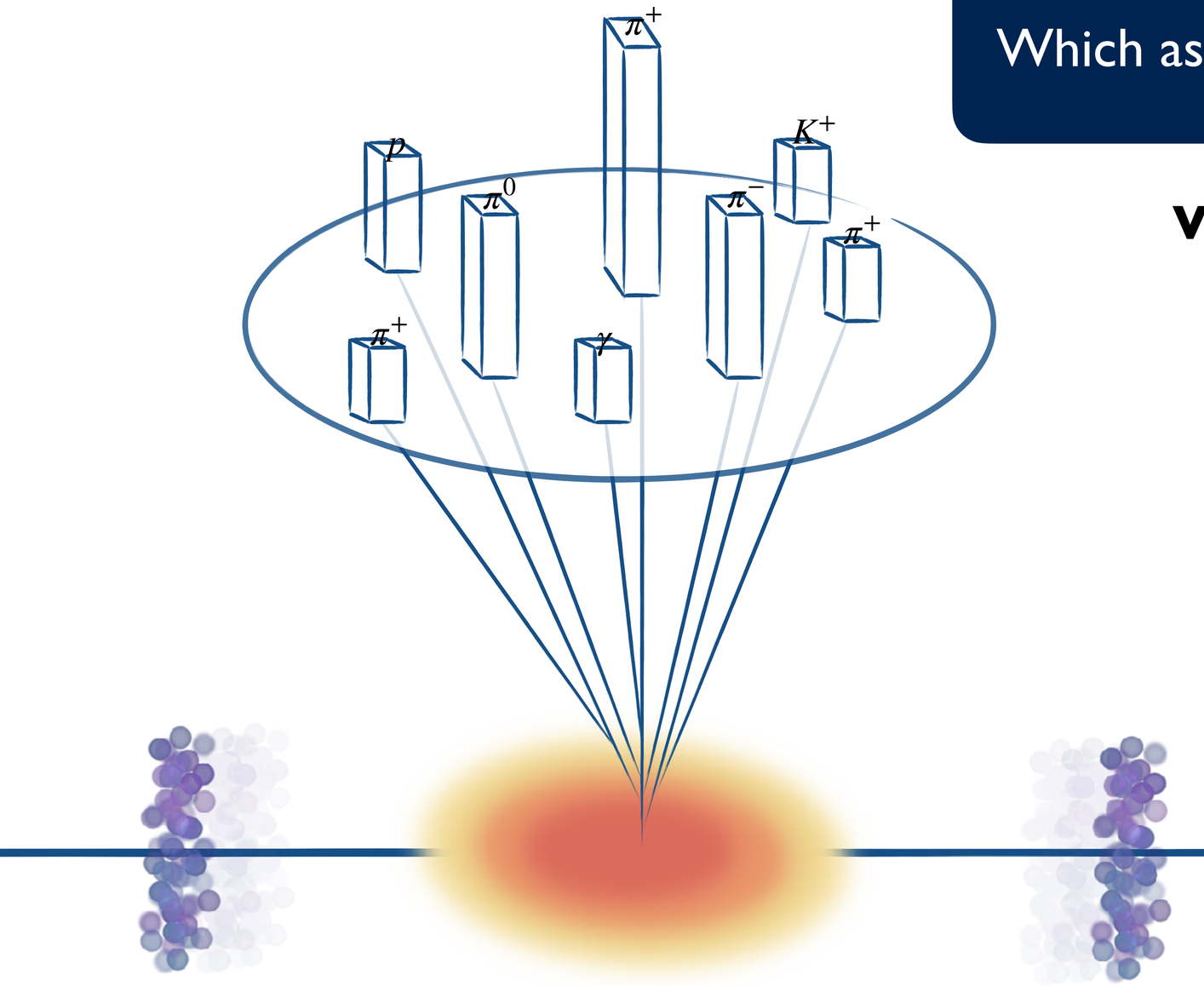
What is the real-time evolution of jet fragmentation?





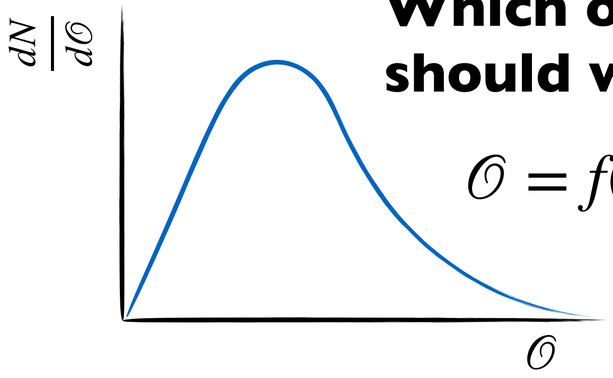
Which medium properties are imprinted onto jets?

Which aspects of the jet contain useful information?



Vast phase space

- $\mathcal{O}(10 - 100)$ correlated particles per jet
- Typically: $1\mathrm{D}$ projection over ensemble

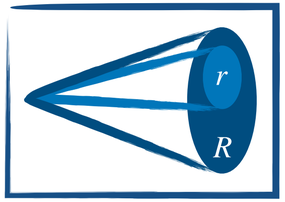


Which observables should we measure?

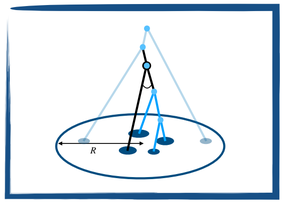
$$\mathcal{O} = f(\mathbf{p_0}, \ldots, \mathbf{p_n})$$

A few highlights:
Jet measurements in pp, AA collisions

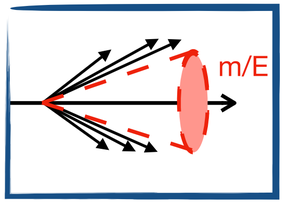
1. Jet radius dependence



2. Jet substructure: angular scales

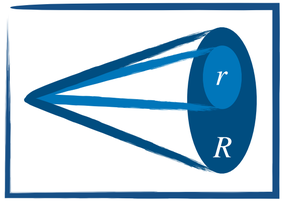


3. Flavor dependence: *q*/*g* and HF



A few highlights:
Jet measurements in pp, AA collisions

1. Jet radius dependence

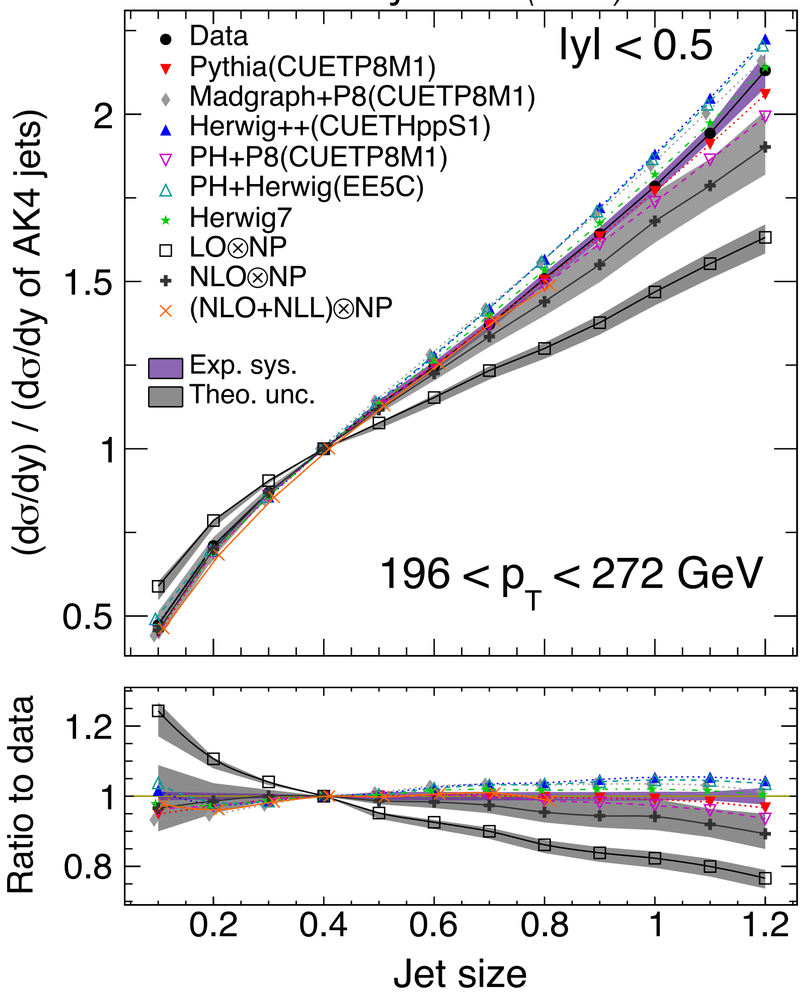


2. Jet substructure: angular scales

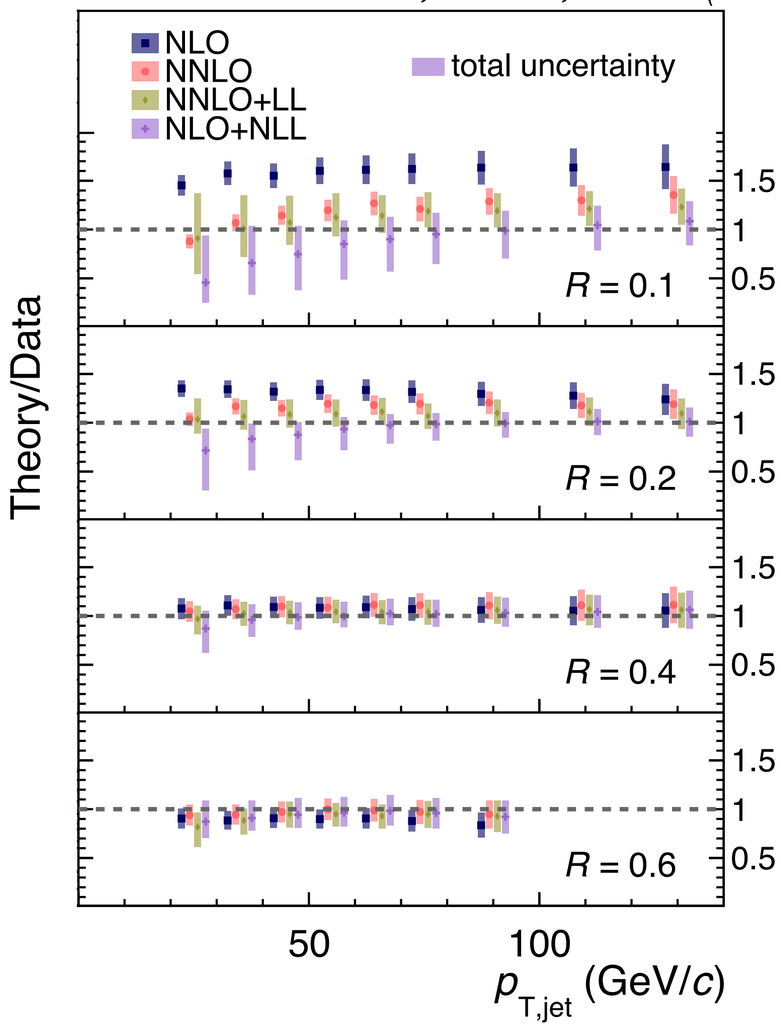
3. Flavor dependence: q/g and HF

Inclusive jet production: pp collisions

***CMS** JHEP 12 (2020) 082*



***ALICE** arXiv:2211.04384, PRC 101, 034911 (2020)*



pQCD calculations are challenging at:

- $R \lesssim 0.2$
- $R \gtrsim 1$

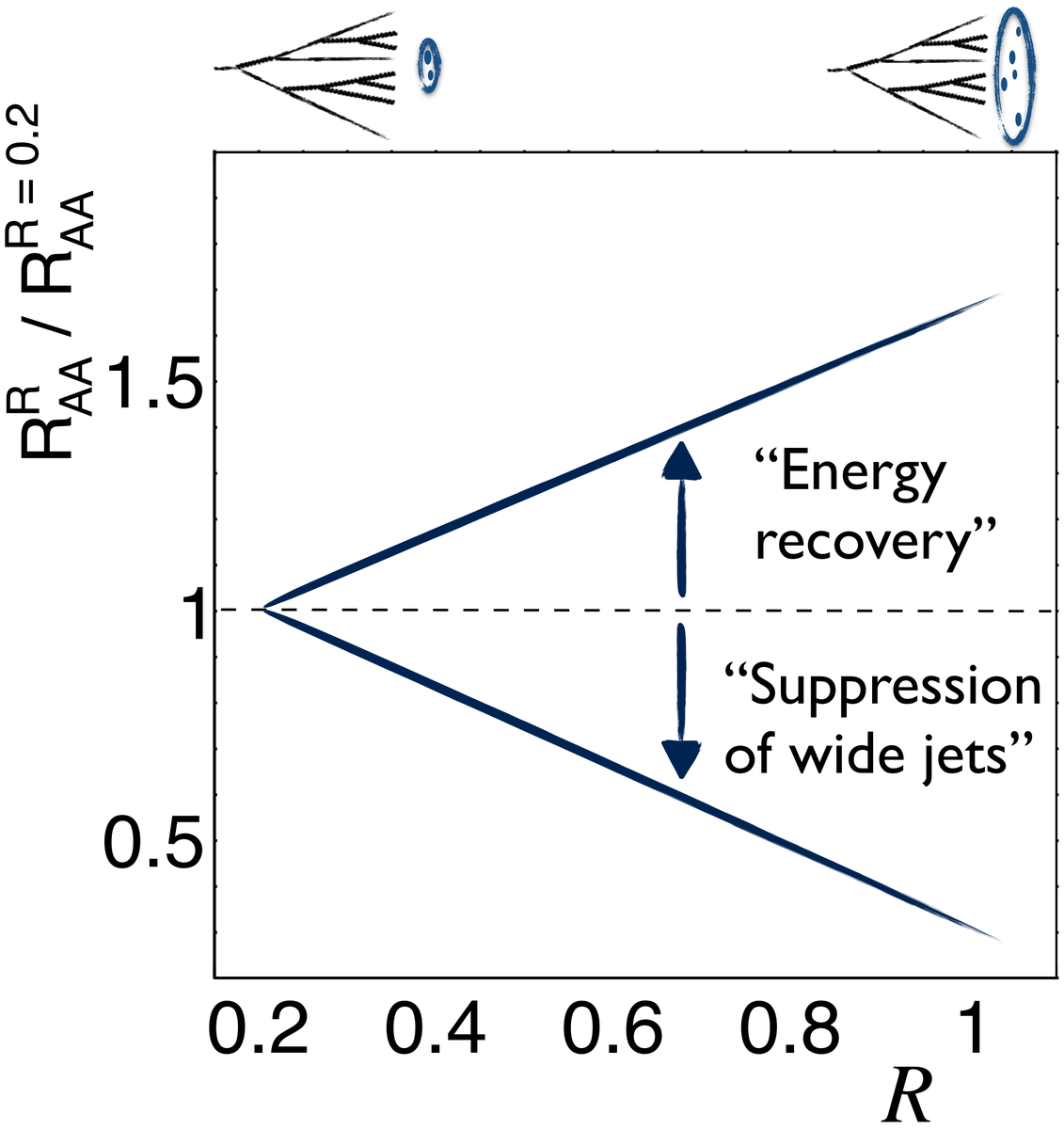
Small R:

- NNLO
- Resummation

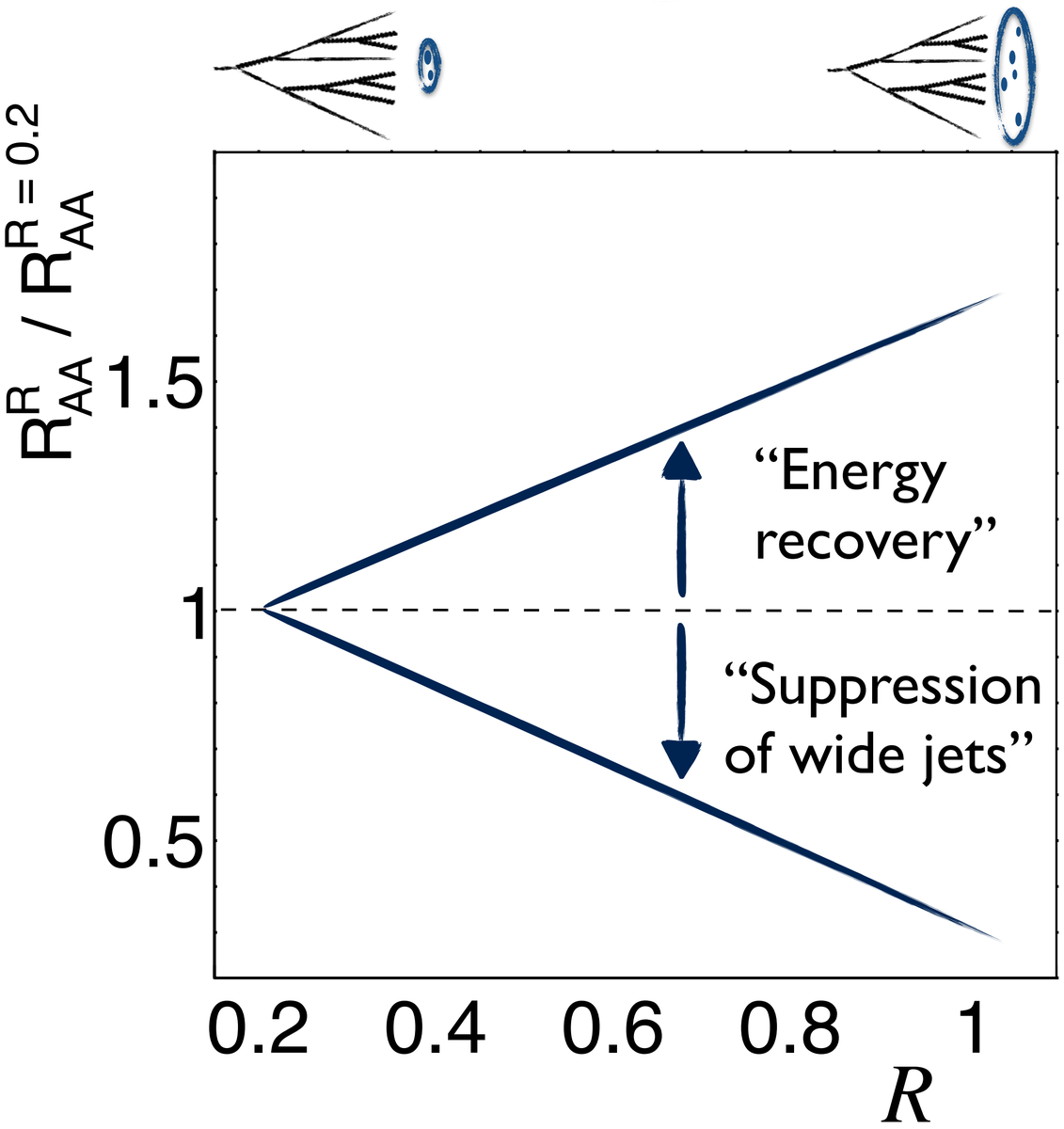
Large R:

- Power corrections?

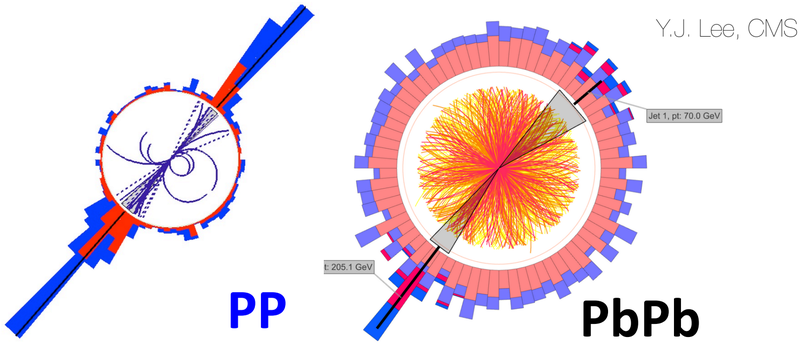
Large-*R* jets in *AA* collisions



Large-*R* jets in *AA* collisions

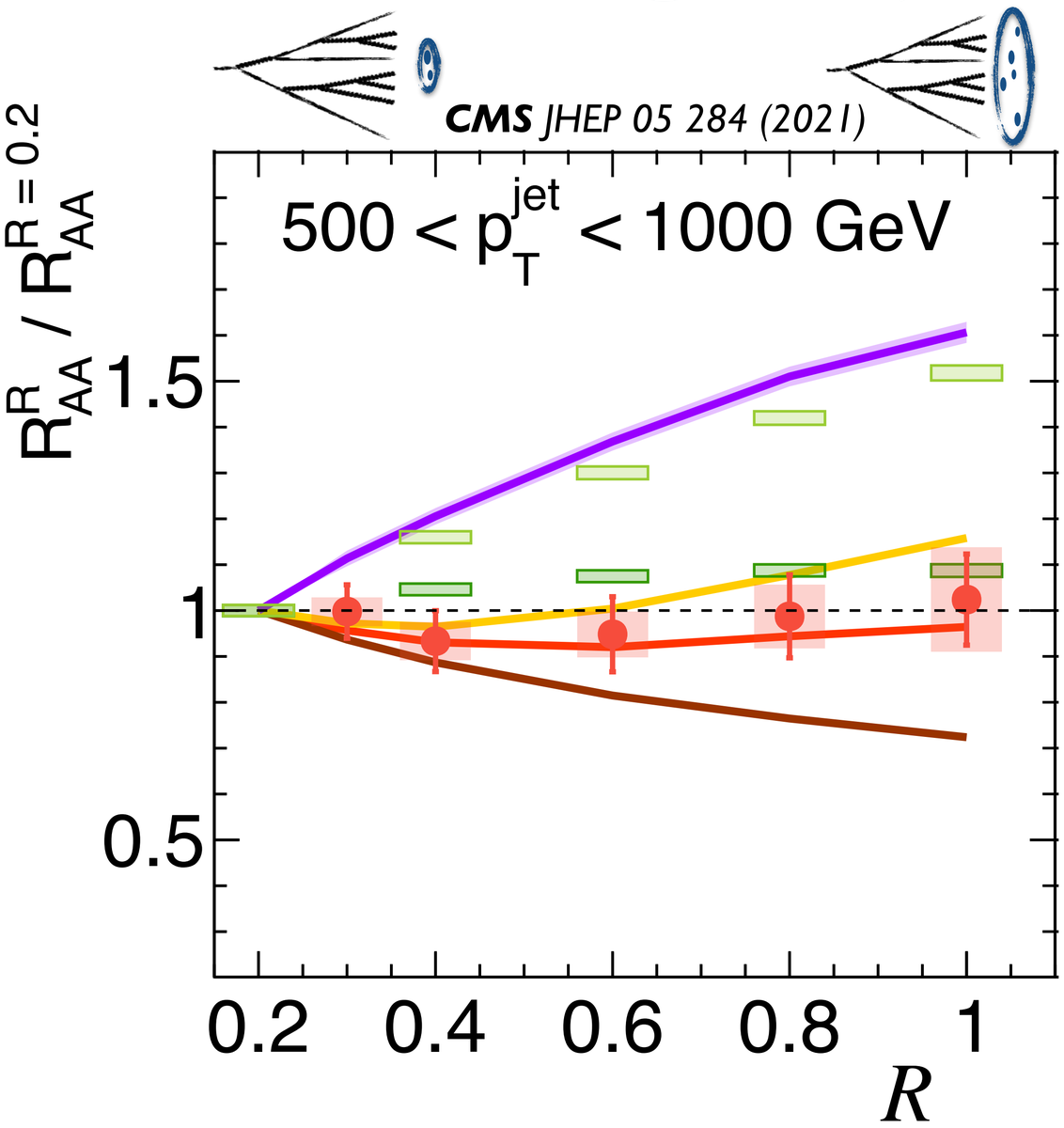


Challenge: Underlying event grows $\propto R^2$

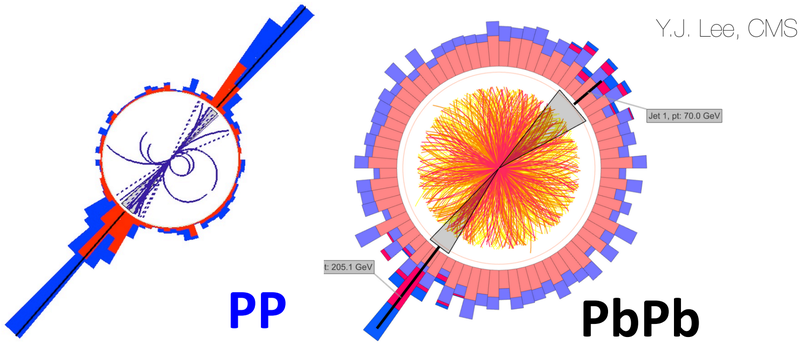


One solution: measure very high-p_T jets

Large-*R* jets in *AA* collisions



Challenge: Underlying event grows $\propto R^2$



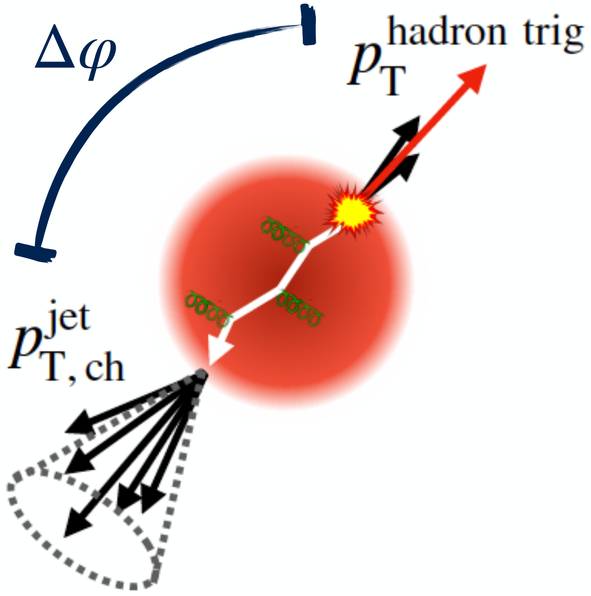
One solution: measure very high-p_T jets

→ No significant dependence of energy loss on jet radius at high p_T

See also:
ATLAS arXiv:2301.05606

Large-*R* jets in *AA* collisions: low-p_T

Semi-inclusive jet correlations allow statistical background corrections at large-*R*, low p_T

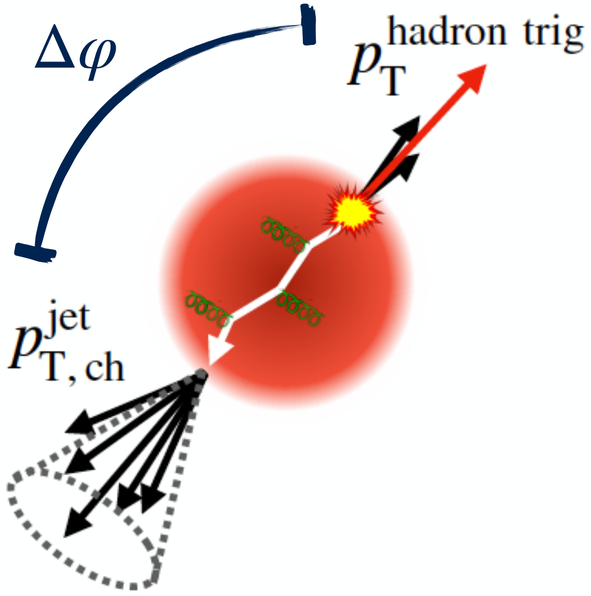


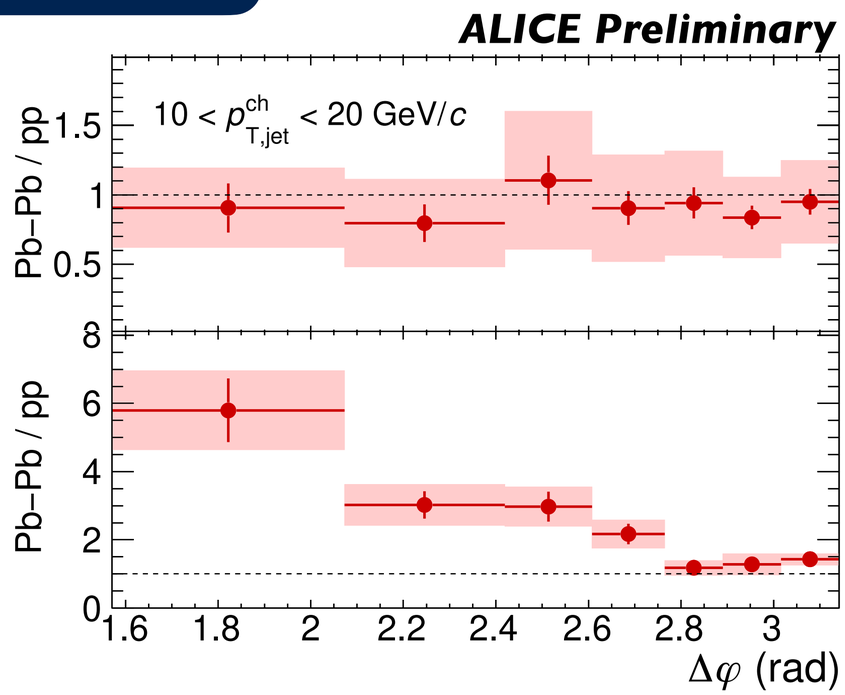
See alternate approach:
ML-based subtraction
ALICE arXiv:2303.00592

Large-*R* jets in *AA* collisions: low-p_T

Semi-inclusive jet correlations allow statistical background corrections at large-*R*, low p_T

See also:
STAR, HP2023





$R = 0.2$

$R = 0.4$

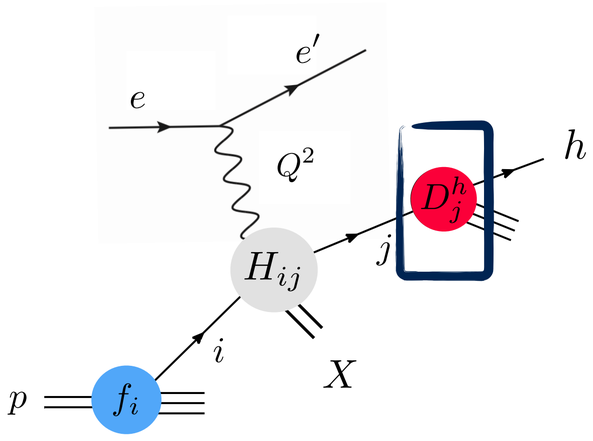
See alternate approach:
ML-based subtraction
ALICE arXiv:2303.00592

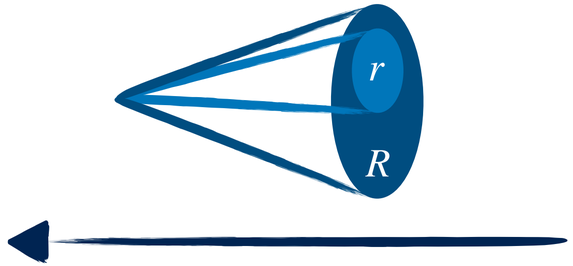
Low-p_{T}, large(ish)-R phase space reveals a large acoplanarity

Hypothesis: non-perturbative medium response

An alternate approach: from jets to subjets

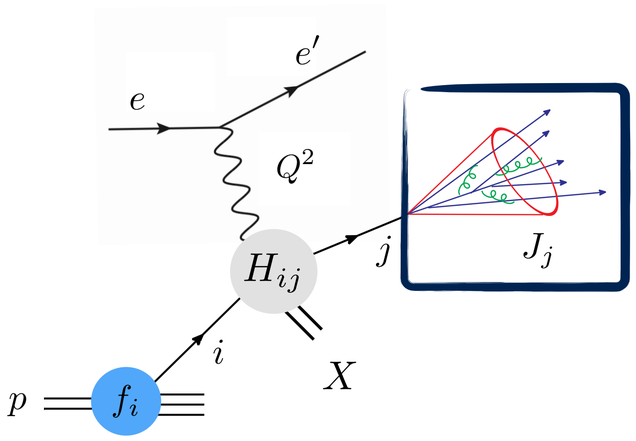
Hadrons





$$z_r = \frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}}$$

Jets

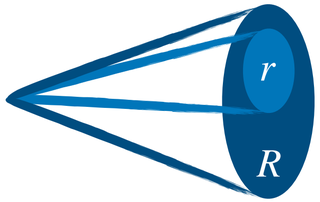


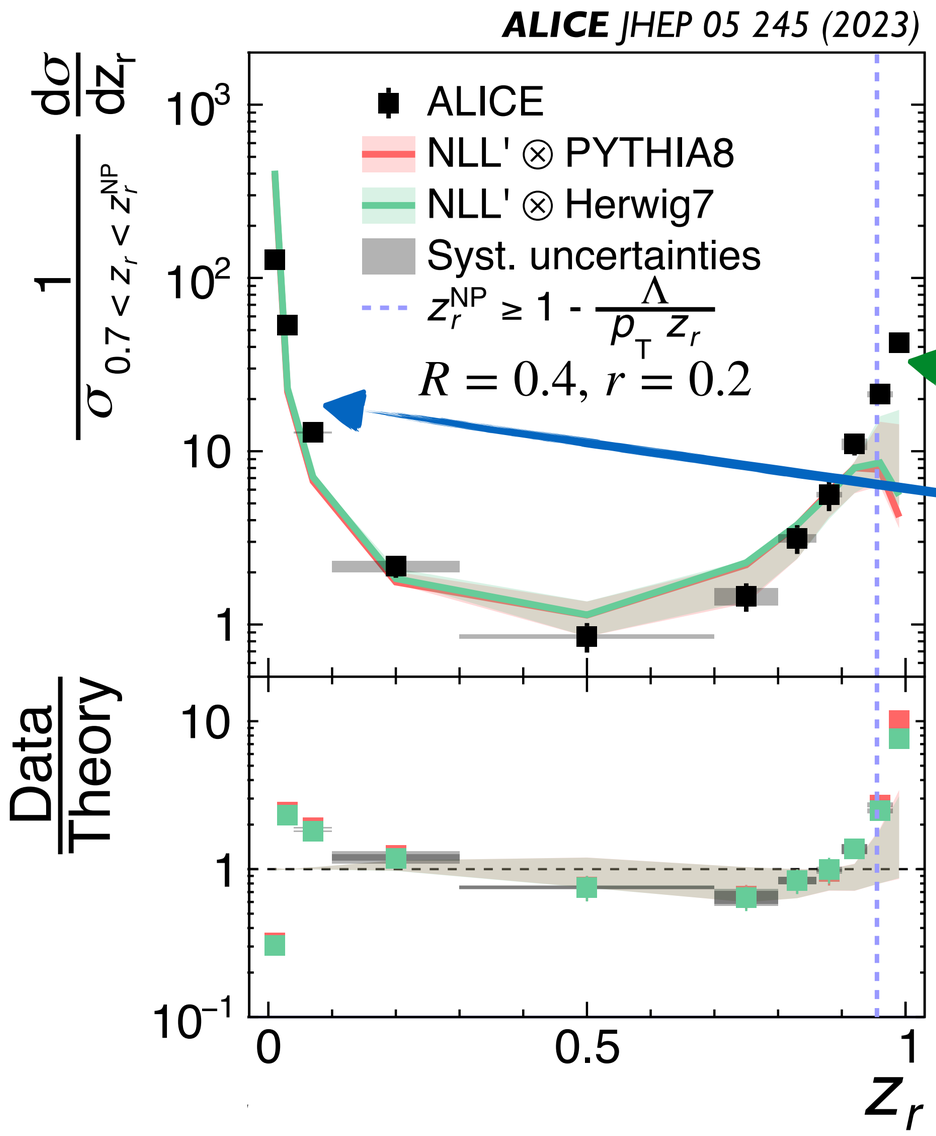
Parton-to-hadron fragmentation function:
nonperturbative, fit from data

Parton-to-jet fragmentation function:
perturbatively calculable

Study the hadronization process using jet substructure

Subjet fragmentation: pp

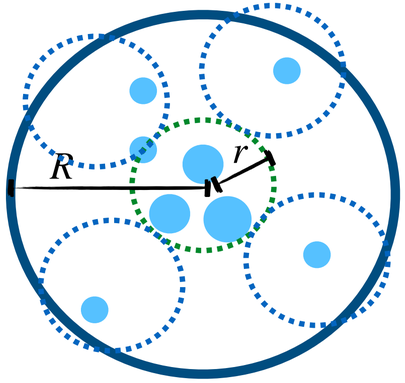




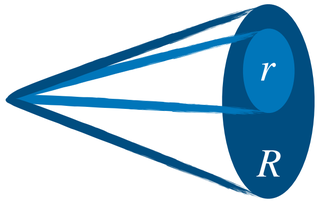
$$z_r = \frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}}$$

Leading parton

Soft emissions



Subjet fragmentation: pp



Comparison to perturbative QCD calculation

Kang, Ringer, Waalewijn JHEP 07 (2017) 064

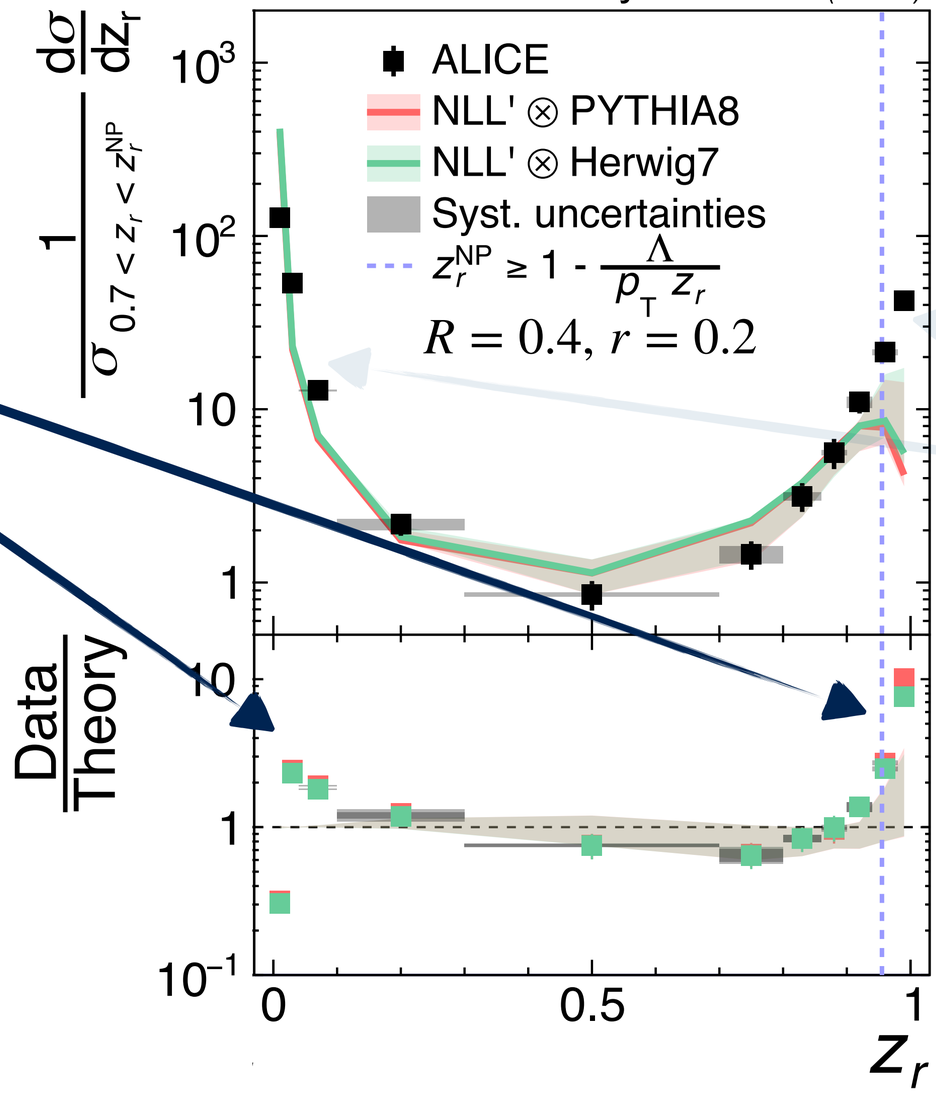
- Large z_r: threshold resummation and hadronization
- Small z_r: relevant for parton-hadron duality

Map parton → hadron transition

Baseline for tests of universality of jet fragmentation in QGP

Qiu, Ringer, Sato, Zurita PRL 122 (2019) 25

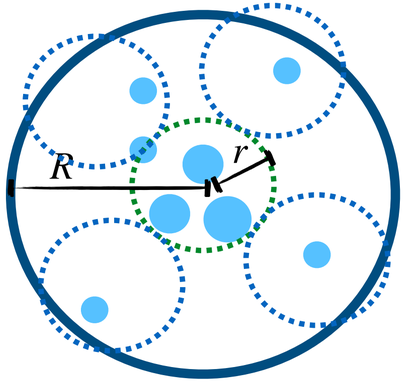
***ALICE** JHEP 05 245 (2023)*



$$z_r = \frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}}$$

Leading parton

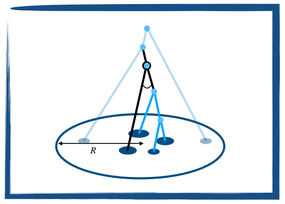
Soft emissions



A few highlights:
Jet measurements in pp, AA collisions

1. Jet radius dependence

2. Jet substructure: angular scales

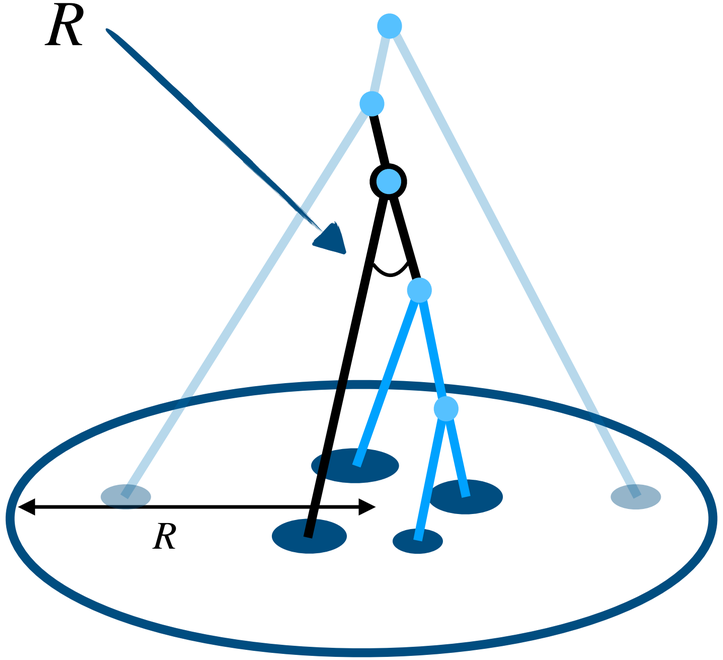


3. Flavor dependence: q/g and HF

Groomed jet radius

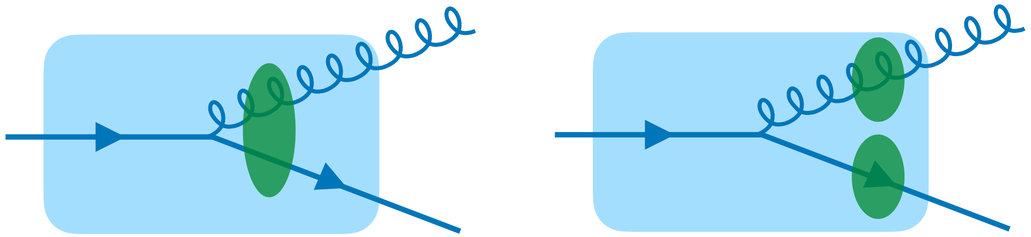
How is the perturbative core of the jet modified in heavy-ion collisions?

$$\theta_g \equiv \frac{r_g}{R}$$



Measure the angle θ_g between the two prongs in the high-Q^2 jet splitting

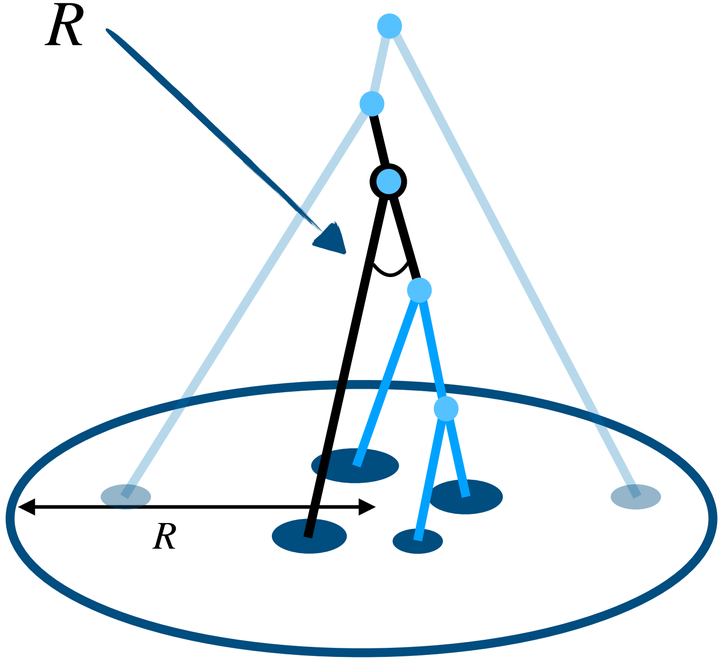
θ_g is sensitive to the angular resolution scale of the quark-gluon plasma

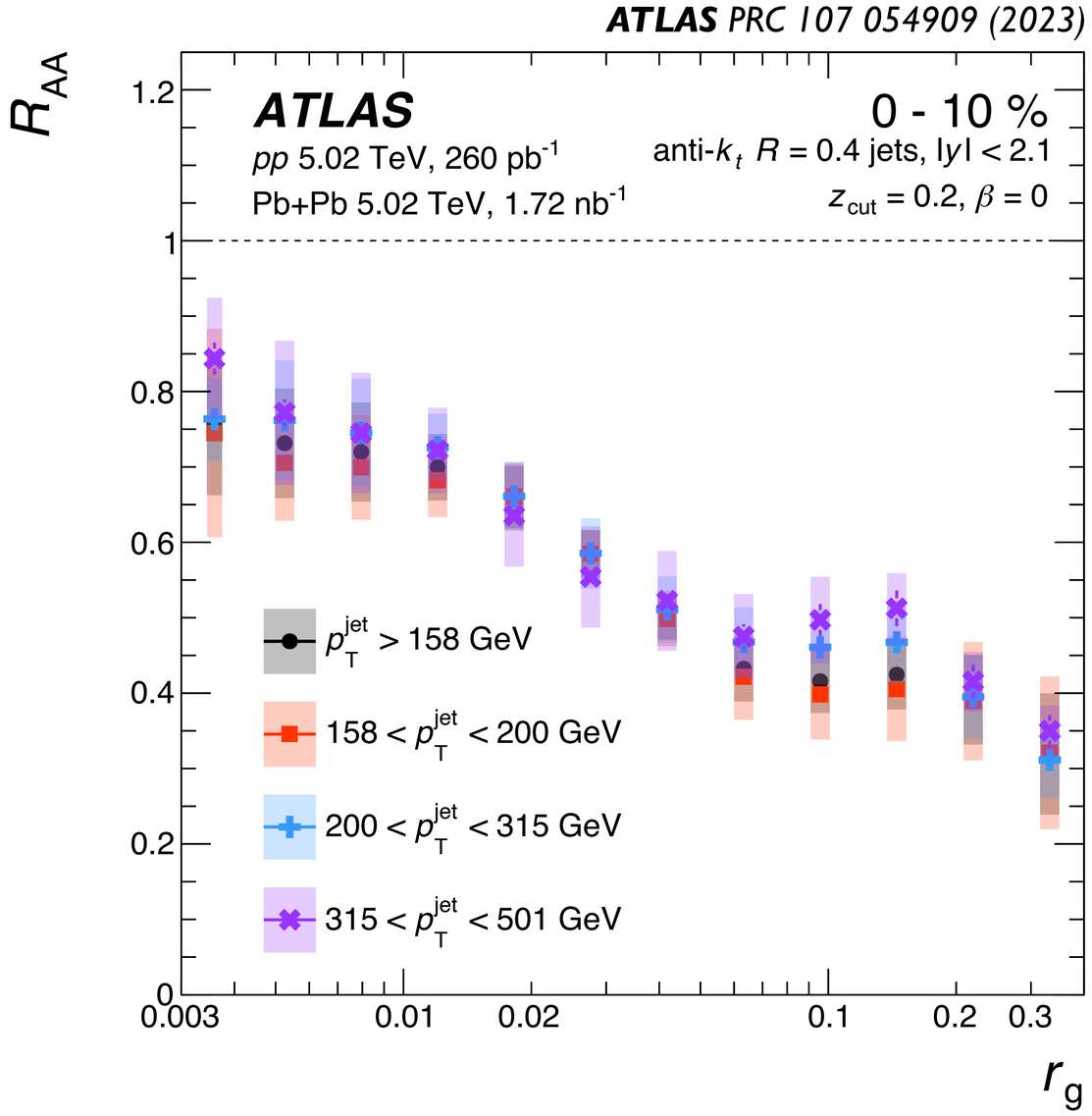


Groomed jet radius

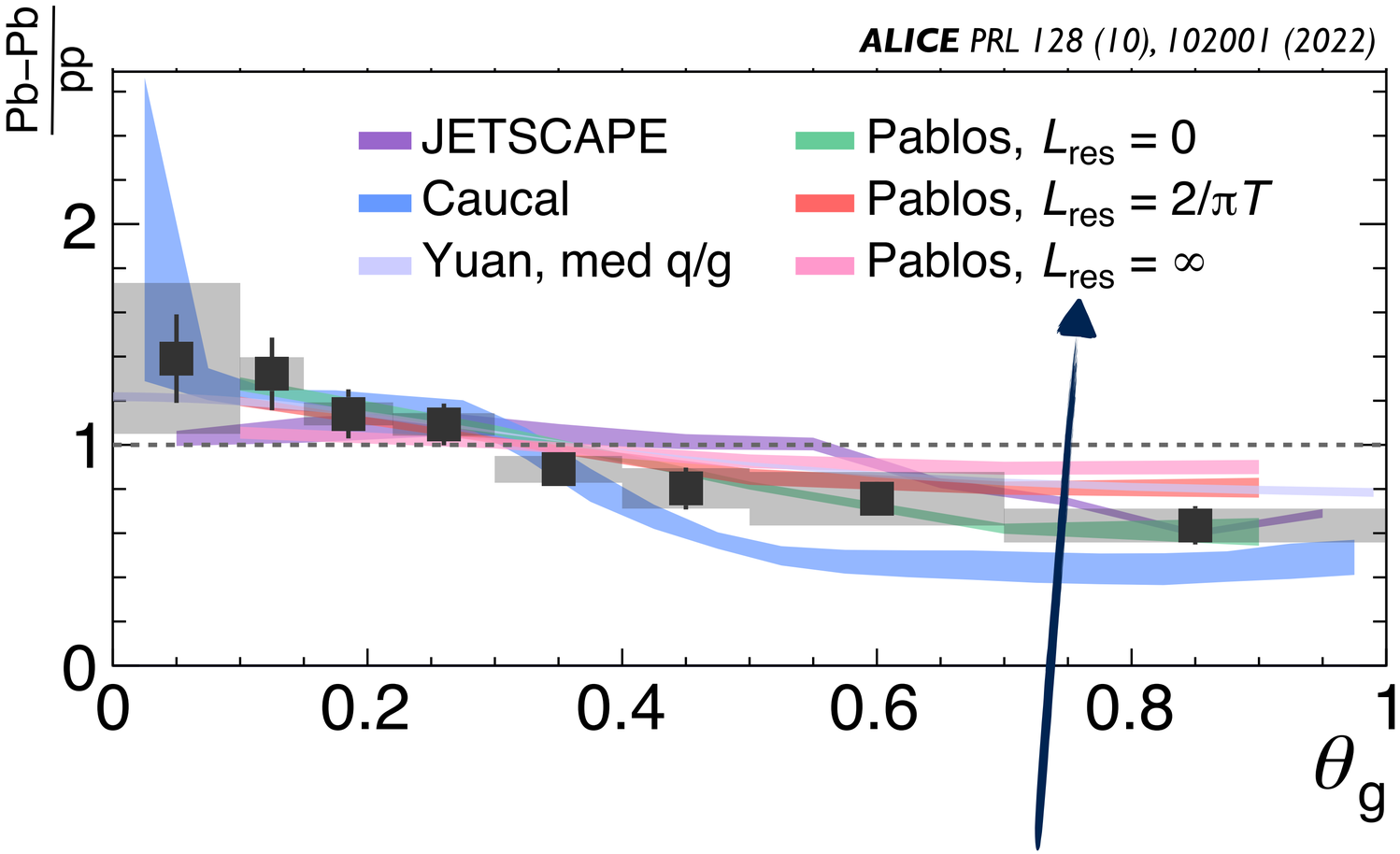
Wide jets are suppressed by the QGP more than narrow jets

$$\theta_g \equiv \frac{r_g}{R}$$





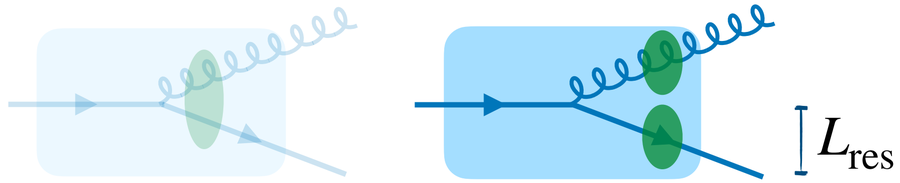
Why are wide jets suppressed by the QGP?



θ_g is sensitive to QGP resolution length L_{res} in models

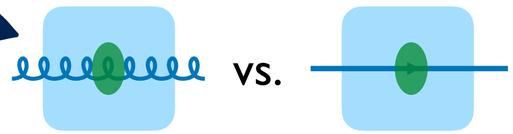
Two compatible possibilities revealed

(1) Wider splittings are resolved as independent color charges



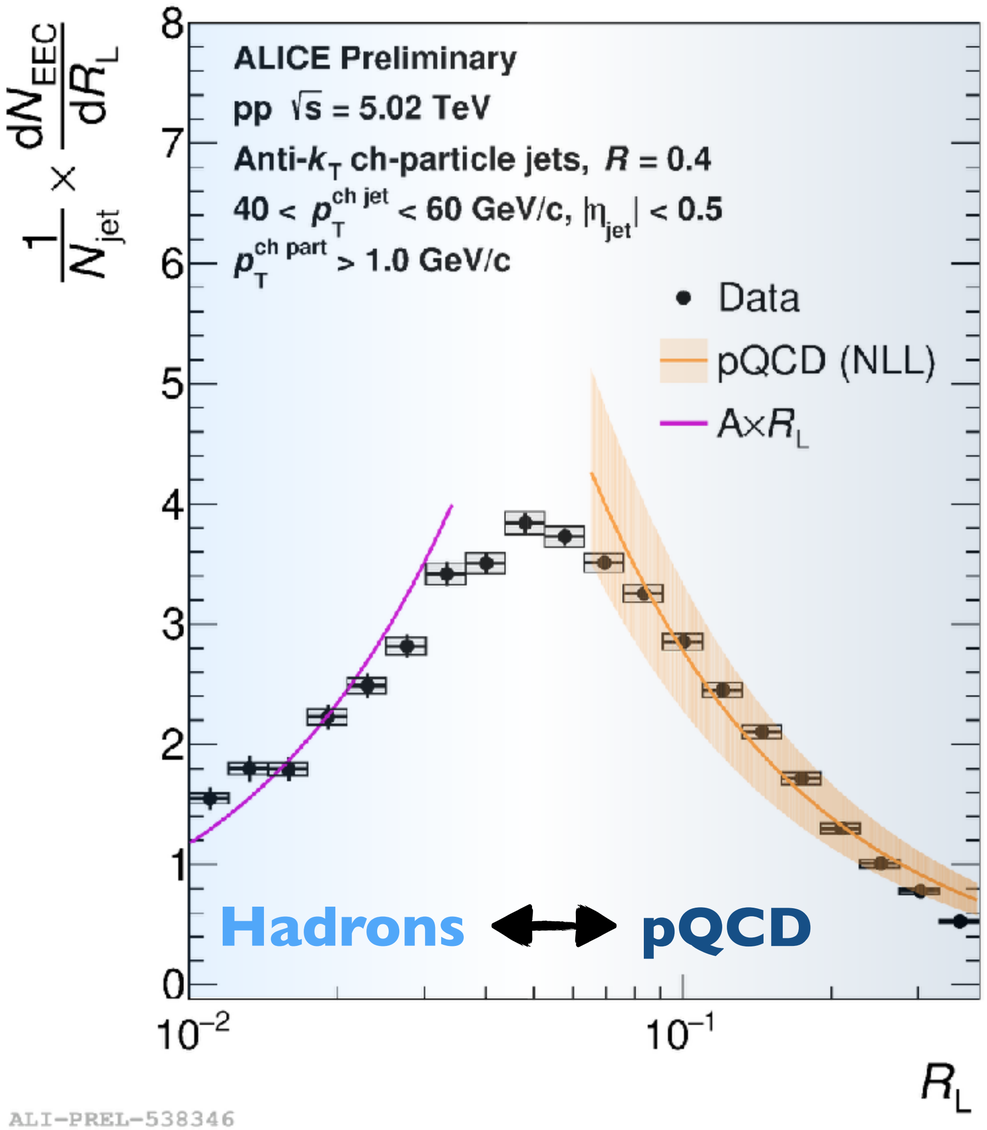
(2) Suppression of gluon vs. quark jets

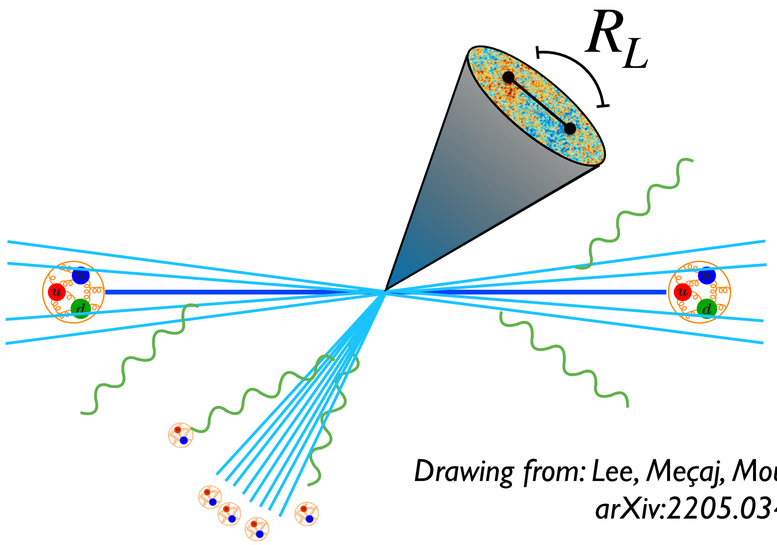
- $C_g/C_q = 9/4$



EECs: A more direct angular probe?

See also: STAR HP2023





Drawing from: Lee, Meçaj, Moult arXiv:2205.03414

Recent measurements in pp collisions

→ Clear separation of perturbative emissions and hadronization

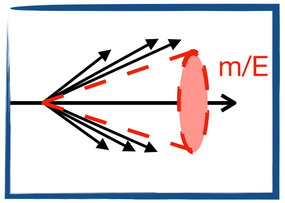
Not yet measured in AA collisions

A few highlights:
Jet measurements in pp, AA collisions

1. Jet radius dependence

2. Jet substructure: angular scales

3. Flavor dependence: *q*/*g* and HF



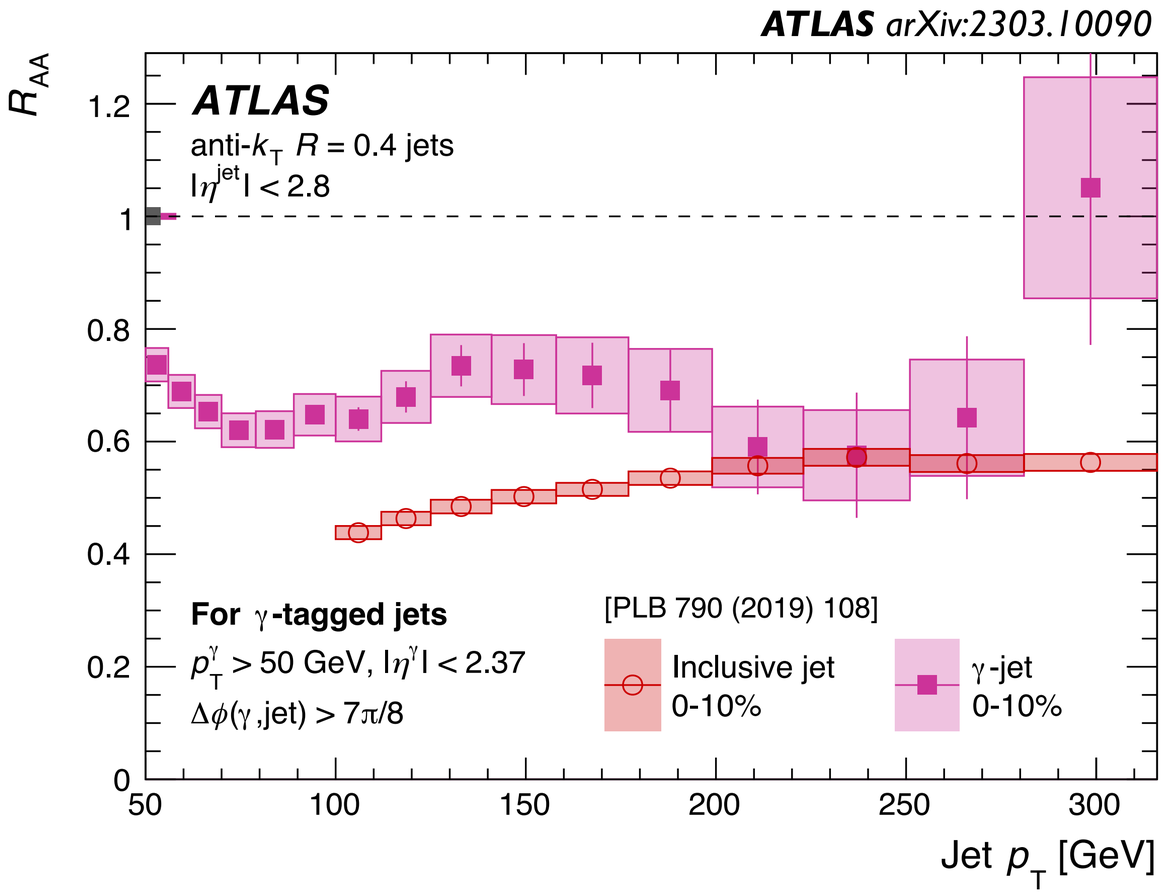
Quark vs. gluon energy loss

How much more are gluon-initiated jets suppressed relative to quark-initiated jets?

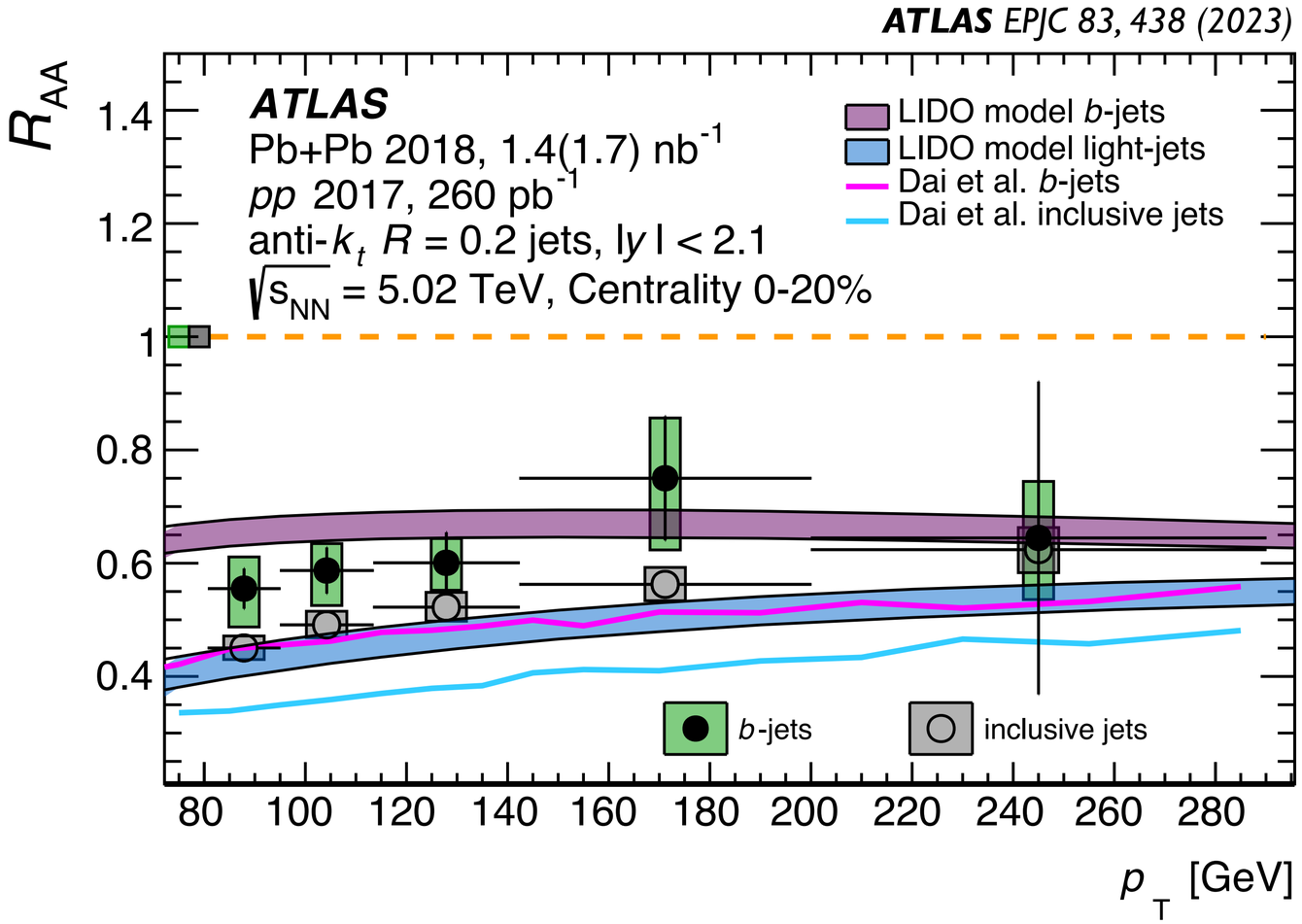
- Key confounding factor in understanding jet substructure modifications

γ-tagged jets show less suppression vs. inclusive jets

- Quantitative implications yet to be worked out…



HF-jet energy loss



Hint of reduced suppression for *b*-jets compared to inclusive jets

Can be due to:

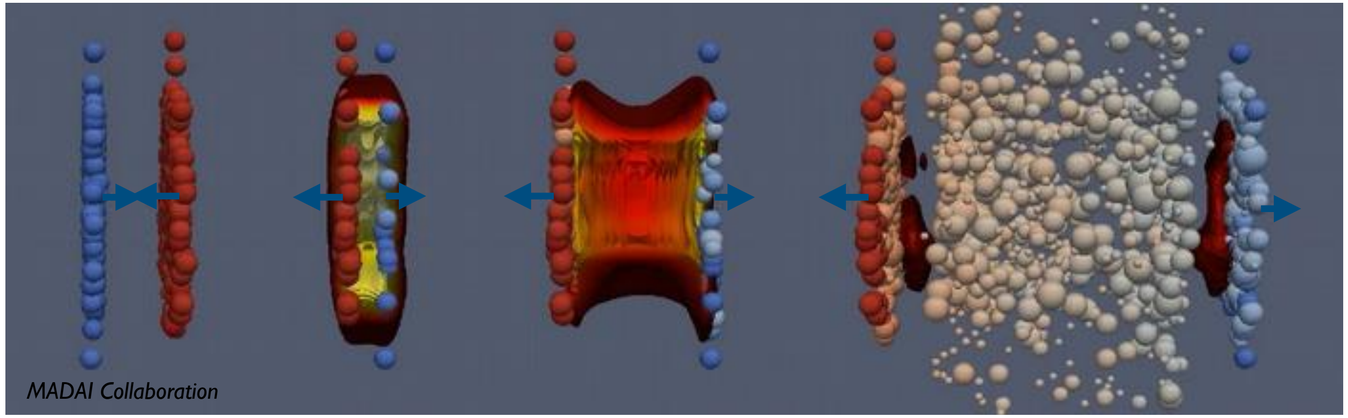
(i) *q* vs. *g*

(ii) mass effect

Still more work to do…

There is no golden observable

Jets traverse multiple stages of heavy-ion collision



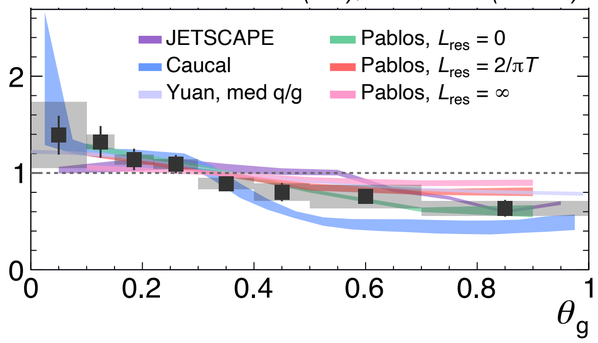
initial state

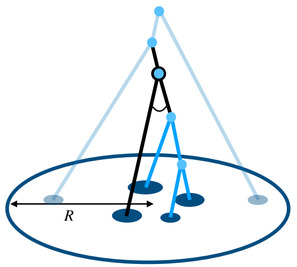
hydrodynamic evolution
medium response

hadronization
hadronic rescattering

Similar predictions for single observables

ALICE PRL 128 (10), 102001 (2022)





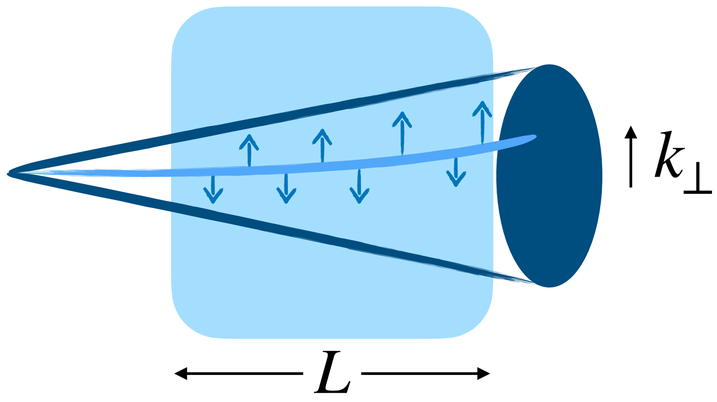
→ **Need multiple observables to constrain medium properties**

Bayesian estimation of $\hat{q}$

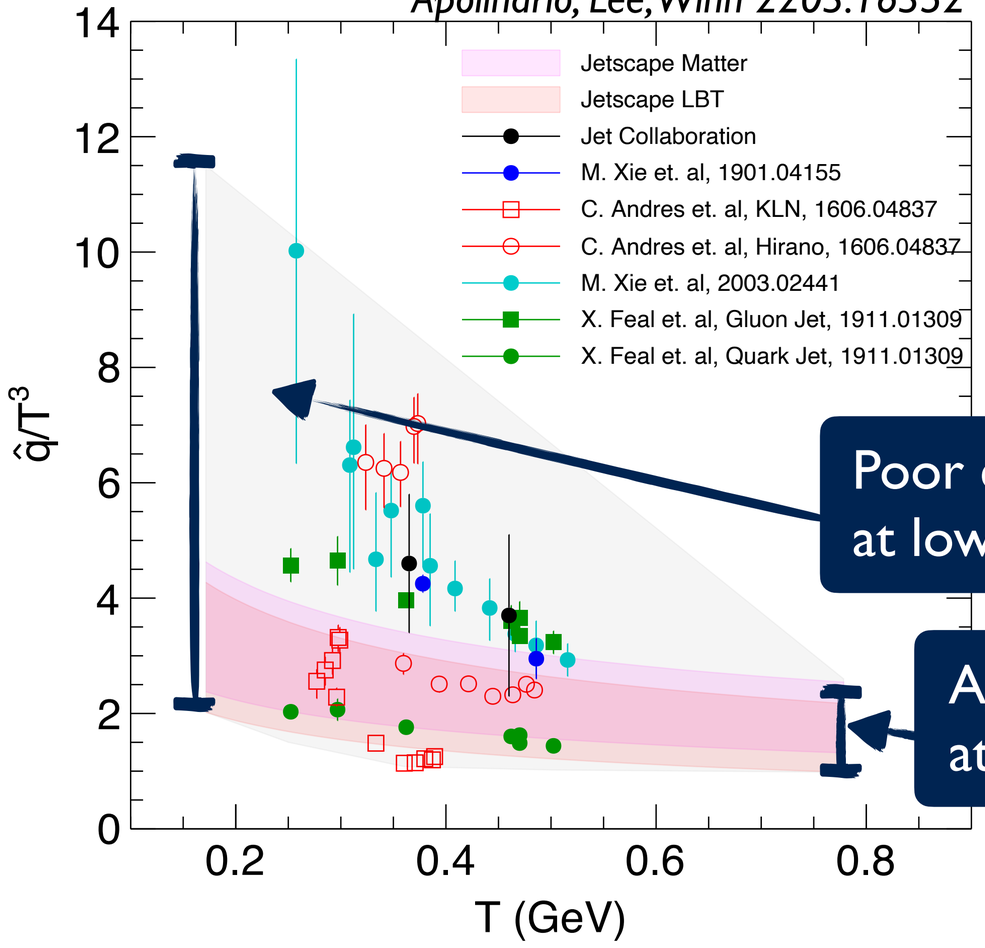
The jet transverse diffusion coefficient $\hat{q}$ encodes the microscopic structure of QGP partons

$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} = \frac{1}{L}\int dk_\perp^2 \frac{dP\left(k_\perp^2\right)}{dk_\perp^2}$$

where $P\left(k_\perp^2\right)$ is a scattering kernel.



Apolinario, Lee, Winn 2203.16352



Poor constraint at low-T

Agreement at large-T

What have we learned about the QGP?

We are developing a consistent phenomenology of UE-corrected, calculable jet observables in heavy-ion collisions

- *Perturbative modification*:
  - Large yield suppression — especially for jets with wide substructure
  - Indications of decreased suppression of quark jets
- *Non-perturbative modification*:
  - Indications of soft, diffuse broadening

We are starting to make connections to QGP properties

- Model-dependent constraints on $\hat{q}$ vs. T
- Model-dependent statements about resolution length: $0 < L_{res} < 2/\pi T$

Outlook — QCD colliders

See also: rich programs at Jefferson Lab, FAIR, …

Large Hadron Collider

CERN

ALICE

ATLAS EXPERIMENT

CMS

LHCb

pp, pA, AA

Run 3	Run 4	Run 5

2023 — 2028 — 2033 — 2038

pp, pA, AA

ep, eA

Relativistic Heavy Ion Collider

Brookhaven National Laboratory

STAR

sPHENIX

Electron-Ion Collider

ePIC

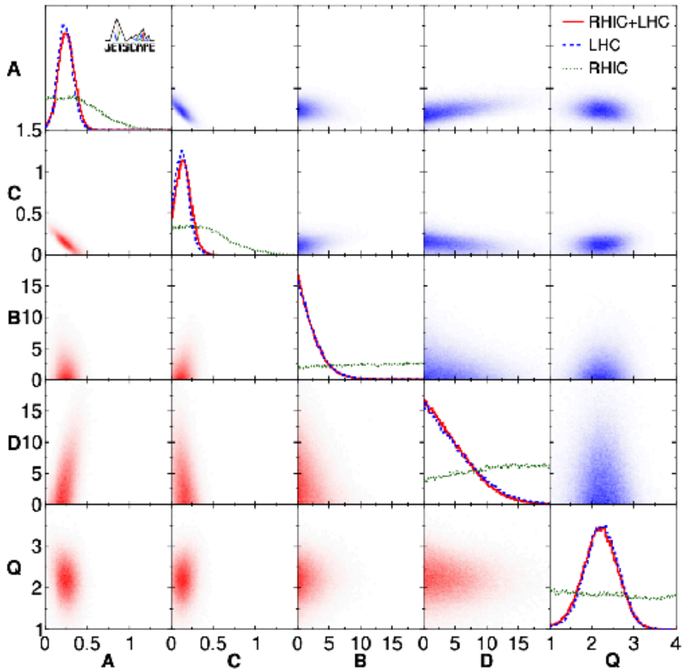
Experimental guidance from Bayesian inference

Long-term planning

Example:
Restrict to either RHIC or LHC data

Fit dominated by LHC data

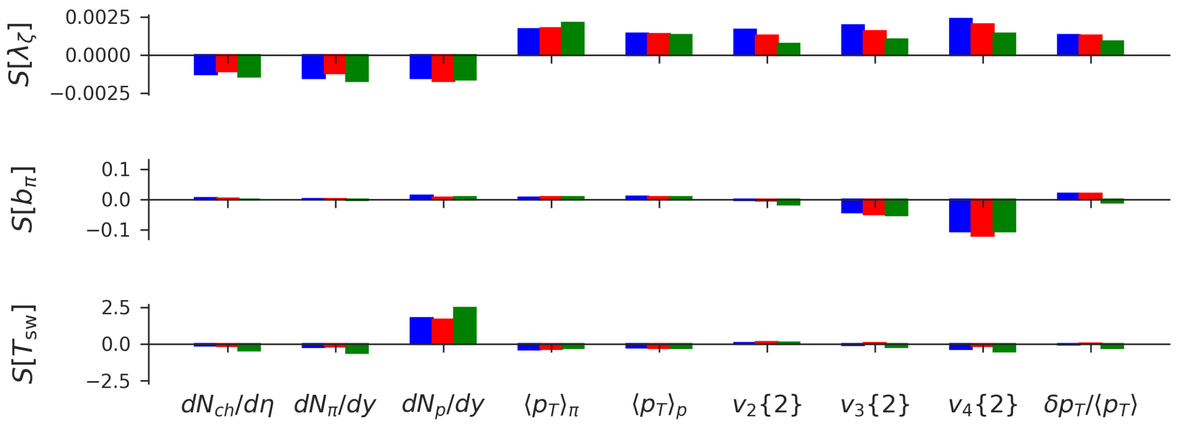
JETSCAPE *PRC 104, 024905 (2021)*



Parameter sensitivity

Quantify impact of a model parameter on measured observables

JETSCAPE *PRC 103, 054904 (2021)*



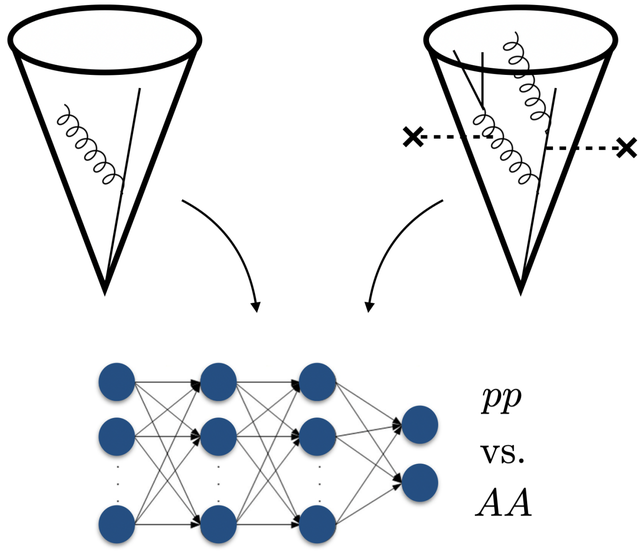
See also:
Lai arXiv 1810.00835
Sangaline, Pratt PRC 93, 024908 (2016)

Model-dependent guidance on where to focus experimental effort

Experimental guidance from ML

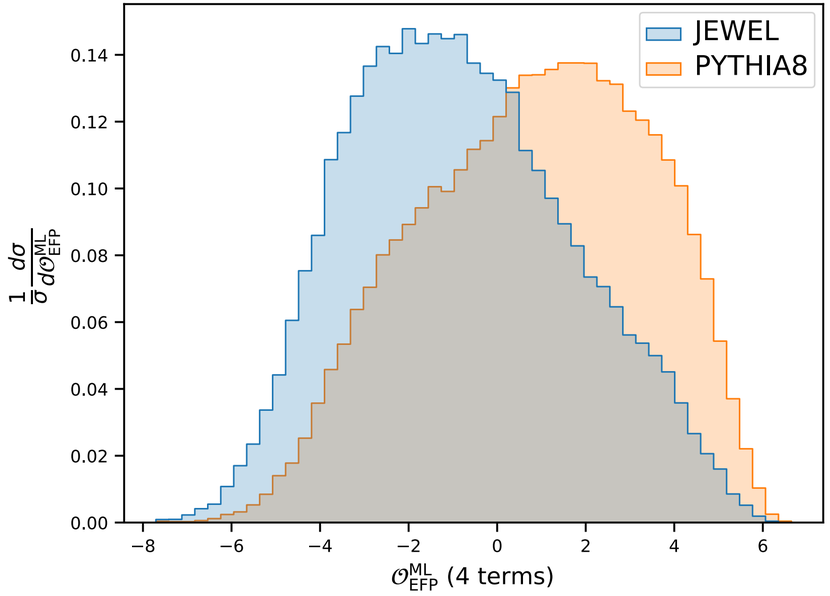
Lai, Mulligan, Płoskoń, Ringer JHEP 10, 011 (2022)

Design the **most strongly modified observable** that is **theoretically calculable**



$$\max_{\theta} \left| \frac{d\sigma_{AA}}{d\sigma_{pp}}(\theta) - 1 \right|$$

Symbolic regression

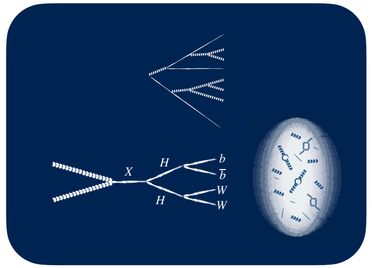


First step in a new paradigm: data-driven design of complete set of calculable observables

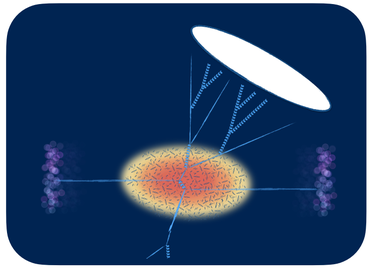
Complementary to Bayesian approach

Summary

There is a rich program using jets to study confinement in both pp and heavy-ion collisions — synergy with HEP community



Jet measurements are beginning to reveal properties of the quark-gluon plasma, from transport coefficient $\hat{q}$ to resolution length L_{res}



We have vast freedom in what we choose to measure at QCD colliders — new ideas will allow us to fully exploit the data

- Systematic guidance to the experimental program