# Jets: What have we learned and where are we going

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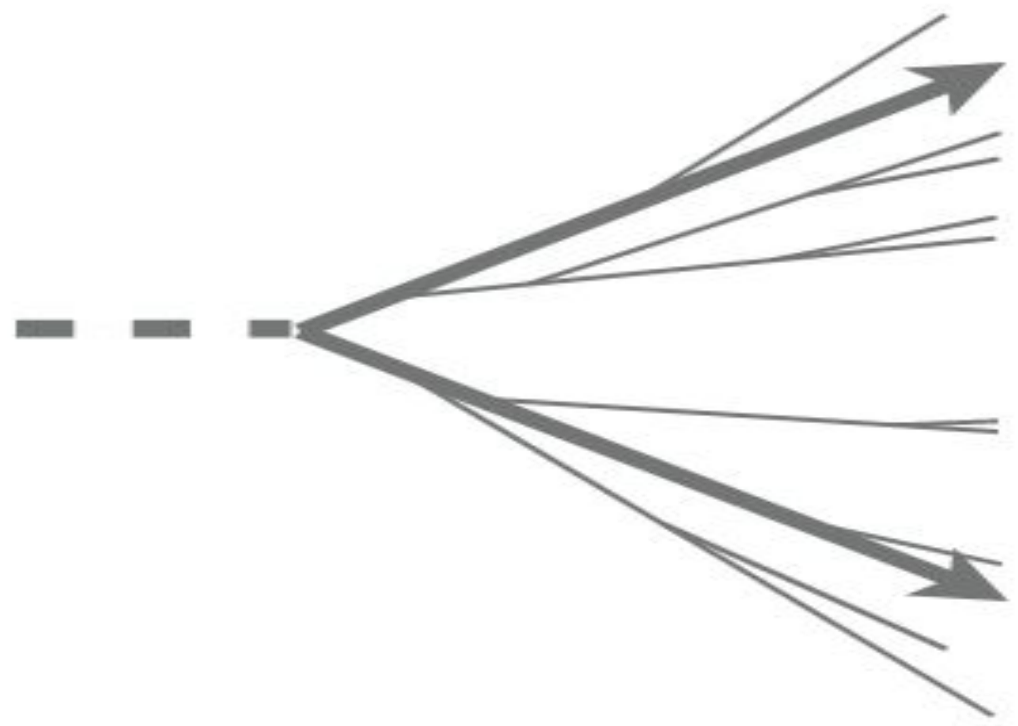
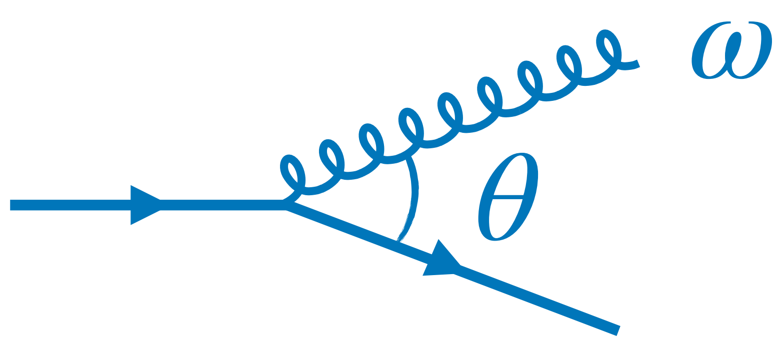
ALICE-USA Meeting
University of Kansas
May 26, 2022

# Jets

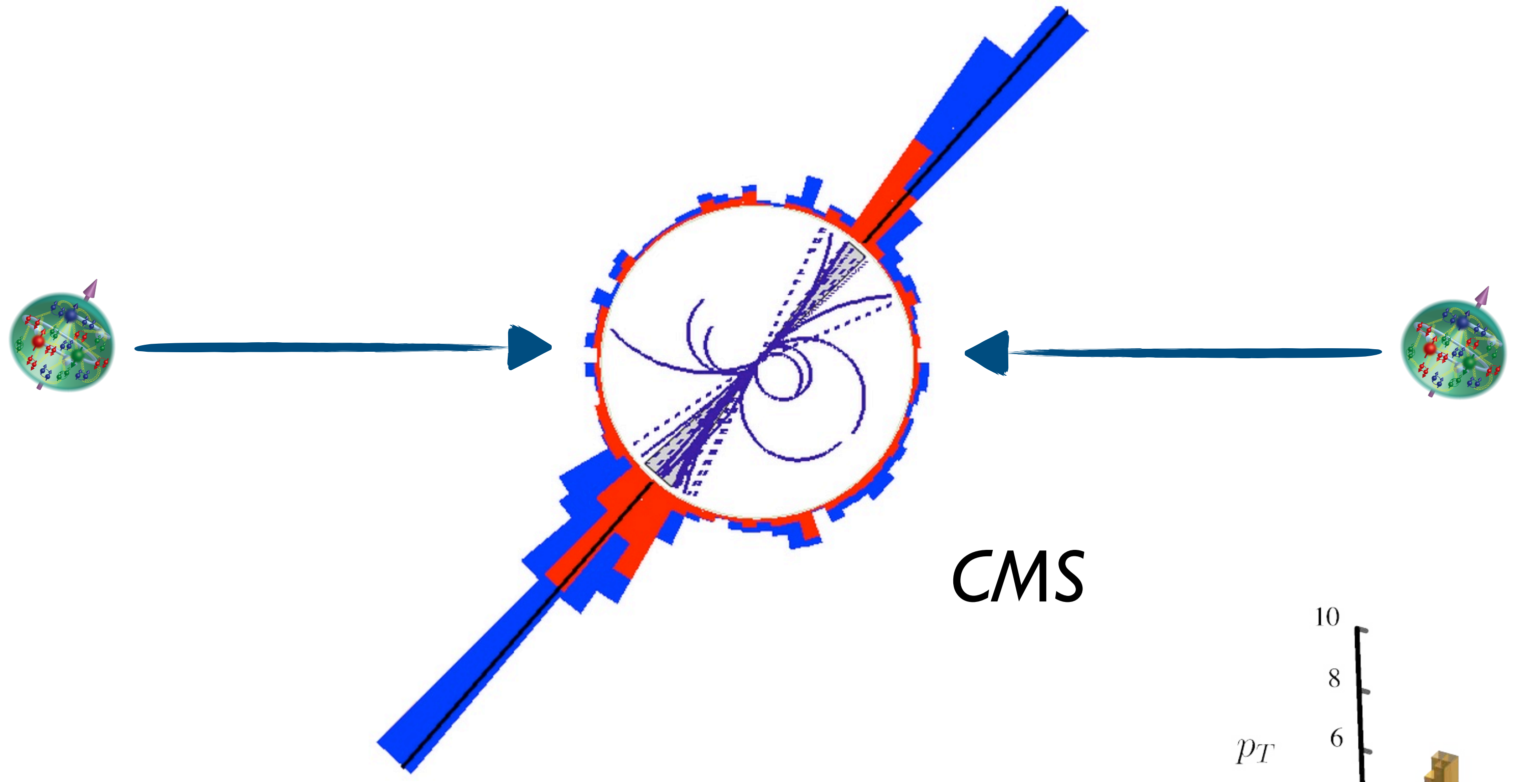
Collimated shower of particles arising from the iterative fragmentation of a **high energy quark or gluon**

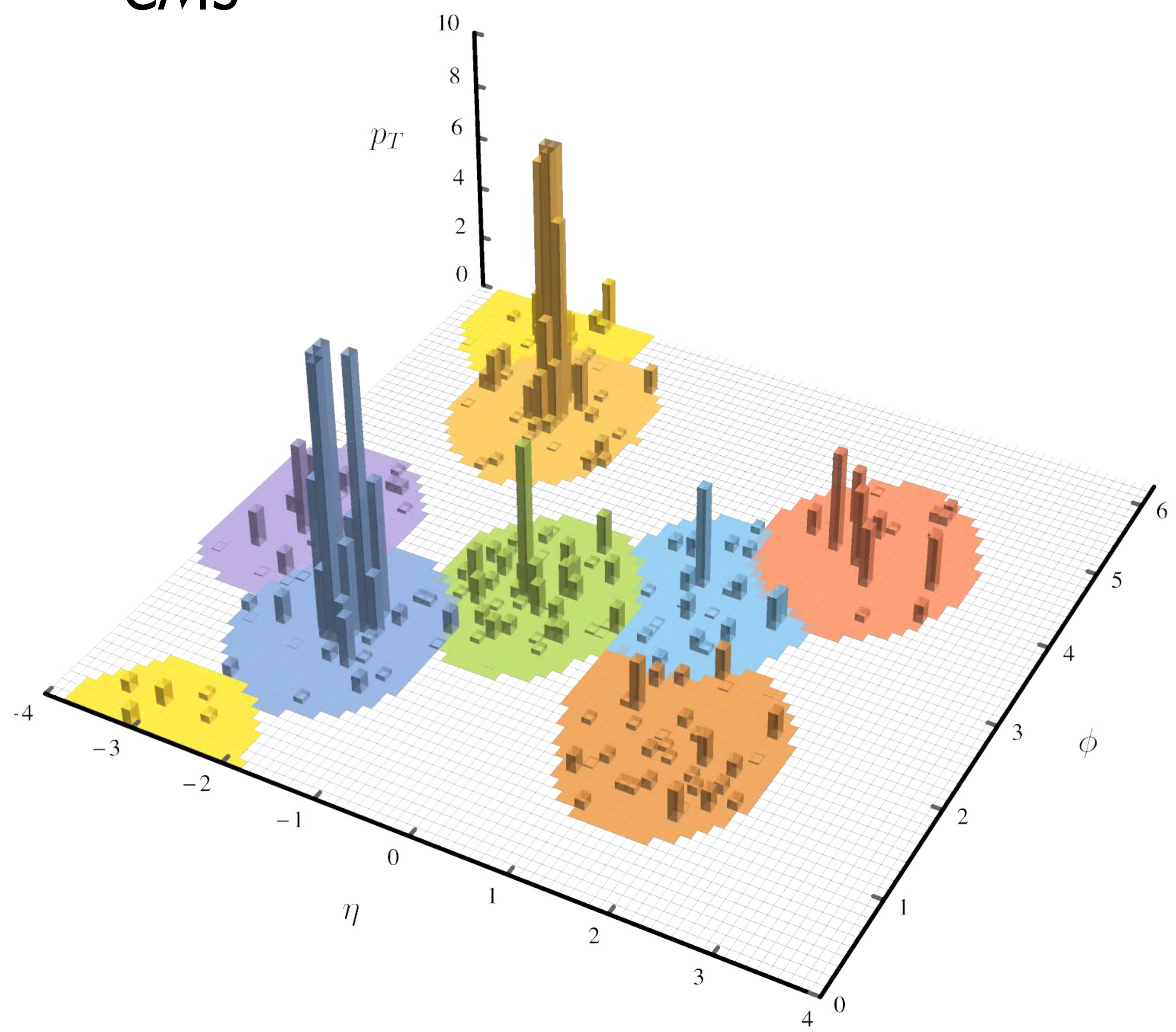


$$dP \sim \alpha_s C_R \frac{d\theta}{\theta} \frac{d\omega}{\omega}$$




Jets are produced abundantly in colliders

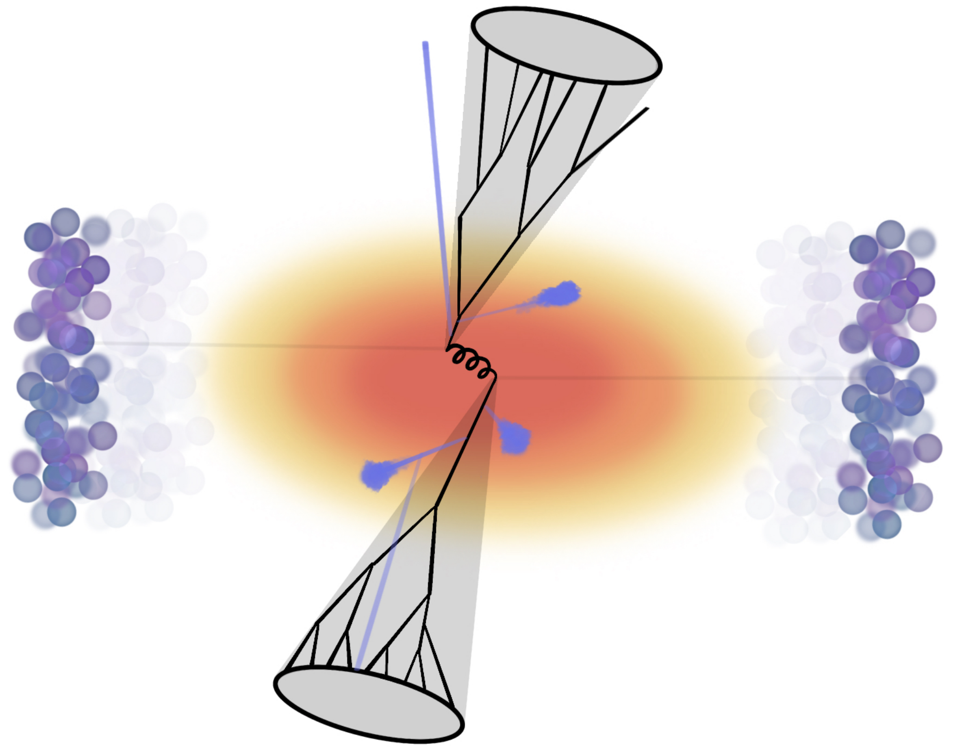


# Jet quenching in the quark-gluon plasma

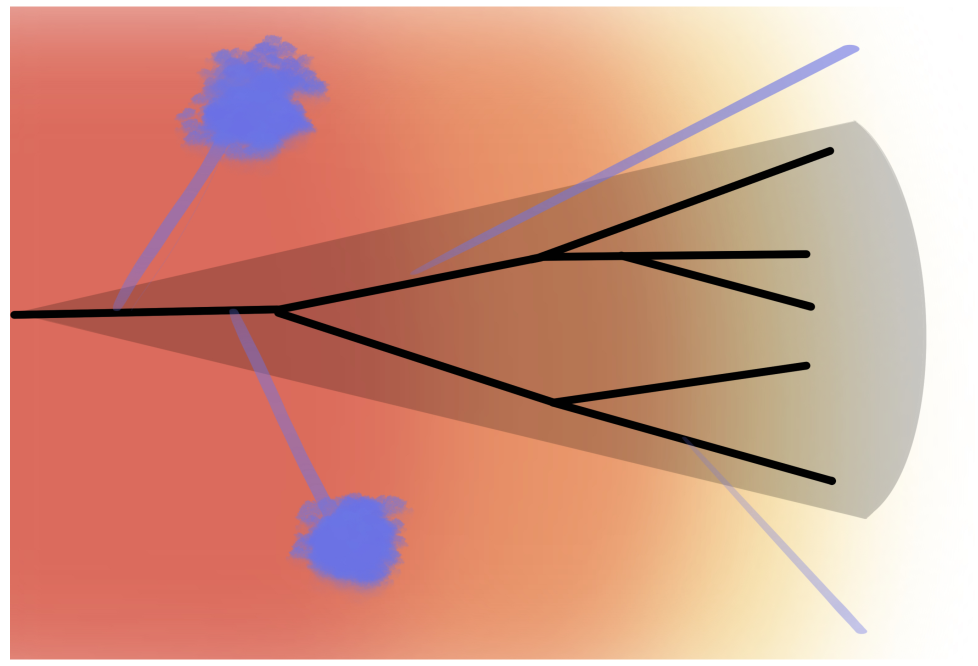
The QGP is too small and short-lived to be probed by traditional scattering beams

→ Use jets as probes

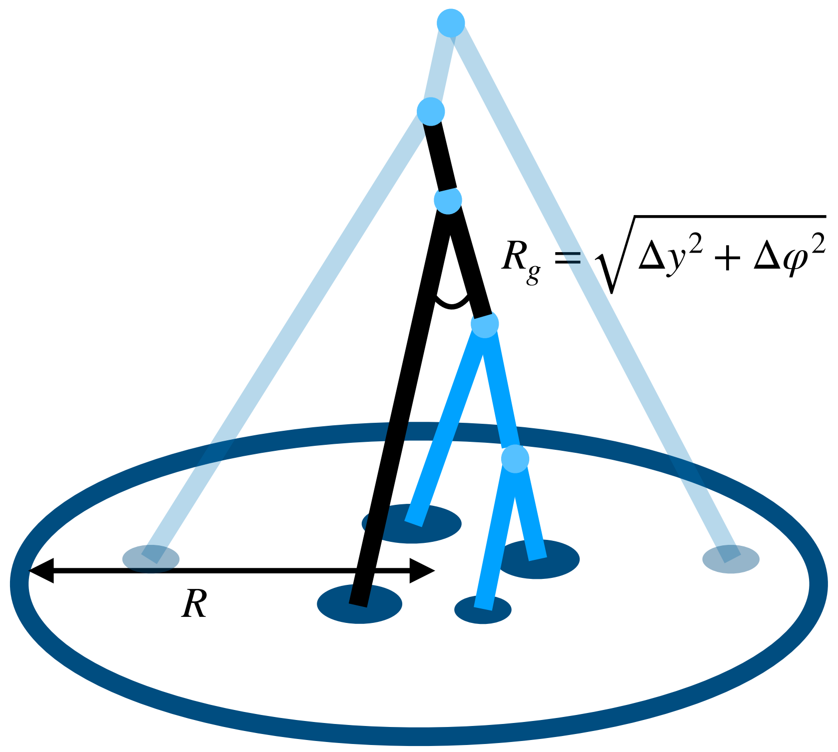


Jets interact with the quark-gluon plasma as they traverse it:

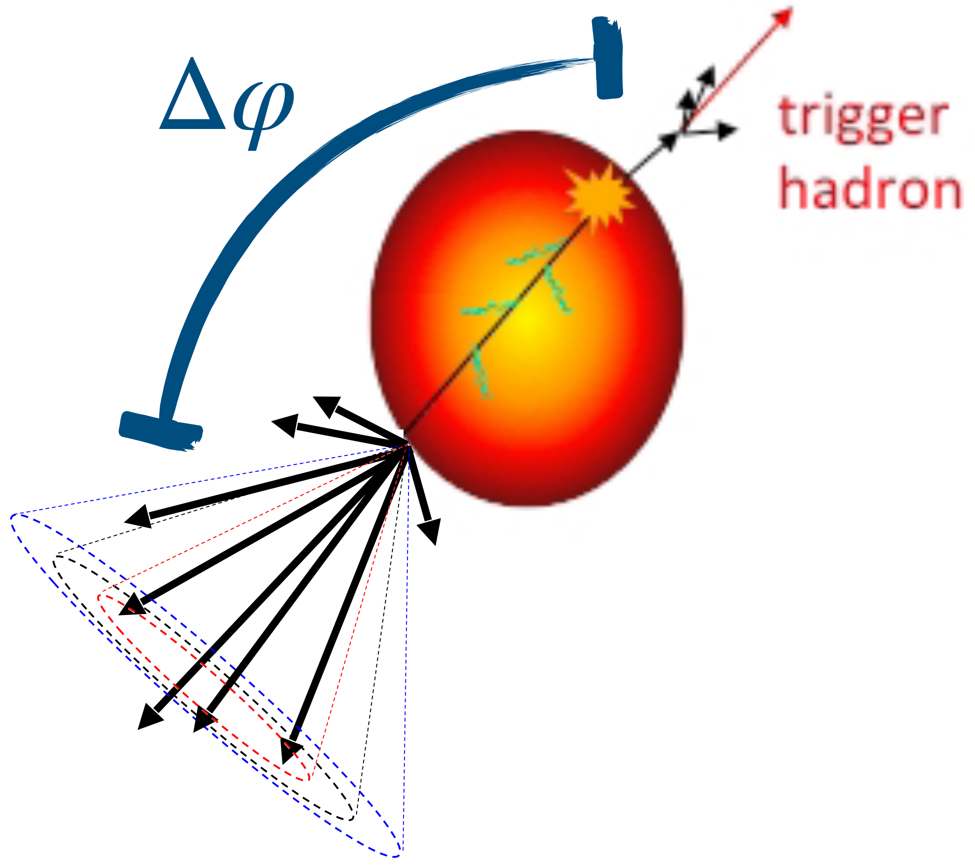
**Energy loss**



**Substructure modification**

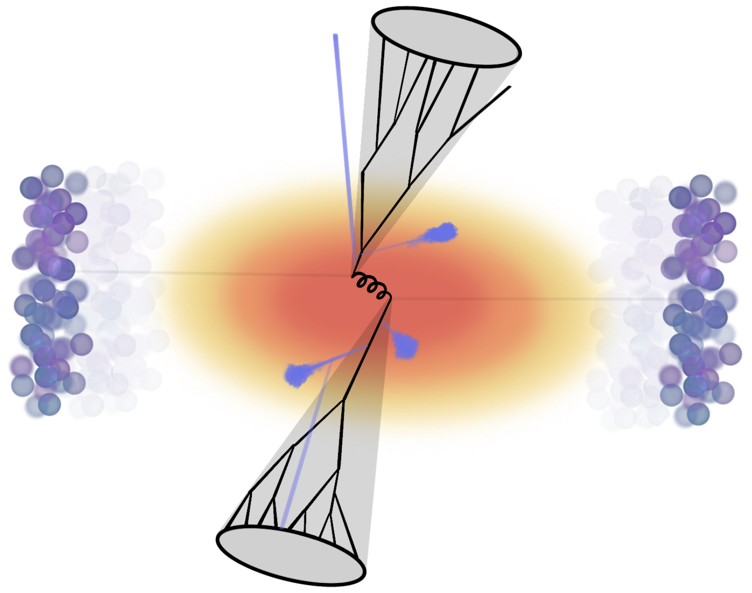



**Deflection**



# Two directions

Jets as probes of the QGP



QGPs as probes of the jet

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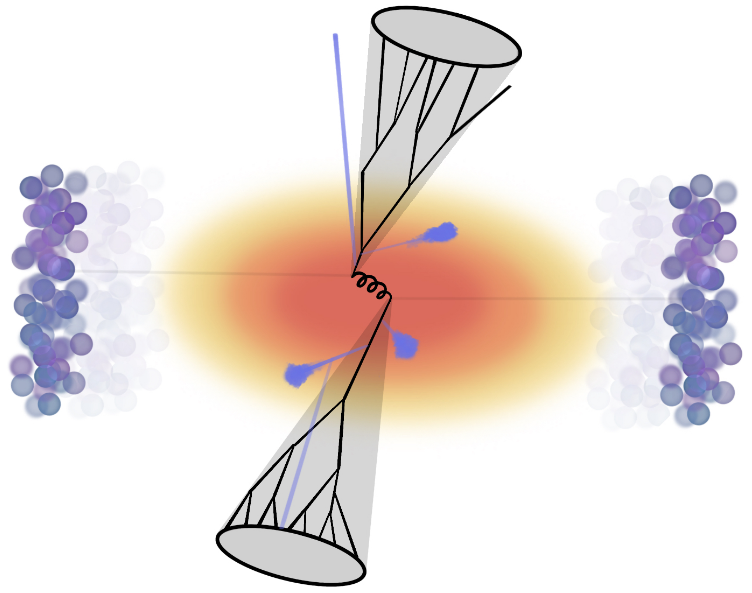
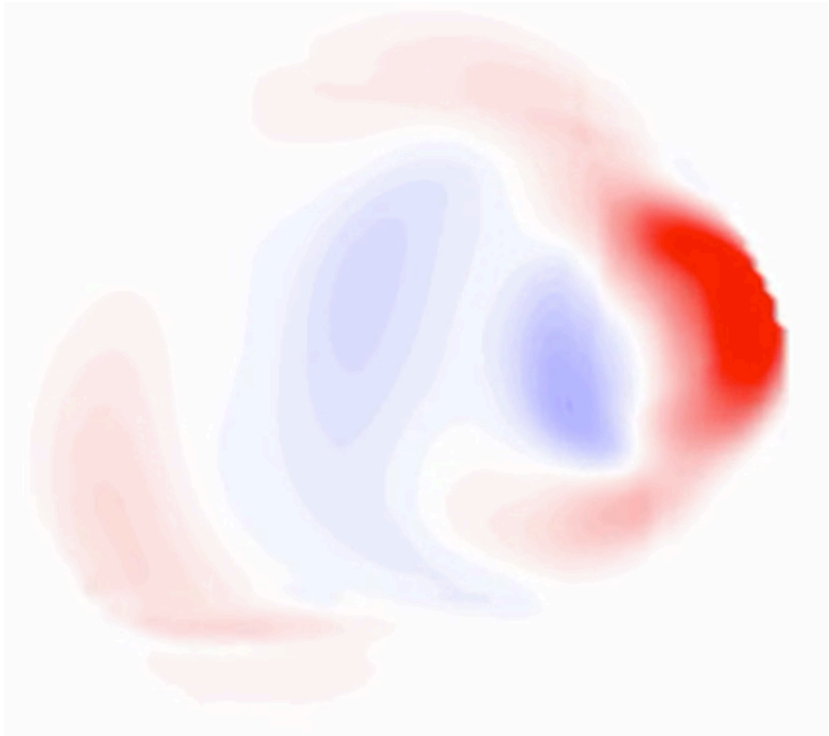
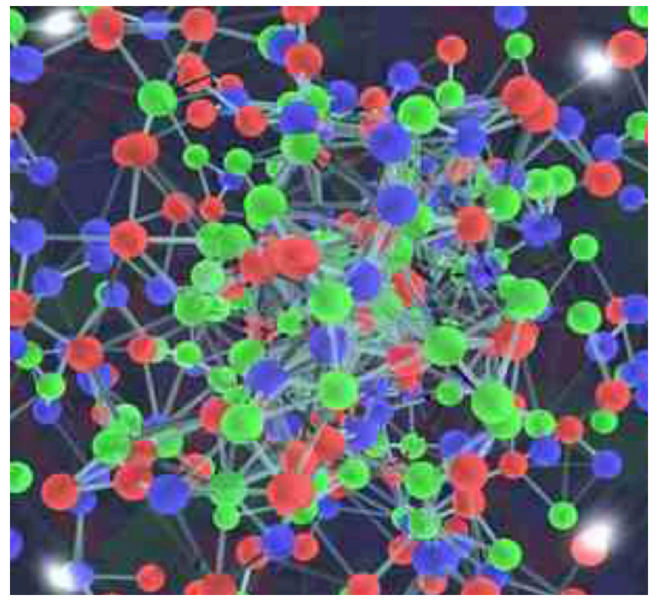


Jets as probes of the QGP

QGPs as probes of the jet

Goal: understand the properties of the QGP as a function of resolution scale





Model jet-medium interactions in order to:

- Extract transport coefficients
- Deduce microscopic structure

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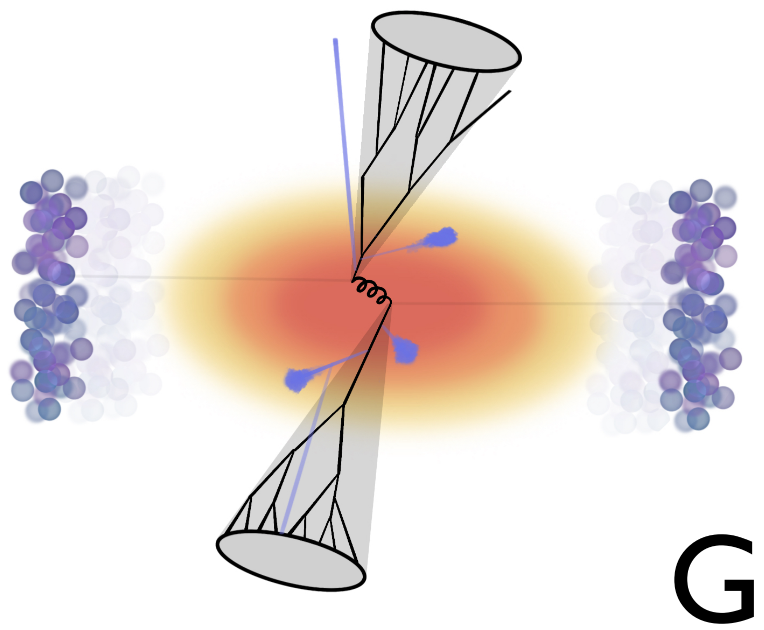
Jets as probes of the QGP



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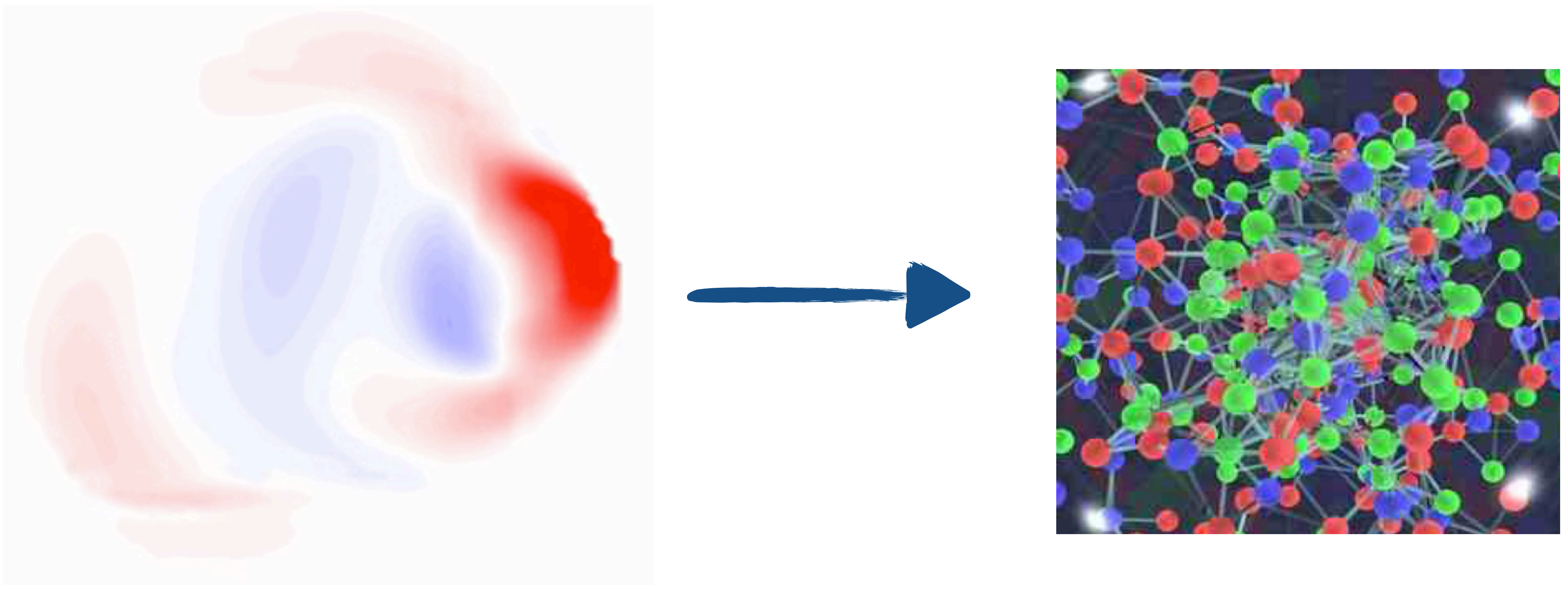

Model jet-medium interactions in order to:

- Extract transport coefficients
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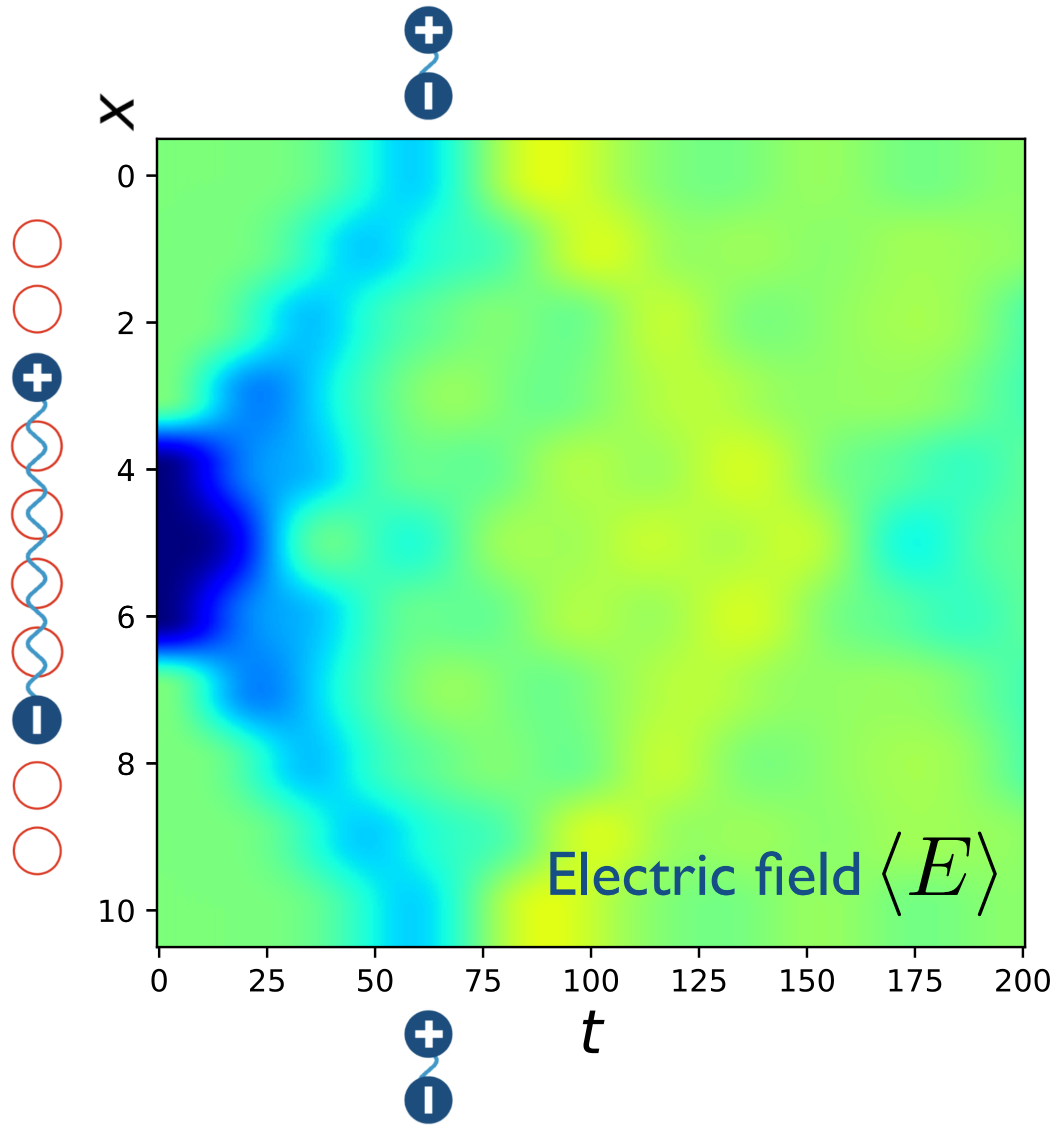
Goal: reveal real-time dynamics of fragmentation and hadronization process

- Does jet fragment at 1fm or 10fm?

Jet quenching is the *unique* experimental probe to study this

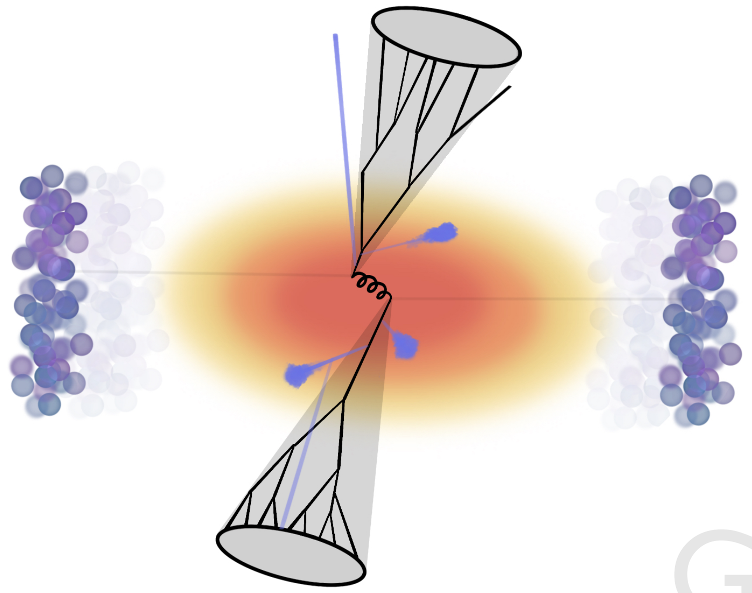
Compare to simulation of QCD on quantum computers




*Jong, Lee, Mulligan, Płoskon, Ringer, Yao*
*In preparation, PRD 104 (2021) 5, 051501*

# Two directions

## Jets as probes of the QGP



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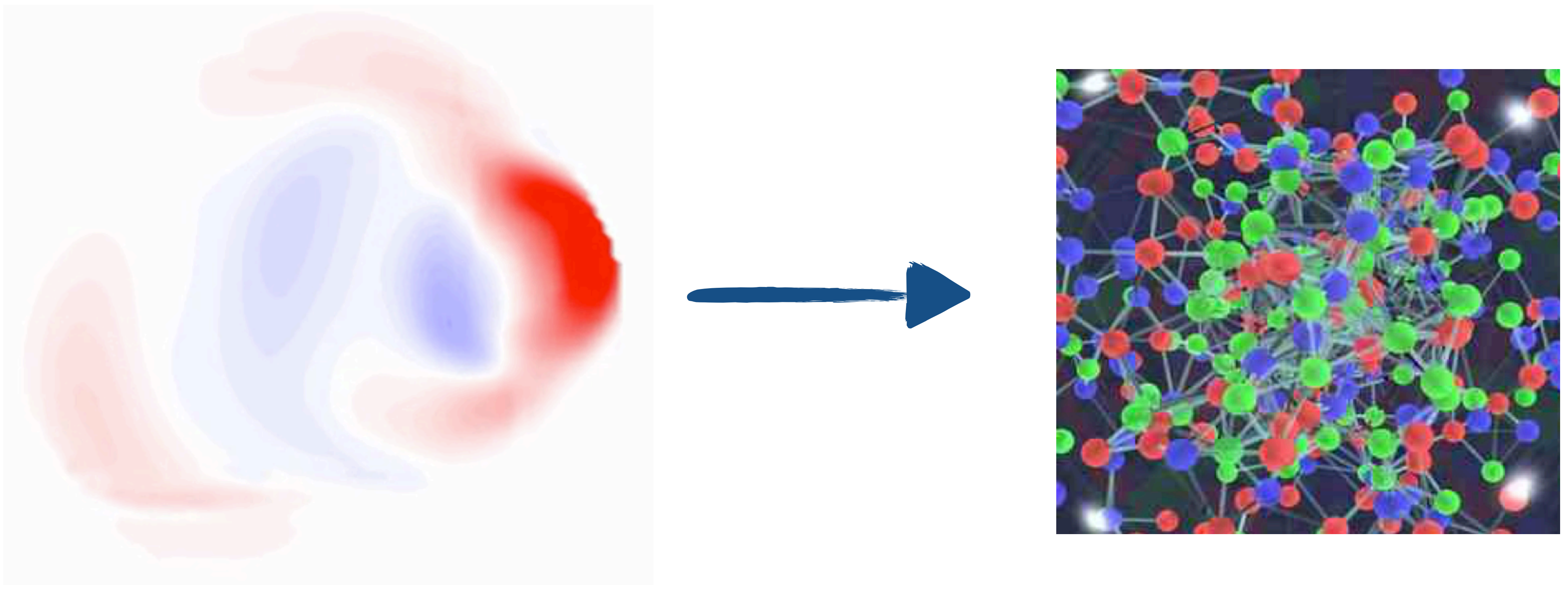

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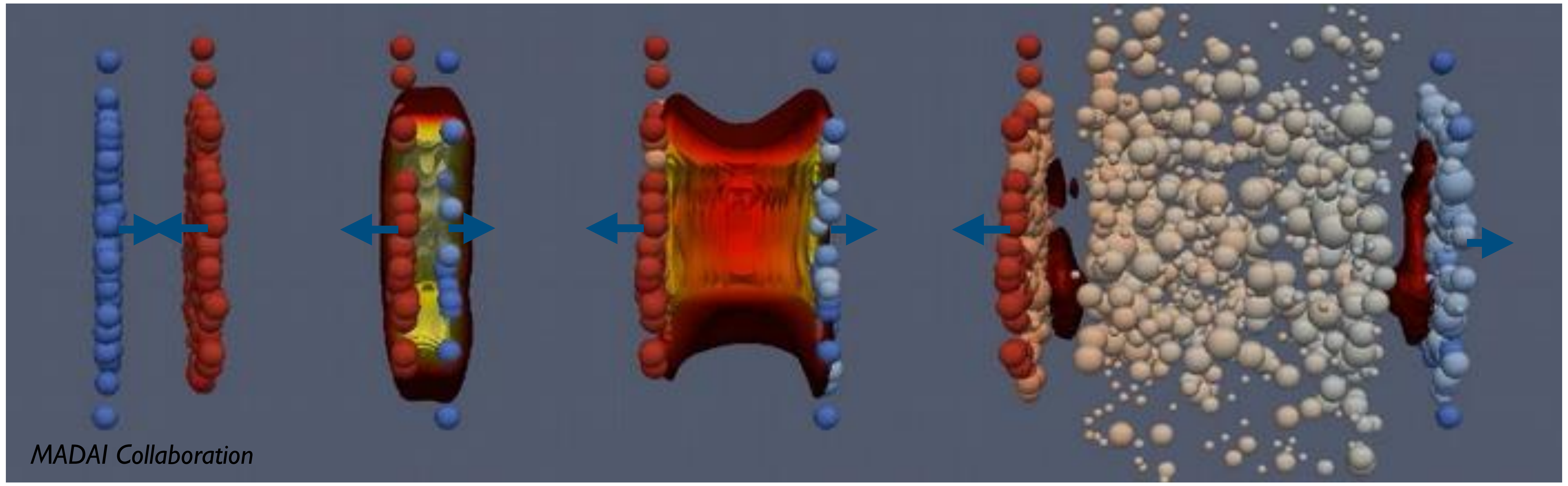
# Challenge #1

**Jet evolution involves physics that is not known from first principles: initial state, hydrodynamic evolution, medium response, hadronic rescattering, hadronization**



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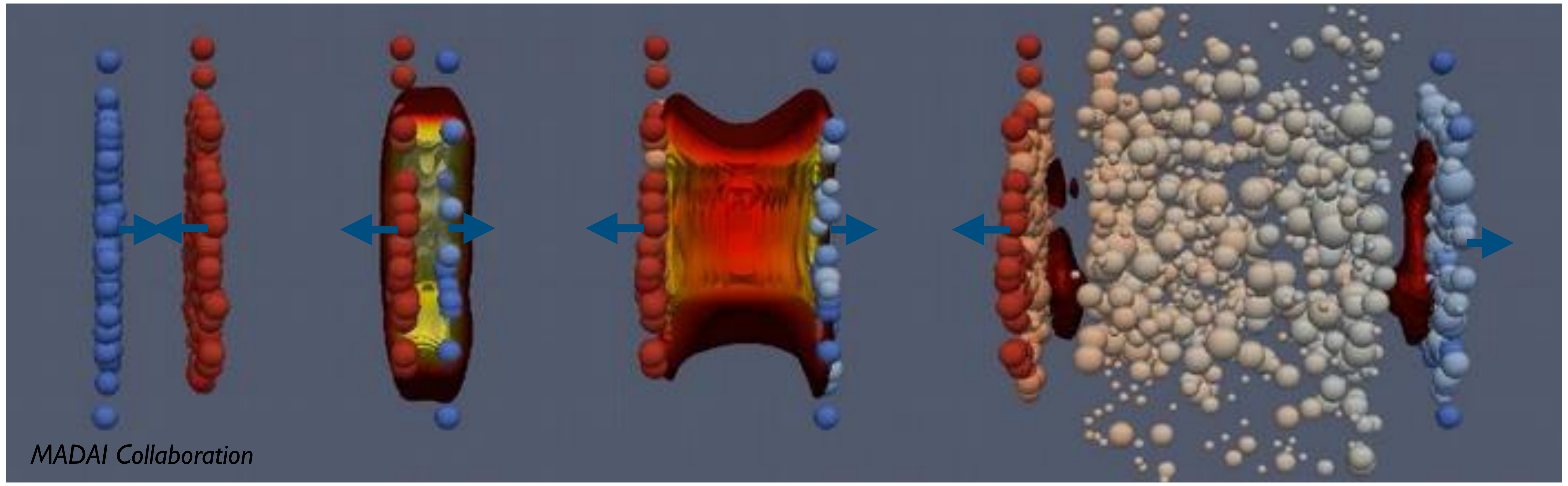
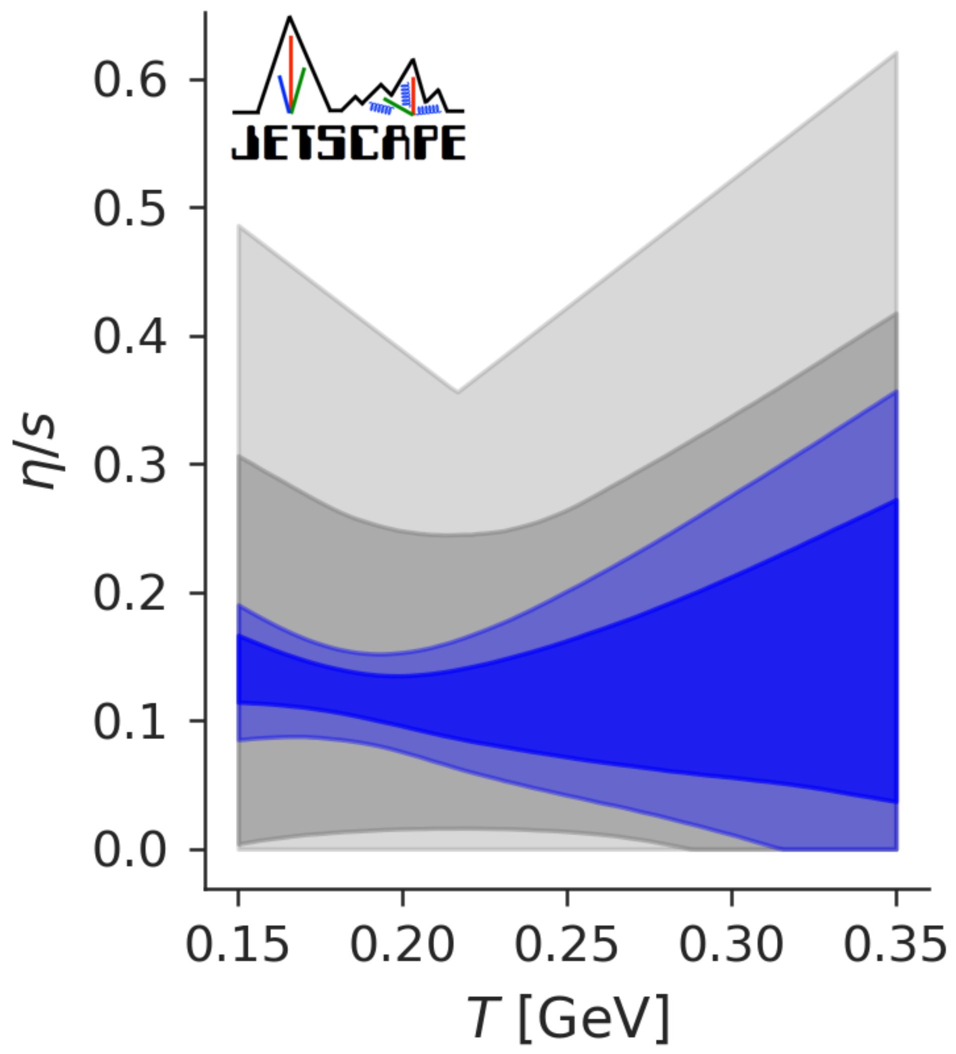



JETSCAPE PRL 126, 242301 (2021)



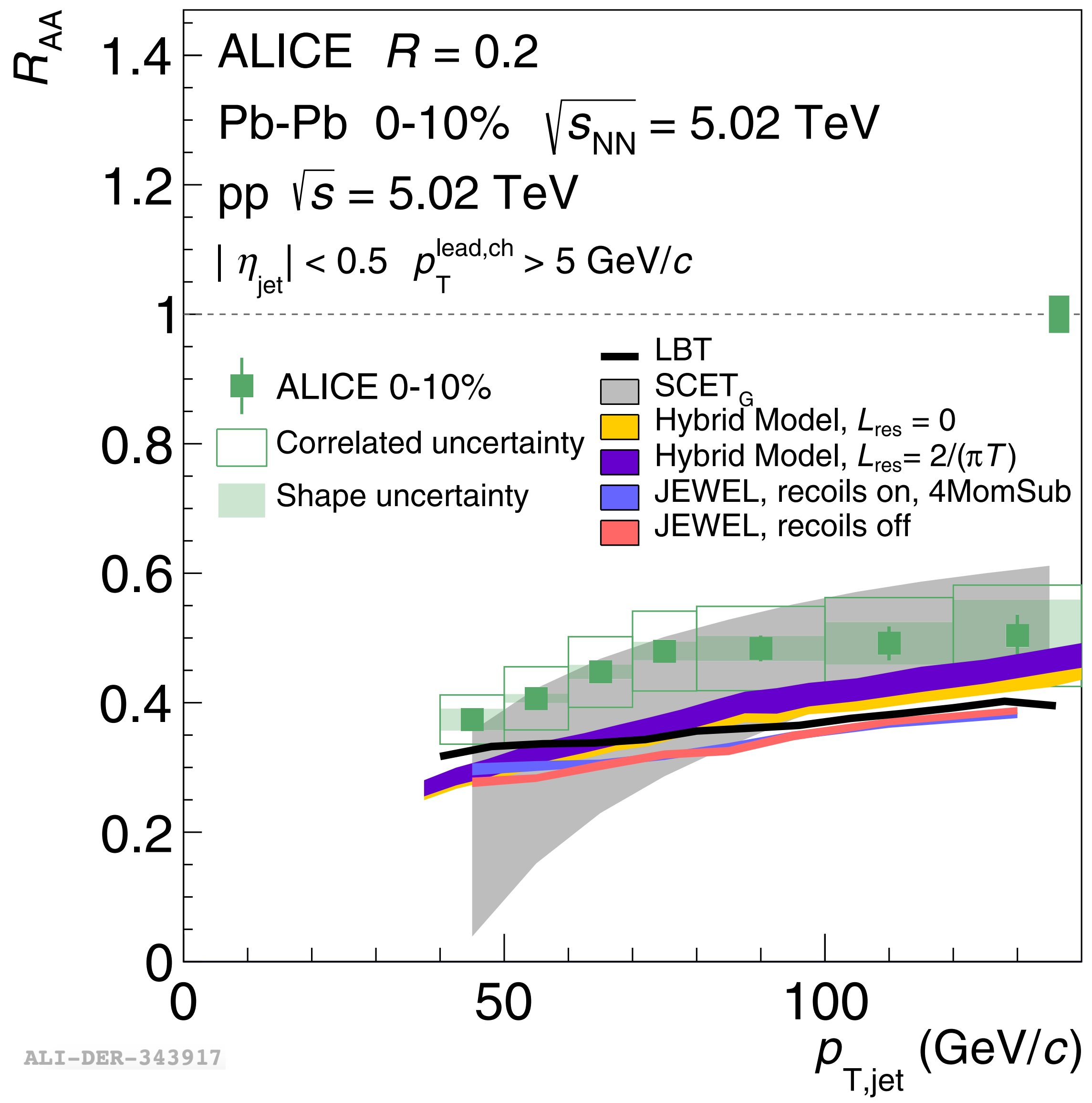

**Global analysis is needed to fit models of the physics that are not known from first-principles**

# Challenge #2

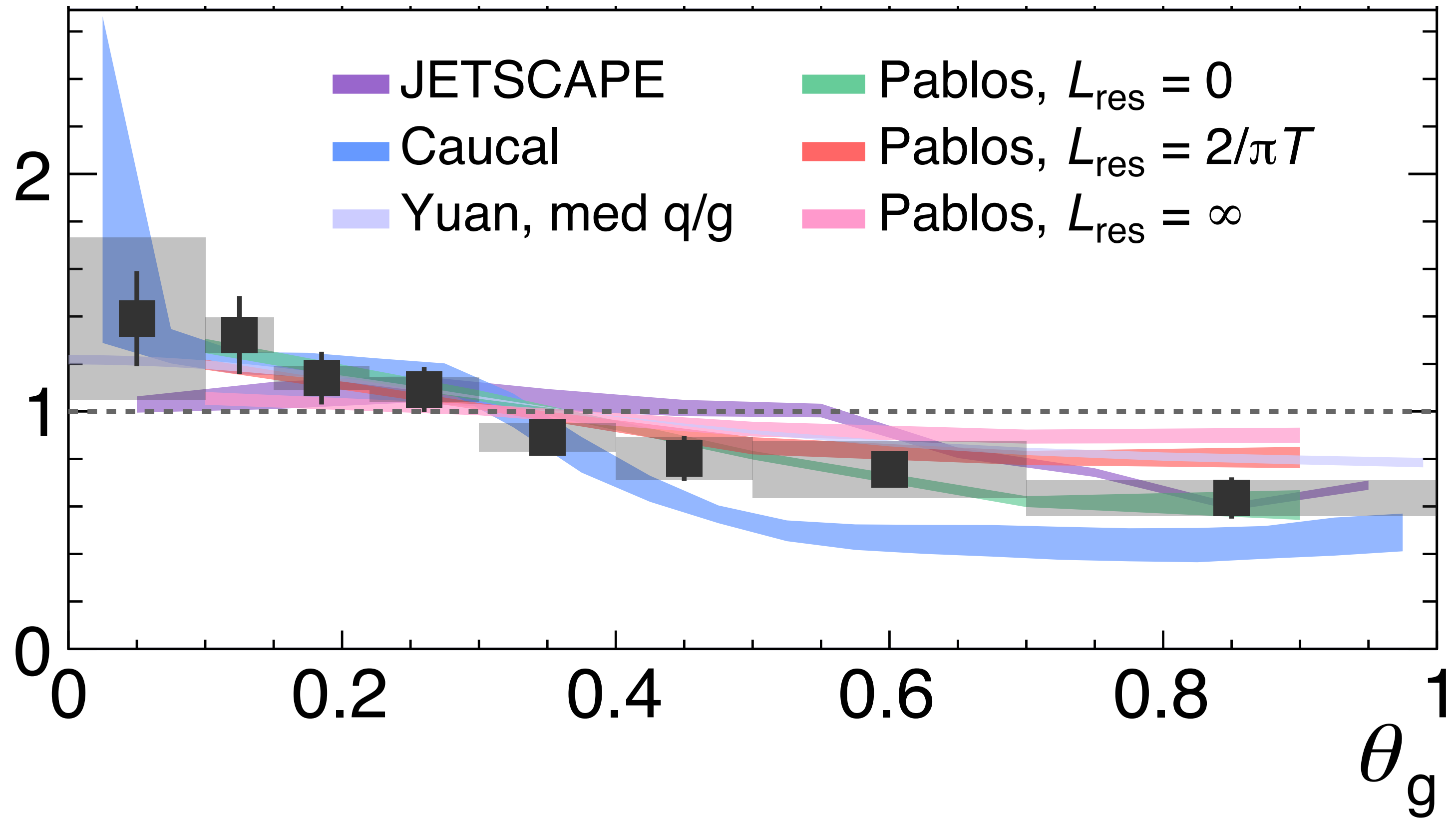
**Jet evolution itself is complicated, and there is no (known) golden observable**

Models with different physics predict similar values for many observables

*PRC 101 034911 (2020)*




*PRL 128 (2022) 10, 102001*



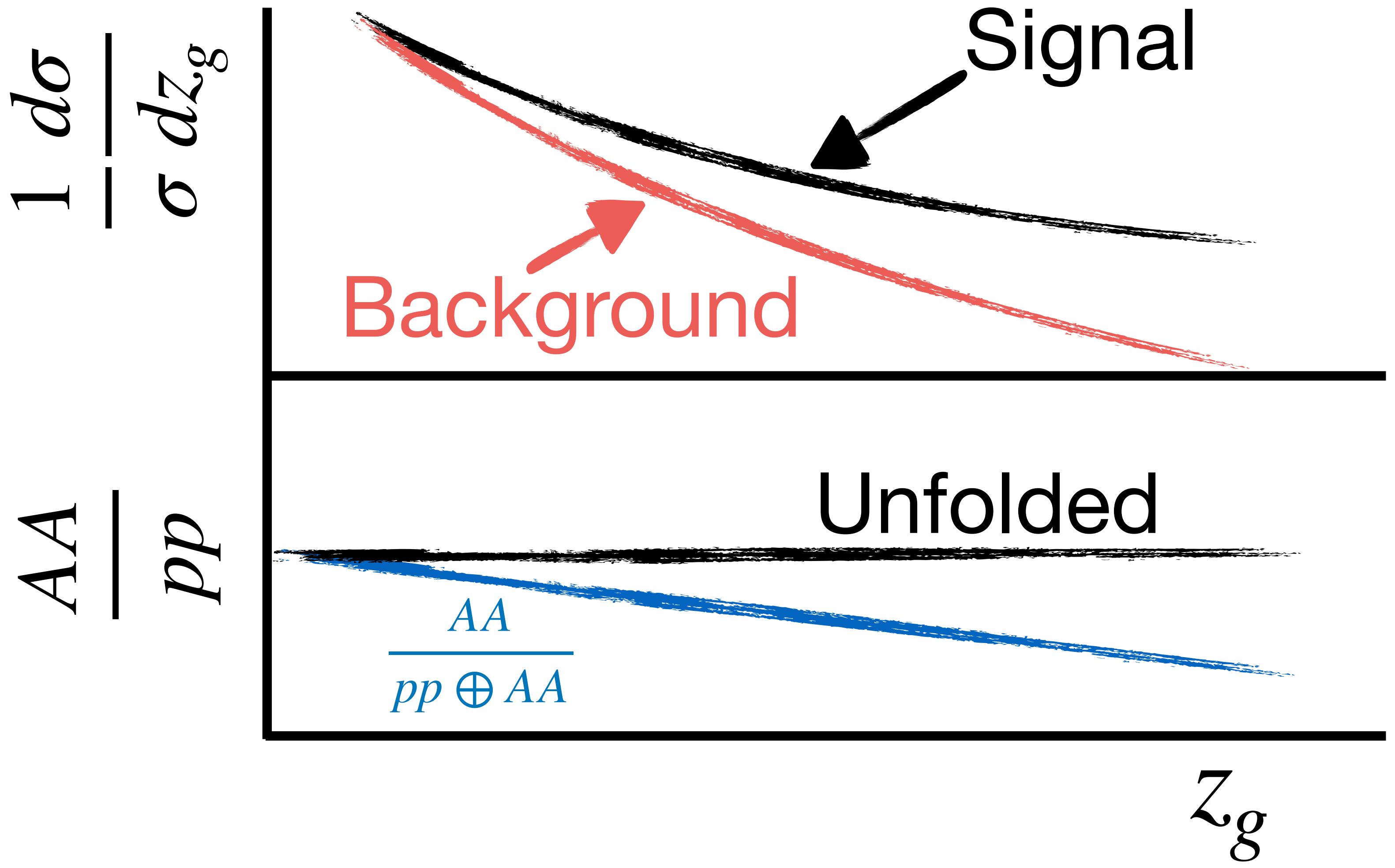

**Need global analysis of multiple jet observables to distinguish theoretical approaches**

# Three criteria for jet measurements

**(I) Measurable**

The observable must be corrected for background

- Not AA vs. pp ⊕ AA!



# Three criteria for jet measurements

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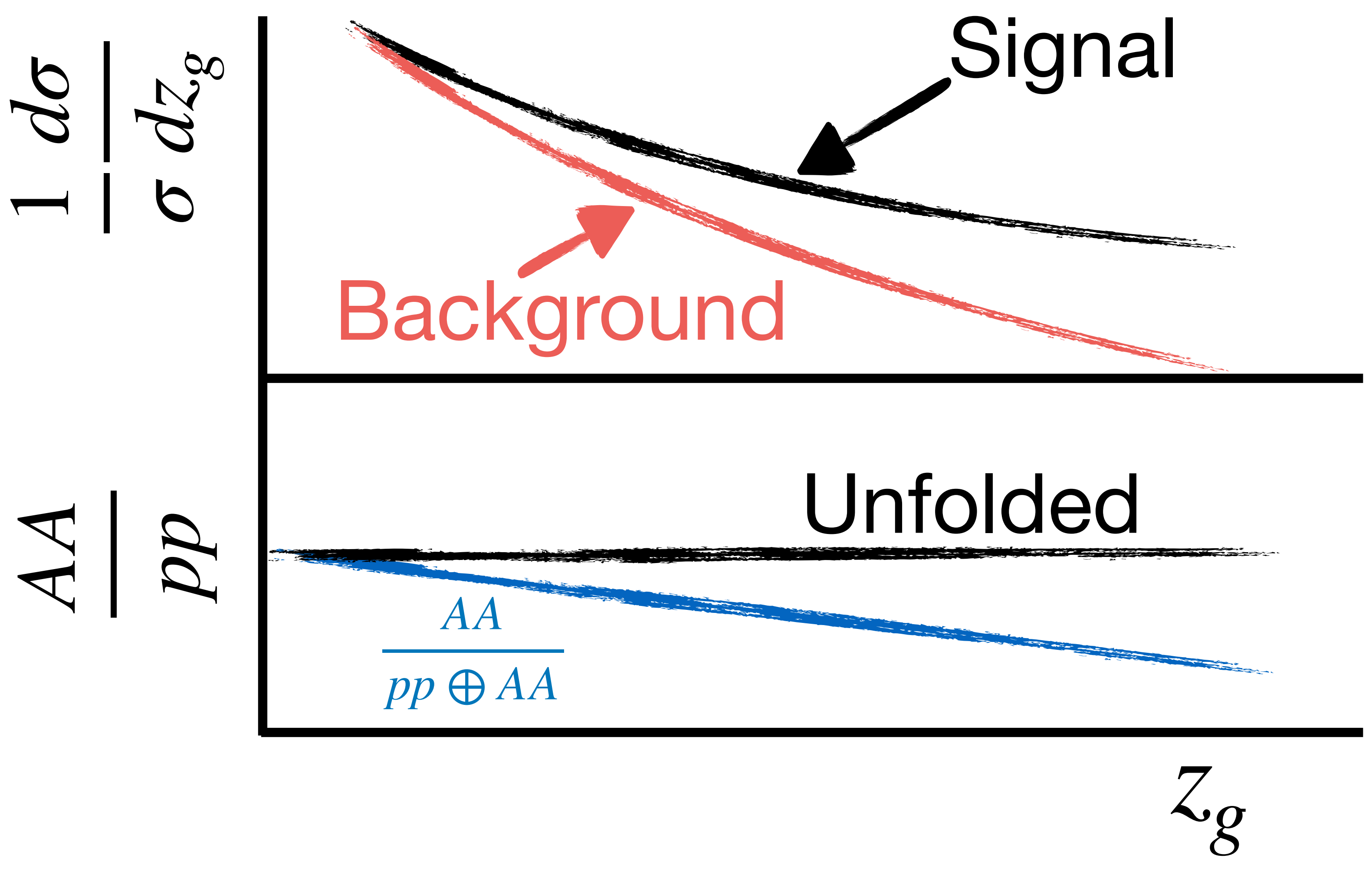


## (2) Calculable

Agreement of pp baseline with pQCD must be understood

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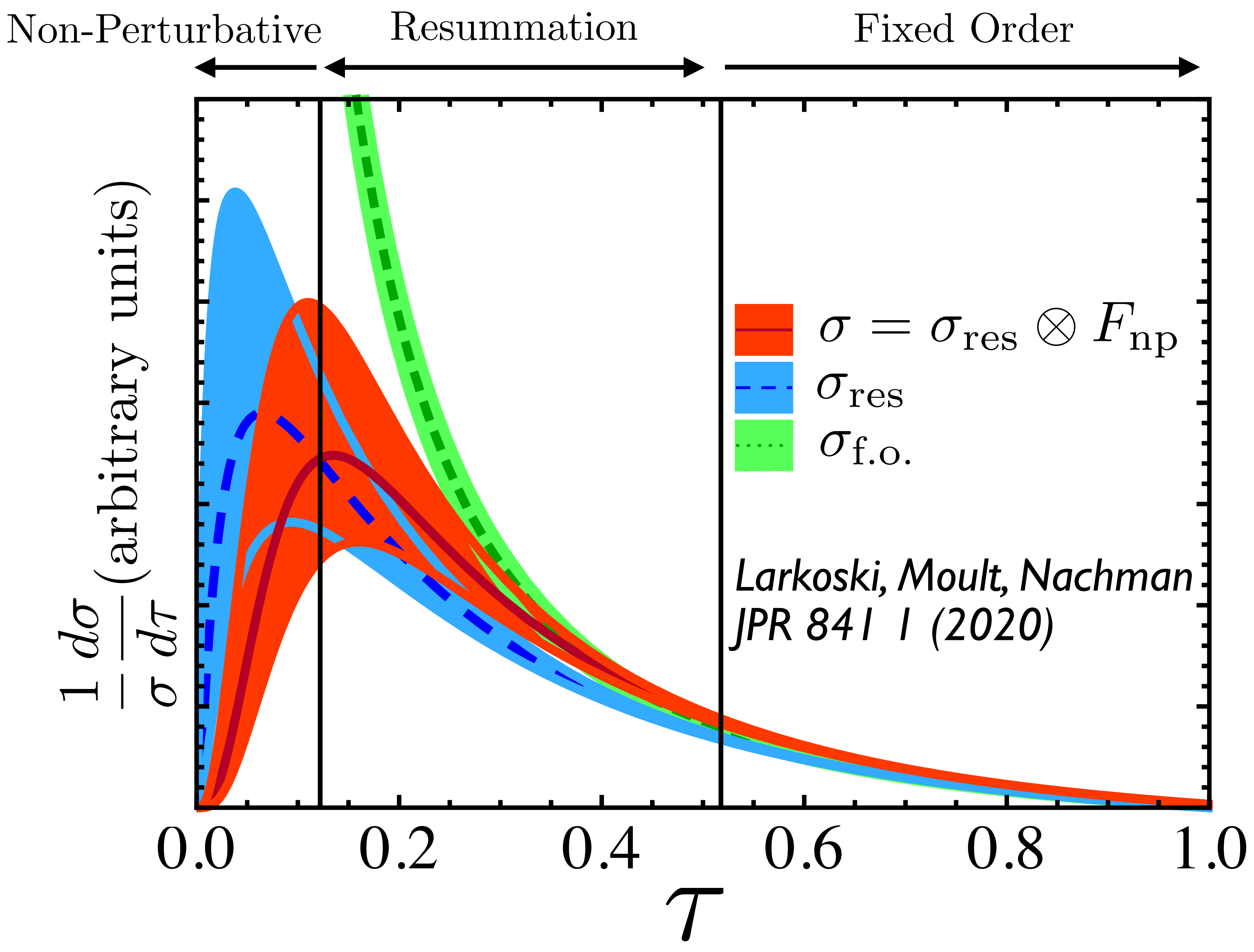

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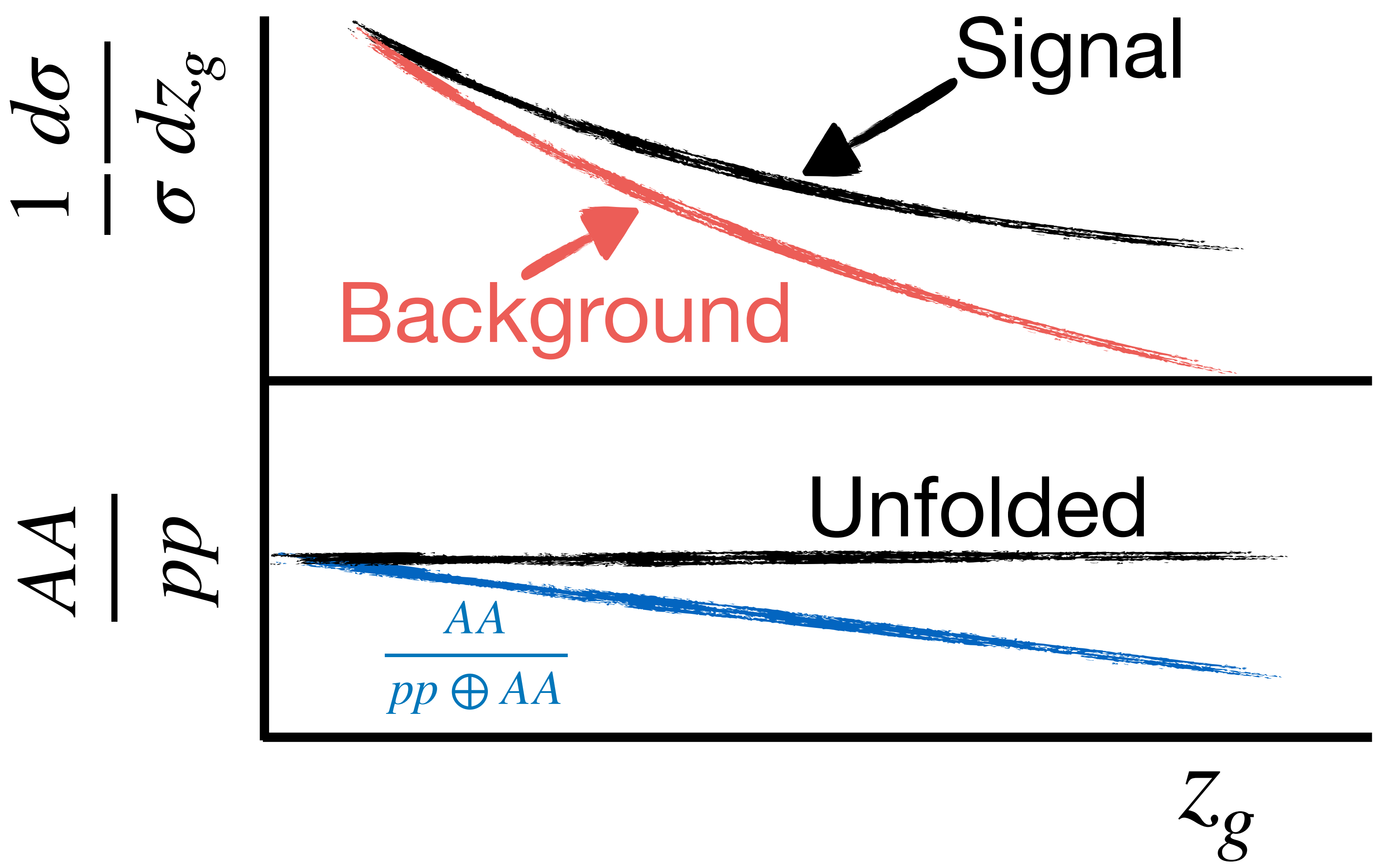


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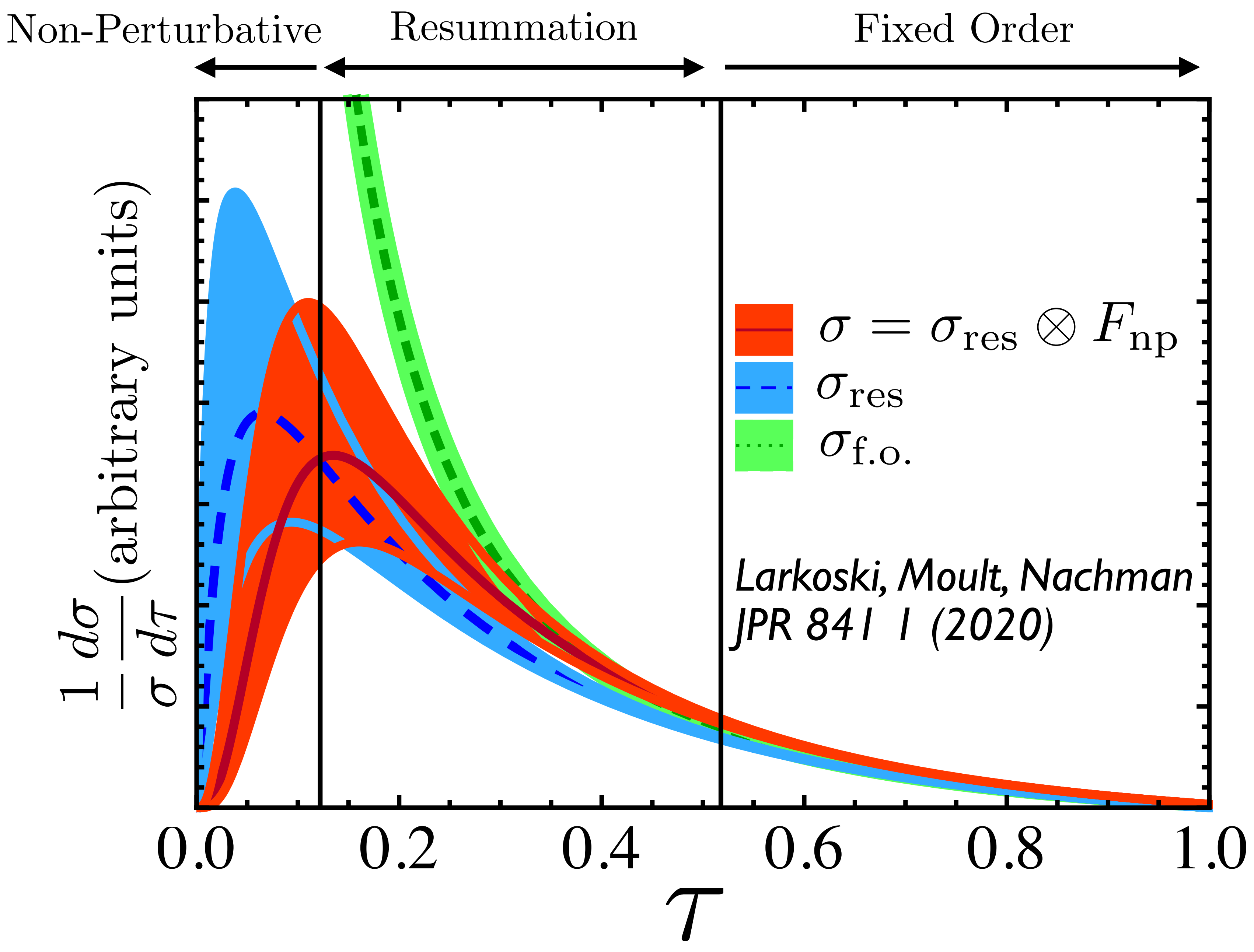



## (3) Informative

Targeted physics motivation

- Quenching effects
- Factorization
- Spacetime evolution
- Nonperturbative effects
- …

Room for creativity!

# What have we learned?

# Wish list from 2019 ALICE-USA

https://indico.cern.ch/event/758653/contributions/3344286/attachments/1813057/2962097/ALICE-USA_Jets.pdf

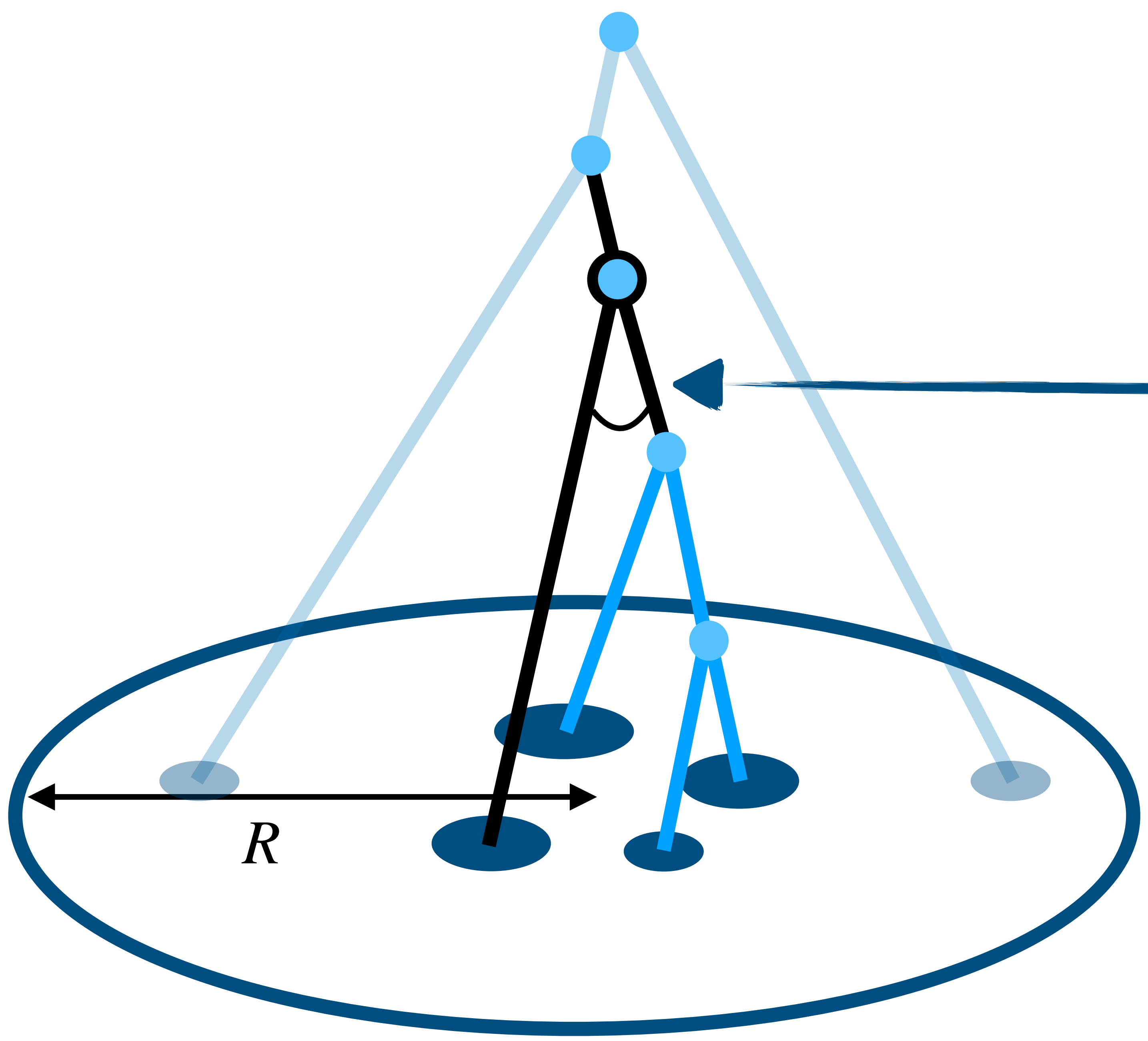
| | | | |
|---|---|---|---|
| 1 | **Jet mass at different *R*** | ✓… | In progress |
| 2 | **Generalized angularities** | ✓ | QM2022, *JHEP* 05 (2022) 061 |
| 3 | **Heavy flavor jets at low-$p_T$** | ✓ | QM2022 |
| 4 | **Higher-precision jet acoplanarity** | ✓ | QM2022 |
| 5 | **Next-generation Jet $R_{AA}$** | ✓ | See Hannah's talk |
| 6 | **Unfolded $z_g$** | ✓ | *PRL* 128 (2022) 10, 102001 |

**Mostly led by ALICE-USA!**

And more: see talks of Caitie, Rey, …

# Example 1: Groomed jet substructure

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

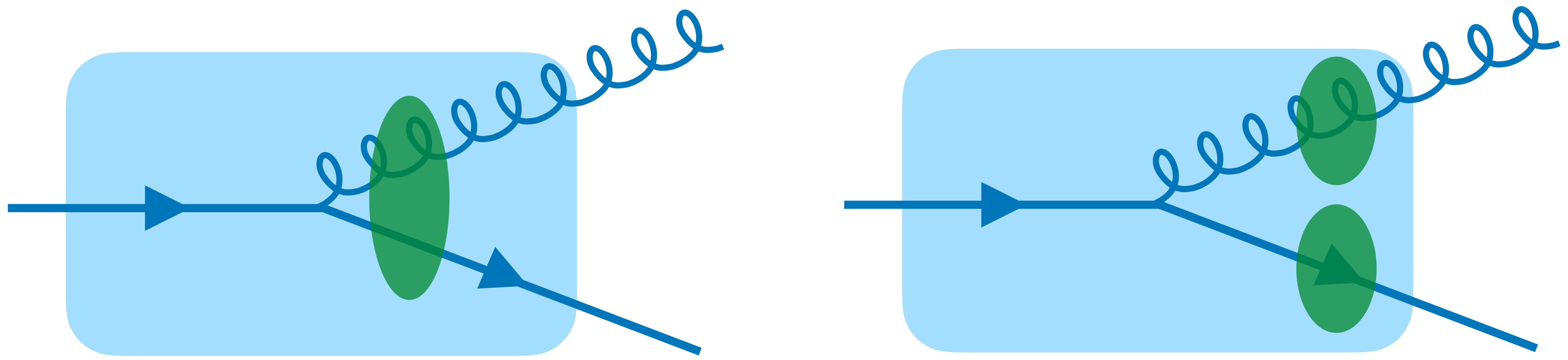



Measure the kinematics of the two prongs in the high-$Q^2$ jet splitting:

$\theta_g$ — angle

$z_g$ — momentum

$\theta_g$ is directly sensitive to the angular resolution scale of the quark-gluon plasma

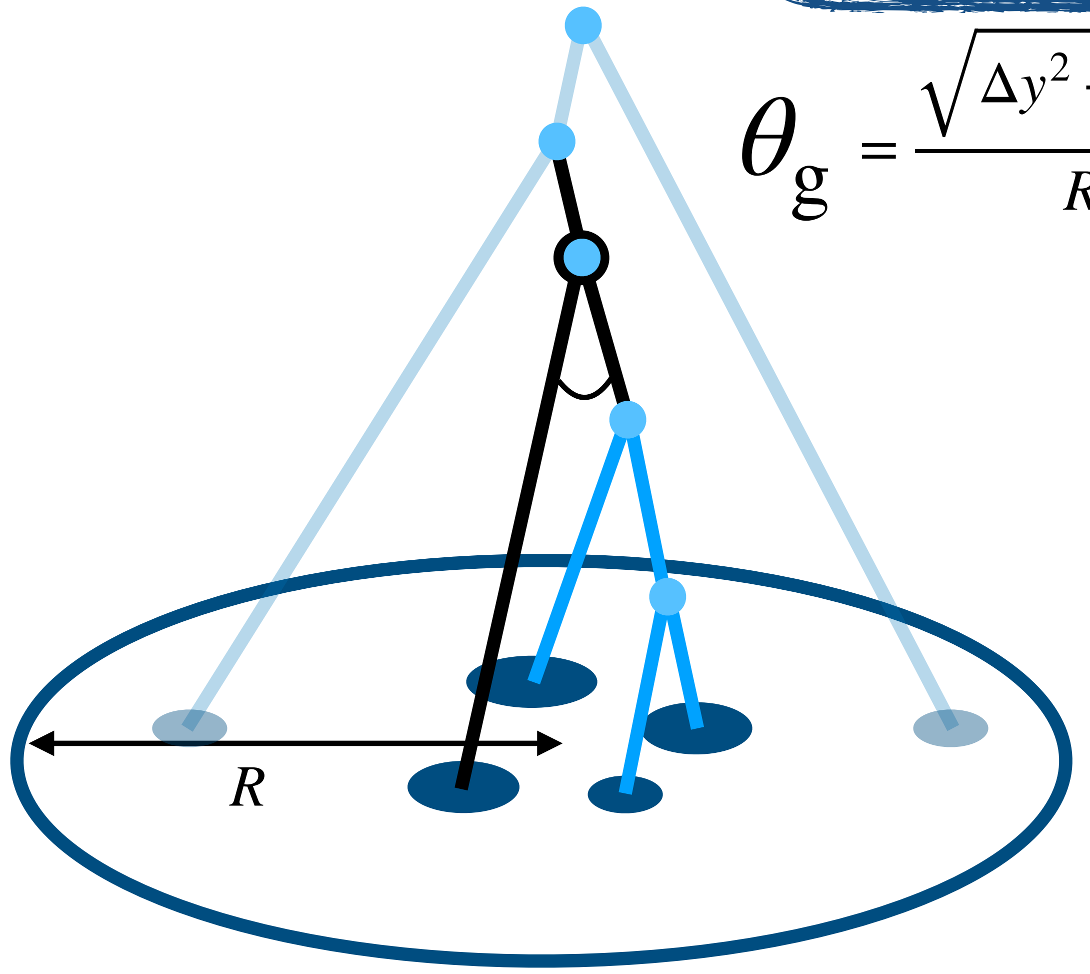


# Example 1: Groomed jet substructure

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

$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

$$\theta_g = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

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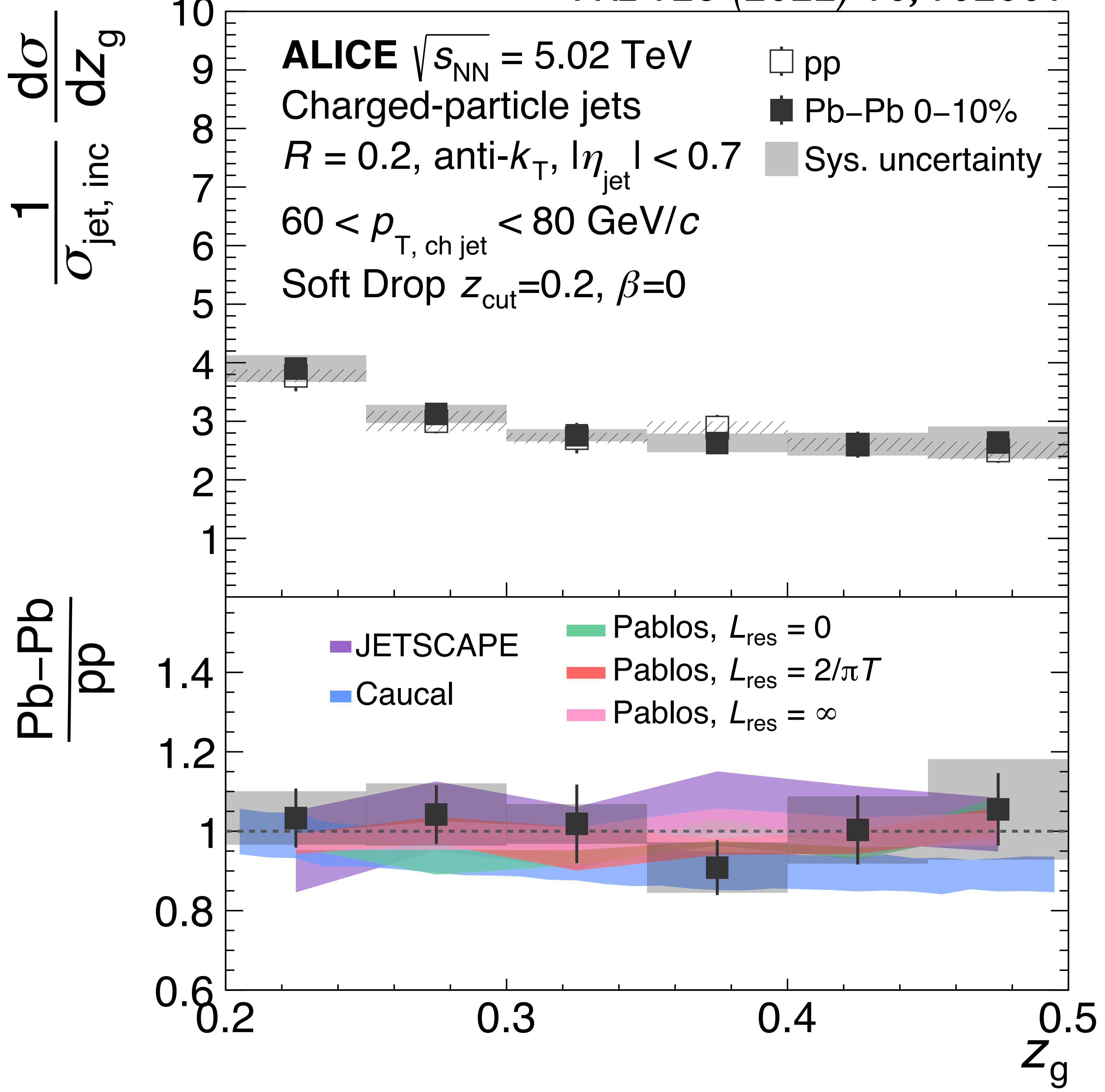


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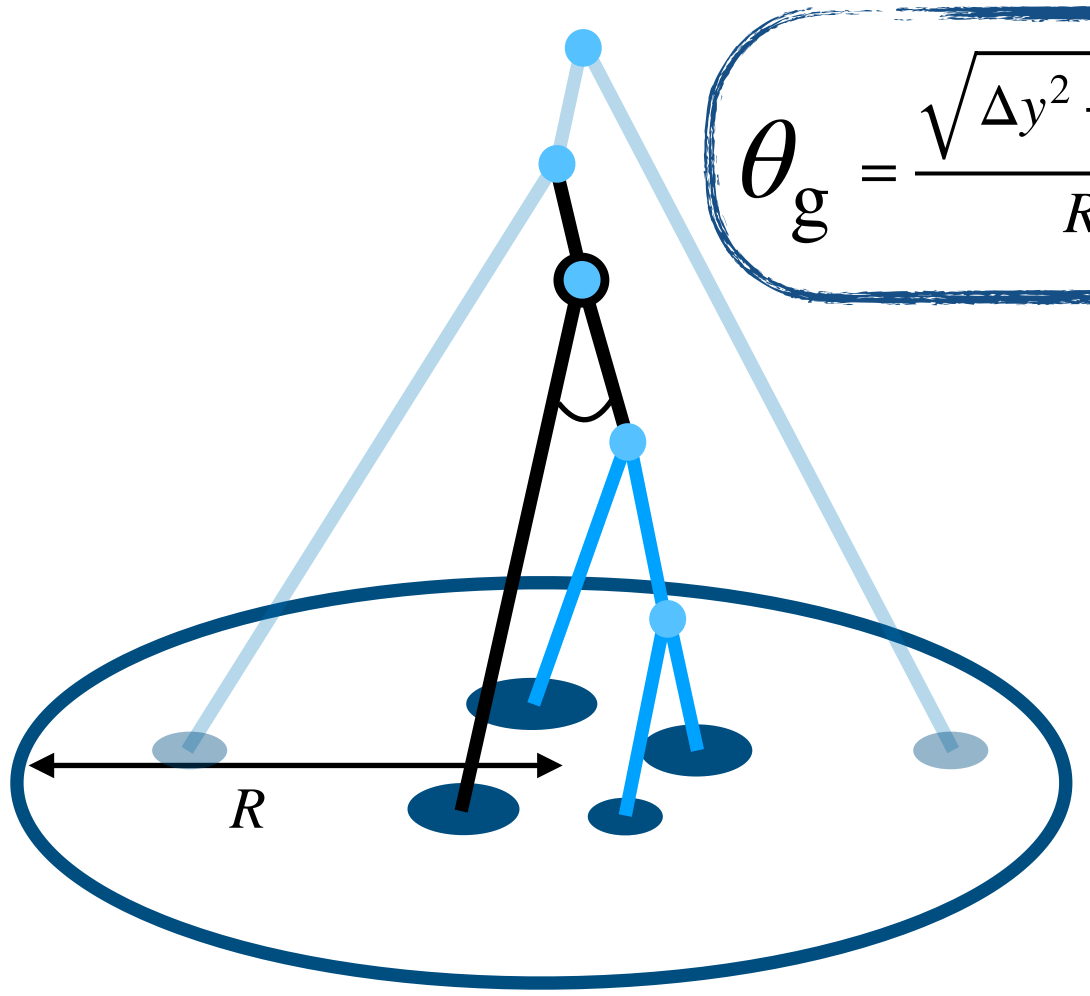


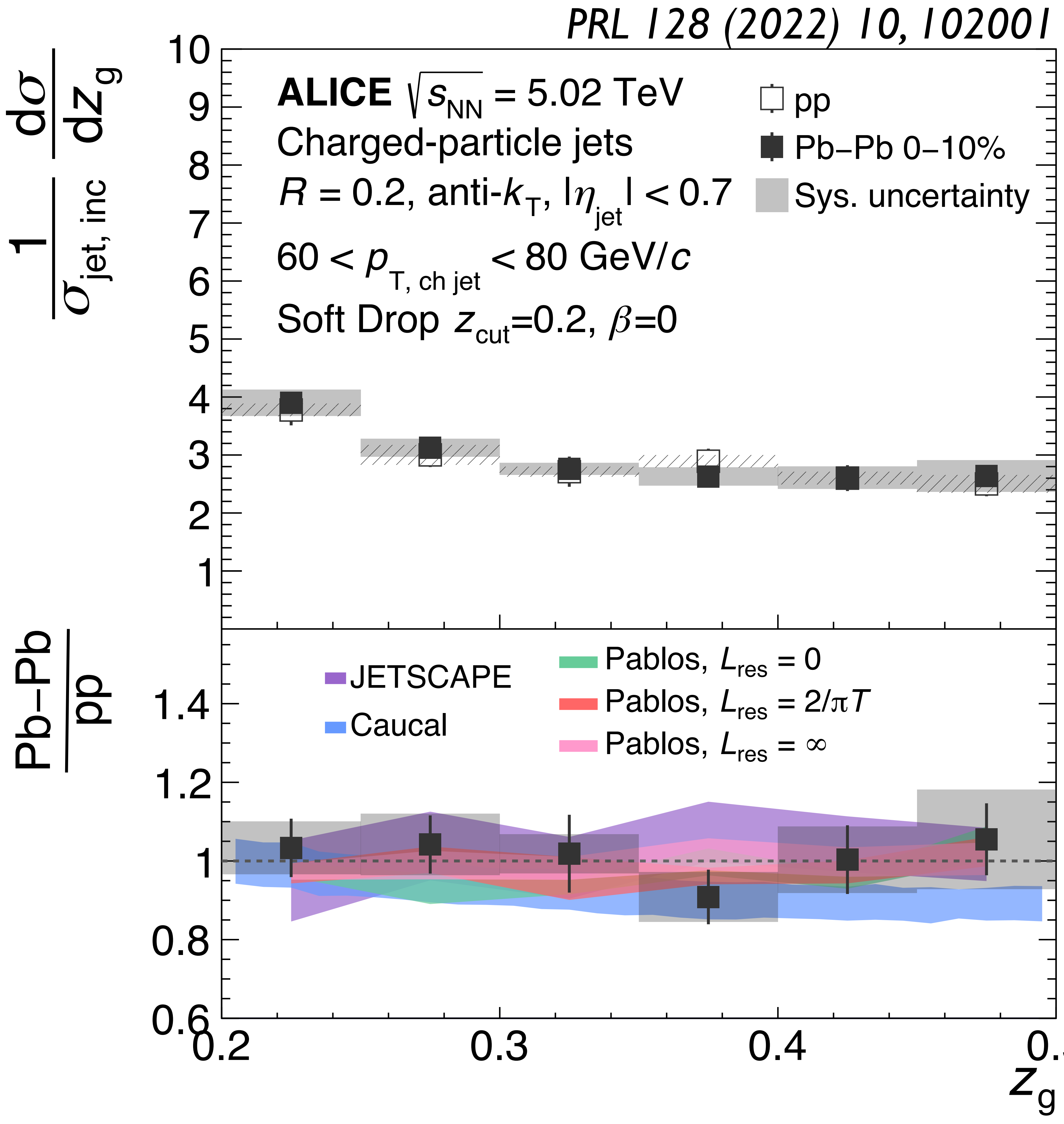


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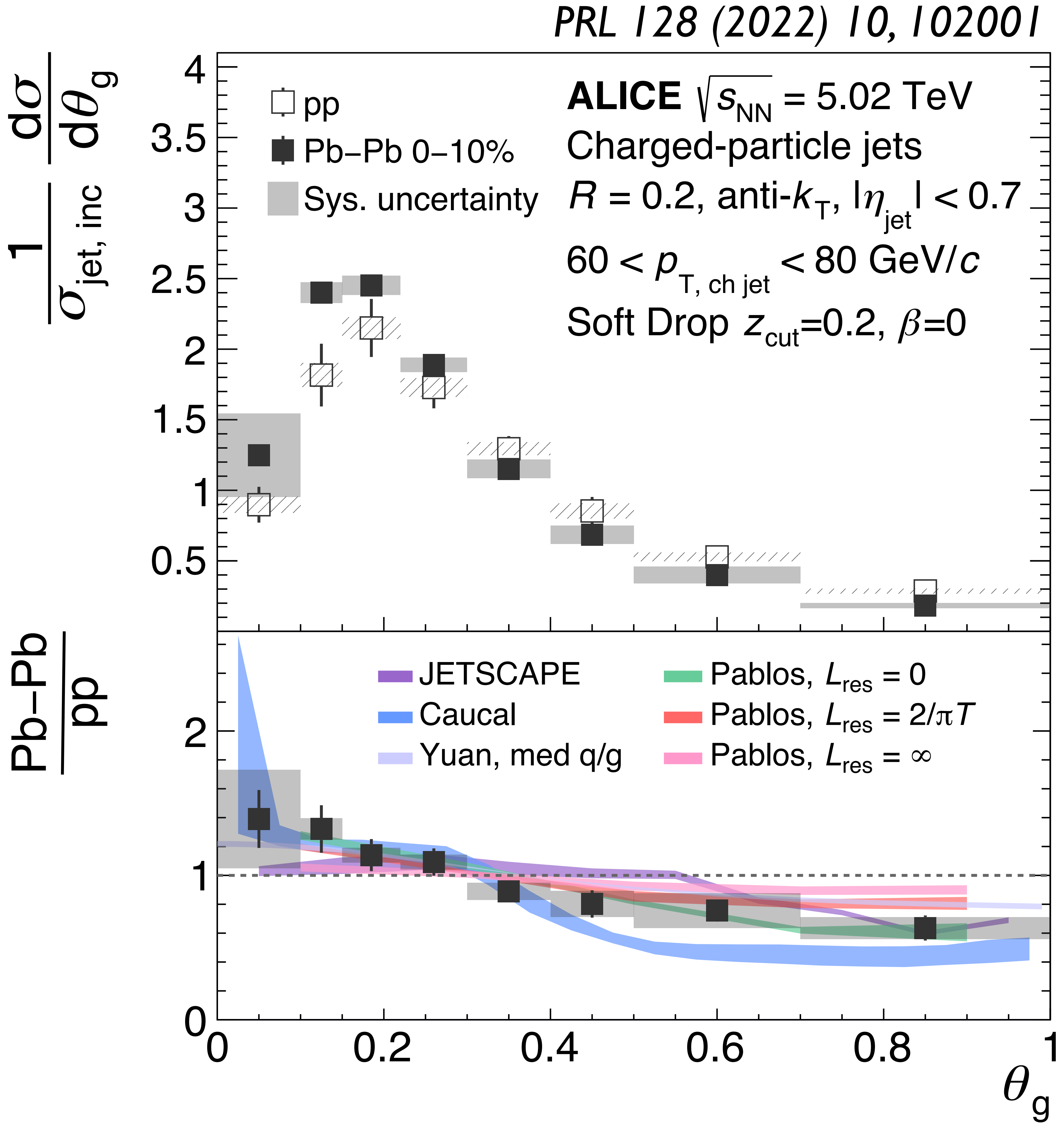


The cores of jets are narrower in Pb-Pb compared to pp collisions

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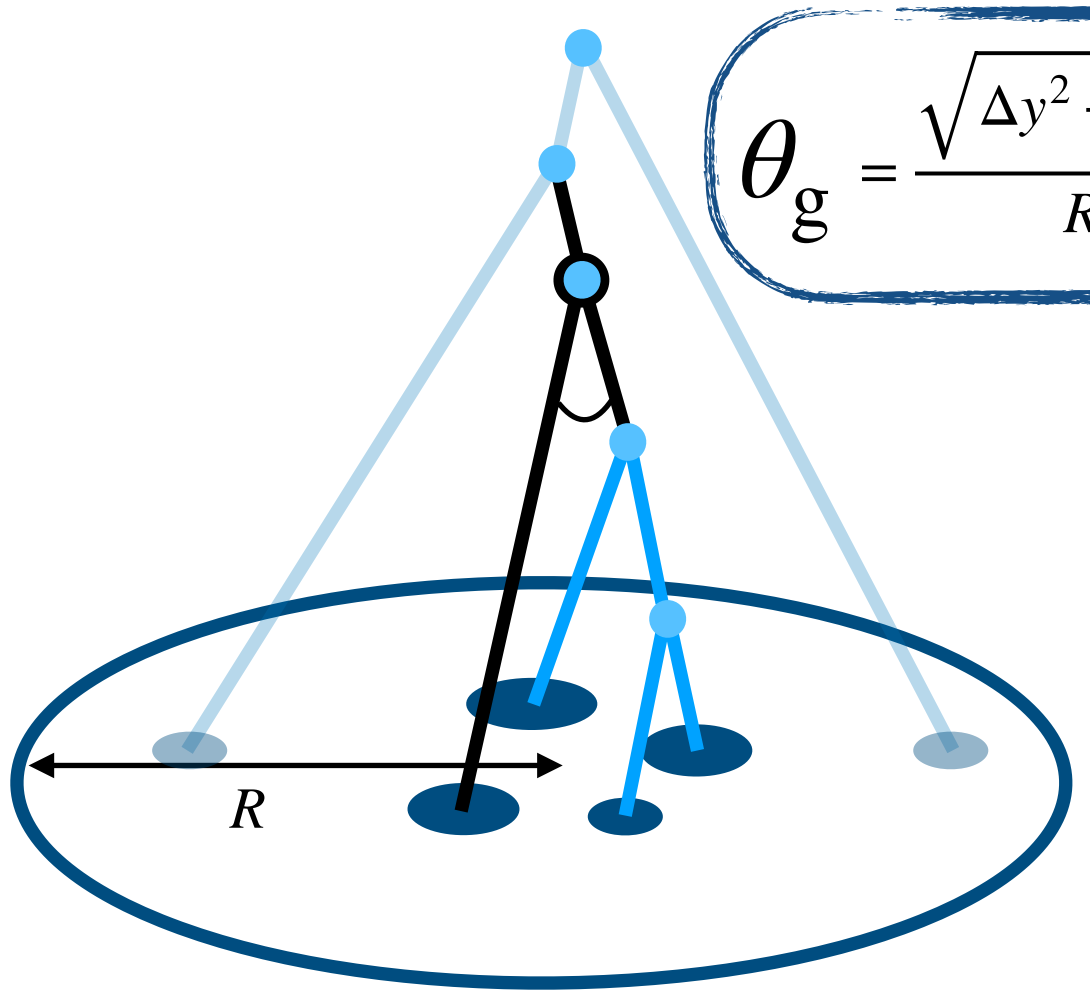


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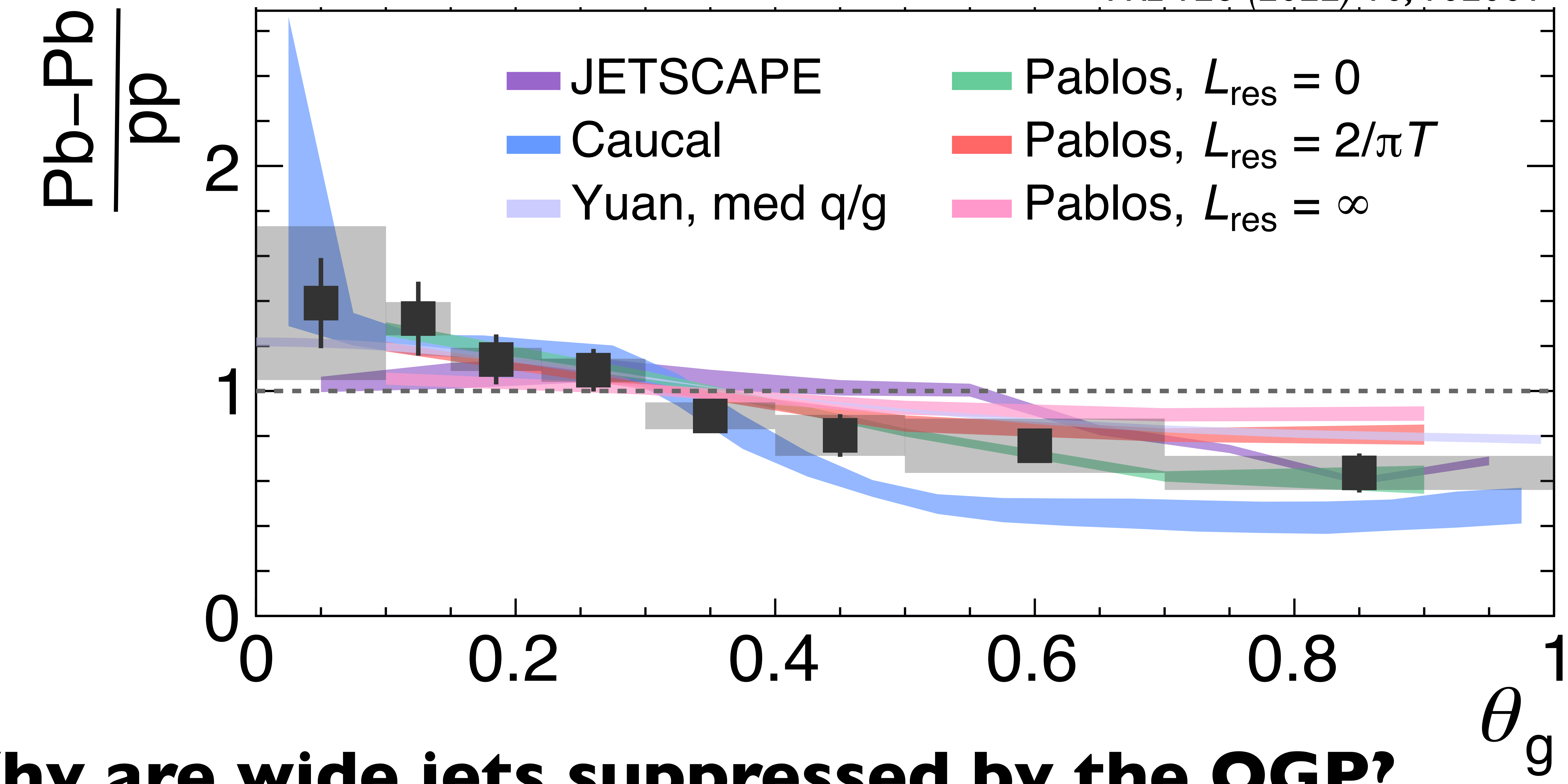
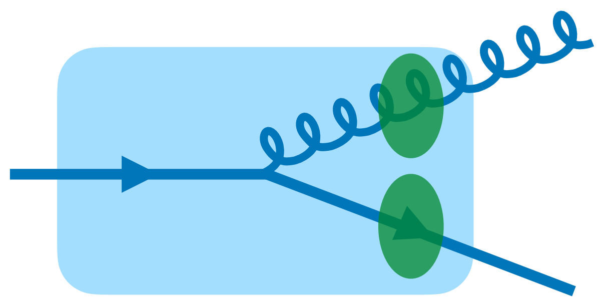
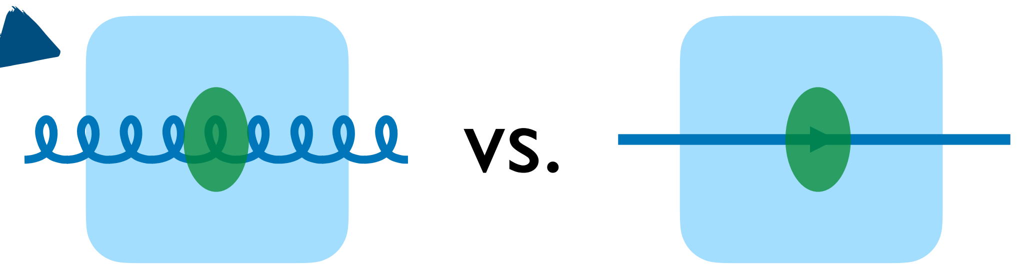



**Why are wide jets suppressed by the QGP?**

(1) Wider splittings are resolved by the medium
- Sensitive to QGP resolution length $L_{\rm res}$

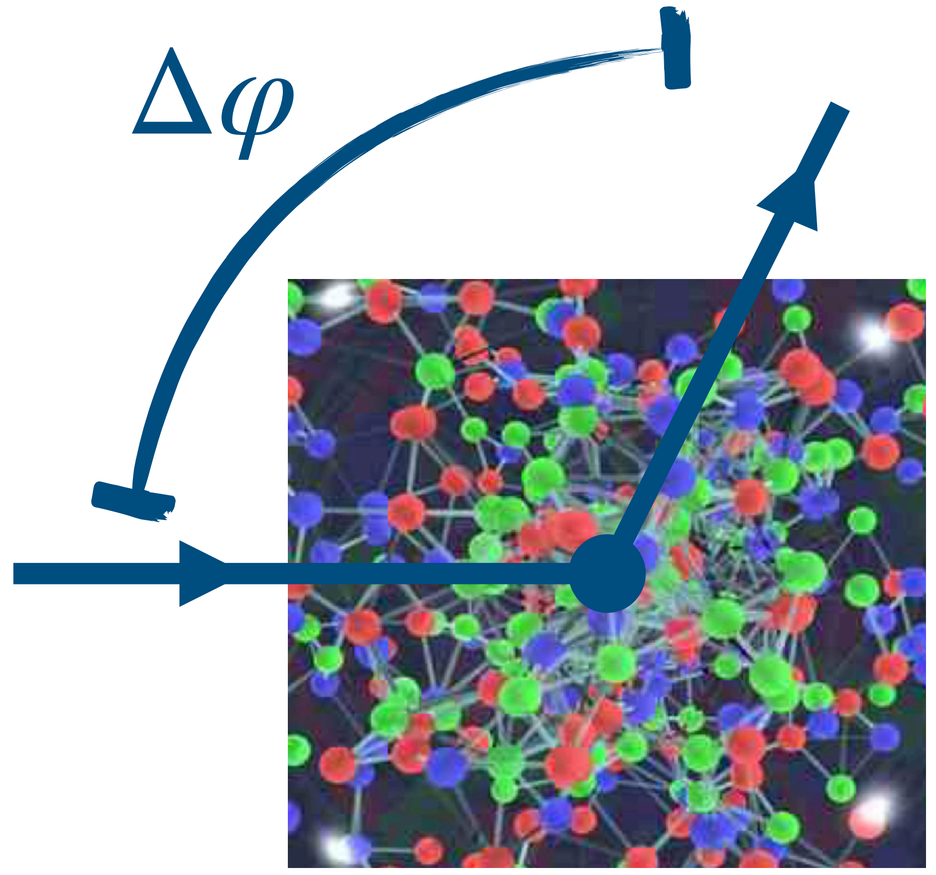


(2) Suppression of gluon jets vs. quark jets
- $C_g/C_q = 9/4$



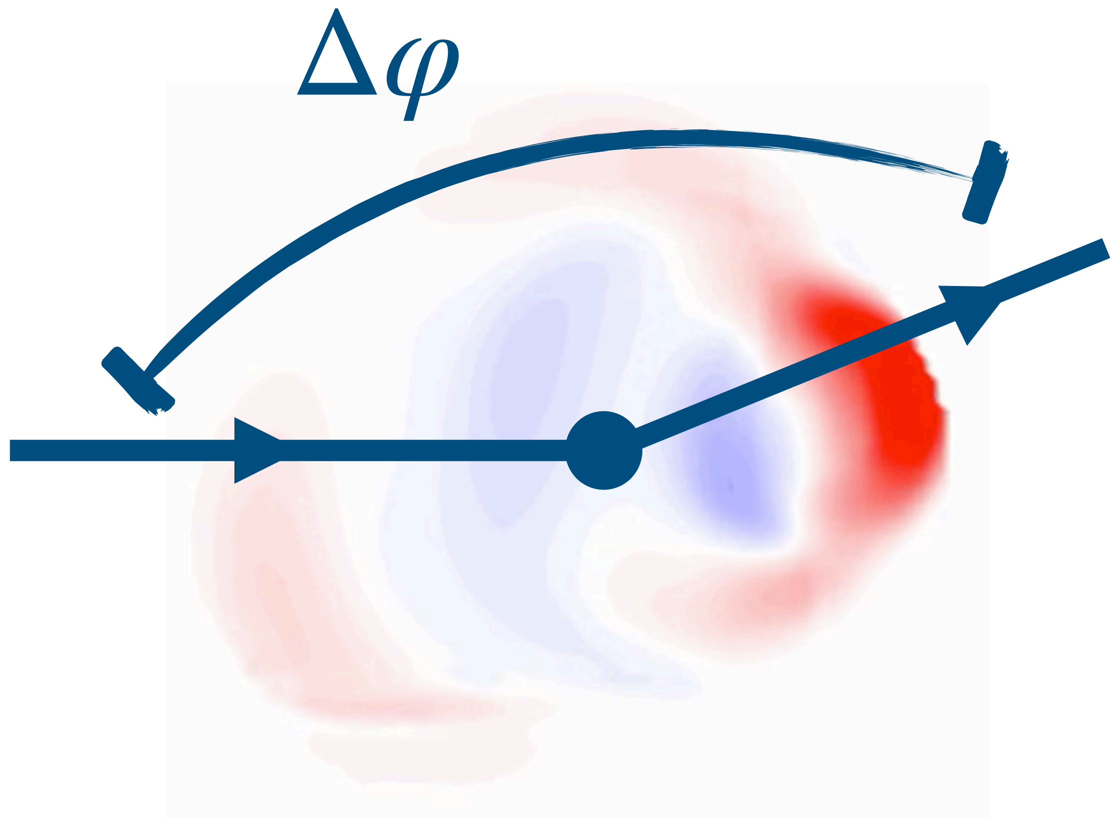
# Example 2: Jet deflection

**Discrete medium**




**Large-angle scattering:**
$P \sim 1/k_T^4$

**Smooth medium**




**Large-angle scattering:**
$P \sim \exp\left(-Ak_T^2\right)$

**Search for large-angle scattering — direct probe of microscopic structure**

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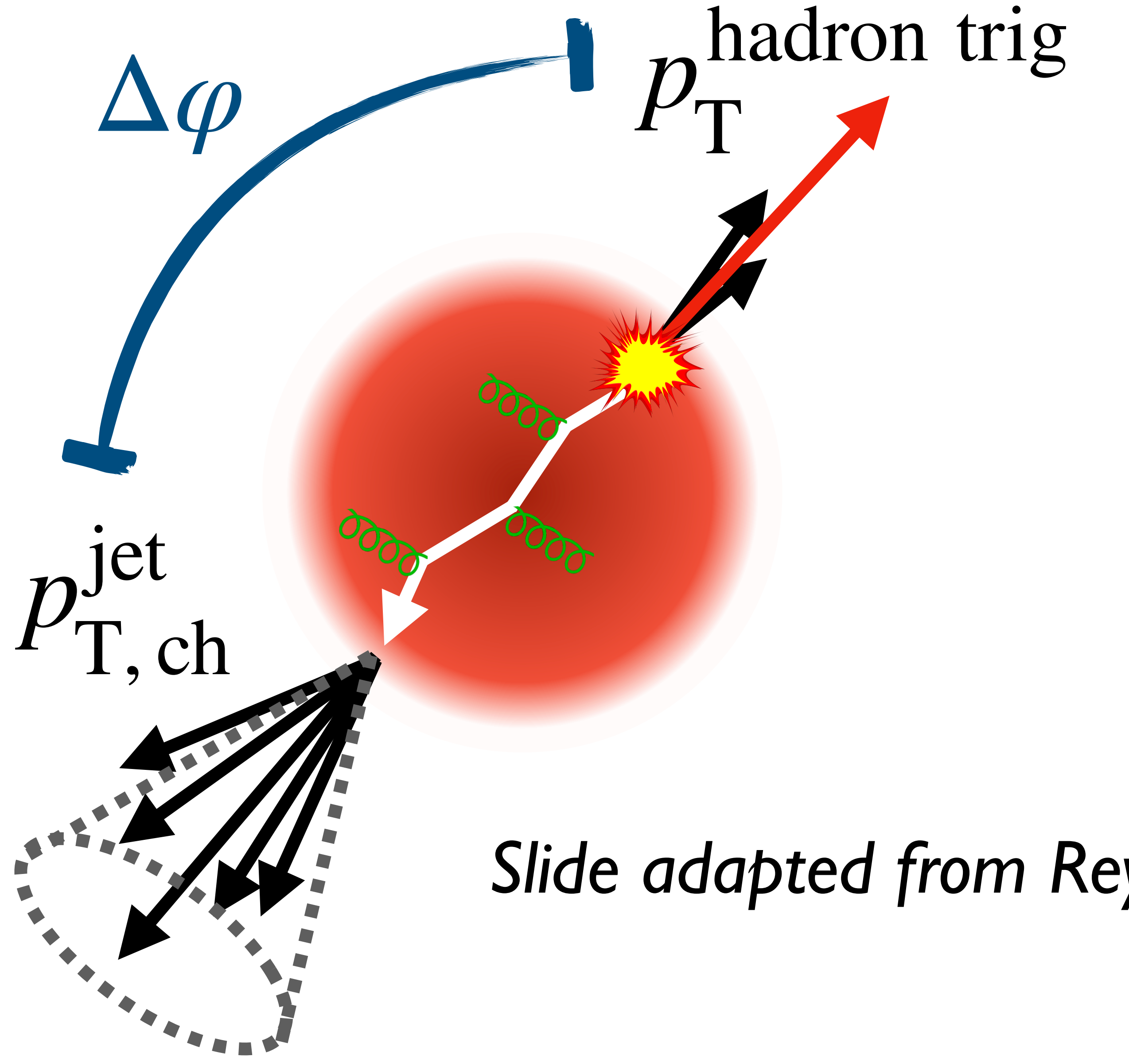
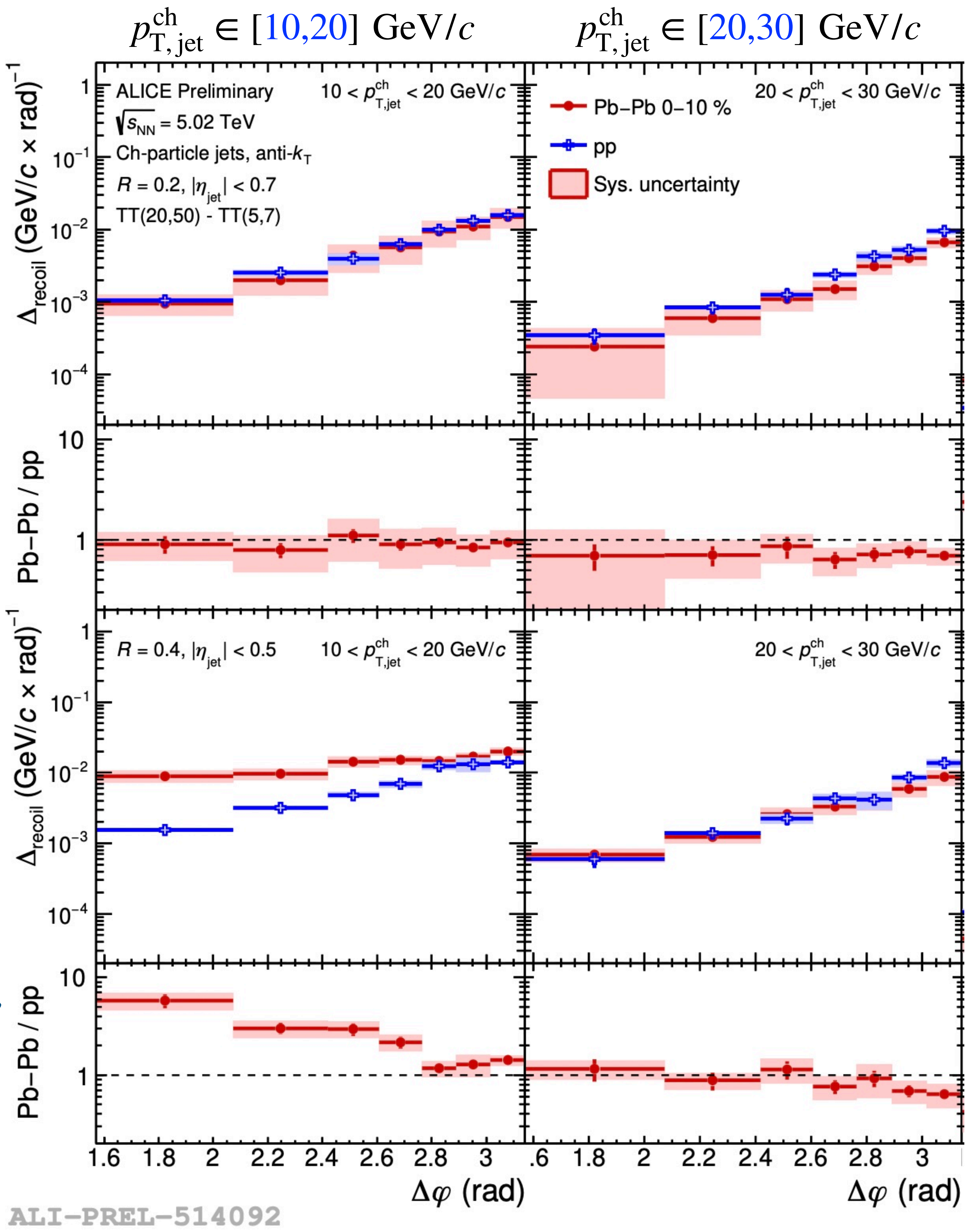



*Slide adapted from Rey Cruz-Torres QM2022*




**Indications of jet broadening at low-$p_T$, large-$R$**

- Jet deflection?
- Fragmentation modification?
- Medium response?

# Medium properties

## Bayesian inference

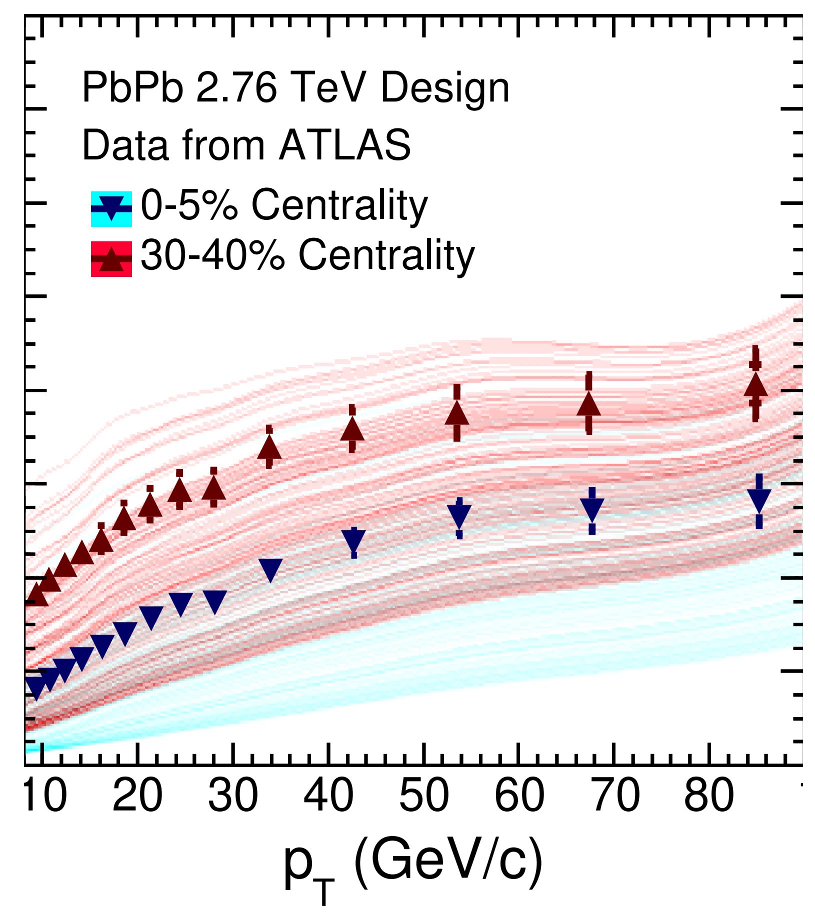
- Jet quenching model parameters: $\theta$
- Experimental data: $D$

$$P(\theta|D) \sim P(D|\theta)P(\theta)$$

Posterior Likelihood Prior

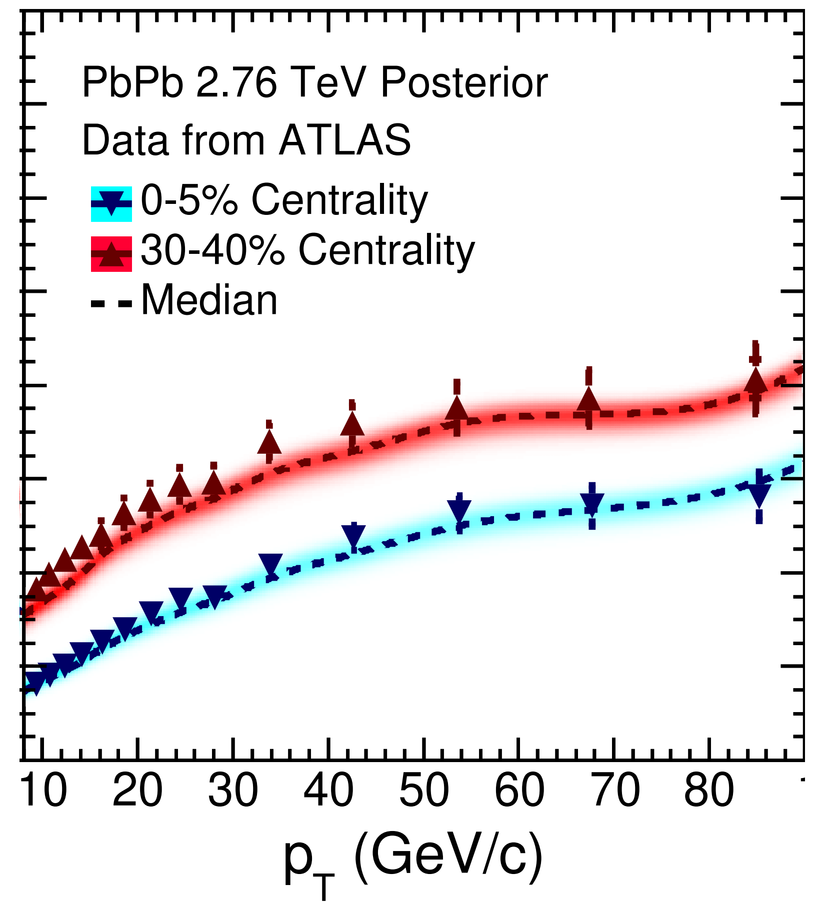
Goal: extract posterior of model parameters $\theta$

- Well-characterized uncertainties




**Prior**

**Posterior**

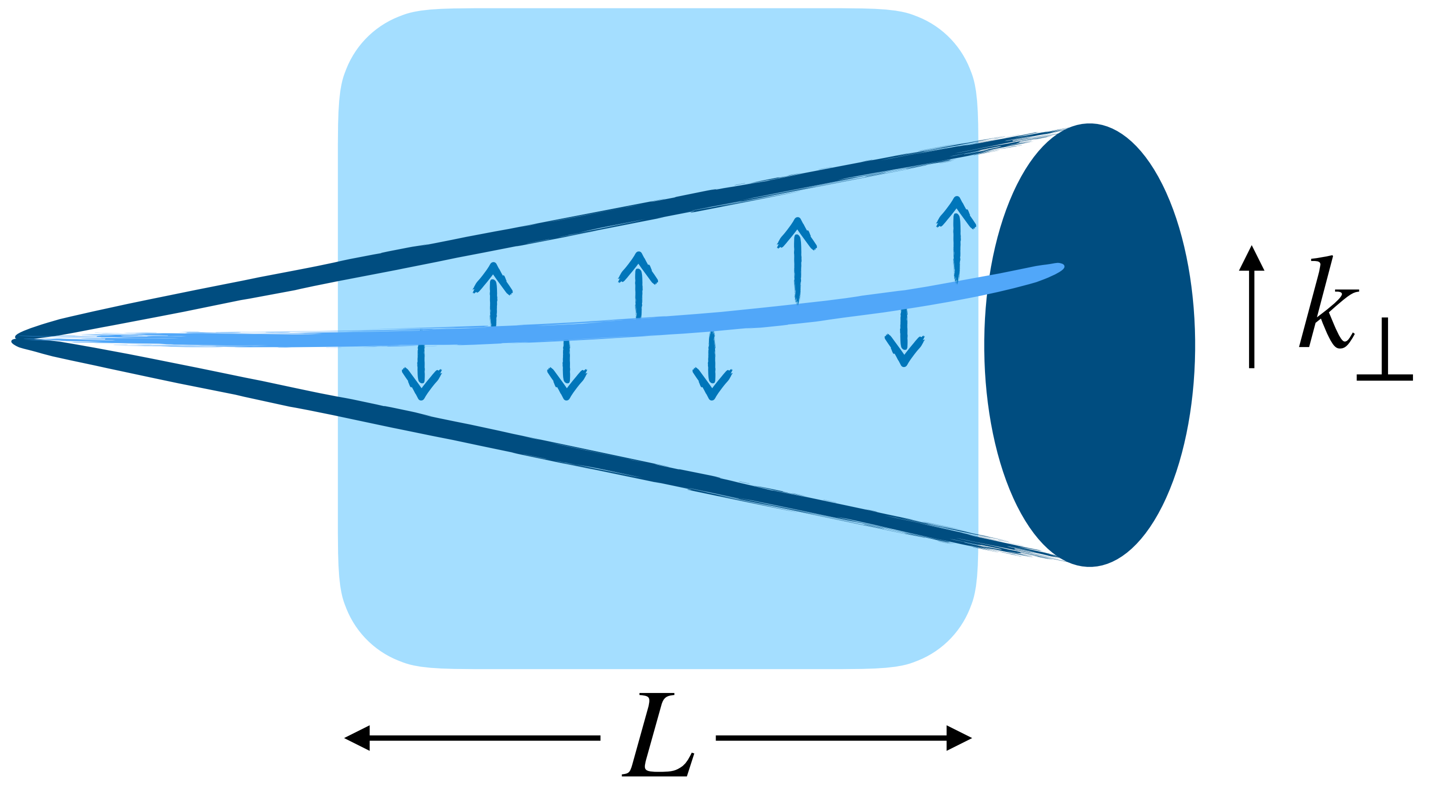


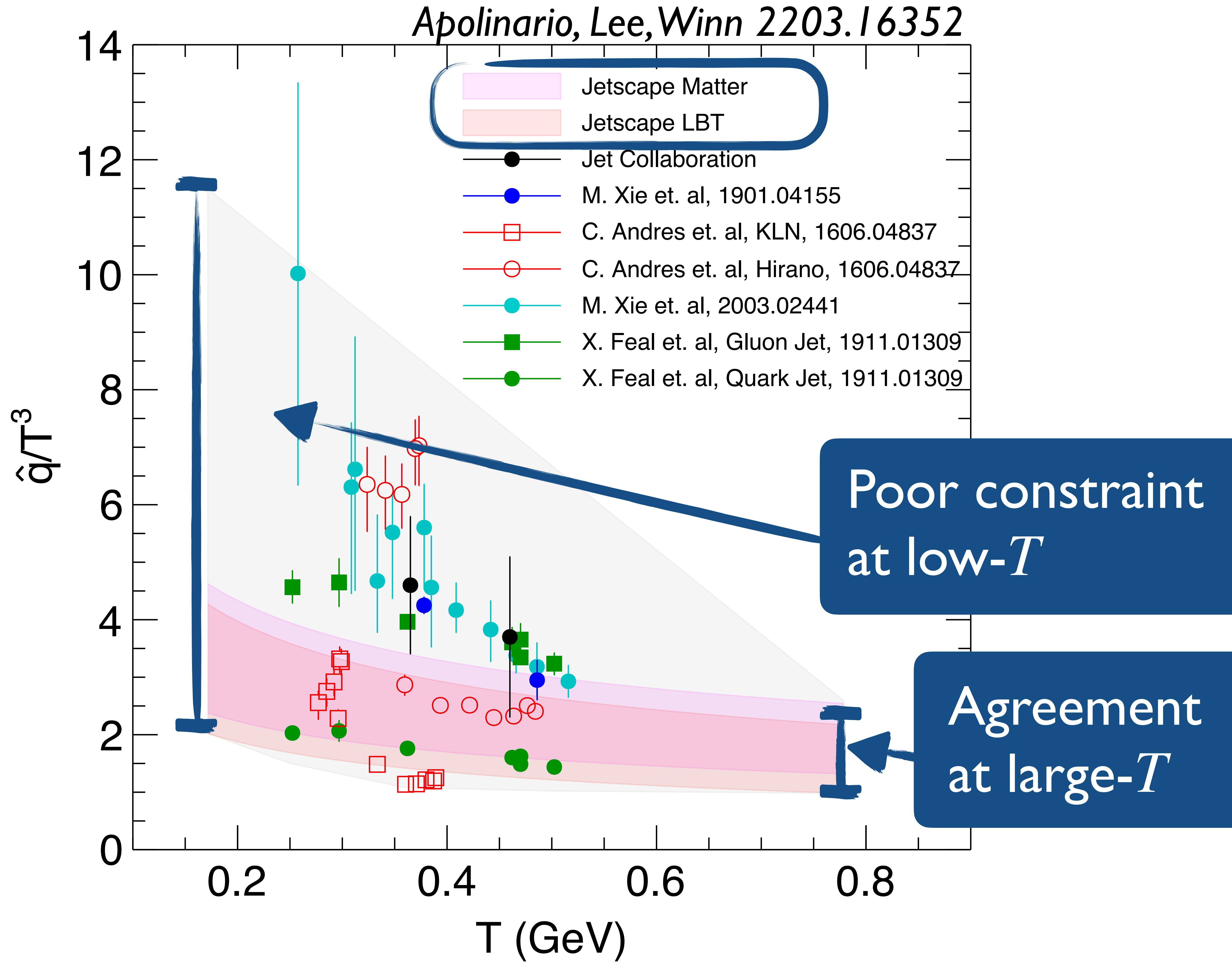
# Bayesian estimation of $\hat{q}$

**Extraction of jet transverse diffusion coefficient as a continuous function of $T, p$ using inclusive hadron $R_{AA}$ data from RHIC+LHC**

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

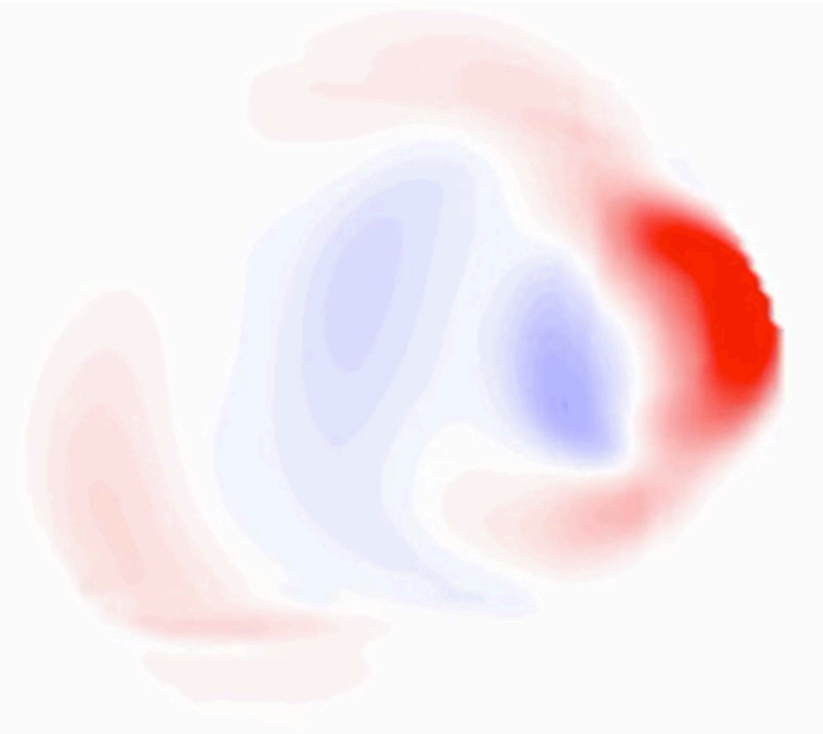
where $P\left(k_\perp^2\right)$ is a scattering kernel.

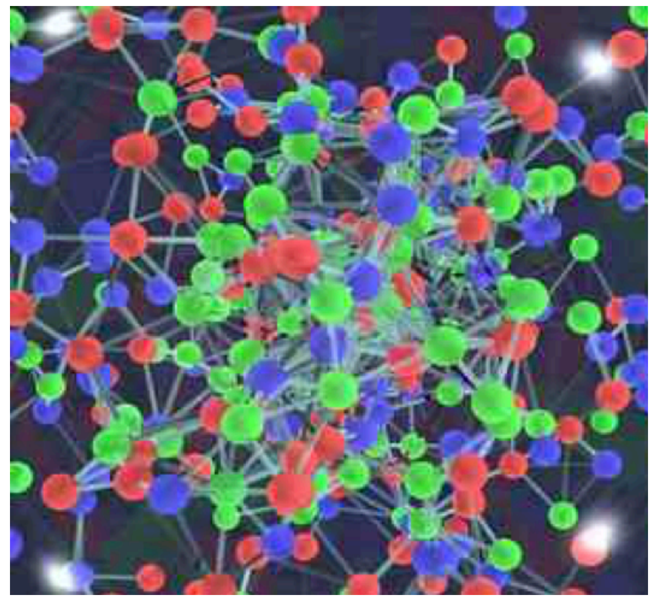


# Where are we going?

# Next-generation Bayesian analysis



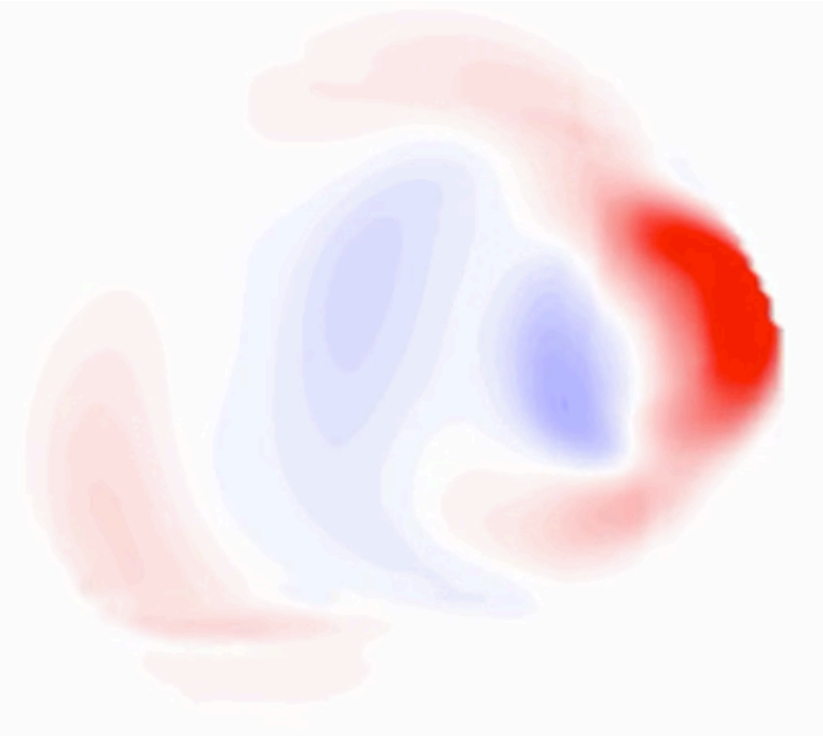


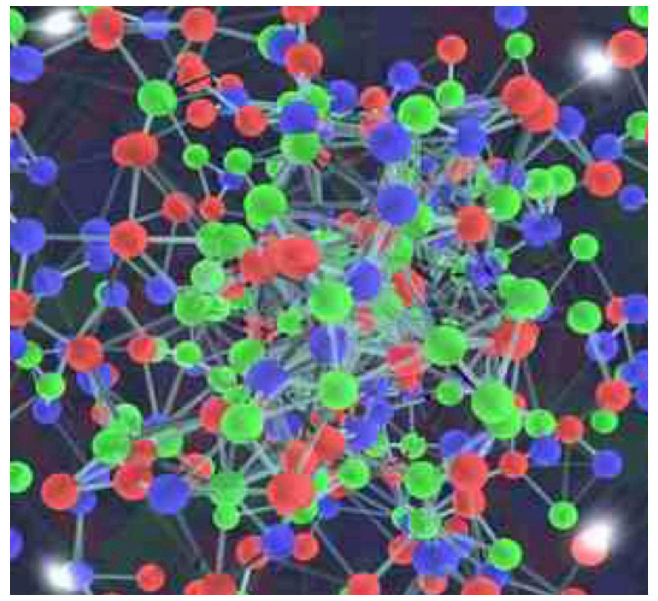
Expand (carefully!) the set of observables used in Bayesian inference

- Towards precision physics: uncertainty correlations and theoretical control

Study constraining power at low-$T$

# Next-generation Bayesian analysis





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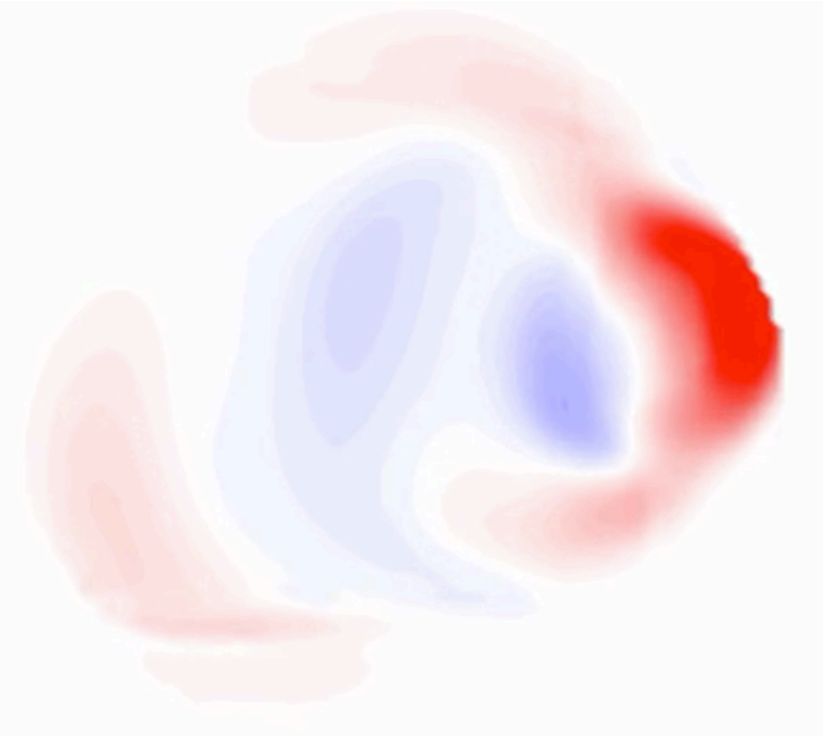
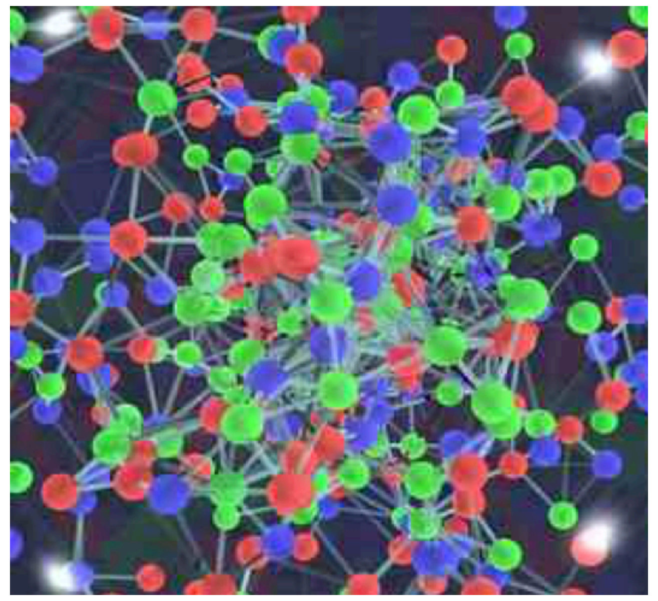
Expand (boldly!) the model parameters that we fit with data

- Theory progress is slow — opportunity to guide field from experimental data

Medium PDF and correlators; splitting formation time; scattering kernel; …

# Next-generation Bayesian analysis





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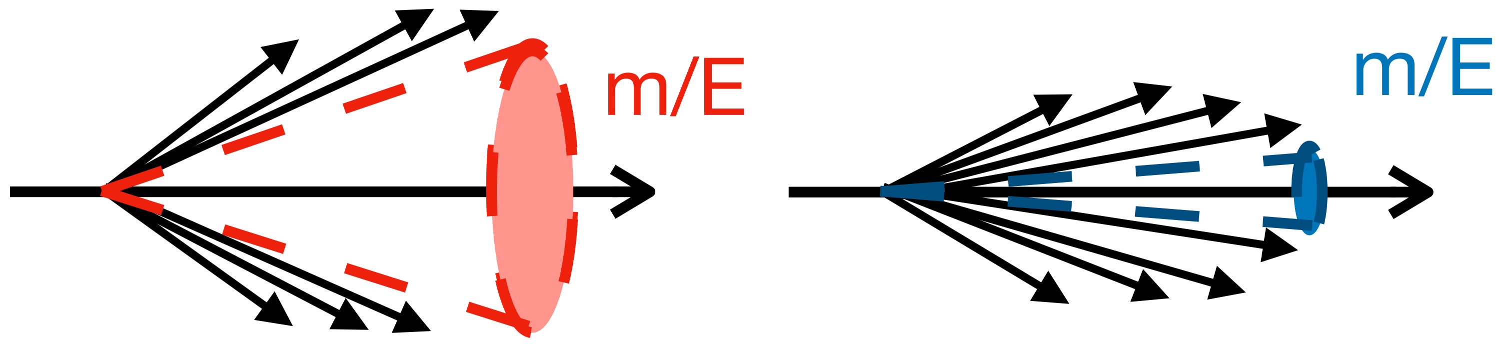
**What should we measure next to best constrain medium properties?**

# (1) New opportunities in Runs 3,4

Models with very different physics can usually describe the data

Measure new phase space: low-$p_T$, large-$R$, high-$z$, …

**Heavy flavor jets**

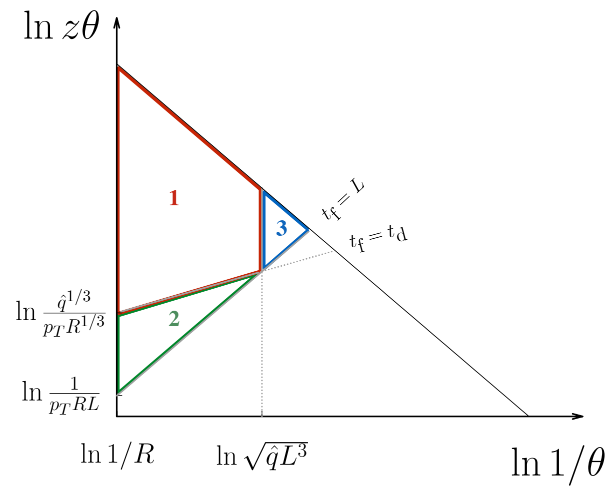



Pin down mass dependence

**EW-boson jets**


Pin down q/g fractions

**Differential substructure**




Isolate phase space

These will not come without challenges

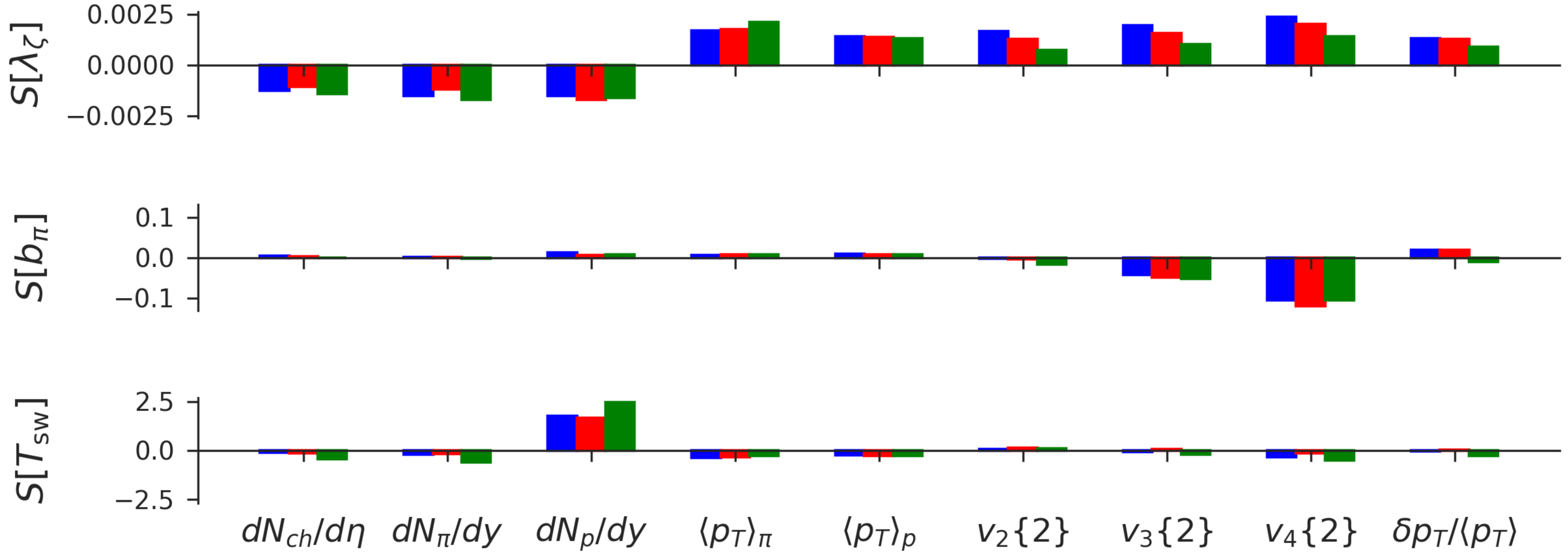
- HF, di-jet topologies — theory control
- Substructure — unfolding
- Large-R — "unbiased" background correction

# (2) Experimental guidance from Bayesian inference

## Sensitivity index

Quantify impact of a model parameter on measured observables

*JETSCAPE PRC 103, 054904 (2021)*

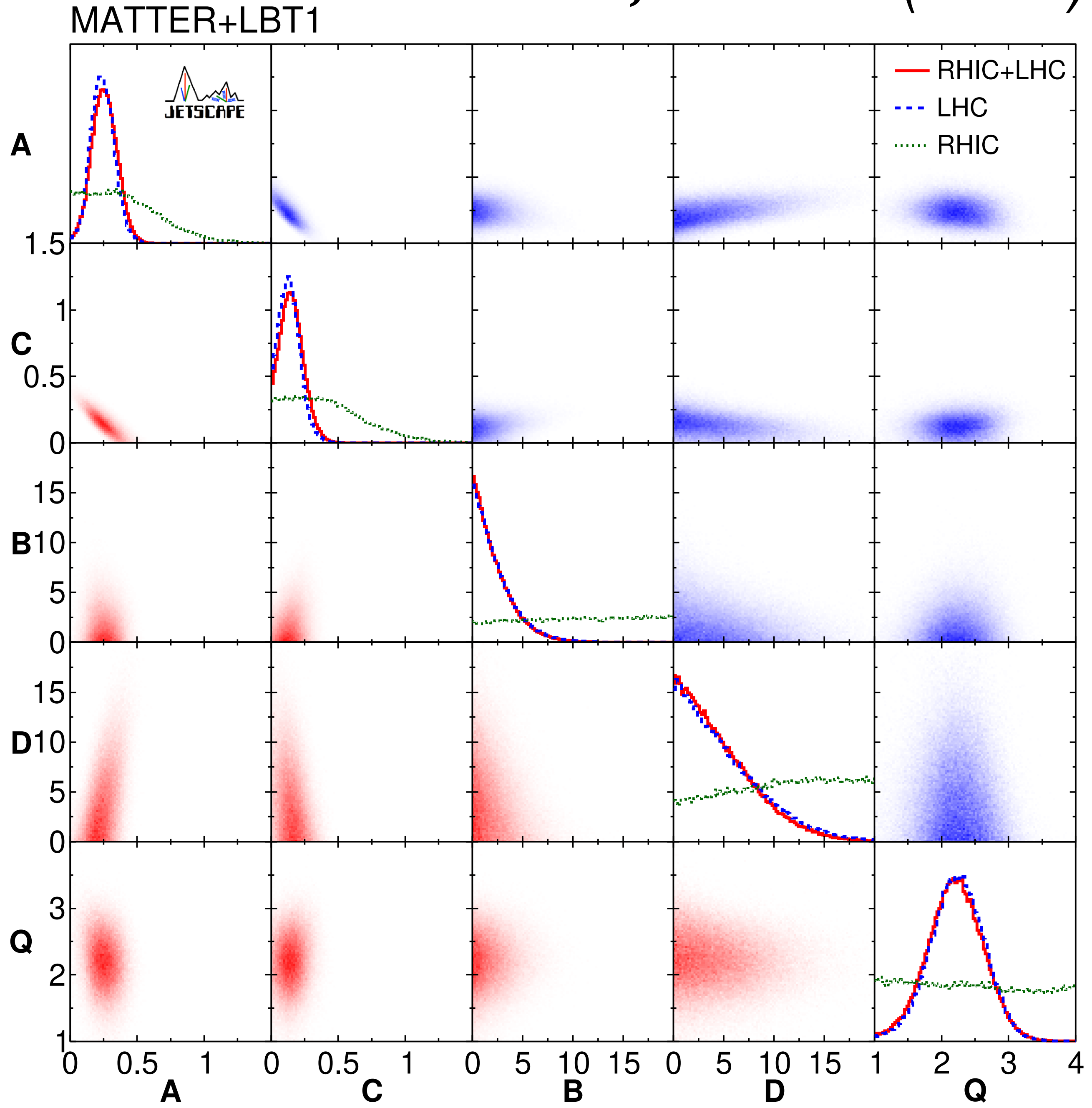



## Long-term planning

Exercise:
Restrict fit to either RHIC or LHC data

→ **Fit dominated by LHC data**

*PRC 104, 024905 (2021)*

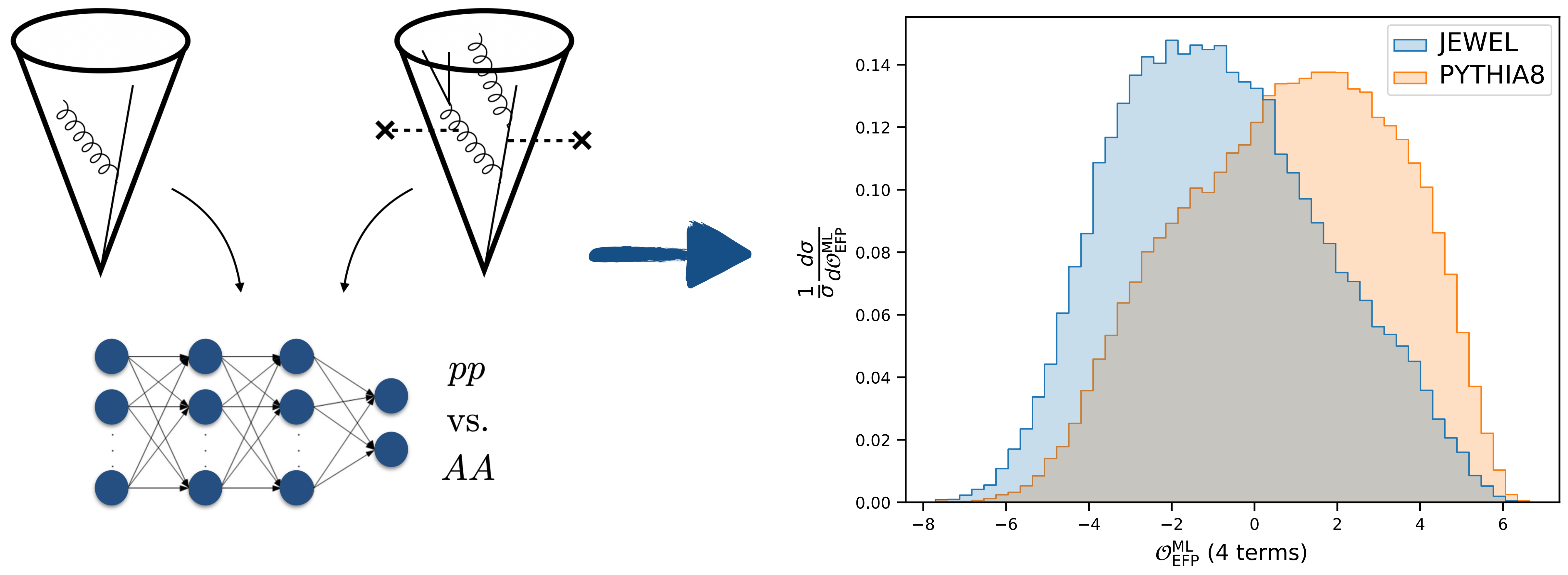



*See also:*
*Lai arXiv 1810.00835*
*Sangaline, Pratt PRC 93, 024908 (2016)*

# (3) Experimental guidance from ML

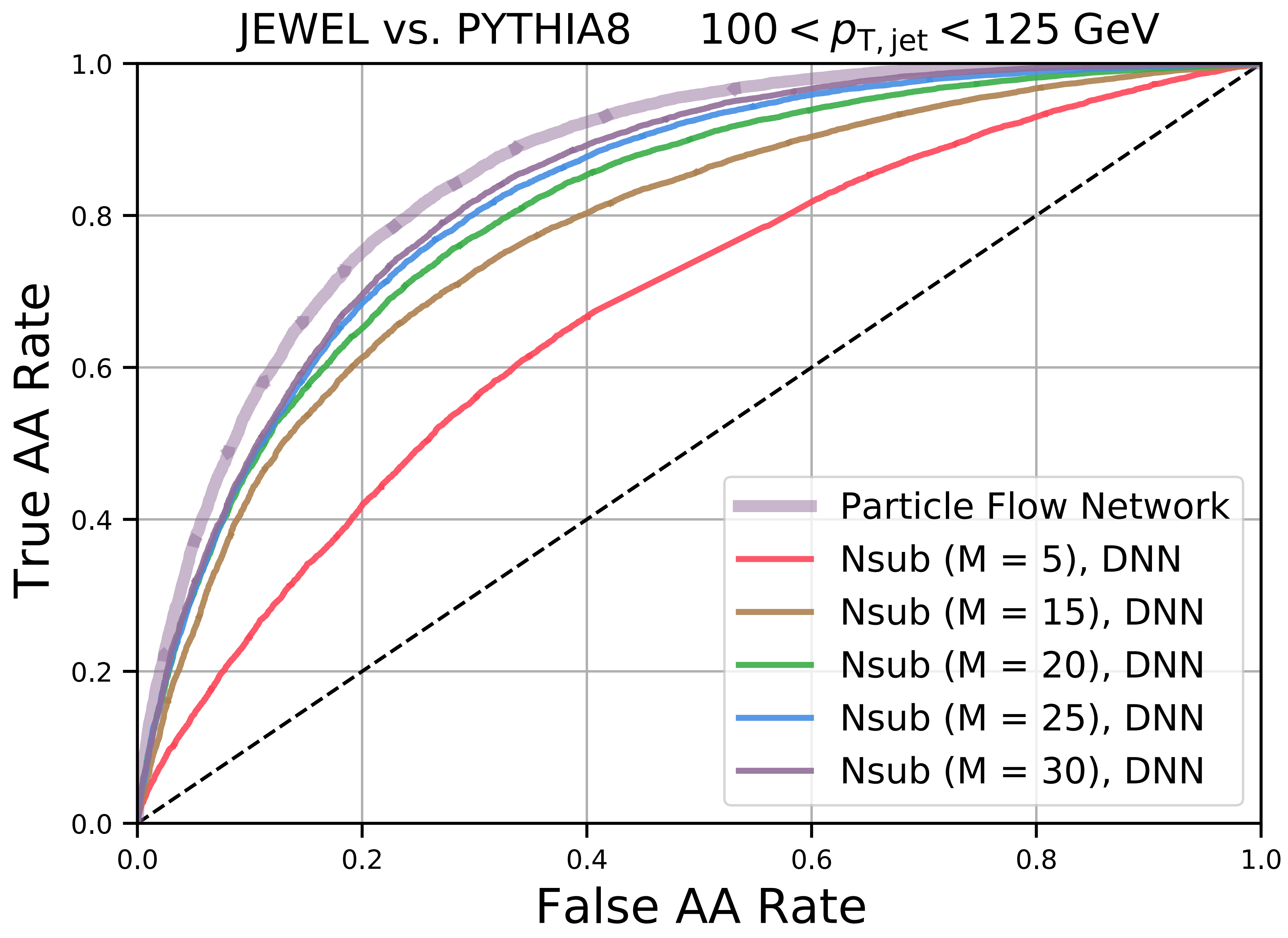
*Lai, Mulligan, Płoskoń, Ringer arXiv 2111.14589*

## ML-assisted observable design




By balancing the tradeoff of discriminating power and complexity, we can design the *most strongly modified* calculable observable

## How many observables does one need to measure to saturate information?




Systematic approach to "solve" the jet quenching problem from the experimental side

# Summary

## Jets are flexible probes of the QGP with direct connection to first principles QCD

- Three criteria for jet observables: measurable, calculable, informative
- Rich phenomenology of jet results: perturbative narrowing, nonperturbative broadening

## Global analysis is needed to to reveal properties of deconfined QCD matter

- First Bayesian extractions of $\hat{q}$ in last couple years

## The future

(1) *Jets as probe of QGP*: systematic guidance for what to measure next

(2) *QGPs as probe of jet*: early days studying real-time dynamics of QCD — jets and quantum computers