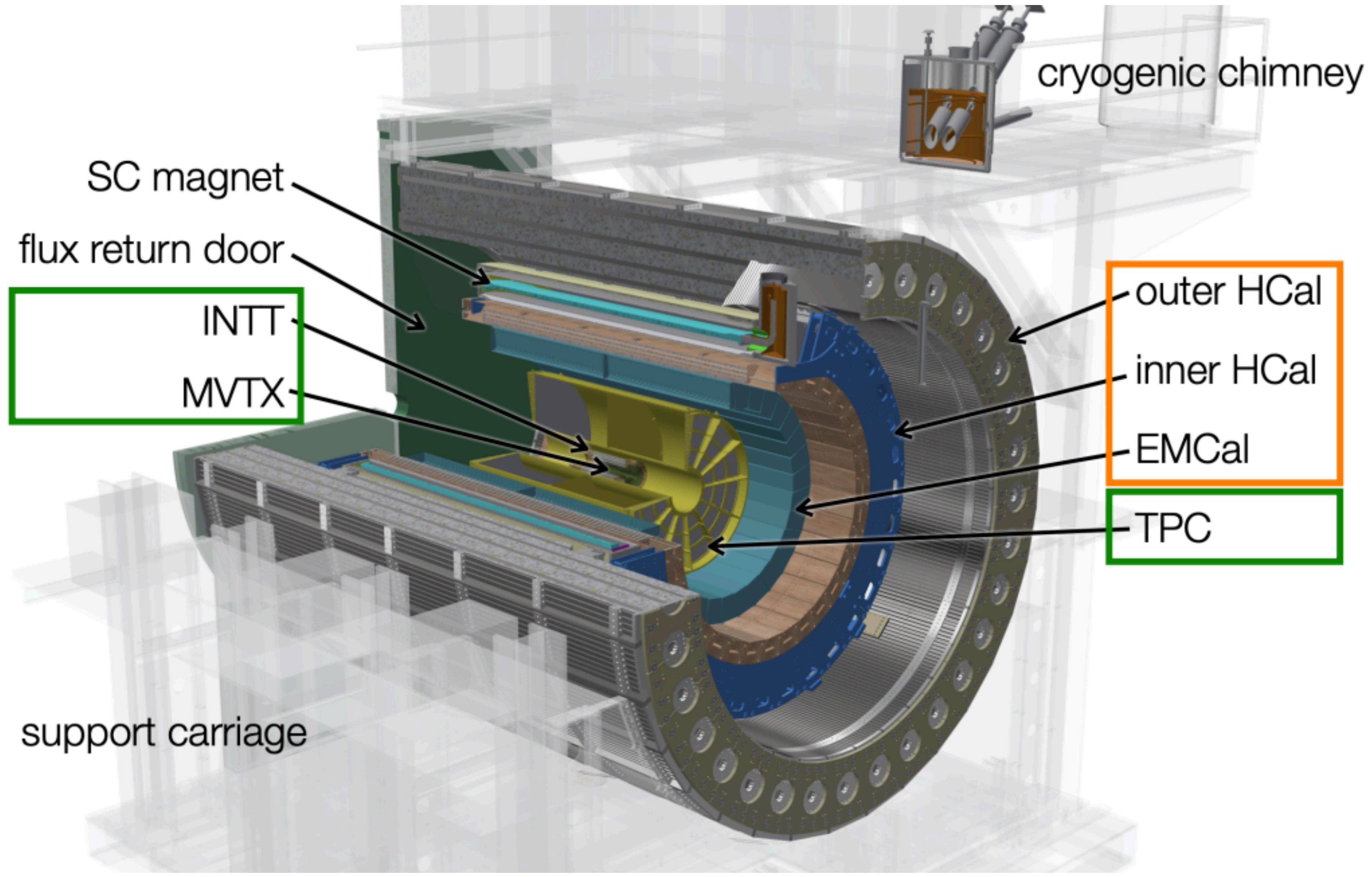
Probing the QGP with inclusive jets and their substructure

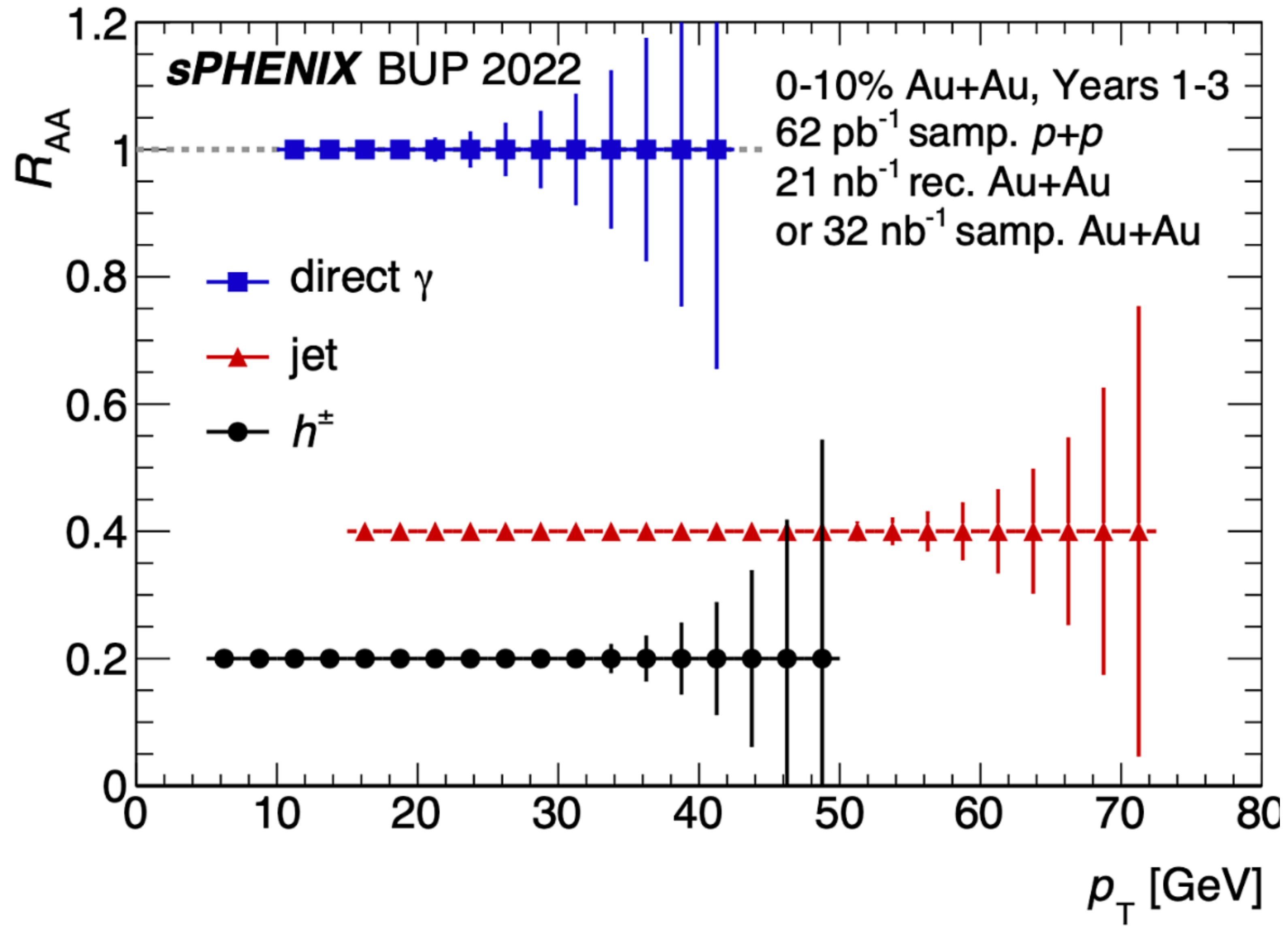
Felix Ringer

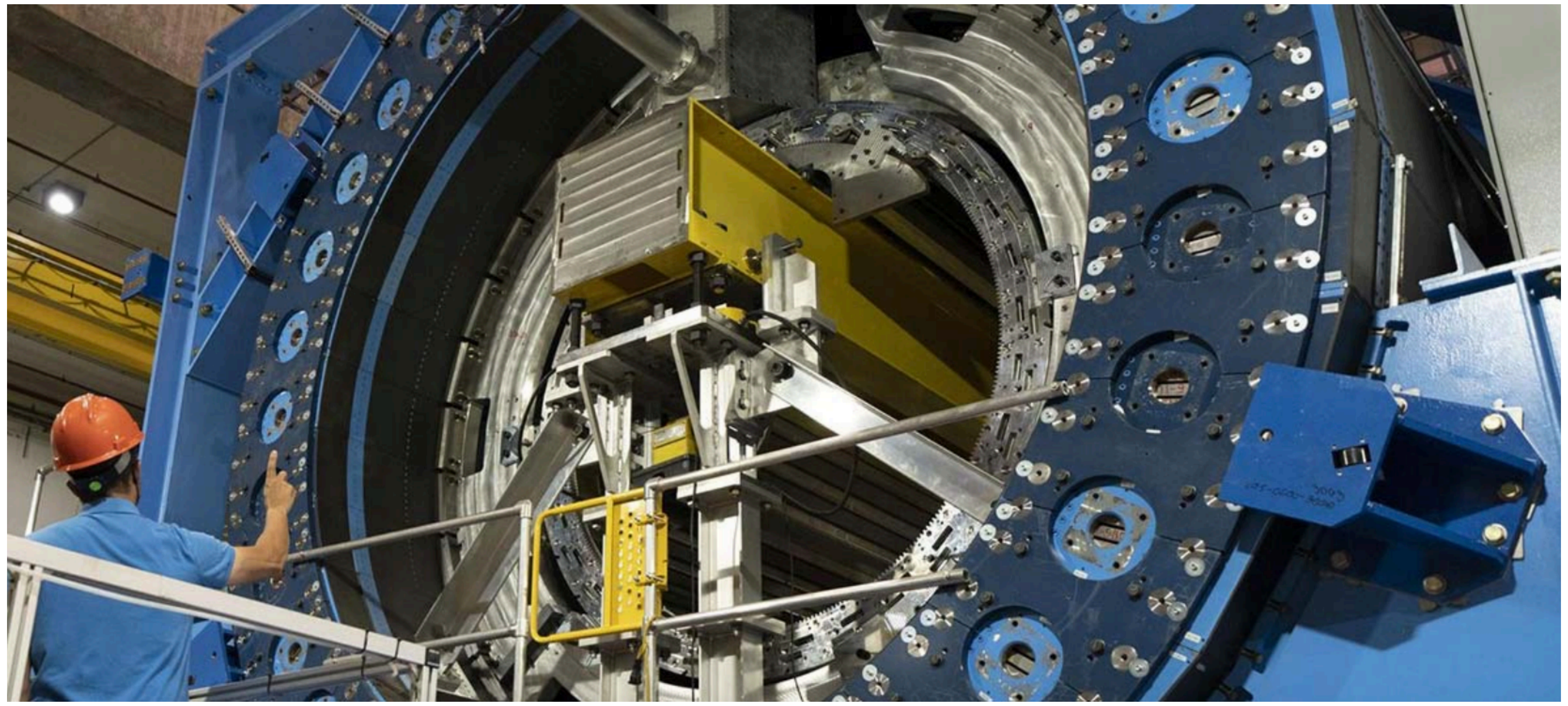
Old Dominion University,
Jefferson Lab

Predictions for sPHENIX, RBRC BNL, 07/21/22

Jet quenching and energy loss



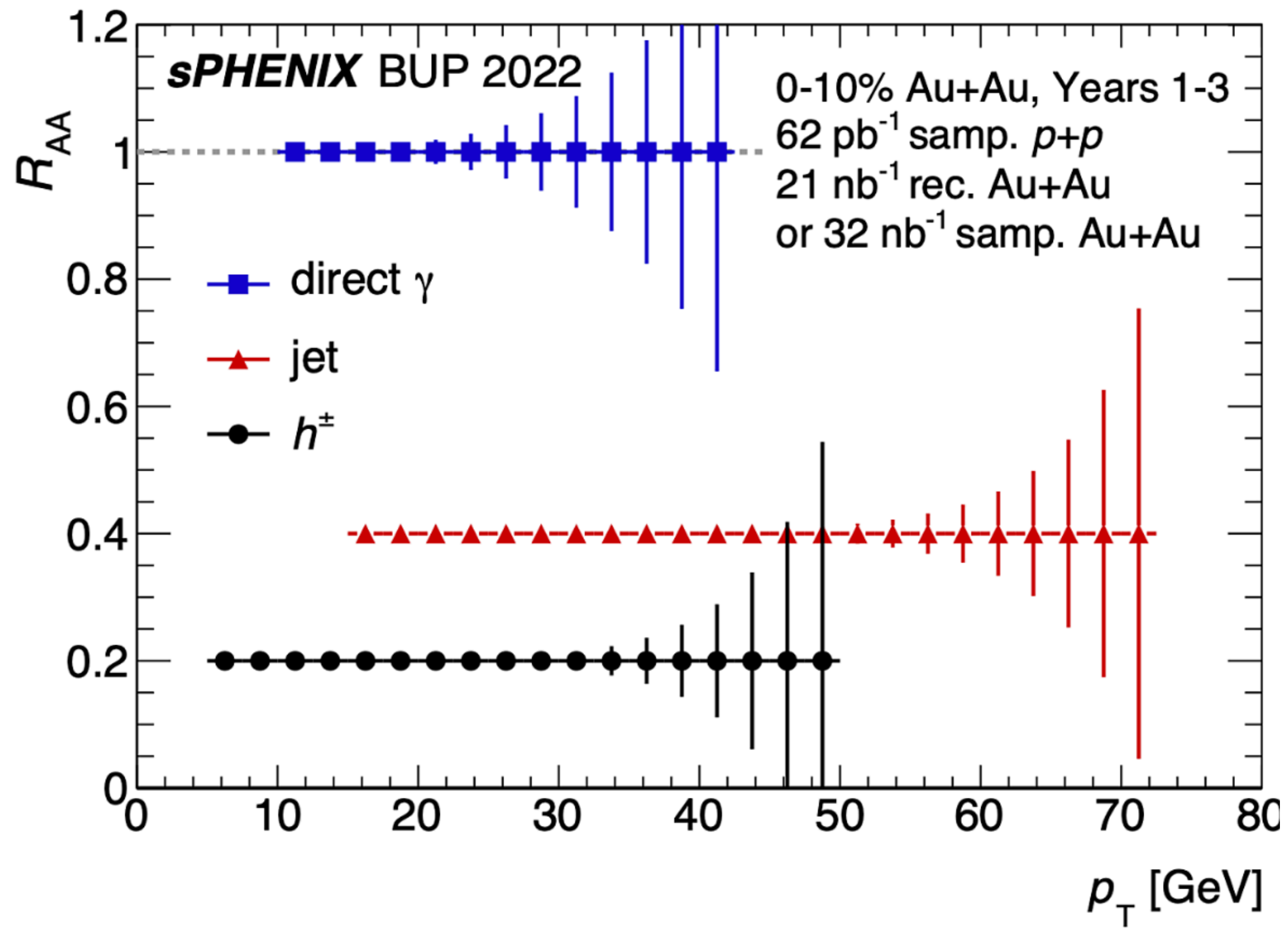




Precision tests of jet quenching with sPHENIX

Jet quenching and energy loss

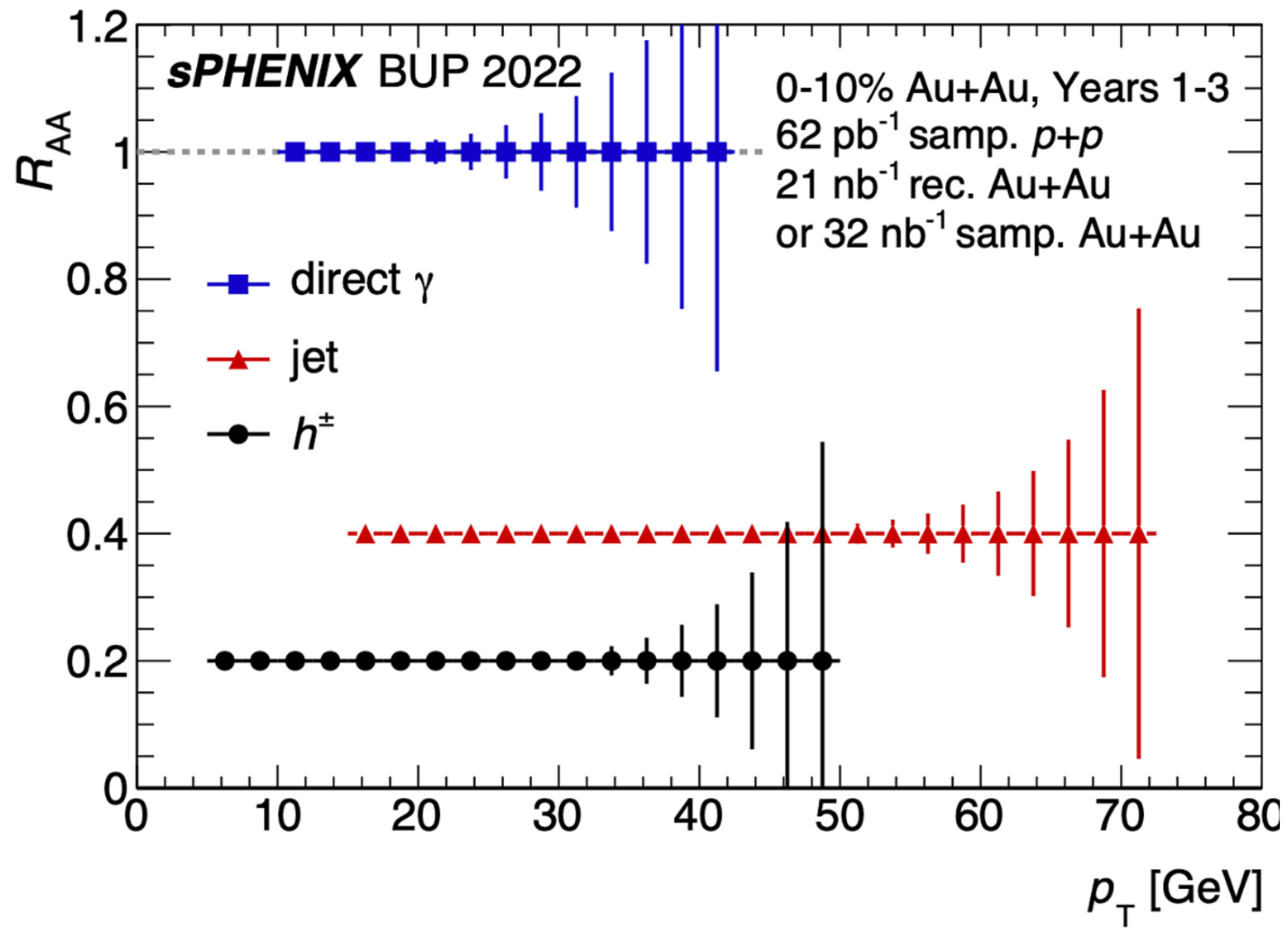
- QCD factorization & universality?



$$\frac{\mathrm{d}\sigma_{pp\to \mathrm{jet}+X}}{\mathrm{d}\eta \mathrm{d}p_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k^{\mathrm{med}}$$

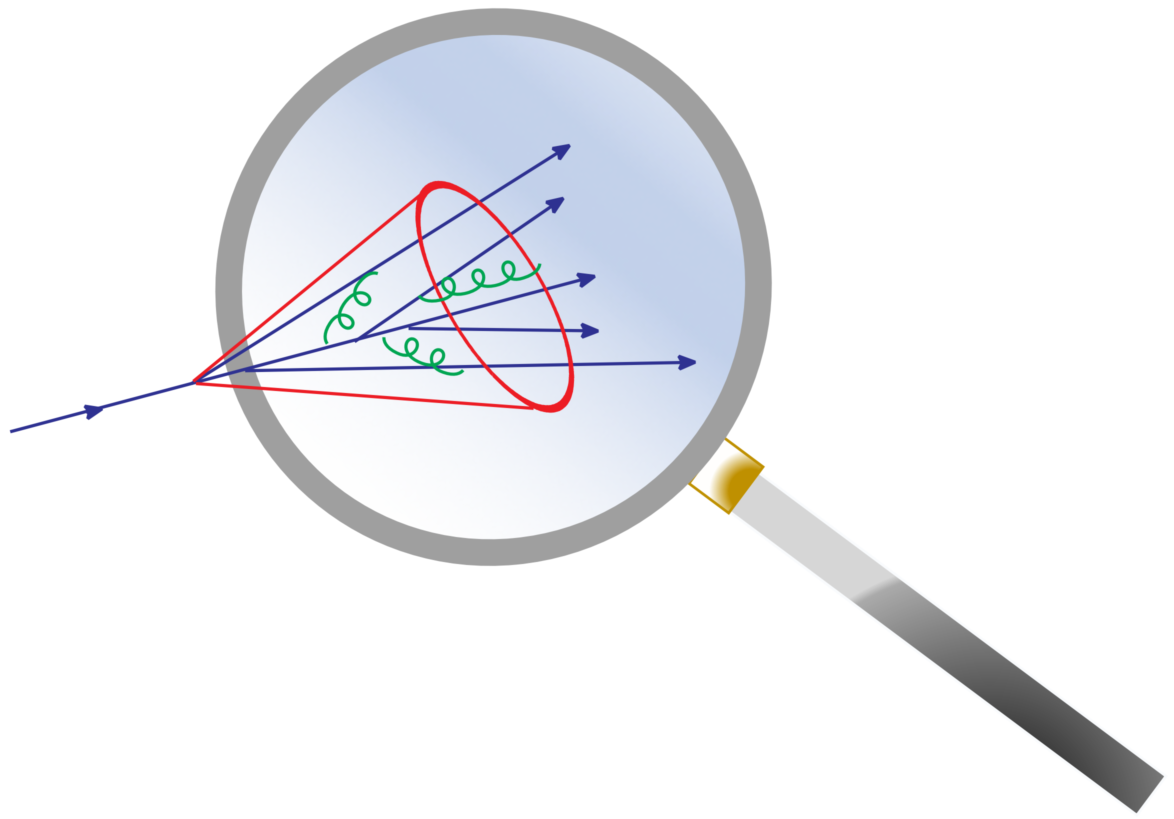
Jet quenching and energy loss

- QCD factorization & universality?



$$\frac{d\sigma_{pp\to \text{jet}+X}}{d\eta dp_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k^{\text{med}}$$

- What is the (maximal) information content of jet substructure observables?
- How many jet substructure observables do we need to measure?
- How to systematically make use of all the information provided by sPHENIX?



Outline

Introduction

Inclusive jets & quark/gluon fractions

Machine-learned jet substructure observables

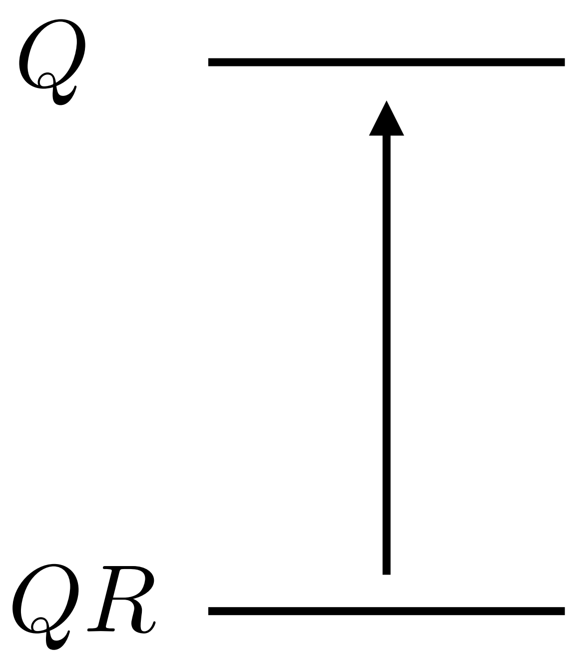
Inclusive jet cross sections

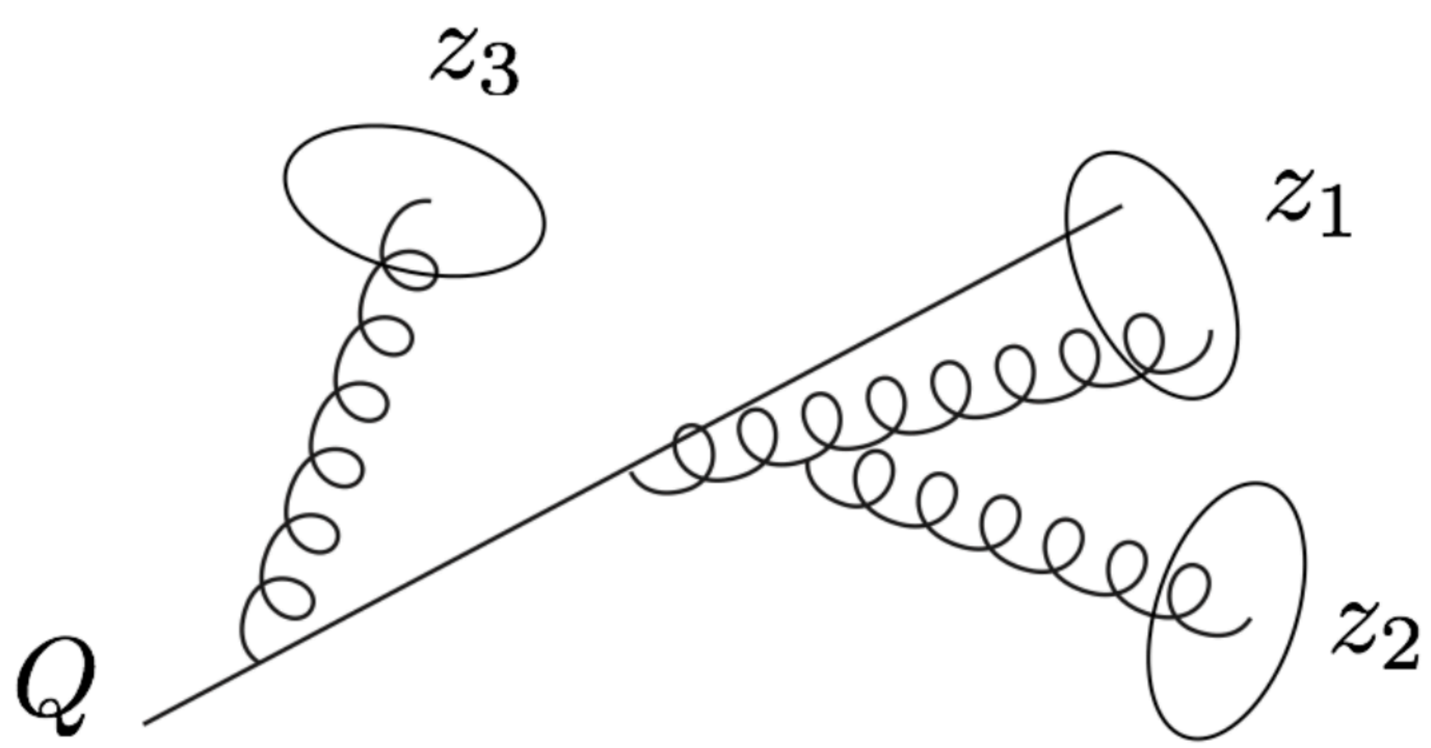
- **Factorization**

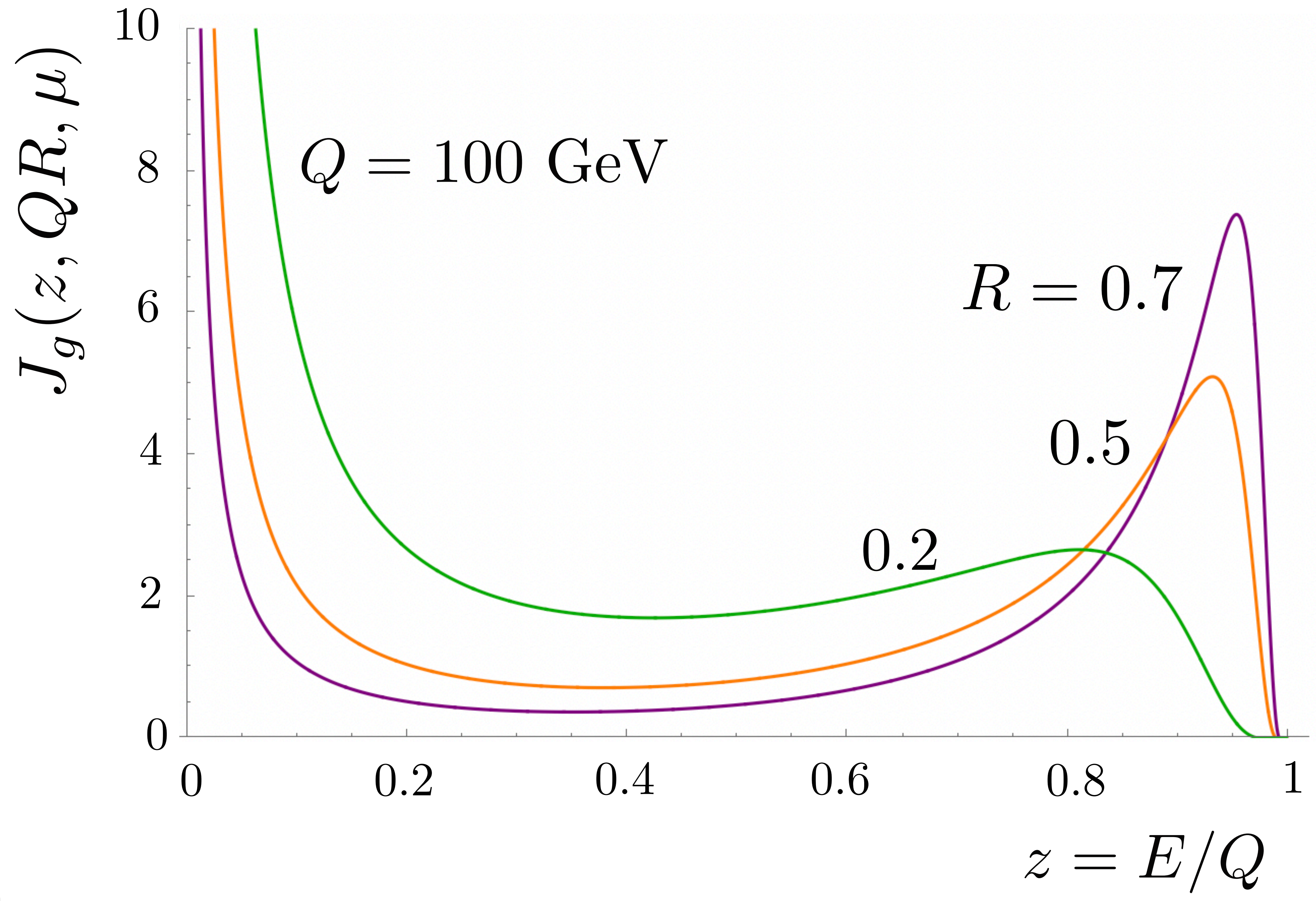
$$\frac{d\sigma_{pp\to \mathrm{jet}+X}}{d\eta dp_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k$$

- **DGLAP evolution**

$$\mu \frac{d}{d\mu} J_i = \frac{\alpha_s}{2\pi} \sum_j P_{ji} \otimes J_j$$







Dasgupta, Dreyer, Salam, Soyez `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16
Liu, Moch, Ringer `18, `19

Inclusive jets in heavy-ion collisions

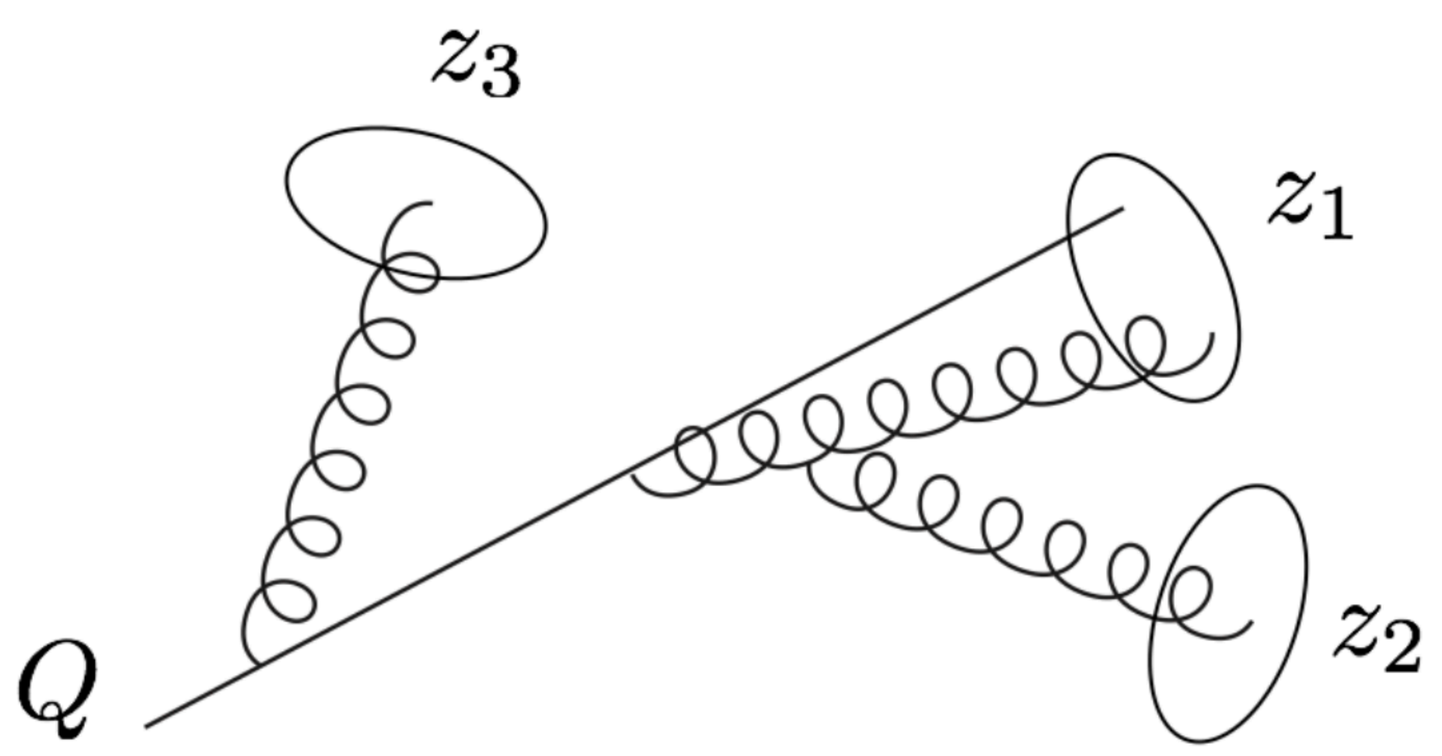
- Factorization - can we systematically extend vacuum factorization theorems in vacuum to heavy-ion collisions?

$$\frac{d\sigma_{pp\to \text{jet}+X}}{d\eta dp_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k$$

→ Heavy-ion collisions? J_k^{med}

- Quark/gluon fractions for jet substructure observables

$$f_q J_q(\tau) + f_g J_g(\tau)$$



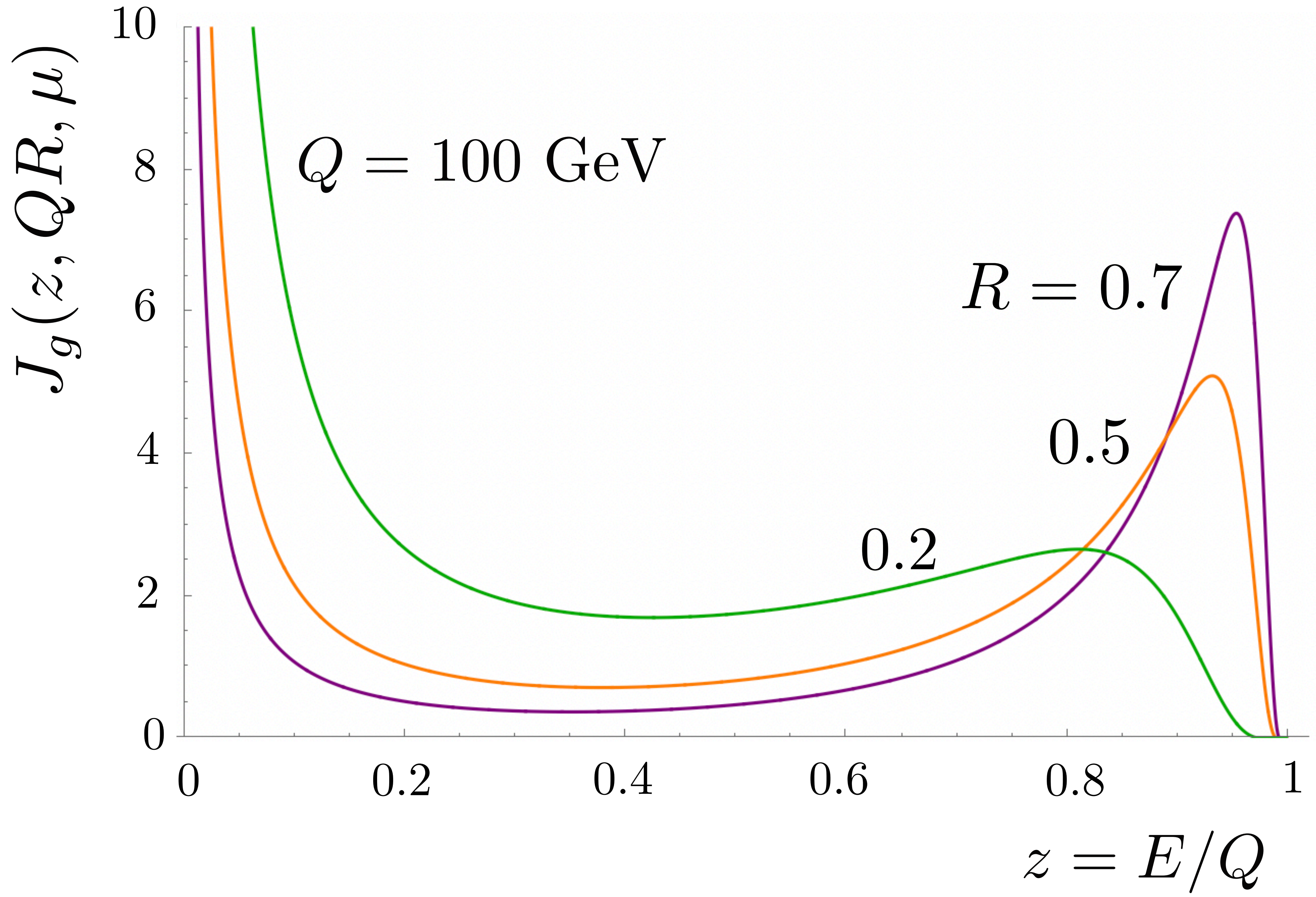
Inclusive jets in heavy-ion collisions

Qiu, FR, Sato, Zurita `19

- Introduce medium modified jet function at the jet scale

$$J_c^{\text{med}}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)$$

$$W_c(z) = \epsilon_c \delta(1-z) + N_c\, z^{\alpha_c} (1-z)^{\beta_c}$$



- Monte Carlo sampling approach

NNPDF `17, JAM `16

nPDFs	*Eskola, Paakkinen, Paukkunen, Salgado `17, Kovarik et al. `16* *de Florian, Sassot, Zurita, Stratmann `12*
nFFs	*Sassot, Stratmann, Zurita `10*

Inclusive jets in heavy-ion collisions

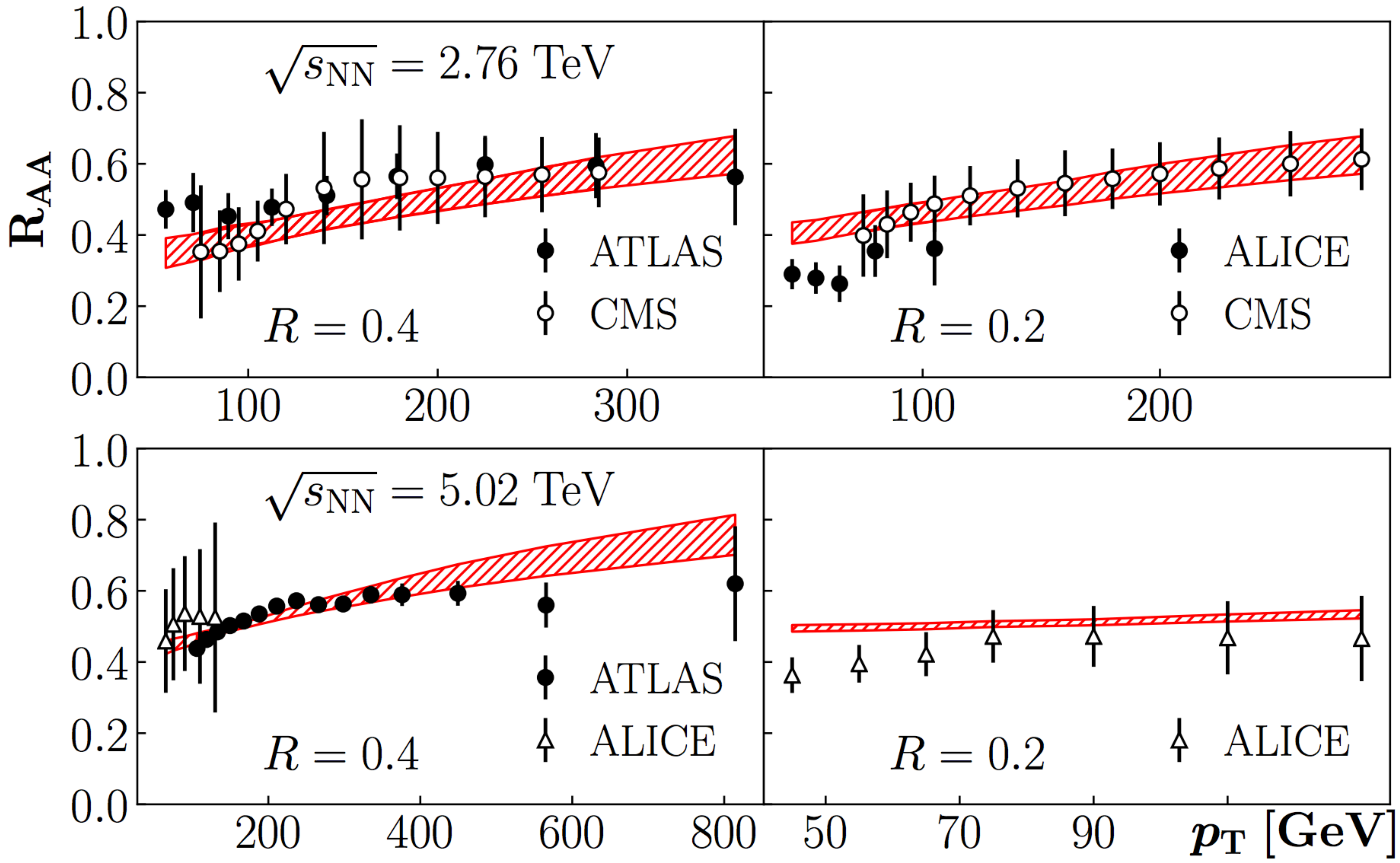
Qiu, FR, Sato, Zurita `19

$\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

$\chi^2/\mathrm{d.o.f.} = 1.1$

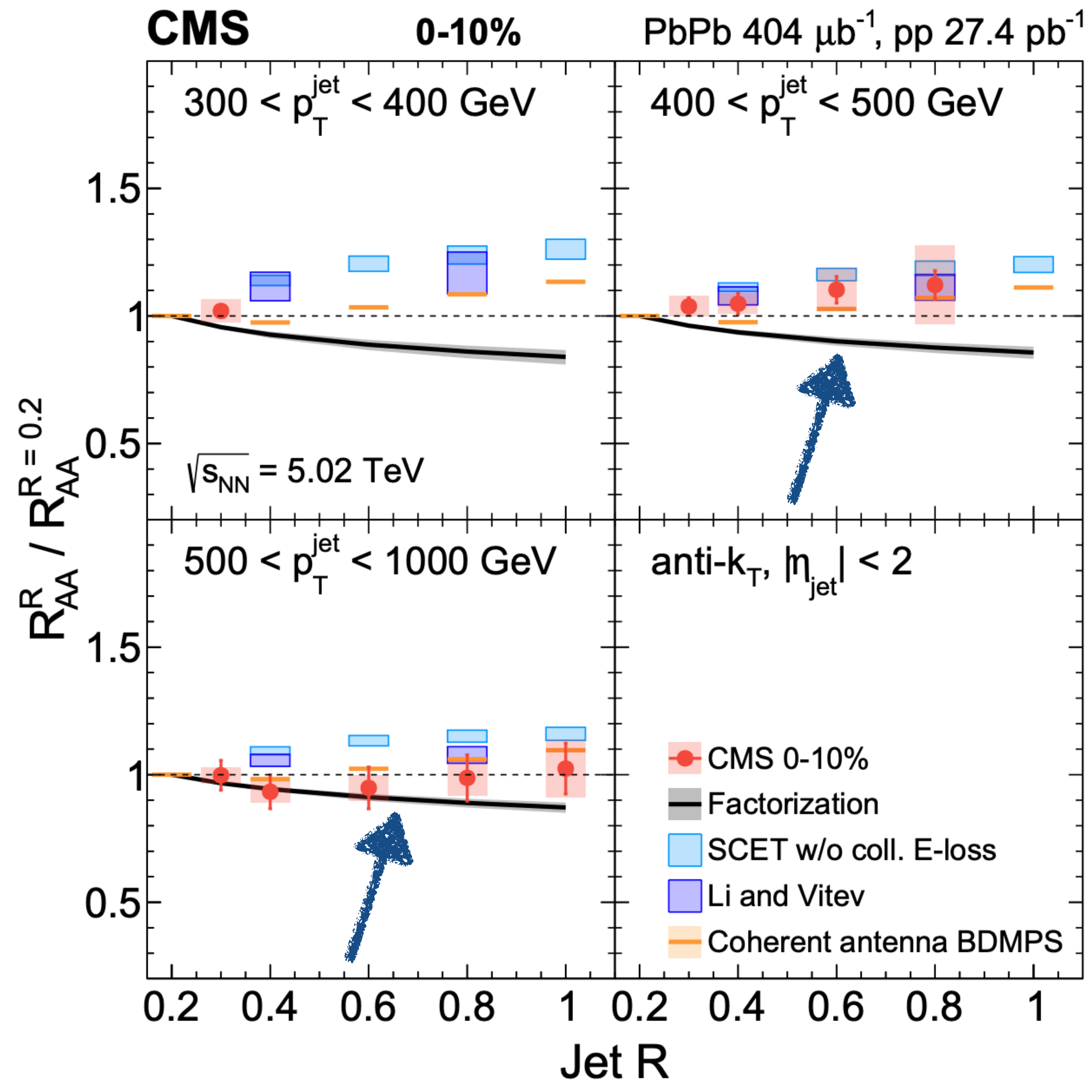
$\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

$\chi^2/\mathrm{d.o.f.} = 1.7$

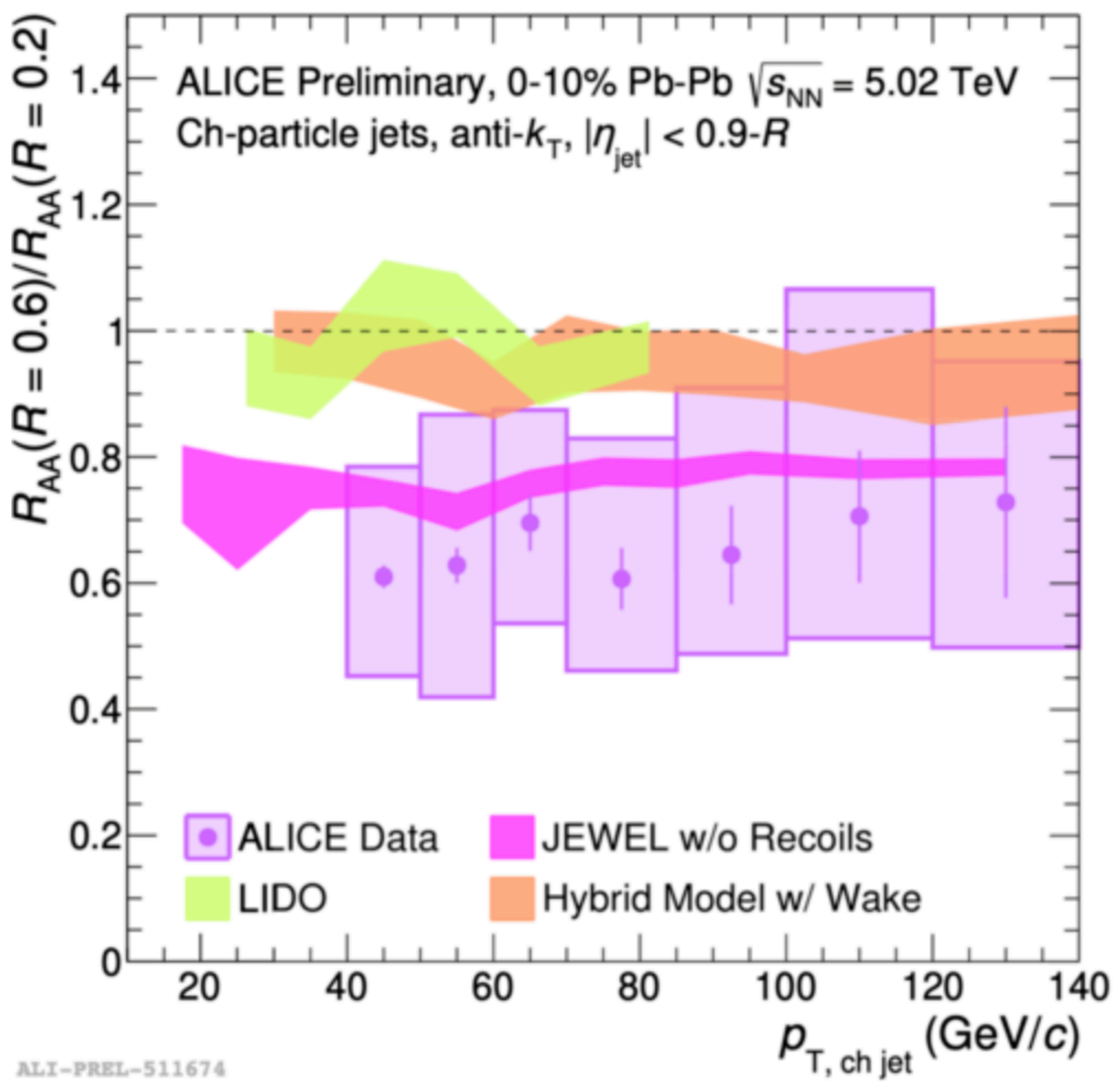


ALICE, PLB 746 (2015) 1
ATLAS, PRL 114 (2015) 072302
CMS, PRC 96 (2017) 015202
ALICE preliminary
ATLAS, PLB 790 (2019) 108

Inclusive jet R_{AA} - radius dependence



CMS, JHEP 05 (2021) 284



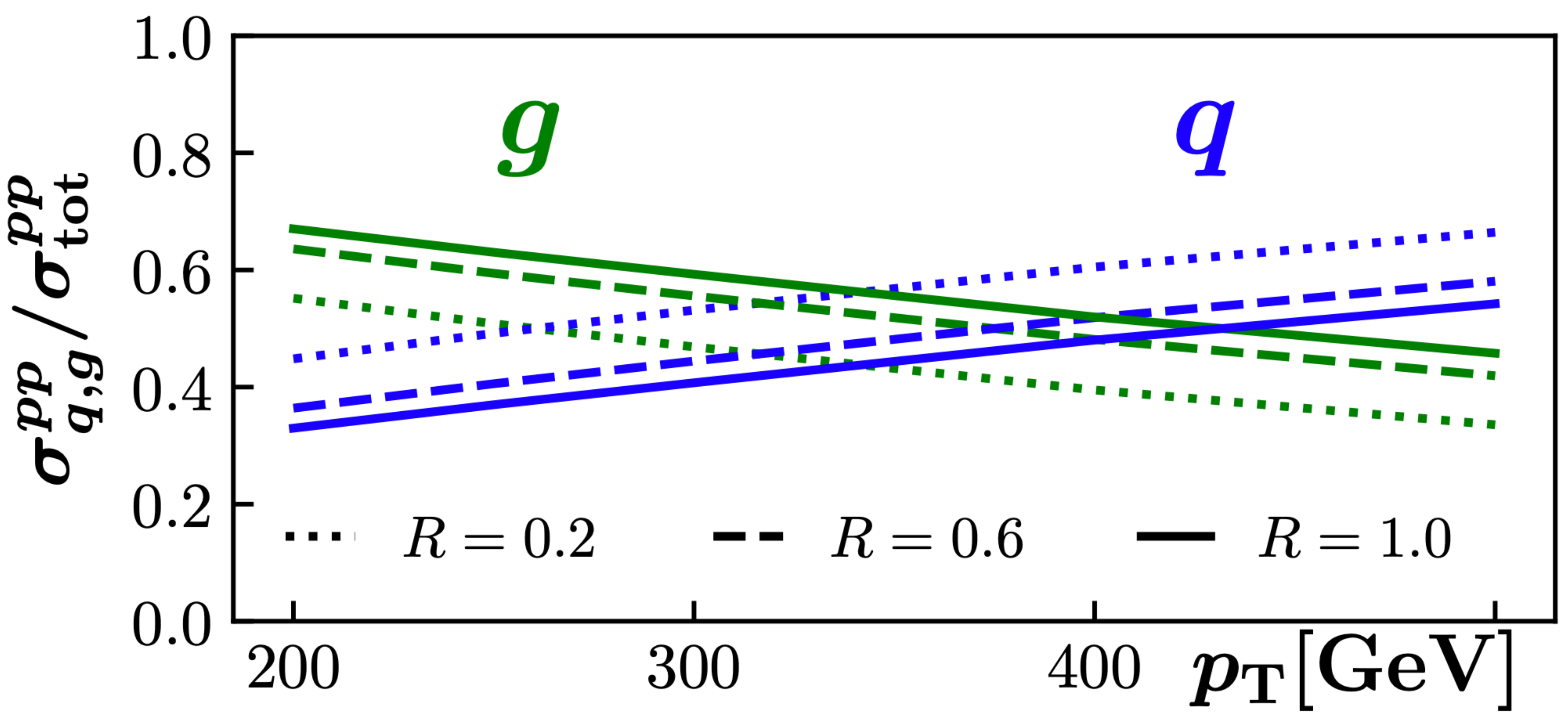
http://alice-figure.web.cern.ch/node/15723/

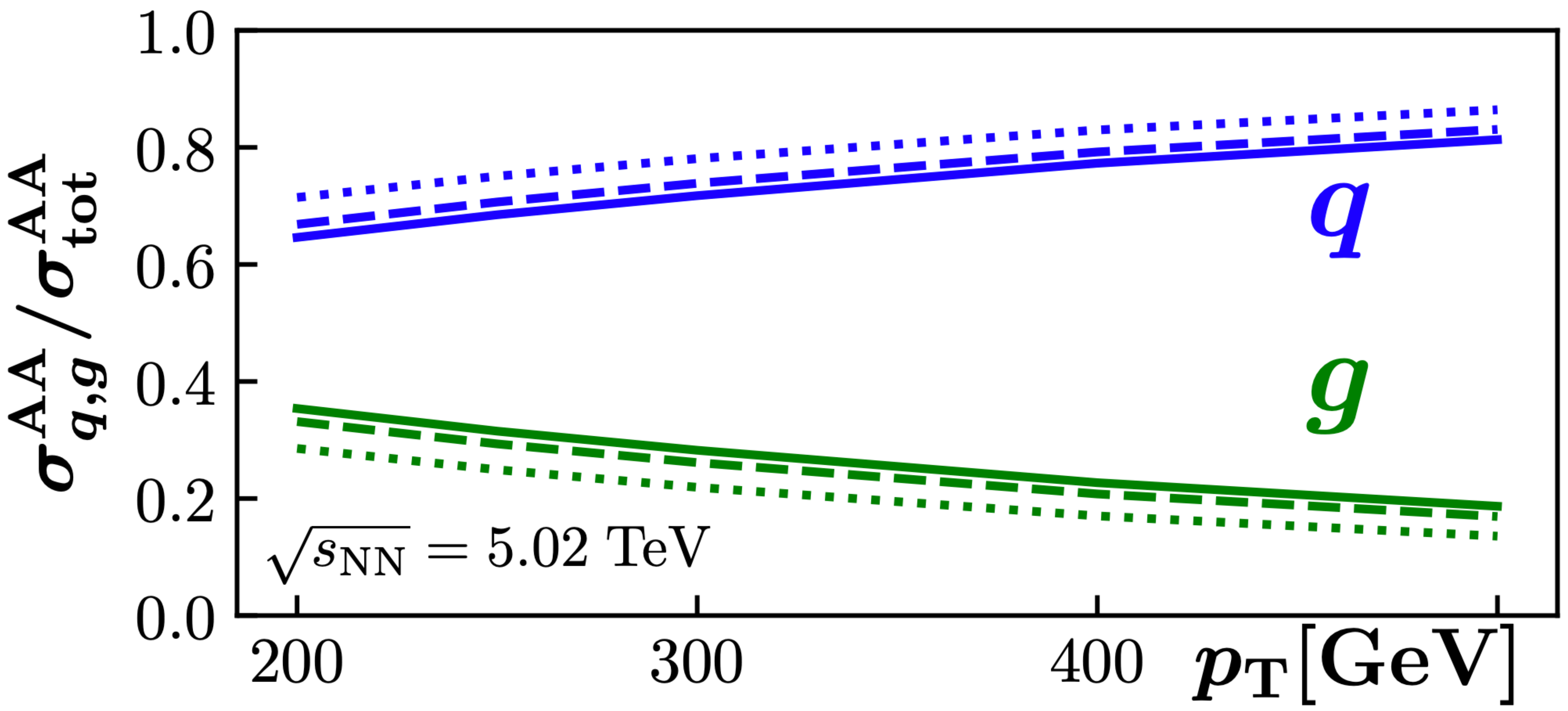
- Data could be included in an updated fit

In-medium quark/gluon fractions

- Quark/gluon fractions defined at leading power in the jet radius
- Significant shift toward quark jets in the medium

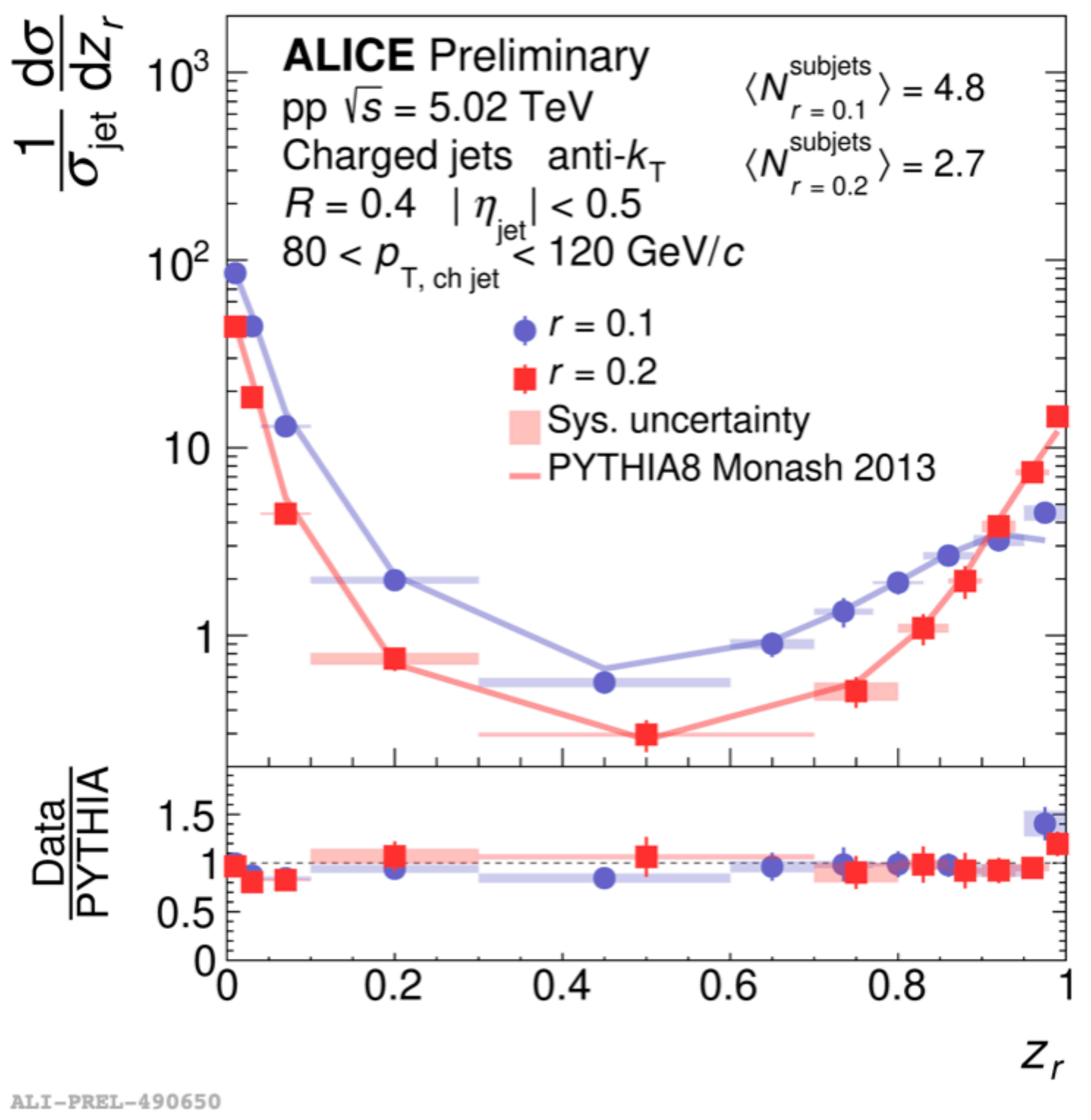
$$f_q J_q(\tau) + f_g J_g(\tau)$$?



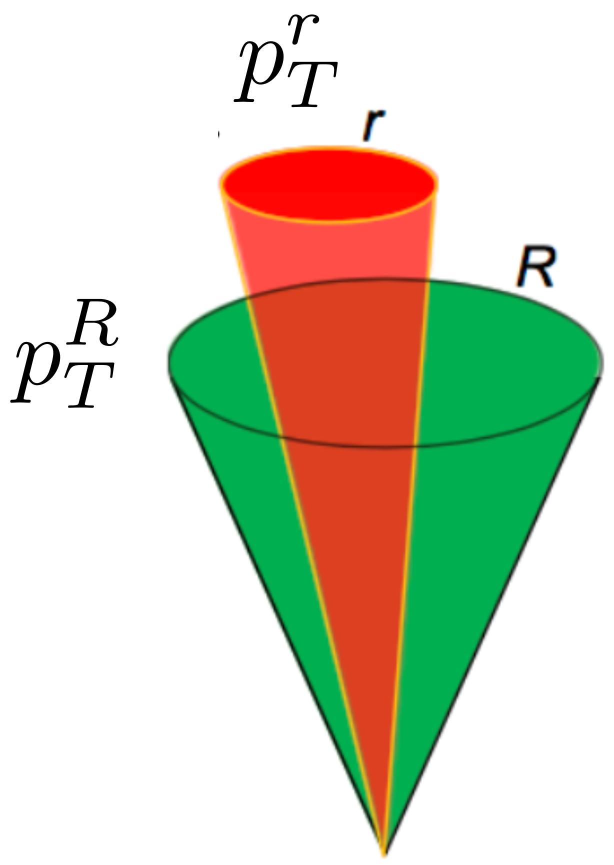


Applications to jet substructure

- Leading & inclusive subjets in pp



$$z_r = p_T^r / p_T^R$$



- Similar factorization in heavy-ion?

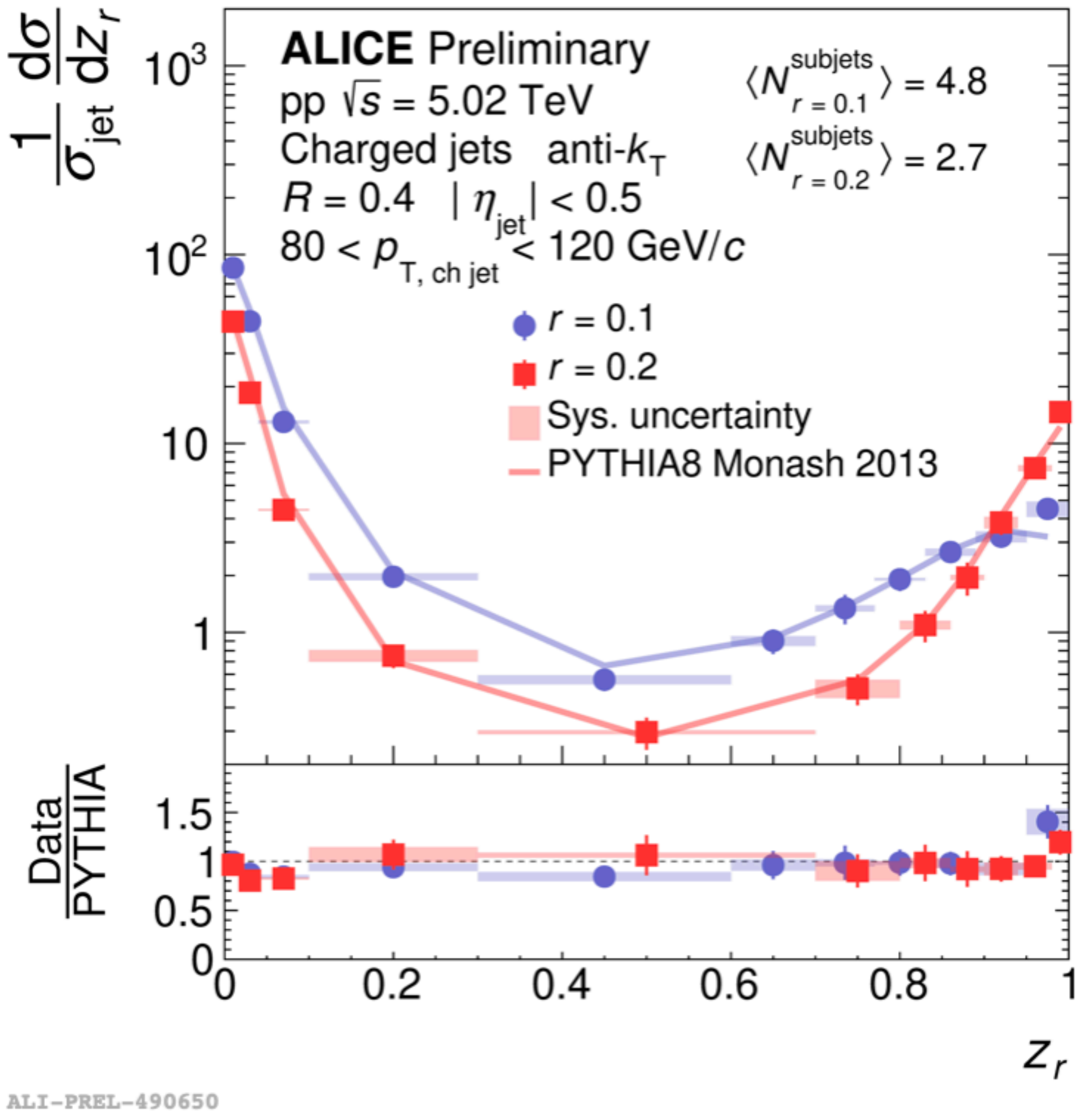
$$\sum_{abcd} f_a \otimes f_b \otimes H_{abc} \otimes J_{cd}^{\rm med} \times J_d^{\rm med}(z_r)$$

see *Dai, Kim, Leibovich `16*
Kang, FR, Waalewijn `17
Neill, FR, Sato `21

<u>*https://alice-figure.web.cern.ch/node/19990*</u>

Applications to jet substructure

- Leading & inclusive subjets in pp



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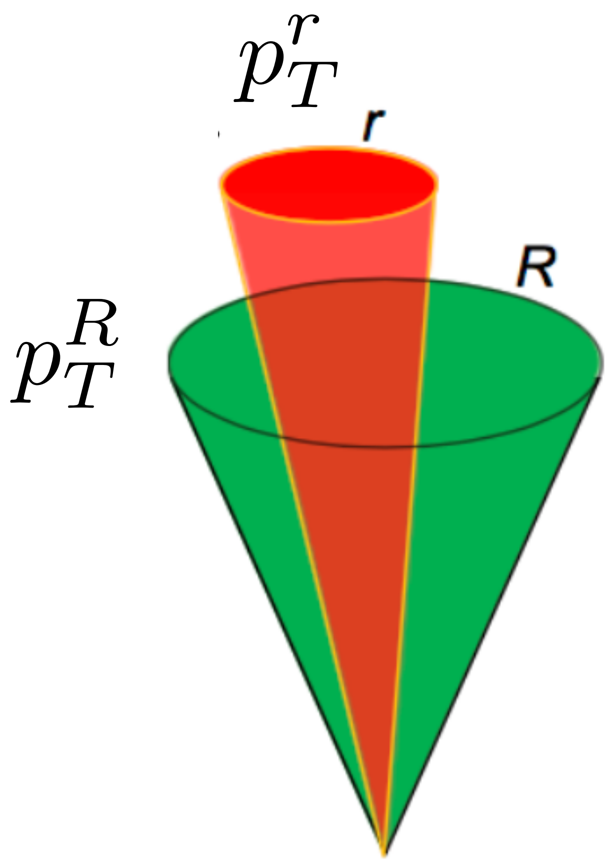
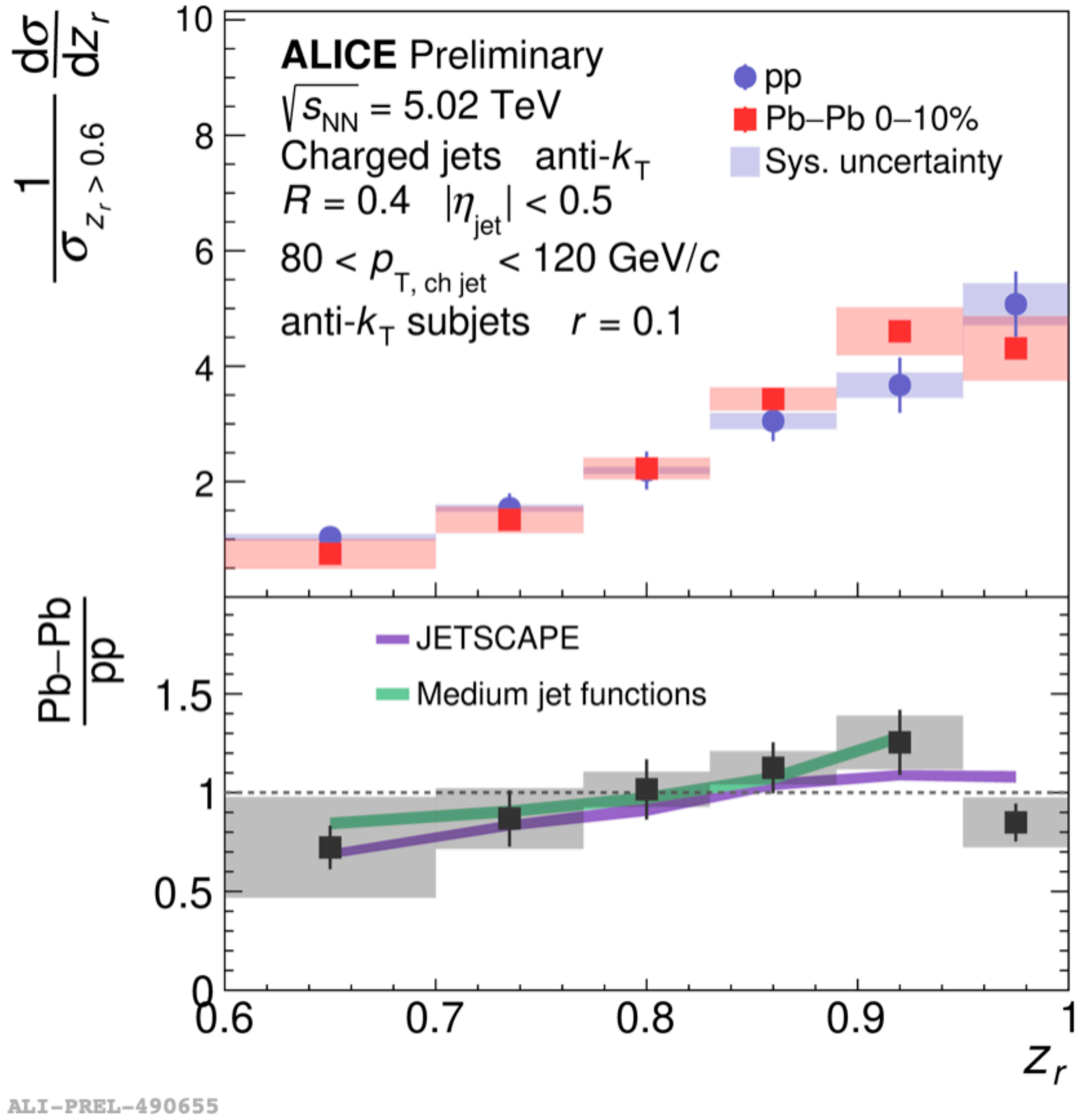


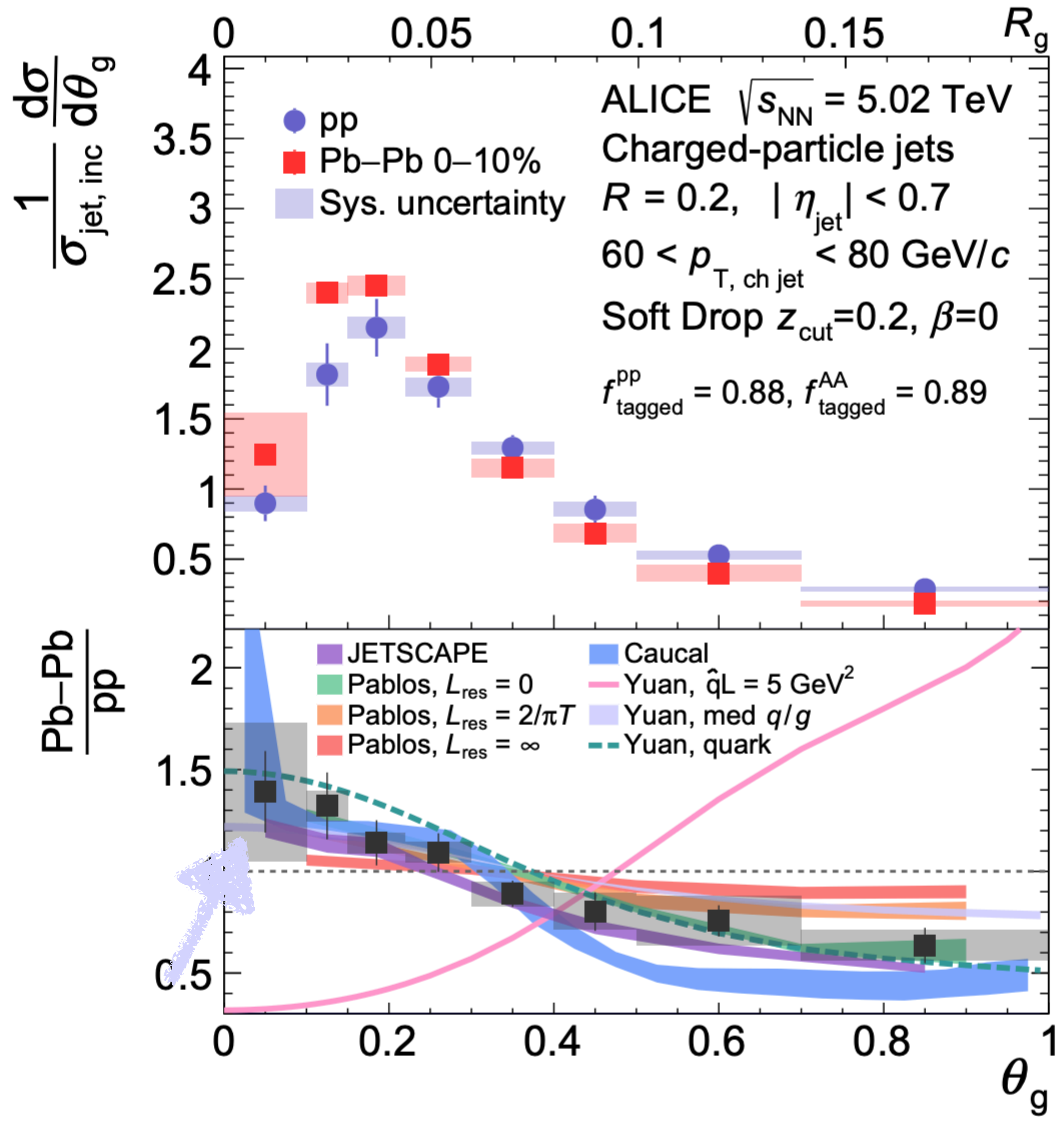


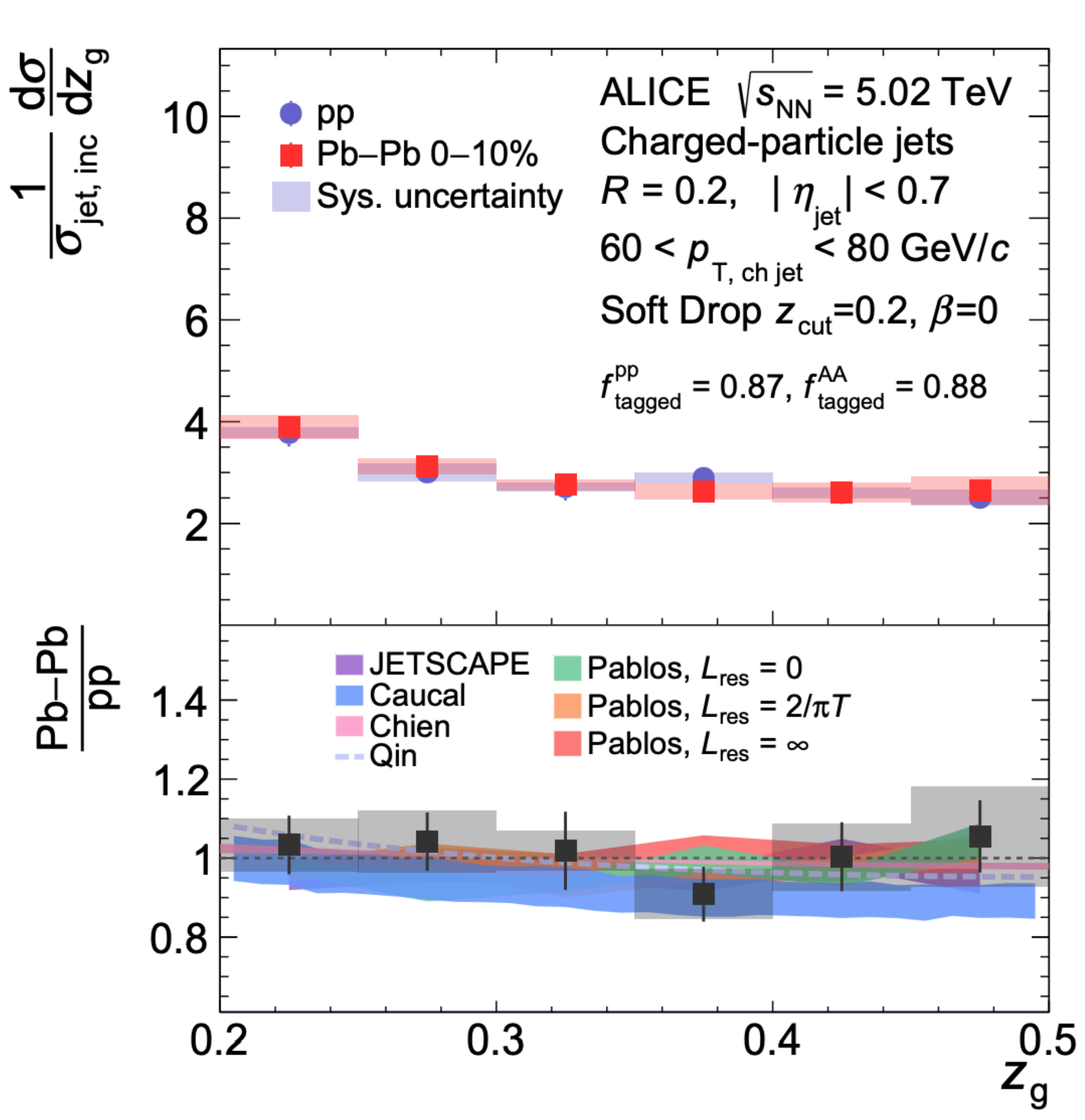
https://alice-figure.web.cern.ch/node/19990

see Dai, Kim, Leibovich `16
Kang, FR, Waalewijn `17
Neill, FR, Sato `21

Applications to jet substructure

- Soft drop groomed observables

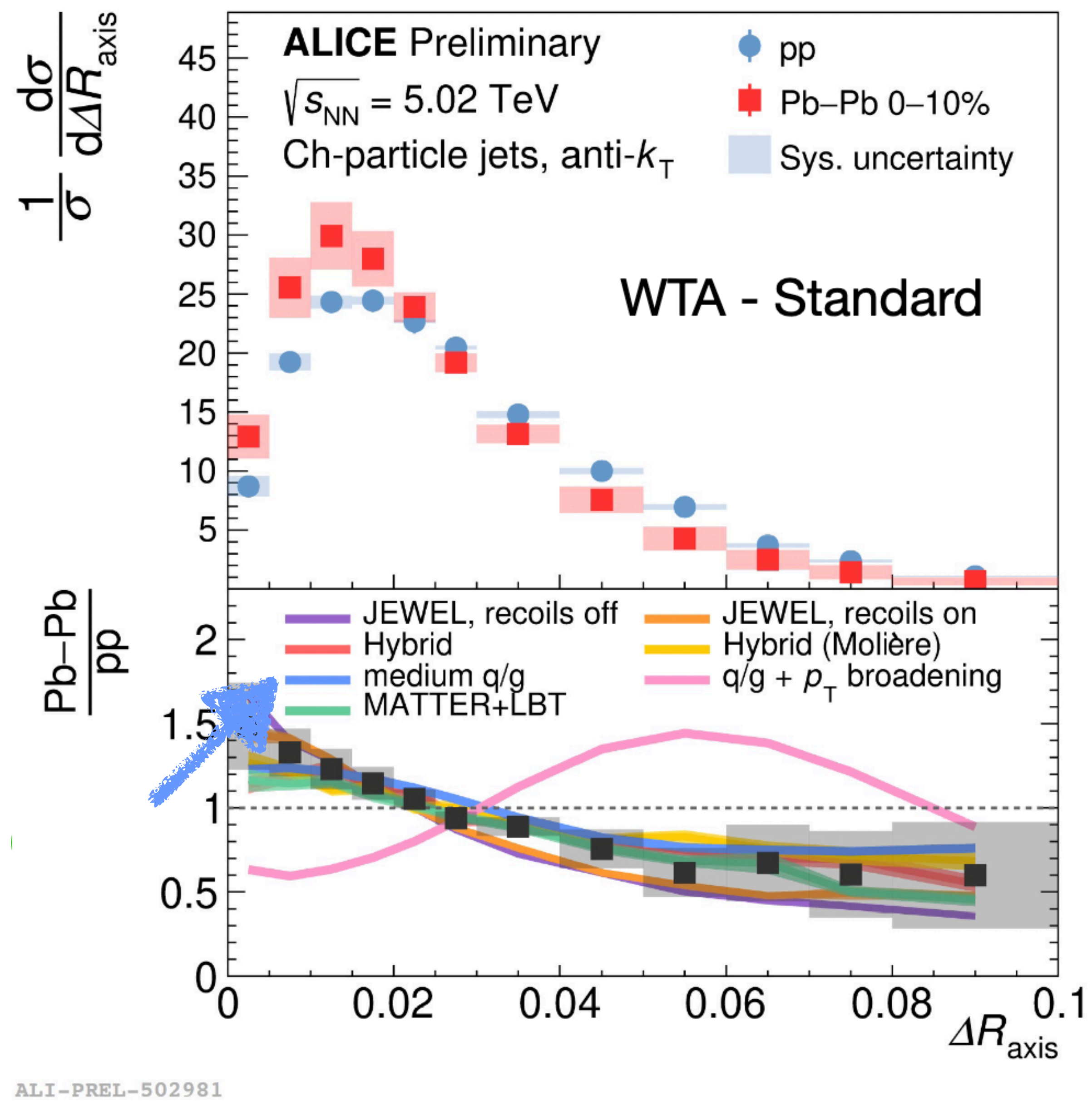




ALICE, 2107.12984

see also recent ATLAS measurement at higher jet p_T

- Angles between jet axes



$$f_q J_q(\tau) + f_g J_g(\tau)$$

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Machine-learned jet substructure observables

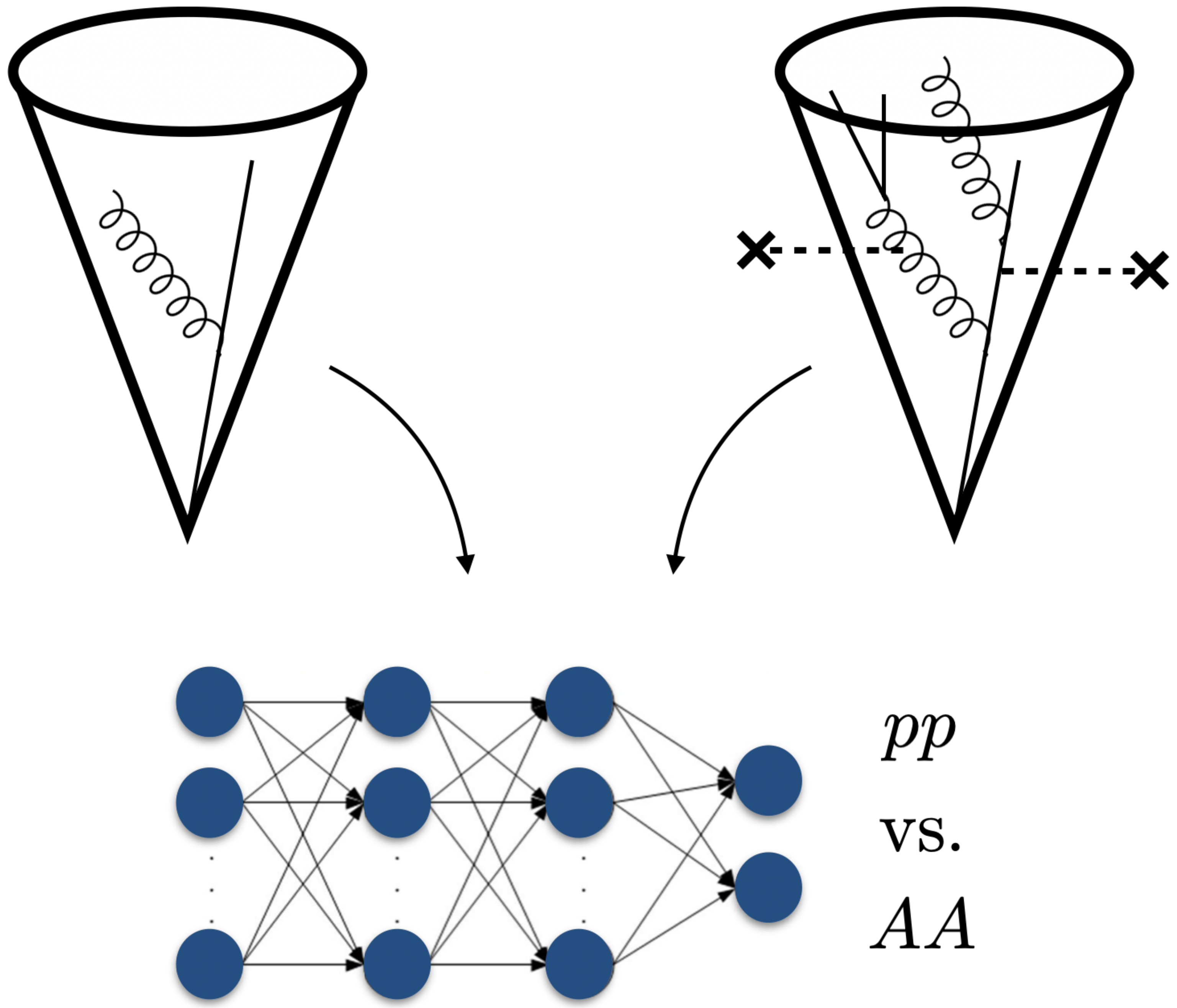
Upper bounds on the information content?

Lai, Mulligan, Ploskon, FR `21

Use machine learning to find an event-by-event "observable"

→ Can formulate as a binary classification problem

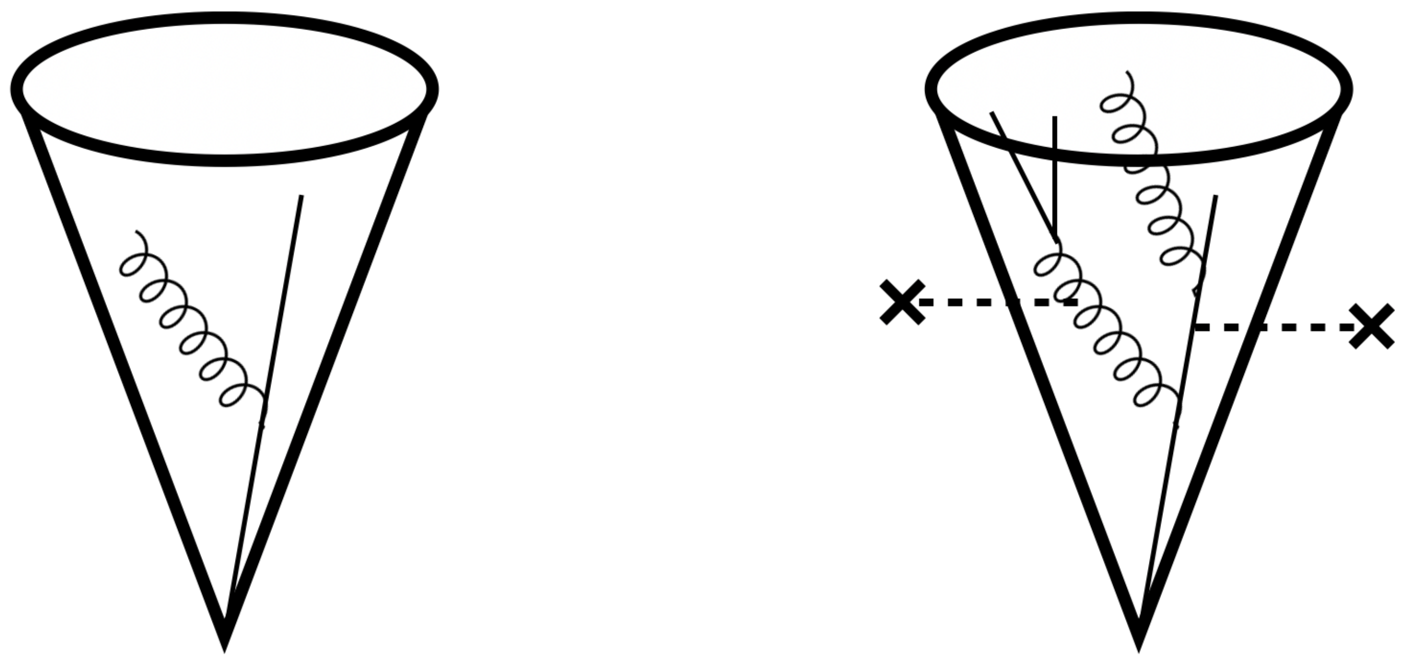
→ Compare performance of classifier to traditional observables



Upper bounds on the information content?

Lai, Mulligan, Ploskon, FR `21

- pp & AA jets generated in Pythia/Jewel
- Use deep sets that are known to be one of the best quark/gluon classifiers



$$f(p_1, \ldots, p_M) = F\left(\sum_{i=1}^{M} \Phi\left(p_i\right)\right)$$

Classifier

DNNs

Zaheer et al. 1703.06114
Wagstaff et al. 1901.09006
Bloem-Reddy, Teh JMLR 21 90 (2020)

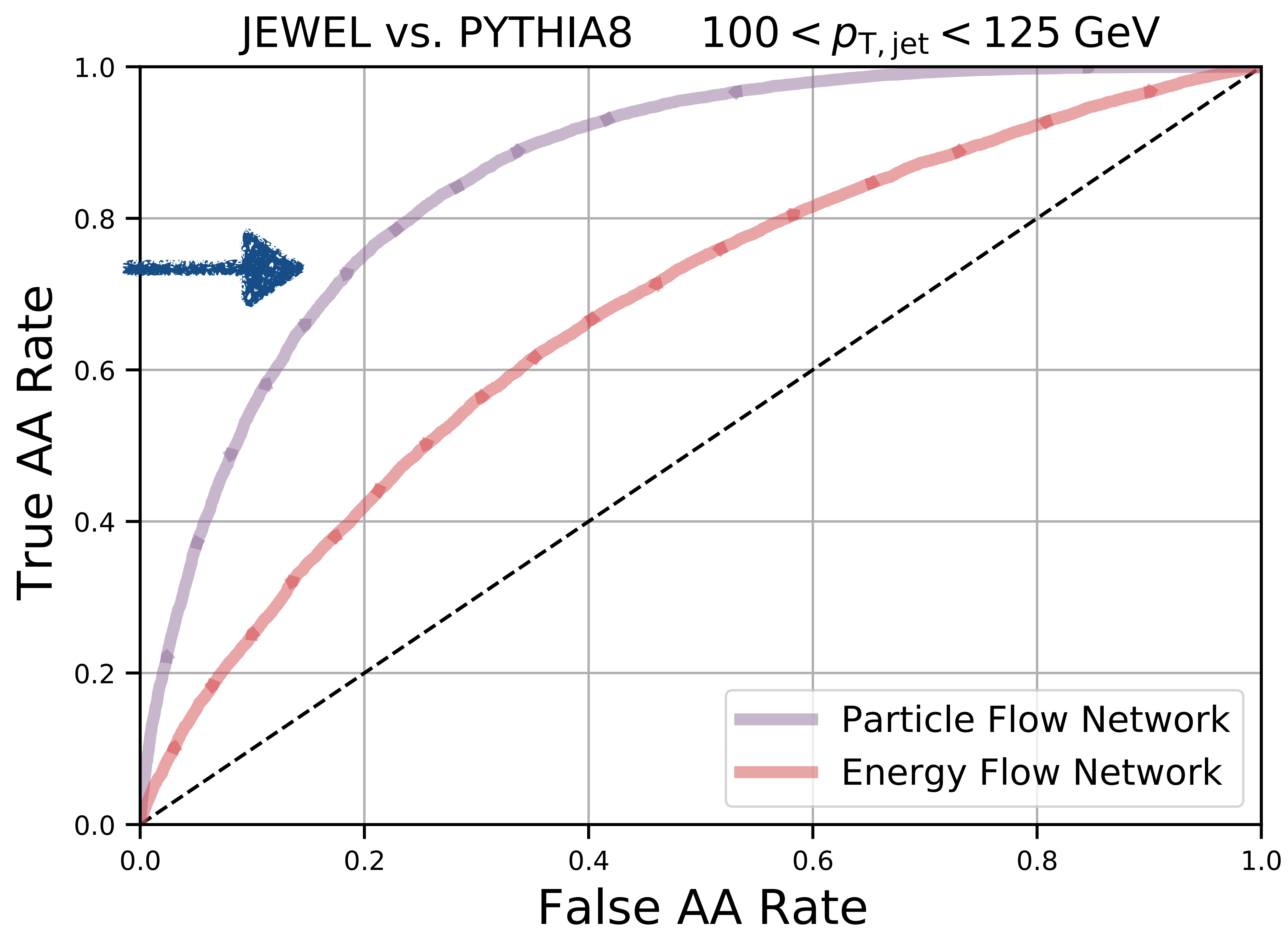
Input is the set of particle 4-momenta

Komiske, Metodiev, Thaler `19

Upper bounds on the information content?

Lai, Mulligan, Ploskon, FR `21

- Quantify performance using ROC curves



- ML significantly outperforms traditional observables

- There is a lot more information in quenched jets that we are currently not making use of

See also Chien, Elayavalli; Apolinario, Castro, Romao, Milhano, Pedro, Peres; Liu, Velkovska, Verweij

Upper bounds on the information content?

Lai, Mulligan, Ploskon, FR `21

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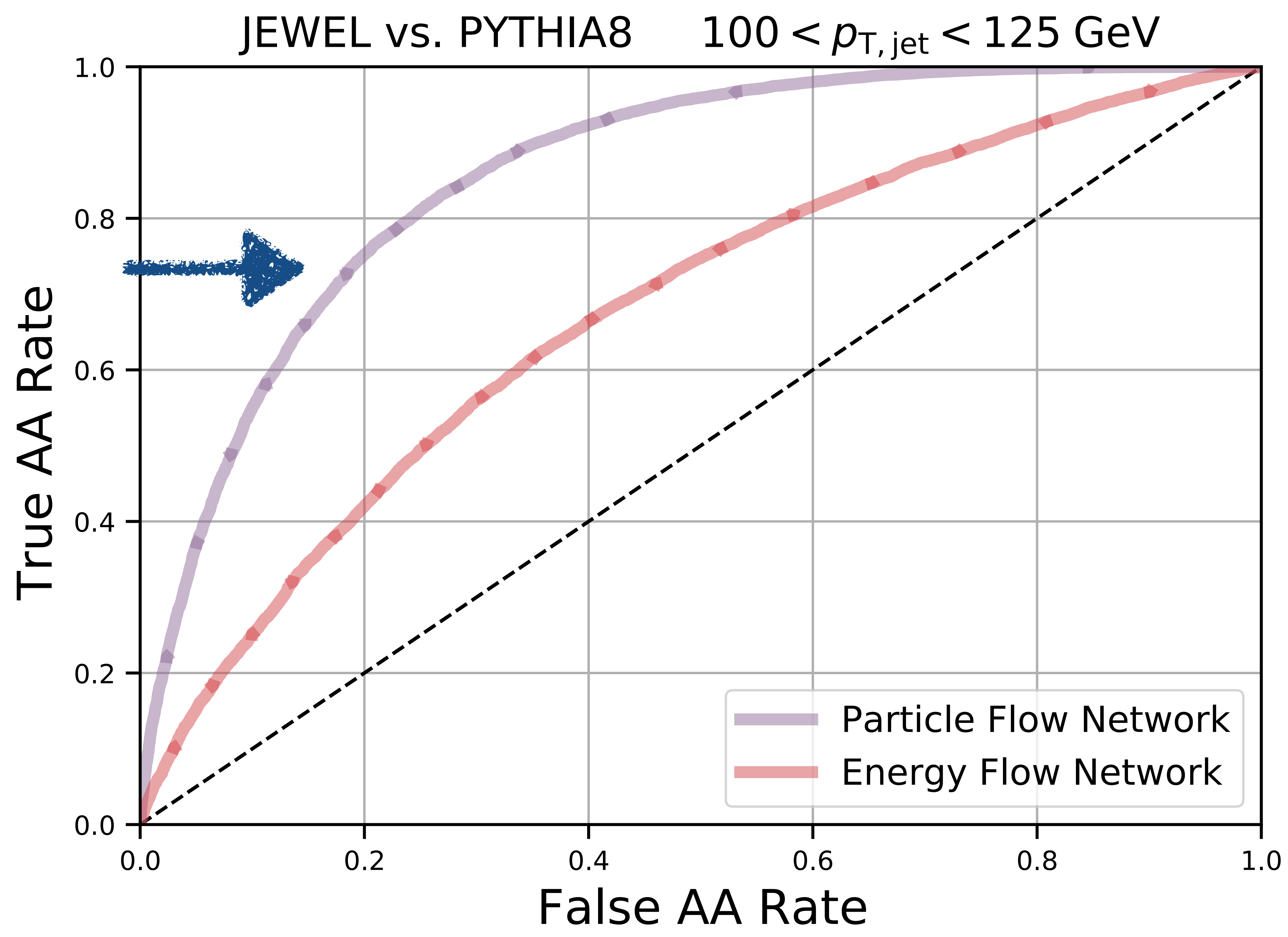

- ML significantly outperforms traditional observables
- There is a lot more information in quenched jets that we are currently not making use of
- Can we identify observables to close the information gap?

How to systematically use all the information?

Lai, Mulligan, Ploskon, FR `21

- Can use complete sets of observables
  - Basis of N-subjettiness observables *Datta, Larkoski `17 - `19*

$$\tau_N^{(\beta)} = \frac{1}{p_T^{\rm jet}} \sum_{i\in {\rm Jet}} p_{Ti} \min\left\{R_{1i}^\beta, R_{2i}^\beta, \ldots, R_{Ni}^\beta\right\}$$

$$\begin{aligned} &\text{2-body}: \ \tau_1^{(1)}, \tau_1^{(2)}, \\ &\text{3-body}: \ \tau_1^{(0.5)}, \tau_1^{(1)}, \tau_1^{(2)}, \tau_2^{(1)}, \tau_2^{(2)}, \\ &\vdots \\ &M\text{-body}: \ \tau_1^{(0.5)}, \tau_1^{(1)}, \tau_1^{(2)}, \ldots, \tau_{M-2}^{(0.5)}, \tau_{M-2}^{(1)}, \tau_{M-2}^{(2)}, \tau_{M-1}^{(1)}, \tau_{M-1}^{(2)}. \end{aligned}$$

  - Basis of Energy Flow Polynomials *Komiske, Metodiev, Thaler `17, Cal, Thaler, Waalewijn `22*

$$\mathrm{EFP}_G = \sum_{i_1=1}^{M} \cdots \sum_{i_V=1}^{M} z_{i_1} \cdots z_{i_V} \prod_{(k,l)\in E} \theta_{i_k i_l}$$

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Lai, Mulligan, Ploskon, FR `21

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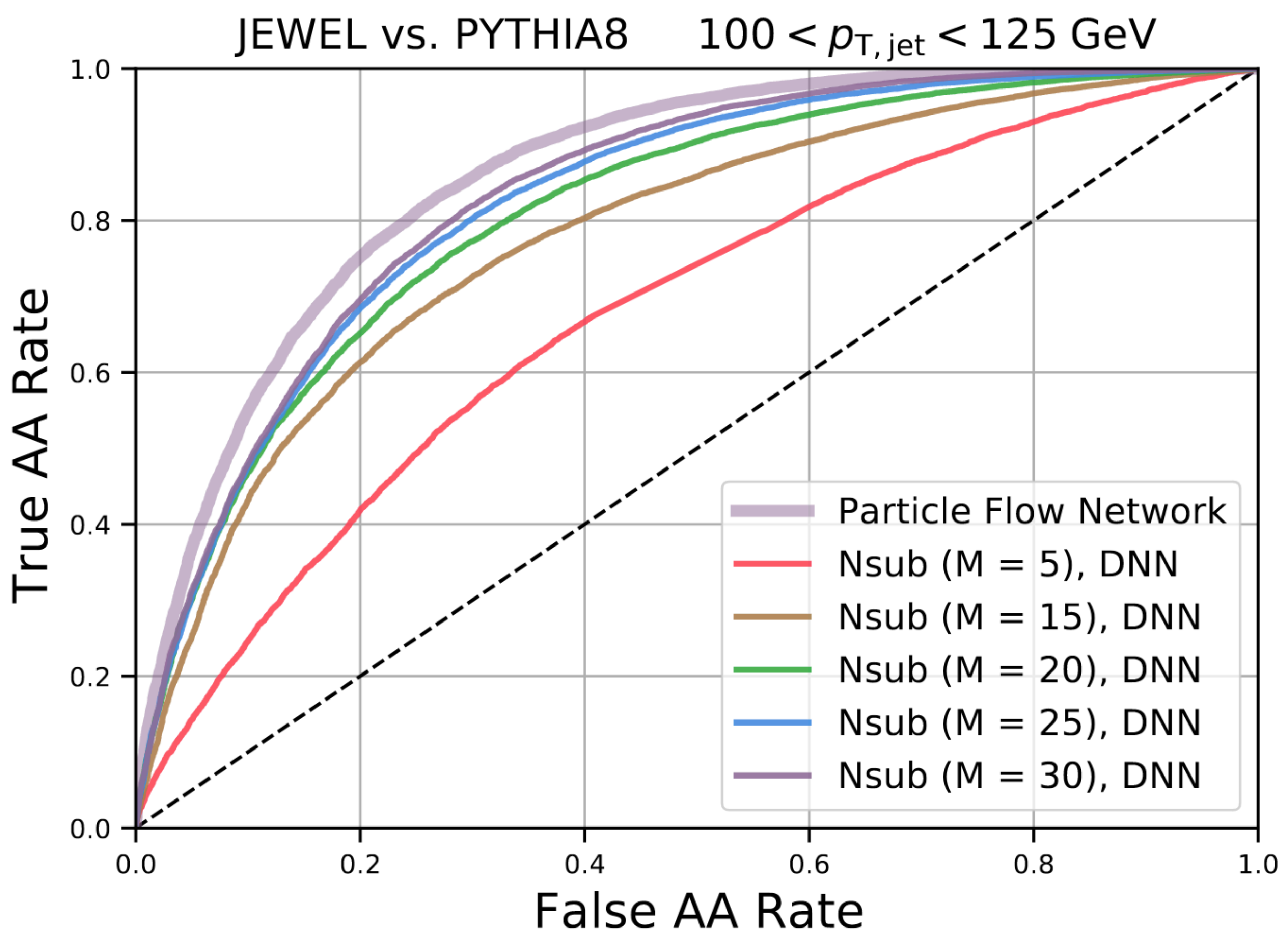

- Allows us to systematically approximate the full information content

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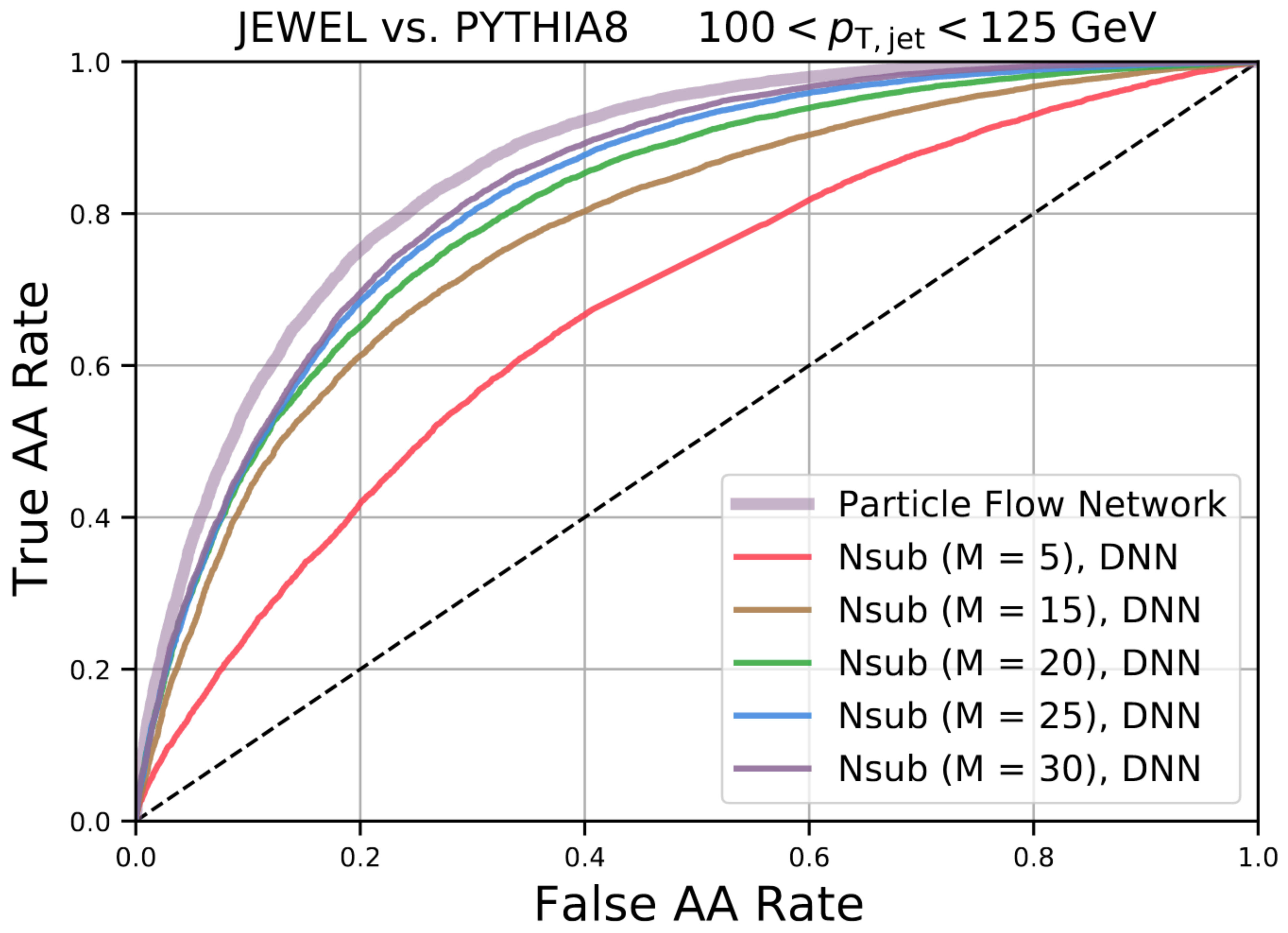

- Allows us to systematically approximate the full information content
- Using symbolic/Lasso regression we can identify the most important ones

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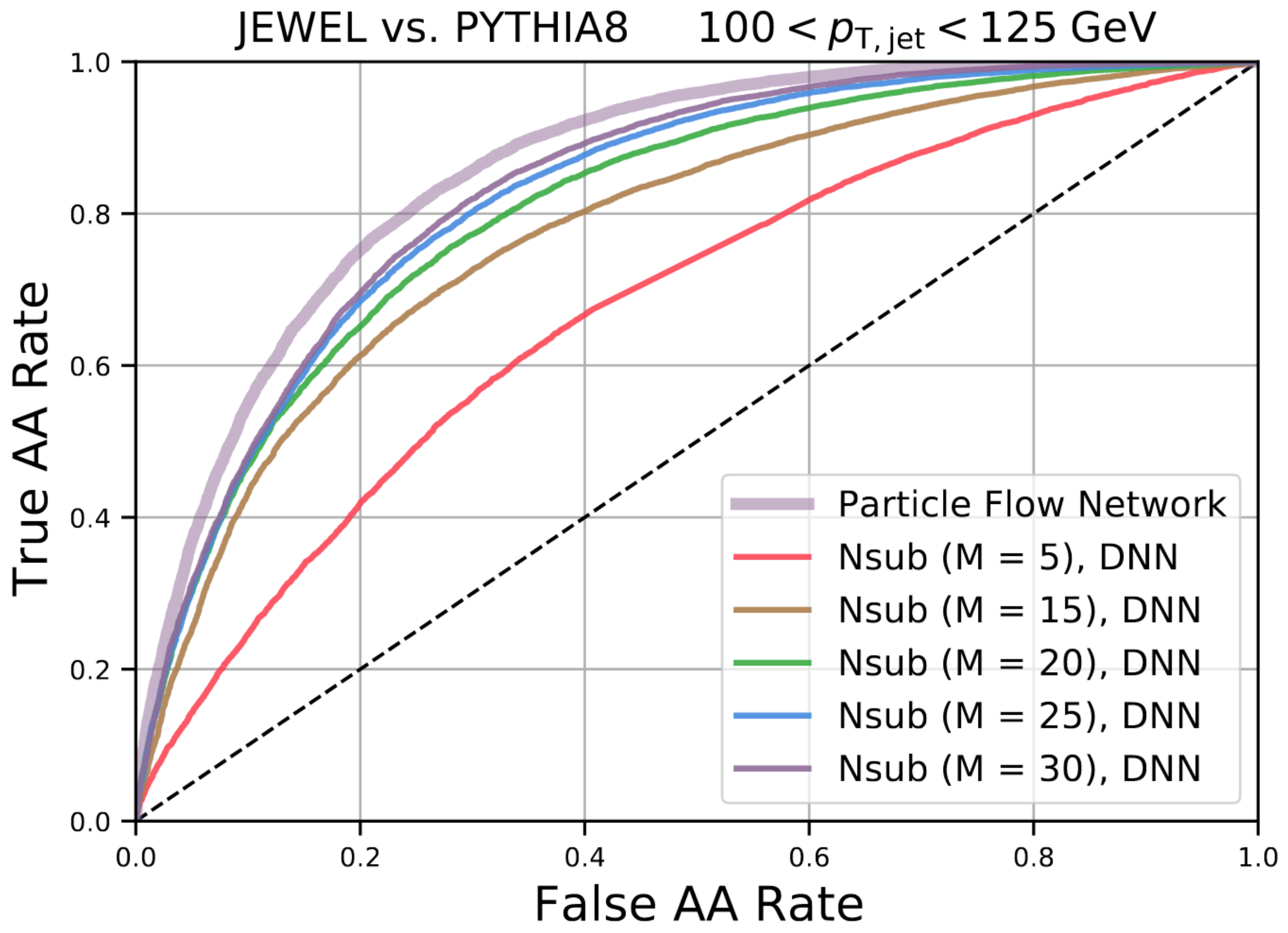

- Allows us to systematically approximate the full information content
- Using symbolic/Lasso regression we can identify the most important ones
- Heavy-ion background & analysis needs to be performed on data instead of simulations

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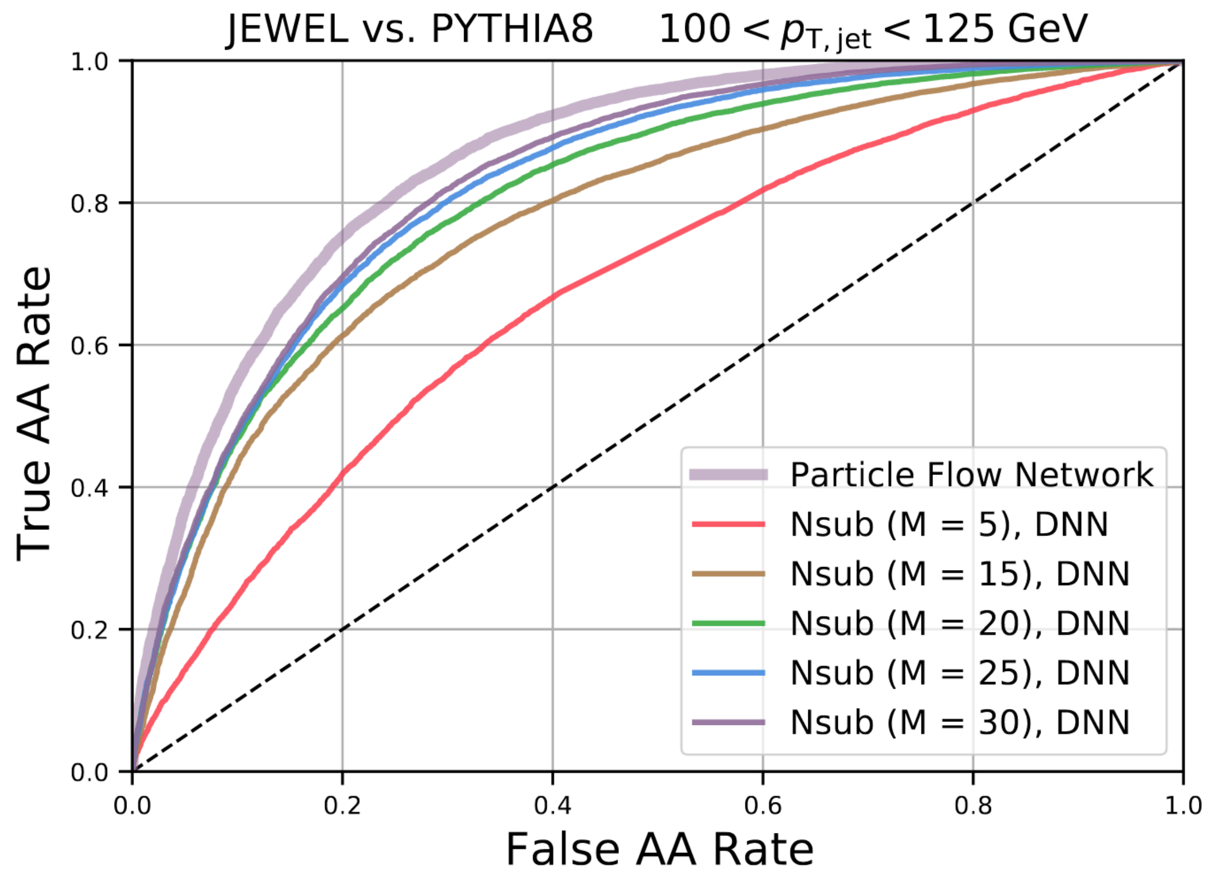
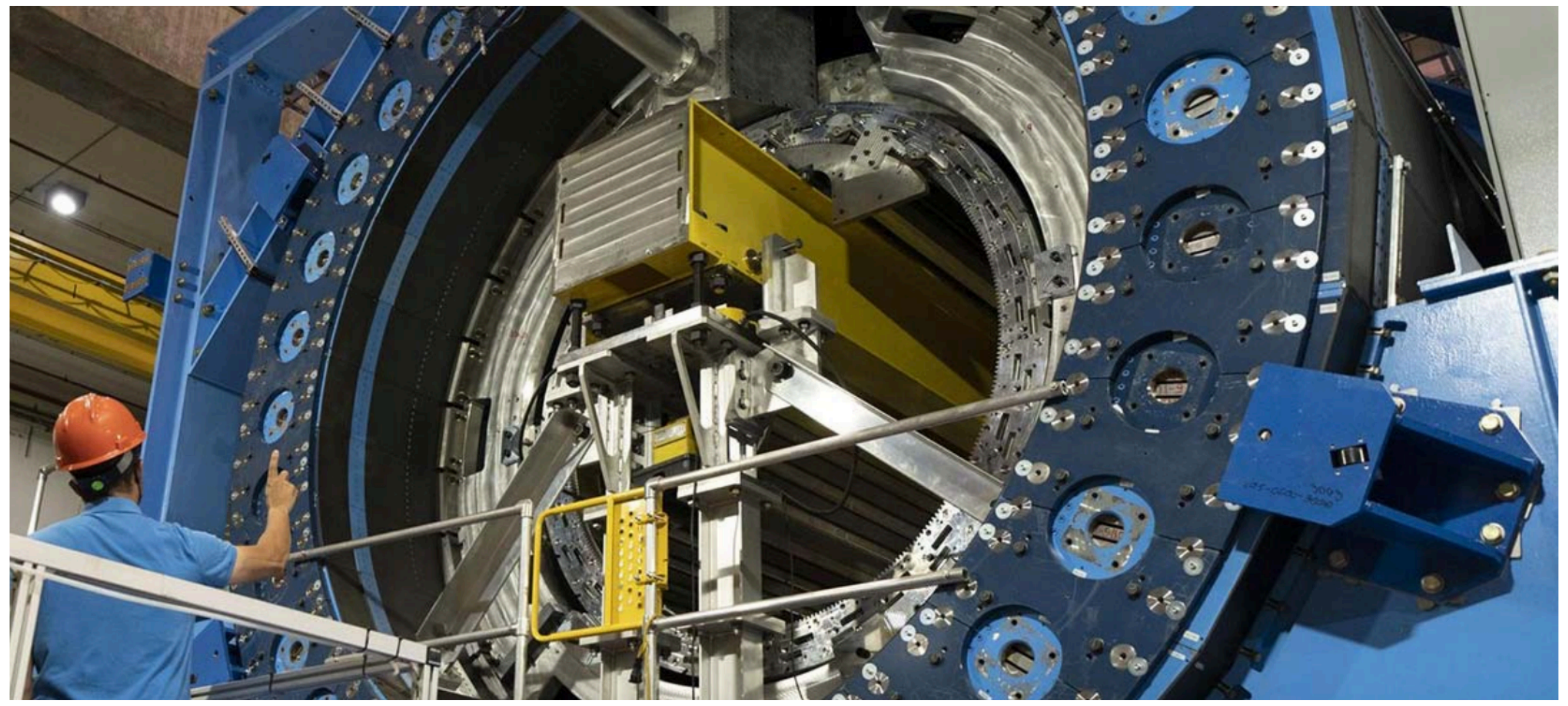
Machine-learned jet substructure observables

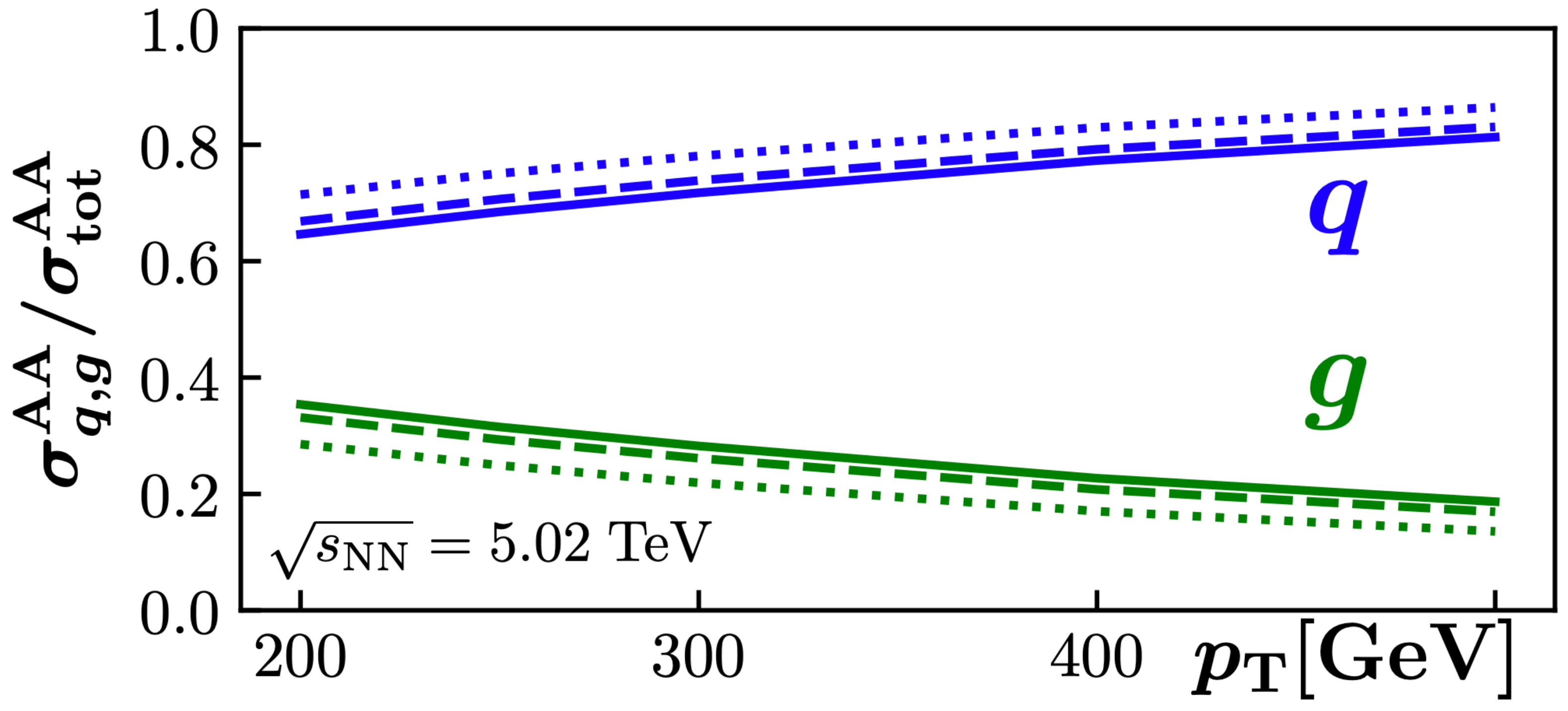
Conclusions

- Factorization and universality at RHIC energies with sPHENIX?
- Further theory developments needed

- Information content of jet substructure observables?
- Improved extraction of medium properties?
- Analyze data using ML?

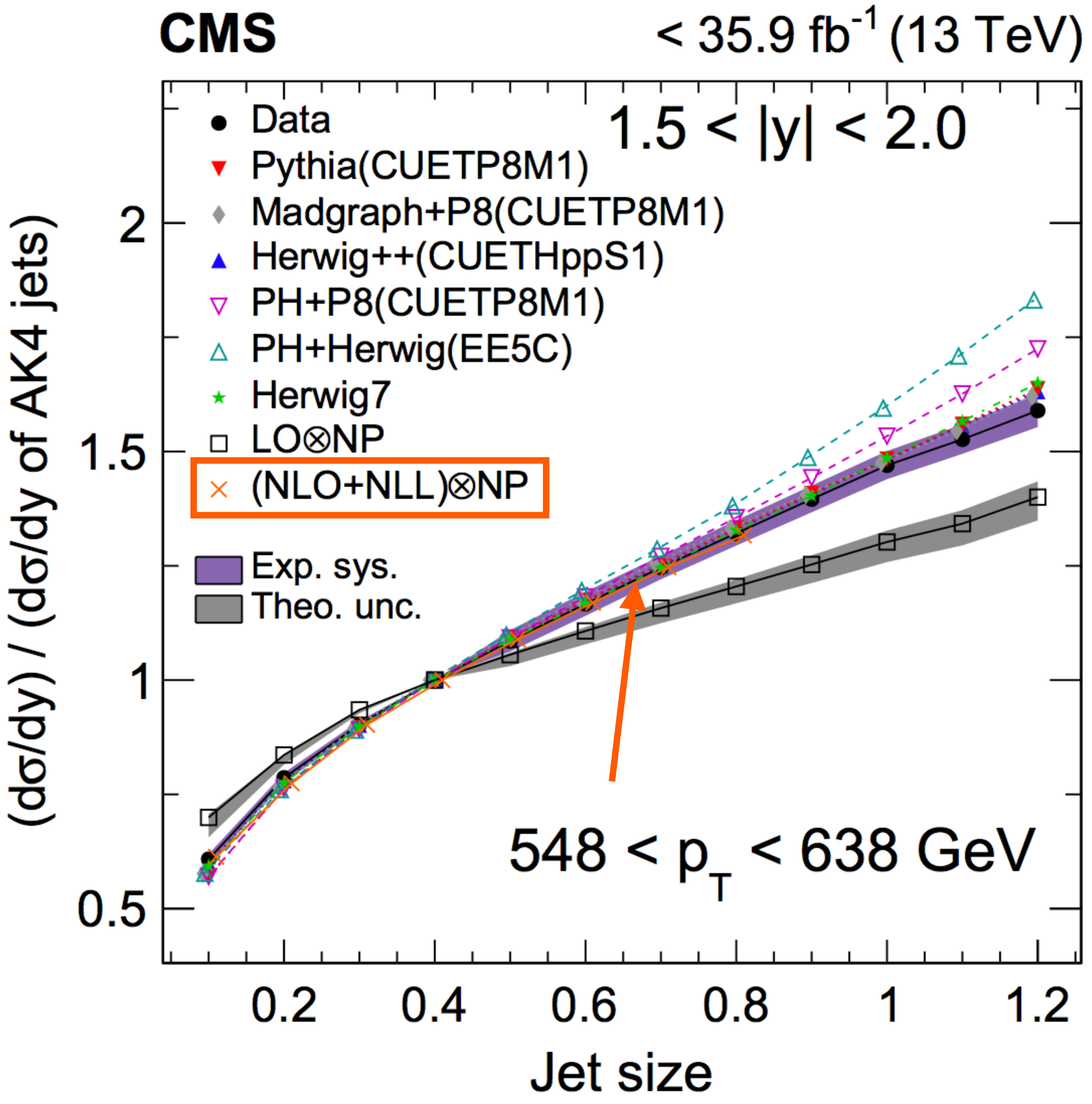






Inclusive jets in proton-proton collisions

- Jet radius dependence of the inclusive jet cross section



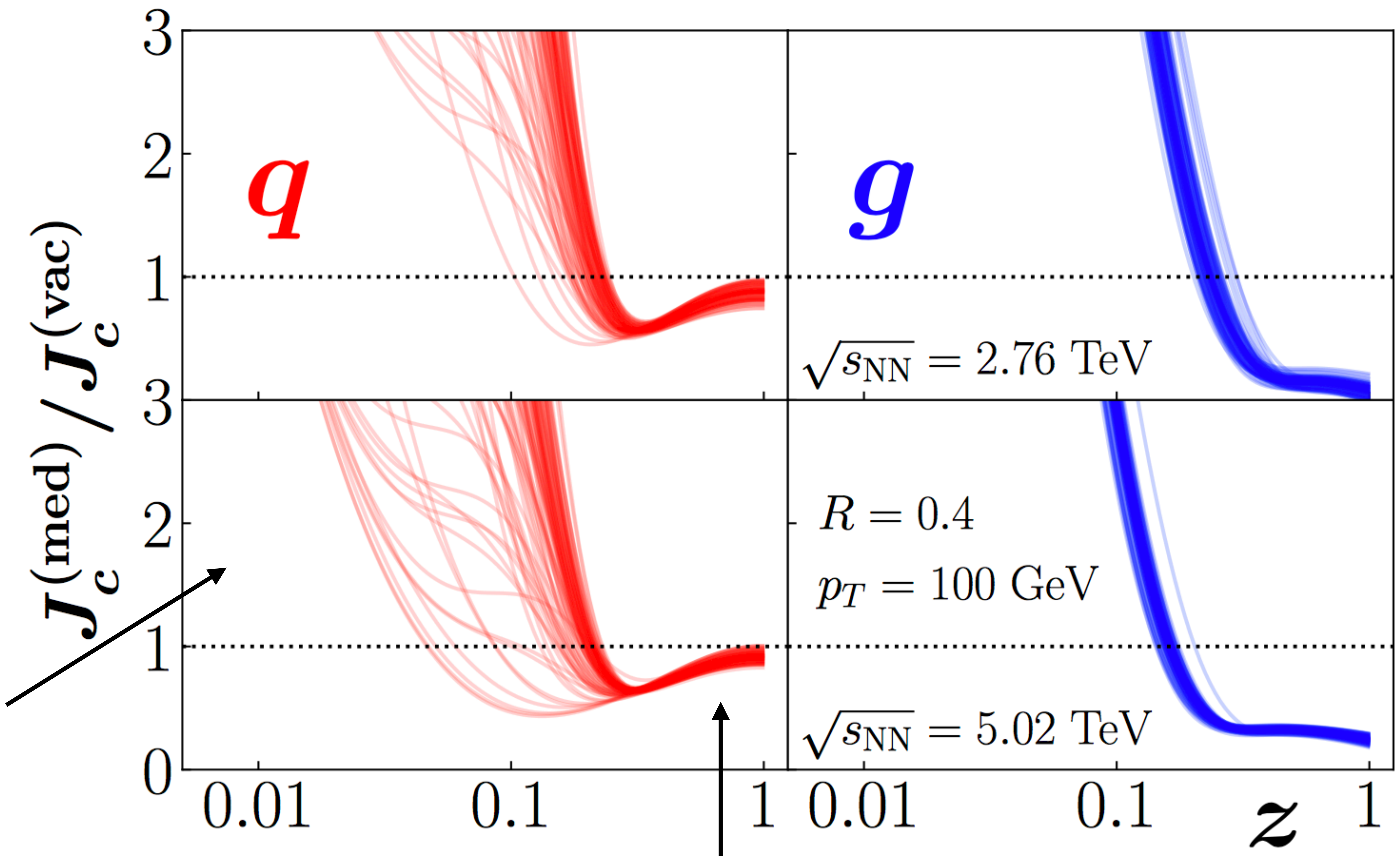
CMS, JHEP 12 (2020) 82
see also recent results from ALICE

Liu, Moch, FR `17, 18

In-medium jet functions

Qiu, FR, Sato, Zurita `19

- Suppression at large-z compensated for by enhancement at small-z



Small-z region generally less constrained

Potentially requires threshold resummation for $z \to 1$