PROBING JET-MEDIUM DYNAMICS WITH HIGHER-POINT ENERGY CORRELATORS

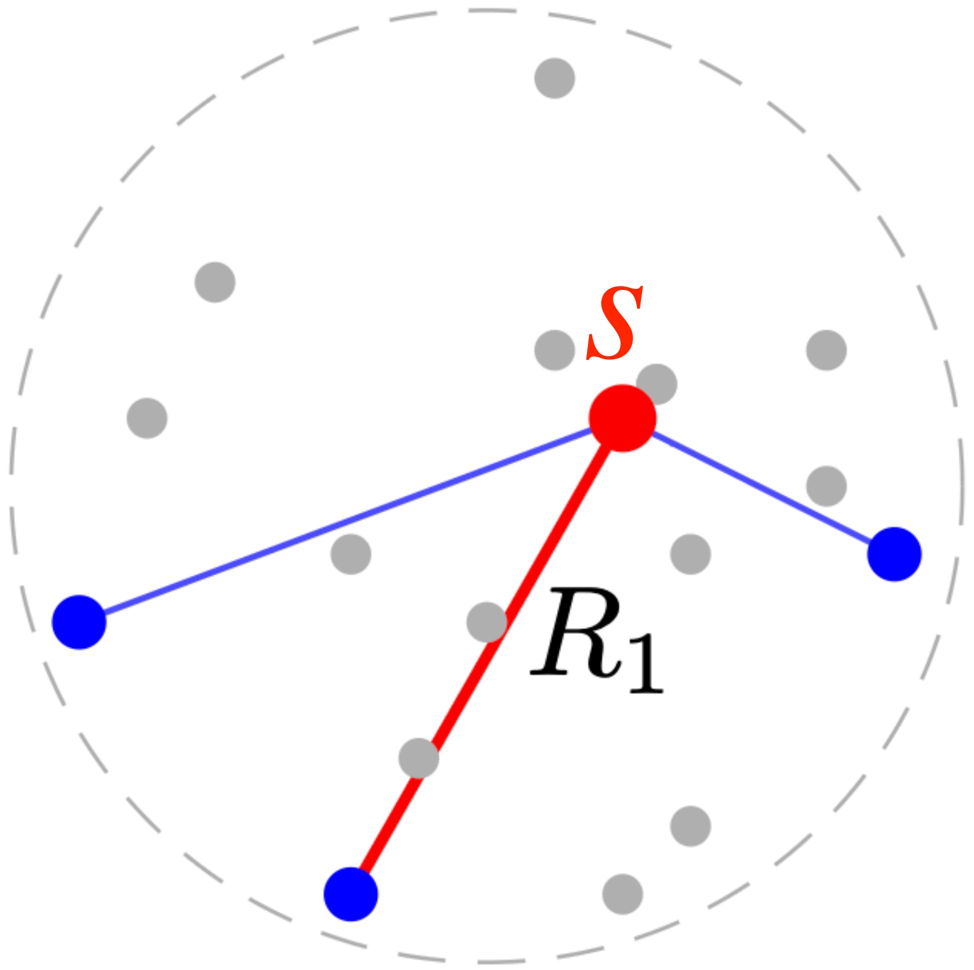
Ankita Budhraja, Nikhef

Probing the early stages with jets

GSI, 16/07/2026

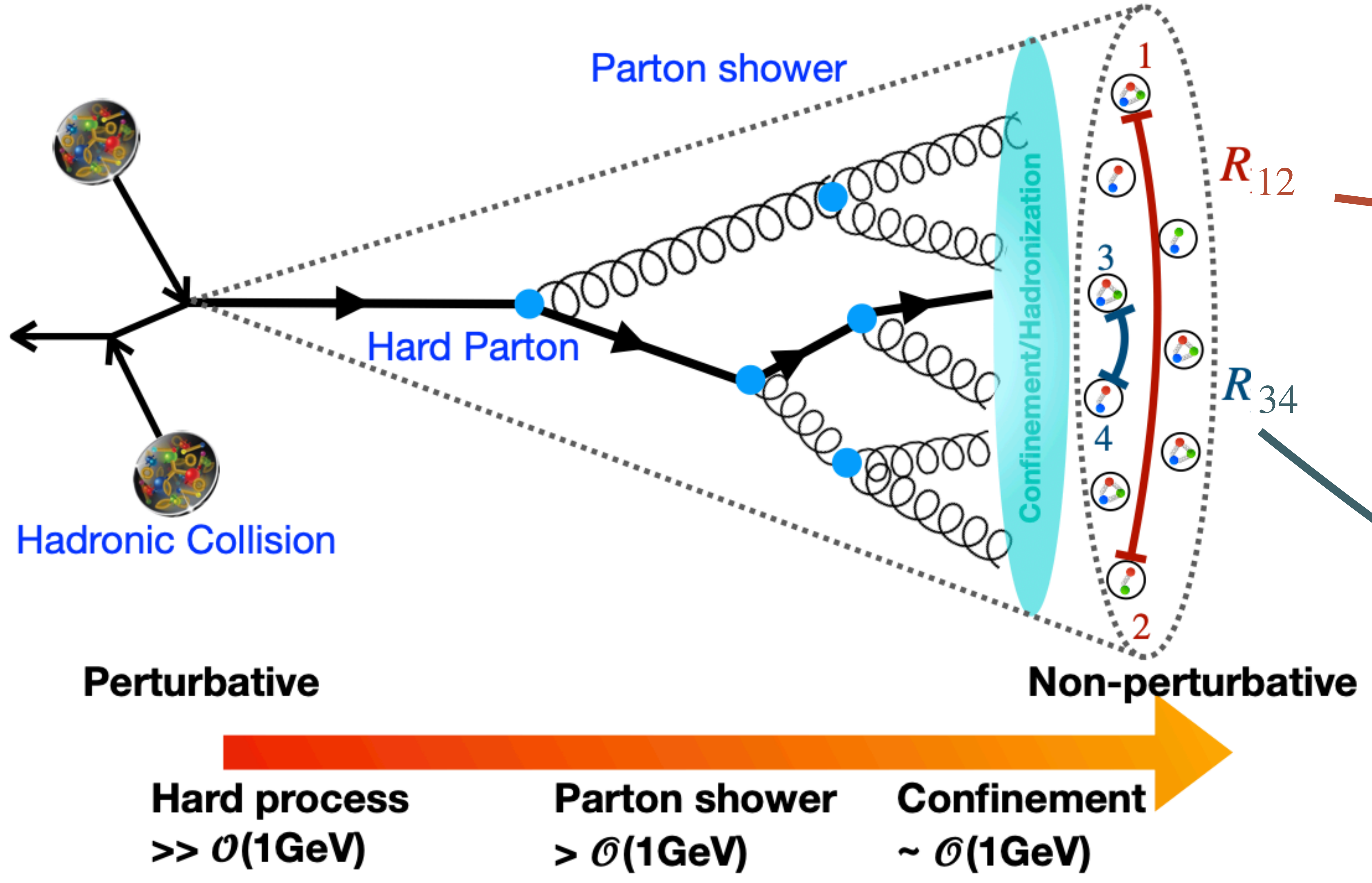
OUTLINE

1. Background
2. Higher point correlators
3. A new parameterization
4. Assessing discrimination ability



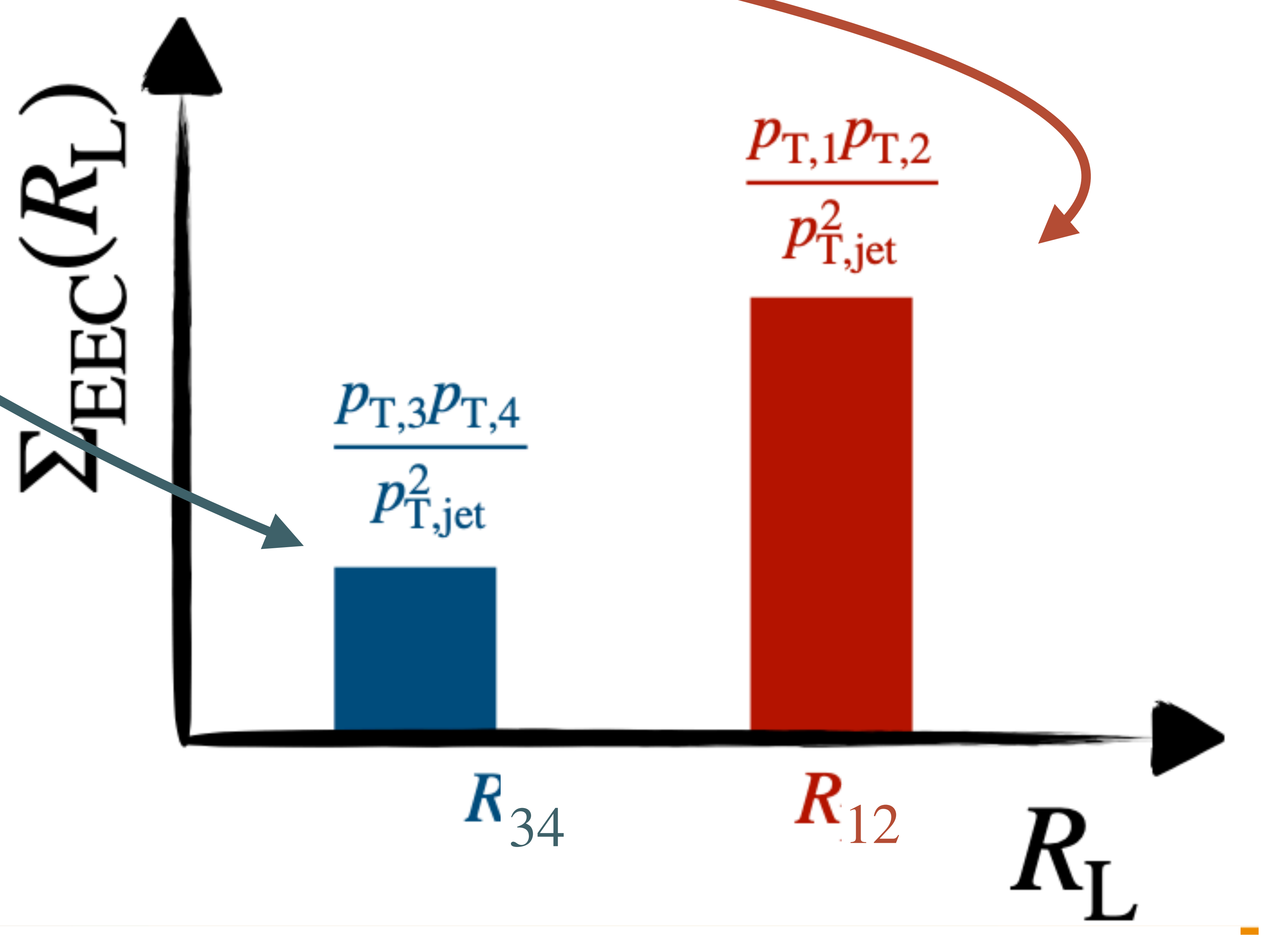
ENERGY CORRELATORS IN JETS

RECAP



Two-point energy-energy correlator

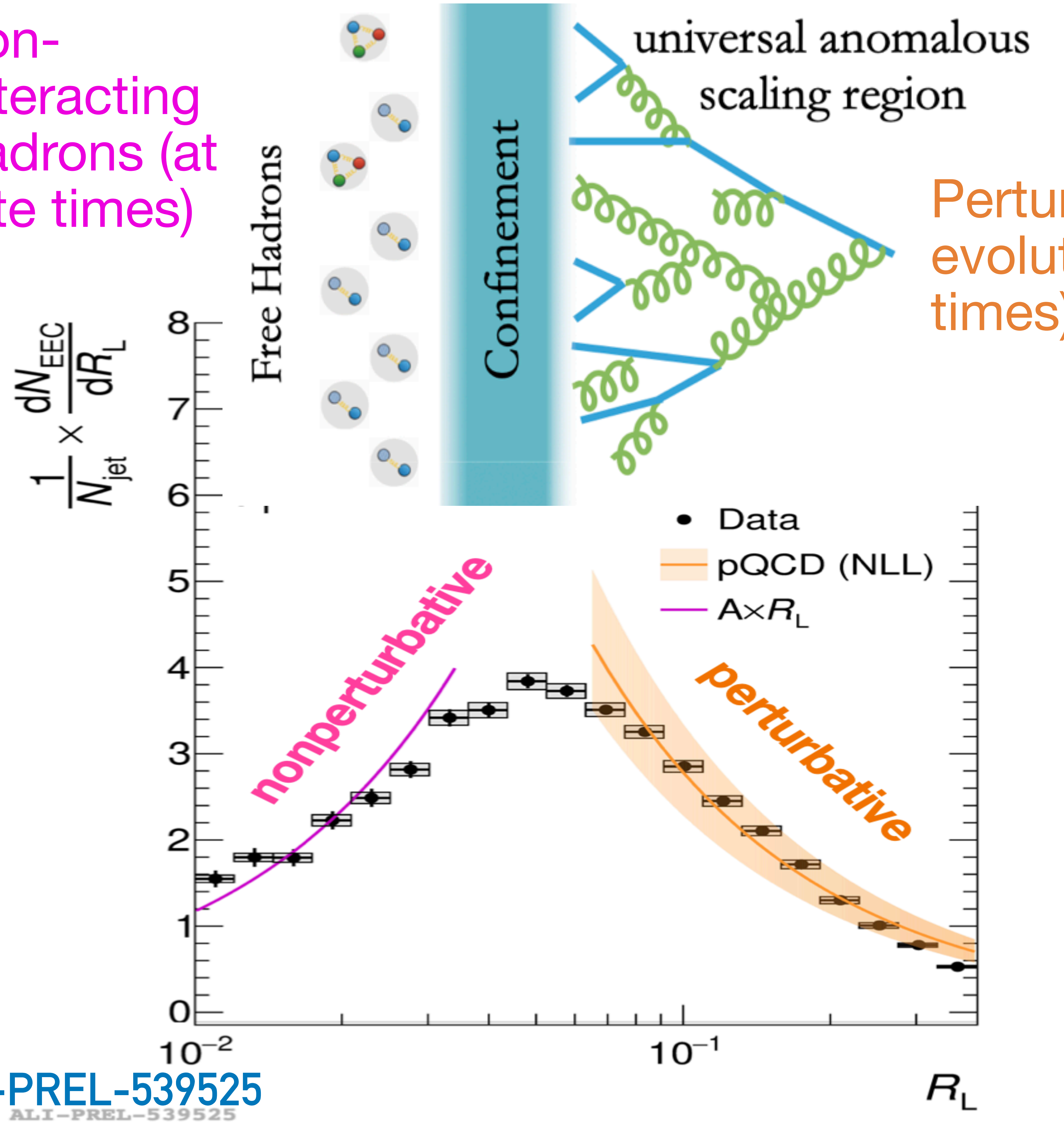
$$\Sigma_{\mathrm{EEC}}(R_L) = \int d\sigma \sum_{i,j} \frac{p_{T,i}\, p_{T,j}}{p^2_{T,\mathrm{jet}}} \delta(R_L - R_{i,j})$$



ENERGY CORRELATORS IN JETS

MOTIVATION

non-interacting hadrons (at late times)



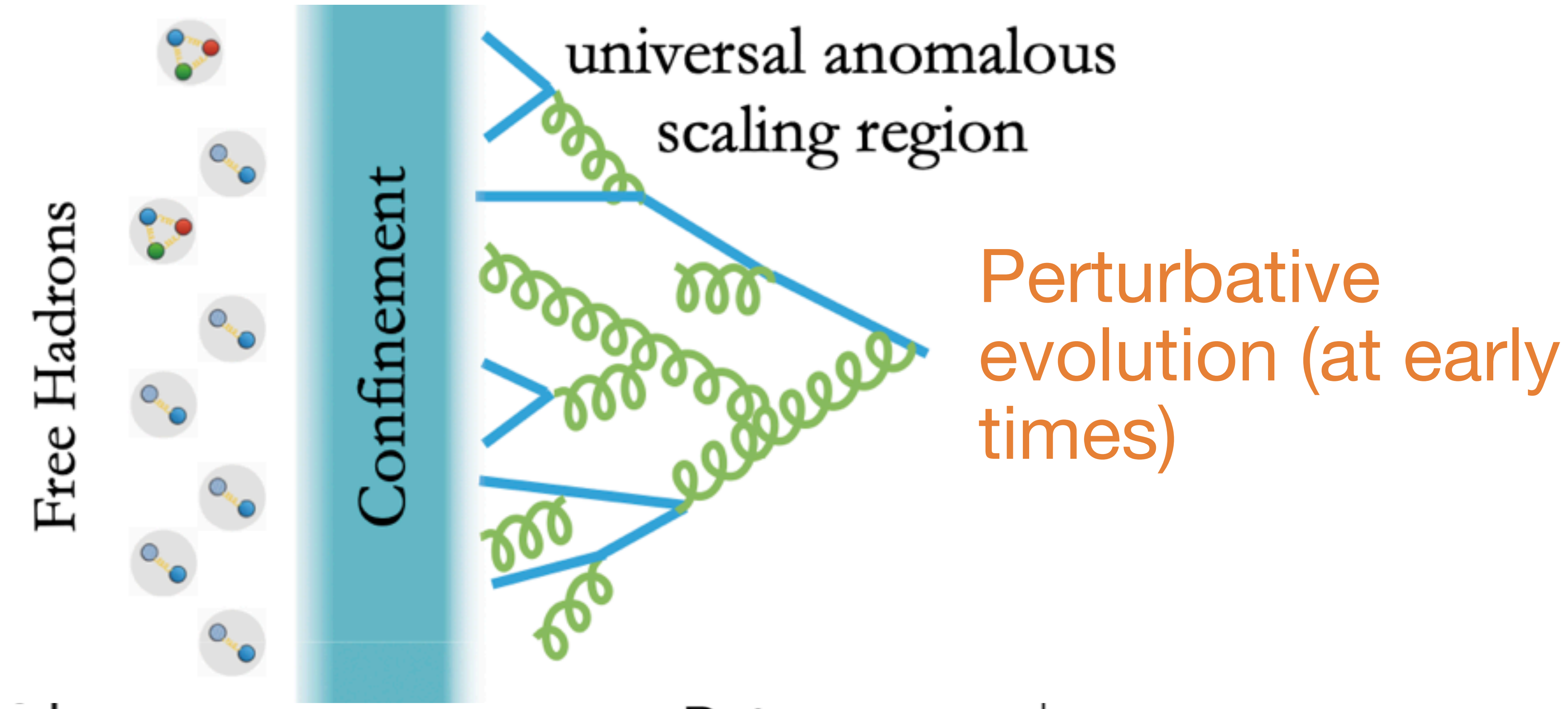
Perturbative evolution (at early times)

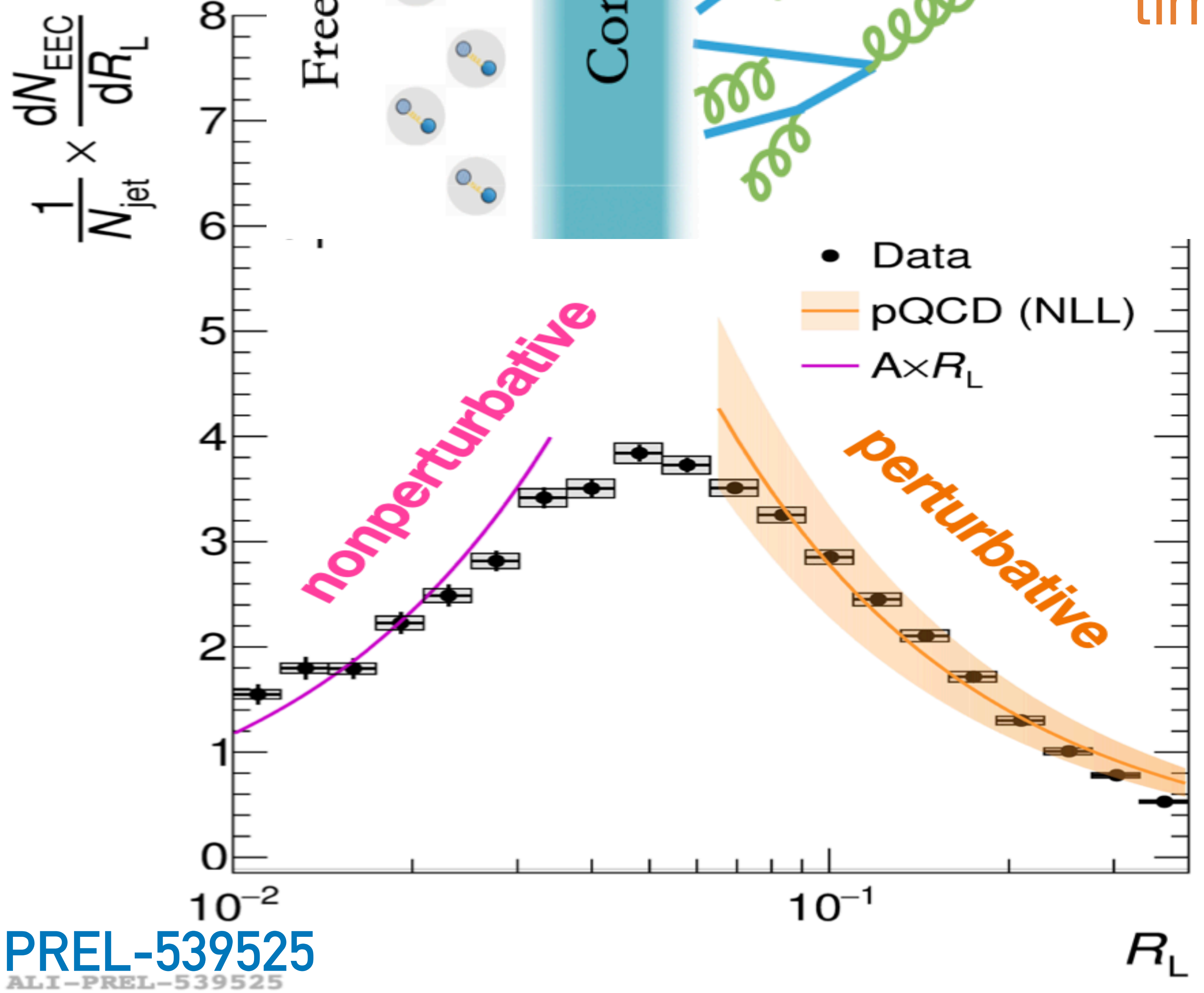
ALI-PREL-539525

ENERGY CORRELATORS IN JETS

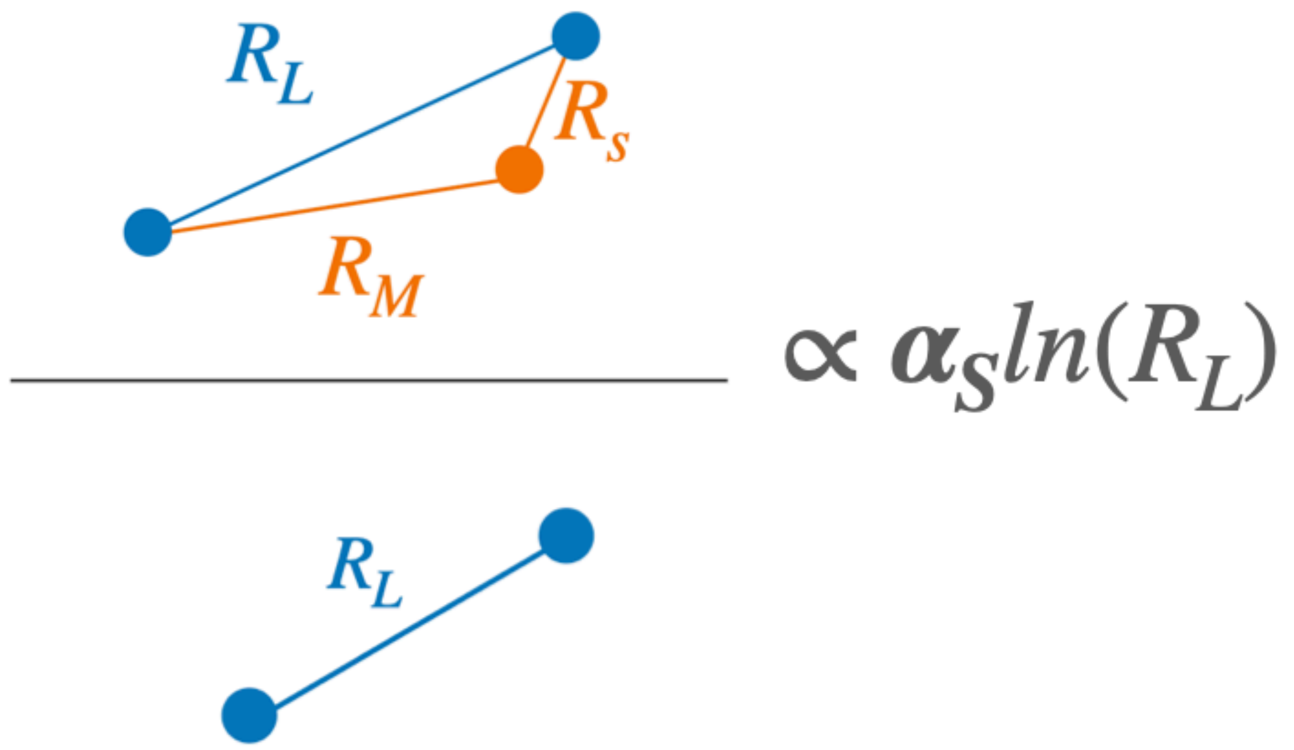
MOTIVATION

non-interacting hadrons (at late times)

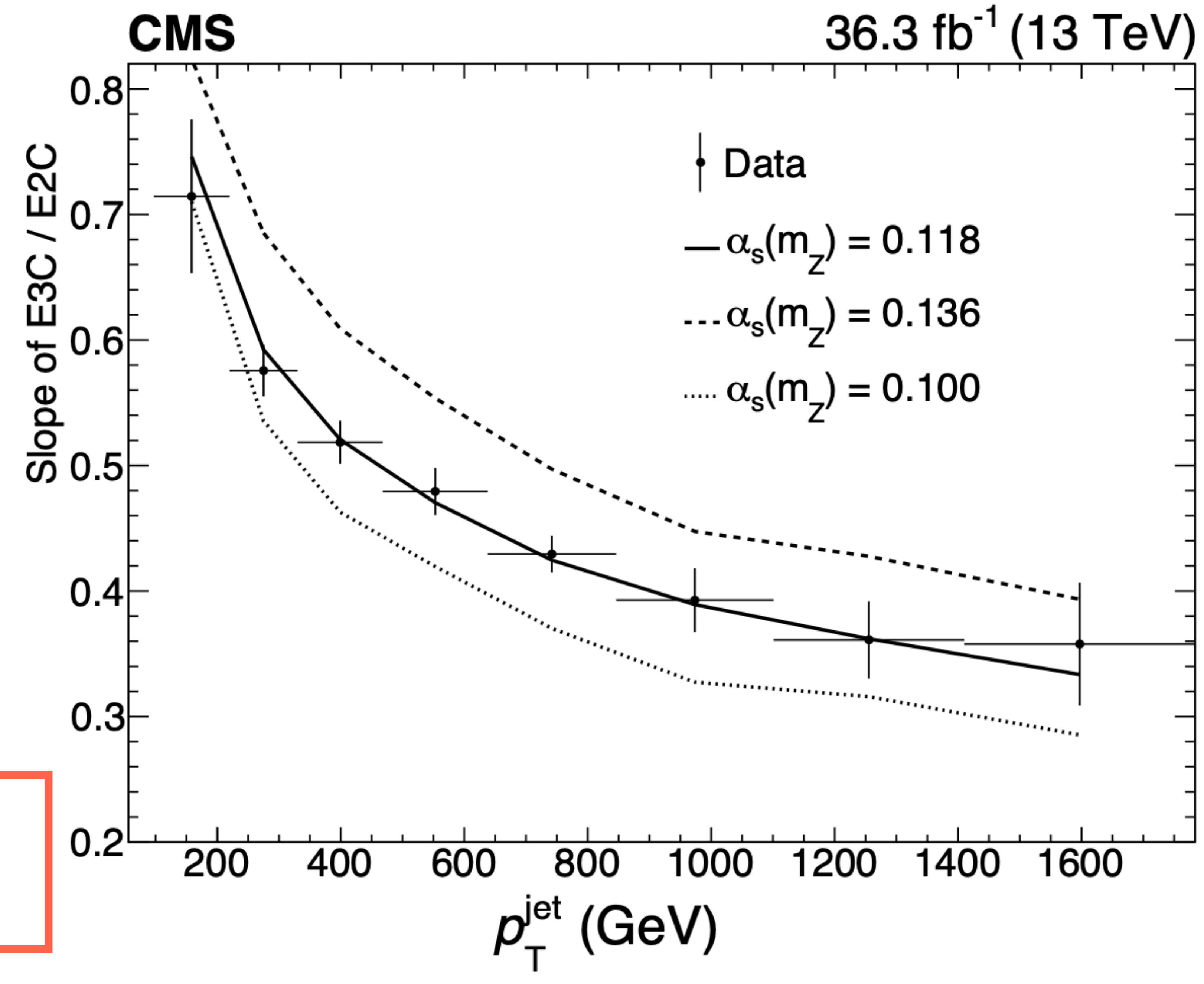




ALI-PREL-539525



CMS Collaboration '24

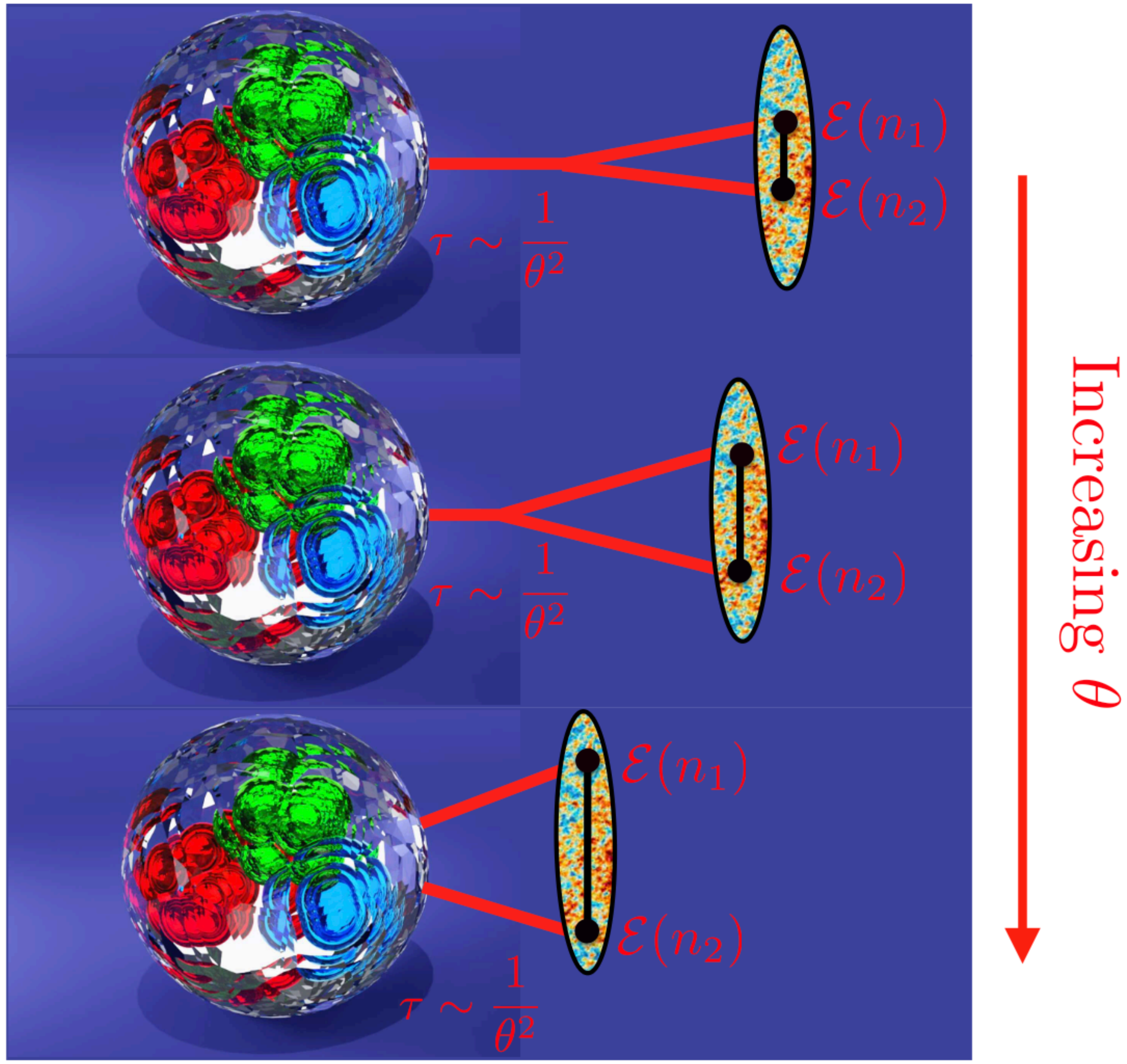


$$\alpha_s(m_Z) = 0.1229^{+0.004}_{-0.005}$$

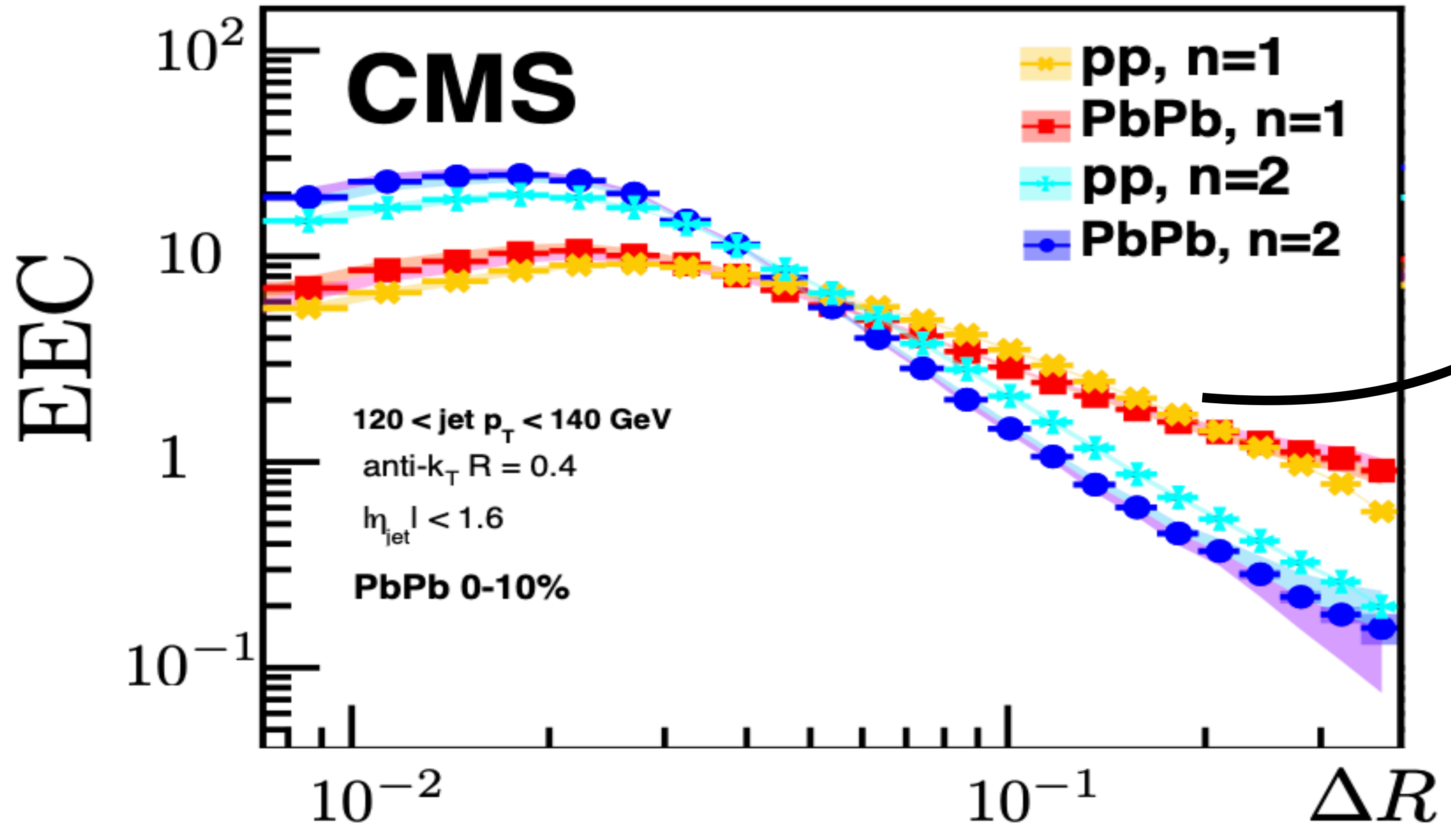
Highest precision constraint on α_s from jet substructure !

ENERGY CORRELATORS IN HEAVY ION JETS

Presence of QGP modifies the scaling behaviour of the 2-point correlator.

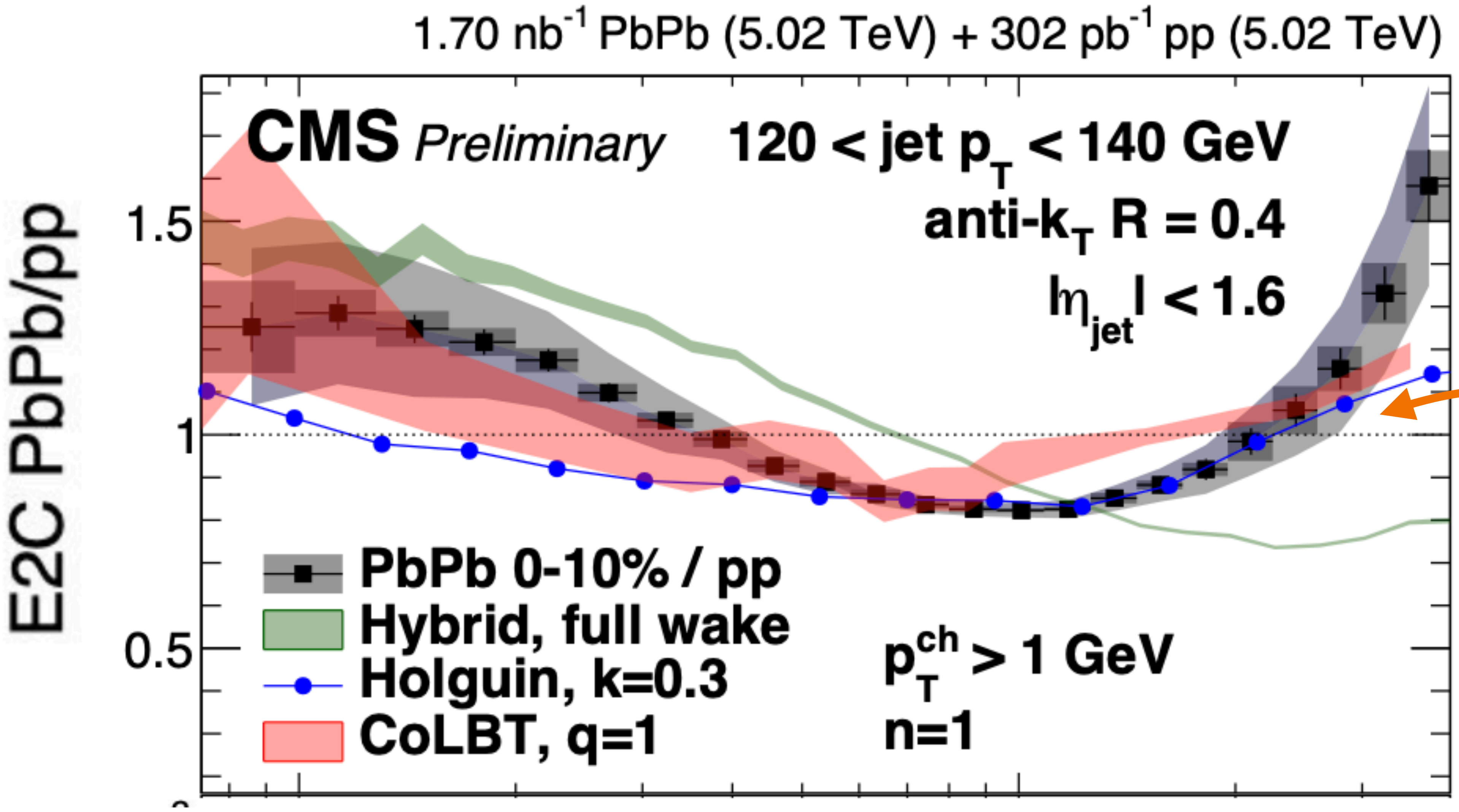


Andres, Dominguez, Holguin, Marquet, Moult ‘23



First observation of this modification

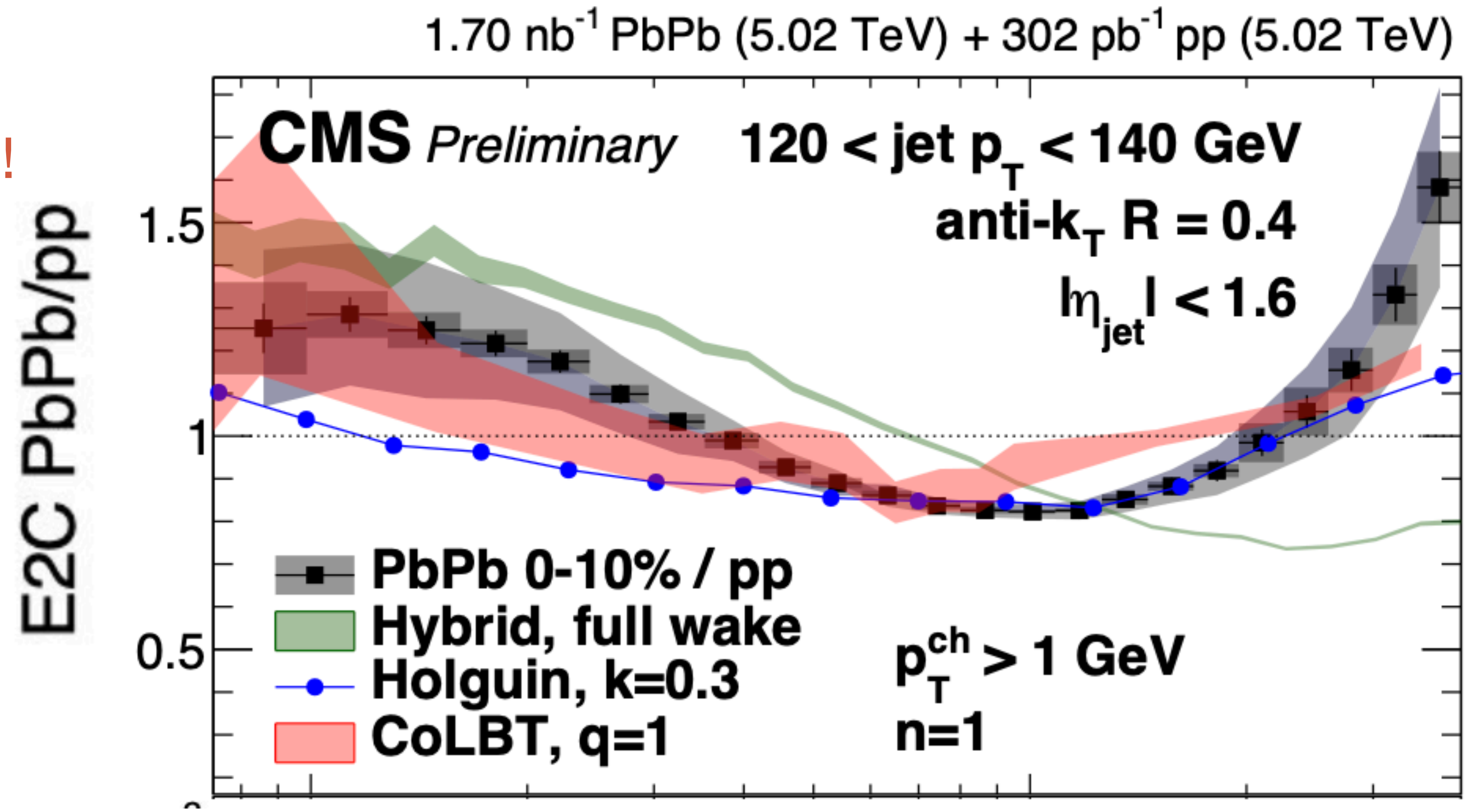
CMS Collaboration ‘24



Comparison with various theoretical approaches

WISHLIST FOR HEAVY ION JETS

- What are the best observables to maximize sensitivity to medium-induced jet modifications ? This talk !
- Can we distinguish different physical mechanisms ?

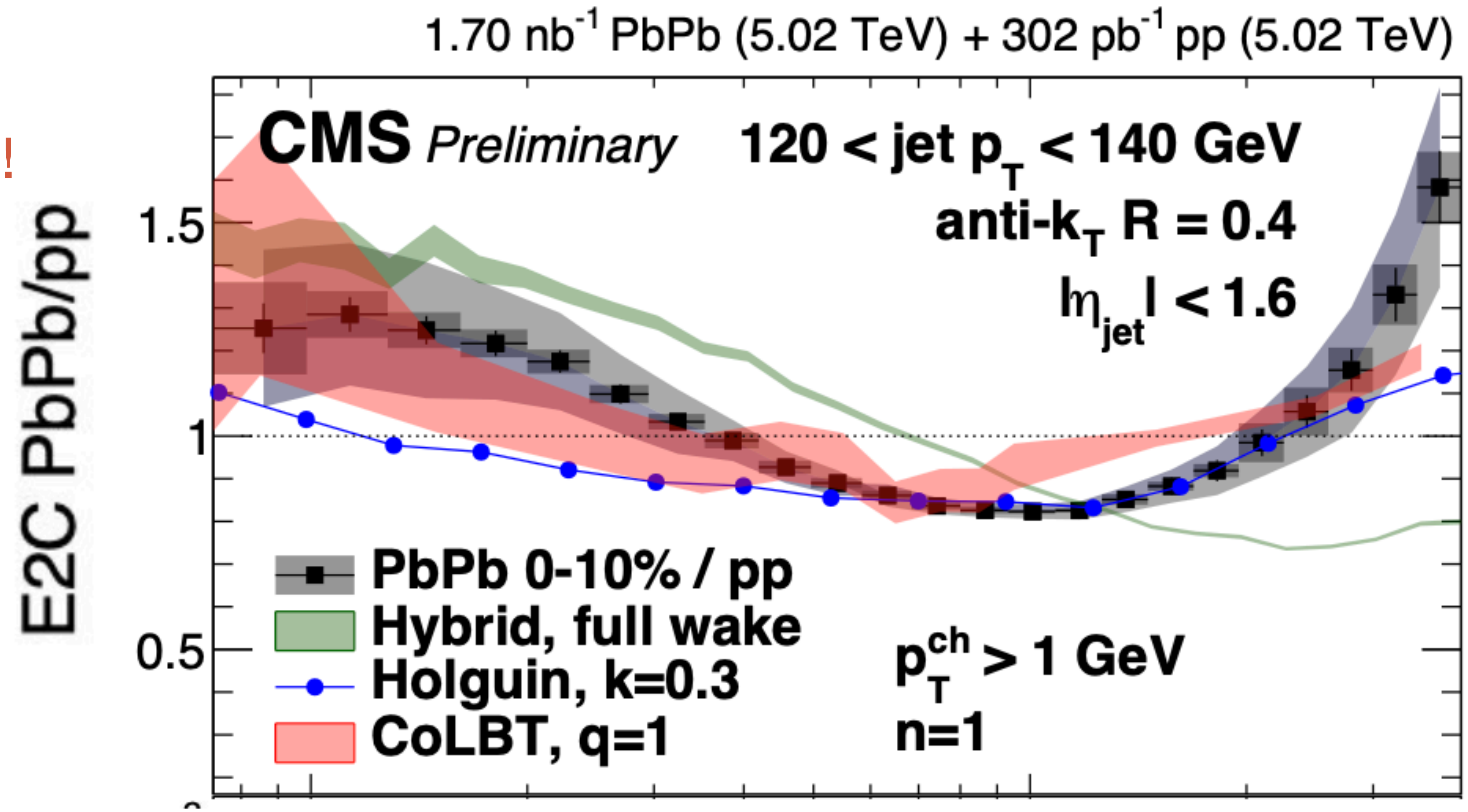


WISHLIST FOR HEAVY ION JETS

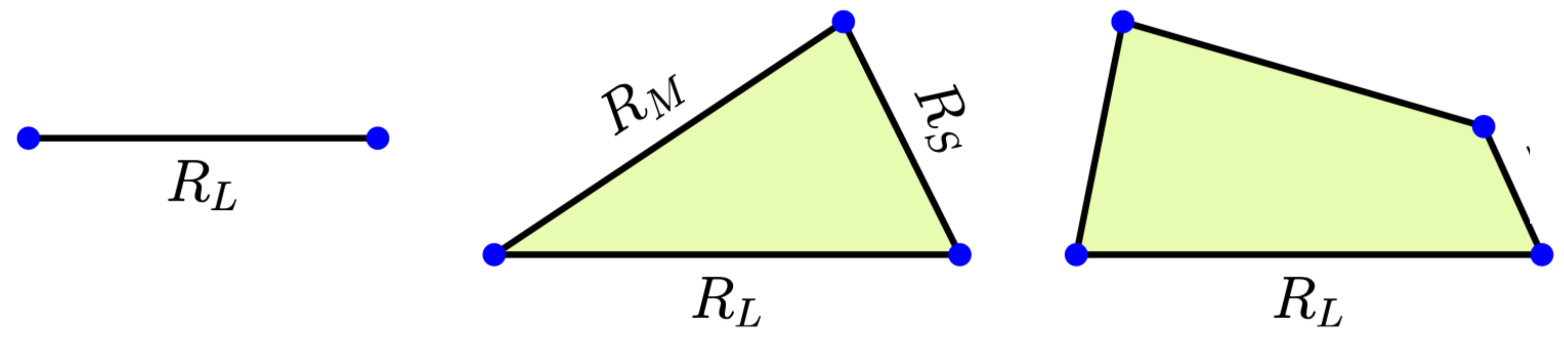
- **What are the best observables to maximize sensitivity to medium-induced jet modifications ?** This talk !
- **Can we distinguish different physical mechanisms ?**

Tools :

- **Higher N-point projected correlators**
- **Full shape dependence**

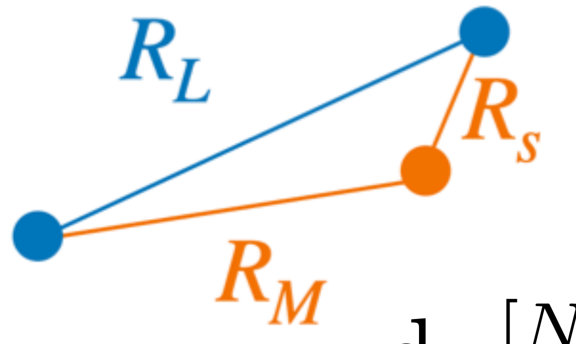


HIGHER-POINT CORRELATORS



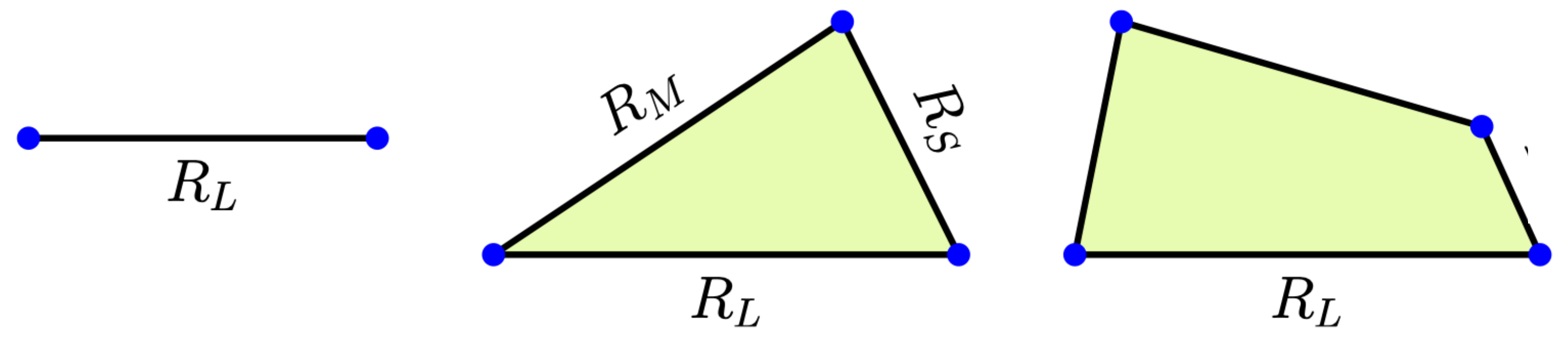
- Multi-point generalization depends on all $N(N-1)/2$ angles

- Projected N-point energy correlators (PENC) tracks largest separation, integrating out shape information



$$\frac{\mathrm{d}\sigma^{[N]}}{\mathrm{d}R_L} = \int \mathrm{d}\sigma \sum_{i_1,\ldots,i_N} \frac{p_{T,i_1}\cdots p_{T,i_N}}{P_T^N}\,\delta(R_L - \max\{R_{i_j i_k}\})$$

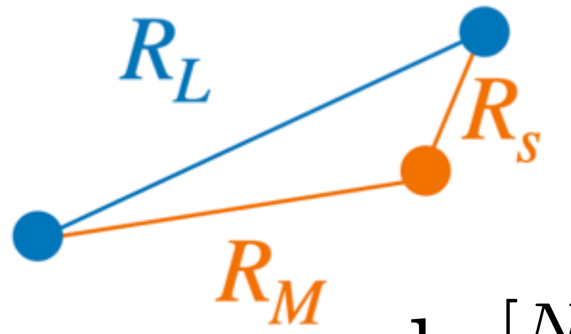
HIGHER-POINT CORRELATORS



➤ Multi-point generalization depends on all $N(N-1)/2$ angles

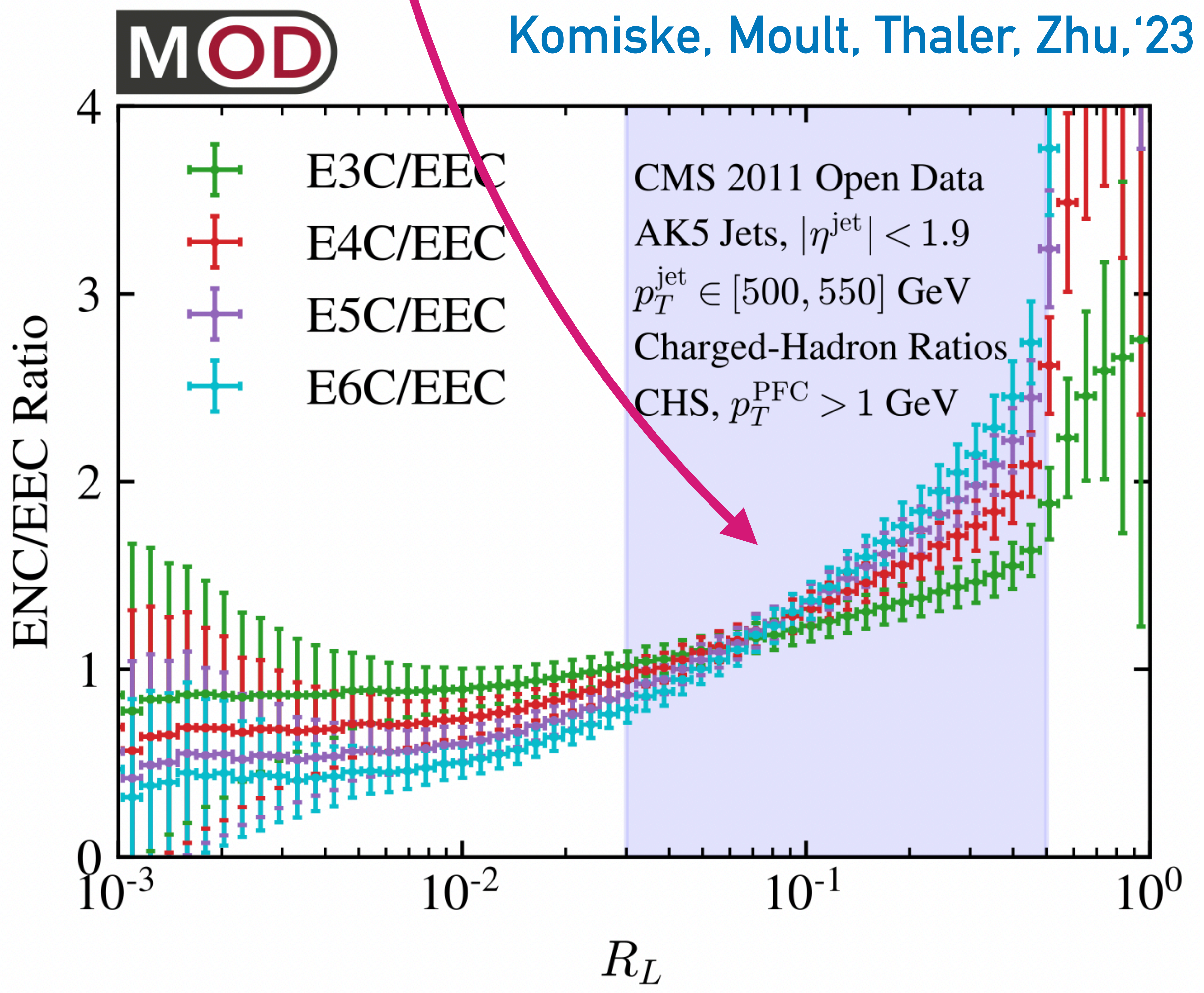
modification in slope with

➤ Projected N-point energy correlators (PENC) tracks largest separation, integrating out shape information



$$\frac{d\sigma^{[N]}}{dR_L} = \int d\sigma \sum_{i_1,\dots,i_N} \frac{p_{T,i_1}\cdots p_{T,i_N}}{P_T^N}\,\delta(R_L - \max\{R_{i_j i_k}\})$$

Komiske, Moult, Thaler, Zhu,'23

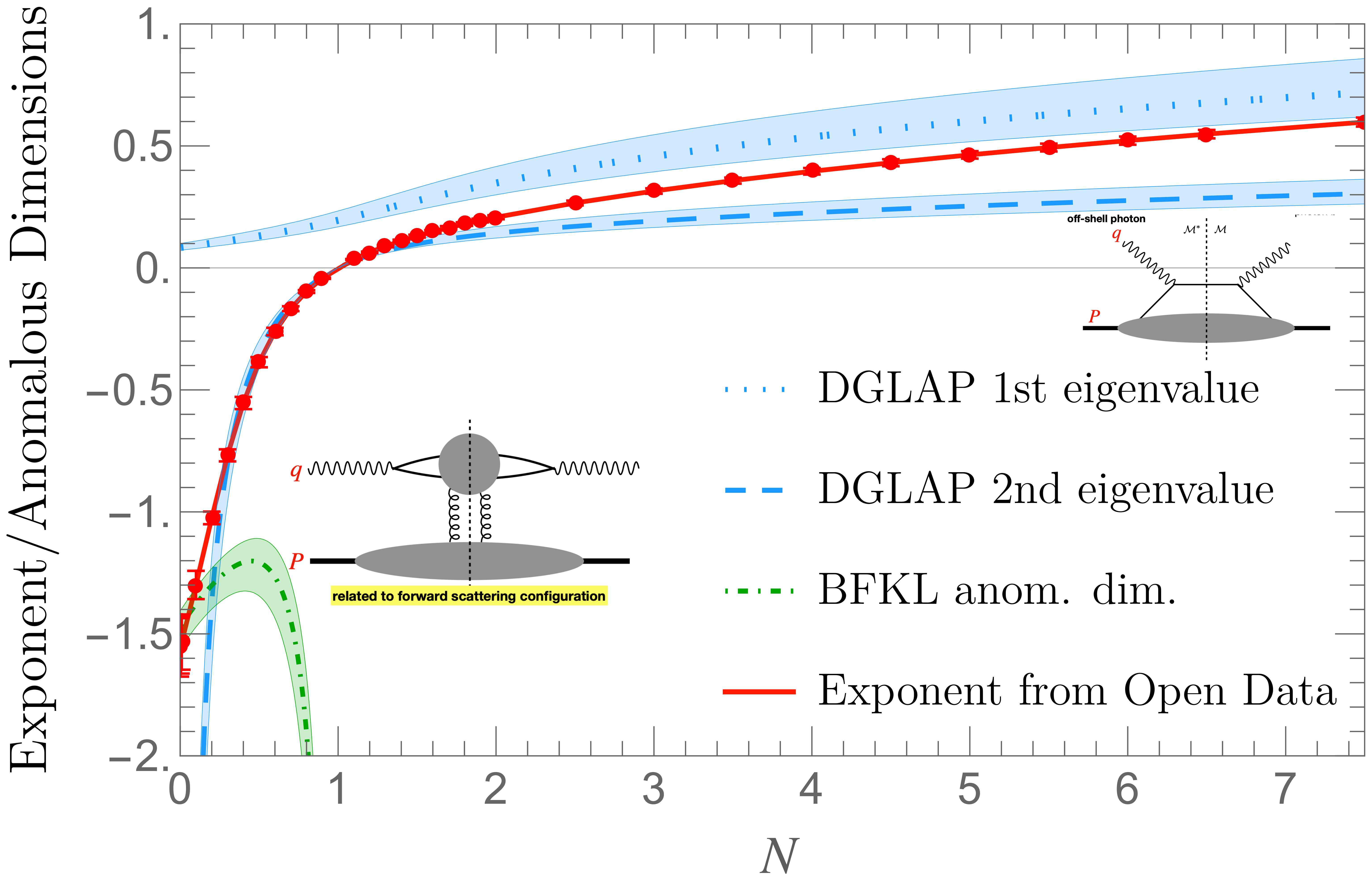


➤ Provides access to anomalous scaling of pQCD.

APPLICATION: ANALYTIC CONTINUATION IN N

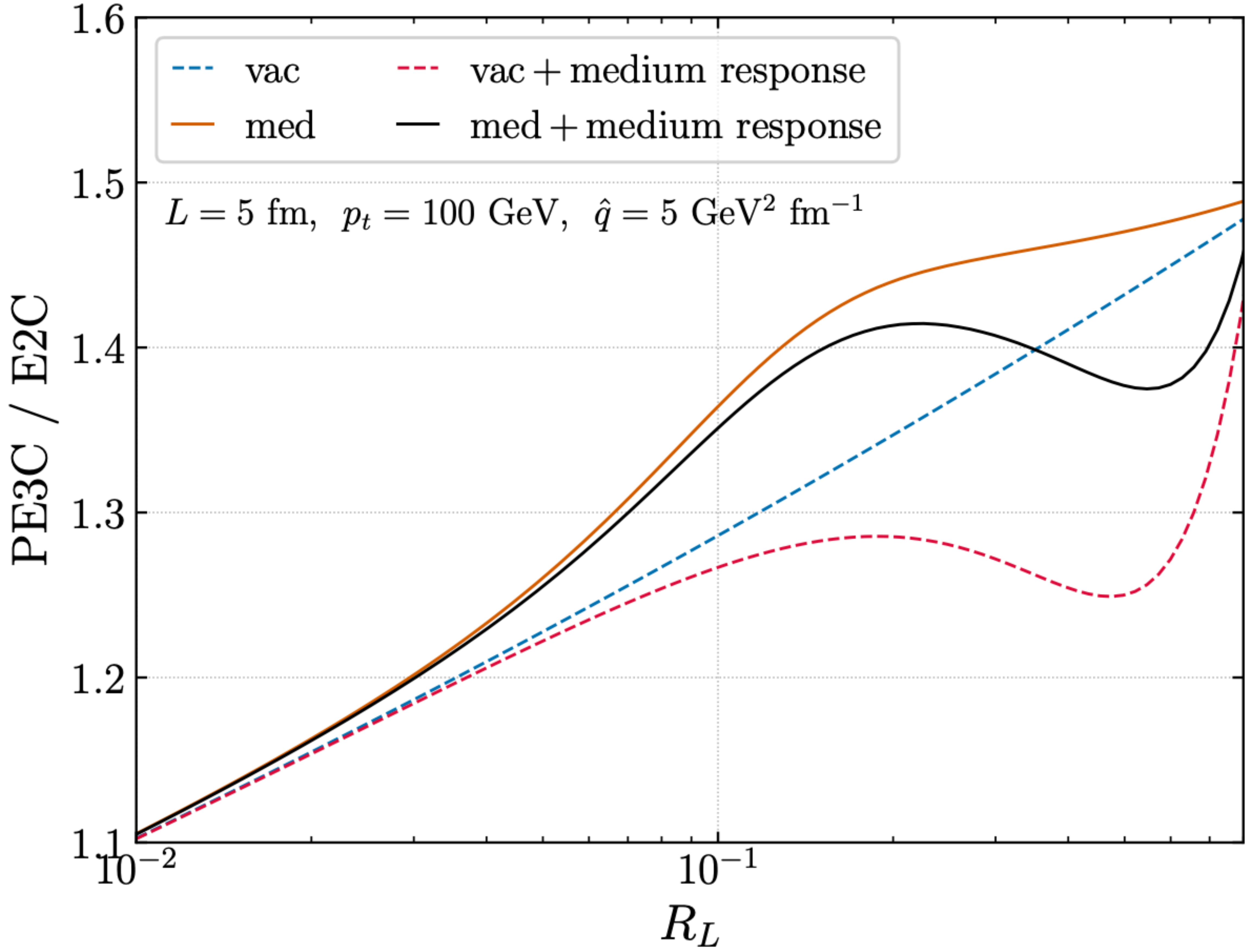
- ➤ Fit CMS Open data to power law.
- ➤ Compare to both DGLAP eigenvalues (no quark/gluon mixing).
- ➤ Interestingly, approaches BFKL for $N \to 0$.

AB, Chen, Waalewijn '24

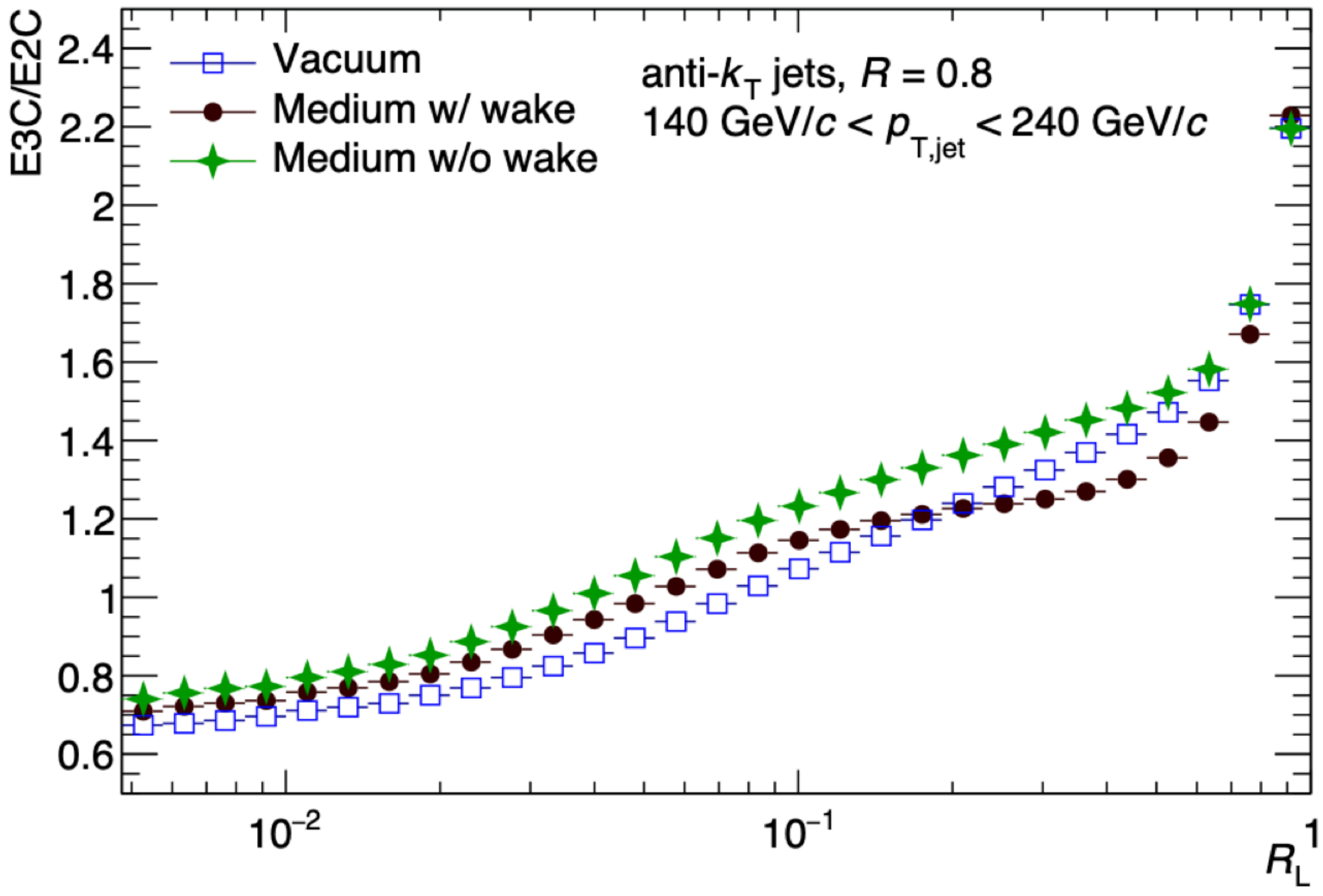


APPLICATION: HEAVY ION COLLISIONS

Barata, Moult, Sadofyev, Silva '25



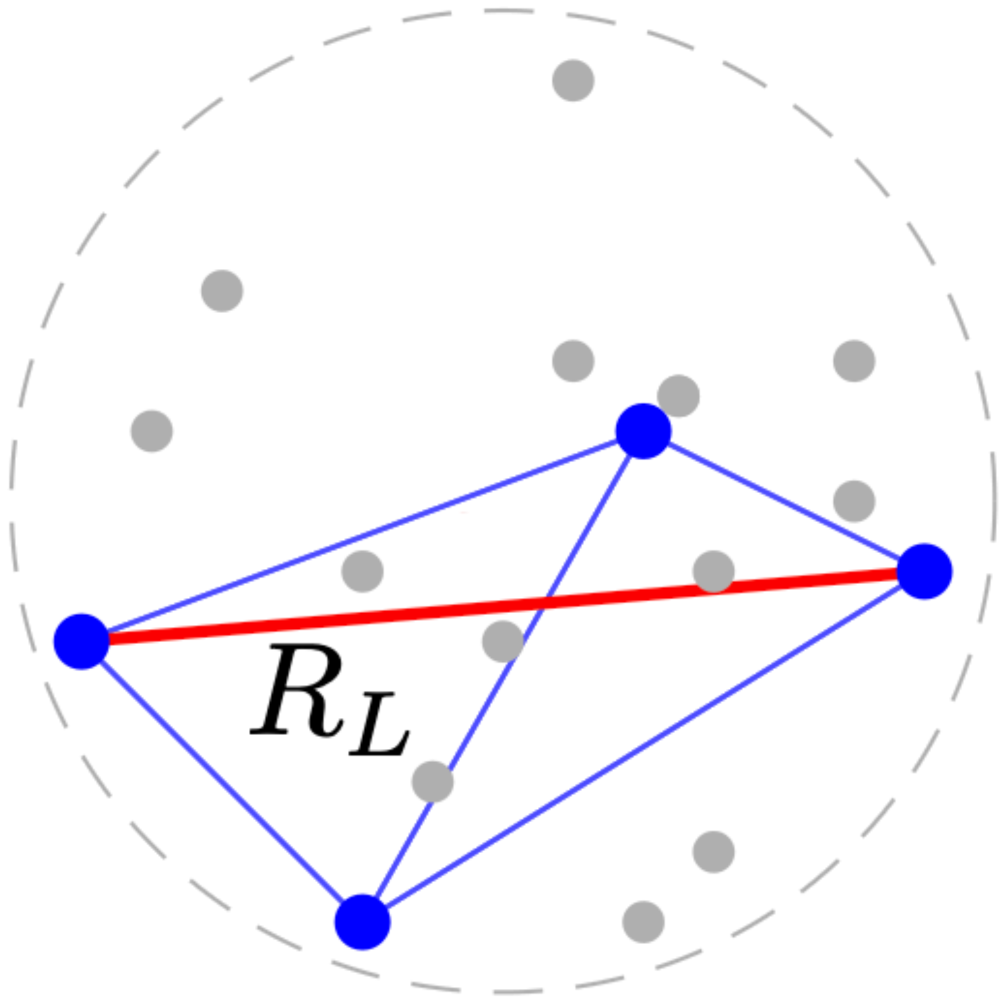
Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal '24



- Large angle medium modifications are enhanced for PE3C.

See Andrey and Joao's talk !

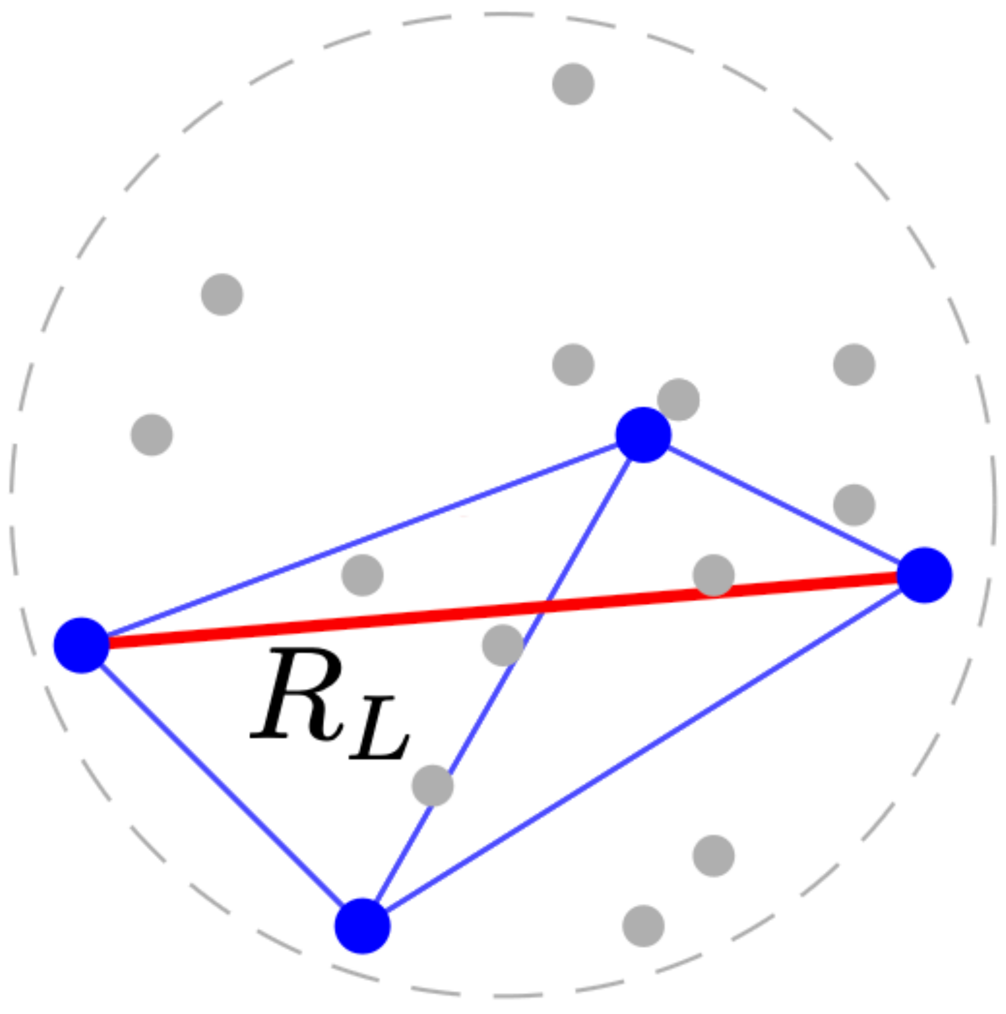
HIGHER-POINT CORRELATORS ARE COMPUTATIONALLY EXPENSIVE



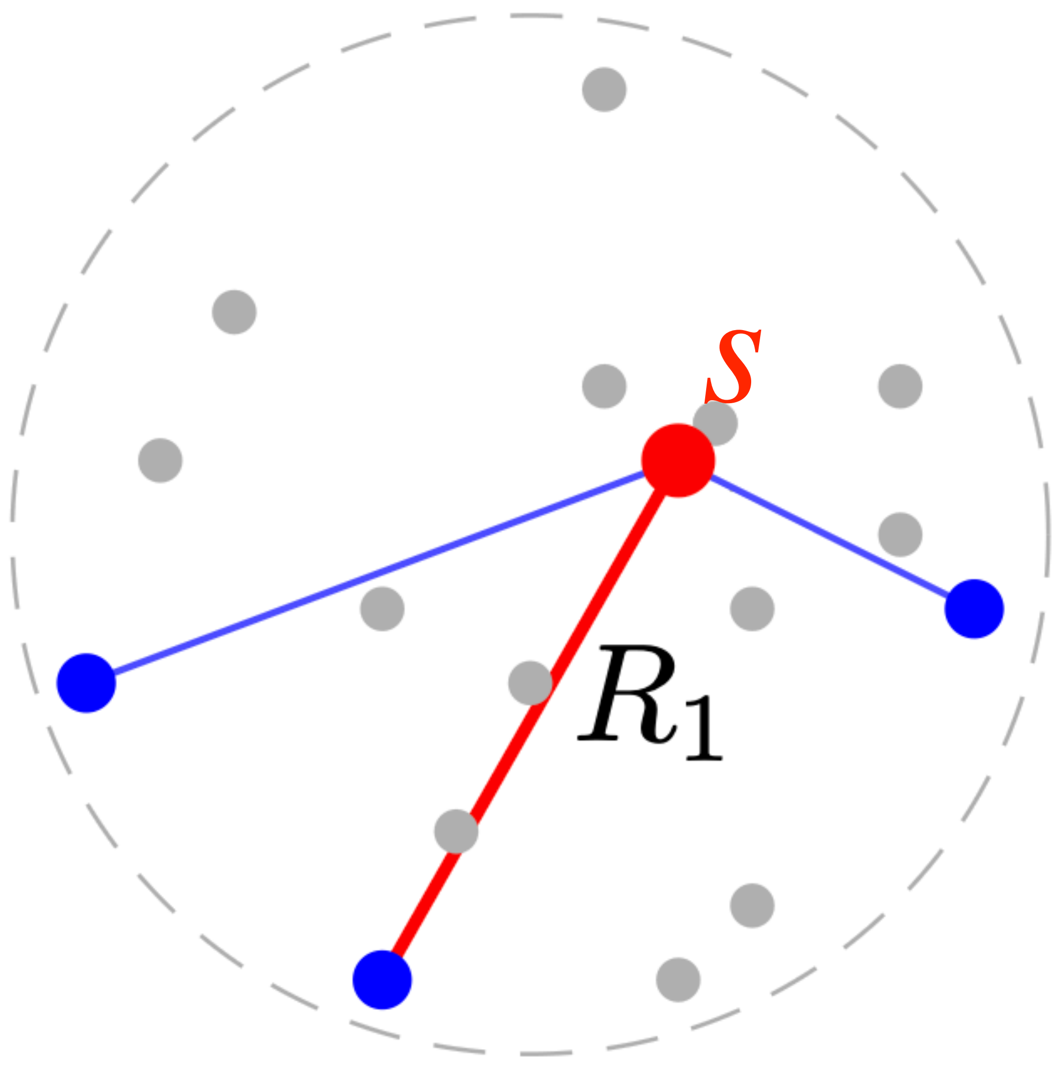
traditional

- Takes $\mathcal{O}(M^N)$ time to evaluate an N-point correlator of M particles.

HIGHER-POINT CORRELATORS ARE COMPUTATIONALLY EXPENSIVE



traditional



new

- Takes $\mathcal{O}(M^N)$ time to evaluate an N-point correlator of M particles.
- Our solution: measure distances relative to a special particle

Alipour-fard, AB, Thaler, Waalewijn '24

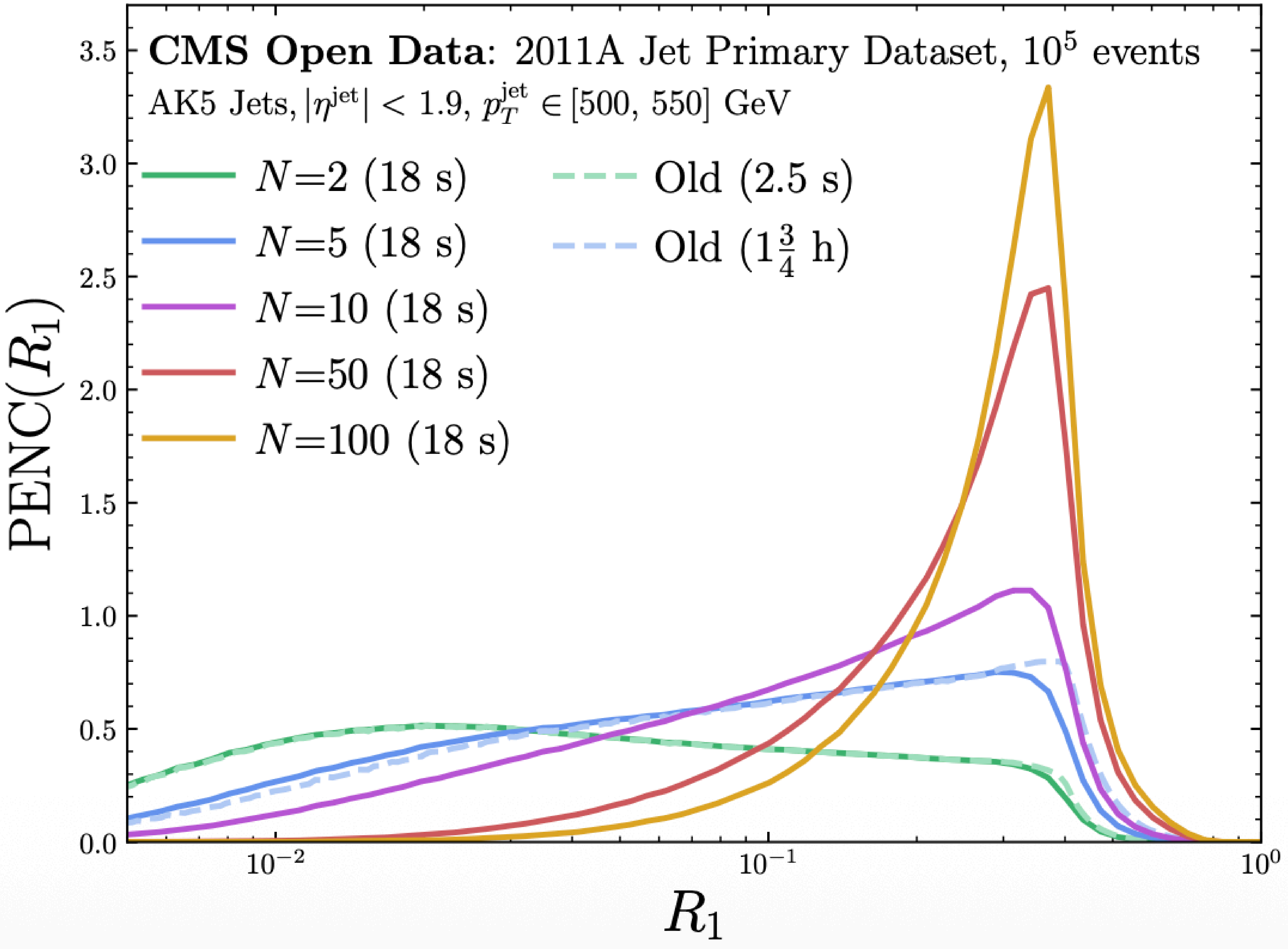
$$\frac{d\sigma^{[N]}}{dR_1} = \int d\sigma \sum_{s} z_s \sum_{i,j,k,\ldots} z_j z_k \cdots \delta(R_1 - \max\{R_{si}, R_{sj}, \cdots\})$$

FAST N-POINT CORRELATORS

- Time is $\mathcal{O}(\mathbf{M^2} \log \mathbf{M})$ for projected correlators for all N values !

- Follows from cumulative:

$$\int^{R_1} \mathrm{d}R_1' \, \frac{\mathrm{d}\sigma^{[N]}}{\mathrm{d}R_1'} = \int \mathrm{d}\sigma \sum_{s} z_s \, z_{\mathrm{disk}}(s, R_1)^{N-1}$$



NEW DEFINITION, SAME PHYSICS

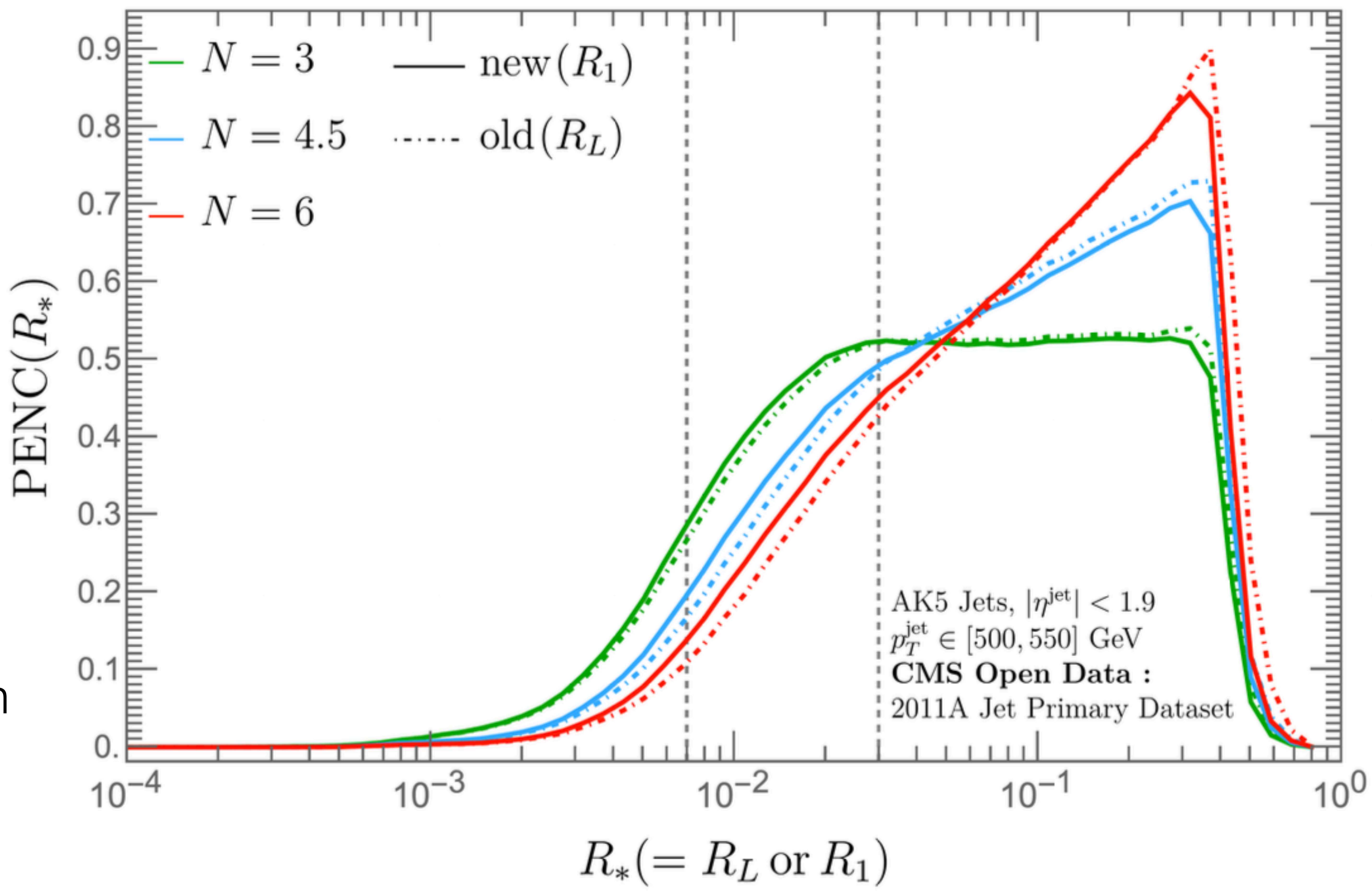
- As $R_1 \leq R_L \leq 2R_1 \;\; \Rightarrow R_1$ provides a good measure of the largest distance.

- Same theory framework

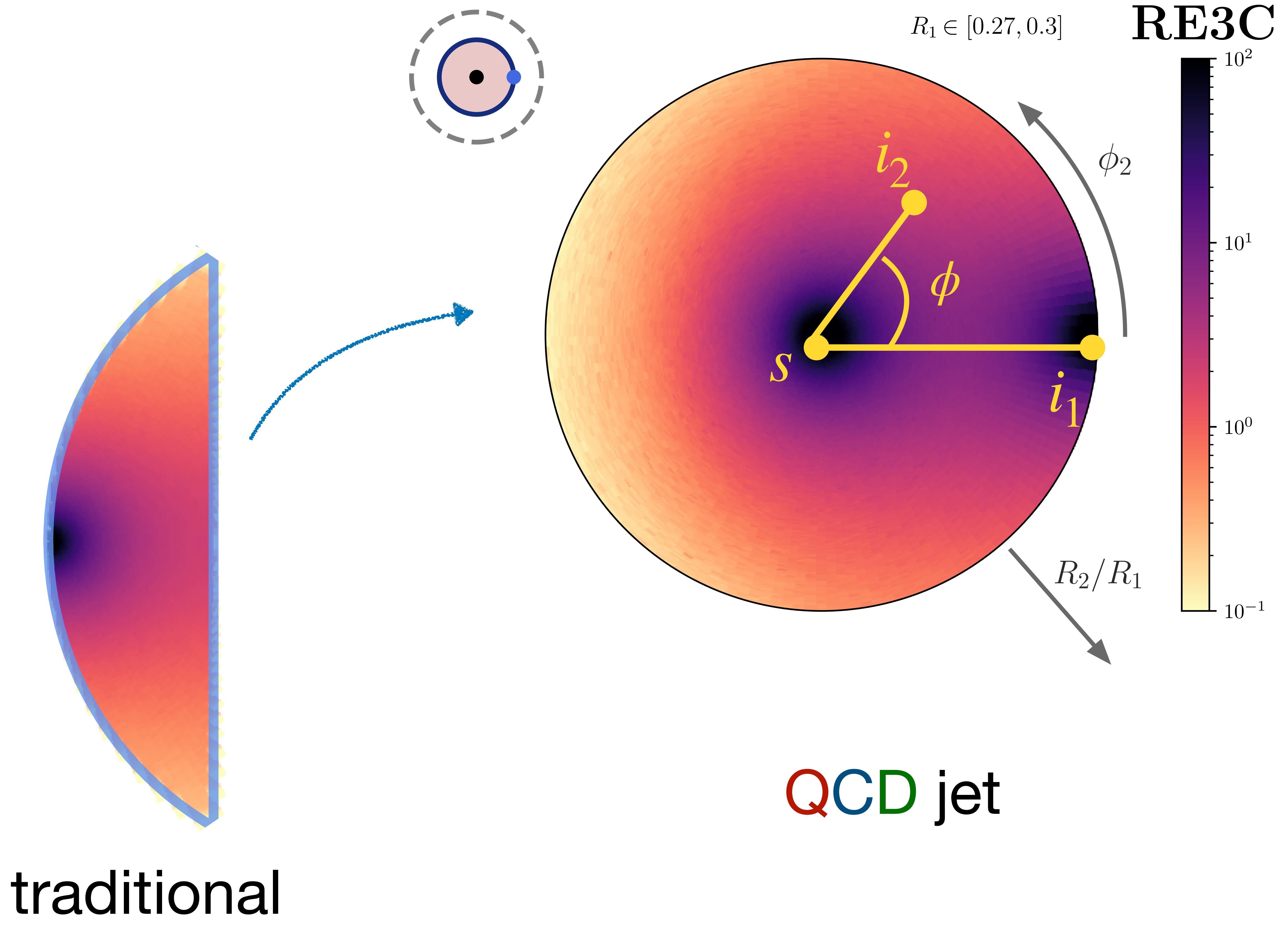
$$\Sigma^{[N]}(R_1, Q) = \int_0^1 \mathrm{d}x\, x^{[N]} \sum_i J_i^{[N]}\left(\frac{x\,Q^2 R_1^2}{\mu^2}\right) \cdot H_i\left(x, \frac{Q^2}{\mu^2}\right)$$

- First differences at $\mathcal{O}(\alpha_s^2)$

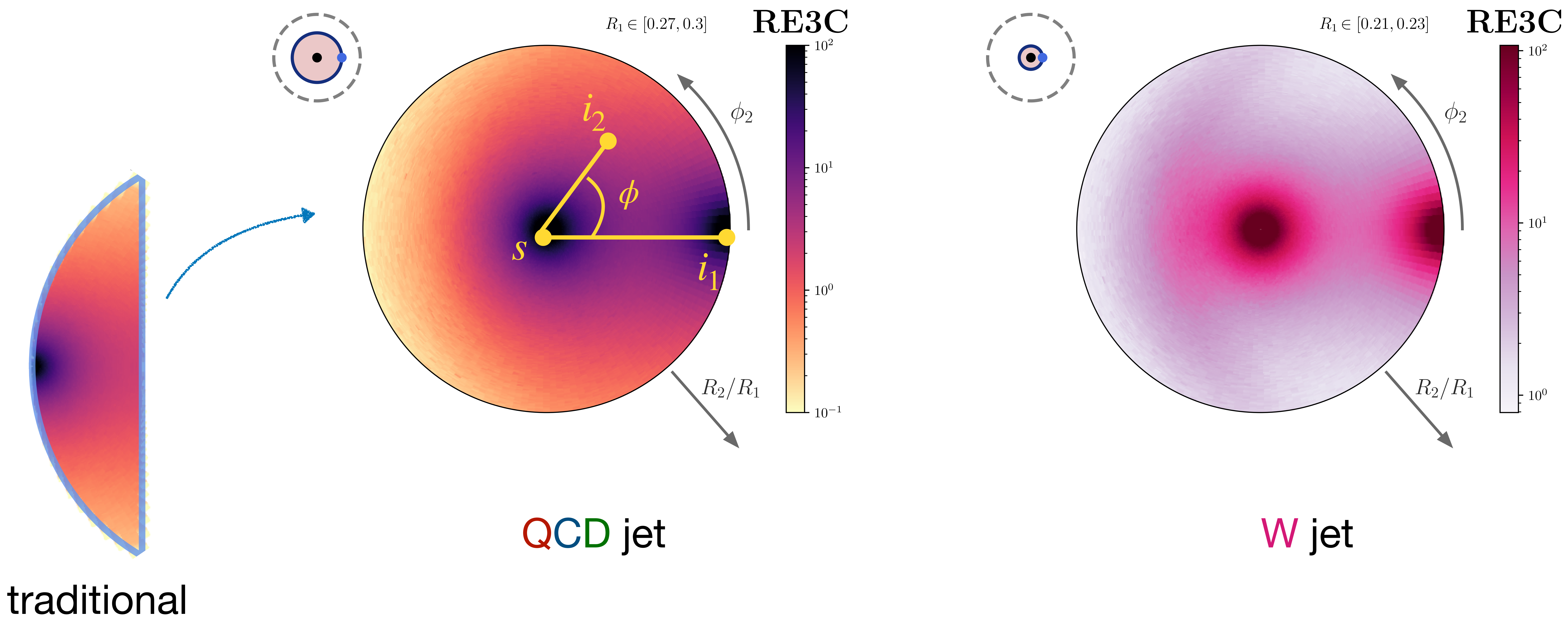
- H_i independent of specific parametrization of $\mathrm{PENC}(R_*) \Rightarrow$ Evolution for J_i remains same, though functional form does not.



RESOLVING JET STRUCTURE



RESOLVING JET STRUCTURE

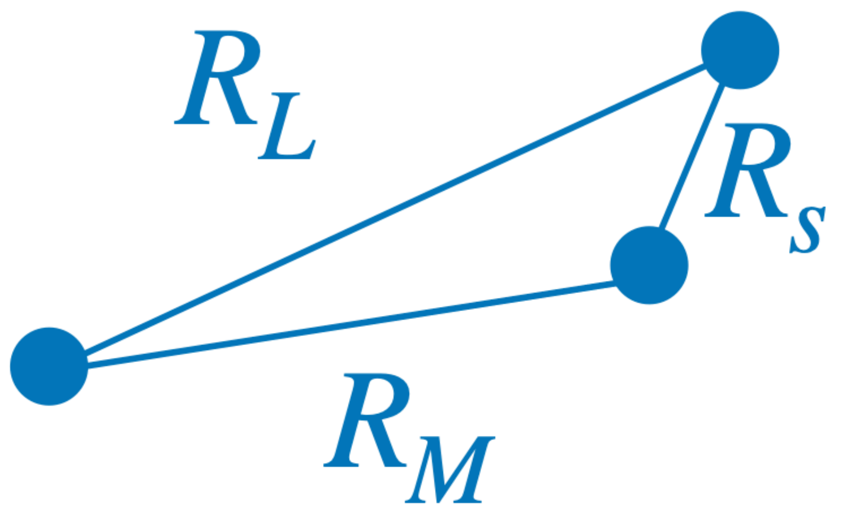


➤ Qualitative differences between QCD jets and W boson jets.

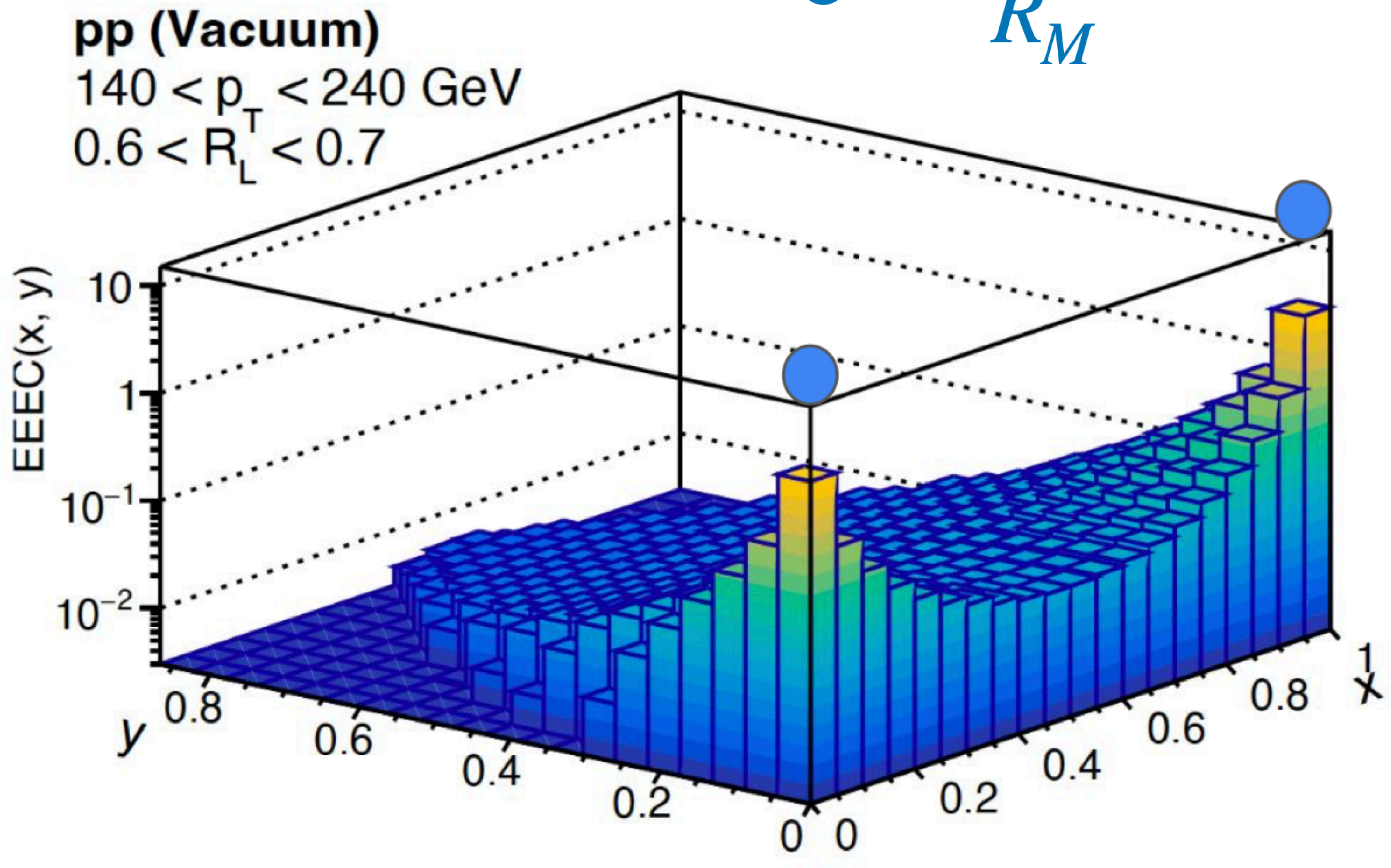
APPLICATION: WAKE POPULATES EQUILATERAL TRIANGLE CONFIGURATIONS

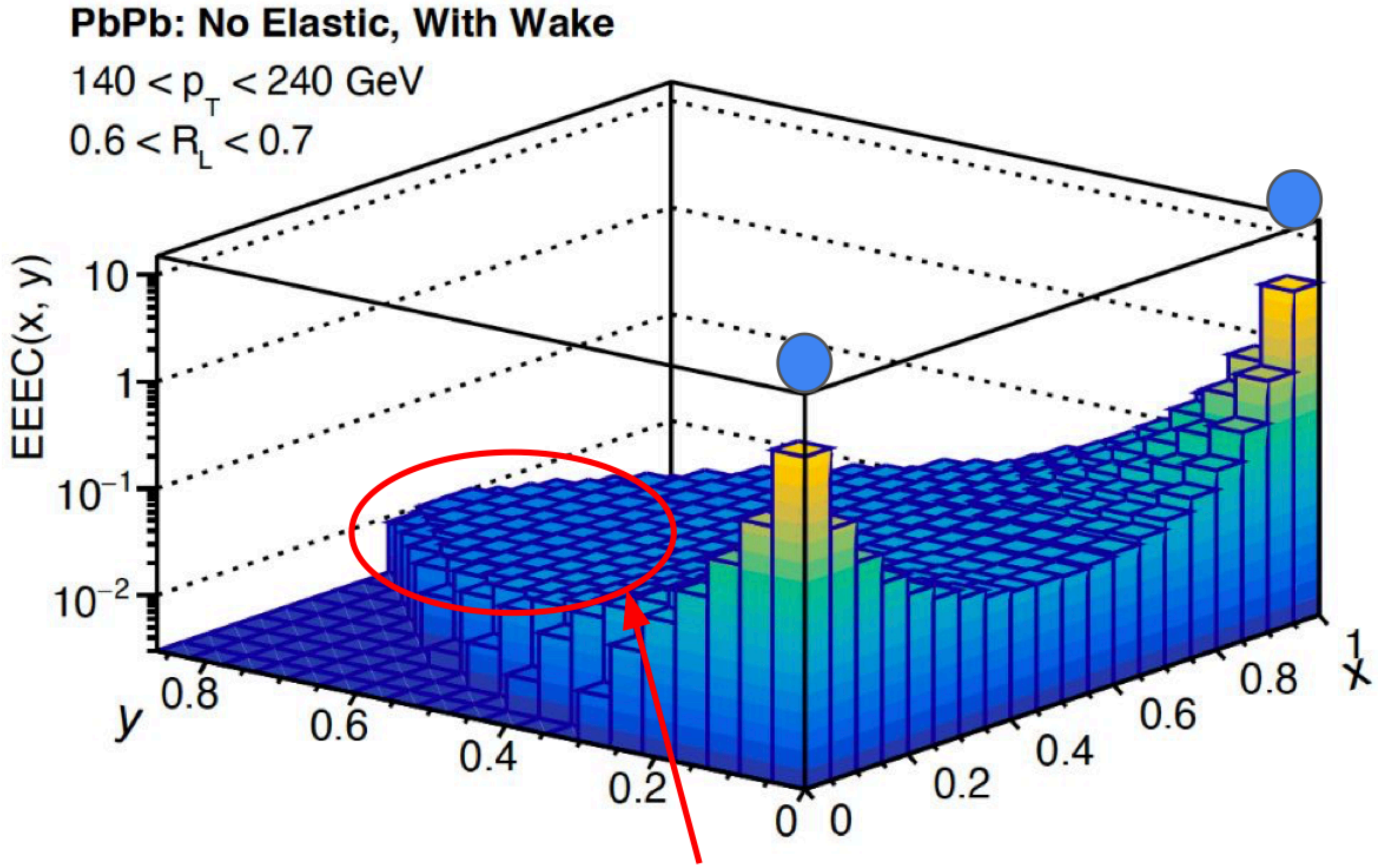
Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal ‘24

$0.6 < R_L < 0.7$



5.02 TeV, 0-5%
Anti-k_t R = 0.8 jets, $|\eta| < 2.0$
$140 < p_T < 240$ GeV





The wake fills in the phase space relatively unpopulated in vacuum.

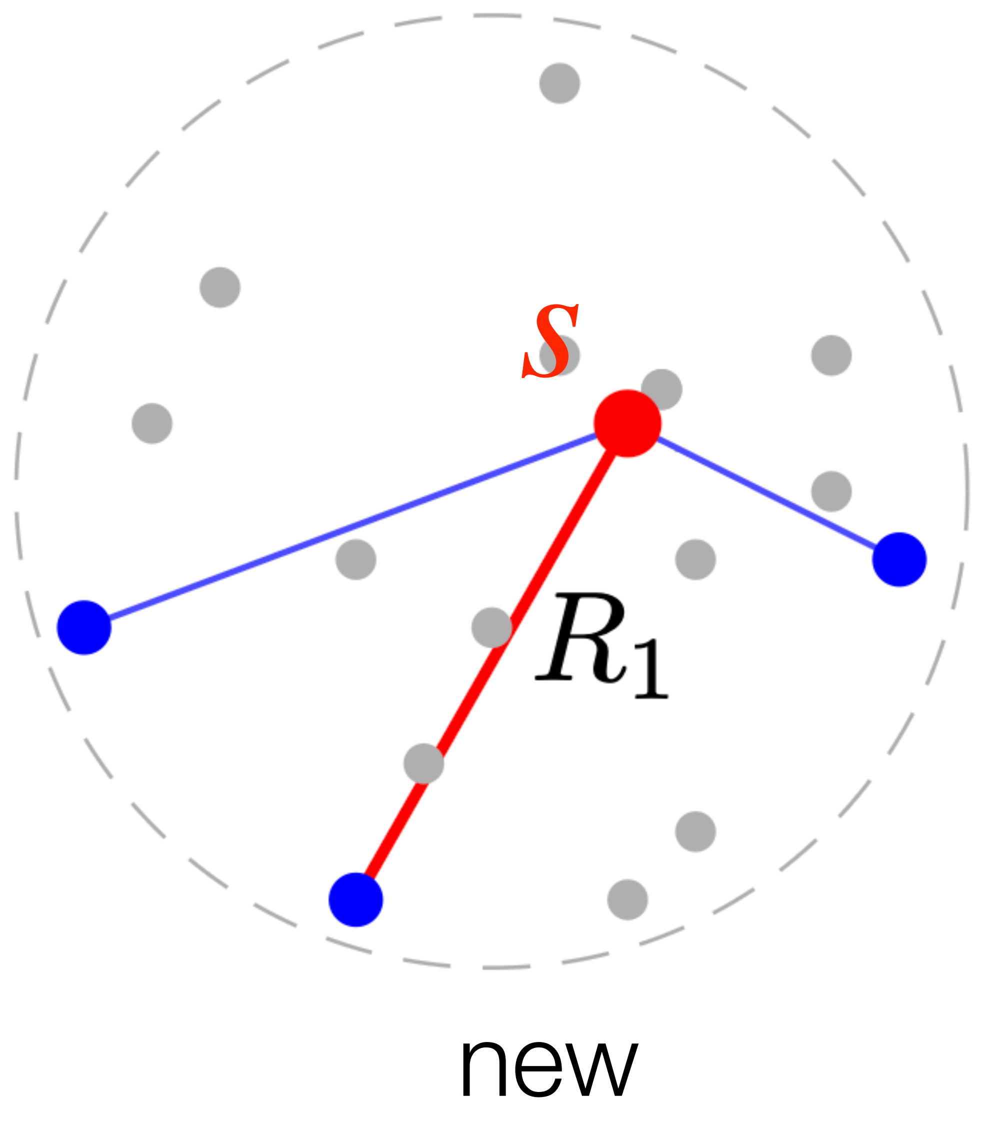
Credits : Arjun Kudinoor

SCANNING THE DOMAIN OF JET OBSERVABLES

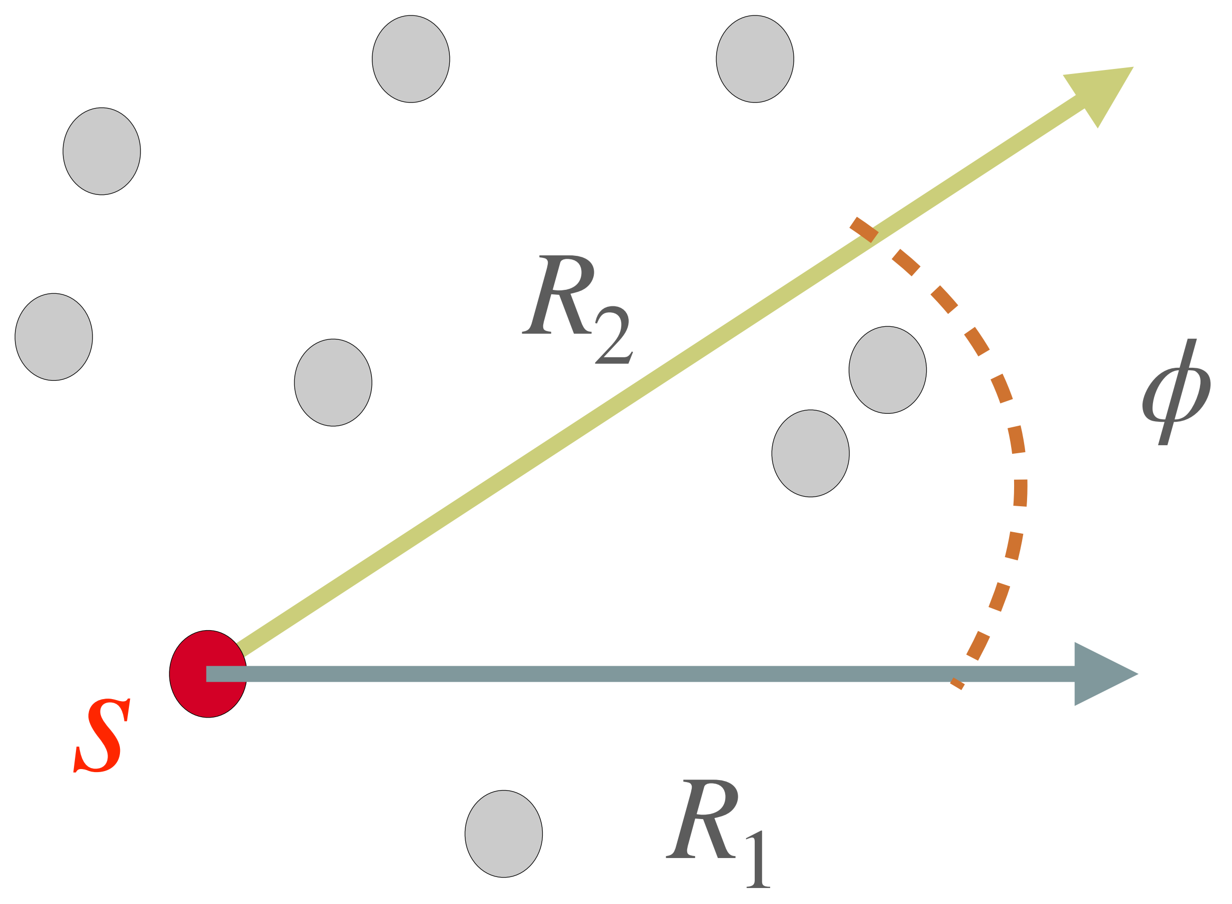
Alipour-fard, AB, Thaler, Waalewijn '24

- Projected N-point correlators

$$\Sigma_N(R_1) = \int d\sigma \sum_{s} z_s [z_{\text{disk}}(s, R_1)]^{N-1}$$



- Time is $\mathcal{O}(M^2 \log M)$ for any N.
- For resolved correlators, we use polar coordinates

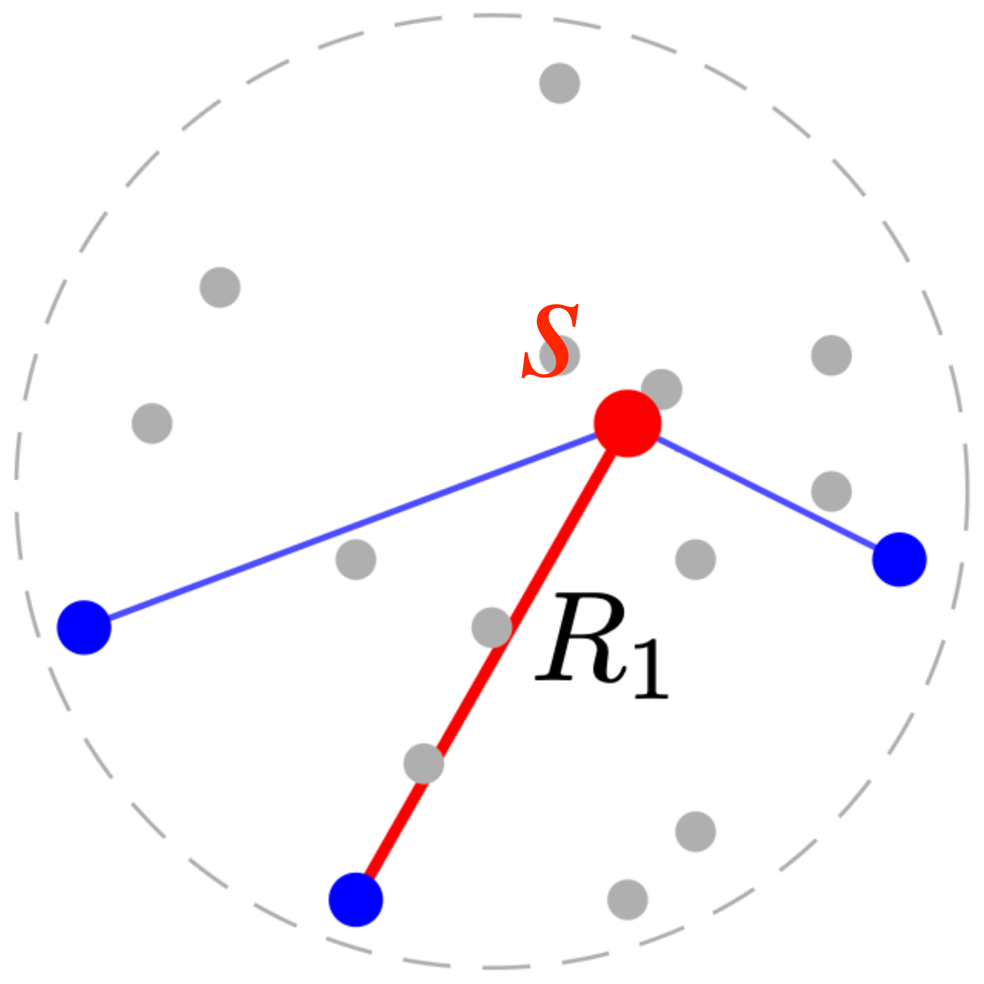


SCANNING THE DOMAIN OF JET OBSERVABLES

Alipour-fard, AB, Thaler, Waalewijn '24

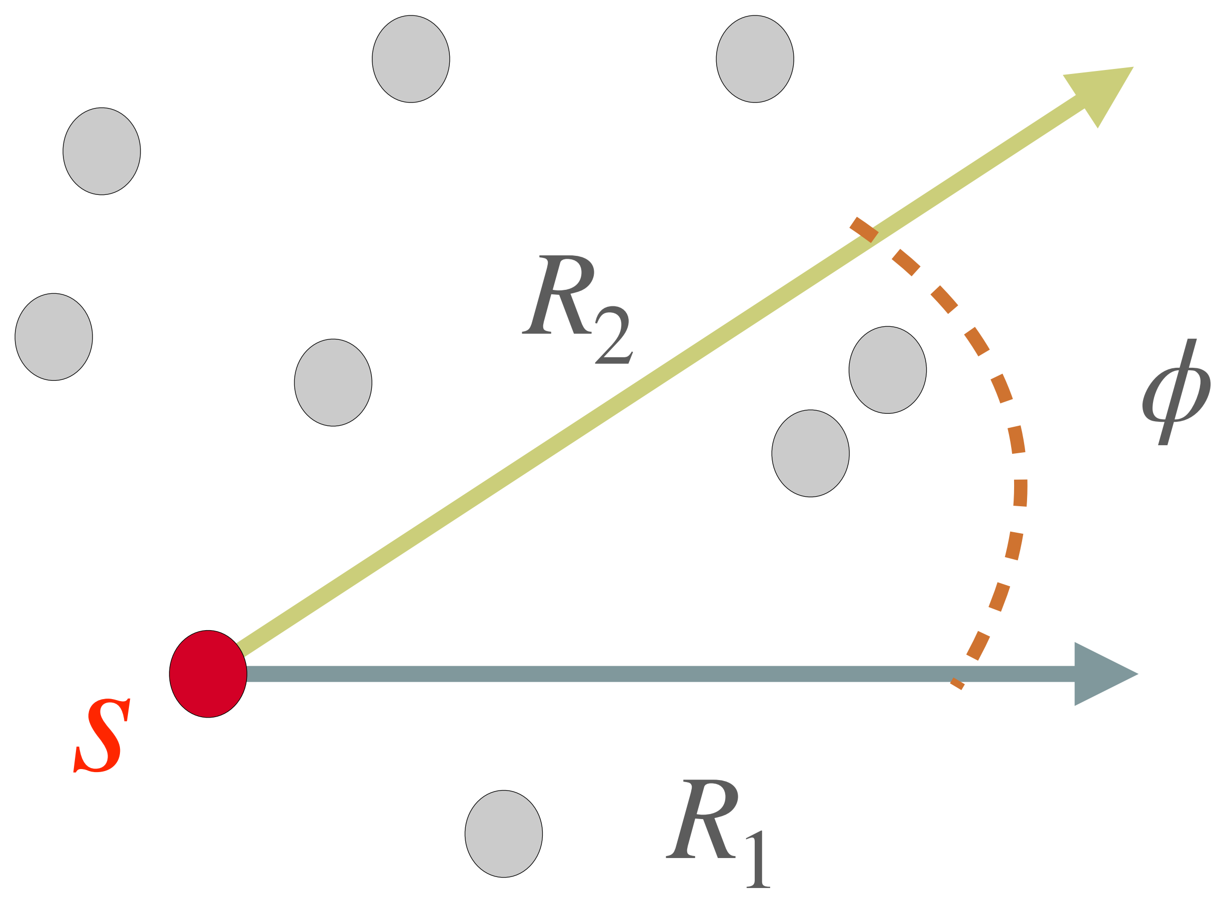
- Projected N-point correlators

$$\Sigma_N(R_1) = \int d\sigma \sum_s z_s [z_{\text{disk}}(s, R_1)]^{N-1}$$



new

- Time is $\mathcal{O}(M^2 \log M)$ for any N.
- For resolved correlators, we use polar coordinates



- Projections onto R_1 and R_2

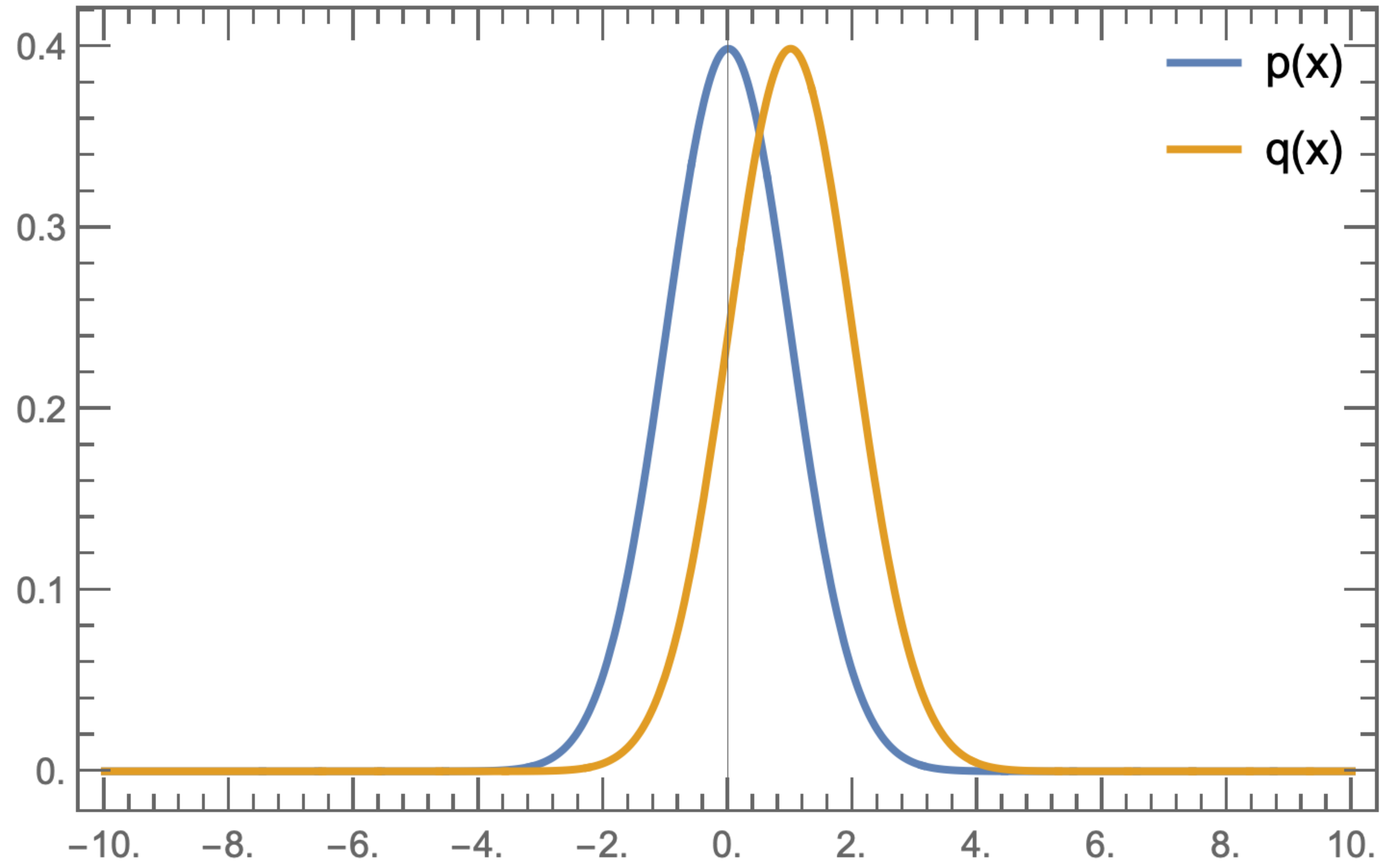
$$\Sigma_{p,q}(R_1, R_2) = \int d\sigma \sum_s z_s [z_{\text{disk}}(s, R_1)]^p \; [z_{\text{disk}}(s, R_2)]^q$$

- No ordering in R_1 and R_2 (for $p \neq q$). Time is $\mathcal{O}(M^3)$ for any p, q.
- **Which observables provide best discrimination ?**
- **Does resolving more structure add differentiating ability ?**

ASSESSING DISCRIMINATION ABILITY: TRADITIONAL CASE

- Consider two Gaussian distribution $p(x)$ and $q(x)$

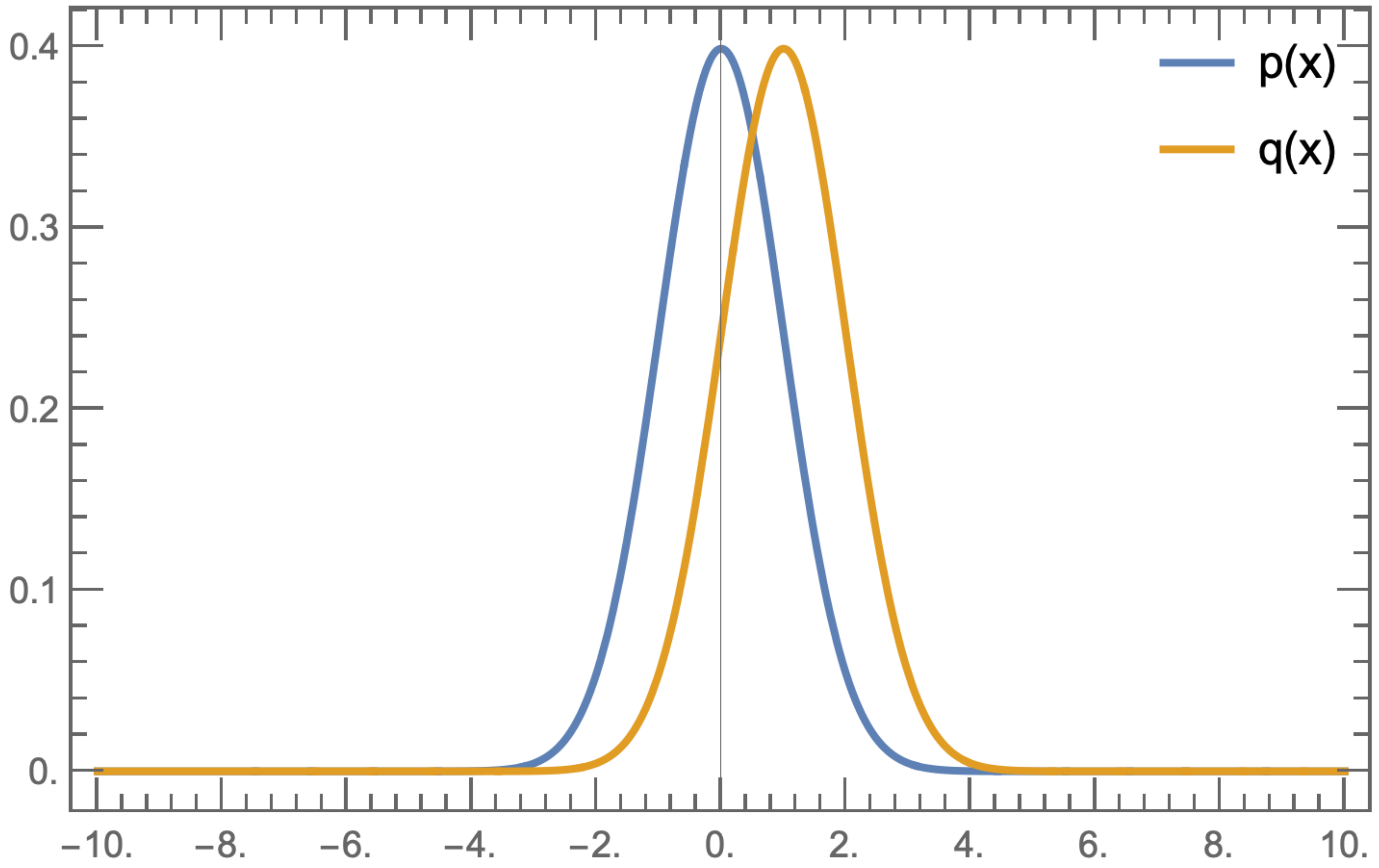
$$p(x) = \frac{1}{\sqrt{2\pi}} \exp[-x^2/2] \qquad q(x) = \frac{1}{\sqrt{2\pi}} \exp[-(x-1)^2/2]$$



ASSESSING DISCRIMINATION ABILITY: TRADITIONAL CASE

- Consider two Gaussian distribution $p(x)$ and $q(x)$

$$p(x) = \frac{1}{\sqrt{2\pi}} \exp[-x^2/2] \qquad q(x) = \frac{1}{\sqrt{2\pi}} \exp[-(x-1)^2/2]$$



- Distinguishability can be assessed through “triangular divergence”

$$\Delta = \frac{1}{2}\int dx \frac{(p(x)-q(x))^2}{p(x)+q(x)}$$

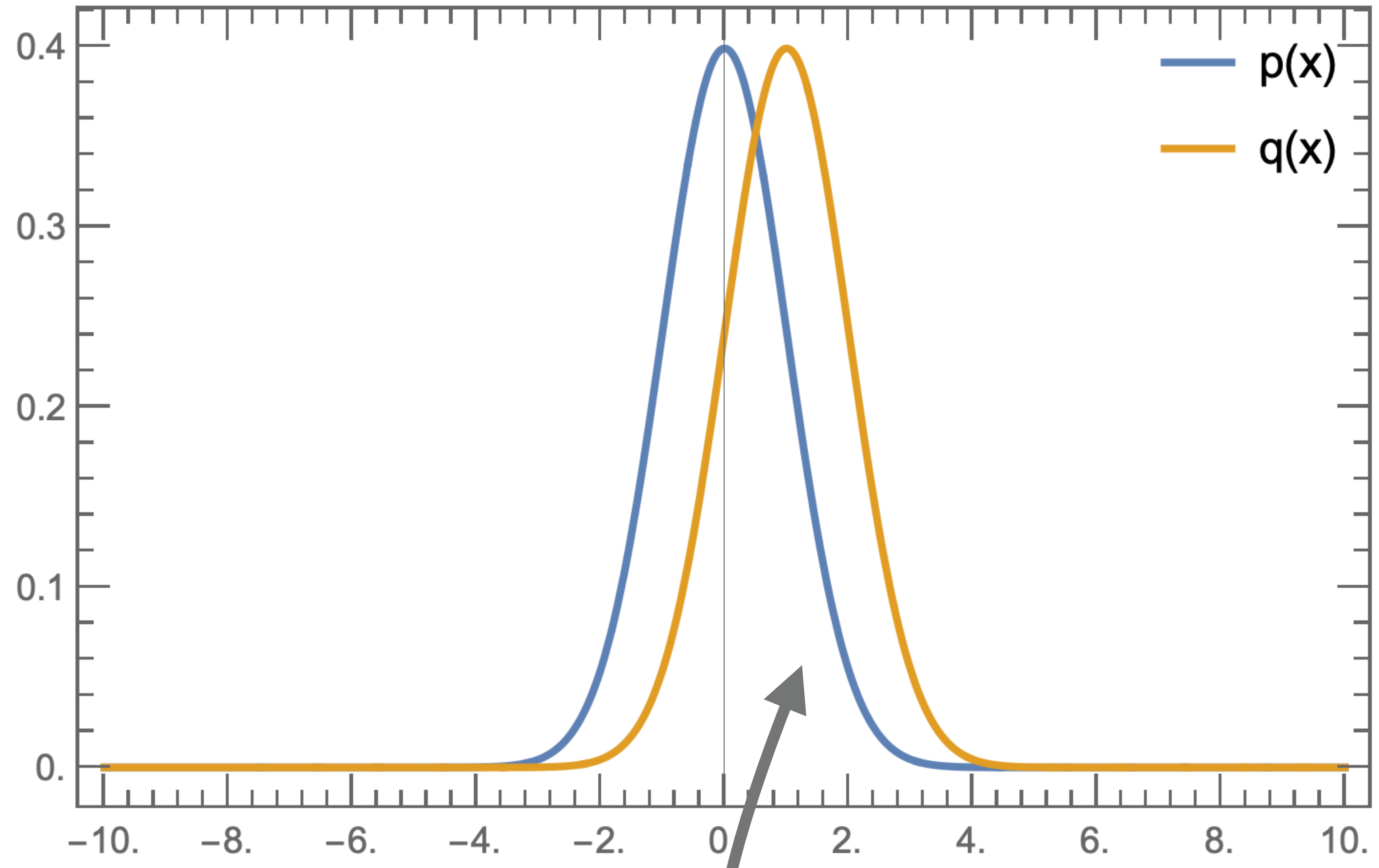
$\Delta = 0:$ No discrimination

$\Delta = 1:$ Perfect discrimination

ASSESSING DISCRIMINATION ABILITY: TRADITIONAL CASE

- Consider two Gaussian distribution $p(x)$ and $q(x)$

$$p(x) = \frac{1}{\sqrt{2\pi}} \exp[-x^2/2] \qquad q(x) = \frac{1}{\sqrt{2\pi}} \exp[-(x-1)^2/2]$$



- Distinguishability can be assessed through "triangular divergence"

$$\Delta = \frac{1}{2}\int dx \frac{(p(x)-q(x))^2}{p(x)+q(x)}$$

$\Delta = 0:$ No discrimination $\qquad \Delta = 1:$ Perfect discrimination

$\boxed{\Delta = 0.204}$

- Can be used as a statistical classifier to find the best observables. $\longrightarrow$ does not work for energy correlators.

- For energy correlators, we get histograms for individual jets $\Rightarrow$ correlations more complicated.

COVARIANCE-AWARE TRIANGULAR (CAT) DIVERGENCE

- To treat intra-jet correlations, we define the modified triangular divergence as

$$\Delta[p,q] = \frac{1}{2}\sum_{i,j}(p_i - q_i)\, C_{ij}^{-1}(p_j - q_j) \qquad\qquad C_{ij} = p_{ij} + q_{ij}$$

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress

- p_i are the binned histogram probabilities and p_{ij} contain bin correlations.
- For single-valued observables, $p_{ij} \to p_i\,\delta_{ij}$ so reduces to the “triangular divergence”.
- Δ is always bounded between 0 and 1.

COVARIANCE-AWARE TRIANGULAR (CAT) DIVERGENCE

- To treat intra-jet correlations, we define the modified triangular divergence as

$$\Delta[p,q] = \frac{1}{2}\sum_{i,j}(p_i - q_i)\, C_{ij}^{-1}(p_j - q_j) \qquad\qquad C_{ij} = p_{ij} + q_{ij}$$

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn: in progress

- p_i are the binned histogram probabilities and p_{ij} contain bin correlations.
- For single-valued observables, $p_{ij} \to p_i\,\delta_{ij}$ so reduces to the "triangular divergence".
- Δ is always bounded between 0 and 1.
- Properties:
  1. If $\Delta[p,q;A] > \Delta[p,q;B] \Rightarrow$ observable A is more discriminating than B.
  2. $\Delta[p,q;A\cup B] \geq \max\{\Delta[p,q;A], \Delta[p,q;B]\}$

Δ FOR PROJECTED CORRELATORS

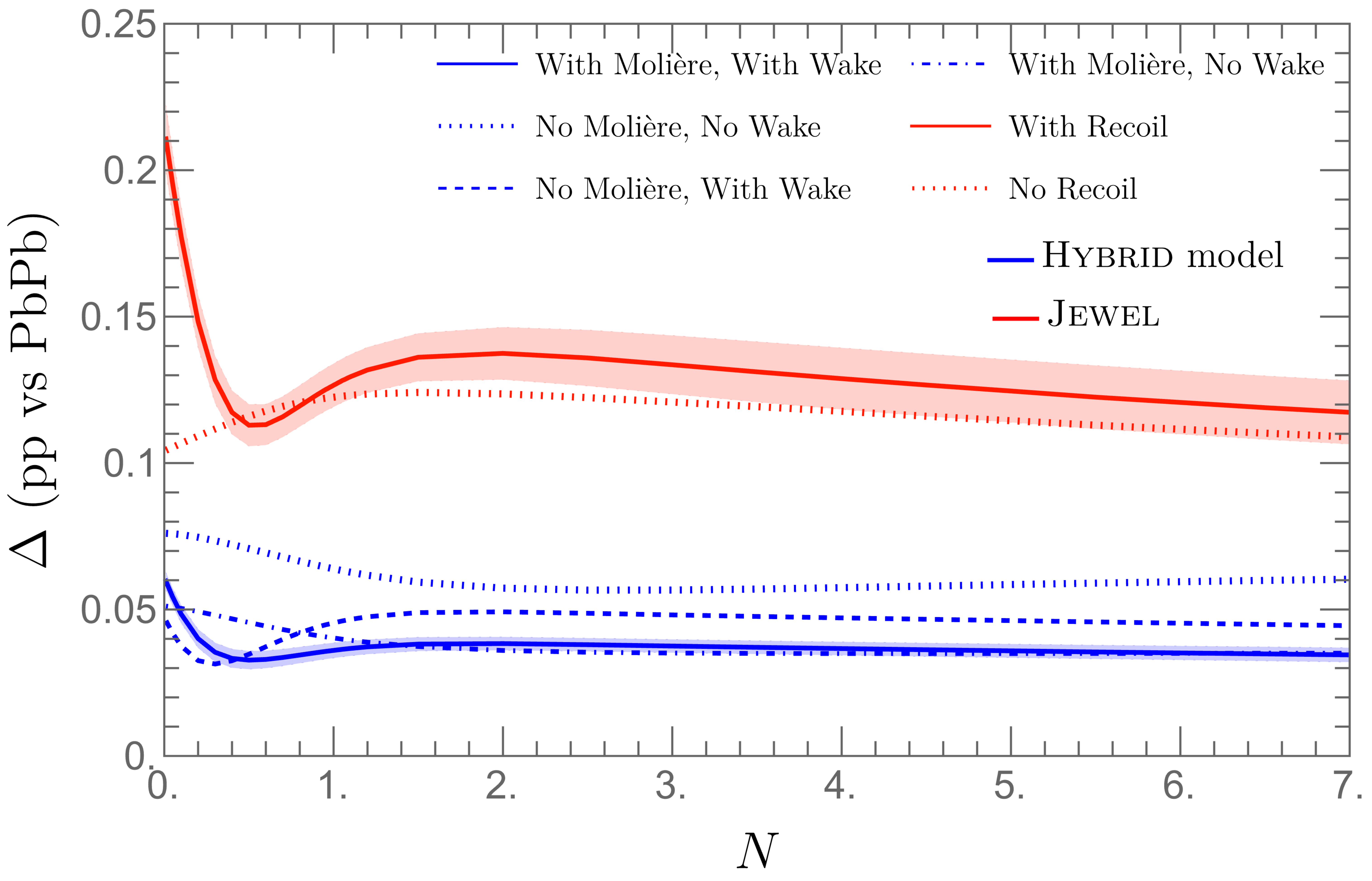
Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress

- We use two jet quenching models.

- Jewel shows larger differences

  related to differences in parton shower ?

- Errors are related to bootstrapping.

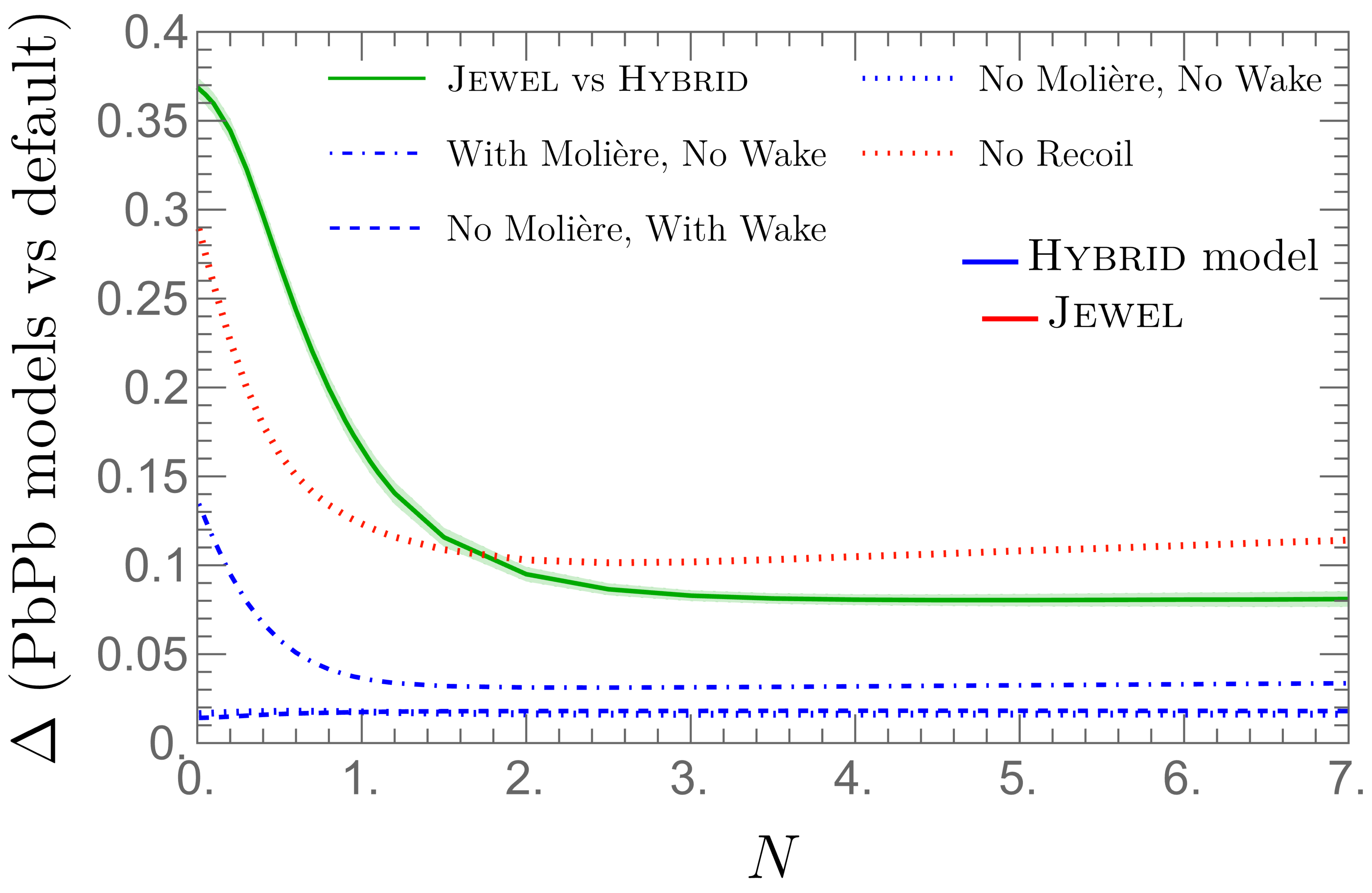


Δ FOR PROJECTED CORRELATORS: DIFFERENTIATING PBPB MODELS

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress

- $N < 1$ correlators show the most sensitivity to different jet quenching models.

See Balbeer's talk !

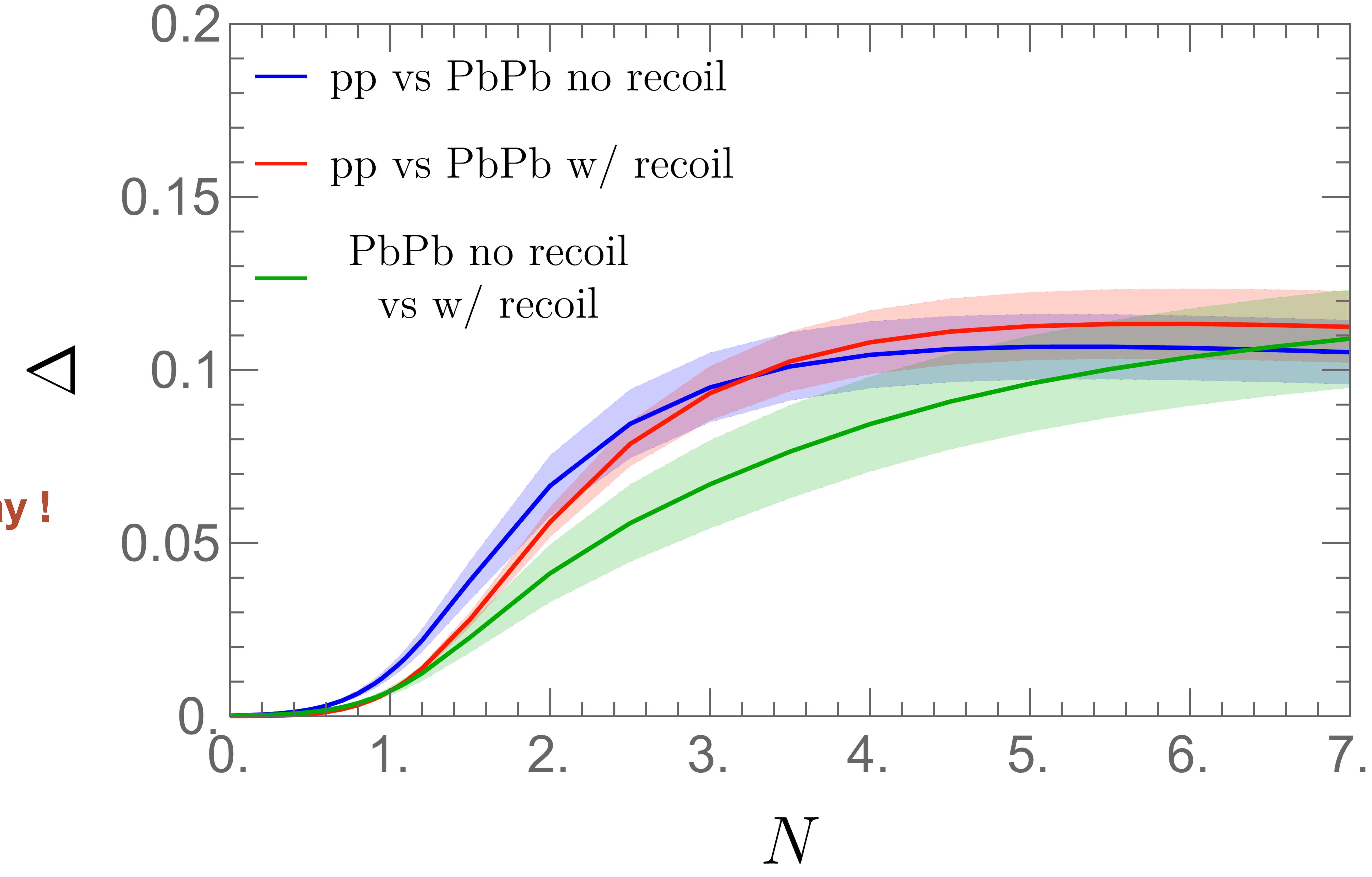


Δ FOR PROJECTED CORRELATORS: DISCRIMINATION FOR SMALL N

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress

- Discrimination in $N < 1$ region dominated by differences in multiplicities.

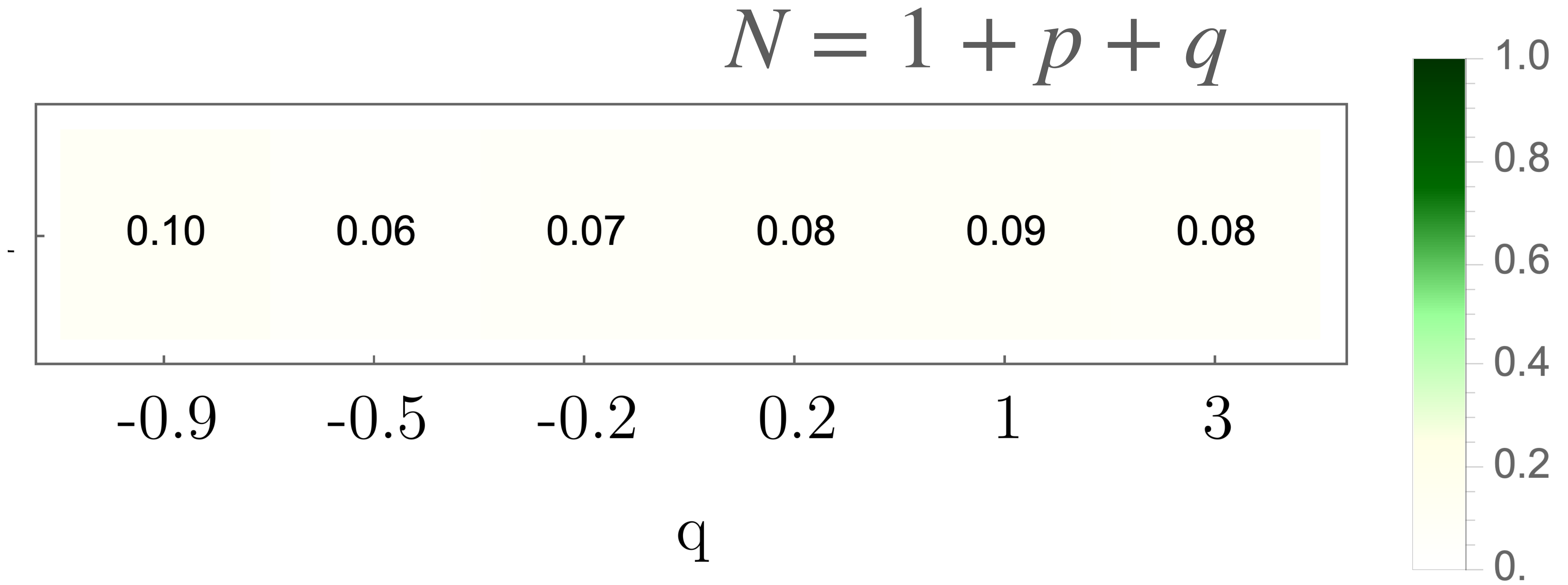
although, in an IRC safe way !

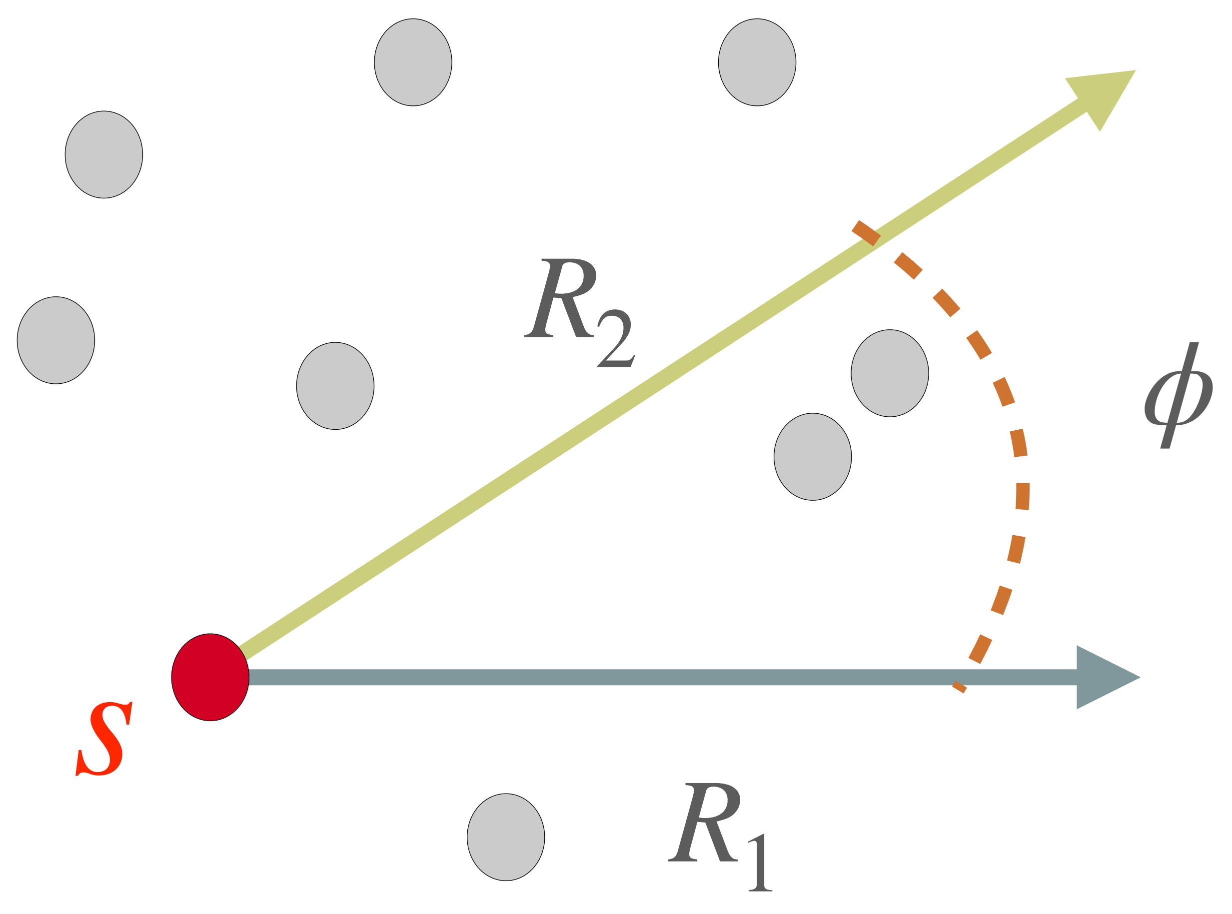


Δ FOR RESOLVED CORRELATORS (R_1 AND ϕ)

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress

- Projecting along R_2 (or, equivalently R_1)

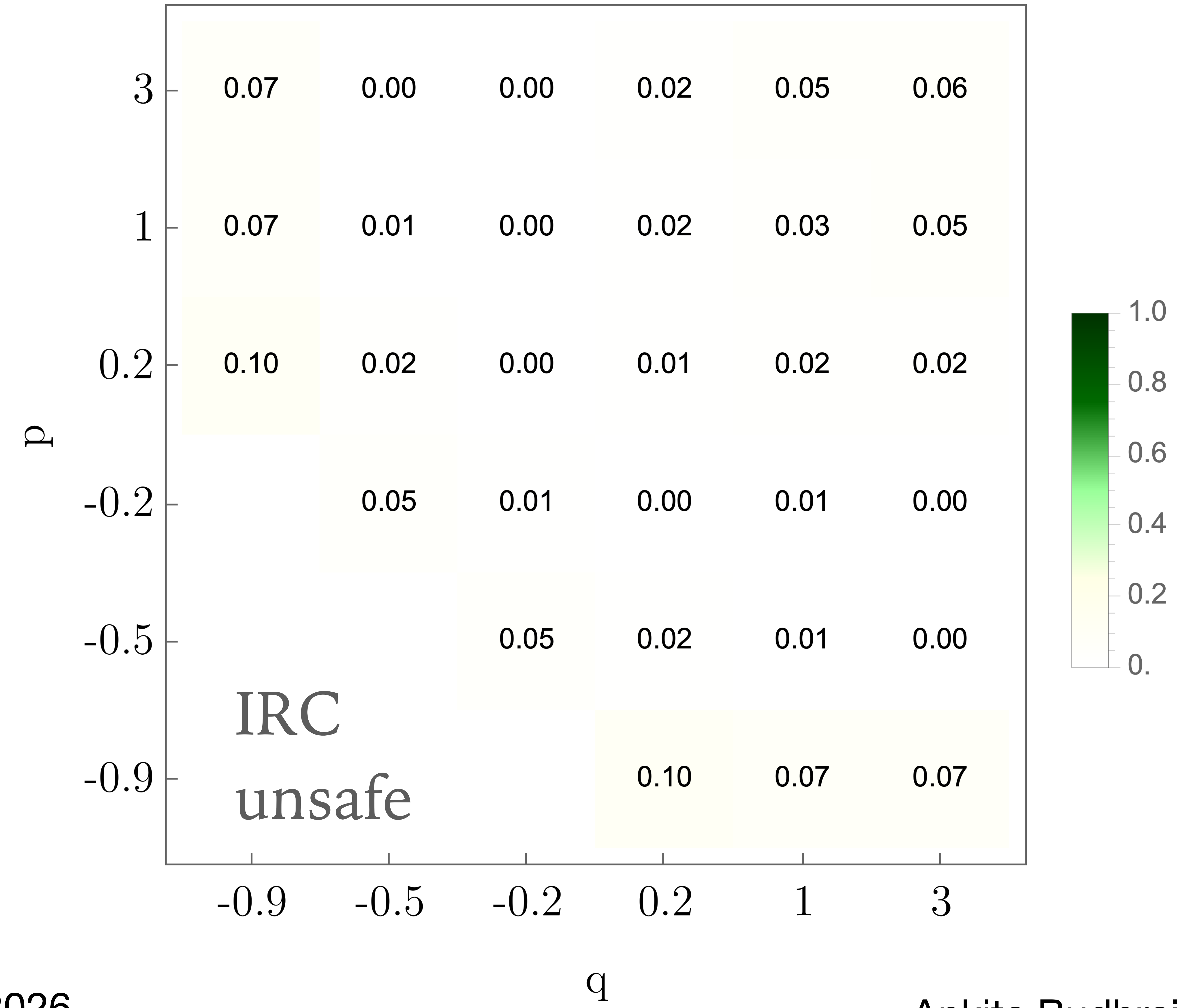




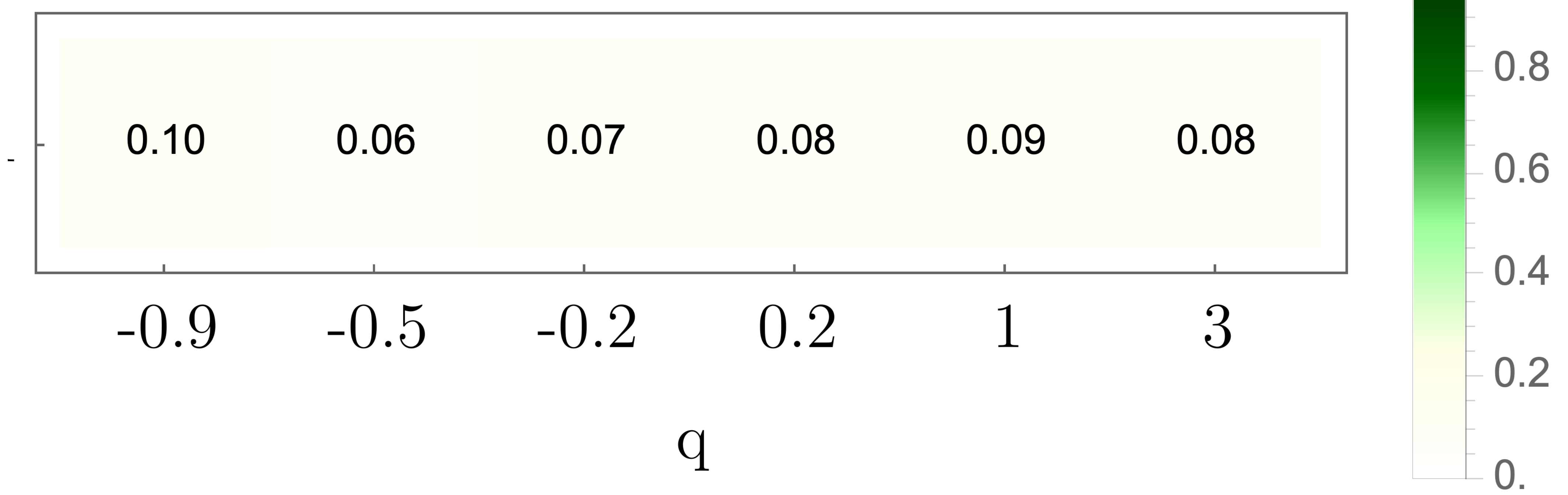
Δ FOR RESOLVED CORRELATORS (R_1 AND ϕ)

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress

- Projecting along R_2 (or, equivalently R_1)



$N = 1 + p + q$



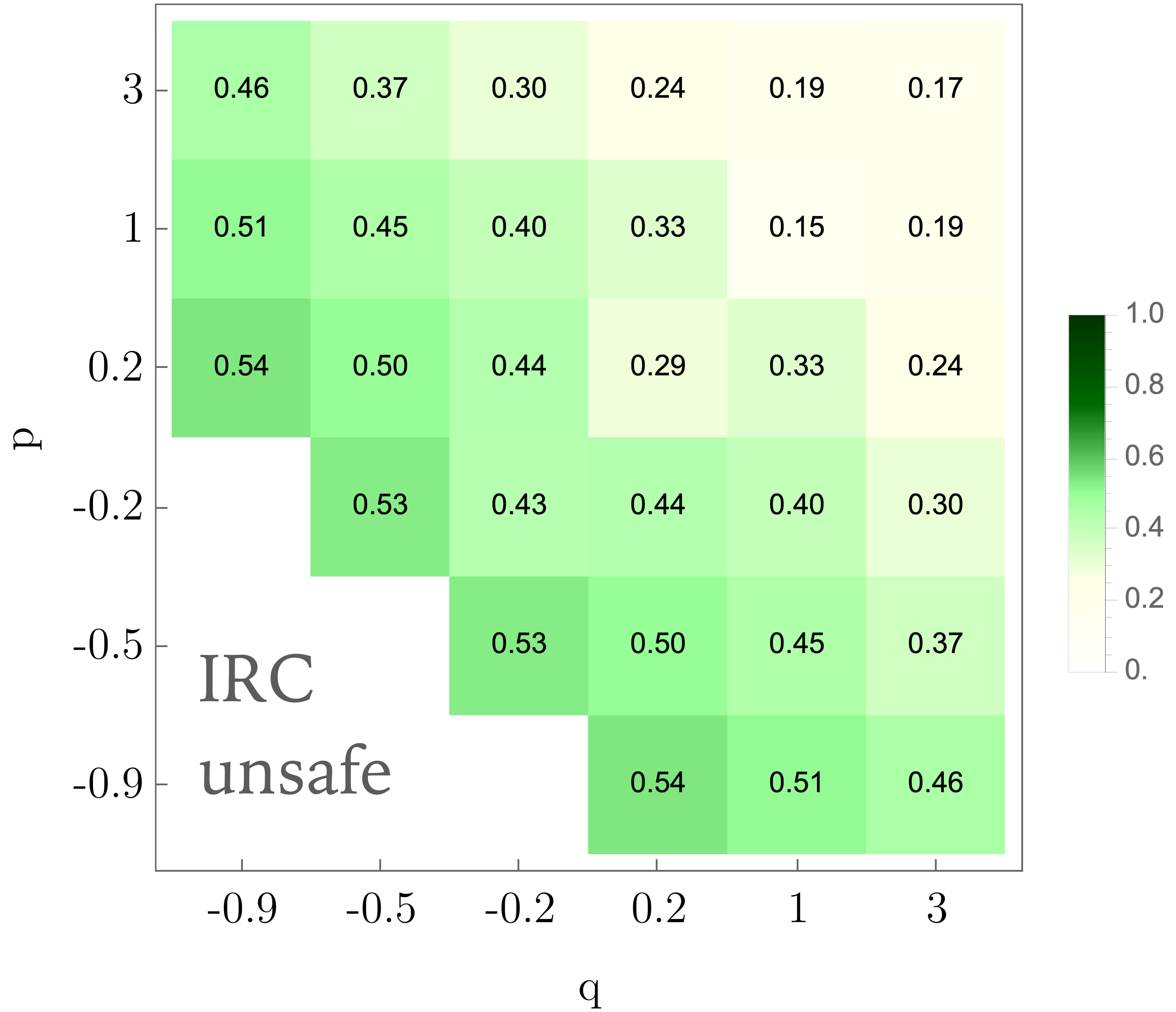
- Projecting along ϕ

Scanning observables to discriminate pp and PbPb jets

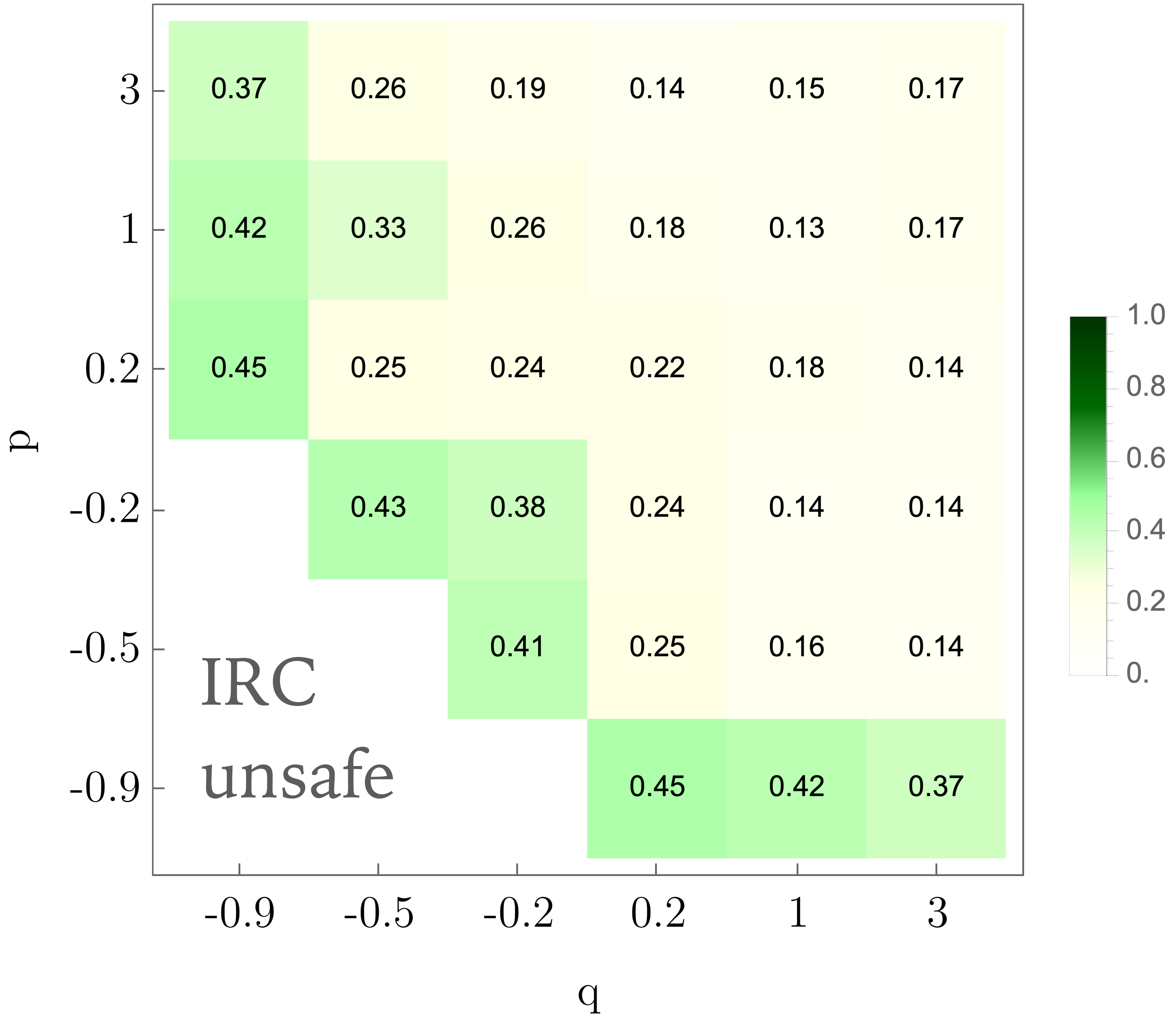
IRC safety requires that $p + q > -1$

△ FOR RESOLVED CORRELATORS (TWO OBSERVABLES)

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress



(R_1, R_2)



(R_1, ϕ)

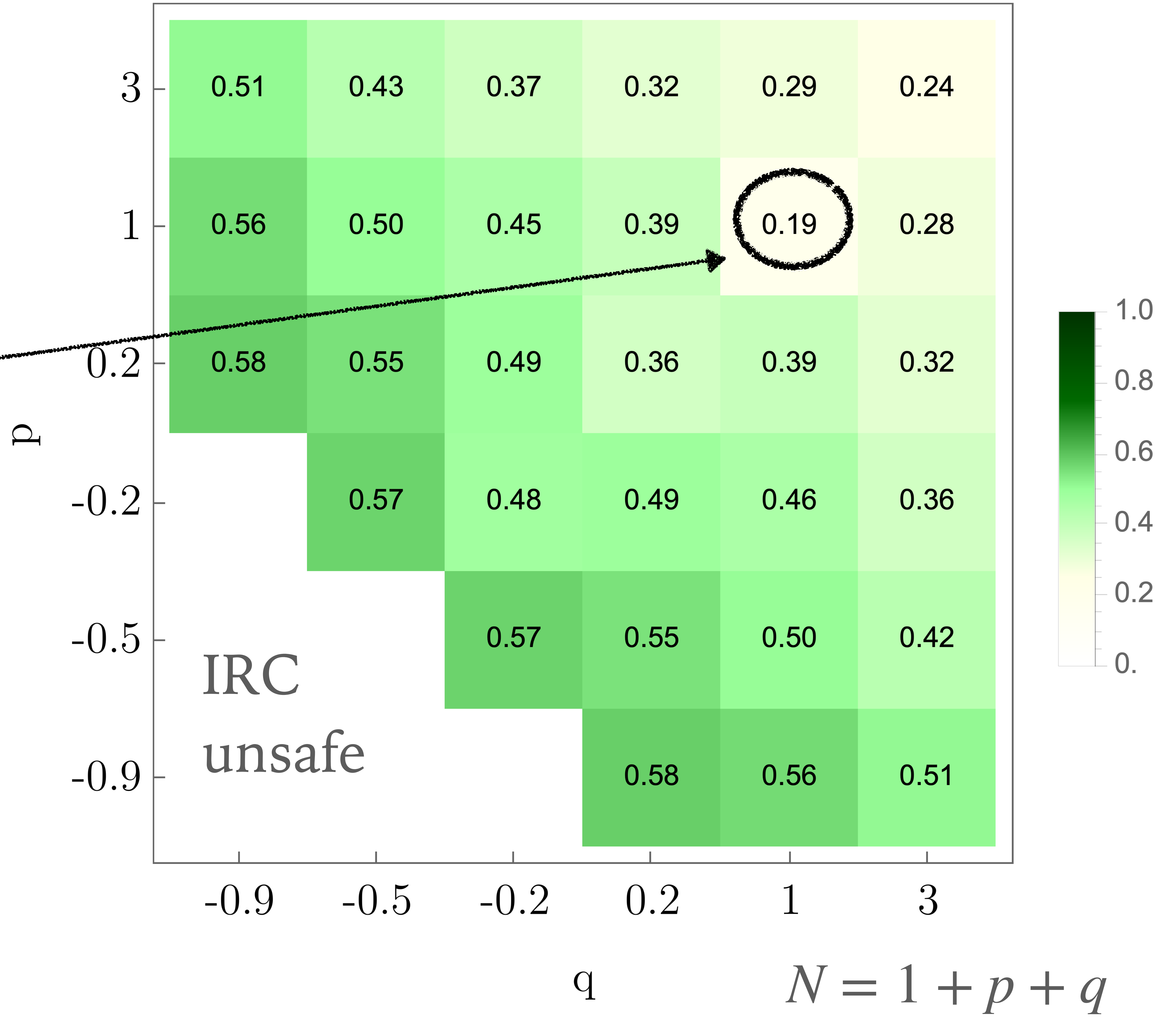
- Adding more information improves the discrimination significantly.

$$N = 1 + p + q$$

△ FOR FULLY RESOLVED CORRELATORS

Alipour-fard, AB, Kudinoor, Thaler, Waalewijn; in progress

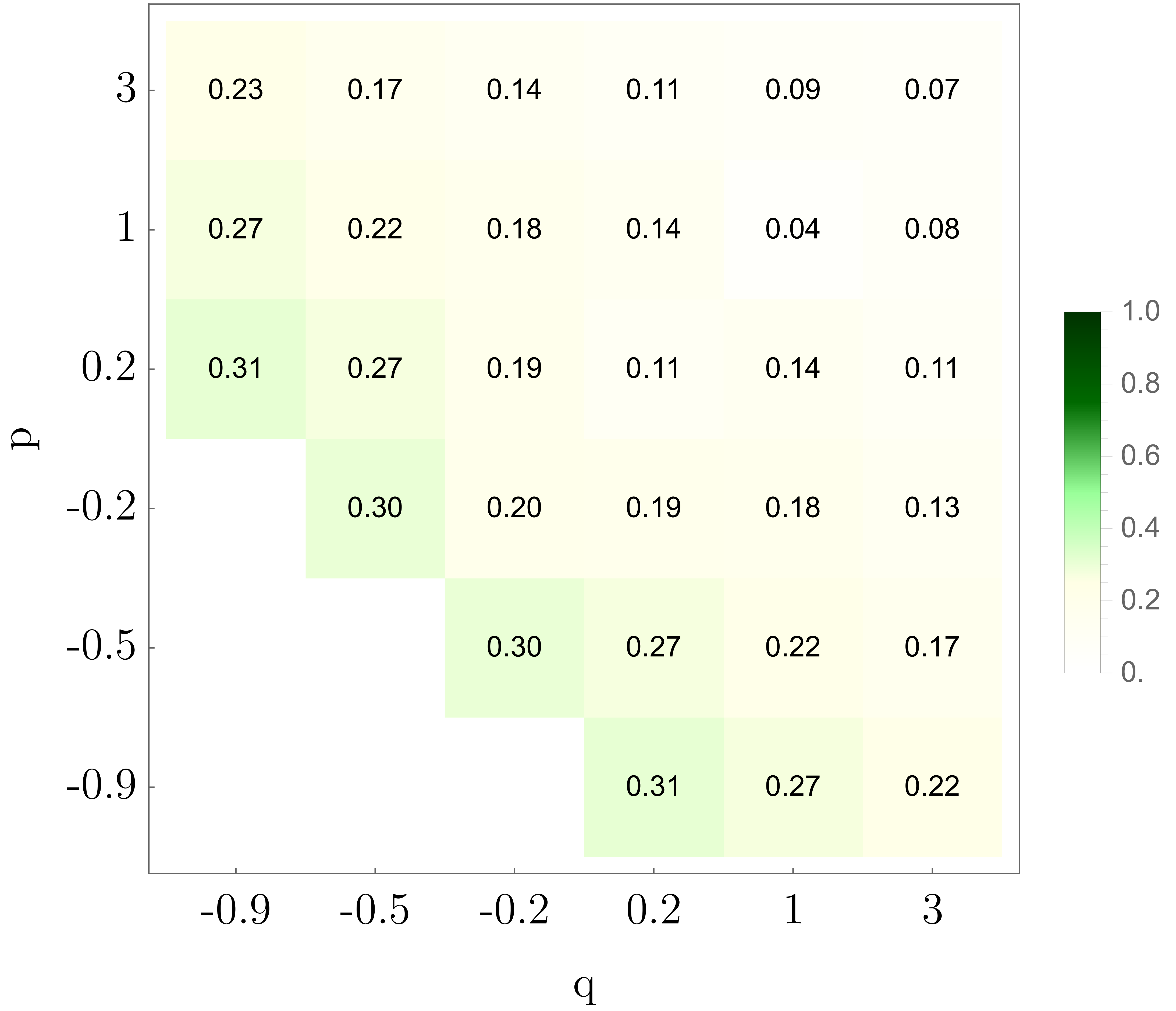
- Fully resolving adds most discrimination, although only slightly more than (R_1, R_2).
- Standard choice $p = q = 1$ is least differentiating.
- Discriminating with $p \neq q$ is better.



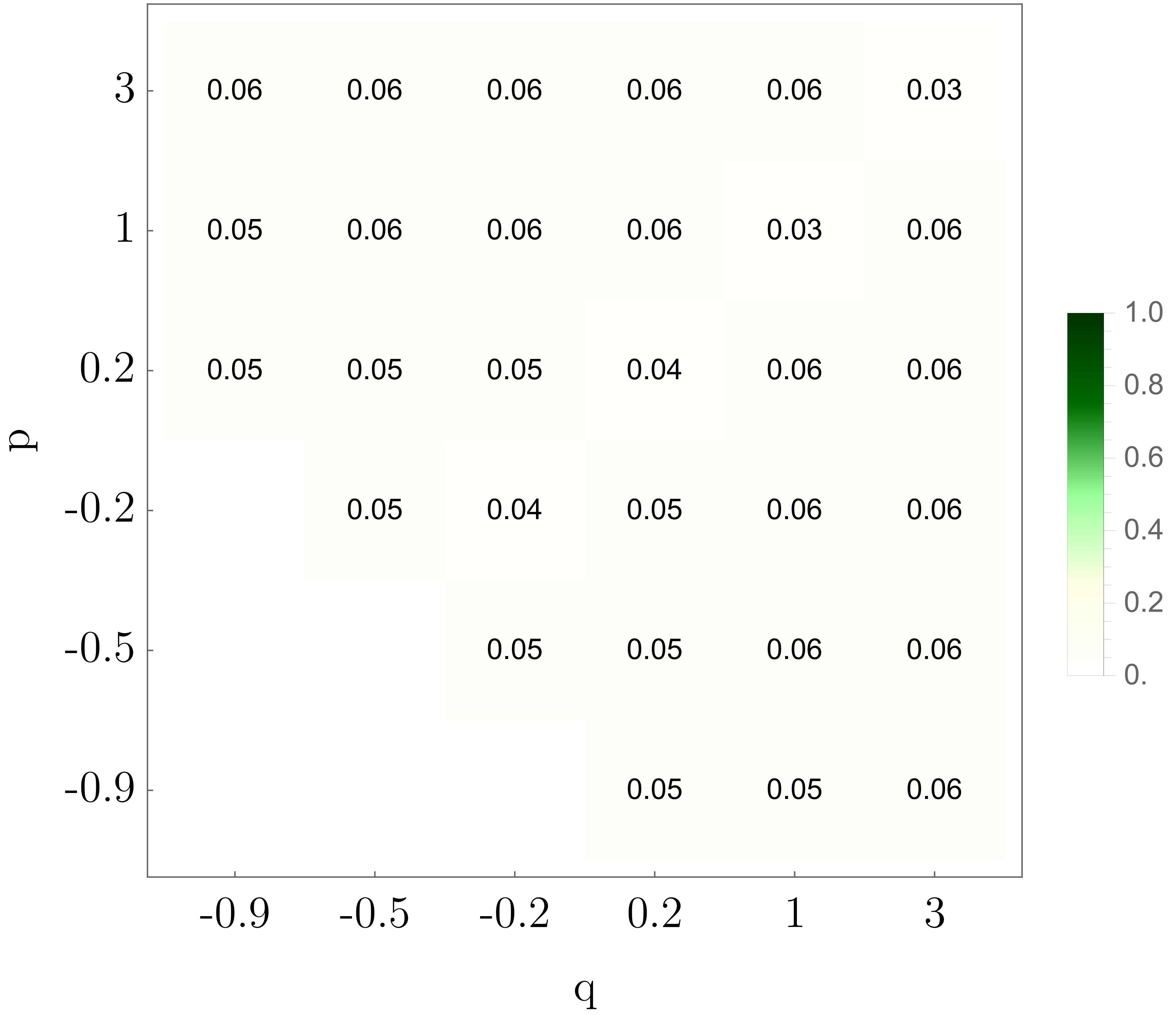
$N = 1 + p + q$

△ FOR RESOLVED: LOOKING FOR WAKE/MOLIERE SCATTERINGS

➤ Finding wake in the presence of Moliere scattering



➤ Finding Moliere scattering in the presence of wakes



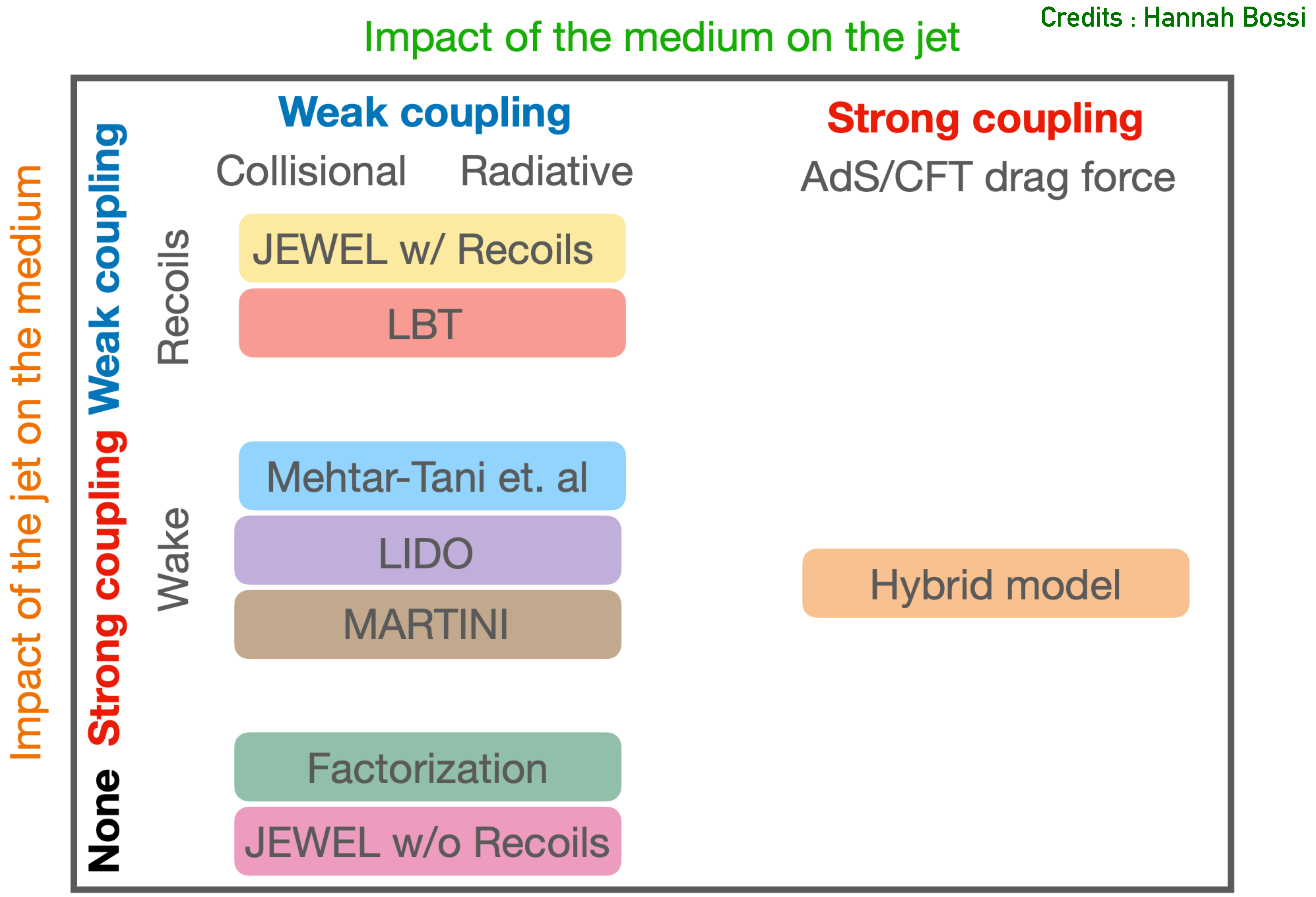
SUMMARY

- Energy Correlators are simple, clean observables with good theoretical control.
- We introduced a new approach featuring non-redundant parameters that allows their practical realization and makes the analytic continuation trivial.
- Provides computational speed-ups and new ways of probing jet structure.
- Defined new observables beyond projected correlators and statistical tools for appropriately probing effects of jet-medium interactions.

BACKUP

JET QUENCHING MODELS

- Many jet quenching models, with different approximations.
- As of now, no clear winner for best description of jet quenching effects.



JET QUENCHING MODELS

- Many jet quenching models, with different approximations.
- As of now, no clear winner for best description of jet quenching effects.
- We would like to find what observables can best differentiate them.

Credits : Hannah Bossi