Probing Non-Perturbative QCD with Jet Substructure Measurements at STAR

Youqi Song, UC Berkeley

RHIC/AGS Users Meeting

5/13/26

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Yale

Wright Laboratory

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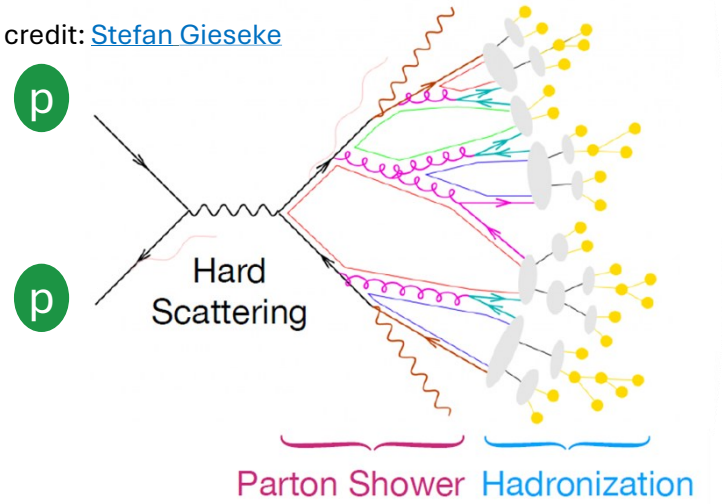
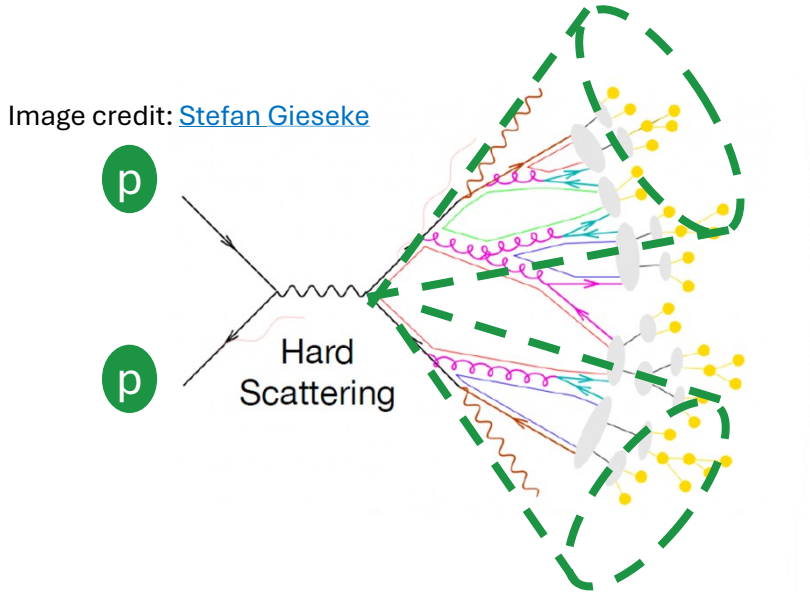
Jets and jet substructure

Image credit: Stefan Gieseke



- Jets: collimated sprays of final-state hadrons

Jets and jet substructure



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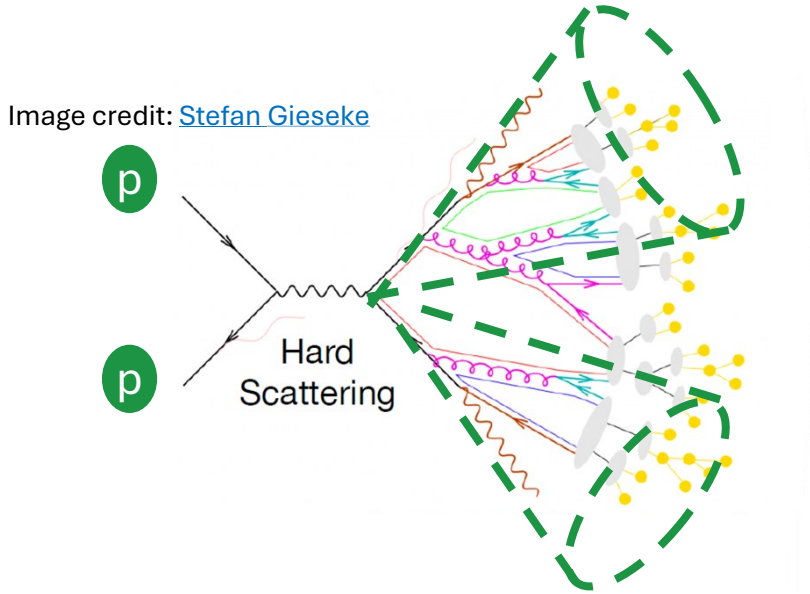

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  - Algorithmic reclustering, e.g. SoftDrop grooming

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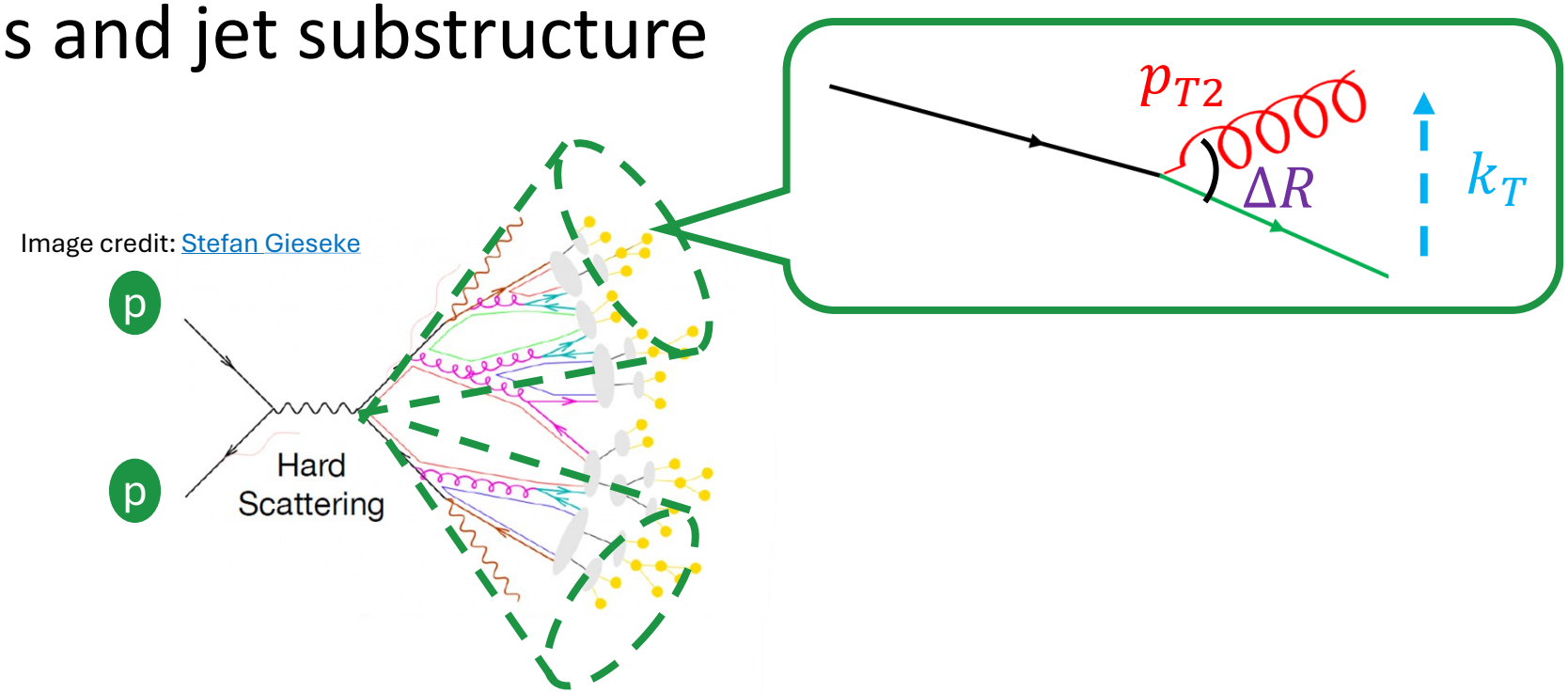

$$k_T = p_{T2} \times \sin(\Delta R)$$
$$z = p_{T2}/p_T$$

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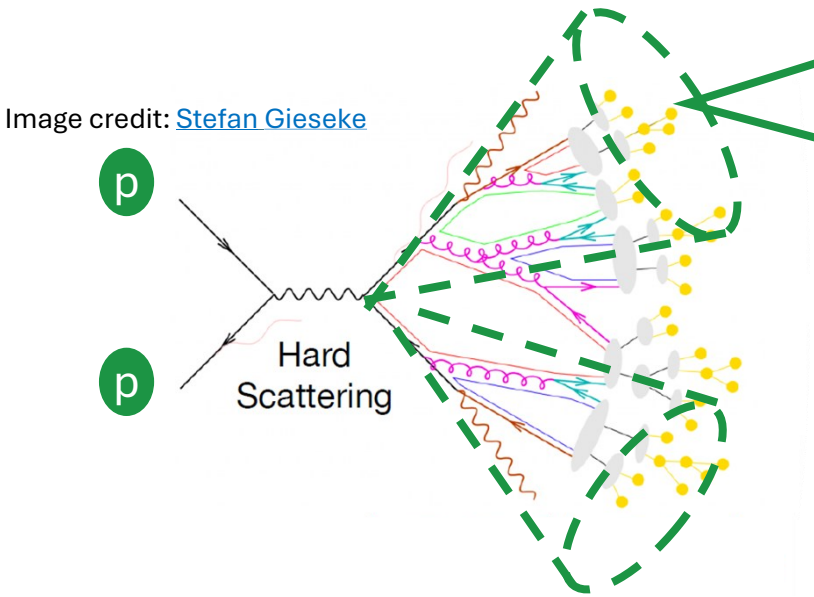

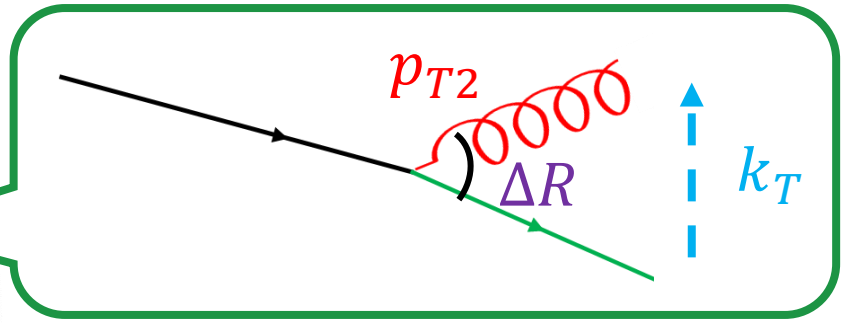

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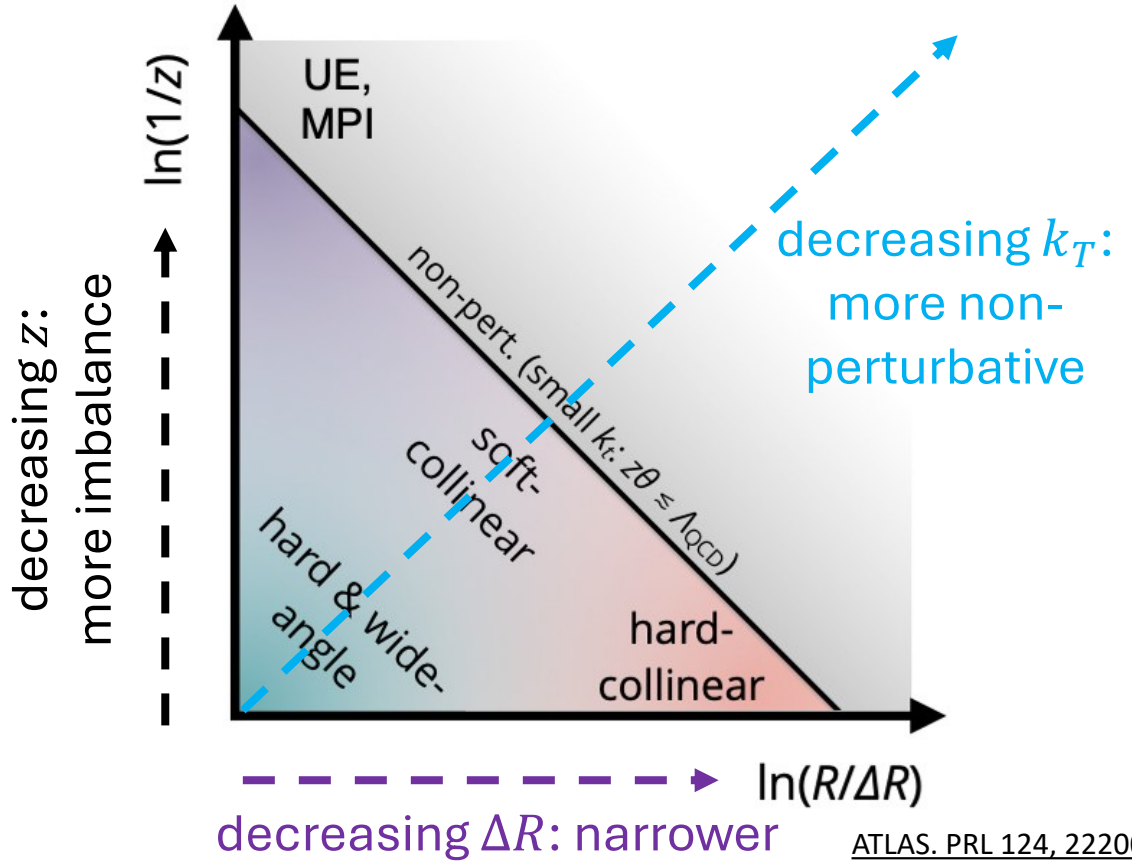
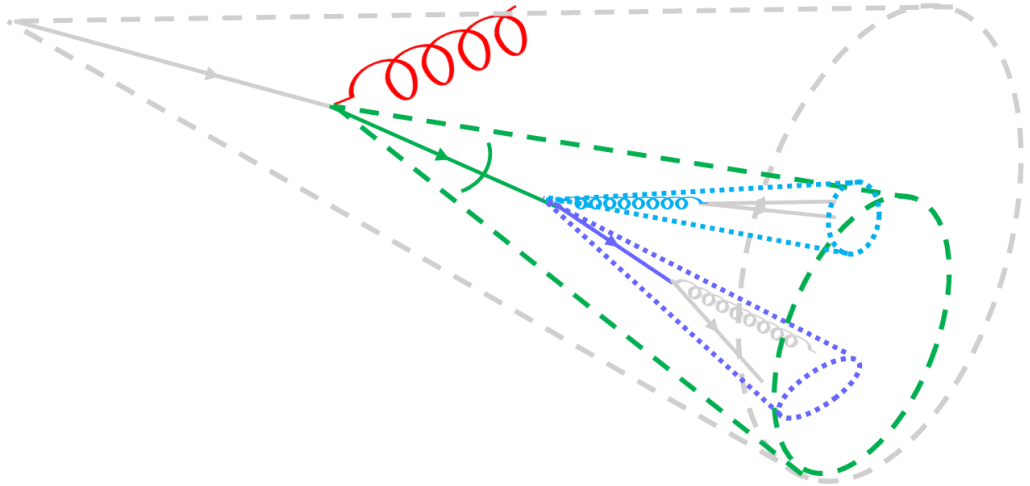


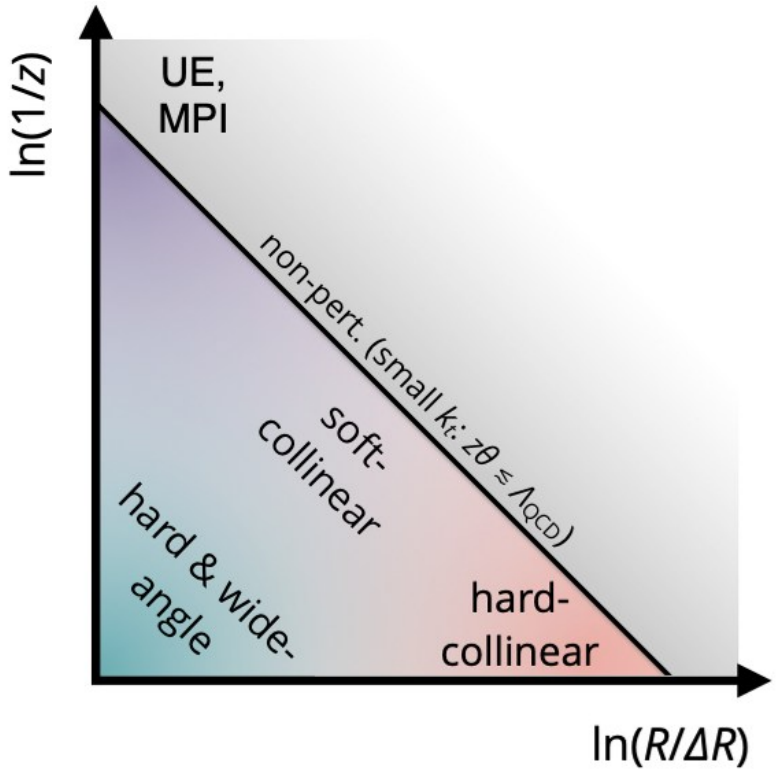
ATLAS. PRL 124, 222002 (2020)

CollinearDrop-SoftDrop correlation

Aims to probe the **soft-hard correlation** within a jet

- How does the amount of soft radiation correlate with the angular and momentum scale of a hard splitting? → How does an **early** emission affect a **later** splitting?*





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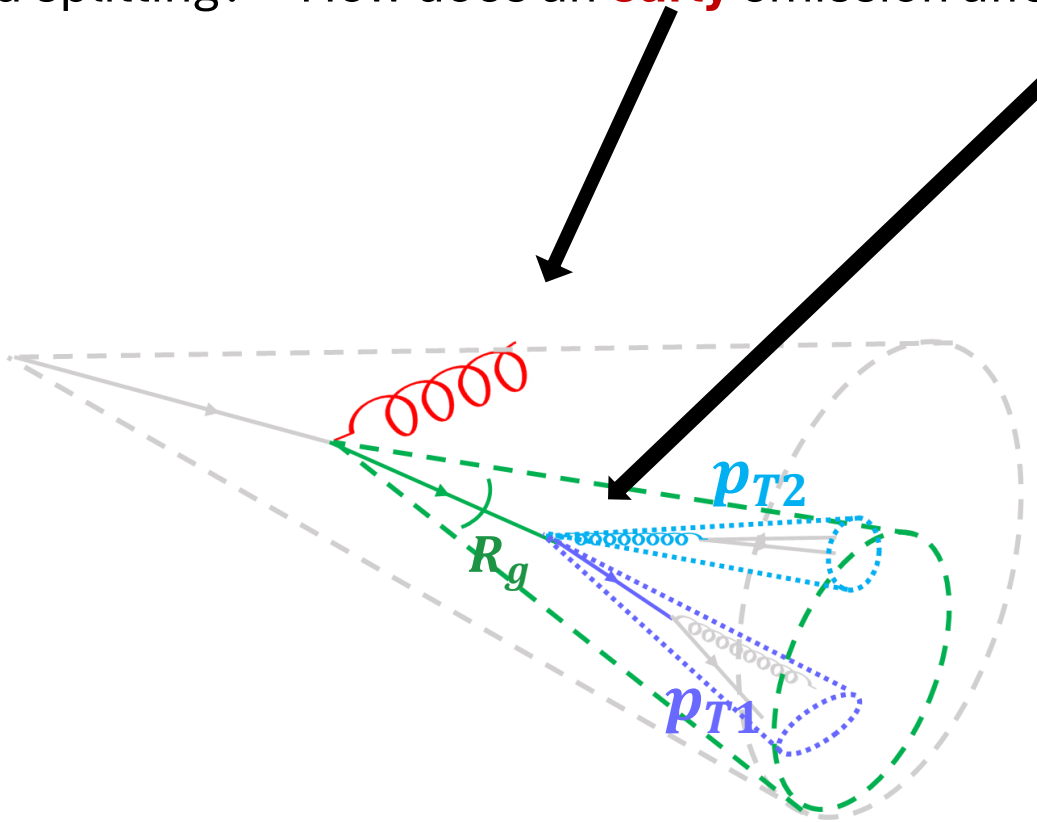
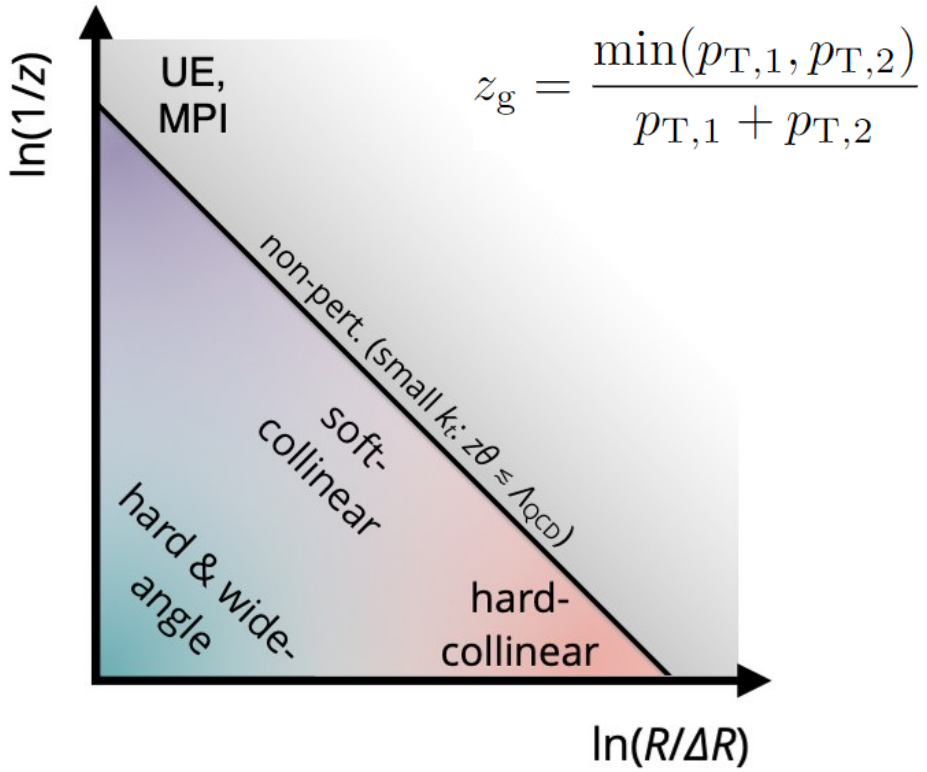


Momentum imbalance and angle of **later**-stage splitting: **SoftDrop** z_g, R_g



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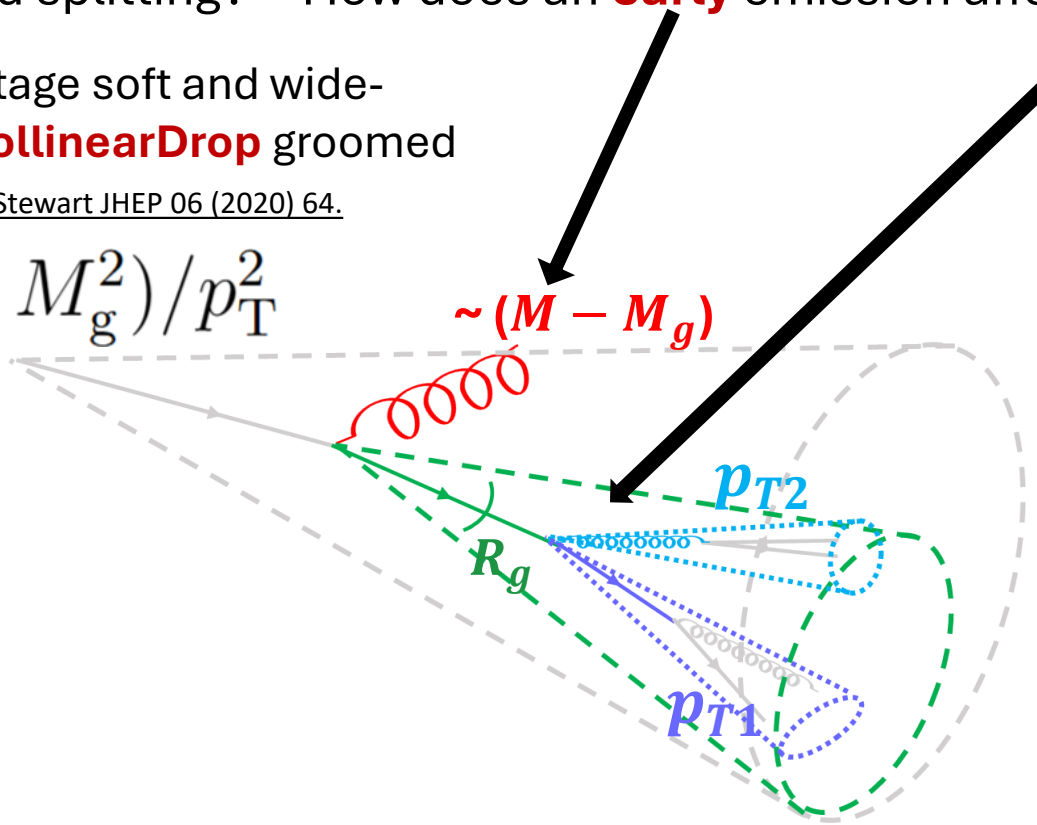

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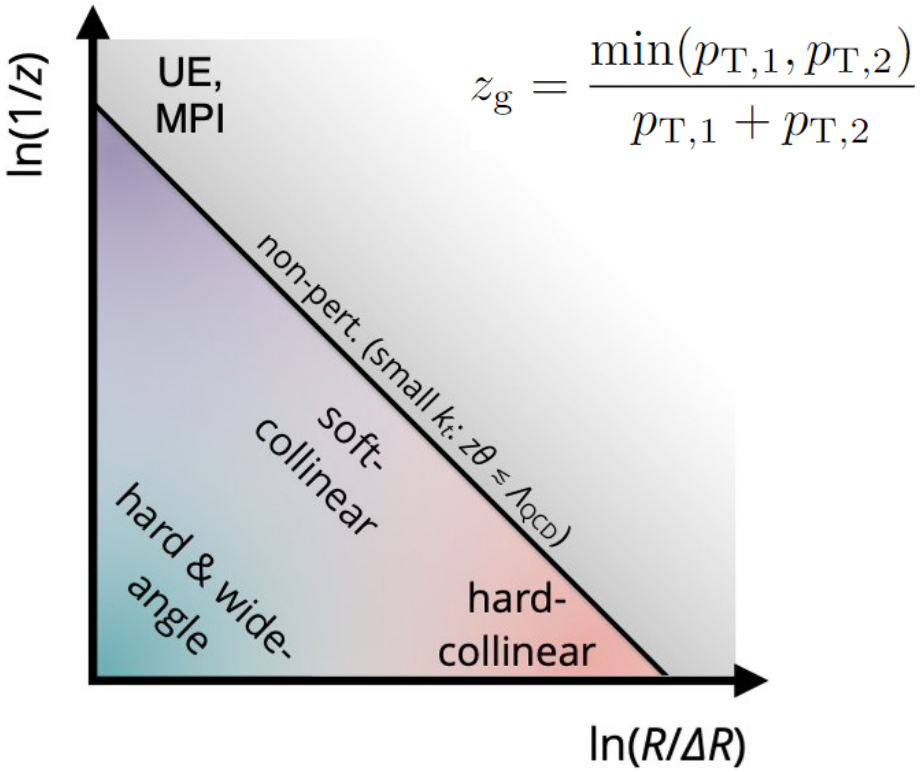

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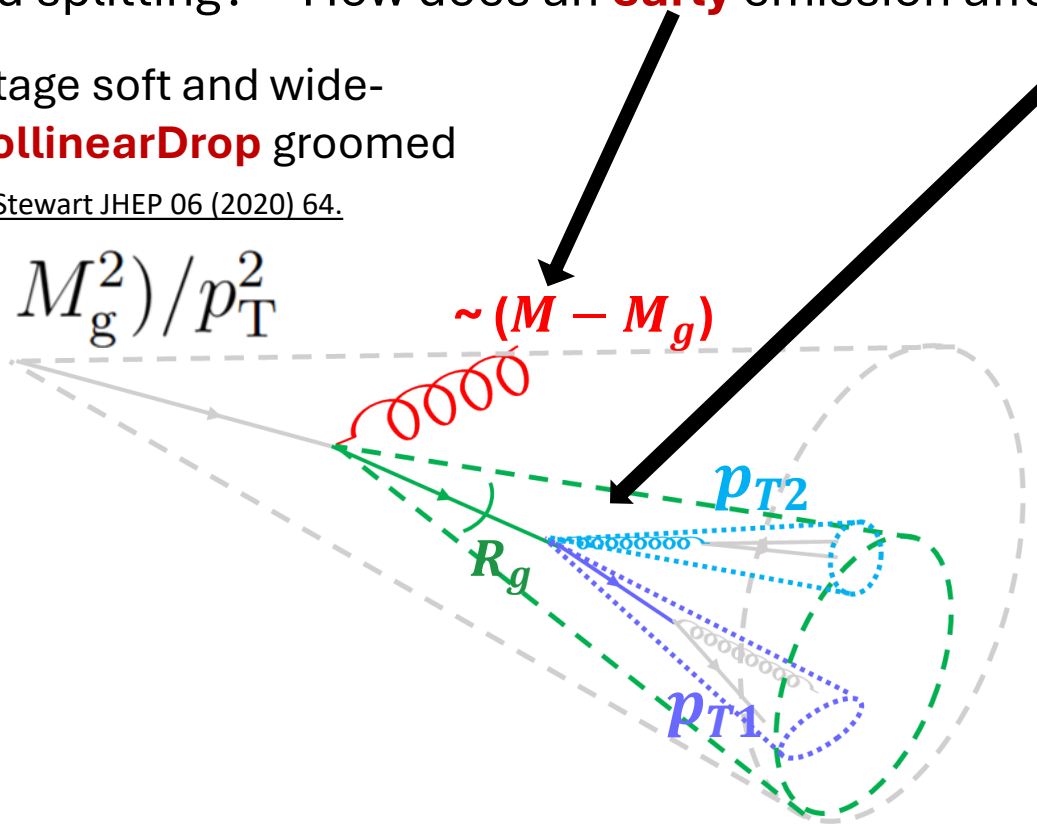

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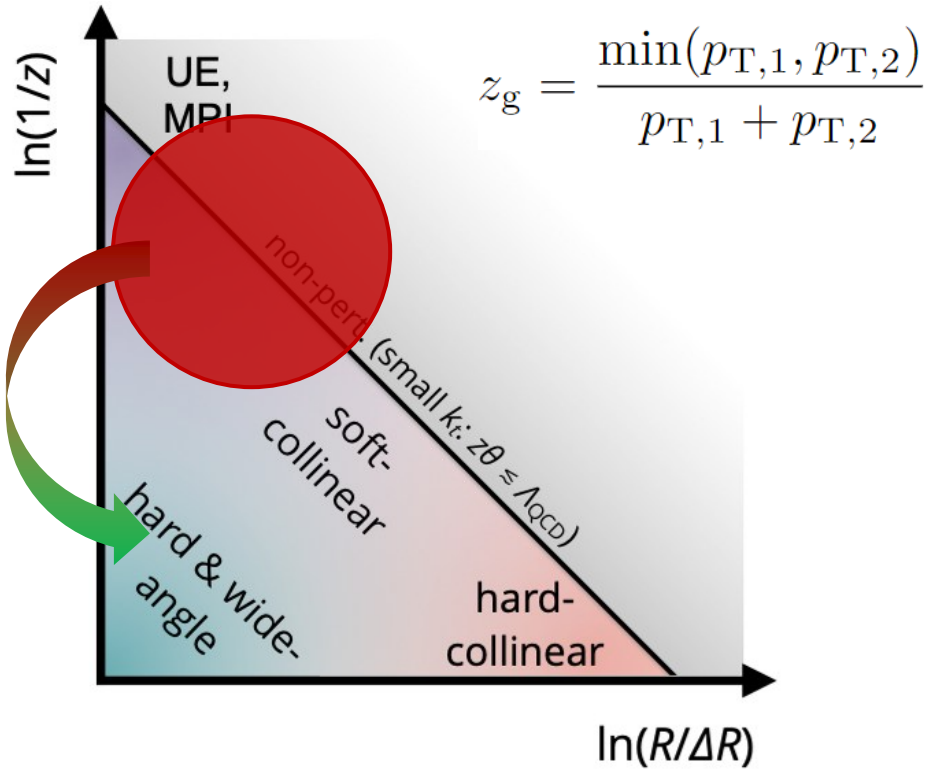

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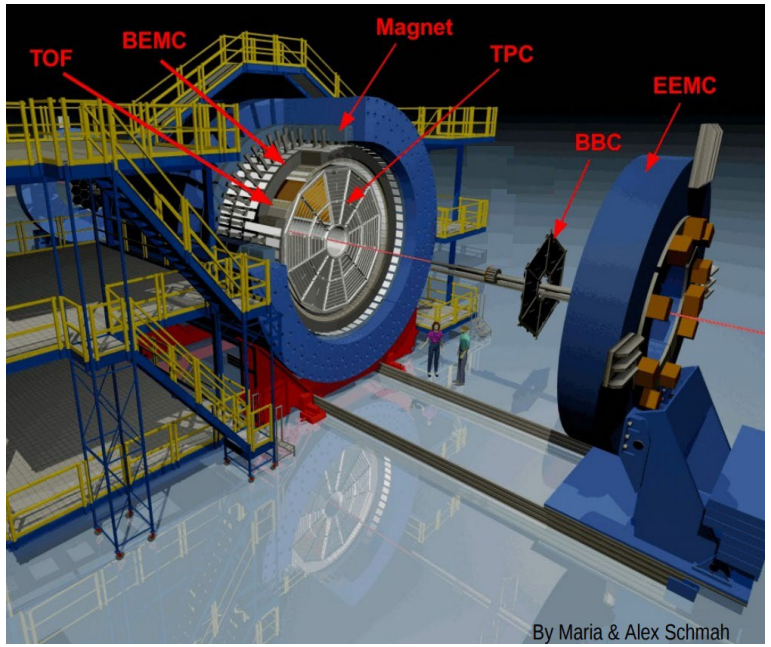
Measurement overview



Measure jets in $\sqrt{s} = 200$ GeV pp collisions with the **STAR** detector

- **Charged** tracks from the **TPC** (Time Projection Chamber)
- **Neutral** energy from the **BEMC** (Barrel Electromagnetic Calorimeter)

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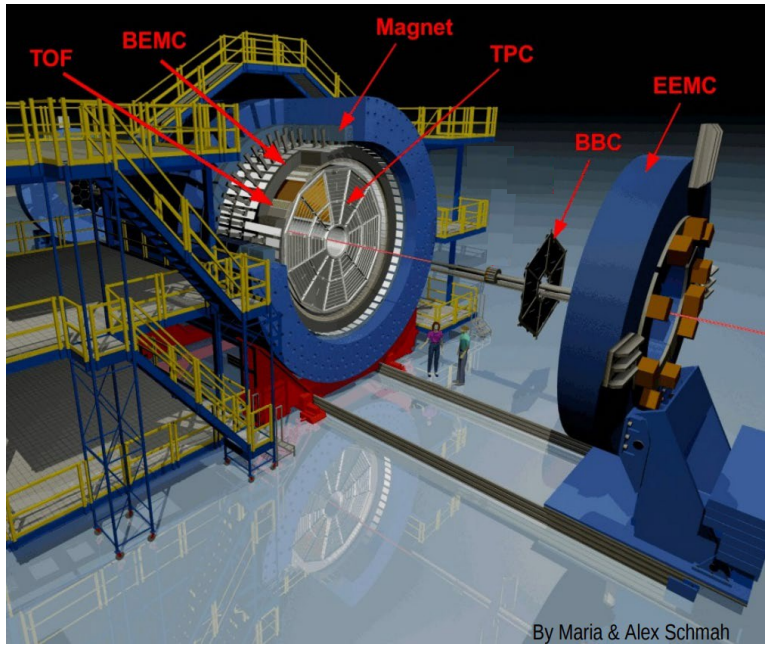

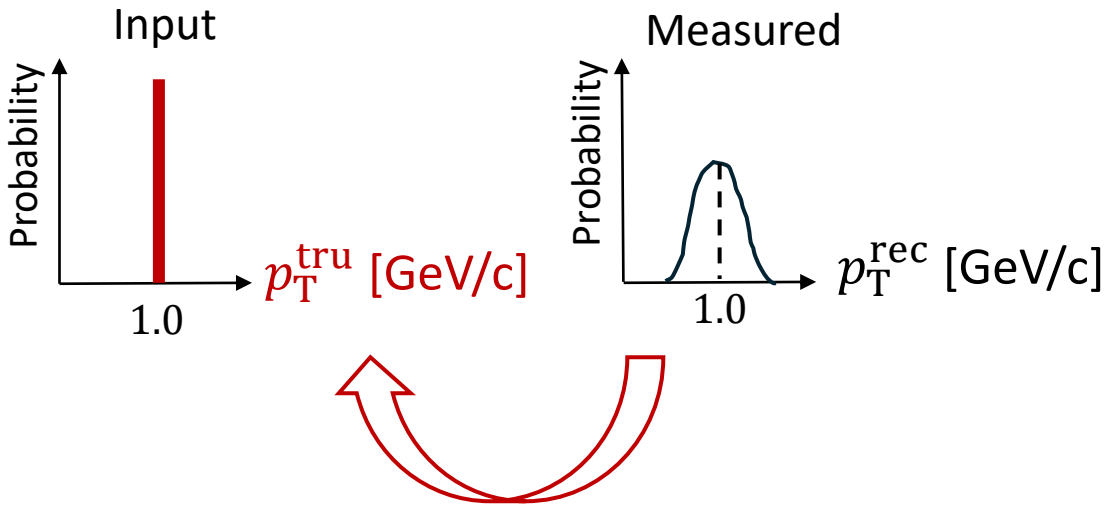

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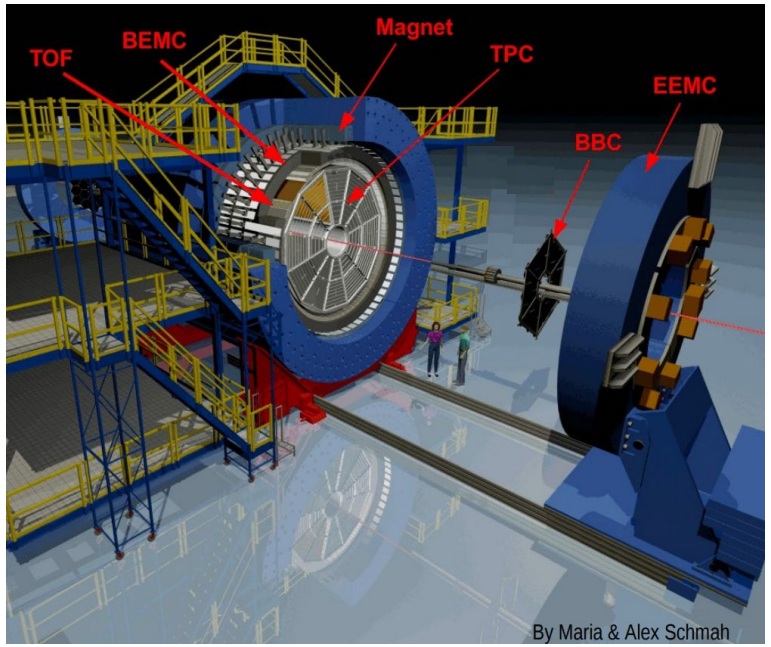

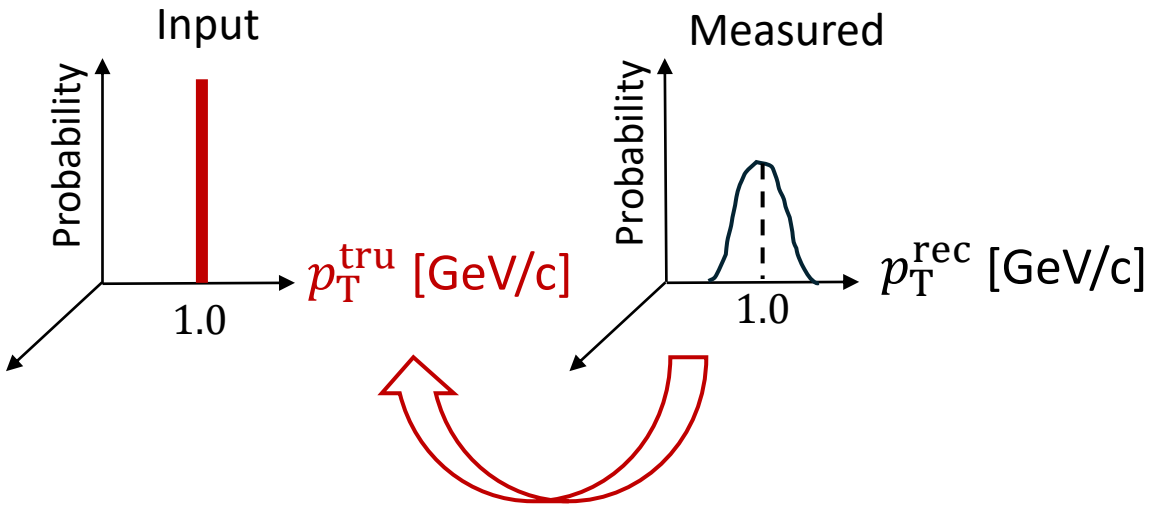

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Method: MultiFold

- Jet observables
  - p_{T}: transverse momentum
  - $Q^{\kappa=0.5}$: jet charge $Q^{\kappa} = \frac{1}{(p_{\mathrm{T\,jet}})^{\kappa}} \sum_{i \in \mathrm{jet}} q_i \cdot (p_{\mathrm{T}i})^{\kappa}$
  - M: jet mass $M = |\Sigma_{i \in \mathrm{jet}}\ p_i| = \sqrt{E^2 - |\vec{p}|^2}$
  - M_{g}: SoftDrop groomed (SD) jet mass
  - R_{g}: SD groomed jet radius
  - z_{g}: SD shared momentum fraction

$$z_{\mathrm{g}} = \frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} (R_{\mathrm{g}}/R_{\mathrm{jet}})^{\beta}$$

- $(M^2 - M_{\mathrm{g}}^2)/p_{\mathrm{T}}^2$ CollinearDrop groomed jet mass obtained from unfolded p_{T}, M and M_{g}

- **First** application of MultiFold on RHIC data!

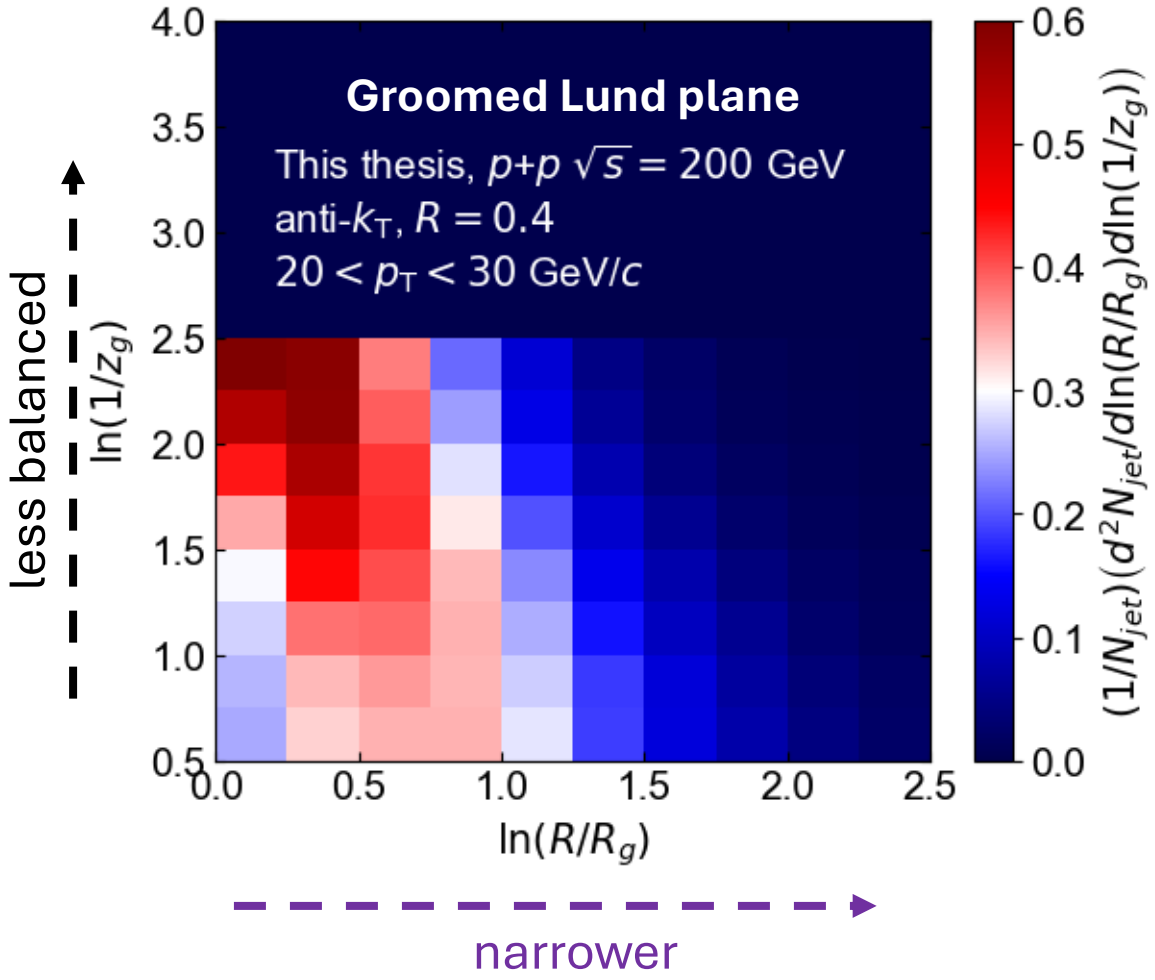
Andreassen et al. PRL 124, 182001 (2020)
Song et al. EPJC (2026) 86:106

All **6 observables** are simultaneously unfolded in an **unbinned** way

ONLY possible with MultiFold

Especially important for exploring high-dimensional **correlations**

Results: Multi-dimensional correlations



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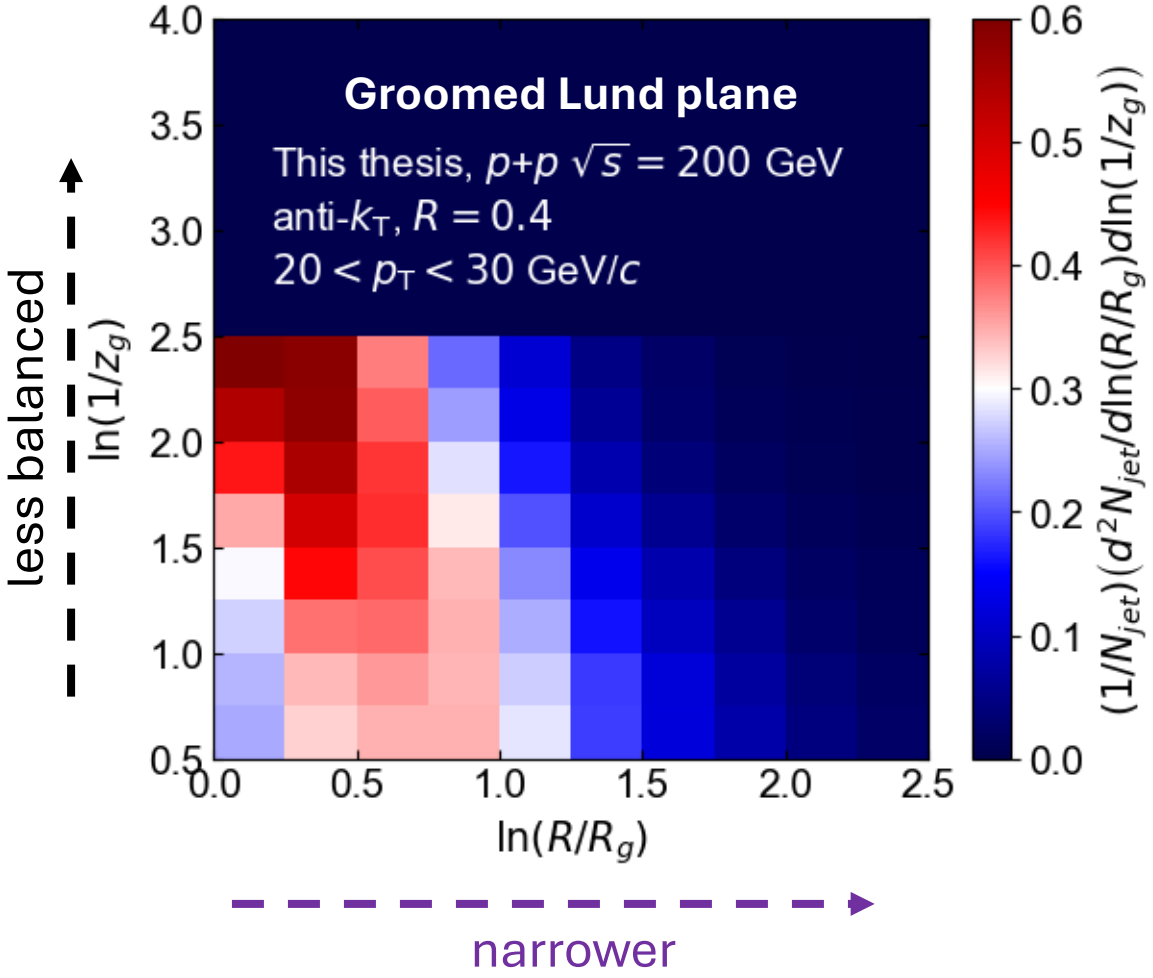
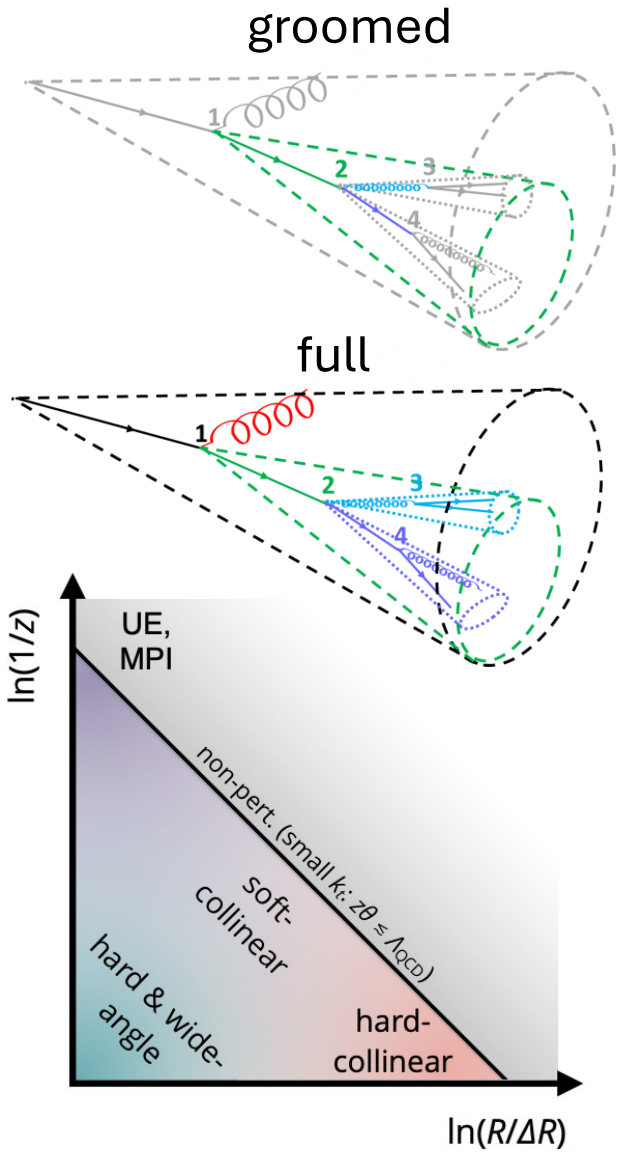


- Groomed Lund plane contains a subset of splittings in the full Lund plane



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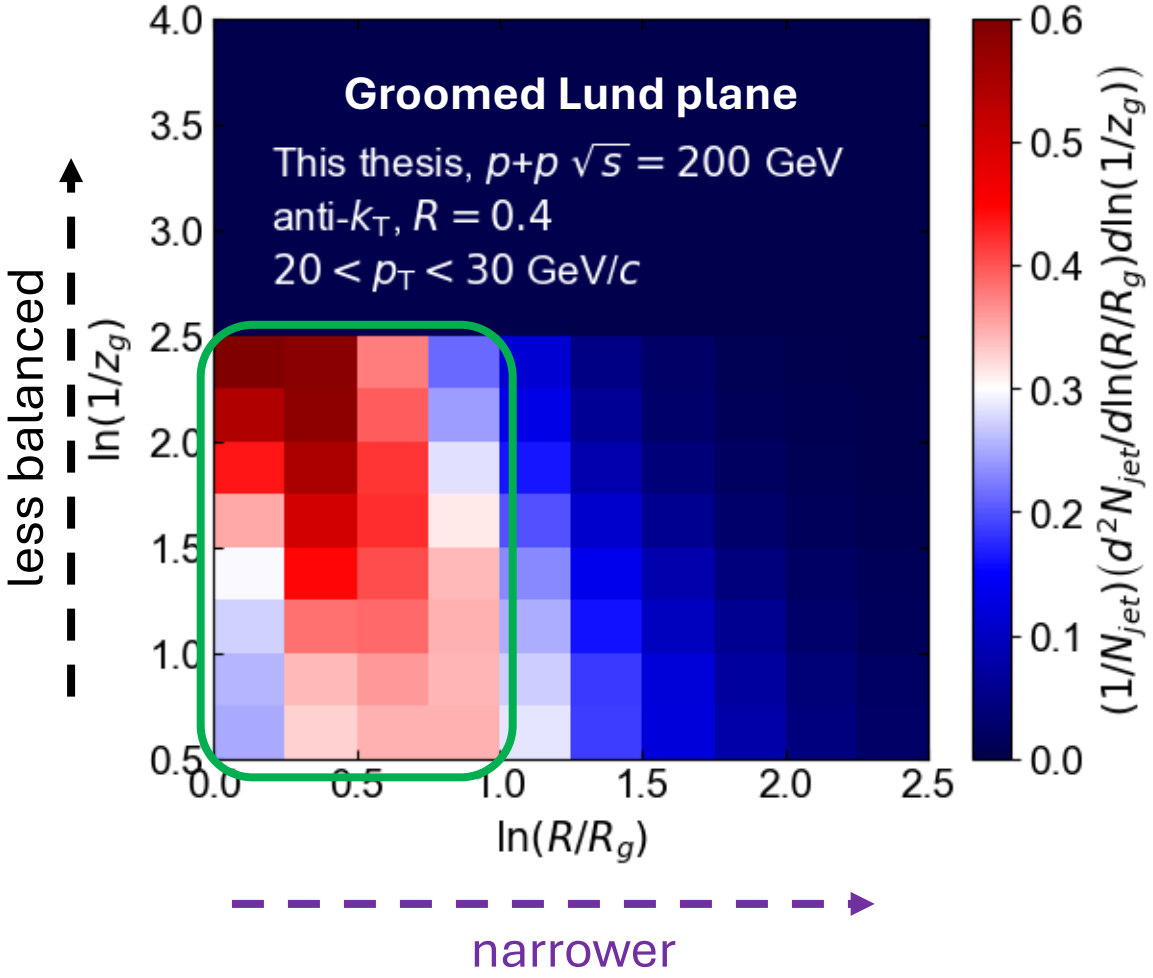

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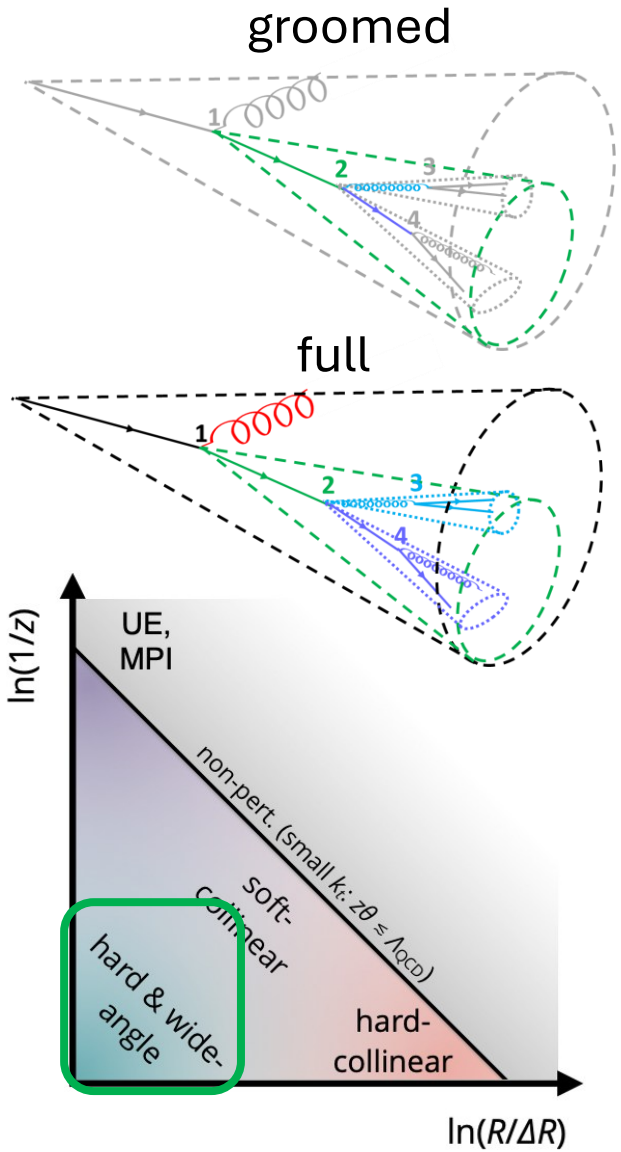
- R_g and z_g describe the angular and momentum scales of **later-stage perturbative splittings**



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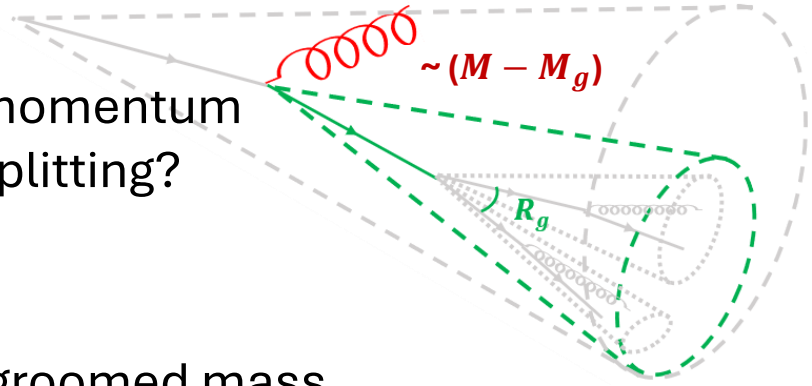
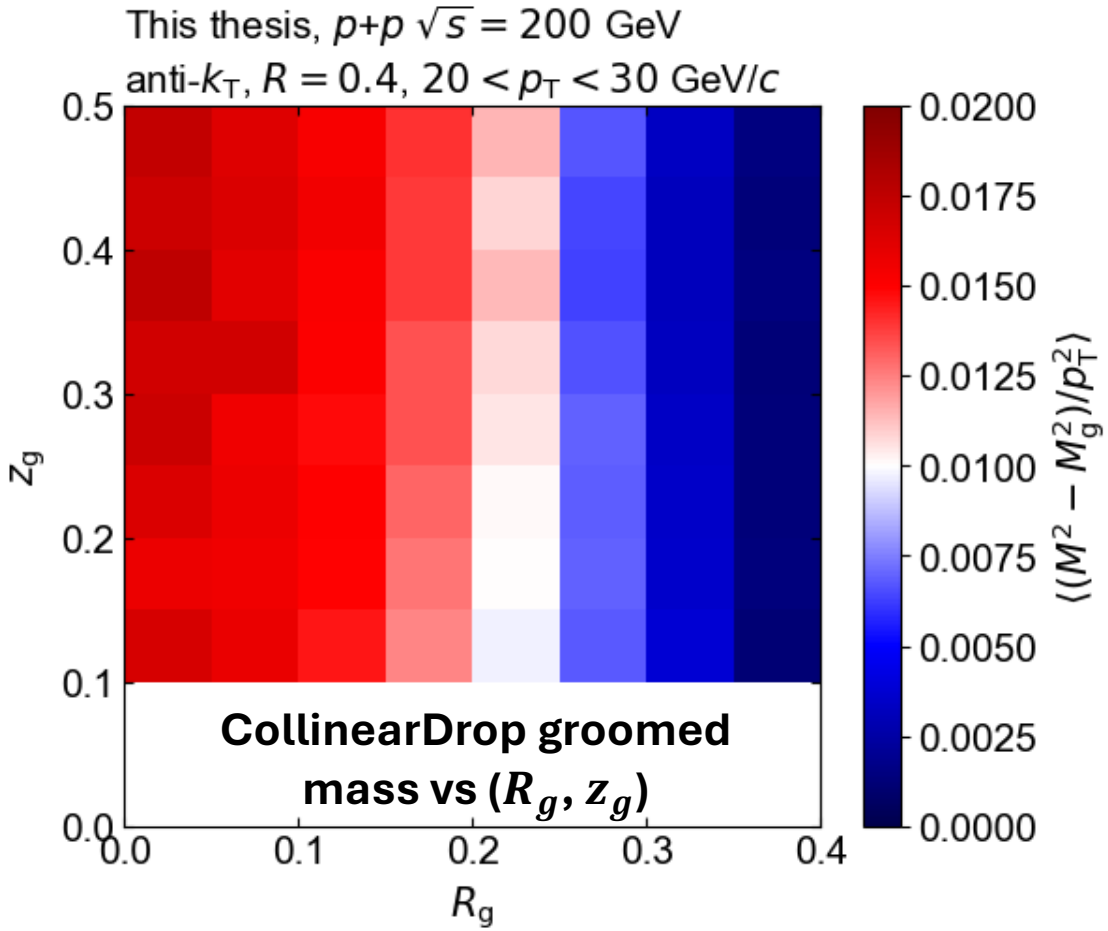
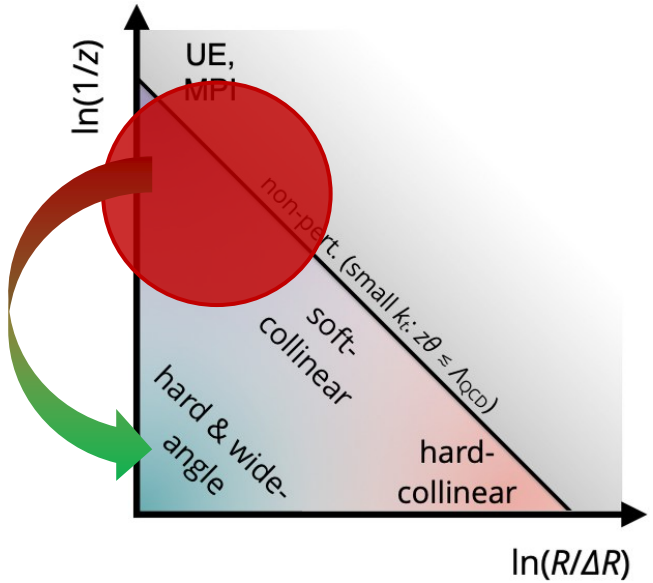


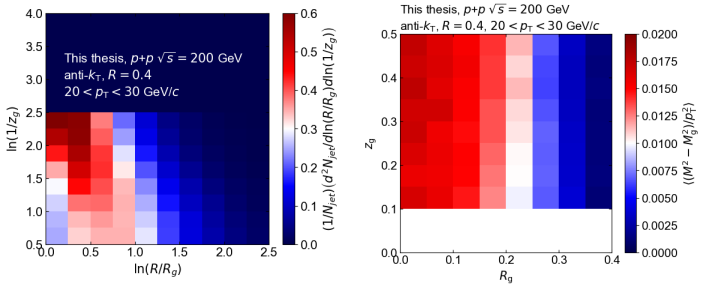


- CollinearDrop groomed mass strongly correlated with R_g and weakly with z_g



Summary and other results

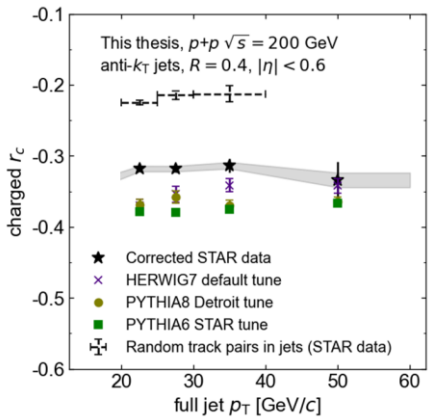
- **Soft radiation** strongly correlated with dynamics of **first perturbative splitting**

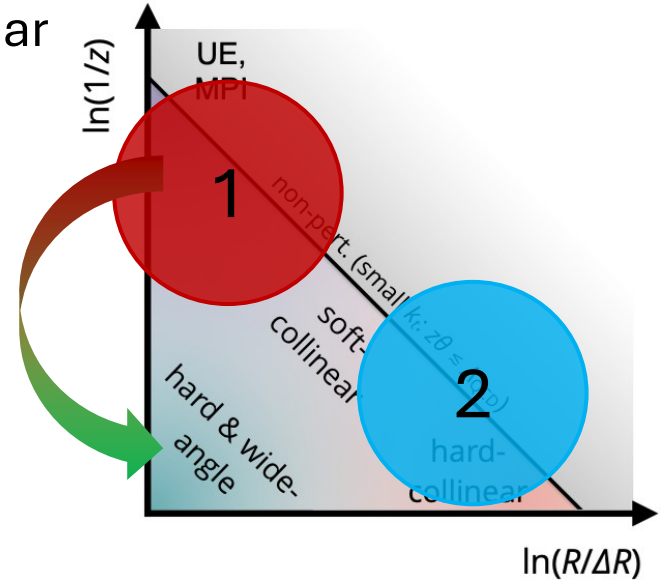


- First application of MultiFold at RHIC
  - MultiFold allows for cutting on **3** different observables, and then study the **4th**
    → ***impossible*** with traditional methods

- Not mentioned in this talk:
  - Charge correlator ratio r_c in pp collisions and isobar collisions, sensitive to hadronization effects
  - First r_c measurements in hadron collisions

- Both measurements to be submitted for publication this year





Backup

High-energy particle collisions:

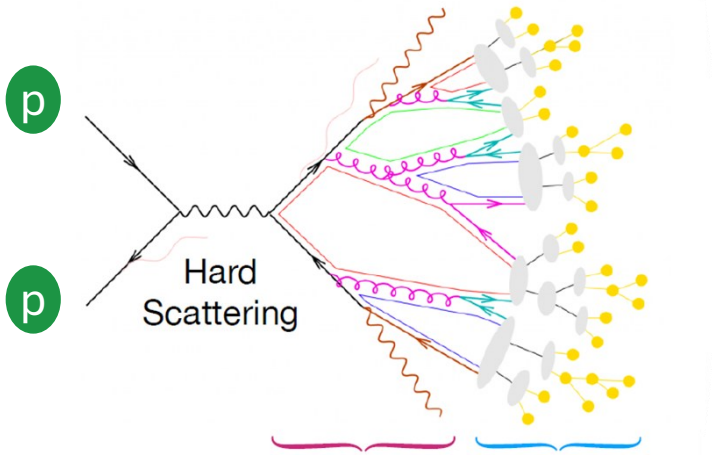


Image credit: Stefan Gieseke

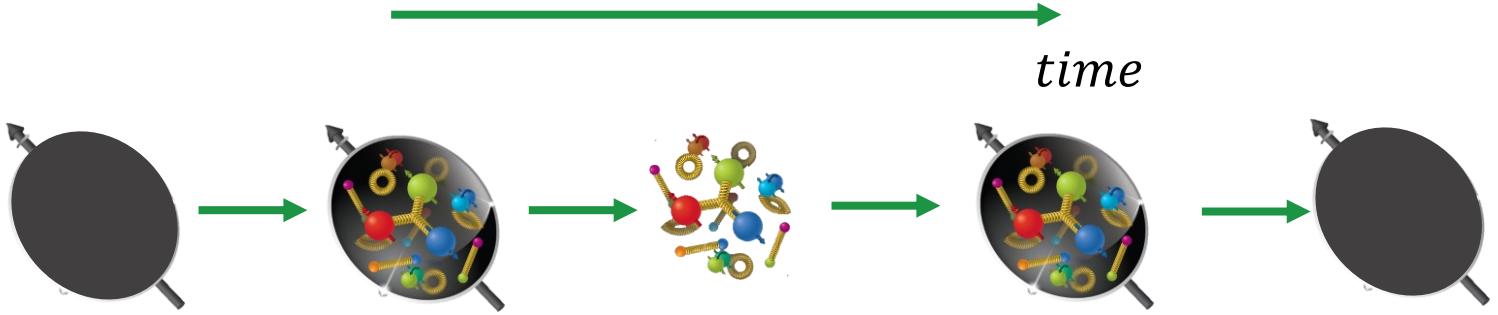


Image credit: BNL

Degrees of freedom: hadrons → partons → hadrons

How do QCD degrees of freedom give rise to hadronic degrees of freedom?
→ What is happening during the parton shower and hadronization?

Study this with jets and jet substructure observables!

MultiFold: Simplified two-jet example

Physics process simulation

Detector response simulation

1. Generate jets in PYTHIA → PYTHIA+GEANT

Observable	$p_{\mathrm{T}}^{\mathrm{tru}} \rightarrow p_{\mathrm{T}}^{\mathrm{rec}}$	$M^{\mathrm{tru}} \rightarrow M^{\mathrm{rec}}$	...	Probability
Jet 1	20 GeV → 18 GeV	3 GeV → 2 GeV	...	0.5
Jet 2	40 GeV → 38 GeV	4 GeV → 3 GeV	...	0.5

2. Measure jets in data

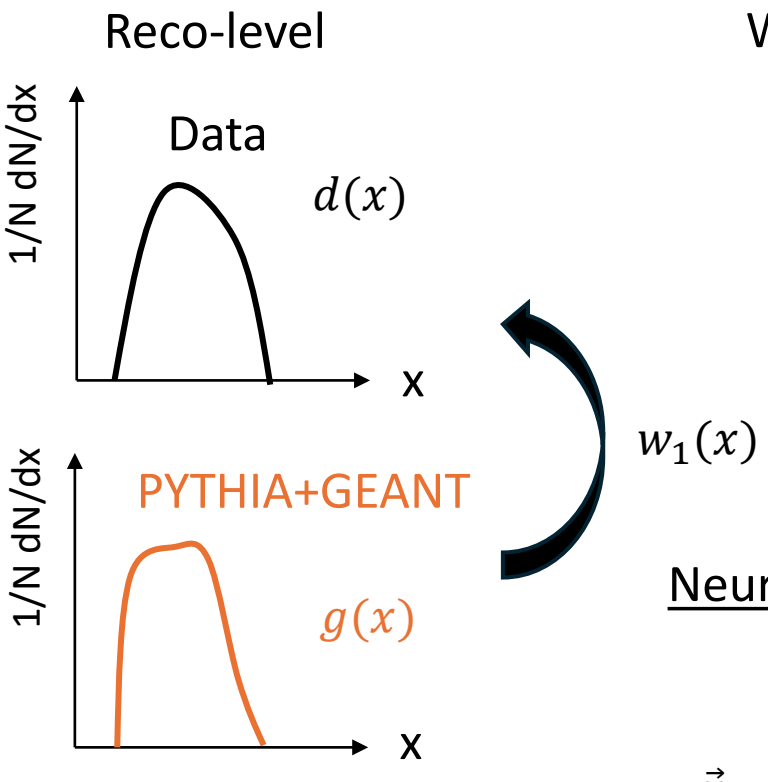
Observable	$p_{\mathrm{T}}^{\mathrm{tru}} \rightarrow p_{\mathrm{T}}^{\mathrm{rec}}$	$M^{\mathrm{tru}} \rightarrow M^{\mathrm{rec}}$	...	Counts
Jet 3	?? GeV → 18 GeV	? GeV → 2 GeV	...	300
Jet 4	?? GeV → 38 GeV	? GeV → 3 GeV	...	100

3. MultiFold

	Probability
Jet 1	0.75
Jet 2	0.25

Density ratio estimation: What weights to apply to jets in simulations, such that they match data?

MultiFold: Step 1, iteration 1



Weights: $w_1(x) = d(x)/g(x)$ Ok for the binned case

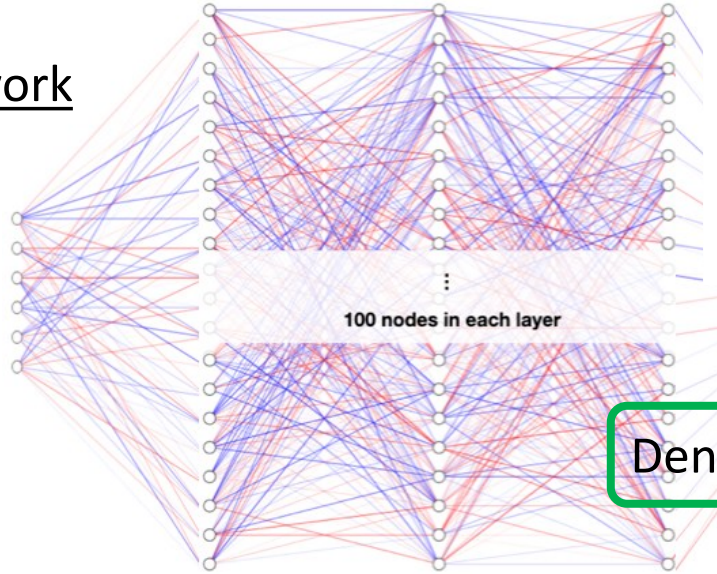
$\approx f(x)/(1 - f(x))$ Using Bayes' Theorem

where $f(x)$ is a neural network and trained with the binary cross-entropy loss function

to distinguish jets coming from data vs from PYTHIA+GEANT

Neural network input

$\vec{x} = \begin{Bmatrix} p_T \\ M \\ \vdots \end{Bmatrix}$



Neural network output

$f(\vec{x}) =$ probability that jet $\vec{x}$ is from data

Density ratio estimation → Classification

MultiFold results: Validation

This thesis

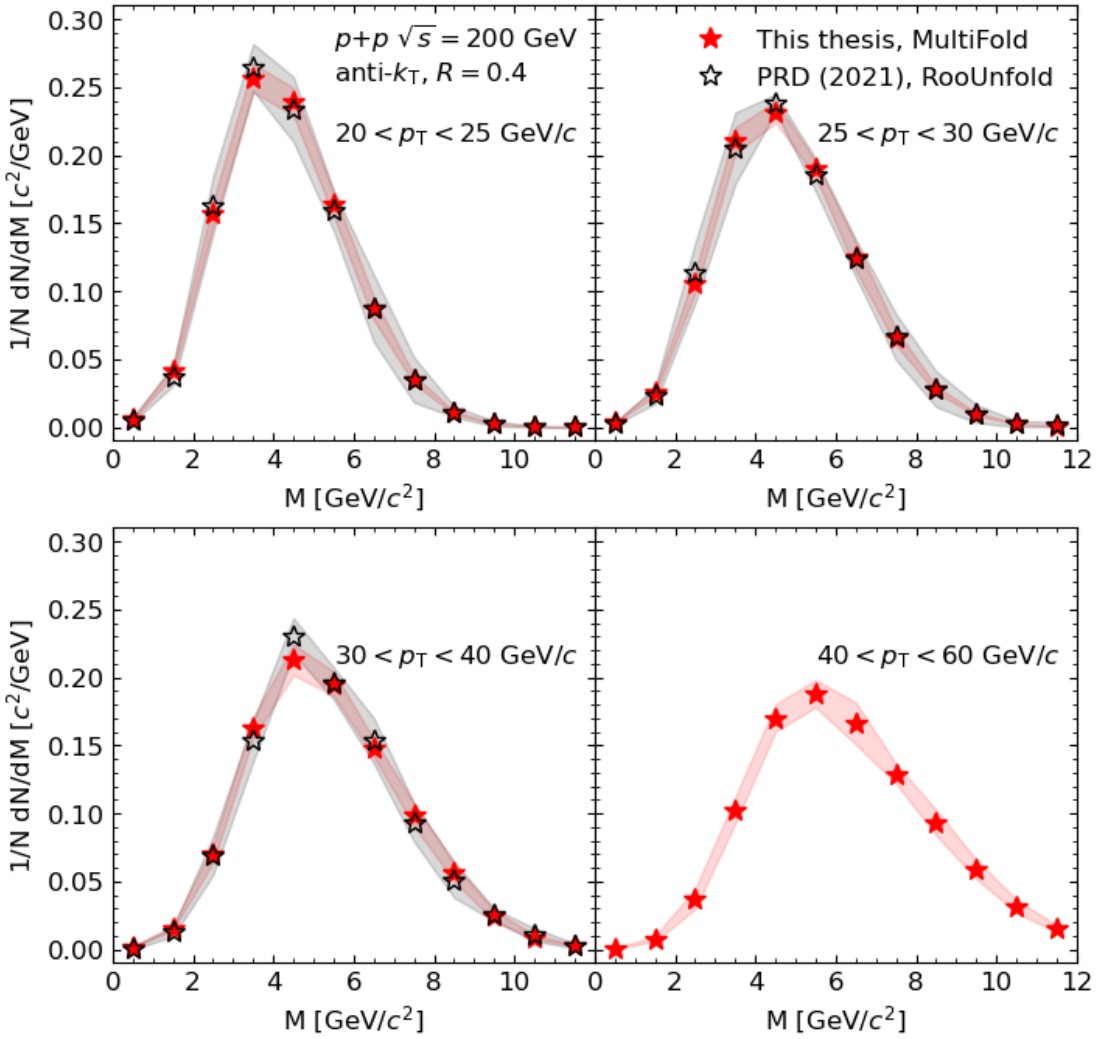
MultiFolded results agree with **RooUnfolded** results (STAR. PLB 811 (2020) 135846, STAR. PRD 104, 052007(2021))

Uses Iterative Bayesian method

- Example: Jet mass M

$$M = |\Sigma_{i\in\text{jet}}\ p_i| = \sqrt{E^2 - |\vec{p}|^2}$$

- See 1D distributions of the other 5 unfolded observables in thesis



MultiFold results: Multi-dimensional correlations

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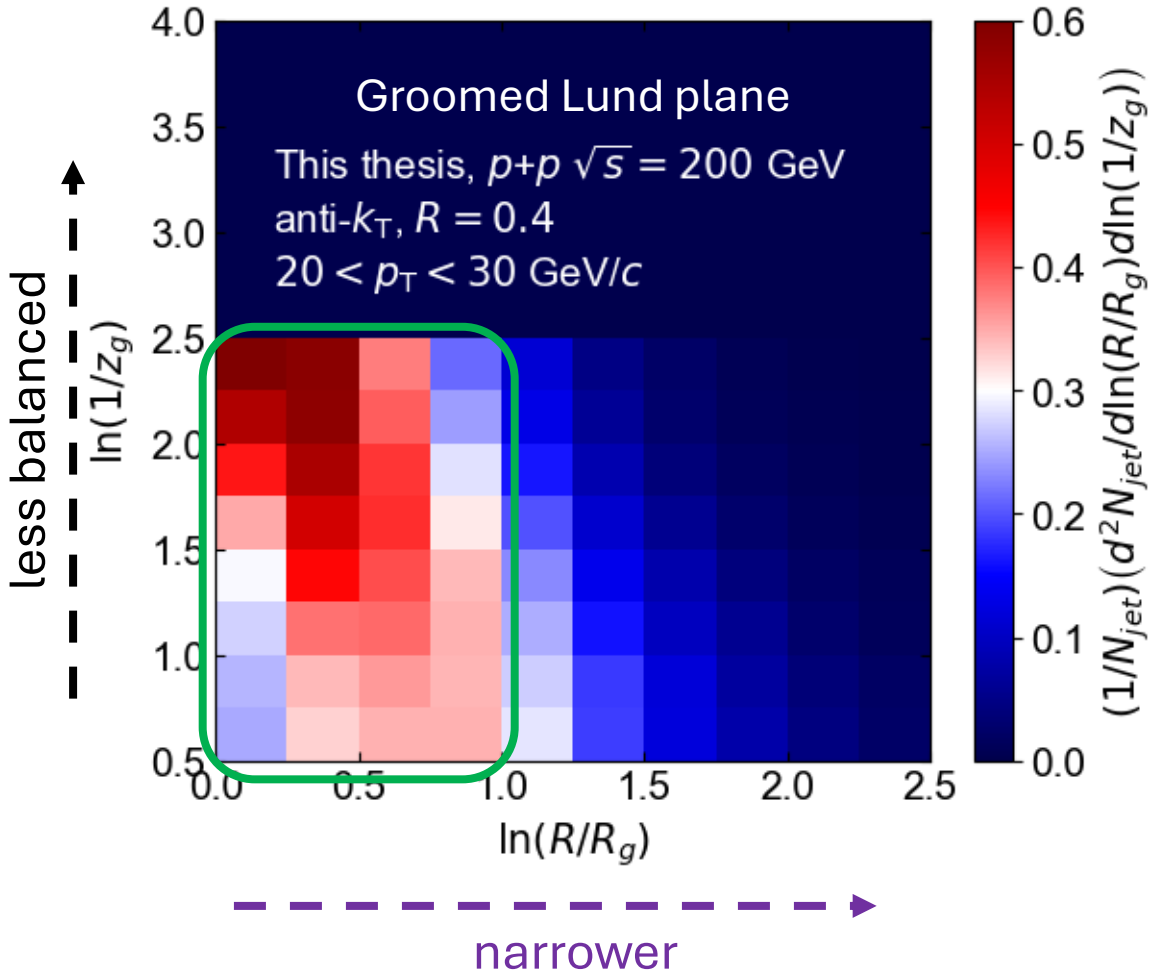

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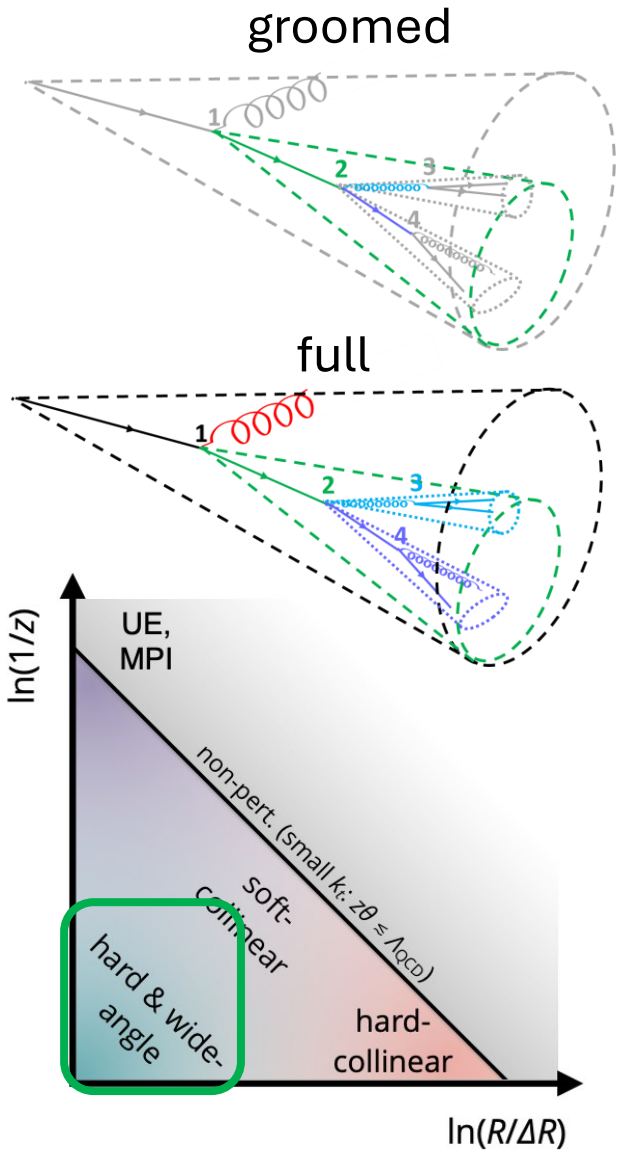

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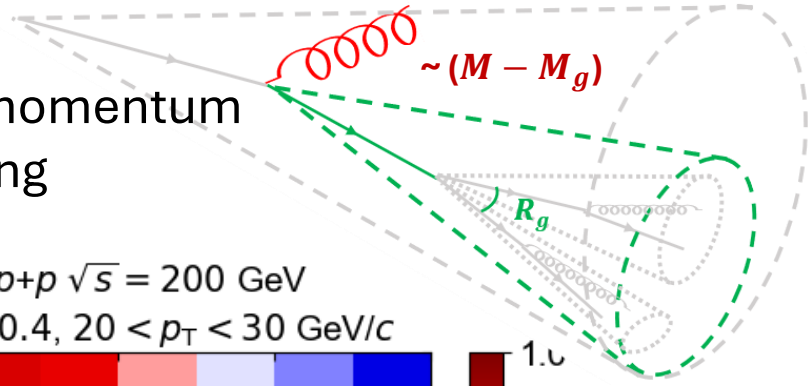

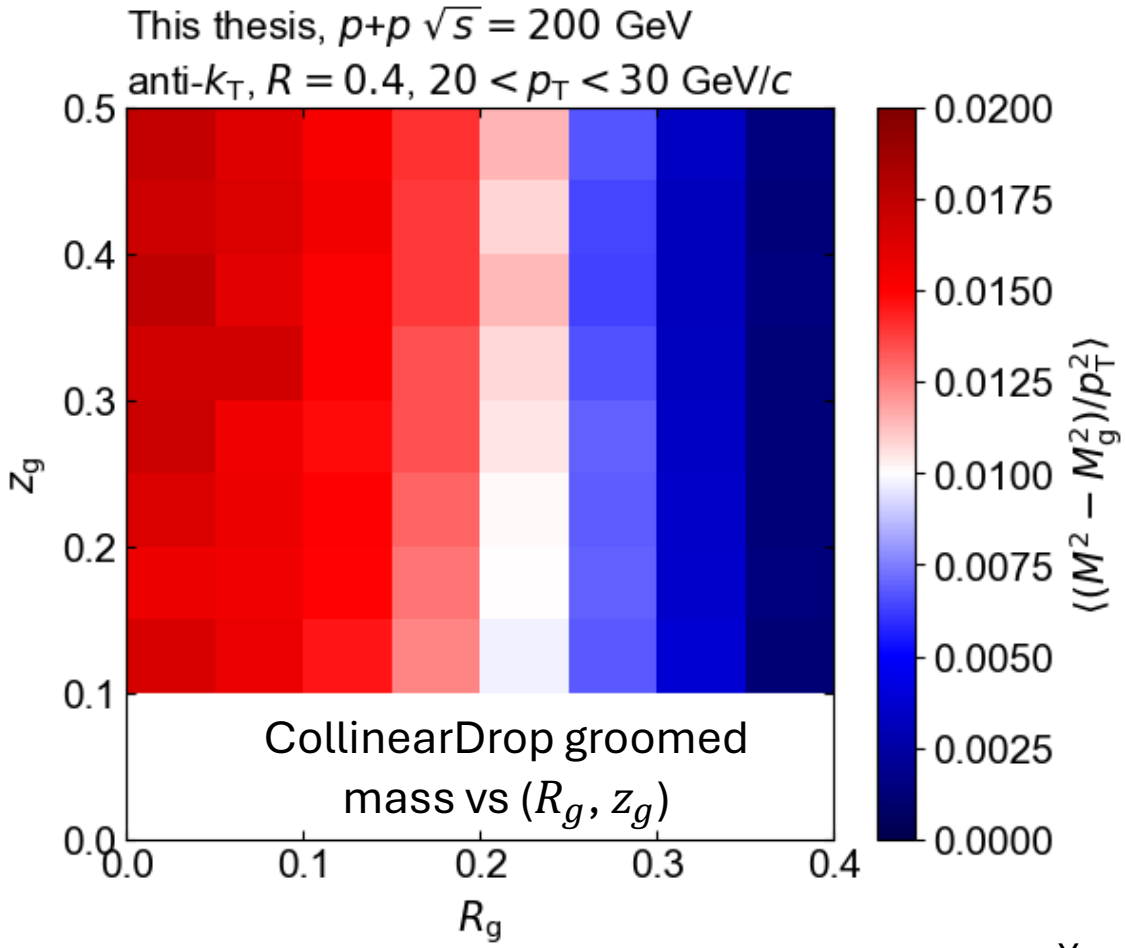

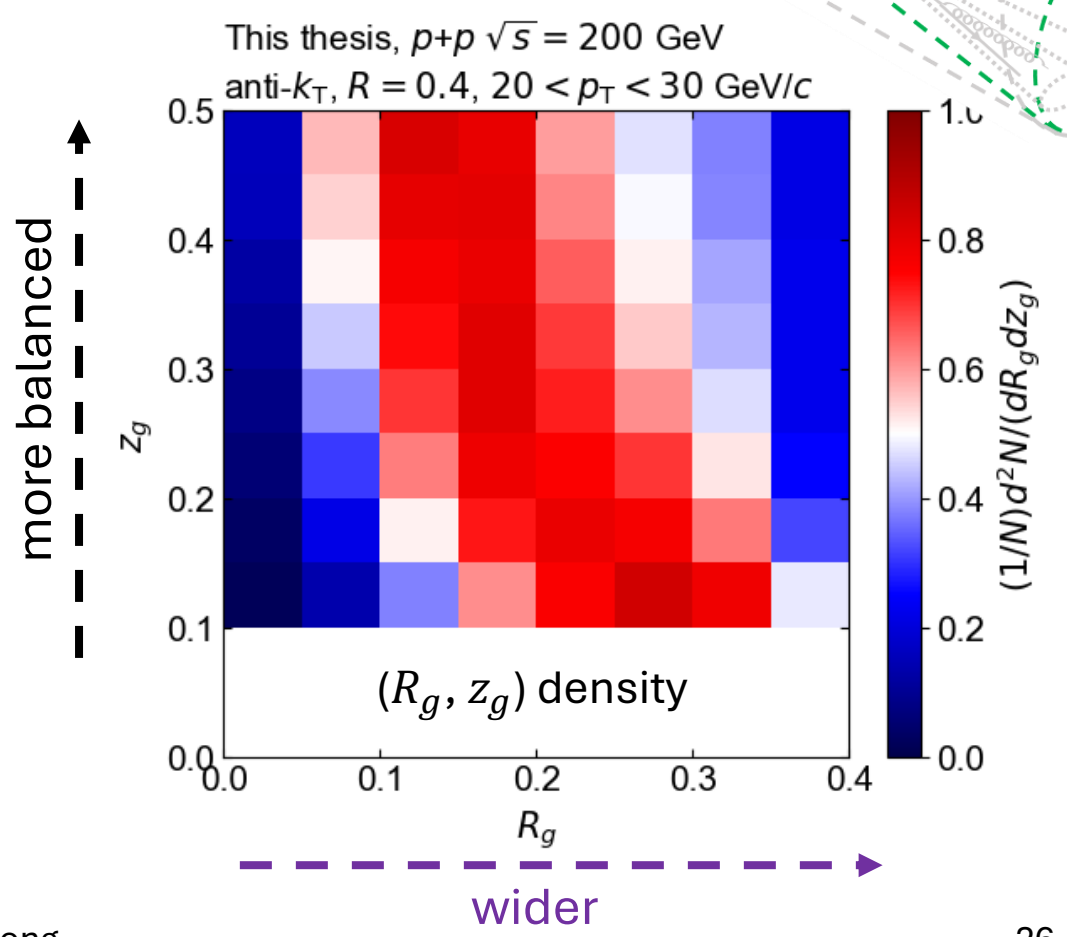

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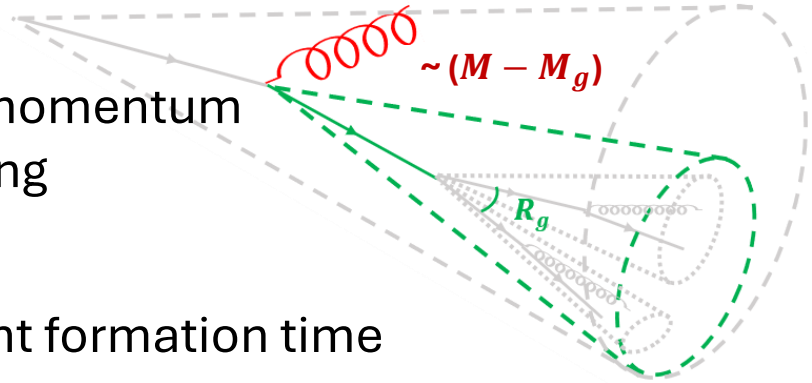
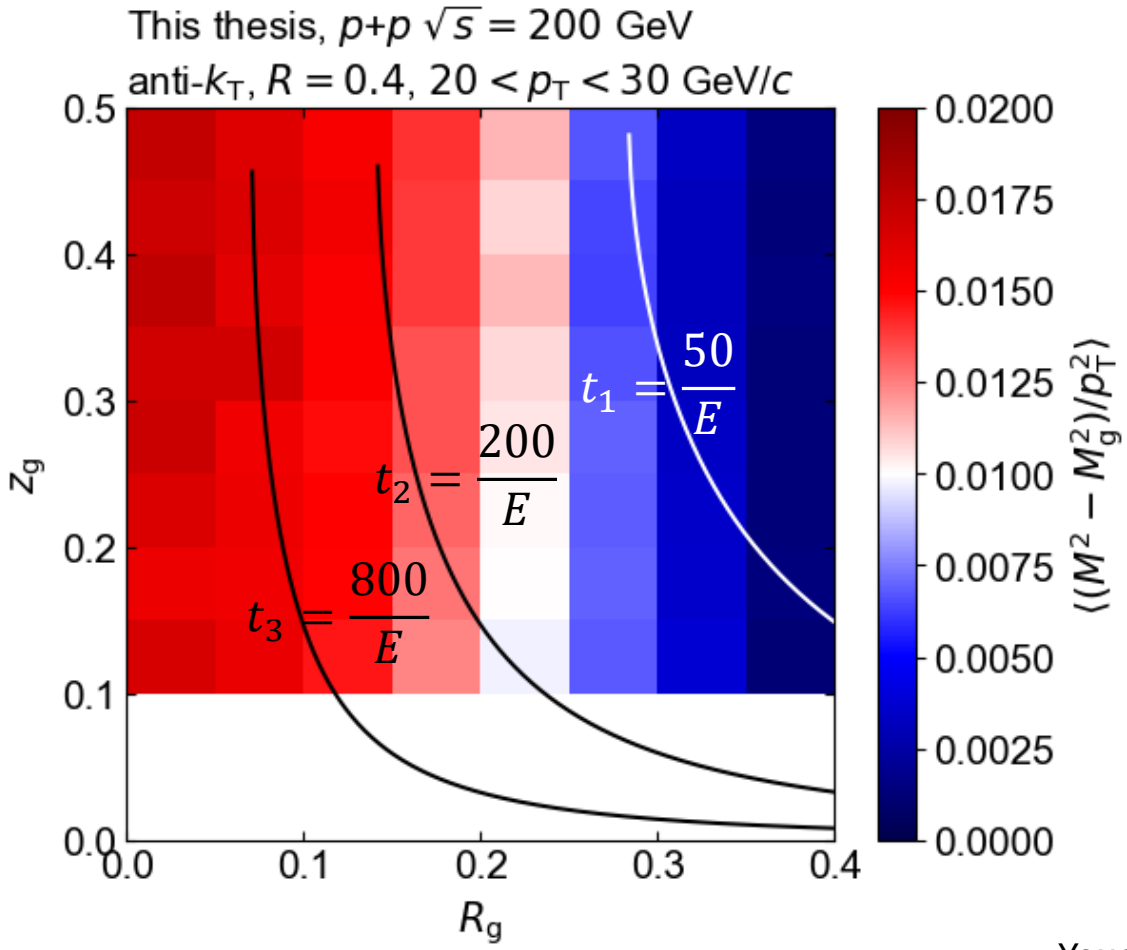
- How does the amount of soft radiation correlate with the angular and momentum scale of a hard splitting? → how an **early** emission affects a **later** splitting





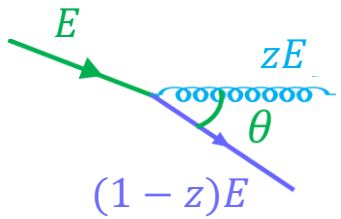
- Lines of constant formation time

Y. L. Dokshitzer, et al. *Basics of Perturbative QCD* (1991).

Using $t_F \sim \frac{1}{2Ez(1-z)(1-\cos(\theta))}$

solve for $z(\theta, z < 0.5)$:

$$z = \frac{1}{2}\left[1 - \sqrt{1 - \frac{2}{tE(1-\cos(\theta))}}\right]$$



- CollinearDrop groomed mass strongly correlated with R_g and weakly with z_g
- To shed a lot of mass at **early** stage, the hard splitting needs to happen **late**