Probing the Parton Shower and Hadronization with Novel Jet Substructure Measurements at STAR

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for the STAR Collaboration

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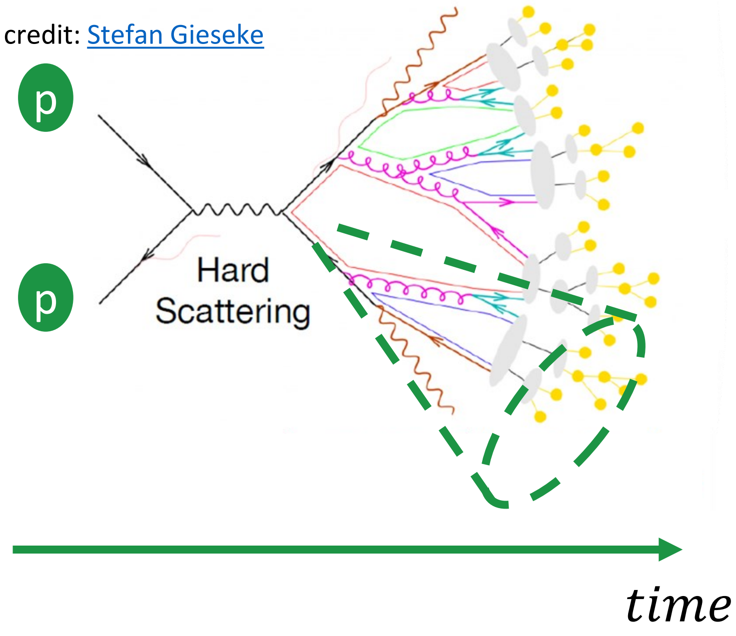
Jets

Image credit: Stefan Gieseke



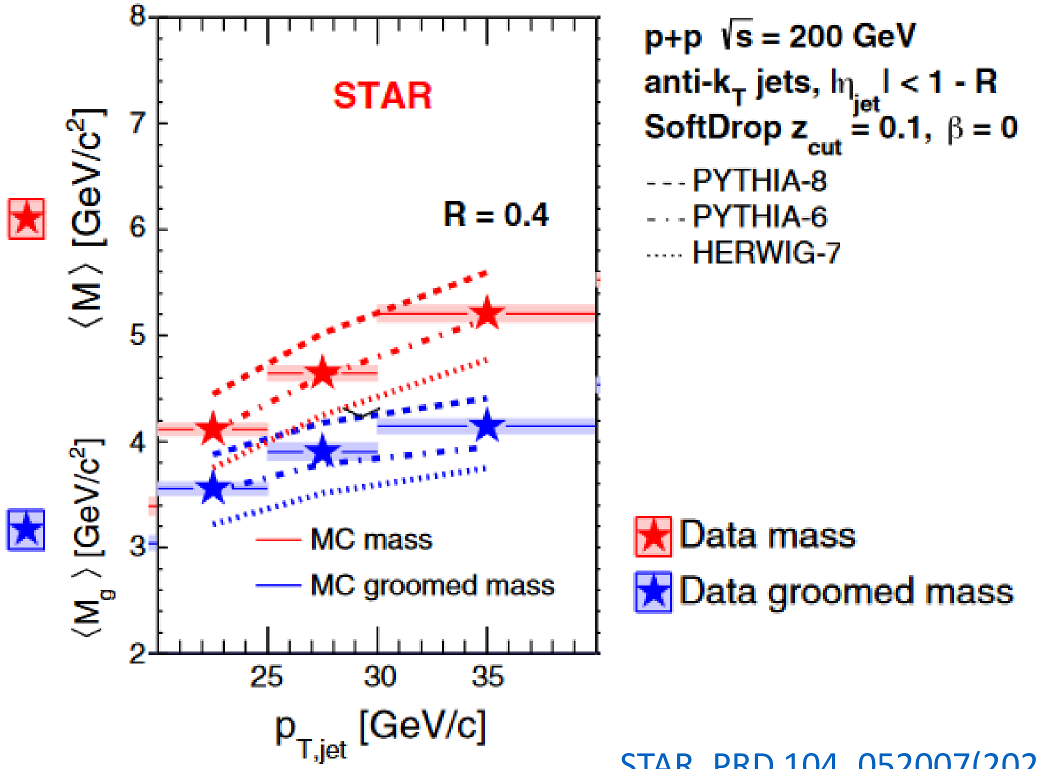
- Jets are collimated sprays of final-state hadrons (rare!).
- Jets can serve as **proxies for the hard-scattered parton** (with a proper choice of clustering algorithm, e.g., anti-k_T).
- Jet substructure measurements can be used to **probe parton shower and hadronization**.
- Note: This presentation will focus on measurements in pp.

Jet substructures

- Use subscript "$_g$" to denote observables obtained through **SoftDrop grooming** which removes soft and wide-angle radiation from the jet

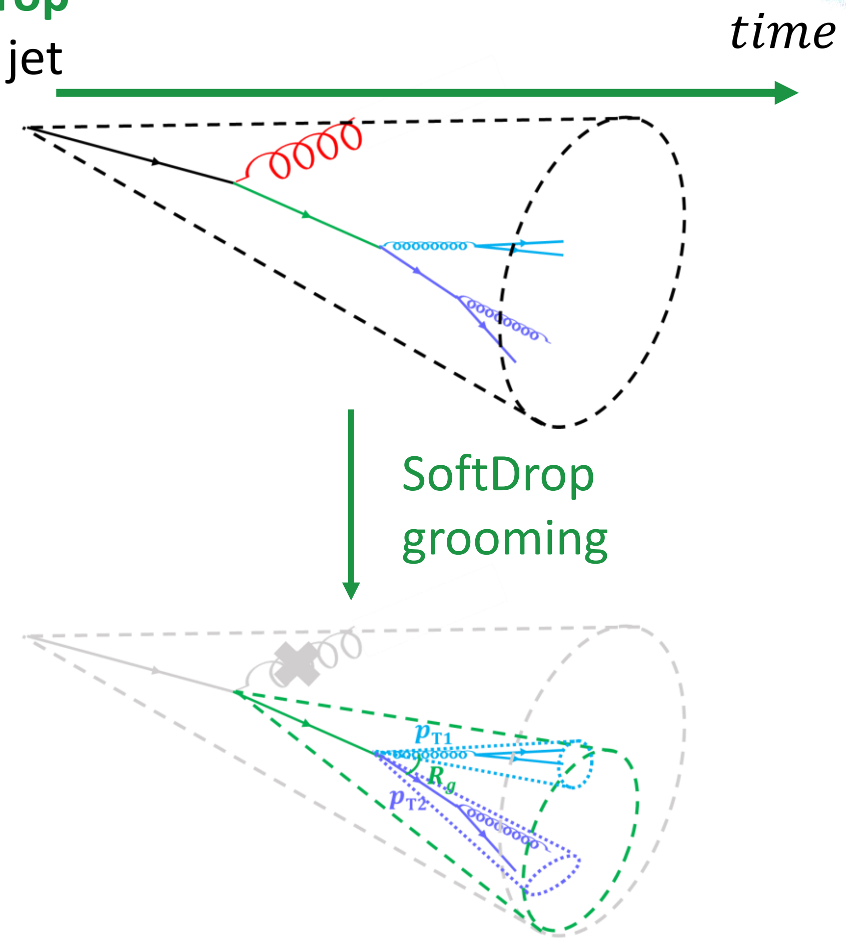
Example:

Ungroomed jet mass M vs SoftDrop groomed jet mass M_g



[STAR. PRD 104, 052007(2021)]

Effect:



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

Jet substructures

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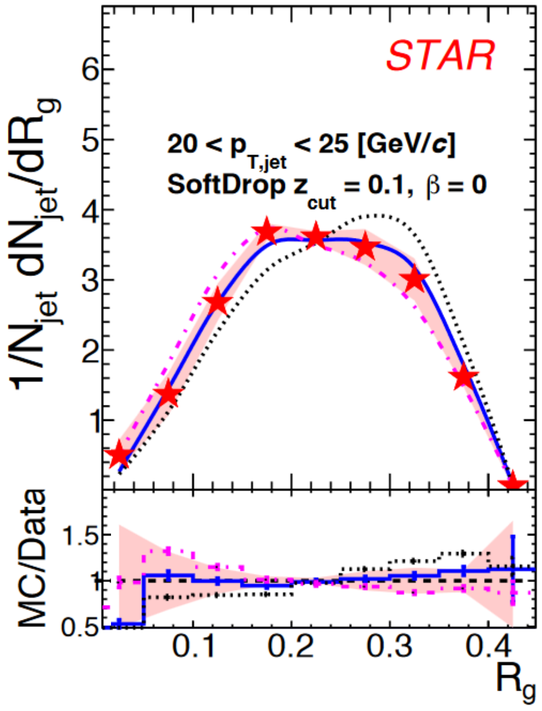
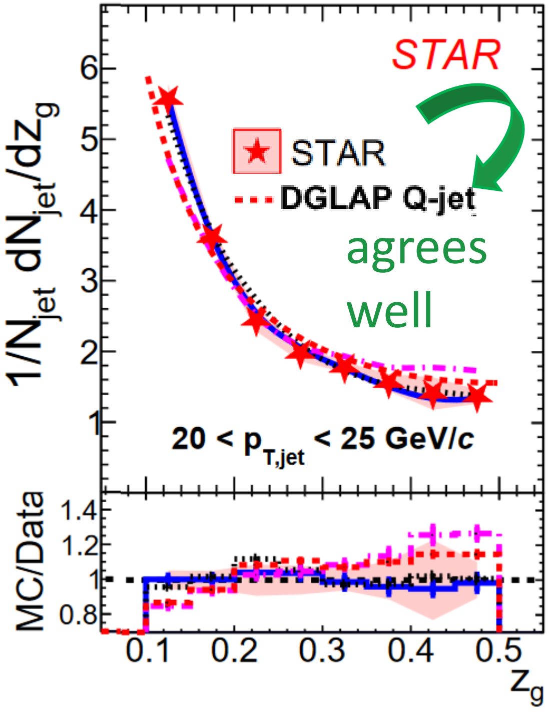
Example:

Groomed jet radius R_g



Momentum imbalance z_g



STAR. PLB 811 (2020) 135846

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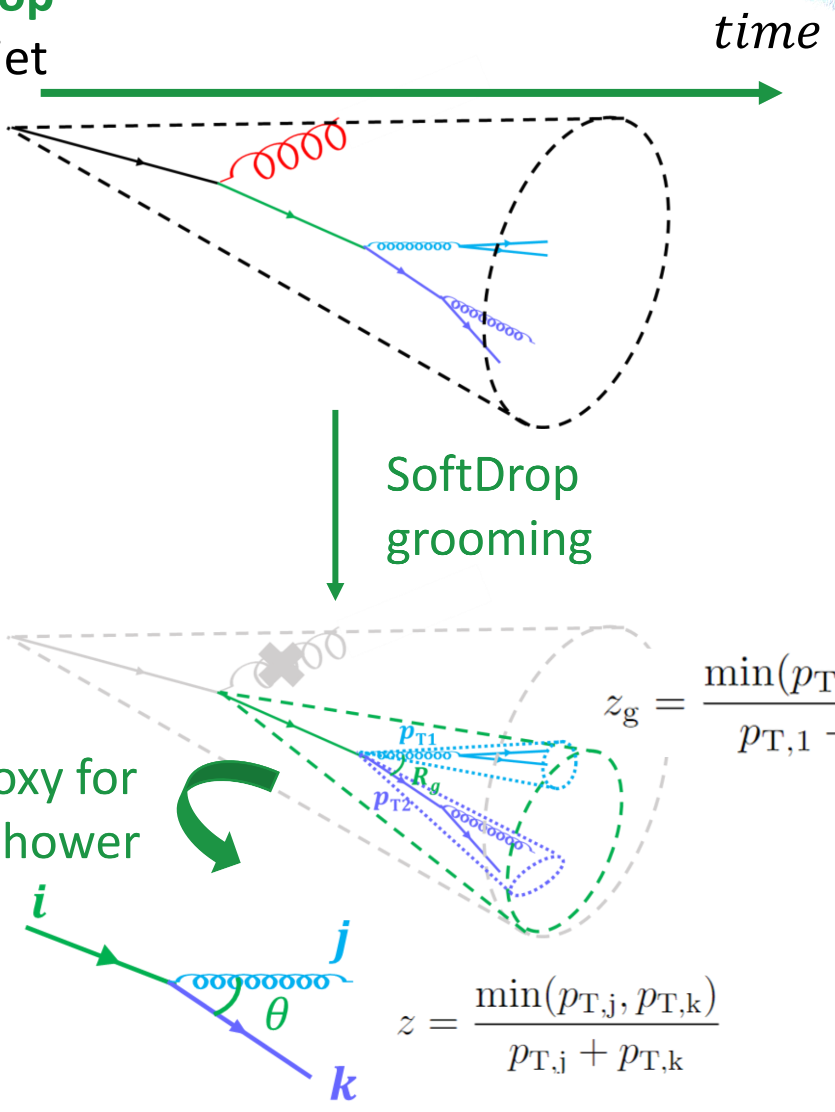


good proxy for parton shower

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

$$z = \frac{\min(p_{T,j}, p_{T,k})}{p_{T,j} + p_{T,k}}$$

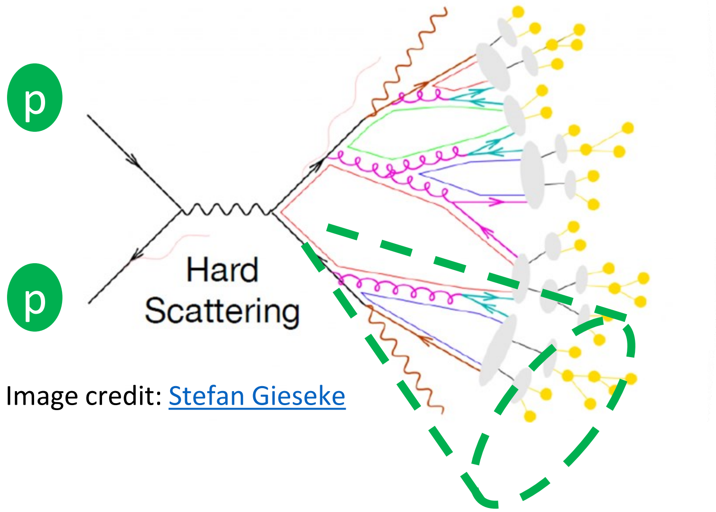


Image credit: Stefan Gieseke

Study the non-perturbative contribution in jets

- Soft component of the parton shower
  → CollinearDrop jet measurement
- Hadronization
  → Charge correlator ratio measurement

Motivation: CollinearDrop

Aims to probe the **soft and wide-angle radiation** within a jet

Chien and Stewart JHEP 06 (2020) 64.

- General case: difference of an observable with two different SoftDrop selections $(z_{cut\ 1}, \beta_1)$ and $(z_{cut\ 2}, \beta_2)$
- For this analysis, $(z_{cut\ 1}, \beta_1)$ = **(0,0)** and $(z_{cut\ 2}, \beta_2)$ = **(0.1,0)**: difference in the original and SoftDrop groomed observable
- Observables: e.g.,

$$\Delta M/M = \frac{M - M_g}{M}$$

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

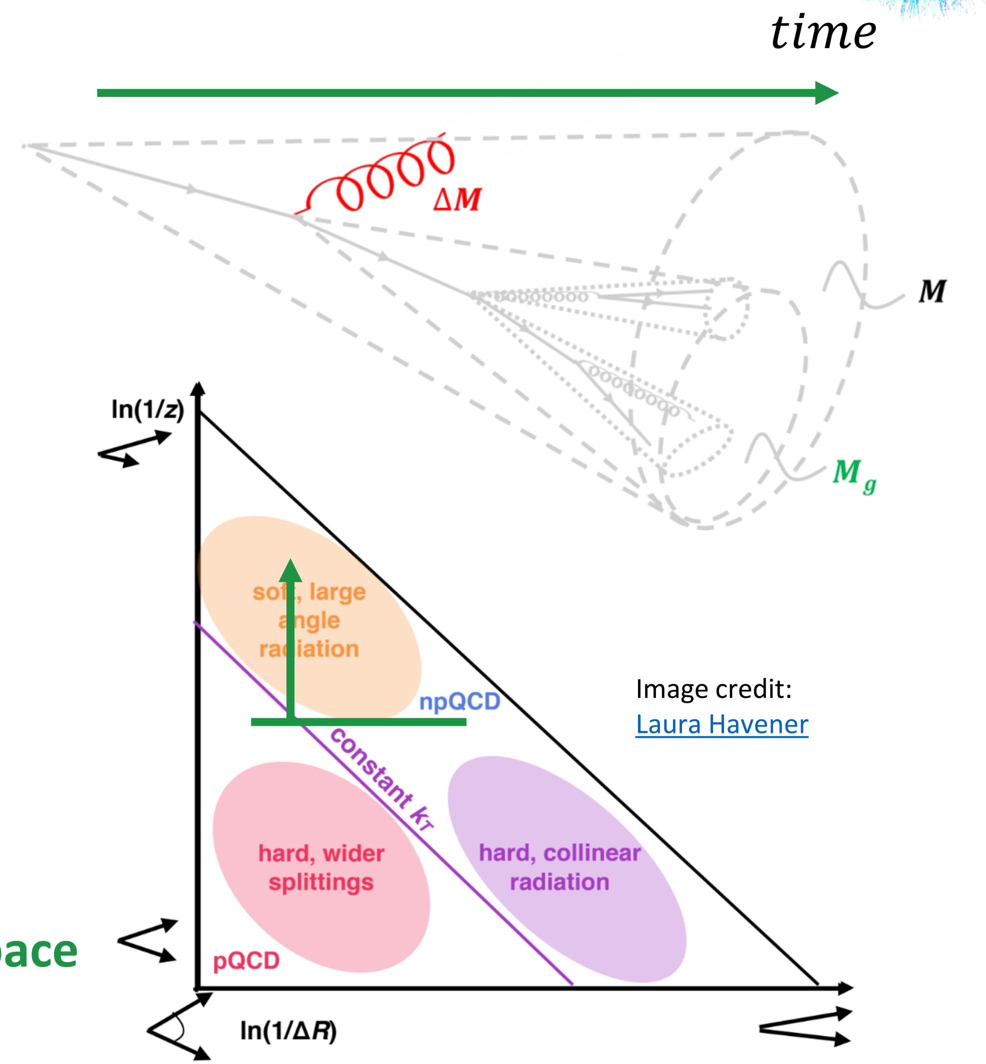


Image credit: Laura Havener

soft and wide-angle radiation: interesting **region of phase space** that deserves more study!

Motivation

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

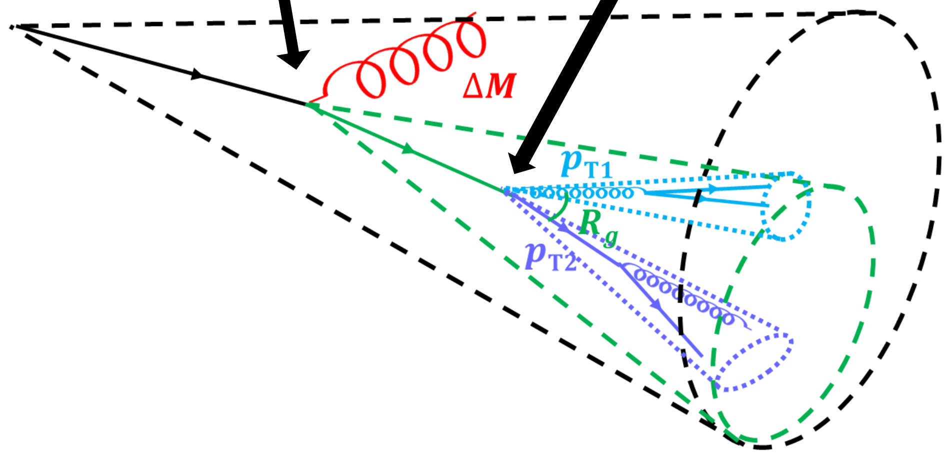
- How does the amount of soft radiation correlate with the angular and momentum scale of a hard splitting? → how an **early** emission affects a **later** splitting

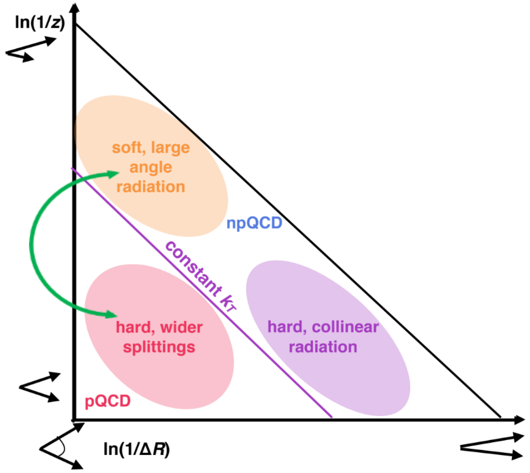
Captured by dM/M:
~ amount of **initial** wide and soft emission

Assuming angular ordering of parton shower

Captured by Zg and Rg:
~ imbalance and angular scale of a **later** splitting

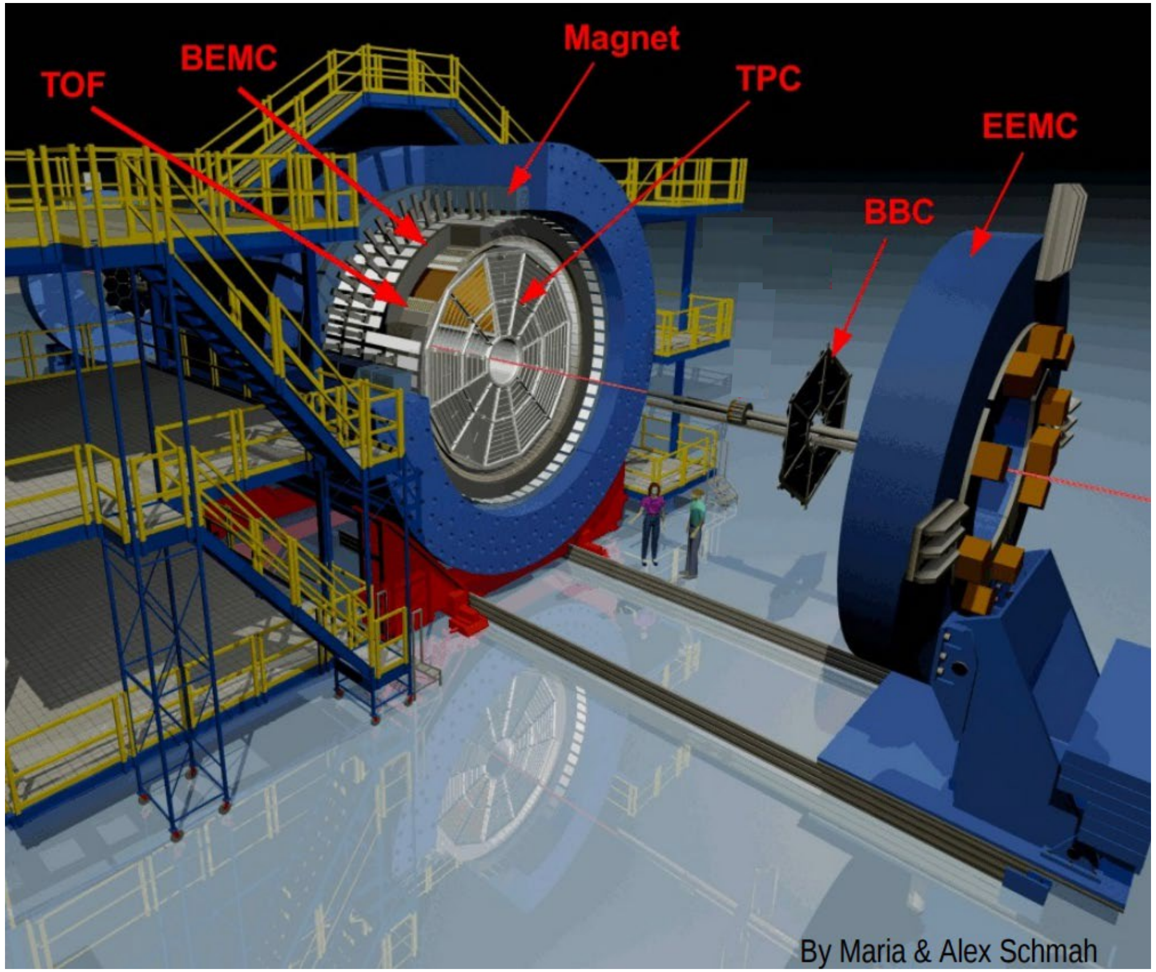
$$\Delta M/M = \frac{M - M_g}{M}$$





Note: Hadronization effects smear the distribution but don't affect the correlations (see backup)

The STAR detector



Important subdetectors for **200 GeV pp** collisions data-taking during 2012 RHIC run

- **TPC** (Time Projection Chamber)
  - For **charged** particle track reconstruction
  - $|\eta| < 1$, full azimuthal coverage
- **BEMC** (Barrel ElectroMagnetic Calorimeter)
  - For **neutral** energy measurement and triggering
  - $|\eta| < 1$, full azimuthal coverage

Analysis method

- Reconstruct anti-k_T full (charged tracks + neutral energy towers) jets with R = 0.4 from 200 GeV pp collisions

- Unfolding methods:
  - Iterative Bayesian unfolding (D'Agostini. arXiv:1010.0632(2010))
  - **MultiFold** (Andreassen et al. PRL 124, 182001 (2020))
    - Machine learning driven
    - Unbinned
    - **Simultaneously** unfolds many observables → **Correlation** information is retained!

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

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

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

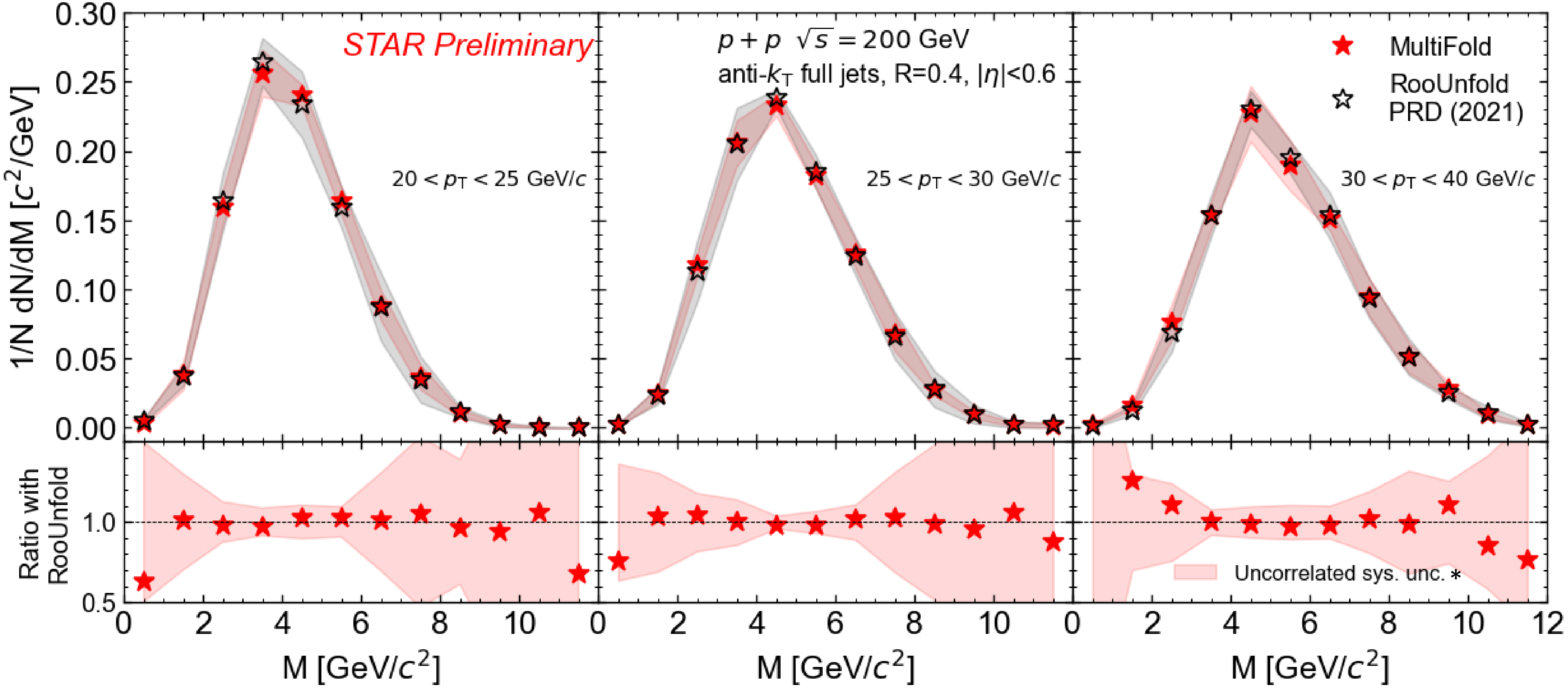
All 6 observables are simultaneously unfolded in an unbinned way!

- Uncertainties due to prior choice accounted for through 6D reweighting based on PYTHIA8 or HERWIG (see backup)

Analysis method: Validation

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

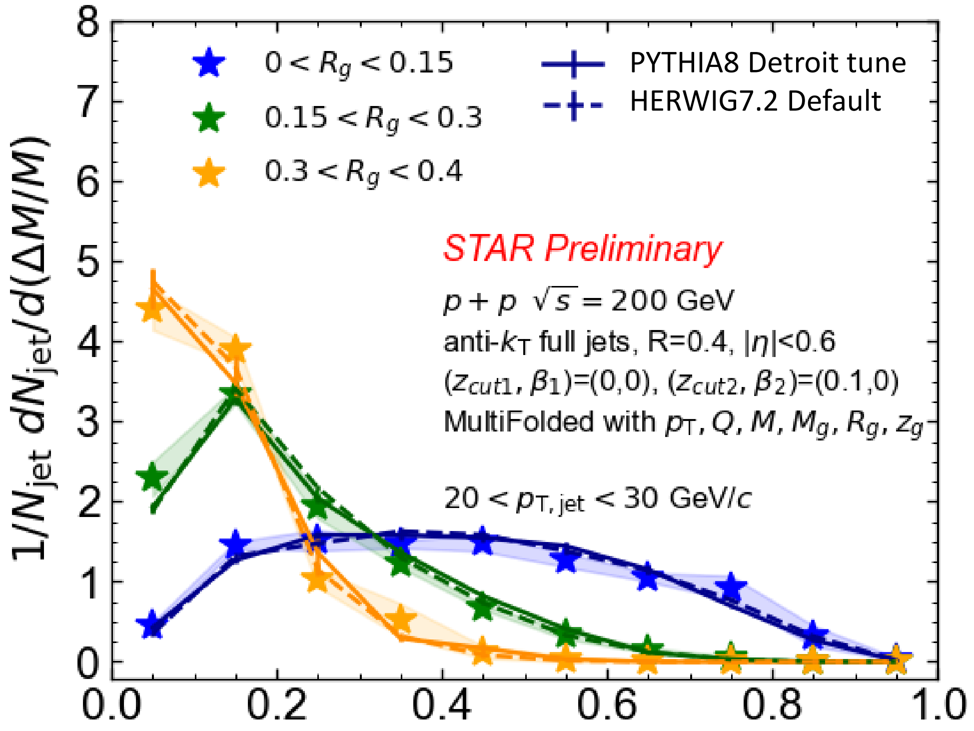
MultiFolded result agrees with **RooUnfolded** result (STAR Collaboration. PRD 104, 052007(2021)) HEPData



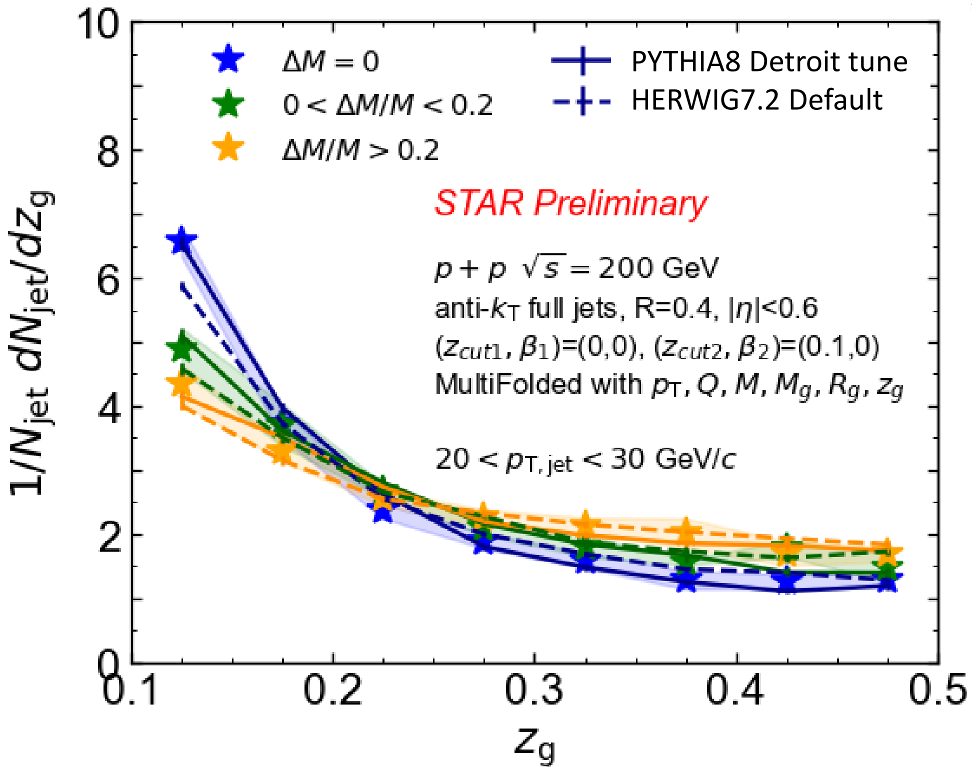
… but **MultiFold** also gives us high-dimensional correlation between observables!

* 2D reweighting used for prior variation, to be consistent with RooUnfolded measurement

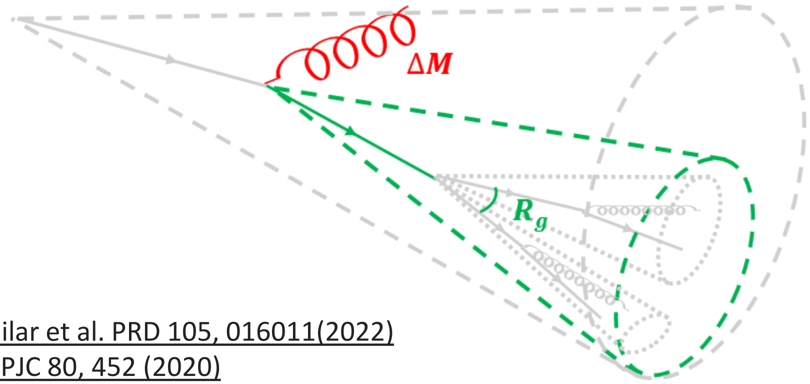
Results



$$\Delta M/M = \frac{M - M_g}{M}$$

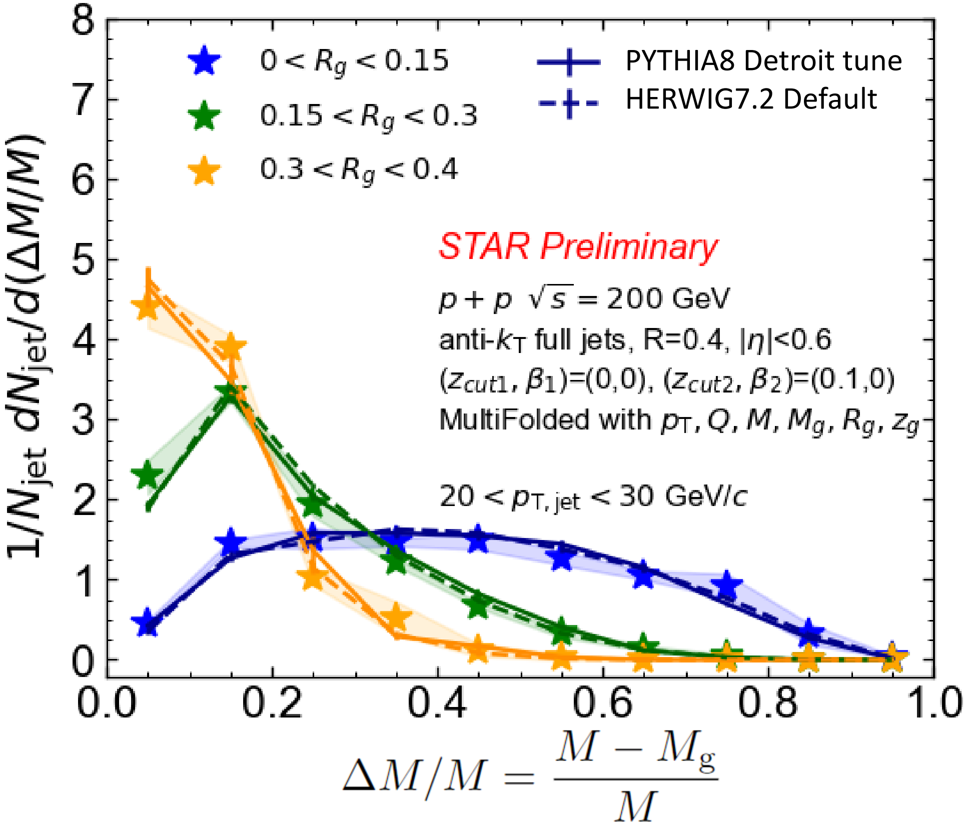


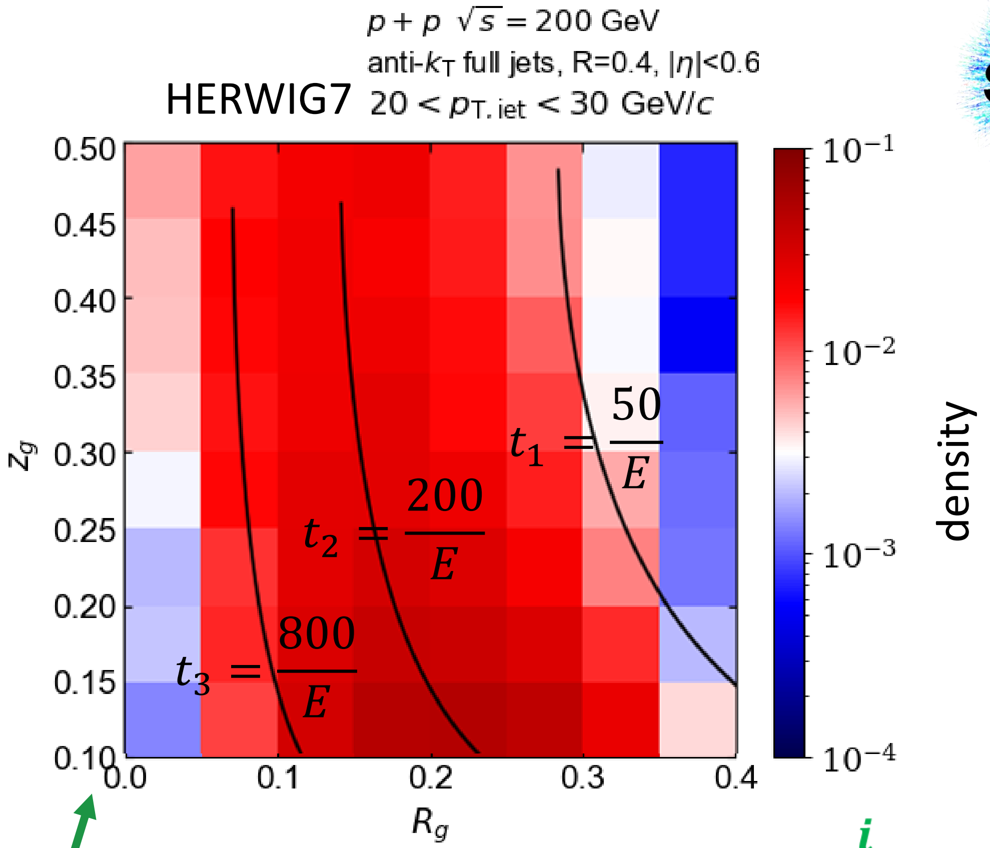
- $\langle \Delta M/M \rangle$ anti-correlated with $\langle R_g \rangle$ → consistent with angular ordered parton shower
- **Early** soft wide-angle radiation constrains the angular and momentum phase space of **later** splittings
- MC models describe the trend of data
- See arXiv:2307.07718 for more details and more results!



PYTHIA8 Detroit tune: Aguilar et al. PRD 105, 016011(2022)
HERWIG7.2: Bellm, et al. EPJC 80, 452 (2020)

Discussion





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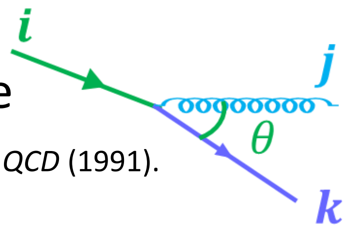
- Lines of constant formation time



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

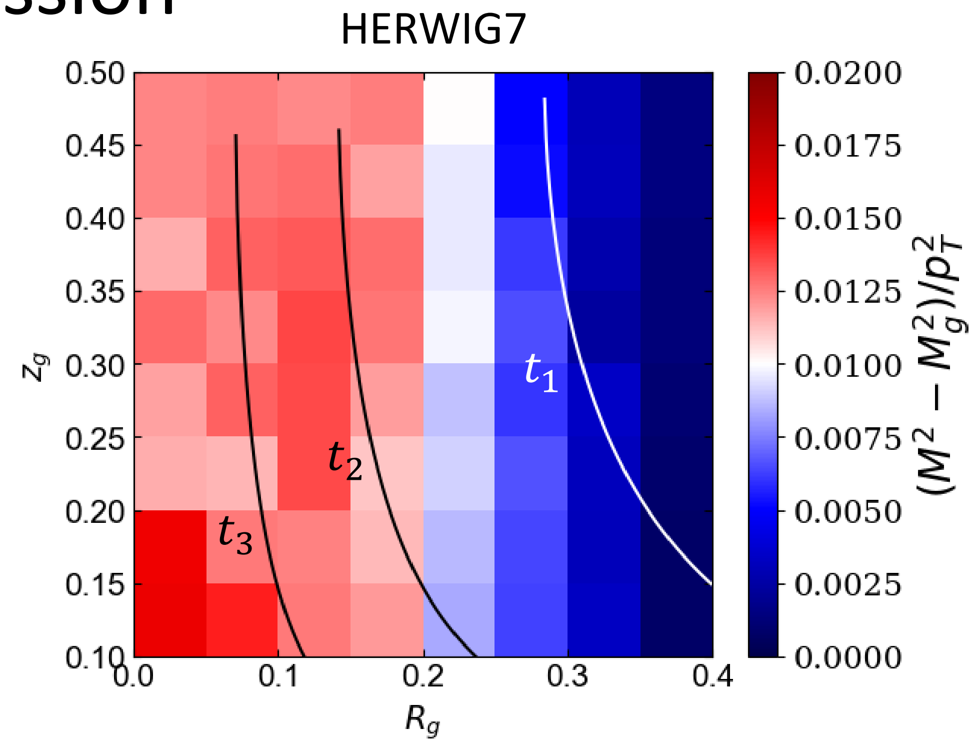
Using $t_F \sim \frac{1}{2Ez(1-z)(1-\cos(\theta))}$

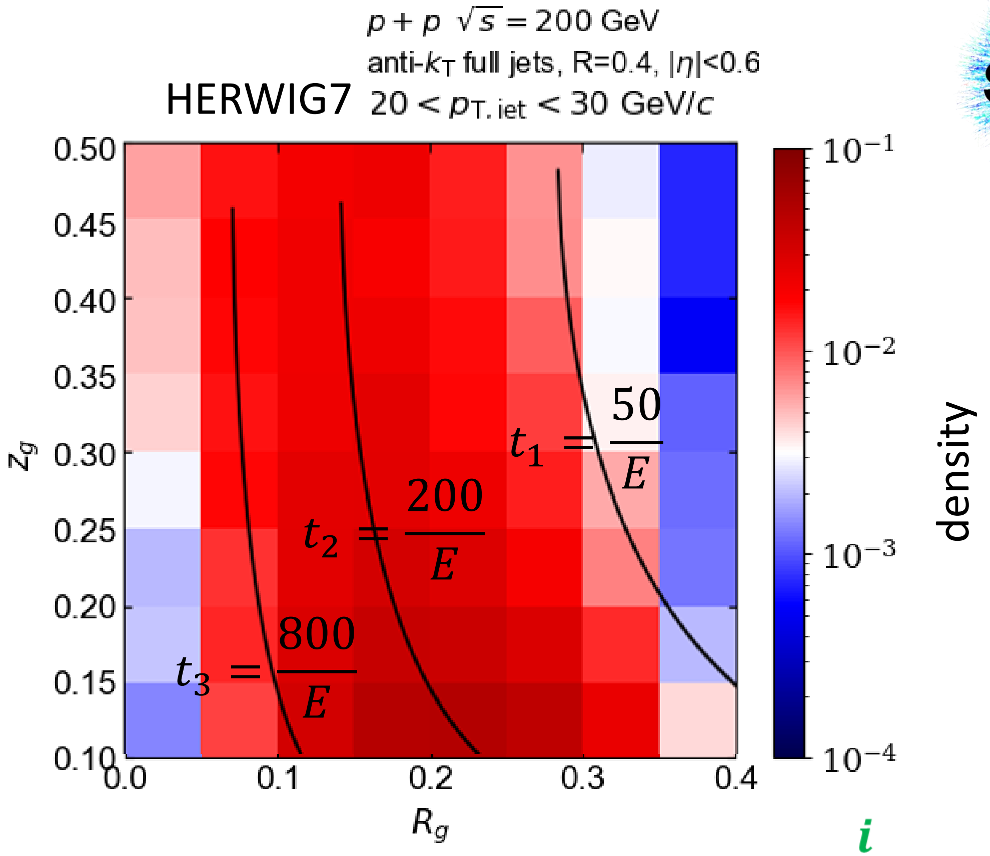
solve for $z(\theta, z < 0.5)$:

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

$$z = \frac{\min(p_{T,j}, p_{T,k})}{p_{T,j} + p_{T,k}}$$

Discussion

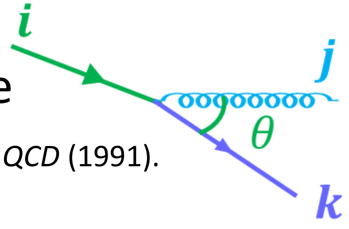




- CollinearDrop groomed mass strongly correlated with R_g and weakly with z_g
- To shed a lot of mass at early stage, the hard splitting needs to happen late
- PYTHIA largely agrees with HERWIG (see backup).

Stay tuned for data!

- Lines of constant formation time



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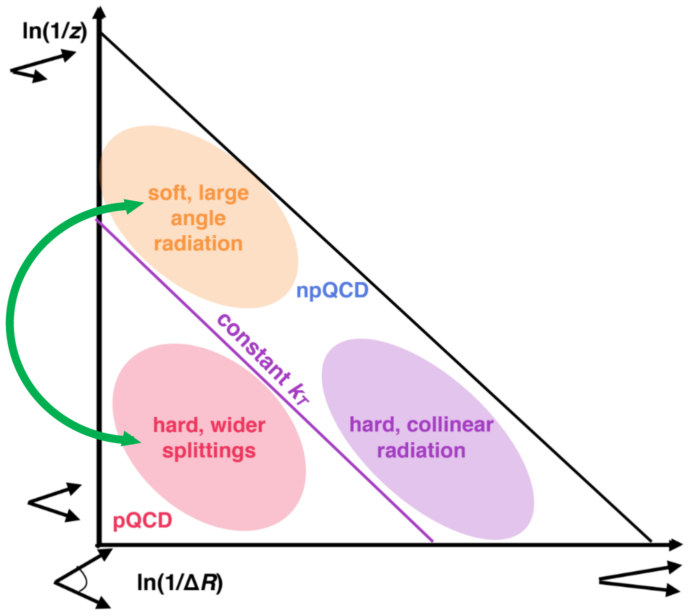
Conclusion (Part 1)

- Study the **soft**-**hard** correlation within jets with CollinearDrop vs SoftDrop jet observables
  - The **early-stage radiation** is correlated with the later-stage splittings
  - MultiFold allows for access of multi-dimensional correlations on a jet-by-jet basis. First application on RHIC data!
  - For example, we can select on a specific region of phase space by cutting on **3** different observables, and then study the **4th**



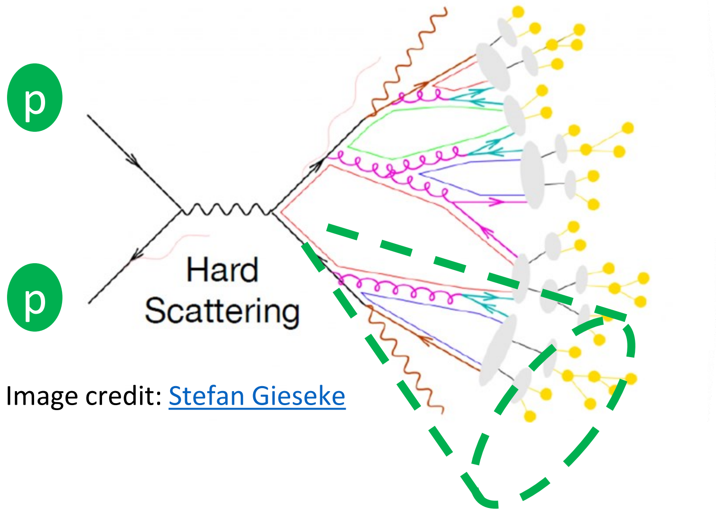


Image credit: Stefan Gieseke

Study the non-perturbative contribution in jets

- Soft component of the parton shower
  → CollinearDrop jet measurement
- Hadronization
  → Charge correlator ratio measurement

Motivation

The **charge correlator ratio r_c** can probe for evidence of **string-like fragmentation**, by distinguishing the charge signs of **leading and subleading** particles within jets.

Chien et al. PRD 105 051502 (2022)

$$r_c(X) = \frac{d\sigma_{h_1 h_2}/dX - d\sigma_{h_1 \bar{h}_2}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 \bar{h}_2}/dX}$$

$h_1 h_2$: same charge hadrons,
$h_1 \bar{h}_2$: opposite charge hadrons

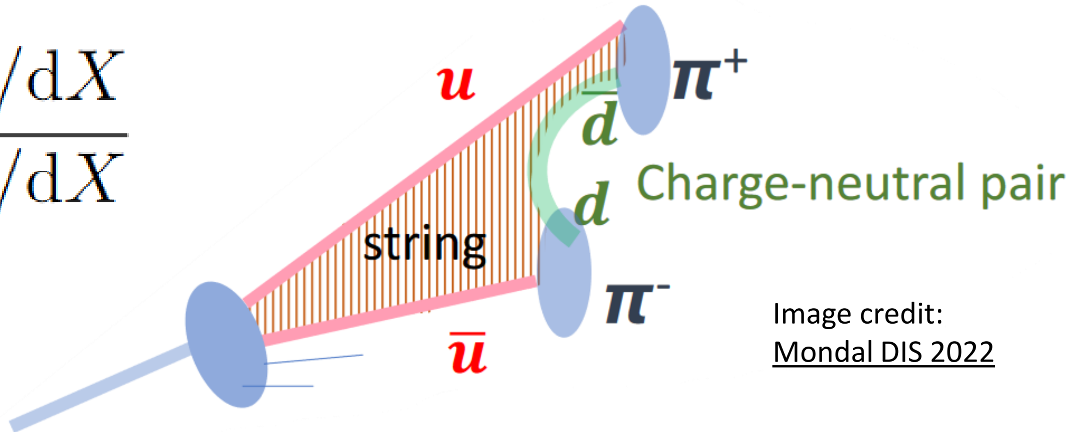


Image credit:
Mondal DIS 2022

This configuration above favors $r_c \rightarrow -1$.

This measurement can also establish a baseline for studying **medium modification of hadronization in the QGP**! The choice of leading dihadrons might make it less susceptible to the background.

→ In the future, interesting to pursue this in heavy ions!

Analysis method

- Reconstruct anti-k_T **full jets** with R = 0.4 from 200 GeV pp collisions
- At detector level, the decay of neutral hadrons affects the ordering of particles in jet, so we consider a **charged $\boldsymbol{r_c}$** measurement. See backup slides for an example.

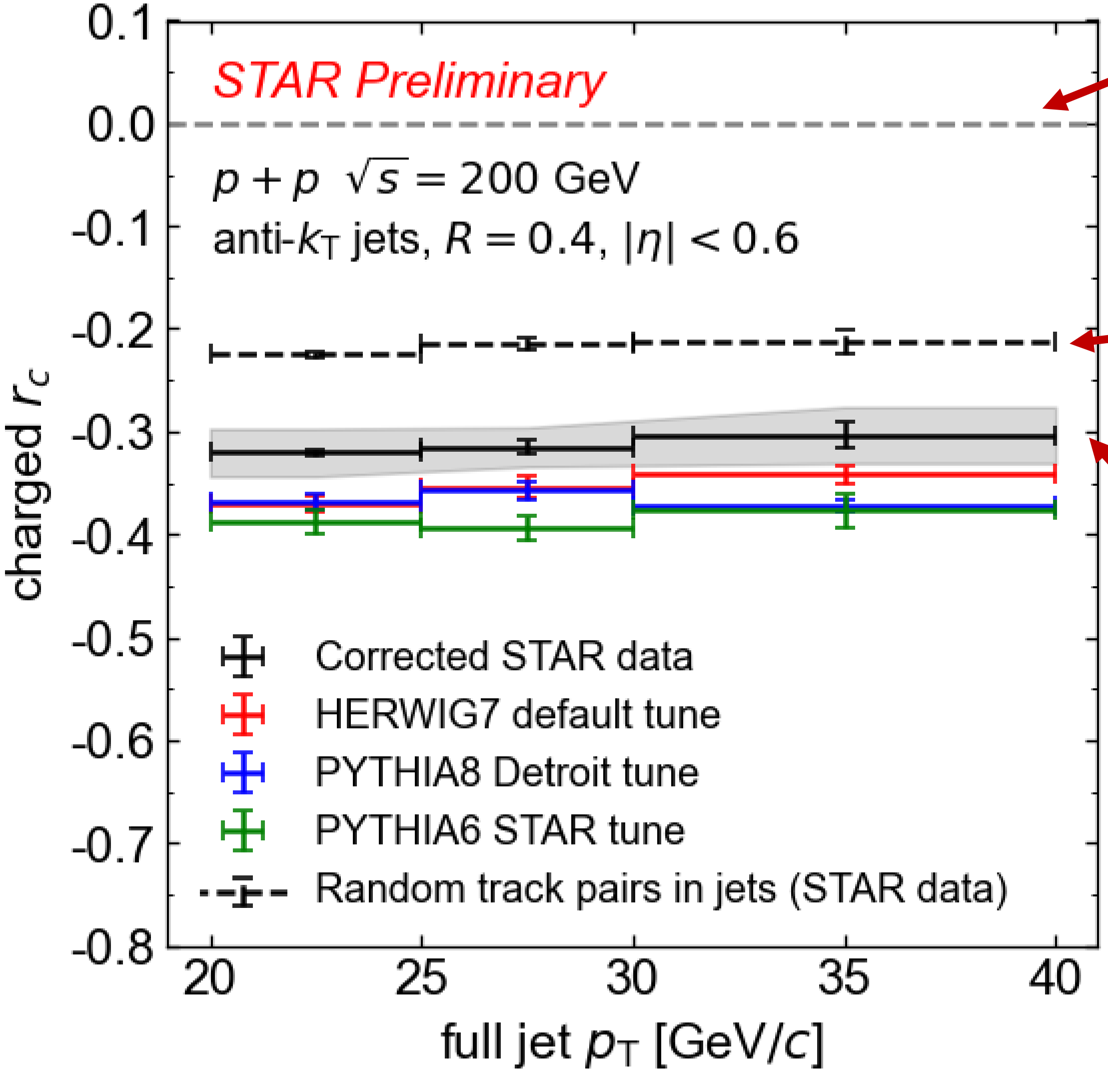
$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1 \bar{h}_2}/\mathrm{d}X}$$

$h_1 h_2$: same charge **tracks**,
$h_1 \bar{h}_2$: opposite charge **tracks**

→ Slightly changed the definition as proposed by theorists, but comparison with MC models is still meaningful!

Result

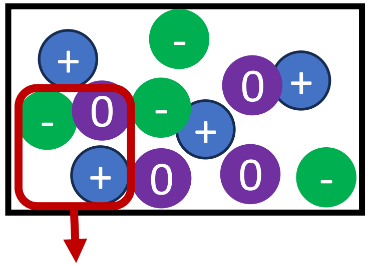
$$r_c(X) = \frac{d\sigma_{h_1 h_2}/dX - d\sigma_{h_1 \bar{h}_2}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 \bar{h}_2}/dX}$$



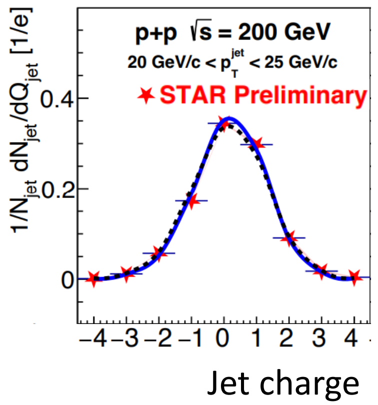
Random pairs in an uncorrelated (infinite) bath with no net charge: $\boldsymbol{r_c = 0}$

Data show a preference of opposite sign pairs over same sign pairs, in:

- pair of random tracks within a jet;
  influenced by jet charge ~ 0 on average: $\boldsymbol{r_c \approx -0.2}$
- leading and subleading tracks in jet.
  additional correlation from fragmentation: $\boldsymbol{r_c \approx -0.3}$



clustered into a jet



PYTHIA6 Perugia + STAR tune: Skands. PRD 82, 074018 (2010)
J. K. Adkins, PhD thesis (Kentucky U., 2015)
PYTHIA8 Detroit tune: Aguilar et al. PRD 105, 016011(2022)
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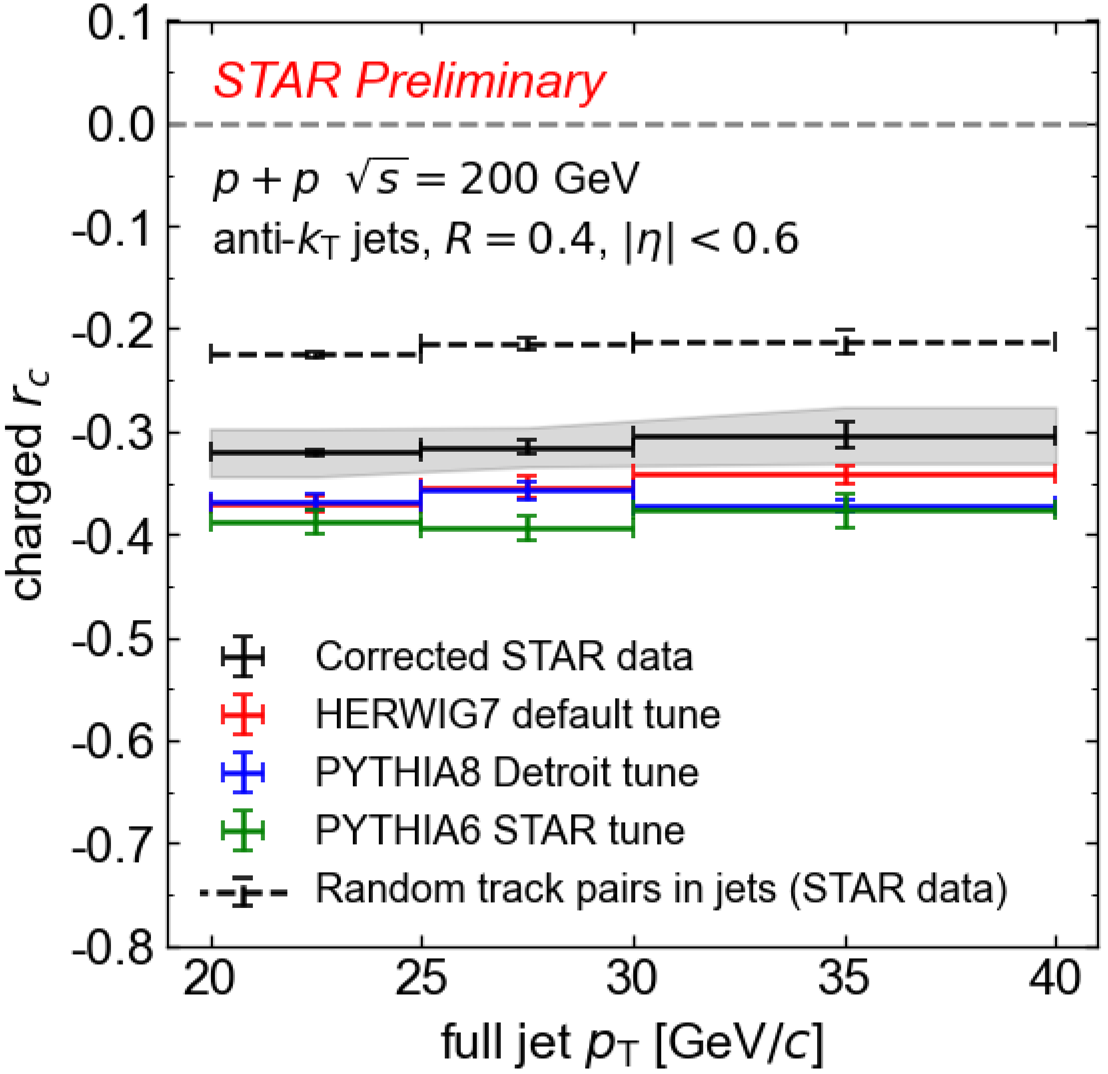
Result

$$r_c(X) = \frac{d\sigma_{h_1h_2}/dX - d\sigma_{h_1\bar{h}_2}/dX}{d\sigma_{h_1h_2}/dX + d\sigma_{h_1\bar{h}_2}/dX}$$



Weak dependence on jet $\boldsymbol{p_T}$ in 20-40 GeV

Models based on Lund string fragmentation and cluster hadronization both underpredict $\boldsymbol{r_c}$ in data.

PYTHIA6 Perugia + STAR tune: Skands. PRD 82, 074018 (2010)
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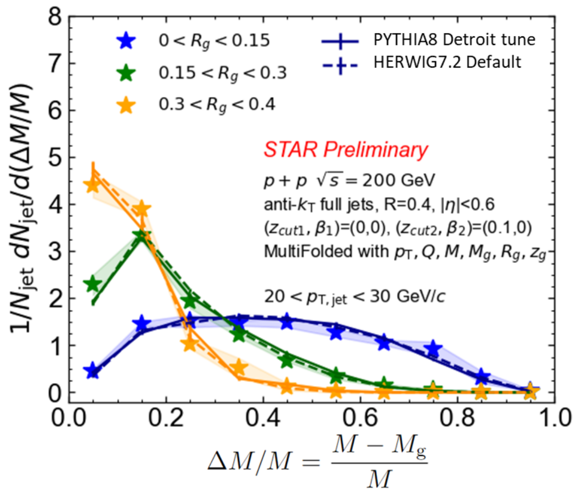
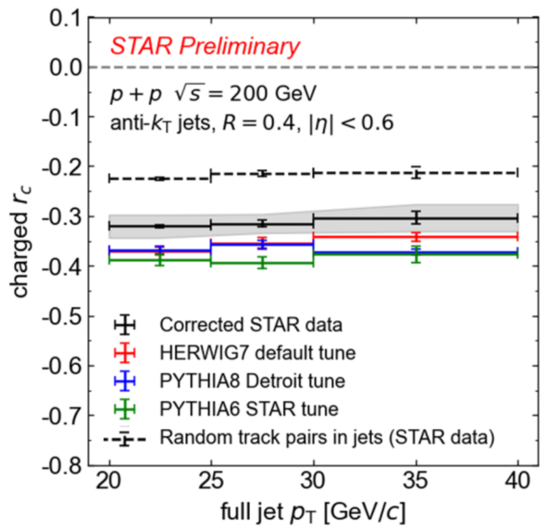
Conclusions

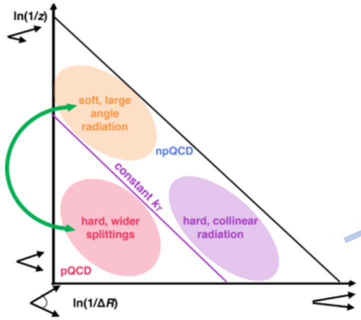
- Study the **soft**-**hard** correlation within jets with CollinearDrop vs SoftDrop jet observables
  - The **early-stage radiation** is correlated with the **later-stage splittings**
  - MultiFold allows for access of multi-dimensional correlations on a jet-by-jet basis. First application on RHIC data!
  - For example, we can select on a specific region of phase space by cutting on **3** different observables, and then study the **4th**

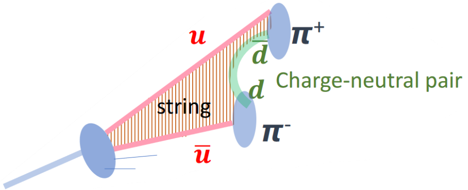


- Study **hadronization** with the charge correlator ratio
  - Data show a **weaker correlation** between leading and subleading particles in jet than models
  - In the future, study r_c as functions of observables sensitive to pQCD→npQCD transition! $(k_T, t_f, z\ldots)$



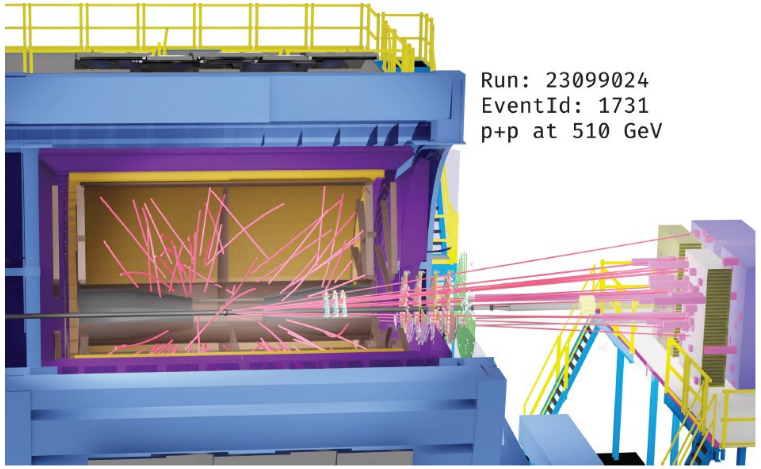
Jet substructure measurements at RHIC → Unique sensitivity to **non-perturbative QCD** effects. See talk by Isaac Mooney for **more** measurements from STAR!





Outlook

STAR in the upcoming run → Unique capability to measure jets in **both midrapidity and forward region** at RHIC energies with the forward upgrade, since 2022. Stay tuned for more data!



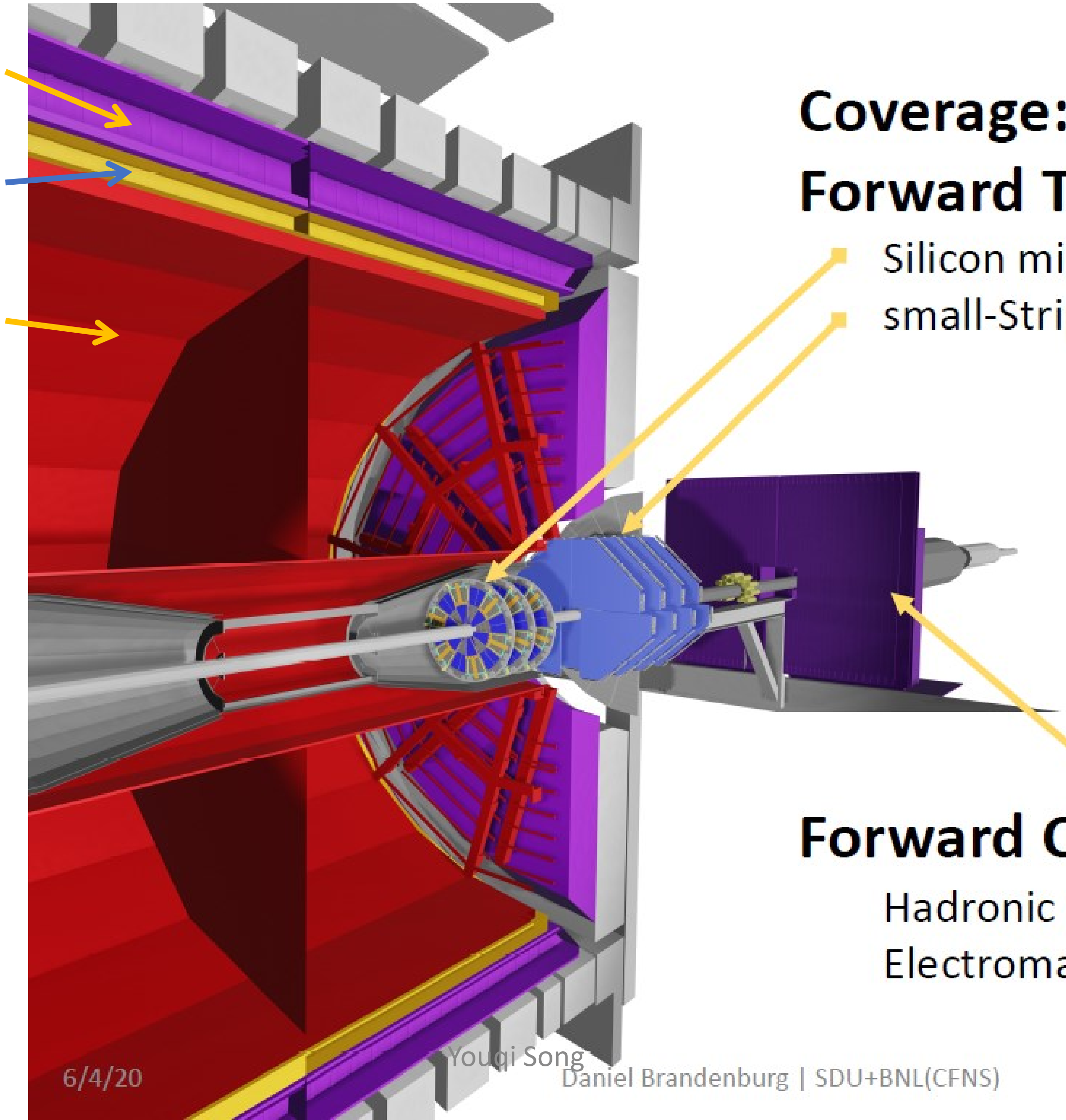
Backup

STAR forward upgrade: forward detector

Electromagnetic calorimeter

Time of flight

Time projection chamber (TPC)
(2m of outer radius)



Coverage: $2.5 < \eta < 4.0$

Forward Tracking System

- Silicon microstrip sensors
- small-Strip Thin Gap Chambers (sTGC)

Forward Calorimetry System

- Hadronic Calorimeter
- Electromagnetic Calorimeter

Jet substructures

- Use "$_g$" to denote observables obtained through **SoftDrop grooming** which removes soft and wide-angle radiation from the jet

Procedure:
- Undo jet clustering
- From the last step of the clustering, check if subjet momentum fraction passes:

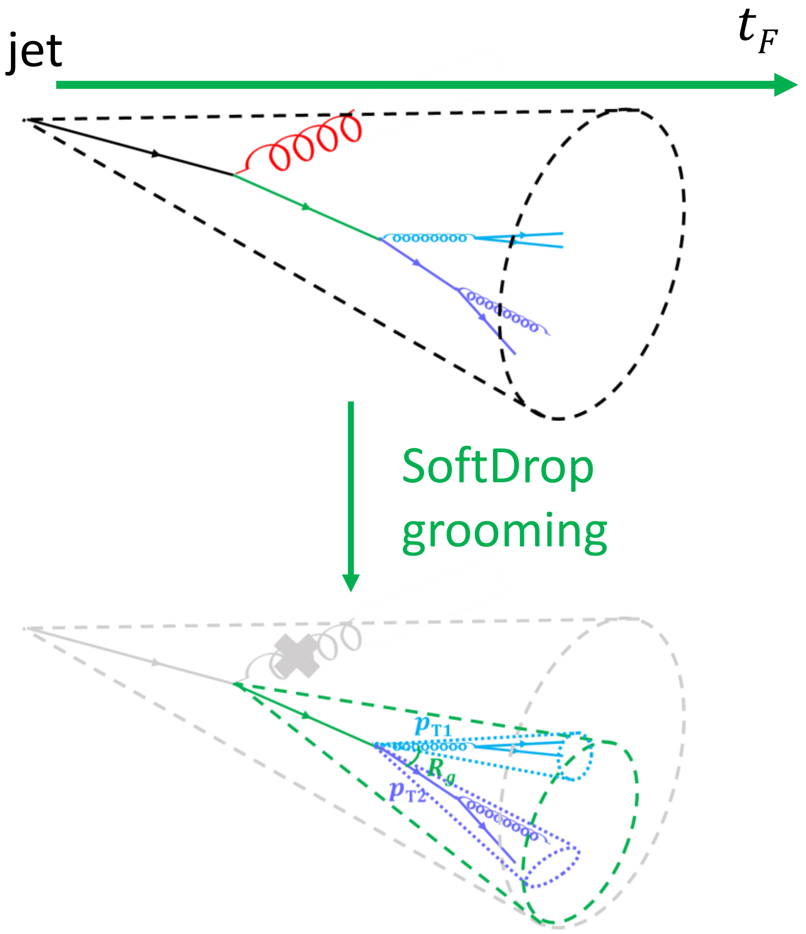
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^\beta \qquad z_{cut} = 0.1, \quad \beta = 0$$

$$\rightarrow \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.1$$

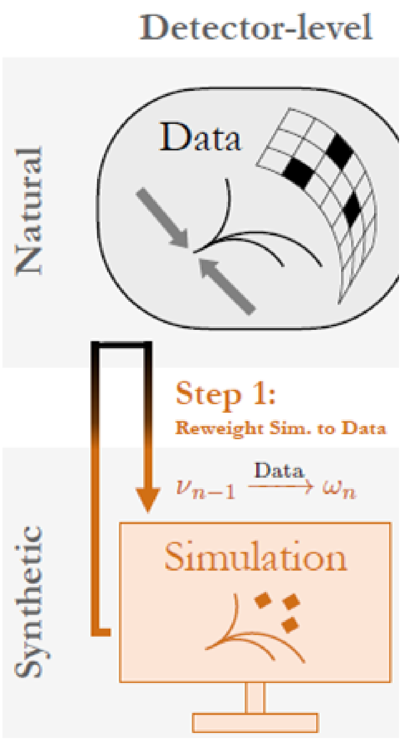
- If so, grooming is done; if not, remove the softer subjet and follow through the second to last step

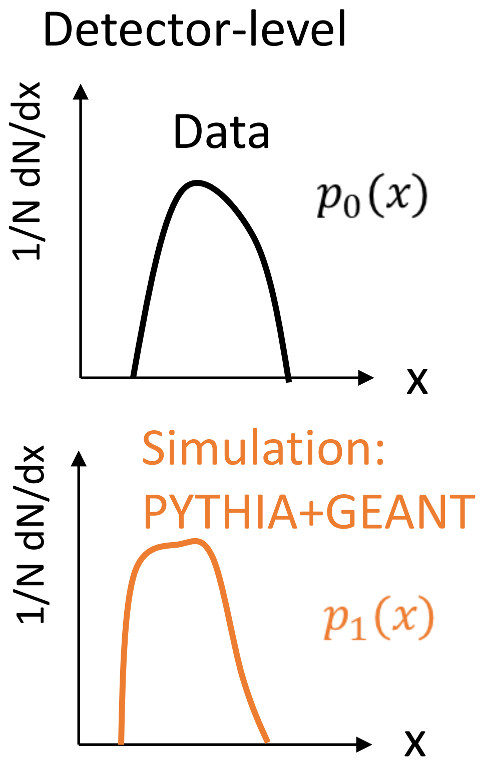
Larkoski, et al. JHEP 2014, 146 (2014).
Dasgupta et al. JHEP 2013, 29 (2013).

Effect:



Method: machine learning





E.g., Iteration 1, step 1:

Weights: $w(x) = p_0(x)/p_1(x)$ Ok for 1D

$\approx f(x)/(1 - f(x))$ (Andreassen and Nachman PRD 101, 091901 (2020))

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

to distinguish jets coming from data vs from simulation

Where does the machine learning part come in?

Unfolding → Reweighting histograms → Classification → Neural network

Method: machine learning

- Architechture: Dense neural network Activation function for dense layers: Rectified linear unit
- Activation function for output layer: Sigmoid
- Loss function: Binary cross entropy

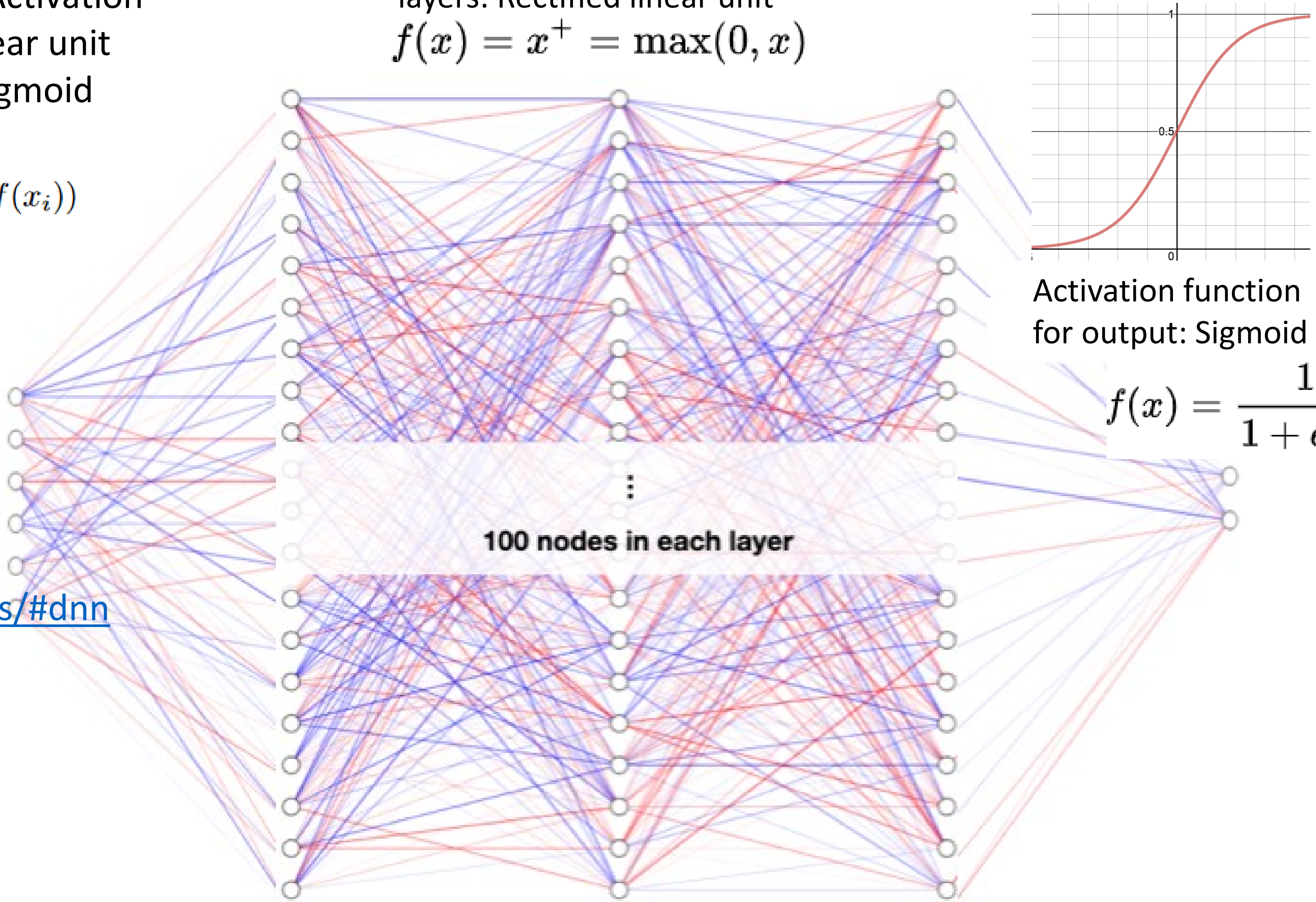
$$\mathrm{loss}(f(x)) = -\sum_{i\in 0} \log f(x_i) - \sum_{i\in 1} \log(1 - f(x_i))$$

- Optimization algorithm: Adam https://arxiv.org/pdf/1412.6980.pdf
- Nodes per dense layer: [100,100,100]
- Output dimension: 2
- Input dimension: 6

- All hyperparameters are default: https://energyflow.network/docs/archs/#dnn

Activation function for dense layers: Rectified linear unit

$$f(x) = x^+ = \max(0, x)$$

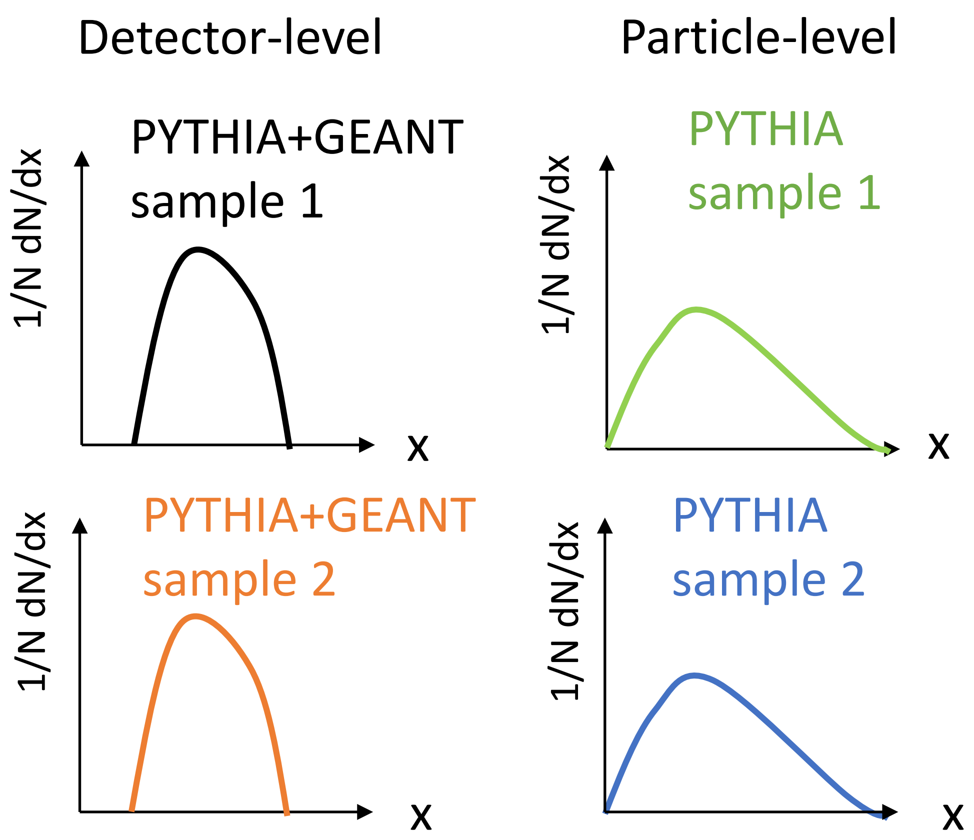


Activation function for output: Sigmoid

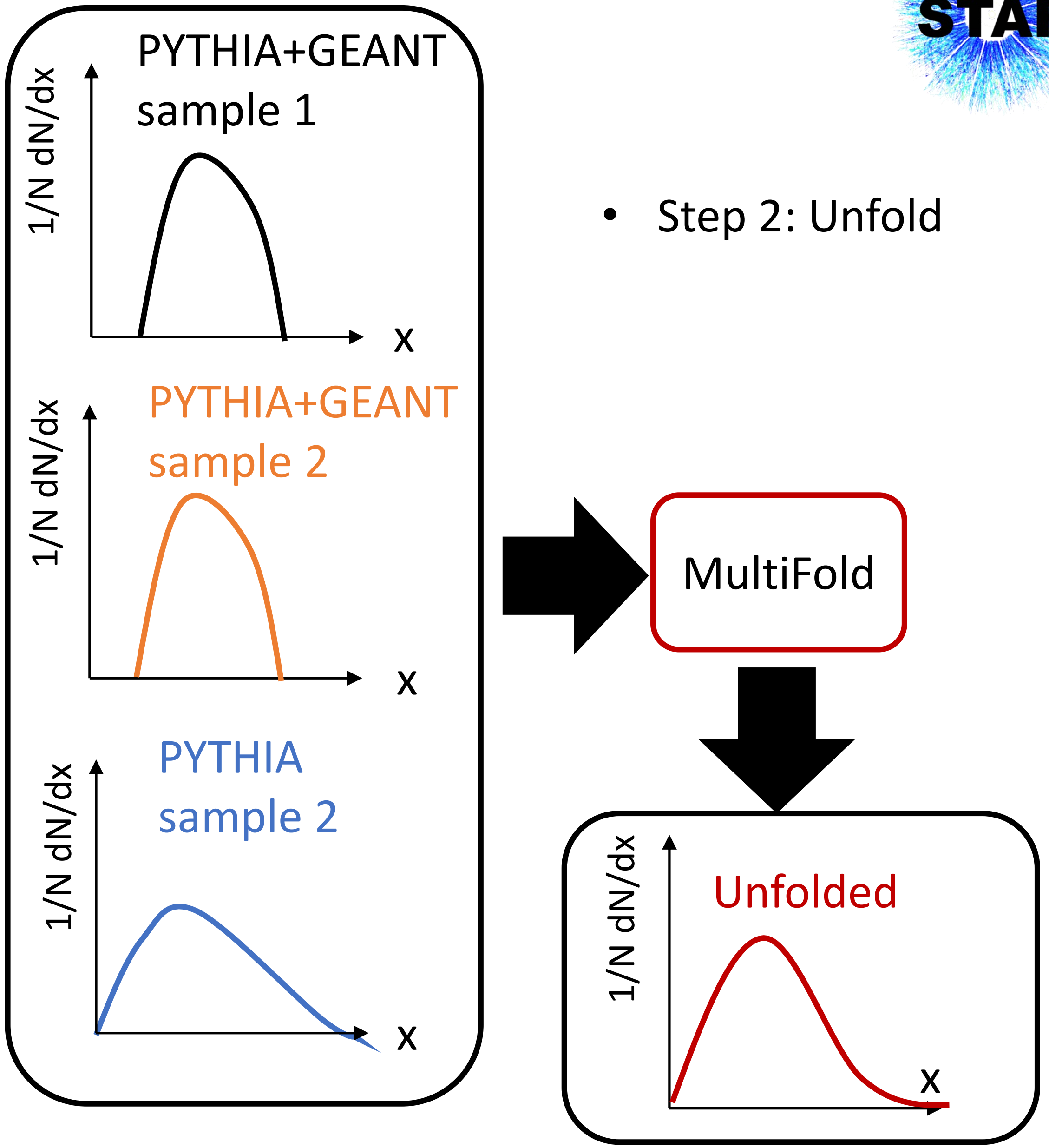
$$f(x) = \frac{1}{1 + e^{-x}}$$

Closure test for unfolding

- Step 1: Separate matched jets from PYTHIA and PYTHIA+GEANT into 2 samples

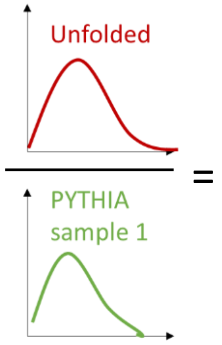


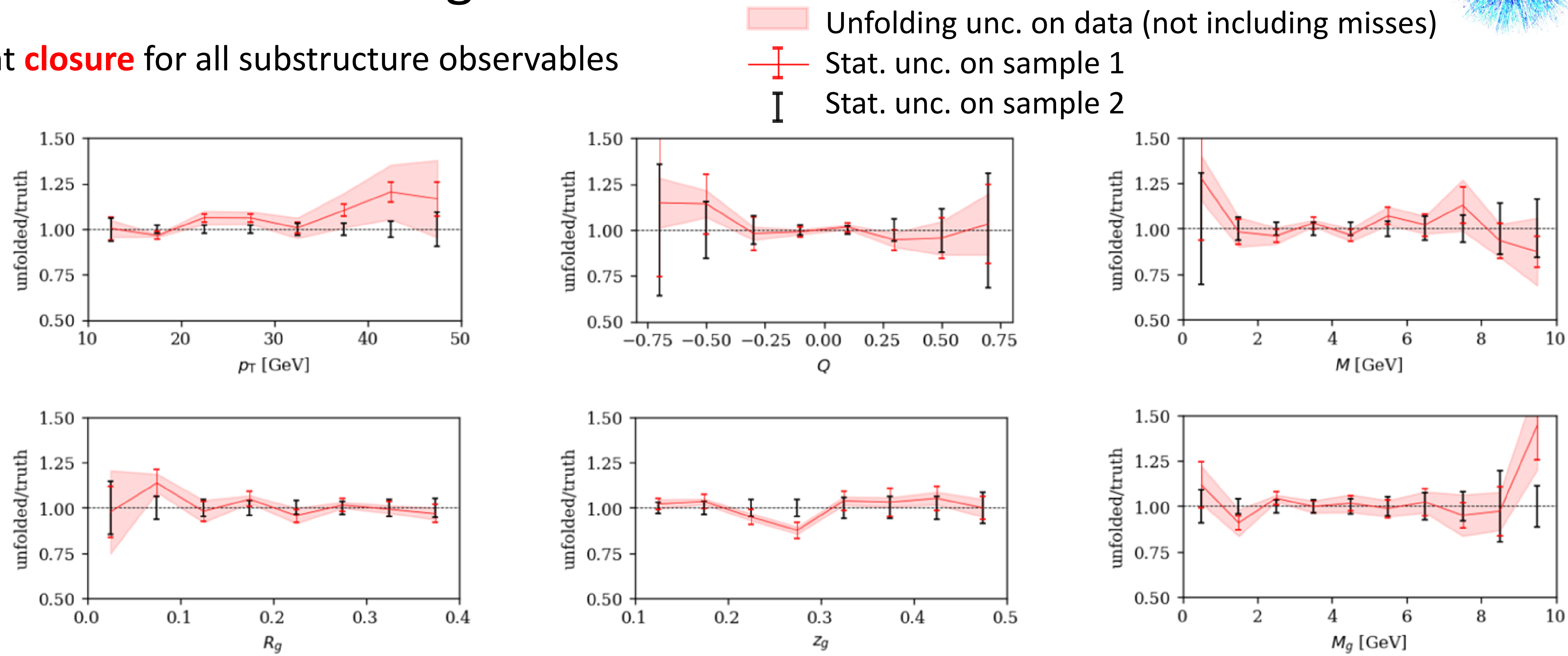
- Step 2: Unfold



Closure test for unfolding

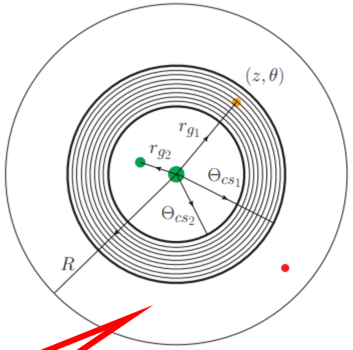
- Decent **closure** for all substructure observables

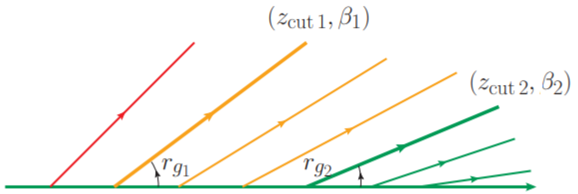




* 2D reweighting used for prior variation

Underlying event





Remove underlying effects and pileup, not necessary for 200 GeV collisions

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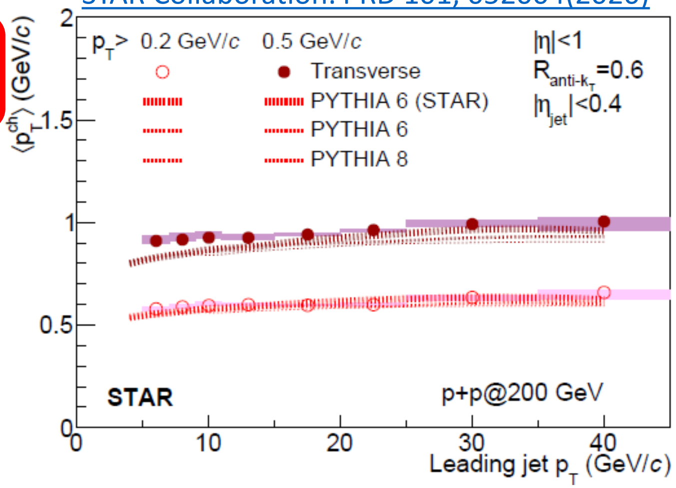
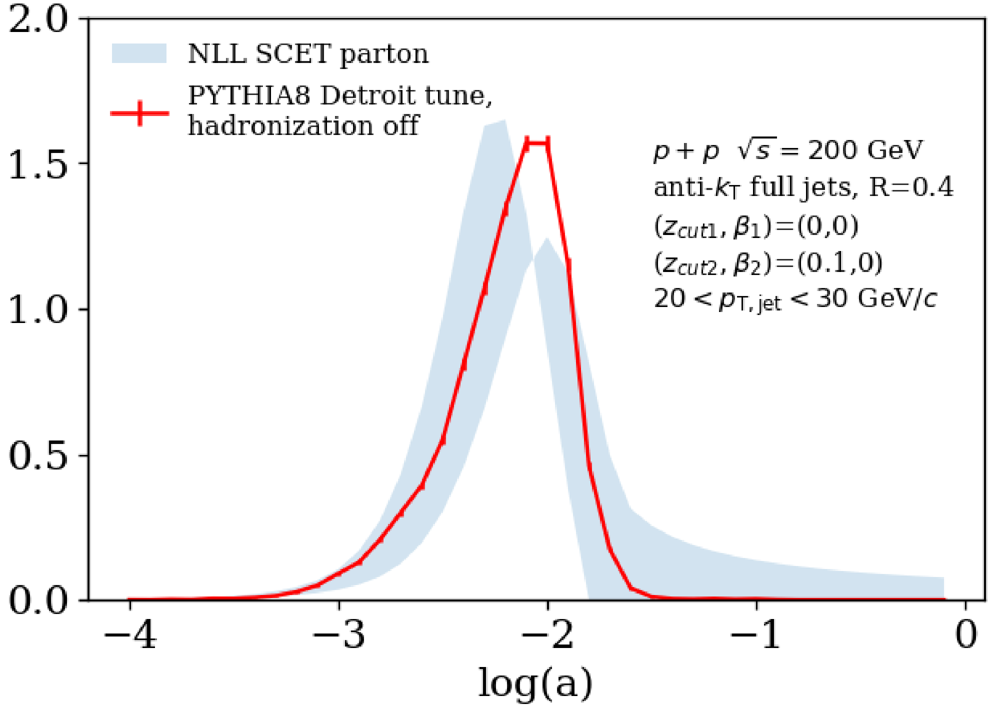
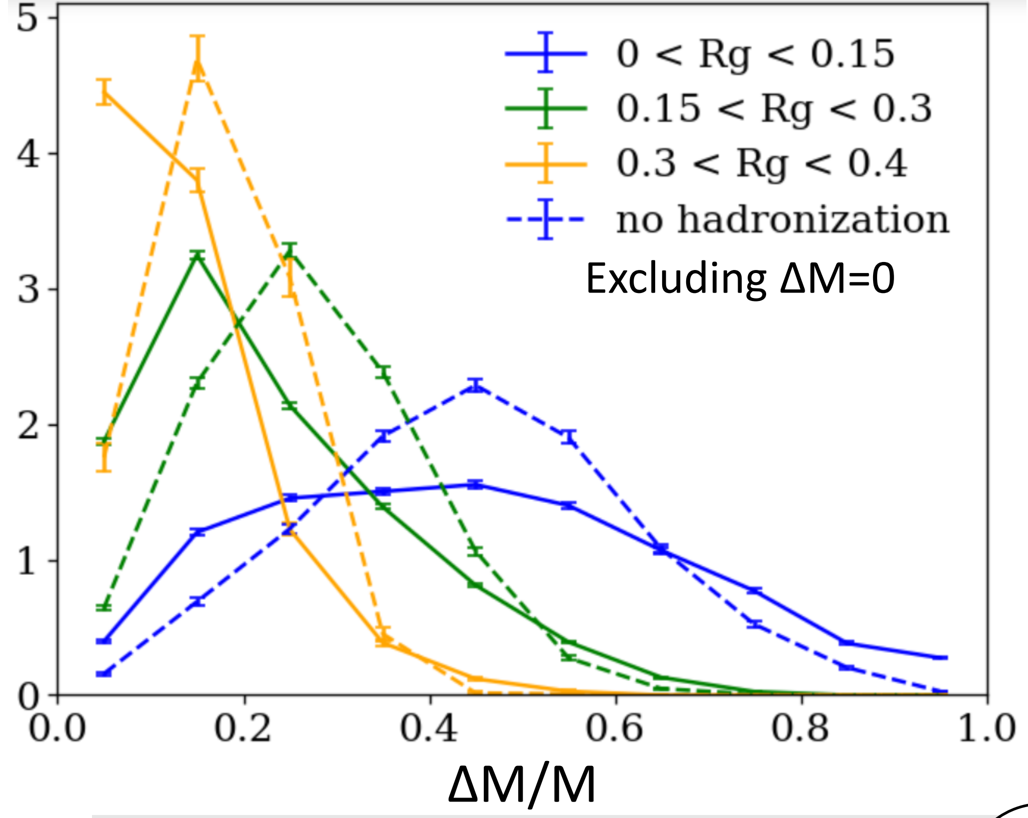


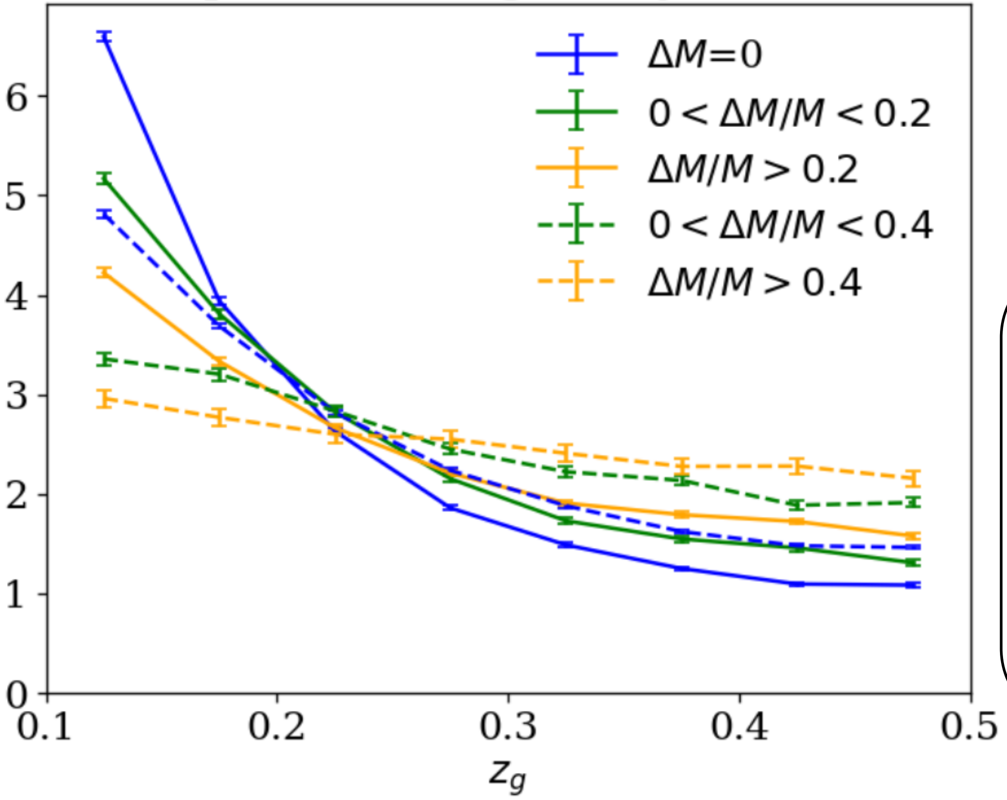
CollinearDrop groomed jet mass

- Theoretical calculation (next-to-leading log precision, using SCET calculational framework, and not including hadronization) agrees with PYTHIA8

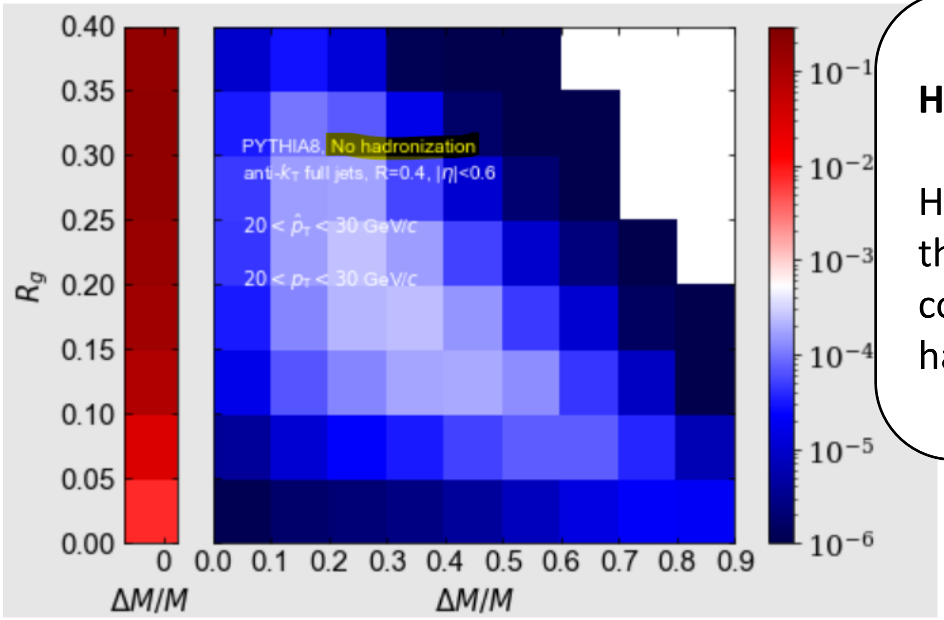


$$a = (M^2 - M_g^2)/p_T^2$$



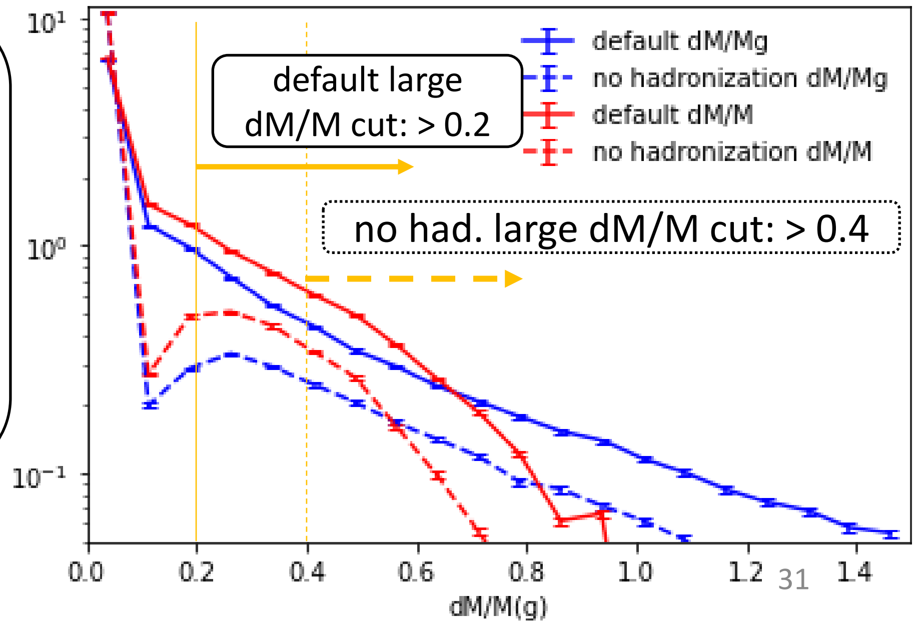


PYTHIA8 Detroit tune
20 < pT,jet < 30 GeV



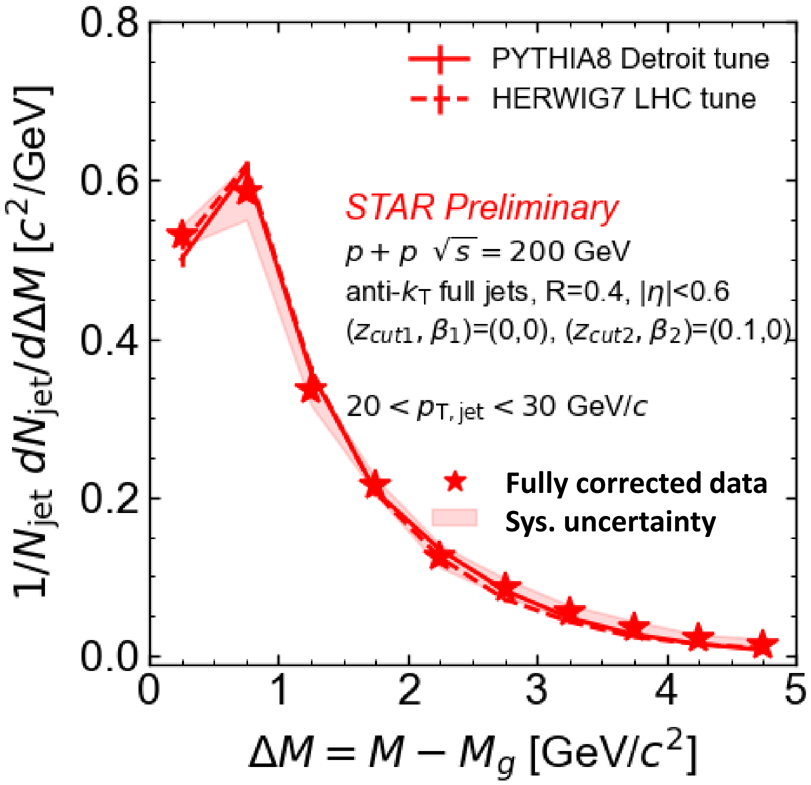
Hadronization effects study:

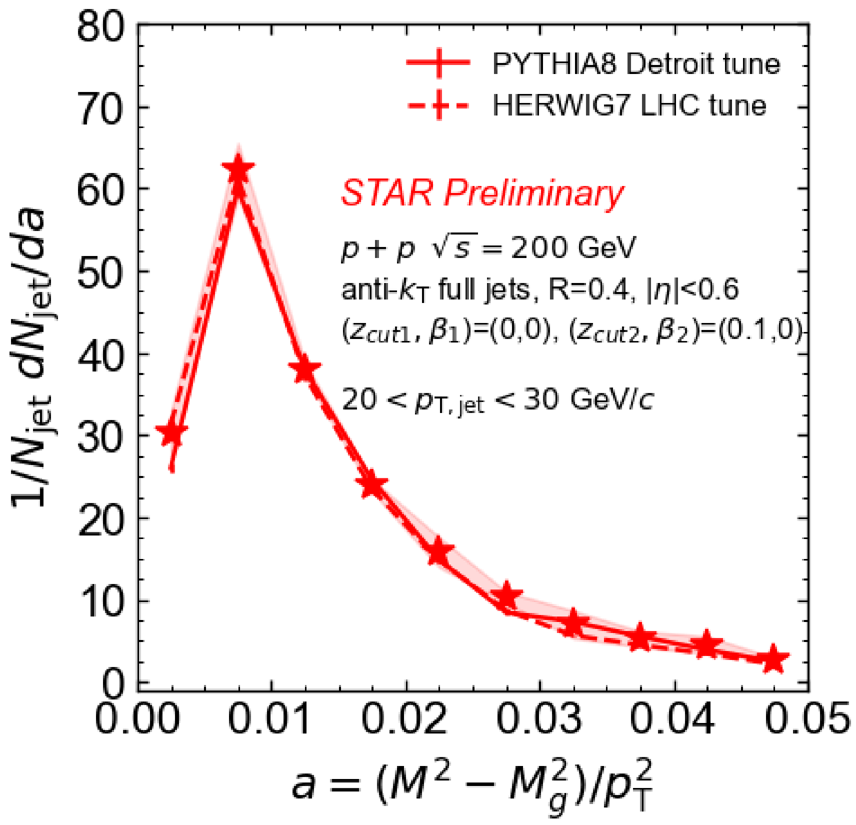
Hadronization smears/shifts the distributions, but the correlation with and without hadronization is the same.



Youqi Song

CollinearDrop groomed jet mass

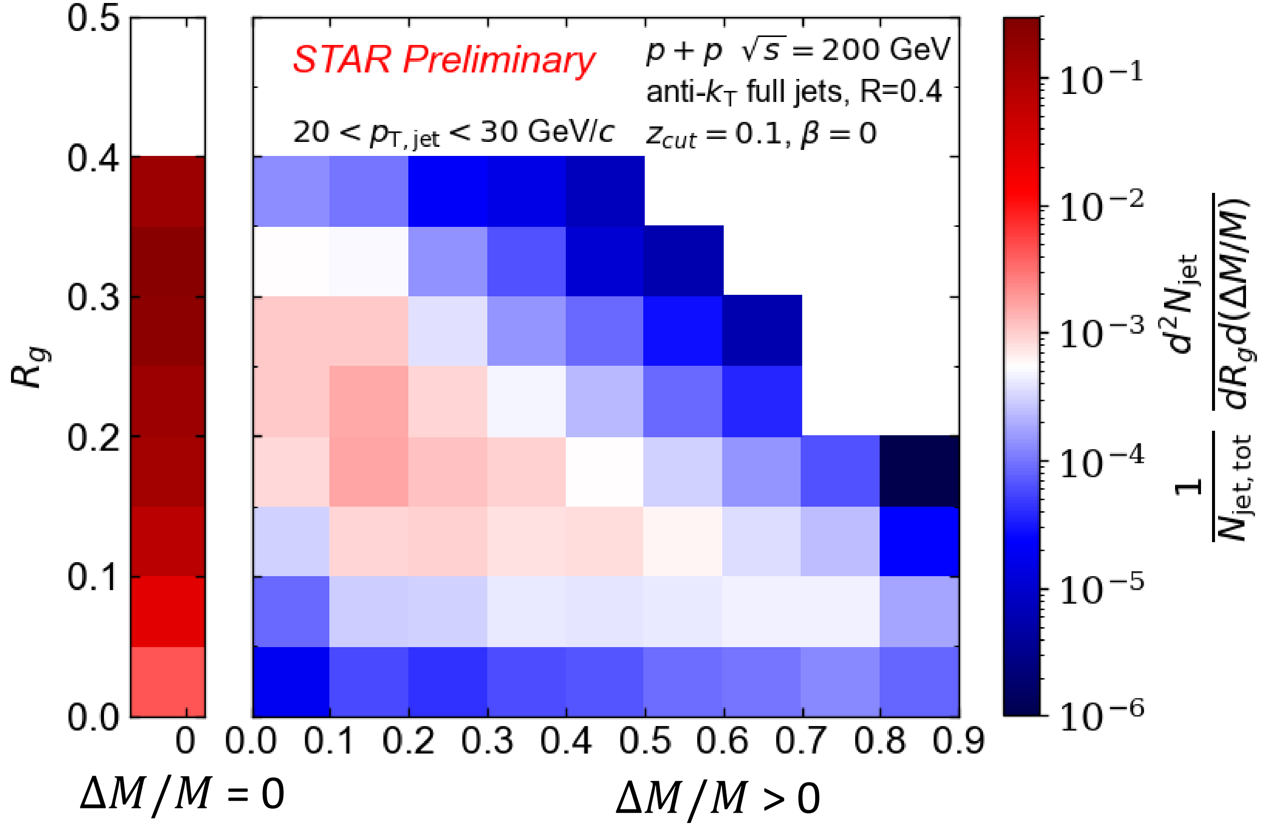




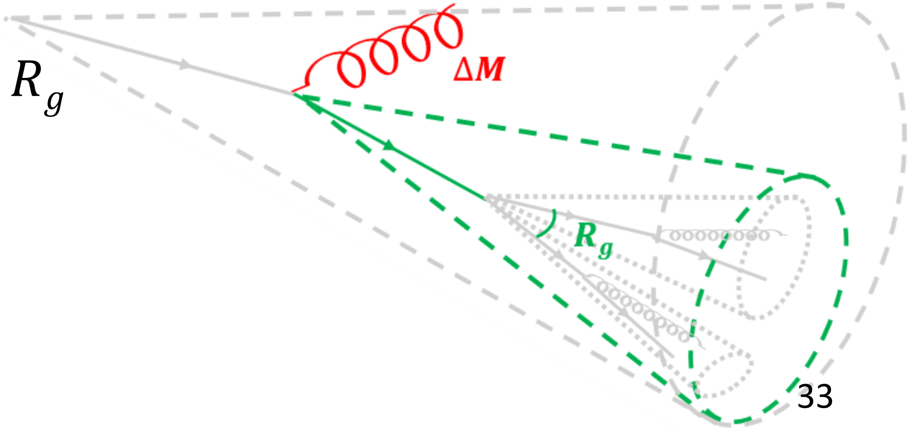
Measurement excludes jets with ΔM = 0

- First CollinearDrop groomed jet measurement, sensitive to soft radiation within jets.
- MC predictions qualitatively consistent with data.
- MultiFold allows us to correlate (combinations of) unfolded quantities.

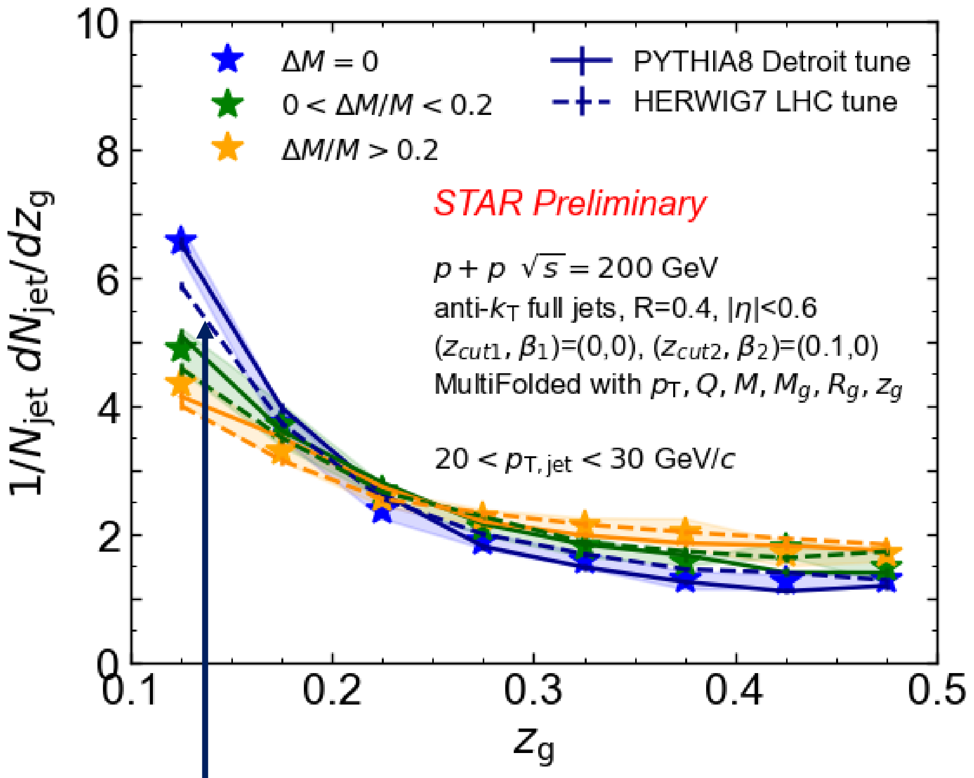
Soft radiation vs hard splitting angle



- The mean of $\Delta M/M$ distribution is anti-correlated with mean of R_g
  → consistent with angular ordered parton showers



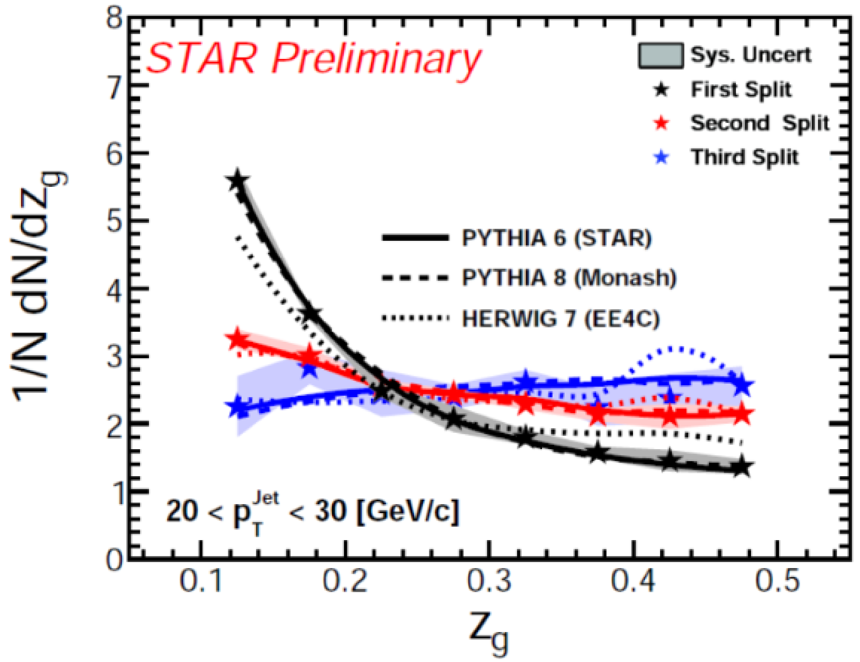
Soft radiation vs hard splitting momentum imbalance



Steeply falling ~ DGLAP 1/z: pQCD

- The more mass that is groomed away relative to the original mass, the flatter the Zg distribution is
  - Demonstrates that **early** soft wide angle radiation constrains the momentum imbalance of & the amount of npQCD contributions to **later** splittings
- MC models describe the trend of data

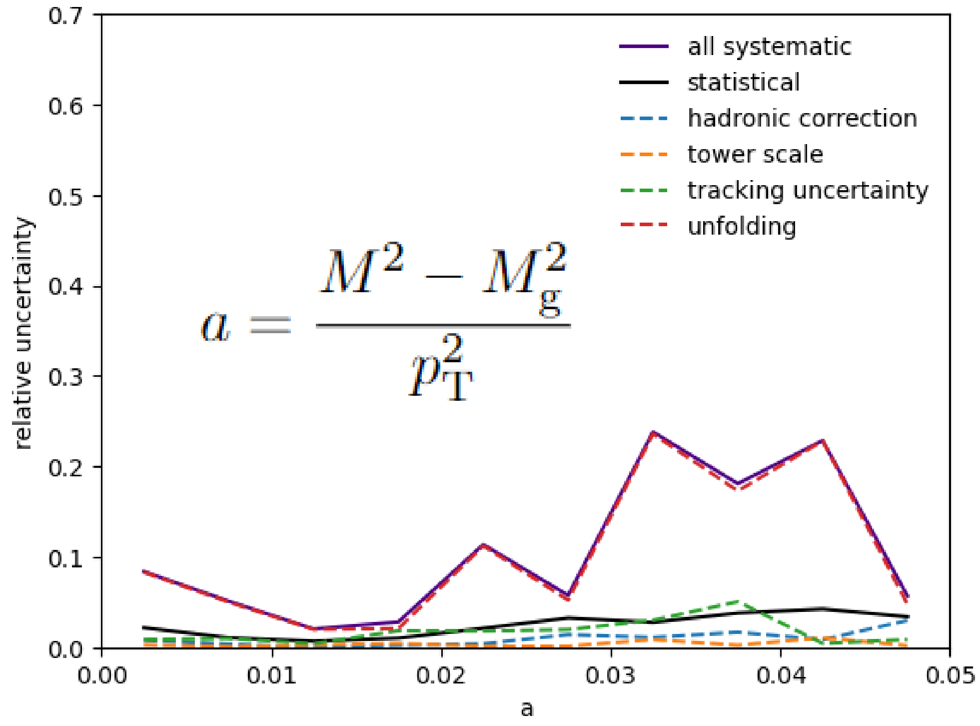
→ The first splitting that passes SoftDrop can still be non-perturbative, but if we apply the $\Delta M = 0$ selection, we can filter out some npQCD contribution due to the parton splitting



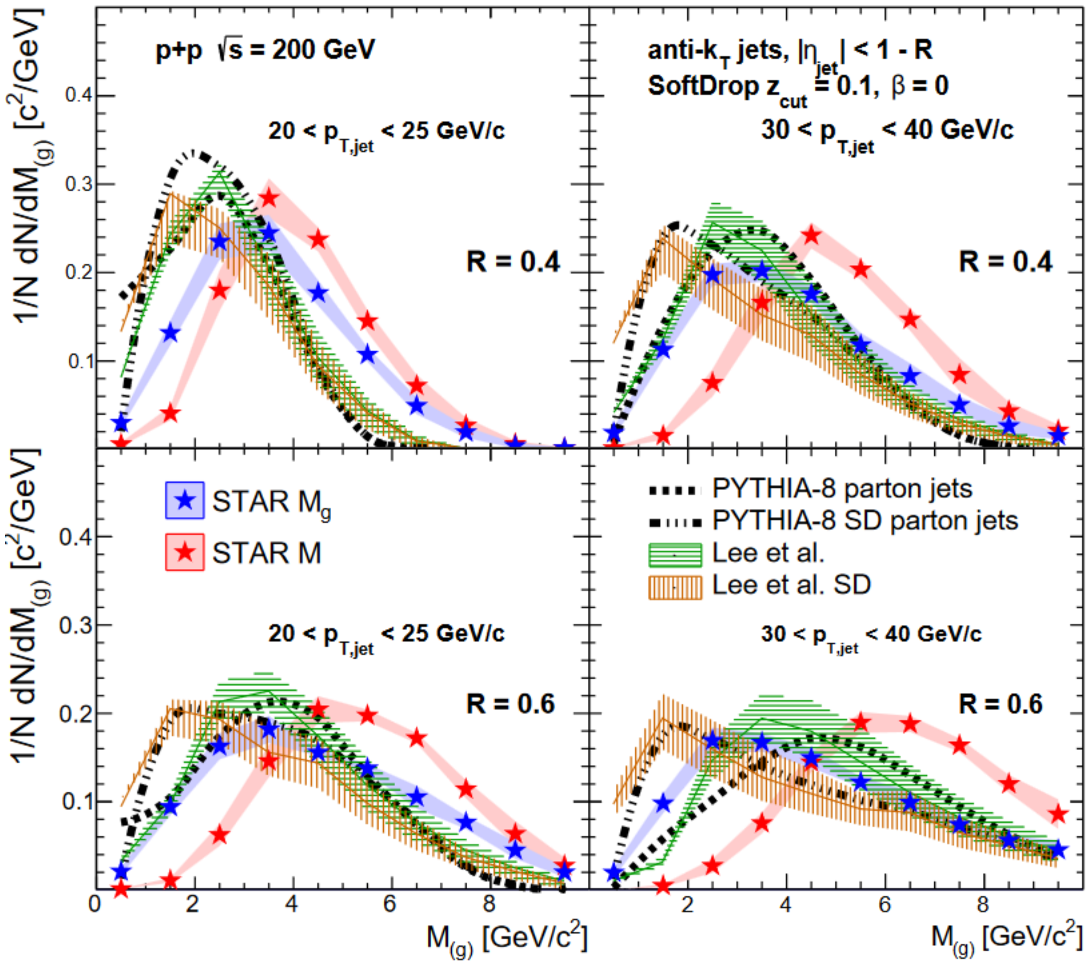
Systematic uncertainties

- Detector systematics
  - Hadronic correction 100% → 50%
  - Tower scale +3.8%
  - Tracking uncertainty -4%
- Unfolding systematics
  - Unfolding seed
  - Iteration number variation
  - Prior shape variation to HERWIG7 and PYTHIA8
    - Nominal: prior = (generation, simulation)
      = (PYTHIA6, PYTHIA6 + GEANT3 + embedding)
    - Varied to: $\text{prior} \to \text{reweight} \bigotimes \text{nominal prior}$,

      with $\text{reweight}(p_{\mathrm{T}}, Q, M, M_{\mathrm{g}}, R_{\mathrm{g}}, z_{\mathrm{g}}) = \dfrac{\text{Herwig truth}(p_{\mathrm{T}}, Q, M, M_{\mathrm{g}}, R_{\mathrm{g}}, z_{\mathrm{g}})}{\text{Pythia6 truth}(p_{\mathrm{T}}, Q, M, M_{\mathrm{g}}, R_{\mathrm{g}}, z_{\mathrm{g}})}$

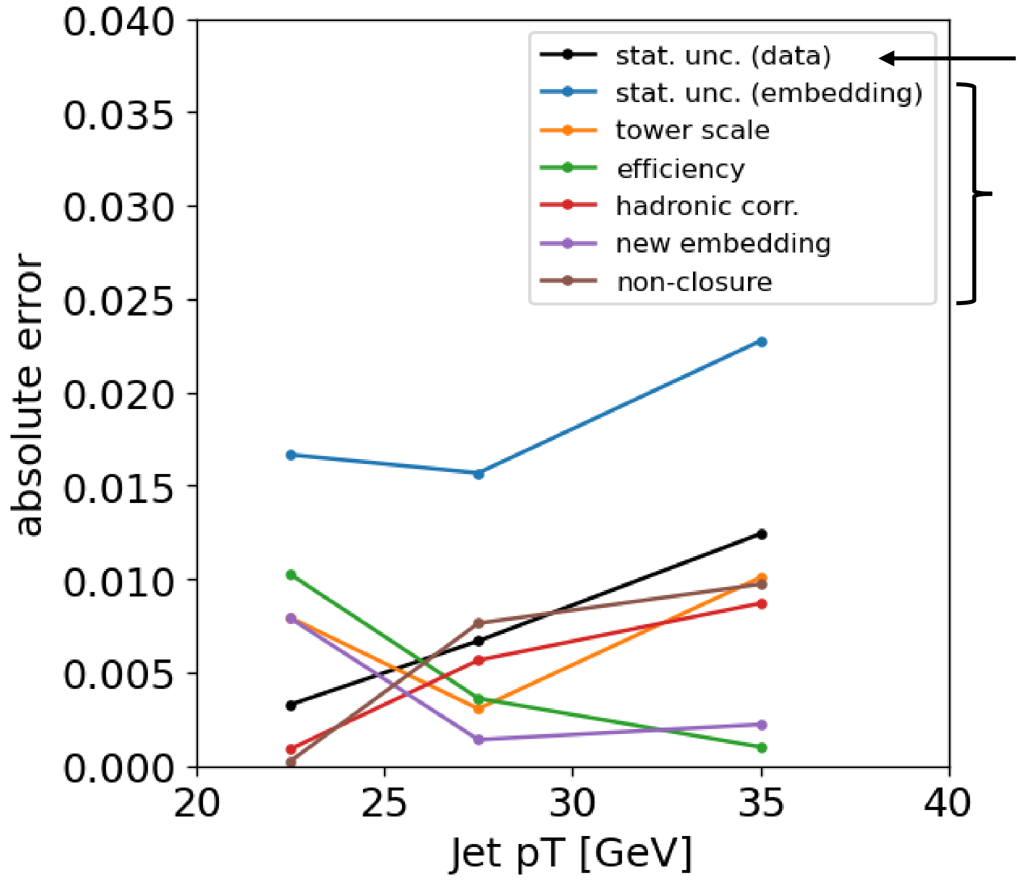


Jet mass: Comparison with models and calcaulations



STAR Collaboration. PRD 104, 052007(2021)

Systematic uncertainty



Statistical uncertainty

Systematic uncertainty

Analysis method

Problem: pi0s (and other neutral hadrons) decay at the detector-level

Example:

jet at truth level	jet at detector level
pi+ 6 GeV	track(+) 6 GeV
pi0 4 GeV	track(-) 3 GeV
pi- 3 GeV	neutral 2 GeV
pi- 1 GeV	neutral 2 GeV
	track(-) 1 GeV

leading/subleading is neutral
→ don't consider this jet

leading/subleading are both charged
→ include this jet for analysis
→ mistagged jet (shouldn't include this jet for analysis, but cannot identify it from data)

- How should we account for the neutral background?

Solution: Switch to a "charged jet" measurement

found in Sec.2.1 of this STAR analysis note. In addition to leptons, protons and anti-protons, several other particles are also deemed as stable particles at the particle level. Their list is available below.

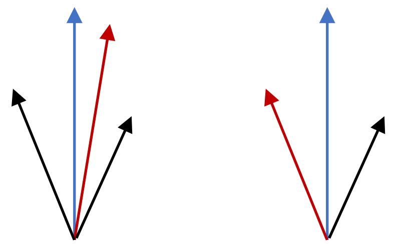
$$\pi^0, \pi^\pm, \eta, K^+, K_S^0, K_L^0, \Sigma^\pm, \bar{\Sigma}^\pm, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+ \quad (3)$$

Analysis method

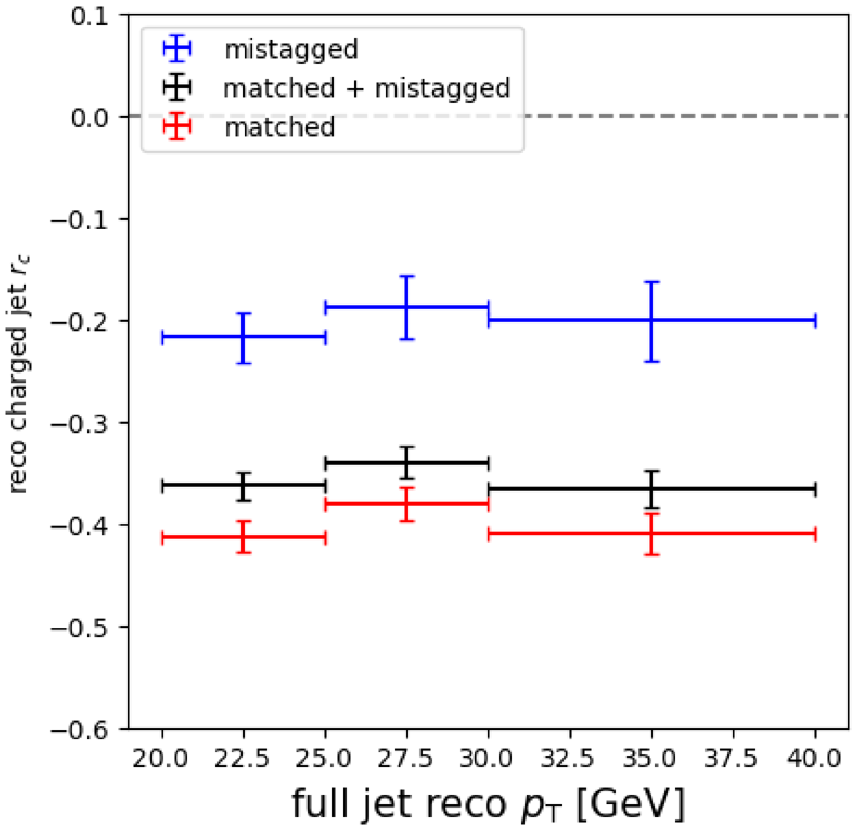
- Correction is needed!
  - mistagged subtraction to account for incorrectly identifying tracks that are not leading/subleading
  - bin-by-bin reweighting procedure to account for the jet energy scale

- Example: Why is mistagged subtraction necessary?

PYTHIA → GEANT



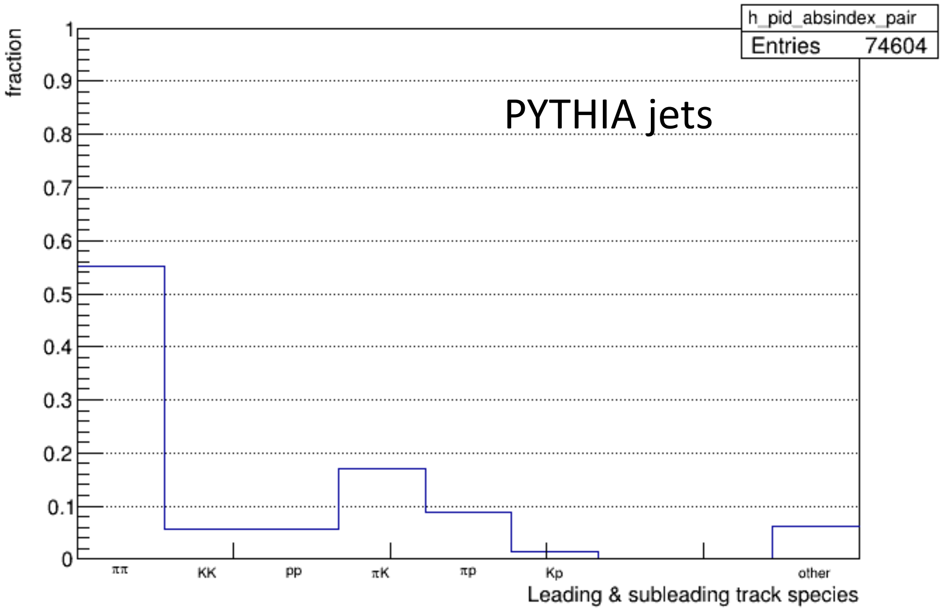
Mistagged example

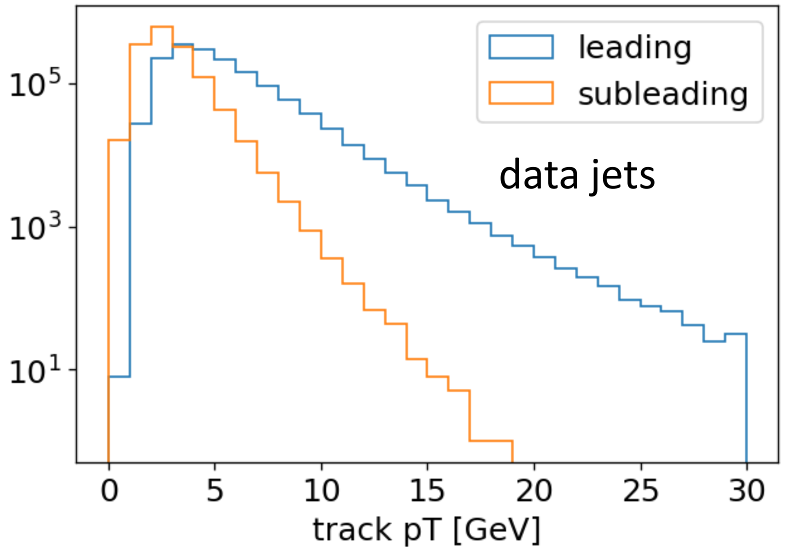


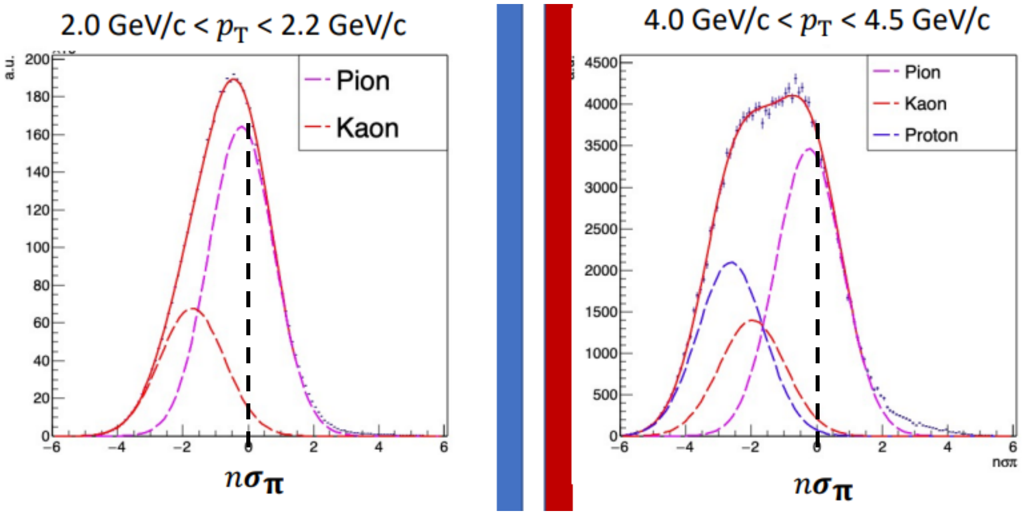
Study done with embedding

Possibility of doing PID?

- It seems challenging to do event-by-event PID for high pT pi, K, p
- Pion selection
  - Cutting on n(sigma pi) > 0 might suffer ~50% efficiency
  - The inclusive case already has ~60% purity



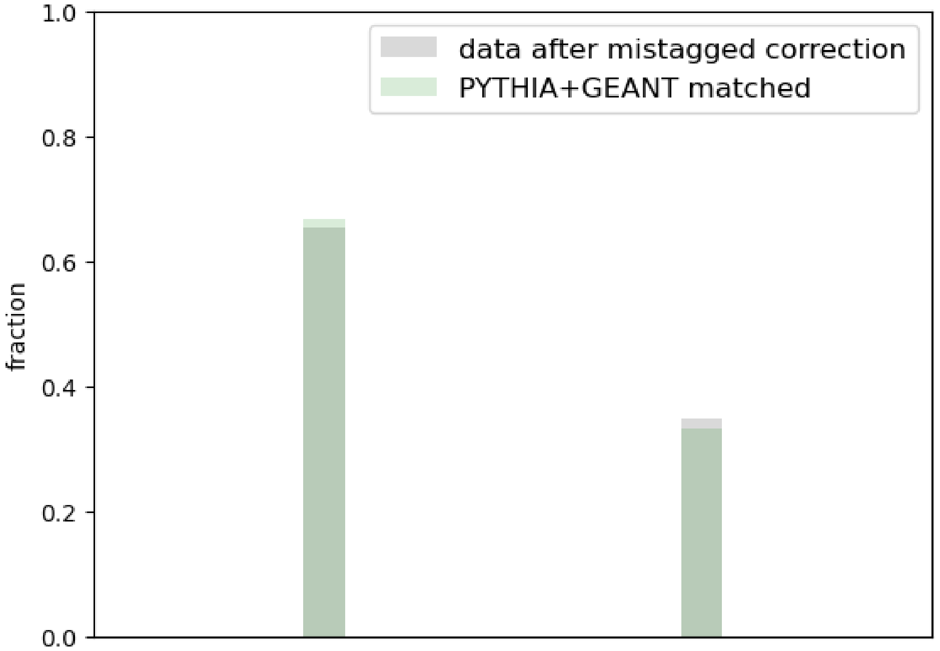


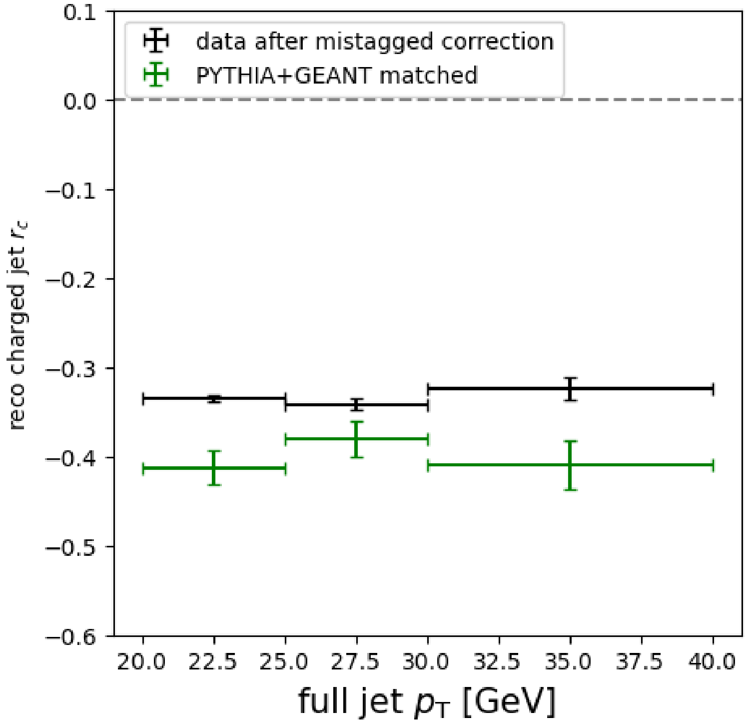


Gabe's talk at HP 2023

More details on the pT correction procedure

- For each detector-level pT bin, reweight the charge sign distribution in embedding, to match data after mistagged correction.





Leading dihadrons are opposite sign | Leading dihadrons are same sign

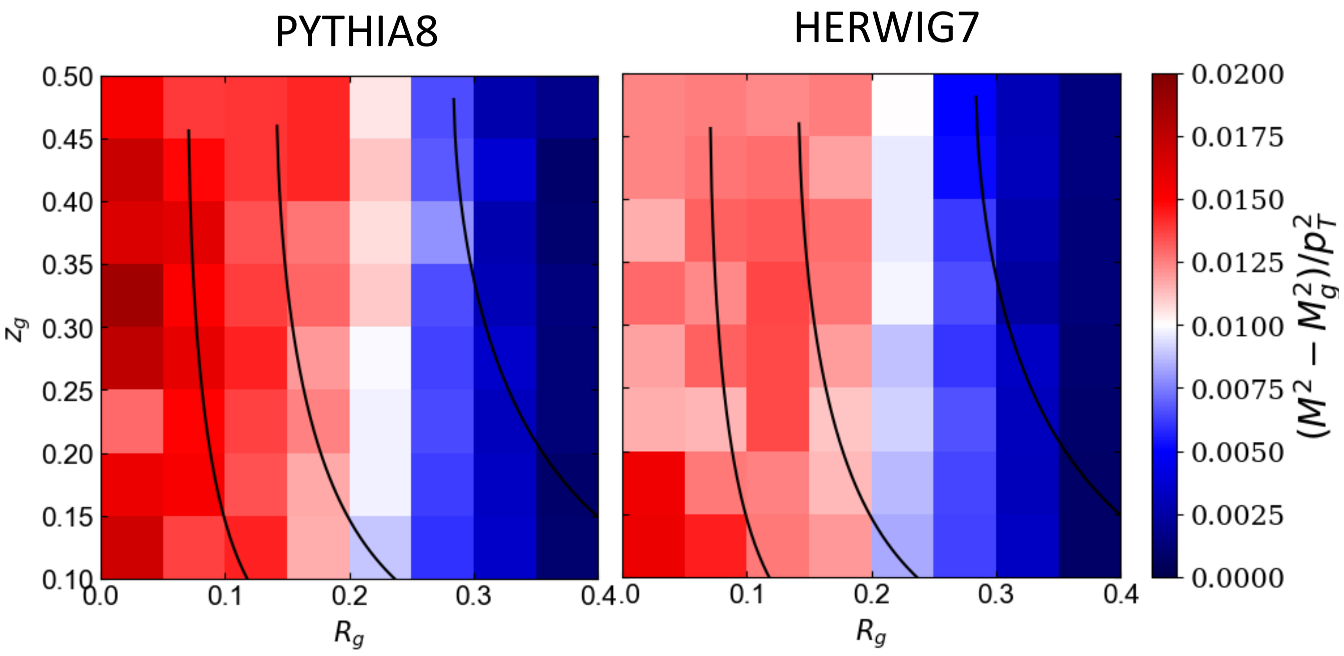
Example: 20 < pT,reco < 25 GeV

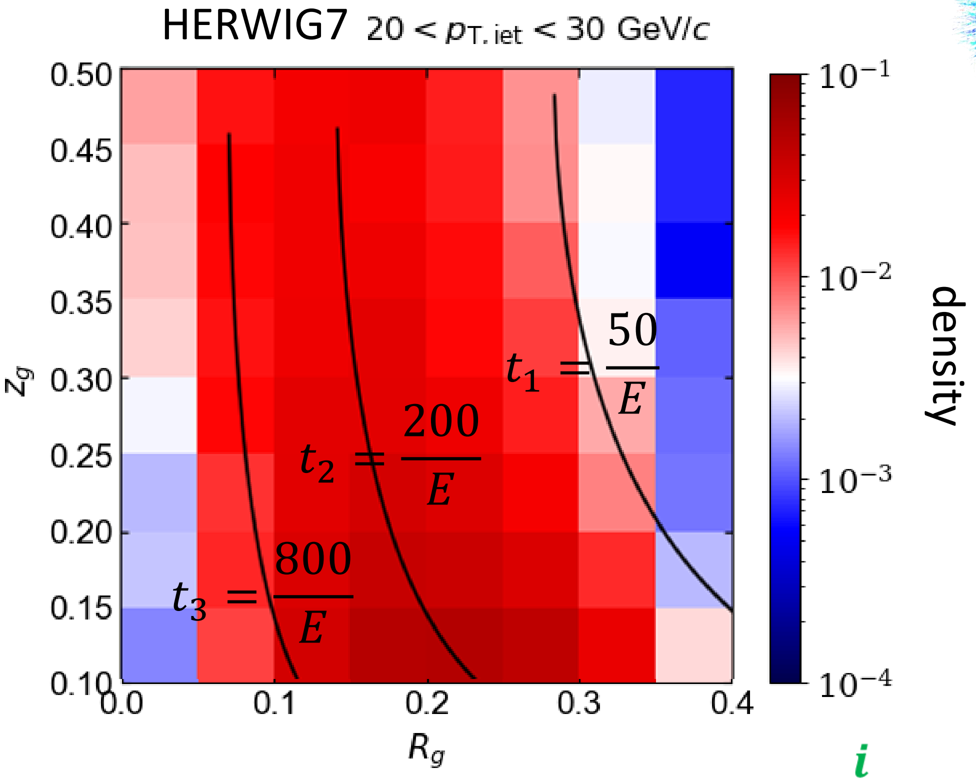
Reweights = [0.94, 1.13]

- This means, if we weight the opposite pair jets down (0.94) and the same sign jets up (1.13) in PYTHIA+GEANT, then we can get the PYTHIA+GEANT rc to match data (after mistagged subtraction).

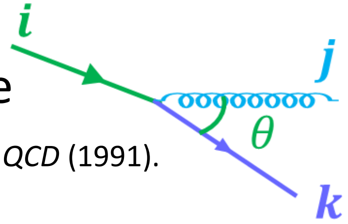
- Since jets are matched between PYTHIA and PYTHIA+GEANT, the reweights automatically carry onto the PYTHIA jets too. This matching essentially serves the role of a response matrix, since it also contains the information such as the truth jet pT distribution given a reconstructed pT.

Discussion





- Lines of constant formation time



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

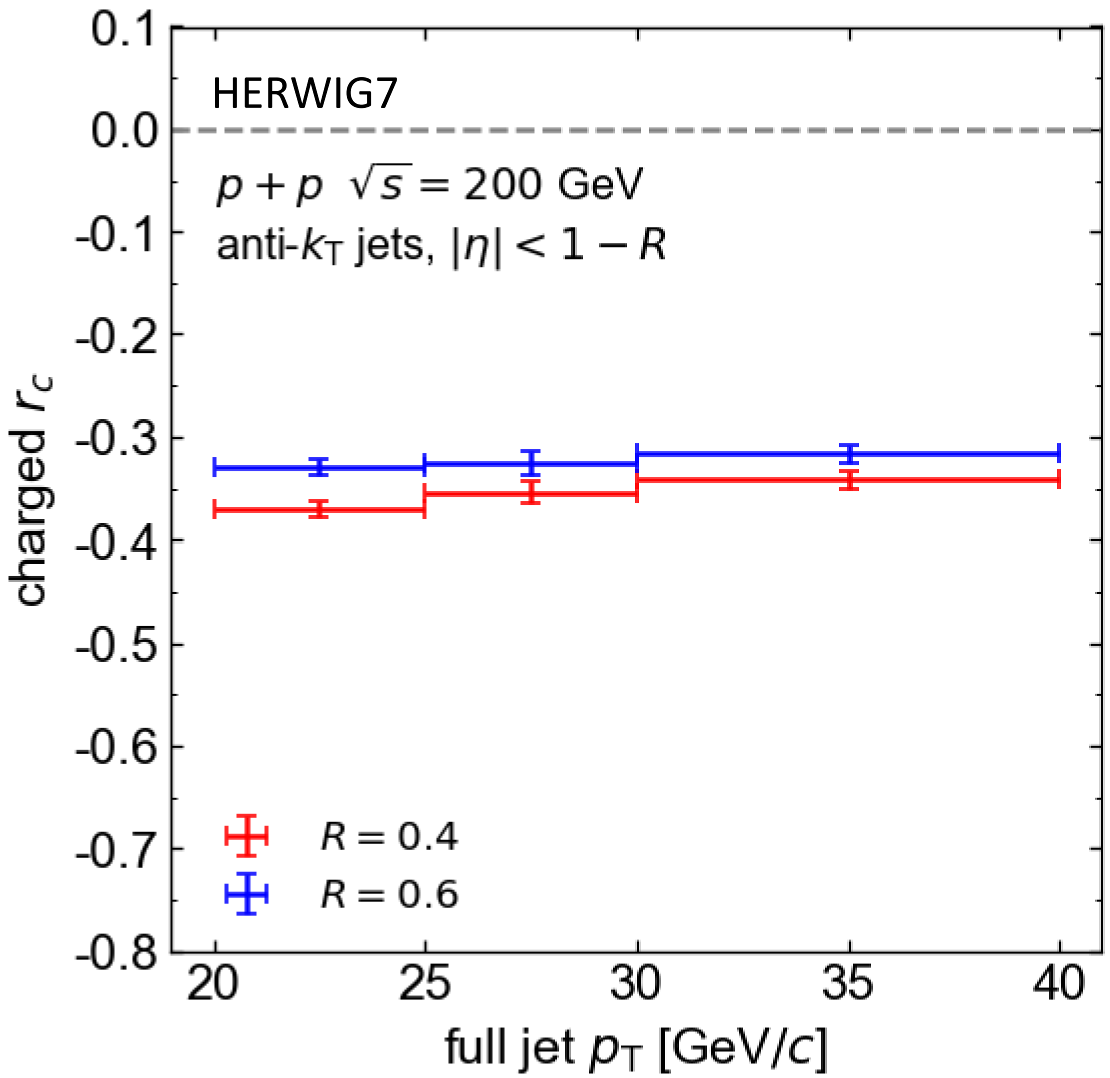
Using $t_F \sim \frac{1}{2Ez(1-z)(1-\cos(\theta))}$

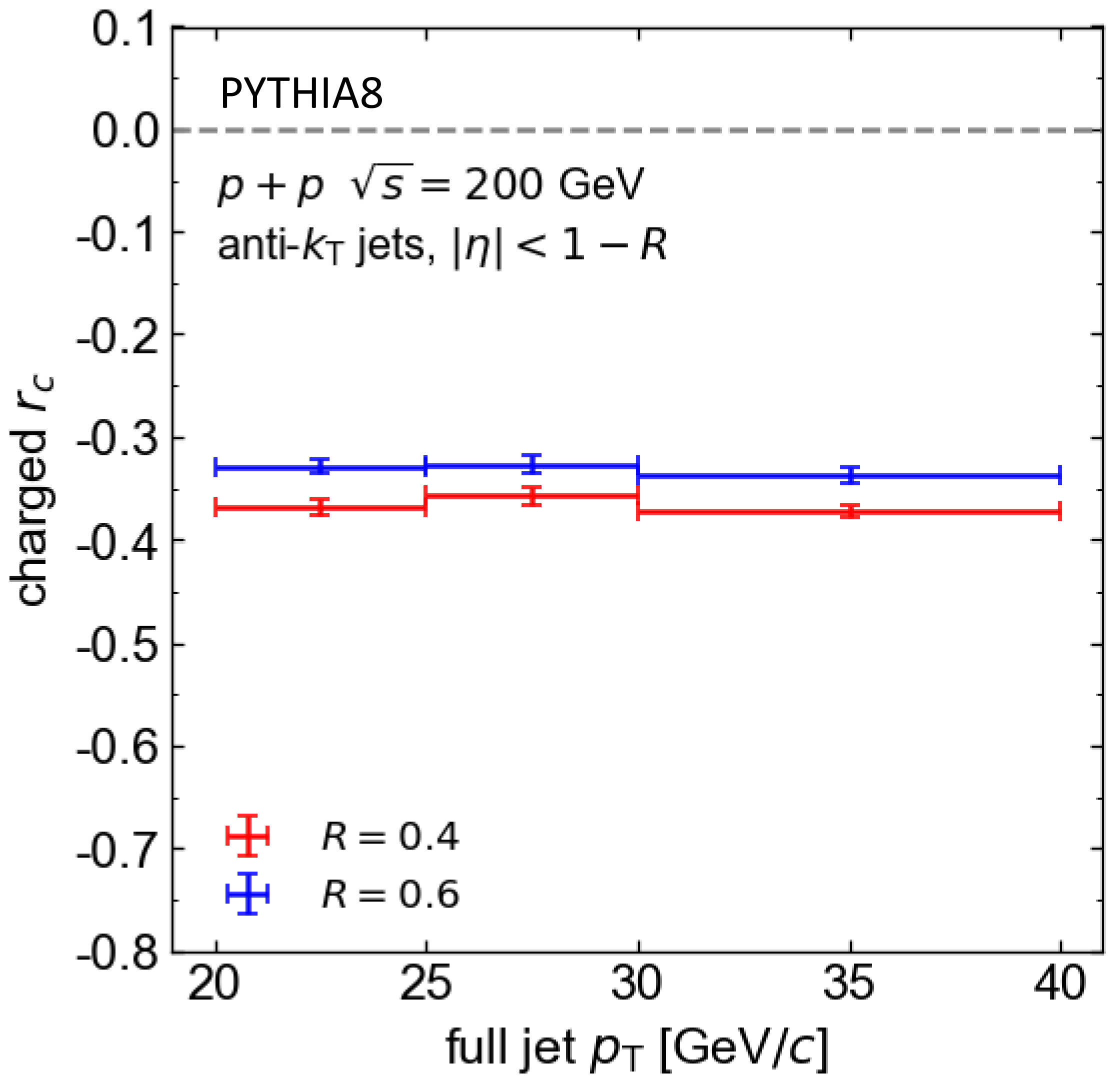
solve for $z(\theta, z < 0.5)$:

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

$$z = \frac{\min(p_{\mathrm{T,j}}, p_{\mathrm{T,k}})}{p_{\mathrm{T,j}} + p_{\mathrm{T,k}}}$$

Discussion

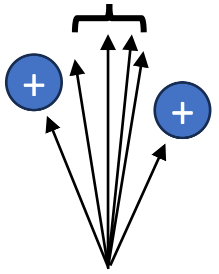

HERWIG7
$p + p$ $\sqrt{s} = 200$ GeV
anti-k_T jets, $|\eta| < 1 - R$
$R = 0.4$
$R = 0.6$
charged r_c
full jet p_T [GeV/c]
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
20
25
30
35
40


PYTHIA8
$p + p$ $\sqrt{s} = 200$ GeV
anti-k_T jets, $|\eta| < 1 - R$
$R = 0.4$
$R = 0.6$
charged r_c
full jet p_T [GeV/c]
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
20
25
30
35
40

Discussion

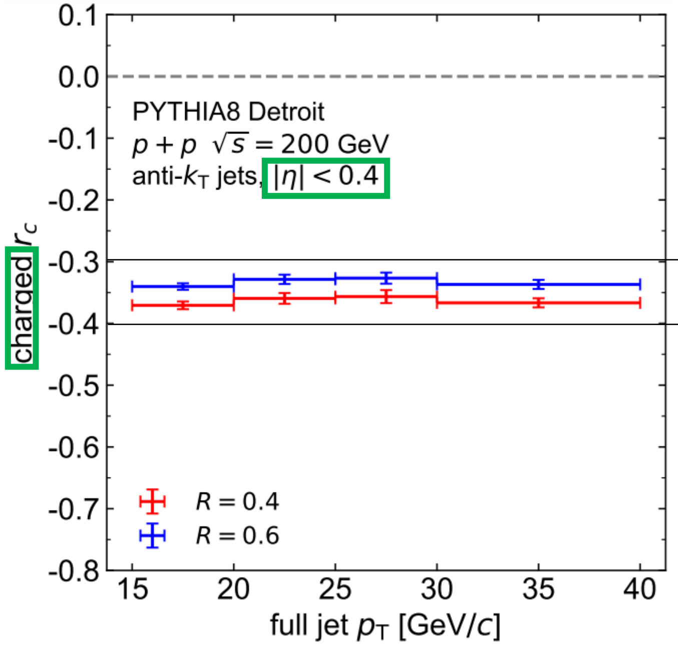
- $\boldsymbol{r_c}$ is less negative with larger jet R → likely that "background" track pairs are included with larger R
- Potentially introduce a jet neutral energy fraction requirement to reduce this effect
  - Fragmentation bias? Or does this bring us closer to the "original definition"?

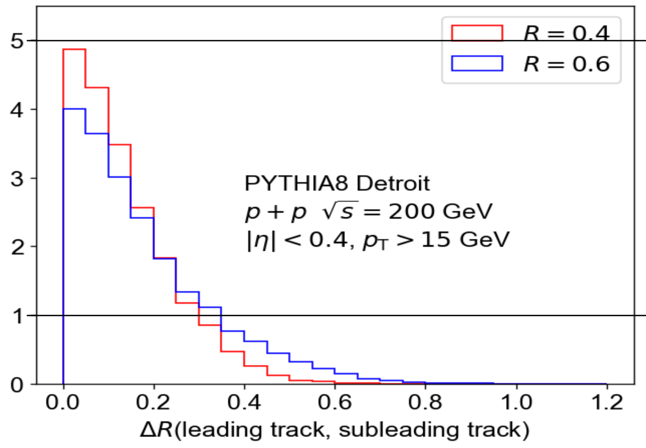
Neutral particles



Example of a jet with a large R and large neutral core

Definition used in our measurement





Original definition as proposed by Chien et al. PRD 105 051502 (2022)