STAR triggering and jet physics

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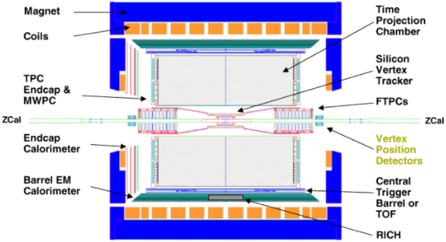
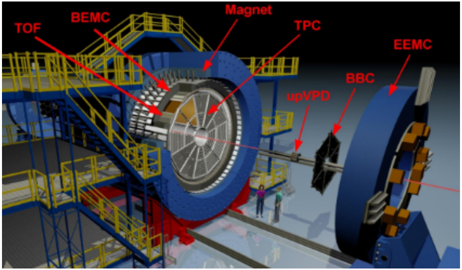
STAR experiment

- Located at the **Relativistic Heavy Ion Collider** (RHIC) in **Brookhaven National Laboratory** (BNL)
- Operations started in 2000





STAR Trigger System

Consists of:

- Detectors

  Vertex detectors:
  - Beam-Beam Counters (*BBC*) - $2.2 < |\eta| < 5.0$
  - Event Plane Detector (*EPD*) - $2.1 < \eta < 5.1$
  - Zero Degree Calorimeter (*ZDC*) - $|\eta| > 6.0$
  - Vertex Position Detector (*VPD*) - $4.25 < |\eta| < 5.1$

  Mid-rapidity detectors:
  - Time-of-Flight (*TOF*) - $|\eta| < 0.9$
  - Muon Tracking Detector (*MTD*) - $|\eta| < 0.5$
  - Barrel Electromagnetic Calorimeter (*BEMC*) - $|\eta| < 1.0$
  - Endcap Electromagnetic Calorimeter (*EEMC*) - $1.07 < \eta < 2.0$

  Forward Rapidity Detectors:
  - Forward Calorimeter System (*FCS*) - $2.5 < \eta < 4.5$
- VME - custom made boards
- PCs and code

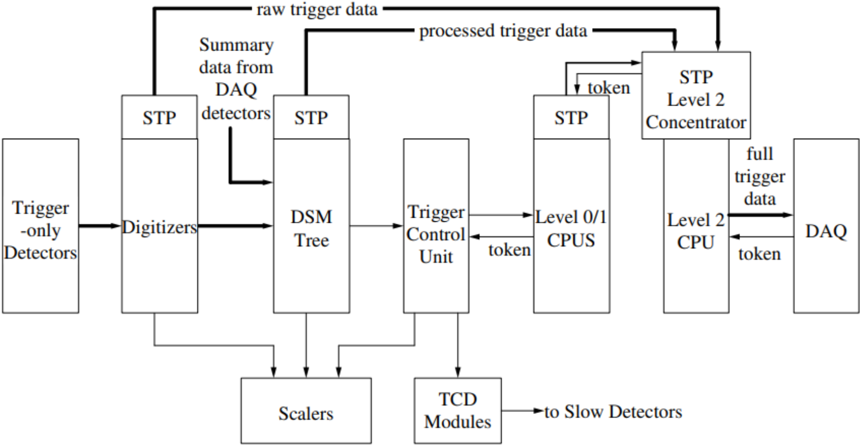
Detector selection

- Trigger communicates with any of the active detector through "Trigger Clock Distribution" boards
- Decision, if we trigger for the physics or special event (command to only one detector)
- Physics events always take the priority over special events
- We decide which detectors should be involved (by default all active detectors are included)

Levels

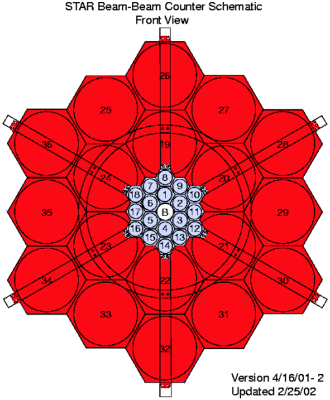
- **Level 0**
  - 1st layer of trigger electronics; consists of two pieces: a tree of **D**ata **S**torage and **M**anipulation (DSM) boards, where the output from one layer feeds the next, and a **T**rigger **C**ontrol **U**nit (TCU)
  - This layer processes the trigger data for every RHIC crossing and accepts the event (initiates data taking) if it is interesting
- **Level 1**
  - Aborts issued here in order to protect against pileup in the TPC
- **Level 2**
  - Final pre-DAQ layer of trigger processing; this layer performs a more detailed analysis of the trigger detector data for just those events that were accepted by level 0

Trigger system scheme



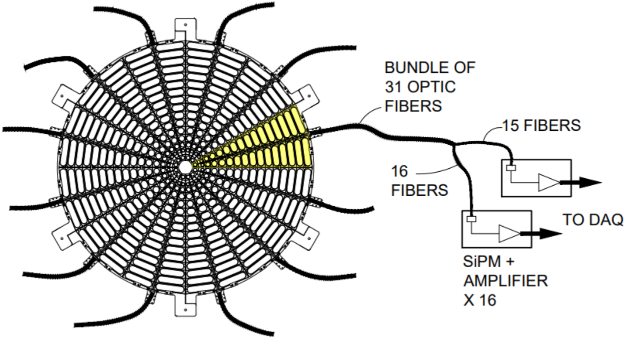
BBC

- Located at the east and west side 374 cm from the center
- 18 inner (small) scintillator tiles only, each tile provides ~ 15 photo-electrons per minimum-ionizing particle
- Fast detector, provides signals to trigger system at the level 0
- Triggers on minimum bias events, monitors overall luminosity, measures relative luminosities and local polarimetry



EPD

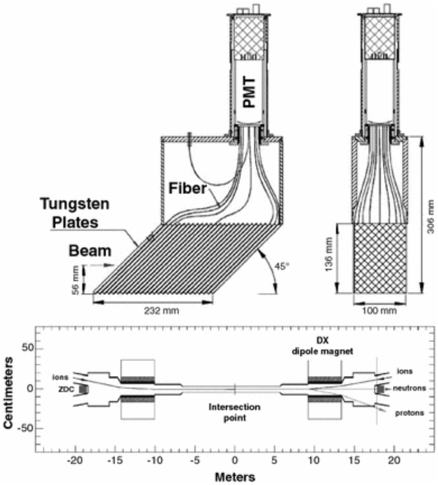
- Located next to the BBC
- Replaced BBC as a minimum bias trigger
- 16 radial and 24 azimuthal segments
- Allows to carry out forward measurements of both centrality and event plane determination
- Trigger connected to the Forward Calorimeter System (FCS)



ZDC

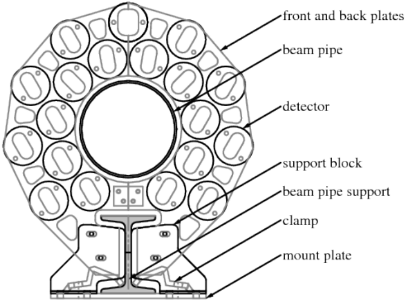
- Intended to detect evaporation neutrons from heavy-ion collisions at small angles close to beam-line
- Located at the east and west sides of the collision center
- Three modules with each 10 cm in width and 13.6 cm in length, multiple alternating quartz and tungsten layers
- Cherenkov light produced by charged particles in showers while neutron hitting the detector → transported by fibers to a single PMT
- Triggers on minimum bias events, monitors overall luminosity and measures relative luminosities

- **ZDC is traditionally maintained by the Czech institutions**



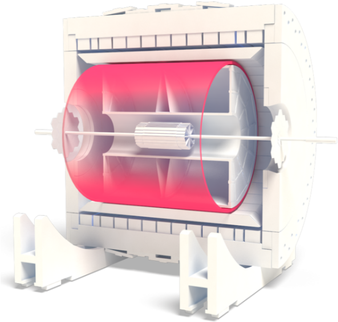
VPD

- Consists of 19 separate PMT/radiator cells (much smaller than BBC)
- Better resolution than BBC (important for heavy-ion collisions)
- Modules designed to measure the arrival time of prompt photons from π^0 decays
- Very fast PMTs directly coupled to 1 cm thick scintillator which views Pb converter plates 1.1 radiation lengths thick
- Triggers on minimum bias events, measures relative luminositiy
- Improves vertex position in heavy-ion collisions



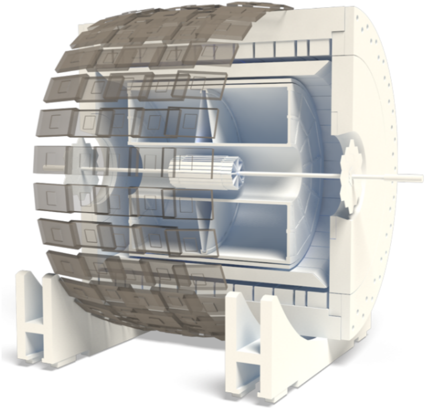
TOF

- Barrel surrounding TPC based on Multi-gap Resistive Plate Chamber (MRPC)
- 3840 MRPC modules installed in 120 trays
- Tray sends a 5-bit hit count to a Data Storage and Manipulation (DSM) board in Trigger System for every RHIC bunch crossing
- All bits are set when tray has more than 24 hits
- Summing the 5-bit numbers gives a measure of the multiplicity in the collisions
- Crucial detector for the particle identification (PID)



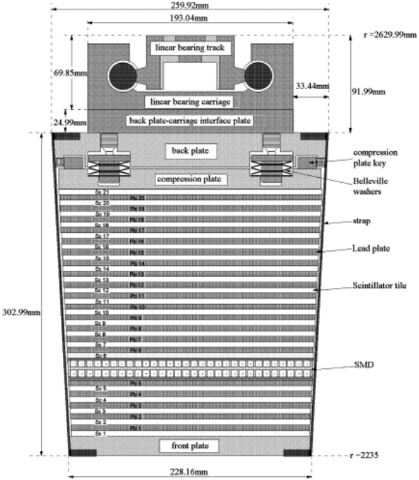
MTD

- Also based on Multi-gap Resistive Plate Chamber (MRPC)
- Modules located on the outside of the magnet $\rightarrow$ steel absorbs most particles except muons
- 120 trays of 12 strips each, grouped into 28 patches in η and ϕ
- Signals from both ends of a hit strip are sent to Trigger electronics to measure hit time
- Hit time compared with VPD hit time to determine muons originating at the primary vertex



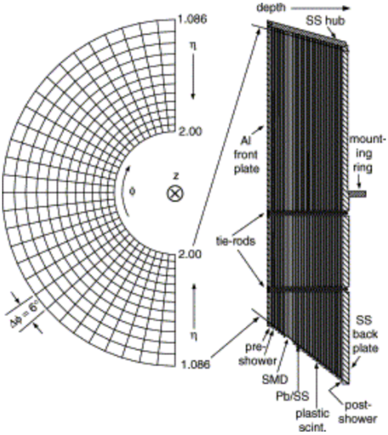
BEMC

- Lead and plastic-scintillator sampling calorimeter
- Includes a shower maximum detector (SMD)
- 4800 separate towers organized into 300 "trigger patches" with 16 towers in each patch
- Trigger System receives a total digital (ADC) sum from each patch (**Jet Patch**), as well as the highest individual tower ADC value called the high-tower (**HT**)
- Allows to trigger on and study high-p_T events like the jet events, leading hadrons, isolated photons (γ), heavy quark production and W/Z boson decay, J/Ψ topology (e^+e^-)



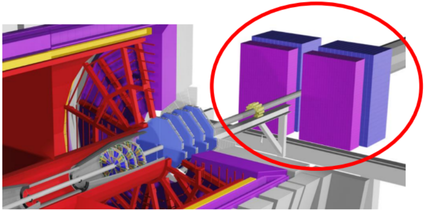
EEMC

- Same scheme as for BEMC
- Built at the west side of the STAR detector with a toroidal shape around the beam-line
- Includes a shower maximum detector (SMD) - located after the fifth lead/stainless steel
    - Uses the scintillator strips, instead of proportional wire counter with strip readout in the BEMC
- Jet patches can not only be formed inside the EEMC, can be combined with the BEMC to form an overlap jet patch to define jet patch triggers



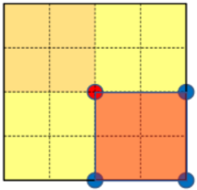
FCS

- ECal + HCal + electronics → installed during 2020, split into two movable halves
- **ECal**
  - Reused PHENIX Pb-Scintillator calorimeter
  - 1496 channels, 66 sampling cells
  - Replaced PMTs with SiPM readout
- **HCal**
  - Developed in collaboration with EIC R&D
  - Fe/Sc (20 mm/3 mm) sandwich, 520 channels
  - Uses same SiPM readout as ECal
- **Preshower**
  - Split signals off from STAR EPD for triggering



FCS Trigger logic

- **EM trigger:** For each ECal patch, if its center projects within the lower-right orange region, the following conditions must be satisfied:
  1. The transverse energy (E_T) ratio of each HCal patch to the ECal patch is less than 1/4 for the four closest HCal patches (centered around the ECal patch)
  2. ECal patch E_T exceeds the triggered threshold of 1 GeV

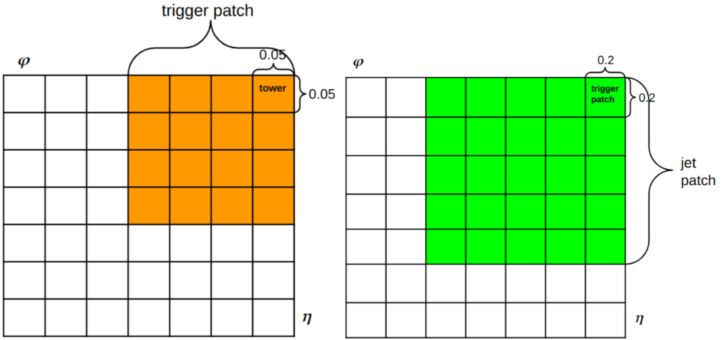


Nearby Hcal patch center

- **Hadron trigger:** For each ECal patch, find its closest HCal patch:
  1. The transverse energy (E_T) ratio of each HCal patch to the ECal patch is more than 1/4
  2. ECal + HCal patch E_T sum exceeds the triggered threshold of 1 GeV
- **EPD trigger:** For the fired ECal patch, if one of the matched EPD tile has energy > 0.5 GeV, then it is fired

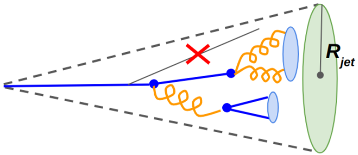
Jet Patch Trigger

- Towers in the BEMC/EEMC are clustered in the "trigger patches" covering 0.2×0.2 in η-φ
- Those patches are additionaly clustered in the "jet patches" contributed by 5 trigger patches (1.0×1.0 in η-φ)
- Triggers required to have a minimal deposited energy E_T in at least one patch (in our case $E_T > 7.3$ GeV)



Jet substructure and SoftDrop

- Study of jet substructure can help understand partonic fragmentation and hadronization processes
- Our goal is to access parton showers through experimental observables
- Grooming technique called SoftDrop used to remove soft wide-angle radiation from the jet in order to mitigate non-perturbative effects
- Connects parton shower and angular tree



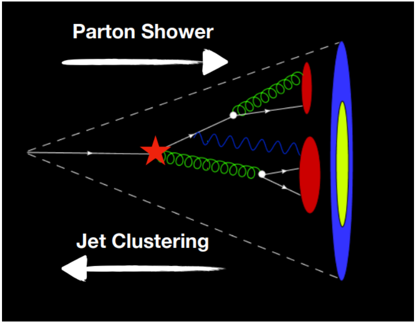
$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}}\theta^{\beta},$$

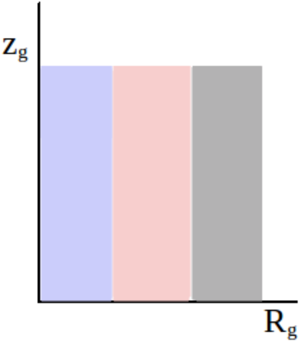
where $\theta = \frac{\Delta R_{12}}{R_{\mathrm{jet}}}$

$p_{\mathrm{T},1}, p_{\mathrm{T},2}$ - transverse momenta of the subjets
z_{cut} - threshold (0.1)
β - angular exponent (0)
ΔR_{12} - distance of subjets in the rapidity-azimuth plane

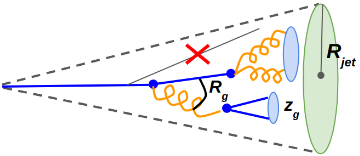
- Iterative SoftDrop used to study first, second, and third splits

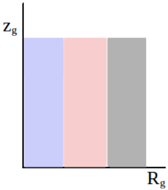
Correlation between substructure observables at the first split



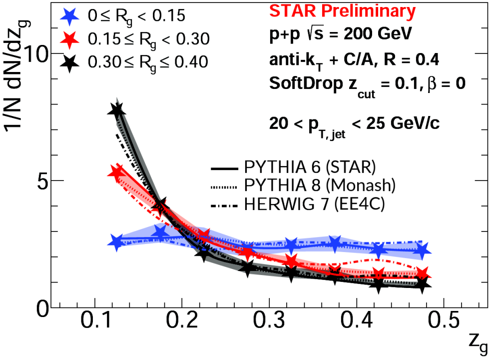


z_g vs. R_g at the first split





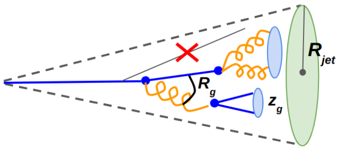
$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$



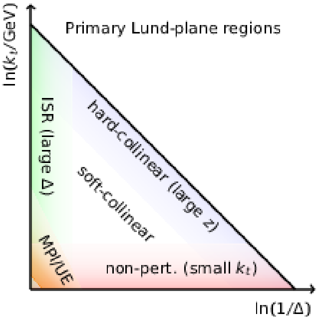
- When we move from collinear hard splitting to softer wide angle splitting, z_g distribution becomes **steeper** and more **perturbative**
- MC models describe the trend of the data

$\log(k_{\mathrm{T}})$ vs. R_{g} at the first split

Dreyer, Salam, Soyez, JHEP 12 (2018) 064

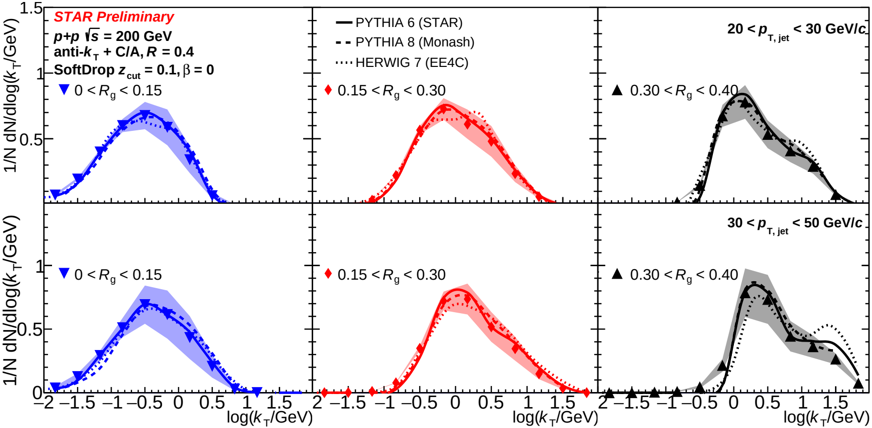


$$k_{\mathrm{T}} = z_{\mathrm{g}} p_{\mathrm{T,jet}} \sin R_{\mathrm{g}}$$



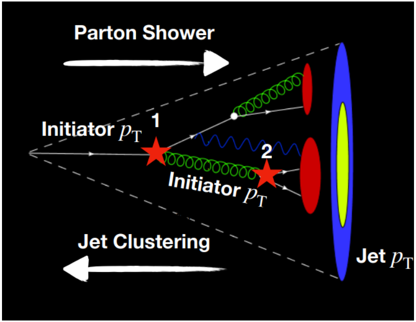
Cutting on R_{g} moves us to different k_{T} $\rightarrow$ we are probing different parts of the Lund Plane

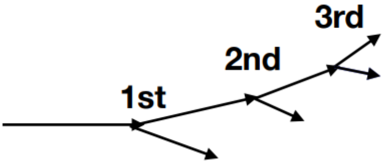
$\log(k_T)$ vs. R_g at the first split for two different $p_{T,jet}$ bins



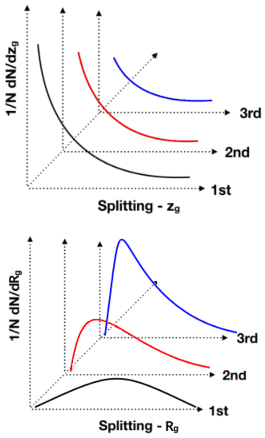
- $\log(k_T)$ has a **strong** dependence on R_g and **weak** dependence on $p_{T,jet}$, MC models describe the trend of the data
- 0 value corresponds to 1 GeV → we move from **non-perturbative** to **perturbative** region

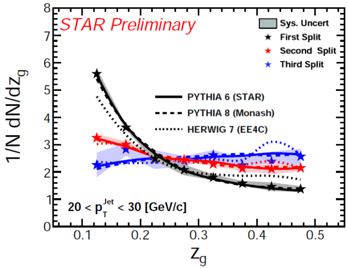
Evolution of the splitting observables as we travel along the jet shower

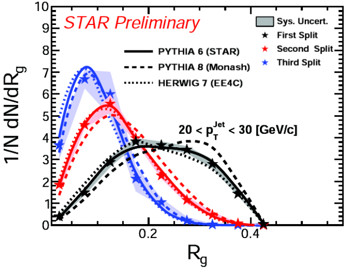




z_g and R_g distributions at 1st, 2nd, and 3rd splits







- Going from 1st $\rightarrow$ 3rd split
  - z_g distribution becomes **flatter**
  - R_g distribution becomes **narrower**
- **Collinear emissions are enhanced when going from 1st to 3rd split**

Summary

- STAR experiment consists of several detectors with different usage, from the trigger point of view, there are three categories of the detectors: vertex, mid-rapidity and forward rapidity

- Many jet analyses in STAR rely on BEMC trigger capabilities, e.g. jet substructure studies used Jet Patch trigger

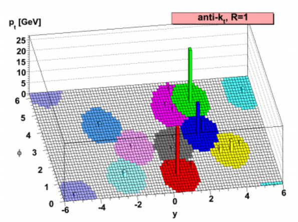
Jet substructure measurements at RHIC energies allow to disentangle perturbative (early, wide splits) and mostly non-perturbative dynamics (late, narrow splits) within jet showers, and test validity of MC models

Thank you for your attention!

Backup

Jet clustering algorithms

- Jets are defined using algorithms

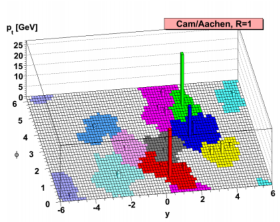


Anti-k_T algorithm

- $d_{ij} = \frac{\min(1/p_{Ti}^2, 1/p_{Tj}^2)\Delta R_{ij}^2}{R}$, $d_{iB} = 1/p_{Tj}^2$
- Clustering starts from the particles with the highest transverse momentum

Cambridge/Aachen (C/A) algorithm

- $d_{ij} = \Delta R_{ij}^2 / R^2$, $d_{iB} = 1$
- Particles are clustered exclusively based on angular separation, ideal to be used to resolve jet sub-structure



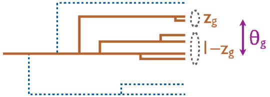
d_{iB} - distance of the particle i from the beam
p_T - transverse momentum
ΔR_{ij} - distance between the particle i and j
R - jet resolution parameter

Cacciari, Salam, Soyez,
JHEP 0804:063 (2008)

SoftDrop

- Grooming technique used to remove soft wide-angle radiation from the jet
- Connects parton shower and angular tree

1. Jets are first found using the anti-k_T algorithm
2. Recluster jet constituents using the C/A algorithm
3. Jet j is broken into two sub-jets j_1 and j_2 by undoing the last stage of C/A clustering
4. Jet j is final SoftDrop jet, if sub-jets pass the condition on the right, otherwise the process is repeated



Larkoski, Marzani, Thaler, Tripathee, Xue, Phys. Rev. Lett. 119, 132003 (2017)

- **Shared momentum fraction** z_g

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}\theta^{\beta},$$

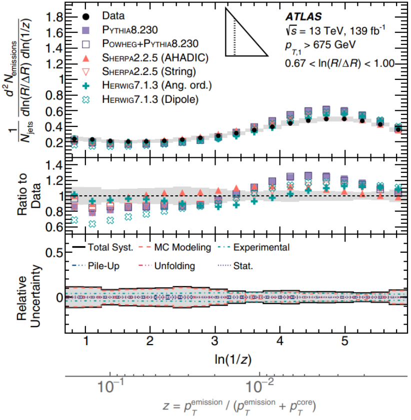
where $\theta = \frac{\Delta R_{12}}{R}$

- **Groomed radius** R_g - first ΔR_{12} that satisfies SoftDrop condition

$p_{T,1}, p_{T,2}$ - transverse momenta of the subjets
z_{cut} - threshold (0.1)
β - angular exponent (0)
ΔR_{12} - distance of subjets in the rapidity-azimuth plane

Lund Plane measurement

- Previous ATLAS measurement uses Lund jet plane
- Significant differences in varying hadronization models at high $p_{\mathrm{T,jet}}$ at the LHC $\rightarrow$ we want to study this at lower $p_{\mathrm{T,jet}}$, where non-perturbative effects are expected to be larger
- While Lund jet plane integrates over all splits, we focus on the first split



ATLAS, Phys. Rev. Lett. **124**, 222002 (2020)

Data analysis

- $p + p$ **collisions at** $\sqrt{s} = 200$ **GeV, 2012**
- $\sim$11 million events analyzed

Event and track selection

- Transverse momenta of tracks: $0.2 < p_{\mathrm{T}} < 30$ GeV/c
- Tower requirements: $0.2 < E_{\mathrm{T}} < 30$ GeV

Jet reconstruction

- Jets reconstructed with anti-k_{T} algorithm, reclustered with the C/A algorithm
- Transverse momenta of jets: $15 < p_{\mathrm{T,jet}} < 40$ GeV/c
- Resolution parameters: $R = 0.4$, $R = 0.6$
- SoftDrop parameters: $z_{\mathrm{cut}} = 0.1$, $\beta = 0$

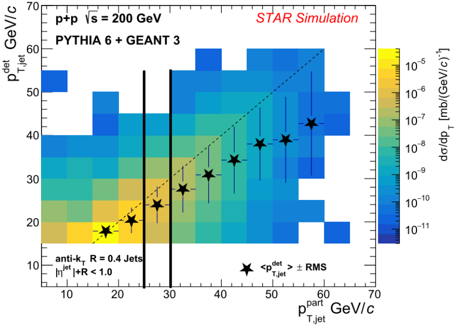
$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R} \right)^{\beta}$$

2D Bayesian Unfolding

- 2D iterative Bayesian method implemented in the RooUnfold
- Procedure has following steps:
  1. The jets at the detector and particle level are reconstructed separately
  2. Jets are matched based on $\Delta R < 0.6$
  3. Jets without match - missed jet (particle level) and fake jets (detector level)
  4. Response between detector level and particle level for observables is constructed
- We use RooUnfold response which contains Matches and Fakes
  - Unfolding is done separately for p_{T}^{det} intervals 15-20, 20-25, 25-30, 30-40 GeV/c
- Then unfolded spectra are weighted with values from our projection and put together
- Together with trigger missed and unmatched weighted spectra we get our fully unfolded spectrum

Correction in 2+1D for z_g, R_g, and $p_{T,jet}$

- Results are in 3D → z_g vs. R_g is unfolded in 2D and correction for $p_{T,jet}$ in 1D is needed
  - For each particle-level $p_{T,jet}$ bin, we do projection of this bin into detector-level $p_{T,jet}$, and get the weights from detector-level $p_{T,jet}$ bins



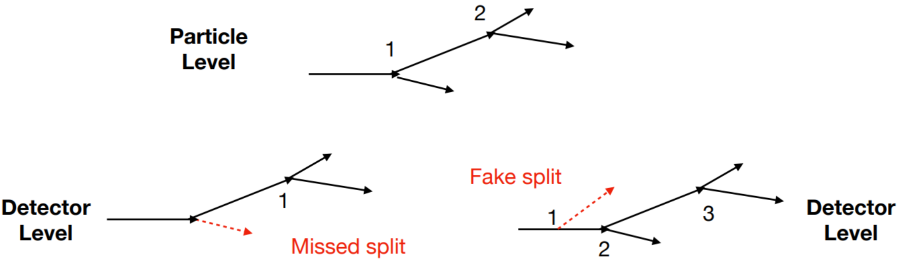
STAR, Phys. Lett. B 811 (2020) 135846

- We unfold z_g vs. R_g via iterative Bayesian unfolding in 2D using RooUnfold and unfolded spectra for each detector-level $p_{T,jet}$ bin are weighted and summed
- Additional corrections for trigger and jet finding efficiencies are applied

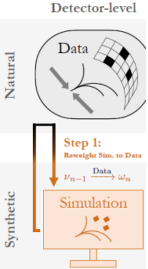
Details on systematic uncertainties available in back up

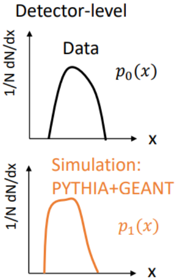
Correction in 2+1D for $p_{\mathrm{T,jet/initiator}}$, z_g, R_g

- Splits can be affected by detector efficiency and resolution
- Observables at a given split are smeared
- Splitting hierarchy is modified going from particle level to detector level



MultiFold





Where does the machine learning part come in?

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

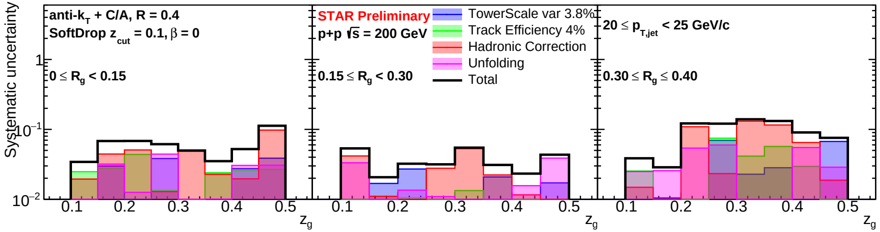
to distinguish jets coming from data vs from simulation

Unfolding → Reweighting histograms → Classification → Neural network

See backup slides for details of the neural networks.

Systematic uncertainties

- Systematic uncertainties estimated by varying the detector response
    - Hadronic correction - fraction of track momentum subtracted is varied
    - Tower scale variation - tower gain is varied by 3.8%
    - Tracking efficiency - efficiency is varied by 4%
    - Unfolding - iterative parameter is varied from 4 to 6
- Systematics due to prior shape variation will be included in the final publication



$0 \leq R_g < 0.15$ $0.15 \leq R_g < 0.30$ $0.30 \leq R_g \leq 0.40$