How to make valid comparisons between data and models

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Acknowledgements

Antonio Da Silva

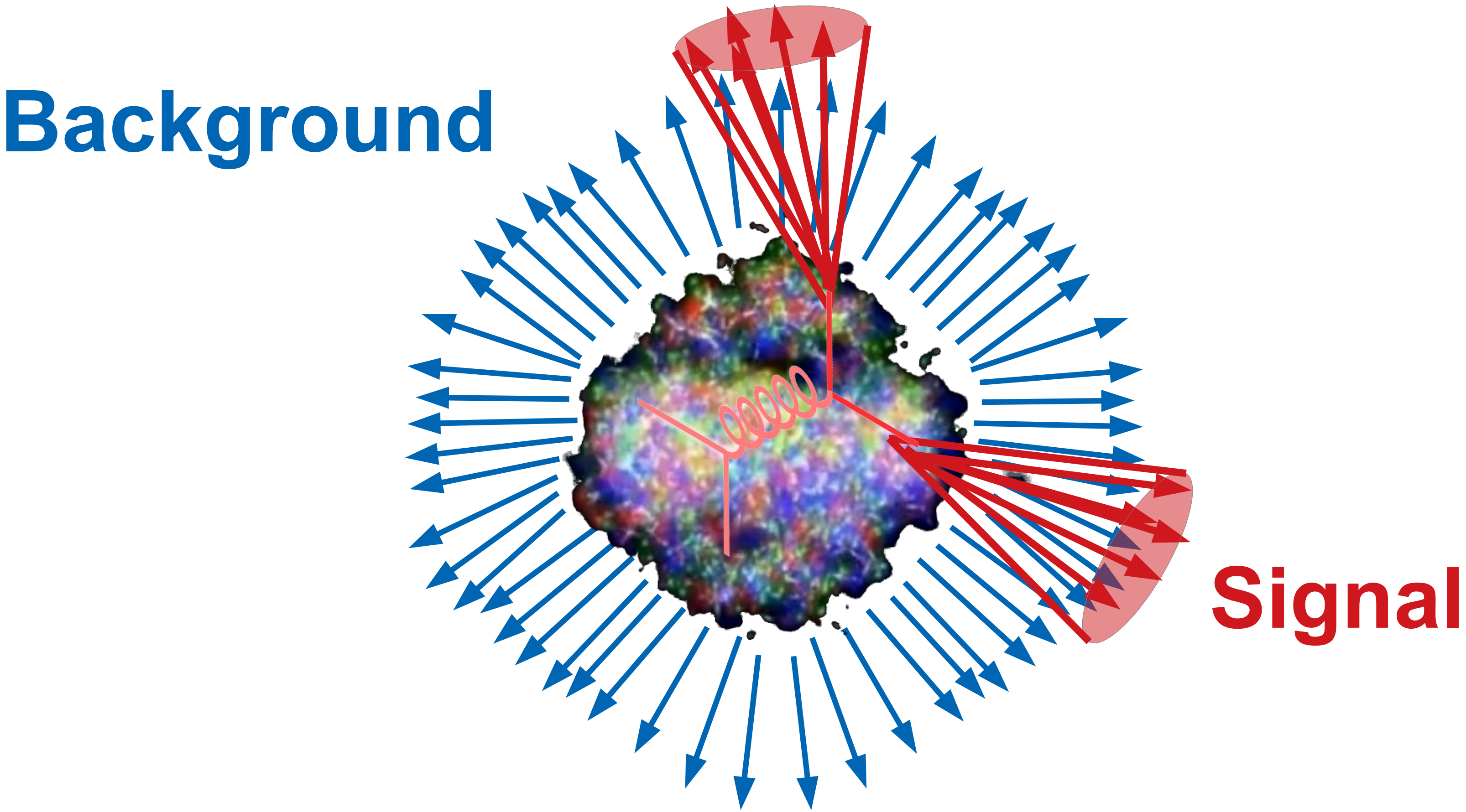
Patrick Steffanic

Tanner Mengel

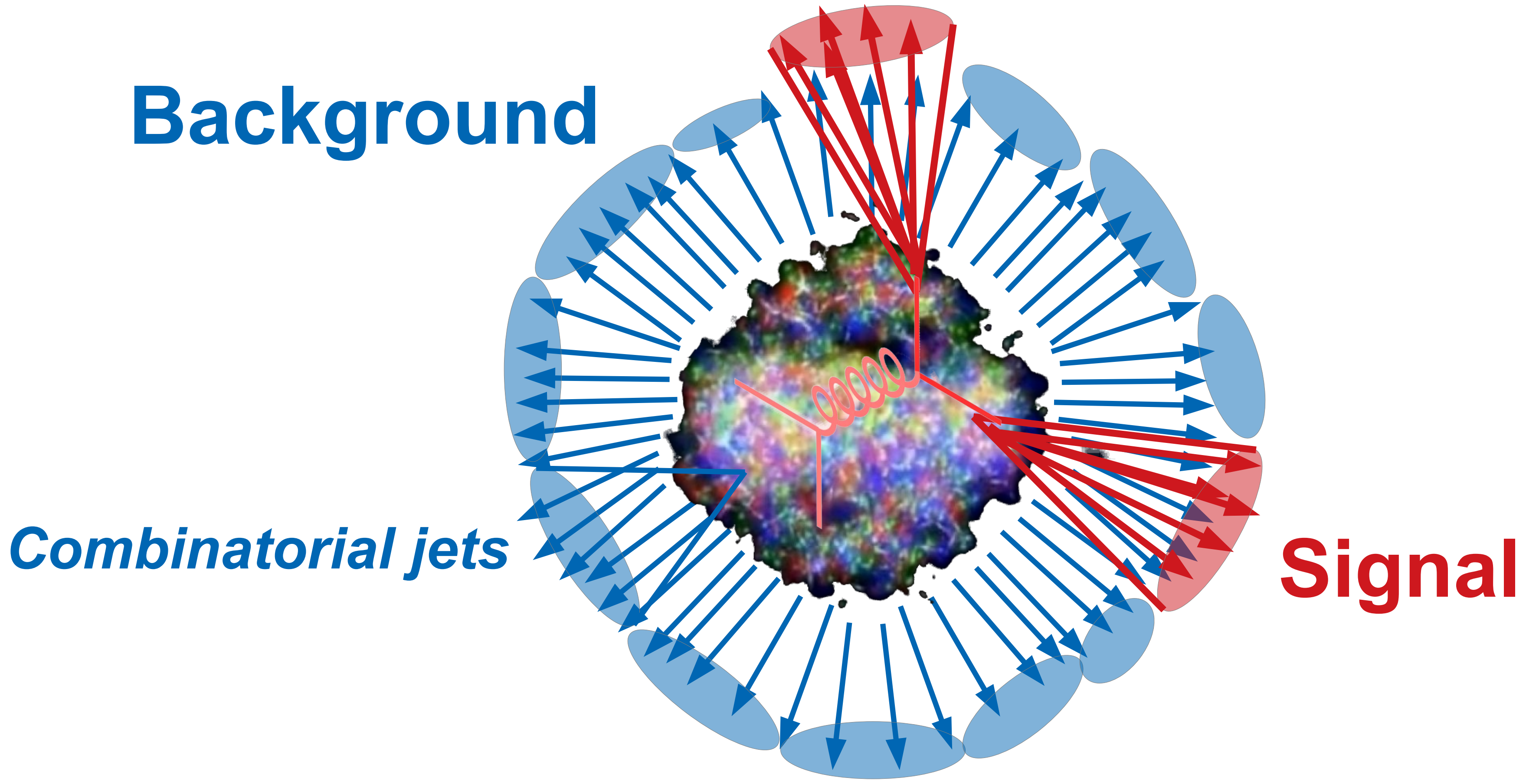
Charles Hughes

1. Standard paradigm of background

Signal vs Background:
The standard paradigm



Signal vs Background:
The standard paradigm



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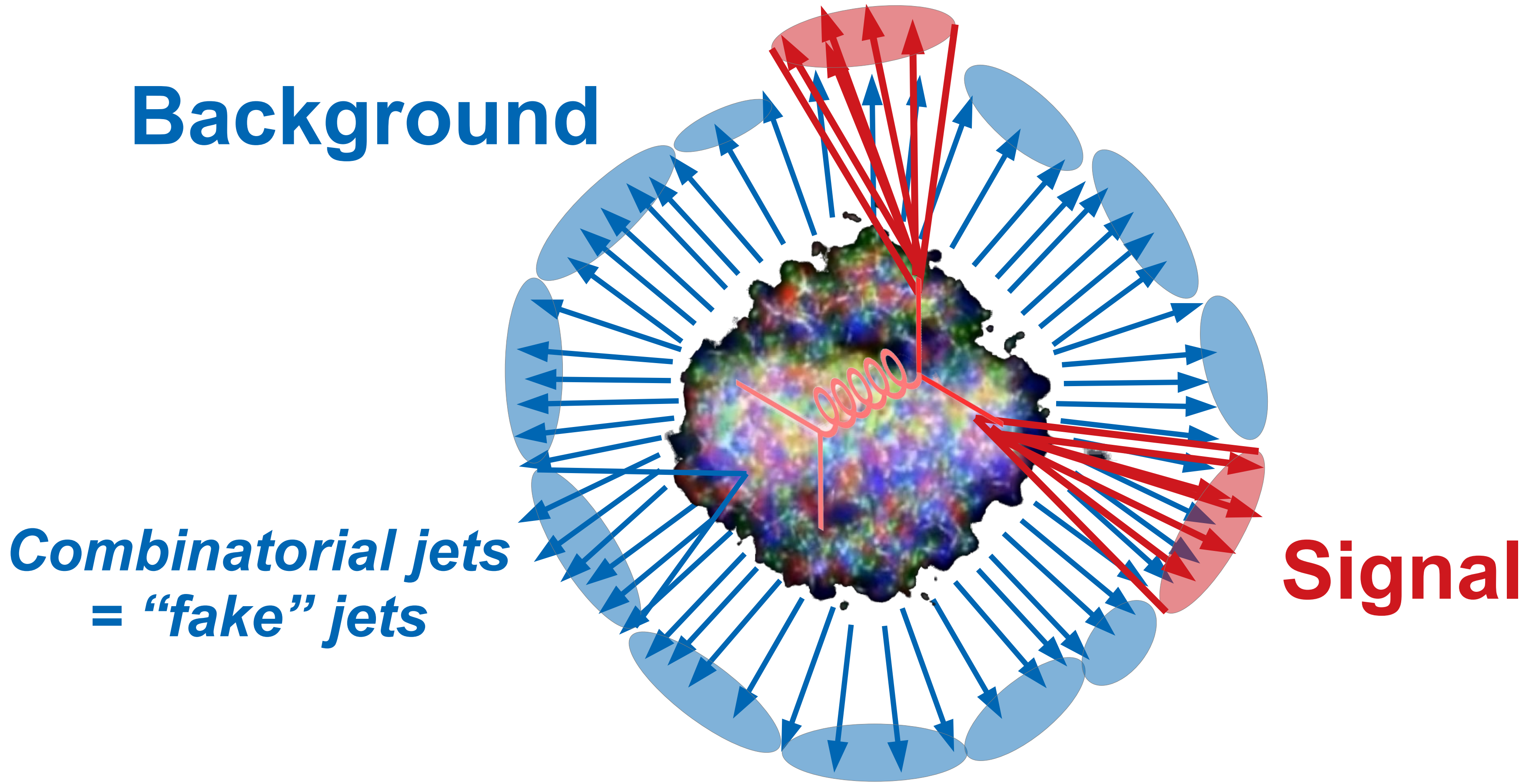

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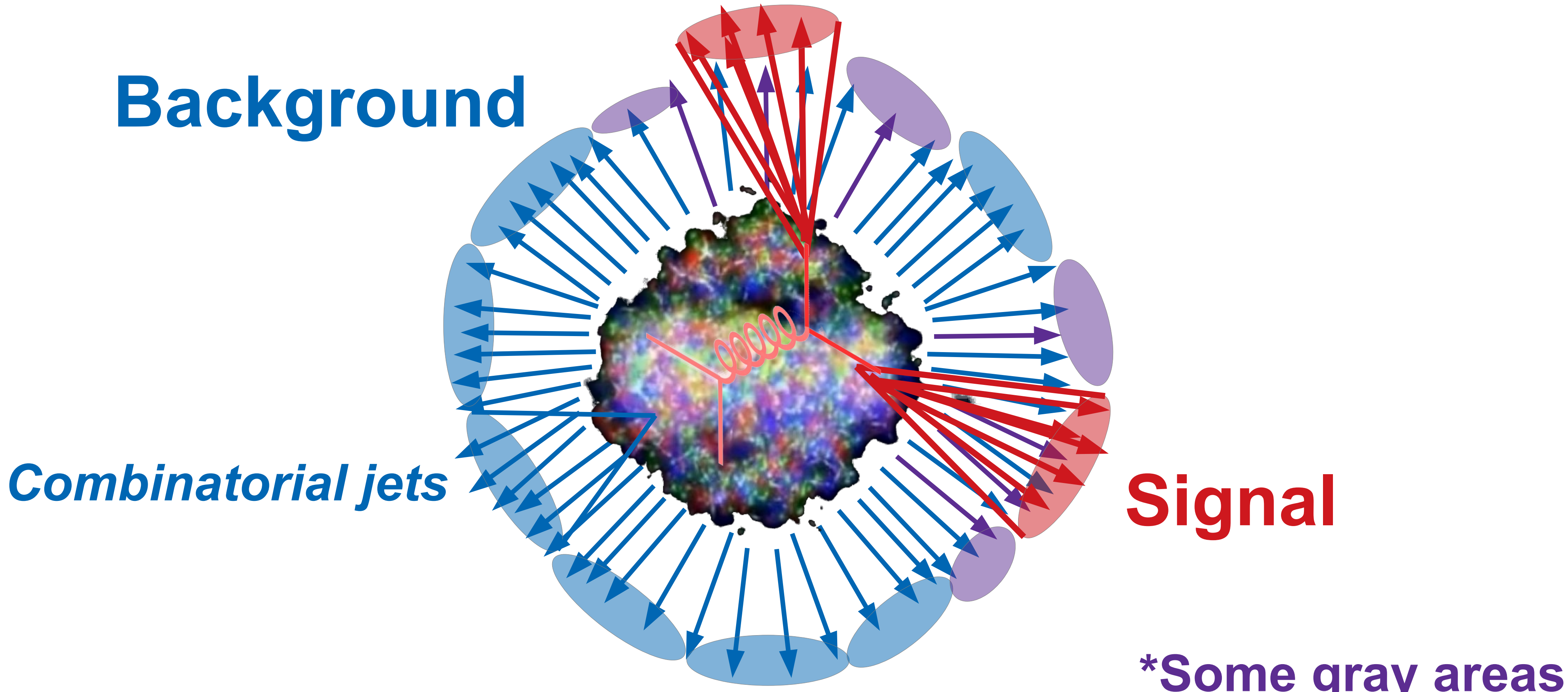
The standard paradigm

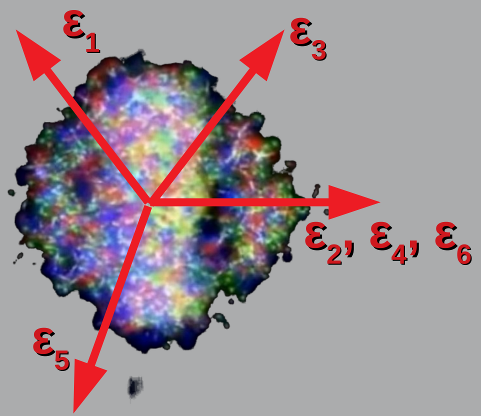


A jet is what a jet finder finds.

2. Models

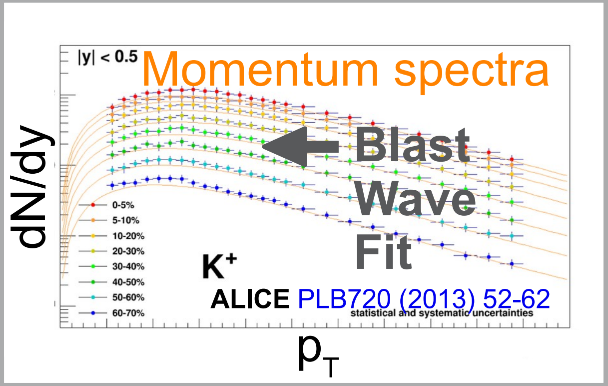
TennGen background generator

Event properties

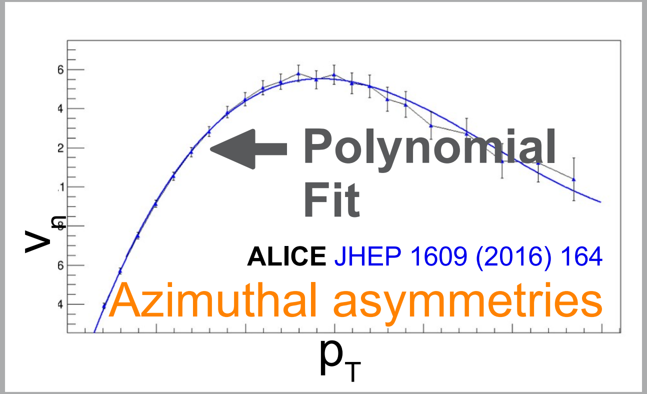


- Even event planes fixed at $\Psi=0$
- Odd planes at random φ
- Multiplies from ALICE PRC88 (2013) 044910

Track properties



→ Random p_T



→ v_n → Random φ

No jets! No resonances
Emulates hydro correlations

TennGen

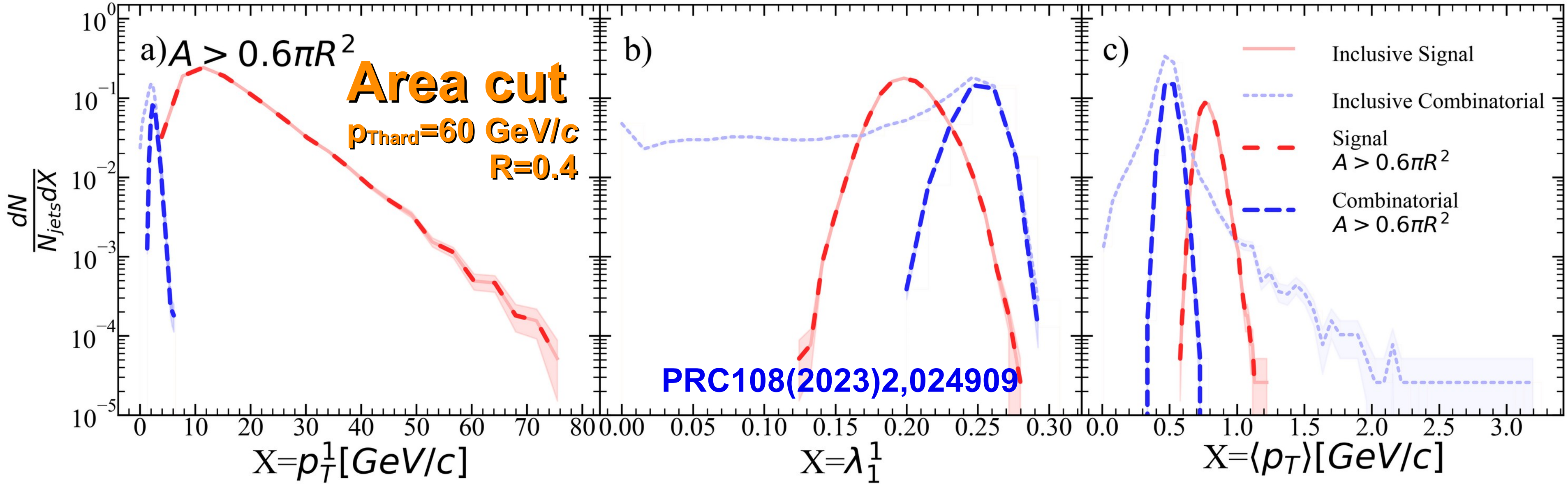
Mix TennGen with PYTHIA

- Merge PYTHIA *pp* collisions into TennGen heavy ion background
- Find charged anti-k_T jets in merged event and geometrically match them back to PYTHIA jets
- Use matched PYTHIA jet momentum as ground truth

\+ TENNGEN

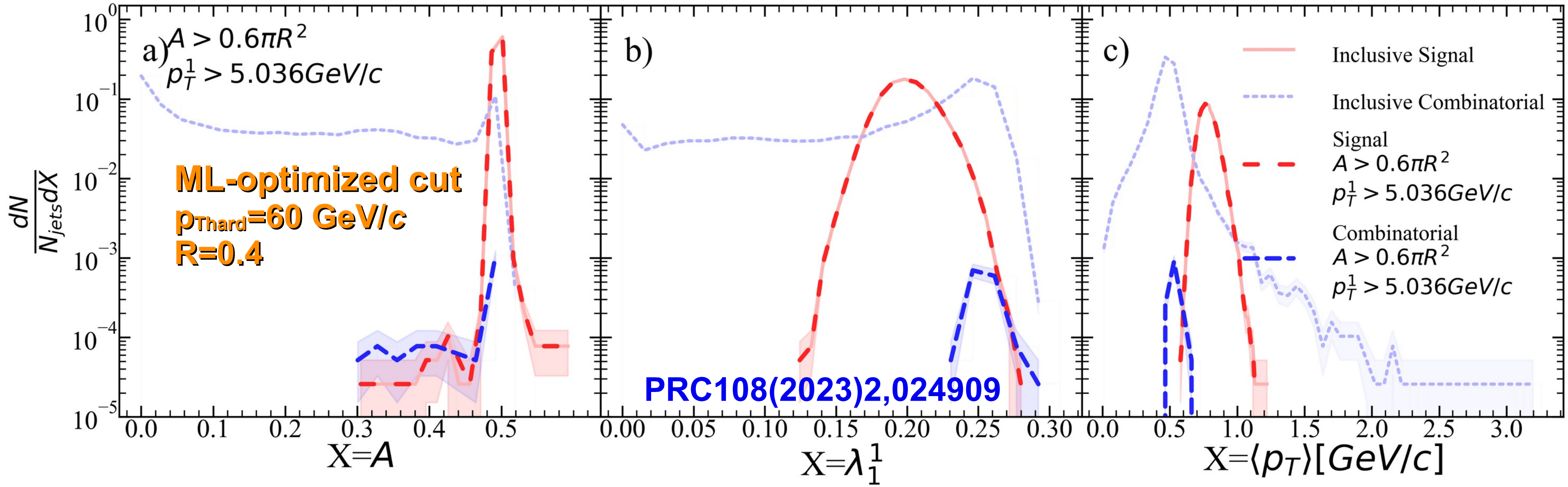
3. Background and signal overlap

What happens to jet properties when you cut background?



Remaining background jets look like signal

What happens to jet properties when you cut background?

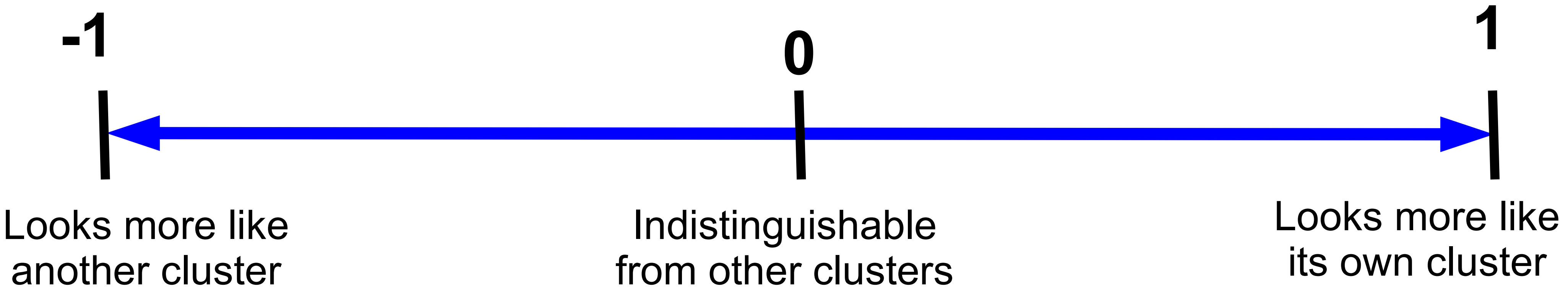


Remaining background jets look like signal

Silhouette Values

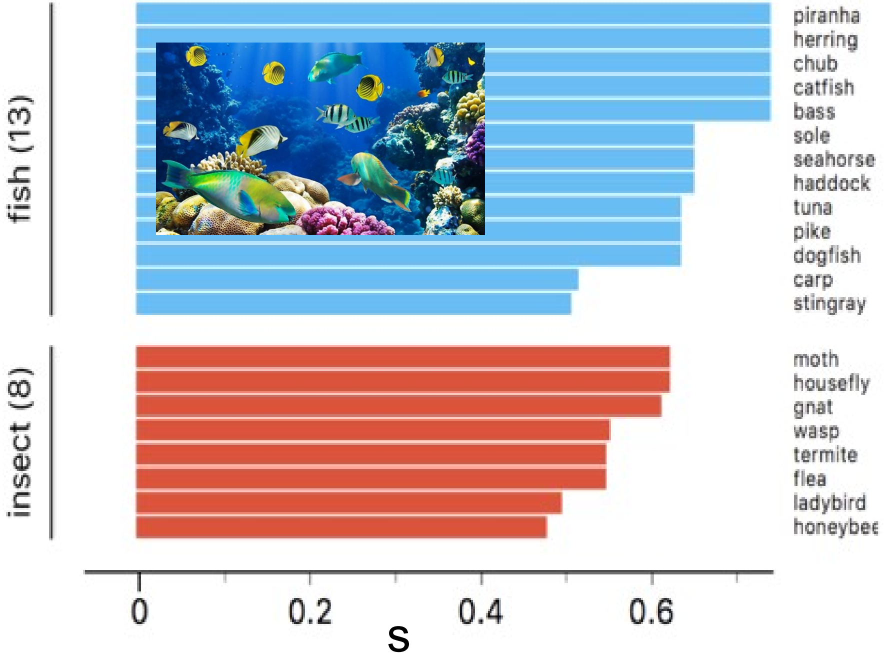
- Average distance between a jet candidate and other jet candidates in its cluster (signal or background) $a_i = \langle d_{i,j} \rangle_{j \neq i}$
- Average distance between jet candidate and jet candidates in the other cluster $b_i = \langle d_{i,j} \rangle$
- Silhouette value

$$s_i = \frac{b_i - a_i}{max[b_i, a_i]}$$

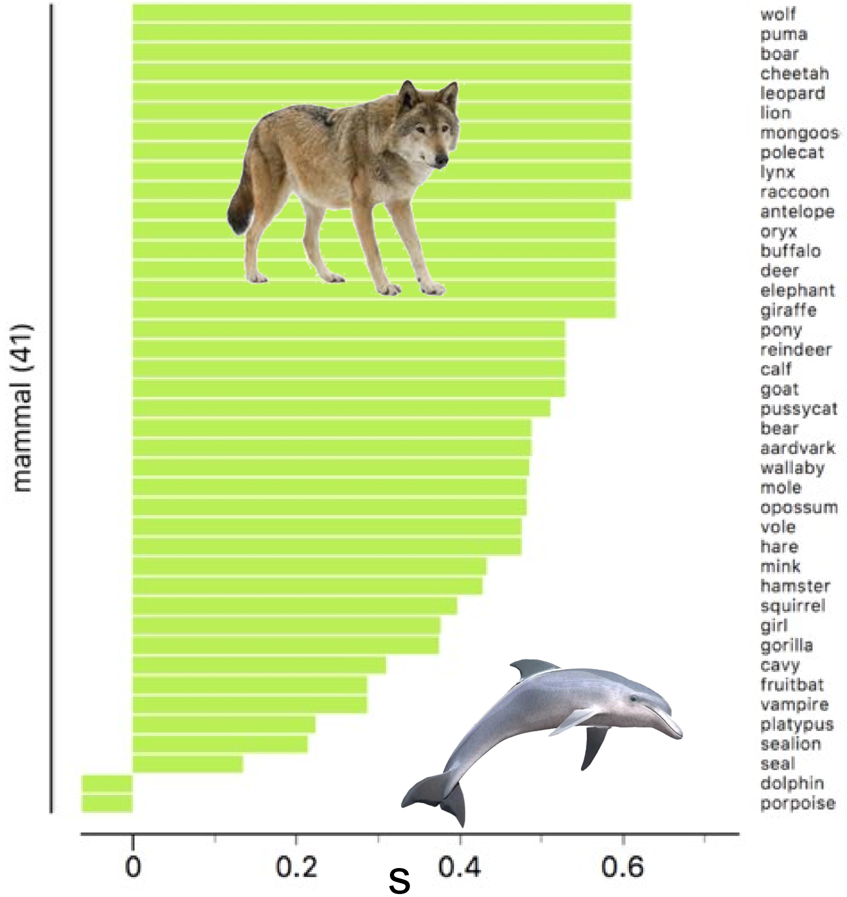


Silhouette values

Example from Wikipedia



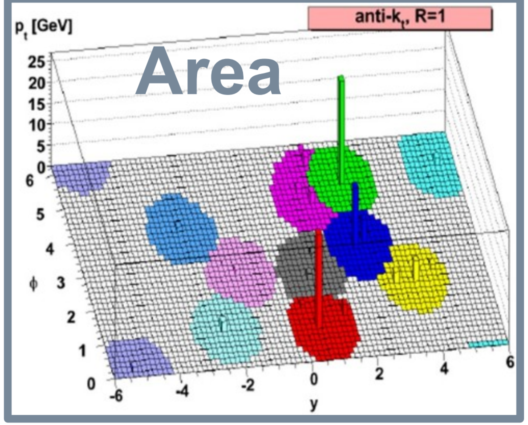
Silhouette scores from three types of animals rendered by Orange data mining suite.



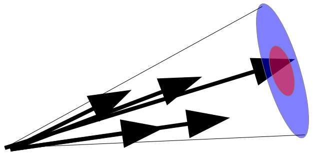
Silhouette Values

- Define a distance between two jet candidates to determine how similar they are

$$d_{i,j}=\sqrt{\left(\frac{A_i-A_j}{A^{max}-A^{min}}\right)^2+\left(\frac{\alpha_i-\alpha_j}{\alpha^{max}-\alpha^{min}}\right)^2+\left(\frac{\langle p_T\rangle_i-\langle p_T\rangle_j}{\langle p_T\rangle^{max}-\langle p_T\rangle^{min}}\right)^2+\left(\frac{p_{T,i}^L-p_{T,j}^L}{p_T^{L,max}-p_T^{L,min}}\right)^2}$$

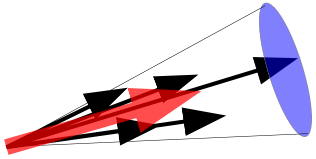


Angularity

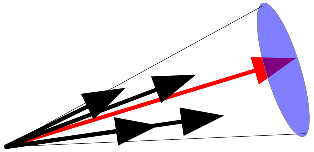


$$\alpha=\frac{1}{p_T^{jet}}\sum_k z_k(\vec{R}_k)$$

Average p_T

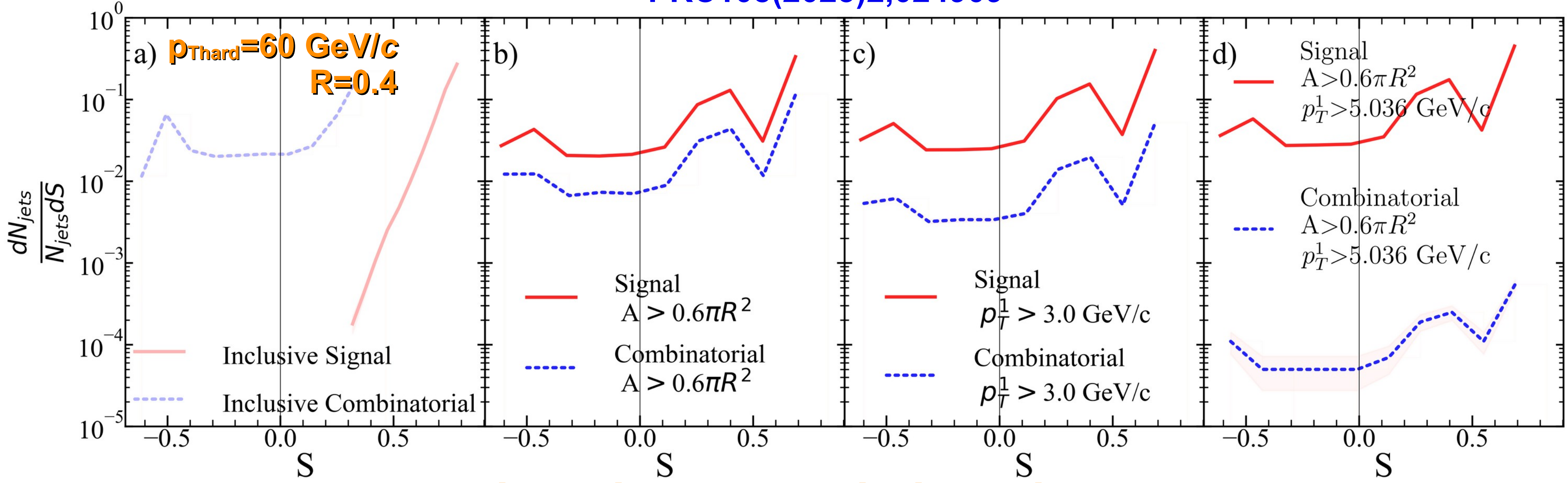


Leading p_T



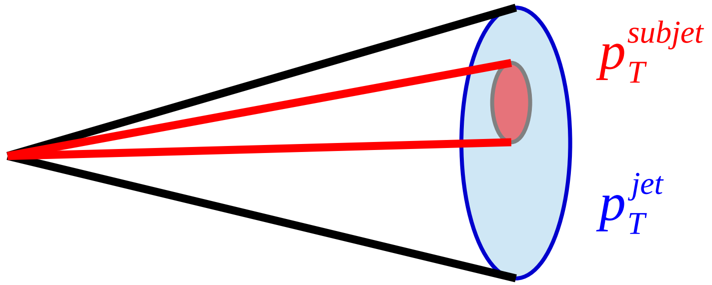
What happens to jet properties when you cut background?

PRC108(2023)2,024909

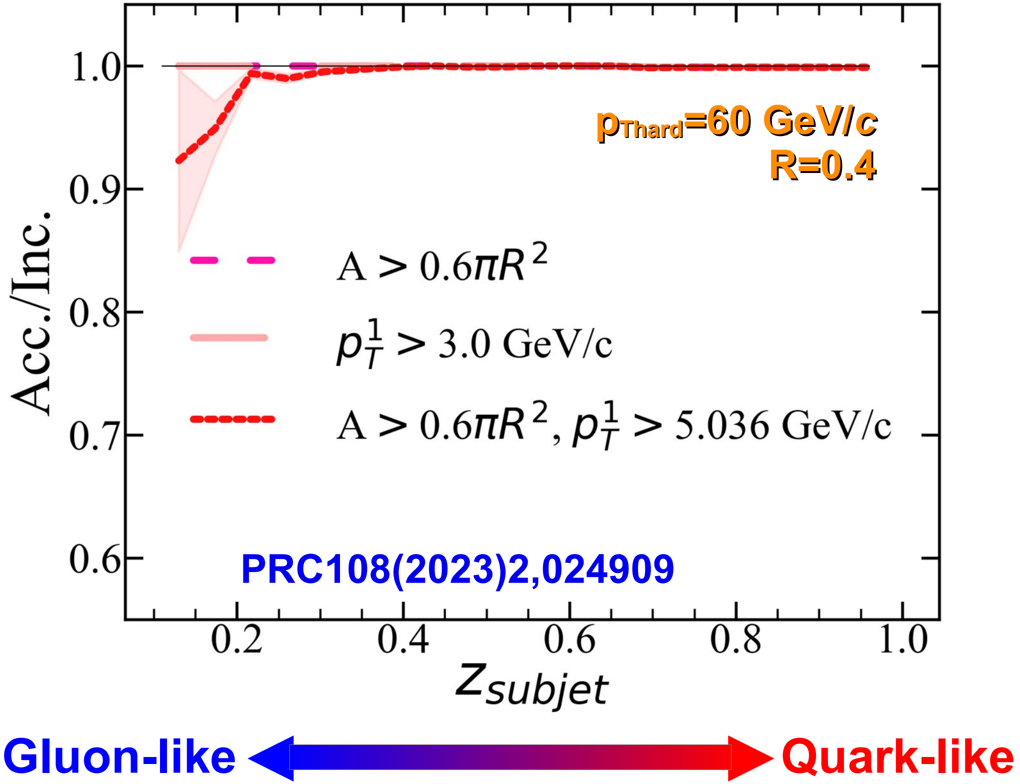


Yes, you can cut background, but it comes at a cost. Background jets which look like signal remain.

What's left is biased towards quark-like jets



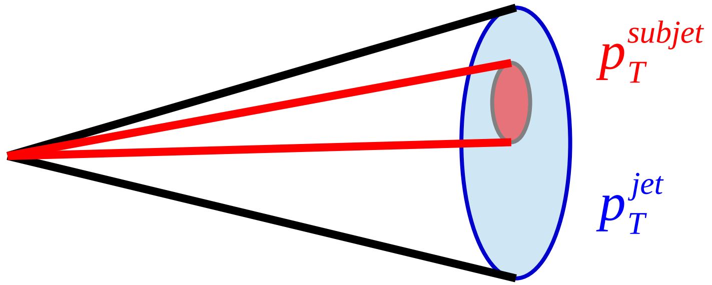
$$z_r = \frac{p_T^{subjet}}{p_T^{jet}}$$



Subjet z

Calculated using PYTHIA particles only

What’s left is biased towards quark-like jets



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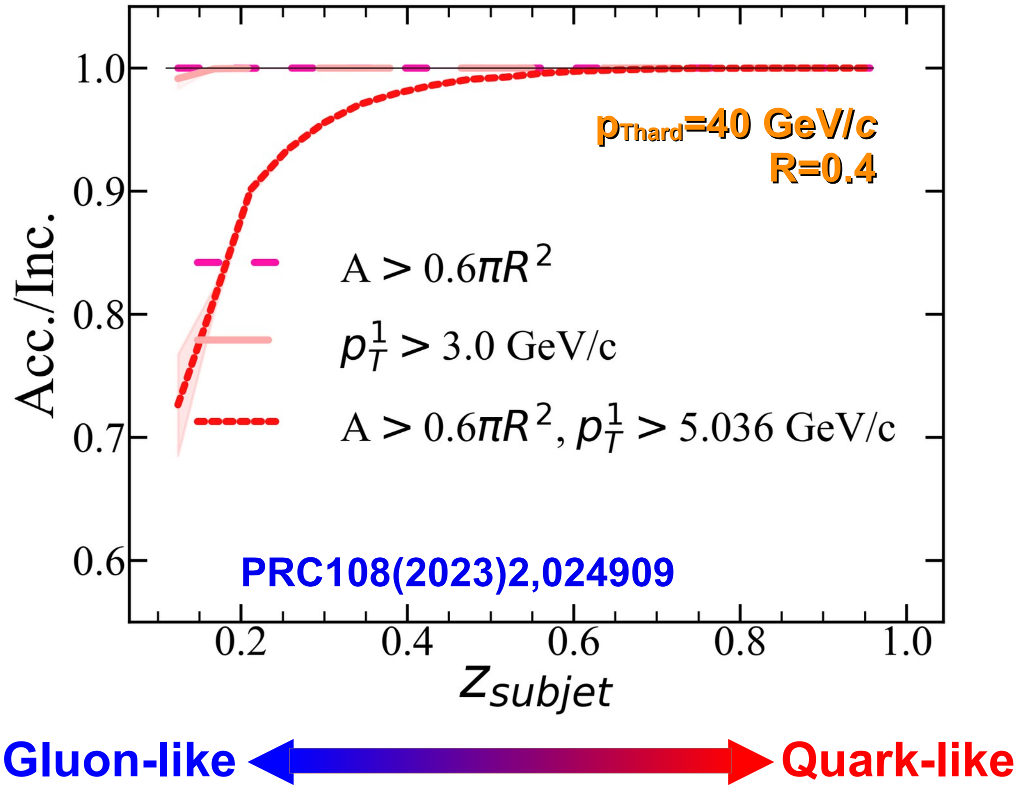
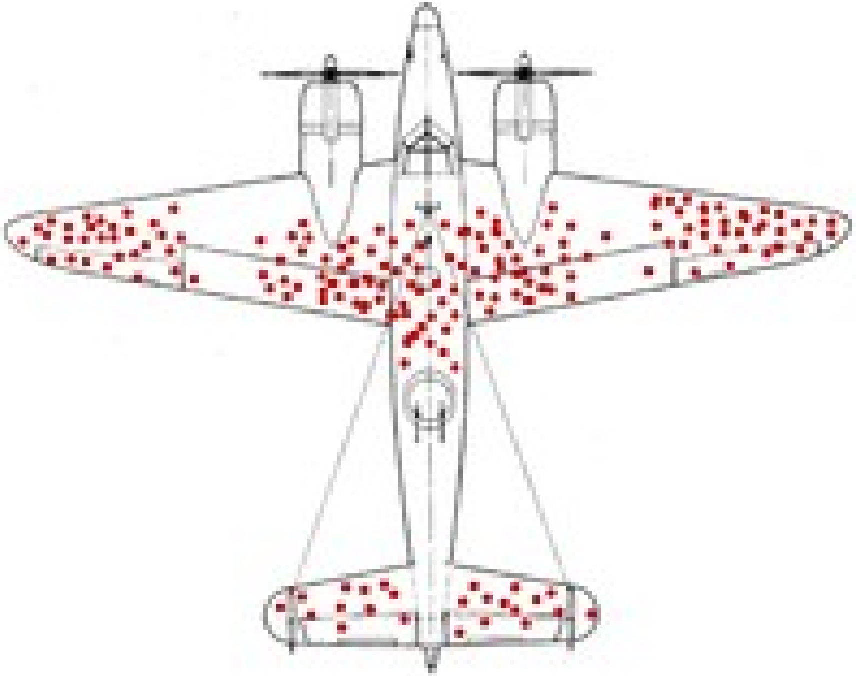


Survivor bias

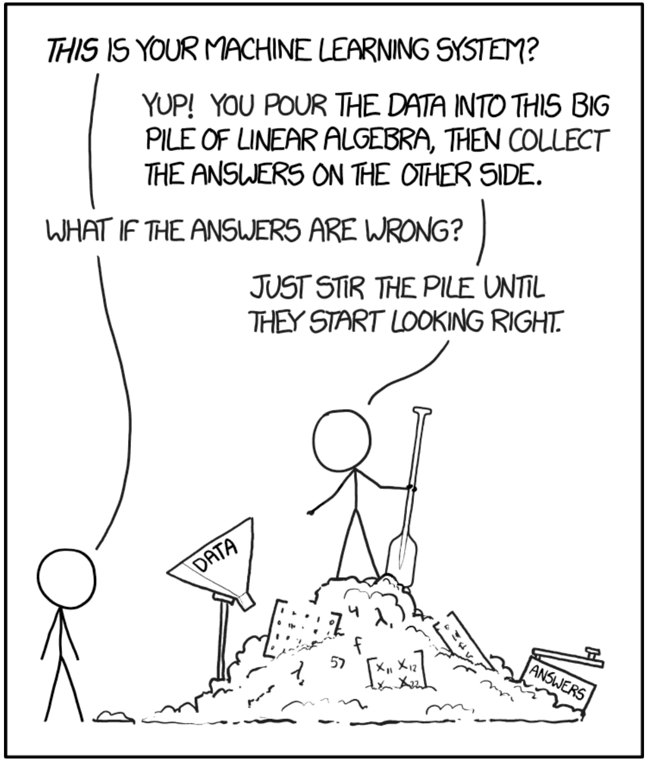
First use of the term for jets in heavy ion collisions?

Rev. Mod. Phys. 90, 025005 (2018)

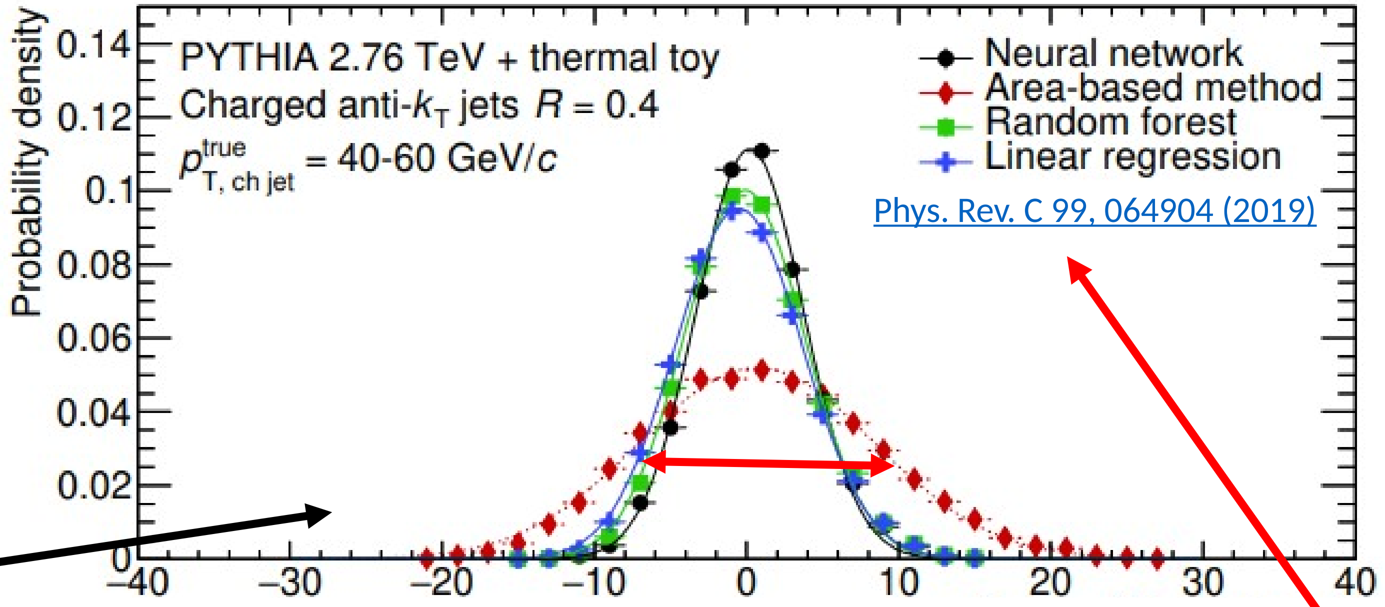


- WWII Example: holes planes returning indicate where it's *safer* to get hit
- We're looking at the jets which *remain*

4. Machine learning only teaches you what you already know!



Observation – ML does better at background



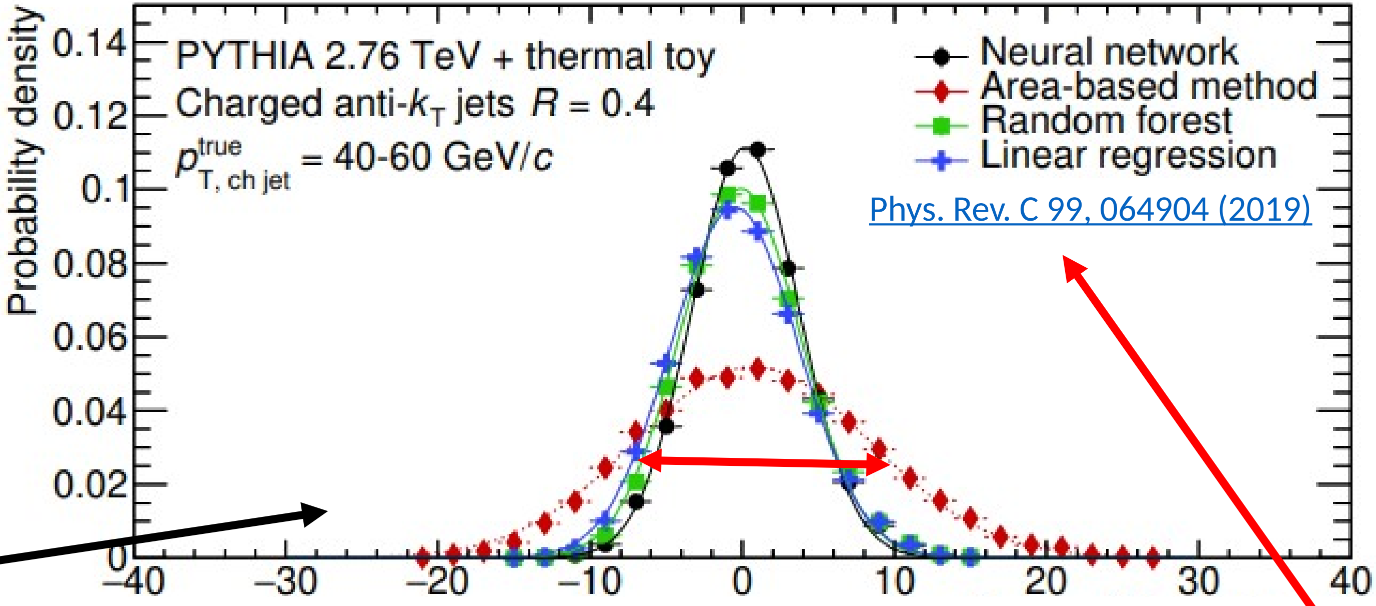
$$\delta\, p_T = \left(p_{T,jet}^{pred.} - p_{T,jet}^{truth} \right)$$

$$\boxed{p_T^{Corr.} = p_T^{raw.} - \rho\, A_{jet}}$$

Width of determines momentum resolution of method.

Applied to data in
ALICE Collaboration, PLB 849 (2024) 138412

Observation – ML does better at background



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Width of determines momentum resolution of method.

$$\boxed{p_T^{Corr.} = p_T^{raw.} - \rho A_{jet}}$$

Applied to data in
ALICE Collaboration, PLB 849 (2024) 138412

A better method?

- Random cone:

Also confirmed in
PRC 106, 044915 (2022)

$$p_T^{corr} = p_T^{raw} - \rho_A A$$

$$\sigma_{total} = \sqrt{N \sigma_{p_T}^2 + \left(N + 2N^2 \sum_n v_n^2\right) \mu_{p_T}^2}$$

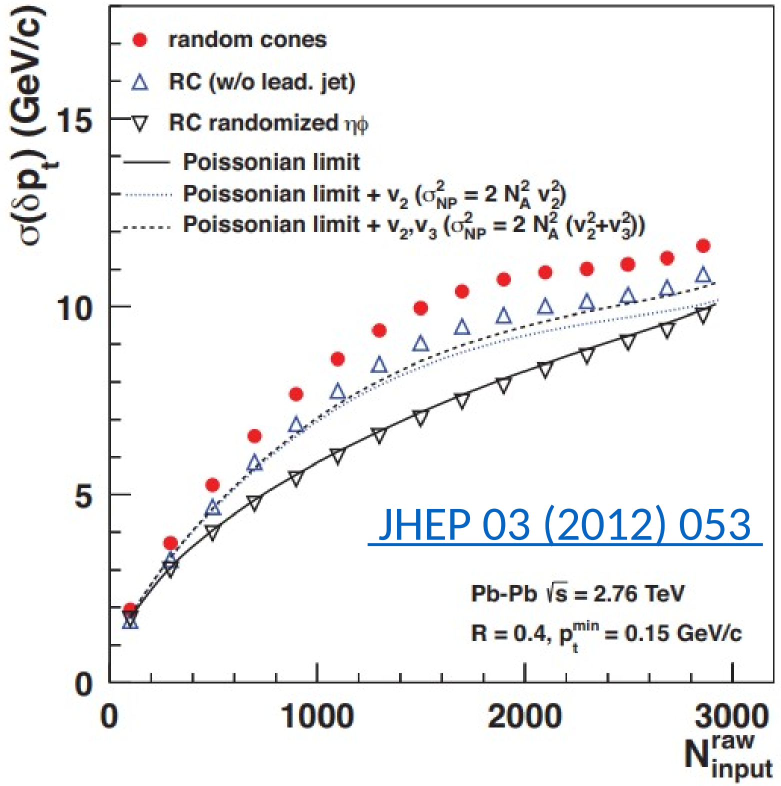
Tannenbaum, PLB(498),1–2,Pg.29-34(2001)

- Multiplicity method:

$$p_T^{corr} = p_T^{raw} - \rho_N \left(N_{tot} - N_{sig}\right)$$

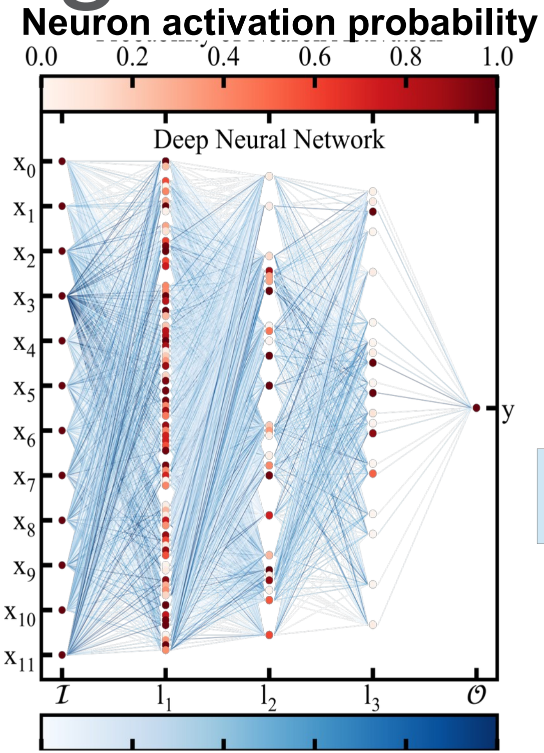
$$\sigma_{total} = \sqrt{N \sigma_{p_T}^2}$$

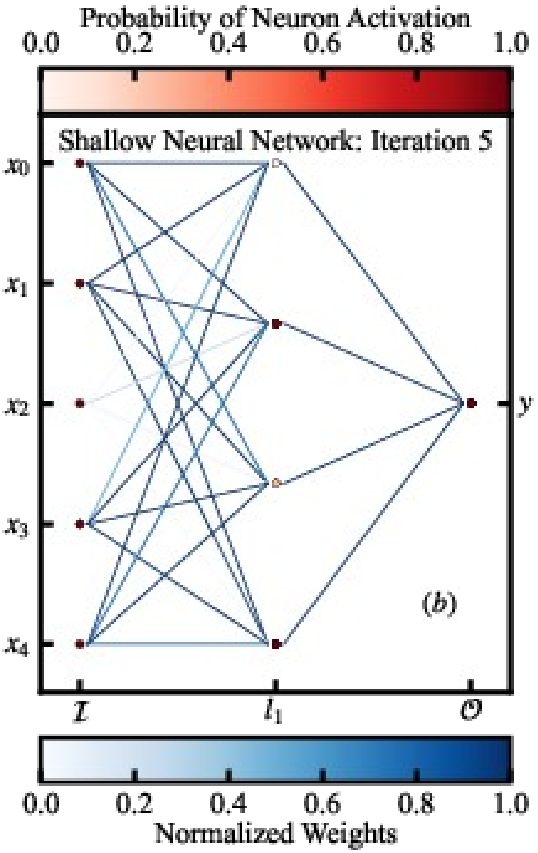
PRC.108.L021901(2023)6



JHEP 03 (2012) 053

Trimming the network



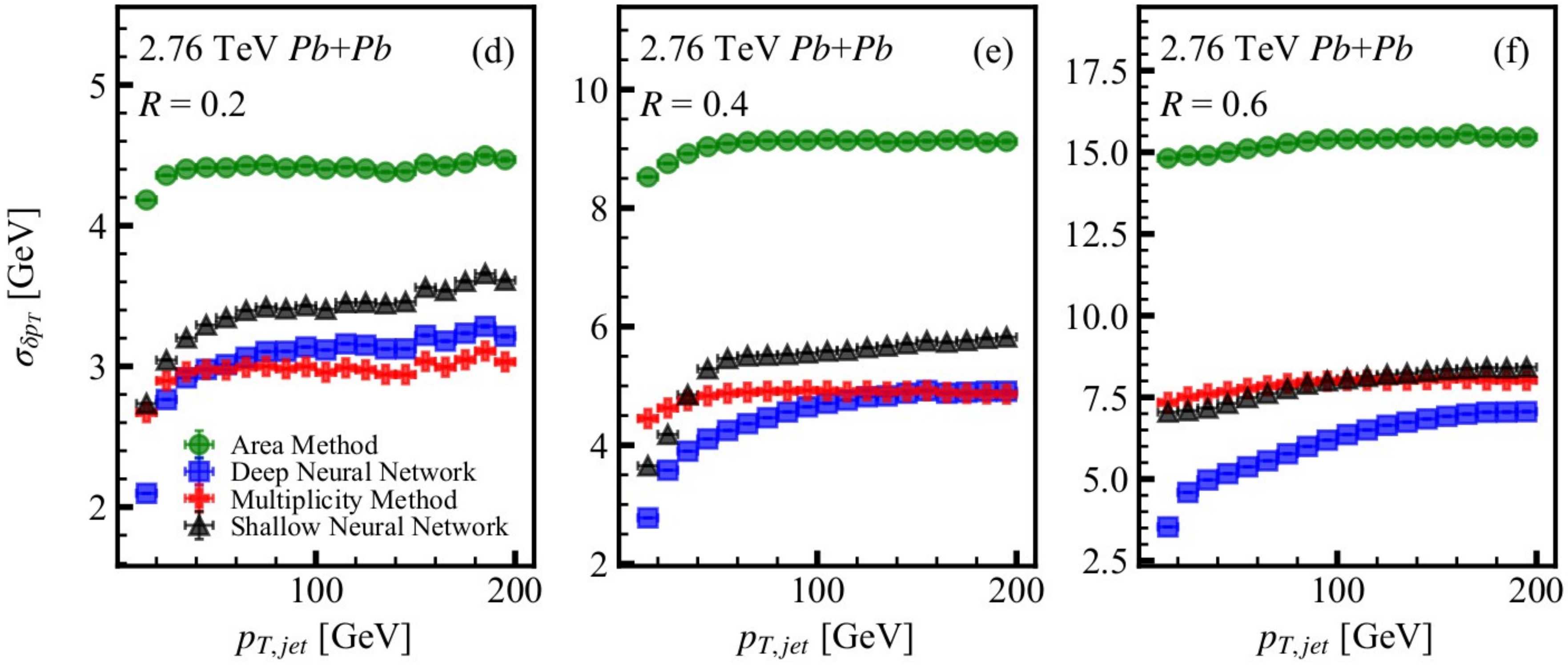


Information flows forward from layer to layer
Nodes are connected by weights

Follow up to
PRC.108.L021901(2023)6
Arxiv pending

Follow up to
PRC.108.L021901(2023)6
Arxiv pending

Algorithm Performance



Symbolic regression

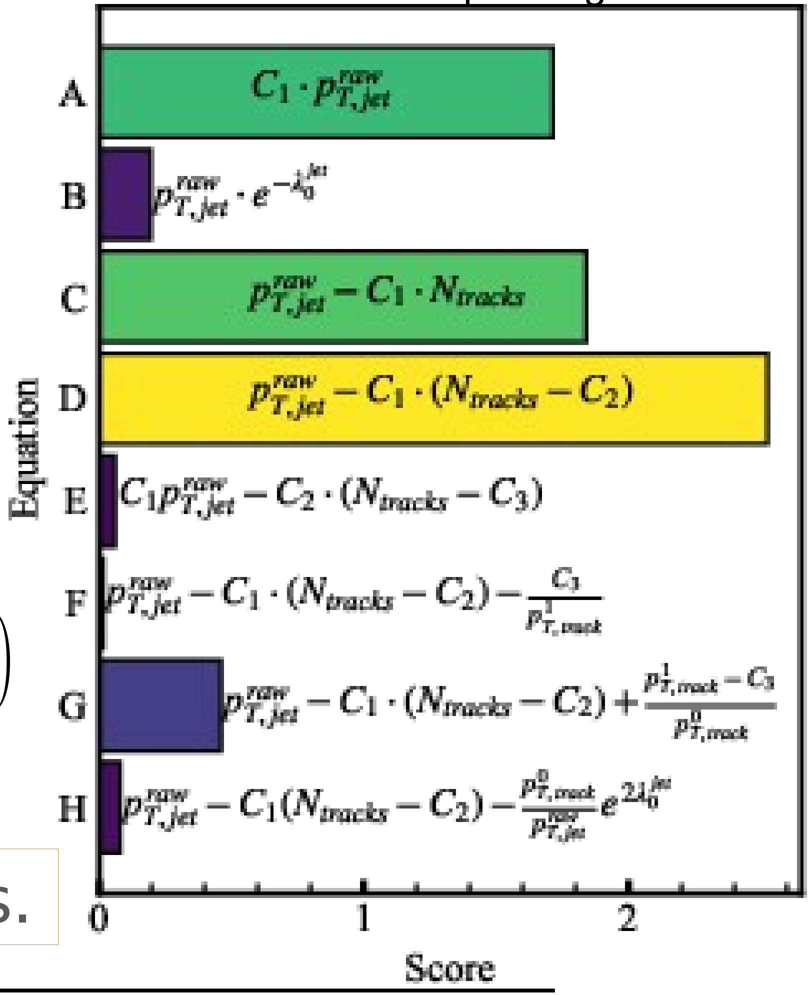
Follow up to
PRC.108.L021901(2023)6
Arxiv pending

- Analytical approximation
- Trained on **all input jet features** with exponential, trigonometric, and arithmetic operations.
- **The best result was a linear combination**.

Jet multiplicity

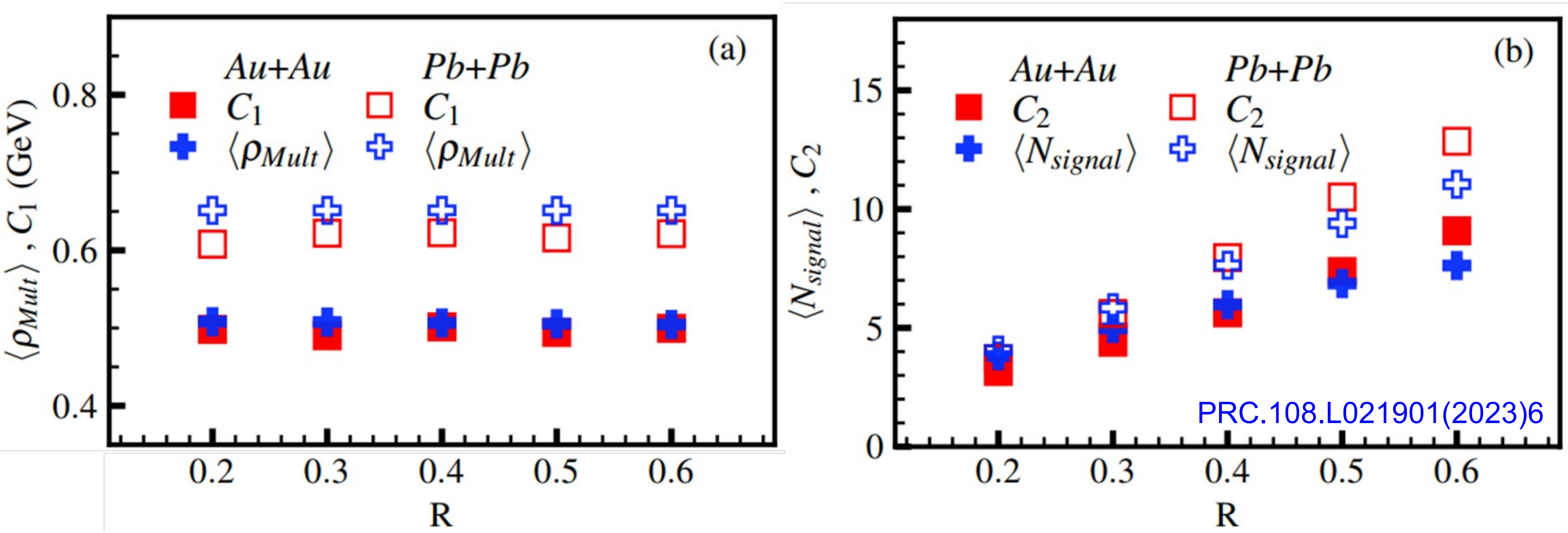
$$p_T^{corr.} = p_T^{raw} - C_1 \cdot (N - C_2)$$

Learned optimization constants.



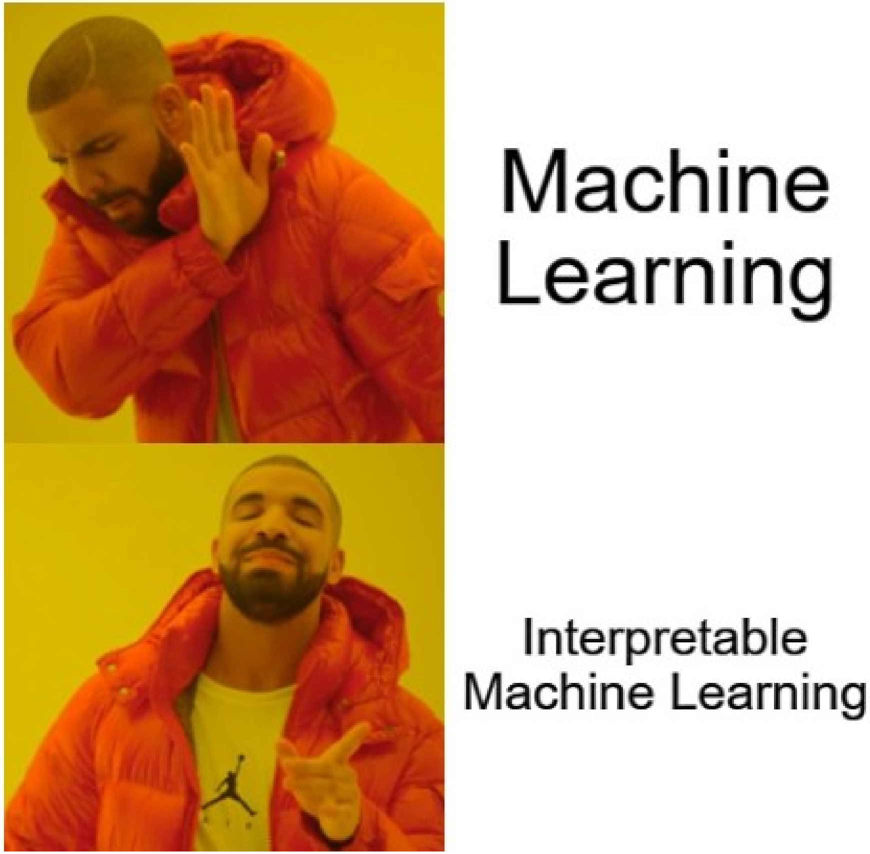
Neural network ≈ Multiplicity method

- Constants learned by PySR are approximately the terms used in multiplicity background subtraction method.



Interpretable ML

1. Method must be equivalently applicable to data and simulation.
2. Predictions must be understood outside the range of training set.
3. Systematic uncertainties can be assessed for predictions.
4. Learned relationships can be directly observed.



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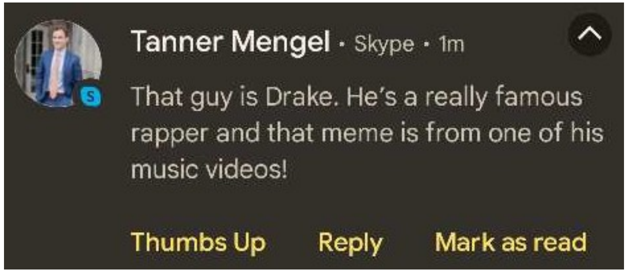
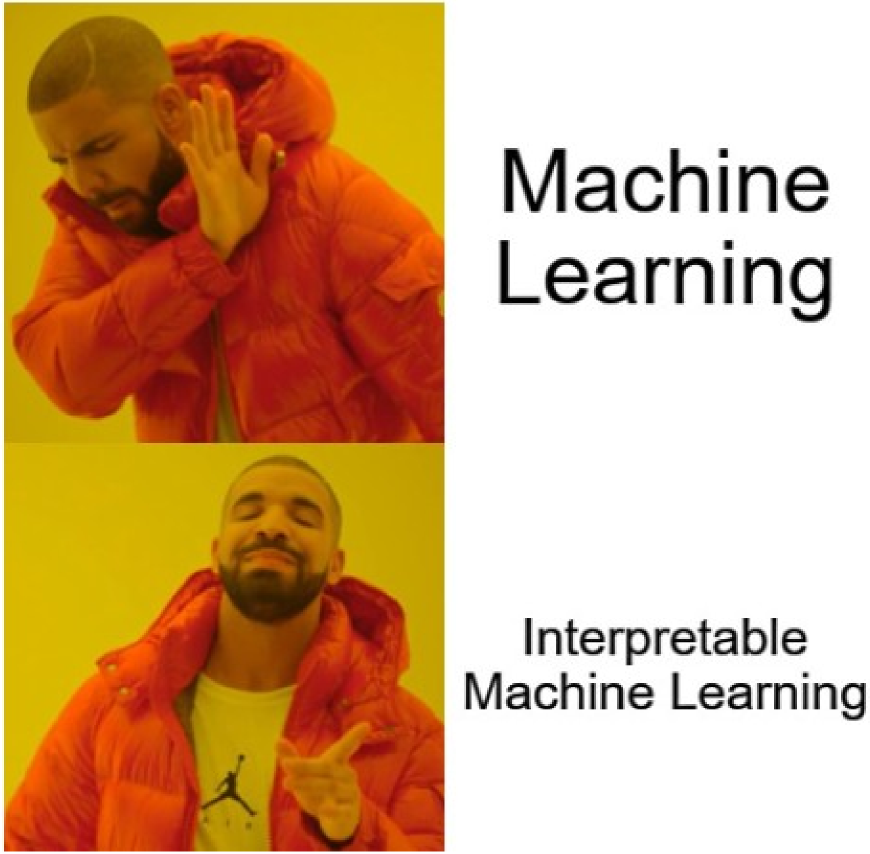
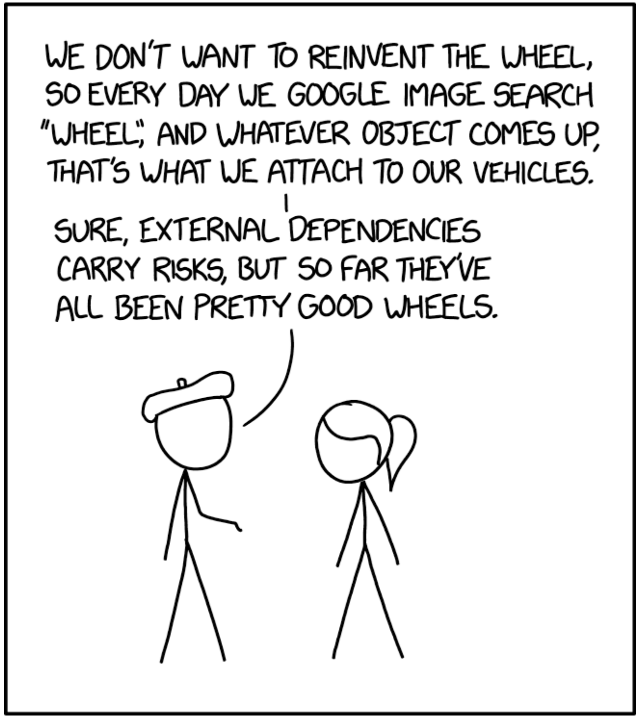


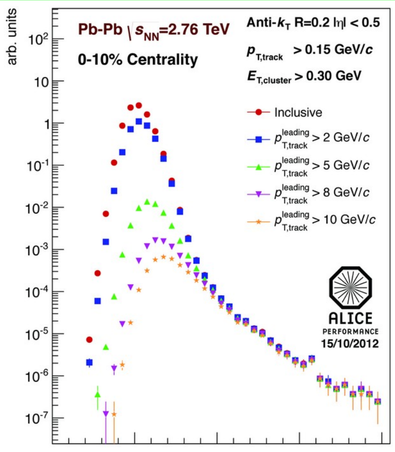


5. How should you compare to models?

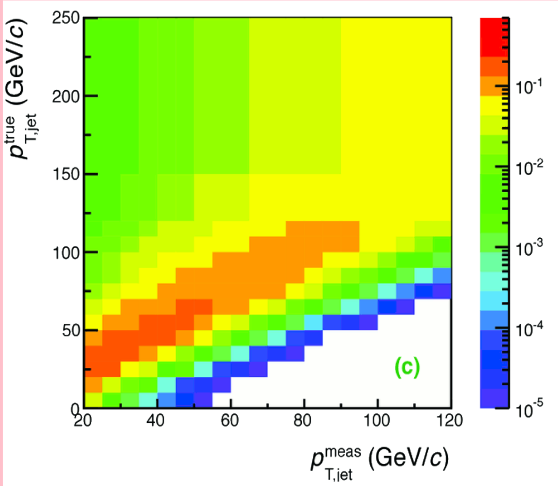


Analysis steps

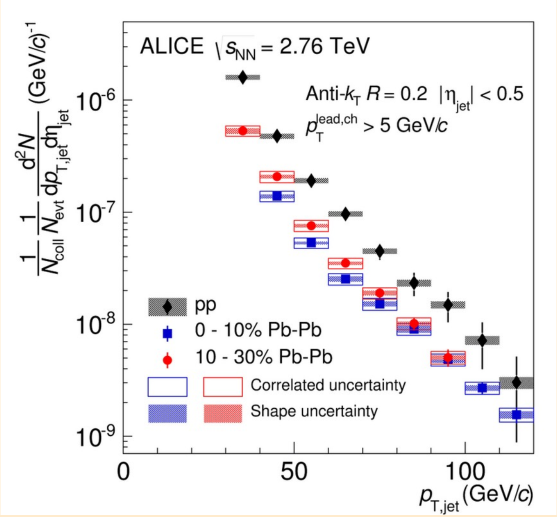
Tracks → Jet finding algorithm
Clusters → Jet finding algorithm
Jet finding algorithm → Jet candidates → Background subtraction



Jet spectrum smeared by energy resolution, background fluctuations



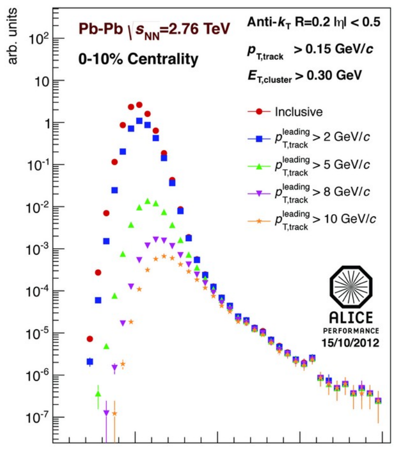
Unfolding – corrects for single track reco ε, E resolution, background fluctuations



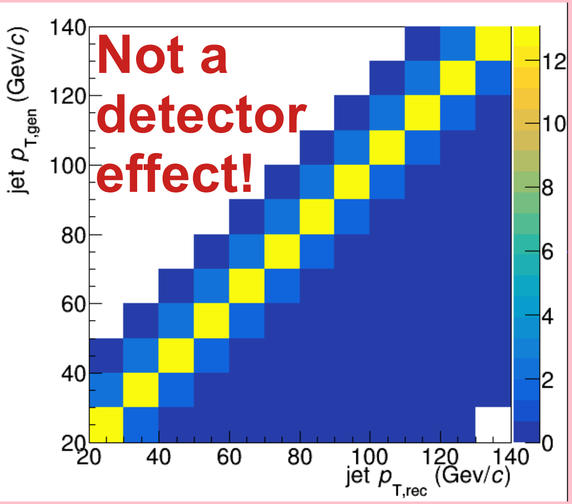
Corrected spectra

Analysis steps: Full Monte Carlo

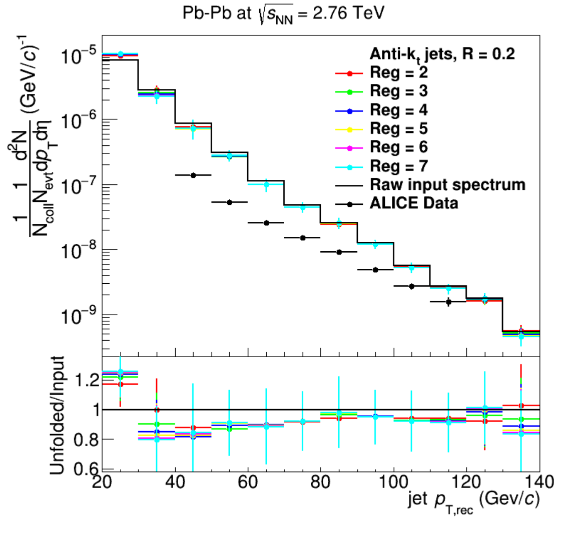
Particles → Jet finding algorithm → Jet candidates → Background subtraction



Jet spectrum smeared by energy resolution

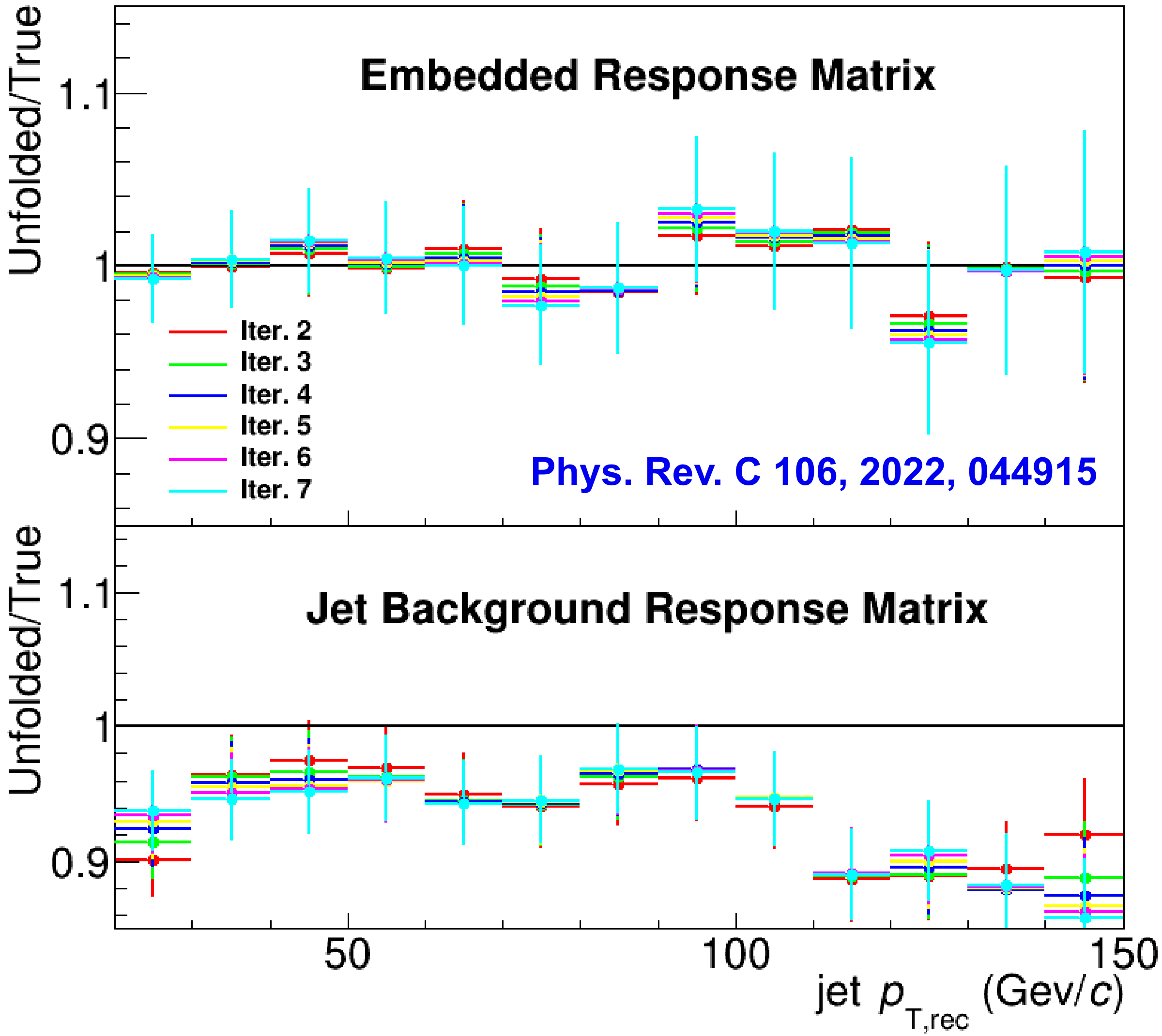


Unfolding – ***corrects for background fluctuations***



Corrected spectra

Closure



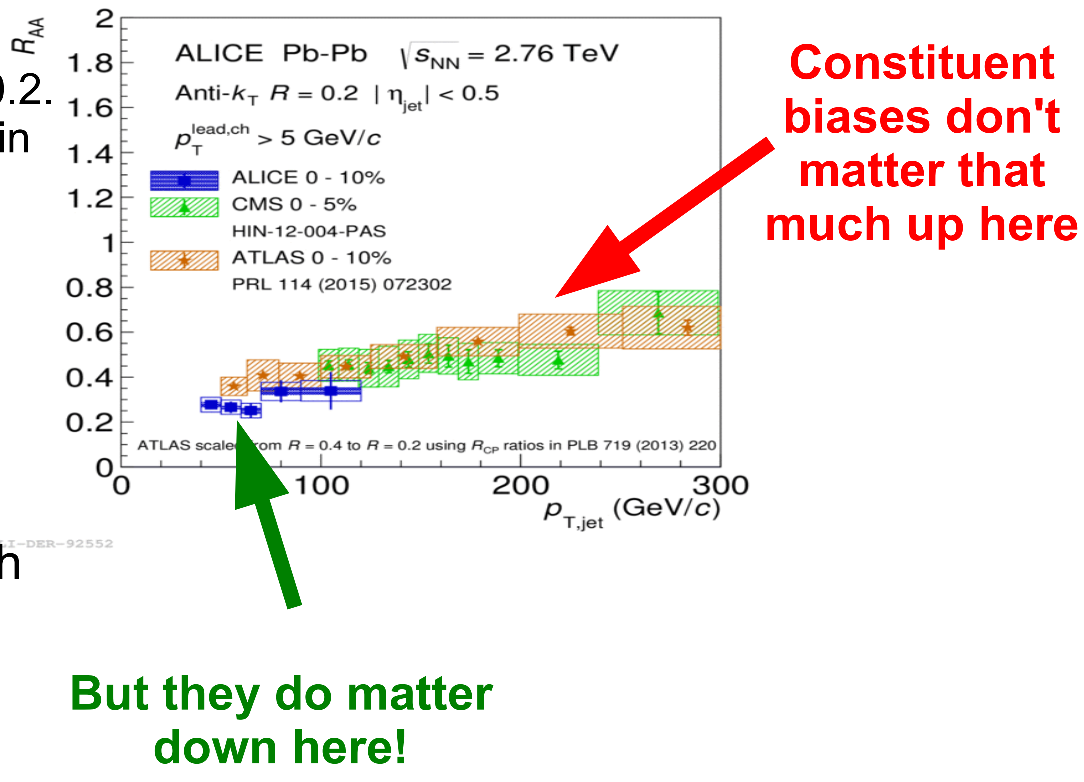
- Methods
  - Use δp_T method to measure width of fluctuations with varying numbers of leading jets (LJ) discarded
  - Embed PYTHIA event into heavy ion event
- **Only embedding leads to full closure in Monte Carlo**

ATLAS

Background subtraction method:

- Iterative procedure
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with $E_{tower} > \langle E_{tower} \rangle$
    Track jets: Use tracks with p_T>4 GeV/c
  - Calorimeter jets from above with E>25 GeV and track jets with p_T>10 GeV/c used to estimate background again.
- Calorimeter tracks matching one track with p_T>7 GeV/c or containing a high energy cluster E >7 GeV are used for analysis down to E_{jet} = 20 GeV

Phys. Lett. B 719 (2013) 220-241



Snowmass Accord: Apply the same algorithm to data and your model. Then the measurement and the calculation are the same.

Rivet: Apply the same algorithm to data and your model. Then the measurement and the calculation are the same.

This is **also** what people have learned in the soft sector in heavy ion collisions.

The Lisbon Accord

- Lisbon Accord proposed that heavy ion analyses adopt RIVET in July 2014

https://www.aworldtotravel.com/things-lisbon-is-famous-for/

PYTHIA AMPT HIJING JETSCAPE

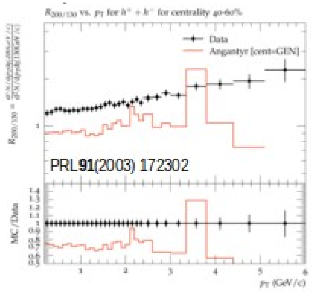
Monte Carlo Model

PHSD JEWEL EPOS smash

HepMC

HEPData → Rivet

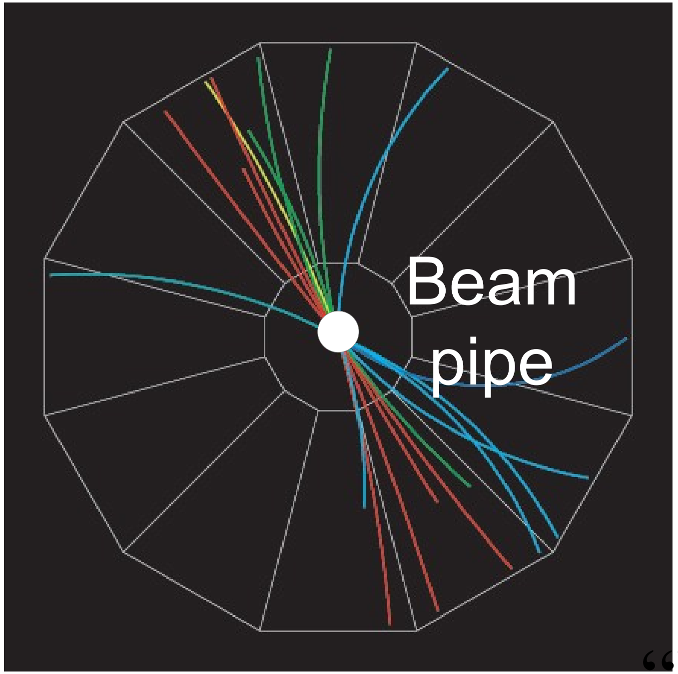
Comparison to data

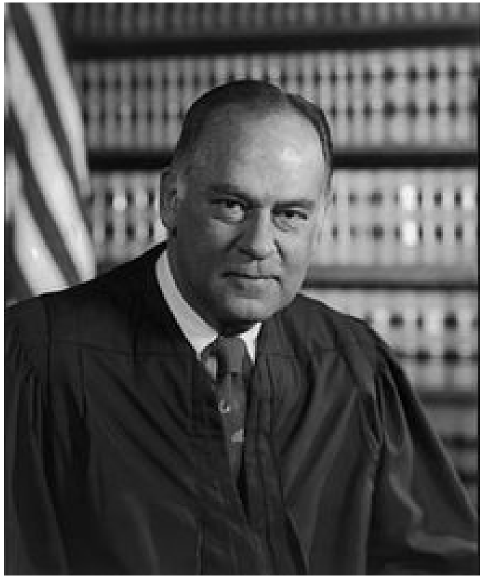


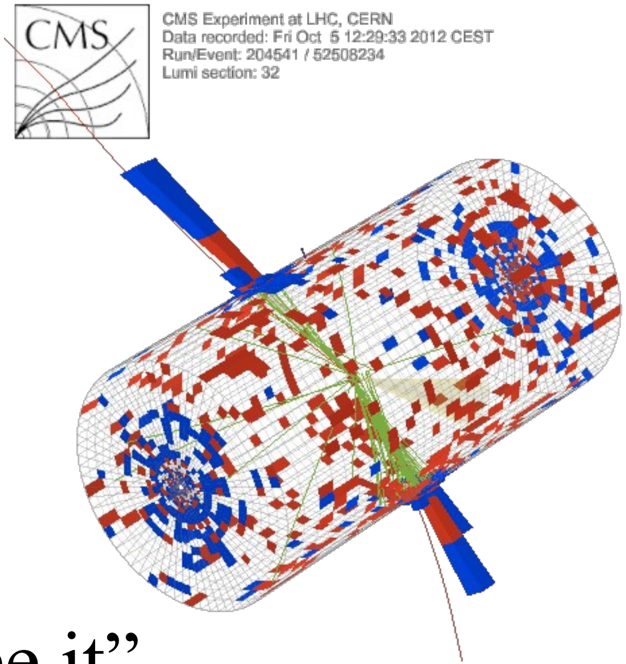
How should you compare to models?
Let’s not reinvent the wheel!

What is a jet?

p+p dijet



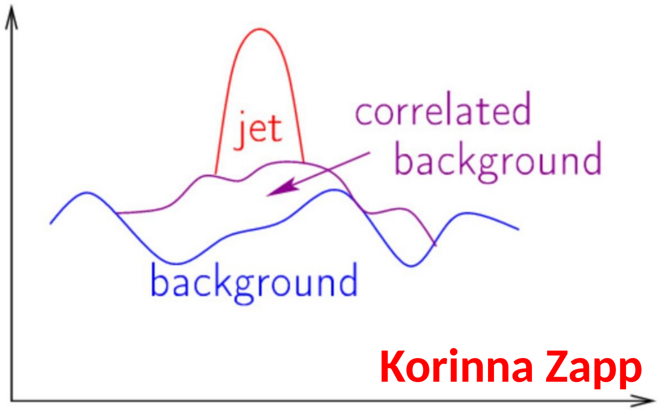


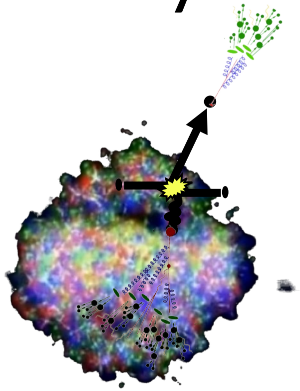


"I know it when I see it"

US Supreme Court Justice Potter Stewart,
Jacobellis v. Ohio

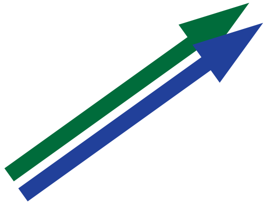
Definition of Jets in a Large Background July 25-27, 2018

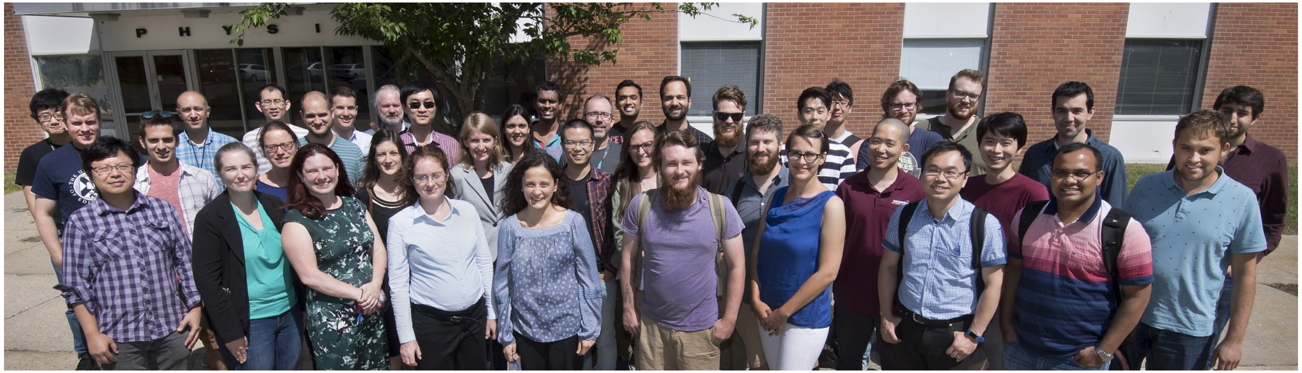




Provide enough details to make comparisons between data and models

Include anything correlated in definition of jet



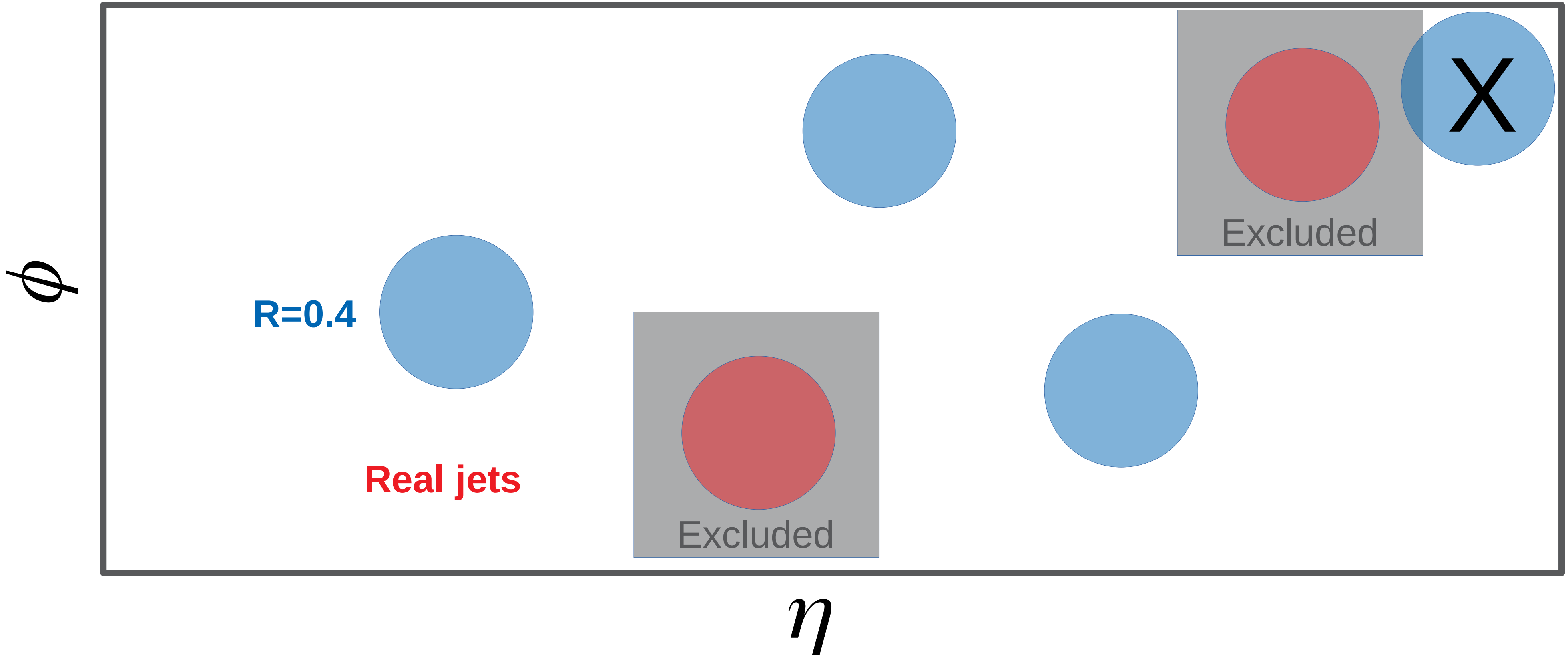


Reconsider role of collinear safety

Discuss and put effort into the problem

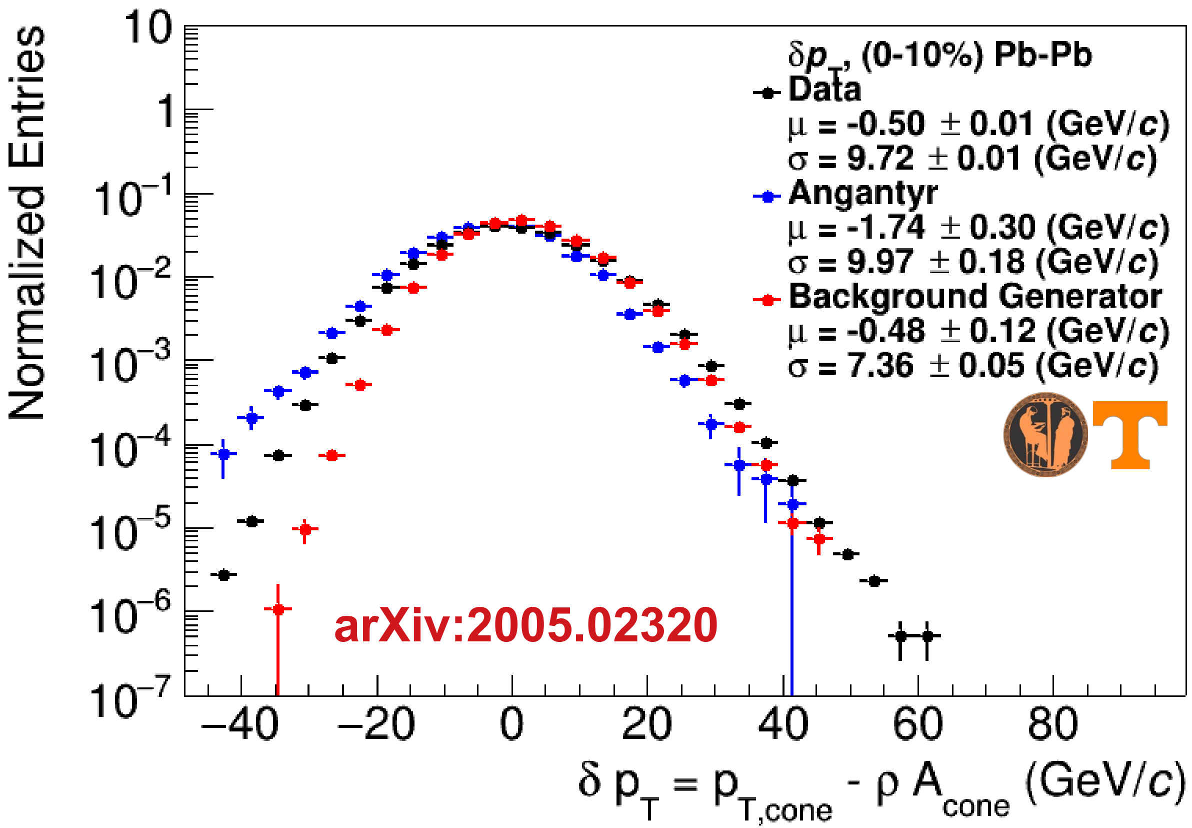
Backup

Random cones



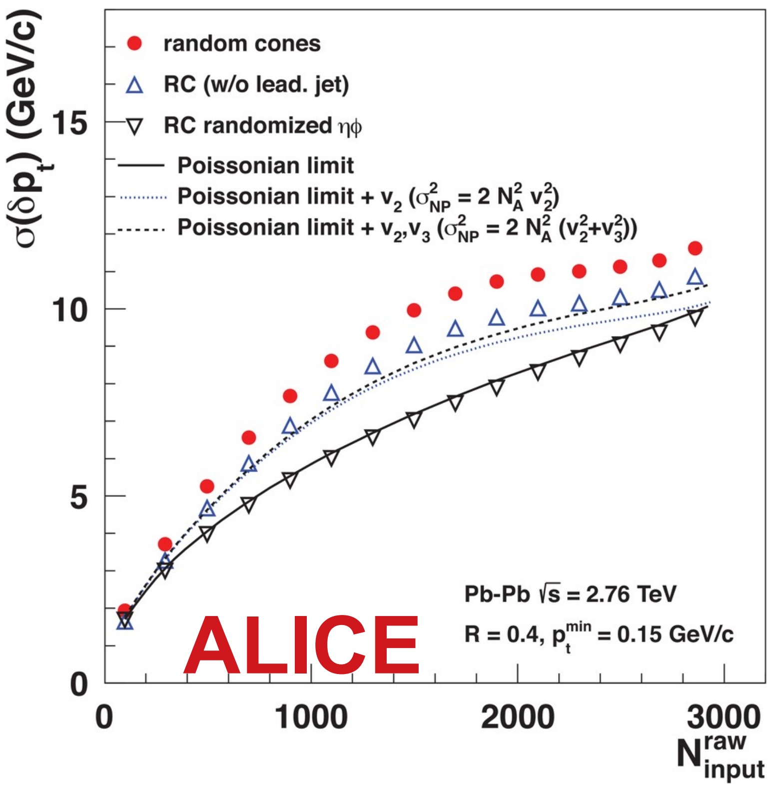
Random cones

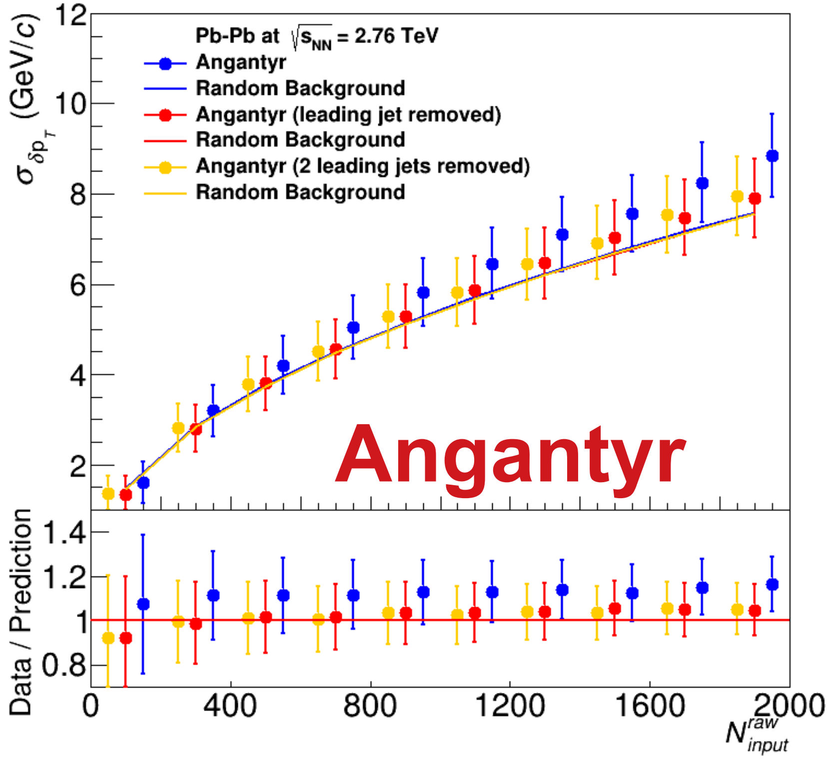
ALICE Data: JHEP 03 (2012) 053



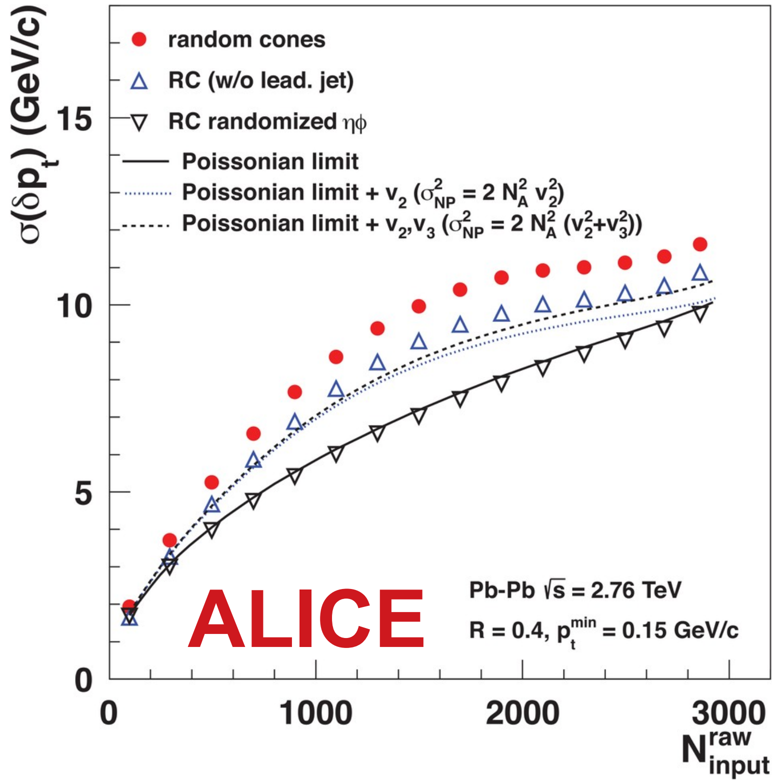
ρ = Median(p_T/A)

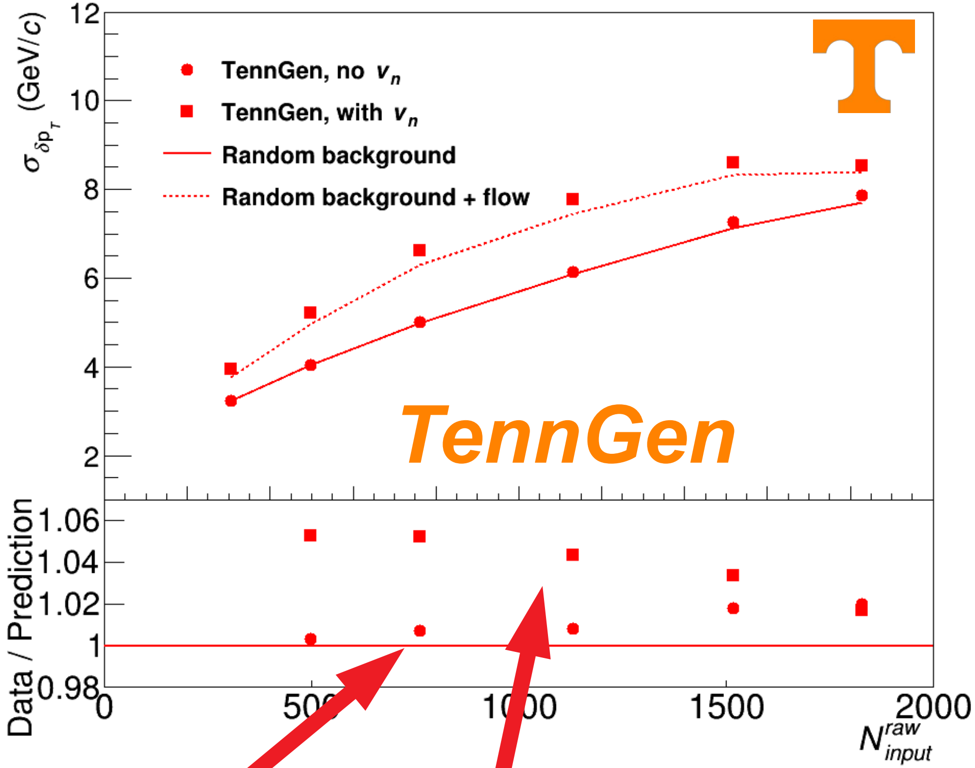
Width vs multiplicity





Width vs multiplicity

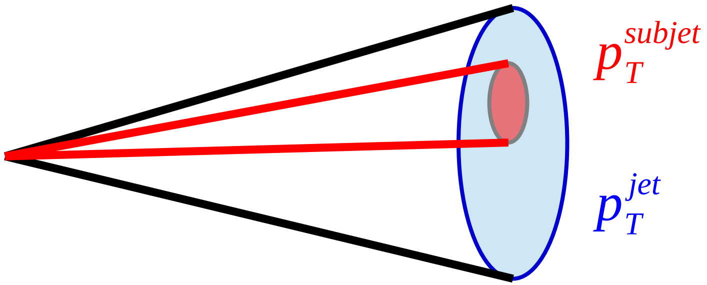




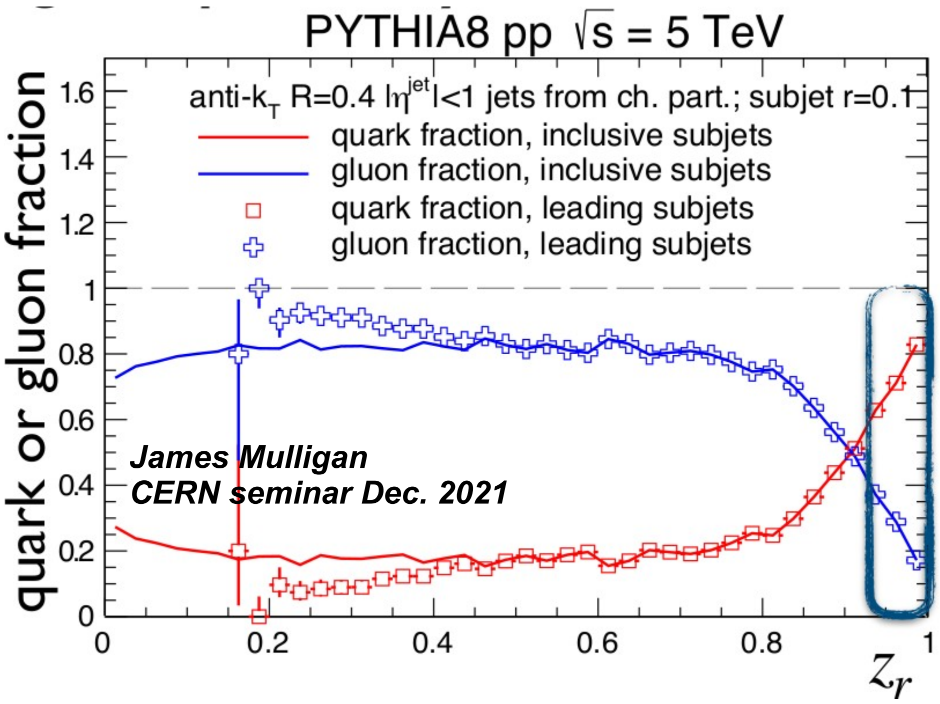
Impact of shape of spectrum

Correlations between event planes

Subjet z

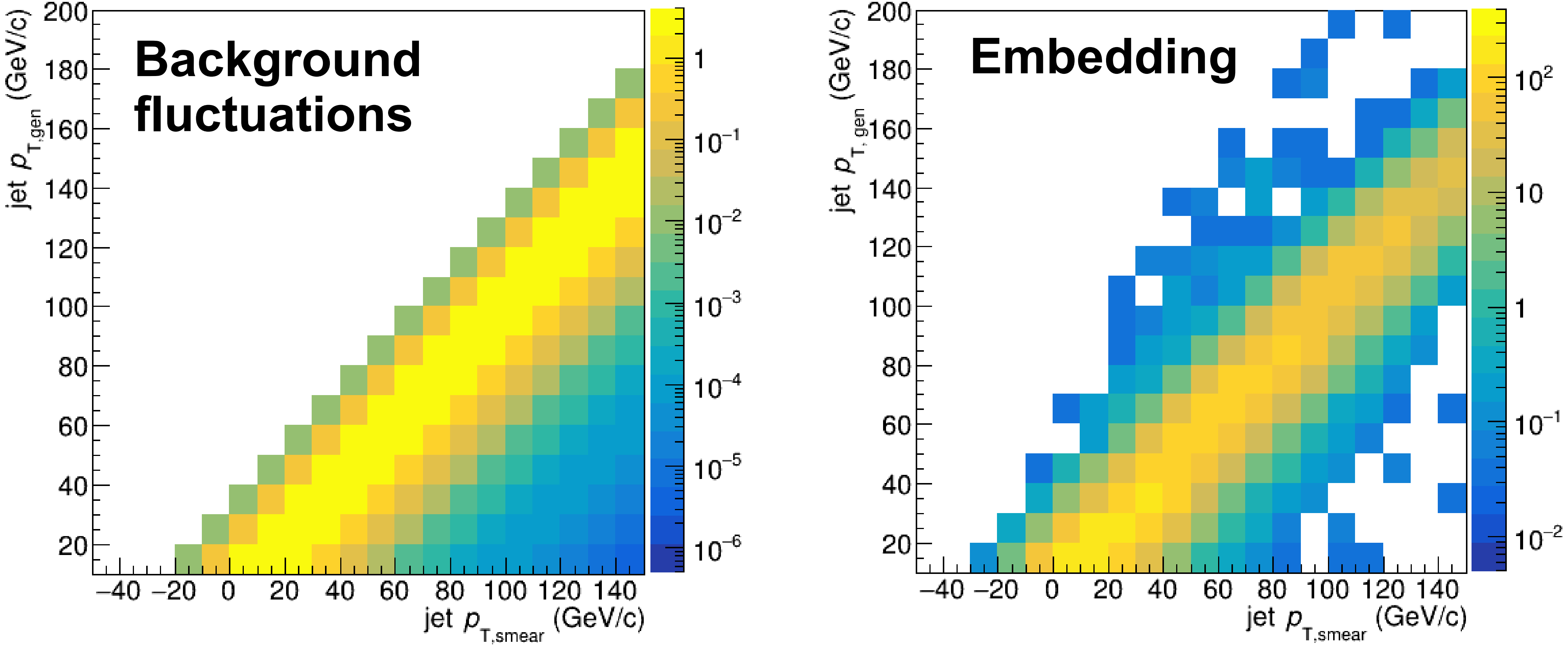


$$z_r = \frac{p_T^{subjet}}{p_T^{jet}}$$



- Cluster jets with anti-k_T with resolution parameter R
- Recluster constituents with anti-k_T with resolution parameter r
- Some discriminating power between quark-like and gluon-like jets
  - Strained at low momentum, small R

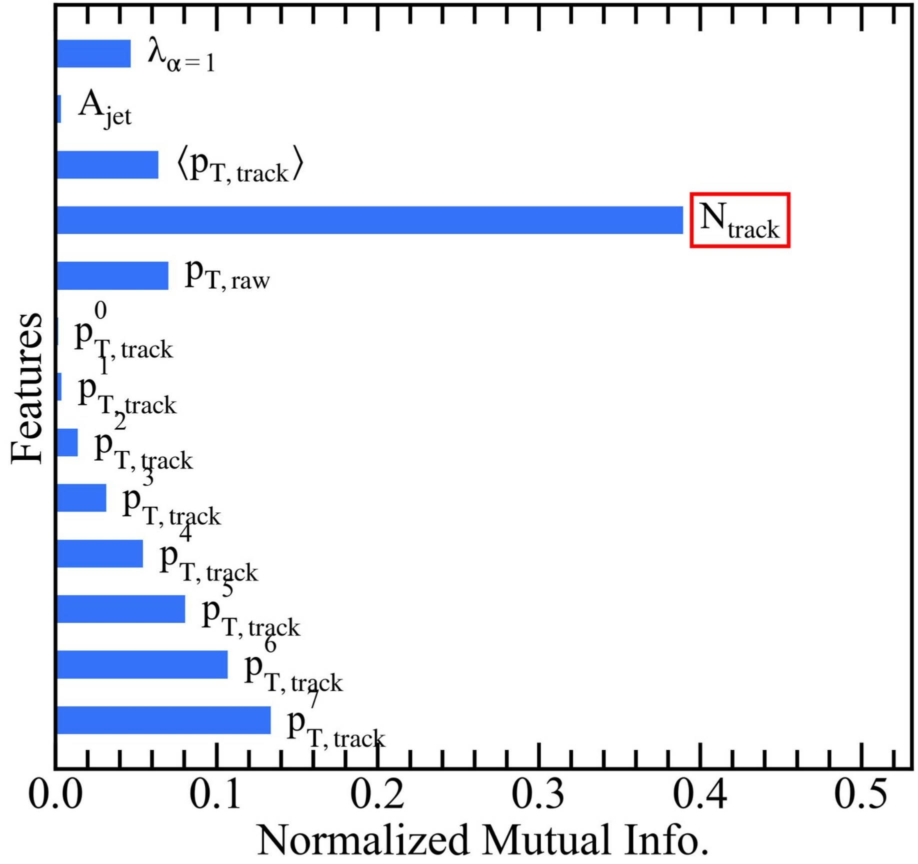
Construct a response matrix in Monte Carlo



Designing a better method

- Jet multiplicity largest mutual information w/jet momentum .
- Background fluctuations are well described by multiplicity fluctuations.

JHEP 03 (2012) 053,
Phys. Rev. C 106, 044915 (2022),
Physics Letters B 498, 29 (2001).



Definition of Jets in a Large Background July 25-27, 2019

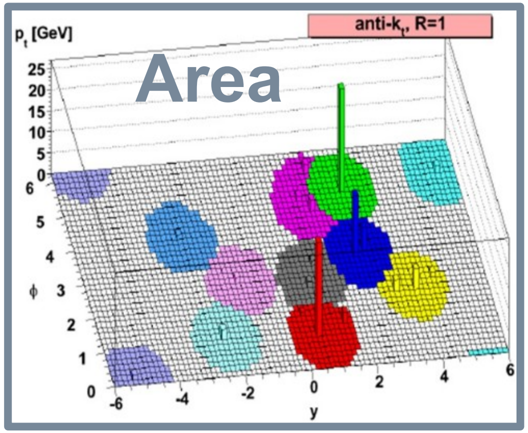
- **Organizers:** M. Connors, G. Milhano, C. Nattrass, R. Reed, S. Salur
- **Spectra conveners:** R. Kunnawalkam Elayavalli, Y. Mehtar-Tani (R. Bertens)
- **Correlation conveners:** J. Noronha-Hostler, J. Huang
- **Substructure conveners:** Y. Lee, Y. Chien

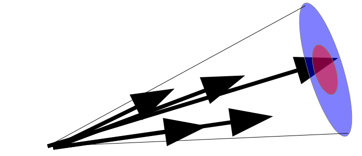
Extensively discussed the interplay between experimental techniques and theoretical calculations with the aim of **reaching an agreement*** on the way forward for extracting jet measurements from large background events such as those in heavy ion collisions and high luminosity p-p or electron-ion collisions.

*Consensus on some points

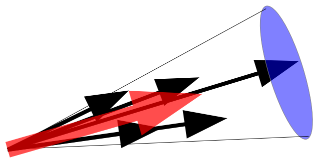
62 Registered but due to various visa & travel complications: 45 + several BNL employees attended.

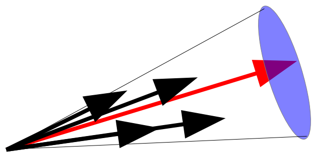
Jet properties





$$\alpha = \frac{1}{p_T^{jet}} \sum_k z_k (\vec{R}_k)$$





Shape of width of the distribution

Single particle spectra

$$f_\Gamma(p_T, p, b) = \frac{b}{\Gamma(p)} (b\, p_T)^{p-1} e^{-b p_T}$$

$$\frac{dN}{dy} \propto f_\Gamma(p_T, 2, b) = b^2\, p_T\, e^{-b\, p_T}$$

$$\mu_{p_T} = \frac{p}{b}, \sigma_{p_T} = \frac{\sqrt{p}}{b}$$

Tannenbaum, PLB(498),1–2,Pg.29-34(2001)

Σp_T of N particles → N-fold convolution:

$$f_N(p_T, p, b) = f_\Gamma(p_T, Np, b) \qquad \frac{dpT^{total}}{dy} \propto f_N(p_T, Np, b)$$

$$N = \frac{N_{total}}{A_{total}} \pi R^2 \qquad \mu_{total} = \frac{Np}{b} = N \mu_{p_T}, \sigma_{total} = \frac{\sqrt{Np}}{b} = \sqrt{N}\, \sigma_{p_T}$$

Add Poissonian fluctuations in N: $\sigma_{total} = \sqrt{N \sigma_{p_T}^2 + N \mu_{p_T}^2}$

Confirmed in
JHEP 03 (2012) 053 ALICE
PRC 106, 044915 (2022) Hughes et al

Add non-Poissonian fluctuations in N due to flow

$$\sigma_{total} = \sqrt{N \sigma_{p_T}^2 + \left(N + 2N^2 \sum_n v_n^2\right) \mu_{p_T}^2}$$