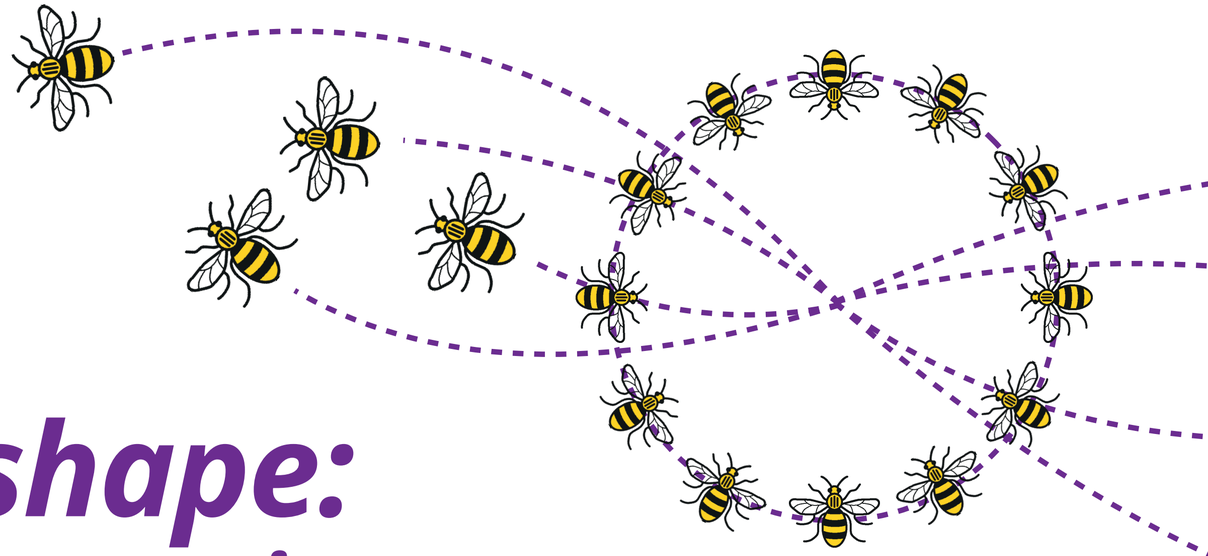


Giving events a new shape:
measurements of multijet event isotropy at ATLAS using optimal transport

ML4Jets @ DESY (Hamburg, German), 6-10 November 2023

2305.16930

Matt LeBlanc (Manchester), o.b.o. ATLAS
matt.leblanc@cern.ch, @TopPhysicist

MANCHESTER 1824
The University of Manchester

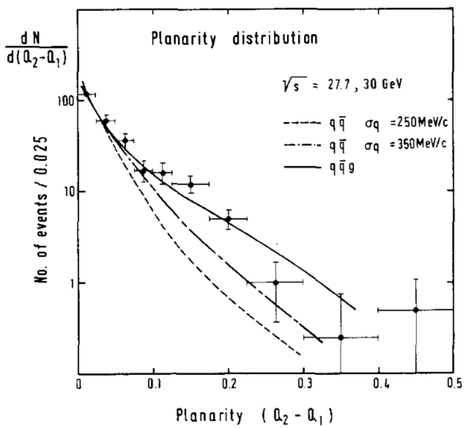
ATLAS EXPERIMENT

Event shapes

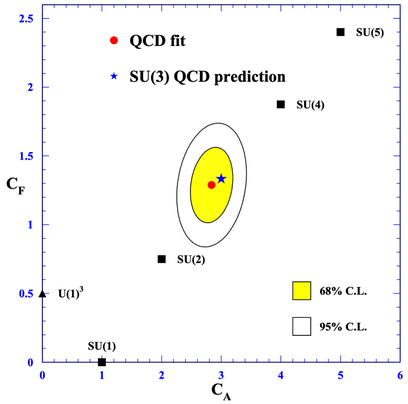
... interpolate between collider event topologies.

They have seen a wide variety of applications in collider physics for over 50 years!

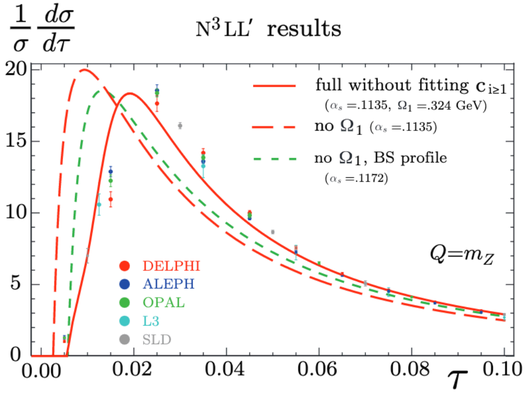
1980 — Gluon observation (JADE) — Planarity



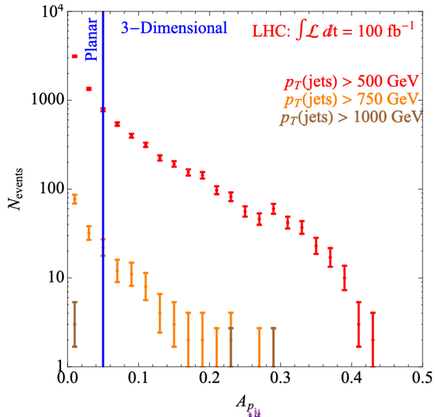
2000 — Colour Factors (Kluth et al.) — Thrust, C-Parameter



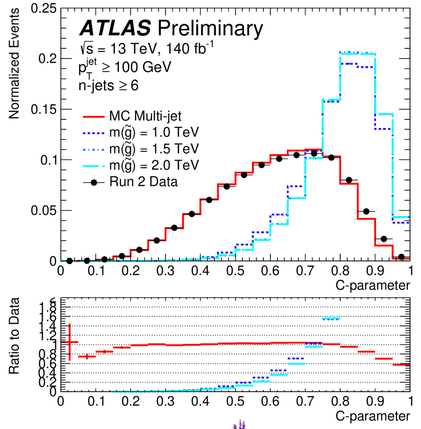
2010+ — Strong Coupling (Aabate et al., Hoang et al.) — Thrust, C-Parameter



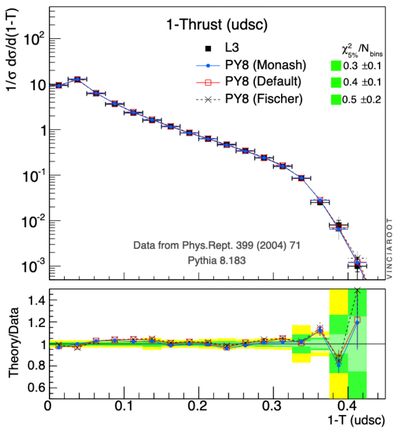
2011 — BSM (Anchordoqui et al.) — Aplanarity



2014 — Monash tune (Skands et al.) — Thrust



2023 — SUSY Searches (ATLAS) — C-Parameter

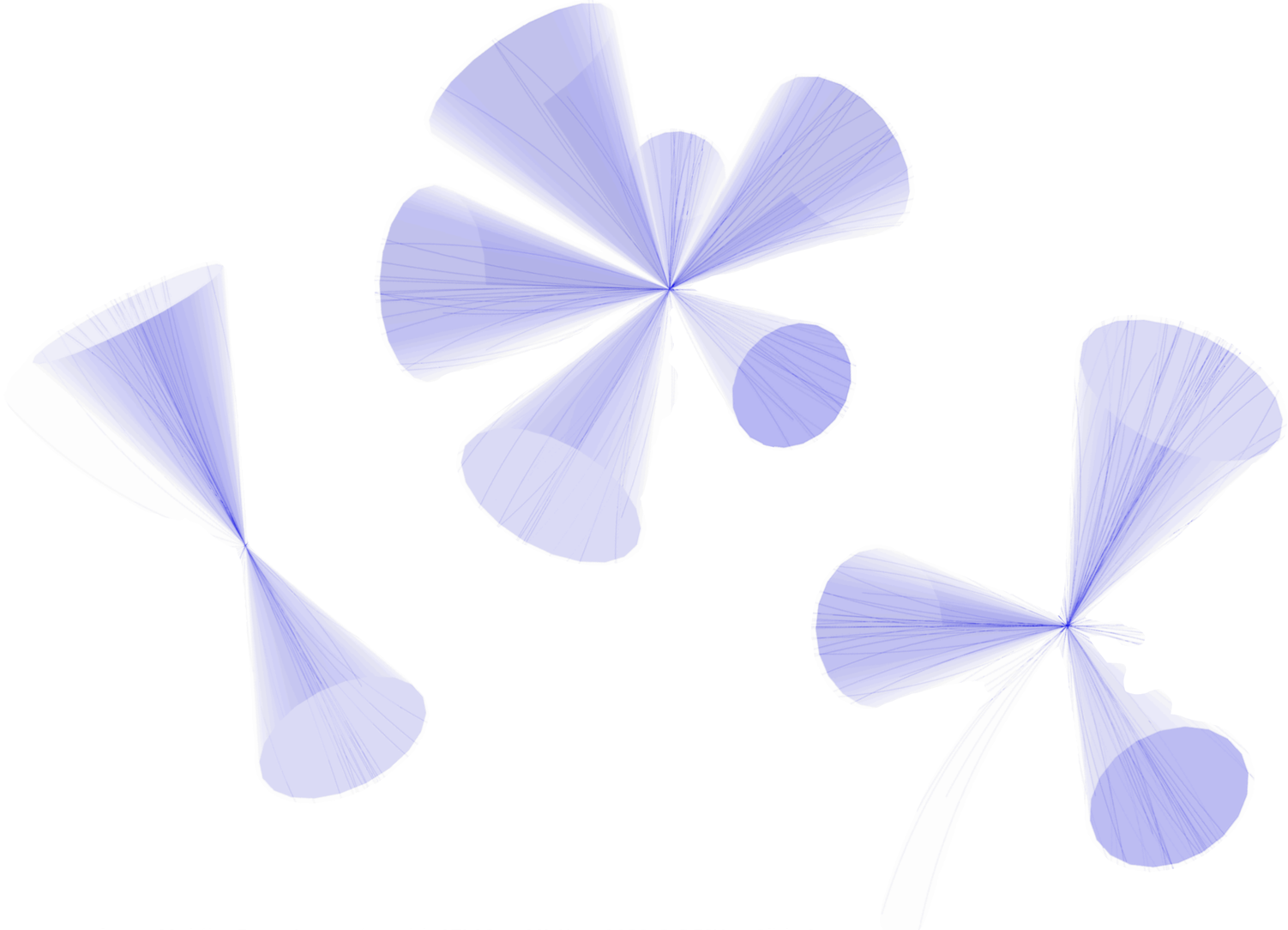


Event shapes

... interpolate between collider event topologies.

Which one is more...

Back-to-back?



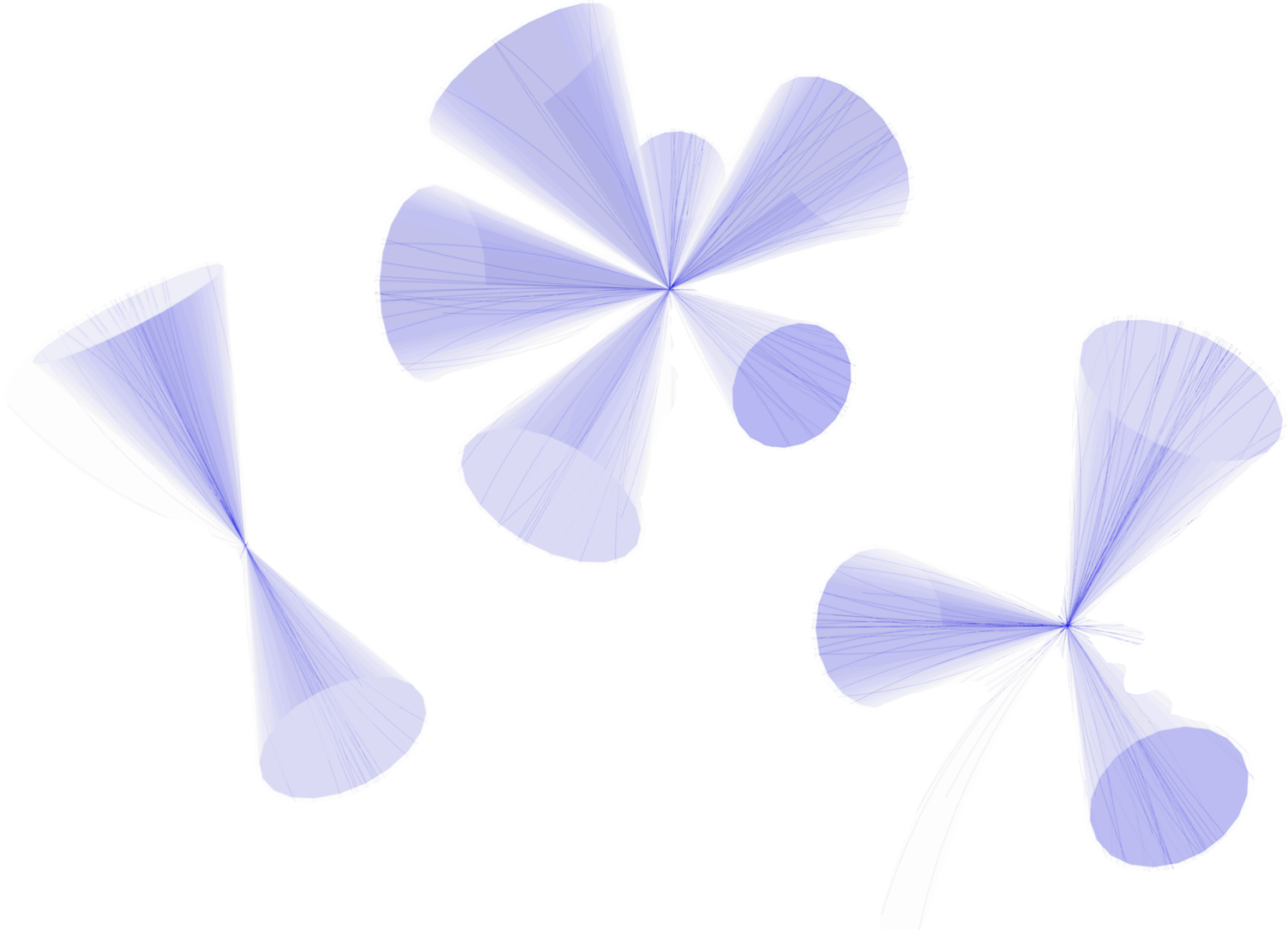
Event shapes

... interpolate between collider event topologies.

Which one is more...

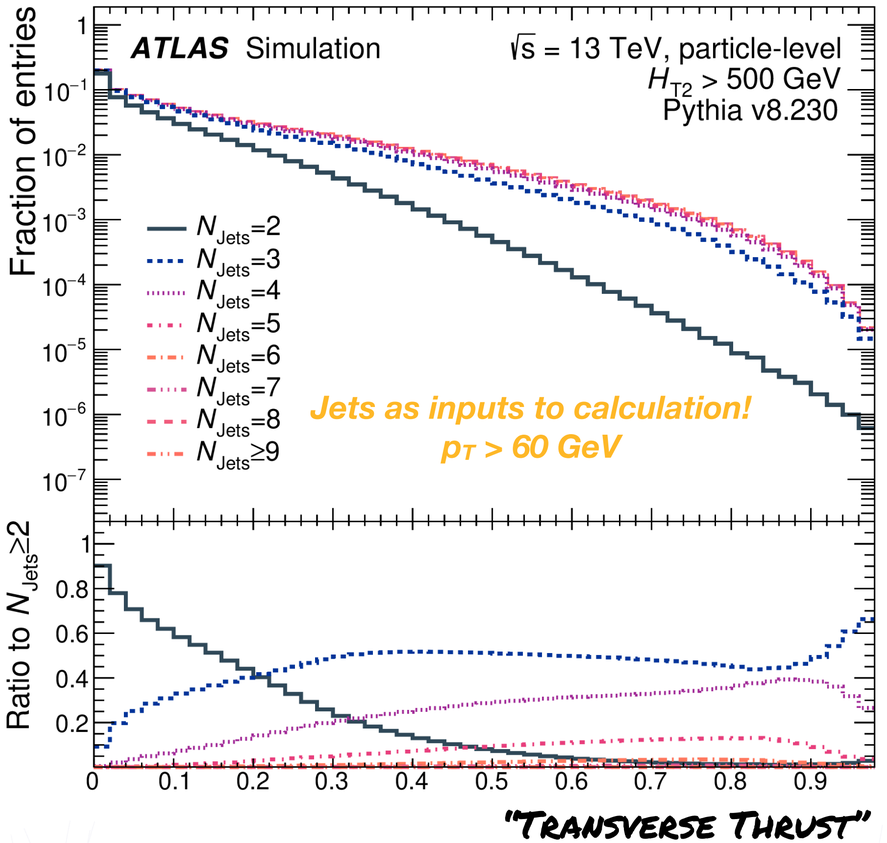
Back-to-back?

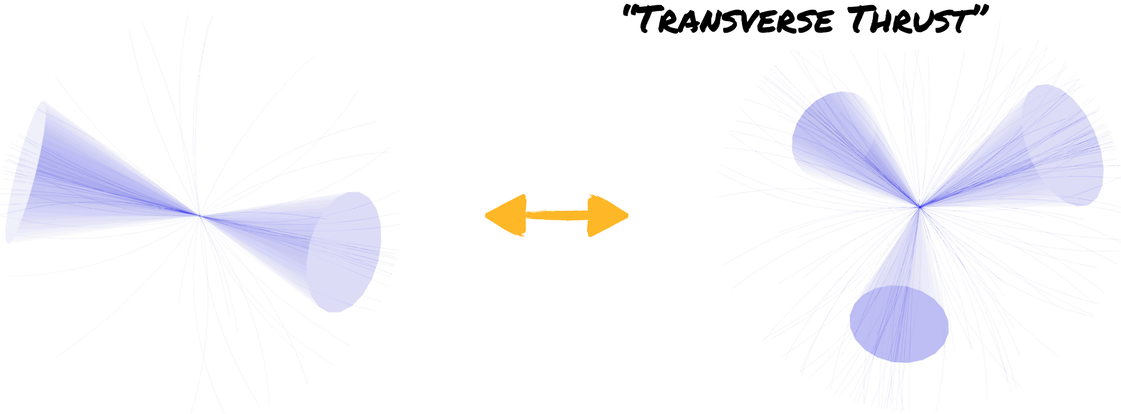
Isotropic?



Transverse thrust

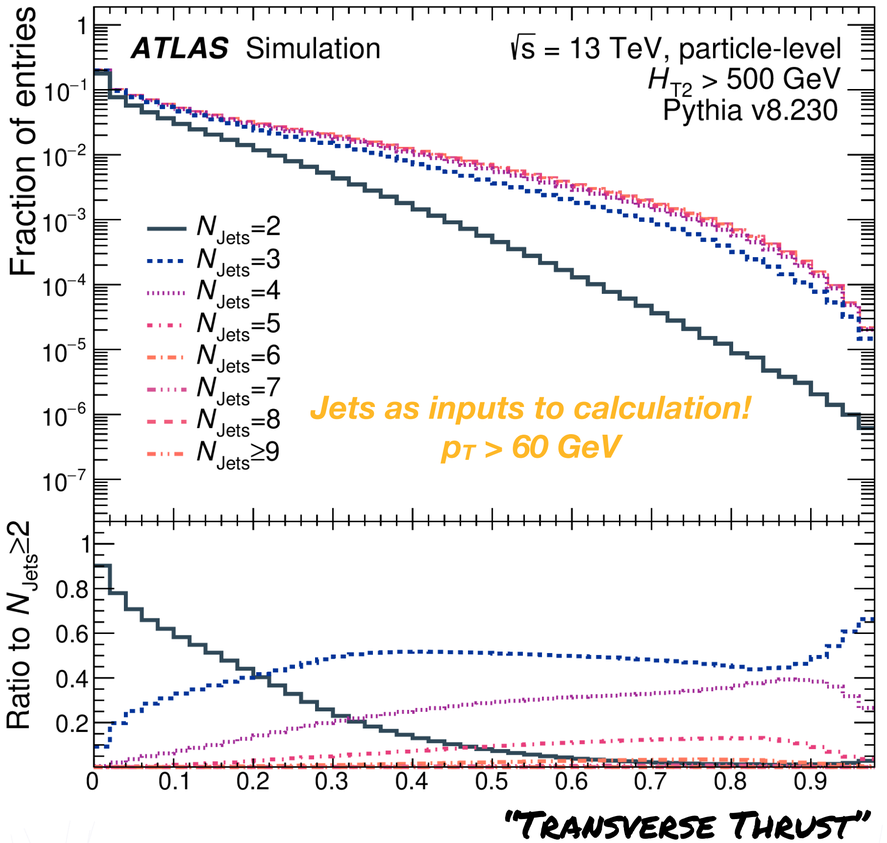
- **Transverse Thrust** is an extremely well-understood event shape in *pp* collisions.
  - Quantifies how “back-to-back” an event is.
    - **Small values:** back-to-back
    - **Large values:** ‘Mercedes’
- ***Are Mercedes events isotropic?***

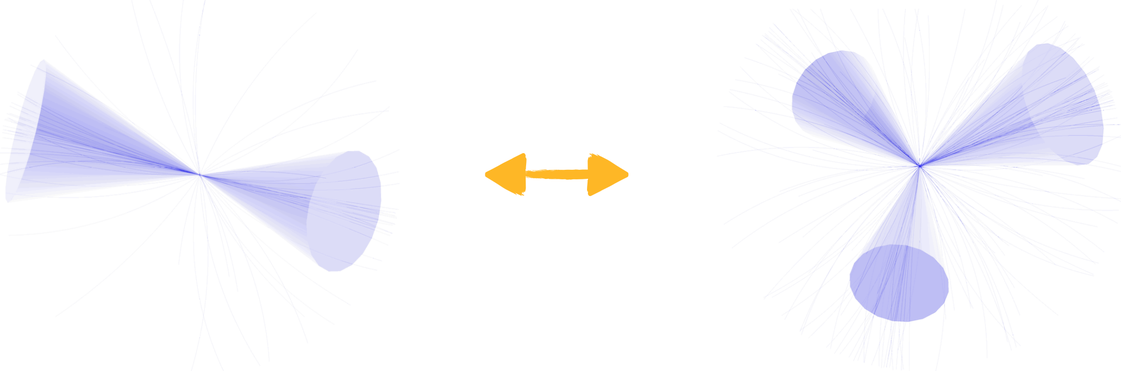


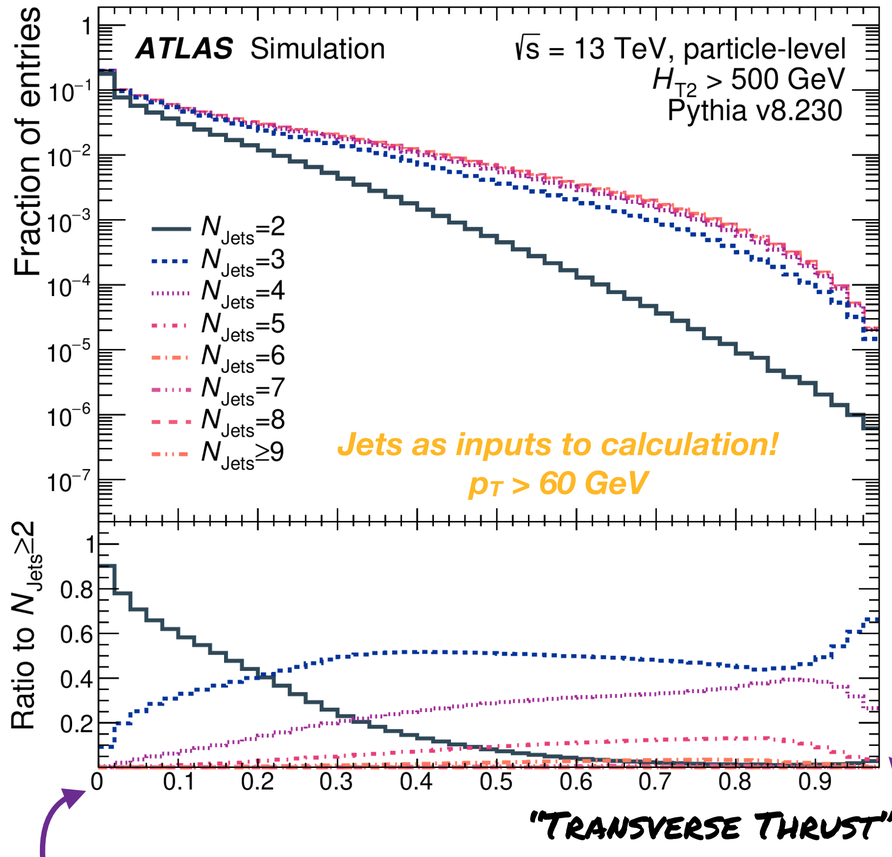


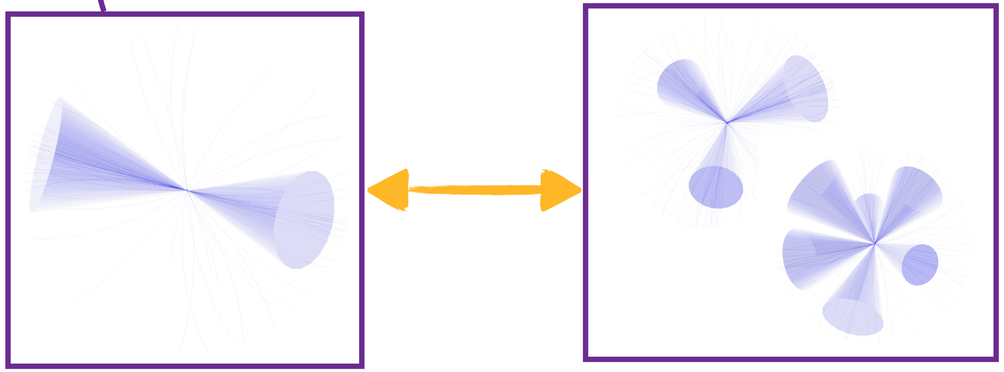
Transverse thrust

- **Transverse Thrust** is an extremely well-understood event shape in *pp* collisions.
  - Quantifies how “back-to-back” an event is.
    - **Small values:** back-to-back
    - **Large values:** ‘Mercedes’
- ***Are Mercedes events isotropic?***
- ***What about the 6-jet event?***









These go in the same bin!

Thrust picks out back-to-back events. To separate isotropic configurations, we need a notion of 'distance'

Komiske, Metodiev & Thaler, PRL 123, 041801 (2019), JHEP 07 (2020) 006

$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta}$$

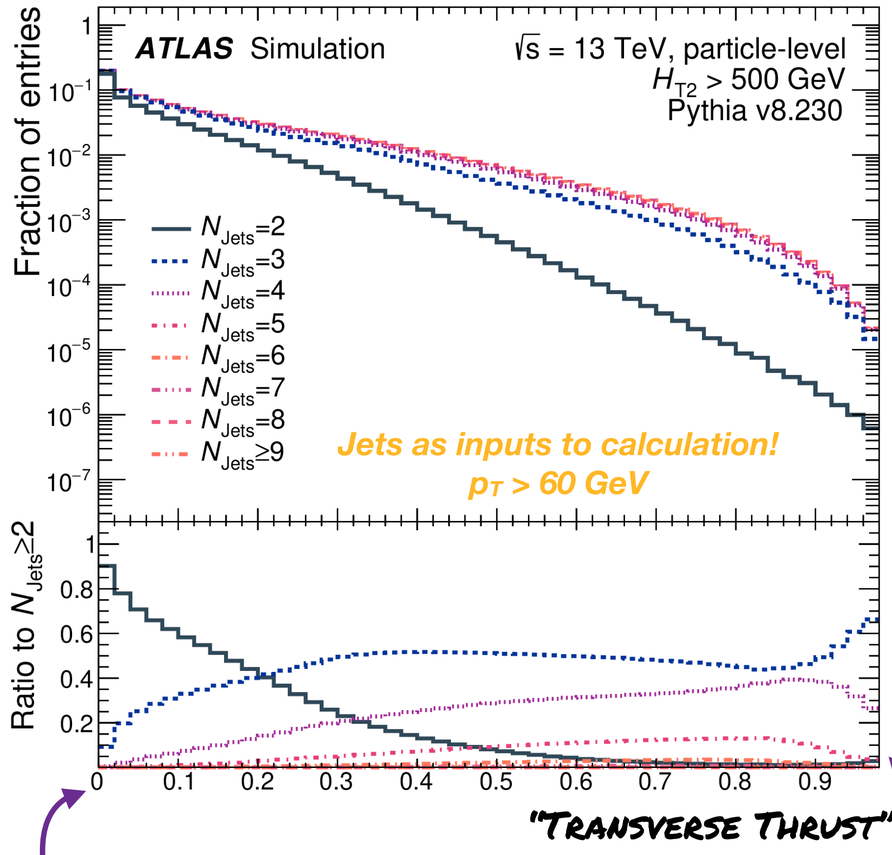
- **Energy Mover's Distance** : minimum 'work' required to re-arrange one event into another.
  - Formulated as Optimal Transport problems
  - Corresponds to the ***p*-Wasserstein** class of metrics.
  - Familiar event shapes like **Transverse Thrust** can be formulated in terms of EMDs:

$$t(\mathcal{E}) = 2\min_{\hat{n}} \sum_{i=1}^{M} \frac{|\vec{p}_i|(1-|\vec{n}_i\cdot\hat{n}|)}{E_{\mathrm{total}}}$$

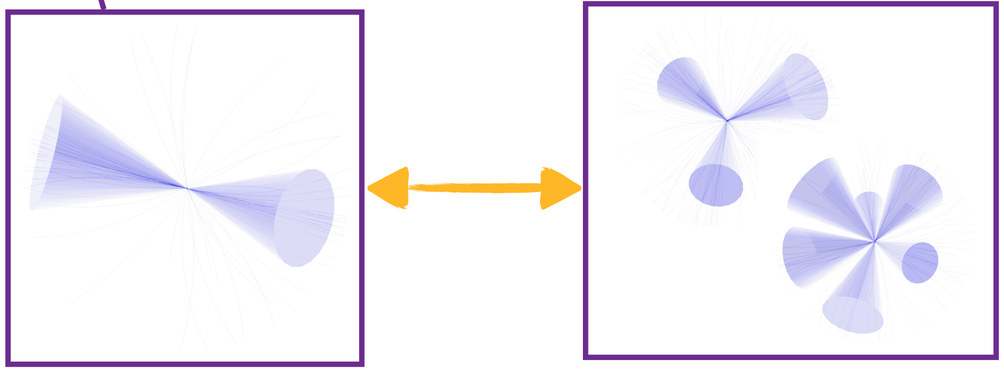
Energy weight

Angular measure

Q: ... what is E' ?



"Transverse Thrust"



These go in the same bin!

Thrust picks out back-to-back events. To separate isotropic configurations, we need a notion of 'distance'

Komiske, Metodiev & Thaler, PRL 123, 041801 (2019), JHEP 07 (2020) 006

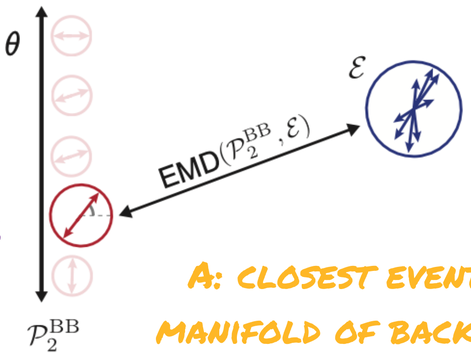
$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta}$$

- **Energy Mover's Distance** : minimum 'work' required to re-arrange one event into another.
  - Formulated as Optimal Transport problems.
  - Corresponds to the ***p*-Wasserstein** class of metrics.
  - Familiar event shapes like **Transverse Thrust** can be formulated in terms of EMDs:

$$t(\mathcal{E}) = 2\min_{\hat{n}} \sum_{i=1}^{M} \frac{|\vec{p}_i|(1-|\vec{n}_i\cdot\hat{n}|)}{E_{\mathrm{total}}}$$

Energy weight

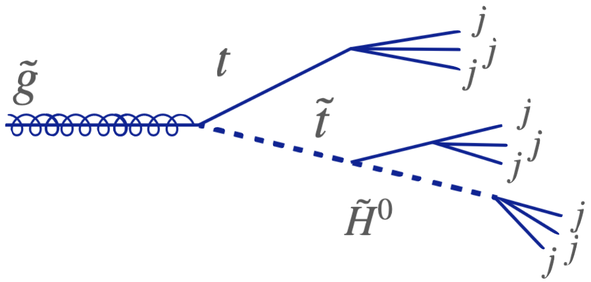
Angular measure

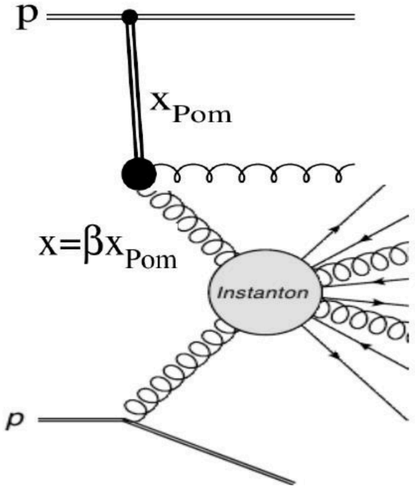


A: closest event in manifold of back-to-back configurations!

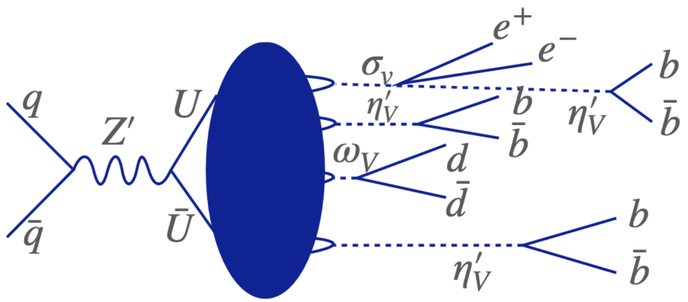
Q: ... what is E' ?

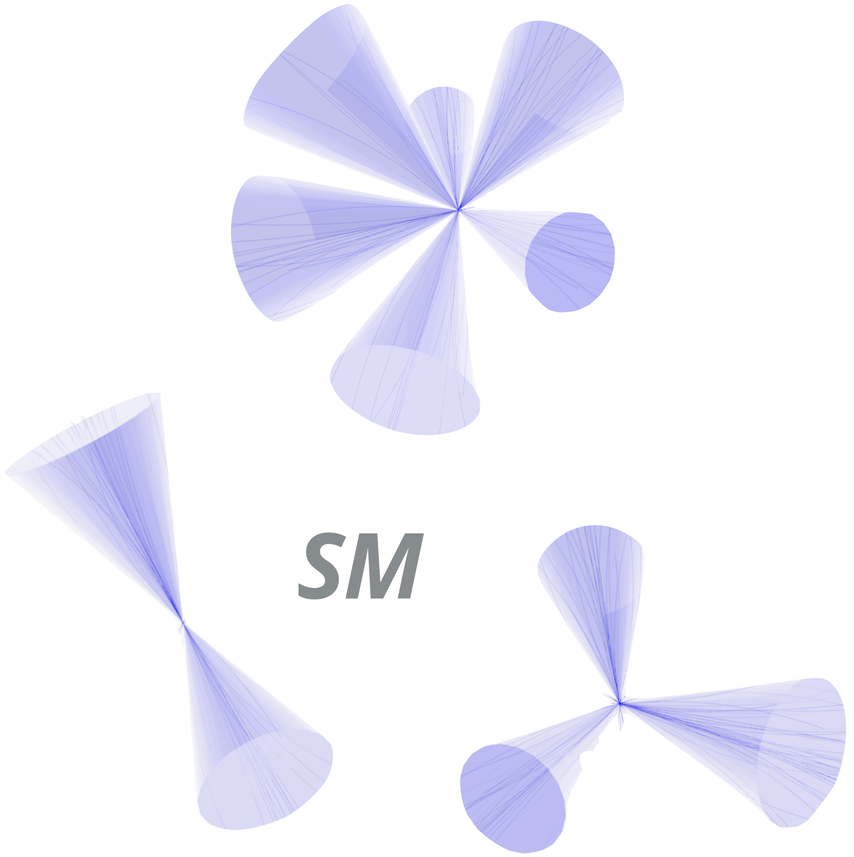
Main idea: we want new event shapes, sensitive to complementary features (symmetries, *etc.*).





BSM



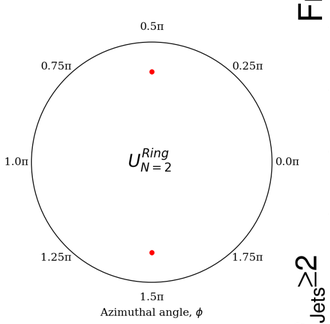


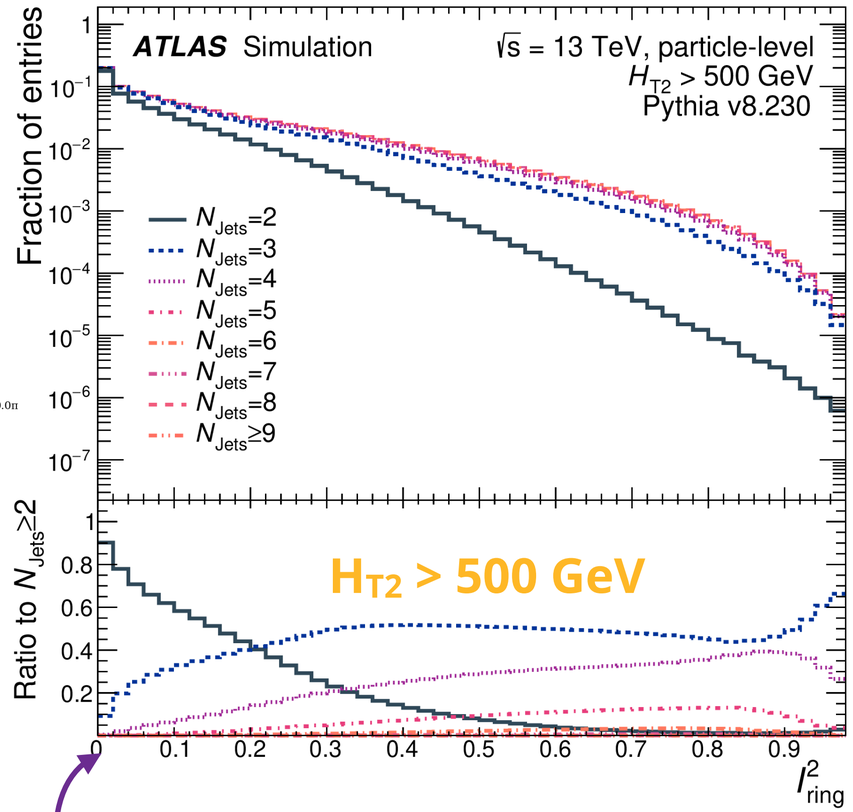
SM

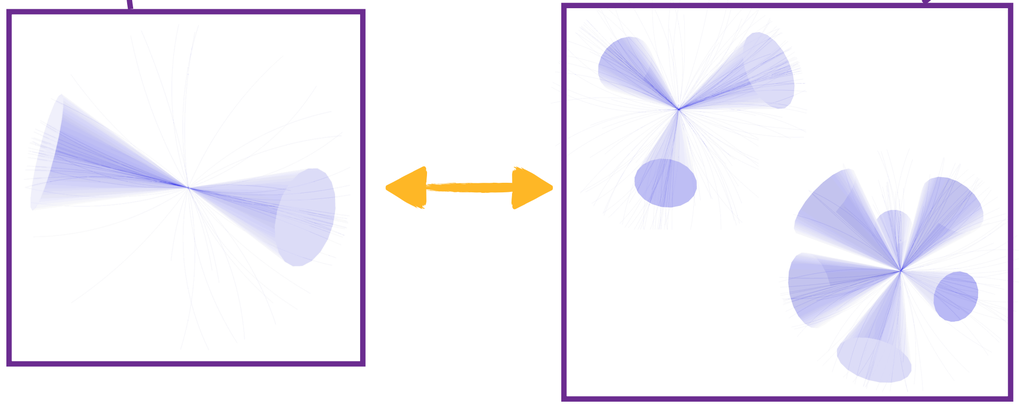
We can design them using EMDs.

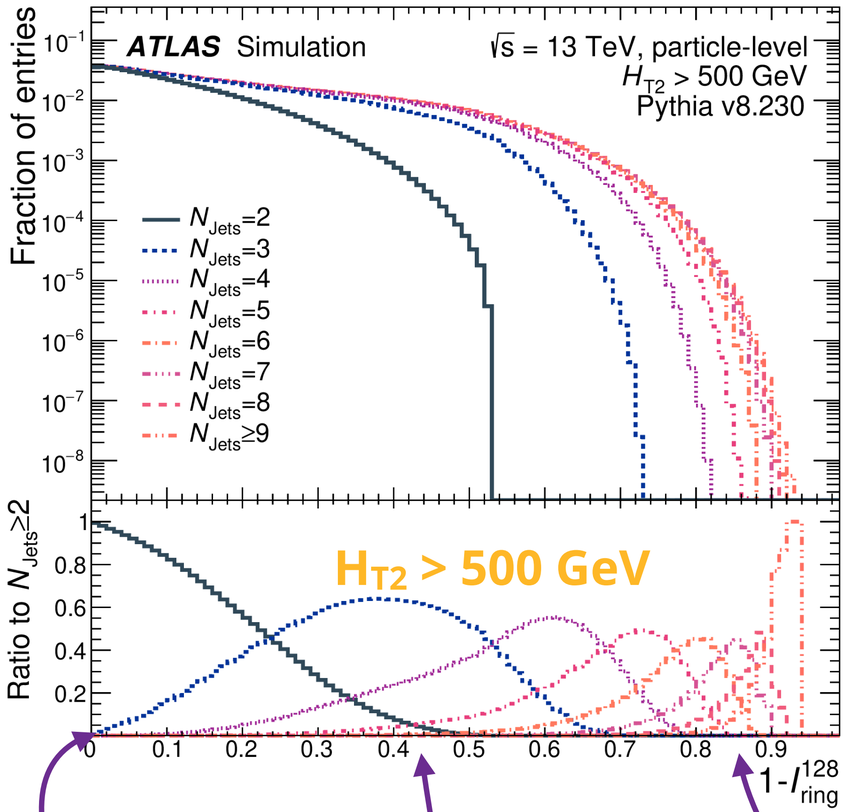
Different properties w/ different references...

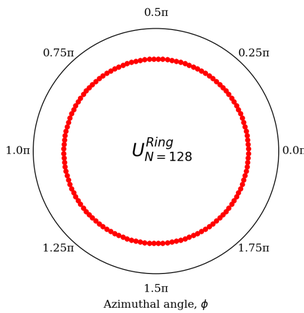
ATLAS JHEP 10 (2023) 060
Based on Cesarotti & Thaler, https://arxiv.org/abs/2004.06125

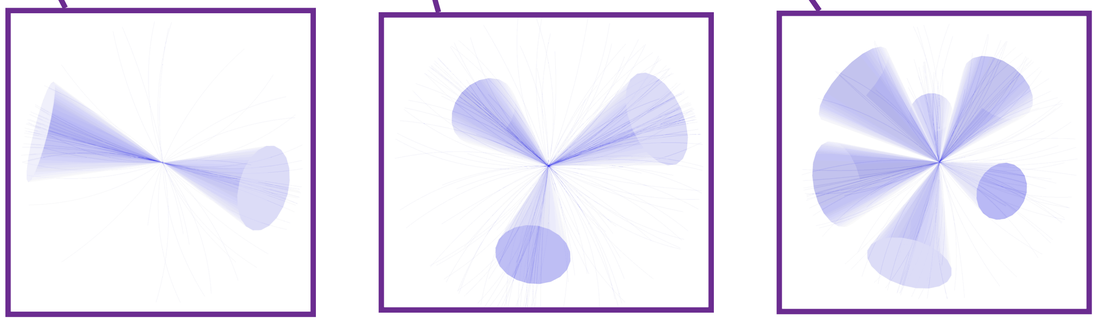






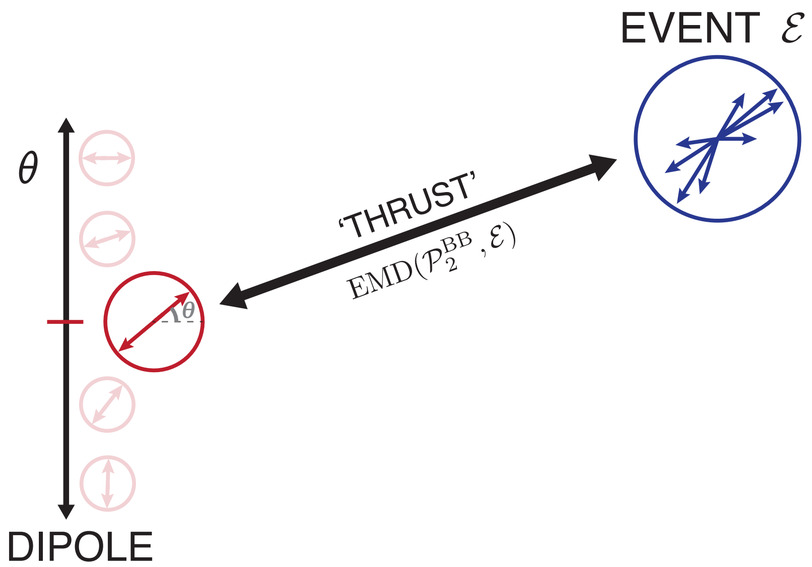






Novel event shapes via OT: ‘event isotropy’

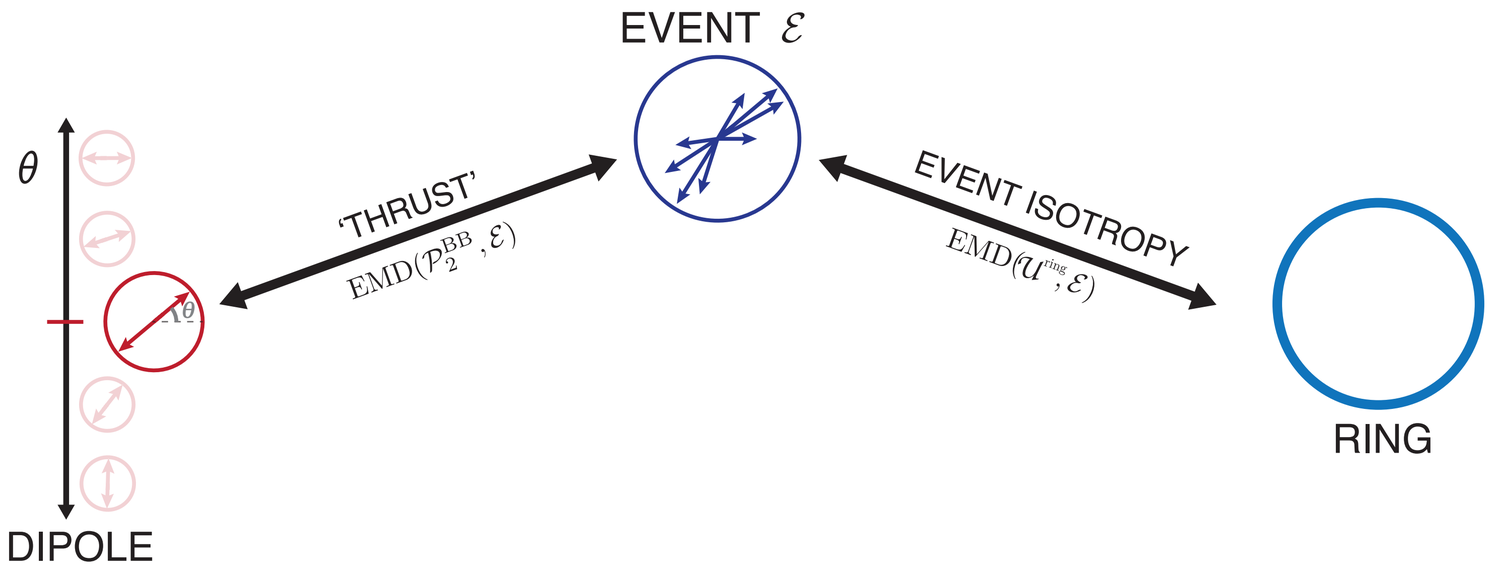
Cesarotti & Thaler, https://arxiv.org/abs/2004.06125
***ATLAS** JHEP 10 (2023) 060*



- **We measured 3 EMDs, per-event:**
  - … to transverse, balanced 2-point event (thrust-like).

Novel event shapes via OT: ‘event isotropy’

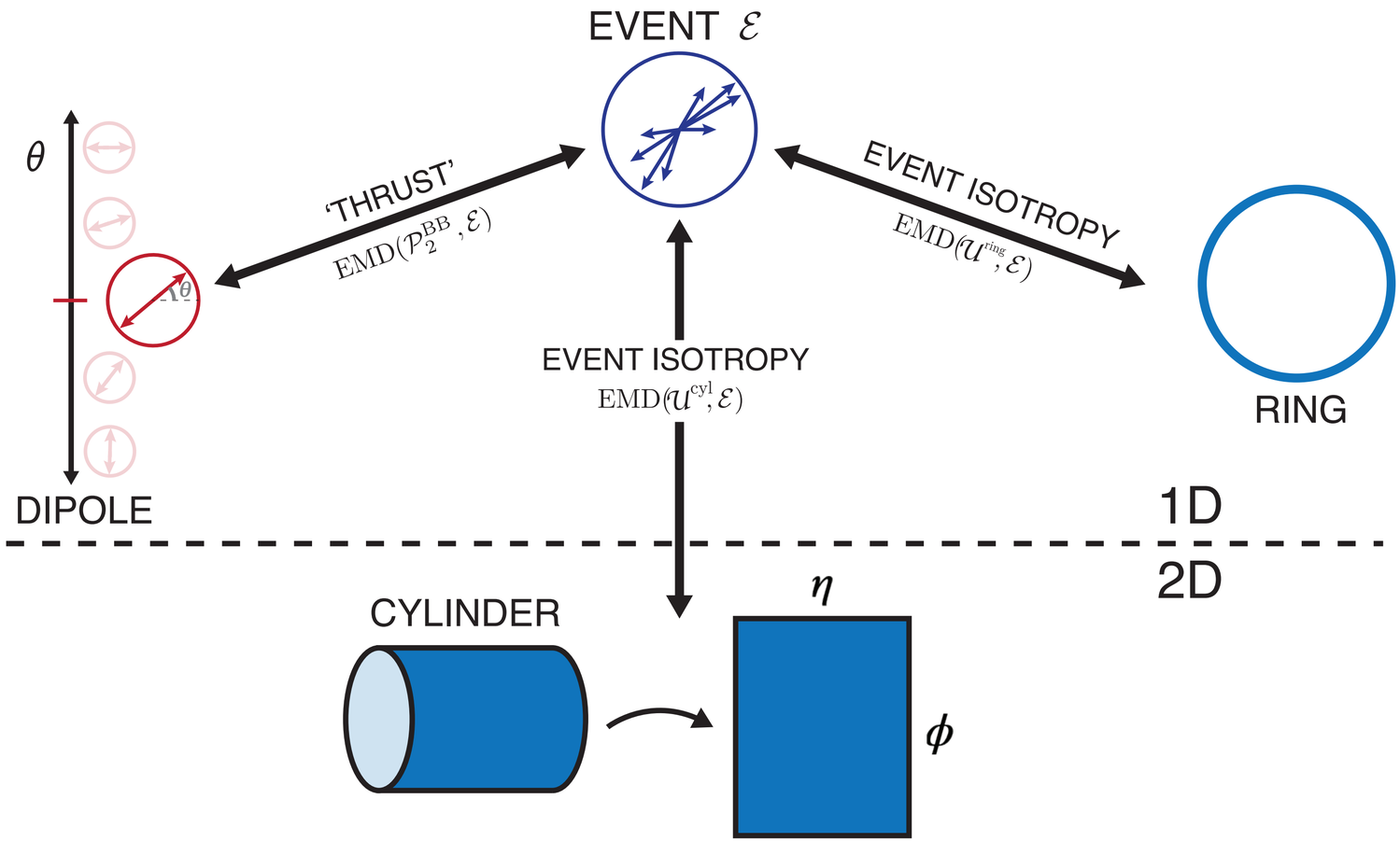
Cesarotti & Thaler, https://arxiv.org/abs/2004.06125
***ATLAS** JHEP 10 (2023) 060*



- **We measured 3 EMDs, per-event:**
  - … to transverse, balanced 2-point event (thrust-like).
  - … to transverse, ring-like geometry.

Novel event shapes via OT: ‘event isotropy’

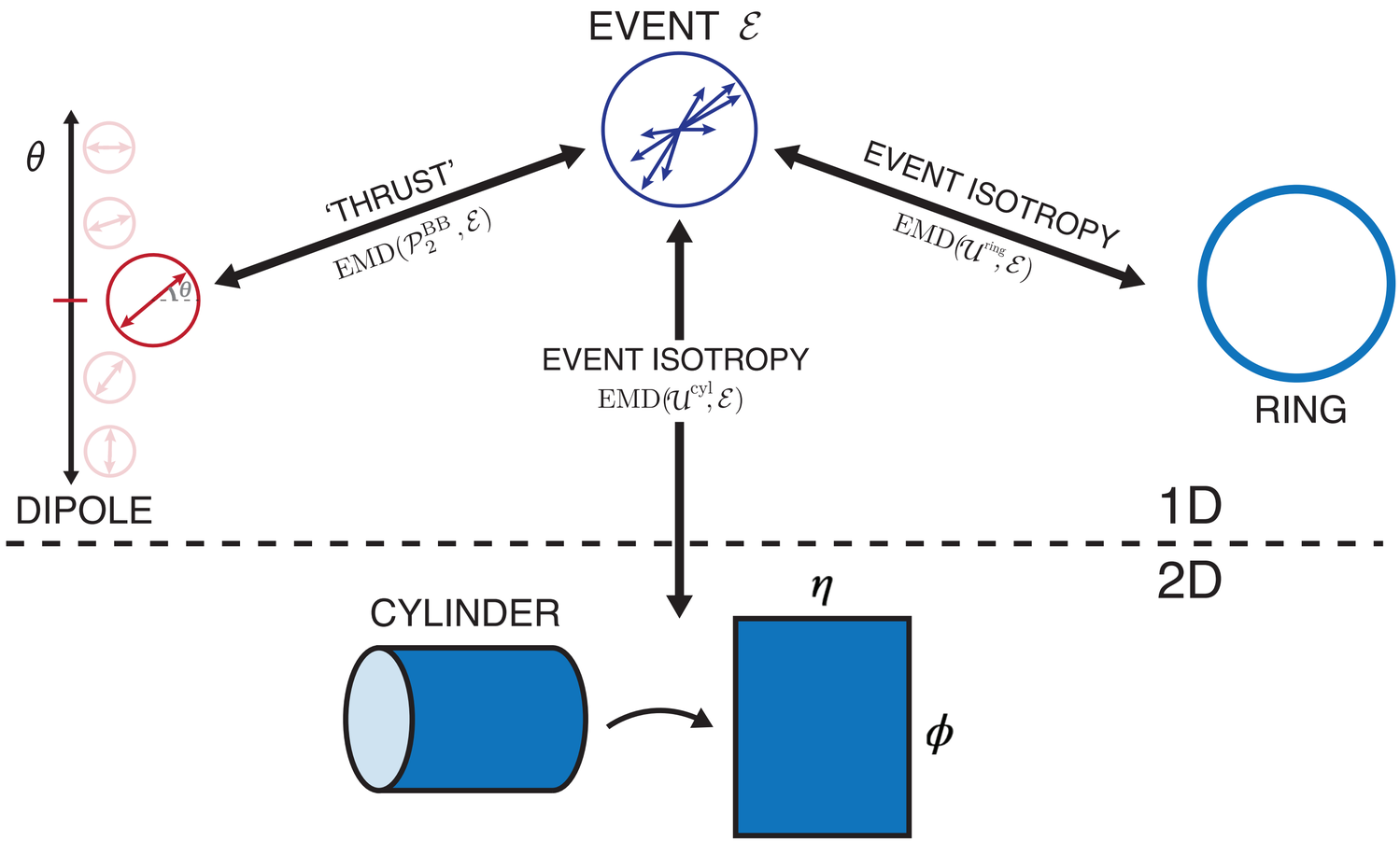
Cesarotti & Thaler, https://arxiv.org/abs/2004.06125
***ATLAS** JHEP 10 (2023) 060*



- **We measured 3 EMDs, per-event:**
  - … to transverse, balanced 2-point event (thrust-like).
  - … to transverse, ring-like geometry.
  - … to uniform 2D (y,phi) grid.

Novel event shapes via OT: ‘event isotropy’

Cesarotti & Thaler, https://arxiv.org/abs/2004.06125
***ATLAS** JHEP 10 (2023) 060*



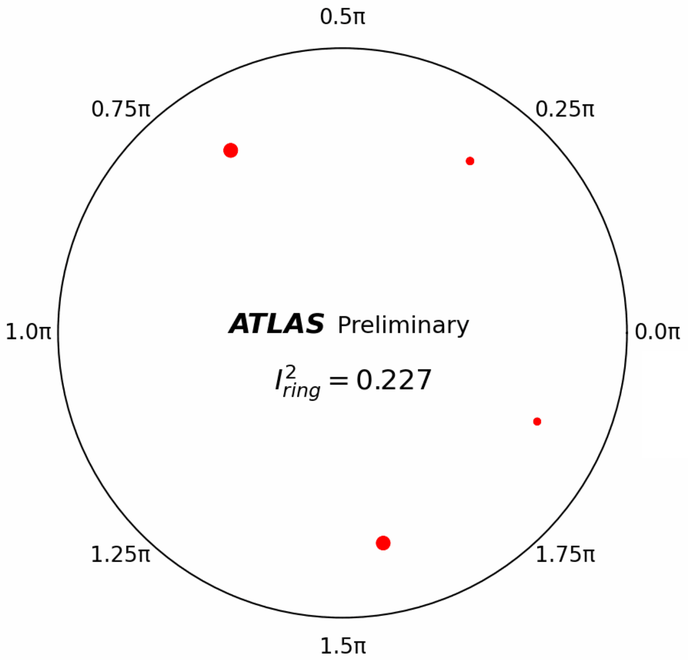
- **We measured 3 EMDs, per-event:**
  - … to transverse, balanced 2-point event (thrust-like).
  - … to transverse, ring-like geometry.
  - … to uniform 2D (y,phi) grid.

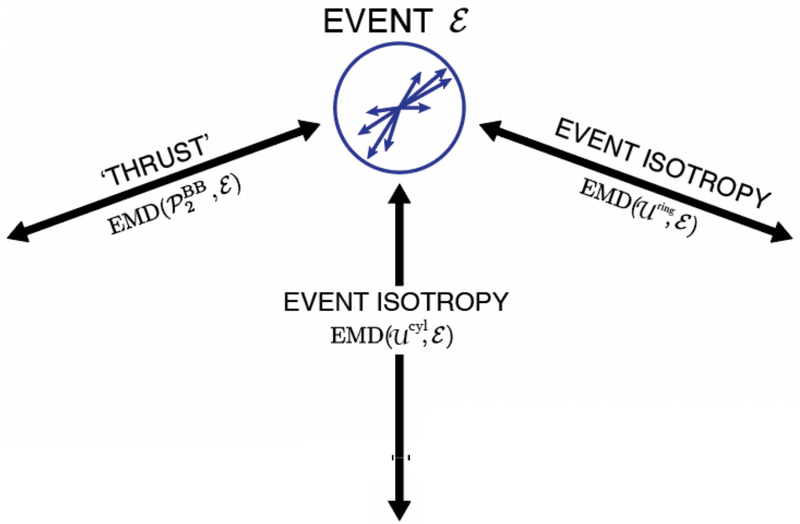
- Used ***R*=0.4 PFlow jets** as inputs to EMD calculations (*ß*=2).
  - $p_{\mathrm{T}} > 60$ GeV, $|y| < 4.4$
  - $H_{\mathrm{T2}} > 500$ GeV
  - Recoil-corrected
- Measurements in inclusive bins of **jet multiplicity** and $\boldsymbol{H_{\mathrm{T2}} = p_{\mathrm{T},1}+p_{\mathrm{T},2}}$.
- Old-fashioned Iterative Bayesian Unfolding (N=2).

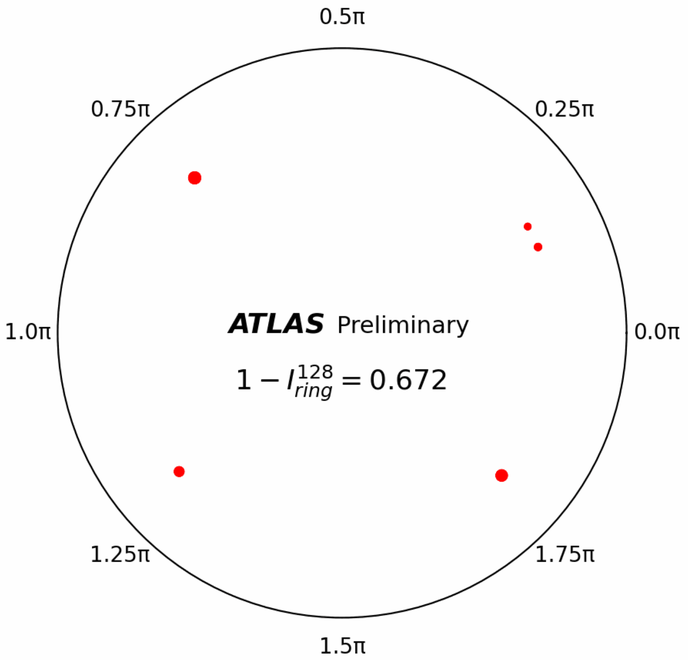
Animations are at this link (bottom of page) :
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2020-20/

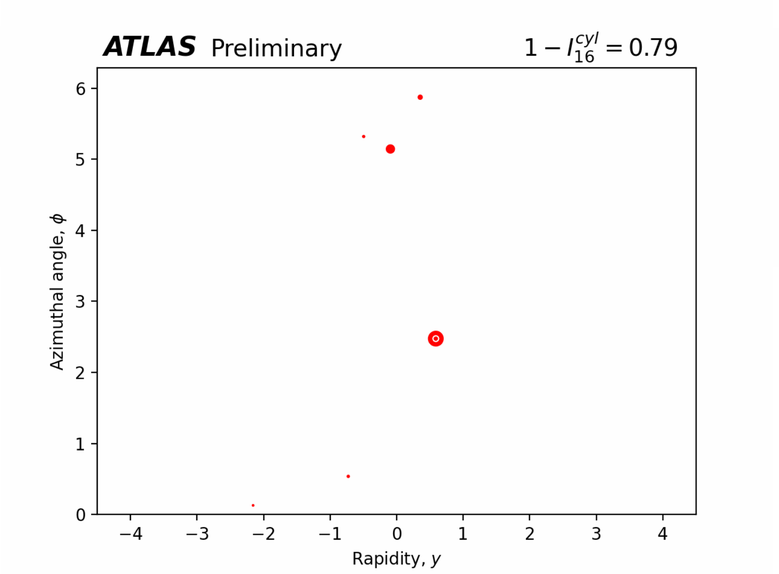
Visualisation of OT calculation

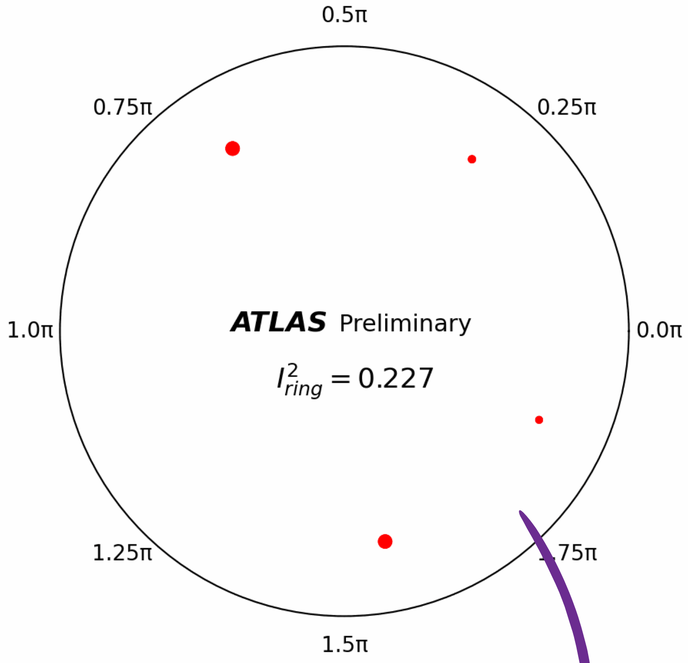
ATLAS *JHEP 10 (2023) 060*

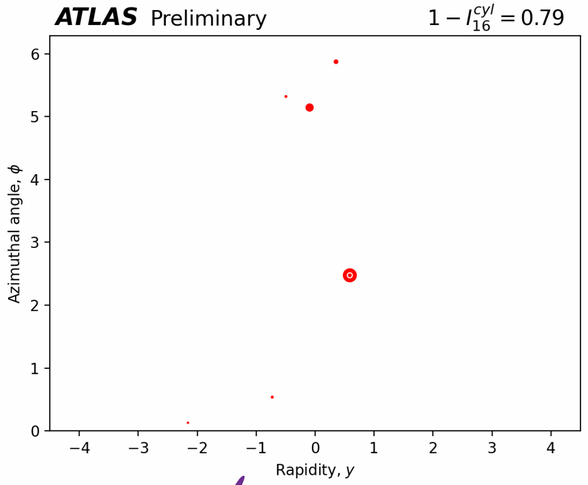


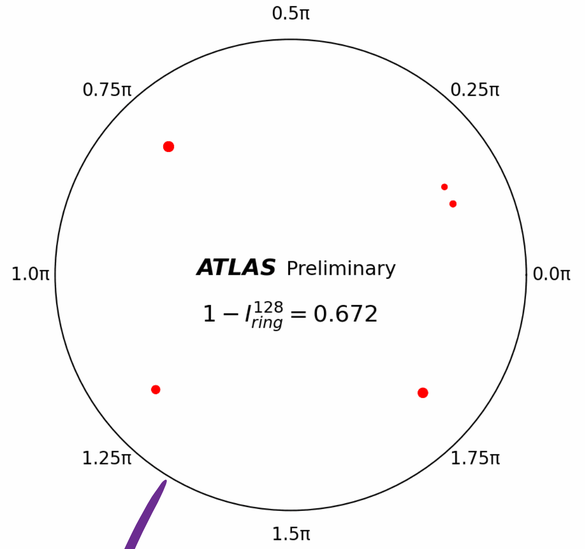


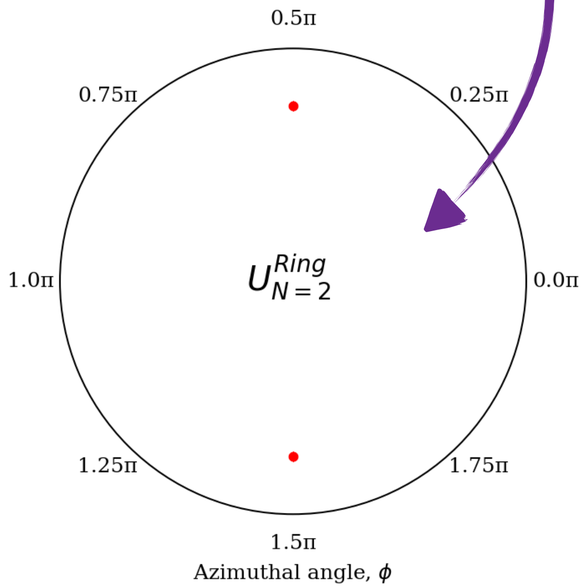


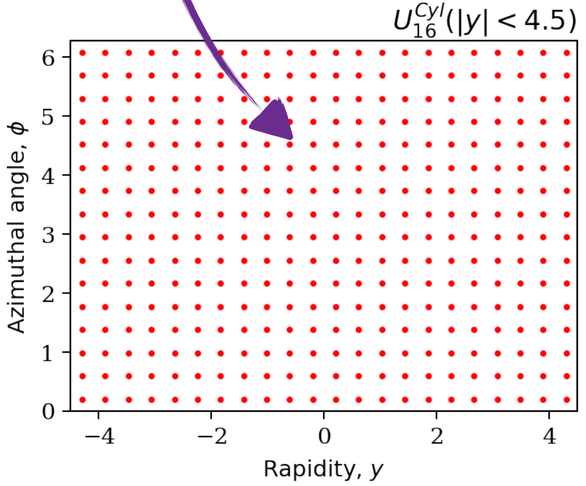


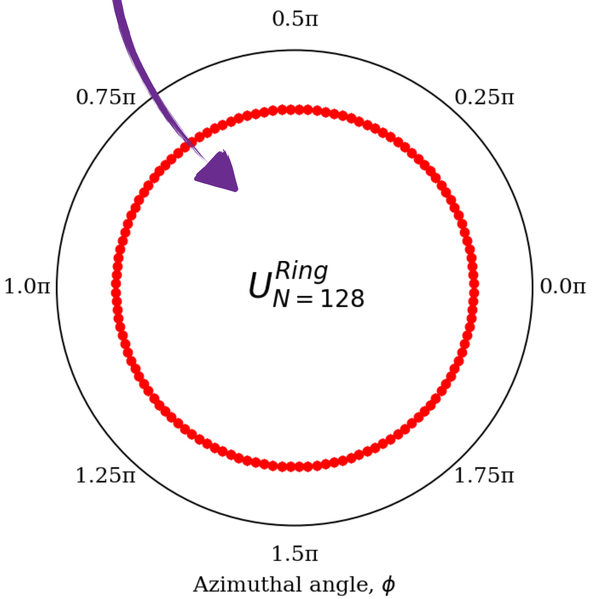










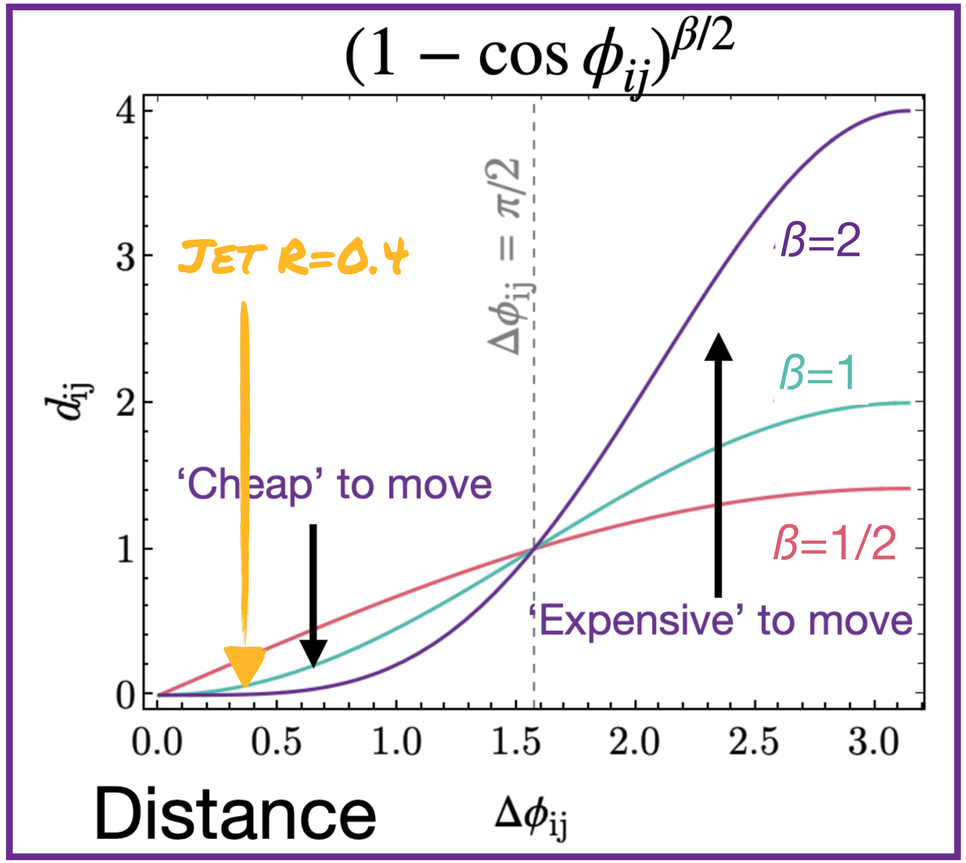


Animations are at this link : https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2020-20/

Technical remarks for #ML4Jets2023

ATLAS *JHEP 10 (2023) 060*

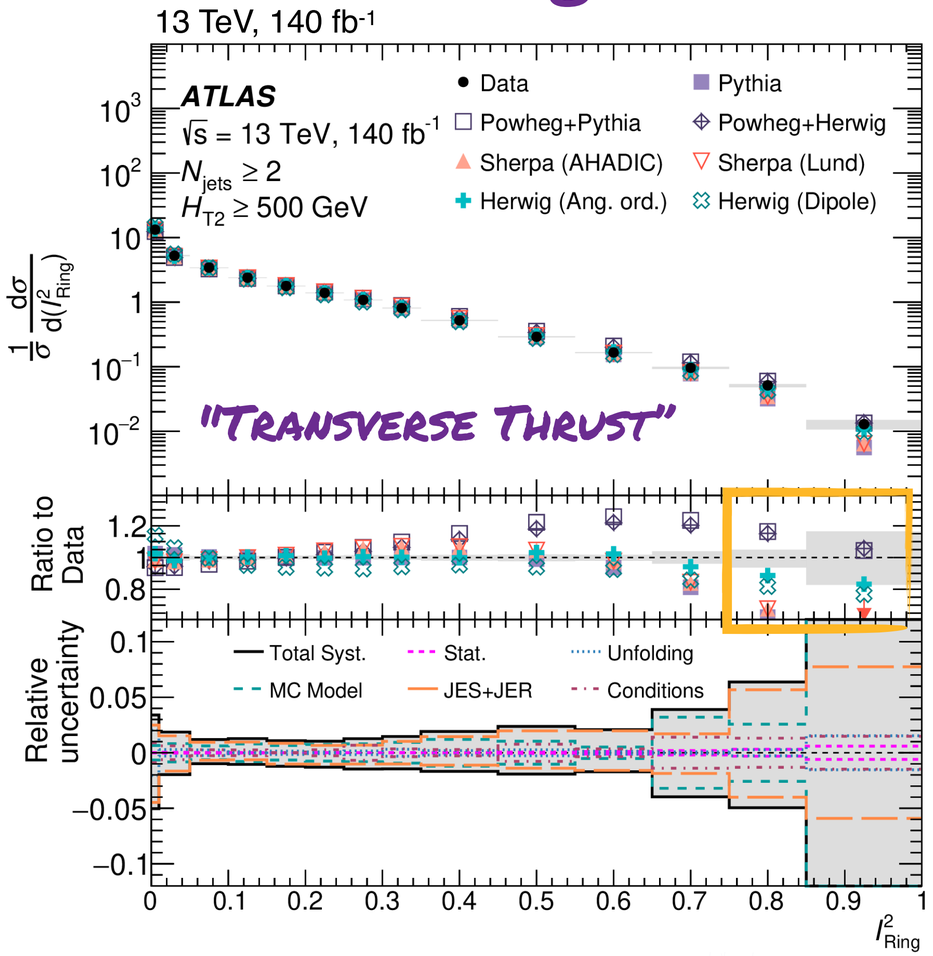
- EMDs calculated with **`Python Optimal Transport (POT)`** library via **`event_isotropy`** implementation (C. Cesarotti), also tested **`Wasserstein`** (P. Komiske *et al.*).
- It was a computational challenge: analysis optimised until last bottleneck was OT calculations, 3x EMDs for…
  - **~80M data events**
  - **~800M Pythia events, x114** JES variations (pushing it)
    - ~45% of runtime for 2D EMD (N=352),
      ~40% for thrust axis minimisation (N=2),
      rest for other operations (I/O, selection, etc.)
  - **Rikab's talk on Wednesday made me hopeful!**
- *n.b.* EMD computational complexity scales as ~$O(N^3\log(N^2))$
  → use jets instead of particles to reduce multiplicity
  (~no difference for β=2).



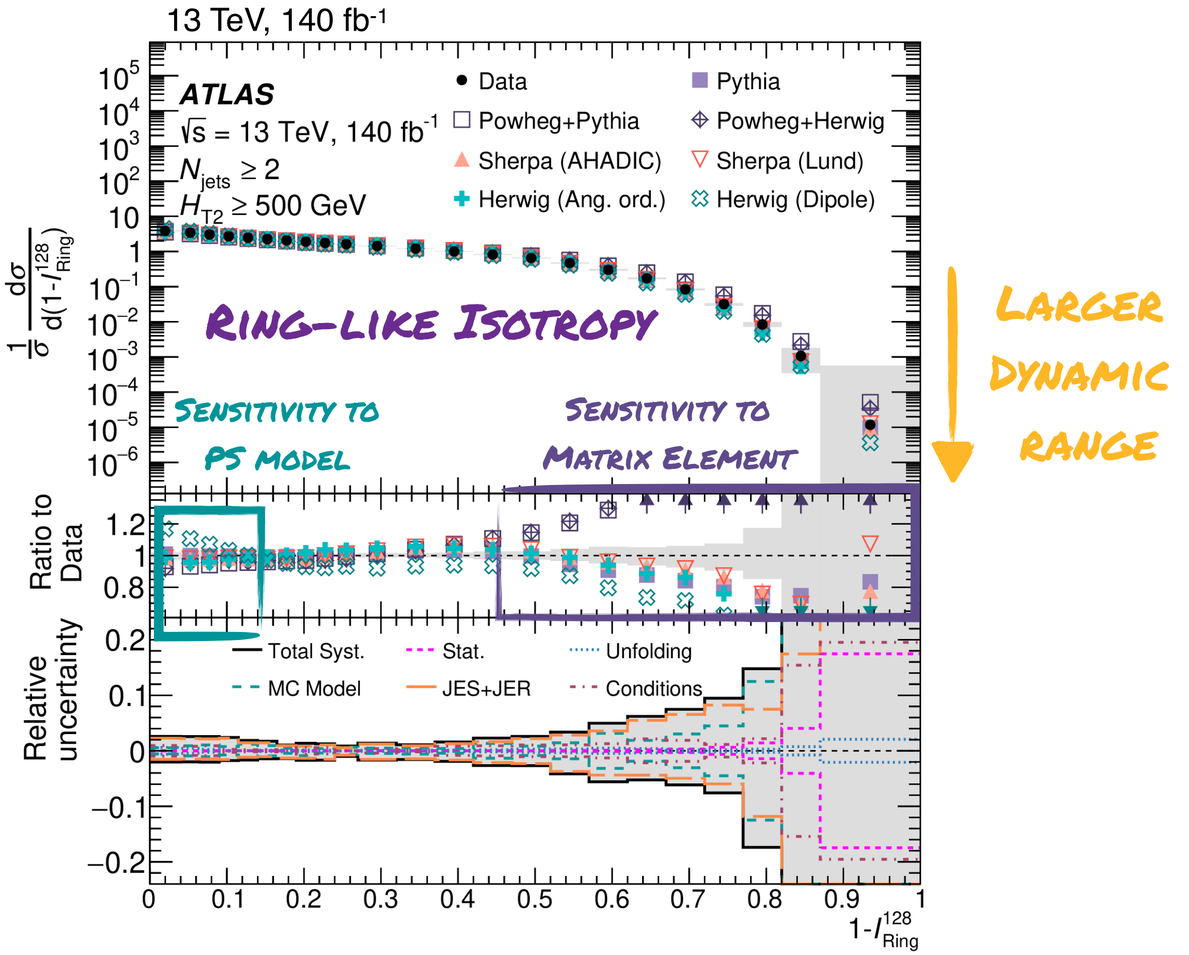
Work-in-Progress, C. Cesarotti (w/MLB) at BOOST 2023

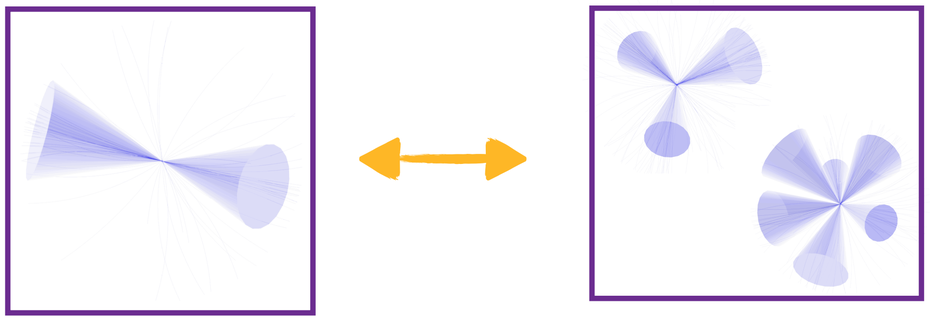
Results: I_{Ring}^{2} and I_{Ring}^{128}

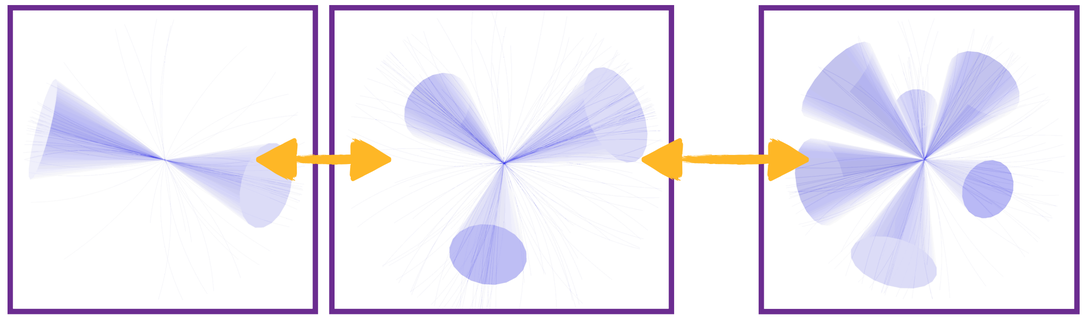
ATLAS JHEP 10 (2023) 060



NLO Performs Best for 3-jet events





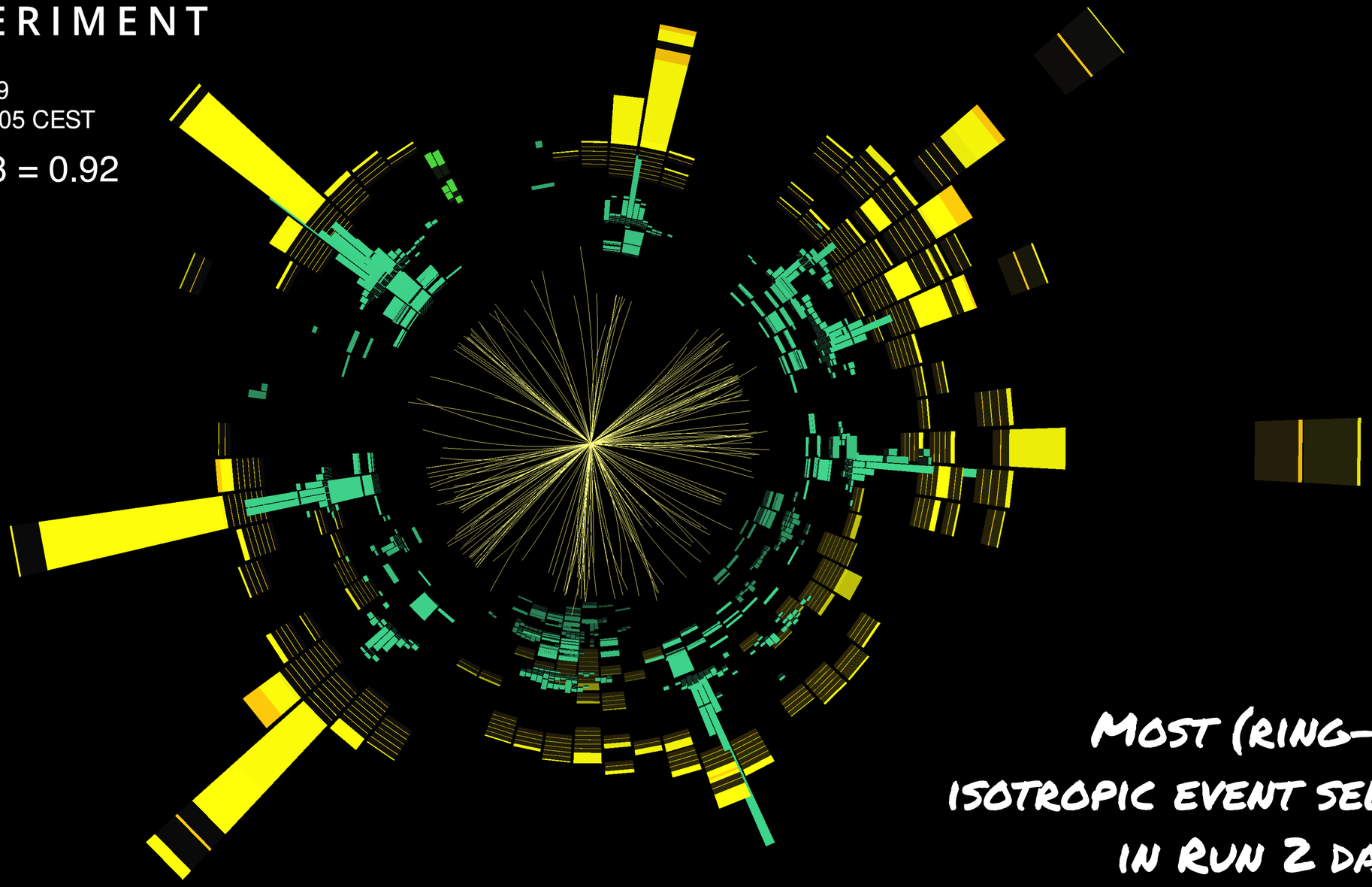


ATLAS JHEP 10 (2023) 060

ATLAS EXPERIMENT

Run: 300687
Event: 1358542809
2016-06-02 18:19:05 CEST

1-IsoRing128 = 0.92
N_{jets} = 12



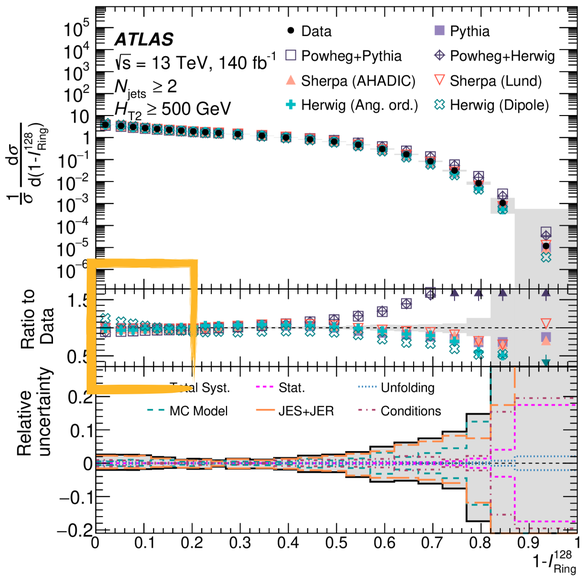
Most (ring-like) isotropic event selected in Run 2 dataset!

Results: I_{Ring}^{128} *vs.* N_{jets}

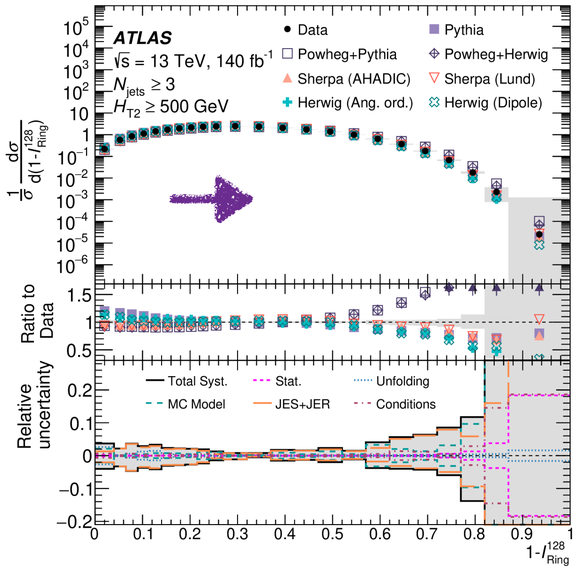
ATLAS JHEP 10 (2023) 060

Increase minimum jet requirement

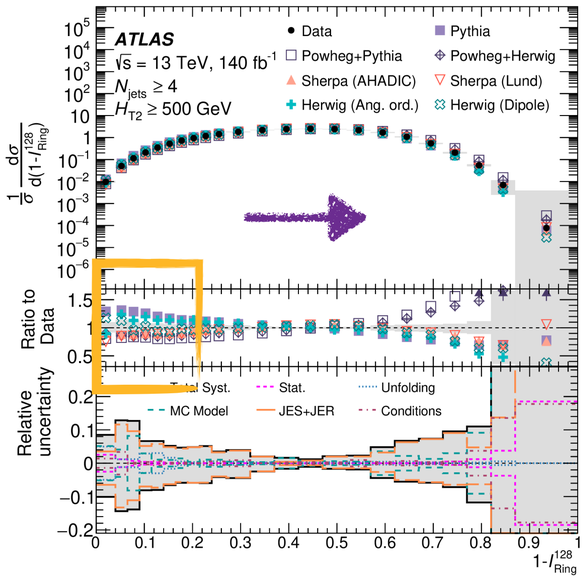
N>=2



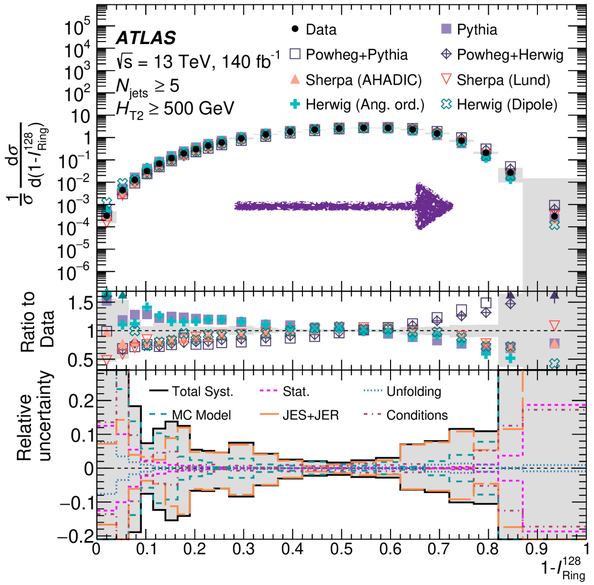
N>=3



N>=4



N>=5



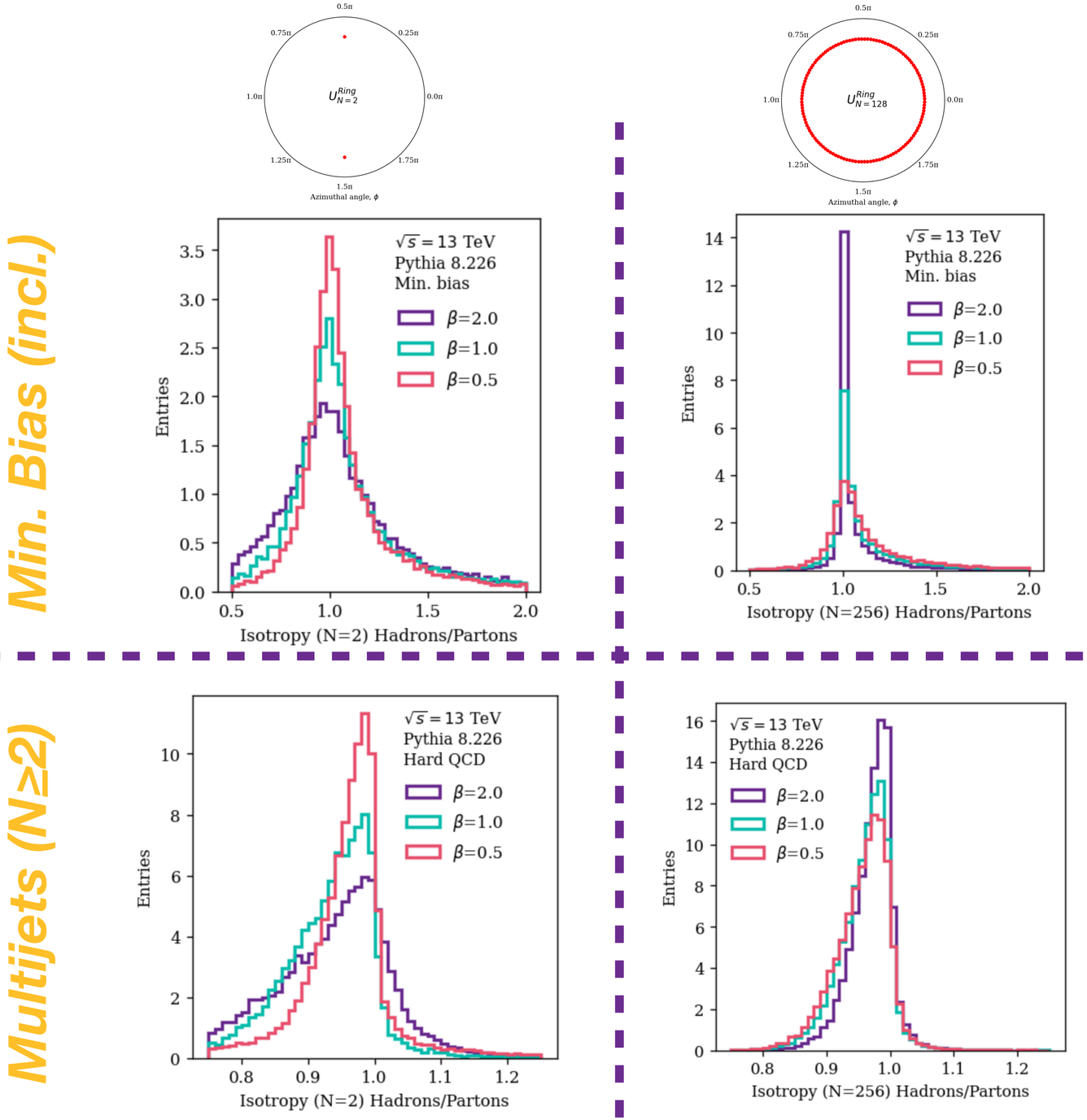
Data/MC disagreement deteriorates at "dijet-like" end: soft activity in the event increases difficulty for MC generators

Events become more isotropic on-average as Njets is increased (expected scaling!)

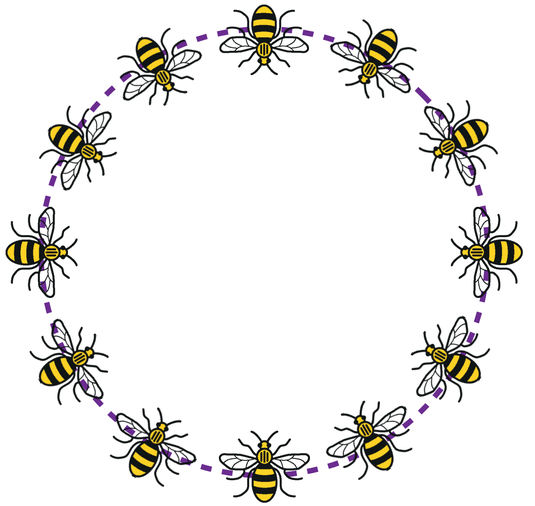
One last thing …

Work-in-Progress, C. Cesarotti & MLB (see also CC @ BOOST 2023)

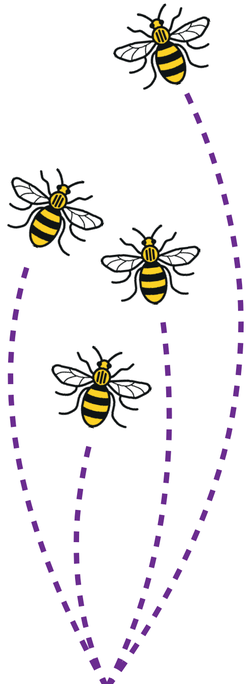
- If you want to try out event shapes like these, remember to keep in mind that there are **many choices to make when defining them!**
  - Symmetry of reference geometry (N=2 vs. Infinity, etc.)
  - Ground space metric (ß value)
  - *etc.*
- … the best choices for one process may not be optimal for another!

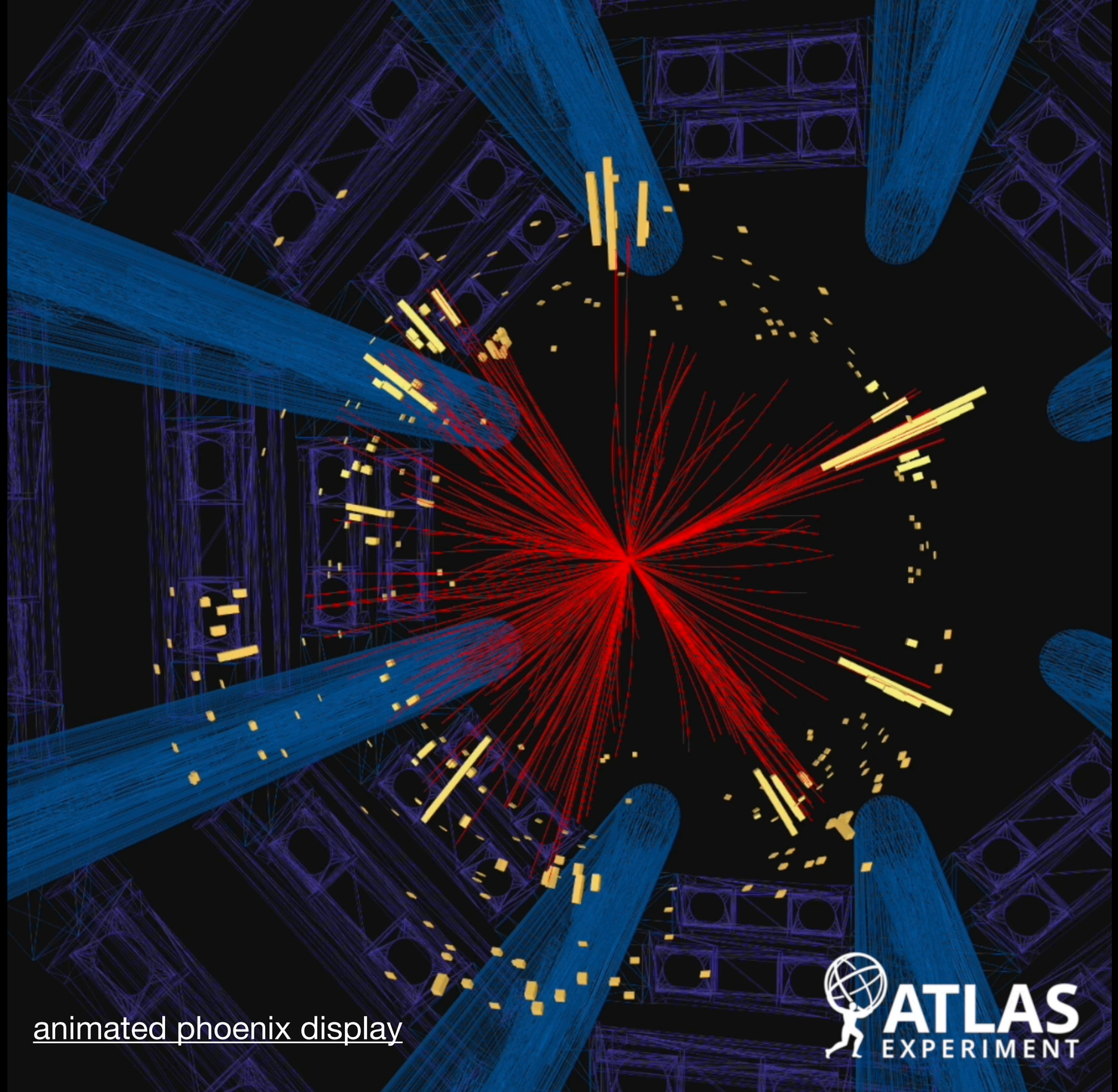


Concluding remarks



- **Event shapes have seen numerous applications over the last 50 years!**
  - From **JADE's gluon observation in 1980** (down the street from us!) to **ATLAS's recent search for RPV SUSY in 2023!**
- Many traditional event shapes pick out simple topologies, but for different symmetries (*e.g.* circular) may be of interest for different applications.
  - EMDs provide an intuitive framework to design new event shapes that possess the symmetries of interest for your application.
- **ATLAS has recently measured three 'event isotropy' observables** defined using EMDs, in multijet events.
  - Novel behaviour continuously interpolates between isotropic events from low to high multiplicity.
    - **Complement to existing measurements:** unfolded data provided to the community for future studies of QCD (modelling, CONTUR, *etc.*)





animated phoenix display

Thanks for Listening!

Want a recap? Read the briefing!

https://atlas.cern/Updates/Briefing/Multijet-Event-Isotropies

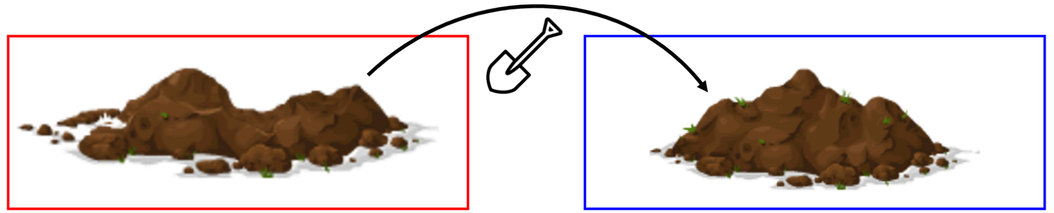
Auxiliary material.

Figures + Cartoons from Komiske et al.

Energy-Mover's Distance (EMD)

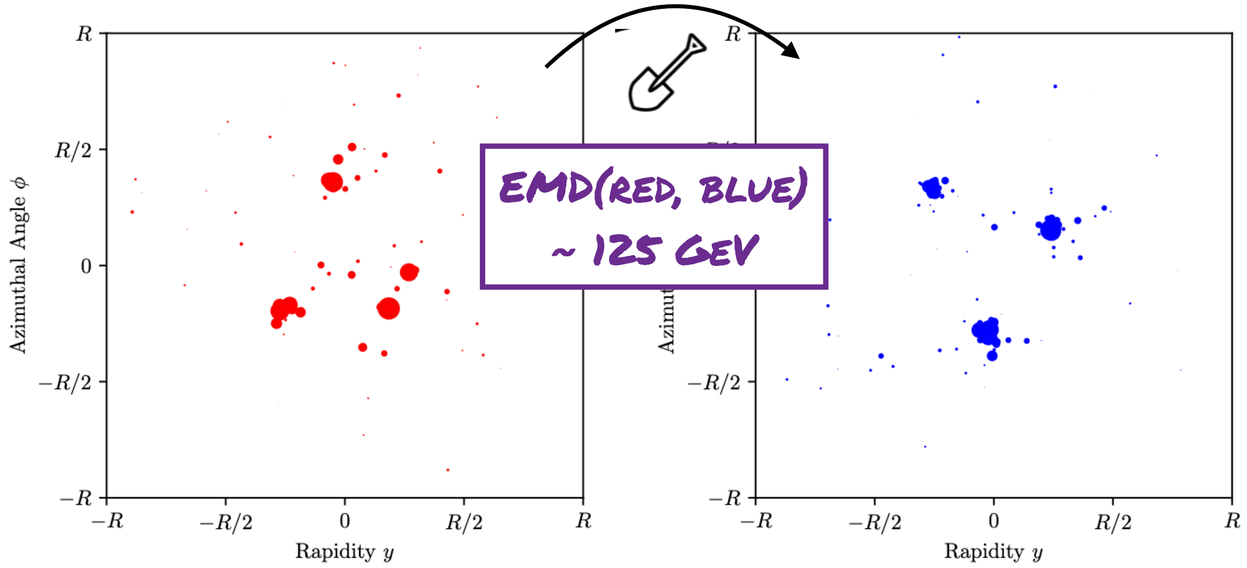
Komiske, Metodiev & Thaler, PRL 123, 041801 (2019), JHEP 07 (2020) 006

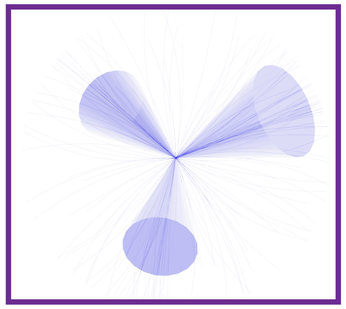
- Need **IRC-safe distance metric** between collider radiation patterns.
  - EMD defined as the **minimum 'work' required to re-arrange one event into another**.
    - Corresponds to the ***p*-Wasserstein** class of metrics.
- **Interdisciplinary tool for QCD analysis!**
  - EMDs used often in **computer vision**: problems solved w/ **Optimal Transport** techniques.
    - Common tools/libraries… 1, 2, 3
      - Some have been adapted for HEP! 4, 5

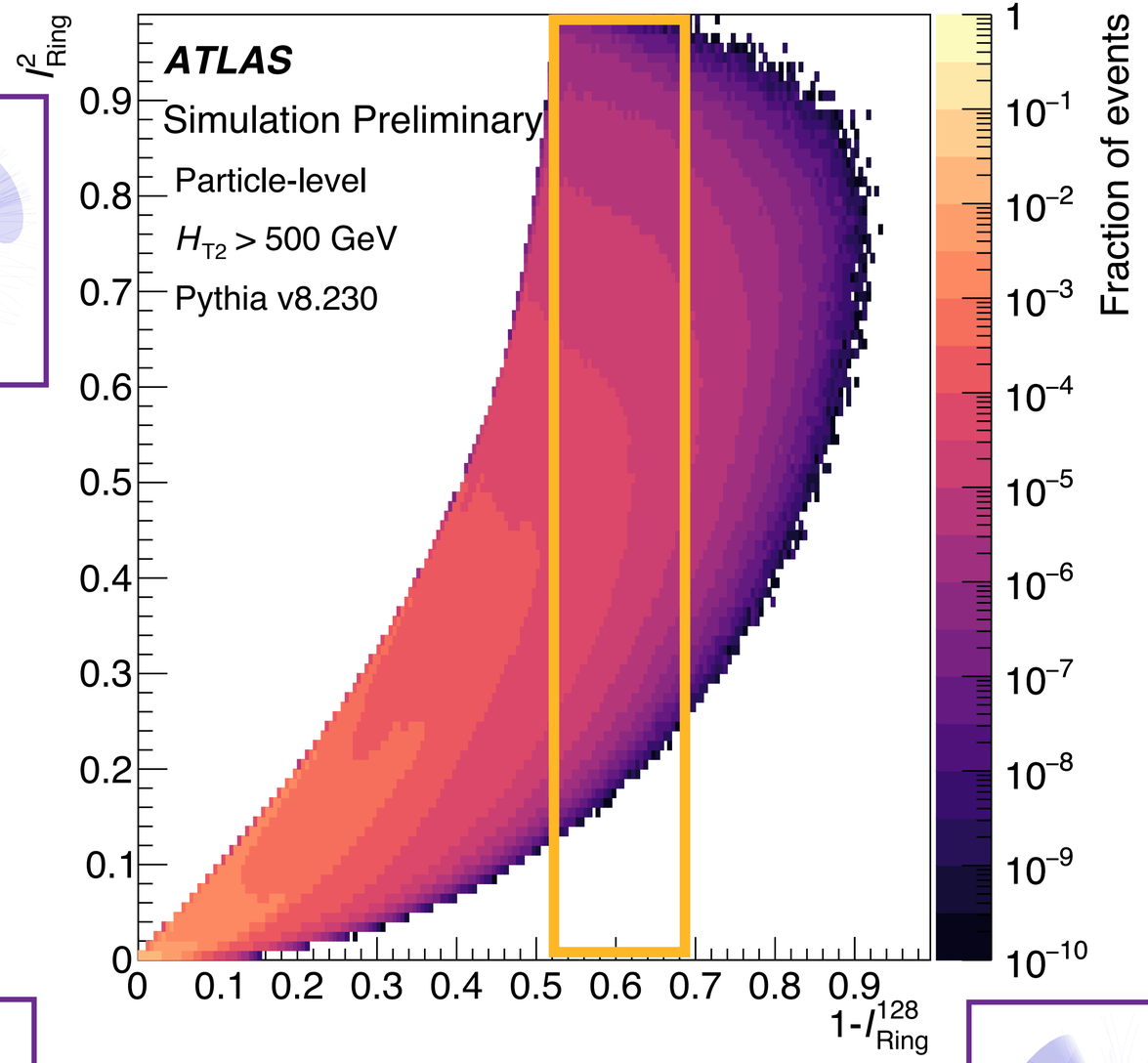


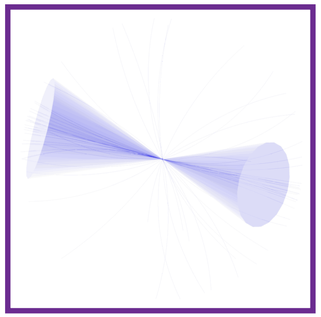
a.k.a. Earth-Mover's Distance

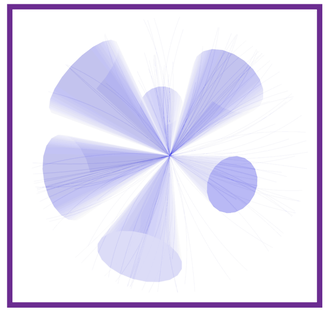
$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta}$$






ATLAS
Simulation Preliminary
Particle-level
$H_{T2} > 500$ GeV
Pythia v8.230
I^2_{Ring}
$1\text{-}I^{128}_{Ring}$
Fraction of events
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}



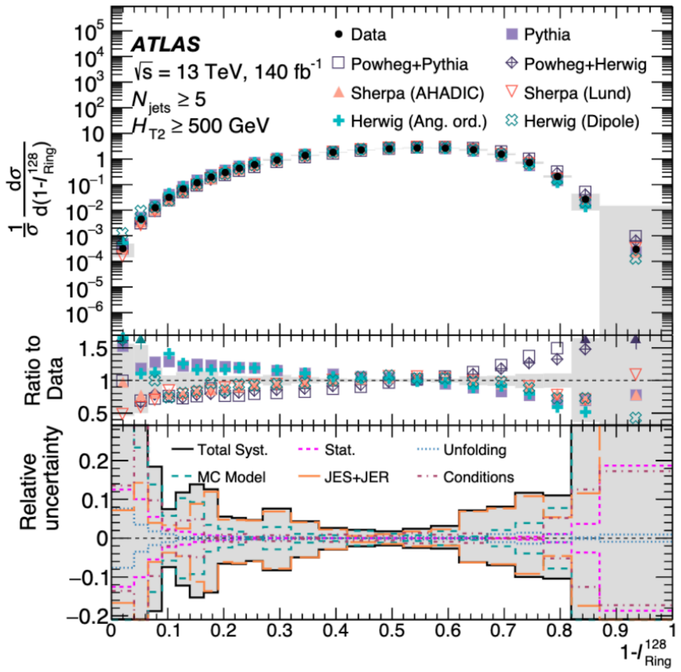


Results: I_{Ring}^{128} vs. H_{T2}

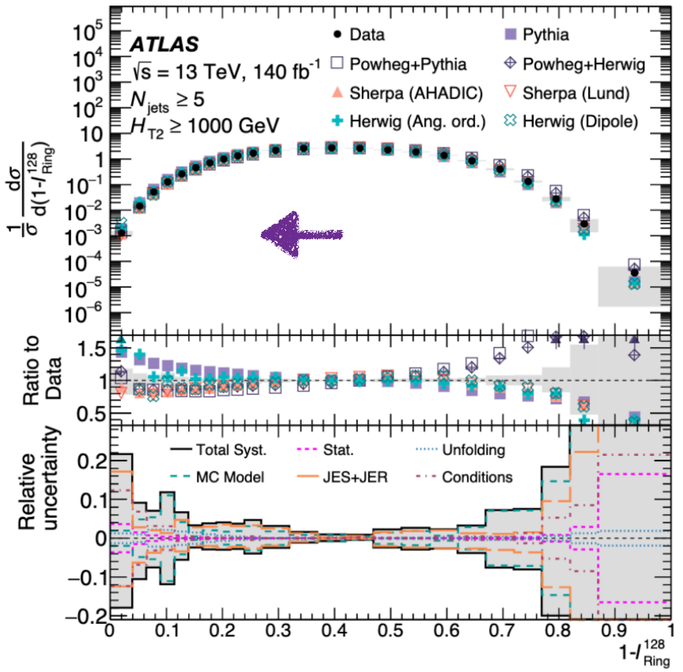
ATLAS JHEP 10 (2023) 060

Increase minimum H_{T2} requirement

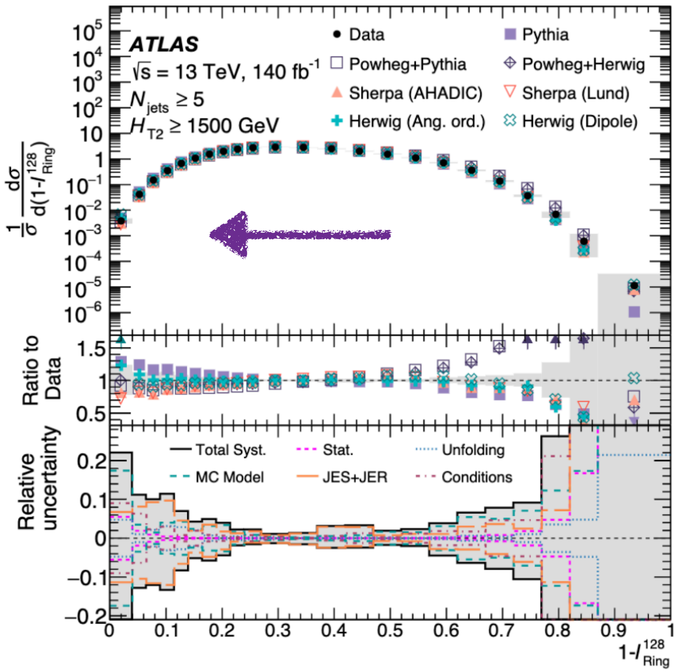
H_{T2} >= 500 GeV



H_{T2} >= 1000 GeV

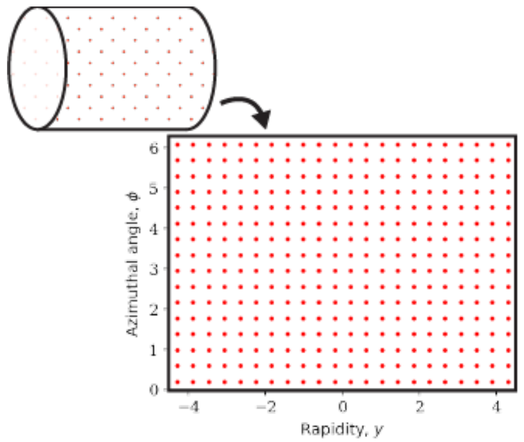


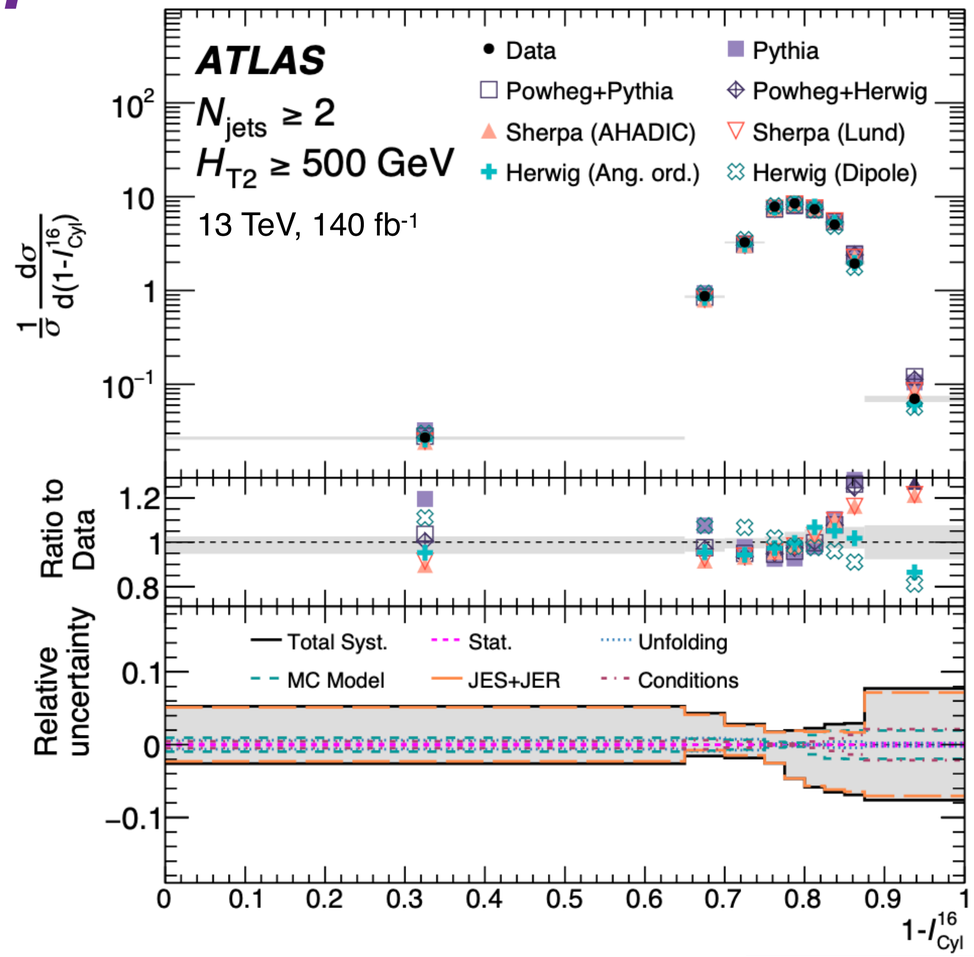
H_{T2} >= 1500 GeV

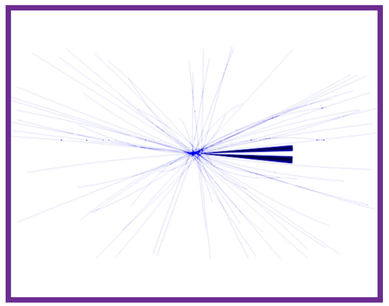


Data/MC disagreement improves at "dijet-like" end: events become more collimated with larger HT2, description is better despite large jet multiplicities.

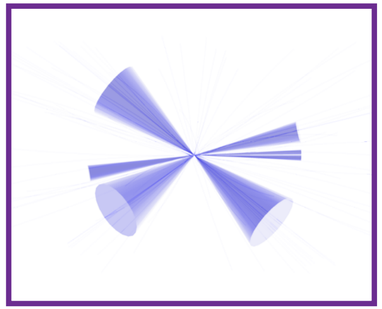
Results: I_{cyl}^{16}

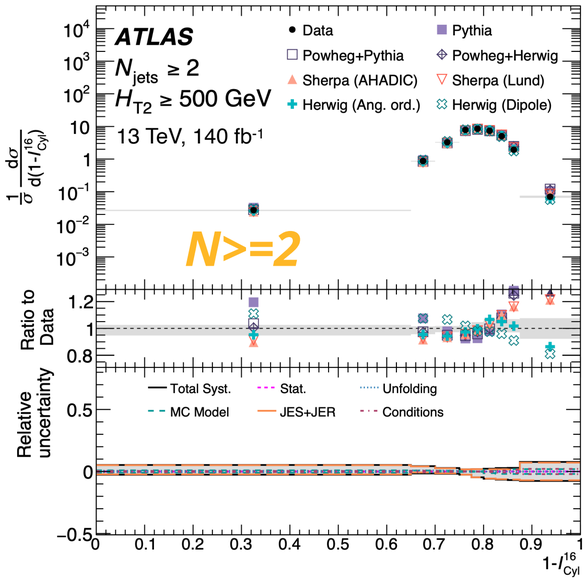




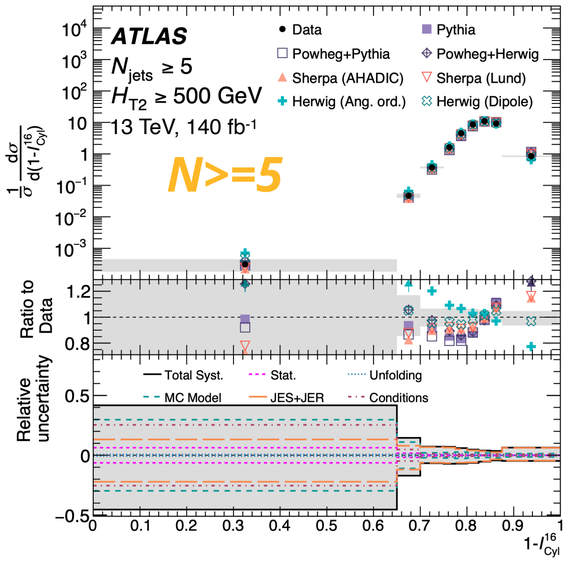


n.b. side view!





Increase N_{Jets}: isotropy increased significantly!



“A version of the painting 'wanderer above the sea' by Caspar David Friedrich, but with an isotropic landscape surrounding the hiker. Make it in the style of an oil painting, and favour circular symmetries in the image.” — DALL-E 3