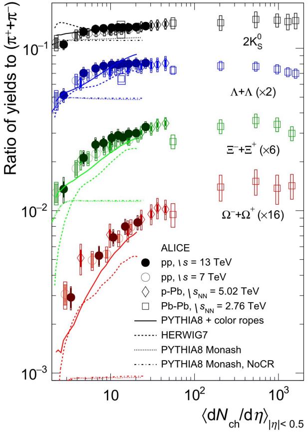
Event Shape Measurement with CMS

K. Cormier on behalf of CMS

Motivation (1): Soft QCD is not well modelled

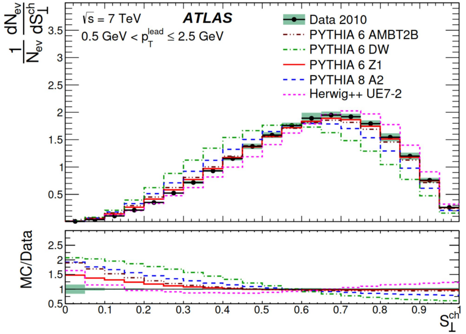
Existing observations of **unexpected effects in event-shapes** and strangeness production **in pp collisions —** Improve understanding of hadronic collisions

Eur. Phys. J. C 80, 693 (2020)



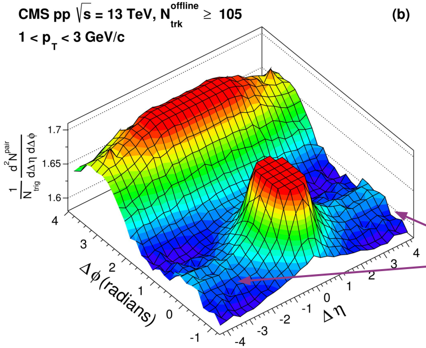
Mechanism of increase in strange particles as a function of particle multiplicity?

https://arxiv.org/abs/1207.6915

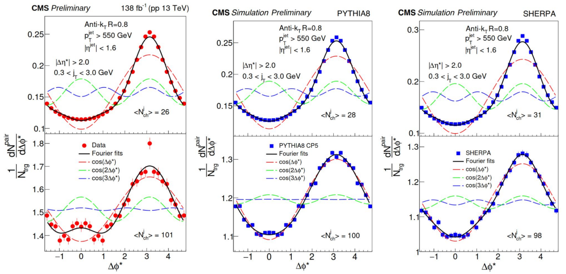


Mismodelling of event shapes in 7 TeV data

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.172302



Unexpected particle production across η, but with Δϕ ~ 0.



Similar correlations recently observed in high-multiplicity jets

Not predicted by simulation

https://arxiv.org/abs/2312.17103

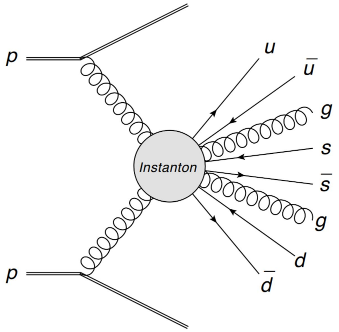
Motivation: Step towards instanton search

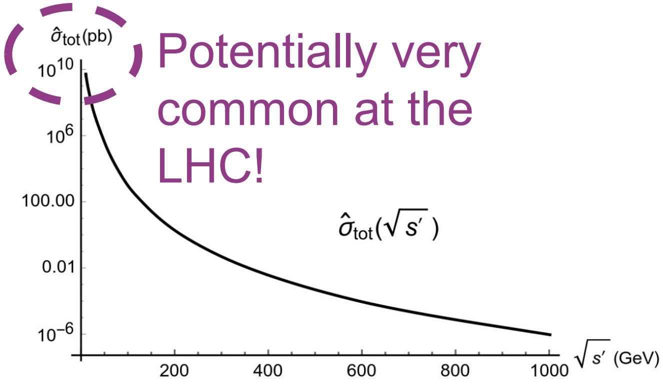
[https://arxiv.org/abs/1911.09726]

QCD Instantons – non-perturbative effect

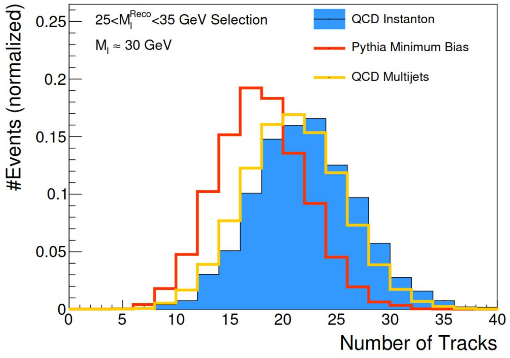
May be directly observable at the LHC

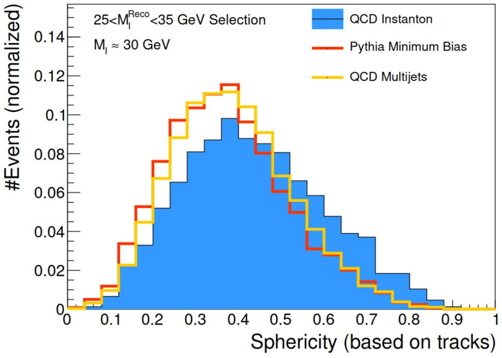
Signature: Soft, Isotropic, “fireball” with $2N_f$ quarks + O(10) gluons

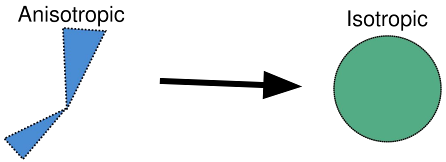




Potentially very common at the LHC!







Measurement Overview

Consider only **charged particles** using tracking information → precise reconstruction
Use **low-pileup data** (64 μb^{-1} collected in 2018)

Measure event-shape observables as a function of particle multiplicity and energy

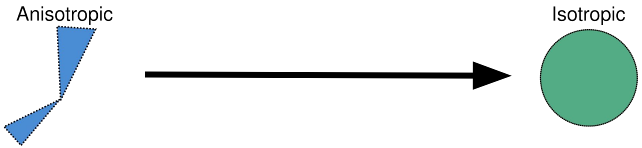
Observables:

Using charged particles, $p_T > 0.5$ GeV, $|\eta| < 2.4$

- **Particle Multiplicity**
- **Invariant Mass**

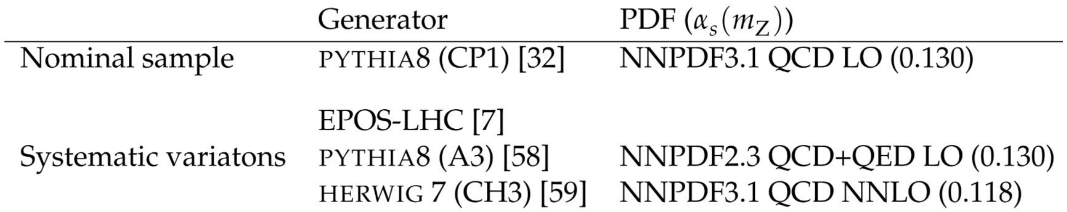
- **Sphericity (+ transverse)**
- **Thrust (+ transverse)**
- **Broadening**
- **Isotropy**

→ Different measures of energy distribution in events, Distinguish between isotropic/anisotropic



Minimum Bias Modelling

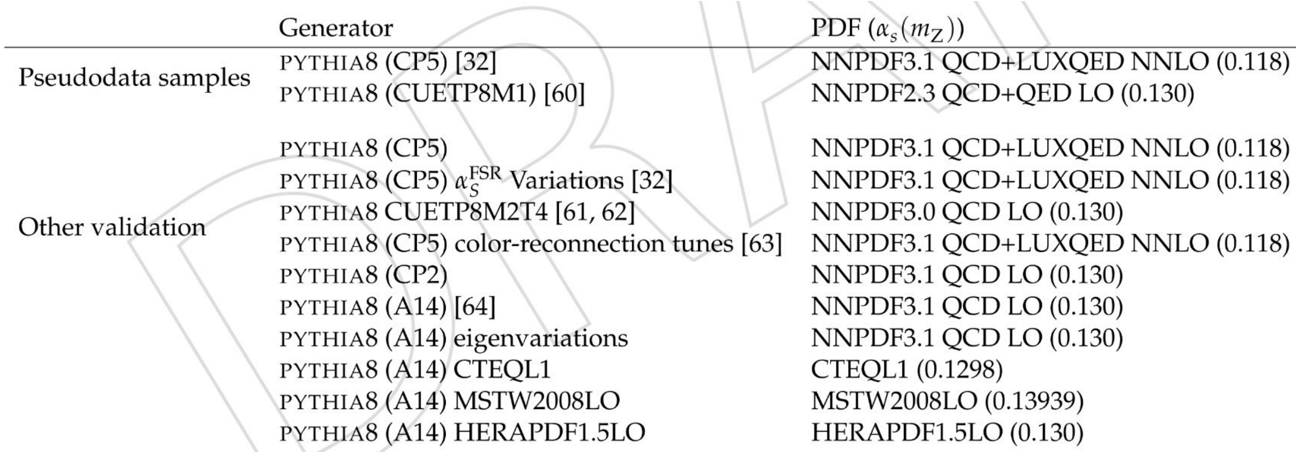
Primary Samples:



	Generator	PDF ($\alpha_s(m_Z)$)
Nominal sample	PYTHIA8 (CP1) [32]	NNPDF3.1 QCD LO (0.130)
Systematic variatons	EPOS-LHC [7]	
	PYTHIA8 (A3) [58]	NNPDF2.3 QCD+QED LO (0.130)
	HERWIG 7 (CH3) [59]	NNPDF3.1 QCD NNLO (0.118)

Different Underlying Models and Tunes

Additional Samples:



	Generator	PDF ($\alpha_s(m_Z)$)
Pseudodata samples	PYTHIA8 (CP5) [32]	NNPDF3.1 QCD+LUXQED NNLO (0.118)
	PYTHIA8 (CUETP8M1) [60]	NNPDF2.3 QCD+QED LO (0.130)
Other validation	PYTHIA8 (CP5)	NNPDF3.1 QCD+LUXQED NNLO (0.118)
	PYTHIA8 (CP5) α_S^{FSR} Variations [32]	NNPDF3.1 QCD+LUXQED NNLO (0.118)
	PYTHIA8 CUETP8M2T4 [61, 62]	NNPDF3.0 QCD LO (0.130)
	PYTHIA8 (CP5) color-reconnection tunes [63]	NNPDF3.1 QCD+LUXQED NNLO (0.118)
	PYTHIA8 (CP2)	NNPDF3.1 QCD LO (0.130)
	PYTHIA8 (A14) [64]	NNPDF3.1 QCD LO (0.130)
	PYTHIA8 (A14) eigenvariations	NNPDF3.1 QCD LO (0.130)
	PYTHIA8 (A14) CTEQL1	CTEQL1 (0.1298)
	PYTHIA8 (A14) MSTW2008LO	MSTW2008LO (0.13939)
	PYTHIA8 (A14) HERAPDF1.5LO	HERAPDF1.5LO (0.130)

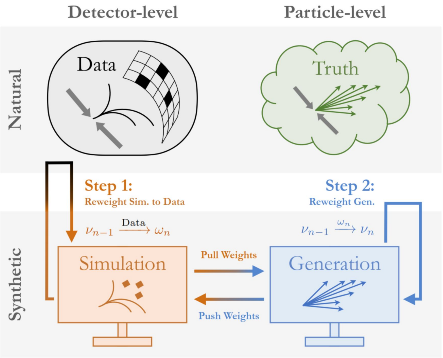
Tunes and Variations used by ATLAS + CMS

Unfolding [https://arxiv.org/abs/1911.09107]

We use an **unbinned unfolding** technique

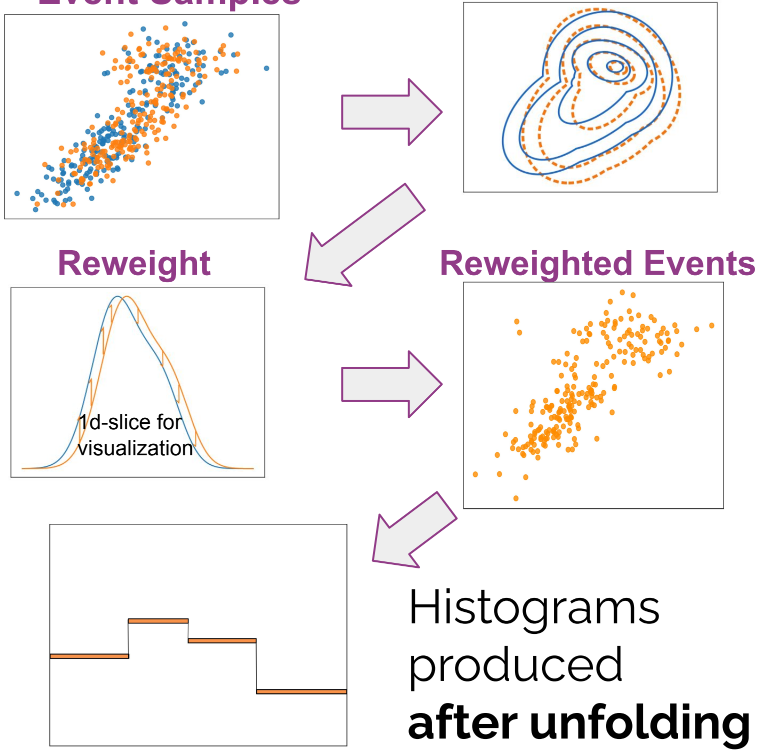
→ **outputs re-weighted Monte Carlo events** estimating the data distribution

“Multifold” variant of Omnifold, which simultaneously unfolds a number of observables



Input: all 8 observable values for every event in simulation and data

Output: reweighted simulated events approximating data



Event Samples

Estimated Density Ratios

Reweight

Reweighted Events

Histograms produced **after unfolding**

Uncertainties

Detector-related uncertainties largely mitigated by use of tracks

We do include an explicit tracking efficiency uncertainty based on randomly dropping a small % of tracks

No obvious prescription for Modelling uncertainties

Our Approach:

Consider 4 samples (nominal + 3 systematic variations)

For **each sample** consider **two categories** of effects:

1. Effect of changes in observables used directly in unfolding
   a. N_{tracks}, Sphericity, Thrust, ….

"Generator distribution uncertainties"

2. Effect of changes in other observables which may change detector response
   a. Track pseudorapidity, particle composition, …

"Migration function uncertainties"

Uncertainty Estimation

Uncertainties **propagated via “toys”** through unfolding

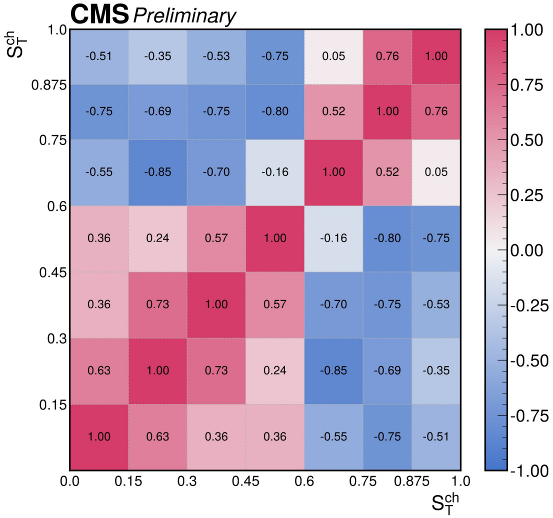
1. Generate Resampled Data
2. Generate Resampled Model
3. Perform unfolding

Repeat this N times, then:
use distribution over N toys to
calculate uncertainties + covariance

Systematic effects also assigned continuous parameter weights:

- **Sampling done with full statistical + systematic effects, preserving correlations**

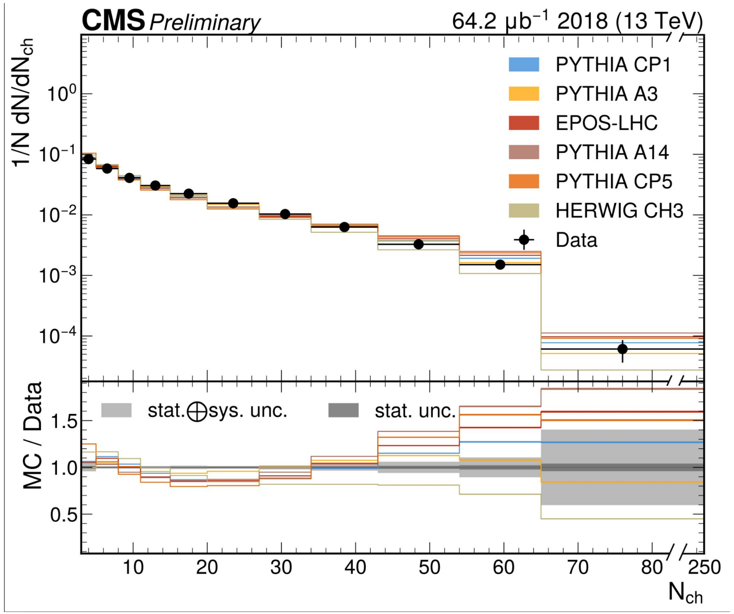
Correlations preserved across all event information (8 observables)

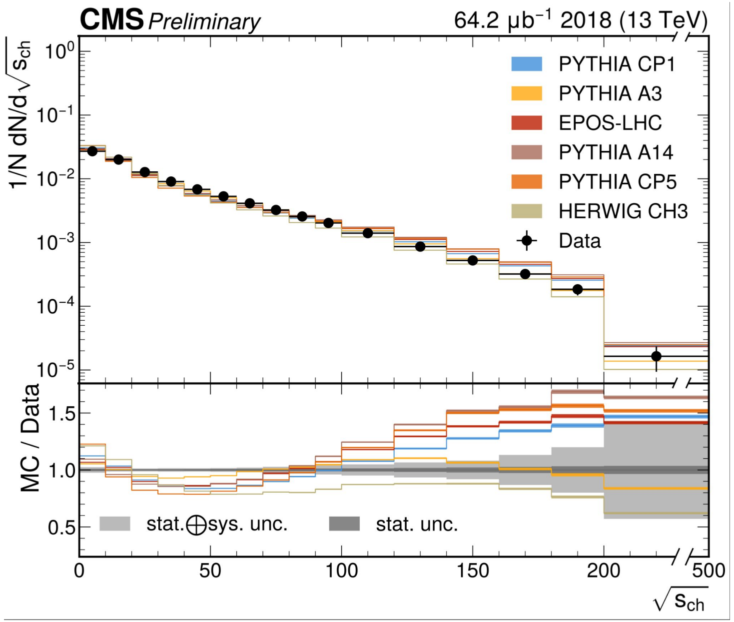


-0.51	-0.35	-0.53	-0.75	0.05	0.76	1.00
-0.75	-0.69	-0.75	-0.80	0.52	1.00	0.76
-0.55	-0.85	-0.70	-0.16	1.00	0.52	0.05
0.36	0.24	0.57	1.00	-0.16	-0.80	-0.75
0.36	0.73	1.00	0.57	-0.70	-0.75	-0.53
0.63	1.00	0.73	0.24	-0.85	-0.69	-0.35
1.00	0.63	0.36	0.36	-0.55	-0.75	-0.51

Results

Multiplicity and Mass – “Event Activity”

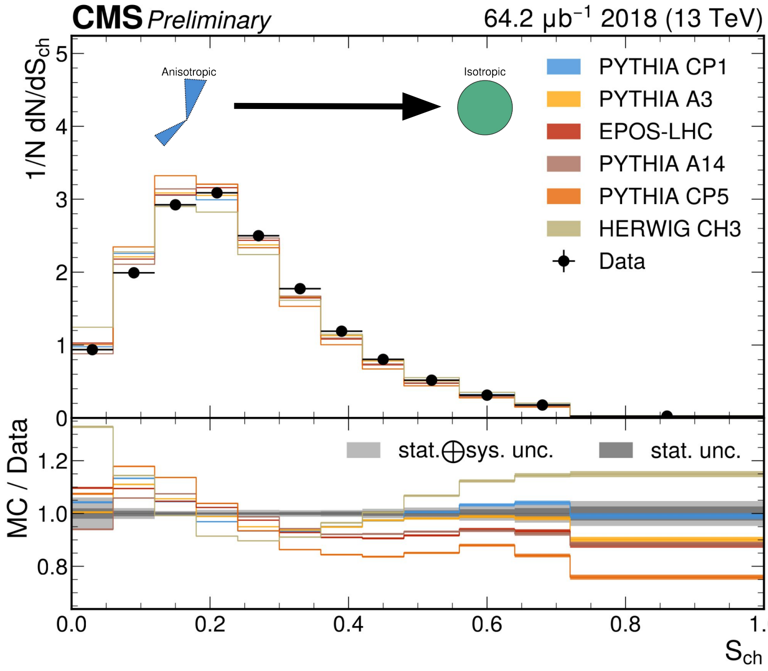


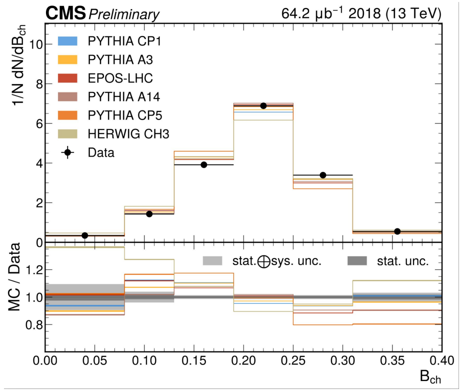


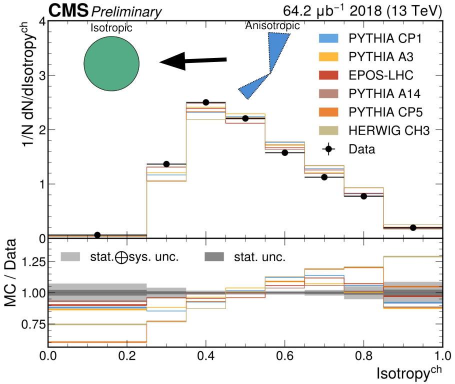
Common trend: Data above all predictions at medium activity values (N_{ch}~20, $\sqrt{s}_{ch}$ ~ 45 GeV) , Predictions above data for very low ($N_{ch} \lesssim 5$, $\sqrt{s}_{ch} \lesssim 10$ GeV).

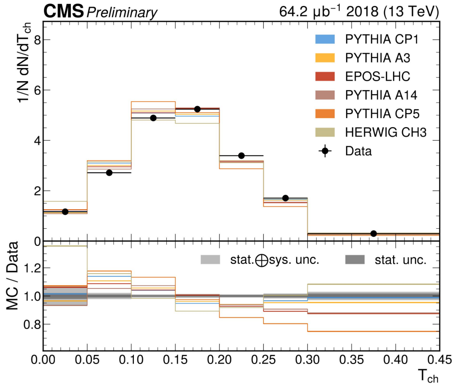
Spread of behaviour in tails, depending on Model + Tune

Event Shapes (Full)



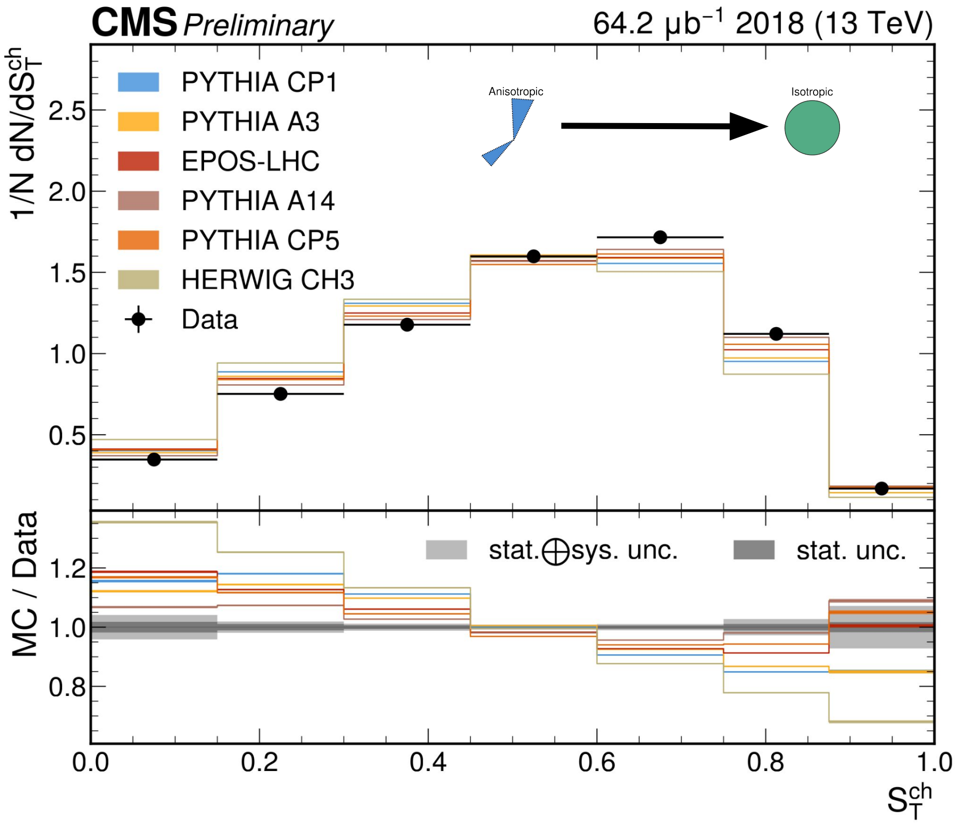


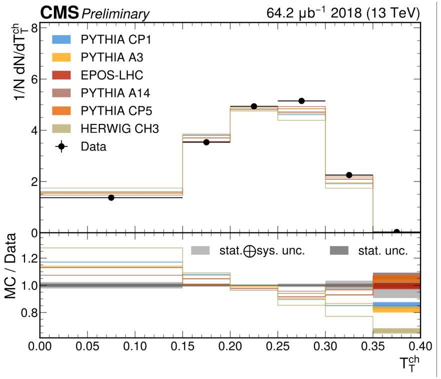




Common Trend: Data tends to be more isotropic than predictions for all observables and models (though to varying degrees)

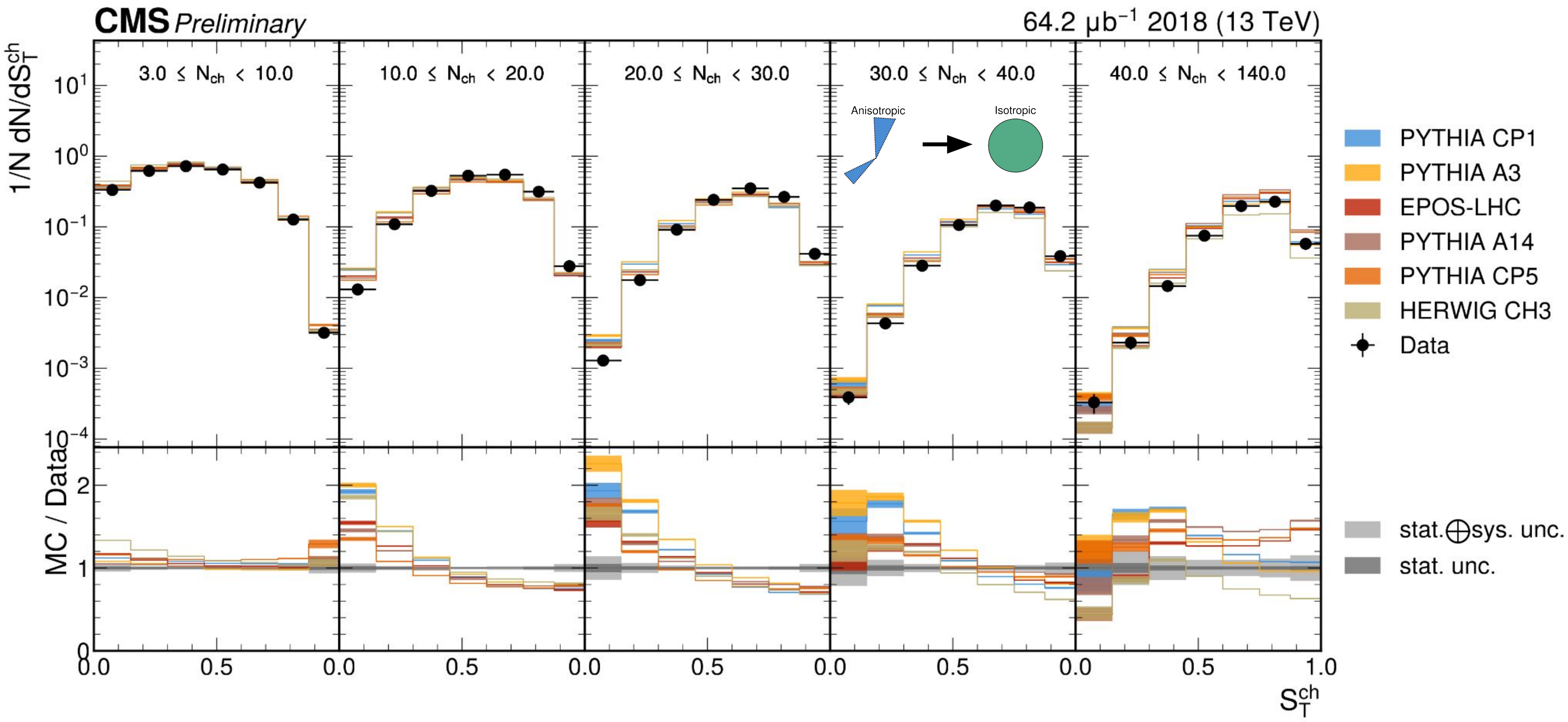
Event Shapes (Transverse)





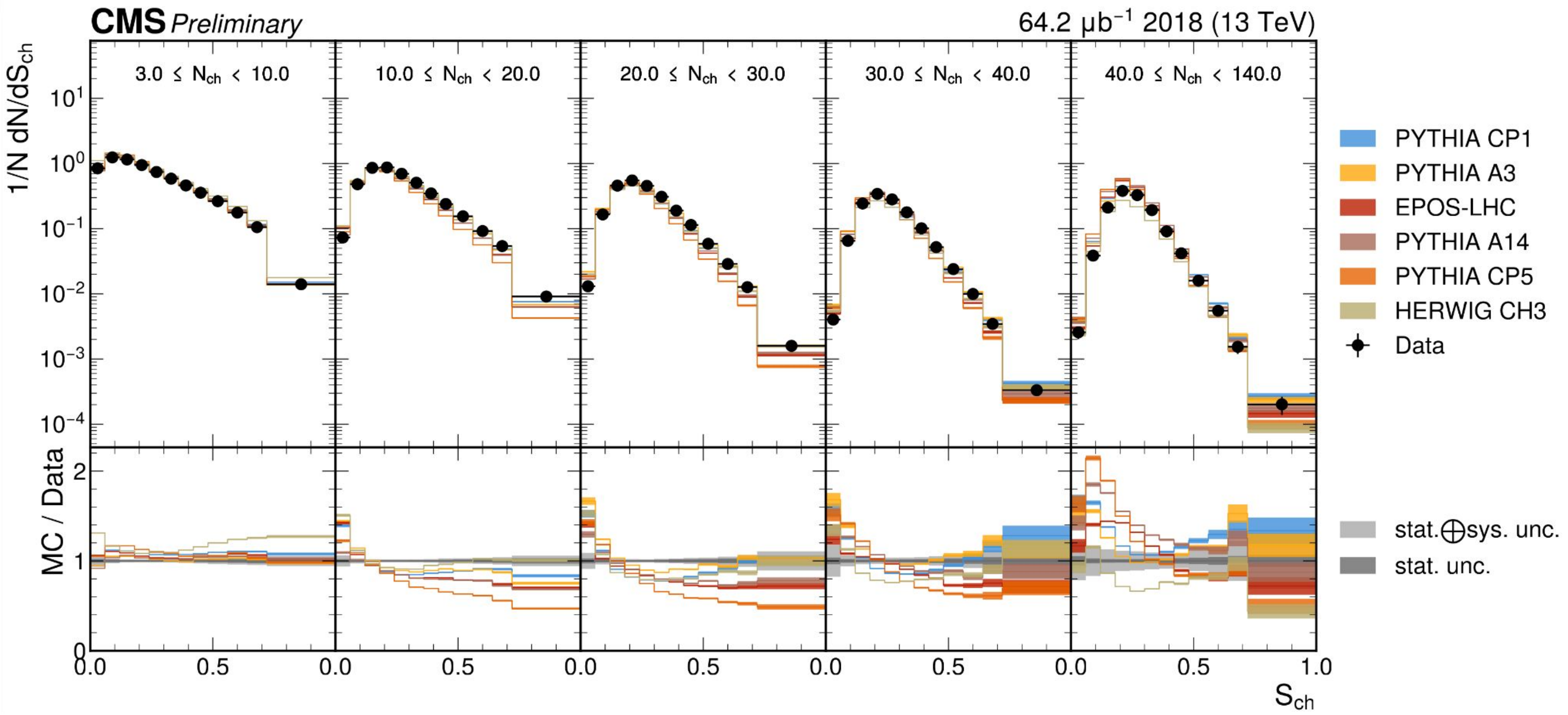
Trend of more isotropic data somewhat more clear in transverse-only observables

Event Shapes as a function of Event Activity



Strong trends of more isotropic data within multiplicity slices
Trends more clear than inclusive event shapes
Most striking in “mid” activity region

(Full) Event shapes as a function of activity



Trend for data to be more istoropic more visible for S than S_T at high N_{ch}

Related to ridge effects?

Further Comparisons

Checks and Comparisons

These trends were checked against a number of samples, and seem consistent other investigated effects include:

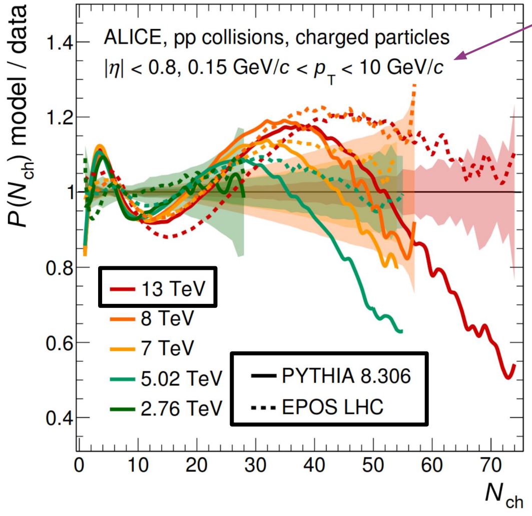
- Colour Reconnection Model
- PDF
- PDF order
- α_s(FSR)

No significant deviations from these trends were found in any of the checks

Checks and Comparisons

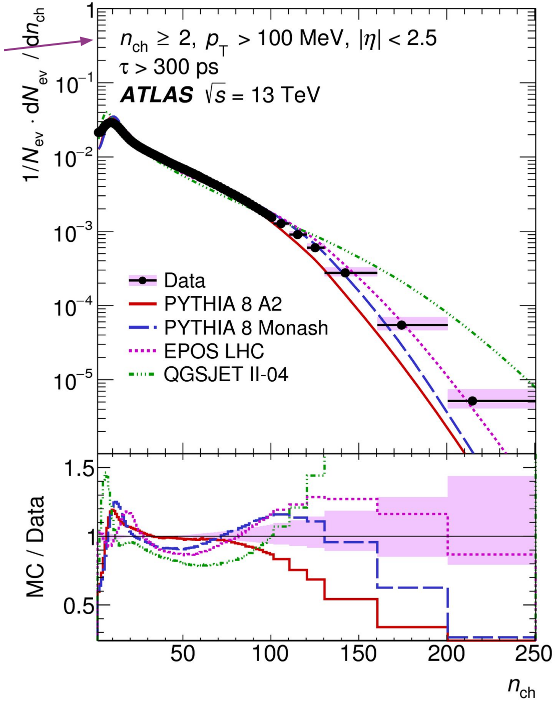
Trend in “Event Activity” Consistent with other measurements

https://arxiv.org/pdf/2211.15326

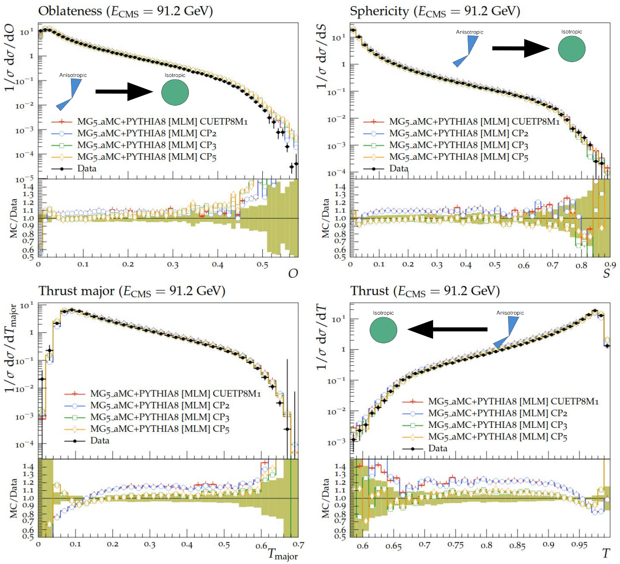


Different kinematic selections

https://arxiv.org/pdf/1606.01133



Other Event Shapes



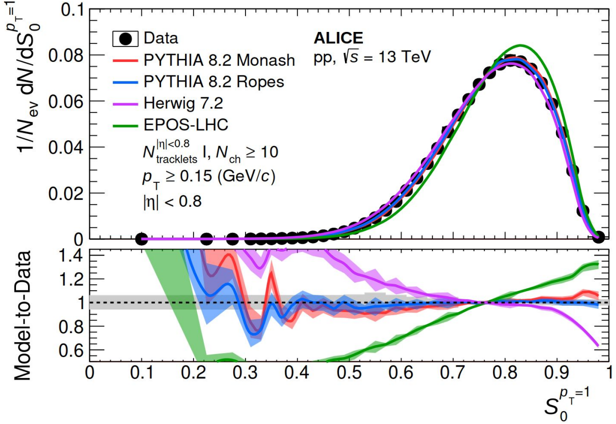
https://arxiv.org/abs/1903.12179v2

Shapes from LEP

Same CMS pythia tunes

Very different trends

https://arxiv.org/abs/2310.10236v1

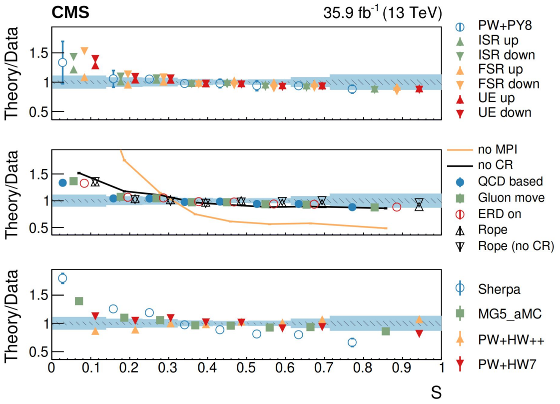


p$_T$-deweighted event shape

(spher**o**city, not spher**i**city)

Different behaviour

http://www.arxiv.org/abs/1807.02810

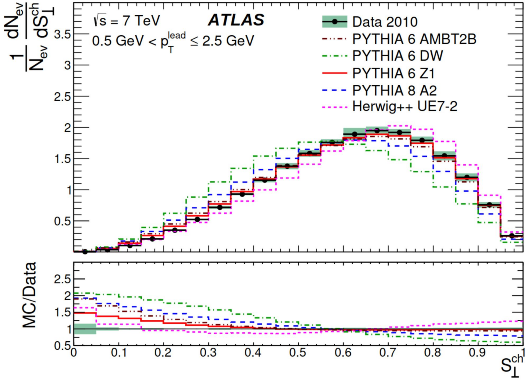


Similar Trend ?
(less clear)
in UE from ttbar

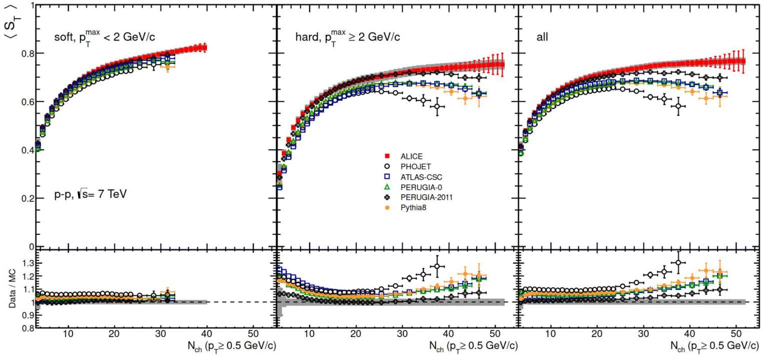
Event Shapes Lower Energy

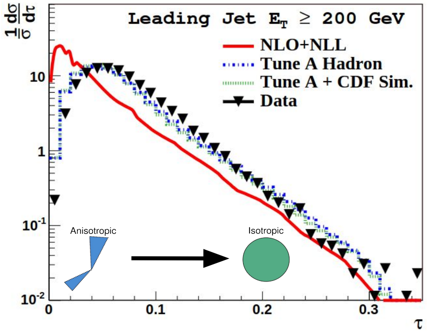
Perhaps also at TeVatron?
(but hard to compare and interpret …)

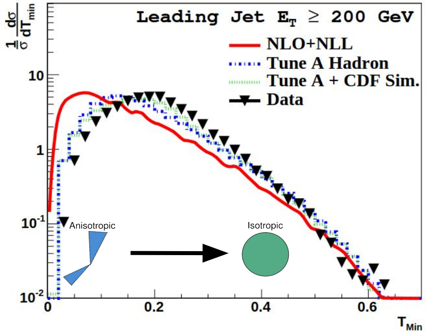
https://arxiv.org/abs/1207.6915



https://arxiv.org/abs/1205.3963







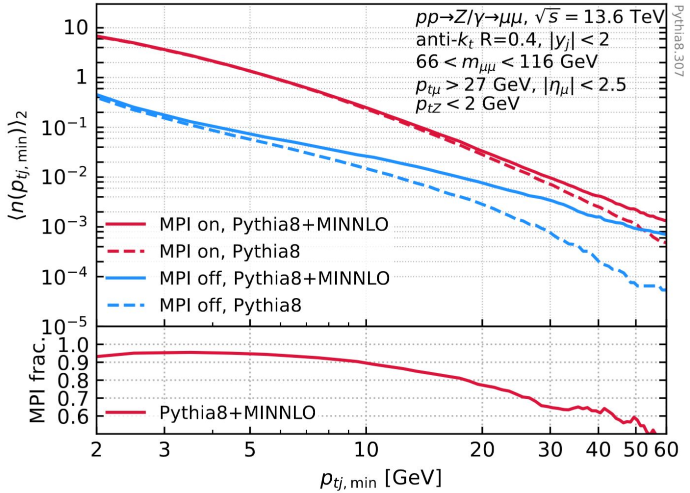
https://arxiv.org/abs/1103.5143

Some observables previously measured at **7 TeV**, Show **qualitatively similar** results for transverse event shapes

Future Directions

- Tuning of event-shape distributions?
  - New results provide better flexibility and correlation information as well as updated centre of mass energy
  - Do any of the current knobs impact this much?
  - Which knobs might?

- Low-p_T Z measurements?
  - As per recent paper and Luca's talk:
    https://arxiv.org/abs/2307.05693
    https://indico.cern.ch/event/1383721/timetable/?view=standard#33-overview-of-multi-parton-in
  - Look at event shape **removing 1 pair or parton-interactions?**
    2 with leading back-to-back jet pair?
  - Compare cumulative jet count delta-phi in minimum bias?



- Observables that could particularly benefit from high-dimensional correlations or exploratory analysis?

Summary

Event Shape measurement from CMS

- Unbinned unfolding → simultaneous unfolding across 8 observables
- Event shape distributions are consistently more isotropic in data than available models
- Models consistently under predict fraction of events with moderate “event activity”
- Some intersection of these two effects?
- Several Candidates for future directions

BACKUP

Motivation (3)

Topological Effects are a generic prediction of Non-Abelian Gauge theories
→ Come from non-trivial winding of the field in space-time

- Important physical consequences
  - Major role in hadron masses (QCD)
  - Chirality Violation
  - Baryon Number Violation (EW)
- Role in the Early universe?
  - Important for QGP
  - Source of Baryogenesis?
- Connections to BSM theories
  - Source of QCD theta-vacuum term, motivation for axions
  - Should appear in any new non-abelian gauge group
  - Topological Monopoles, Strings, …

Topological effects predict terms which are 0 to all orders in pertrubative expansions at α = 0.

$$f(\alpha_s) \sim \boxed{\exp\left(-\frac{const}{\alpha_s}\right)}\left(\sum_{n=0}^{\infty}(\alpha_s)^n B_n\right)$$

https://arxiv.org/abs/1812.01509

We have an opportunity to try to study these experimentally

Measurement Goals

Measure event shapes as a function of track multiplicity + mass

Focus on charged particles → Precise reconstruction

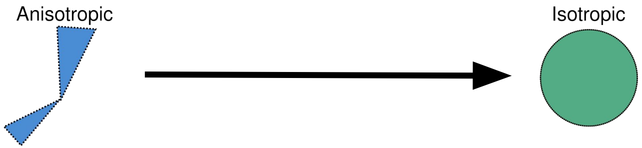
Observables:

Using charged particles, $p_T > 0.5$ GeV, $|\eta| < 2.4$

- **Particle Multiplicity**
- **Invariant Mass**

- **Sphericity (+ transverse)**
- **Thrust (+ transverse)**
- **Broadening**
- **Isotropy**

Different measures of energy distribution in events, Distinguish between isotropic/anisotropic



Samples

Data: 2018 low-pileup data-taking + Zerobias trigger (15 μb^{-1})

Simulation

Nominal Samples and Uncertainties

Pythia: **CP1 (CMS)**, A3 (ATLAS) ← **Different tunes, same MC model**

EPOS-LHC ← **Regge-Gribov Model, collective flow**

Herwig7: CH3 ← **Separate shower/hadronization models**

Validation and Comparisons not used in the Analysis

Pythia: CP5 (CMS), CUETP8M1 (CMS), CUETP8M2T4 (CMS), A14 (ATLAS), A14 Variations,

Uncertainties

Detector-related uncertainties largely mitigated by use of tracks

We do include an explicit tracking efficiency uncertainty based on randomly dropping a small % of tracks

No obvious prescription for Modelling uncertainties

Our Approach:

Consider 4 samples (nominal + 3 systematic variations)

For **each sample** consider **two categories** of effects:

“Generator distribution uncertainties”

“Migration function uncertainties”

3 alternative samples x 2 uncertainties per sample

6 independent modelling uncertainties

Unfolding (1)

We perform a **simultaneous unbinned unfolding** of all our observables.

Unfolding is done using an iterative machine-learning based approach
➜ multiple steps of unbinned reweighting

Results of unfolding are (re)weighted simulated events

➜ Binning is performed only for visualization and studying specific distributions *after* unfolding

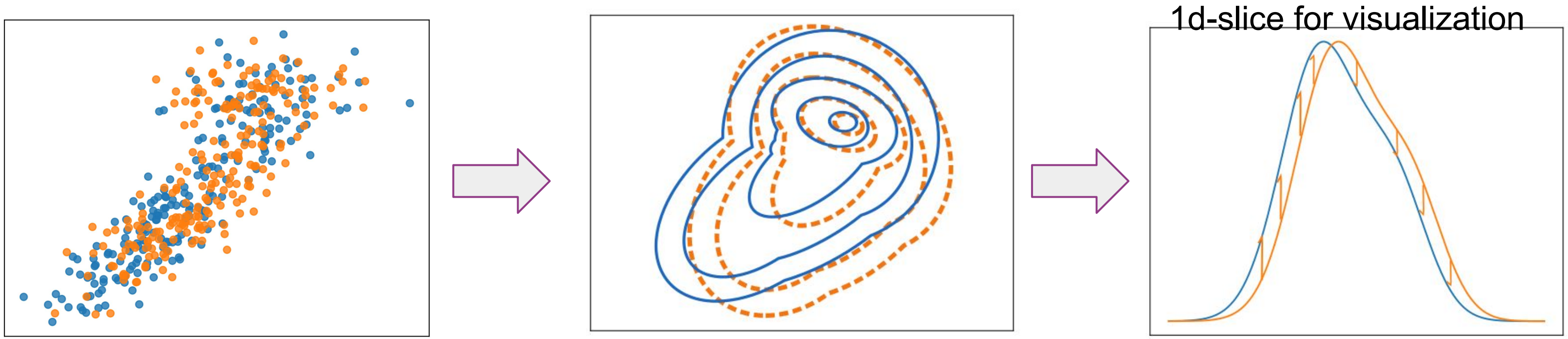
Unbinned Reweighting

1. Train a classifier to distinguish two samples: **A** and **B**
   a. The classifier should ‘learn the likelihood ratio’

→ outputs the estimated probability **p** that an event is from sample **A**

2. Reweight events from sample **B** by **p/(1-p)**

   → Reweighted sample **B** now approximates sample **A**



1d-slice for visualization

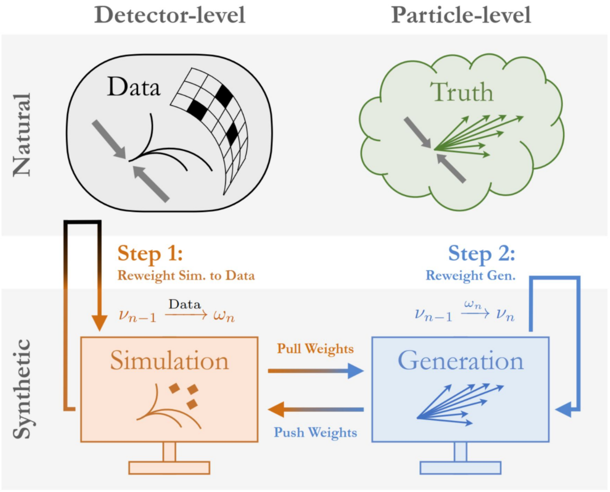
Event Samples

Estimated Density Ratios

Reweight

Unfolding [https://arxiv.org/abs/1911.09107]

1) Reweight simulation to data at detector-level
2) Reweight original simulation to reweighted simulation at gen-level
3) Repeat



Input: all 8 observable values for every event in simulation and data

Output: reweighted simulated events approximating data

Increasing the number of iterations should decrease the bias towards the original simulation

Covariance Construction (2)

Toy example: 3 events, 2 systematic uncertainties (statistical unc. not shown here)

New Simulated sample
→Use it for unfolding

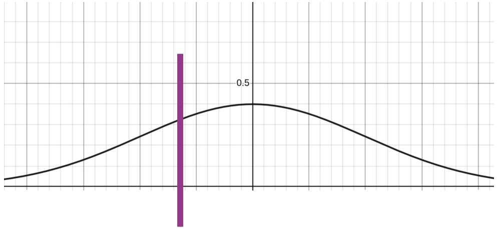
$W_1 = (0.9)\cdot(1.15)$

$W_2 = (0.95)\cdot(1.3)$

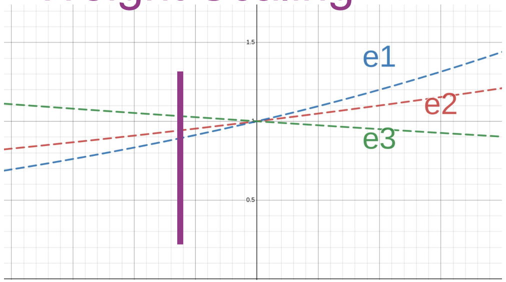
$W_3 = (1.05)\cdot(0.85)$

Syst. 1

Nuisance PDF



Weight Scaling

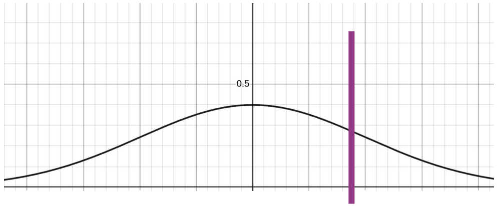


Nuisance value

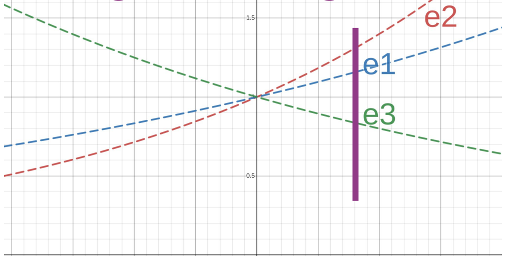
■ ■ ■

Syst. 2

Nuisance PDF



Weight Scaling



Nuisance value

Covariance Construction (2)

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→Use it for unfolding

$W_1 = (0.9)\cdot(1.15)$

$W_2 = (0.95)\cdot(1.3)$

$W_3 = (1.05)\cdot(0.85)$

New Simulated sample #2
→Use it for unfolding

$W_1 = (0.95)\cdot(1.3)$

$W_2 = (0.98)\cdot(1.7)$

$W_3 = (1.02)\cdot(0.6)$

. . .

New Simulated sample #N
→Use it for unfolding

$W_1 = \ldots.$

$W_2 = \ldots.$

$W_3 = \ldots$

(Co)variances constructed from (Co)variances of unfolded sample population

Event Selections

Detector-level:

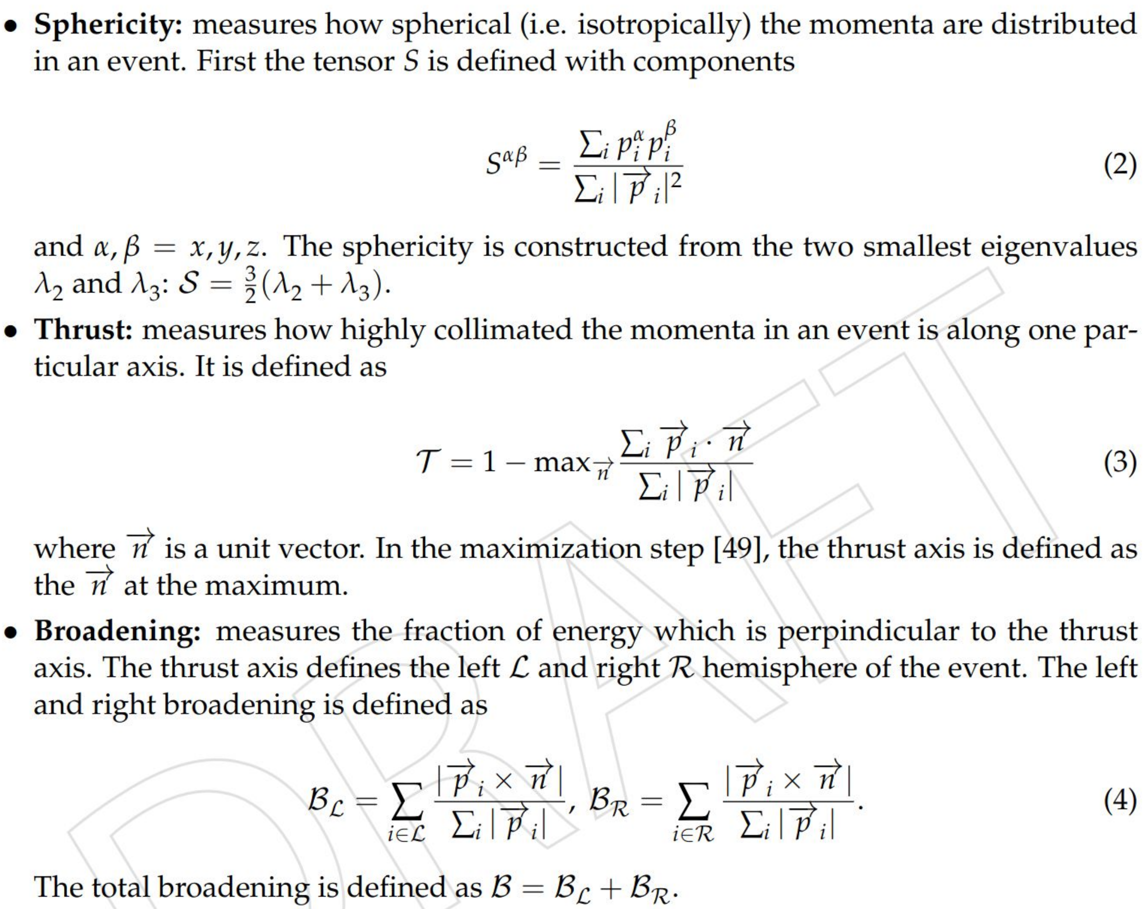
At least 1 well-reconstructed vertex

At least 3 well-reconstructed tracks

Generator-level:

At least 2 charged particles

Event Shape Observables



- **Sphericity:** measures how spherical (i.e. isotropically) the momenta are distributed in an event. First the tensor S is defined with components

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\overrightarrow{p}_i|^2} \tag{2}$$

  and $\alpha, \beta = x, y, z$. The sphericity is constructed from the two smallest eigenvalues λ_2 and λ_3: $\mathcal{S} = \frac{3}{2}(\lambda_2 + \lambda_3)$.

- **Thrust:** measures how highly collimated the momenta in an event is along one particular axis. It is defined as

$$\mathcal{T} = 1 - \max_{\overrightarrow{n}} \frac{\sum_i \overrightarrow{p}_i \cdot \overrightarrow{n}}{\sum_i |\overrightarrow{p}_i|} \tag{3}$$

  where $\overrightarrow{n}$ is a unit vector. In the maximization step [49], the thrust axis is defined as the $\overrightarrow{n}$ at the maximum.

- **Broadening:** measures the fraction of energy which is perpindicular to the thrust axis. The thrust axis defines the left $\mathcal{L}$ and right $\mathcal{R}$ hemisphere of the event. The left and right broadening is defined as

$$\mathcal{B}_{\mathcal{L}} = \sum_{i\in\mathcal{L}} \frac{|\overrightarrow{p}_i \times \overrightarrow{n}|}{\sum_i |\overrightarrow{p}_i|}, \quad \mathcal{B}_{\mathcal{R}} = \sum_{i\in\mathcal{R}} \frac{|\overrightarrow{p}_i \times \overrightarrow{n}|}{\sum_i |\overrightarrow{p}_i|}. \tag{4}$$

  The total broadening is defined as $\mathcal{B} = \mathcal{B}_{\mathcal{L}} + \mathcal{B}_{\mathcal{R}}$.