The Future is Open

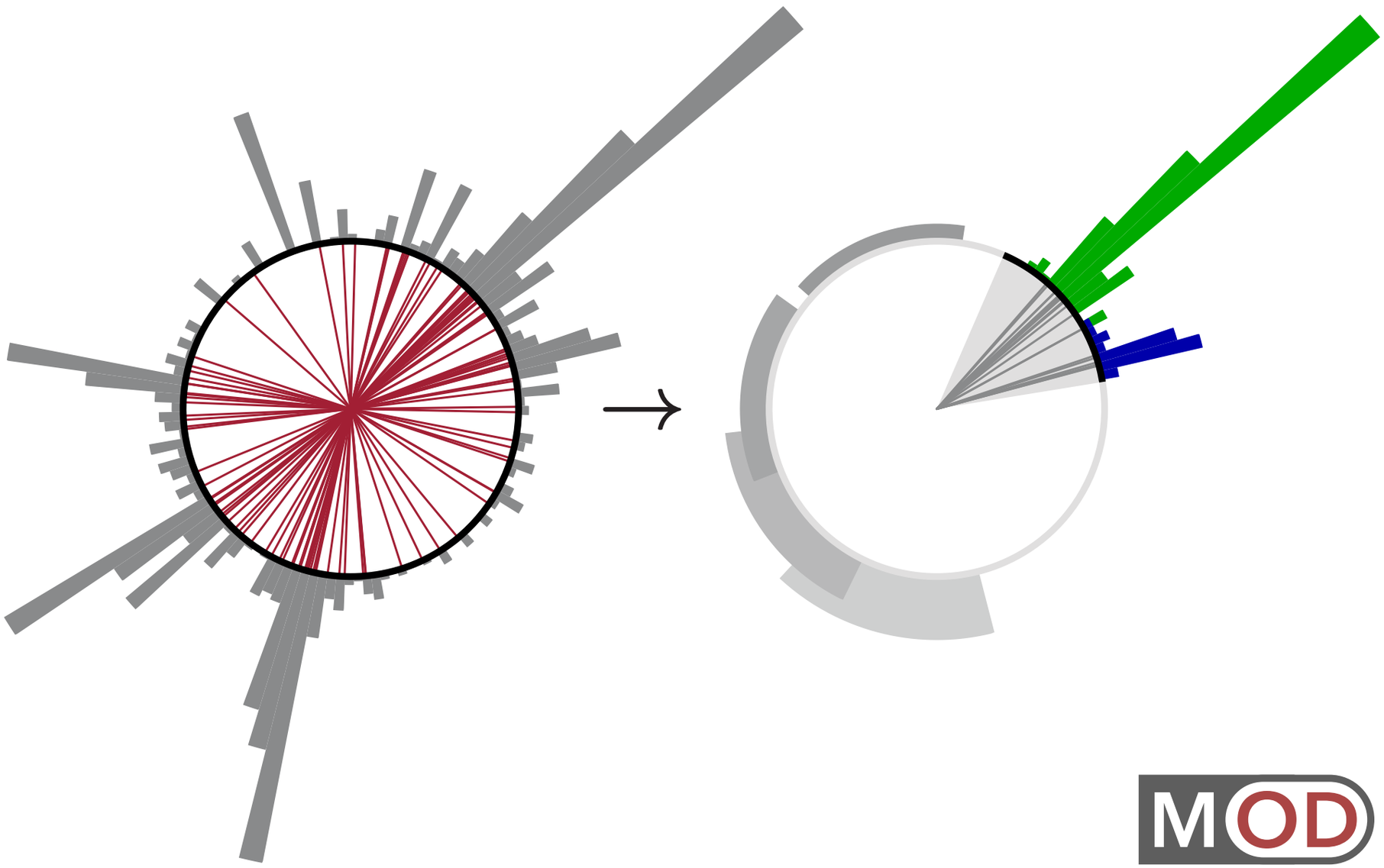
Jet Substructure with CMS Public Data

Jesse Thaler

Reinterpretation Forum, Fermilab — October 17, 2017

Exposing the QCD Splitting Function with CMS Open Data

Andrew Larkoski,[1,*] Simone Marzani,[2,†] Jesse Thaler,[3,‡] Aashish Tripathee,[3,§] and Wei Xue[3,‖]



Exposing the QCD Splitting Function with CMS Open Data

Andrew Larkoski,[1,*] Simone Marzani,[2,†] Jesse Thaler,[3,‡] Aashish Tripathee,[3,§] and Wei Xue[3,‖]

A Milestone for Public Collider Data

A Milestone for Jet Physics

An Opportunity/Challenge for our Community

Jet substructure studies with CMS open data

Aashish Tripathee,[1,*] Wei Xue,[1,†] Andrew Larkoski,[2,‡] Simone Marzani,[3,§] and Jesse Thaler[1,‖]

V. ADVICE TO THE COMMUNITY

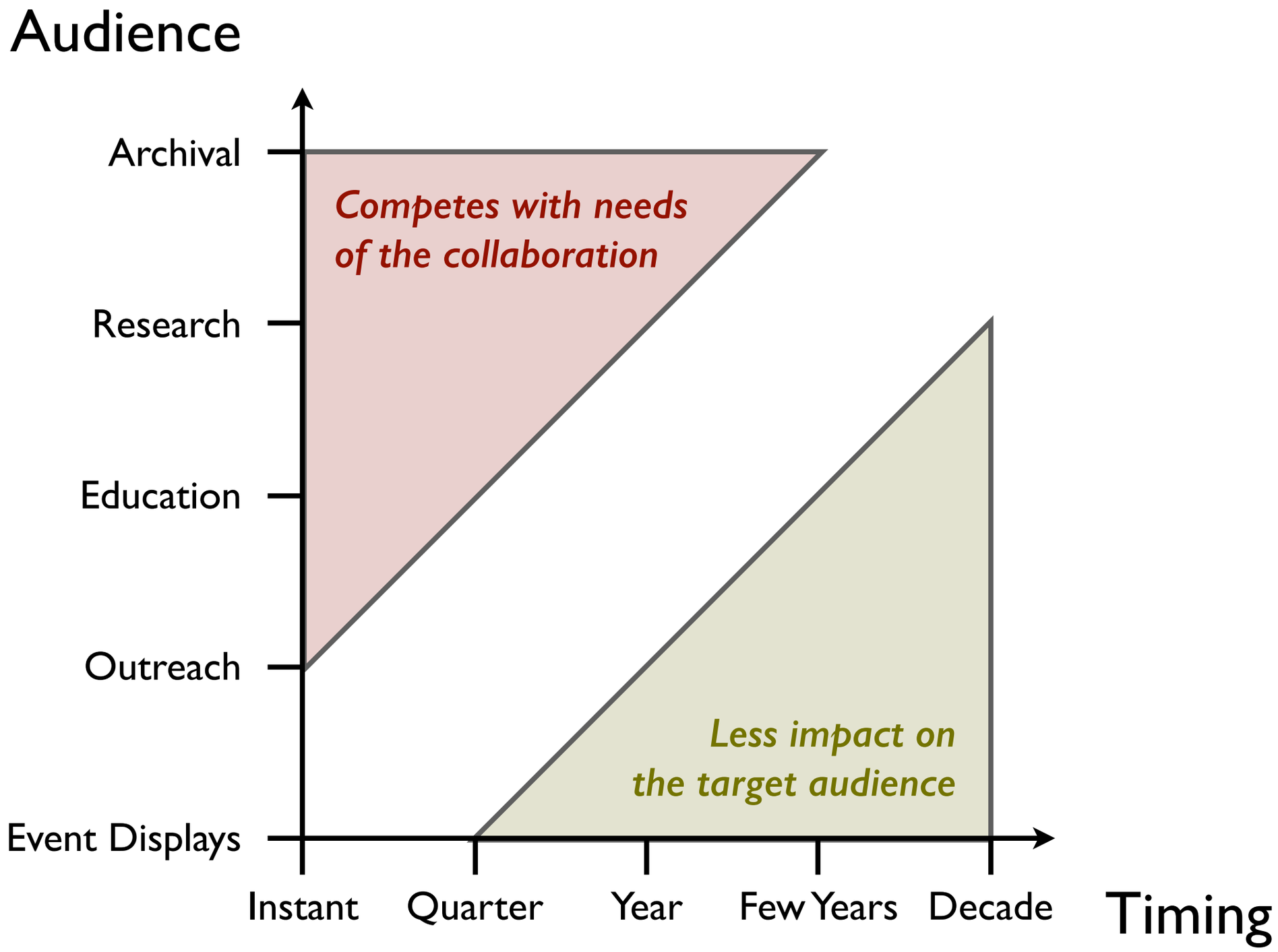
A. Challenges

B. Recommendations

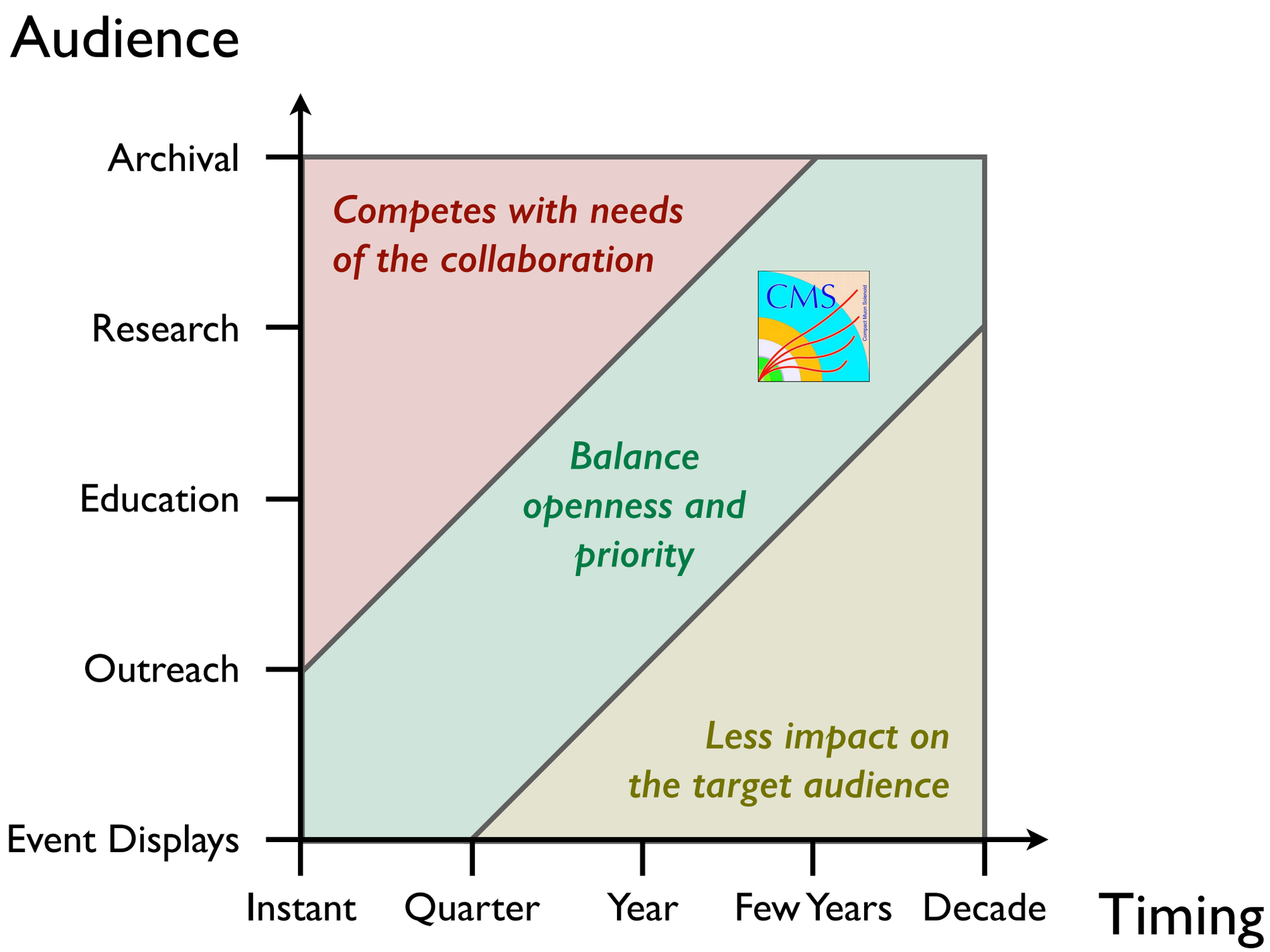
VI. CONCLUSION

As the LHC explores the frontiers of scientific knowledge, its primary legacy will be the measurements and discoveries made by the LHC detector collaborations. But there is another potential legacy from the LHC that could be just as important: granting future generations of physicists access to unique high-quality data sets from proton-proton collisions at 7, 8, 13, and 14 TeV.

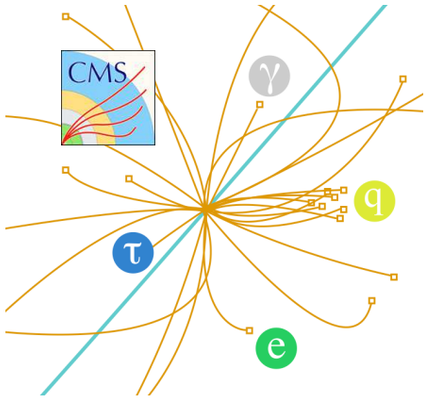
Different Options for "Public Data"



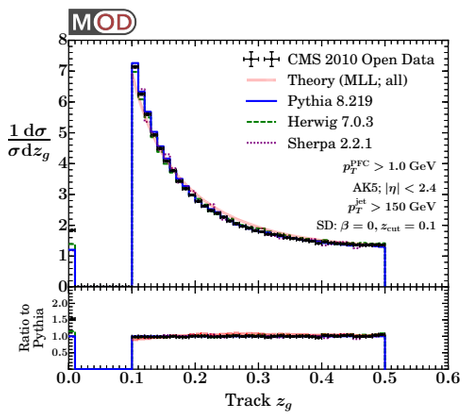
Different Options for "Public Data"



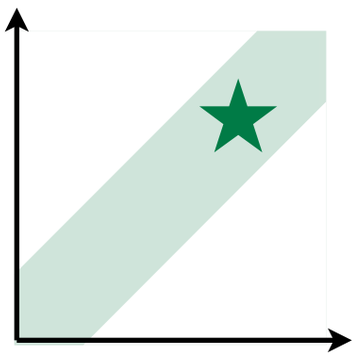
Outline



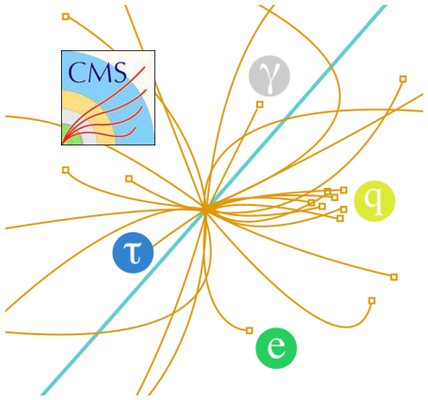
Using the CMS Open Data



Jet Substructure and QCD Splittings



The Future of Public Collider Data



Using the CMS Open Data

Jet Substructure and QCD Splittings

The Future of Public Collider Data

opendata
CERN

opendata.cern.ch/research/CMS

November 2014:

Run 2010B
7 TeV, 32 pb^{-1}

>20 TB, no MC

(Today: QCD)

April 2016:

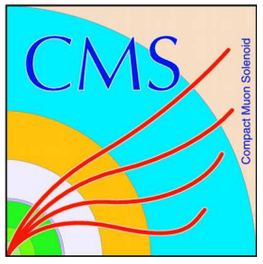
Run 2011A
7 TeV, 2.5 fb^{-1}

>100 TB, with MC

(In the Pipeline: BSM)

Translating to "MIT Open Data"

Jet Primary Dataset



CernVM + CMSSW 4.2.8

AOD Format (CMS Root)

RAW → RECO → "Analysis Object Data"

2.0 TB

20,022,826 events
1664 files

Access via XRootD

MODAnalyzer + FastJet 3.1.3

MOD Format (ASCII + gzip)

Cross-check with flat Root n-tuples

200 GB

20 GB after
baseline selection

Access via External Hard Drive

```
BeginEvent Version 5 CMS_2010 Jet_Primary_Dataset
 # Cond     RunNum  EventNum LumiBlock validLumi intgDelLumi intgRecLumi AvgInstLumi       NPV    timestamp     msOffset
   Cond     147926 188160899       201         1    21496.19    21208.58       92.03         4   1287023343       516890
 #  Trig                 Name Prescale_1 Prescale_2      Fired?
    Trig HLT_DiJetAve100U_v1          1          1           0
    Trig      HLT_DiJetAve15U        500         10           0
    Trig      HLT_DiJetAve30U          1        500           0
    Trig      HLT_DiJetAve50U          1         65           0
    Trig HLT_DiJetAve70U_v2          1         25           0
    Trig      HLT_Jet100U_v2          1          1           1
 # AK5        px         py         pz     energy        jec       area no_of_const chrg_multip neu_had_frac neu_em_frac chrg_had_frac chrg_em_frac
   AK5      9.31      -3.42      27.29      29.21       1.03       0.82           8          4        0.35       0.18        0.46       0.00
   AK5      6.77       2.40      13.35      15.30       0.99       0.72           6          4        0.55       0.11        0.33       0.00
   AK5      7.08       0.93     -61.18      61.62       0.93       0.82           2          0        1.00       0.00        0.00       0.00
 #  PFC        px         py         pz     energy      pdgId
   PFC     -0.95      -0.05       0.65       1.16       -211
   PFC     -0.75      -0.24      -1.06       1.33       -211
   PFC      1.27      -1.27     -11.10      11.25        130
   PFC     -0.00      -0.59       0.50       0.79        211
   PFC     -0.41       0.54       0.59       0.91       -211
   PFC      1.55       0.57       5.99       6.22        211
   PFC      0.12      -0.52       1.36       1.47       -211
   PFC      0.76       0.36      -1.59       1.81        211
   PFC      0.43       0.78       2.04       2.23        211
   PFC      1.90      -0.09       5.88       6.19        130
   PFC      0.71       1.71       0.94       2.08        211
EndEvent
```

Luminosity*

```
BeginEvent Version 5 CMS_2010 Jet_Primary_Dataset
 # Cond    RunNum  EventNum LumiBlock validLumi intgDelLumi intgRecLumi AvgInstLumi       NPV     timestamp      msOffset
   Cond    147926 188160899       201         1    21496.19    21208.58       92.03         4    1287023343        516890
 #  Trig                Name Prescale_1 Prescale_2      Fired?
    Trig HLT_DiJetAve100U_v1          1          1           0
    Trig      HLT_DiJetAve15U        500         10           0
    Trig      HLT_DiJetAve30U          1        500           0
    Trig      HLT_DiJetAve50U          1         65           0
    Trig HLT_DiJetAve70U_v2          1         25           0
    Trig      HLT_Jet100U_v2          1          1           1
 # AK5          px          py          pz      energy         jec        area no_of_const chrg_multip neu_had_frac neu_em_frac chrg_had_frac chrg_em_frac
   AK5        9.31       -3.42       27.29       29.21        1.03        0.82           8          4        0.35       0.18        0.46       0.00
   AK5        6.77        2.40       13.35       15.30        0.99        0.72           6          4        0.55       0.11        0.33       0.00
   AK5        7.08        0.93      -61.18       61.62        0.93        0.82           2          0        1.00       0.00        0.00       0.00
 #  PFC          px          py          pz      energy       pdgId
   PFC       -0.95       -0.05        0.65        1.16        -211
   PFC       -0.75       -0.24       -1.06        1.33        -211
   PFC        1.27       -1.27      -11.10       11.25         130
   PFC       -0.00       -0.59        0.50        0.79         211
   PFC       -0.41        0.54        0.59        0.91        -211
   PFC        1.55        0.57        5.99        6.22         211
   PFC        0.12       -0.52        1.36        1.47        -211
   PFC        0.76        0.36       -1.59        1.81         211
   PFC        0.43        0.78        2.04        2.23         211
   PFC        1.90       -0.09        5.88        6.19         130
   PFC        0.71        1.71        0.94        2.08         211
EndEvent
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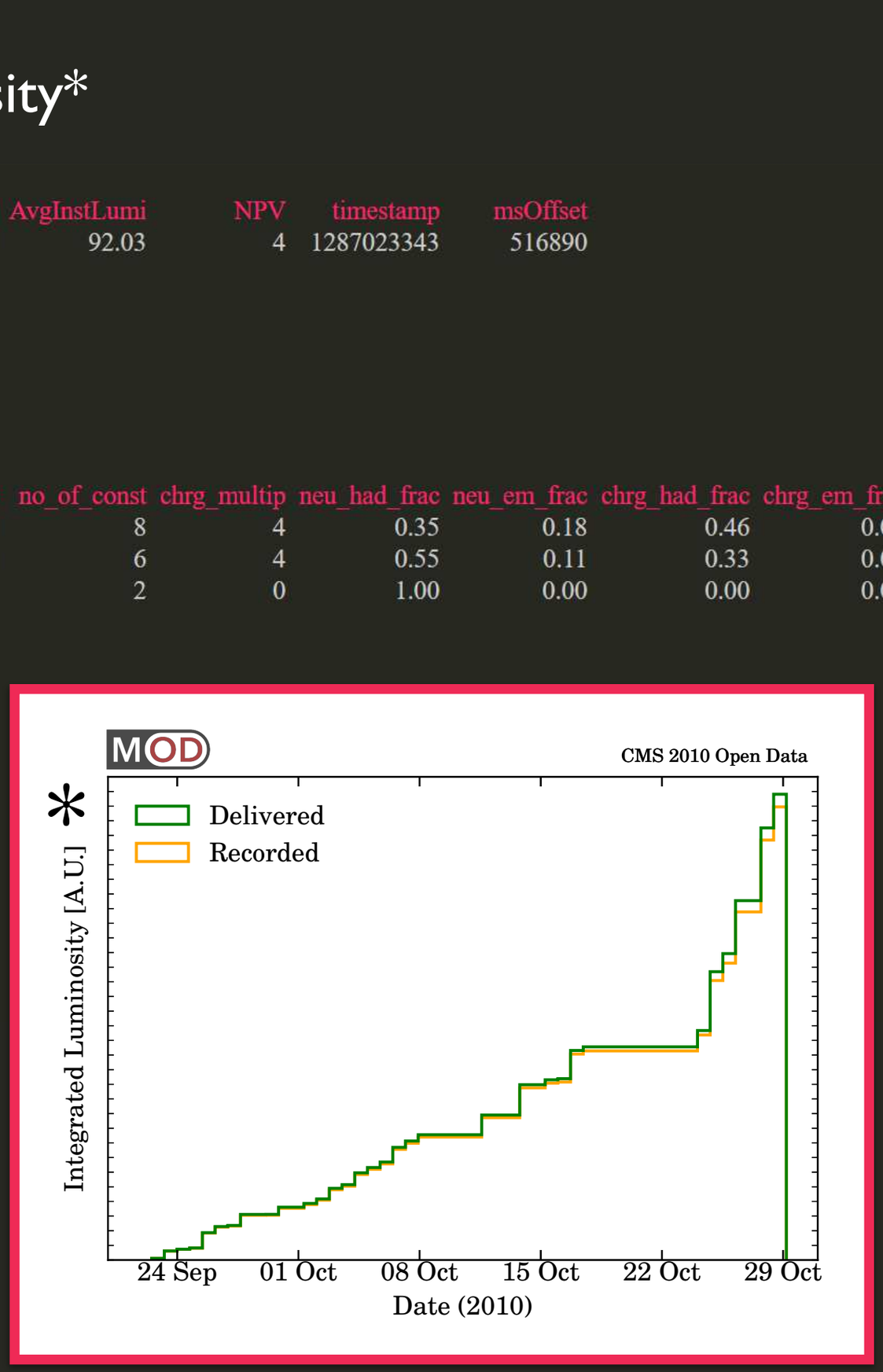
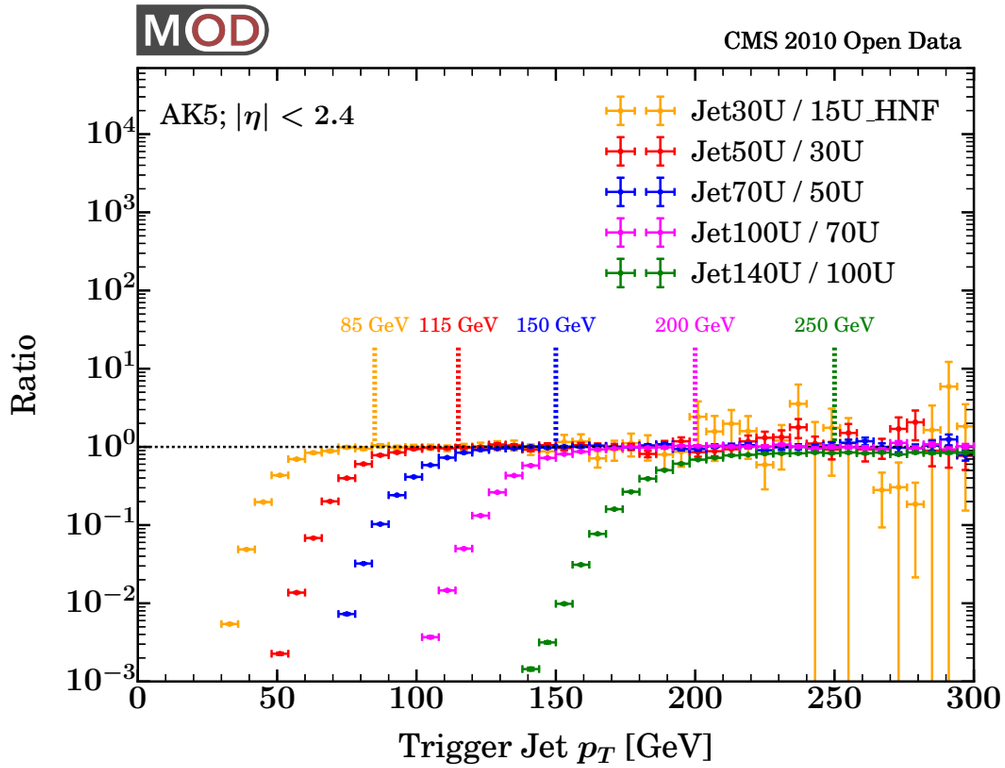


** Not official luminosity table!*
Important to stress-test
while collaboration is active

```
BeginEvent Version 5 CMS_2010 Jet_Primary_Dataset
 # Cond    RunNum  EventNum LumiBlock validLumi intgDelLumi intgRecLumi AvgInstLumi       NPV     timestamp     msOffset
   Cond    147926 188160899       201         1    21496.19    21208.58       92.03         4    1287023343       516890
 #  Trig                Name Prescale_1 Prescale_2      Fired?
    Trig HLT_DiJetAve100U_v1          1          1           0
    Trig      HLT_DiJetAve15U        500         10           0
    Trig      HLT_DiJetAve30U          1        500           0
    Trig      HLT_DiJetAve50U          1         65           0
    Trig HLT_DiJetAve70U_v2          1         25           0
    Trig      HLT_Jet100U_v2          1          1           1
 # AK5       px       py       pz   energy      jec     area no_of_const chrg_multip neu_had_frac neu_em_frac chrg_had_frac chrg_em_frac
   AK5     9.31    -3.42    27.29    29.21     1.03     0.82           8          4        0.35       0.18        0.46       0.00
   AK5     6.77     2.40    13.35    15.30     0.99     0.72           6          4        0.55       0.11        0.33       0.00
   AK5     7.08     0.93   -61.18    61.62     0.93     0.82           2          0        1.00       0.00        0.00       0.00
 #  PFC       px       py       pz   energy    pdgId
   PFC    -0.95    -0.05     0.65     1.16     -211
   PFC    -0.75    -0.24    -1.06     1.33     -211
   PFC     1.27    -1.27   -11.10    11.25      130
   PFC    -0.00    -0.59     0.50     0.79      211
   PFC    -0.41     0.54     0.59     0.91     -211
   PFC     1.55     0.57     5.99     6.22      211
   PFC     0.12    -0.52     1.36     1.47     -211
   PFC     0.76     0.36    -1.59     1.81      211
   PFC     0.43     0.78     2.04     2.23      211
   PFC     1.90    -0.09     5.88     6.19      130
   PFC     0.71     1.71     0.94     2.08      211
EndEvent
```

Triggers

No magic. (see Achim's talk)
Have to reproduce most aspects of official analysis pipeline



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2	# Cond	RunNum	EventNum	LumiBlock	validLumi	intgDelLumi	intgRecLumi	AvgInstLumi	NPV	timestamp	msOffset				
3	Cond	147926	188160899	201	1	21496.19	21208.58	92.03	4	1287023343	516890				
4	# Trig		Name	Prescale_1	Prescale_2	Fired?									
5	Trig	HLT_DiJetAve100U_v1		1	1	0									
6	Trig	HLT_DiJetAve15U		500	10	0									
7	Trig	HLT_DiJetAve30U		1	500	0									
8	Trig	HLT_DiJetAve50U		1	65	0									
9	Trig	HLT_DiJetAve70U_v2		1	25	0									
10	Trig	HLT_Jet100U_v2		1	1	1									
11	# AK5	px	py	pz	energy	jec		area	no_of_const	chrg_multip	neu_had_frac	neu_em_frac	chrg_had_frac	chrg_em_frac	
12	AK5	9.31	-3.42	27.29	29.21	1.03		0.82	8	4	0.35	0.18	0.46	0.00	
13	AK5	6.77	2.40	13.35	15.30	0.99		0.72	6	4	0.55	0.11	0.33	0.00	
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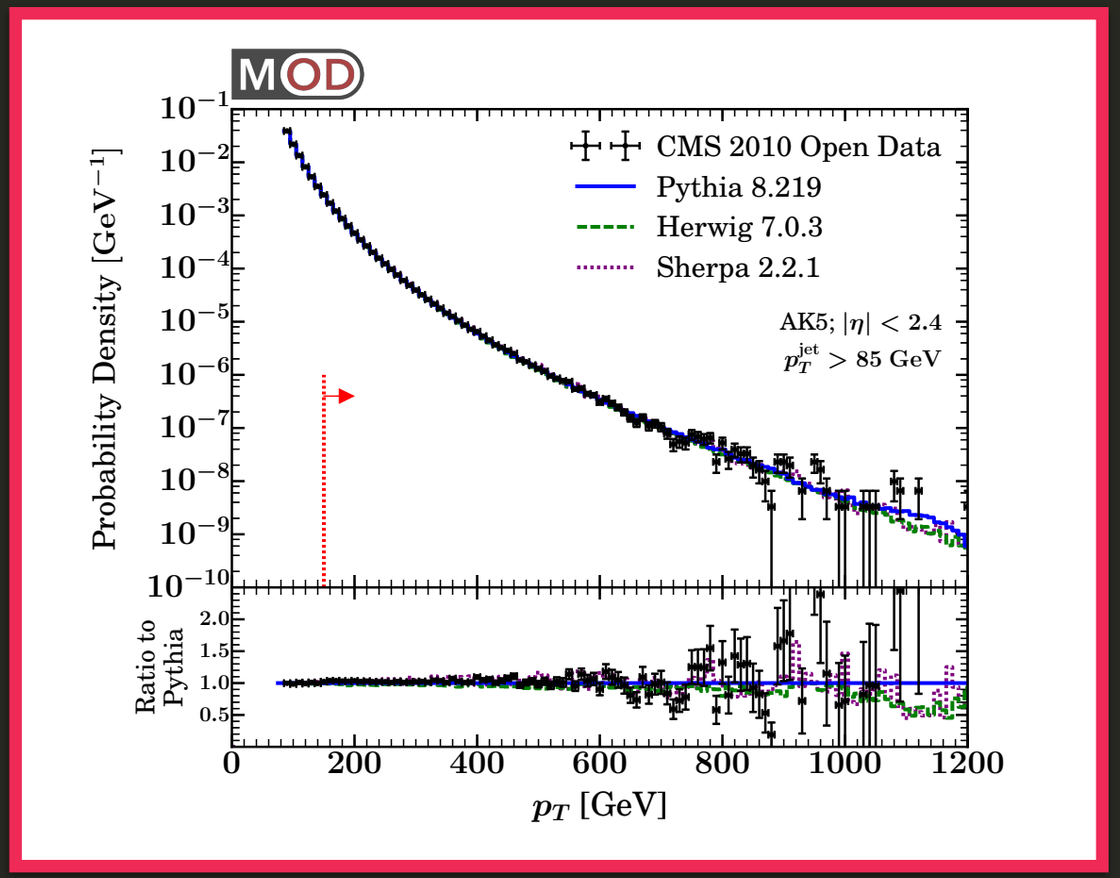
15	# PFC	px	py	pz	energy	pdgId									
16	PFC	-0.95	-0.05	0.65	1.16	-211									
17	PFC	-0.75	-0.24	-1.06	1.33	-211									
18	PFC	1.27	-1.27	-11.10	11.25	130									
19	PFC	-0.00	-0.59	0.50	0.79	211									
20	PFC	-0.41	0.54	0.59	0.91	-211									
21	PFC	1.55	0.57	5.99	6.22	211									
22	PFC	0.12	-0.52	1.36	1.47	-211									
23	PFC	0.76	0.36	-1.59	1.81	211									
24	PFC	0.43	0.78	2.04	2.23	211									
25	PFC	1.90	-0.09	5.88	6.19	130									
26	PFC	0.71	1.71	0.94	2.08	211									
27	EndEvent														

Jets: anti-k_t R = 0.5

Remarkable!
Good data/MC agreement
"out of the box"…



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3	Cond	147926	188160899	201	1	21496.19	21208.58	92.03	4	1287023343	516890			
4	# Trig		Name	Prescale_1	Prescale_2	Fired?								
5	Trig	HLT_DiJetAve100U_v1		1	1	0								
6	Trig	HLT_DiJetAve15U		500	10	0								
7	Trig	HLT_DiJetAve30U		1	500	0								
8	Trig	HLT_DiJetAve50U		1	65	0								
9	Trig	HLT_DiJetAve70U_v2		1	25	0								
10	Trig	HLT_Jet100U_v2		1	1	1								
11	# AK5	px	py	pz	energy	jec	area	no_of_const	chrg_multip	neu_had_frac	neu_em_frac	chrg_had_frac	chrg_em_frac	
12	AK5	9.31	-3.42	27.29	29.21	1.03	0.82	8	4	0.35	0.18	0.46	0.00	
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15	# PFC	px	py	pz	energy	pdgId								
16	PFC	-0.95	-0.05	0.65	1.16	-211								
17	PFC	-0.75	-0.24	-1.06	1.33	-211								
18	PFC	1.27	-1.27	-11.10	11.25	130								
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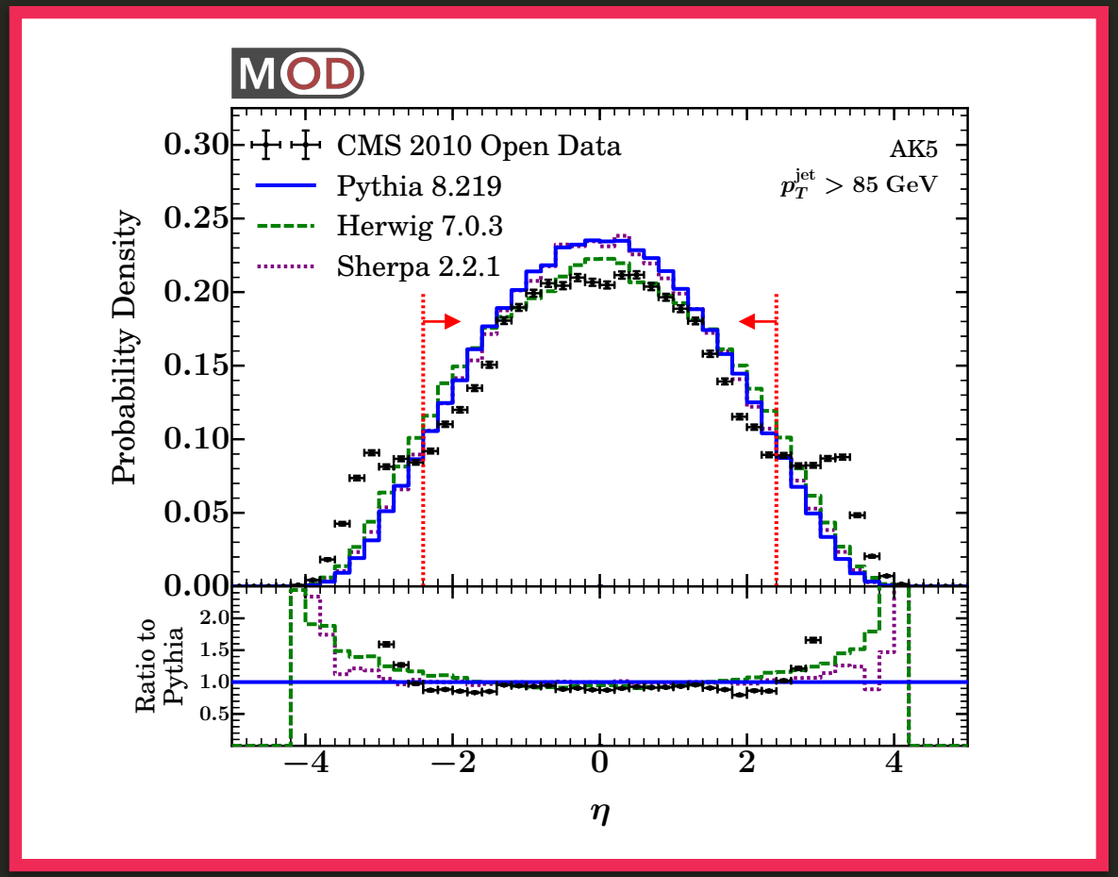
21	PFC	1.55	0.57	5.99	6.22	211								
22	PFC	0.12	-0.52	1.36	1.47	-211								
23	PFC	0.76	0.36	-1.59	1.81	211								
24	PFC	0.43	0.78	2.04	2.23	211								
25	PFC	1.90	-0.09	5.88	6.19	130								
26	PFC	0.71	1.71	0.94	2.08	211								
27	EndEvent													

Jet Energy Corrections

Jet Area

Jet Quality Criteria

…oh wait, no magic.
Important to consolidate information on best practices



1	BeginEvent	Version	5	CMS_2010	Jet_Primary_Dataset							
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4	# Trig		Name	Prescale_1	Prescale_2	Fired?						
5	Trig	HLT_DiJetAve100U_v1		1	1	0						
6	Trig	HLT_DiJetAve15U		500	10	0						
7	Trig	HLT_DiJetAve30U		1	500	0						
8	Trig	HLT_DiJetAve50U		1	65	0						
9	Trig	HLT_DiJetAve70U_v2		1	25	0						
10	Trig	HLT_Jet100U_v2		1	1	1						
11	# AK5	px	py	pz	energy	jec	area	no_of_const	chrg_multip	neu_had_frac	neu_em_frac	chrg_had_frac	chrg_em_frac
12	AK5	9.31	-3.42	27.29	29.21	1.03	0.82	8	4	0.35	0.18	0.46	0.00
13	AK5	6.77	2.40	13.35	15.30	0.99	0.72	6	4	0.55	0.11	0.33	0.00
14	AK5	7.08	0.93	-61.18	61.62	0.93	0.82	2	0	1.00	0.00	0.00	0.00
15	# PFC	px	py	pz	energy	pdgId							
16	PFC	-0.95	-0.05	0.65	1.16	-211							
17	PFC	-0.75	-0.24	-1.06	1.33	-211							
18	PFC	1.27	-1.27	-11.10	11.25	130							
19	PFC	-0.00	-0.59	0.50	0.79	211							
20	PFC	-0.41	0.54	0.59	0.91	-211							
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22	PFC	0.12	-0.52	1.36	1.47	-211							
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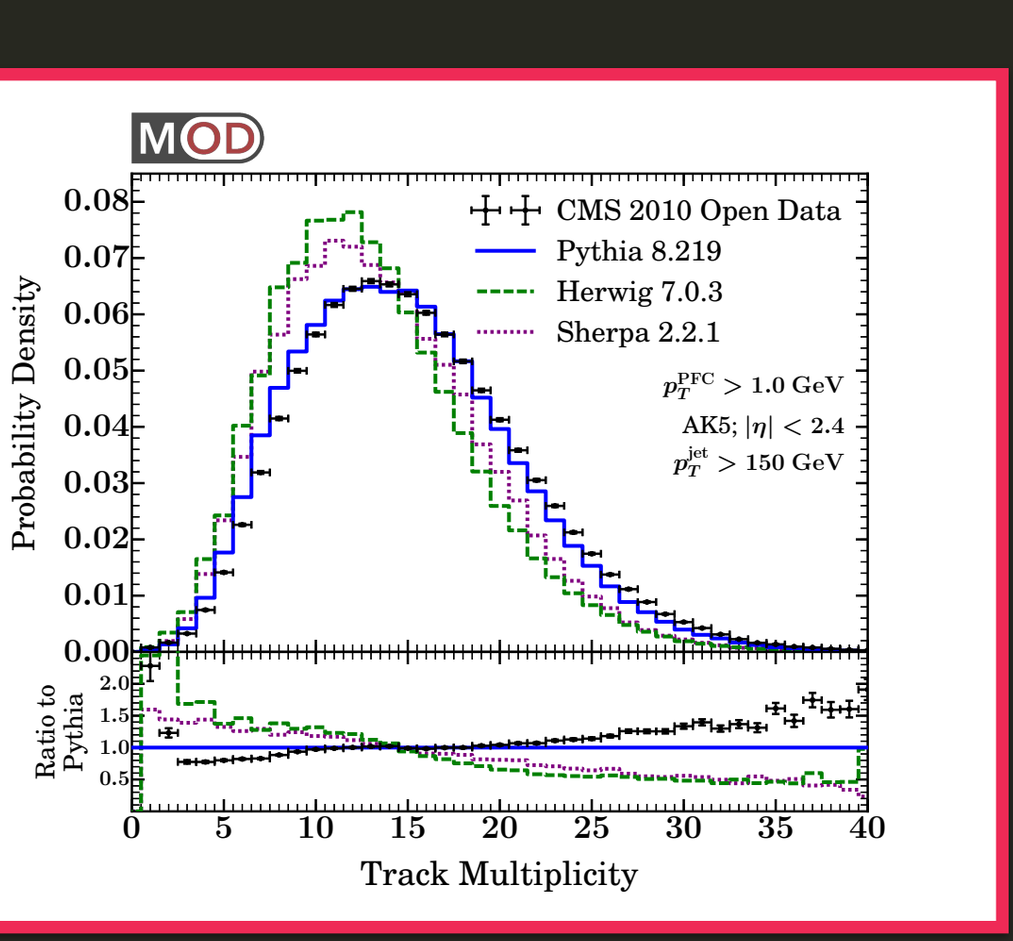
24	PFC	0.43	0.78	2.04	2.23	211							
25	PFC	1.90	-0.09	5.88	6.19	130							
26	PFC	0.71	1.71	0.94	2.08	211							
27	EndEvent												

Particle Flow Candidates

Opportunity: Novel analyses

Challenge: Calibration



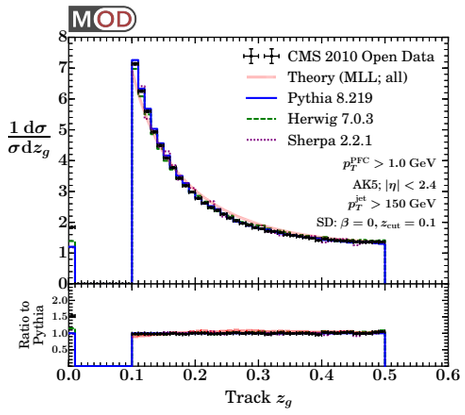
For this study:

Detector-object data (with statistical errors only)
overlaid on
Truth-hadron parton shower generators (no simulation)

Run 2010B data does not include information for calibration/unfolding (beyond JEC factors)

Run 2011A does include MC,
allowing an estimate of systematic uncertainties

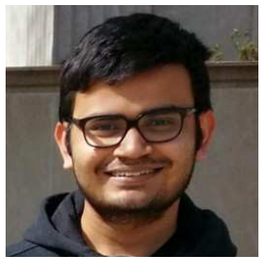
Using the CMS Open Data



Jet Substructure and QCD Splittings

The Future of Public Collider Data

Kati Lassila-Perini,
Achim Geiser, ...



Aashish Tripathee

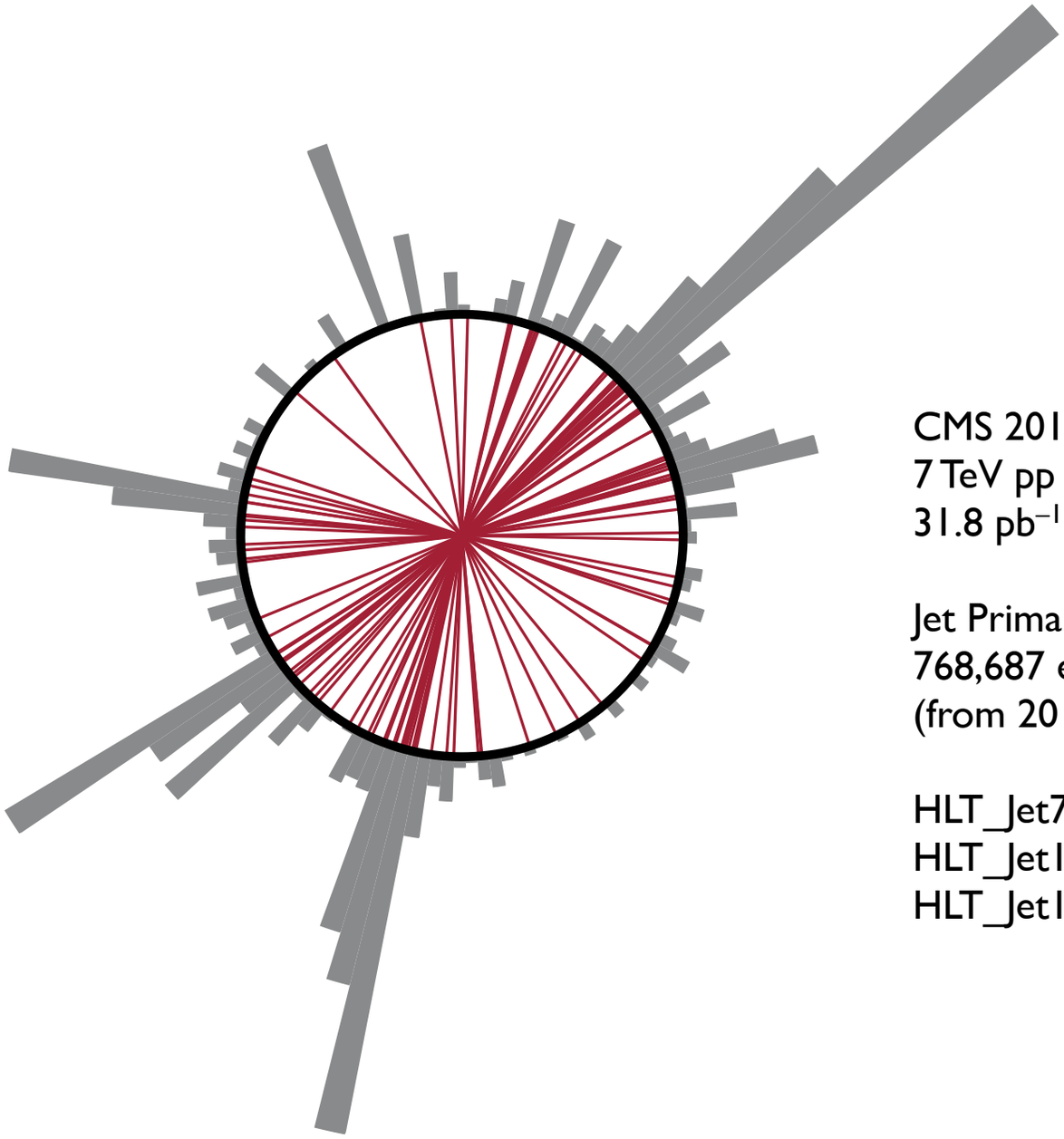
Wei Xue

Andrew Larkoski

Simone Marzani

Summer intern:
Alexis Romero

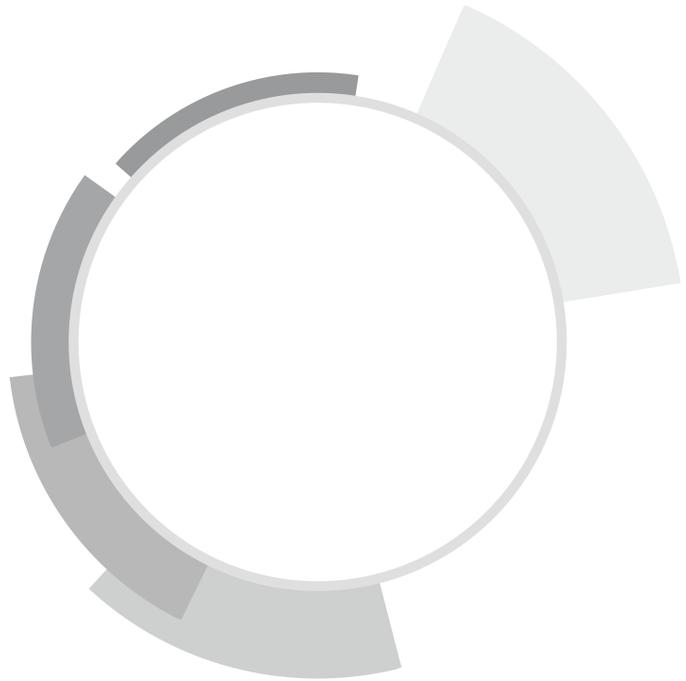
CMS advice:
Sal Rappoccio



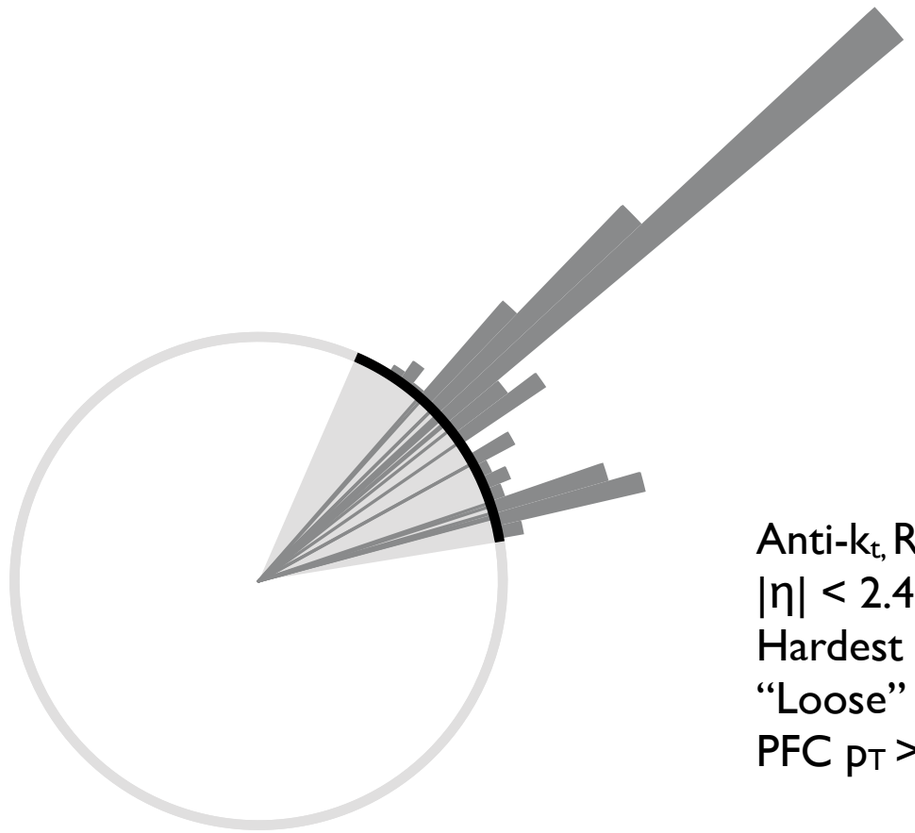
CMS 2010 Run B
7 TeV pp
31.8 pb^{-1}

Jet Primary Dataset
768,687 events
(from 20 million)

HLT_Jet70U
HLT_Jet100U
HLT_Jet140U

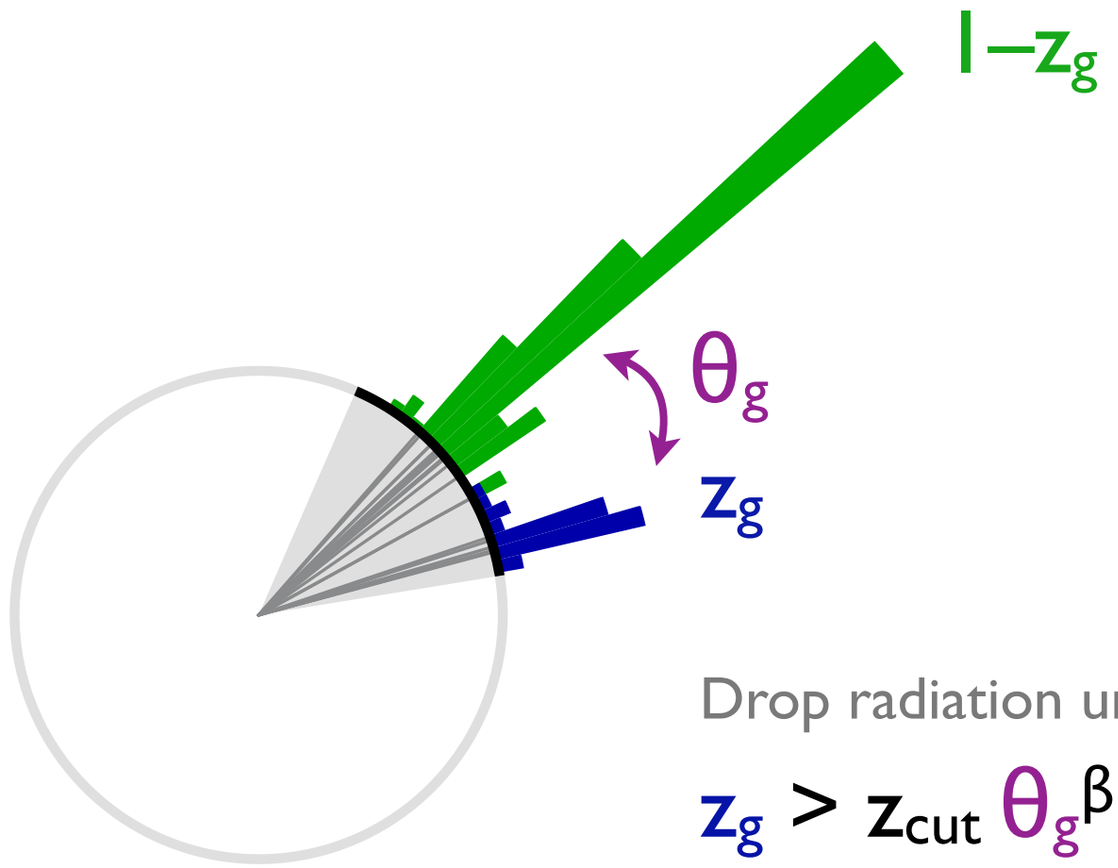


Anti-k_t, R = 0.5
$|\eta| < 2.4$
$p_T > 20$ GeV
"Loose" JQC



Anti-k_t, R = 0.5
$|\eta| < 2.4$
Hardest p_T > 150 GeV
“Loose” JQC
PFC p_T > 1 GeV

mMDT/Soft Drop



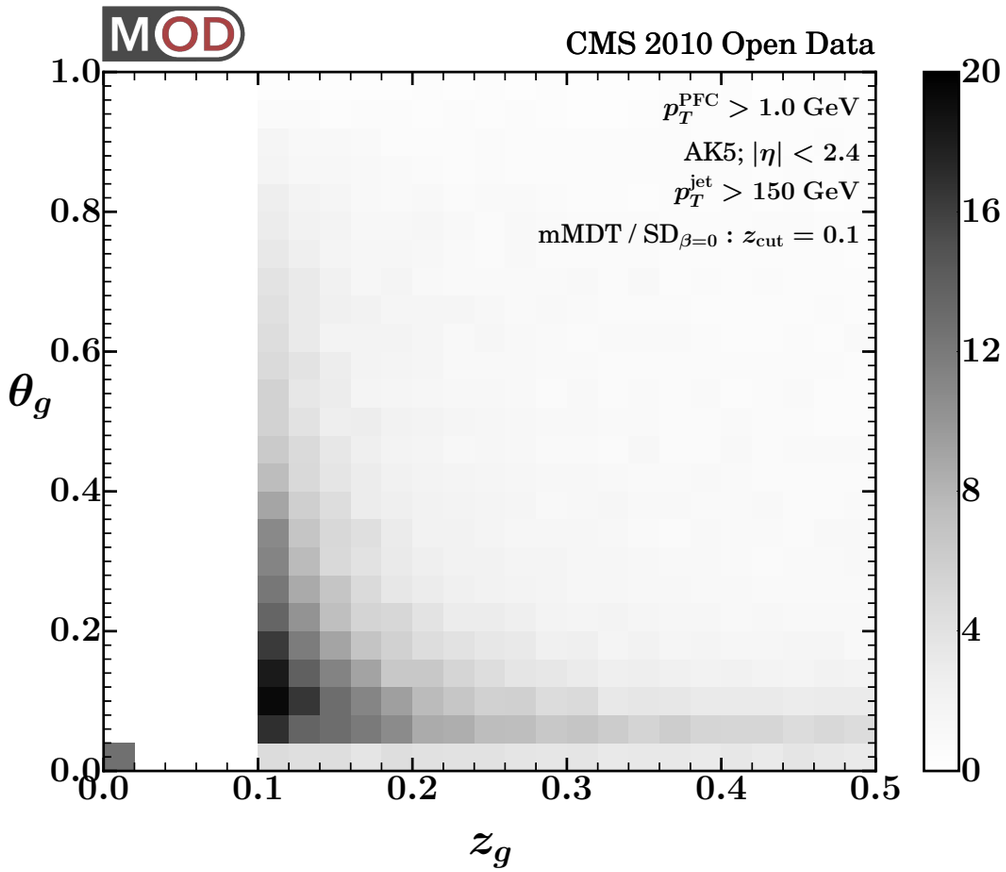
Drop radiation until:

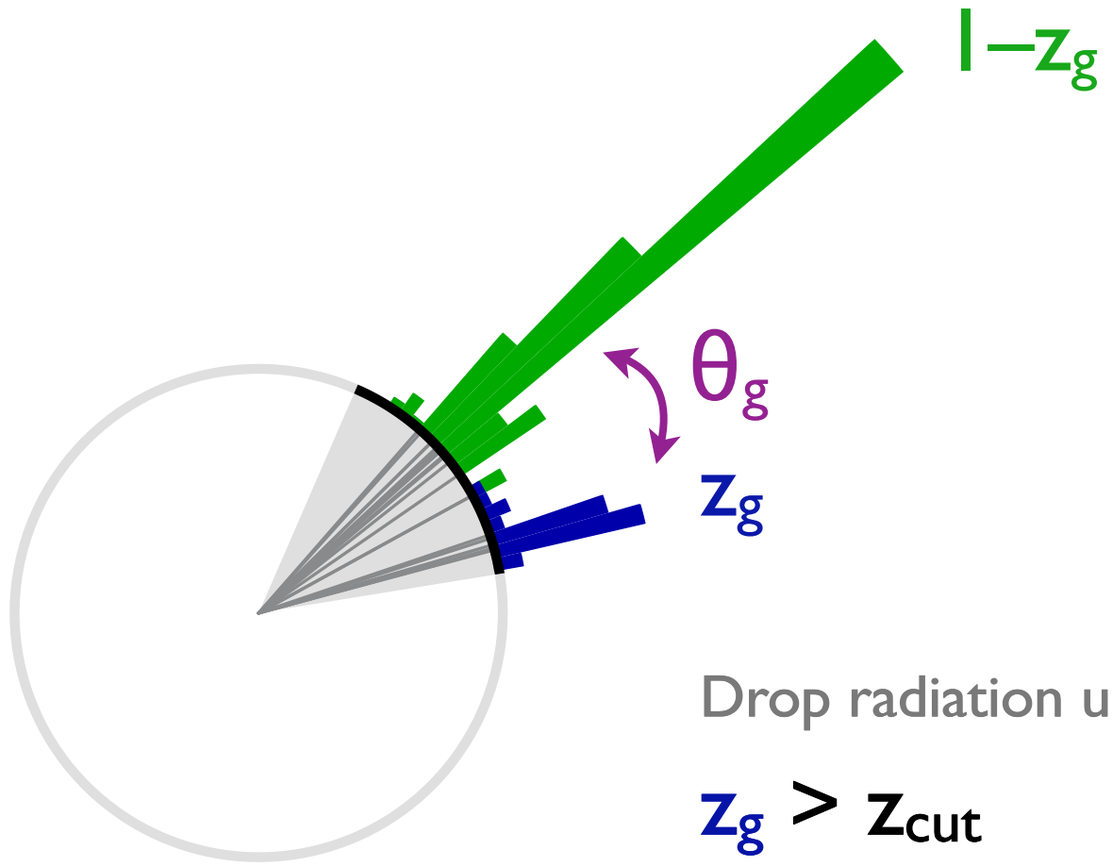
$$z_g > z_{cut}\,\theta_g^{\beta}$$

Scale-invariant: $\beta = 0$

[Larkoski, Marzani, Soyez, JDT, 1402.2657; Dasgupta, Fregoso, Marzani, Salam, 1307.0007;
see also Butterworth, Davison, Rubin, Salam, 0802.2470]

Grooming Highlights Soft/Collinear Behavior



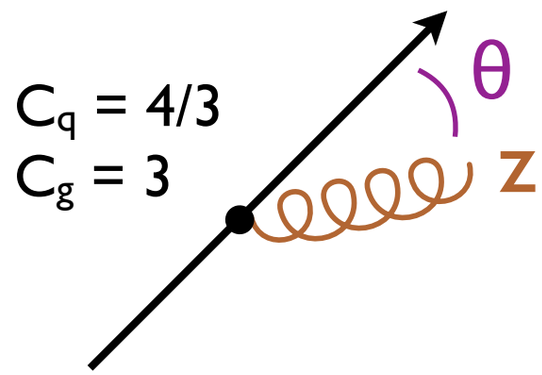


Drop radiation until:

$z_g > z_{\mathrm{cut}}$

$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

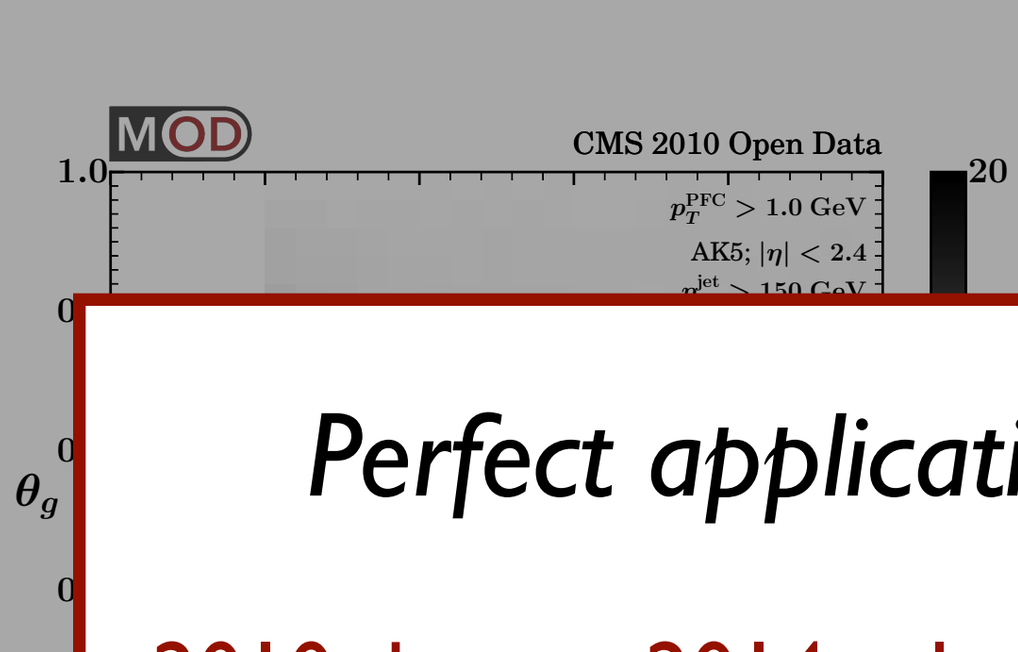
Collinear Soft



$$z \approx z_g \quad (!)$$

[Larkoski, Marzani, JDT, 1502.01719; see also Larkoski, JDT, 1307.1699]

Grooming Highlights Soft/Collinear Behavior



$1-z_g$

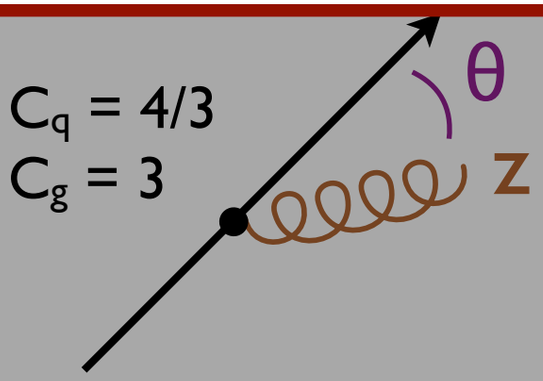
Perfect application of CMS Open Data

2010 data ⇒ 2014 release ⇒ 2015 idea ⇒ 2017 analysis

Benefits from low trigger thresholds and low pileup

$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

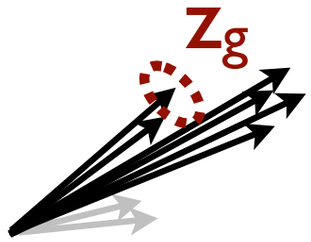
Collinear Soft



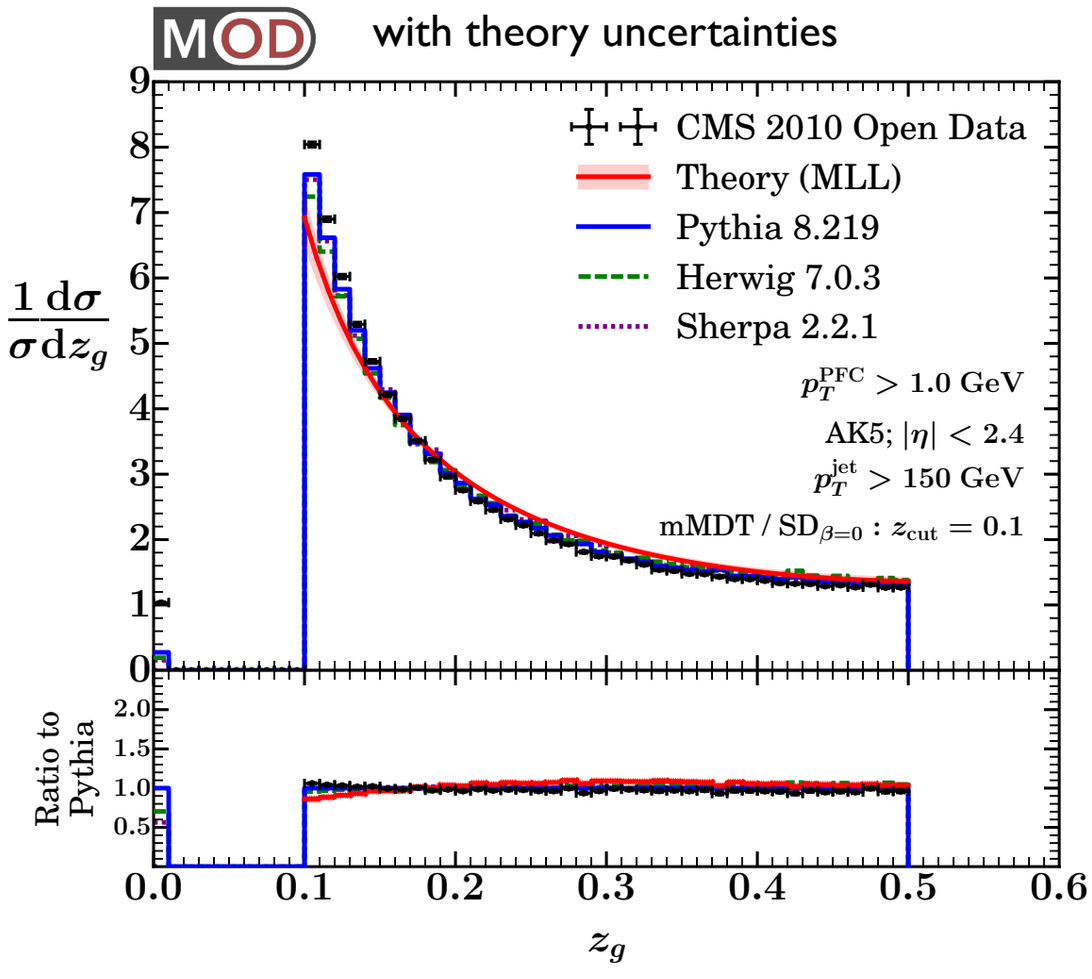
$z \approx z_g$ (!)

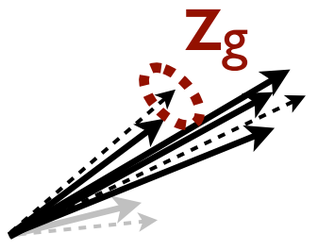
[Larkoski, Marzani, JDT, 1502.01719; see also Larkoski, JDT, 1307.1699]

Exposing the QCD Splitting Function

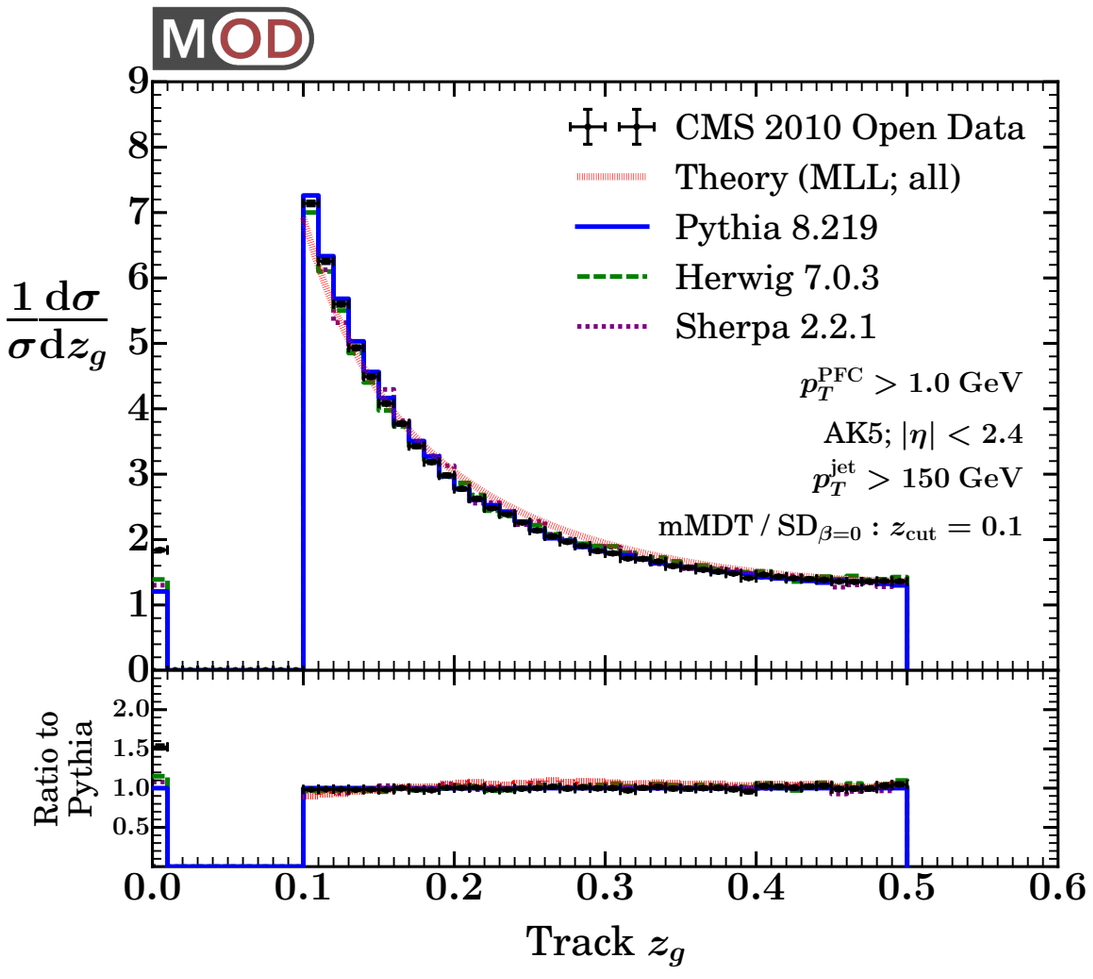


All particle





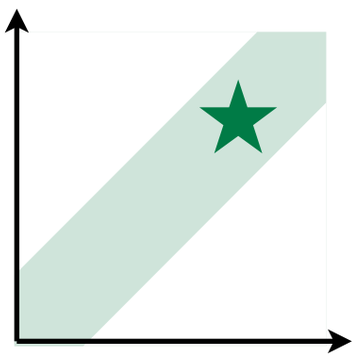
Track-only



[Larkoski, Marzani, JDT, Tripathee, Xue, 1704.05066]

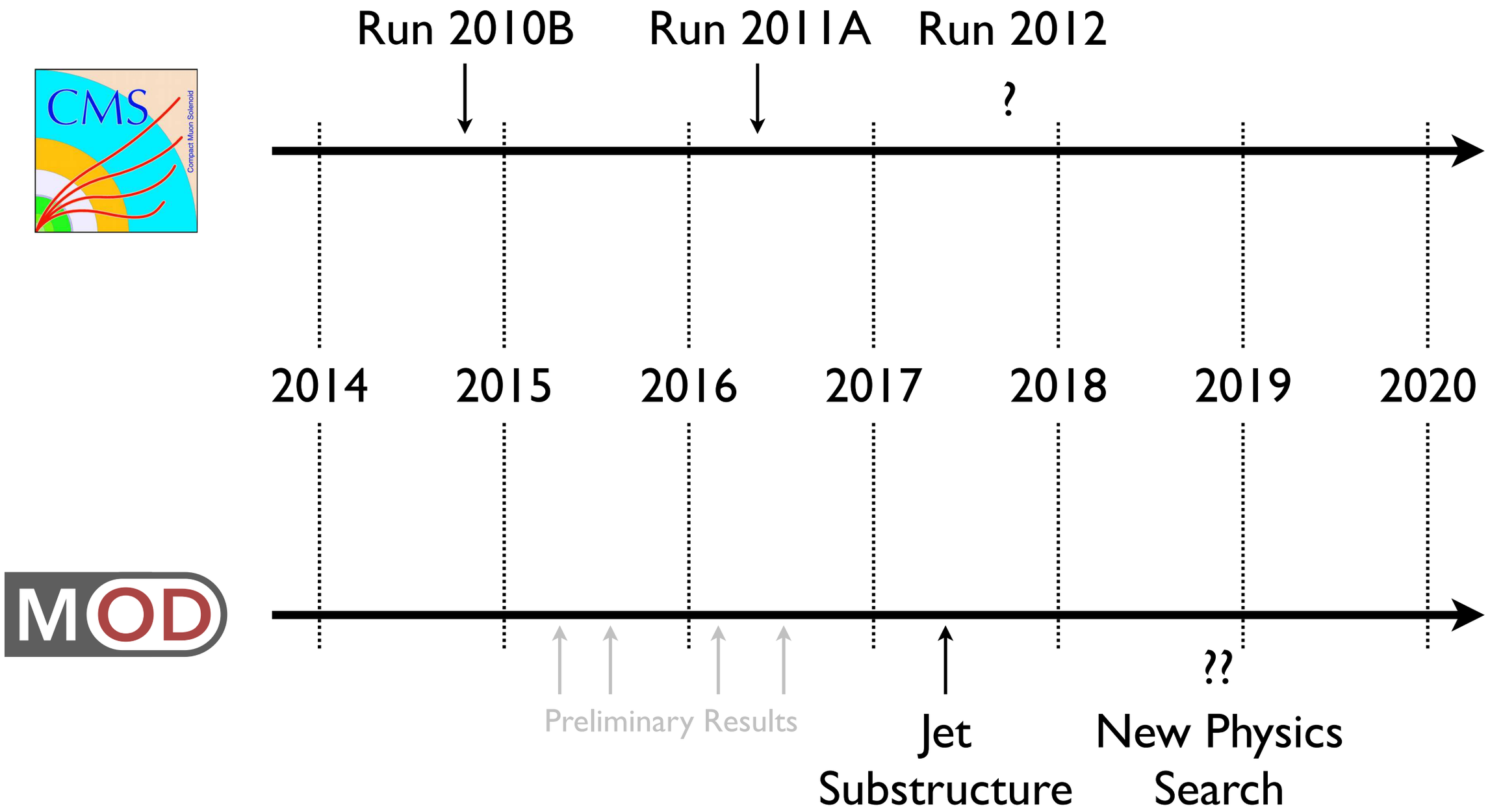
Using the CMS Open Data

Jet Substructure and QCD Splittings



The Future of Public Collider Data

The Open Data Pipeline



Data preservation (and outside analyses)
require significant resources:

People, time, ideas, and money

Viability of CMS Open Data (and expansion to other experiments)
depends on interest/enthusiasm of particle physics community

Let me address some concerns about public data raised by our work
(not exact quotes, not exhaustive, not really representative)

Confronting the Steep Learning Curve

"I support open data on principle, but it seems to require an excessive amount of effort to use the CMS Open Data"

CMS Primary Datasets

CMS primary datasets are AOD (Analysis Object Data) files, which contain the information that is needed for analysis

Years: **2010**, **2011**

Total records:

33

CMS Simulated Datasets

This collection contains CMS Simulated Datasets.

Years: **2010**, **2011**

Total records:

381

vs.

CMS Learning Resources

This collection includes learning resources that use CMS public data

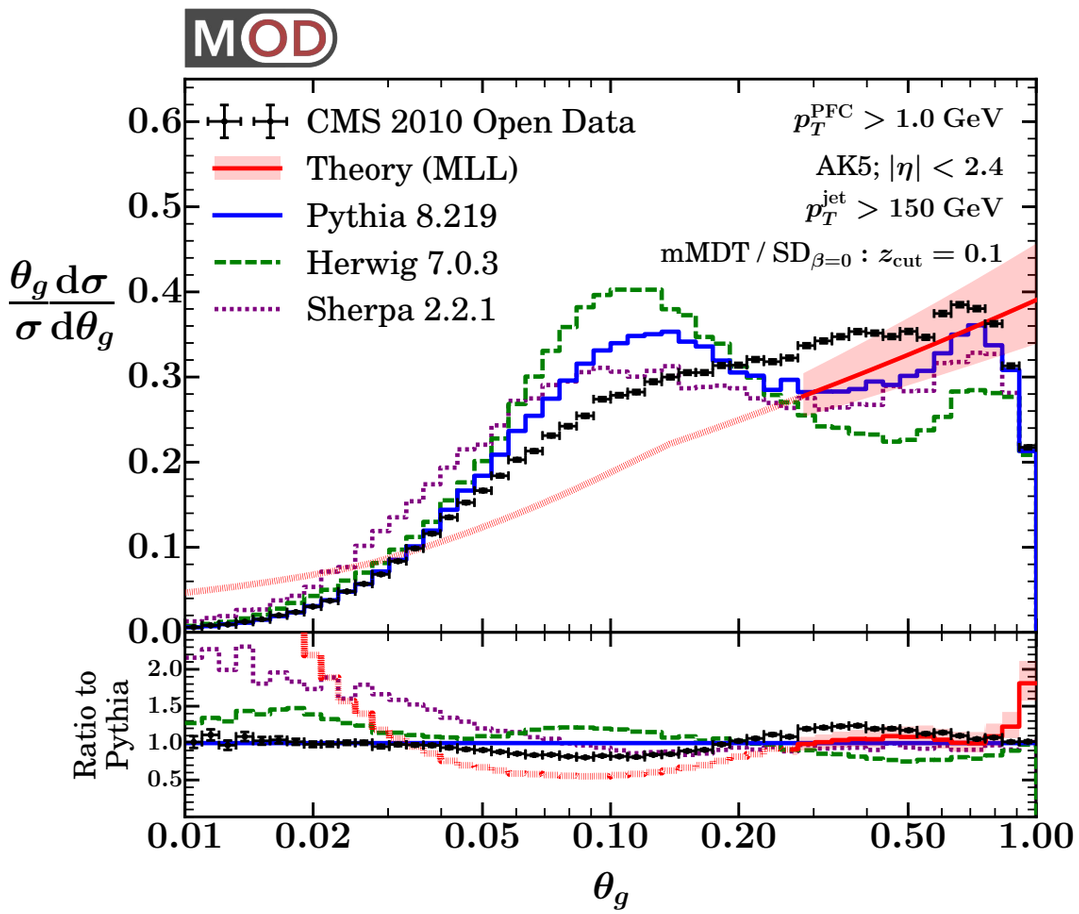
Total records:

7

No magic, but with suitable investment, open data could be as straightforward to parse and interpret as detector-simulated Monte Carlo (e.g. MOD format)

Balance between Sophistication and Exploration

"There is no way you can do an external analysis with the same degree of sophistication as within the collaboration"



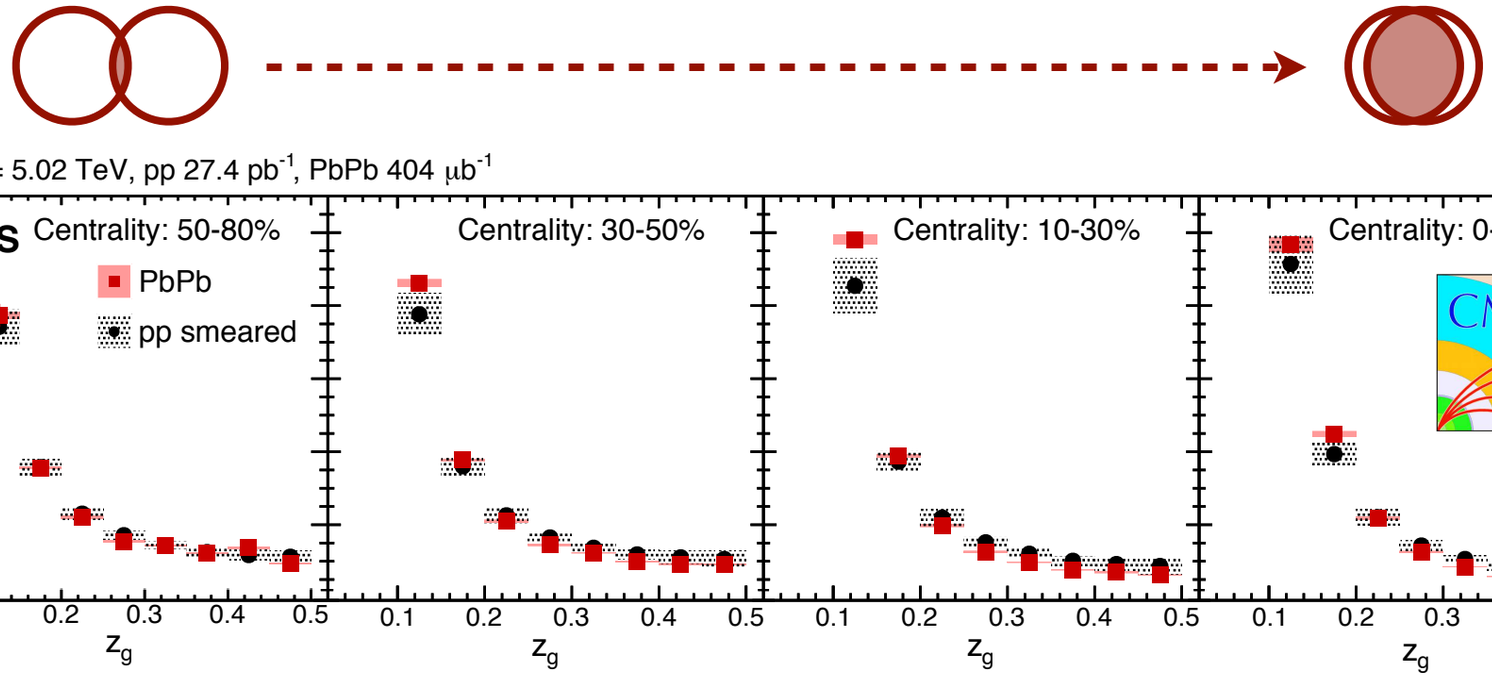
Agreed (mostly)

But with unexpected theoretical/experimental issues at play, value in exploratory studies

[Tripathee, Xue, Larkoski, Marzani, JDT, 1704.05842]

Synergy between Internal and External Efforts

"This work competes with ongoing collaboration analyses without the scrutiny of internal review; careers are at stake"

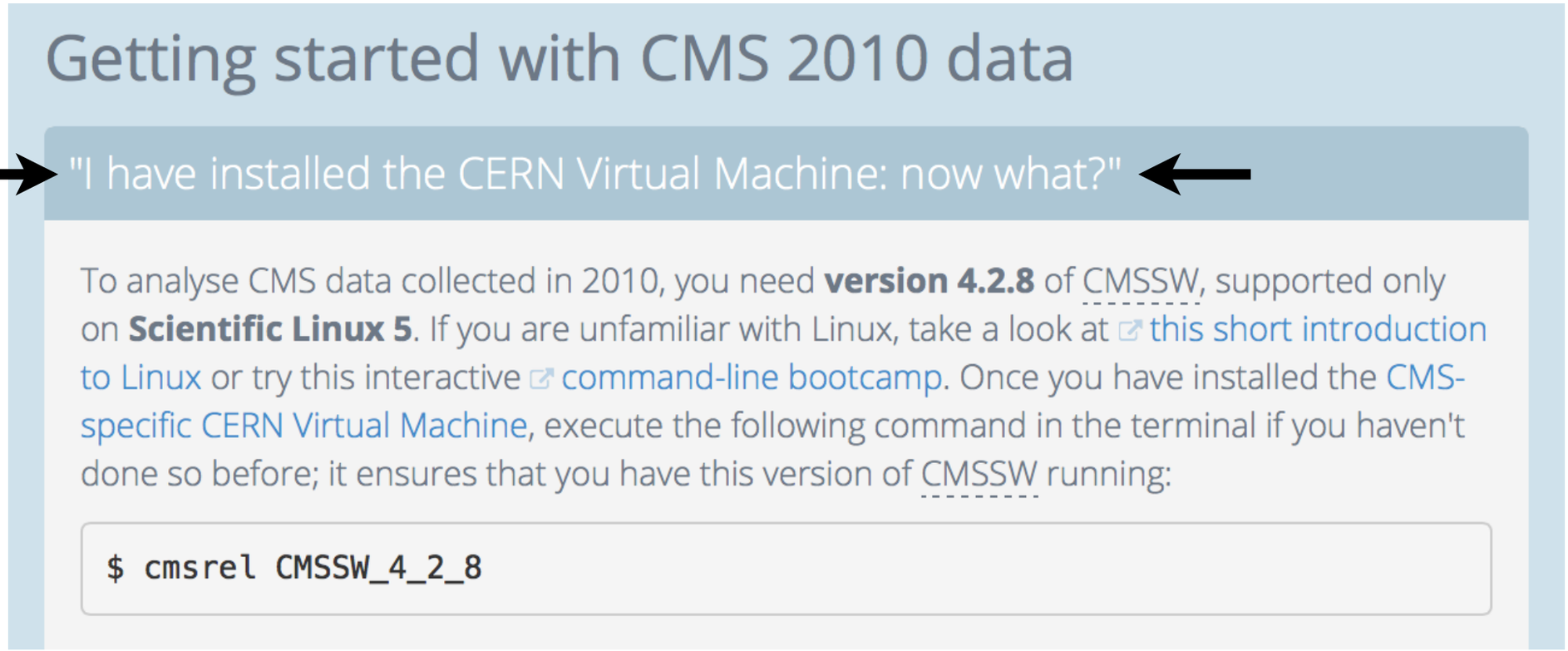


I will be heartbroken if open data adversely impacts experimental progress, and I hope our work inspires more vigorous investigations into jets and QCD

[CMS, 1708.09429]

Value of Open-Ended Investigations

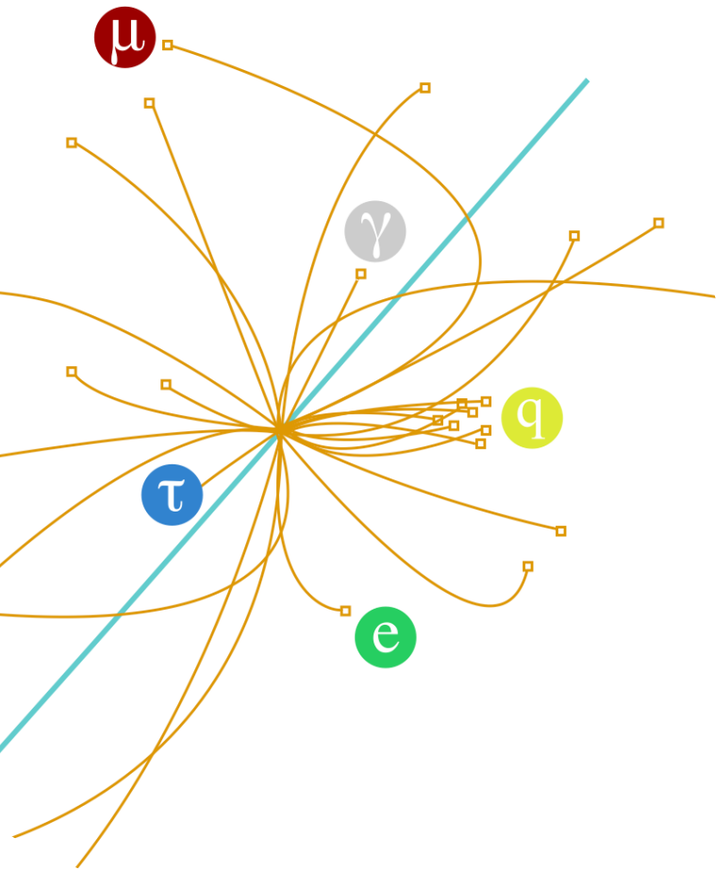
"If you really wanted to do this jet substructure measurement, you should have joined CMS as a short term associate"



Agreed, but what I really wanted to do is figure out the answer to this question (curiosity-driven research)

My View

The CMS Open Data is a fantastic resource, with many exciting applications



Educating future scientists

Stress-testing archival data strategies

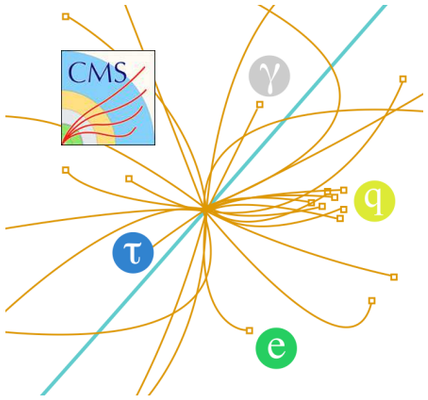
Enabling exploratory/proof-of-principle studies

Facilitating dialogue between theory and experiment

Researching physics in and beyond the standard model

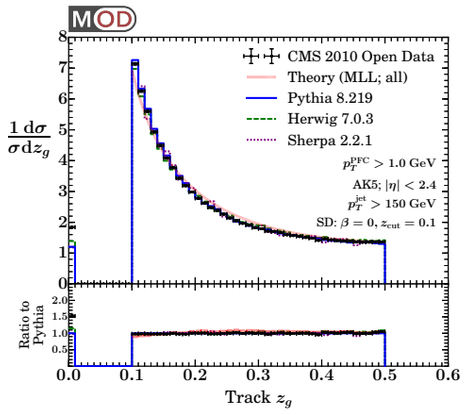
These are only possible with sustained investment in public data initiatives

Summary



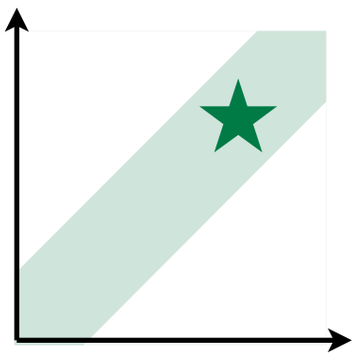
Using the CMS Open Data

Unique collider data set, ideal for exploratory studies



Jet Substructure and QCD Splittings

Exposing the universal singularity structure of gauge theories

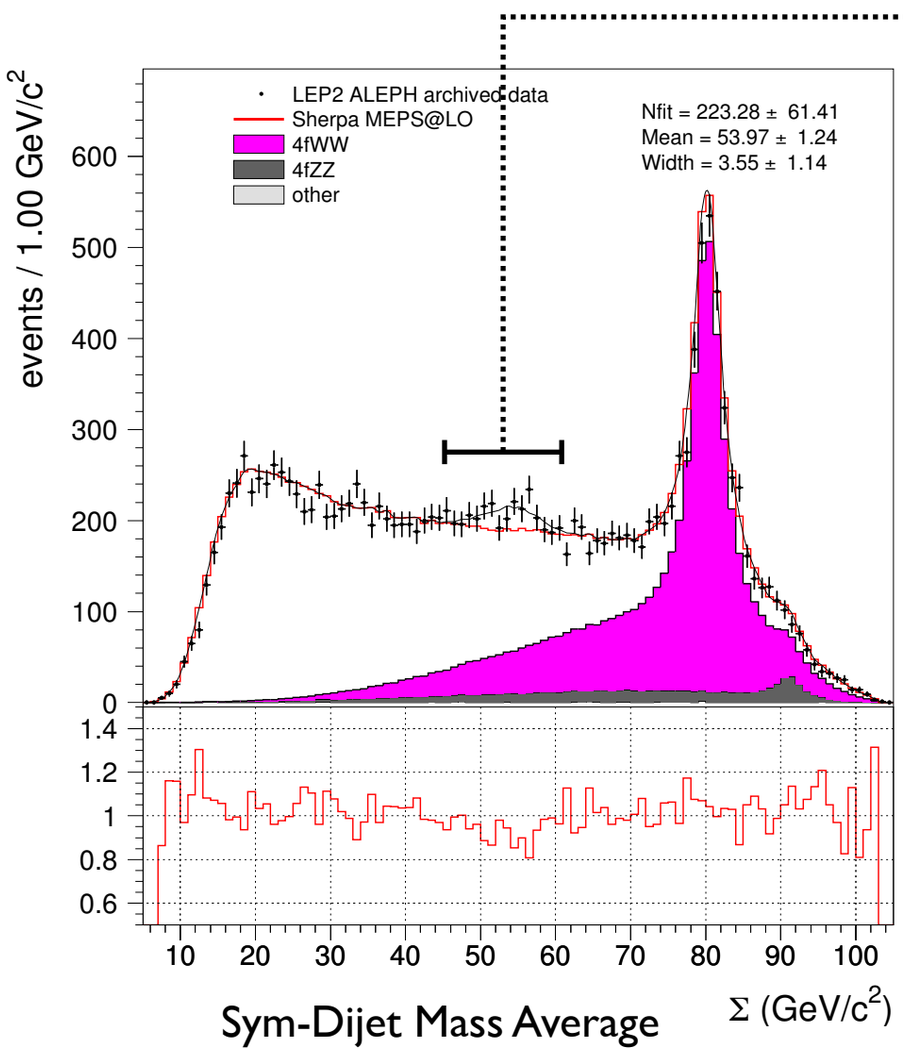


The Future of Public Collider Data

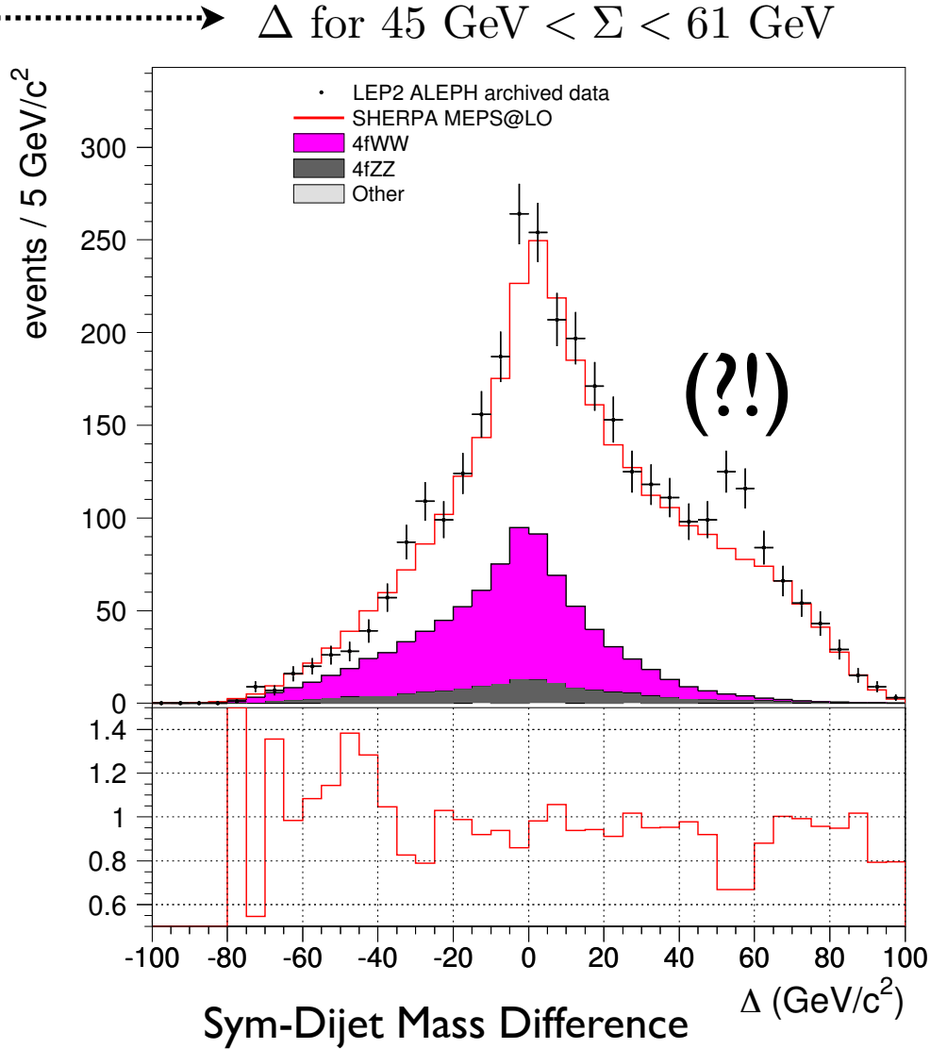
Sustained investment from outreach to research to archives

Backup Slides

A Quad-Jet Puzzle in Archival ALEPH Data



Δ for 45 GeV $< \Sigma <$ 61 GeV



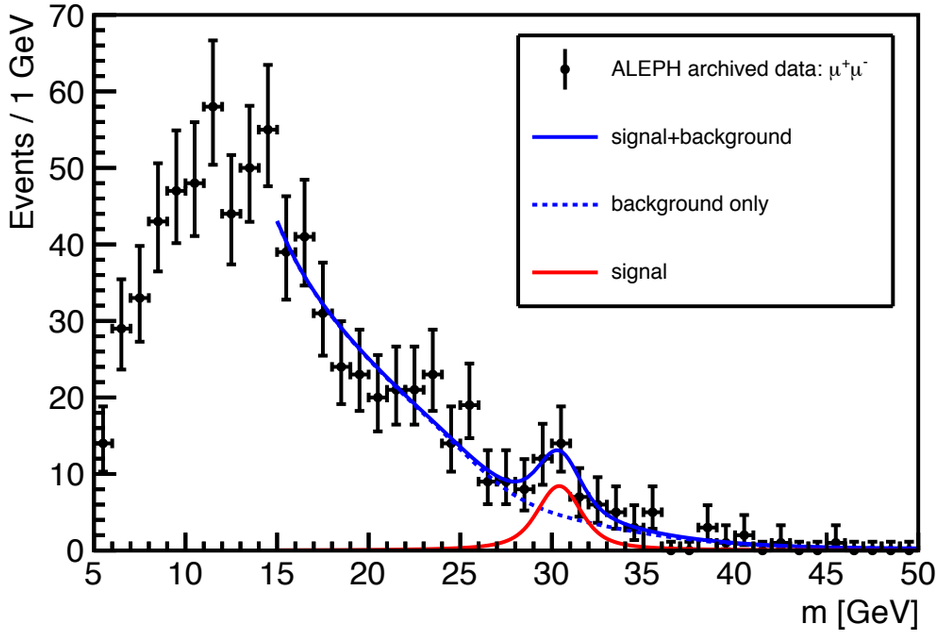
Science thrives on openness, reproducibility, and intense scrutiny

What role should legacy data sets play in collider physics?

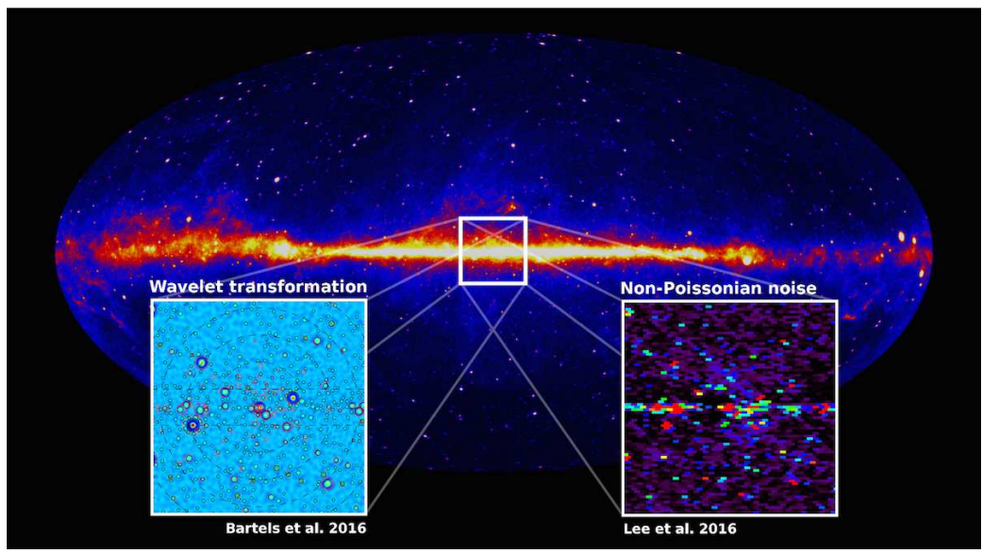
[Kile, von Wimmersperg-Toeller, 1706.02242, 1706.02255, 1706.02269]

Openness as a Vehicle for Scrutiny

"Thank goodness the CMS Open Data is so hard to use, otherwise there would be countless rogue analyses"



vs.

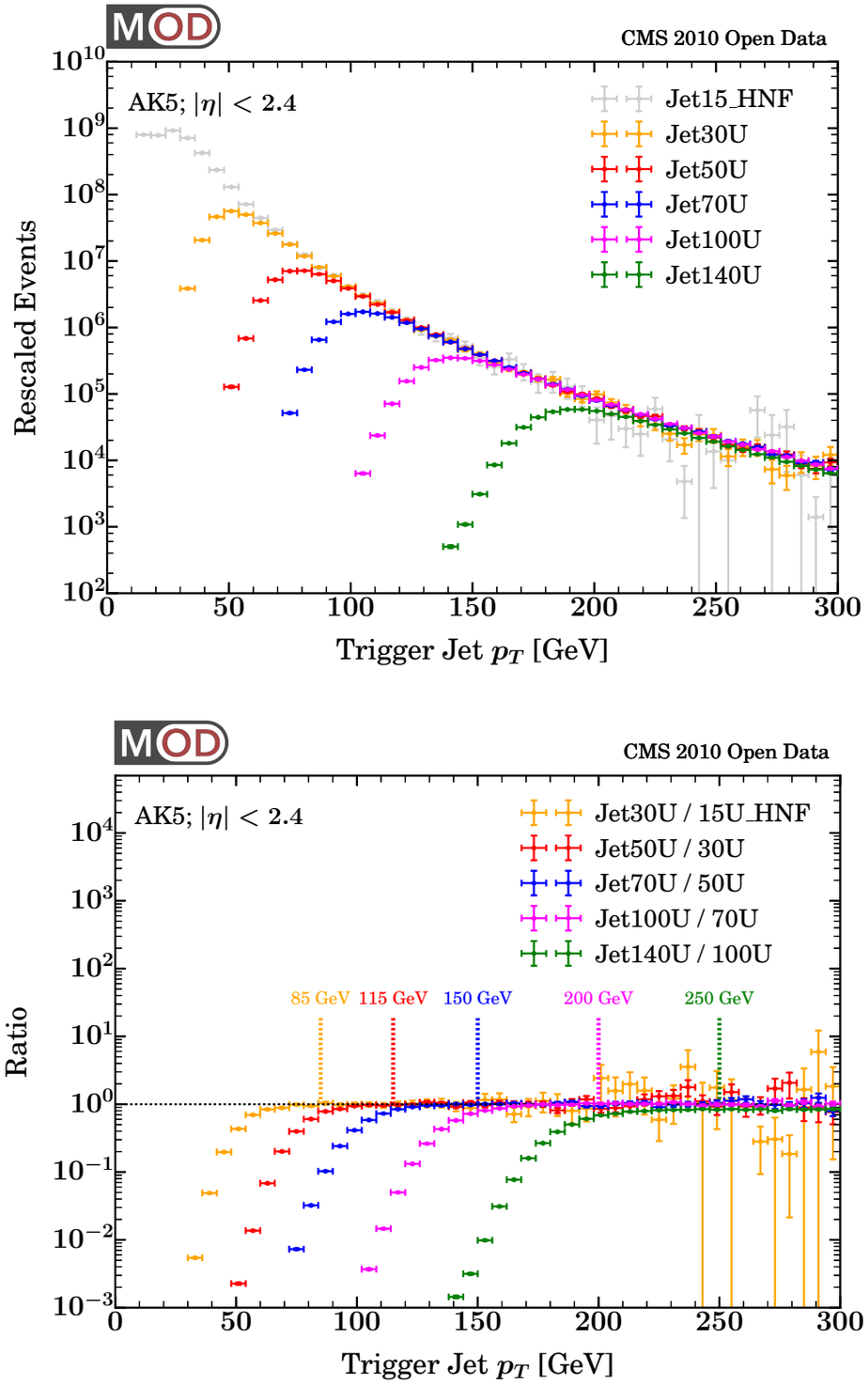


Possibly the opposite: the easier the data is to use, the more likely it will be used correctly and the results cross-checked by other groups

[Heister, 1610.06536; Bartels, Krishnamurthy, Weniger, 1506.05104; Lee, Lisanti, Safdi, Slatyer, Xue, 1506.05124]

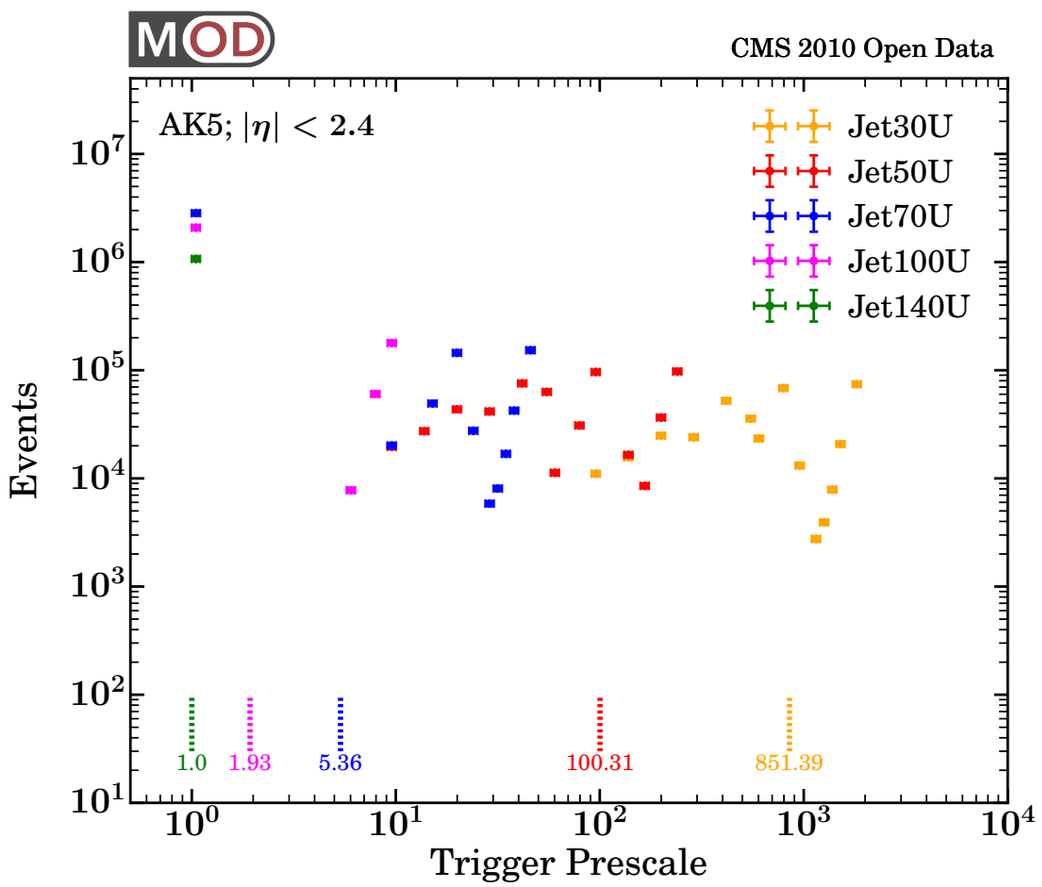
Trigger Selection and Efficiency

	Trigger	Present?	Fired?
Single-jet	HLT_Jet15U	16,341,190	1,342,155
	* HLT_Jet15U_HNF	16,341,190	1,341,930
	* HLT_Jet30U	16,341,190	604,287
	* HLT_Jet50U	16,341,190	870,649
	* HLT_Jet70U	16,341,190	5,257,339
	* HLT_Jet100U	16,341,190	3,689,951
	* HLT_Jet140U	5,989,945	1,898,874
	HLT_Jet180U	2,595,038	553,331
Di-jet	HLT_DiJetAve15U	16,341,191	1,067,561
	HLT_DiJetAve30U	16,341,191	648,000
	HLT_DiJetAve50U	16,341,191	859,292
	HLT_DiJetAve70U	16,341,191	2,310,033
	HLT_DiJetAve100U	5,989,945	1,252,661
	HLT_DiJetAve140U	2,595,038	452,222
Quad-jet	HLT_QuadJet20U	10,351,245	677,451
	HLT_QuadJet25U	10,351,244	219,256
H_T	HLT_HT100U	10,351,245	7,369,985
	HLT_HT120U	10,351,245	4,090,218
	HLT_HT140U	10,351,245	2,430,208
	HLT_EcalOnly_SumEt160	10,351,246	208,718



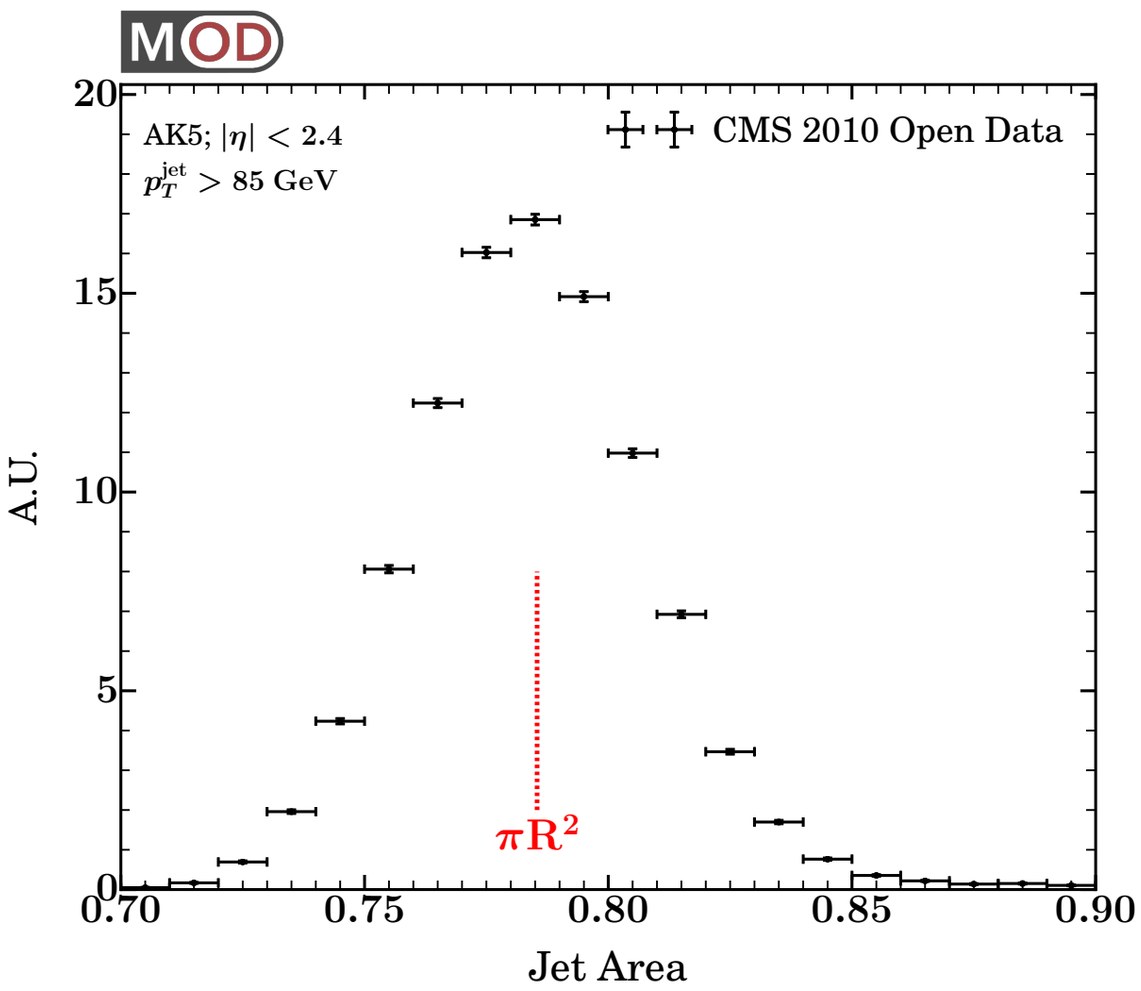
Event Selection, Prescale Factors, Pileup

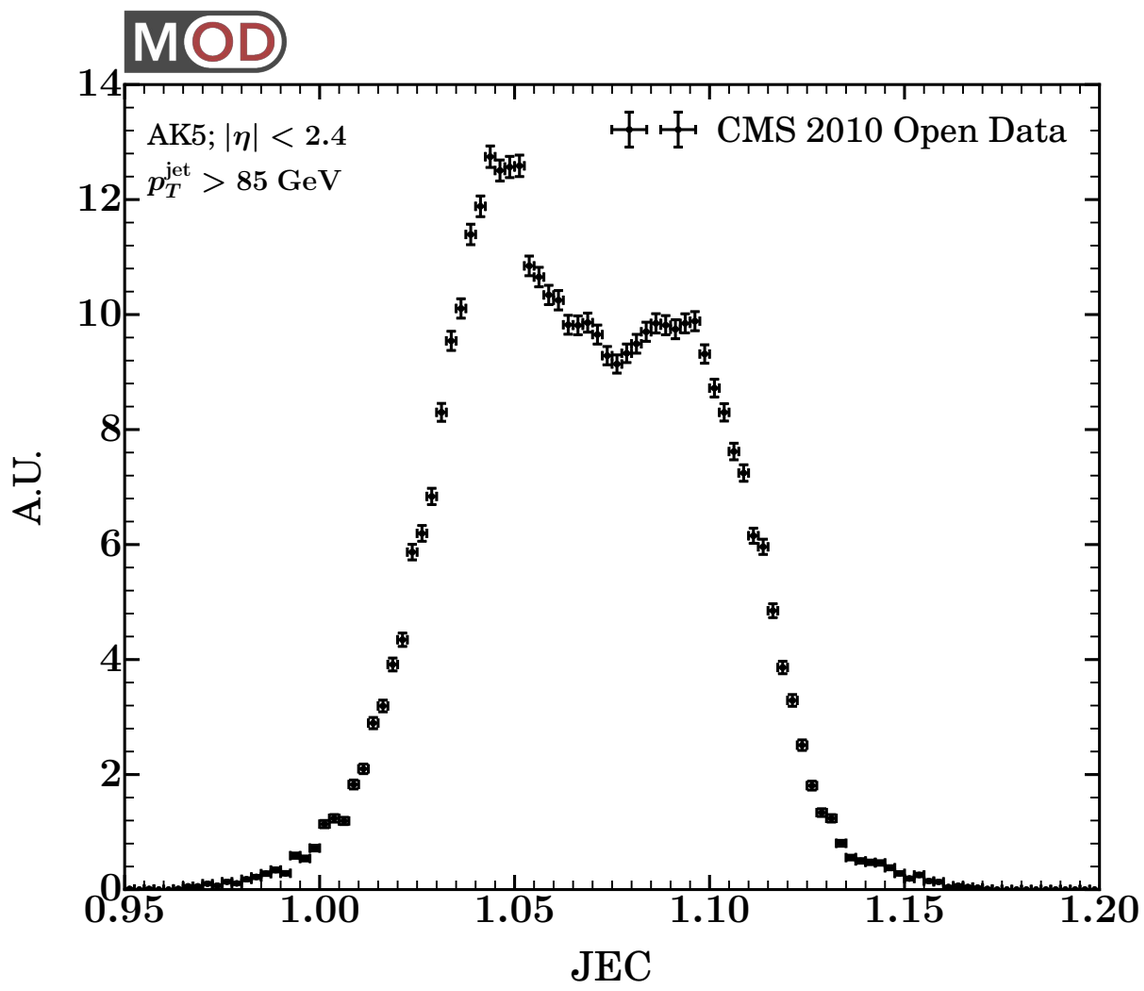
Hardest Jet p_T	Trigger Name	Events	⟨Prescale⟩
$[85, 115]$ GeV	`HLT_Jet30U`	33,375	851.514
$[115, 150]$ GeV	`HLT_Jet50U`	66,412	100.320
$[150, 200]$ GeV	`HLT_Jet70U`	365,821	5.362
$[200, 250]$ GeV	`HLT_Jet100U`	216,131	1.934
> 250 GeV	`HLT_Jet100U`	34,736	1.000
	`HLT_Jet140U`	177,891	1.000



	Jet Primary Dataset		Hardest Jet Selection	
N_{PV}	Events	Fraction	Events	Fraction
1	4,716,494	0.289	190,277	0.248
2	4,814,495	0.295	246,387	0.321
3	3,630,413	0.222	180,021	0.234
4	1,933,832	0.118	93,587	0.122
5	819,835	0.050	38,598	0.050
6	294,612	0.018	13,805	0.018
7	93,714	0.006	4,318	0.006
8	27,550	0.002	1,242	0.002
9	7,481	0.000	330	0.000
10	2,041	0.000	91	0.000
11	540	0.000	21	0.000
12	125	0.000	6	0.000
13	41	0.000	3	0.000
14	9	0.000	1	0.000
≥ 15	5	0.000	0	0.000

Jet Corrections





Jet Area Subtraction ⇢ Jet Energy Corrections

Workflow

Instrumentation

Physics

	Events	Fraction	
Jet Primary Dataset	20,022,826	1.000	
Validated Run	16,341,187	0.816	Provided by CMS
Assigned Trigger Fired (Table II)	894,366	0.045	Derived by us, consistent with CMS
Loose Jet Quality (Table V)	843,129	0.042	Provided by CMS
AK5 Match	843,128	0.042	Numerical rounding issue
$\|\eta\| < 2.4$	768,687	0.038	Central jets
Passes Soft Drop ($z_g > z_{\rm cut}$)	760,055	0.038	Jet grooming (more later)

Factor of 20 reduction in events by using
≈100% efficient triggers on high-quality jets

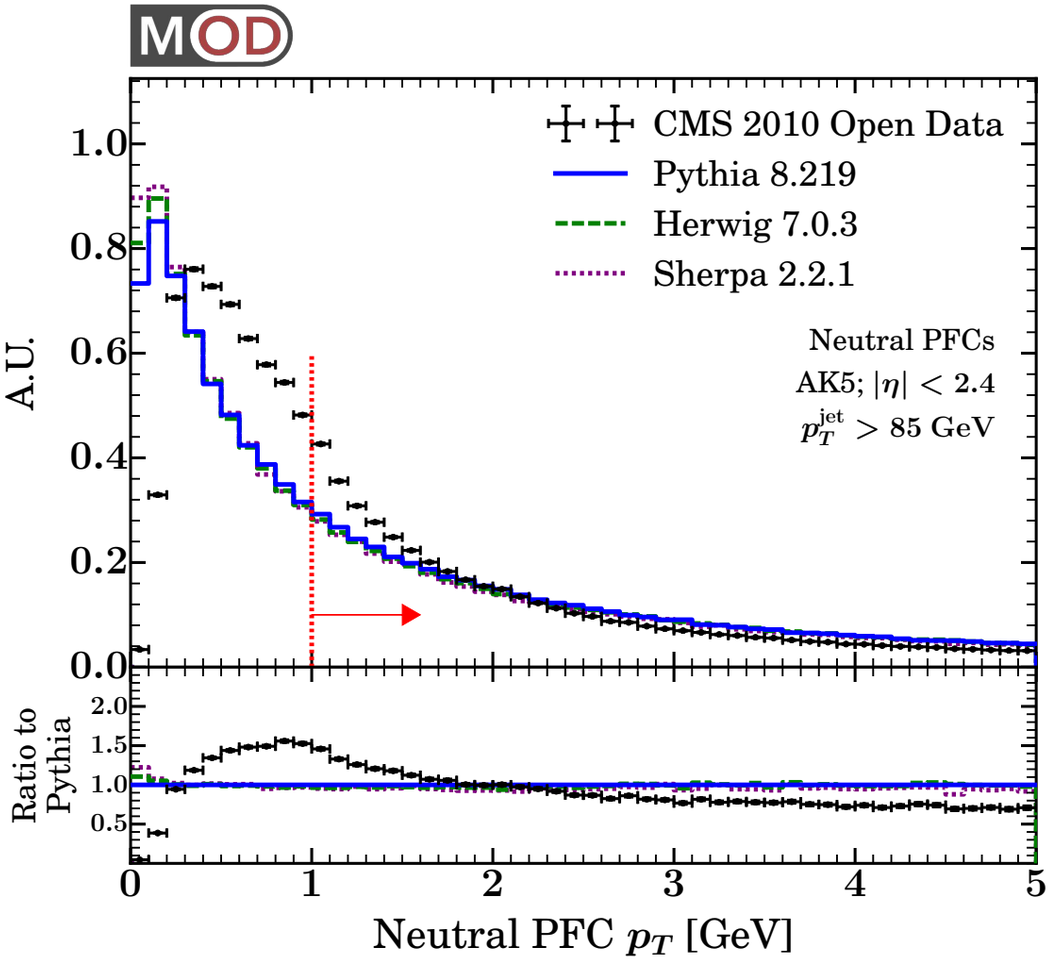
Particle Flow Reconstruction

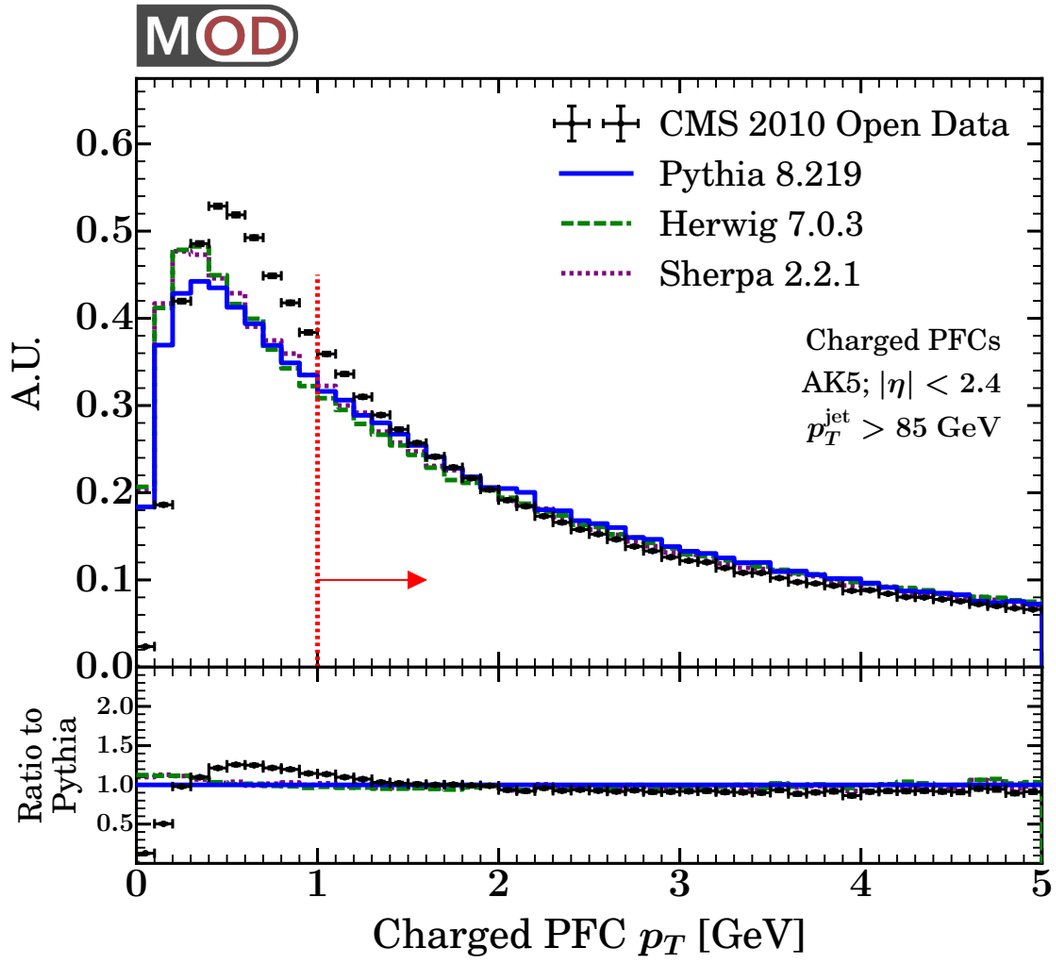
Workhorse of every CMS substructure analysis

Code	Candidate	Total Count	$p_T > 1$ GeV
11	electron (e^-)	32,917	32,900
−11	positron (e^+)	32,984	32,968
13	muon (μ^-)	12,941	12,653
−13	antimuon (μ^+)	13,437	13,110
211	positive hadron (π^+)	6,908,914	5,183,048
−211	negative hadron (π^-)	6,729,328	5,027,146
22	photon (γ)	9,436,530	4,805,173
130	neutral hadron (K_L^0)	2,214,385	1,658,892

Without detector simulation, difficult to assess performance of neutral hadrons (esp. $\pi_0 \to \gamma\gamma$)

Particle Flow Fiducialization

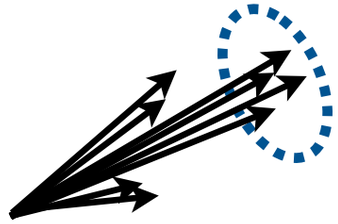


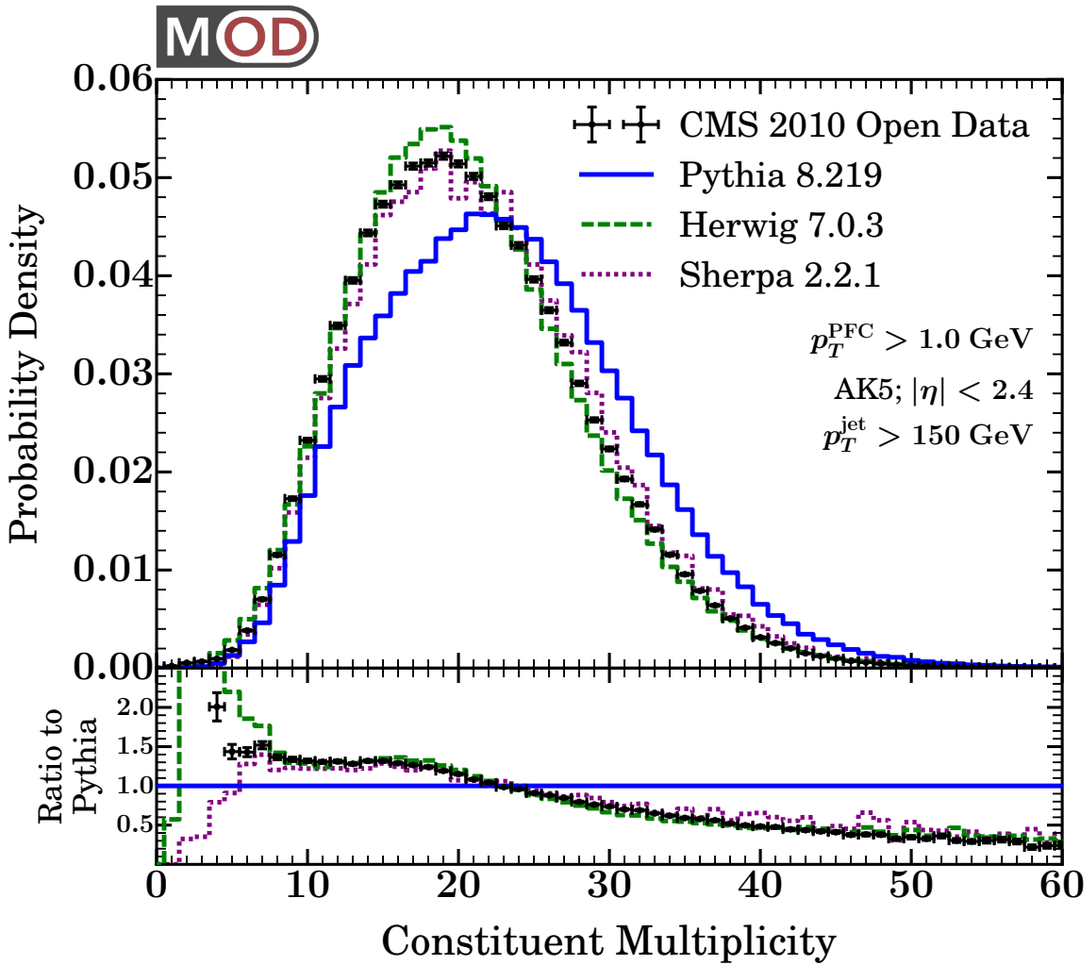


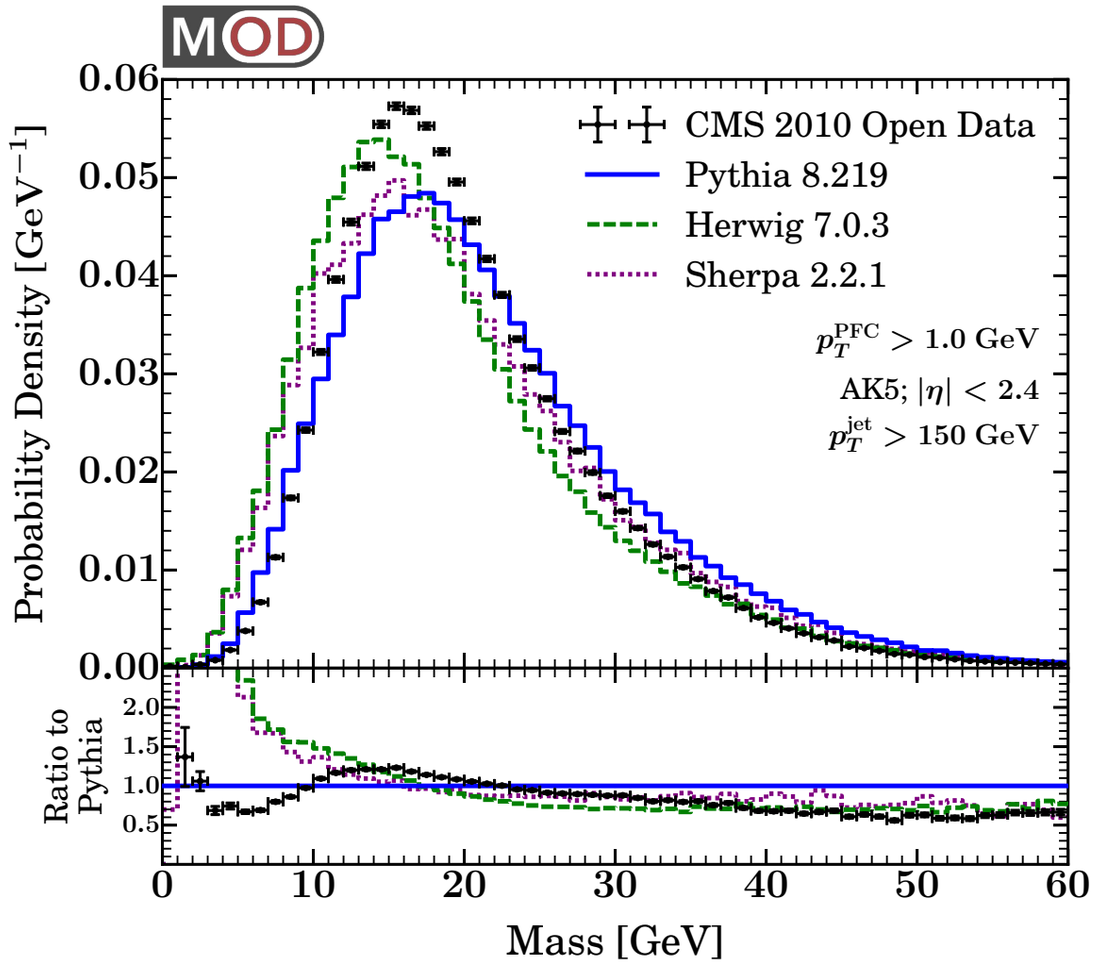
Motivation to focus on charged PFCs with $p_T > 1$ GeV

Basic Substructure

No grooming applied





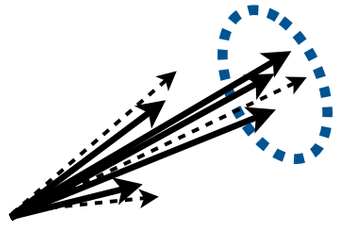


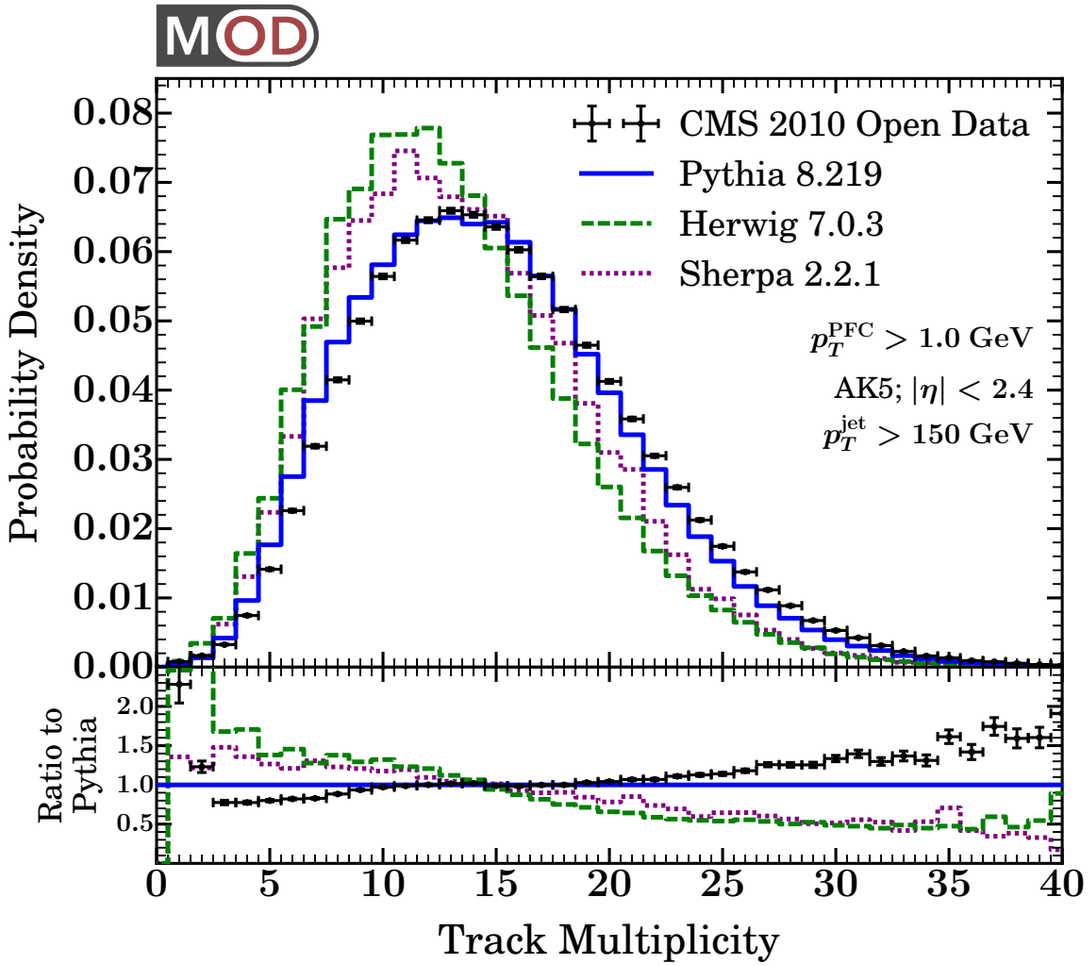
Careful! Can't assess data/MC (dis)agreement without unfolding

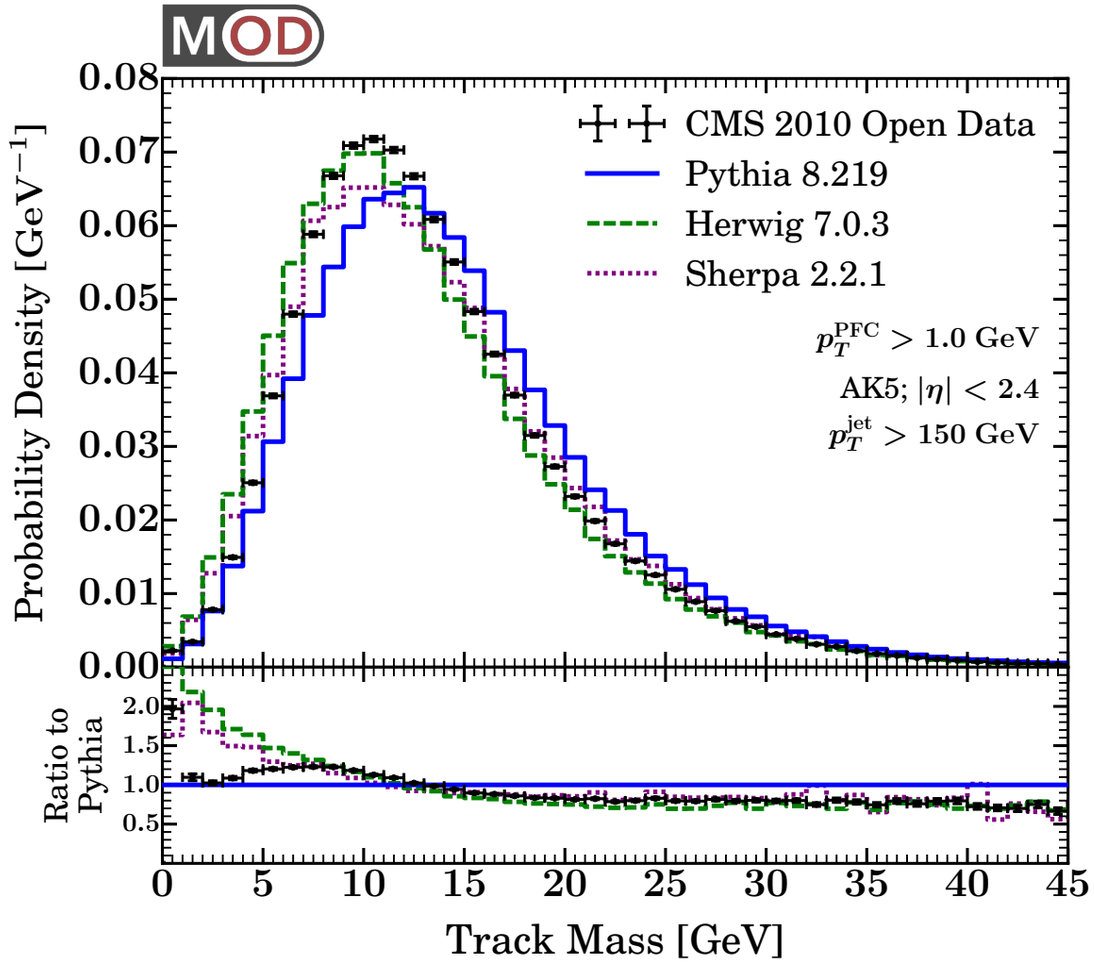
Still interesting to investigate MC/MC differences

Track-Based Substructure

No grooming applied



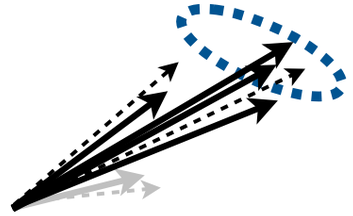


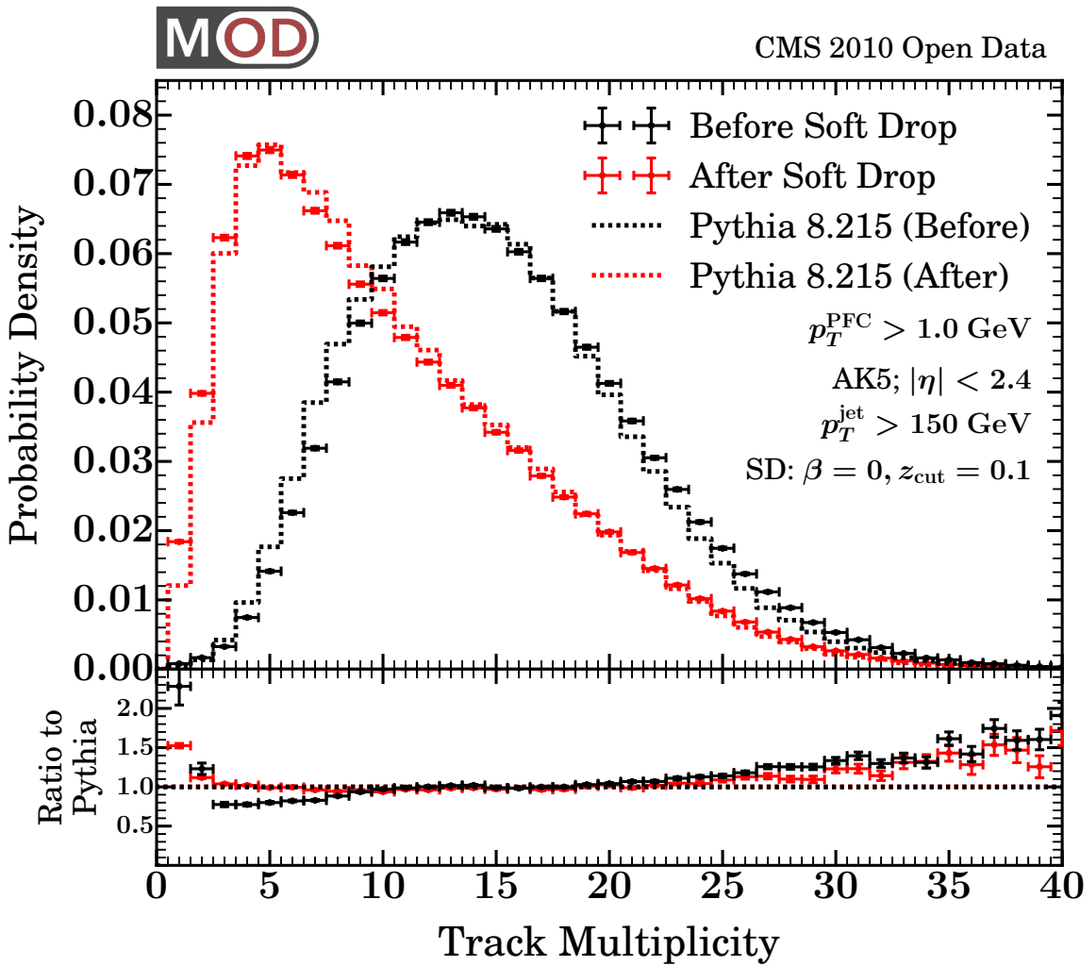


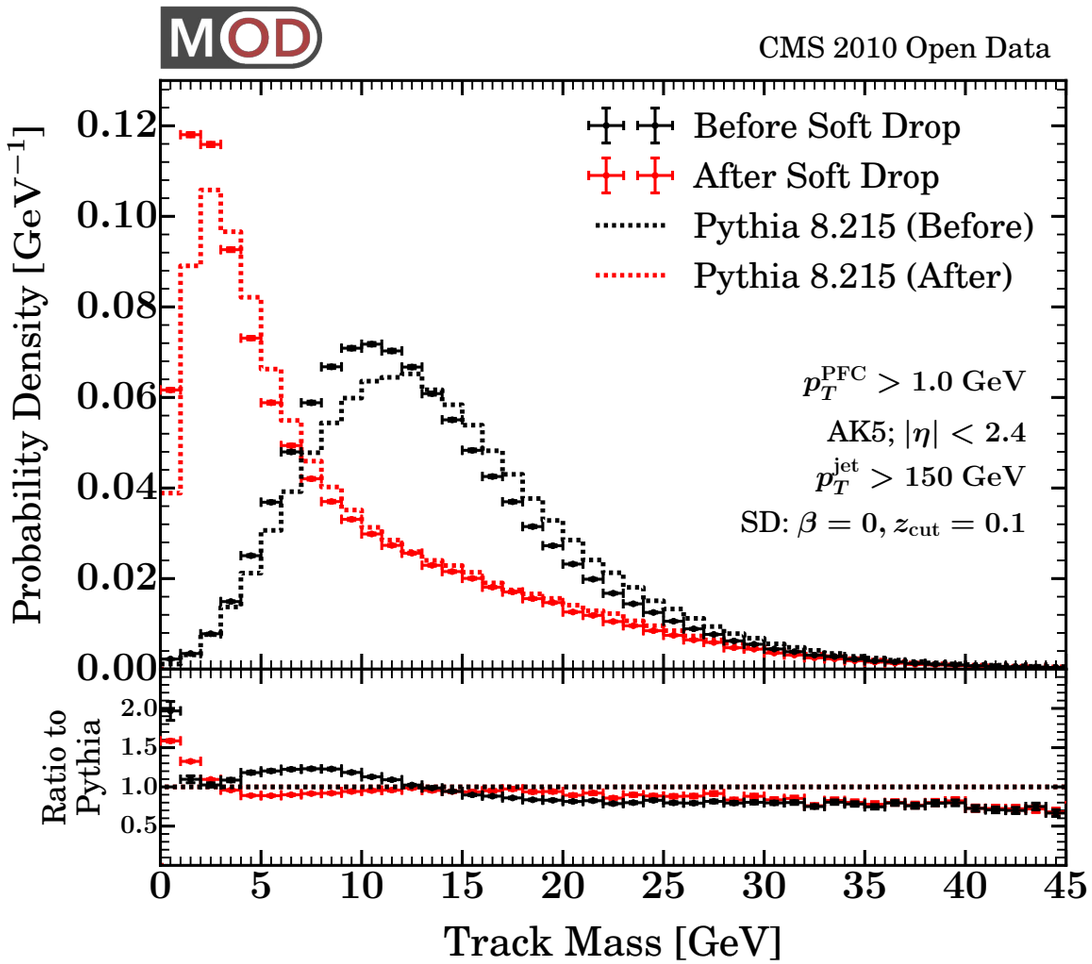
Restricting to charged particles typically improves data/MC agreement (but not always)

Track-Based Substructure

With and without soft drop grooming

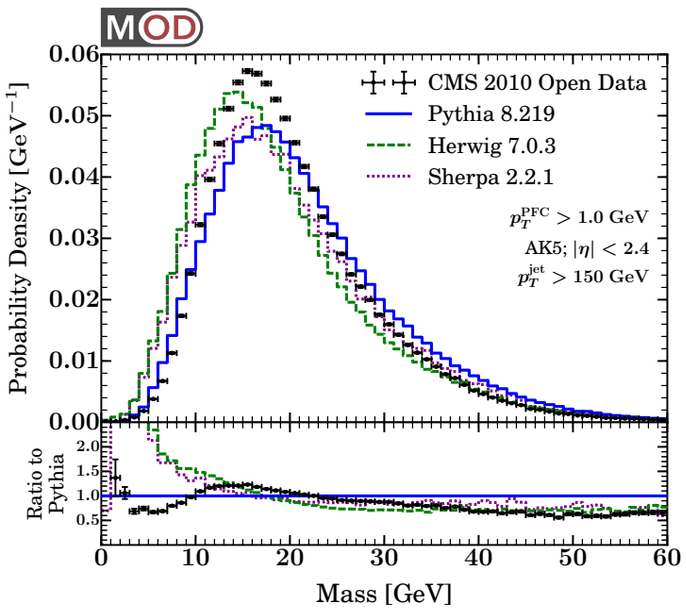


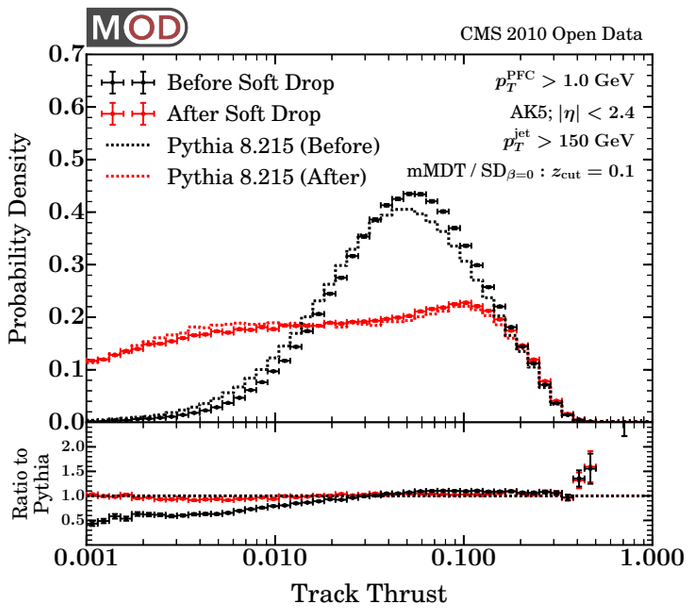


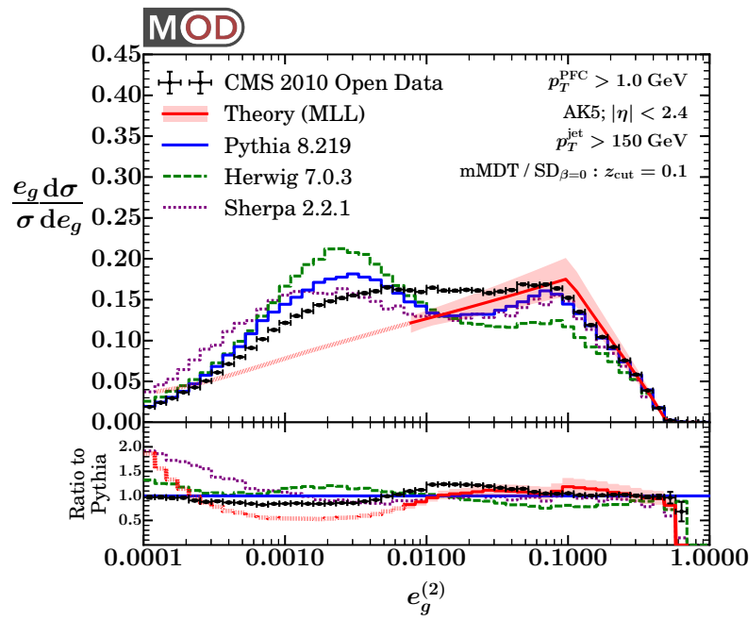


Jet grooming does not typically affect data/MC agreement

Explorations in Jet Substructure

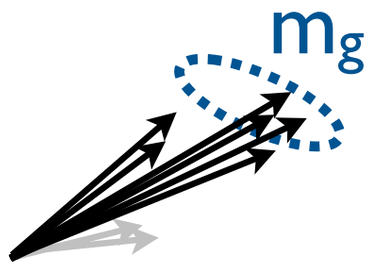




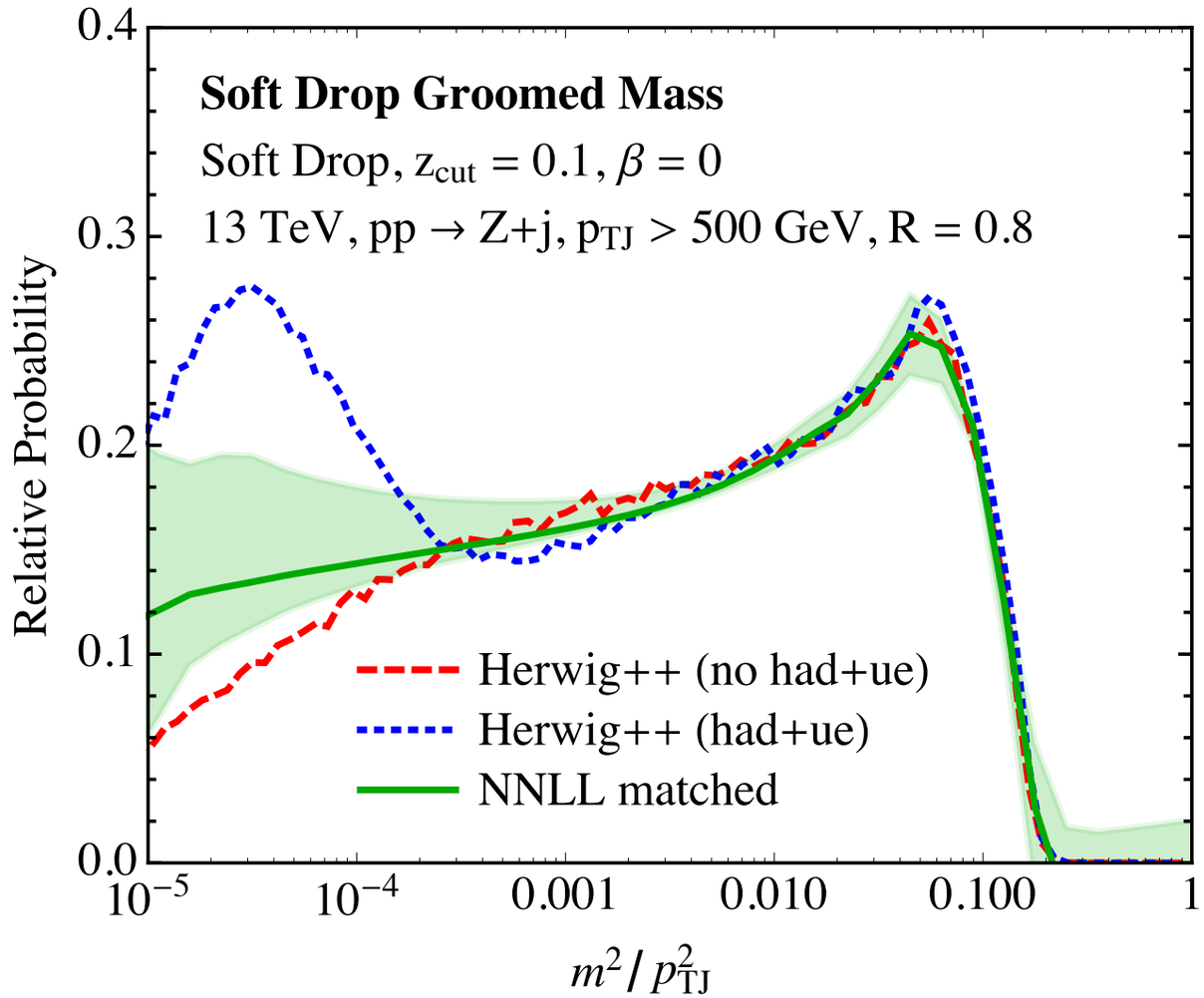


Three different probes of jet mass
with different experimental and theoretical challenges

Soft Drop Jet Mass



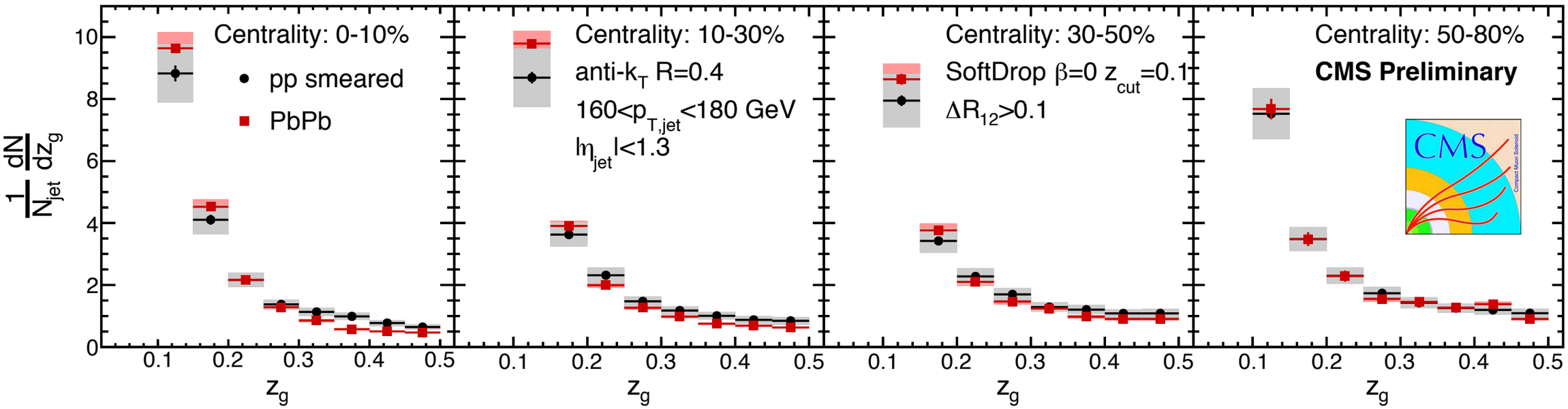
First NNLL + $O(\alpha_s^2)$ result for substructure in pp (!)

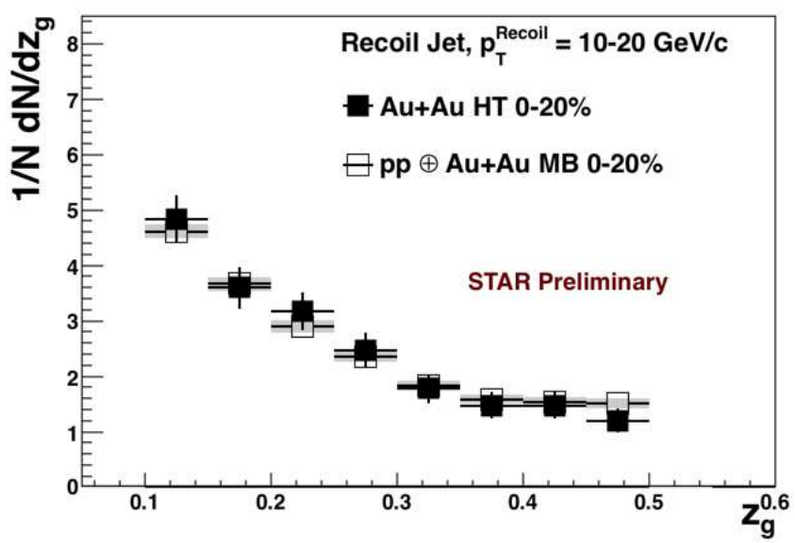


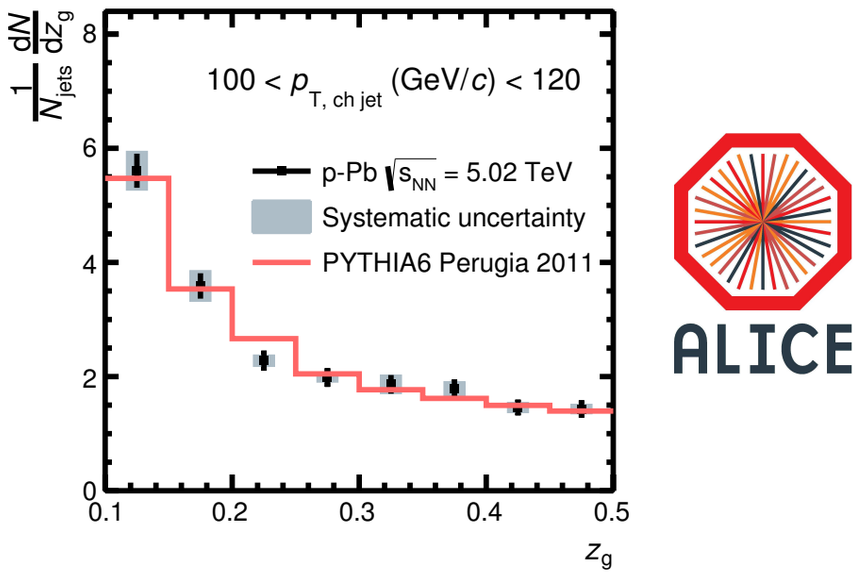
Grooming *simplifies* structure of calculation, *reduces* NP effects

[Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338; see also Marzani, Schunk, Soyez, 1704.02210]

Preliminary Results from Heavy Ions



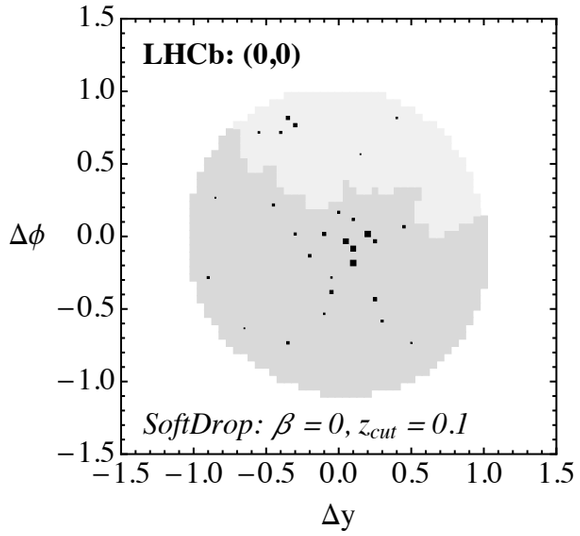




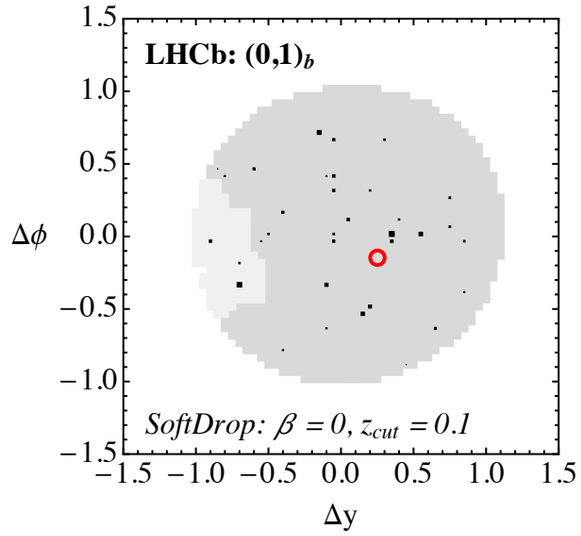
[CMS-PAS-HIN-16-006, STAR preliminary, ALICE preliminary]

Possibilities for Heavy Flavor

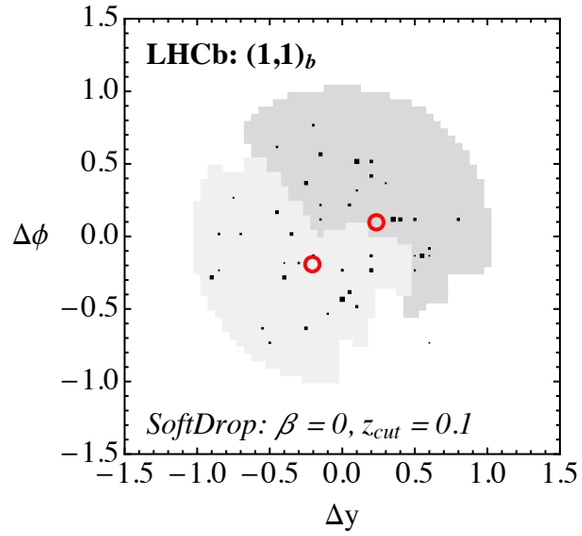
$g \to gg$

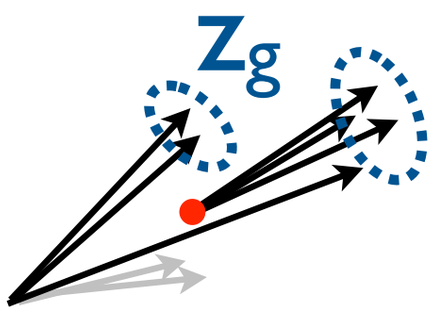


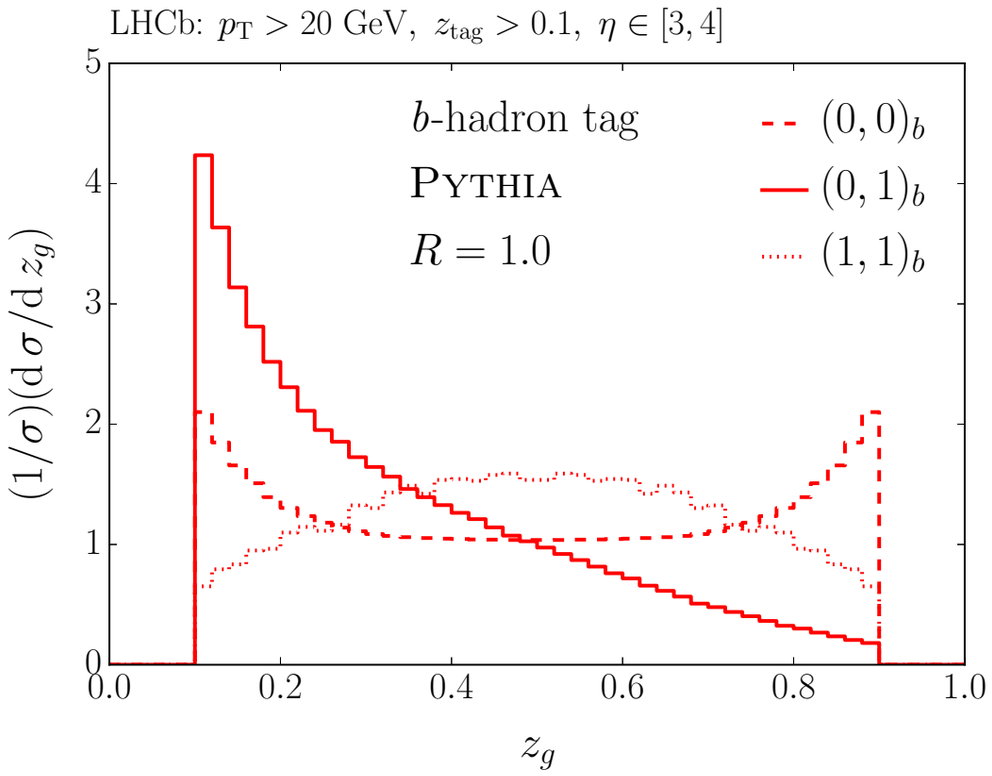
$b \to bg$

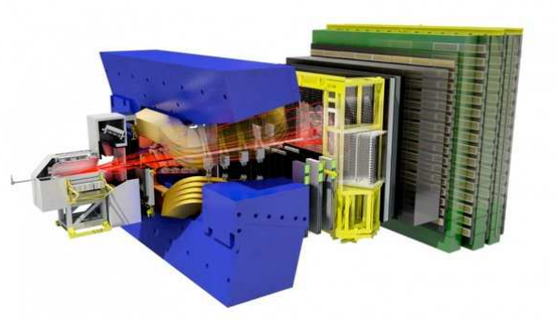


$g \to b\bar{b}$



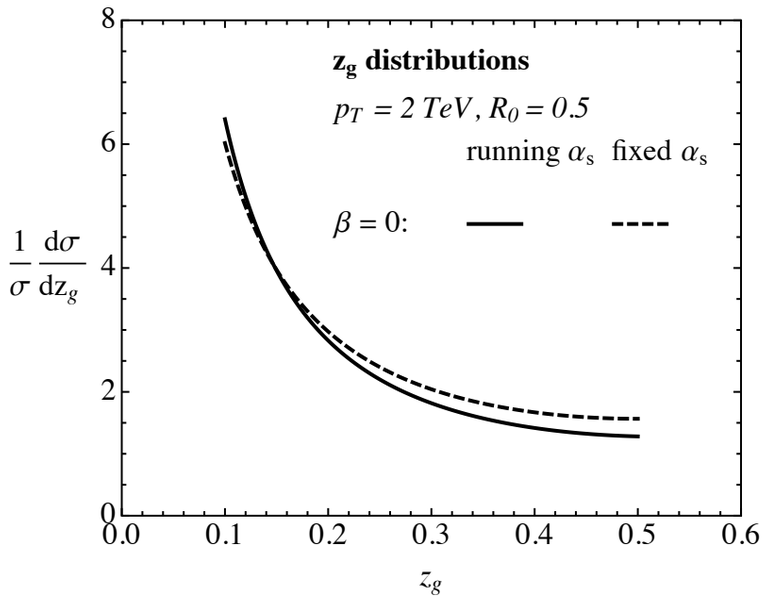




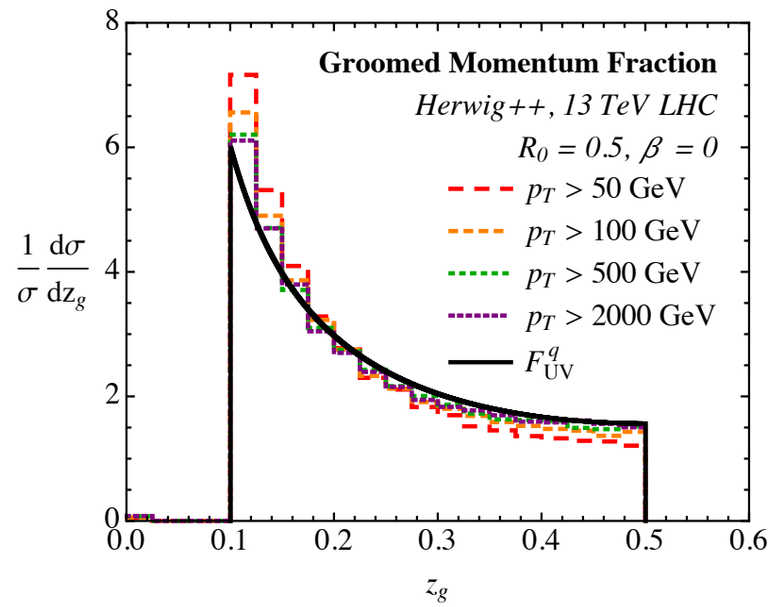


[Ilten, Rodd, JDT, Williams, 1702.02947]

First-principles QCD



Parton Shower Study



Collider Data

?

CMS Experiment CERN @CMSexperiment · Apr 19

Here's the first-ever physics analysis published using CMS #opendata! arxiv.org/abs/1704.05066 More: opendata.cern.ch/research/CMS #cernopendata

20 21

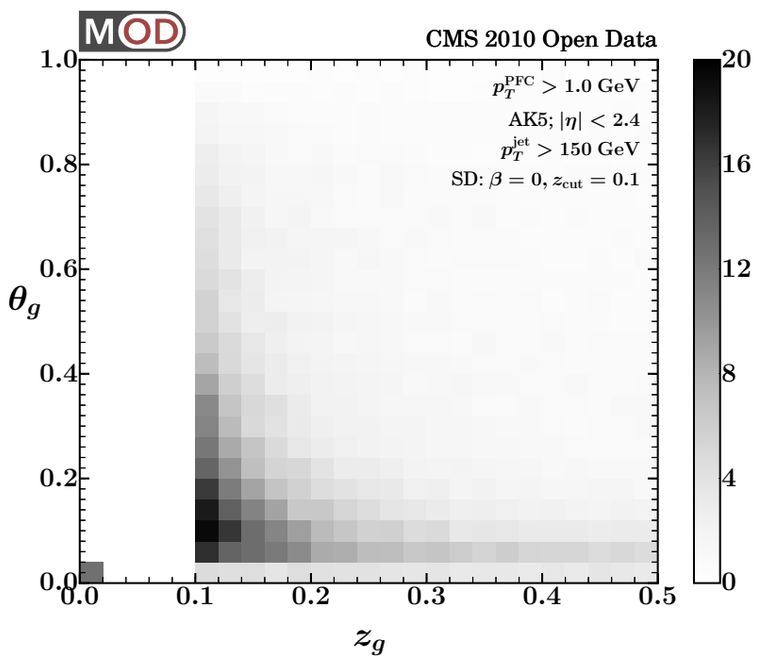
Steven Lowette @StevenLowette · Apr 19

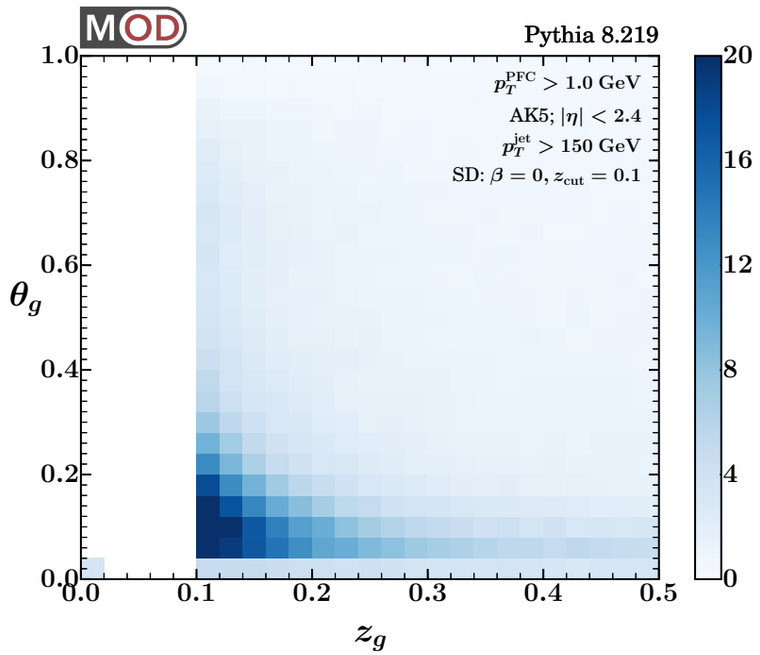
Forget the R(K*) ambulance chasing, this is the interesting paper of the day, using **CMS open data**: arxiv.org/abs/1704.05066

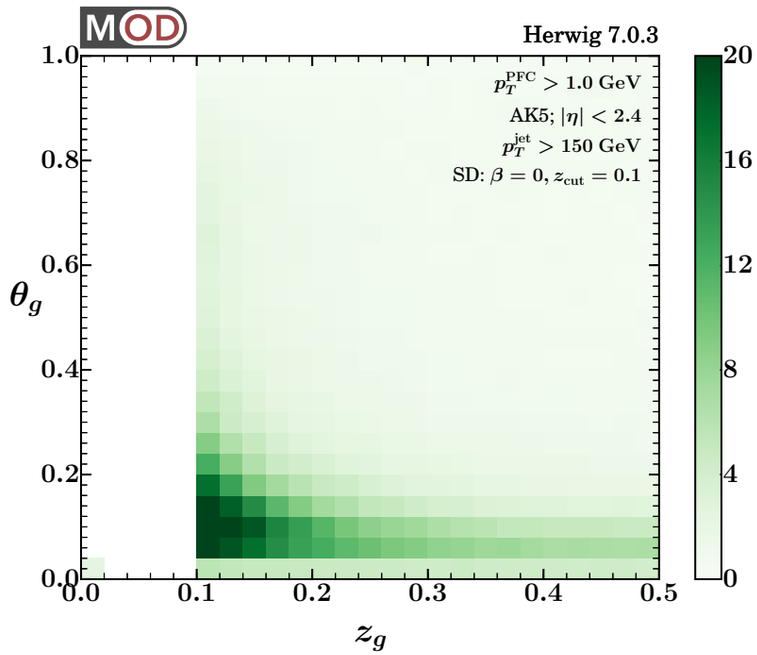
2 4

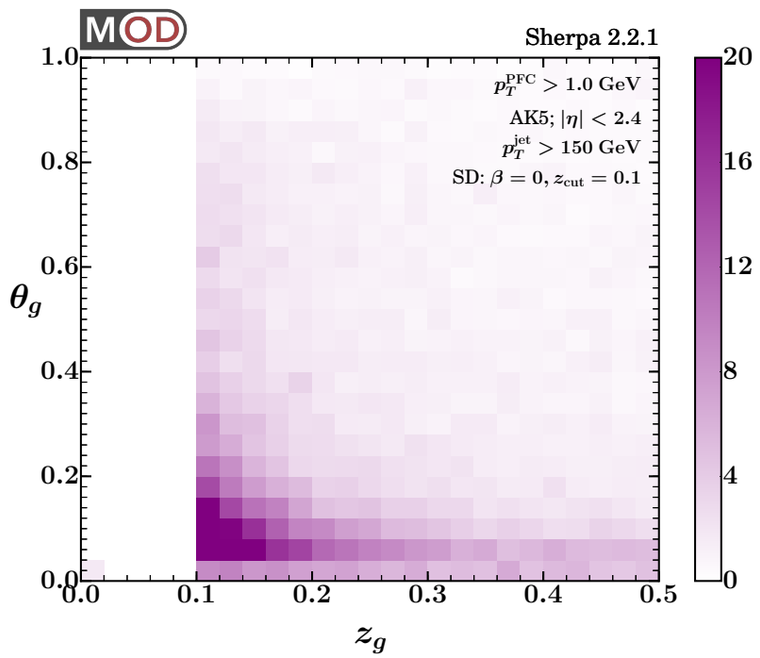
Visualizing the Singularity Structure of QCD

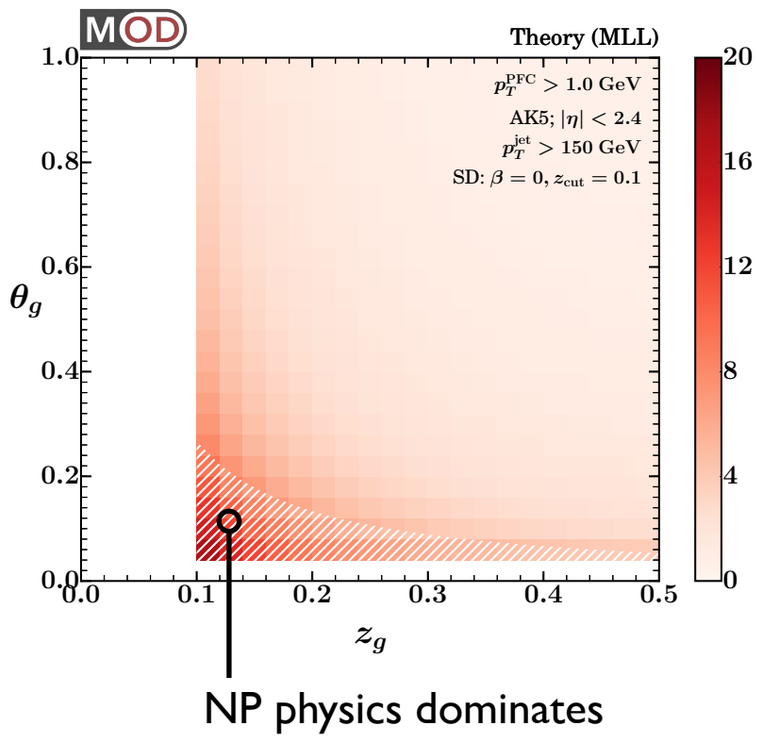
Linear scale







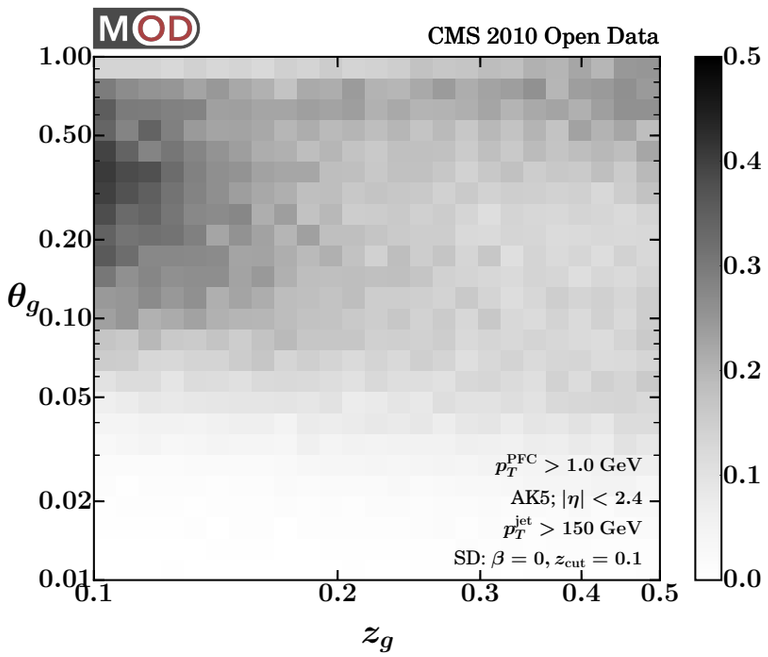


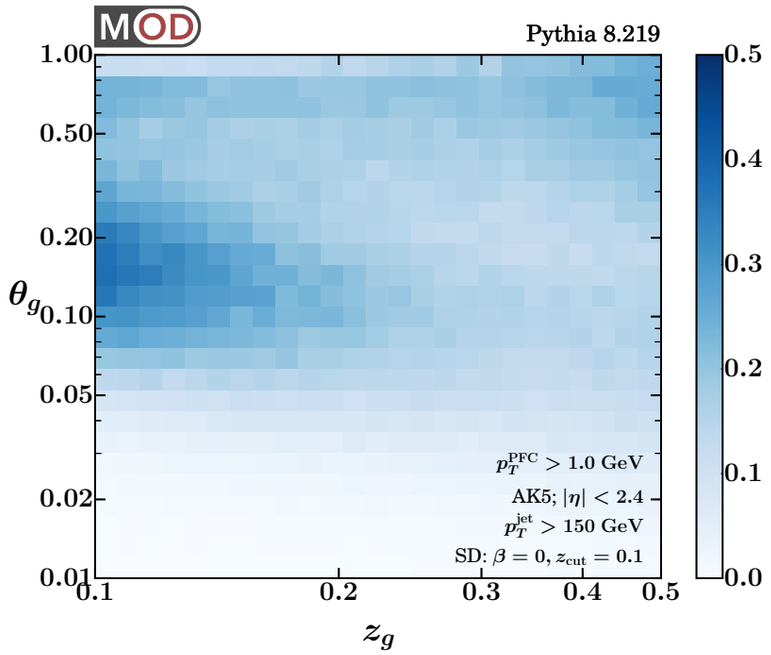


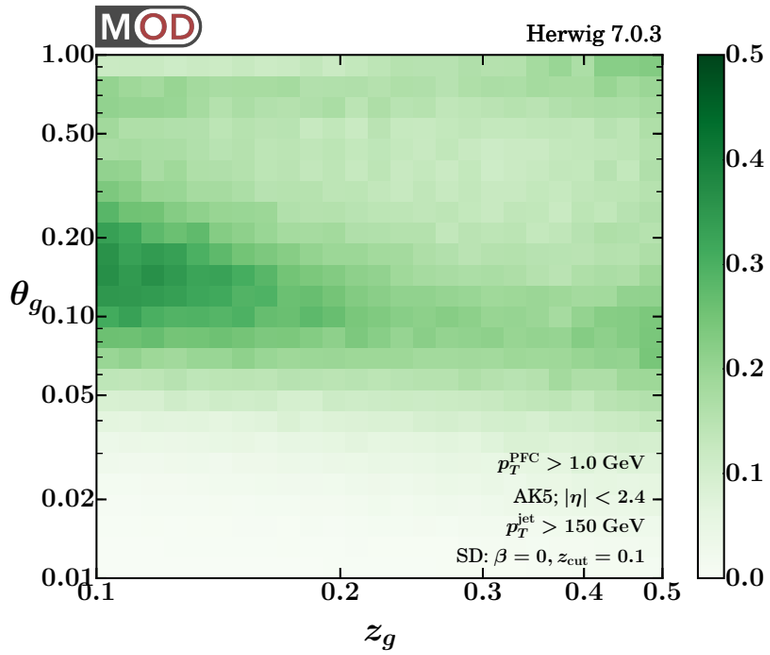
$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

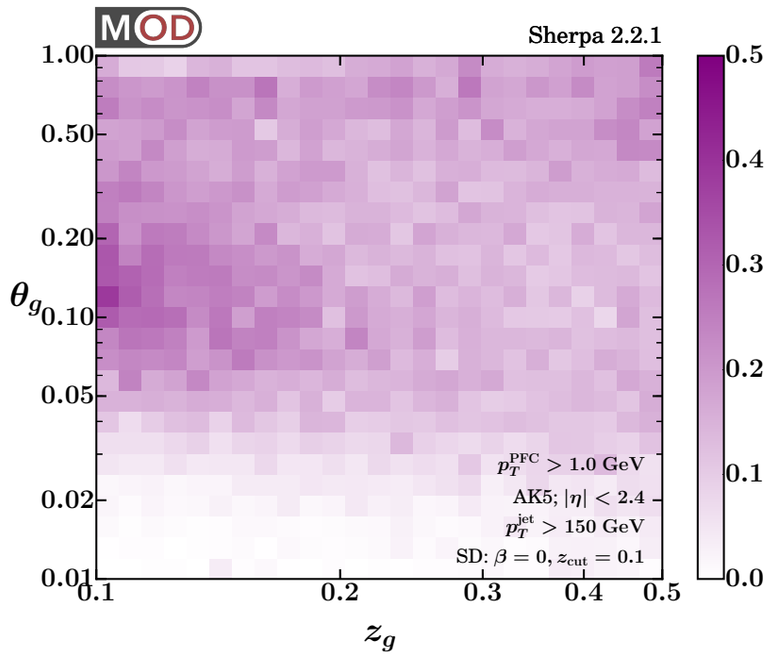
Visualizing the Singularity Structure of QCD

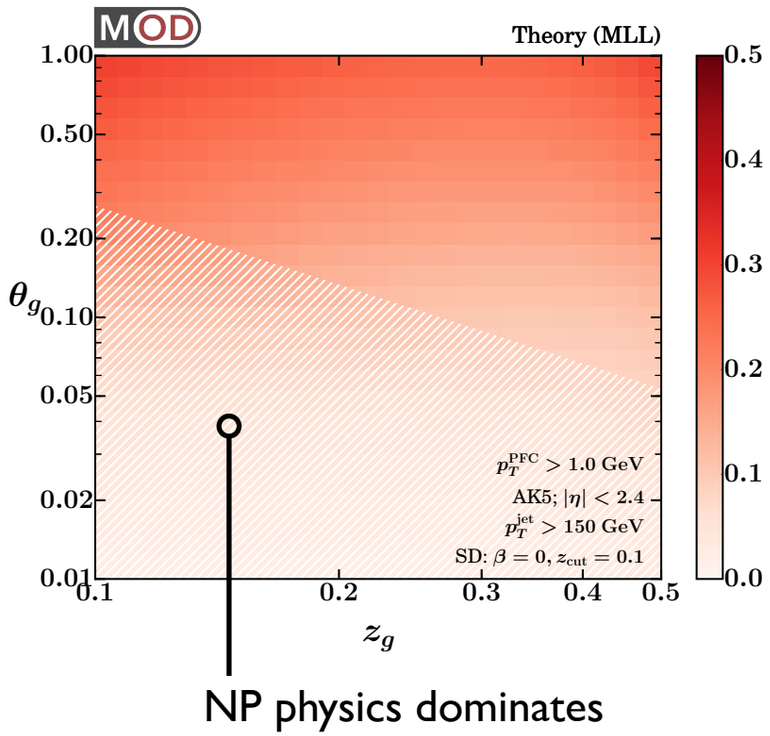
Logarithmic scale











$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$