Jet substructure measurements with CMS and ATLAS

Andreas Hinzmann and Benjamin Nachman
On behalf of the CMS and ATLAS collaborations

CERN-TH workshop: Jets and their substructure from LHC data
June 2, 2021

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Universität Hamburg
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CMS Compact Muon Solenoid

BERKELEY LAB

ATLAS EXPERIMENT

Outline

- Introduction: Why jet substructure? (Ben)
- Overview of measurements in ATLAS (Ben)
- Overview of measurements in CMS (Andreas)
- Brief analysis highlights in ATLAS and CMS (Ben, Andreas)
- Analysis Highlight: Lund plane (Ben)
- Analysis Highlight: Angularities in Z+jet and dijets (Andreas)
- Where is jet substructure going in the future? (Andreas)

Why jet substructure?

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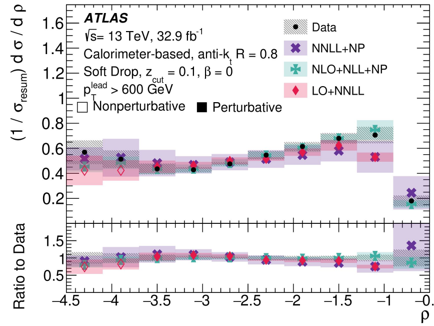
- Precision tests of the Standard Model
    - Grooming makes proton-proton “look like” electron-positron; *amenable to precise calculations in extreme phase space (high energy/multiplicity)*



Phys. Rev. D 101 (2020) 052007

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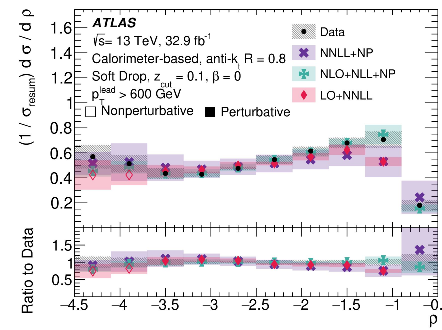

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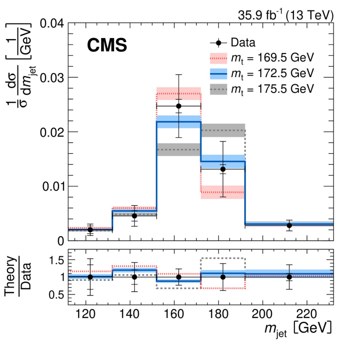
Phys. Rev. Lett. 124 (2020) 202001



- (Beyond the) Standard model parameters
  - Strong coupling constant (+ running), top quark mass, EFT params? …

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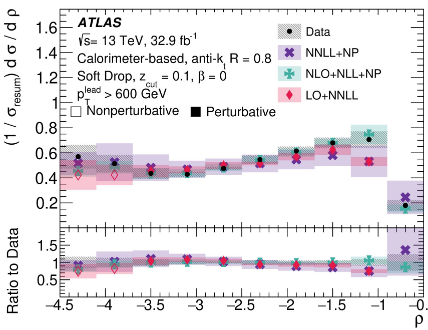

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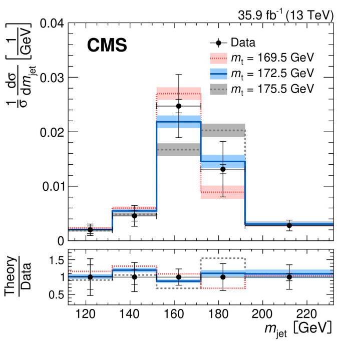

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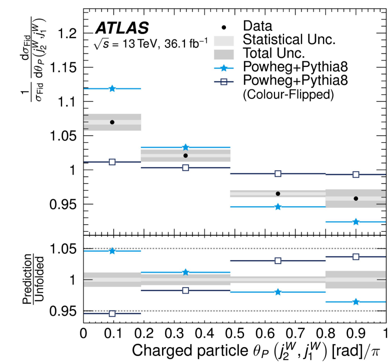

Eur. Phys. J. C78 (2018) 847

- Unique probes of emergent quantum properties of QCD
  - Interference (e.g. dead cone), entanglement (e.g. collectivity), …

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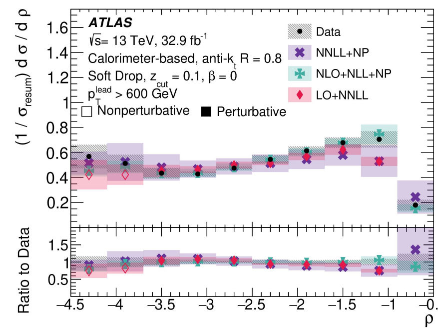

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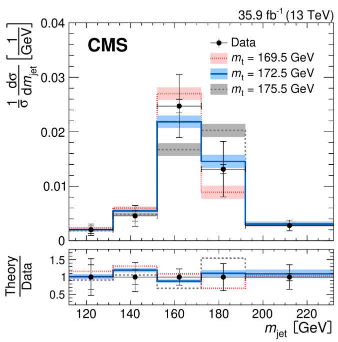

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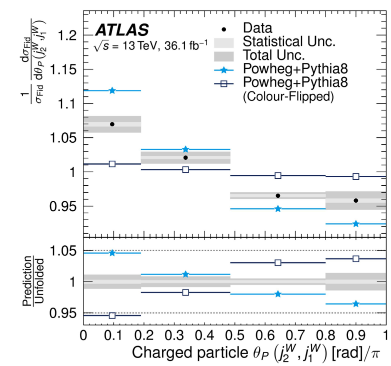

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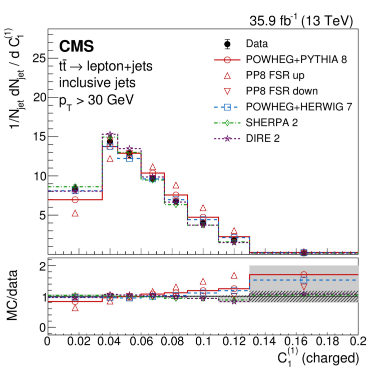


Phys. Rev. D 98 (2018) 092014

- General purpose Monte Carlo generator development and tuning
  - Higher order corrections, empower other measurements / searches

Measurement Program in ATLAS

Mostly focused in our Standard Model jet/photon physics group

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Click “Jets and photons”

example:

Lund Plane measurement with charged particles	Phys. Rev. Lett. 124 (2020) 222002	07-APR-20	13	140 fb^{-1}	Documents | 2004.03540 | Inspire Rivet | HepData | Briefing | Internal

A variety of other measurements across the Standard Model physics group, and also in top quark physics, heavy ions, …

Close connections with “Combined Performance” groups:

- Jet definitions & calibration, Jet tagging & scale factors, … (in Jet/ ETmiss)
- Clustering and Tracking in Dense Environments (in Inner Tracking)
- *bb* tagging (in Flavour Tagging)
- Jet and Photon process (in Physics Modeling Group)

(names given in parentheses are the ones to search on the ATLAS public pages)

Reference	System [data 1/fb]	Energy	Final State	Jets, p_T (GeV)	Observables
2004.03540	pp [140]	13	jets	0.4 AKT, >675	Lund plane
1912.09837	pp [33]	13	jets	0.8 AKT, > 600	Soft drop mass, rg, zg
1907.07093	pp [36]	13	Z(→bb)γ	1.0 AKT, 200	Groomed jet mass
1906.09254	pp [36]	13	jets	0.4 AKT, 100	n_{trk}, z, r, p_T^{rel}
1903.02942	pp [36]	13	top, jets	1.0 AKT, 200	Many (trimmed)
1812.09283	pp [36]	13	jets (g→bb)	1.0 AKT, 450	ΔR, Δφ, z, mass
1711.08341	pp [33]	13	jets	0.8 AKT, 600	Soft drop mass
1805.02935	pp [36]	13	top	0.4 AKT, 25	Jet pull
1509.05190	pp [20]	8	jets	0.4 AKT, 50	Jet charge
1602.00988	pp [20]	8	jets	0.4 AKT, 50	n_{trk}
1506.05629	pp [20]	8	top	0.4 AKT, 25	Jet pull
1609.07045	pp [20]	8	jets (q→Wq)	0.4 AKT, 500	ΔR

+ many jet fragmentation and substructure measurements at 7 TeV

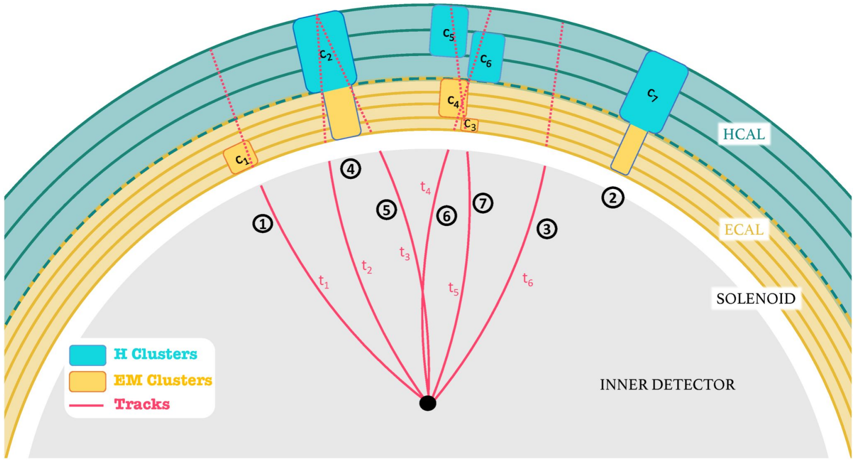
+ many jet fragmentation and substructure measurements in heavy ions

See also https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

Substructure reconstruction in ATLAS: Inputs

We have three options in ATLAS:

- ***Calorimeter-only***. *Our calorimeter clusters are locally calibrated, but are pileup sensitive and angular resolution is imprecise.*
- ***Tracker-only***. *Very precise, but not C-safe. Can compute per-object uncertainties in all cases (see next slide).*



- ***Particle-flow****(s)*. (See also another particle-flow alternative via "track assisting")
    a. *"Particle Flow": calorimeter cell-level matching (beneficial at low p_T)*
    b. *"Track Calo Clusters": calorimeter cluster-level matching (beneficial at high p_T)*
    c. *"Unified Flow Objects": combination of (a) and (b).*

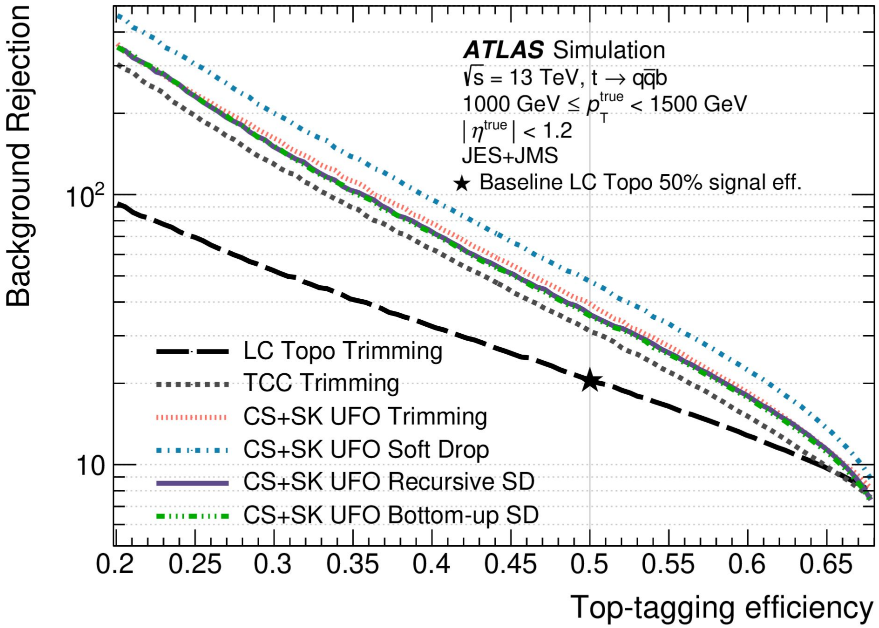
Make use of tracking and calorimeter information. (a) is ATLAS default for small-radius jets now, but no jet substructure results yet (in part because per-object uncertainties are much harder). (c) is the default for large-radius jets but results so far use calorimeter-only.

Substructure reconstruction in ATLAS: Algorithms

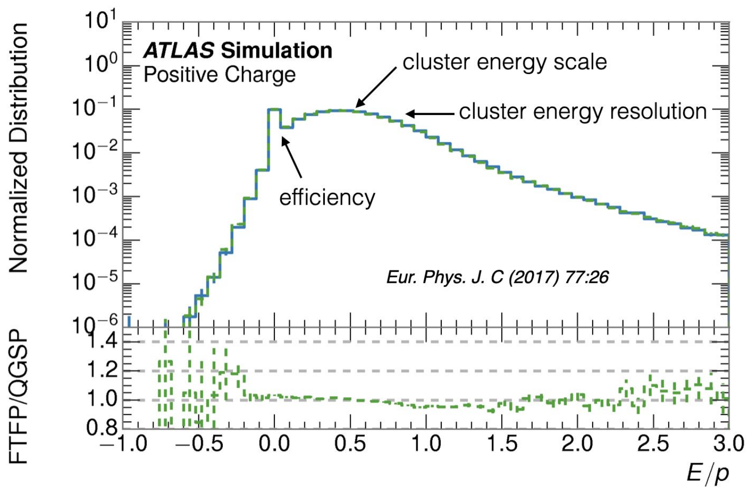
For jet substructure, we have mostly used R = 1.0 anti-k_t with trimming (parameters changed between Run 1 and 2, but otherwise, unchanged)

A few measurements have used soft drop and some measurements use small-radius jets (R = 0.4, no grooming).

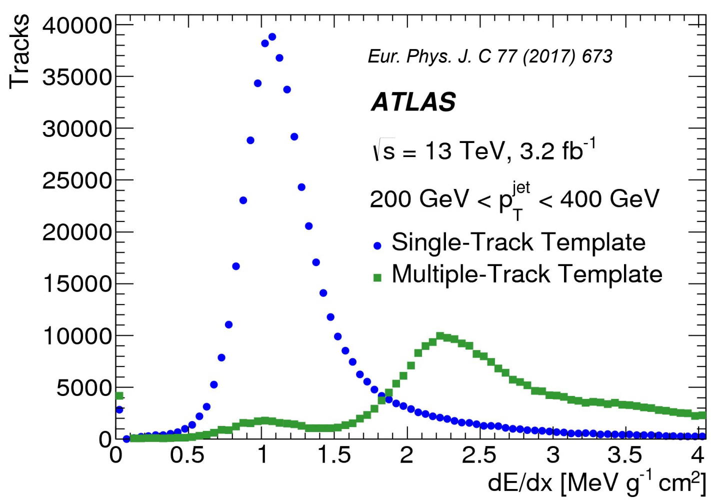
There is always a compromise between what is good for tagging and what is good for measurements. See Eur. Phys. J. C 81 (2021) 334 for a very detailed study of various algorithm combinations.

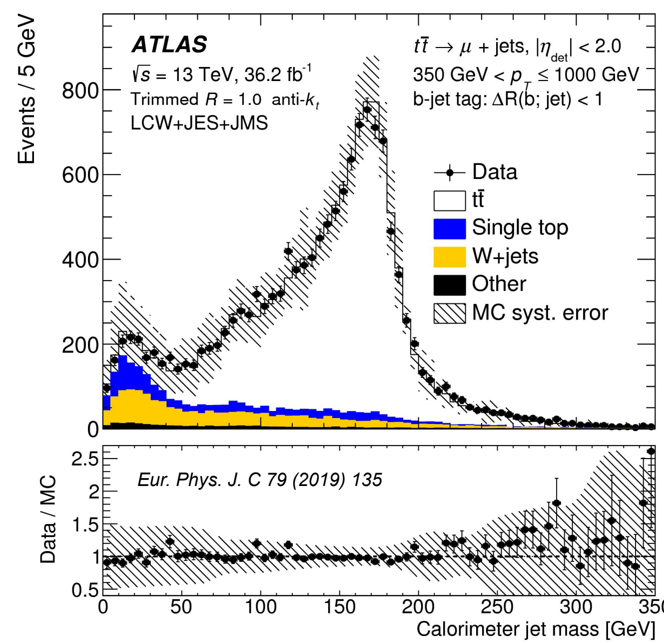


Substructure reconstruction in ATLAS: Uncertainties



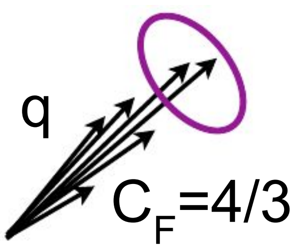
Per-object uncertainties for isolated calorimeter clusters and any tracks. Per-observable uncertainties using standard candles, calo/track balancing, and convolution method (e.g. predict jet energy scale uncertainty using per-object uncerts).

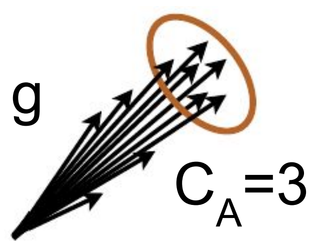


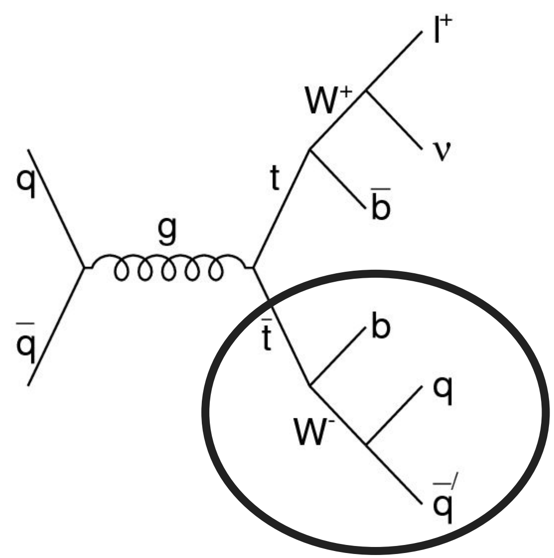


Measurement Program in CMS

- Goals
  - Understanding of perturbative QCD
  - Measurement of SM parameters (α_S, m_t)
  - Improvement of non-perturbative models in MC event generators
  - Understanding of QGP (PbPb vs. pp)
- Public results page (SMP, TOP, HIN):
  http://cms-results.web.cern.ch/cms-results/public-results/publications/

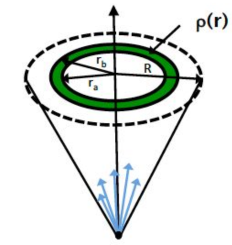




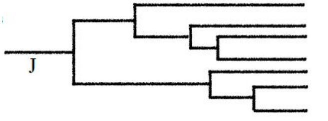


Reference	Final state	Jets, p_T (GeV)	Jet substructure observables
1204.3170 7 TeV pp	jets	q/g-jets (AK7), $20<p_T<1000$ q/g-jets (AK5), $50<p_T<1000$	jet shapes, charged hadron multiplicity, width
1205.5872 2.76 TeV pp/PbPb	dijets	q/g-jets (AK3), $40<p_T<320$	fragmentation functions
1310.0878 2.76 TeV pp/PbPb 1406.0932 2.76 TeV pp/PbPb	jets	q/g-jets (AK3), $100<p_T<300$	fragmentation functions
1310.0878 2.76 TeV pp/PbPb	jets	q/g-jets (AK3), $p_T>100$	jet shapes
1809.08602 5.02 TeV pp/PbPb		q-jets (AK3), $p_T>30$	jet shapes
HIN-19-003 5.02 TeV pp/PbPb	dijets	q/g-jets (AK4), $p_T>50$	jet shapes
QCD-10-041 7 TeV pp	dijets	q/g-jets (KT6), $97<p_T<1032$	subjet multiplicities and p_T^{rel}
1706.05868 8 TeV pp	jet	q/g-jets (AK5), $400<p_T<1500$	jet charge
2004.00602 5.02 TeV pp/PbPb	jets	q/g-jets (AK4), $p_T>120$	jet charge
1703.06330 8 TeV pp	ttbar	top-jets (CA12), $p_T>400$	jet mass
1303.4811 8 TeV pp	dijets W/Z+jets	q/g-jets (AK7), $220<p_T<1500$ q-jets (AK7, CA8/12), $125<p_T<450$	jet mass, pruned/trimmed/filtered jet mass
1805.05145 5.02 TeV pp/PbPb	jets	q/g-jets (AK4), $140<p_T<300$	softdrop jet mass
1807.05974 13 TeV pp	dijets	q/g-jets (AK8), $200<p_T<1300$	jet mass, softdrop jet mass
1911.03800 13 TeV pp	ttbar	top-jets (XC12), $p_T>400$	XCone-grommed jet mass
1708.09429 5.02 TeV pp/PbPb	jets	q/g-jets (AK4), $140<p_T<500$	softdrop splitting function
1808.07340 13 TeV pp	ttbar	q-jets (AK4), $p_T>30$ g-jets (AK4), $p_T>30$ b-jets (AK4), $p_T>30$	jet substructure and softdrop observables
SMP-20-010 13 TeV pp	dijets Z+jets	q/g-jets (AK4), $50<p_T<4000$ q-jets (AK4), $50<p_T<1000$	jet angularities

"shapes"



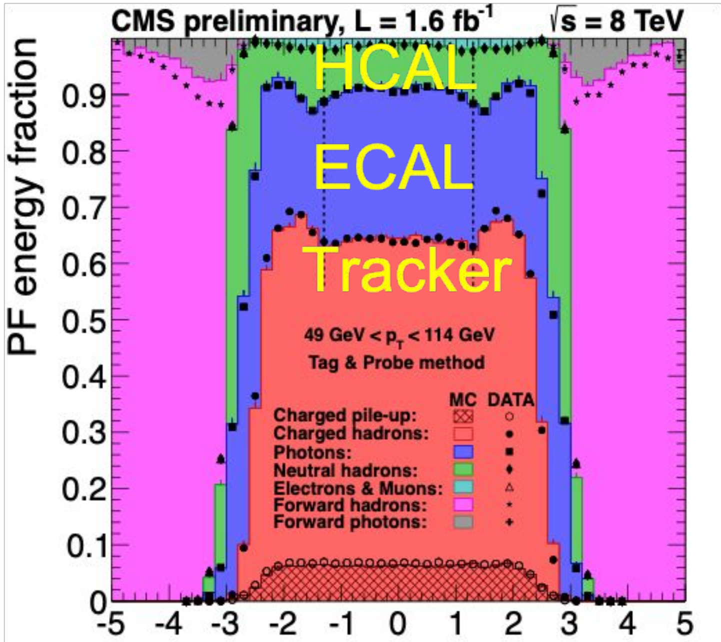
"substructure"



Jet substructure reconstruction in CMS

- Charged and neutral hadrons from Particle Flow
- Neutral hadron candidate momenta calibrated within 3-10% (using simulation)
- Anti-k_T jet momenta calibrated within 0.5-2%* (using dijet, Z/g-jet data)

*in pT>30, |eta|<2

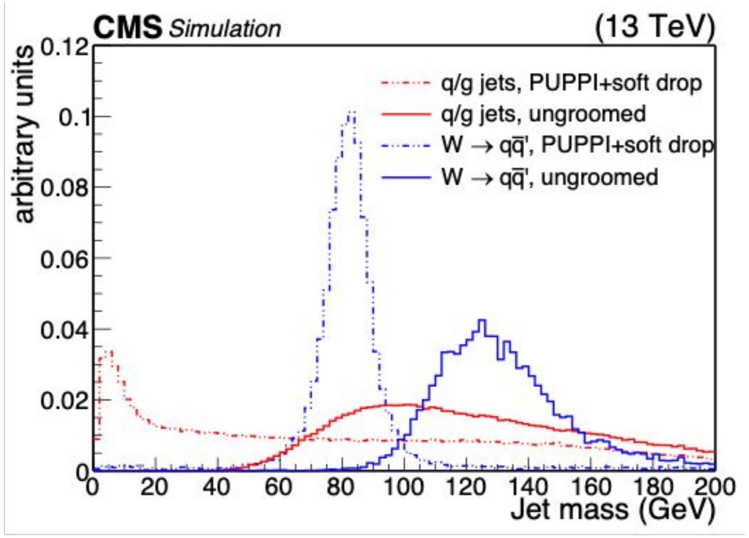


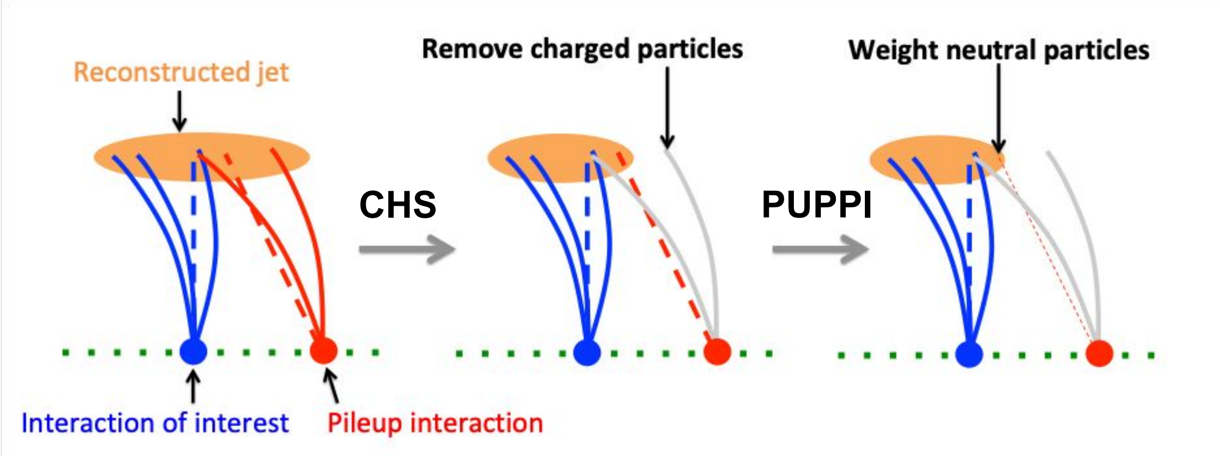
CMS-DP-2012/012

Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (|η|<1.48)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (|η|<1.74) 0.175 x 0.175 (|η|>3)

Jet substructure reconstruction in CMS – pileup

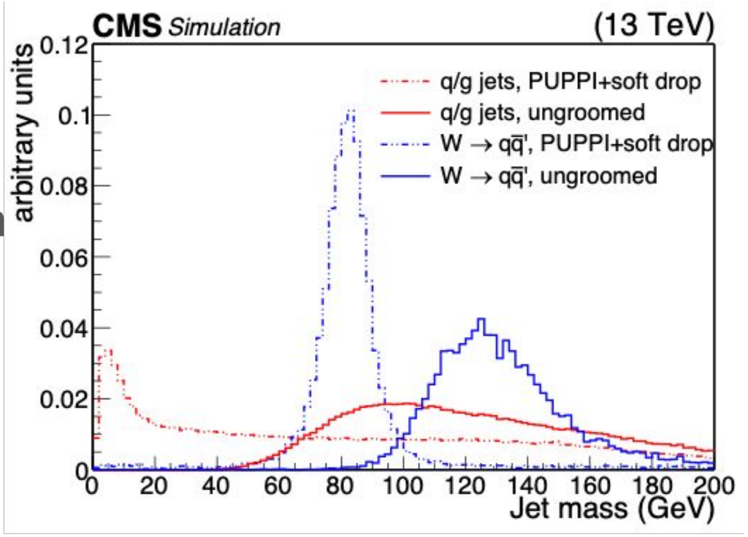
- Jet substructure highly sensitive to pileup interactions (~30 in Run2)
- Remove pileup before jet clustering
  - Charged particles (CHS)
  - Scale momentum of neutral particles according to probability to not originate from pileup (PUPPI)

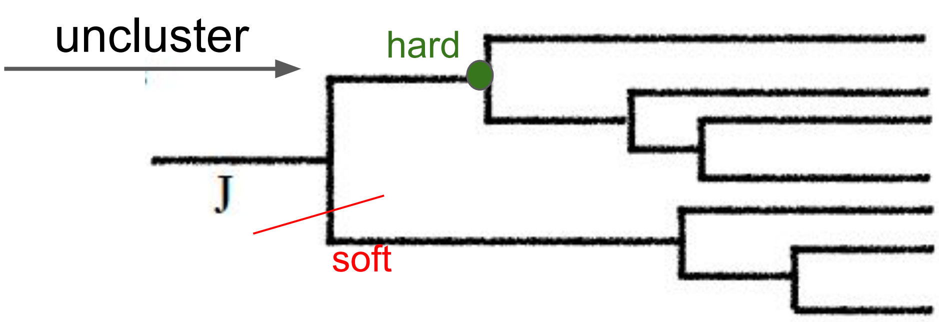




Jet substructure reconstruction in CMS – grooming

- Grooming algorithm to remove soft and wide-angle radiation: Softdrop (β=0) = mMDT
- Use calibrated p_T before grooming, also when studying groomed substructure observables
- Dedicated calibration for jet mass at 1% level (using ttbar data)
- Other jet substructure observables out-of-the box from particle flow



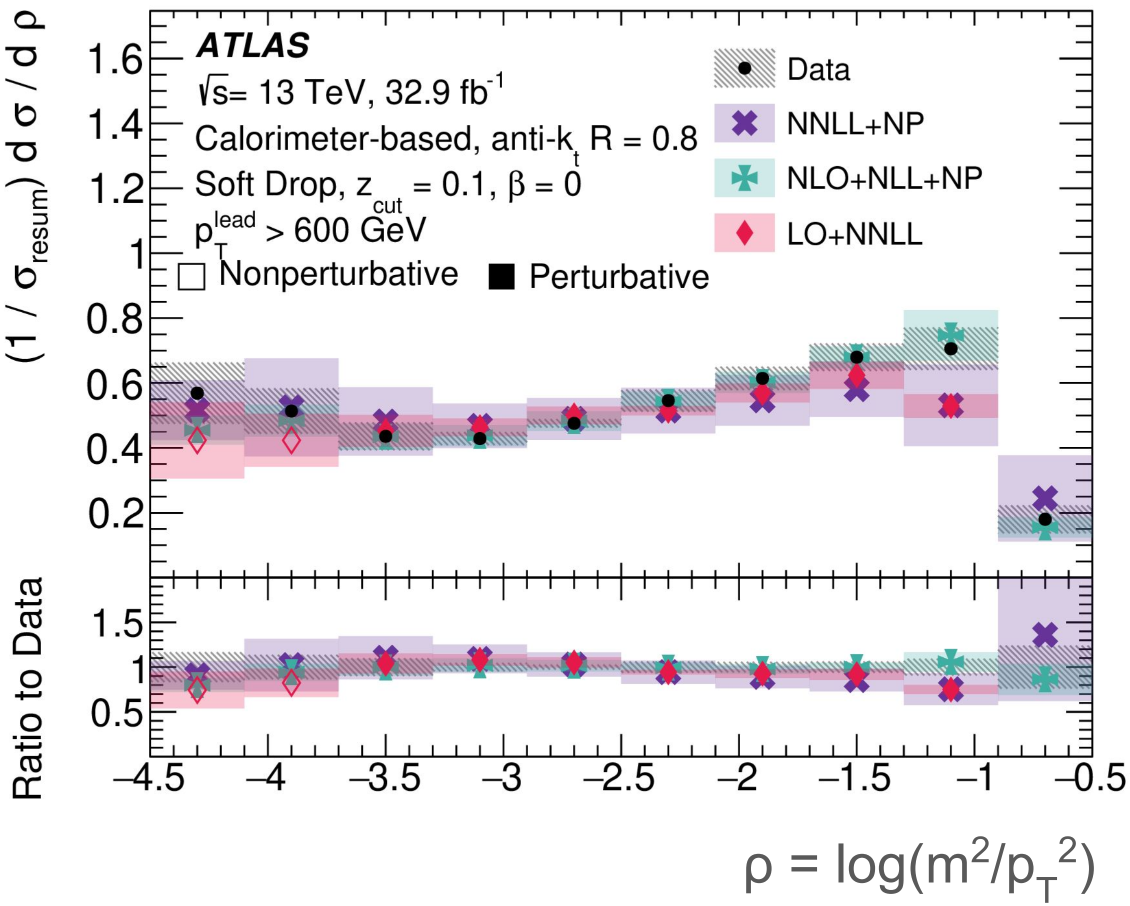


Soft-drop criterion

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

Brief analysis highlights

Jet Mass (ATLAS) [1912.09837 and 1711.08341]



Groomed jet mass in dijet events. In addition to the jet mass in bins of p_T and with different grooming parameters, also measured (1) track versus calo and (2) forward/central (→ quark/gluon)

One of the most precisely known quantities: compared with independent calculations from multiple groups

(C. Frye, A. Larkoski, M. Schwartz, K. Yan; S. Marzani, L. Schunk, G. Soyez; Z. Kang, K. Lee, X. Liu, F. Ringer)

Jet Mass (CMS) [1807.05974]

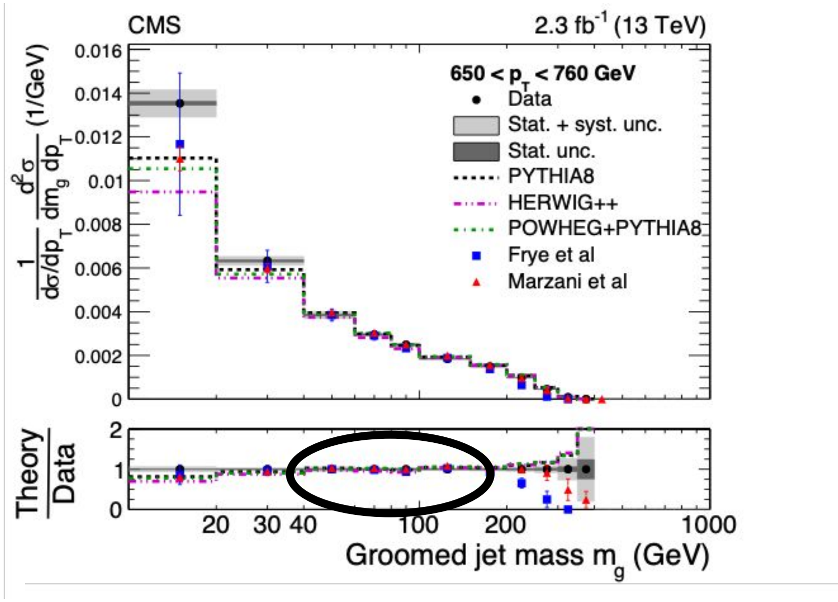
- Jet mass with soft-drop (β=0) = mMDT

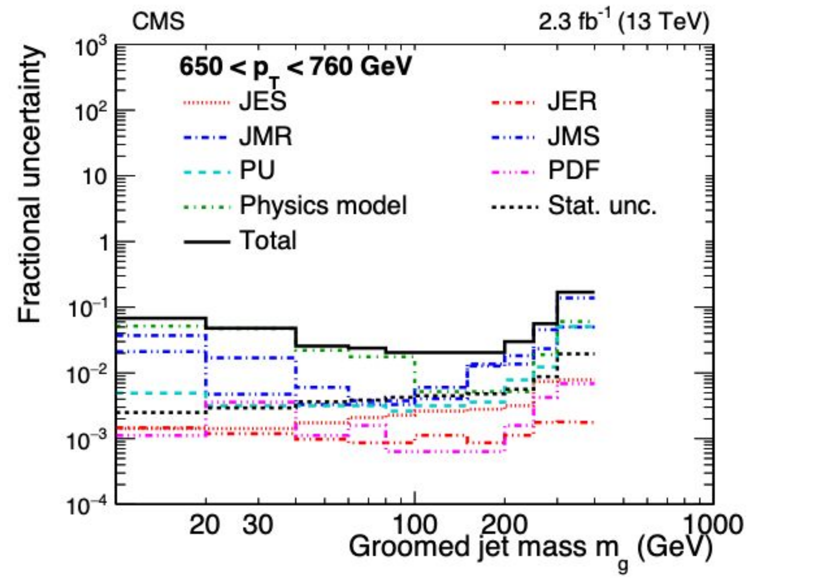
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}}$$

- Low mass ~ non-perturbative
- Intermediate mass ~ resummation
- High mass ~ perturbative

- LO+NLL prediction describes intermediate mass very well

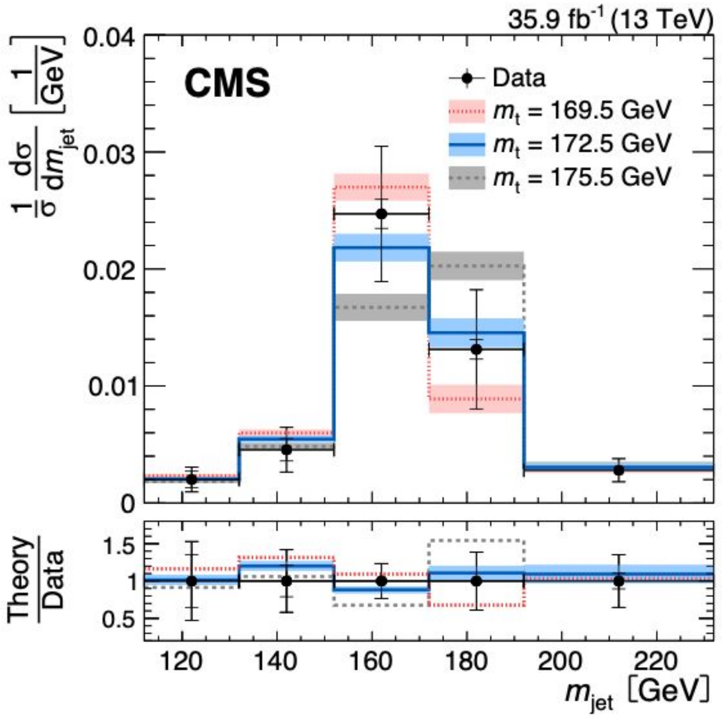
- Dominant uncertainty from physics model





Boosted top mass (CMS) [1911.03800]

- Idea: boosted top jet mass could avoid ambiguity in top mass definition in direct measurements
- Variable radius X-cone algorithm to find top jets and subjets with "grooming" (subjet p_T>30 GeV)
- Dominant experimental uncertainty: subjet energy scale
- Dominant model uncertainty from parton shower FSR



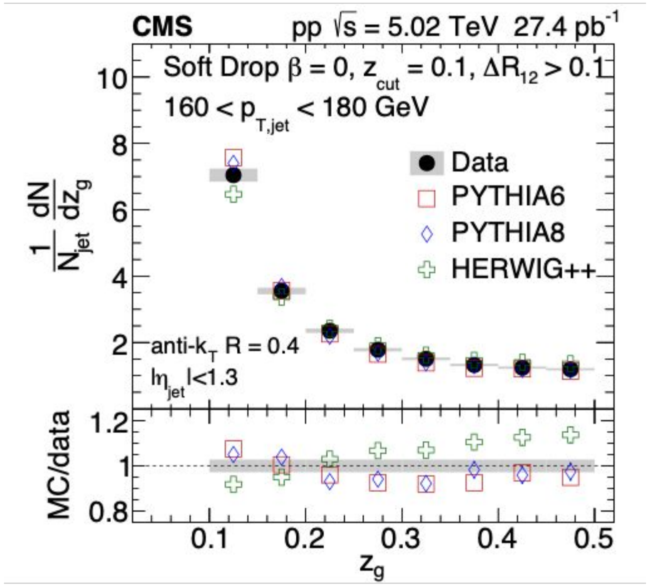
$$m_t = 172.6 \pm 0.4\,(\text{stat}) \pm 1.6\,(\text{exp}) \pm 1.5\,(\text{model}) \pm 1.0\,(\text{theo})\,\text{GeV}$$

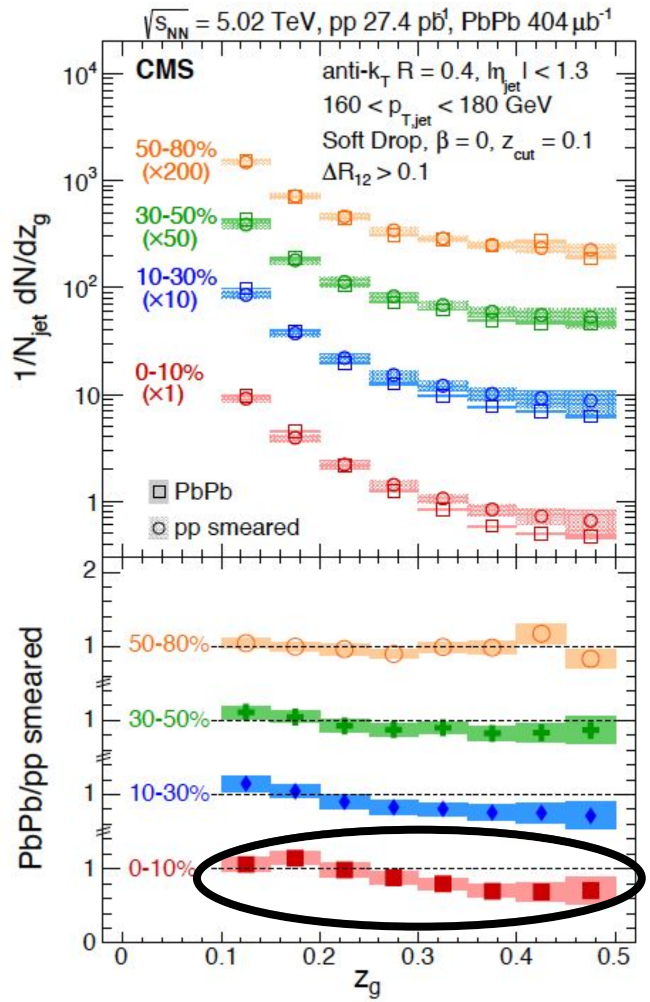
Soft-drop splitting function z_g (CMS) [1708.09429]

- Access first splitting in the parton evolution

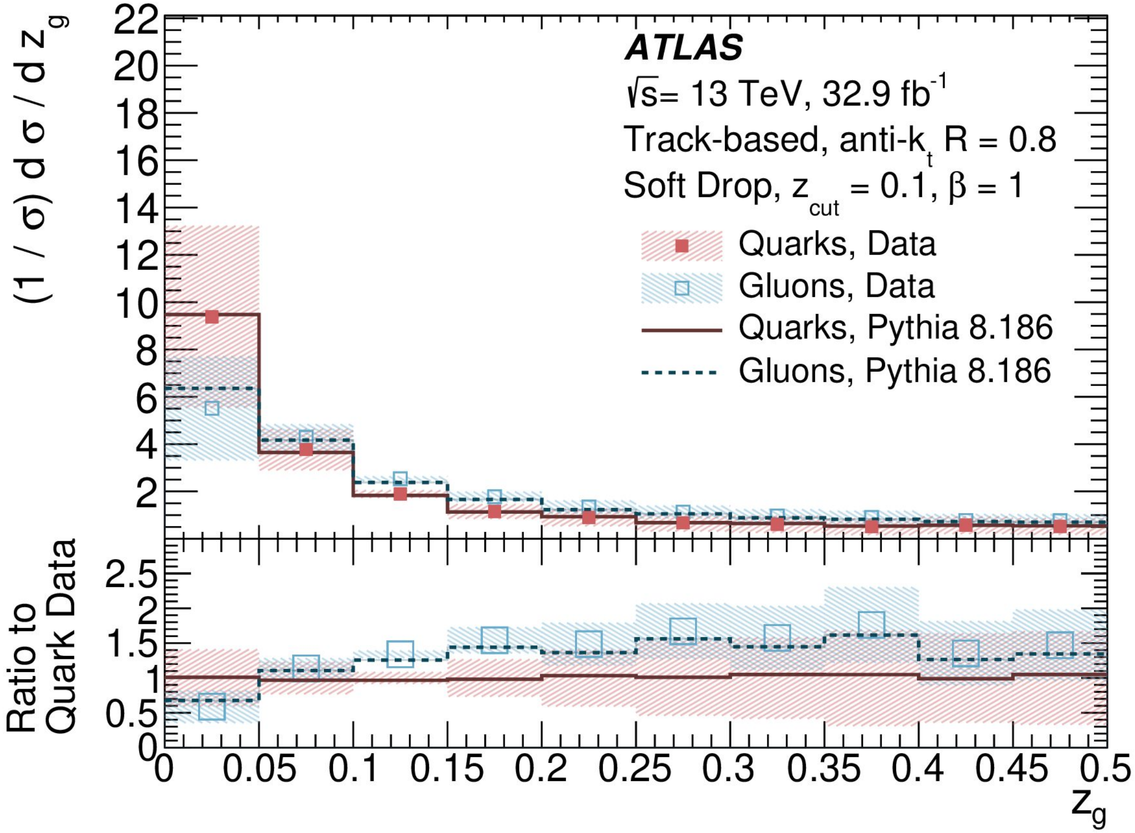
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

- Modification by QGP observed



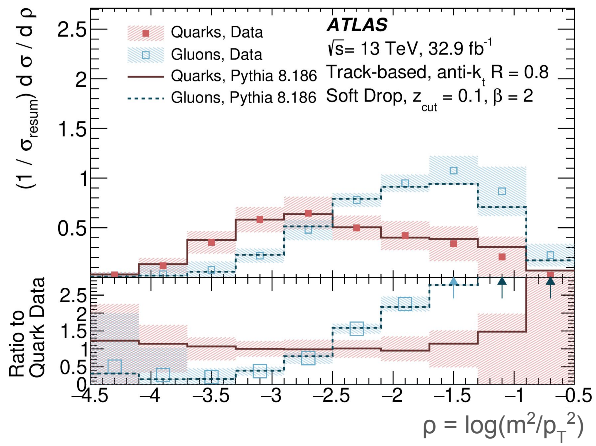


Soft-drop splitting function z_g (ATLAS) [1912.09837]



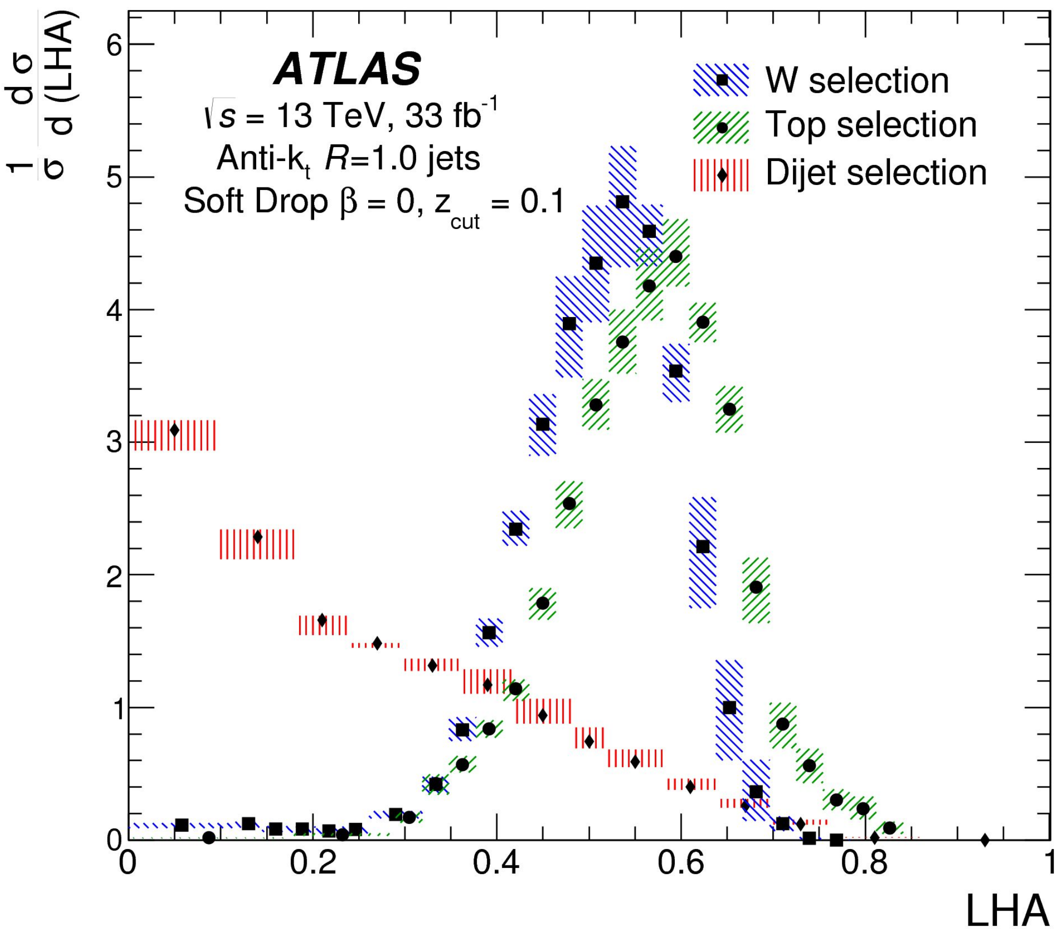
In addition to groomed mass, we have measured the momentum fraction (z_g) and opening angle (r_g) of the softdrop splitting in dijet events.

Forward/central differences can be used to extract q/g distributions. More different for mass than for z_g !



Predicted to have some difference for this β; uncertainties too large for β = 0.

Jet Angularities (ATLAS) [1903.02942]



Measurement of multiple properties of groomed jets in three different systems: W (from top), top, and inclusive dijets. Note that the p_T is not the same for the three systems.

Measurements using calorimeter / all-particles information.

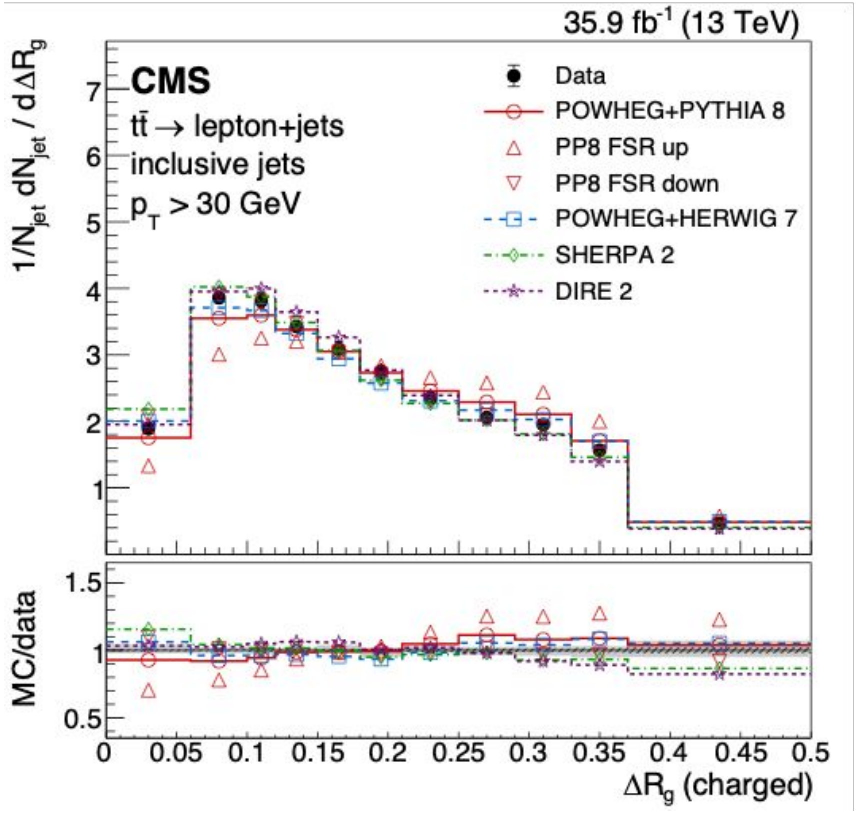
Observables: $n_{subjets}$, LHA, ECF2, ECF3, C_2, D_2, t_{21}, t_{32}

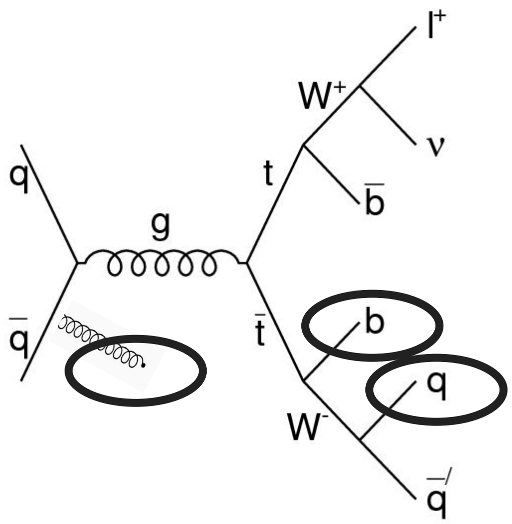
LHA = Les Houches Angularity = generalized angularity with sqrt angular weighting.

Jet substructure in ttbar (CMS)

[1808.07340]

- Measured many jet substructure observables with/without grooming
- Light quark, gluon and b-quark enriched samples from ttbar events



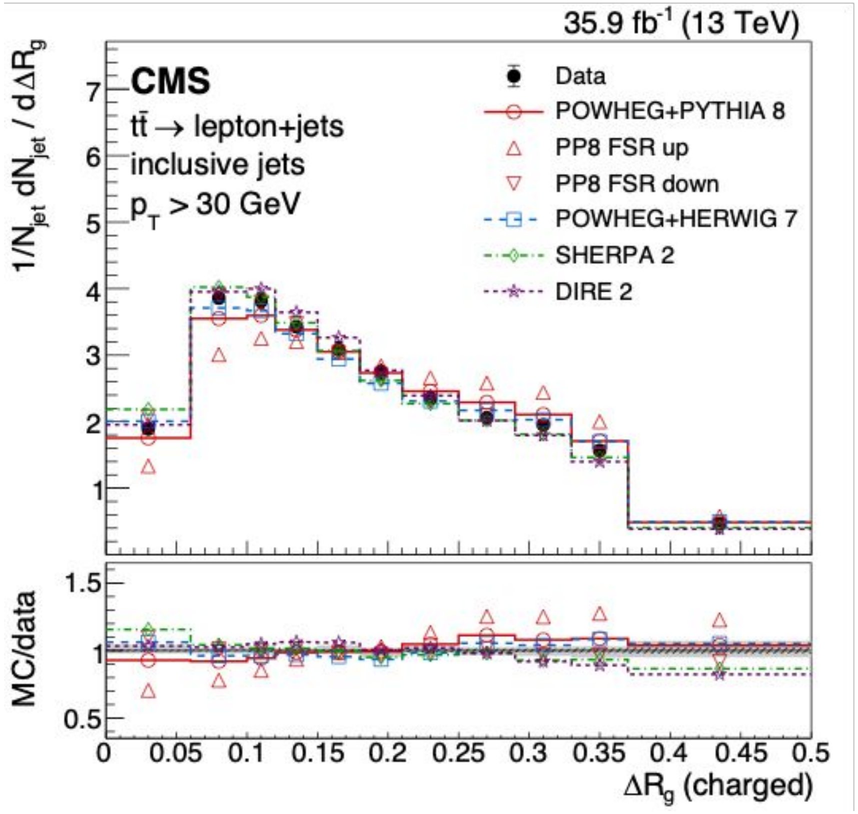


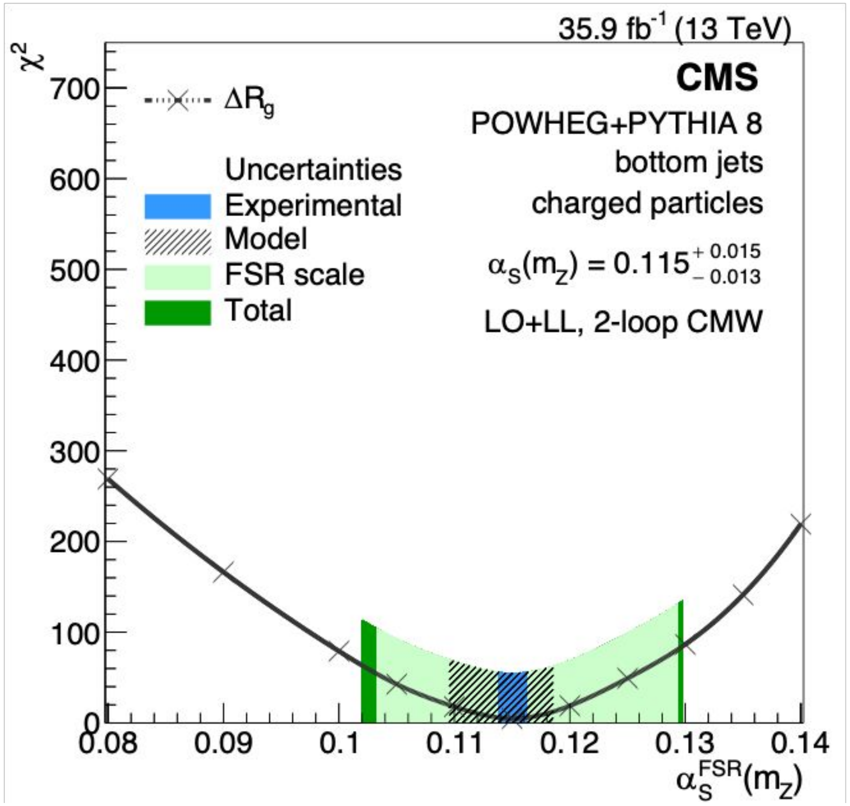
Observables: 5 generalized angularities,
21 energy-correlation functions ratios,
3 N-subjettiness ratios,
Softdrop multiplicity, zg, dRg, eccentricity

Jet substructure in ttbar (CMS) - α_S measurement

[1808.07340]

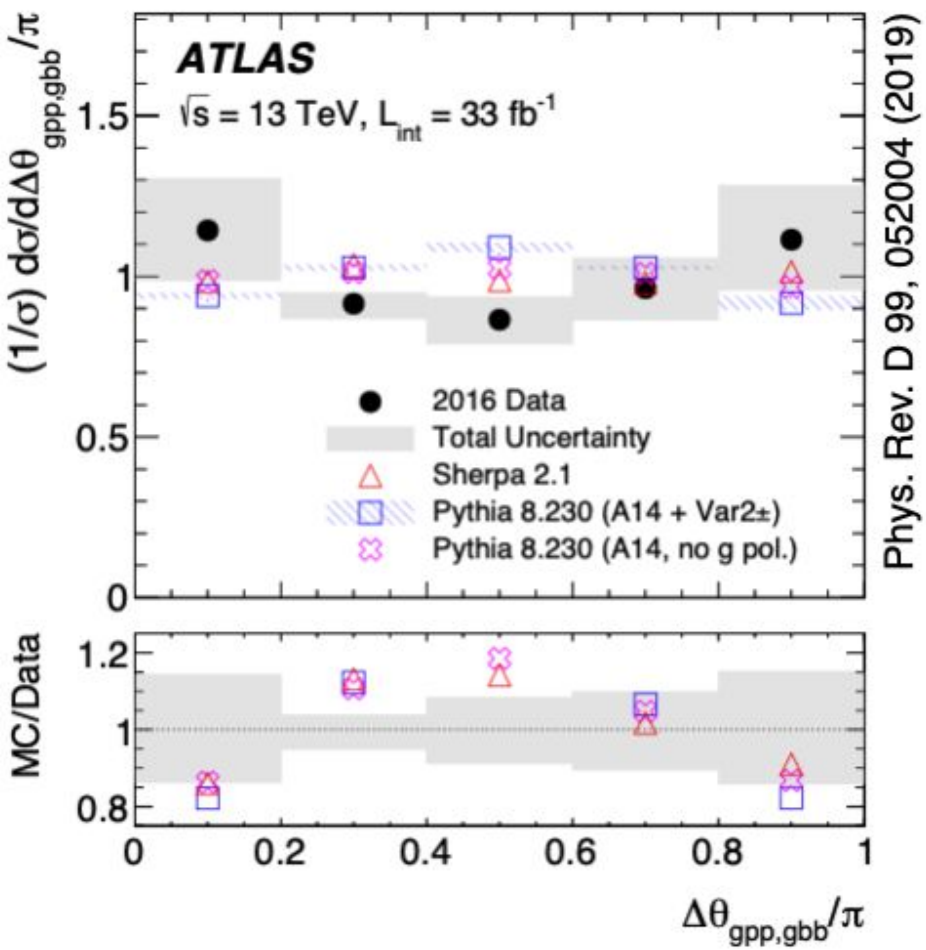
- Measure $\alpha_S(m_Z)= 0.115^{+0.015}_{-0.013}$ from most sensitive observable
- Dominant uncertainty from FSR scale uncertainty of PS prediction

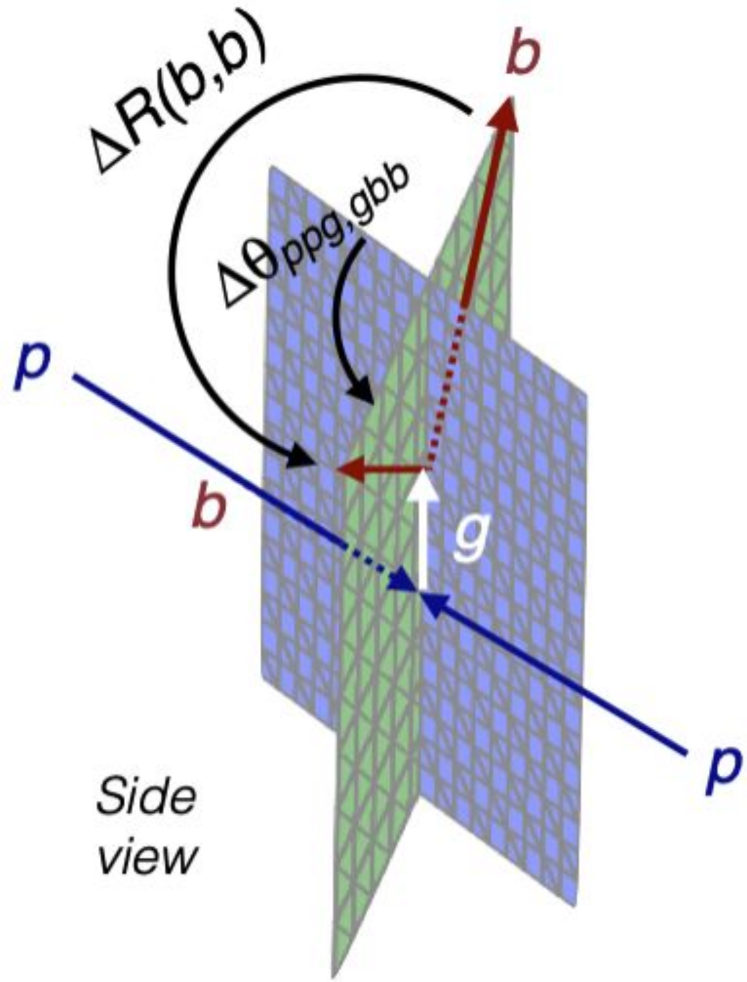




g→bb (ATLAS) [1812.09283]

Unique opportunity to study specific jet fragmentation function

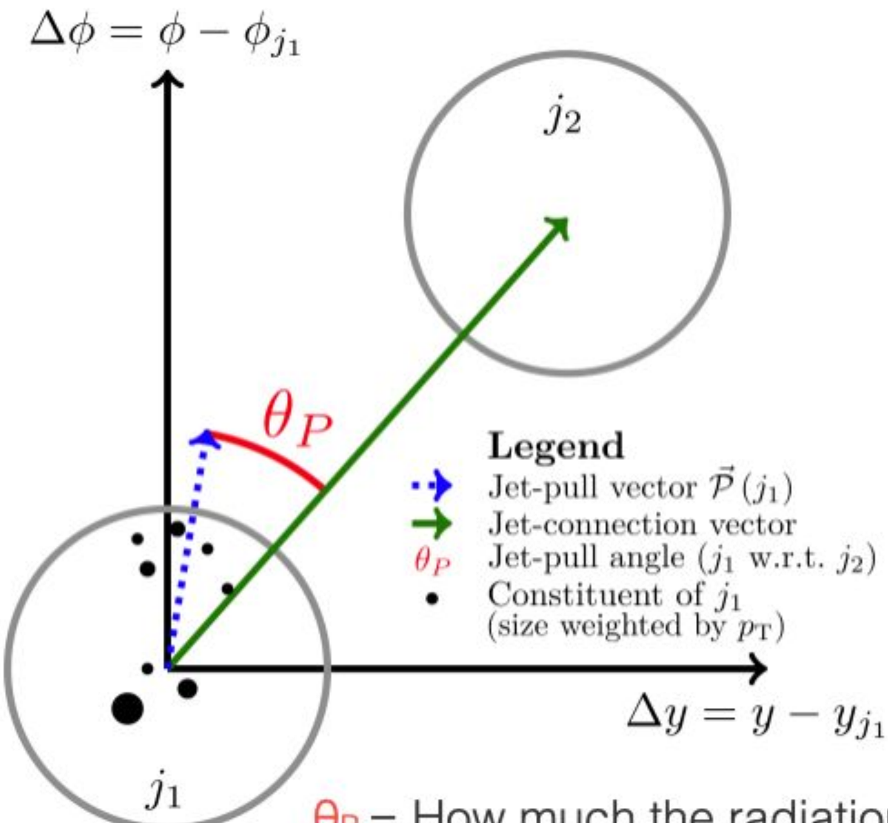


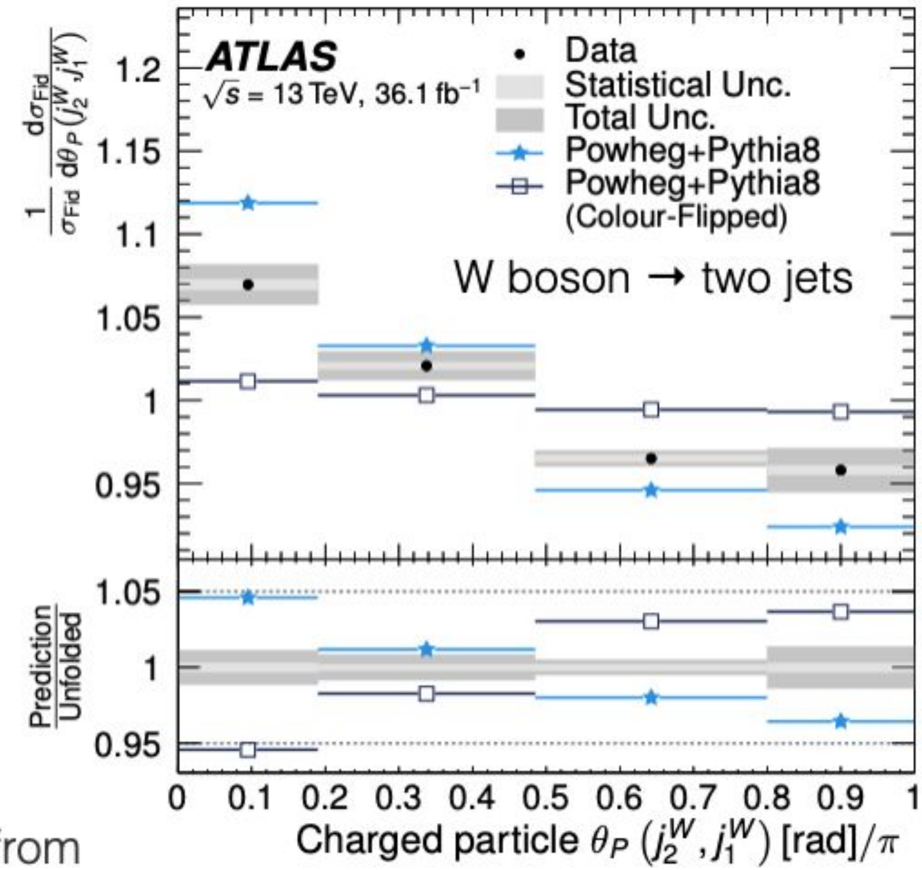


Slight improvement with matrix element corrections (Sherpa has 2 → 3)

Jet Pull (ATLAS) [1805.02935]

Precise measurement, poor modeling !

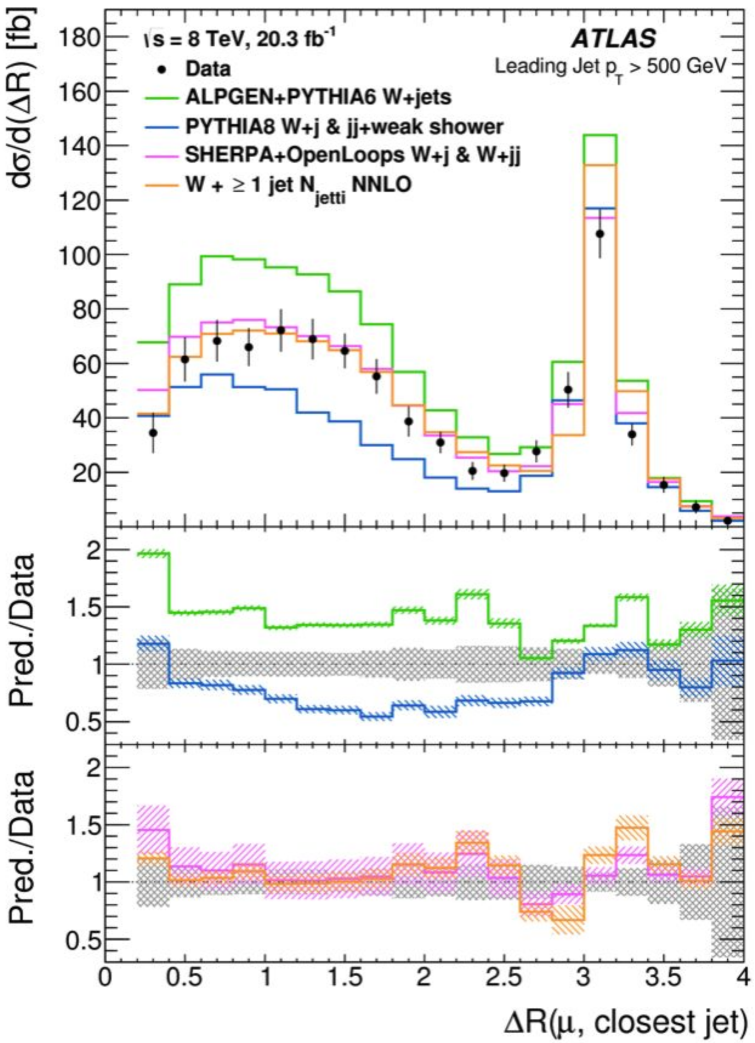




θ_P = How much the radiation from one jet "leans" toward the other.

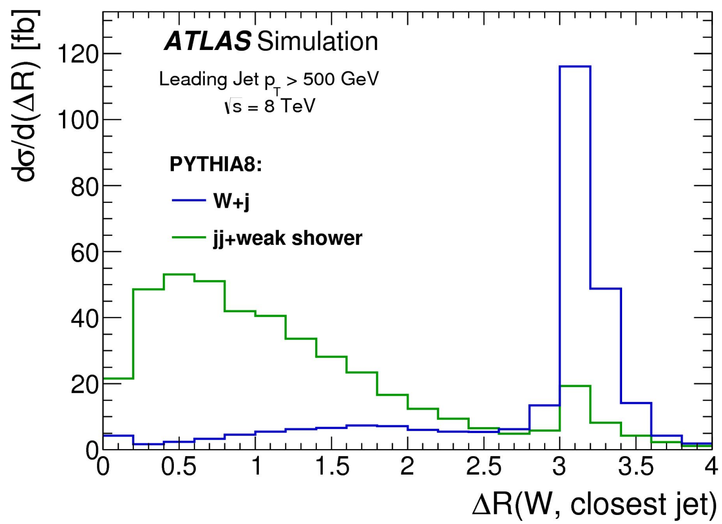
See also a recent theory prediction: https://arxiv.org/abs/1903.02275

Collinear W's (ATLAS) [1609.07045]

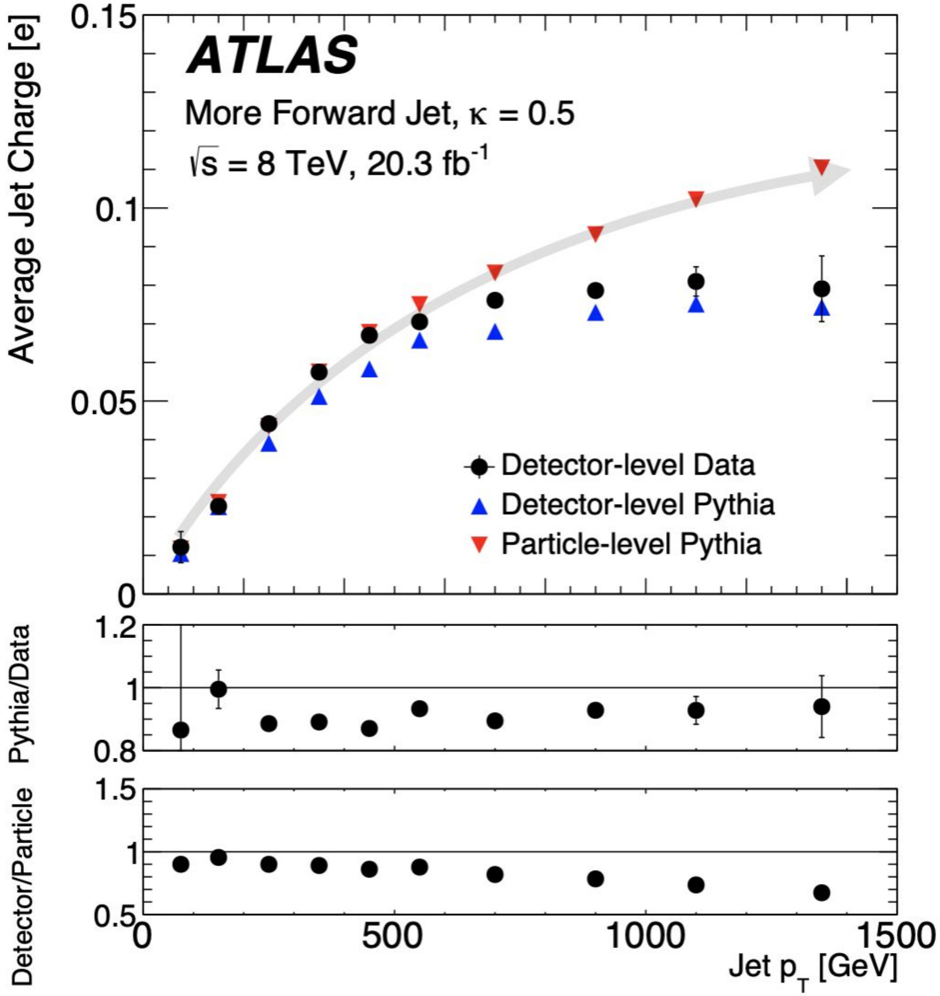


We can probe (real) electroweak effects directly using jet substructure!

This is just the start of an exciting program to explore the structure of these jets in more detail.



Jet Charge (ATLAS) [1509.05190]



$$Q_J = p_{\mathrm{J}}^{-\kappa} \sum_{i \in J} p_{\mathrm{T,i}}^{\kappa} q_i$$

Higher p_T → higher x
→ more valence quarks
→ more up quarks
→ more positive

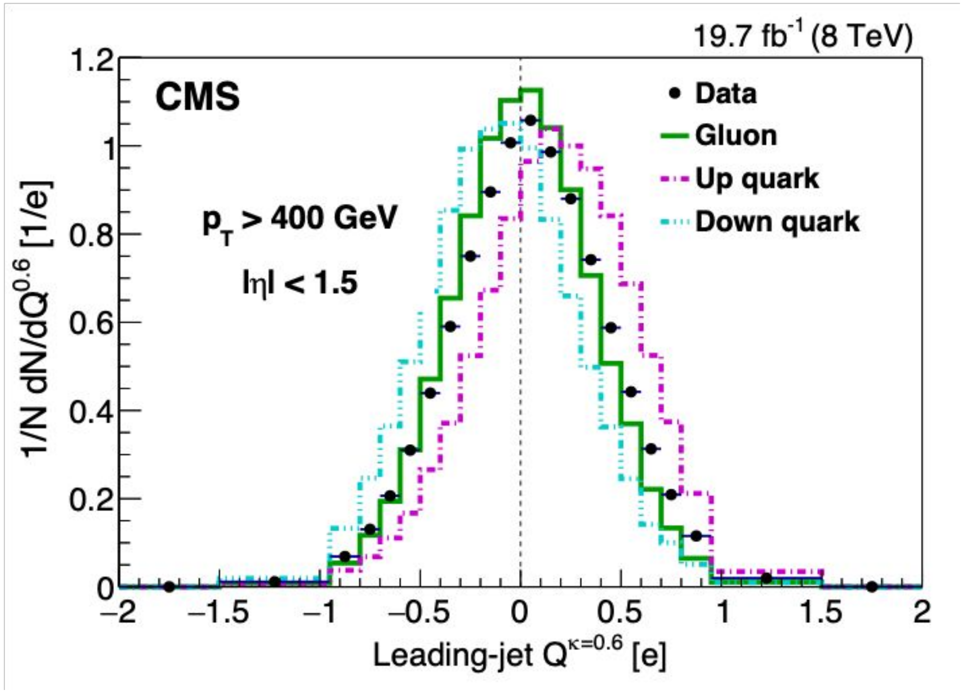
But is there a residual change aside from PDFs?

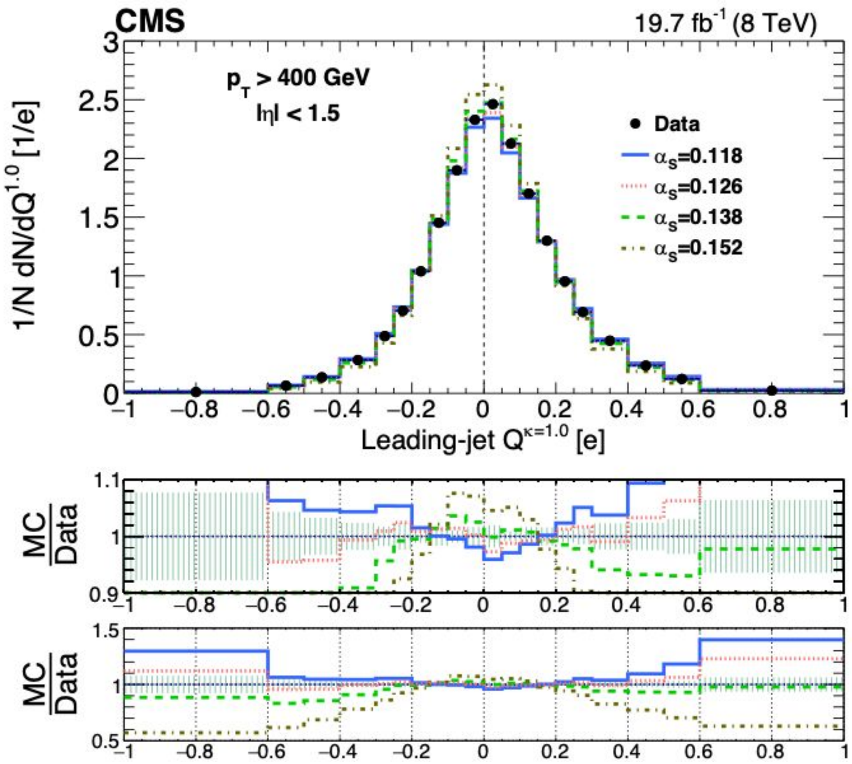
A: yes! We extracted the up/down charge and measured the scale violation (see paper)

Jet Charge (CMS) [1706.05868]

- Jet charge estimator for parton charge
- Sensitive to α_S used in FSR shower

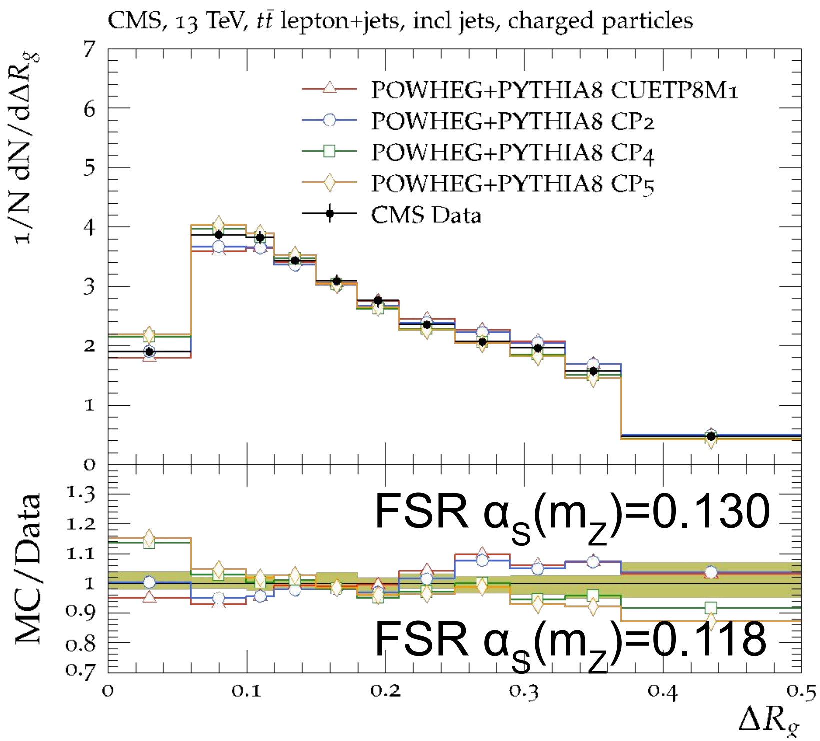
$$Q^{\kappa} = \frac{1}{(p_T^{\text{jet}})^{\kappa}} \sum_i Q_i (p_T^i)^{\kappa}$$

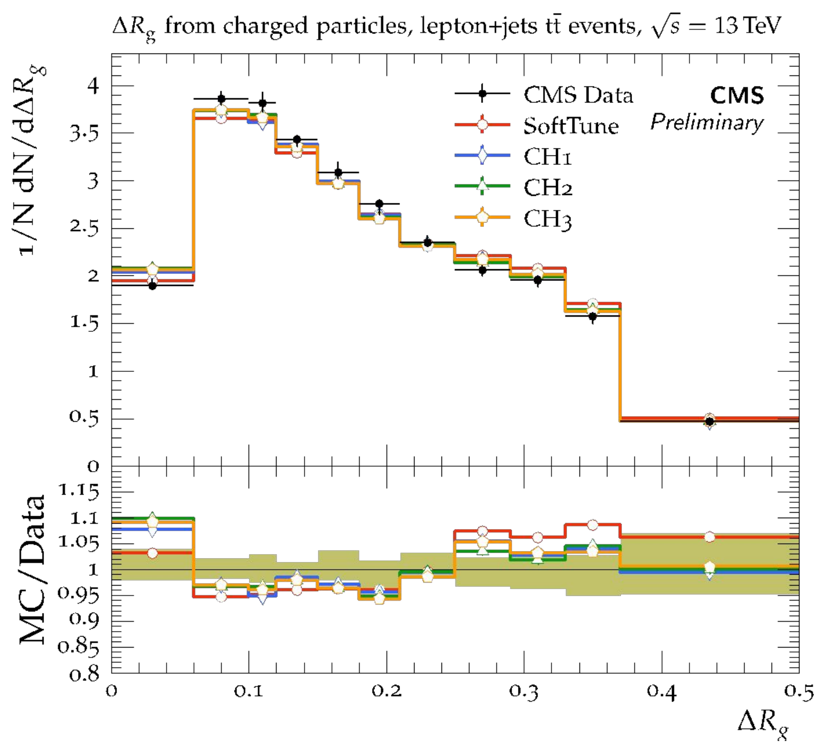




MC Tuning (CMS) [GEN-17-001, GEN-19-001]

- Jet substructure modeling affected by UE tuning
- CMS checks jet substructure observables for new tunes



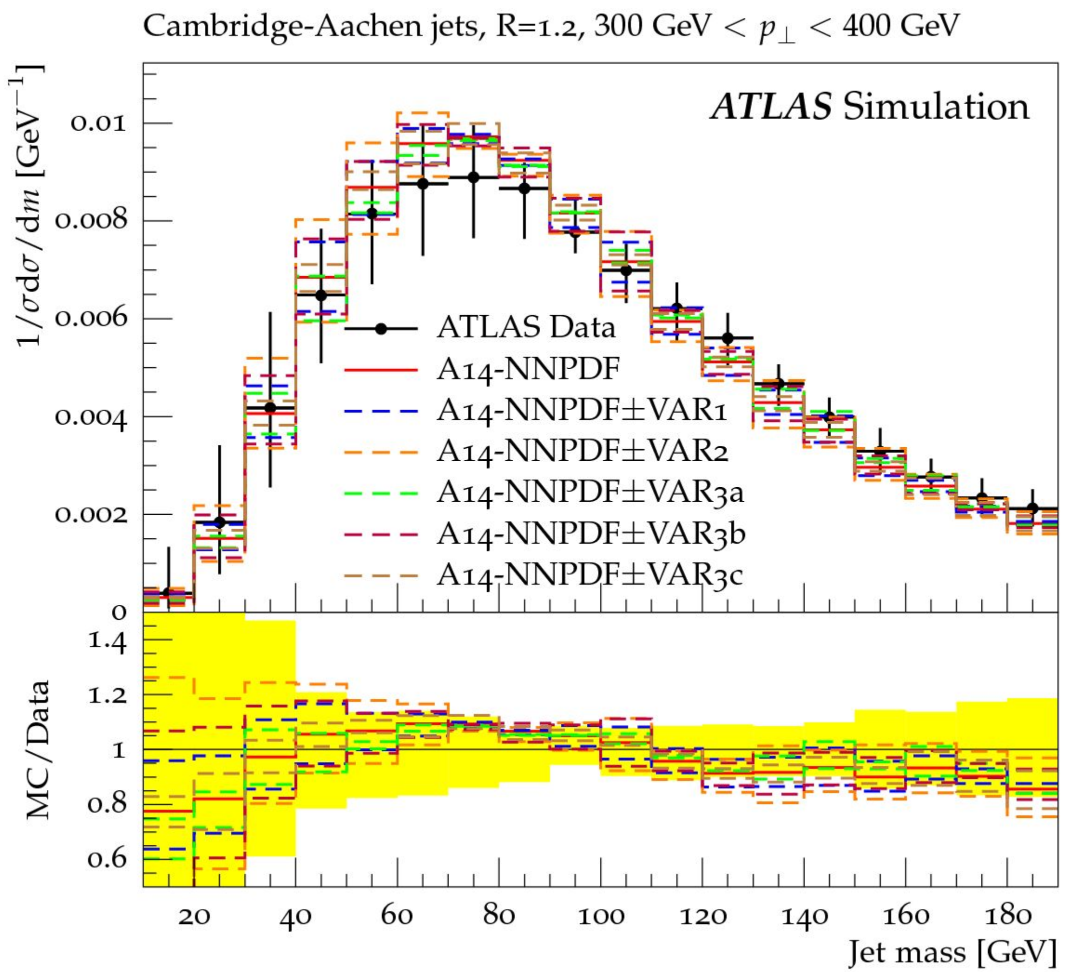


MC Tuning (ATLAS) [ATL-PHYS-PUB-2014-021]

Our default Pythia tune in ATLAS is A14, for which the FSR is strongly influenced by 7 TeV jet substructure measurements.

Furthermore, there are “eigentunes” which are used to estimate the uncertainty from the parton shower.

N.B. favors slightly higher α_S FSR than default Pythia.



See also multijet MC studies in ATL-PHYS-PUB-2019-017

Questions?

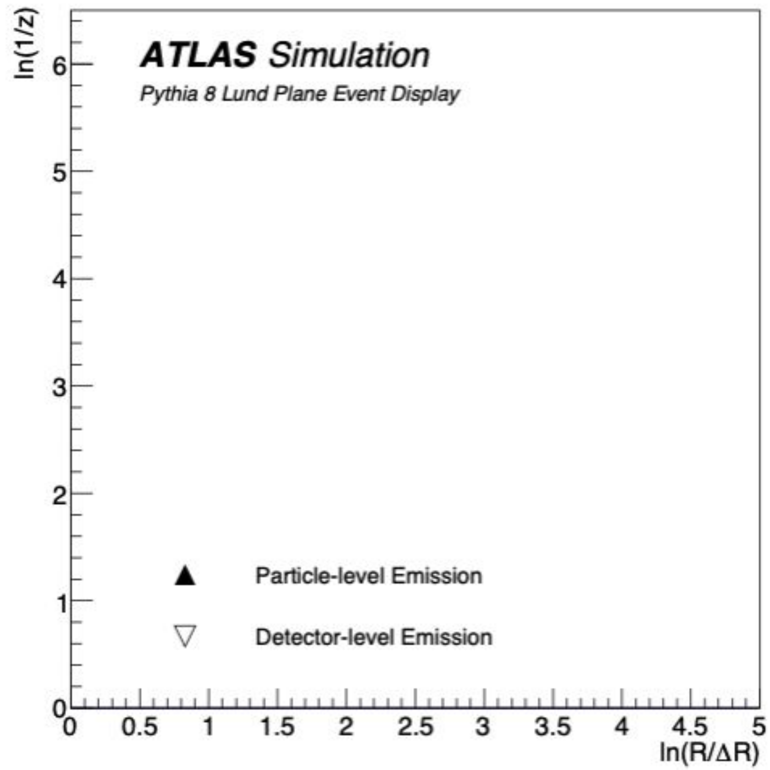
Pause for discussion...

The Lund plane [2004.03540]

The Lund plane [2004.03540]

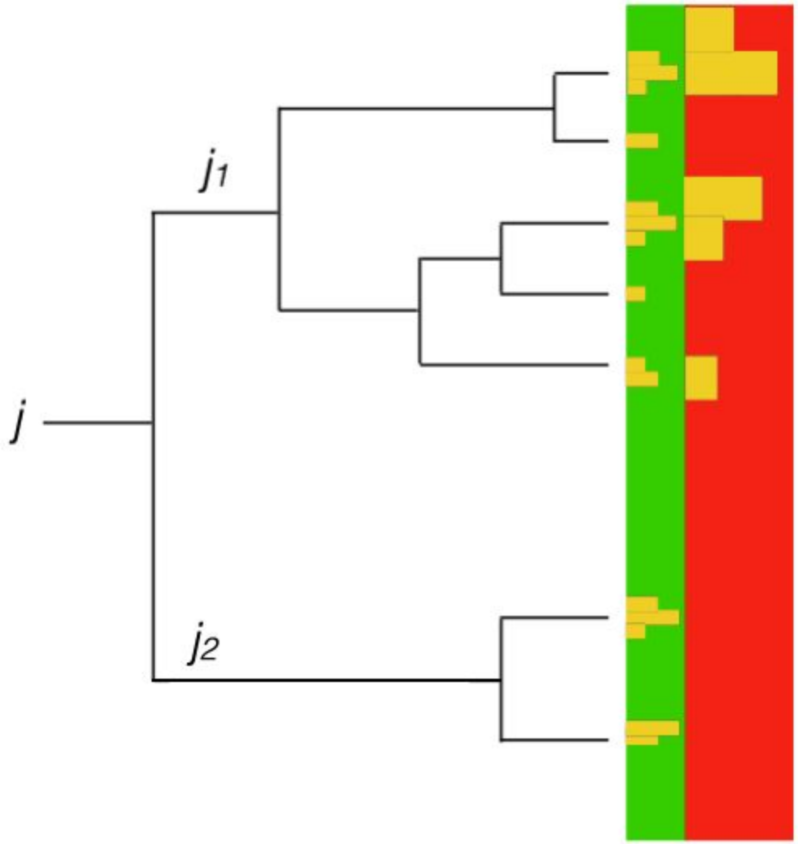
Important: isolate effects with different physical origin

Tool: Lund jet plane to categorize all hard splittings at once



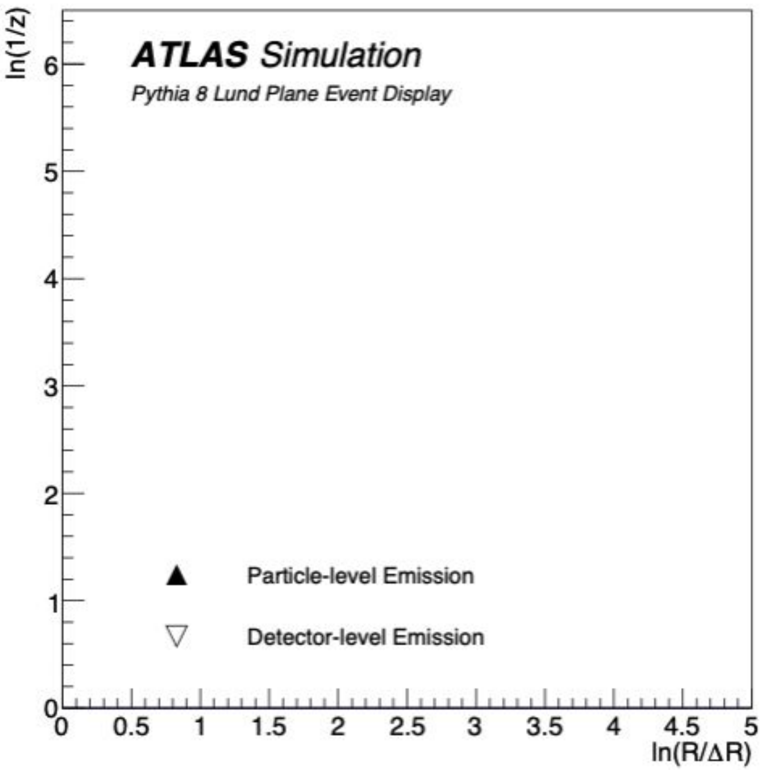
[Dreyer, Salam, Soyez, JHEP 12 (2018) 064]

The Lund plane [2004.03540]



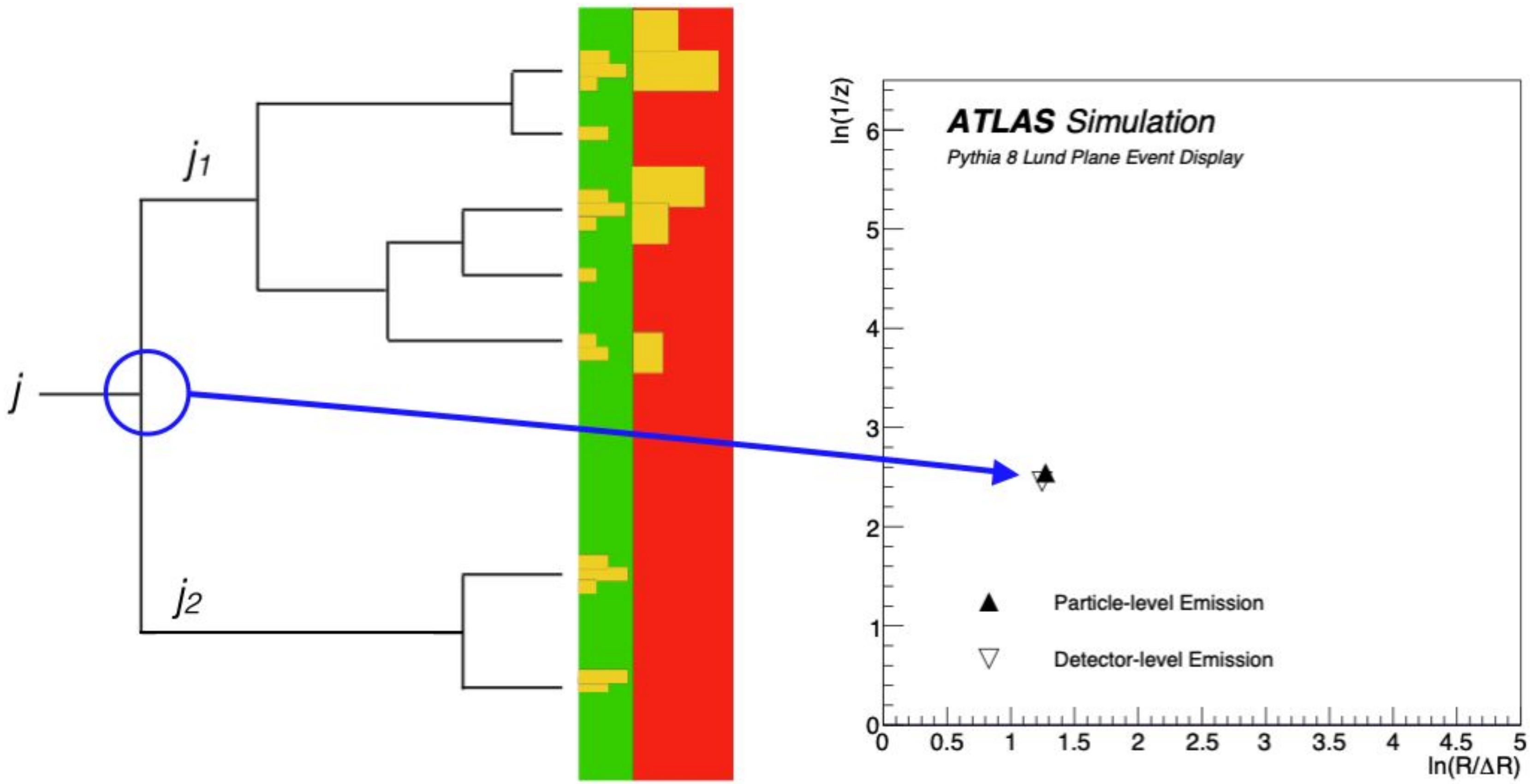
$z = j_1$ momentum fraction of j

ΔR = angle between j_1 and j_2



Use tracks inside jets for precise reconstruction

The Lund plane [2004.03540]



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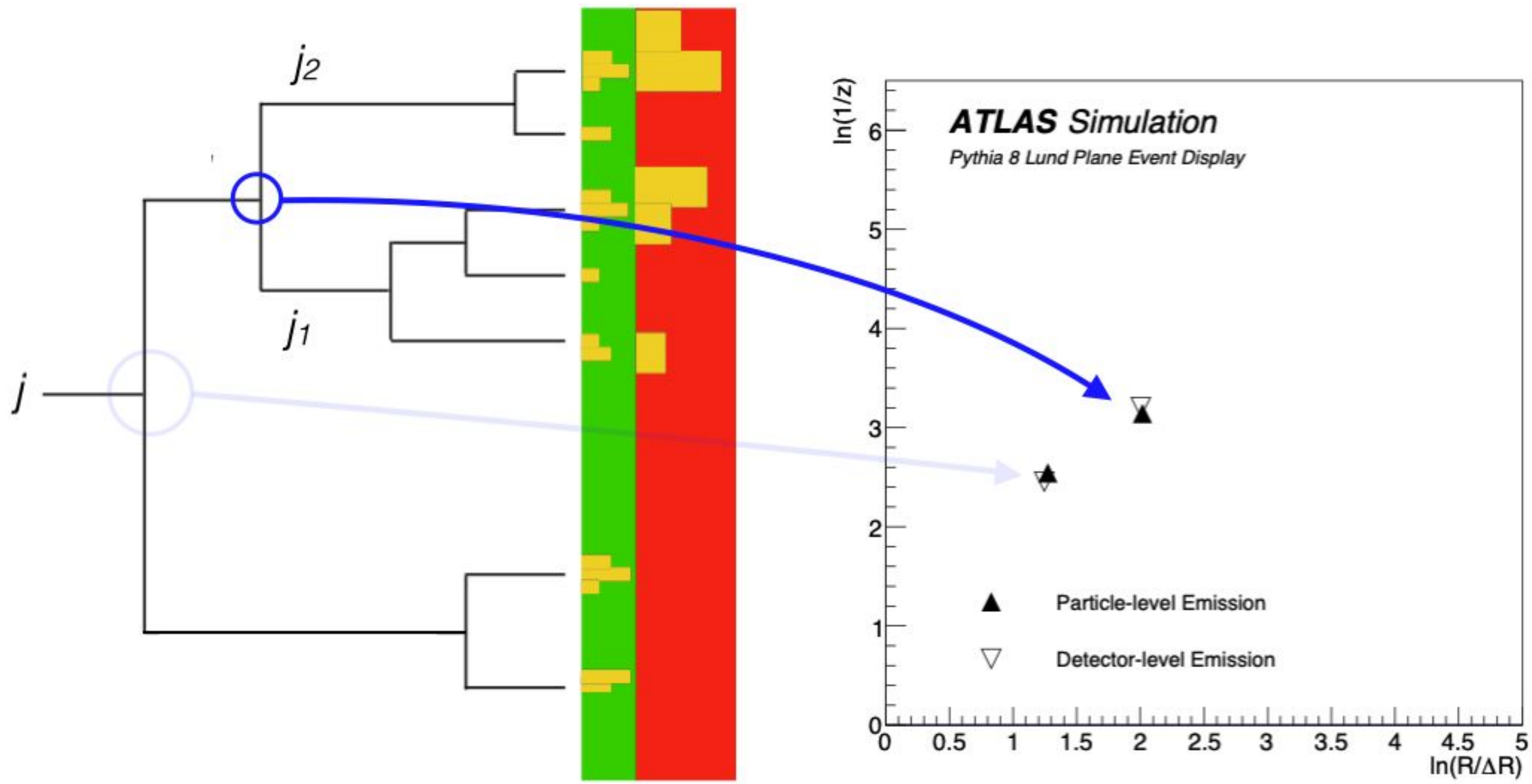

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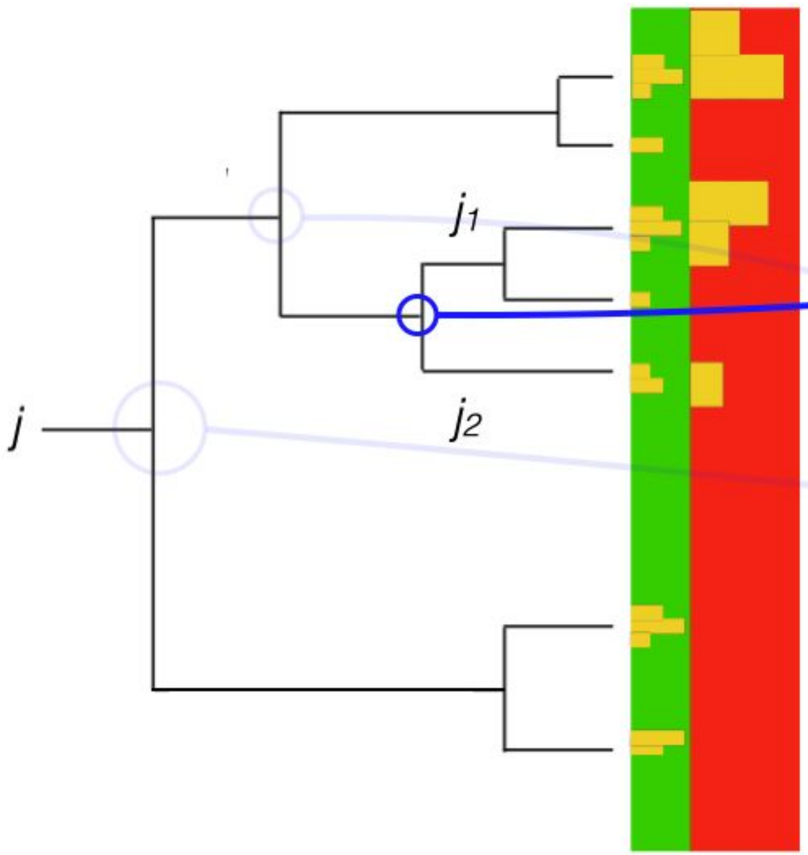

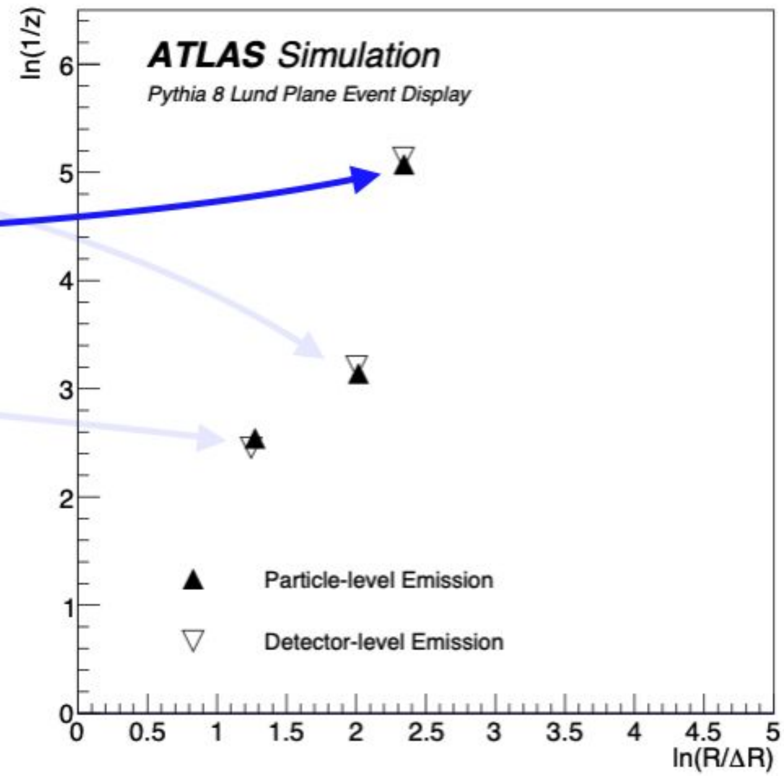

$z = j_1$ momentum fraction of j

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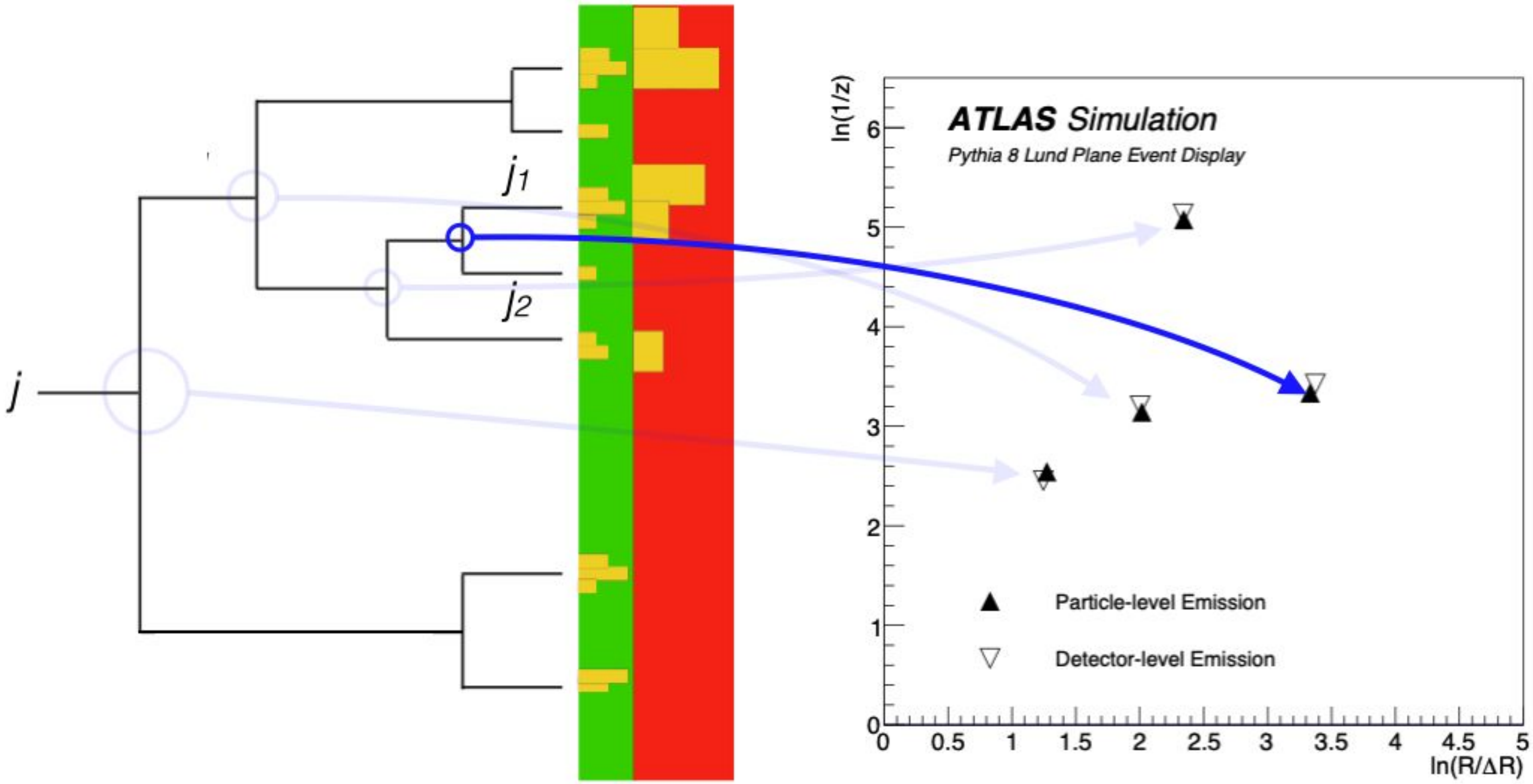

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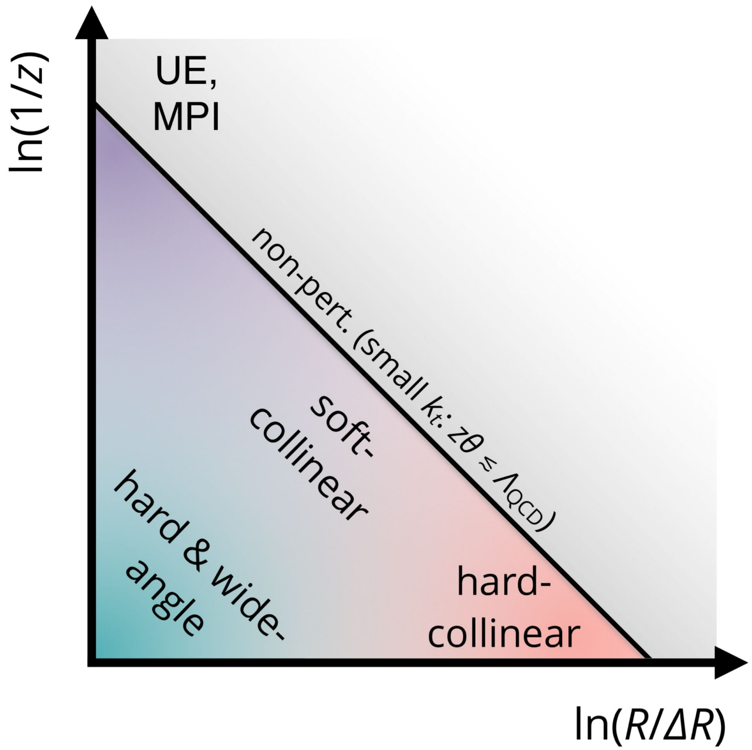
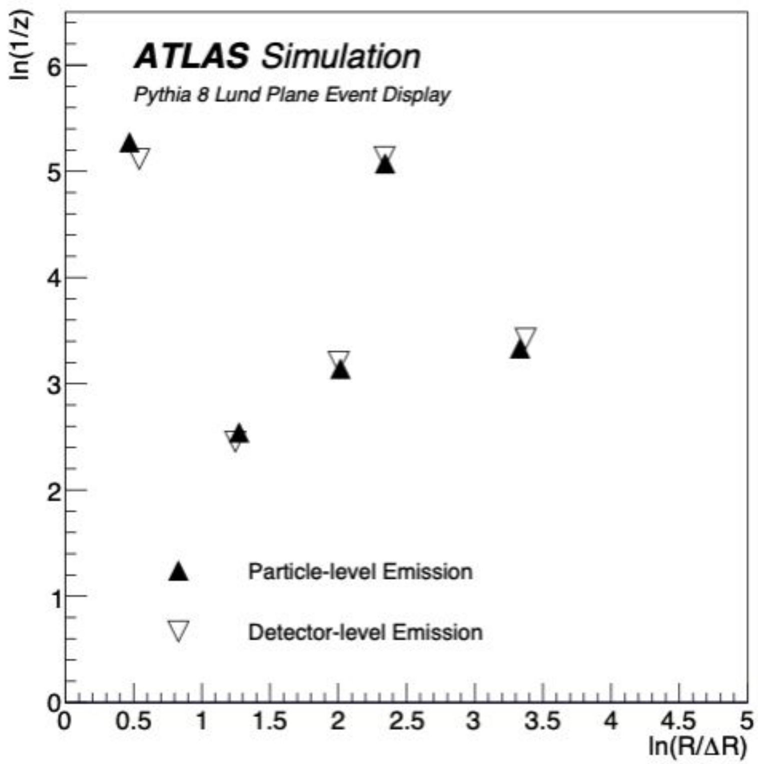
Use tracks inside jets for precise reconstruction

The Lund plane [2004.03540]





Use tracks inside jets for precise reconstruction

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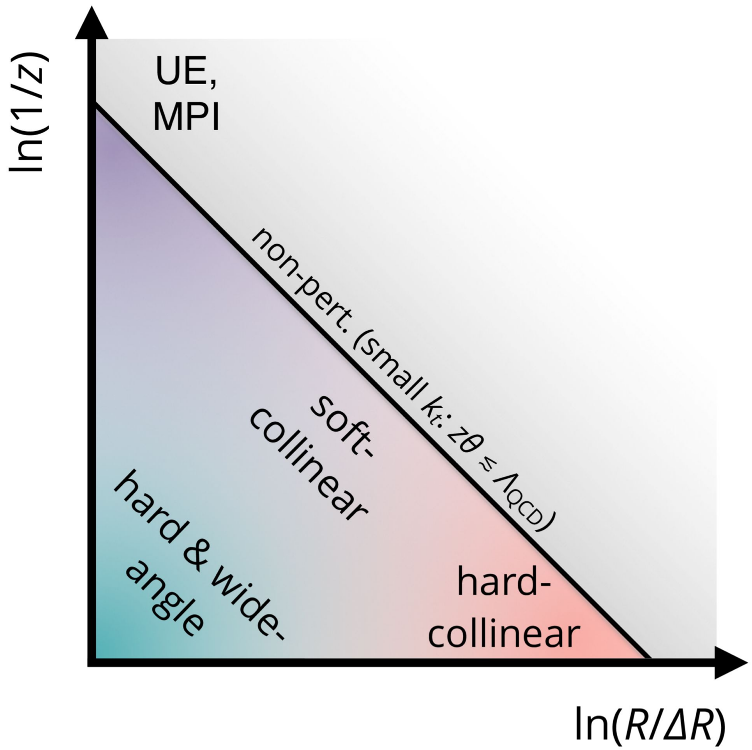

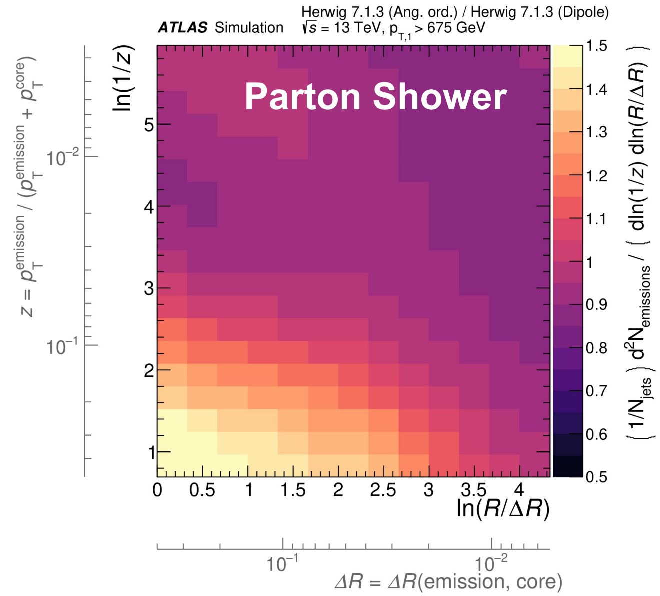

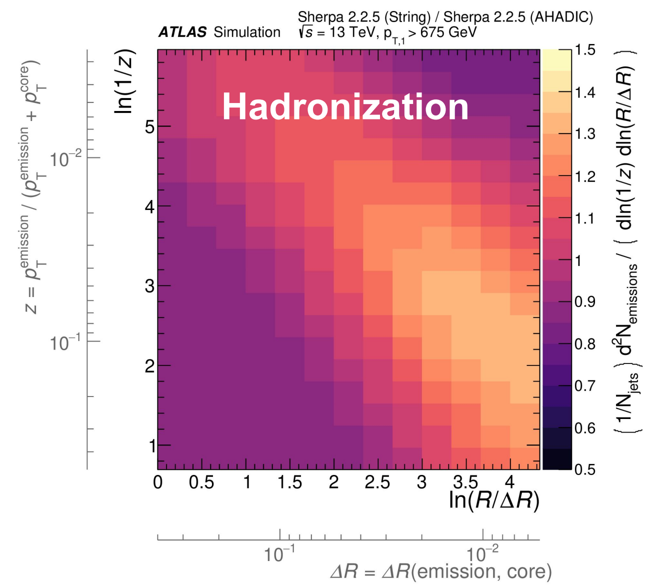

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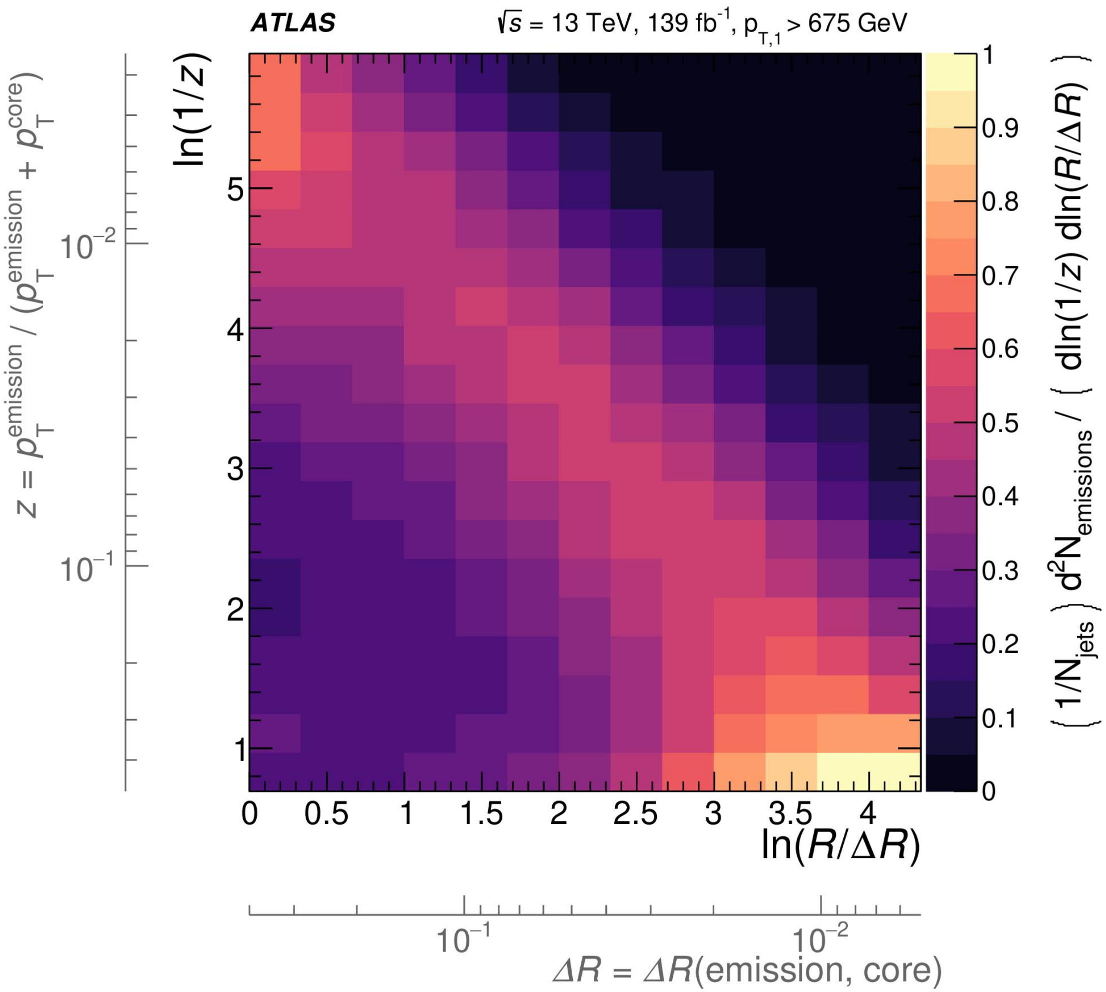


R = 0.4 jets, anti-k_t
Dijets, lead p_T > 675 GeV

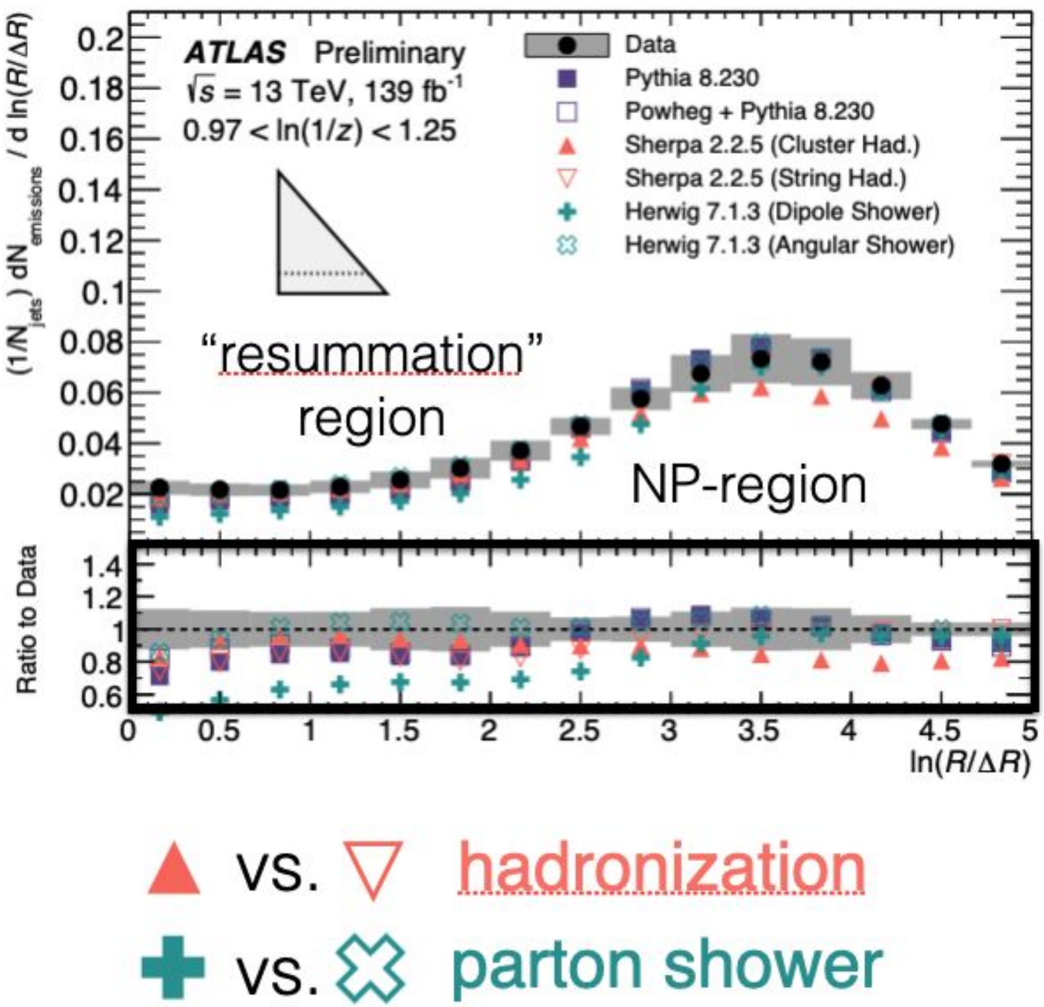
z is between 0.5 and
500 MeV / jet p_T

Reconstructed-level: tracks
Particle-level: charged particles

Reco-truth matching
done in η-φ following
declustering order

Uncertainty dominated by
fragmentation modeling

The Lund plane [2004.03540]



First measurement of the Lund jet plane!

…powerful tool for isolating **hadronization**, **parton shower effects**, and fixed-order effects

Key experimental challenge*: **tracking inside dense environments**

(probing angular scales ~ comparable to pixel detector granularity)

*And the non-trivial unfolding. Maybe fixed by going unbinned and with ML?

See also a recent theory prediction: https://arxiv.org/abs/2007.06578

Questions?

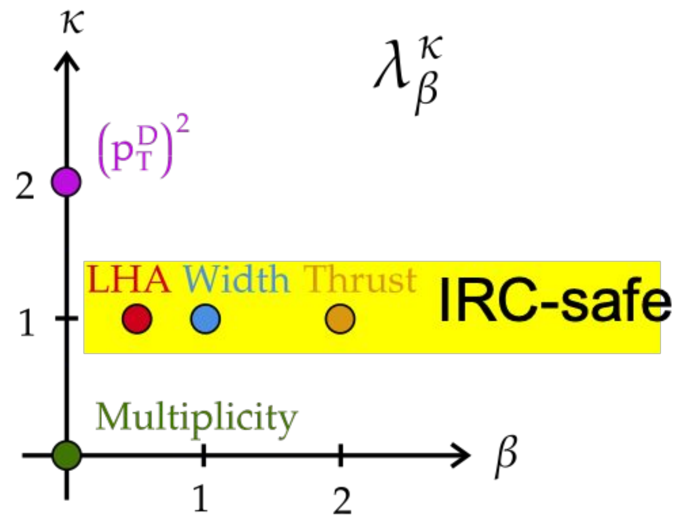
Pause for discussion...

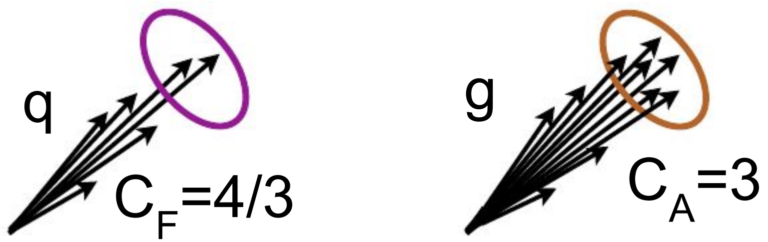
Angularities in Z+jets and dijets

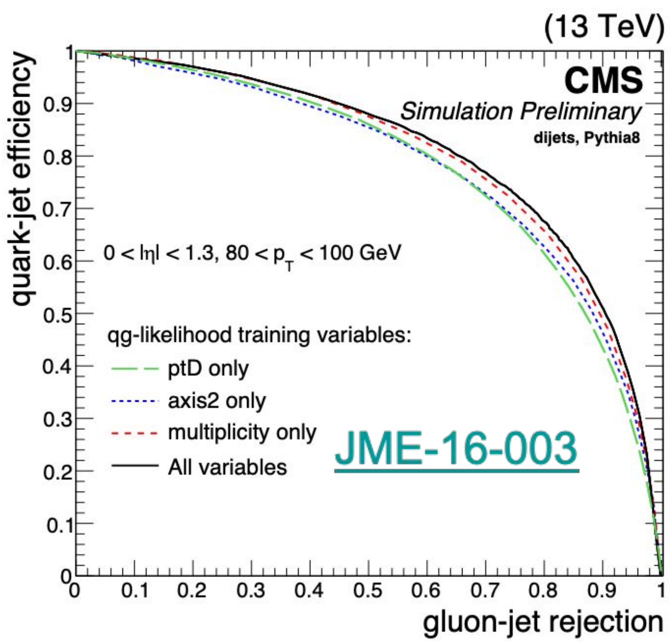
[CMS-PAS-SMP-20-010]

- Generalized angularities

$$\lambda_\beta^\kappa = \sum_{\mathrm{i}\in\mathrm{jet}} z_\mathrm{i}^\kappa \left(\frac{\Delta R_\mathrm{i}}{R}\right)^\beta \qquad z_i \equiv \frac{p_{Ti}}{\sum_{j\in\mathrm{jet}} p_{Tj}}$$







Angularities in Z+jets and dijets

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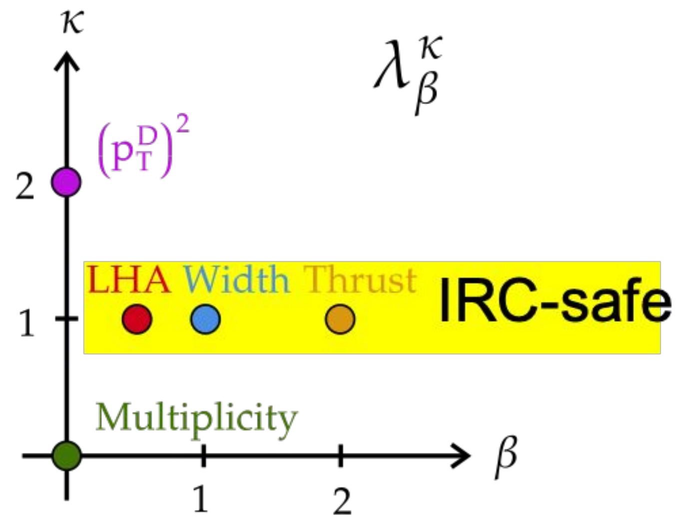
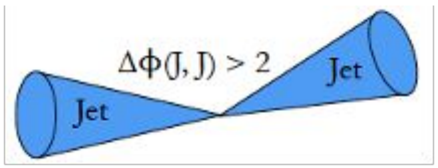


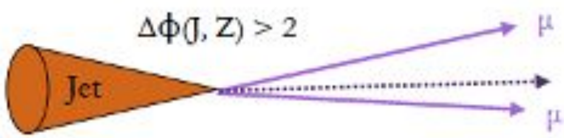
- Systematic study of large phase-space and multiple variants to understand interplay of soft+hard physics in q/g jets (Gras et al.)

Dimension	Variants
Region	Z+jet vs. central dijet vs. forward dijet
Observable λ_{β}^{κ}	LHA, width, thrust, multiplicity, $(p_{\mathrm{T}}^{D})^2$
Jet p_{T}	$50 < p_{\mathrm{T}} < 65\,\mathrm{GeV}$, ..., $p_{\mathrm{T}} > 1000\,\mathrm{GeV}$
Jet size parameter R	0.4 vs. 0.8
Constituents	Charged+neutral vs. charged-only
Grooming	Ungroomed vs. groomed

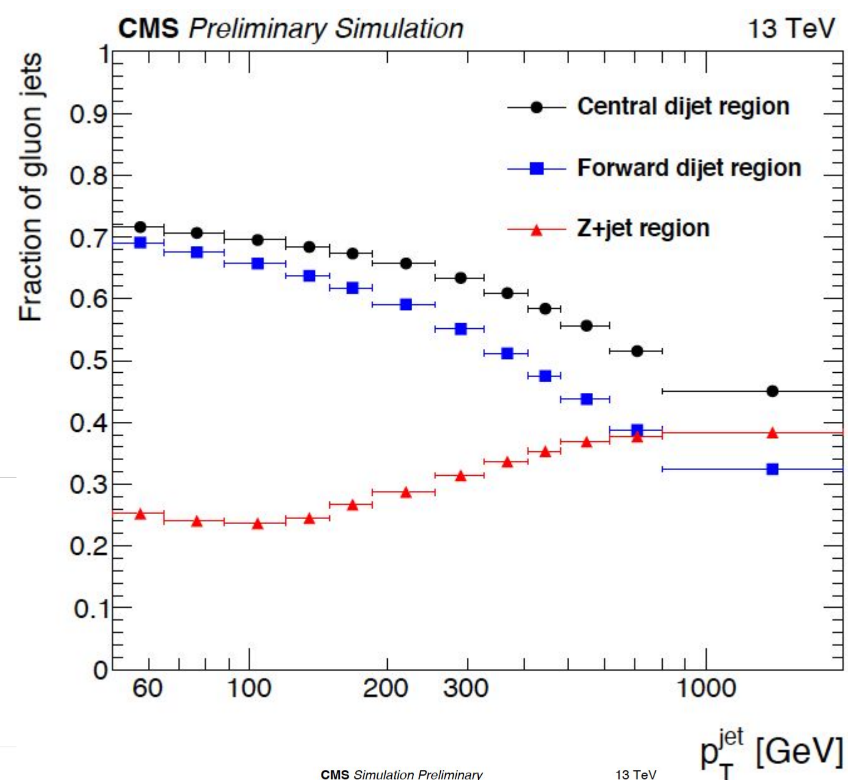
Event samples

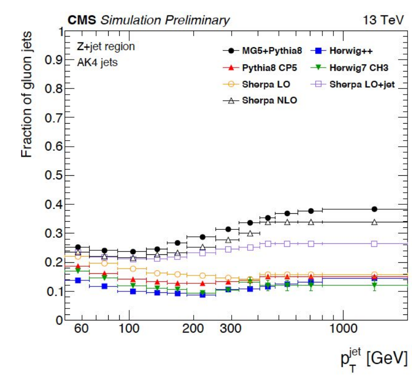


$\geq$2 jets with $|y| < 1.7$ and $p_{\mathrm{T}}^{j} > 30\,\mathrm{GeV}$
$\Delta\phi(j_1, j_2) > 2$
$|p_{\mathrm{T}}^{j_1} - p_{\mathrm{T}}^{j_2}|/(p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}) < 0.3$

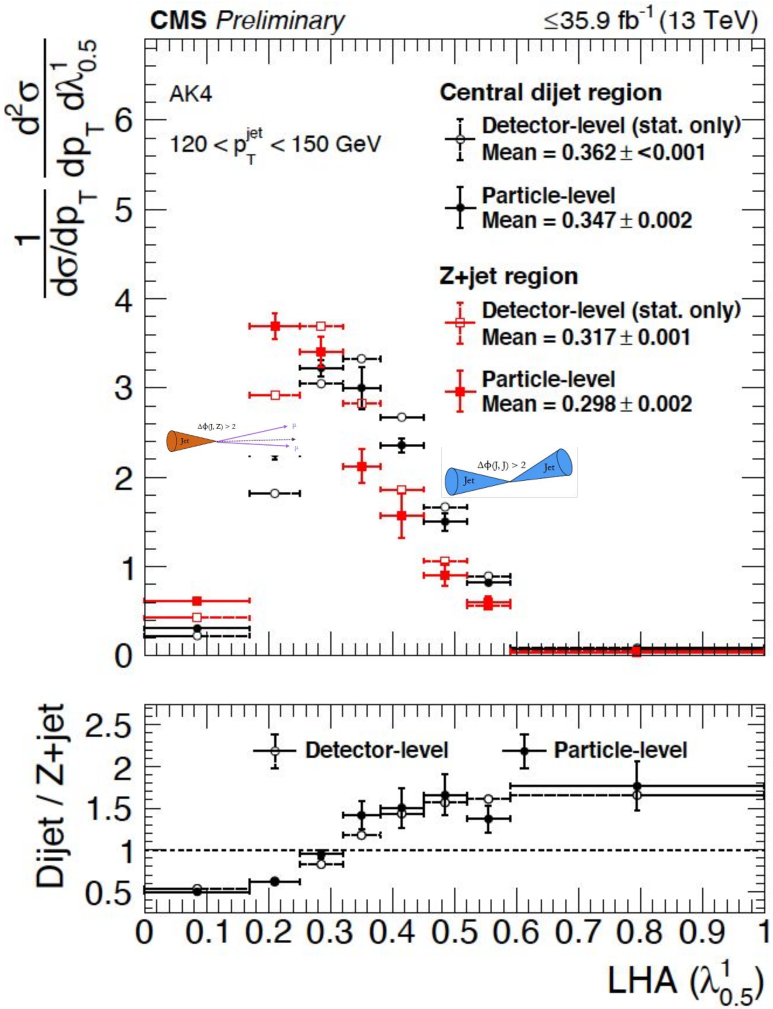


$\geq$2 muons with $|\eta| < 2.4$ and $p_{\mathrm{T}}^{\mu} > 26\,\mathrm{GeV}$
Opposite charge muons
$|m_{\mu\mu} - m_{\mathrm{Z}}| < 20\,\mathrm{GeV}$
$\geq$1 jet with $|y| < 1.7$ and $p_{\mathrm{T}}^{j} > 30\,\mathrm{GeV}$,
not overlapping with muons of the Z boson candidate
$\Delta\phi(j_1, \mathrm{Z}) > 2$
$|p_{\mathrm{T}}^{j_1} - p_{\mathrm{T}}^{\mathrm{Z}}|/(p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{\mathrm{Z}}) < 0.3$

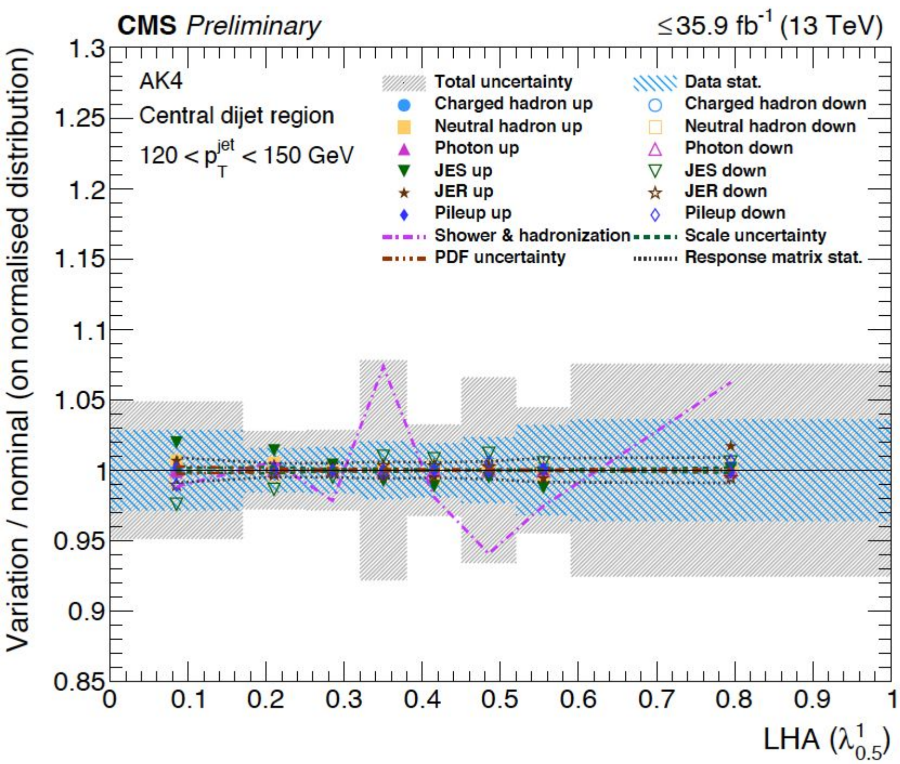




Unfolding and uncertainties

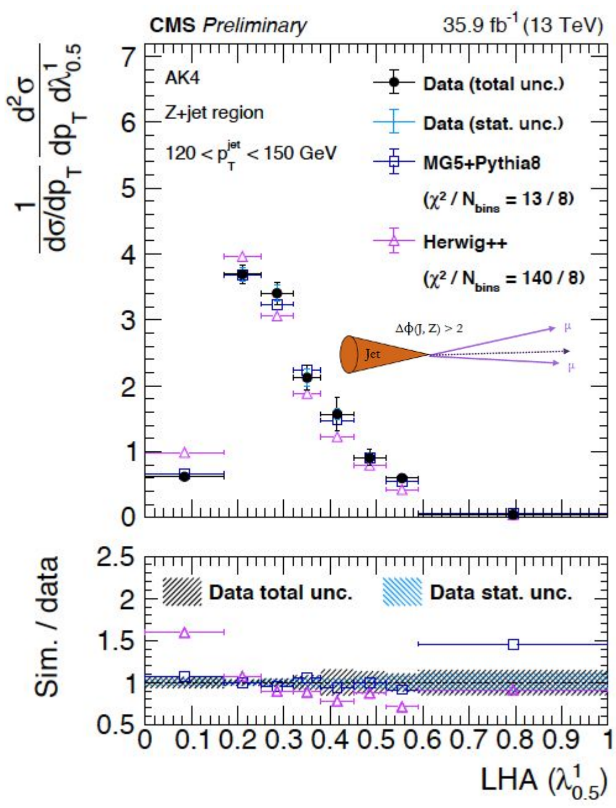


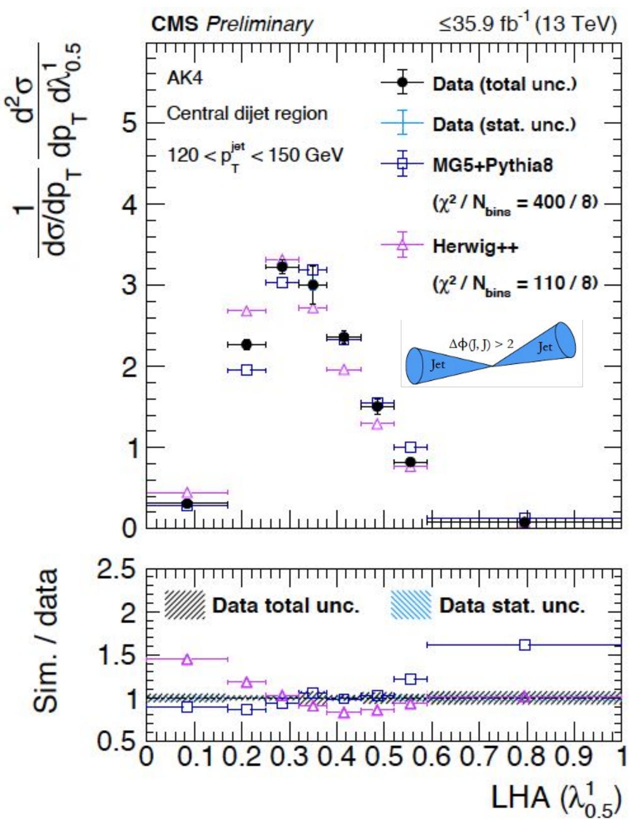
- Z+jet / dijet ratio insensitive to detector
- Dominant uncertainty from shower/hadronization model



LHA distribution

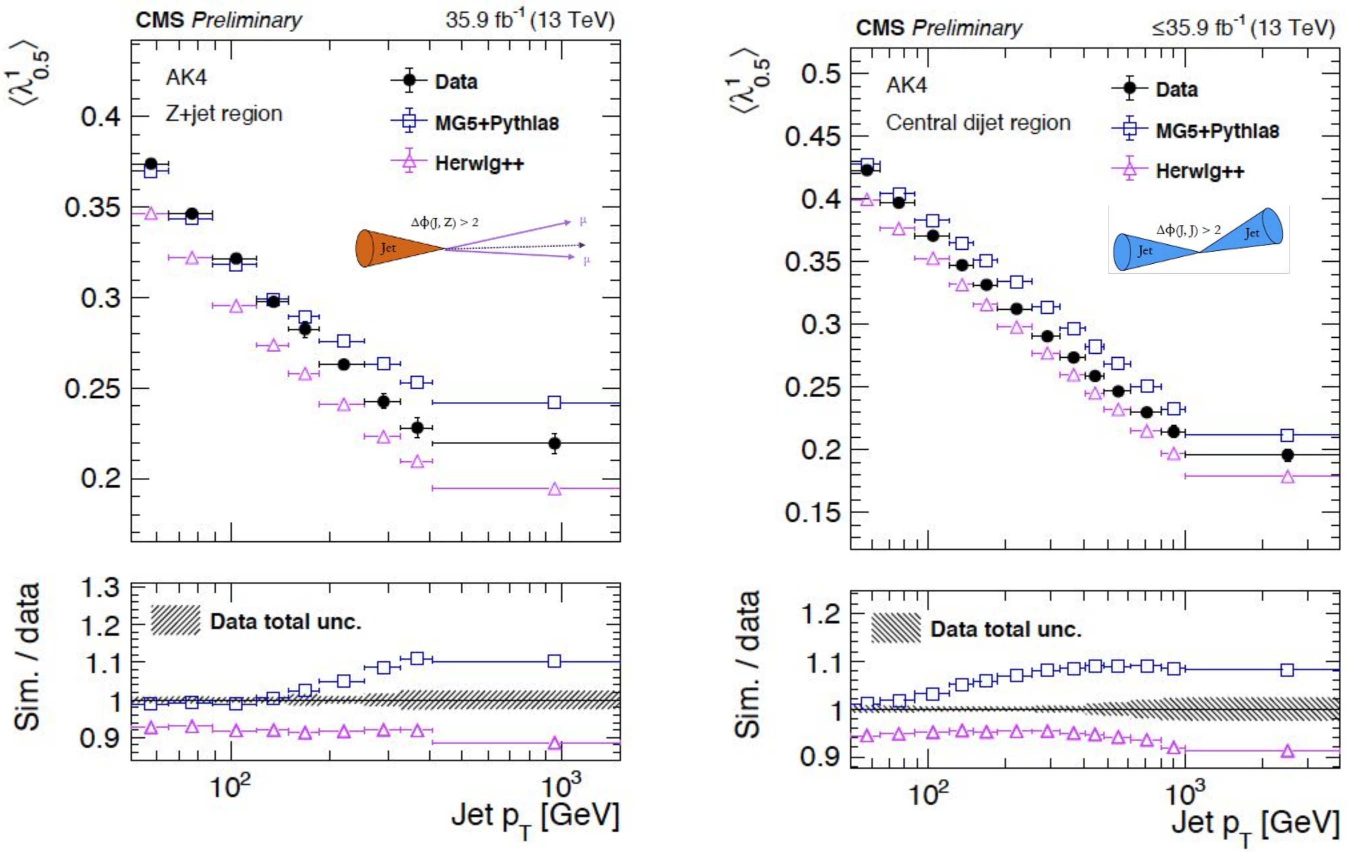
- Quark-enriched sample well described by Madgraph+Pythia8-CUETP8M1
- Gluon-enriched not well described, data “between Pythia and Herwig”





LHA distribution vs. transverse momentum

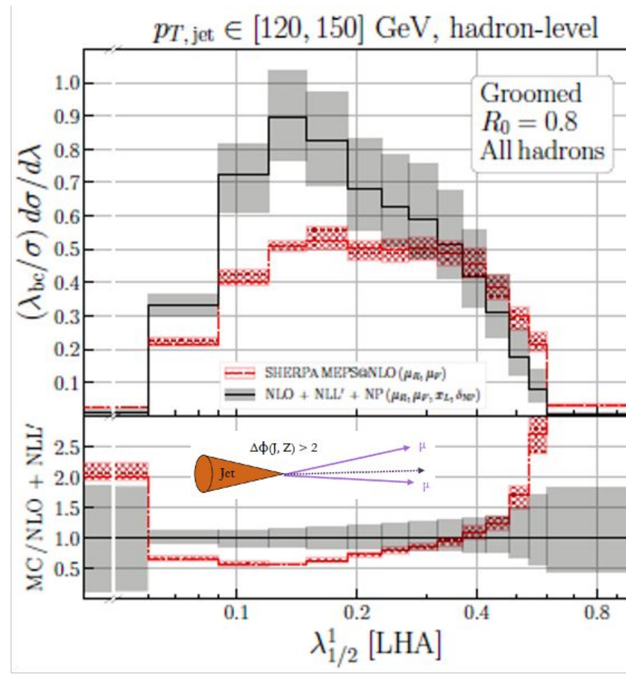
- Madgraph+Pythia8 description worsen at high pT



State of the art predictions

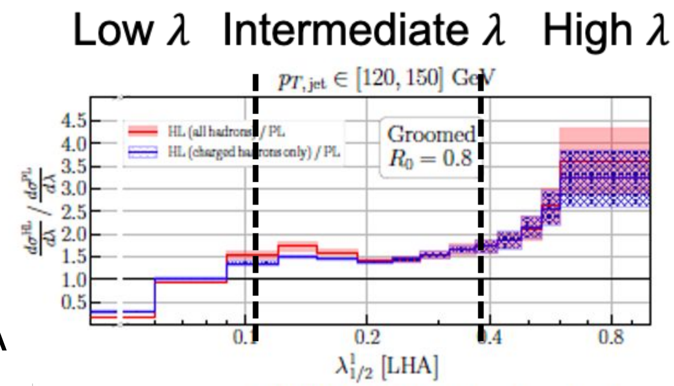
[2104.06920]

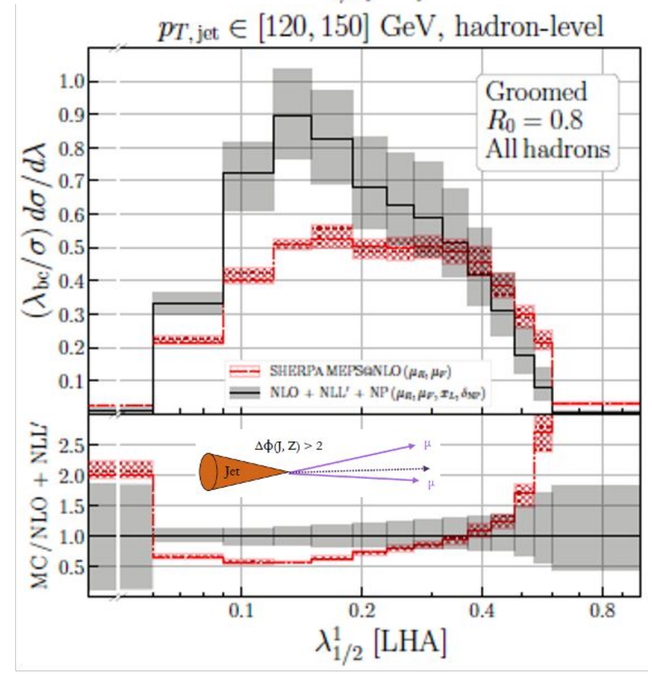
- Jet Angularities in Z+jet production at the LHC, S Caletti, O Fedkevych, S Marzani, D Reichelt, S Schumann, G Soyez, V Theeuwes
- Analytic resummation of large logarithms at next-to-leading logarithmic accuracy (NLL), matched to the exact NLO result, plus non-perturbative corrections from Sherpa: NLO+NLL'+NP
- Compared to: Sherpa MEPS@NLO multijet merging, combining the NLO QCD matrix elements for μμj and μμjj production, matched with dipole shower
- Uncertainties: 6 μ_R,μ_F scale variations, resummation scale x_L, non-perturbative effects (PYTHIA, HERWIG and SHERPA)



State of the art predictions - expectations [2104.06920]

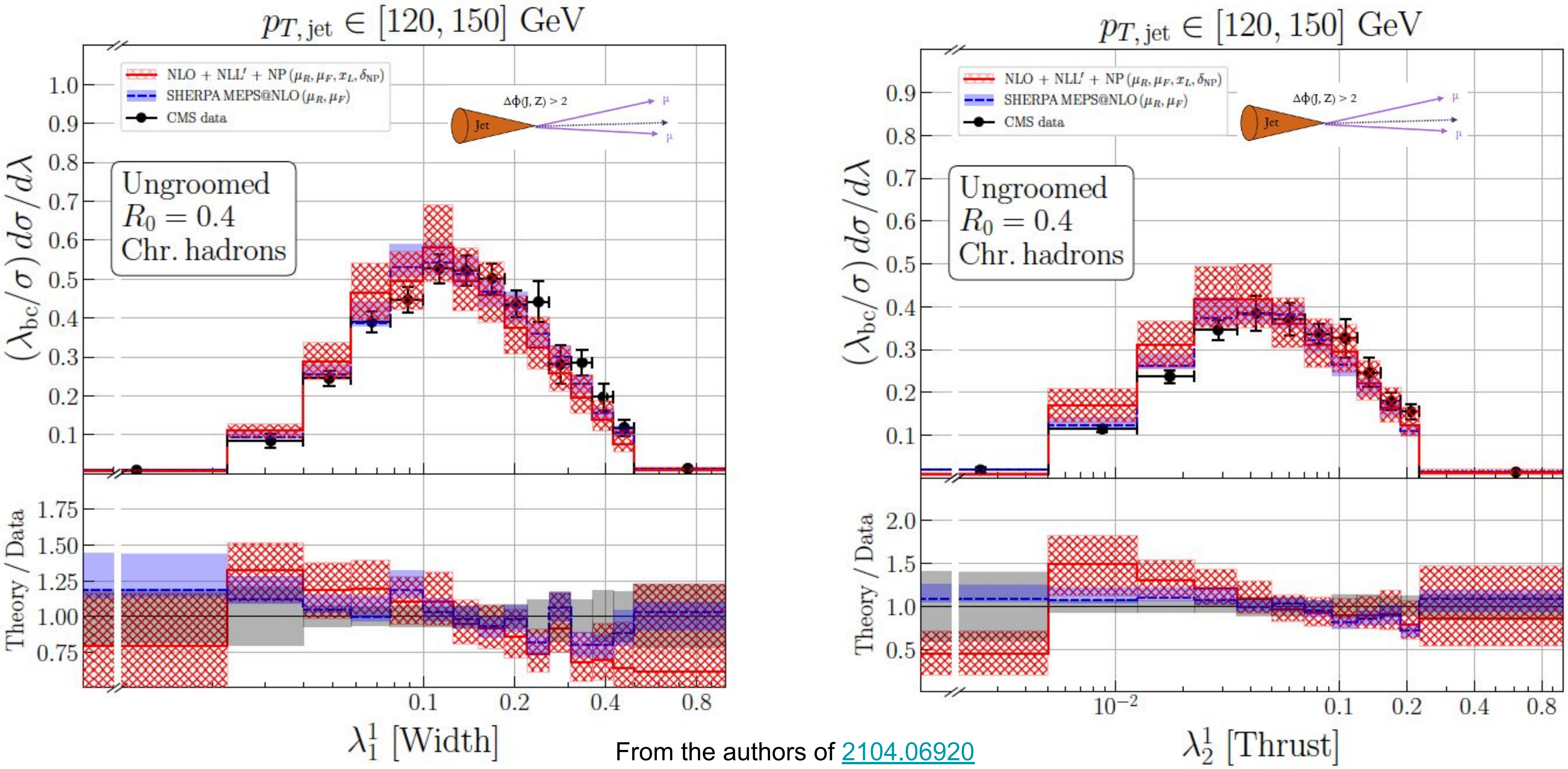
- Regions:
  - Low λ (Infrared): non-perturbative dominate
  - Intermediate λ: (resummed) perturbation theory good
  - Large λ (kinematic endp.): non-perturbative matter (UE)
- Transition point between low λ and intermediate λ ~1/(R p_T) (except groomed thrust)
- Where NLO+NLL'+NP and MEPS@NLO agree, expect agreement with data
  - Width, Thrust
  - Intermediate λ
  - High p_T, large R (lower transition point)
- Where NLO+NLL'+NP and MEPS@NLO disagree, data can guide
  - LHA, especially groomed LHA
  - Low λ, Large λ
  - Low p_T, small R





Width and thrust - data vs. predictions

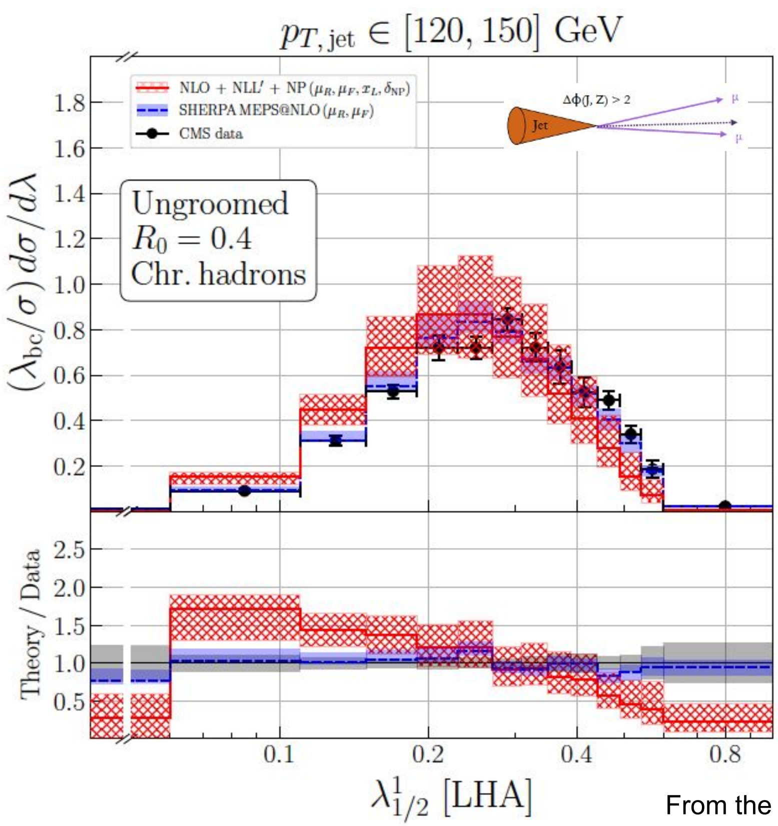
- Sherpa MEPS@NLO describes data well
- NLO+NLL'+NP describes width+thrust well, slight disagreement low λ

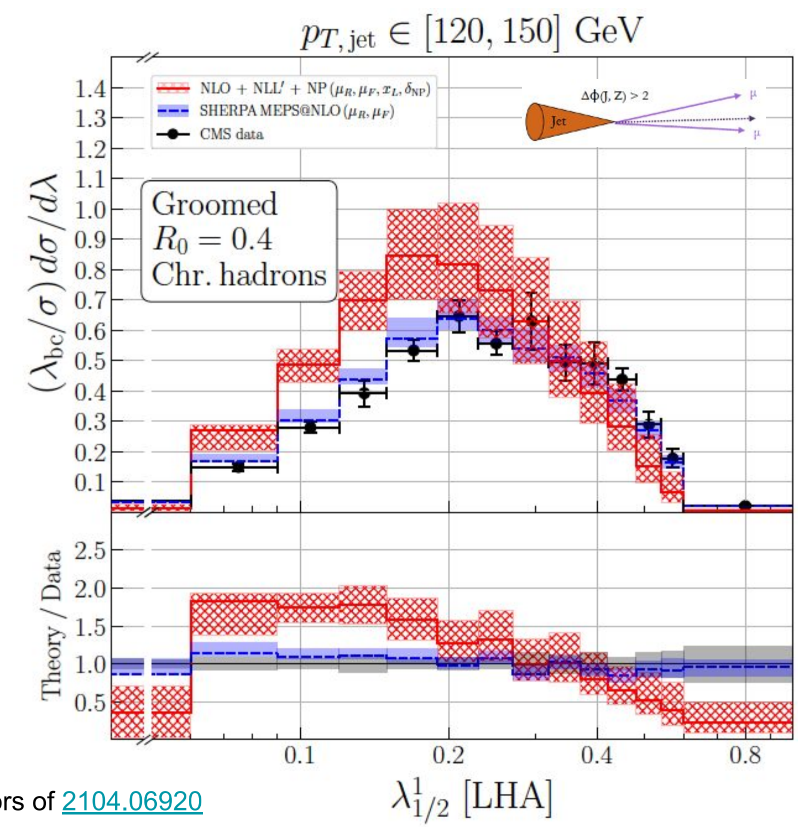


From the authors of 2104.06920

LHA - data vs. predictions

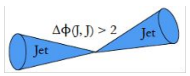
- Sherpa MEPS@NLO describes data well
- NLO+NLL’+NP does not describe LHA well, groomed LHA even worse

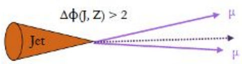


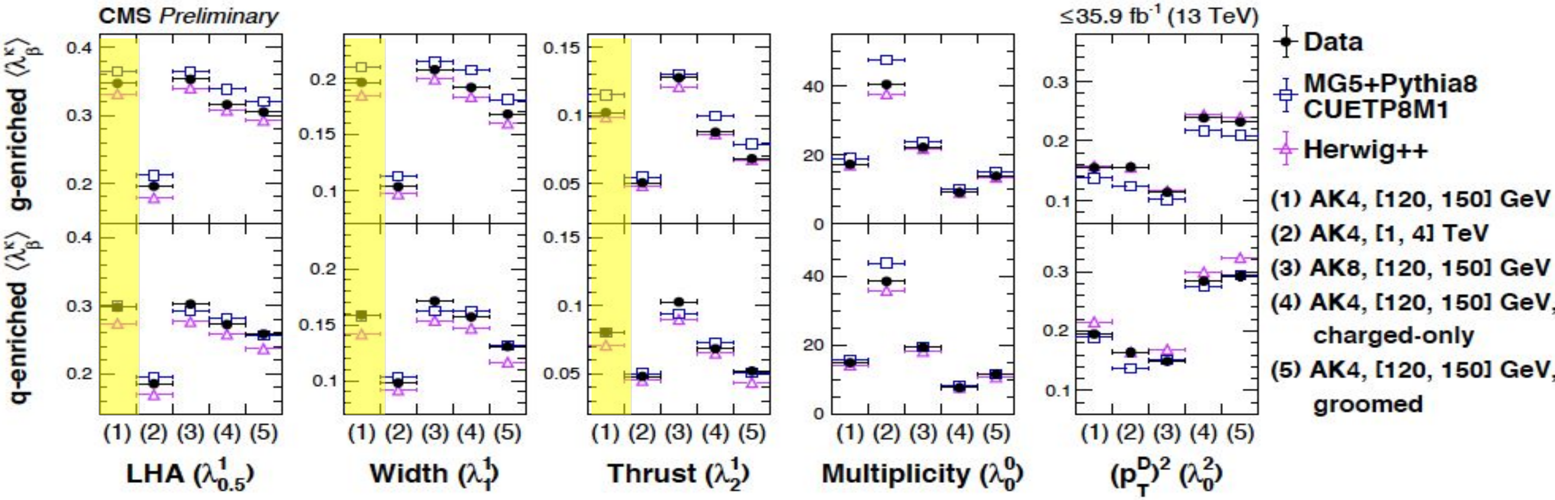


From the authors of 2104.06920

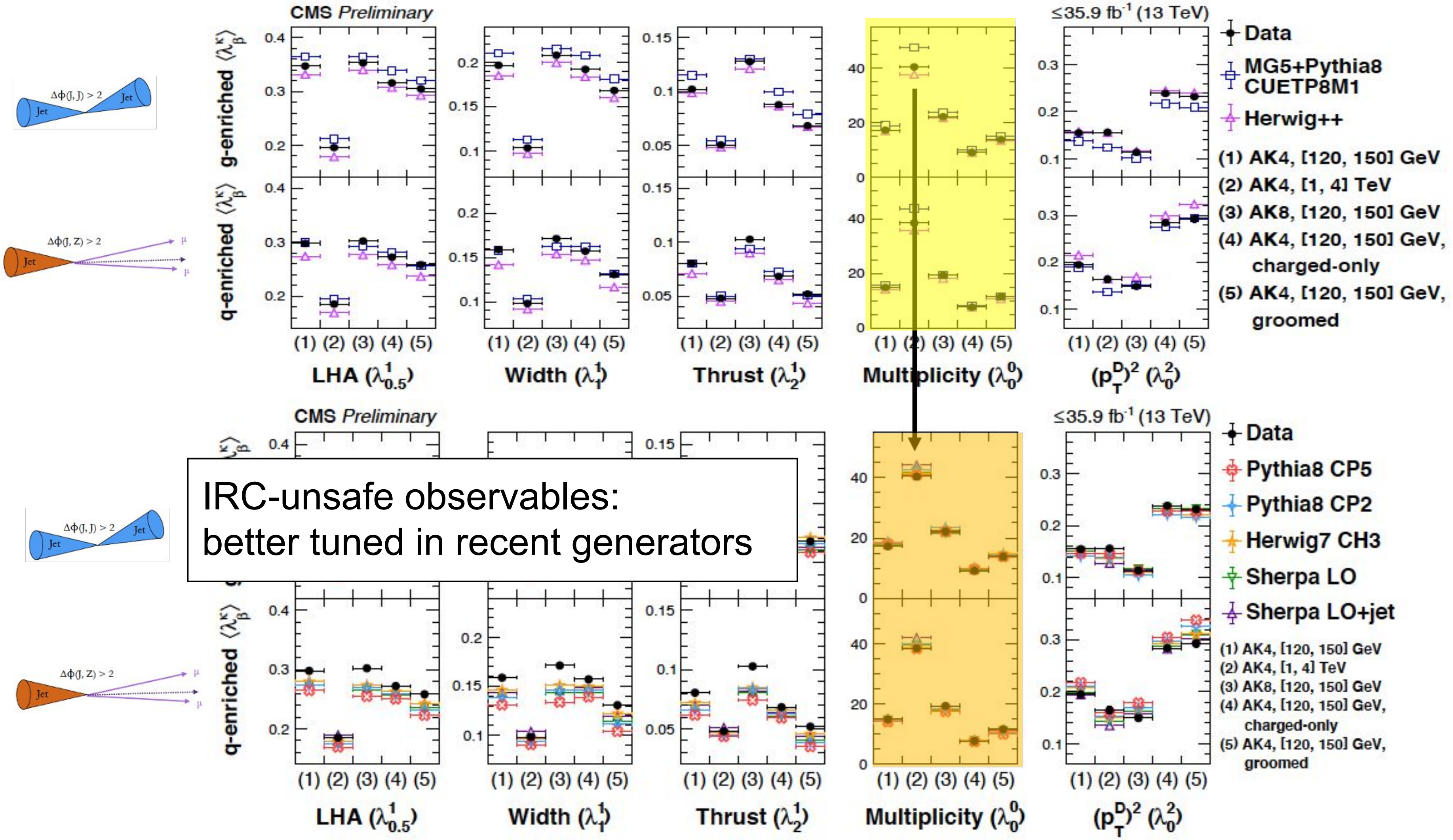
Summary of observables







Summary of results - recent generators



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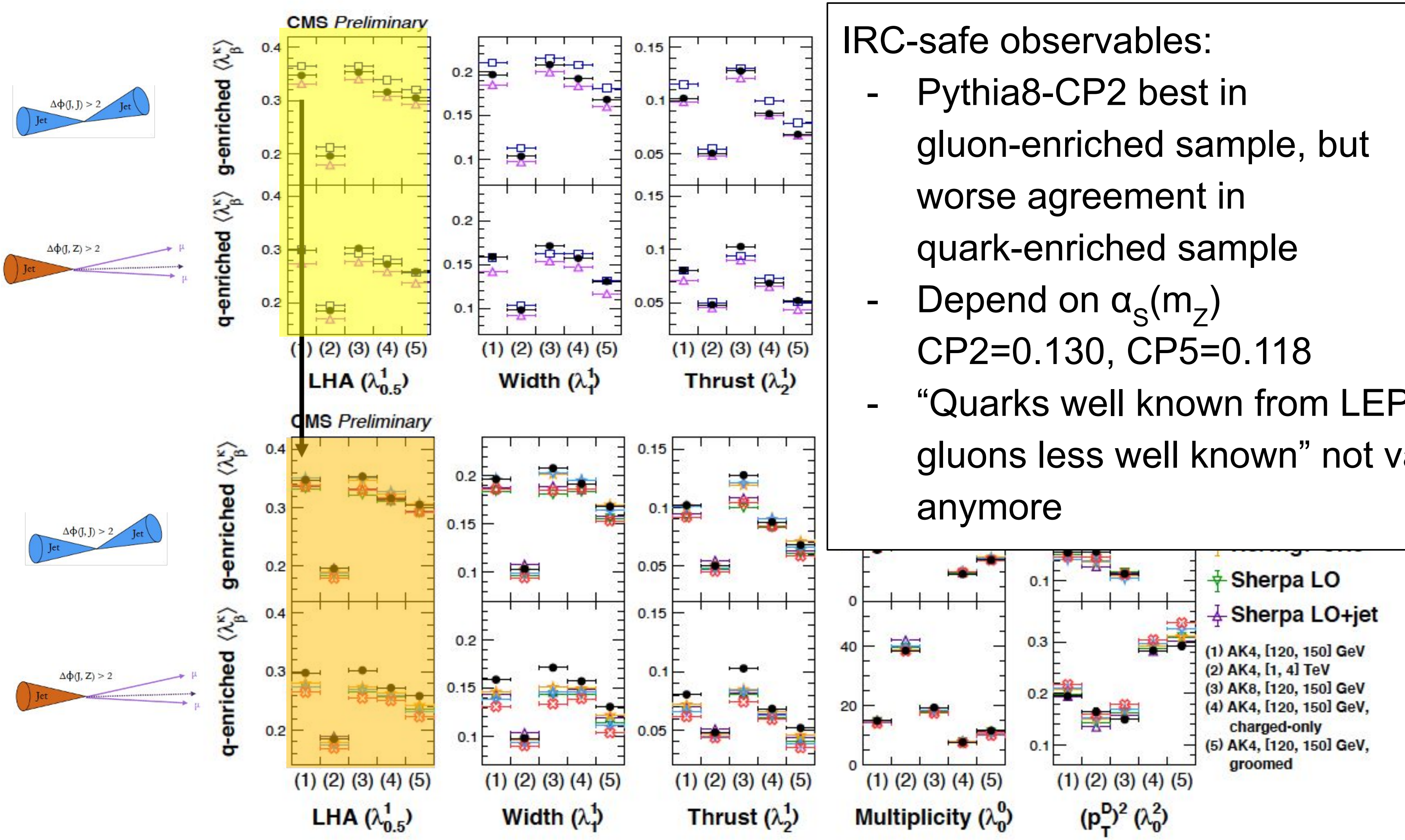
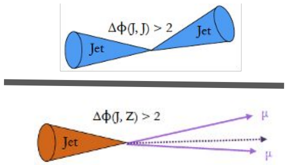


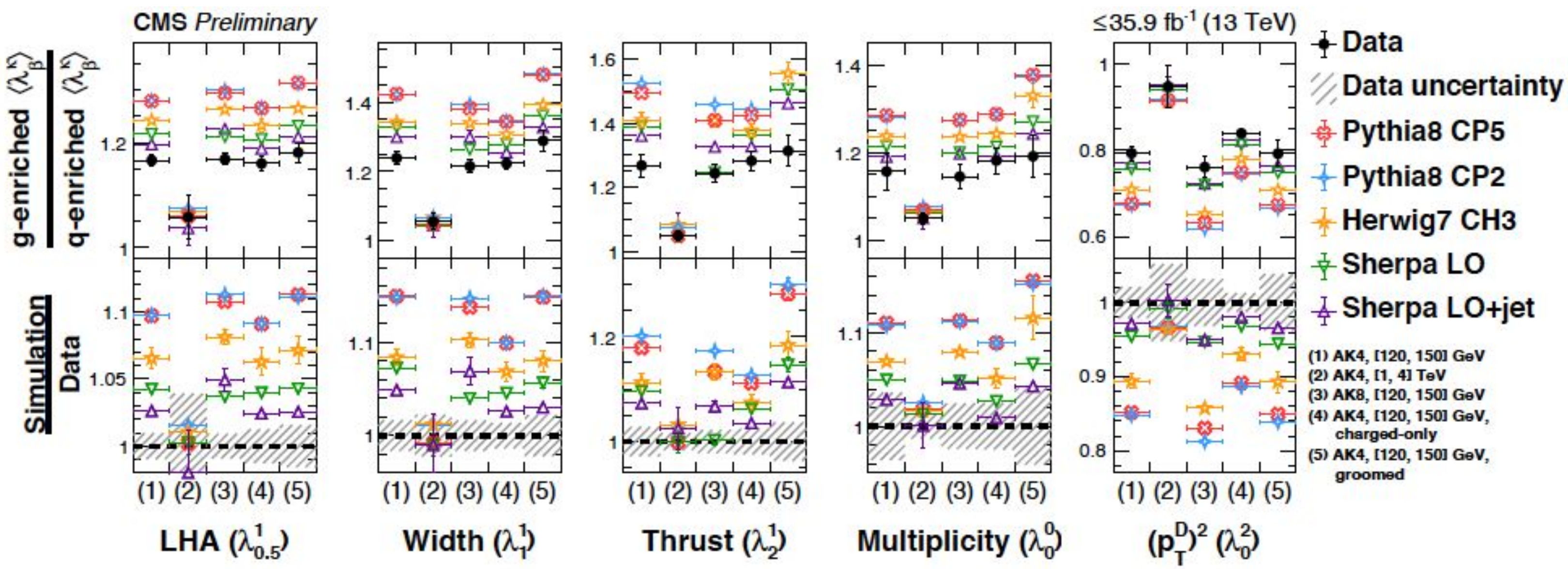
IRC-safe observables:

- Pythia8-CP2 best in gluon-enriched sample, but worse agreement in quark-enriched sample
- Depend on $\alpha_S(m_Z)$ CP2=0.130, CP5=0.118
- “Quarks well known from LEP, gluons less well known” not valid anymore

Dijet / Z+jet (gluon/quark) ratio



- All generators in LO+PS mode overestimate the ratio of gluon-enriched and quark-enriched
- Sherpa (MEPS@LO) best

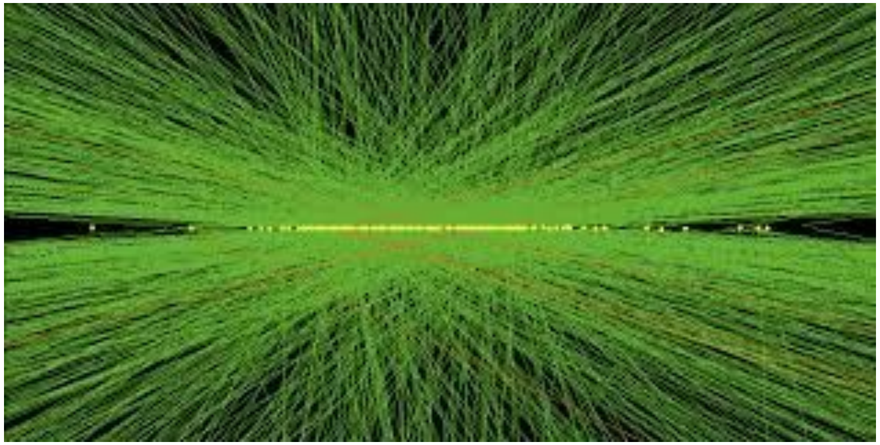


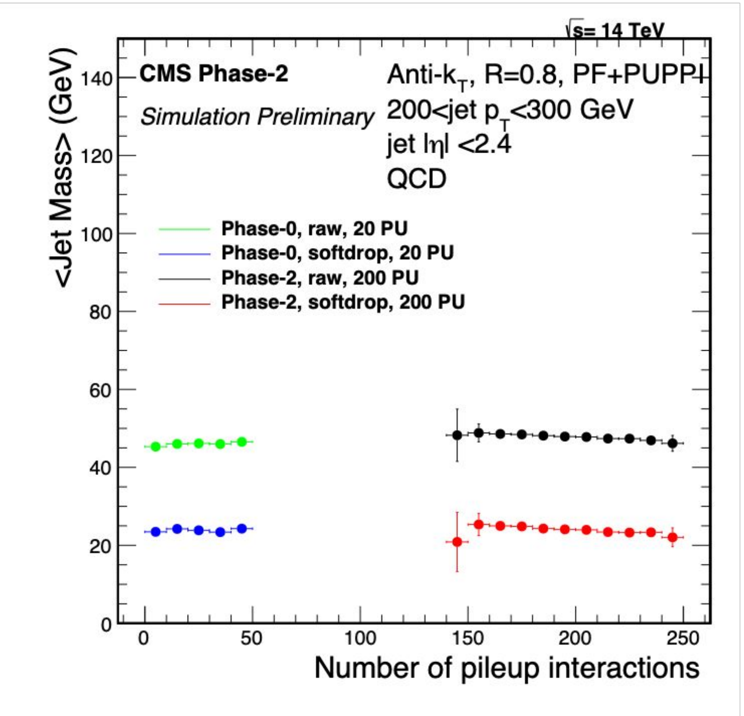
Questions?

Pause for discussion...

Where is jet substructure going in the future?

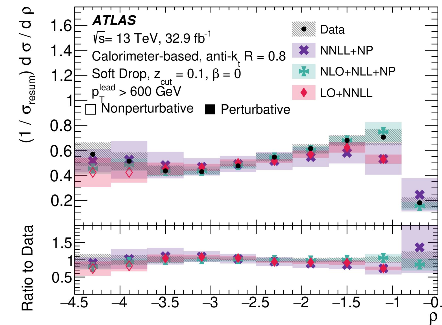
- HL-LHC detectors designed to keep up or improve compared to current performance despite more pileup
  → Exciting future ahead





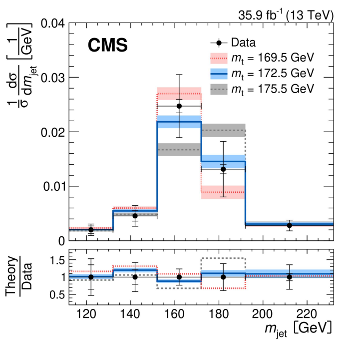
Where is jet substructure going in the future?

- Precision tests of the Standard Model

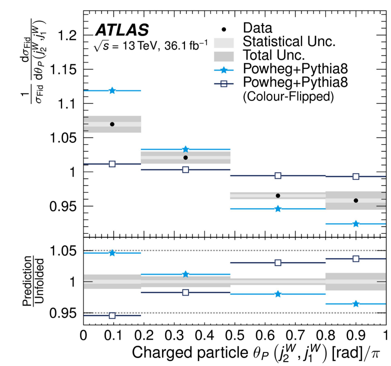


Phys. Rev. D 101 (2020) 052007

Phys. Rev. Lett. 124 (2020) 202001



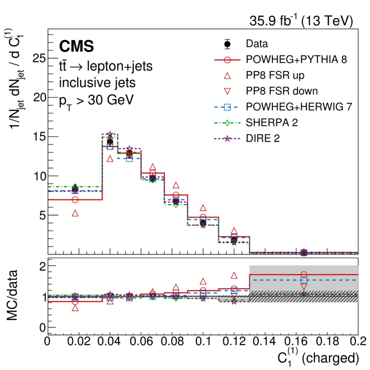
- (Beyond the) Standard model parameters



Eur. Phys. J. C 78 (2018) 847

- Unique probes of emergent quantum properties of QCD

Phys. Rev. D 98 (2018) 092014

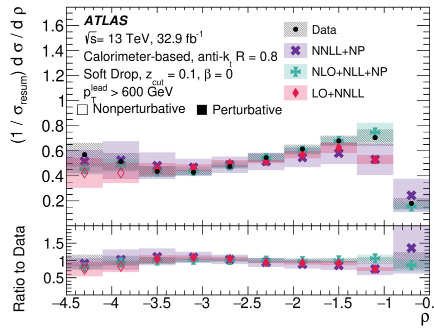


- General purpose Monte Carlo generator development and tuning

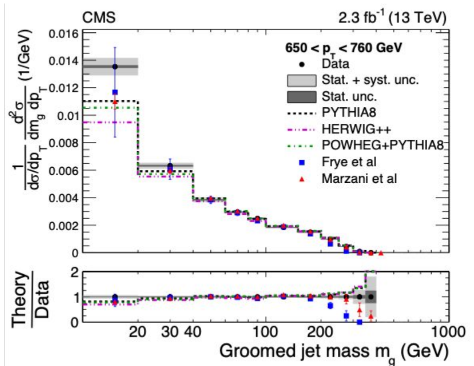
Where is jet substructure going in the future?

- Precision tests of the Standard Model
  cross-experiment comparisons, higher precision theory

  Cross-experiment coordination in LHC-EW-WG:
  - Many observables have measurements from multiple experiments, but none in exactly the same phase-space, e.g. softdrop jet mass, splitting function, etc.: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

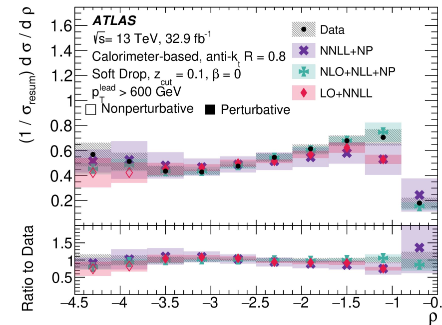


Phys. Rev. D 101 (2020) 052007

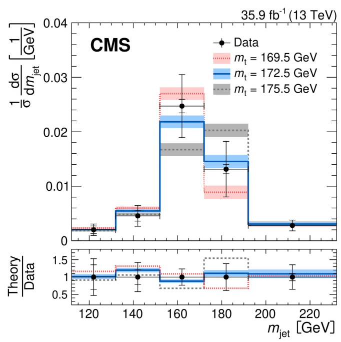


Where is jet substructure going in the future?

- Precision tests of the Standard Model
  cross-experiment comparisons, higher precision theory

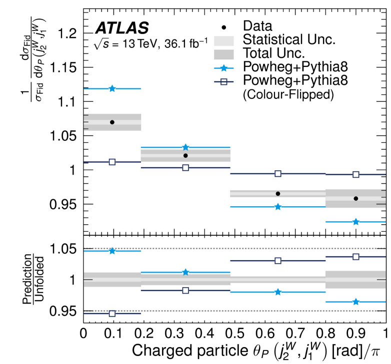


Phys. Rev. D 101 (2020) 052007



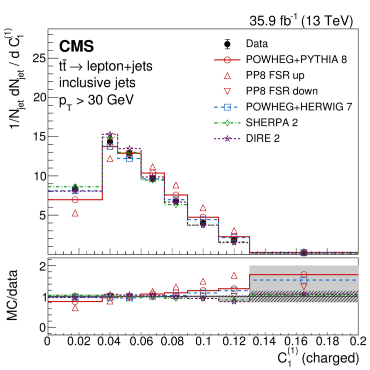
Phys. Rev. Lett. 124 (2020) 202001

- (Beyond the) Standard model parameters
  become competitive with classical measurements?



Eur. Phys. J. C78 (2018) 847

- Unique probes of emergent quantum properties of QCD
  new ideas?



Phys. Rev. D 98 (2018) 092014

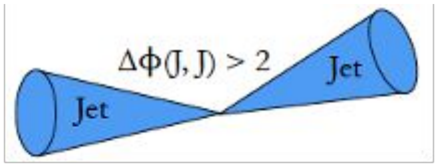
- General purpose Monte Carlo generator development and tuning
  combining all available information, simultaneous description of UE and jet substructure

Questions?

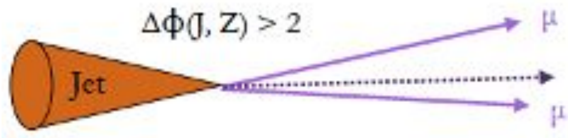
Pause for discussion...

Backup

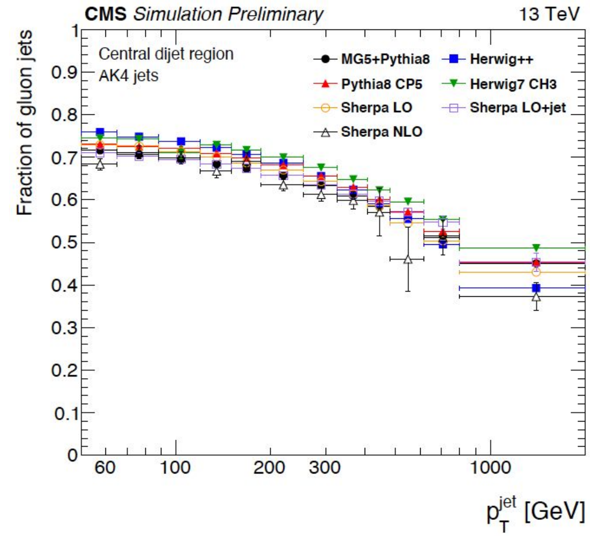
Event samples

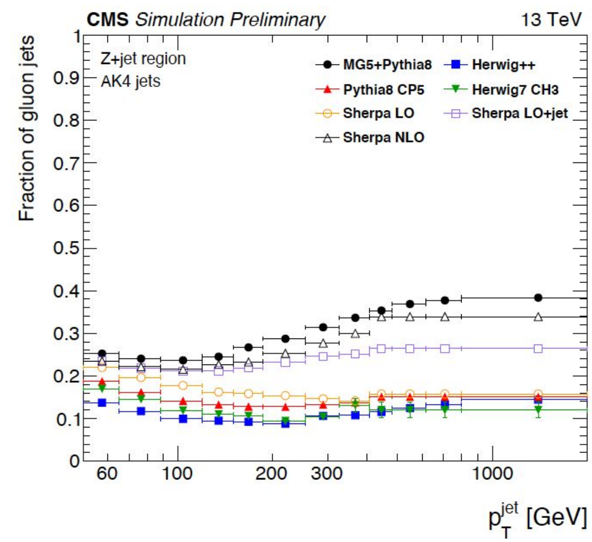


$\geq$2 jets with $|y| < 1.7$ and $p_T^j > 30\,\text{GeV}$
$\Delta\phi(j_1, j_2) > 2$
$|p_T^{j_1} - p_T^{j_2}| / (p_T^{j_1} + p_T^{j_2}) < 0.3$



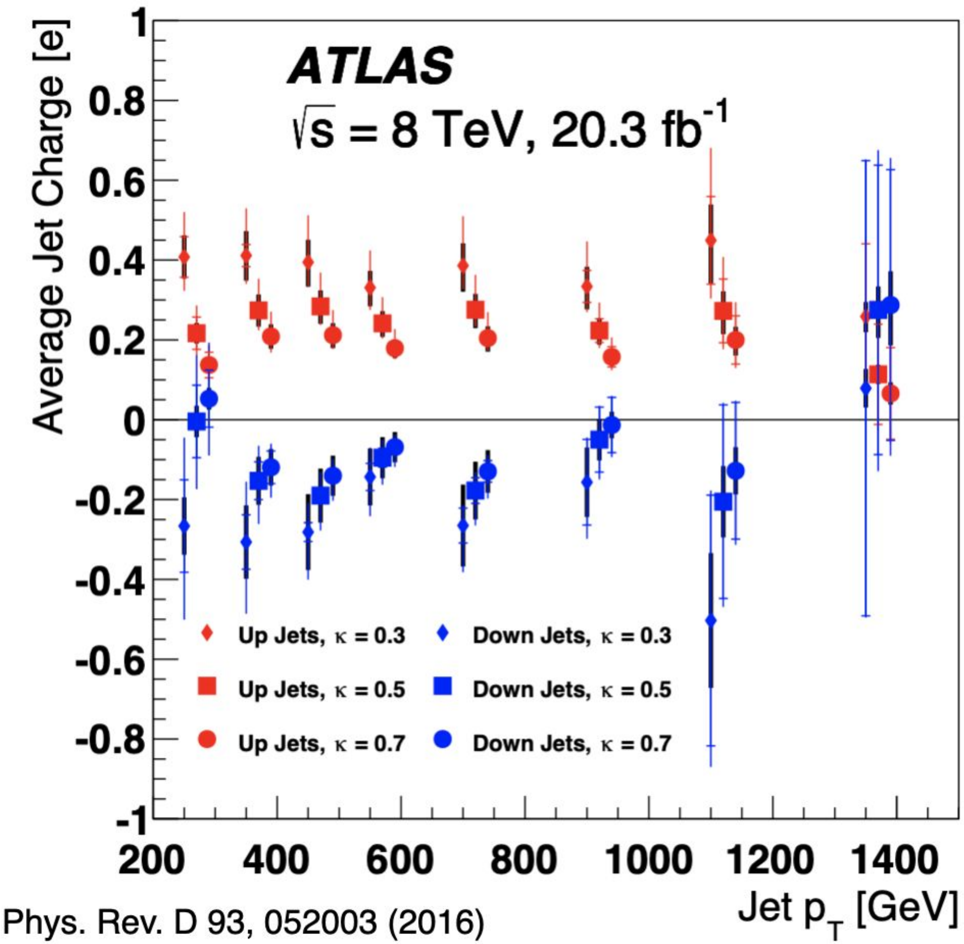
$\geq$2 muons with $|\eta| < 2.4$ and $p_T^\mu > 26\,\text{GeV}$
Opposite charge muons
$|m_{\mu\mu} - m_Z| < 20\,\text{GeV}$
$\geq$1 jet with $|y| < 1.7$ and $p_T^j > 30\,\text{GeV}$,
not overlapping with muons of the Z boson candidate
$\Delta\phi(j_1, Z) > 2$
$|p_T^{j_1} - p_T^Z| / (p_T^{j_1} + p_T^Z) < 0.3$





$$\langle Q_i^{\text{forward}} \rangle = \left(f_{\text{up,i}}^{\text{forward}} - f_{\text{anti-up,i}}^{\text{forward}}\right) Q_i^{\text{up}} + (f_{\text{down,i}}^{\text{forward}} - f_{\text{anti-down,i}}^{\text{forward}}) Q_i^{\text{down}}$$

$$\langle Q_i^{\text{central}} \rangle = \left(f_{\text{up,i}}^{\text{central}} - f_{\text{anti-up,i}}^{\text{central}}\right) Q_i^{\text{up}} + (f_{\text{down,i}}^{\text{central}} - f_{\text{anti-down,i}}^{\text{central}}) Q_i^{\text{down}}$$



Phys. Rev. D 93, 052003 (2016)

Exploit **h**-dependence of u/d/g fractions