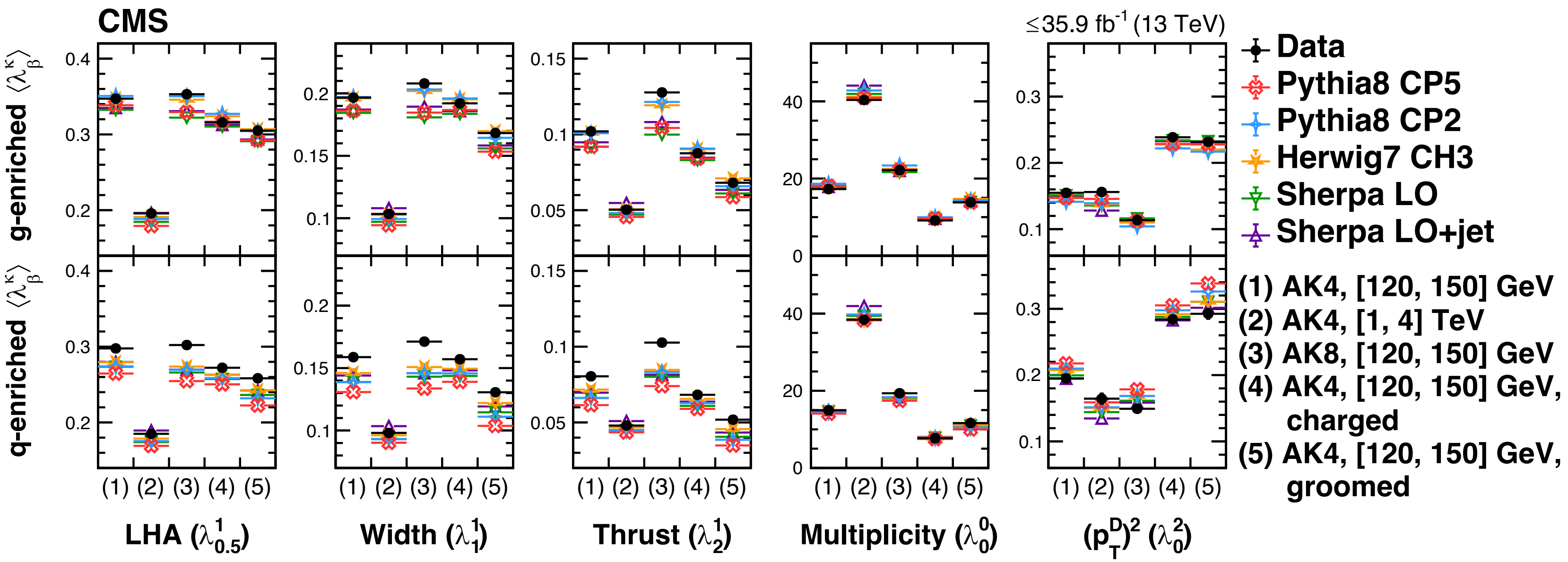
Jet angularities measurement with CMS



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Outline

- Introduction
- Jet substructure reconstruction in CMS
- Angularities and quark/gluon separation
- Predictions
- Measurement of jet angularities in Z+jets and dijets
- Measurement of jet angularities in ttbar
- Summary

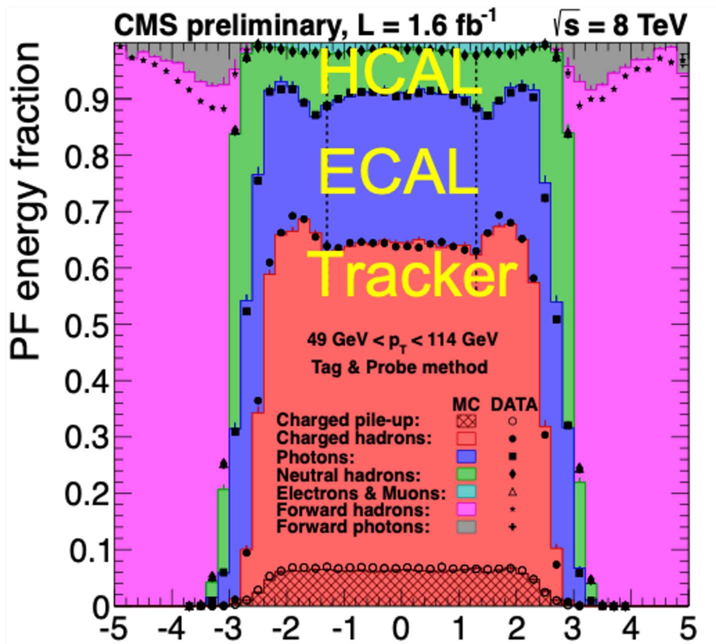
Introduction

- Goals of jet substructure measurements
  - Understanding of perturbative QCD
  - Measurement of SM parameters (α_S, m_t)
  - Improvement of non-perturbative models in MC event generators
    - Important for many searches and measurements relying on jet substructure tagging to distinguish boosted W/Z/H/top jets from q/g jet background
  - Understanding of QGP (PbPb vs. pp)

- Measurements of jet angularities:
  - 2109.03340 13 TeV pp → dijet and Z+jet
  - 1808.07340 13 TeV pp → ttbar

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)

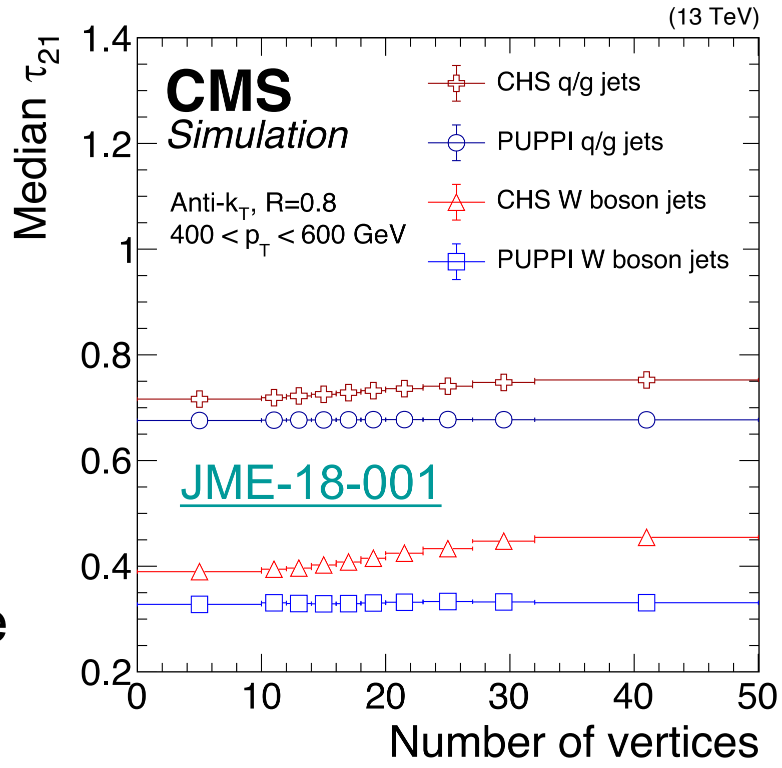


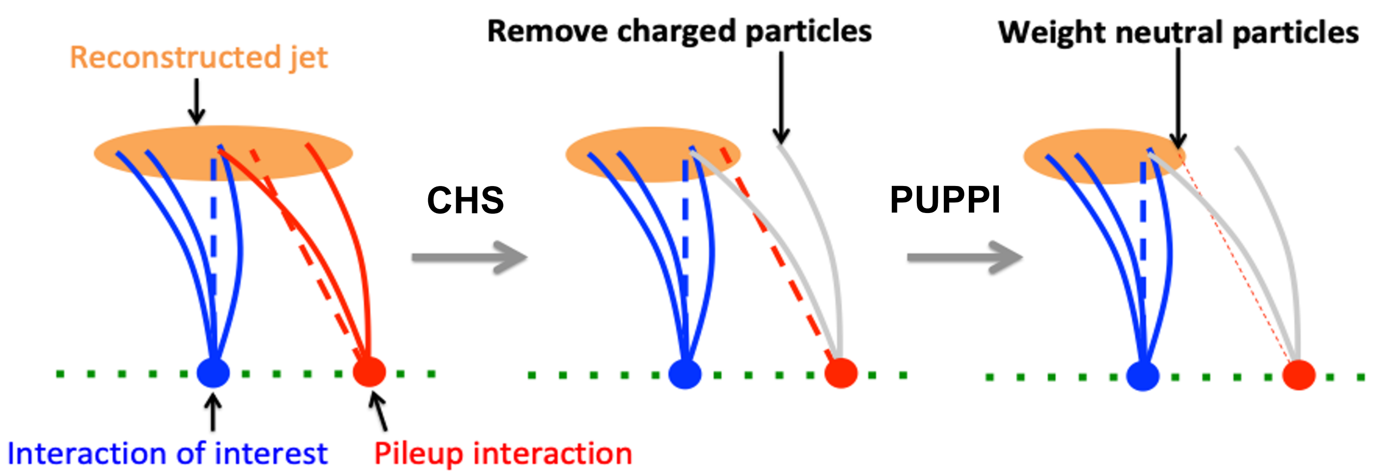
CMS-DP-2012/012

*in pT>30, |eta|<2

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 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)





Quark and gluon separation

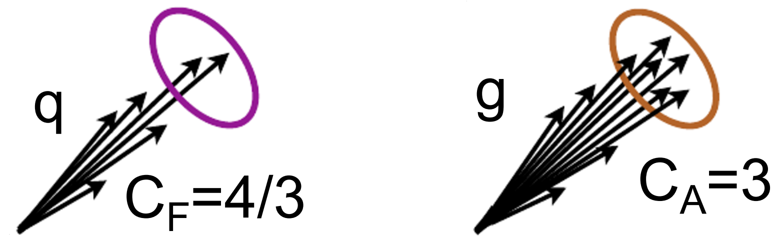
- Gluon jets differ from quark jets
  - More particles
  - Wider
- CMS reference tagger combines

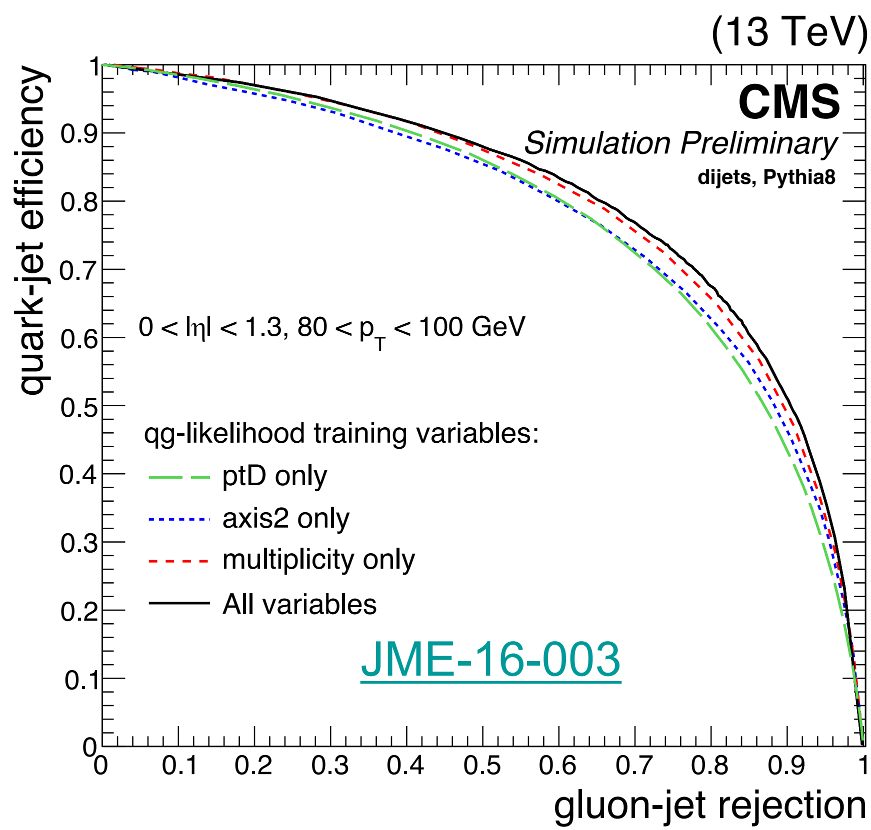
jet constituents multiplicity

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

jet minor angular opening (σ_2)

- Mild separation, not a yes/no
  - Used as ingredient to multivariate event selection
- Not well described by simulation
  - Reweighted to match data
  - Yet more difficult with ML taggers
- Example physics use case
  - VBF Higgs→bb



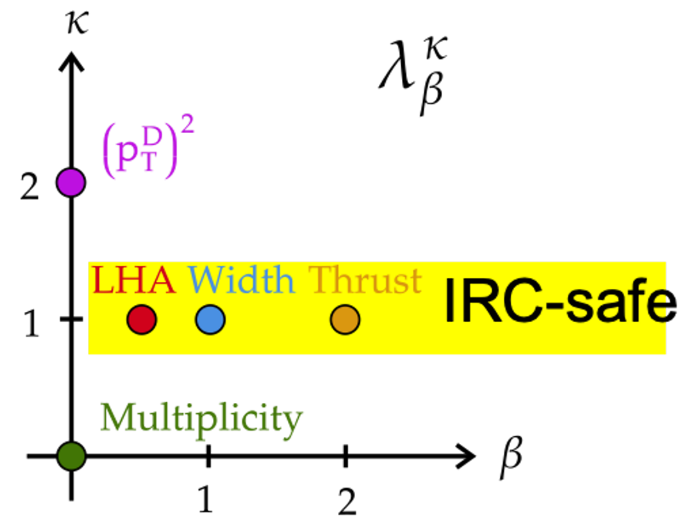


Angularities in Z+jet and dijet

- Generalized angularities

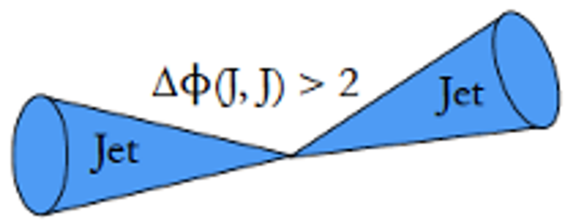
$$\lambda_\beta^\kappa = \sum_{\mathrm{i}\in\mathrm{jet}} z_\mathrm{i}^\kappa \left(\frac{\Delta R_\mathrm{i}}{R}\right)^\beta \qquad z_i \equiv \frac{p_{Ti}}{\sum_{j\in\mathrm{jet}} p_{Tj}}$$

- Winner-Take-All axis (except for thrust)
- Constituent p_T>1 GeV for multiplicity

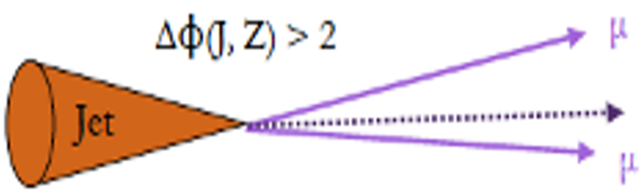


Dimension	Variants
Region	Z+jet vs. central dijet vs. forward dijet
Observable λ_β^κ	LHA, width, thrust, multiplicity, $(p_T^D)^2$
Jet p_T	$50 < p_T < 65$ GeV, ..., $p_T > 1000$ GeV
Jet size parameter R	0.4 vs. 0.8
Constituents	Charged+neutral vs. charged-only
Grooming	Ungroomed vs. groomed

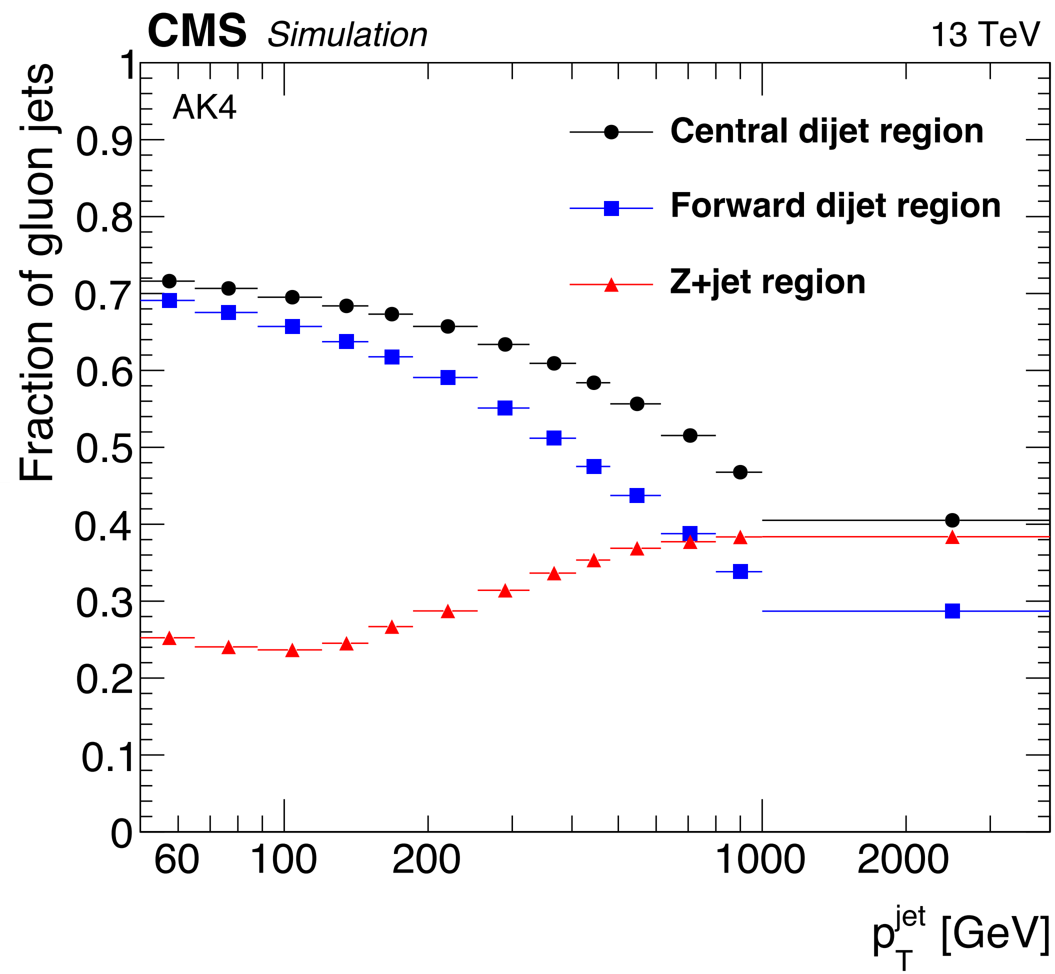
Z+jet and dijet event samples



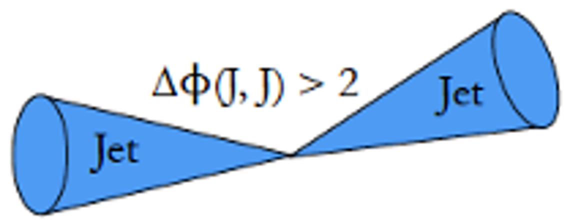
$\geq$2 jets with $|y| < 1.7$ and $p_{\mathrm{T}}^{j} > 30\,\mathrm{GeV}$
$\Delta\phi(j_1, j_2) > 2$
$|p_{\mathrm{T}}^{j_1} - p_{\mathrm{T}}^{j_2}| / (p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}) < 0.3$



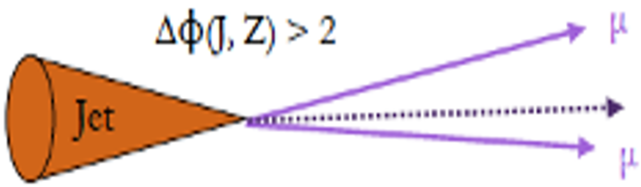
$\geq$2 muons with $|\eta| < 2.4$ and $p_{\mathrm{T}}^{\mu} > 26\,\mathrm{GeV}$
Opposite charge muons
$|m_{\mu\mu} - m_{\mathrm{Z}}| < 20\,\mathrm{GeV}$
$\geq$1 jet with $|y| < 1.7$ and $p_{\mathrm{T}}^{j} > 30\,\mathrm{GeV}$,
not overlapping with muons of the Z boson candidate
$\Delta\phi(j_1, \mathrm{Z})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



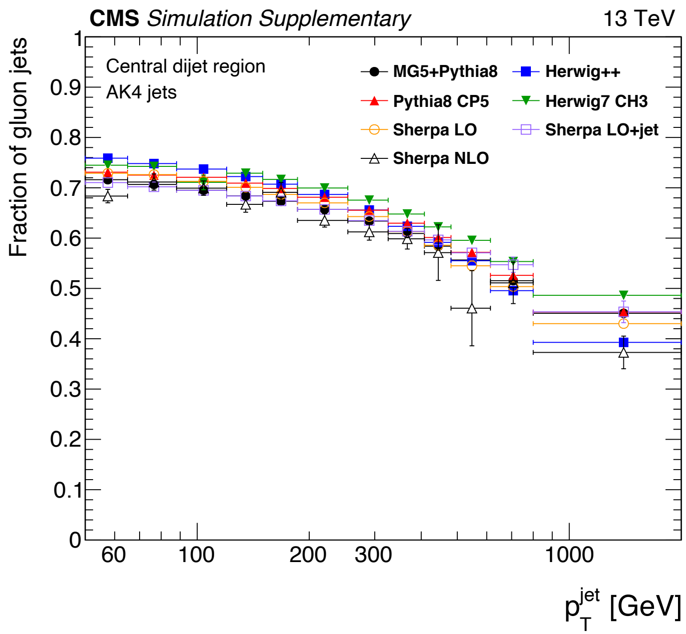
Prediction of quark and gluon jet fraction

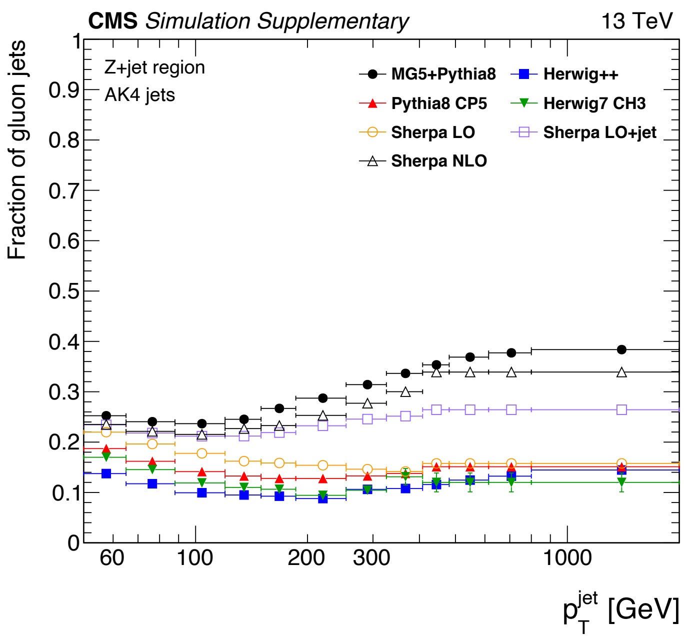


$\geq$2 jets with $|y| < 1.7$ and $p_T^j > 30\,\text{GeV}$
$\Delta\phi(j_1, j_2) > 2$
$|p_T^{j_1} - p_T^{j_2}|/(p_T^{j_1} + p_T^{j_2}) < 0.3$

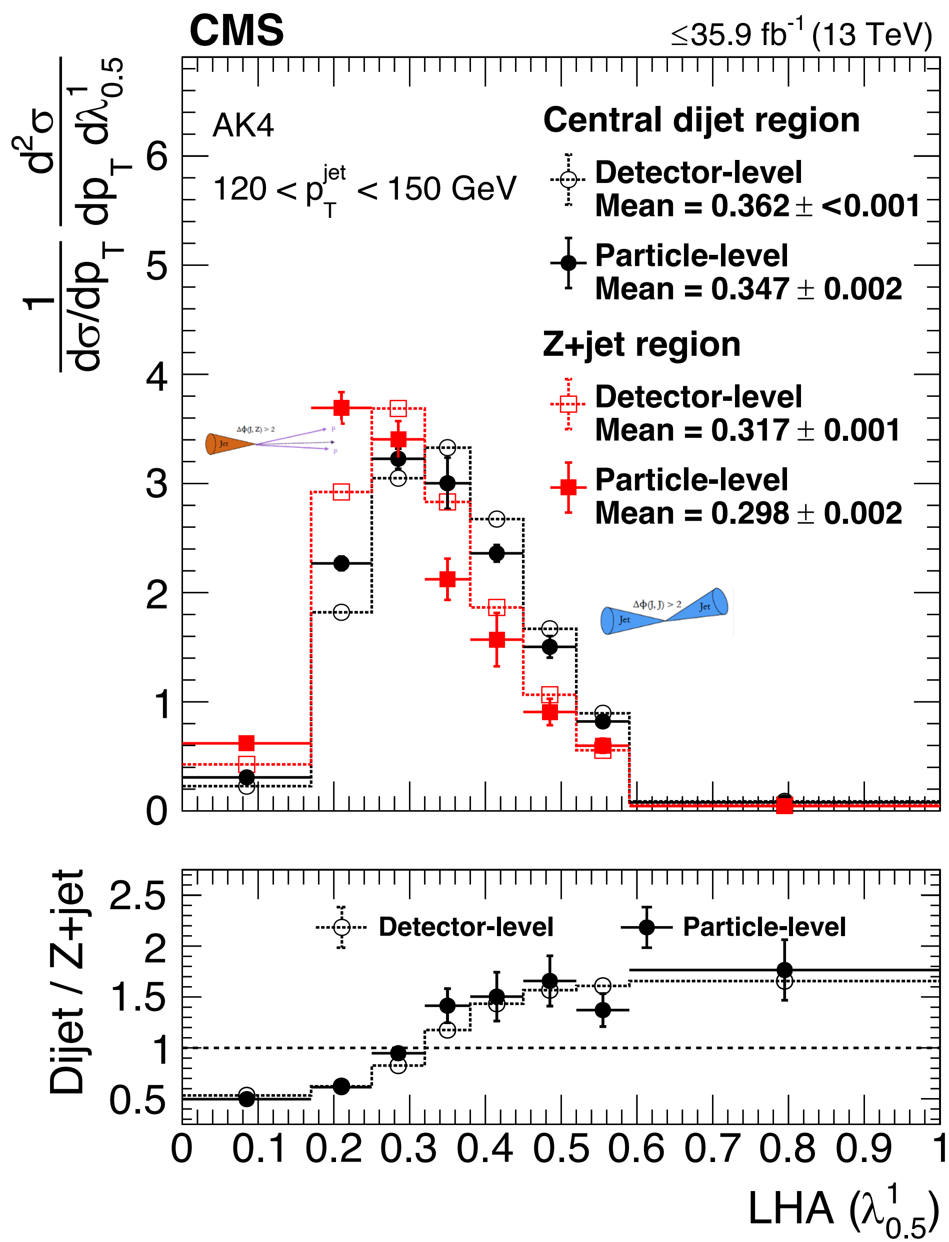


$\geq$2 muons with $|\eta| < 2.4$ and $p_T^\mu > 26\,\text{GeV}$
Opposite charge muons
$|m_{\mu\mu} - m_Z| < 20\,\text{GeV}$
$\geq$1 jet with $|y| < 1.7$ and $p_T^j > 30\,\text{GeV}$,
not overlapping with muons of the Z boson candidate
$\Delta\phi(j_1, Z) > 2$
$|p_T^{j_1} - p_T^Z|/(p_T^{j_1} + p_T^Z)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

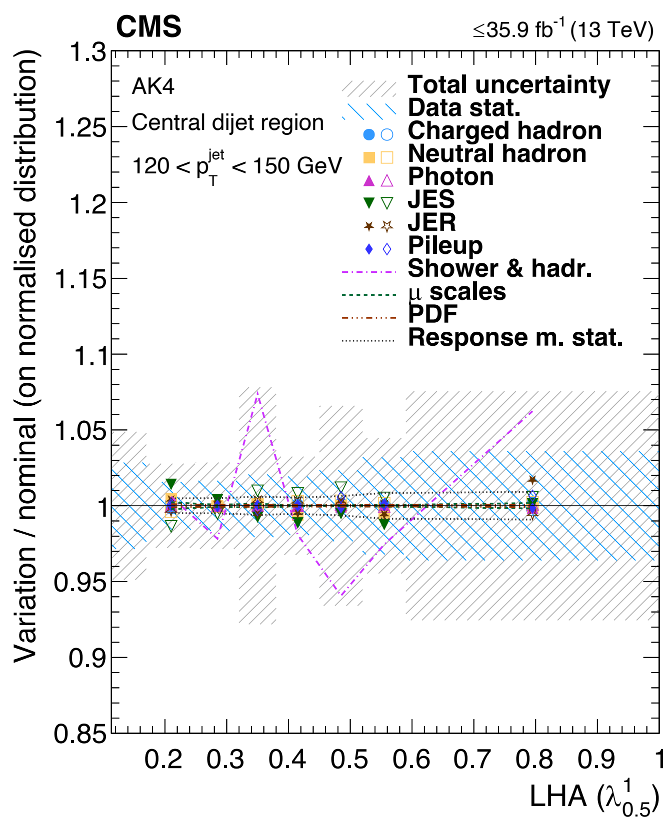




Unfolding and uncertainties

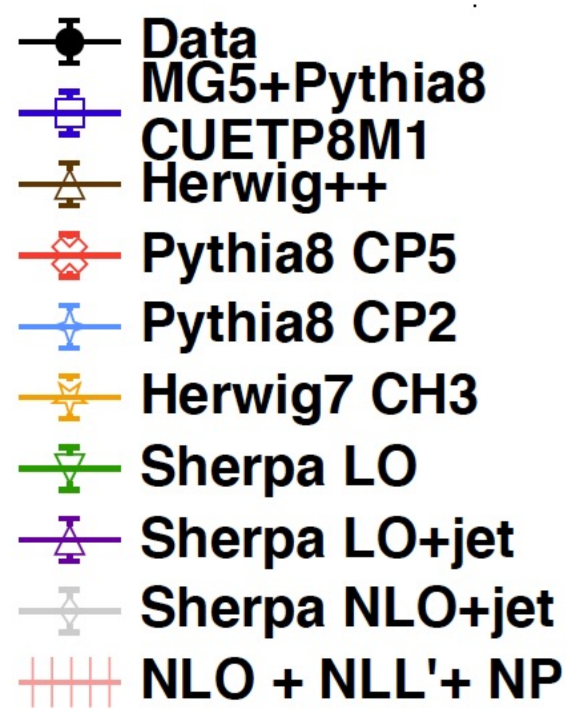


- Z+jet / dijet ratio insensitive to detector effects
- Unfold λ and p_T
- Dominant uncertainty from shower/hadronization model



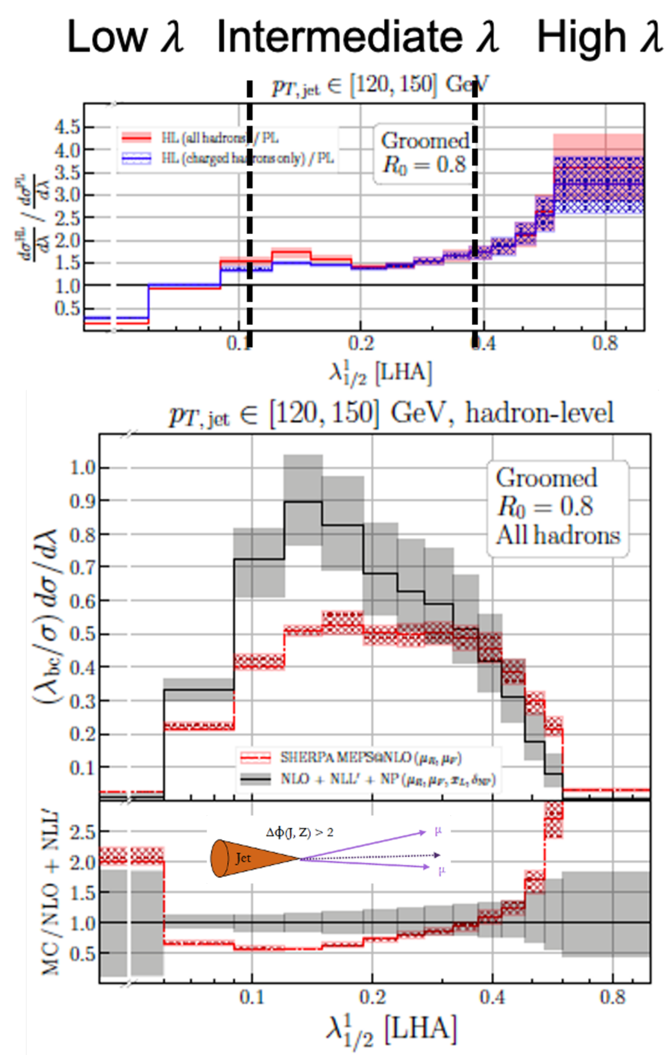
Predictions

- CMS early Run2 MC
  - Madgraph+Pythia8 multijet merging CUETP8M1
  - Herwig++ LO
  - Drawn without systematic uncertainties
- More recent (using legacy Run2 CMS UE tunes)
  - Pythia8 LO CP2, CP5 tunes with $\alpha_S(m_Z)$=0.130, 0.118
  - Herwig7 LO CH3 tune
  - Sherpa LO and multijet merging ("+jet")
  - Drawn without systematic uncertainties
- [2104.06920] Angularities in Z+jets
  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
  - Uncertainties: 6 μ_R,μ_F scale variations, resummation scale x_L, non-perturbative effects (PYTHIA, HERWIG and SHERPA)
  - Compared to: Sherpa MEPS@NLO multijet merging, combining the NLO QCD matrix elements for μμj and μμjj production, matched with dipole shower (backup)



Predictions – trends in Z+jets

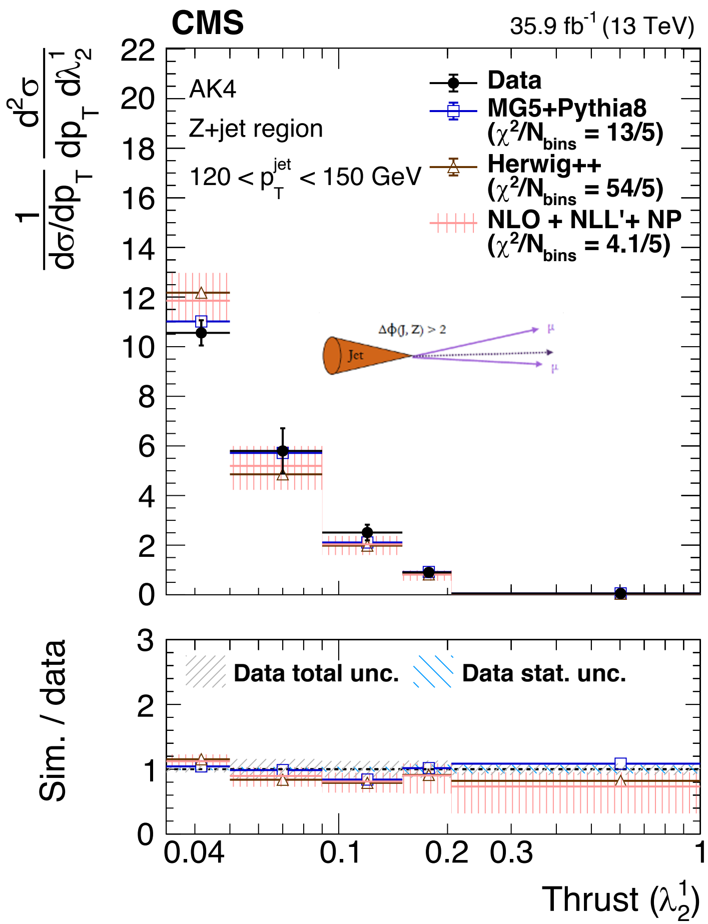
- Regions:
  - Low λ (Infrared): non-perturbative dominate
  - Intermediate λ: (resummed) perturbation theory good
  - Large λ (kinematic endp.): non-perturbative matter (UE)
- Transition point between low λ and intermediate λ: ~$1/(R\, p_T)$ (except groomed thrust)
- Where NLO+NLL'+NP and MEPS@NLO agree, 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

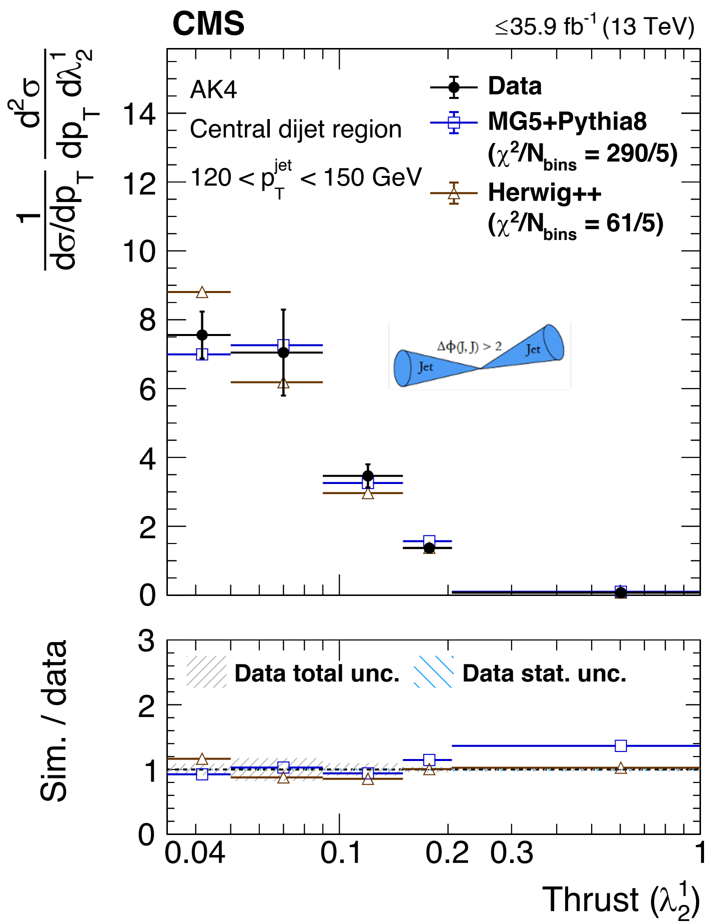


[2104.06920]

Thrust distribution

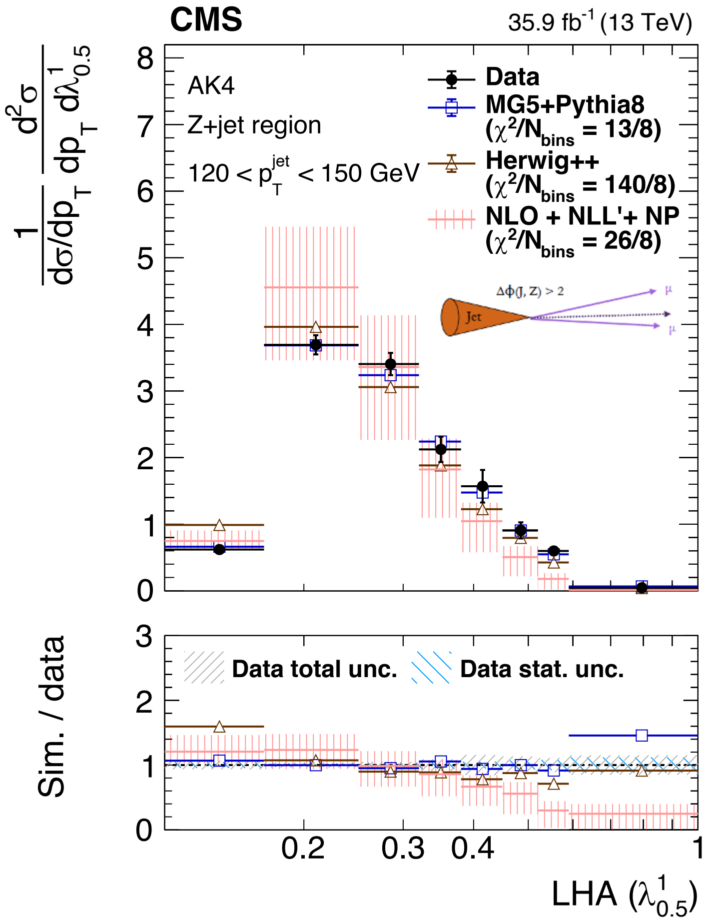
- Quark-enriched sample reasonably well described by Madgraph+Pythia8-CUETP8M1
- Gluon-enriched not well described, data “between Pythia and Herwig”
- NLO+NLL’+NP gives reasonable description of trust

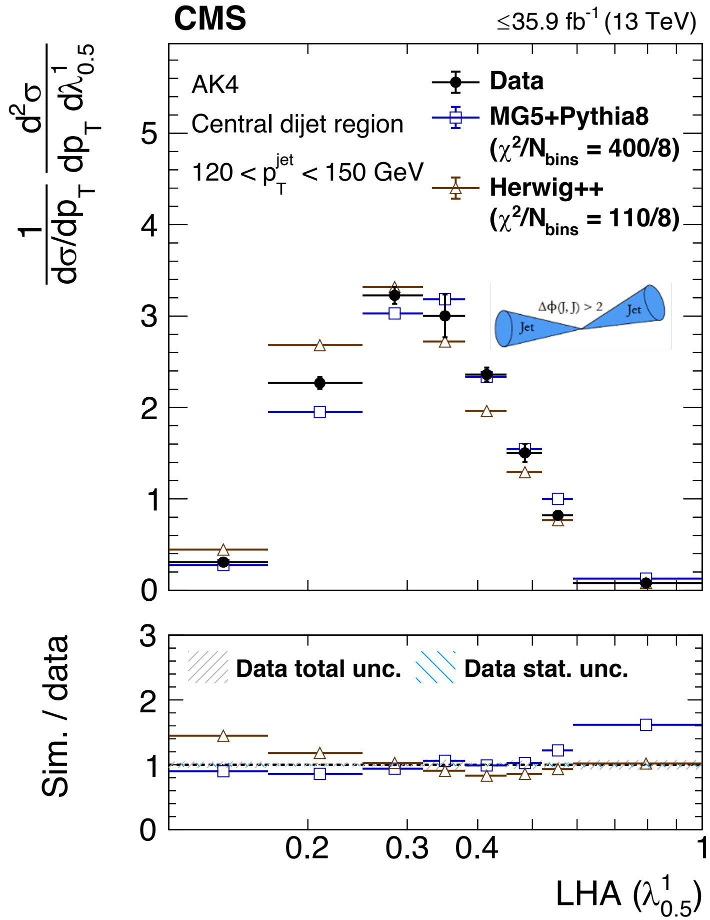




LHA distribution

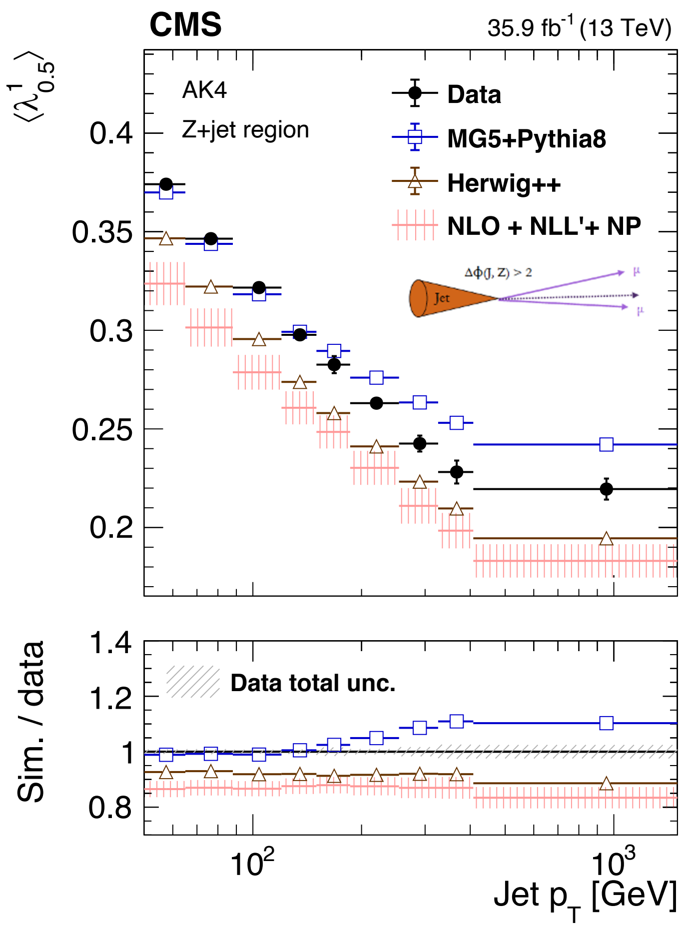
- Quark-enriched sample reasonably well described by Madgraph+Pythia8-CUETP8M1
- Gluon-enriched not well described, data “between Pythia and Herwig”
- NLO+NLL’+NP does not describe LHA well, MEPS favoured by data

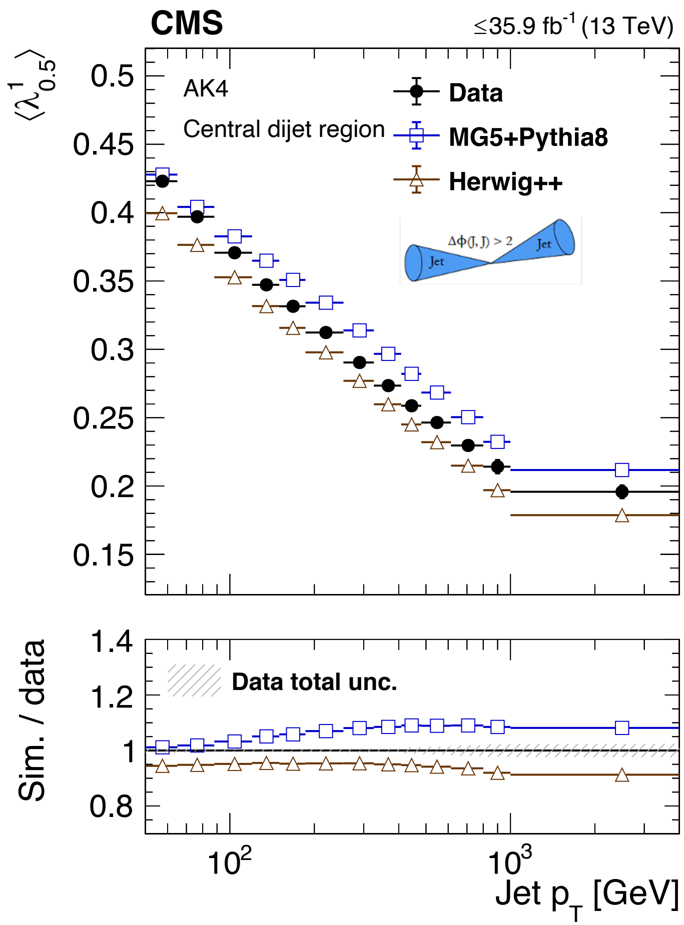




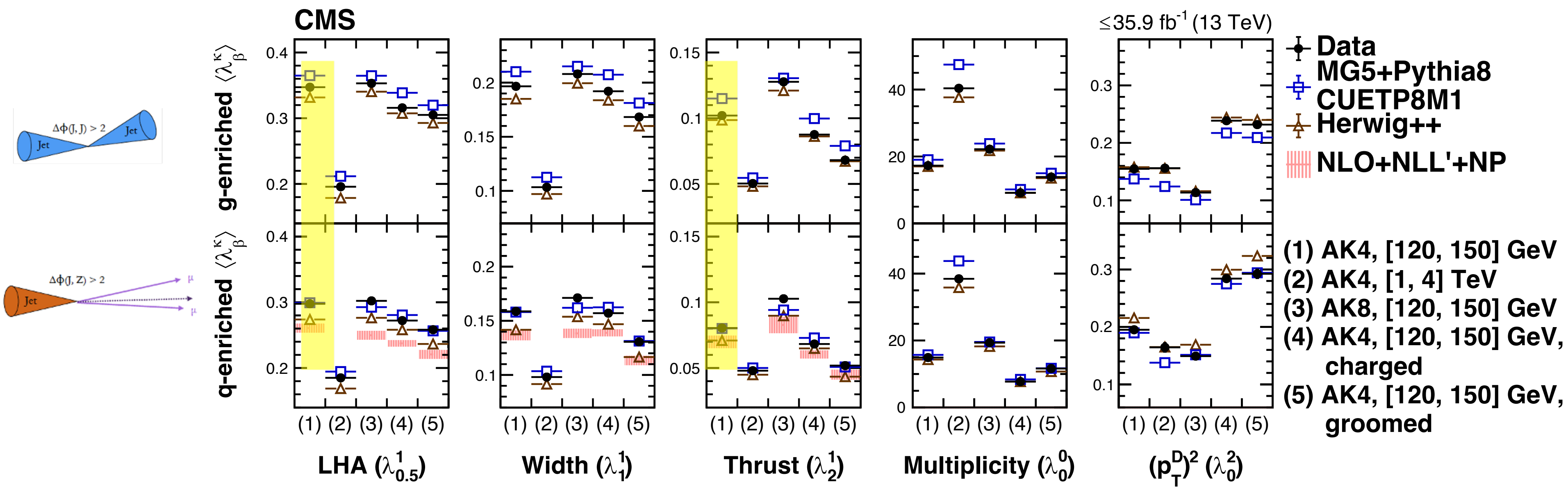
LHA mean vs. transverse momentum

- Trend vs. p_T differs across predictions
- Madgraph+Pythia8 description worsen at high p_T



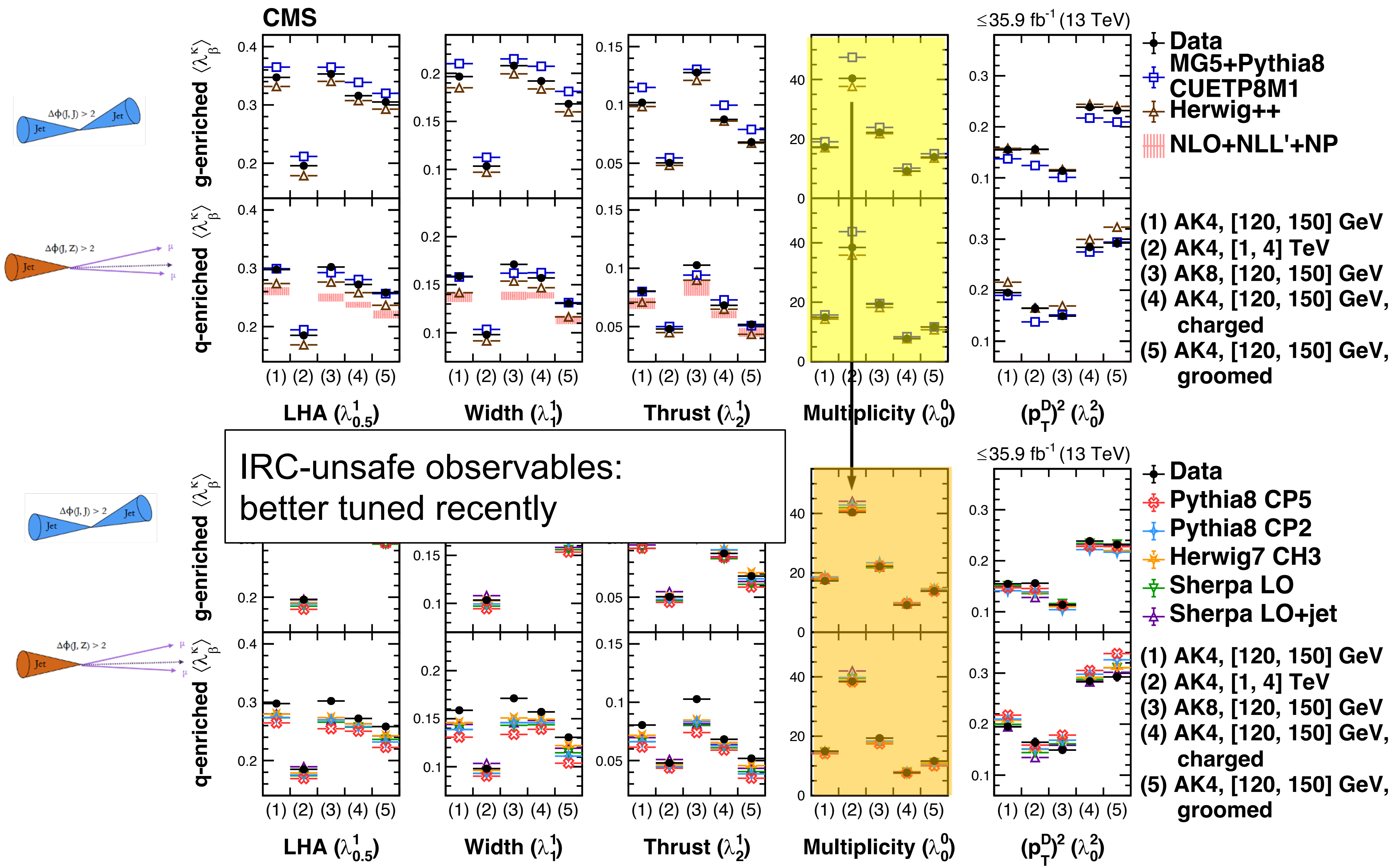


Summary of observables



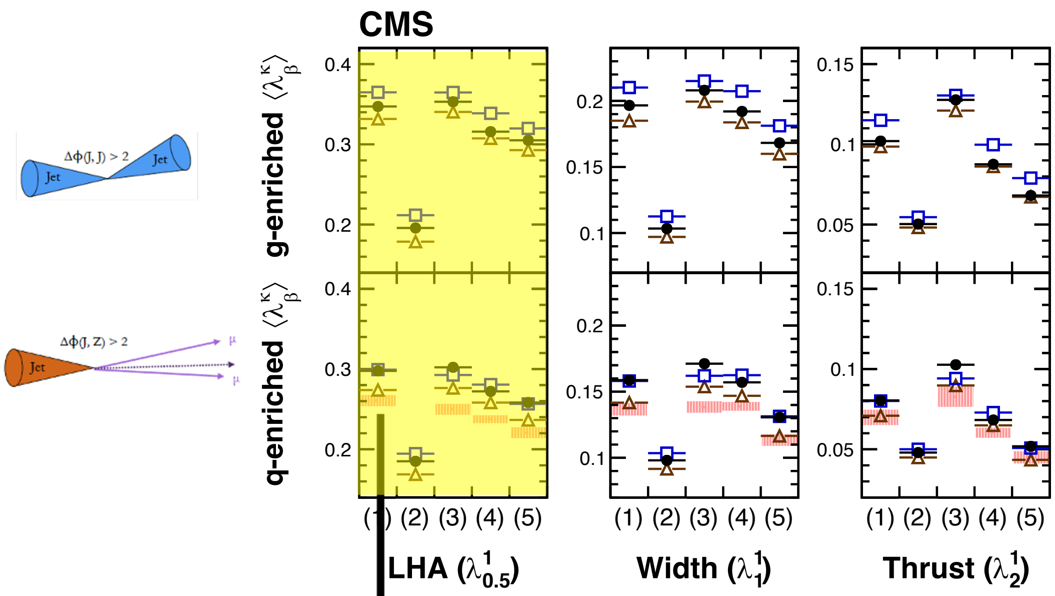
- Data “between Pythia and Herwig” holds for mean of all observables

Summary of results - recent generator tunes



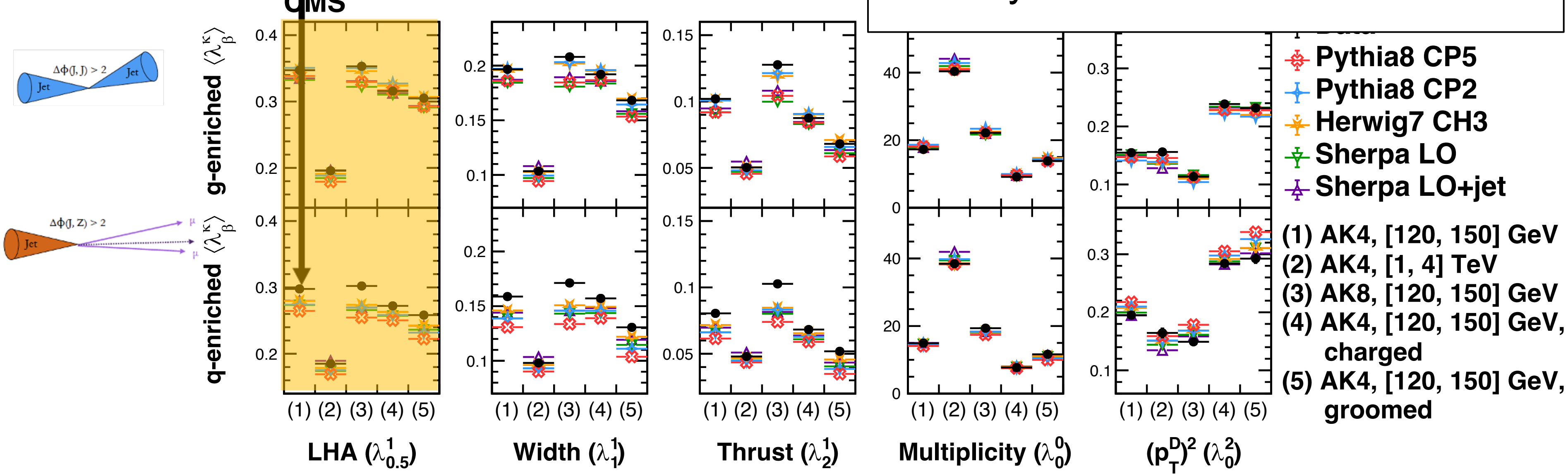
IRC-unsafe observables:
better tuned recently

Summary of results - recent generator tunes



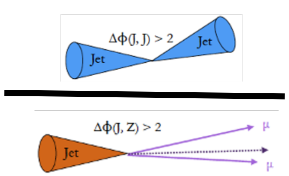
IRC-safe observables:

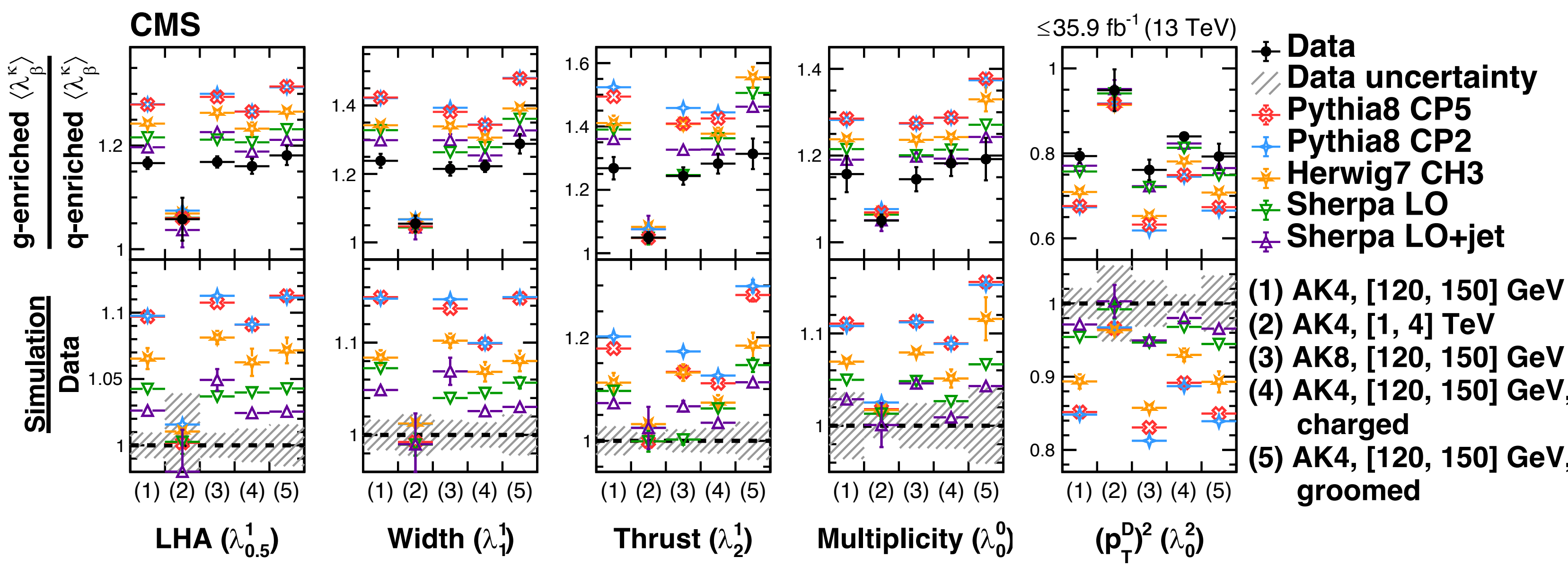
- Pythia8-CP2 best in gluon-enriched sample, but worse agreement in quark-enriched sample
- Depend on $\alpha_S(m_Z)$ in FSR CP2=0.130, CP5=0.118
- “Quarks well known from LEP, gluons less well known” not valid anymore



Dijet / Z+jet (gluon/quark) ratio

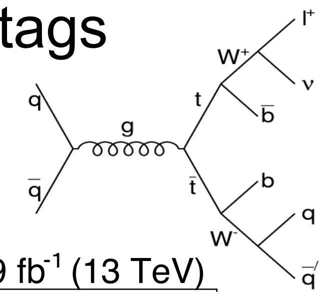
- Sensitive to
  - Prediction of gluon fraction (see earlier slide)
  - Prediction of shape differences between quarks and gluons
- All generators in LO+PS mode overestimate the ratio of gluon-enriched and quark-enriched
  - Insensitive to choice of $\alpha_S(m_Z)$ in FSR
- Sherpa (MEPS@LO) best across considered generators

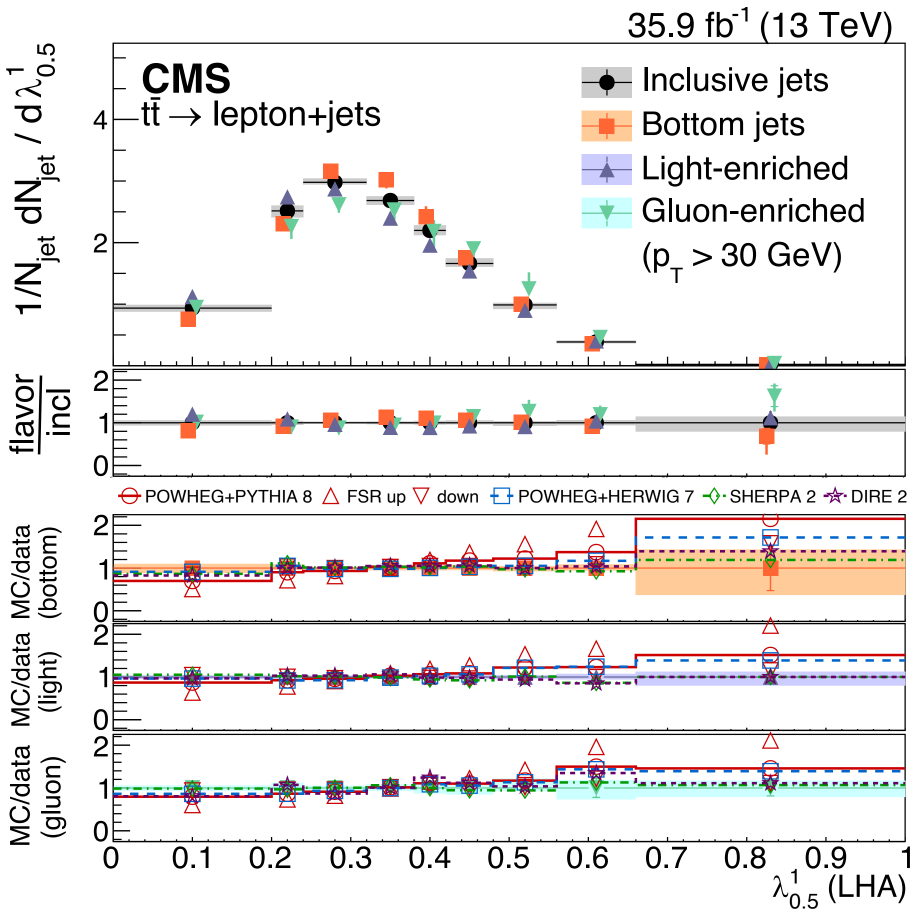


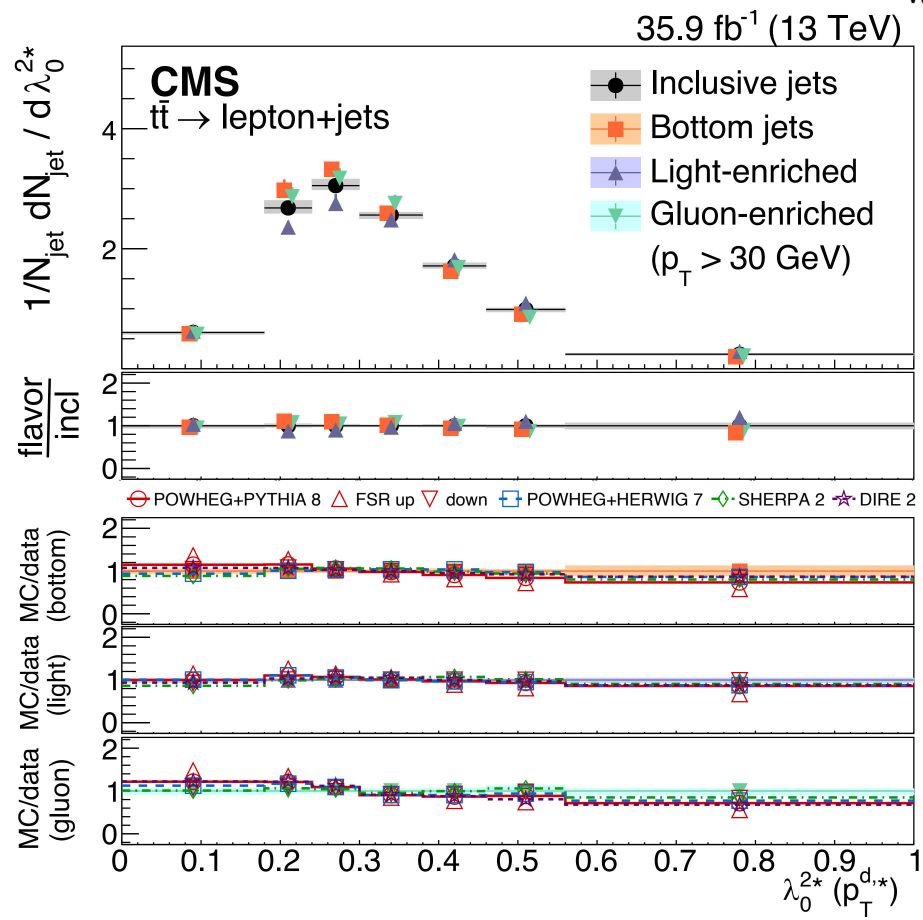


Jet angularities in ttbar

- Study semileptonic ttbar events with at least 4 jets with 2 b-tags
  - Enriched in 80% quarks
  - Also dedicated study in samples with 99% b-quarks







- Lower FSR favored. Best fit $\alpha_S(m_Z)= 0.115^{+0.015}_{-0.013}$

Summary

- Angularities useful for quark and gluon separation
  - Improved understanding and simulation necessary for large variety of searches and measurements relying on jet substructure

- Measurements carried out by CMS in dijet, Z+jet and ttbar samples, covering a large range of phase-space

- Sensitive to the choice of FSR $\alpha_S(m_Z)$ im MC event simulation
  - MC event generator tuning may benefit from these measurements

- Measurement in agreement with Z+jet NLO+NLL'+NP predictions for thrust and width

- Measurement favors MEPS predictions over NLO+NLL'+NP for LHA

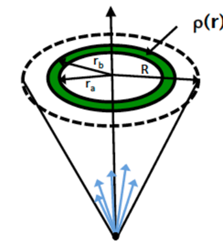
- All considered simulations overpredict the dijet to Z+jet ratio of the angularities mean

Backup

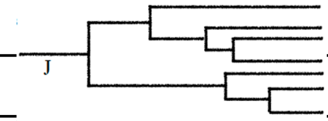
CMS measurements

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
2109.03340 13 TeV pp	dijets Z+jets	q/g-jets (AK4), 50<p_T<4000 q-jets (AK4), 50<p_T<1000	jet angularities

“shapes”

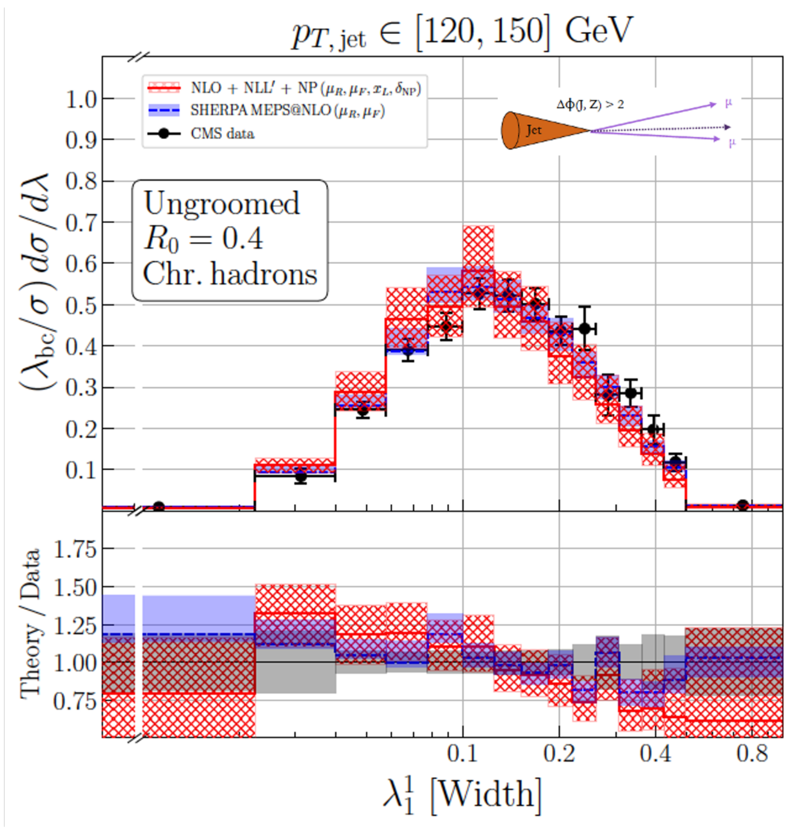


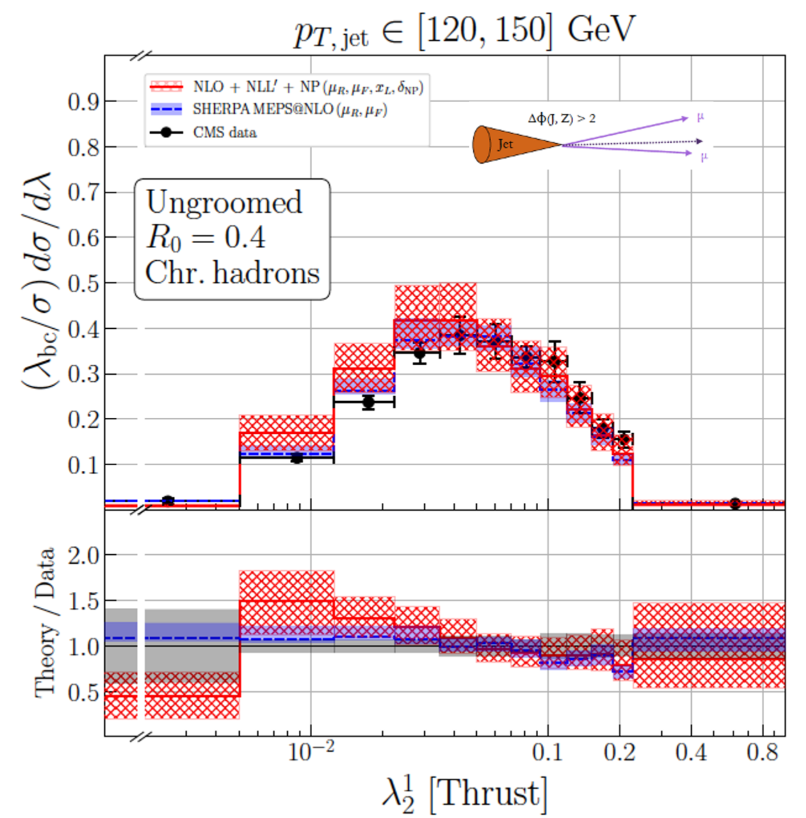
“substructure”



Width and thrust - data vs. predictions

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

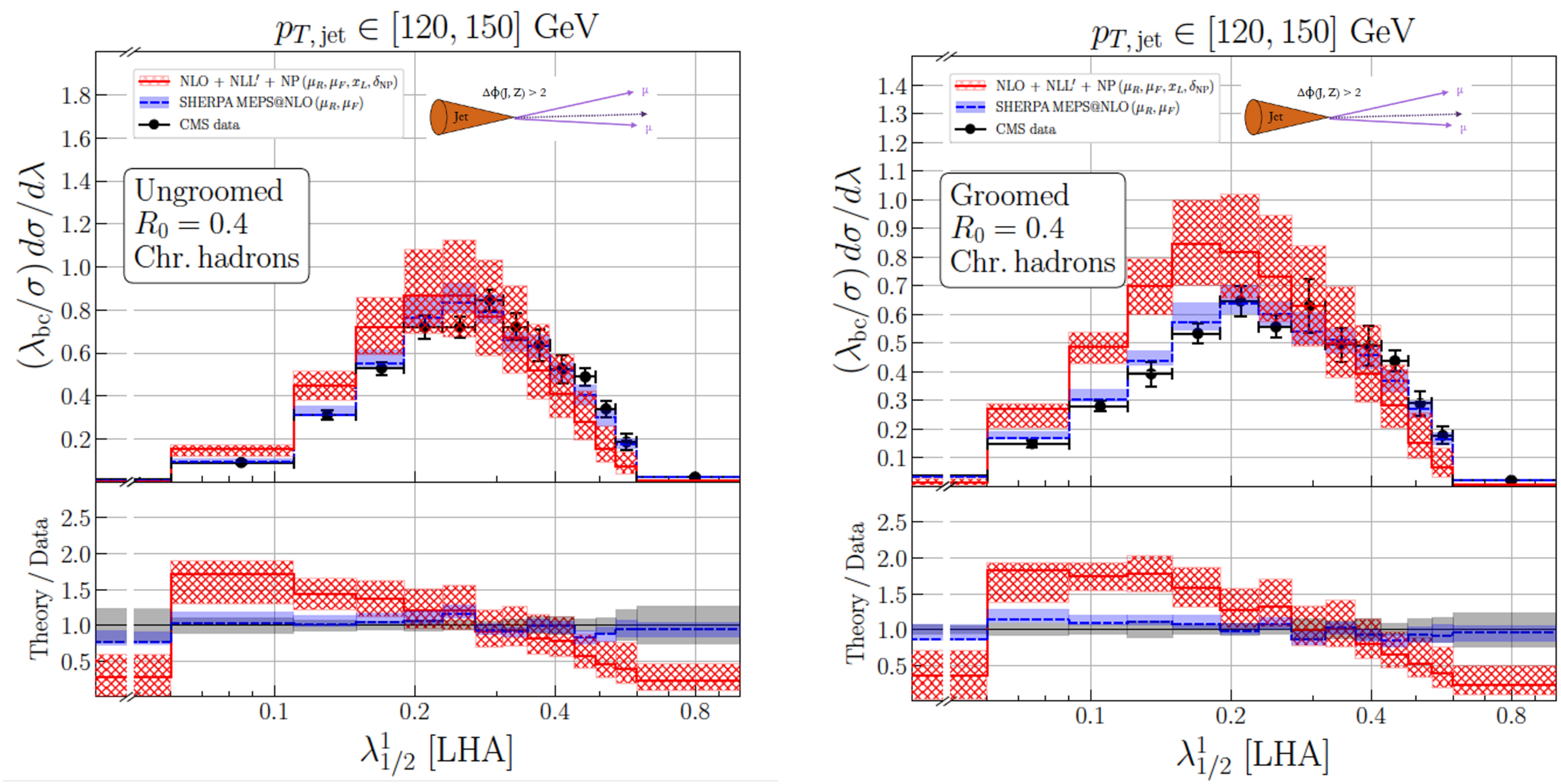




From the authors of 2104.06920

LHA - data vs. predictions

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



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