Jet substructure and boosted jet measurements at CMS

Deniz SUNAR CERCI
Adiyaman – Istanbul University
On behalf of the CMS Collaboration
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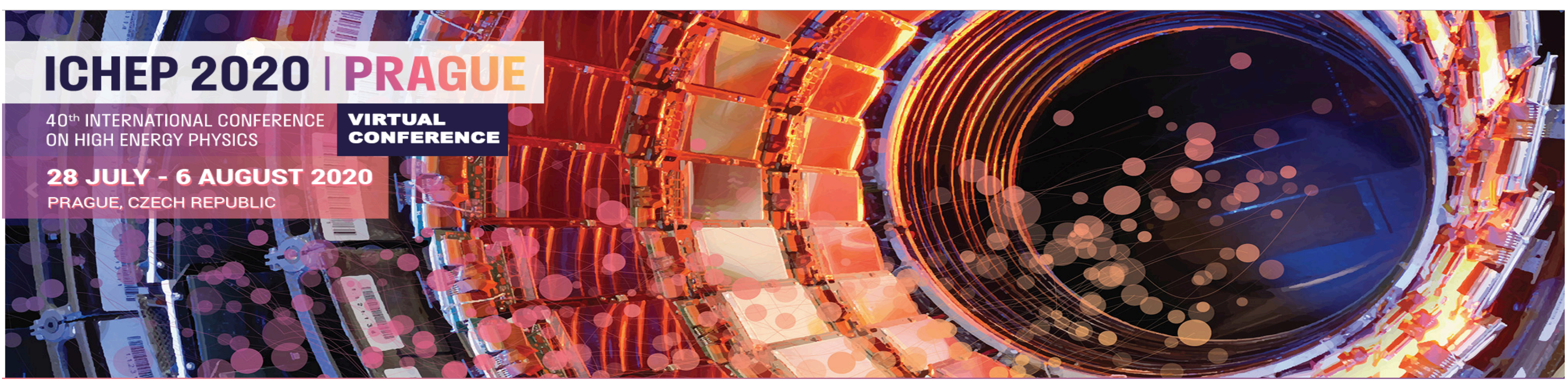
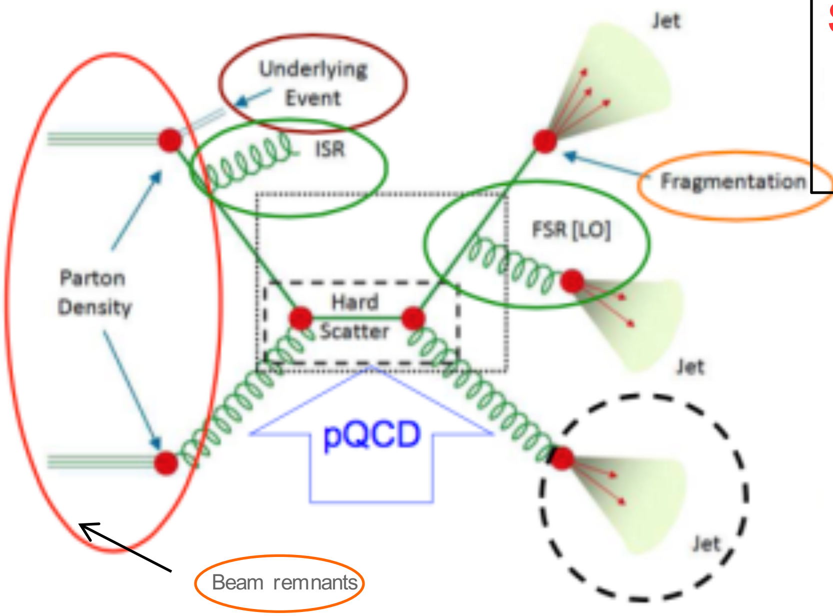


QCD at the LHC

- The main goal of QCD studies is to improve our detailed description of the SM physics.
- QCD is the theory of strong interaction describing the interactions between quarks & gluons
- Jets, experimental signature of quarks & gluons, are abundantly produced at the LHC!

Hard QCD
- Perturbation theory pQCD
- PDFs, ISR, FSR
- Parton shower & hadronization



Soft QCD
- MPI, UE activity
- Fragmentation

- Solid and insightful description of jets and their substructure relies on a deep understanding of the dynamics of strong interactions in collider experiments.

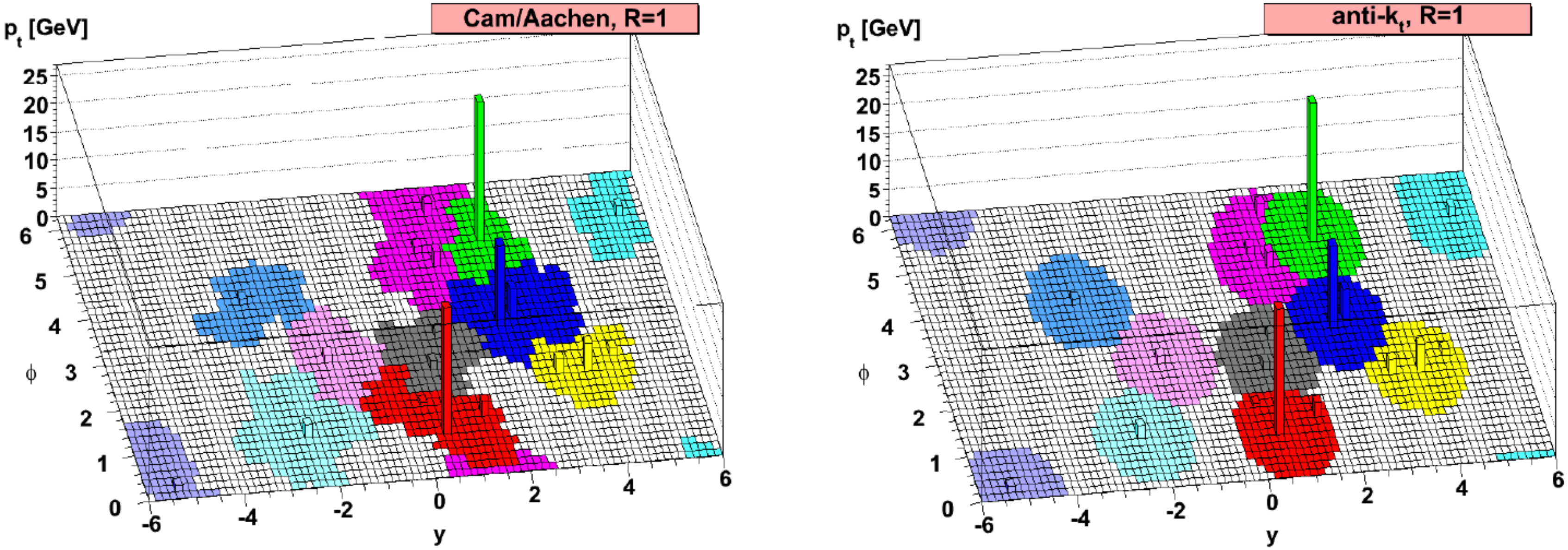
- Better knowledge of jet substructure will help to improve:
  - Precision measurements involving jets (Higgs, top)
  - BSM searches with boosted objects
  - Flavour tagging, pileup ID

Jets and jet algorithms

- Jets are the product of successive parton branchings.
- Sequantial jet clustering algorithms defined with inter-particle distance & beam distance:

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})\Delta R_{ij}^2 \qquad d_{iB} = p_{t,i}^{2p} R^2$$

arXiv: 1901.10342v3



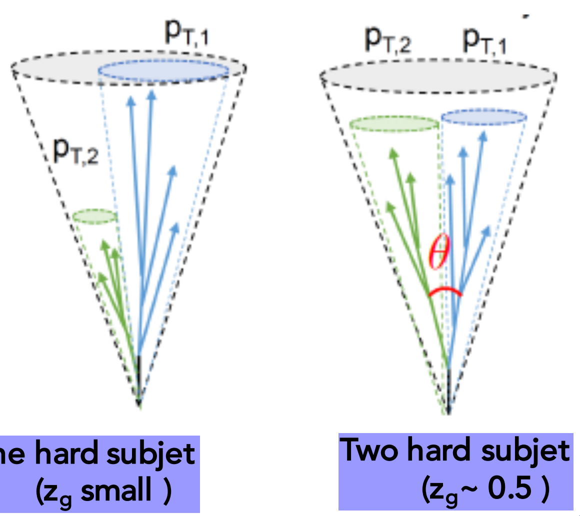
- Behavior controlled with free parameter p:
  - p = 1 k_t algorithm
  - p = 0 Cambridge/Aachen algorithm
  - p = -1 anti-k_t algorithm
- Typical choice for jets by CMS:
  - R = 0.4 (small cone)
  - R = 0.8 (large cone)

Grooming and jet substructure observables

- Grooming: jet is cleaned up i.e., remove soft and wide-angle radiation → reduce PU/UE contamination
  - Focus on more harder jet core
  - Makes comparison easier with theoretical calculations – removes large logarithms
- Modified mass drop tagger :
  - Condition: min ($p_{T,l}$, $p_{T,j}$) > z_{cut} ($p_{T,l}$ + $p_{T,j}$)

- Shared momentum fraction z_g

$$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$



Jet substructure observables

- Hard splitting opening angle

$$R_g = \Delta R\,(j_1, j_2)$$

- Groomed jet radius θ_g

$$\theta_g = \frac{\Delta R\,(j_1, j_2)}{R_0}$$

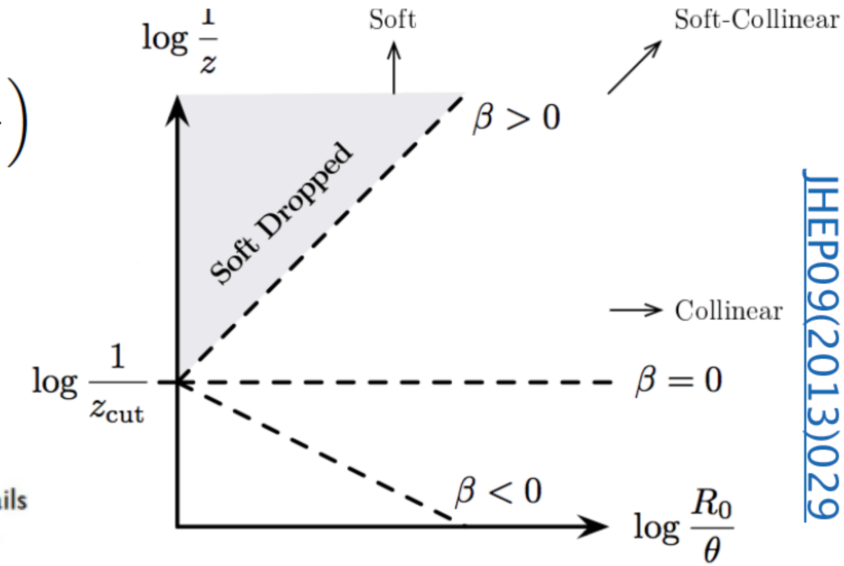
- Groomed jet mass M_g
  - Depends on opening angle
  - Small mass: collimated jet, few constituents
  - Large mass: broad jet, many constituents

$$\rho = 2\ log_{10}(\frac{m_g}{p_{T,j} R})$$

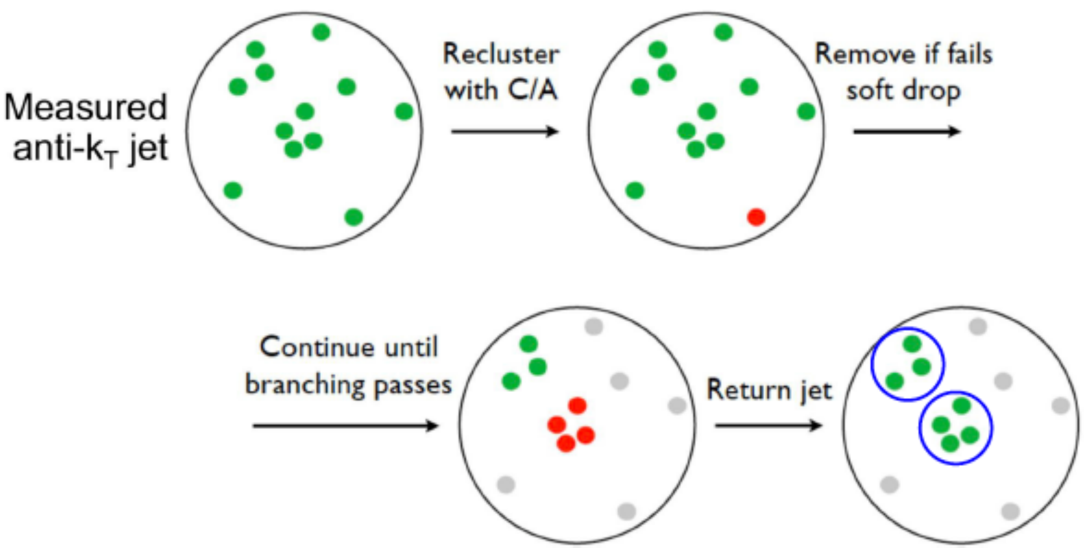
Soft drop grooming algorithm

- Jets are first reconstructed with anti-k_t algorithm, and then reclustered with the Cambridge-Aachen scheme to create a pairwise tree of subjets.

Soft drop condition: $$\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\mathrm{cut}}\left(\frac{\Delta R_{12}}{R_0}\right)$$



JHEP09(2013)029

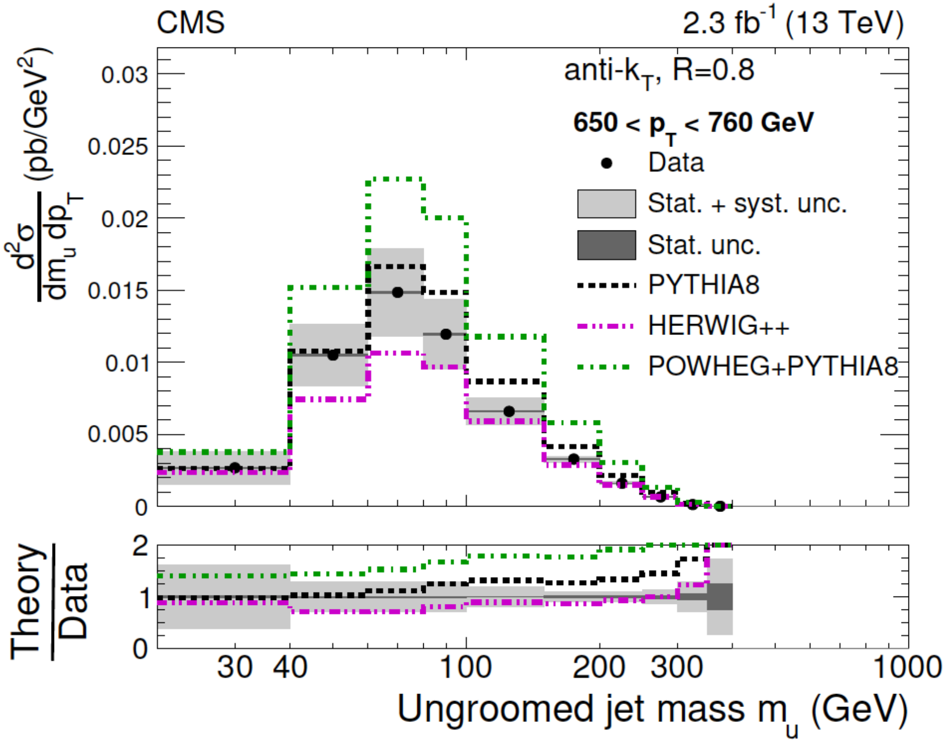


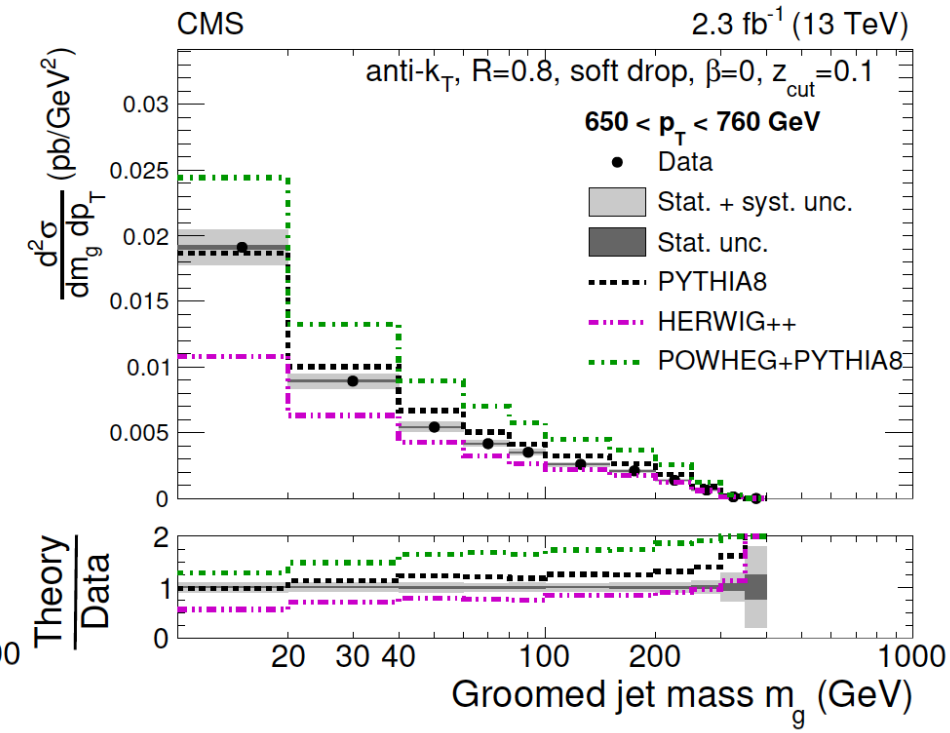
- After C/A finishes: decluster iteratively starting form the last step.

Jet mass in dijet events

JHEP 11 (2018) 113

- Differential jet cross section determined as a function of ungroomed and groomed (anti-k_t jets with R = 0.8 and p_T > 200 GeV) in p_T bins
- Dijet-like topology: $(p_{T1} - p_{T2})/(p_{T1} + p_{T2}) < 0.3$ and $\Delta\phi > \pi/2$

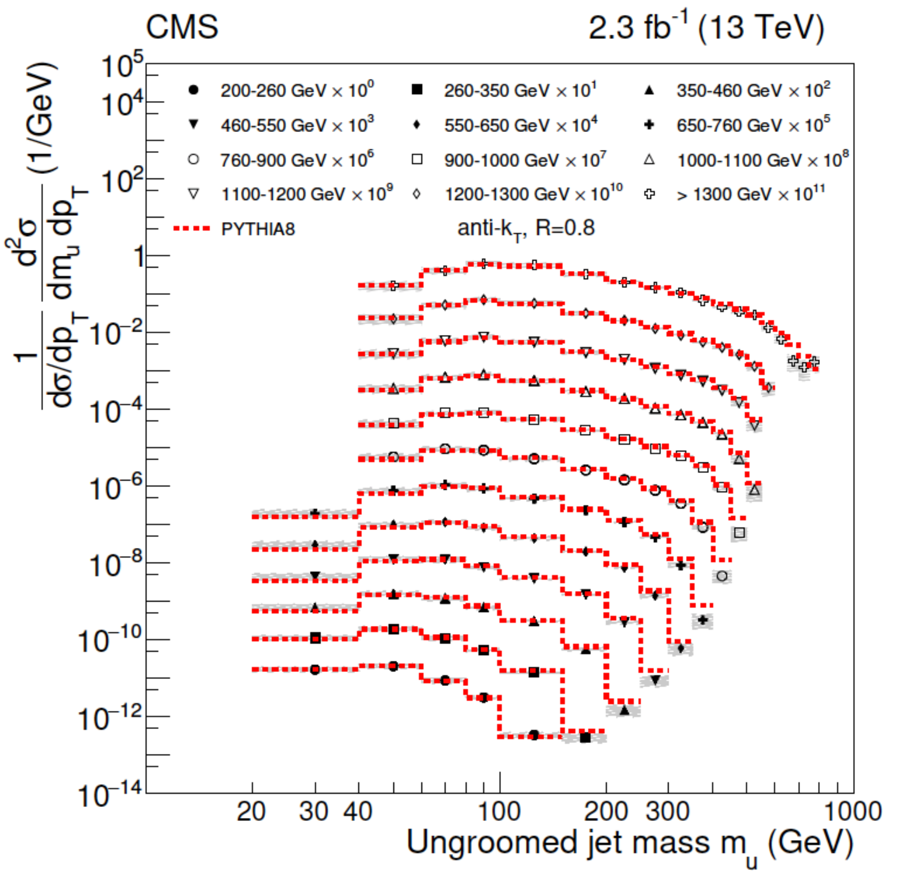


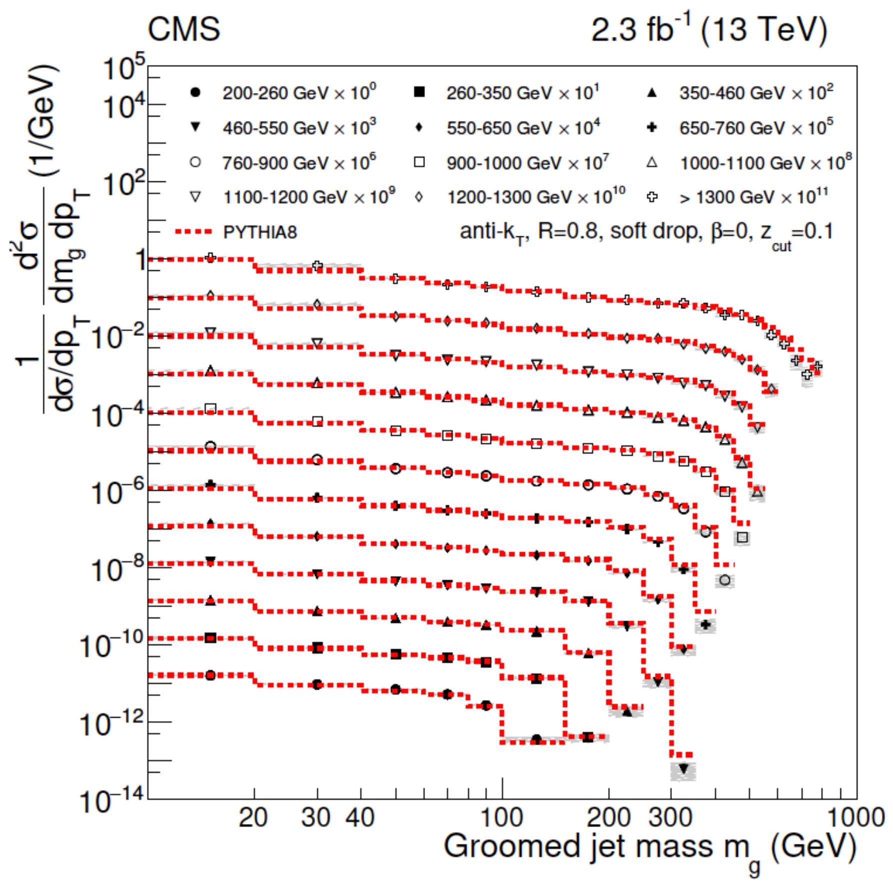


- Higher syst. unc. in ungroomed than groomed jets
- Grooming algorithm considerably lowers the jet mass and suppresses the Sudakov peak
- Improves measurement precision by removing contamination from soft particles and pileup

Jet mass in dijet events: differential jet cross section

JHEP 11 (2018) 113

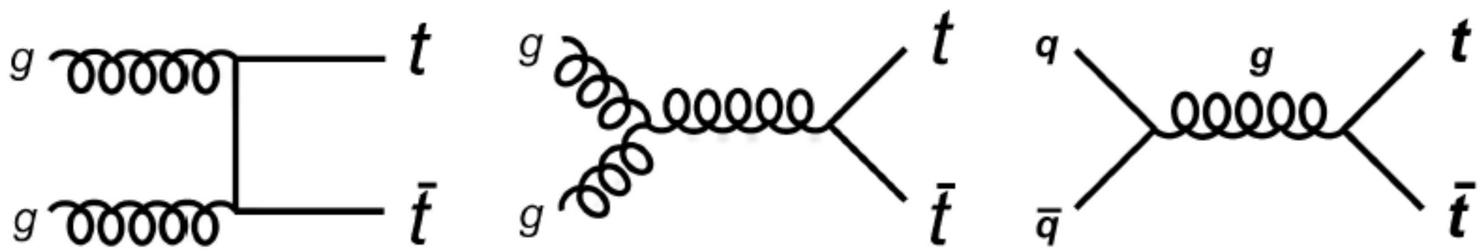




- Normalized cross section for ungroomed/groomed jets for all p_T bins
- Theoretical predictions agree with the measured cross sections within the uncertainties for masses from 10 to 30% of the jet p_T

Jet substructure in $t\bar{t}$ events

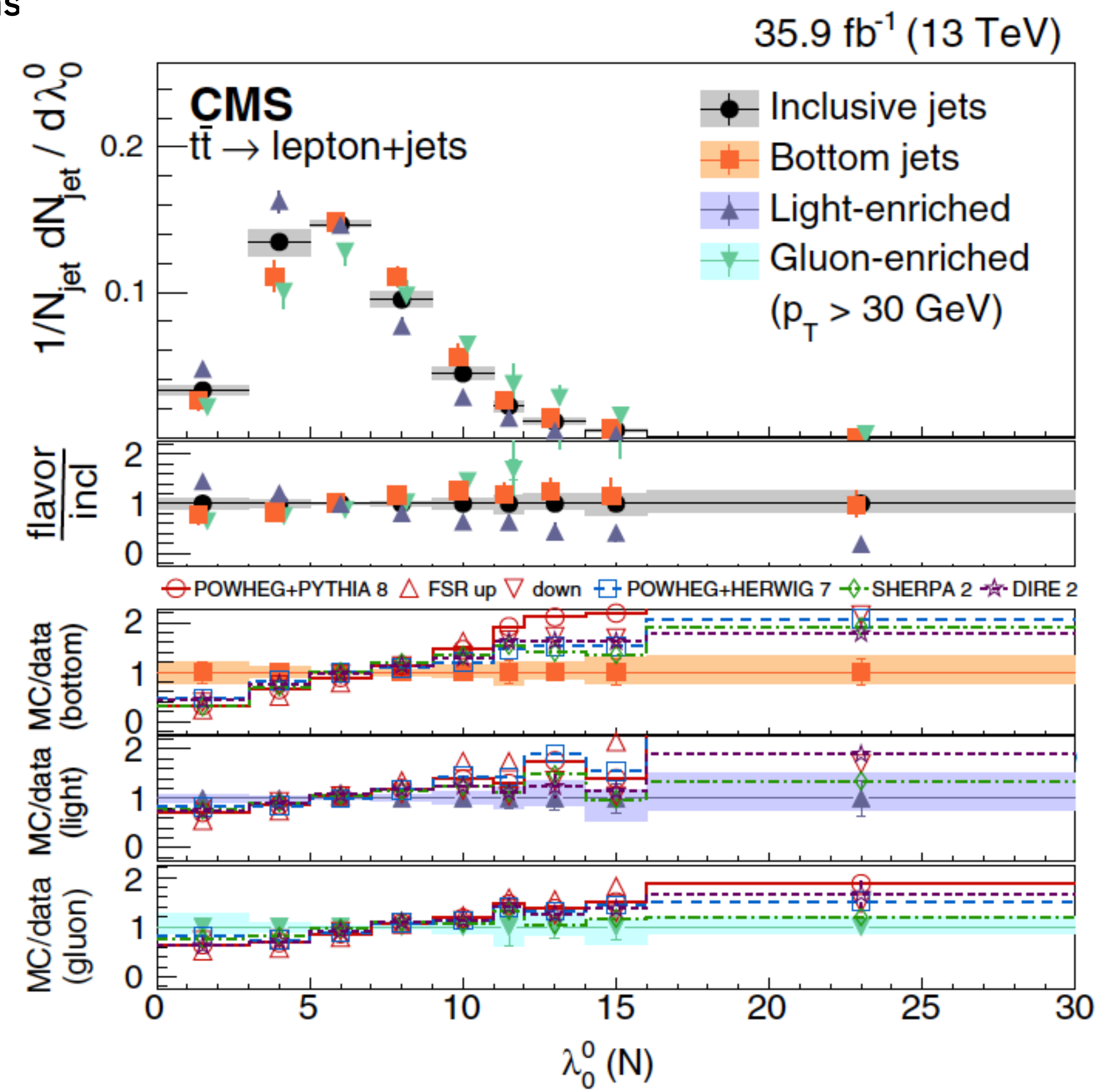
- Top quark pair events
  - abundantly produced at the LHC!
  - ideal probes for jet substructure measurements
  - very rich final states: light quarks, b quarks, gluon with high p_T, boosted W and top
  - High purity, and relatively orthogonal event selection criteria (for lepton + jets event samples)



Jet substructure observables in $t\bar{t}$ events

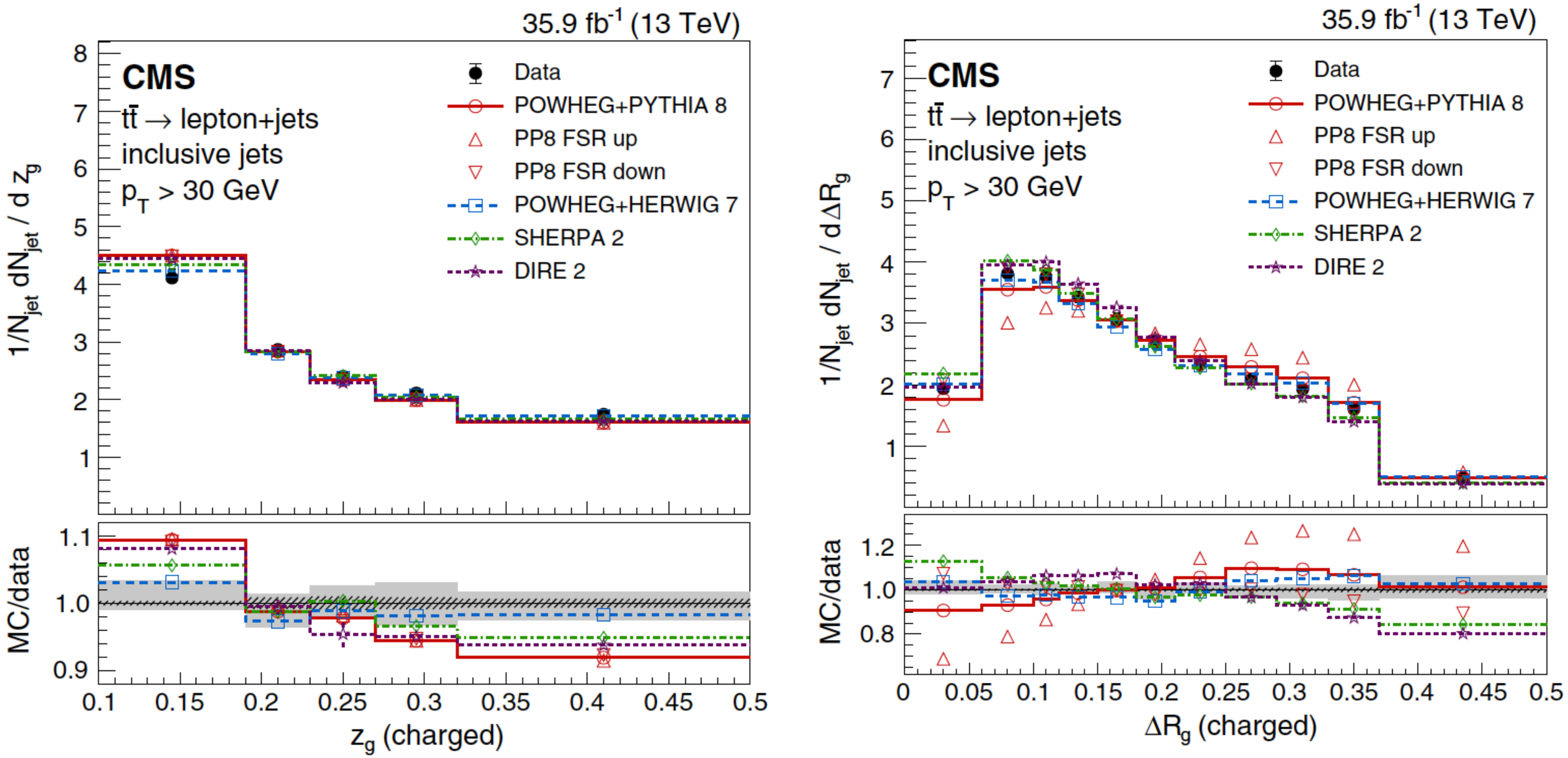
PRD 98, 092014 (2018)

- Various observables measured
  - generalized angularities, eccentricity, groomed momentum fraction, N-subjettiness ratios, and energy correlation functions
- Samples enriched in jets:
  - inclusive, bottom quarks, light quarks, gluons.
- Charged multiplicity relevant for q/g discrimination
  - differences between the quark- and gluon-enriched samples do not seem to be very strong.



Jet substructure observables in $t\bar{t}$ events (II)

PRD 98, 092014 (2018)

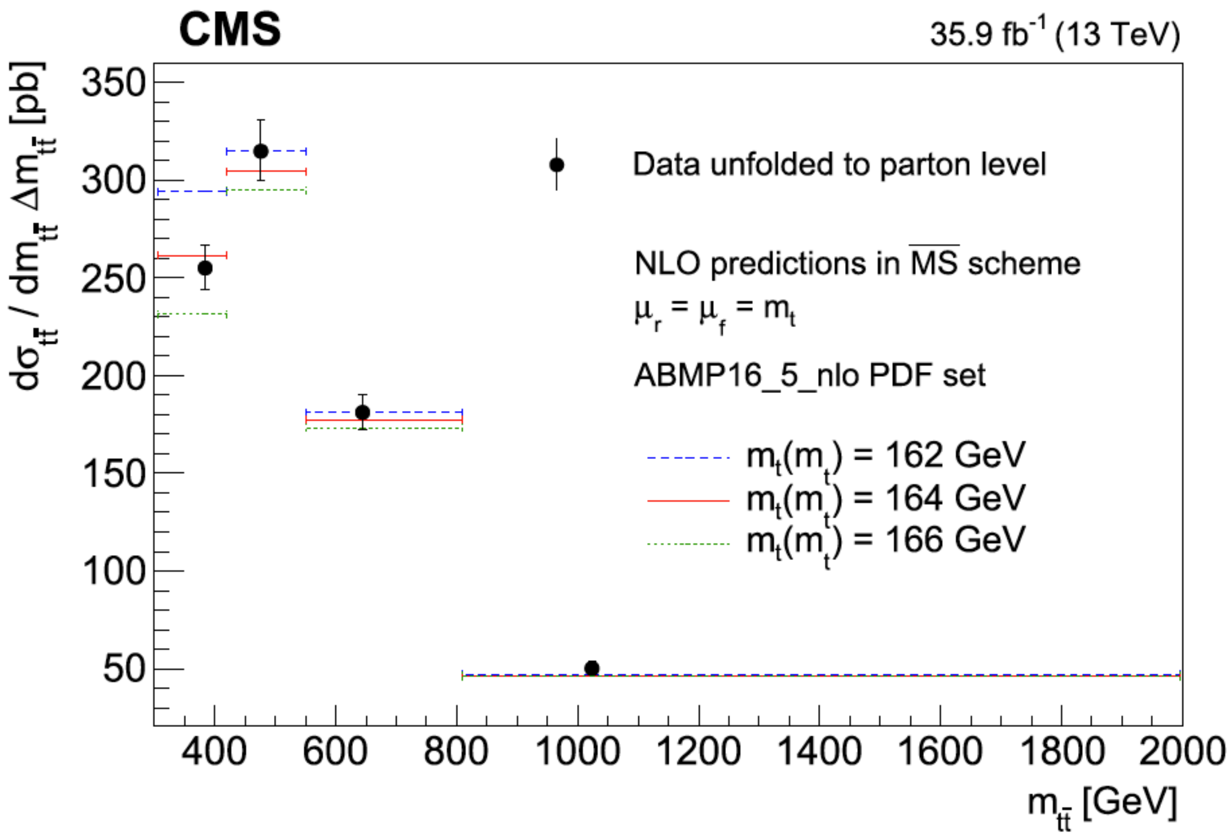


- Comparison to various generators
- Unfolded distributions for charged and charged+neutral particles for all jet samples
  - z_g distribution (first time!)
    - Good data/model agreement in this observable for HERWIG 7; large spread in generator predictions
  - Angle between groomed subjets, ΔR_g depends strongly on the amount of FSR.

Jet mass in $t\bar{t}$ events

Phys.Lett. B 135263 (2020)

- Running of top quark mass experimentally investigated for the first time
  - Measure $m_t(\mu)$ as a function of the scale $\mu = m_{t\bar{t}}$
  - Perform precise measurements of $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$
  - Extract running by comparing to differential theory predictions in $\overline{MS}$ scheme



- Measurement compared to NLO predictions in $\overline{MS}$ scheme obtained with different values of m_t

Extraction of running in $t\bar{t}$ events

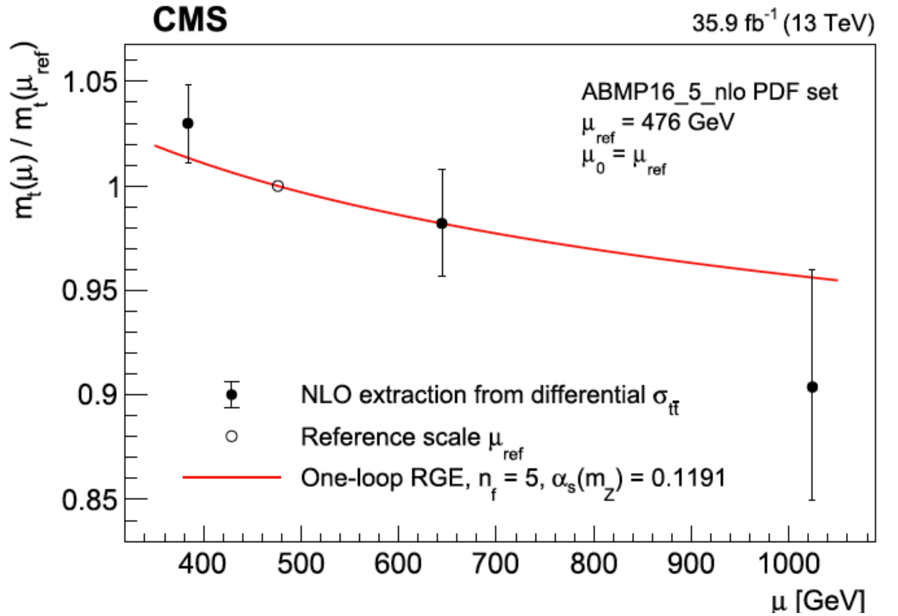
Phys.Lett. B 135263 (2020)

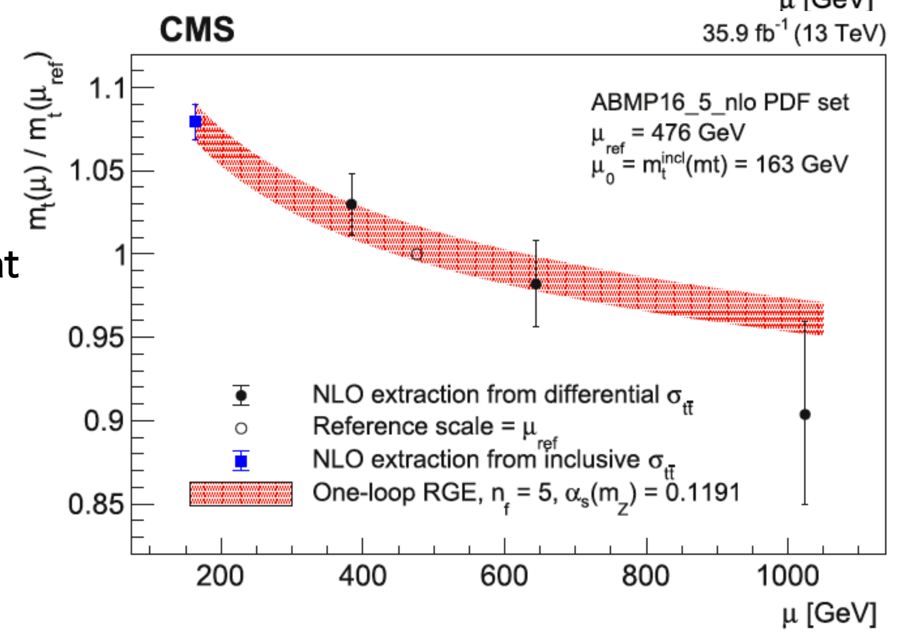
- Running $r(\mu)$ is defined as ratio of $m_t(\mu)$ to reference mass $m_t(\mu_{ref})$

Thoery: $r(\mu) = m_t(\mu) = m_t(\mu_{ref})$

Exp. : $r_k = m_t(\mu_k) / m_t(\mu_{ref})$

- $r(\mu)$ depends solely on RGE
- r_k benefits from cancellation of correlated unc.
- initial scale choice: $\mu_{ref} = \mu_2 = 476$ GeV





- result compared to value of $m_t(\mu)$ extracted at NLO from inclusive $\sigma_{t\bar{t}}$
- good agreement with RGE on a wide range of scales, up to > 1TeV

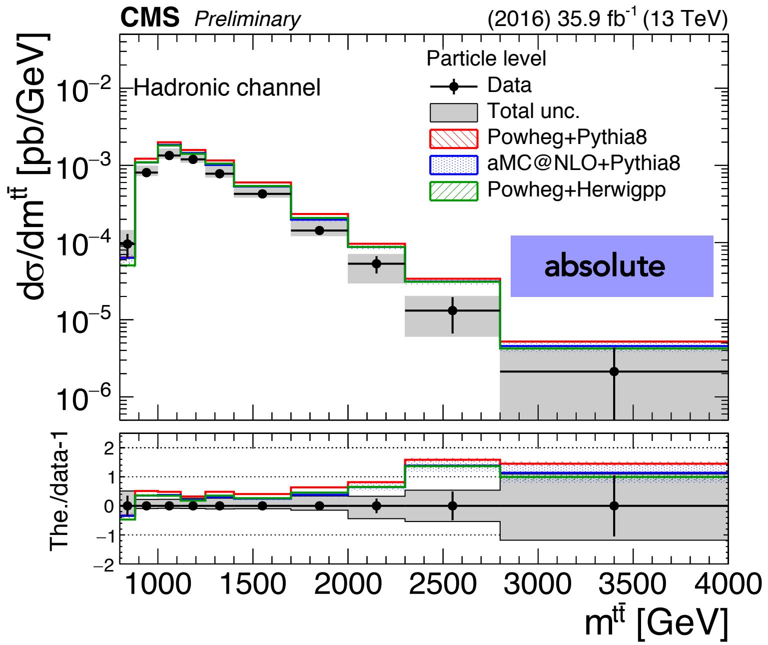
Differential $t\bar{t}$ cross sections

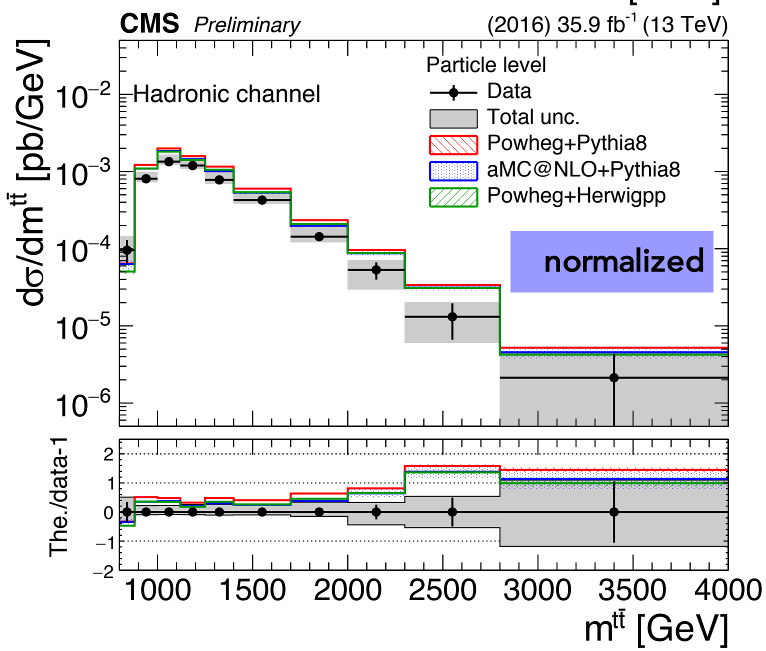
CMS PAS TOP-18-013

- Production cross section for high p_T top quark pairs (l+jets & hadronic ttbar decay channels)
- Substructure observables used extensively for t tagging
- N-subjettiness variables τ_3 , τ_2 and τ_1

$$\tau_N = \frac{1}{\sum_k p_{T,k} R} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots \Delta R_{N,k}\}$$

- Hard radiation centers found with exclusive k_t algorithm
- Grooming technique applied
  - to remove soft, wide-angle radiation from jet
  - To improve mass resolution





Summary

- Significant ongoing effort to improve our understanding of QCD with jet substructure measurements
- Jet substructure measurements shed light on SM in extreme phase space regions
- Inclusive and differential cross section measurements performed by CMS
  - can tackle different modeling aspects at different phase space regions
- Ranging from low p_T to high p_T various interesting measurements allow us to see the strengths of different MC tunes
- We are not done! Still more measurements and efforts on-going stay tuned!

Thank you for your attention!

BACKUP

What are jets?

- **Jets**

–Collimated spray of particles

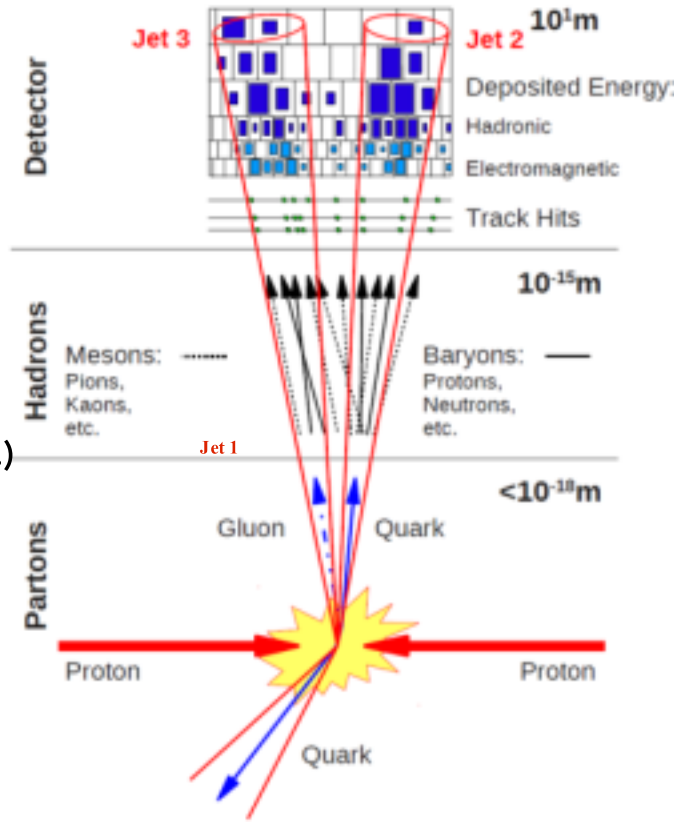
–The experimental signatures of quarks and gluons.

–Invaluable objects to probe QCD

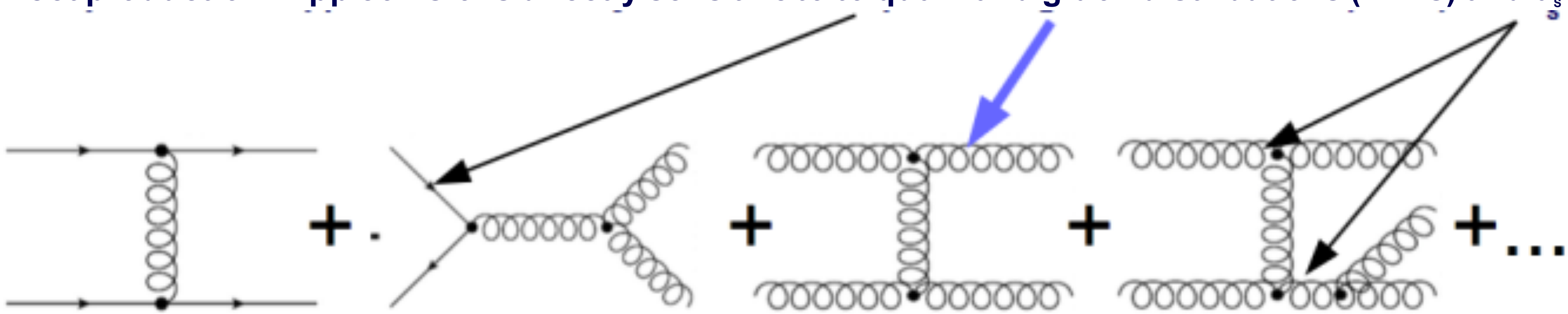
–Abundantly produced at hadron colliders ("jet laboratories")

–Important signature for many physics processes (Higgs, top, SUSY, …)

–Important for almost all LHC physics analyses!

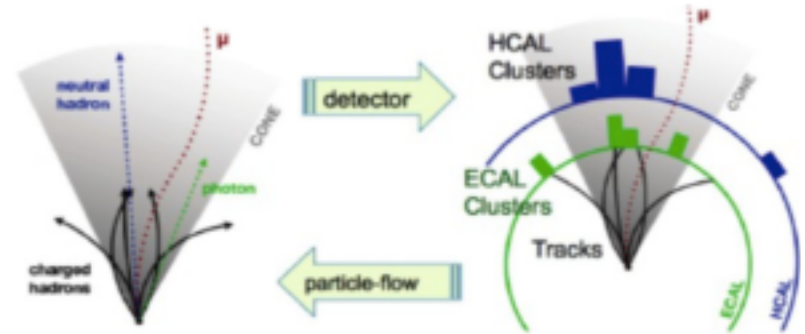


- **Jet production in pp collisions directly sensitive to to quark and gluon distributions (PDFs) and α_s**

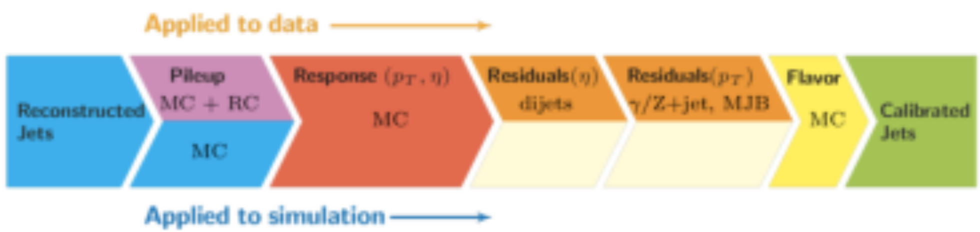


Jet reconstruction and jet calibration @ CMS

- A jet in CMS is seen as a bunch of particles in the detector
- Jet reconstruction procedure: input objects (e.g. particles)→ apply jet finding algorithm → jet reconstruction
- Anti-k_t algorithm (infrared and collinear safe) is used
- Particle Flow (PF) Jets: Clustering of Particle Flow candidates constructed by combining information from all sub-detector systems.



- Factorized Jet Energy Correction approach in CMS:



- × **Pileup → corrects for "offset" energy**
- × **Response → Make jet response flat on η and p_T**
- × **Data/MC residuals → residual differences between data & MC**
- × **Flavor (optional) → corrects dependence on jet flavor**

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