Jets in Vector Boson Fusion Events

GK/KCETA Workshop · Bad Liebenzell · 30 September 2013

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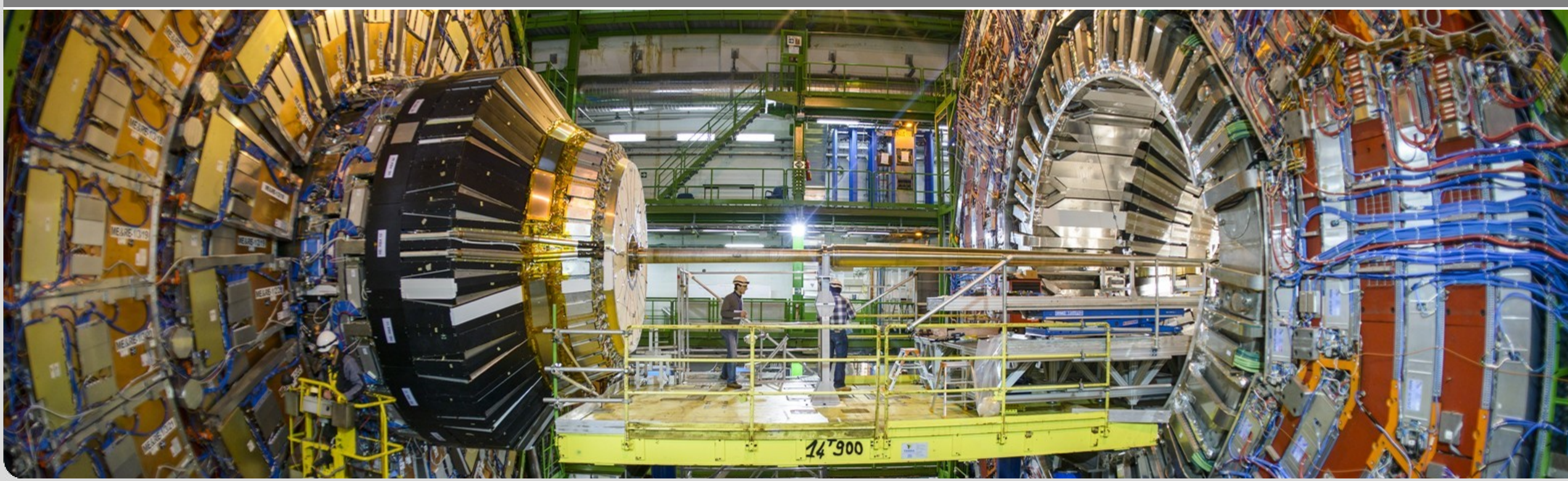

Contents

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- The search for $H \longrightarrow \tau\tau$ ($\longrightarrow \mu\mu$)
  - Vector Boson Fusion category
- Jet measurement and jet energy calibration
  - Calibration scheme in CMS
  - Data-driven calibration using Z+jet events
  - Time dependence corrections
  - Calibration of VBF-like events
- Systematic uncertainties in the $H \longrightarrow \tau\tau$ VBF category
  - Jet energy scale uncertainties
  - Theory uncertainties
- Conclusion

Higgs Production Channels

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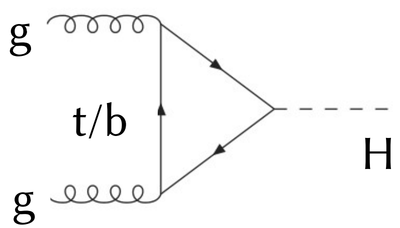
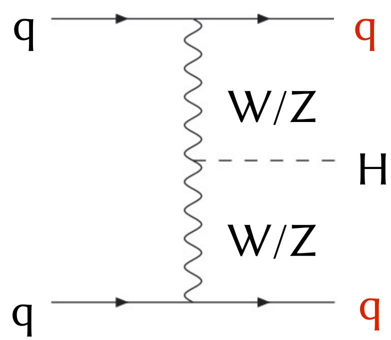
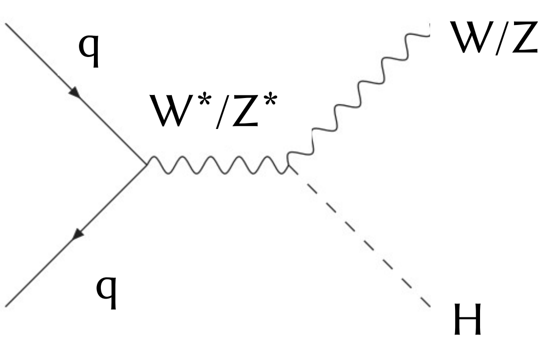


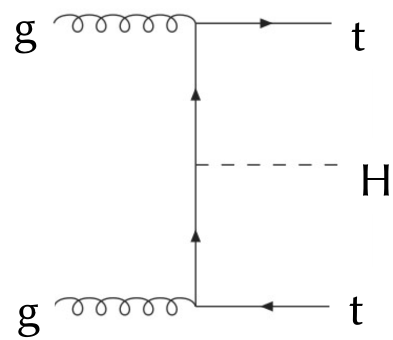
gluon fusion



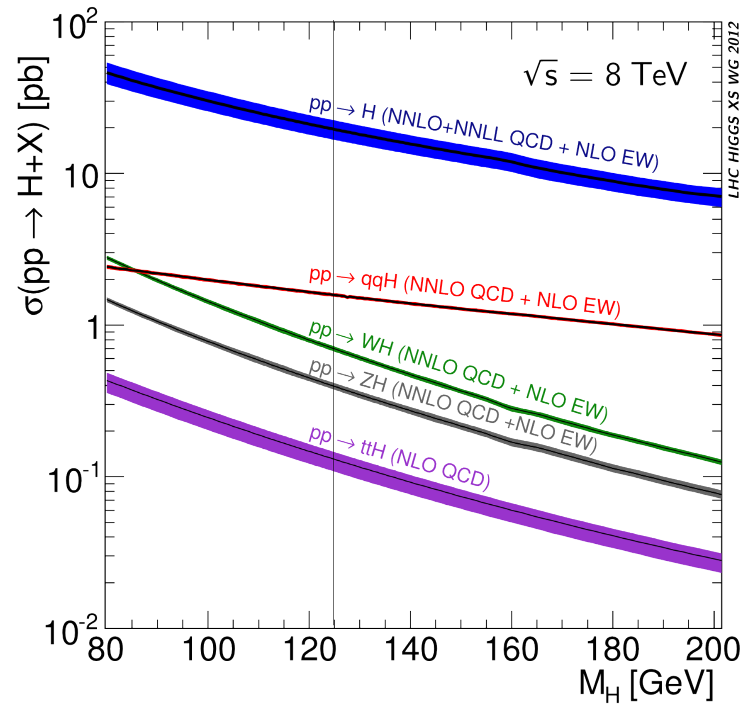
vector boson fusion



VH

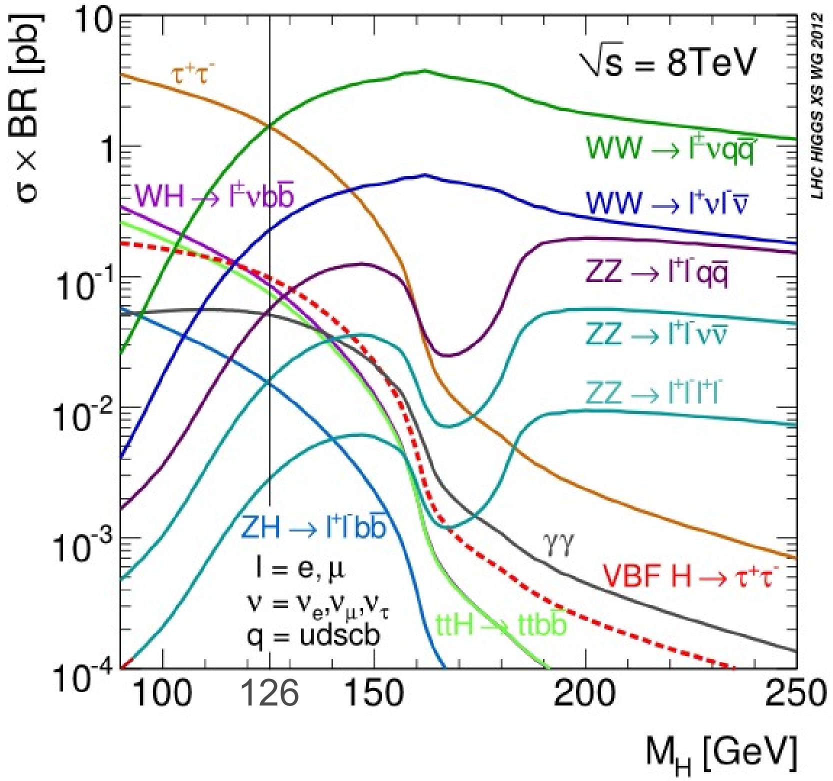


$t\bar{t}H$



- VBF is not the major prod. channel
- clear signature with 2 additional jets

The H → ττ → μμ Analysis



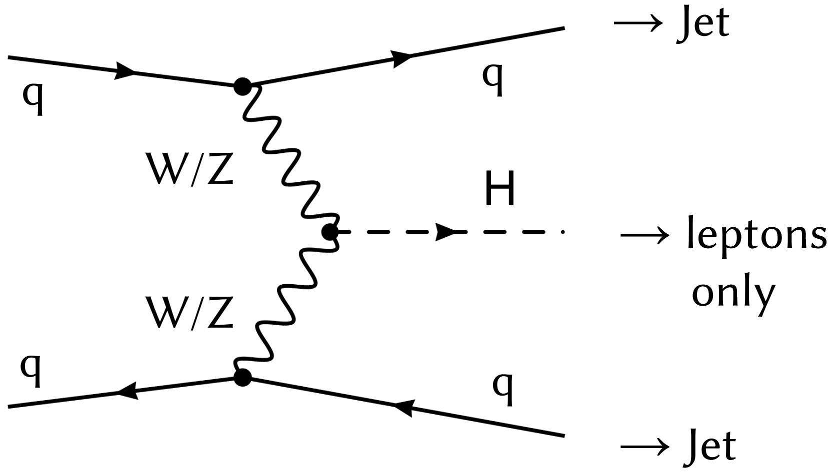
- bosonic channels (γγ, WW, ZZ) led to the Higgs discovery in 2012
- evidence for direct coupling to fermions in Higgs decays yet to be shown

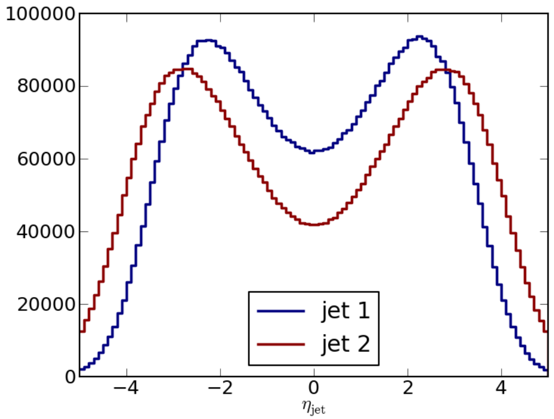
⇒ H → ττ (→ μμ) analysis

  - precise μμ measurement
  - no hadronic decay products

- difficulties and challenges:
  - low branching ratio (3%)
  - 4 neutrinos in τ-decays
  - large irreducible backgrounds (Drell-Yan, etc.)
- analysis in categories of jet multiplicity
  - most significant: VBF (2 jet)

The VBF Topology (Category Definition)





- Pair of jets in forward region
- VBF selection is based on jet kinematics

⟹ requires precise jet measurement

  - 2 tagging jets (high rapidities)
  - central jets (central region)

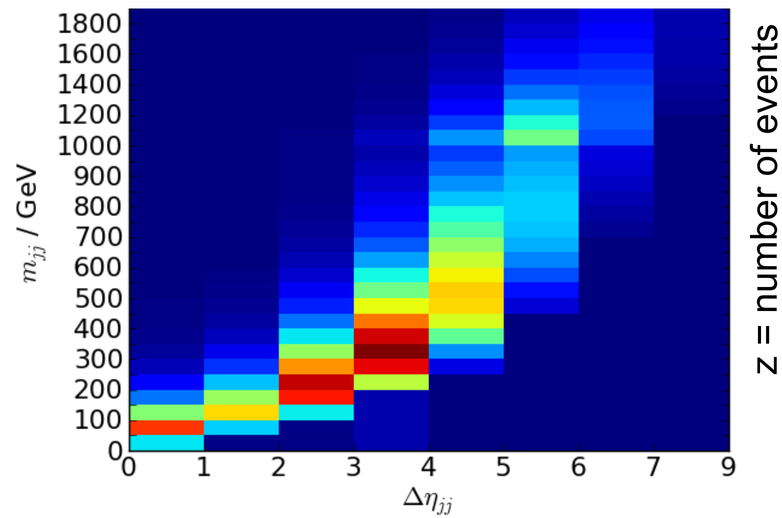
category definition

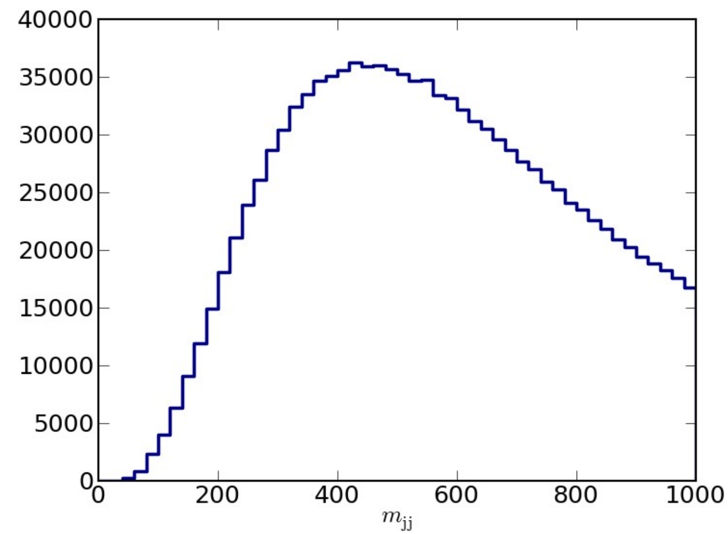
$|p_T^{\mathrm{jet}1,2}| > 30$ GeV
$|\eta^{\mathrm{jet}1,2}| < 5.0$
no 3rd jet between $\mathrm{jet}_{1,2}$

The VBF Topology (Discriminating Variables)

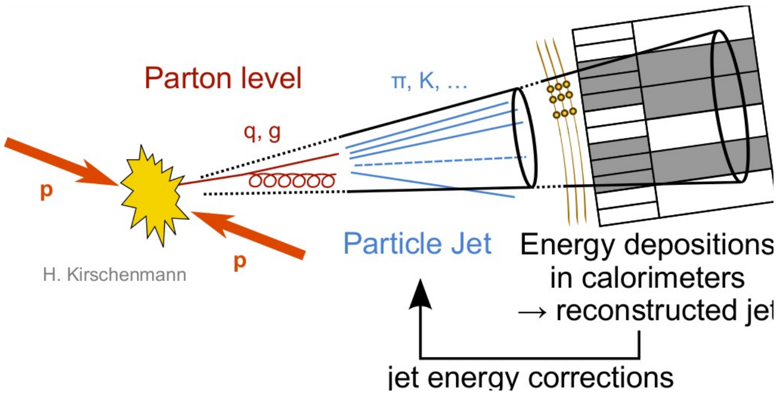
- Within the VBF category, a combination of BDTs is used to discriminate between signal and background

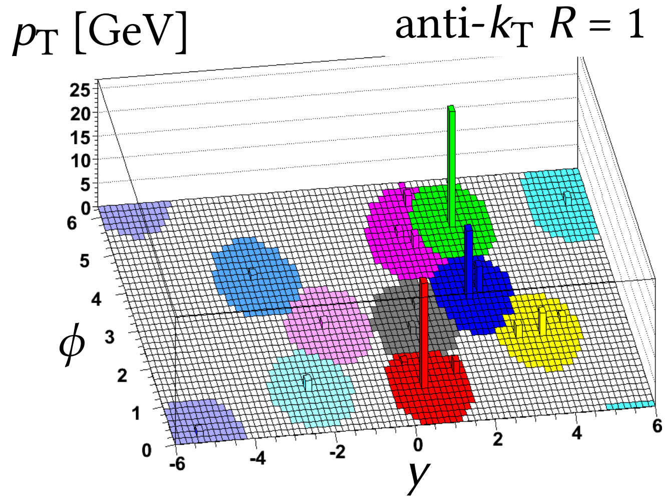
- MVA input variables:
  → **Talk by Thomas Müller on Wednesday**
  - $m_{\mu\mu}$
  - $m_{\tau\tau}$
  - $\Delta\phi\,(\mu^+, p_T^{miss})$
  - $\cos\,\Omega^*$
  - $\log_{10}(\text{DCASig}(2\mu))$
  - $\cos\,\Theta\,(\mu^+)$
  - Validity of coll. Approx.
  - Missing energy E_T^{miss}
  - **Pseudo rapidity difference of tagging jets** $\boldsymbol{\Delta\eta_{jj}}$
  - ***Invariant mass of tagging jets*** $\boldsymbol{m_{jj}}$





Jet Measurement and Clustering Algorithms

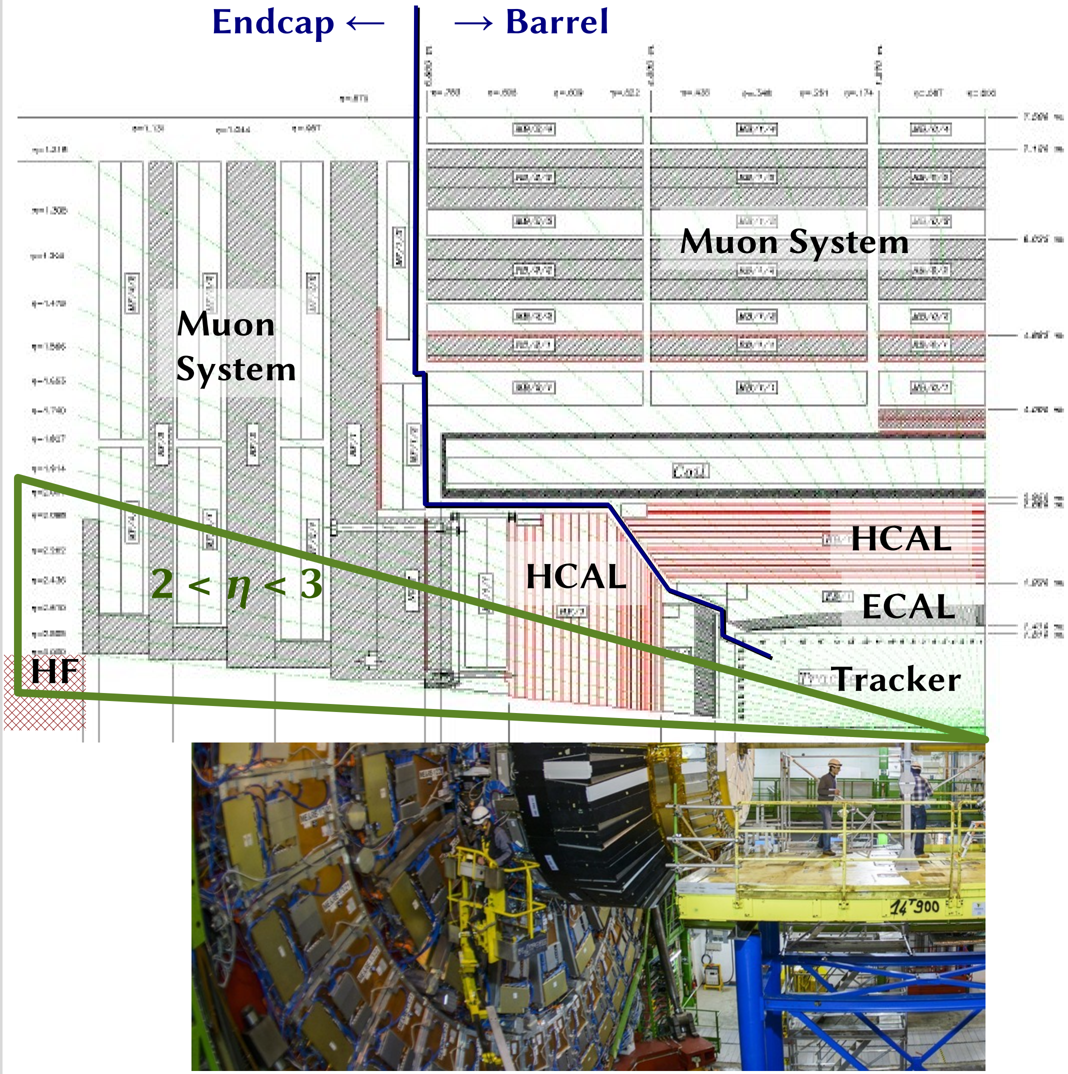




- Jet are collimated streams of particles which
- *Particle Flow*: Individual particles are reconstructed prior to jet clustering
- UE, MPI, ISR, FSR, out-of-cone
- electronic noise and pile-up

- Corrections are determined for several jet algorithms
  - default: anti-k_T 0.5
  - infrared and collinear safe

Central and Forward Jets in the CMS Detector



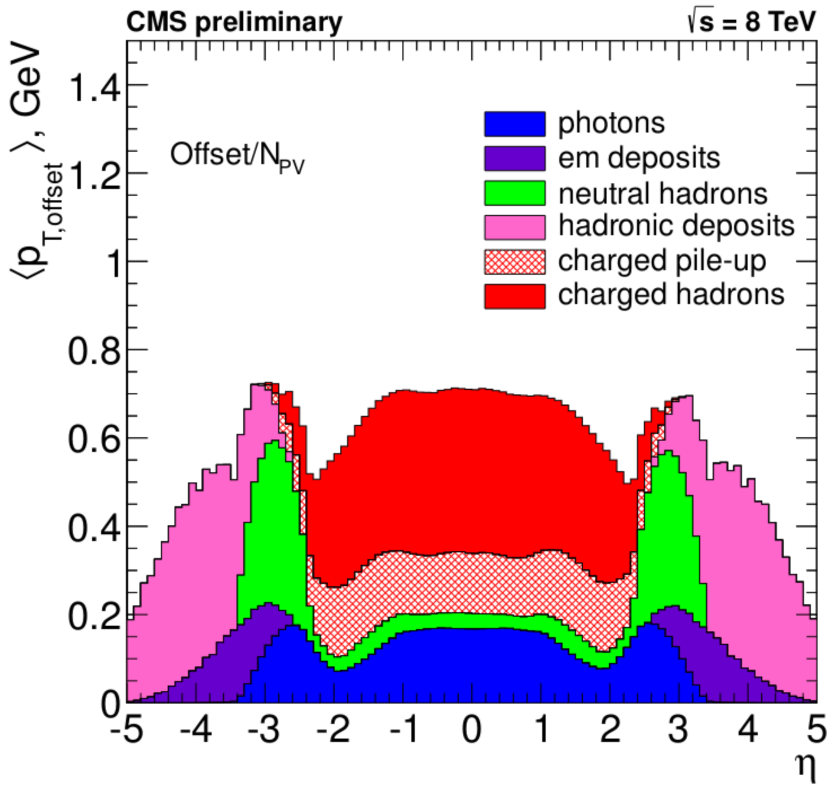
central detector:

- homogeneous barrel

issues in forward region:

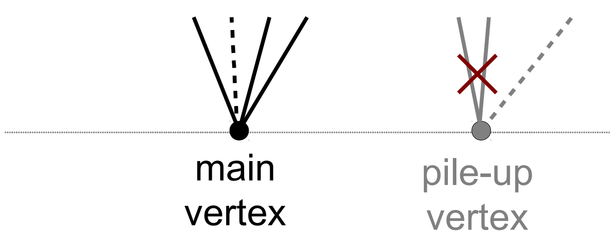
- transitions between detector components (endcap/forward)
- end of tracker coverage
  - no vertex association
- dense material and gaps
- radiation damages near beam pipe
  - response changes during data-taking

Pile-Up in 2012 Data and Pile-Up Subtraction



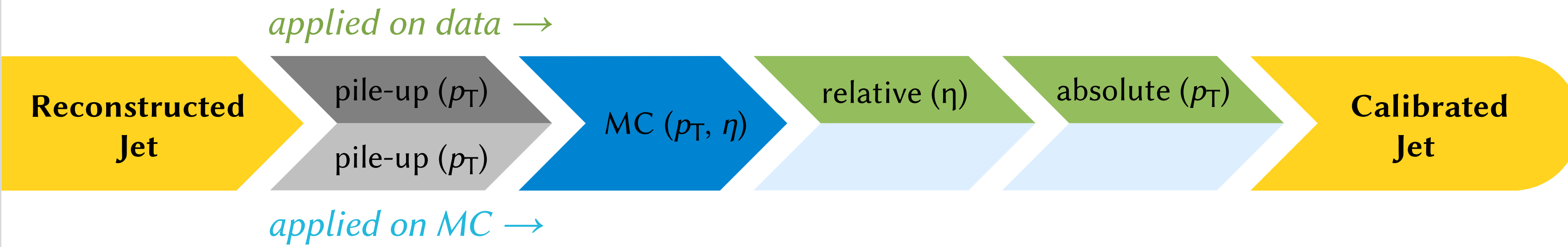
- dramatic increase of pile-up due to higher luminosity in 2012
- > 12 primary vertices per event

- methods for **pile-up mitigation**:
  - Charged Hadron Subtraction *removes charged hadrons from pile-up vertices*



  - validated in Z+jet calibration sample
  - included in $H \longrightarrow \tau\tau \longrightarrow \mu\mu/ee$ analysis

Jet Energy Corrections in CMS



Factorized approach for jet calibration in CMS

1) offset corrections for ***pile-up*** and ***electronic noise***
2) corrections for **detector** calibration and **reconstruction** efficiencies from MC — MC based
3) relative residual corrections for η dependence
4) residual corrections to absolute p_T

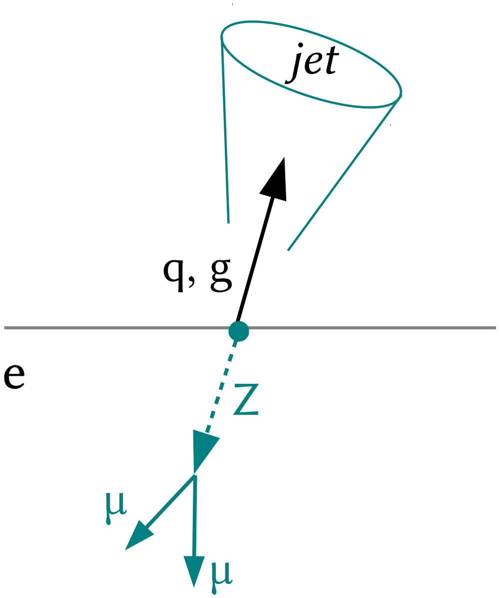
} data driven (3, 4)

CMS jet energy corrections combine

- ✔ the advantages of MC based studies with
- ✔ the robustness and accuracy of data-driven methods

Jet Energy Calibration with Z($\rightarrow \mu\mu$) + Jet Events

- Reference: Z decaying into pair of muons
  - high accuracy of muon measurement
- Probe jet:
  - leading jet barrel/extended to all η regions
  - only soft additional jets



- Data-driven calibration of absolute jet energy scale
  - determined JEC for 2011 dataset
  - *here*: full 2012 dataset (19.5 fb^{-1})
- Independent cross-checks for all calibration levels
- Used by all CMS analyses

Z+Jet Event Selection

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Reconstruction of the Z

- muon transverse momentum $p_{\mathrm{T}}^{\mu} > 20\ \mathrm{GeV}$
- muon pseudorapidity $|\eta^{\mu}| < 2.3$
- muon isolation $\sum_{\text{tracks}} p_{\mathrm{T}} < 3\ \mathrm{GeV} \quad \text{within } \Delta R < 0.3$
- mass of muon pair $|m_{\mu\mu} - m_{\mathrm{Z}}| < 20\ \mathrm{GeV}$
- Z transverse momentum $|p_{\mathrm{T}}^{\mathrm{Z}}| > 30\ \mathrm{GeV}$

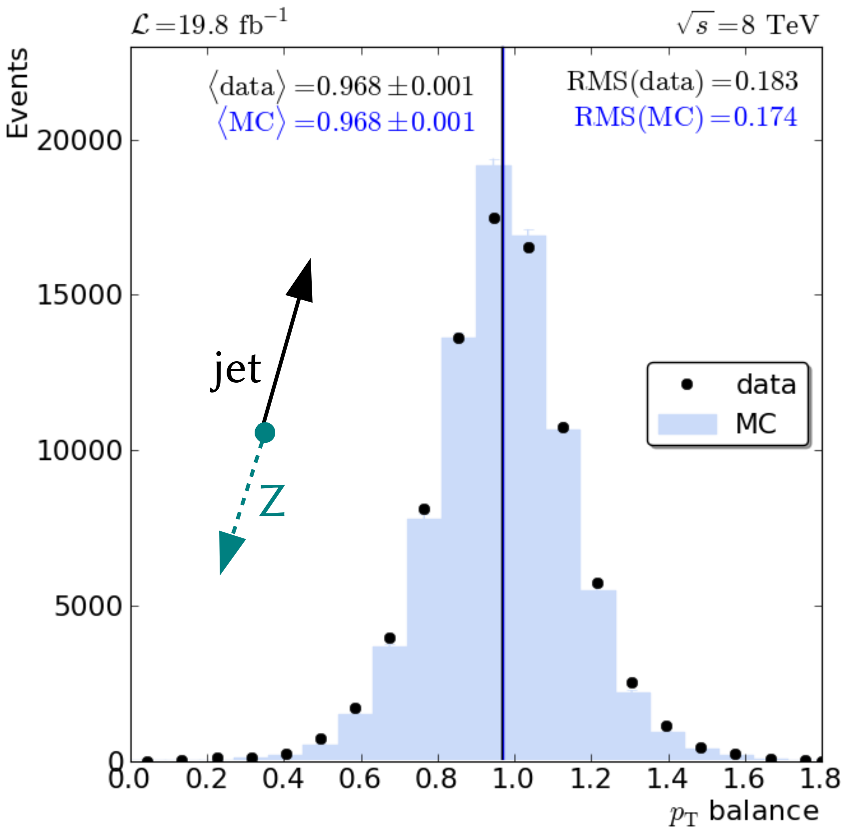
Jet selection

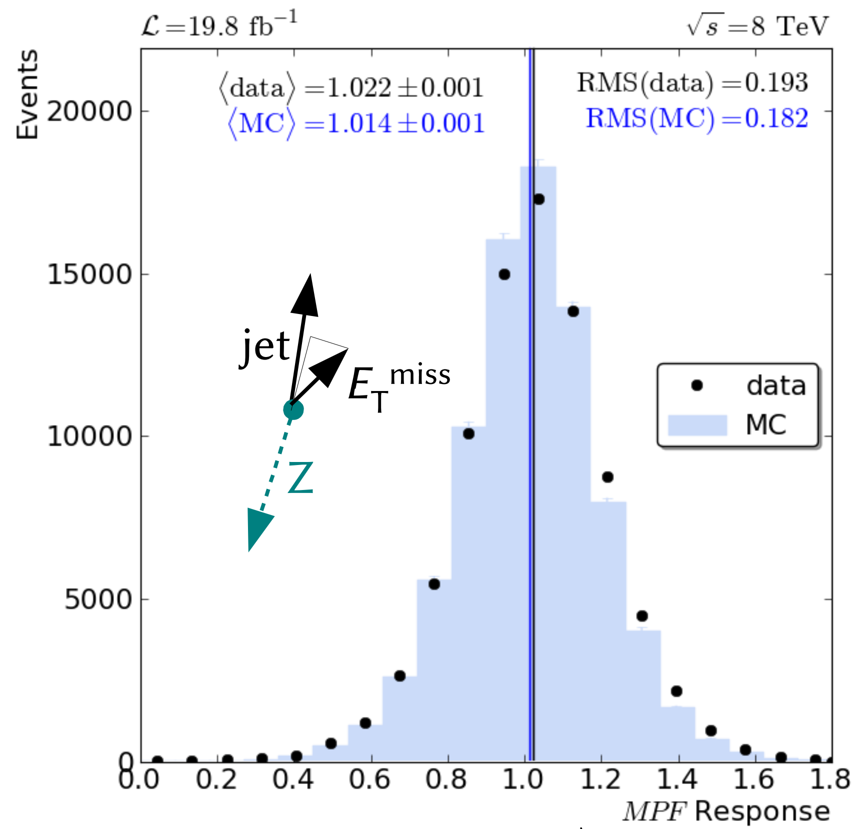
- transverse momentum $|p_{\mathrm{T}}^{\mathrm{jet}}| > 12\ \mathrm{GeV}$
- pseudorapidity of leading jet $|\eta^{\mathrm{jet}}| < 1.3$

Z plus one jet selection

- second leading jet $\frac{p_{\mathrm{T}}^{\mathrm{jet2}}}{p_{\mathrm{T}}^{\mathrm{Z}}} < 0.2 \qquad \text{and extrapolation} \to 0$
- Z-jet-balancing $|\Delta\phi_{\mathrm{Z,jet1}} - \pi| < 0.34$

Two Methods to Measure the Jet Response





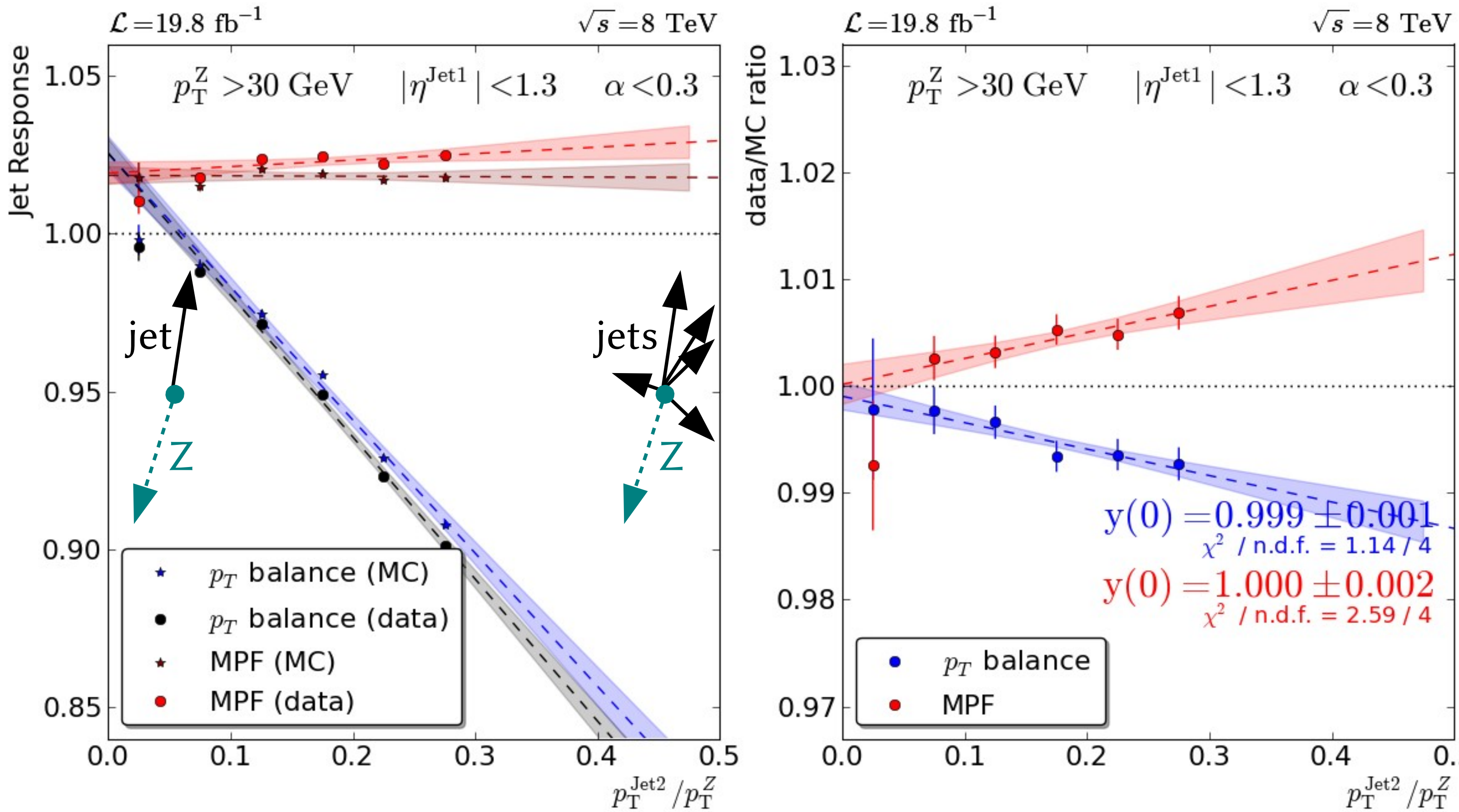
$$R_\mathrm{balance} = \frac{p_\mathrm{T}^\mathrm{jet}}{p_\mathrm{T}^\mathrm{Z}}$$

direct ratio between leading jet and Z
(biased by final state radiation)

$$R_\mathrm{MPF} = 1 + \frac{\vec{E}_\mathrm{T}^\mathrm{miss} \cdot \vec{p}_\mathrm{T}^\mathrm{Z}}{\left(p_\mathrm{T}^\mathrm{Z}\right)^2}$$

Missing Energy Projection Fraction (MPF)
(full recoil, assuming uniform PU on avg.)

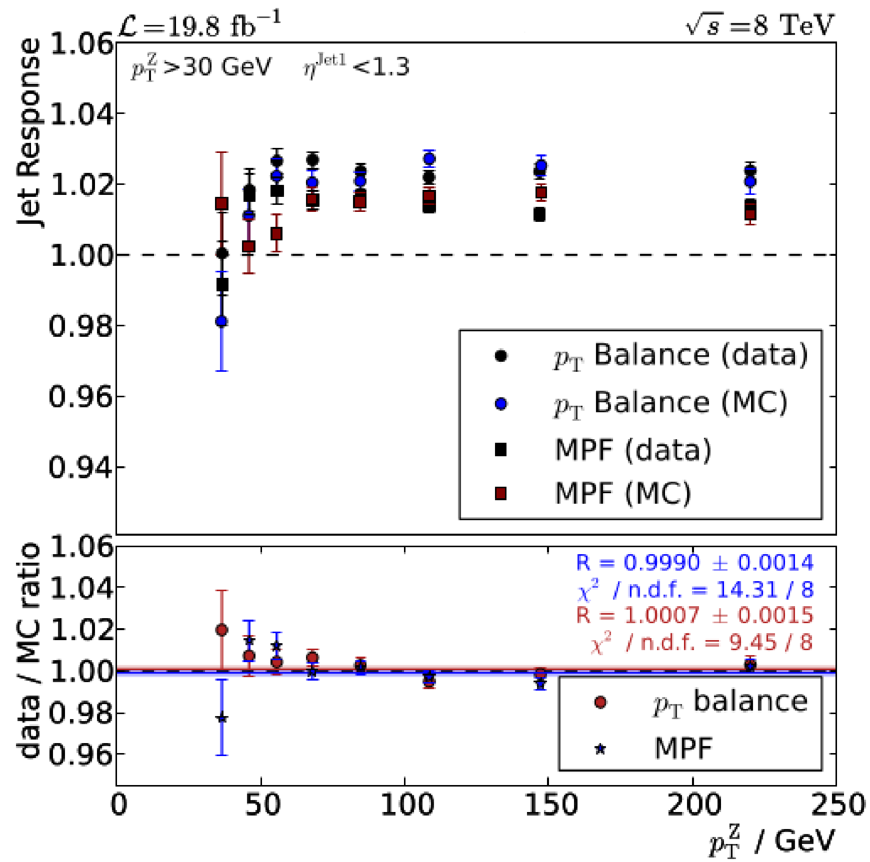
Extrapolation to Perfect Topology



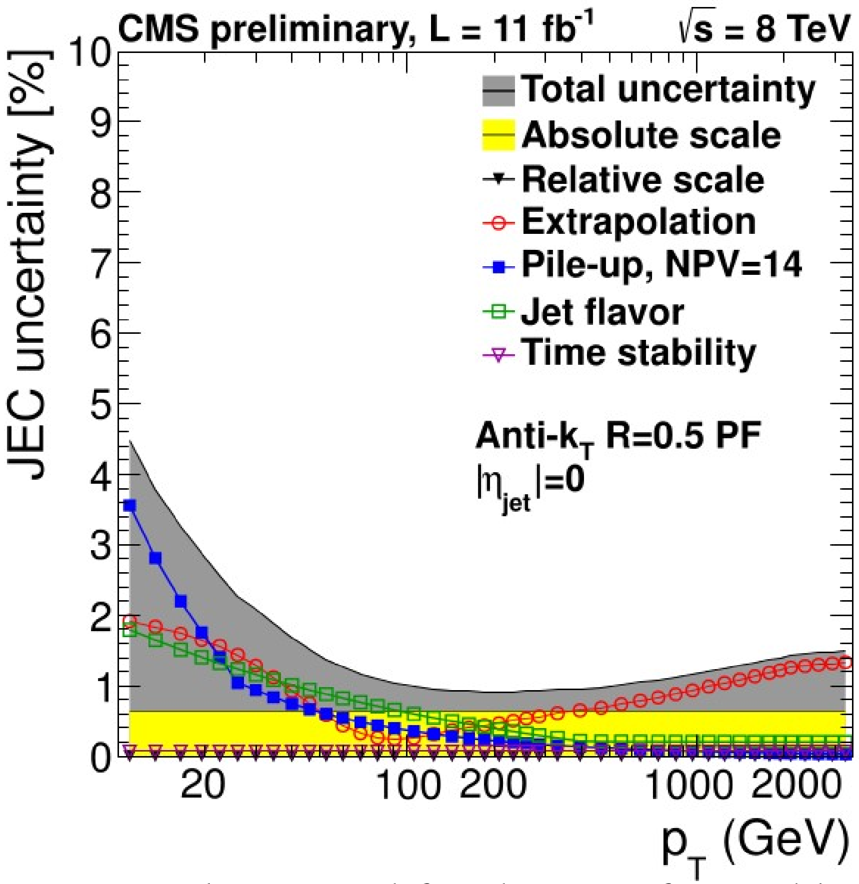
- In real world: 1 jet events very rare
- Extrapolation: Radiation bias in p_T balance is accounted for

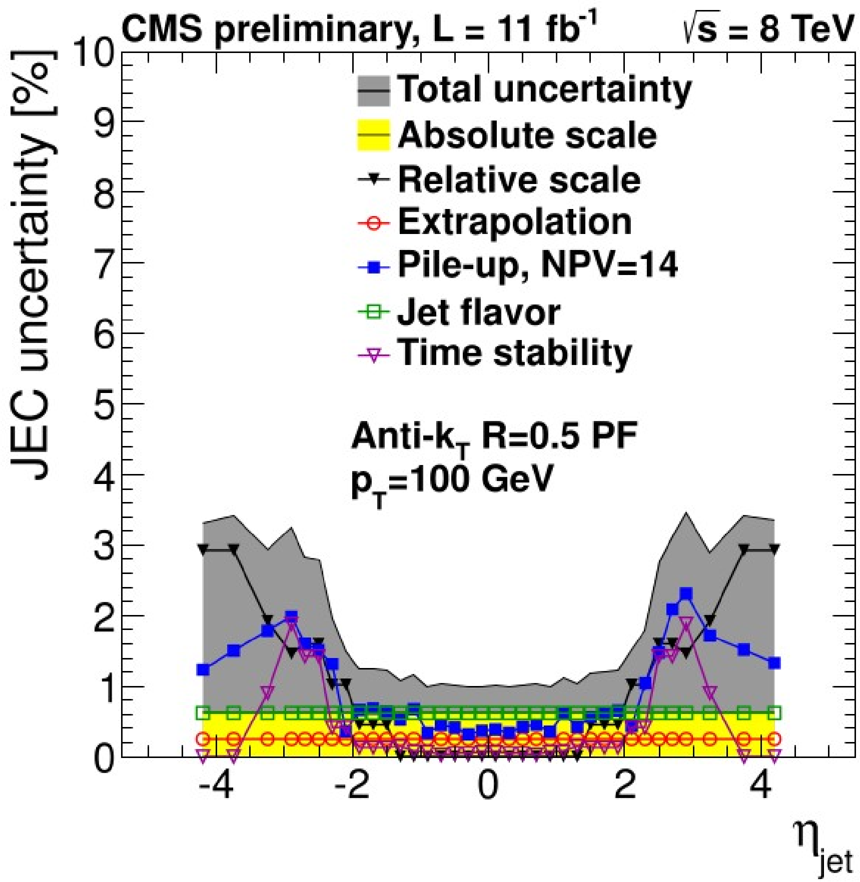
Response Measurement in Bins of Z p_T

- both methods agree
- transverse momentum range: 30 .. 500 GeV
- parton/particle jet differences visible in jet response
- data and Monte-Carlo simulation in agreement after applying corrections
- statistical precision on per-mil level
- results combined with photon+jet and Z(⟶ee)+jet to final correction level
- Flavour studies ongoing



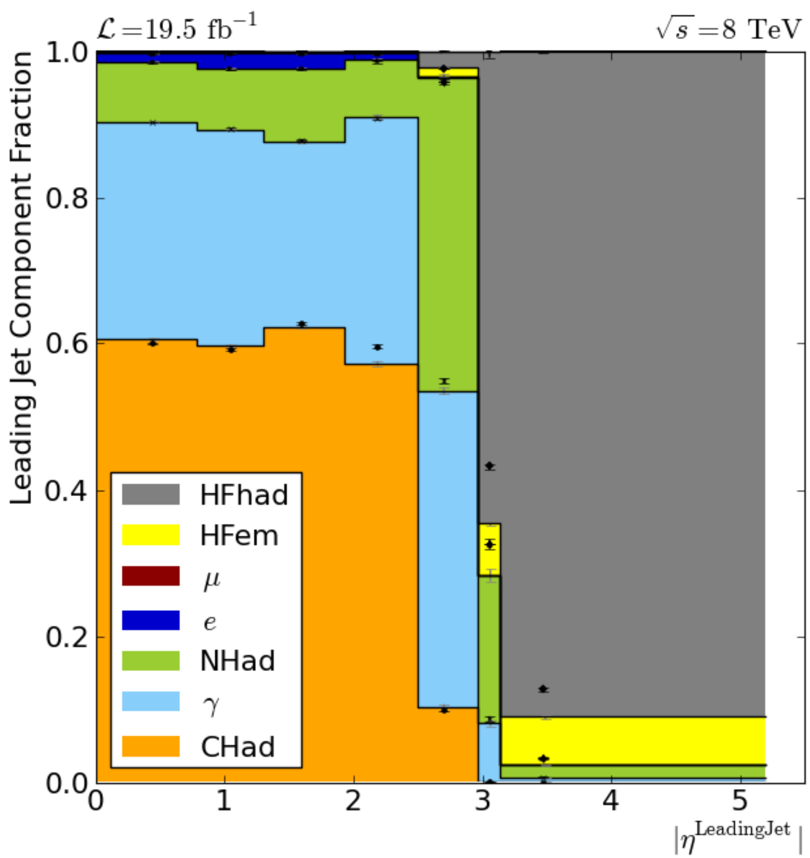
Jet Energy Correction Uncertainties

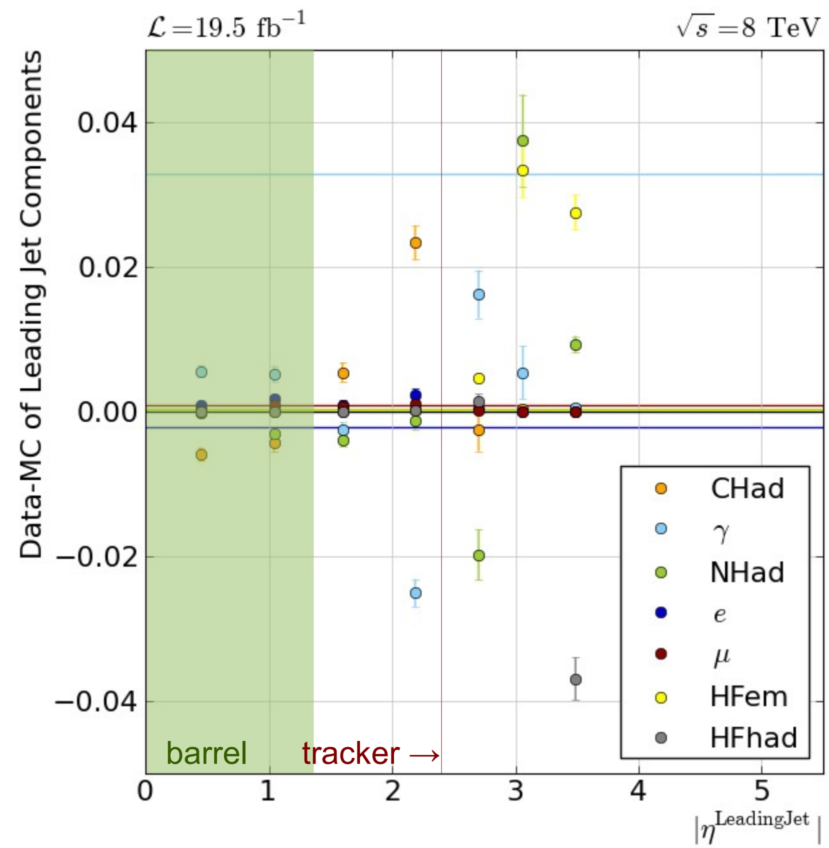




- Has been used for the very first calibration in CMS with 2010 data
- Jet energy scale uncertainties could be **halved** in the **last 2 years**
- Total uncertainty of the jet energy scale is close to **1%** for $|\eta| < 2.4$

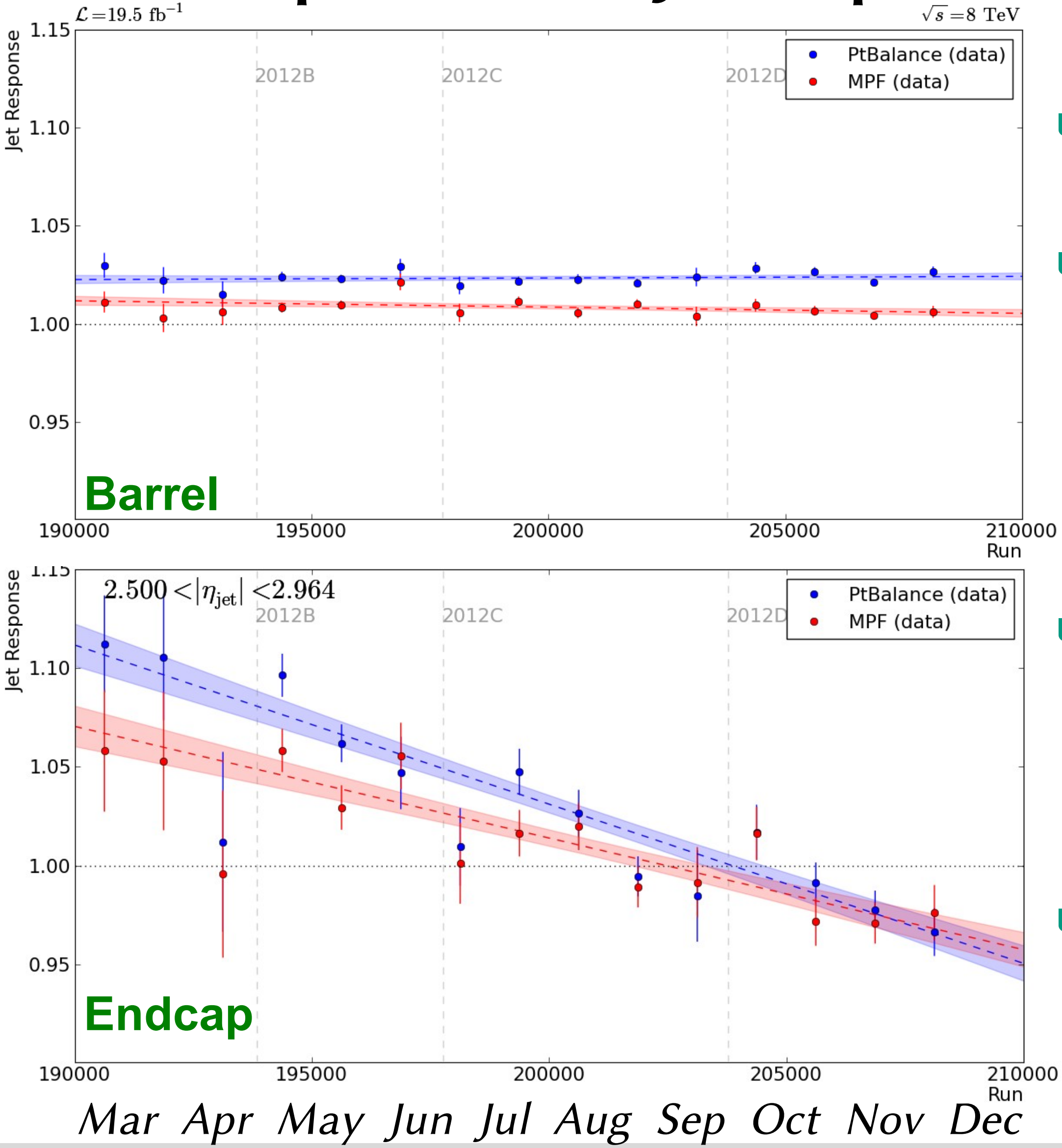
Extending to Higher η: Leading Jet Composition





- Energy deposits in detector components in the barrel well described
- Less agreement in endcaps, especially ***outside tracking***

Time Dependence of Jet Response in Endcap



- jet measurement should be stable over the run periods
- stable jet response in the **barrel** over all run periods

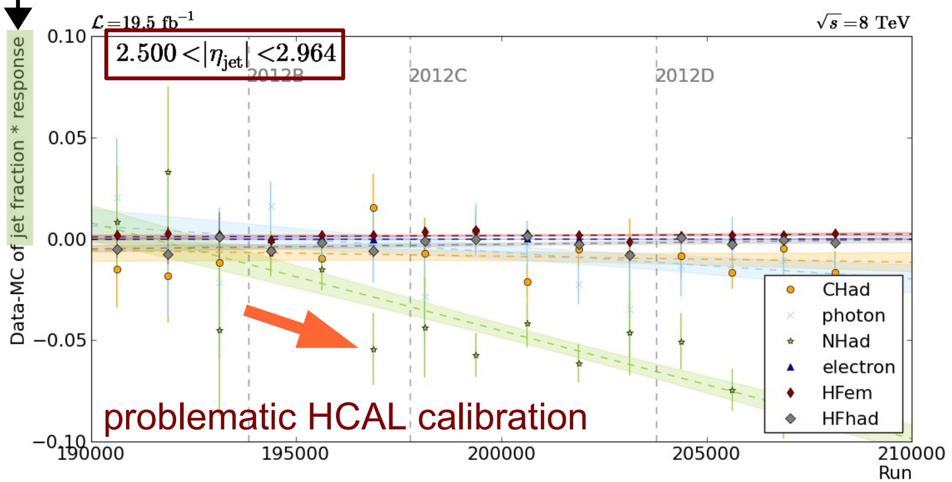
- Drastically decreasing jet response in the ***endcaps*** (difference: 15%)

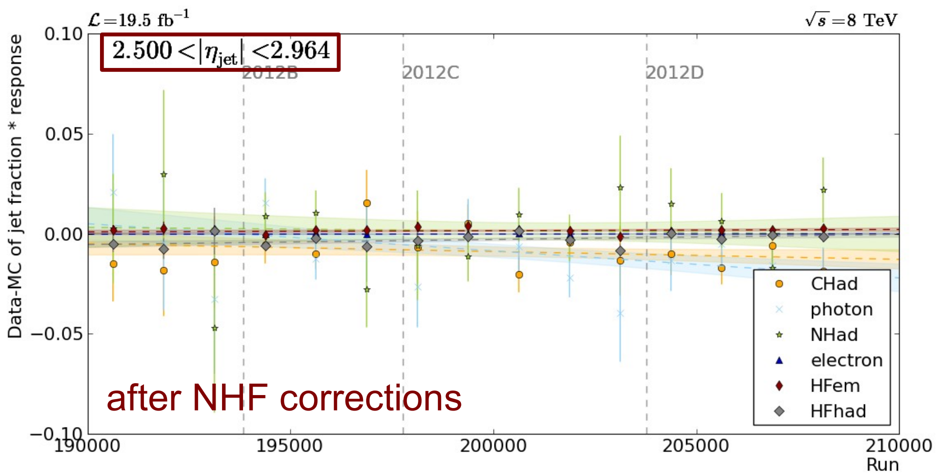
- Partially recovered by new HCAL calibration and new reconstruction of the events

Reason: Radiation Damage in HCAL

Response in detector components

$E_{\text{component of leading jet}}/E_Z (= f_{\text{component}} \cdot R)$

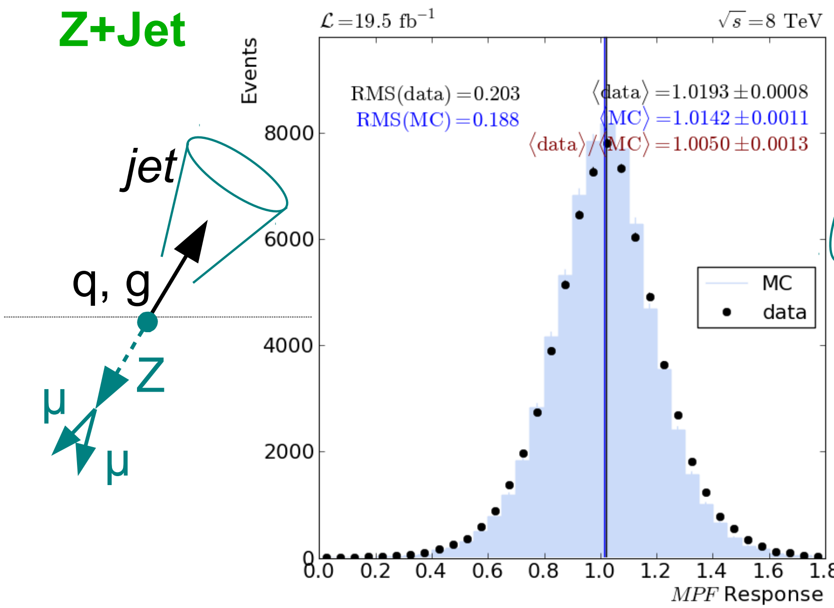




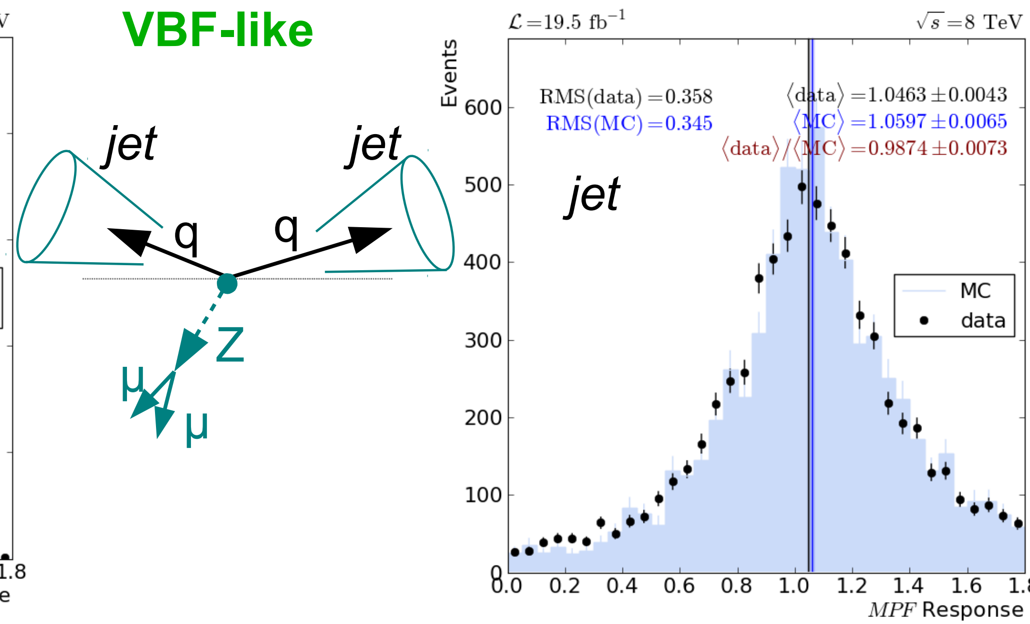
- Intransparency due to radiation damage in HCAL
  - $\rightarrow$ falling trend in the neutral hadron energy fraction (NHF)
  - $\rightarrow$ bias in jet response in endcaps
- A dedicated run dependent residual calibration of the neutral hadron energy fraction (NHF) corrects for this effect
- Implemented in $H \rightarrow \tau\tau \rightarrow \mu\mu$ analysis

Validation of Jet Energy Scale in VBF Topology

Z+Jet



VBF-like



$$R_{\mathrm{balance}} = \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\mathrm{Z}}}$$

- high statistics
- perfectly suitable sample

$$R_{\mathrm{balance}} = \frac{(p^{\mathrm{jet1}} + p^{\mathrm{jet2}})_{\mathrm{T}}}{p_{\mathrm{T}}^{\mathrm{Z}}}$$

- less statistics
- worse resolution
- wide tails

VBF jet selection

2 jets with a rapidity gap

$|p_{\mathrm{T}}^{\mathrm{jet1,2}}| > 30$ GeV

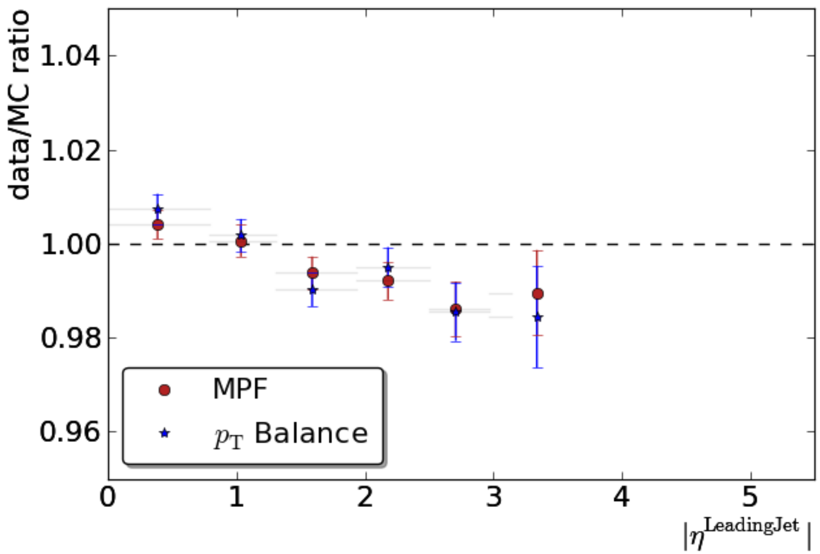
$|\eta_{\mathrm{jet1}} - \eta_{\mathrm{jet2}}| > 4.0$

$\eta_{\mathrm{jet1}} \cdot \eta_{\mathrm{jet2}} < 0$

$|m_{\mathrm{jet1,jet2}}| > 500$

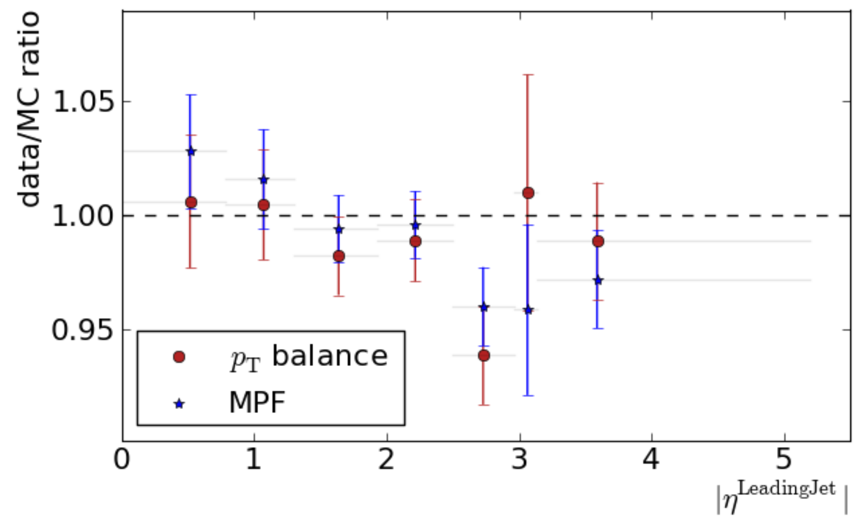
Jet Energy Scale in Z+Jet and VBF Topology

Z+Jet



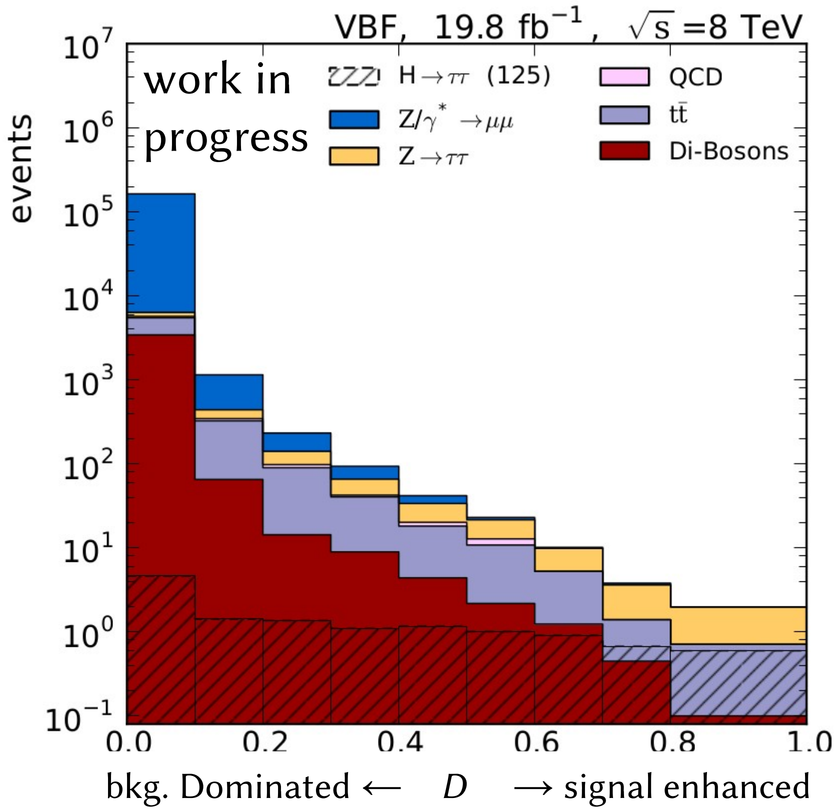
- High statistics
- Perfectly suitable sample
- Jet energy calibration in endcap and forward region is doable with Z(⟶μμ)+jet events

VBF-like



- compatible with Z+jet results
- link between dijet and Z+jet derived corrections
- **default calibration is valid for VBF-shaped events**

Back to H ⟶ ττ: Final Discriminator in VBF Category



Advanced treatment of jets in $H \longrightarrow \tau\tau \longrightarrow \mu\mu/ee$ analyses:

- Official jet energy calibration
- Charged Hadron Subtraction
- Pile-up jet identification
- Run dependent corrections

Propagating jet related uncertainties through the analysis

⇒ 6% jet energy scale uncertainty

- Data-driven background estimation
- Uncertainties on theory predictions for signal samples?

Theory Uncertainties in the VBF Category

- evaluation of theory uncertainties in the VBF category
- discriminator influenced by jet kinematics via $\Delta\eta$ and m_{jj}
- Reweighting of signal samples to follow the $\Delta\eta$ and m_{jj} variations on generator level
- 30% ggH in VBF category signal
  $\longrightarrow$ qqH *and* ggH samples

List of variations

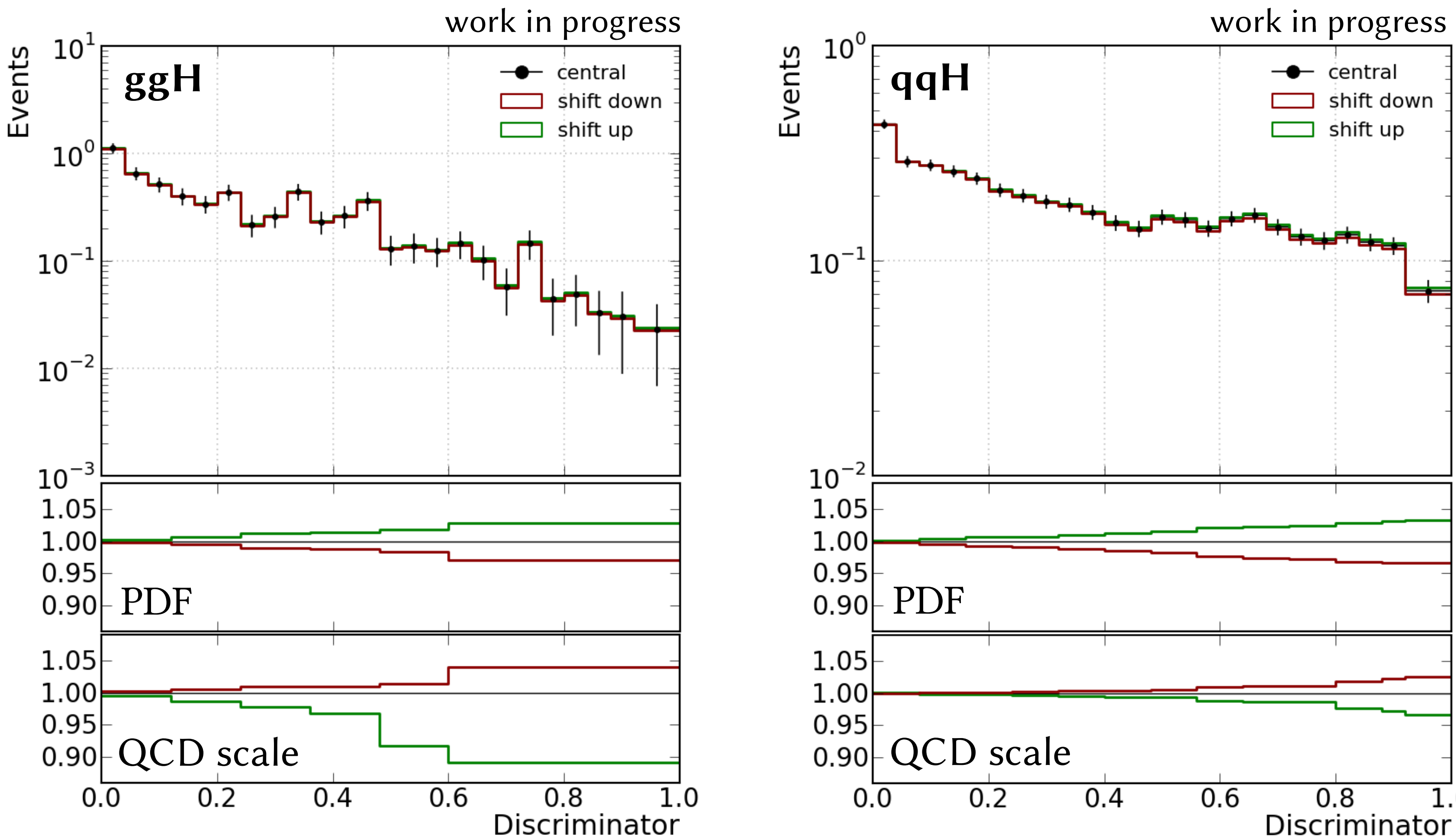
- PDF (using LHAPDF 5.9)
  - CT10
  - MWST
  - NNPDF

  qqH: ± 3.6%
  ggH: ± 9.7%
- matching scale
  - 30 GeV compared to 1 GeV
- renorm., factorization scale
  - $\mu_r = \mu_f = 0.5$
  - $\mu_r = \mu_f = 2.0$

  qqH: ± 0.9%
  ggH: ±18.2%
- MC generators compared with Powheg
  - Madgraph
  - MiNLO

  qqH: ± 1.4%
  ggH: ± 7.4%
- Parton shower/underlying event

Shape Uncertainties in the VBF Category



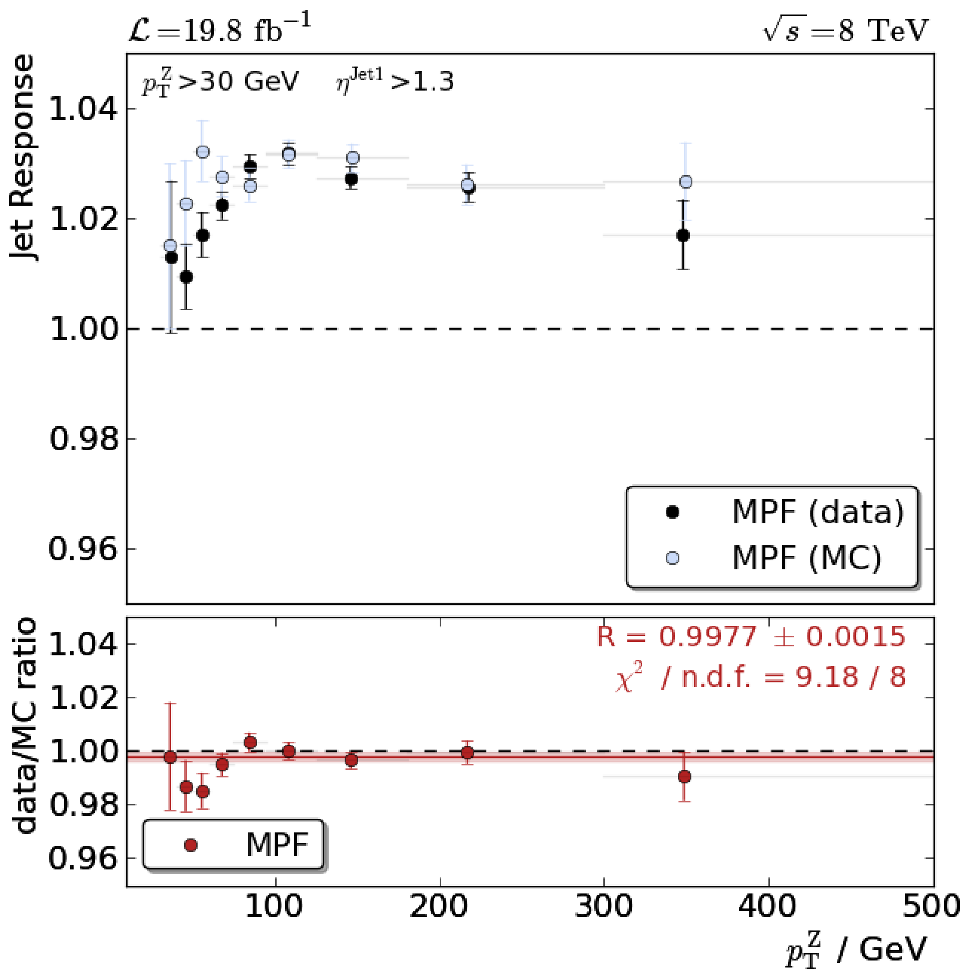
- only small additional shape uncertainty

Conclusion

- data-driven jet energy calibration in CMS
  - uncertainties on jet energy scale could be reduced down to 1%
  - methods and first calibration described in
    JINST 6 (2011) P11002 http://iopscience.iop.org/1748-0221/6/11/P11002
  - recent results are available in
    CMS-DP 2013/011 http://cdsweb.cern.ch/record/1545350
  - paper planned
- advanced pile-up mitigating techniques help to cope with increased pile-up
  - jet corrections for pile-up, Charged Hadron Subtraction, pile-up jet ID
- $H \longrightarrow \tau\tau \longrightarrow \mu\mu$ analysis
  - VBF is the most sensitive category
  - jet kinematics are the defining properties
  - estimation of jet related systematic uncertainties
  - paper is in preparation
  - full analysis will be presented by Thomas Müller on Wednesday

Backup

Jet Response at High Rapidities



Pile-Up Corrections

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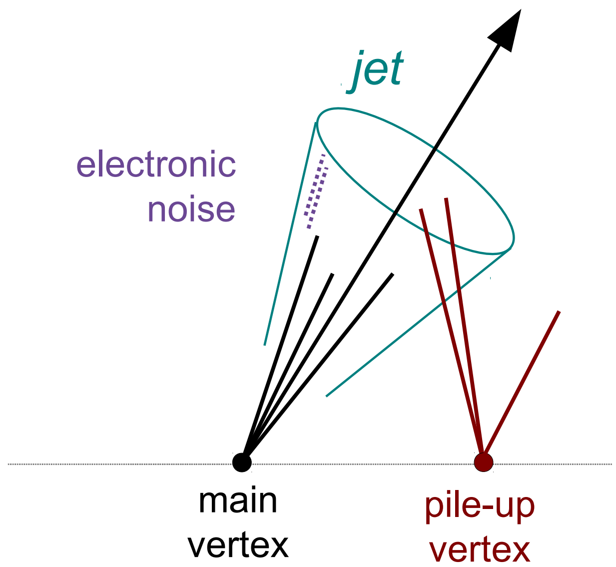
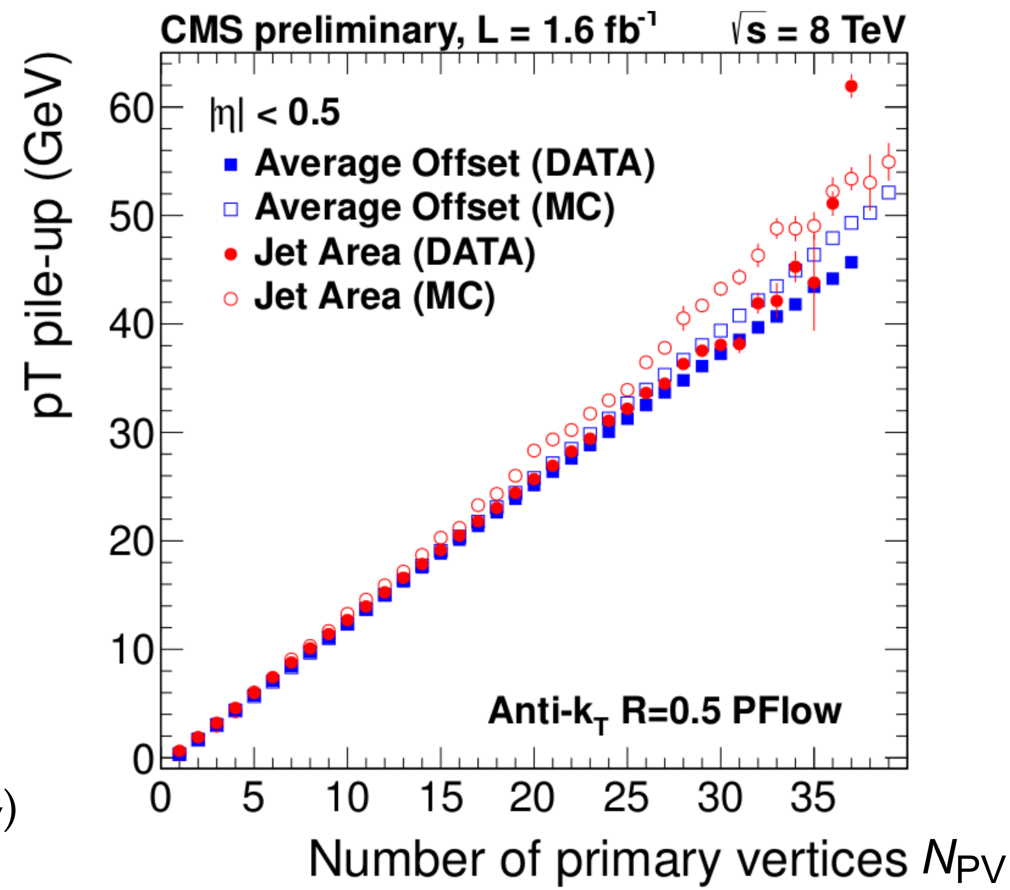
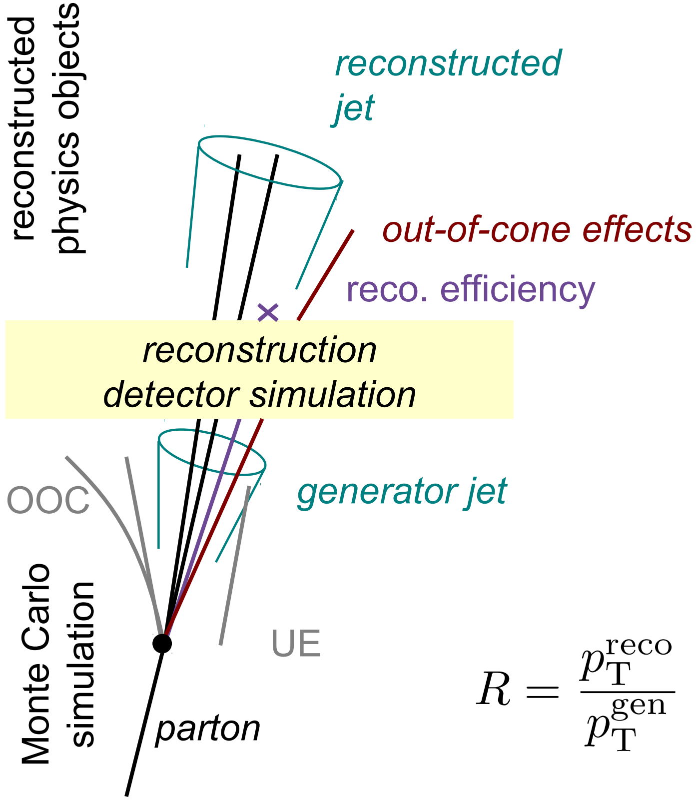




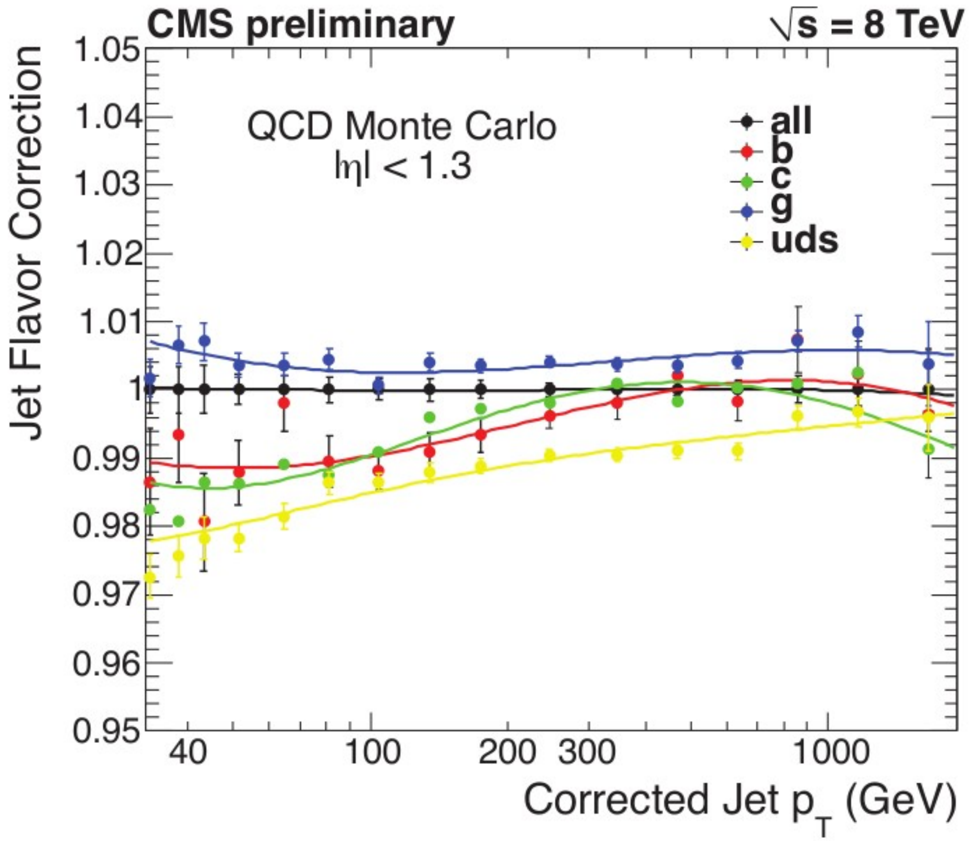
2 combined methods to measure and correct for pile-up and noise

- Average Offset Correction (N_{PV})
- Jet Area Correction (A_j, ρ)
  A_j: jet area
  ρ: energy density from pile-up in the event
  [arXiv:0707.1378v2] Salam. et al.

Corrections Based on MC Simulation



$$R = \frac{p_T^{reco}}{p_T^{gen}}$$



- correction for p_T and η dependence
- reconstructed jet p_T is corrected to the generator jet (based on QCD MC)

- Particle Flow minimizes flavor dependence (< 3% in barrel)
- no flavor corrections by default

Closure Test of MC Corrections

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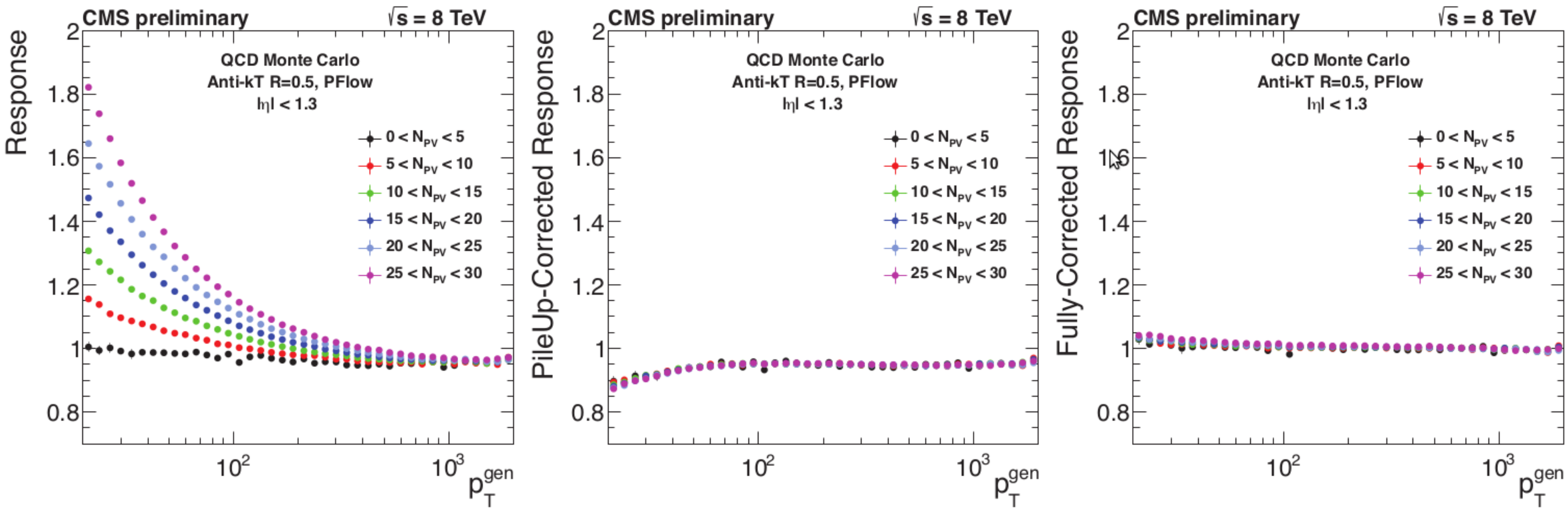


Before corrections

- high contribution of PU especially at low p_T
- additional $p_T \sim N_{PV}$

After pile-up corrections

- pile-up dependence removed
- consistent for any number of PU interactions N_{PV}

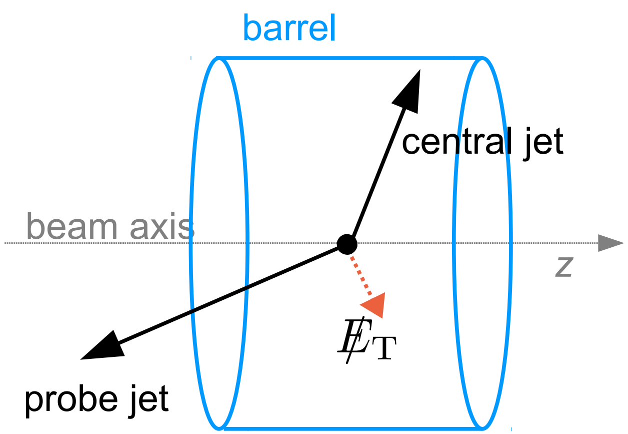
After MC truth corrections

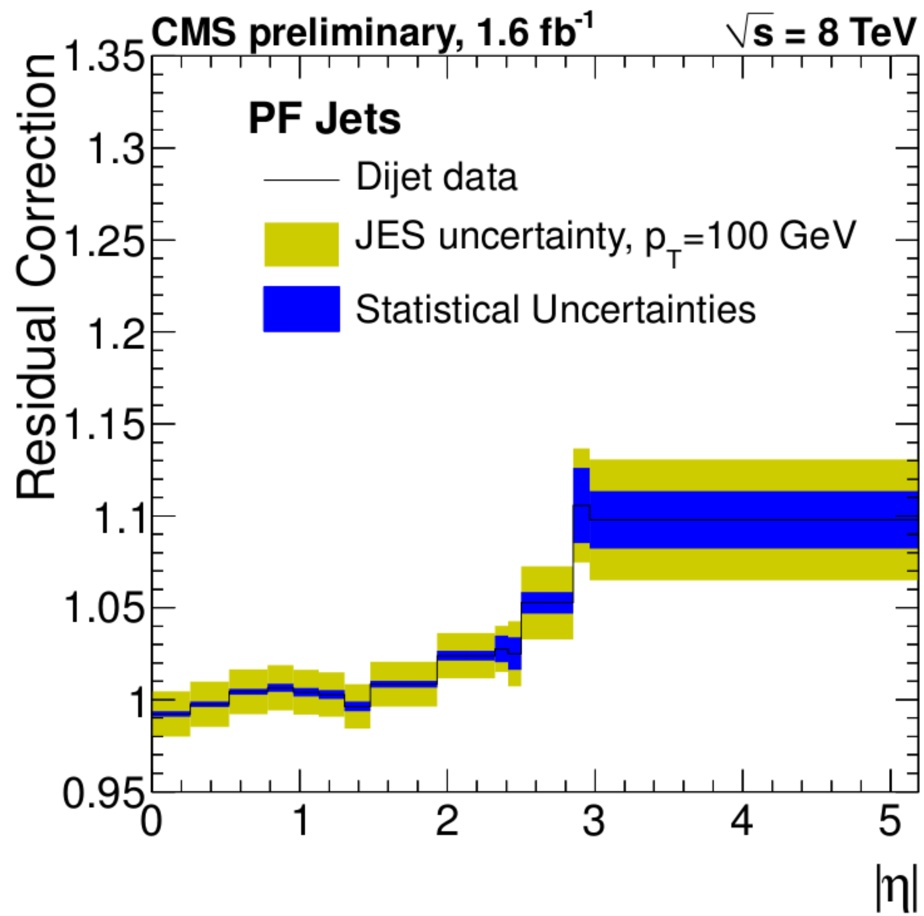
- closure at unity over the whole p_T and η range

final correction for simulation, additional corrections for data needed

Data-Driven Corrections for η Dependence

- correct for residual difference in η between data and MC
- derived from dijet balance



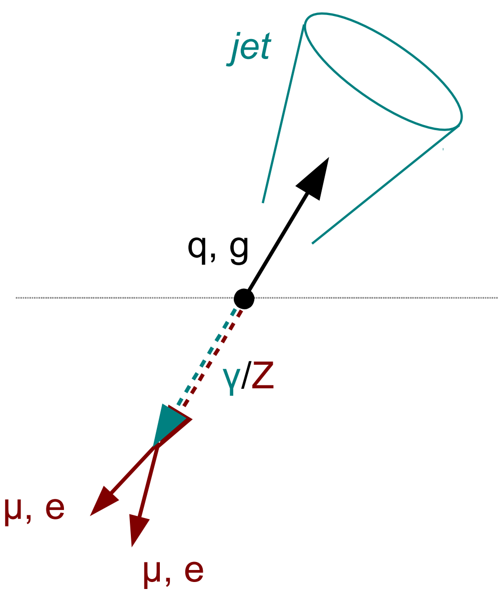


- calibration factor is derived such that reconstructed MET vanishes

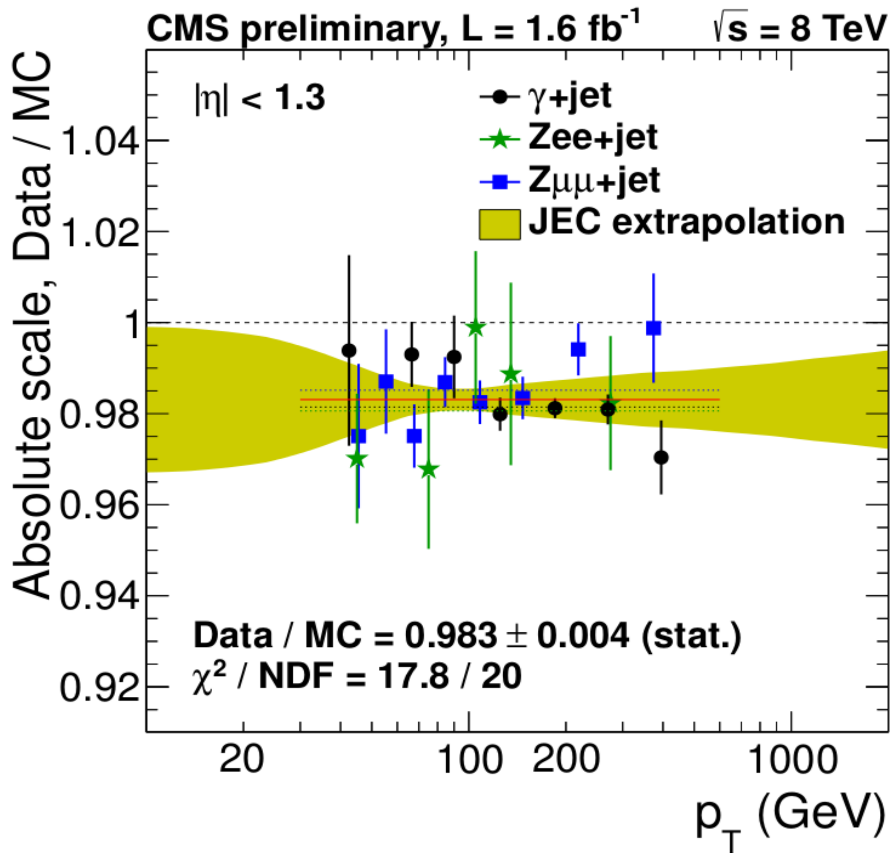
  (MPF method, → backup)
- extrapolation to perfect topology with no additional jet activity

Data-Driven Corrections of the Absolute Scale

- correction for residual differences in p_T between data and MC
- 3 complementary topologies:
  - γ + jet
  - $Z(\longrightarrow ee)$ + jet
  - $Z(\longrightarrow \mu\mu)$ + jet

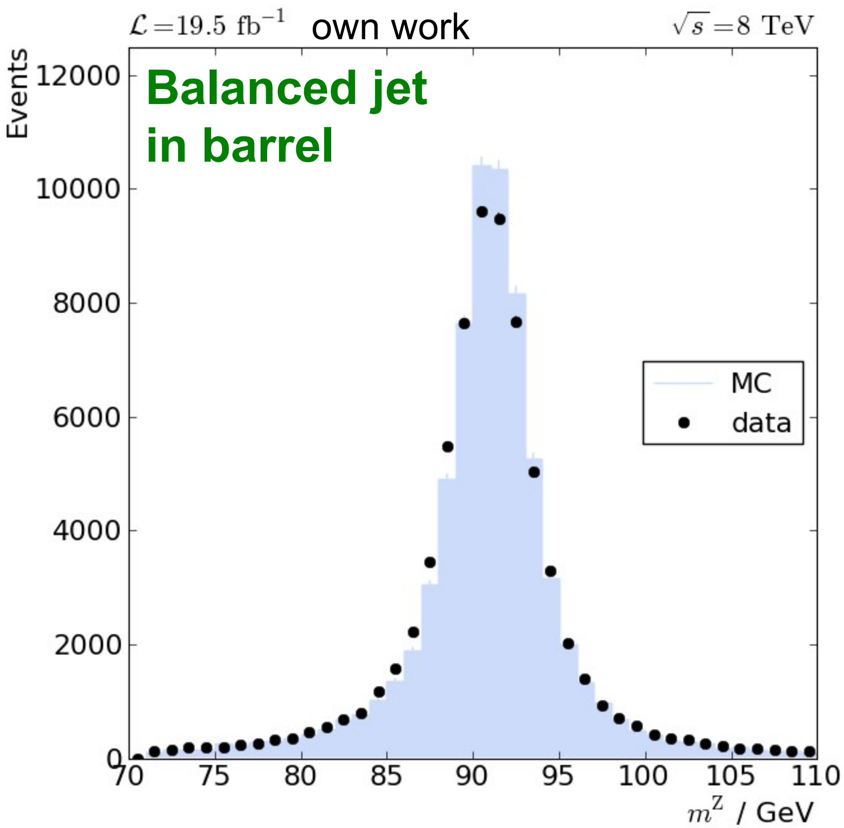


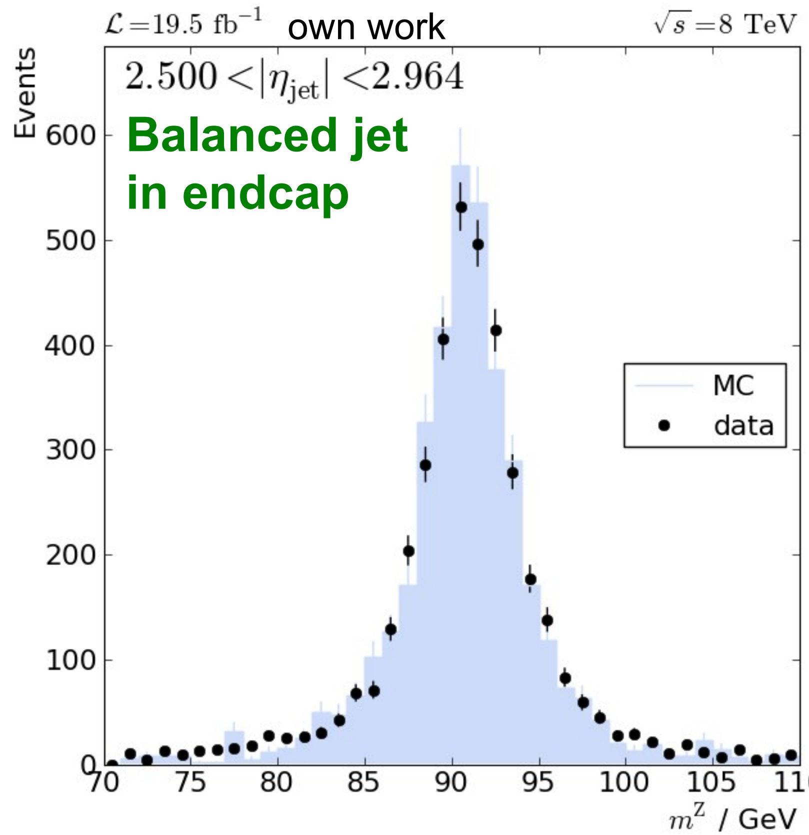
⇒ *final correction of jet p_T*



- γ/Z measurement with high precision
- absolute scale with MPF method
- extrapolation to perfect topology

Reference Object Measurement: Z Boson





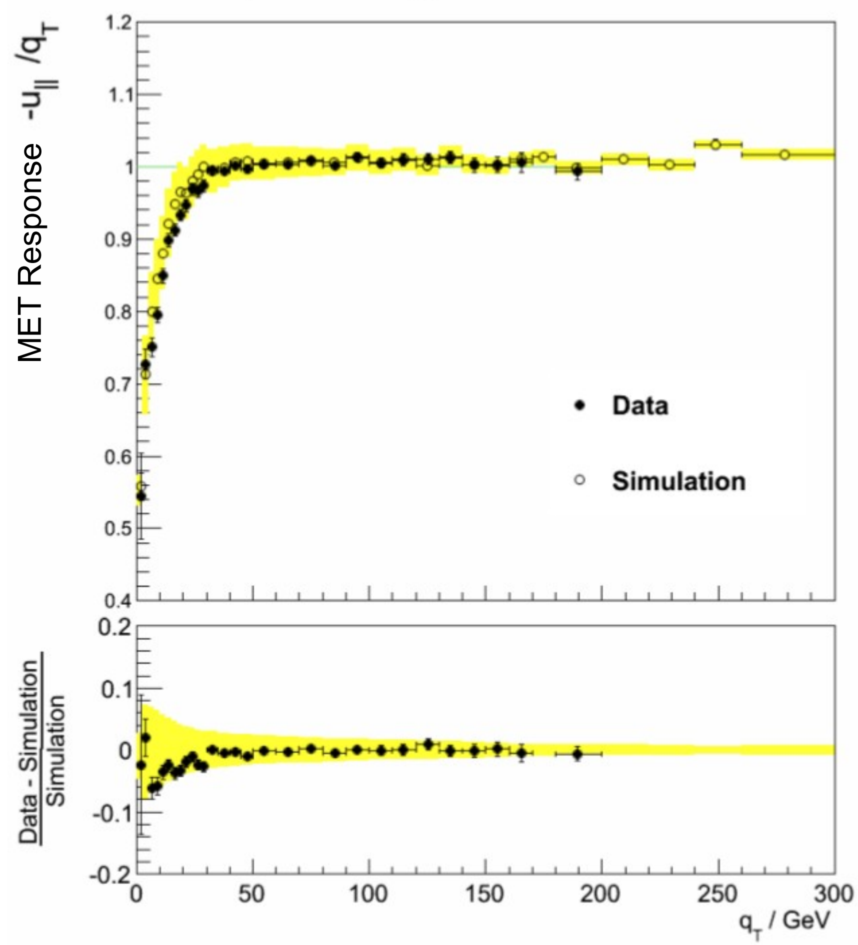
- High accuracy in muon reconstruction
  $\longrightarrow$ Data/MC difference ~ 0.1%

- Less events in endcap
- **Still high accuracy in muon measurement with endcap jets**

Missing Energy Corrections

- corrected MET:
  - (1) jet corrections are applied
  - (2) MET is recalculated
- MET response is close to unity after corrections in data and MC

CMS preliminary, $\sqrt{s}$=8 TeV L = 0.7 fb^{-1}



VBF Z Event Selection

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Reconstruction of the Z

- muon transverse momentum — $p_{\mathrm{T}}^{\mu} > 20\ \mathrm{GeV}$
- muon pseudorapidity — $|\eta^{\mu}| < 2.3$
- muon isolation — $\sum_{\mathrm{tracks}} p_{\mathrm{T}} < 3\ \mathrm{GeV} \quad \mathrm{within}\ \Delta R < 0.3$
- mass of muon pair — $|m_{\mu\mu} - m_{\mathrm{Z}}| < 20\ \mathrm{GeV}$
- Z transverse momentum — $|p_{\mathrm{T}}^{\mathrm{Z}}| > 10\ \mathrm{GeV}$ — lower than for Z+Jet

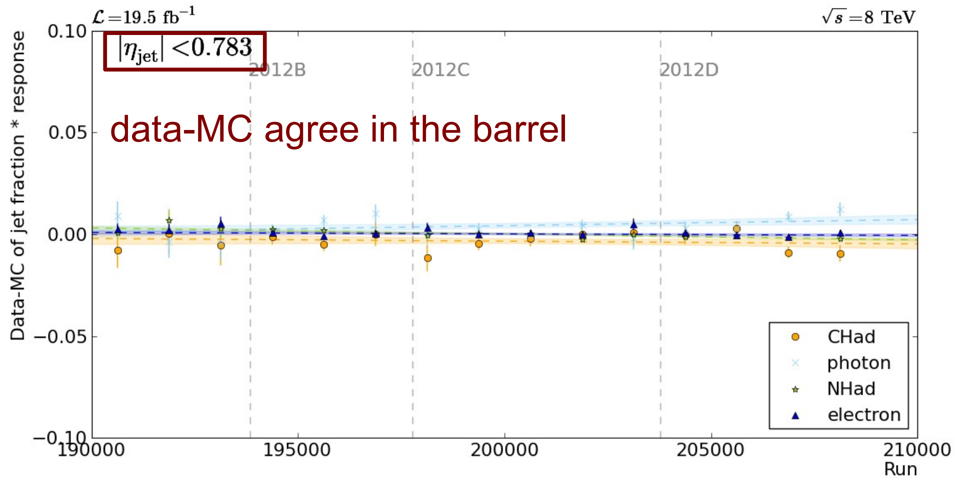
Jet selection

- transverse momentum — $|p_{\mathrm{T}}^{\mathrm{jet1,2}}| > 30\ \mathrm{GeV}$
- pseudorapidity of leading jet — $|\eta^{\mathrm{jet1,2}}| < 5.0$
- rapidity gap — $|\eta_{\mathrm{jet1}} - \eta_{\mathrm{jet2}}| > 4.0$, $\eta_{\mathrm{jet1}} \cdot \eta_{\mathrm{jet2}} < 0$
- invariant mass — $|m_{\mathrm{jet1,jet2}}| > 500$

VBF jets

- *no balancing*
- *no 3rd jet cut*

Leading Jet Composition in the Barrel



Run-Dependent HCAL Correction

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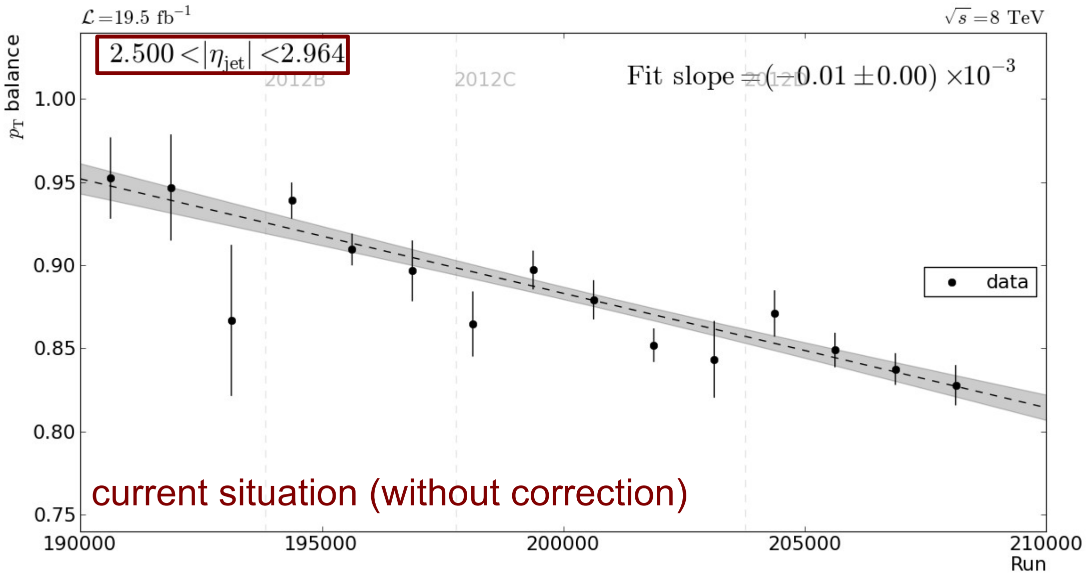

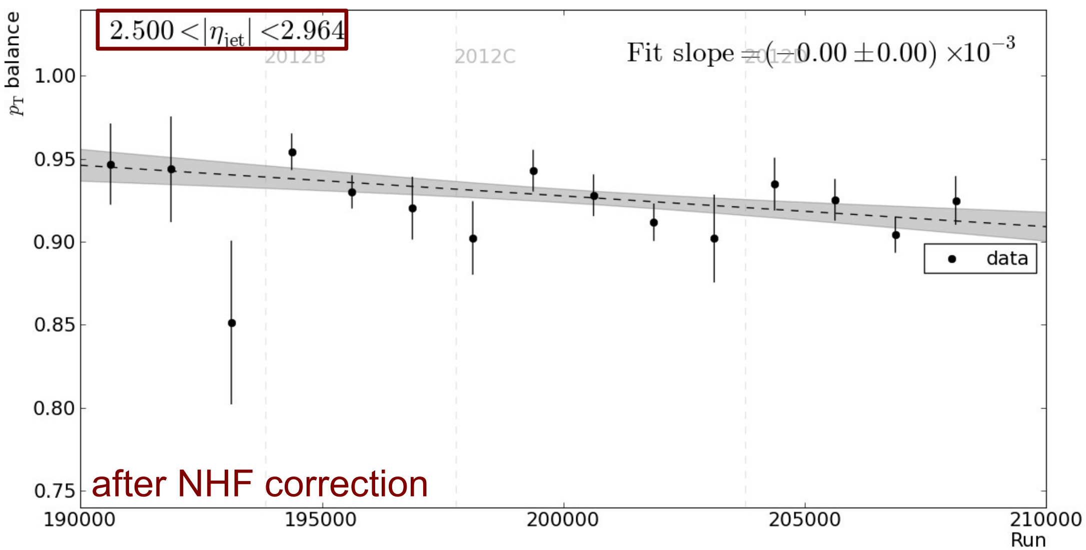

- Effect on response:
  - Slope is drastically ***reduced*** by this correction

→ The decreasing HCAL response is the relevant part of the problem

- Compatible with a flat line
- Other influences possible

Background Estimation for L = 19.5 fb^{-1}

Dataset	Data	DY+jets	QCD	W+jets	$t\bar{t}$+jets
σ / pb^{-1} (NNLO)		3 503.71	3.64×10^8	225.20	37 509.00
Filter efficiency		1	3.7×10^{-4}	1	1
Events in sample		30 459 503	21 484 602	5 186 494	57 709 905
Z selection	1 235 419	1 226 784	< 341	7 130	243
			$< 0.03\%$	0.58%	0.02%
Final selection	69 138	73 719	< 341	46	< 35
			$< 0.49\%$	0.07%	$< 0.05\%$

Signal

- Absolute scaling agrees within uncertainties
- Reminder: Scaling factor to luminosity has no influence on the final result

Background

- Negligible contribution from other processes