Multi jet measurements with the CMS detector at $\sqrt{s}$ =7 TeV

Joanna Weng

(ETH Zurich)

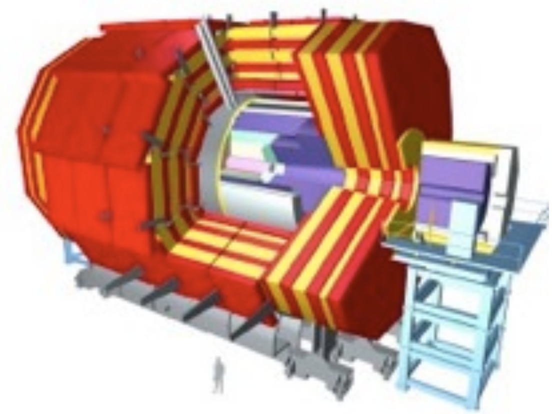
on behalf of the CMS Collaboration

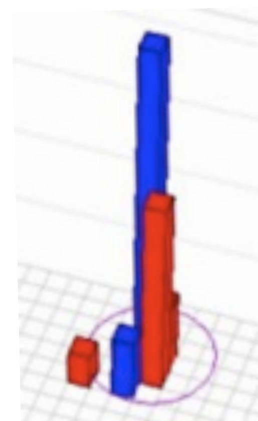
DIS 2011

XIX International Workshop on Deep-Inelastic Scattering and Related Subjects
Newport News, VA USA

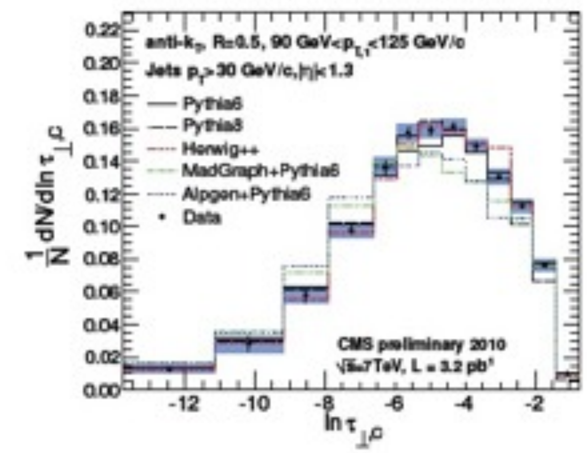
Outline

1. Jet reconstruction and performance in CMS

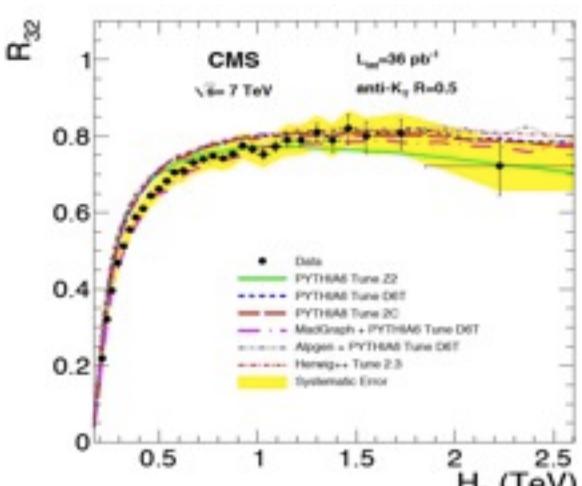




2. Hadronic Event Shapes



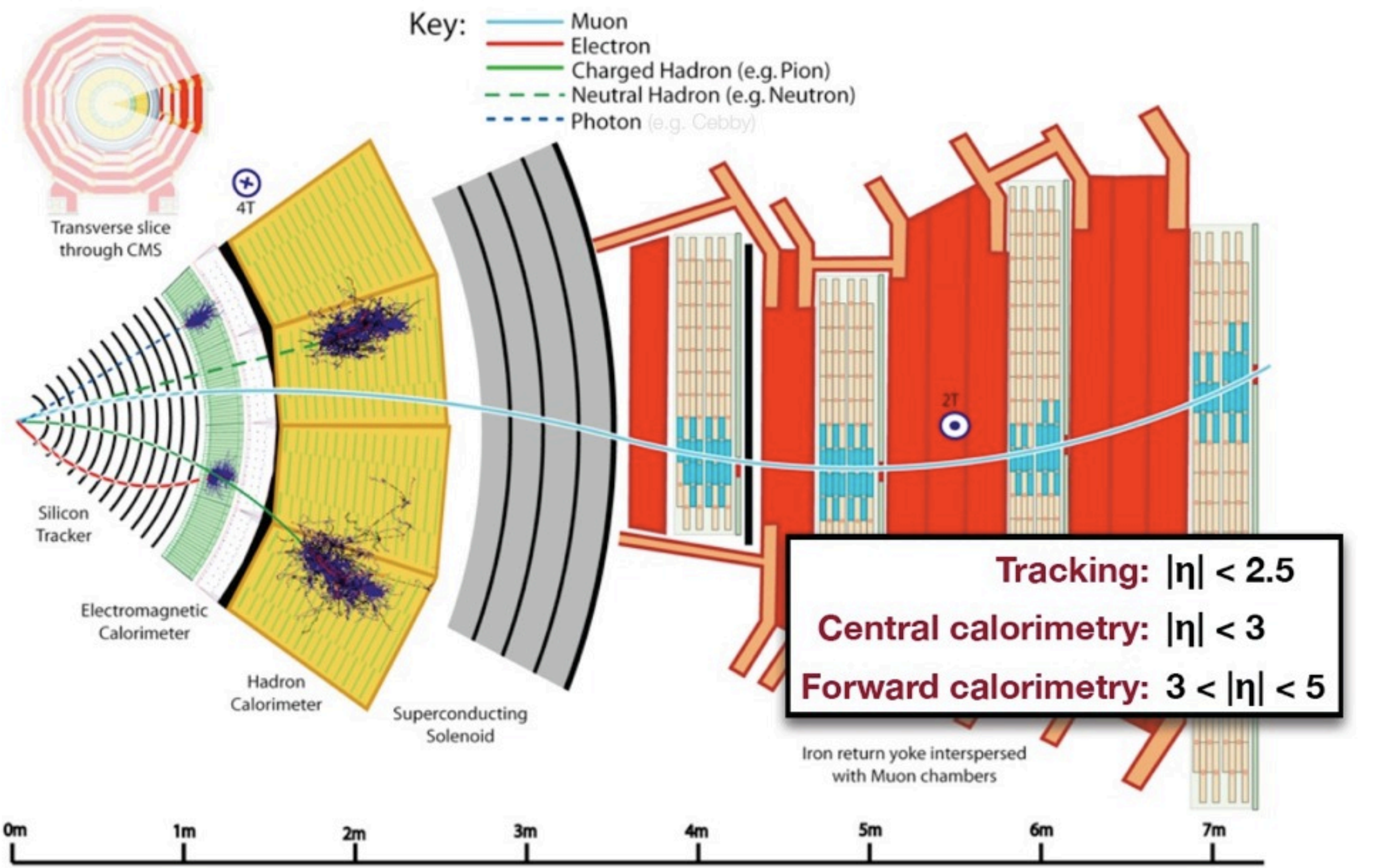
3. Three to two jet ratio (R_{32})



More Jet Results:
"Jet Results from CMS" by C.Dragoiu
(Tuesday 12th of April 2011, "Jet Cross Sections")

- Inclusive jet cross section
- Dijet mass cross section
- Dijet azimuthal decorrelations
- Dijet angular distributions

The CMS Detector

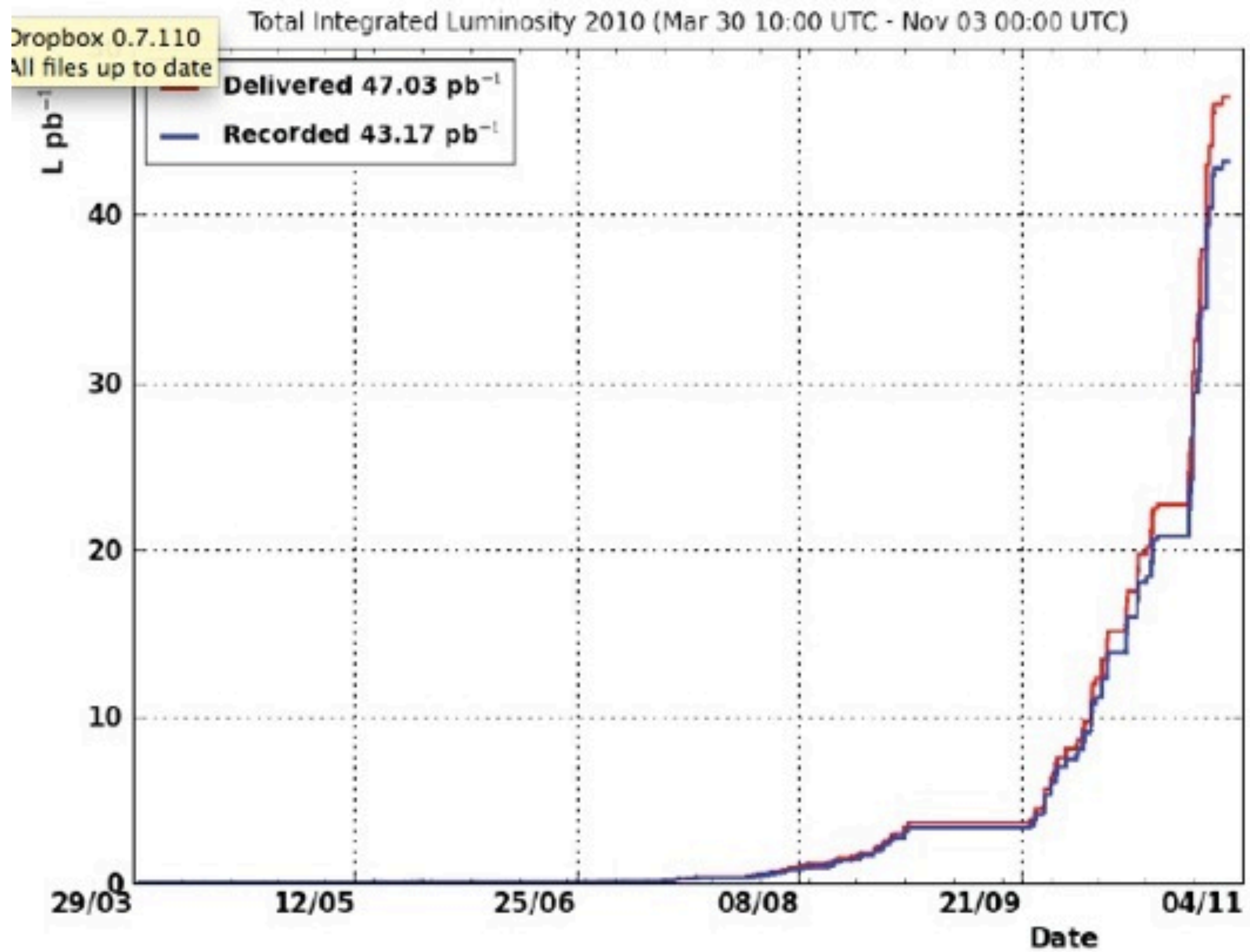


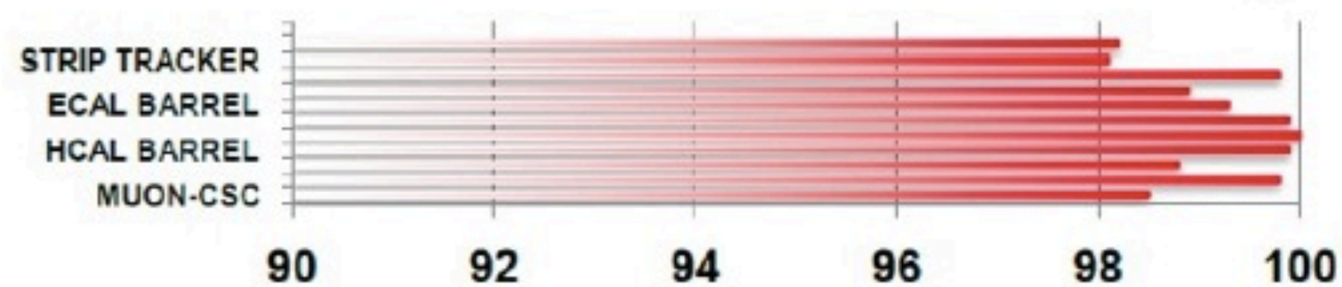
J.Weng

CMS Performance in 2010

ETH Institute for Particle Physics

- 47 pb^{-1} pp data at $\sqrt{s}$ = 7 TeV delivered by the LHC
- 43 pb^{-1} recorded by CMS
- Overall data taking efficiency greater than 90%
- All subdetectors have at least 98% of all channels operational





	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER	
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2	

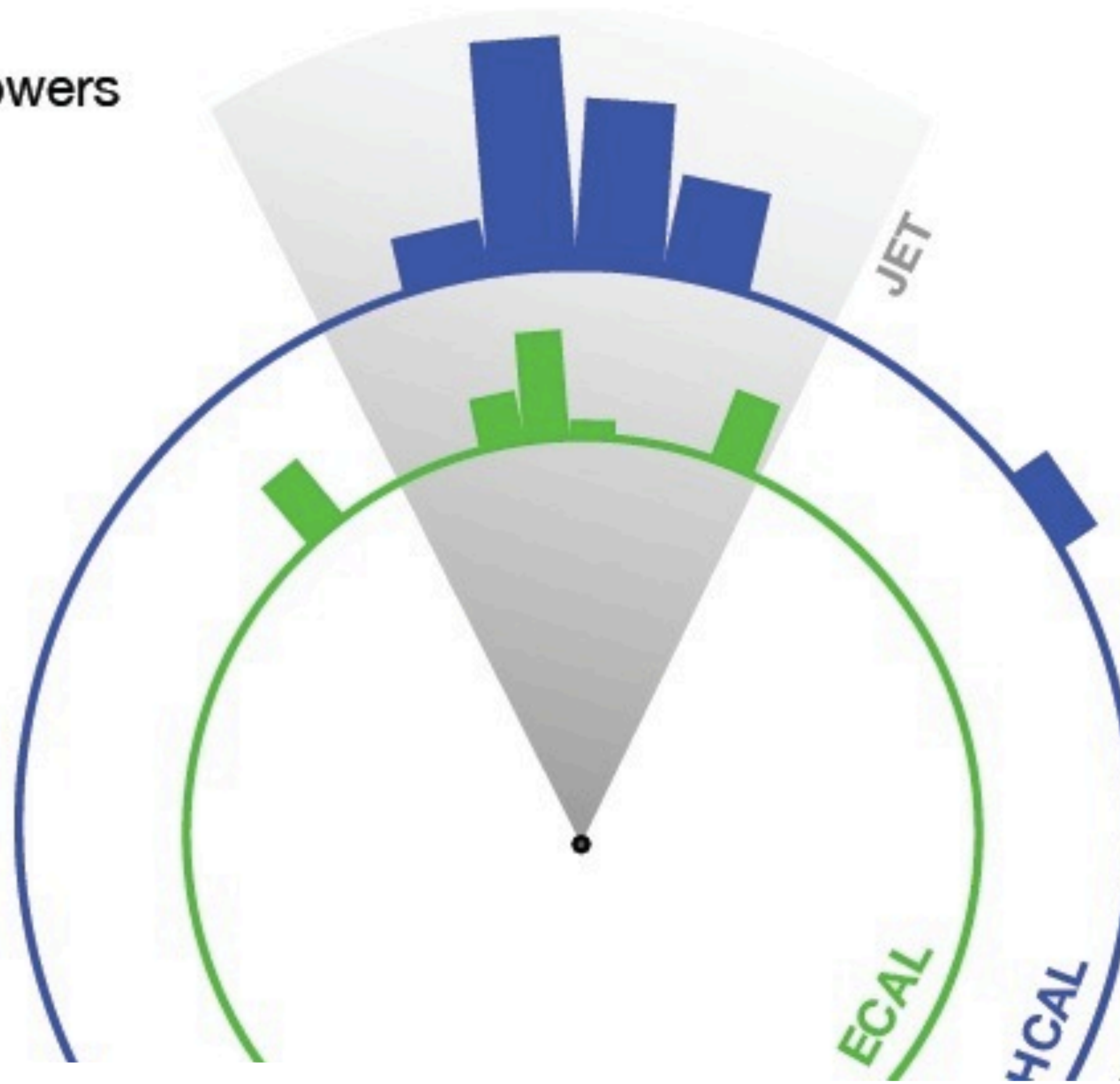
=> New Results based on up to **~35 pb^{-1}**
(**~ 85%** recorded with all sub detectors in perfect condition)

J.Weng

Jets in CMS

Default Jet Algorithm: Anti K_T with R=0.5

1. **Calorimeter Jets:** calorimeter towers



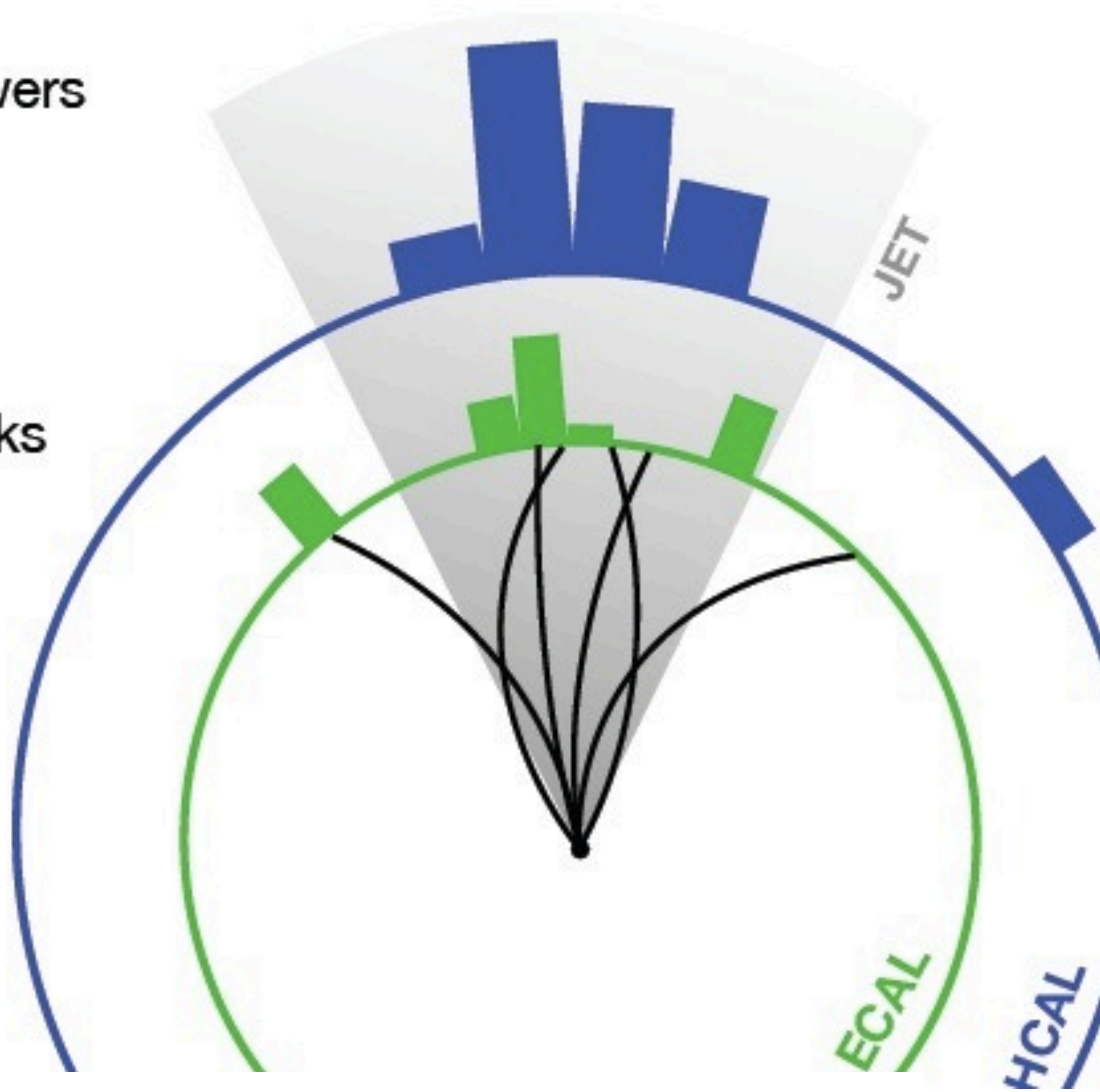
J.Weng

Jets in CMS

Default Jet Algorithm: Anti K_T with R=0.5

1. Calorimeter Jets: calorimeter towers

2. **Jet Plus Tracks:** correct for tracks



J.Weng

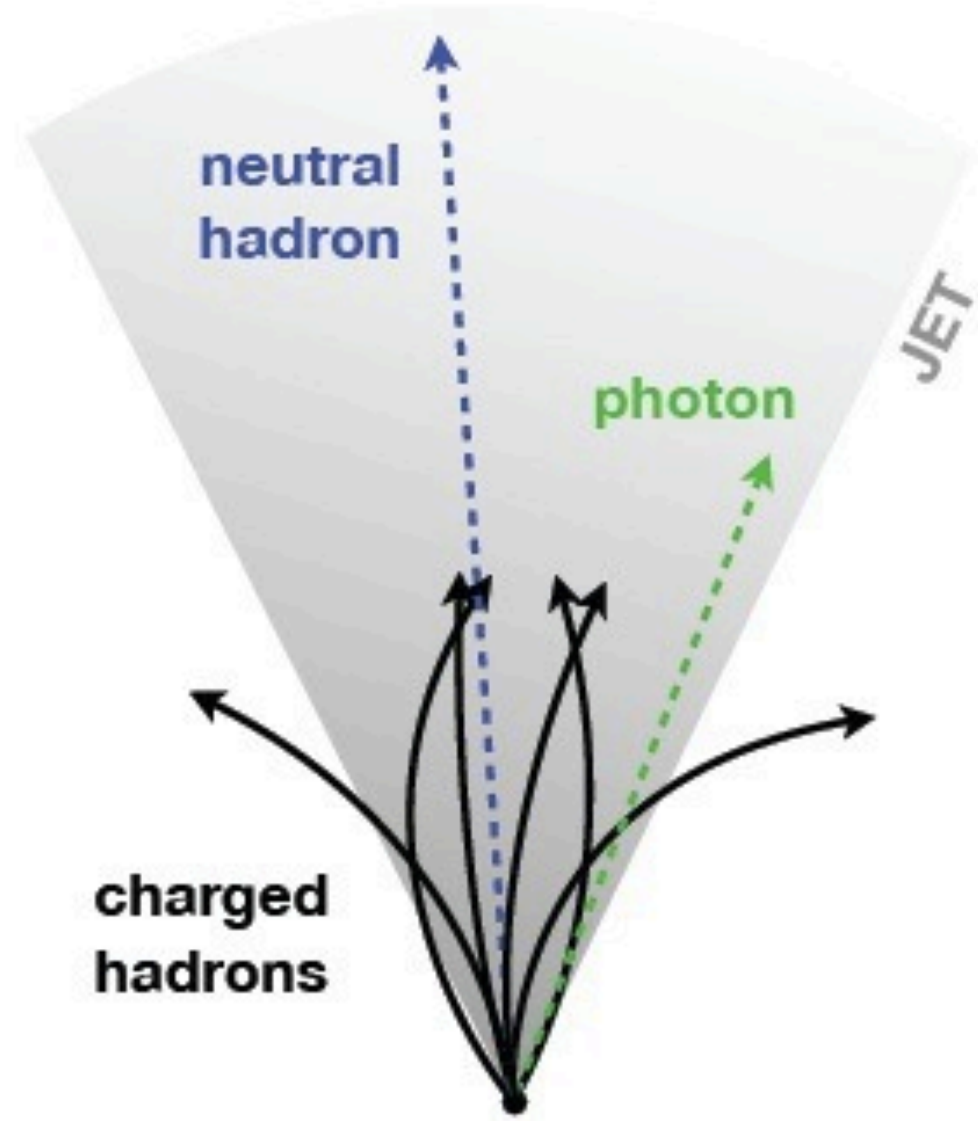
Jets in CMS

Default Jet Algorithm: Anti K_T with R=0.5

1. Calorimeter Jets: calorimeter towers

2. Jet Plus Tracks: correct for tracks

3. **Particle Flow:** particle candidates
(Unique list of already calibrated particles “a la Generator Level”)



J.Weng

Jets in CMS

1. Calorimeter Jets: calorimeter towers

PROS: robust

CONS: worst resolution

2. Jet Plus Tracks: correct for tracks

PROS: improve resolution with tracks

CONS: seeded on calorimeter jets

3. **Particle Flow:** particle candidates

best resolution

used in most analyses

=> Using different inputs allows CMS to make cross-checks and study experimental systematics
=> PF jets show best performance so far

J.Weng

Jet Calibration

Corrections derived on MC and applied to data
=> if non-closure → residual correction

$$\text{Response} = \frac{\text{Reco Jet } p_T}{\text{True Jet } p_T}$$

Physics Object

Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet

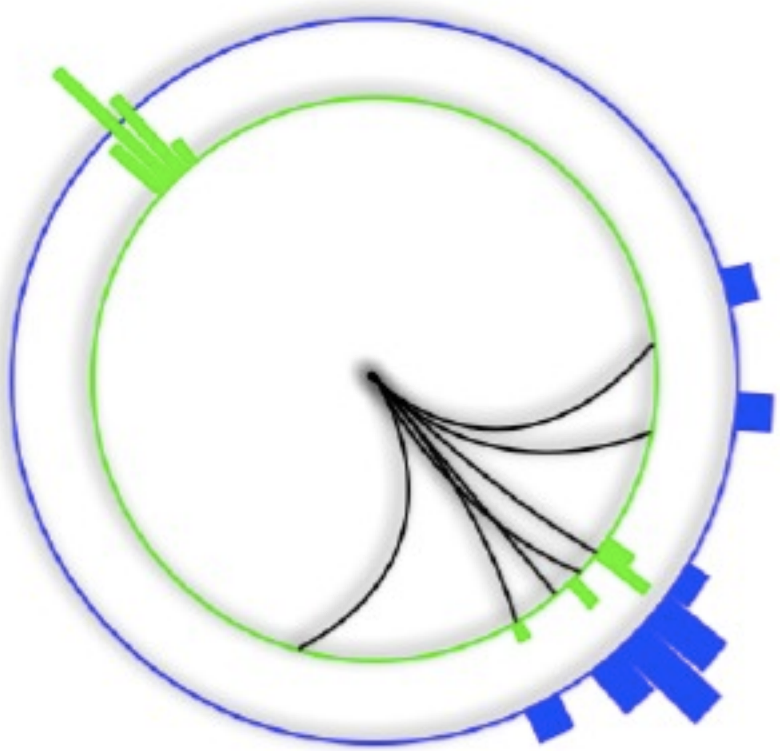
Di-jet p_T balance method:
Jet calibration vs. η in barrel ~1%, 2% in endcap

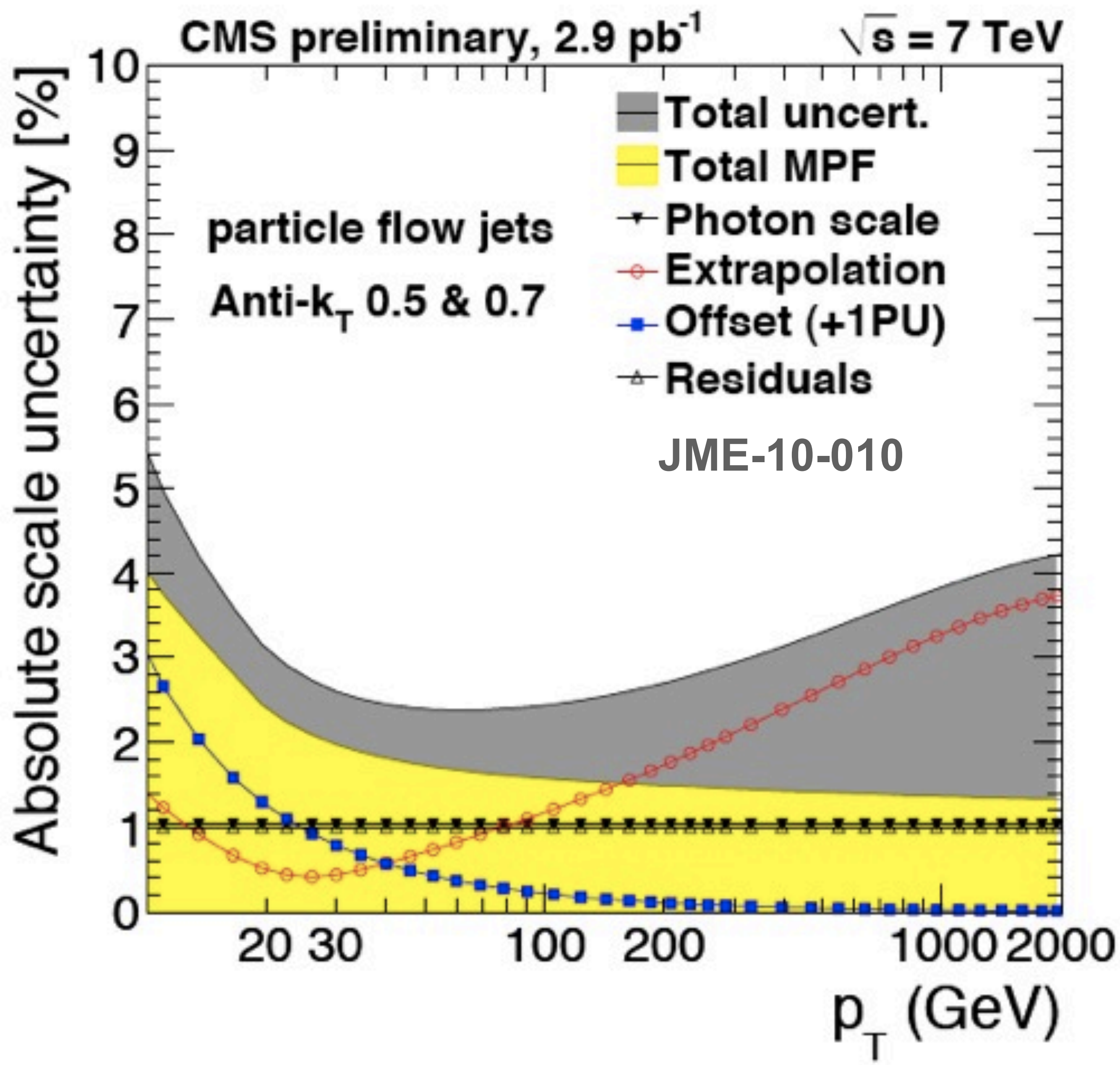
Jet Absolute Response

Transverse Plane balancing:
- Photon vs jet (pT balance)
- Photon vs Missing E_T: MPF

(Missing-ET Projection Fraction)

γ+Jet events:





- Jet energy scale uncertainty: 3-5% over whole p_T range
  (Recent studies (~35 pb^{-1}) show improvements)

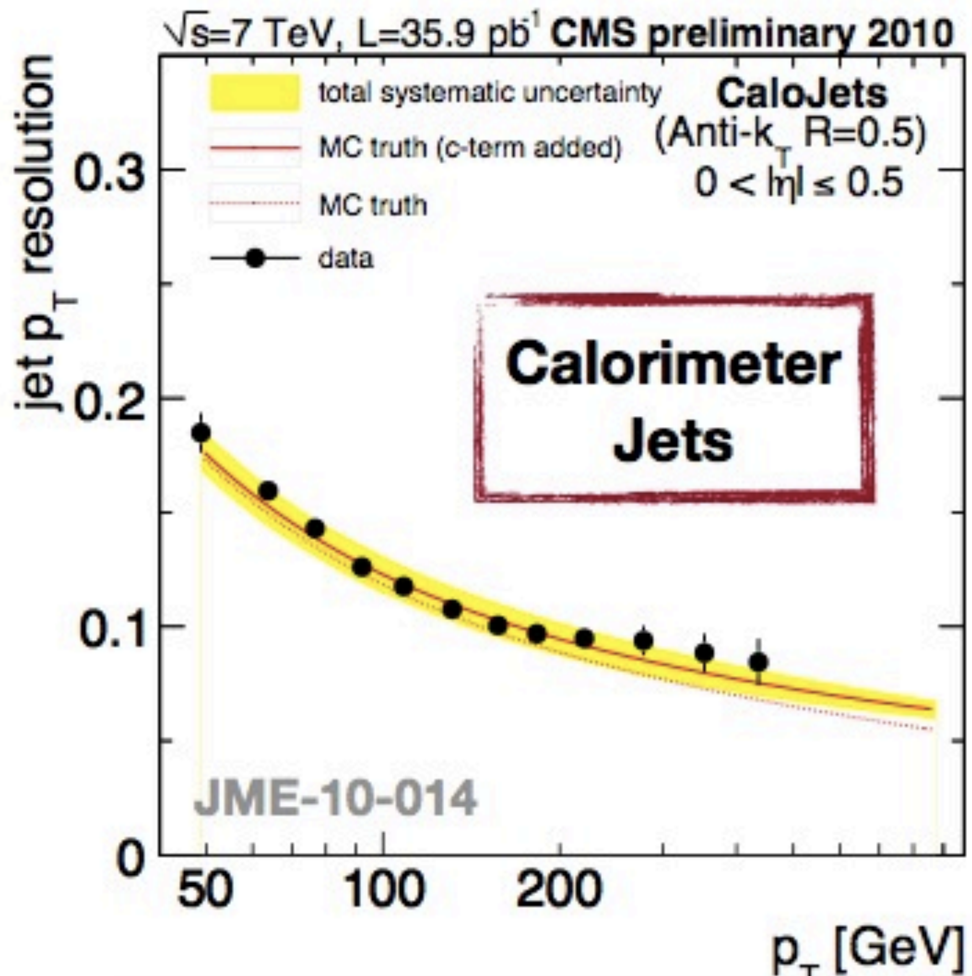
J.Weng

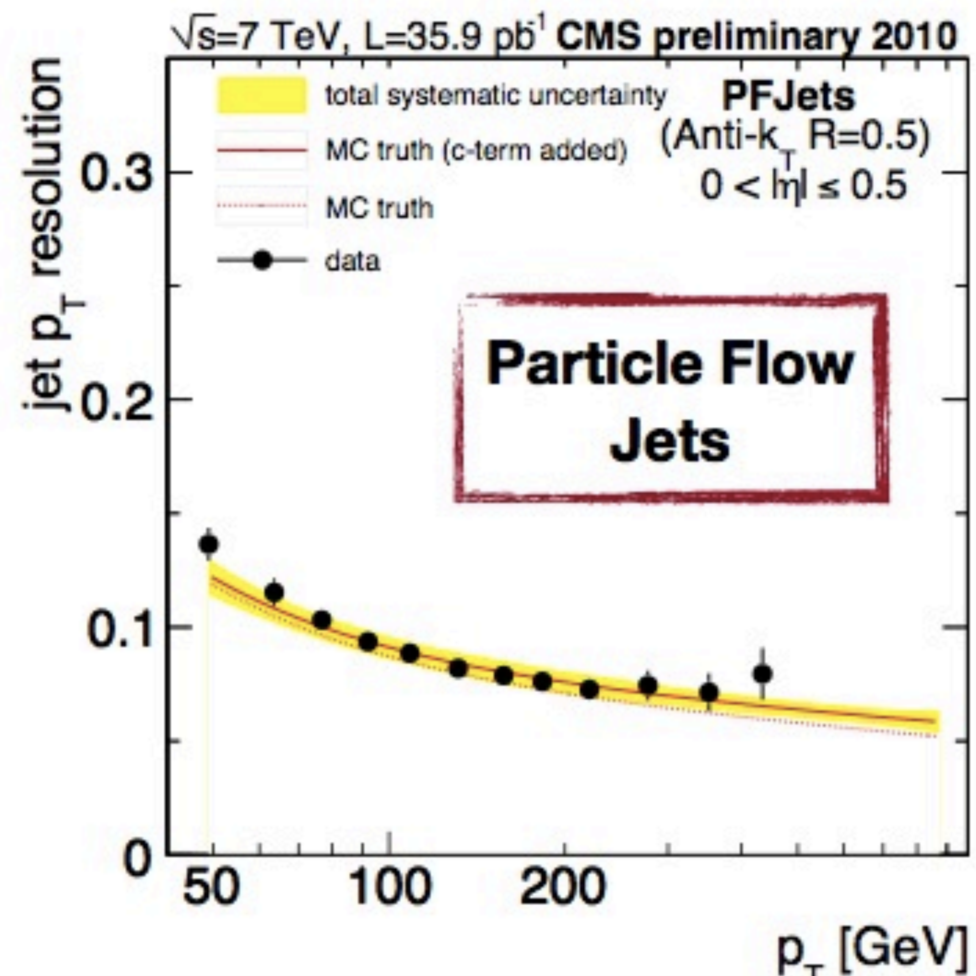
Jet Resolution

ETH Institute for Particle Physics

- Dijet asymmetry method:

$$\mathcal{A} = \frac{p_T^{\mathrm{Jet1}} - p_T^{\mathrm{Jet2}}}{p_T^{\mathrm{Jet1}} + p_T^{\mathrm{Jet2}}} \longrightarrow \frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_{\mathcal{A}}$$



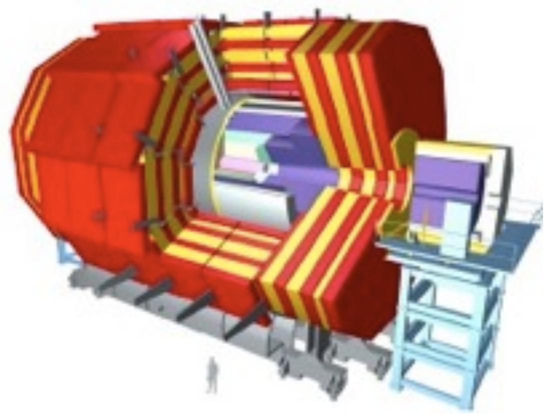


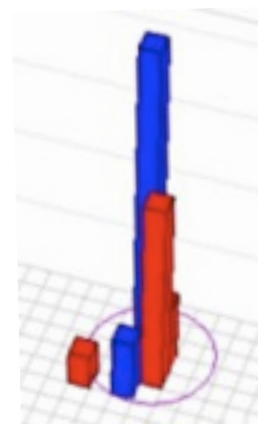
Some Numbers:
- Jet energy resolution from this method: 10% @ p_T = 100 GeV
- Jet position resolution in Φ and η: ~0.01 @ p_T = 100 GeV

J.Weng

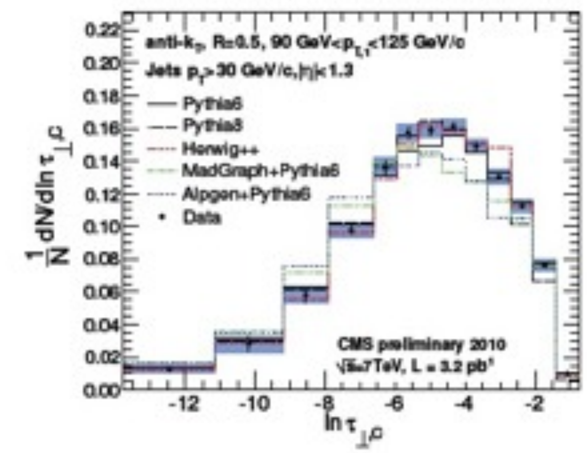
Outline

1. Jet reconstruction and performance in CMS

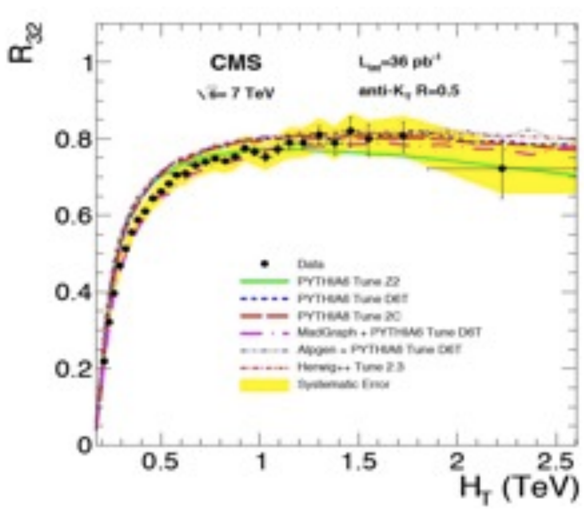




2. Hadronic Event Shapes



3. Three to two jet ratio (R_{32})



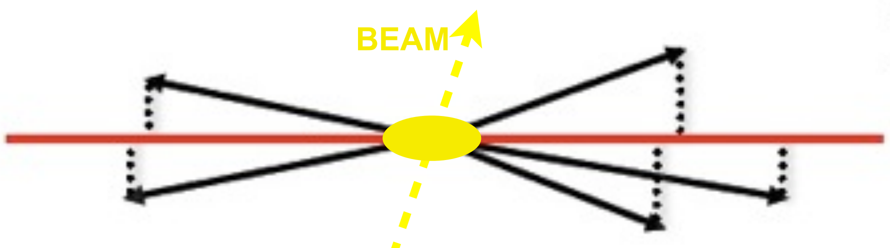
More Jet Results:
"Jet Results from CMS" by C.Dragoiu
(Tuesday 12th of April 2011, "Jet Cross Sections")

- Inclusive jet cross section
- Dijet mass cross section
- Dijet azimuthal decorrelations
- Dijet angular distributions

Event Shape Variables

Event Shapes can be used to distinguish between different models of QCD jet production
=> this is our goal for first measurement

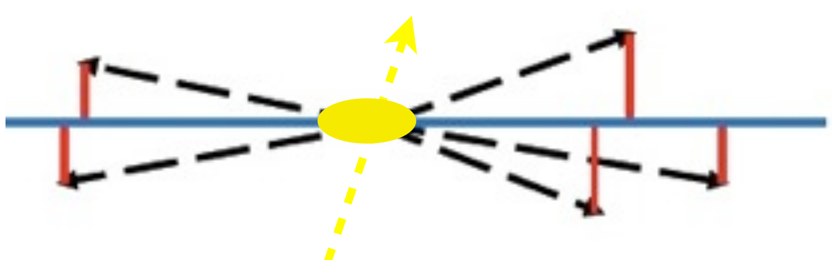
Central transverse thrust:



$$T_{\perp,\mathcal{C}} \equiv \max_{\vec{n}_T} \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i}\cdot\vec{n}_T|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

=> Maximum of projection on a transverse axis n_T

Central thrust minor:



$$T_{m,\mathcal{C}} \equiv \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i}\times\vec{n}_{\mathrm{T},\mathcal{C}}|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

=> Projection out of the plane of beam axis and transverse axis n_T

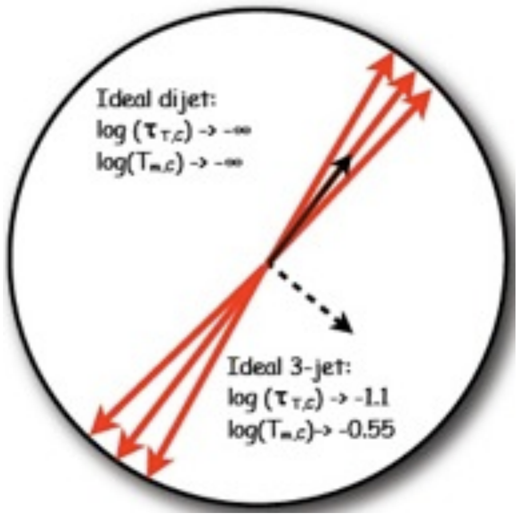
Banfi, Salam, Zanderighi, JHEP **0408** (2004) 62

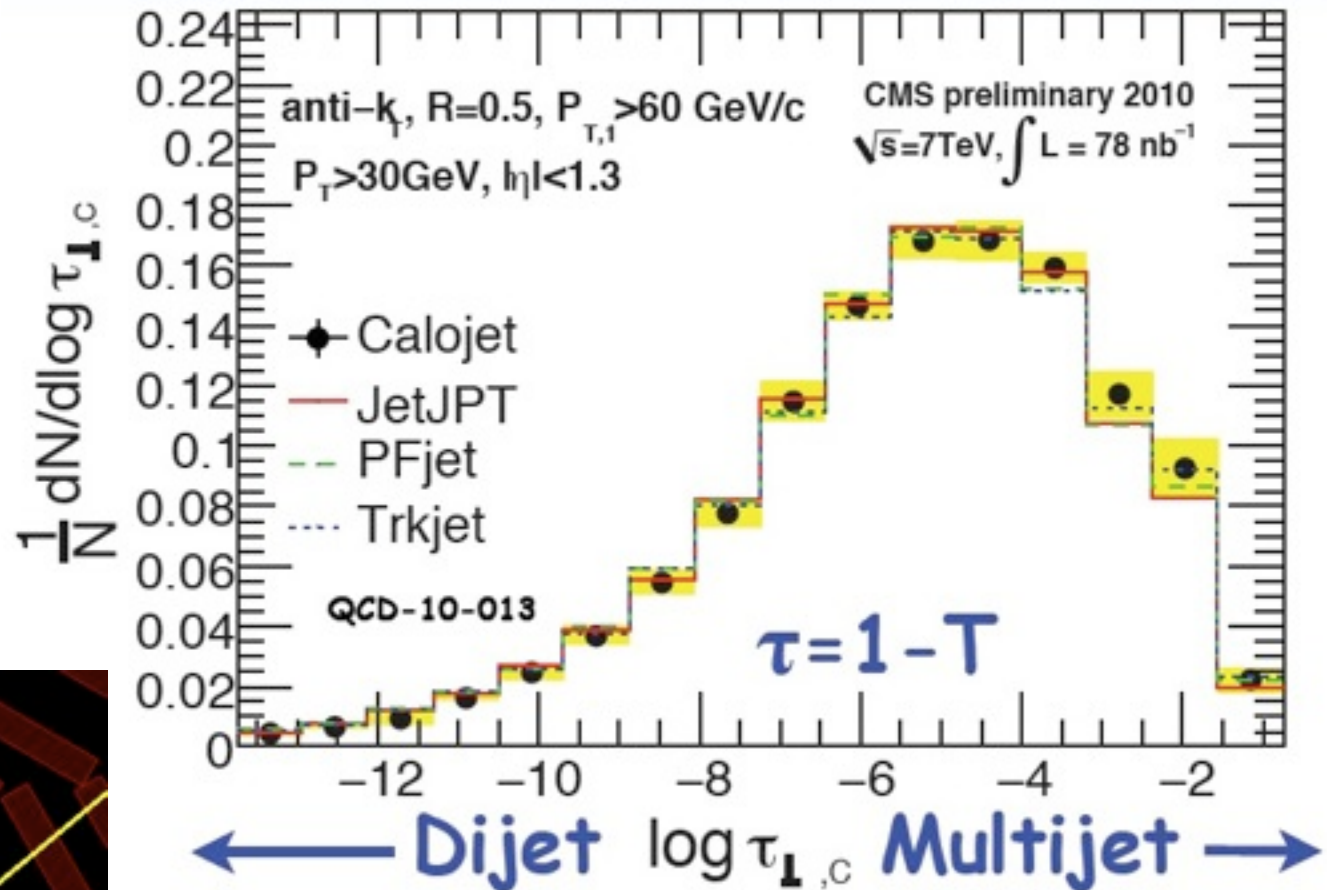
=> Jet momenta are used as input for the event shape calculation

J.Weng

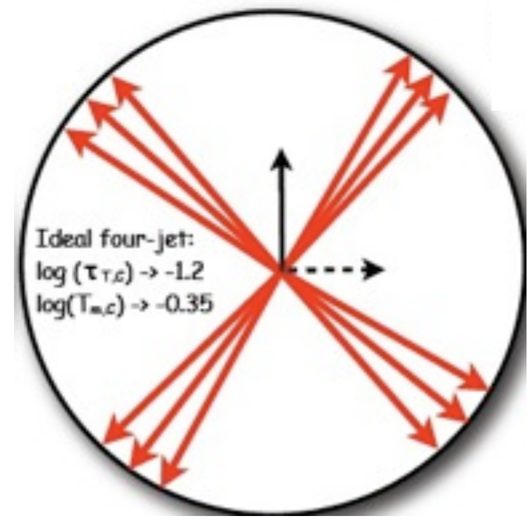
Event Shape Variables

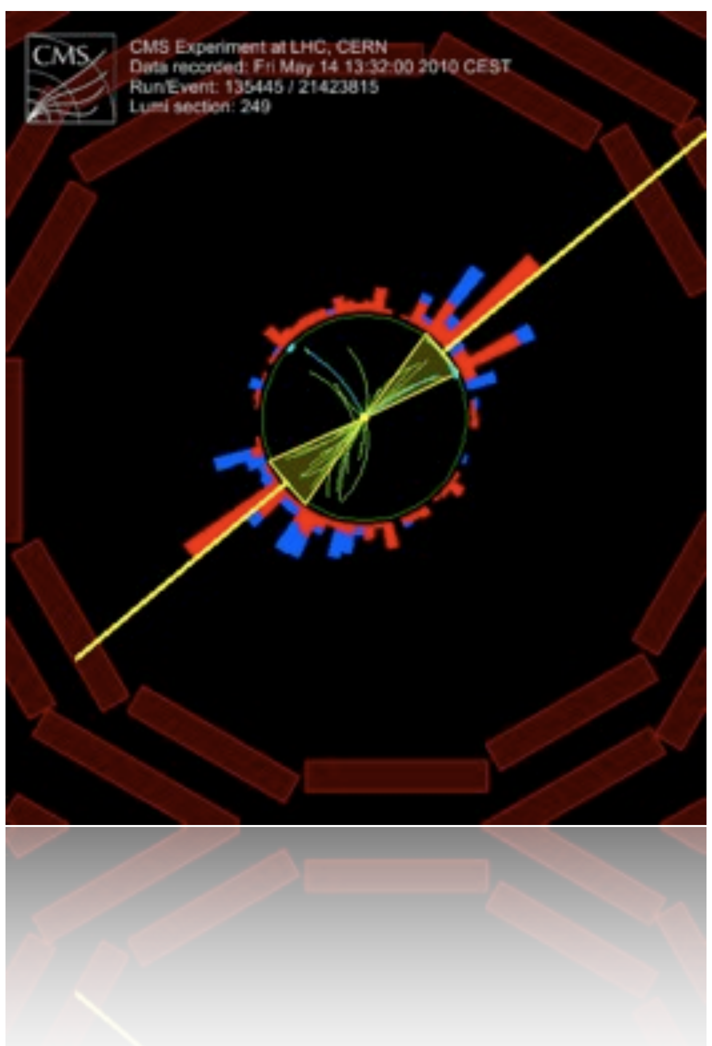
$\tau_{\perp,C} = 0$





$\tau_{\perp,C} = 1 - \frac{2}{\pi}$

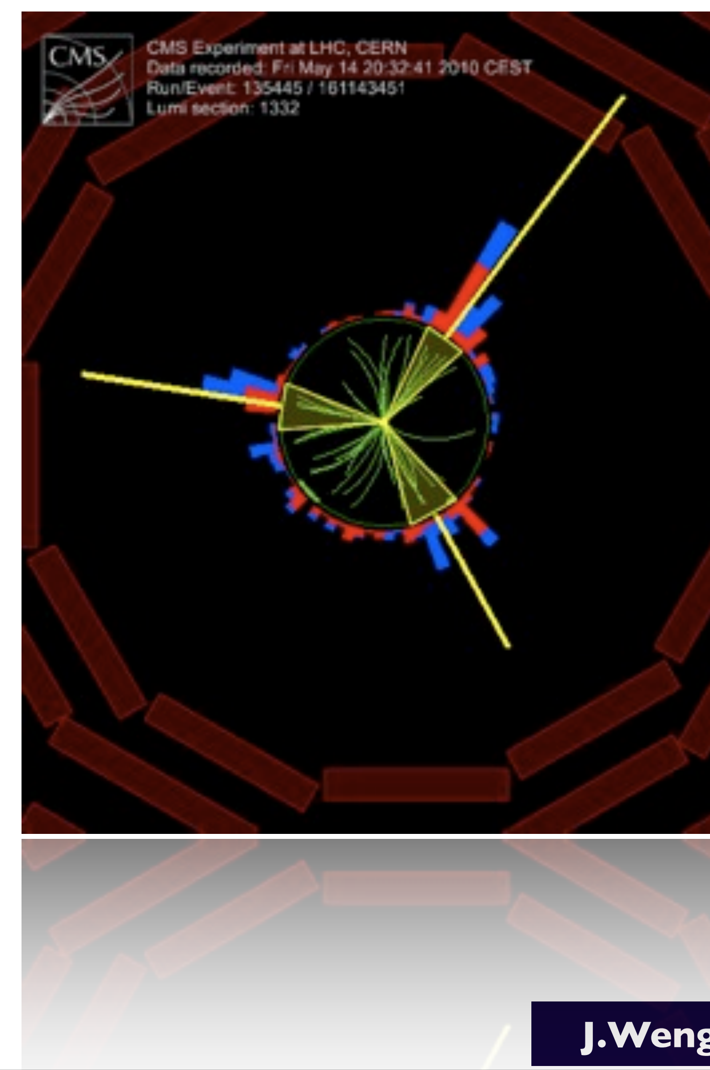




$$\ln \tau_{\perp,C} = \ln(1 - T_{\perp,C})$$

=> Event Shapes provide information about hadronic final states

=> Distributions in agreement for all jet types, results based on PF jets



J.Weng

Event Selection

- Dataset from jet-triggered data: integrated luminosity $L=3.2\ pb^{-1}$

- The leading two jets should be central $|\eta_{j1,j2}|<1.30$

- Use central jets with $p_T>30$ GeV for event shape calculation (jet algorithm: anti-k_T , $R=0.5$)

- Divide phase space in exclusive bins of the leading jet pT:
  - 90 GeV $< p_{T,1} <$ 125 GeV (**low**),
  - 125 GeV $< p_{T,1} <$ 200 GeV (**medium**),
  - $p_{T,1} >$ 200 GeV (**high**)

CERN-PH-EP2010-072

- Previous results ($L=78\ nb^{-1}$) also available, using inclusive bins
  - $p_{T,1}>60$ GeV
  - $p_{T,1}>90$ GeV

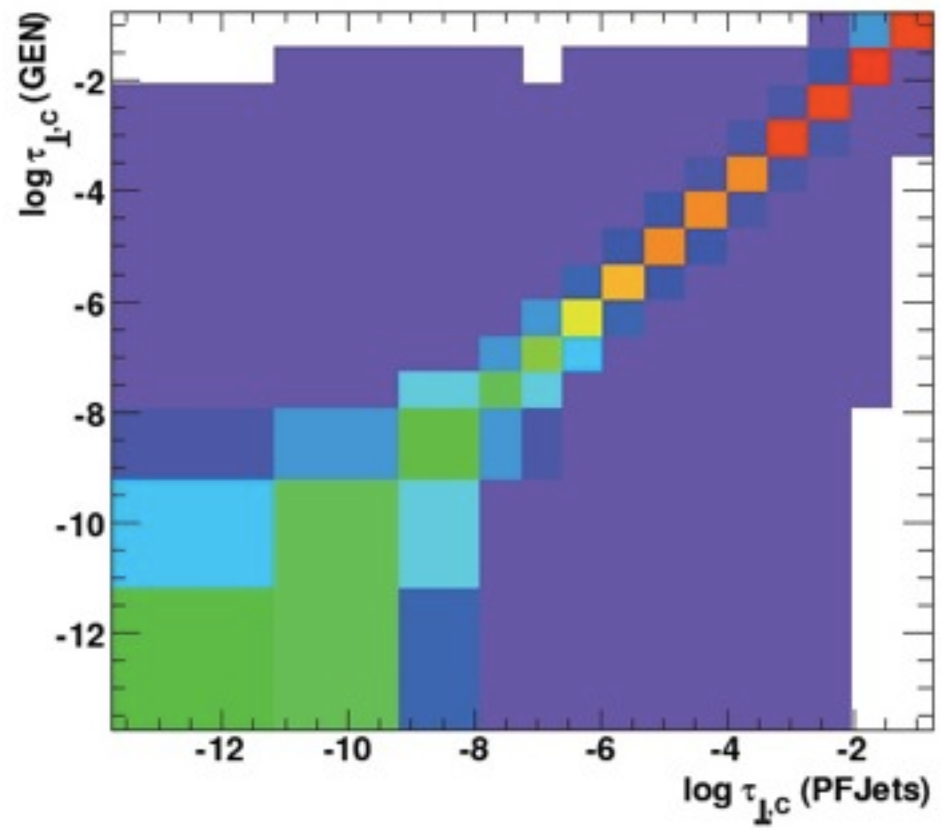
CMS-PAS-QCD-10-013

Unfolding and Systematics

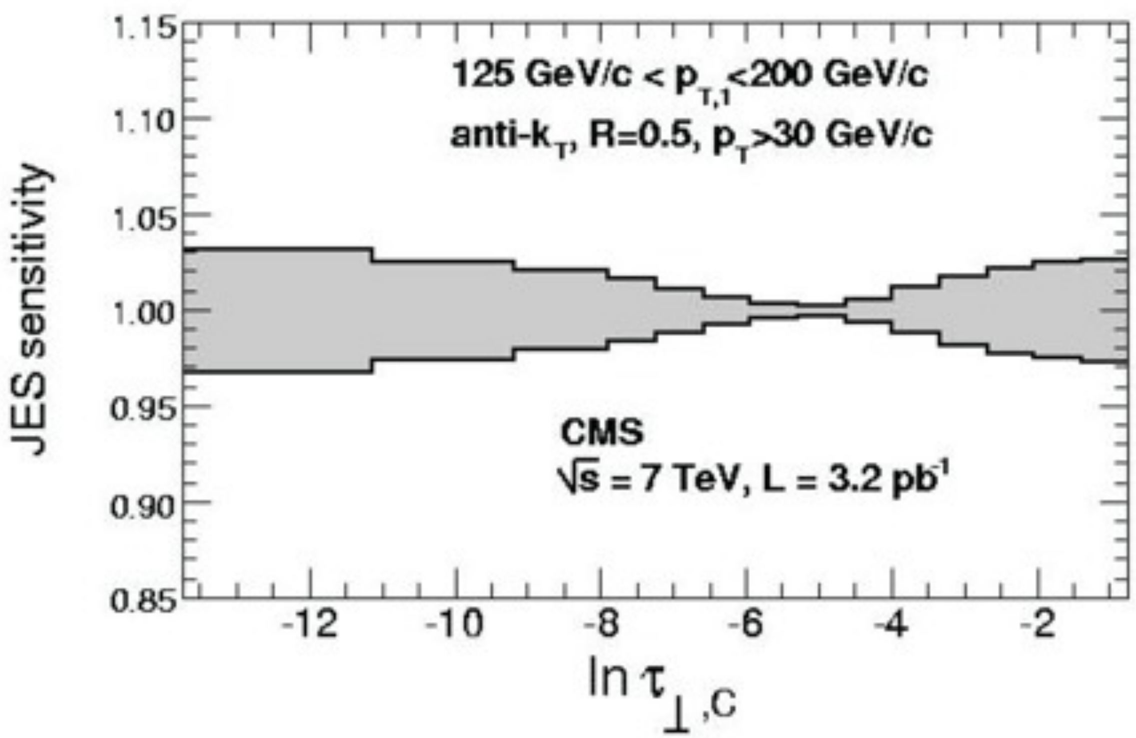
Unfolding:
SVD method, based on the singular value decomposition of the response matrix (Hoecker, Kartvelishvili, Nucl.Instrum.Methods A 312 (1996))

• The response matrix is obtained from Pythia6 D6T QCD samples

• Compare different unfolding procedures: iterative bayesian unfolding, and SVD unfolded data distributions agree within 1 % for most bins



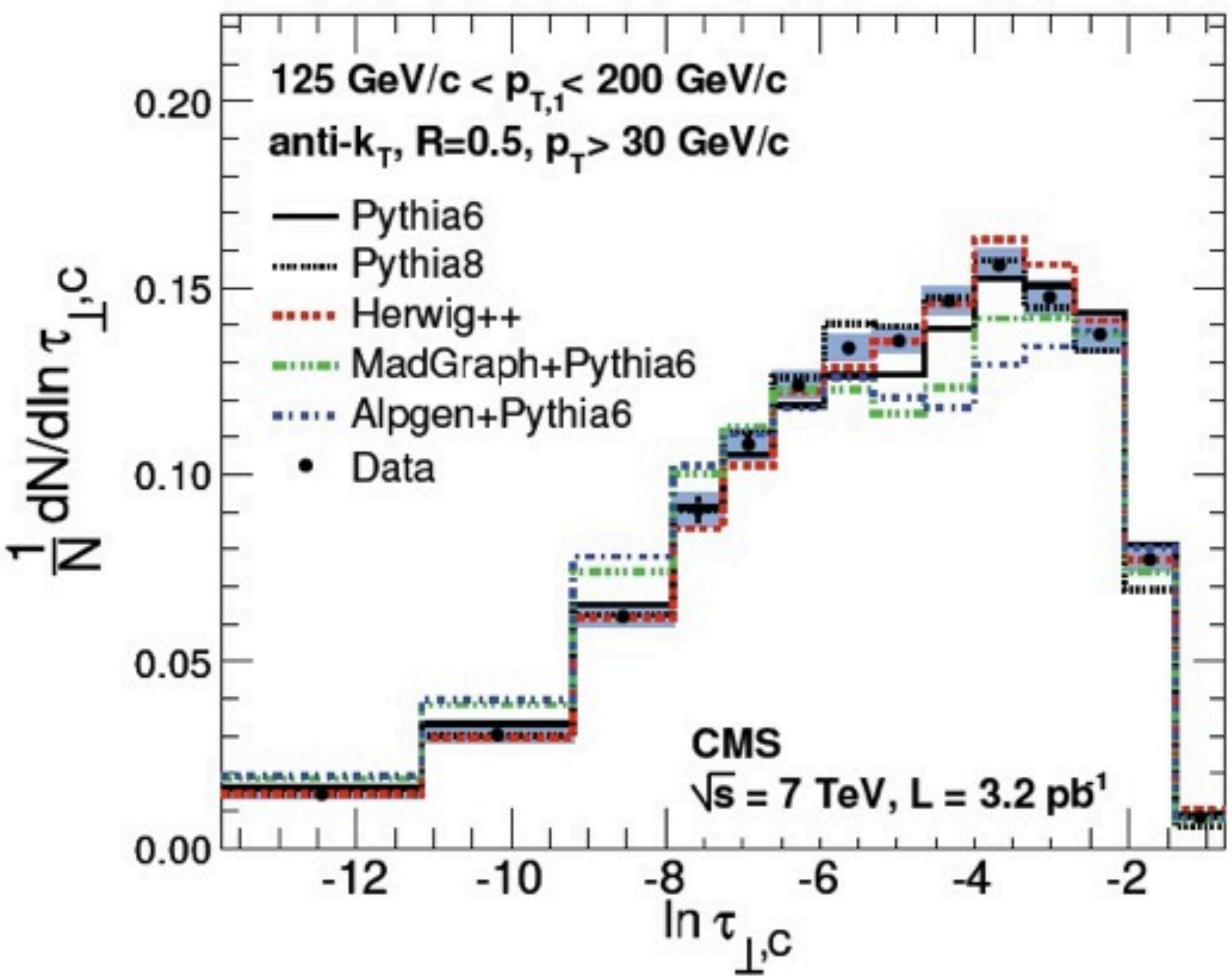
Systematics:
• Study effect of jet resolution
=> Deviations within **1%** for most bins
• Study of η and p_T - dependent jet correction uncertainties
=> Deviations within **3%**

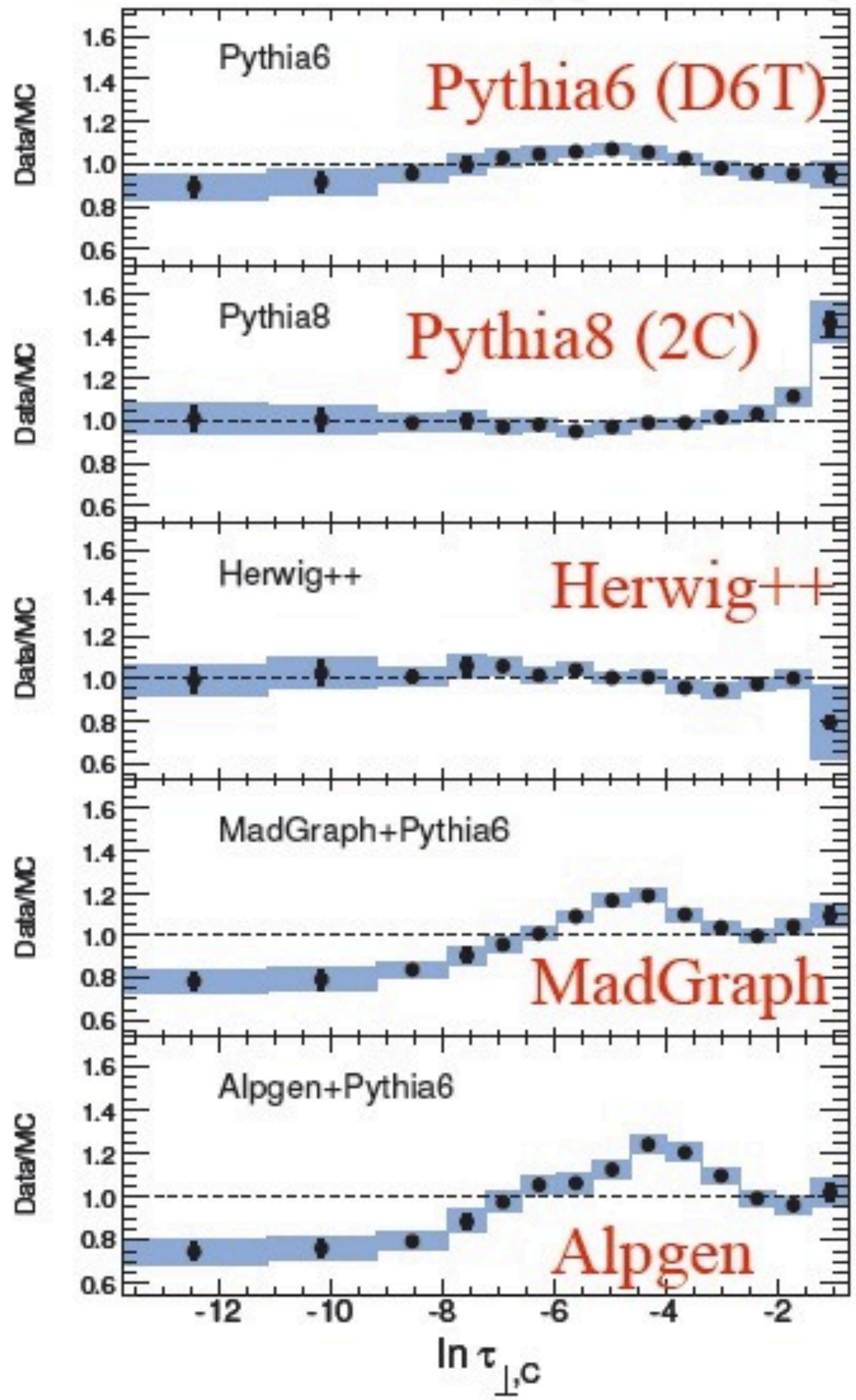


J.Weng

Central Transverse Thrust

Black error bar = statistical error
Blue error band = systematic + statistical errors





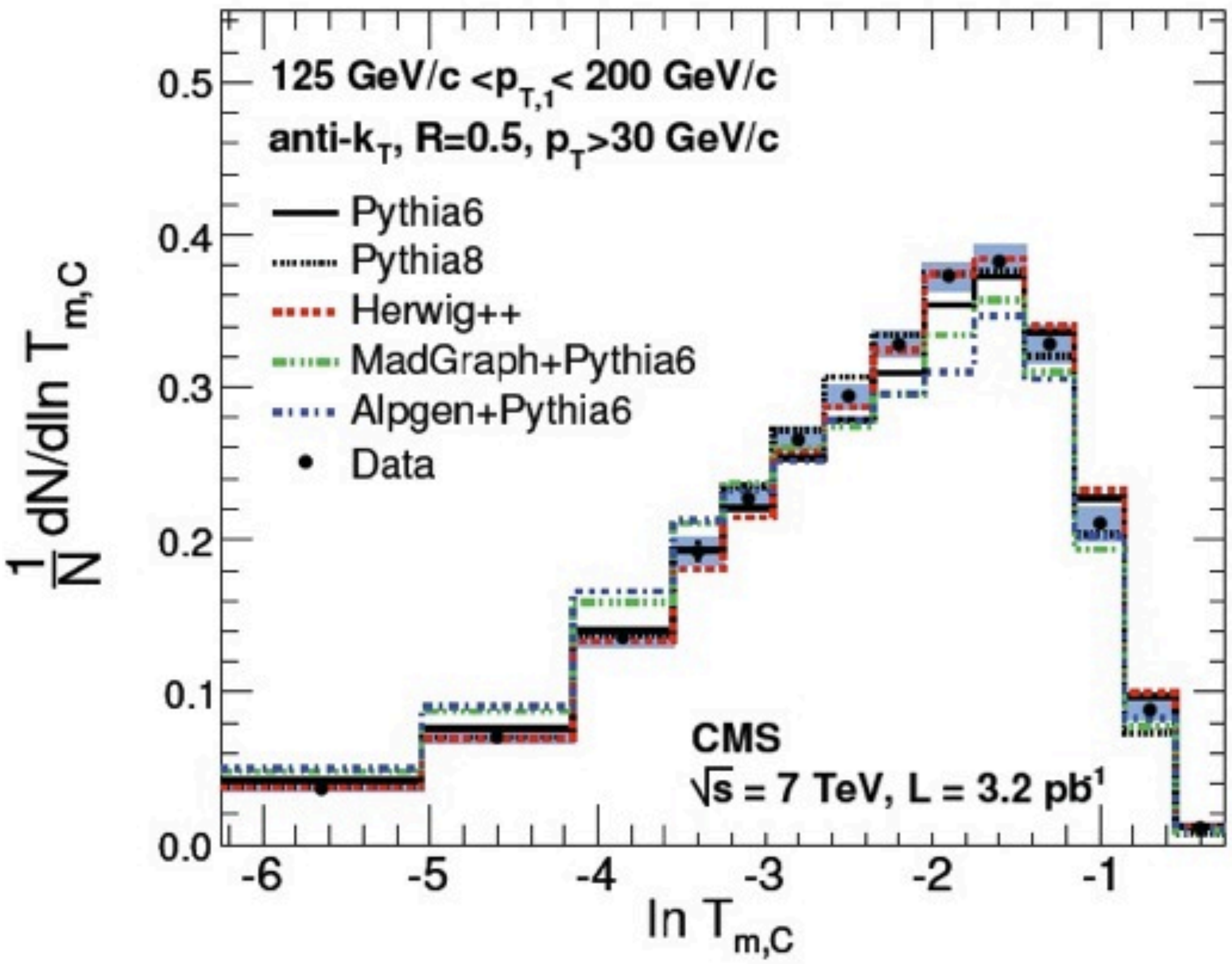
Pythia6, Pythia8 and Herwig++ close to the data,
Alpgen, **MadGraph** show discrepancies
(with CMS parameter choice)

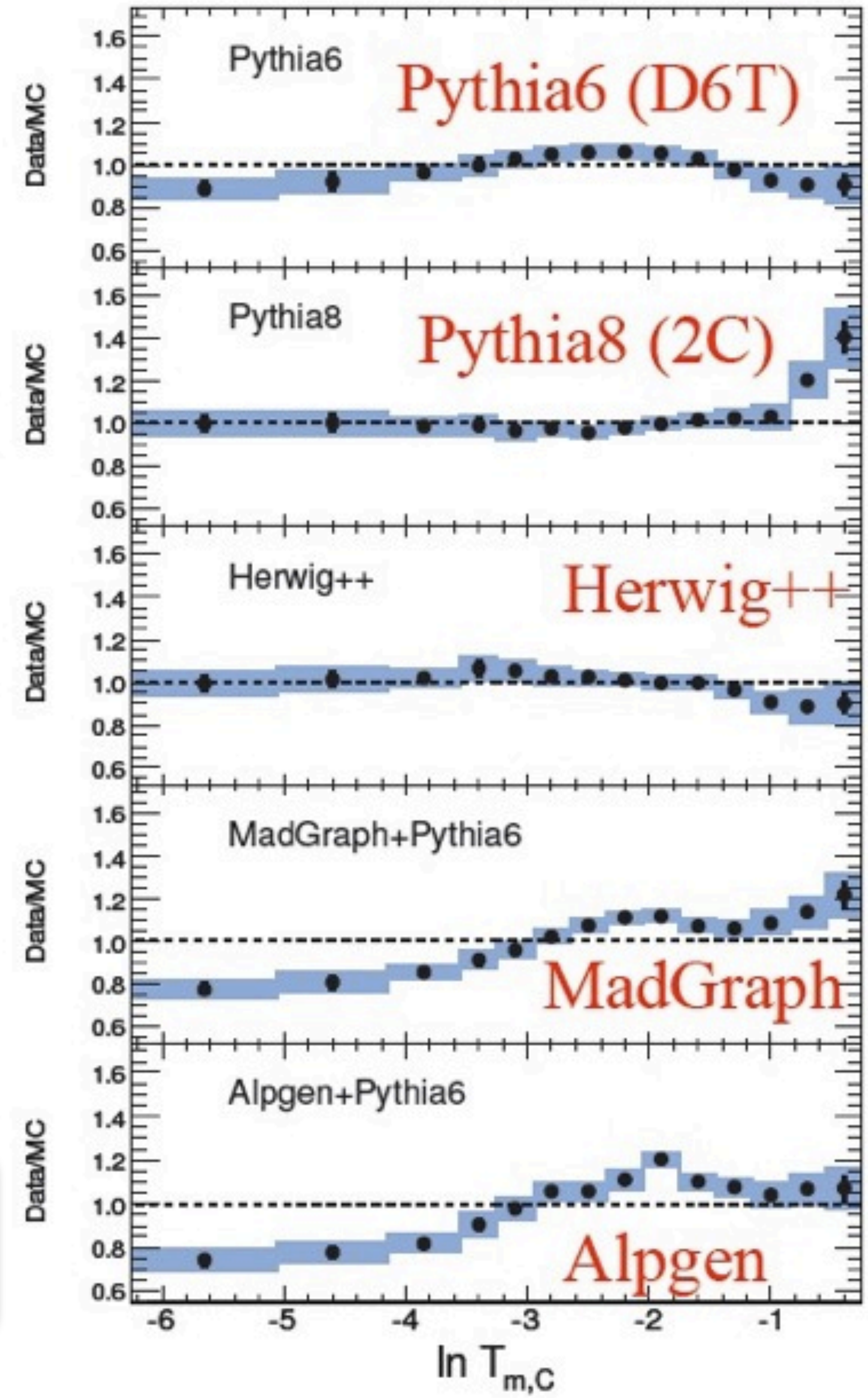
J.Weng

Central Thrust Minor

ETH Institute for Particle Physics

Black error bar = statistical error
Blue error band = systematic + statistical errors



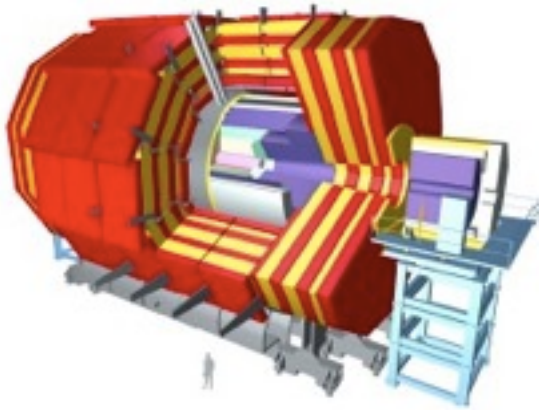


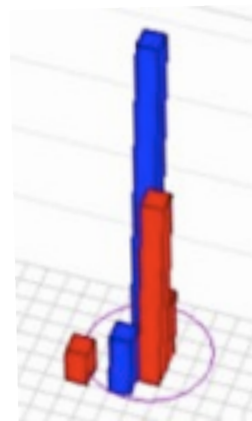
Pythia6, Pythia8 and Herwig++ close to the data,
Alpgen, **MadGraph** show discrepancies
(with CMS parameter choice)

J.Weng

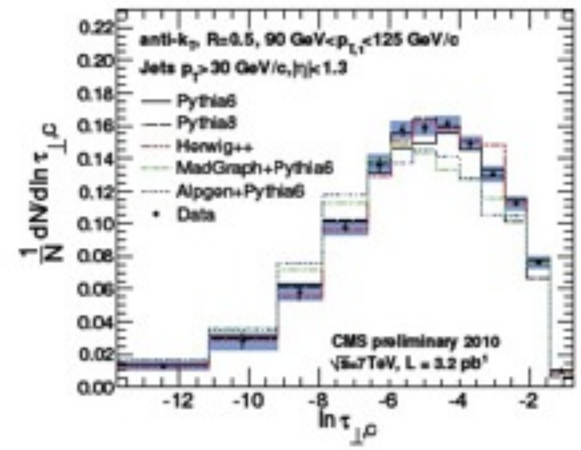
Outline

1. Jet reconstruction and performance in CMS

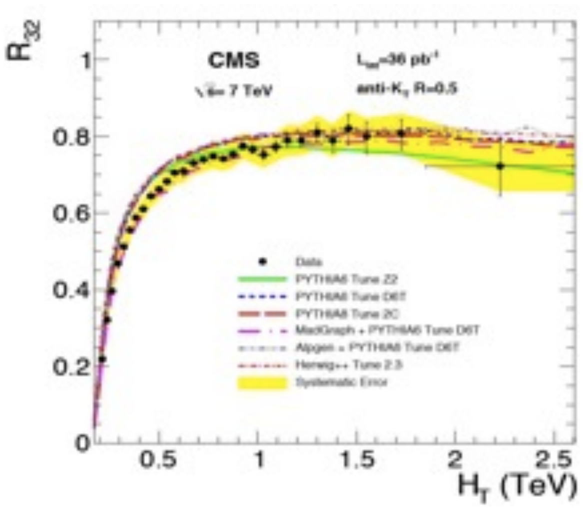




2.Hadronic Event Shapes



3. Three to two jet ratio (R_{32})



More Jet Results:

"Jet Results from CMS" by C.Dragoiu

(Tuesday 12th of April 2011, "Jet Cross Sections")

- Inclusive jet cross section
- Dijet mass cross section
- Dijet azimuthal decorrelations
- Dijet angular distributions

R_{32} Measurement

ETH Institute for Particle Physics

We present a measurement of the ratio of the inclusive 3-jet to 2-jet cross section (R_{32}) defined as :

$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \to n \ \ \text{jets} + X;\ n \geq 3)}{\sigma(pp \to n \ \ \text{jets} + X;\ n \geq 2)} \quad \text{vs} \quad H_T = \sum p_T^{jet}$$

$$p_T > 50\,GeV$$
$$|y| < 2.5$$
$$0.2 < H_T < 2.5\,TeV$$

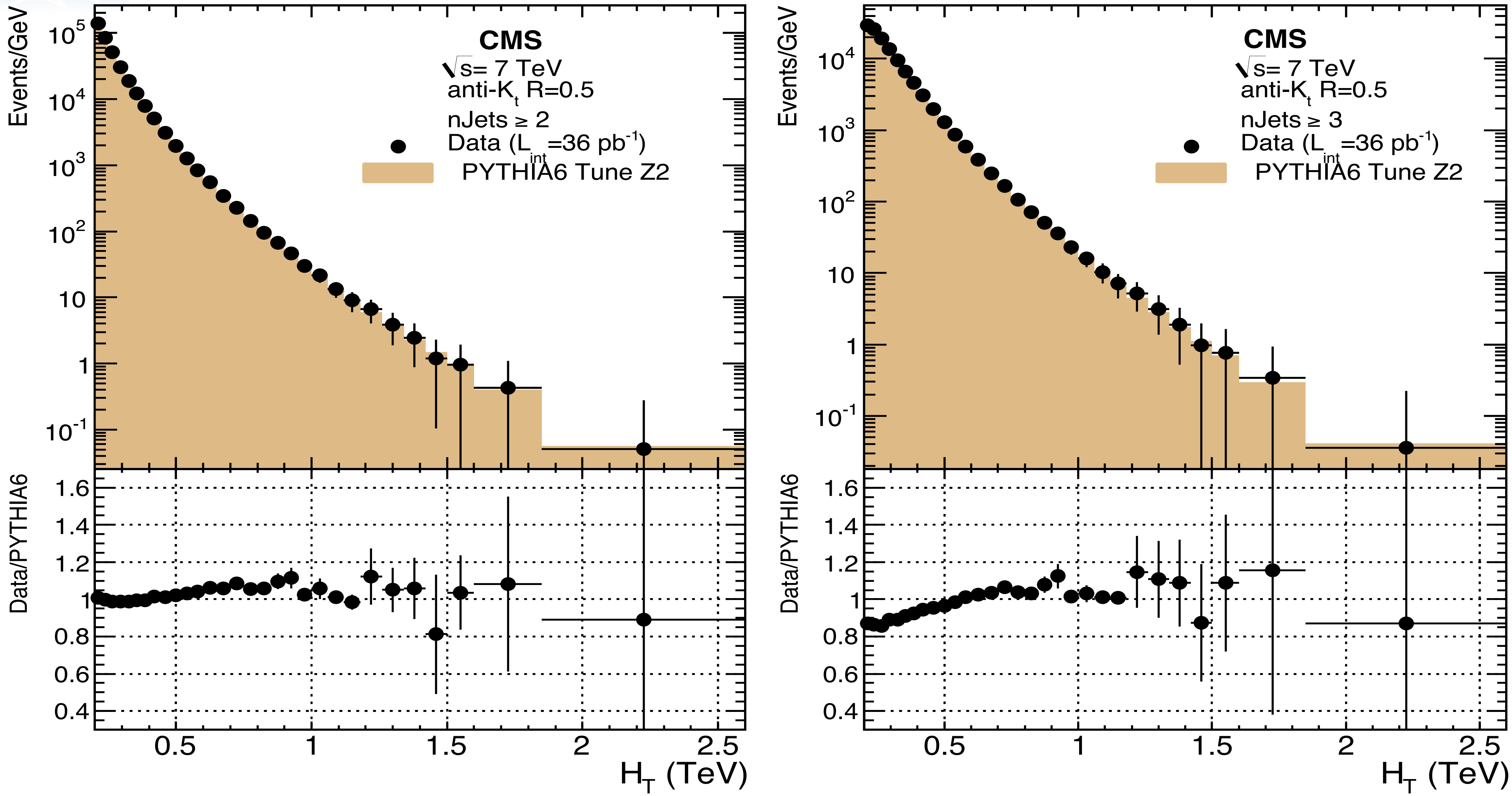
- Extend transverse momentum reach beyond 600 GeV of the Tevatron measurement

- Major systematic uncertainties (jet energy scale, jet selection efficiency, luminosity measurement) largely cancel in R_{32}

- R_{32} provides another complimentary probe for different pQCD based MC models
=> Measurement was compared with following MC generators:
  1. Pythia6 in tunes Z2 and D6T
  2. Pythia8 in tune 2C
  3. Herwig++ in tune 2.3
  4. Madgraph (+ Pythia6 in tune D6T)
  5. Alpgen (+ Pythia6 in tune D6T)

J.Weng

Data over MC : H_T



- Basic jet kinematic and H_T data distributions for ≥ 2 and ≥3 jets have been compared with MCs

=> Absolute MC predictions agreement is better than 20%.
=> PYTHIA6 tune Z2 agrees best with data and was used to perform all corrections

Extraction of R_{32} and Systematics

$$\frac{d\sigma_i}{dH_T} = \frac{C_i}{L \cdot \varepsilon_i} \cdot \frac{N_i}{\Delta H_T}$$

C : The smearing correction
ΔH_T : the H_T bin size
N : The number of selected events
L: The integrated luminosity
ε : The detection efficiency

$$\longrightarrow \quad R_{32} = \frac{d\sigma_3 / dH_T}{d\sigma_2 / dH_T}$$

- Corrected to Hadron Level using bin by bin corrections derived from Pythia6 Tune Z2

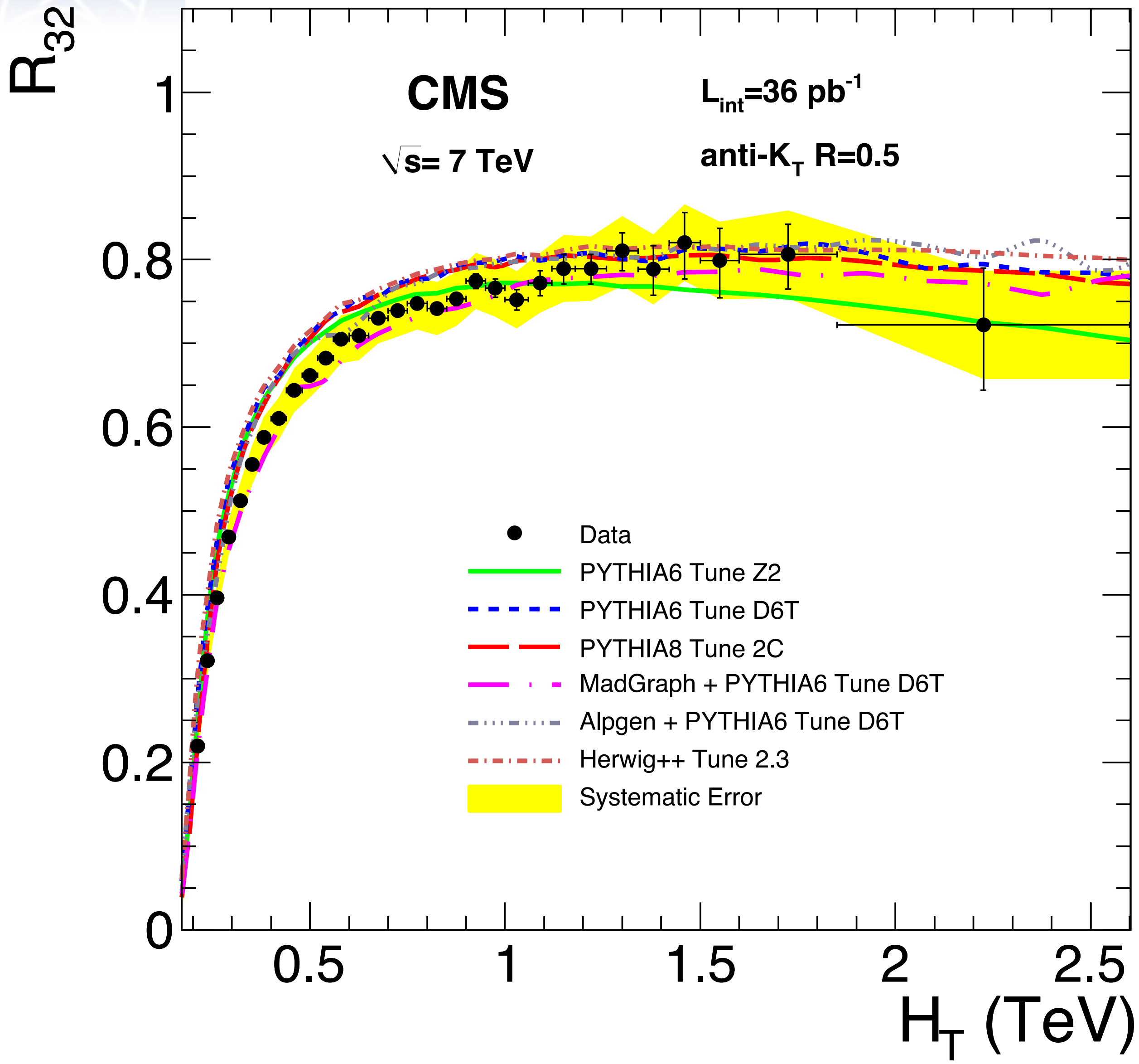
- Analysis with Calorimeter Jets gives very similar result (difference ~1%)

Systematics considered:

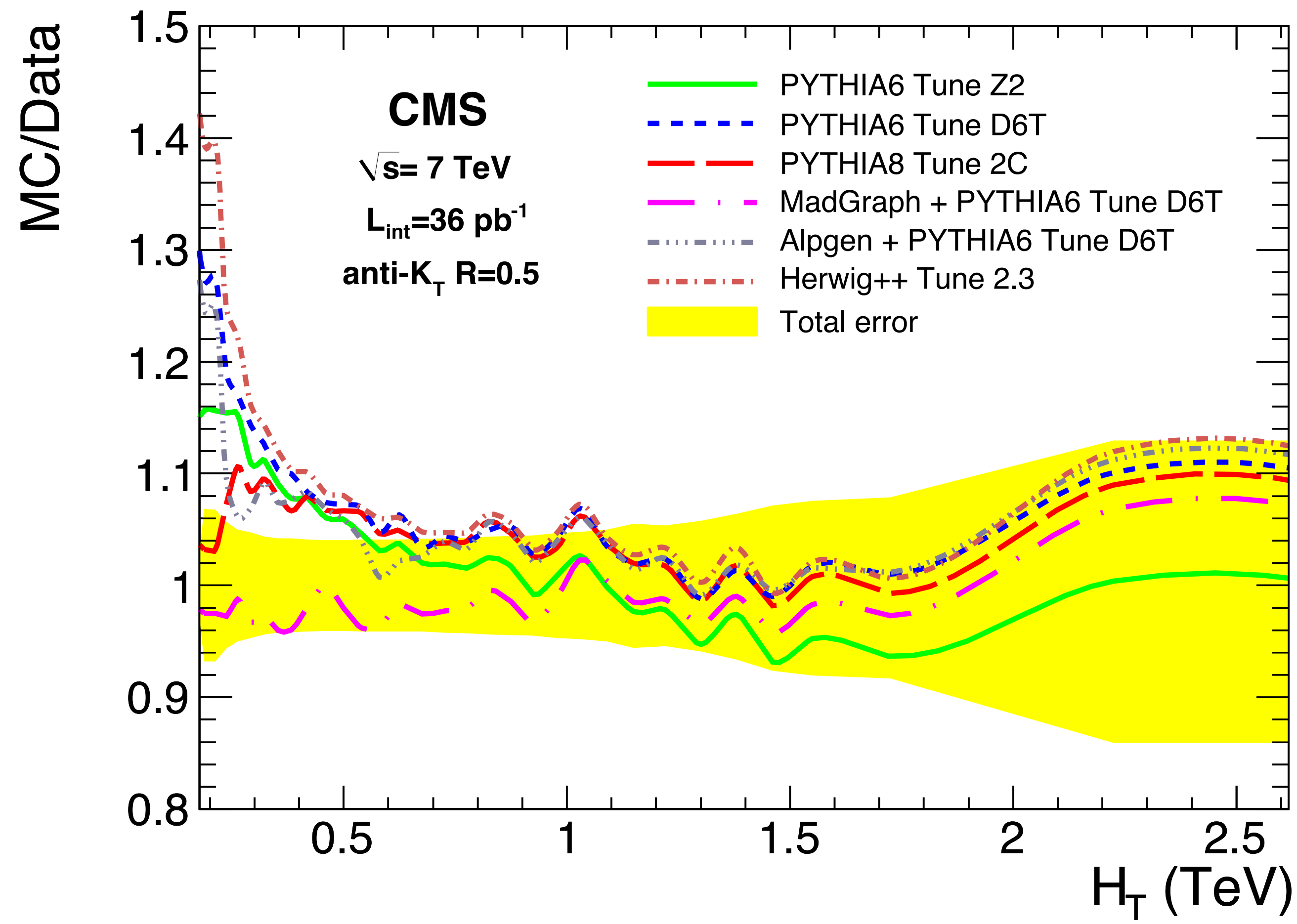
- Uncertainty from Closure Studies : **1%**
- Systematics due to Jet Energy Scale (JES) uncertainty: **1 %**
- Systematic uncertainty due insufficient knowledge of MC shape: **3-5% for H_T< 1 TeV**
- Systematics due to Pile-up: **0.5 %**
- Systematics due to Jet Energy Resolution (JER) uncertainty: **1%**

J.Weng

Final Result



- **Error bars:** statistical uncertainty
- **Yellow band:** systematic error



- Madgraph describes best the R_{32} data
- Pythia 6, Pythia 8, Alpgen and Herwig++ in agreement for H_T > 0.5 TeV, but overestimate R_{32} for lower values of H_T (with current CMS setup)

Conclusions

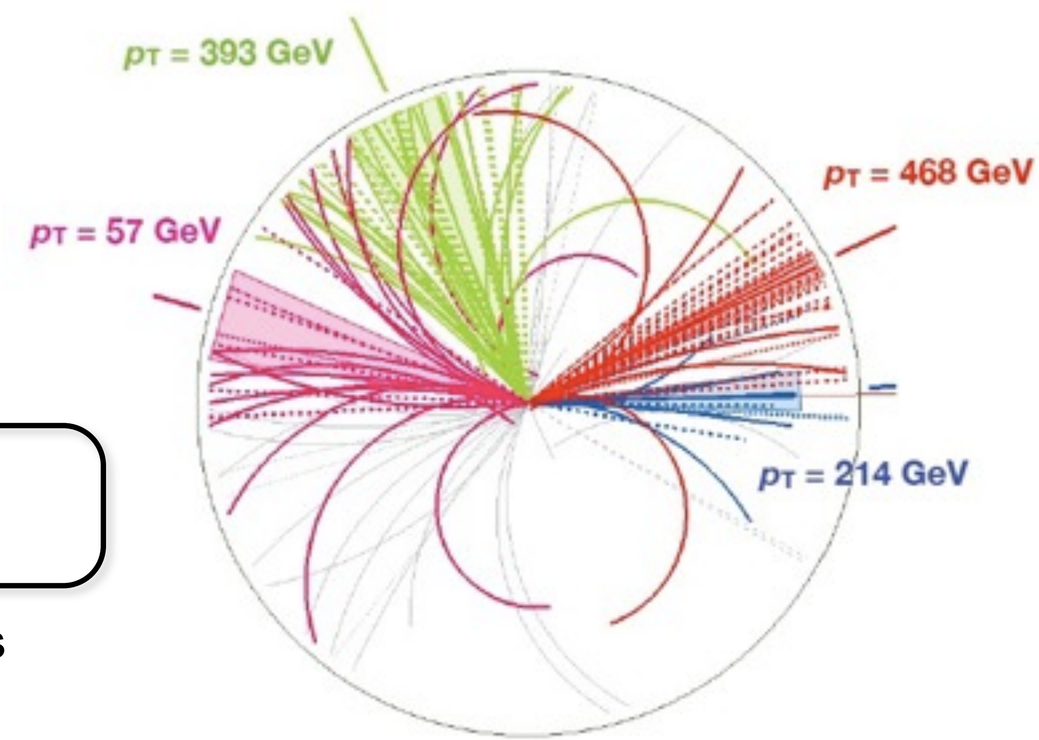
- **Jets** in CMS calibrated in situ to a few percent level

- **Probing MC generator modeling of multi jet dynamic at 7 TeV:**

  I. **First unfolded measurement of hadronic event shapes with the CMS detector, using particle flow jets as input**
  => Good agreement with Pythia6, Pythia8 and Herwig++
  - discrepancies with Alpgen and MadGraph

  II. Ratio of the inclusive 3-jet to 2-jet cross sections R_{32} with has been measured in the range 0.2 TeV < H_T < 2.5 TeV
  => Madgraph gives best description, Pythia 6, Pythia 8, Alpgen and Herwig++ in agreement for H_T > 0.5 TeV, but overestimate R_{32} for lower values

- **Outlook**: provide the results in RIVET format



An event recorded in 2010

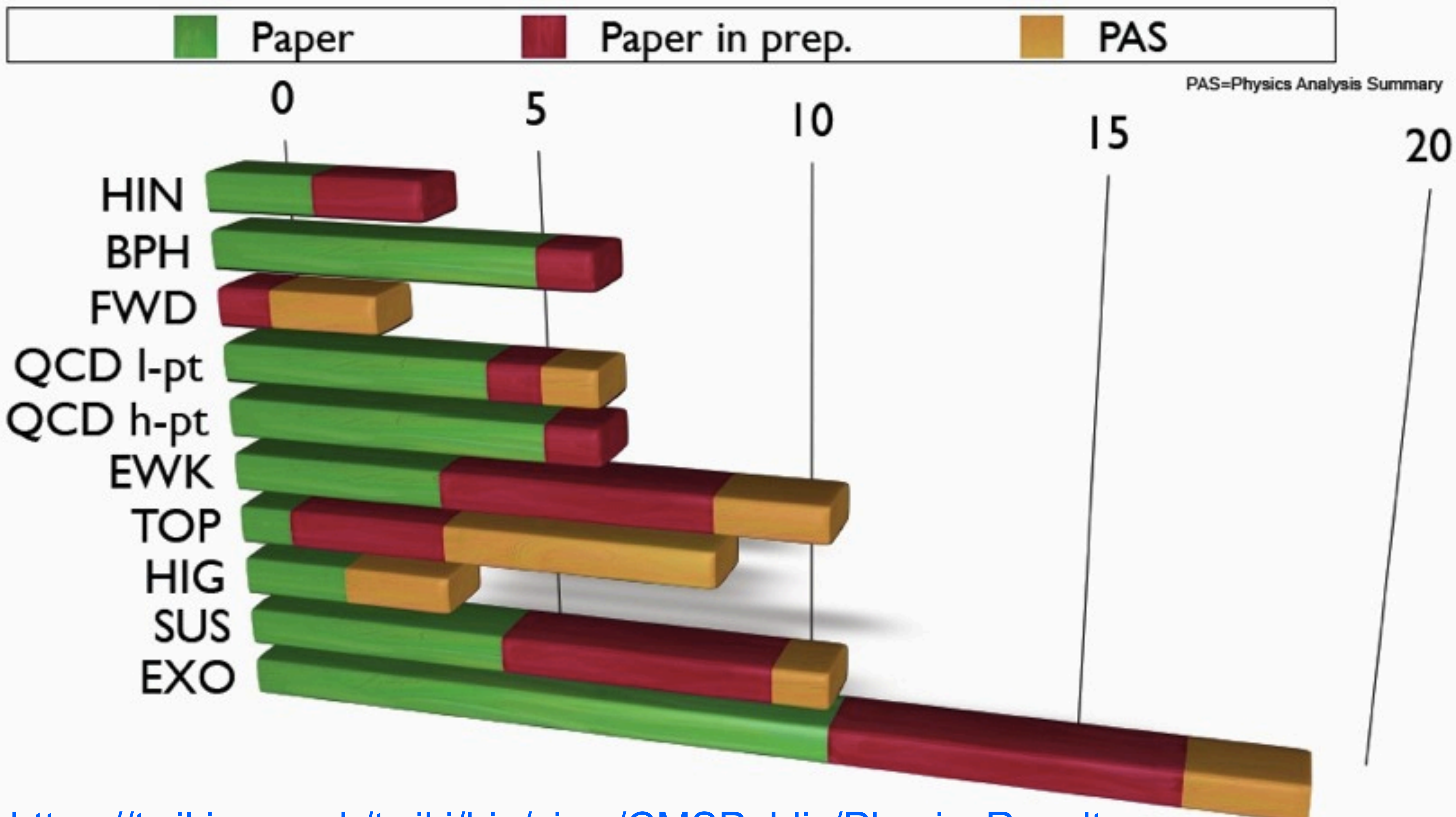
Looking forward to 2011 data !!!

Many thanks to F. Pandolfi, M. Weber, P. Kokkas

All CMS public results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Backup

List of Physics Analyses



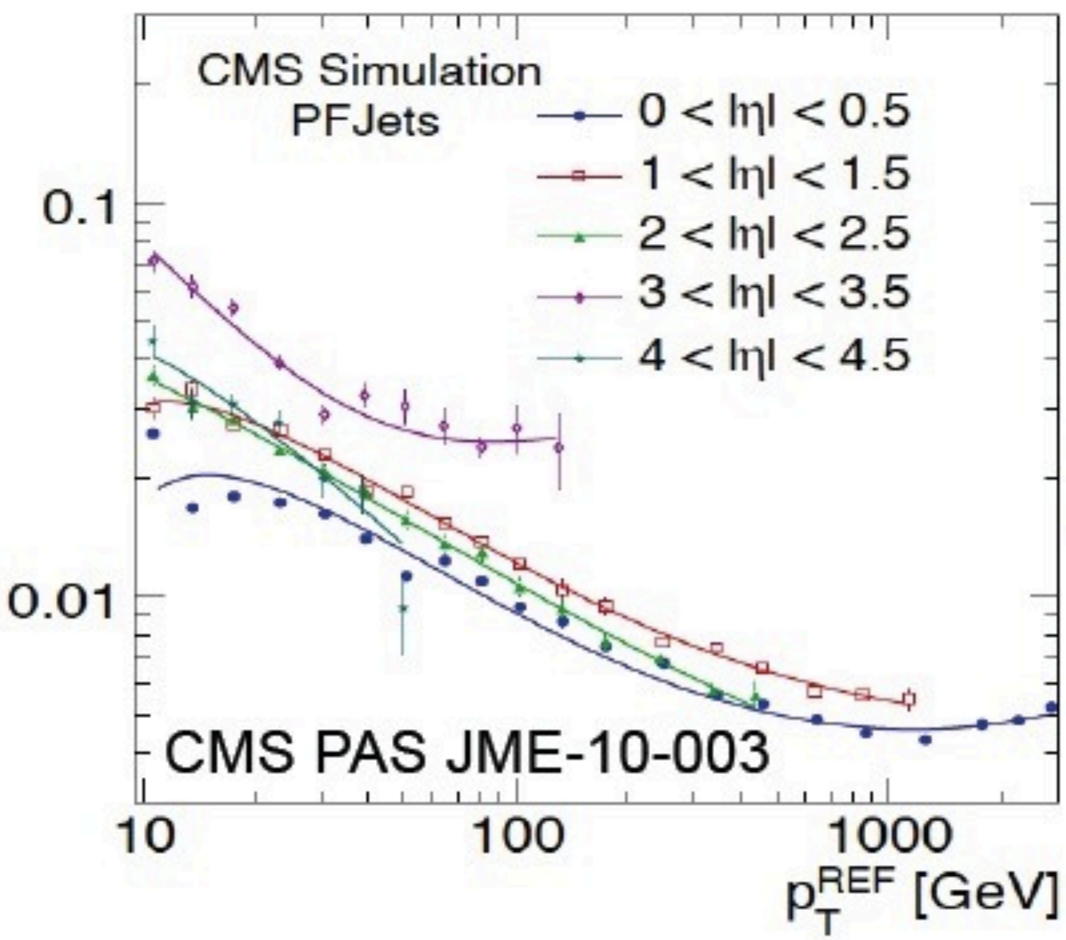
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

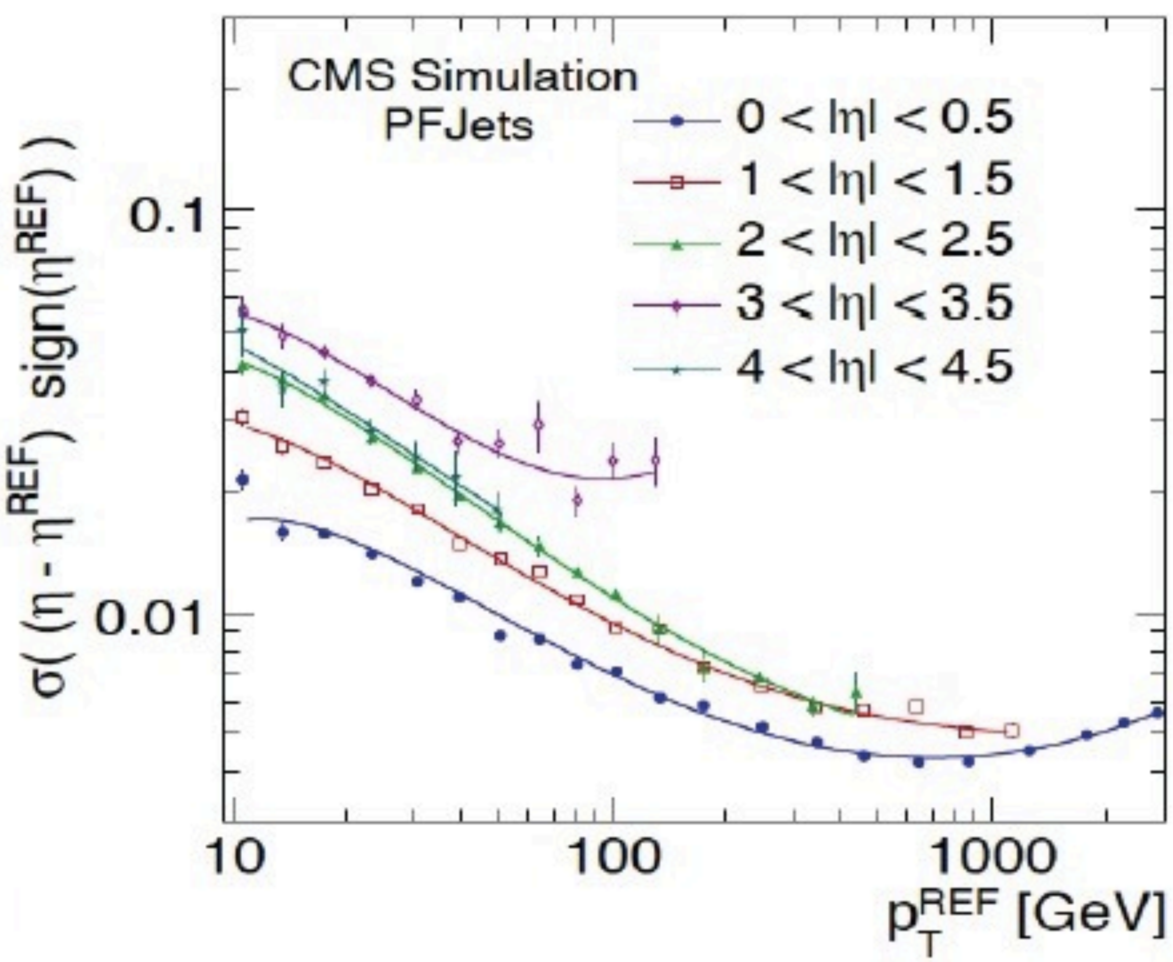
In total : **82** analyses approved based on 2010 data
42 papers (published, submitted, or close to submission)

=> Only a few analyses examples will be shown here

J.Weng

Jet Performance



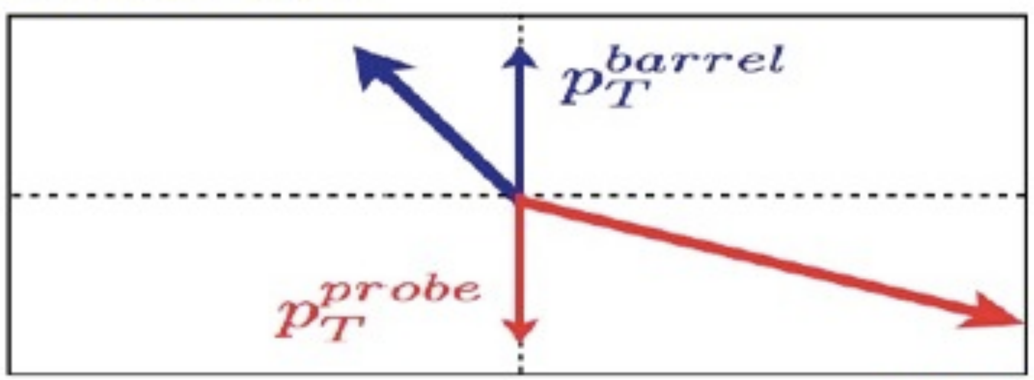


J.Weng

Relative JEC: dijet p_T balance

Relative JEC removes jet response variation in η
A priori estimate of uncertainty: ±2% x |η|

Barrel Jet



Probe Jet

$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

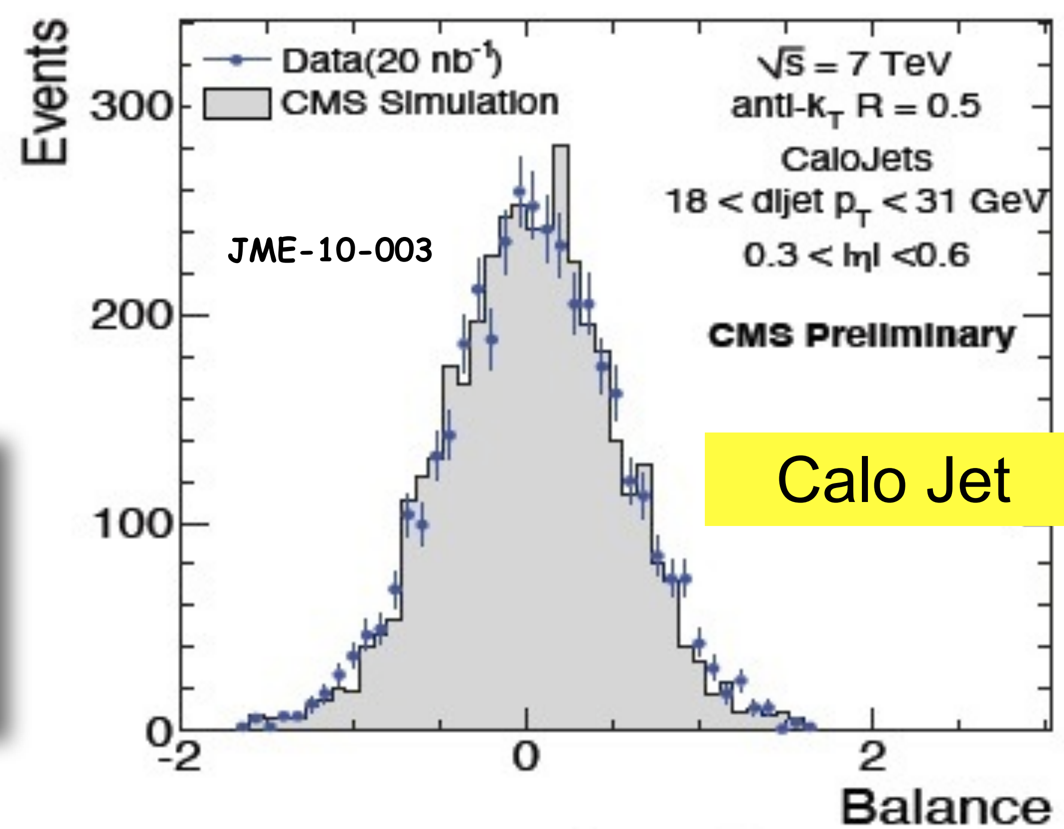
$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

r:= relative response in a given ($p_T^{\ dijet}$, |η|) bin

- Require at least 2 jets, one jet in the barrel region |η|<1.3
- Azimuthal separation ΔΦ > 2.7
- Third jet veto $p_T^{\ 3rd}/p_T^{\ dijet} < 0.2$

=> Measure distributions of balance variable B in representative ($p_T^{\ dijet}$, |η|) bins for all jet types



J.Weng

Absolute JEC: MPF methode

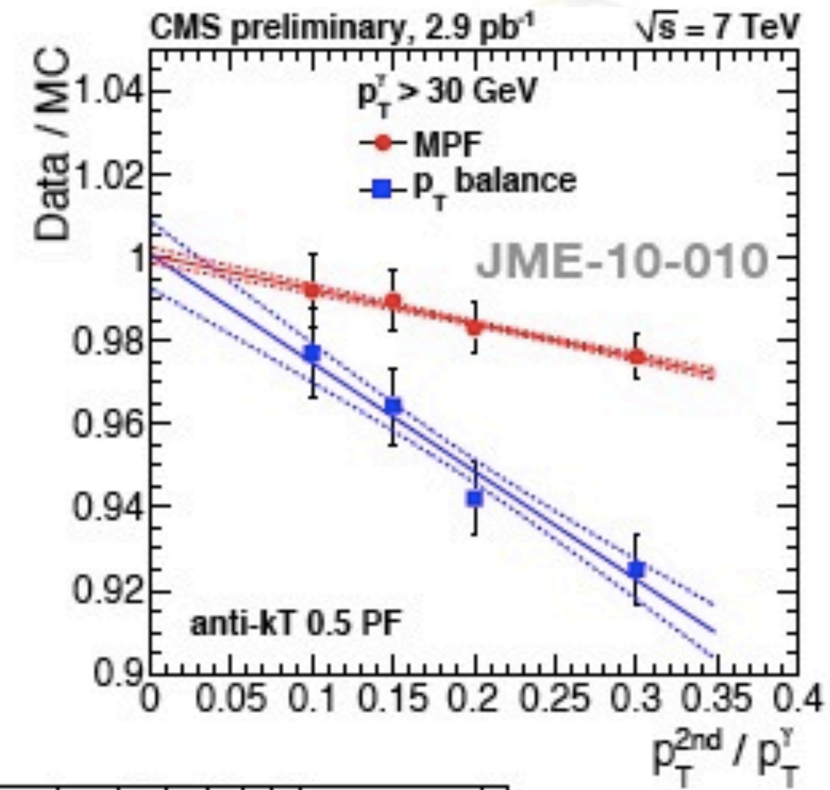
ETH Institute for Particle Physics

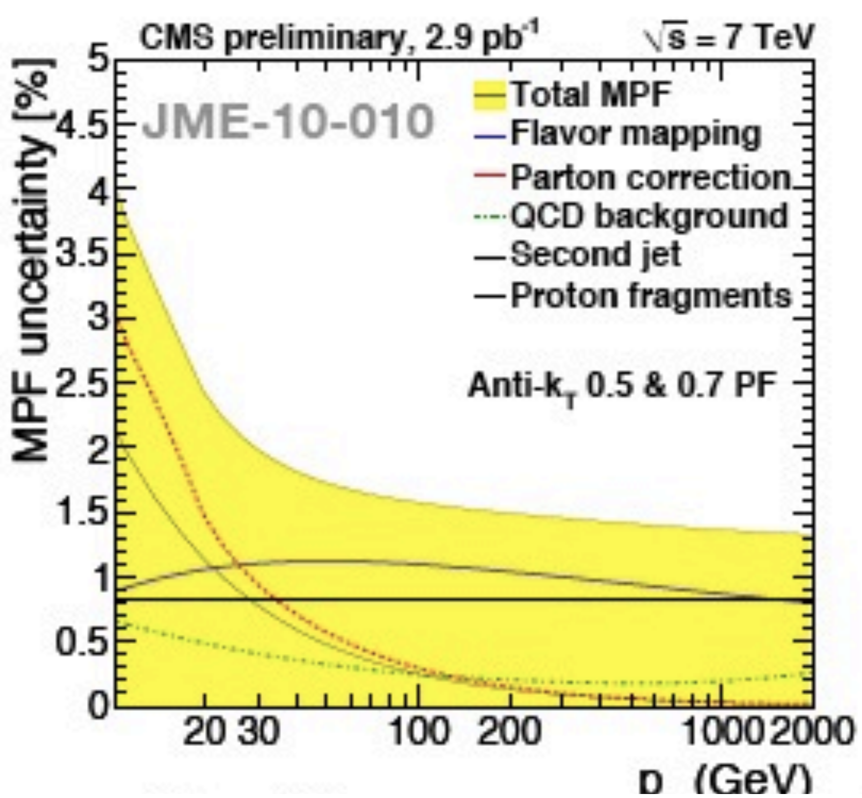
- **IDEALLY:** $\vec{p}_{\mathrm{T}}^{\,\gamma} + \vec{p}_{\mathrm{T}}^{\,\mathrm{recoil}} = \vec{0}$

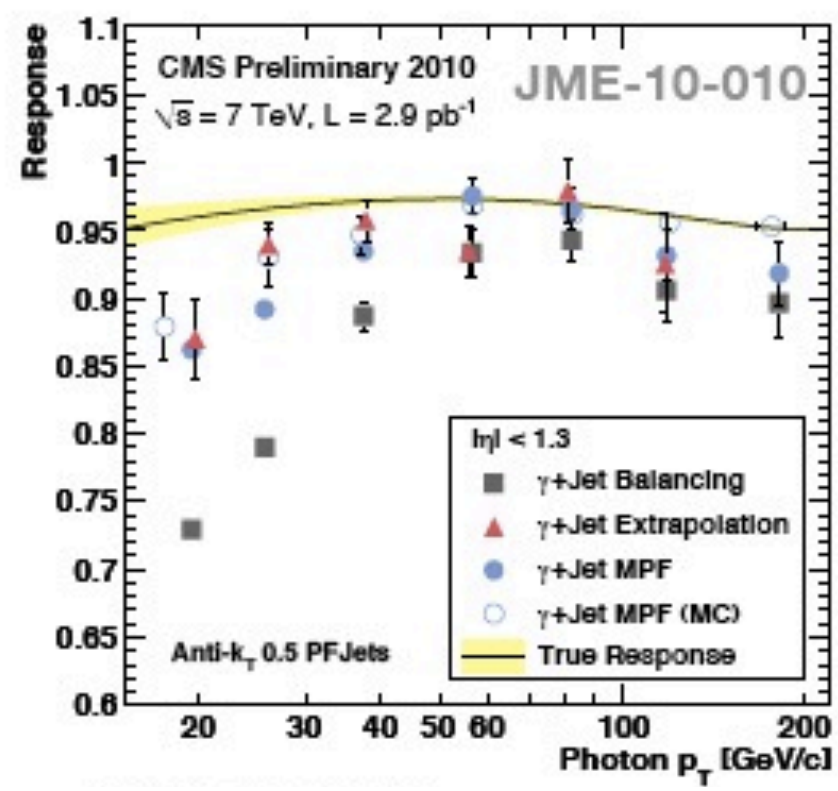
- **ADD IN THE DETECTOR:**

$$R_{\gamma}\vec{p}_{\mathrm{T}}^{\,\gamma} + R_{\mathrm{recoil}}\vec{p}_{\mathrm{T}}^{\,\mathrm{recoil}} = -\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$$

$$\rightarrow \quad R_{\mathrm{recoil}}/R_{\gamma} = 1 + \frac{\vec{E}_{\mathrm{T}}^{\mathrm{miss}} \cdot \vec{p}_{\mathrm{T}}^{\,\gamma}}{|\vec{p}_{\mathrm{T}}^{\,\gamma}|^2} \equiv R_{\mathrm{MPF}}$$

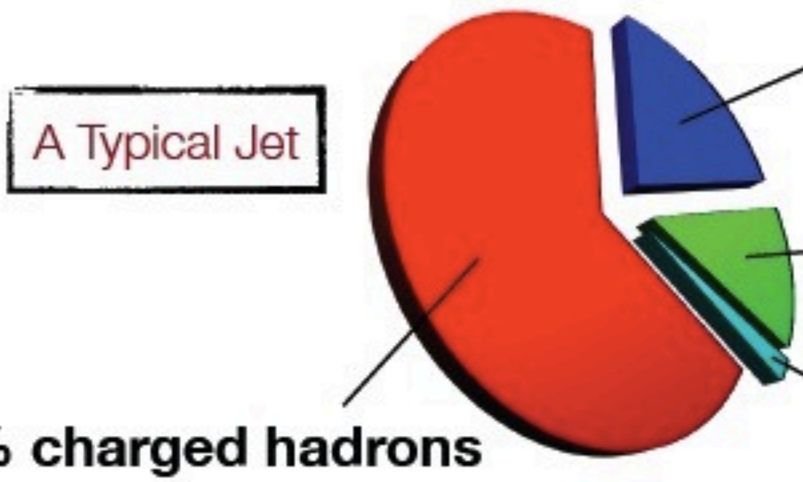


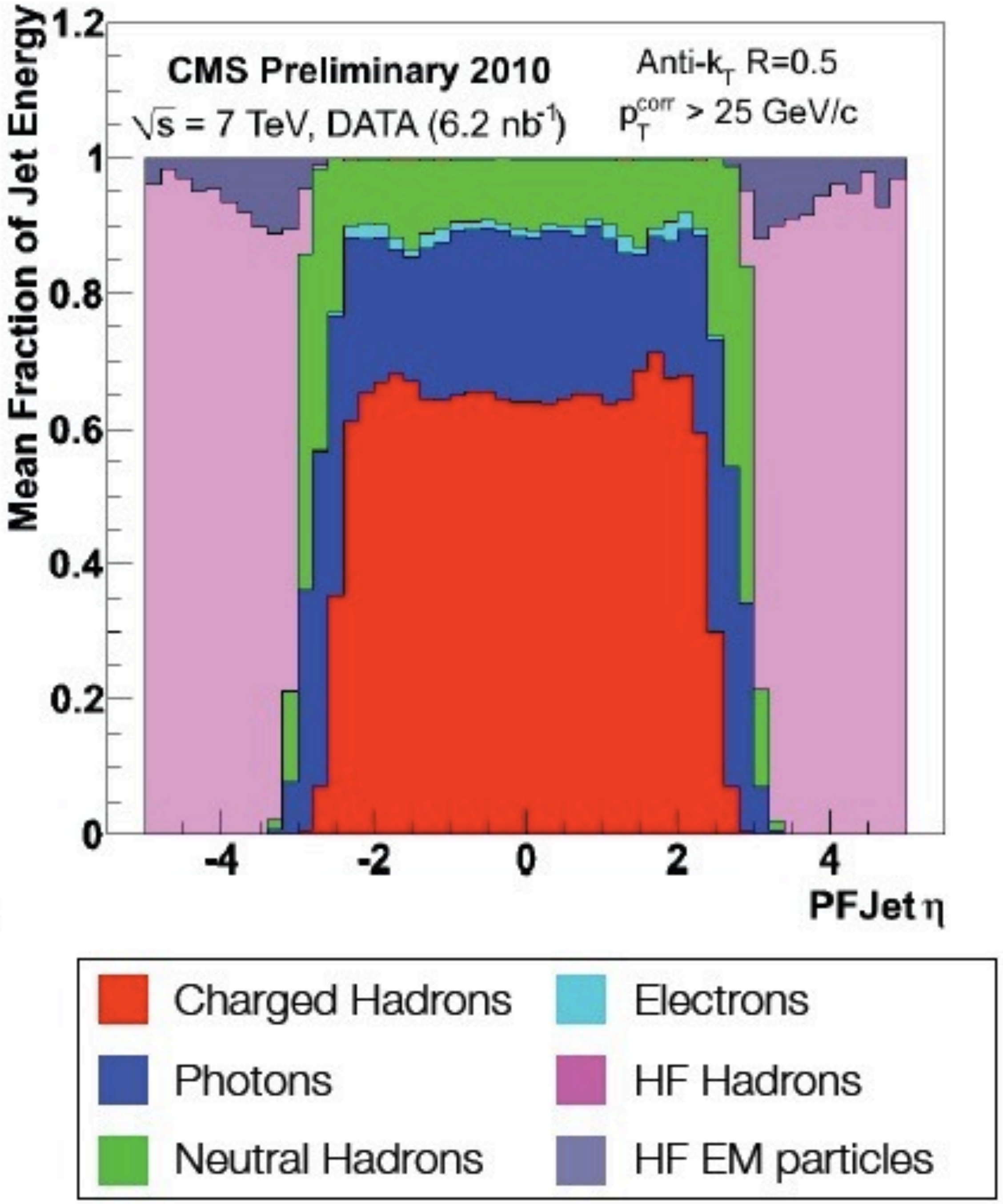


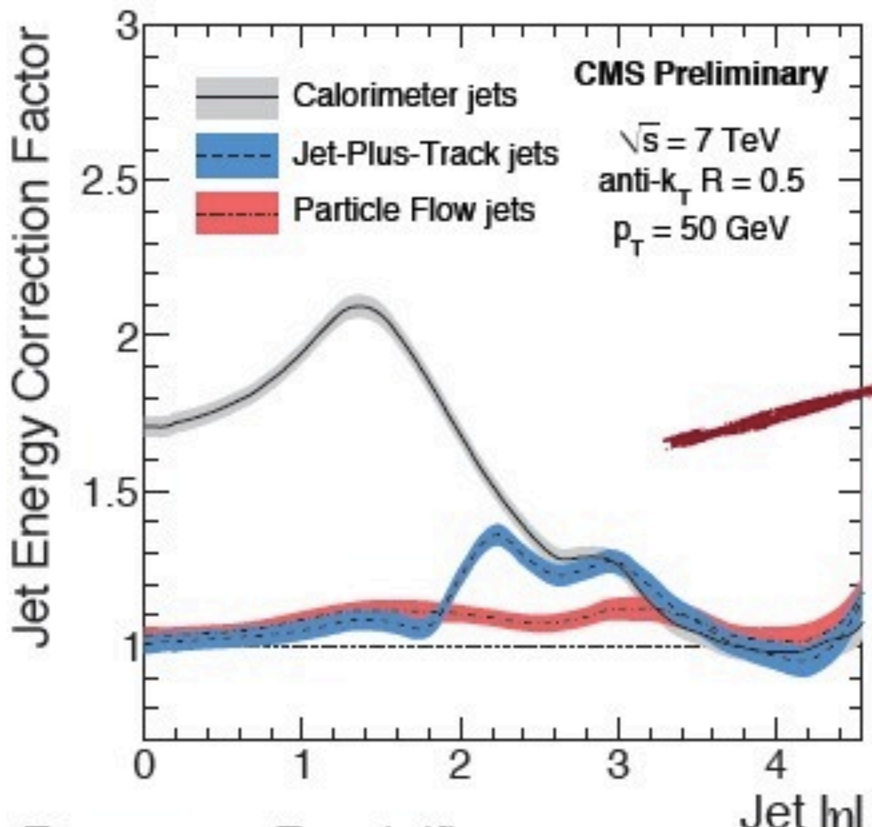


- Advantage of MPF: Low sensitivity to extra radiation

Particle Flow Jets







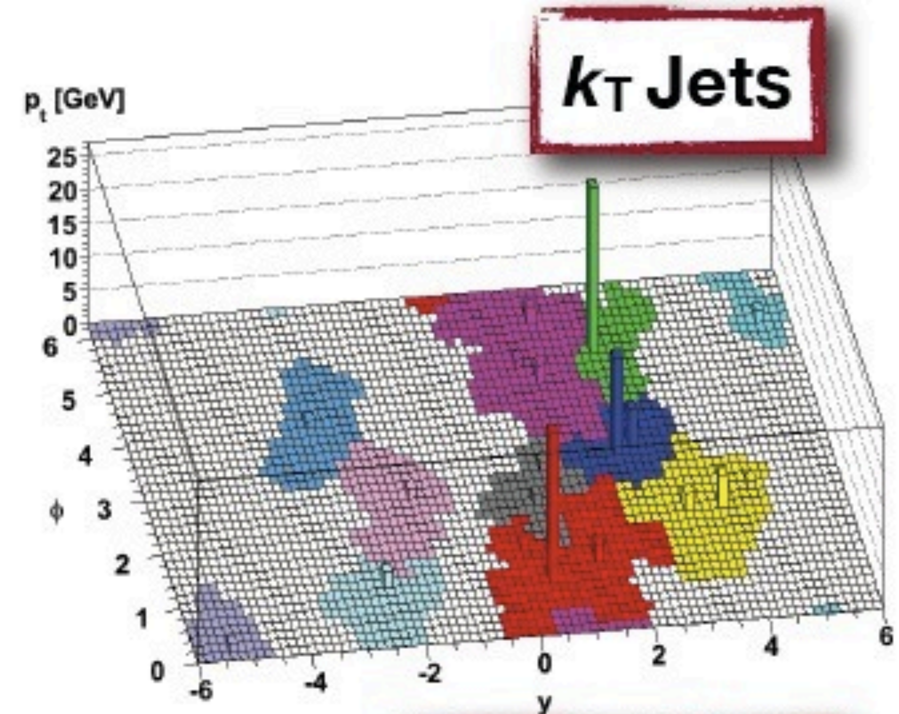
Total JES Correction Factor

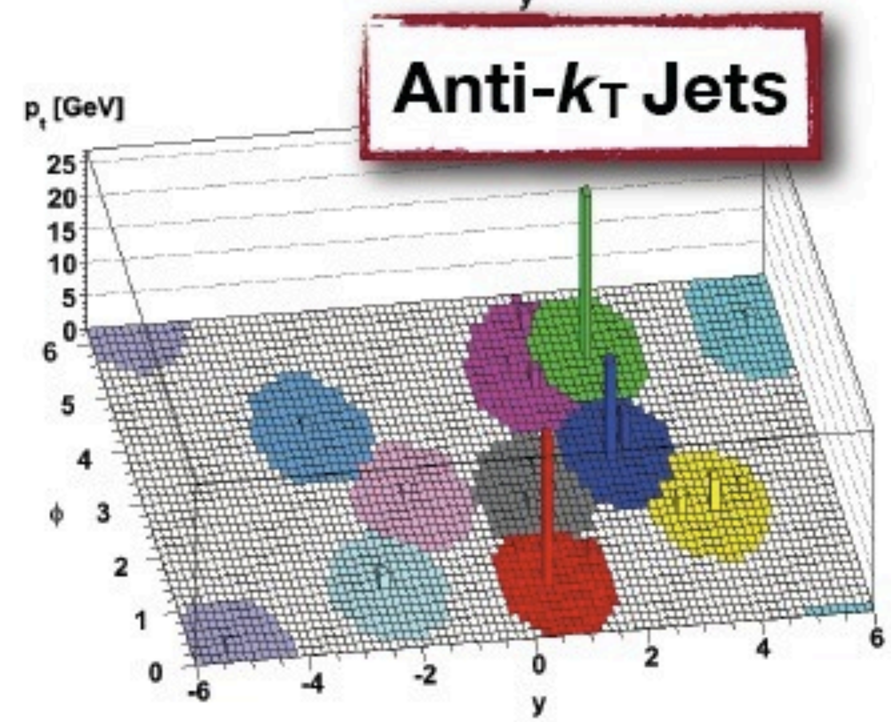
J.Weng

Tuesday, April 12, 2011

The Anti K_T

- Reference jet algorithm at CMS
- It's a k_T class algorithm (sequential recombination)
  - Infrared/collinear safe
  - One parameter: "cone size" parameter R
- But with inverse-momentum weights
  - Clusters soft particles around hard ones
  - Resulting jets are circular
  - Cannot extend beyond R



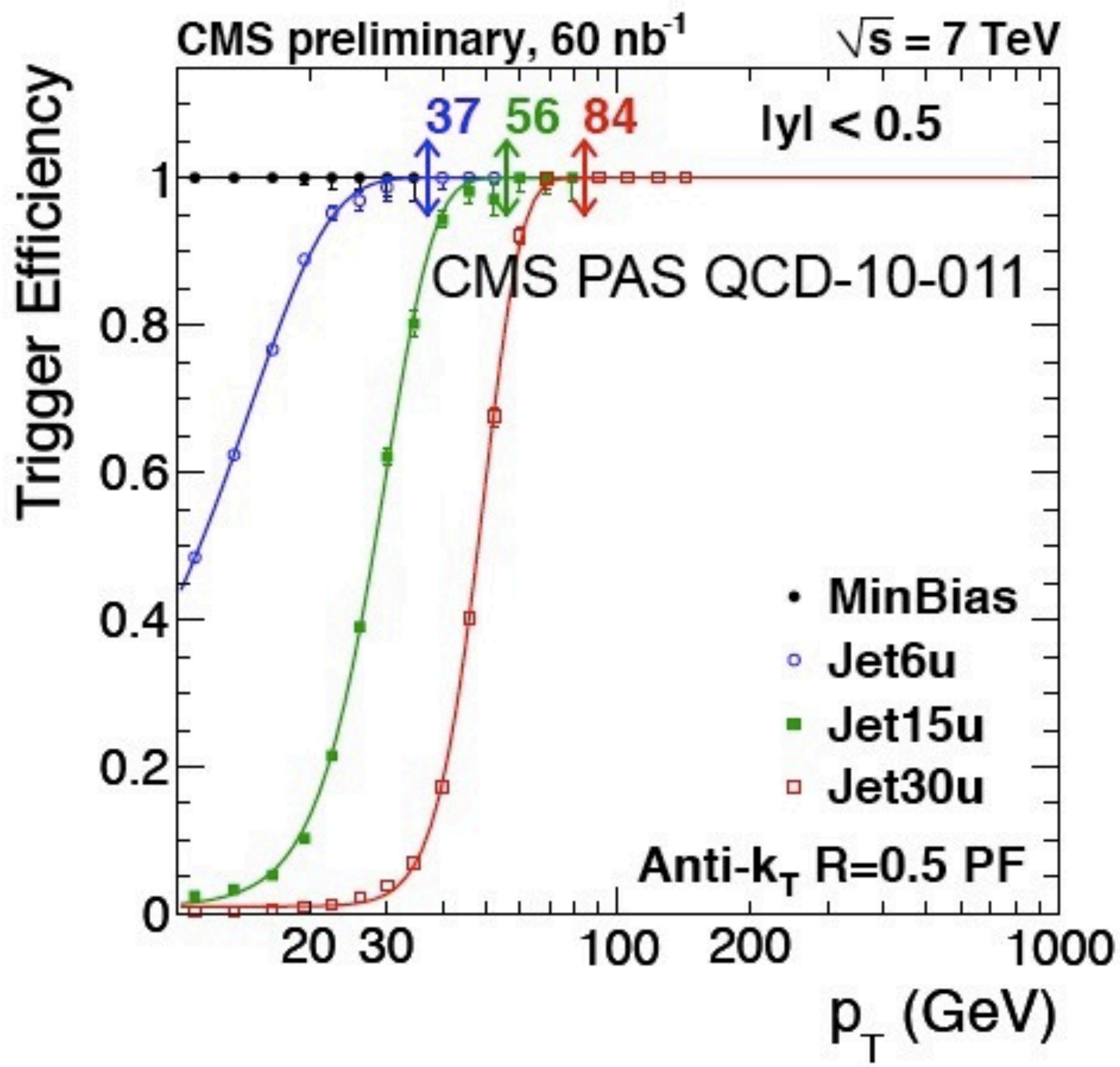


J.Weng

CMS Trigger System

ETH Institute for Particle Physics

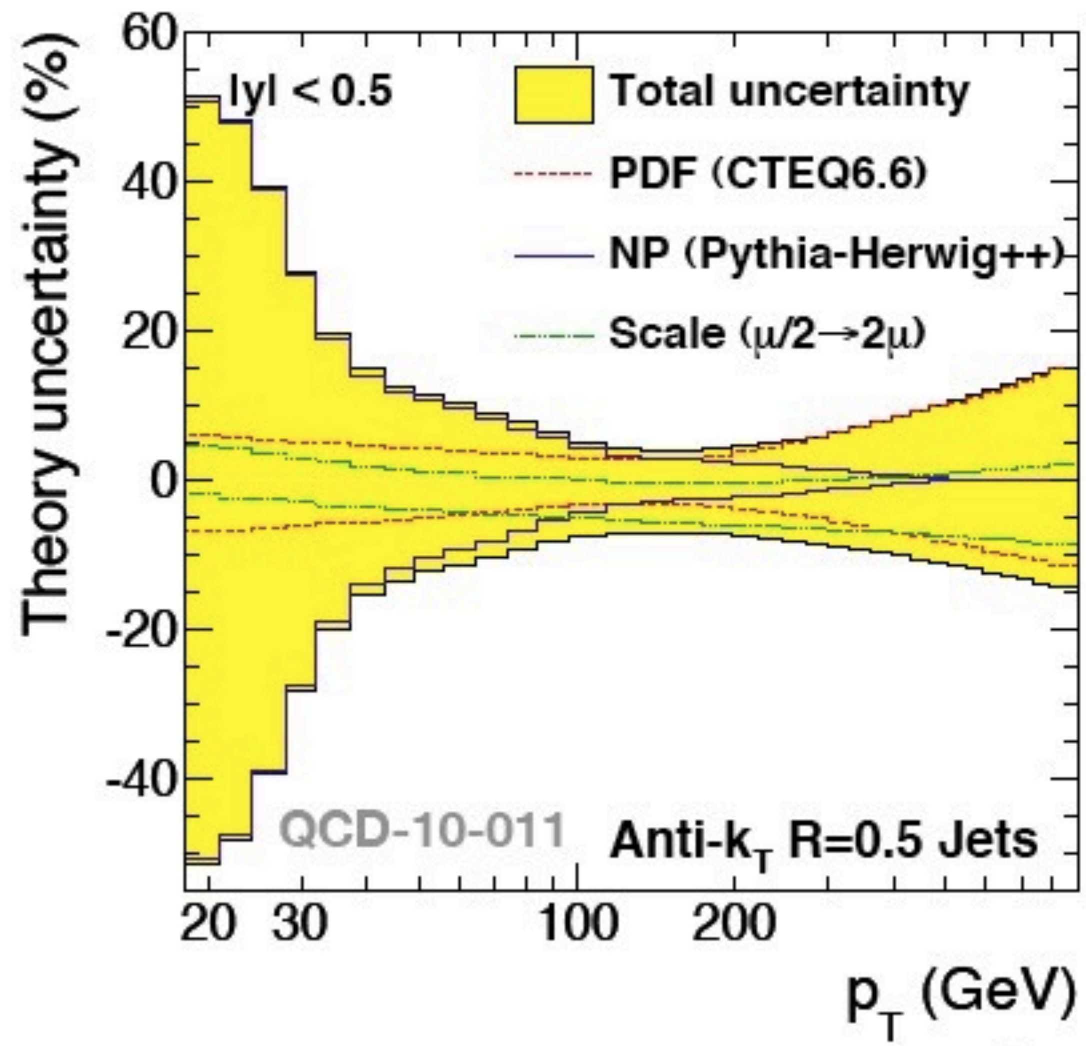
- Two-tiered system:
  - L1: hardware, firmware (40 MHz → 100 kHz)
  - HLT: high-level software (100 kHz → ~100-200 Hz)
- Minimum Bias Trigger
  - Coincidence of Beam Scintillator Counters
- Jet Triggers
  - Using uncalibrated Calorimeter Jets
  - >99% efficient above turn-on
  - Lowest threshold trigger unprescaled over 2010 run: Jet140u



J.Weng

Theory Predictions

- Central value:
  - **NLO prediction** from NLOJet++ in fastNLO framework
  - **Non-perturbative corrections:** mean of Pythia6 and Herwig++
  - **PDF** set: CT10
- Uncertainty:
  - **PDF:** PDF4LHC recommendation: envelop of CT10/MSTW2008/NNPDF2.0 around CTEQ6.6
  - **Scale:** vary μ_R μ_F in 6-point scheme ($\mu/2 \rightarrow 2\mu$)
  - **Non-perturbative:** half of Pythia-Herwig
  - **Strong coupling:** $\Delta\alpha_S(M_Z) = \pm 0.002$



J.Weng

Tuesday, April 12, 2011

Previous R_{32} Measurements

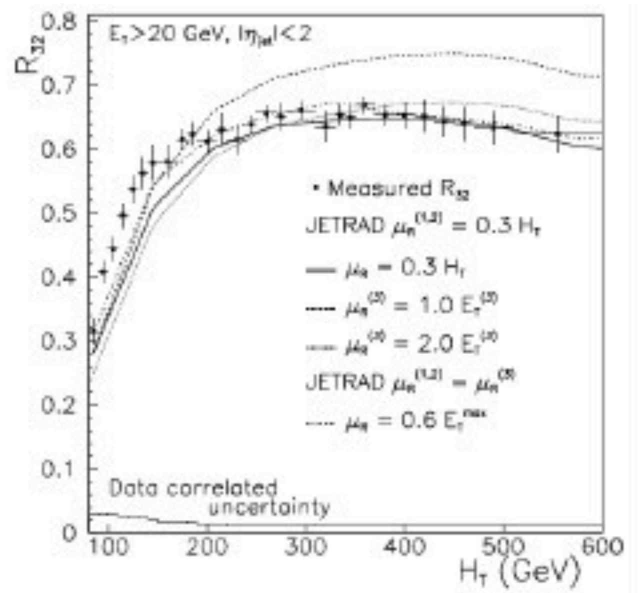
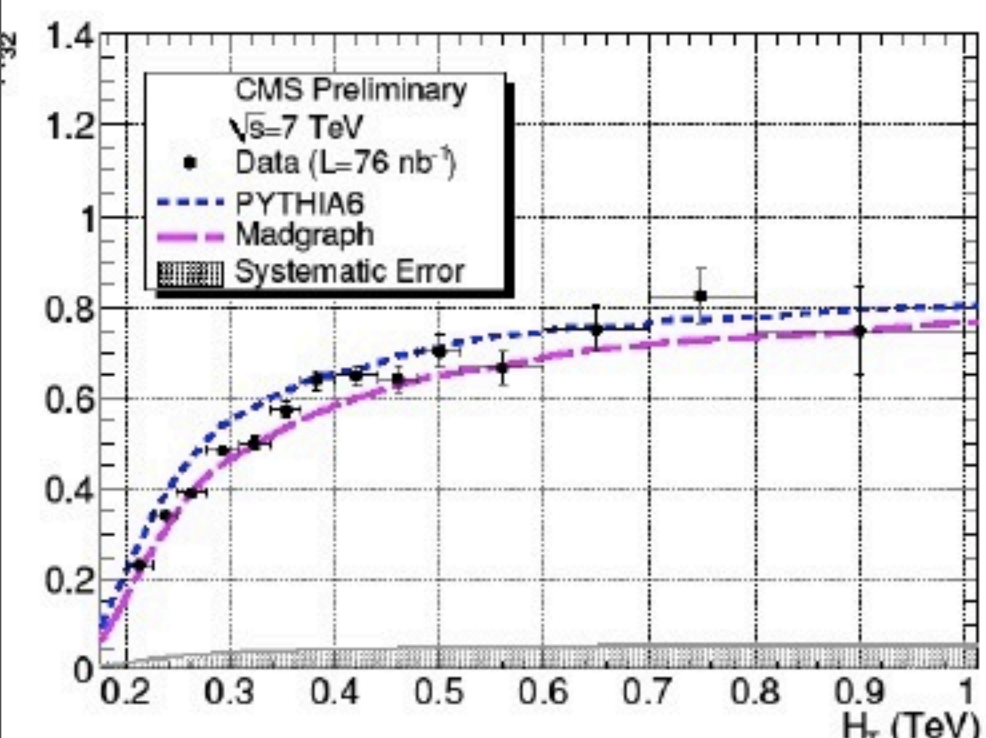


FIG. 2. The ratio R_{32} as a function of H_T, requiring jet $E_T >$ 20 GeV and $|\eta_{jet}| < 2$. Error bars indicate statistical and uncorrelated systematic uncertainties, while the histogram at the bottom shows the correlated systematic uncertainty. The four smoothed distributions show the JETRAD prediction for the renormalization scales indicated in the legend.

- D0 measurement
  - 100 GeV < H_T < 600 GeV
  - E_T>20GeV, $|\eta|$<2
  - Center of mass energy: 1.8 TeV
  - PRL 86, p1955 (2001)



- **First CMS result with 76nb^{-1} consistent with the predictions of PYTHIA 6 and MadGraph (PAS QCD-10-012)**
- The measured ratio rises, due to phase space, with H_T . Above H_T≈0.7 TeV it reaches a plateau which is most sensitive to α_s.
- Two sources of systematic uncertainties were considered:
  - Uncertainties due to absolute (10%) and eta-dependent (2%xη) Jet Energy Scale lead to R_{32} uncertainties of 5%.
  - Systematic uncertainty due to difference in shape between data and MC is 5%.

J.Weng