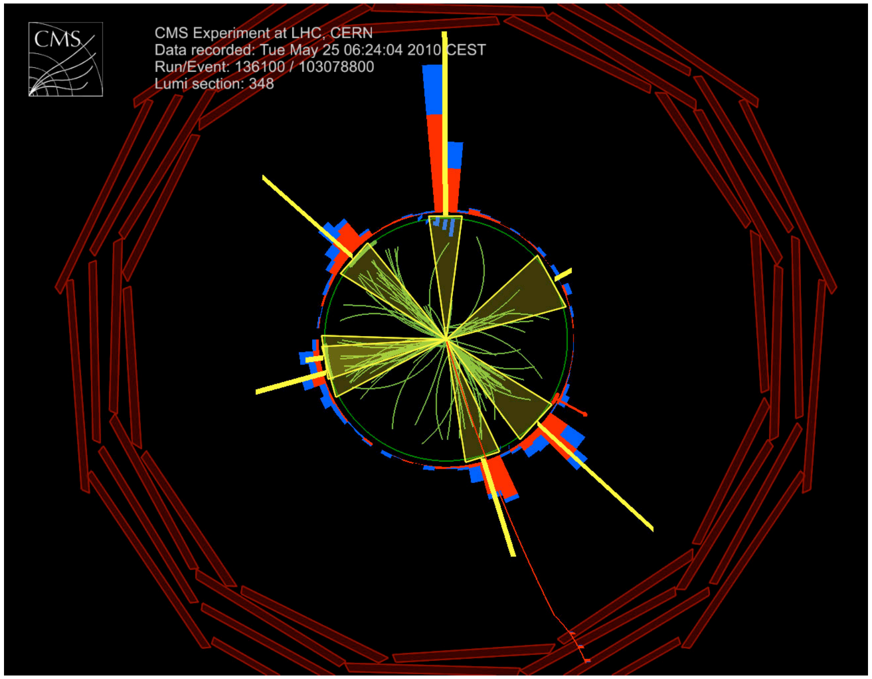
Hard QCD results in CMS

Suvadeep Bose

University of Nebraska Lincoln

(on behalf of CMS collaboration)



A·S·P·E·N Center for Physics

February 14 , 2011

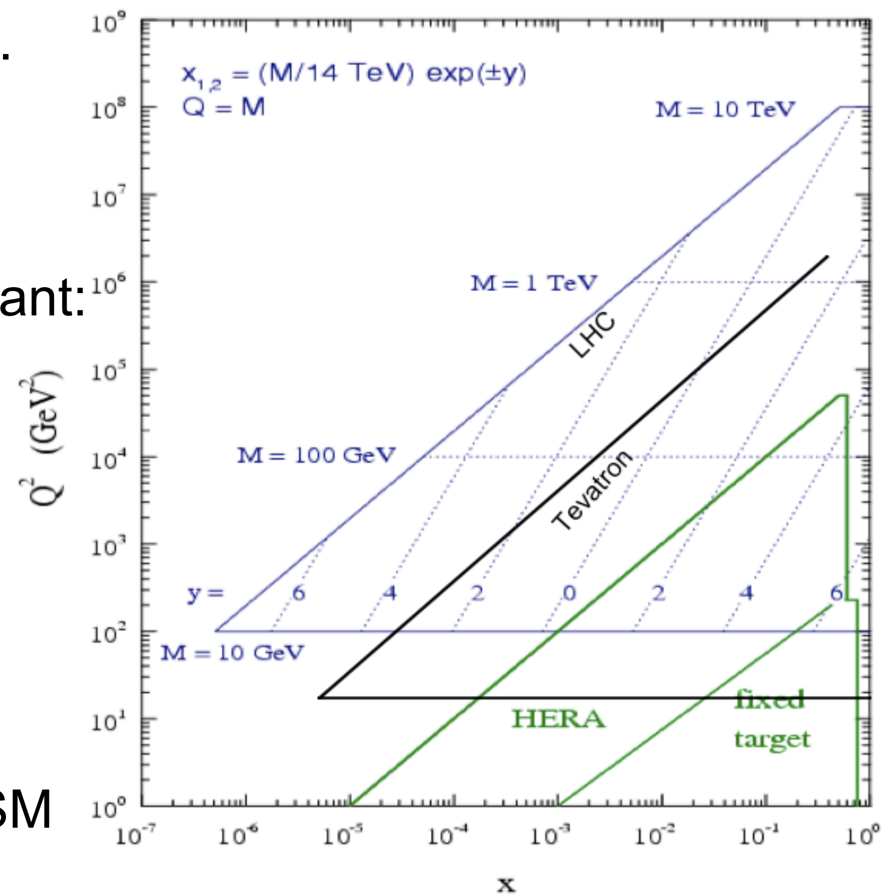
Outline

- Introduction
- Jet Reconstruction and Performance
  - Jet clustering algorithms
  - Jet energy scale (CMS PAS JME-10-003, CMS PAS JME-10-010)
- Jet Measurements
  - Jet Shapes (CMS PAS QCD-10-014)
  - Inclusive Jet Cross Section (CMS PAS QCD-10-011)
  - Dijet Mass Spectrum (PRL **105**, 211801)
  - Dijet Angular Distribution (arXiv:1102.2020, submitted to PRL)
  - Dijet Centrality Ratio (PRL **105**, 262001)
  - Dijet Azimuthal Decorrelation (arXiv:1101.5029, submitted to PRL)
  - 3-jet to 2-jet ratio (CMS PAS QCD-10-012)
  - Event Shapes (arXiv:1102.0068, submitted to PLB)
- Photon reconstruction and Performance (CMS PAS EGM-10-006)
- Direct Photon measurements
  - Inclusive Isolated Photon Production (arXiv:1012.0799)

Introduction

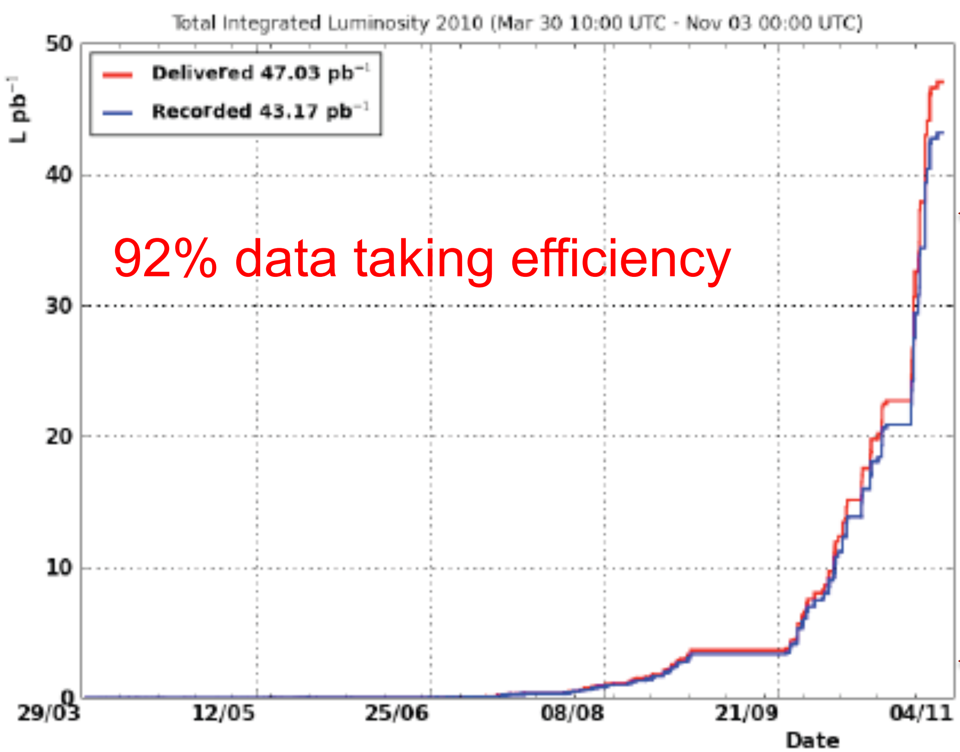
- The goal at startup was to re-establish the standard model (i.e., QCD, SM candles) in the LHC energy regime.

- QCD is the dominant process in LHC.
- The LHC detectors' rapidity coverage allows probing a Large Q^2 vs x phase space.
- Jet measurements at LHC are important:
- confront pQCD at the TeV scale
- constrain PDFs
- Probe strong coupling constant, α_S
- sensitive to new physics (quark substructure, excited quarks, dijet resonances, etc)
- understand multijet production (important background for SUSY and BSM searches)
- QCD processes are not statistics limited.



Integrated Luminosity in 2010

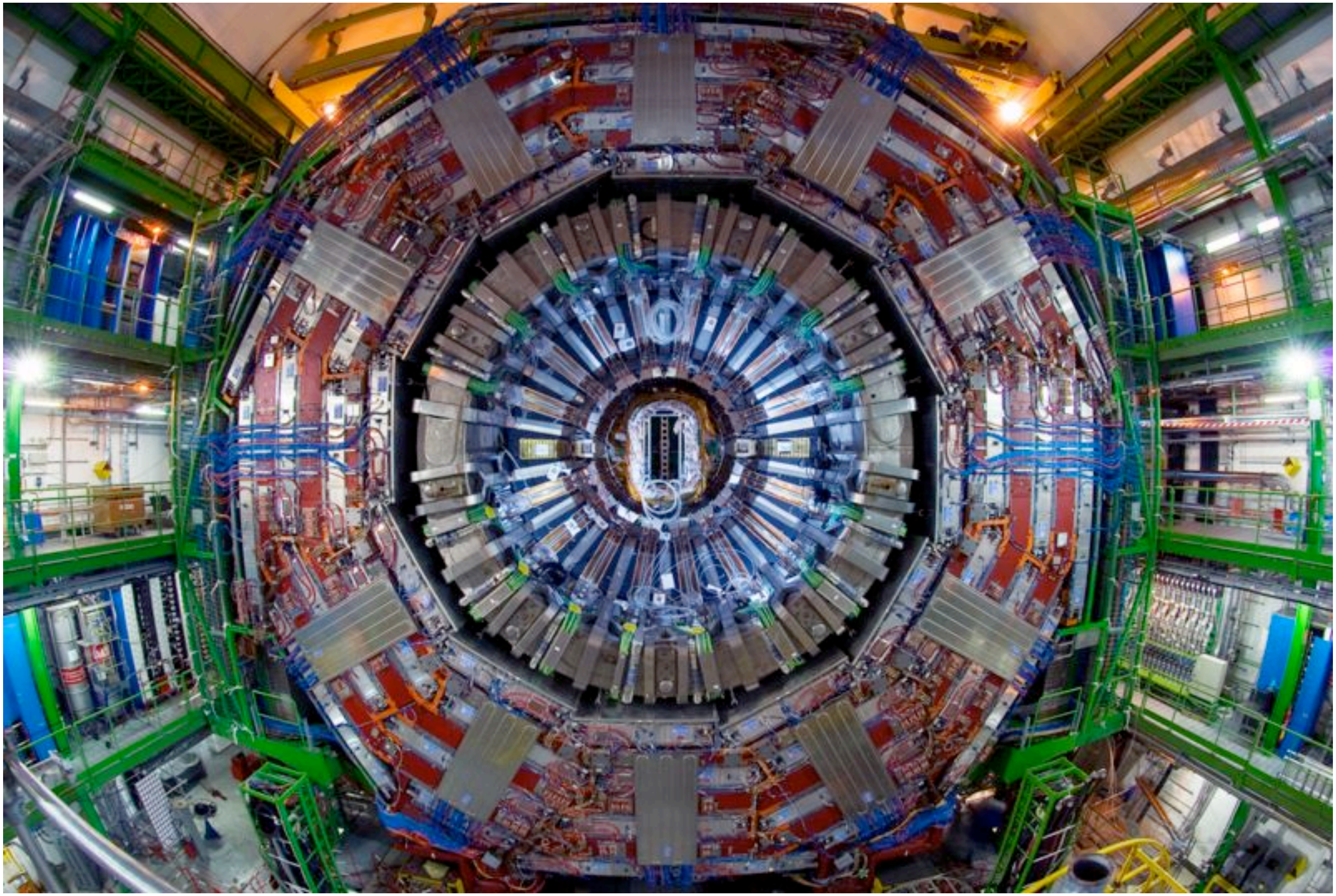
- Excellent machine performance by LHC since last August
- 47 pb^{-1} *pp* data delivered; 43 pb-1 recorded by CMS
- ~85% recorded with all sub-detectors in perfect condition
- All sub-detectors have at least 98% of all channels operational
- Luminosity uncertainty is currently 11%



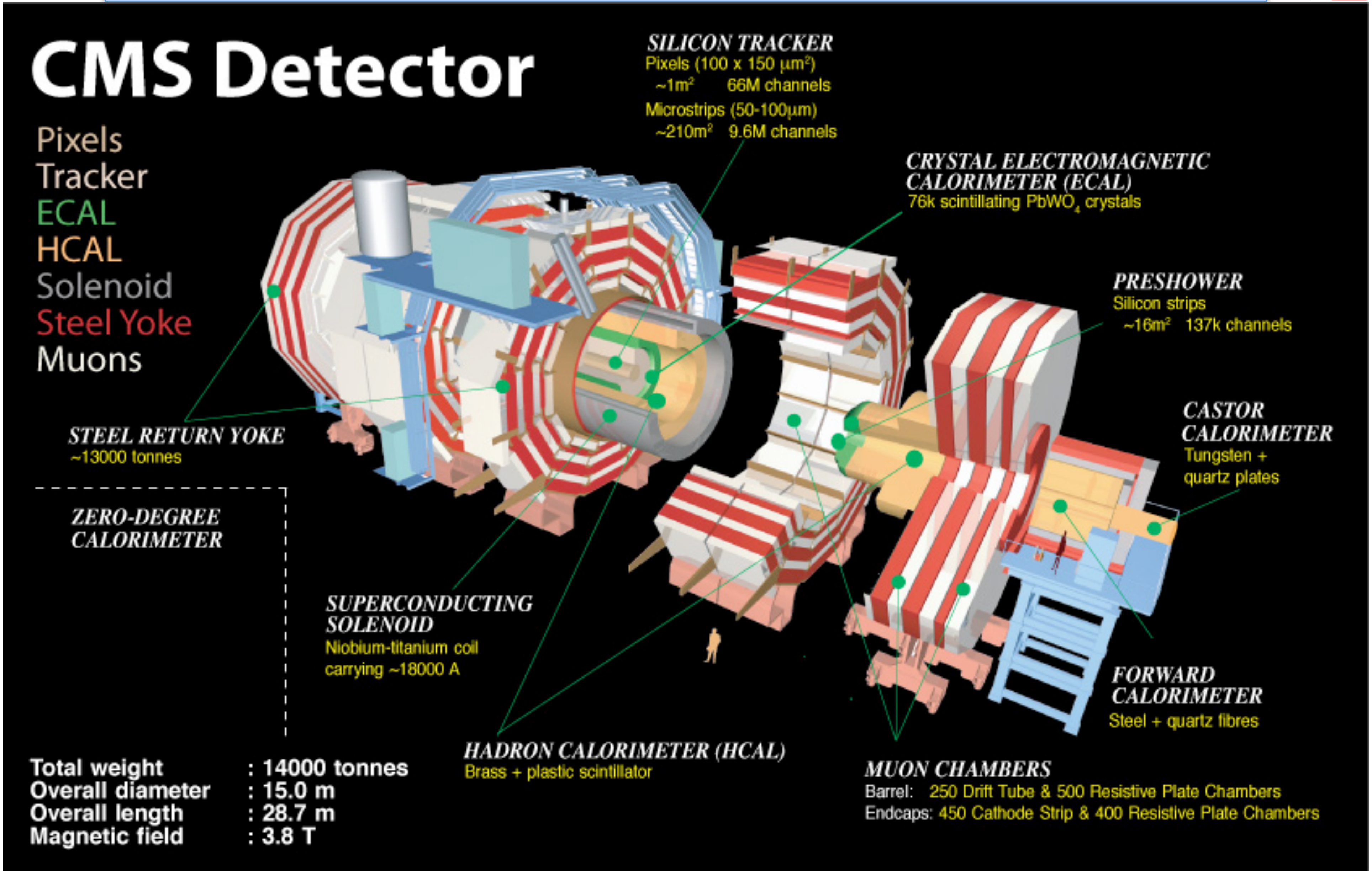
Most of the Results (only 2 months after end of run) (published/ heading for)

A few 'basic' analyses (published)

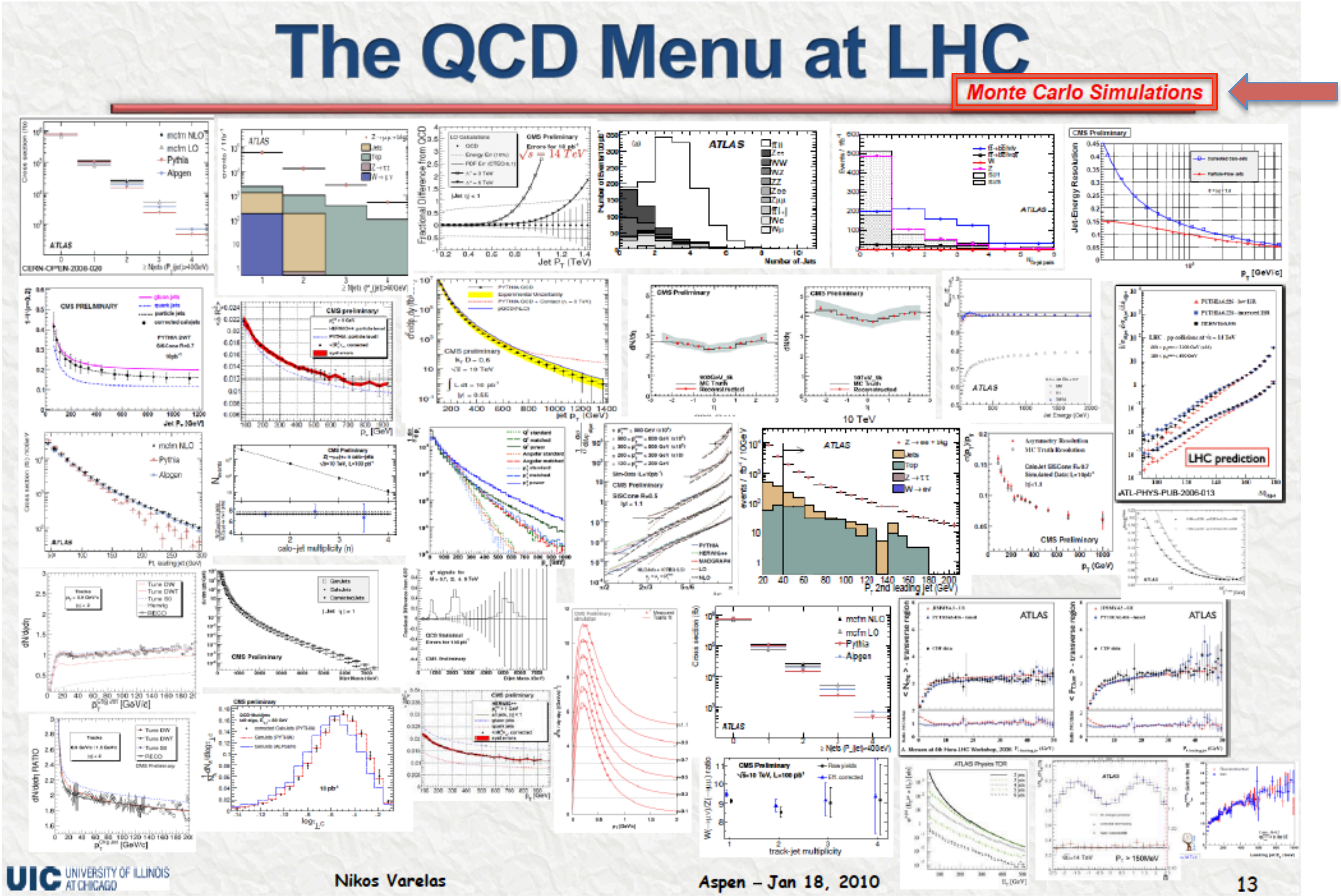
The CMS detector



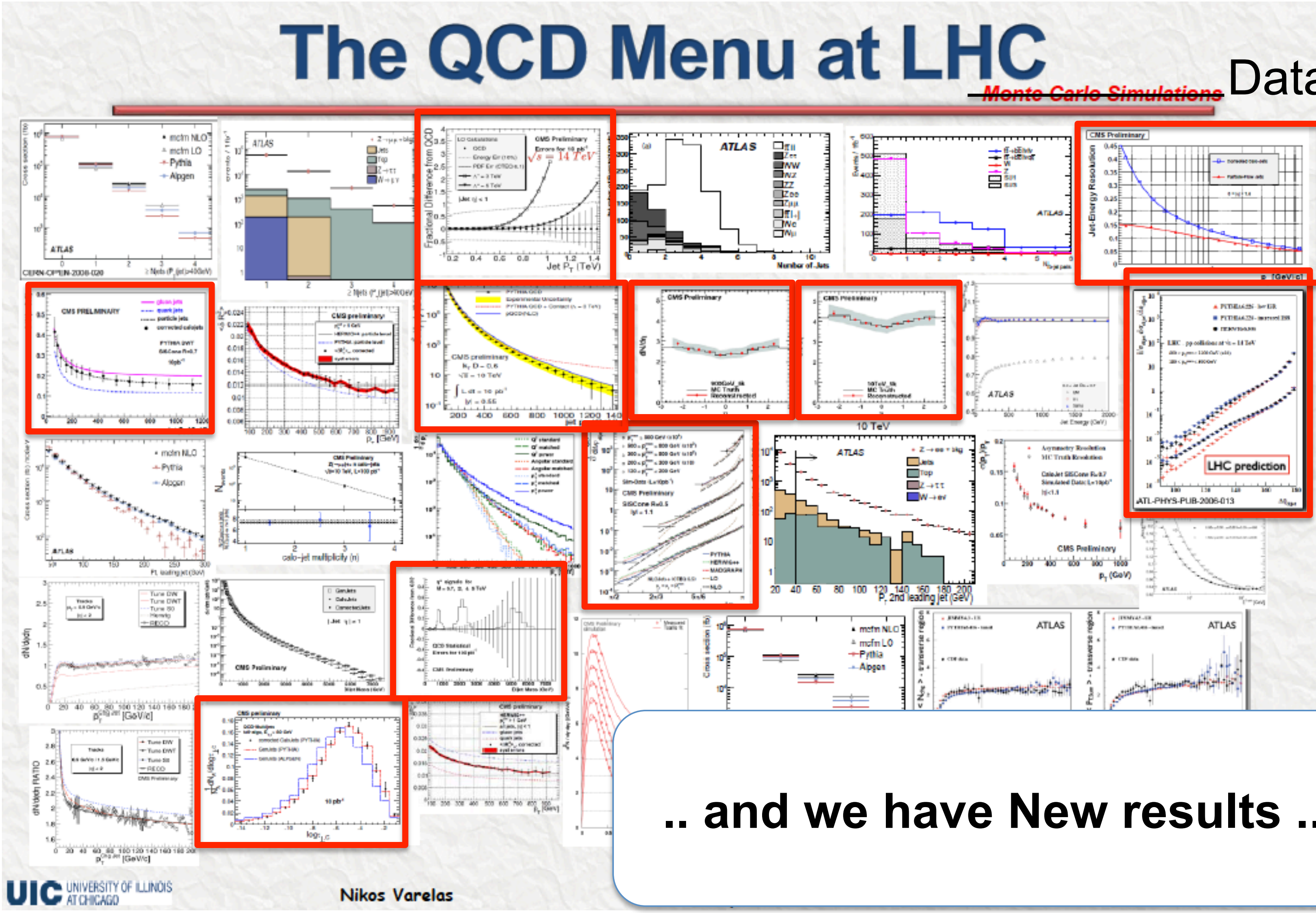
The CMS detector



What CMS showed a year back ..

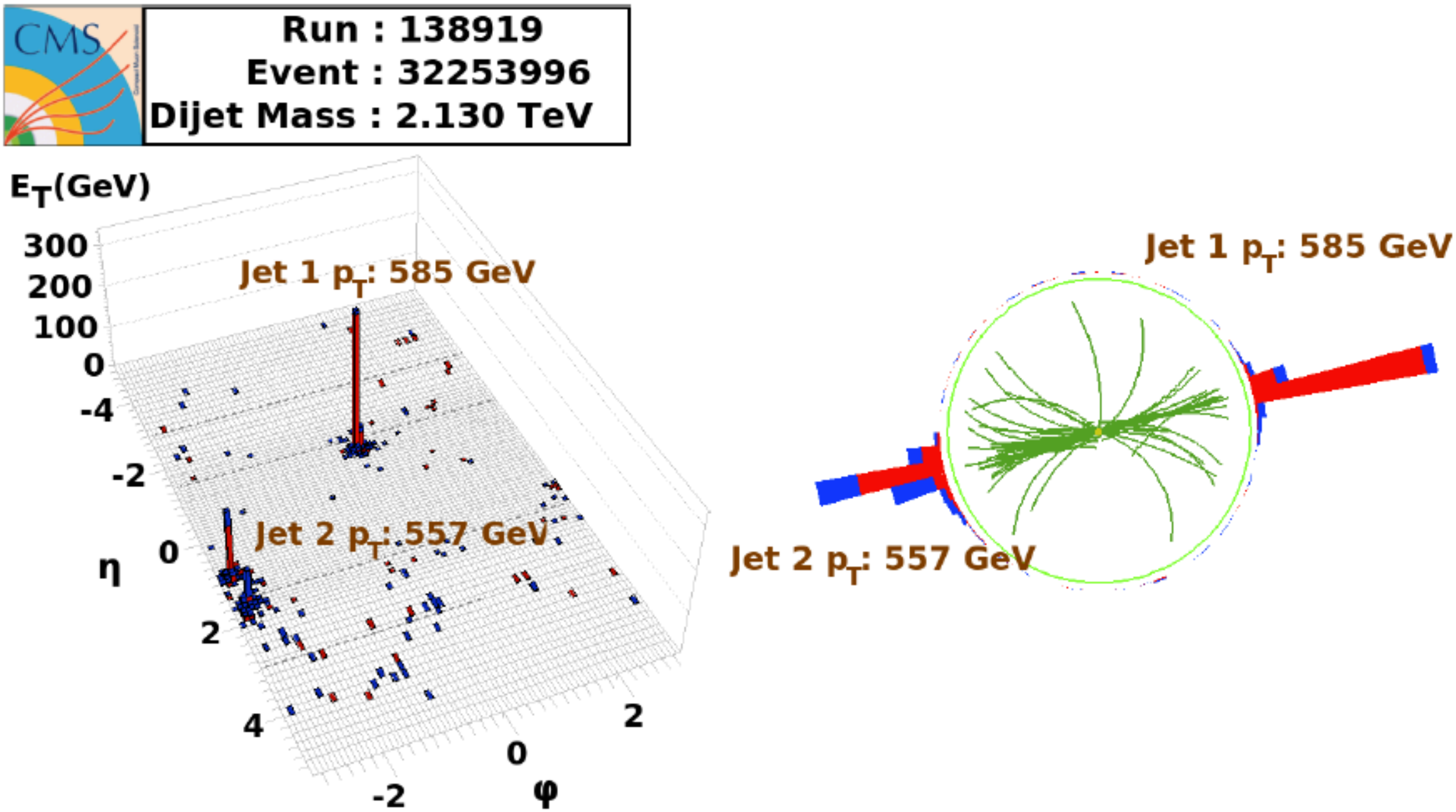


Now we have data ..



.. and we have New results ..

Jets in CMS



Run : 138919
Event : 32253996
Dijet Mass : 2.130 TeV
E_T(GeV)
300
200
100
0
-4
-2
0
2
4
η
-2
0
2
φ
Jet 1 p_T: 585 GeV
Jet 2 p_T: 557 GeV
Jet 1 p_T: 585 GeV
Jet 2 p_T: 557 GeV

Jet measurements in CMS

- Jets are the experimental signature of quarks and gluons, observed as highly collimated sprays of particles.
- A *jet algorithm* is a set of mathematical rules that reconstruct unambiguously the properties of a jet.
- Fixed cone algorithms:
  - Iterative Cone (CMS) / JetClu (ATLAS)
  - Seedless Infrared Safe Cone (SISCone)
- Successive recombination algorithms:

$$d_{ij} = p_{T,i}^{2p} \qquad d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{D^2}$$

p=1 -> k_T jet algorithm
p=0 -> CA jet algorithm
p=-1 -> "Anti-k_T" jet algorithm

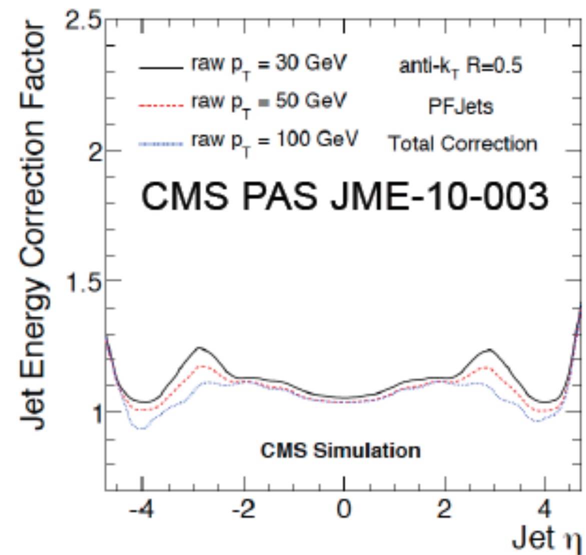
CMS default

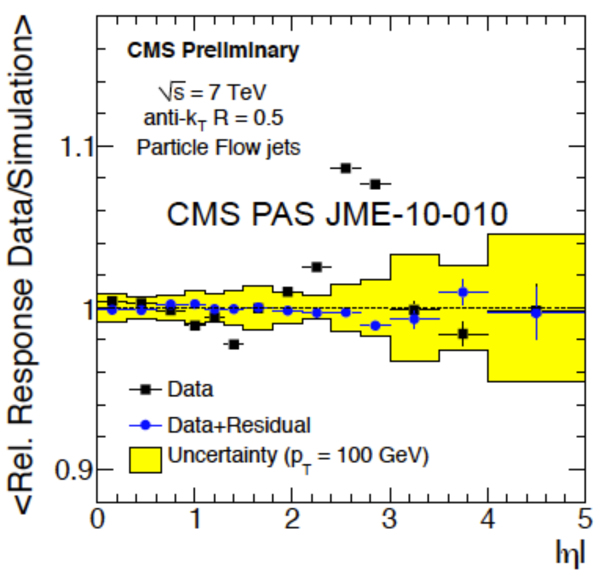
- Different inputs to the jet algorithm lead to different types of jets:

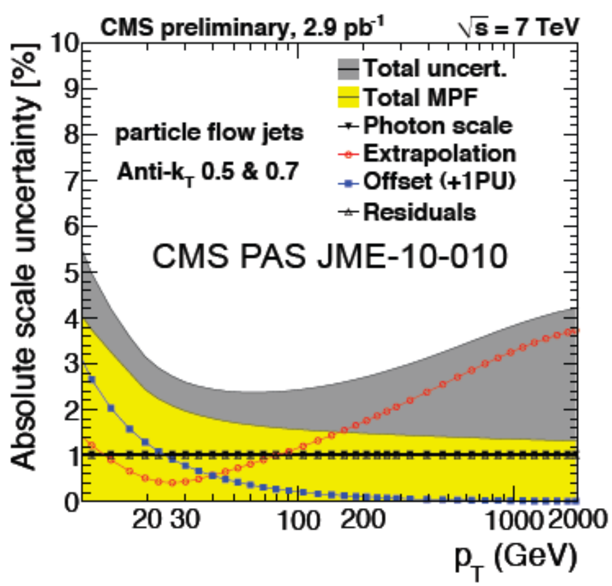
  - **Calorimeter jets (CaloJets)**: Clustered from CaloTowers
  - **Track Jets**: Clustered from charged particle tracks
  - **Jets plus Tracks**: Correct calorimeter jets using momentum of tracks.
  - **Particle Flow Jets**: Clustered from identified particles, reconstructed using all detector components.

Jet Energy Calibrations in CMS

- ❑ Factorized approach (like Tevatron):
  - offset correction (removes pile-up and noise contribution)
  - relative correction (flattens jet response in pseudorapidity)
  - absolute correction (flattens the jet response in p_T)
- ❑ In-situ residual correction:
  - Flattens jet response in η using dijet p_T balance
  - Flattens jet response in p_T using photon+jet Missing-E_T projection fraction method (MPF adopted from D0)







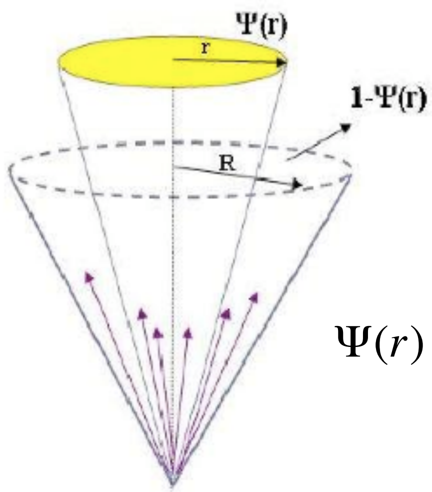
- ❑ Jet calibration vs. η better than 1% per unit of pseudorapidity.
- ❑ Jet energy scale uncertainty: 3-5% over whole p_T range.

Jet Shapes - I

- Jet shapes probe the transition between hard pQCD and soft gluon radiation.

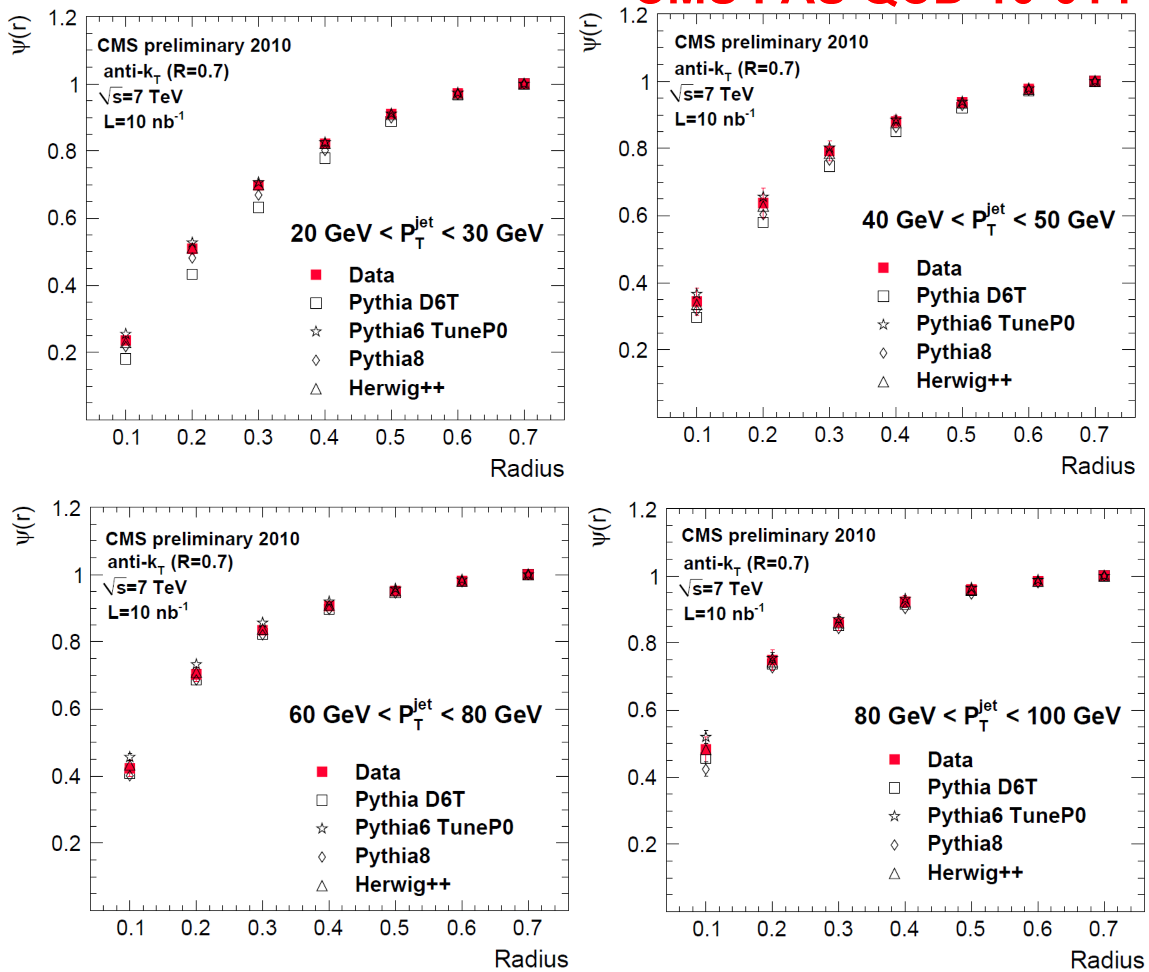
CMS PAS QCD-10-014

- Sensitive to the quark/gluon jet mixture
- Test of parton shower event generators at non-perturbative levels
- Useful for jet algorithm development and tuning



$$\Psi(r) = \frac{1}{N_{jets}} \frac{\sum_{r_i<r} p_{T,i}}{\sum_{r_i<R} p_{T,i}}$$

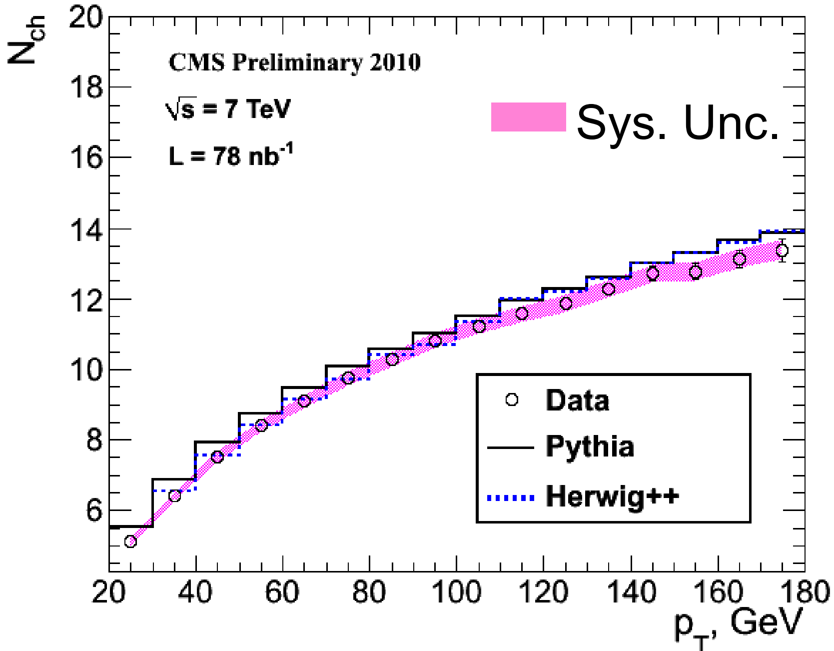
Integrated jet Transverse shape



CMS PAS QCD-10-014

Jet Shapes - II

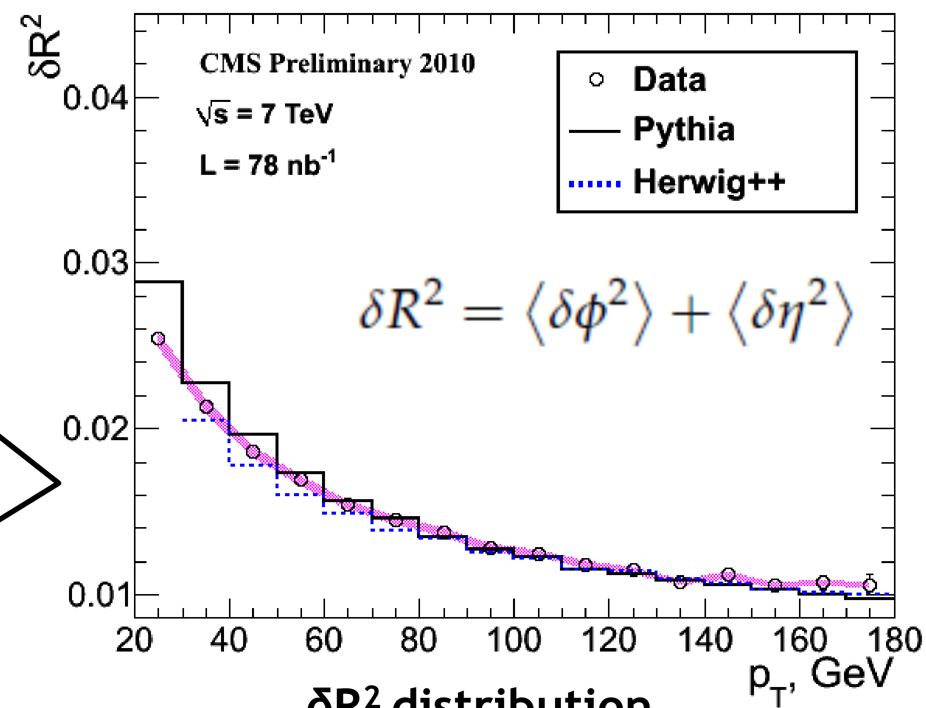
CMS PAS QCD-10-014



Charged particle multiplicity (N_{ch})

- Charged particle transverse shape variable (δR^2):
  A measure of the width of a jet in the η-Φ plane.

$$< \delta R^2 > (p_T) =< \delta \varphi^2 > (p_T) + < \delta \eta^2 > (p_T)$$



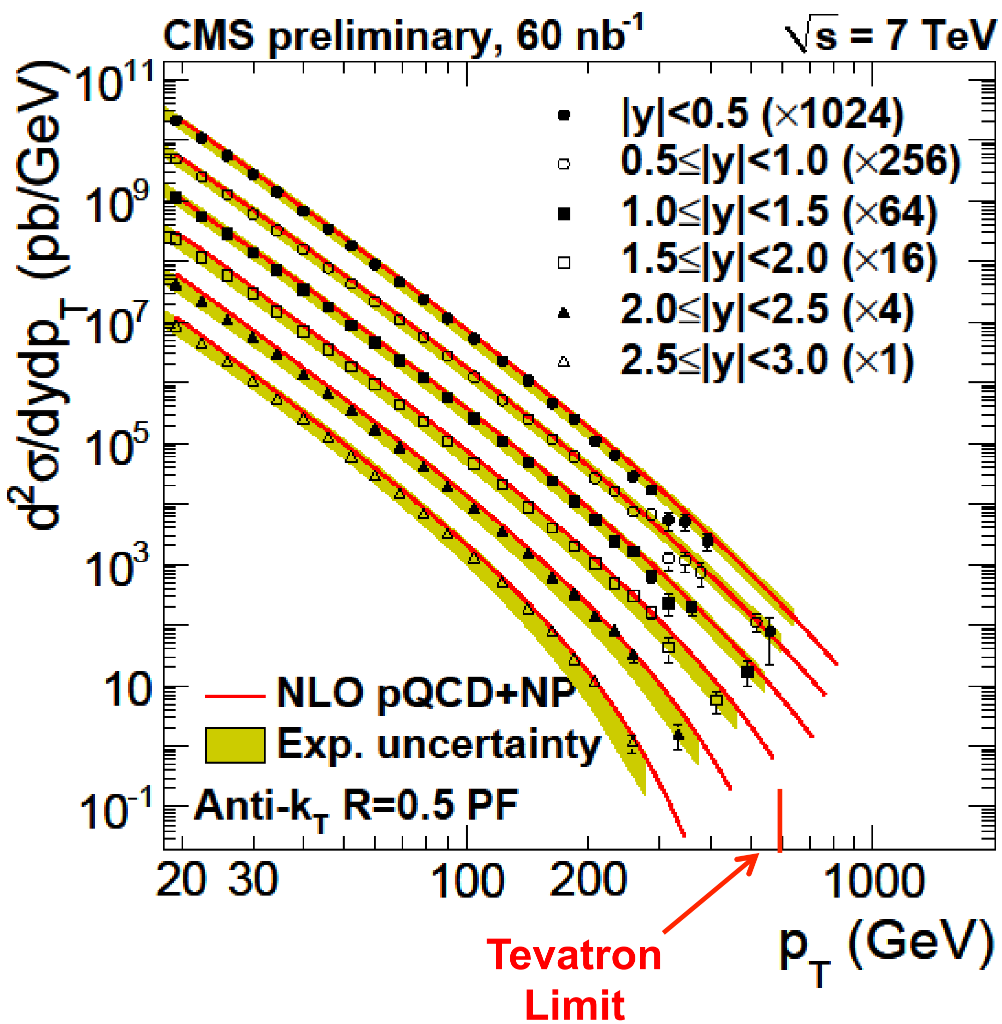
$$\delta R^2 = \langle \delta\phi^2 \rangle + \langle \delta\eta^2 \rangle$$

δR^2 distribution

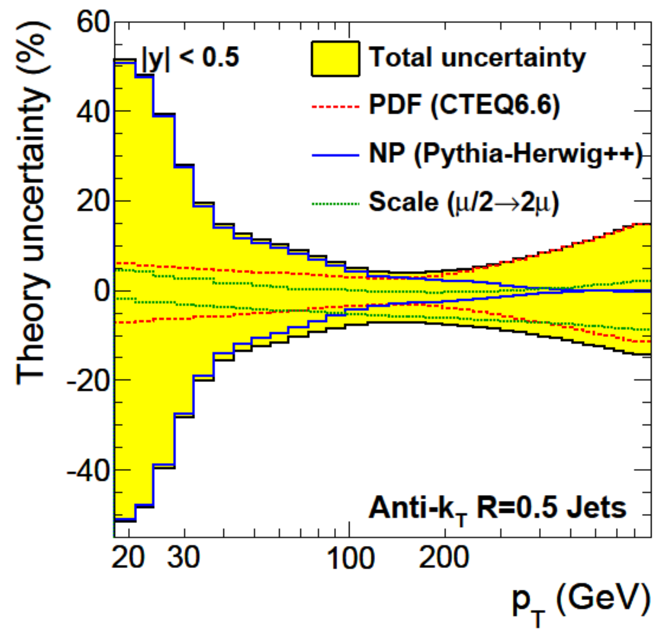
- At low jet transverse momentum ($20 < p_T < 50$ GeV) the measured jets are a few percent broader than predicted by HERWIG++ and narrower than predicted by PYTHIA D6T

Inclusive Jet Cross Section

CMS PAS QCD-10-011



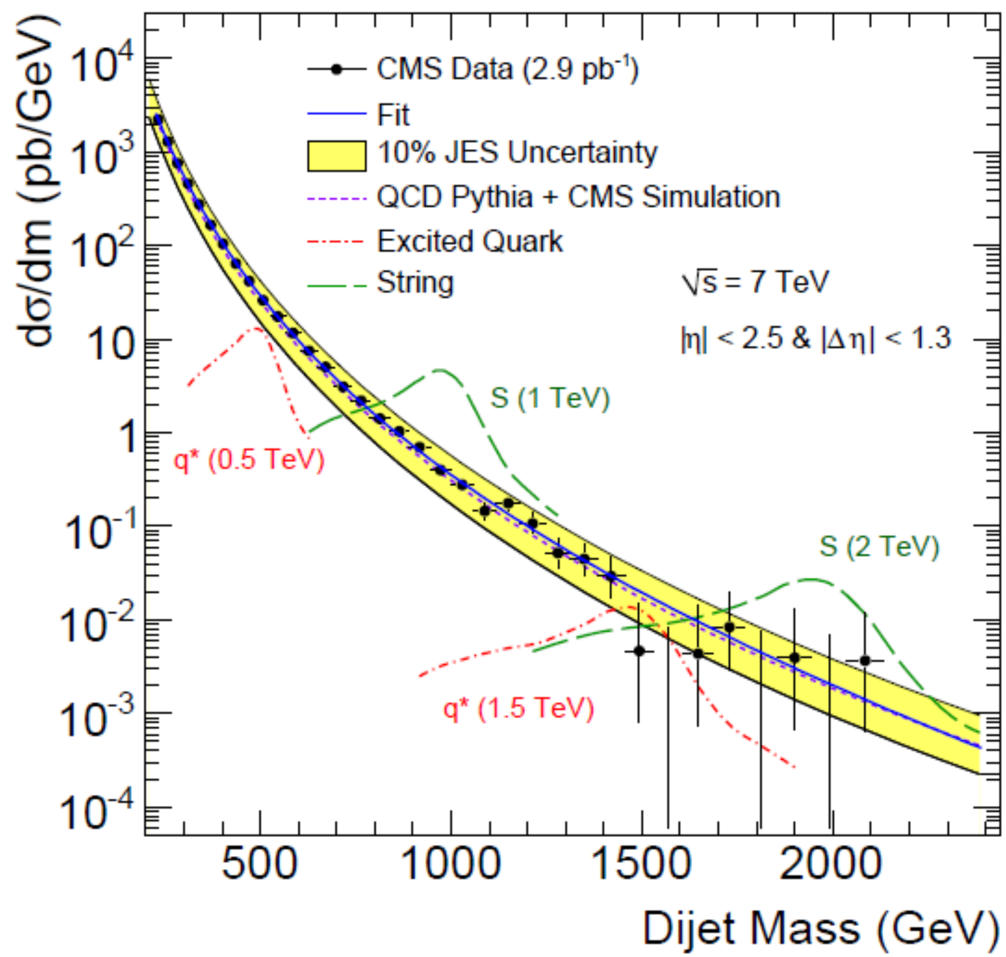
- Fundamental jet measurement
  - Used to constrain PDF's
  - Can probe contact interactions
- Large rapidity coverage (upto |y|<3)
- Measurement extends to very low p_T (~20 GeV) with Particle Flow jet reconstruction.
- **Good agreement between data and Next to Leading Order QCD theory**



Dijet Mass Distribution

- Mass reach beyond Tevatron limit
- Good agreement between data and CMS simulation of QCD using PYTHIA
- Search for narrow resonances decaying to dijets with natural width less than experimental resolution
  (*More in C. Hill's talk*)

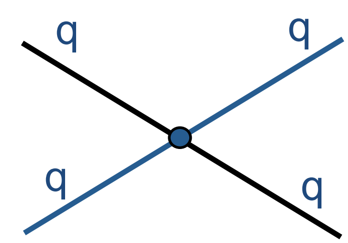
PRL 105, 211801 (2010)



Dijet Angular Distributions

$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$

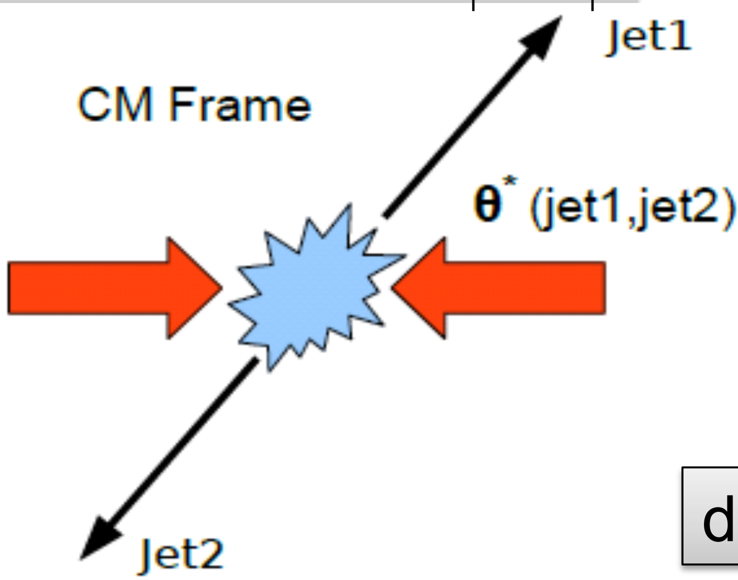


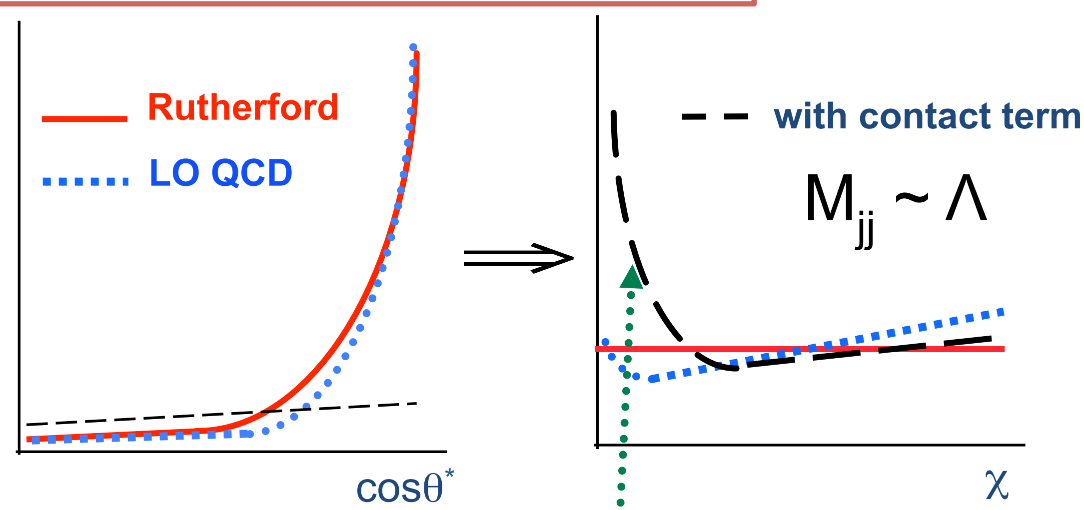
$$\sqrt{\hat{s}} << \Lambda$$

$d\sigma \sim 1/(1-\cos\theta^*)^2$ angular distribution

$$\chi_{dijet} = \exp(|y_1 - y_2|) = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

$d\sigma \sim (1+\cos\theta^*)^2$ angular distribution



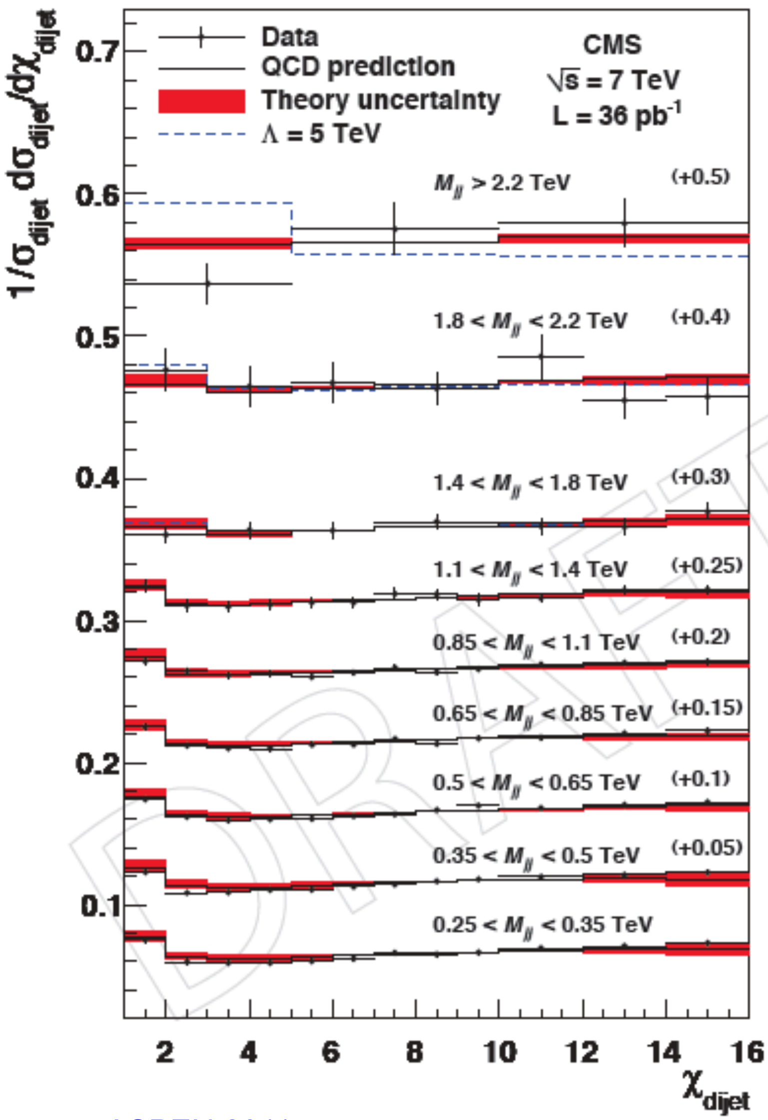


dN/dχ sensitive to contact interactions

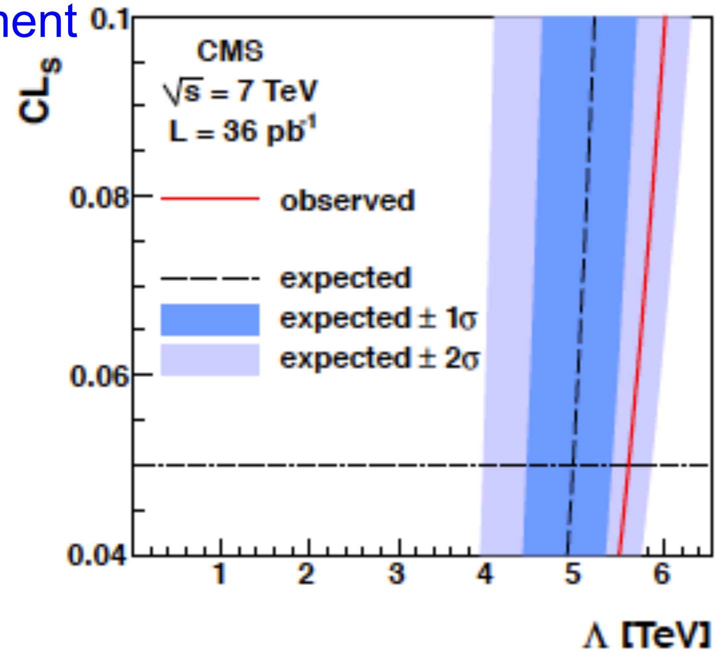
Dijet Angular Distributions

arXiv:1102.2020

$$\chi_{dijet} = \exp(|y_1 - y_2|) = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$



- Good agreement with pQCD
- Low systematic uncertainties due to normalization in each mass bin



Observed limit with systematics: $\Lambda > 5.6$ TeV

Expected limit: $\Lambda > 5.0^{+0.4}_{-0.5}$ TeV

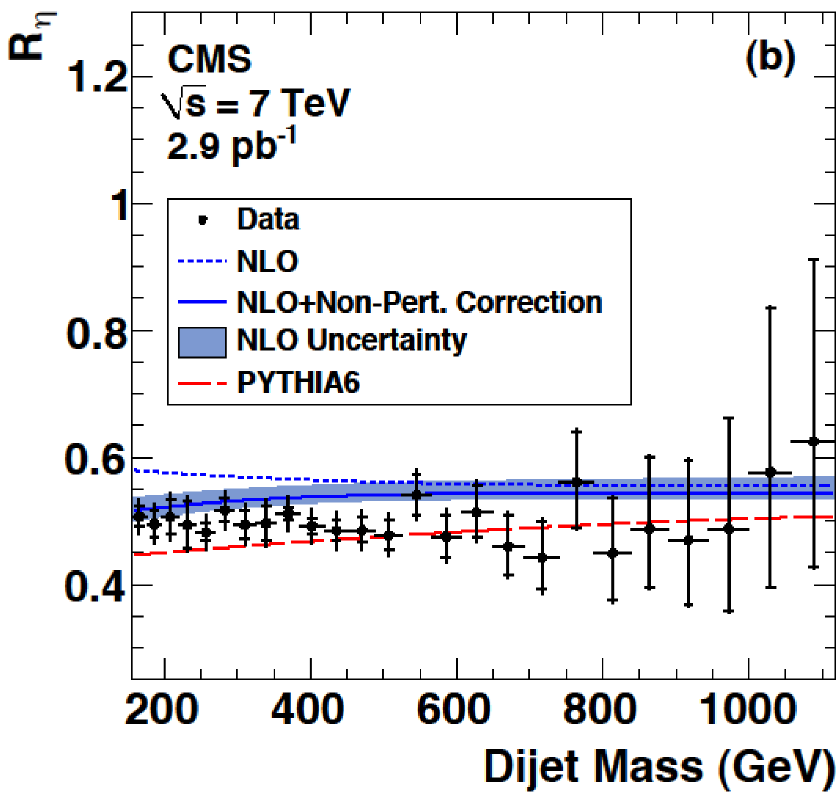
★ **Most stringent limit to date**

Dijet Centrality Ratio

- The dijet ratio is a simple measure of dijet angular distributions

$$R_\eta = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)}$$

  - Sensitive to contact interactions and dijet resonances



(arXiv:1010.4439 / PRL 105, 262001)

- Dijet ratio has low systematic uncertainties and is a precision test of QCD at startup

- The data agree with the theory prediction resonably well

- Set limit on contact interaction scale Λ

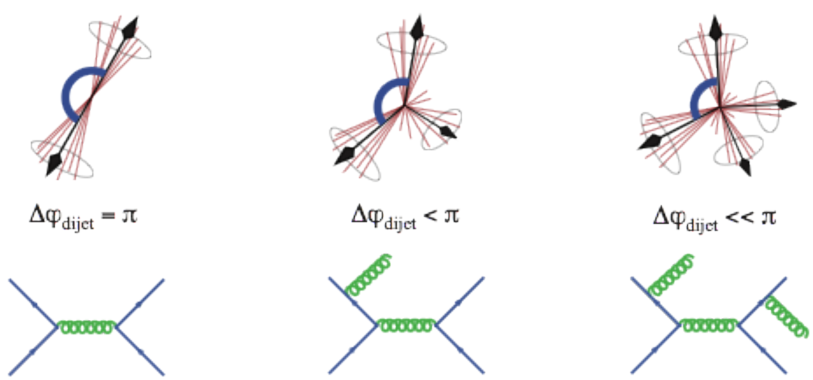
(*More in C. Hill's talk*)

Dijet Angular Decorrelations

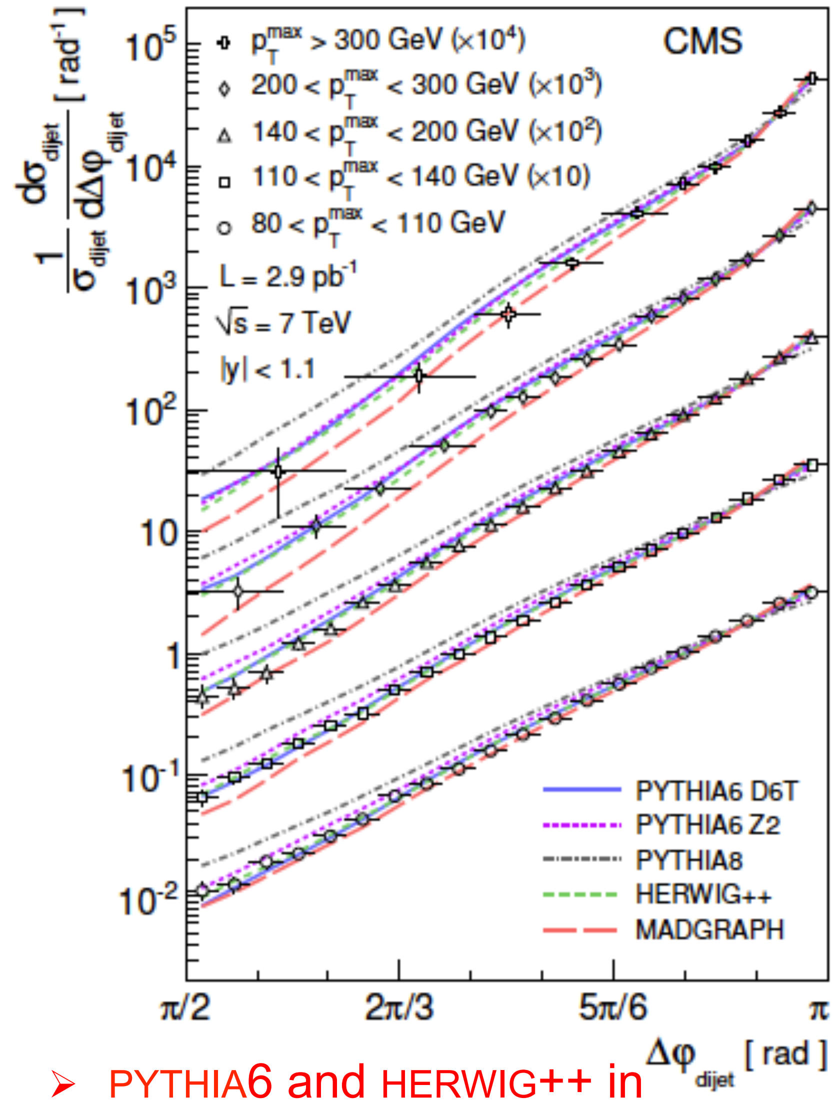
arXiv:1101.5029

- Measurement of the azimuthal angle between the two leading jets.
- Δφ distribution of leading jets is sensitive to higher order radiation without explicitly measuring the radiated jets
- Shape Analysis:

$$f(\Delta\varphi_{dijet}) = \frac{1}{\sigma_{dijet}}\left|\frac{d\sigma_{dijet}}{d\Delta\varphi_{dijet}}\right|$$



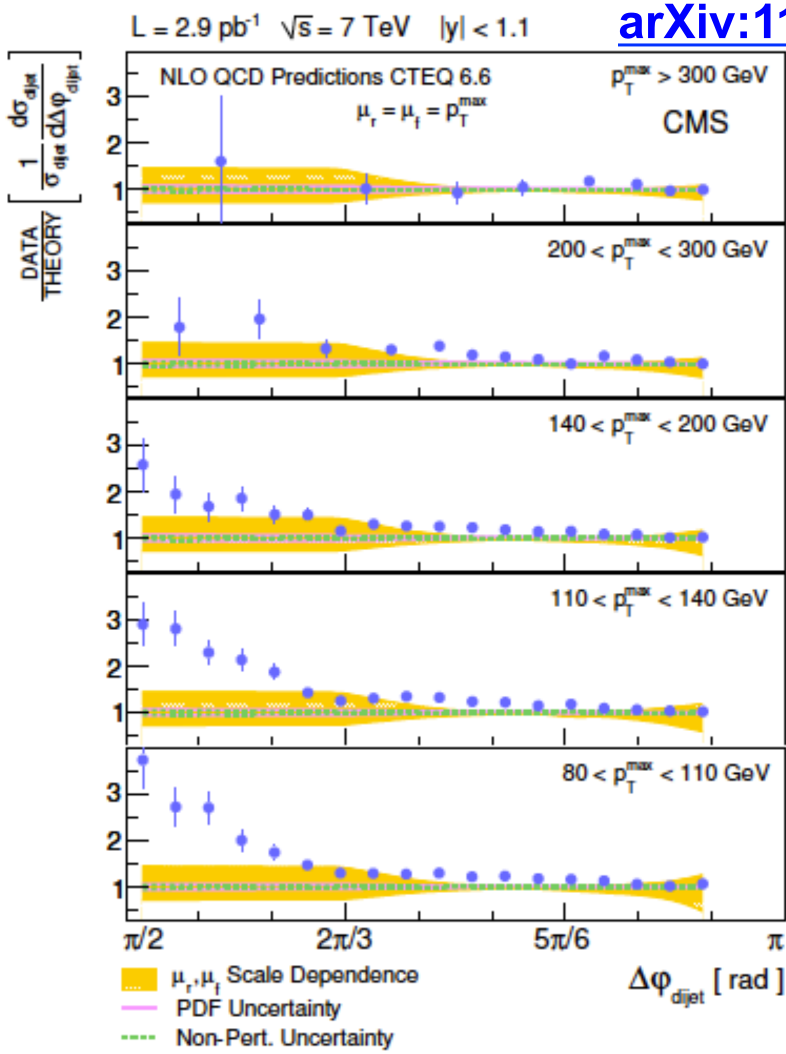
- Reduced sensitivity to theoretical (hadronization, underlying event) and experimental (JEC, luminosity) uncertainties

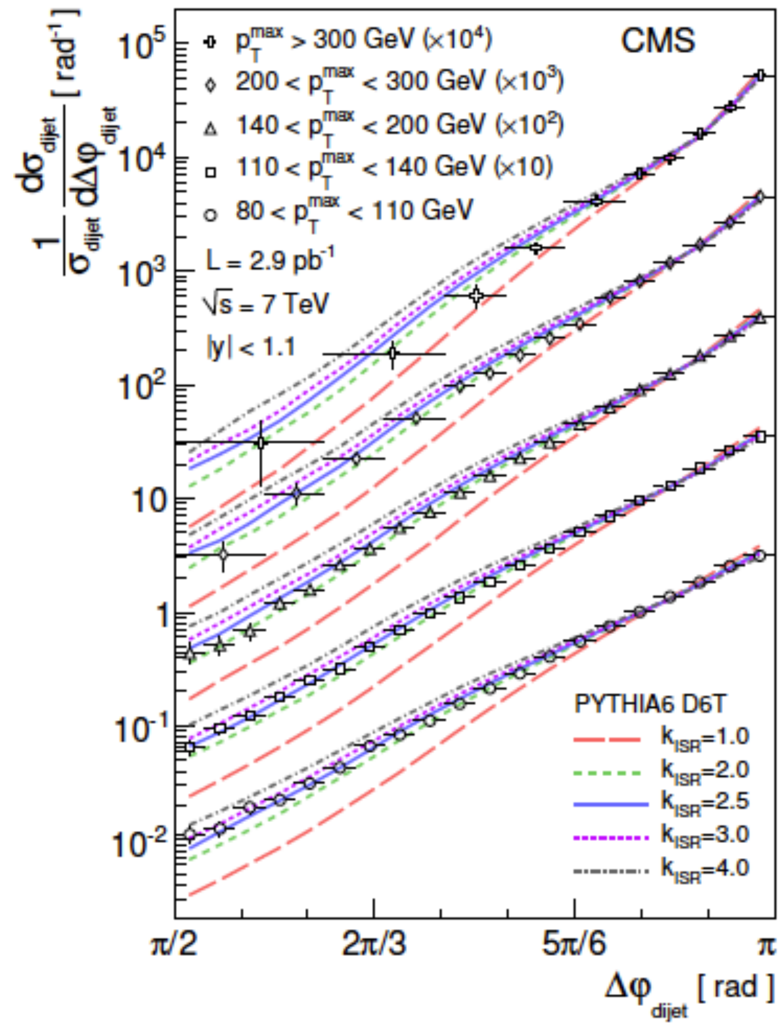


➢ PYTHIA6 and HERWIG++ in reasonable agreement with the data

Dijet Angular Decorrelations

arXiv:1101.5029

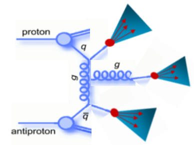


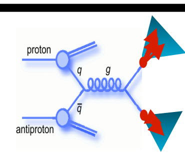


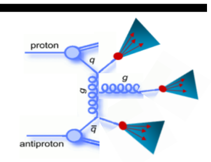
- ❑ Reduced decorrelation in theoretical prediction
- ❑ Increased sensitivity to scale variations
- ❑ Early measurement shown to be useful for tuning phenomenological parameters (ISR) in MC event generators.

3-Jet to 2-Jet Ratio

$$R_{32} = \frac{d\sigma_3 / dH_T}{d\sigma_2 / dH_T} = \frac{\sum [\text{diagram}] + \ldots}{\sum [\text{diagram}] + [\text{diagram}] + \ldots}$$



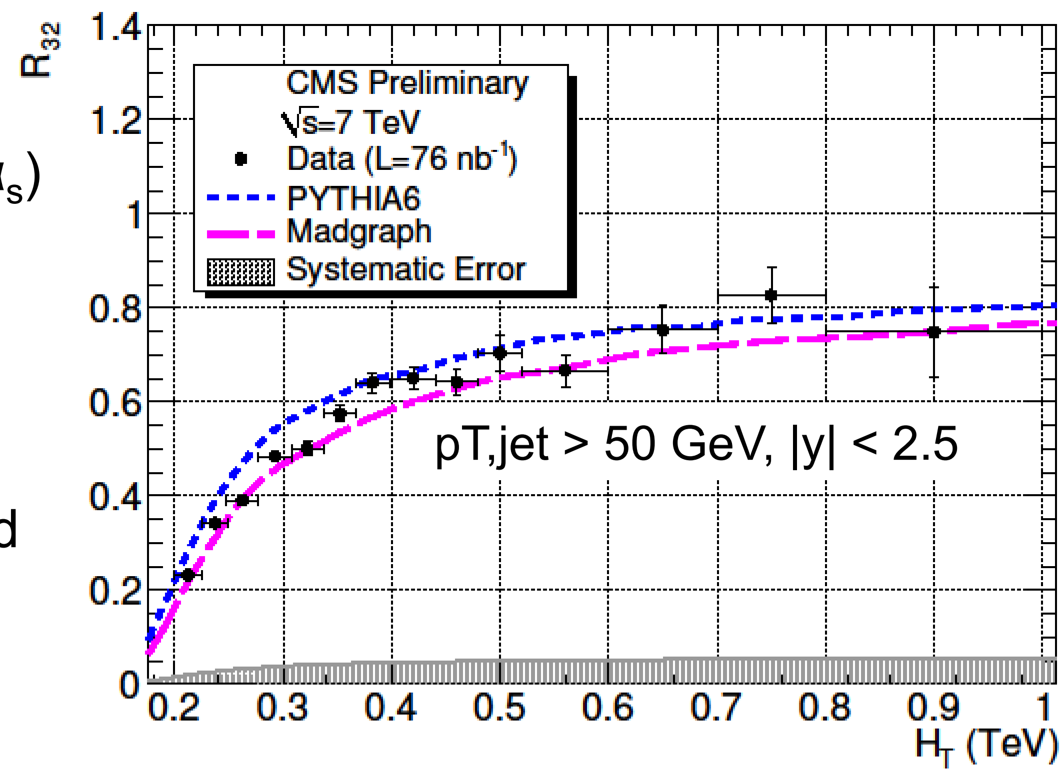




- ❑ Insensitive to PDFs, reduced luminosity, JEC uncertainty
- ❑ Sensitive to strong coupling (α_s)

- ➢ Good agreement found with PYTHIA and Madgraph within uncertainties
- ➢ Updated results with increased luminosity coming up

CMS PAS QCD-10-012



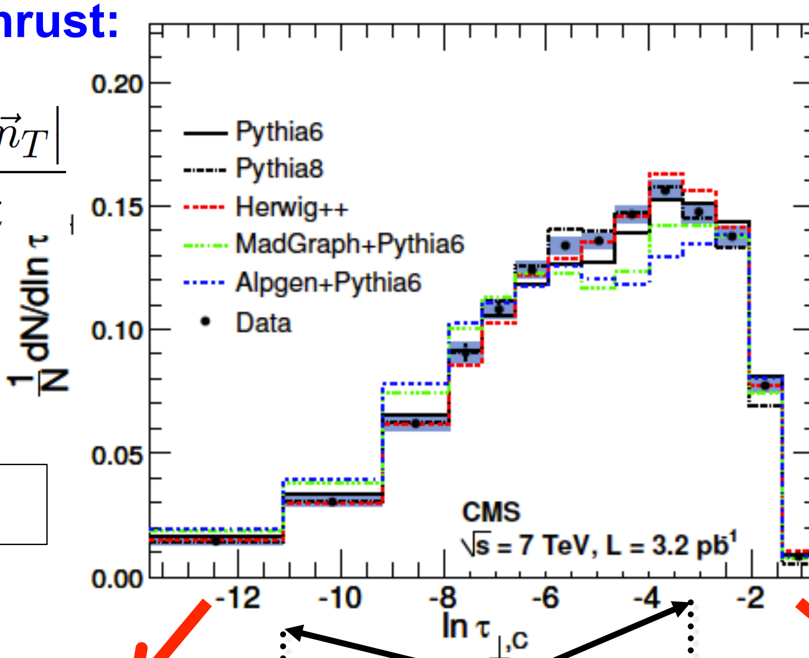
Event Shapes

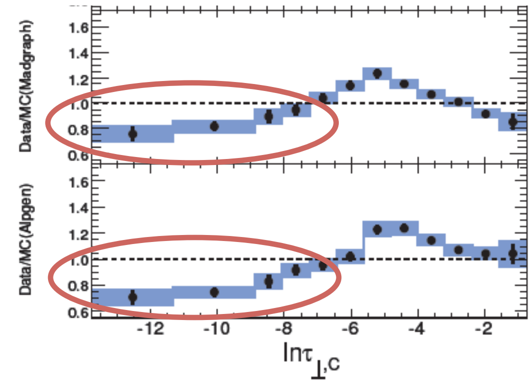
- ❑ Event shapes provide geometric information about energy flow in hadronic events
- ❑ Sensitive to the amount of hard gluon radiation
- ❑ Can help in tuning of Monte Carlo models for non-perturbative effects
- ❑ **Central transverse thrust:**

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

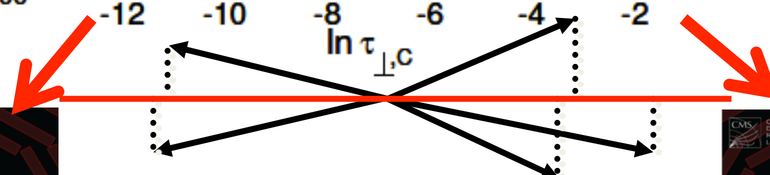
$$\ln \tau_{\perp,\mathcal{C}} = \ln(1 - T_{\perp,\mathcal{C}})$$

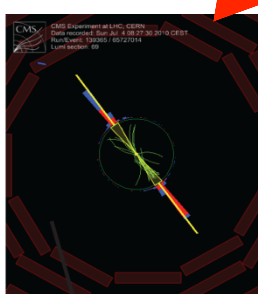
arXiv:1102.0068



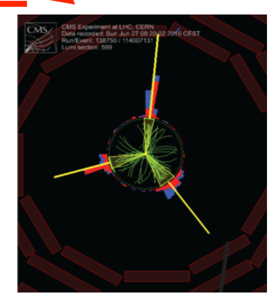


❑ Differences observed with Matrix element calculations

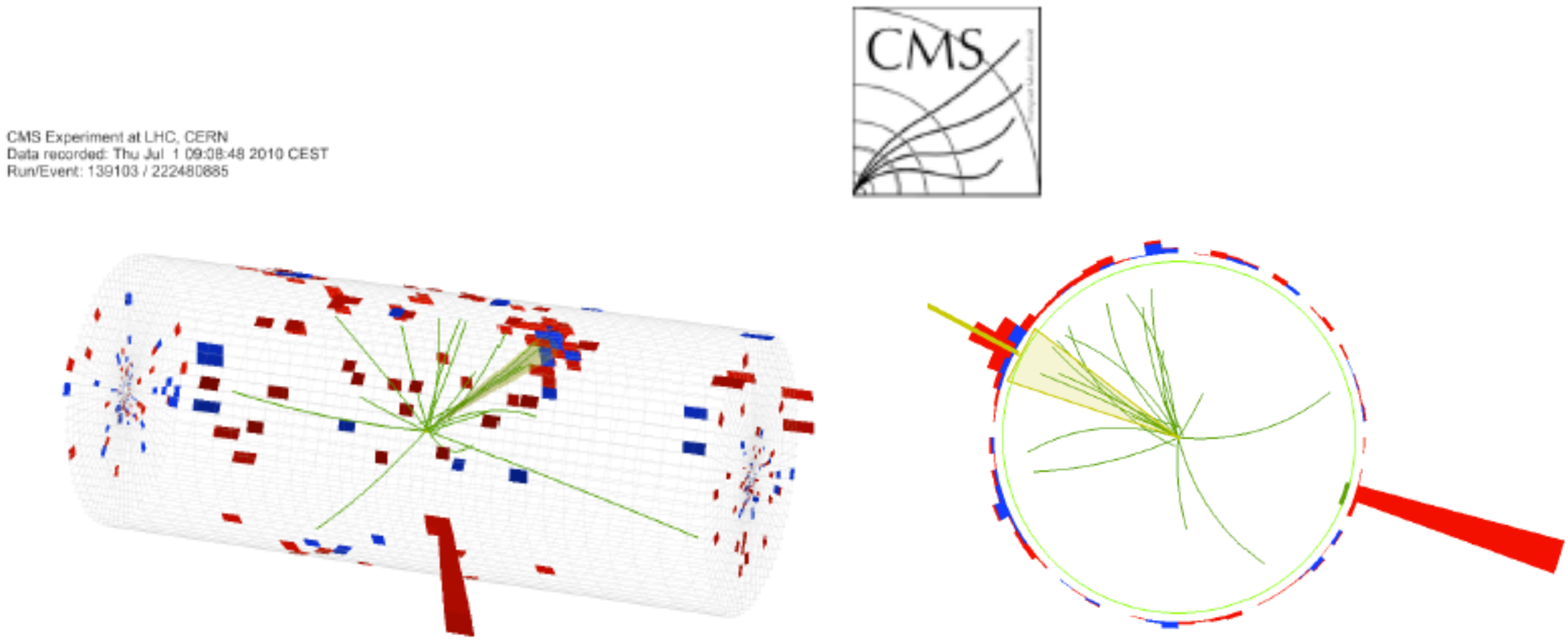




maximum of projection on a transverse axis

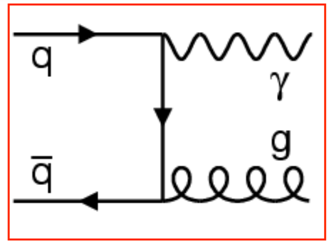


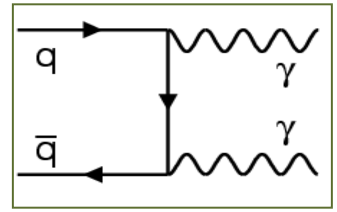
Photons in CMS



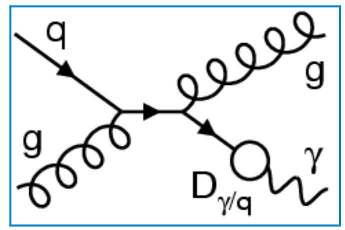
Prompt Photons

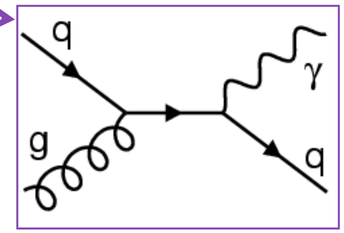
- Photon processes:
  - Annihilation
  - Compton
- Also fragmentation contributes
  - But suppressed with isolation

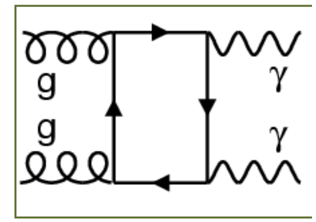




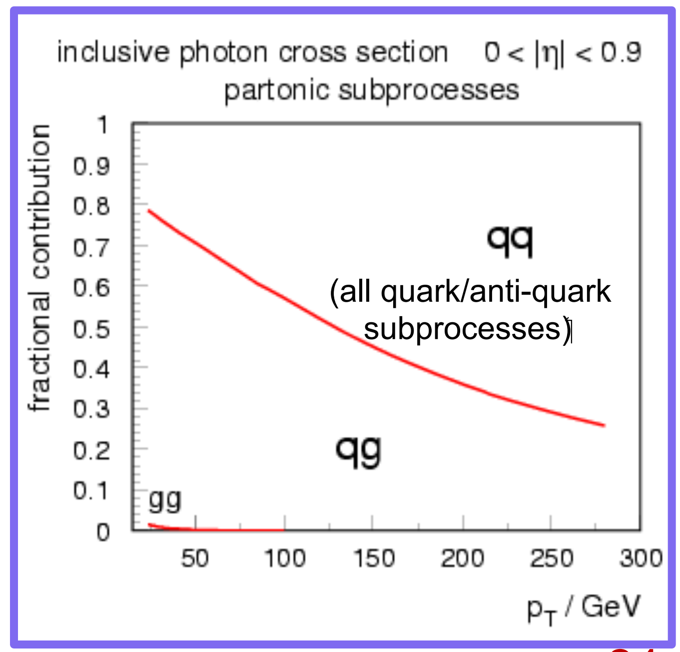
Diphotons







- Directly sensitive to hard scatter
- Important for QCD studies, detector calibration, gluon PDFs, background to new physics
- Challenging measurement
- Large QCD jet background
  - Observable: isolated photons



Isolated Photons

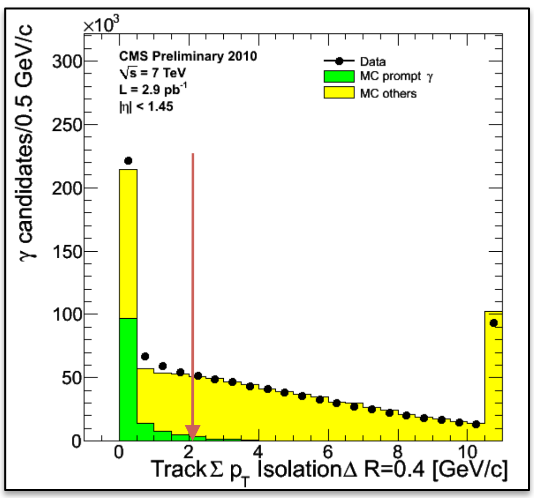
- ❑ Measuring prompt photons experimentally
  - An isolation criterion around the photon candidates is applied to suppress the background from neutral hadrons (π^0's) etc.
  - Requiring isolation also reduces the fragmentation contribution

Definition of isolated photons:

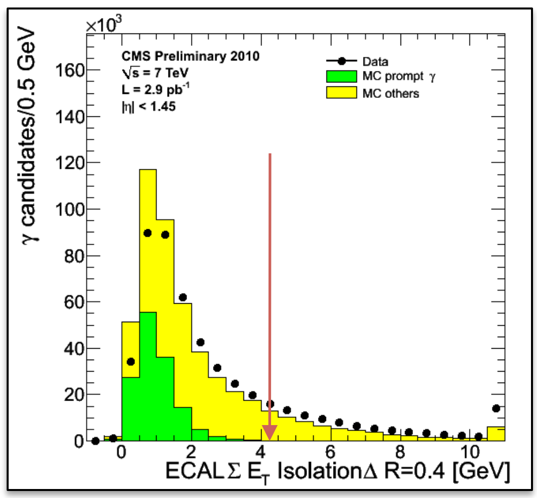
$$\sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} \leq R$$

$$E_{had}(R) \leq E_{uppercut}$$

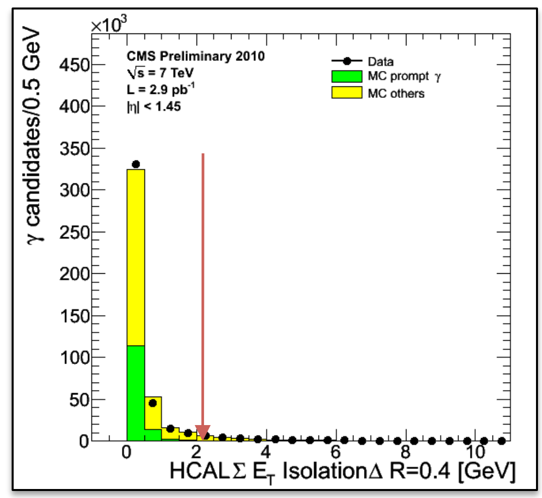
$Iso_{TRK} = \Sigma_{R<0.4}$ track p_T



$Iso_{ECAL} = \Sigma_{R<0.4}$ $E_{T\ ECAL}$



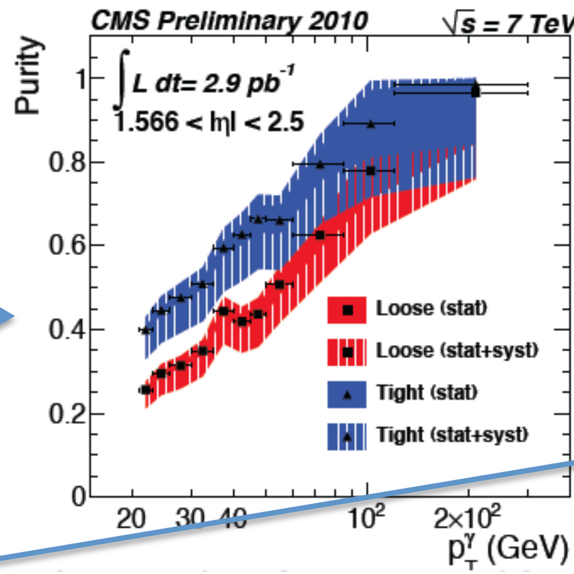
$Iso_{HCAL} = \Sigma_{R<0.4}$ $E_{T\ HCAL}$



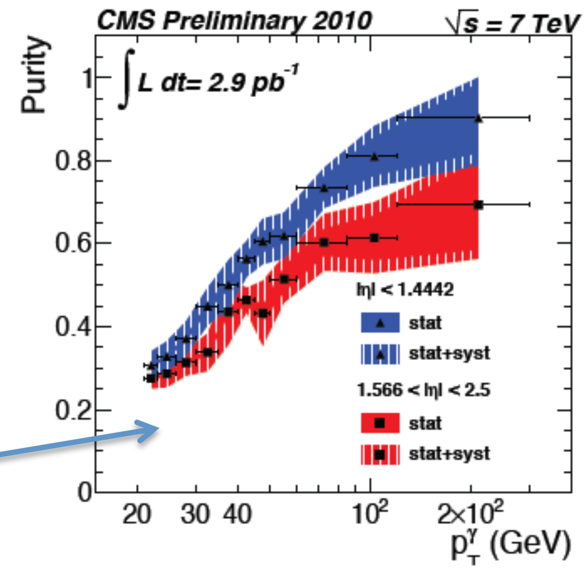
✧ Fraction of energy deposited in calorimeters: $H/E = \Sigma_{R<0.15} E_{HCAL}/E_{ECAL} < 0.05$

Photon Reconstruction and Performance

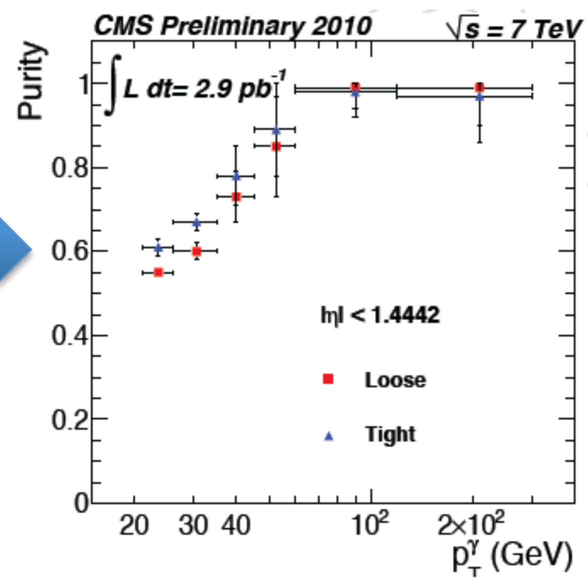
- Measured purity for the sample defined by the cluster shape method as a function of p_T

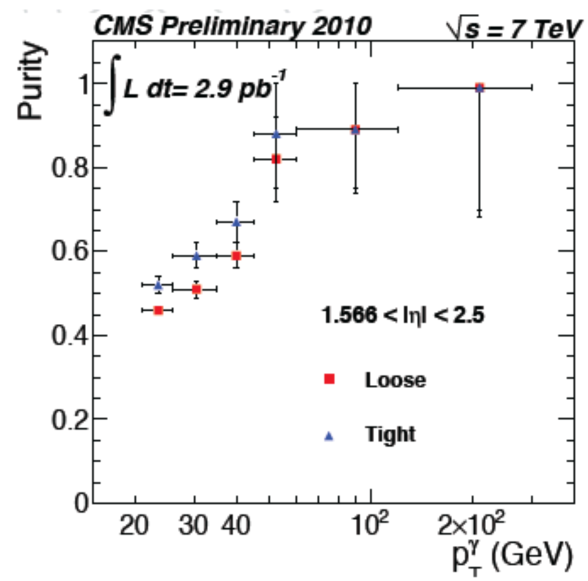


- Measured purity for the sample defined by the isolation method as a function of photon p_T



- Purity for the sample defined by the conversion method



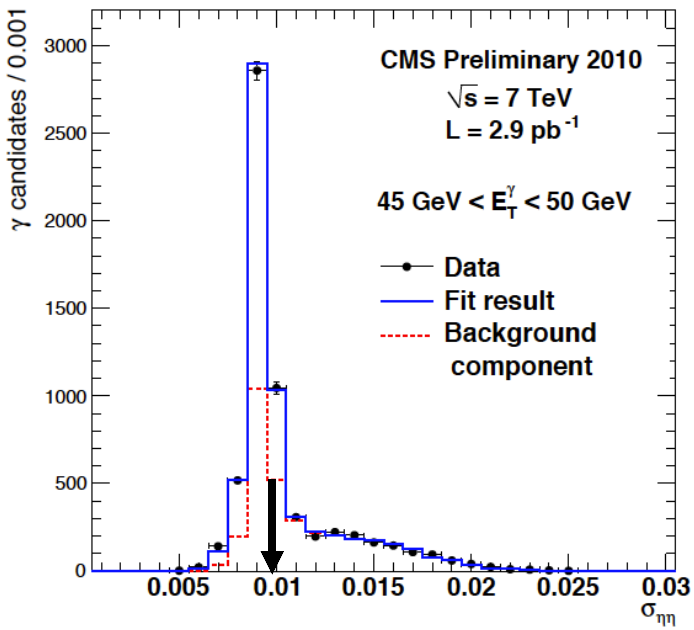


CMS PAS EGM-10-006

Inclusive Isolated Photon Spectrum

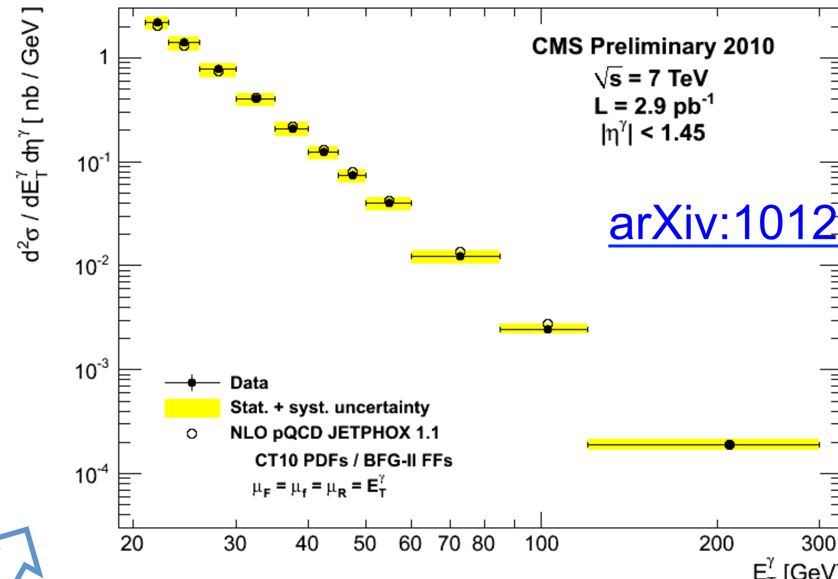
Isolated prompt photon yield:

$$\sigma_{\eta\eta}^2 = \sum_{i=1}^{25} w_i(\eta_i - \overline{\eta})^2 \Big/ \sum_{i=1}^{25} w_i$$

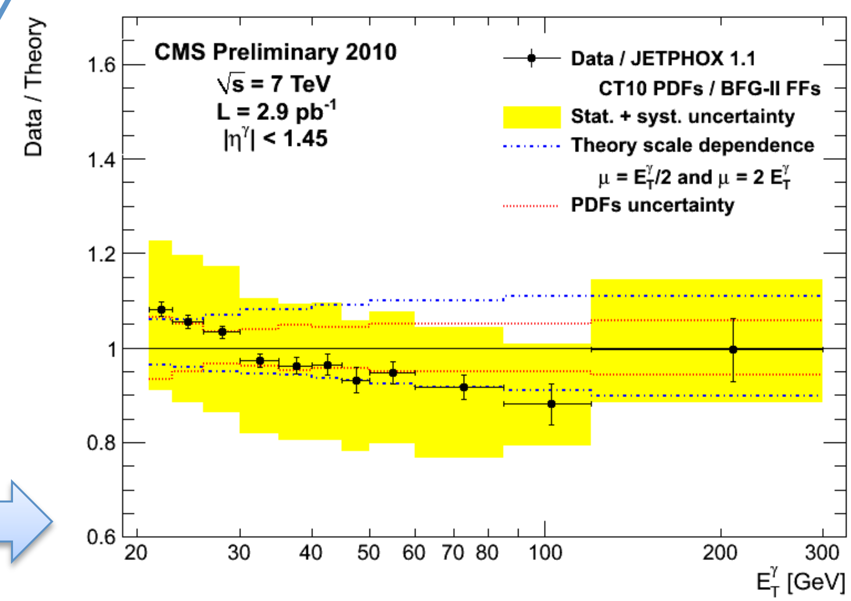


$$\frac{d^2\sigma}{dE_T^\gamma d\eta^\gamma} = \frac{N^\gamma}{L \cdot U \cdot \varepsilon \cdot \Delta E_T^\gamma \cdot \Delta \eta^\gamma}$$

- ❑ The NLO calculations agree well with the data at CMS even at low p_T.



arXiv:1012.0799



Conclusions and Outlook

- ❑ The LHC and CMS performed extremely well in 2010
- ❑ Have already started producing high quality results from hard QCD analyses at CMS
- ❑ Most analyses are ready / getting updated to the full data recorded by CMS in 2010 (~36 pb^{-1})
- ❑ Many analysis are already beginning to exceed the Tevatron reach
- ❑ CMS has set the world's best limit on quark compositeness
- ❑ Most of these results have been submitted for publication (or already published)
- ◆ All major hard QCD analyses will have results with full CMS data by the timeline of Moriond
- ◆ CMS will continue publishing quality hard QCD results in 2011

❑ Details of public CMS results can be found at:

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