Hard QCD Results on Jets and Photons at CMS

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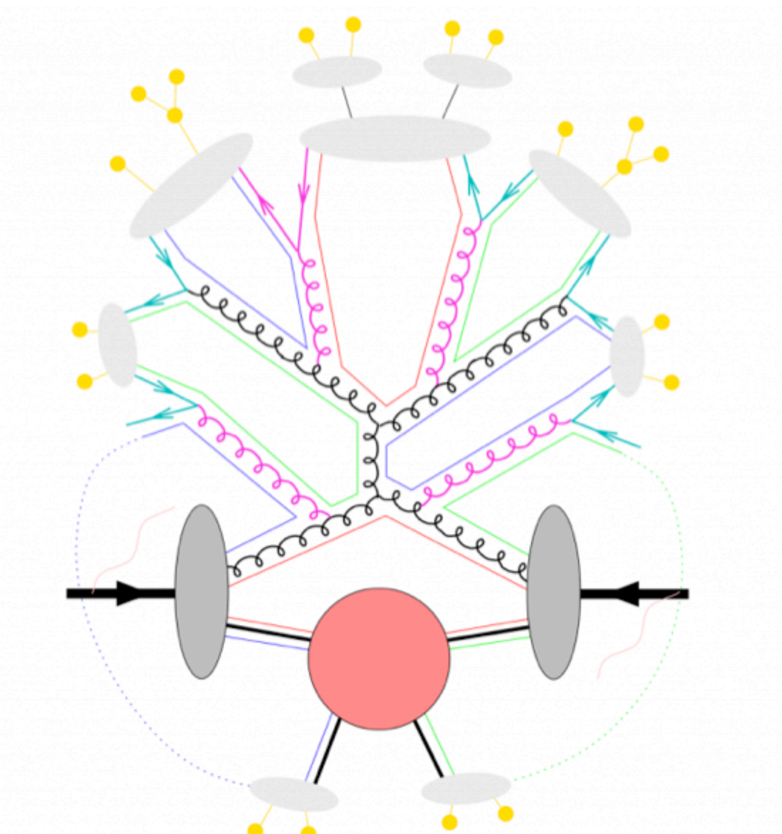
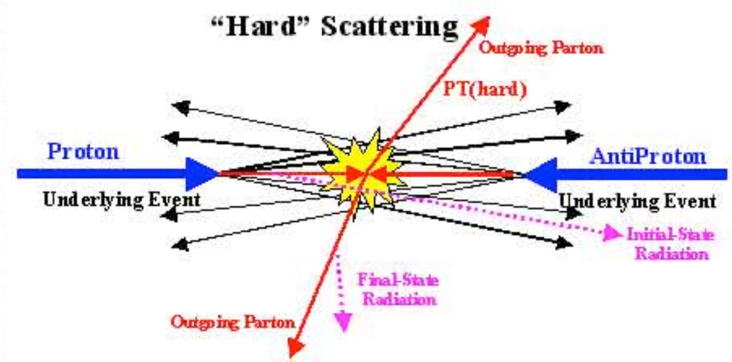
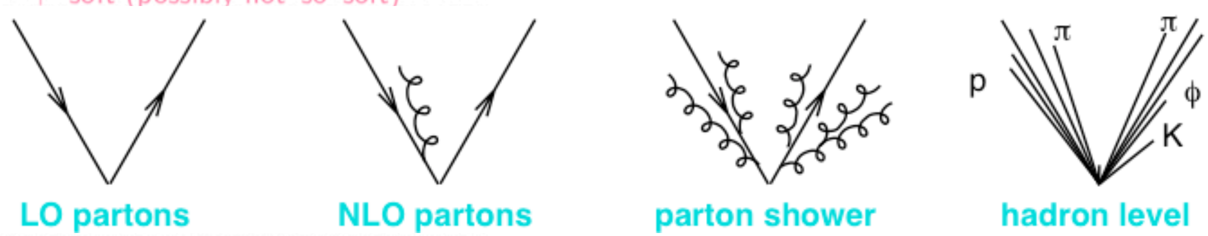
for the CMS collaboration

Jet physics

- Main goal is to improve our detailed description of **Standard Model physics**
  - hard QCD: proton parton distribution functions (PDFs), perturbation theory, initial and final state radiation, parton showers
  - soft QCD: multiparton scattering, fragmentation, underlying event, etc.
- Collaboration with Exotica group on searches of **New Physics at high p_T**
- QCD jets are **background** for searches and high statistics **calibration source**

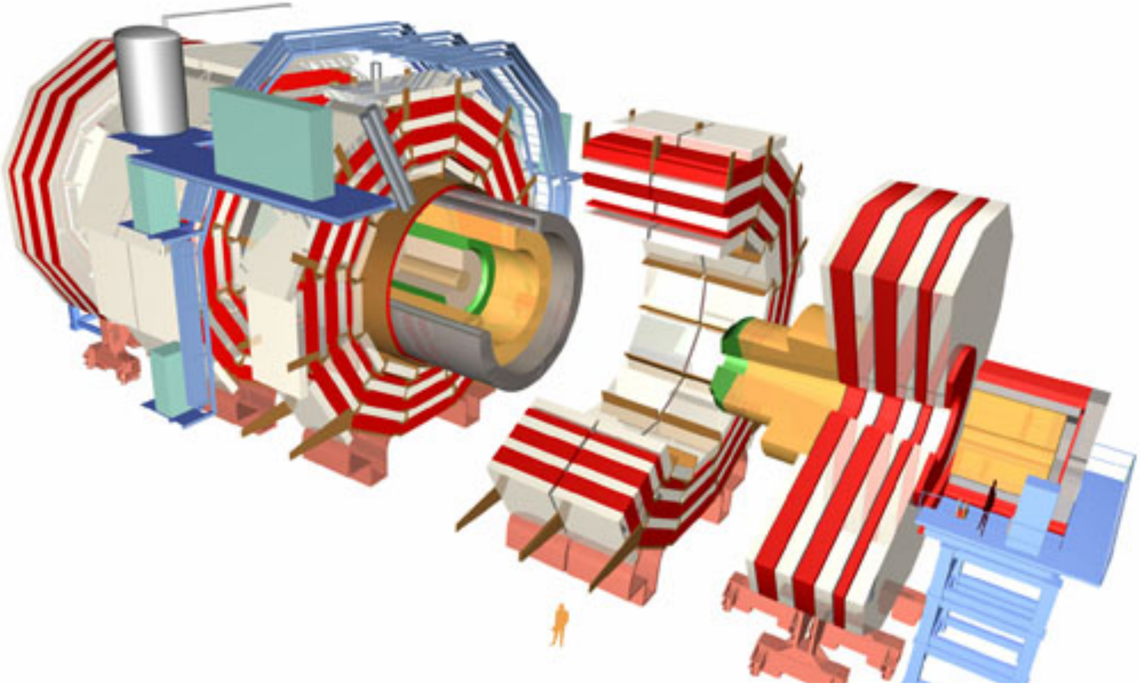


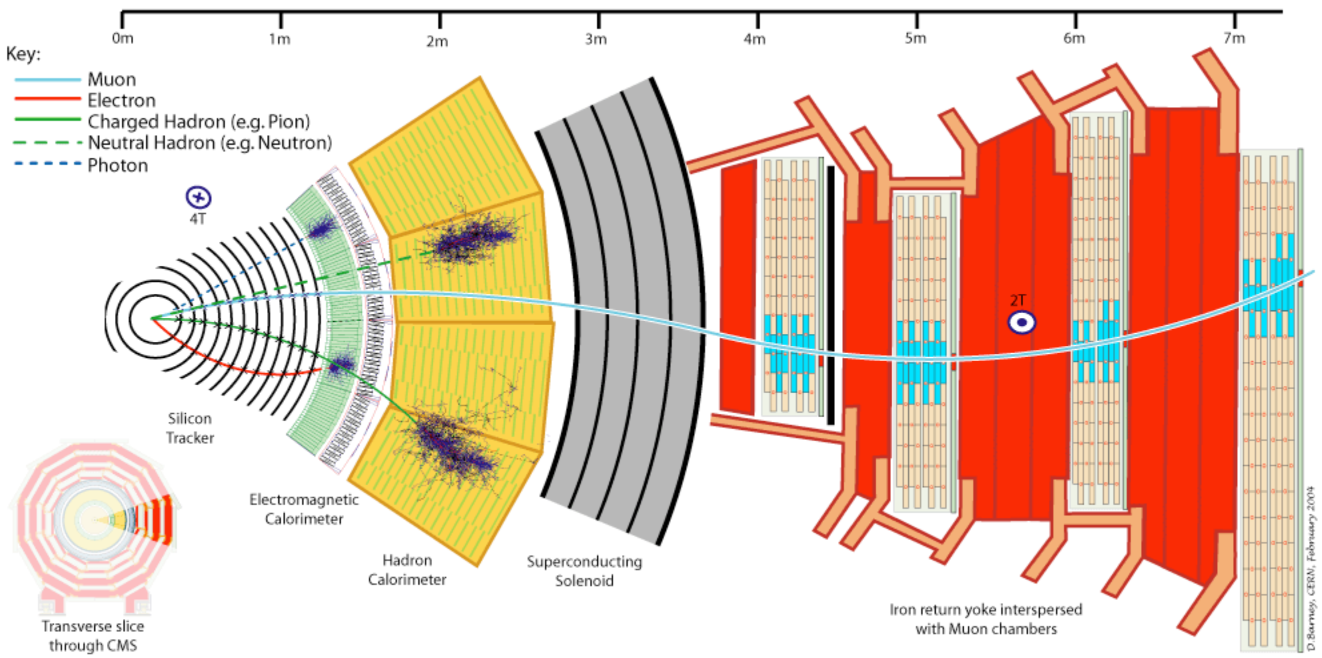




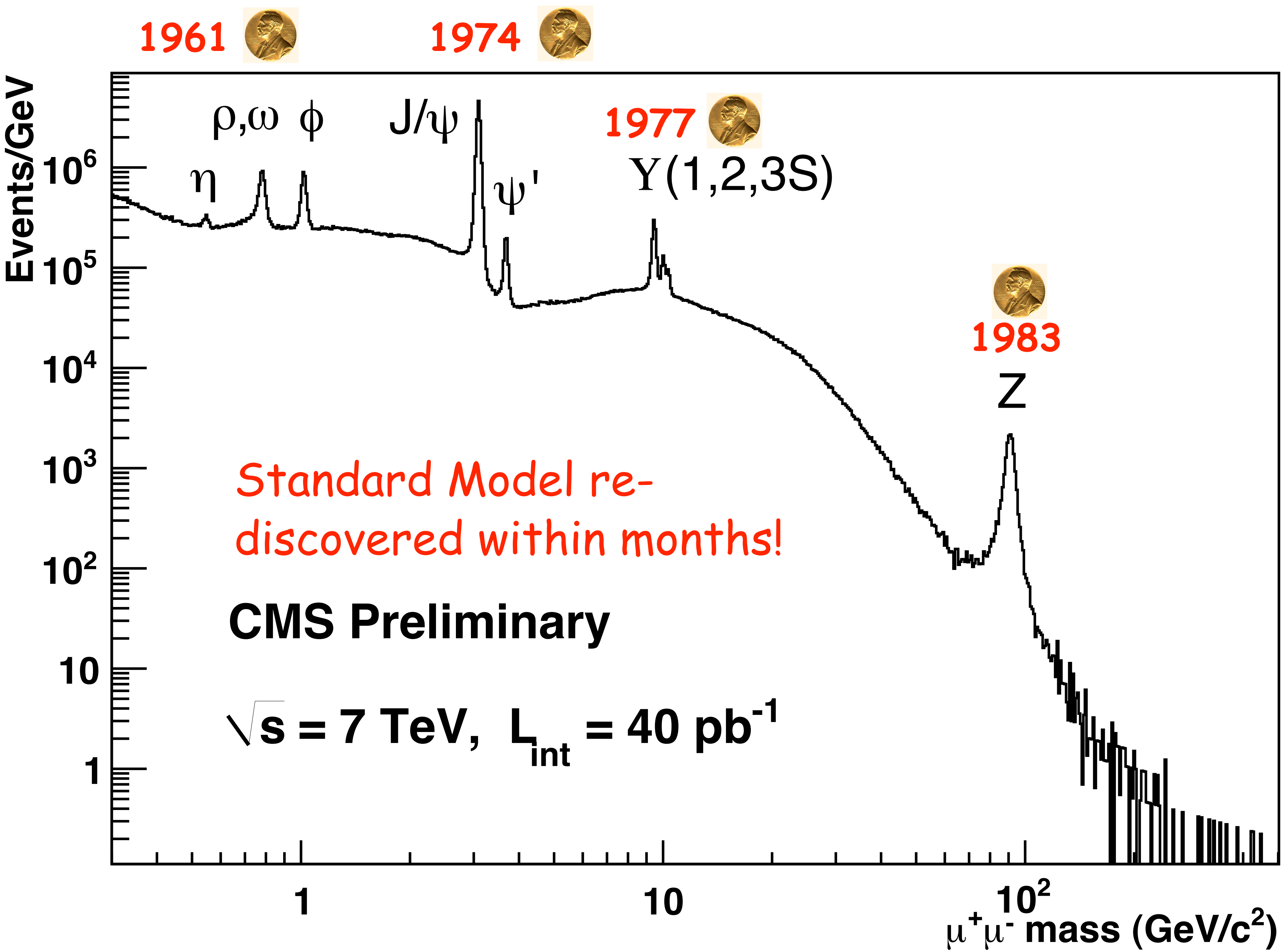
Compact Muon Solenoid

- Precise silicon pixel and silicon strip tracking at $|\eta| < 2.4$
- Fine-grained lead tungstate crystal ECAL at $|\eta| < 3.0$
- Brass+scintillator HCAL at $|\eta| < 3.0$
- Tracking, ECAL and HCAL embedded inside 3.8 T solenoid magnet
- Muon chambers outside magnet, interleaved with iron return yoke



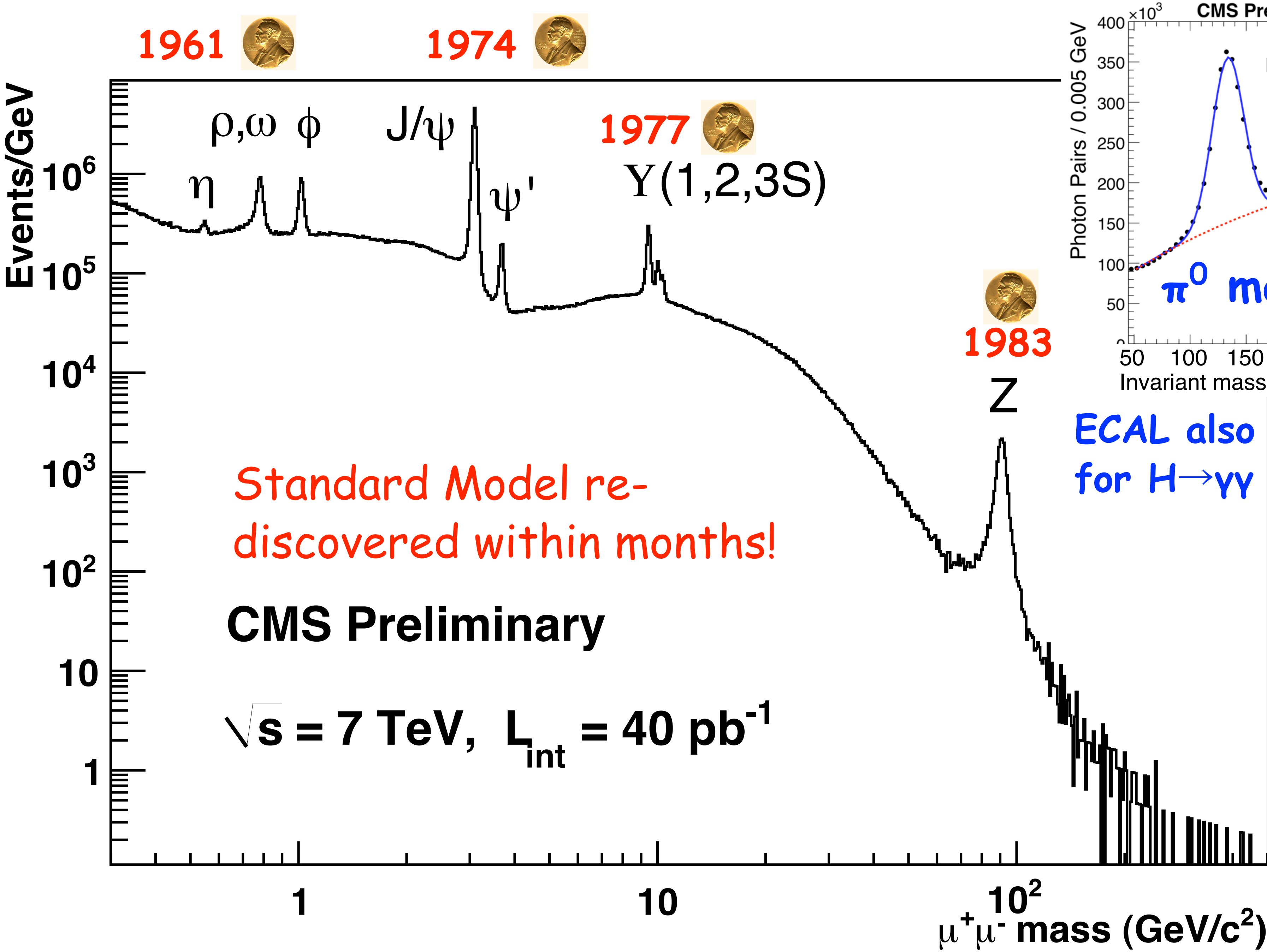


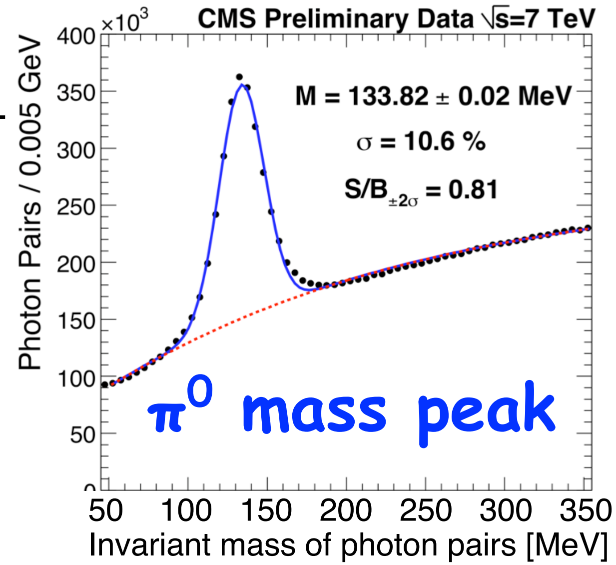
Calorimeter granularity:
ECAL 5×5 vs HCAL 1×1



Standard Model re-discovered within months!

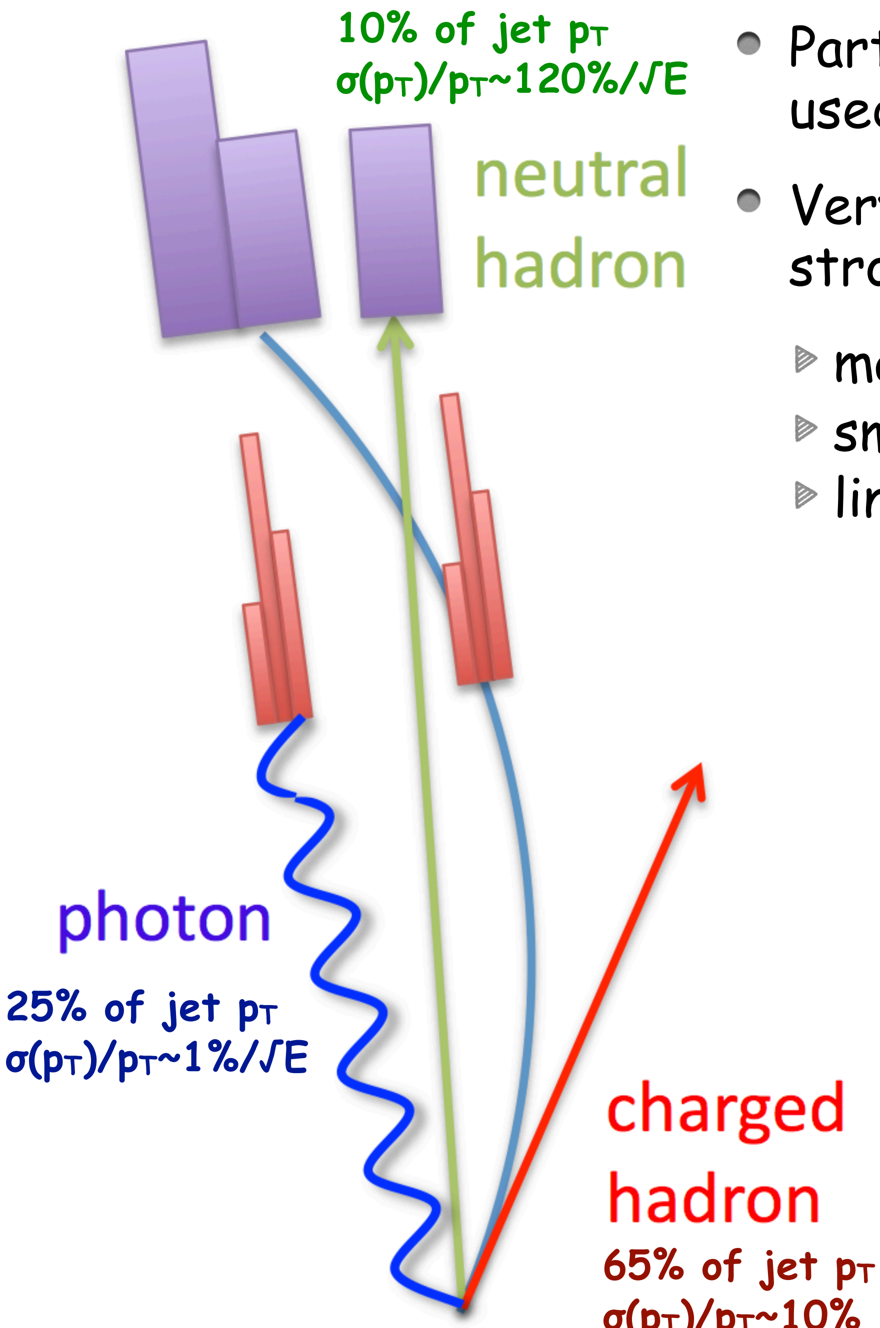
Compact Muon Solenoid





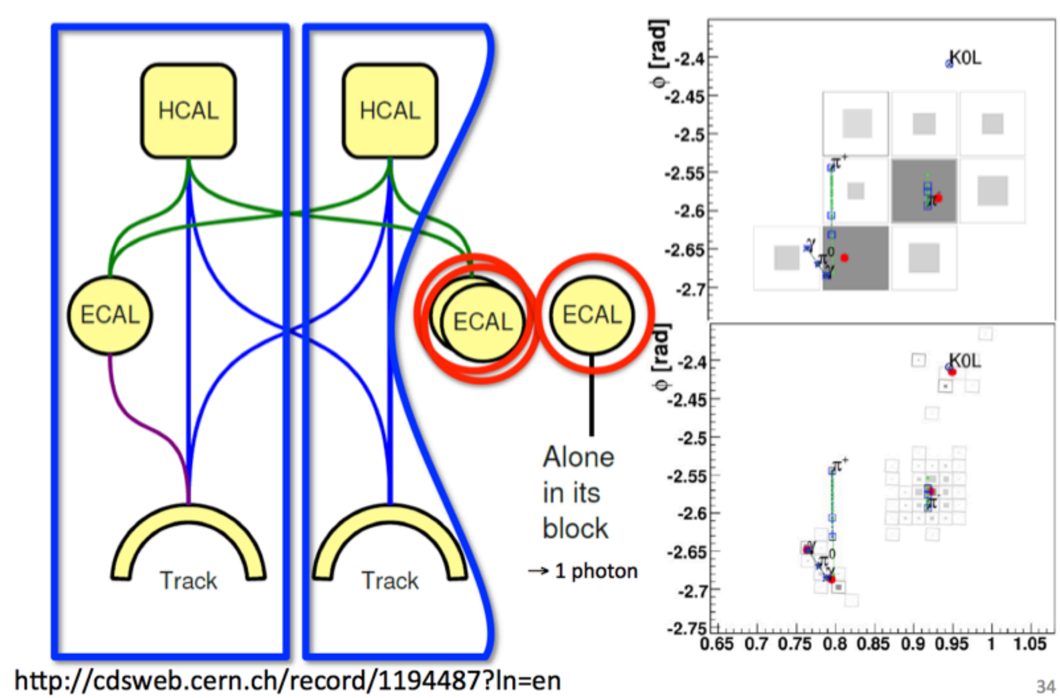
ECAL also working well for $H \to \gamma\gamma$ discovery

Particle Flow algorithm

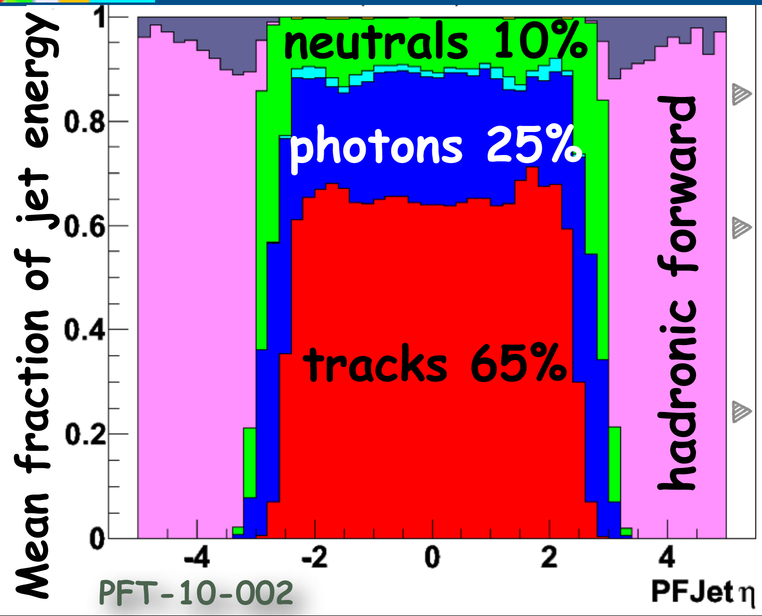


- Particle Flow is a novelty at hadron colliders, but used before at LEP (Aleph)
- Very precise tracker, highly granular ECAL and strong magnetic field are CMS specialities
  - magnetic field separates charged particles
  - small fraction of p_T measured with HCAL only
  - linking stage optimizes subdetector consistency

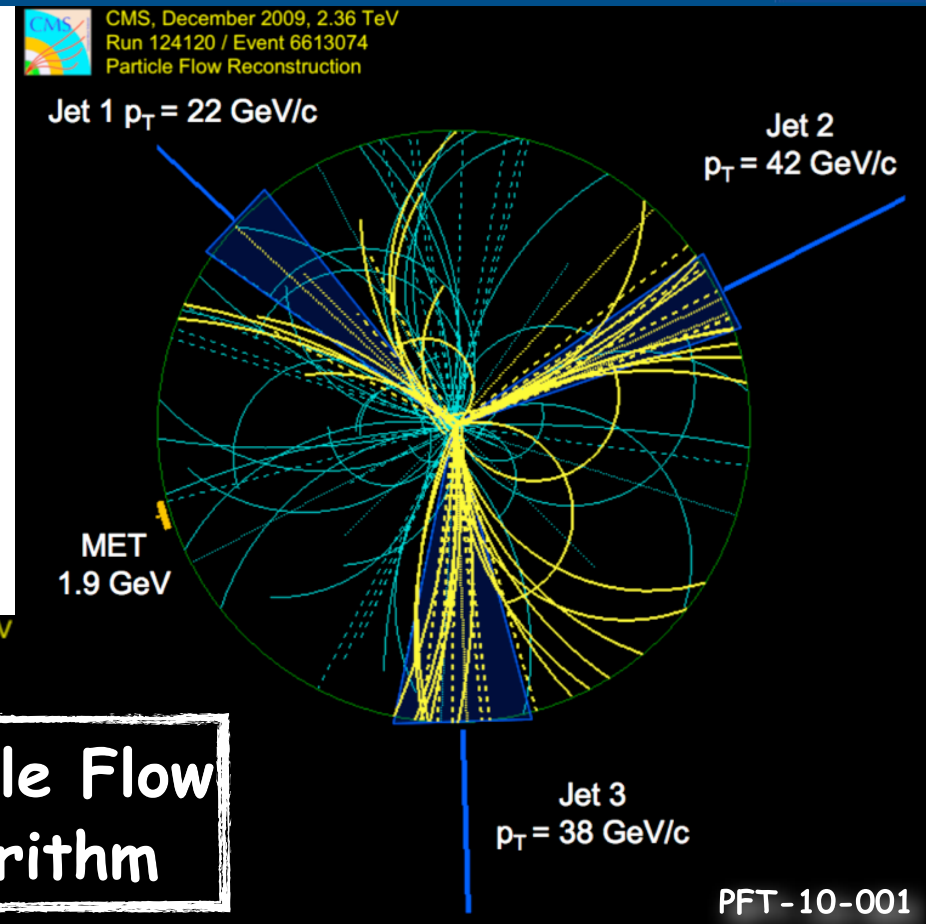
2 charged hadrons, 3 photons

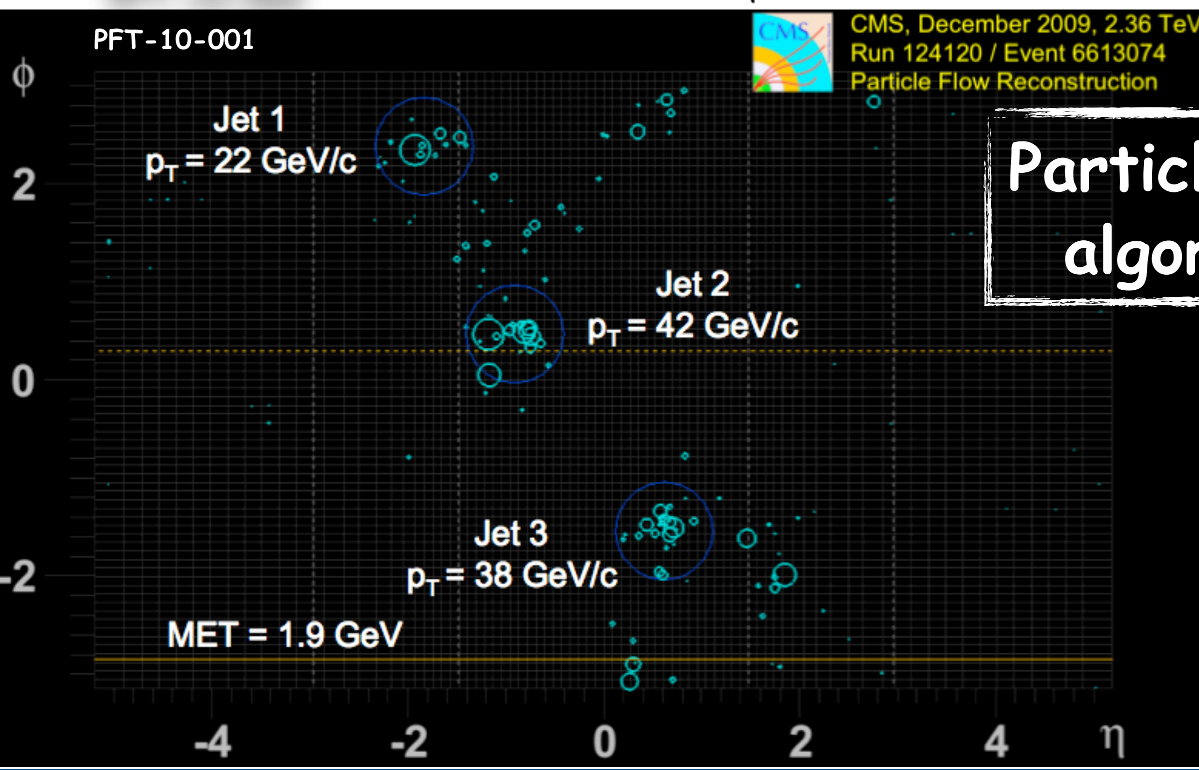


http://cdsweb.cern.ch/record/1194487?ln=en



- charged hadrons ($\pi^{\pm}$, $K^{\pm}$): tracks
- photons ($\pi^0 \to \gamma\gamma$, $\eta^0 \to \gamma\gamma$): isolated ECAL clusters
- neutral hadrons (K_L, Λ, n): isolated HCAL clusters

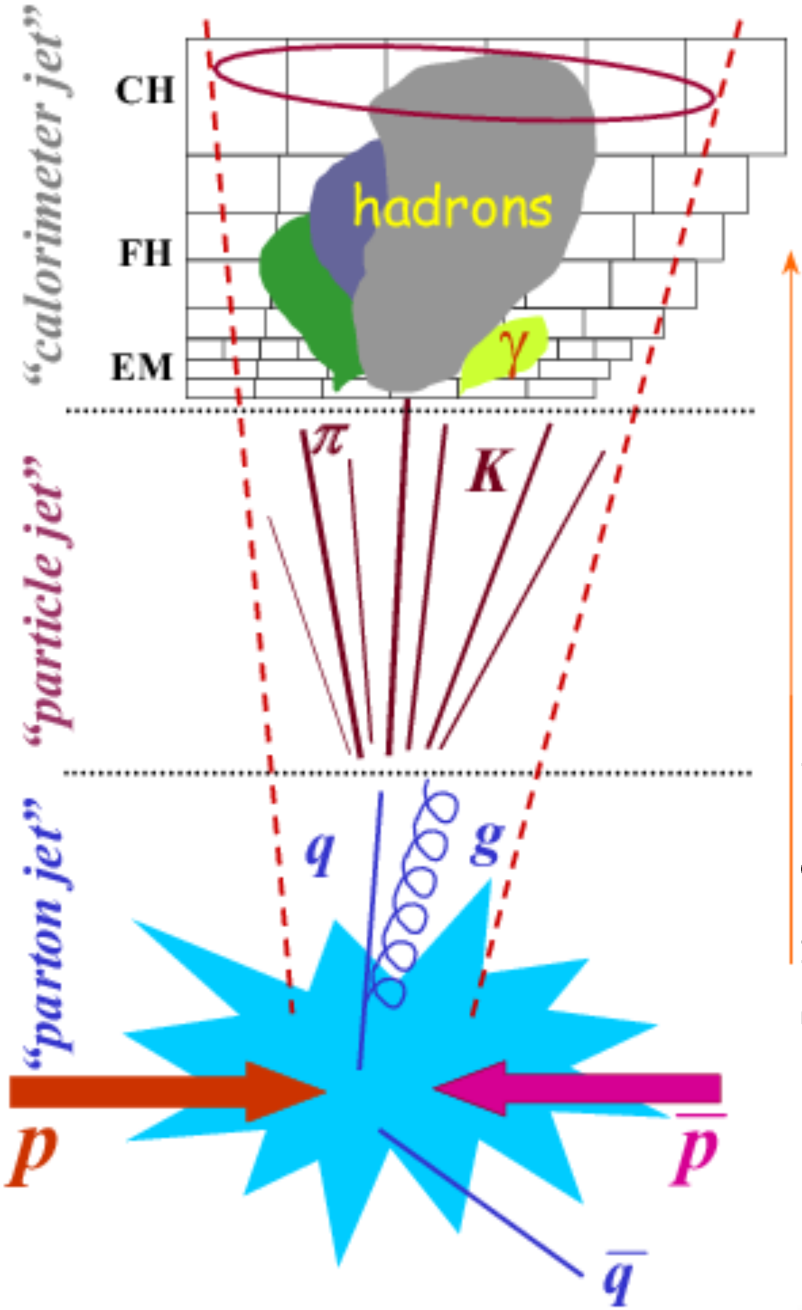




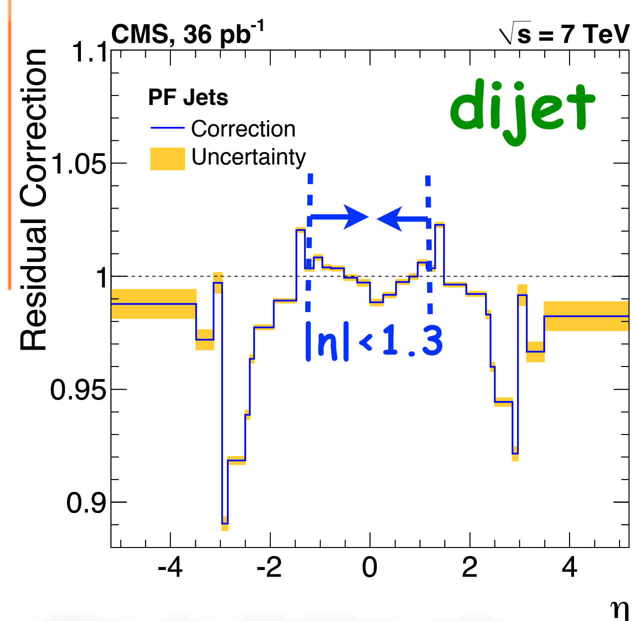
Particle Flow algorithm

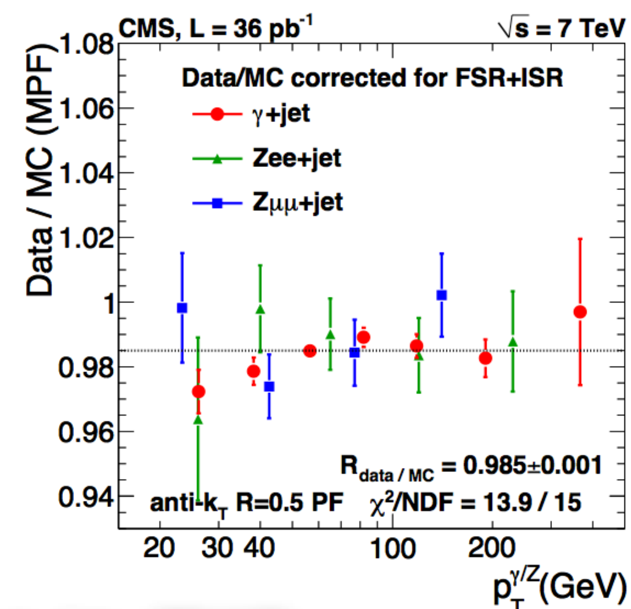
Combining detector inputs optimally before jet clustering allows CMS to tackle bent tracks, non-linear calorimeter response and overlapping collisions in an ideal way

Jet energy correction



- JEC corrects sum of tracks and calorimeter deposits on average back to particle level
- η-dependent correction relative to |η|<1.3 is done with high statistics **dijet events**
- Absolute correction is fixed with **Z/γ+jet events** to precise ECAL and tracker scales
- Detector simulation has already very good (~1.5%) precision in barrel region

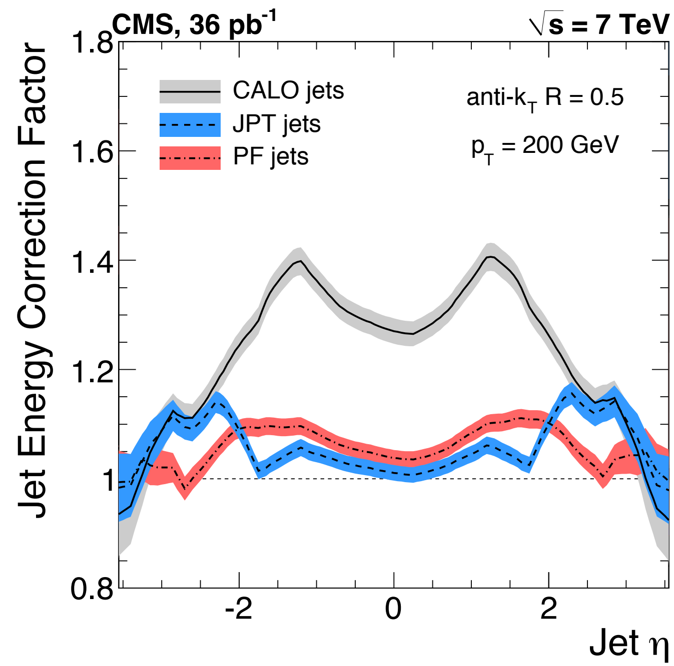


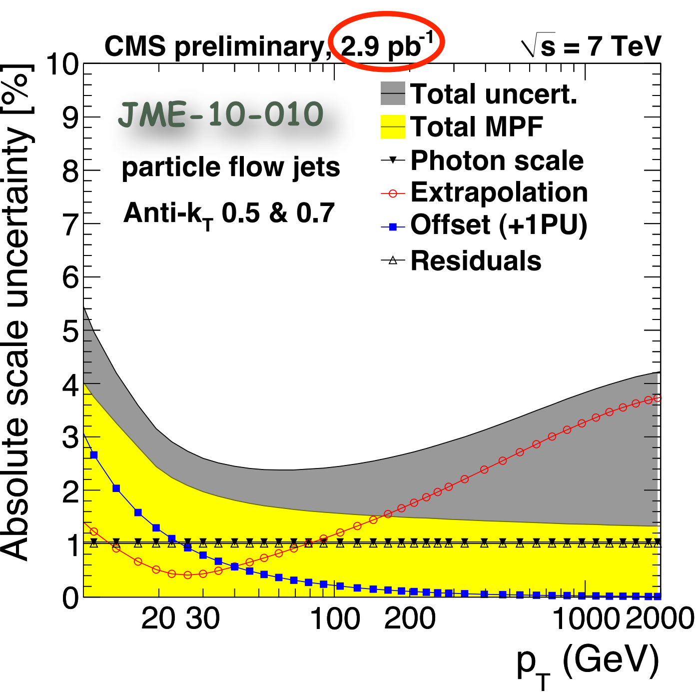


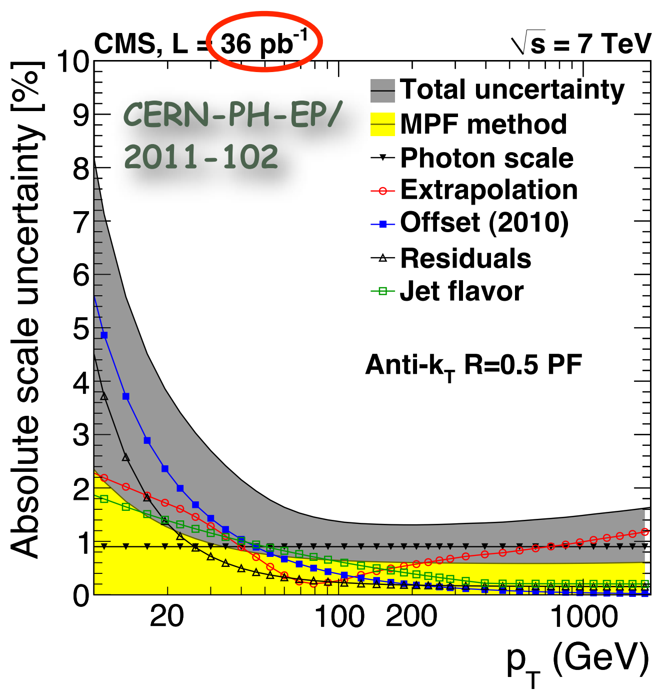
CERN-PH-EP/2011-102, accepted to JINST

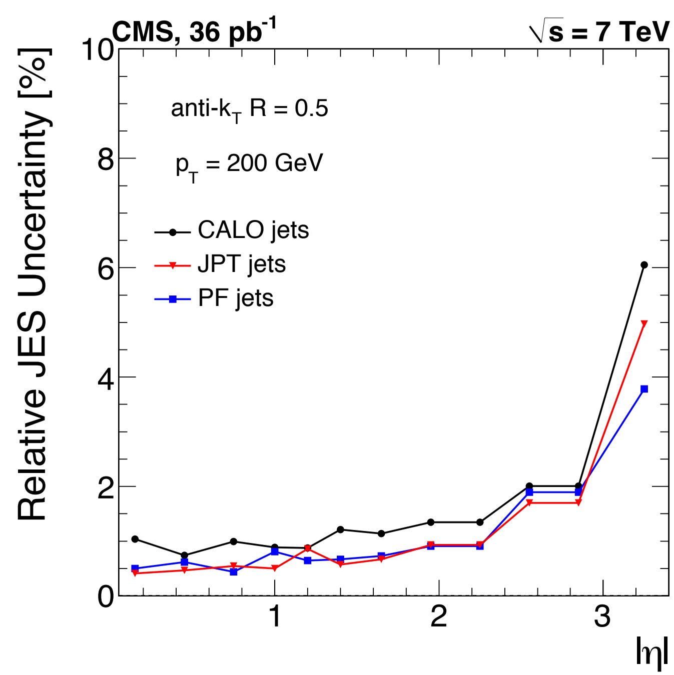
JEC uncertainty

- JEC dominant uncertainty in most jet analyses
- Big improvement in going from early 2010 (3/pb) to final 2010 (36/pb) data; however, due to time constraints most analyses used 3/pb uncertainty
- Uncertainties between 1-2% over much of the kinematic range at $p_T > 50$ GeV and $|y| < 3$
- Already competitive with Tevatron; improvements and uncertainty correlations expected with 5/fb



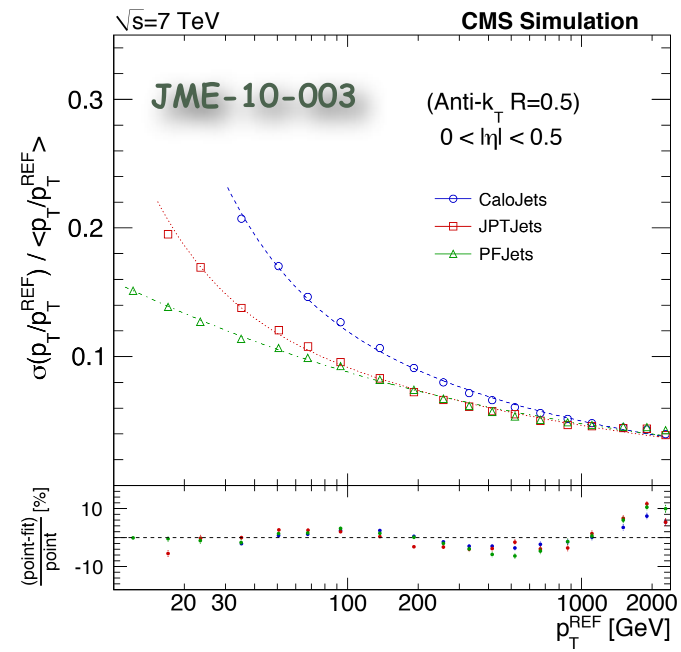


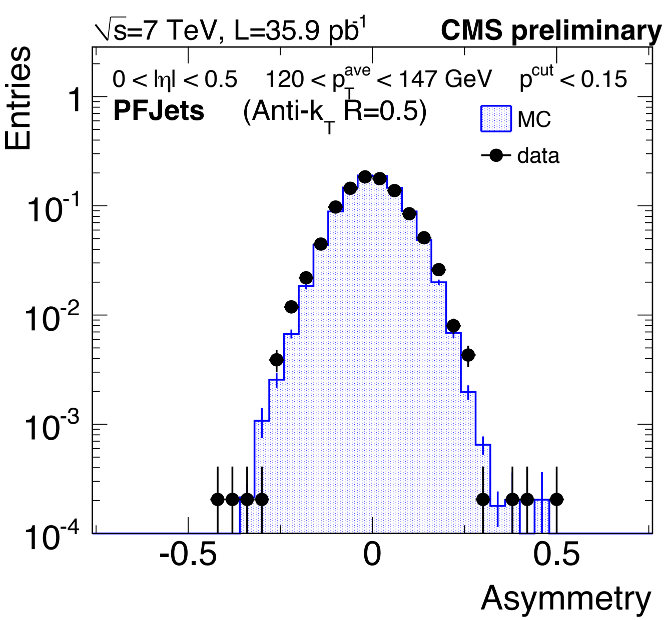


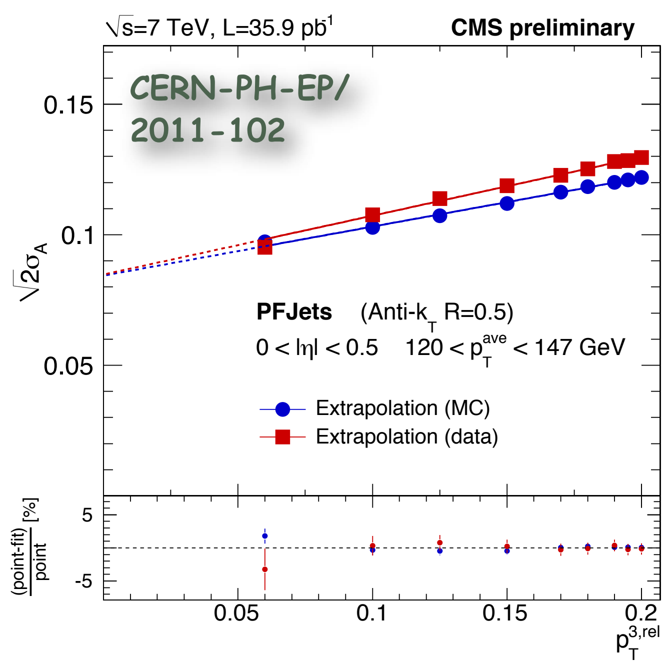


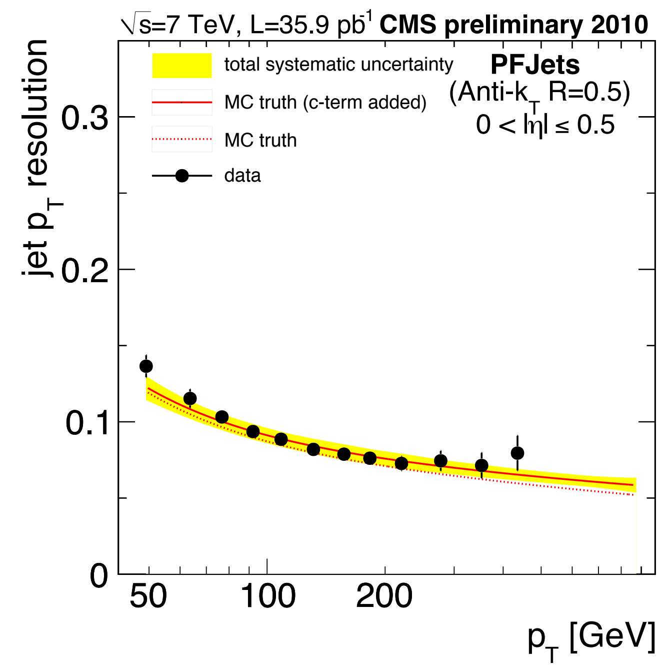
Jet p_T resolution

- Jet p_T resolution measured from data using dijet asymmetry, $A = (p_T - p_{T,ref}) / (p_T + p_{T,ref})$, $|\eta_{ref}| < 1.3$
- Main bias are additional soft jets in the event; corrected by extrapolating jet activity to $p_T^{3,rel} = 0$
- Remaining biases from out-of-cone radiation and underlying event estimated using simulation
- Data and MC agree to about 10% at central rapidities, with 5-10% systematic uncertainty



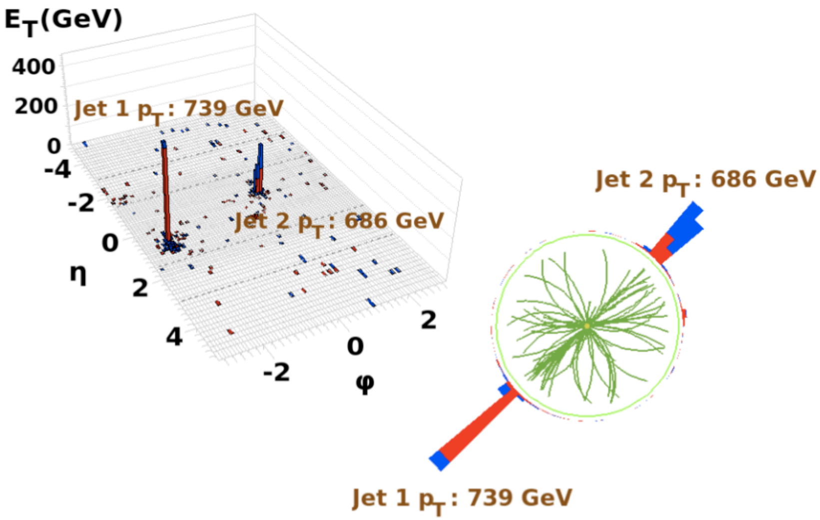


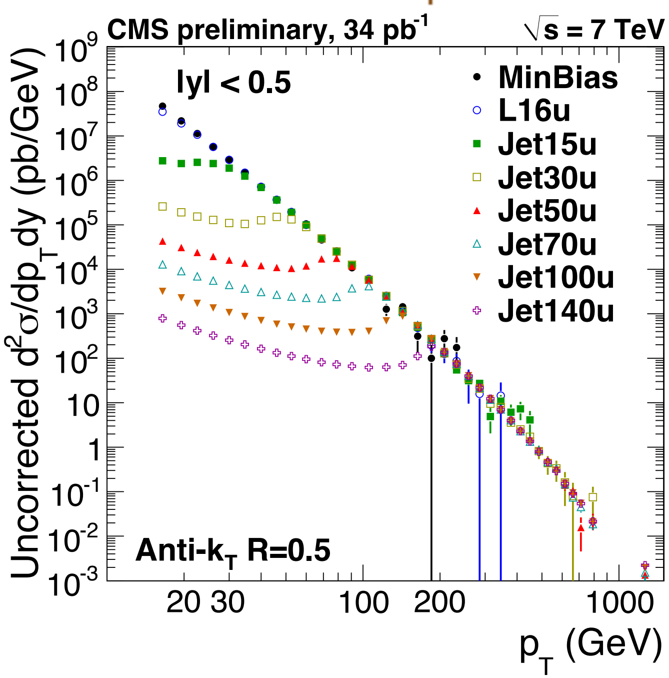


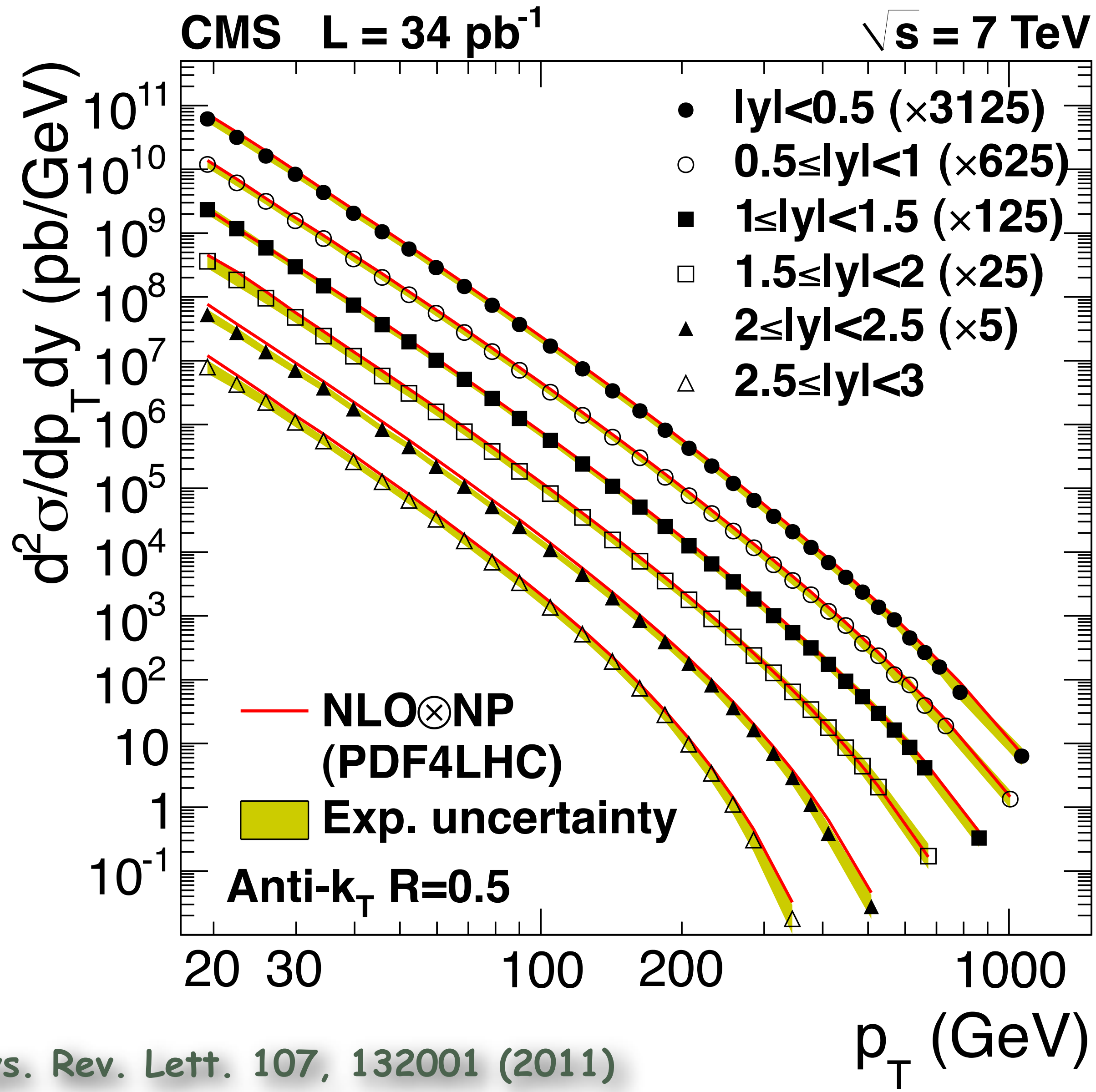


Inclusive jets

- Inclusive jet p_T spectrum is measured over 10(!) orders of magnitude, extending to new energy regime at TeV scale



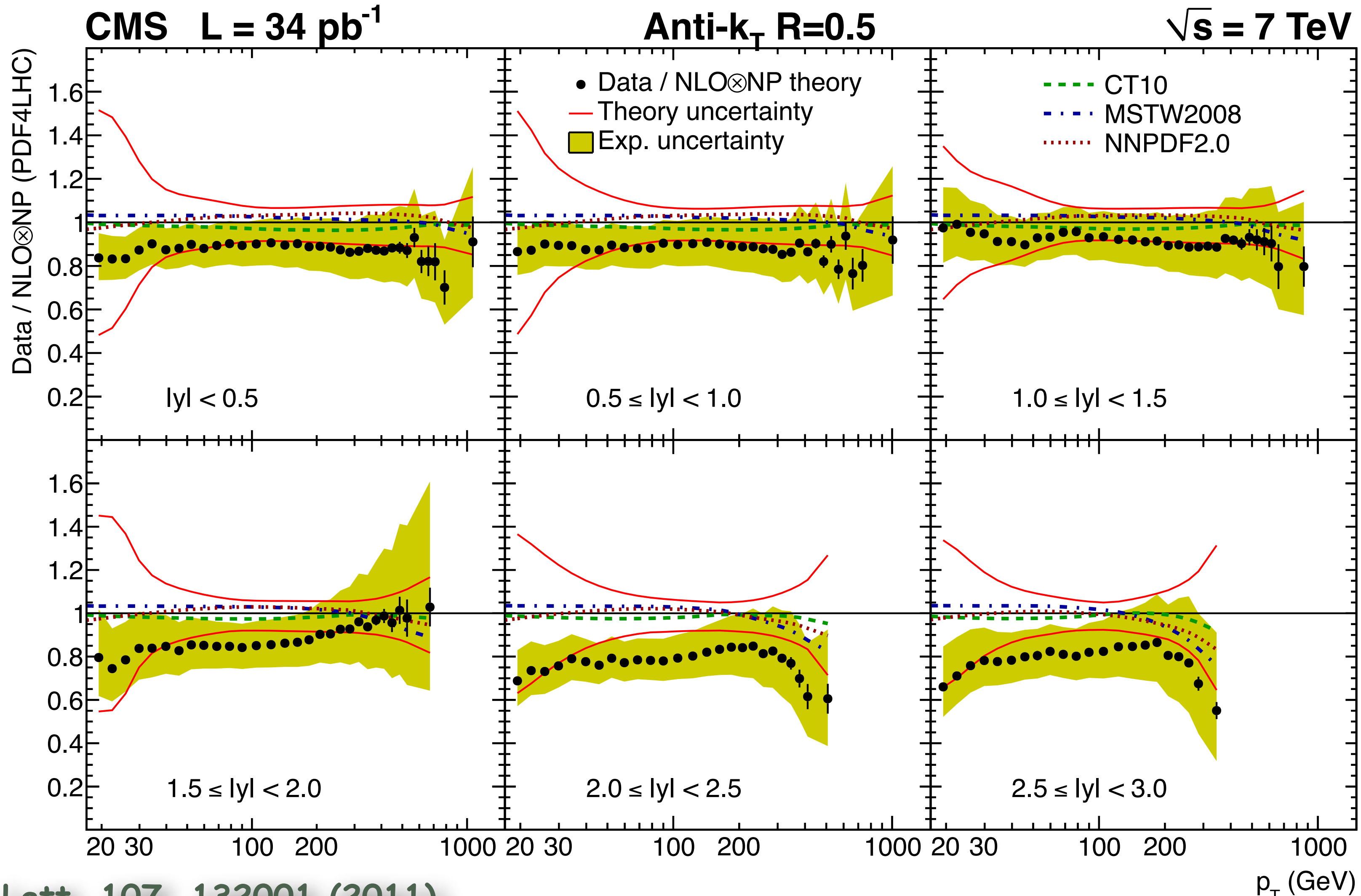




Phys. Rev. Lett. 107, 132001 (2011)

Inclusive jets

- Good agreement between data and theory (perturbative QCD with world average PDF), on a challenging measurement that took years at Tevatron
- Not yet sensitive enough to discriminate PDFs, but this is the long term goal

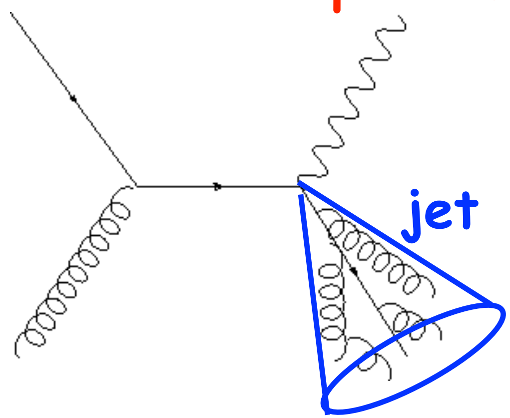


3/pb JEC

Phys. Rev. Lett. 107, 132001 (2011)

Prompt photons

- Isolated prompt photons produced in association with jets give a direct handle on the interaction at parton level
- Main background "π^0-jets"
  - isolation, conversion methods
  - final result combination of both



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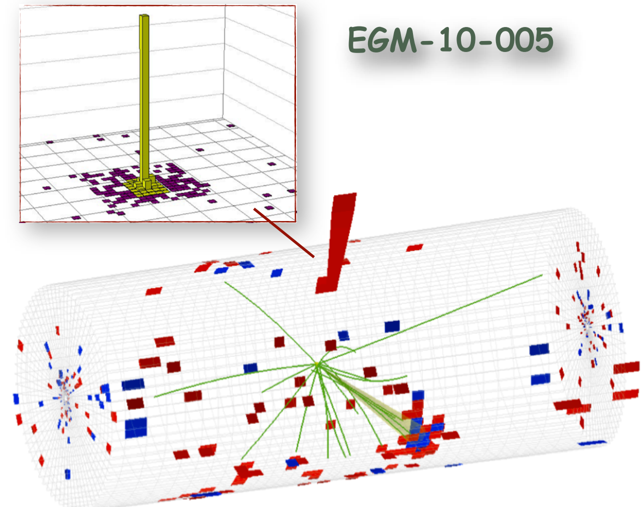
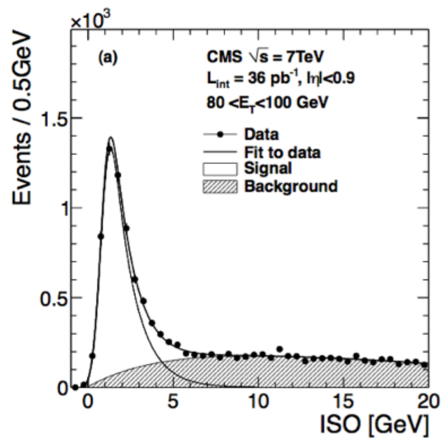
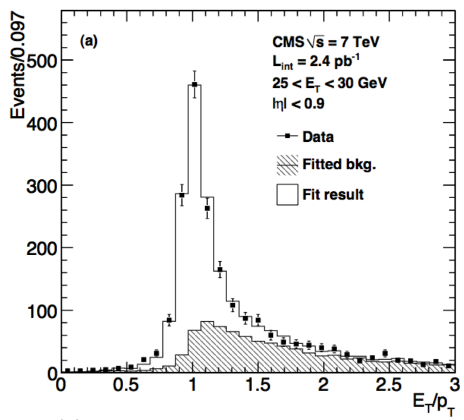
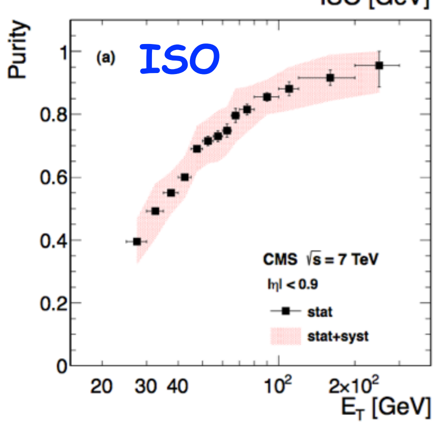
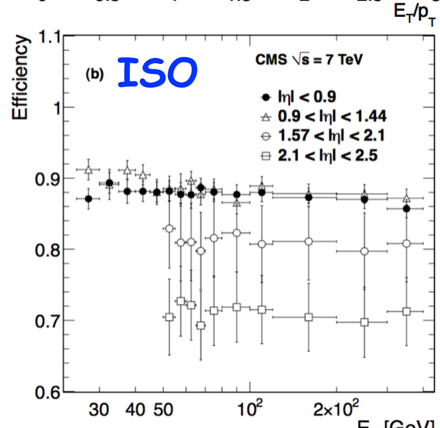
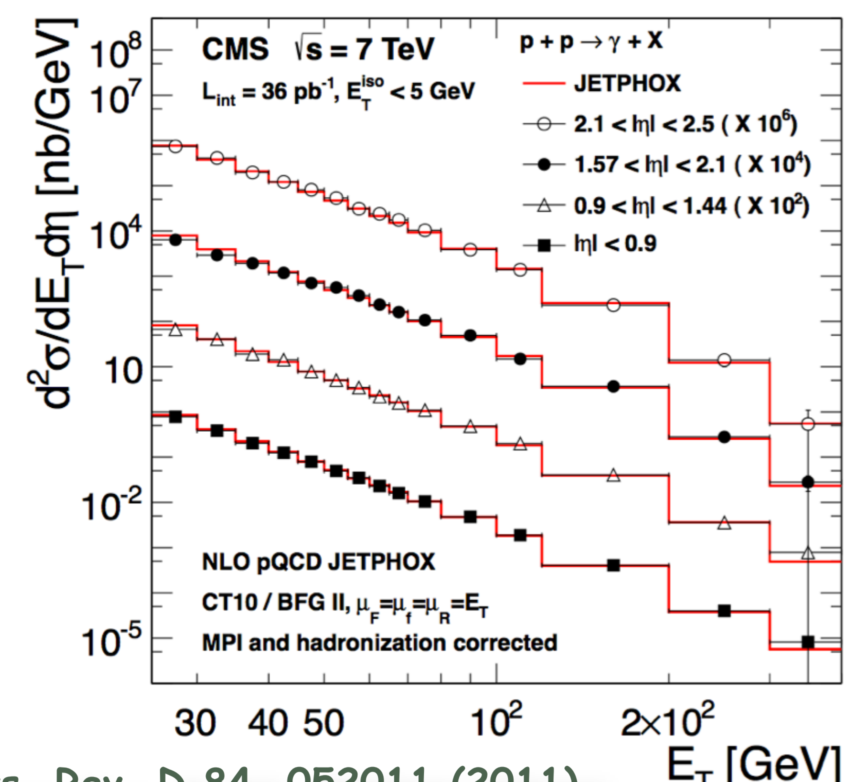








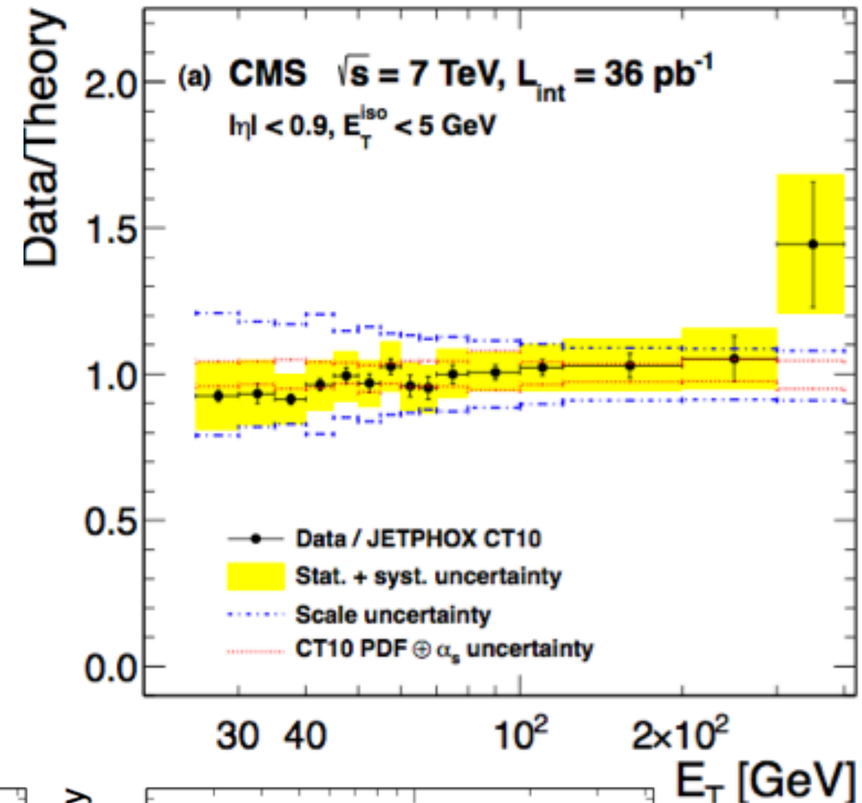




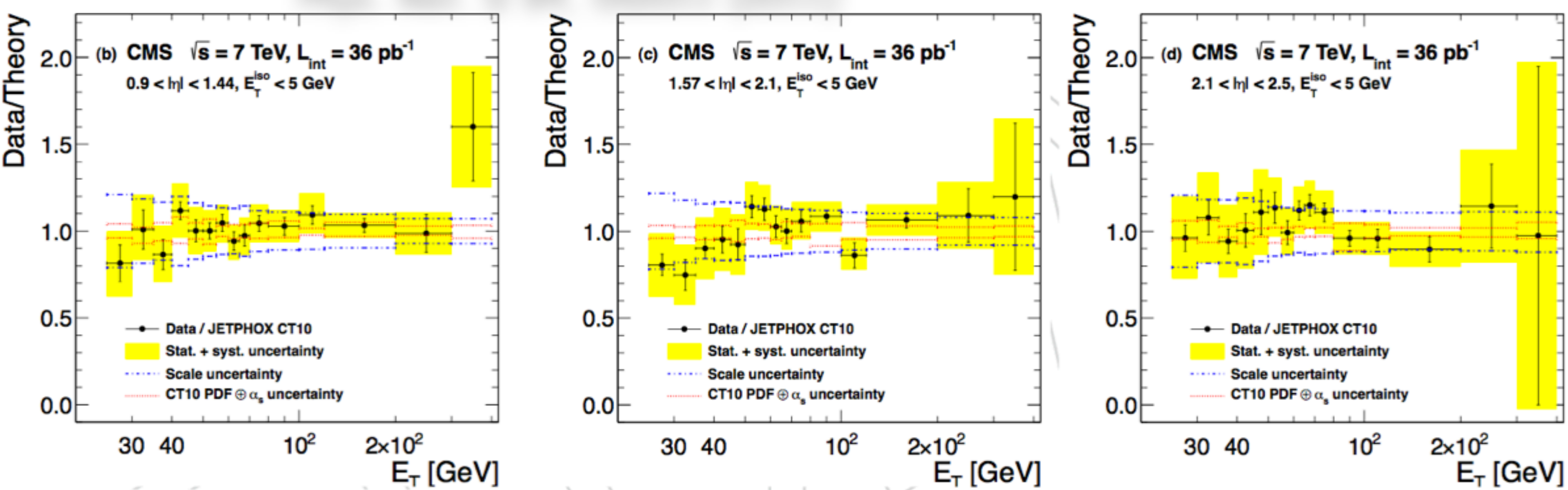
Phys. Rev. D 84, 052011 (2011)

Prompt photons

- Photon+jet data long advertised to constrain PDFs, but never used by global fitters due to data/theory disagreements at Tevatron
- NLO predictions in agreement with data at CMS, although experimental and theory uncertainties still large
- With 5/fb can extend to higher p_T and to triple differential distributions

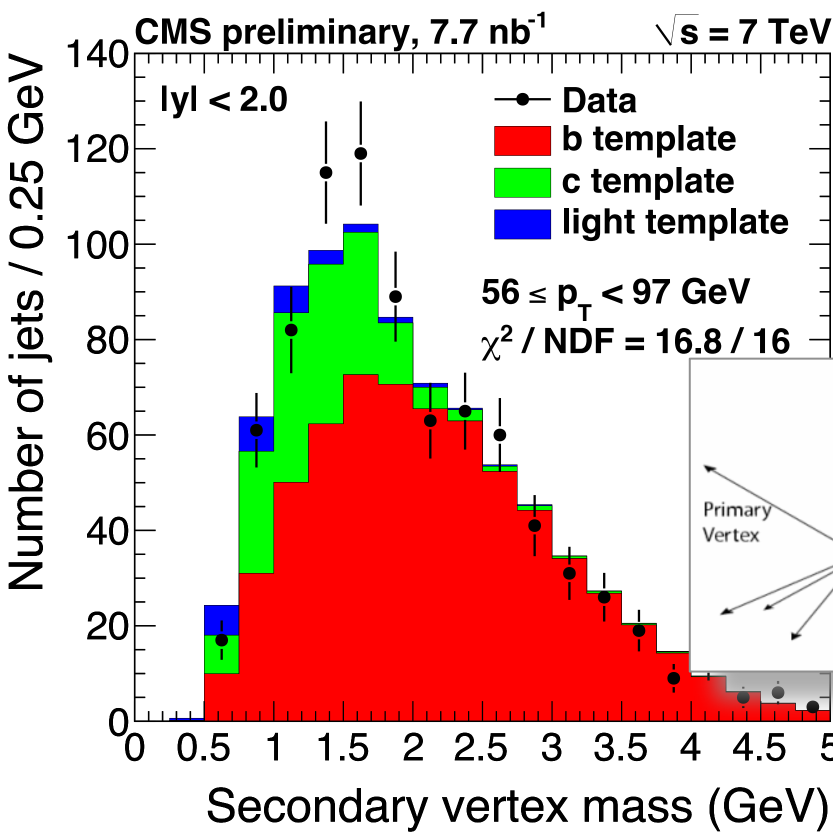


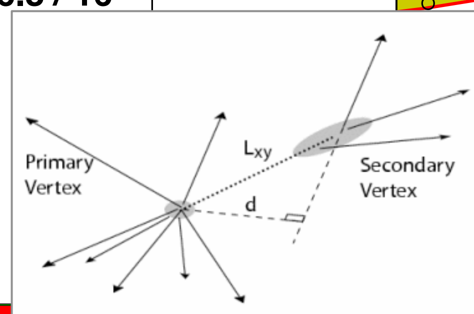
Phys. Rev. D 84, 052011 (2011)

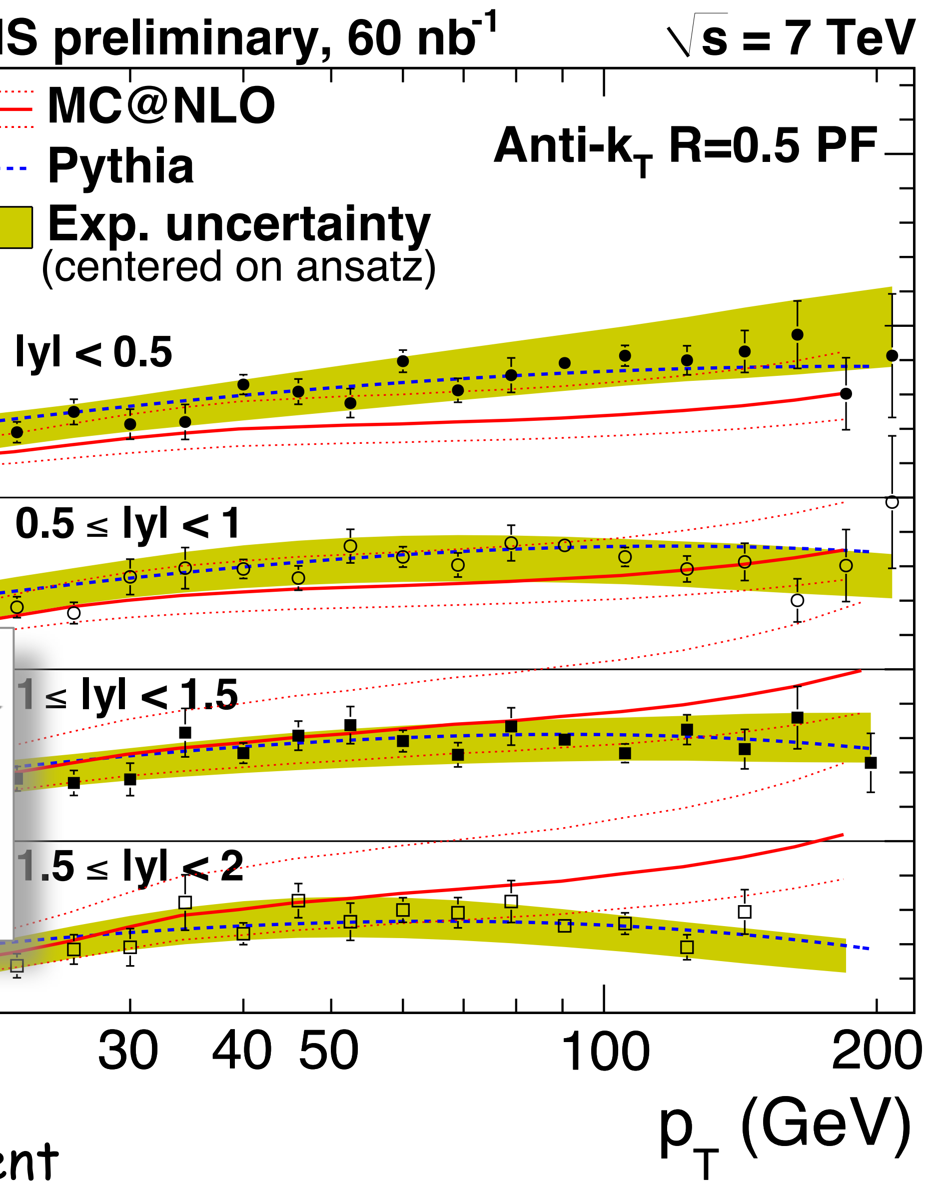


B-tagged jets

- B-tagging is one of most demanding experimental tools, but worked from start
- B-jet purity determined from data with template fits
- Efficiency checked with μ-tags







- B-fraction of jets measured to be consistent with theory predictions, MC@NLO and Pythia 6

CMS PAS BPH-10-009

B-tagged jets

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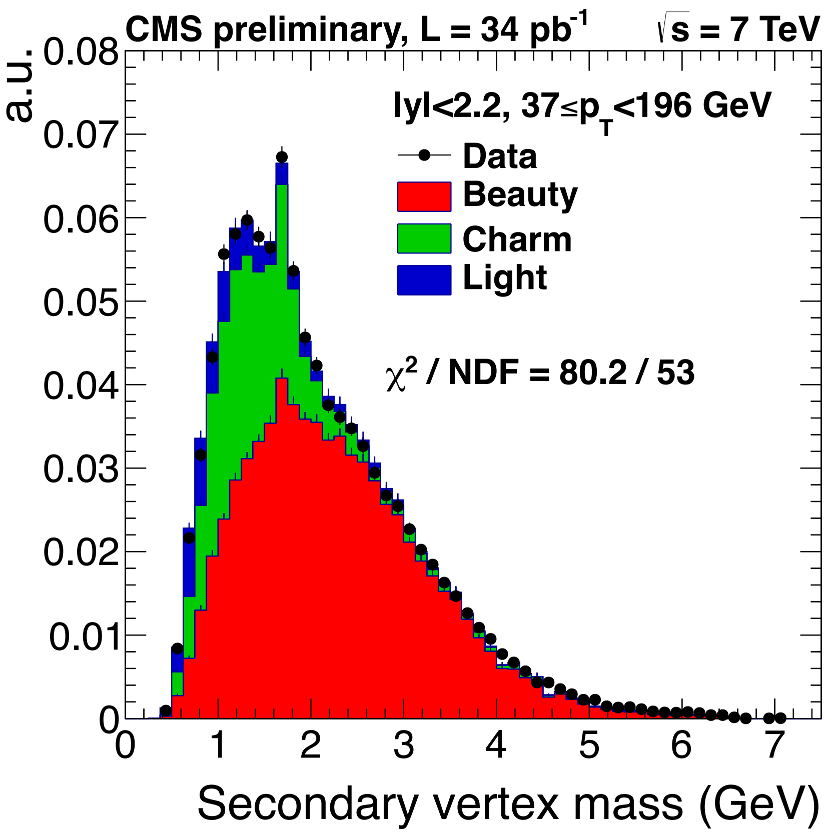
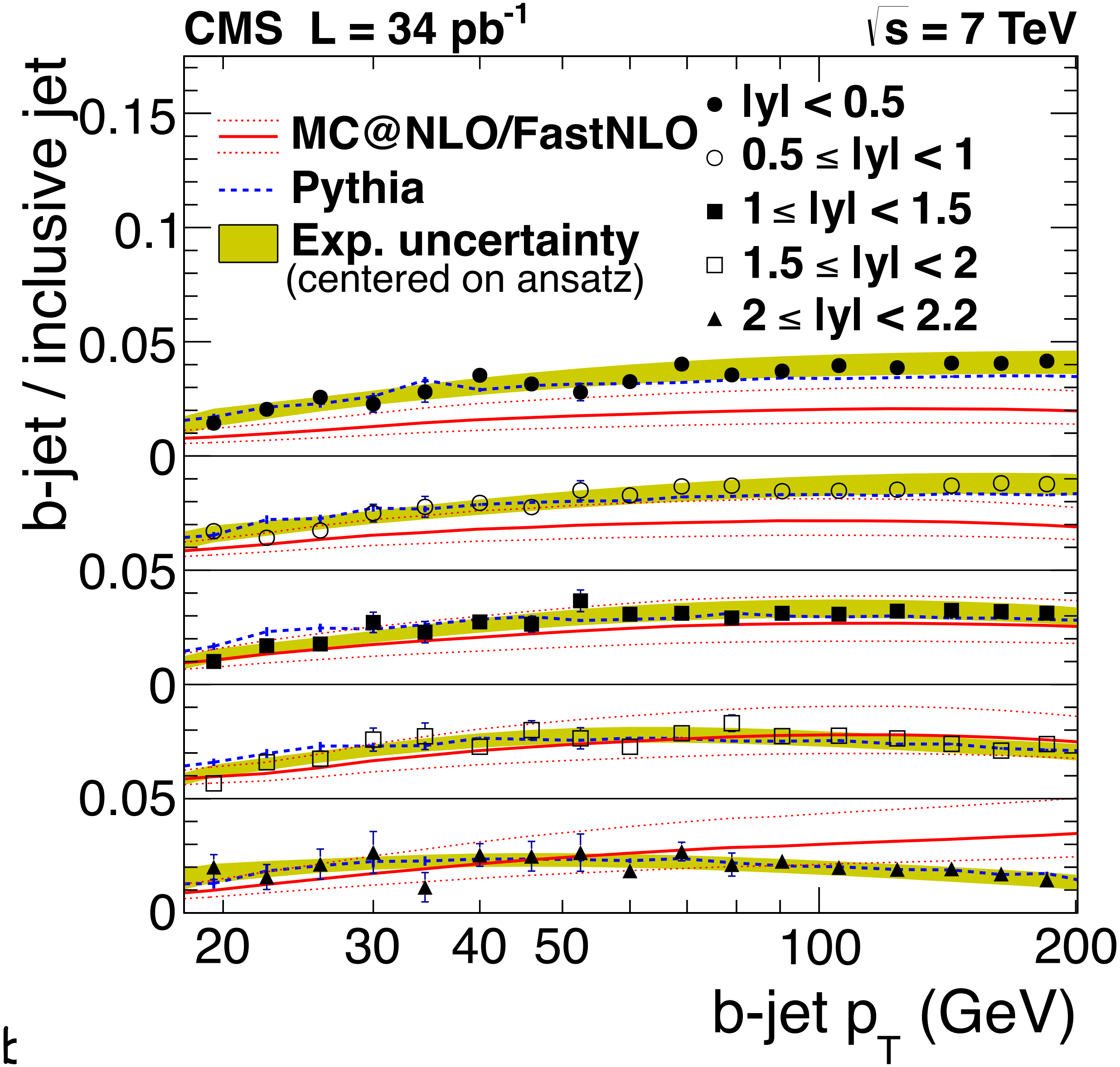


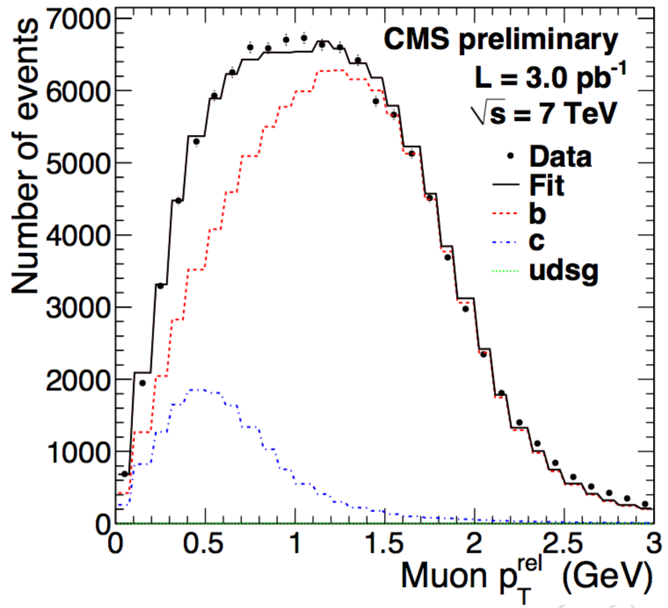


- B-fraction of jets measured to b… with theory predictions, MC@NLO and Pythia 6

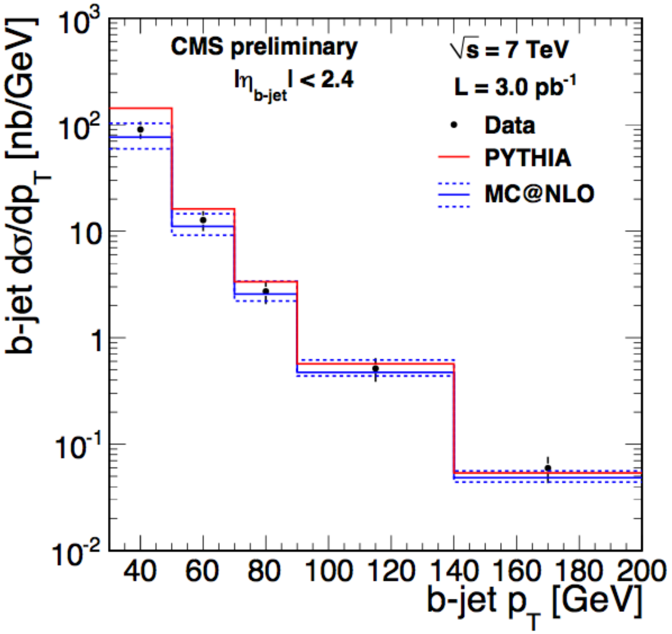
CMS PAS BPH-11-022

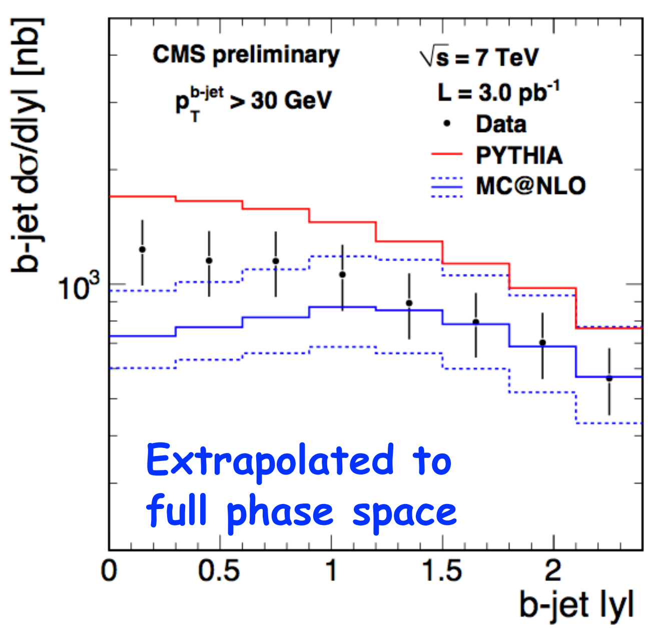
B-tagged jets with muons

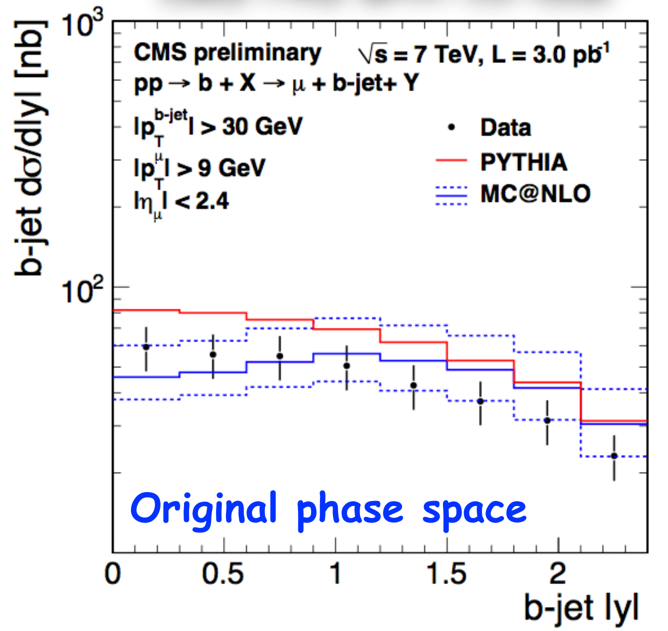
- Complementary b-jet sample with muon triggers
- Double-tagged jets (muon and secondary vertex) => both efficiency and purity with fits to muon $p_{T,rel}$
- Consistent results with jet triggered analysis:
  - Pythia models shape vs η better than MC@NLO, but is off on the overall cross section for both inclusive b-jets and inclusive jets (ratio ok)
  - MC@NLO agreement better before extrapolation

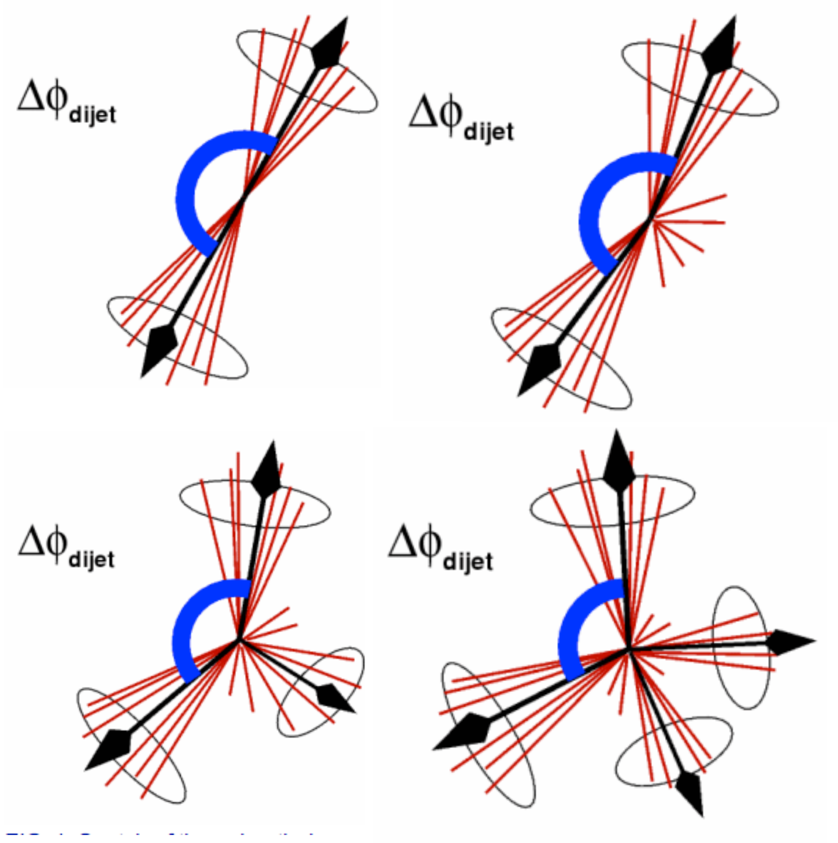


CMS PAS BPH-10-008



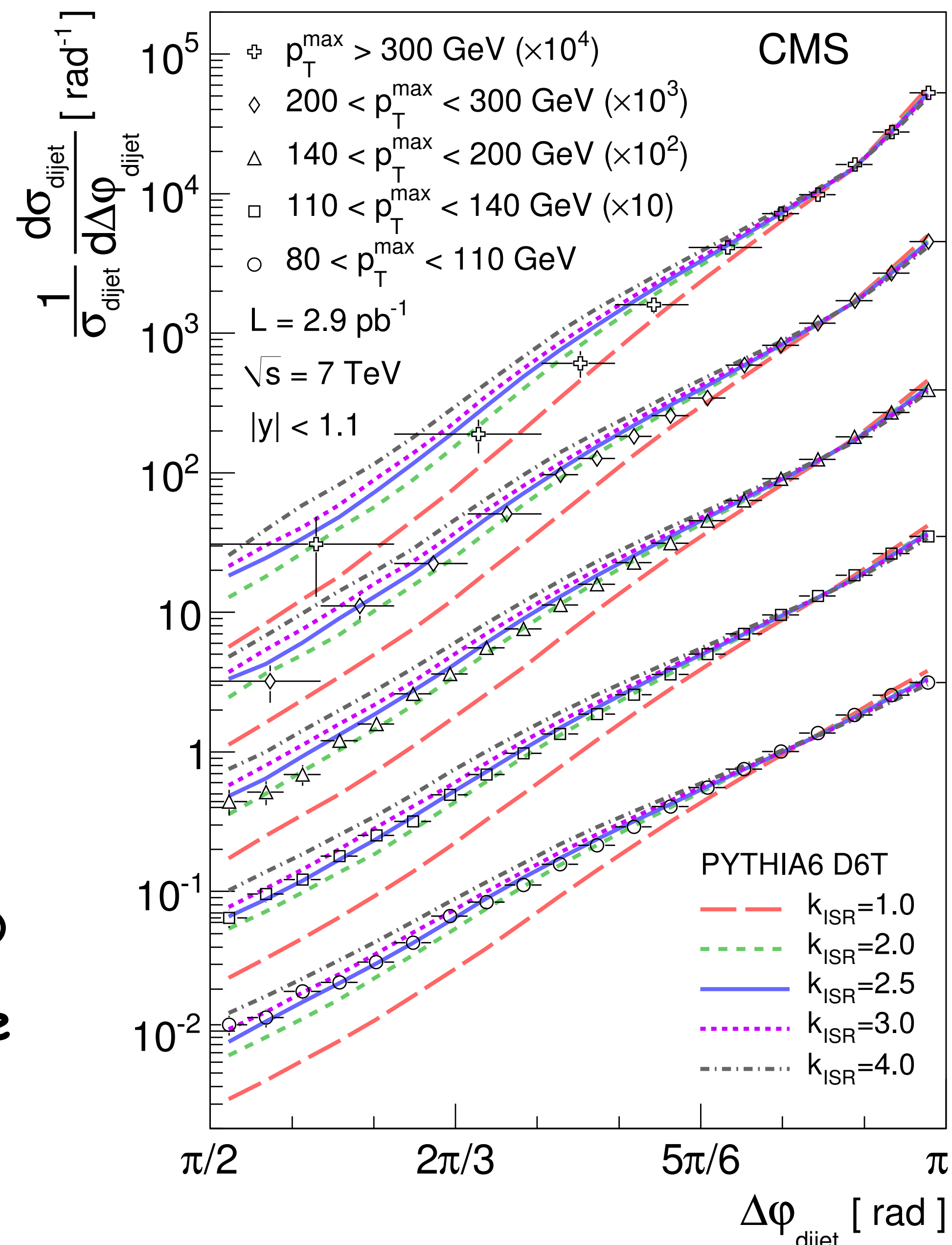






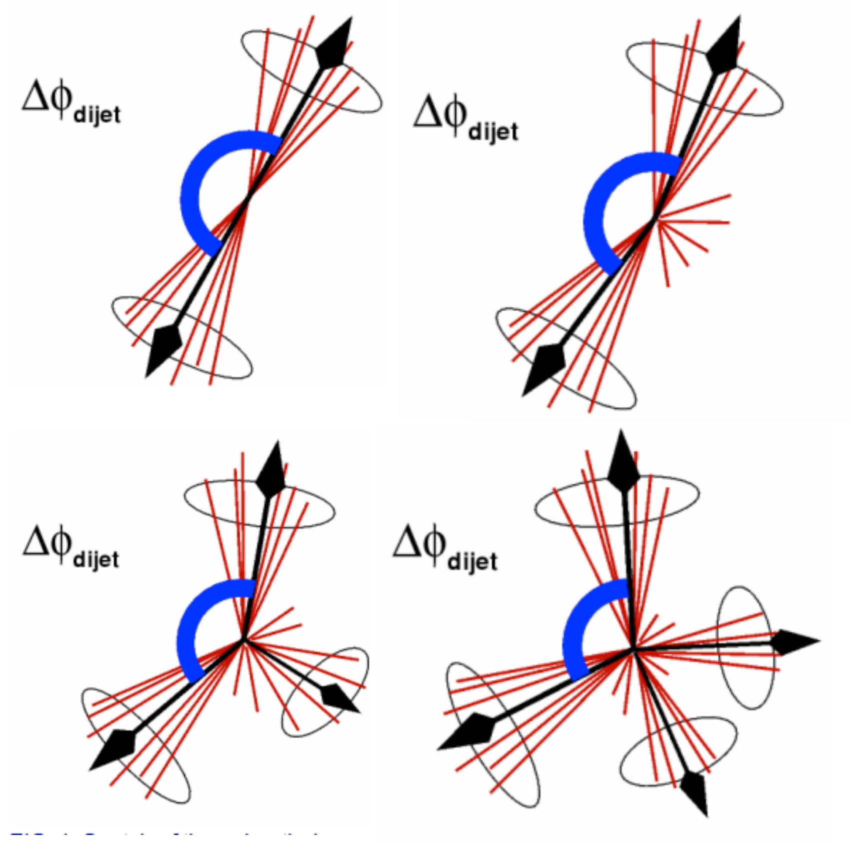
graphics: D0

- Dijet topologies probe specifics of QCD
- Dijet ΔΦ is a good probe of **initial state radiation** (ISR)
- Good agreement with NLO predictions, within range of pQCD applicability



Phys. Rev. Lett. 106, 122003 (2011)

Azimuthal decorrelations



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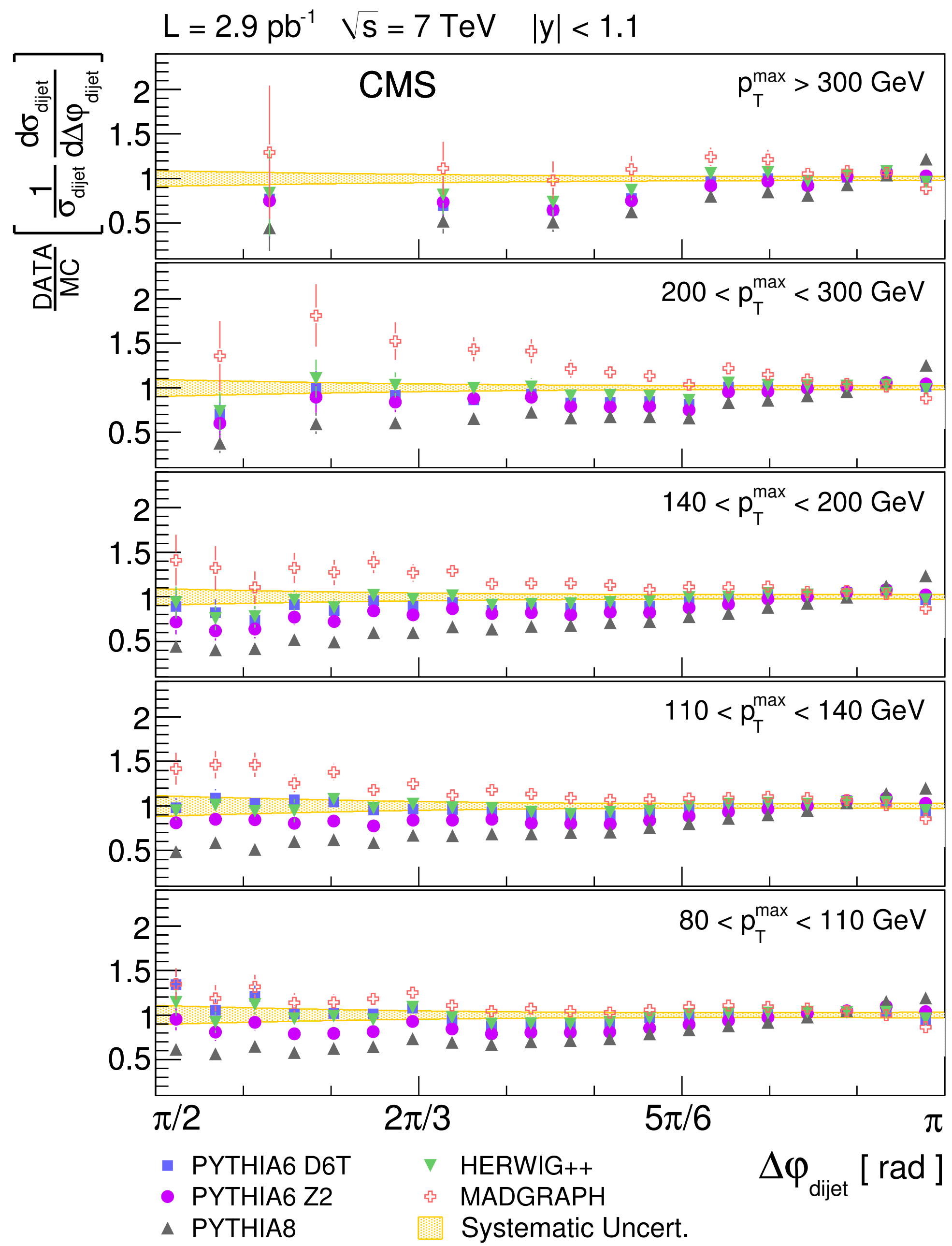


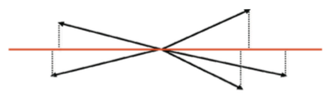
- Comparing to different MC models, Pythia 6 (Z2 and D6T) and Herwig++ do well, while Pythia 8 and MadGraph struggle to model the azimuthal decorrelation correctly

Phys. Rev. Lett. 106, 122003 (2011)

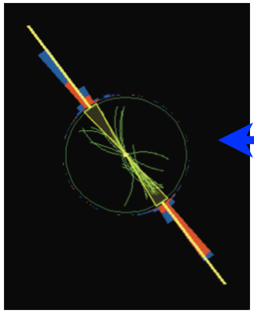
Hadronic event shapes

- Geometric shape of the hadronic final state sensitive to details of QCD multijet production, but robust against experimental systematics, e.g. jet energy scale
- Pythia 6 (D6T), Pythia 8 (2C) and Herwig++ (2.3) agree with data, while MadGraph and Alpgen do not

central transverse thrust:

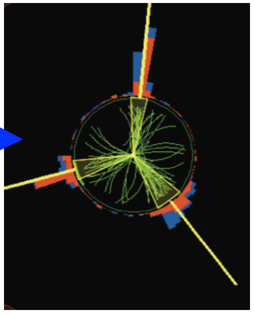


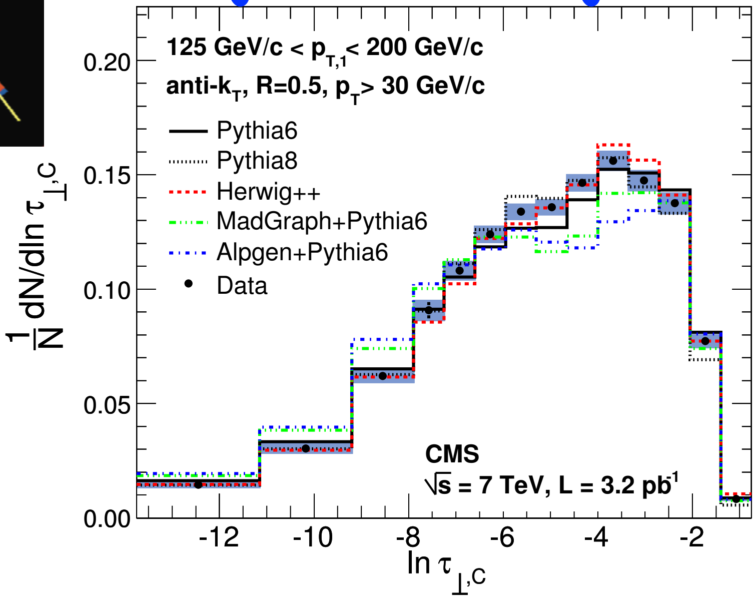
$$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_{\mathrm{T}}} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_{\mathrm{T}}|}{\sum_i p_{\perp,i}}$$

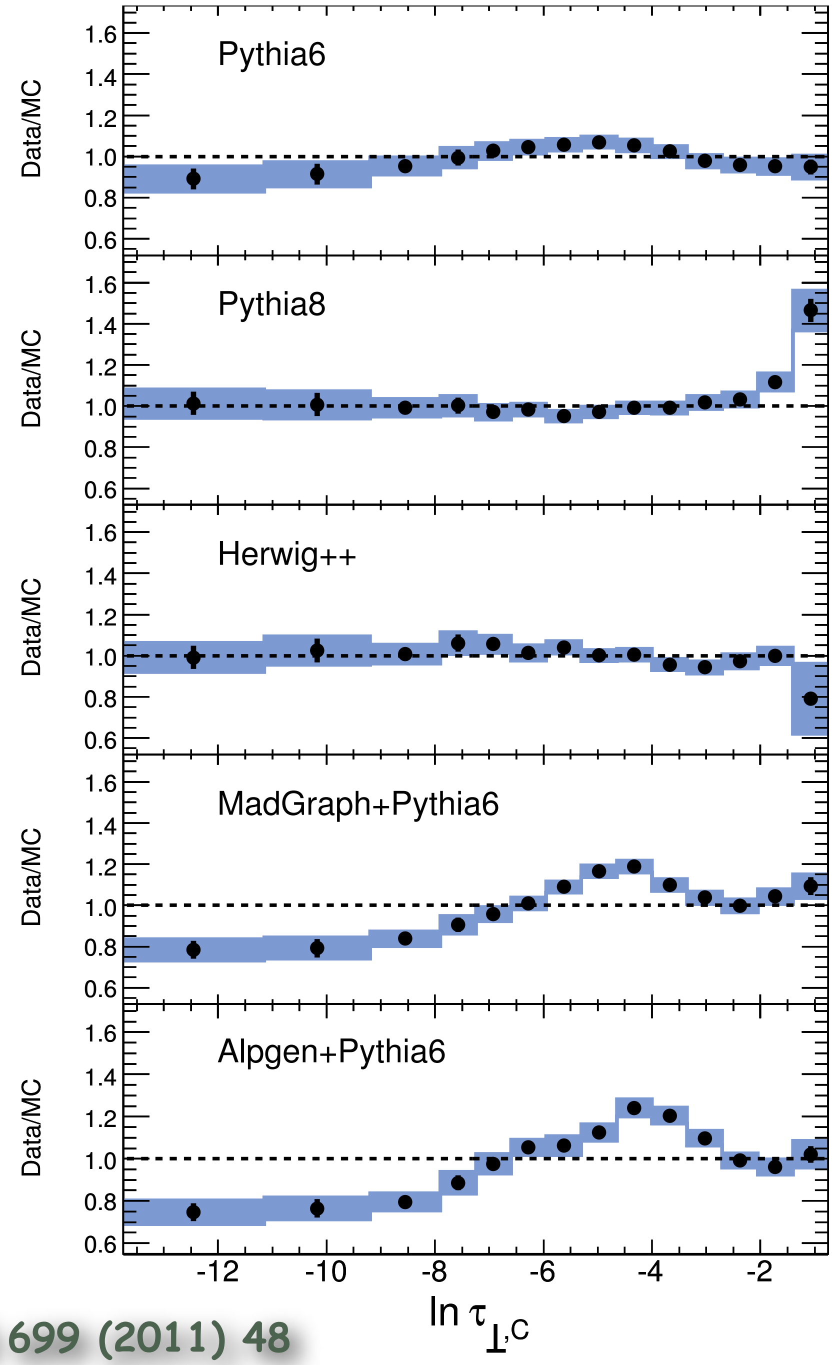


Dijet

Multijet

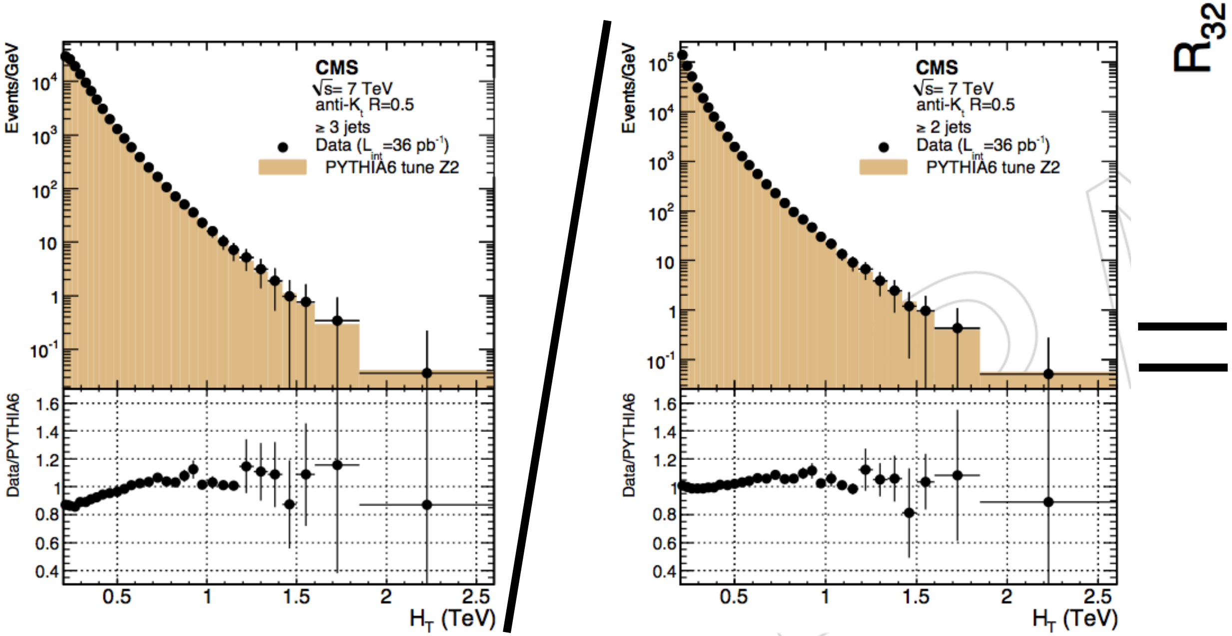


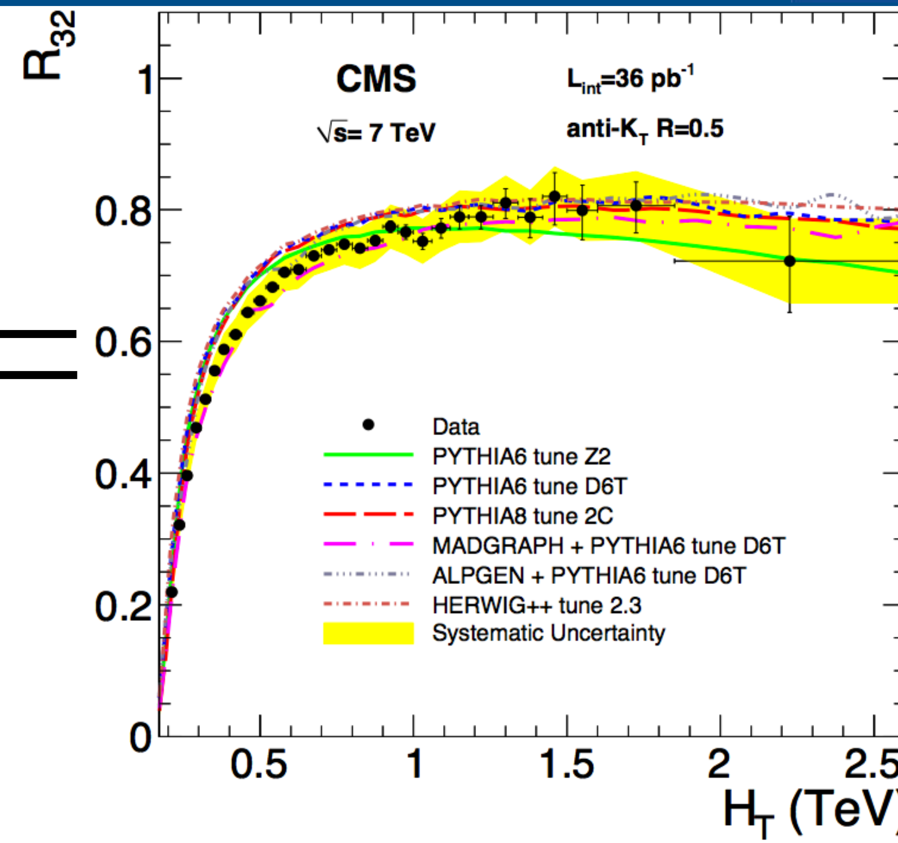




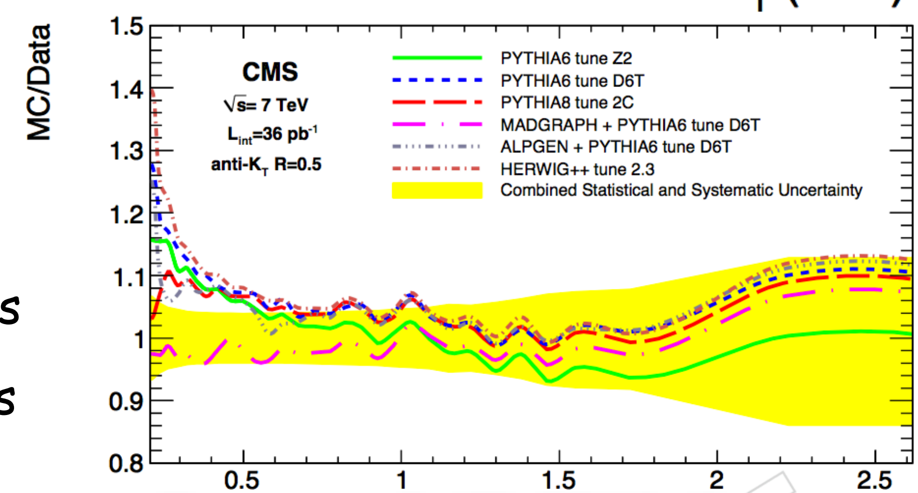
Phys. Lett. B 699 (2011) 48

3-jet/2-jet ratio





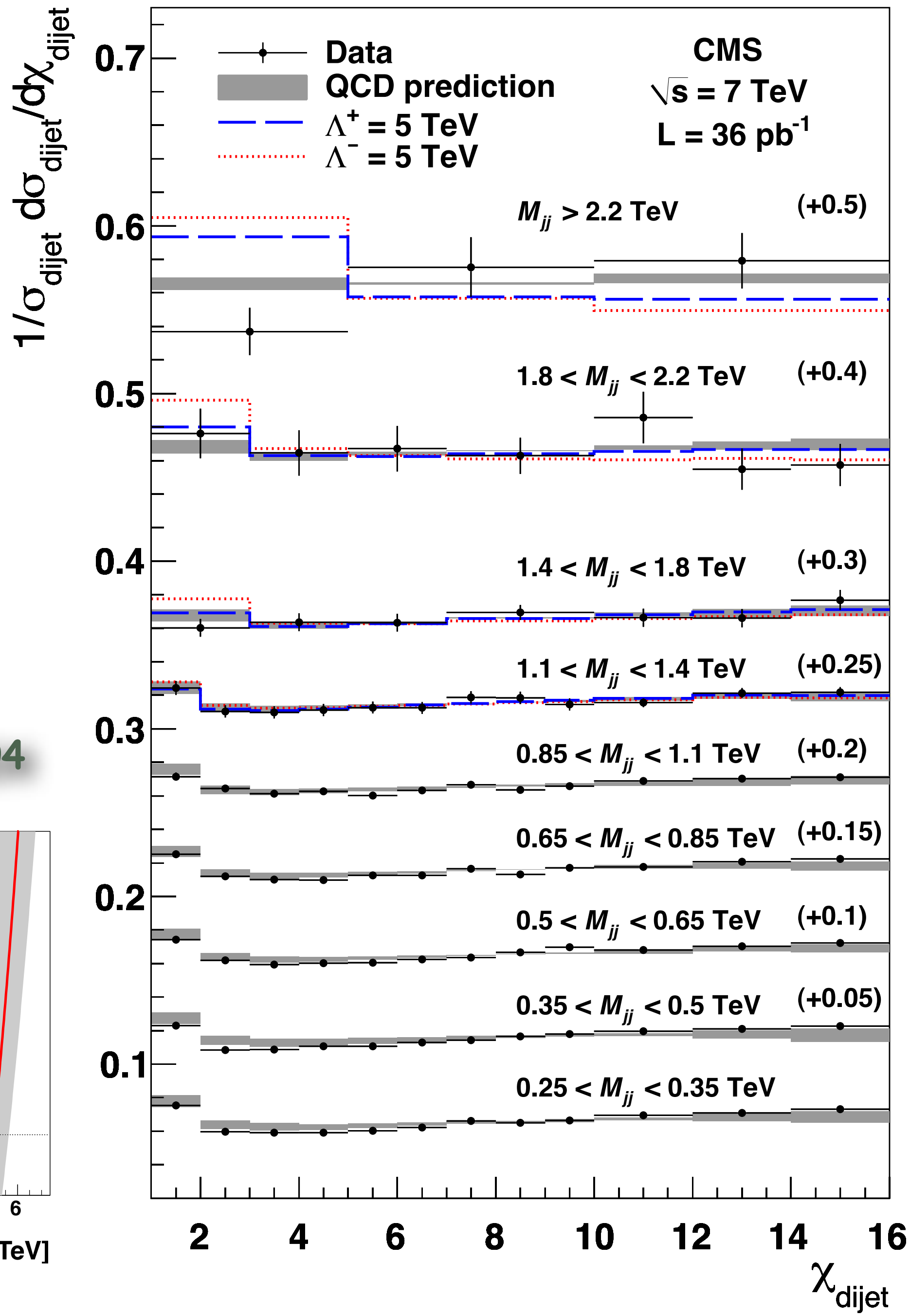
- Jets with $p_T > 50$ GeV, $|y| < 2.5$:
  - $R_{32} = (d\sigma_3/dH_T) / (d\sigma_2/dH_T)$
  - $H_T = \Sigma_i \, p_{T,i}$
- Ratio rises as phase space open up, plateau sensitive to strong coupling α_s
- MadGraph, Alpgen differences from parton matching, both use tree-level helicity amplitudes
- Although MadGraph struggled with event shapes and angular decorrelations, probability of 3rd parton emission correct



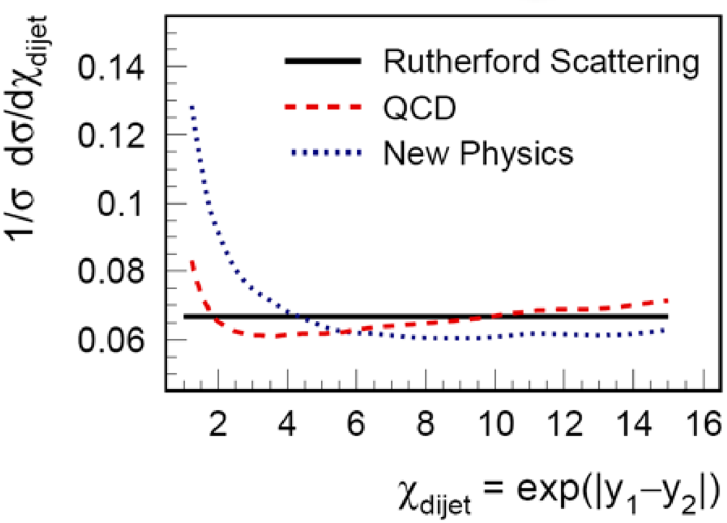
Phys. Lett. B 699 (2011) 48

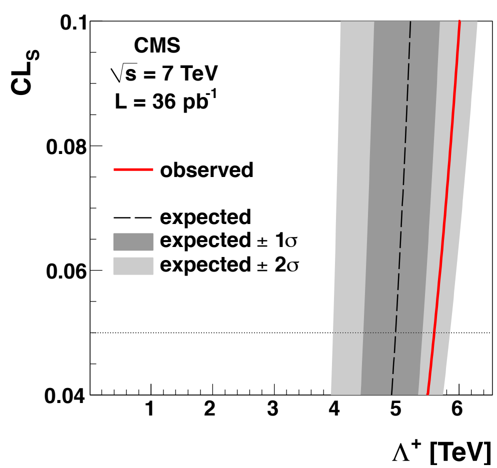
Dijet angular distributions

- Isotropic new physics peaks at low X ($y_1 \sim y_2$), e.g. contact interactions
- QCD mostly t-channel => flat in $X_{dijet} = \exp(|y_1 - y_2|)$
- Sensitivity up to Λ=5 TeV with few pb^{-1}; Tevatron limits Λ > 2.8-3 TeV
- No evidence of new physics, but can confirm QCD over Rutherford scattering



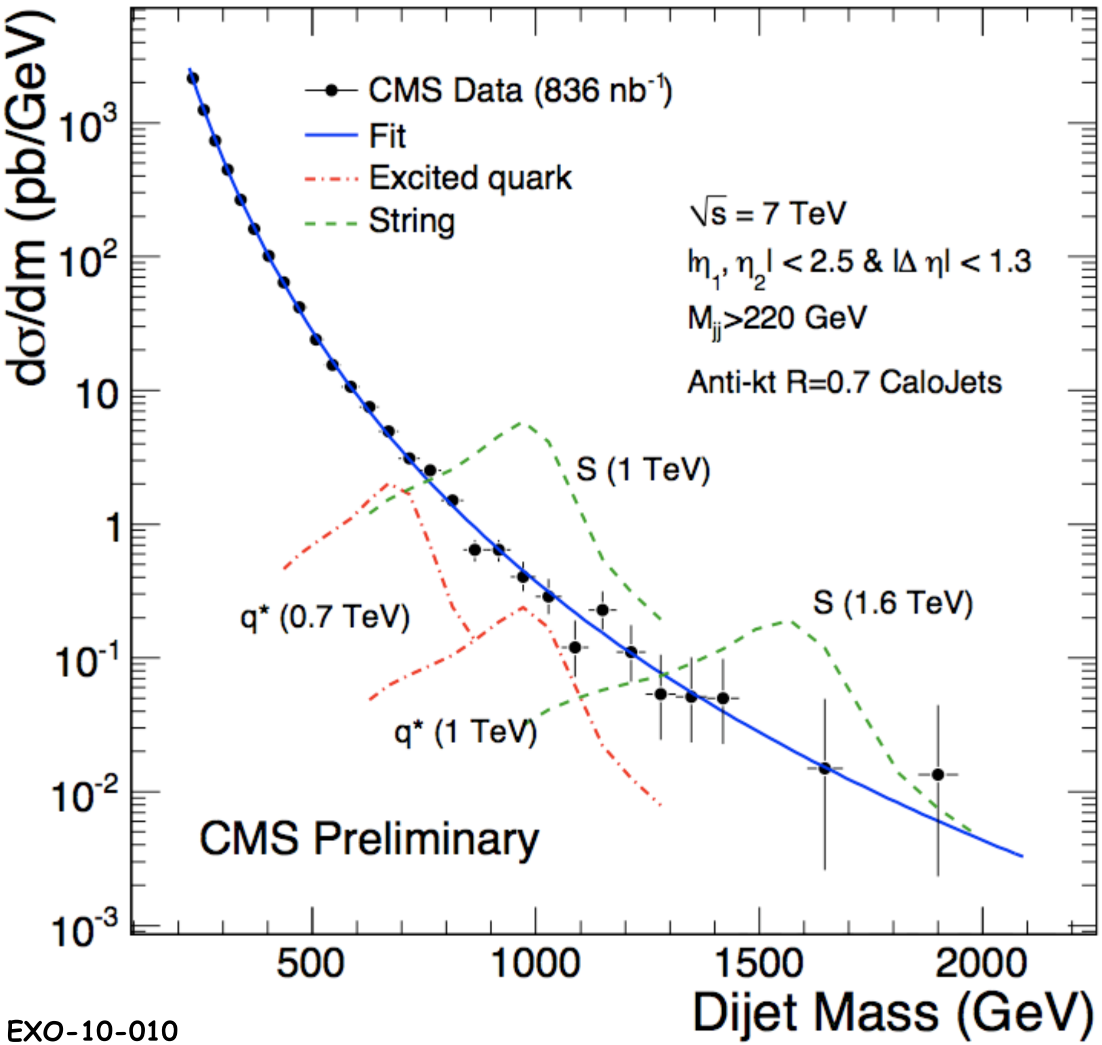
Phys. Rev. Lett. 106 (2011) 201804





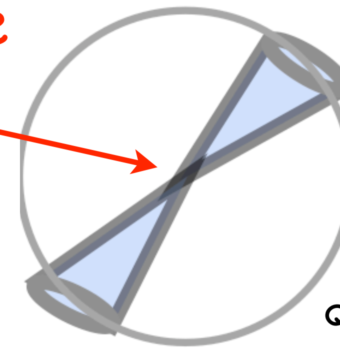
Bump hunts with dijets

- Dijet mass spectrum doubles as a bump hunt for new resonances
- Consistent results with NLO predictions and with inclusive jets (smaller cone); no bumps found in 2010 data set

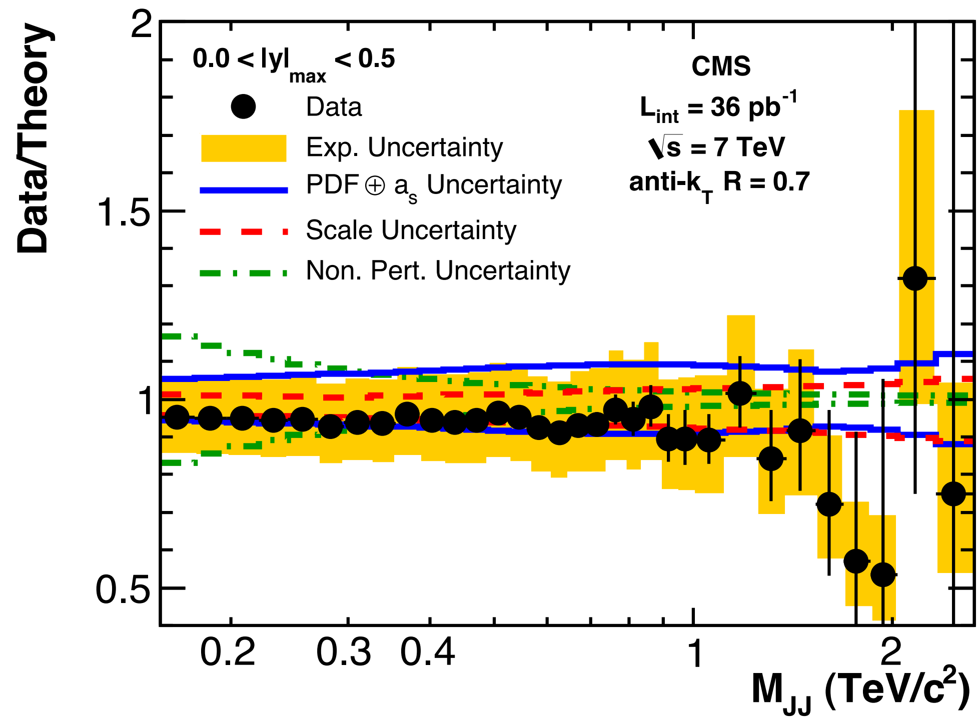


EXO-10-010

Heavy particle decaying?



QCD-10-025



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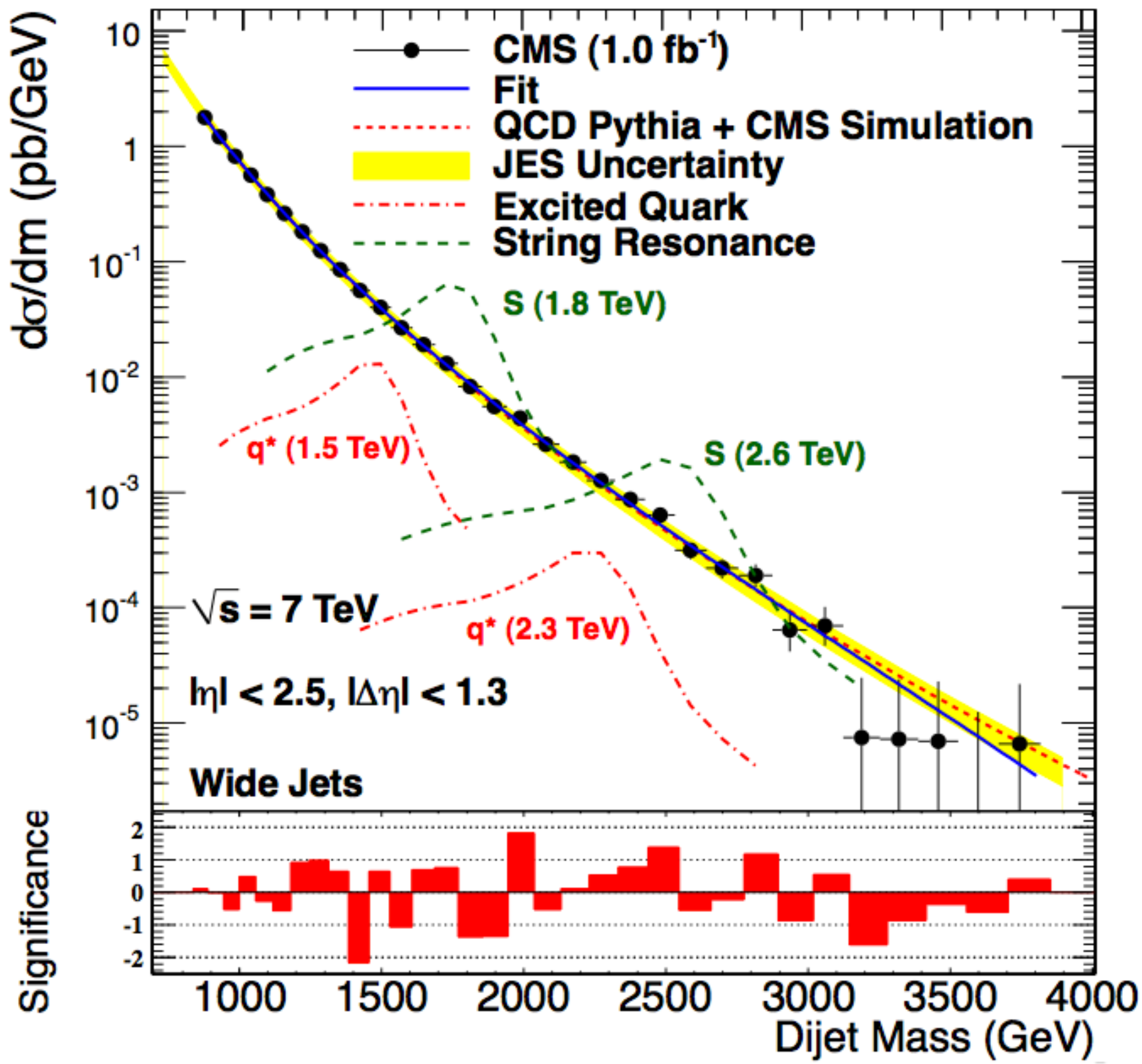
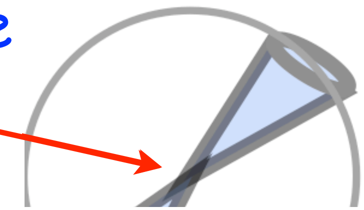
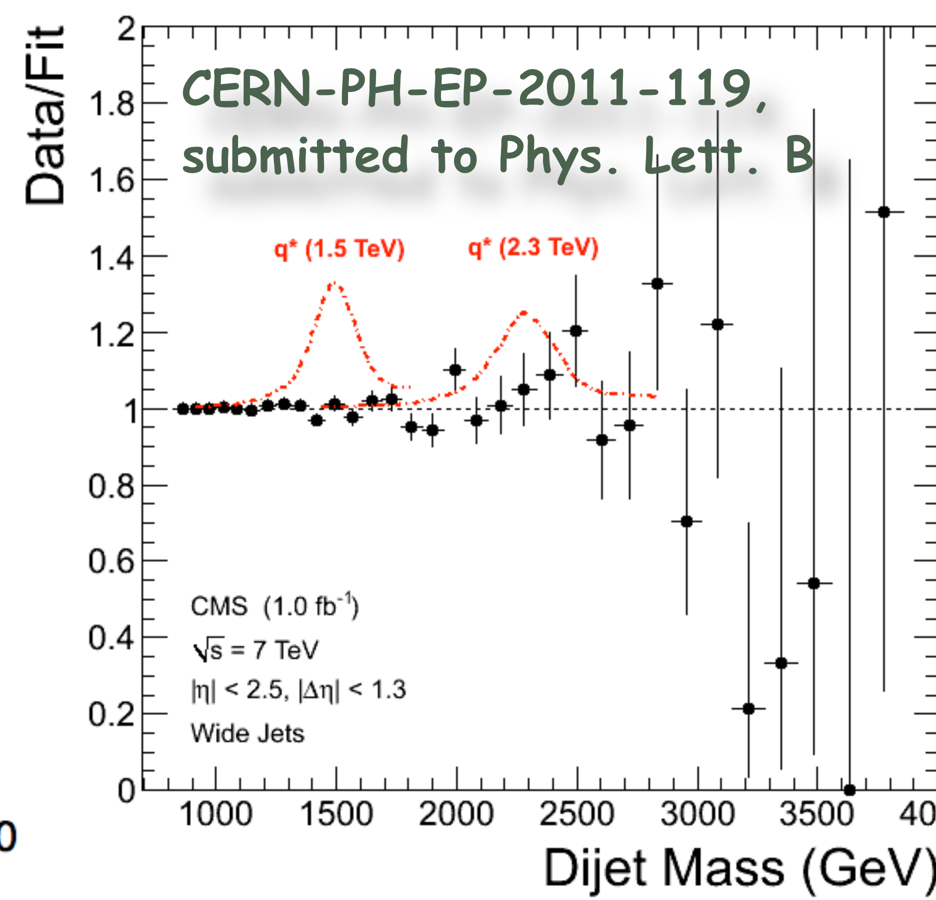


Heavy particle decaying?

No.

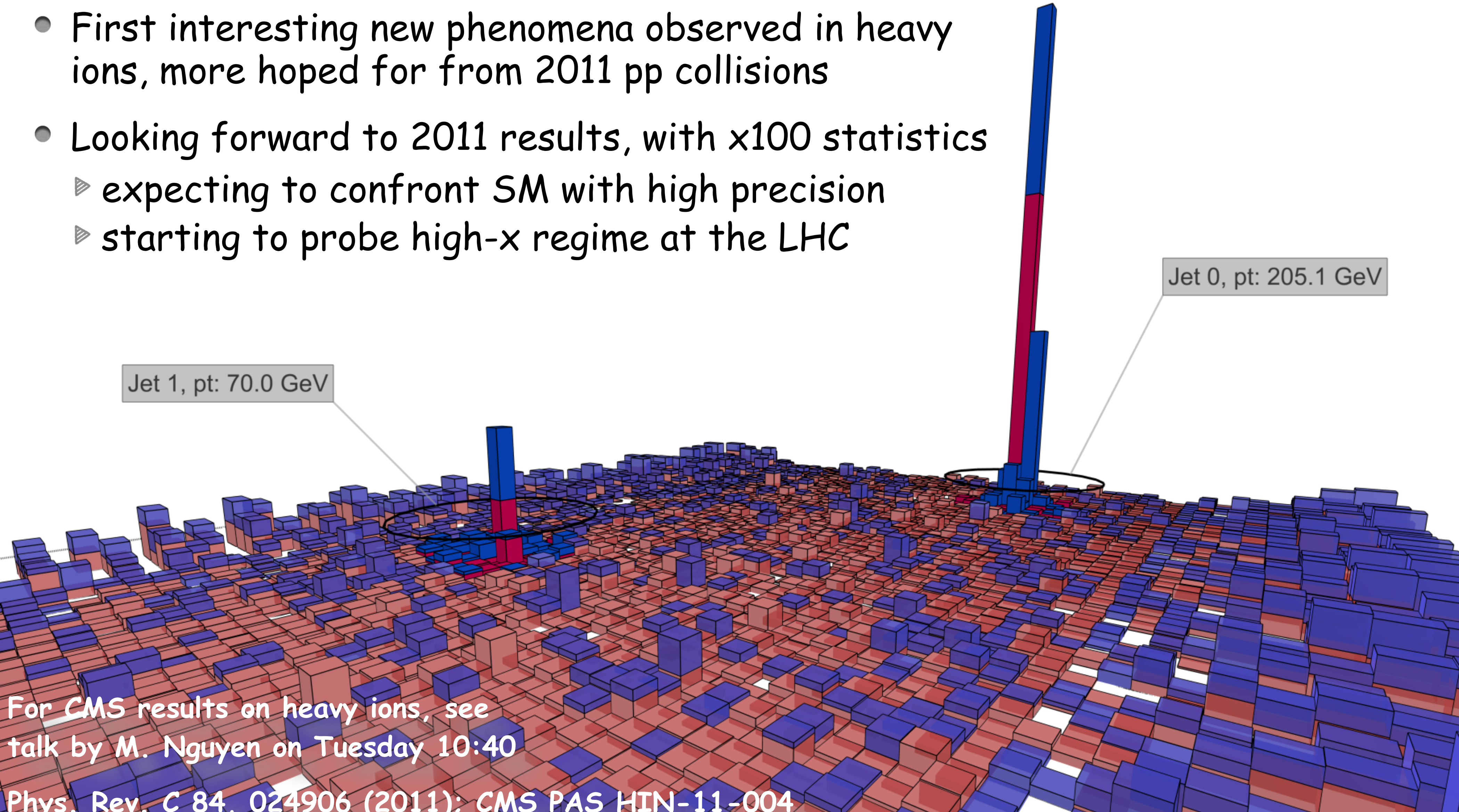


CERN-PH-EP-2011-119, submitted to Phys. Lett. B



Conclusions and outlook

- Wealth of precise Standard Model results coming out from CMS
  - Good agreement between data and theory predictions so far
- First interesting new phenomena observed in heavy ions, more hoped for from 2011 pp collisions
- Looking forward to 2011 results, with x100 statistics
  - expecting to confront SM with high precision
  - starting to probe high-x regime at the LHC



For CMS results on heavy ions, see talk by M. Nguyen on Tuesday 10:40

Phys. Rev. C 84, 024906 (2011); CMS PAS HIN-11-004

Backup slides

LHC re-start

LHC re-start November 23, 2009

7 TeV physics run started on **March 30, 2010 at 12:57**


Geneva (airport)
The Large Hadron Collider
27 km of tunnel across franco-swiss border
3.5+3.5 trillion electronvolt (TeV) proton beams
287+287 TeV lead ion beams
1.9K superconducting magnets
CMS

Unfolding

- Inclusive jet cross section uses **ansatz** unfolding to get to the particle level
- Phenomenological power law motivated by parton model (Feynman/Field/Fox), extended at the Tevatron, and updated at CMS for low p_T and b-jets

$$f(p_T) = N_0 p_T^{-\alpha} \underbrace{\left(1 - \frac{2p_T \cosh(y_{\min})}{\sqrt{s}}\right)^{\beta}}_{\text{high } p_T} \underbrace{\exp(-\gamma/p_T)}_{\text{low } p_T \text{ and b-jets}}$$

new

$$C_{\text{smear}}(p_T) = \frac{f(p_T)}{F(p_T)}, \qquad F(p_T) = \int_{x=0}^{x=\infty} f(x) g(p_T - x) dx,$$