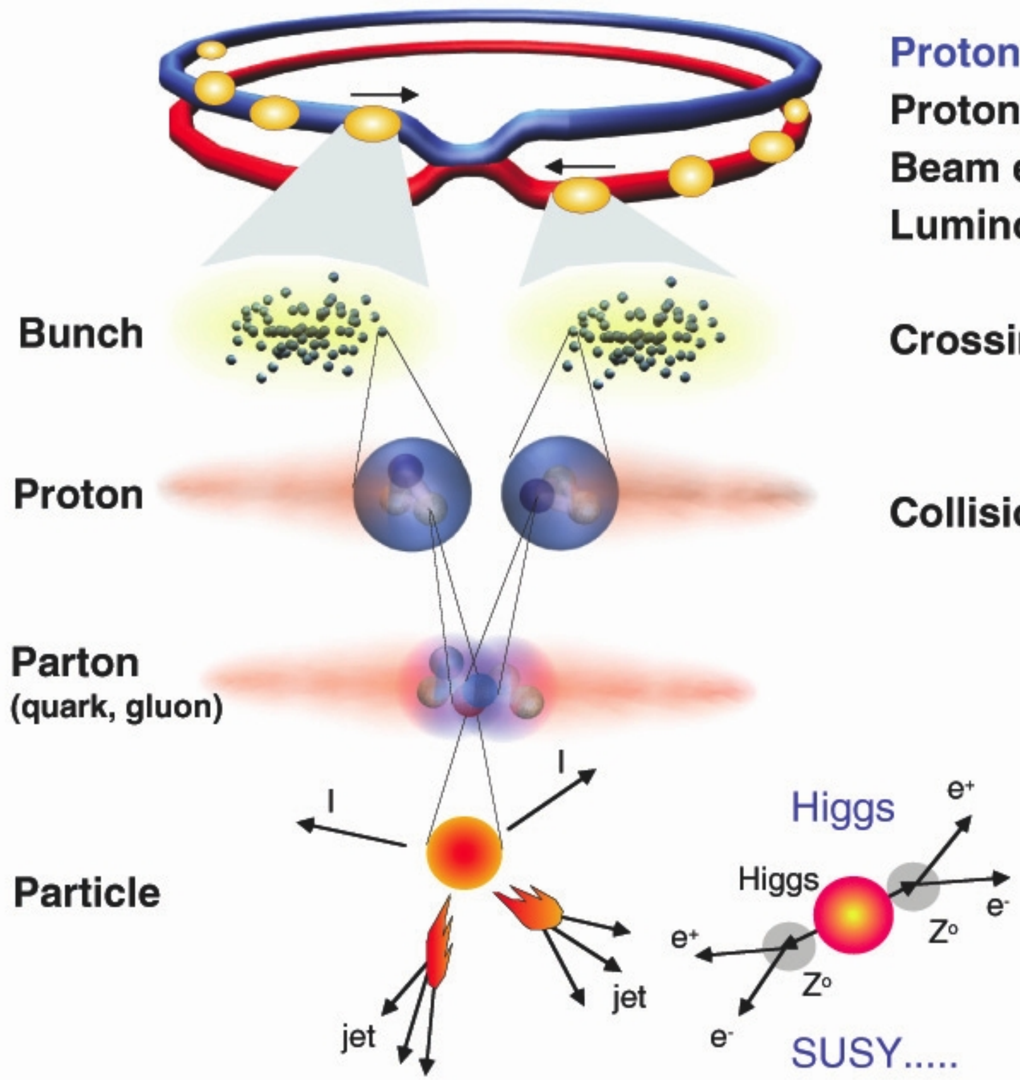
Establishing Standard Model @ LHC

Physics at the Energy Frontier

- QCD
  - Soft Particles → Hard Jets
- Flavor sector
  - J/ψ, Upsilon, B mesons, b-jets
- Electroweak
  - Direct Photons → Z cross section

The Large Hadron Collider

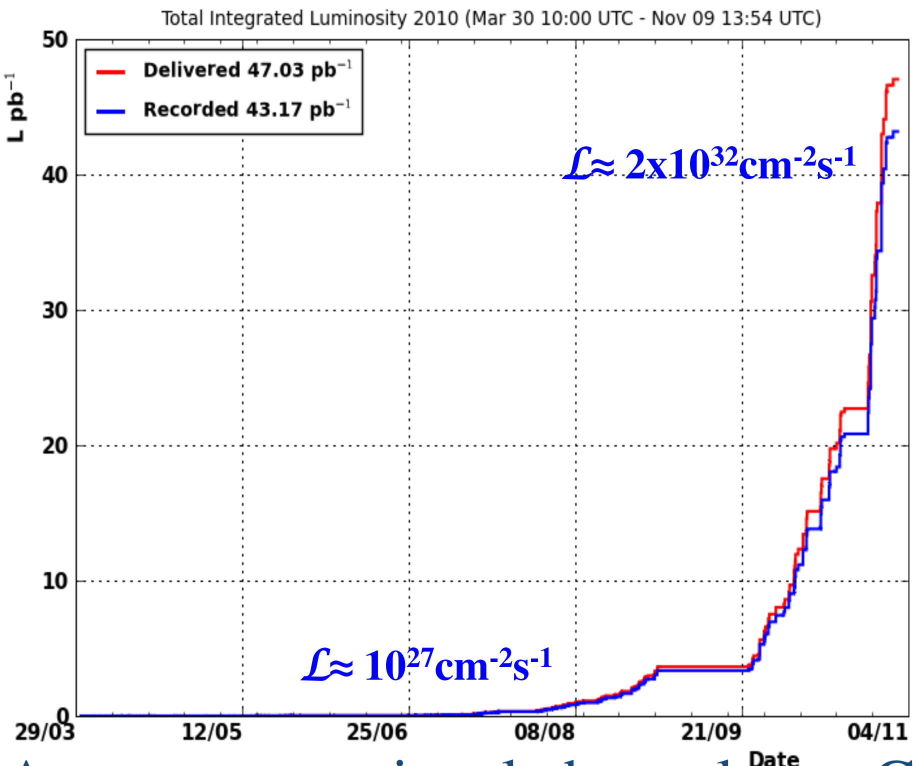


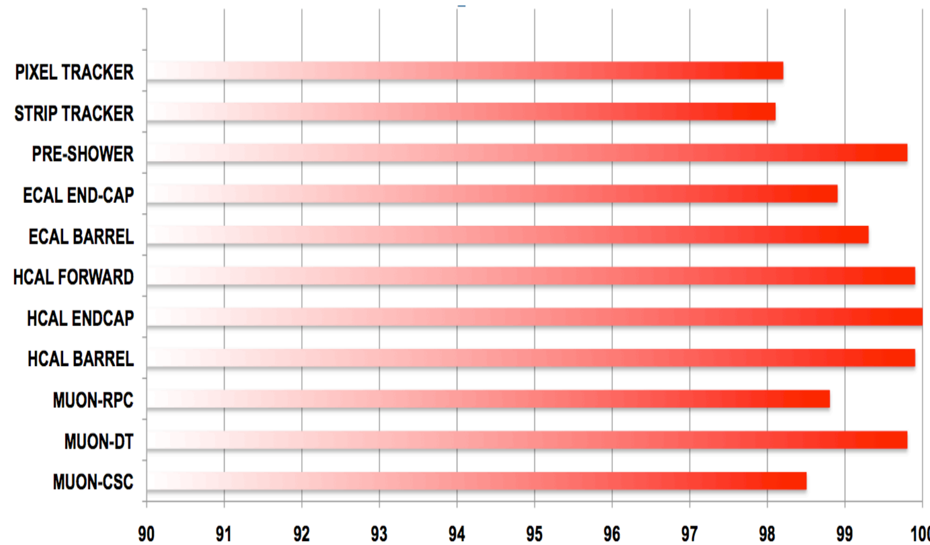
		2010
Proton-Proton	2835 bunch/beam	200
Protons/bunch	10^{11}	10^{11}
Beam energy	7 TeV (7×10^{12} eV)	3.5 TeV
Luminosity	10^{34} cm^{-2} s^{-1}	10^{32} cm^{-2}s^{-1}
Crossing rate	40 MHz	40 MHz
Collisions ≈	10^7 - 10^9 Hz	10^6 Hz

Selection of 1 in 10,000,000,000,000

LHC and CMS operations

About **47pb^{-1}** delivered by LHC and **~43pb^{-1}** of data collected by CMS. Overall data taking efficiency **~92%. 6pb^{-1}** of data integrated in a good fill**.** Excellent performance in coping with more than 5 order of magnitude increase in instantaneous luminosity.

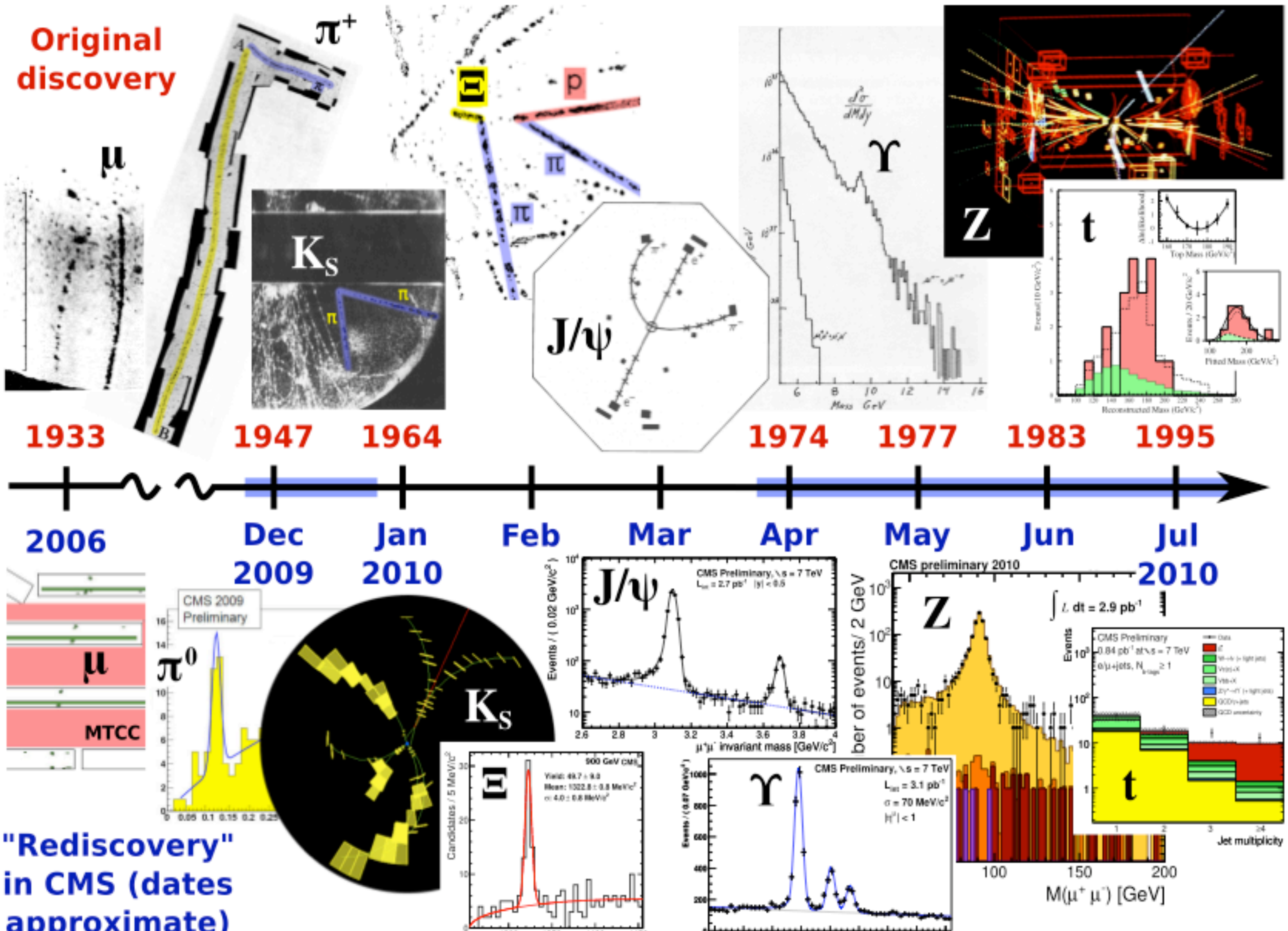




	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

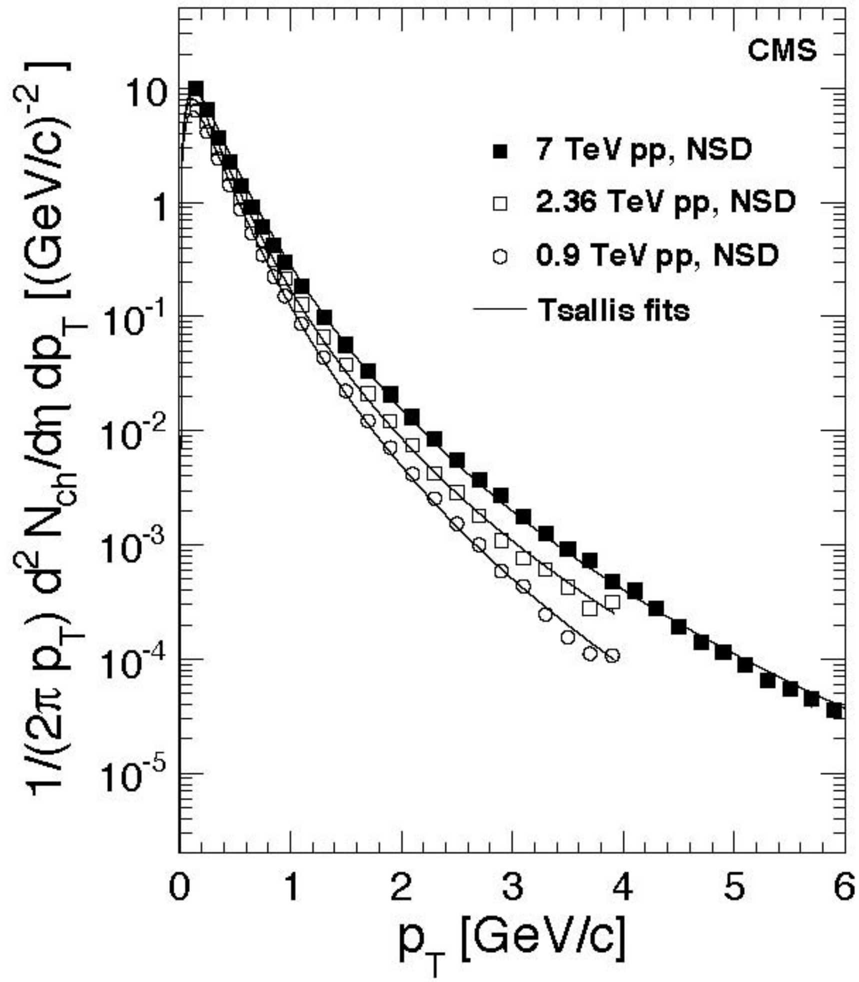
Average operational channels per CMS sub-system still **>99%.**
Quality of the data for physics **~80%** (likely **85%** after re-reco)

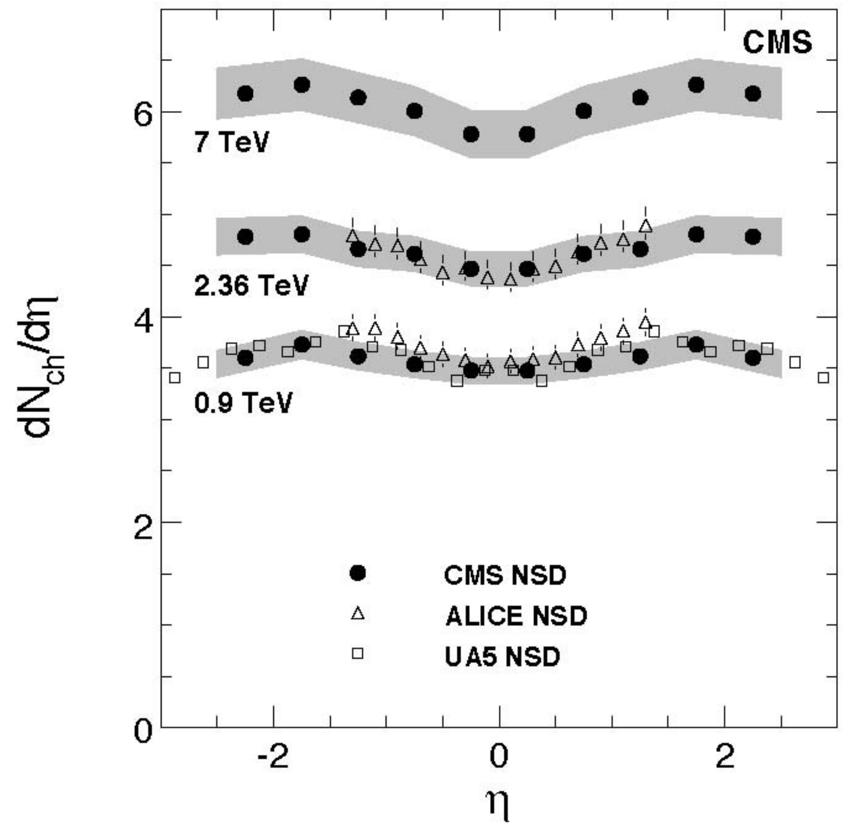
Established the Standard Model at 7 TeV



Particle P_T, Rapidity Spectra

arXiv:1005.3299v2 [hep-ex] 6 Jul 2010





Pseudo-rapidity, $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$

Charged Particle Production

arXiv:1011.5531v1 [hep-ex] 24 Nov 2010

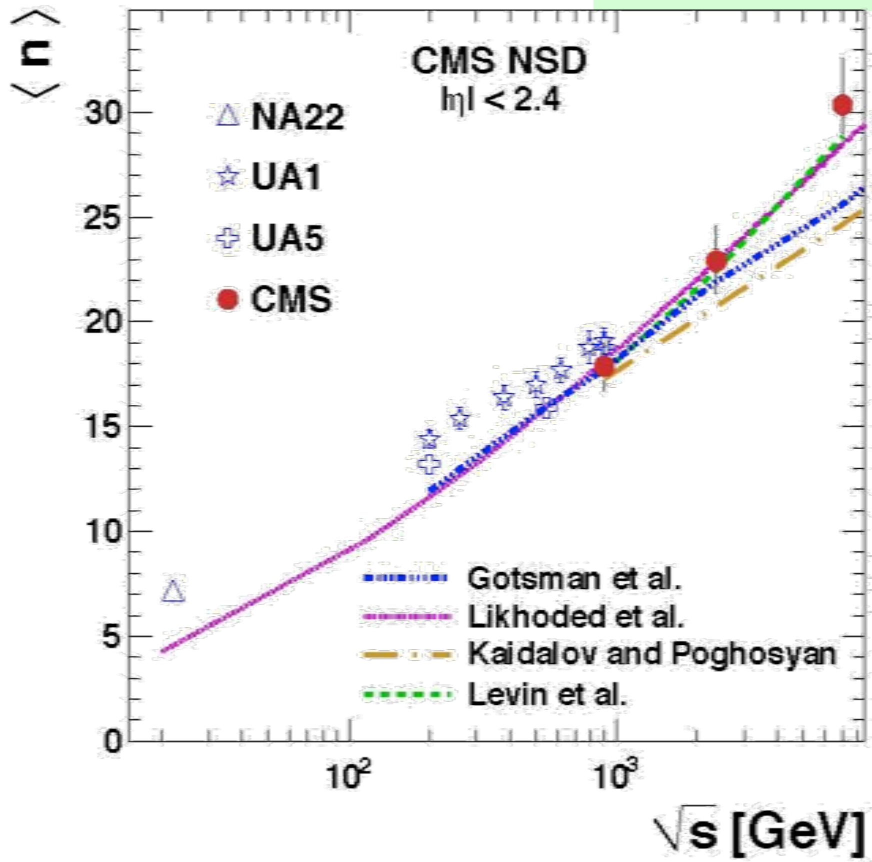
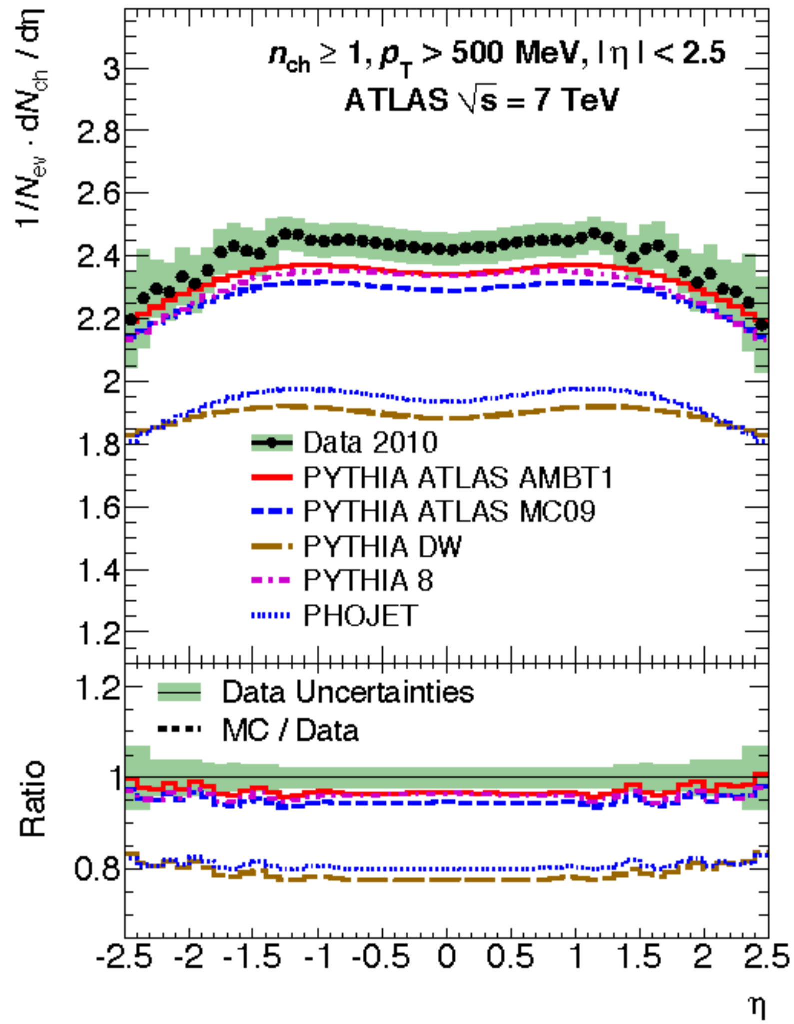
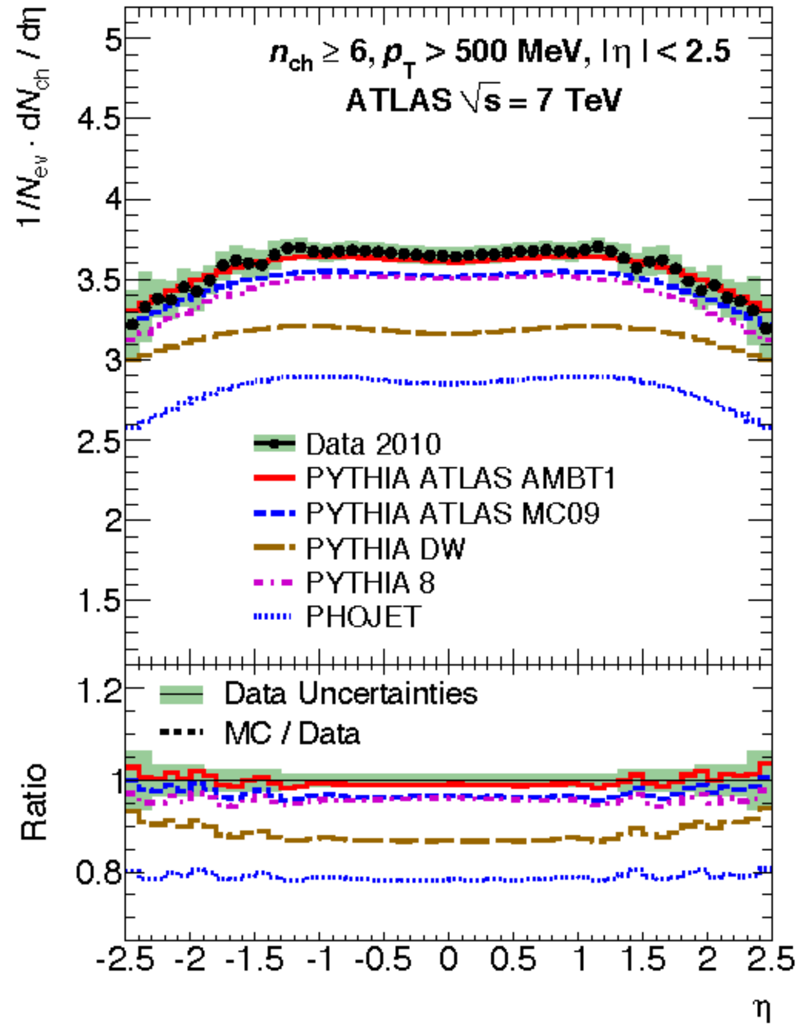


Figure 7: The evolution of the mean charge multiplicity with the centre-of-mass energy for $|\eta| < 2.4$, including data from lower-energy experiments for $|\eta| < 2.5$ [37, 70–72]. The data are compared with predictions from three analytical Regge-inspired models [41–43] and from a saturation model [44].

Charged Multiplicity vs η

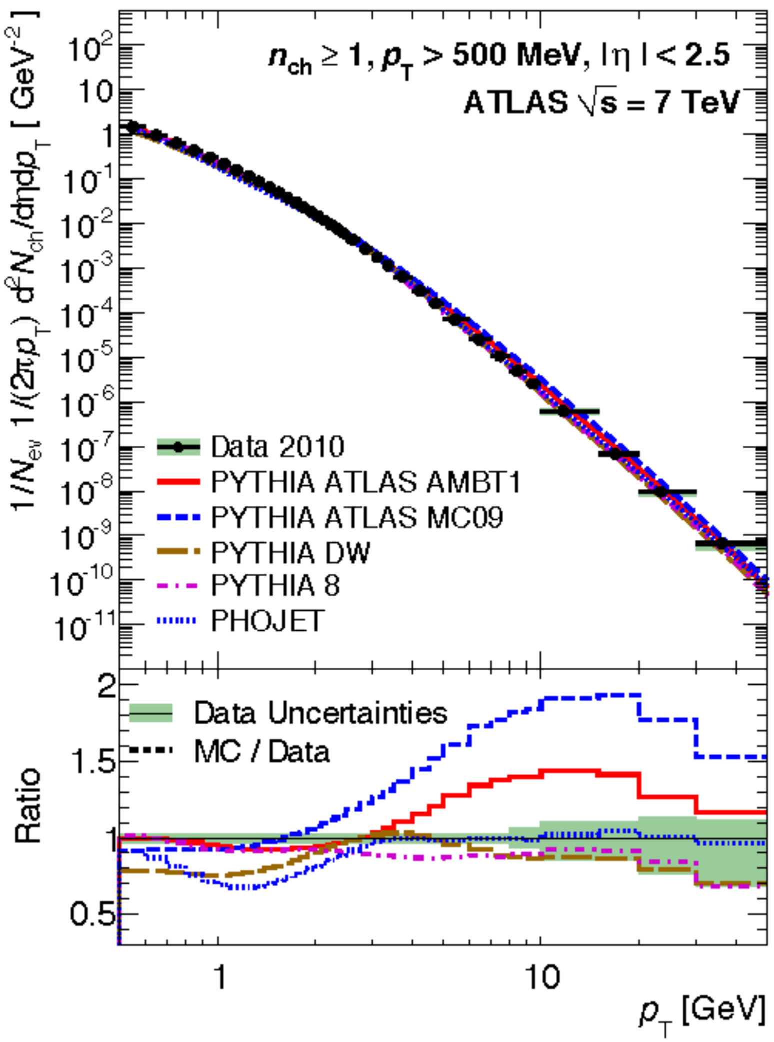
arXiv:1012.5104 v1 [hep-ex] 22 Dec 2010

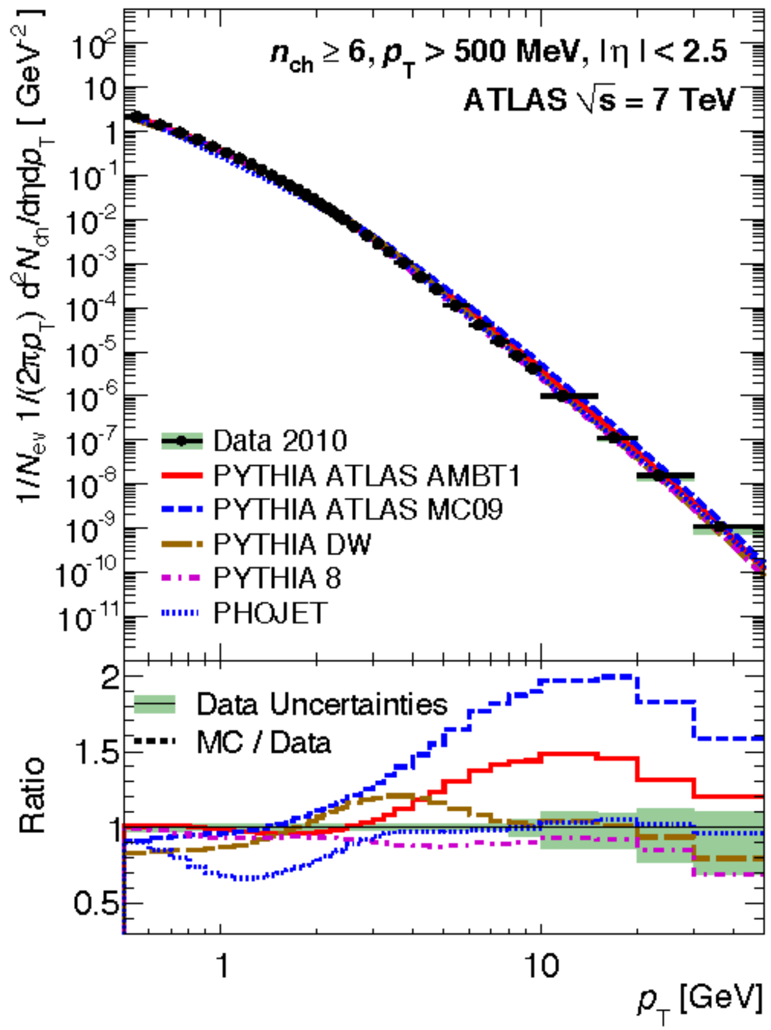




Charged Multiplicity vs P_T

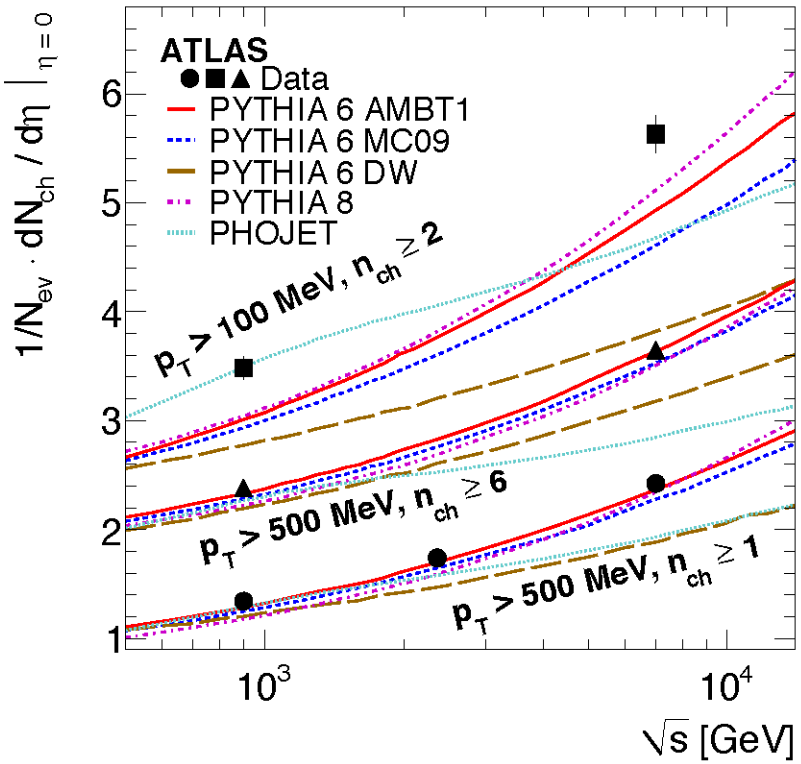
arXiv:1012.5104 v1 [hep-ex] 22 Dec 2010

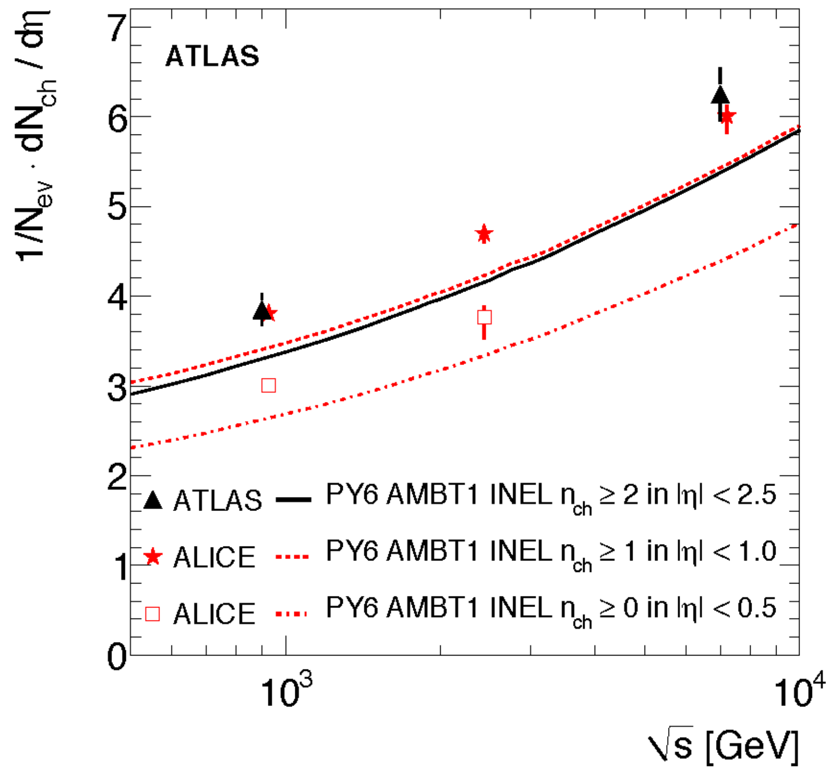




Charged Multiplicity

arXiv:1012.5104 v1 [hep-ex] 22 Dec 2010

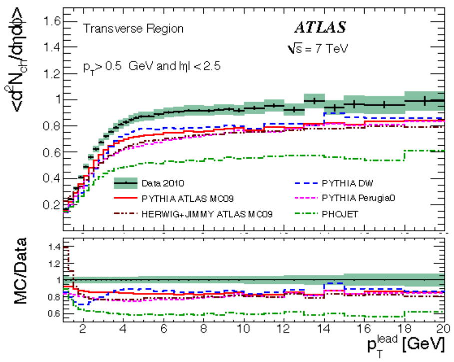


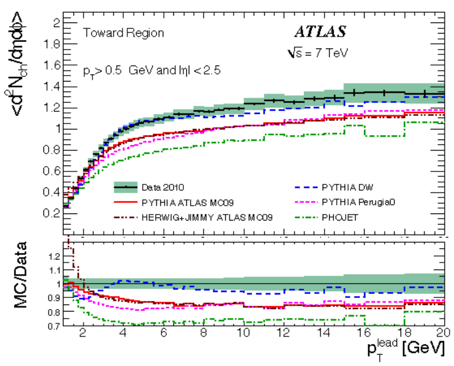


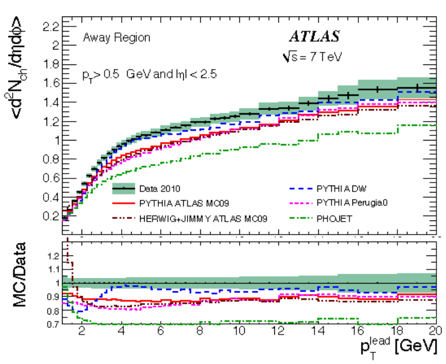
Charged Particles

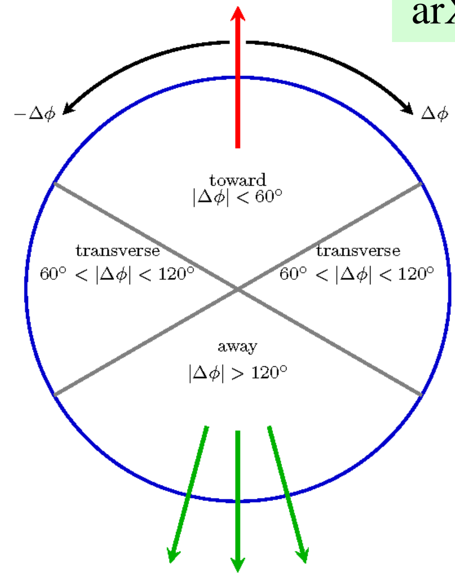
arXiv:1012.0791v1 [hep-ex] 3 Dec 2010

Multiplicity vs P_T



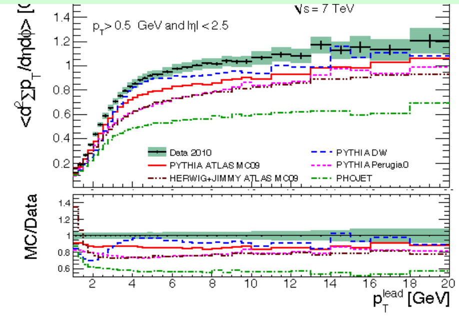


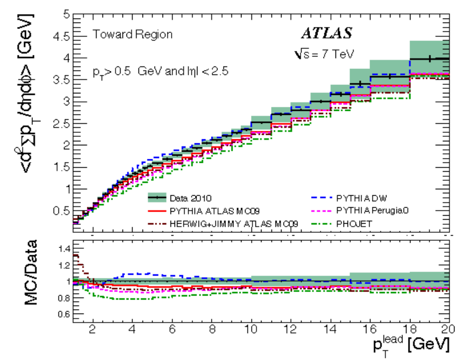


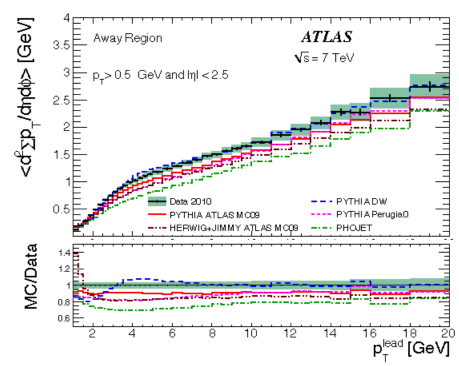


Study underlying event characteristics using particles transverse to leading track

Sum P_T vs P_T



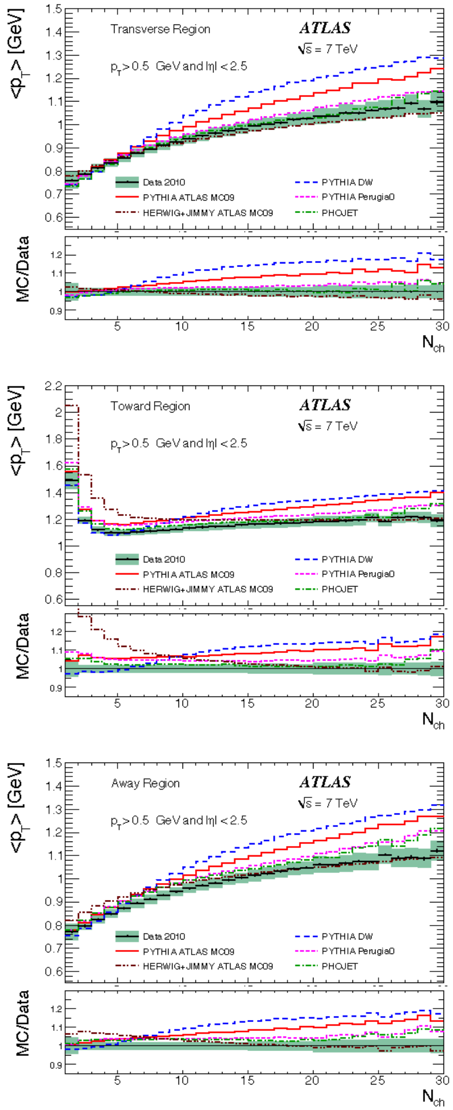




Charged Particles

arXiv:1012.0791v1 [hep-ex] 3 Dec 2010

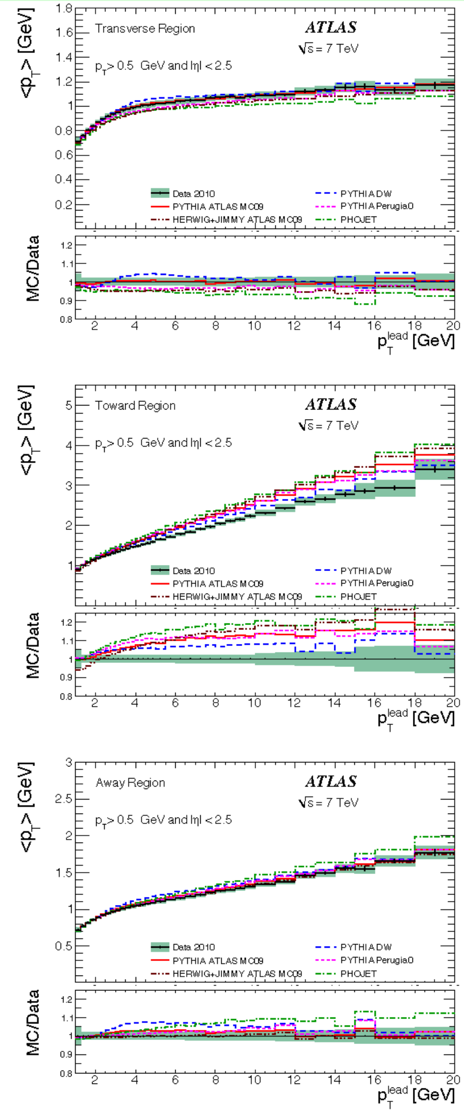
Mean vs Multiplicity



Both ATLAS and CMS have determined best "tunes" for pythia underlying event soft QCD model

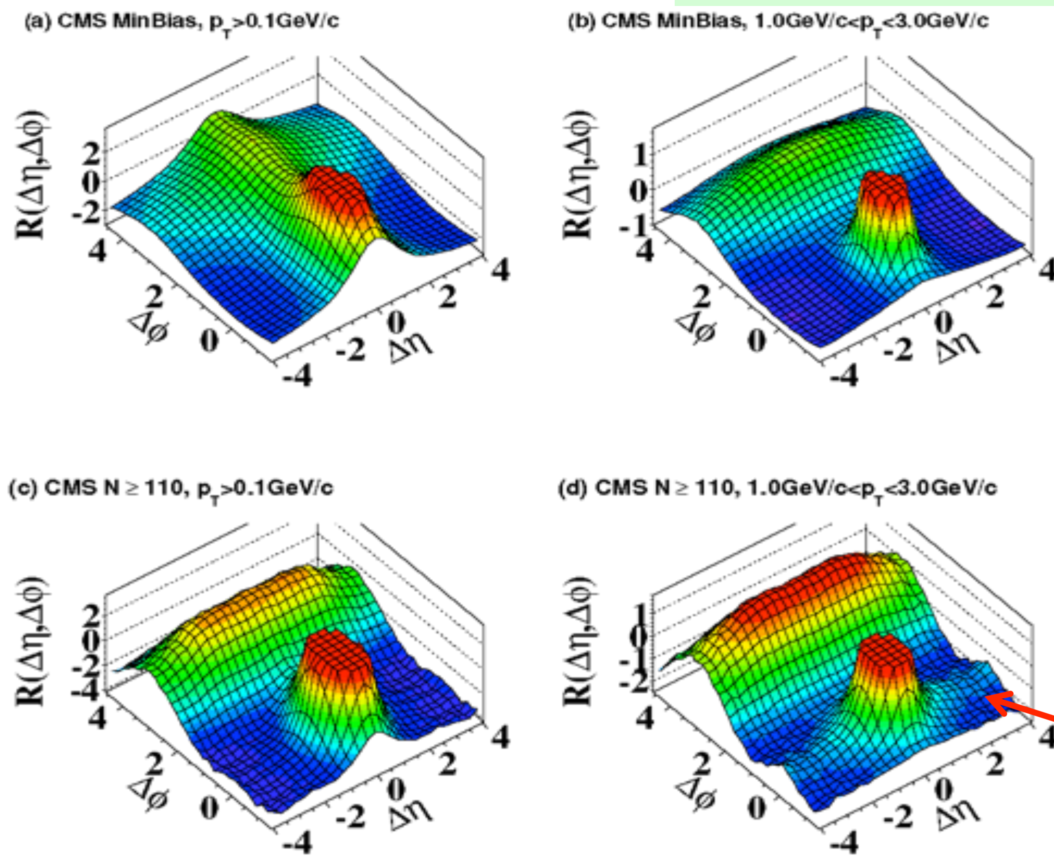
Especially important for data-MC agreement needed for event quantities (MET) and isolation …

Mean P_T vs P_T



Two Particle Correlations

arXiv:1009.4122v1 [hep-ex] 21 Sep 2010

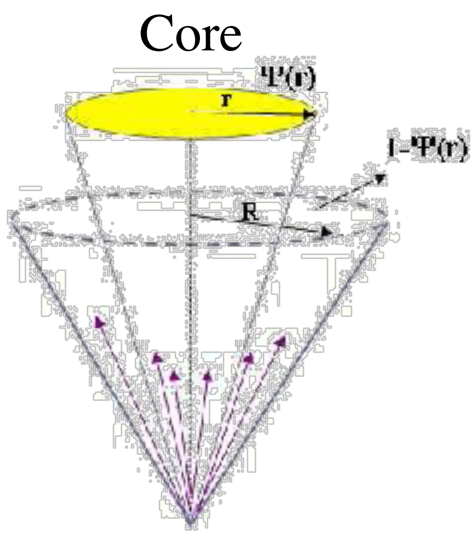


Unexpected correlations seen for high multiplicity events

Figure 7: 2-D two-particle correlation functions for 7 TeV pp (a) minimum bias events with $p_T > 0.1\,\mathrm{GeV}/c$, (b) minimum bias events with $1 < p_T < 3\,\mathrm{GeV}/c$, (c) high multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}} \geq 110$) events with $p_T > 0.1\,\mathrm{GeV}/c$ and (d) high multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}} \geq 110$) events with $1 < p_T < 3\,\mathrm{GeV}/c$. The sharp near-side peak from jet correlations is cut off in order to better illustrate the structure outside that region.

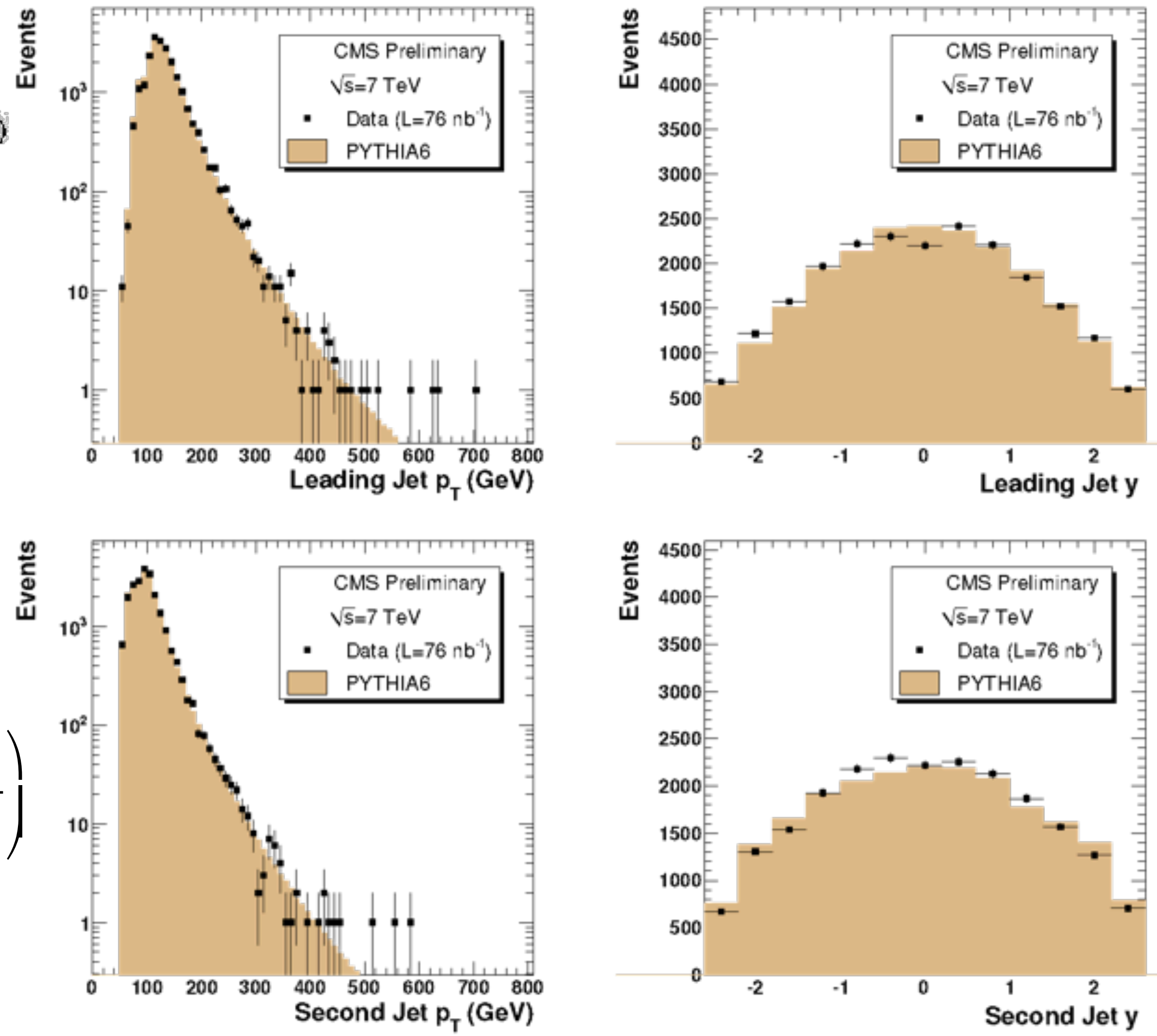
Jet P_T, Rapidity Spectra

CMS PAS QCD-10-012 6 Jul 2010



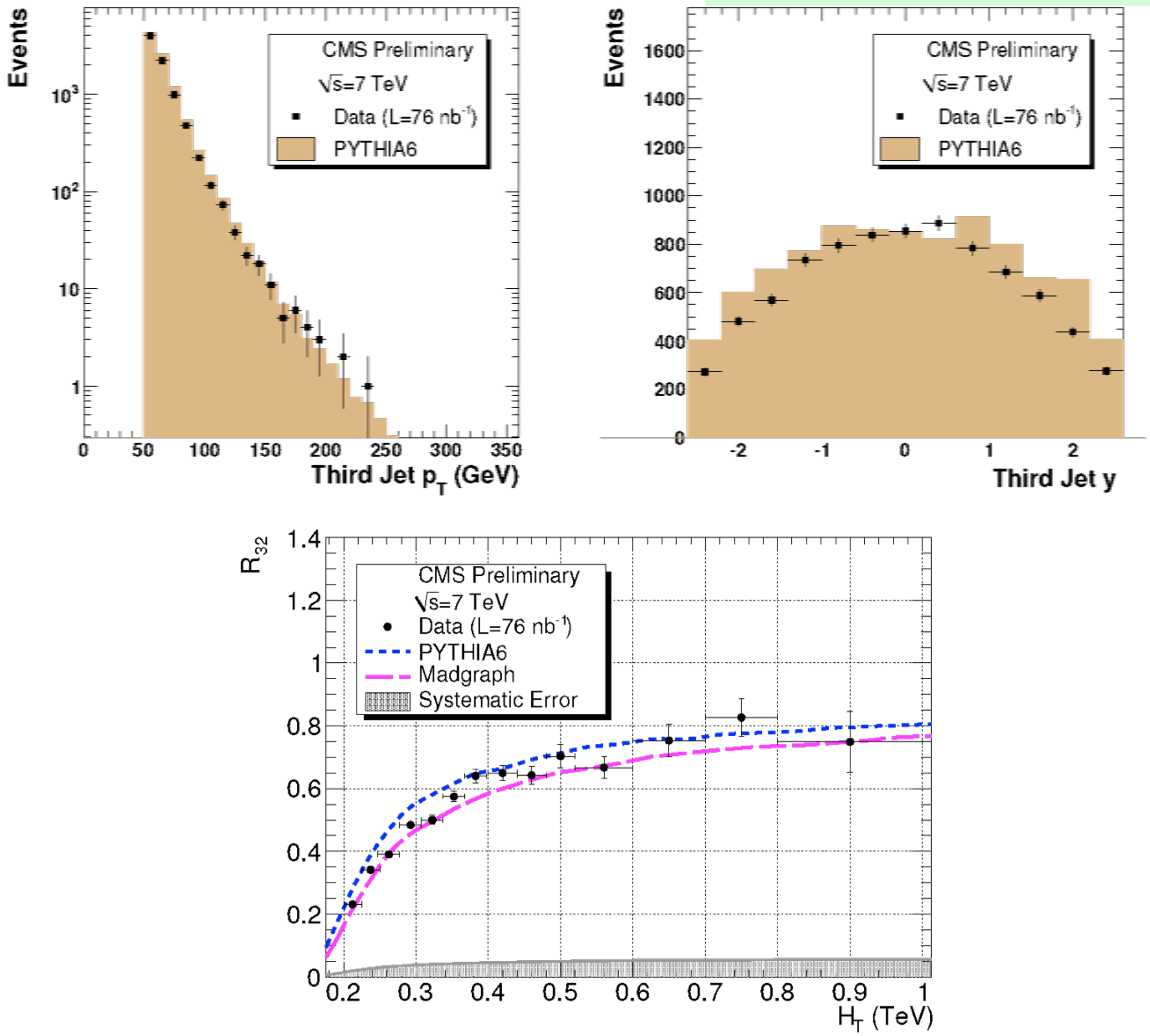
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$$

$$\text{Rapidity}, \; y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$



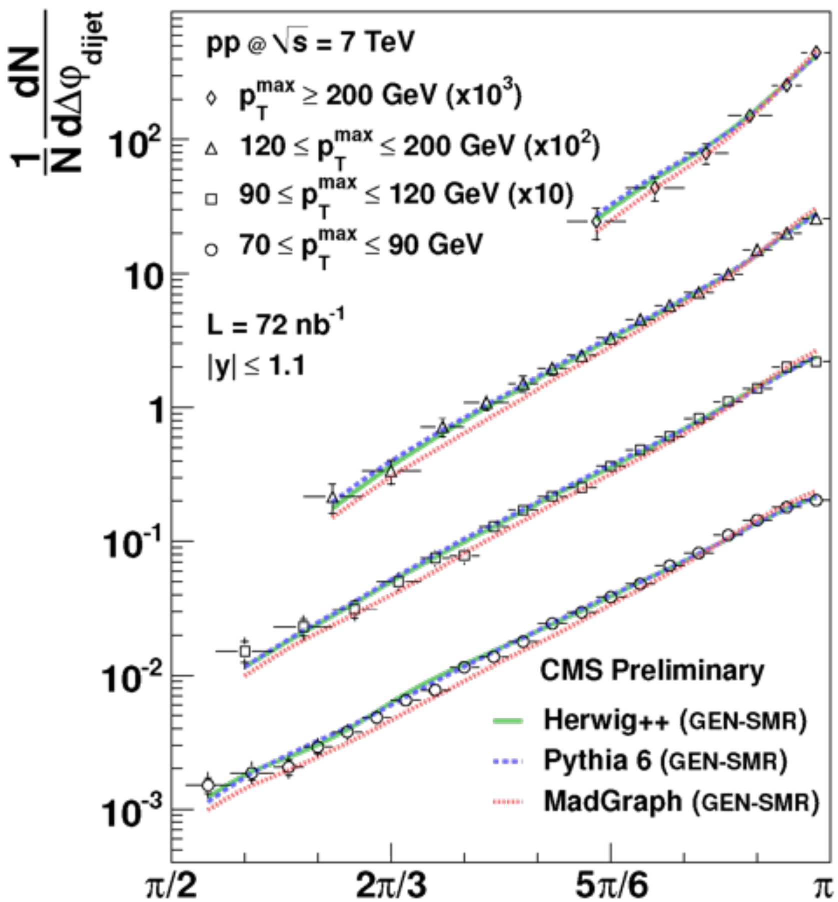
3rd Jet P_T, Rapidity Spectra

CMS PAS QCD-10-012 6 Jul 2010



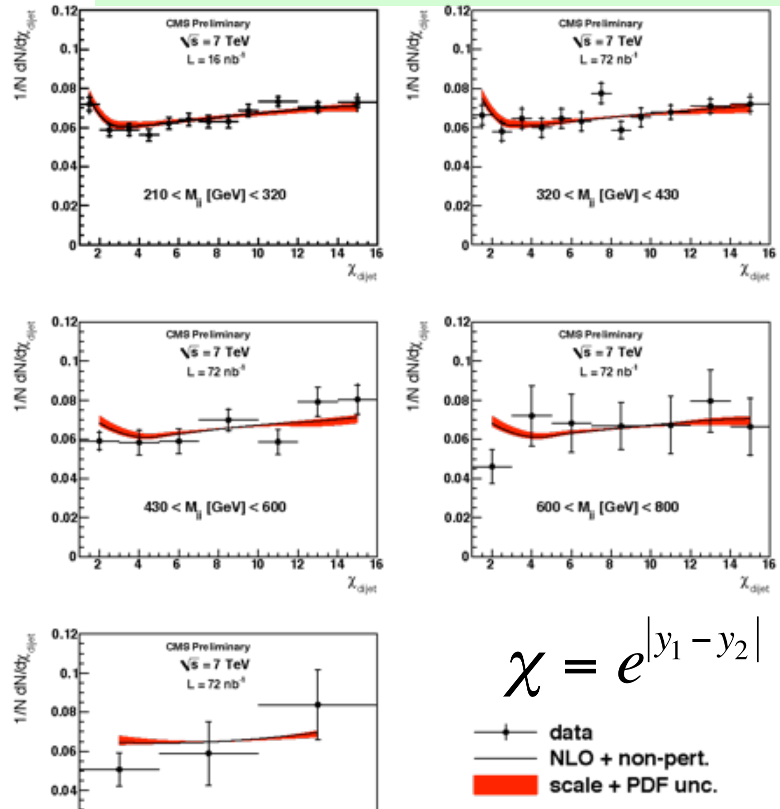
Dijet Angular Correlations

CMS PAS QCD-10-015 20 Jul 2010



Azimuthal Angle

Figure 1: $\Delta\varphi_{dijet}$ distributions in different leading jet p_T^{max} regions. The curves represent predictions from PYTHIA, HERWIG++, and MADGRAPH. Detector resolution effects on jet p_T and position have been included in the MC predictions at the generated particle level (GEN-SMR). The data points include statistical (inner ticks) and systematic uncertainties.



$$\chi = e^{|y_1 - y_2|}$$

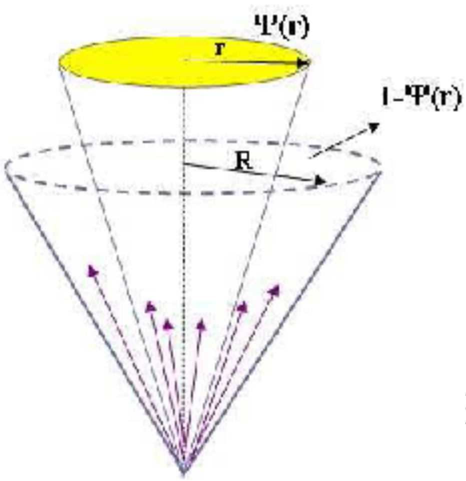
Rapidity

Figure 5: χ_{dijet} distributions in dijet invariant mass regions. The data distributions are compared to NLO QCD predictions including non-perturbative corrections. The data points include statistical (inner ticks) and systematic uncertainties. The theory band includes uncertainties from factorization and renormalization scale variations and the CTEQ6.6 PDF uncertainties.

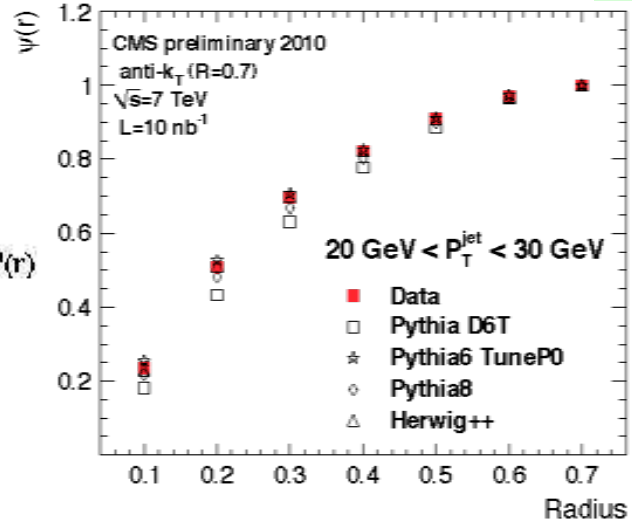
Jet Structure

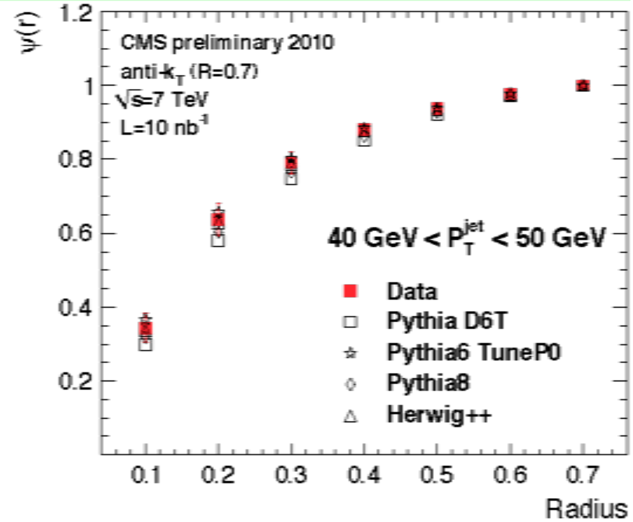
CMS PAS QCD-10-014 20 Jul 2010

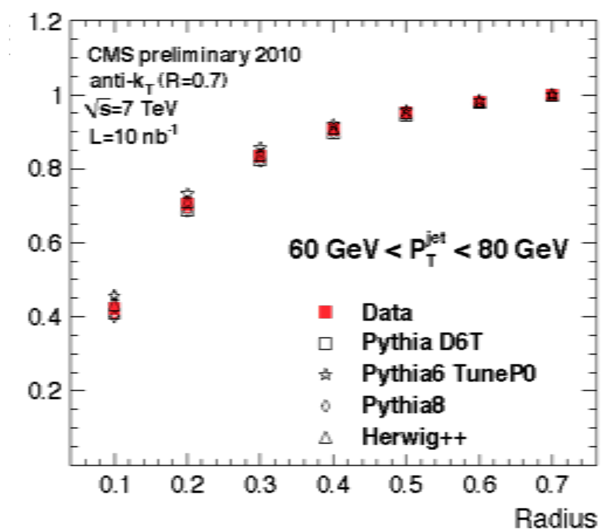
Core

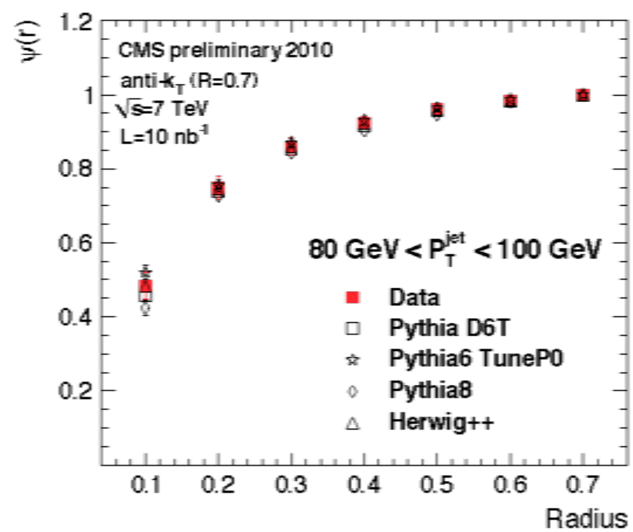


$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$$



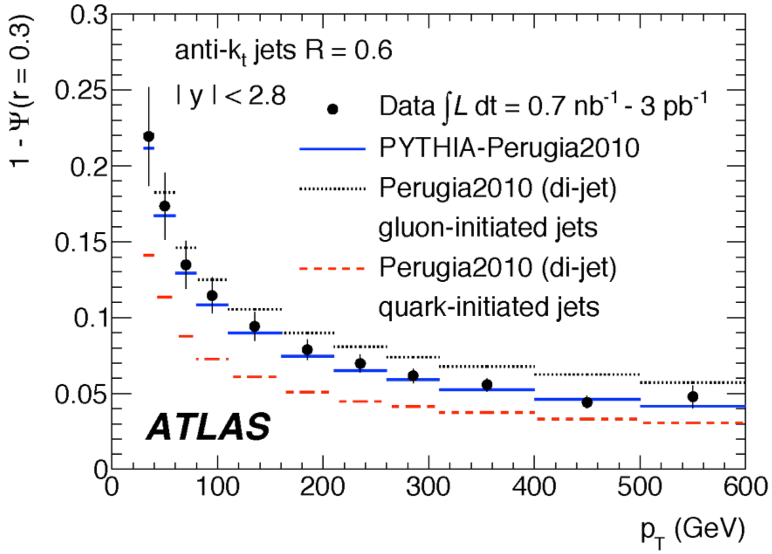


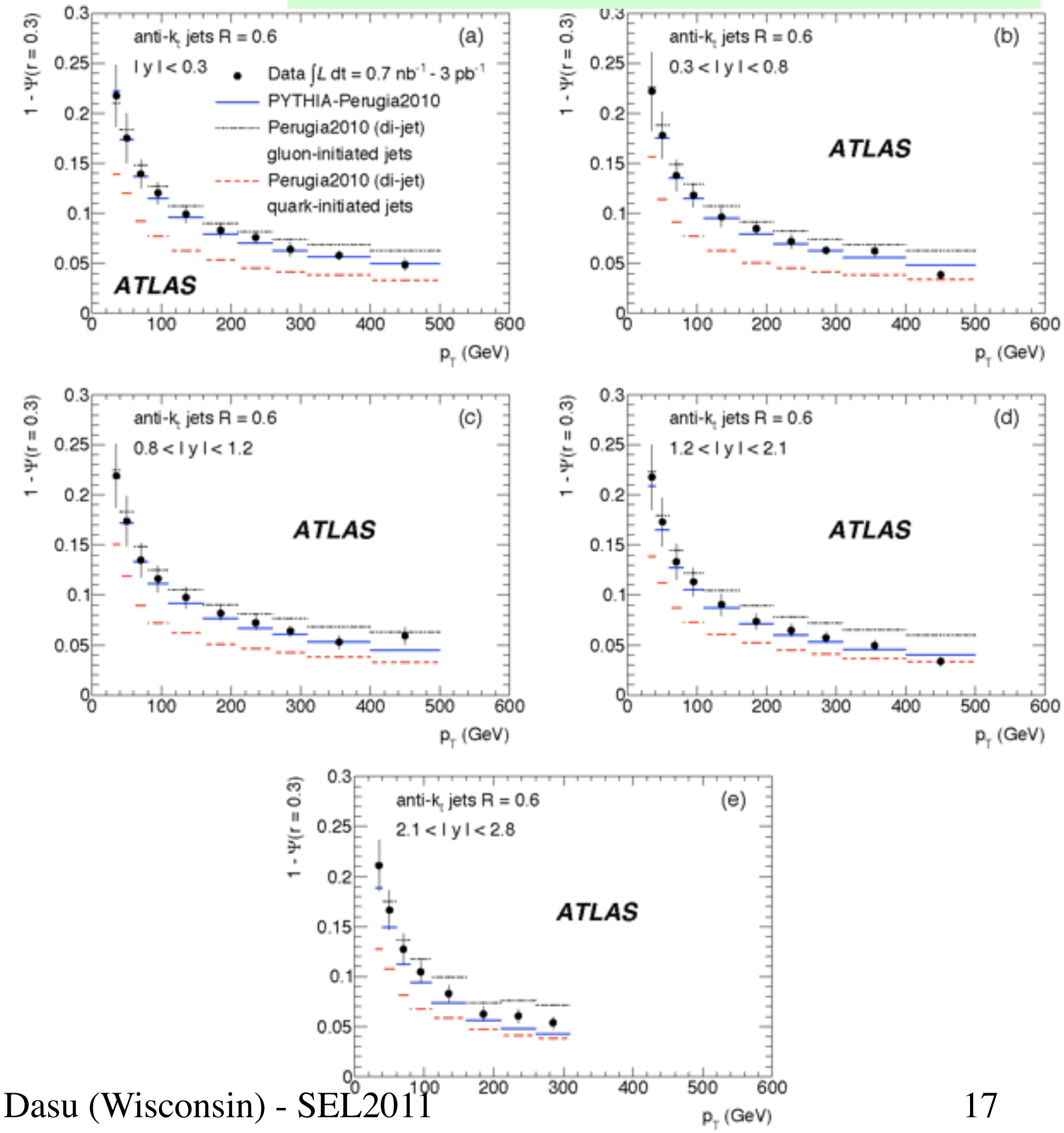




Integrated Shape vs P_T

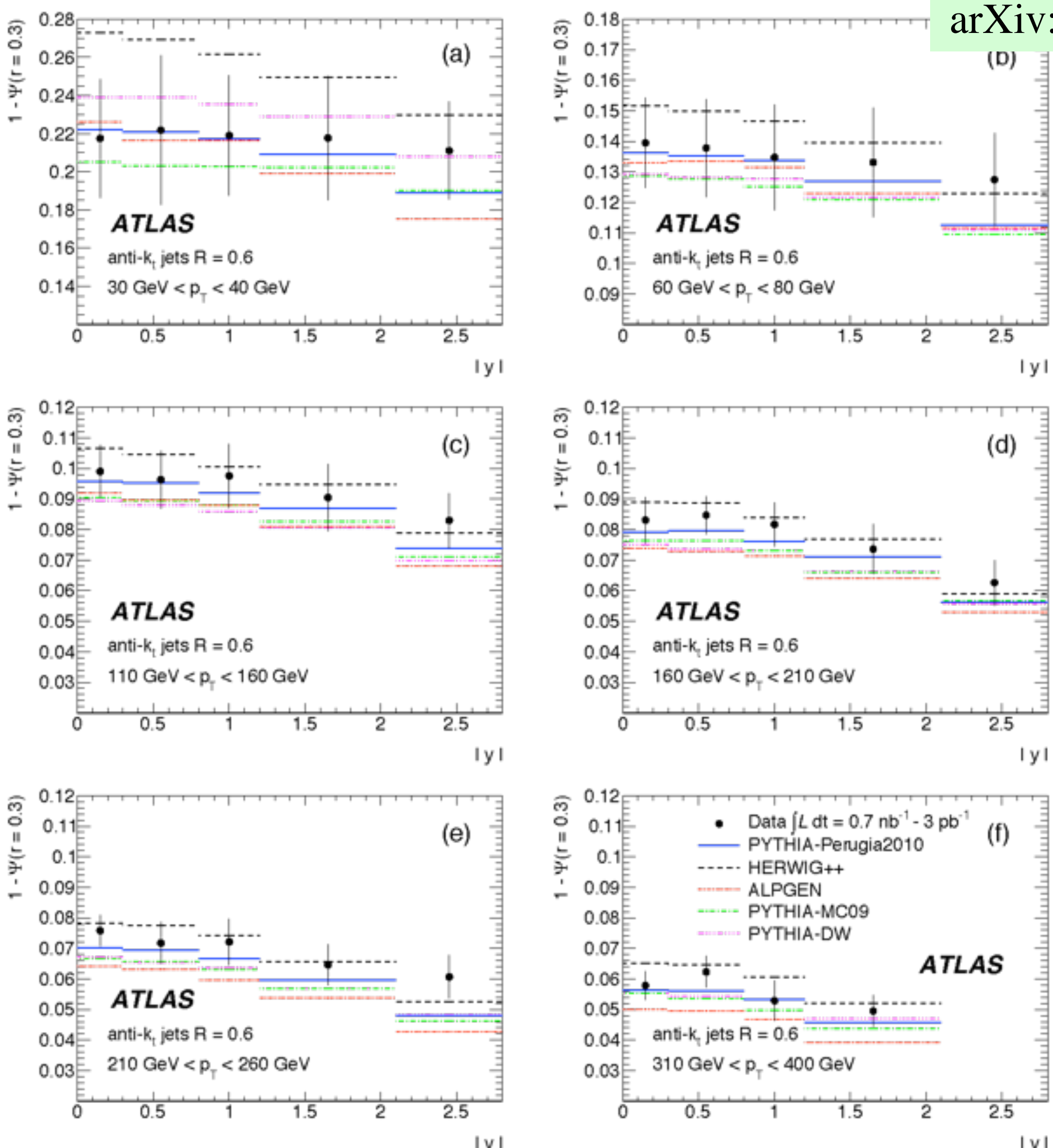
arXiv:1101.0070v1 [hep-ex] 30 Dec 2010





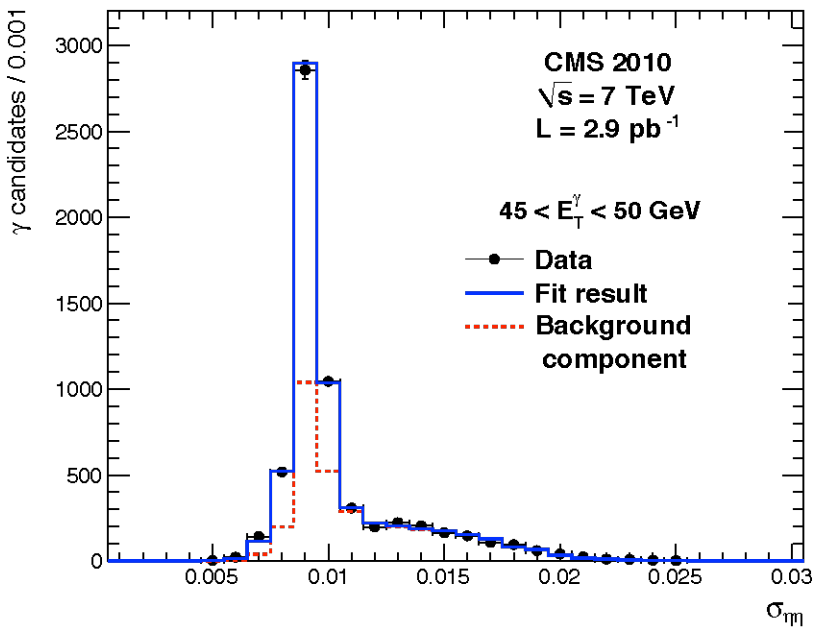
Integrated Shape Comparison

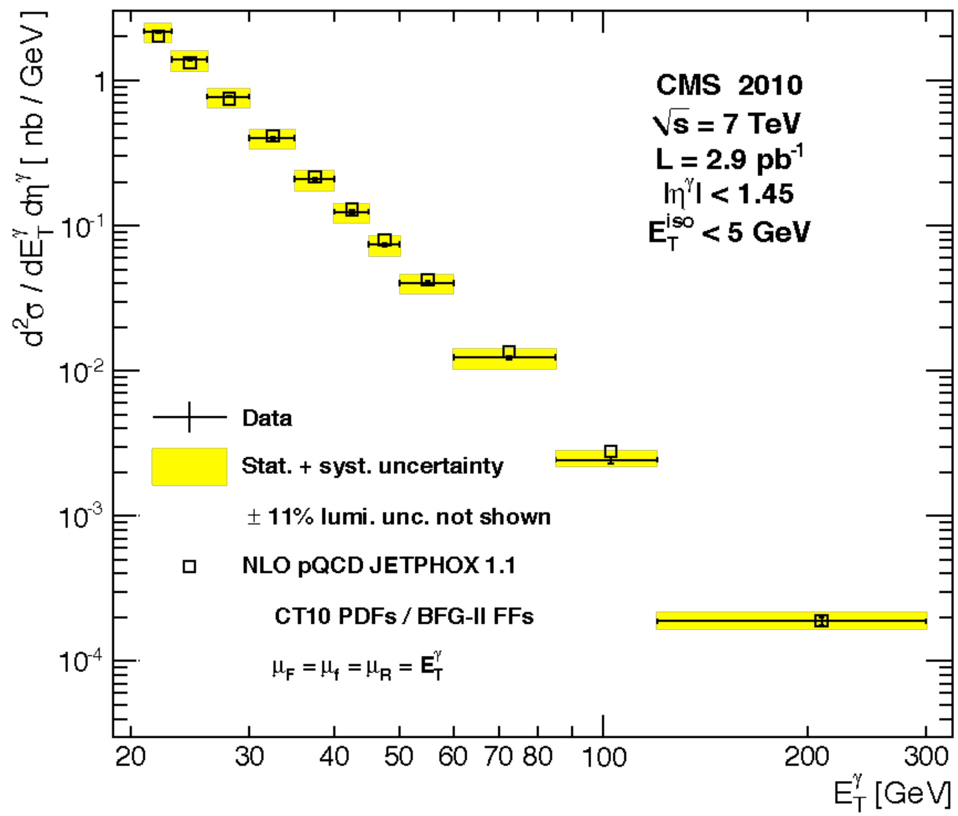
arXiv:1101.0070v1 [hep-ex] 30 Dec 2010



Isolated Photon Spectrum

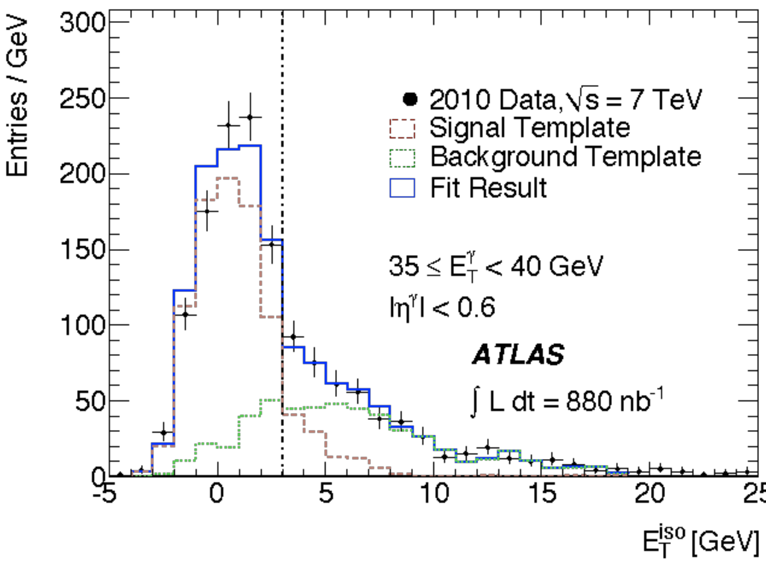
arXiv:1012.0799v1 [hep-ex] 3 Dec 2010

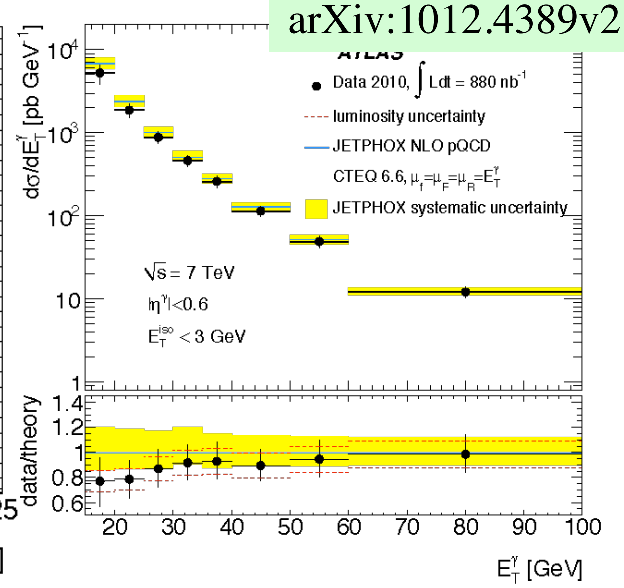


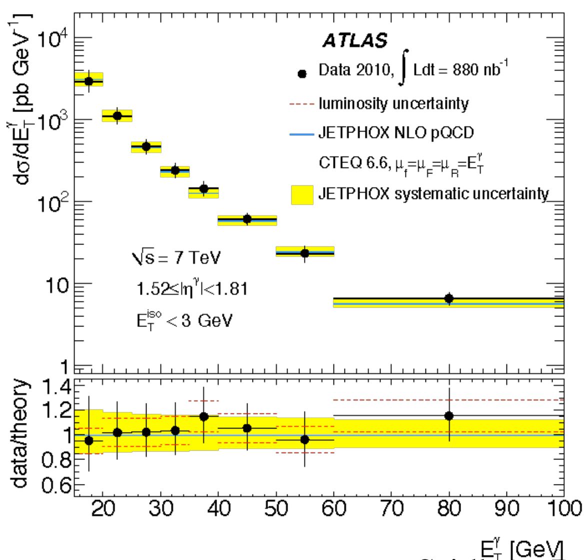


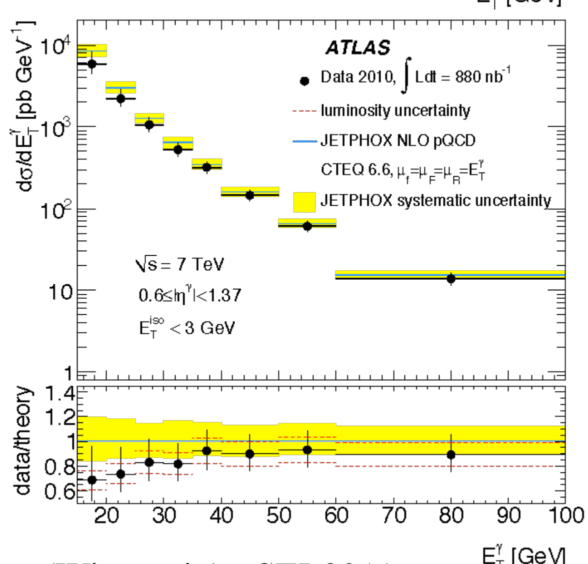
Isolated Photon Spectra

arXiv:1012.4389v2 [hep-ex] 21 Dec 2010

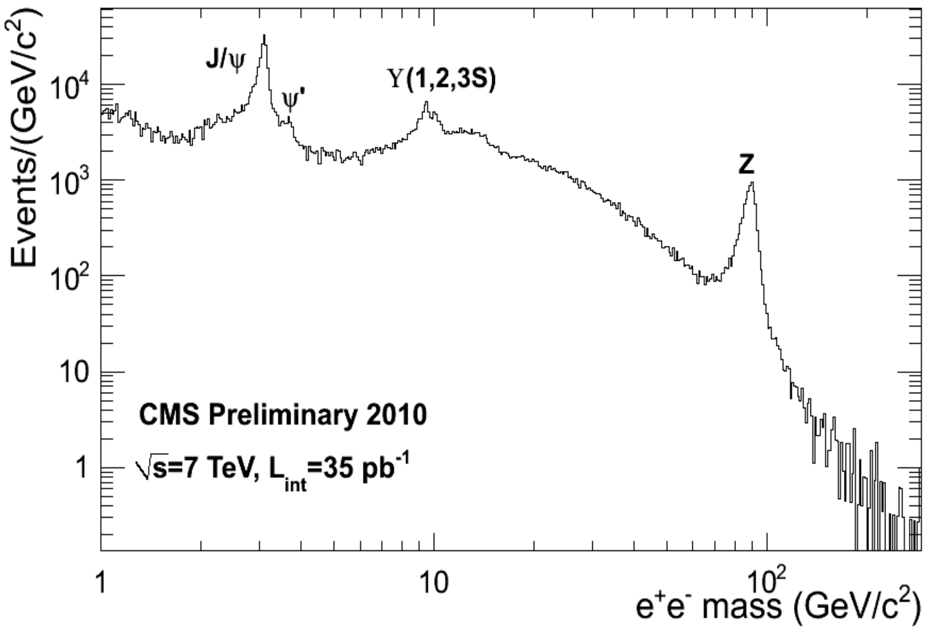


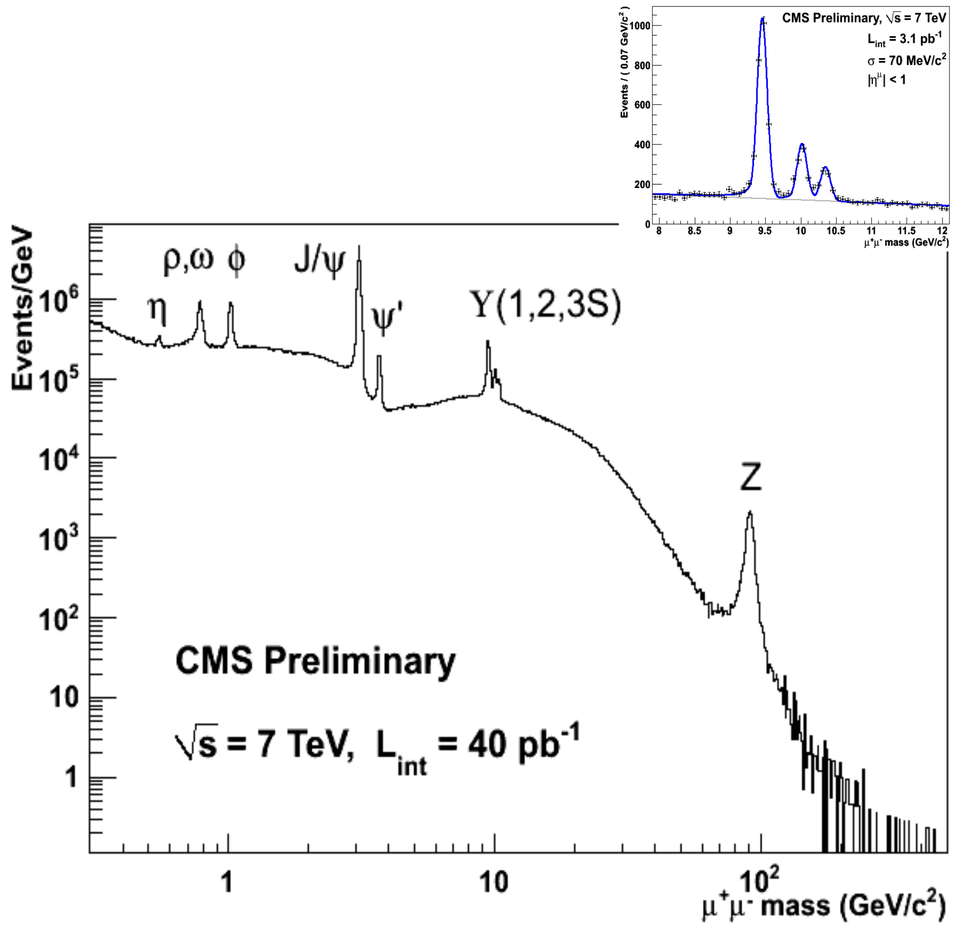






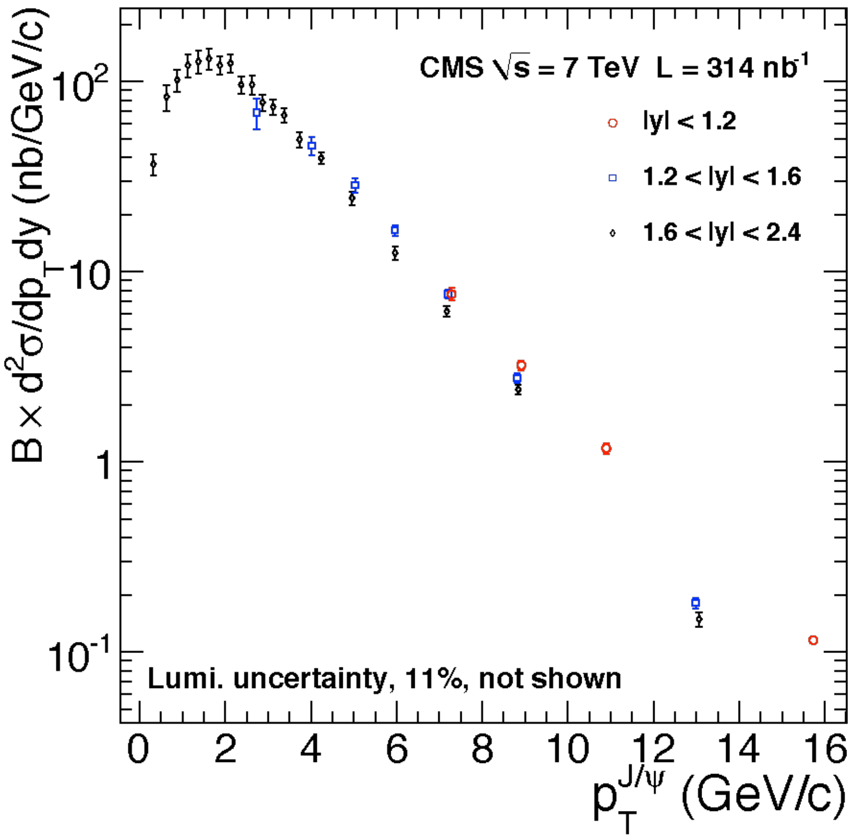
Resonances at 7 TeV

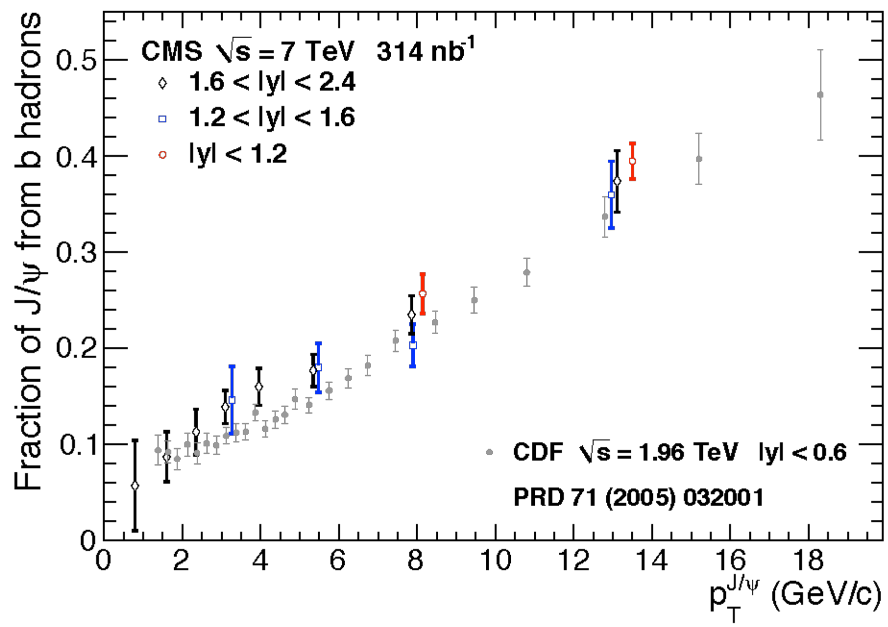




J/Ψ Production

arXiv:1011.4193v1 [hep-ex] 18 Nov 2010



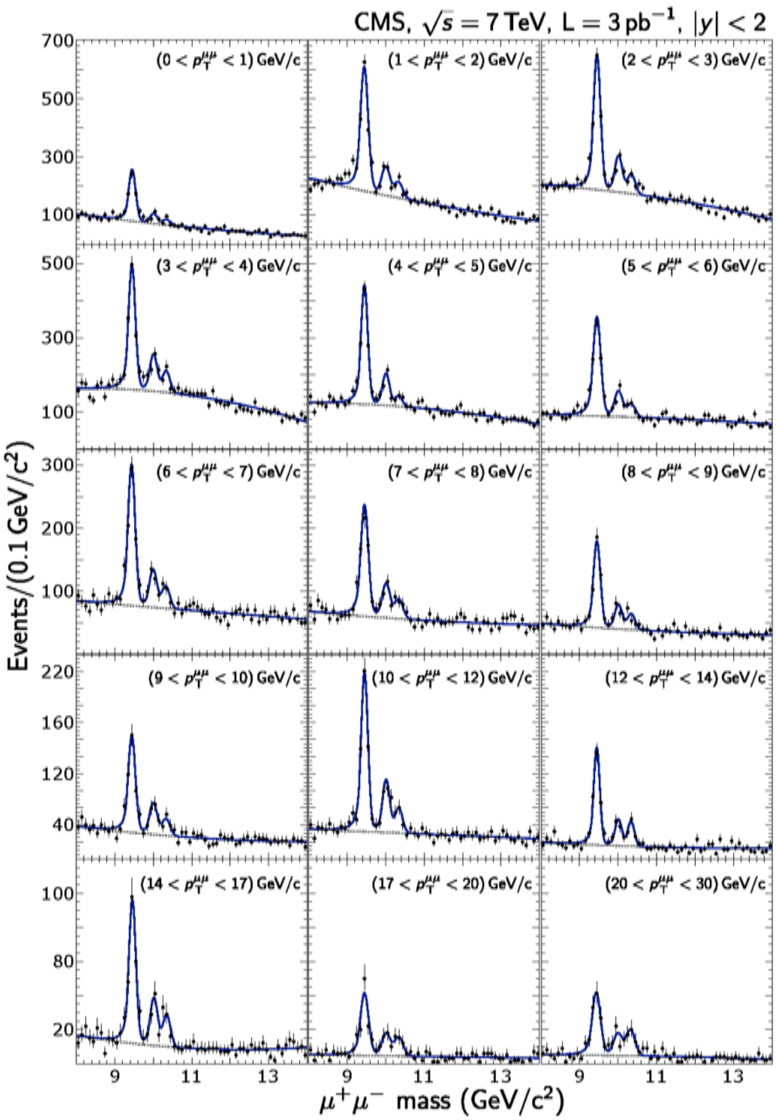


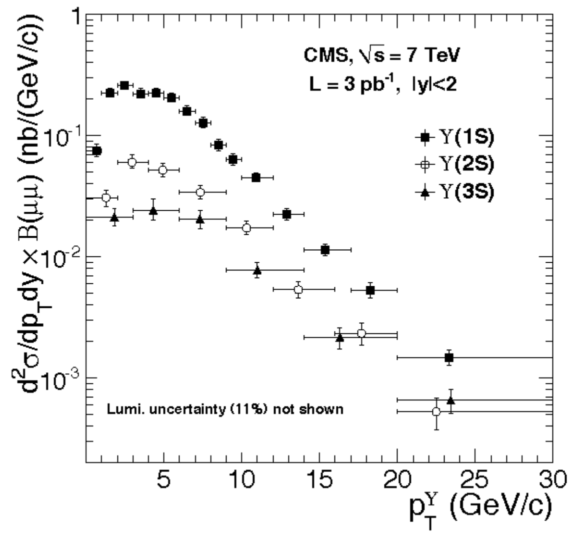
$$\sigma(pp \to \Psi X) \bullet \mathrm{BR}(\Psi \to \mu^+\mu^-) = 70.9 \pm 2.1 \pm 3.0 \pm 7.8 \text{ nb}$$

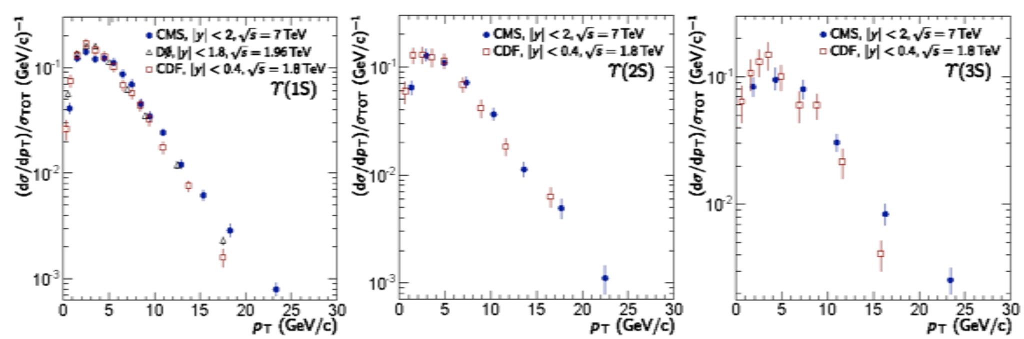
$$\sigma(pp \to bX \to \Psi X) \bullet \mathrm{BR}(\Psi \to \mu^+\mu^-) = 26.0 \pm 1.4 \pm 1.6 \pm 2.9$$

Upsilon Production

arXiv:submit/0170551 [hep-ex] 26 Dec 2010







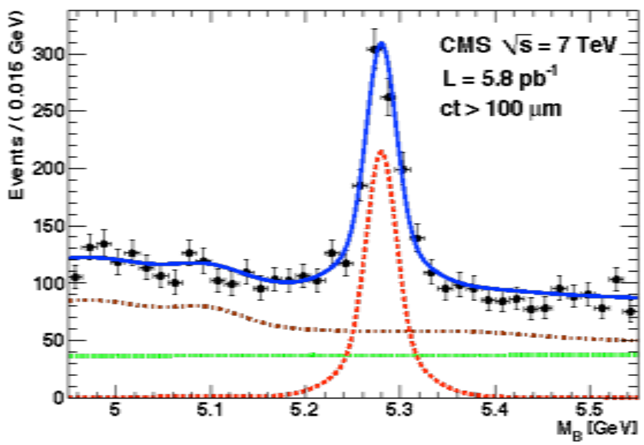
$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 7.37 \pm 0.13(\text{stat.})^{+0.61}_{-0.42}(\text{syst.}) \pm 0.81(\text{lumi.})\,\text{nb},$$

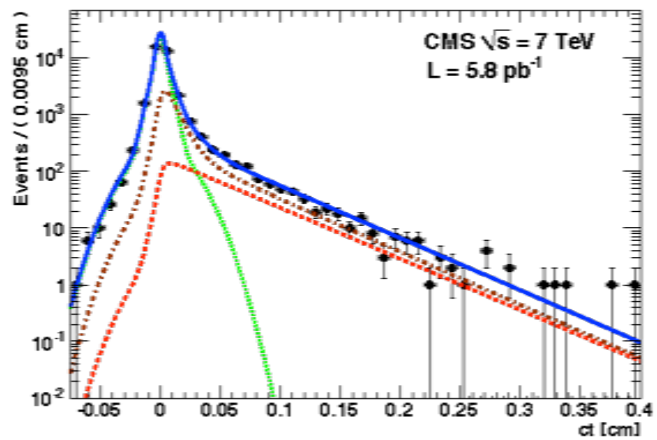
$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 1.90 \pm 0.09(\text{stat.})^{+0.20}_{-0.14}(\text{syst.}) \pm 0.24(\text{lumi.})\,\text{nb}, \quad (7)$$

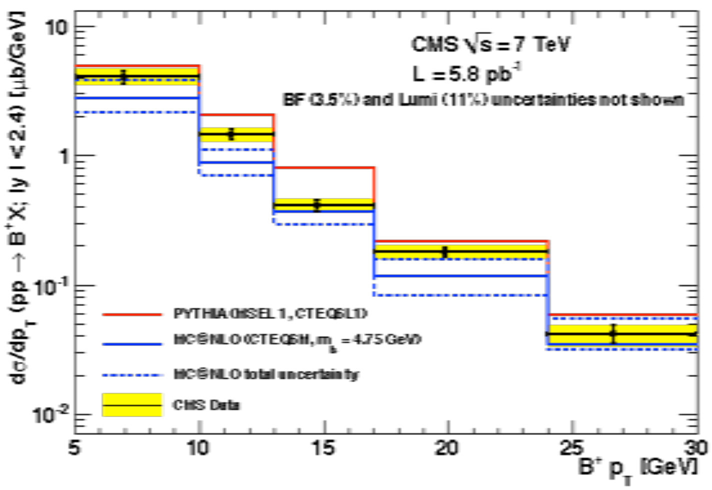
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 1.02 \pm 0.07(\text{stat.})^{+0.11}_{-0.08}(\text{syst.}) \pm 0.11(\text{lumi.})\,\text{nb}. \quad (8)$$

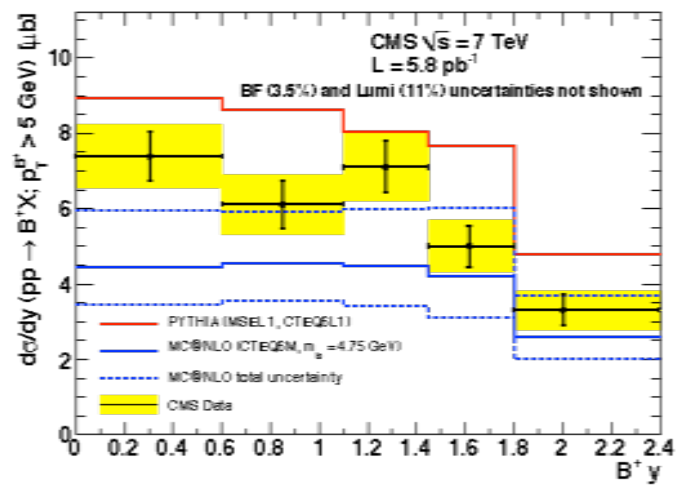
B⁺→ψK Production

arXiv:submit/0172289 [hep-ex] 30 Dec 2010



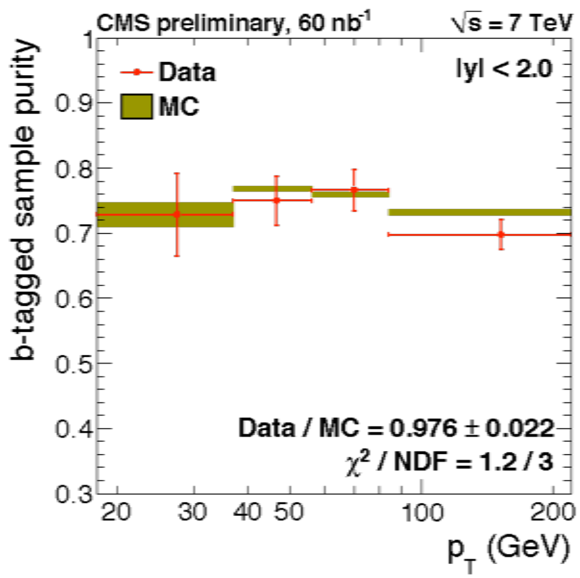


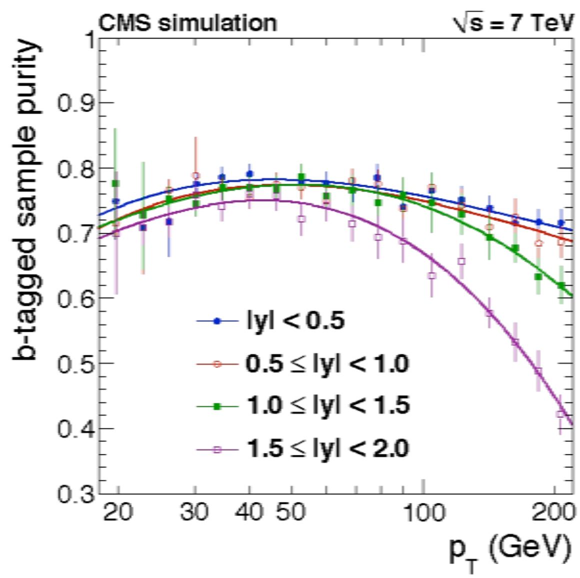


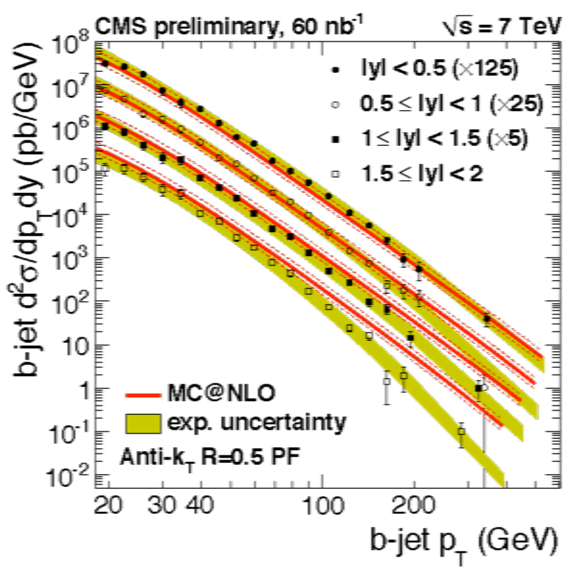


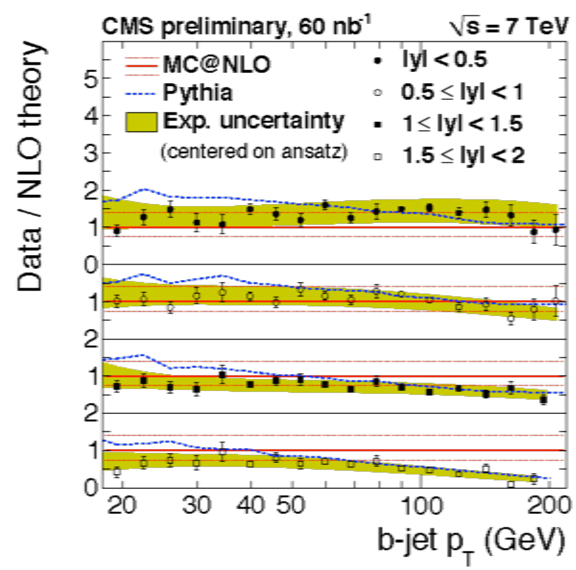
b-Jet Production

CMS PAS BPH-10-009 23 Jul 2010



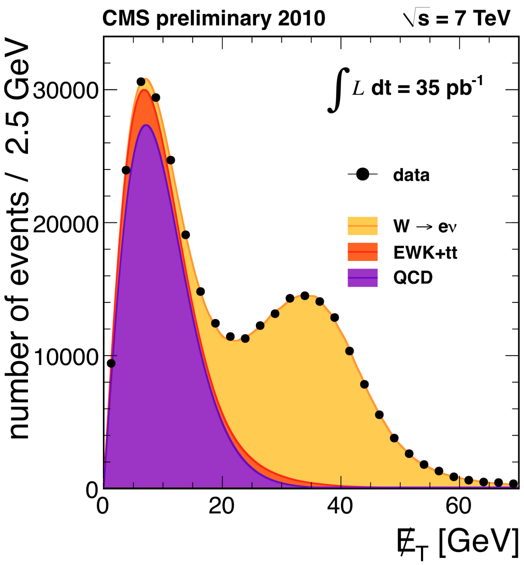


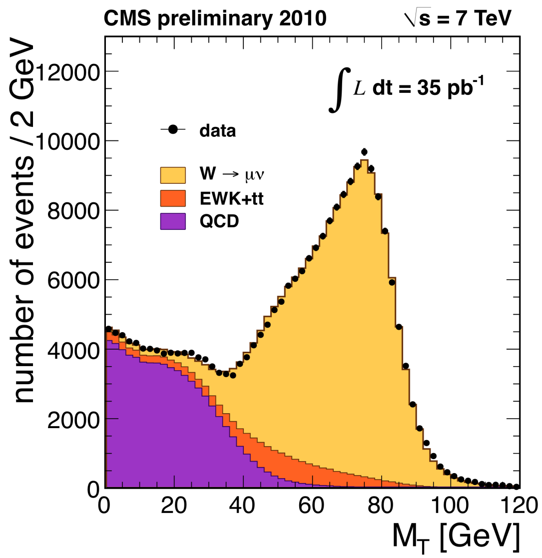




Weak Bosons at 7 TeV

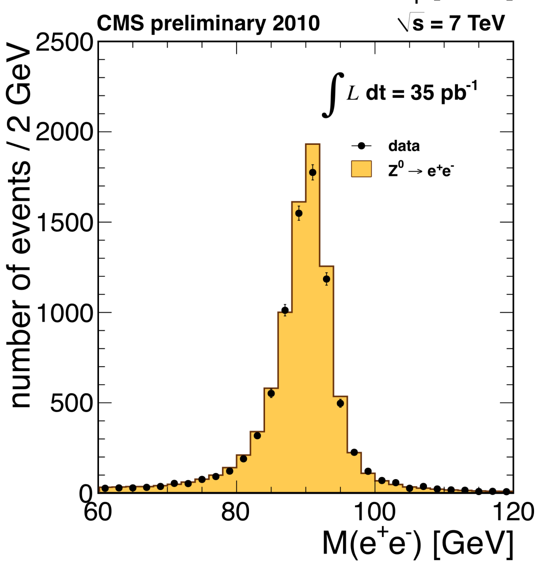
After lepton selection

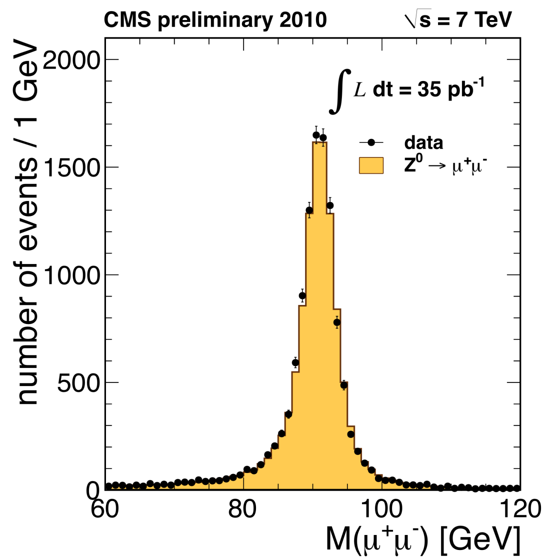


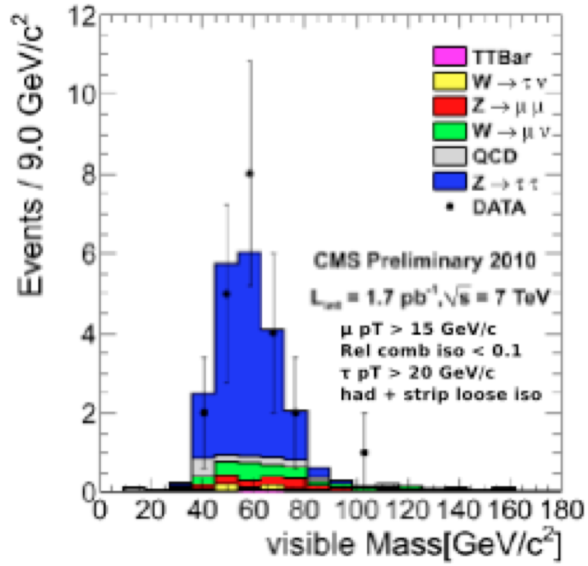


Transverse Mass,

$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1 - \cos\Delta\phi_{e,miss}}$$

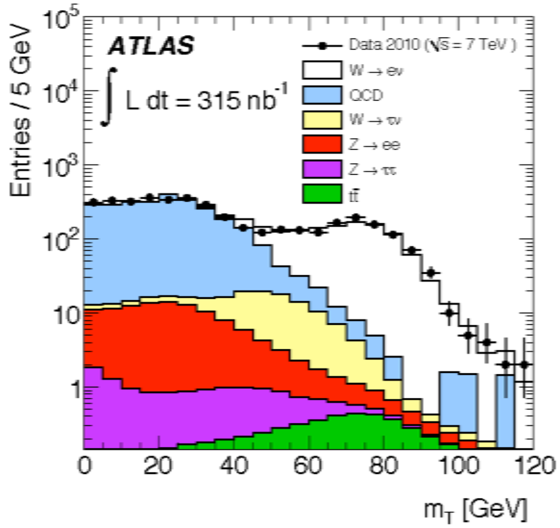


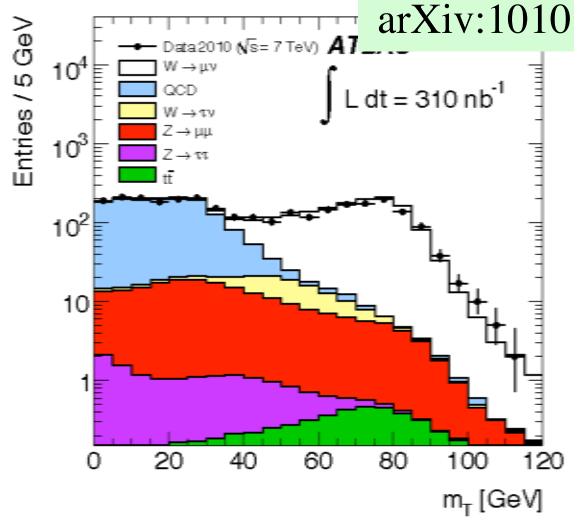


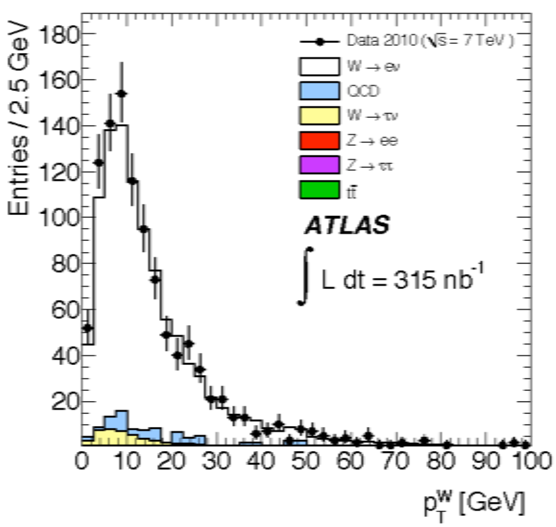


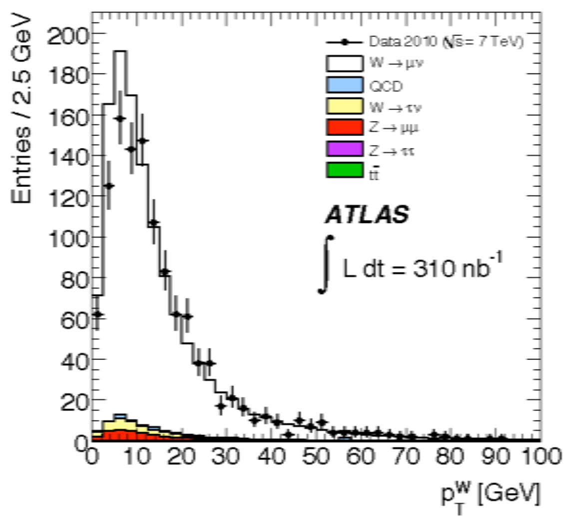
W Signal and P_T Spectrum

arXiv:1010.2130v1 [hep-ex] 11 Oct 2010





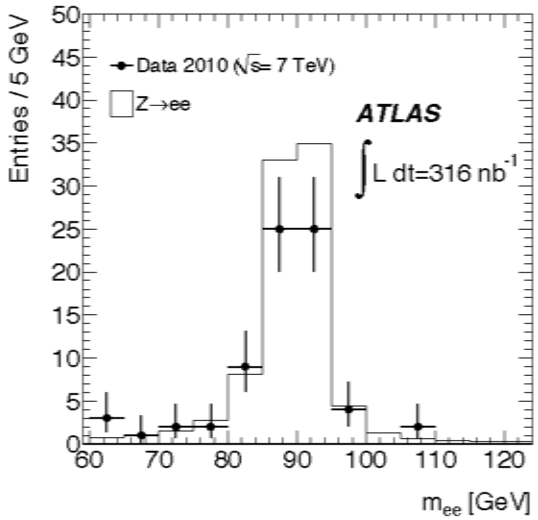


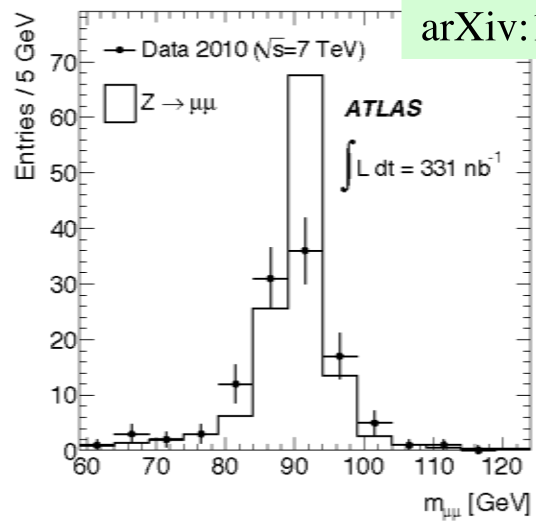


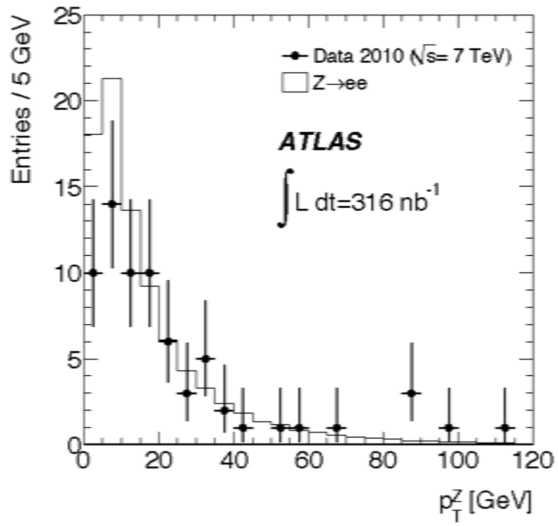
P_T of the boson is a laboratory for understanding soft QCD at low P_T and hard QCD (NLO) at high P_T

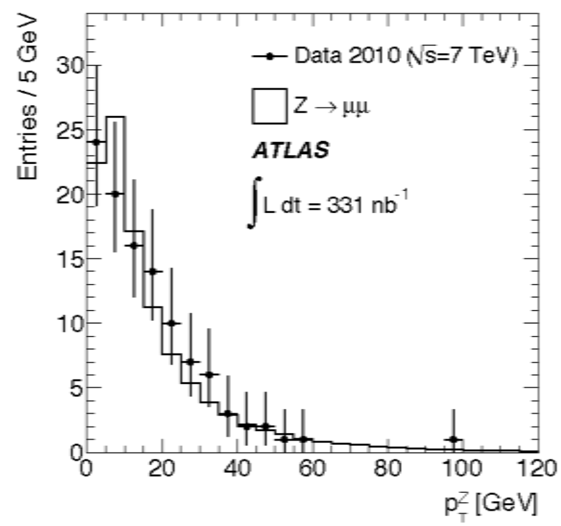
Z Signal and P_T Spectrum

arXiv:1010.2130v1 [hep-ex] 11 Oct 2010





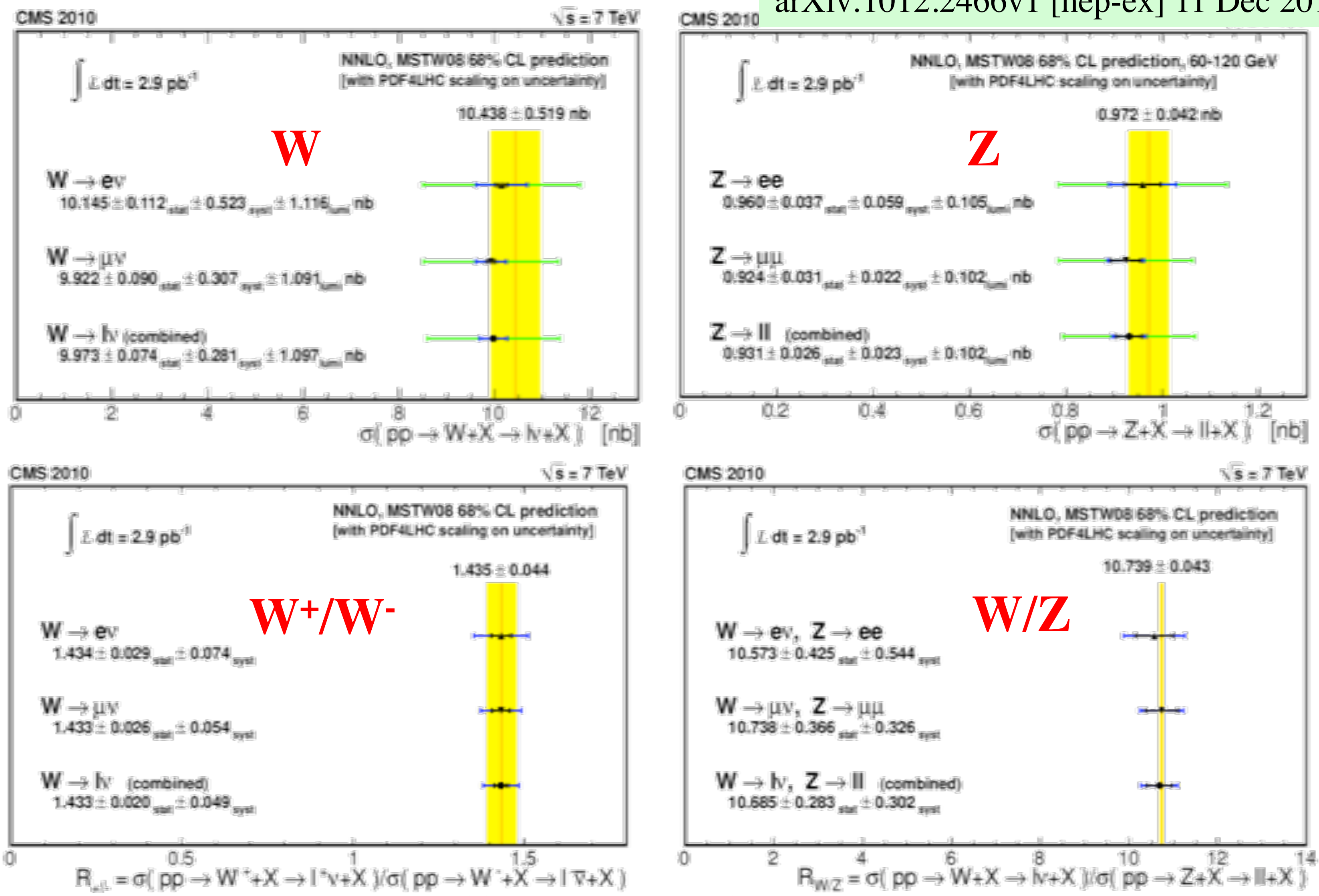




P_T of the boson is a laboratory for understanding soft QCD at low P_T and hard QCD (NLO) at high P_T

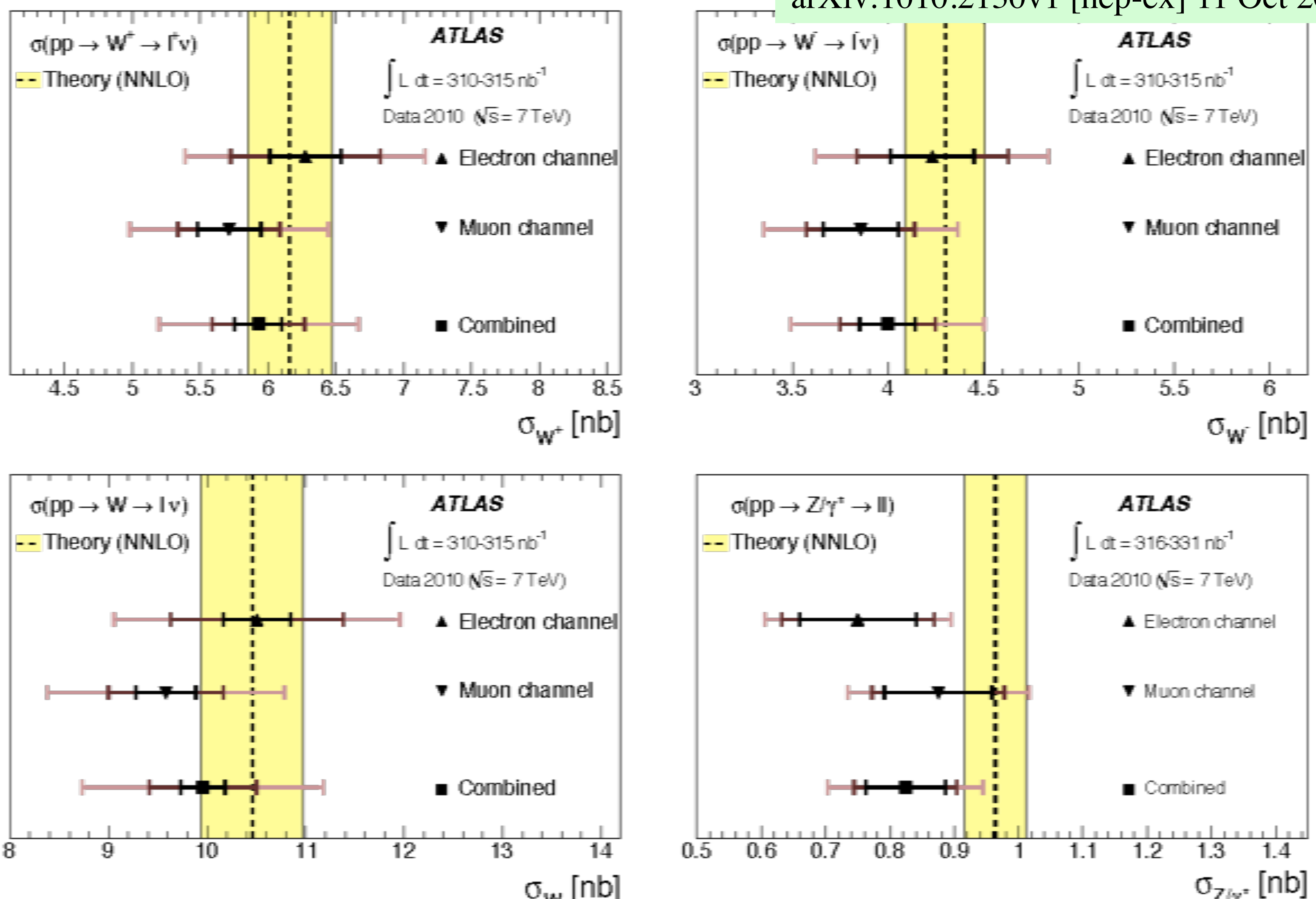
EWK Cross-sections

arXiv:1012.2466v1 [hep-ex] 11 Dec 2010



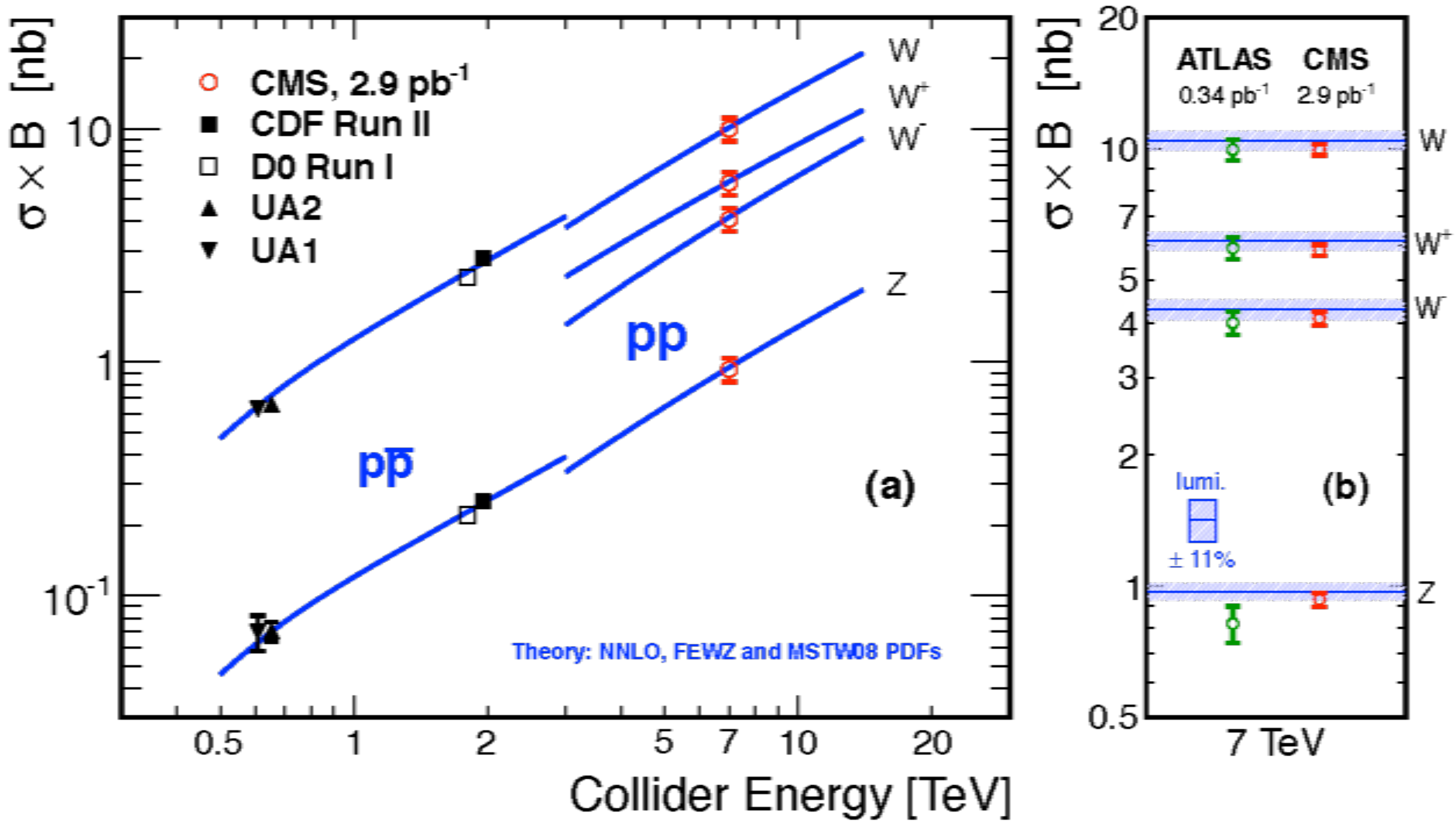
W & Z Cross section

arXiv:1010.2130v1 [hep-ex] 11 Oct 2010



W, Z Cross Section vs √s

arXiv:1012.2466v1 [hep-ex] 11 Dec 2010



Jet production with Ws

CMS PAS EWK-10-001 22 Jul 2010

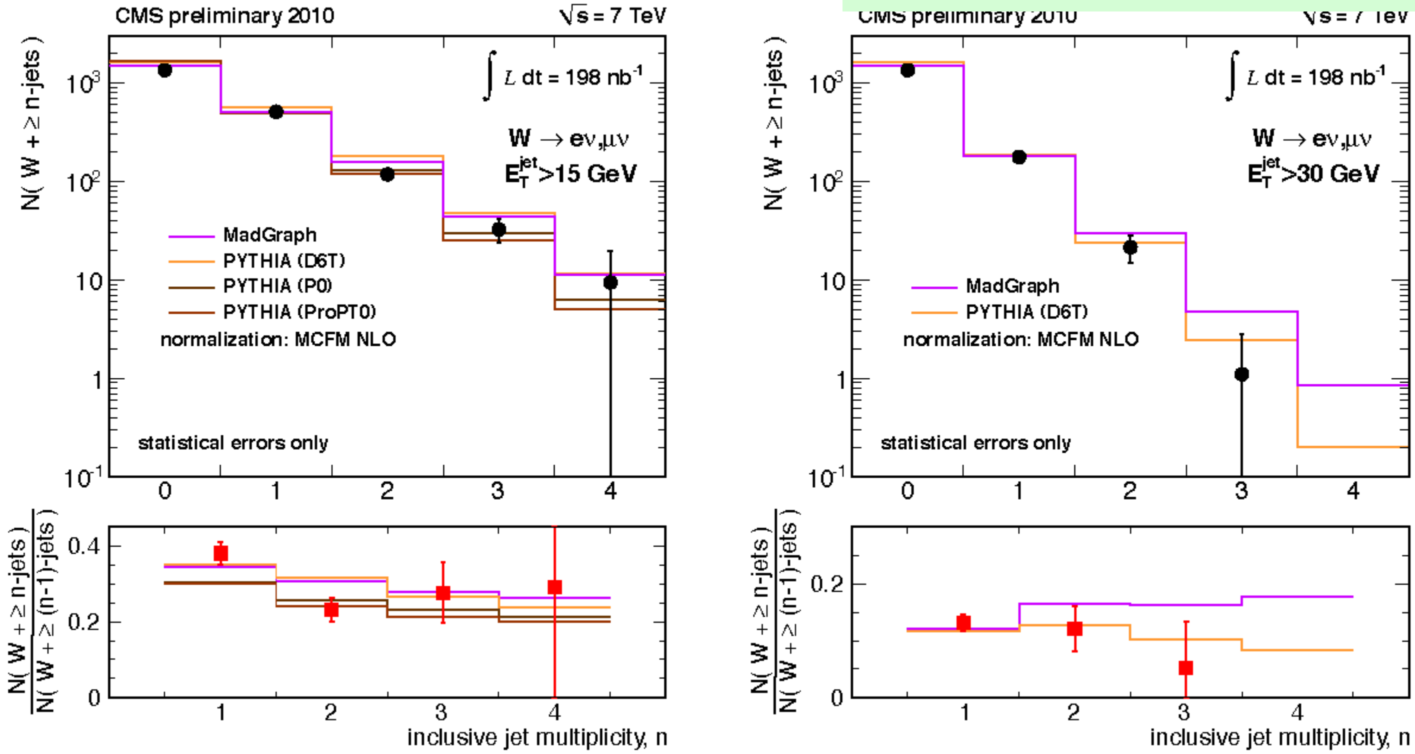
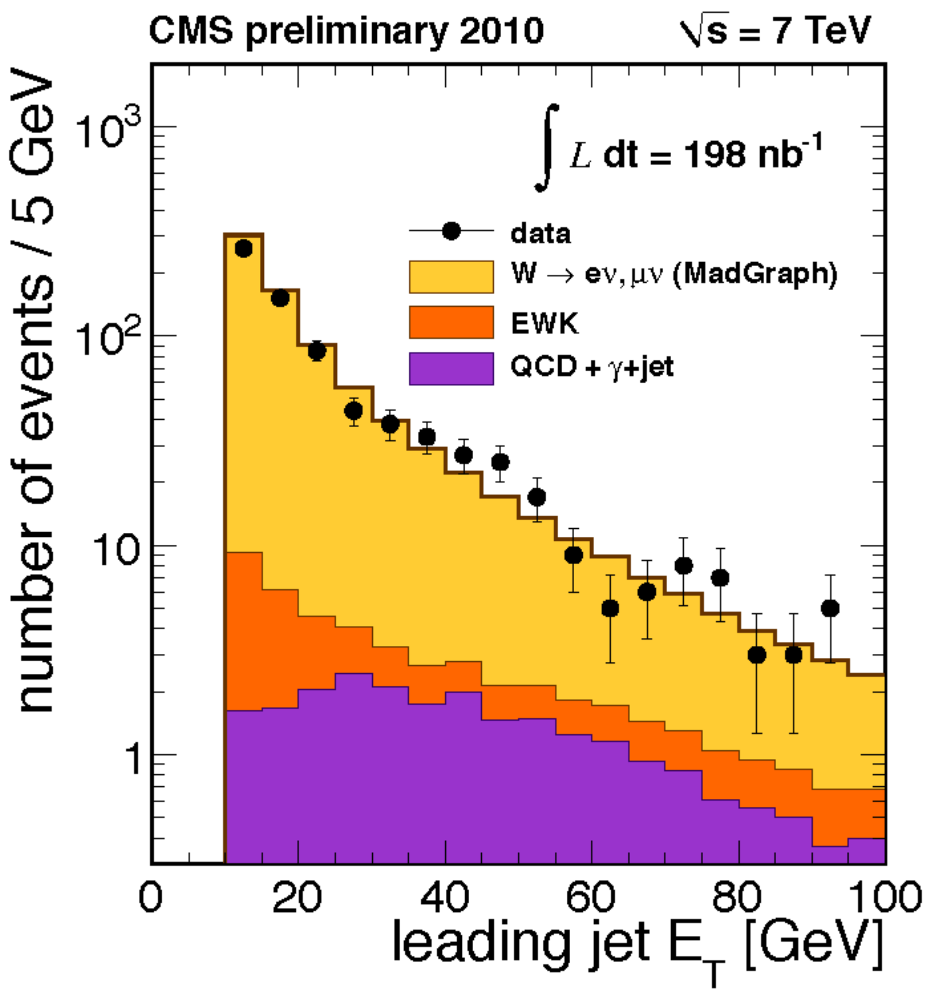


Figure 16: As a function of the inclusive jet multiplicity n, number of $\mathrm{W} \to \ell\nu$ events ($\ell = e, \mu$) containing n jets above threshold or more (top plots) and ratio $N(\mathrm{W} \to \ell\nu, \geq n\,\mathrm{jets})/N(\mathrm{W} \to \ell\nu, \geq (n-1)\,\mathrm{jets})$ (bottom plots). Predictions obtained with PYTHIA (D6T [37]) and MADGRAPH are shown, normalized to the NLO cross section from MCFM. On the left, the jet E_T threshold is 15 GeV; predictions obtained from PYTHIA with different tunes (P0 [38] and ProPT0 [39]) are also shown. On the right, the jet E_T threshold is 30 GeV. The error bars are statistical only.

Leading Jet P_T balancing W

CMS PAS EWK-10-001 22 Jul 2010

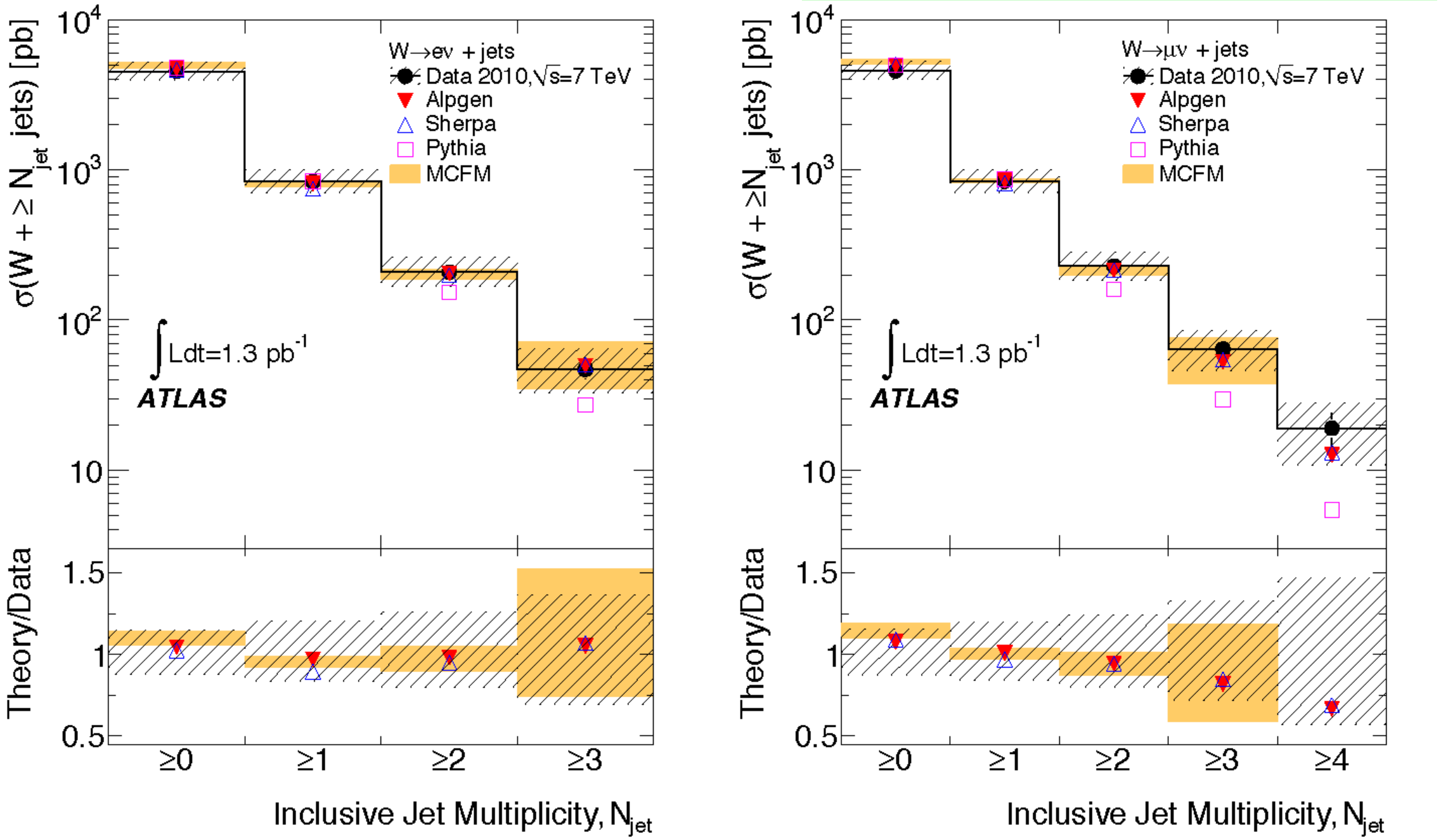


Jets produced in association with vector bosons are primary final-state of many new physics processes.

Important to understand quantitatively the differential production cross sections

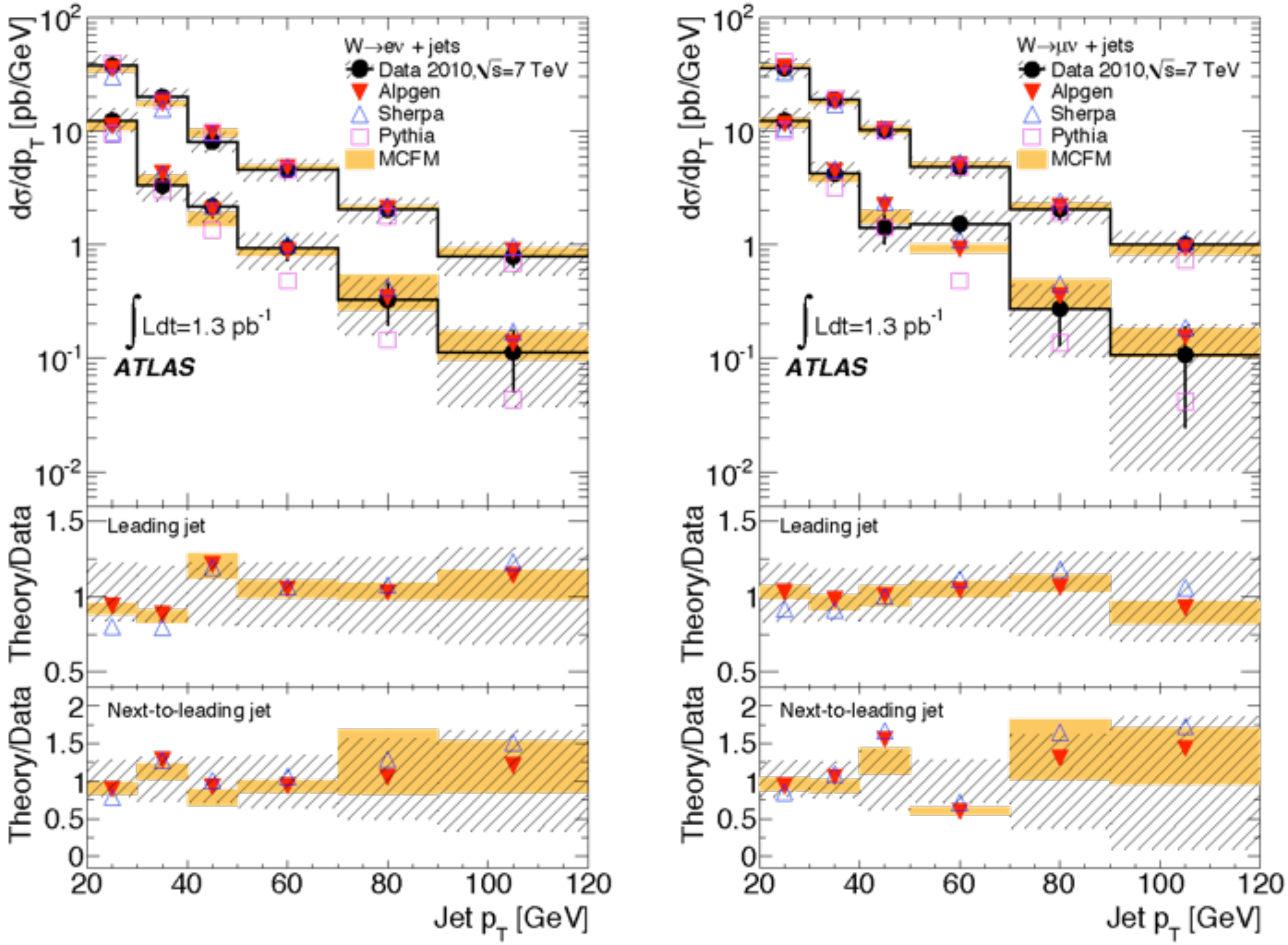
W + Jets Multiplicity

arXiv:1012.5382v1 [hep-ex] 24 Dec 2010



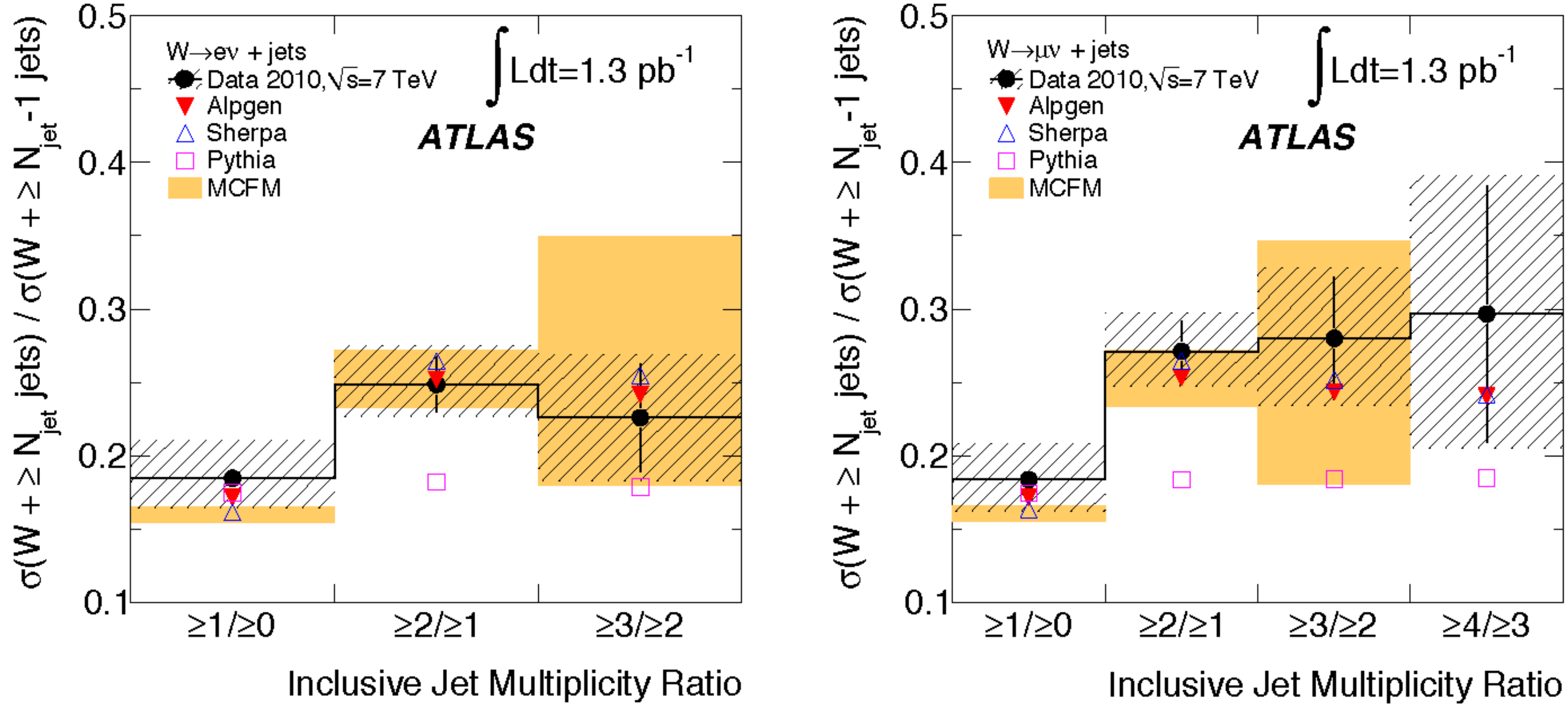
W + Jets P_T

arXiv:1012.5382v1 [hep-ex] 24 Dec 2010



W + Jets Ratio

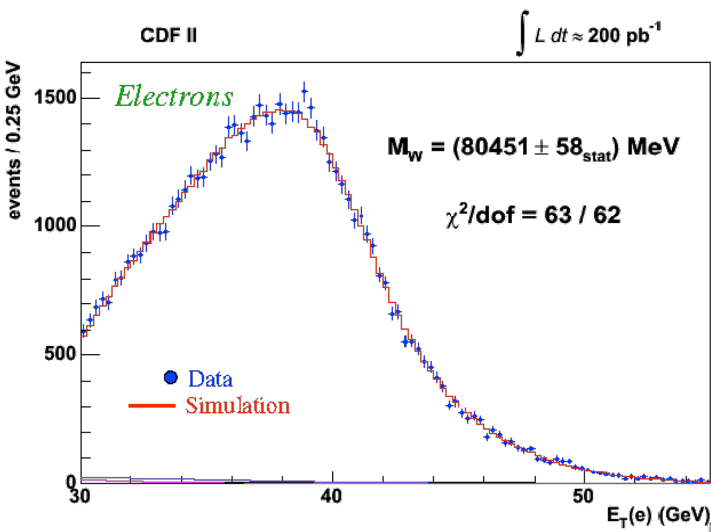
arXiv:1012.5382v1 [hep-ex] 24 Dec 2010



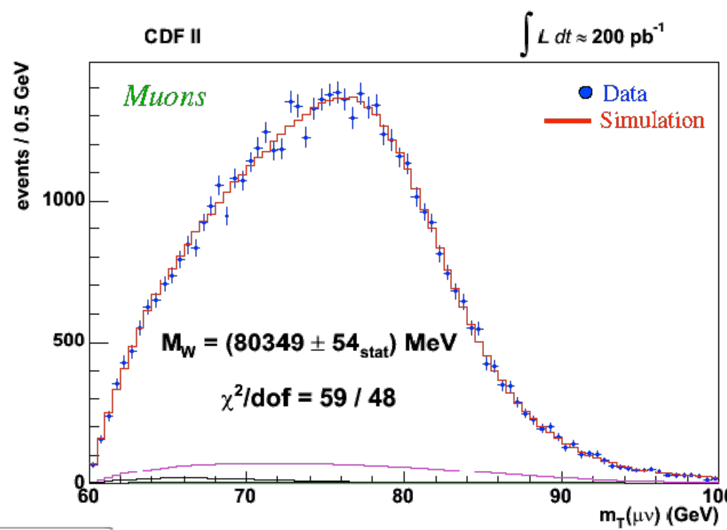
Early study comparing to NLO QCD event generators
Both CMS and ATLAS have x30 data already
Expect new results in Spring for both W and Z

W Mass – CDF Work

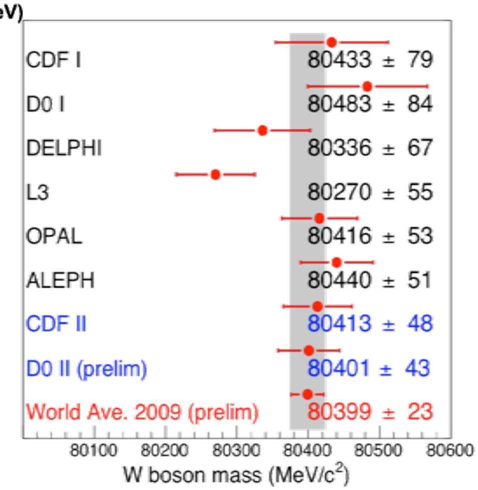
W Lepton p_T Fits



W Transverse Mass Fits



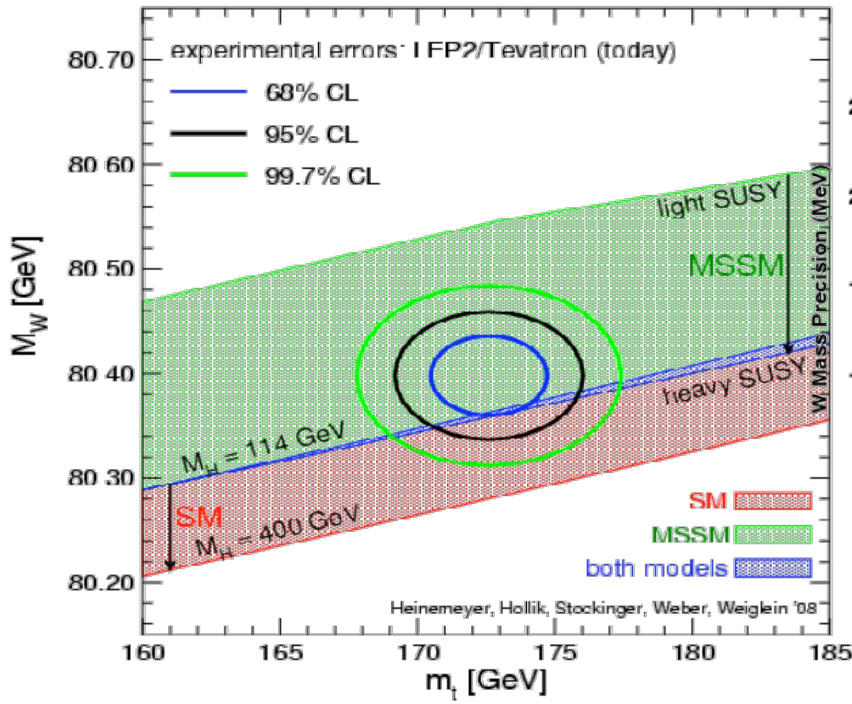
Comparisons

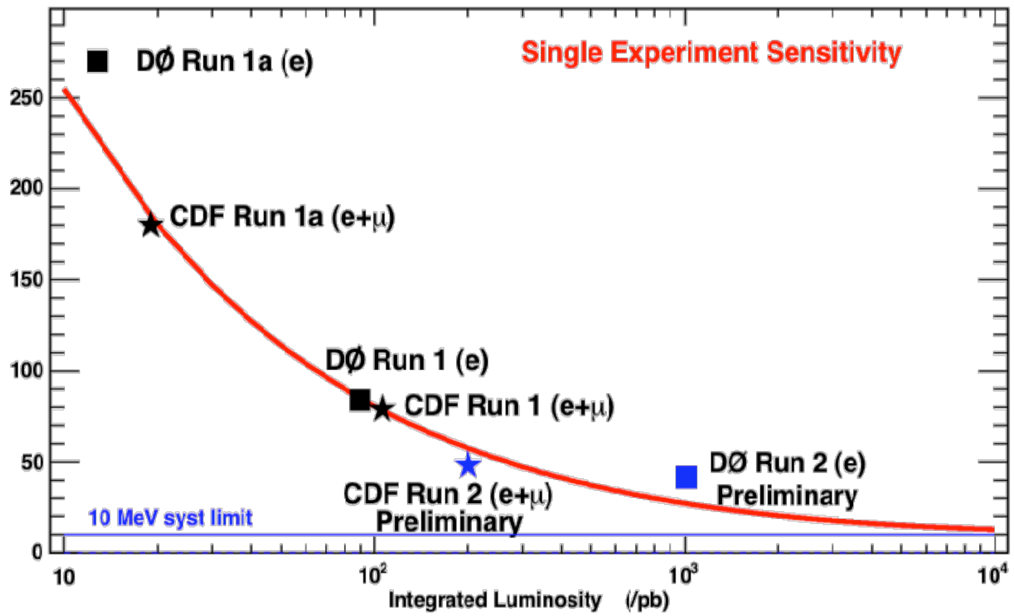


(CDF Run II: PRL 99:151801, 2007; PRD 77:112001, 2008)

What Next? Precision EWK?

M_W *vs* M_{top}





Summary

LHC is off to a wonderful start in 2010

- The detectors and accelerator are working well
- The Standard Model is well established at 7 TeV scale
  - Several strong and electro-weak processes are measured already
- Look forward to several fb^{-1} data at 8 TeV in 2011-2012
  - Detailed measurements, e.g., charge asymmetries, to improve parton distribution functions, improve W, top mass …
  - Firmly establish vector-boson + jets and other processes to validate QCD NLO calculations and event generators
  - Multi-boson production
  - Prepare stage for unambiguous discoveries of higgs, SUSY and exotic new physics