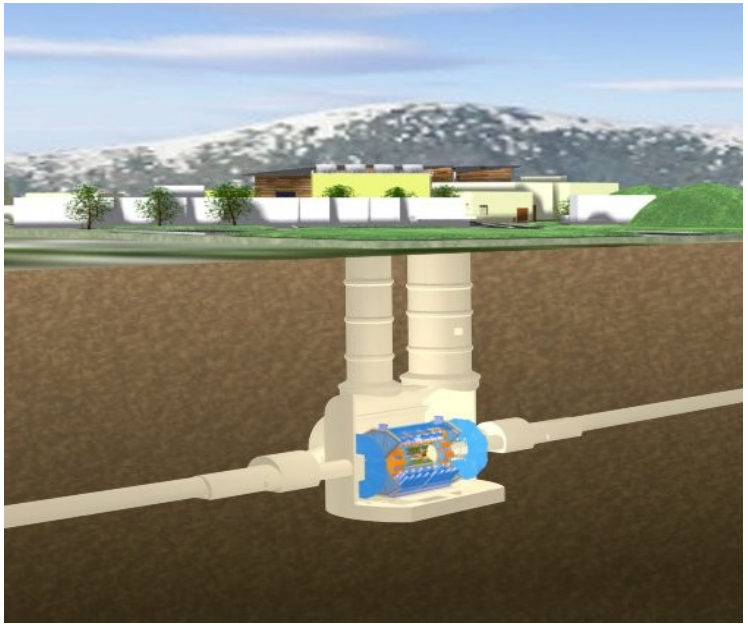
Standard Model Results from the ATLAS Experiment

S.Chekanov (ANL)
for the ATLAS collaboration

The Cracow Epiphany Conference
10-12 January, 2011



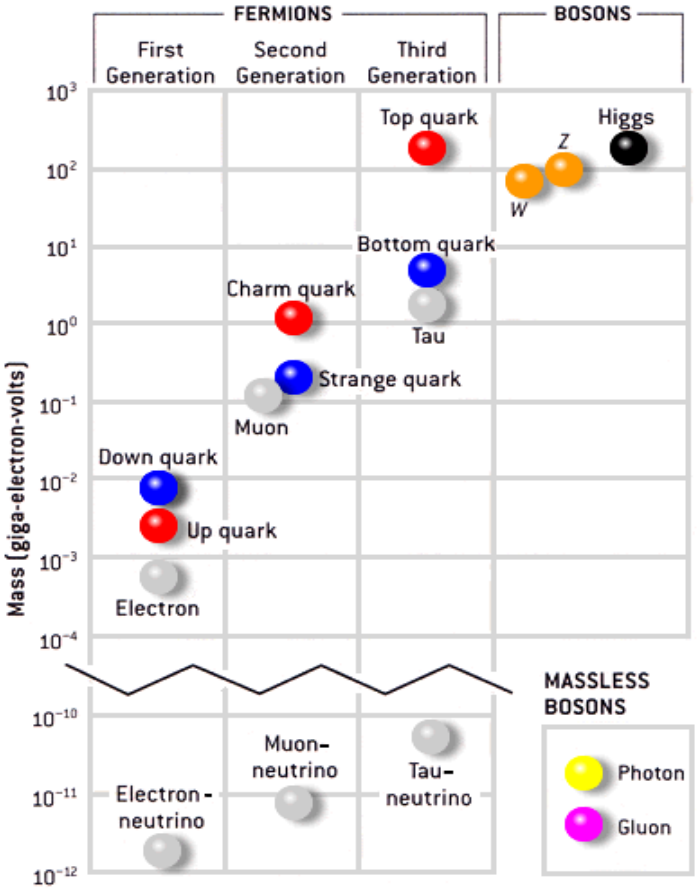


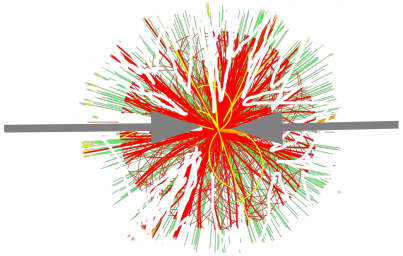
Chart from Scientific American::
17 particles in the Standard Model, together with their masses:

Introduction. SM tests with early data

Standard Model - theory concerning the electroweak and strong interactions

View from the "bird flight" and the scope of the SM tests at the LHC:

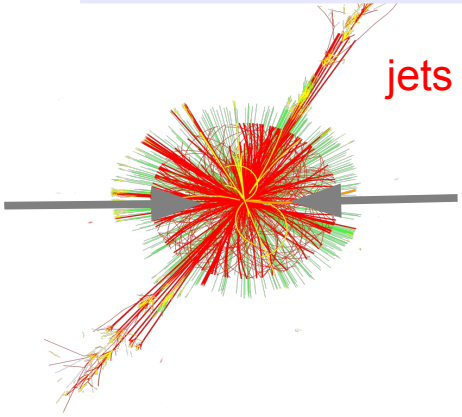
"softQCD"
p_T < few GeV



>99.999% collisions:

Tests:
- LO matrix elements
- LL parton showers (PS)
- models for softQCD
- consistency in tunings
- etc.

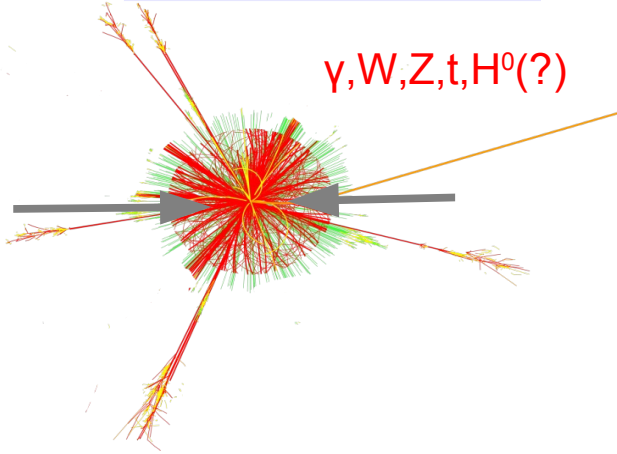
"Hard QCD"
p_T > tens of GeV



~10^{-5} % collisions

Tests:
- **NLO QCD ($O(\alpha_s^3)$)**
- running α_s
- PDF
- LO QCD $O(\alpha_s^2)$ +PS
- etc.

"Hard EWK"
p_T > tens of GeV



~10^{-6} - 10^{-8} % collisions

Tests:
- **NLO, NNLO QCD**
- mass measurements
- PDF
- LO QCD $O(\alpha_s^2)$ +PS
- etc.

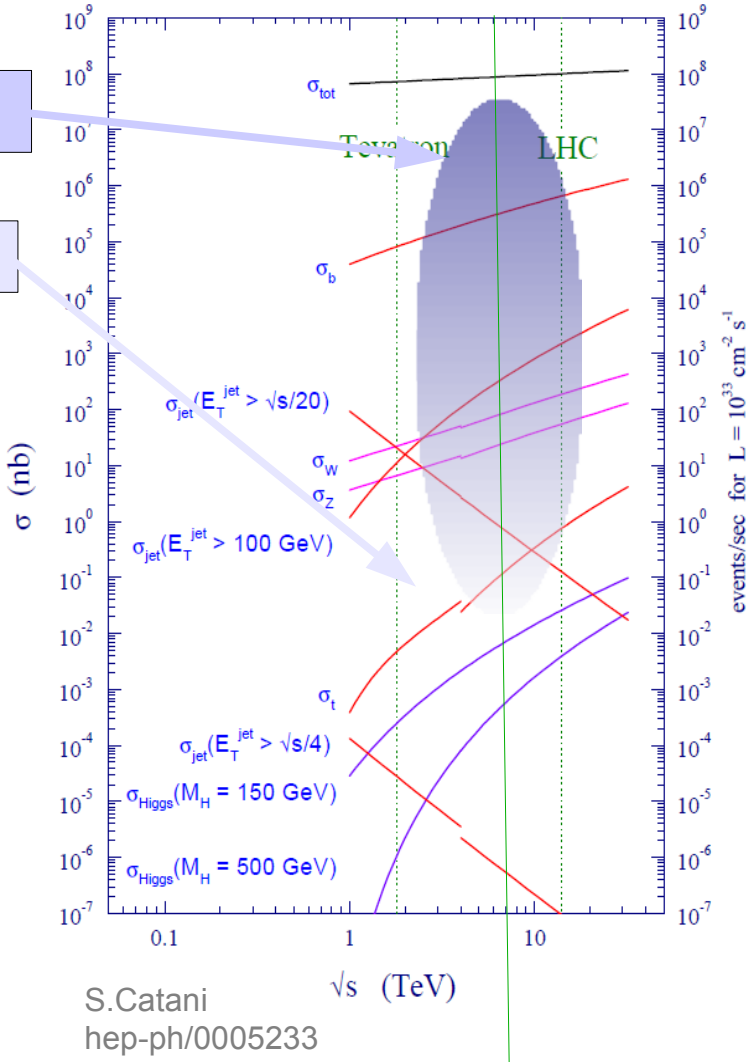
SM processes at the LHC

Current Luminosity
~30 pb^{-1}

"measurements"

"observations"

Process	σ (nb)	Events (∫Ldt = 100 pb^{-1})*
Min bias	10^8	~10^{13}
bb	$5 \cdot 10^5$	~10^{12}
Jets p_T > 200 GeV	100	~ 10^7
W → lepton+ ν	15	~ 10^6
Z → l+ l-	1.5	~ 10^5
tt	~0.1	~ 10^4
Higgs (M=150 GeV)	~0.001	~100



current energy
7 TeV

* we have 1/3 of this data

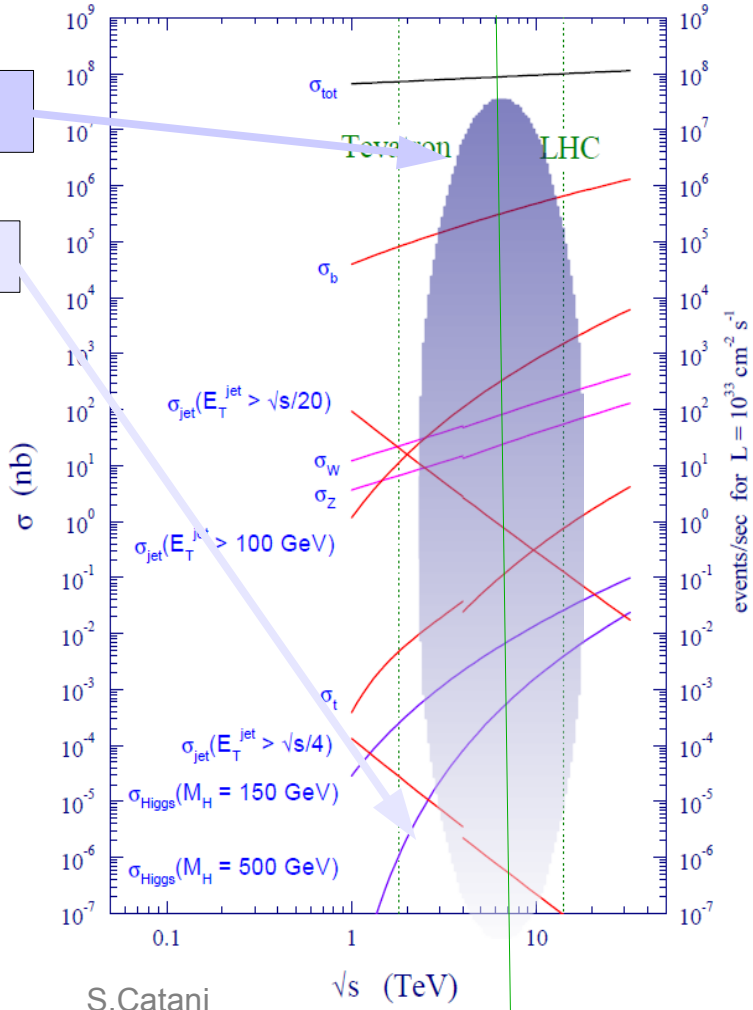
SM processes at the LHC

~ 1 year from now
~1 fb^{-1}

"measurements"

"observations"

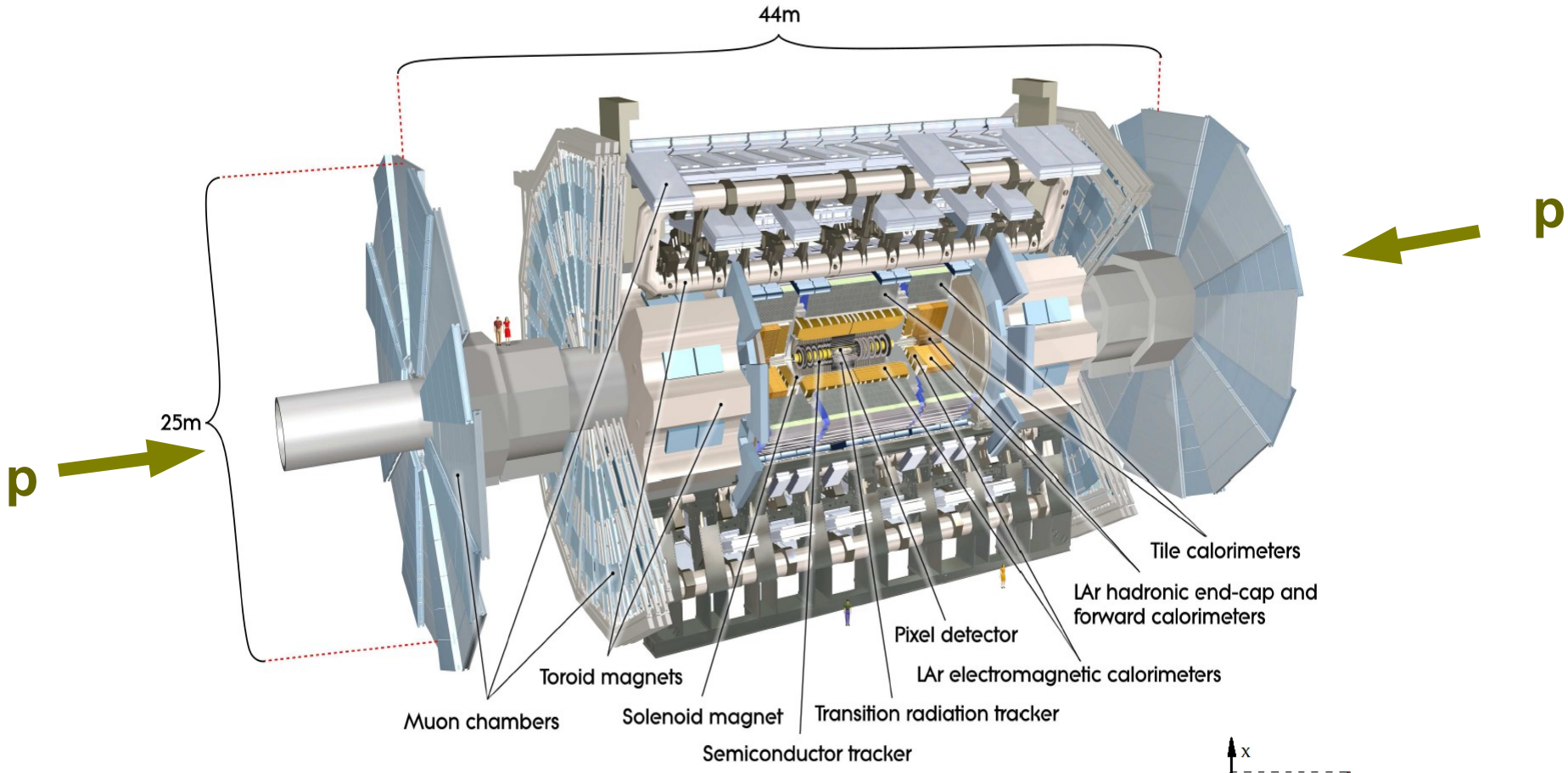
Process	σ (nb)	Events (∫Ldt = 1 fb^{-1})
Min bias	10^8	~10^{14}
bb	$5 \cdot 10^5$	~10^{13}
Jets p_T > 200 GeV	100	~ 10^8
W → lepton+ ν	15	~ 10^7
Z → l+ l-	1.5	~ 10^6
tt	~0.1	~ 10^5
Higgs (M=150 GeV)	~0.001	~1000

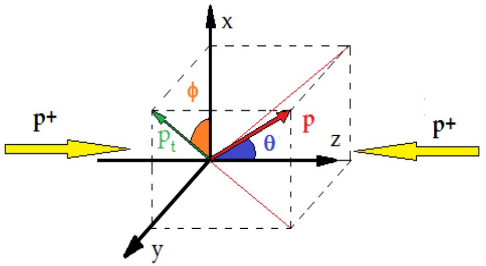


S.Catani
hep-ph/0005233

current energy
7 TeV

ATLAS detector

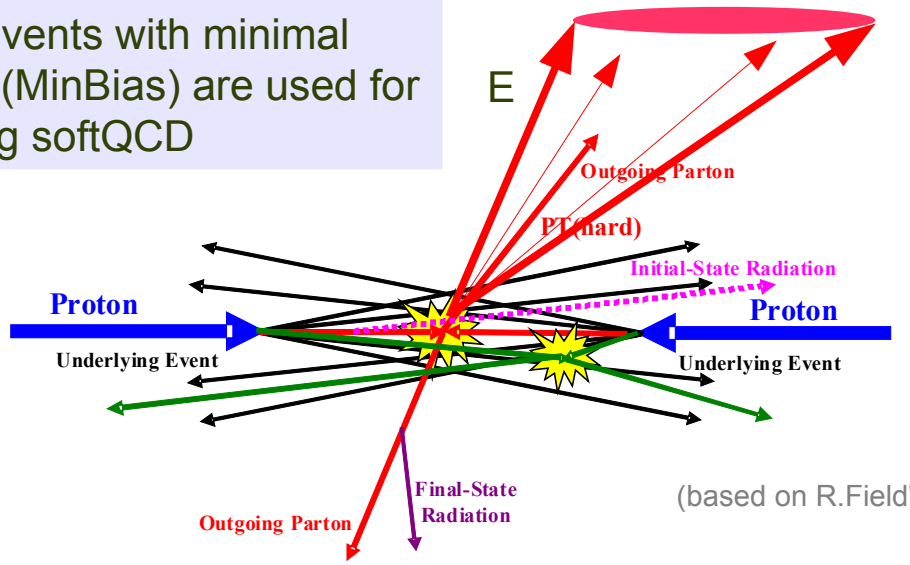




See M.Schatt's talk

New energy frontier: from soft to hard QCD

Inelastic pp events with minimal selection criteria (MinBias) are used for testing softQCD



(based on R.Field's figure)

~ log² E pQCD

~ log(s)? Models.. Models..

- **MinBias events:**
  - measurements can be done with small luminosity
  - Examples:
    - basic properties of particle production, multiplicity measurements, energy flows etc
- **High-precision measurements for high-pT physics require substantial statistics**

Monte Carlo models

pre-LHC tunes

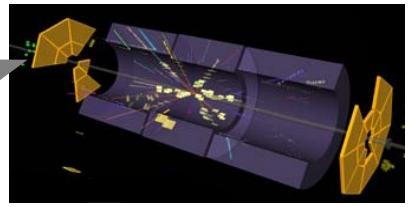
- **PYTHIA 6**, actually 6.4.21: pT-ordered parton shower, MRST LO PDF, multiple parton-parton scattering, string fragmentation
- **PYTHIA ATLAS MC09**: parameters tuned to underlying events and minimum bias data from Tevatron at 630 GeV to 1. 8 TeV (ATLAS optimization)
- **PYTHIA ATLAS MC09c**: MC09 optimizing the strength of the color reconnection to describe pT dependence on N(ch) in the CDF data at 1.96 TeV
- **PYTHIA Perugia0**: soft QCD part is tuned using only minimum bias data from Tevatron and CERN ppbar data
- **PYTHIA DW**: uses the virtuality-ordered showers and used to describe the CDF II underlying events and Drell-Yan process data
- **PHOJET:** two-component Dual Parton Model with soft hadronic processes by Pomeron exchange and semi-hard processes by perturbative parton scattering
- **HERWIG+JIMMY**: cluster fragmentation model + MI interactions using JIMMY model
- **HERWIG++**: reimplemented in C++ cluster fragmentation model (+many new features)
- **PYTHIA ATLAS AMBT1:** P6 tuned by ATLAS to the low-multiplicity data

Main scope of comparison with Monte Carlo models: tune softQCD phenomenological models in order to use such models for better understood SM processes (pQCD, EWK measurements)

softQCD: Charged particle multiplicities

ATLAS arXiv:1012.5104

Minimum Bias Trigger Scintillators (MBTS)



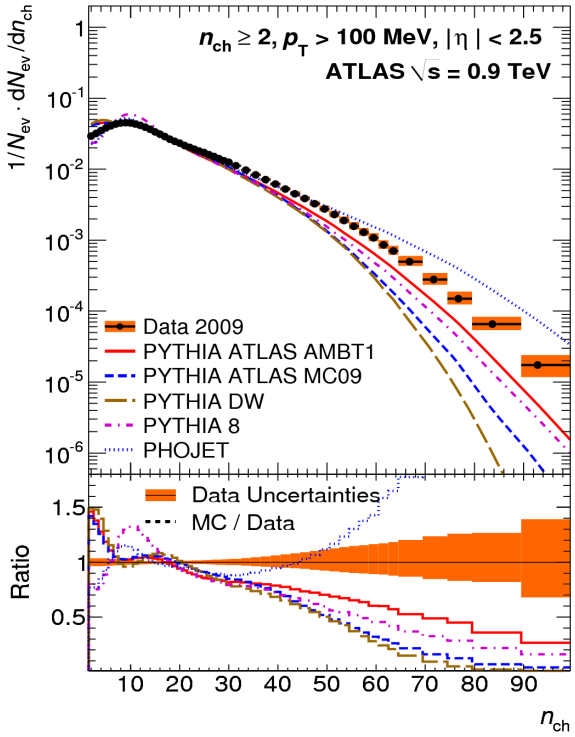
32 plastic scintillators with coverage: 2.09< η < 3.84

Trigger and event selection in MinBias events

- Data: 900 GeV and 7 TeV (~10M events)
- Selection:
  ≥ 1 MBTS counter to fire on either side

Primary track selection:

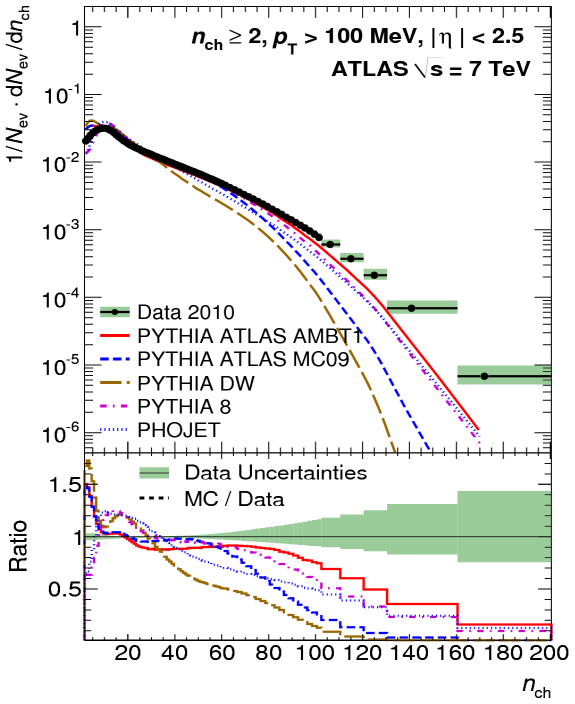
- pT > 100 MeV, | η| < 2.5 + other track quality cuts



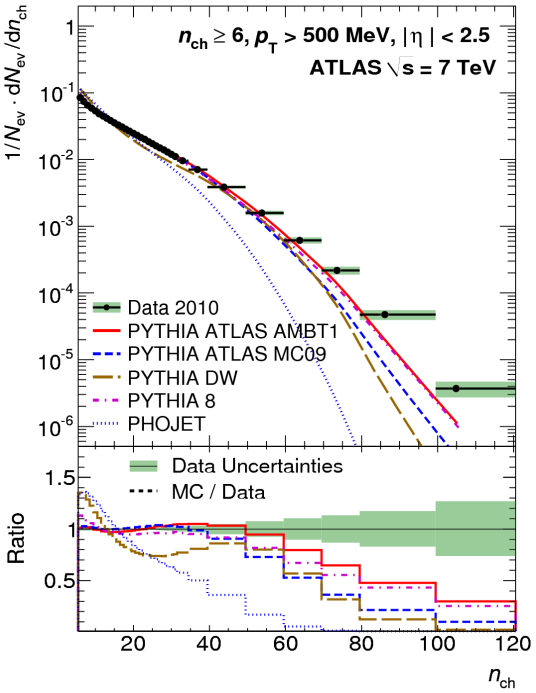
900 GeV

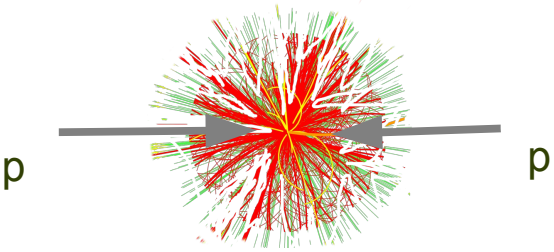
7 TeV

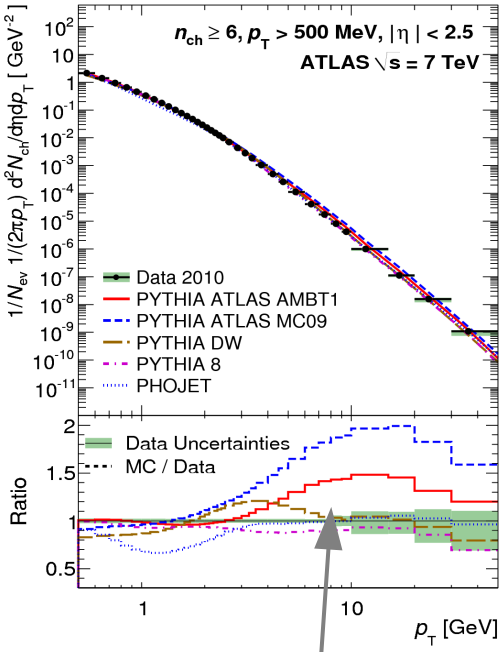
- 7 TeV: up to ~200 charged particles per event!
- All pre-LHC MC fail
- PYTHIA AMBT1 is closest to data
- PHOJET overestimates 900 GeV and underestimates 7 TeV
- Low n(ch) region affected by diffraction

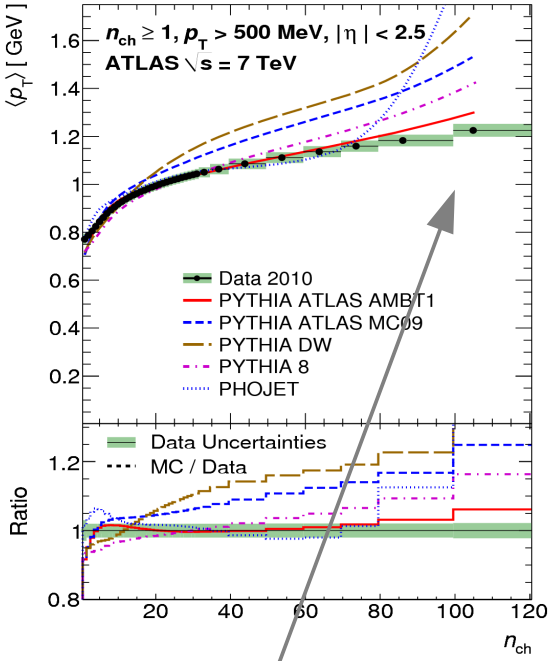


Particle spectra with reduced contribution from diffraction









All pre-LHC tunes of MC models fail

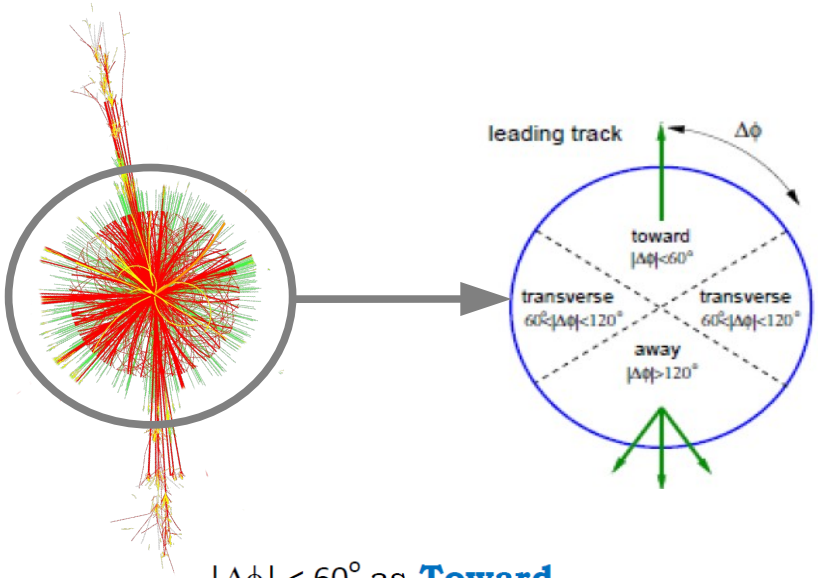
Entering hard QCD

PHOJET completely fails

AMBT1 tune improves agreement (but still has problems!):

- increasing probability for head-on collisions (more events with large N(ch), PARP84)
- reducing color reconnection for high-momentum hadrons (reduces <pT>, PARP(77))

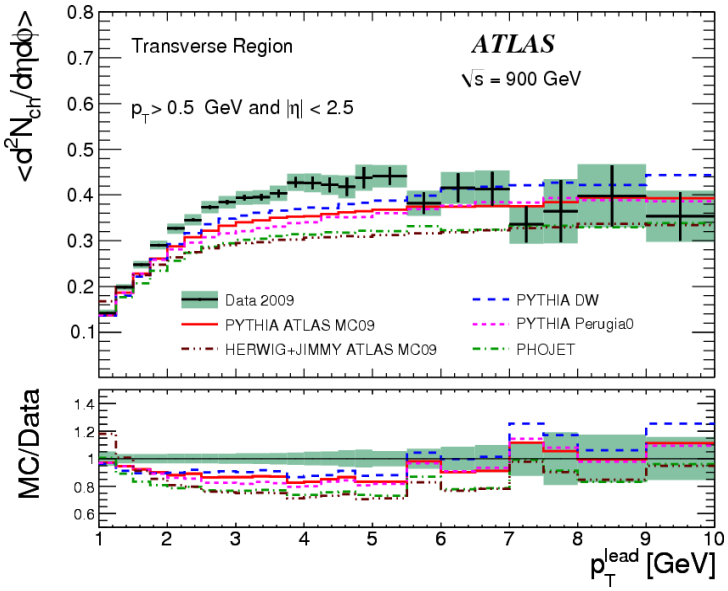
Studies of Underlying Event in MinBias data

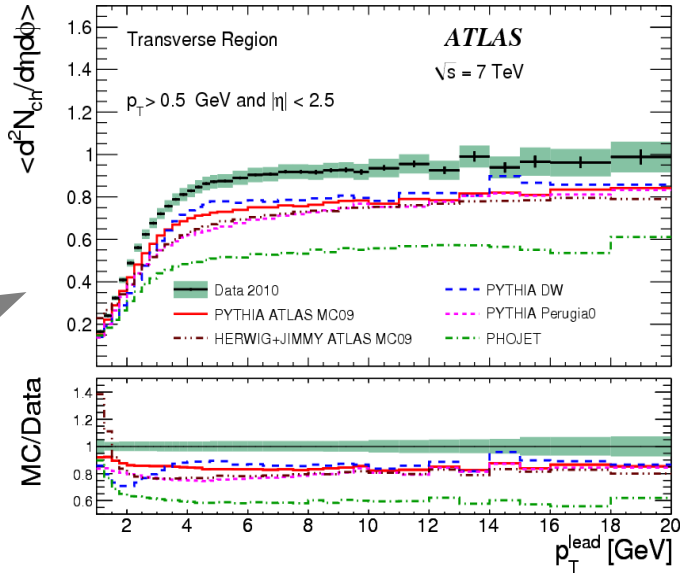


$|\Delta\phi| < 60^\circ$ as **Toward**

$60^\circ < |\Delta\phi| < 120^\circ$ as **Transverse**

$|\Delta\phi| > 120^\circ$ as **Away**





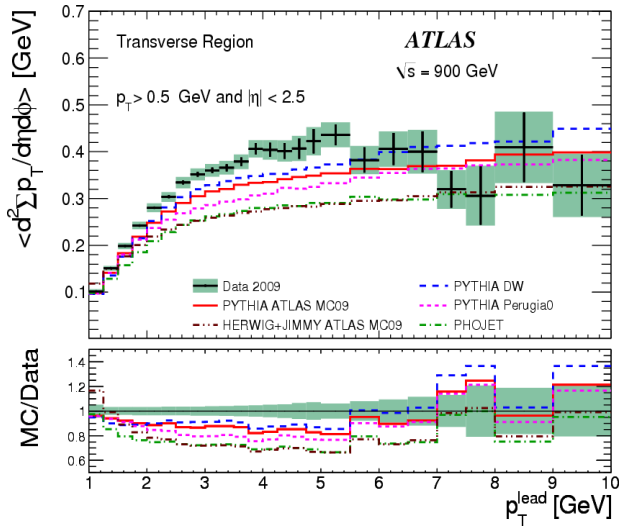
All MC models have lower activity in the transverse region

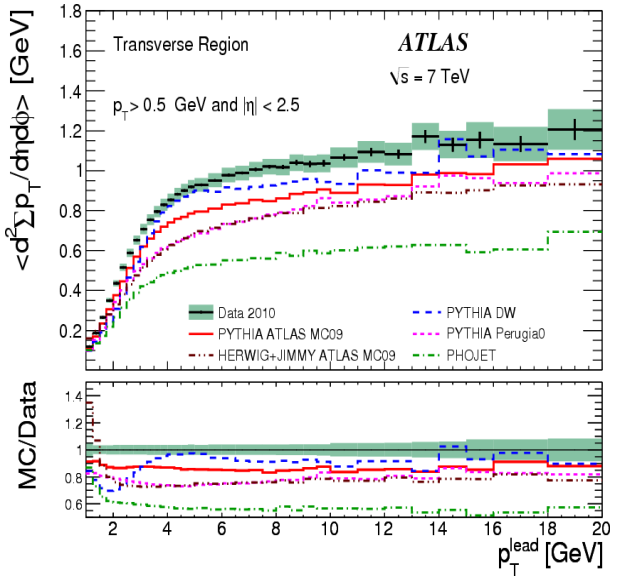
Discrepancies increase with CM energy

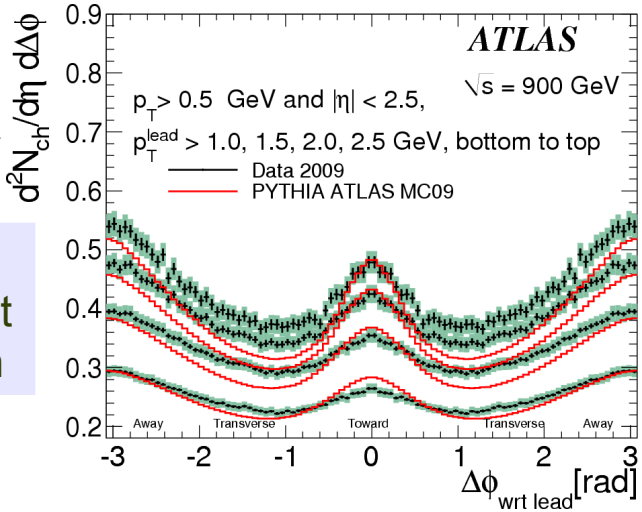
ATLAS arXiv:1012.0791

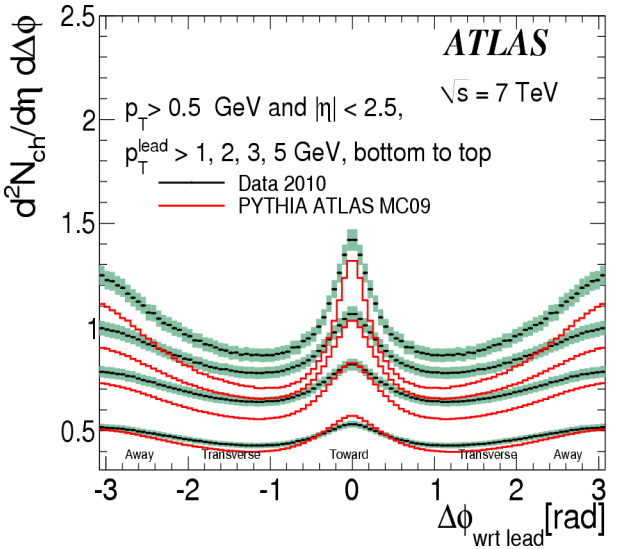
Studies of Underlying Event in MinBias data

- Scalar sum-PT shows similar discrepancies
- PHOJET fails for 7 TeV
  - not enough particle activity at large pT
- development of 'jet-like' structure





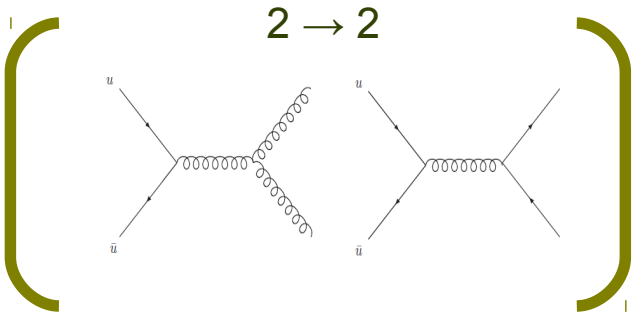




Pre-LHC MC models describe general features, but fail in quantitative description

Jets

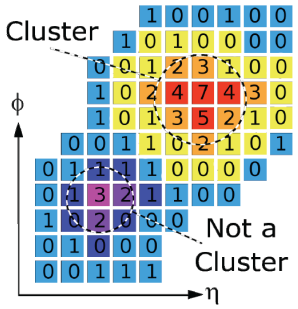
- Jets are sensitive probe of many aspects of pQCD:
  - matrix elements at LO(+PS) and NLO QCD
  - PDF's
  - running α_s
  - refine our understanding of soft QCD
  - important for searches beyond SM
- For 30 pb^{-1}, the reach in jet transverse momentum at the LHC is twice that attained by previous experiments

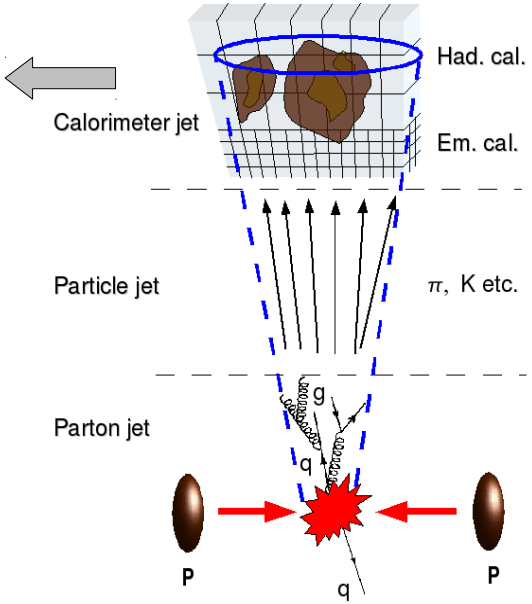


LO processes $O(\alpha_s^2)$

Input for jet algorithms:

Topological clusters built from calorimeter cells
- follow shower development
- reduce noise



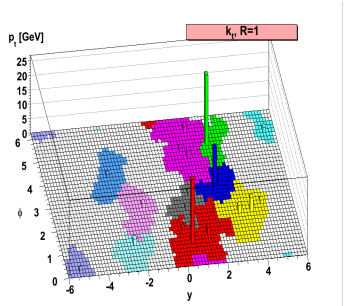


Seeded by cells with |E| > 4 x (noise level)
Neighboring cells with |E| > 2 x noise iteratively added (in 3D)
All neighbors around cluster (|E| > 0) added

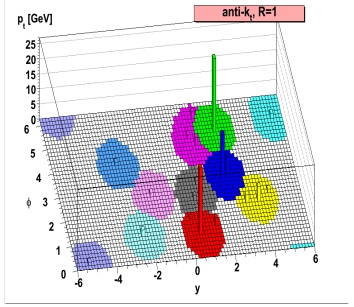
image by P.Weber

Building jets

- Jets reconstructed using the anti-kT algorithm
  - M. Cacciari and G. P. Salam, Phys. Lett. B 641, 57 (2006)
- Infrared and collinear safe
- Produces geometrically well-defined cone-like jets
- Size parameters R=0.4 or 0.6

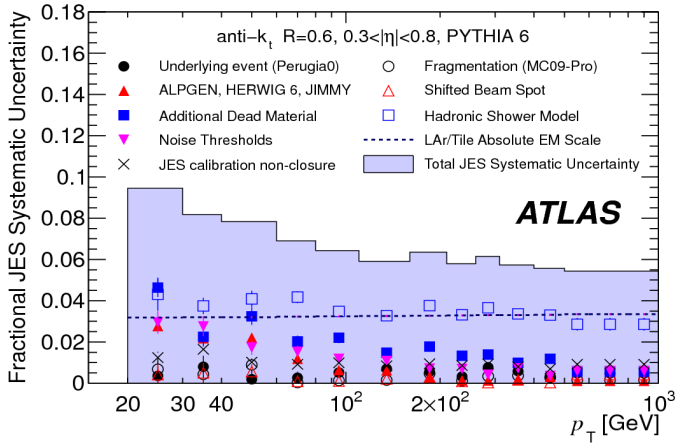


from kT
to
antiKt



Jet-energy scale

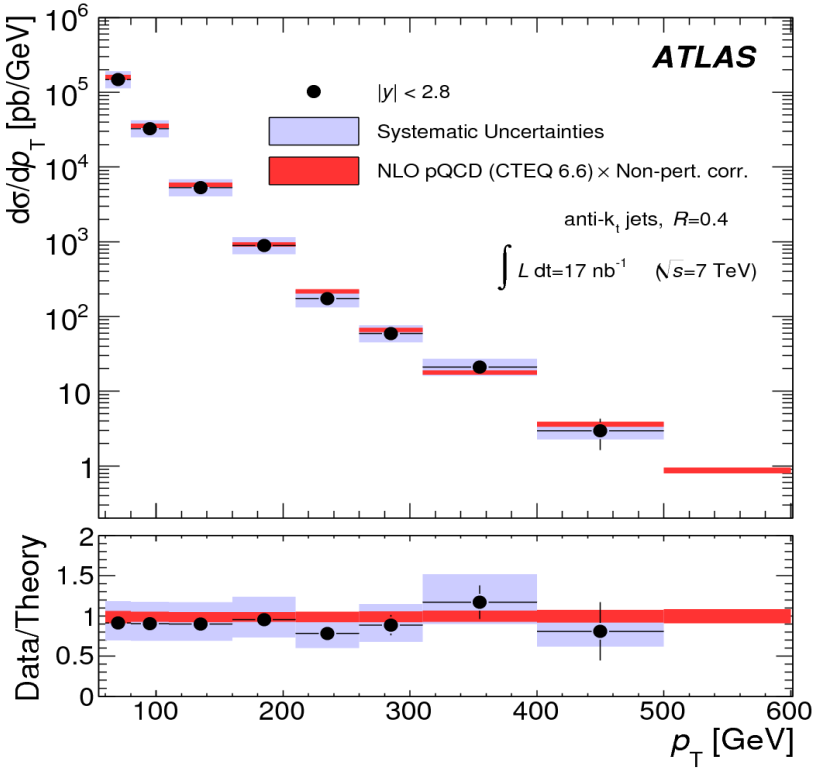
- Dominant uncertainty for all jet-related measurements
- Currently: pT and η dependent correction applied to uncalibrated objects ("EM" scale)
- Other corrections are coming:
  - "Global Cell Weighting" cell weights based on cell energy density
  - Local Cluster Weighting: use properties of topological clusters to classify (EM, hadronic) and calibrate clusters; weights depend on shower topology



- Overall uncertainty 6-10% for |η| <2.8
- Depends on pT and η

Inclusive jet production

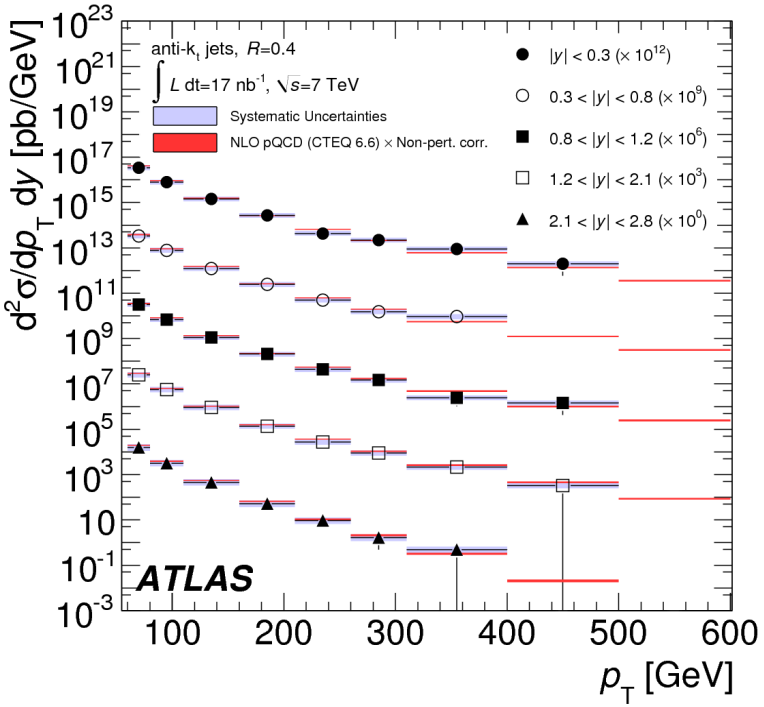
ATLAS arXiv:1009.5908



Very good agreement with NLO QCD &CTEQ6.6

- measurement is dominated by systematical uncertainties (pT<400 GeV)
- dominant uncertainty– jet-energy scale

cross section differential in **rapidity**

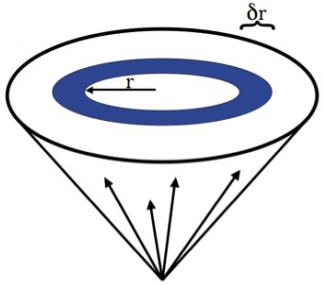


Theory:
NLO QCD (NLOJET++/JETRAD) together with softQCD corrections (~5%) from PYTHIA model

11% uncertainty on luminosity measurement is not shown

Jet shapes

Hard interaction is always associated with extra QCD radiation

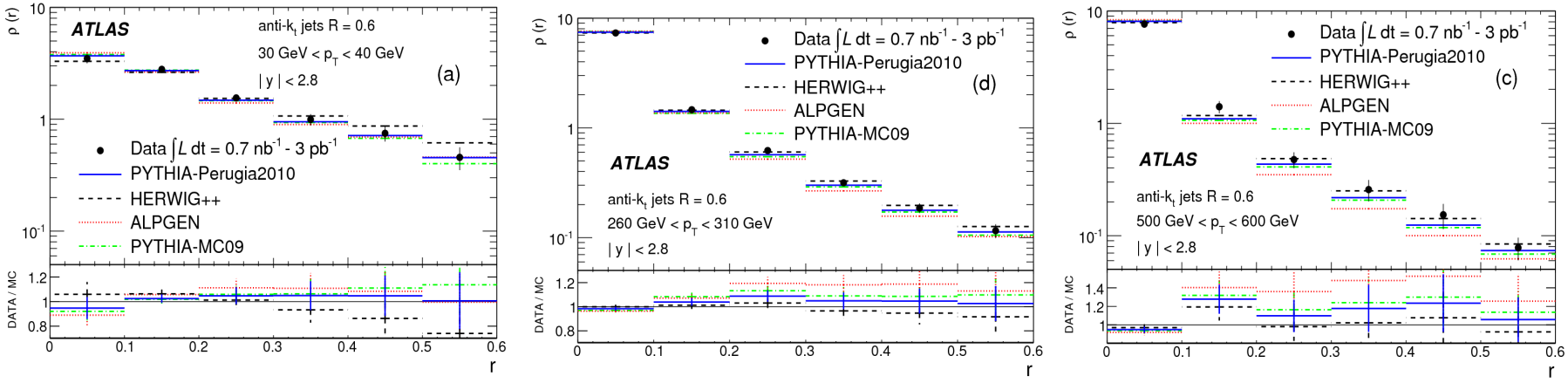


Essential for understanding:

- Soft QCD effects inside jets. Testing PS models
- Sensitive to quark/gluon jet mixture
- For searches of boosted particles (Higgs) and new physics beyond the Standard Model

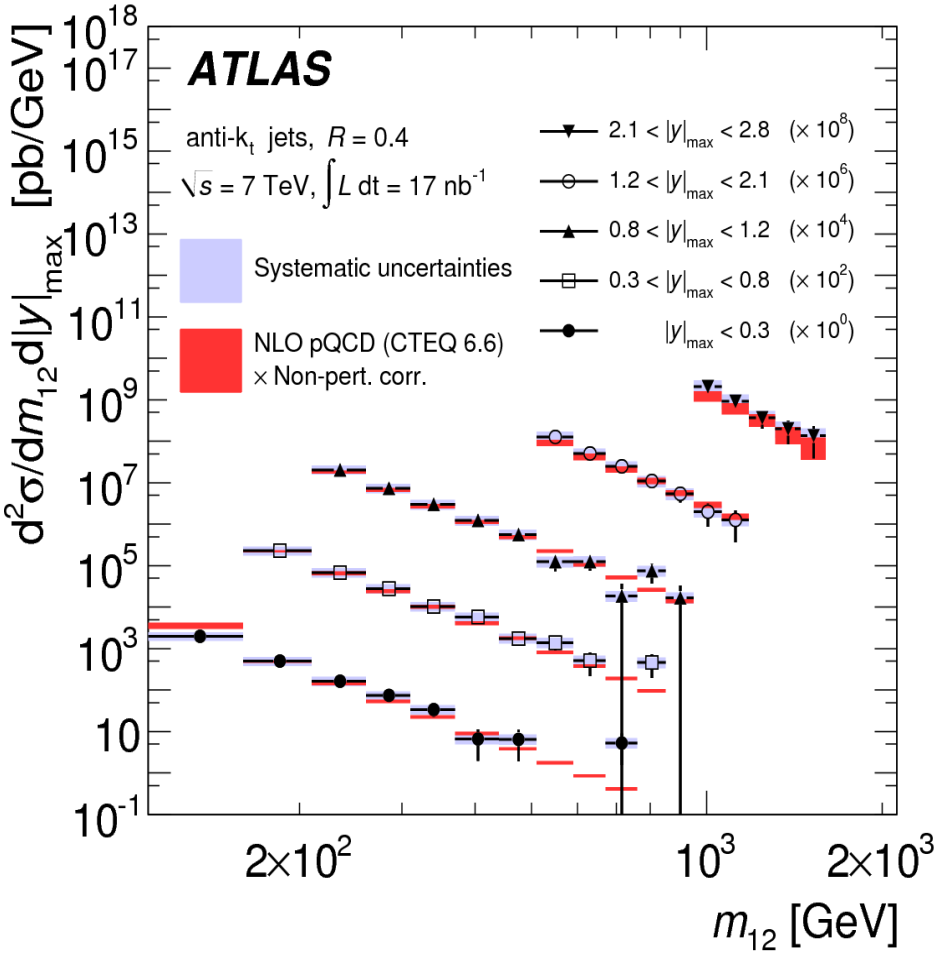
$$\left\langle \frac{1}{r}\frac{dp_T}{dr} \right\rangle_{jets} = \frac{1}{A}\frac{1}{N_{\text{jet}}}\sum_{jets} p_{\text{T}}(r-\Delta r/2, r+\Delta r/2)$$

Jets are reconstructed with antiKT=0.6 using topological clusters & corrected



- Jets become narrower as jet pT increases
- Good agreement with LO+PS Monte Carlo models
- ALPGEN (with HERWIG 6.5+JIMMY) generates too narrow jets at large pT

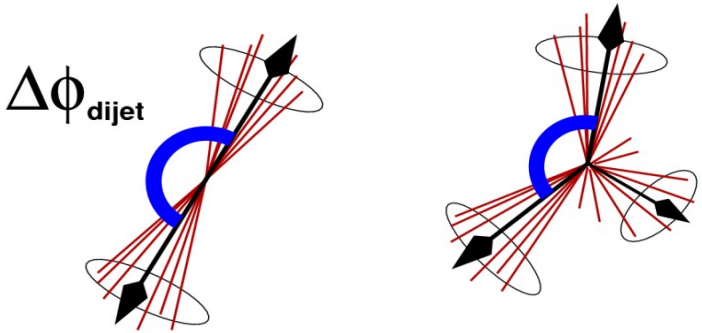
Dijet measurements

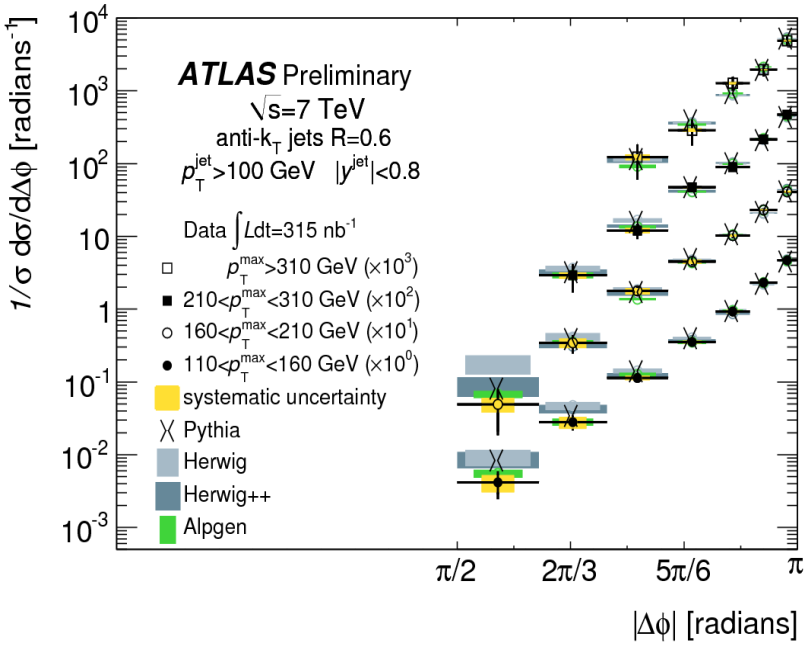


Perfect agreement with NLO QCD & CTEQ6.6.

Azimuthal decorrelation:

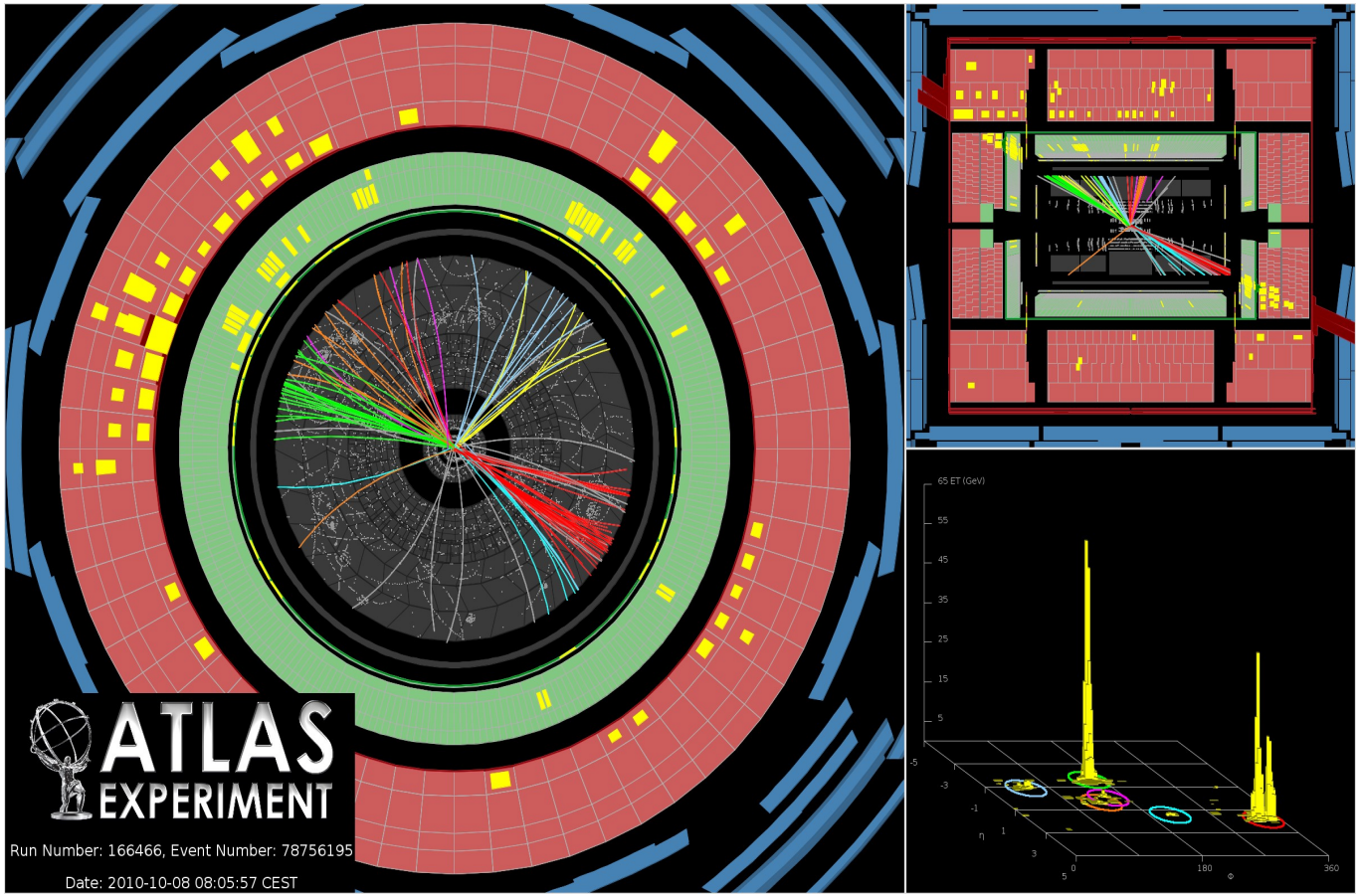
Looking at softer QCD without reconstructing soft jets!





Highest-mass dijet event

pT(Jet1)=670 GeV pT(jet2)=610 GeV M(jj)=3.4 TeV

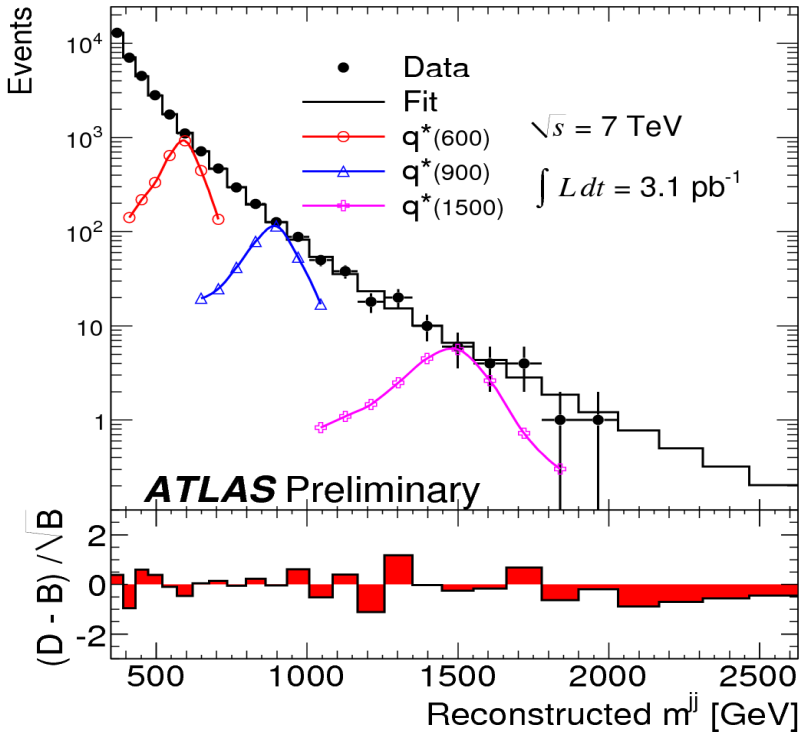


Search for New Particles in Two-Jet Final States

ATLAS arXiv:1008.2461

- Model-independent search for resonances on top of a smooth falling M_{jj} spectrum

$$M_{jj} = \sqrt{(E_1 + E_2)^2 - (P_1 + P_2)^2}$$

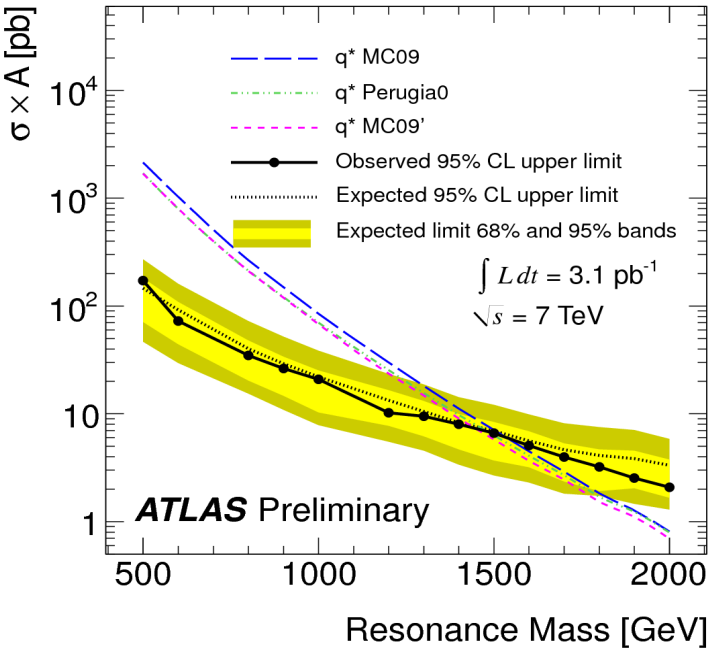


3.1/pb: ATLAS-CONF-2010-093

Excited-quarks excluded at the 95% CL for 0.3<m(q*)<1.53 TeV

TEVATRON exclusion m(q*)<870 GeV

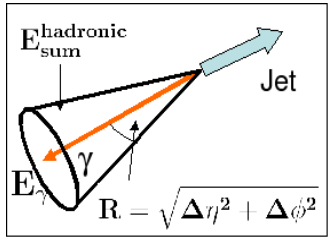
Note: model dependent exclusion for standard parameters in PYTHIA MC09

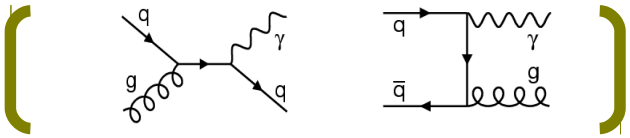


Direct photon production

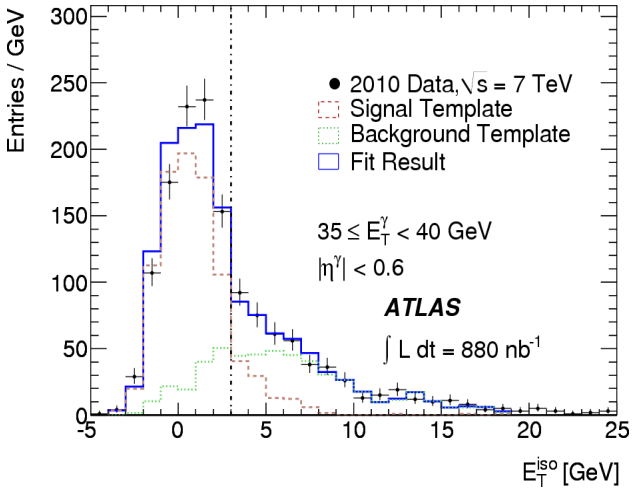
ATLAS
arXiv:1012.4389

- On theoretical level, considered to be a clean environment to study QCD (no jet reconstruction)
- But difficult in practice as one should deal with large background from hadrons

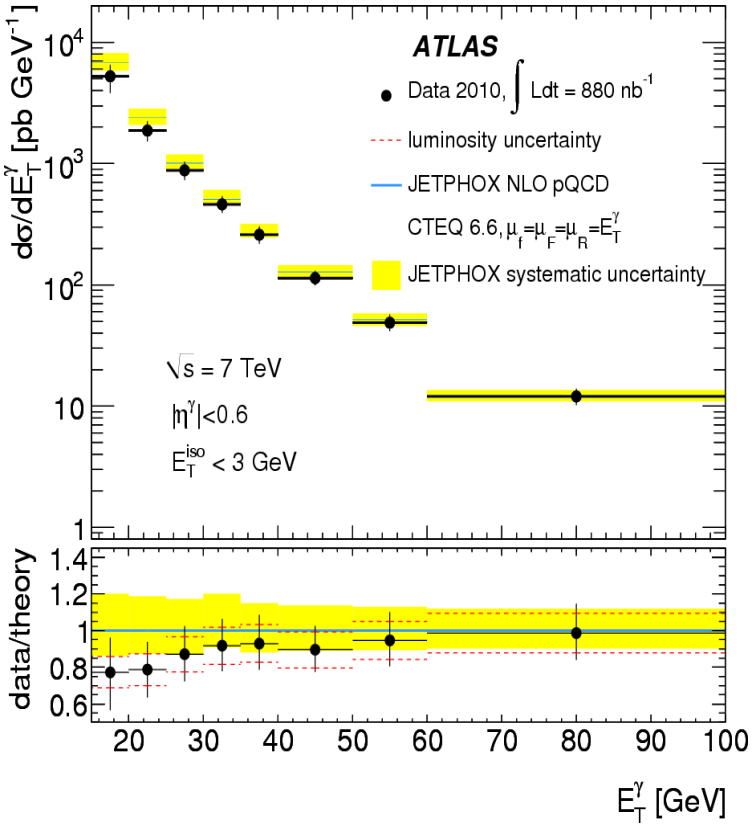




~90% ~10%



E_T^{ISO} - isolation energy in the cone excluding 5x7 cells around barycenter

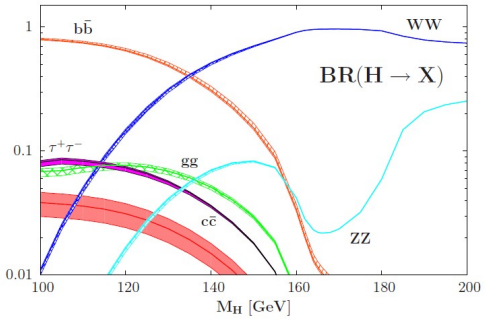


Good agreement with NLO QCD & CTEQ6.6

From QCD to high-pT EWK sector

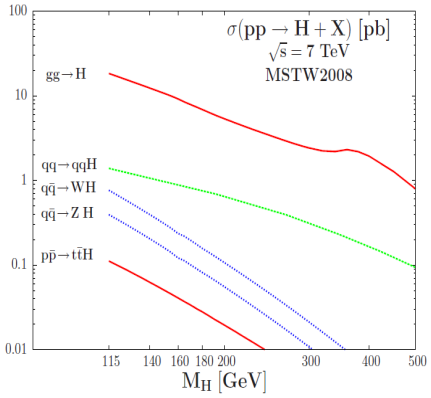
J.Baglio, A.Djouadi arXiv:1012.0530

- Better theoretically understood (in many cases with 1% precision)
- Simpler environment to test SM (electron, muon signatures)
- W and Z cross sections are among the first measurements
  - <1% precision measurement after for 1 fb^{-1} (next year!)
- Main channel for Higgs hunting (and main background!)



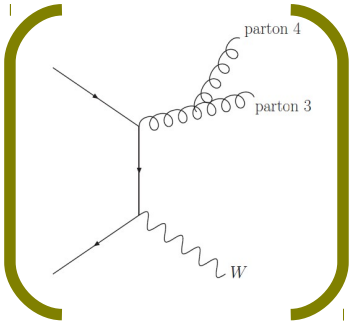
Inclusive W/Z measurements: (See Pawel Malecki's talk)

- Precise test of NNLO QCD, probing PDF
- Experimental view:
  - Establishing experimental procedure for calibration, trigger, alignment, luminosity and finally a gateway to probe SM at highest CM energies



W+jet measurements

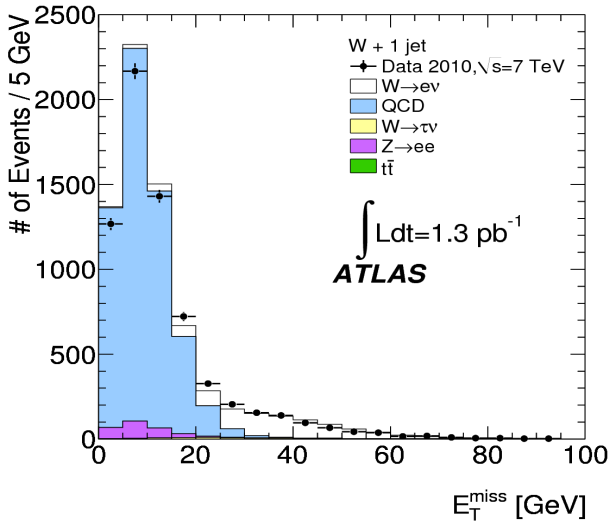
- Constrain measurements to well-known physics
- Precise test of QCD matrix elements & PDF
- Important background for top-antitop, single-top, Higgs searches, etc

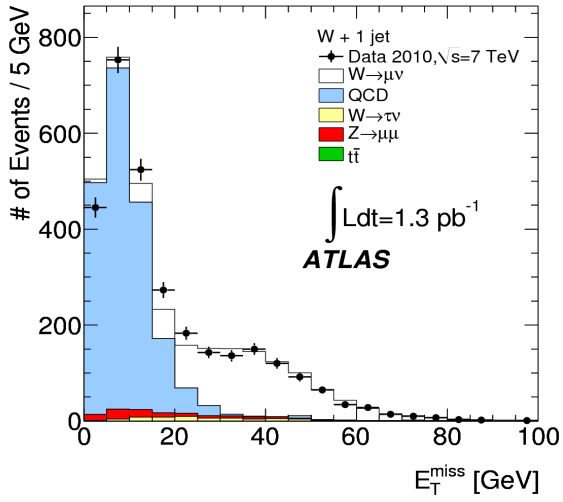


W+ jets measurements

ATLAS arXiv:1012.5382

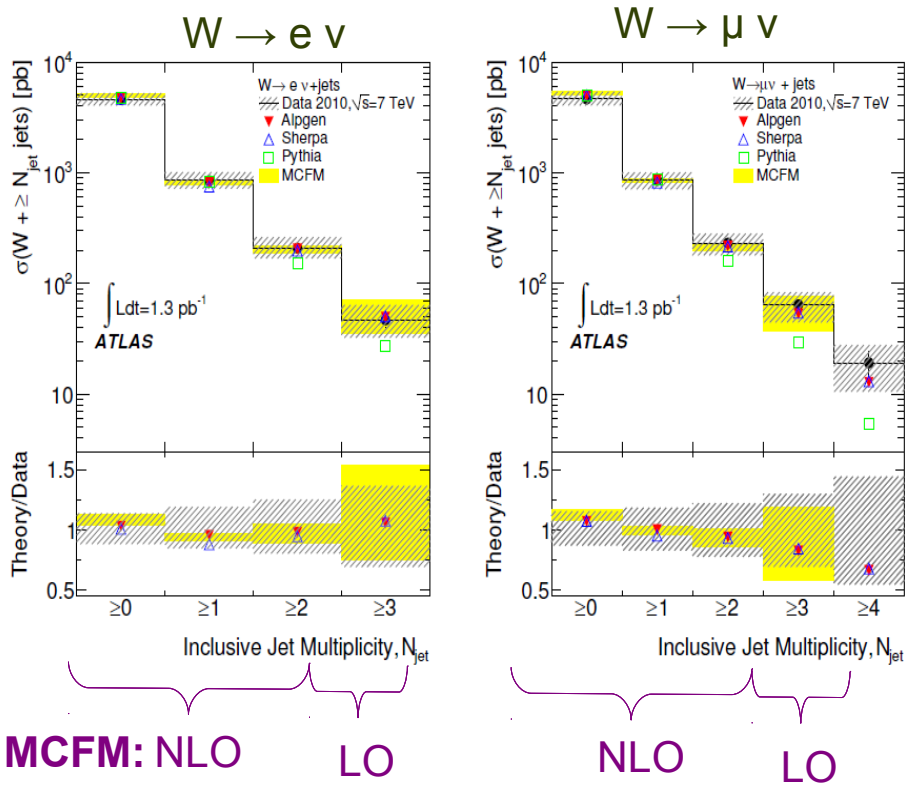
- Events are selected by requiring:
  - E_T (e) >20 GeV or E_T (μ)>20 GeV & |η|<2.4
  - E_T(miss)>25 GeV & M_T>40 GeV
  - antiKT(jet) with R=0.4 & pT>20 & |η|<2.8. Pileup is removed using jet-vertex association
- W+jet signal yield was obtained as difference between data and sum of all background contributions
- Background calculations:
  - Leptonic channels: ALPGEN/PYTHIA with NNLO or NNLL normalizations
  - QCD background: fitting E_T^{miss} using data using template shapes

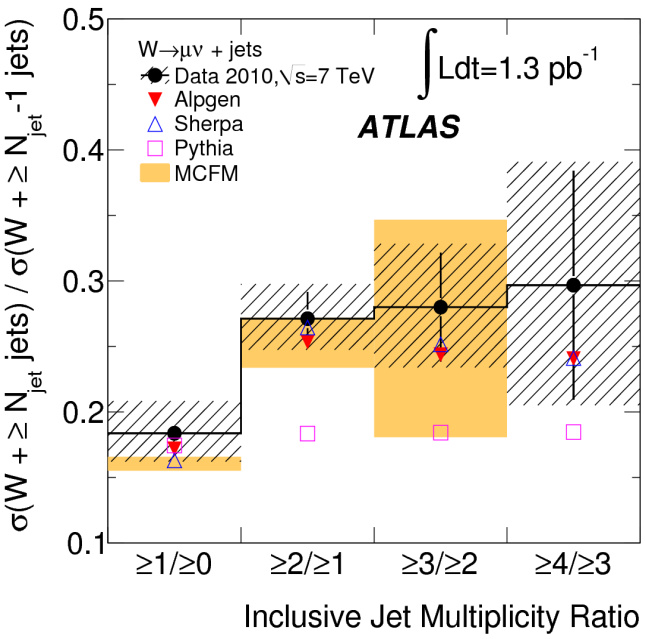




W+ jets measurements

ATLAS arXiv:1012.5382

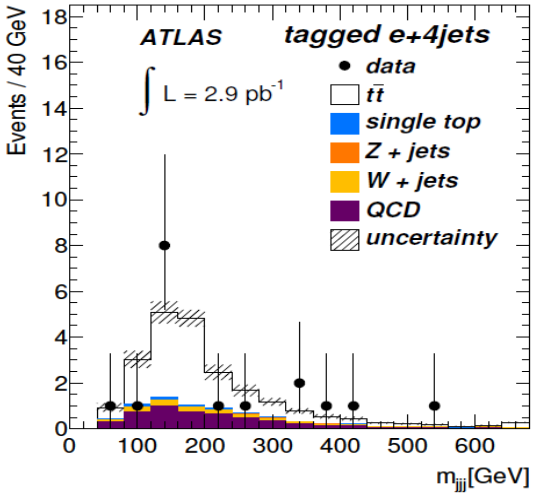




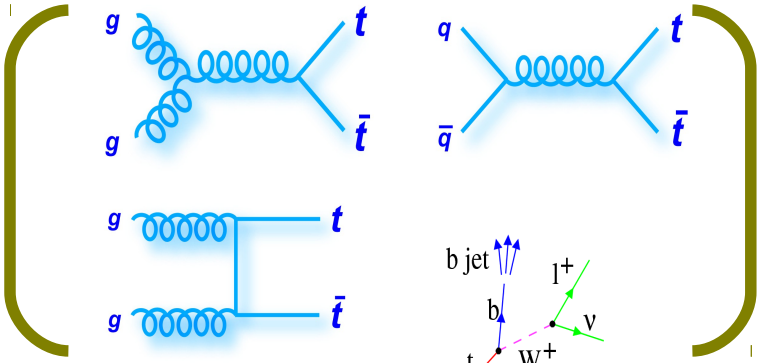
- Good agreement with ALPGEN & SHERPA
- Good agreement with MCFM (NLO QCD) & CTEQ6.6 for <3 jets & LO for >2 jets
  - includes corrections (~10%) for hadronisation & underlying events using AMBT1 tune
- Only MC+PS available for W+4 jets (muon channel)

Top cross-section measurements

ATLAS arXiv:1012.1792



2 topologies:
- single-lepton channel (+ >3 jets)
- double lepton channel (+ miss ET)



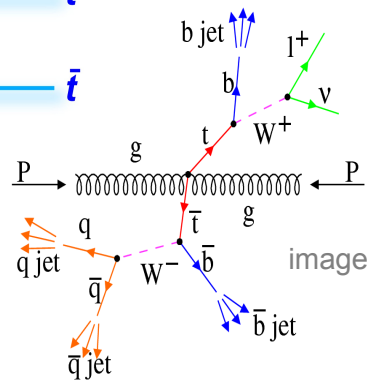
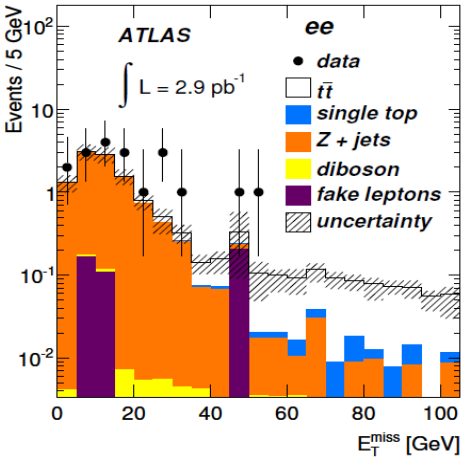
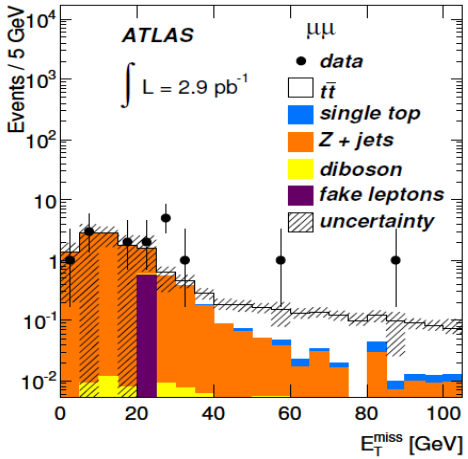
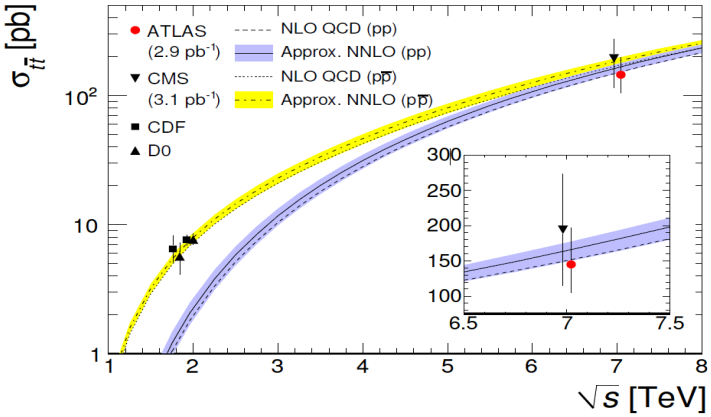


image by P.Bell

- 4.8 σ statistical significance
- confirmation of the Tevatron observation







Good agreement with NLO & NNLO (app) QCD

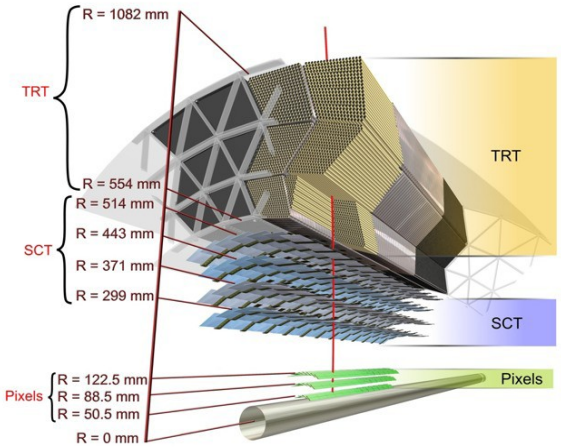
Summary

- **First benchmark measurements confirm the Standard Model**
  - rediscovered many particles that lie at the heart of the SM
  - masses agree with the SM (but no high-precision measurements yet)
  - cross section measurements agree with the SM predictions (NLO,NNLO)
- **Working on MC tunes to describe softQCD**
  - must be ready for high-precision measurement
  - important for searches for new physics
- **Very good detector performance**.
  - ATLAS is well prepared to enter new territory – physics beyond the SM
- **The LHC is still in its early days of operation but makes steady progress toward its ultimate operating conditions**

Only a small fraction of SM results was covered
More results can be found on: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Backup

ATLAS detector

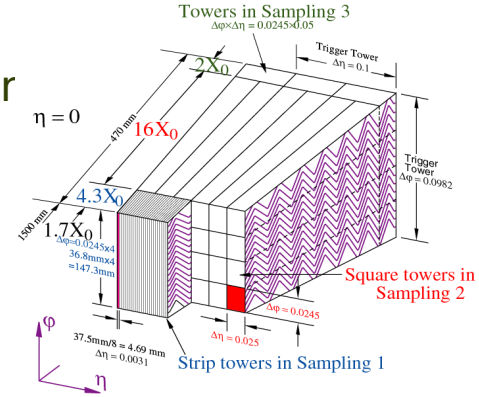


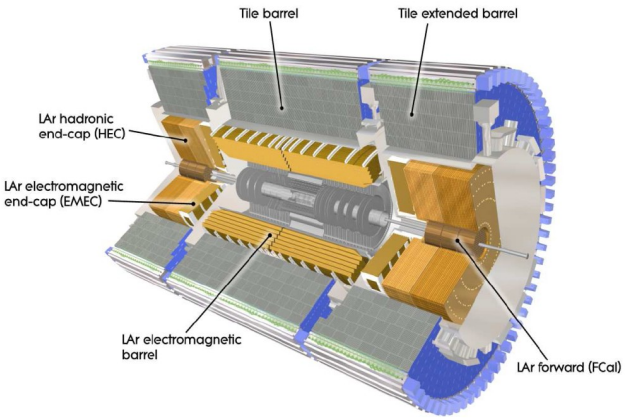
Inner Detector (ID) in 2 T solenoidal B-field

- Pixel: 3 layers(b)+2x3 disks(e) $\sigma_{r\varphi}$~10μm,σ_z~115μm
- SCT: 4 layers(b)+2x9 disks(e) $\sigma_{r\varphi}$~ 17μm,σ_z~580 μm
- TRT: 73 layers (b) + 2 x 160 layers (e) $\sigma_{r\varphi}$~ 130 μm

Electromagnetic Calorimeter - Liquid Argon - with an 'accordion geometry :

170000 readout channels
3 longitudinal layers with cell of Δr
- (0.003-0.006)x0.1 (1st layer)
- 0.025x0.025 (2nd layer),
- 0.050x0.025 (3rd layer)
- active depth X0=6,16,3 at η=0





Presampler for |η|<1.8

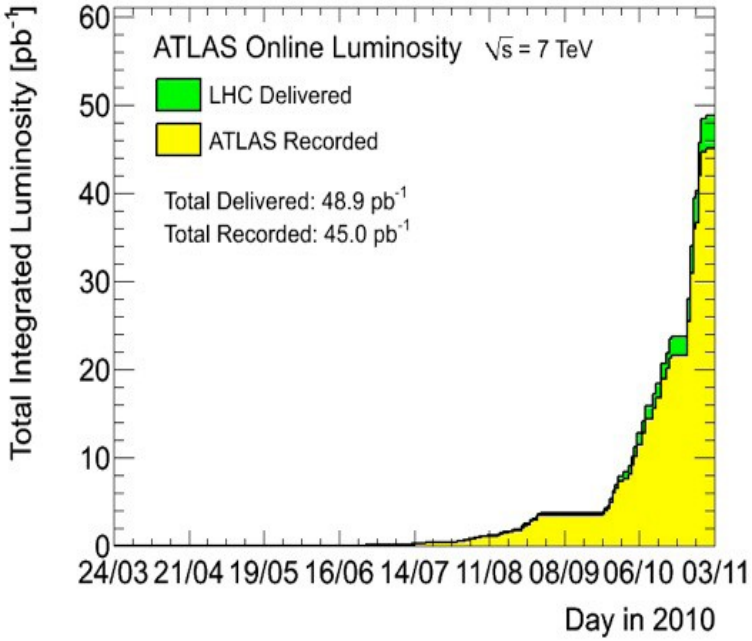
- ΔηxΔφ~0.025x0.1
- σ(E)/E = (10-17%) (η) / √E (GeV) ⊕0.7 %

Hadronic Tile Calorimeter - sampling calorimeter (iron + scintillating tiles)

- 5000 readout channels

ATLAS data taking

LHC News: http://lpc.web.cern.ch/lpc/



Main emphasis of this talk – pp collisions at 7 TeV

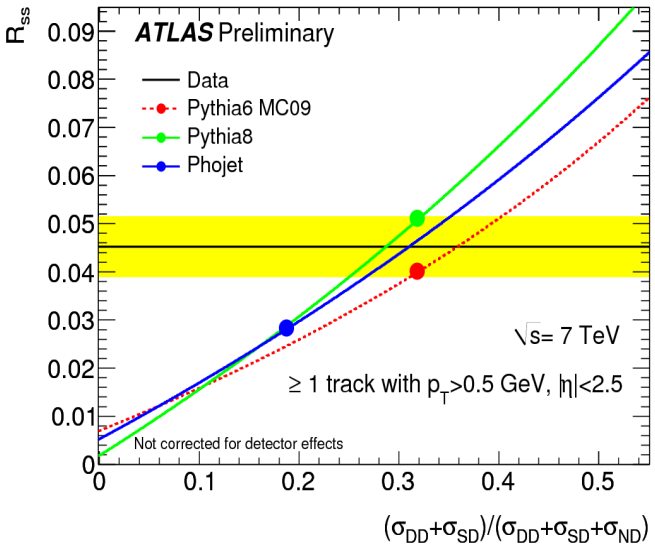
- **pp collisions at 0.9, 2.36 and 7 TeV**
- **Total number of collisions at 7 TeV (31/10/2010): ~3.2 trillion (ATLAS)**
- **Heavy-ion collisions**
  - see I.Grabowska-Bold's talk
- **Recent configuration for pp collisions:**
  - ~300 colliding bunches in ATLAS
  - peak luminosity ~10^{32} cm^{-2} s^{-1}
- **Plans for 2010-11(12?) runs:**
  - increase peak luminosity by x 2
  - up to 800 bunches per beam
  - collect ~1 fb^{-1}

Observation of diffraction

$$\sigma(pp) = \sigma(el) + \sigma(ND) + \sigma(SD) + \sigma(DD)$$

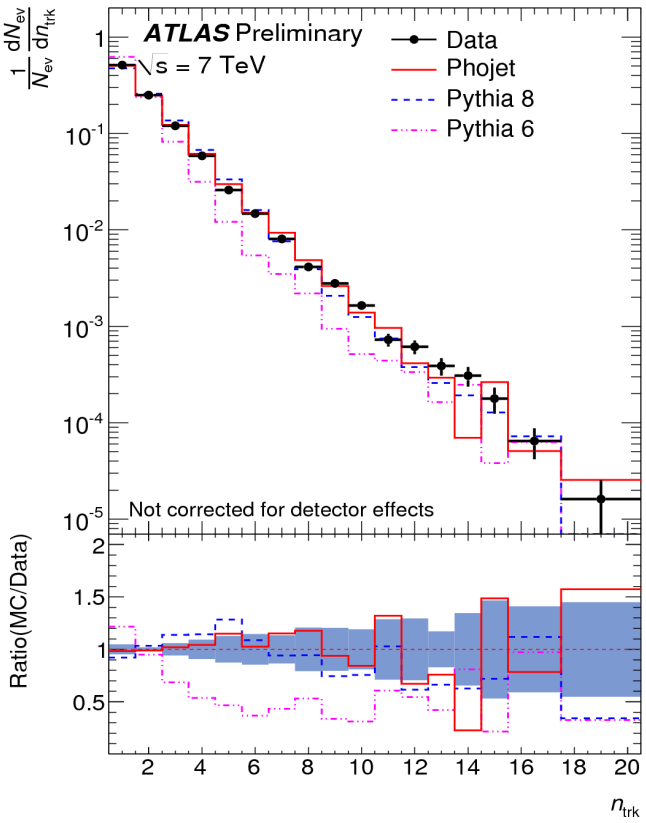
30%

- Uncertainty for luminosity measurements
- Introduce uncertainty for MC tuning
- Hard component is not well known



The ratio of events with hits only on one side of the MBTS scintillators to events with any hits in the MBTS scintillators

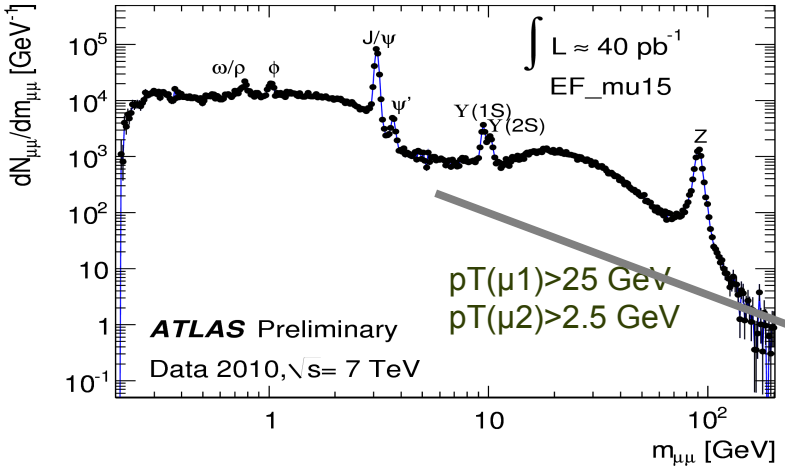
(single-sided MBTS requirement)



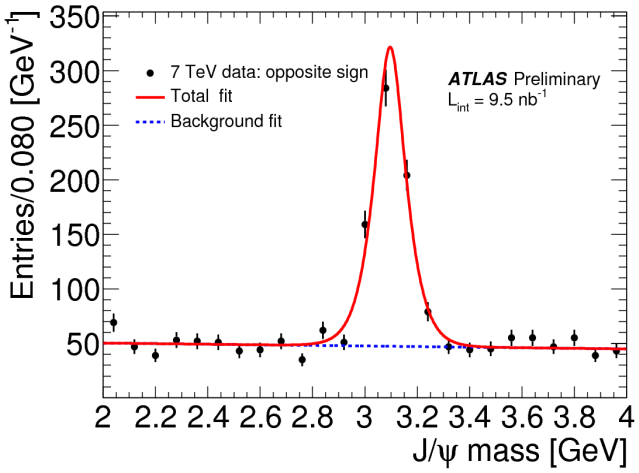
PYTHIA8 & PHOJET (with 30% diffraction) describes well the rate & multiplicities for diffractive events

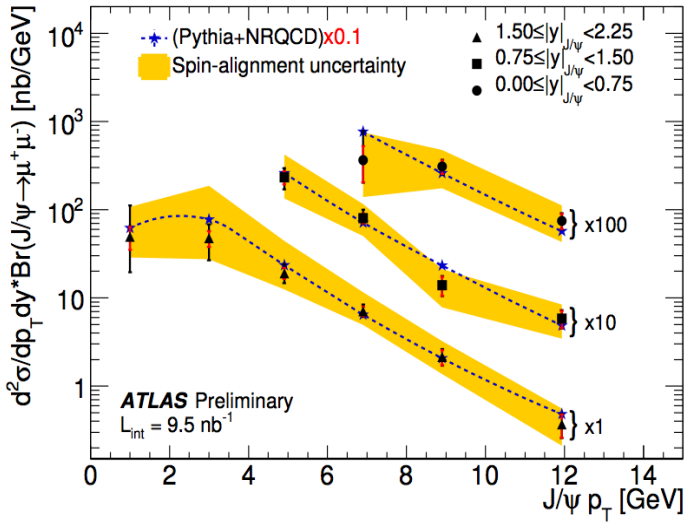
Charmonium production

- In many areas, ATLAS is still in the phase of "rediscovery" of heavy-flavor states
- High-precision measurements at the new energy frontier have started to emerge



First measurement of the differential cross section for the J/ψ→μμ resonance



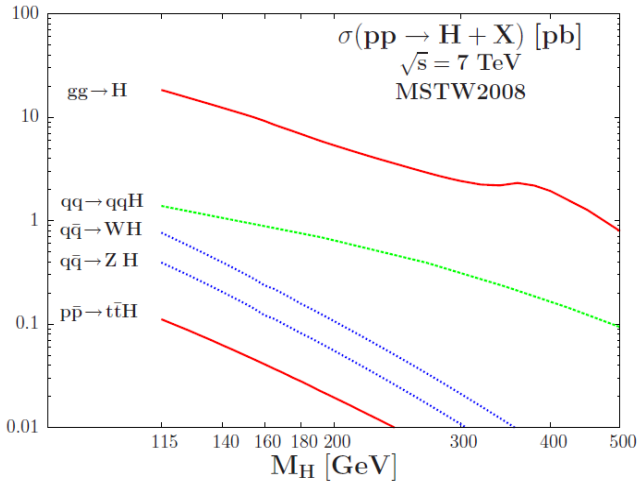


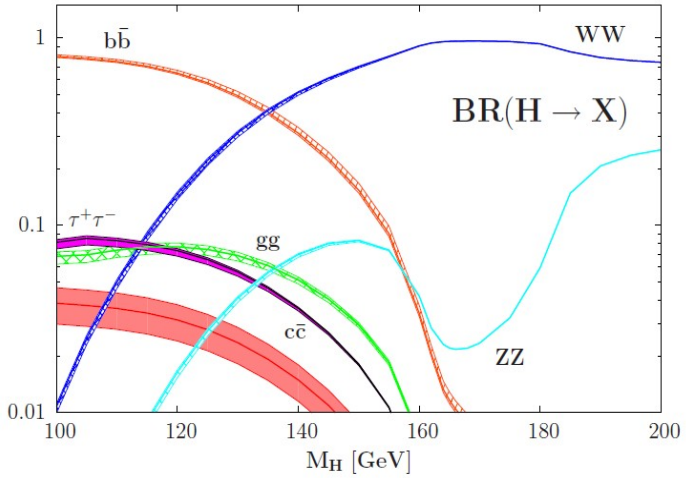
PYTHIA (+Colour-Octet Mechanism) with MC09 tune is in good agreement with the data
(note spin-alignment uncertainty)

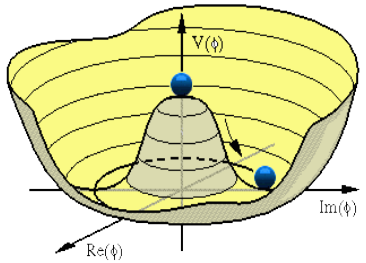
From QCD to high-pT EWK sector

- Better theoretically understood (in many cases with 1% precision)
- Simpler environment to test SM (electron, muon signatures)
- W and Z cross sections are among the first measurements
  - <1% precision measurement after for 1 fb^{-1} (next year!)
- Main channel for Higgs hunting (and main background!)

J.Baglio, A.Djouadi arXiv:1012.0530



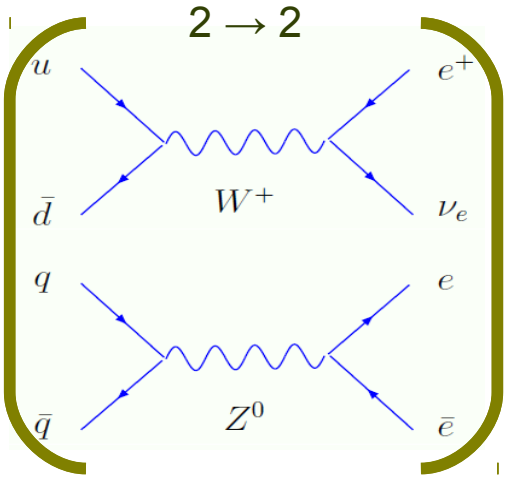




Probing High-pT EWK sector

Inclusive W/Z measurements:

- Precise test of NNLO QCD
- Probing PDF
- Tune MC model parameters
- Decay into easily identifiable leptonic states
- Experimental view:
  - Establishing experimental procedure for calibration, trigger, alignment, luminosity and finally a gateway to probe SM at highest CM energies



W+jet measurements

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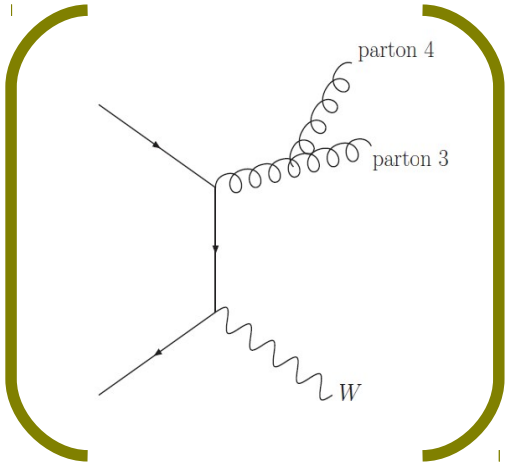
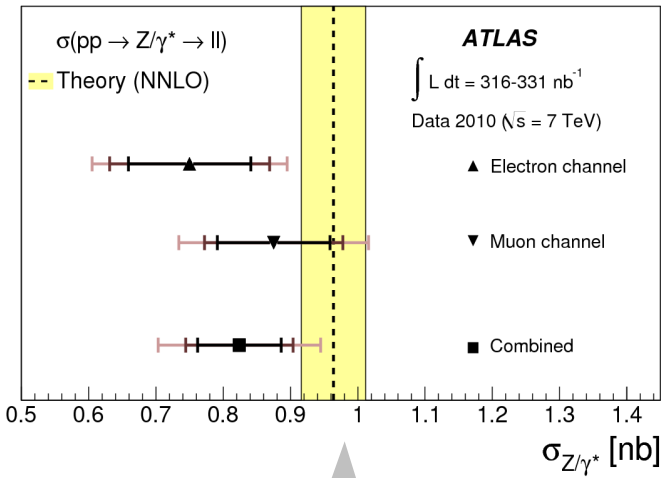
- Precise test of QCD matrix elements, PDF
- Important background for tt, single-top, Higgs searches

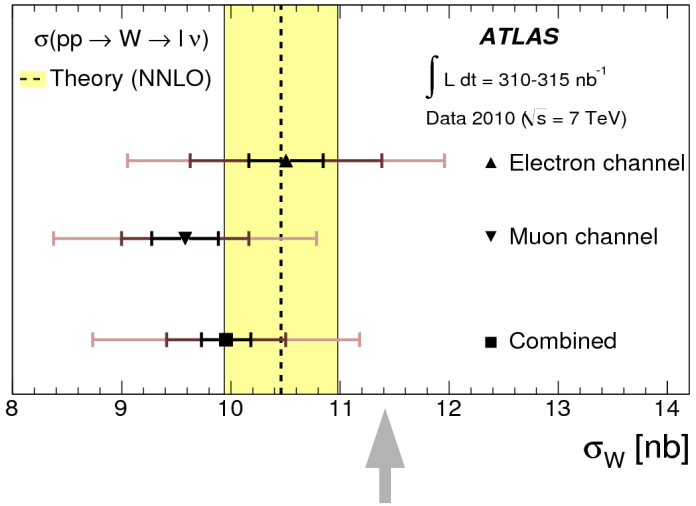


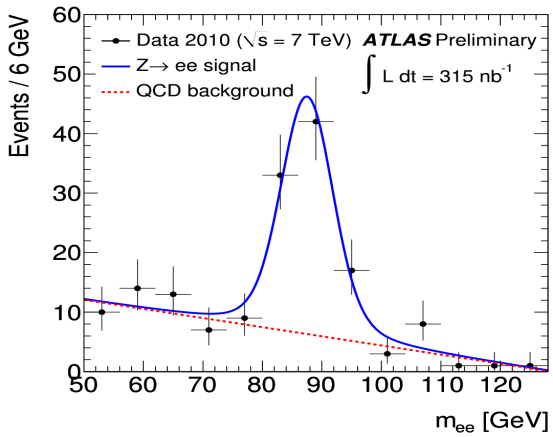
(See Pawel Malecki's talk)

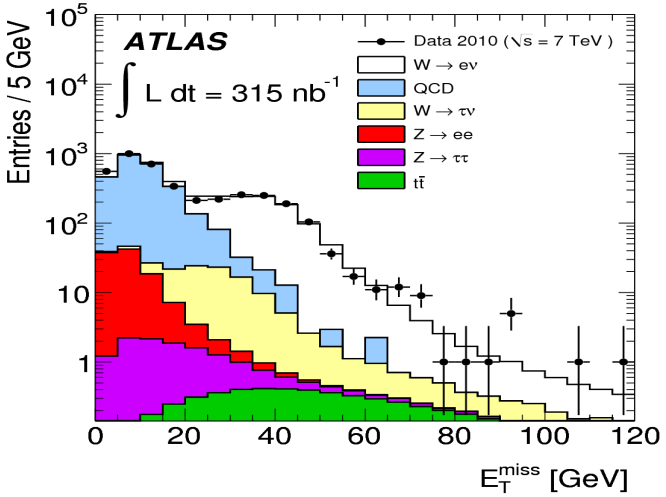
Probing High-pT EWK sector

ATLAS arXiv:1010.2130









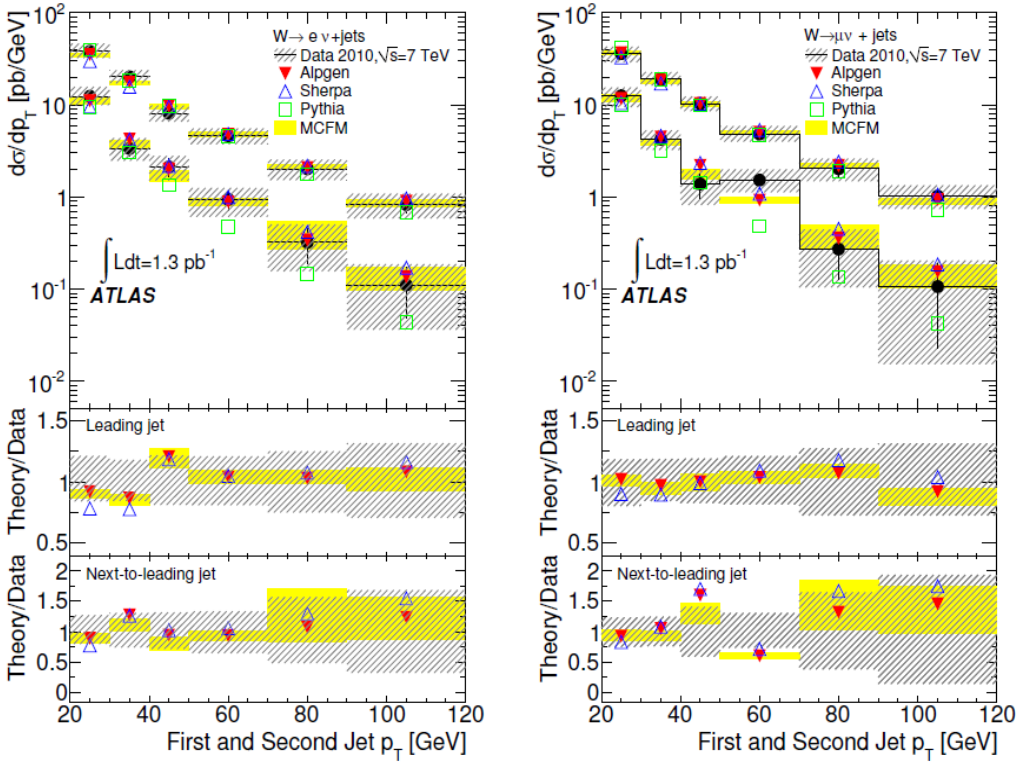
"Golden" channels

- $Z \rightarrow e+ e-$ ($\mu+\mu-$)
- W: isolated lepton + missing E_T

- EWK cross sections at highest CM energies!
- Perfect agreement with the SM

W+ jets measurements

ATLAS arXiv:1012.5382



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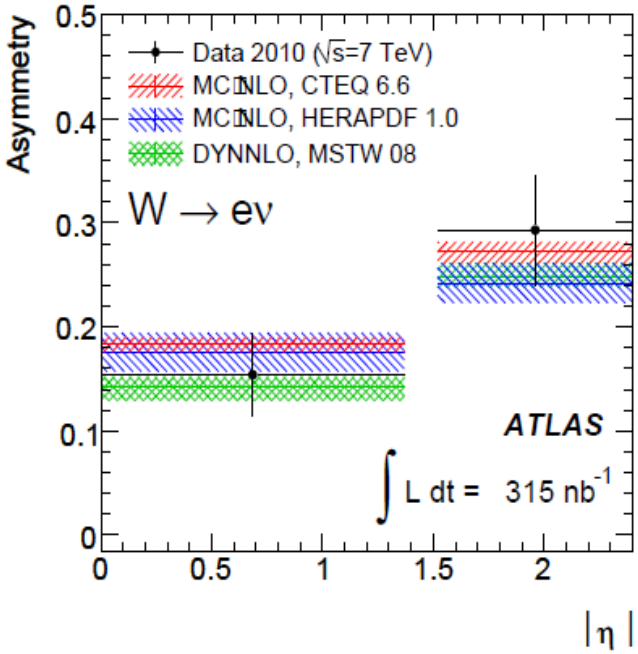
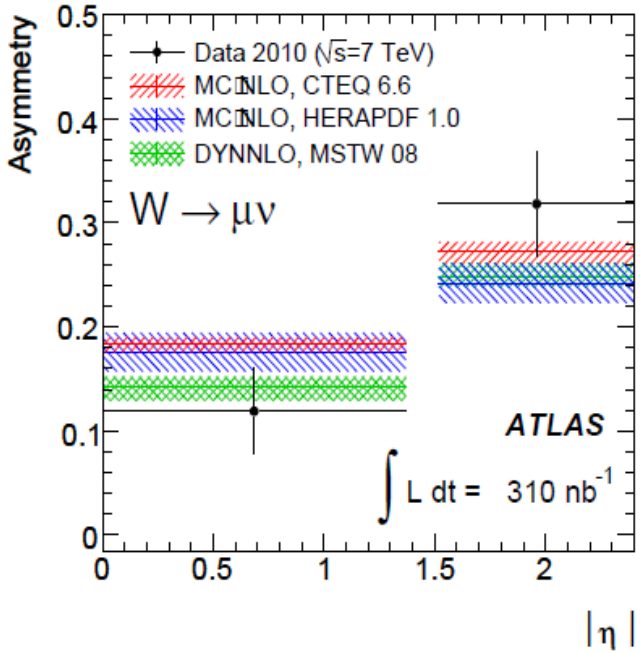
- Good agreement with MCFM (NLO QCD) & CTEQ6.6 for <3 jets & LO for >2 jets
  - includes corrections (~10%) for hadronisation & underlying events using AMBT1 tune
- Only MC+PS available for W+4 jets (muon channel)

Lepton charge asymmetries





$$A_\ell = \frac{\sigma^{\text{fid}}_{W^+} - \sigma^{\text{fid}}_{W^-}}{\sigma^{\text{fid}}_{W^+} + \sigma^{\text{fid}}_{W^-}}$$

- charge asymmetry is related to the dominance of **u** quarks to **d** quarks in the proton
  - for proton-anitprotons, W+ and W- are produced in equal quantities
- provides important information about parton distribution functions
- with the current statistics, data agree with all models & all PDF