

Standard Model Results from the ATLAS Experiment

S.Chekanov (ANL)

for the ATLAS collaboration

The Cracow Epiphany Conference

10-12 January, 2011

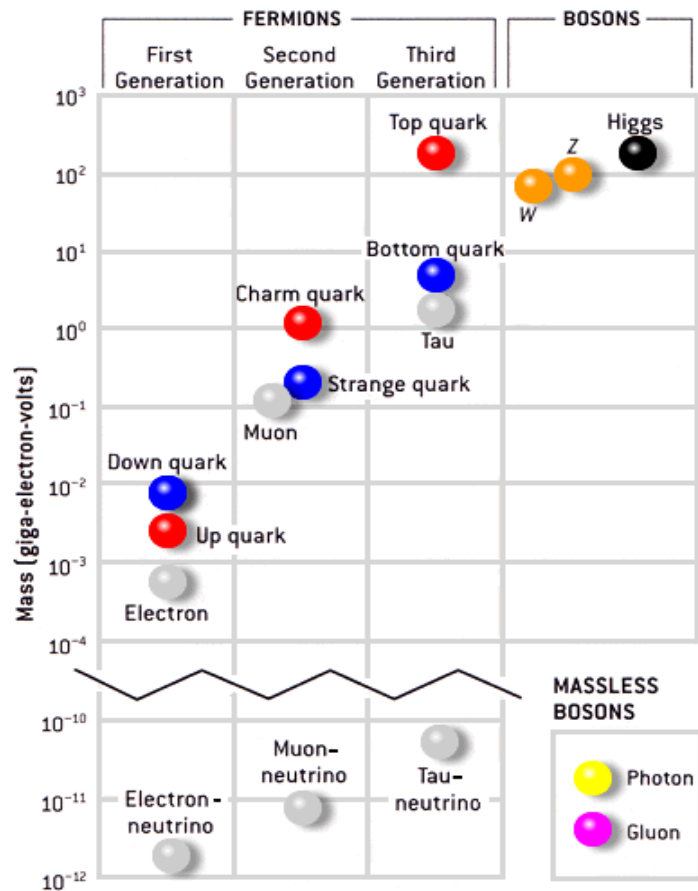
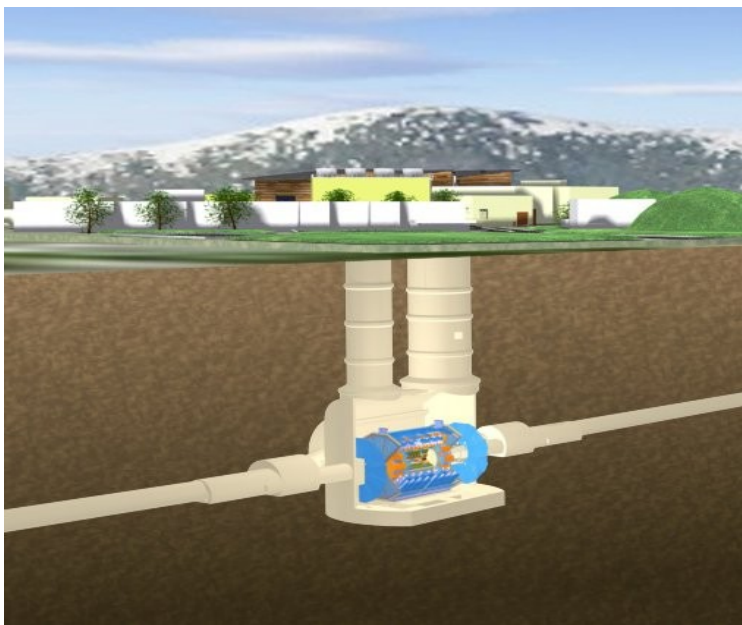


Chart from Scientific American::

17 particles in the Standard Model, together with their masses:

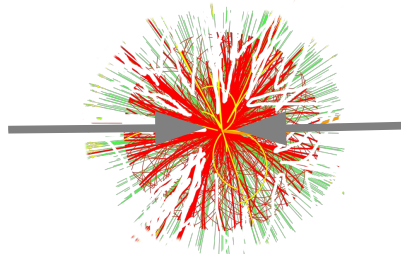


Introduction. SM tests with early data

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”
 $p_T < \text{few GeV}$

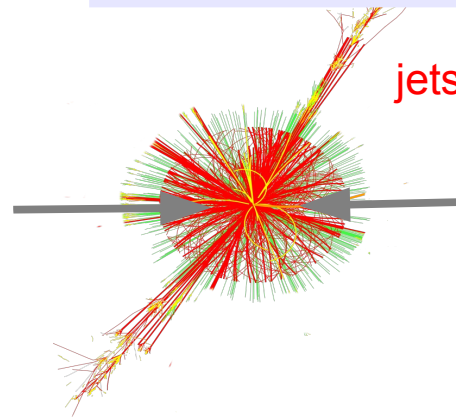


>99.999% collisions:

Tests:

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

“Hard QCD”
 $p_T > \text{tens of GeV}$

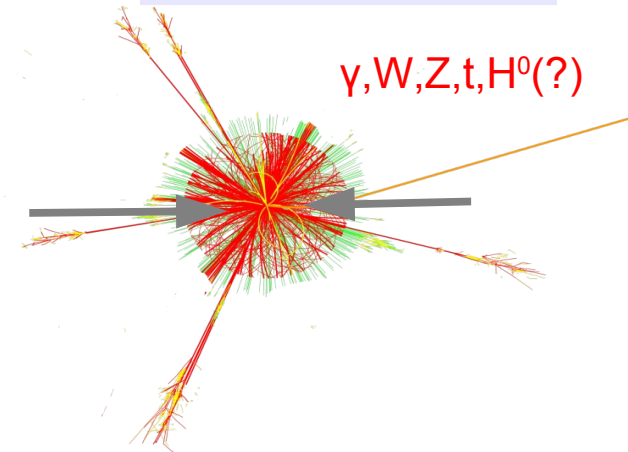


$\sim 10^{-5}$ % collisions

Tests:

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

“Hard EWK”
 $p_T > \text{tens of GeV}$



$\sim 10^{-6} - 10^{-8}$ % collisions

Tests:

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





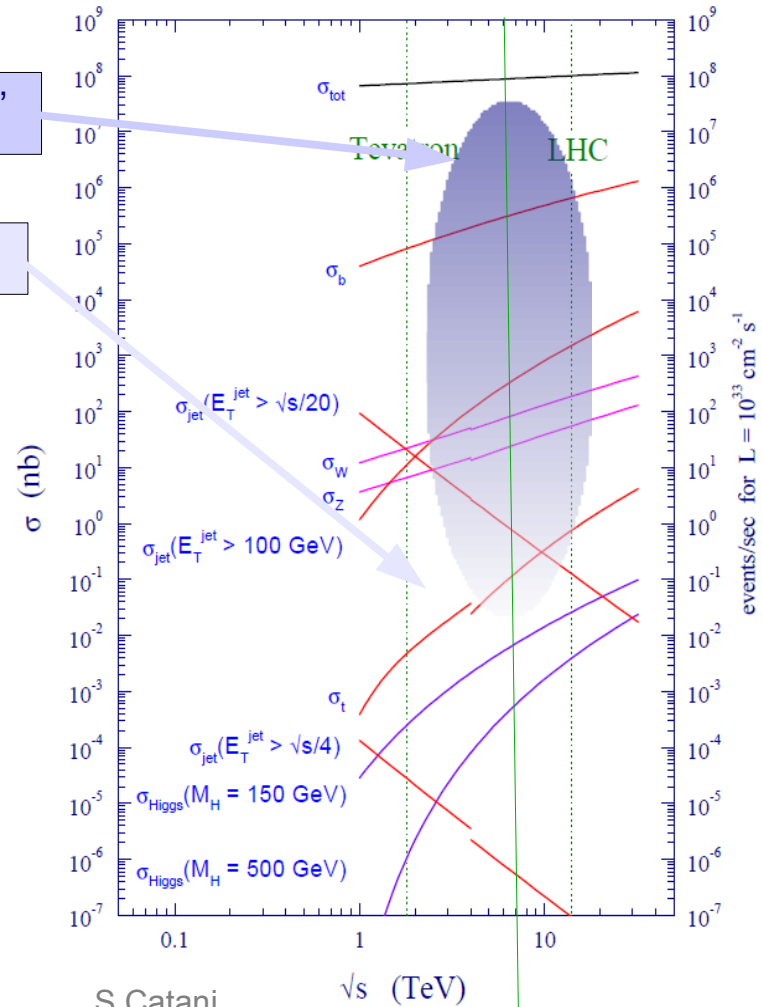
SM processes at the LHC

Current Luminosity
~30 pb⁻¹

“measurements”

“observations”

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



S.Catani
hep-ph/0005233

current energy
7 TeV

* we have 1/3 of this data

SM results from the ATLAS experiment. S.Chekanov (ANL)





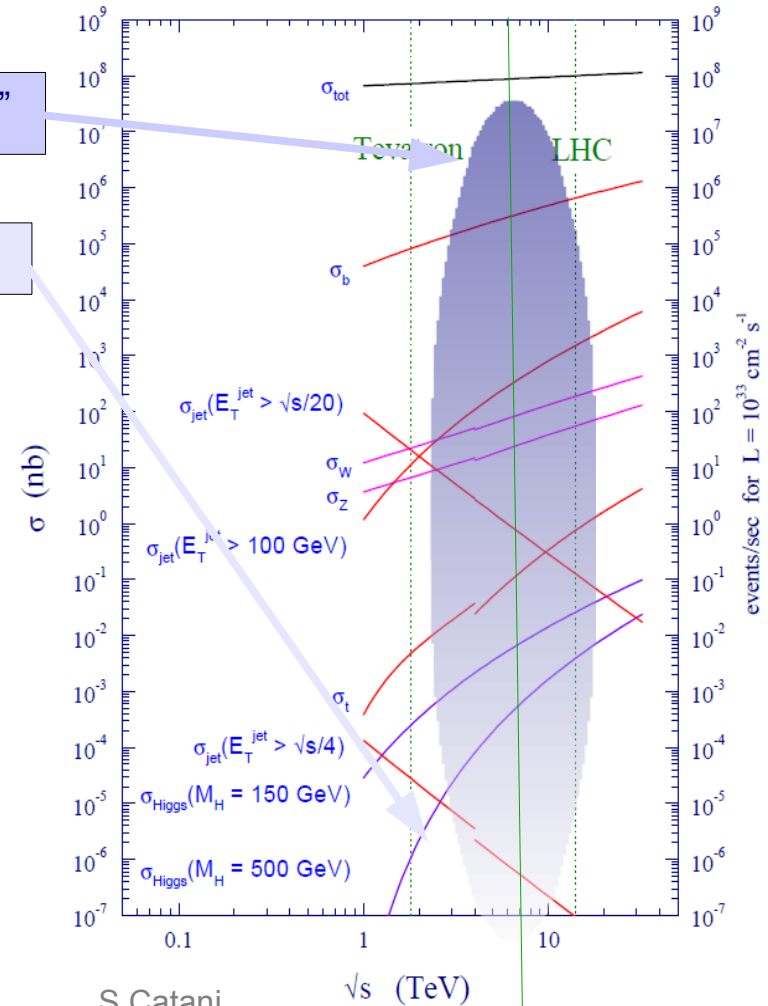
SM processes at the LHC

~ 1 year from now
~1 fb⁻¹

“measurements”

“observations”

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

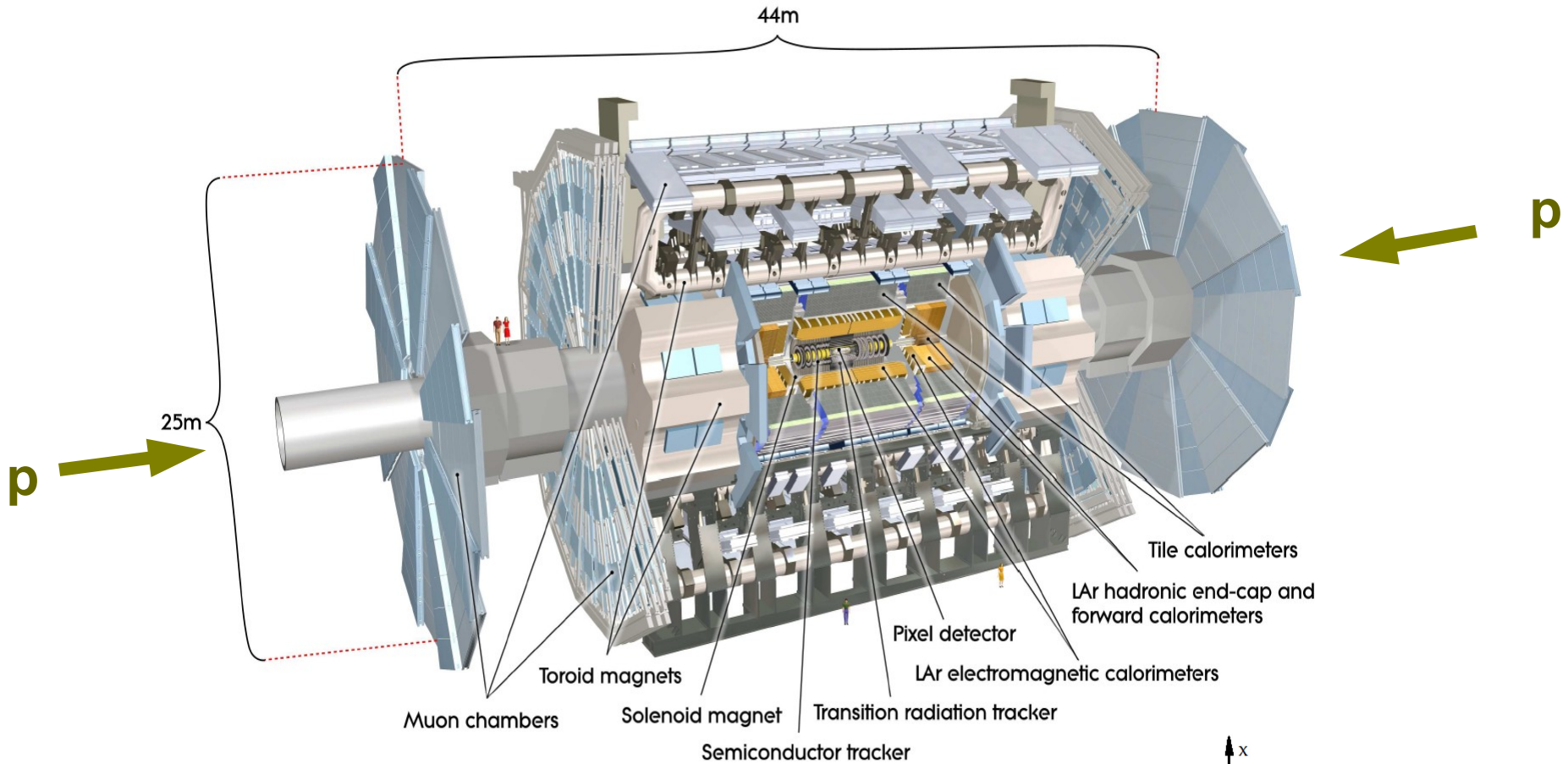


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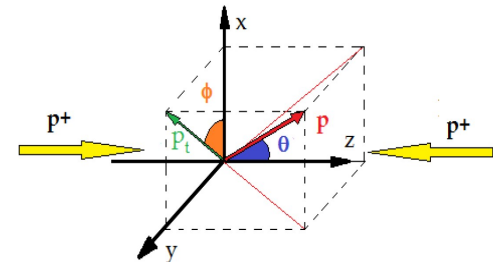
current energy
7 TeV



ATLAS detector



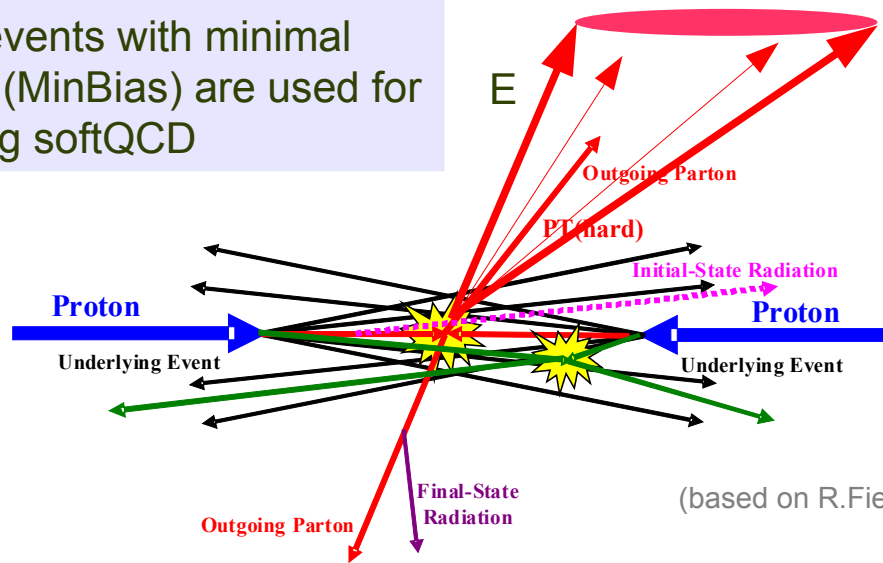
See M.Schatt's talk





New energy frontier: from soft to hard QCD

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



$\sim \log^2 E$ pQCD

$\sim \log(s)?$ Models.. Models..

(based on R.Field's figure)

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)

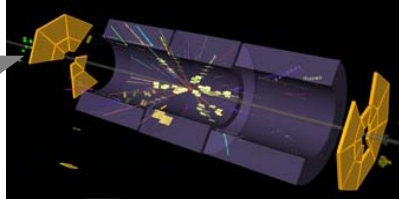




softQCD: Charged particle multiplicities

ATLAS arXiv:1012.5104

Minimum Bias Trigger Scintillators (MBTS)



MBTS

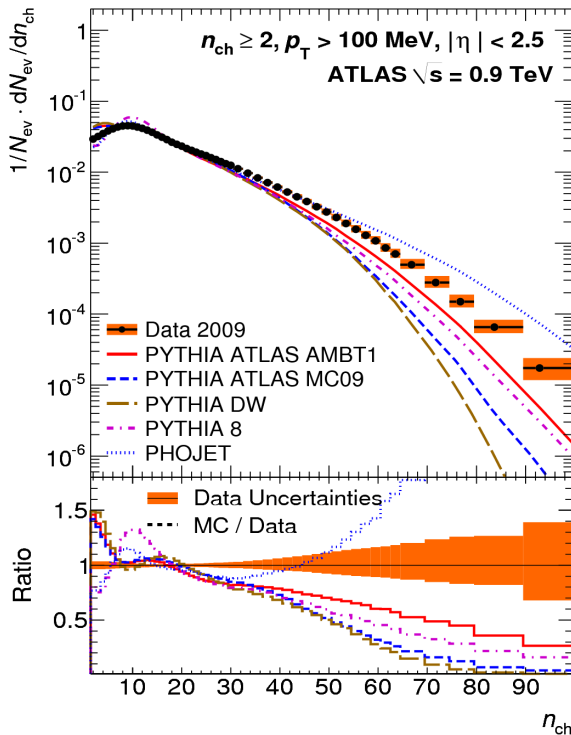
32 plastic scintillators with coverage: $2.09 < \eta < 3.84$

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:

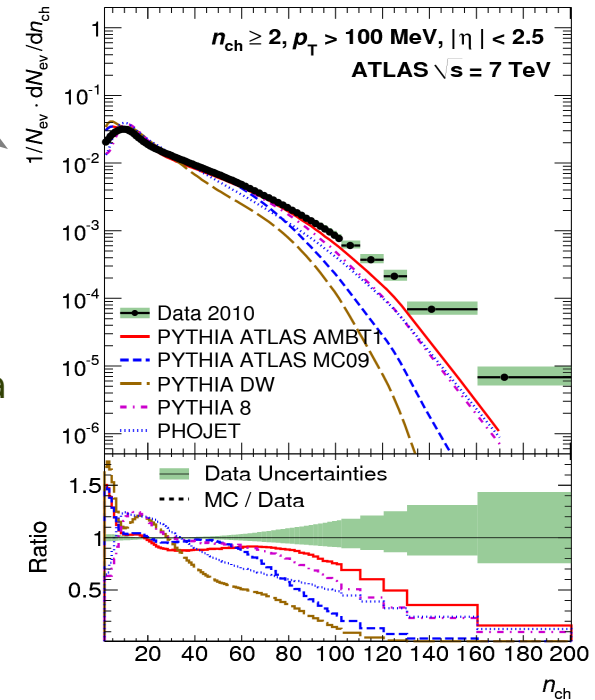
- $p_T > 100$ MeV, $|\eta| < 2.5$ + other track quality cuts



900 GeV

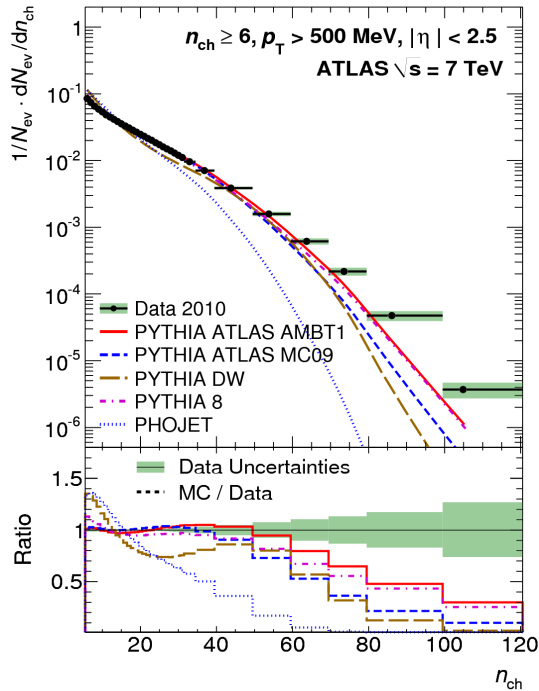
7 TeV

- 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

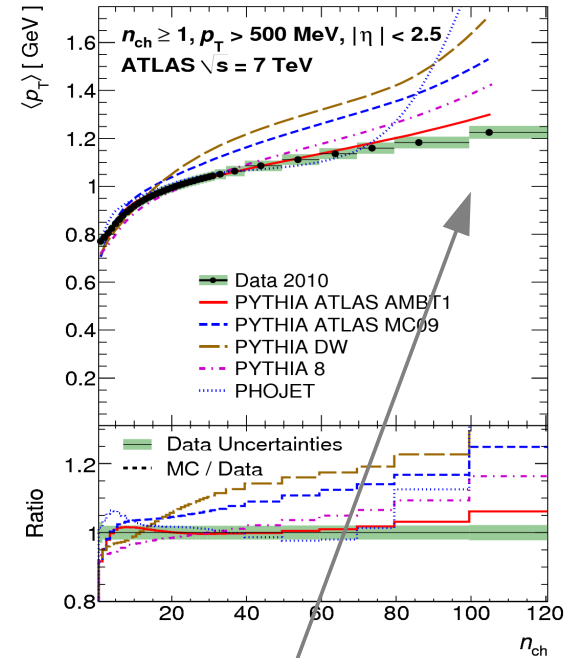
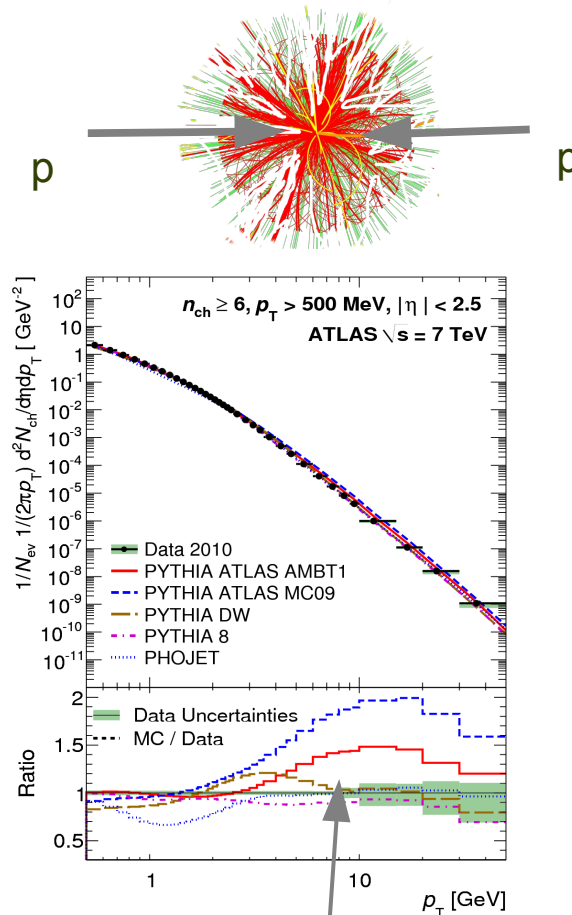




Particle spectra with reduced contribution from diffraction



All pre-LHC tunes of MC models fail



Entering hard QCD

PHOJET completely fails

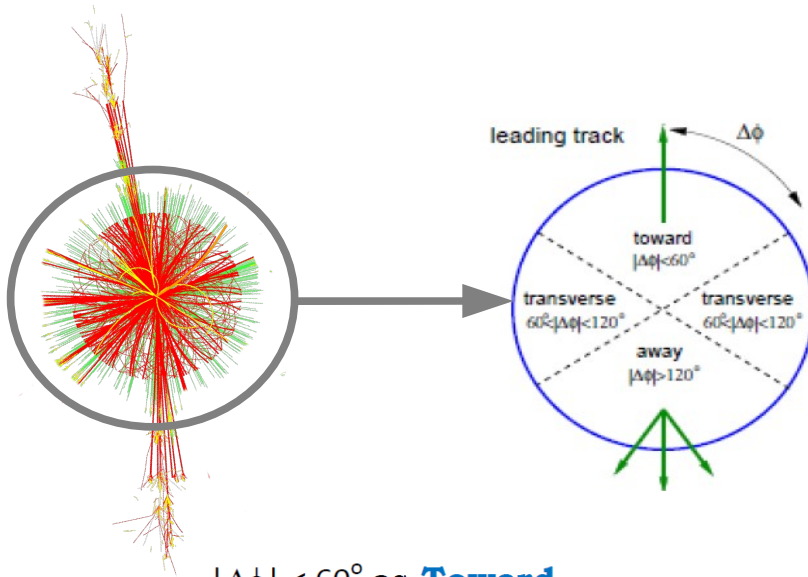
AMBT1 tune improves agreement (but still has problems!):

- increasing probability for head-on collisions (more events with large $N(ch)$, PARP84)
- reducing color reconnection for high-momentum hadrons (reduces $\langle p_T \rangle$, PARP(77))





Studies of Underlying Event in MinBias data



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

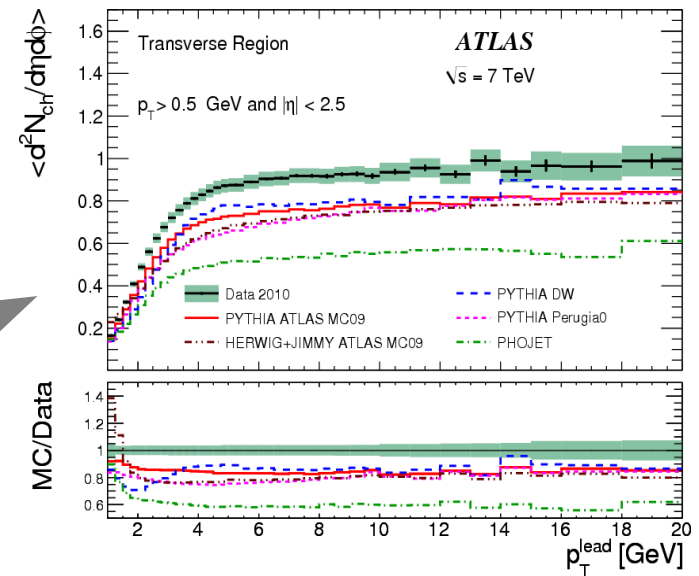
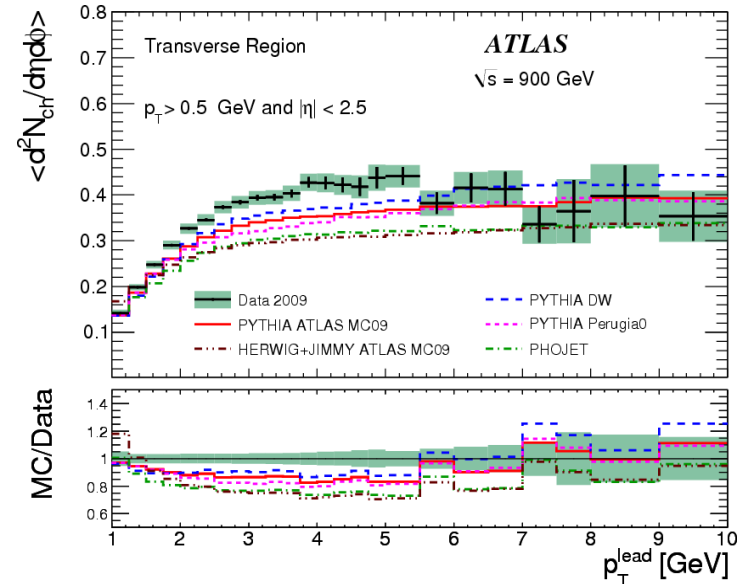
$60^\circ < |\Delta\phi| < 120^\circ$ as **Transverse**

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

All MC models have lower activity in the transverse region

Discrepancies increase with CM energy

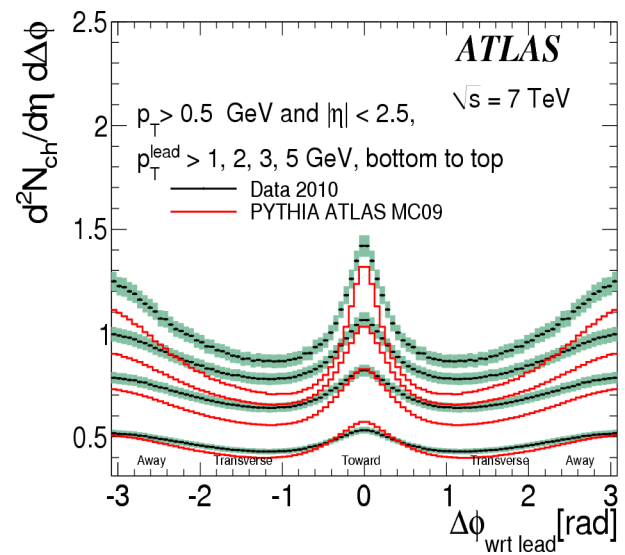
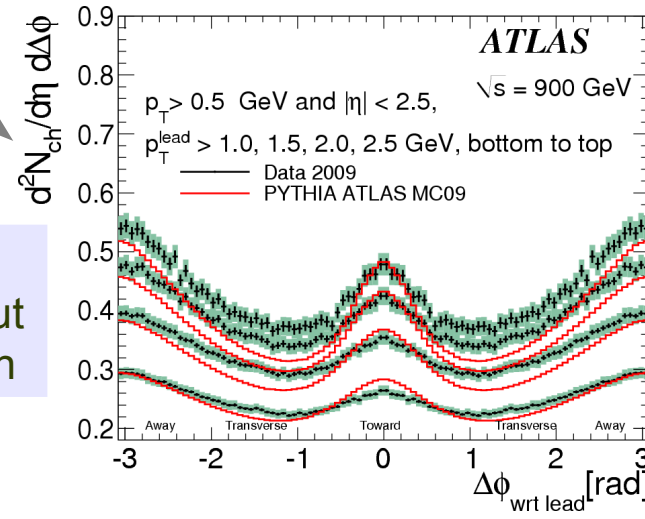
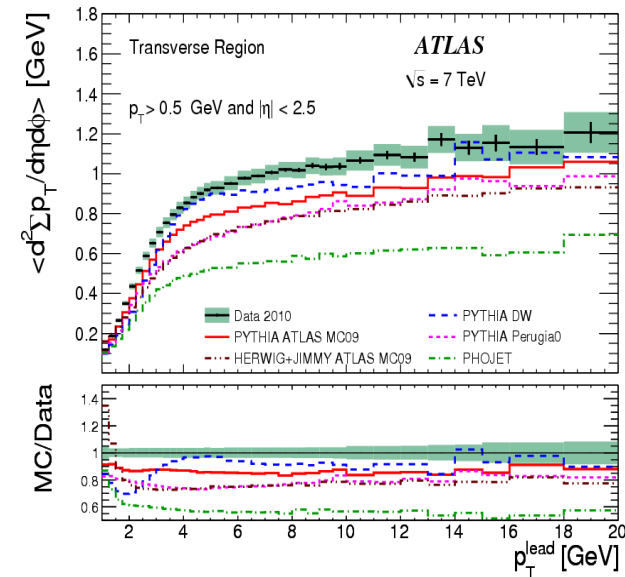
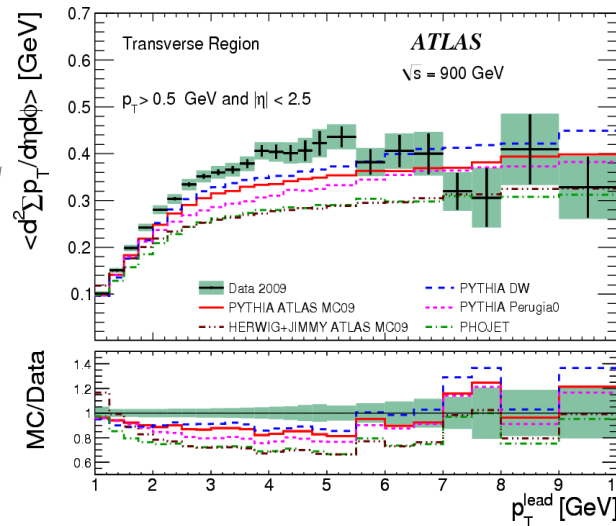
ATLAS arXiv:1012.0791





Studies of Underlying Event in MinBias data

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

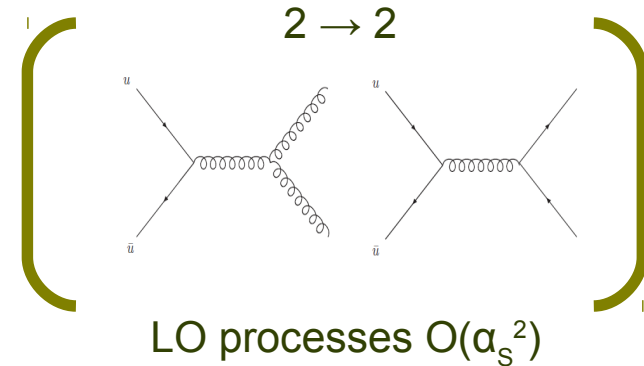


Pre-LHC MC models describe general features, but fail in quantitative description



Jets

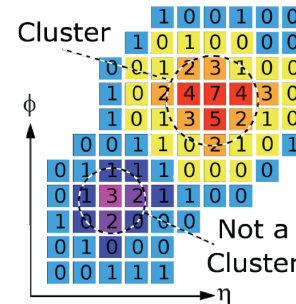
- Jets are sensitive probe of many aspects of pQCD:
 - matrix elements at LO(+PS) and NLO QCD
 - PDF's
 - running α_s
 - refine our understanding of soft QCD
 - important for searches beyond SM
- For 30 pb^{-1} , the reach in jet transverse momentum at the LHC is twice that attained by previous experiments



Input for jet algorithms:

Topological clusters built from calorimeter cells

- follow shower development
- reduce noise



Seeded by cells with $|E| > 4 \times$ (noise level)

Neighboring cells with $|E| > 2 \times$ noise iteratively added (in 3D)

All neighbors around cluster ($|E| > 0$) added

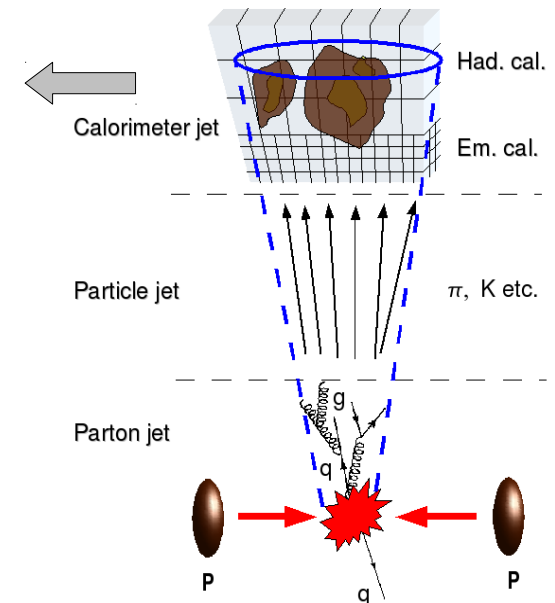


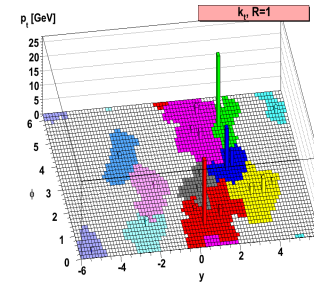
image by P.Weber



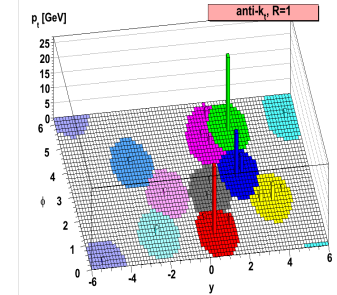


Building jets

- 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

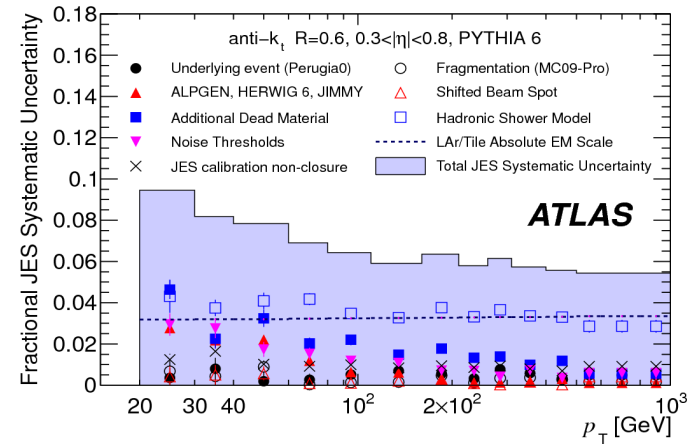


from k_T
to
antiKt



Jet-energy scale

- Dominant uncertainty for all jet-related measurements
- Currently: p_T 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 $|\eta| < 2.8$
- Depends on p_T and η



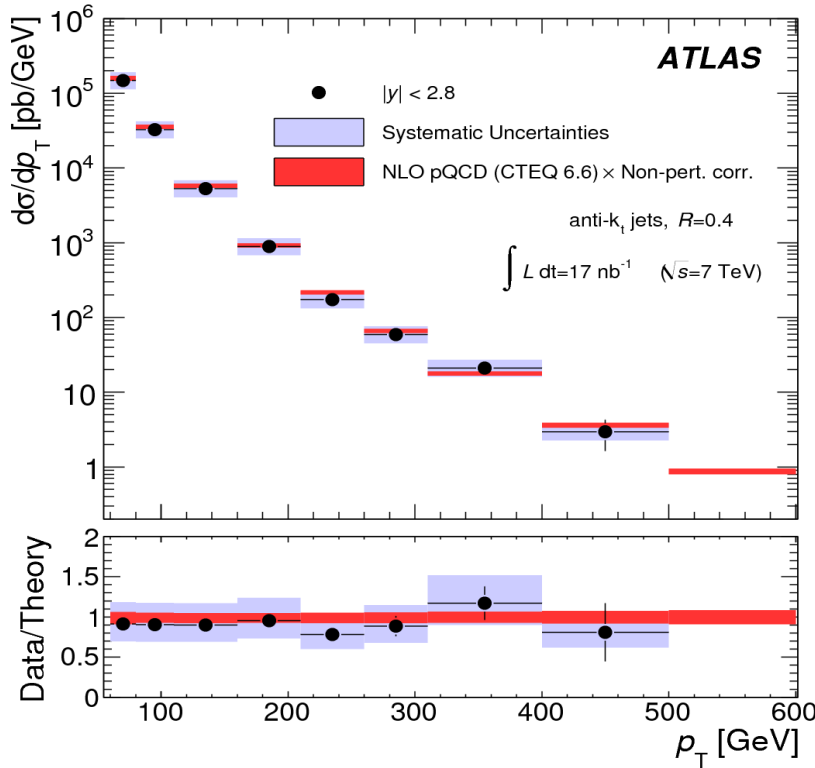


Inclusive jet production

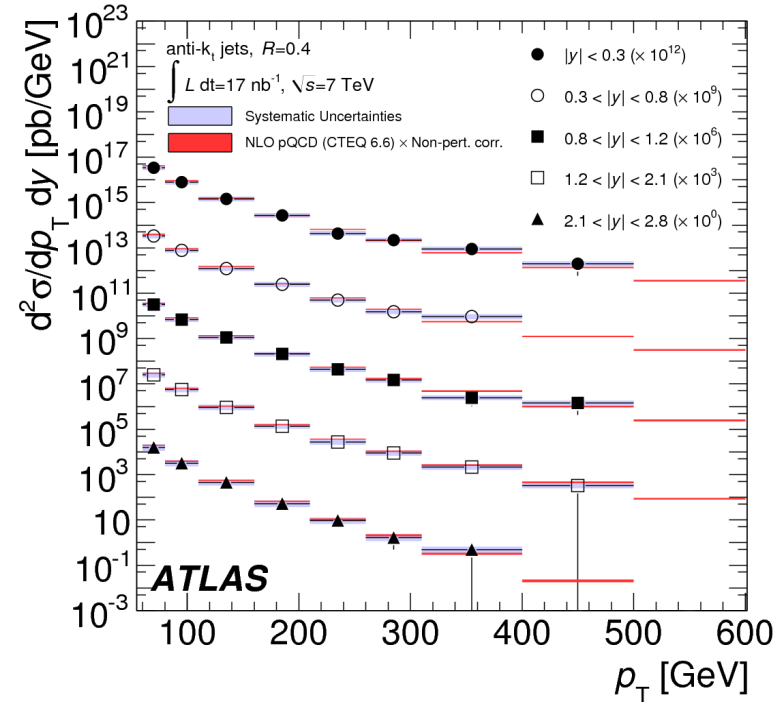
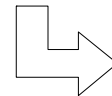
ATLAS arXiv:1009.5908

Very good agreement with NLO QCD & CTEQ6.6

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



cross section differential in rapidity



Theory:

NLO QCD (NLOJET++/JETRAD) together with softQCD corrections ($\sim 5\%$) from PYTHIA model

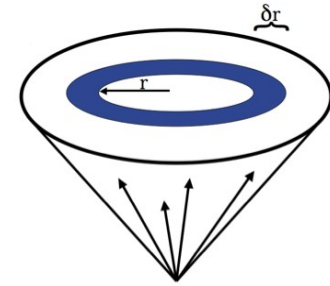
11% uncertainty on luminosity measurement is not shown





Jet shapes

Hard interaction is always associated with extra QCD radiation

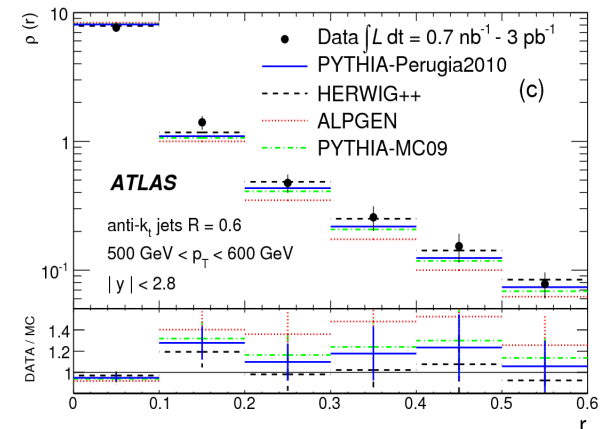
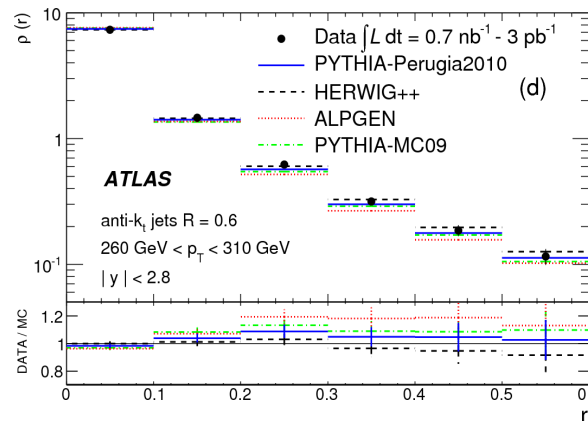
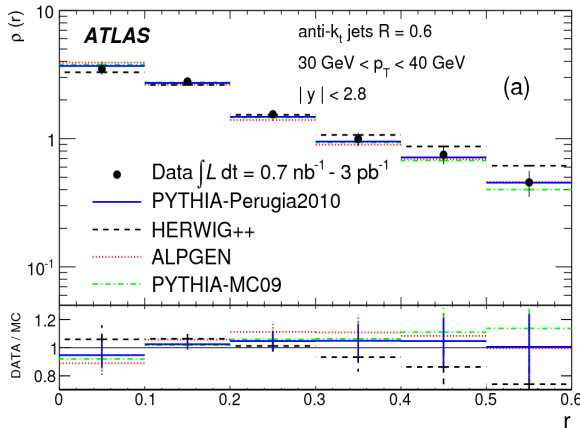


Essential for understanding:

- 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

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

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

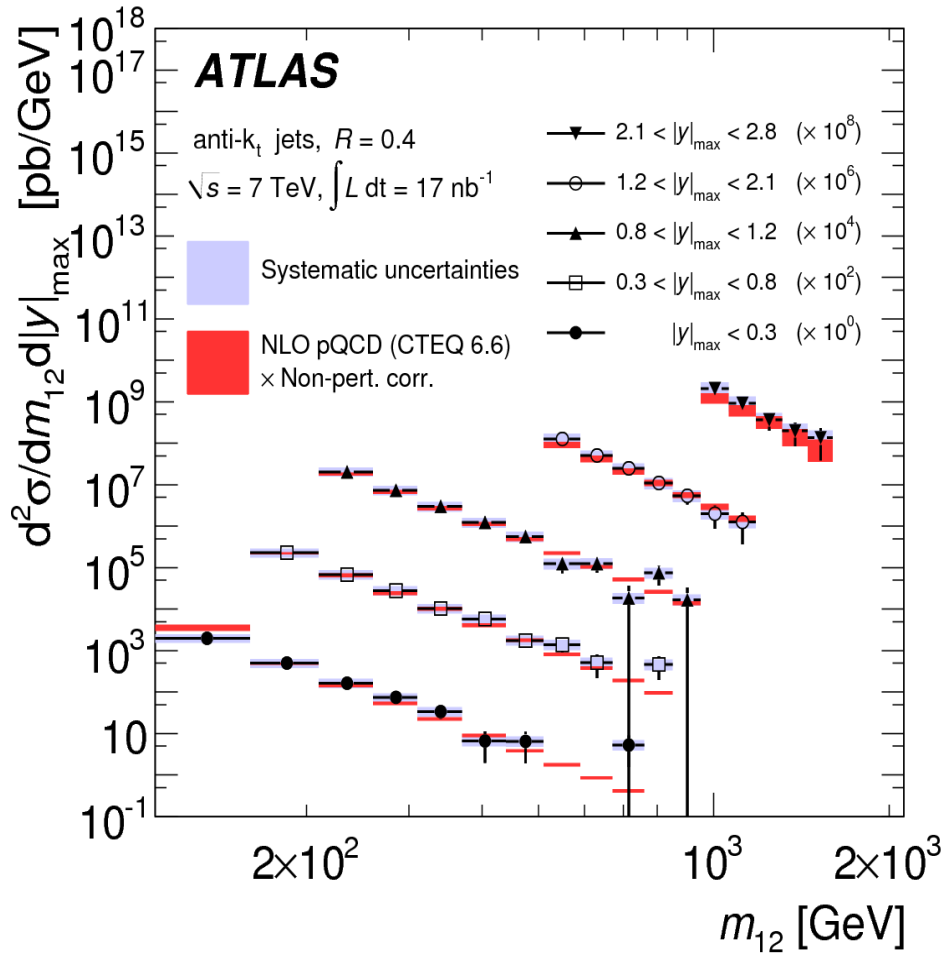


- Jets become narrower as jet p_T increases
- Good agreement with LO+PS Monte Carlo models
- ALPGEN (with HERWIG 6.5+JIMMY) generates too narrow jets at large p_T





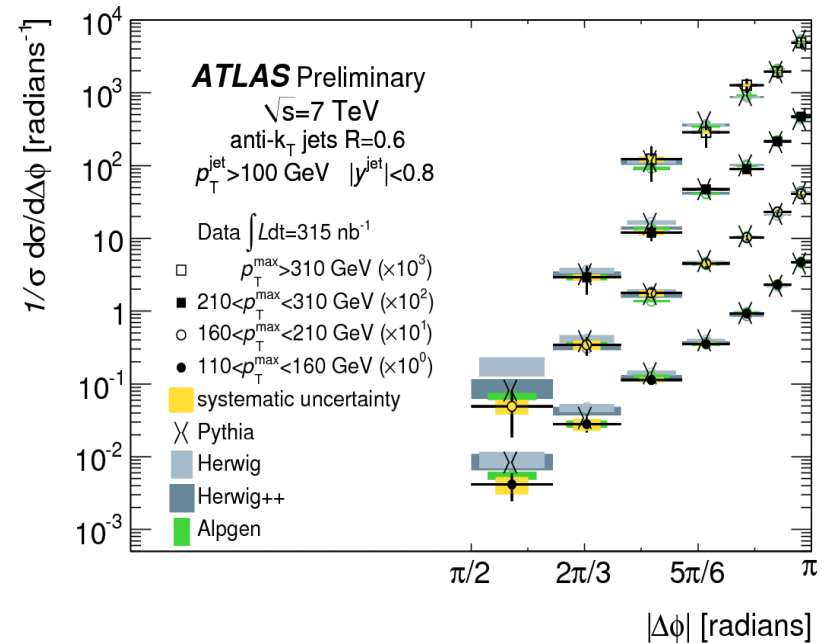
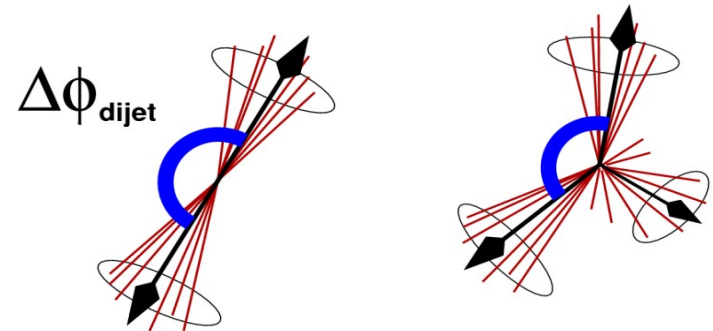
Dijet measurements



Perfect agreement with NLO QCD & CTEQ6.6.

Azimuthal decorrelation:

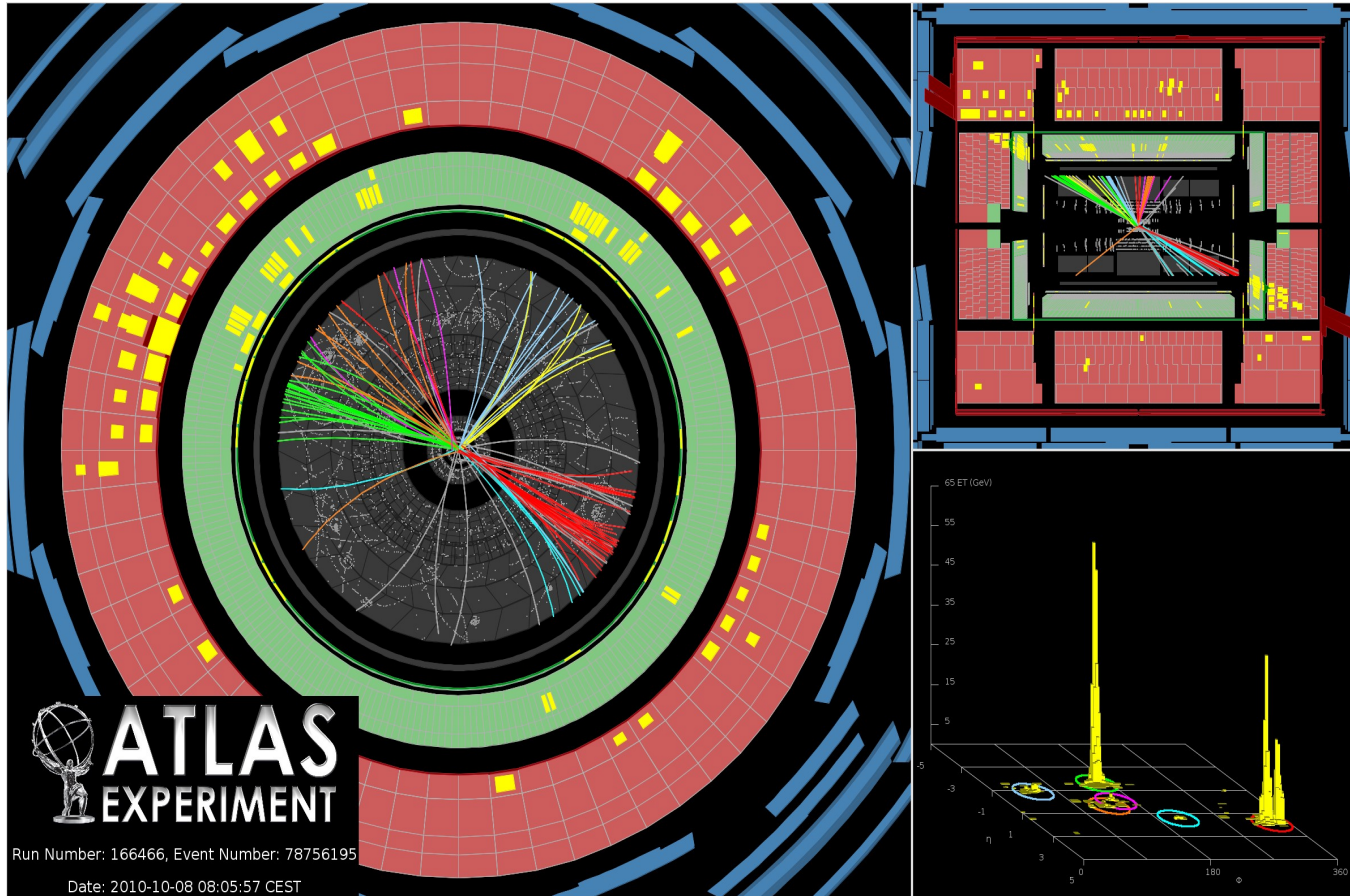
Looking at softer QCD without reconstructing soft jets!





Highest-mass dijet event

$p_T(\text{Jet1})=670 \text{ GeV}$ $p_T(\text{jet2})=610 \text{ GeV}$ $M(\text{jj})=3.4 \text{ TeV}$



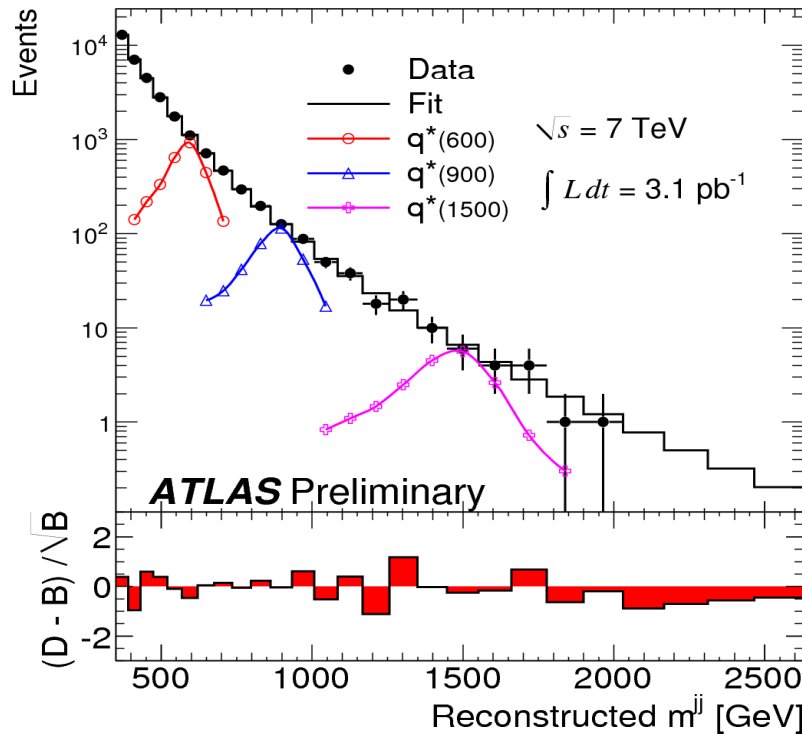


Search for New Particles in Two-Jet Final States

ATLAS arXiv:1008.2461

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

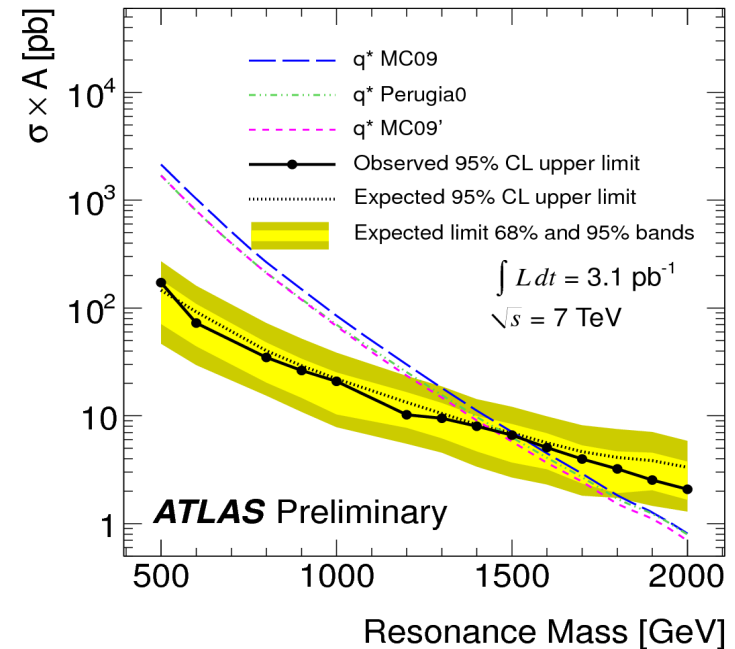
$$M_{jj} = \sqrt{(E_1 + E_2)^2 - (P_1 + P_2)^2}$$



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



3.1/pb: ATLAS-CONF-2010-093

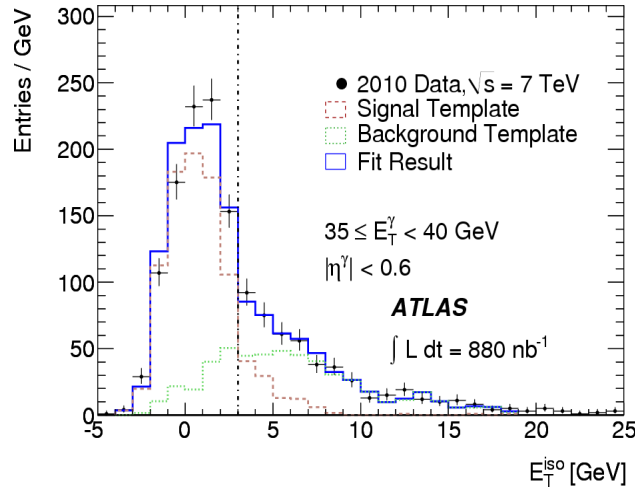
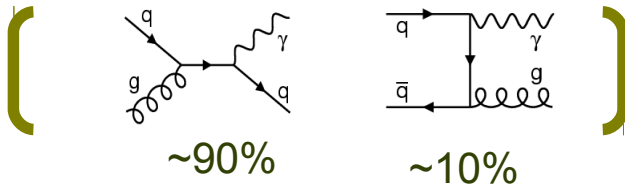
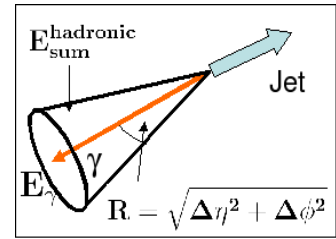




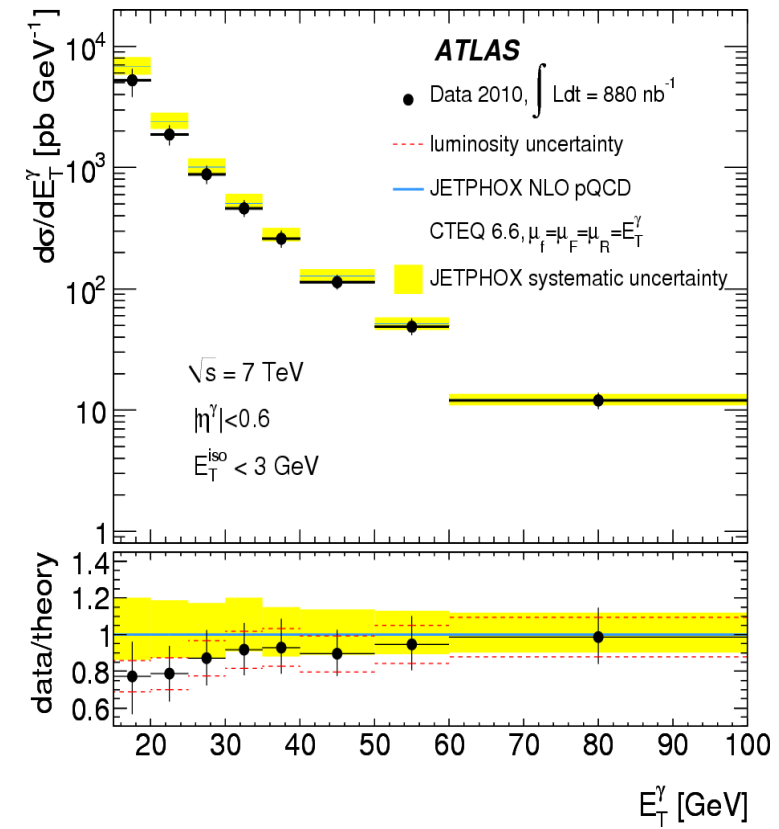
Direct photon production

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



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



Good agreement with NLO QCD & CTEQ6.6

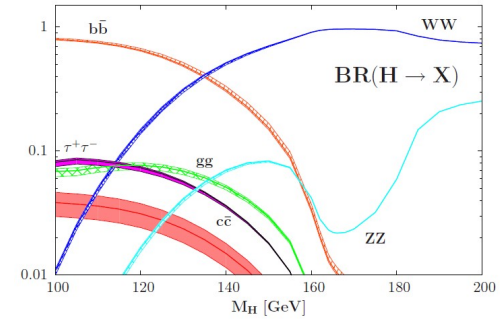




From QCD to high-pT EWK sector

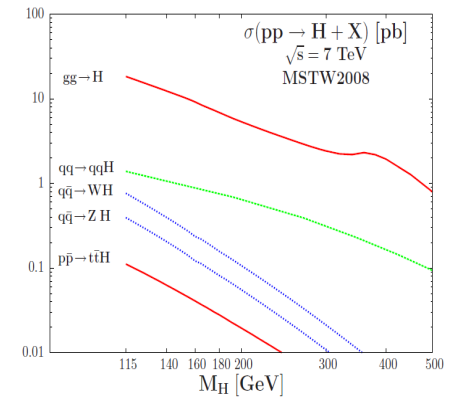
J.Baglio, A.Djouadi arXiv:1012.0530

- 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!)



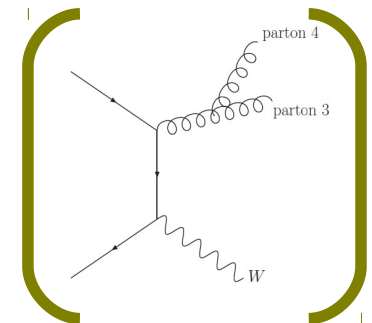
Inclusive W/Z measurements: (See Pawel Malecki's talk)

- 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

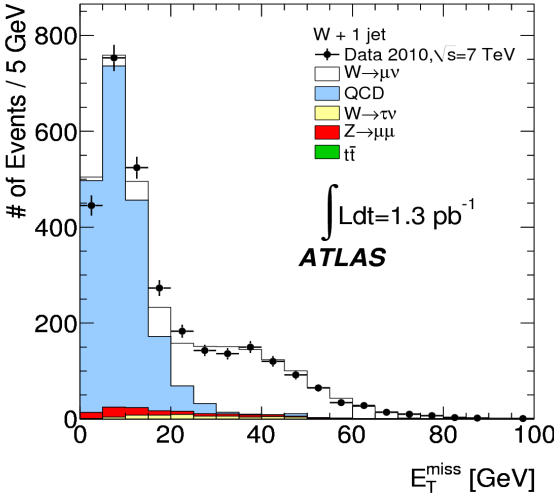
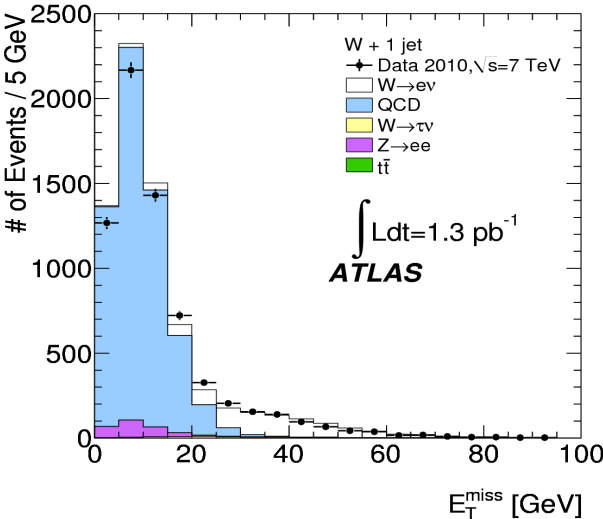
- Constrain measurements to well-known physics
- Precise test of QCD matrix elements & PDF
- Important background for top-antitop, single-top, Higgs searches, etc





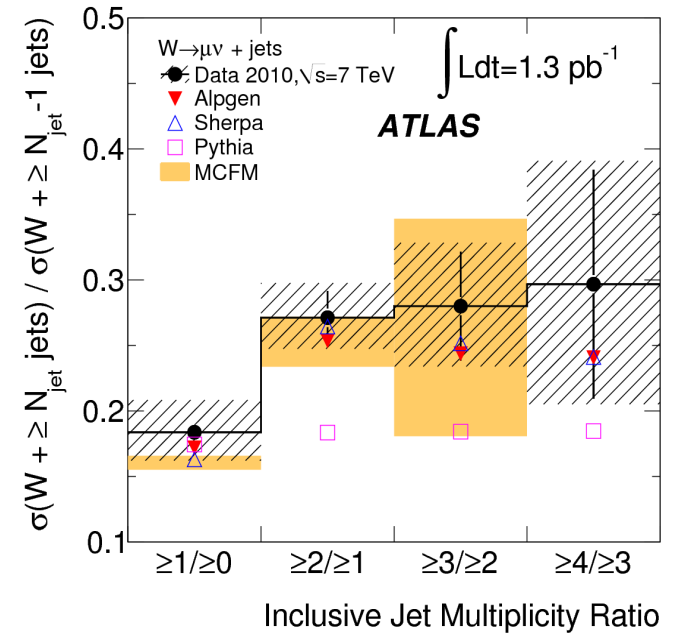
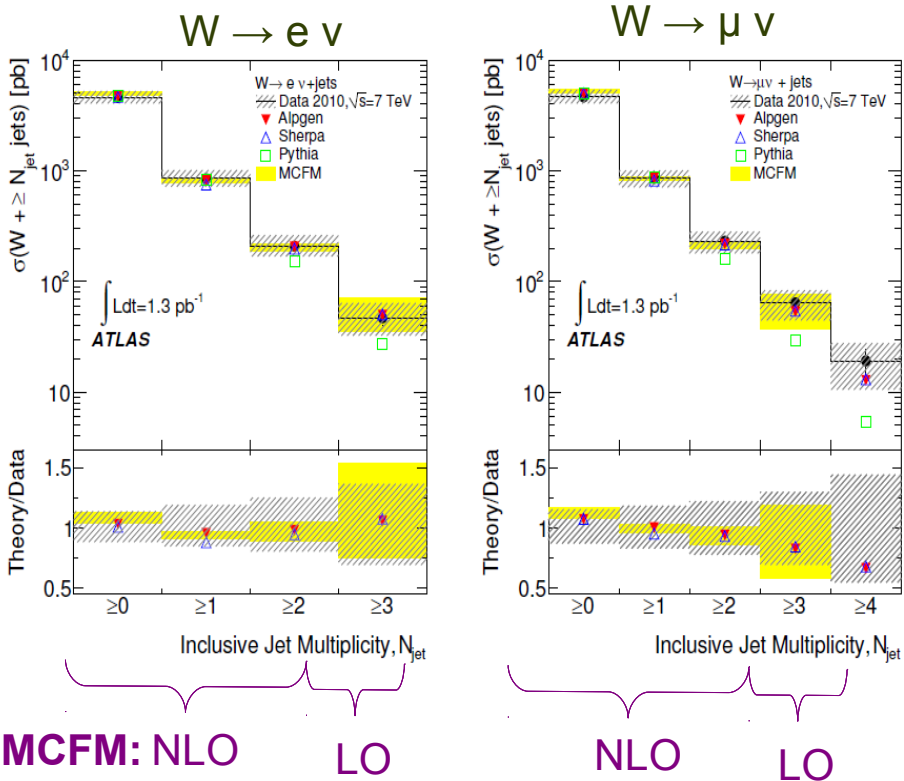
W+ jets measurements

- Events are selected by requiring:
 - $E_T(e) > 20 \text{ GeV}$ or $E_T(\mu) > 20 \text{ GeV}$ & $|\eta| < 2.4$
 - $E_T(\text{miss}) > 25 \text{ GeV}$ & $M_T > 40 \text{ GeV}$
 - antiKT(jet) with $R=0.4$ & $p_T > 20$ & $|\eta| < 2.8$. 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





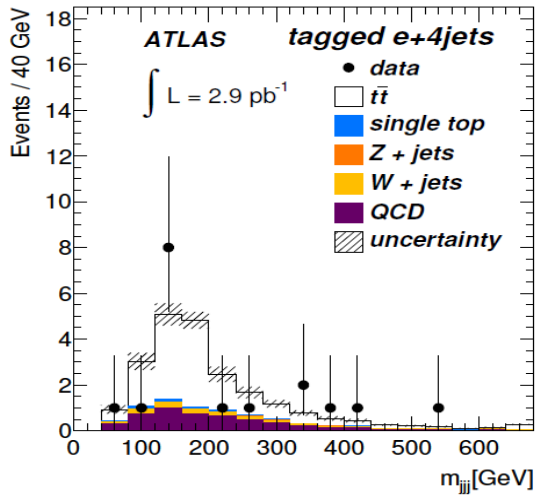
W+ jets measurements



- 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)

- 4.8 σ statistical significance
- confirmation of the Tevatron observation

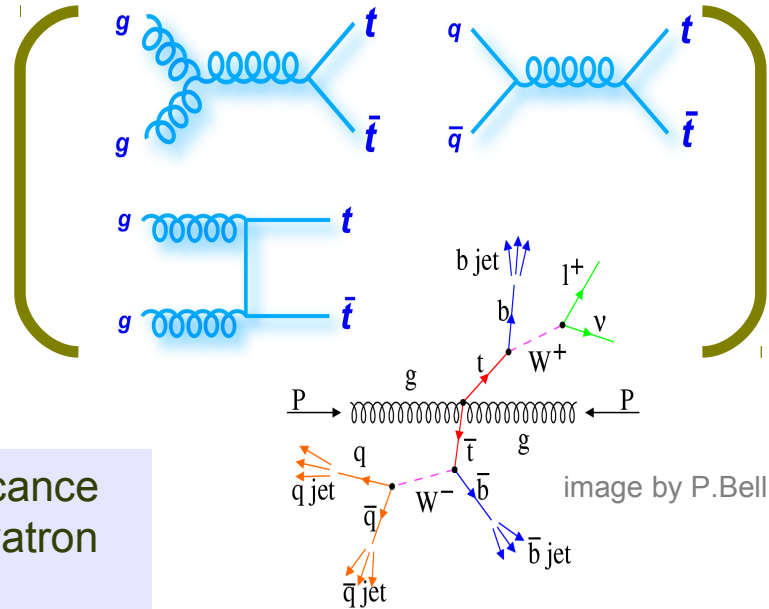
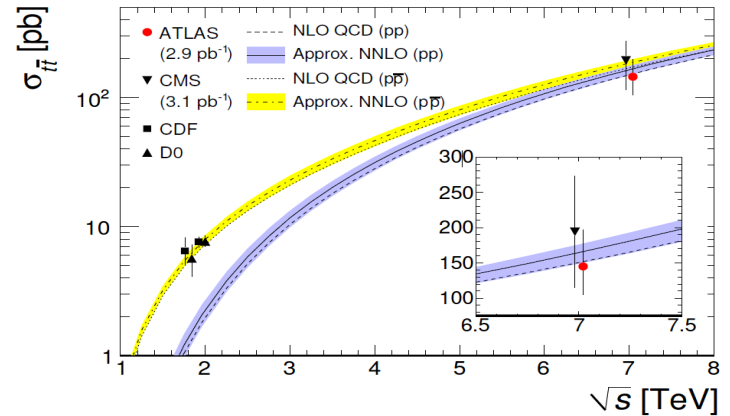
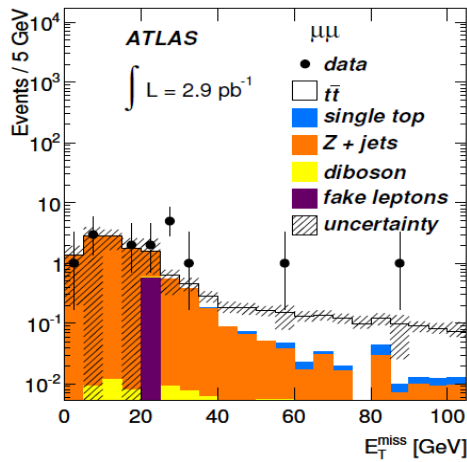
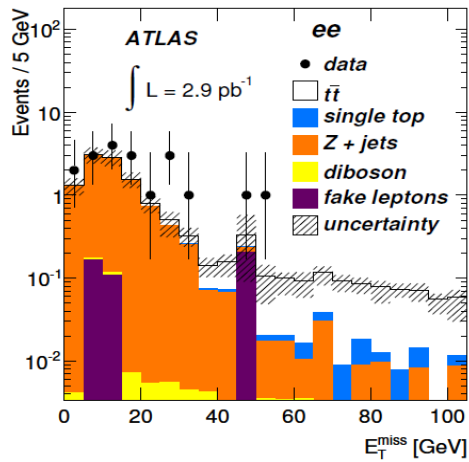


image by P.Bell



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>



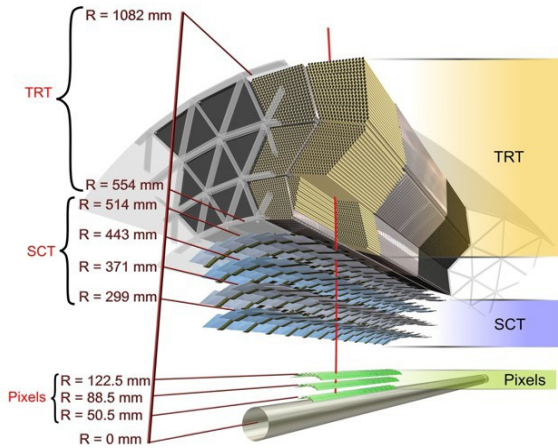


Backup





ATLAS detector



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

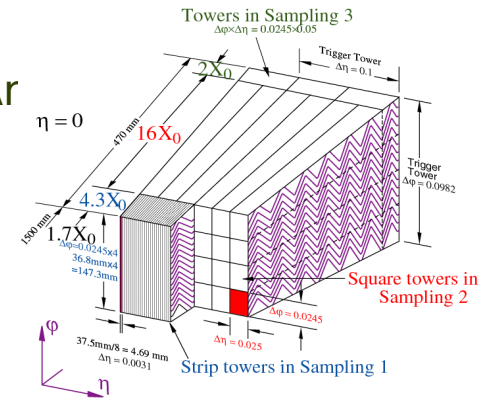
- Pixel: 3 layers(b)+2x3 disks(e) $\sigma_{r\phi} \sim 10\mu\text{m}, \sigma_z \sim 115\mu\text{m}$
- SCT: 4 layers(b)+2x9 disks(e) $\sigma_{r\phi} \sim 17\mu\text{m}, \sigma_z \sim 580\mu\text{m}$
- TRT: 73 layers (b) + 2 x 160 layers (e) $\sigma_{r\phi} \sim 130\mu\text{m}$

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

170000 readout channels

3 longitudinal layers with cell of Δr

- $(0.003-0.006) \times 0.1$ (1st layer)
- 0.025×0.025 (2nd layer),
- 0.050×0.025 (3rd layer)
- active depth $X_0 = 6, 16, 3$ at $\eta = 0$

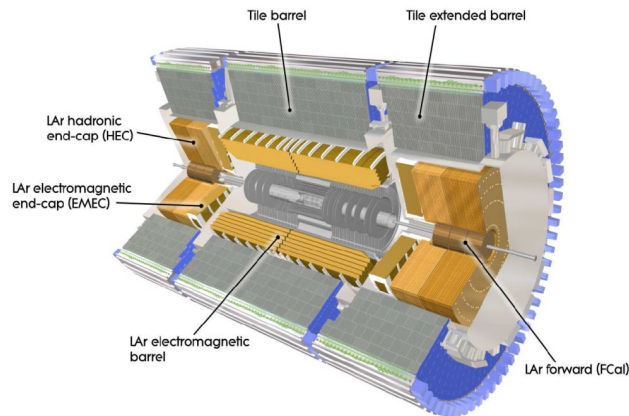


Presampler for $|\eta| < 1.8$

- $\Delta\eta \times \Delta\phi \sim 0.025 \times 0.1$
- $\sigma(E)/E = (10-17\%) (\eta) / \sqrt{E} \text{ (GeV)} \oplus 0.7\%$

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

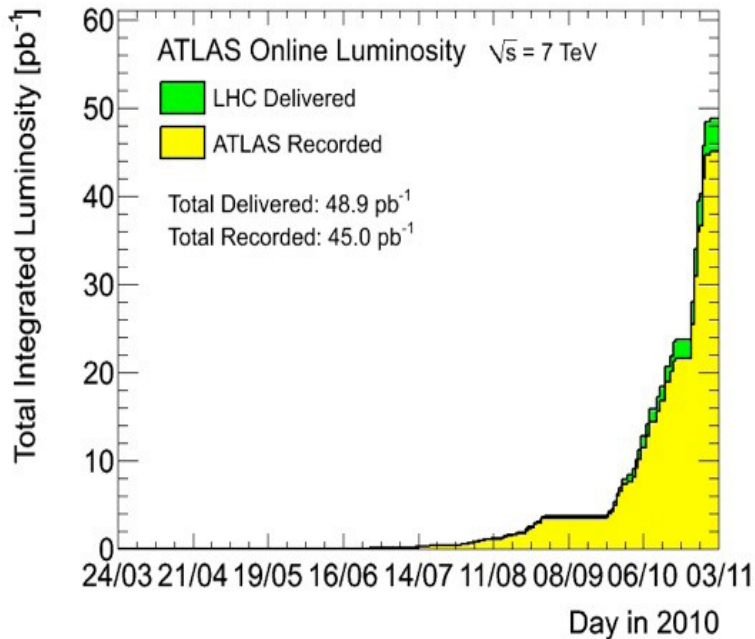
- 5000 readout channels





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 $\sim 10^{32}$ 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

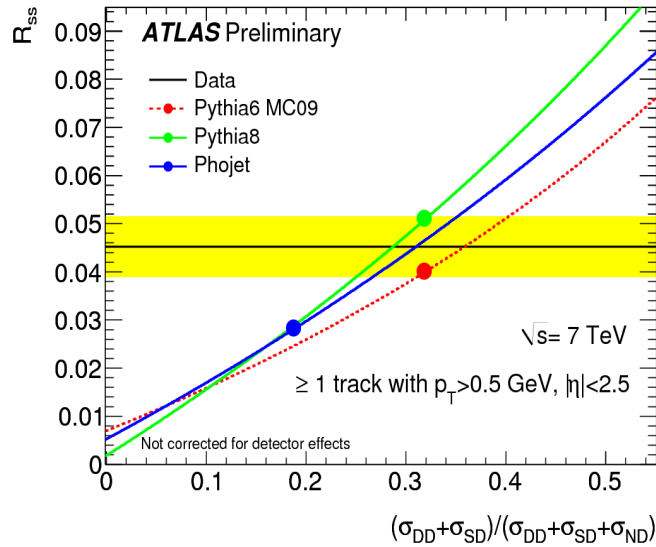




Observation of diffraction

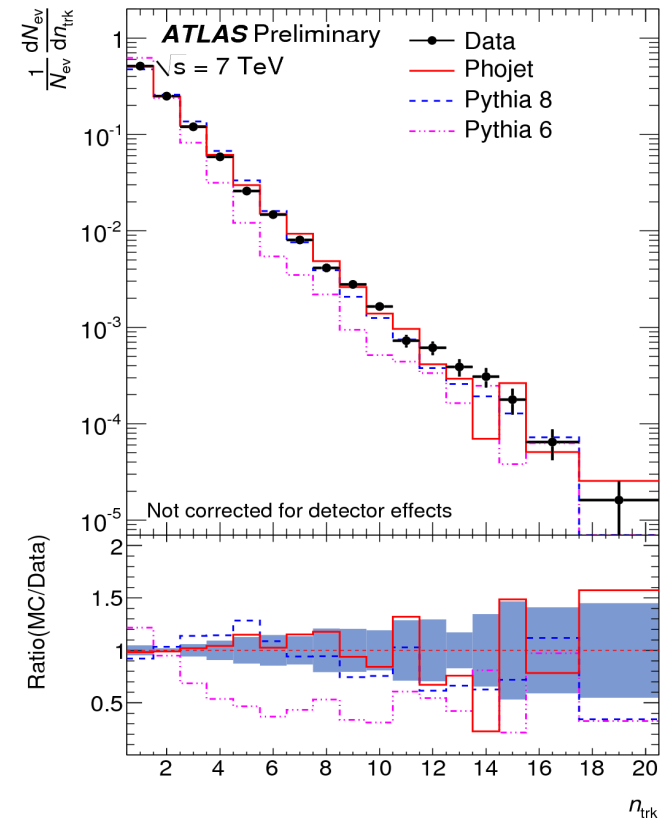
$$\sigma(pp) = \sigma(eI) + \sigma(ND) + \underbrace{\sigma(SD) + \sigma(DD)}_{30\%}$$

- 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)



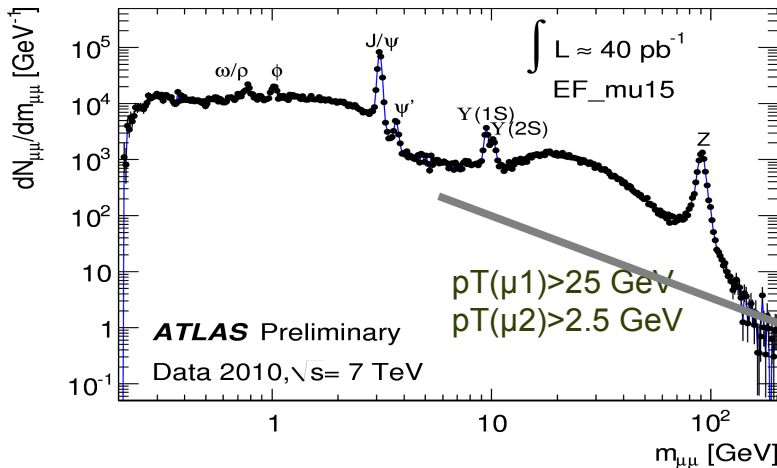
PYTHIA8 & PHOJET (with 30% diffraction) describes well the rate & multiplicities for diffractive events



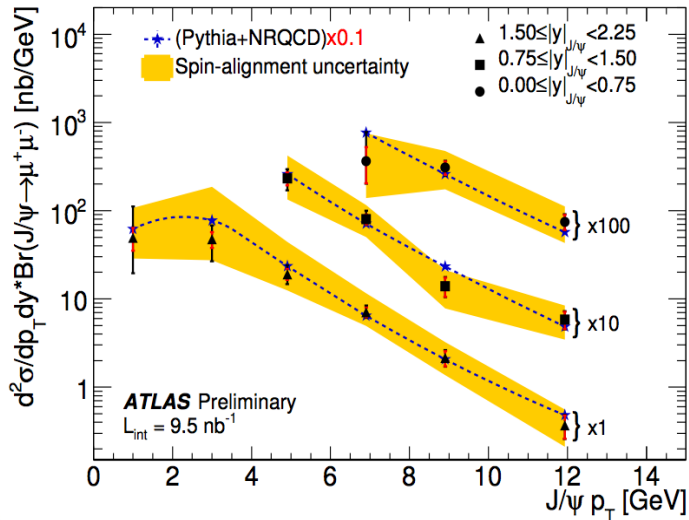
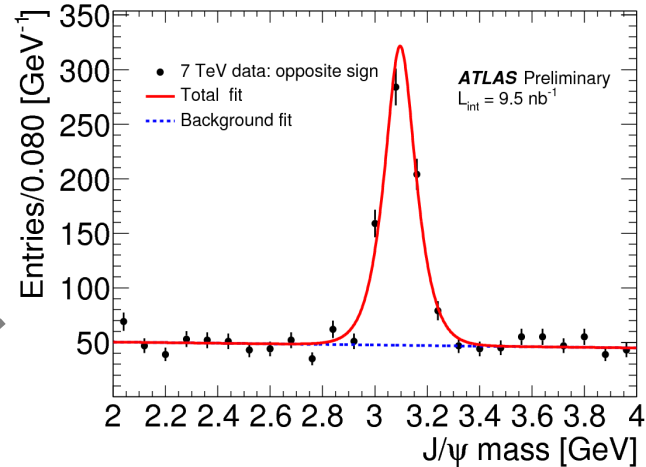


Charmonium production

- 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 $J/\psi \rightarrow \mu\mu$ resonance



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

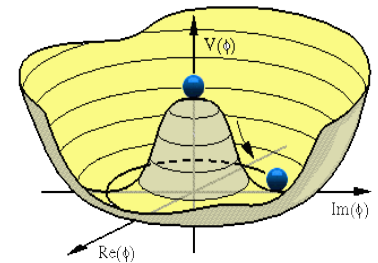
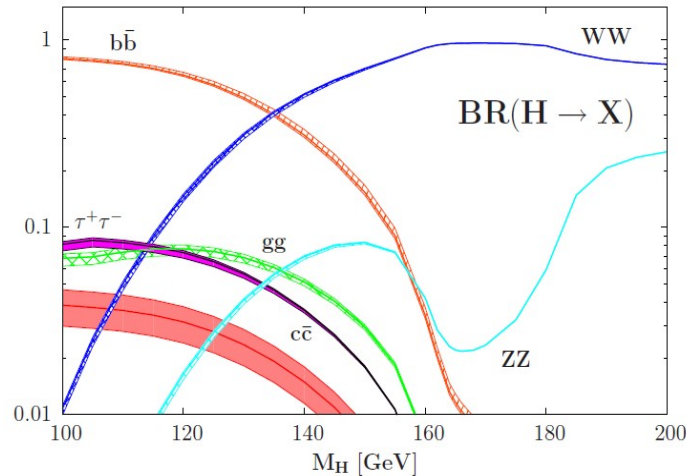
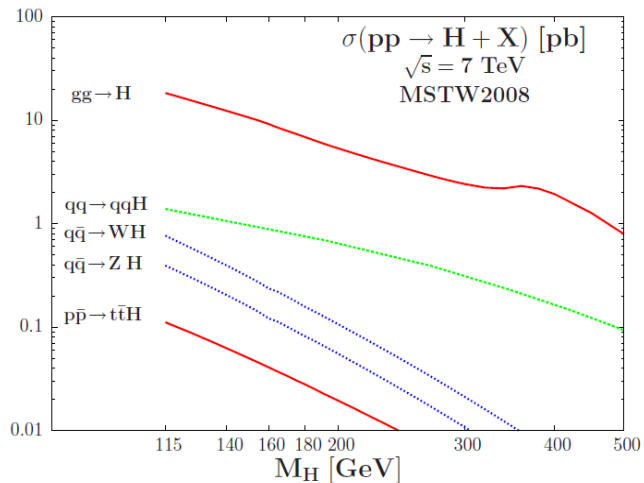




From QCD to high-pT EWK sector

- 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

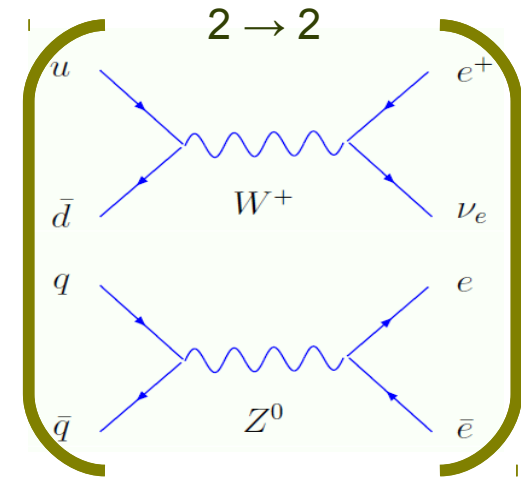




Probing High-pT EWK sector

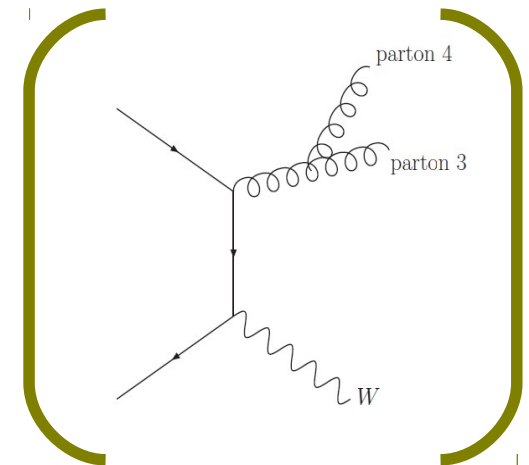
Inclusive W/Z measurements:

- 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

- Constrain measurements to well-known physics
- Precise test of QCD matrix elements, PDF
- Important background for $t\bar{t}$, single-top, Higgs searches



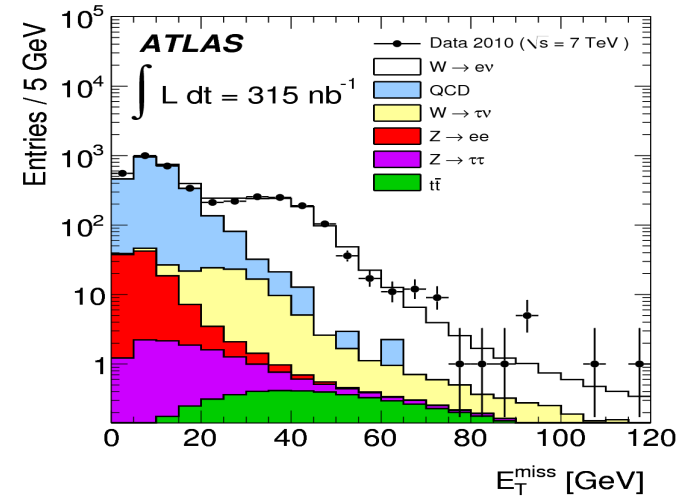
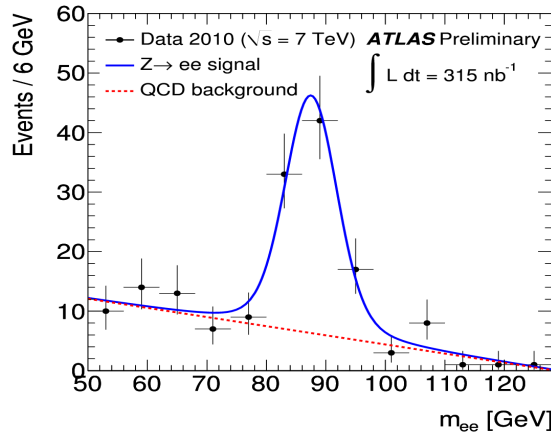
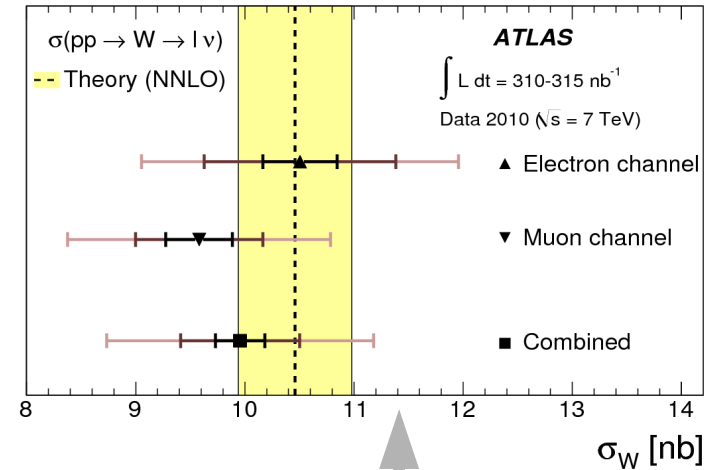
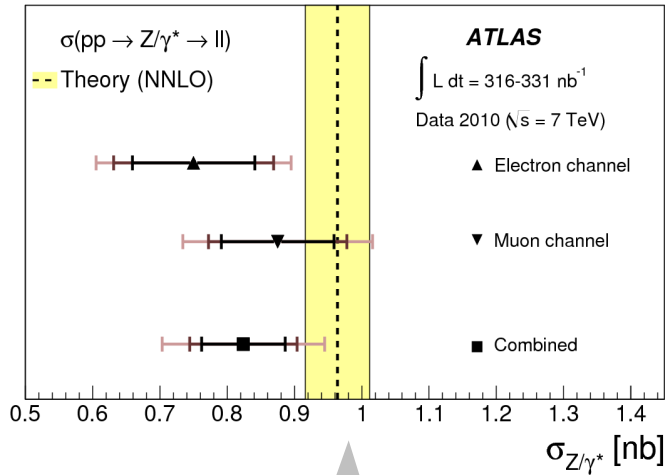
(See Pawel Malecki's talk)





Probing High-pT EWK sector

ATLAS arXiv:1010.2130



“Golden” channels

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

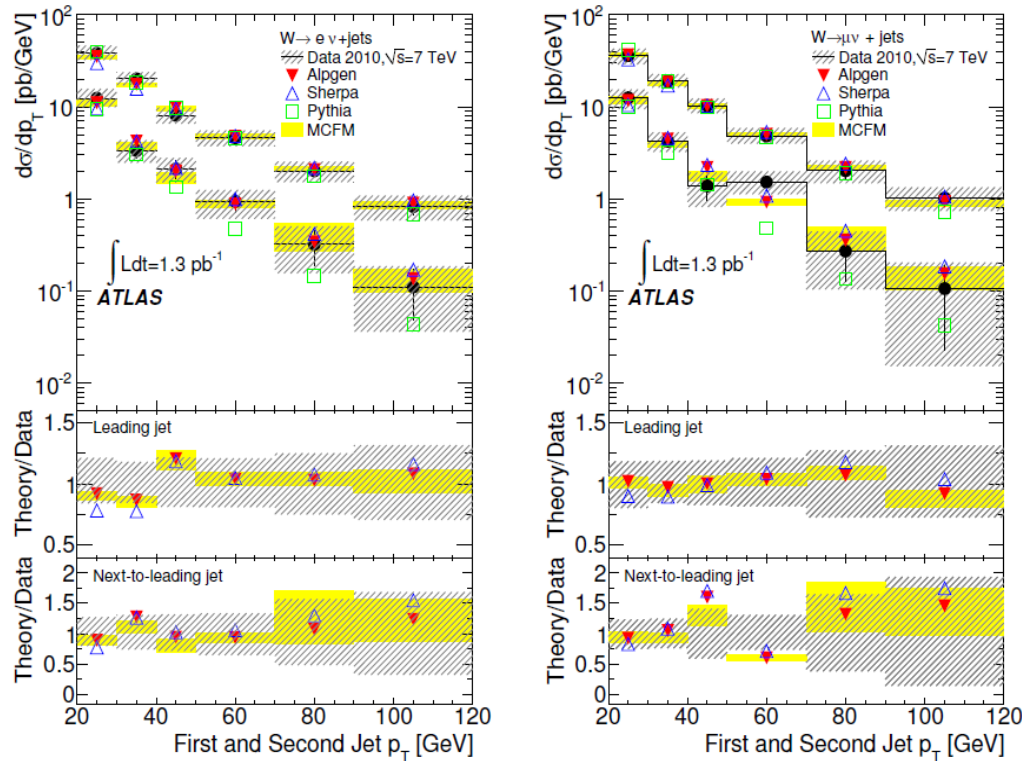
- EWK cross sections at highest CM energies!
- Perfect agreement with the SM





W+ jets measurements

ATLAS arXiv:1012.5382

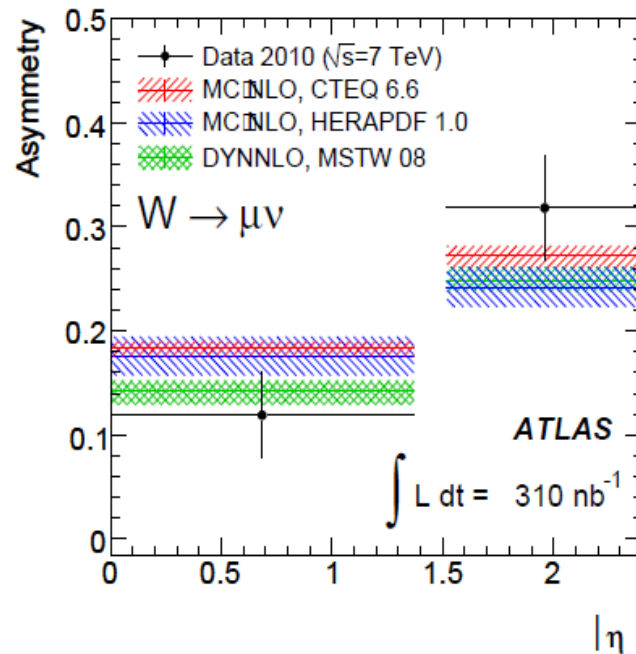
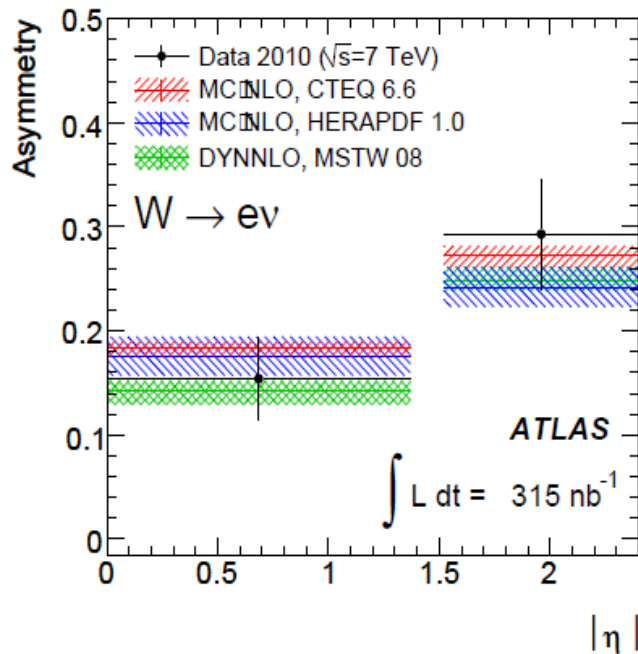


- Good agreement with ALPGEN & SHERPA
- Good agreement with MCFM (NLO QCD) & CTEQ6.6 for <3 jets & LO for >2 jets
 - includes corrections (~10%) for hadronisation & underlying events using AMBT1 tune
- Only MC+PS available for W+4 jets (muon channel)





Lepton charge asymmetries



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

- charge asymmetry is related to the dominance of **u** quarks to **d** quarks in the proton
 - for proton-antiprotons, 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

