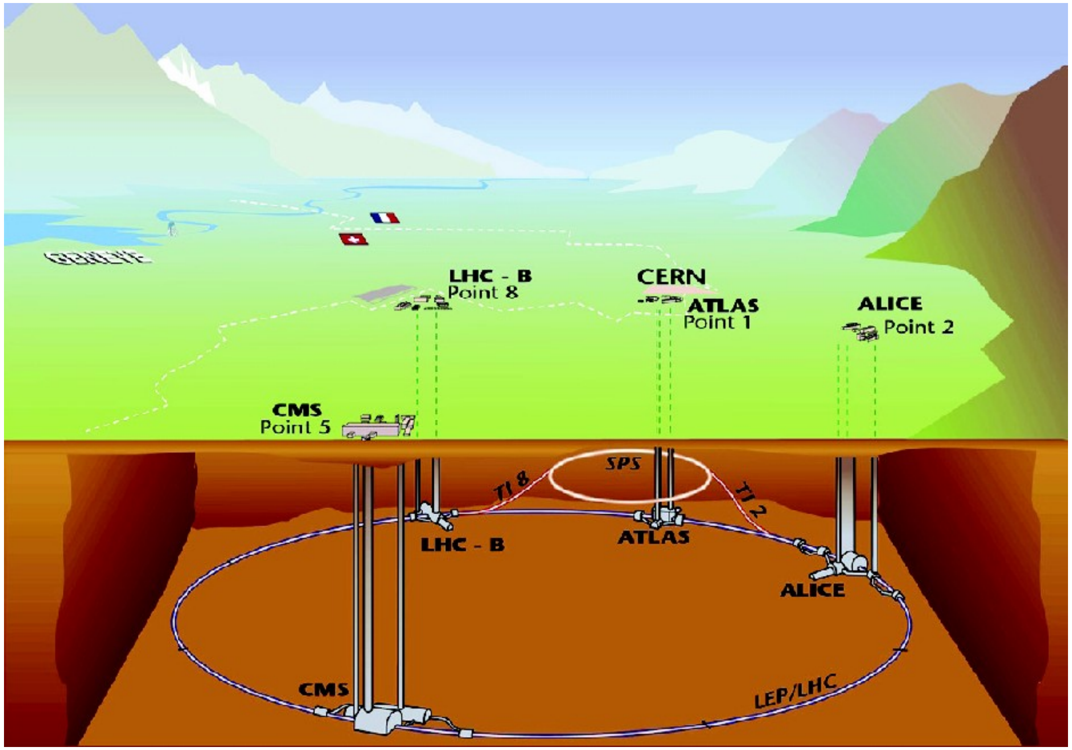
Standard Model Results from the ATLAS Experiment at the Large Hadron Collider

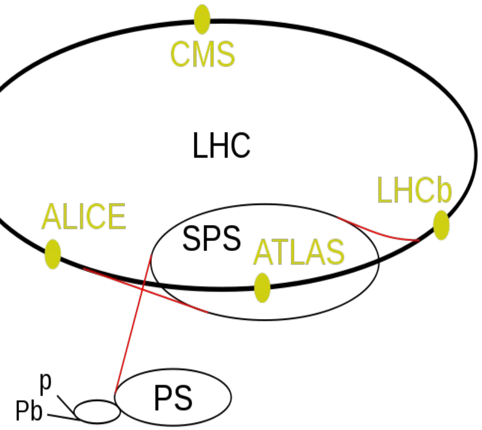
S.Chekanov (HEP/ANL)

ANL Physics Colloquium.   April 1, 2011 (April Fool's Day)

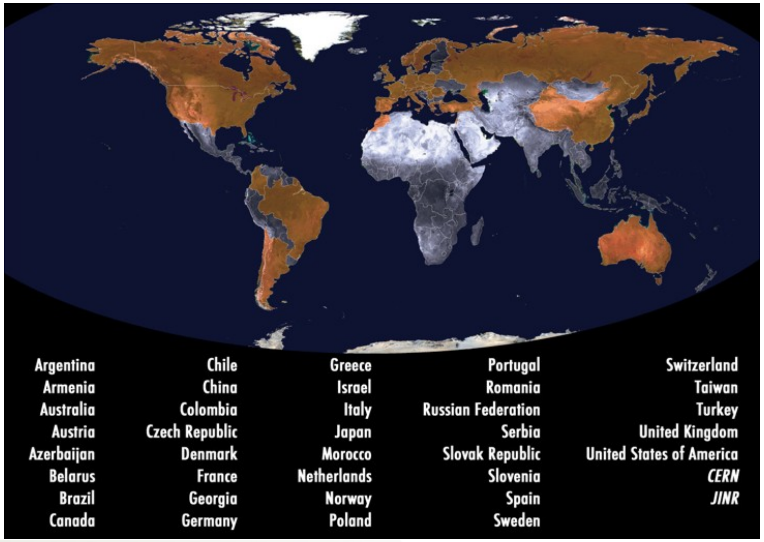


Opening A Coconut The Easy Way

The ATLAS Collaboration

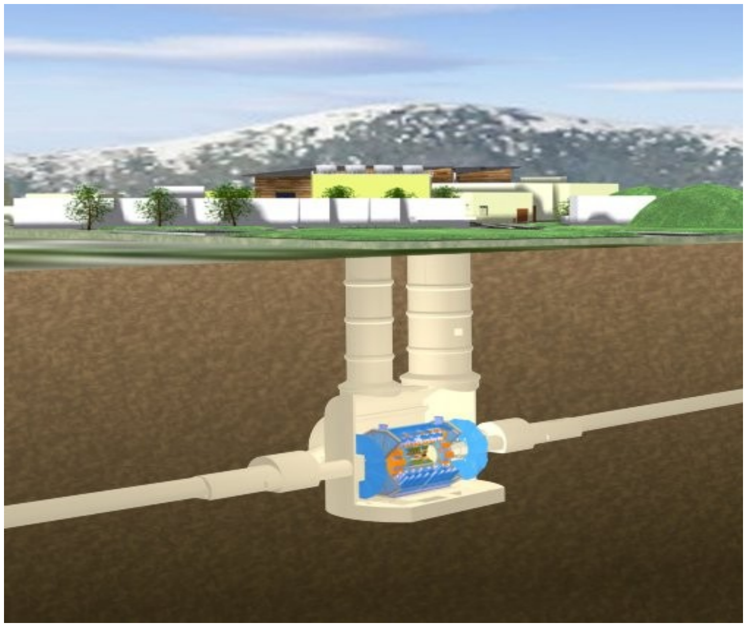


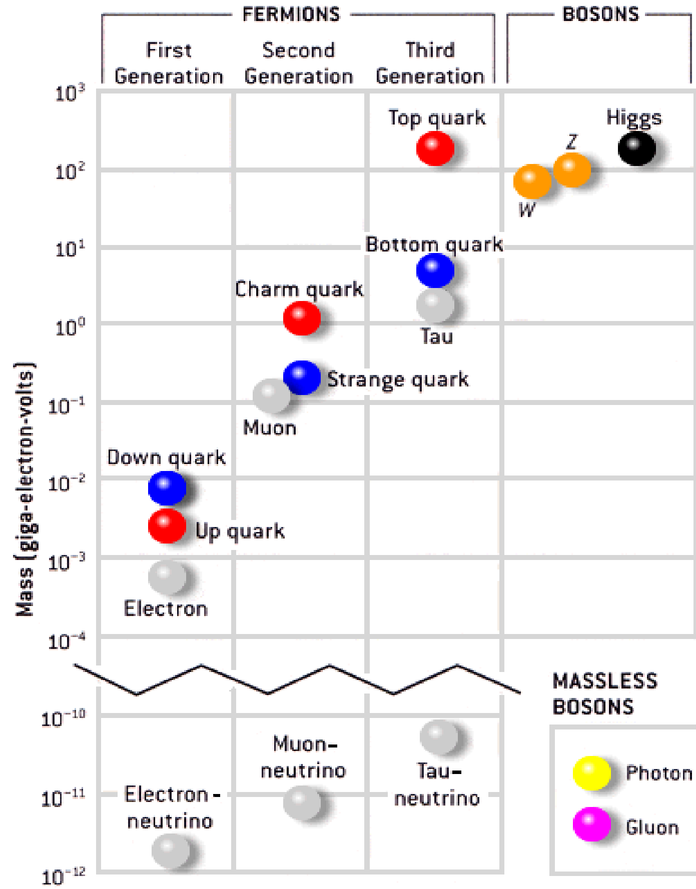
- 3000 scientists
  - 174 institutions
  - 38 countries
  - all continents
- More than 1000 PhD students
- More than 1.200 working meetings each month



Standard Model (SM)

a model of fundamental forces and particles - building blocks of the universe





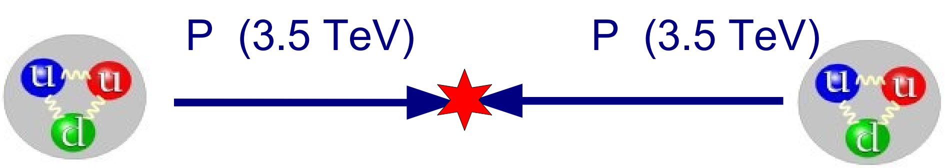
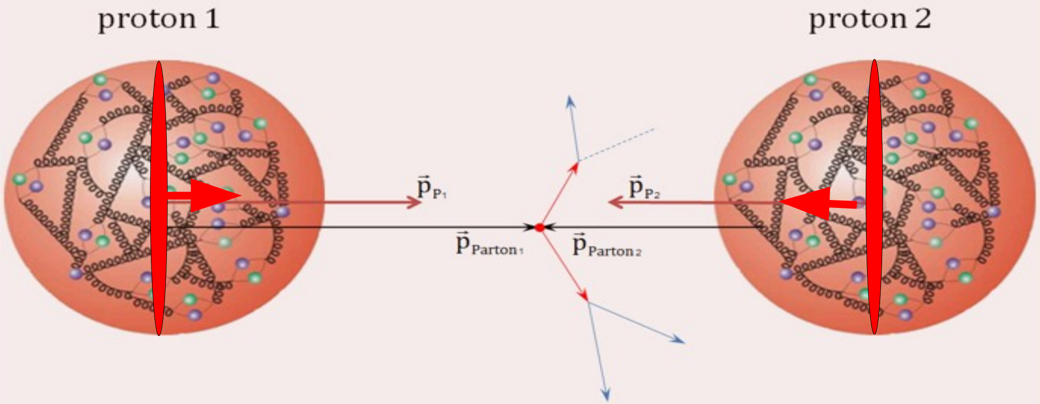


Chart from Scientific American::
17 particles in the Standard Model, together with their masses:

Proton-proton collisions at the Large Hadron Collider

Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)



$\vec{p}_{P_1}$ ... momentum proton 1

$\vec{p}_{P_1}$ ... momentum proton 2

• interaction vertex

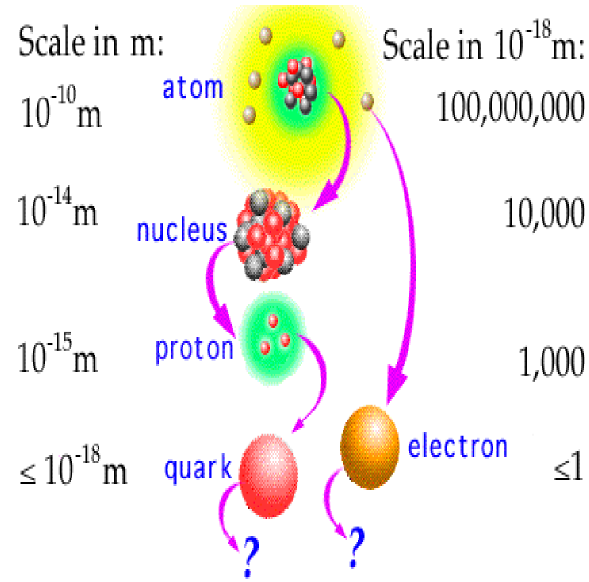
$\vec{p}_{Parton_1}$ ... momentum parton 1

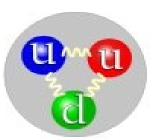
$\vec{p}_{Parton_2}$ ... momentum parton 2

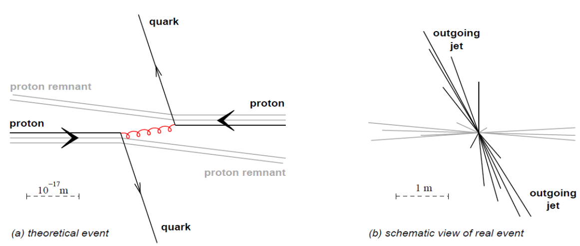
Heisenberg uncertainty principle:

$$\Delta x \sim \hbar / \Delta p$$

ħ - Planck's constant







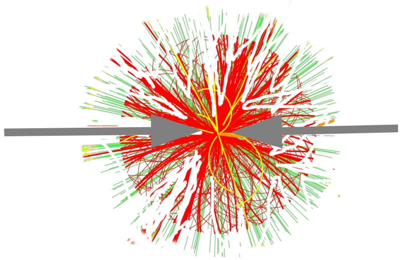
LHC: Word's strongest microscope: probed distance ~ 10^{-19} m

Introduction. SM tests with early LHC data

Standard Model - theory concerning the electroweak and strong interactions

Scope of the SM tests at the LHC:

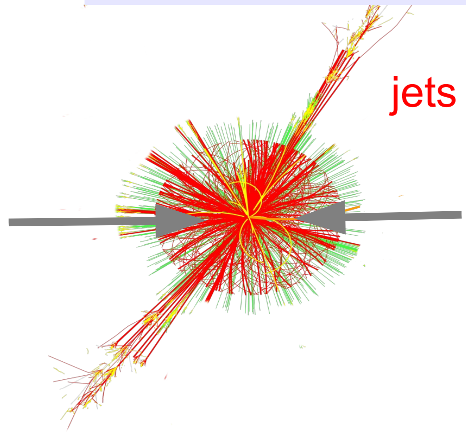
"soft QCD"
p_T < few GeV



>99.999% collisions:

Tests:
- LO matrix elements
- LL parton showers (PS)
- models for soft QCD
- consistency in tunings

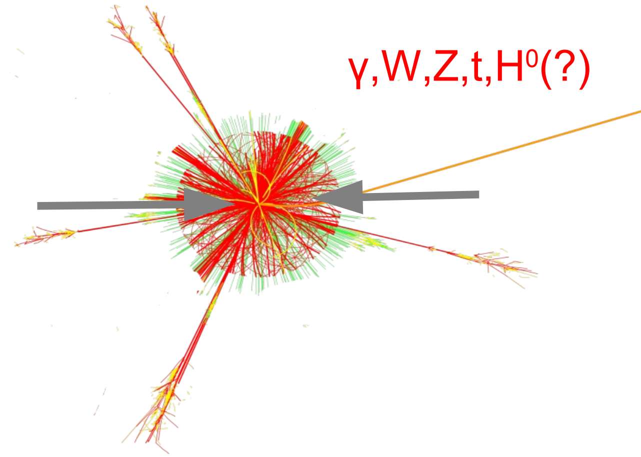
"Hard QCD jets"
p_T > tens of GeV



~10^{-5} % collisions

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

"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

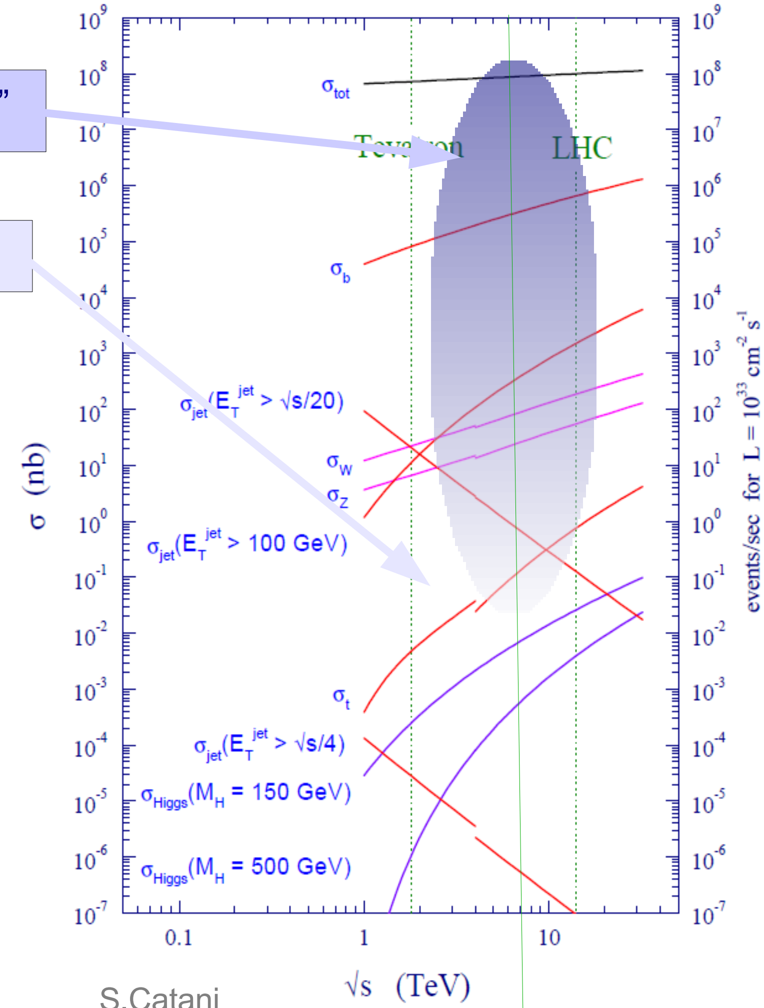
SM processes at the LHC

Current Luminosity
~50 pb^{-1}

"measurements"

"observations"

Process	σ (nb)	Events ($\int Ldt$ = 50 pb^{-1})*
Inclusive pp events	10^8	~10^{13}
bb	$5\cdot10^5$	~10^{12}
Jets p_T > 200 GeV	100	~ 10^7
W → lepton+ ν	15	~ 10^6
Z → l+ l-	1.5	~ 10^5
top - antitop	~0.1	~ 10^4
Higgs (M=150 GeV)	~0.001	~50



S.Catani
hep-ph/0005233

current energy
7 TeV

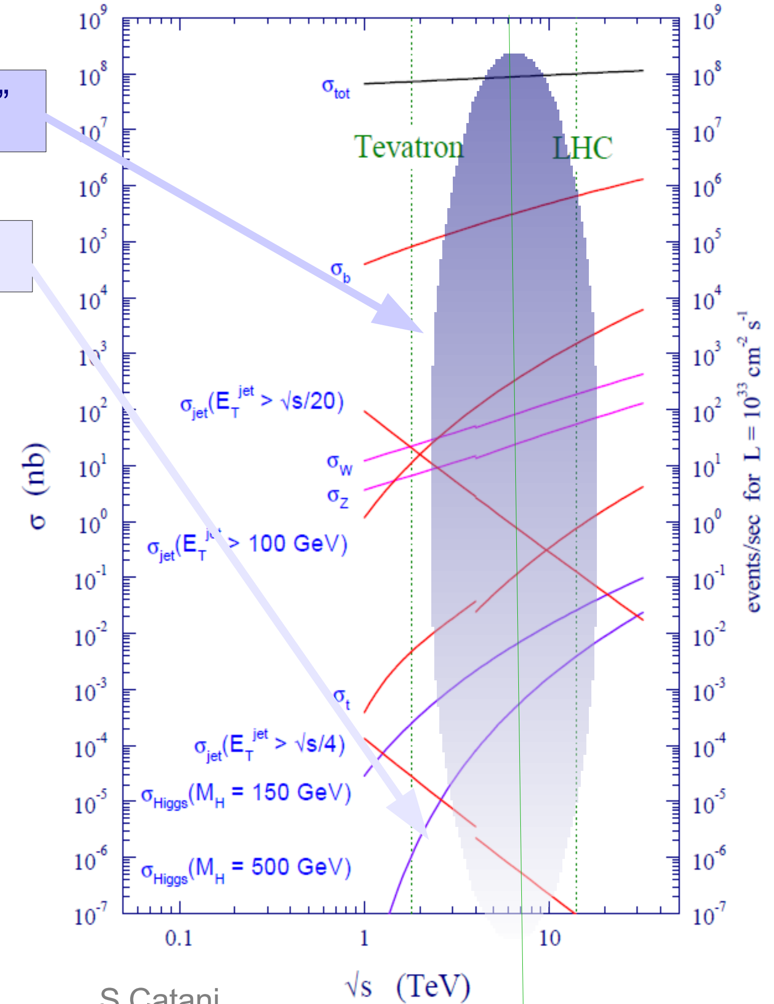
SM processes at the LHC

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

"measurements"

"observations"

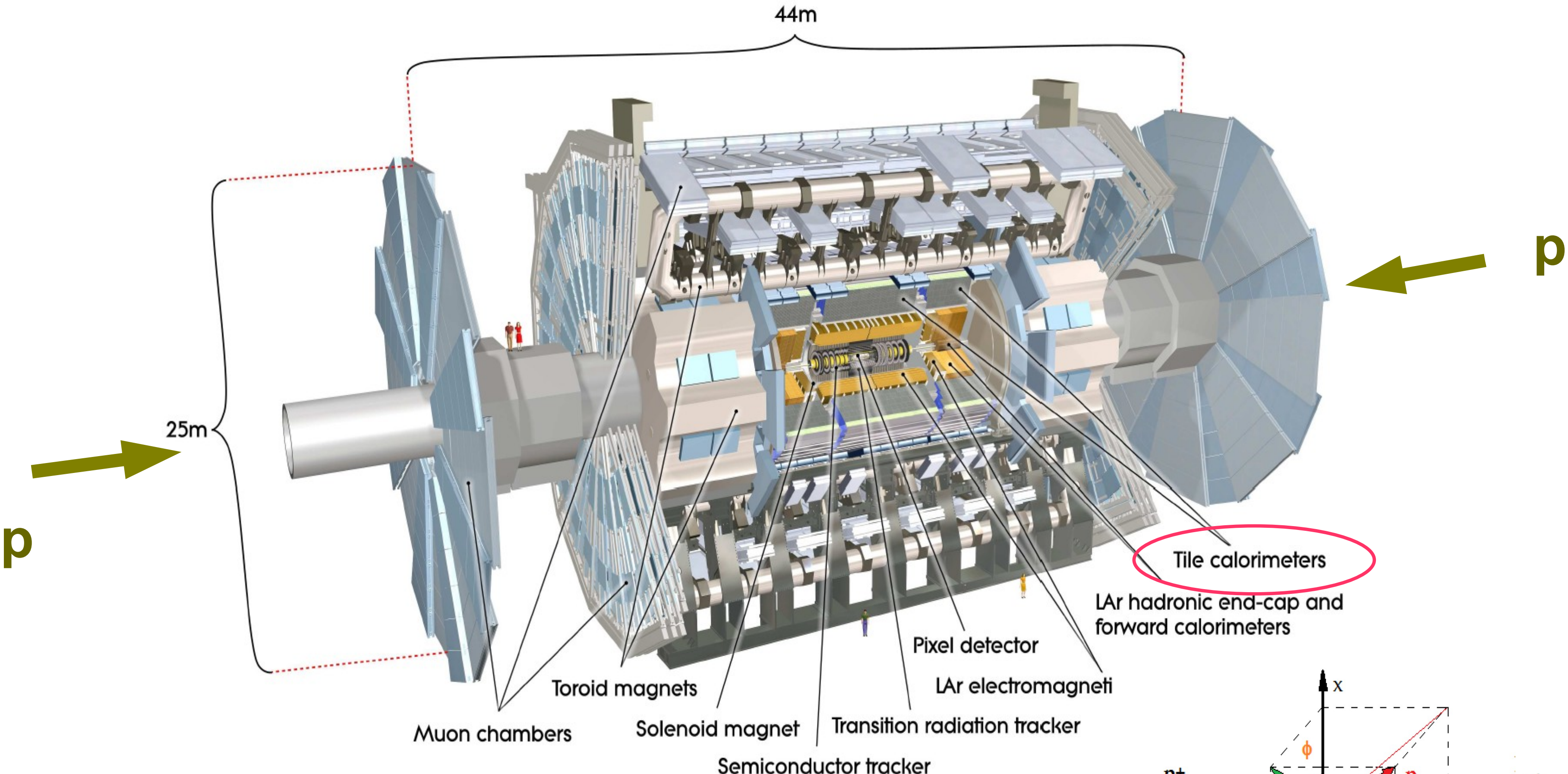
Process	σ (nb)	Events ($\int Ldt$ = 1 fb^{-1})
Inclusive pp events	10^8	$\sim 10^{14}$
bb	$5 \cdot 10^5$	$\sim 10^{13}$
Jets p_T > 200 GeV	100	$\sim 10^8$
W → lepton+ ν	15	$\sim 10^7$
Z → l+ l-	1.5	$\sim 10^6$
top - antitop	~0.1	$\sim 10^5$
Higgs (M=150 GeV)	~0.001	~1000



S.Catani
hep-ph/0005233

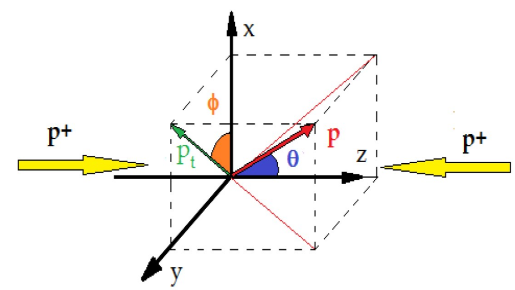
current energy
7 TeV

The ATLAS detector - world's largest scientific experiment



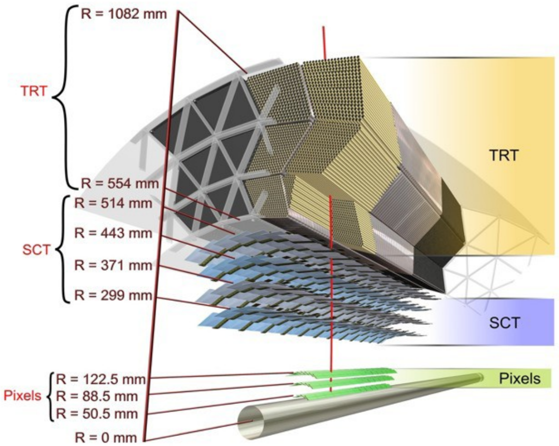
ANL ATLAS group http://atlaswww.hep.anl.gov/group/:

- all phases of the ATLAS Tile Calorimeter (design, prototyping, and fabrication of modules and electronics)
- trigger/data acquisition
- performance studies and data monitoring
- analysis-support center (ASC) for MidWest USA
- physics analysis (contribution to ~20% ATLAS papers)



pseudorapidity: $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$

ATLAS detector



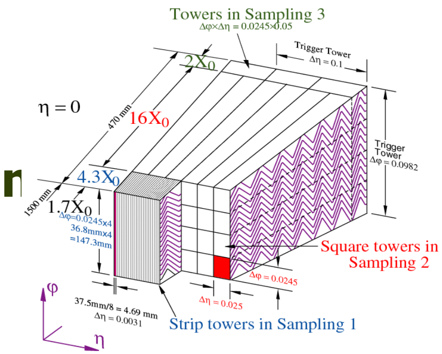
Inner Detector (ID) in 2 T solenoidal B-field

- Pixel: $\sigma_{r\varphi}$~10μm σ_z~115μm
- SCT: $\sigma_{r\varphi}$~ 17μm σ_z~580 μm
- TRT: $\sigma_{r\varphi}$~ 130 μm

Muon spectrometer

Designed goal: Δ pT/pT ~ 10% for 1 TeV muons

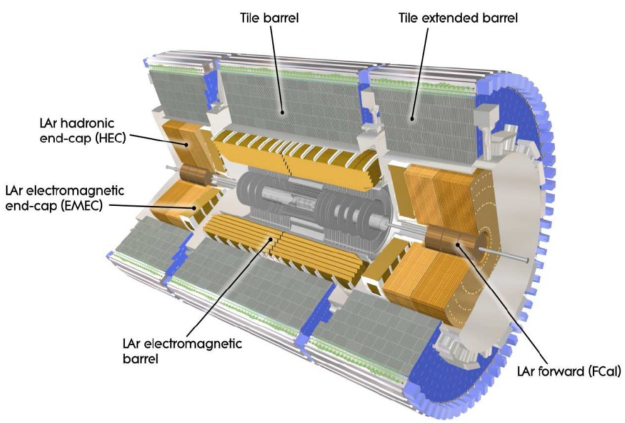
Electromagnetic Calorimeter - Liquid Argon - with an 'accordion



170000 readout channels

3 longitudinal layers with cell of ΔηxΔφ:

Active depth X0=6,16,3 at η=0

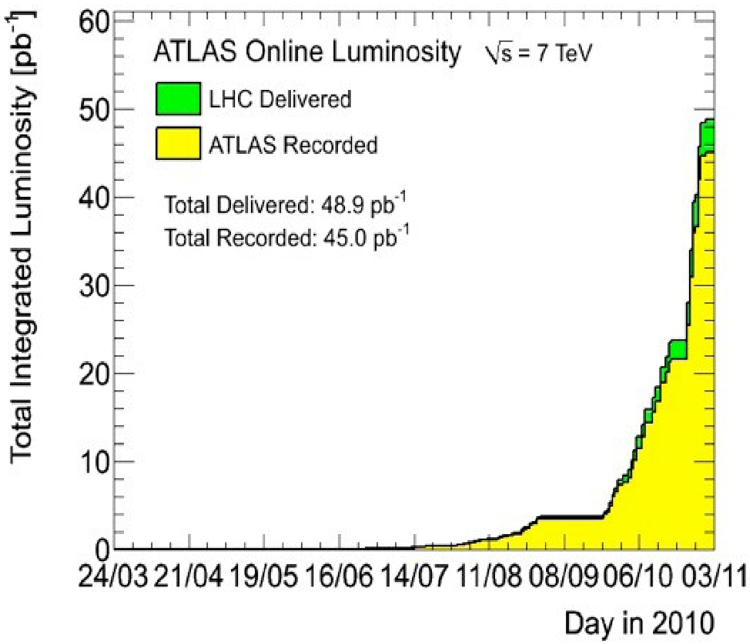


Hadronic Tile Calorimeter - sampling calorimeter (iron + scintillating tiles)

- 10000 readout channels

ATLAS data taking

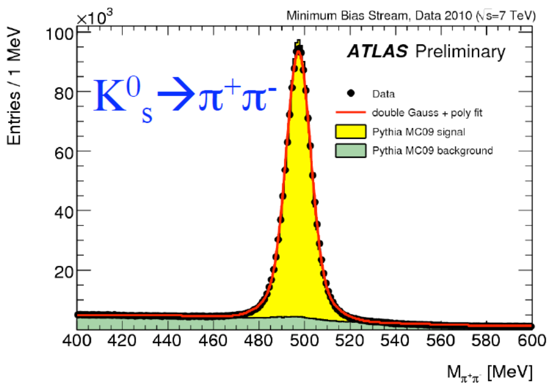
LHC News: http://lpc.web.cern.ch/lpc/

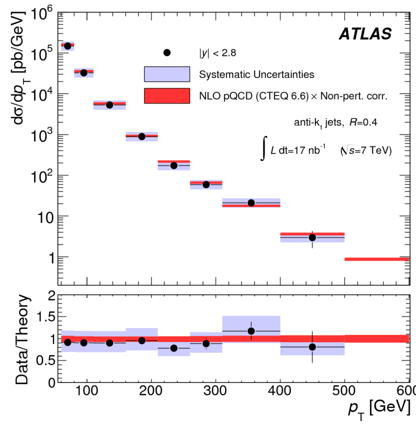


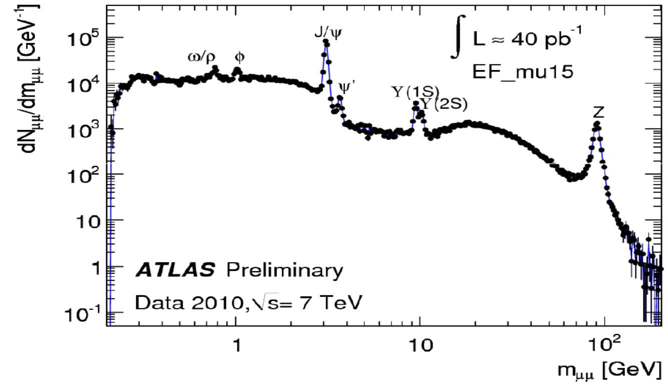
Main emphasis of this talk – pp collisions at 7 TeV

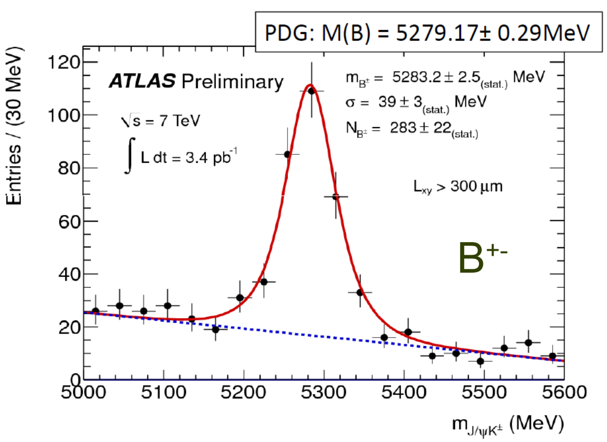
- **pp collisions at 0.9, 2.36 and 7 TeV**
- **Total number of collisions at 7 TeV (31/10/2010): ~3.2 trillion (ATLAS)**
- **Heavy-ion collisions**
- **Recent configuration for pp collisions:**
  - ~300 colliding bunches in ATLAS
  - peak luminosity ~10^{32} cm^{-2} s^{-1}
- **Plans for 2011-2012 runs:**
  - increase peak luminosity by x 2
  - up to 800 bunches per beam
  - collect ~1-2 fb^{-1}

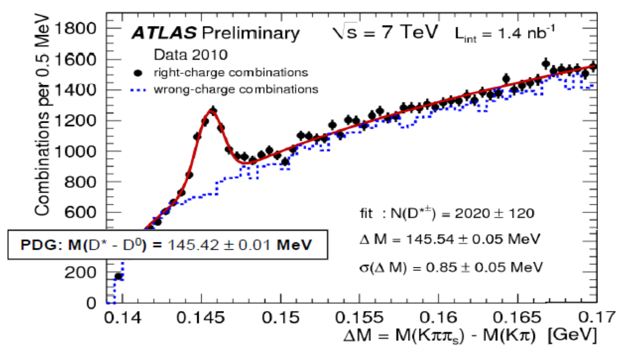
ATLAS data after ~1 month of data taking

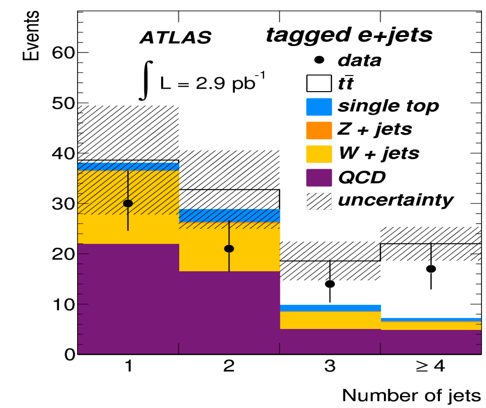


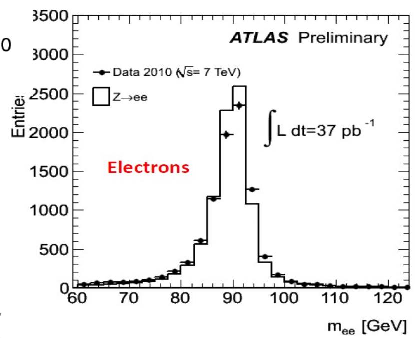


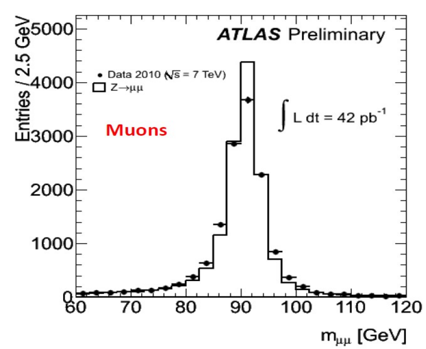






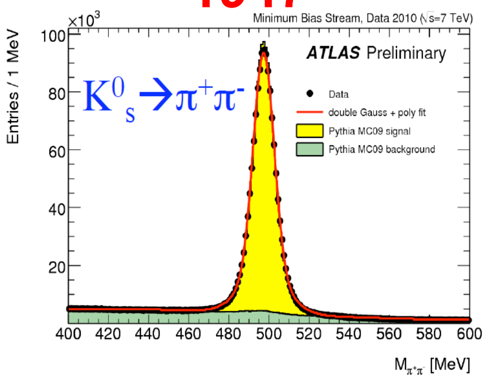




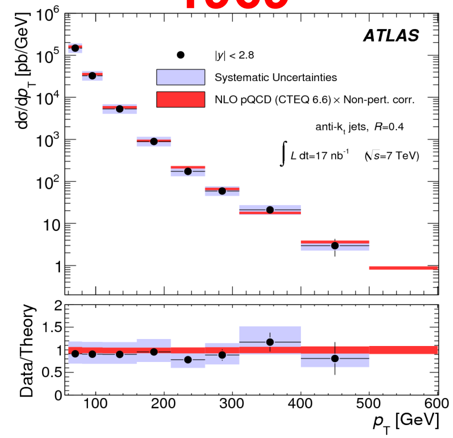


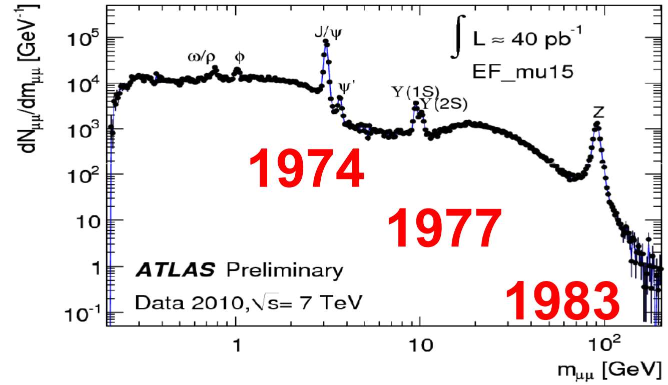
ATLAS data after ~1 month of data taking

1947

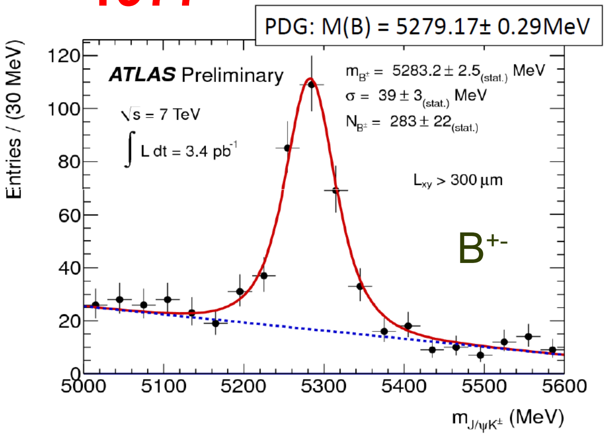


1969

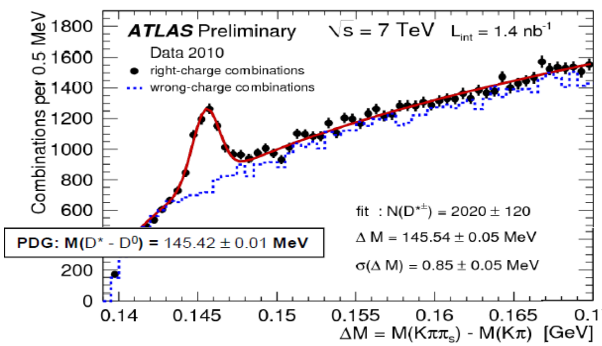




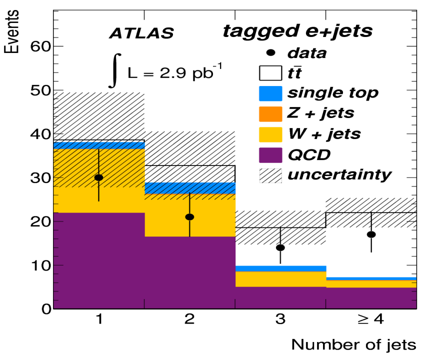
1977



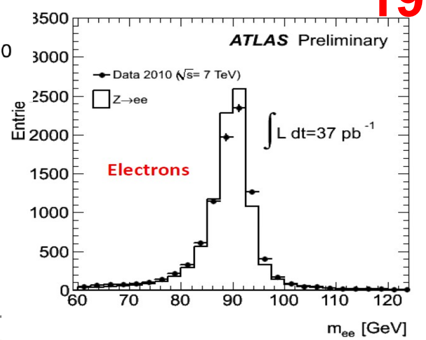
1976

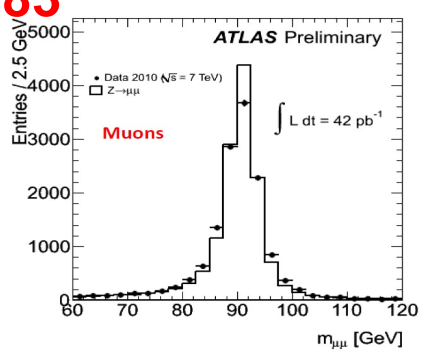


1995



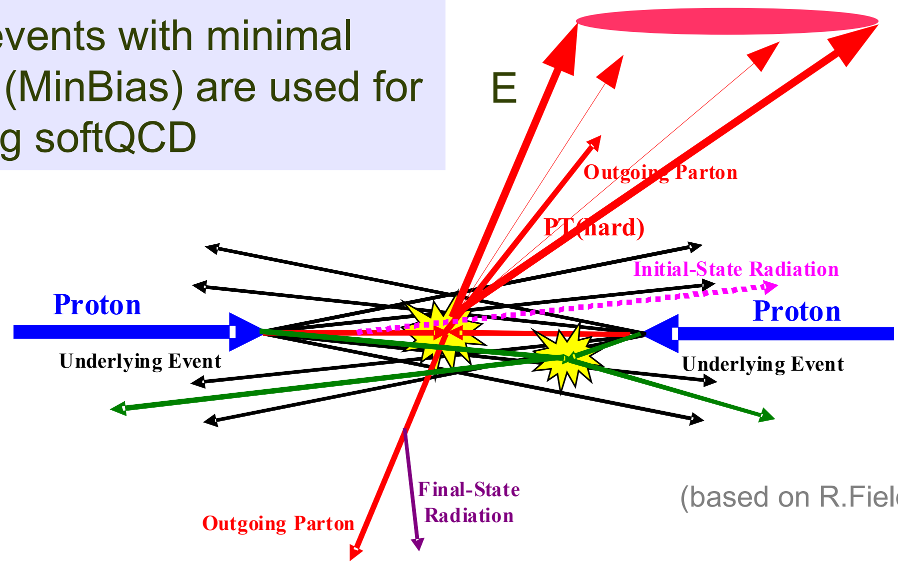
1983





New energy frontier: from soft to hard QCD

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



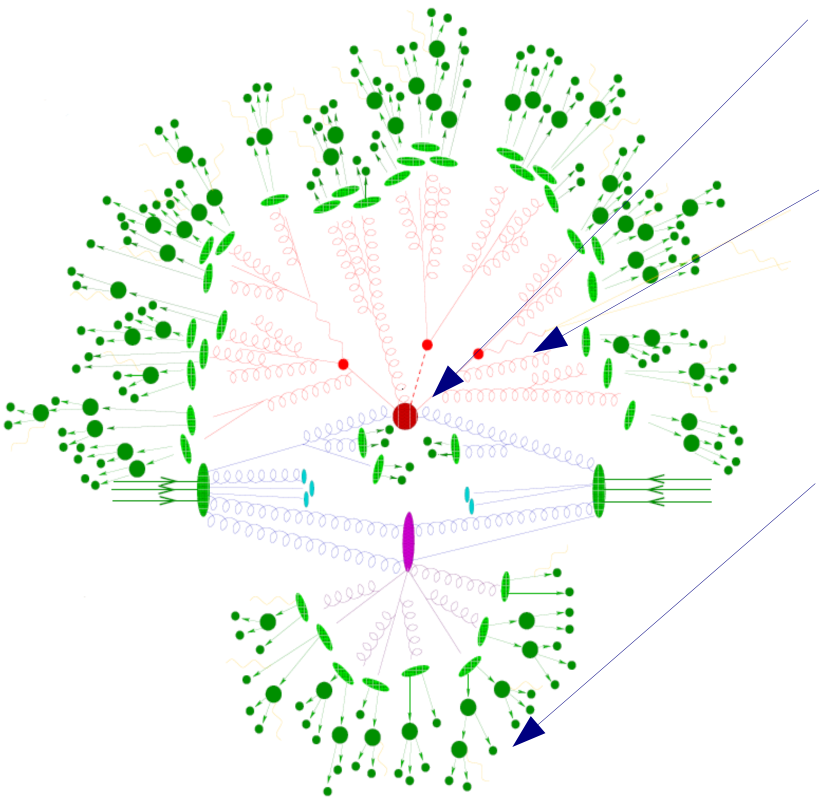
~ log² E pQCD

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

(based on R.Field's figure)

- **Inelastic (MinBias) pp 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**

Theory



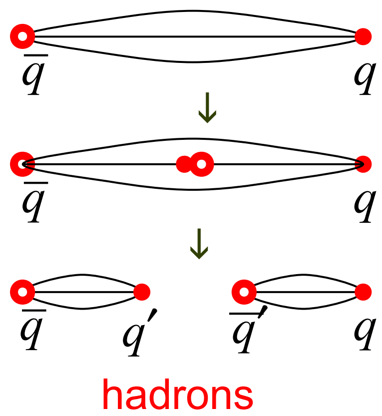
- **Hard QCD parton interactions**
  - Calculable from first principles for known parton densities inside protons
- **QCD parton cascade**
  - fixed-order QCD methods are not suitable – use approximations and models
- **Hadronization**
  - Assume factorization
  - Perturbative approach does not work!
  - Use models and empirical knowledge (like decay branching ratios)
- **Other effects are included using various models**
  - Multiplarton interactions, soft effects involving proton remnants, etc.

All steps are included in Monte Carlo generators

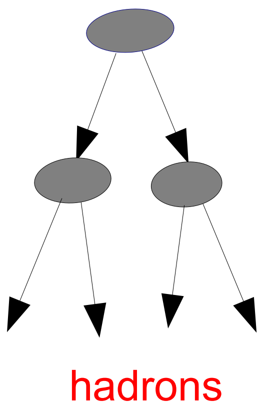
Monte Carlo (MC) models

- Incorporate models for soft QCD on top of better understood hard QCD calculations
- 2 popular types of fragmentation:

String fragmentation



Cluster fragmentation

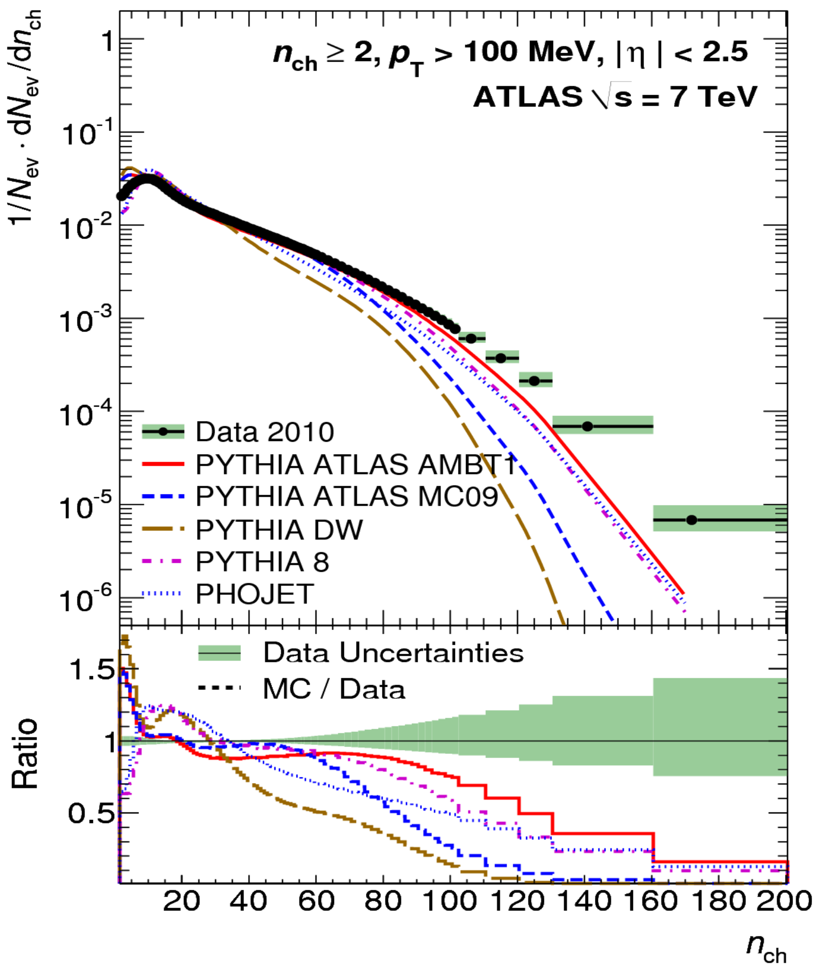


- Many adjustable parameters. Need to tune them!
- pp have extra complication: proton remnants, multiple interactions etc.
- ATLAS uses ~10 variations of MC generators using different phenomenology and different tunes to the previous pre-LHC experiments

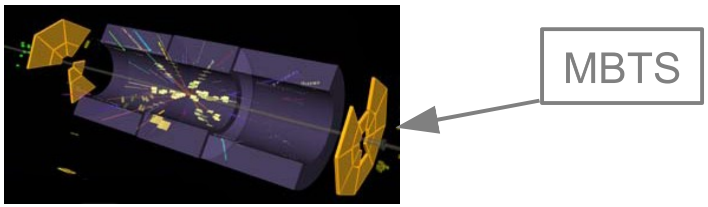
Main scope of comparison with Monte Carlo models: tune soft QCD phenomenological models in order to use such models for better understood SM processes (jets, EWK measurements)

softQCD: Charged particle multiplicities

ATLAS arXiv:1012.5104



Minimum Bias Trigger Scintillators (MBTS)



Trigger and event selection in MinBias events

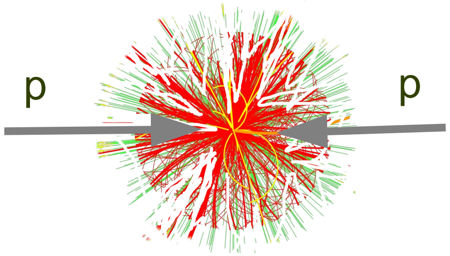
- Data: 7 TeV (~10M events)
- Selection: ≥ 1 MBTS counter to fire on either side

Primary track selection:

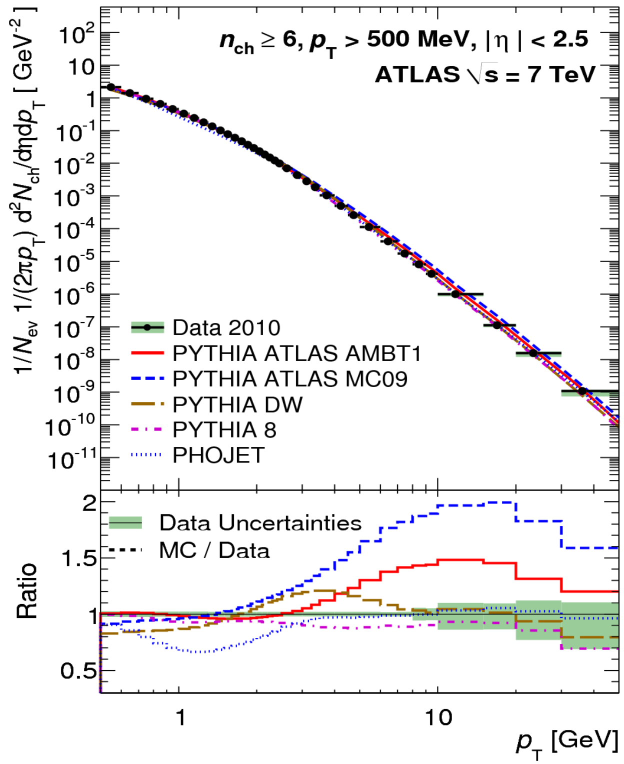
- pT > 100 MeV, $|\eta| < 2.5$ + other track quality cuts

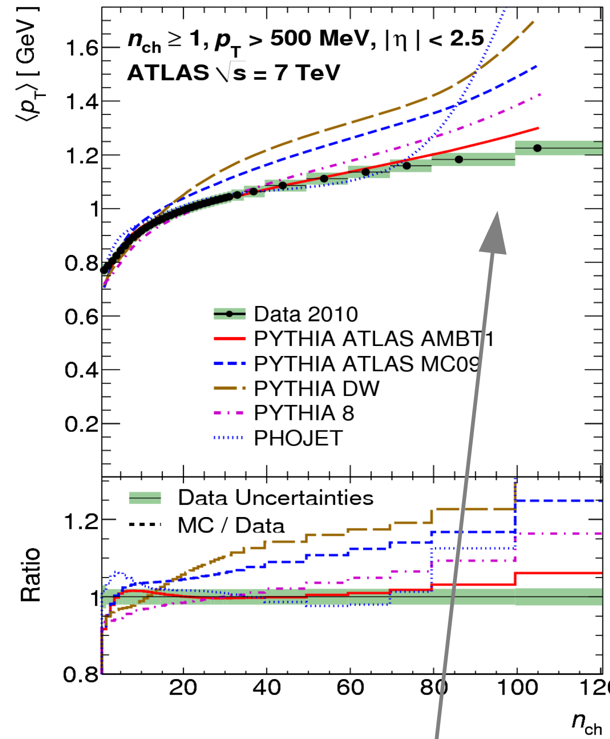
- **up to ~200 charged particles per event!**
- **All pre-LHC MC fail**
- **Low n_{nc} affected by diffraction**
- **PYTHIA AMBT1 is closest**
  - **but .. tuned to ATLAS data!**

Charged-particle spectra



All pre-LHC tunes fail





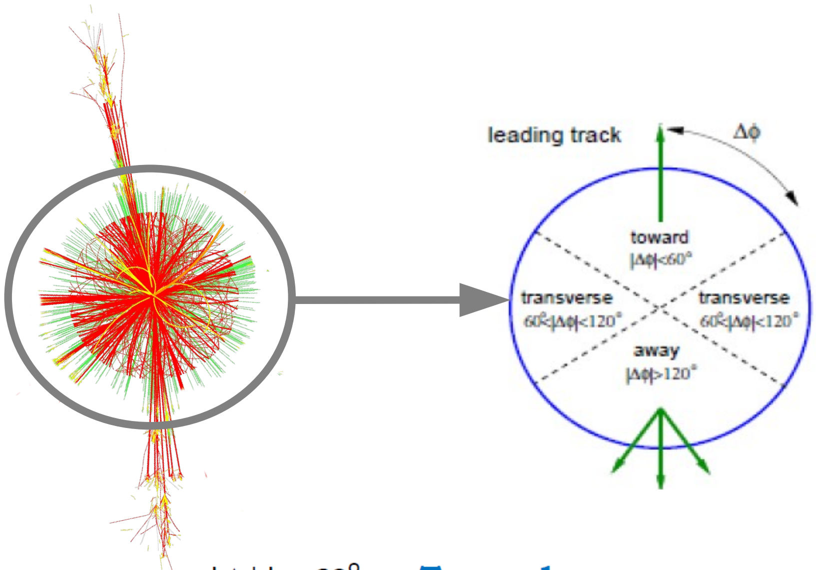
Entering hard QCD

AMBT1 tune improves agreement (but still has problems!):
- increasing prob. for head-on collisions (more events with large N(ch))
- reducing color reconnection for high-momentum hadrons (reduces<pT>)

~50% failure (with respect previous tunes) can be fixed by phenomenological parameters

Bad news for searches!

Studies of Underlying Event in MinBias data

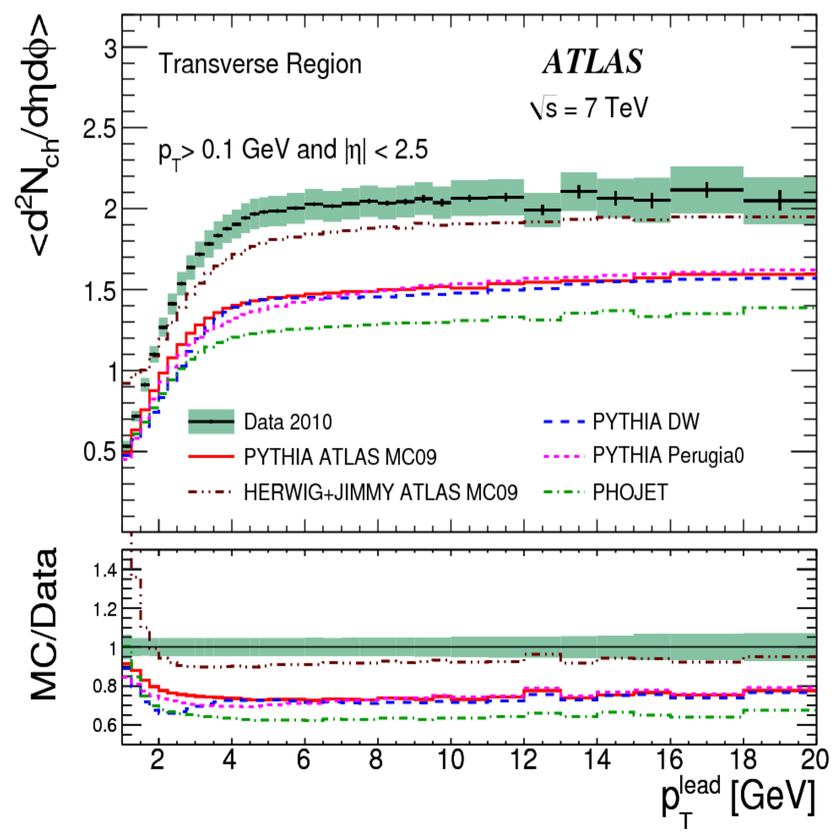


$|\Delta\phi| < 60^\circ$ as **Toward**

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

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

Particle density as a function of pT(lead)



All MC models have lower particle activity in the transverse region (by ~40%!)

ATLAS arXiv:1012.0791

Towards a complete final state

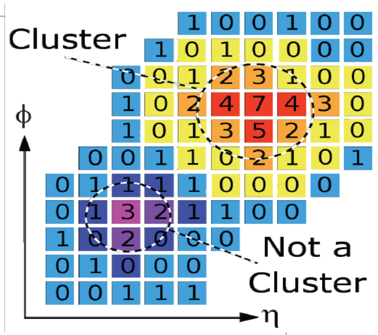
- **Measurements using calorimeters have some advantages:**
  - Sensitive to a complete final state including neutrals (extra ~40%)
  - Many high-precision jet measurements are based on energy deposition, and calorimeter-based UE studies can be directly used for such measurements

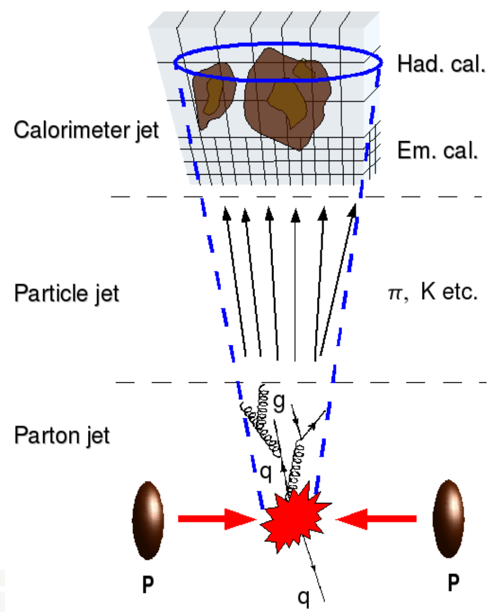
- **Calorimeter UE can take advantage of unique ATLAS calorimeter:**
  - 190k channels for electromagnetic & hadronic calorimeter

Excellent transverse and longitudinal segmentation allows reconstruction of "topological" clusters in 3D which are closely related to single particles (on average)

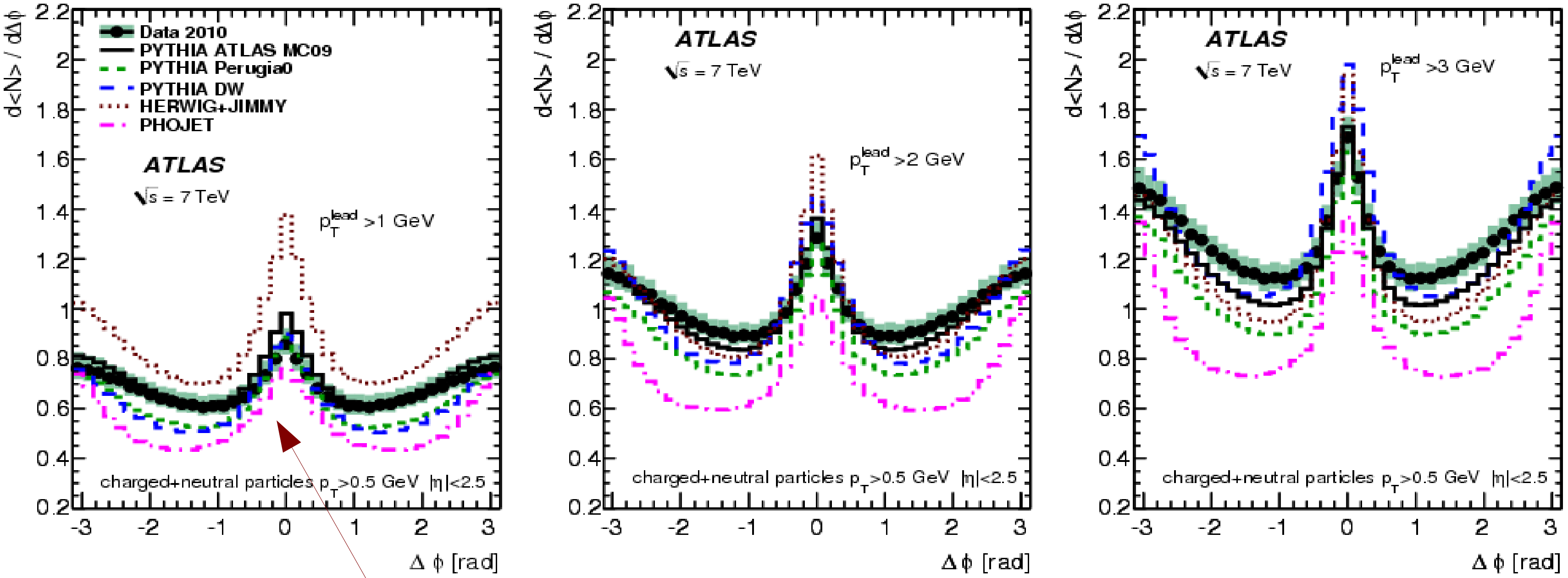
Topological clusters built from calorimeter cells
- follow shower development
- calorimeter noise
- used for *jet reconstruction*

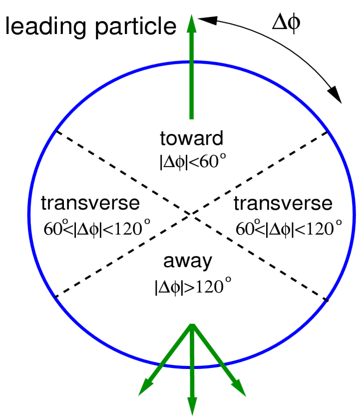
Method:
Seeded by cells with |E| > 4 x (noise level)
Neighboring cells with |E| > 2 x noise iteratively added (in 3D)
All neighbors around cluster (|E| > 0) added





Particle densities as a function of Δφ





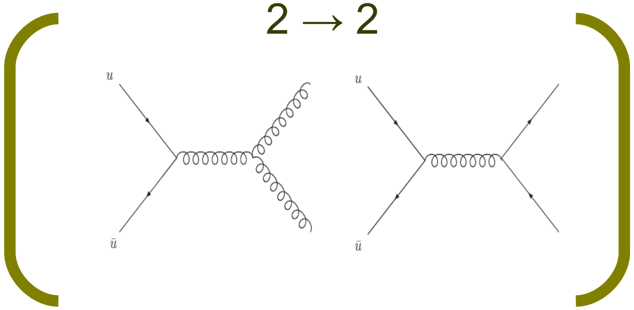
jet activity

All Monte Carlo models fail

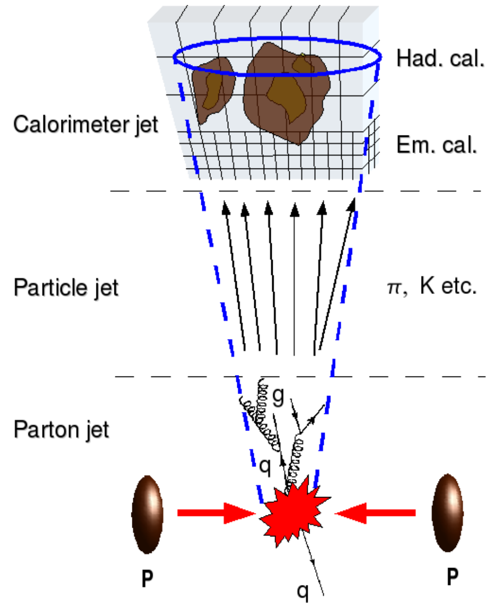
Distributions are used as input to tune MC modes

Jets

- Jets are sensitive probe of many aspects of pQCD:
  - matrix elements at LO+Parton Showers and NLO QCD
  - parton density function (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 $O(\alpha_S^2)$



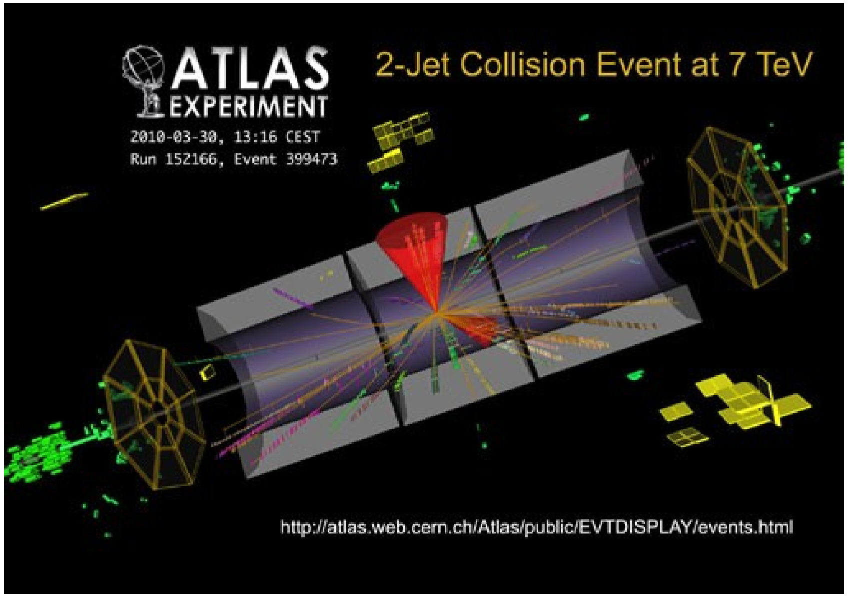


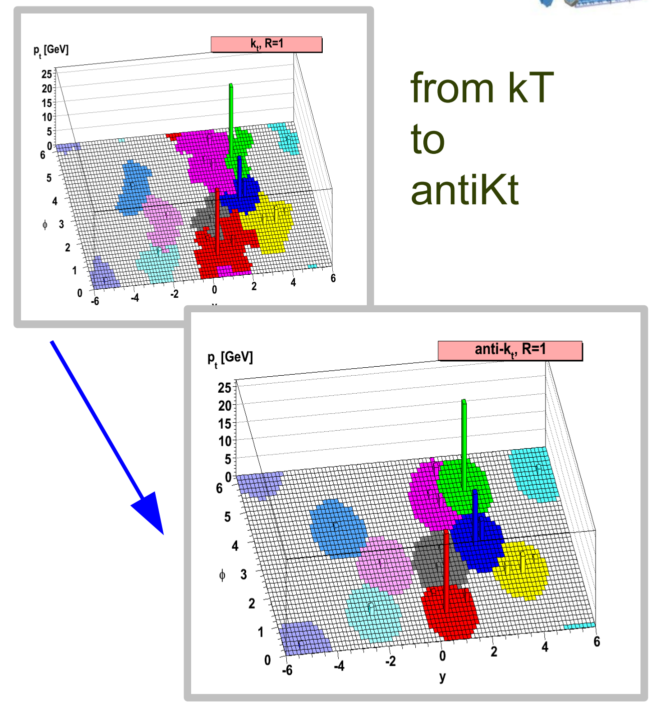
image by P.Weber

Movie

Real 7 TeV event!

Building jets

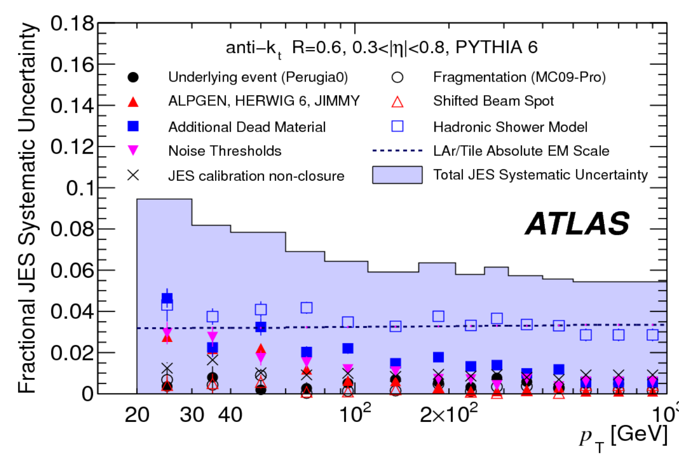
- Jets reconstructed using the anti-kT algorithm
  - M. Cacciari and G. P. Salam, Phys. Lett. B 641, 57 (2006)
- Infrared and collinear safe
- Produces geometrically well-defined cone-like jets
- Size parameters R=0.4 or 0.6



from kT
to
antiKt

Jet-energy scale

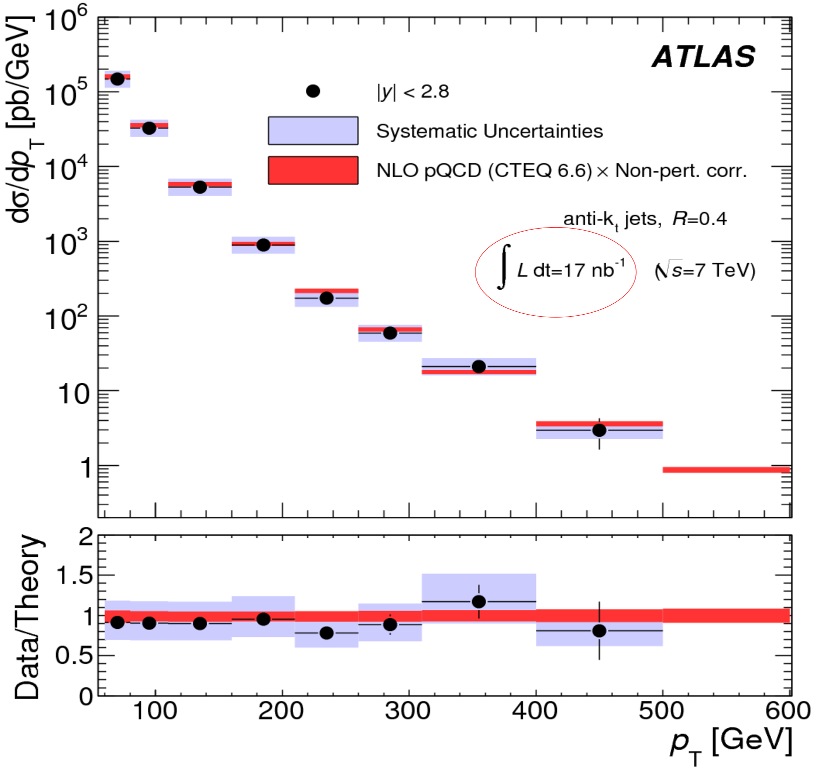
- Dominant uncertainty for all jet-related measurements
- Currently: pT and η dependent correction applied to uncalibrated objects
- Why it is important? See next!



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

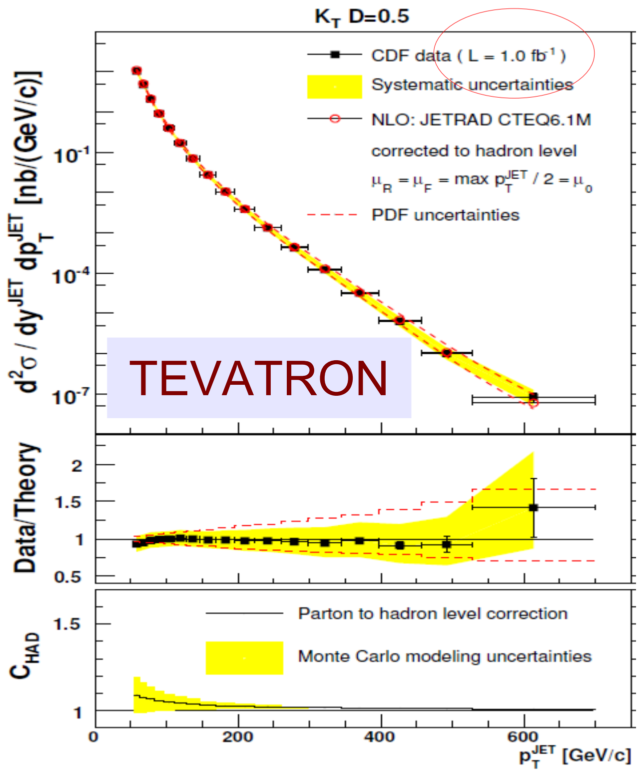
Jet production

ATLAS arXiv:1009.5908



Good agreement with NLO QCD

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

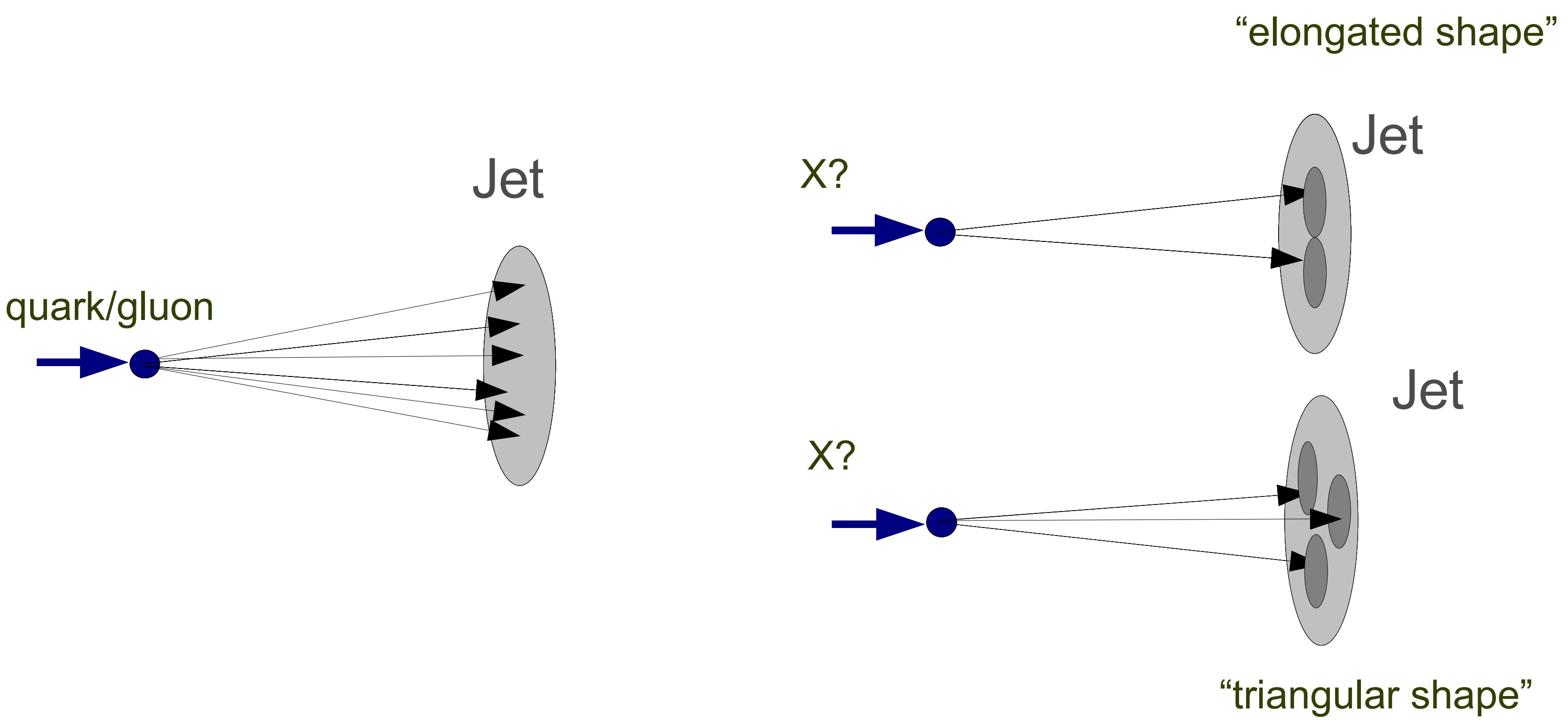


Theory:
NLO QCD (NLOJET++/JETRAD) together with softQCD corrections (~5%) from PYTHIA model

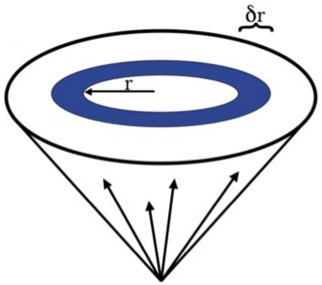
11% uncertainty on luminosity measurement is not shown

Jet shapes

Hard interaction is always associated with extra QCD radiation



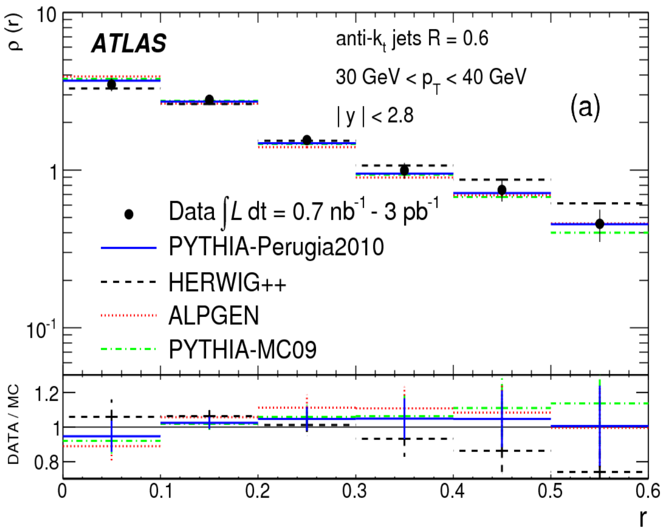
Jet shapes

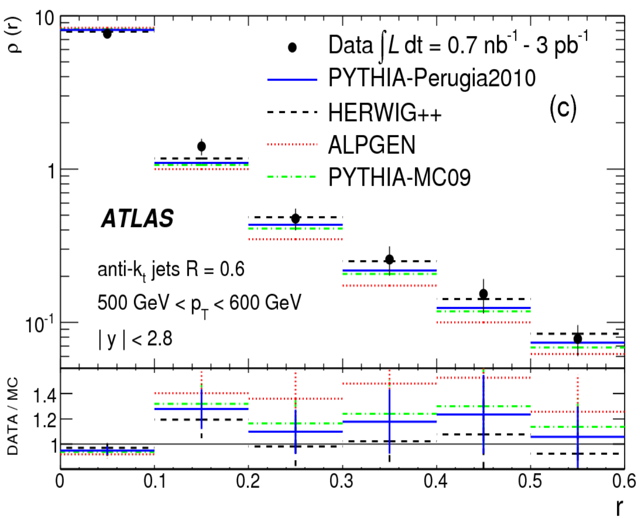


$$\left\langle \frac{1}{r}\frac{dp_T}{dr} \right\rangle_{jets} = \frac{1}{A}\frac{1}{N_{\text{jet}}}\sum_{jets} p_{\text{T}}(r-\Delta r/2, r+\Delta r/2)$$

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



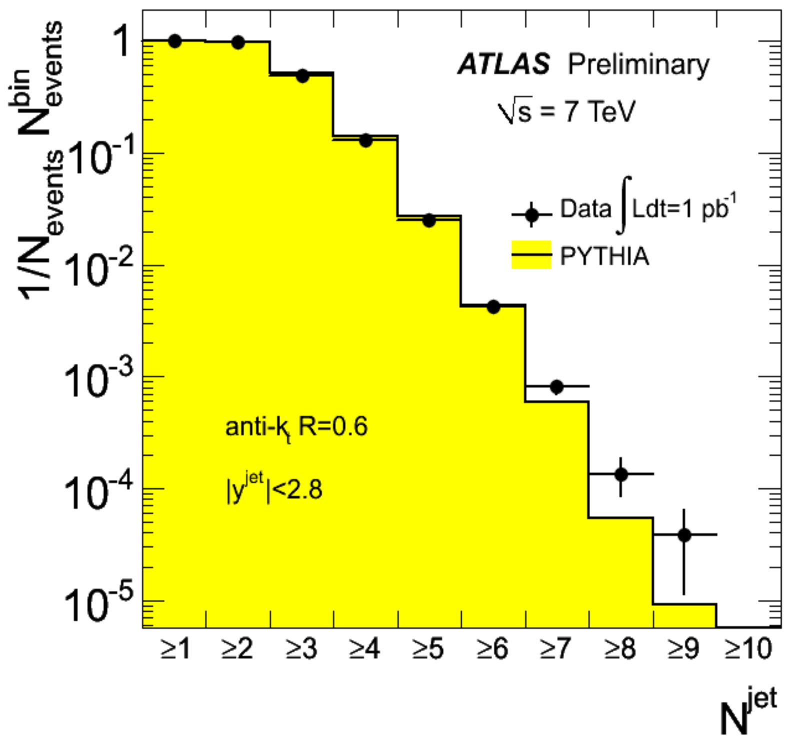


- Jets become narrower as jet pT increases
- Reasonable agreement with Monte Carlo models

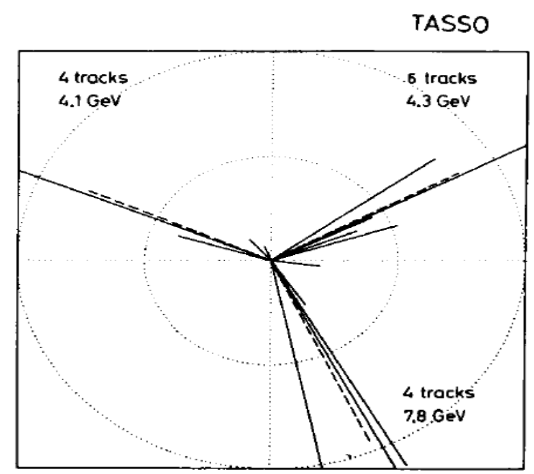
Multi-jet measurements

At 7 TeV, ATLAS routinely records events with more than 8 jets!

~1 pb $^{-1}$ - one day of data taking



First 3-jet event. 1979

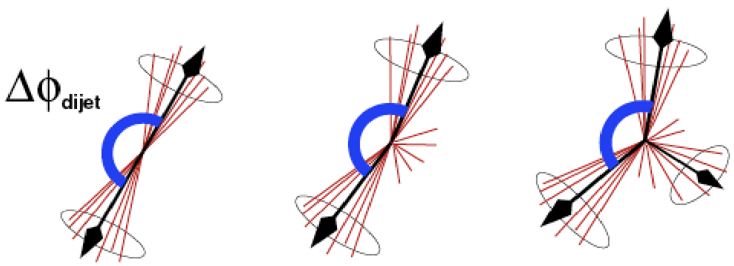


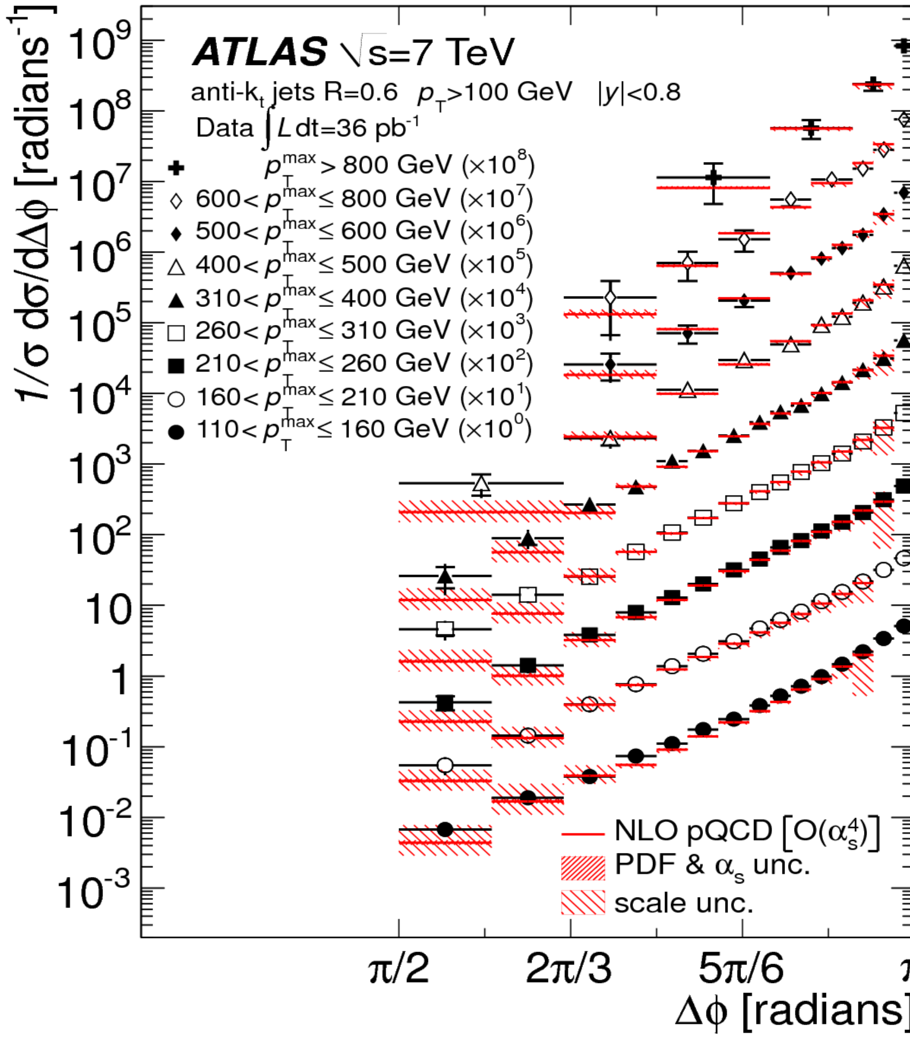
First 3-jet event observed by TASSO at PETRA. Plotted are vectors of charged particles projected into the principal event plane

Testing high-order QCD processes. Theory agrees?
Remember, this is a comparison with a MC generator (undefined scale uncertainty)

Azimuthal correlations

Looking at QCD without reconstructing soft jets!



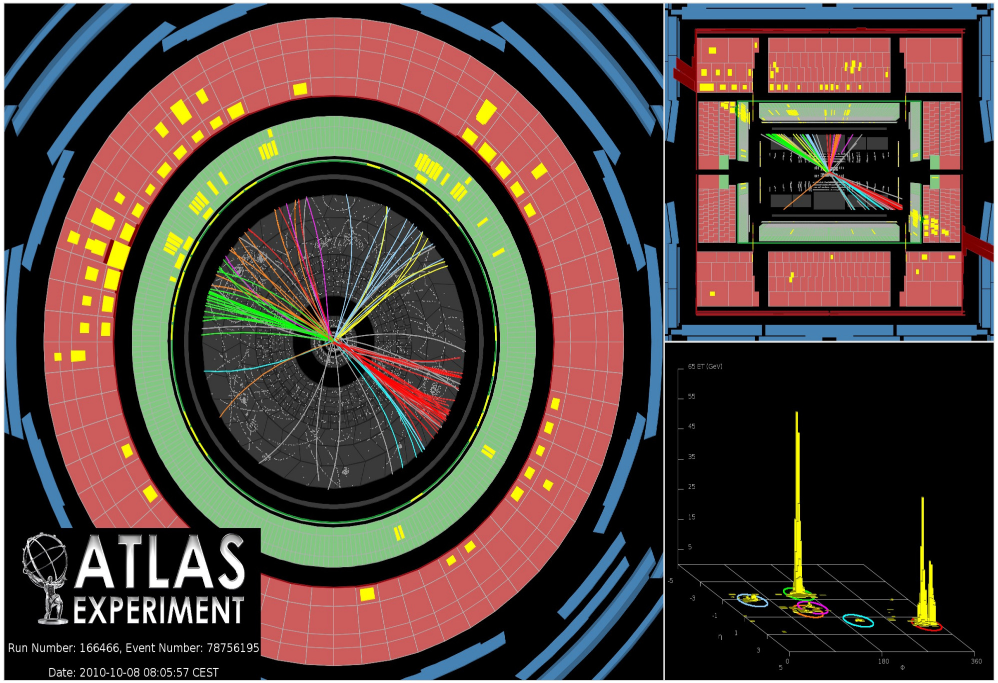


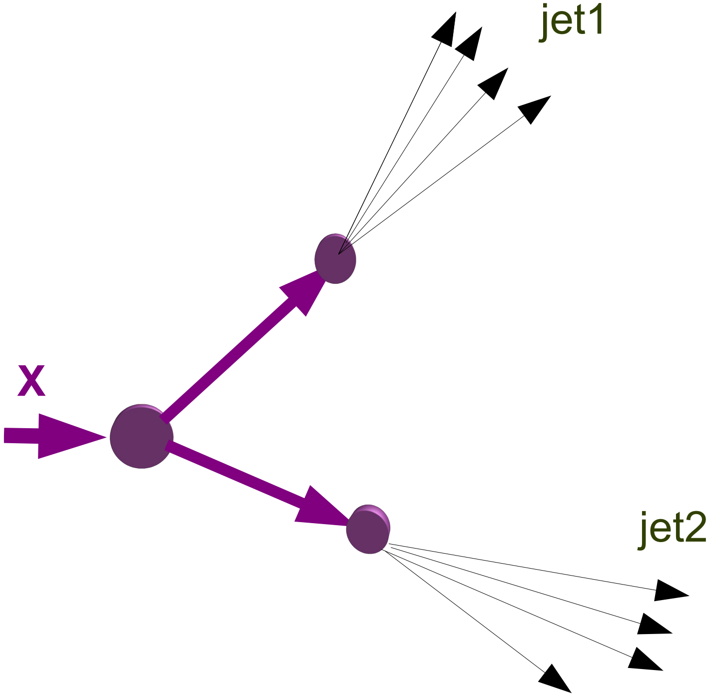
Sensitive probe for many QCD aspects!

Agreement with NLO QCD predictions
Significant theoretical uncertainties

Highest-mass dijet event

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





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

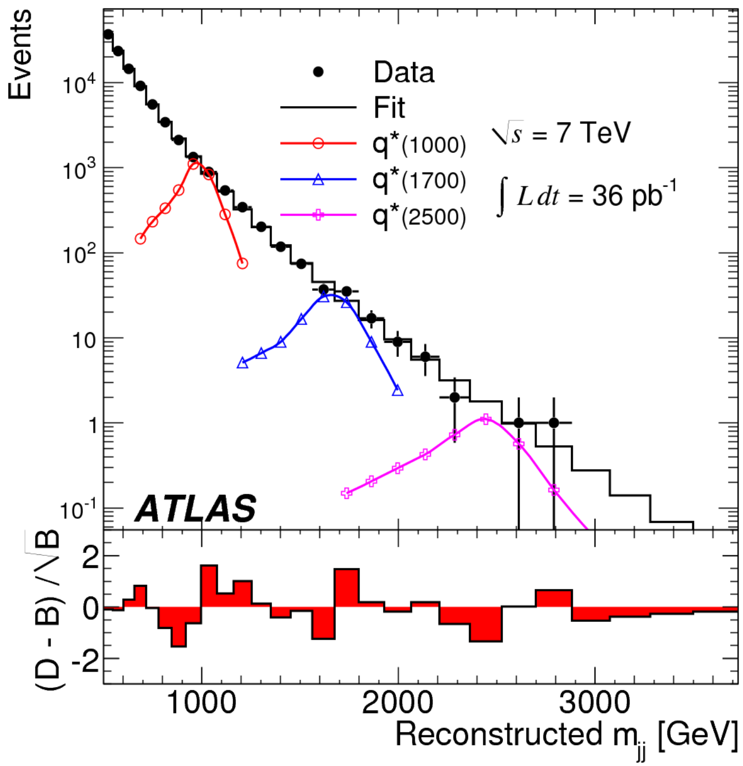
Search for New Particles in Two-Jet Final States

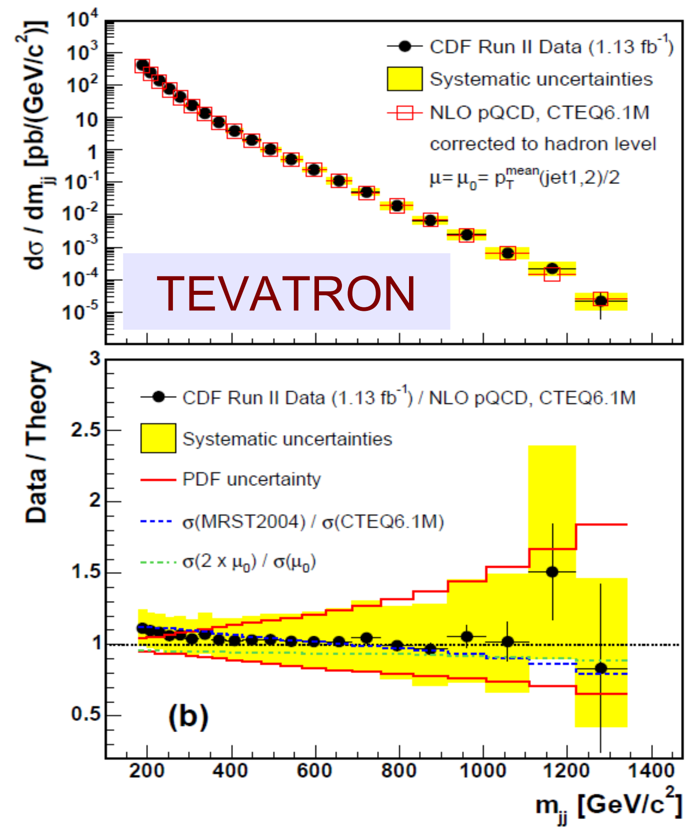
ATLAS arXiv:1103.3864

- Model-independent search for resonances on top of a smooth falling M_{jj} spectrum (pT>150 GeV)

Excited-quarks excluded at the 95% CL for 0.6<m(q*)<2.64 TeV

TEVATRON exclusion m(q*)<870 GeV

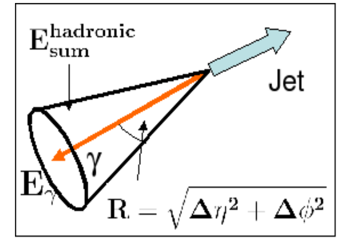




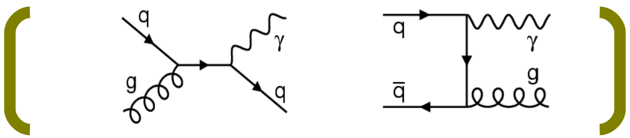
But what if widths of new states are large?
Can only be studied when the SM is well understood!
~ 50% theoretical uncertainties seen by TEVATRON

Direct photon production

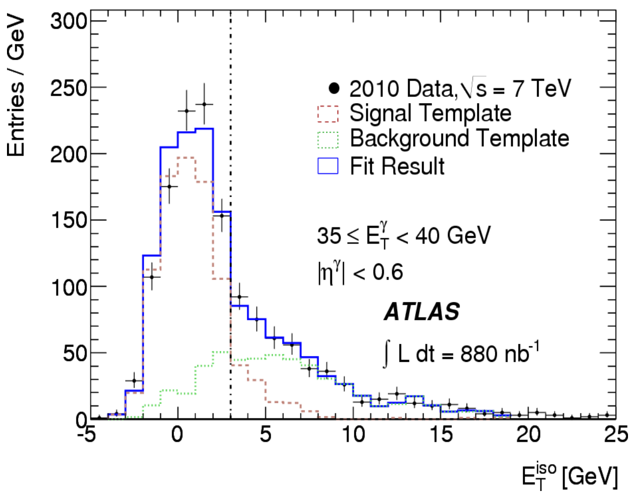
ATLAS arXiv:1012.4389

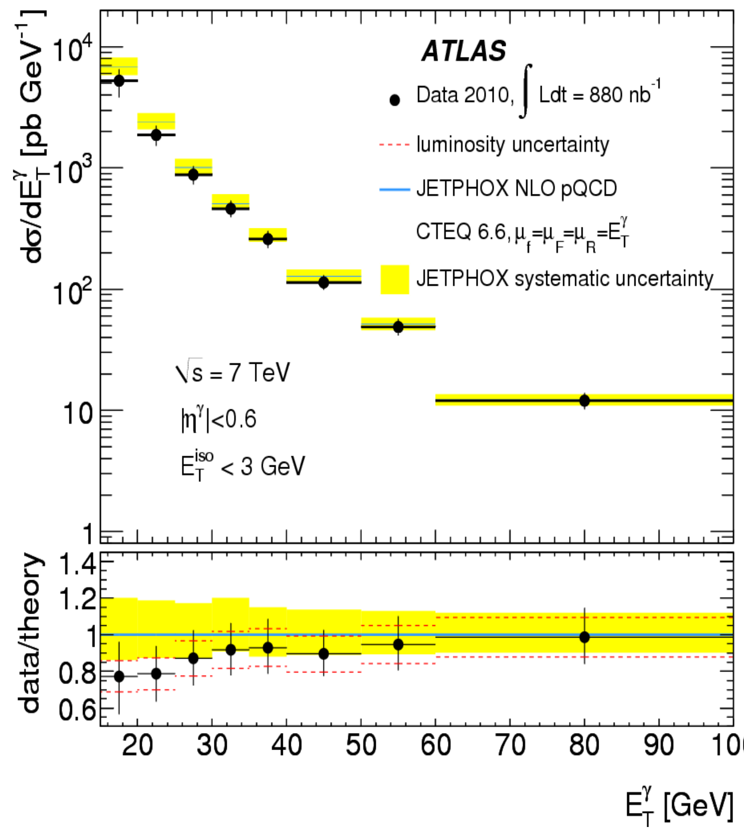


- On theoretical level, considered to be a clean environment to study QCD (no jet reconstruction)
- But difficult in practice as one should deal with large background from hadrons



~90% ~10%



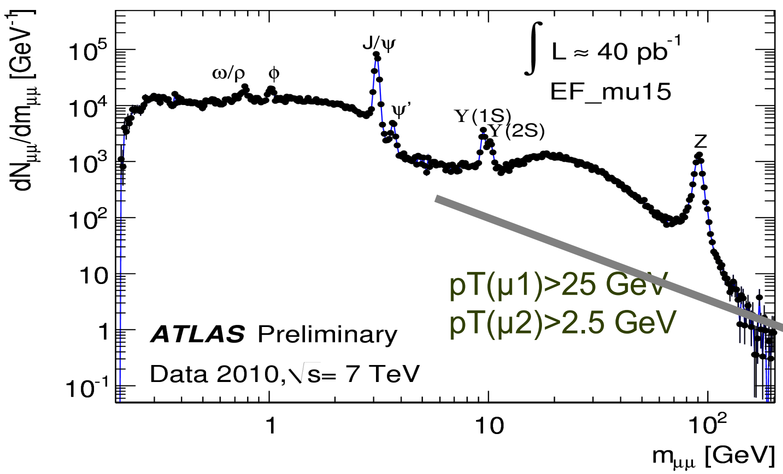


E_T^{ISO} - isolation energy in the cone excluding 5x7 cells around barycenter

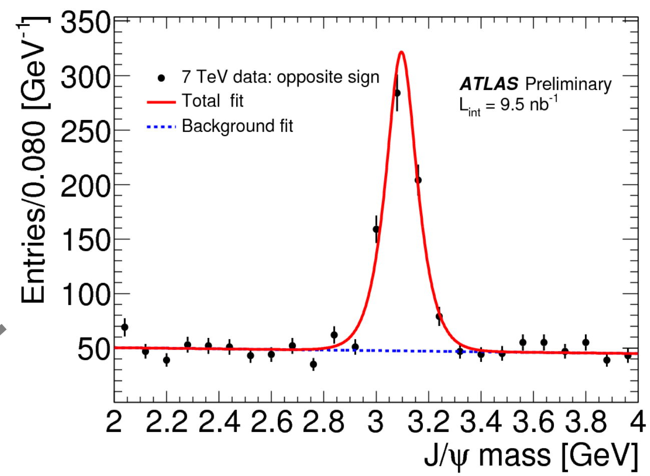
Good agreement with NLO QCD & CTEQ6.6

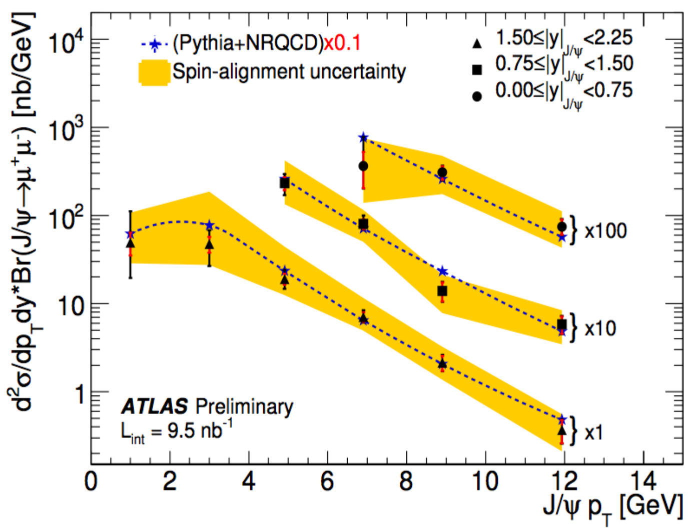
Charmonium (bound state of a charmed quark and a charmed antiquark)

- 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

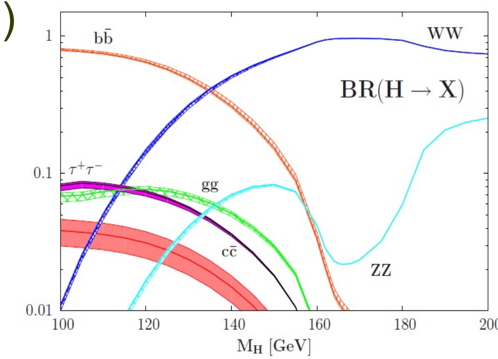




PYTHIA (+Colour-Octet Mechanism) with MC09 tune is in good agreement with the data
(note spin-alignment uncertainty)

From QCD to high-pT EWK sector

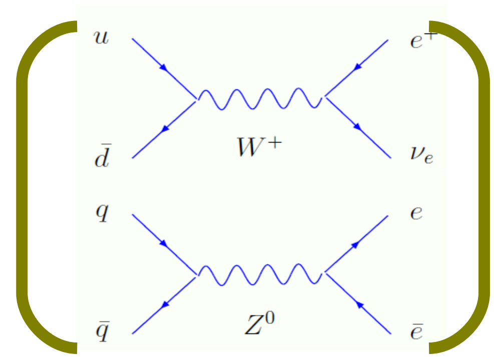
J.Baglio, A.Djouadi arXiv:1012.0530



- Better theoretically understood (in some cases with a few % 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} (this year!)
- Main channel for Higgs hunting (and main background!)

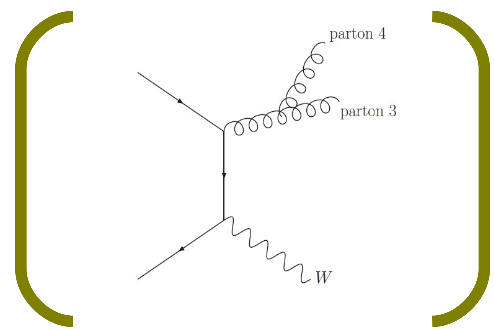
Inclusive W/Z measurements:

- 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



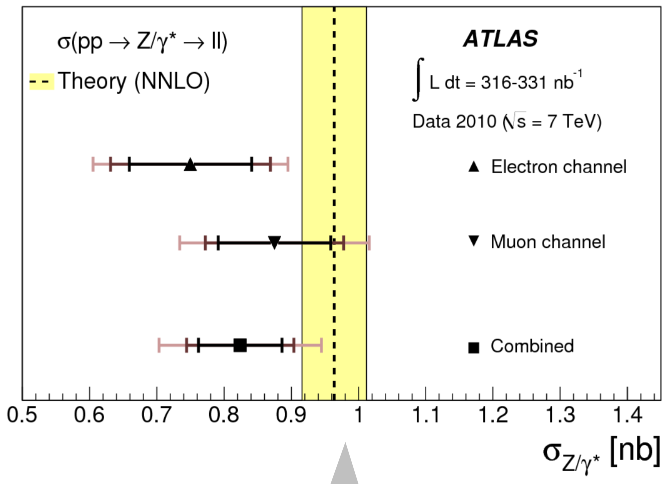
W+jet measurements

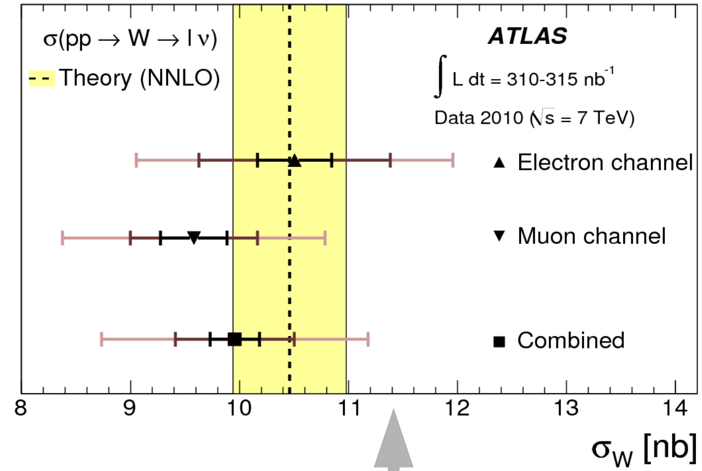
- Constrain measurements to well-known physics
- Precise test of QCD matrix elements & PDF
- Important background for top-antitop, single-top, Higgs searches

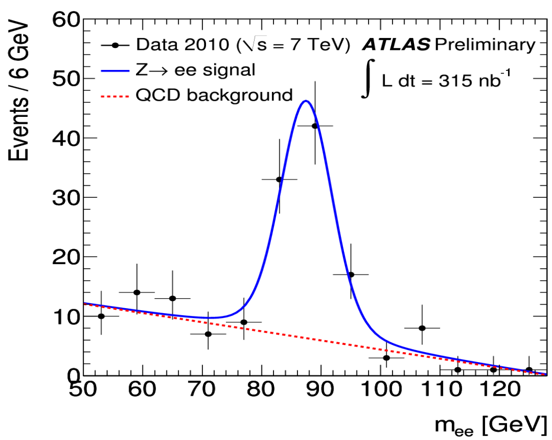


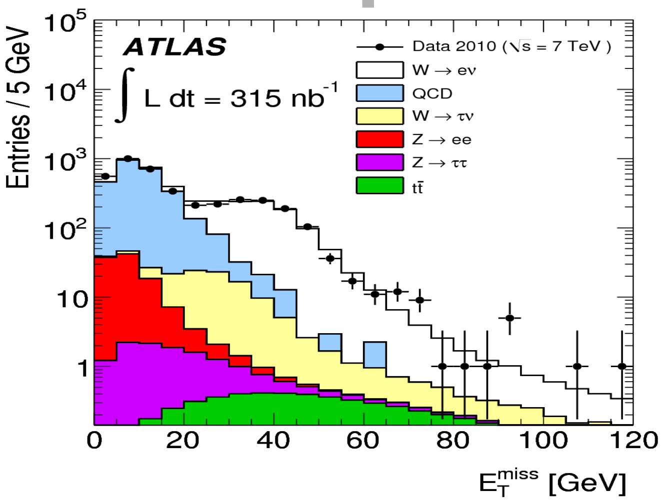
Probing High-pT EWK sector

ATLAS arXiv:1010.2130









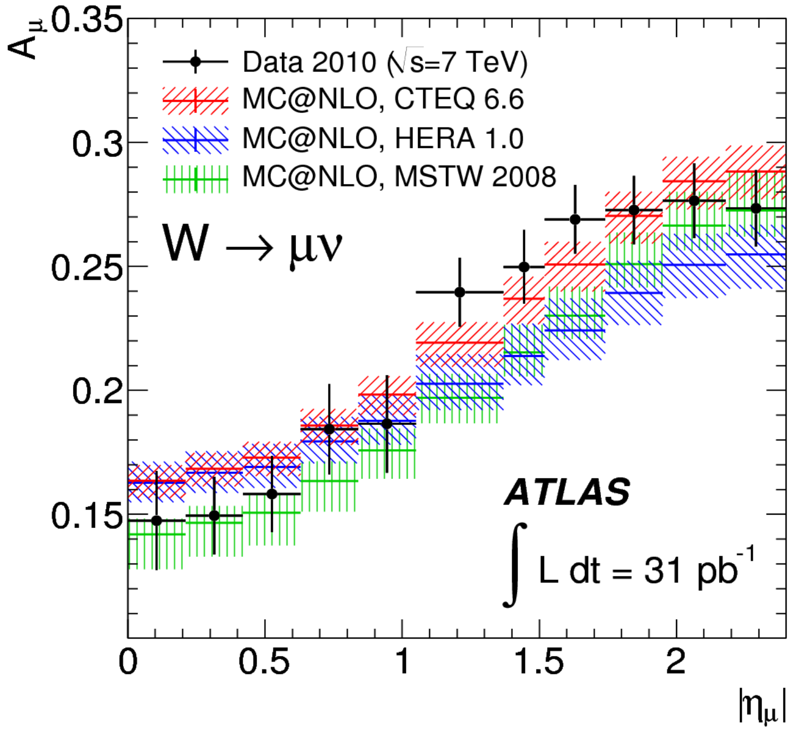
"Golden" channels

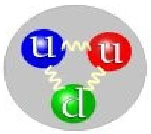
- $Z \to e^+ e^-$ ($\mu^+\mu^-$)
- W: isolated lepton + missing E_T

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

Lepton charge asymmetries

arXiv:1103.2929v1





up quark: +3/2 e
down quark: -1/3 e

$u\bar{d} \rightarrow W^+$ $\bar{u}d \rightarrow W^-$

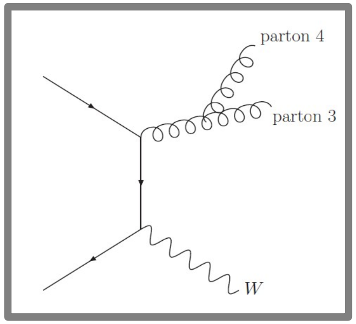
$$A_\mu = \frac{d\sigma_{W\mu^+}/d\eta_\mu - d\sigma_{W\mu^-}/d\eta_\mu}{d\sigma_{W\mu^+}/d\eta_\mu + d\sigma_{W\mu^-}/d\eta_\mu}$$

- 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
- Data agree with all models & CTEQ6.6
- First precise measurement of the ratio of u/d quarks in this kinematic region (x<0.05)

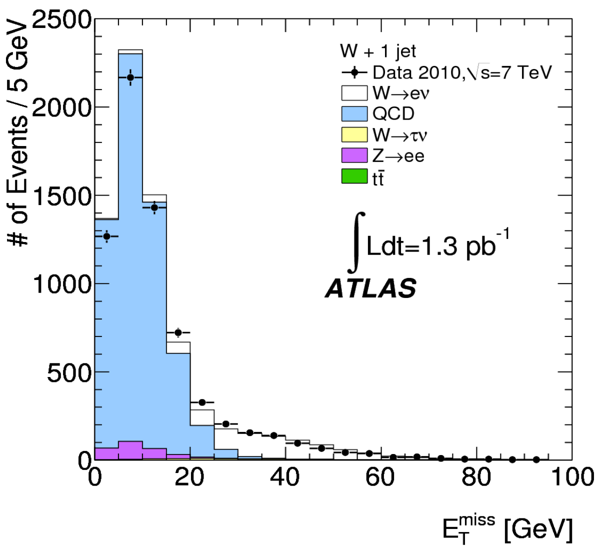
W+ jets measurements

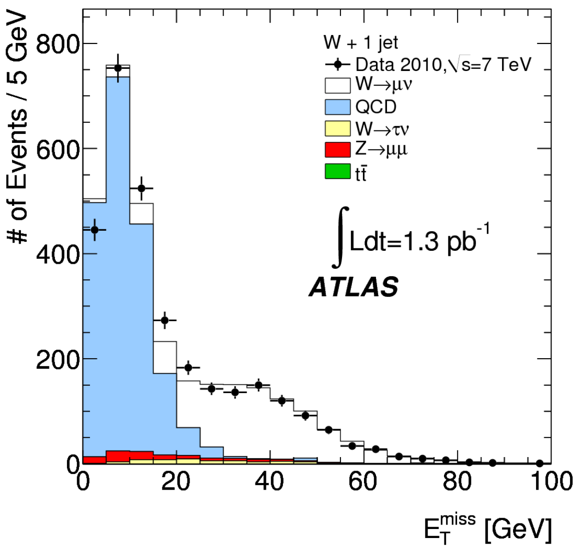
ATLAS arXiv:1012.5382

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



- W+jet signal yield was obtained as difference between data and sum of all backgrounds
- Background calculations: Leptonic channels: ALPGEN/PYTHIA with NNLO or NNLL normalizations; QCD background: fitting E_T^{miss} using data using template shapes

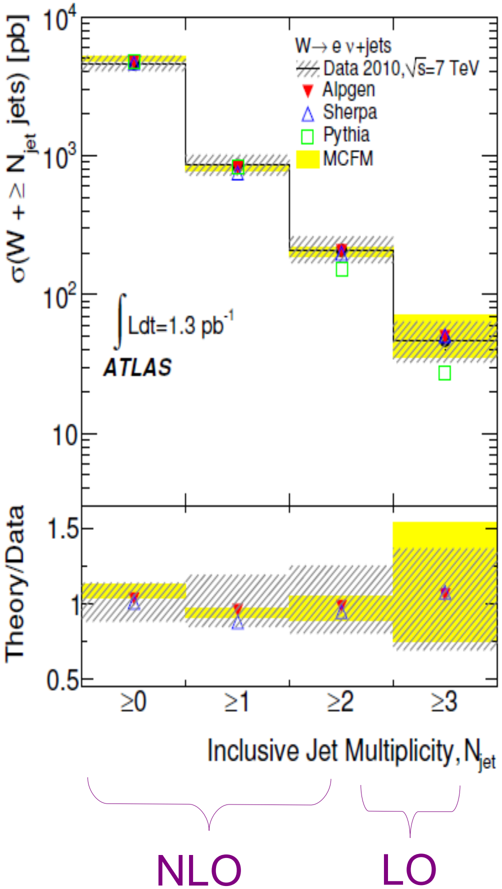




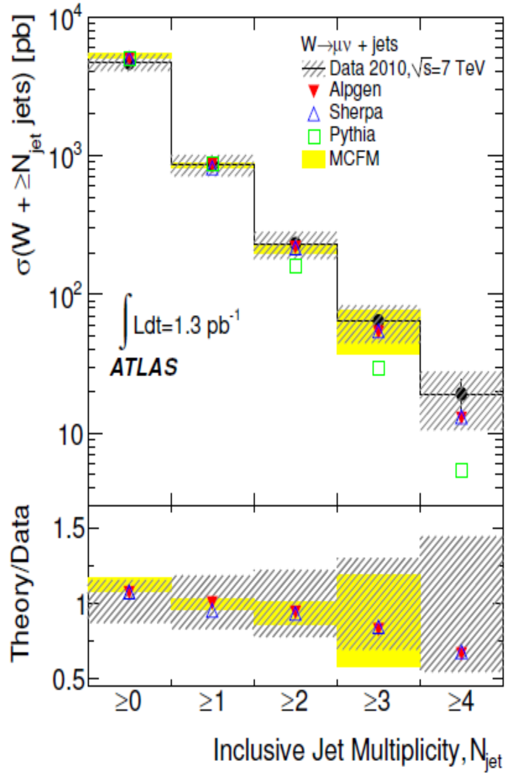
W+ jets measurements

ATLAS arXiv:1012.5382

W → e ν



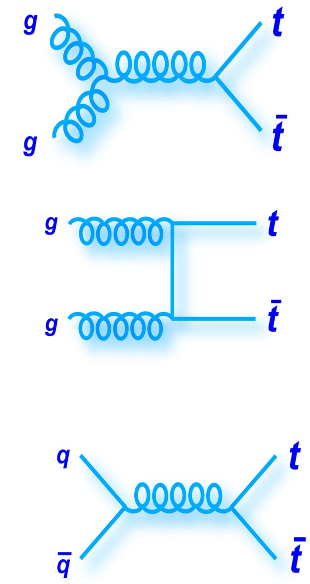
W → μ ν

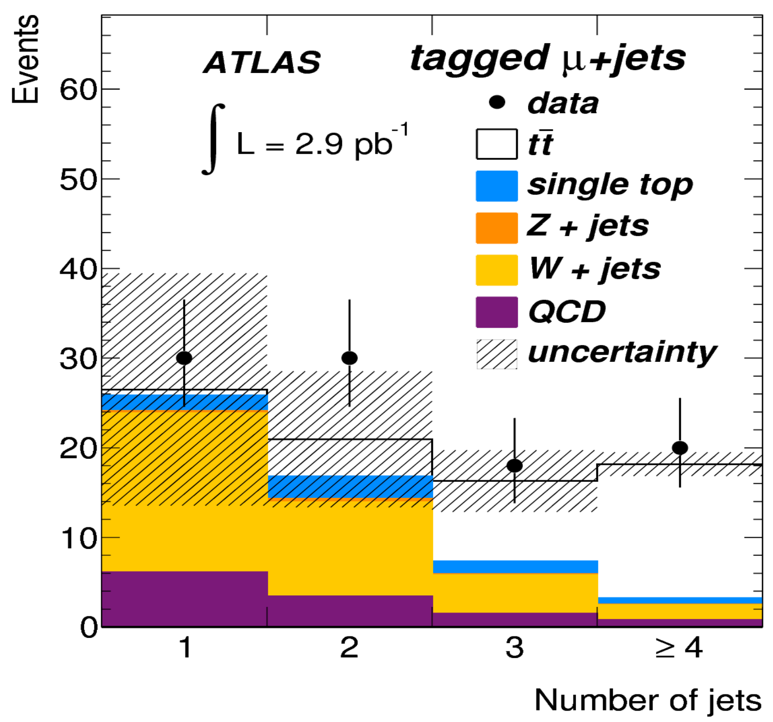


- Good agreement with NLO QCD for <3 jets
  - + corrections (~10%) for hadronization & underlying events using AMBT1 tune
  - ~50% theoretical uncertainty for W+3 jets
- Monte Carlo models available for W+4 jets (muon channel)

Top rediscovery

- Discovered in 1995 at Tevatron
- The most massive fundamental particle which completes the third generation of the SM quarks
- The most likely place for new physics to show up?
- ~90% top quarks are produced by gluon-gluon fusion





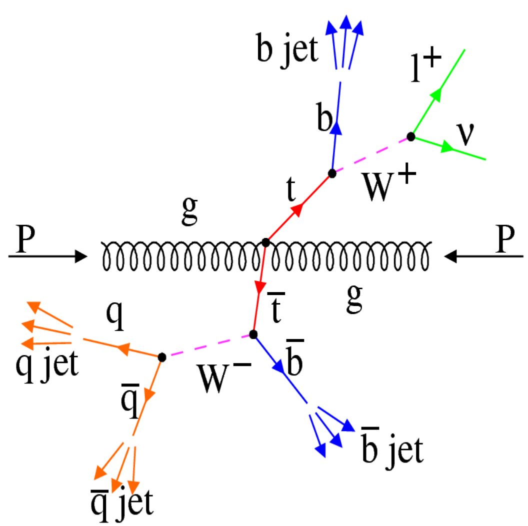
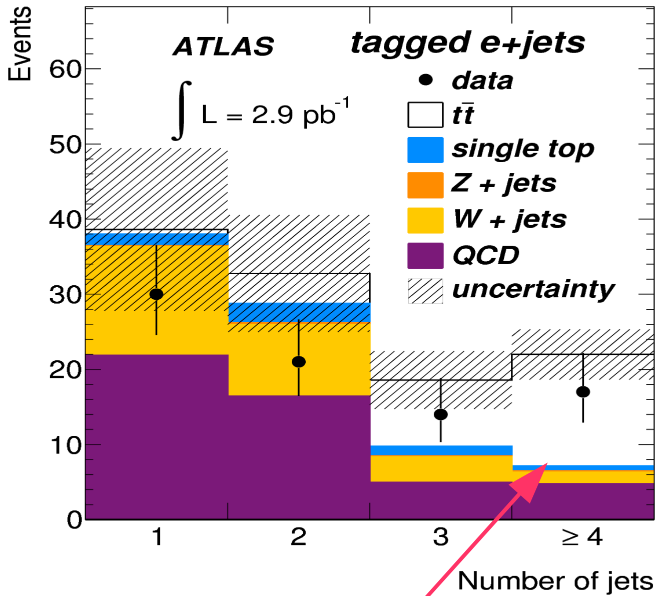
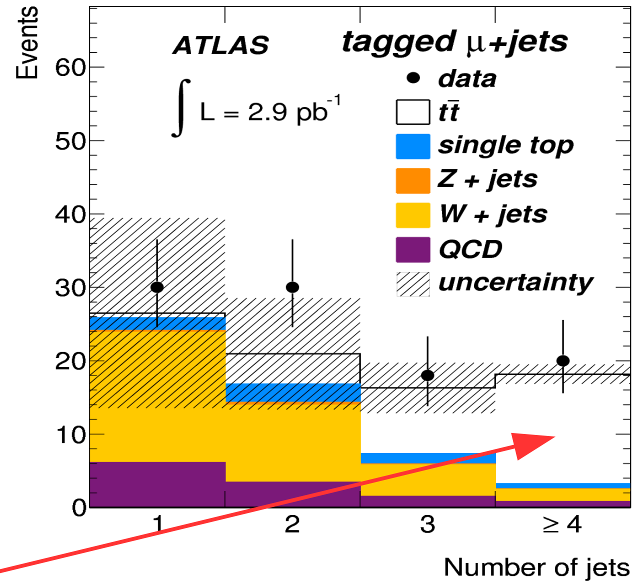


image by P.Bell

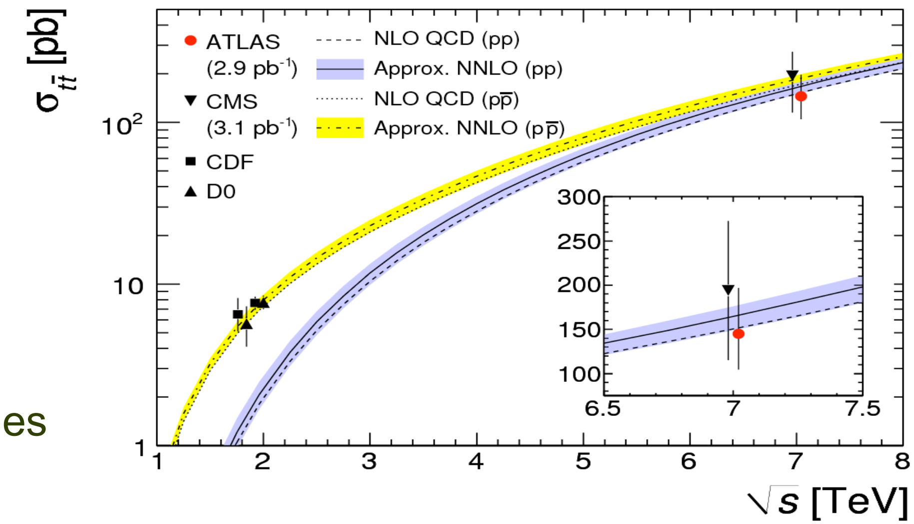
Top cross-section measurements





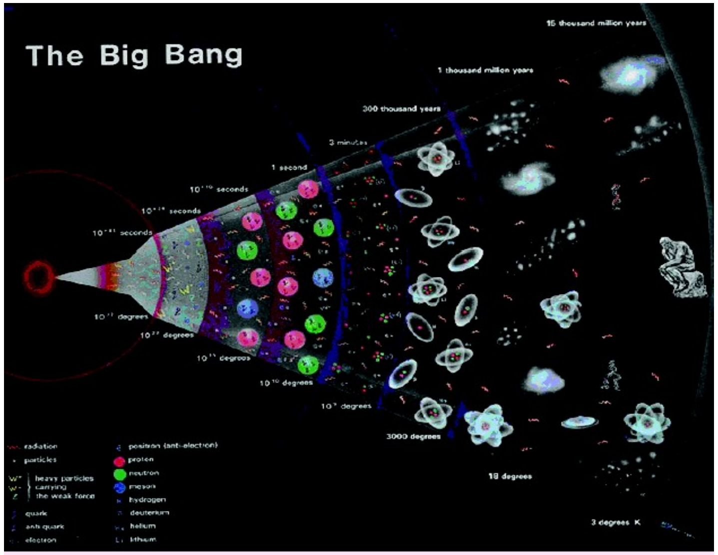
top-quark signal!

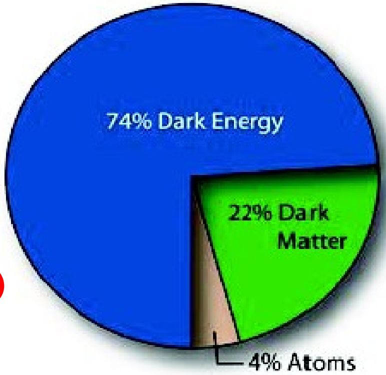
Good agreement with NLO & NNLO (app) QCD

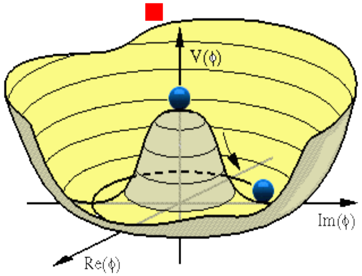


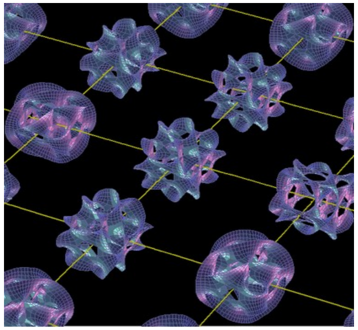
For ~40 pb-1:
theory uncertainties ~ experimental uncertainties

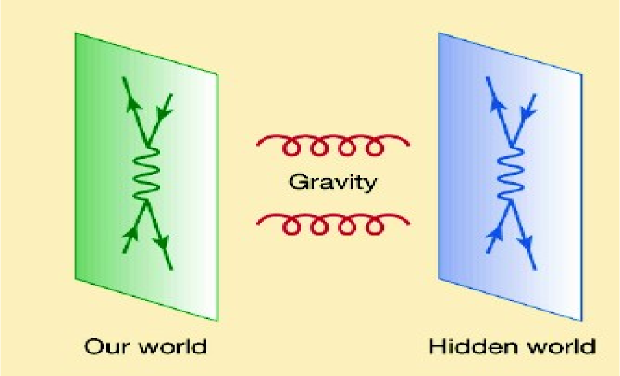
Where are discoveries?

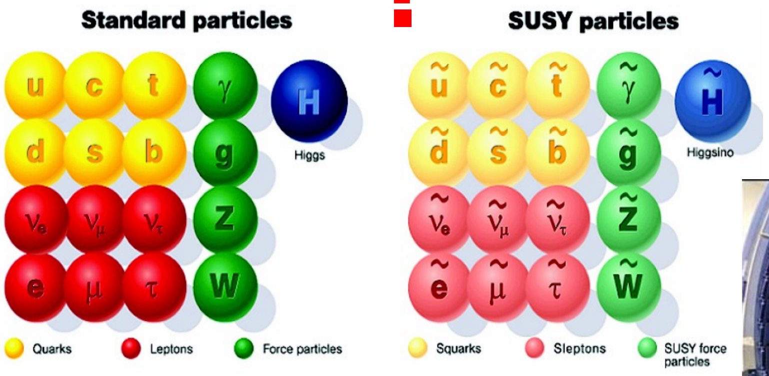












"black hole"

For many, many discovery signatures, the knowledge of the SM processes is the limiting factor!

New physics and SM (experimental view) *


- **Inclusive inelastic pp collision events (event pT <10 GeV)**
  - Significant volume of data at new energies (7 TeV)
  - No reliable theory. MC disagree by ~20-40%. Must be tuned to data but some quantum-mechanical events are missing (azimuthal angle ordering, Bose-Einstein effect, etc.)
    → Experiment is ahead of theory

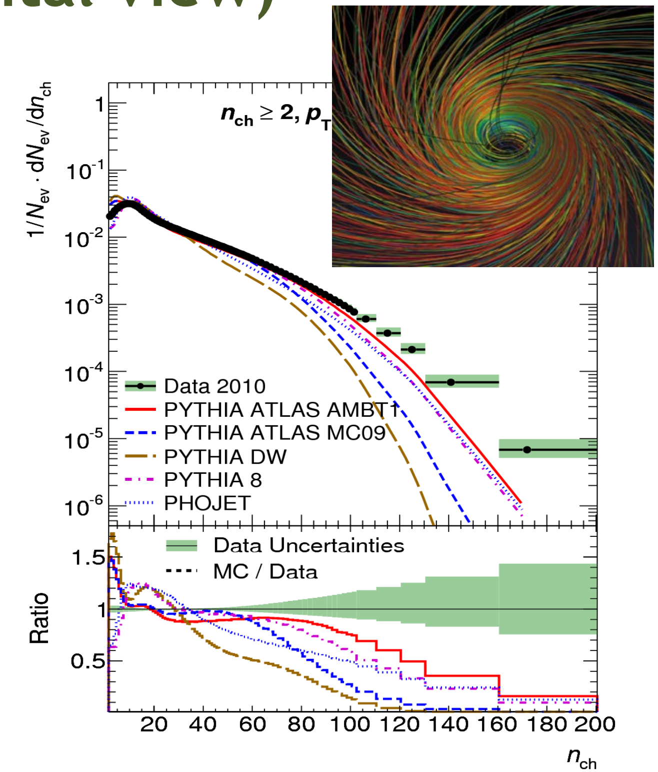
- **Medium-pT (10 GeV <pT<1 TeV) – current LHC, Tevatron**
  - QCD uncertainties: ~10-20% uncertainty (jets) and <3-5% (EWK)
  - theory uncertainty is even larger for multijet events
    - difficult to ping down new physics with x-cross section smaller than this uncertainty
  - MCs to estimate soft effect and/or data from other channels to estimate background

- **High-PT physics (pT>1 TeV)**
  - Reliably QCD predictions, but new uncertainties emerging (large x for parton densities)
  - A lot of theory development, but no much data.
    - **→ Theory is ahead of experiment. Theory-driven experimental research!**
    - Probably will remain so until the LHC starts its designed operation.

* Unless new physics has easy-to-separate or highly unusual signatures

New physics and soft QCD (experimental view) *

- **Is it possible that we miss new physics in the existing data?**
  - Examples: mini black holes, instantons, quirks, "hidden valleys", etc. in which large amounts of energy may be emitted by a large multiplicity of soft particles.
- **Very likely - we do.**
  - Fixing ~50% discrepancies by tuning MC generators
  - Real discrepancy can even be larger since 50% with respect to old tunes!
  - Not unreasonable to think that new physics is already a part of MC tunes or data-driven background



Moving from "predictive" science to "descriptive" due to slow progress in theory?

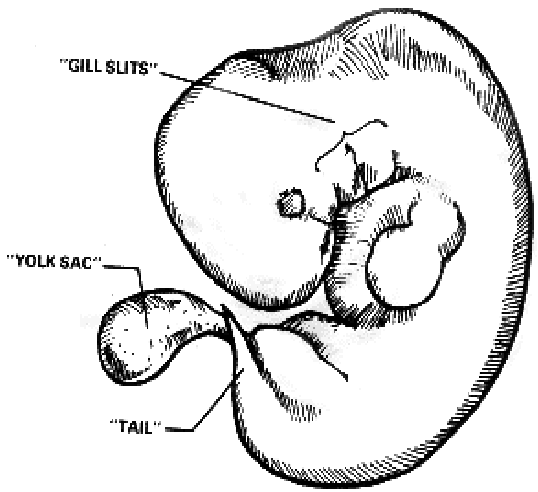
* Unless new physics has easy-to-separate or highly unusual signatures

Same (philosophical) remark

If you still believe in the evolutionary theory:

"Each child as he develops is retracing the whole history of mankind, physically and spiritually, step by step. A baby starts off in the womb as a single tiny cell, just the way the first living thing appeared in the ocean. Weeks later, as he lies in the amniotic fluid of the womb, he has gills like a fish..

-child development author Dr. Spock-



An early stage in human development

So do the newborn LHC experiments when retracing the whole history of HEP in their early measurements

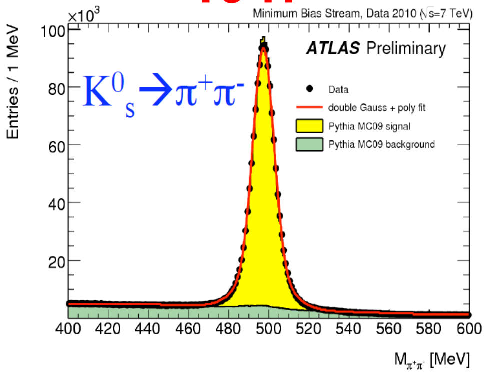
Many discussed topics are known for 40-50! years

ATLAS repeated many historic measurements during 1st year of data taking

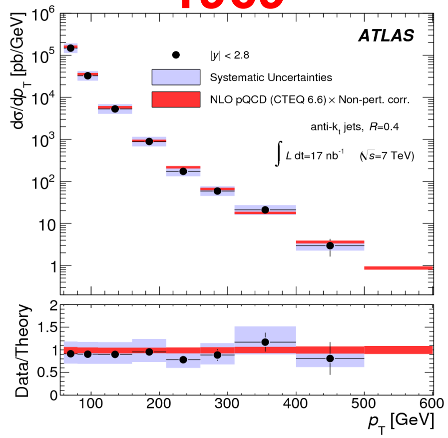
Many limits on new physics are close or better than at Tevatron!

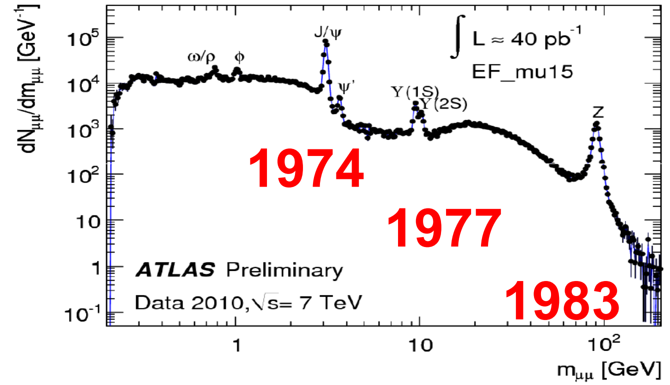
ATLAS data after ~1 month of data taking

1947



1969

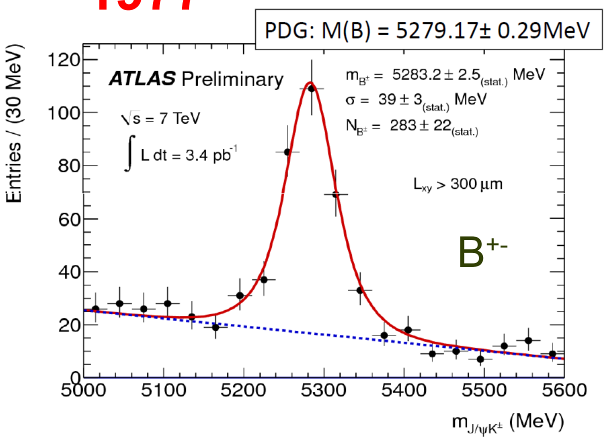


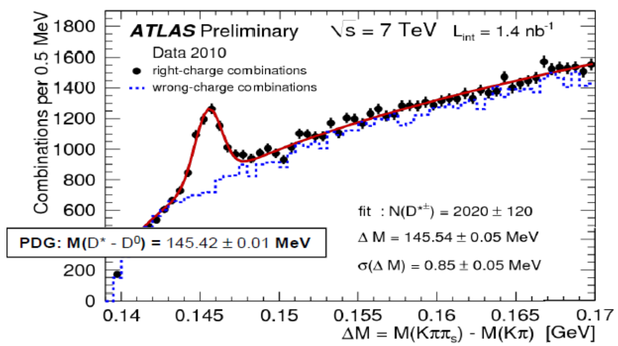


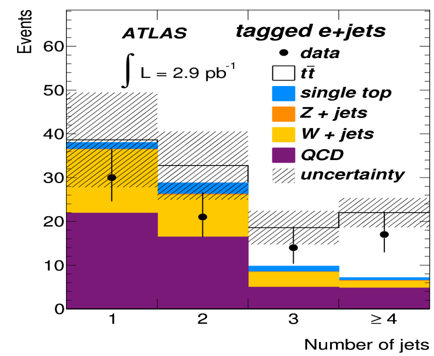
1976

1995

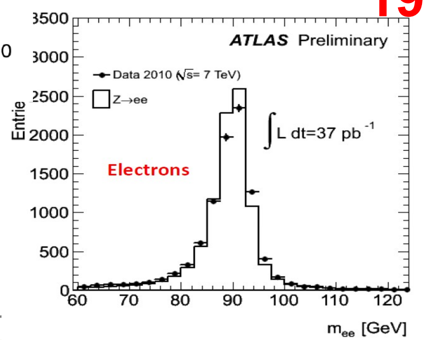
1977

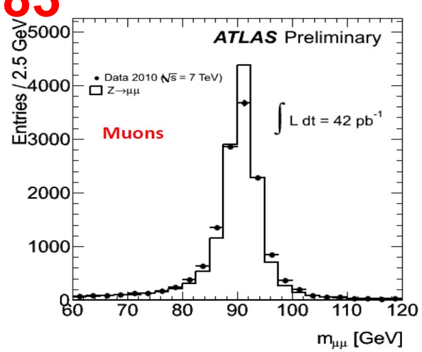






1983





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 SM predictions (NLO,NNLO)
- **Working on MC tunes to describe soft QCD**
  - must be ready for high-precision measurement
  - important for searches for new physics

several results shown in my talk have been done at HEP ANL!

- **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

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

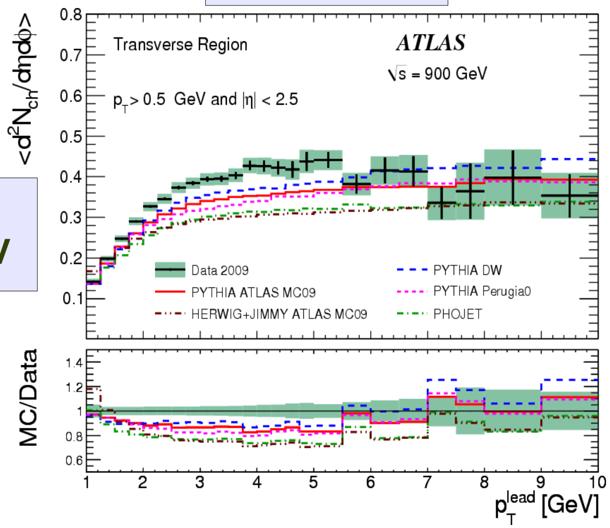
Main scope of comparison with Monte Carlo models: tune softQCD phenomenological models in order to use such models for better understood SM processes (pQCD, EWK measurements)

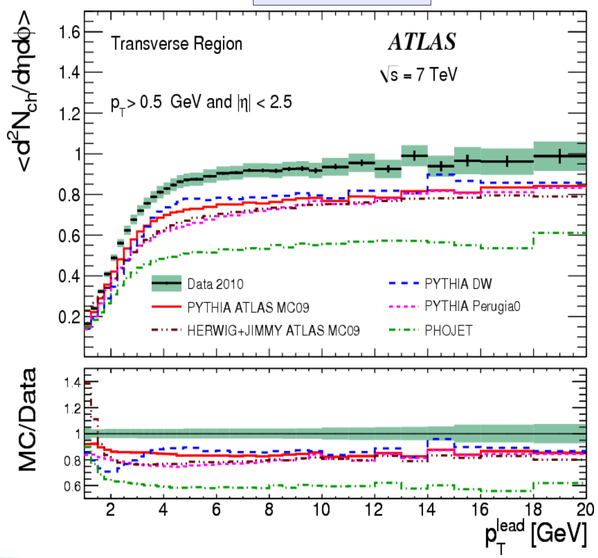
Particle densities in the transverse region

900 GeV

7 TeV

pT> 0.5 GeV



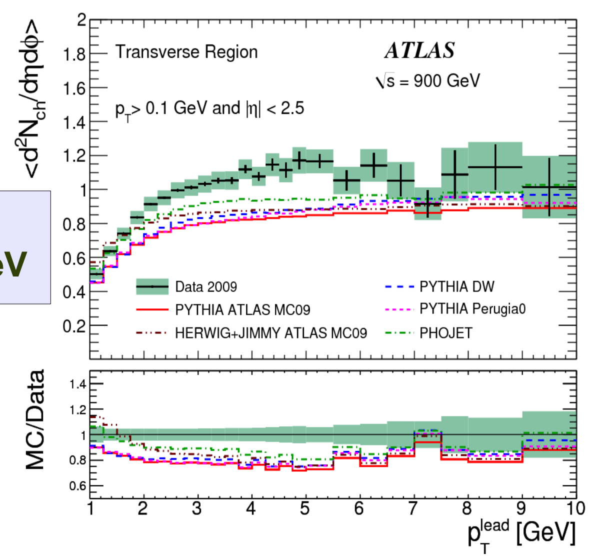


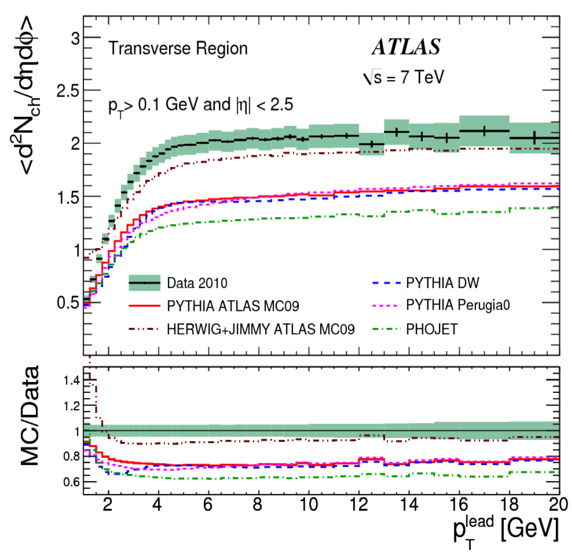
Smaller discrepancies going to 900 GeV

or

moving to pT>0.5 GeV

pT> 0.1 GeV





Closer to the final state used for MC tunes?