Standard Model Measurements at the Energy Frontier

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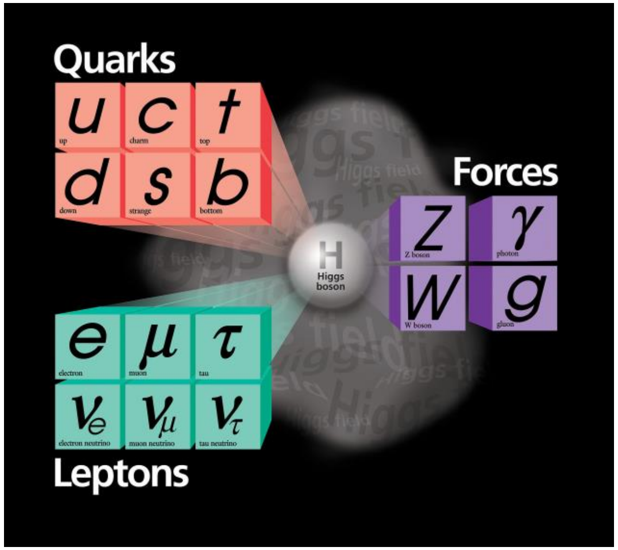
Outline

- The Standard Model (SM)
- Energy Frontier
  - Hadron colliders and their experiments
- How a SM measurement is performed
- **SM measurements at hadron colliders**
  - **QCD**
    - Jet production, photon production, W/Z production
  - **Electroweak**
    - W/Z decays, di-boson production, tri-boson production, Vector Boson Fusion, Vector Boson Scattering
- Summary

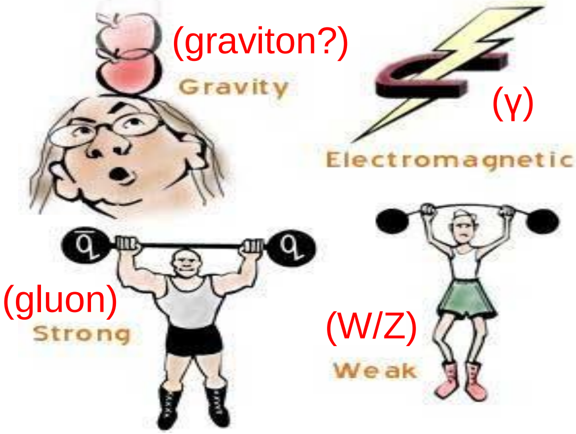
Elementary Particles and Forces

Elementary particles

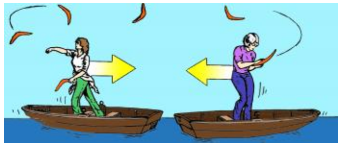


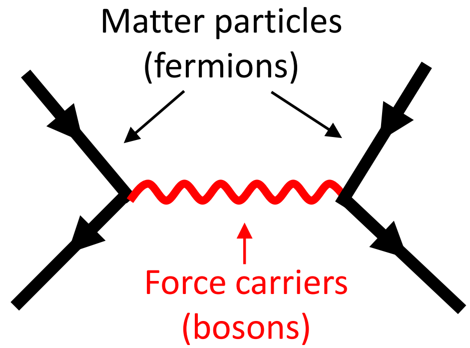
- Matter particles
  - Quarks and leptons, all fermions, spin ½
  - Matter building blocks
- Force carriers
  - All bosons, spin 1 (or 2?)
  - Mediators of interactions between particles
- Higgs boson
  - Spin 0, the only scalar in SM
  - Electroweak symmetry "breaker" and mass "giver" for massive elementary particles

The four fundamental interactions (forces)



How interactions take place





The Standard Model

- The Standard Model classifies the elementary particles and describes how they interact with each other in the framework of quantum field theory with gauge symmetries. It represents our best understanding of the world so far.

$$\mathcal{L} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}D\psi \quad \longrightarrow \quad \text{Gauge sector}$$

$$+\psi_i\lambda_{ij}\psi_j h + h.c. \quad \longrightarrow \quad \text{Flavor sector}$$

$$+|D_\mu h|^2 - V(h) \quad \longrightarrow \quad \text{Higgs sector}$$

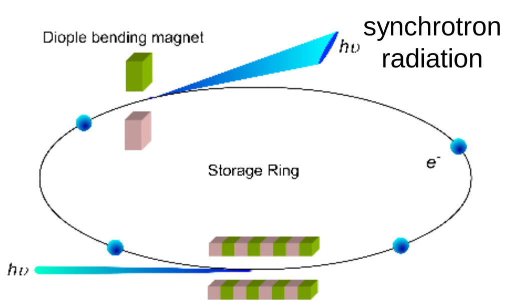
+ *Neutrino mass sector (in view of the well-established experimental fact of neutrino oscillation)*

Gauge sector : **QCD** [SU(3)] + **Electroweak** theory [SU(2) × U(1)]

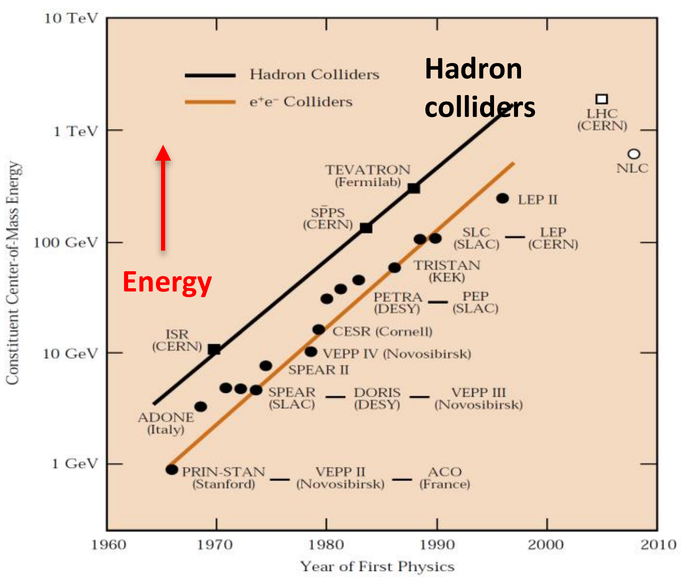
→ *The two main topics to be discussed experimentally in this seminar.*

Energy Frontier

- λ=h/p : We need high energy to probe small structure and access high mass particles
  - Particle colliders are required
- Hadron colliders lead the energy frontier
  - much less energy loss due to synchrotron radiation than e^+e^- (circular) collider
  - the only proven and realized approach to access **TeV** energy regime as yet

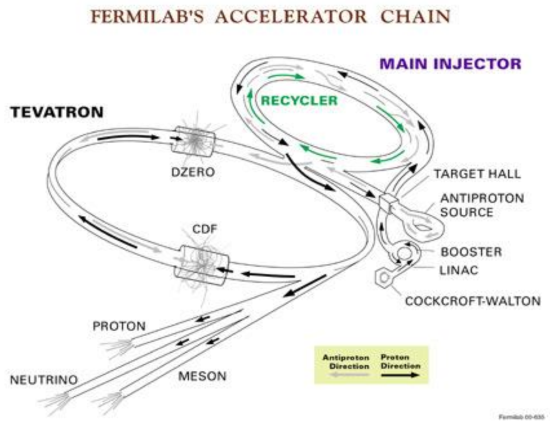


Energy loss: e vs p $\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$



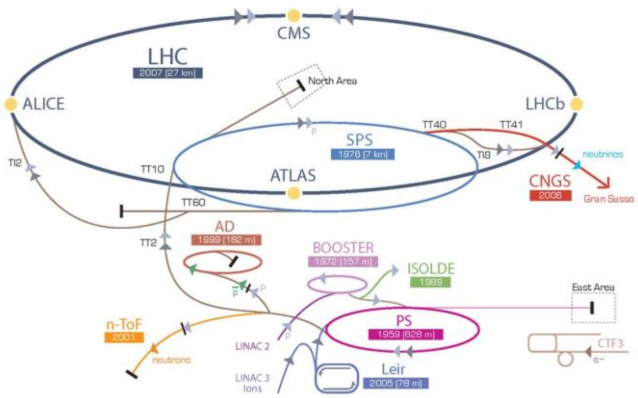
TeV Hadron Colliders

Tevatron @ Fermilab



A ppbar collider
$\sqrt{s}$ = 1.96 TeV
(shut down in Sep. 2011)

Large Hadron Collider (LHC) @ CERN



A pp collider
$\sqrt{s}$ = 7-8 TeV
(ramped up to 13 TeV this year)

Energy is not everything

- Number of events observed from collisions $N_{evt} = \sigma \bullet A \bullet \int L dt$
  - A: acceptance
  - σ: cross section of the process observed
  - L: luminosity of collisions
- Our capacity and reach in physics depend on N_{evt} which is directly proportional to the luminosity.
  - Luminosity is a parameter of extreme importance for a collider

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi \sigma_x \sigma_y}$$

f_{rev}: revolving frequency
n_{bunch}: number of bunches
N_p: number of protons per bunch
$4\pi\sigma_x\sigma_y$: beam cross section

Peak luminosity achieved: LHC vs. Tevatron
$7.7 \times 10^{33}\ cm^{-2}s^{-1}$ vs. $4 \times 10^{32}\ cm^{-2}s^{-1}$
20 : 1

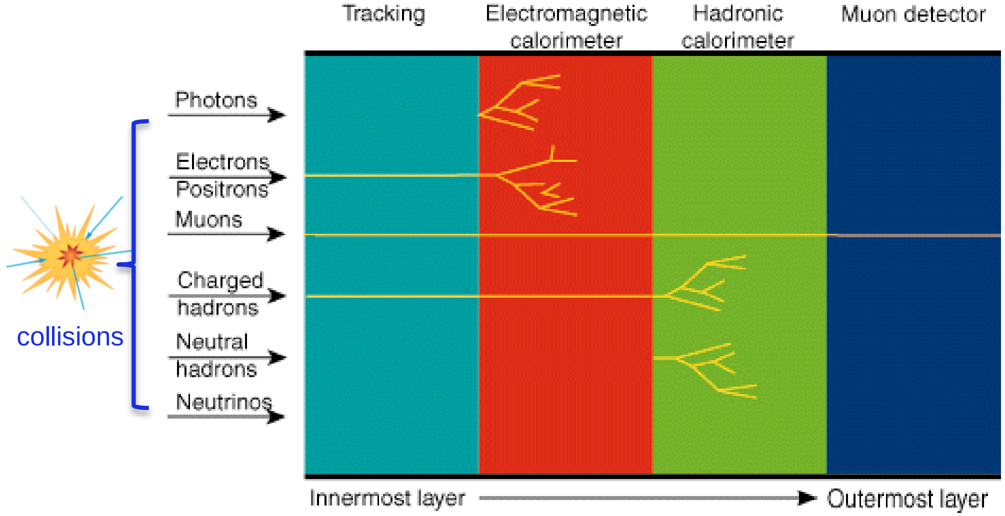
$\longrightarrow$ *1-day data taking at LHC would take 20 days at Tevatron, letting alone the big energy difference.*

We want colliders with high luminosity as well as high energy.

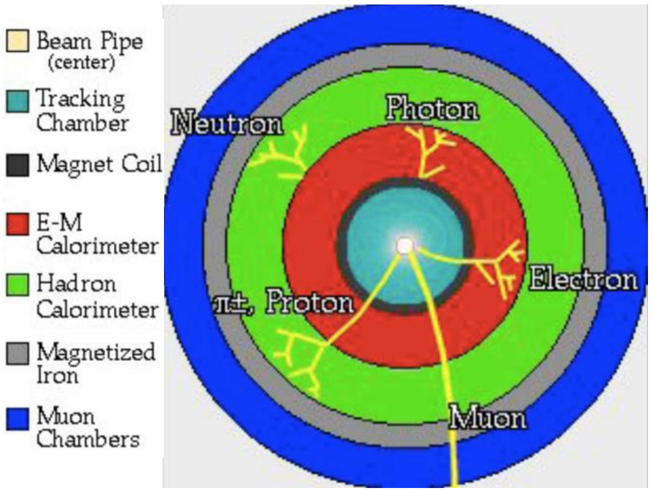
Particle Detectors

Cameras at high energy experiments

General particle detection principles
in modern high energy experiments



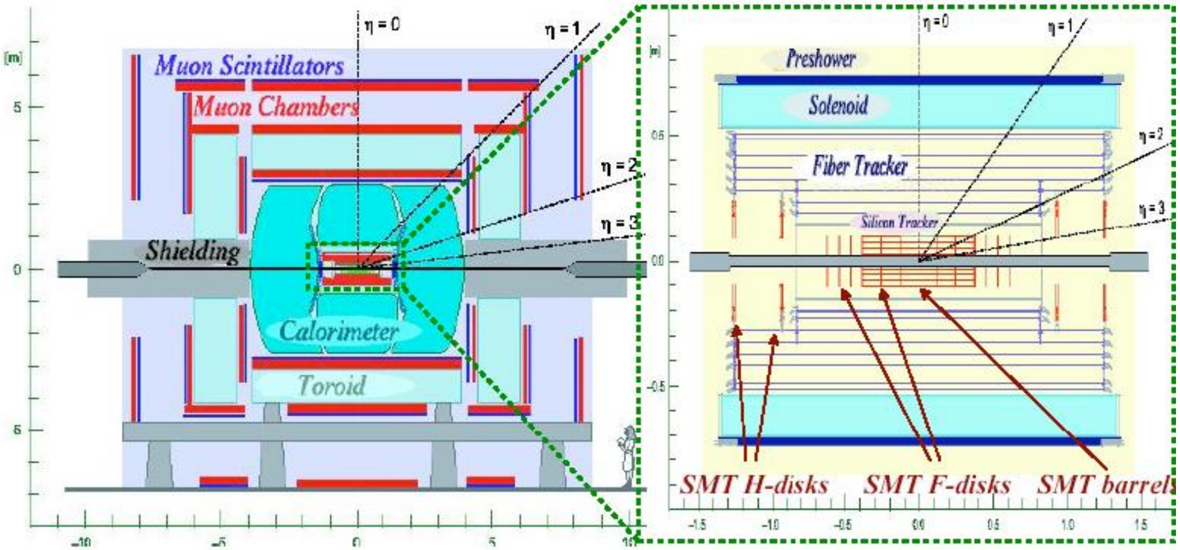
A General purpose detector



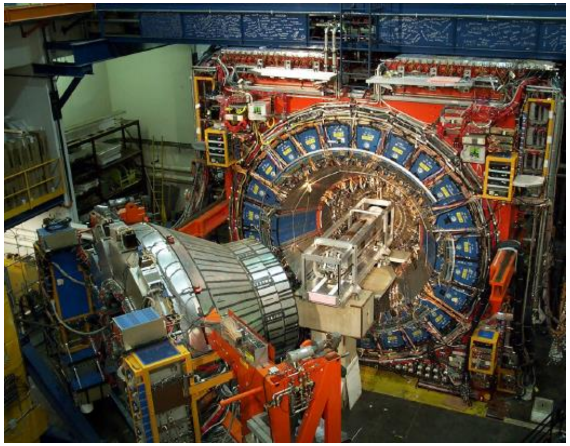
- Exploit distinguishing characteristics of different particles in interactions with matter
  - EM ionization, EM showering, hadronic showering …
- Employ multiple sub-detectors with different detection capabilities in a layer-by-layer structure.
- Achieve eventual detection goal (sensitive to all final state particles of interest to reconstruct the complete final state) by combining information from all sub-detectors.

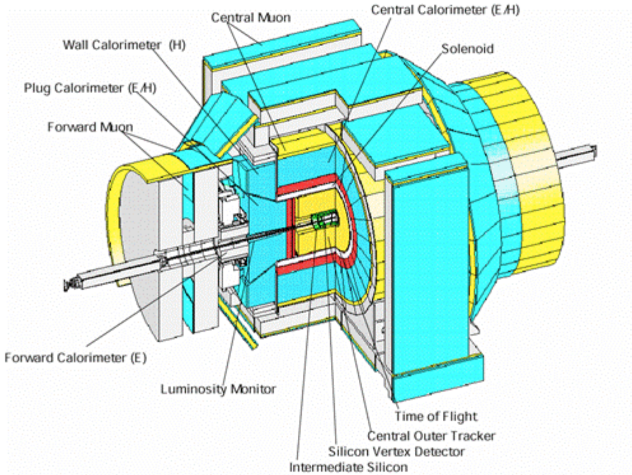
Detectors @ Tevatron

D0 experiment

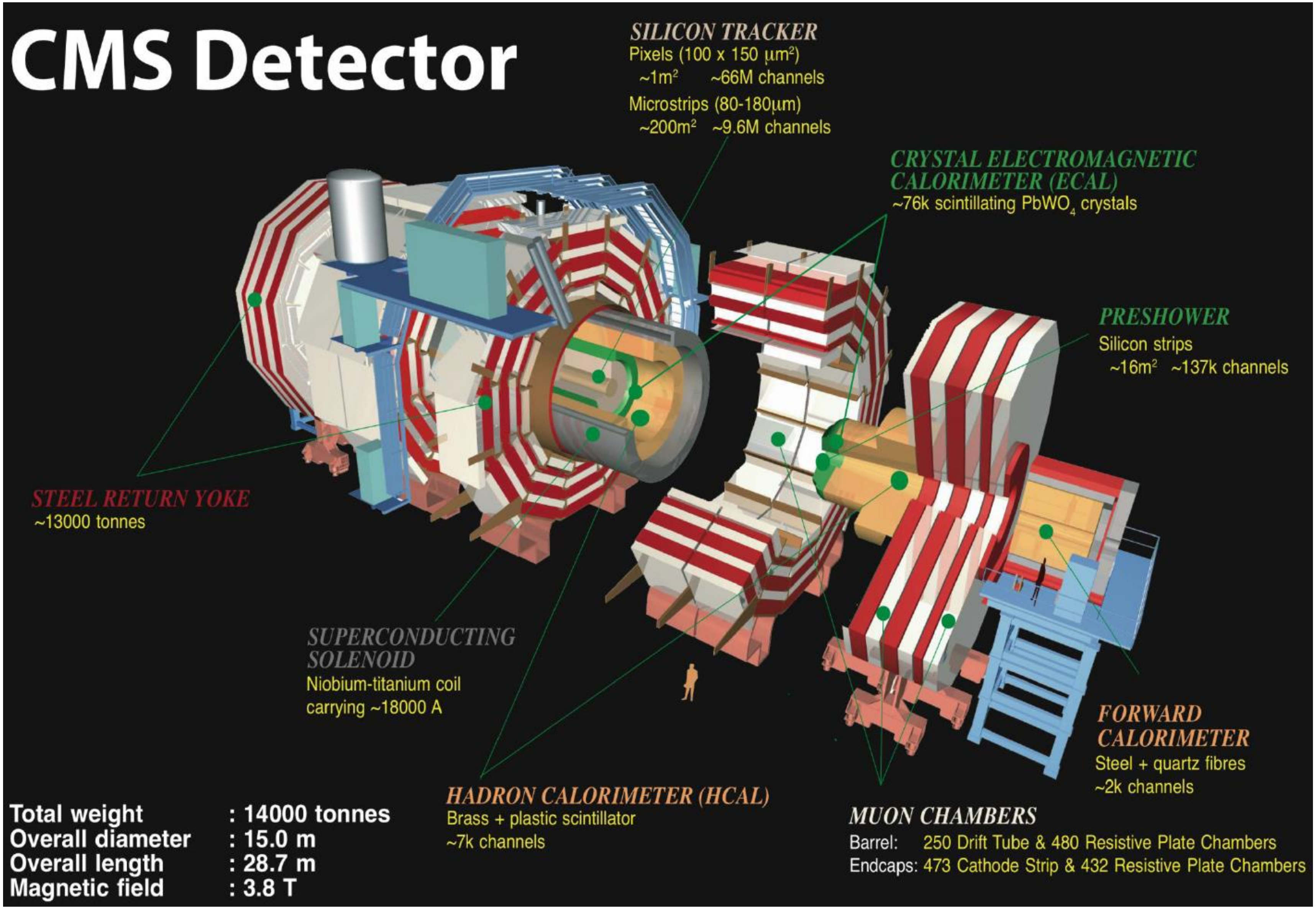


CDF experiment

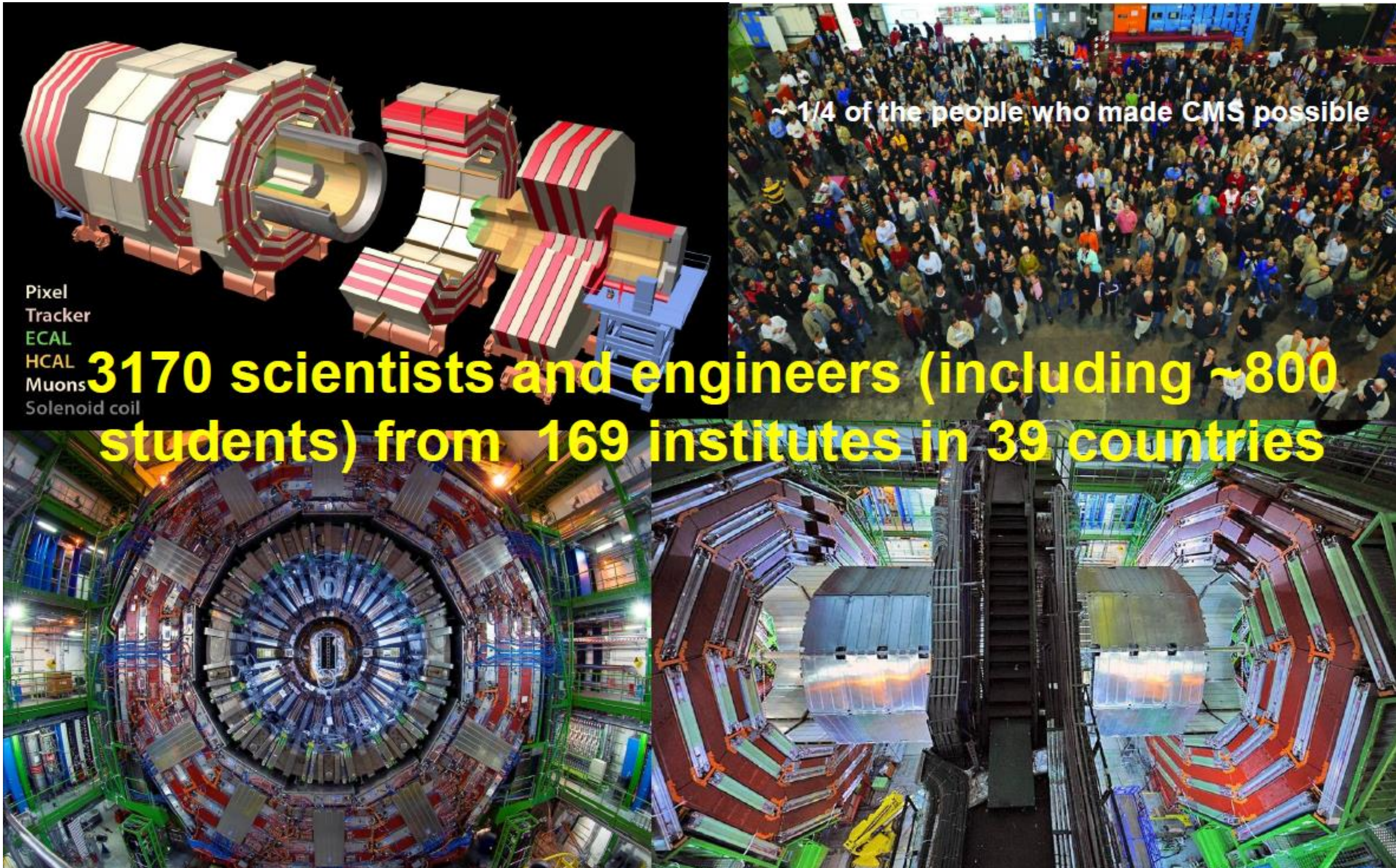




CMS @ LHC


CMS Detector
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

The CMS Collaboration



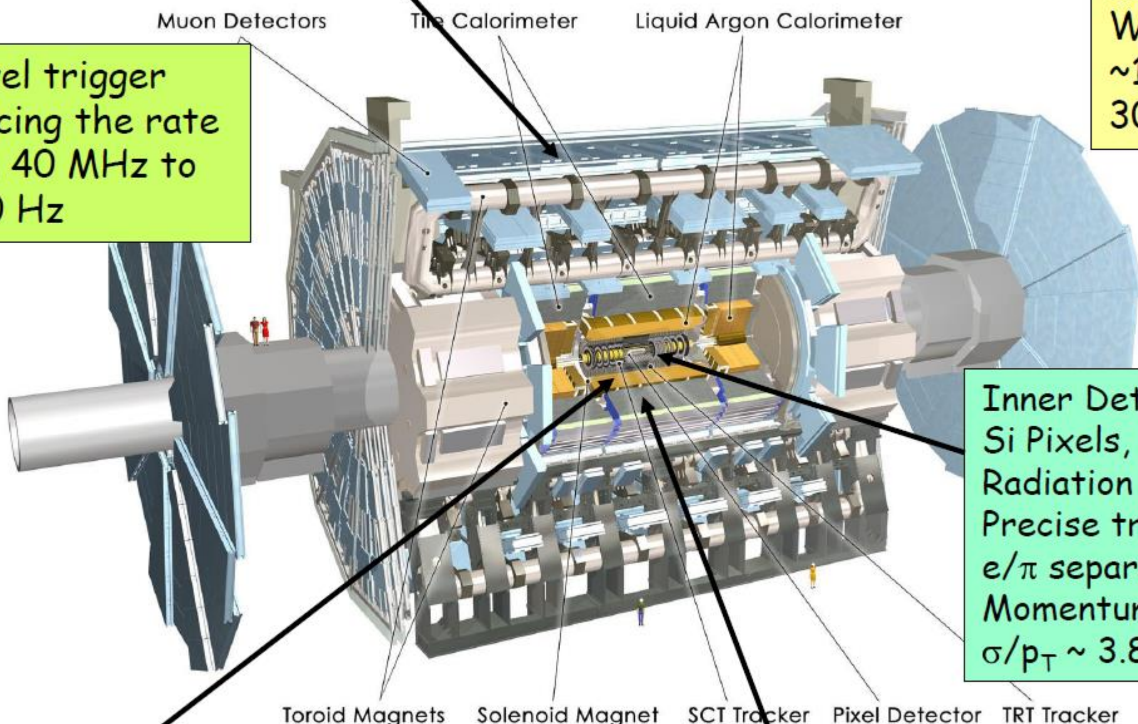
3170 scientists and engineers (including ~800 students) from 169 institutes in 39 countries

ATLAS @ LHC

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

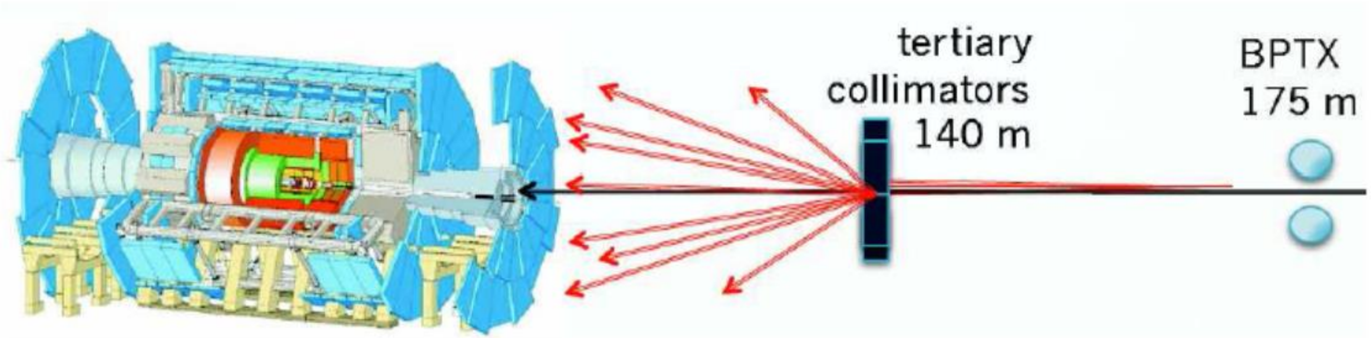
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

The ATLAS Collaboration

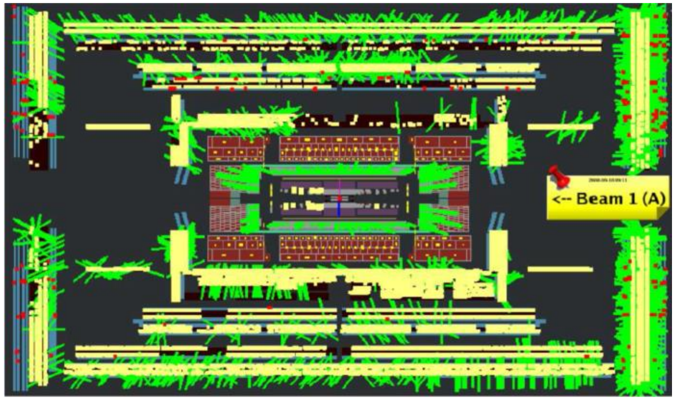
~170 institutions from ~40 countries with ~3,000 members

ATLAS Exciting Startup



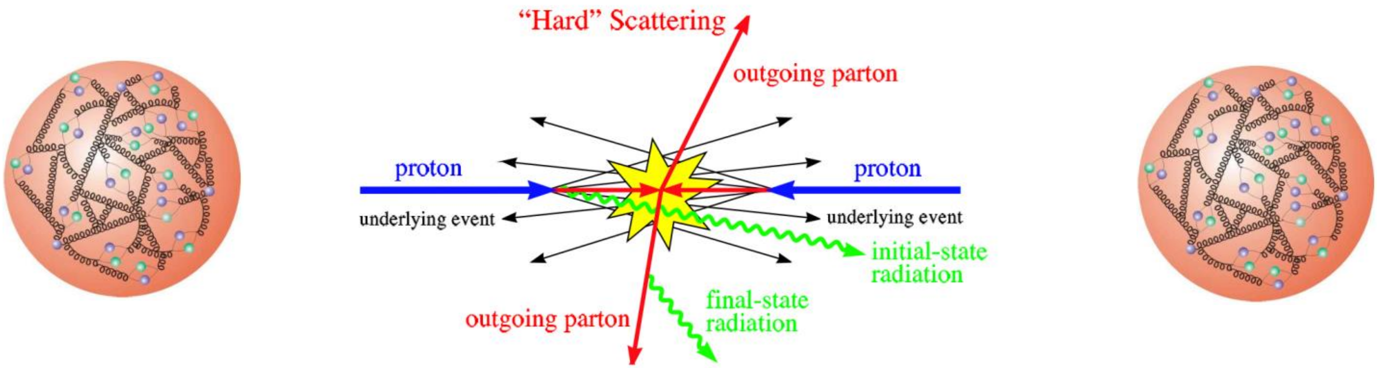
What did they see that made them so excited?

First beam splash event recorded by ATLAS



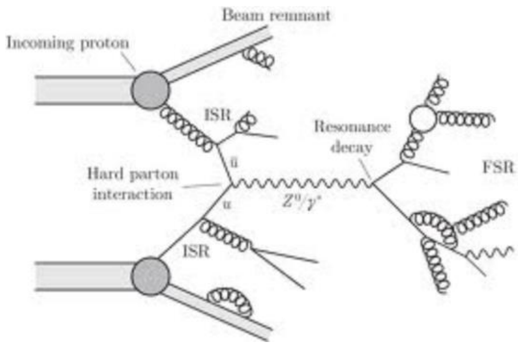
- 1million hits in the inner tracking detectors
- 1 million hits in the muon spectrometer
- 3000 TeV energy deposited in the calorimeters.

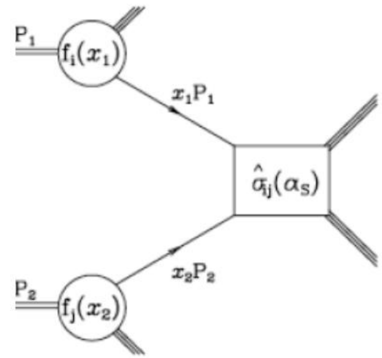
Hadron-hadron Collisions



- A hadron (e.g. a proton) is a very complex object composed of a lot of point-like constituents called partons: valence quarks, sea quarks, gluons, resulting in very "busy" final states in hadron-hadron collisions.
- The composition of a proton is quantitatively described by parton distribution functions (**PDF**s) ($f_i(x, Q^2)$: probability to find a parton(i) with a certain longitudinal momentum fraction of x at a scale of Q^2)

Theoretical Calculation





Physical cross section

Parton distribution function

Renormalization scale μ_R

$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2\ f_i(x_1,\mu_F)f_j(x_2,\mu_F)\ \hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R,\mu_F).$$

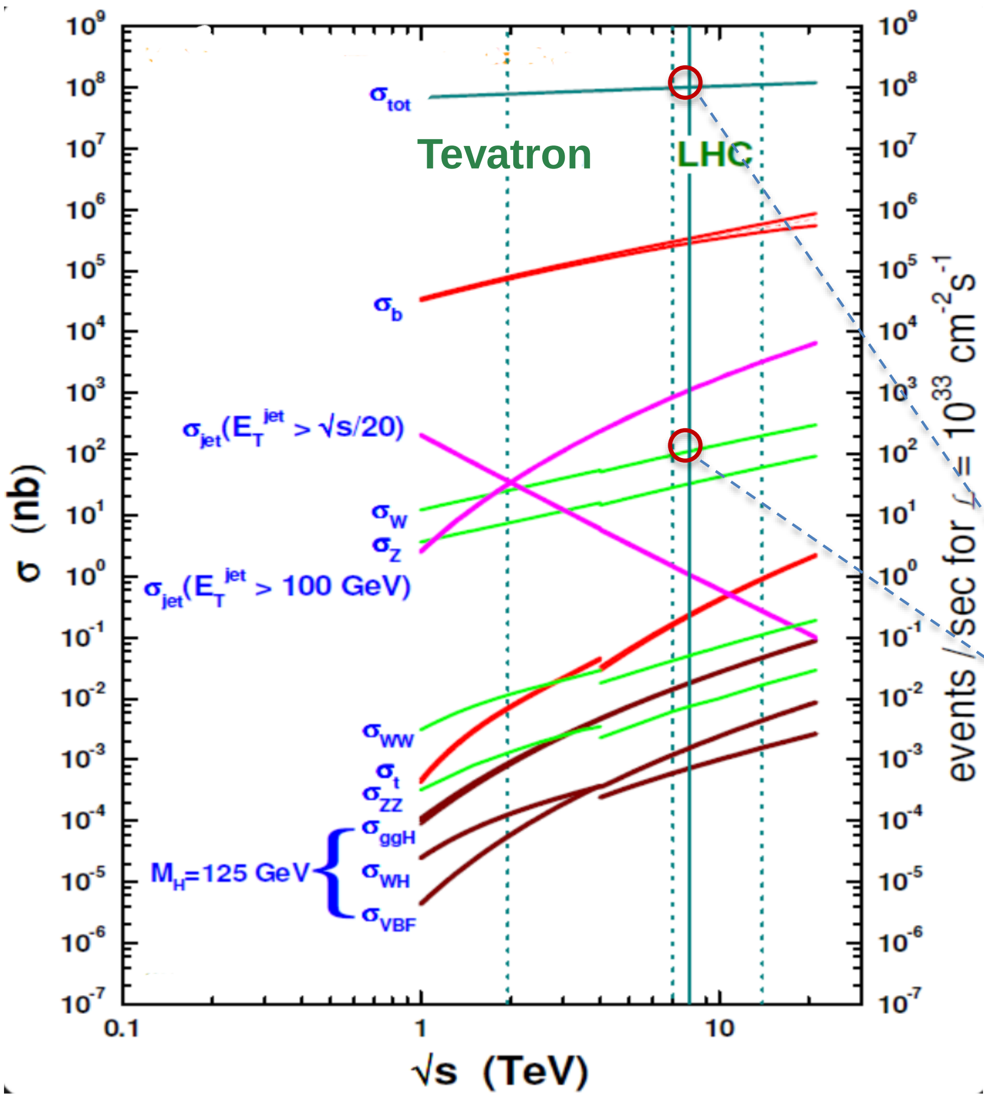
Factorization scale μ_F

Short distance cross section, calculated as a perturbation series in α_S

- Factorization theorem makes theoretical calculations possible
  - by separating long-distance effects from short-distance behavior

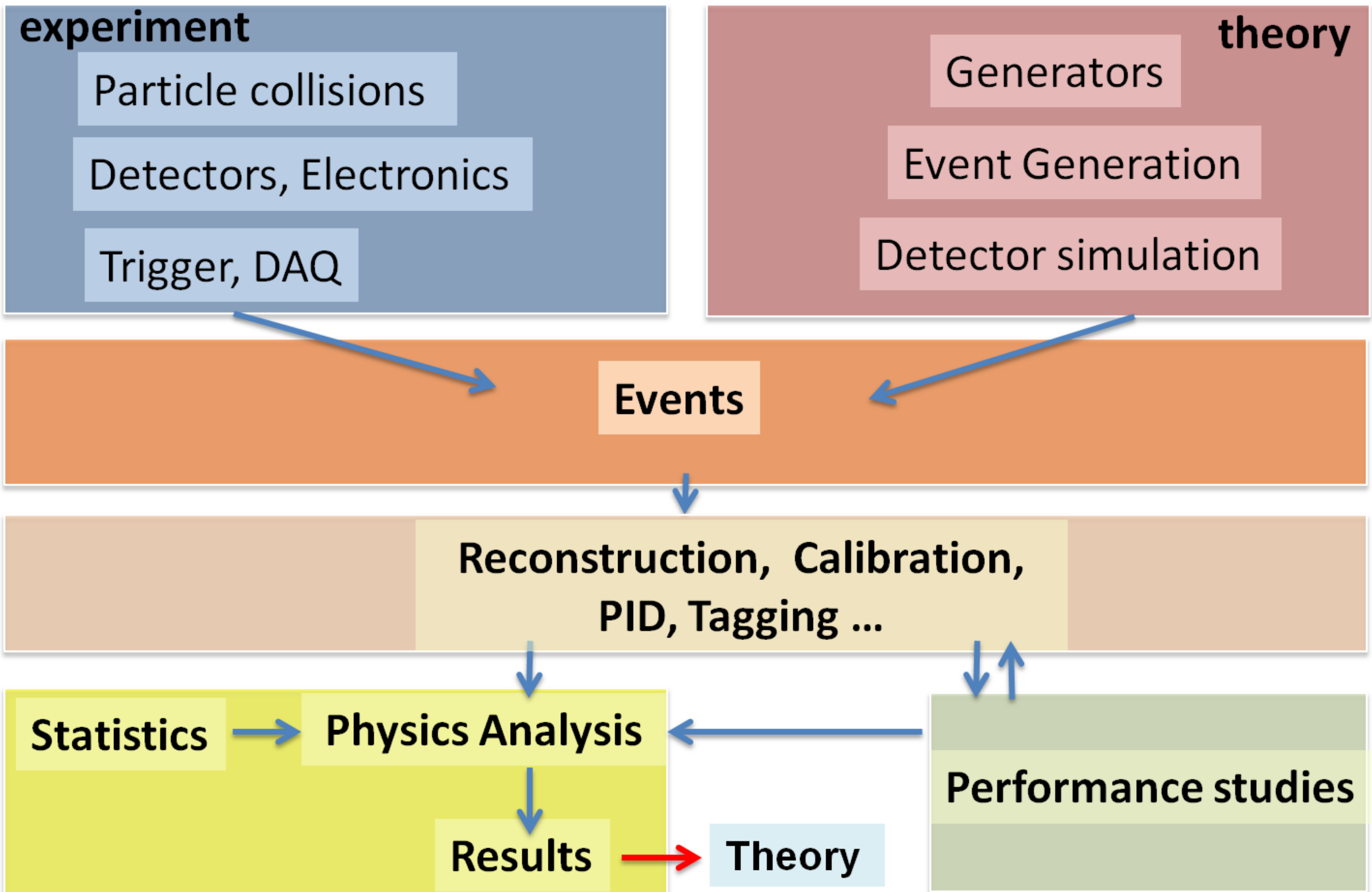
Long-distance : universal PDFs (derived from data directly)
Short-distance: perturbative QCD (theoretically calculable)

Production Processes at Hadron Colliders

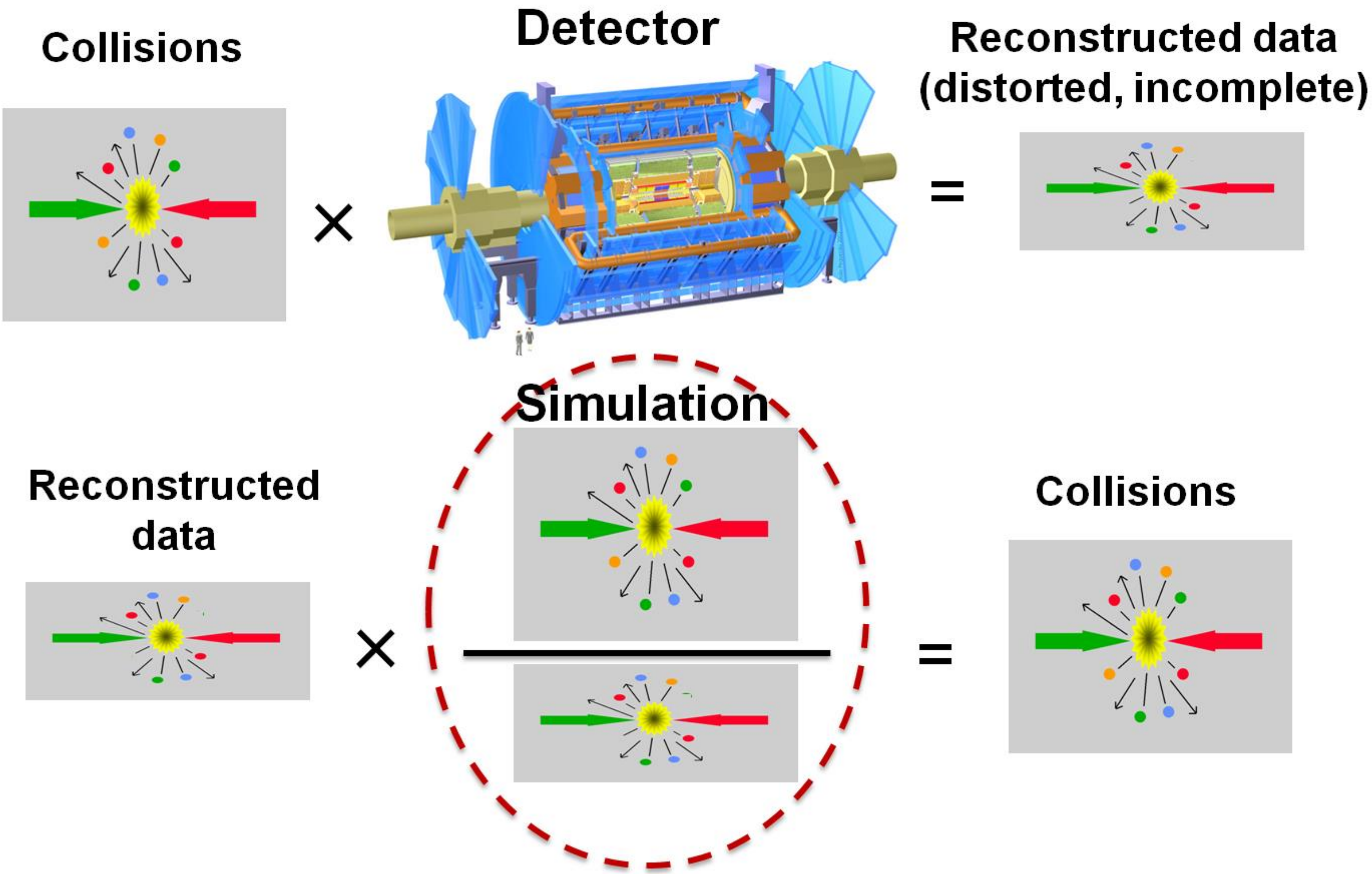


- Processes of interest
  - Jet production
  - Photon production
  - W/Z production
  - Multi-boson production
  - Electroweak production of vector bosons
  - ……
- Processes of no interest much more than those of interest
  - Any event: 10^8 /second
  - W boson: 10^2 /second
  - 6 orders of magnitude !!!
- We need selection
  - **Online: trigger**
  - Offline: physics analysis

High Energy Physics Work Flow

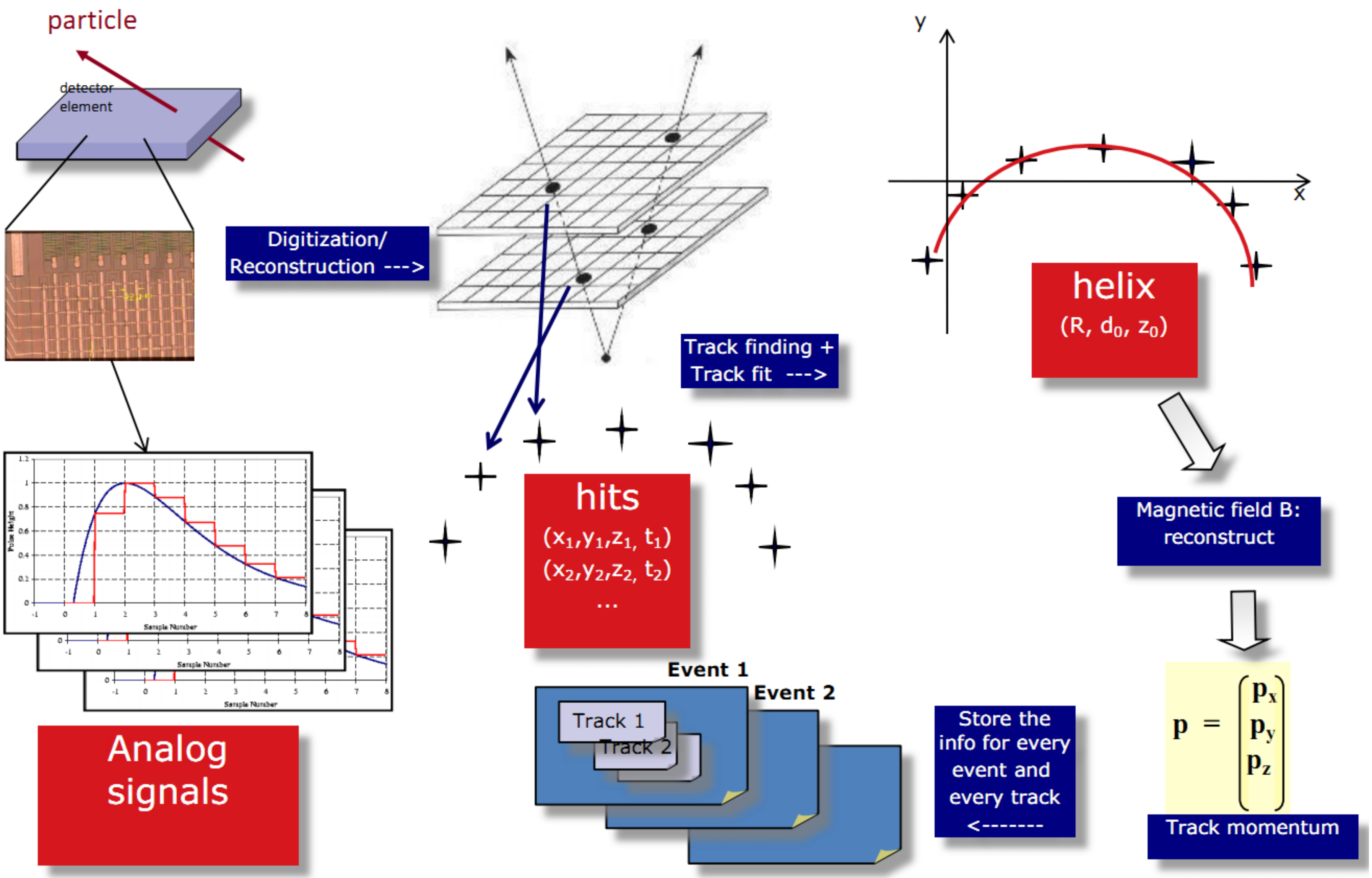


Why Simulation ?



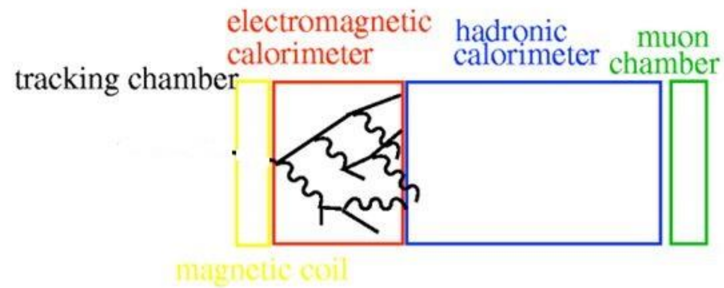
We need simulation to restore data to “truth”

Reconstruction

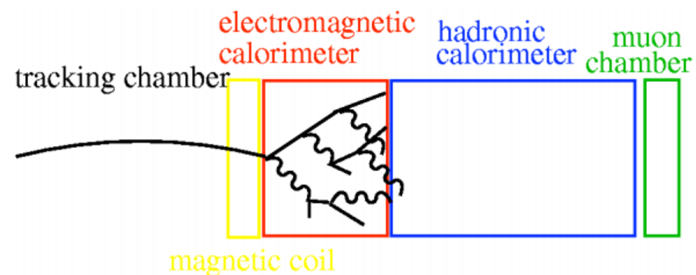


Particle Identification (PID)

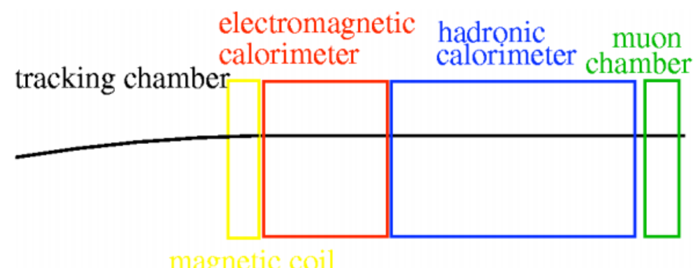
- Photons
  - A compact electromagnetic cluster
  - No track matched



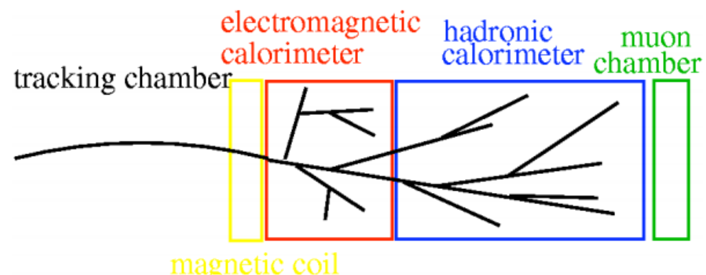
- Electrons
  - A compact electromagnetic cluster
  - Matched to a track



- Muons
  - hits in muon chambers
  - Matched to a track



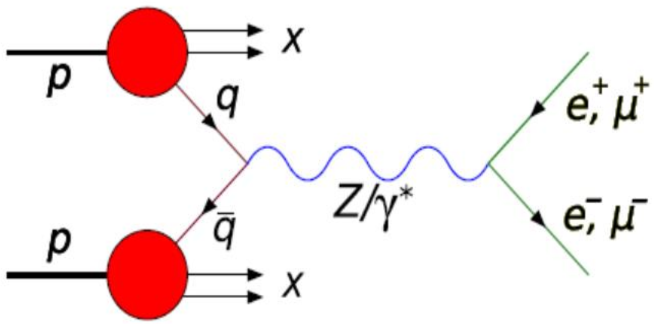
- Taus
  - Clusters in both electromagnetic and hadronic calorimeters
  - Matched to one or three tracks



Performing a SM measurement

- **What to measure**

pp→Z→ll production cross section



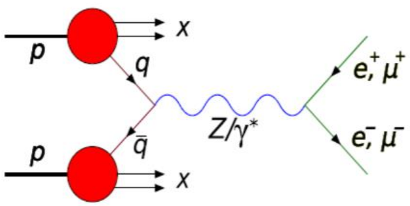
$$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to \ell\ell)$$

- **How to measure**

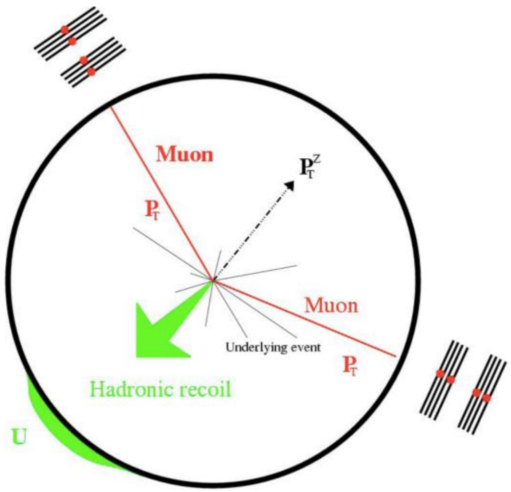
$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times \int L dt}$$

Event Selection

- Main characteristics of pp→Z→ll events
  - Two high p_T and isolated leptons
  - Invariant mass of the two leptons: $m_{ll} \sim m_Z$



- Event selection criteria are devised accordingly to retain pp→Z→ll signal and reject background as much as possible



  - Triggers: e_E_T_15, mu_p_T_18
  - Lepton ID: “combined” muons, “medium” electron
  - p_T>20 GeV, $|\eta|$<2.4 and $\sum p_T^{ID}/p_T < 0.2$
  - $|m_{ll} - m_Z| < 25$ GeV

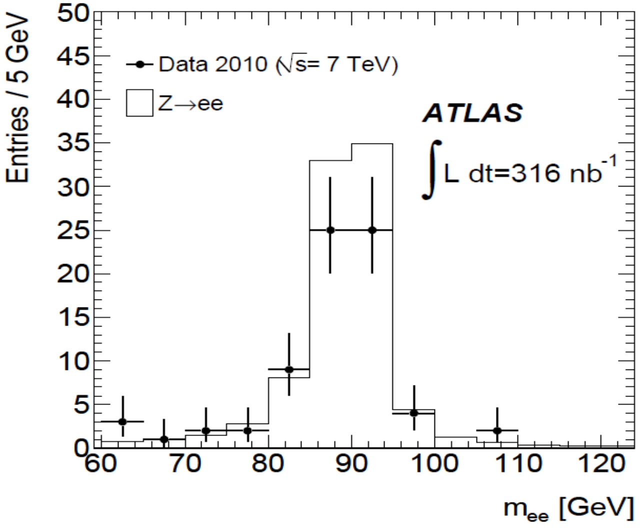
$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times \int L dt}$$

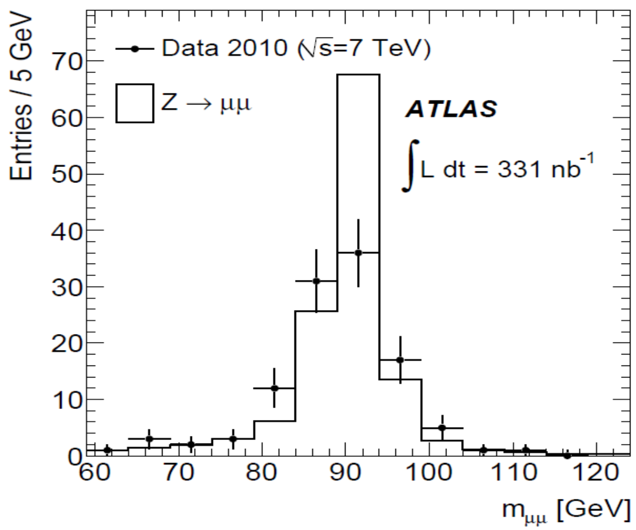
Integrated luminosity, $\int L dt$, depends on the data sample being used

Run Period	Int.Luminosity (nb)
A-C : 152844-156682	16.65
D1: 158045-158392	26.89
D2: 158443-158582	29.03
D3: 158632-158975	32.85
D4: 158041-159086	79.49
D5: 159113	28.04
D6: 159179-159224	97.05
Total	**310±34**

$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times \int L dt}$$

N_{obs} = number of events in data that pass the event selection





Requirement	Number of candidates	
	$Z \to ee$	$Z \to \mu\mu$
Trigger	6.5×10^6	5.1×10^6
Two leptons (ee or $\mu\mu$ with $E_T(p_T) > 20$ GeV)	83	144
Muon isolation: $\sum p_T^{ID}/p_T < 0.2$	–	117
Opposite charge ee or $\mu\mu$ pair:	78	117
$66 < m_{\ell\ell} < 116$ GeV	70	109

$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times \int L dt}$$

Acceptance, A, is estimated using simulation

$A = N_{acc} / N_{all}$

N_{all} : total number of simulated events
N_{acc} : number of simulated events that pass the event selection

MC	A_Z $Z \to ee$	A_Z $Z \to \mu\mu$
PYTHIA MRSTLO*	0.446	0.486
MC@NLO HERAPDF1.0	0.440	0.479
MC@NLO CTEQ6.6	0.445	0.485

$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times \int L dt}$$

***N**$_{bkg}$* = number of events from processes other than pp→Z →ll that pass the event selection (**background**)

***N**$_{bkg}$* is estimated using simulation or data driven approaches.

ℓ	Observed candidates	Background (EW+$t\bar{t}$)	Background (QCD)
$e^{\pm}$	70	$0.27 \pm 0.00 \pm 0.03$	$0.91 \pm 0.11 \pm 0.41$
$\mu^{\pm}$	109	$0.21 \pm 0.01 \pm 0.01$	$0.04 \pm 0.01 \pm 0.04$

Cross Section

- Getting a cross section result now seems as simple as doing the following quick math

$$\boxed{\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times \int L dt}}$$

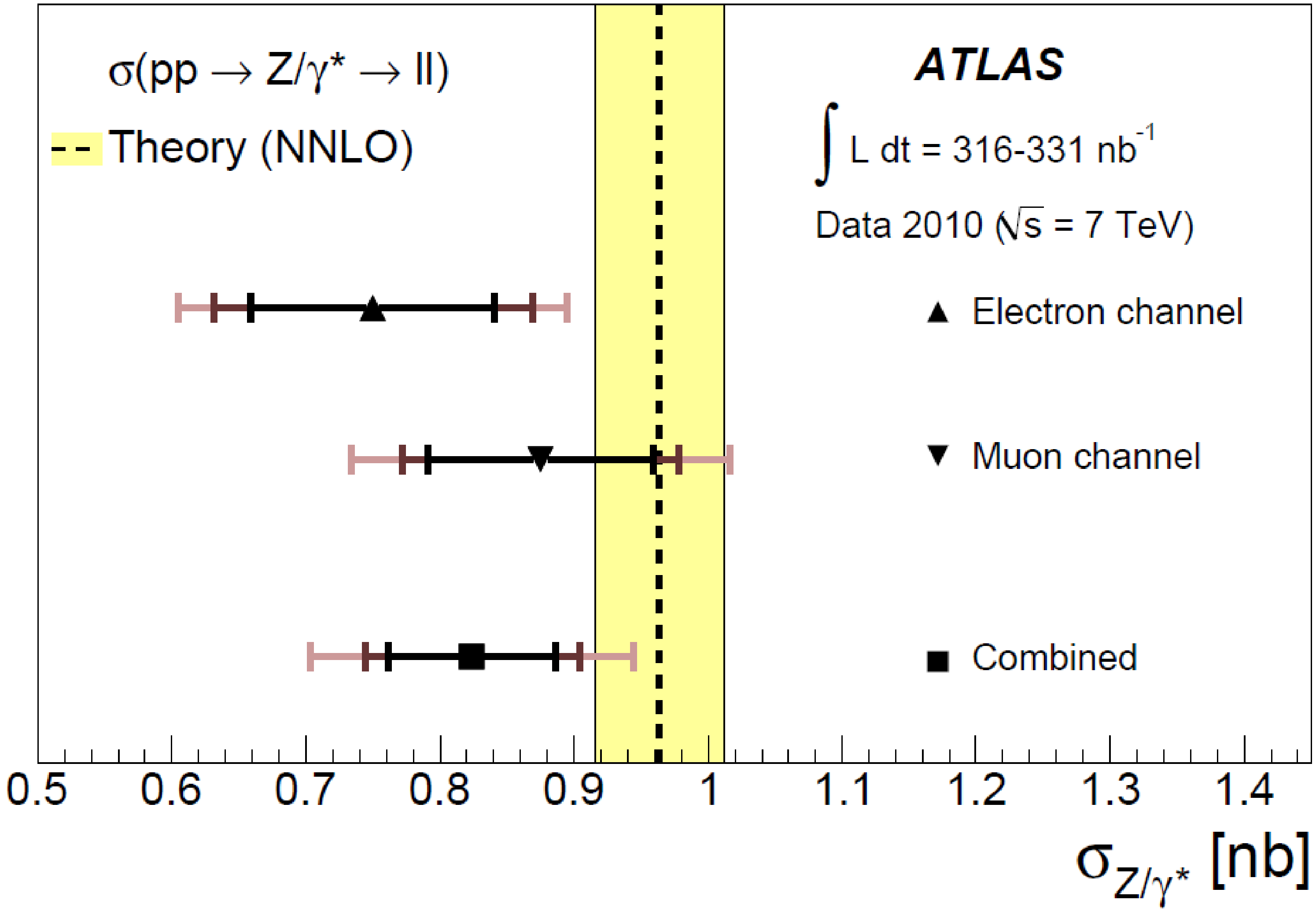
- But is this all? No! Any results without uncertainties make no sense! We need to estimate uncertainties on the measured cross section, particularly, the systematic uncertainties.

Uncertainties

- Statistic uncertainty : δN_{obs}
  - Comes from N_{obs} that follows a Possion distribution. Quite trivial.
- Systematic uncertainties (represent our lack of knowledge, need to be assessed on every aspect of the measurement)
  - Uncertainty on A : δA
  - Uncertainty on L : δL
  - Uncertainty on N_{bkg} : δN_{bkg}

$$\frac{\delta(\sigma\times Br)}{\sigma\times Br}=\sqrt{\frac{(\delta N_{obs})^2+(\delta N_{bkg})^2}{(N_{obs}-N_{bkg})^2}+(\frac{\delta A}{A})^2+(\frac{\delta L}{L})^2}$$

Final Results

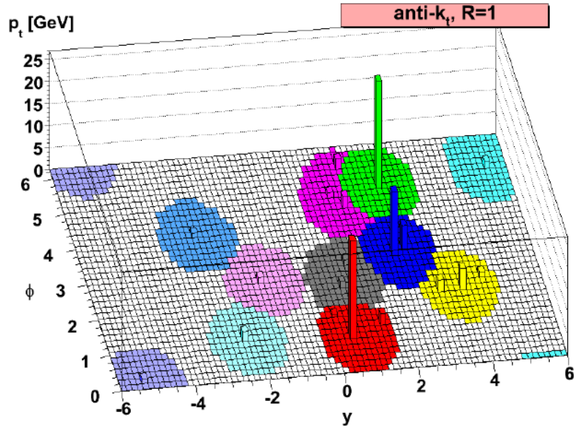


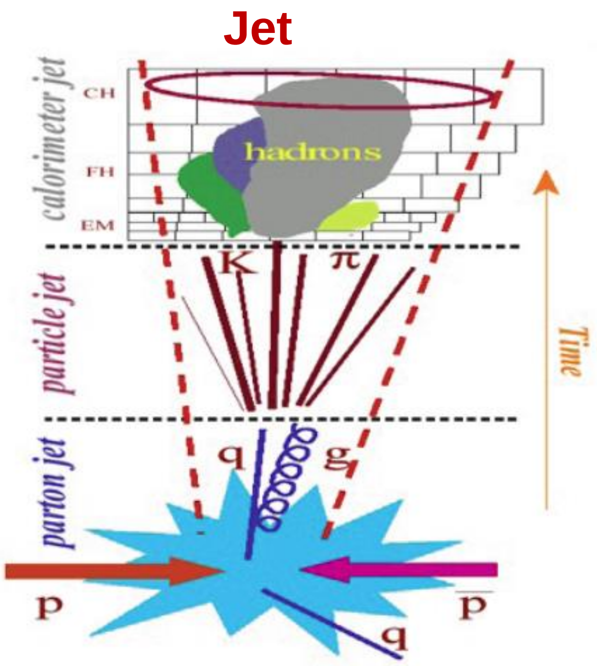
Measurements as QCD tests

- Jet production
- Photon production
- W and Z production

Jets

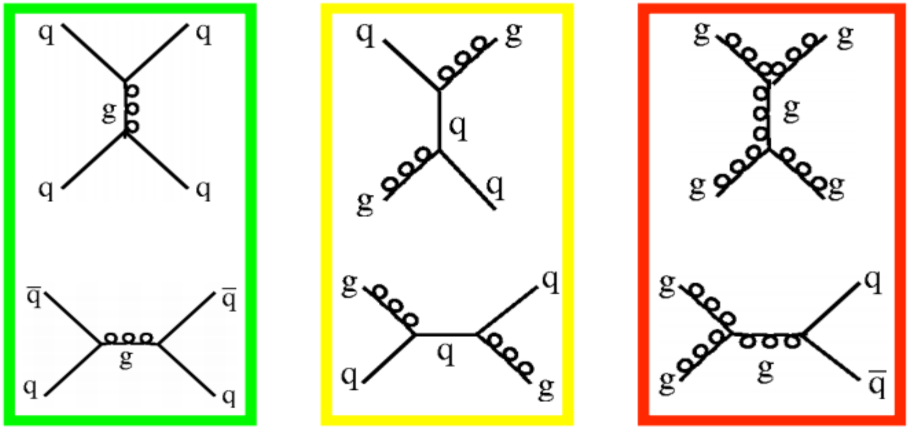
- Jets are bundle of hadrons
  - A typical QCD product
  - Experimental signature of quarks and gluons
- Jets can be clustered with a variety of algorithms
  - Cone algorithms at Tevatron
  - Anti-Kt algorithms at LHC



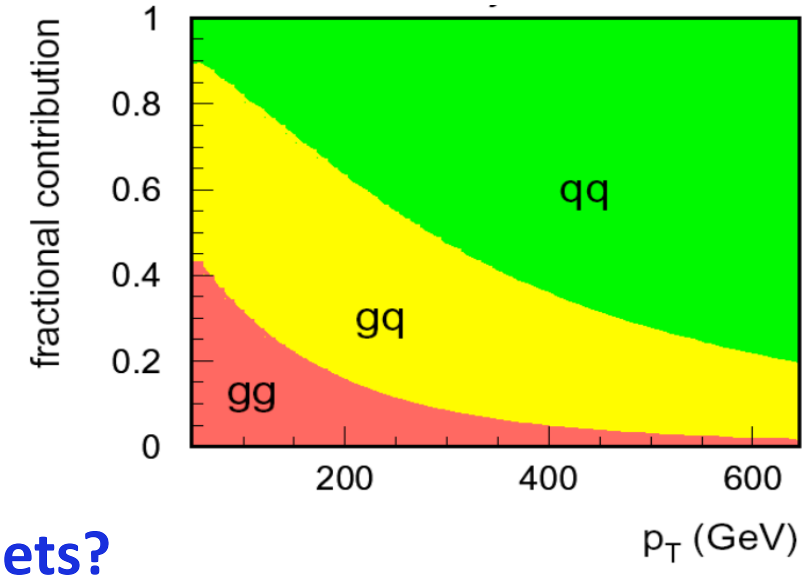


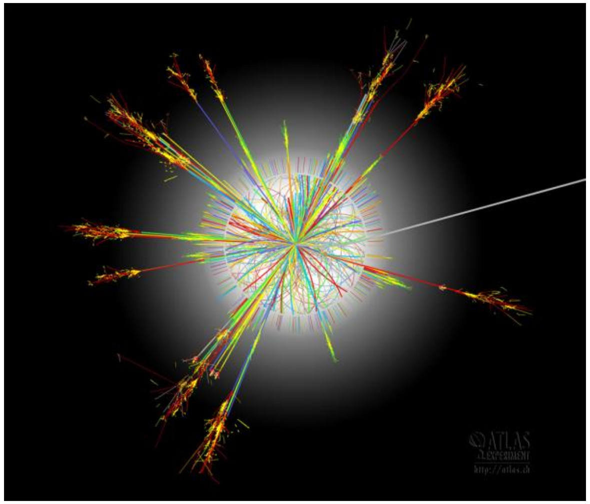
Jet Production

LO jet production: qq, qg, gg



Production fractions

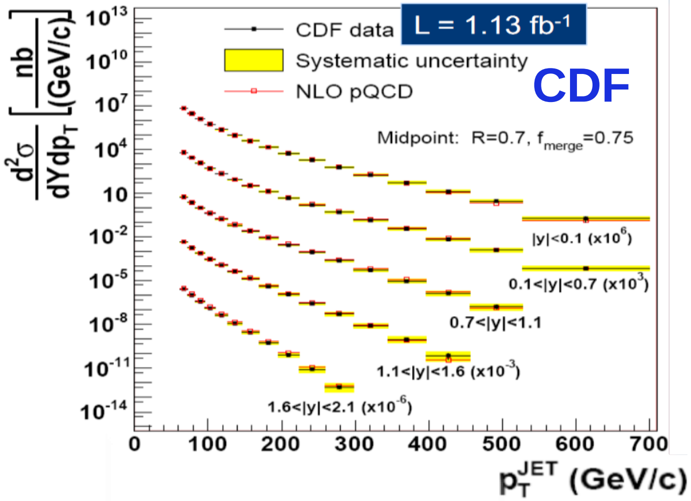


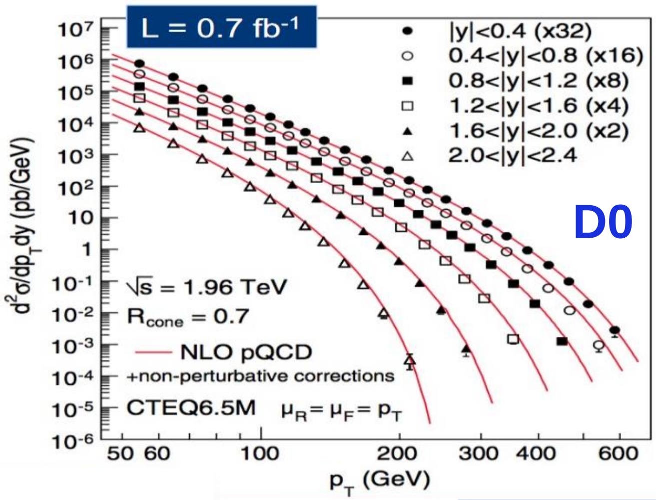


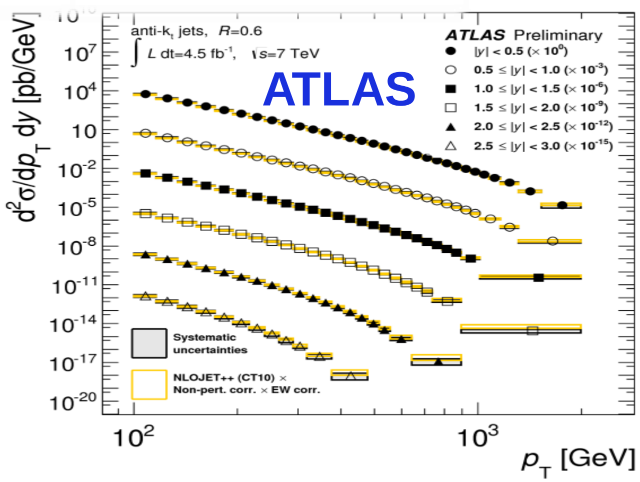
Why study Jets?

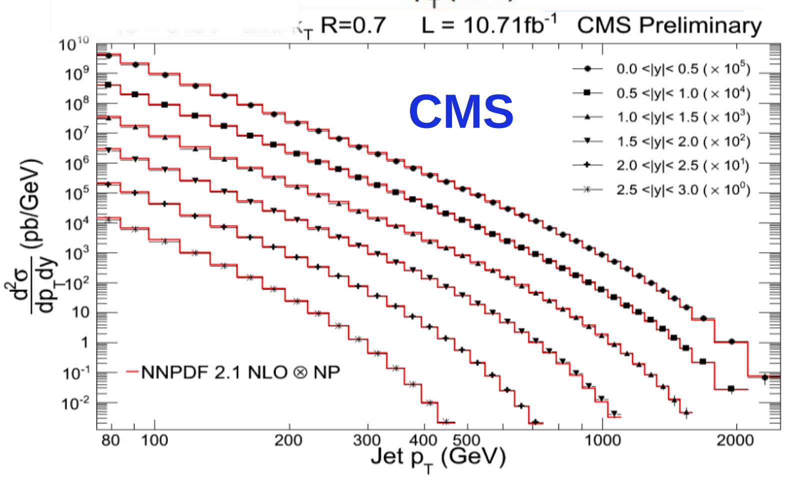
- Test QCD at highest energies and in a vast range of phase space.
- Measure the fundamental QCD parameter of α_s (strong coupling)
- Understand and constrain PDFs in space space unprobed before
- Probe new physics at shortest distances (e.g. substructure of quarks)

Inclusive Cross Sections







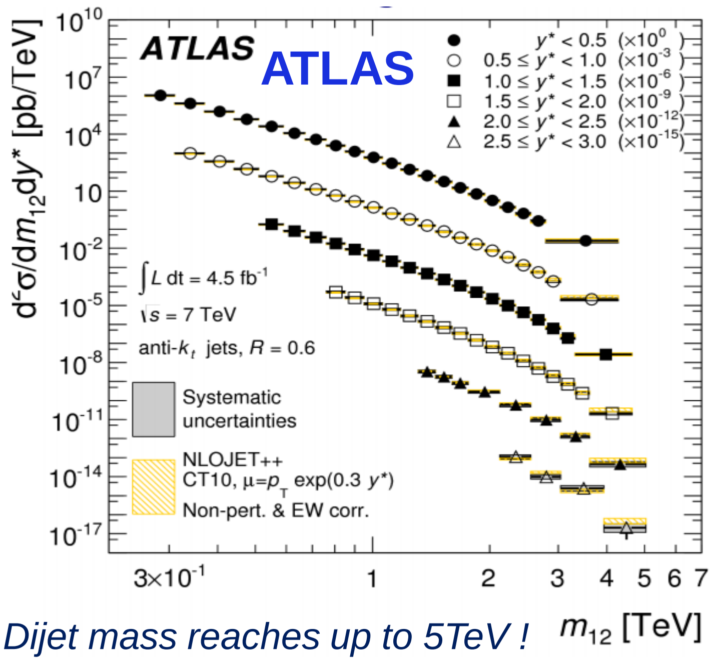


Good data and theory agreement across orders of magnitude : 10^3 in Jet pT (up to 2TeV), 10^{20} in cross section !

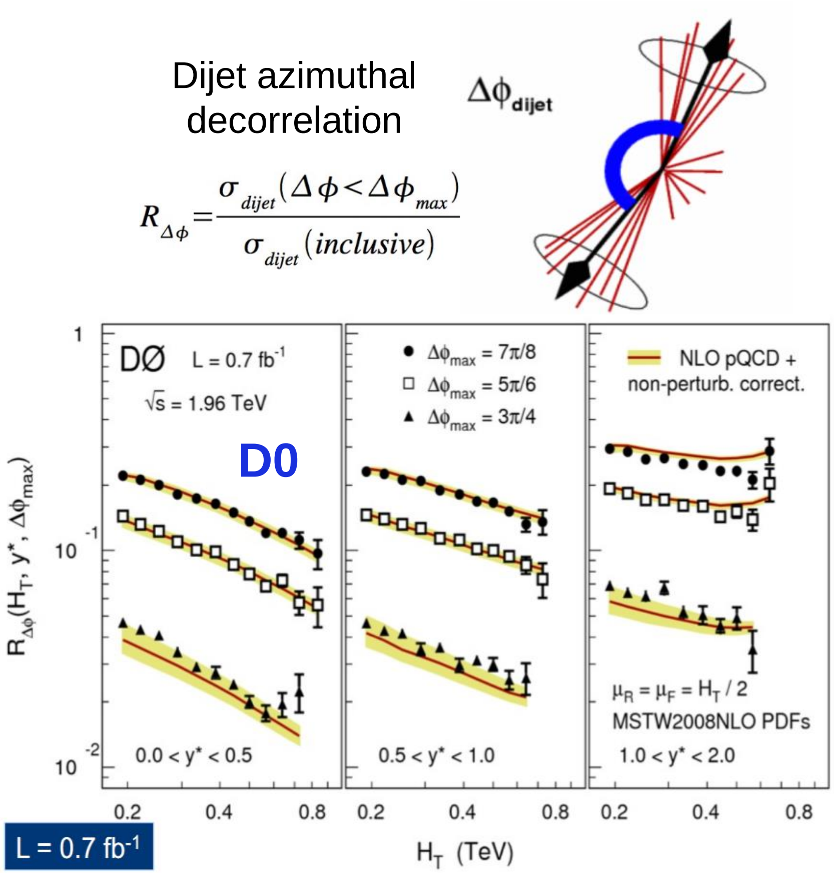
→ Only made possible by the high energy and high luminosity of the colliders

Dijet Cross Sections

Double differential cross section or differential ratio using events with at least two jets to go deeper in phase space



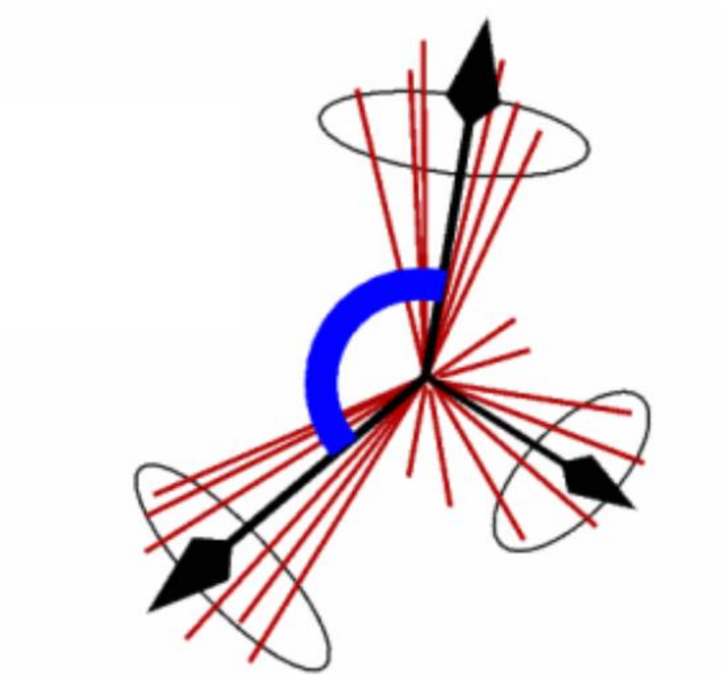
Dijet mass reaches up to 5TeV !



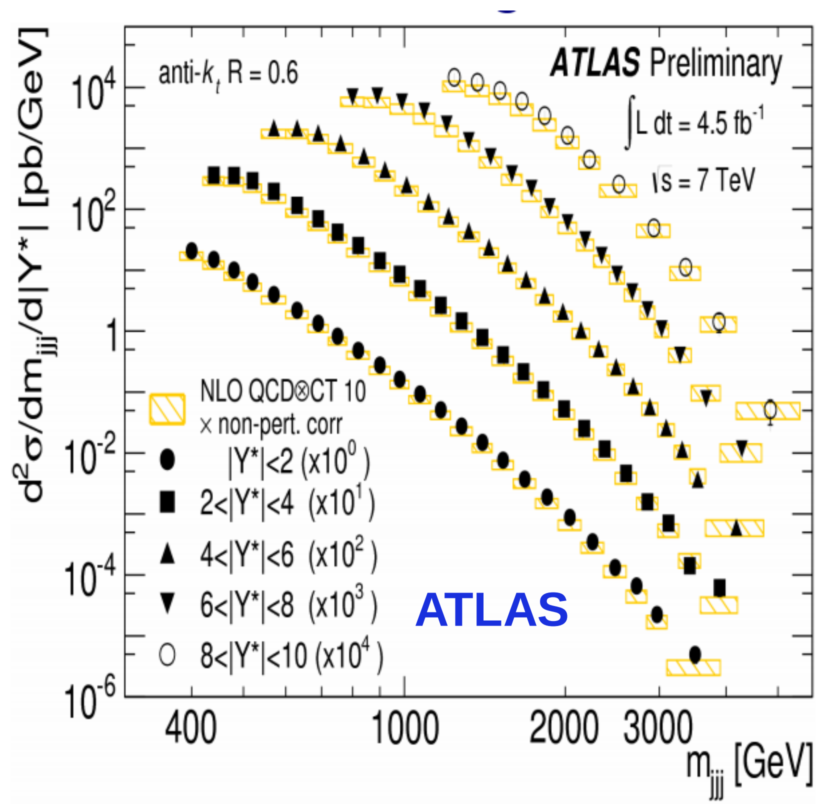
Explore QCD in new kinematic regions

Going even higher !

A Triple-jet event

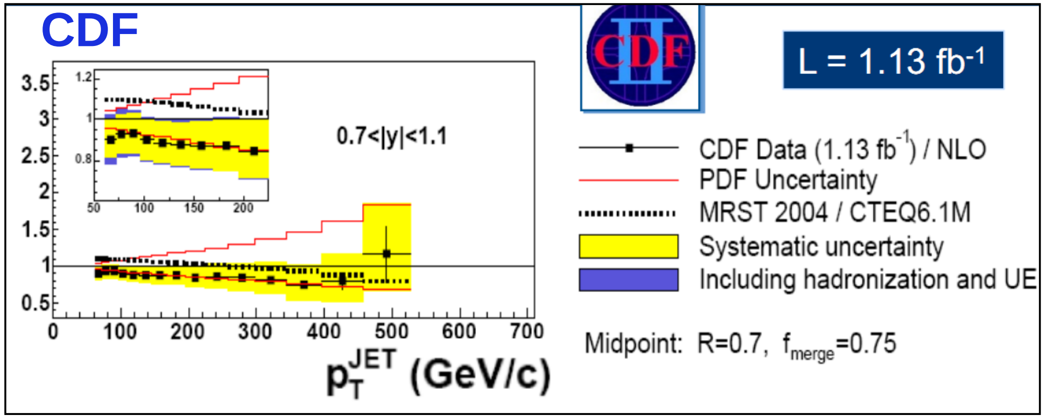


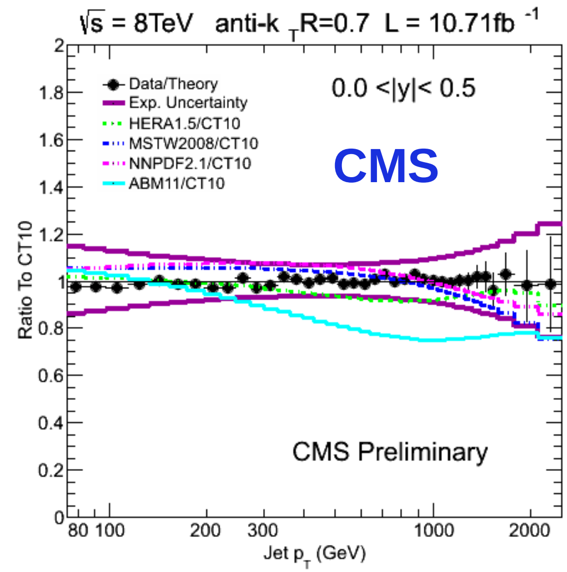
Double differential cross section

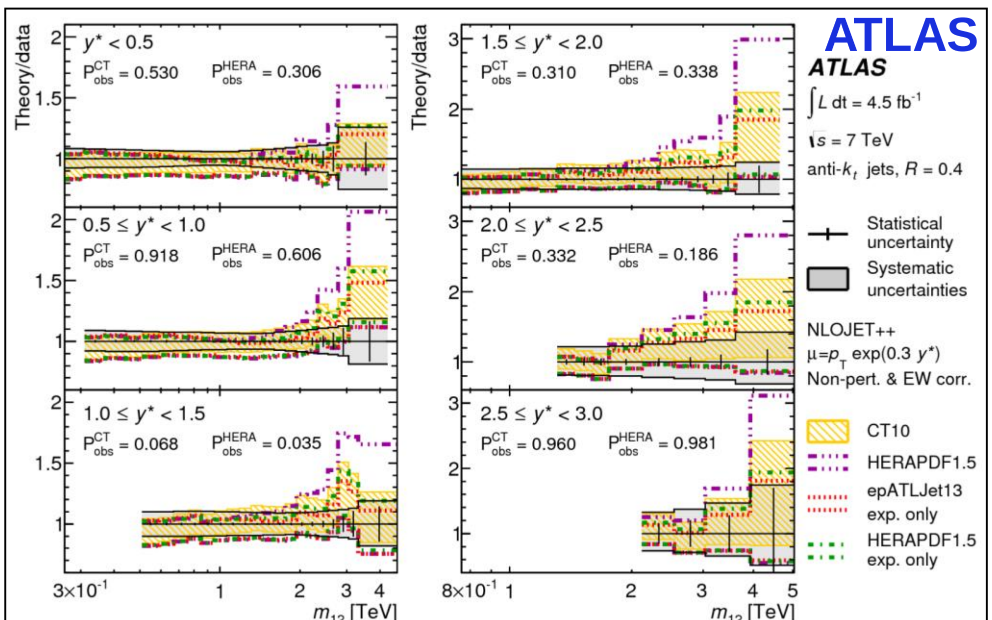


Test QCD in more extreme phase space

PDF comparisons



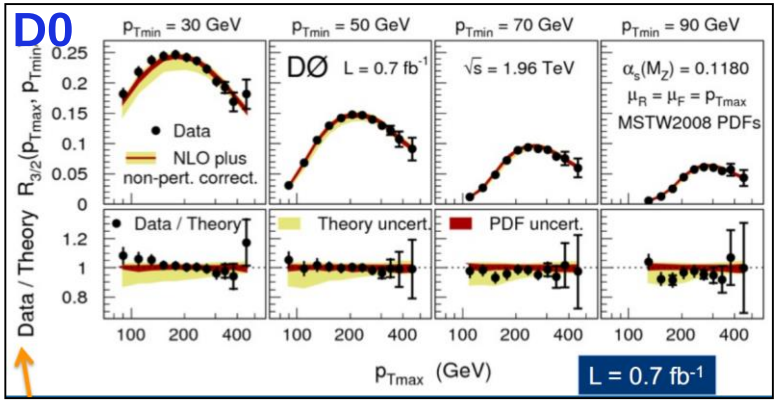


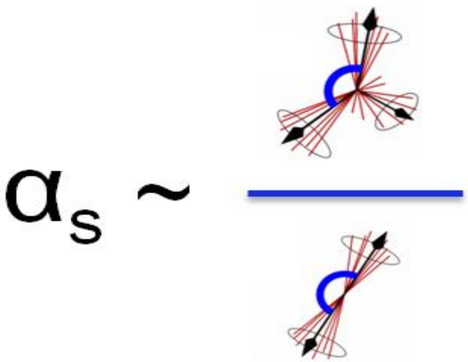


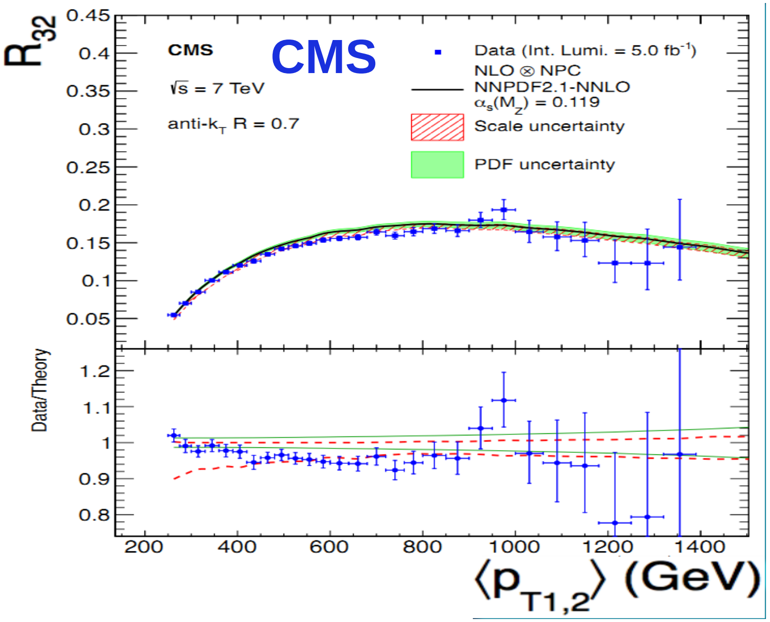
- Level of agreement depends on PDF sets and phase space regions
  - Sensitive to PDFs
- Valuable input to constrain PDFs. Important ingredients in PDF global fit.

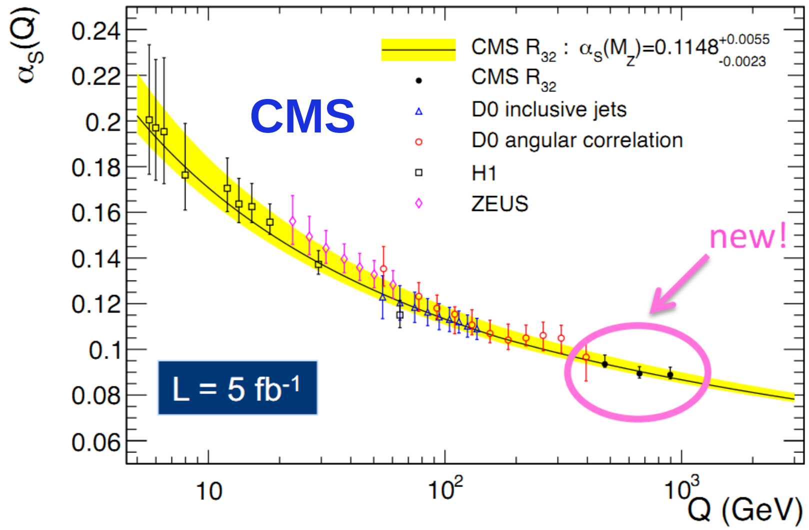
αs Extraction

$$R_{3/2} = \frac{\sigma_{3\text{-jet}}}{\sigma_{2\text{-jet}}}$$





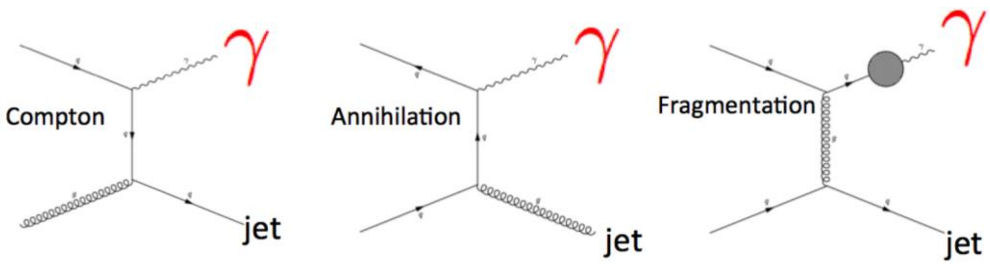




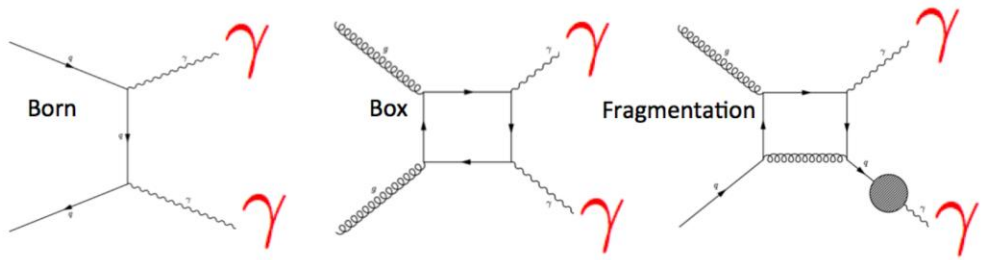
- α_s measurement extended to much higher energy scales
- Test of α_s running

Photon Production

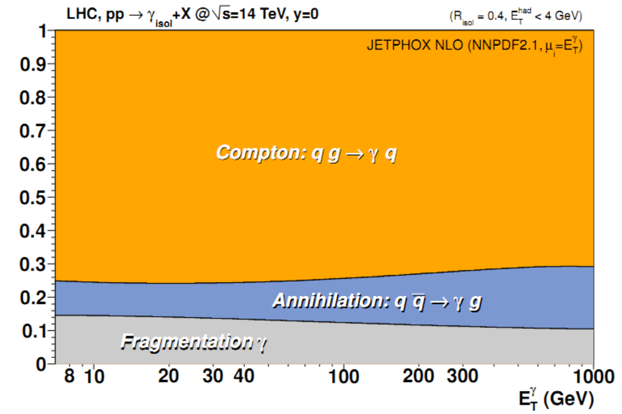
Prompt Photon Production



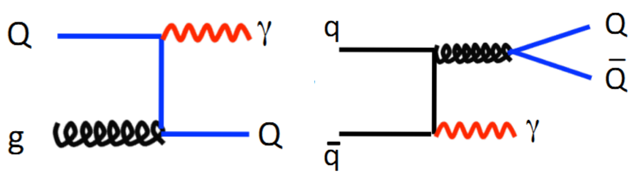
Prompt Di-Photon Production



qg compton process dominates at LHC



γ + heavy quarks

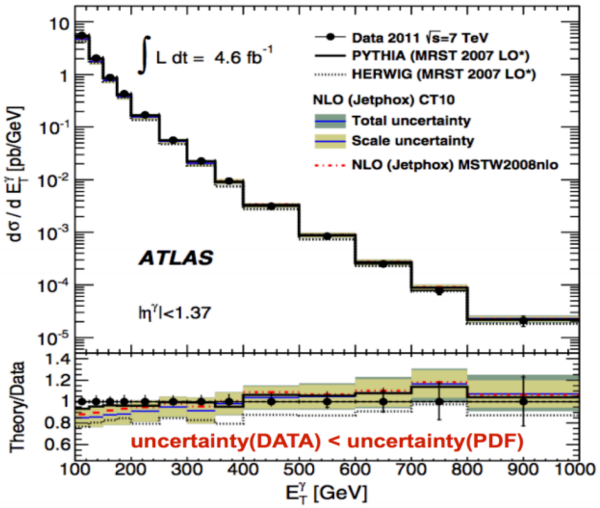


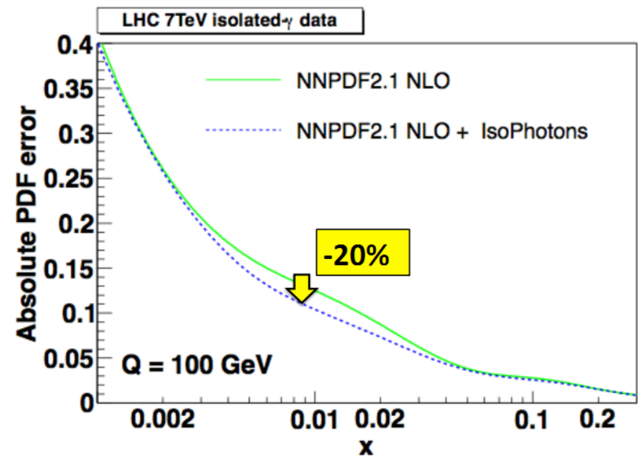
Why study Photons?

- Colorless and clean probe to test QCD
- Understand and constrain the gluon PDF
- Probe heavy flavor components and gluon splitting to heavy flavor quarks in the proton
- Important background to measurements or searches with photons

Photon + X cross sections

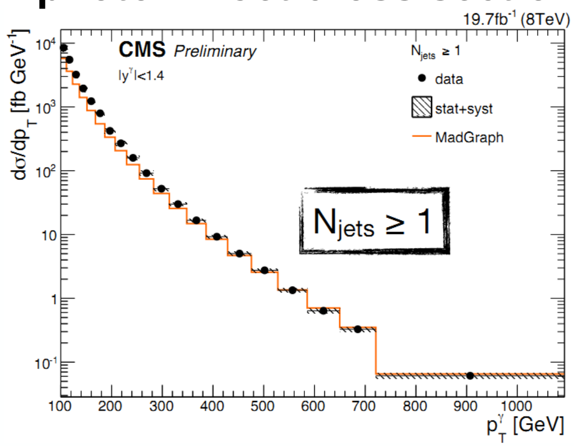
Inclusive photon cross section



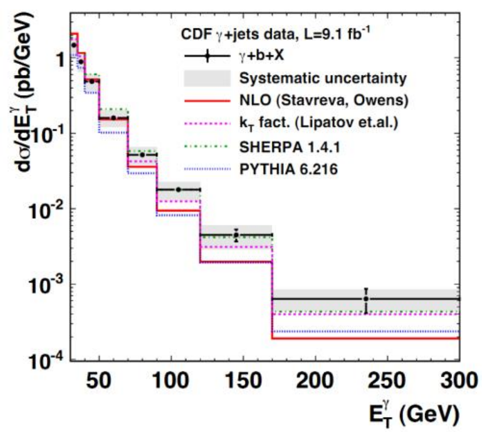


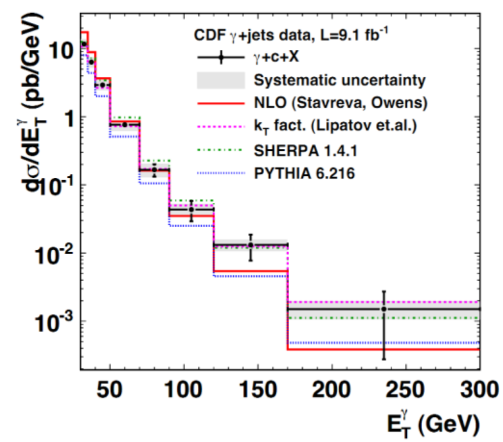
7TeV LHC photon data can typically reduce gluon PDF uncertainty by 10-20%

photon + Jet cross section



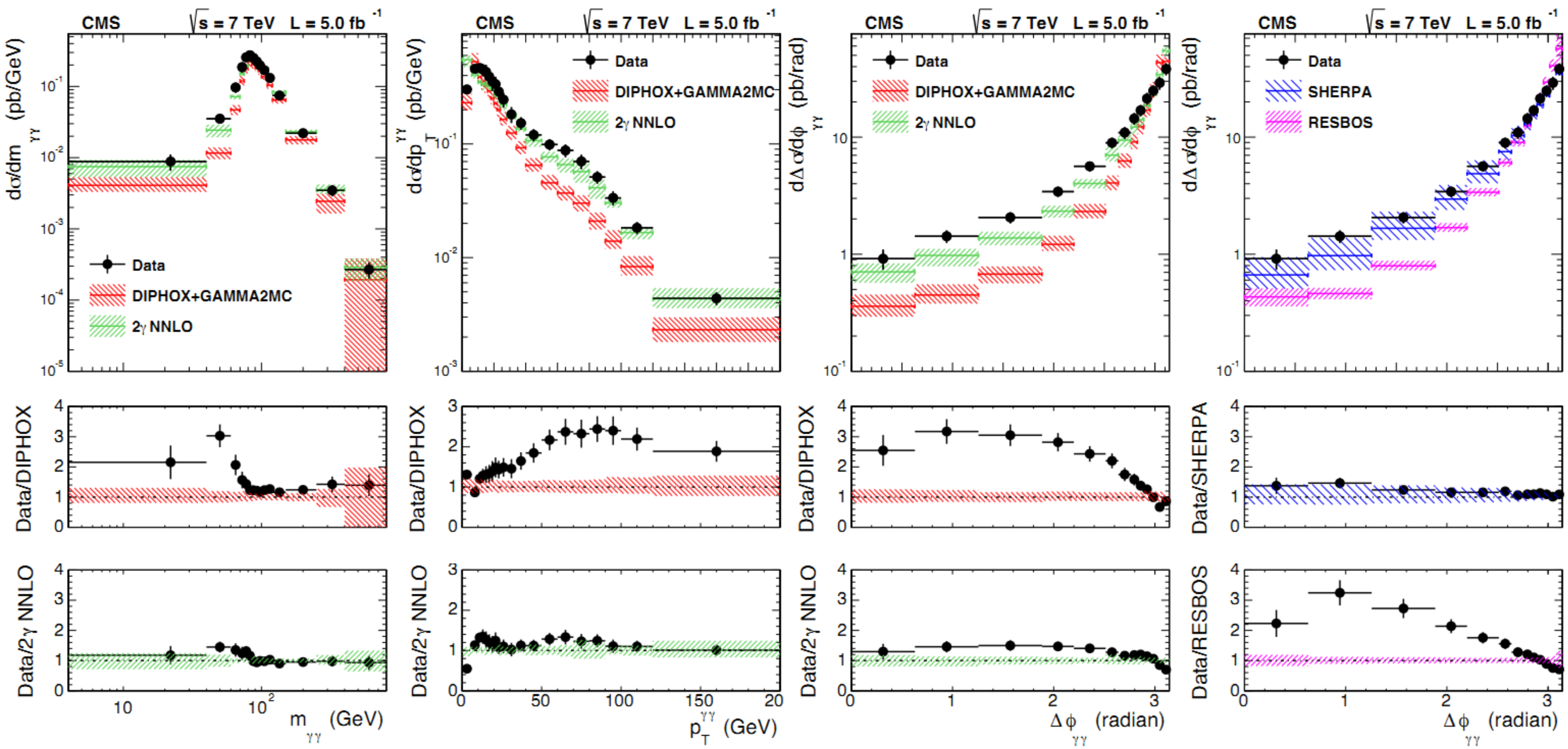
photon p_T up to ~1 TeV





NLO fails to describe data in high photon p_T region possibly due to missing high order effects in gluon splitting.

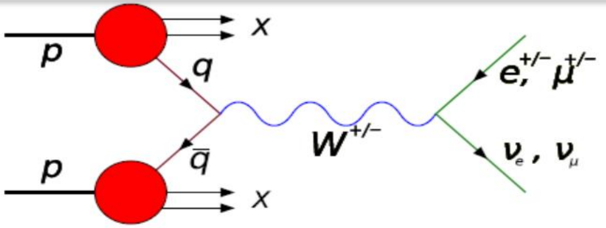
Di-Photon Cross Sections

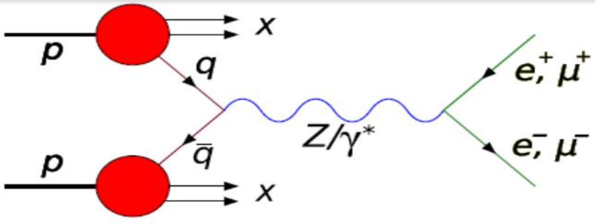


- NNLO calculation is needed to describe data in low $m_{\gamma\gamma}$ and small $\Delta\phi_{\gamma\gamma}$ regions.
- Sherpa (up to 3 partons) agrees with data rather well.

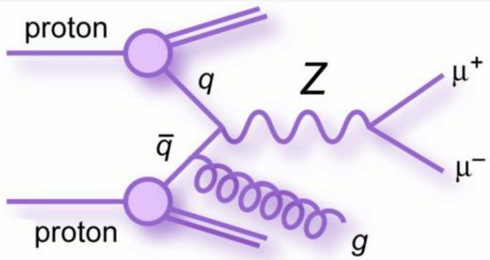
W/Z Production

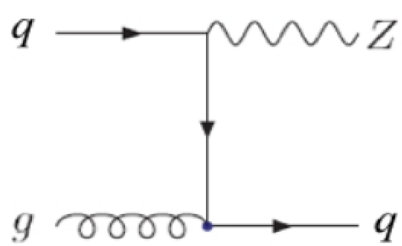
Production at LO : boson $p_T = 0$





Production at NLO (W/Z + jets) : non-vanishing boson p_T





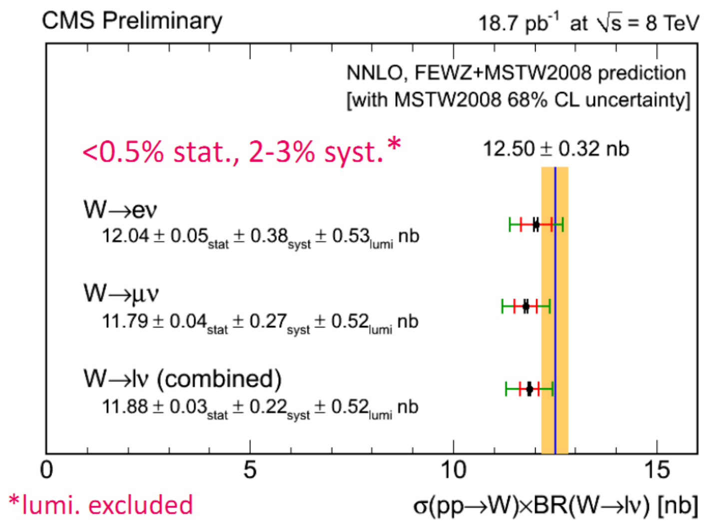
Simple and clean experimental signatures (W/Z selections)

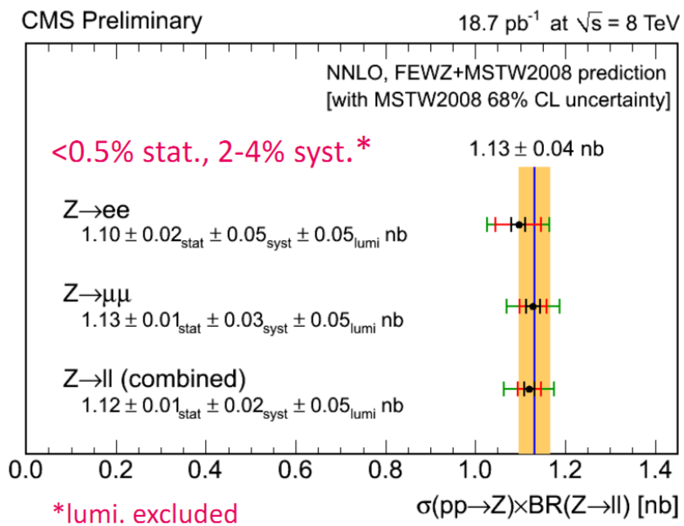
- $W \rightarrow l\nu$: one isolated high-p_T lepton and large missing energy due to the neutrino.
- $Z \rightarrow ll$: an opposite-sign same-flavor high-p_T lepton pair with m_{ll} close to m_Z

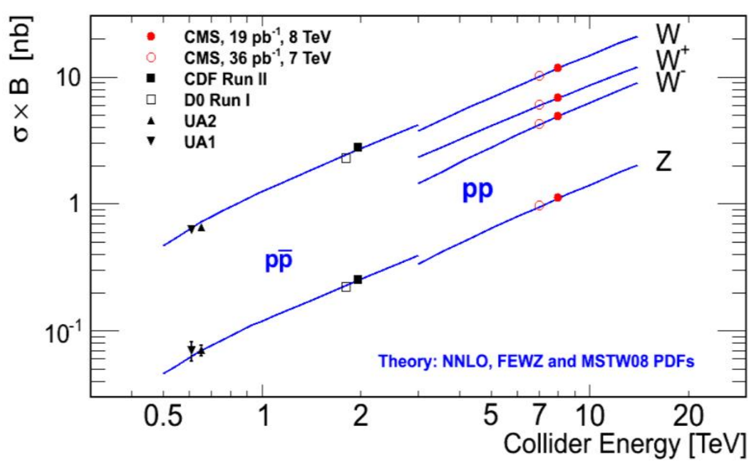
Why study W/Z ?

- Good testing ground for QCD
- Test and constraint of PDFs
- Detector calibration
- Simulation tuning and validation
- Important background to searches

Inclusive Cross Section



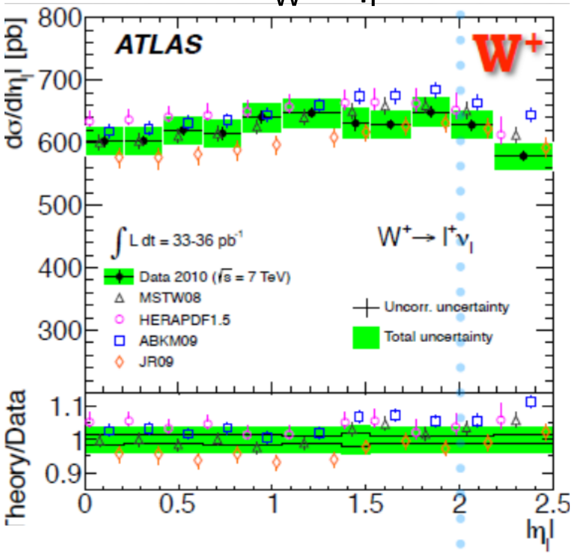




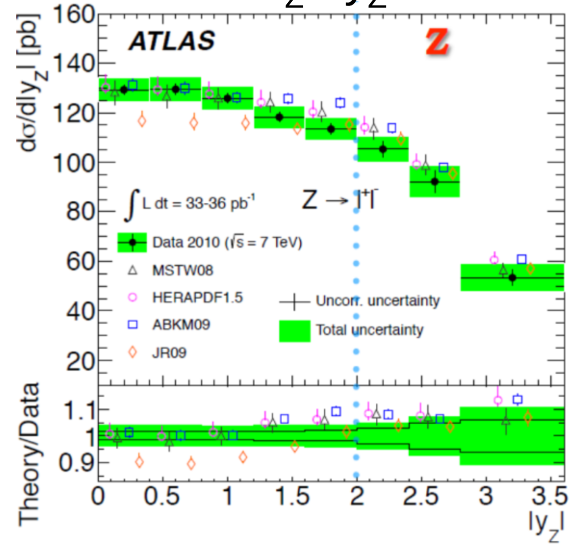
- Statistical uncertainties become negligible very soon due to the quite large production rates.
- Measured cross sections agree with theoretical predictions in a large range of energy
  - QCD is doing a good job!

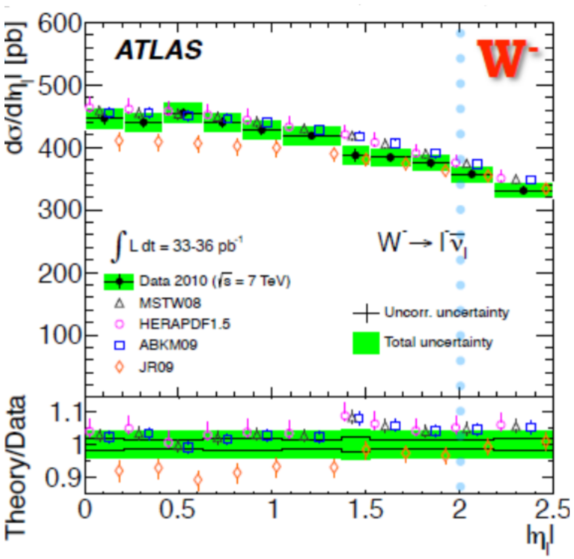
Going differential and for ratio

$d\sigma_W/d\eta_l$



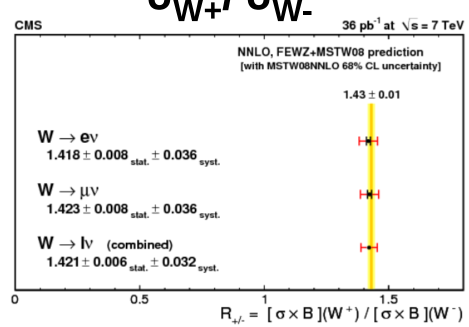
$d\sigma_Z/dy_Z$



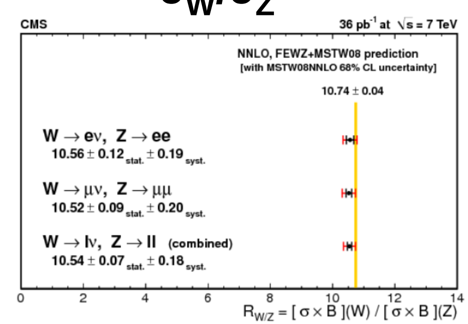


- More information extracted to constrain PDFs
- Improved precision in cross section ratios due to partial cancellation in systematics

σ_{W+}/σ_{W-}

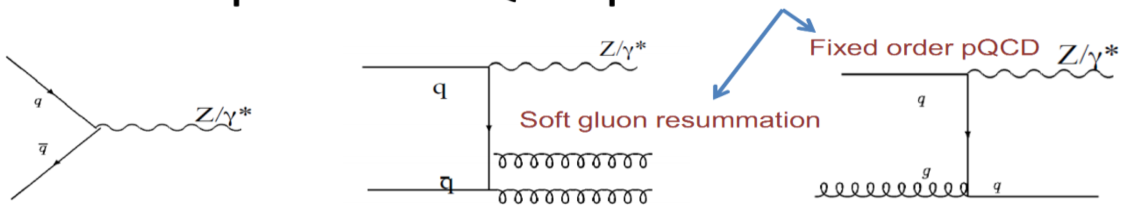


σ_W/σ_Z



Transversal Momentum Distribution

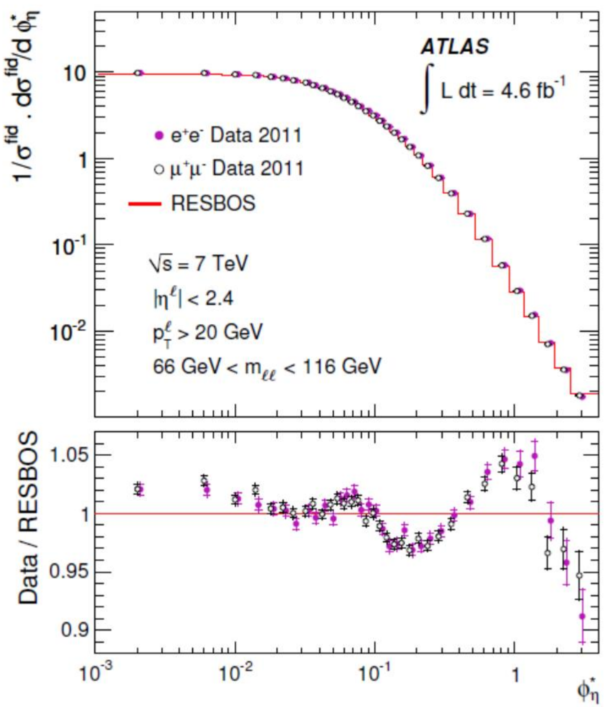
P_T^Z is an effect beyond LO, which can serve as an ideal probe of QCD predictions.

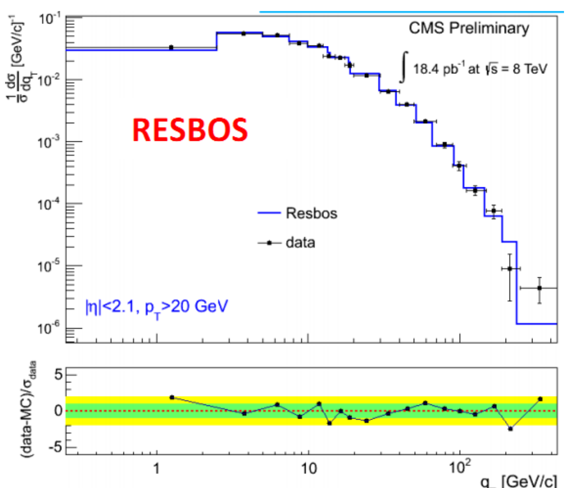


$P_T^Z = 0$ at LO

Multiple soft gluon emission (low P_T^Z)

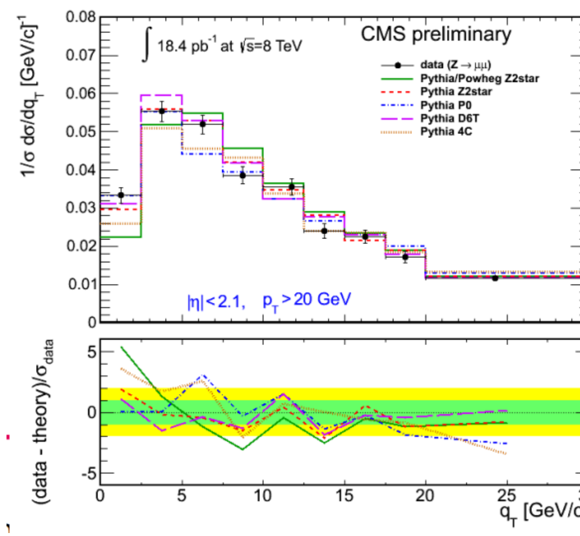
Radiation of a single parton (high P_T^Z)





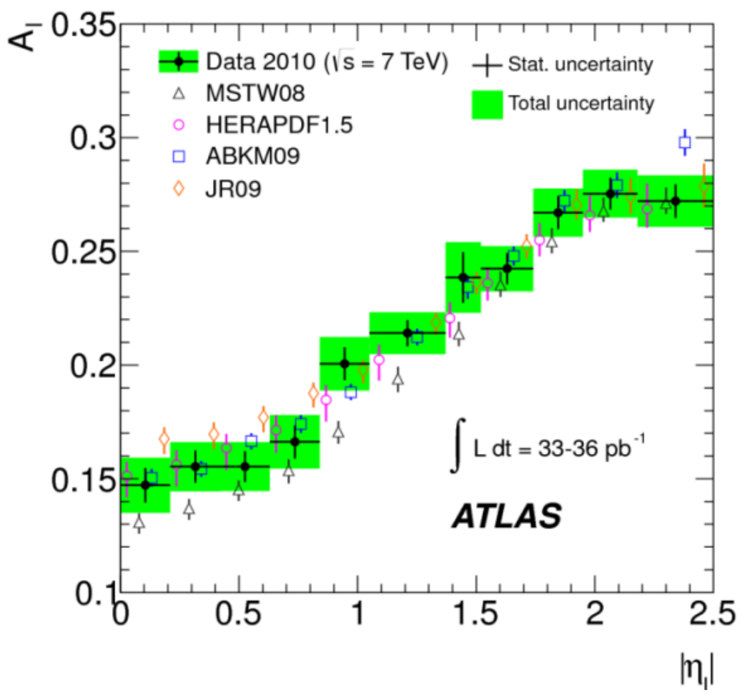
Comparison to theory (RESBOS: resummation + NLO* pQCD). Agreement at a few percent level.

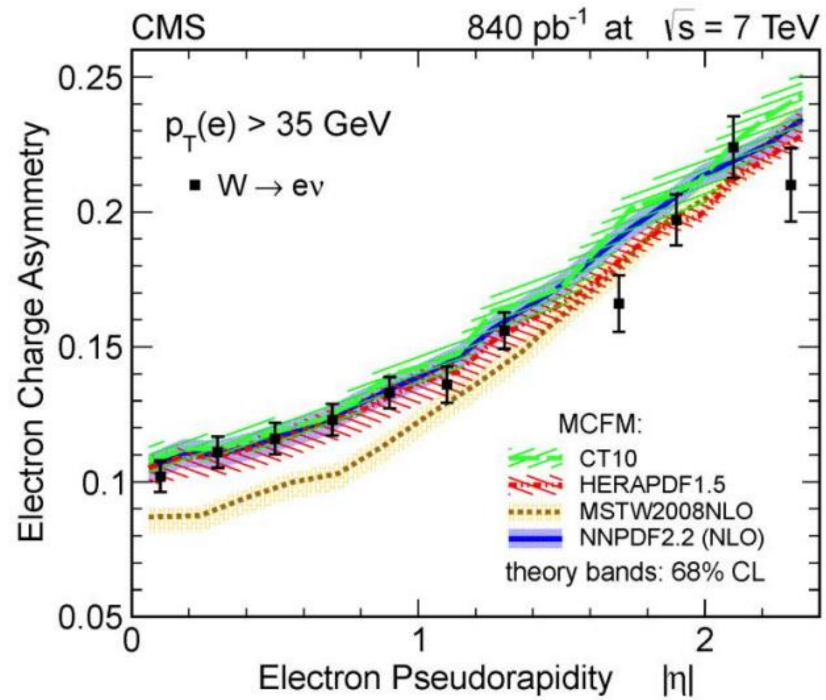
Also a very important input for MC tuning



W Charge Asymmetry

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



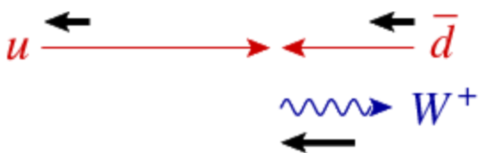


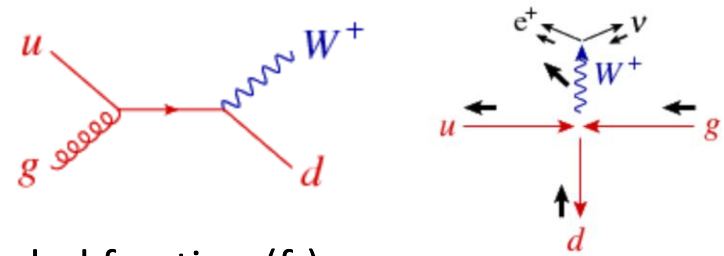
- Sensitive to valence quark distributions.
- An important input to PDF fit. Complementary to DIS data.
- Discrimination between PDF sets observed at low rapidity.

W Production Polarization

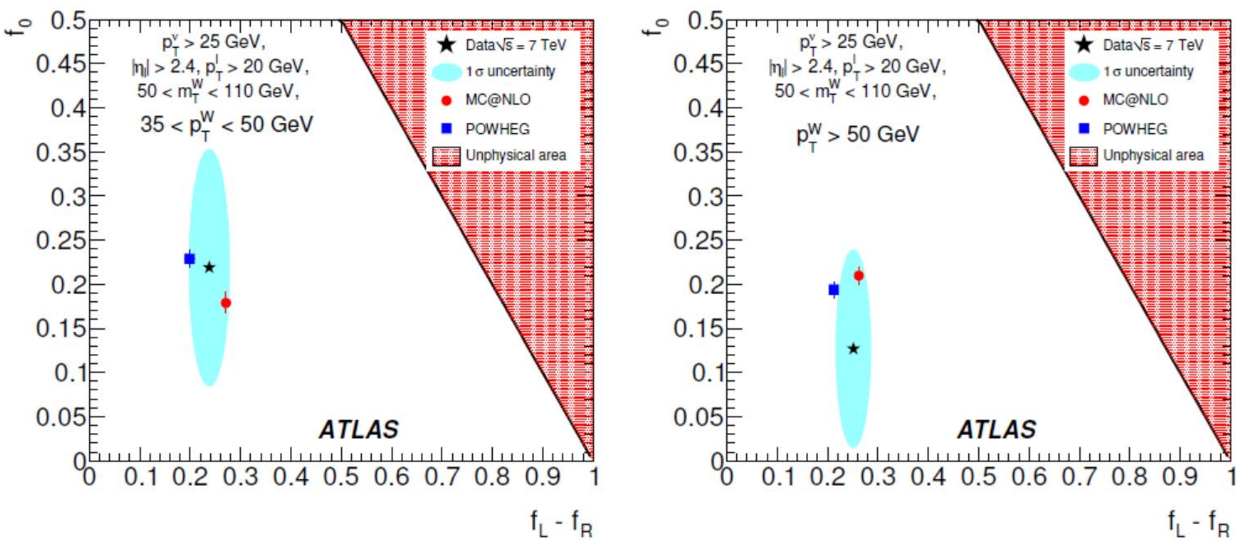
Definite W polarization in LO production

W polarization gets indefinite in higher-order production





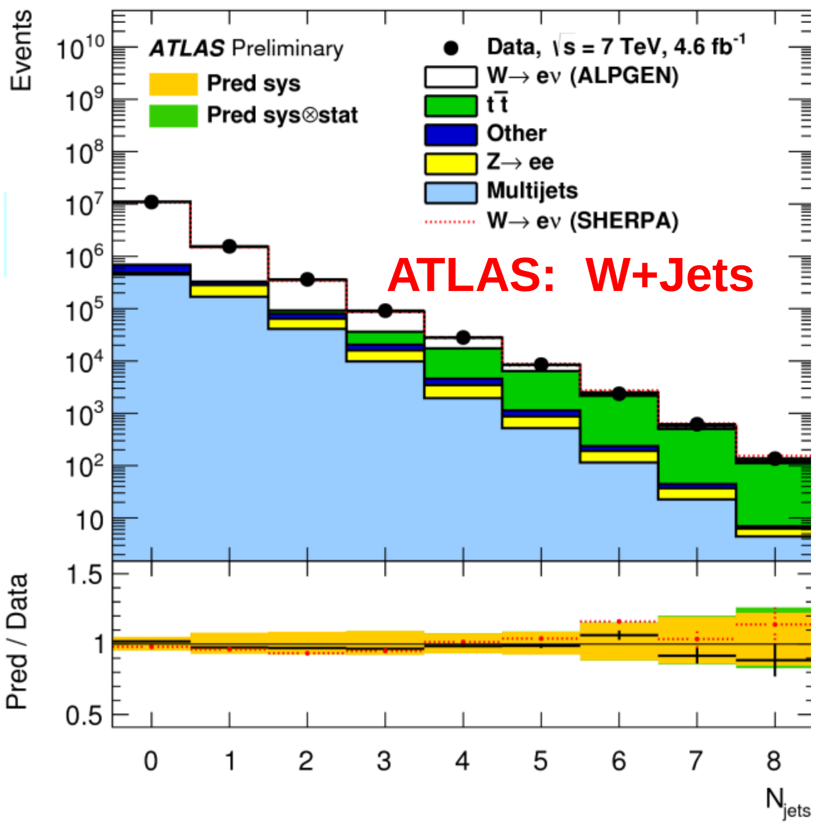
- W helicity states in production: left-handed fraction (f_L), right-handed fraction (f_R) and longitudinal polarized fraction (f_0).
- Measured the W helicity composition in high W P_T regime.

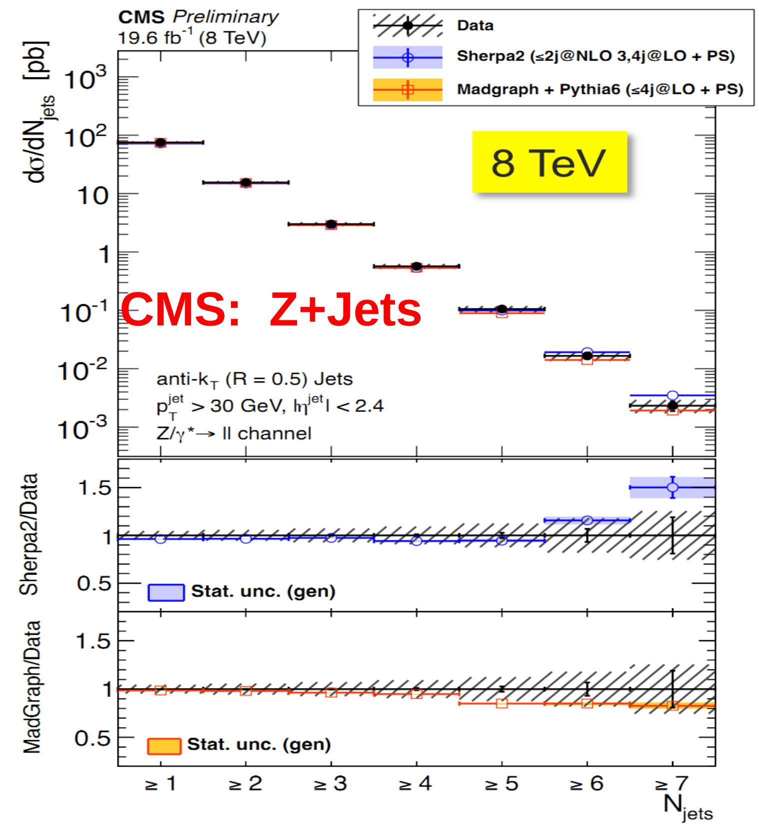


- Good agreement between data and MC@NLO

W/Z + jets production

- Can be "neatly" tagged by W/Z.
- Very important testing ground for pQCD

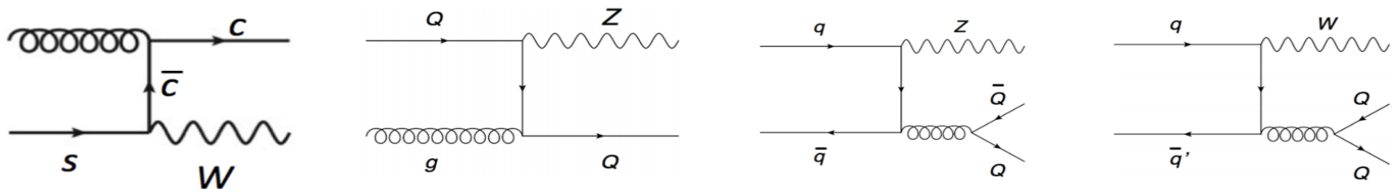




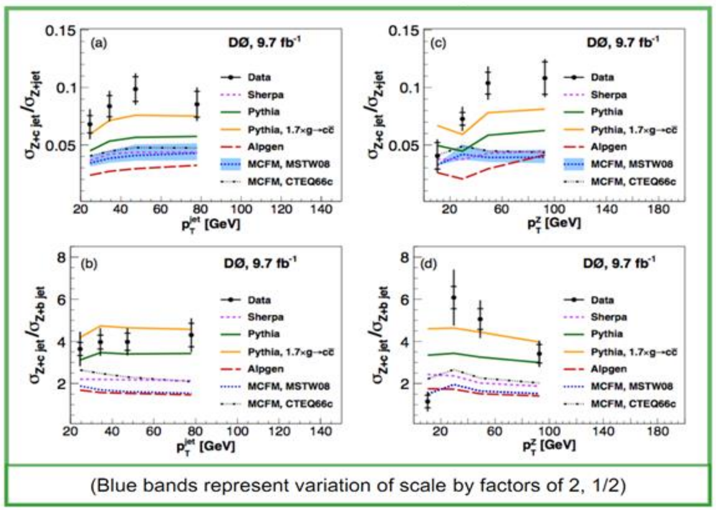
- Good description of data with N_{jets} up to 8, "deeply" testing QCD.
- A lot more derivative measurements performed: pT(j), Δϕ(j,j), Δy(j,j), M(j,j), Wj/Zj ratio, (n+1)jets/njets ratio …

W/Z + heavy flavor jets

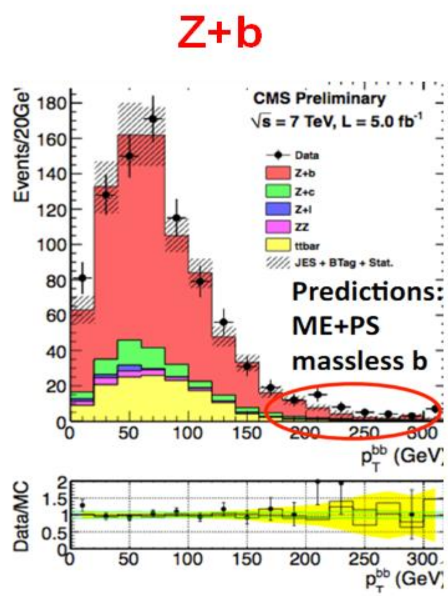
- Probe strange and heavy flavor contents in a proton
- Test gluon splitting into heavy flavor quarks
- Important background for rare processes and new physics searches

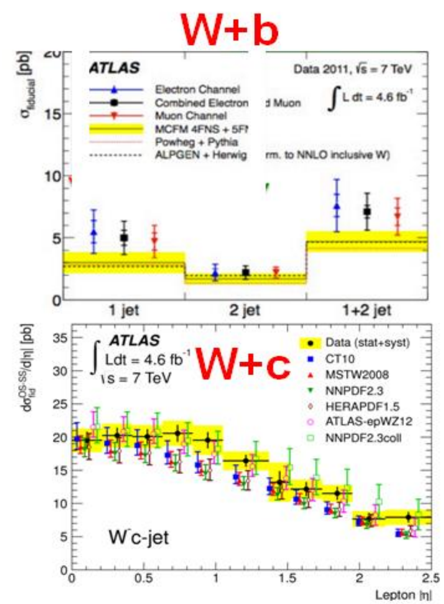


$$\frac{\sigma(Z+c_{jet})}{\sigma(Z+\text{jet})} \text{ and } \frac{\sigma(Z+c_{jet})}{\sigma(Z+b_{jet})}$$



(Blue bands represent variation of scale by factors of 2, 1/2)





Heavy flavor modeling is a very hot topic, also one of the keys to new physics discoveries. Mis-modeling observed in some kinematic regions due to missing high order effects or imperfect matching schemes/tuning .

Electroweak Measurements

- W/Z boson decays
  - Tau polarization in W decay
  - W mass
  - Z forward and backward asymmetry
  - $Z \rightarrow 4l$
- Di-boson production
- Triple-boson production
- Electroweak production of vector bosons
  - Vector Boson Fusion: VBF
  - Vector Boson Scattering: VBS

τ polarization

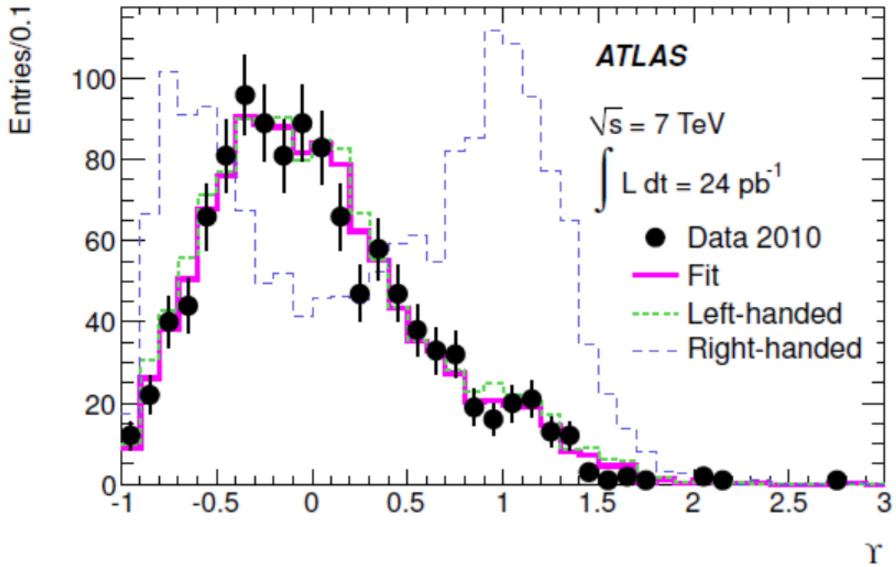
Study polarization of τ from W decays:

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

Using τ→a single charged meson + ν decay modes

Observable adopted

$$\frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T} \approx 2\frac{p_T^{trk}}{p_T} - 1 = \Upsilon$$



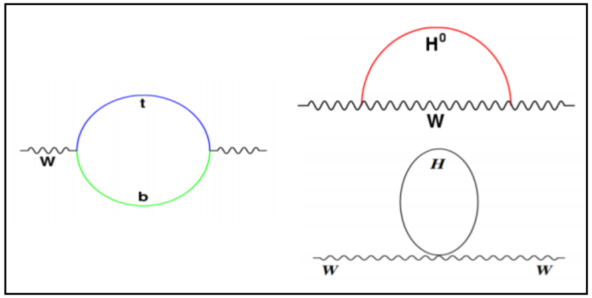
$$P_\tau = -1.06 \pm 0.04\,(stat)\,^{+0.05}_{-0.07}\,(syst)$$

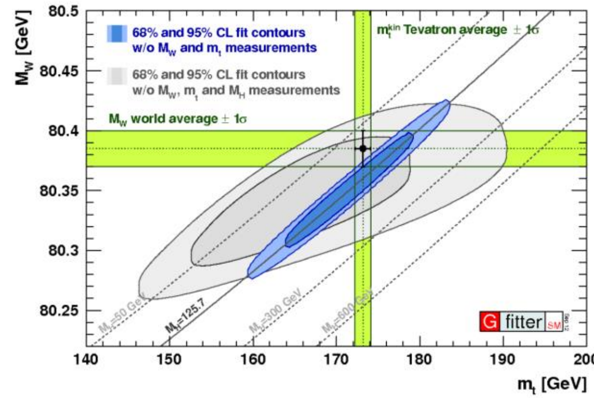
Compatible with left-handed hypothesis as predicted in SM

First measurement of such kind at hadron colliders.

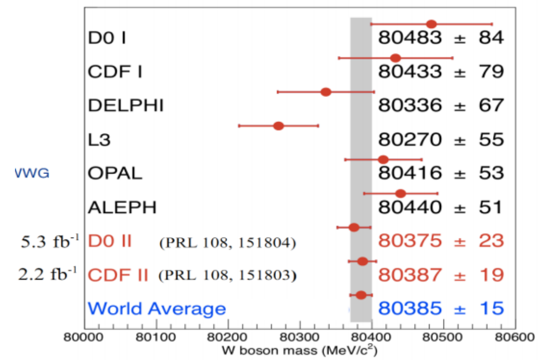
W Mass

Together with top quark mass and Higgs mass, W mass provides a stringent test of the SM

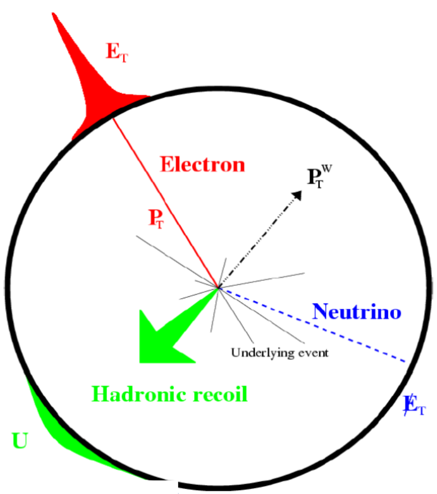




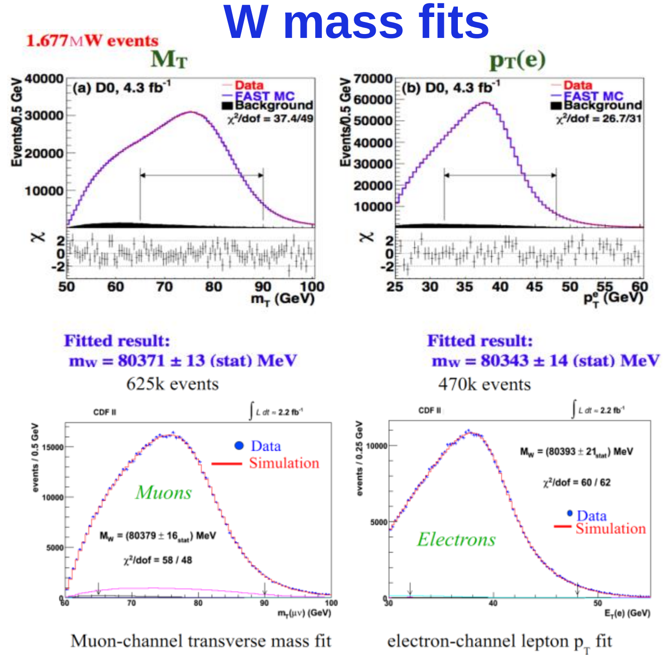
Fitted W mass



W→lv event topology



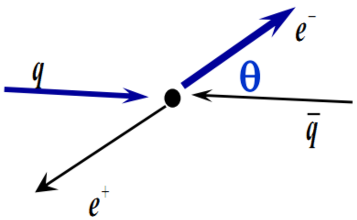
W mass fits



Systematic errors

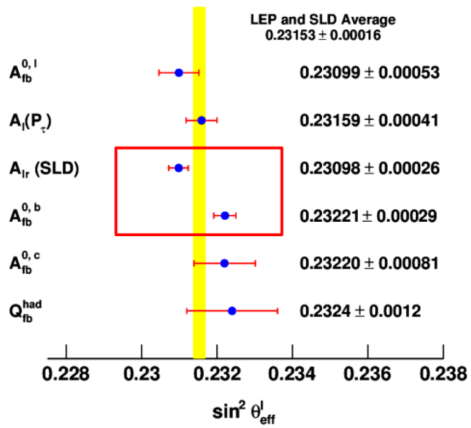
Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

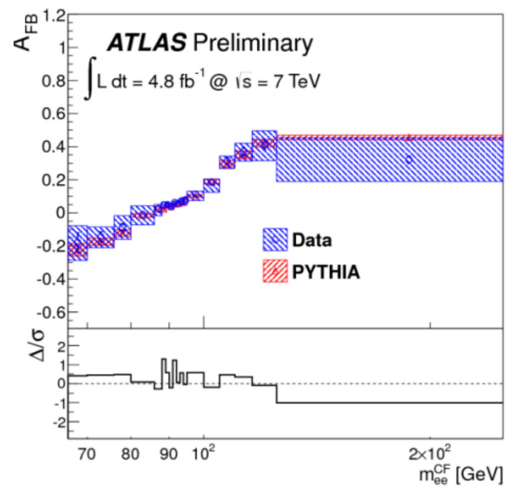
Z forward and backward asymmetry

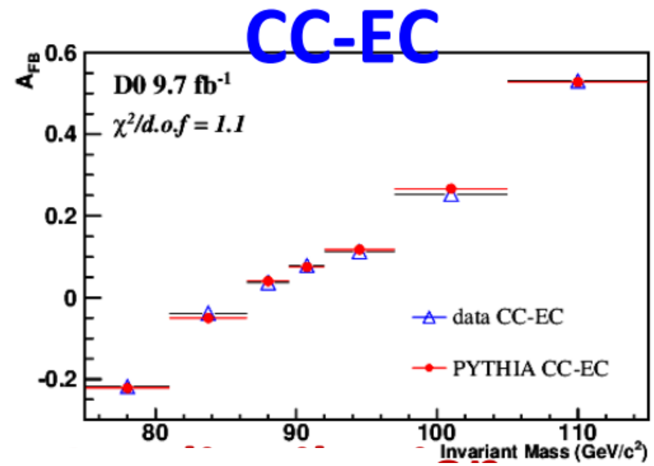


→ **cosθ > 0: forward**
cosθ < 0: backward → $A_{FB} = \dfrac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$ → $\sin^2\theta^{eff}_W$

Why so interesting?





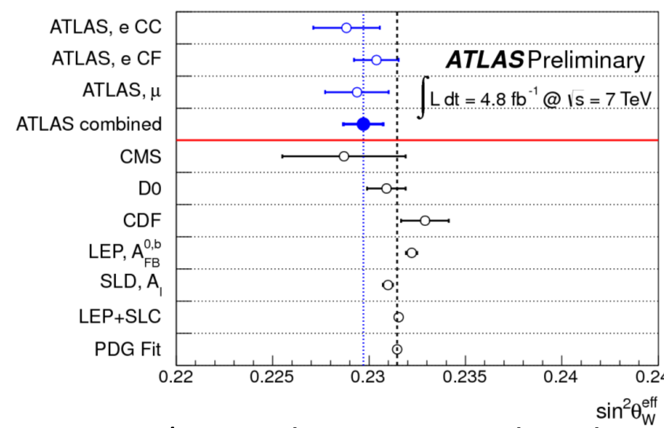


D0: $\sin^2\theta^l_{eff} = 0.23146 \pm 0.00047$

CDF: $\sin^2\theta_{eff} = 0.23150 \pm 0.00090(stat) \pm 0.00011(sys) \pm 0.00035\ (PDF)$

ATLAS: $\sin^2\theta^{eff}_W = 0.2297 \pm 0.0004 \pm 0.0009$

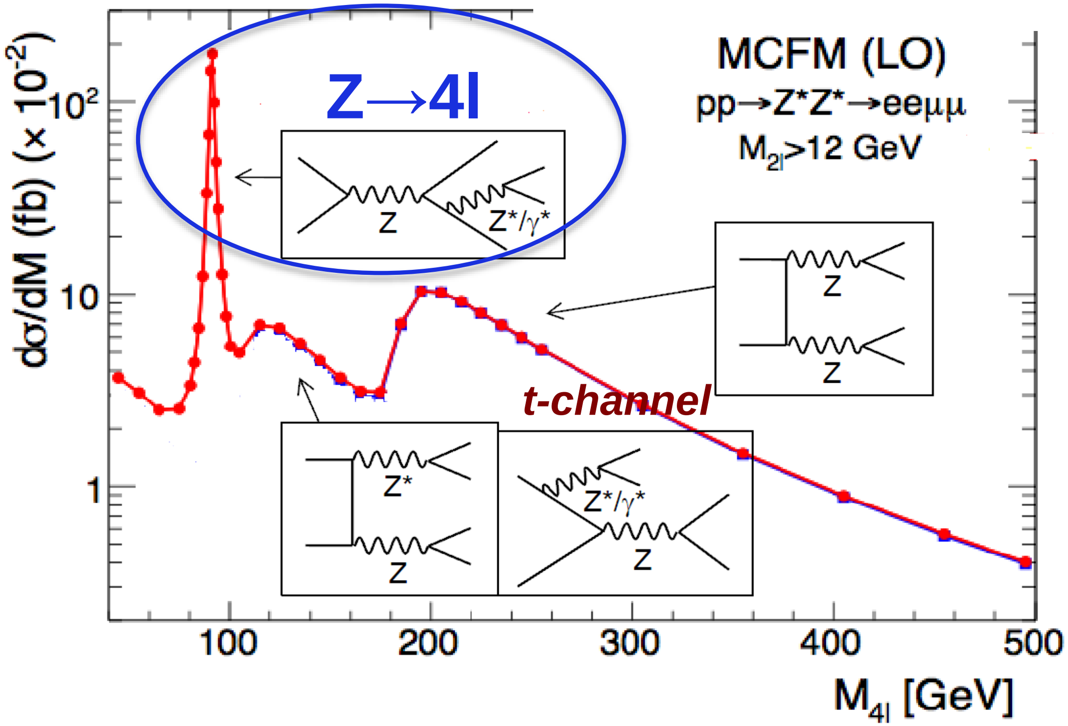
Weak mixing angle, $\sin^2\vartheta^{eff}_W$, a very important electroweak parameter to measure

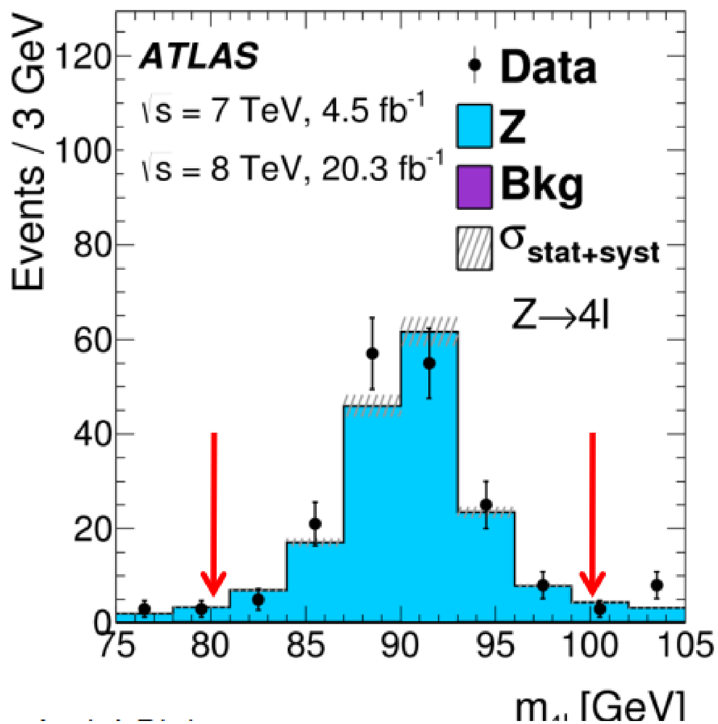


(D0 and CDF not updated yet)

Z→4l

A relatively rare SM process, providing calibration for 4-lepton event topology.





$\sigma_{Z\rightarrow 4\ell} = 107 \pm 9\ (\text{stat}) \pm 4\ (\text{syst}) \pm 3\ (\text{lumi})$ fb

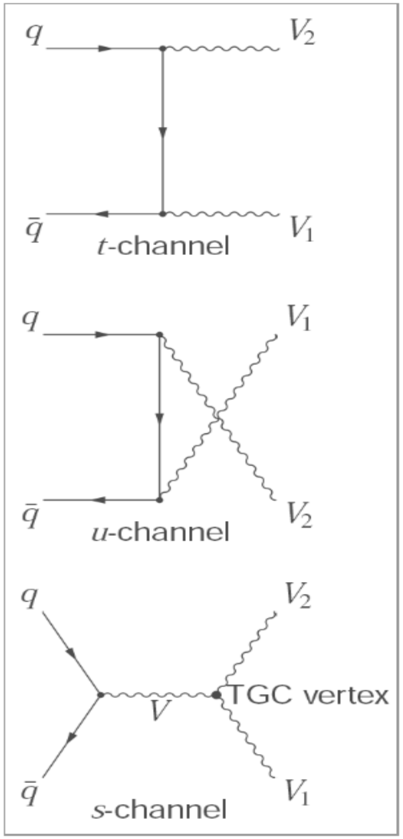
SM (NLO, 8 TeV): $\sigma_{Z\rightarrow 4\ell} = 104.8 \pm 2.5$ fb

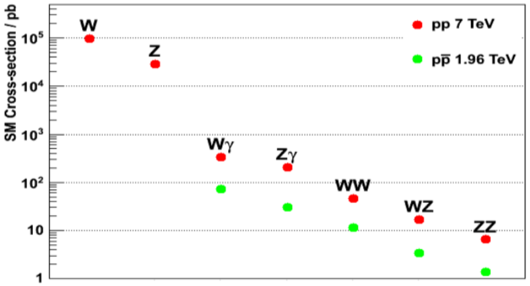
$\Gamma_{Z\rightarrow 4\ell}/\Gamma_Z = (3.20 \pm 0.25\ (\text{stat}) \pm 0.13\ (\text{syst})) \times 10^{-6}$

SM expectation: $(3.33 \pm 0.01)\times 10^{-6}$

First measurement of its kind at 8TeV

Di-Boson Production



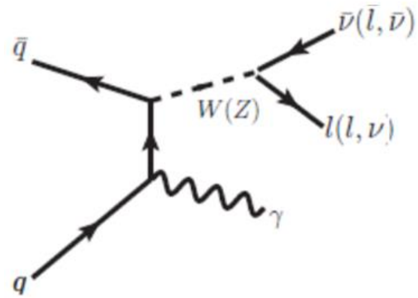


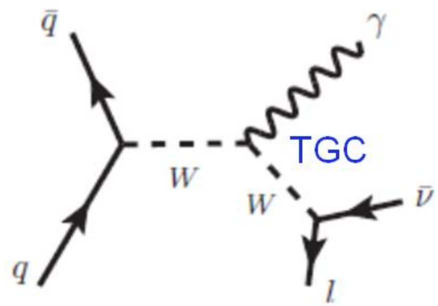
- Unique test of the electroweak sector of the SM
  - Triple gauge couplings (vector-boson self-couplings) are fundamental prediction resulting from the non-Abelian structure of the Electroweak gauge symmetry group of SU(2)*U(1), and are completely fixed in the SM.
  - Anomalous triple gauge couplings (**aTGCs**) are indication of new physics
- Irreducible background to Higgs boson measurement.
- Sensitive to new resonances decaying to boson pairs.

Wγ, Zγ, WW, WZ, ZZ

(W and Z are selected in a similar way to the previous "QCD" W/Z selections).

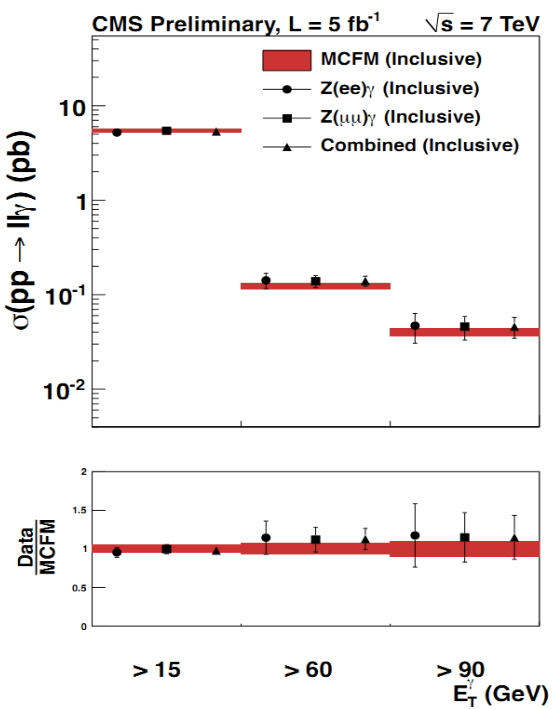
Wγ, Zγ



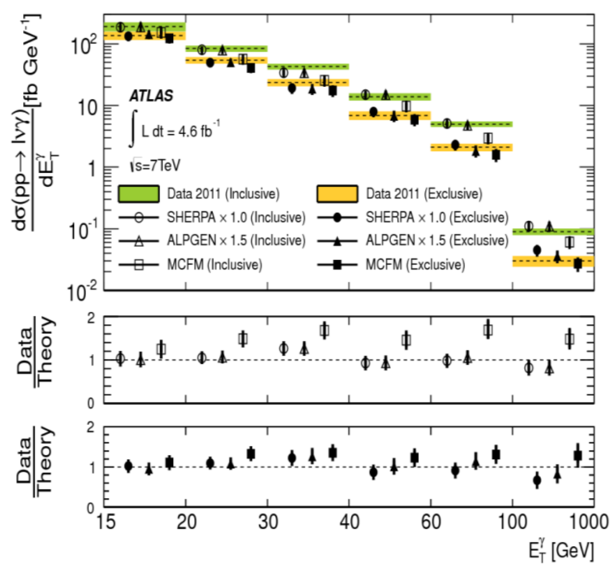


- Wγ ➔ lνγ and Zγ ➔ llγ
  - W/Z + isolated photon, $E_T(\gamma)$ > 15 GeV
  - Δ R(l,γ) > 0.7 (suppress FSR)
  - Background: W/Z/γ+jets
- Zγ ➔ ννγ
  - Missing transverse energy + isolated photon
  - $E_T(\gamma)$ > 100 GeV (ATLAS)
  - $E_T(\gamma)$ > 145 GeV (CMS)
  - Background: W, Wγ, γ+jets

Zγ cross section

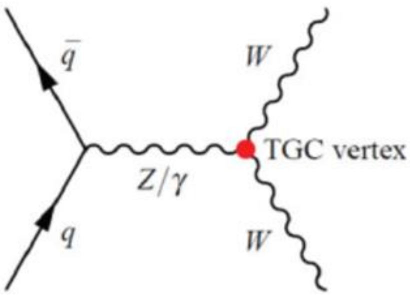


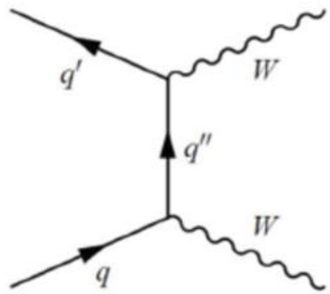
Wγ cross section



- Wγ: Data agrees with MCFM NLO prediction in low E_T, but overshoots the prediction in high E_T.
- Zγ: Data agrees MCFM NLO prediction for exclusive (no jets)

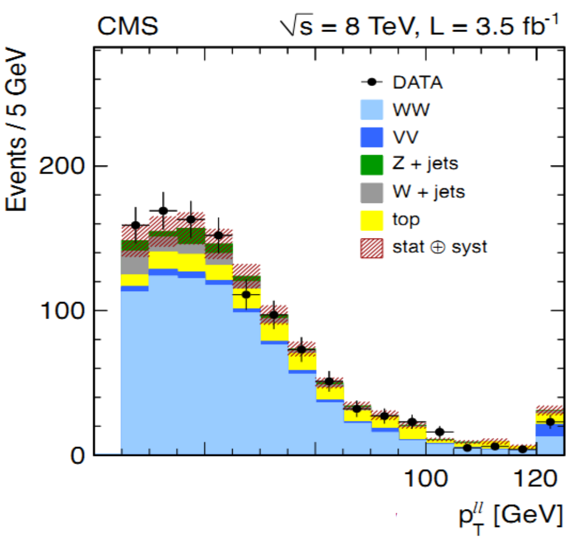
WW→lνlν



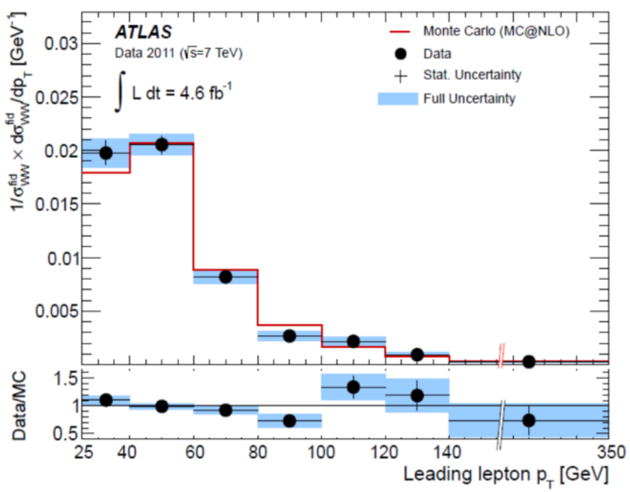


- Signal selection
  - Opposite-sign high-p_T isolated leptons (ee, μμ, eμ)
  - Missing transverse energy (reduce Drell-Yan)
  - Jet veto (reduce ttbar)
    - Any high-p_T jet
    - Lower p_T b-tagged jet (CMS)

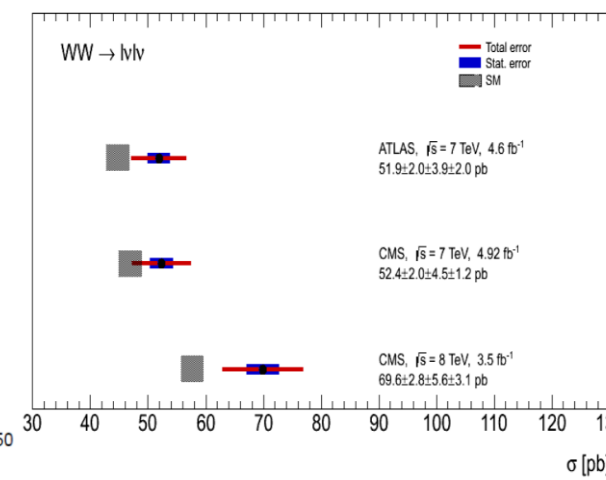
Data vs. Prediction after selection



Unfolded leading lepton p_T

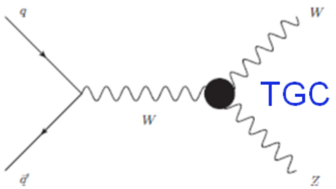


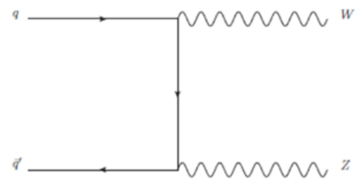
Cross sections



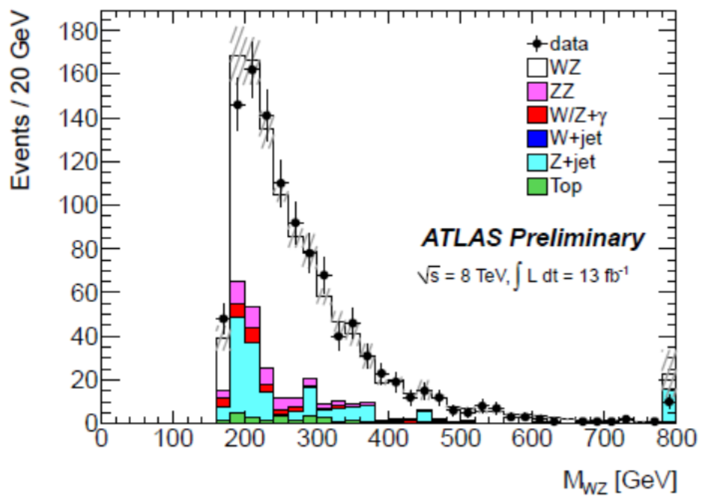
10-20% higher than SM (1-2 σ)

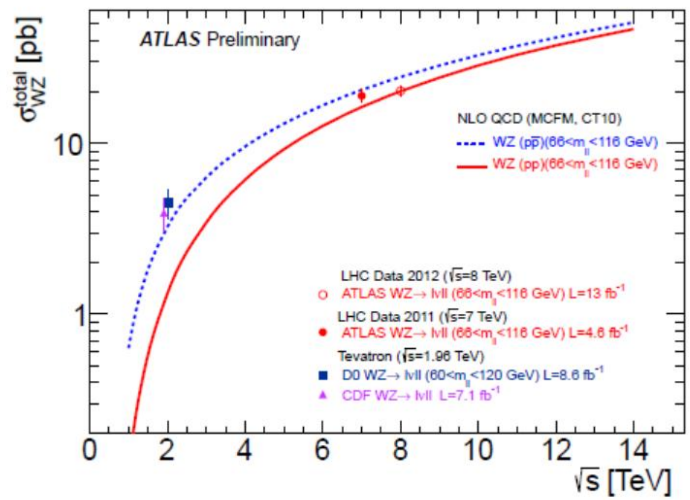
WZ→lllv





- Signal selection
  - Opposite-sign lepton pair forming Z
  - Lepton + missing E_T forming W



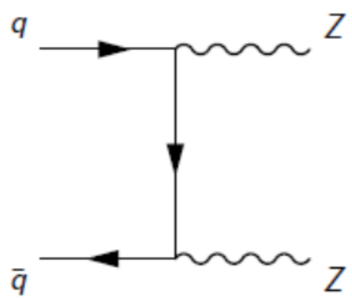


$$\sigma^{\mathrm{fid}}_{W\pm Z} = 99.2^{+3.8}_{-3.0}(\mathrm{stat.})^{+5.1}_{-5.4}(\mathrm{syst.})^{+3.1}_{-3.0}(\mathrm{lumi.})\ \mathrm{fb}$$

$$\sigma_{W\pm Z} = 20.3^{+0.8}_{-0.7}(\mathrm{stat.})^{+1.2}_{-1.1}(\mathrm{syst.})^{+0.7}_{-0.6}(\mathrm{lumi.})\ \mathrm{pb}$$

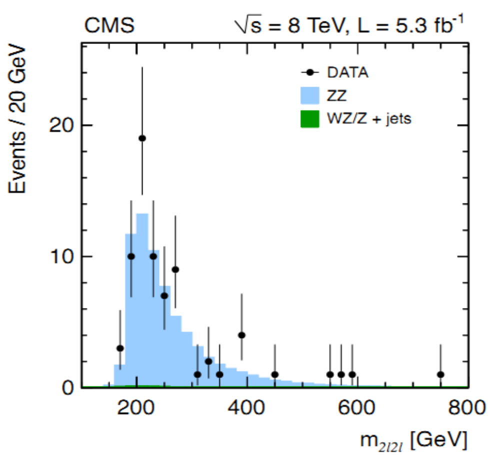
Measured and predicted cross sections agree.

ZZ→llll, llvv

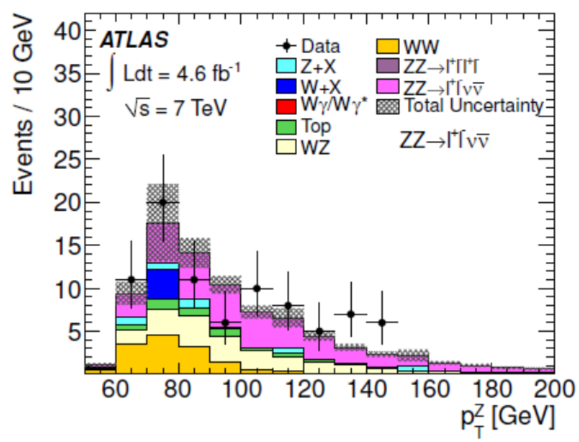


- ZZ→llll
  - four good leptons forming two Z bosons
  - low branching ratio but very clean
- ZZ→llvv
  - two good leptons forming one Z boson + large missing energy
  - higher rate but also higher background

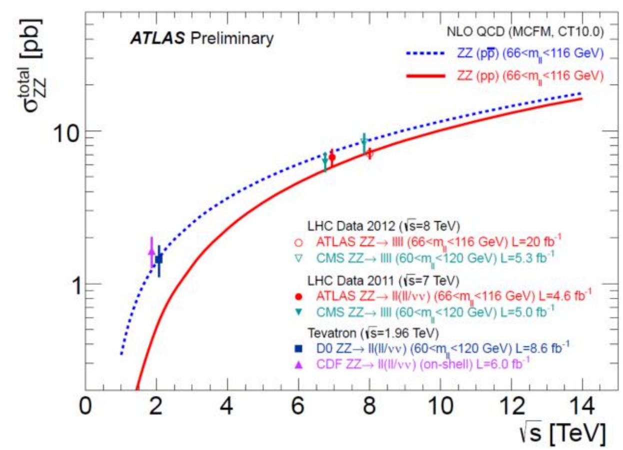
ZZ→llll



ZZ→llvv



cross sections



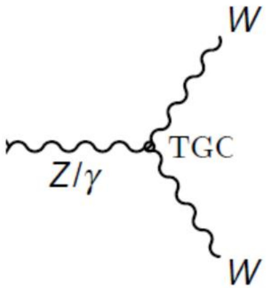
measured cross sections agree with predicted ones

aTGCs

Diboson production sensitive to aTGCs

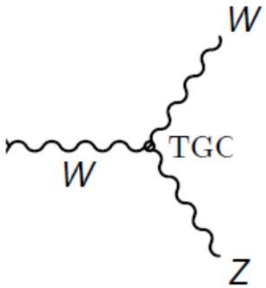
WWV ($V = Z/\gamma$) couplings ↔ WW and WZ (also Wγ)

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^+_{\mu\nu}W^{\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{\mu\nu}) + i\kappa_V W^+_{\mu}W_{\nu}V^{\mu\nu} + \frac{i\lambda_V}{m_W^2}W^+_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$$



- 5 parameters: $\Delta g_1^Z (\equiv g_1^Z - 1)$, $\Delta\kappa_Z (\equiv \kappa_Z - 1)$, $\Delta\kappa_\gamma (\equiv \kappa_\gamma - 1)$, λ_Z, λ_γ
- Additional constraints may be imposed

Equal coupling	$\Delta g_1^Z = 0$, $\Delta\kappa_Z = \Delta\kappa_\gamma$, and $\lambda_Z = \lambda_\gamma$
LEP scenario	$\Delta g_1^Z - \Delta\kappa_Z = \Delta\kappa_\gamma \tan^2\theta_W$ and $\lambda_Z = \lambda_\gamma$
HISZ scenario	$\Delta\kappa_Z = \Delta g_1^Z(\cos^2\theta_W - \sin^2\theta_W)$, $\Delta\kappa_\gamma = 2\Delta g_1^Z\cos^2\theta_W$ and $\lambda_Z = \lambda_\gamma$

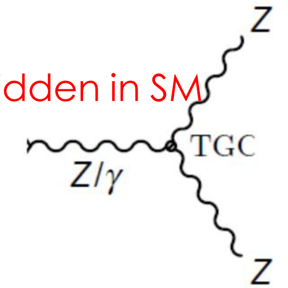


ZZV ($V = Z/\gamma$) couplings ↔ ZZ (also Zγ)

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_4^V V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right]$$

- 4 parameters: f_4^Z, f_4^γ, f_5^Z, f_5^γ

Forbidden in SM



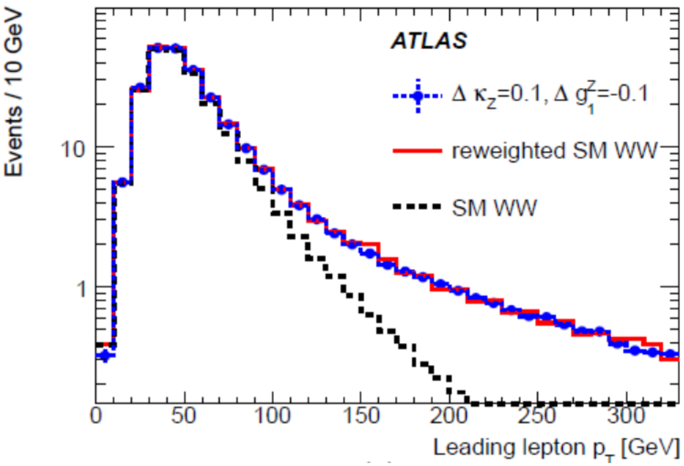
Parameters in red (*anomalous TGCs*) are zero in the SM

* *Introduce a form factor to each parameter to ensure unitarity* $\alpha \rightarrow a(s) \equiv \frac{\alpha}{(1+\hat{s}/\Lambda_{FF}^2)^n}$

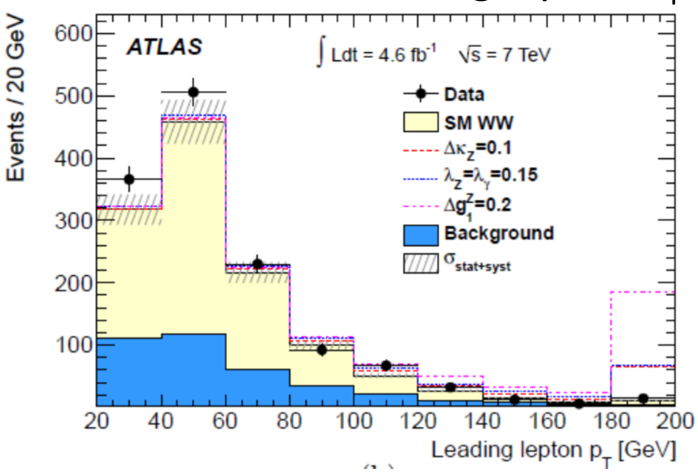
aTGC Analysis

- Use reweighting techniques (kinematic or matrix-element based) to access full TGC parameter space.
- Exploit kinematic distributions that are sensitive to aTGCs to derive limits on aTGCs.
  - Wγ,Zγ: γ transverse energy
  - WW: leading lepton P_T
  - WZ: Z transverse P_T
  - ZZ: leading Z transverse P_T
- NLO calculations are required for aTGC extraction.
  - NLO corrections (or even EW corrections) are substantial at large energy scale

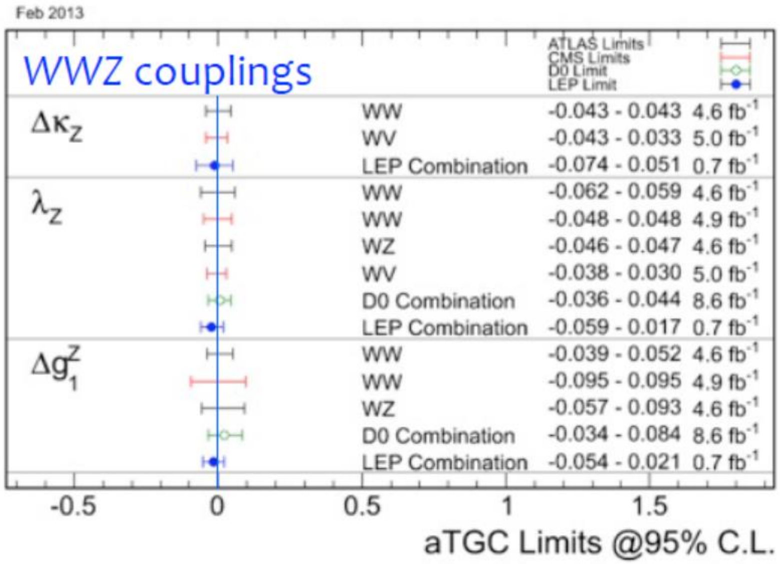
Kinematic reweighting

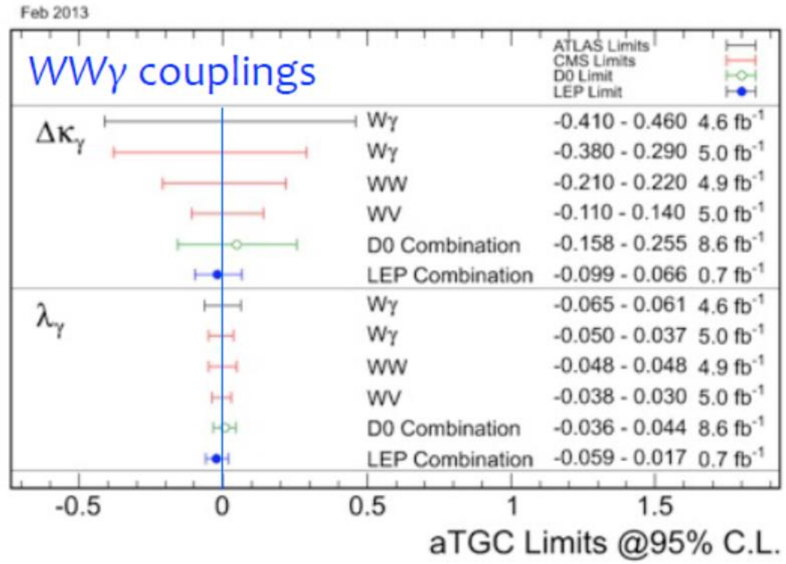


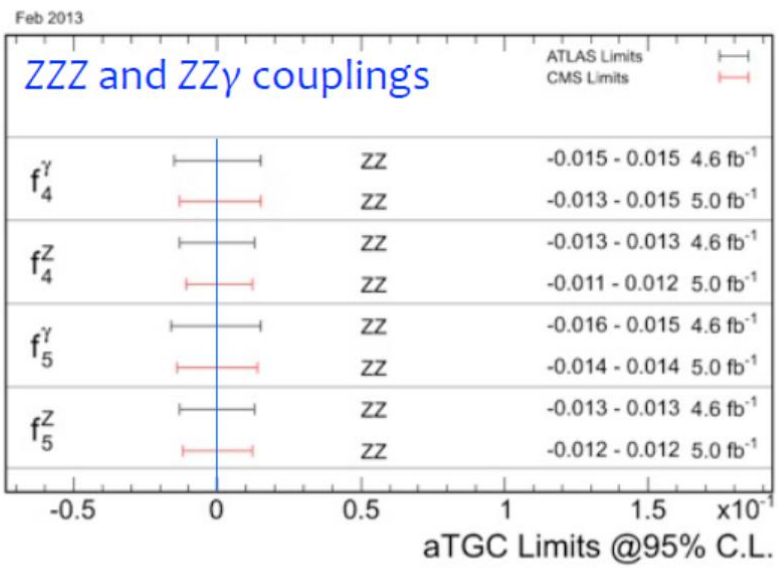
aTGC effects on leading lepton P_T



aTGC limits





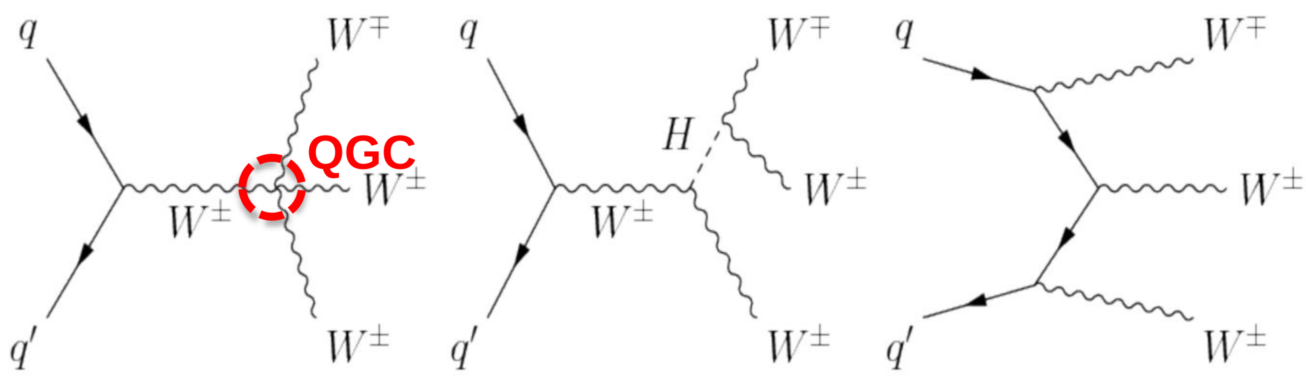


TGCs consistent with the SM

- Four of the *WWZ* and *WWγ* couplings are constrained to O(0.05)
  - Caveat: LEP scenario is used
  - $\Delta\varkappa_\gamma$ remains less precise
- *ZZZ* and *ZZγ* couplings are constrained by the LHC results to O(0.01)

8 TeV data not included yet

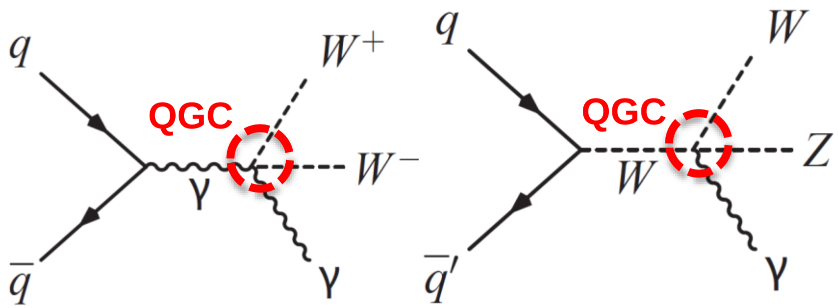
Triple-Boson Production



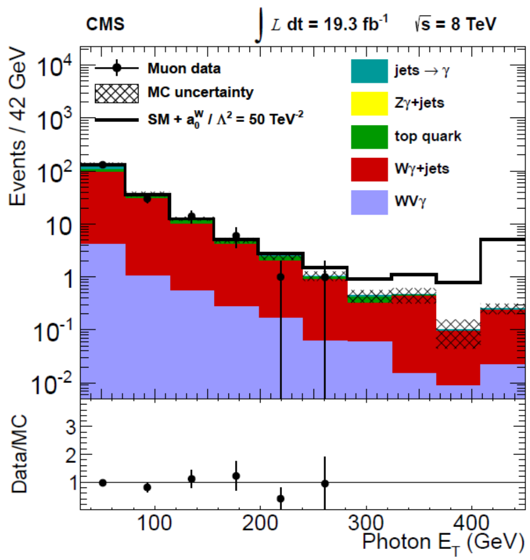
(example diagrams for WWW production)

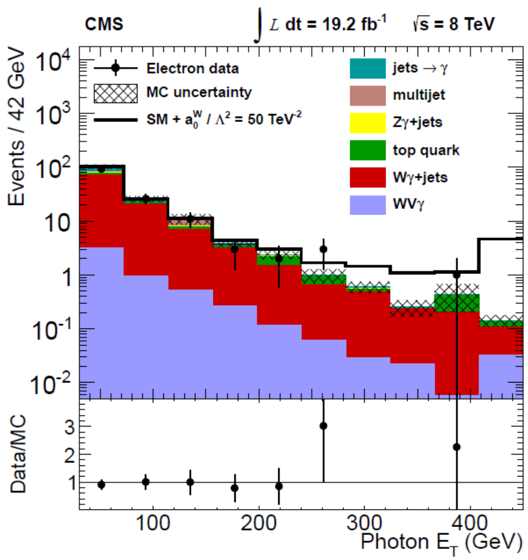
- Triple-Boson production not observed yet at LHC, rare processes
- An important testing ground for the electroweak theory.
- Sensitive to quartic gauge couplings (QGCs) and HVV couplings.
- Probe new physics through anomalous quartic gauge couplings (**aQGCs**) or anomalous HVV couplings.

WVϒ (V=W/Z)



- Choose decays of W→lv and V→jj. So the final state is lvjjϒ
  - One good lepton
  - A dijet pair with mass ~ W/Z
  - Missing energy





No sign of WVϒ signal

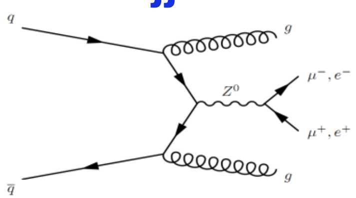
CL=95% upper limit on production cross section: 311 fb ~ 3.4*SM

Triple-boson production will become largely accessible in LHC Run2.

Electroweak Production of Vjj and VVjj

- Two categories of production of Vjj and VVjj at LHC:
  - Strong production: $\mathcal{O}(\alpha_s) = 2$

Vjj



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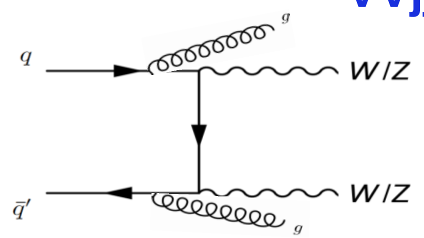
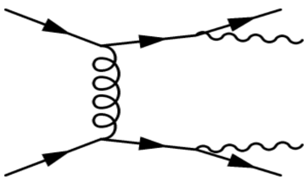
VVjj





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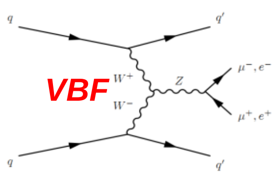
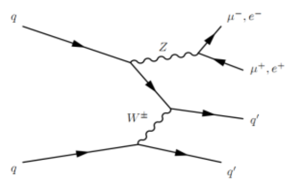
<u>important background to electroweak production processes</u>

  - **Electroweak production** :$\mathcal{O}(\alpha_s) = 0$

Vjj





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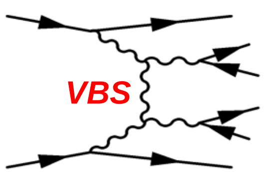
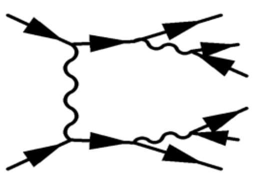
VVjj





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Purely electroweak interactions at born level

- **VBF**: Similar topology to Higgs VBF production

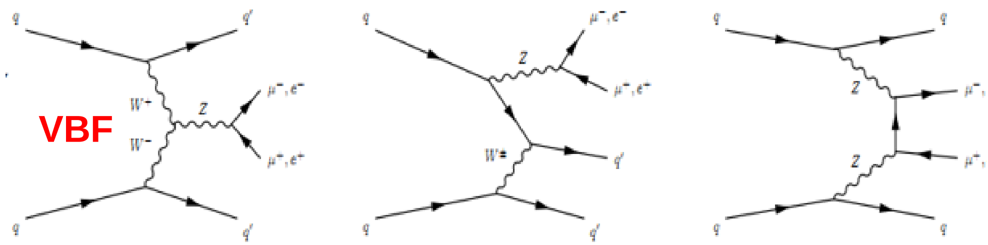
Characteristics of VBF and VBS event topology:
Two well-separated high p_T jets (tag jets) in the final states.

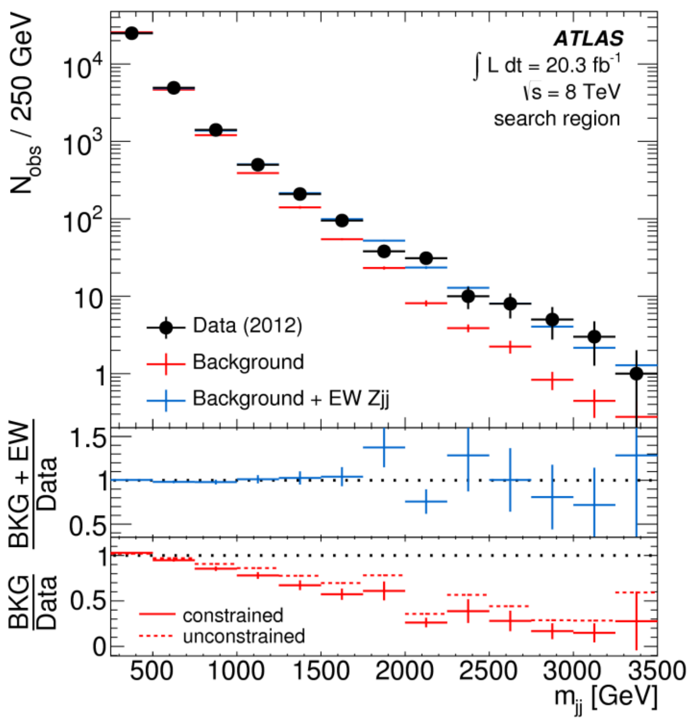
- **VBS**: **Crucial to studies of electroweak symmetry breaking mechanism (regardless of the Higgs discovery)**

Unitarity of V_LV_L scattering , search for new VV resonances, ideal laboratory for measuring HVV couplings …

Electroweak Zjj

Signal Processes





Object selections:

- two electron/muon
- two high-p_T forward jets

Kinematic selections:

- $81 < m_{ll} < 101$ GeV
- $p_T^{ll} > 20$ GeV
- $p_T^{balance} < 0.15$
- $N_{jet}^{gap} = 0$
- $m_{jj} > 250$ GeV

Fiducial Cross Section:

$$\sigma_{EW} = 54.7 \pm 4.6\,(\mathrm{stat})\,^{+9.8}_{-10.4}\,(\mathrm{syst}) \pm 1.5\,(\mathrm{lumi})\ \mathrm{fb}.$$

Cross Section Prediction (POWHEG):

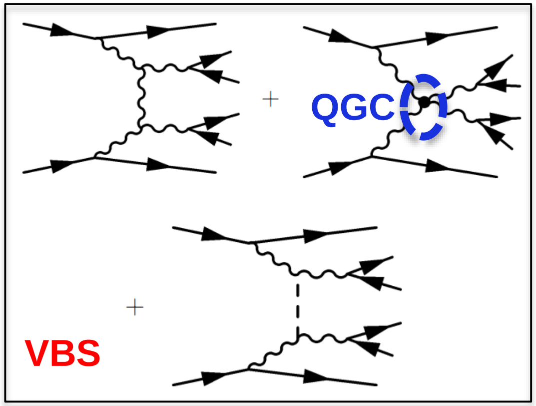
$$46.1 \pm 0.2\,(\mathrm{stat})\,^{+0.3}_{-0.2}\,(\mathrm{scale}) \pm 0.8\,(\mathrm{PDF}) \pm 0.5\,(\mathrm{model})\ \mathrm{fb}$$

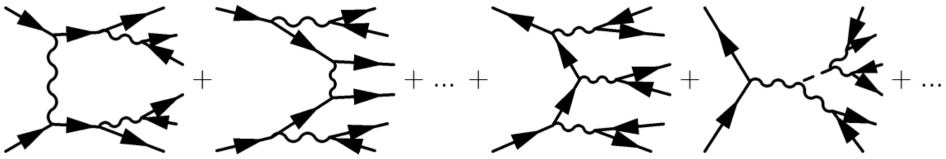
Limits on aTGC parameters (mjj > 1 TeV)

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

Electroweak $W^{\pm}W^{\pm}jj$

Signal Processes





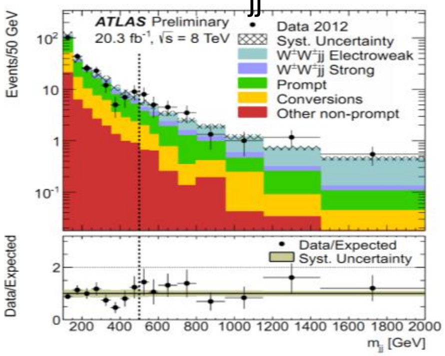
Gauge-invariantly inseparable with VBS

Triple-boson production, separable

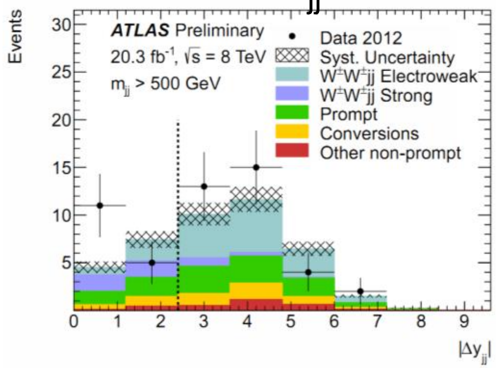
Cross Sections

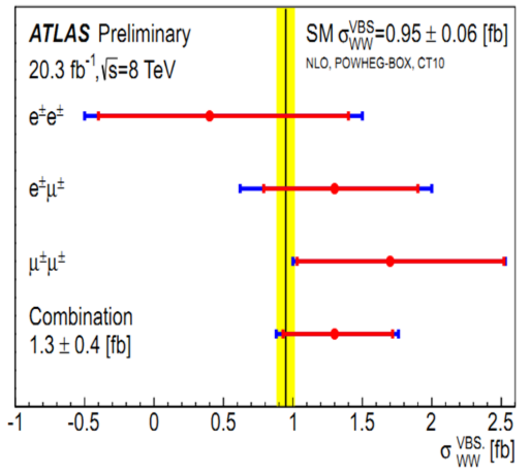
(Mjj>500GeV, |dYjj|>2.4)

m_{jj}



dY_{jj}





- Rather complicated background composition. Heavily used control regions to validate background estimations.
- Most powerful discriminating variables: invariant mass (m_{jj}) and separation (dY_{jj}) of the two tag jets

First evidence for EWK $W^{\pm}W^{\pm}jj$ production !

aQGCs

aQGC parameterization

- Effective field theory approach
  - New physics can appear as aQGC

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\mathrm{dimension}\ d} \sum_i \frac{c_i^{(d)}}{\Lambda_i^{d-4}} \mathcal{O}_i^{(d)}$$

Λ: scale for hypothetical new physics

- Parameterisations used in the LHC measurements
  - "linear" realisation (d=8): $f_{S,i}/\Lambda^4$, $f_{M,i}/\Lambda^4$, $f_{T,i}/\Lambda^4$ arXiv:hep-ph/0606118
  - "non-linear" realisation (d=6): $a_{0,C}/\Lambda^2$, $\kappa_{0,C}/\Lambda^2$ arXiv:hep-ph/9908254
  - Chiral Lagrangian (d=4): α_4, α_5 arXiv:11309.7890

some d=4, 6 parameters can be translated into d=8 ones

- "$f_i/\Lambda^4 \sim O(1)$ for a new physics scale above 1 TeV"
- "Λ (TeV) ~ $0.25/\sqrt{\alpha_i}$ ($\alpha_i \sim 0.06$ for new physics at 1 TeV)"

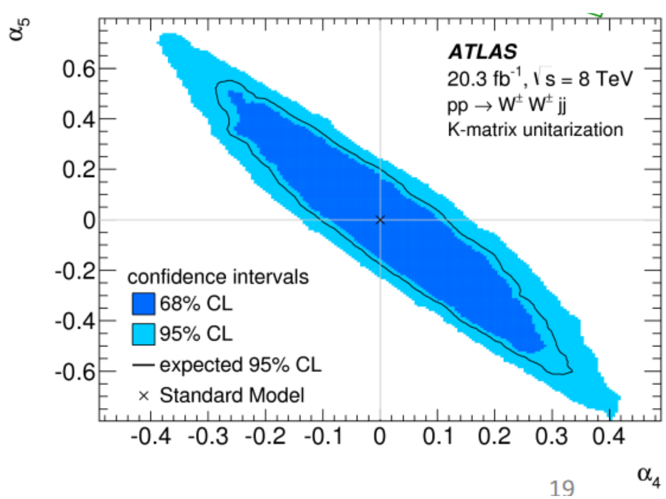
Both triple-boson production and VBS are sensitive to aQGCs.

aQGC limits

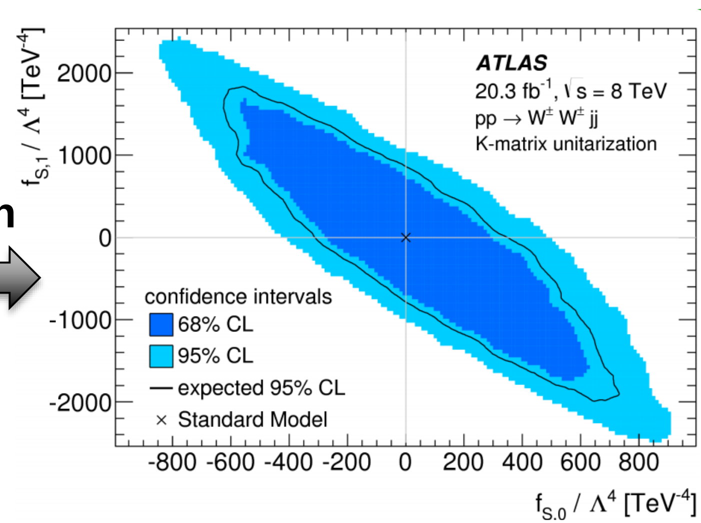
From WVϒ analysis

Observed limits	Expected limits
$-21 < a_0^W/\Lambda^2 < 20\,\mathrm{TeV}^{-2}$	$-24 < a_0^W/\Lambda^2 < 23\,\mathrm{TeV}^{-2}$
$-34 < a_C^W/\Lambda^2 < 32\,\mathrm{TeV}^{-2}$	$-37 < a_C^W/\Lambda^2 < 34\,\mathrm{TeV}^{-2}$
$-25 < f_{T,0}/\Lambda^4 < 24\,\mathrm{TeV}^{-4}$	$-27 < f_{T,0}/\Lambda^4 < 27\,\mathrm{TeV}^{-4}$
$-12 < \kappa_0^W/\Lambda^2 < 10\,\mathrm{TeV}^{-2}$	$-12 < \kappa_0^W/\Lambda^2 < 12\,\mathrm{TeV}^{-2}$
$-18 < \kappa_C^W/\Lambda^2 < 17\,\mathrm{TeV}^{-2}$	$-19 < \kappa_C^W/\Lambda^2 < 18\,\mathrm{TeV}^{-2}$

From $W^\pm W^\pm jj$ analysis



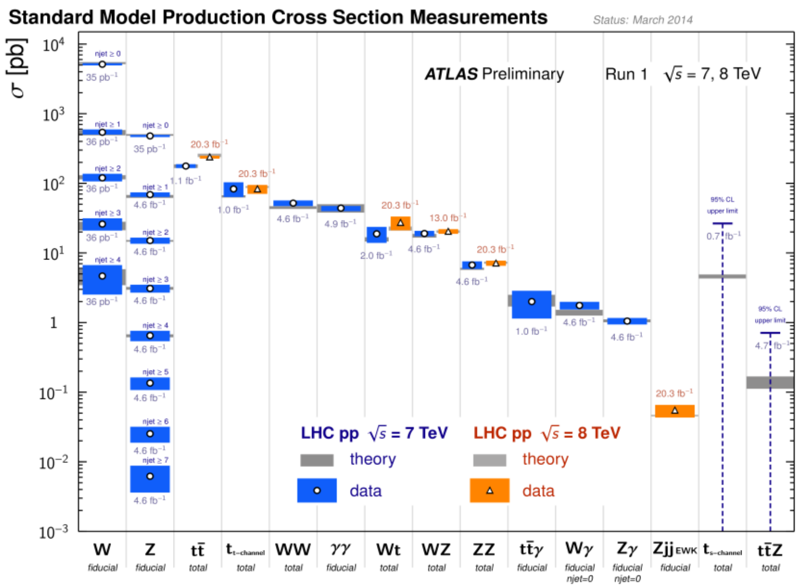
Linear transformation

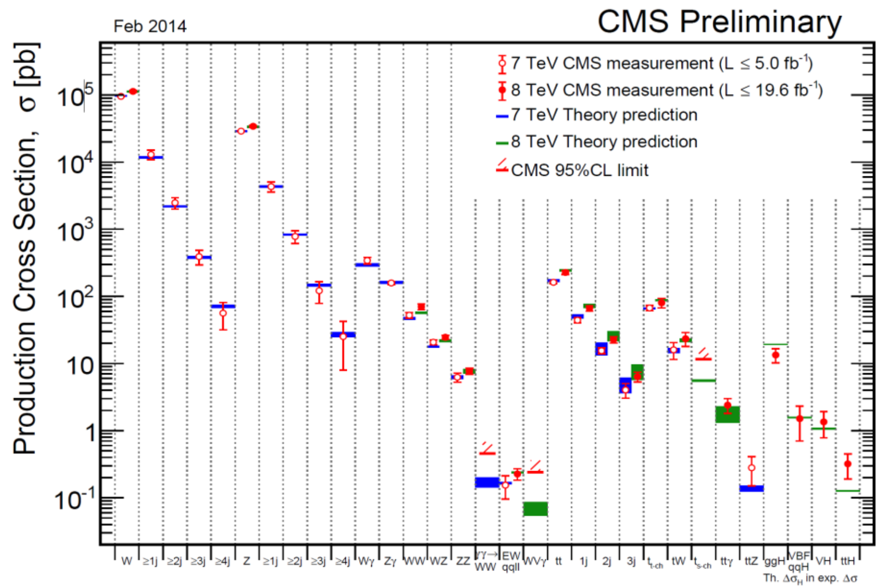


$-0.14 < \alpha_4 < 0.16$ (obs.) : $-0.10 < \alpha_4 < 0.12$ (exp.) ($\alpha_5=0$)
$-0.23 < \alpha_5 < 0.24$ (obs.) : $-0.18 < \alpha_5 < 0.20$ (exp.) ($\alpha_4=0$)

$-420 < f_{S,0}/\Lambda^4 < 490$ [TeV^{-4}](obs: $f_{S,1}=0$)
$-1010 < f_{S,1}/\Lambda^4 < 1060$ [TeV^{-4}](obs: $f_{S,0}=0$)

Summary





- TeV hadron colliders put the SM to the test at the energy frontier.
- It’s impressive to see agreement with the SM across orders of magnitude.
- In addition to testing the SM and indirectly searching for new physics, SM measurements lay groundwork for an experiment and are mandatory
  - reconstruction, calibration and performance
  - detector and physics simulation, MC tuning
  - Irreducible backgrounds to new physics searches

SM measurements are just important