Standard Model Electroweak Processes at LHC (and ILC)

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Introductory School to Particle Physics
DESY Hamburg
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Outline

- Snapshot of the Electroweak Standard Model
- Electroweak Processes at LHC
- LHC Detectors
  - Calibration and Performance with Standard Model Physics
- Electroweak Measurements at the LHC
  - W Mass
  - Gauge Boson Couplings
  - Electroweak Mixing Angle
- Beyond LHC: ILC
- Summary

Snapshot of the Electroweak Standard Model

- Electroweak Standard Model:
  - developed by Glashow, Salam and Weinberg in the 1960s
  - unified gauge theory of QED and weak interactions → gauge group $SU(2)_L xU(1)_Y$




NP 1979

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$e^-_R \quad \mu^-_R \quad \tau^-_R$$

$$[\nu_{e,R} \quad \nu_{\mu,R} \quad \nu_{\tau,R}]$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

- matter particles are fermions
  - leptons and quarks
  - left-handed doublets
  - right-handed singlets

- interactions are mediated by gauge bosons
  - $W^\pm$ and Z bosons, photons
  - mixing of neutral fields
  - weak mixing angle θ_w
  - non-abelian theory:
    - gauge bosons can couple to themselves

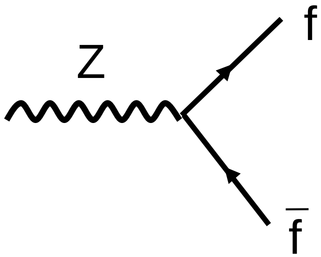
$$\begin{pmatrix} A \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w \\ -\sin\theta_w & \cos\theta_w \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$

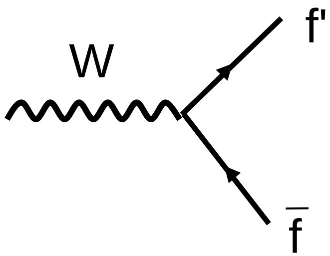
- Higgs mechanism provides masses for fermions and bosons (lecture on Thursday)

Electroweak Measurements

- masses of gauge bosons: M_W, M_Z
- masses of fermions: the most important is the mass of the top quark m_t
  (lecture on Thursday)
- important prediction of the Standard Model: $\frac{M_W}{M_Z} = \cos\theta_w$ or $\rho = \frac{M_W}{M_Z \cos\theta_w} = 1$
  (to lowest order)
- couplings of fermions to gauge bosons

$$-ig\tfrac{1}{2}(c_V\gamma^\mu - c_A\gamma^\mu\gamma^5)$$



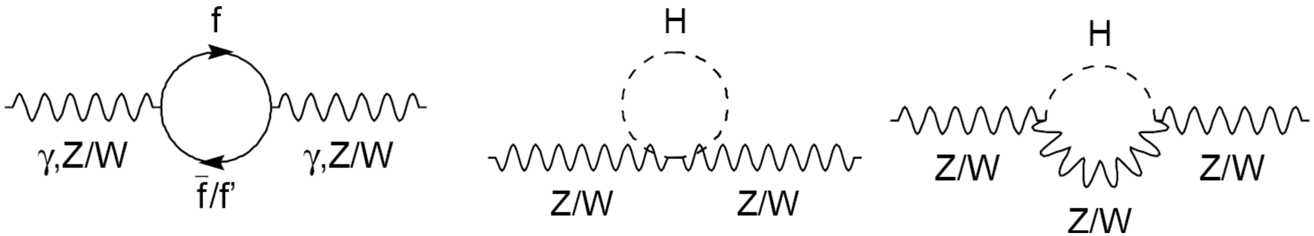


- couplings to Z- and W-bosons involve θ_w:

$$c_A^{f,Z} = T_3 = \pm\tfrac{1}{2}, 0$$
$$c_V^{f,Z} = T_3 - 2Q\sin^2\theta_w$$

$$g_z = \frac{e}{\sin\theta_w \cos\theta_w} \qquad g_w = \sqrt{2}\frac{e}{\sin\theta_w}$$

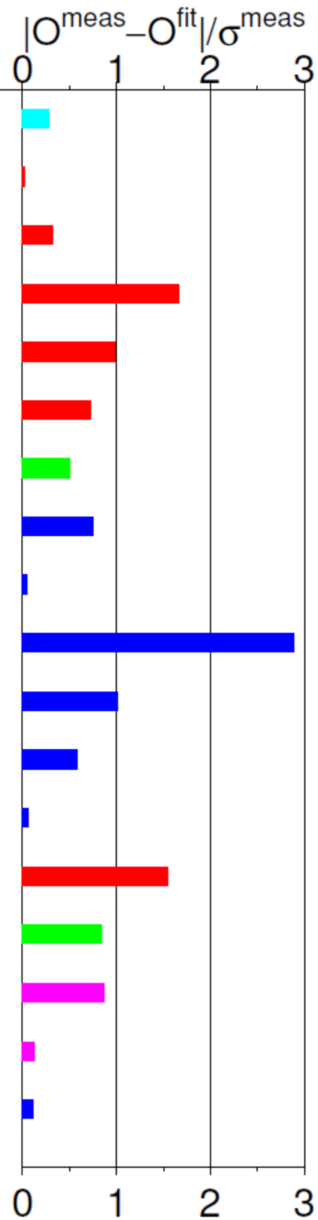
- consequence: measurement of masses and couplings test Standard Model relations
  → M_Z, M_W, $\sin^2\theta_w$ are precisely measured → radiative corrections need to be included



~ m_t^2
~ log (M_H/M_W)

Test of the Electroweak Standard Model

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

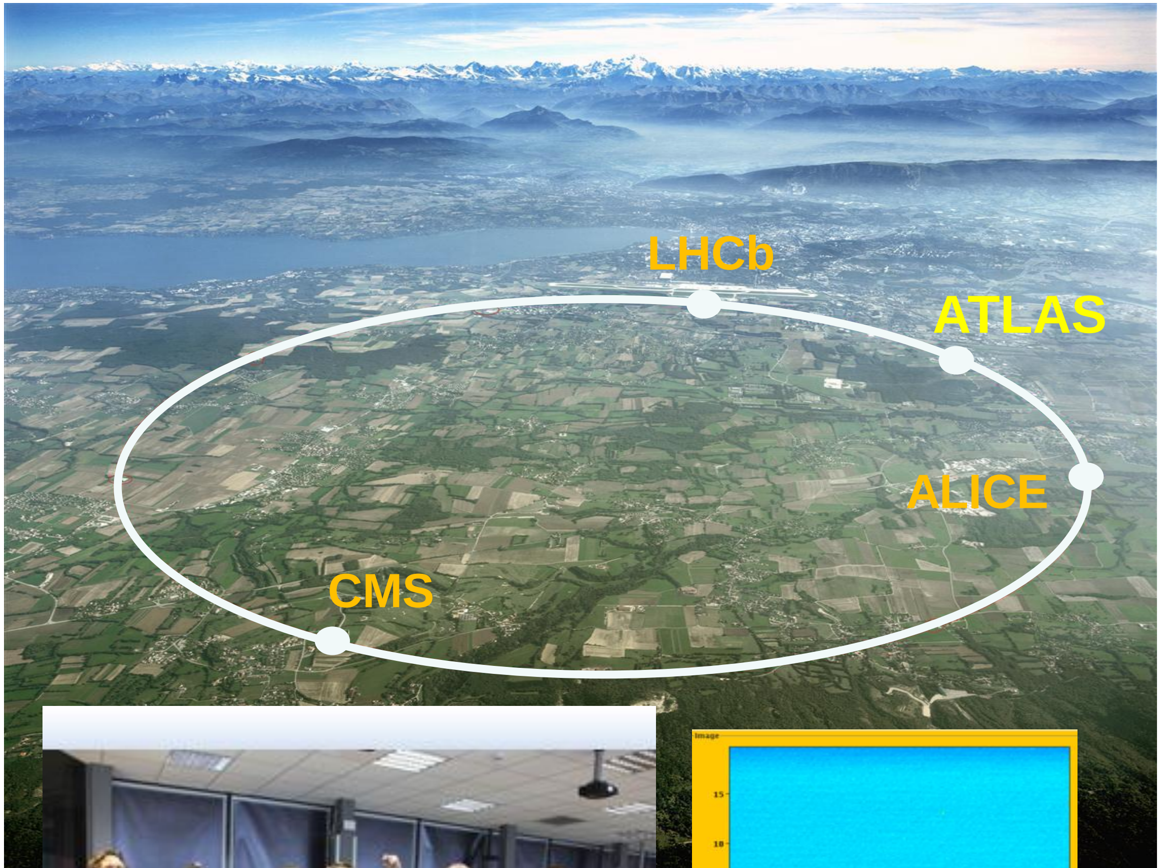


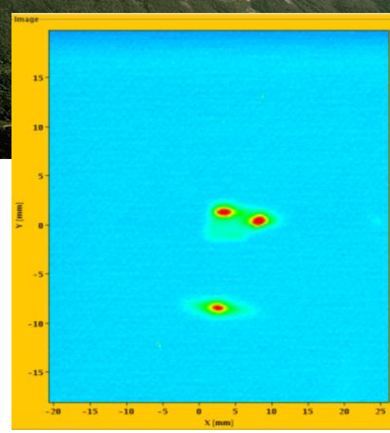
August 2009

- bars show difference between measurement and theory
- relatively good agreement of measurements with predictions
- but room for new physics (SUSY, ...)

Physics at the LHC

- the proton-proton collider LHC and the 4 experiments:





- number of physics events:

$$N = L \cdot \sigma$$

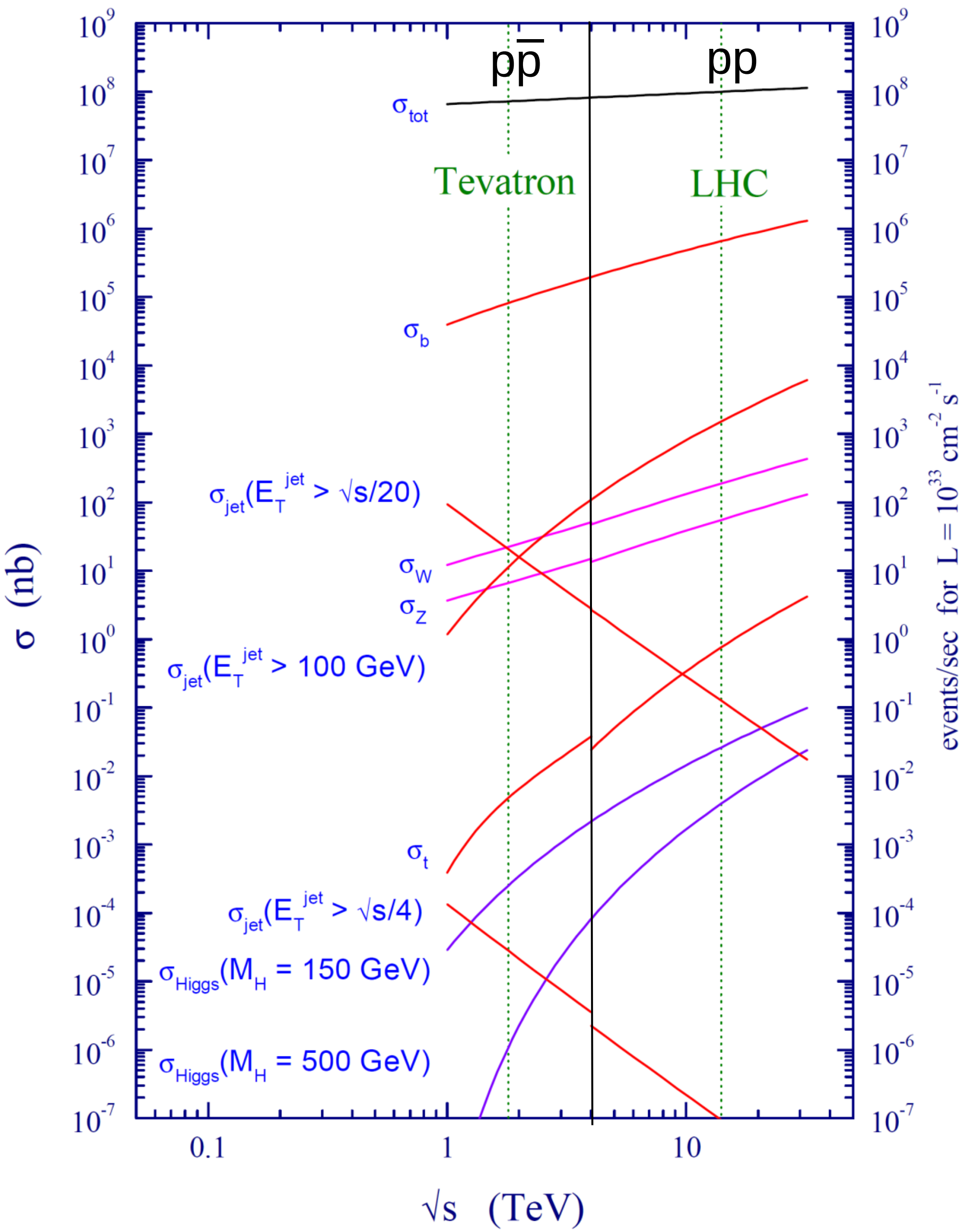
L = luminosity
σ = cross-section

- LHC luminosities and centre-of-mass energies

- 2009:
  - 900 GeV injection energy
  - 9 μb^{-1}
- 2010/2011
  - 7 TeV max. energy
  - up to 1 fb^{-1}
- later
  - 13-14 TeV ultimate energy
  - 50-70 fb^{-1} until 2016
  - 3000 fb^{-1} until 2030

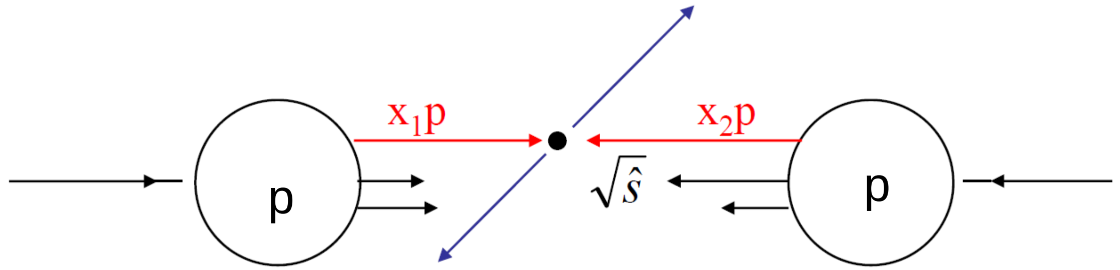
Overview of Production Rates at LHC

- typical production cross-sections at Tevatron and LHC:

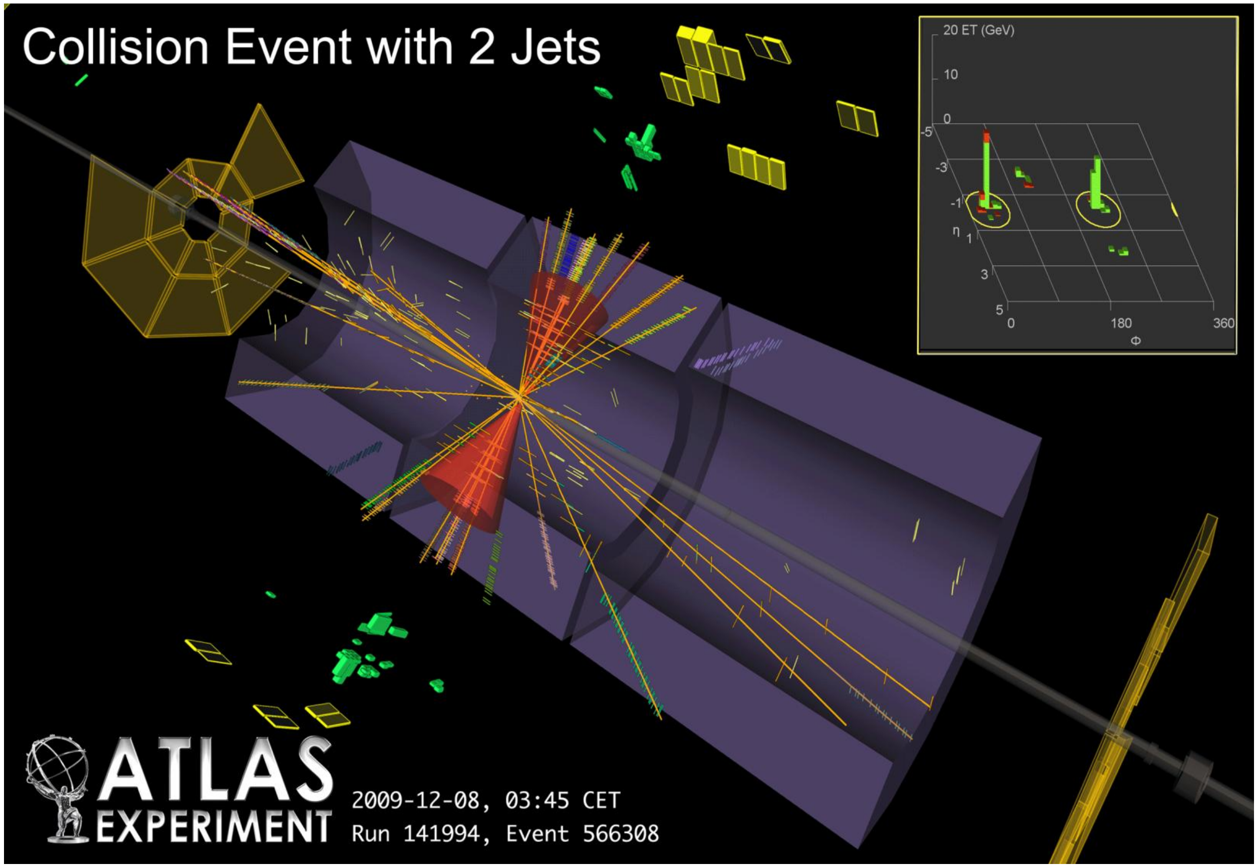


- inelastic pp scattering dominates → "minimum bias"
- QCD processes have large cross-sections → 2-jet events, 3-jet events, ...
- many events with W and Z bosons
- top-pair production
- new particles: Higgs, SUSY, ..
- 13 orders of magnitude

Properties of pp-Collision Events



- a 2-jet event at 900 GeV in ATLAS:



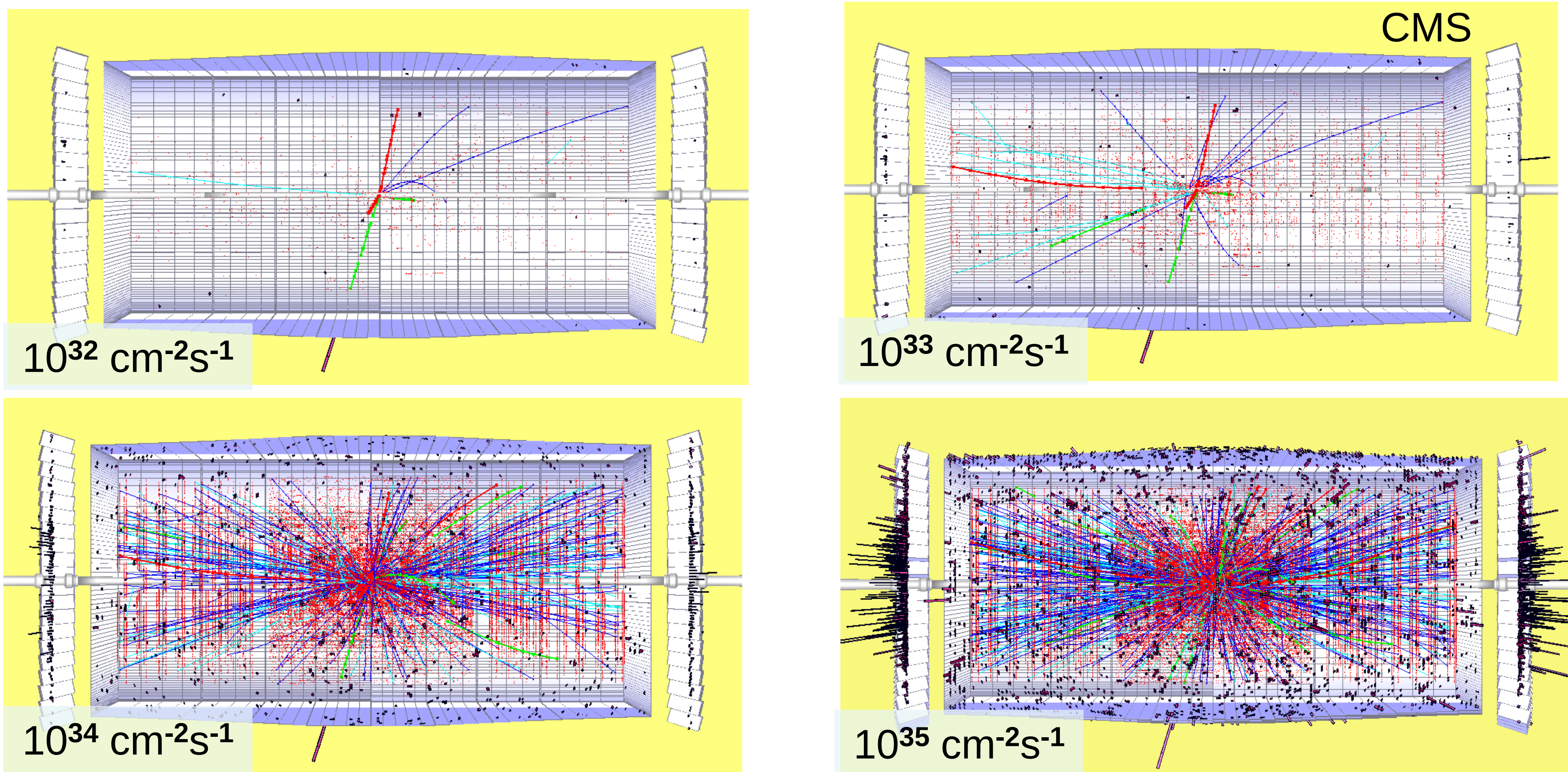
- hard scattering of partons inside proton:
- gluons and quarks carry momentum fractions x_1, x_2
- in the event picture: qq→qq, gg→gg , gq→gq
- QCD events are more frequent than EW events

- many hadrons produced from proton remnants: "underlying event"
- the typical LHC event has no hard scattering: "minimum bias" → pile-up

- strategy: identify the interesting physics with high-p_T leptons, photons and jets or missing transverse energy E_T^{miss}

Effect of Event Pile-Up

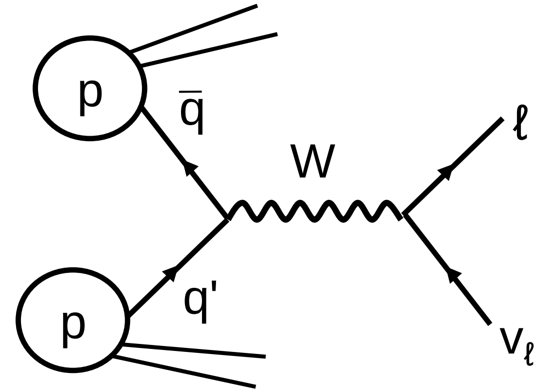
- number of simultaneous pp reactions increase with luminosity:

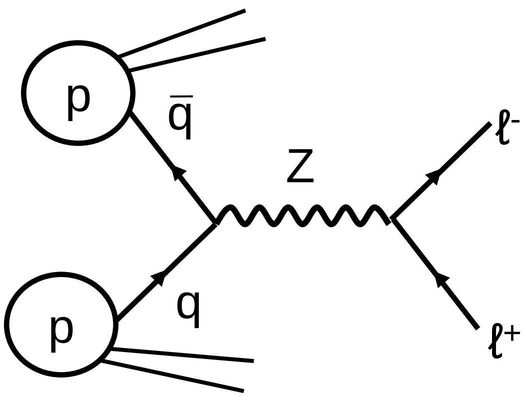


- at nominal LHC luminosity of 10^{34} $cm^{-2}s^{-1}$ about 25 events per bunch crossing

Electroweak Physics at the LHC

- W boson production:
  - cross-section measurement in W→eν, μν, τν channels (hadronic final states are difficult to select at LHC)
  - measurement of the W boson mass
  - background to search channels (W+jets)





- Z boson production:
  - cross-section measurement in Z→ee,μμ,τ τ channels
  - calibration of the detector
  - $\sin^2\theta_W$ from forw.-backw. asymmetry in Z→ee events
  - measurement of systematic uncertainties for other processes, background to search channels (Z+jets)

Process	σ_{LO} @ 7 TeV [pb]	σ_{LO} @ 14 TeV [pb]	Evts (7 TeV) in 200 pb^{-1}	Ratio 7 TeV/14 TeV
QCD pt>100 GeV	3.2 E+05	1.4 E+06	64 M	0.2
Z inclusive	2.4 E+04	5.7 E+04	5 M (3% Z→ℓℓ)	0.4
W inclusive	9.5 E+04	2.1 E+05	19 M (11% W→ℓν)	0.5
top pairs	8.4 E+01	4.7 E+02	17000	0.2
H (m=150 GeV)	4.0	16.0	800	0.3

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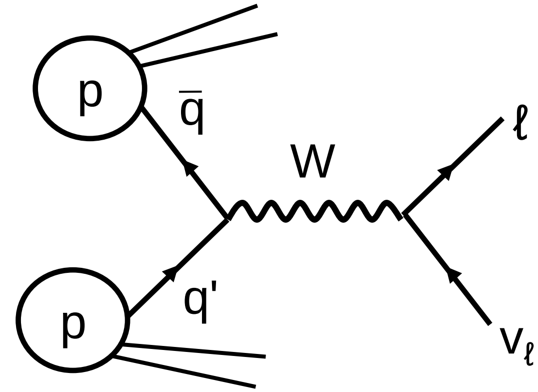

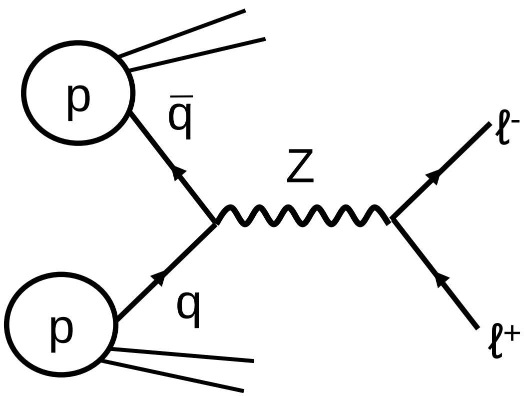

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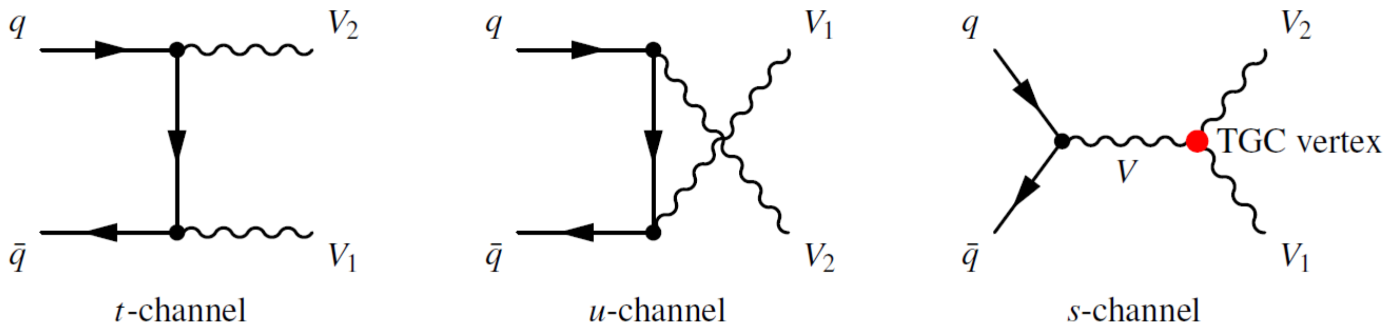
Di-boson Production at the LHC

- measurement of W-pairs, Z-pairs, WZ, Wγ, and Zγ final states



- determination of production cross-sections
- measurement of the couplings between gauge bosons → prediction of the SM
  - triple-gauge boson vertex

- examples of cross-sections:

Diboson mode	Conditions	$\sqrt{s} = 14$ TeV $\sigma\,[pb]$
W^+W^- [15]	W-boson width included	111.6
$W^\pm Z$ [15]	Z and W on mass shell	47.8
ZZ [15]	Z's on mass shell	14.8
$W^\pm\gamma$ [16]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell,\gamma) > 0.7$	451
$Z\gamma$ [17]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell,\gamma) > 0.7$	219

factor 100-1000 smaller than W, Z production

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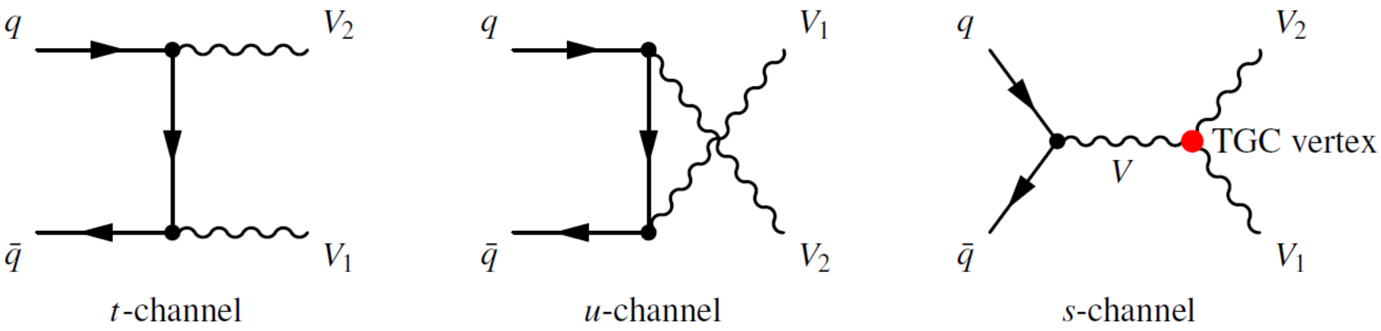

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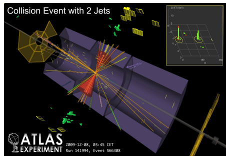
ATLAS and CMS Detectors



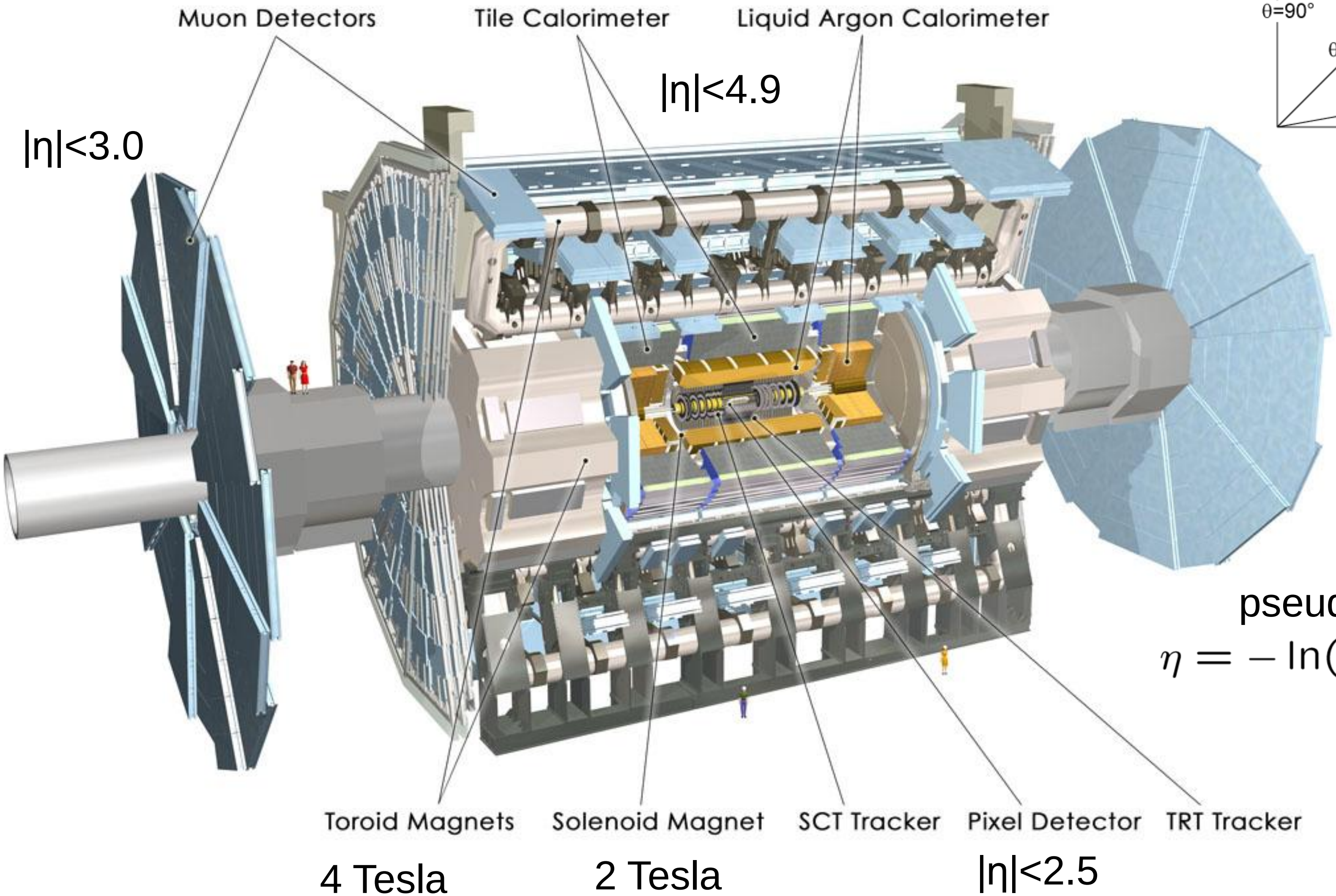
- challenges for LHC detectors:
  - high collision rate: 25 ns proton bunch-crossing
  - up to 25 minimum-bias events/crossing → pile-up
  - radiation hardness → detectors and electronics tolerate 10^{15} particles/cm^2
  - high granularity → isolate interesting leptons/photons/jets from pile-up
  - very good angular coverage → measure missing energy (neutrinos, SUSY)
  - fast trigger with high background suppression rate (~1 accepted event/10^6)
- performance goals:
  - get high efficiency for particle detection
  - suppress background from QCD jets

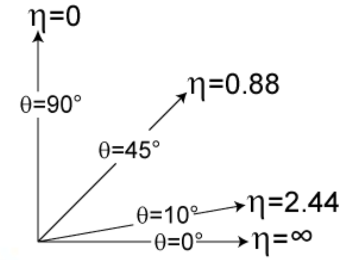
K. Desch

Object	Efficiency	BG suppr.	Motivation
electrons	>70%	100000	Z,W,top,H→4ℓ,...
photons	80%	1000	H→γγ
muons	>97% for p_T>1GeV		H→4ℓ,..., Z, W
tau leptons	50%	100	H/A→ττ, SUSY,...
b-jets	50%	100	top, H→bb,SUSY,...

The ATLAS Detector

- dimensions: 46m x 22m x 22m
- weight: 7000 t

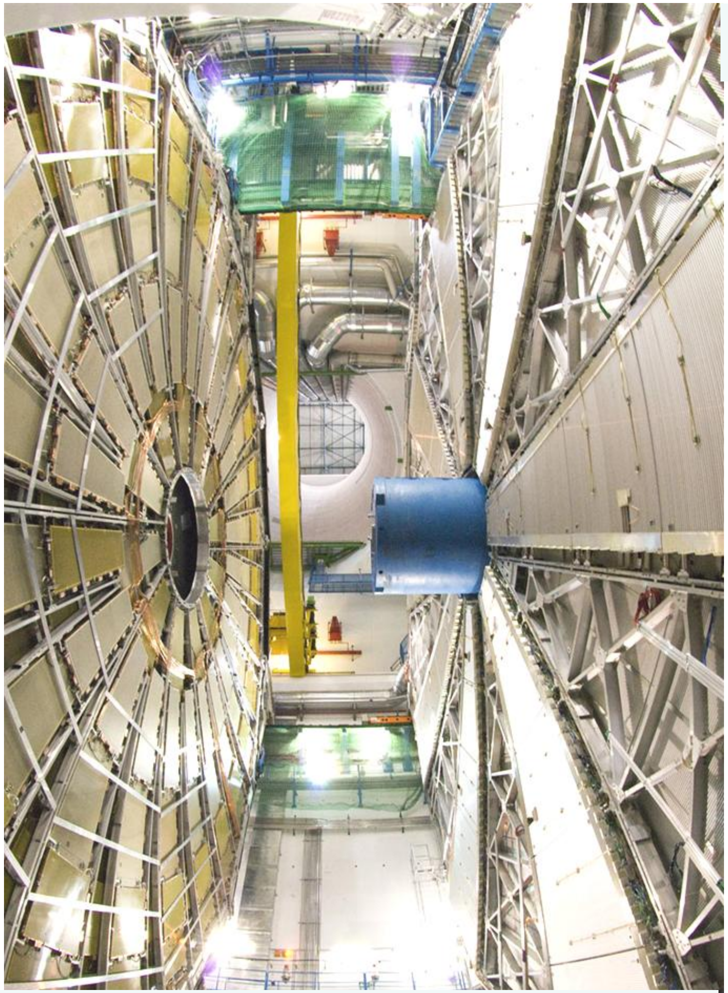




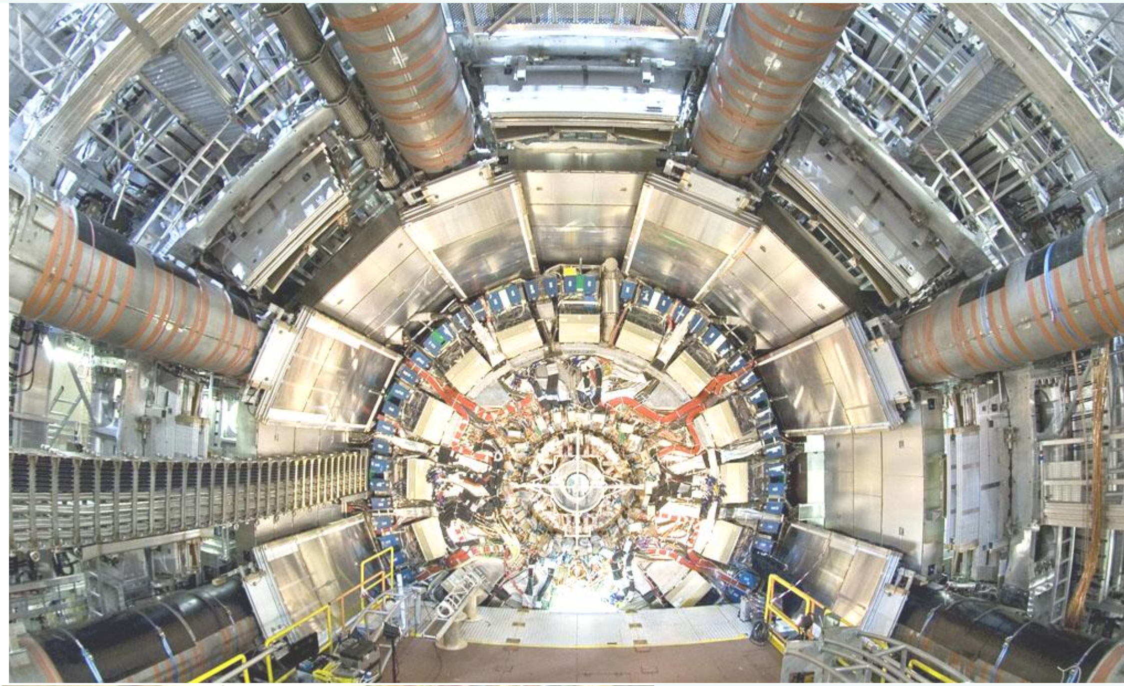
pseudo-rapidity

$$\eta = -\ln(\tan(\theta/2))$$

Components of the ATLAS Detectors



toroid magnet - LAr/Tile calorimeter - silicon tracker

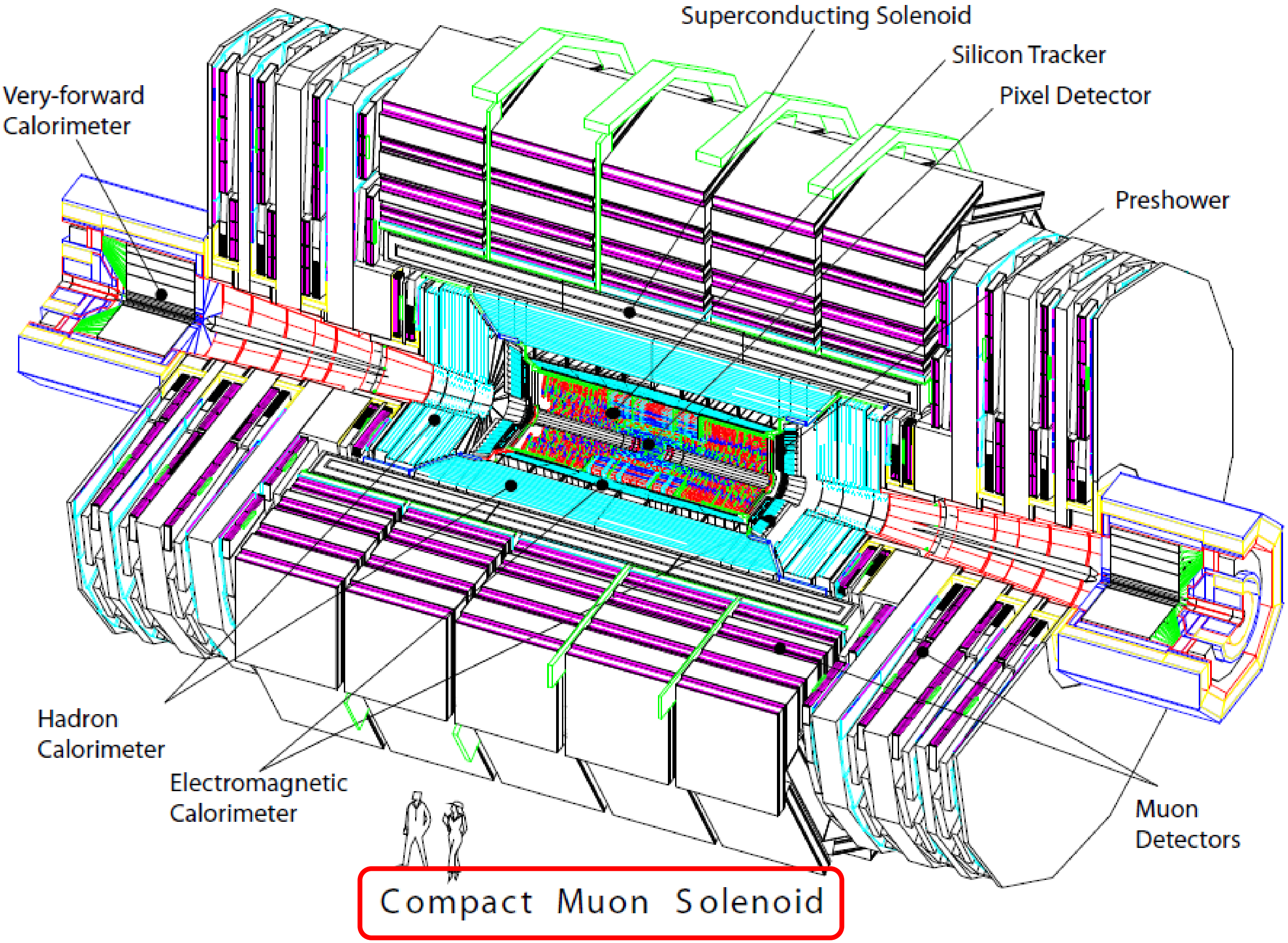


pixel detector:
80 M channels
pixel size 50x400 μm^2

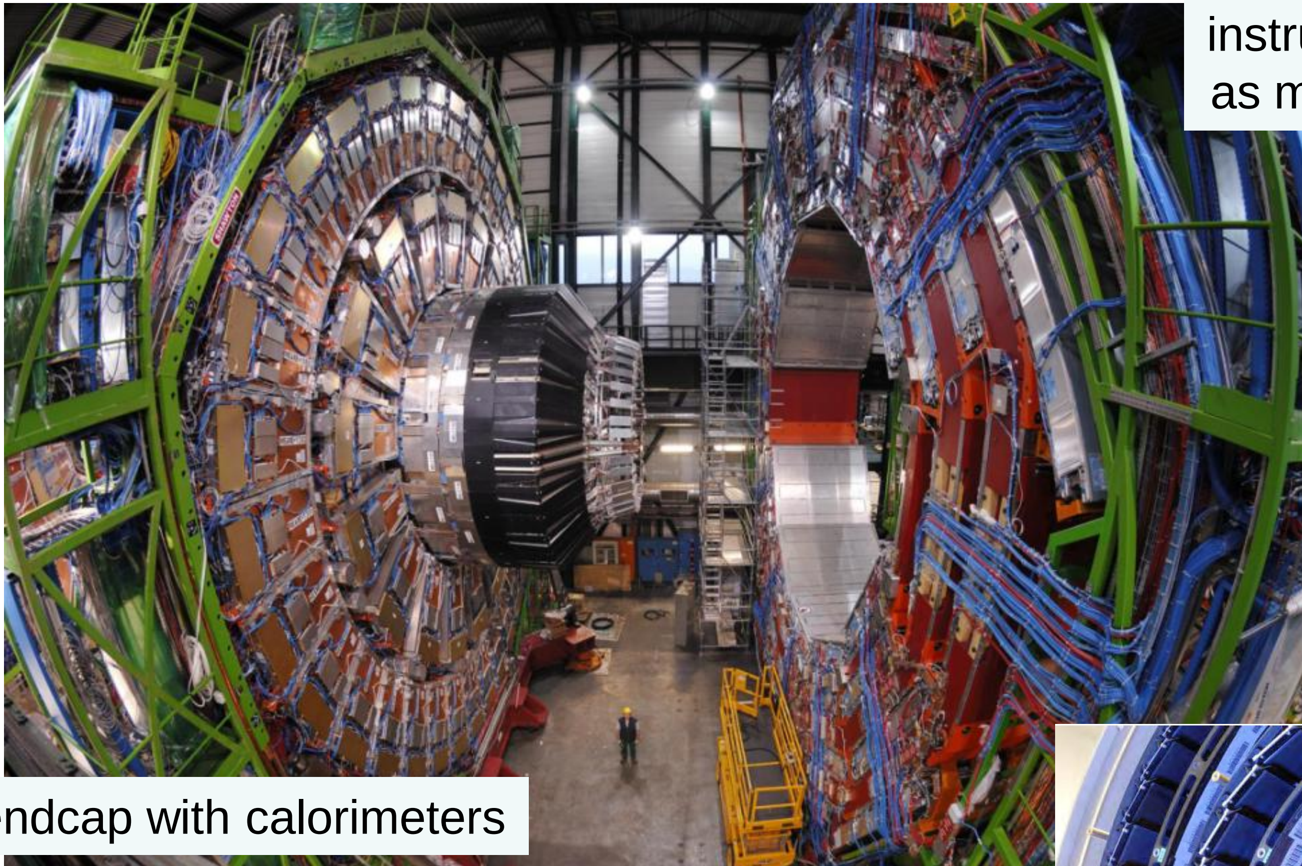
muon spectrometer:
1000 chambers with monitored drift tubes
500 trigger RPC chambers

The CMS Detector

- dimensions: 22m x 15m x 15m
- weight: 12500 t

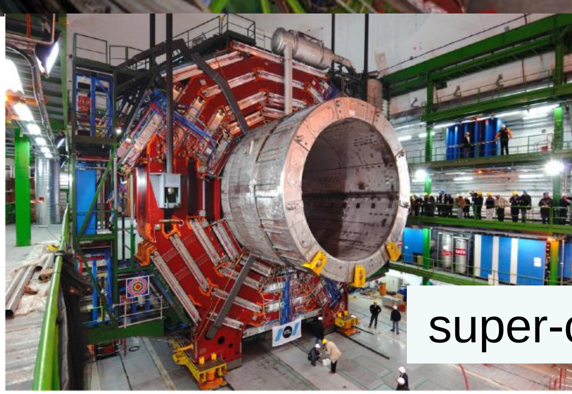


Detector Components of CMS

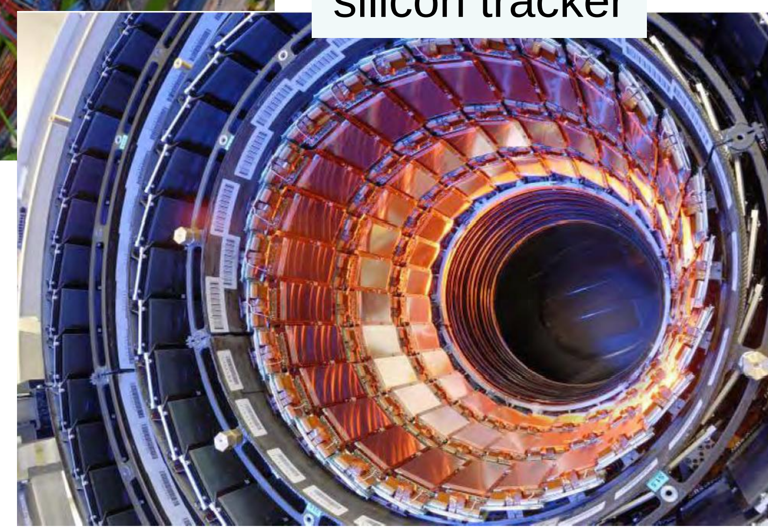


instrumented iron yoke as muon spectrometer

endcap with calorimeters

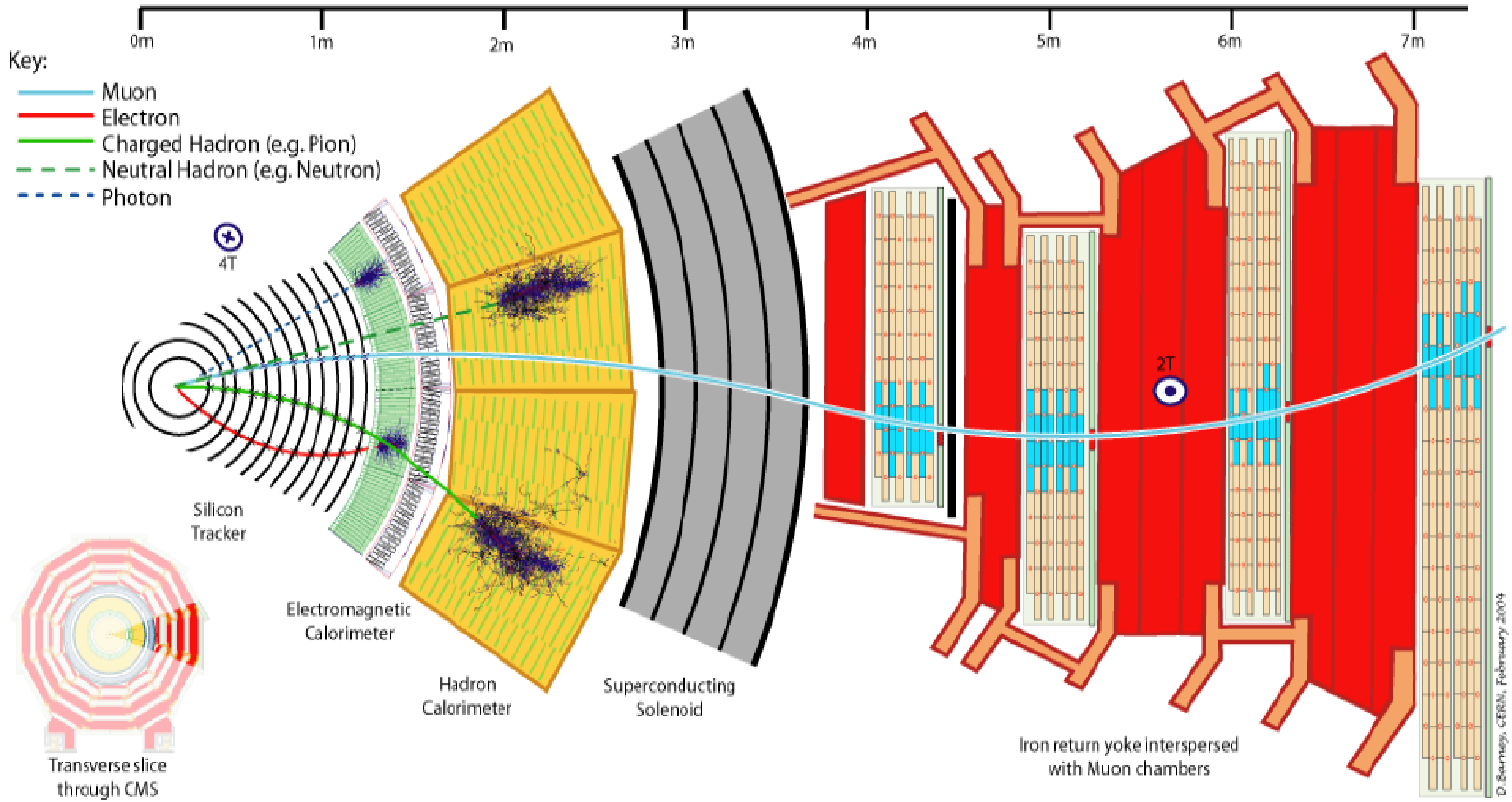


super-conducting magnet



silicon tracker

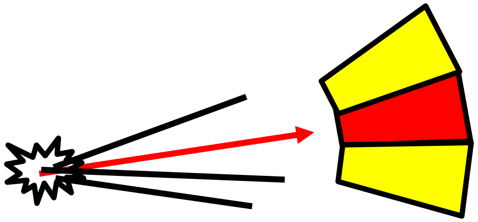
Particle Identification



Charged Particles | Electrons Photons | Hadrons | 3.8 Tesla Solenoid | Iron yoke (return flux) Muons

Particle Identification

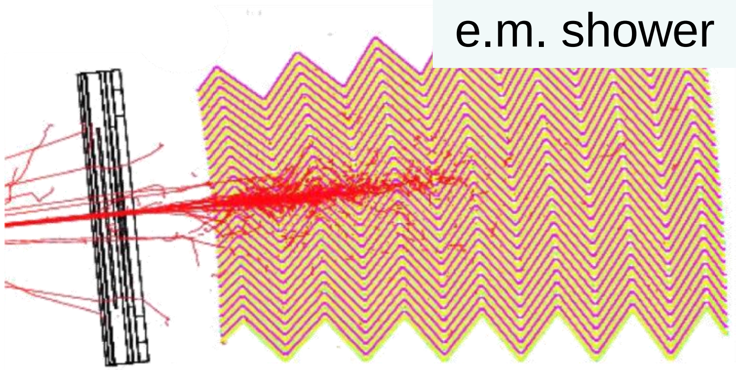
- e.g. electron:
  - energy and shower shape measured in calorimeter
  - track matched to energy cluster using angles

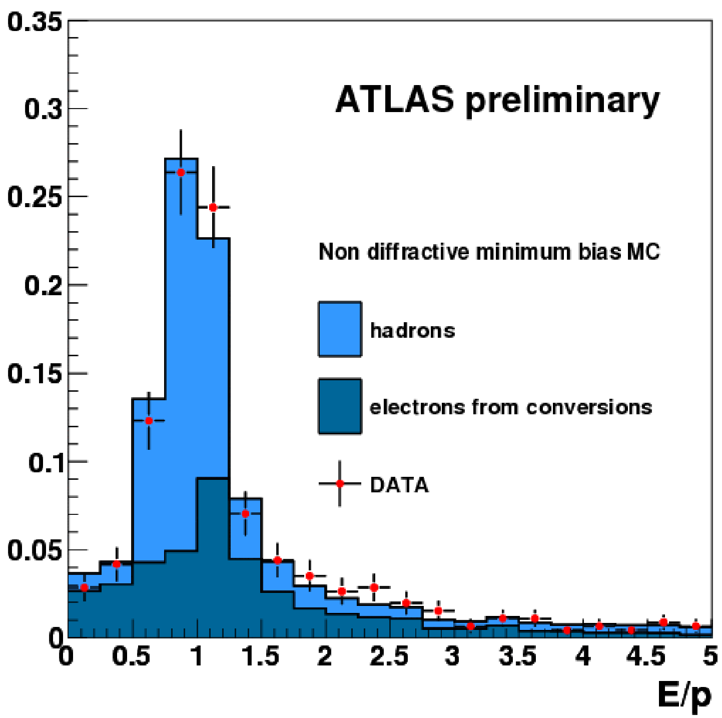


$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

  - compare calorimetric energy and momentum measurement in tracker: E/p ≈ 1
  - no leakage of energy into hadronic calorimeter
- combined performance is important

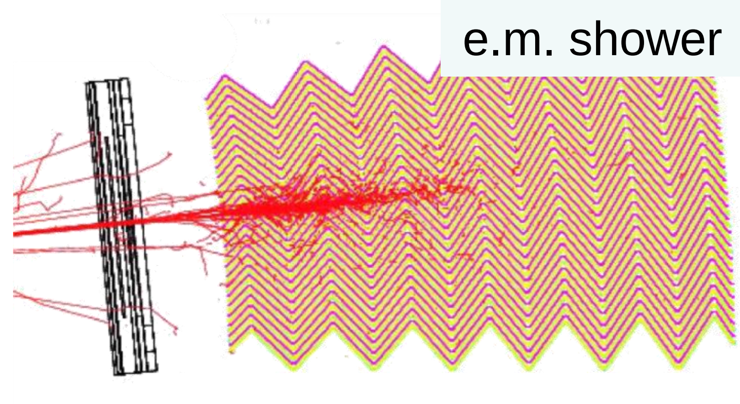
e.m. shower





2009 data

Particle Identification



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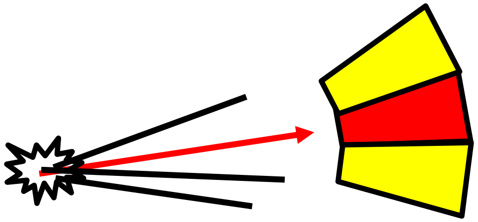

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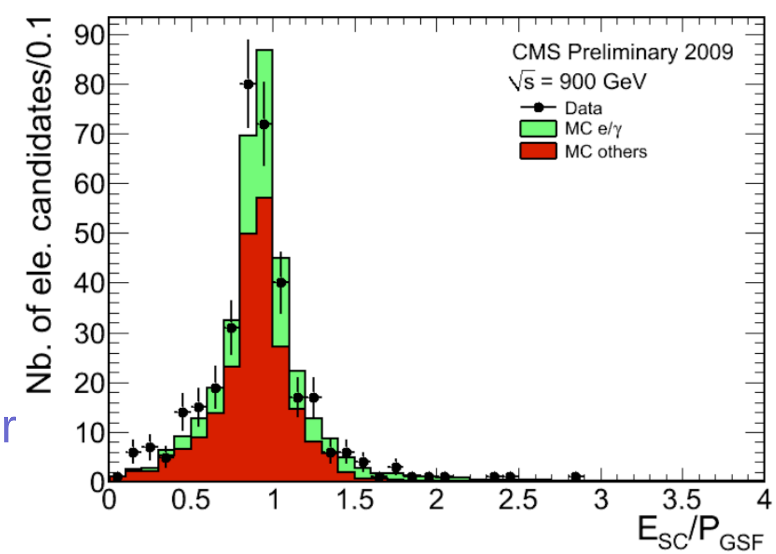

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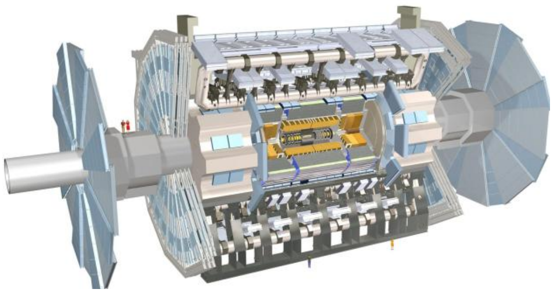
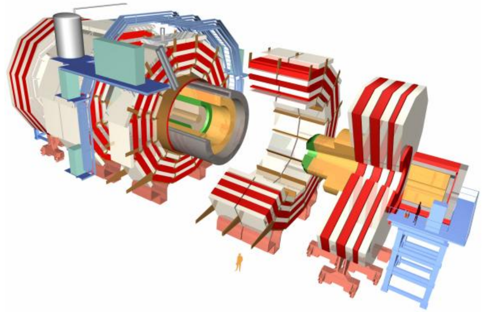
2009 data

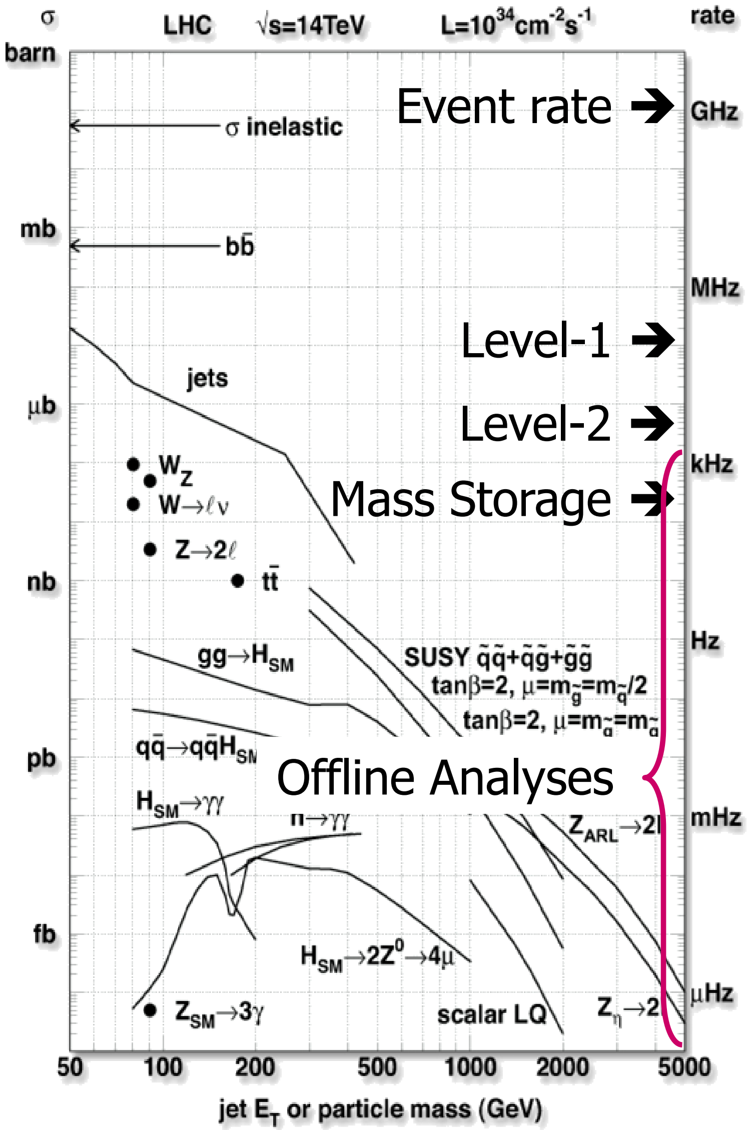
Performance Comparison





	ATLAS		CMS	
B-Field	2 T (solenoid)	4 T (toroid)	3.8 T (solenoid)	
Tracking	Si (strips+pixel) + Gas (TRT)	$\sigma(p_T)/p_T$ at 100 GeV: 3.8 %	Si (strips+pixel)	$\sigma(p_T)/p_T$ at 100 GeV: 1.5 %
ECAL	Pb - LAr (high granularity)	$\sigma(E)/E = 9\%/\sqrt{E} + 0.7\%$	$PbWO_4$ crystals (high E resolution)	$\sigma(E)/E = 3\%/\sqrt{E} + 0.25\%$
HCAL	Fe – scintillator (10 λ)	$\sigma(E)/E$ (ECAL+HCAL)= $70\%/\sqrt{E} + 3.3\%$	Brass – scintillator (7 λ)	$\sigma(E)/E$ (ECAL+HCAL)= $70\%/\sqrt{E} + 8\%$
Muon Spectrometer	ion. chambers, air-core magnet	$\sigma(p_T)/p_T$ at 1TeV: 7 %	ion. chambers, instrumented iron	$\sigma(p_T)/p_T$ at 1TeV: 5 %

- D. Froidevaux, P. Sphicas, General-purpose Detectors for the Large Hadron Collider, Annu. Rev. Nucl. Part. Sci. 2006. 56:375–440

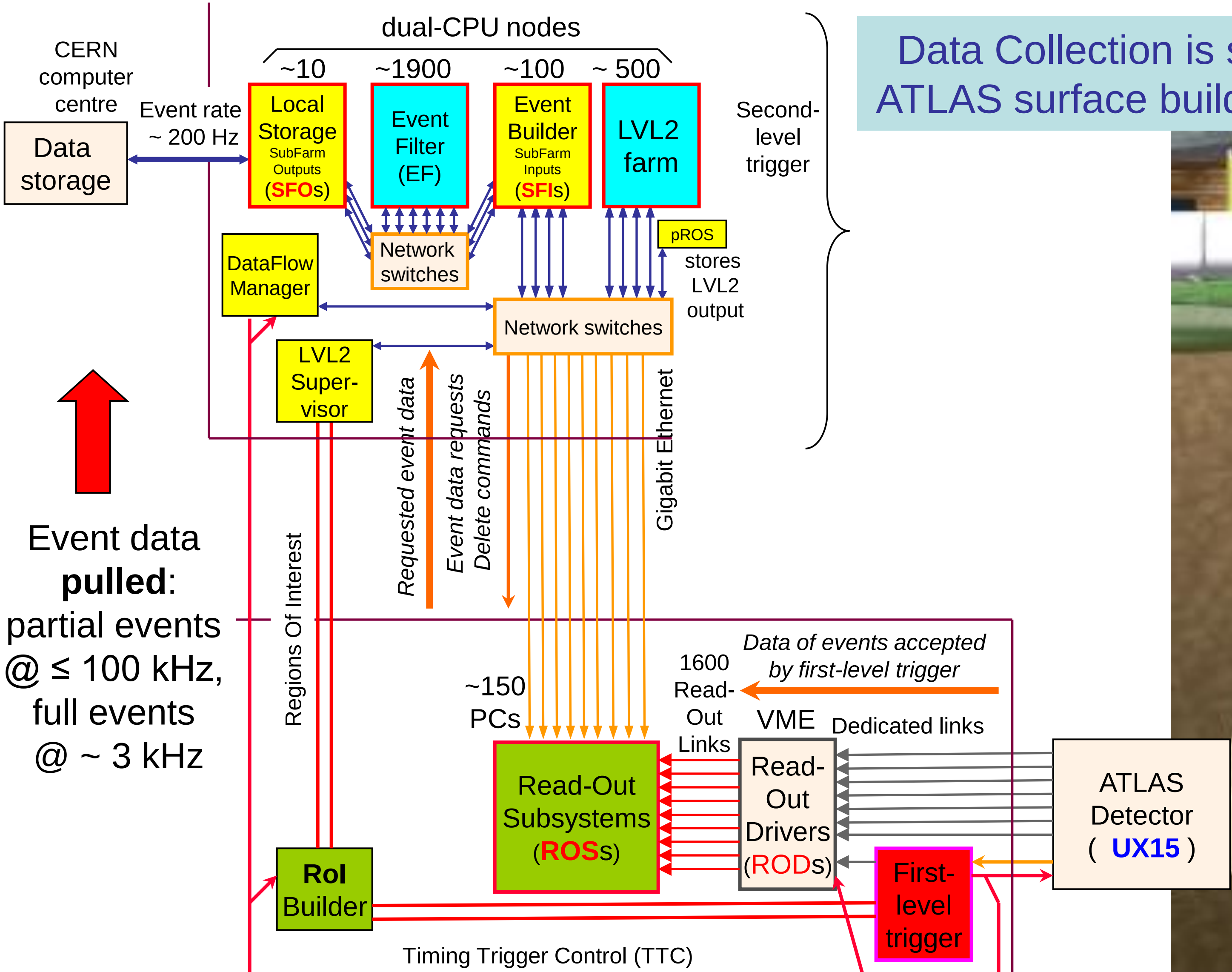


•	Bunch crossing	40 MHz
•	σ total	70 mb
•	Event rate	~1 GHz
•	Number of events/BC	~25
•	Number of particles/event	~1500
•	Event size	~1.5 MB
•	Mass storage rate	~200 Hz

- Need to have trigger of high performance
  - 6 orders of rate reduction
  - complex events and 140 M channels

- Level-1: hardware based at 40 MHz
- Level-2: software based at 100 kHz } PC farms
- Level-3: event filter at 3 kHz } PC farms
- Storage at 200 Hz

ATLAS Trigger & Data Acquisition at Point-1



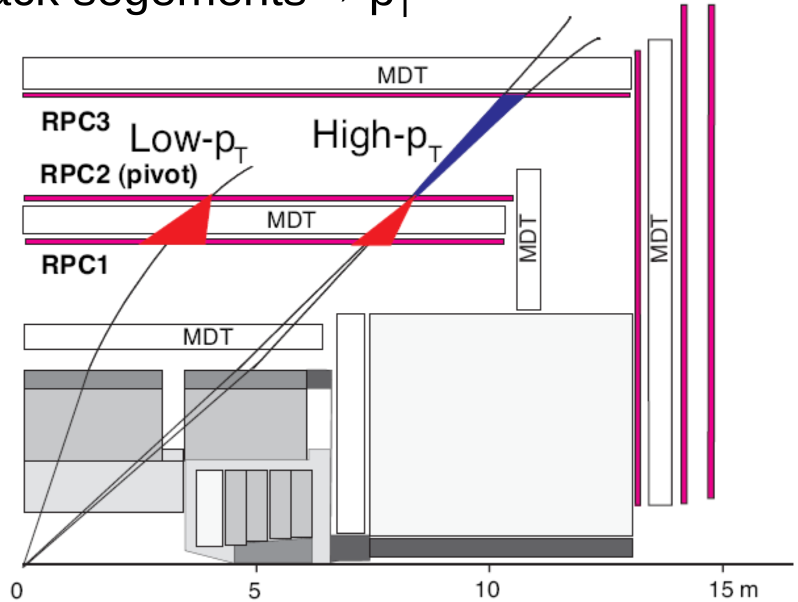
Event data **pulled**: partial events @ ≤ 100 kHz, full events @ ~ 3 kHz

Data Collection is situated in ATLAS surface building (SDX1)

Event data **pushed** @ ≤ 100 kHz, 1600 fragments of ~ 1 kByte each

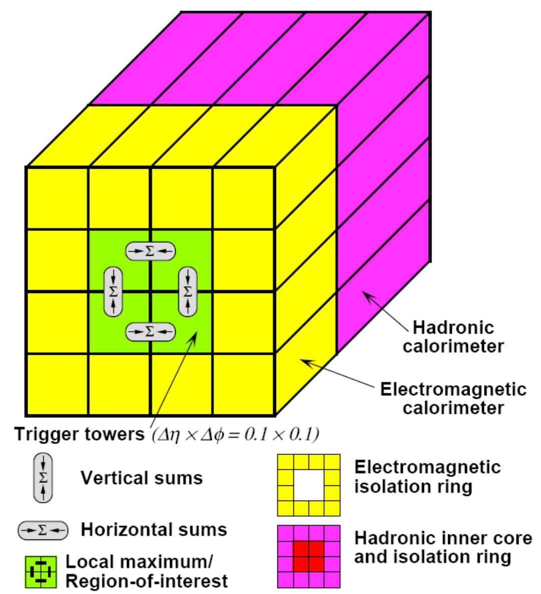
Muon and Calorimeter Level-1 Triggers

- muon trigger detectors: RPC = resistive plate chamber
- pre-defined track segements→ p_T



muon trigger receiver

- calorimeter: "trigger-tower"
- energy sums in pre-defined (η,φ) regions



calo trigger receiver

ATLAS Trigger Concept

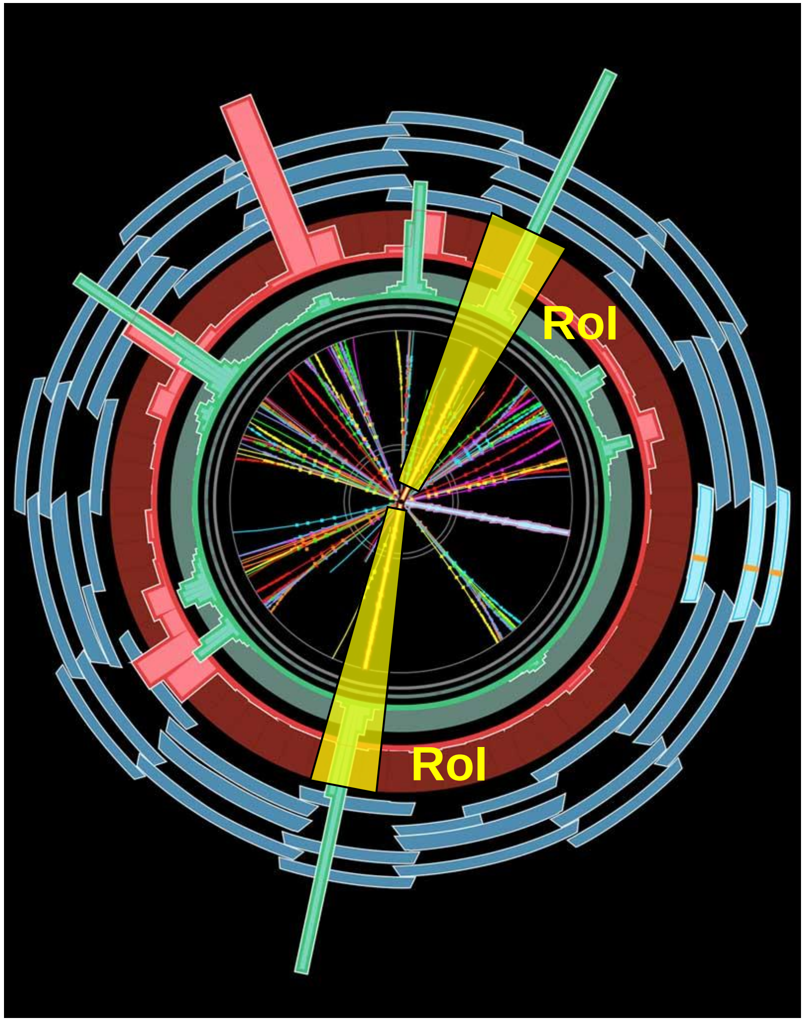
- early event rejection in each stage

- L1 muon trigger:
  low/high p_T signatures
- L1 calo trigger:
  energy sums in calorimeter towers

- L1 Region-of-Interest $\rightarrow$ L2

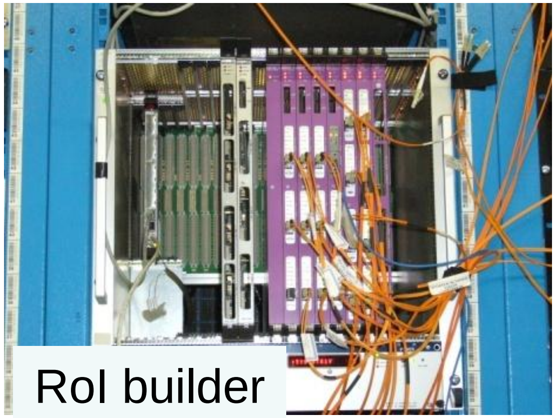
- high level trigger (software):
  - L2:
    - local reconstruction within RoI
    - tracking information available
  - event filter (EF):
    - access to fully reconstructed event

- CMS trigger is conceptually similar



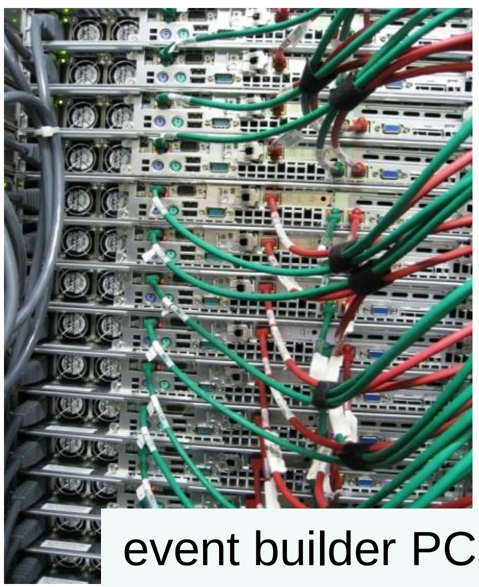
High Level Trigger

- trigger hardware:

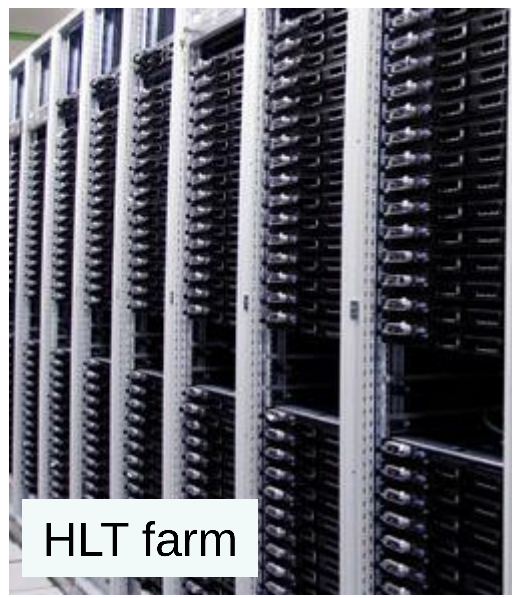


RoI builder

read-out buffer PCs



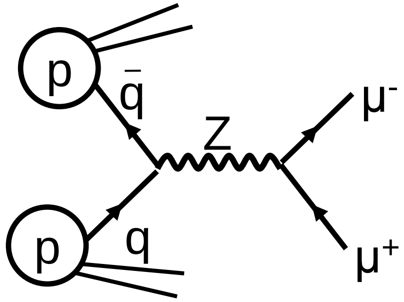
event builder PCs

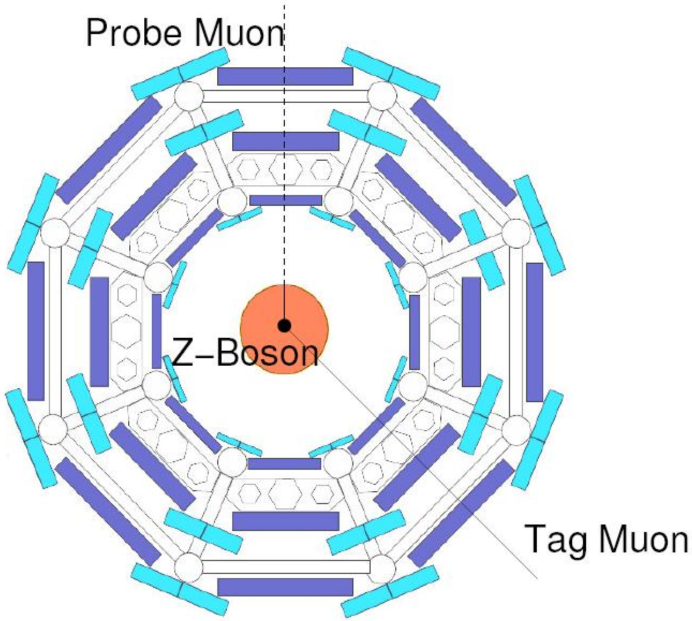


HLT farm

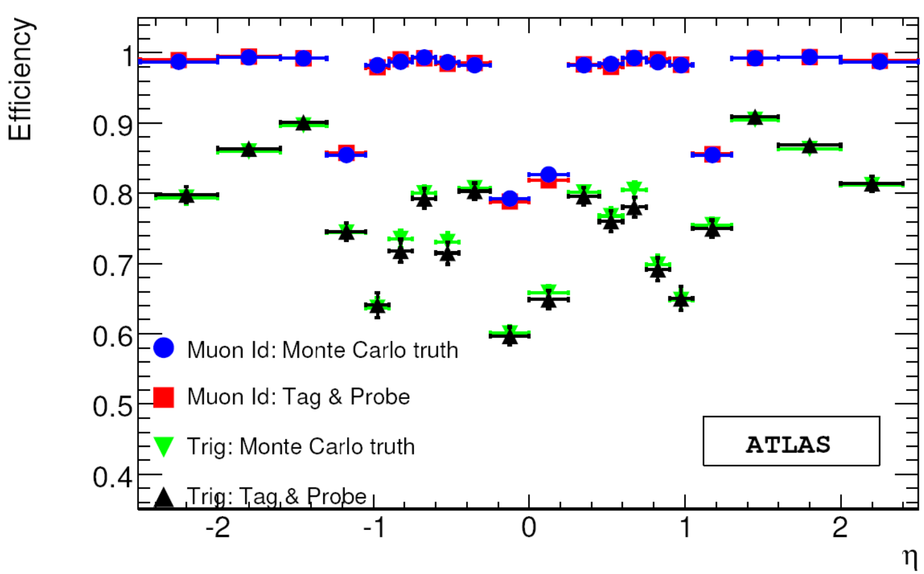
farm output

Detector Performance with Z Bosons



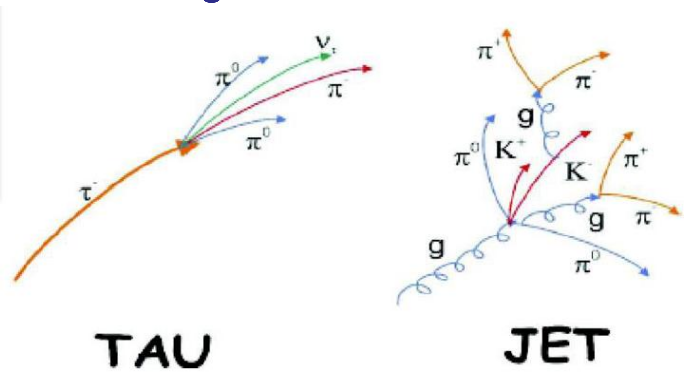


- commonly applied method to measure performance in data: → tag & probe
- example: measure muon identification efficiency in Z→μμ events
  - identify triggered and well measured muon: → tag
  - use Z decay kinematics to find the 2nd reconstructed muon: → probe
  - check if 2nd muon passed selection → muon identification efficiency
  - similar for muon trigger and muon reconstruction efficiency
- many more examples:
  - Z→ ee, J/psi → ee, ...

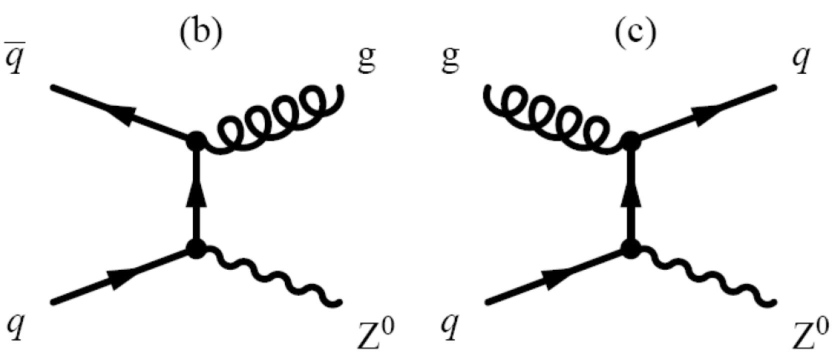


Detector Performance with Z Bosons

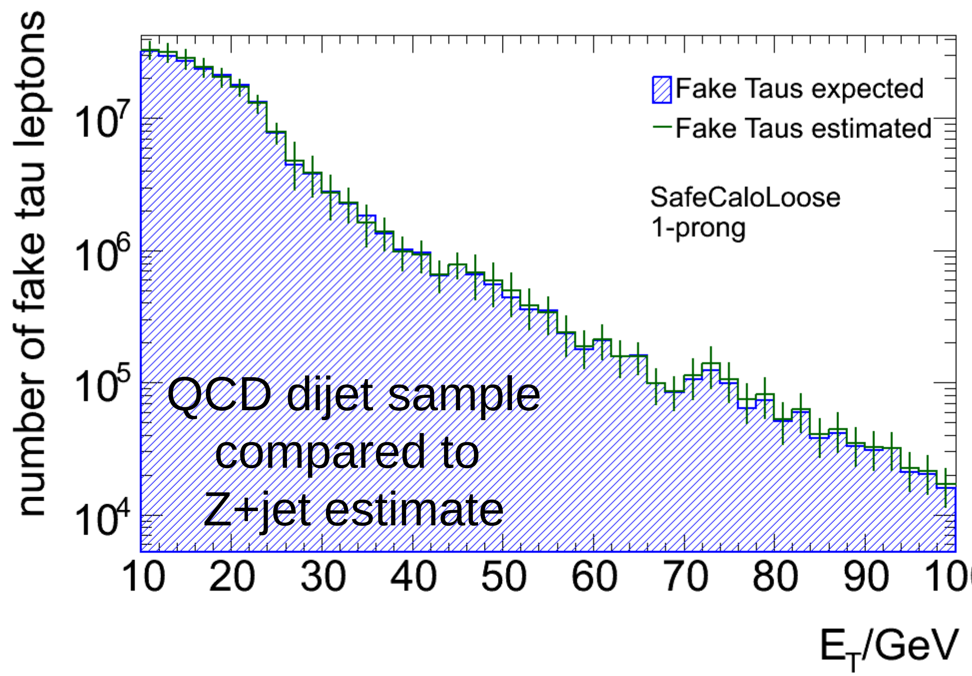
- identification of hadronic tau leptons
  - narrow hadronic jet
  - 1 or 3 particle tracks
- tau may look like hadronic jets from quarks and gluons



- Z+jet → ℓℓ+jet events help to estimate how often a jet is misidentified as a tau



τ^- decay mode	BR %		
$e^-\bar{\nu}_e\bar{\nu}_\tau$	17.85	leptonic	
$\mu^-\bar{\nu}_\mu\bar{\nu}_\tau$	17.36		
$\pi^-\bar{\nu}_\tau$	10.91	hadronic 1-prong	72%
$\pi^-\pi^0\bar{\nu}_\tau$	25.52		
$\pi^-2\pi^0\bar{\nu}_\tau$	9.27		
$\pi^-3\pi^0\bar{\nu}_\tau$	1.04		
$K^-\bar{\nu}_\tau$ + Neutrals	1.57		
$\pi^-\pi^+\pi^-\bar{\nu}_\tau$	9.32	hadronic 3-prong	23%
$\pi^-\pi^+\pi^-\pi^0\bar{\nu}_\tau$	4.61		
$K^-\pi^+\pi^-\bar{\nu}_\tau$ + Neutrals	0.48		



F.Friedrich

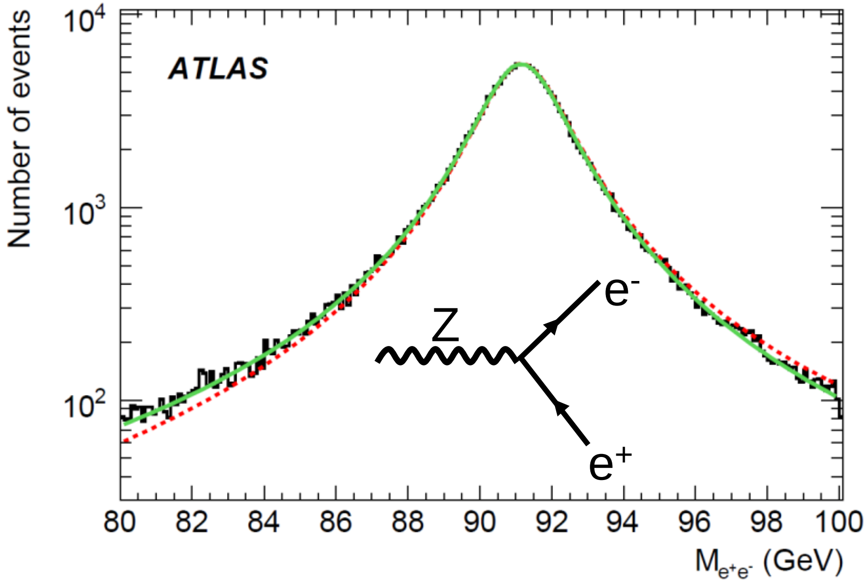
Detector Calibration with Z Bosons

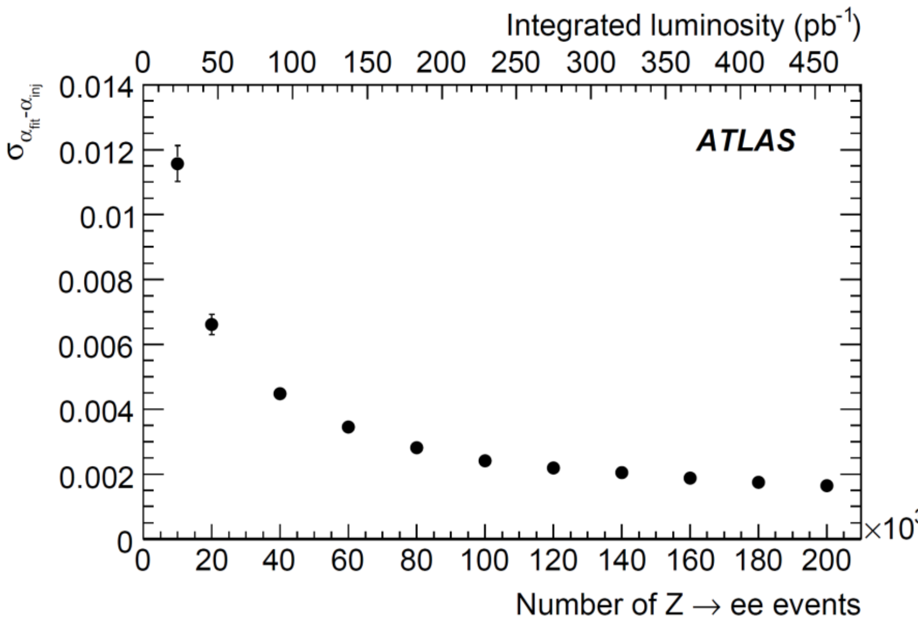
- reconstruct pairs of electrons and positrons in the detector
- measure the invariant mass of electron and positron M_{ee}
- the mass spectrum should peak at the Z boson mass M_Z
- line-shape modelled with Breit-Wigner distribution:

$$\mathrm{BW}(M) \sim \frac{M^2}{(M^2 - M_Z^2)^2 + \Gamma_Z^2 M^4 / M_Z^2}$$

- use the Z mass constraint from LEP M_Z=91.1875 GeV to calibrate the energy scale of the calorimeter

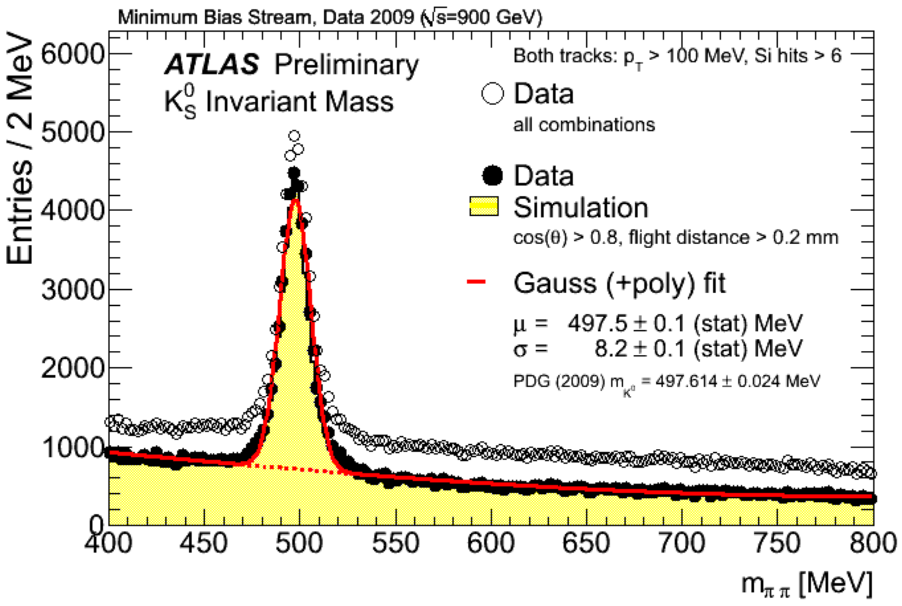
- e.g. constant term of the energy resolution: 140k Z→ee events needed to reach 0.2%





Detector Performance with First Physics Data

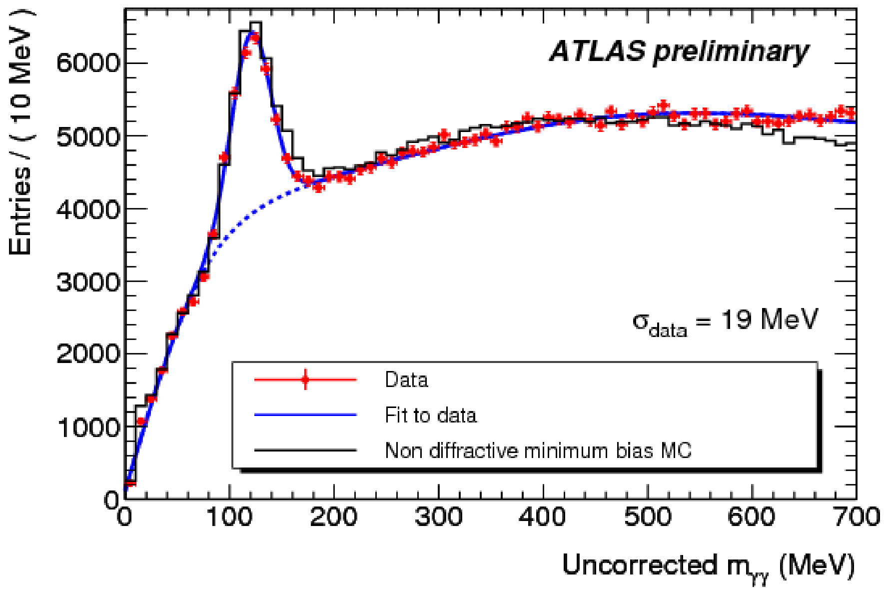
- tracking performance using K_S mesons:



- calorimeter performance with $\pi^0 \to \gamma\gamma$

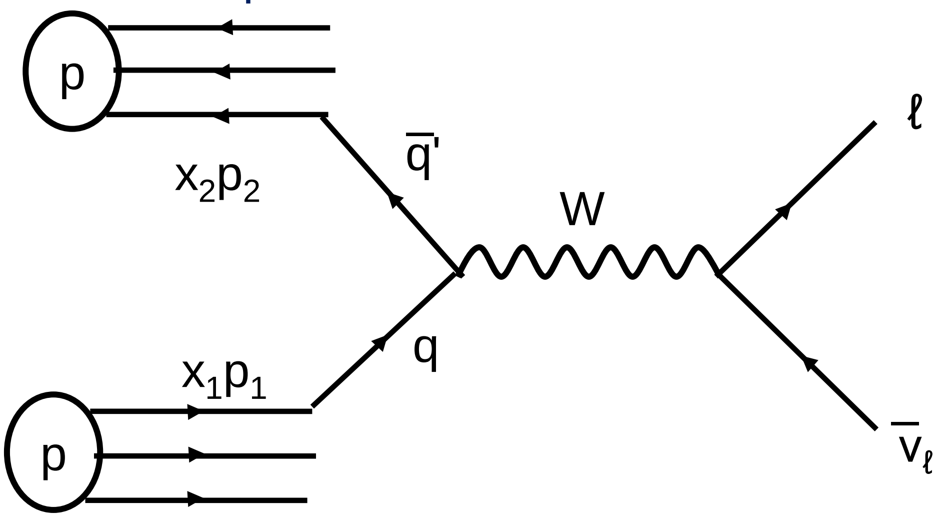
  peak value agrees with pion mass to 1% (1.5 MeV)

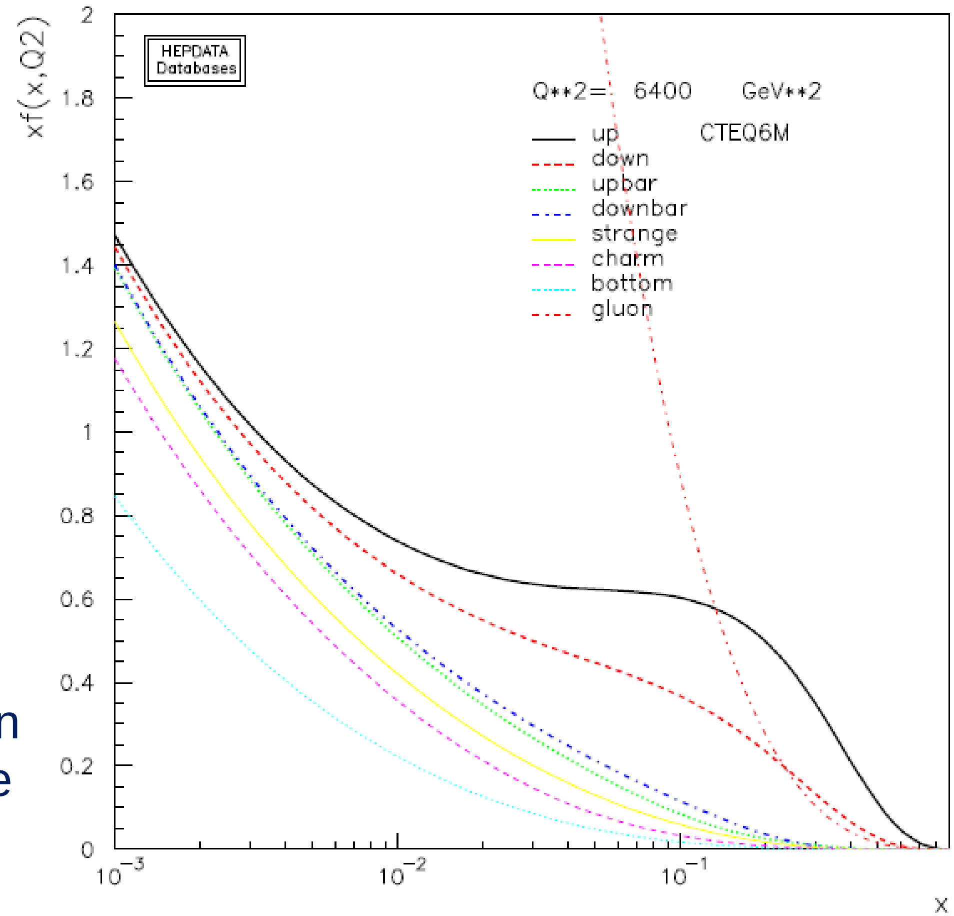
  resolution is 19 MeV ~ 2%



A more detailed example: W production

- W boson production to lowest order:





- quarks carry momentum fractions x_1, x_2
- the probability to find a parton i with a given energy fraction x in a proton is given by the parton distribution function $f_i(x,Q^2)$

- it is easy to calculate that the mass of the object produced (e.g. a W) is given by

$$\sqrt{\hat{s}} = \sqrt{x_1\, x_2\, s}$$ with s = centre-of-mass energy squared

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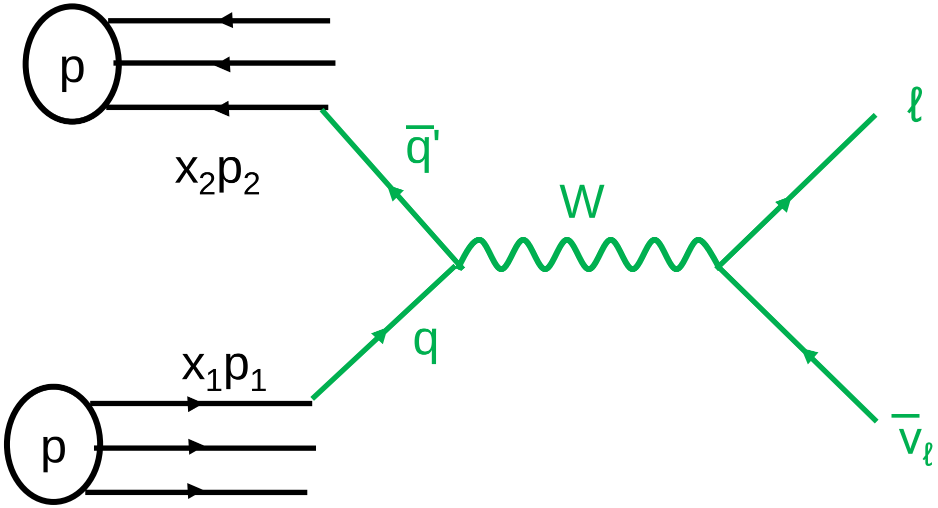

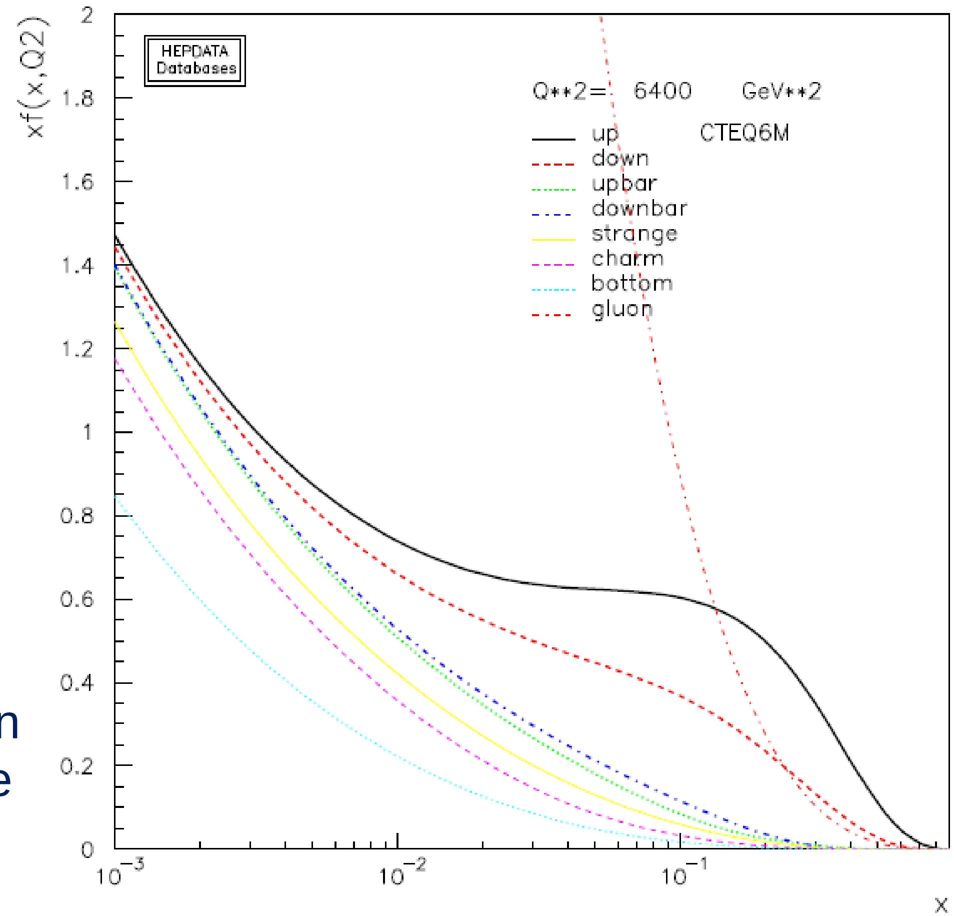

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- the production cross section can then be written as

$$\sigma_{ij}(\hat{s})$$

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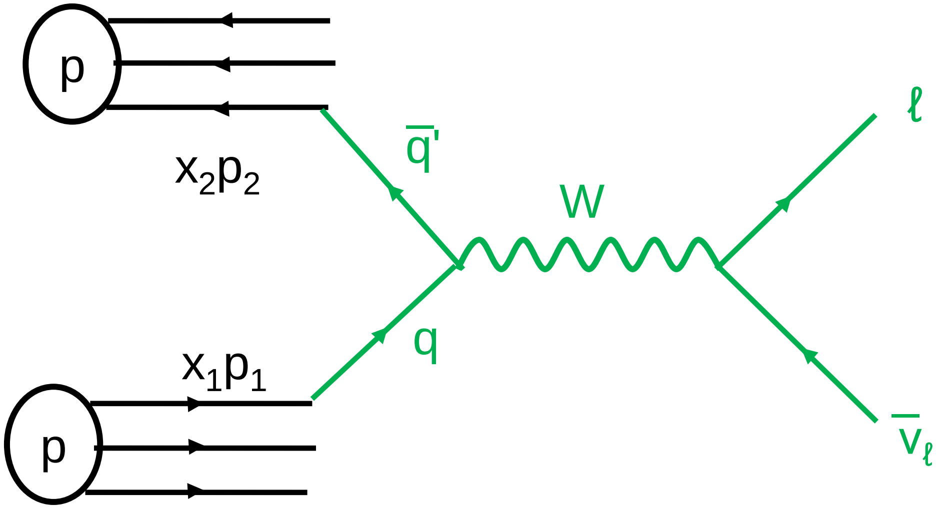

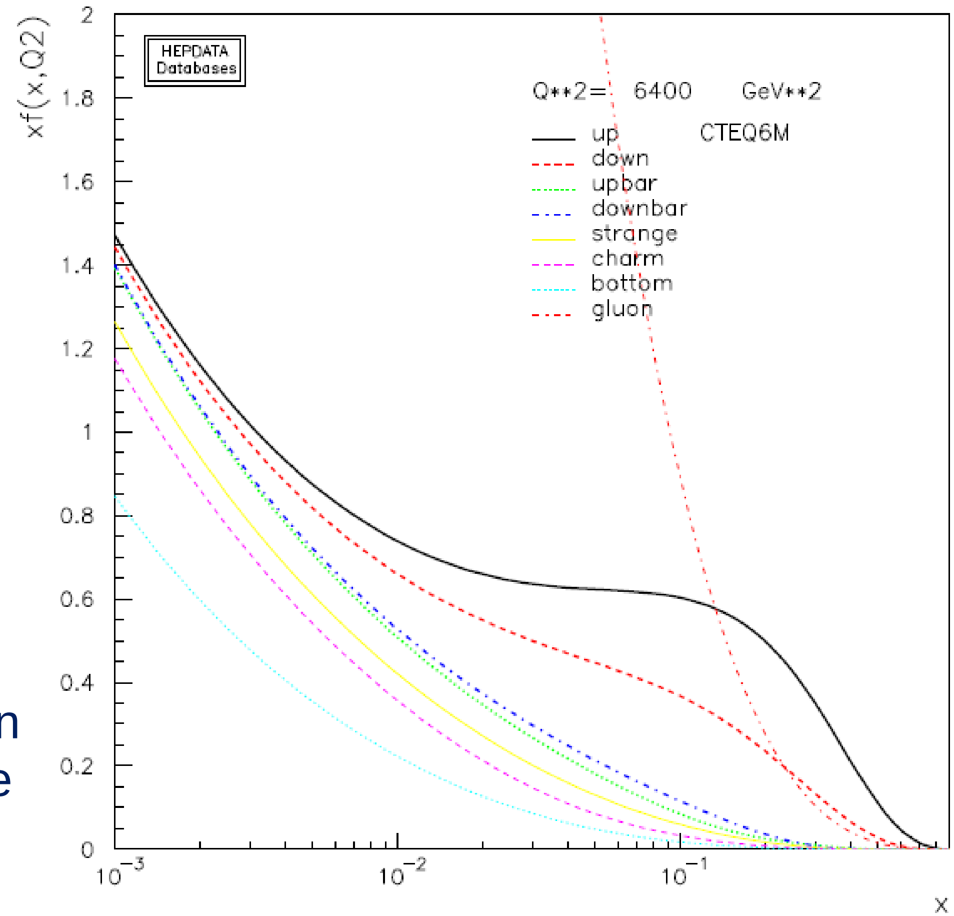

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$$\sigma_{ij}(\hat{s}) \qquad \delta(\hat{s} - x_1 x_2 s)$$

A more detailed example: W production

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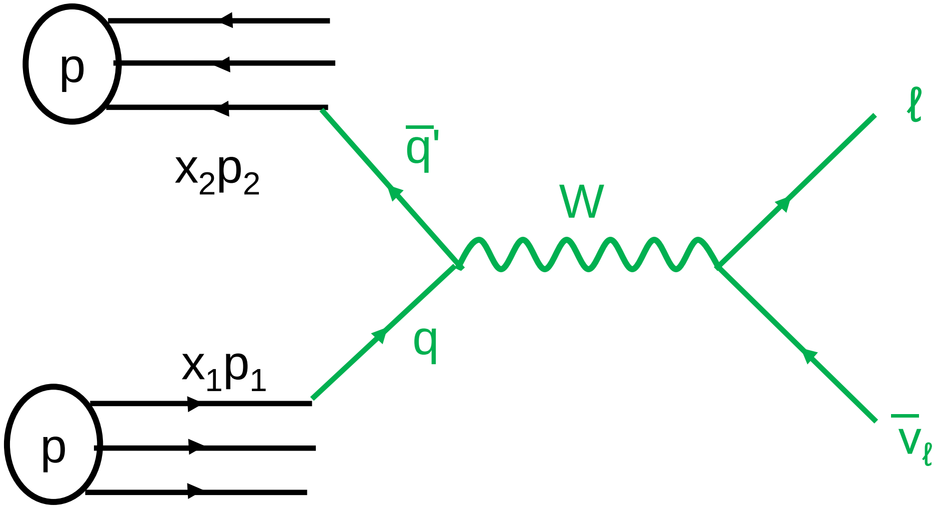

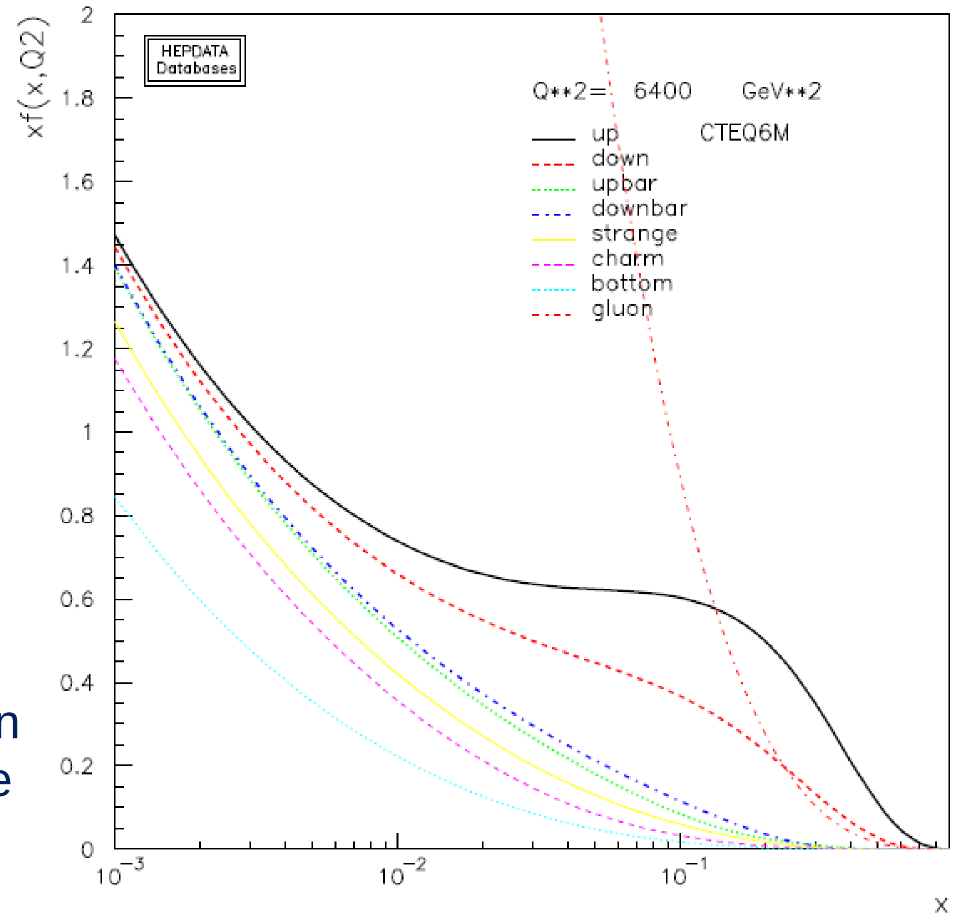

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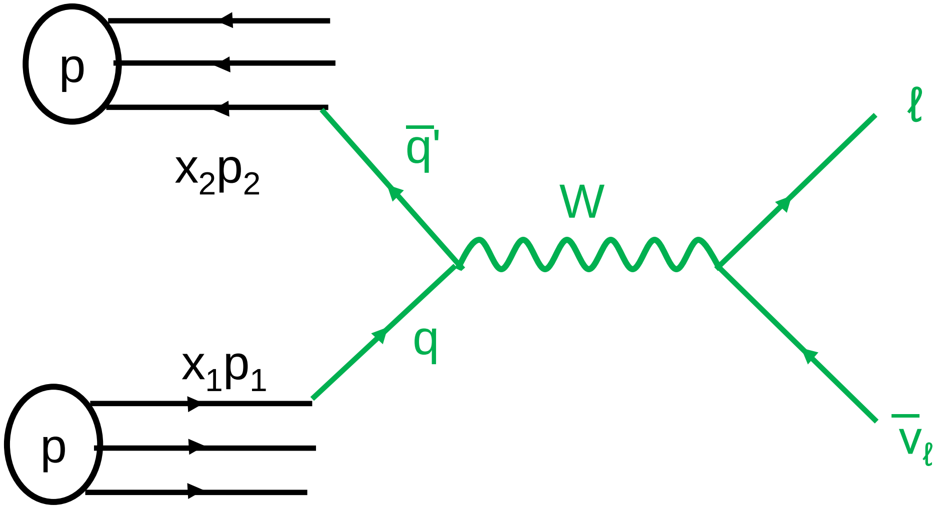
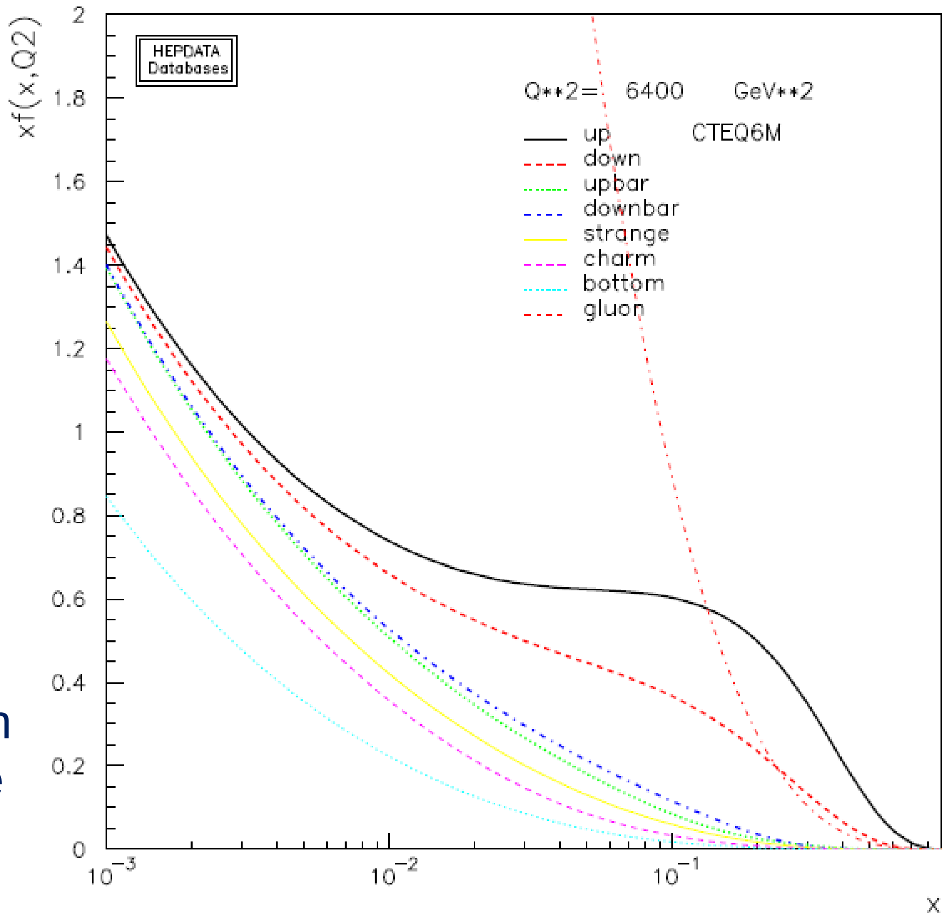
$$\sigma_{ij}(\hat{s}) \int_0^1 \int_0^1 f_i(x_1) f_j(x_2) \delta(\hat{s} - x_1 x_2 s)\, dx_1\, dx_2$$

A more detailed example: W production

- W boson production to lowest order:





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- it is easy to calculate that the mass of the object produced (e.g. a W) is given by

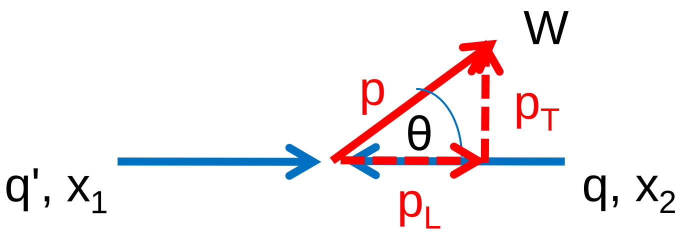
$$\sqrt{\hat{s}} = \sqrt{x_1\, x_2\, s}$$ with s = centre-of-mass energy squared

- the production cross section can then be written as

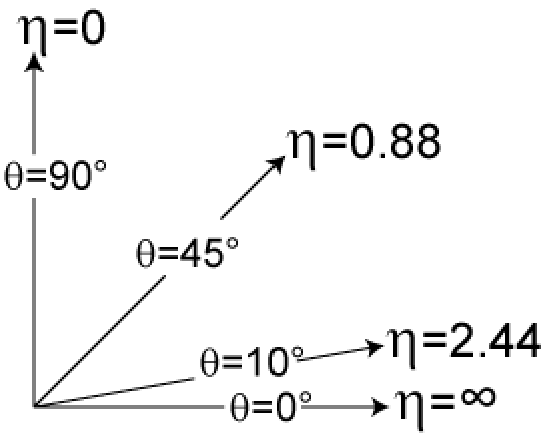
$$\sigma = \sum_{i,j} \int \sigma_{ij}(\hat{s}) \int_0^1 \int_0^1 f_i(x_1) f_j(x_2) \delta(\hat{s} - x_1 x_2 s)\, dx_1\, dx_2 d\hat{s}$$

W production kinematics

- At hadron machines the scattering direction is usually given in terms of pseudo-rapidity



$$\eta = \frac{1}{2} \ln \frac{|\vec{p}| + p_L}{|\vec{p}| - p_L} = - \ln \tan \left(\frac{\theta}{2} \right)$$



- in a simplified picture x_1, x_2 are related to the pseudorapidity of the boson with mass M:

$$x_1 \approx \frac{M}{\sqrt{s}} e^{+\eta} \qquad x_2 \approx \frac{M}{\sqrt{s}} e^{-\eta}$$

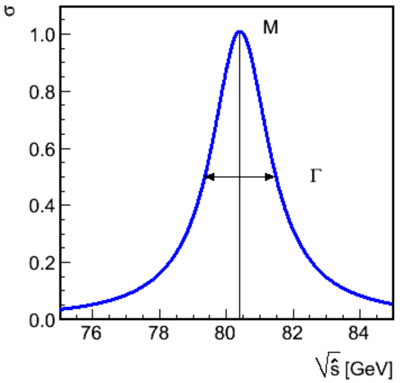
- examples: $\eta = 0$ then $x_1 = x_2 \approx 0.01$ for M=80.4 GeV and $\sqrt{s}$=7 TeV
  $\eta = 0.88$ then $x_1 \approx 0.03$ and $x_2 \approx 0.005$
  $\eta = 3.0$ then $x_1 \approx 0.23$ and $x_2 \approx 0.0006$

- at different scattering directions, different regions of the parton distribution functions are probed

W differential cross-section

- If you assume that the W boson resonance has zero width ($\Gamma_W \approx 0$)

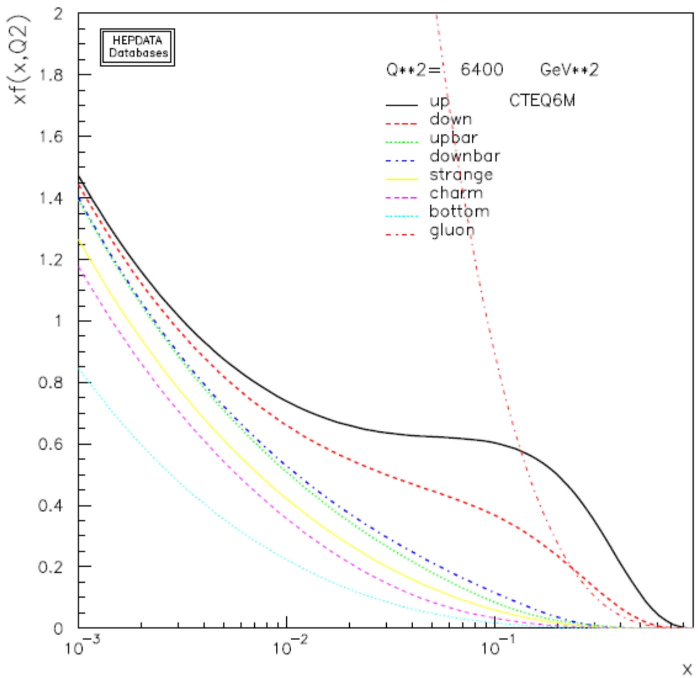
$$\hat{\sigma}_{ij}(\hat{s}) = \sigma_{ij}\delta(\hat{s} - M^2)M^2 \qquad \sigma_{ij} = \sigma(ij \rightarrow W)$$



one can perform the integrals easily and one obtains:

$$\frac{d\sigma}{d\eta}(pp \rightarrow X) \approx \sum_{i,j} \sigma_{ij} \frac{M^2}{s} f_i\left(\frac{M}{\sqrt{s}}e^{+\eta}\right) f_j\left(\frac{M}{\sqrt{s}}e^{-\eta}\right)$$

- consequence: you can calculate the diff. cross-section by simply multiplying the pdf's (and by summing over the possible intermediate states ij)



plots and numerical tables:
http://durpdg.dur.ac.uk/HEPDATA/PDF

try it yourself!
(works also for Higgs at LO, ...)

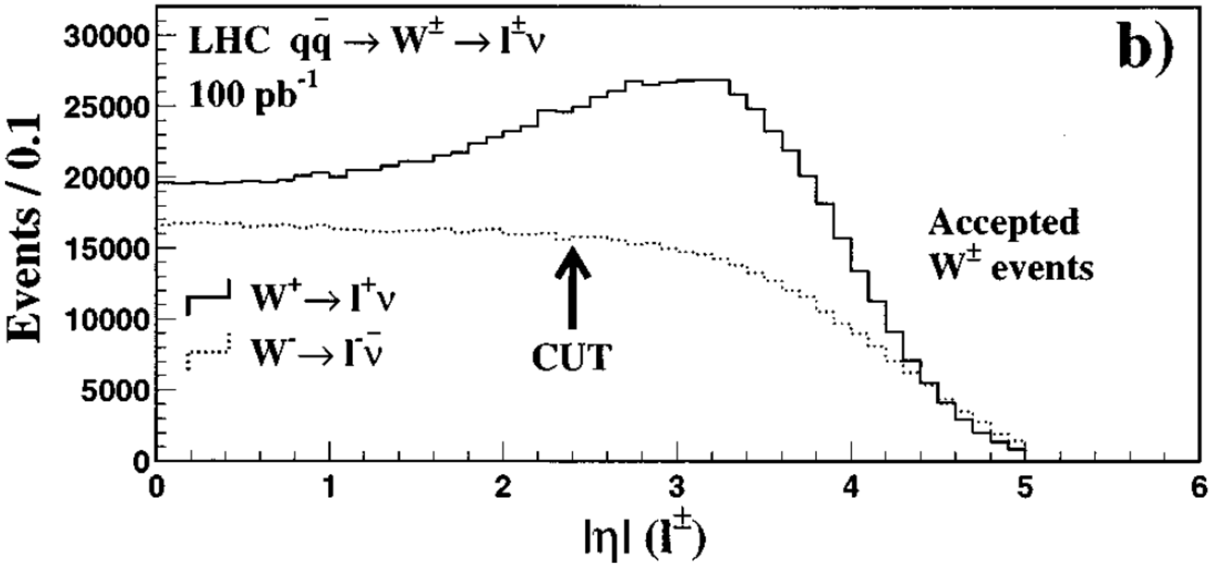
W differential cross-section

$$\frac{d\sigma}{d\eta}(pp \to X) \approx \sum_{i,j} \sigma_{ij} \frac{M^2}{s} f_i(\frac{M}{\sqrt{s}} e^{+\eta}) f_j(\frac{M}{\sqrt{s}} e^{-\eta})$$

- example: $u + \bar{d} \to W^+$ $\quad \bar{u} + d \to W^-$

$$\sigma(u + \bar{d} \to W^+) = \sigma(\bar{u} + d \to W^-) \equiv \sigma_W$$

- anti-u and anti-d pdf's are about the same (sea-quarks)
- at $\eta = 3.0$ ($x_1 \approx 0.23$, $x_2 \approx 0.0006$)
  → the u- and d-pdf differ by a factor of 2 (valence quarks)
  → W^+ production is enhanced with respect to W^-

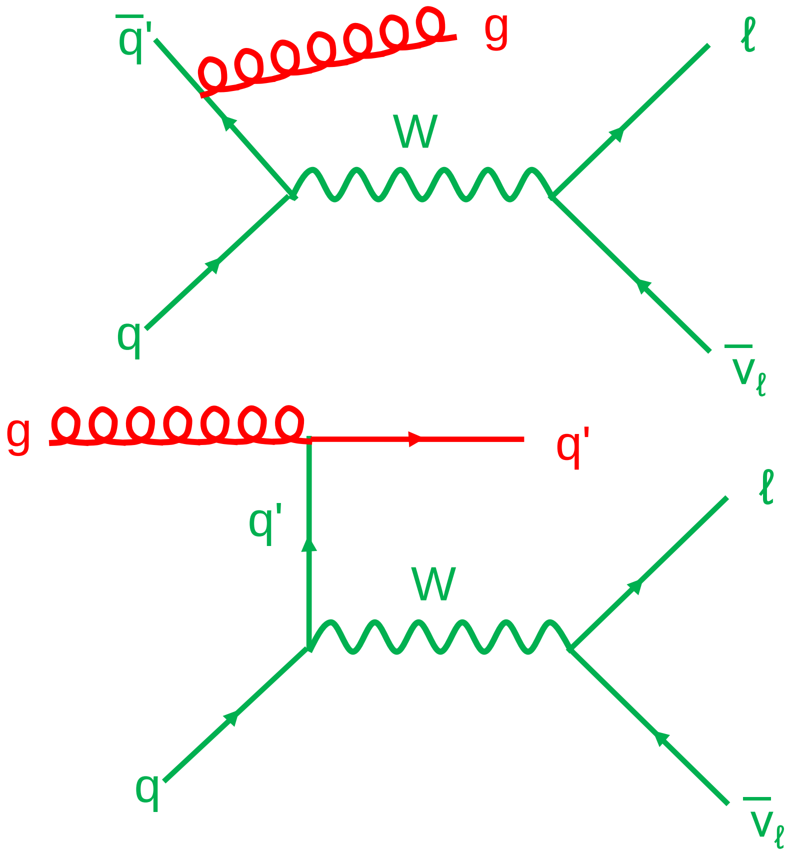


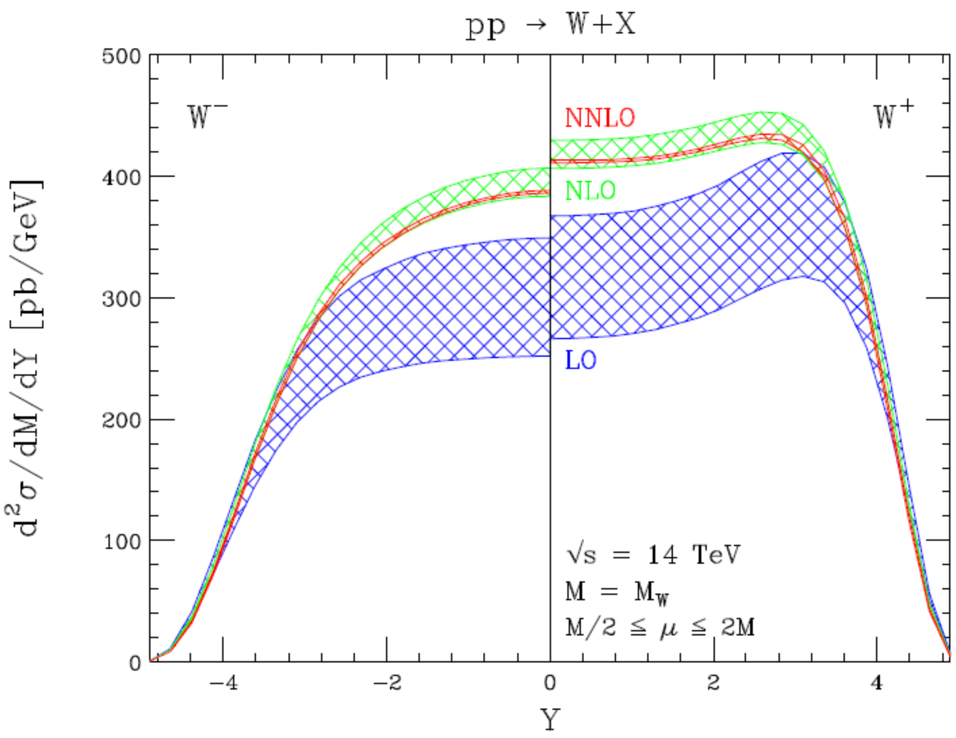
- possibility to test/measure pdf's

M. Dittmar et al., Phys. Rev. D 56 (1997) 7284

W+jet Production

- there are correction to the lowest order description, e.g. due to gluon radiation
- corrections are next-to-leading order (NLO) in α_s or even NNLO, N^3LO, ...
  → W+jet production





- theoretical uncertainties are typically reduced when going to higher order calculations

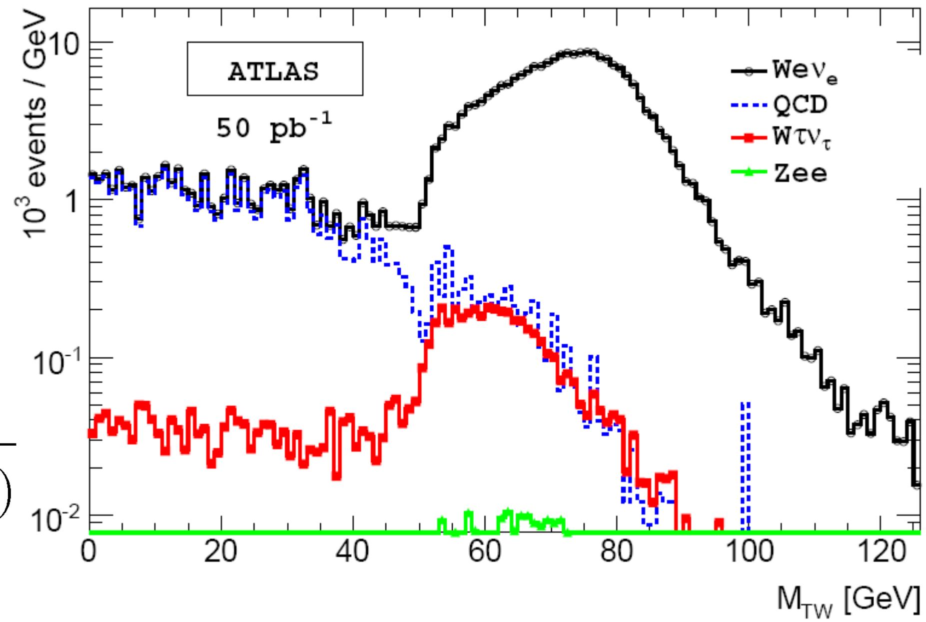
W and Z production cross-sections

- W selection:
  - lepton p_T>25 GeV
  - E_T^{miss}>25 GeV → neutrino
  - W mass would be

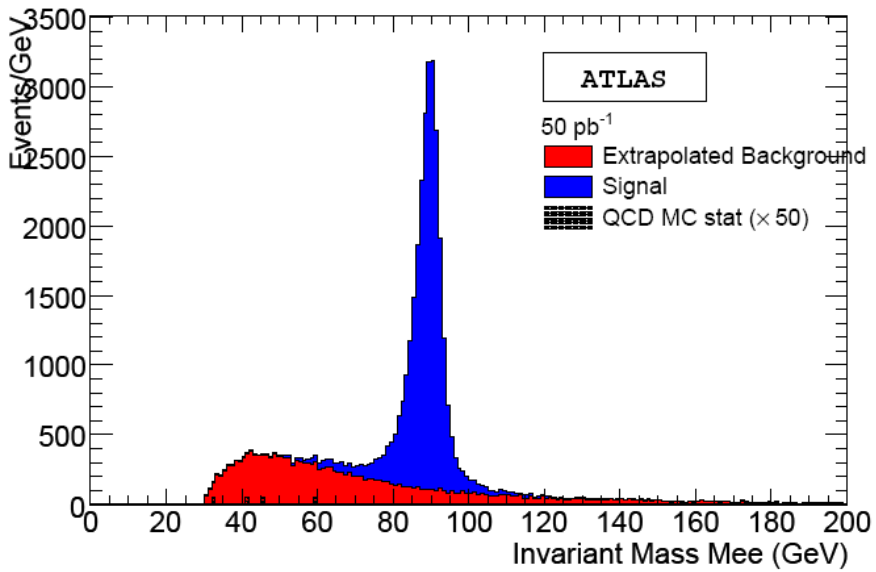
$$M_W \approx \sqrt{E^\ell E^\nu (1-\cos\alpha(\ell,\nu))}$$

  but E^ν and angle can not be measured
  → transverse mass: M_T>40 GeV

$$M_T = \sqrt{p_T^\ell p_T^{miss}(1-\cos\Delta\phi(p_T^\ell, p_T^{miss}))}$$



- Z selection:
  - lepton p_T>15 GeV
  - 80<$M_{\ell\ell}$<100 GeV
  - isolated electrons and muons

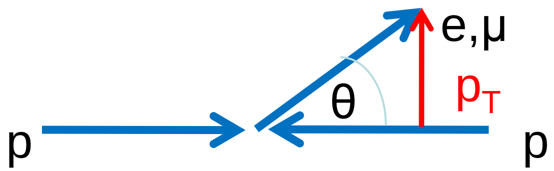


- background at 10% level (QCD)

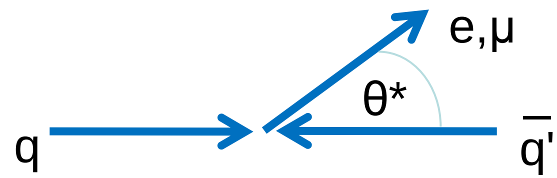
- stat. uncertainty ~ 1/√N will be very small
- systematics will dominate:
  background uncertainties, luminosity and theory (PDF, gluon radiation, underlying event,...)

Measurement of M_W

- kinematics of the $W \rightarrow \ell \nu_\ell$ decay → only the lepton is measured in the detector:



lab frame

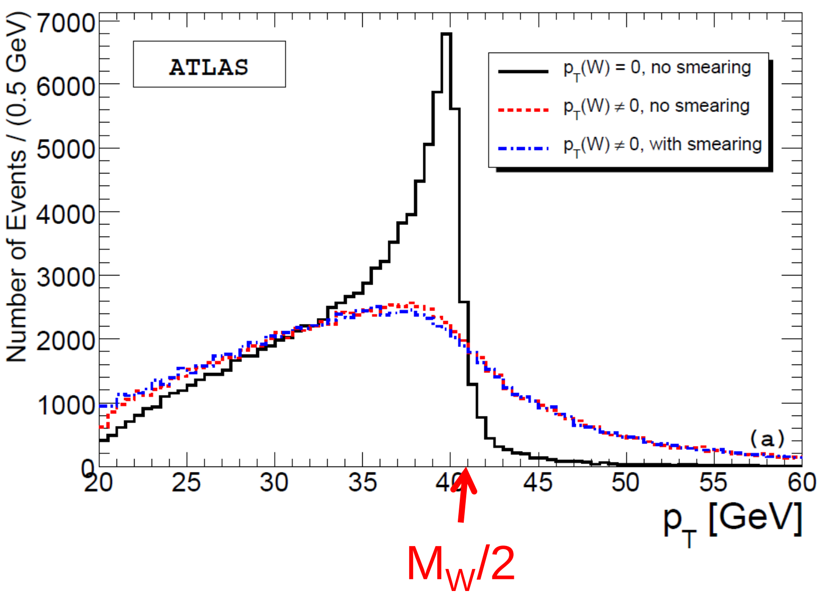


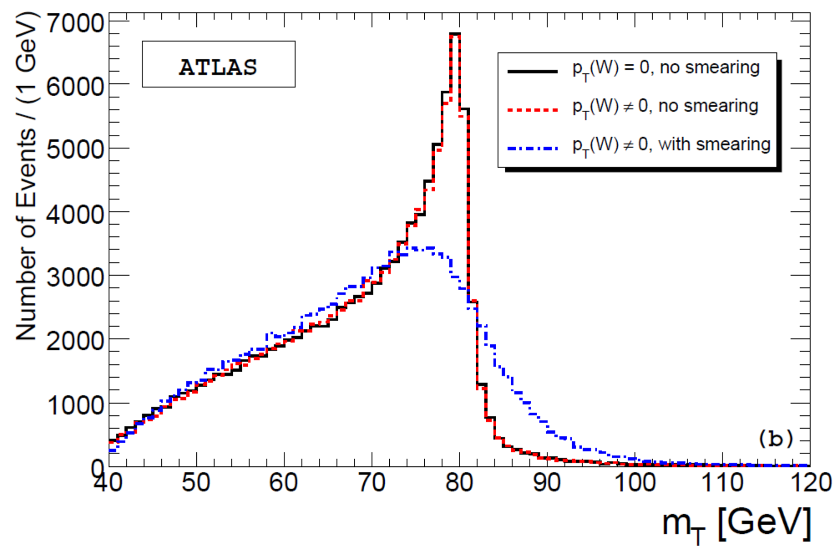
W rest frame

- differential decay rate in the lab frame can be traced back to decay rate in rest frame:

$$\frac{dN}{dp_T} = \frac{2p_T}{M_W} \frac{1}{\sqrt{\left(\frac{M_W}{2}\right)^2 - p_T^2}} \frac{dN}{d\cos\theta^*}$$

- Jacobian factor is singular at $p_T = M_W/2$ → Mass peak in p_T spectrum



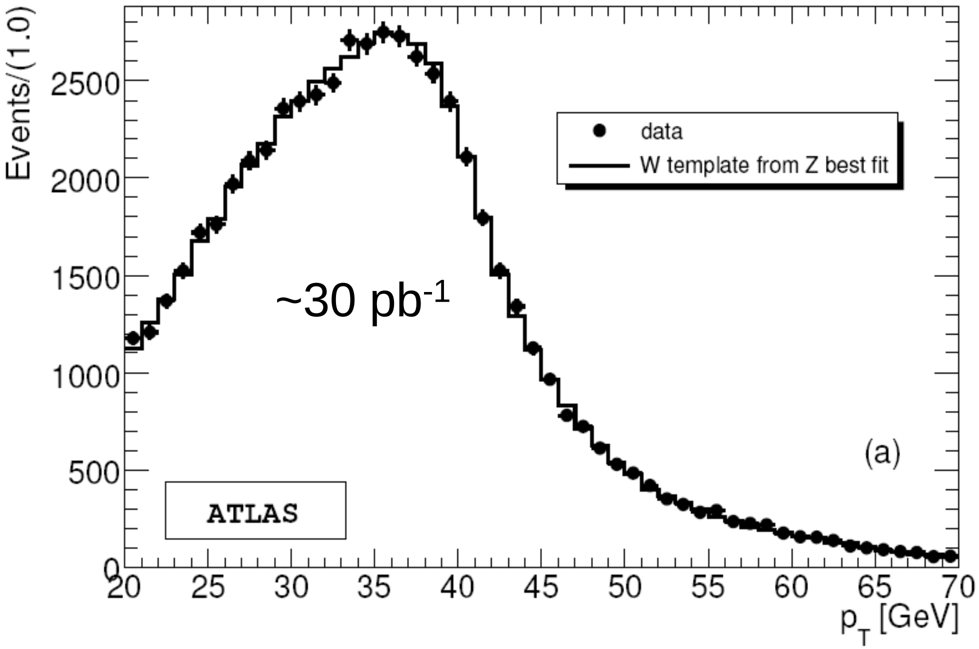


$$M_T = \sqrt{p_T^\ell p_T^{miss}(1 - \cos\Delta\phi(p_T^\ell, p_T^{miss}))}$$

- p_T of W is non-zero → changes spectrum

Measurement of M_W

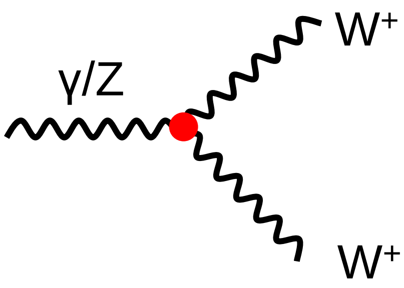
- fit spectra of lepton p_T and $M_T = \sqrt{p_T^\ell p_T^{miss}(1-\cos\Delta\phi(p_T^\ell, p_T^{miss})}$
- lepton energy scale from Z events
- adjust Monte Carlo samples with different M_W to fit best to data spectrum
- most sensitive region is upper edge of the Jacobian peak (~40 GeV)



- statistical uncertainty in ~30 pb^{-1} is ~ 60 MeV in W→μν and W→eν channel
- systematics: lepton energy scale 110 MeV and 200 MeV due to W recoil, p_T^W
- "warm-up" for the ultimate 15 MeV precision → 10-20 fb^{-1}
- W mass precision today: 23 MeV (LEP+Tevatron)

Couplings between Gauge Bosons

- non-abelian nature of SM predicts
  → triple gauge boson couplings (TGC)



- coupling strength in the SM:
  $g_{WW\gamma} = e$ $g_{WWZ} = e \cot \theta_W$

- measure these couplings and test for anomalous contributions
- effective Lagrangian is used to model these (V= γ or Z):

$$L/g_{WWV} = i g_1^V (W^*_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + i \kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W^*_{\rho\mu} W^\mu_\nu V^{\nu\rho}$$

- in the SM: $g_1^\gamma = g_1^Z = 1$ $\kappa^\gamma = \kappa^Z = 1$ $\lambda^\gamma = \lambda^Z = 0$

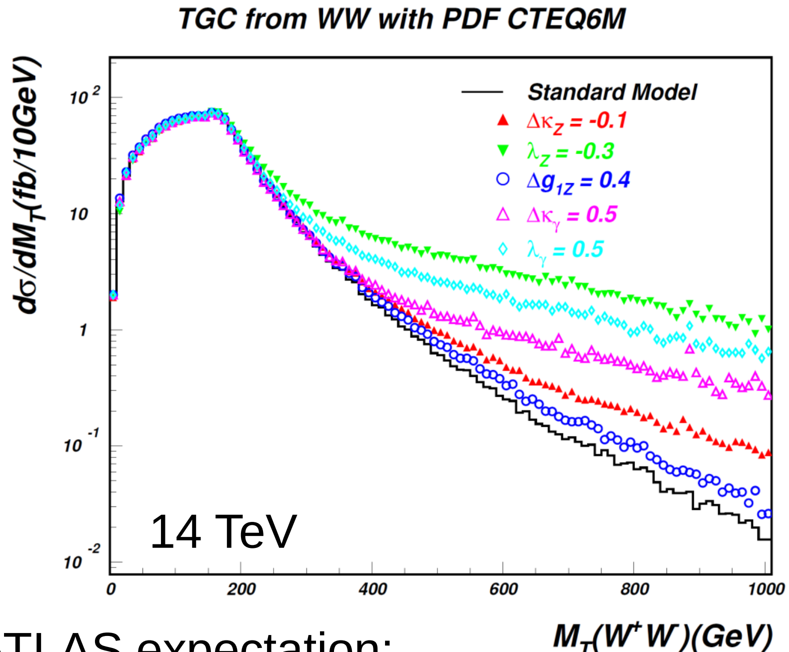
- at LHC the di-boson decays to electrons and muons will be measured:
  - pp → ZW → ℓℓ ℓν
  - pp → WW → ℓν ℓν
  - pp → ZZ → ℓℓ ℓℓ, ℓℓ νν
  - pp → Zγ → ℓℓ γ
  - pp → Wγ → ℓν γ

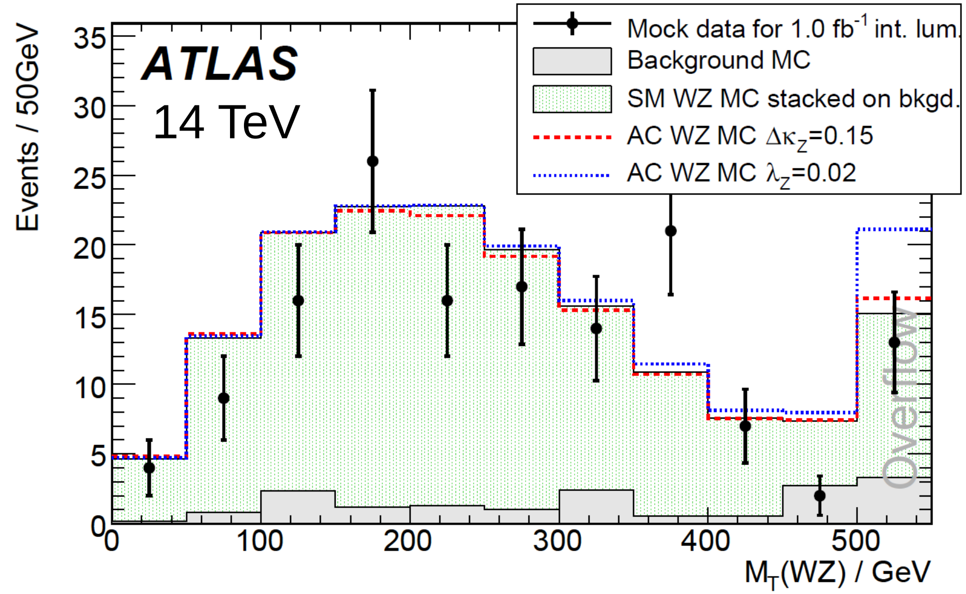
  } high p_T leptons and photons; Z mass and transverse mass constraints

- anomalous couplings between ZZZ and ZZγ are studied, too → do not exist in SM

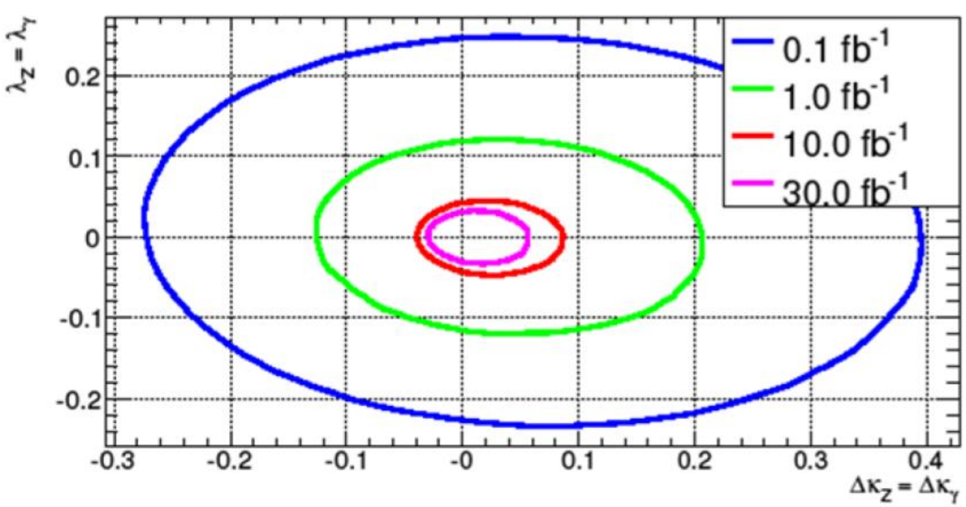
Gauge boson self-couplings

- high energy reach of LHC will help to improve the coupling measurements:

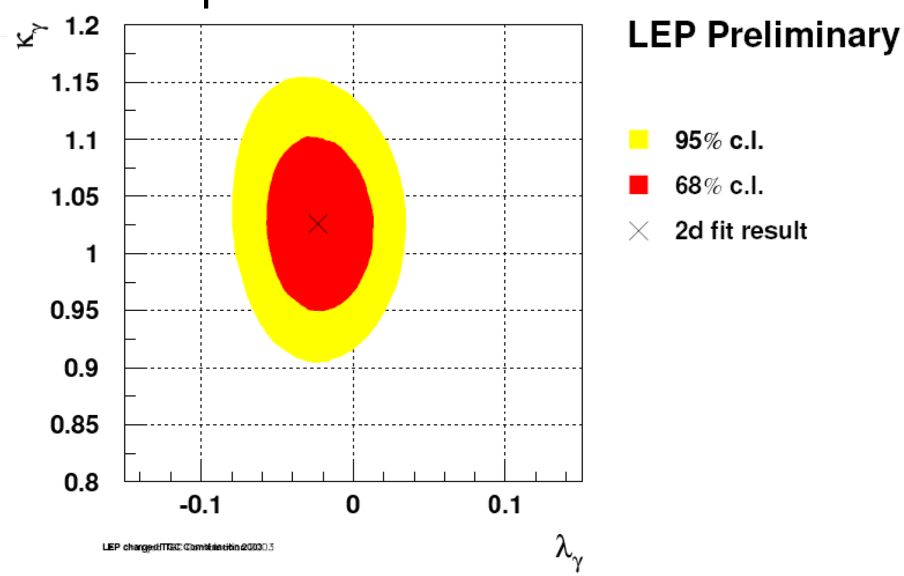




ATLAS expectation:



compared to LEP:



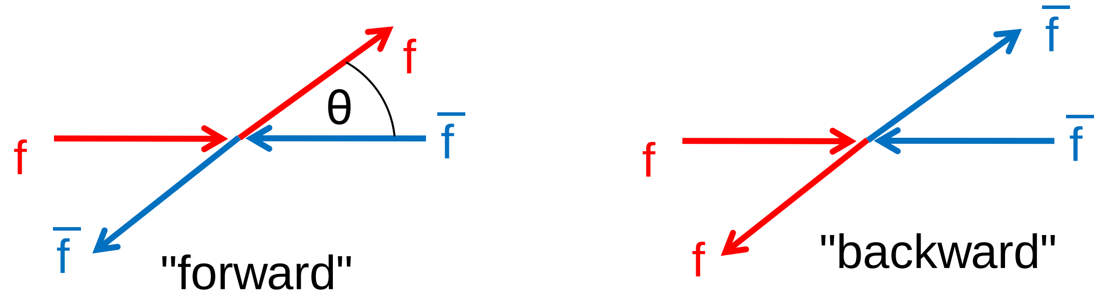
Weak Mixing Angle at the LHC

- Z boson production at LHC is the "inverse" of the LEP process

  LHC: $q\bar{q} \to Z/\gamma^* \to e^+e^-$ LEP: $e^+e^- \to Z/\gamma^* \to q\bar{q}$

- in the Z rest frame:
  measurement of forward-backward asymmetry

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



- A_{FB} depends on Z-to-fermion couplings

$$A_{FB} = A_{FB}(c_V^f, c_A^f) = A_{FB}(\sin^2\theta_w)$$

→ precise measurement of $\sin^2\theta_w$

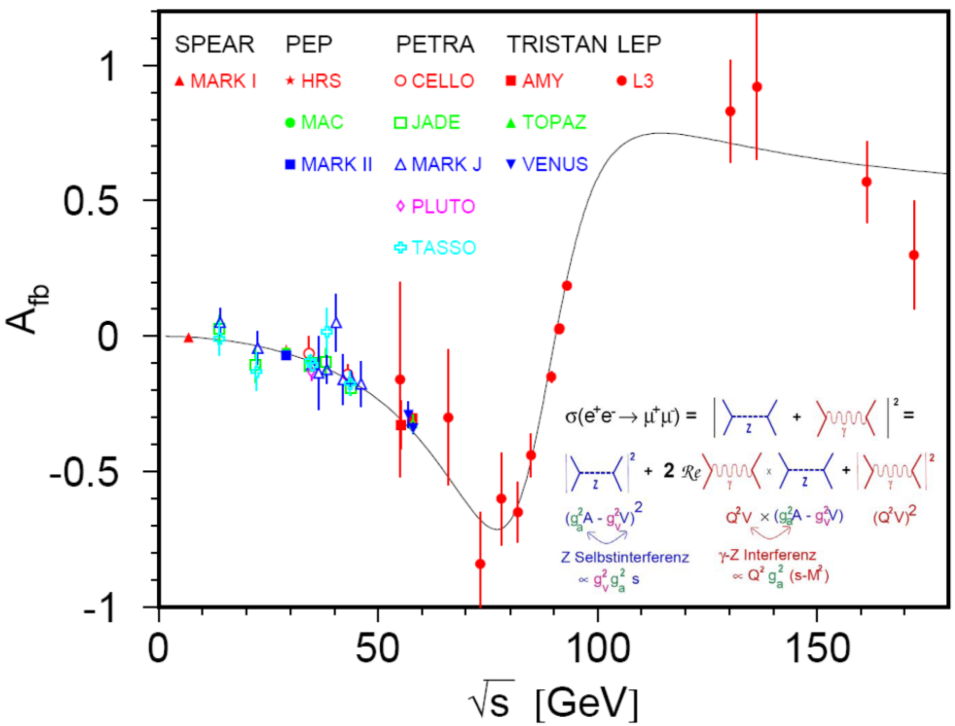
$\delta\sin^2\theta_w = 1.6 \cdot 10^{-4}$

$\delta M_W/M_W = 2.8 \cdot 10^{-4}$

$\delta M_Z/M_Z = 0.2 \cdot 10^{-4}$

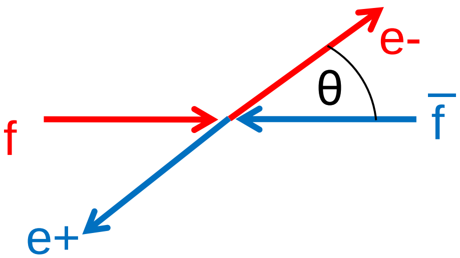
→ test the Standard Model

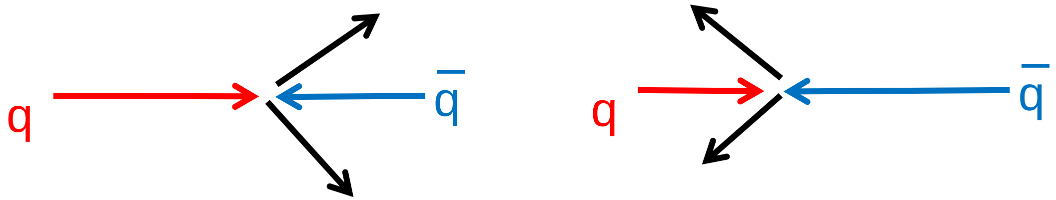
$$\rho = \frac{M_W}{M_Z \cos\theta_w} = 1 + \Delta\rho(\text{rad. corr.})$$



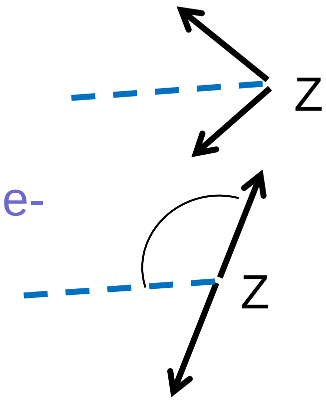
Weak Mixing Angle Measurement

- LEP was a e+e- collider with symmetric beam energies
  - automatically in Z rest frame
- quark-quark system at LHC has varying longitudinal momentum → depends on share between x_1 and x_2

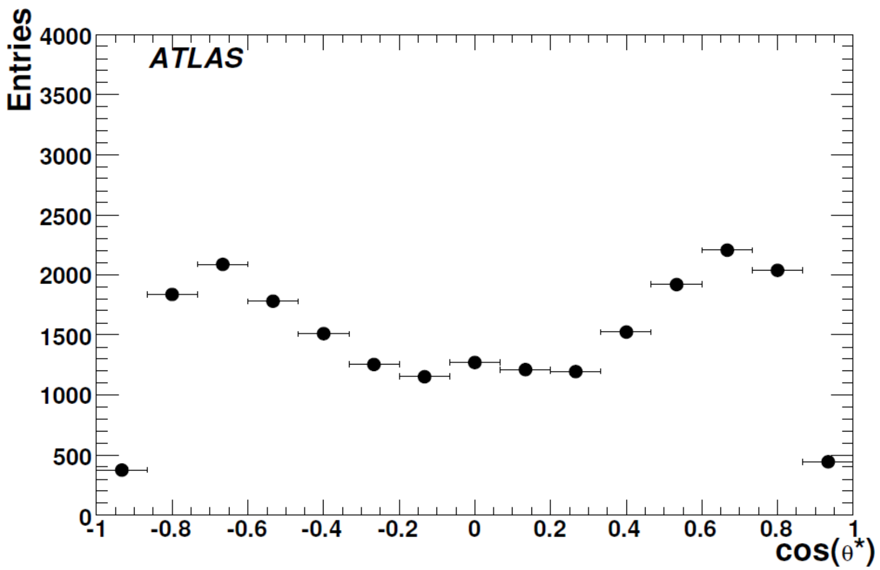




- a trick has to be done: we know the Z decays to e+e-
  → the reference direction is the bi-section between e+ and e-
  → go into the e+e- rest frame = Z boson rest frame



"Collins-Soper frame"



- good enough approximation to measure the asymmetry

$$A_{FB} = b(a - \sin^2 \theta^{\ell}_{eff})$$

- LHC expects a precision of $\delta\sin^2\theta_w = 3 \cdot 10^{-4}$
- 100 fb^{-1} and includes forward detectors
- compare to LEP: $\delta\sin^2\theta_w = 1.6 \cdot 10^{-4}$

Summary of LHC Electroweak Measurements

- production cross-sections of W and Z boson
- W mass with 15 MeV ultimate precision

- di-boson production WW, WZ, ZZ, ...
- triple gauge boson couplings to precision beyond $\Delta\kappa/\Delta\lambda/\Delta g_1=0.01$

- perform a new measurement of the weak mixing angle
- $\delta\sin^2\theta_w = 3 \cdot 10^{-4}$ and maybe better

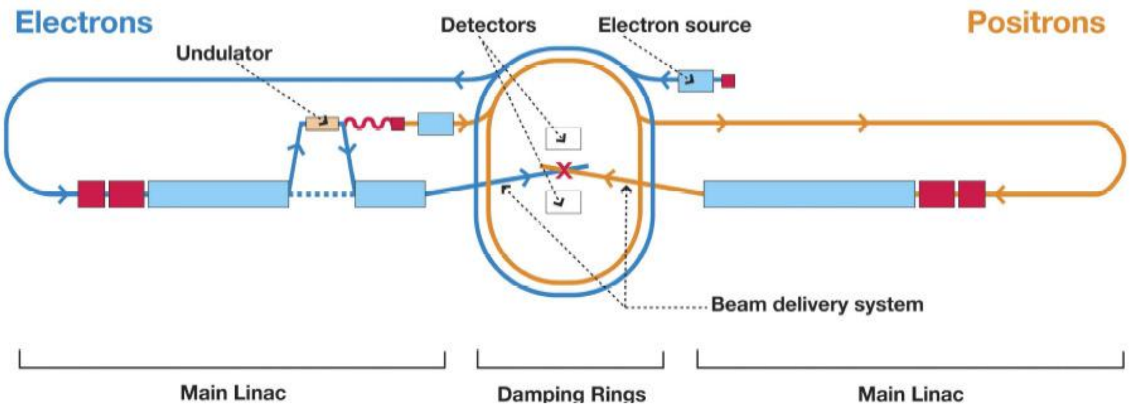
- need a very good understanding of the ATLAS and CMS detectors
  - known electro-weak processes are a main reference

- need a well-performing LHC machine to deliver good data

- we know that the Standard Model is just an effective theory which will need extensions at very high energies
  - keep your eyes open when looking at invariant mass spectra, etc.

A Quick Look into the Future: the ILC

- International Linear Collider



e+e- machine
500 GeV centre-of-mass energy
luminosity 2×10^{34} cm^{-2} s^{-1}
polarization e- 80% e+ 30% (60%)
L=500 fb^{-1} in 4 years

- detectors better than at LEP: jet measurement, e.m. calorimetry, tracking

- mainly for
  - studying SUSY physics
  - measuring Higgs boson properties

- and...
  - very precise top mass determination→ top-pair threshold scan $\Delta m_t \approx 100$ MeV
  - further improved TGC measurements
  - more precise measurement of $\sin^2\theta_w$ → GigaZ option at Z peak energies

Backup for Further Questions

ATLAS Detectors at Start-up

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.9%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	98.2%
LAr EM Calorimeter	170 k	98.8%
Tile calorimeter	9800	99.2%
Hadronic endcap LAr calorimeter	5600	99.9%
Forward LAr calorimeter	3500	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	98.4%
RPC Barrel Muon Trigger	370 k	98.5%
TGC Endcap Muon Trigger	320 k	99.4%
LVL1 Calo trigger	7160	99.8%

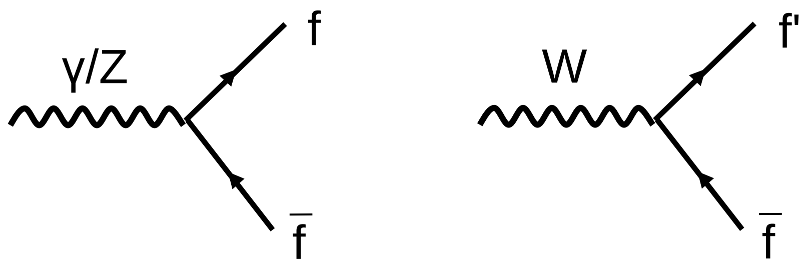
Presented by J. Kanzaki at KEK in Feb. 19, 2010

Fermion-Boson Couplings

- couplings of fermions to gauge bosons

$$-ig\frac{1}{2}(c_V\gamma^\mu - c_A\gamma^\mu\gamma^5)$$

  - coupling to Z-bosons involves θ_w:



	γ	W	Z
c_V	$2Q$	$T_3 = \pm\frac{1}{2}, 0$	$T_3 - 2Q\sin^2\theta_w$
c_A	0	T_3	T_3

	γ	W	Z
g	e	$\sqrt{2}\frac{e}{\sin\theta_w}$	$g_z = \frac{e}{\sin\theta_w\cos\theta_w}$

Cross-sections at LHC

LO cross sections in pb, inclusive

E_{cm} [TeV]/ Process	7	10	14	Evts (7 TeV) in 200/pb	Ratio 7/14
QCD pt>100 GeV	3.2E+05	6.8E+05	1.4E+06	6.4E+07	0.2
Z incl	2.5E+04	3.6E+04	5.7E+04	5.0E+06	0.4
W incl	9.5E+04	1.4E+05	2.1E+05	1.9E+07	0.5
ttbar	8.4E+01	2.2E+02	4.8E+02	1.7E+04	0.2
H(150 GeV)	4.0	8.2	16.0	8.0E+02	0.3

no branching ratios included !

G. Dissertori

Particle Identification

- combined performance is important

	Tracker	ECAL	HCAL	Muon-System	Vertex-Detector
Electrons	++	+++	+	-	-
Photons	+	+++	+	-	-
Muons	+(+)	+	+	+++	(+)
Taus	++	++	++	++	++
B-Jets	++	+	+	+	+++
Jets	+	+++	+++	(+)	-
Missing E_T	+	+++	+++	+	-

K. Desch