MEASUREMENT OF THE INCLUSIVE ISOLATED PROMPT PHOTON CROSS SECTION AT $\sqrt{s}$ = 7 TeV WITH THE ATLAS DETECTOR

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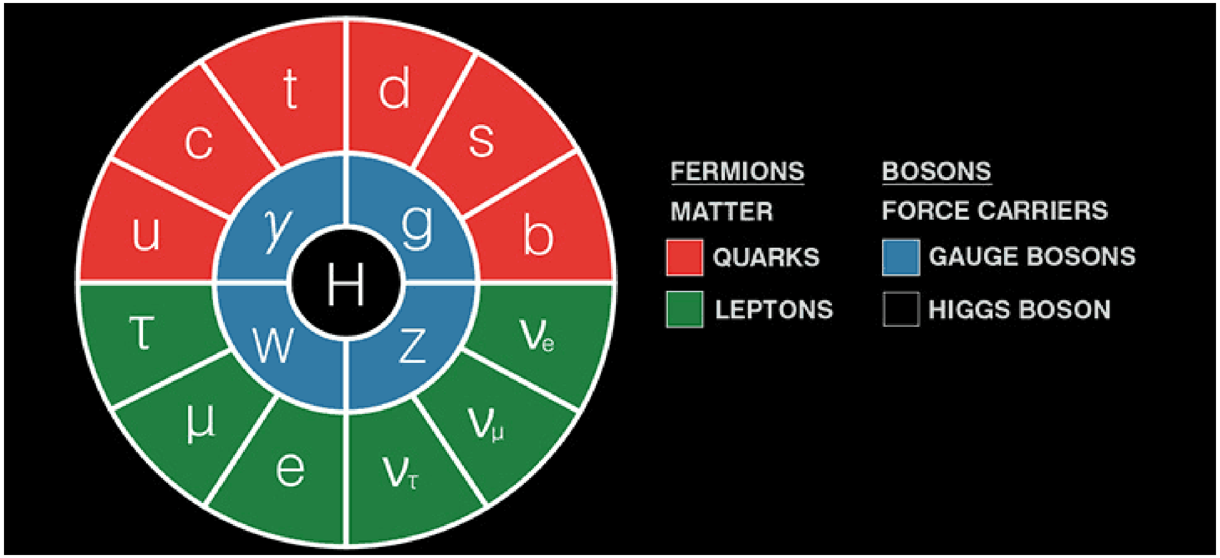
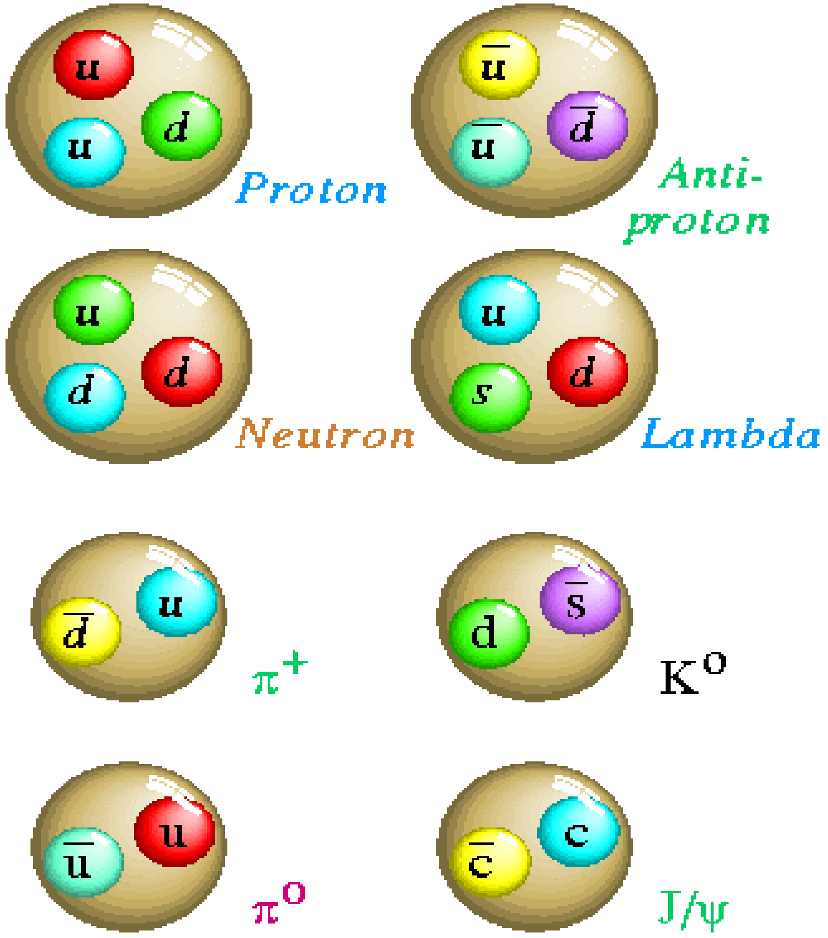
Standard Model



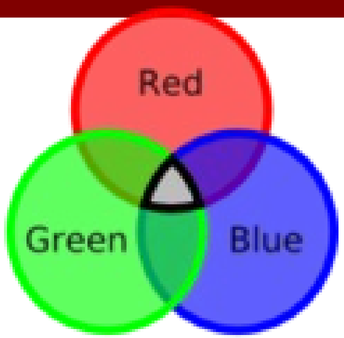
- Fermions have fractional integer spin (1/2,3/2,...)
  - Quarks have fractional integer charge
    - Up, Charm, Top 2/3 charge
    - Down, Strange, Bottom -1/3 charge
  - Leptons have integer charge
    - Tau, Muon, Electron -1 charge, Neutrino 0 charge
- Bosons have integer spin(1) Higgs spin(0)

Particle Definitions

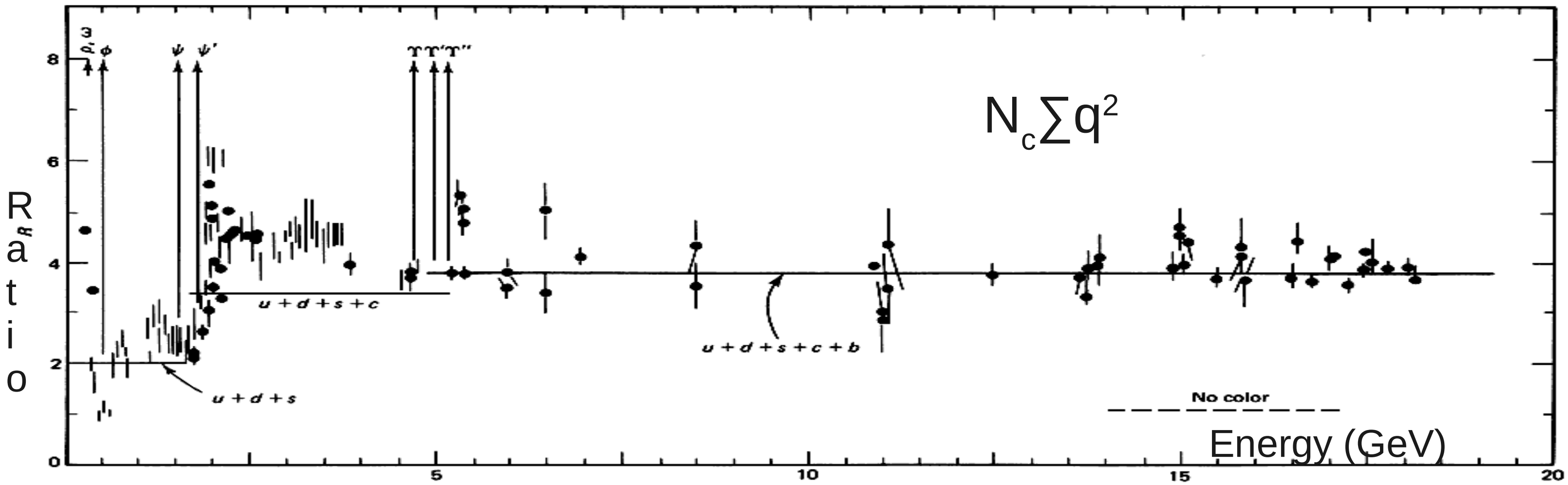
- Partons
  - Quarks and gluons
- Hadrons
  - Particles participating in the strong force
- Mesons
  - Quark anti-quark pair
- Baryons
  - Three quarks



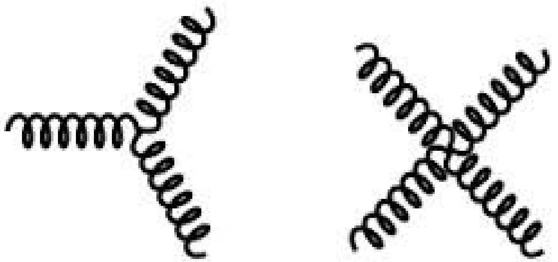
QCD



- Gluons are the force carrier for the strong force
- There are three color states

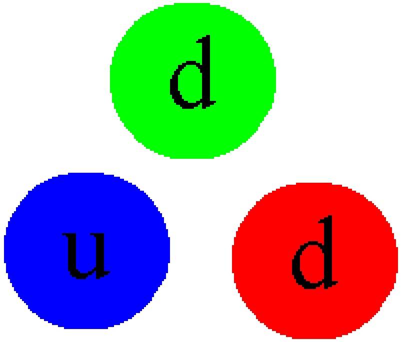


- The ratio of e^+e^- decaying to hadrons and muons shows that three colors do exist.
- All objects we see are colorless
- Gluons contain color and can couple to quarks and other gluons leading to asymptotic freedom



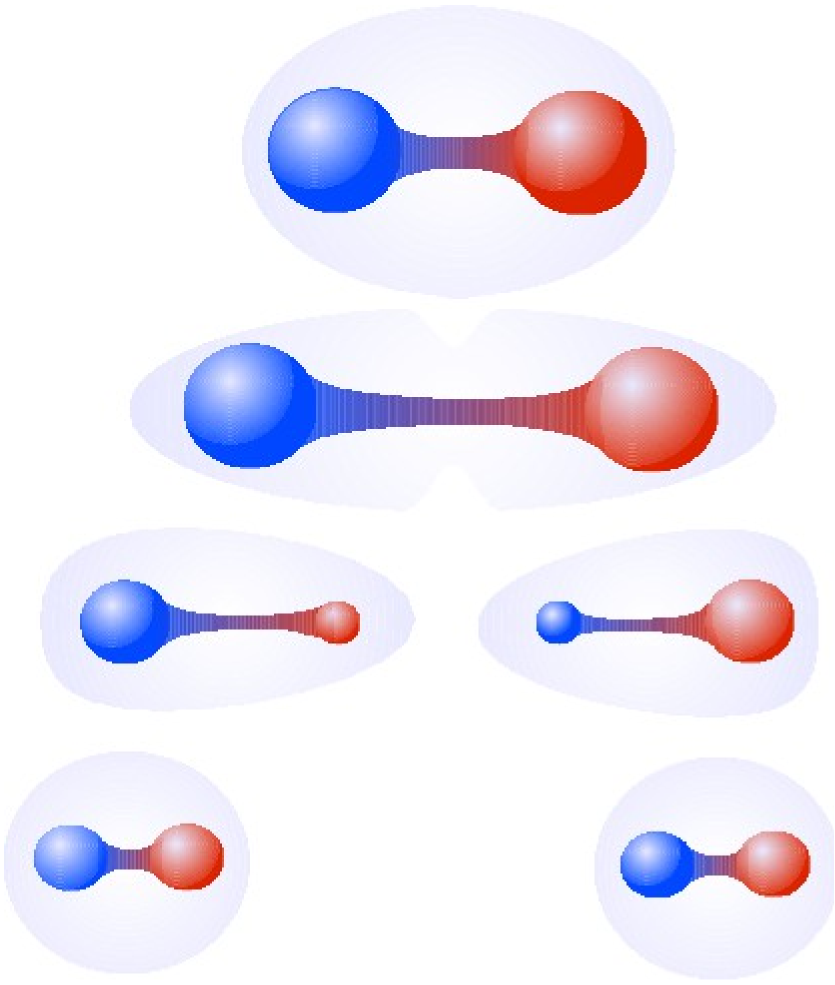
QCD

- Asymptotic freedom
  - is the effect where quarks and gluons at small distances and high energies the coupling constant decreases instead of increasing (quarks and gluons could be considered free)
- Confinement
  - is defined as the effect that at large distances and low energies the coupling constant is large and quarks and gluons are not seen as free



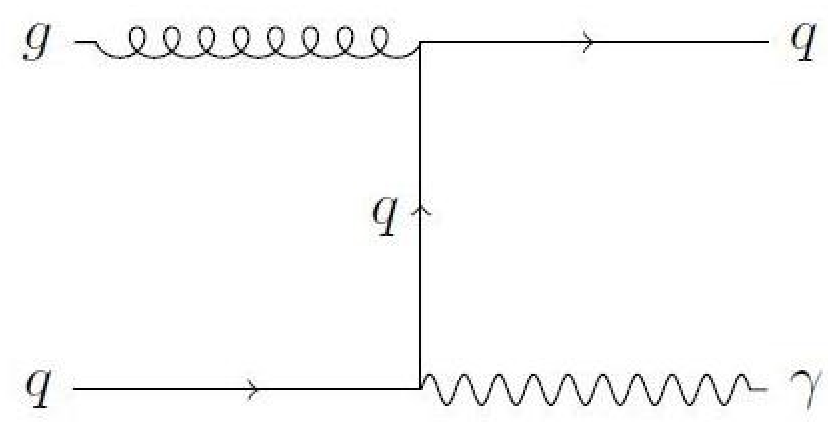
Fragmentation

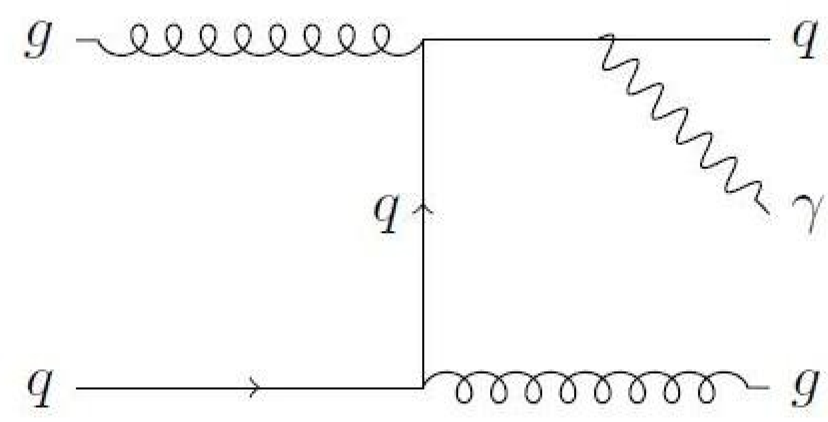
- Fragmentation
  - Confinement leads to hadronization
    - Quarks and gluons start to form colorless hadrons
- Particles come in colorless combinations
- Three colors
  - Red, Blue, Green
- Three anticolors
- Mesons, Baryons



PQCD

- Because gluons can self couple the number of diagrams gets larger making it difficult to calculate QCD
- Use the fact that at small distances and high energy the coupling constant (α_s) is small ~0.118
  - Coupling constant is a running coupling constant
- Expanding in powers of α_s
- The series is ~ $1+\alpha_s+\alpha_s^2+...$
- Leading Order and Next to Leading Order





Feynman diagrams for a direct photon process

Simplified Version of a Calculation

$$A+B\rightarrow\gamma+X$$

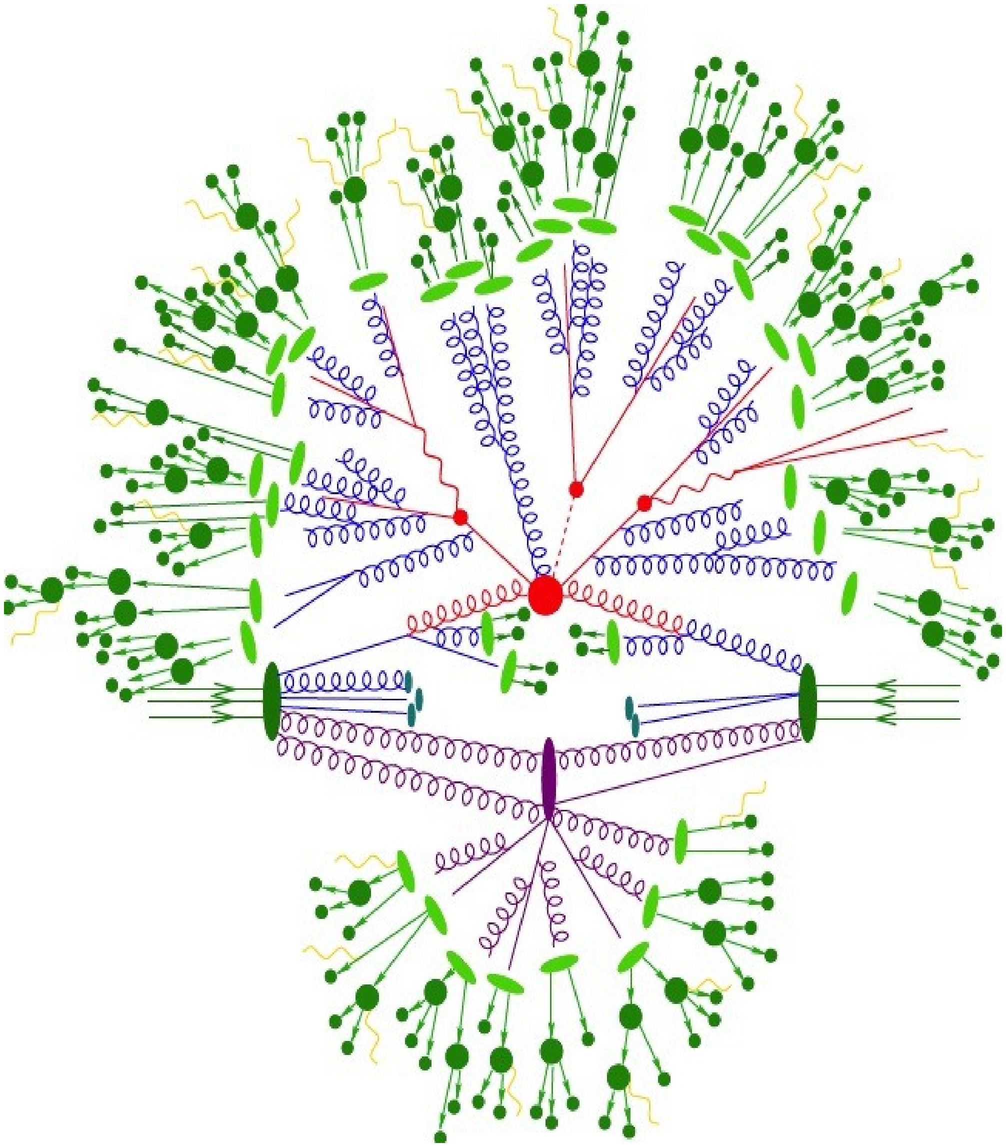
- Cross section

$$\sigma\sim\int\left|M_{parton}\right|^2 G_A G_B D+\left|M_{photon}\right|^2 G_A G_B$$

- M is defined as the matrix element of the Feynman diagrams
- G is defined as the parton distribution functions (PDFs)
- D is the fragmentation function
- Photons can be useful in testing PQCD
- Partons can fragment into photons but photons do not fragment into anything

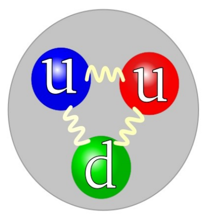
Fragmentation Function

- Probability that a quark or gluon will fragment into a particular hadron or photon with a portion of the momentum of the colliding partons
- Modeled after experimental data
- Universal and not dependent on the hard scatter
- The function Incorporates the non-PQCD effects

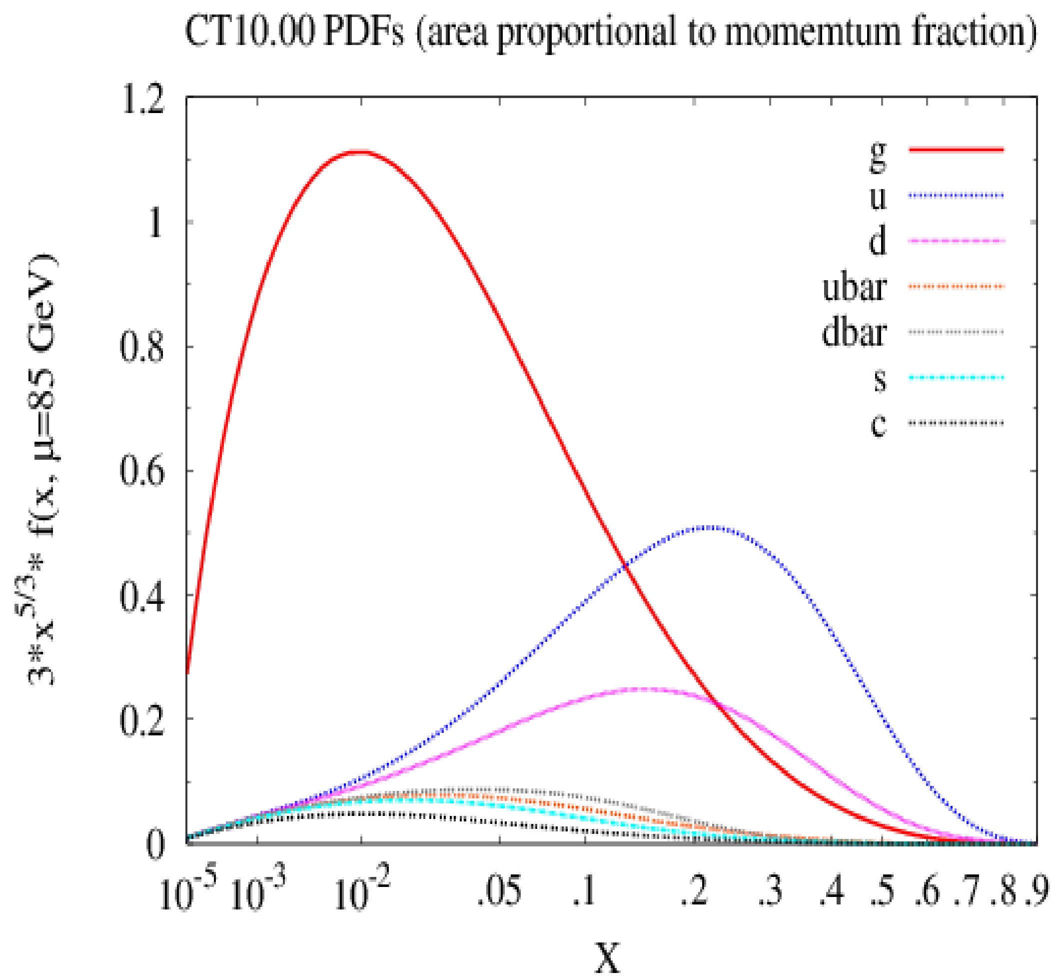


Parton Distribution Functions

- Describes the momentum distribution of the partons within the proton
- The valence quarks are the up and down quarks



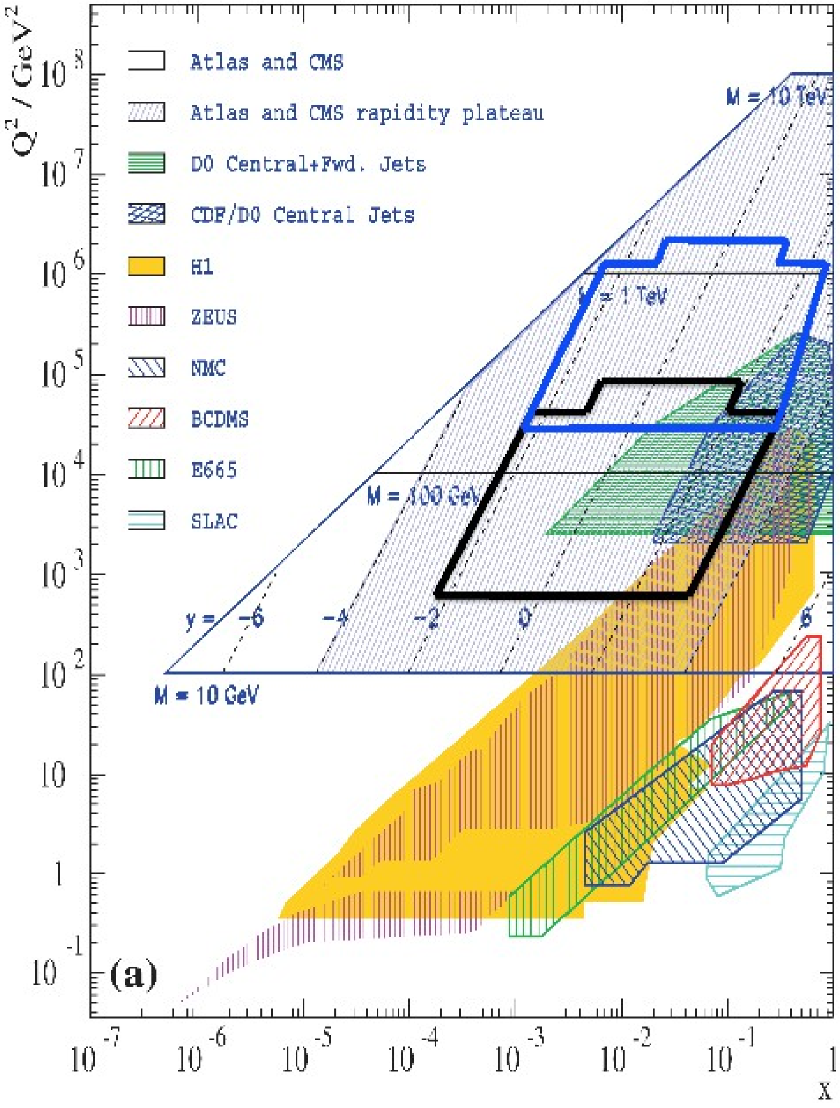
- The sea quarks here are the anti up, anti down, charm, strange
- Photons are colorless probes so could be used to constrain these



X is defined as the fractional momentum of the partons within the proton

Reach of Analysis

- Blue box
  - Reach of current analysis
- Black box
  - Reach of previous results
- Q^2
  - momentum transfer of the partons in the collision
- x
  - fractional momentum of the partons within the proton



Monte Carlo

- Used to simulate different physics processes
- Typically events are simulated in three separate steps:
  - parton showering (PS)
    - simulating a successive generation of random gluon emissions or splitting (for example ($g \rightarrow \bar{q}\, q$))
  - hadronization
    - converting partons into hadrons
  - multiple interactions (MI)
    - underlying events not included in the PS
- Specifically used is PYTHIA and HERWIG

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Cross Section

- is the effective area that gives the probability of some scattering event
  - Likelihood that a reaction will occur
- $N = L\sigma$
- N :is the number of particles found at a particular time
- L :is instantaneous luminosity (beam intensity or the amount of particles that can collide)
- σ :is cross section (probability an event will occur)
- Barn
  - Is a unit of area
  - 10^{-28} m^2
  - Such small measurements use picobarns

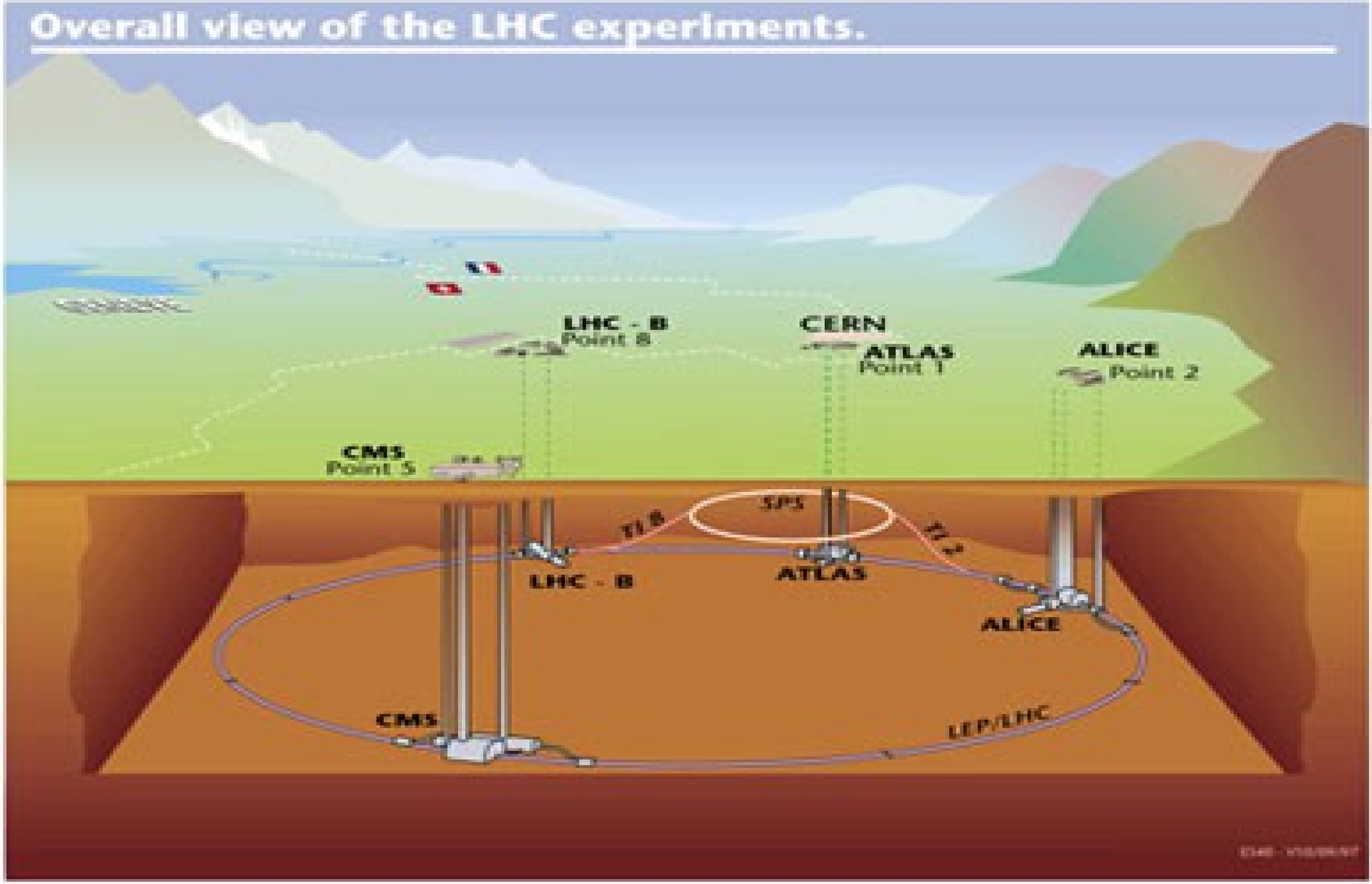
Differential Cross Section

- Differential cross section are in bins of a variable $\frac{d\sigma_i^{isol,k}}{dE_T^{true}}$, $\frac{d\sigma_i^{isol,k}}{d\eta}$

$$\left\langle \frac{d\sigma_i^{isol,k}}{dE_T^{true}} \right\rangle = \frac{1}{\int L\,dt} \frac{N_i^{\gamma,sel,isol,k}}{C_i(\gamma)\,\Delta E_{T,i}^{reco}}$$

- $N_i^{\gamma,sel,isol,k}$ is the number of prompt photons in the selected sample after correcting for the signal direct-purity measurement
- $\Delta E_{T,i}^{reco}$ the bin width
- $\int L\,dt$ Is equal to 4.64/+-0.09 fb^{-1} which is the data sample under study.
- $C_i(\gamma)$ is the correction factor

Accelerator and Detectors



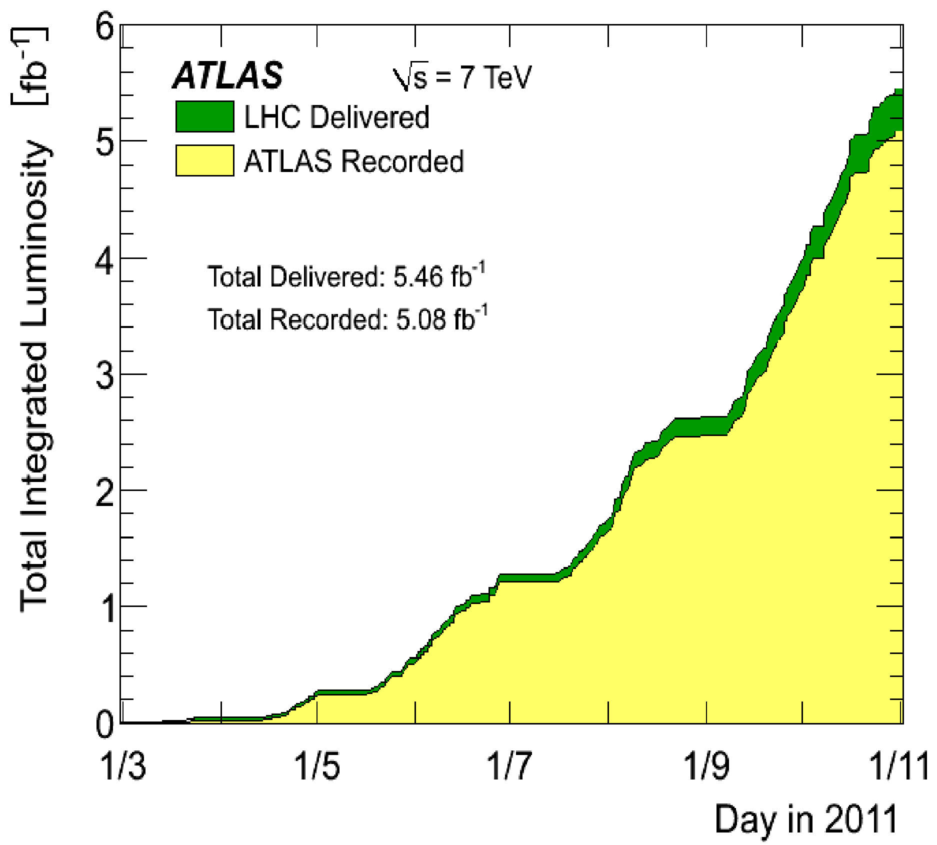
Large Hadron Collider (LHC)

- 27 km ring
- Design $\sqrt{s}$ =14 TeV CME
- Design instantaneous luminosity
  - $L=10^{34} cm^{-2}s^{-1}$
- My analysis $\sqrt{s}$ =7 TeV CME
- My analysis instantaneous luminosity
  - $L=10^{32} cm^{-2}s^{-1}$
- Near Geneva, Switzerland
- Super conducting magnets
  - Steering
- Radio Frequency (RF) system
  - Accelerating

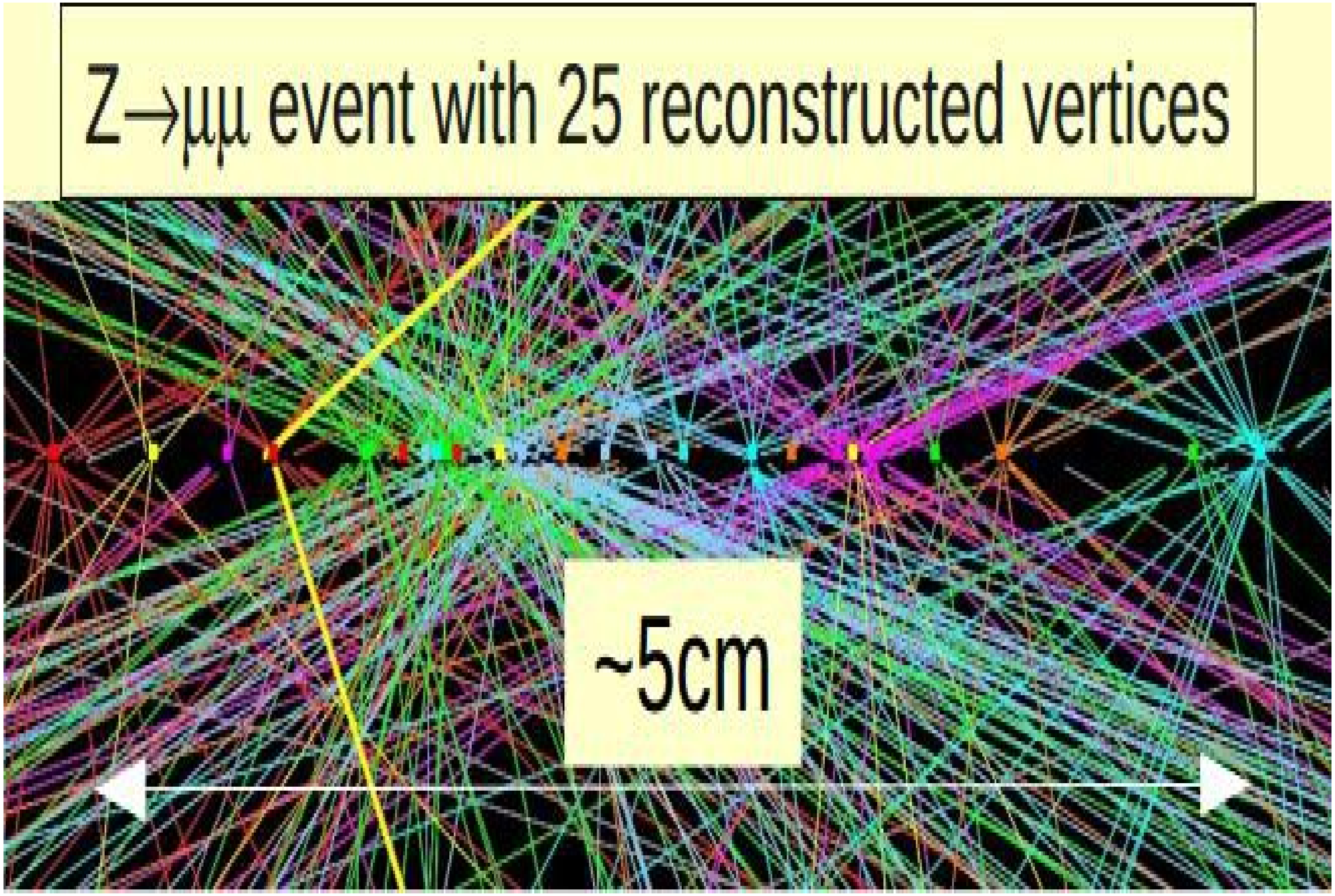
- Proton Proton collision

Luminosity

- Integral of instantaneous luminosity
- The amount of data available
- Large luminosities are preferred
  - reduce the statistical uncertainty in rare physics processes
- To obtain high luminosities in a reasonable time
  - High interaction rates are required

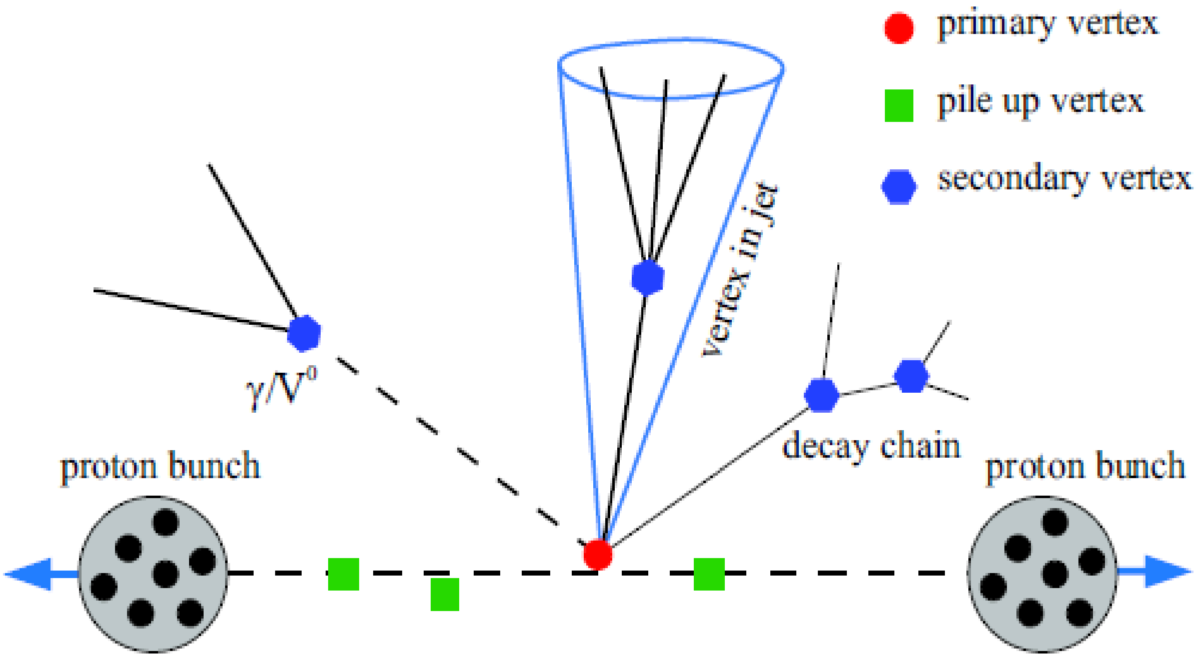


Pileup



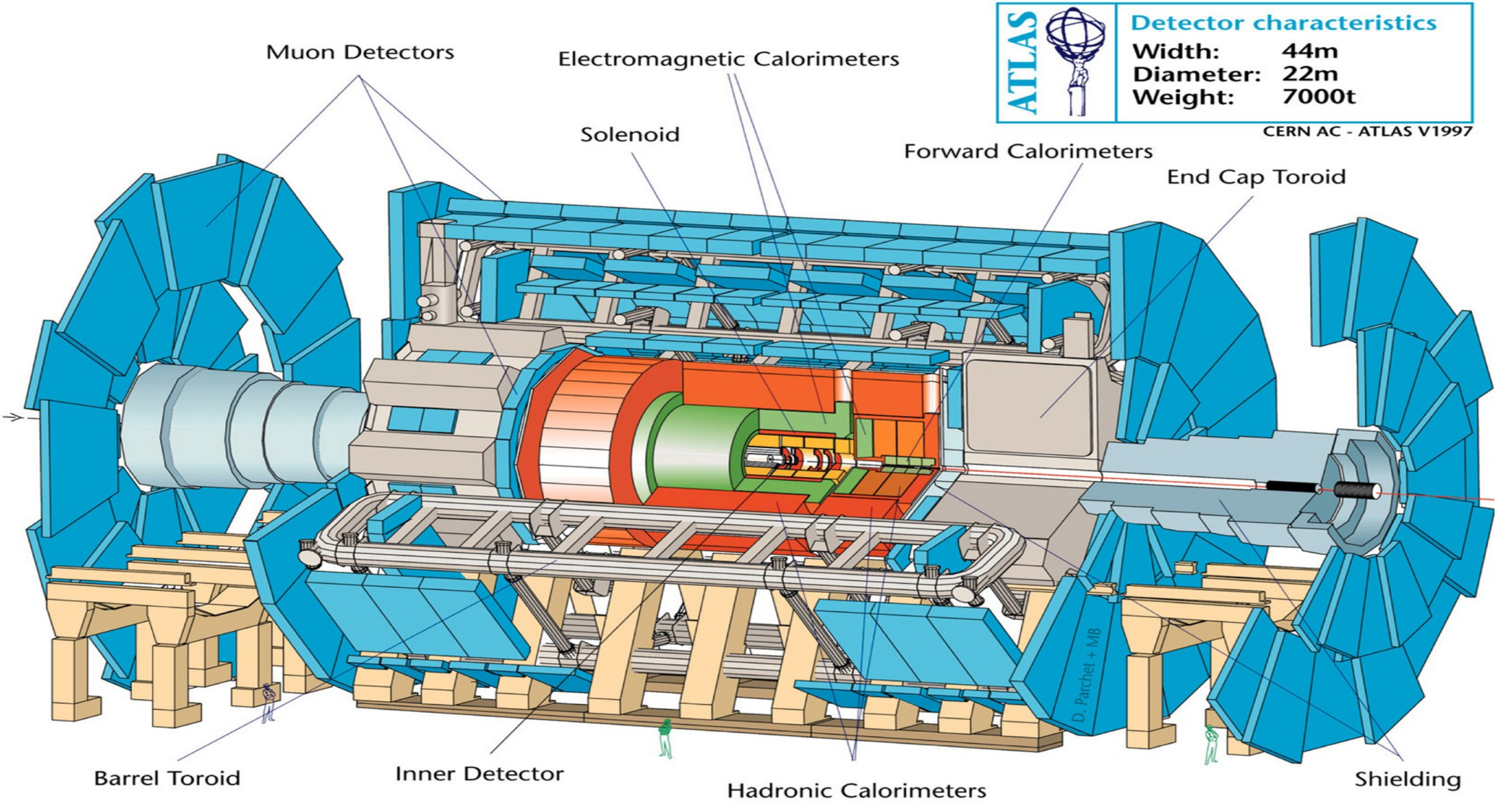
Pileup

- Large collision rates lead to multiple interactions
  - This is caused by additional soft interactions that accompany a hard interaction
    - In time
    - Out of time
- In time
  - Other partons in protons in the same bunch
- Out of time
  - Other bunches have colliding partons in the protons



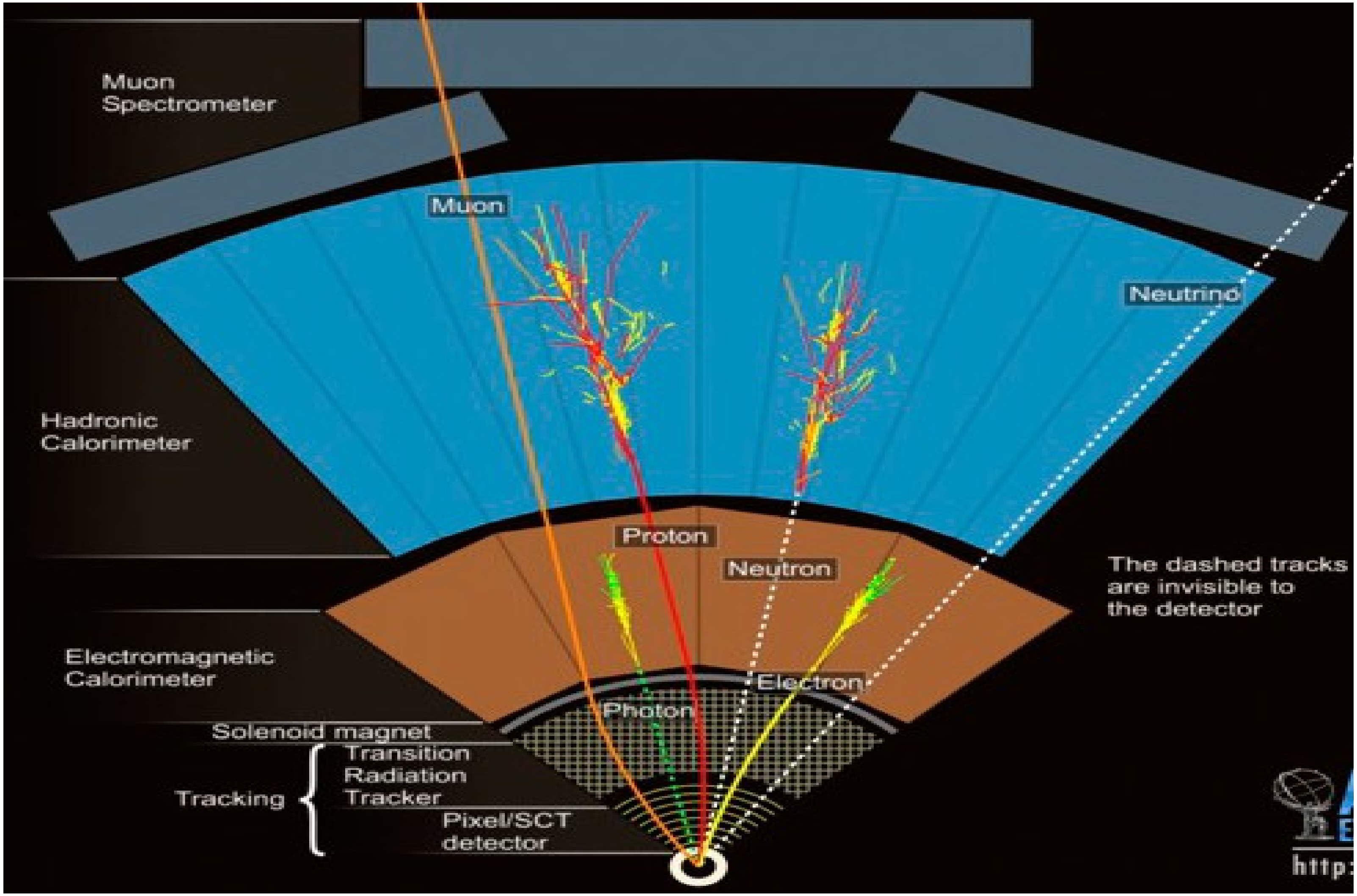
- Time difference is ~ 10^{-9} s for in time and out of time pileup

A Toridal LHC ApparatuS



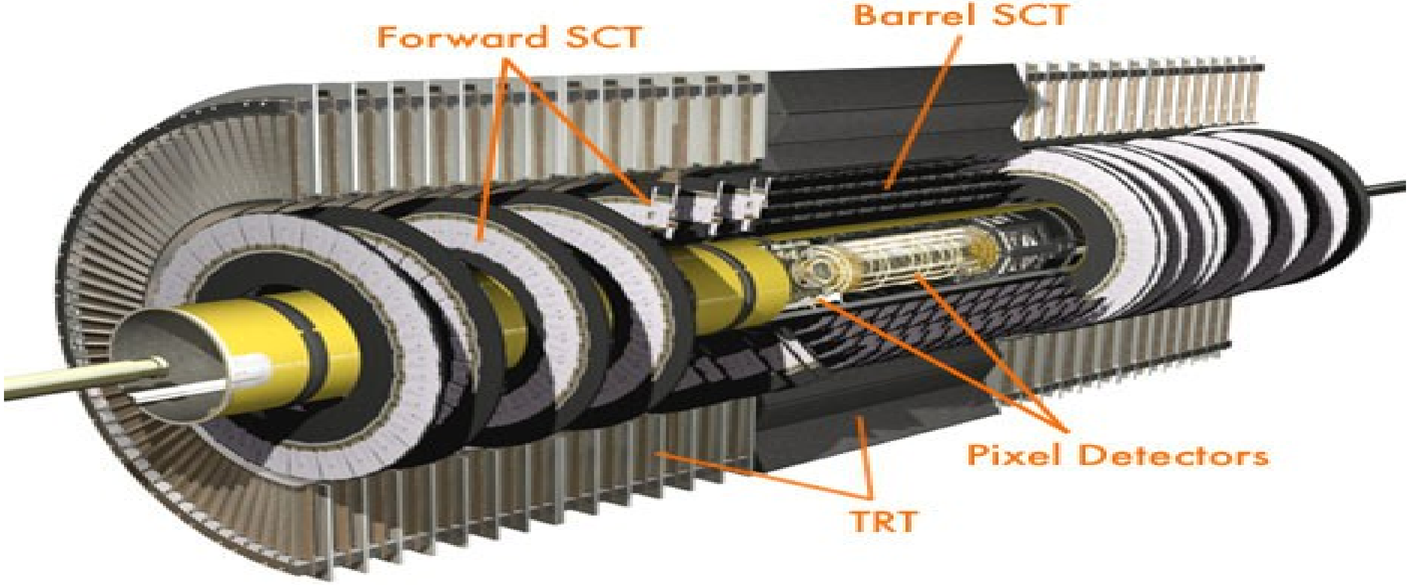
- ATLAS

Particle Detection



- Particles interact with matter leaving energy to be detected

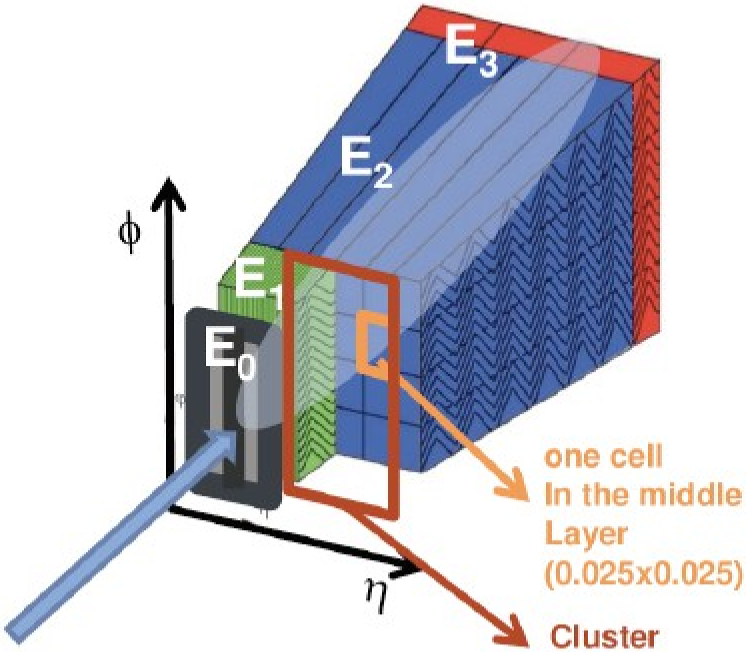
Inner Detector

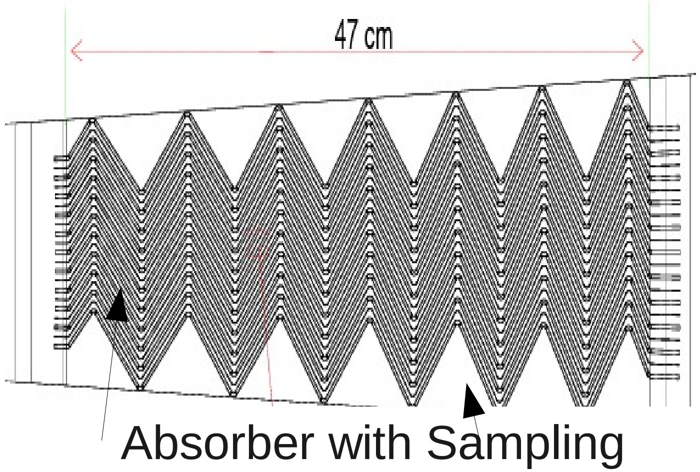


- Accurately reconstructs charged tracks
- Accurately reconstruct primary, soft(pileup) and secondary vertices
- Accurately reconstruct conversion photons out to 80 cm
- Resolution along the beam pipe 130 μm

ECAL

- Sampling calorimeters
- Only measure a portion of the energy
- Lead acts as the absorbing material
- Liquid argon as the sampling material
- At least 22 radiation lengths thick
- A radiation length is the distance in which an electron loses 1/e of its energy





Absorber with Sampling in-between

ECAL calibration

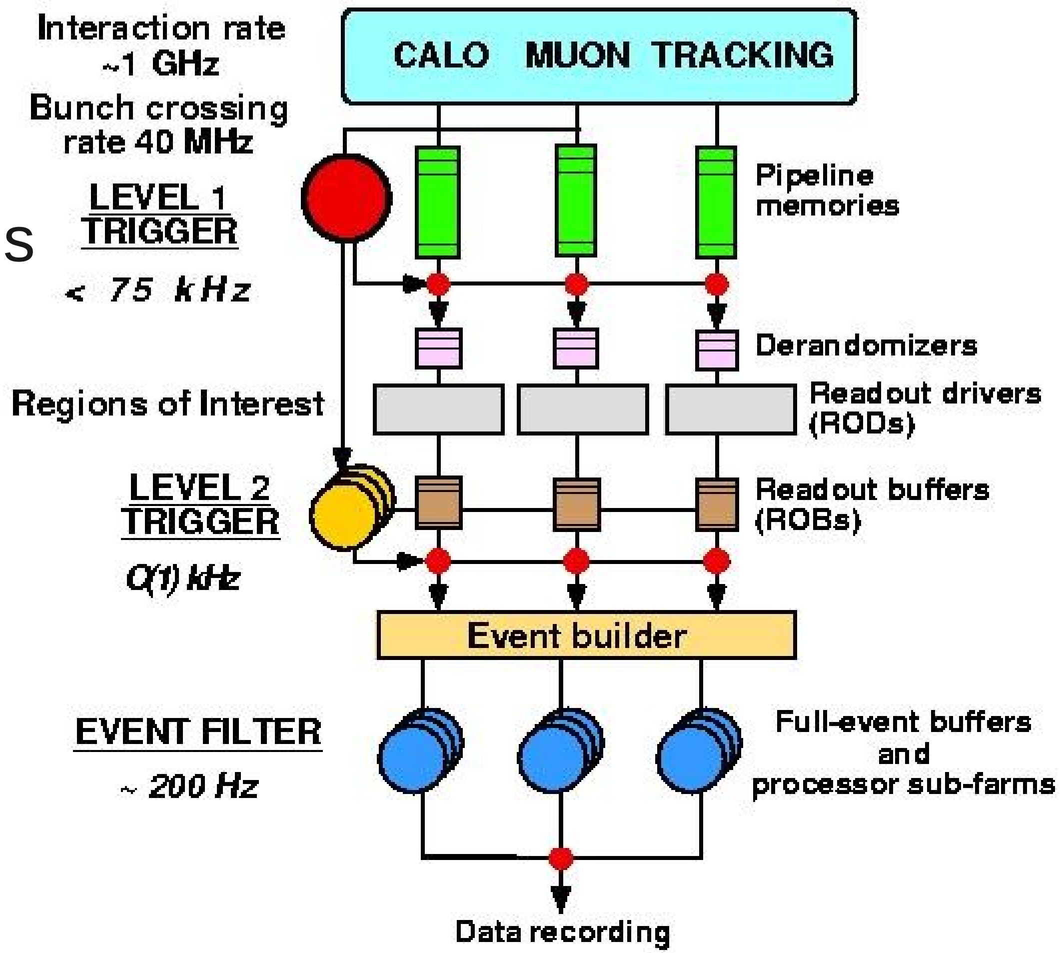
- Send a voltage pulse of known energy through the detector
  - This energy is read out with the raw electronic signals and then converted to an energy value.
  - This change in energy gives the sampling change in energy
- A correction factor due to energy loss not from sampling just from inner detector material is applied
  - This correction factor is based on MC simulations of the detector.
- Then as a cross check can be done with the Z mass being reconstructed using $Z \rightarrow e^+e^-$
  - in data and compare it to the MC simulations.

ECAL Resolution

- $\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \otimes \frac{b}{E} \otimes c$
- a is the stochastic term (sampling term)
- b is the noise term
- c is the constant term
- $\otimes$ represents a quadratic sum
- a is the largest contributer to resolution up to about 200 GeV and varies between 10% and 17%
- c takes over then and is ~0.7%

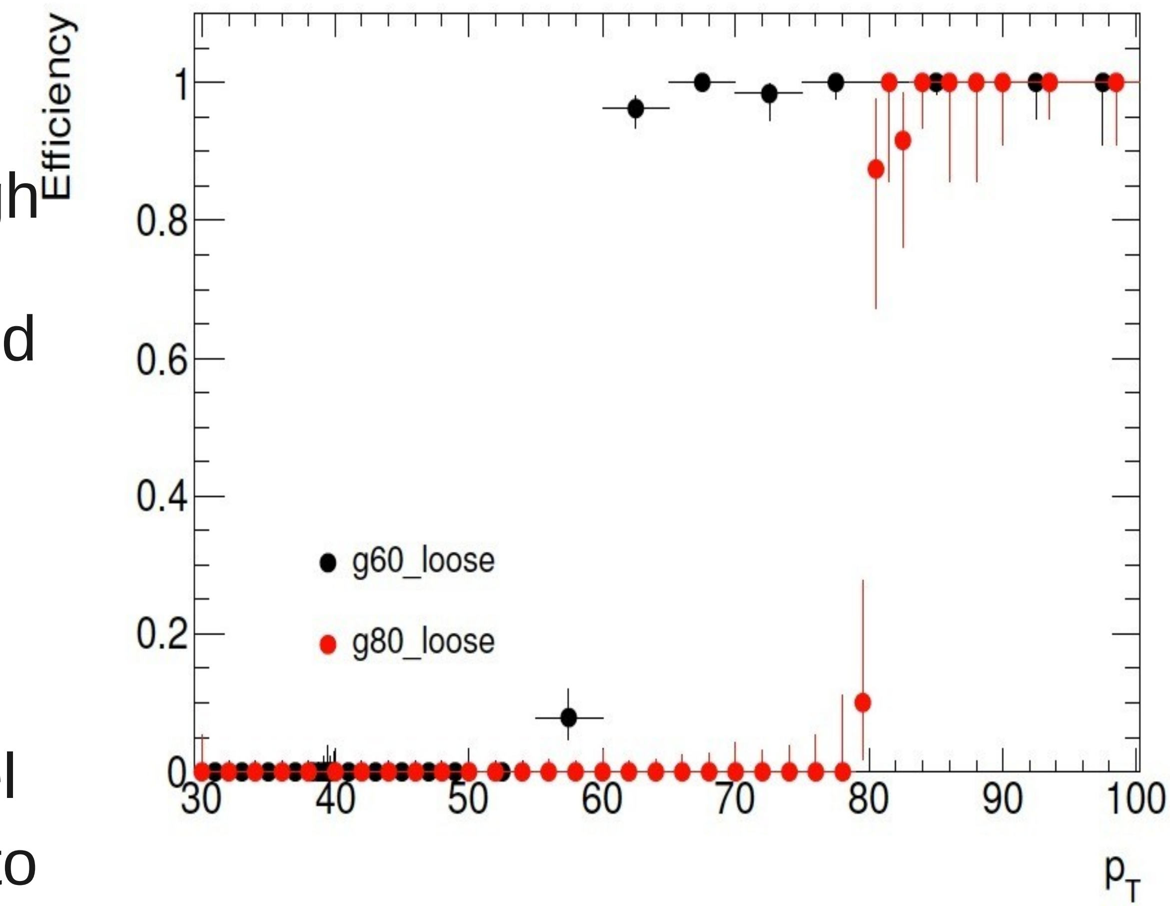
Trigger System and Requirements

- Level 1
  - Electronic based
  - ECAL energy deposited needs to be greater than 30 GeV
- Level 2
  - Combining information from more detectors
- High Level Trigger
  - Loose, medium, tight
  - Photons that are greater than 80 GeV and is loose (only a couple of shape variable cuts)

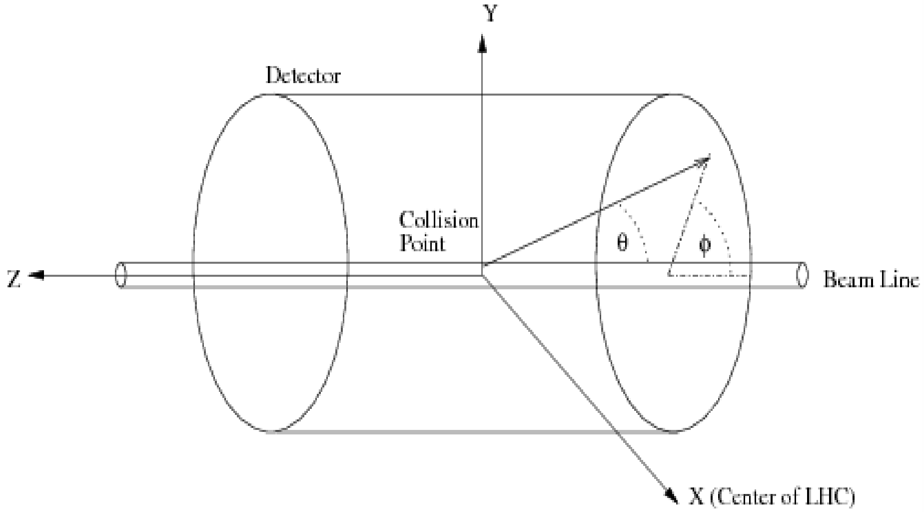


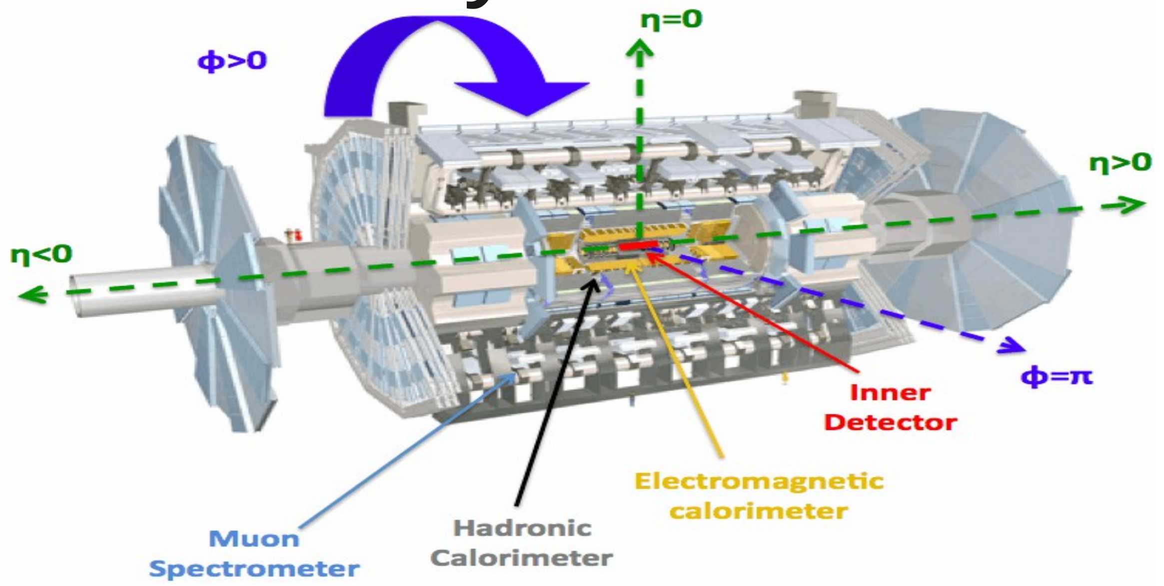
Trigger

- Trigger efficiency
  - Is defined as the efficiency for an event to pass through a photon trigger with a transverse energy threshold greater than the trigger
- The trigger efficiency is
  - determined using a data-driven technique based on low-E_T^γ threshold high-level triggers, and is measured to be 100^{+0}_{-3}% for $E_T^\gamma > 100$ GeV



ATLAS Coordinate System

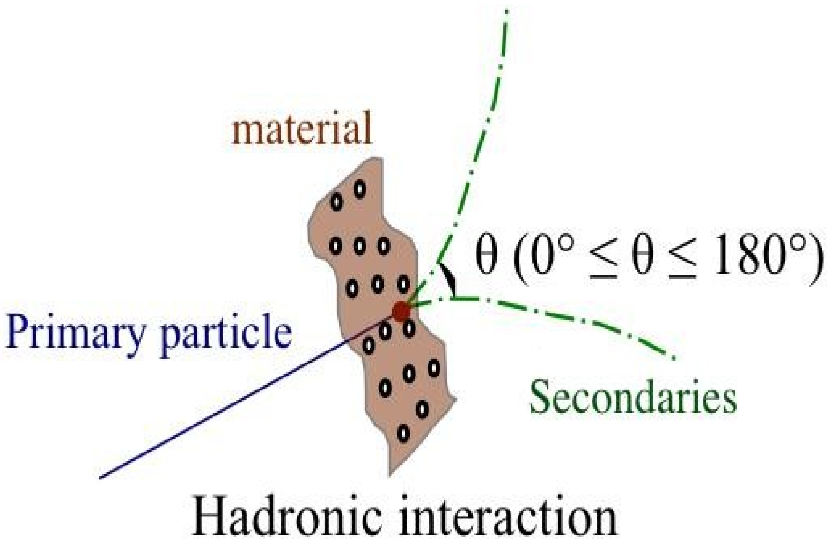


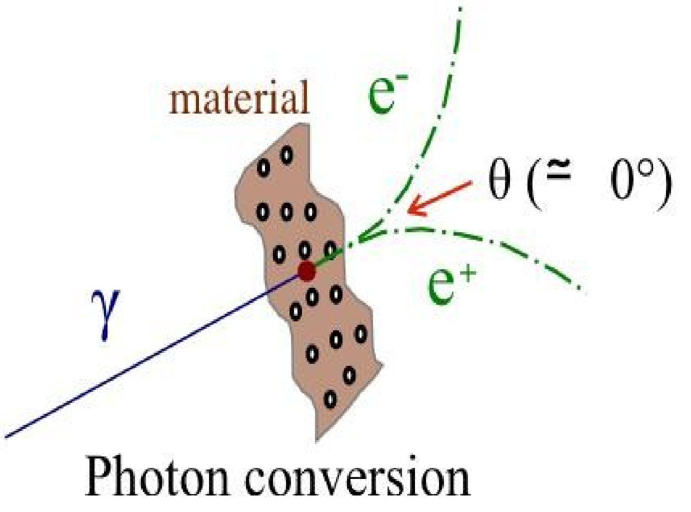


- $y=\frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$ Rapidity: Invariant under boost
- when mass is zero this equals pseudorapidity $\eta=-\ln(\tan(\frac{\theta}{2}))$
- Polar angle θ is measured from the z-axis
- η, ϕ, $E_T=E\sin(\theta)$, $p_T=p\sin(\theta)$, side note: $E_T=p_T$, $E^2=p^2+m^2$
- In the transverse direction the energy and momentum is approximately zero of the colliding partons, therefore any significant transverse energy indicates a hard scatter

Converted vs Unconverted photon

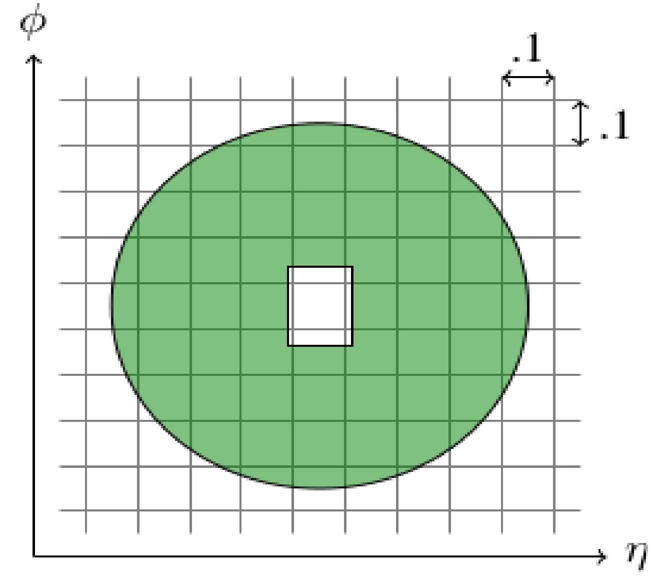
- Unconverted photons
  - Have energy in the ECAL with no track
- Converted photons
  - Have tracks
  - Photons convert because of the amount of material in the inner detector
  - Photons convert to an electron positron pair
  - Inner most detector, opening angle



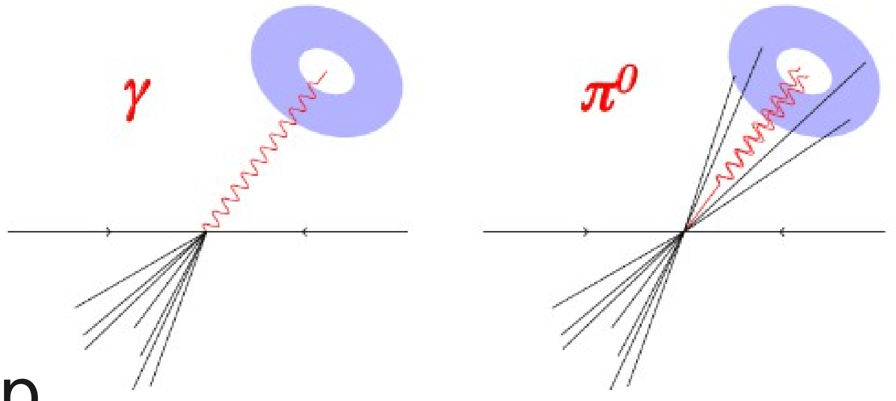


Isolation

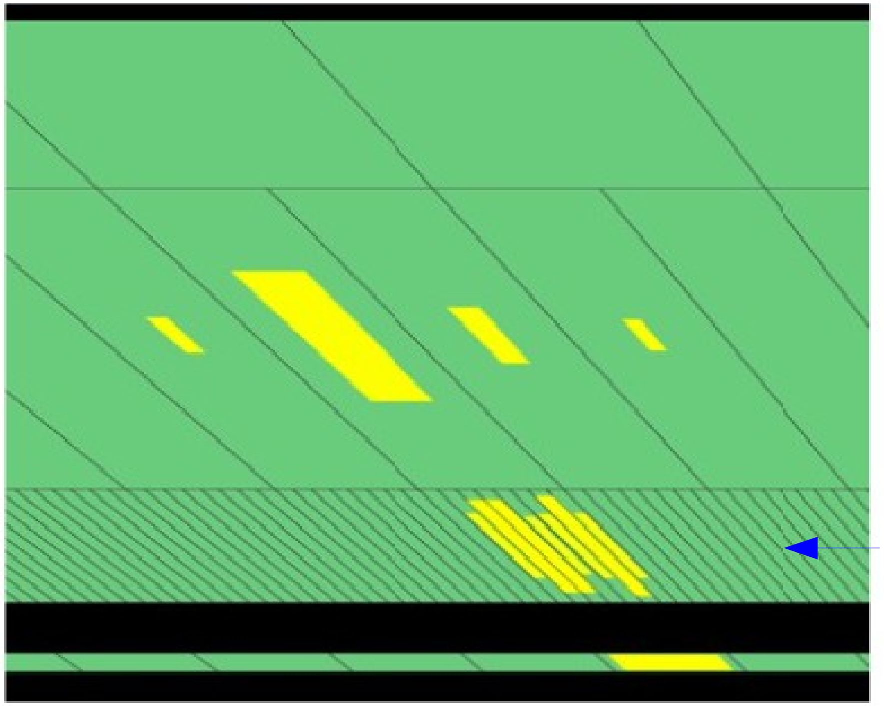
- Isolation requirements are designed to be highly efficient for signal events and used to reject fake photons such as $\pi^0 \rightarrow \gamma\gamma$ + jet and underlying events.
- Helps to remove some QCD background
- The isolation requirements are applied using the isolation energy.
  - $E_T^{iso} < 7$ GeV, cone 0.4
- Excluding the photon energy
- Removes the contribution from the underlying events and pileup



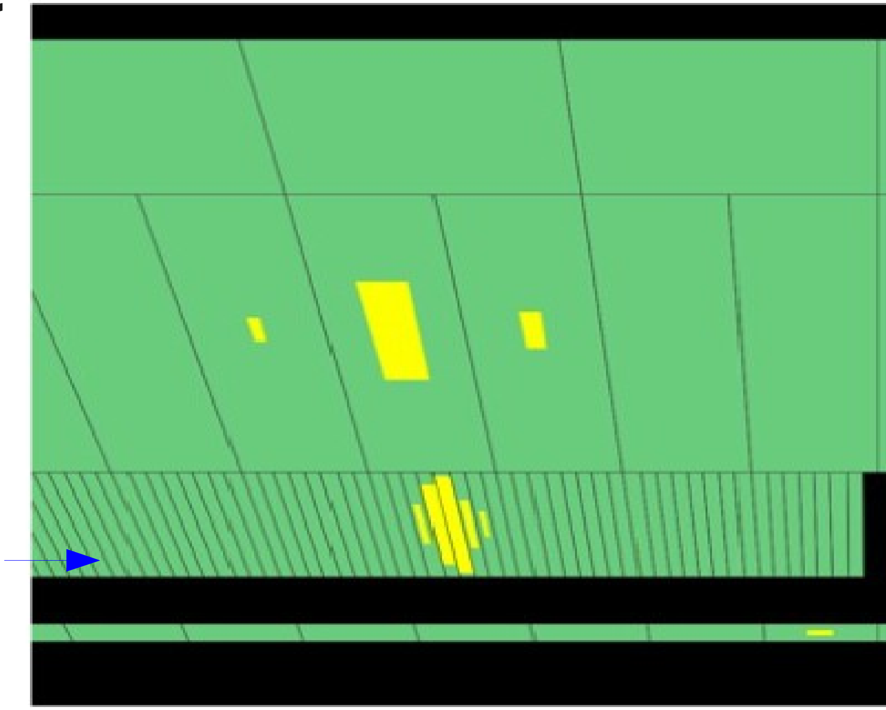
$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



Tight



π⁰ candidate → γγ



Prompt photon candidate

- Non-Tight
  - Larger energy deposited in the first layer
  - Two separate maxima in that layer
- Tight
  - Narrow energy in the first layer
  - One single maxima in the first layer

Tight Variables

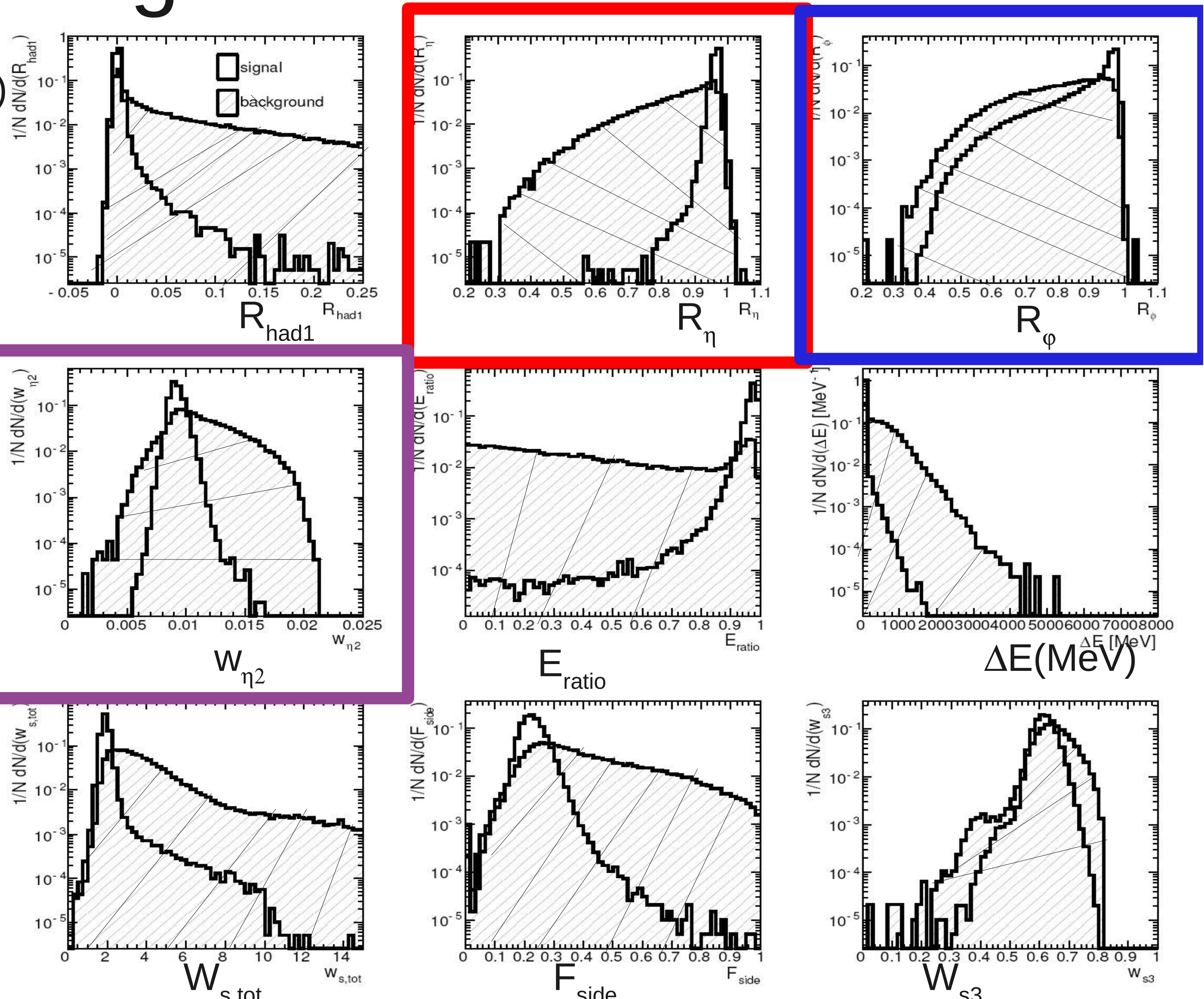
1/N(dN/ dvariable)

- List of tight variables

$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}}$$

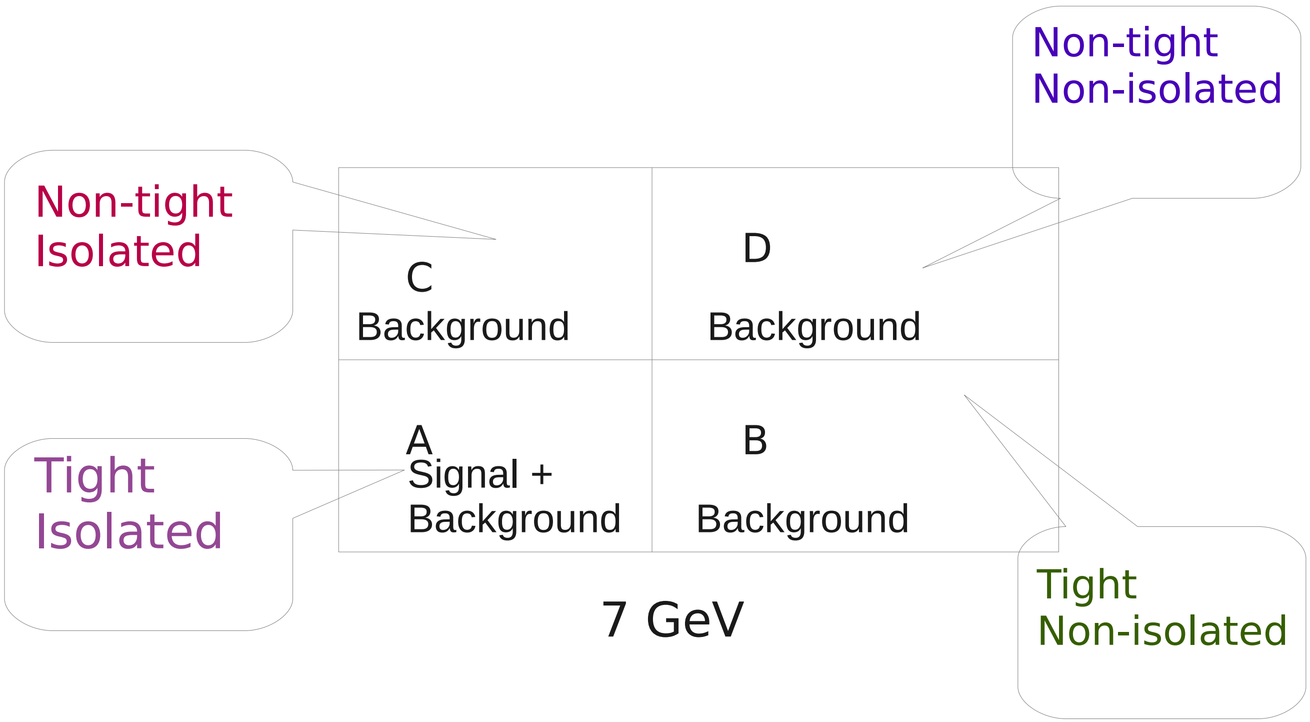
$$R_\phi = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$$

$$w_{\eta^2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left[\frac{\sum E_i \eta_i}{\sum E_i}\right]^2}$$



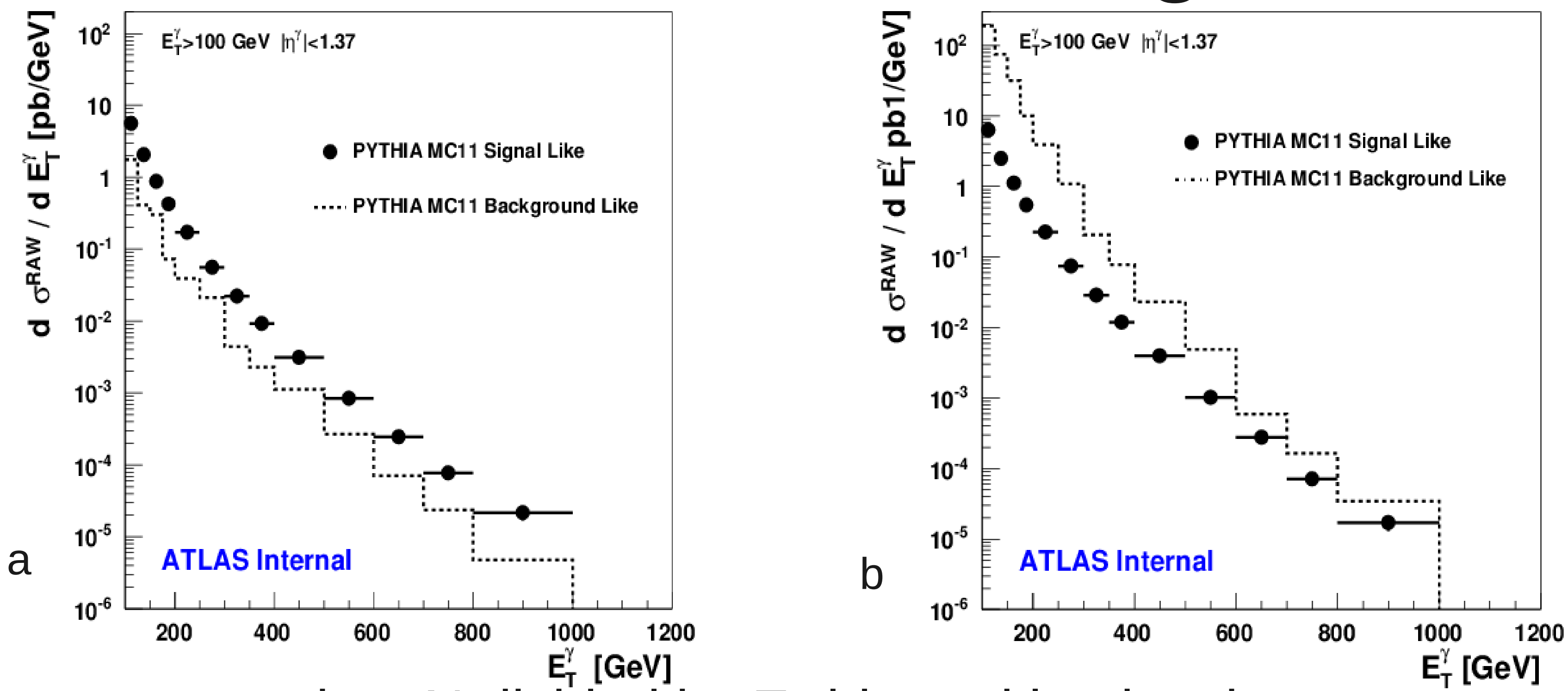
Two-Dimensional Side Band Method

- No knowledge of signal is required
- Background is deduced from observed data



- Two assumptions
  - Background has weak signal contamination
  - The shape of the background is independent of tight or non-tight.

Raw Cross Section Region A/D



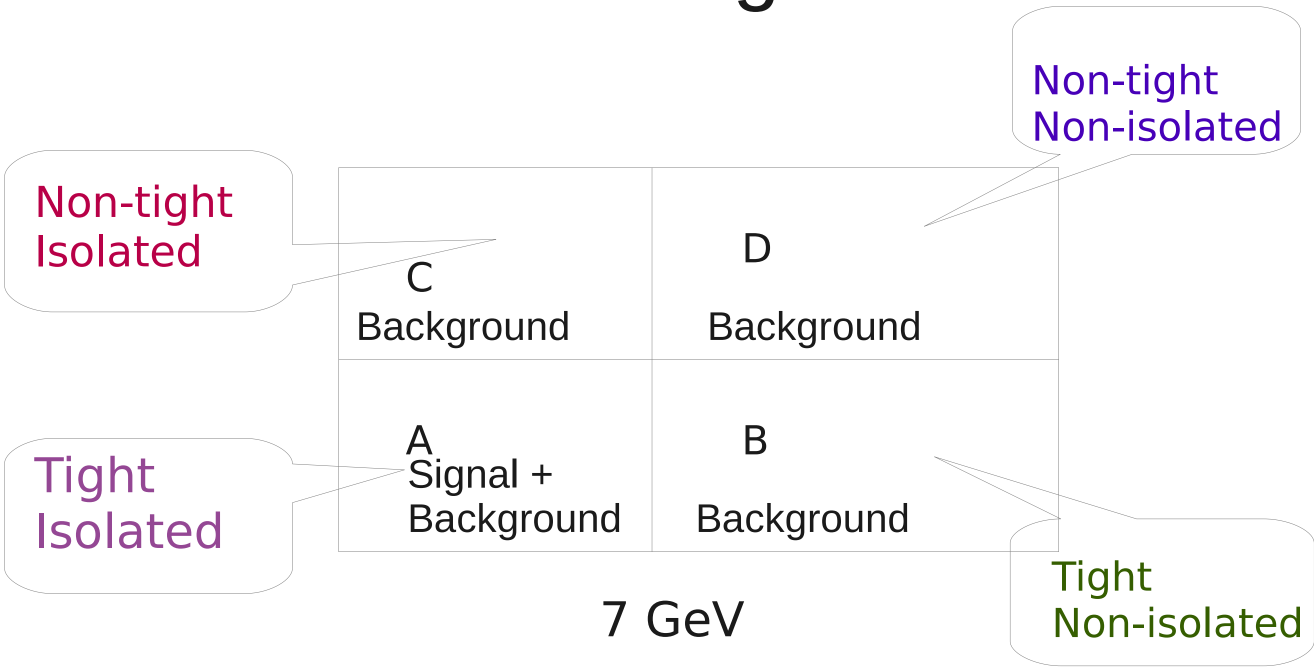
- Raw cross section: N divided by E_T bin and luminosity
- E_T^γ event distributions for signal MC and background MC before the detector corrections are applied.
- Figure (a) is for the signal like region, region A.
- Figure (b) is for the background region, region D.

Basic 2D Side Band Subtraction

- The **uncorrelated method** assumes that
  - there is no signal contamination in the background control region
  - And that the isolation and identification variables are uncorrelated for background events

$$N_A^{SIG} = N_A^{OBS} - N_A^{BKG}$$

$$N_A^{SIG} = N_A^{OBS} - \frac{N_C^{OBS} N_B^{OBS}}{N_D^{OBS}}$$



Correction for contamination

- Signal in the control regions is not completely negligible, it is on the order of 10%

$$c_K = \frac{N_K^{SIG}}{N_A^{SIG}}$$

K includes {B,C,D}

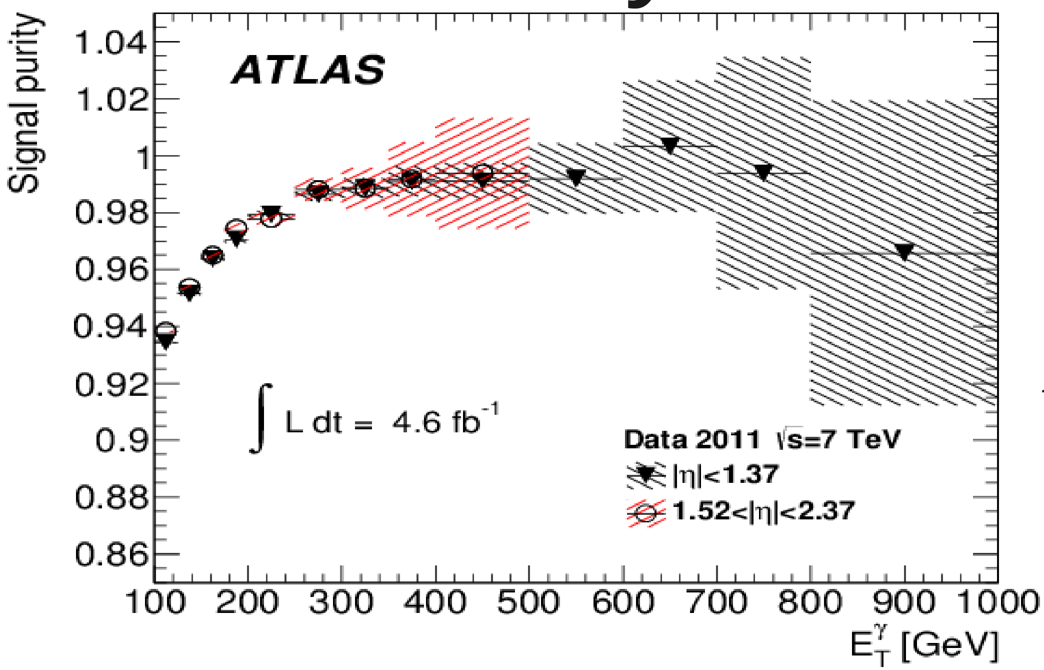
- To account for these effects a modified equation is used

$$N_A^{SIG} = N_A^{OBS} - \frac{\left(N_B^{OBS} - c_B N_A^{SIG}\right)\left(N_C^{OBS} - c_C N_A^{SIG}\right)}{N_D^{OBS} - c_D N_A^{SIG}}$$

- The variables in yellow come from Monte Carlo

Purity

- N_{true} is based on the Monte Carlo,
- N_{reco} is the reconstructed photons for data



$$P = \frac{N_{true}}{N_{reco}}$$

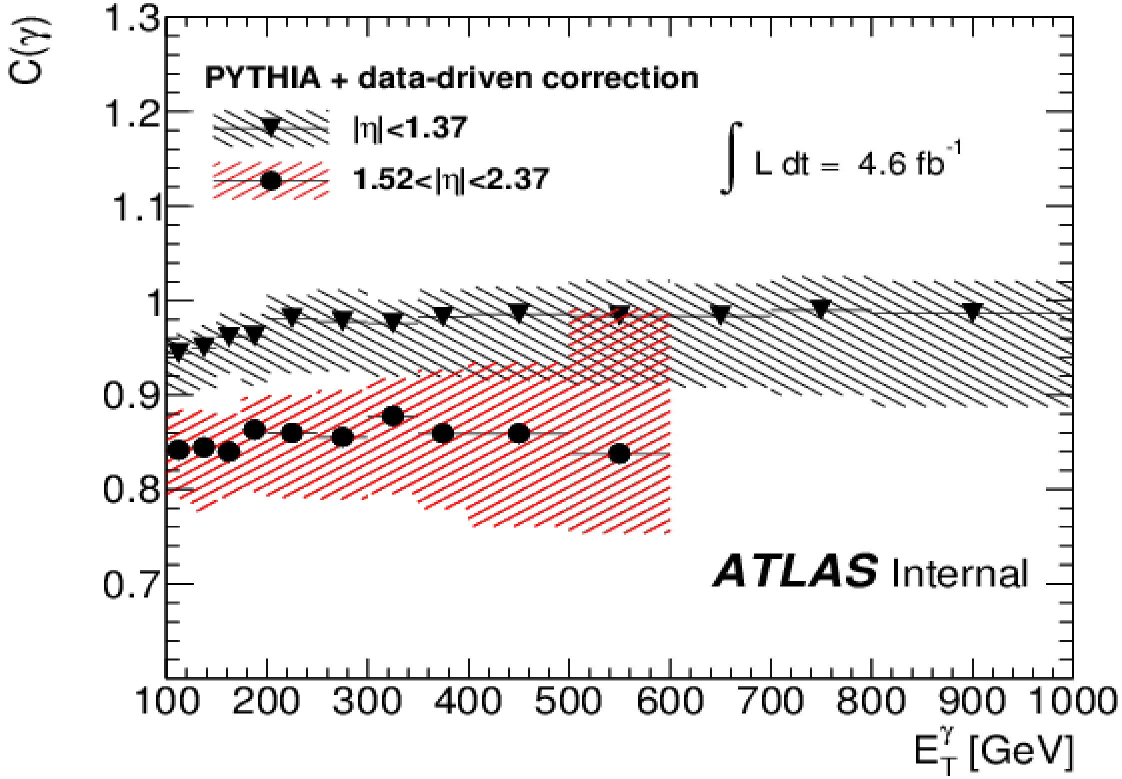
- Background is not all subtracted, so purity is how much background is left
- The signal purity for the barrel and endcap η^γ regions
- Estimated from the data using the two-dimensional side band approach shown in the “correlated” method
- The shaded bands indicate statistical uncertainty.

Correction Factor

$$C_i(\gamma) = \frac{N_i(reco)}{N_i(gen)}$$

- Accounting for detector issues: for example material
- N(reco) is the number of reconstructed photons
- N(gen) is the number of generated
- The correction factor $C_i(\gamma)$ accounts for
  - photon reconstruction efficiency, selection efficiency, event selection efficiency, identification efficiency, Bin by Bin migrations are taken into account, which deals with the resolution and is found to be very small

Correction Factor



- The correction factors as a function of E_T^γ used in this analysis.
- The shaded bands indicate the systematic uncertainties

Systematics

- Changing the isolation selection by +/-700 MeV, respectively, for the reconstructed-level MC approximately 2%;
- Scaling the transverse energies (low and upper variation, respectively) approximately 2 to 6%;
- Using HERWIG to evaluate the bin-by-bin correction factors on average 3.5%
- Using an alternative background subtraction technique (i.e. the uncorrelated side-band subtraction) approximately 3.5%;
- Systematic uncertainties associated to the different isolation selection approximately 1%;

Systematics

- Systematics on photon resolution approximately 1%;
- Systematics for the correction factor with +/-50% change to the number of photons from fragmentation respectively, approximately 0.5%
- Uncertainty on the cross section due to insufficient knowledge of the photon identification efficiency. 3%
- Systematics on the luminosity measurement approximately 1.8%

Energy Scale

- Uncertainty due to photon energy measurement
- Important because of the falling cross section
  - the error will increase because of this
- This is calculated by varying the photon energy scale within the expected uncertainty using Monte Carlo
- The effect of such a variation leads to an uncertainty between 2% at low E_t^γ and 6% at large E_T^γ

Monte Carlo

- Leading Order (LO)
  - PYTHIA
  - HERWIG
    - Use different hadronization methods
- Next to Leading Order (NLO)
  - a better description of the hard sub-processes
    - JETPHOX calculations
      - CT10, Martin-Stirling-Thorne-Watt (MSTW)

JETPHOX NLO uncertainties

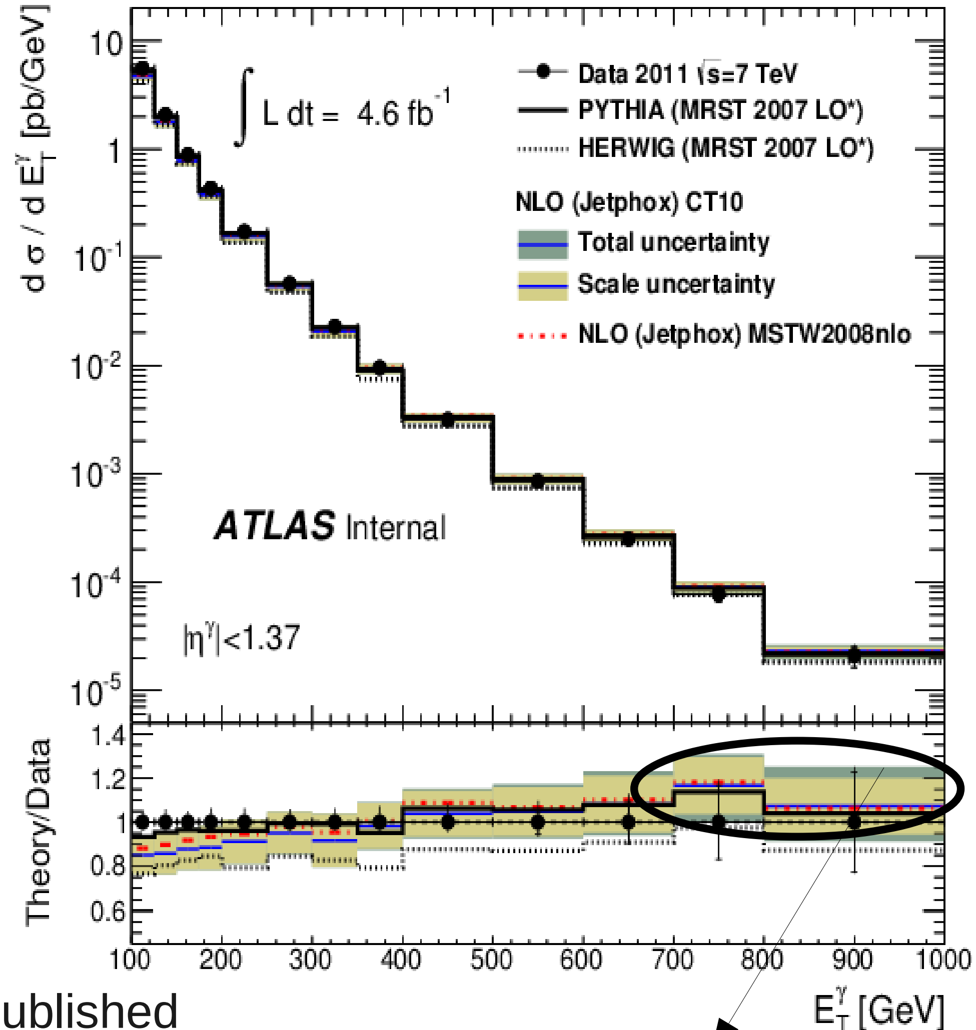
- Renormalization μ_R
  - takes into account infinities
  - includes them in the known quantities
- Factorization and fragmentation μ_F , μ_f
  - Small distance scales (PQCD) need to be separated from the large distance scales (non PQCD) this is taken into account through factorization
- Both set to Q^2 the momentum transfer
  - calculation should not depend on the choice for the scales as long as it is set on the order of the momentum transfer

NLO Systematics

- NLO uncertainties are calculated as follows:
  - scale changed by a factor of 2
  - Parton Distribution Functions (PDFs) uncertainties are calculated for
    - CT10 PDF
    - MSTW PDF
      - due to insufficient knowledge
- On the next slide the blueish green area shows both the scale+PDF errors

Differential Cross Section in E_T

- Isolation: 7 GeV. Cone size of .4
- Kinematic regions:
  - 100 GeV<Pt<1000 GeV
  - |η (γ)|<1.37
- The agreement between NLO calculations in data are good especially at higher p_T.
- The agreement for LO MC
  - PYTHIA is good
  - HERWIG underestimates
- Entering the regime where PDF (gluon) uncertainties are large (pT>700 GeV)!



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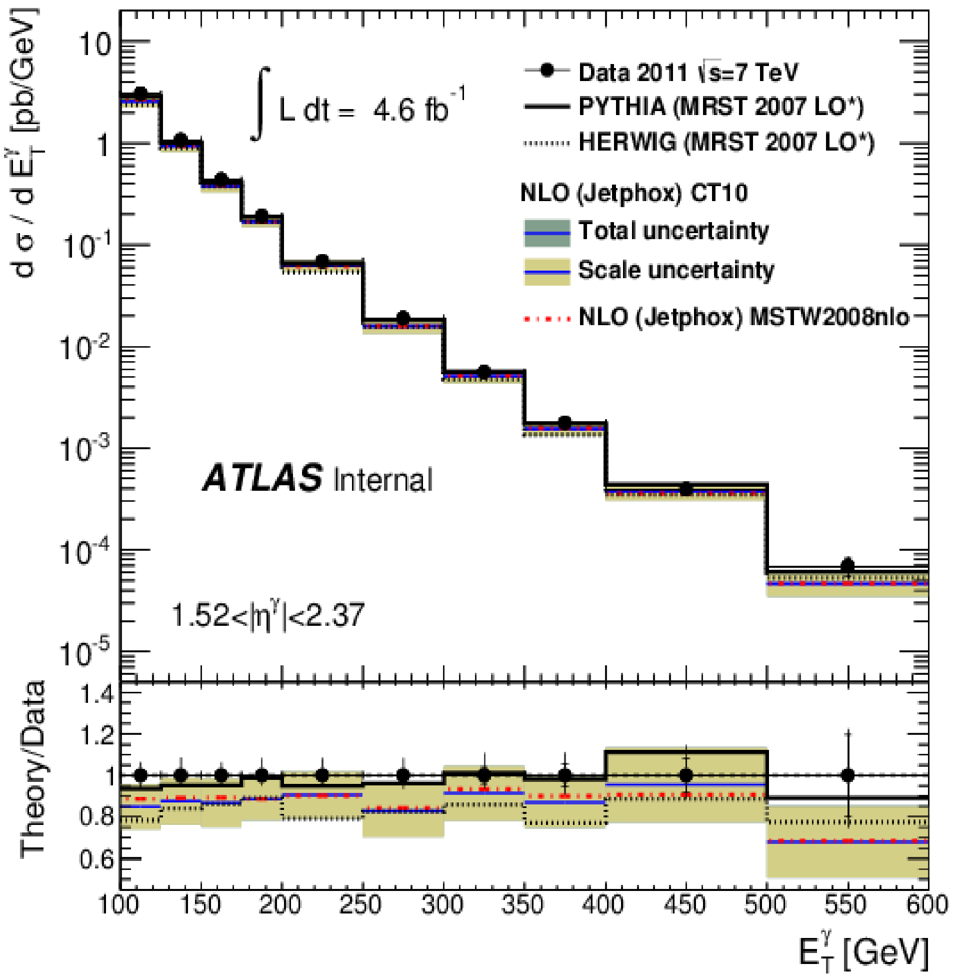
PDF uncertainties dominate

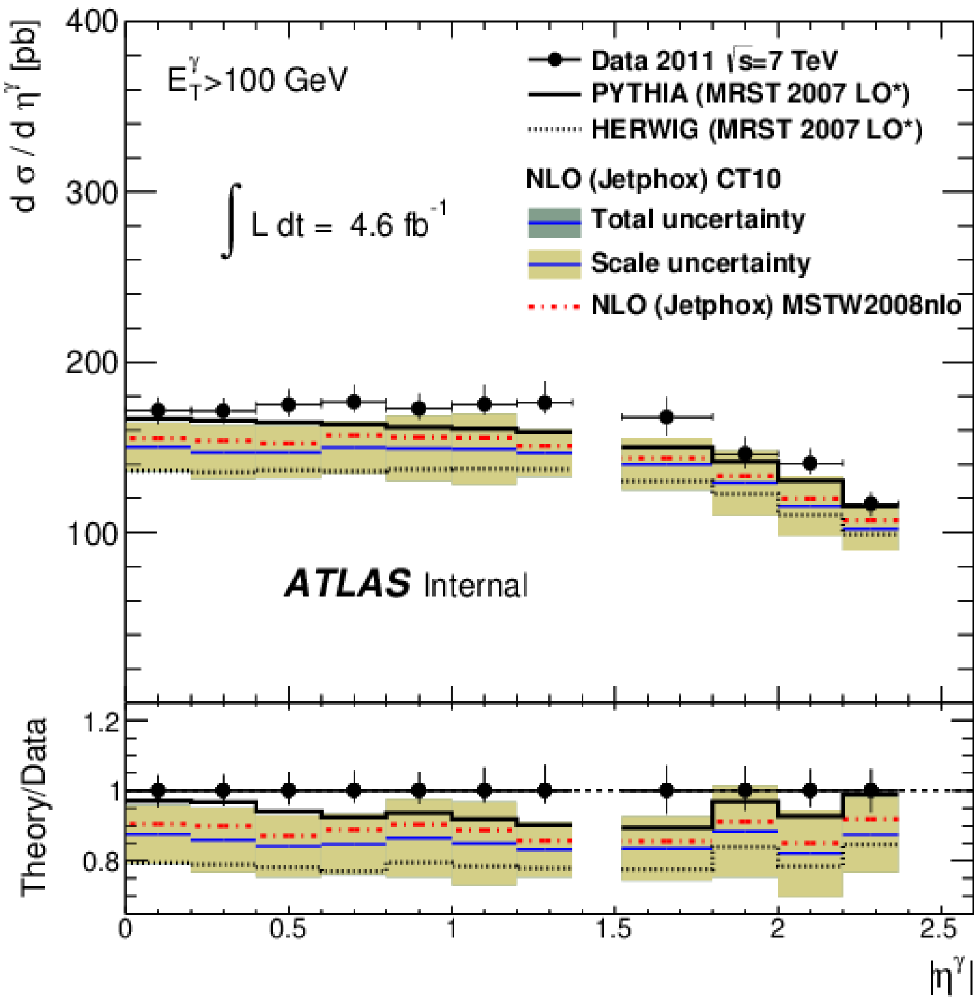
Differential Cross Section in E_T Forward Region

- The agreement between NLO calculations and data are good especially at higher E_T.
- PYTHIA has better agreement than HERWIG
- Large theoretical uncertainties
  - (~40% at large pT)



Differential Cross Section in η

- The NLO calculations slightly under estimates the cross section for the lower η bins
- The agreement between PYTHIA LO MC is the best
- HERWIG underestimates the differential Cross Section in η by 20%



Cross Section Numbers
Barrel region

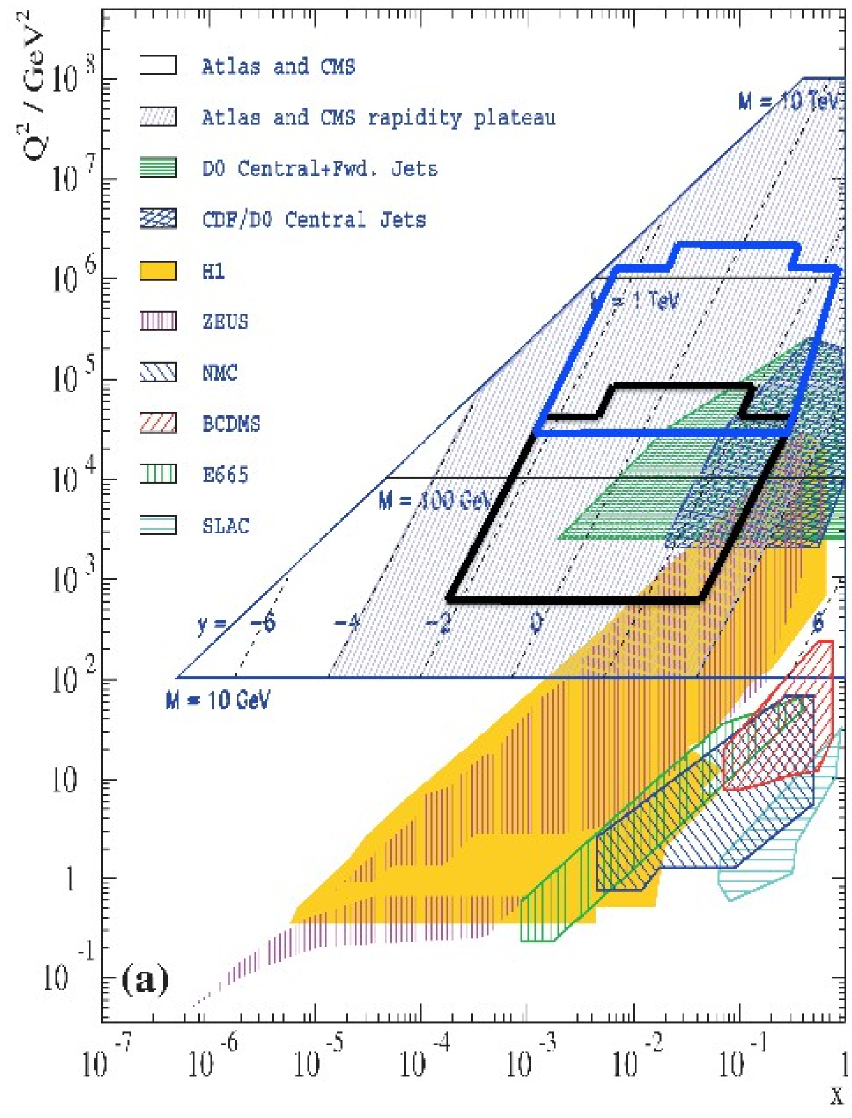
- Cross Section for data is:
  - $\sigma(\gamma + X) = 236 \pm 2$ (stat)+13/-9 (syst) $\pm$ 4 (lumi) pb
- The cross section for PYTHIA is:
  - 224 pb
- The cross section for HERWIG is:
  - 187 pb
- The cross section for CT10
  - 203 ± 28 (theory) pb
- The cross section for MSTW2008NLO
  - 212 ± 27 (theory) pb

Cross Section Numbers EndCap

- Cross Section for data is:
  - $\sigma(\gamma + X) = 123 \pm 2\ (\text{stat}) {+9/-7}\ (\text{syst}) \pm 2\ (\text{lumi})$ pb
- The cross section for PYTHIA is:
  - 118 pb
- The cross section for HERWIG is:
  - 99 pb
- The cross section for CT10
  - 105 ± 17 (theory) pb
- The cross section for MSTW2008NLO
  - 109 ± 17 (theory) pb

Reach of Analysis

- Blue box
  - Reach of current analysis
- Black box
  - Reach of previous results
- Q^2 (y-axis)
  - momentum transfer of the partons in the collision
- x (x-axis)
  - fractional momentum of the partons within the proton



Conclusion

- The first photon cross section to extend to 1 TeV
- There is better agreement at higher E_T.
- There is good agreement between both NLO sets and PYTHIA
- The HERWIG generator used under estimates the cross section
- The data in the barrel differential cross section at higher E_T can be used to constrain gluon PDFs

Backup Slides
Published papers 192
Internal notes 5
1 paper of First author

Prompt Photons

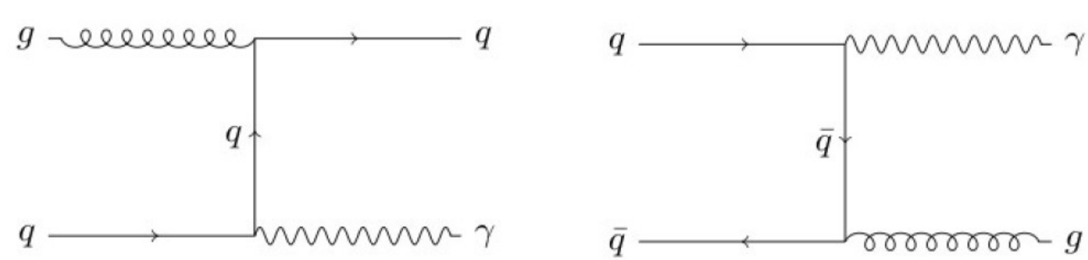
- The prompt photon is mainly produced via quark-gluon scattering ($qg \rightarrow \gamma q$) in proton-proton collisions.

Introduction

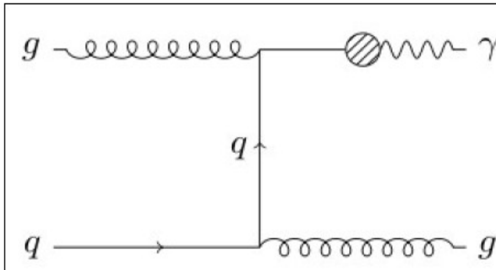
- Isolated prompt photons
- E_T > 100 GeV using 4.6 fb^{-1}
- Two $|\eta(\gamma)|<1.37$ and $1.52<|\eta(\gamma)|<2.37$
- Two categories of photons:
  - Direct: from the hard process
  - Fragmentation: fragment of a colored high p_T parton
- Cross section extended to 1 TeV
- Comparison between LO and NLO MC

Motivation

- Prompt photons are colorless probes of hard scattering processes.
- Useful in testing of perturbative QCD
- Can help to understand backgrounds for searches
- Can be used to constrain gluon PDF



Direct photons



Fragmentation photons

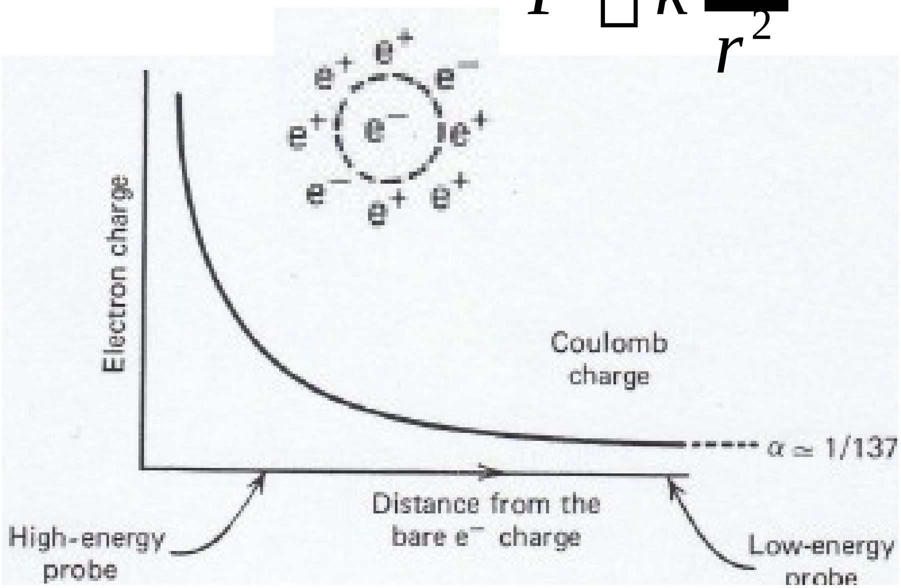
Higgs/SUSY

- Higgs Gives mass to all particles Standard model particle
- Explains difference in massless photon and massive W,Z
- Higgs mechanism/Scalar bosons
- Mass is exclude in this range 158 $GevC^{-2}$ to 175 $GevC^{-2}$
- Greater then 114GeV less than ~300GeV

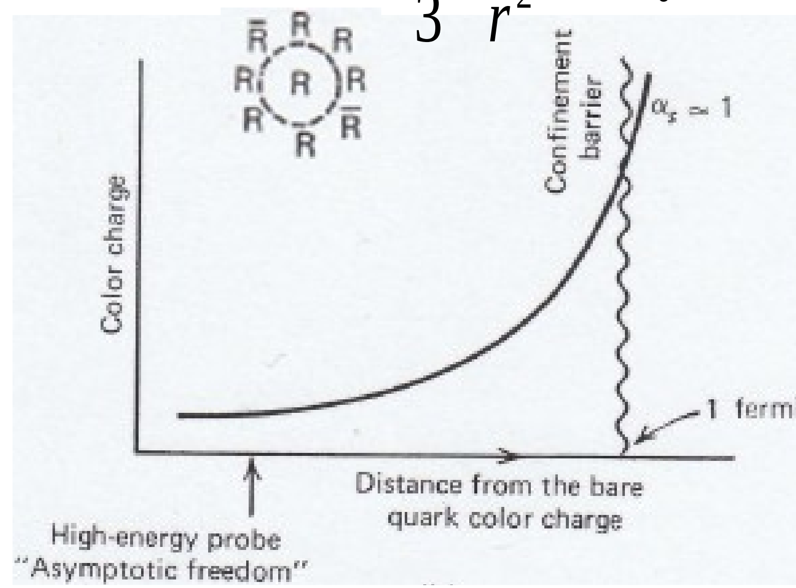
- Supersymmetry
- Relates elementary particles of one spin to other particles that differ by half a unit of spin known as super partners
- For every fermion there is a boson
- Beyond the standard model physics

Screening vs Anti Screening

QED $F = k\frac{qq}{r^2}$



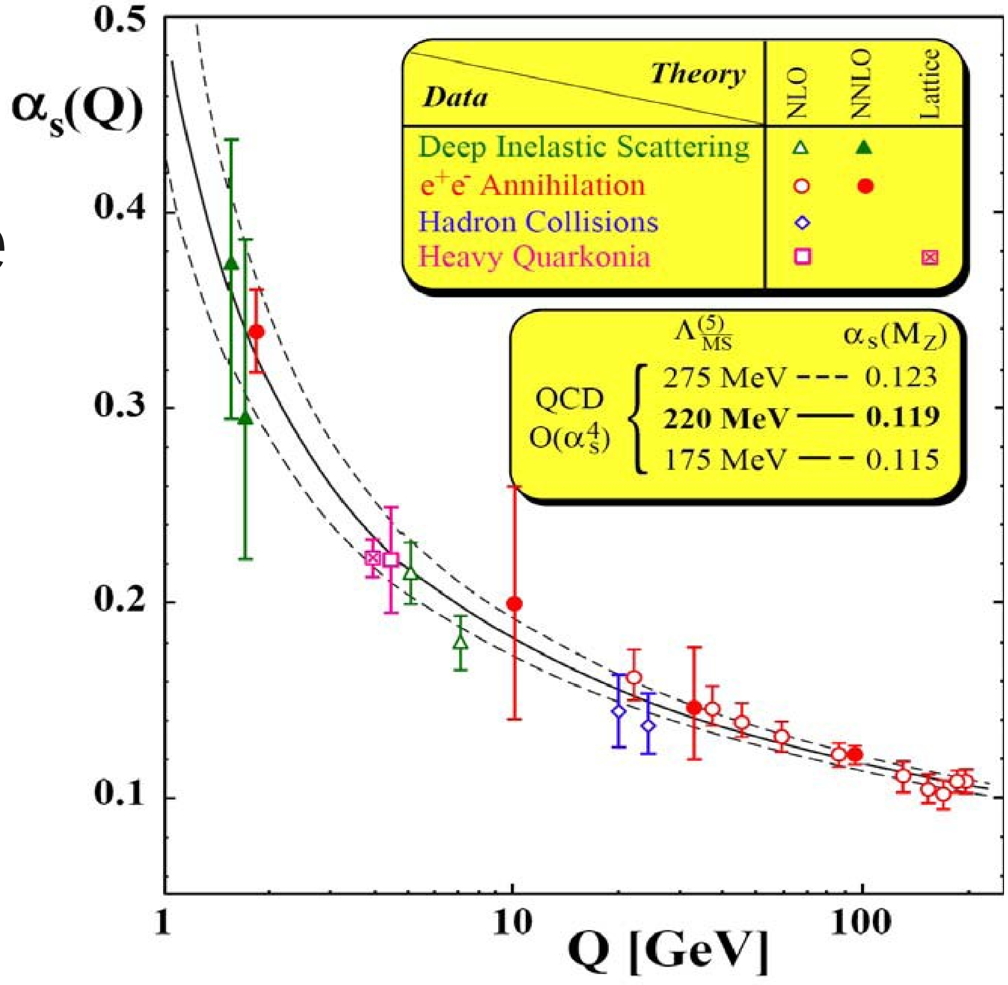
QCD $F = \frac{2}{3}\frac{\alpha_s \hbar c}{r^2} + F_0 r$



- Screening deals with QED
- Anti-Screening deals with QCD
- The coupling constants depend on distance

Asymptotic Freedom

- When quarks have high energies at close distances the strong force becomes weak.
- This was first observed from deep inelastic scattering.



LHC

- LINAC2
  - Ionize hydrogen: through the electric field that removes the electrons leaving the proton bare
- Linear accelerator
  - Photons are injected into
- PSB
  - Proton synchrotron booster
- PS
  - Proton synchrotron
  - Grouped into bunches
- SPS
  - Super proton synchrotron
  - Accelerate to 450 GeV
- Moved into the LHC ring

LHC

$$r = La$$

$$a = \frac{4\pi \varepsilon_n \beta^{star}}{\gamma_R F}$$

- Rate equals instantaneous luminosity times cross sectional area of the beam at the interaction point

- β_{star} measure of beam width
- γ_r relativistic lorentz
- F angle at crossing
- ε normalized transverse beam emittance

LHC

$$L = \frac{N_P^2 k_P f_{rev} \gamma_r}{4\pi \beta^{star} \varepsilon_n}$$

- N_p number of photons per bunches
- K_p number of bunches per beam
- Frev frequency of revolutions
- β_{star} measure of beam width
- γ_r relativistic lorentz
- ε normalized transverse beam emittance

PQCD

- with an energy of the Z mass 90 GeV
- Hadrons, along with the valence quarks (qv) that contribute to their quantum numbers, contain virtual quark–antiquark (qq) pairs known as sea quarks (qs).
- Sea quarks form when a gluon of the hadron's color field splits; this process also works in reverse in that the annihilation of two sea quarks produces a gluon. The result is a constant flux of gluon splits and creations colloquially known as "the sea". Sea quarks are much less stable than their valence counterparts, and they typically annihilate each other within the interior of the hadron. Despite this, sea quarks can hadronize into baryonic or mesonic particles under certain circumstances

Calculations

$$A+B\rightarrow C+X$$

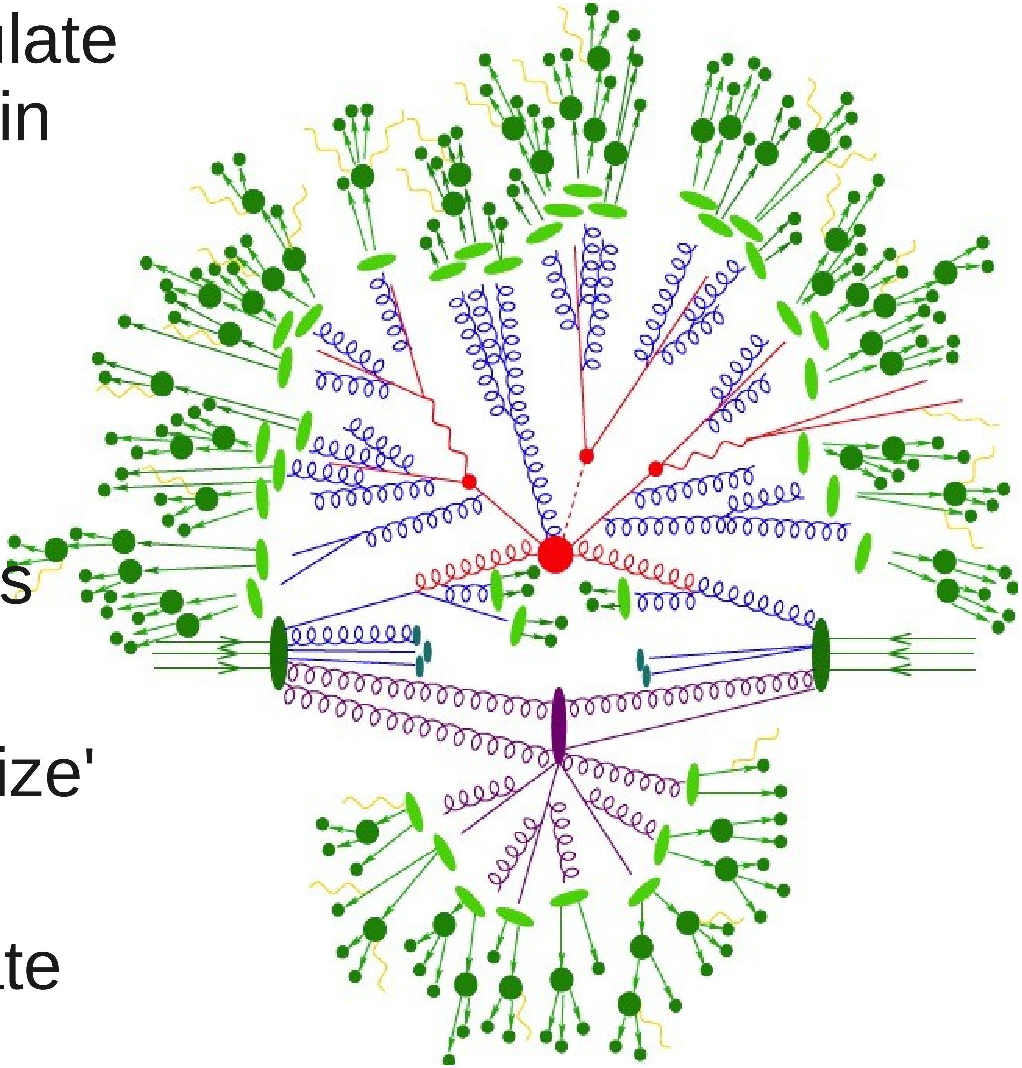
- For the hadronic decay the cross section is calculated:

$$\sigma_{a_i b_i}=\int dz_c D_{c_k}\left(z_c,\mu_f^2\right)\sigma_{a_i b_j\rightarrow c_k+X}\left(\mu_F^2,\mu_R^2\right)$$

- Where A is a hadron that is composed of a_i partons,
- B is a hadron composed of b_j partons.
- C is a hadron and contains c_k partons
- D_{ck} is the fragmentation function and the
- Momentum fraction is z_c of the parton
- Things can fragment into photons but photons do not fragment

Sherpa collision simulation

- Matrix element generators simulate 'hard' part of scattering (shown in red).
- Parton showers produce Bremsstrahlung (blue).
- Multiple interaction models simulate 'secondary' interactions (purple).
- Fragmentation models 'hadronize' QCD partons (green).
- Hadron decay packages simulate unstable hadron decay (dark green).



Bremsstrahlung

- Bremsstrahlung is the radiation produced by the deceleration of a charged particle when it is deflected by another charged particle.
- In Bremsstrahlung, photons lose energy through the radiation of additional photons.
- This is described by:
- $E(x)=E_0e^{\frac{-x}{x_0}}$,
- where x_0 is the radiation length and x is the material thickness.

Pair production

- Pair production is when a photon transverses close to a nucleus and the resultant energy causes an electron positron pair to be created.
- This is described by:
- $I(x)=I_0e^{\frac{-7x}{9x_0}}$.
- The energy lost is similar to Bremsstrahlung but has a linear absorption coefficient of $7/9$.

PDFs

- Deep Inelastic scattering

Transition Radiation

- Transition radiation (TR) is a form of electromagnetic radiation emitted when a charged particle passes through inhomogeneous media, such as a boundary between two different media

ECAL calibration

- Send a pulse laser of known energy through the detector
  - The raw electronic signals converted to an energy value.
- Apply a correction factor due to energy loss.
  - This correction factor is based on MC simulations of the detector.
- Then reconstruct the $Z\rightarrow e^+e^-$ mass
  - in data and compare it to the MC simulations.
  - The equation is:

$$E_{meas}=E_{true}\left(1+\alpha_J\right)$$

Energy Resolution

- Where a is the stochastic term (sampling term), b is the noise term, c is the constant term, and $\otimes$ represents a quadratic sum.
- The stochastic term deals with the statistical fluctuations in shower development.
- The noise term deals with the readout electronics chain as well as pileup.
- The constant term deals with non energy dependent effects such as:
  - the material non-uniformity, temperature, radiation, and leakage.

Energy Resolution

- The systematic uncertainty on the cross section due to the photon energy resolution.
- This is calculated by calculating the nominal width of a known decay like $z \rightarrow e^{+} e^{-}$ and then smearing that width with a Gaussian of smaller and larger widths.
- This uncertainty effects both the reconstructed energy in the MC simulations, which is used for the background subtraction and $C_i(\gamma)$.
- This uncertainty is typically 1% for all E_T^{γ} explored in this measurement.

Energy Resolution

- What is shown above is fractional energy resolution
- Overall resolution gets worse and is dissected like a piece wise function
- Always given in fractional resolution so just say resolution

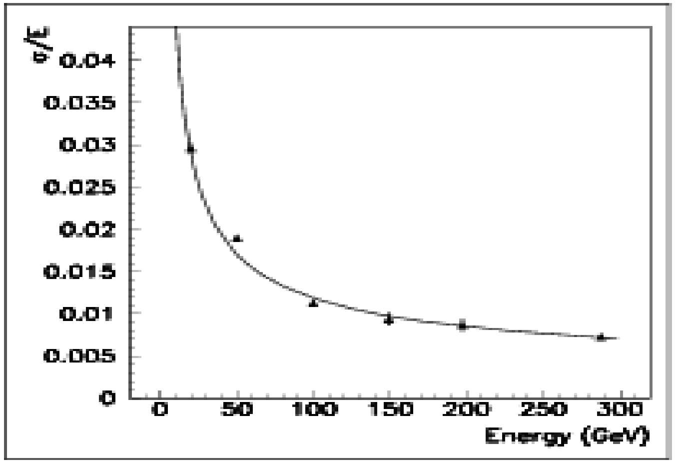


Figure 2-8 Energy resolution as a function of the incident electron energy measured at $\eta = 0.59$.

MC

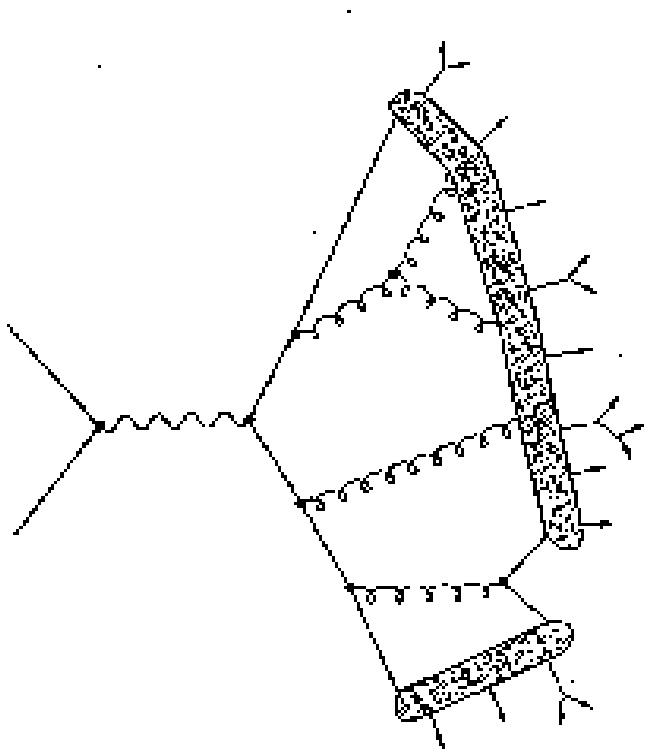
- MPI: multiple parton interactions
  - When the hard scatter actually has two collisions instead of one
- Underlying event:
  - In addition there can also be multiple interactions between different constituents of the two protons

Lund-String Model

- The Lund String Model is a simulation of the production of q bar{q} pairs from the gluon field connecting two quarks at large distances.
- As the distance between two quarks increases, then the field lines between them narrow into a small region, which looks like a string.
- At some point the energy/force stored in the string causes it to split, producing quark-antiquark pairs.

PYTHIA

- Orders in momentum
- Hadronization is simulated with a Lund-String model
  - performed by stretching a color “string'' across quarks and gluons which leads to a breaking into hadrons
- Implement MI
  - ATLAS AUET2



Lund-String Model

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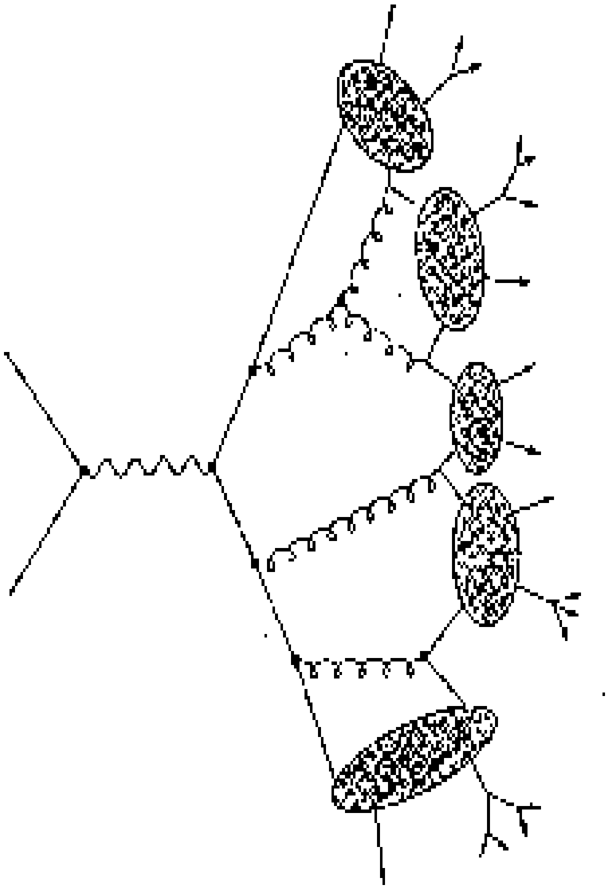
- As the distance between two quarks increases, then the field lines between them narrow into a small region, which looks like a string.
- At some point the energy/force stored in the string causes it to split, producing quark-antiquark pairs.

HERWIG

- Orders in angle
- Hadronization for this generator is done with cluster-hadronization
  - each quark is grouped into quark anti-quark pairs ($q \bar q$).
  - These pairs are grouped to give rise to colorless clusters which form hadrons.
- Implement MPI
  - ATLAS AUET2



Cluster Model

- In the cluster model, colour-neutral clusters are created by following the colour flow through the gluons produced in the parton shower.
- This event structure is more closely correlated to perturbative results from the parton shower, whereas the Lund String Model carries out non-perturbative splitting of $q\bar{q}$ pairs.
- The hadrons created are then decayed if they are unstable.

NLO Systematics PDF

- The uncertainty on the differential cross section due to insufficient knowledge of the PDFs was obtained by repeating the JETPHOX calculation for 52 eigenvector sets of the CT10 PDF and applying a scaling factor in order to obtain the uncertainty for the 68\% C.L. interval.
- The corresponding uncertainty on the cross section increases with ETg and varies between a few \% at $\ETg\simeq 100$~GeV and 15\% at $\ETg\simeq 900$~GeV.

Background Subtraction

- The **correlated method** takes the signal contamination into account by subtracting the signal contribution in each background region

$$N_{SIG}^{A}=N_{OBS}^{A}-\frac{\left(N_{OBS}^{C}-C_{C}N_{SIG}^{A}\right)\left(N_{OBS}^{B}-C_{B}N_{SIG}^{A}\right)}{\left(N_{OBS}^{D}-C_{D}N_{SIG}^{A}\right)}$$

- The **modified correlated** method takes into account that there is signal in the background control regions
- Also it takes into account possible correlations between the isolation and identification variables for background events

$$N_{SIG}^{A}=N_{OBS}^{A}-N_{OBS}^{C}\frac{N_{OBS}^{B}}{N_{OBS}^{D}}*N_{BKG}^{C}\frac{N_{BKG}^{B}}{N_{BKG}^{D}}\frac{N_{BKG}^{D}+C_{D}N_{SIG}^{A}}{\left(N_{BKG}^{B}+C_{B}N_{SIG}^{A}\right)*\left(N_{BKG}^{C}+C_{C}N_{SIG}^{A}\right)}$$

Identification Efficiency

- This uncertainty is calculated by using different techniques for the photon identification as described in.
- Such uncertainties include a number of systematic effects, including sources of uncertainty on the amount of material upstream of the calorimeter and on the definition of “tightness”.
- An effect of 3% or less for all E_T^γ explored in this measurement is observed.

Cross Section Numbers EndCap

- Cross Section for data is:
  - $\sigma(\gamma + X) = 123 \pm 2$ (stat)+9/-7 (syst) $\pm$ 2 (lumi) pb
- The cross section for PYTHIA is:
  - 118 pb within 1 sigma
- The cross section for HERWIG is:
  - 99 pb within 3 sigma
- The cross section for CT10
  - 105 ± 17 (theory) pb within 1 sigma
- The cross section for MSTW2008NLO
  - 109 ± 17 (theory) pb within 1 sigma

LHC