Introduction to particle physics: experimental part

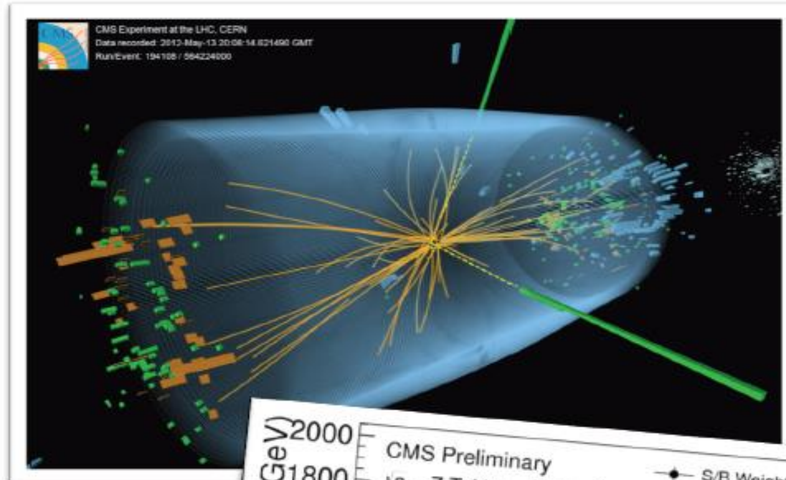
First data at LHC

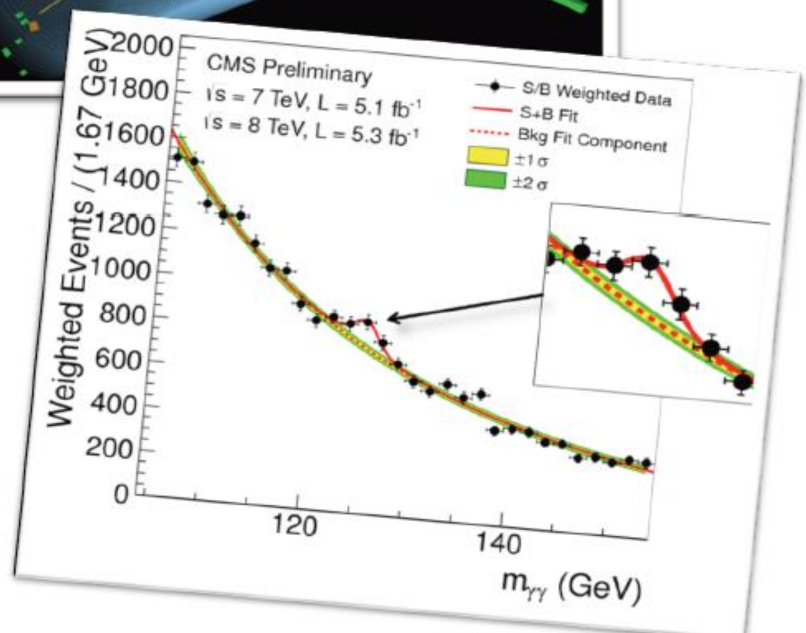
Standard Model measurements

- **Soft and hard QCD**
- **b-jets**
- **W and Z bosons**
- **Prompt photons**
- **Top quarks**
- **Tau leptons**

Prof. dr hab. Elżbieta Richter-Wąs

Experiment = probing theories with data



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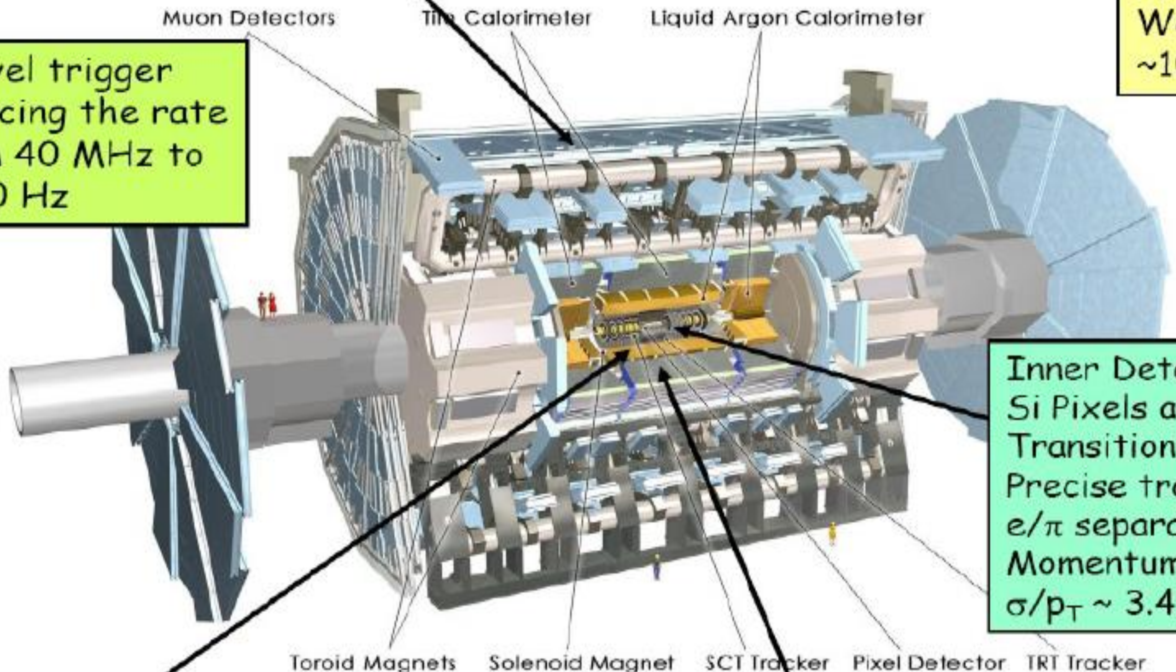
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ATLAS
Collaboration

The ATLAS detector

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

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels

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

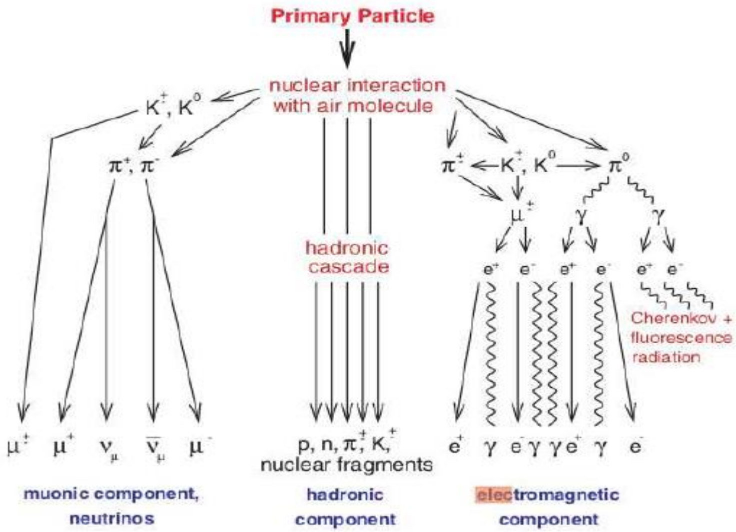


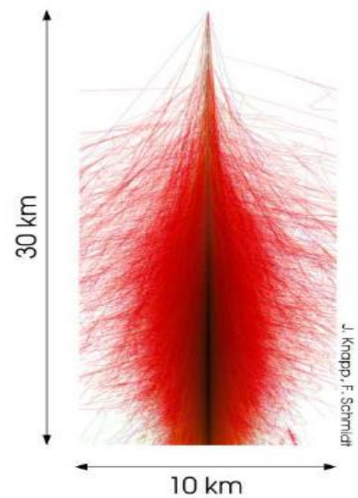
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels and strips (SCT) +
Transition Radiation straws
Precise tracking and vertexing,
e/π separation (TRT).
Momentum resolution:
$\sigma/p_T \sim 3.4\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

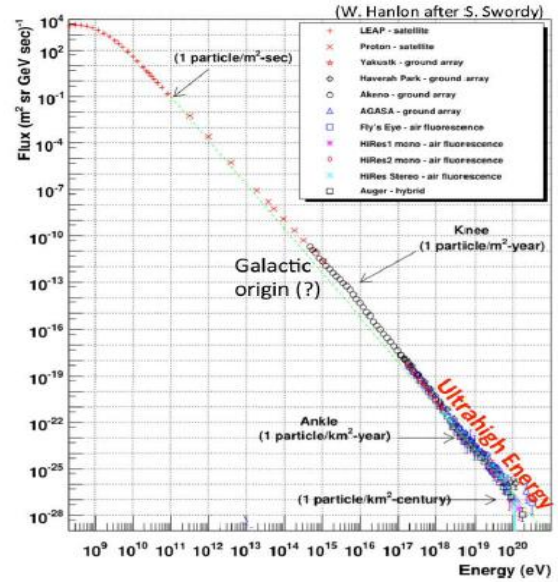
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: ~ 1% at 100 GeV, 0.5% at 1 TeV

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

Cosmic rays







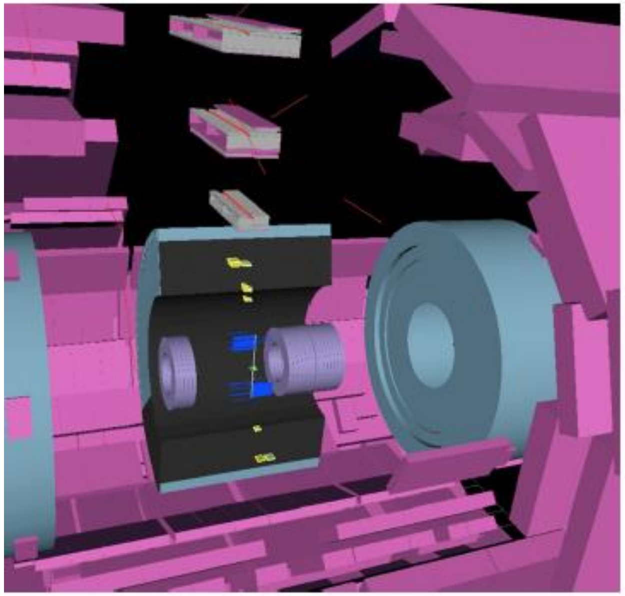
Simulation proton 10^{14} eV

- The most penetrating component of atmospheric showers: the muon component
- At sea level muons represent about 80% of the cosmic ray flux
    - averaged over all energies
    - above E ≈ 1 GeV they contribute almost 100%
- Below 1 GeV the energy spectrum of muons is almost flat
- Above 100 GeV falls exponentially
- It extends to extremely high energies
- The average cosmic ray muon energy is 4 GeV

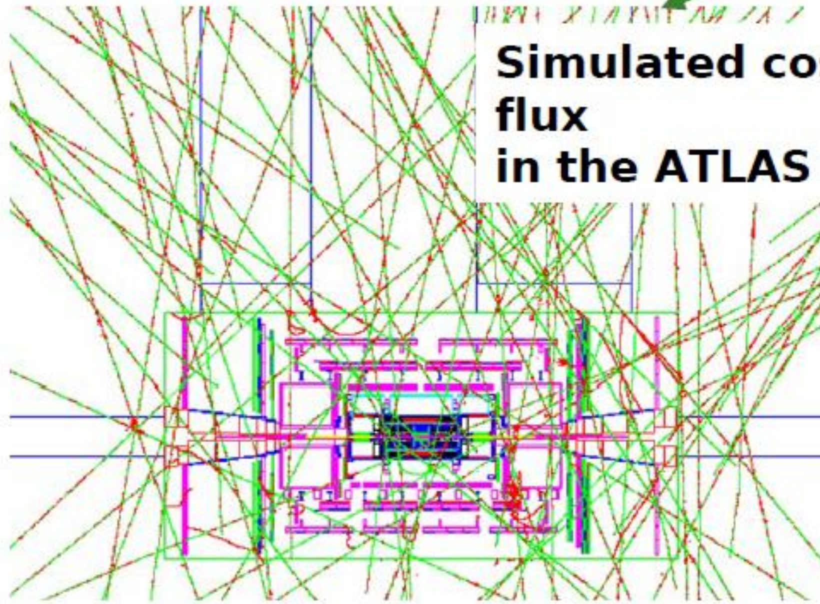
Cosmic Muons in ATLAS

2008

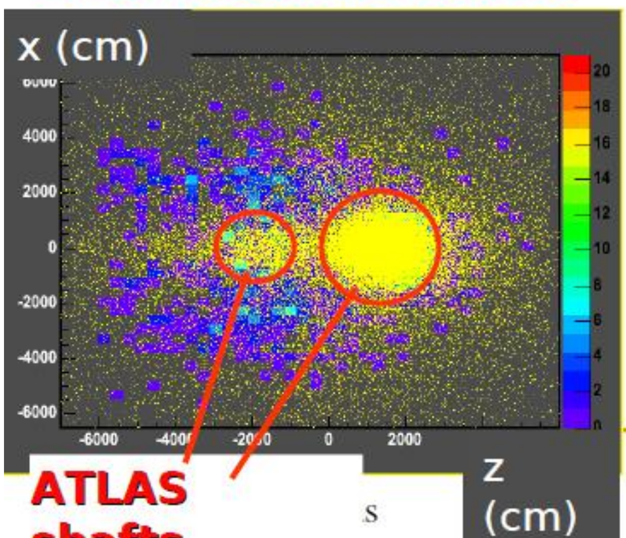
10 ms



Real Cosmic Event



Simulated cosmics flux
in the ATLAS cavern



ATLAS shafts

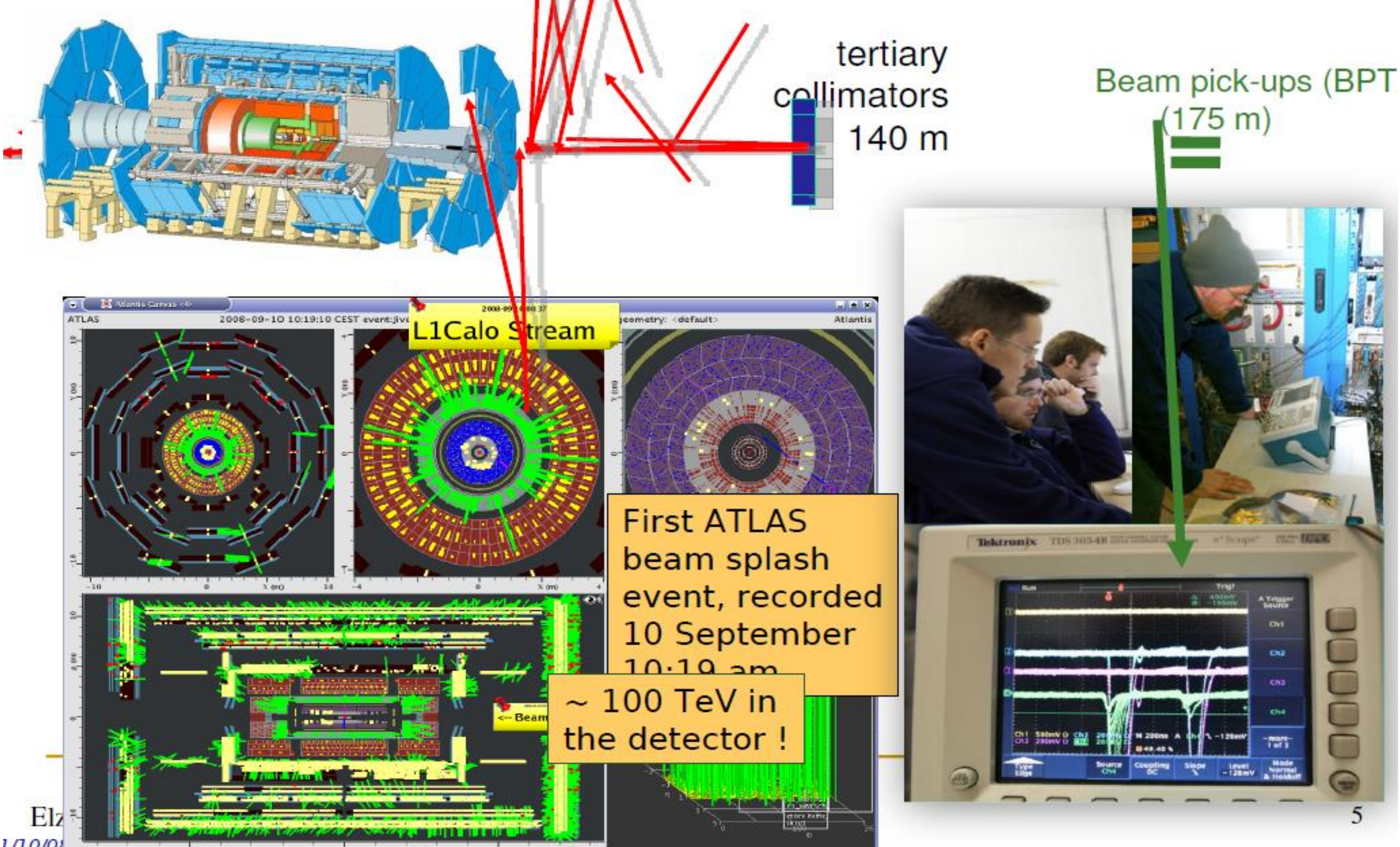
Muon impact points extrapolated to surface as measured by Muon Trigger chambers (RPC)

(Calorimeter trigger also

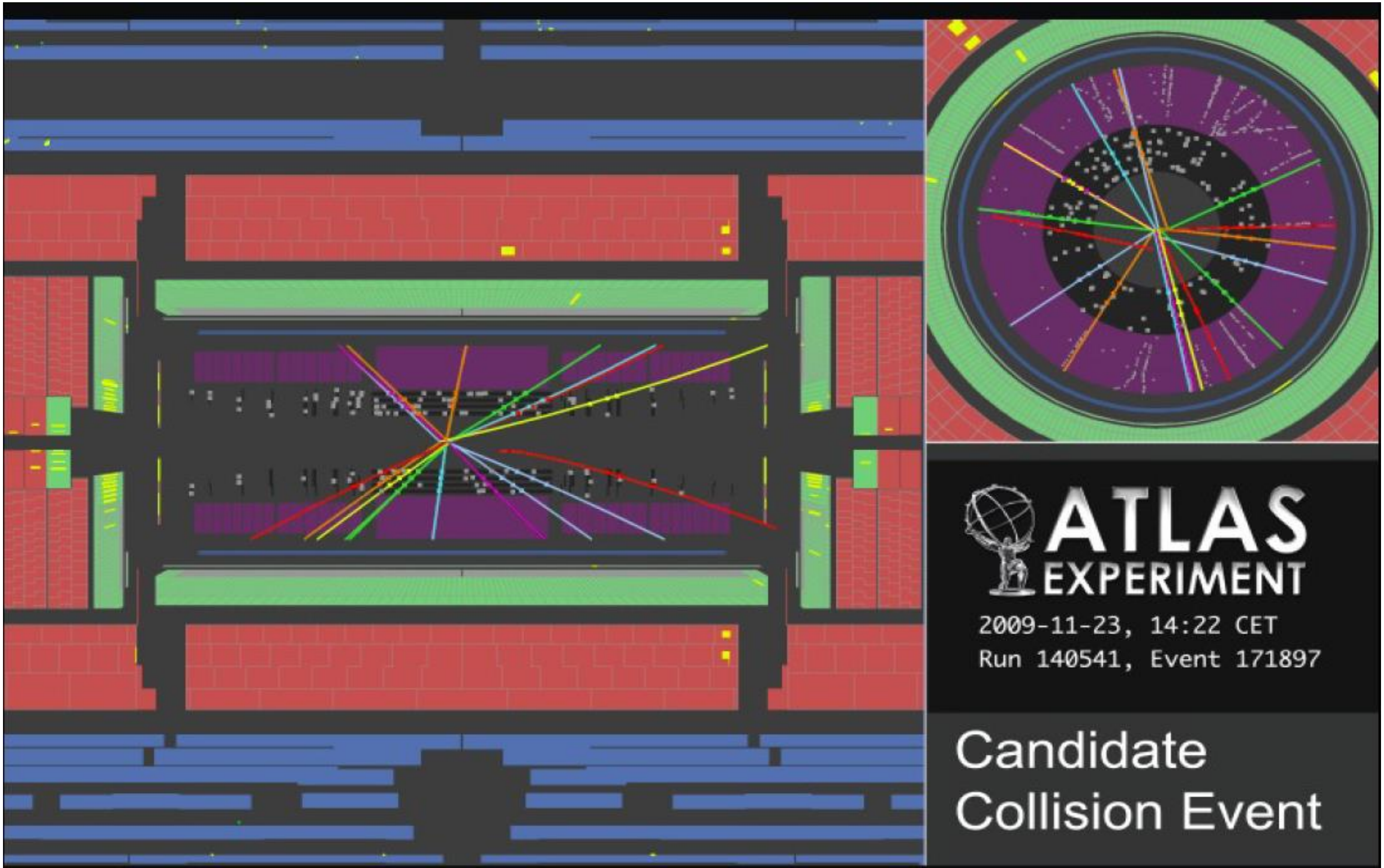
Rate ~100 m below ground:
~ O(15 Hz) crossing Inner Detector

2008

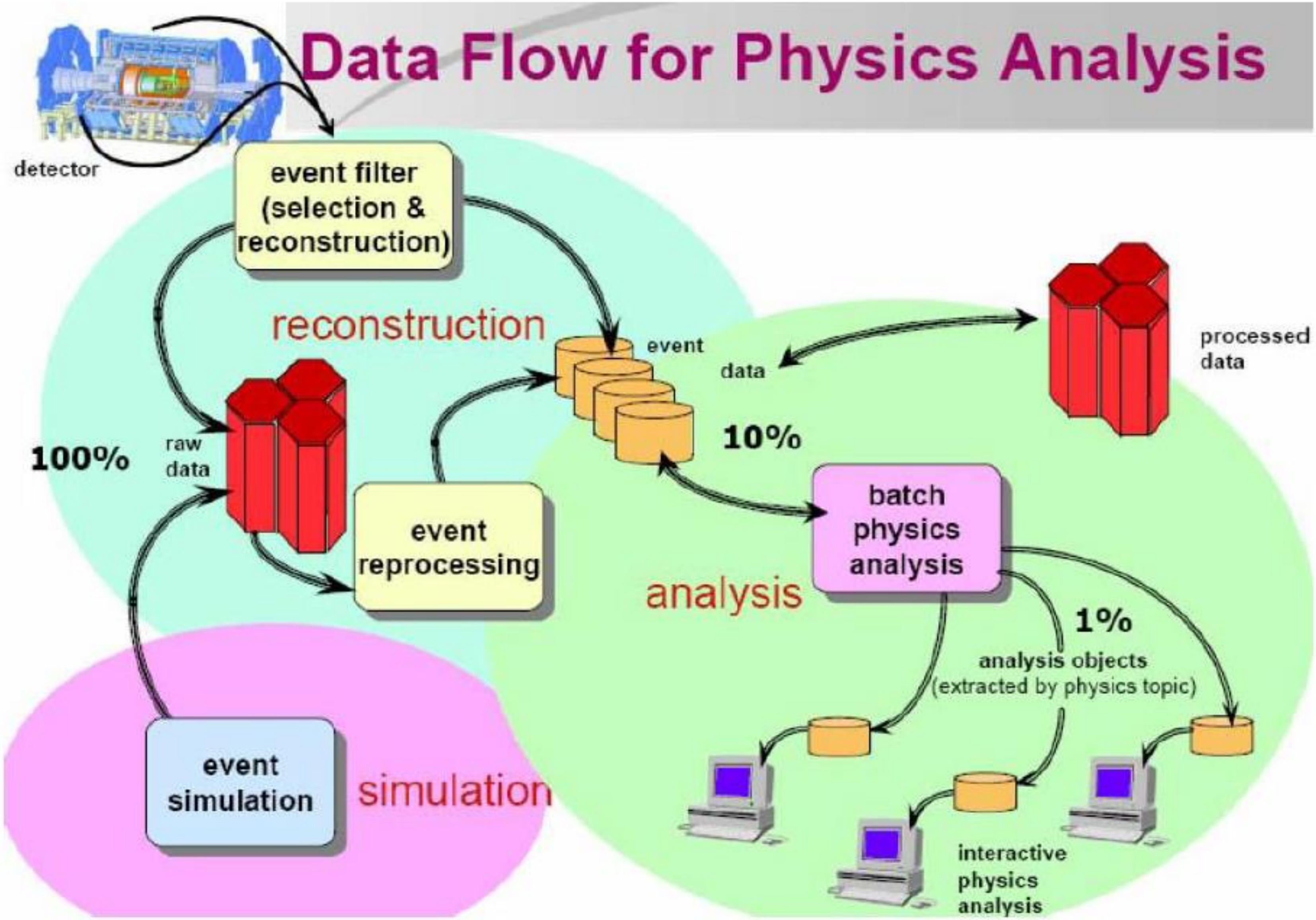
Beam bunches ($2x10^9$ protons at 450 GeV) stopped by (closed) collimators upstream of experiments → "splash" events in the detectors (debris are mainly muons)

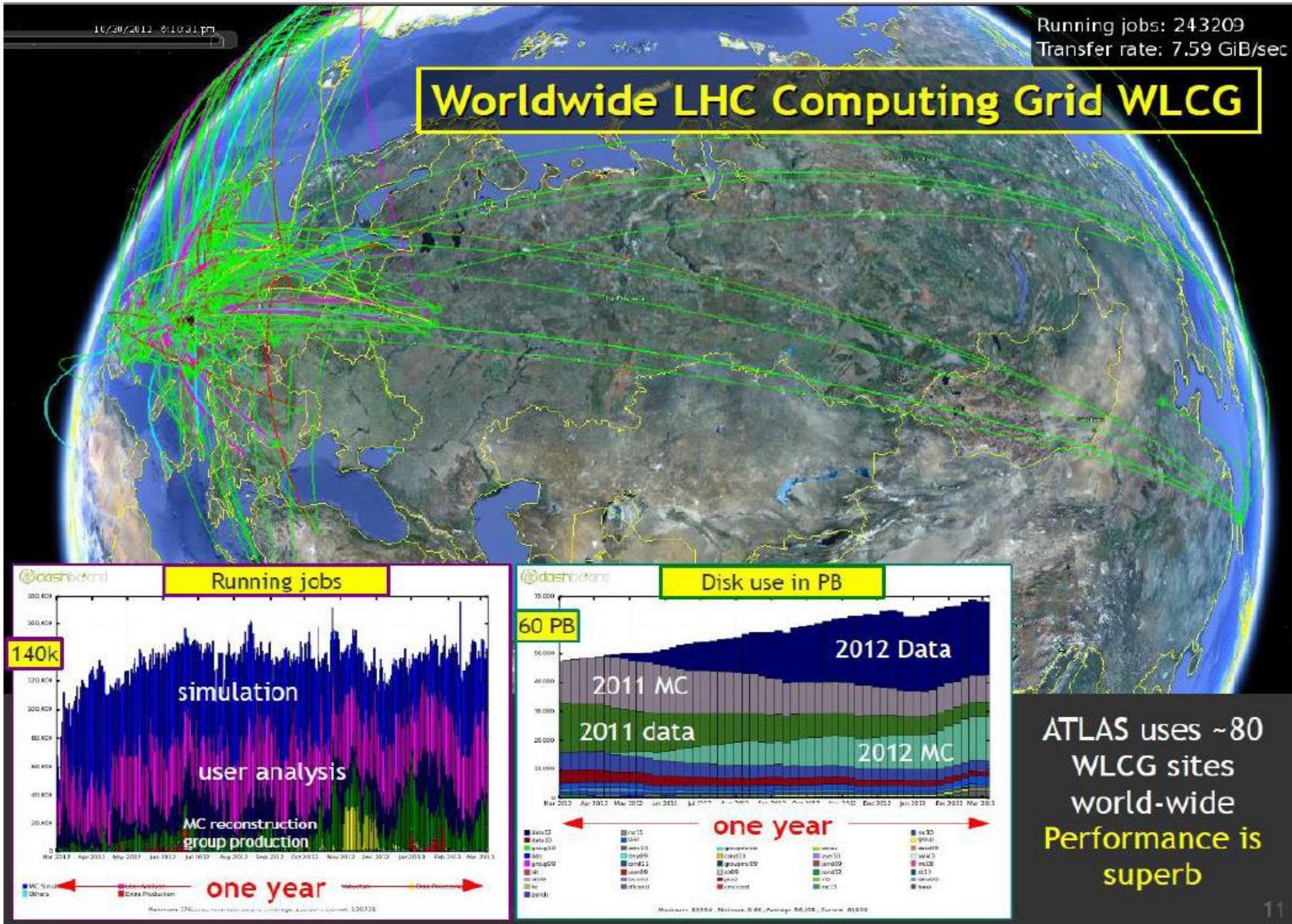


First collisions in ATLAS (2009)



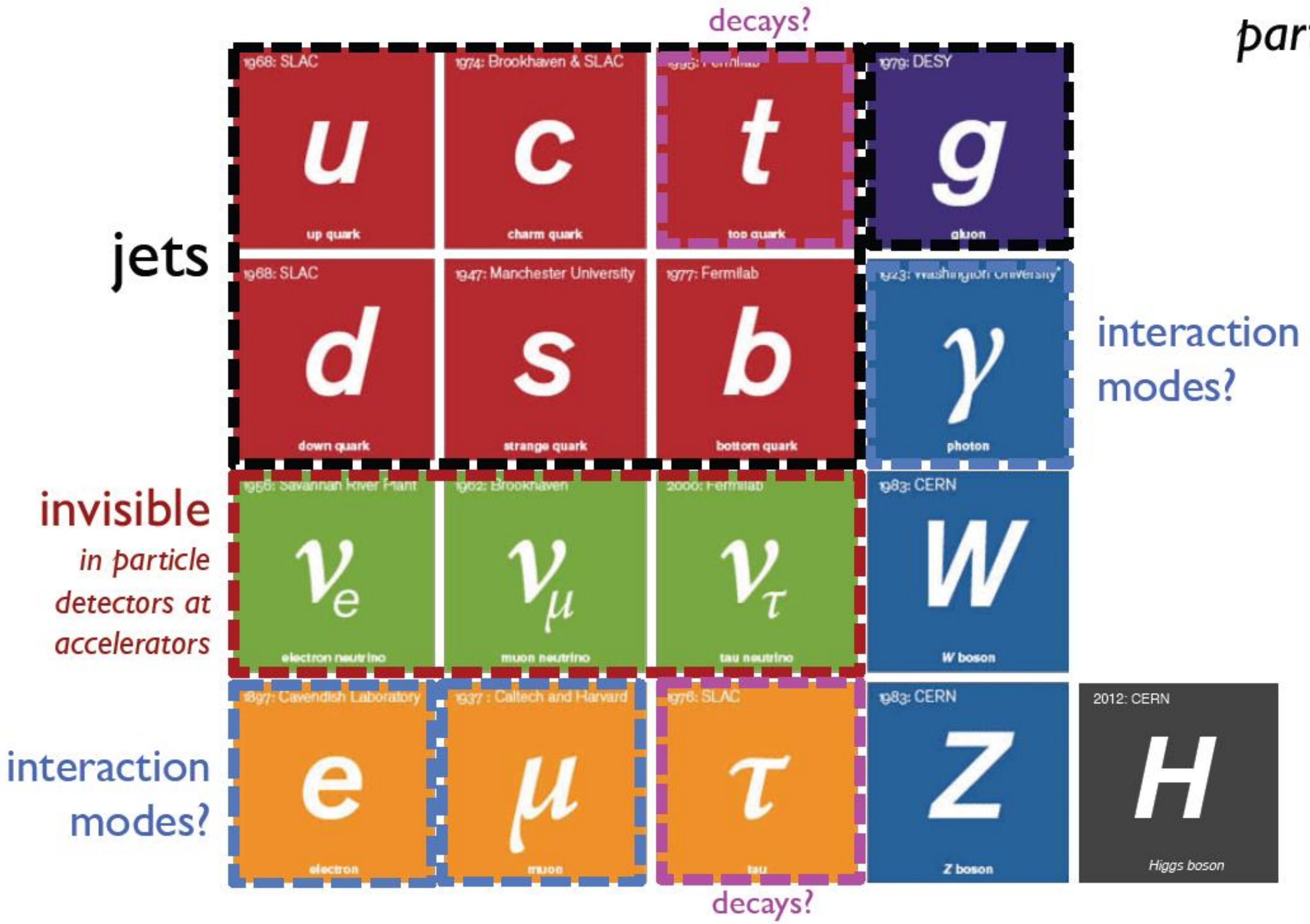
Data Flow for Physics Analysis




Running jobs: 243209
Transfer rate: 7.59 GiB/sec
Worldwide LHC Computing Grid WLCG
Running jobs
140k
simulation
user analysis
MC reconstruction
group production
one year
Disk use in PB
60 PB
2012 Data
2011 MC
2011 data
2012 MC
one year
ATLAS uses ~80 WLCG sites world-wide
Performance is superb
11

What do we want to measure?

… “stable” particles!

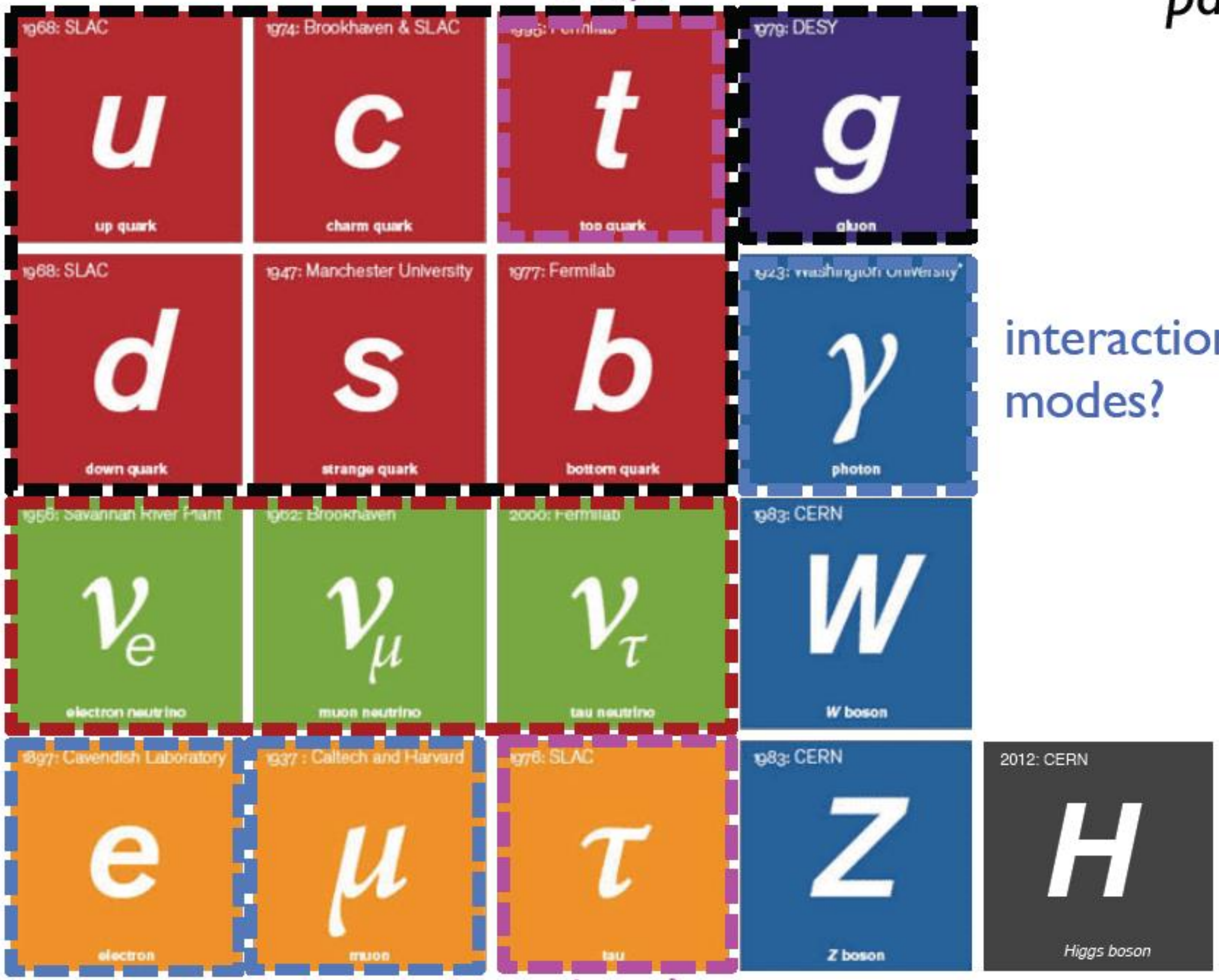


What do we want to measure?

… "stable" particles!

decays?

jets

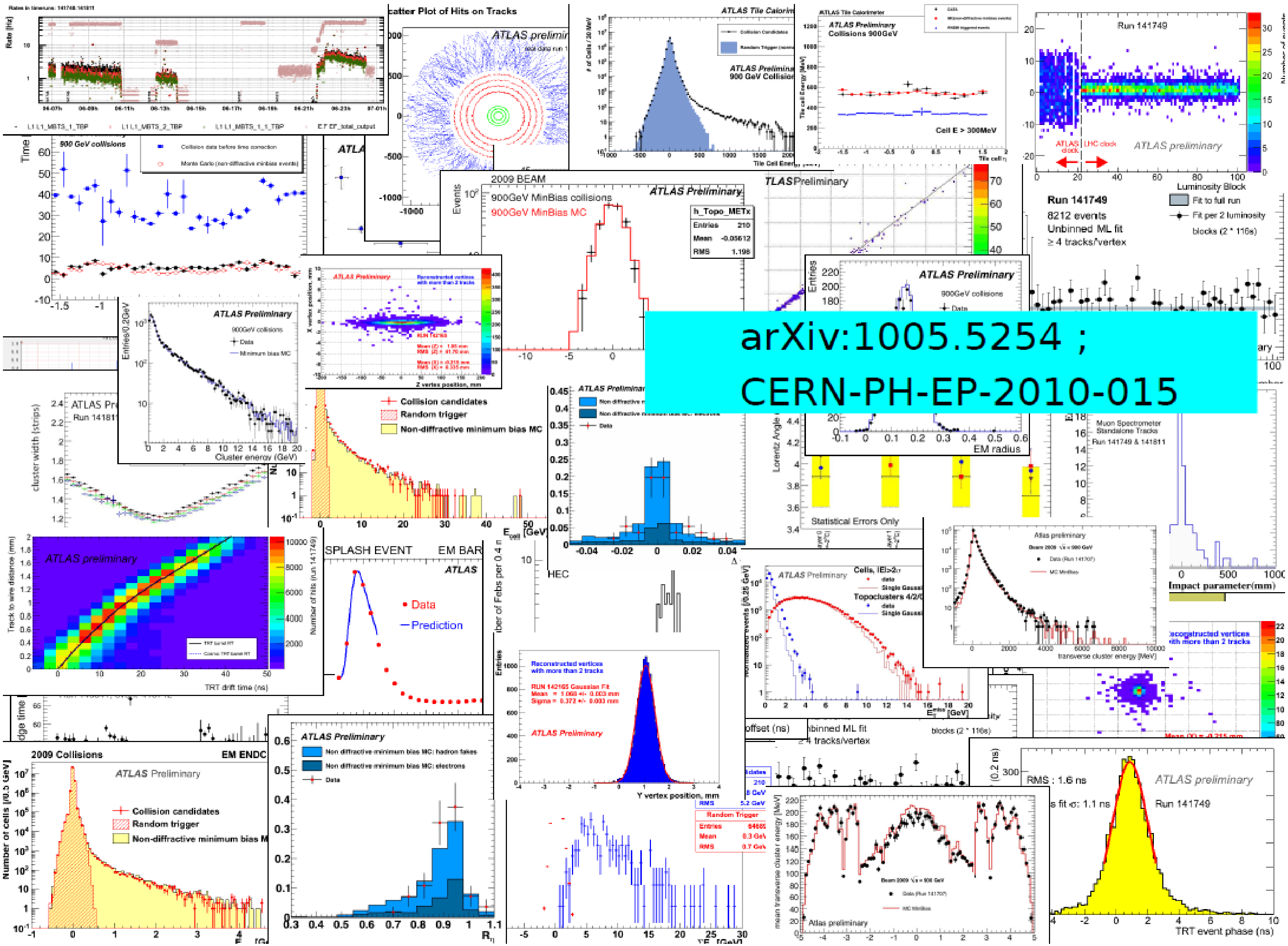


interaction modes?

invisible *in particle detectors at accelerators*

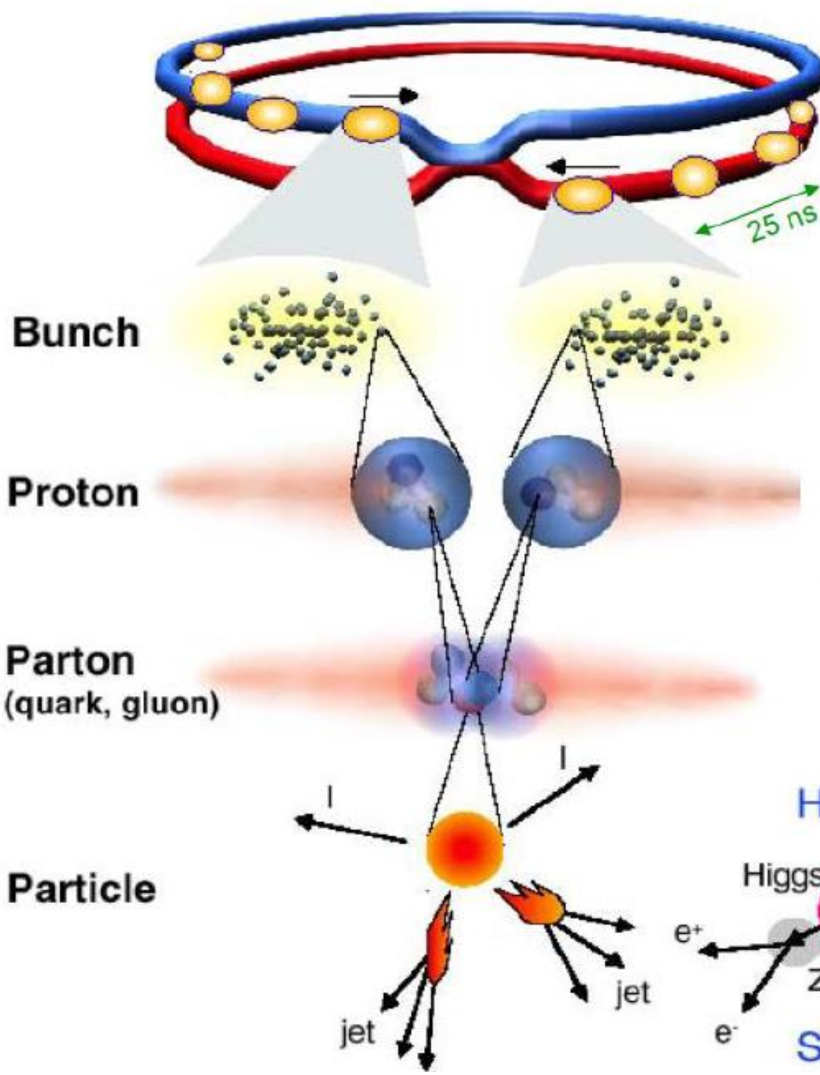
interaction modes?

decays?



arXiv:1005.5254 ;
CERN-PH-EP-2010-015

Collisions at LHC

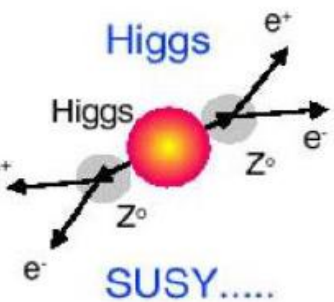


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

In the experiments:

10^9 pp interactions per second

~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

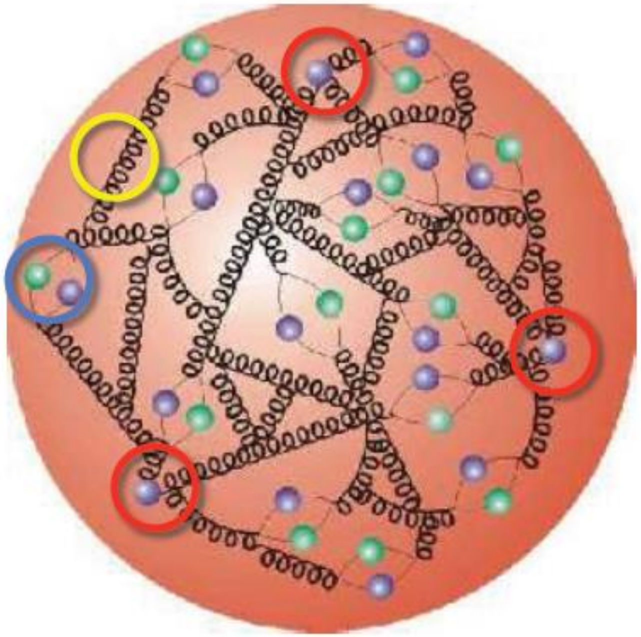


Selection of 1 in 10,000,000,000,000

Inner structure of a proton

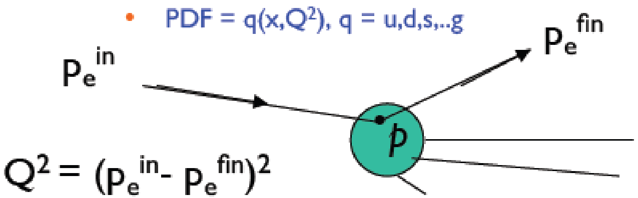
protons have substructures

- ✓ partons = quarks & gluons
- ✓ 3 valence (colored) quarks bound by gluons
- ✓ Gluons (colored) have self-interactions
- ✓ Virtual quark pairs can pop-up (sea-quark)
- ✓ p momentum shared among constituents
  - described by p structure functions



Parton energy not 'monochromatic'

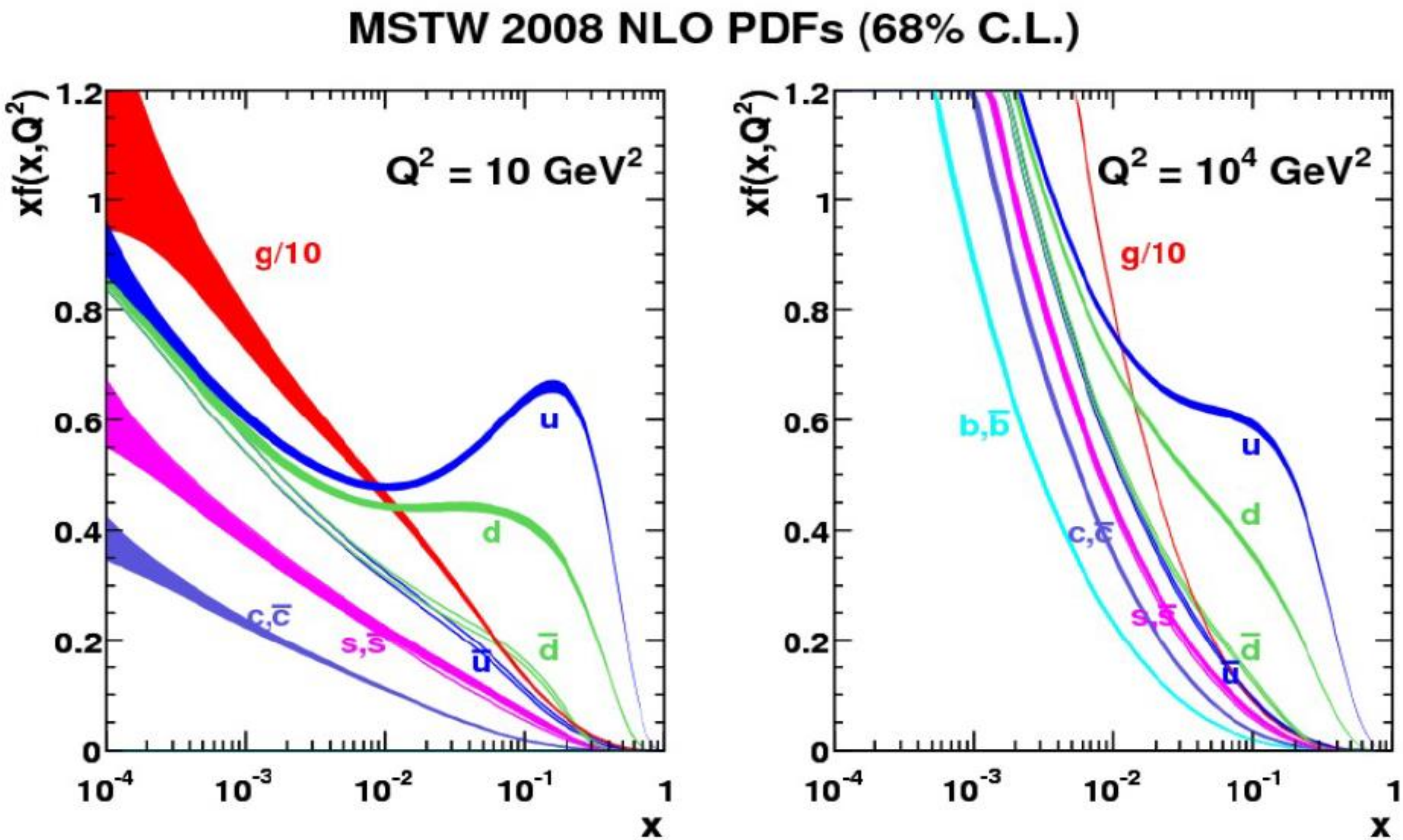
- ✓ Parton Distribution Function
  - PDF = $q(x,Q^2)$, q = u,d,s,..g



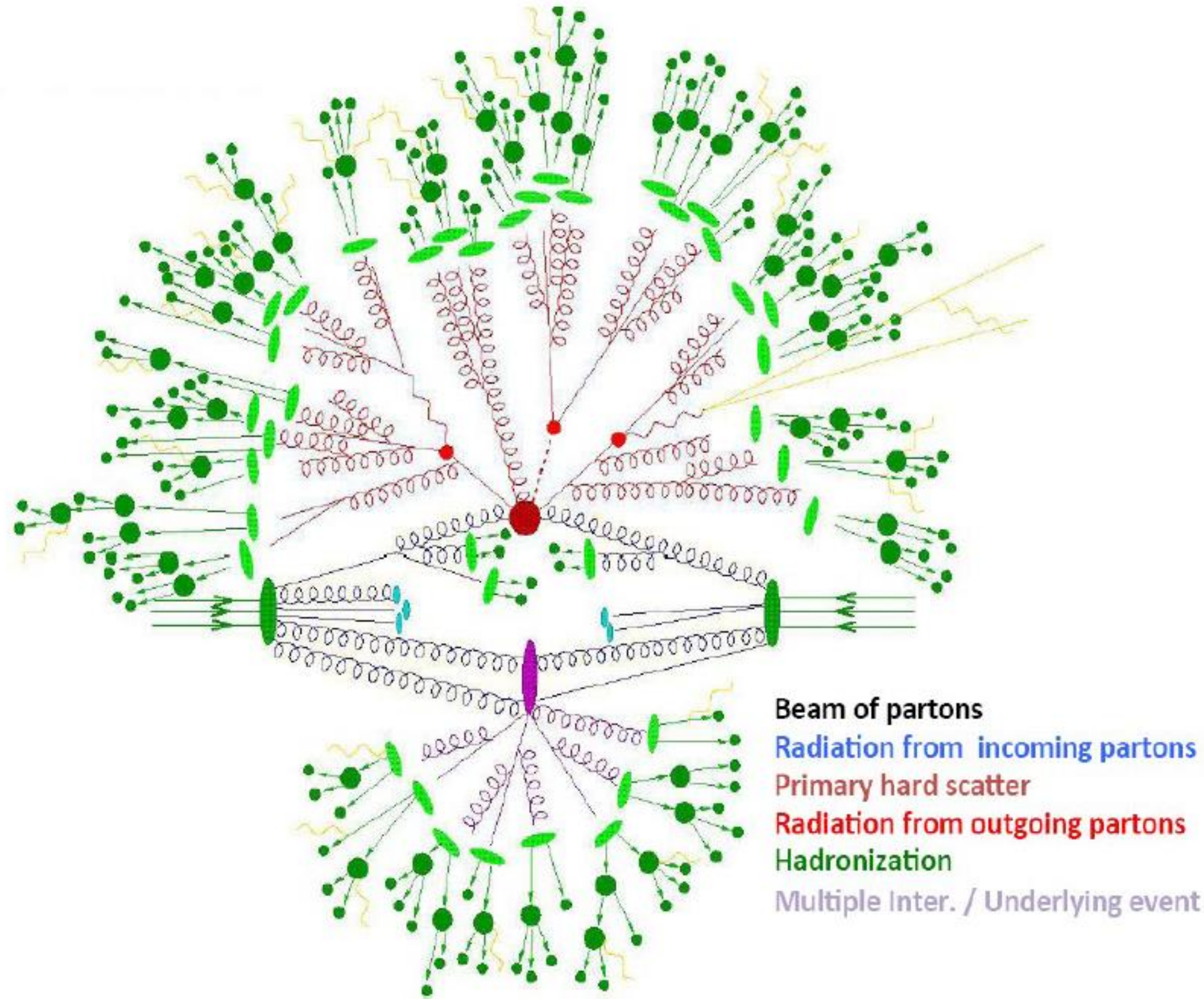
Kinematic variables

- ✓ Bjorken-x: fraction of the proton momentum carried by struck parton
  - $x = p_{parton}/p_{proton}$
- ✓ Q^2 : 4-momentum^2 transfer

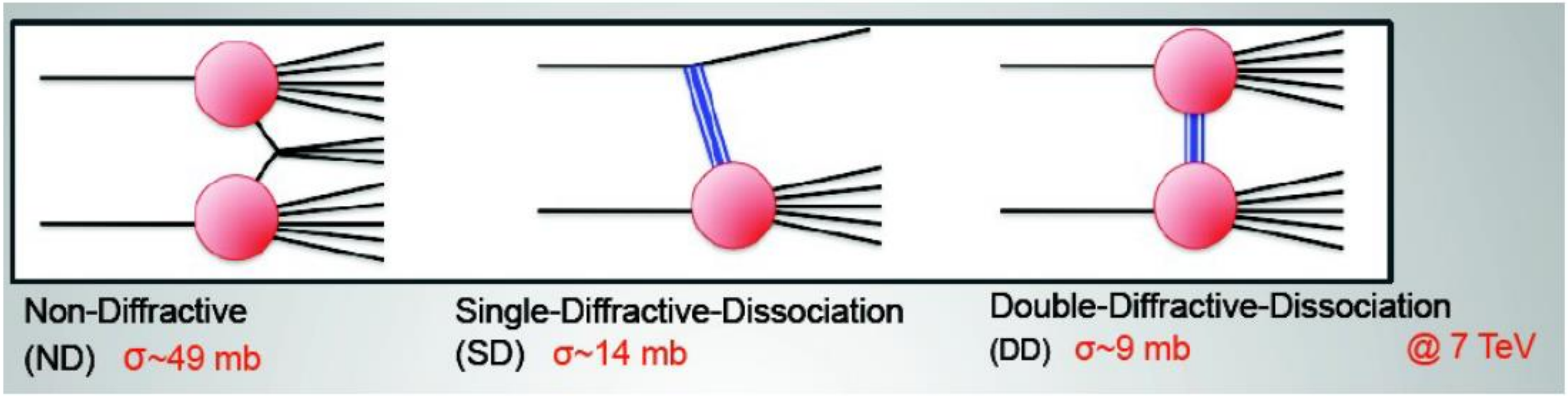
Inner structure of a proton



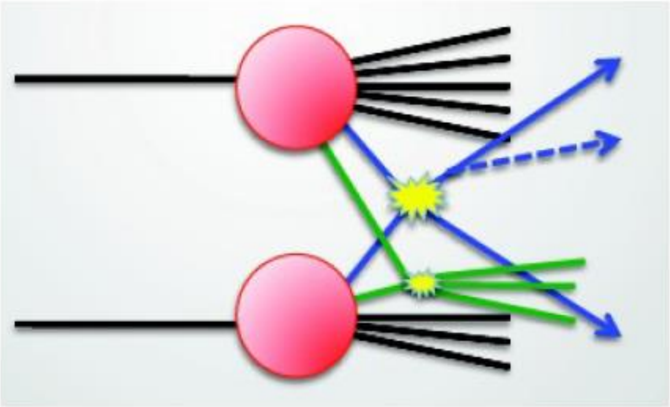
Monte Carlo model for typical pp collision



Dominant QCD processes



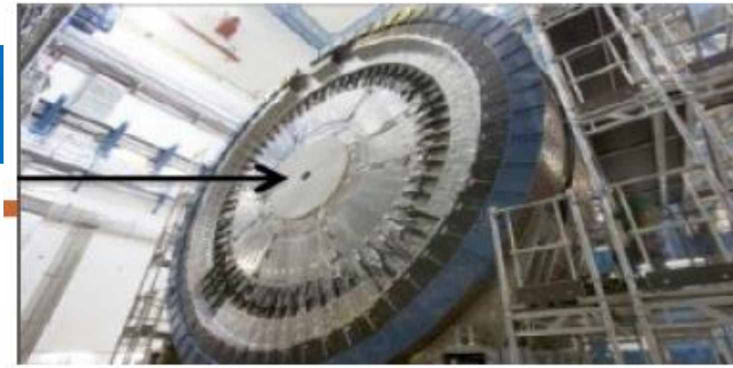
- Multi-parton interactions (**Underlying Event**)

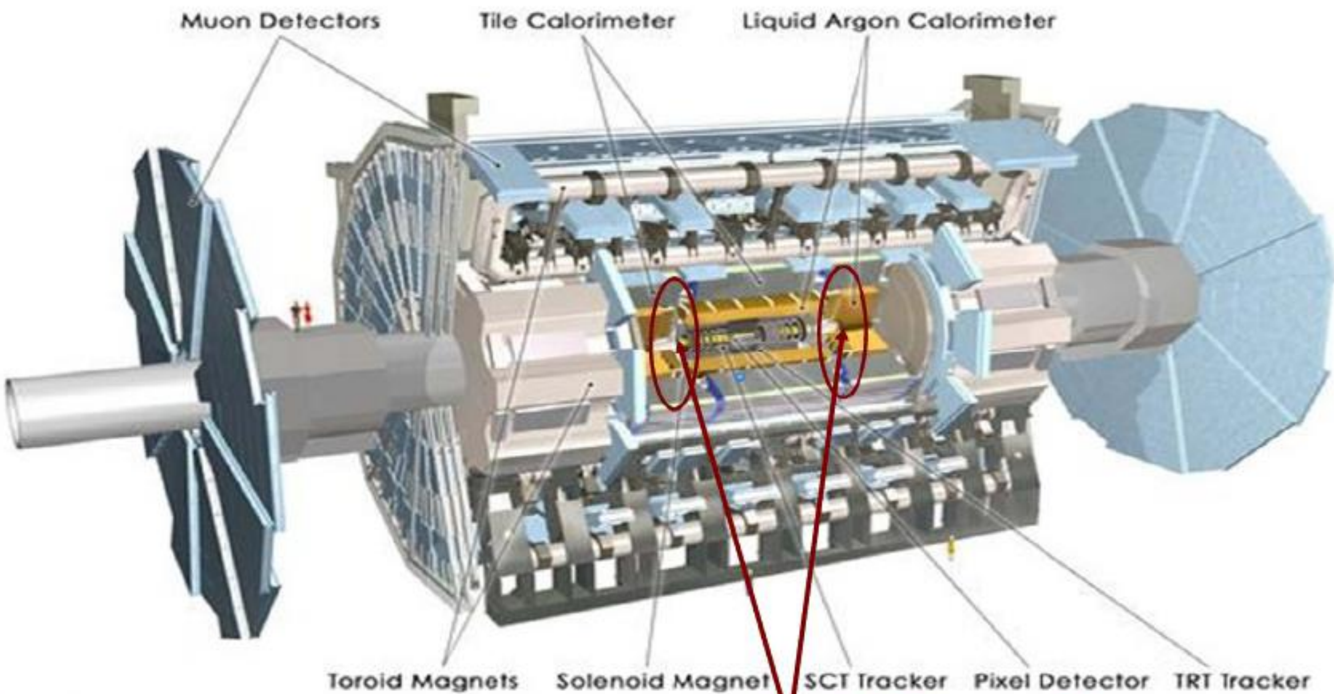


Inelastic cross-sections

- Use only few runs: 7 TeV data (190 μb^{-1}) + 900 GeV data (7μb^{-1}) and 2.36TeV data (0.1μb^{-1})
  - We want to study **all** inelastic pp interactions
  - Instantaneous luminosity very low for these runs: on average ~0.007 interactions per bunch crossing → **99.3% of crossings are empty**.
  - Need to **"trigger"** on inelastic interactions: **Minimum Bias Scintillator Trigger (MBTS)**
    - ➔ sensitive to any charged particle $2.09<|\eta| < 3.84$
    - ➔ 16 counters on each side of ATLAS
- Correct for detector inefficiencies and resolution, eg. present **spectrum of charge particles** not tracks
- **No extrapolation** to regions not seen by ATLAS

MBST Trigger





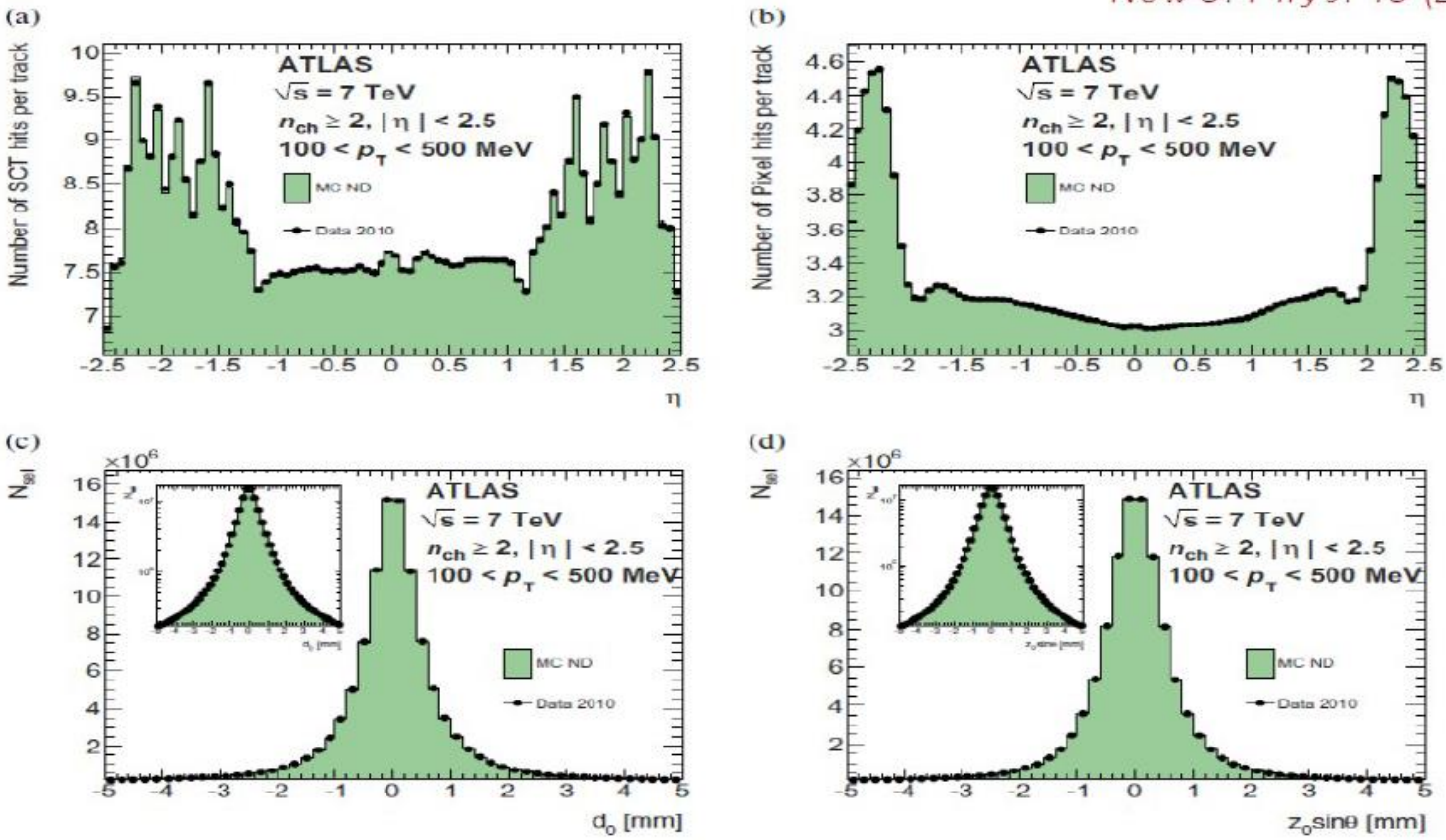
Trackers: $|\eta|<2.5$

Calorimeters: $|\eta|<4.9$

Minimum **B**ias
Trigger **S**cintillator
$2.1< |\eta|<3.8$

How well we undrstood detector?

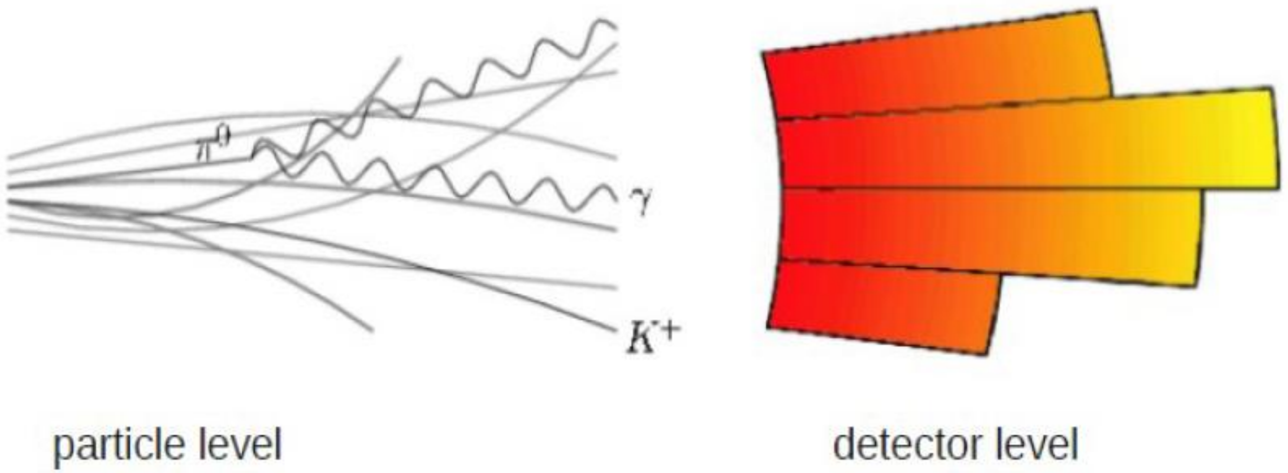
New J. Phys. 13 (2011) 053033



- Excellent agreement between data and MC: Pixel and Silicon hits per track

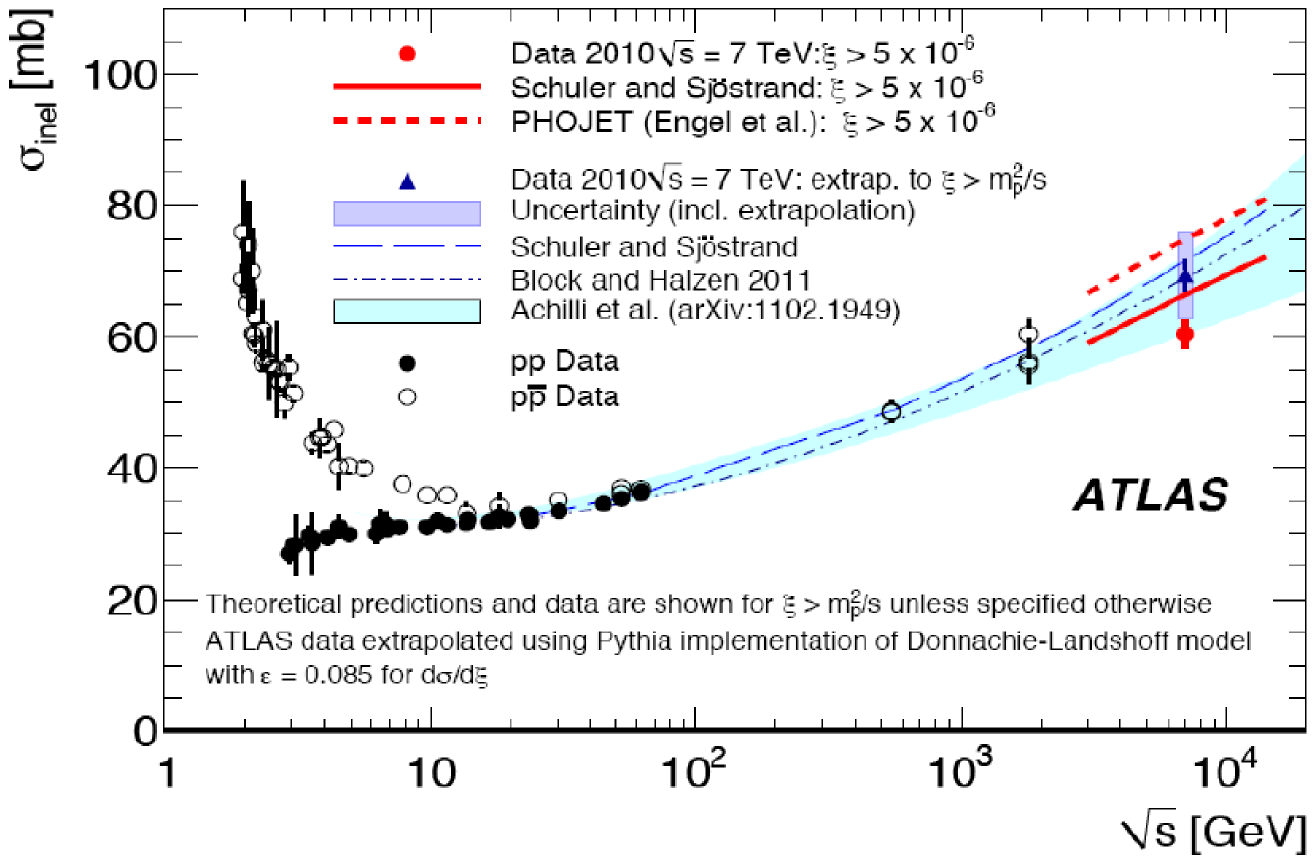
Unfolding to particle level

- Bayesian iterative unfolding used to correct tracks and clusters back to particle level.
  - Use mapping of truth particles on reconstructed objects (use Monte Carlo)

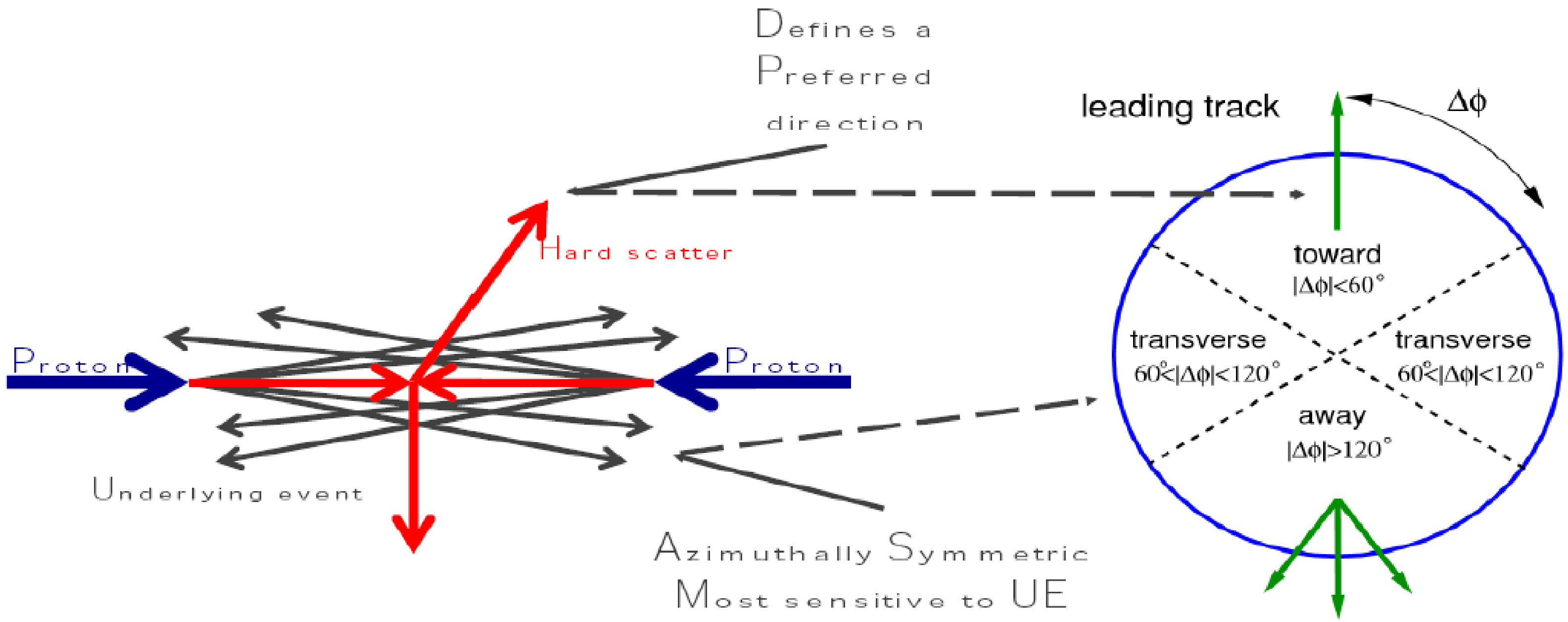


Total inelastic cross-section

$$\sigma(\xi > 5 \cdot 10^{-6}) = 60.3 \pm 0.05\,(\text{stat.}) \pm 0.5\,(\text{sys.}) \pm 2.1\,(\text{lumi})\,\text{mb}$$
$$\sigma_{inel} = 69.1 \pm 2.4\,(\text{exp.}) \pm 6.9\,(\text{extr.})\,\text{mb}$$

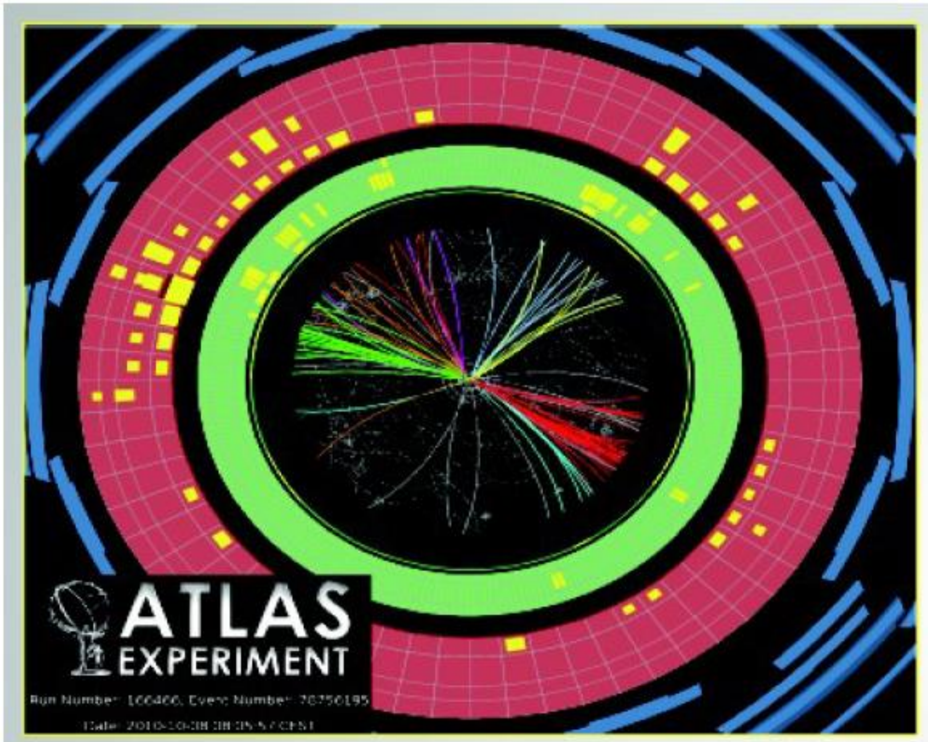


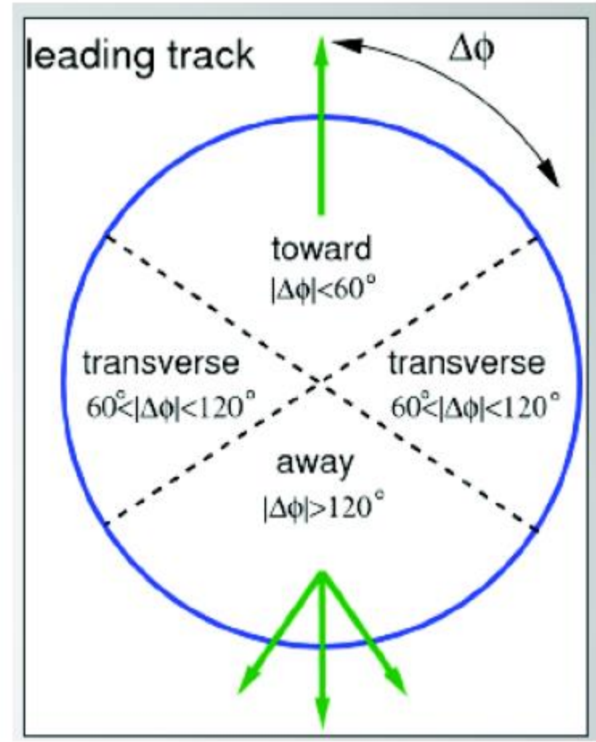
Underlying event



- UE = "everything" - "hard scatter" = beam-beam remnants, MPI, ISR
- Study: charged particle density, transverse momentum, average p_T. Transverse region considered most sensitive to UE

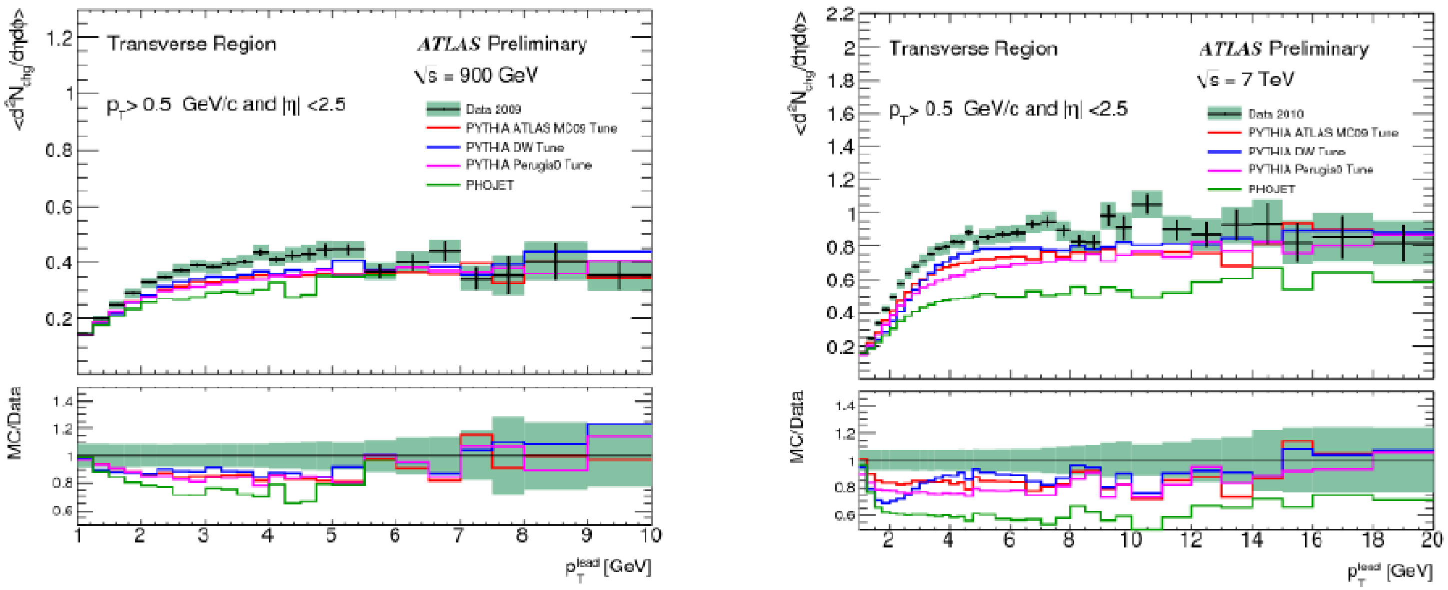
Underlying event





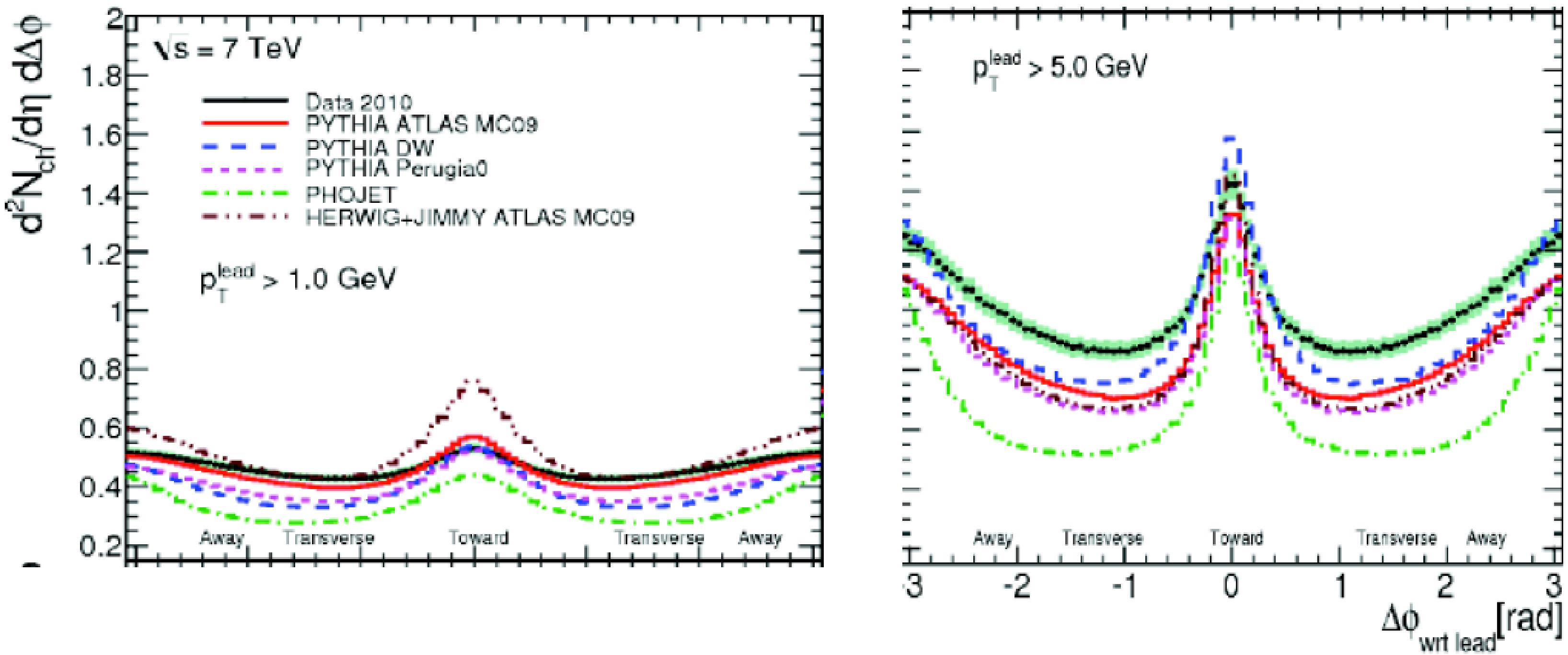
- Define the direction of "hard scatter" as the highest p_T particle
- Study the activity (#of particles) in the region "transverse" to the hard scatter.

Transverse region particle density



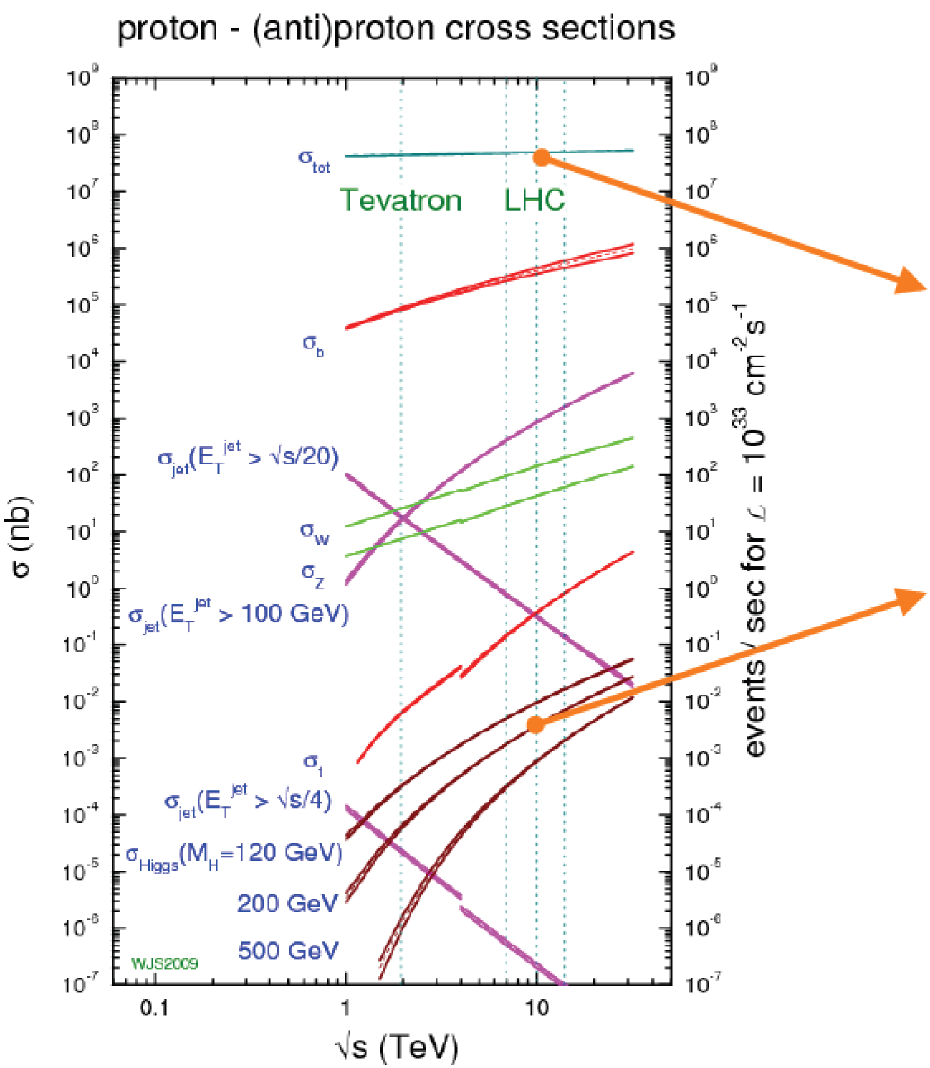
- All tunes underestimate particle density by 10%-15% in the plateau region
- There is factor of ~2 increase in activities between 900 GeV and 7 TeV
- In the plateau region the measured density corrsponds to ~ 2.5 per unit η at 900 GeV and 5 particle at 7 TeV

Particle density angular correlations



- Define the event orientation by the azimuthal angle on the track with the highest p_T.
- MC tunes only reproduce the general features, disagreement in rates both in the transverse region (UE) and in the away region (MPI/Hard Core)

Cross-sections at LHC



10^8 events/s

$\sim 10^{10}$

10^{-2} events/s ~

10 events/min

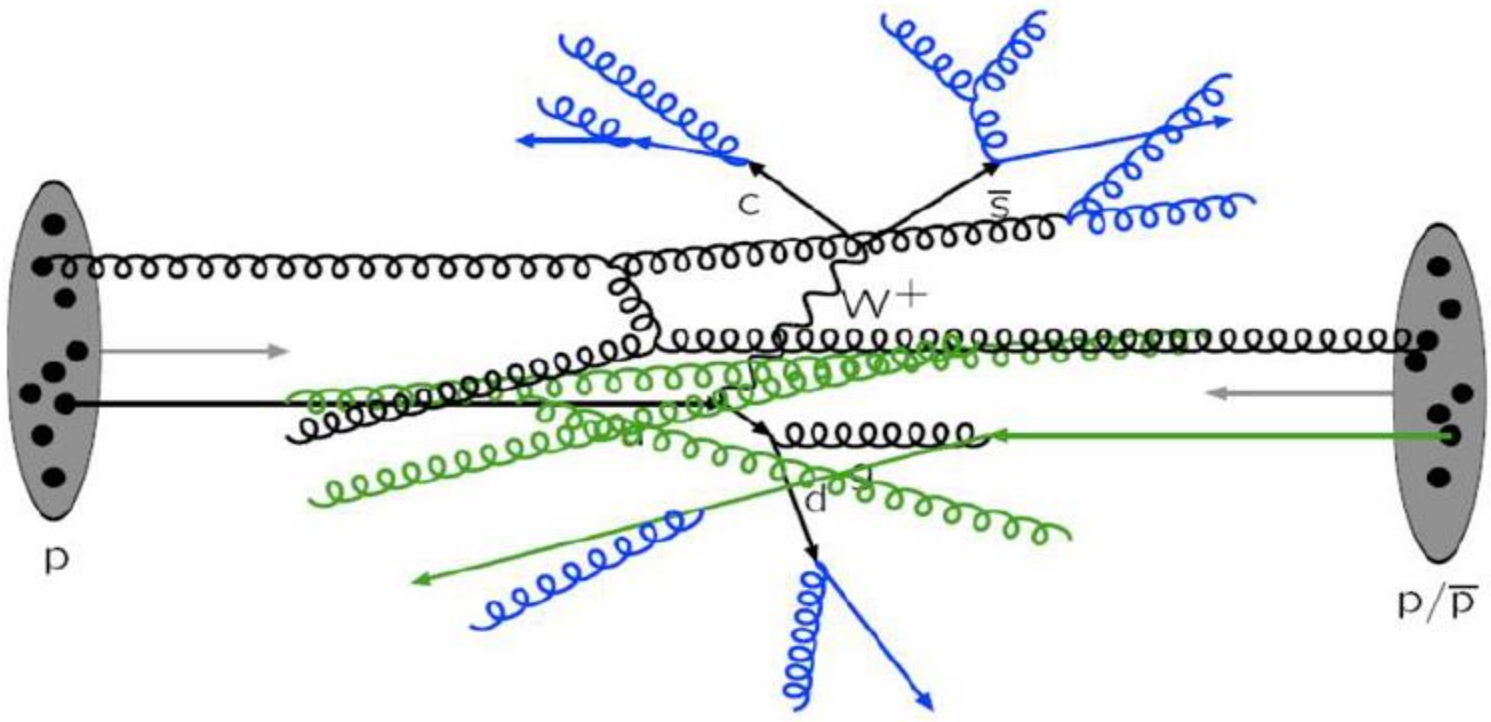
[m_H ~ 120 GeV]

0.2% H → γγ

1.5% H → ZZ

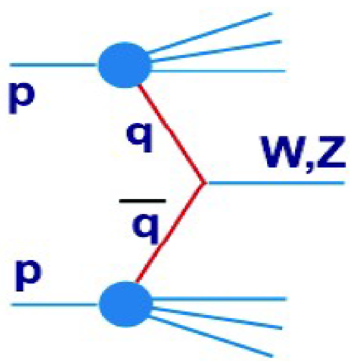
Proton-proton scattering at LHC

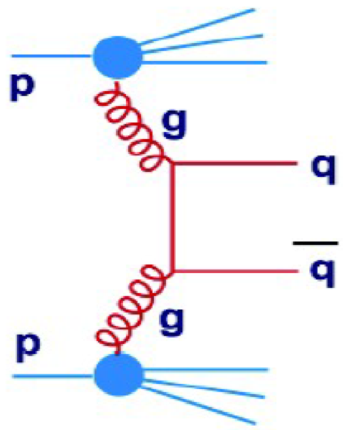
- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction ["underlying event"]

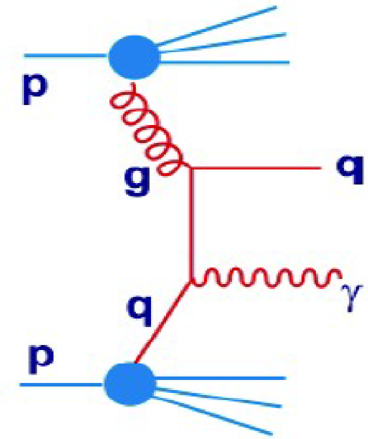


QCD hard scattering processes

- EW gauge bosons Di-jets Direct photons



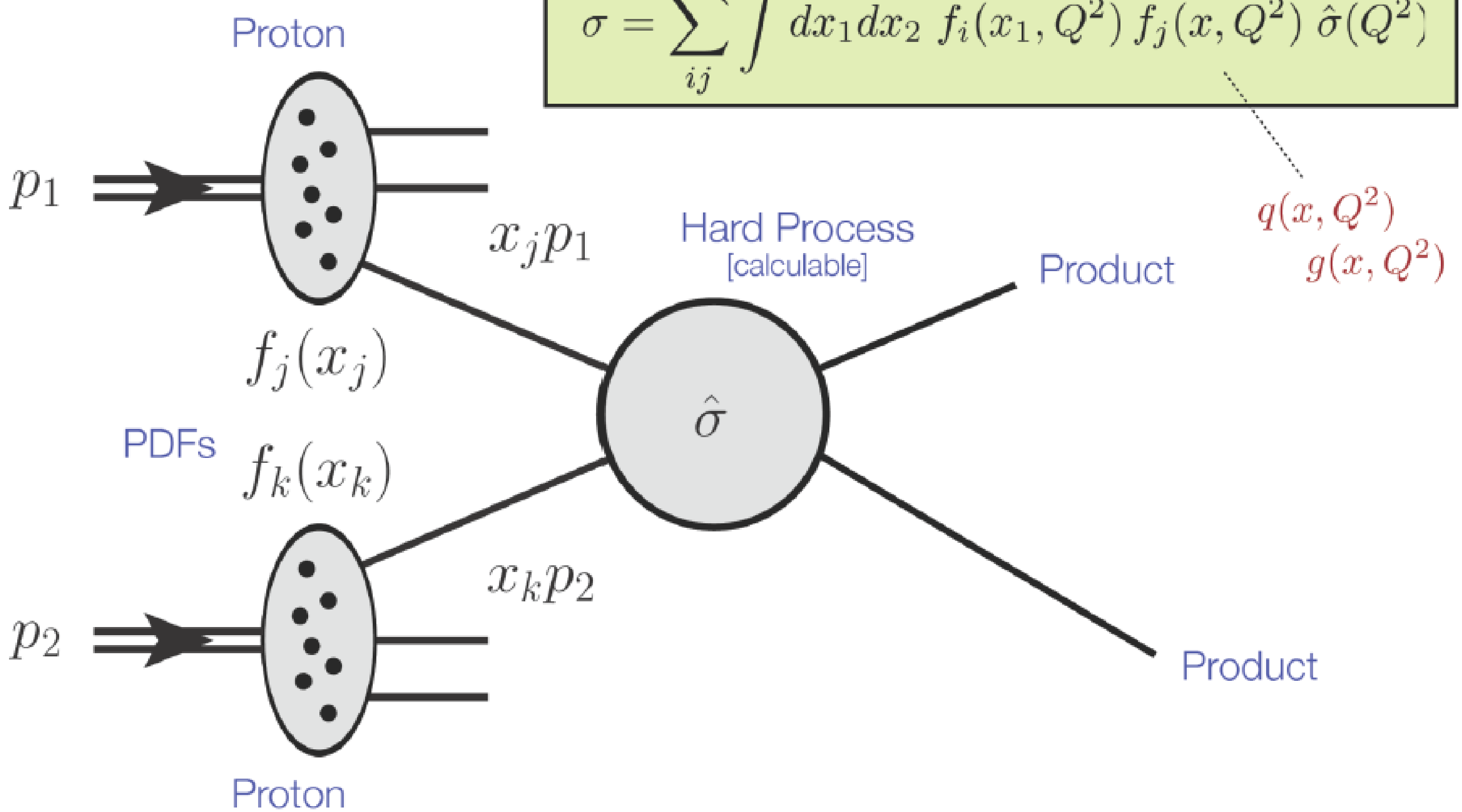




- Measuring those processes test our understanding of:
  - Partonic structure of protons
  - QCD scattering via calculations of N(NLO)
  - Hadronisation/underlying event
  - What makes a good jet algorithm
  - Data driven background estimates for rare processes

Proton-proton scattering at LHC

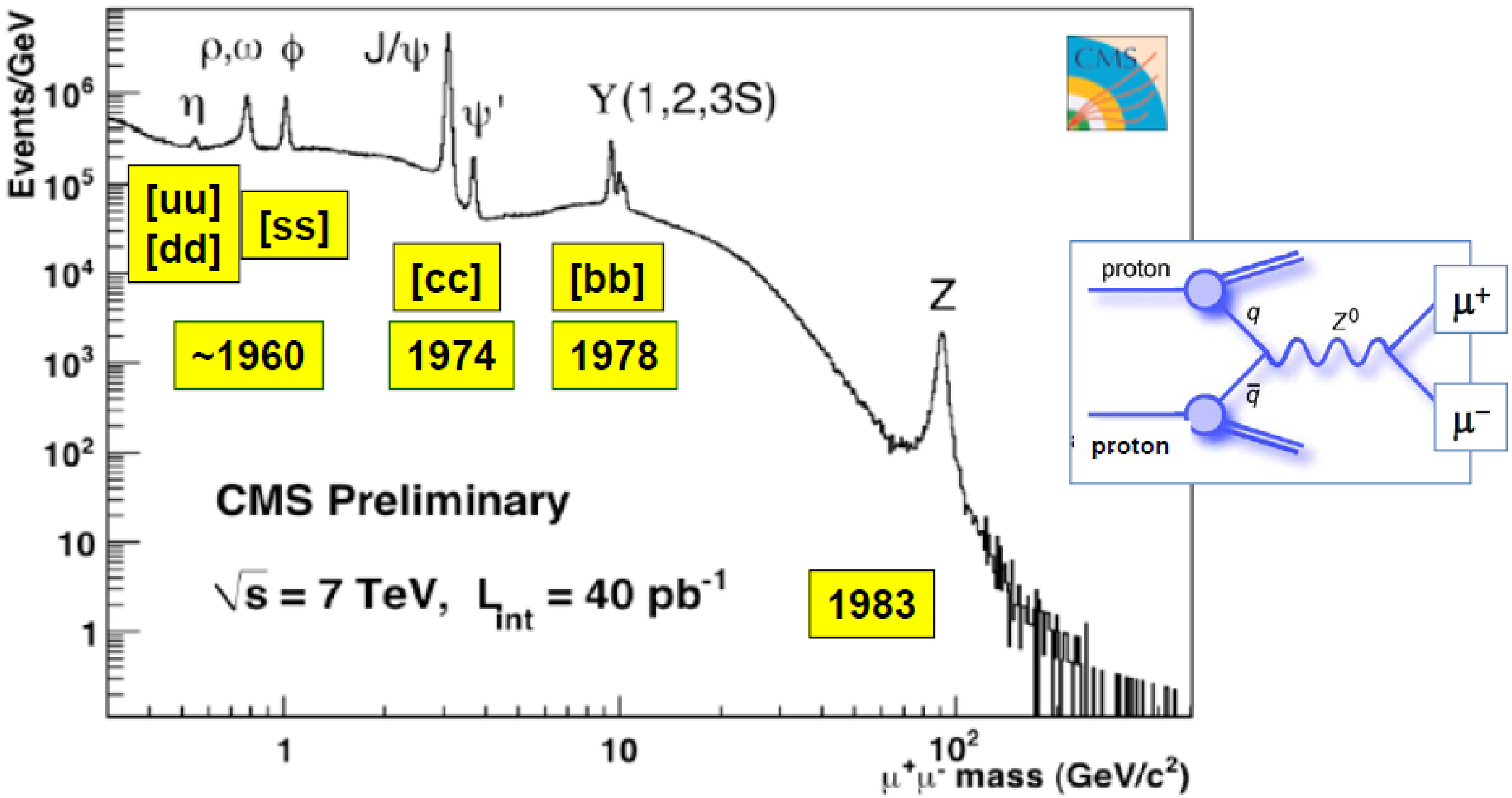
$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \, f_j(x, Q^2) \, \hat{\sigma}(Q^2)$$



Year 2010: Retracing history of particle physics

2010

Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model



The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

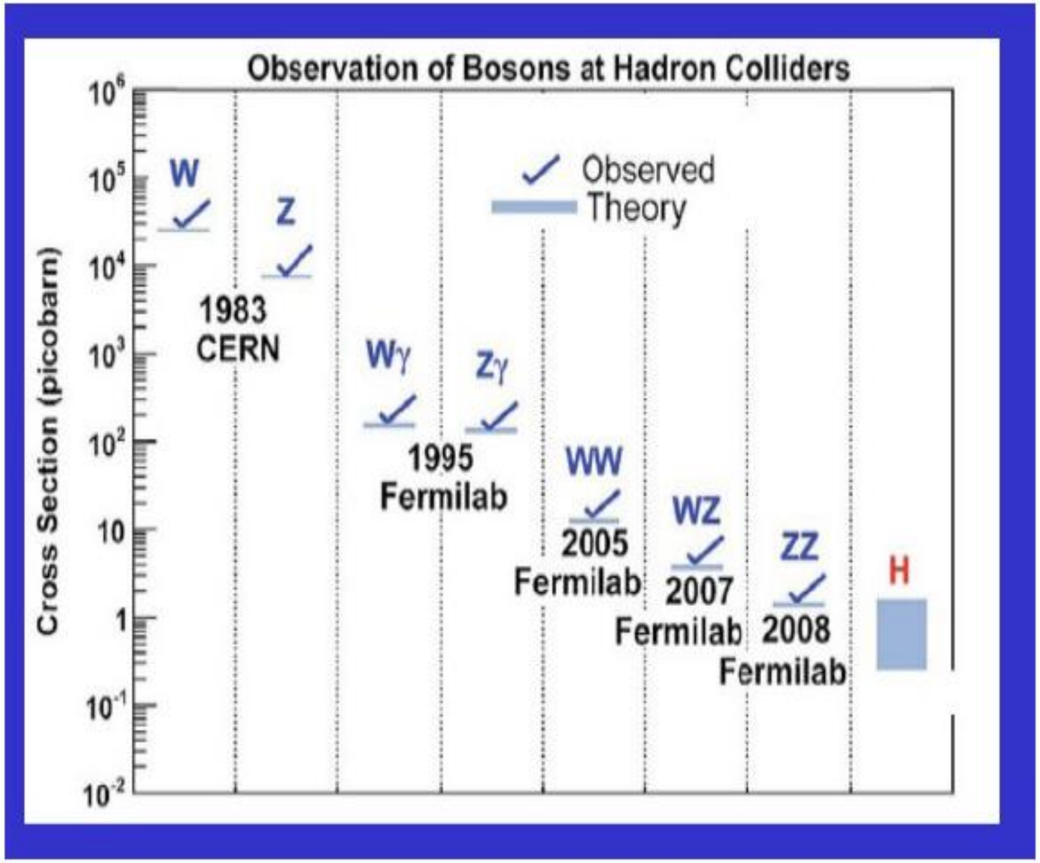
Bosons at hadron colliders

The primary decay chanel is through leptonic decays:

- BR(W→e ν) ~ 10%
- BR(Z→ ee) ~ 3%

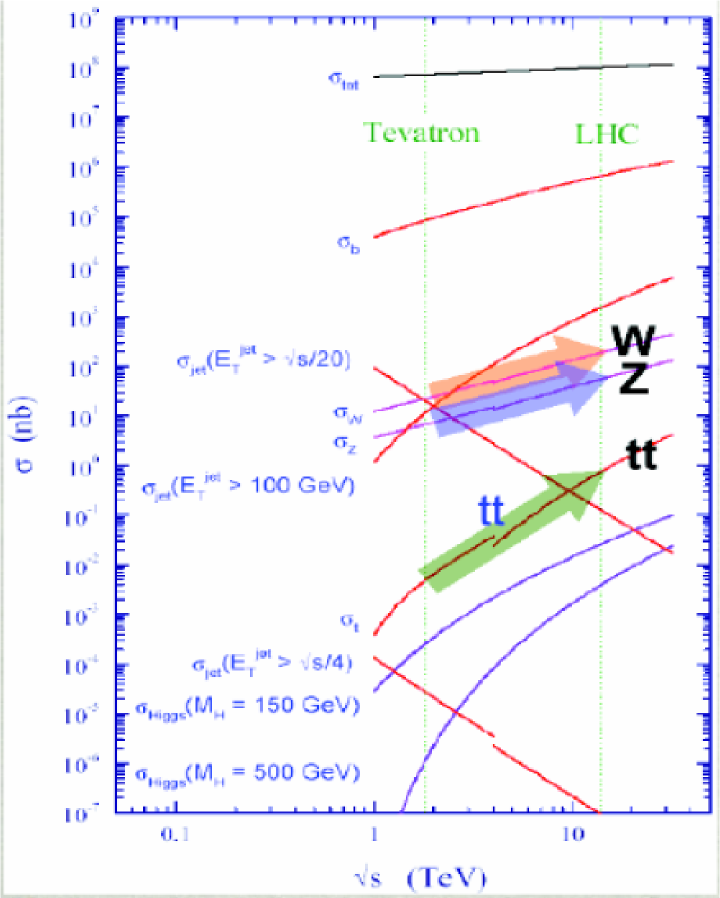
- It means that we are probing σ x BR values orders of magnitude smaller
- At LHC cross-section 5-10 x higher than at Tevatron at Fermilab.

2010

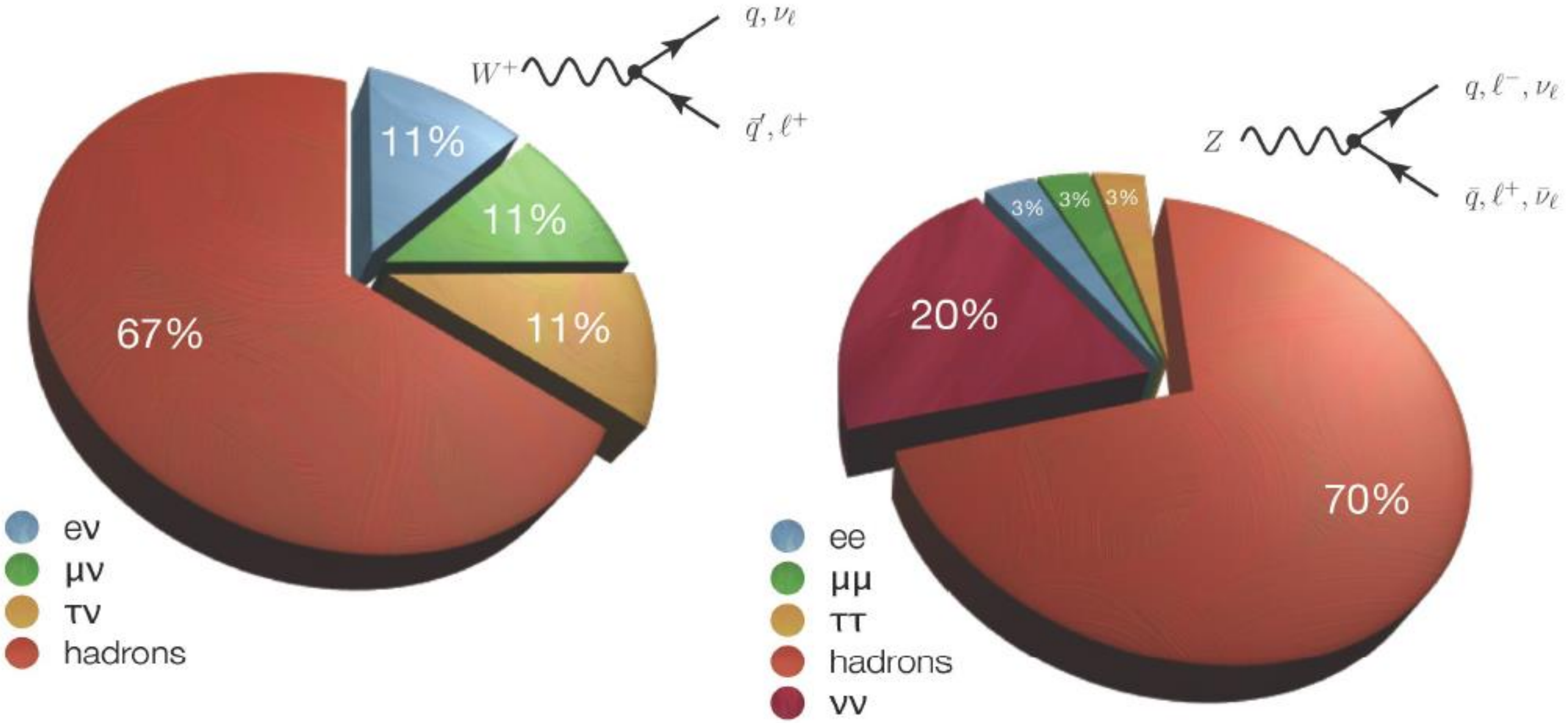


Bosons and top quark at LHC

- Well measured by previous experiments
- Still educational at LHC
  - Cross-sections
  - New PDF constraints
- „Standard candles” for high p_T analyses
  - Calibration, alignment
  - Independent luminosity measurements

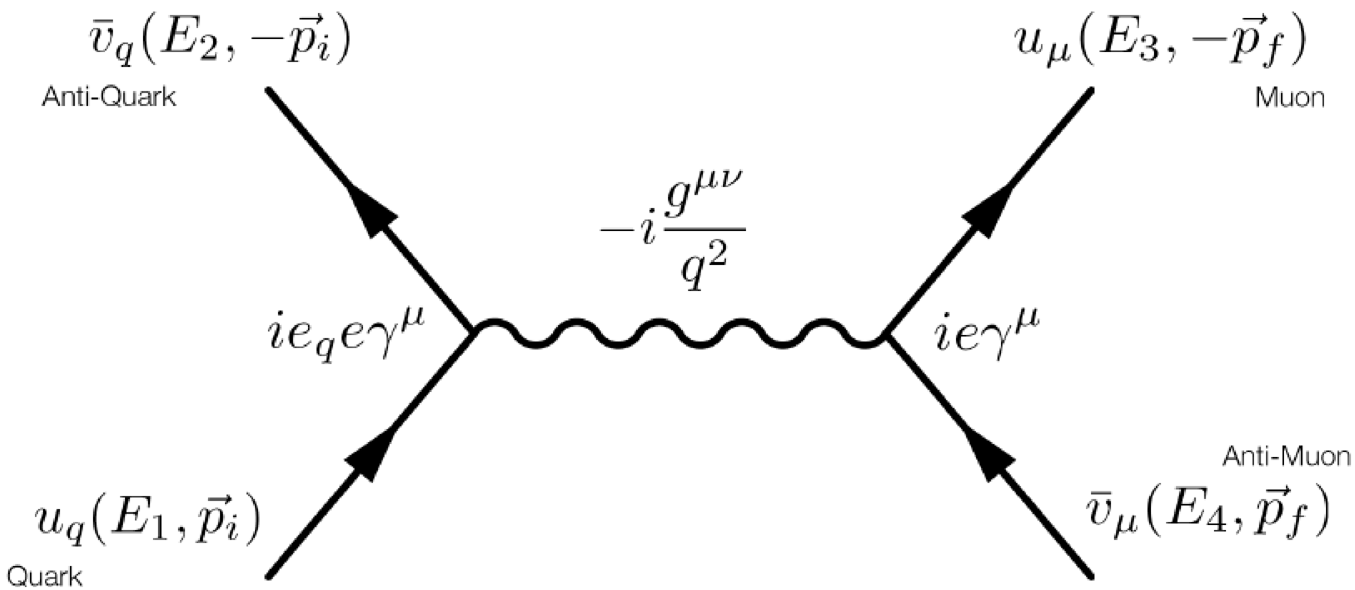


W and Z boson decays



Leptonic decays (e/μ): very clean, but small(ish) branching fractions
Hadronic decays: two-jet final states; large QCD dijet background
Tau decays: somewhere in between…

Example: Drell-Yan process

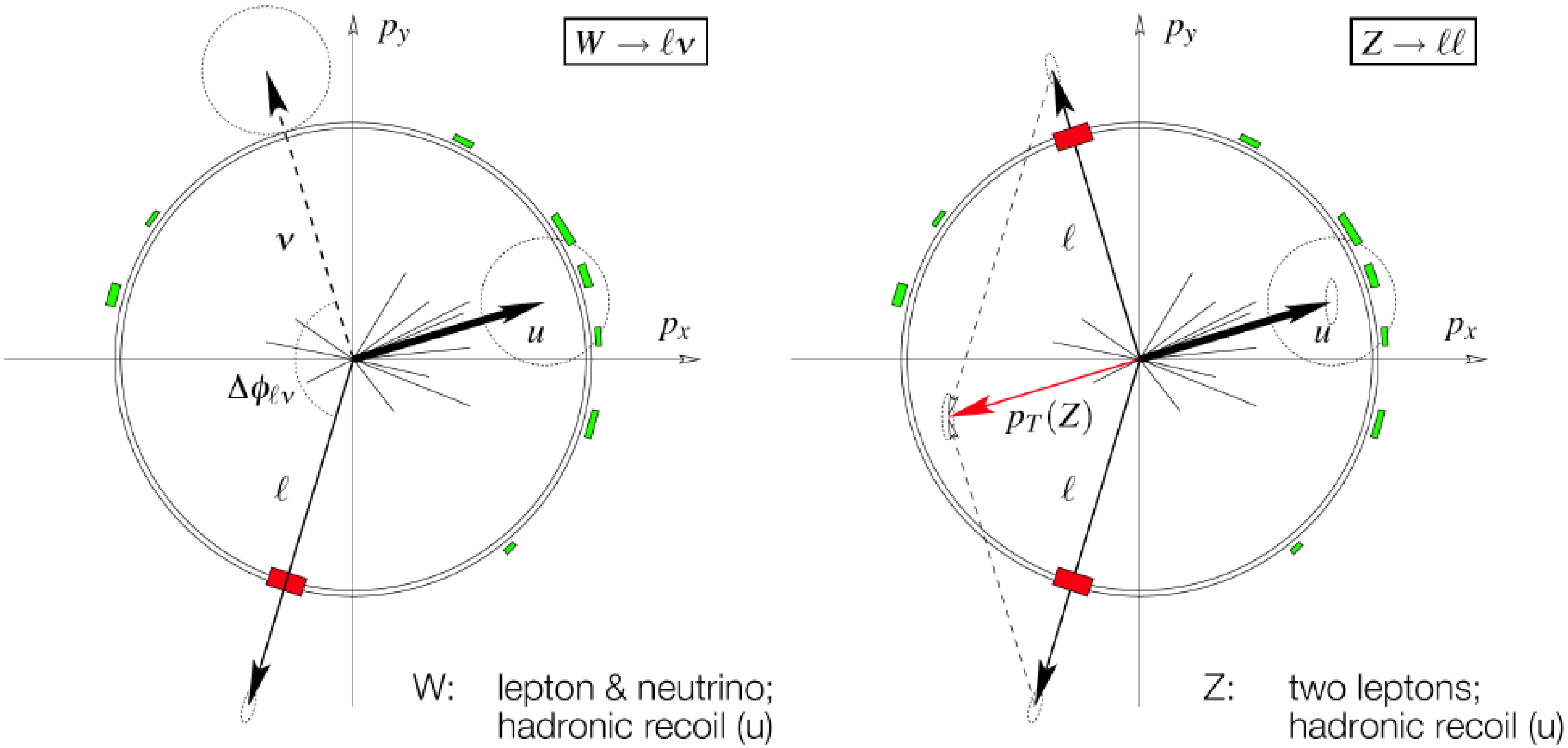


Averaging over initial spins

Summing over initial and final spins

$$|M_{fi}|^2 = \frac{1}{(2s_q+1)^2} \cdot \sum_{s_q, s'_q} \sum_{s_\mu, s'_\mu} |M_{fi}|^2$$

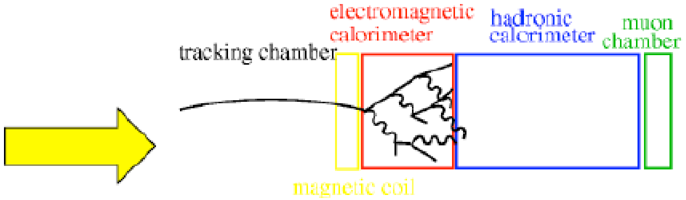
W and Z boson signatures



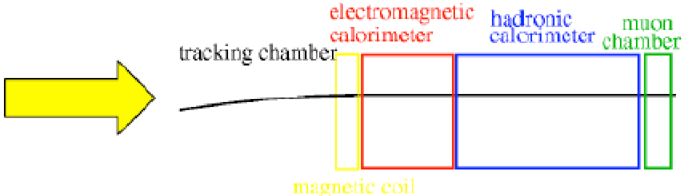
Additional hadronic activity ➛ recoil, not as clean as e^+e^-
Precision measurements: only leptonic decays

Lepton identification

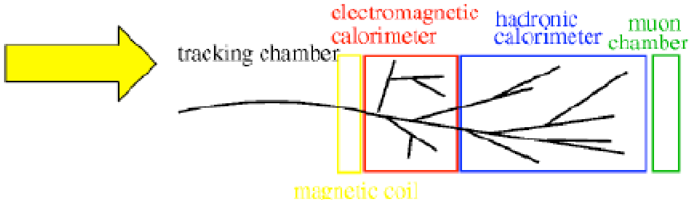
- Electron:
  - Compact electromagnetic cluster in calorimeter
  - Matched to track



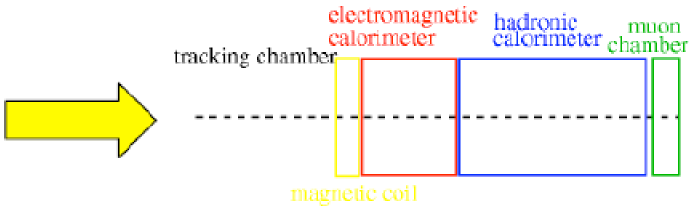
- Muons:
  - Track in the muon chambers
  - Matched to track



- Taus:
  - Narrow jet
  - Matched to one or three tracks

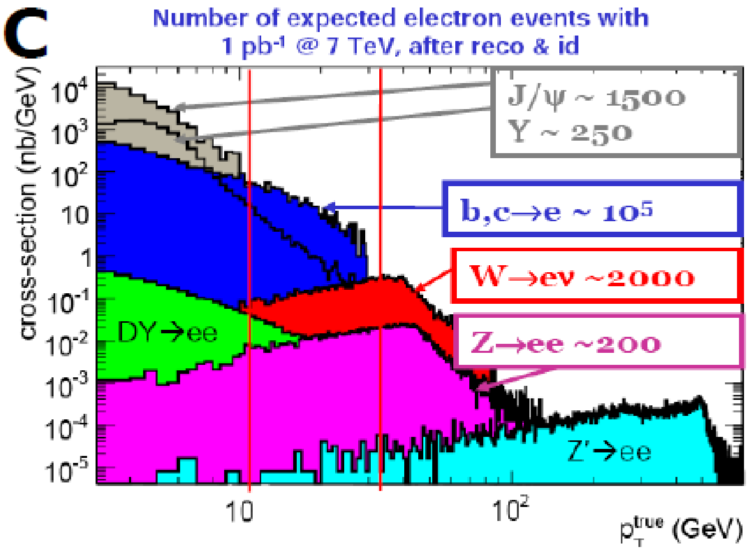


- Neutrinos
  - Imbalanse in transverse momentum
  - Inferred from total transverse energy in detector



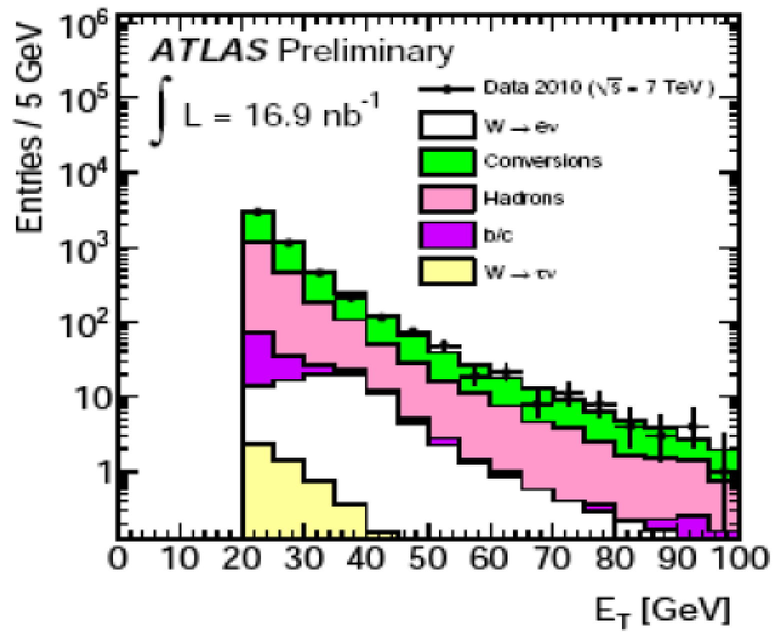
Electrons and jets

MC



- There is also lot of true electrons from semileptonic decays inside jets

DATA: loose electron ID



- Jets can look like electrons
  - Photon conversion from π^0's
  - Early showering charged pions
- And there is lot of jets
- Difficult to model in Monte Carlo
  - Detailed simulation in tracking and calorimeter volume

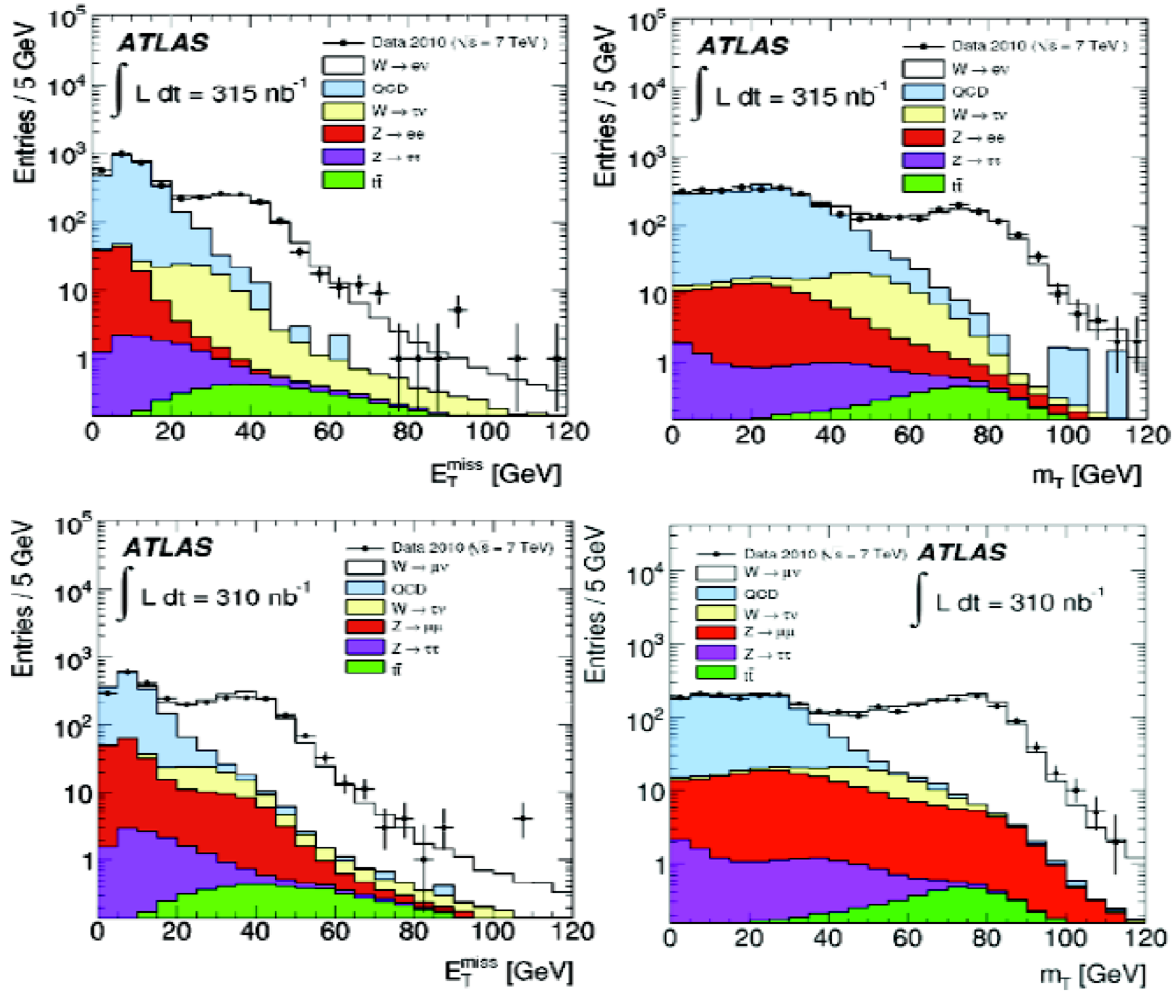
W selection (2010)

Electrons:

- $E_T > 20$ GeV
- *Tight ID*
- *Missing* $E_T > 25$ GeV
- $m_T > 40$ GeV
- ➢ *1069 Candidates*

Muons:

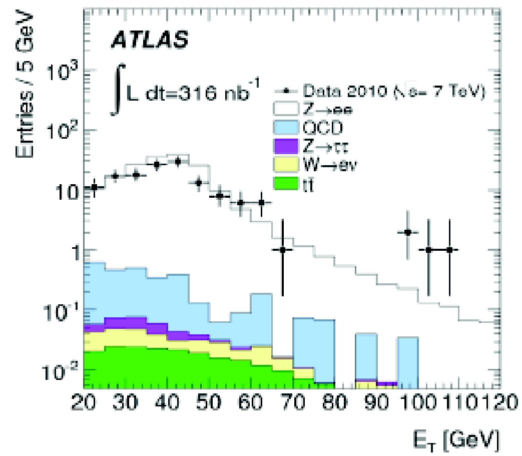
- $p_T > 20$ GeV
- *Track isolation*
- *Missing* $E_T > 25$ GeV
- $m_T > 40$ GeV
- ➢ *1181 Candidates*

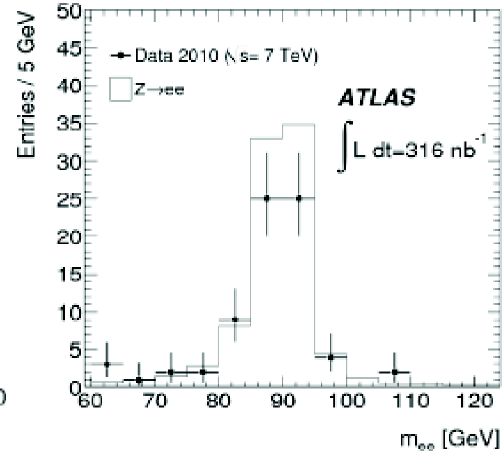


Z selection (2010)

2 Electrons :

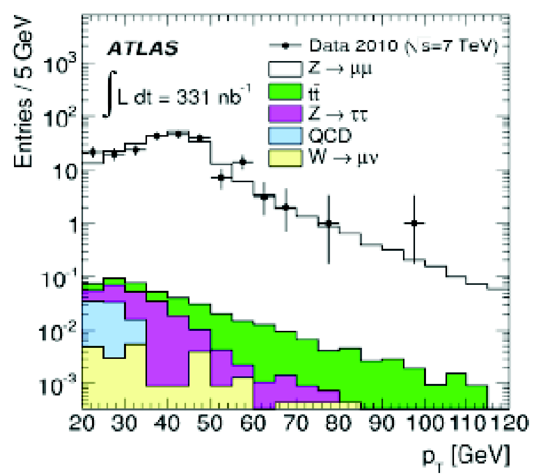
- $E_T > 20$ GeV
- *Opposite charge*
- *Medium ID*
- $66 < m_{ee} < 116$ GeV
- ➢ *70 Candidates*

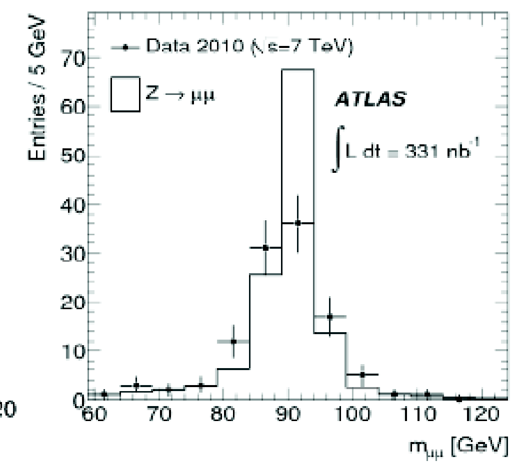




2 Muons :

- $p_T > 20$ GeV
- *Track isolation*
- *Opposite charge*
- $66 < m_{\mu\mu} < 116$ GeV
- ➢ *109 Candidates*





W backgrounds

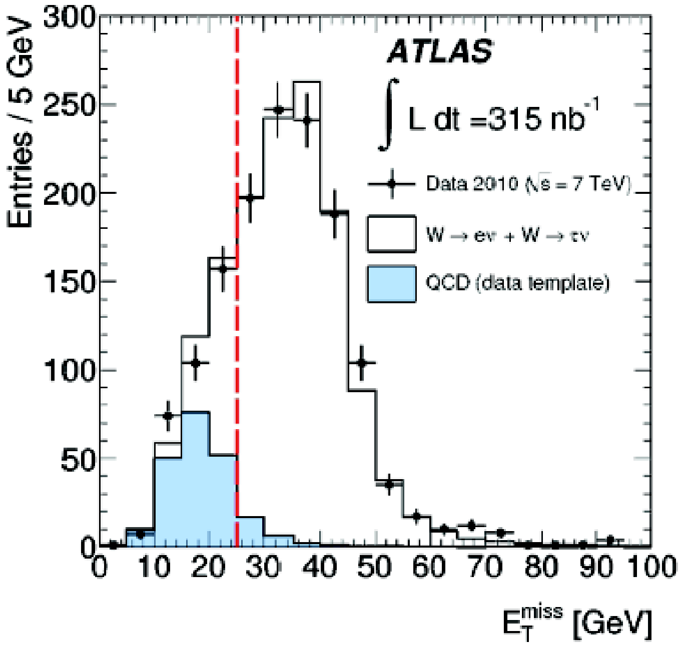
Electrons:

- EW + top background: $W \rightarrow \tau \nu + Z \rightarrow e^+e^- + t\bar{t}$

  $N_{EW+TOP} = 33.5 \pm 0.2(\text{stat}) \pm 3.0(\text{syst})$

- QCD background is estimated with the template method using the missing energy distribution.

  $N_{QCD} = 28.0 \pm 3.0(\text{stat}) \pm 10.0(\text{syst})$



Muons:

- EW + top background: $Z \rightarrow \mu^+\mu^- + W \rightarrow \tau \nu + t\bar{t}$

  $N_{EW+TOP} = 77.6 \pm 0.3(\text{stat}) \pm 5.4(\text{syst})$

- QCD background estimated from comparison of events seen in data after the full selection to number of events observed if the isolation is not applied.

  $N_{QCD} = 22.8 \pm 4.6(\text{stat}) \pm 8.7(\text{syst})$

$$N_{loose} = N_{nonQCD} + N_{QCD}$$
$$N_{iso} = \epsilon^{iso}_{nonQCD} N_{nonQCD} + \epsilon^{iso}_{QCD} N_{QCD}$$

Cross-section & Luminosity

Number of observed events
just count …

Background
measured from data or calculated from theory

$$\sigma = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\int \mathcal{L}\,\mathrm{d}t \cdot \varepsilon}$$

Luminosity
determined by accelerator, triggers, …

Efficiency
many factors, optimized by experimentalist

W cross-section measurement

The total cross section for each lepton channel can be obtained by:

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

A_W is the geometrical acceptance calculated at generator level:

$$A_W = \left(\frac{N^{acc}}{N^{all}}\right)_{gen}$$

MC	A_W $W^+ \to e^+\nu$	A_W $W^- \to e^-\nu$	A_W $W \to e\nu$	A_W $W^+ \to \mu^+\nu$	A_W $W^- \to \mu^-\nu$	A_W $W \to \mu\nu$
PYTHIA MRST LO*	0.466	0.457	0.462	0.484	0.475	0.480
PYTHIA CTEQ6.6	0.479	0.458	0.471	0.499	0.477	0.490
PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.496	0.479	0.489
MC@NLO HERAPDF1.0	0.475	0.454	0.465	0.494	0.472	0.483
MC@NLO CTEQ6.6	0.478	0.452	0.465	0.496	0.470	0.483

W cross-section measurement

The total cross section for each lepton channel can be obtained by:

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MC	A_W $W^+ \to e^+\nu$	A_W $W^- \to e^-\nu$	A_W $W \to e\nu$	A_W $W^+ \to \mu^+\nu$	A_W $W^- \to \mu^-\nu$	A_W $W \to \mu\nu$
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PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.496	0.479	0.489
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MC@NLO CTEQ6.6	0.478	0.452	0.465	0.496	0.470	0.483

C_W correction factor and uncertainties

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

- C_W is a factor correcting for reconstruction, identification and trigger efficiencies of the lepton.

	$W \to e\nu$	$W \to \mu\nu$
C_W	0.66	0.76

- Components to systematic uncertainties, are summarized below:

Parameter	$\delta C_W/C_W(\%)$
Trigger efficiency	<0.2
Material effects, reconstruction and identification	5.6
Energy scale and resolution	3.3
E_T^{miss} scale and resolution	2.0
Problematic regions in the calorimeter	1.4
Pile-up	0.5
Charge misidentification	0.5
FSR modelling	0.3
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	7.0

Electrons

Parameter	$\delta C_W/C_W(\%)$
Trigger efficiency	1.9
Reconstruction efficiency	2.5
Momentum scale	1.2
Momentum resolution	0.2
E_T^{miss} scale and resolution	2.0
Isolation efficiency	1.0
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	4.0

Muons

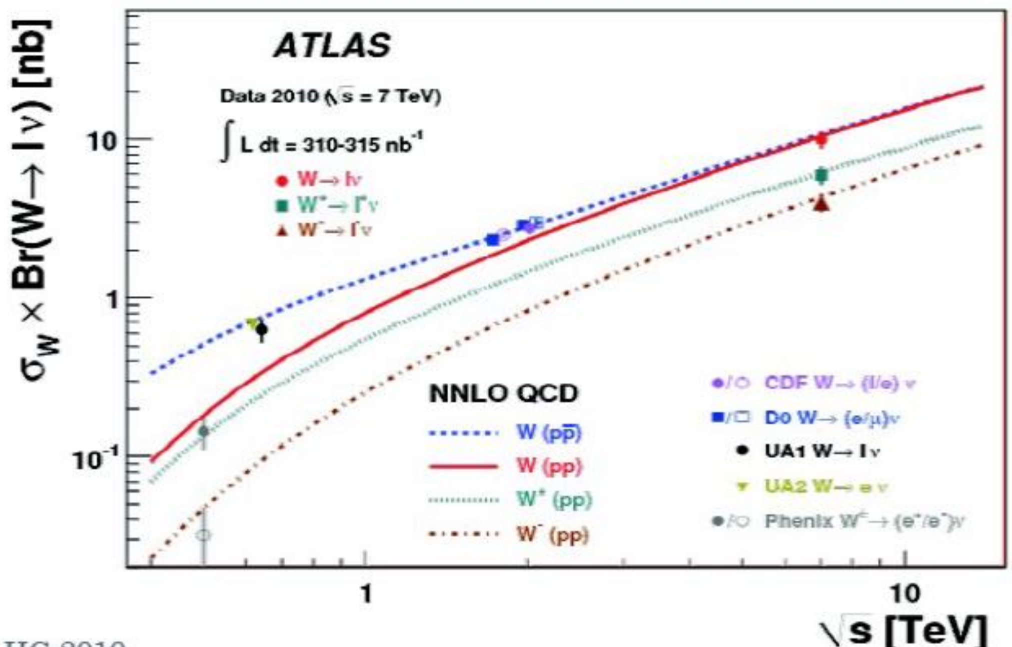
W cross-section measurement

L ≈ 310 - 315 nb[-1]

Theory prediction : 10.46 ± 0.42 nb

$\sigma_W \times BR(W \to e\nu) = [10.51 \pm 0.34(stat) \pm 0.81(sys) \pm 1.16(lumi)]\, nb$

$\sigma_W \times BR(W \to \mu\nu) = [9.58 \pm 0.30(stat) \pm 0.50(sys) \pm 1.05(lumi)]\, nb$



Jose E. Garcia - HEP-LHC-2010

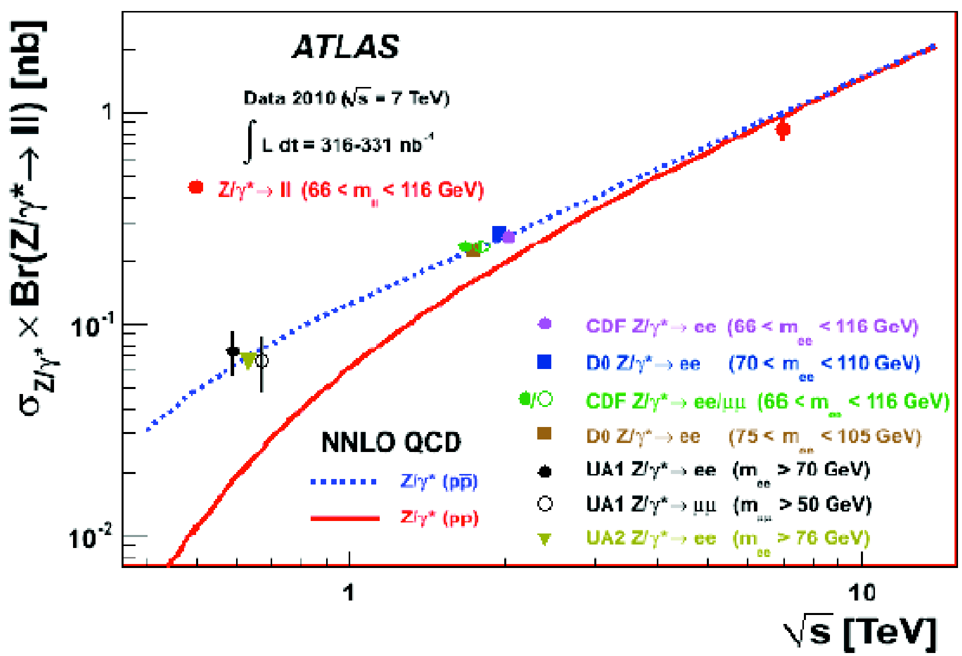
Z cross-section measurement

$L \approx 310 - 315\, nb^{-1}$

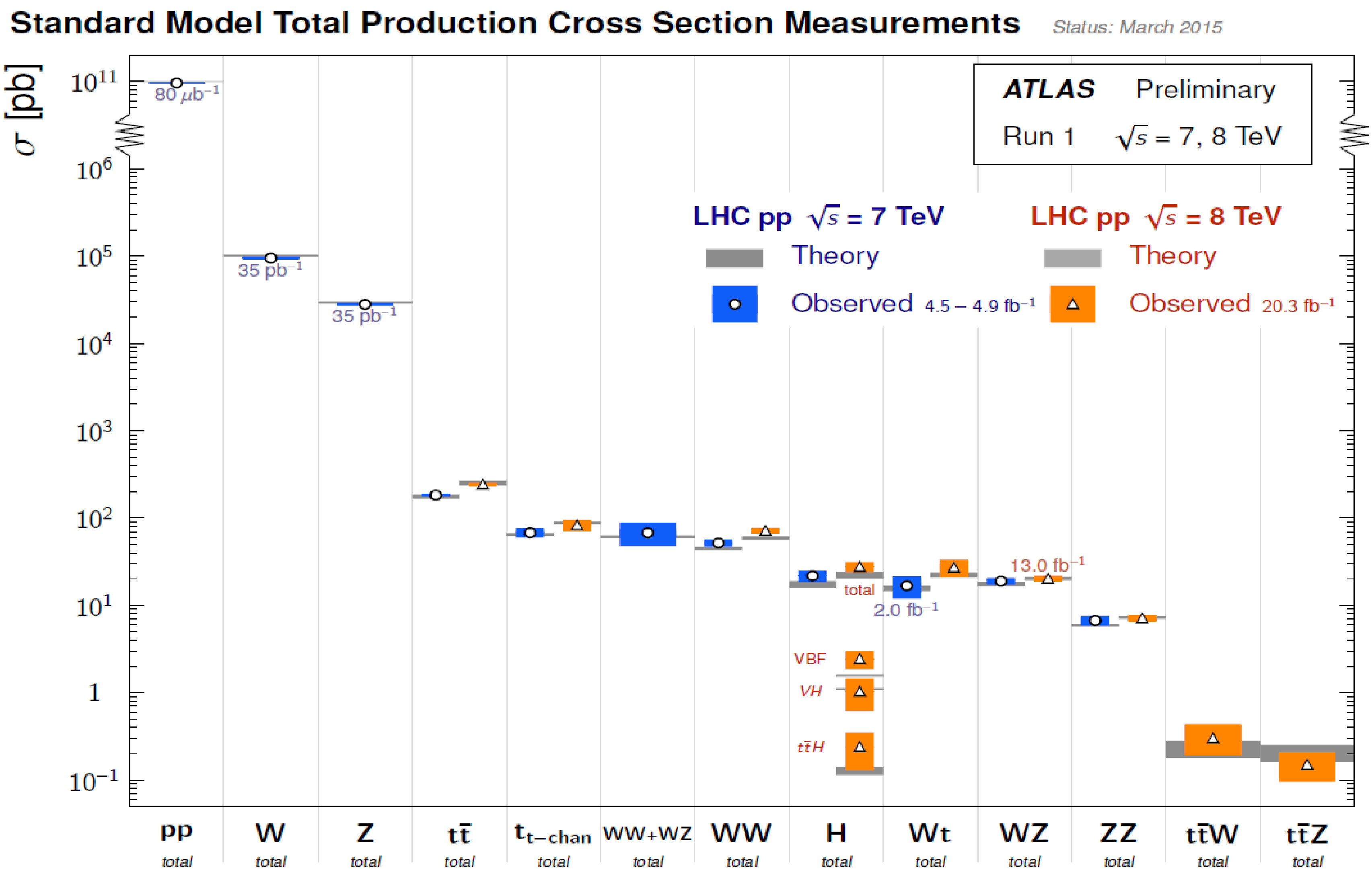
Theory prediction : 0.96 ± 0.04 nb for [66 – 116] GeV mass window

$$\sigma_Z \times BR(Z \to e^+e^-) = [0.75 \pm 0.09(stat) \pm 0.08(sys) \pm 0.08(lumi)]\, nb$$

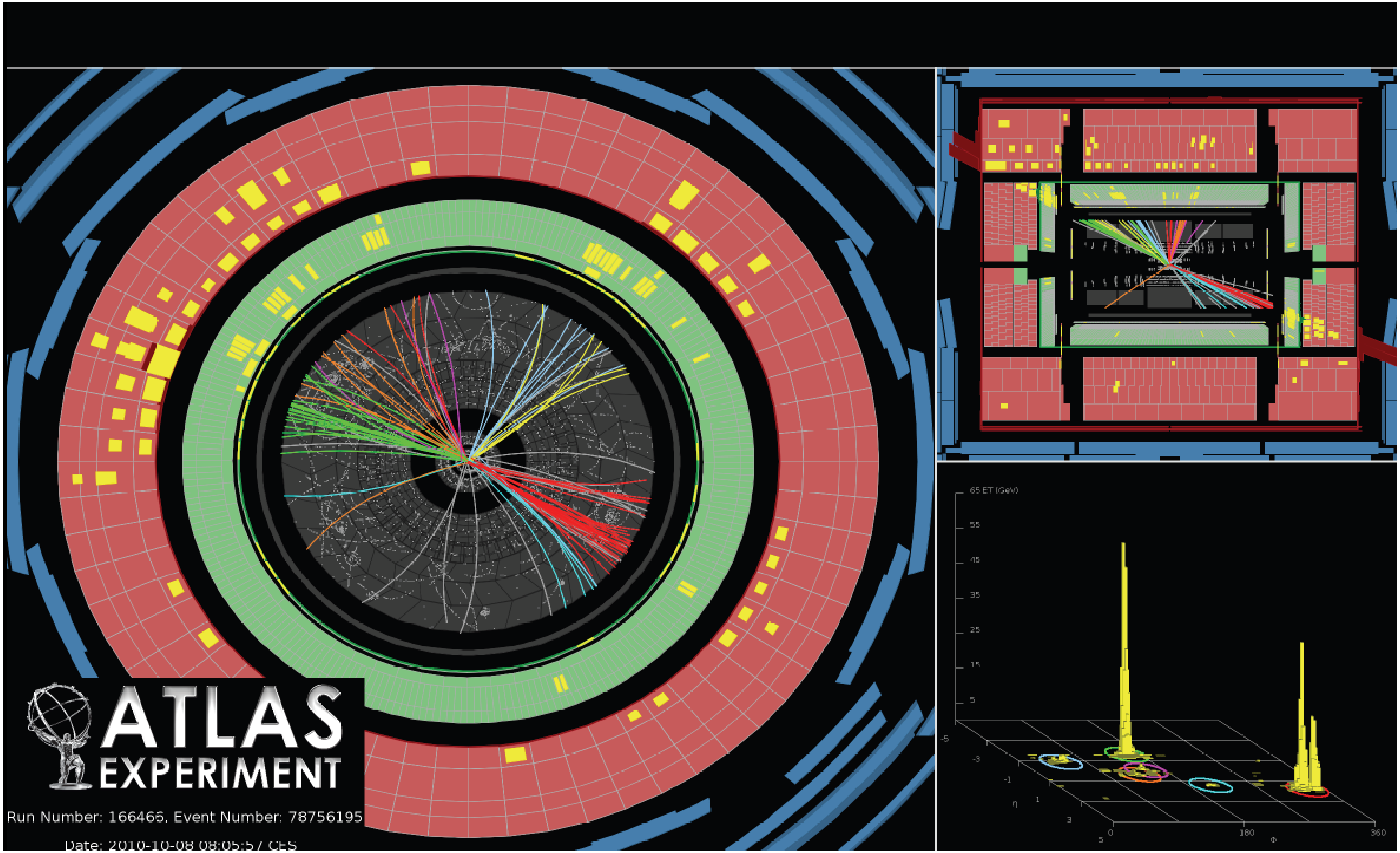
$$\sigma_Z \times BR(Z \to \mu^+\mu^-) = [0.87 \pm 0.08(stat) \pm 0.06(sys) \pm 0.10(lumi)]\, nb$$



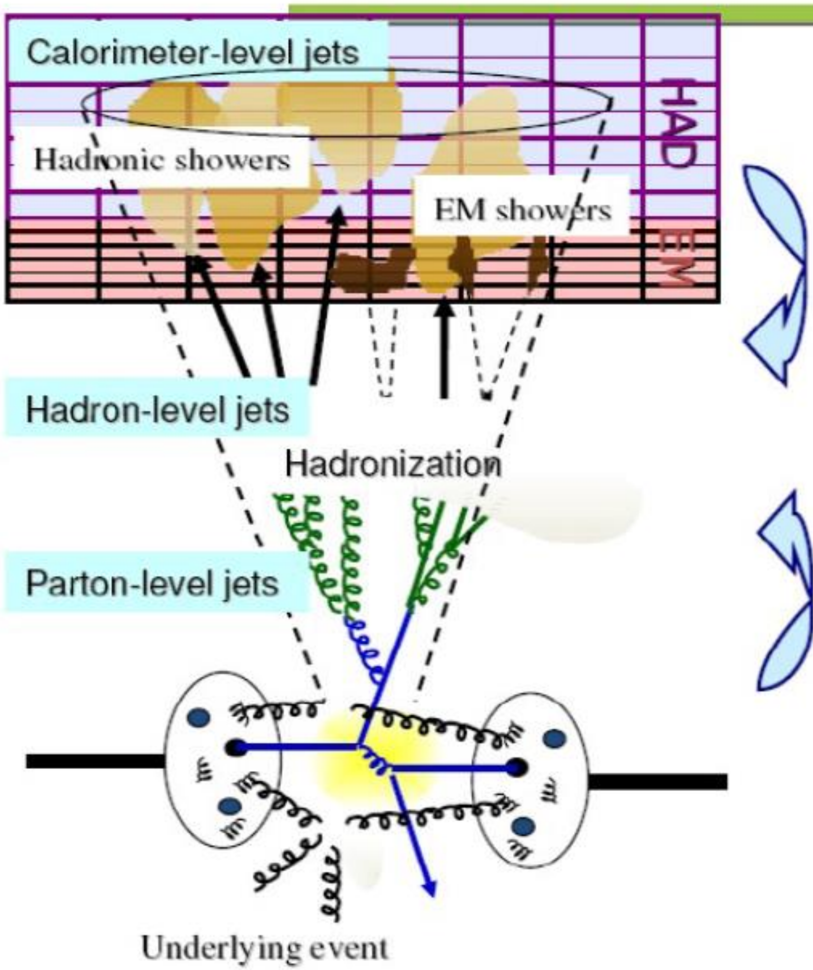
Production cross-sections



Confinement, hadronisation, jets….



Inclusive jet production



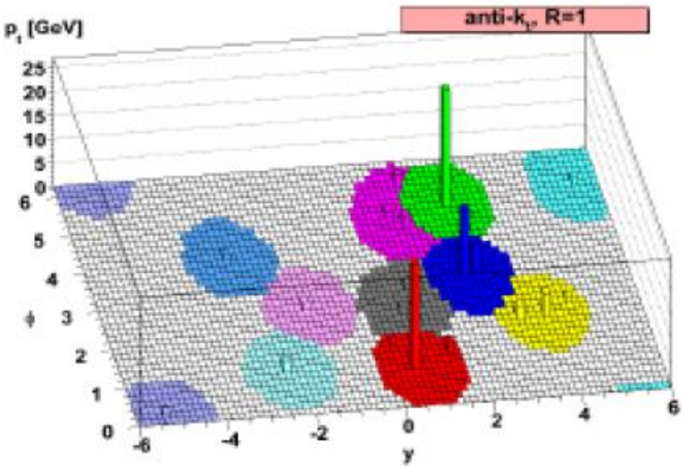
Unfold measurements to the hadron (particle) level

Correct parton-level theory for non-perturbative effects (hadronization & underlying event)

Jets are collimated spray of particles originating from parton fragmentation.
→ To be defined by an algorithm

Jet reconstruction

- Jet finding: from partons/particles/energy deposits to jet

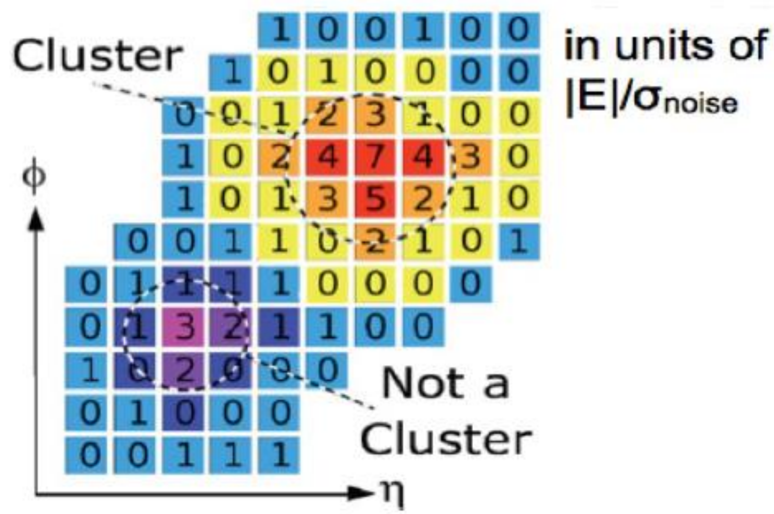


[Cacciari, Salam, Soyez JHEP 0804:063,2008]

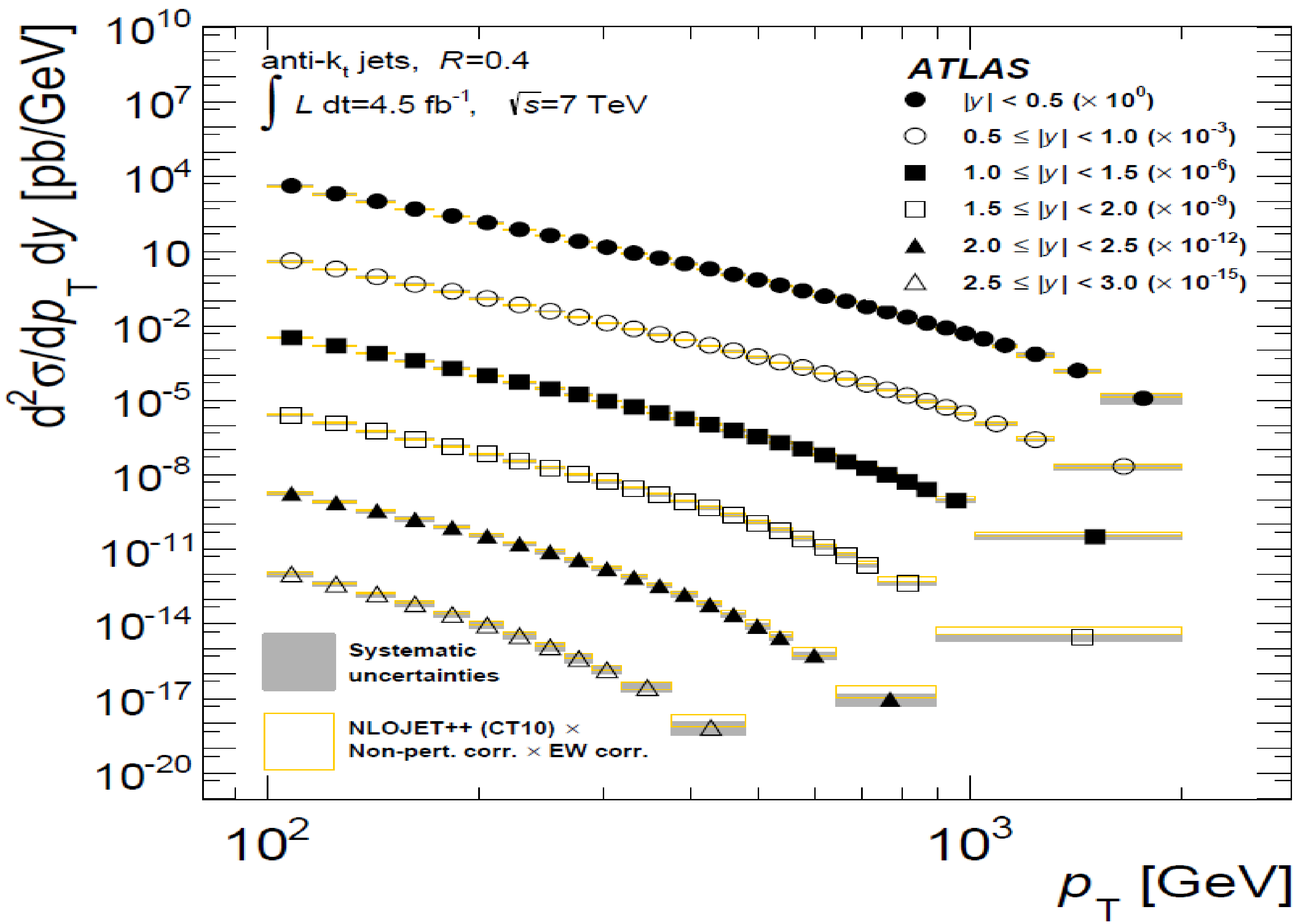
Energy deposits → noise-suppressed 3D clusters:
exploit transverse and longitudinal calorimeter segmentation

Jet inputs clustered with anti-k_T algorithm:

- Infrared safe, collinear safe (⇒ NLO comparisons)
- Regular, cone-like jets in calorimeters
- Distance parameter 0.4, 0.6

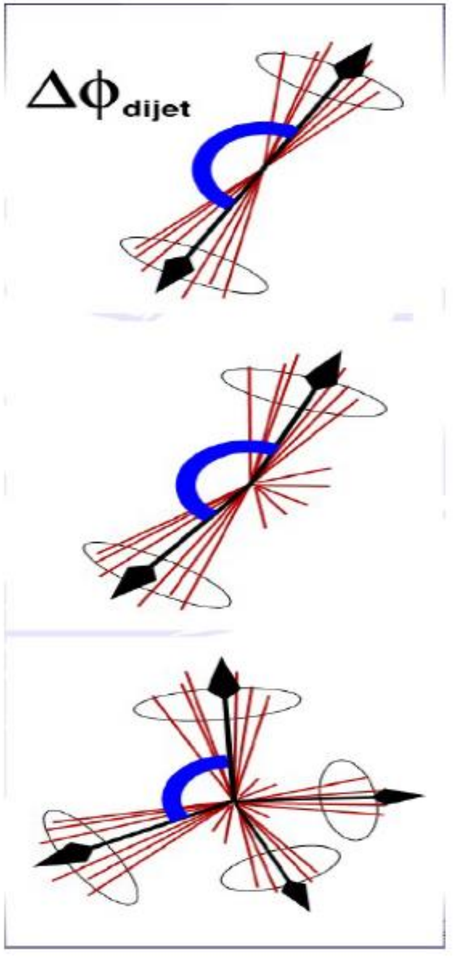


Di-jet cross-section



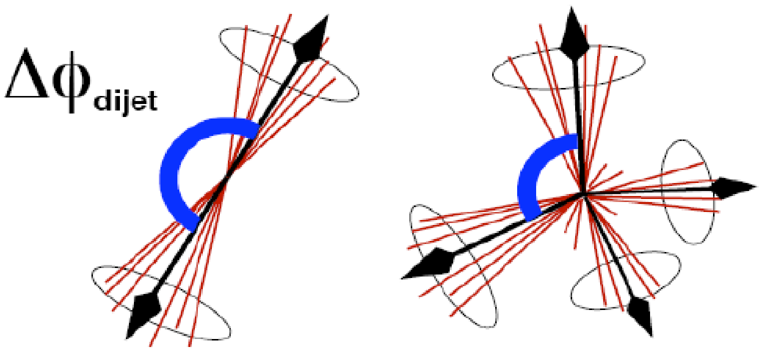
Multi-jet events

- Azimuthal decorrelations in dijet events and distribution of energy within jets sensitive to QCD radiation structures
  - Probing higher order QCD radiation
  - Main systematics: cluster energy scale (separate from JES) and unfolding

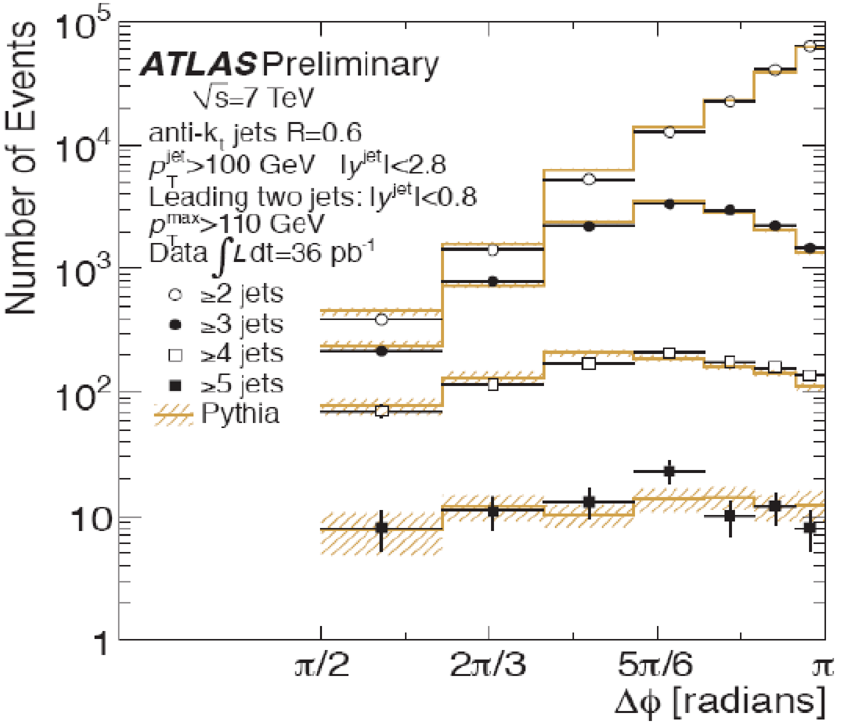


Azimuthal decorrelations

- Complementary to multi-jet cross section measurement.
- Pure di-jets have azimutal angle Φ between jets equal to π.
- With additional hard radiation, i.e. extra jets, phi becomes smaller.



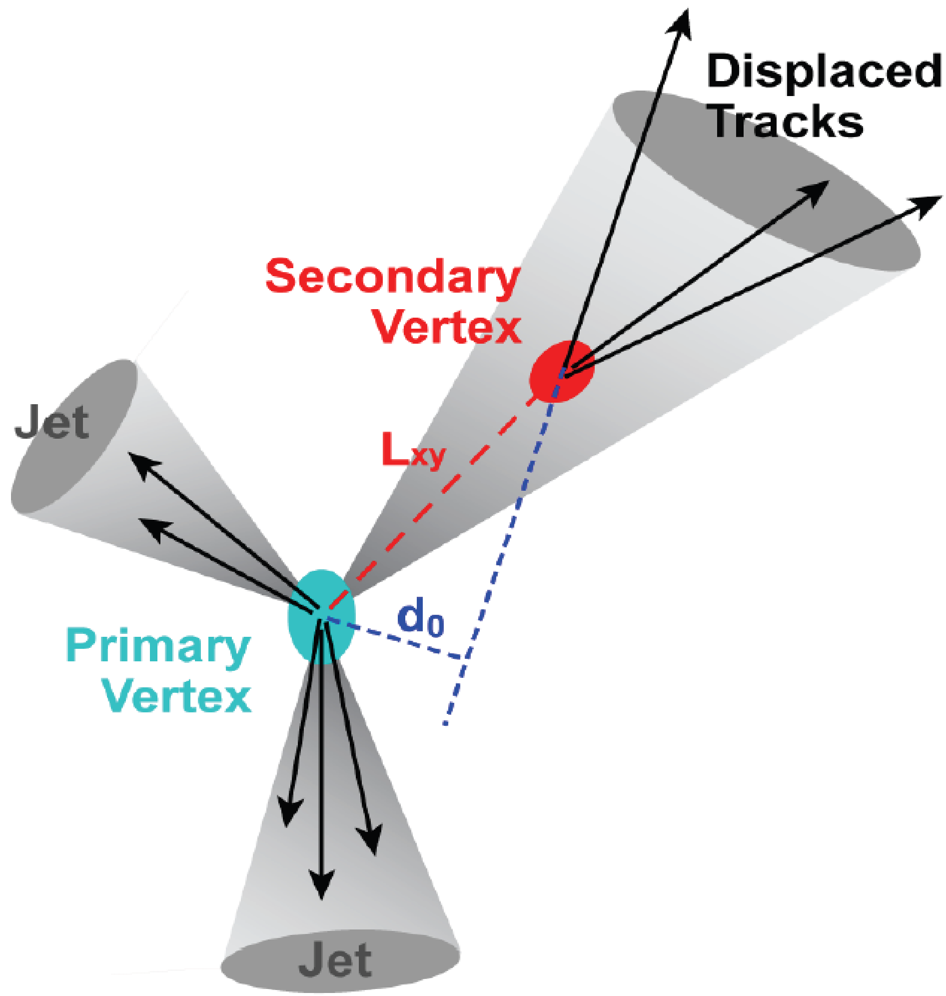
- Requiring additional jets flattens distribution.



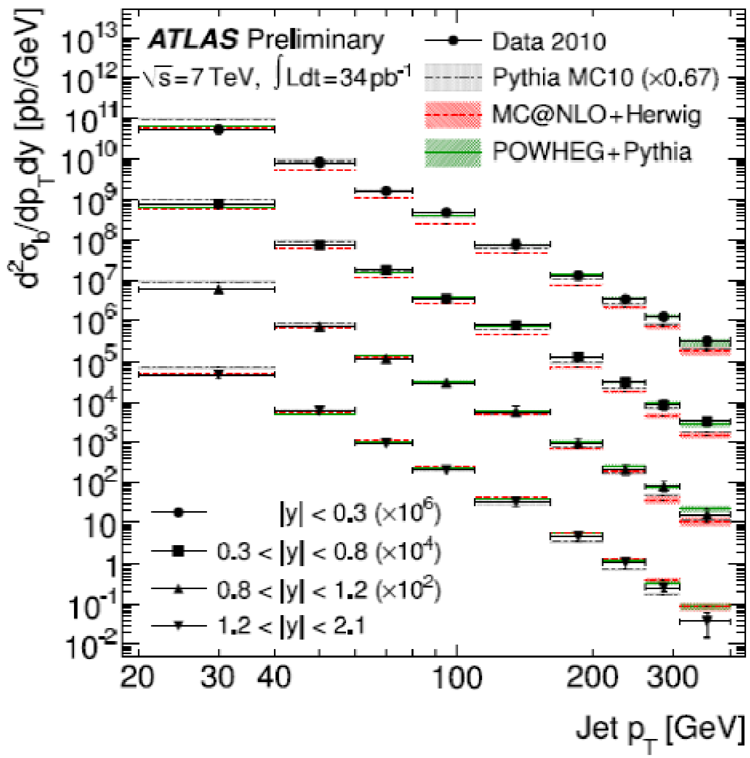
Confinement, hadronisation, jets….

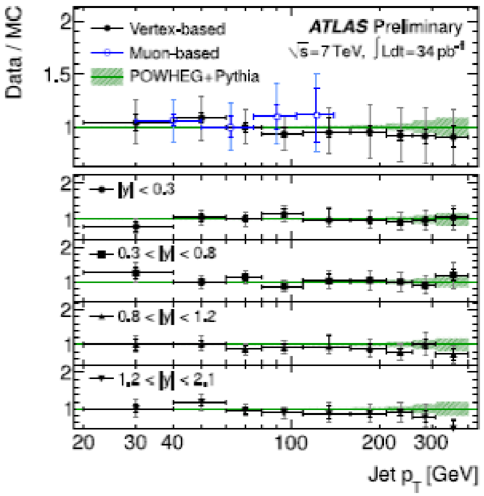
B-tagging

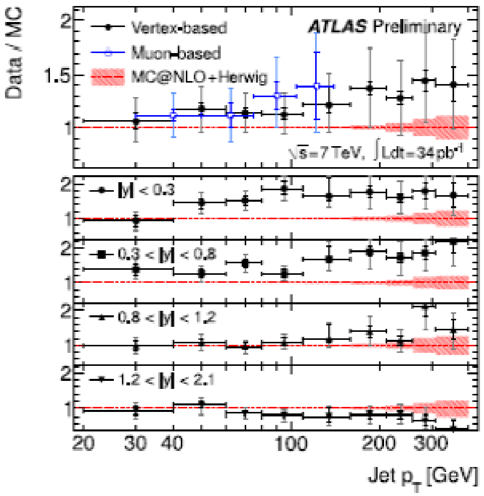
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark content
- Similar procedure for c quark…



b-jet cross-sections

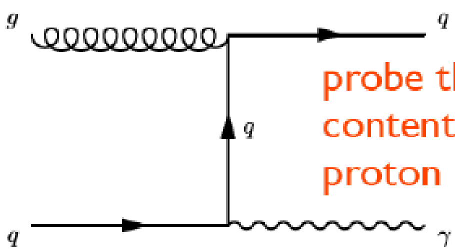




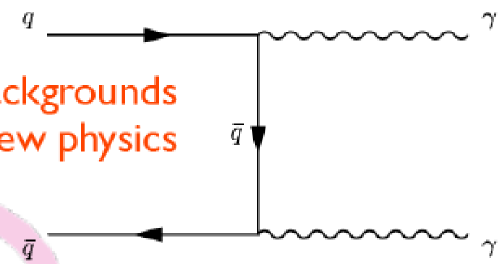


- Good agreement with Powheg+PYTHIA
- MC@NLO+Herwig predicts too few central jets, too many forward jets

Why measure prompt photons

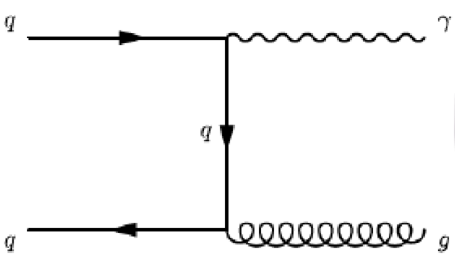


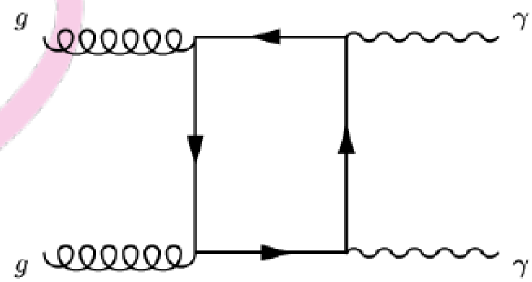
probe the gluon content of the proton



QCD backgrounds to new physics

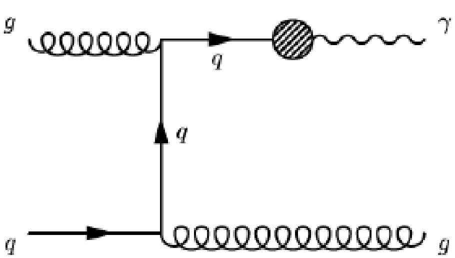
test NLO pQCD predictions using a measurement without jets



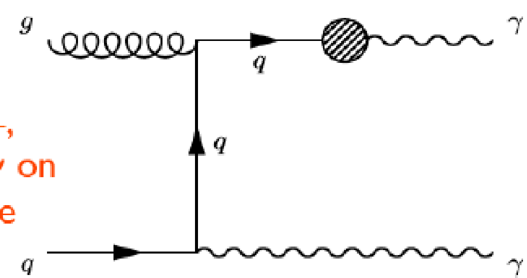


resummation

k_T factorisation

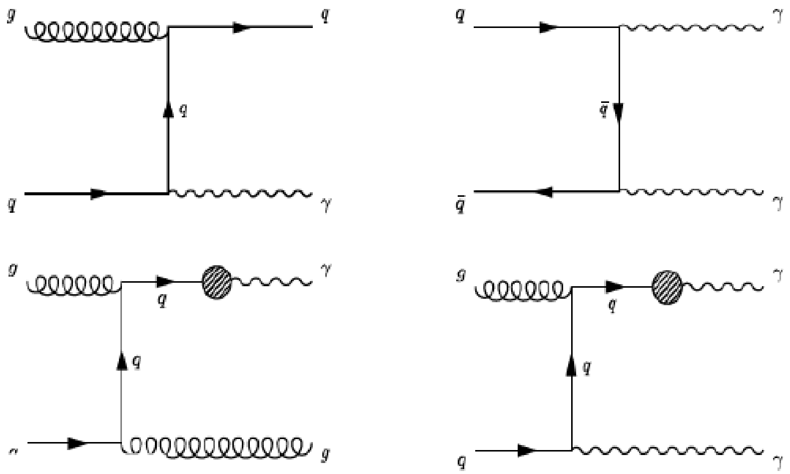


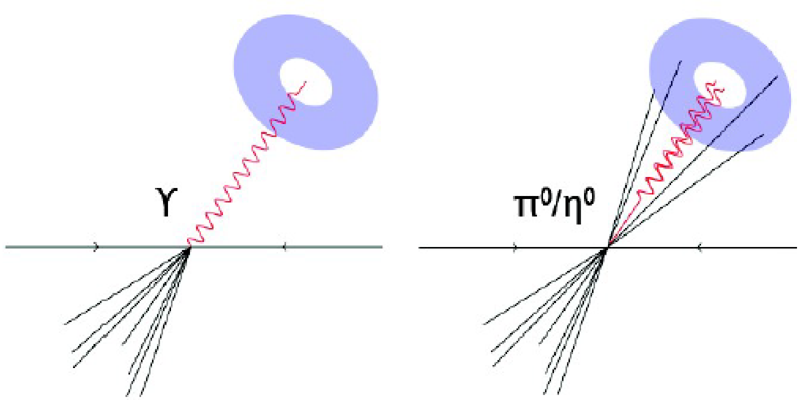
fragmentation important at low E_T, suppressed by isolation cut. MCs rely on fragmentation function to compute



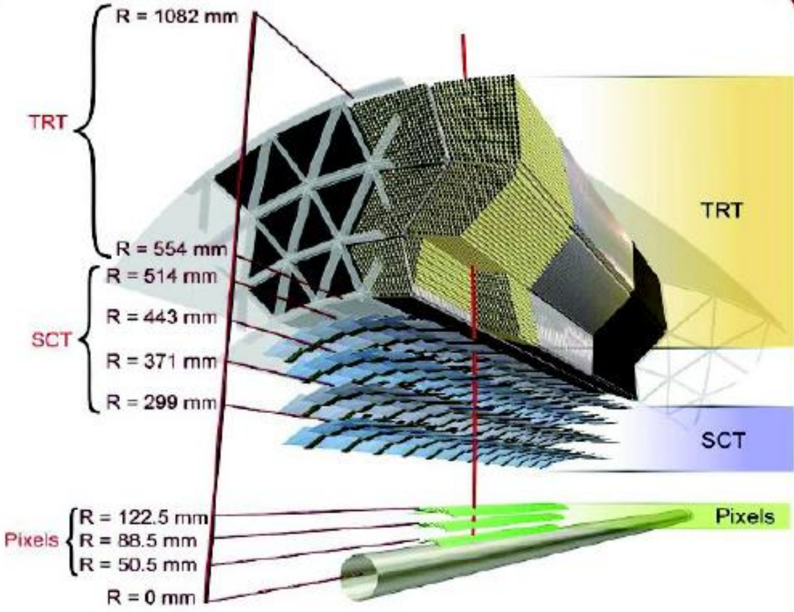
Prompt and isolated photons

- Prompt:
  - Direct from the hard scattering
  - Parton fragmentation more important at low E_T
- Isolated:
  - Isolation criteria to reduce bgd from QCD jets
    - Photons from neutral meson decay in jets
  - Reduced fragmentation component:
    - ~30% reduction at 15 GeV
    - <10% above 35 GeV

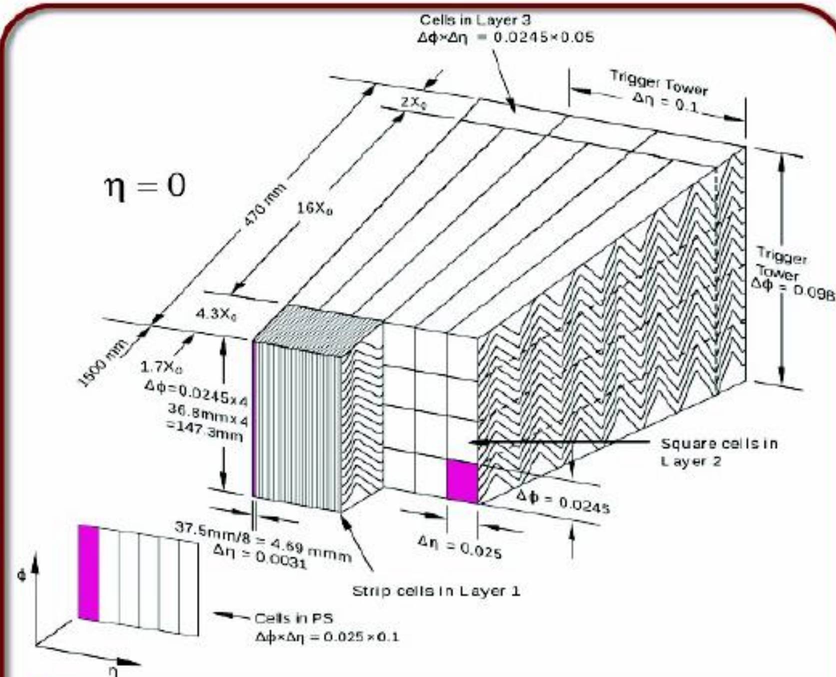




Measuring photons with ATLAS

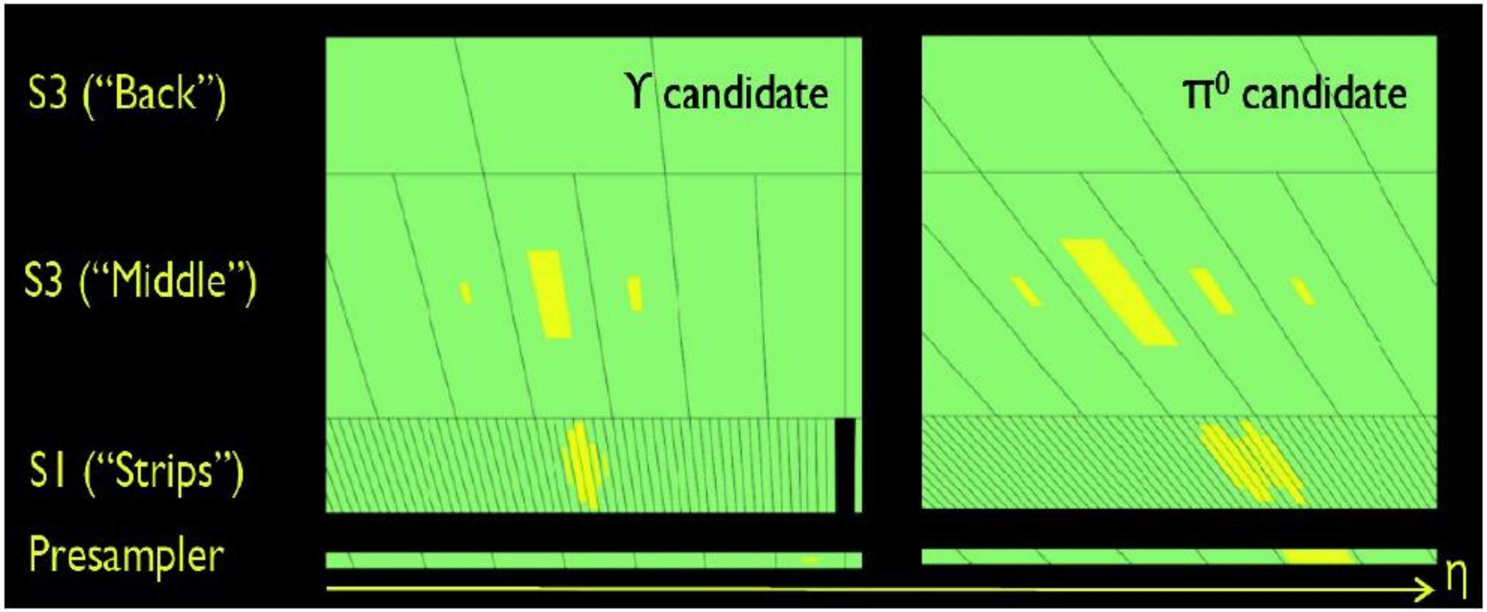


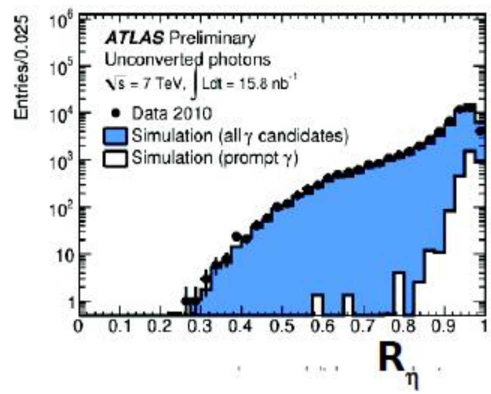
- Inner detector
  - ✓ track charged particles
  - ✓ measure transition radiation
  - ✓ e/γ discrimination
  - ✓ γ conversion reconstruction

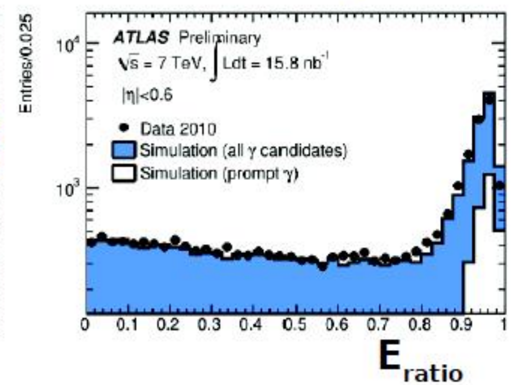


- Pb-LAr EM calorimeter
  - ✓ η/φ/longitudinal segmentation
  - ✓ fine granularity in 1st layer up to η<2.37
  - ✓ γ energy and direction
  - ✓ γ/π⁰ separation (EM shower moments)

Photon identification



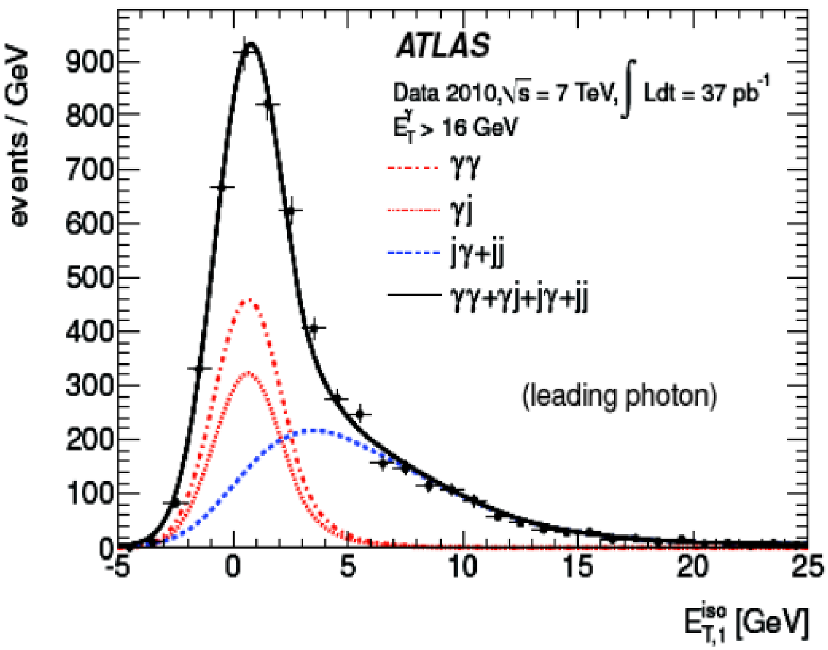


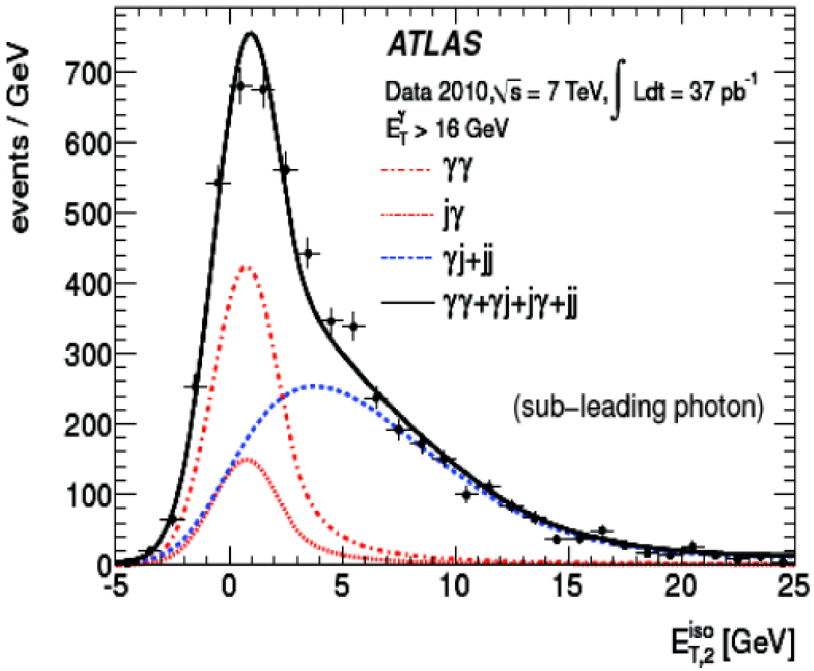


- loose and tight selection
- optimised separately for unconverted and converted photons

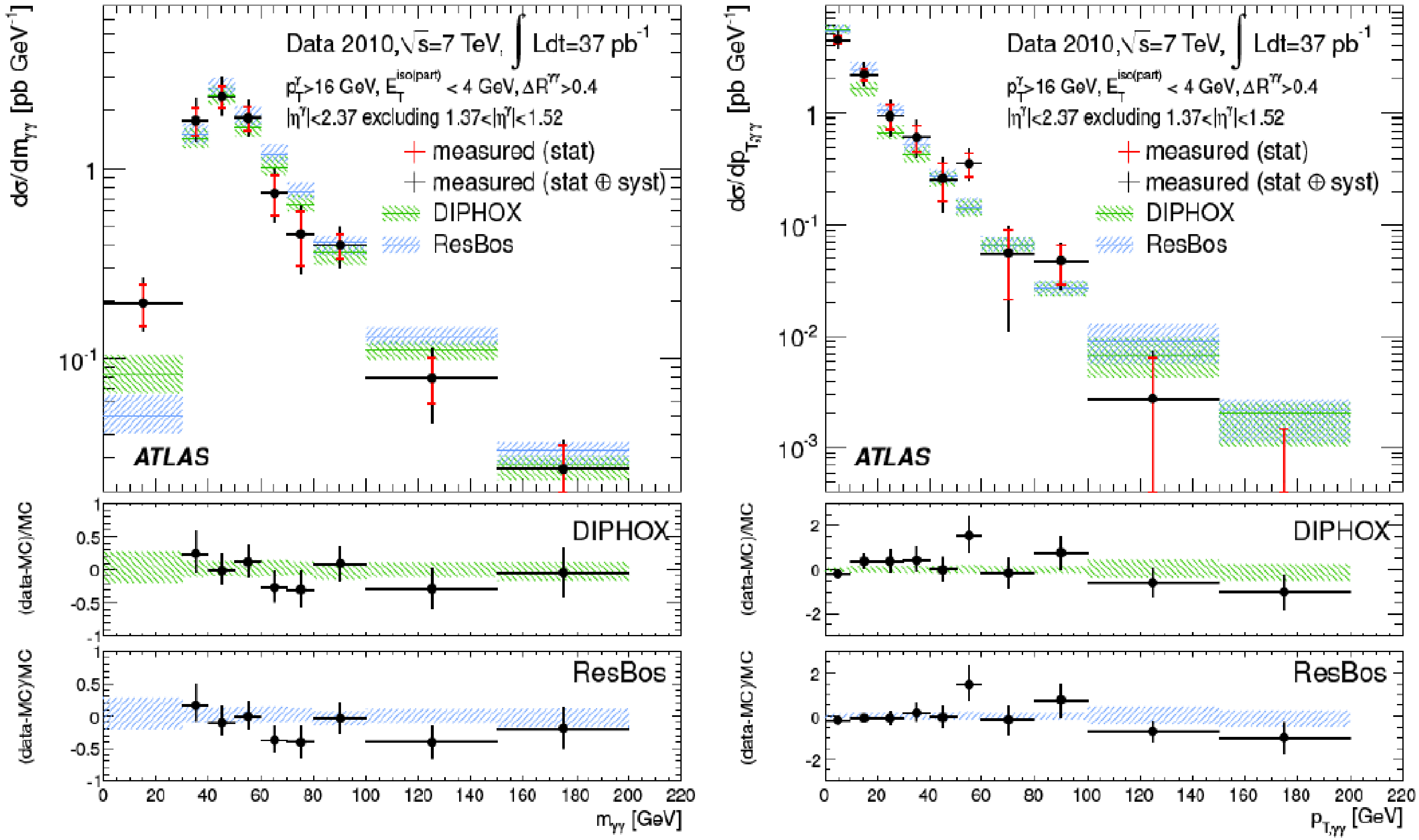
Photon isolation and background estimate

- Background estimated with two methods:
  - ABCD method: extrapolate from the bgd enriched control regions
  - here shown example of 2D template fit





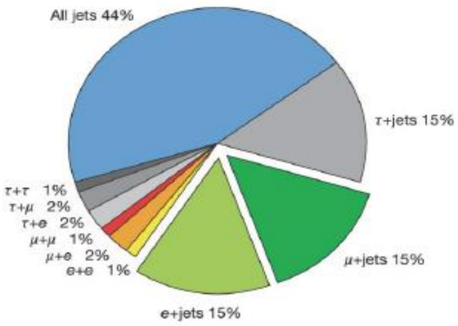
Isolated di-photon cross-section

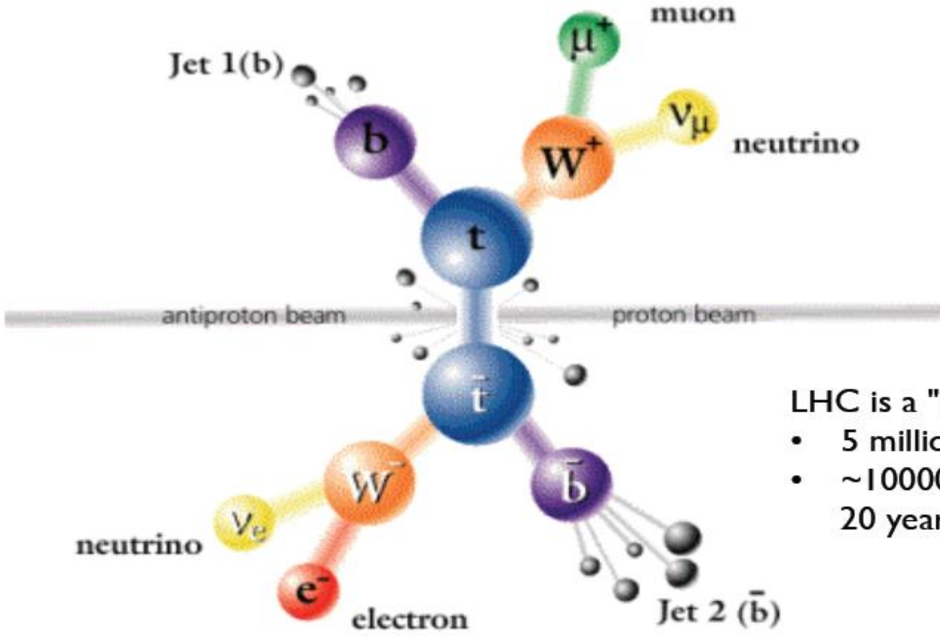


Complicated topologies….

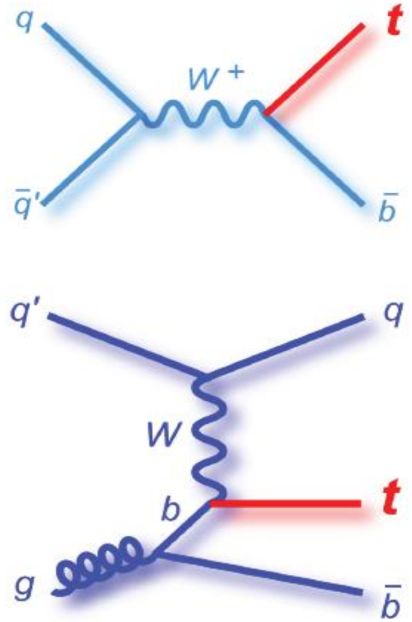
top quark

- Top quark has a mean lifetime of 5×10^{-25} s, shorter than time scale at which QCD acts: no time to hadronize!
  - ✓ It decays as $t \rightarrow Wb$
- Events with top quarks are very rich in (b) jets…



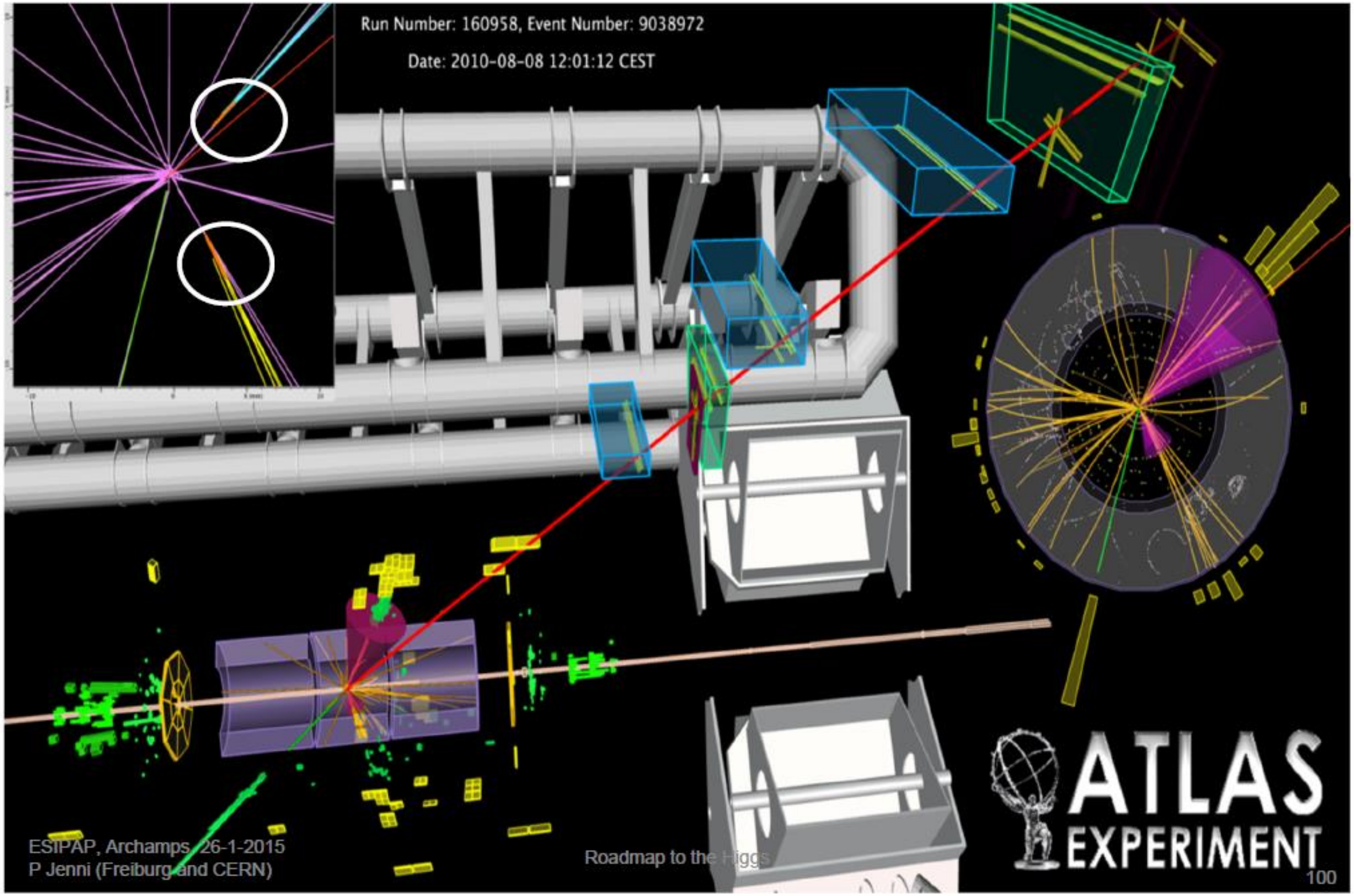


LHC is a "top factory"!
- 5 millions of tt pairs
- ~100000 in Tevatron in 20 years



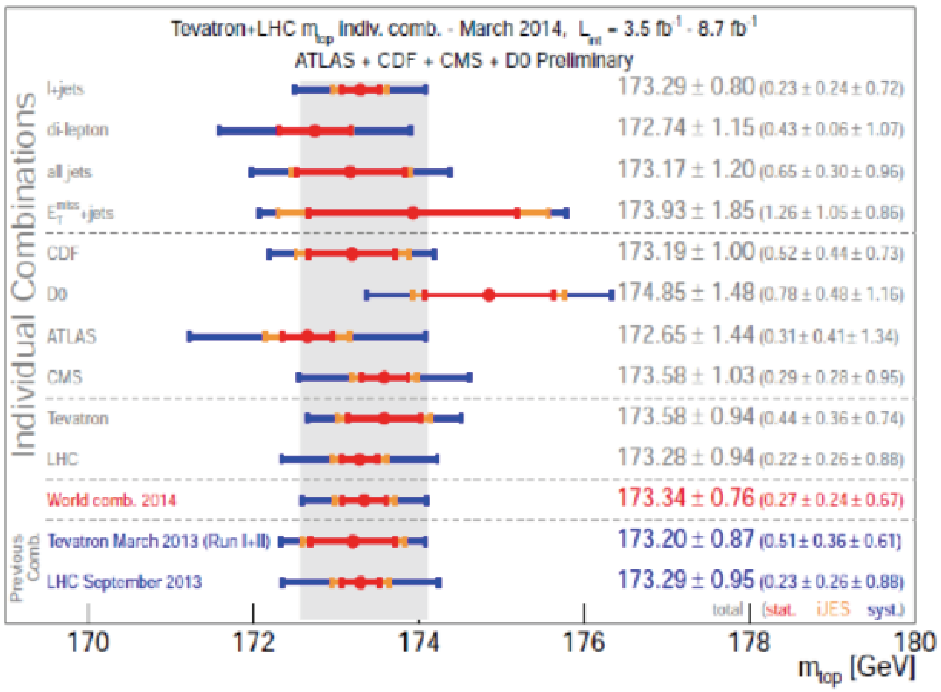
$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss

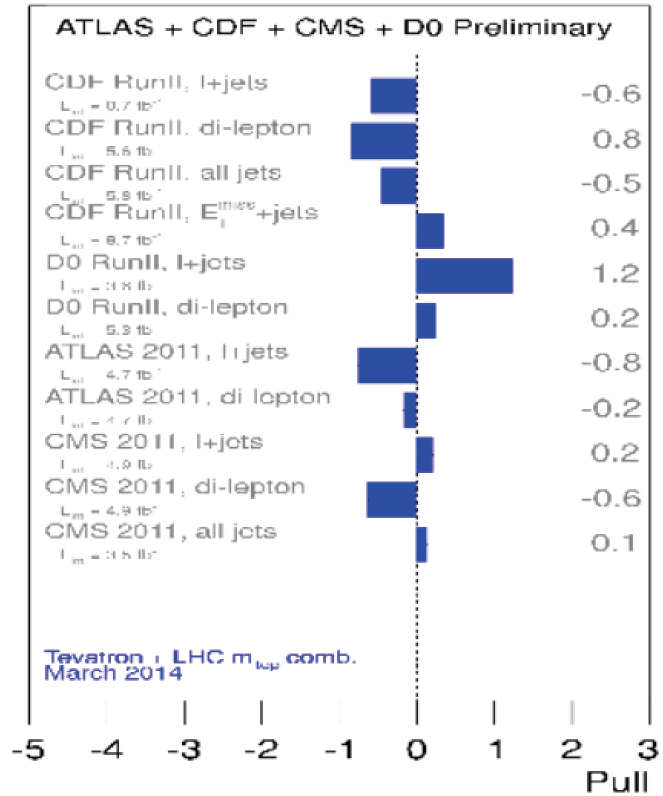


Mass of the top quark

Tevatron combination November 2012 May 2013
LHC combination July 2012 September 2013
World combination March 2014 arXiv:1403.4427



Combination using BLUE



$$m_{top} = 173.34 \pm 0.27\,(\text{stat}) \pm 0.24\,(\text{iJES}) \pm 0.67\,(\text{syst})\ \text{GeV}$$

precision on M_{top} 0.44%

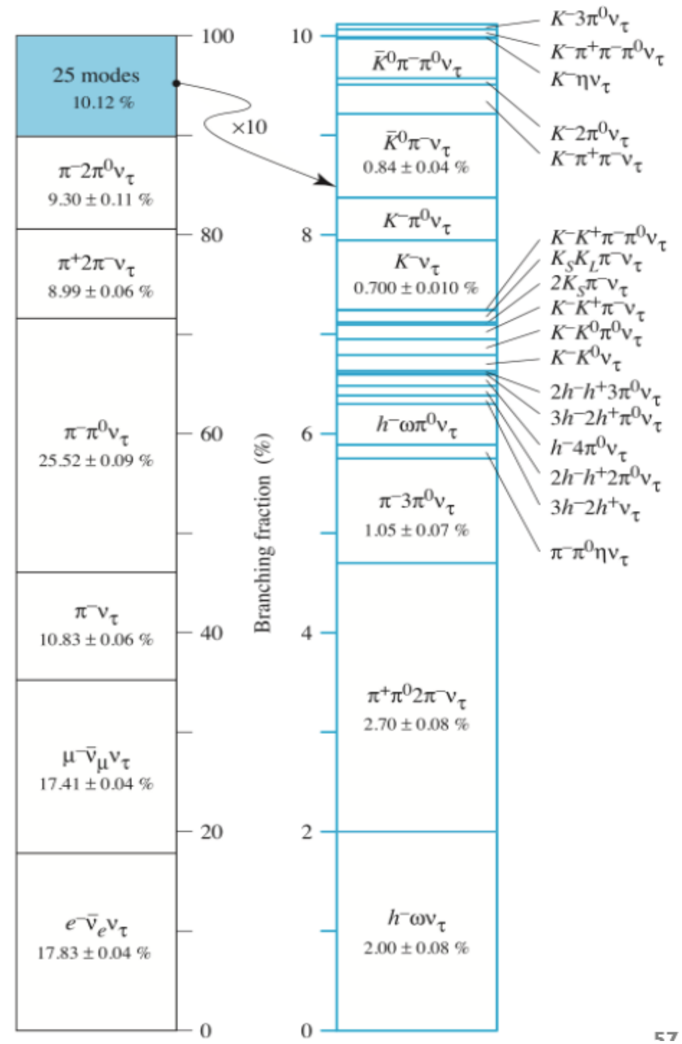
Consistency χ^2=4/10

Highest precision in l+jet channel
Dilepton channel good precision
Fully hadronic channel respectable

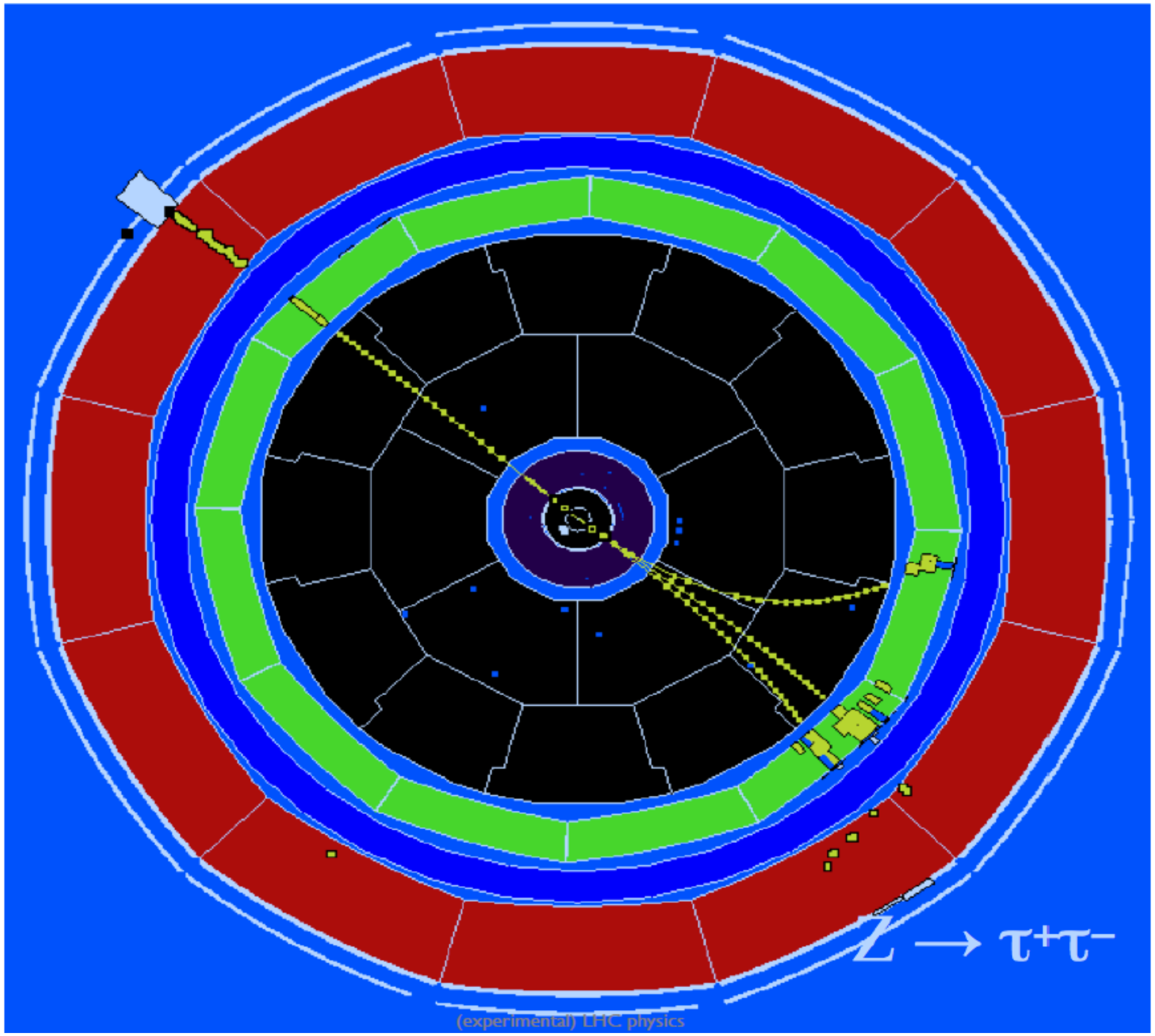
Complicated topologies….

Tau

- Tau are heavy enough that they can decay in several final states
  - ✓ Several of them with hadrons
  - ✓ Sometimes neutral hadrons
- Lifetime = 0.29 ps
  - ✓ 10 GeV tau flies ~ 0.5 mm
  - ✓ Typically too short to be directly seen in the detectors
- Tau needs to be identifies by their decay products
- Accurate vertex detectors can detect that they do not come exactly from the interaction point



Complicated topologies....



Electroweak measurements at LHC