Introduction to particle physics: experimental part

Making predictions for hadron colliders

- **From Feynman diagrams to cross-sections**
- **From cross-sections to events**

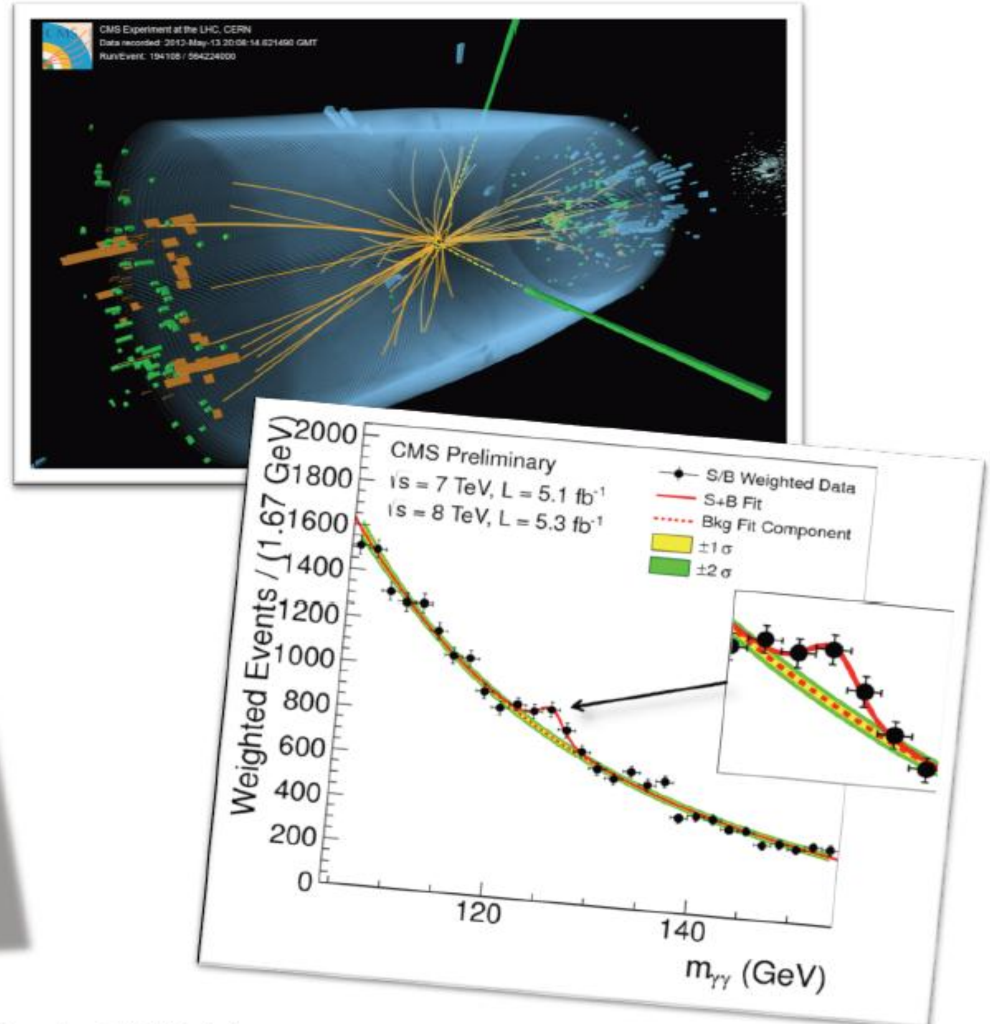
Standard Model measurements

- **W and Z bosons**
- **Hard QCD**
- **Prompt photons**
- **b-jets**
- **Top quarks**

Parts based in part on M. Seymour lecture at CERN Summer School, 2018

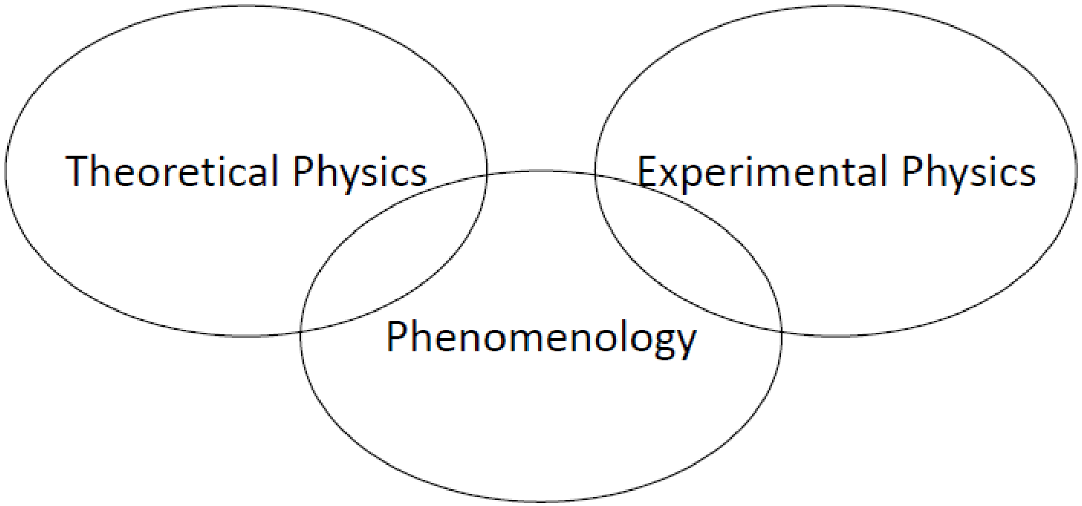
Prof. dr hab. Elżbieta Richter-Wąs

Experiment = probing theories with data



Making predictions for hadron colliders

Phenomenology



Making predictions for hadron colliders

Calculating Event Rates

$$N = \mathcal{L}\,\sigma$$

- N: Number of events
- $\mathcal{L}$: Integrated Luminosity
- σ: Cross section

Calculating Cross Sections

$$\mathrm{d}\sigma = \frac{1}{F} |\mathcal{M}|^2 \, \mathrm{d}LIPS$$

Flux factor

$= 2s = 4E_1E_2$

(Quantum mechanical) amplitude squared

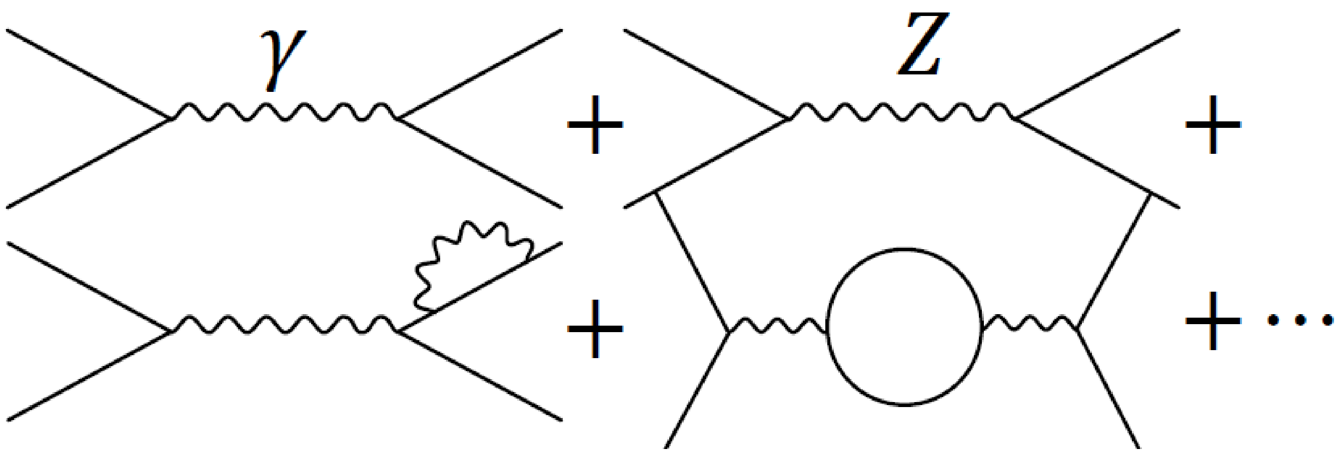
Lorentz Invariant Phase Space

$$= \frac{\mathrm{d}^4 p_i}{(2\pi)^4}(2\pi)\delta\left(p_i^2 - m_i^2\right) \frac{\mathrm{d}^4 p_j}{(2\pi)^4}(2\pi)\delta\left(p_j^2 - m_j^2\right) \ldots (2\pi)^4\delta(p_1 + p_2 - p_i - p_j - \ldots$$

Calculating Cross Sections

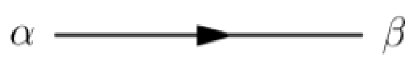
$$\mathrm{d}\sigma = \frac{1}{F}\,|\mathcal{M}|^2\,\mathrm{d}LIPS$$

$$\mathcal{M} =$$



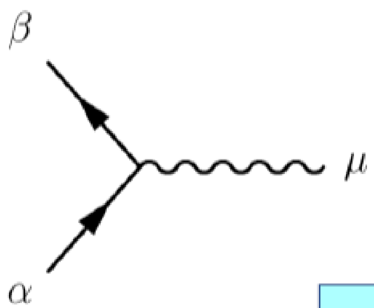
Making predictions for hadron colliders

Feynman Rules



$$\rightarrow \left(\frac{i}{\not{p} - m + i\varepsilon}\right)_{\beta\alpha}$$

$$\rightarrow \frac{-i\eta_{\mu\nu}}{p^2 + i\varepsilon}$$



$$\rightarrow -ie\gamma^{\mu}_{\beta\alpha}(2\pi)^4\delta^{(4)}(p_1 + p_2 + p_3).$$

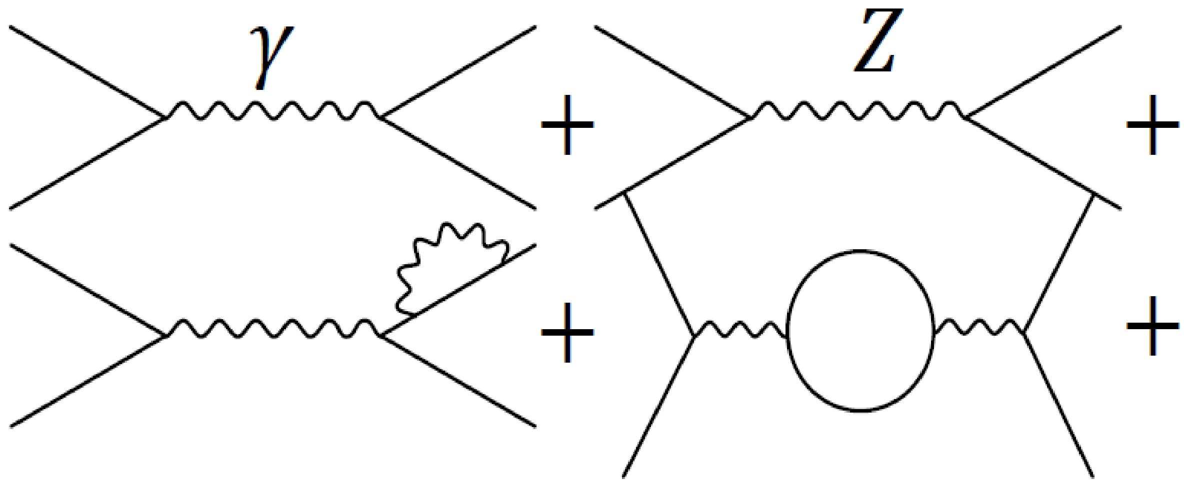
Elementary charge

$$e = \sqrt{4\pi\alpha} \quad \alpha \approx {}^{1}/_{137}$$

Making predictions for hadron colliders

Tree Diagrams as Leading Order of Expansion in α

$\mathcal{M} =$



$+ \quad \mathcal{O}(\alpha)$

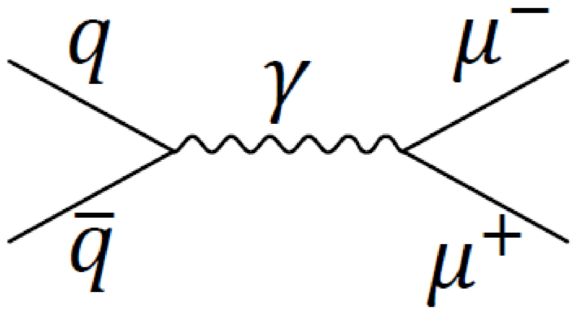
$+ \cdots \quad \mathcal{O}(\alpha^2)$

$\alpha \approx {}^{1}/_{137}$ but $\alpha_s \approx 0.1$

$\Rightarrow$ QCD corrections important

Making predictions for hadron colliders

Example: The Drell-Yan process ($pp \to \mu^+\mu^-$)

$\mathcal{M} =$ 

$$\Rightarrow |\mathcal{M}|^2 \propto e_q^2 \alpha^2 \frac{t^2 + u^2}{s^2} \propto e_q^2 \alpha^2 (1 + \cos^2\theta)$$

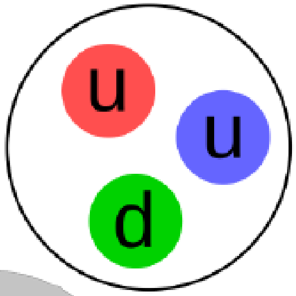
$$\Rightarrow \sigma = \frac{4\pi\alpha^2}{9Q^2} e_q^2$$

$\left(s = Q^2 = \left(p_q + p_{\bar{q}}\right)^2\right)$

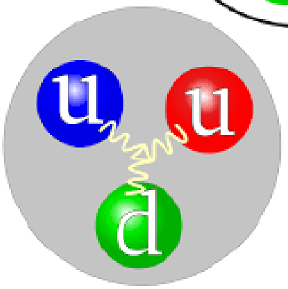
Making predictions for hadron colliders

Proton structure

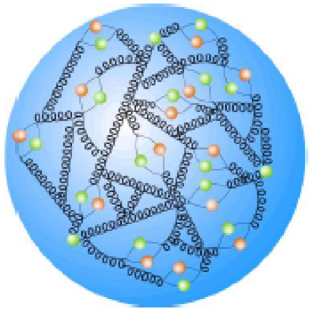
- Proton = uud ?



- Held together by gluons?



- Quantum Field Theory: gluons can create $q\bar{q}$ pairs



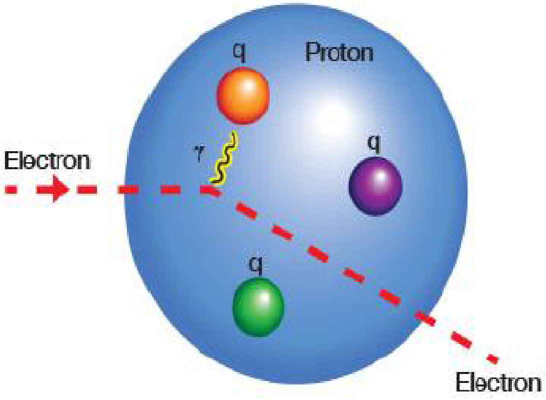
- Proton can interact through any of its partons

Making predictions for hadron colliders

Proton structure: parton distribution functions

- How is the proton's energy shared between its parton constituents?
- Measure in deep inelastic electron scattering
- Quantify by *parton distribution function*

  $f_i(x)\mathrm{d}x$ = probability that parton of type i is found with fraction of proton's momentum between x and $x + \mathrm{d}x$

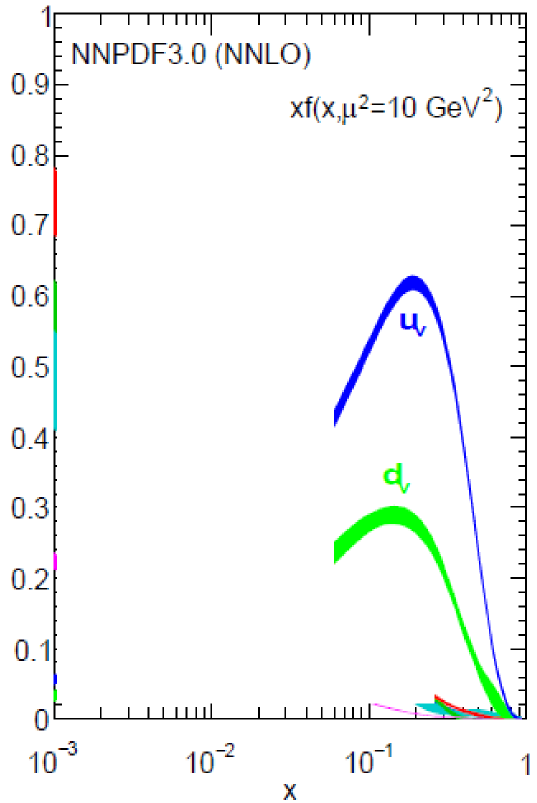


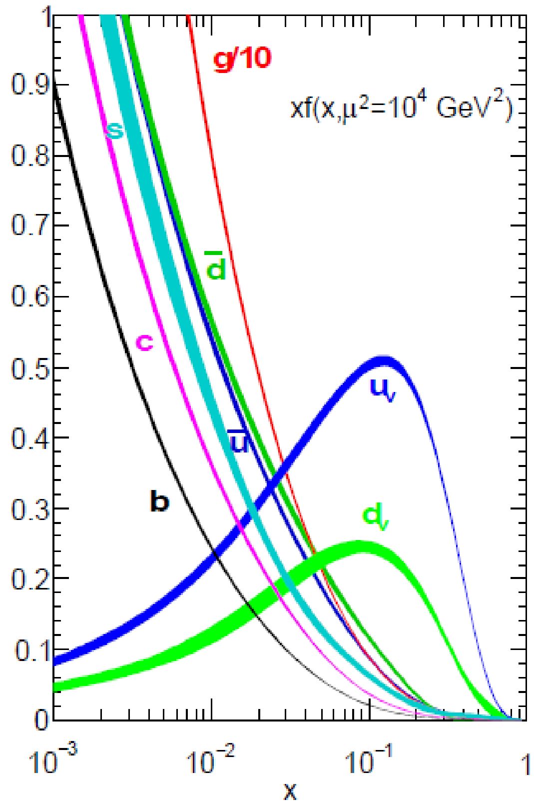
- But how long do those quantum fluctuations live?

⇒ PDFs depend on the momentum scale of the probe $f_i(x, Q^2)\mathrm{d}x$

Making predictions for hadron colliders

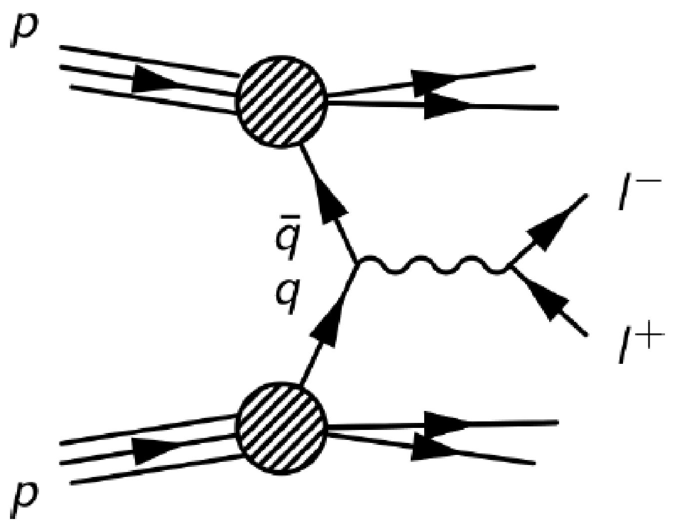
Proton structure: parton distribution functions





Making predictions for hadron colliders

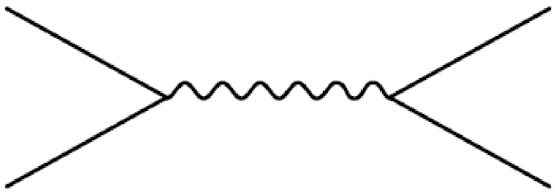
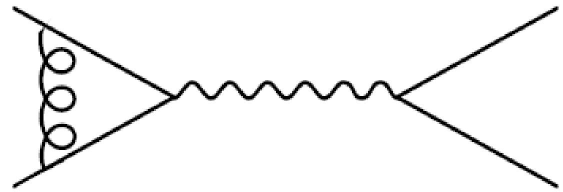
The Drell-Yan process ($pp \rightarrow \mu^+\mu^-$)



$$\frac{d\sigma}{dQ^2} = \sum_q \int dx_1\, f_q(x_1, Q^2)\, dx_2\, f_{\bar{q}}(x_2, Q^2) \frac{4\pi\alpha^2}{9Q^2} e_q^2\, \delta(x_1 x_2 s - Q^2)$$

Making predictions for hadron colliders

Loop Diagrams as Higher Order Corrections

$\mathcal{M} =$  $+$  $+ \cdots$

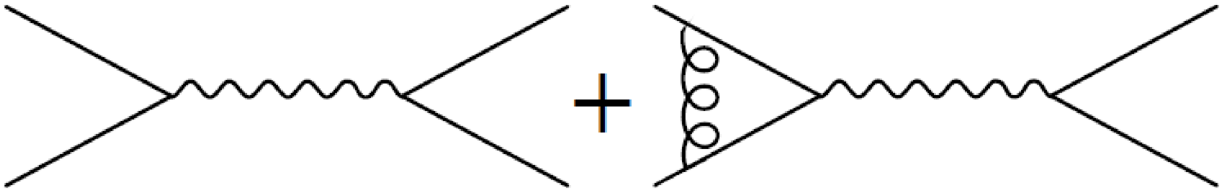
$\mathcal{O}(\alpha)$ $\qquad\qquad$ $\mathcal{O}(\alpha\alpha_s)$

$$|\mathcal{M}|^2 = |\mathcal{M}_0|^2 + 2\Re(\mathcal{M}_0^*\mathcal{M}_1) + |\mathcal{M}_1|^2 + \cdots$$

$\mathcal{O}(\alpha^2)$ $\qquad\qquad$ $\mathcal{O}(\alpha^2\alpha_s)$

- Quantum mechanics: sum over unobserved quantum numbers = integrate over gluon momenta

Loop Diagrams as Higher Order Corrections

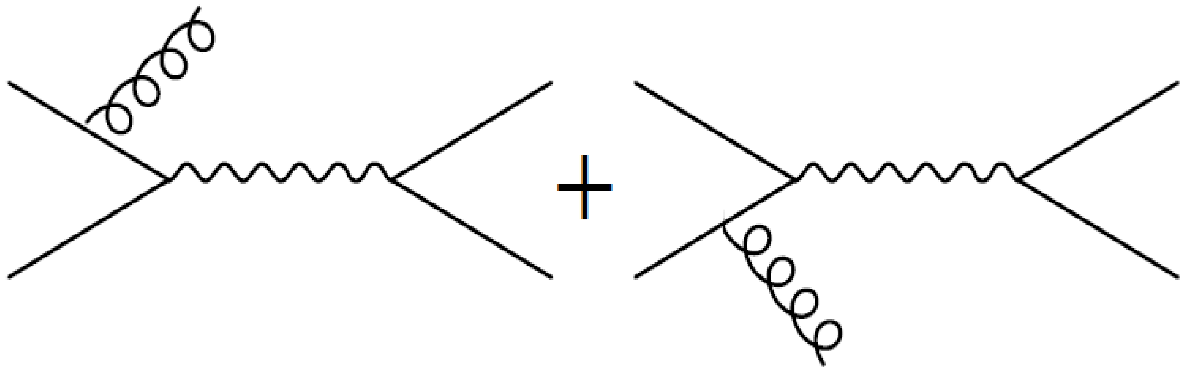
$\mathcal{M} =$  $+ \cdots$

$\mathcal{O}(\alpha)$ $\qquad$ $\mathcal{O}(\alpha\alpha_s)$

- Gluon momentum integral is divergent! (= *minus* infinity)
- Divergence comes from:
  - Momentum = 0
  - Momentum = parallel to quark or antiquark

Gluon Emission as Higher Order Correction

$\mathcal{M} =$



$\mathcal{O}(\alpha\sqrt{\alpha_s})$

- Gluon emission describes a different process $(q\bar{q} \rightarrow \mu^+\mu^- g)$
- But if we are only interested in the total cross section for Drell-Yan pairs, must integrate over gluon momenta
- Divergent from momentum = 0 or parallel to quark or antiquark
- Cancels loop divergence

Making predictions for hadron colliders

Next-to-Leading Order (NLO) cross section

- $\sigma_{NLO} = \sigma_{tree} + \sigma_{loop} + \sigma_{emission}$
- σ_{loop} and $\sigma_{emission}$ each divergent
  - must regularize and expose singularities of each
  - *Subtraction algorithms*
- Fully automated,
  - e.g. in Madgraph/aMC@NLO, MCFM, Sherpa, Herwig …

Making predictions for hadron colliders

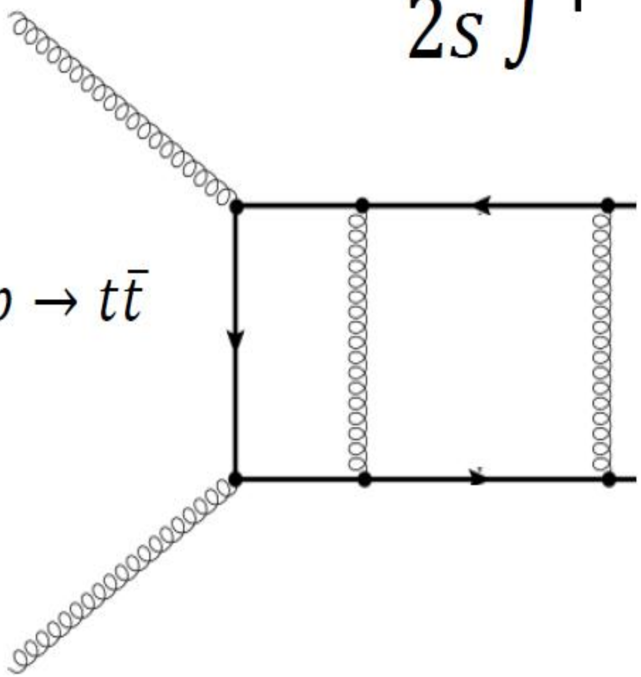
From Feynman Diagrams to Cross Sections

- Major part of phenomenology = calculating cross sections
- LO = write down all tree diagrams, integrate phase space numerically
- Convolute with parton distribution functions (fitted to data)
- NLO = one-loop diagrams, one-emission processes
  - Extract singularities from integrals, integrate analytically
  - Integrate remainders numerically
- NNLO = two-loop diagrams, one-emission at one-loop, and two emissions
- But LHC events contain *hundreds* of additional particles…

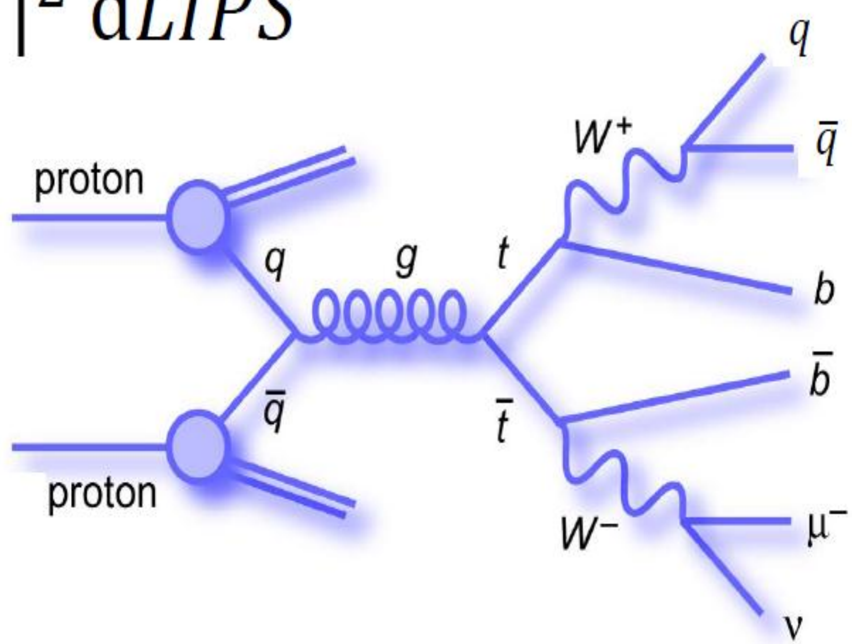
Making predictions for hadron colliders

Cross Sections

$$\sigma = \frac{1}{2s}\int |\mathcal{M}|^2 \, \mathrm{d}LIPS$$

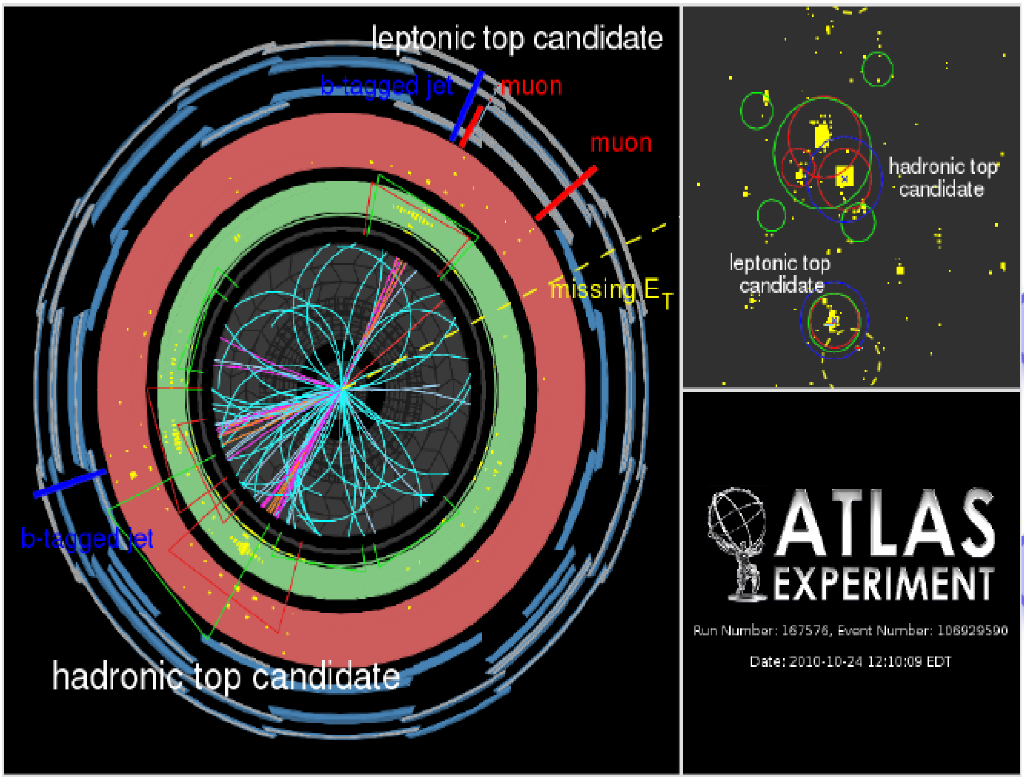


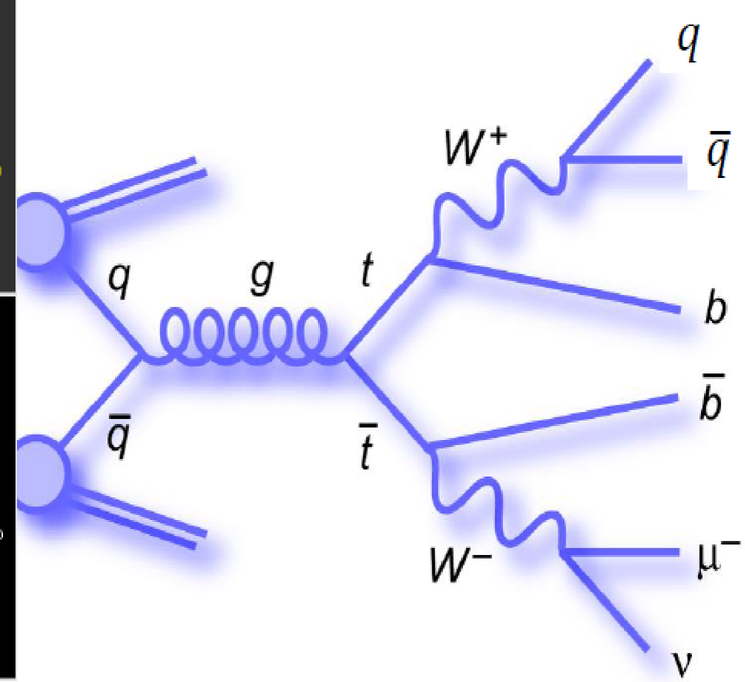
e.g. $pp \to t\bar{t}$
NNLO



Making predictions for hadron colliders

Cross Sections are not enough

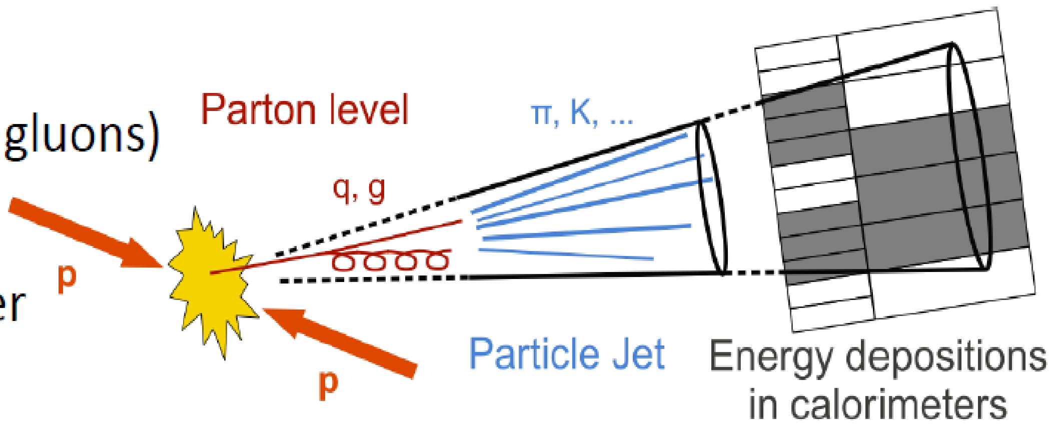




Monte Carlo event structure

Need to describe *event structure*

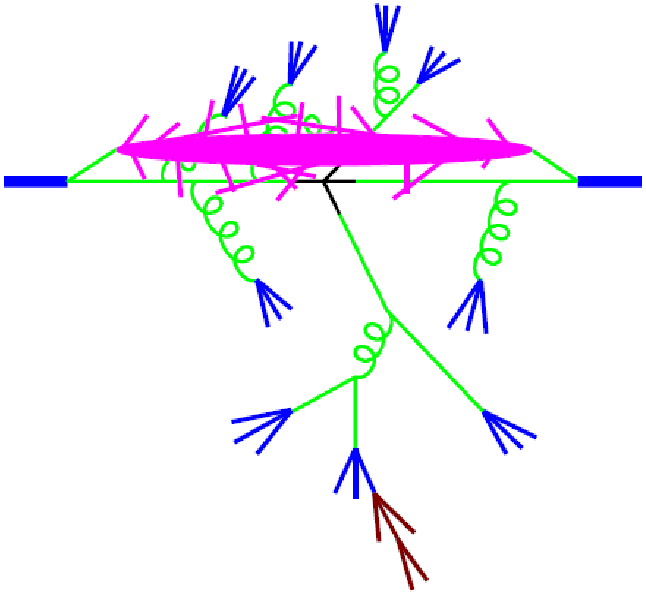
- Hadrons (not quarks and gluons)
- Jets of hadrons
- Remnants of protons after parton extracted
- Unstable particle decays



Monte Carlo event structure

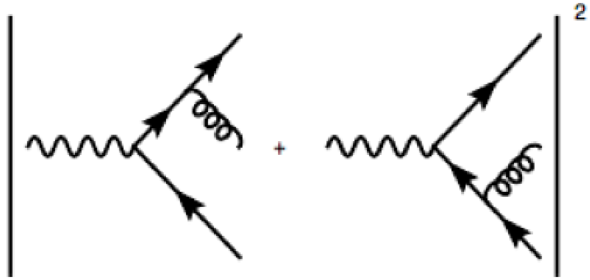
Need Event Generators

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Gluon emission is universal

e.g. $e^+e^- \to 3$ partons:



$$\frac{d\sigma}{d\cos\theta\, dz_g} \sim \sigma_0\, C_F\, \frac{\alpha_s}{2\pi} \frac{2}{\sin^2\theta} \frac{1+(1-z_g)^2}{z_g}$$

$E_g/E_{g,max}$

$e^+e^- \to 2$ partons

"quark charge squared"

QCD running coupling ~ 0.1

Divergent in collinear limit $\theta \to 0,\pi$ (for massless quarks)
and soft limit $z_g \to 0$

$$d\sigma = \sigma_0 \sum_{\text{jets}} C_F \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2}\, dz \frac{1+(1-z)^2}{z}$$

Parton showers

Parton branching is universal

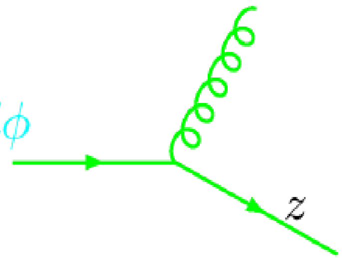
$$d\sigma = \sigma_0 \, \frac{\alpha_s}{2\pi} \, \frac{d\theta^2}{\theta^2} \, dz \, P(z, \phi) d\phi$$

$P(z, \phi) =$

"Splitting function":
dependent on flavour and spin but not on how parton was produced

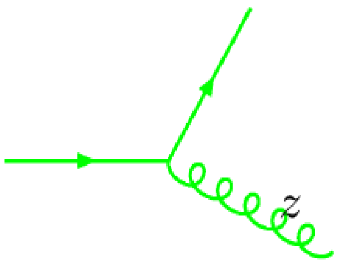
→Probability distribution for parton branching

→Simulation



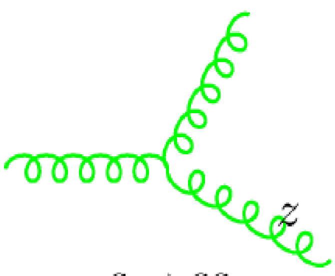
$q \to qg$

$C_F \frac{1+z^2}{1-z}$



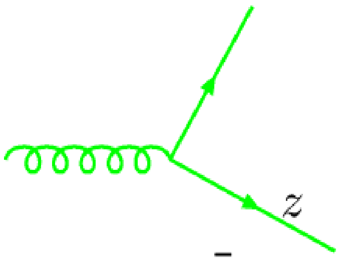
$q \to gq$

$C_F \frac{1+(1-z)^2}{z}$



$g \to gg$

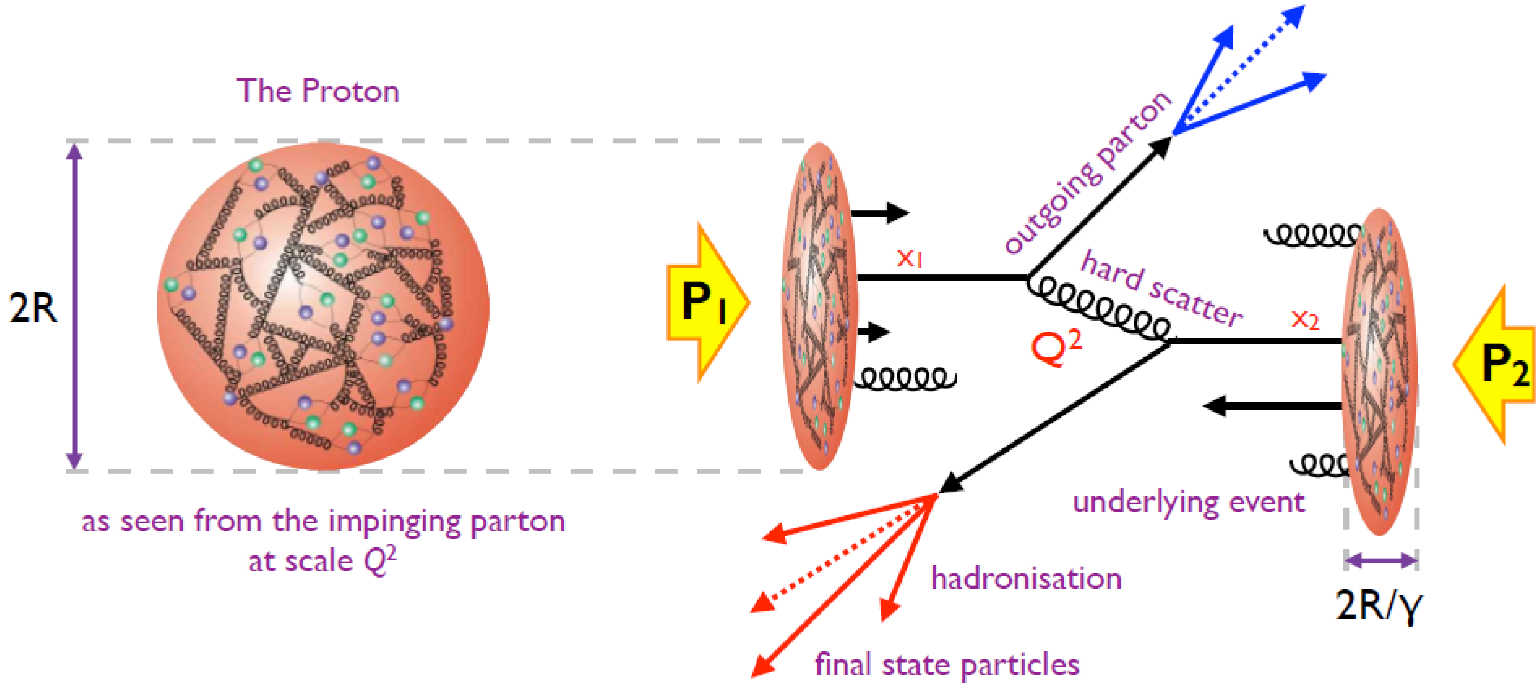
$C_A \frac{z^4+1+(1-z)^4}{z(1-z)}$



$g \to q\bar{q}$

$T_R \left(z^2 + (1-z)^2\right)$

Proton-(anti)proton collisions



Underlying event

- proton remnants from collective interaction of partons not involved in hard scatter
- description necessitate "tuning" of non-perturbative MC parameters based on data

Parton shower and hadronisation

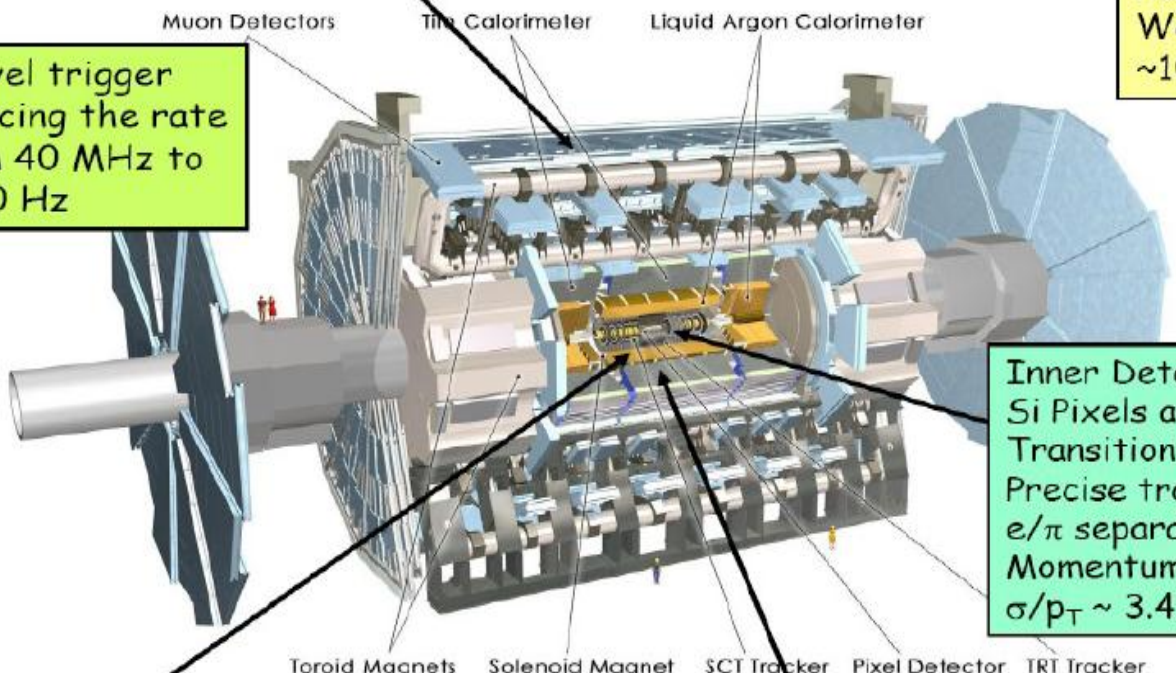
- ISR/FSR emission of gluons
- production of final states hadrons scale < Λ_{QCD} (non-perturbative)
- MC models tuned on data

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

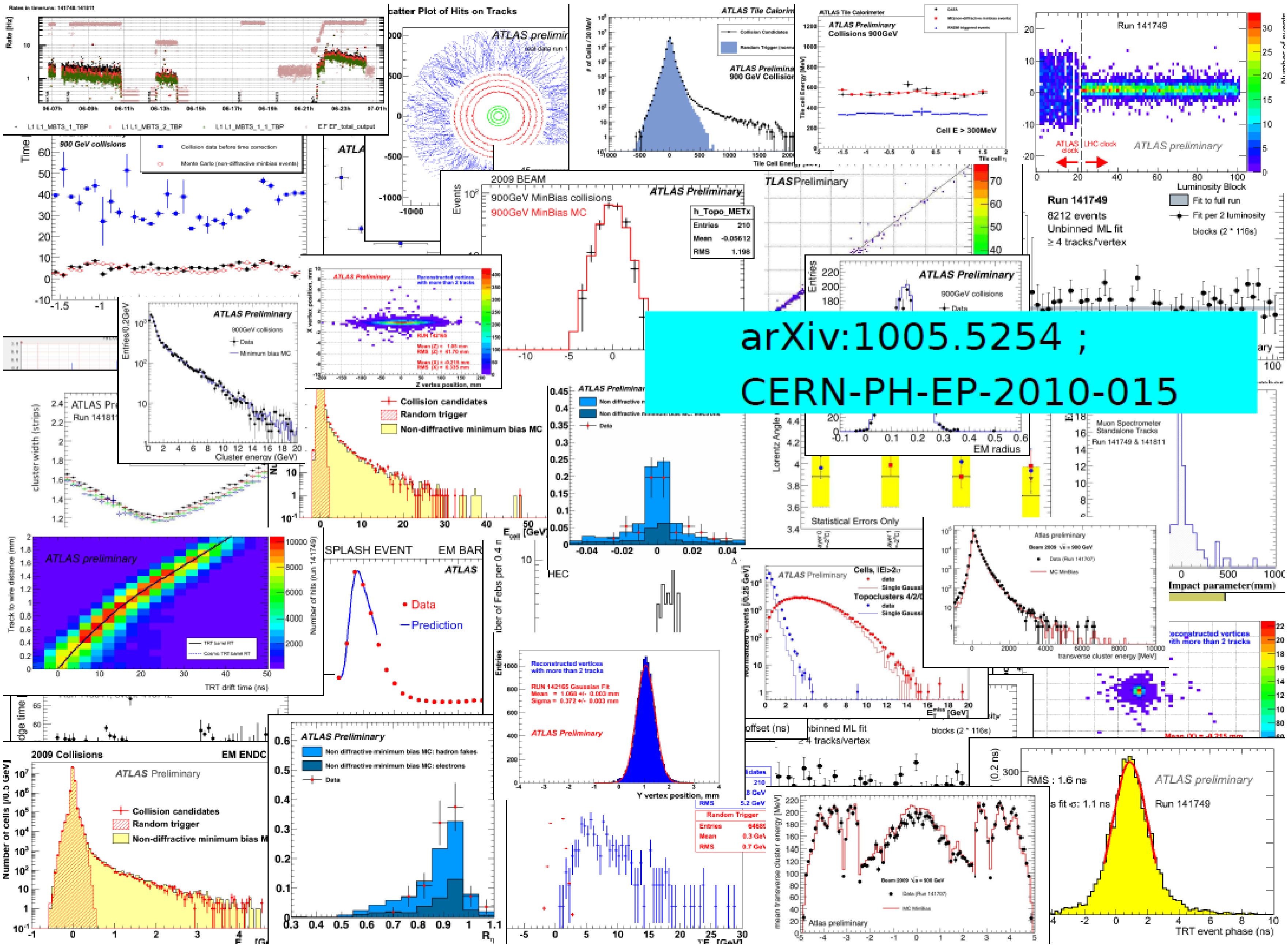
3-level trigger reducing the rate from 40 MHz to ~200 Hz



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

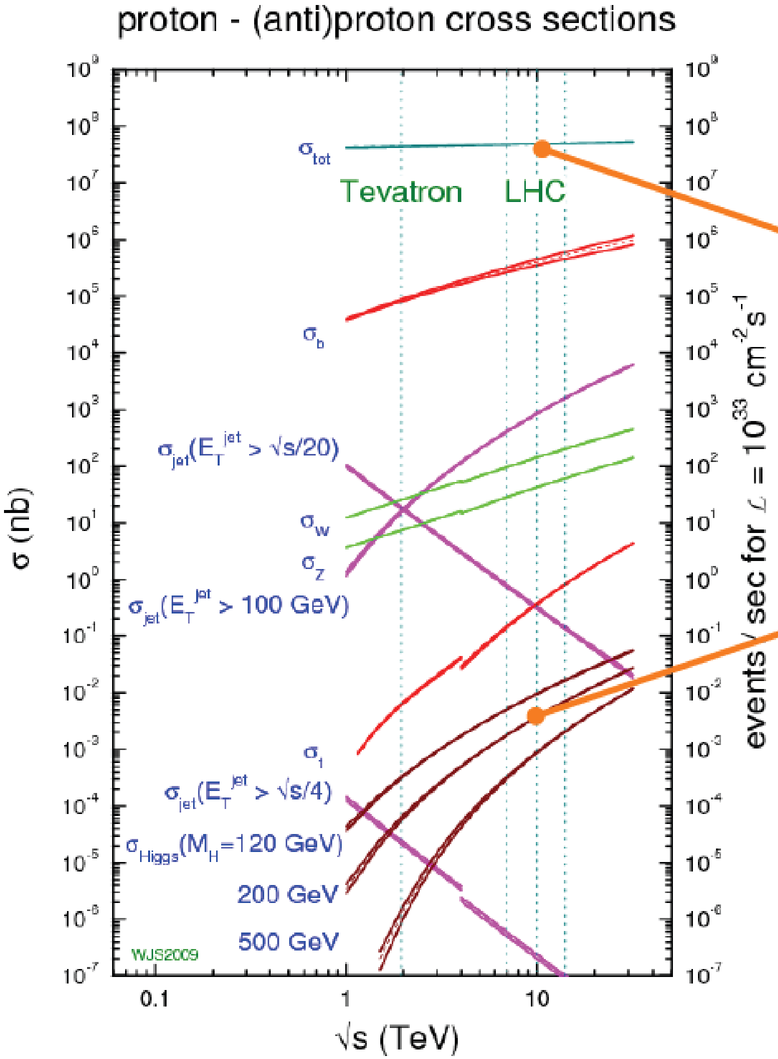
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Tilecal Fe/scintillator (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$



arXiv:1005.5254 ;

CERN-PH-EP-2010-015

Cross-sections at LHC



10^8 events/s

$\sim 10^{10}$

10^{-2} events/s ~

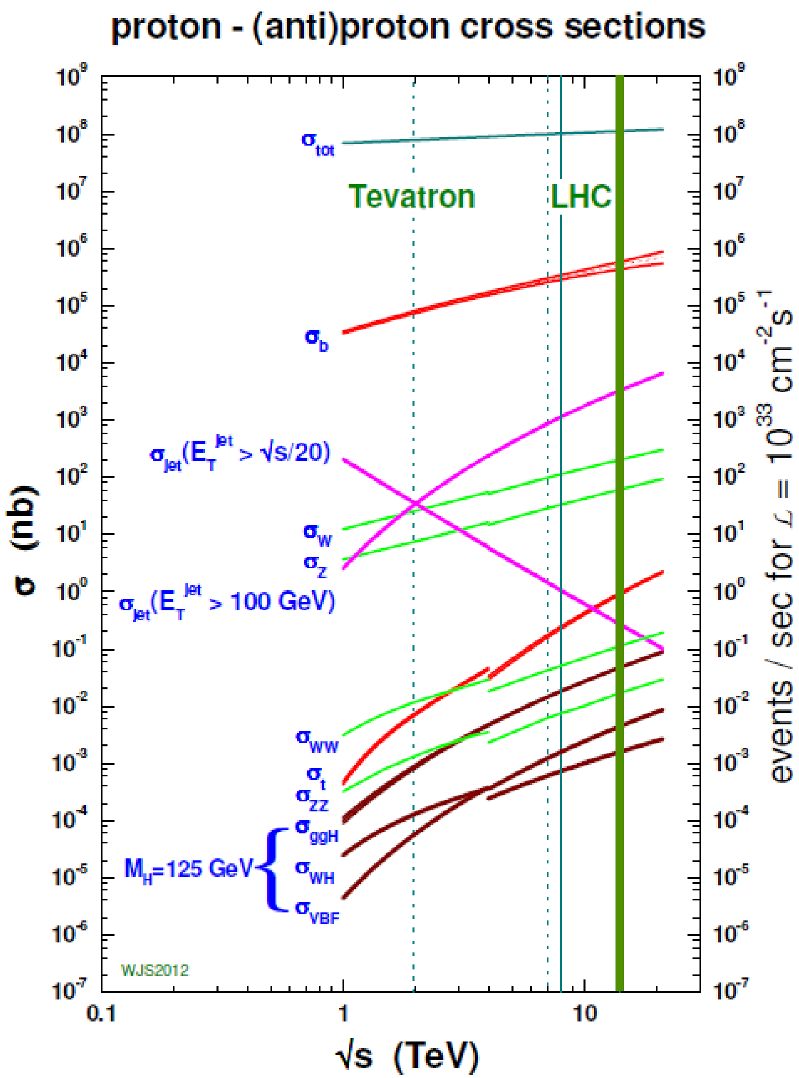
10 events/min

[m_H ~ 120 GeV]

0.2% H → γγ

1.5% H → ZZ

Cross-sections at LHC



- Cross sections in pp collisions at 13 TeV
  - total ≃ 100 mb
  - inelastic ≃ 80 mb (diffractive ≃25 mb)
- b-quark pair production ≃ 400 μb
- jet with E_T > 100 GeV ≃ 3 μb
- W and Z bosons : 200 and 60 nb
- top quark pair ≃ 1.0 nb
- WW ≃ 100 pb
- H(125 GeV) ≃ 60 pb
- ZZ ≃ 20 pb

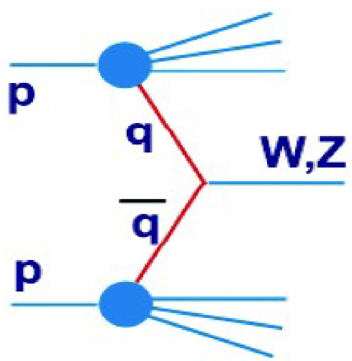
W & Z in leptonic modes

$\sigma(pp \rightarrow W) \times (W \rightarrow \ell\nu) = 20$ nb

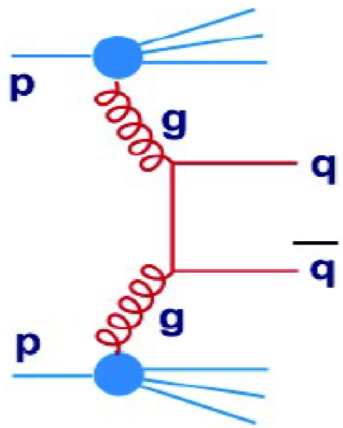
$\sigma(pp \rightarrow Z) \times (Z \rightarrow \ell\ell) = 2$ nb

QCD hard scattering processes

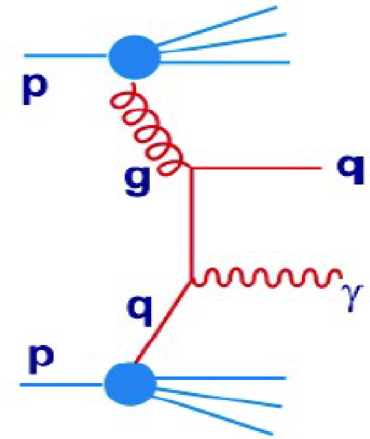
- EW gauge bosons



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

Parton kinematics

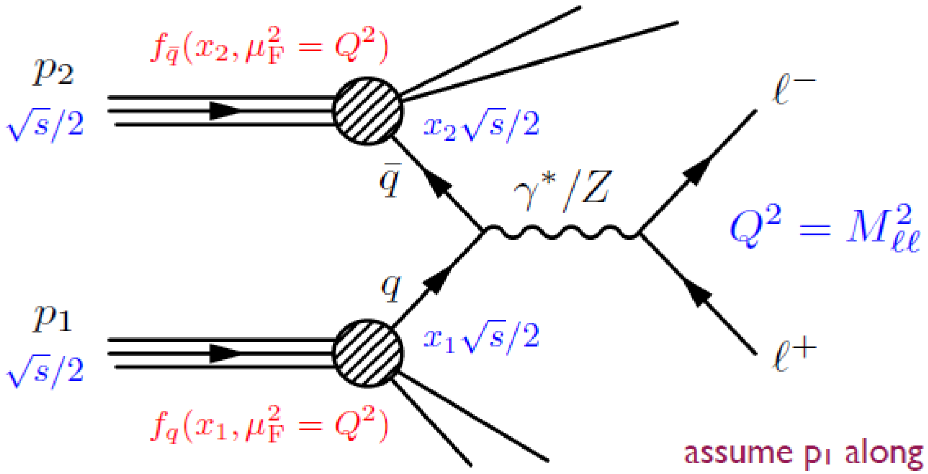
Example of the Drell-Yan process

- lepton pair production via quark-antiquark annihilation

4-momentum of lepton pair (LO)

$$\begin{cases} E = (x_1 + x_2)\sqrt{s}/2 \\ p_z = (x_1 - x_2)\sqrt{s}/2 \end{cases}$$

$$q(x_1) + \bar{q}(x_2) \to \gamma^*/Z \to \ell^+\ell^-$$



$$Q^2 = E^2 - p_z^2 = x_1 x_2 s$$

assume p_1 along positive beam axis

Define "rapidity" y such that

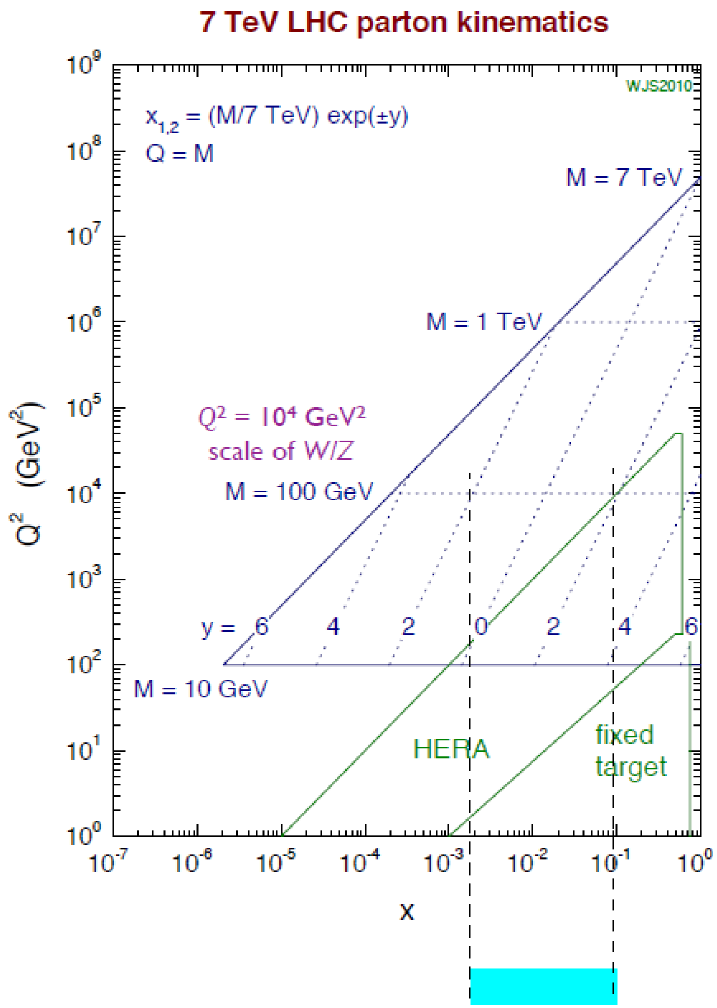
$$\frac{x_1}{x_2} = \frac{E + p_z}{E - p_z} \equiv e^{2y}$$

$$x_1\, x_2 = Q^2/s$$
$$x_1/x_2 = e^{2y}$$

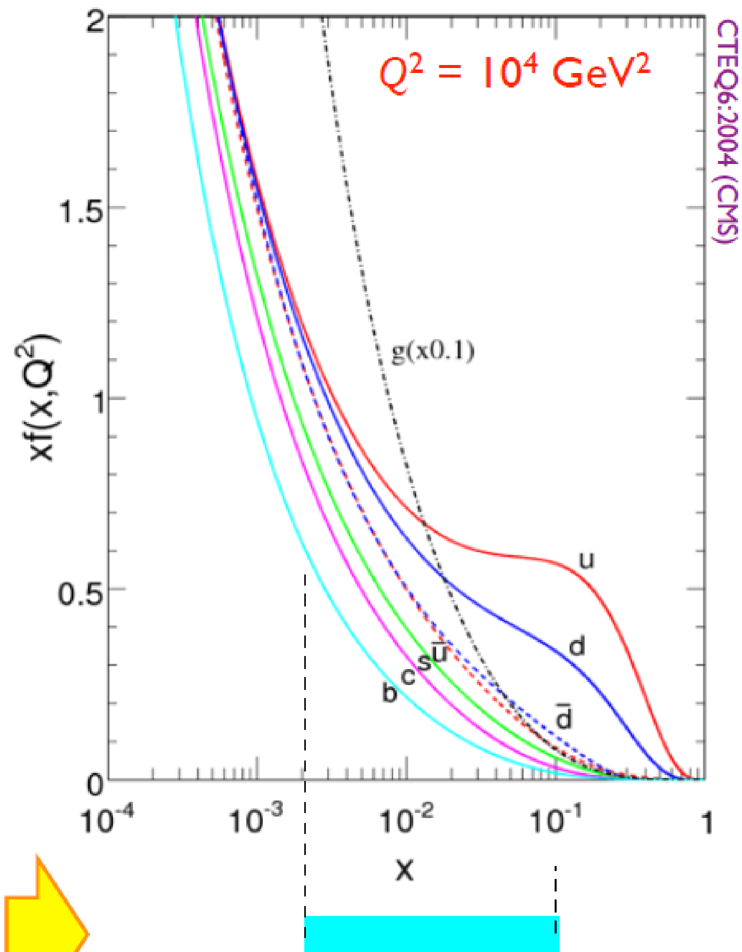
$$x_{1,2} = \frac{Q}{\sqrt{s}}\, e^{\pm y}$$

for a given Q^2,
the rapidity y relates
the x_1 and x_2 of the two partons

Parton kinematics

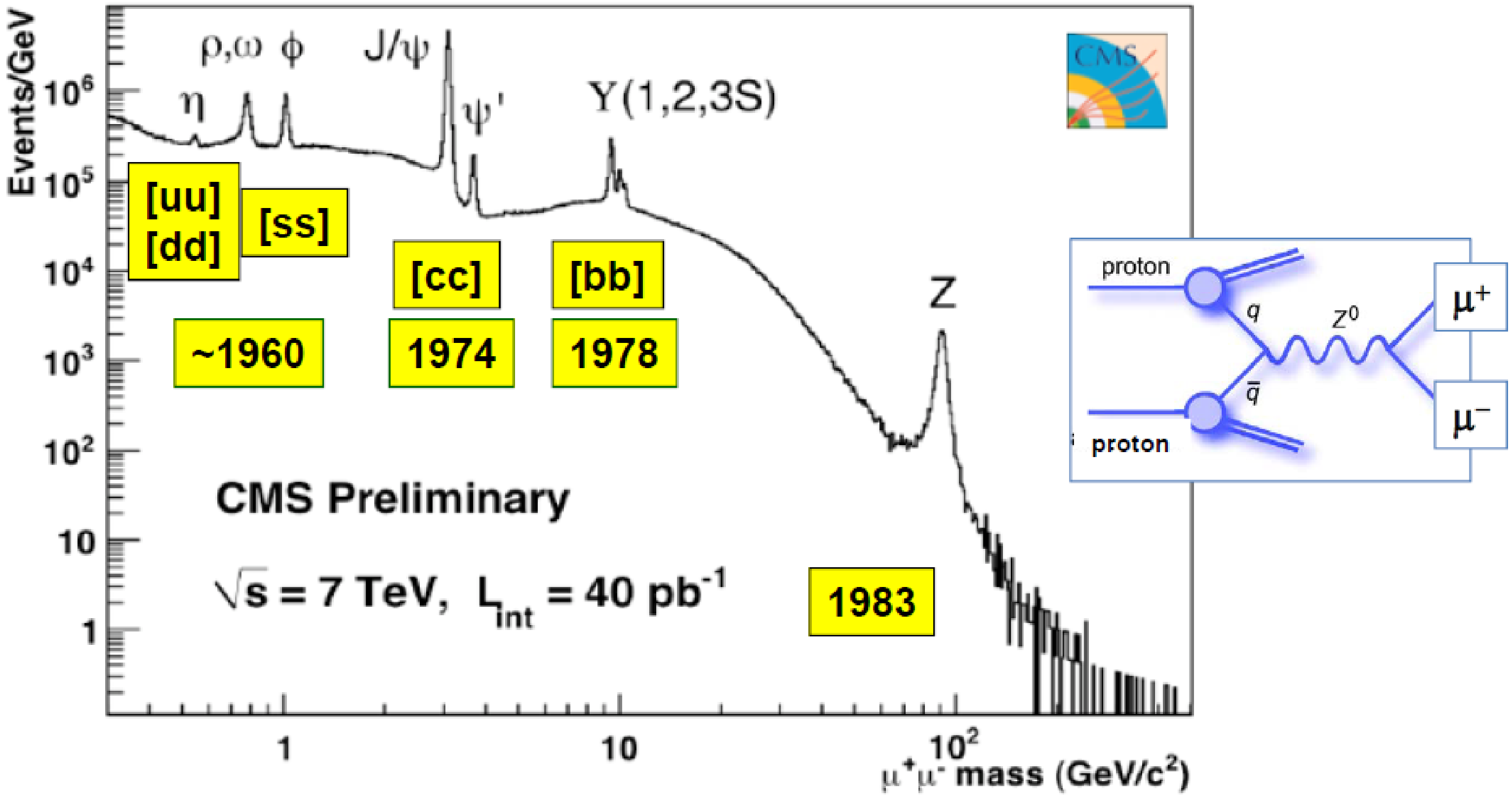


range in x for
the central production ($|y|<2$)
of W/Z boson



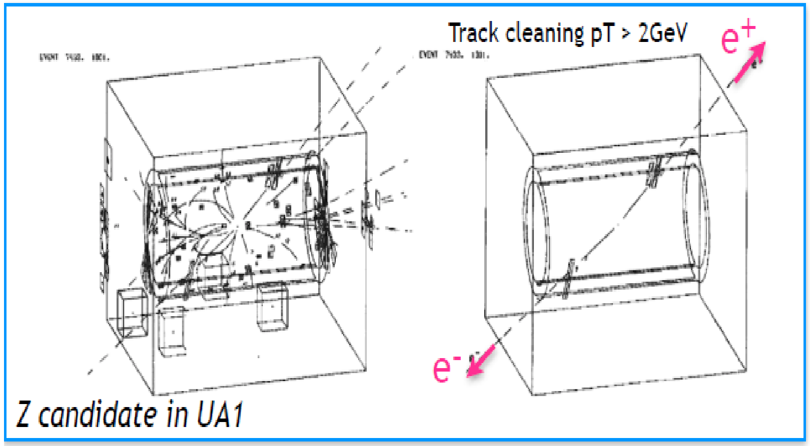
Year 2010: Retracing history of particle physics

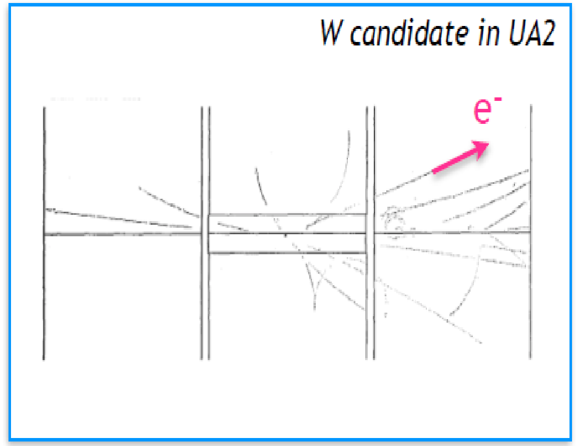
2010 Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model



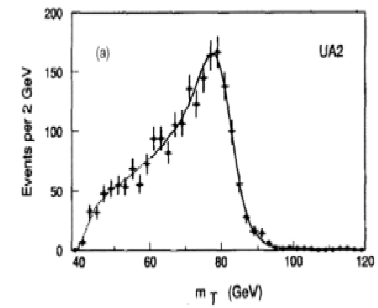
The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

The discovery of the W and Z bosons at CERN SppS





Transverse Mass distribution in UA2



$$m_T^2 = m^2 + p_x^2 + p_y^2$$

Altogether O(100) Z events.

Already important measurements (examples):

$$M_Z = 91.5 \pm 1.2 \pm 1.7\,(\mathrm{GeV}) \quad \textit{(UA1)}$$

$$M_W = 81.0 \pm 0.8 \pm 1.3\,(\mathrm{GeV}) \quad \textit{(UA2)}$$

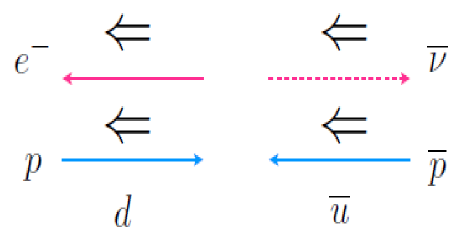
$$\rho = 1.004 \pm 0.052 \quad \textit{(UA1)}$$

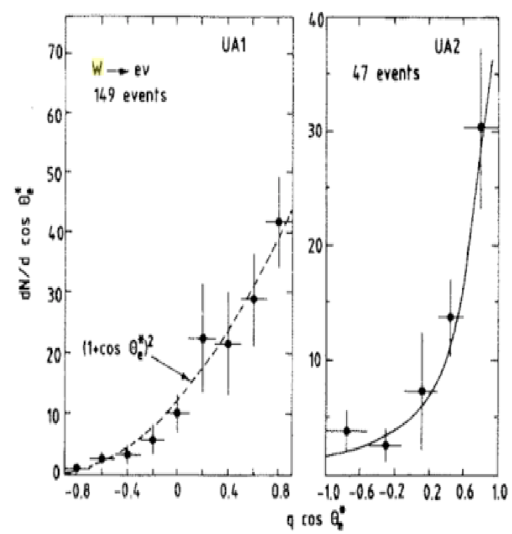
$$\sin^2\theta_W = 0.226 \pm 0.014 \quad \textit{(UA1)}$$

Altogether O(1000) W events

At SppS W production dominated by valence quarks

W polarised in the anti-proton direction.





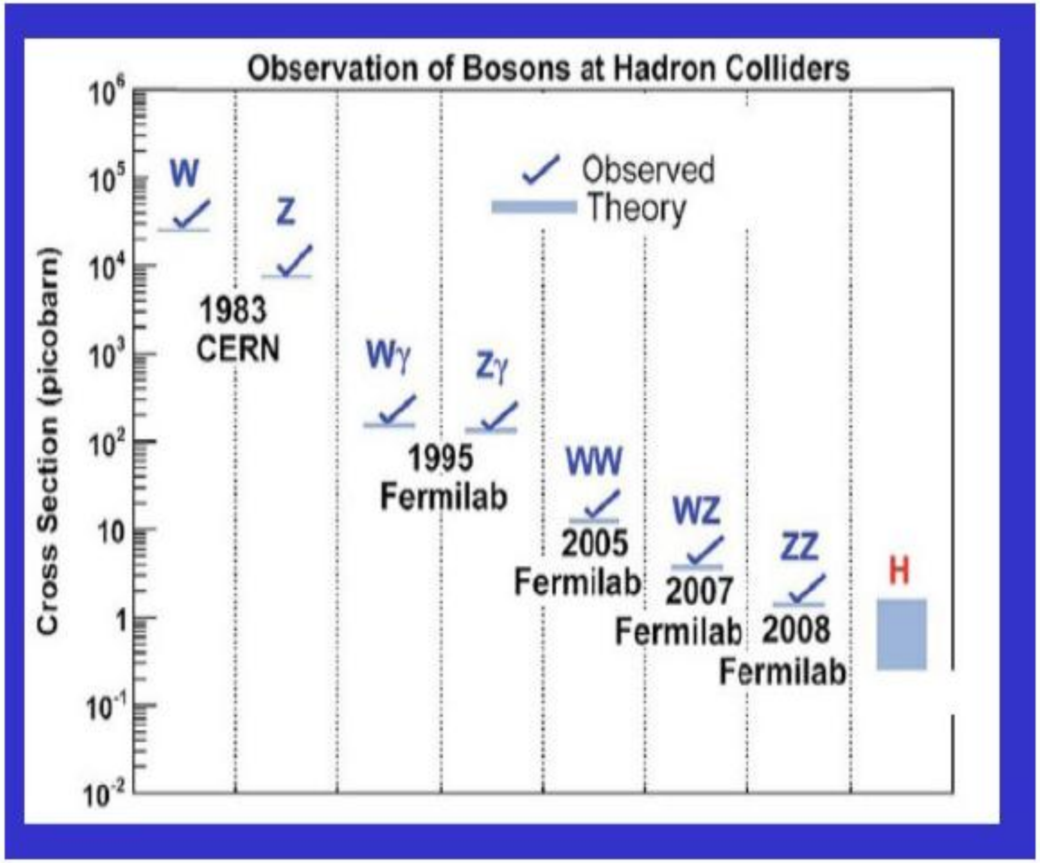
Bosons at hadron colliders

The primary decay chanel is through leptonic decays:

- BR(W→e ν) ~ 10%
- BR(Z→ ee) ~ 3%

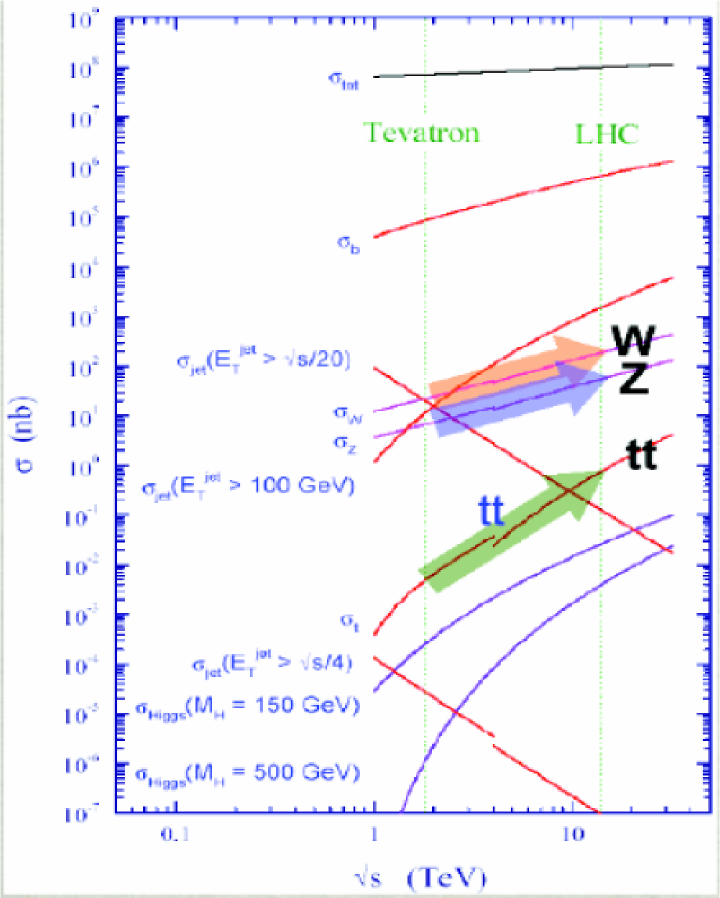
- It means that we are probing σ x BR values orders of magnitude smaller
- At LHC cross-section 5-10 x higher than at Tevatron at Fermilab.

2010

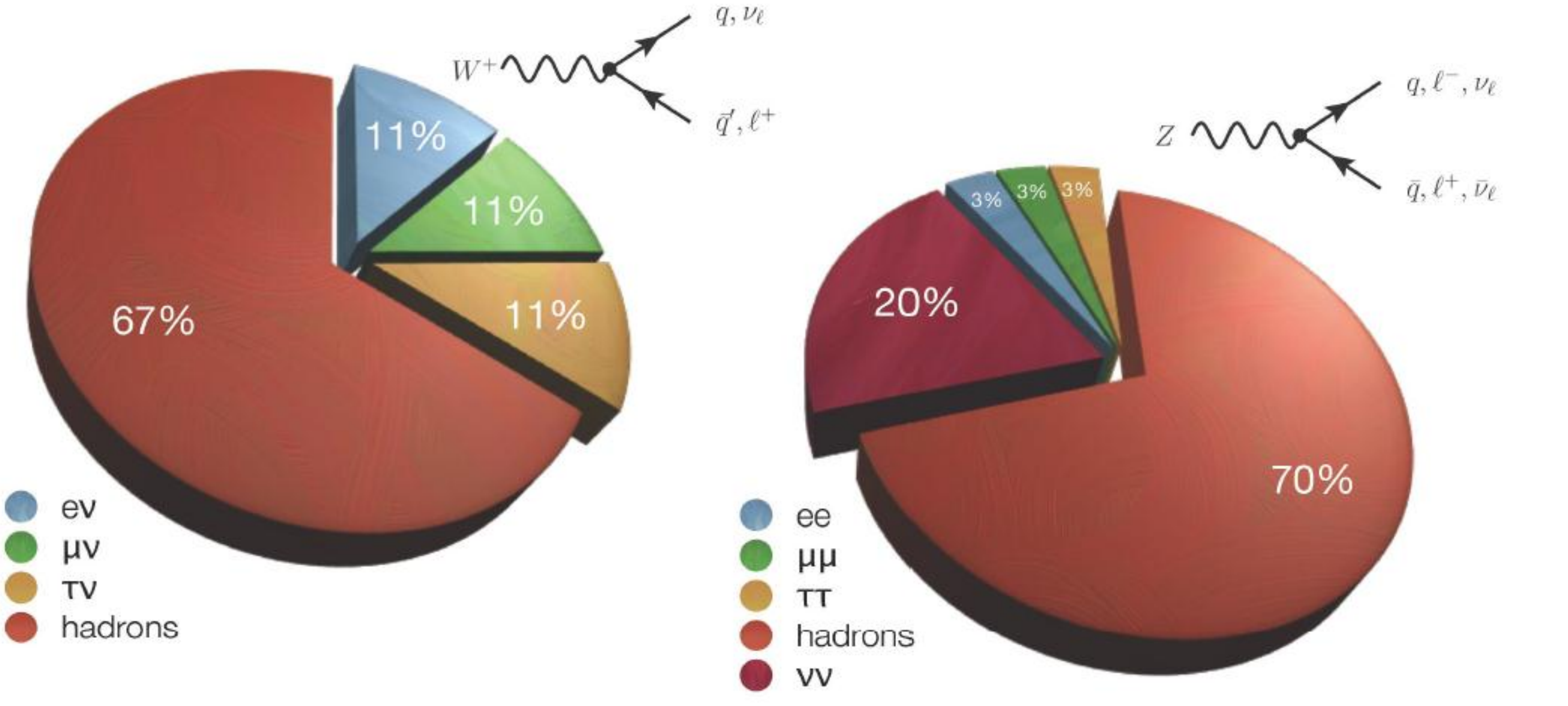


Bosons and top quark at LHC

- **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**

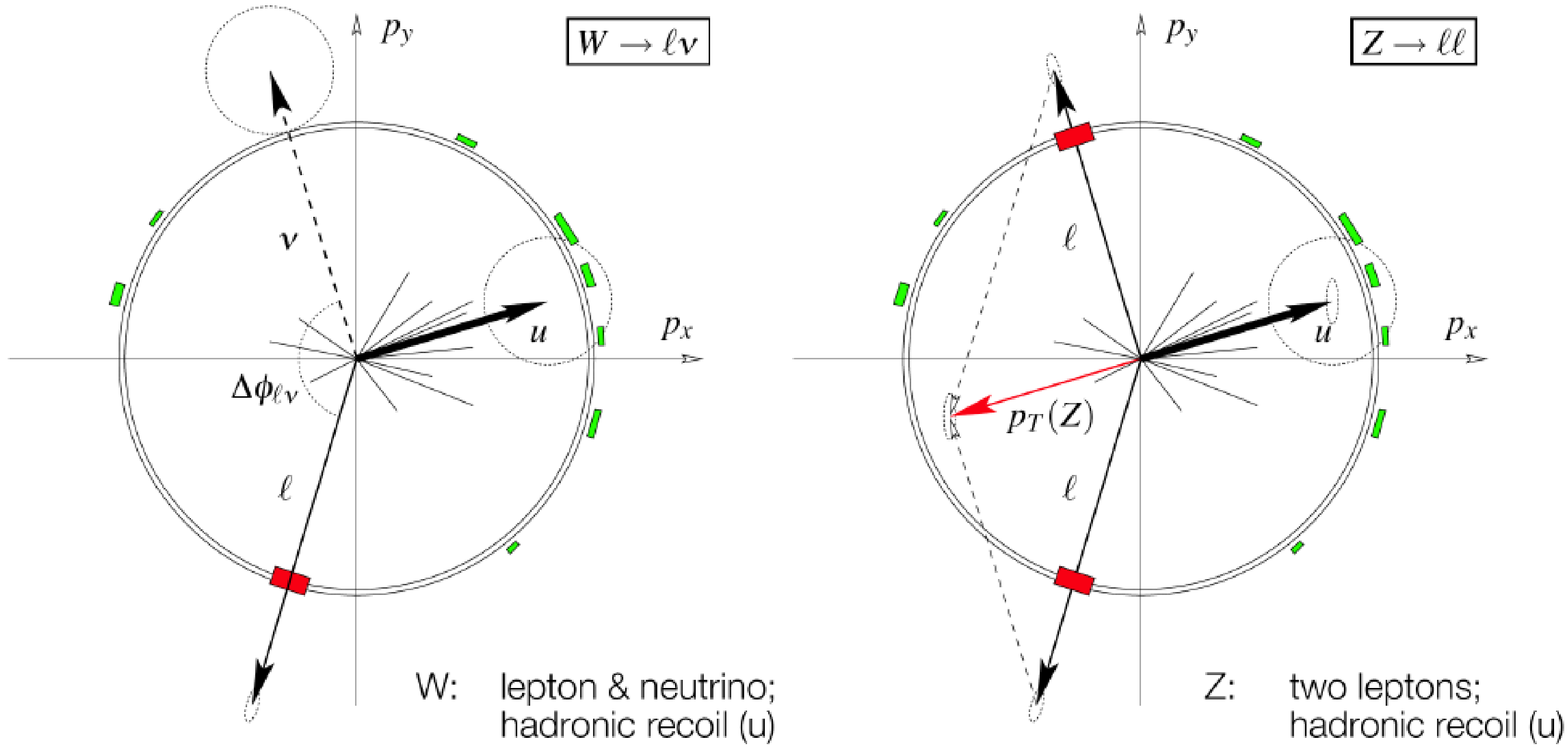


W and Z boson decays



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…

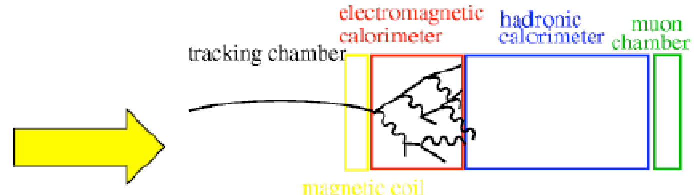
W and Z boson signatures



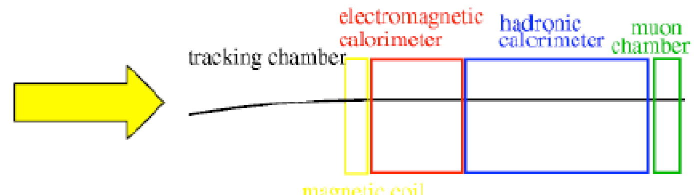
Additional hadronic activity ➛ recoil, not as clean as e^+e^-
Precision measurements: only leptonic decays

Lepton identification

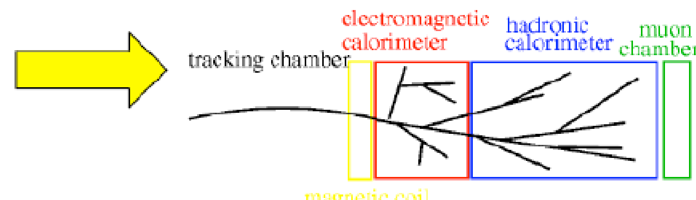
- Electron:
  - Compact electromagnetic cluster in calorimeter
  - Matched to track



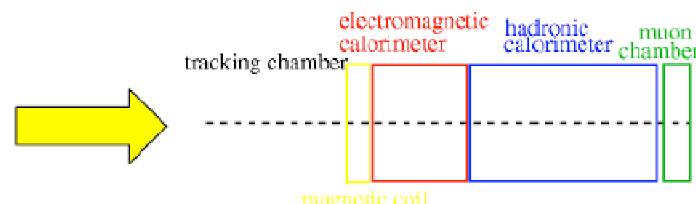
- Muons:
  - Track in the muon chambers
  - Matched to track



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

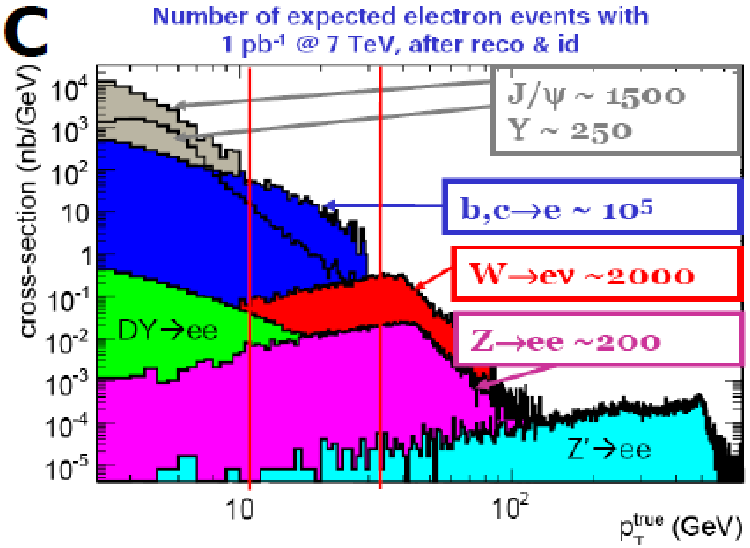


- Neutrinos
  - Imbalanse in transverse momentum
  - Inferred from total transverse energy in detector



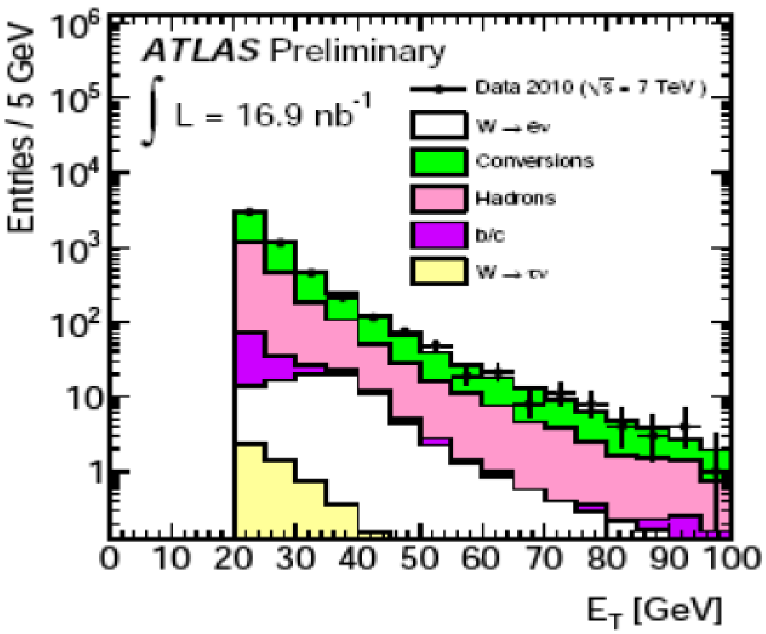
Electrons and jets

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

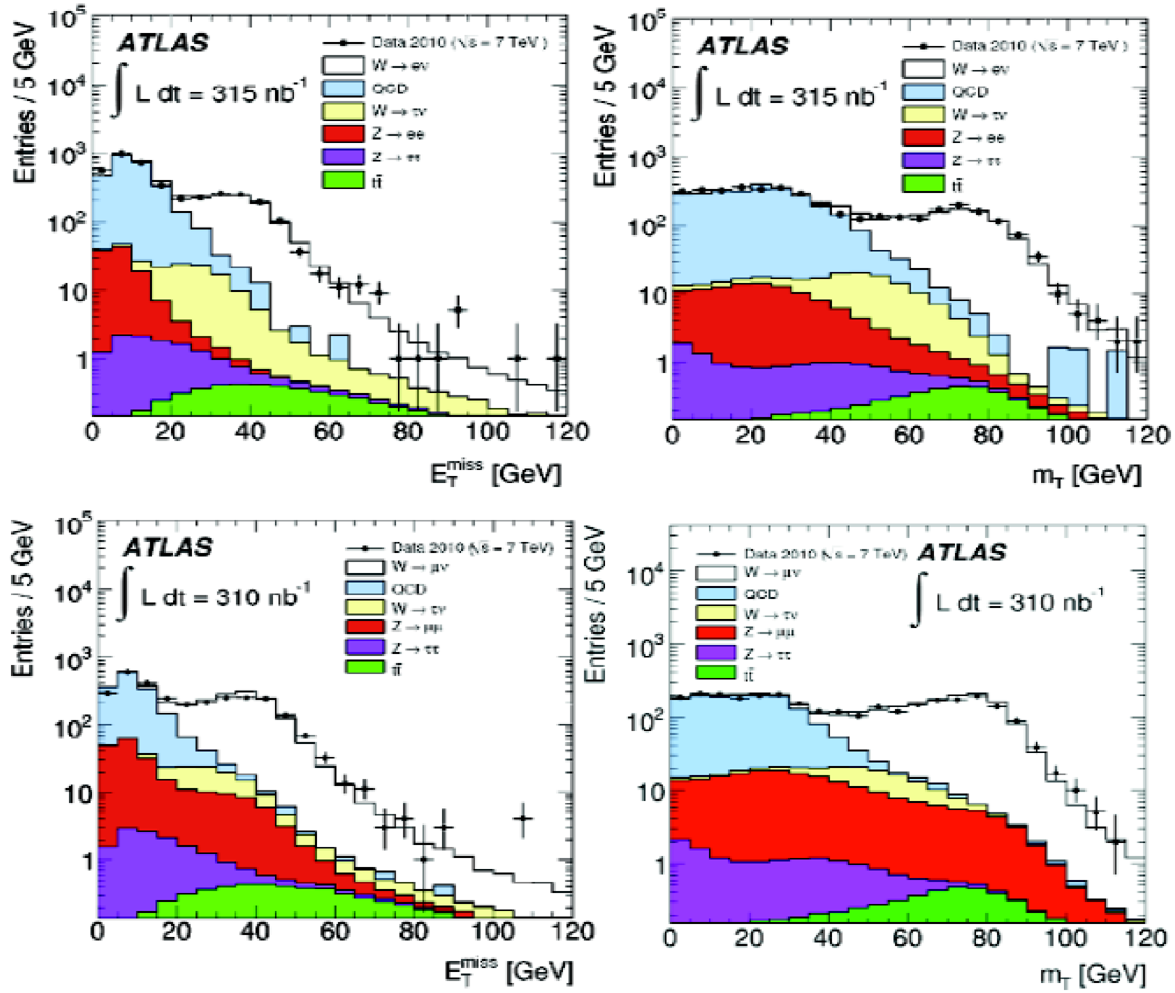
W selection (2010)

Electrons:

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

Muons:

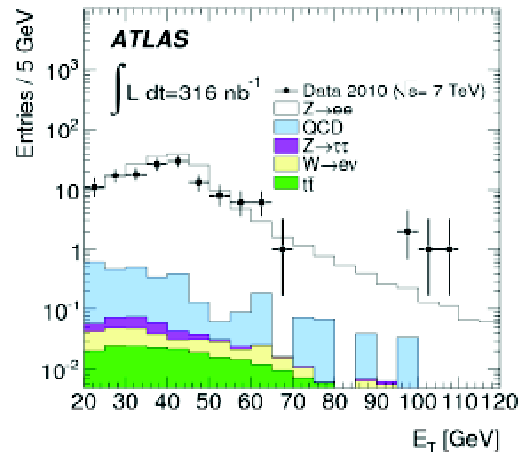
- $p_T > 20$ GeV
- *Track isolation*
- Missing $E_T > 25$ GeV
- $m_T > 40$ GeV
- ➢ *1181 Candidates*

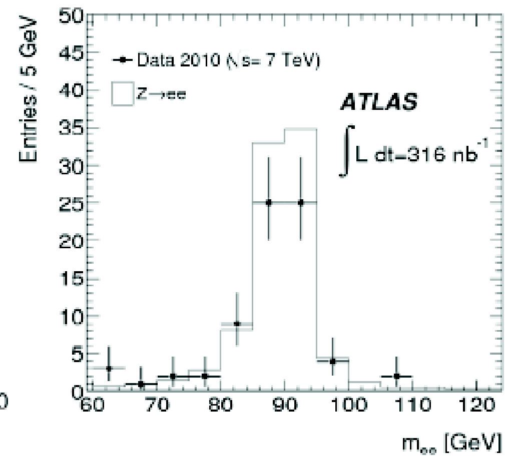


Z selection (2010)

2 Electrons :

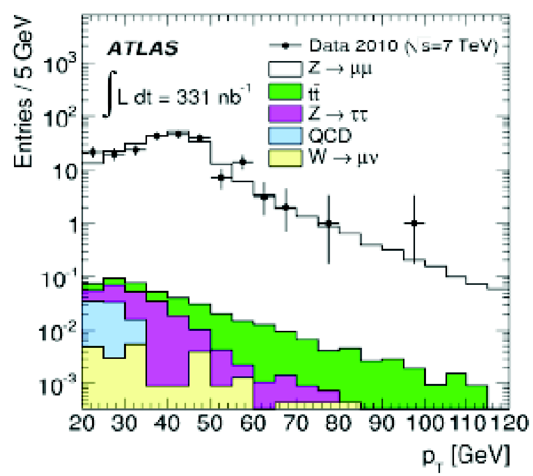
- $E_T > 20$ GeV
- Opposite charge
- Medium ID
- $66 < m_{ee} < 116$ GeV
- ➤ 70 Candidates

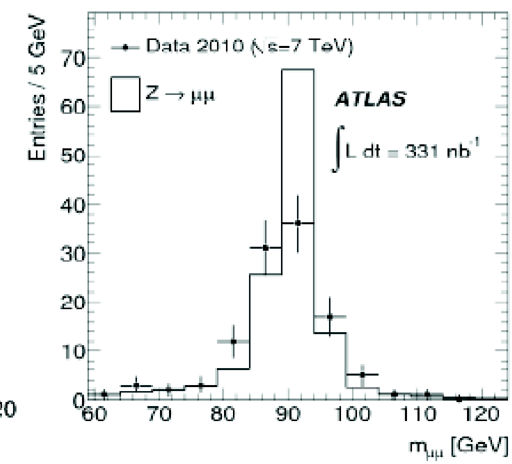




2 Muons :

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





W backgrounds

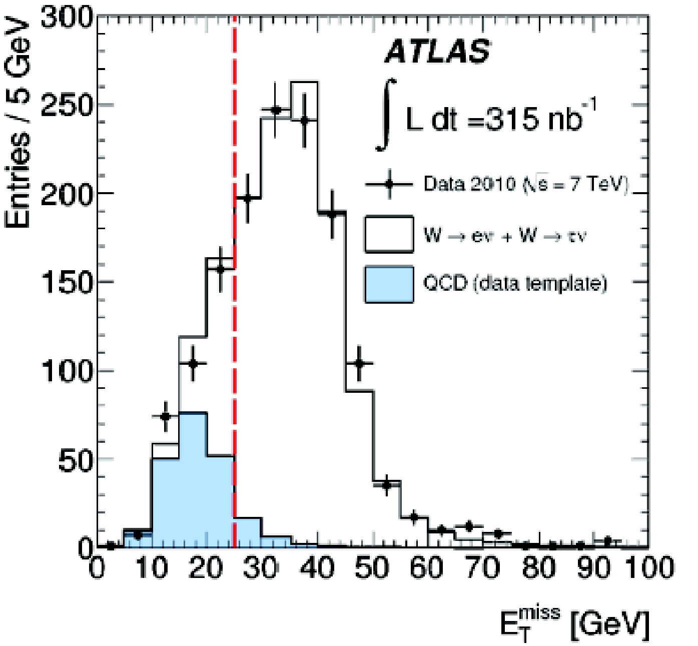
Electrons:

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

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

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

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



Muons:

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

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

- 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.

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

$$N_{loose} = N_{nonQCD} + N_{QCD}$$

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

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:

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

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MC	A_W $W^+ \rightarrow e^+\nu$	A_W $W^- \rightarrow e^-\nu$	A_W $W \rightarrow e\nu$	A_W $W^+ \rightarrow \mu^+\nu$	A_W $W^- \rightarrow \mu^-\nu$	A_W $W \rightarrow \mu\nu$
PYTHIA MRST LO*	0.466	0.457	0.462	0.484	0.475	0.480
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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

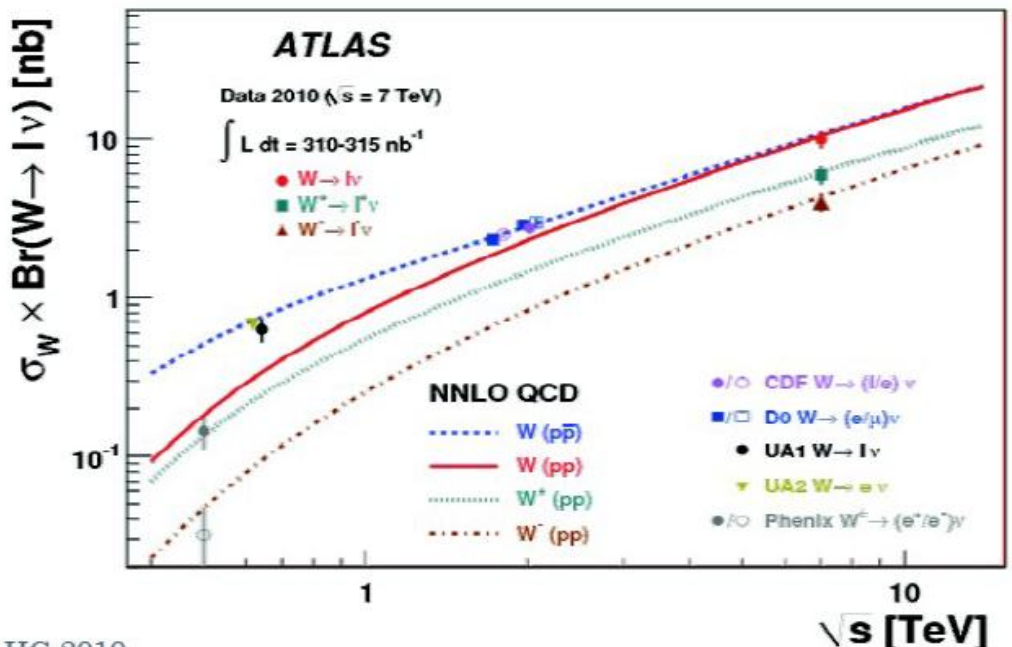
W cross-section measurement

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

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

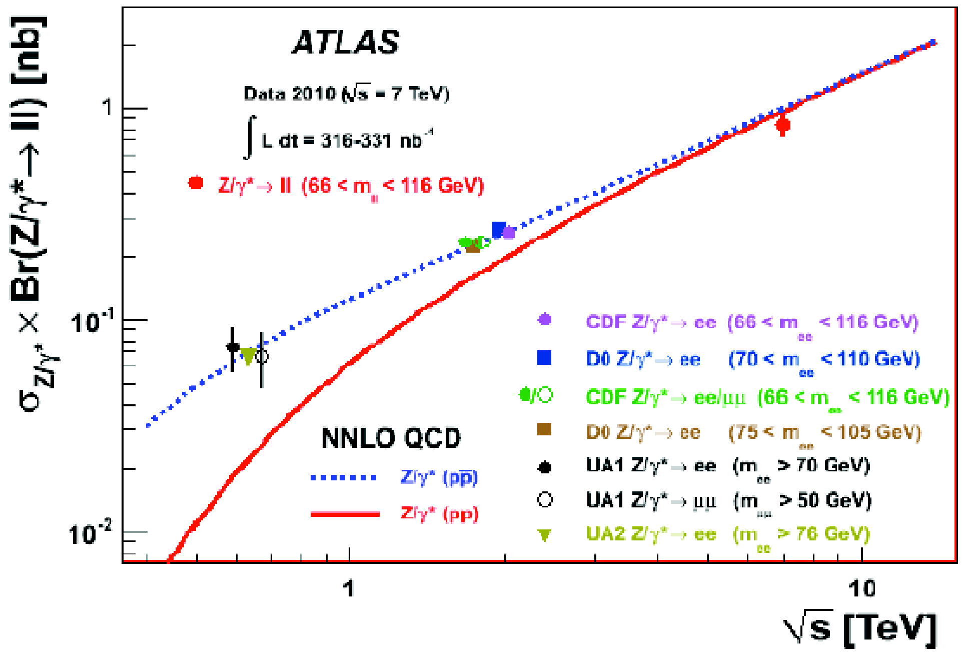
Z cross-section measurement

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

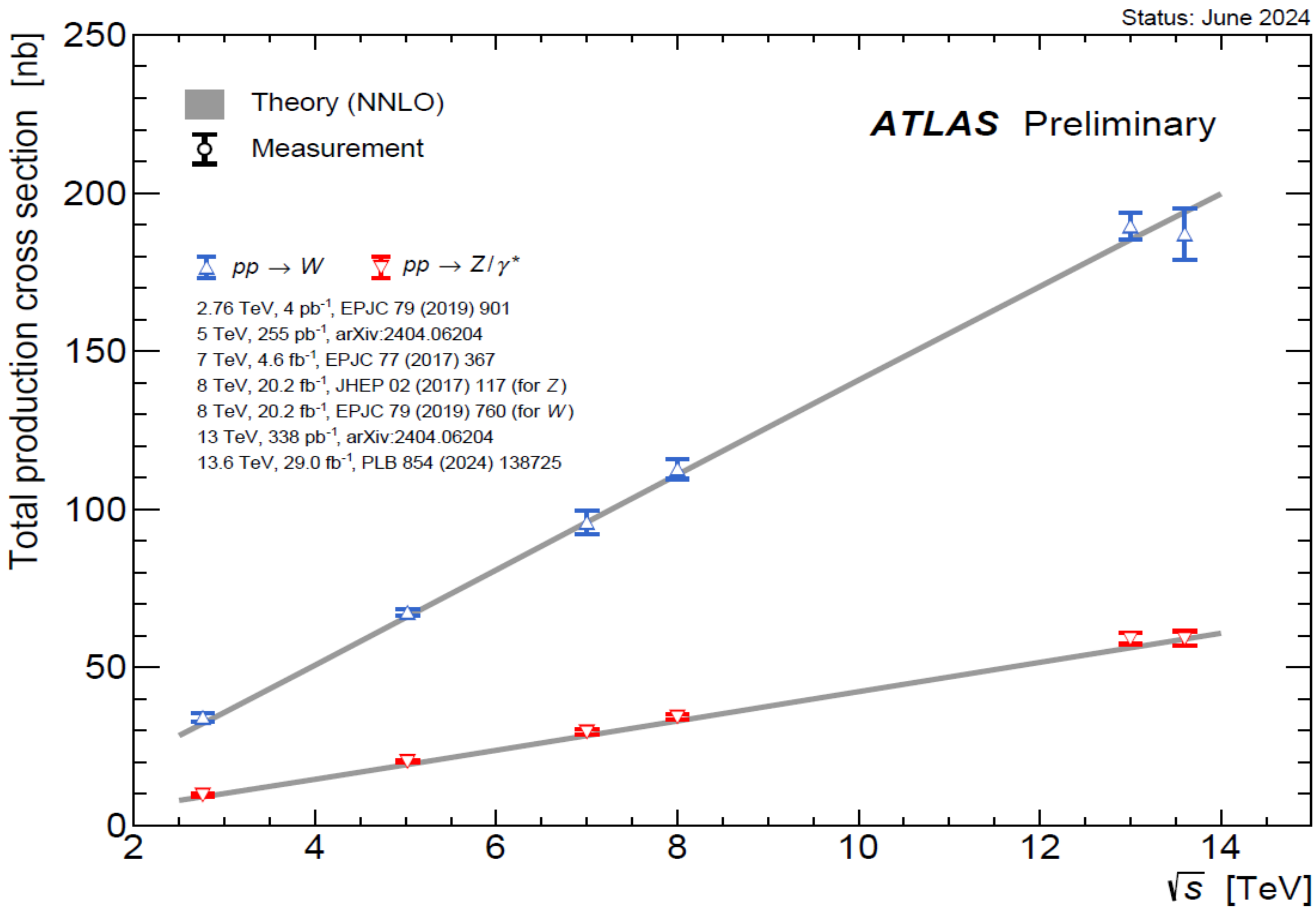
Theory prediction : 0.96 ± 0.04 nb for $[66 - 116]$ GeV mass window

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

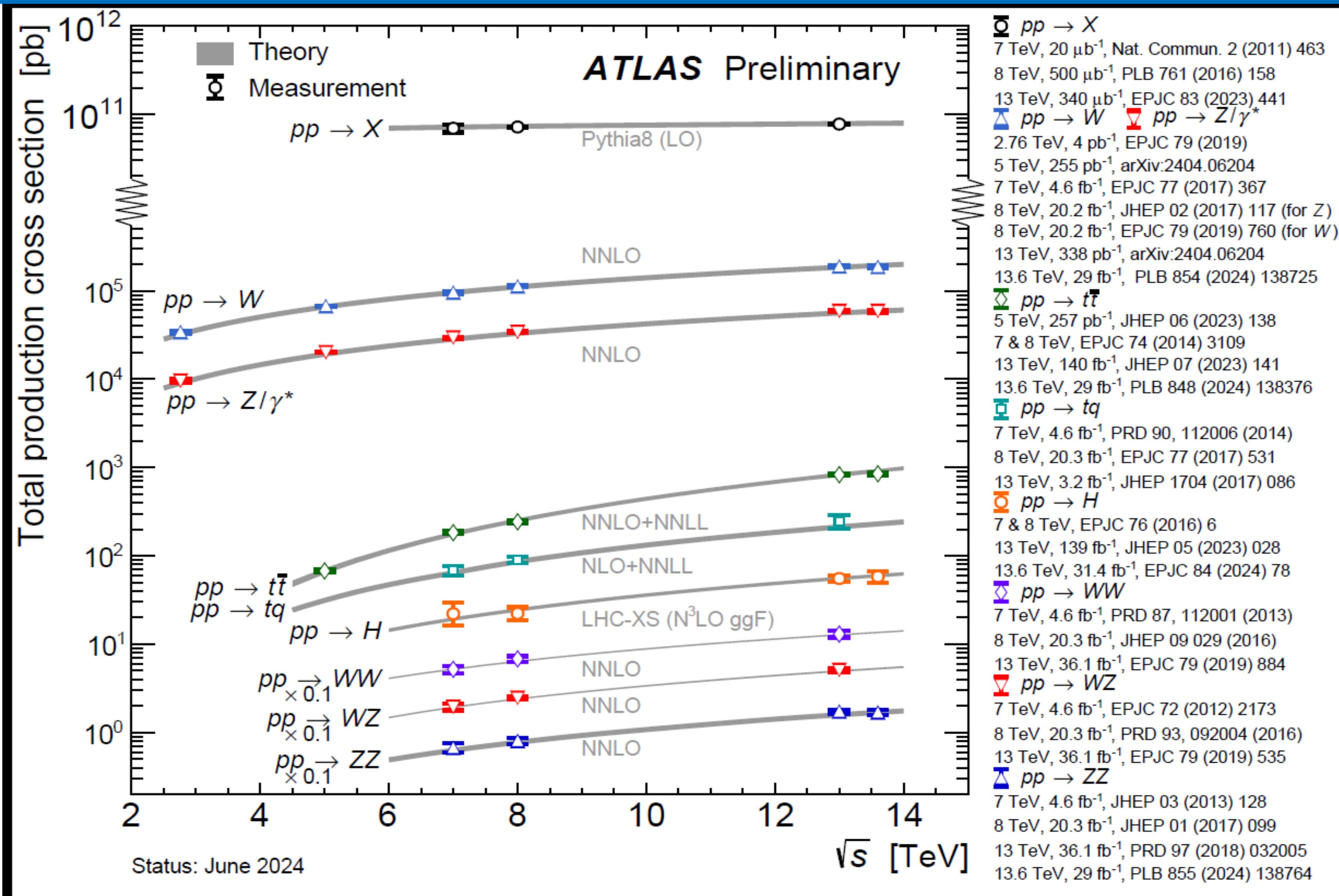
$$\sigma_Z \times BR(Z \to \mu^+\mu^-) = [0.87 \pm 0.08(stat) \pm 0.06(sys) \pm 0.10(lumi)]\, nb$$



W and Z cross-section measurement



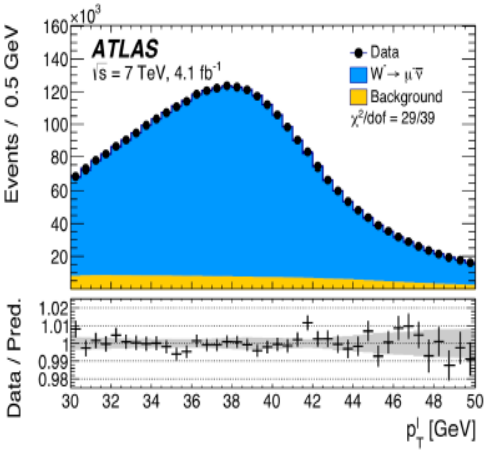
Production cross-sections

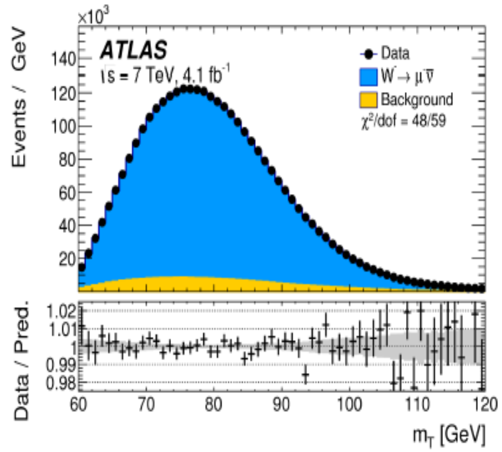


Measurement of the M_W at the LHC

A Milestone measurement!

Analysis strategy based on two kinematic distributions fitted in several categories





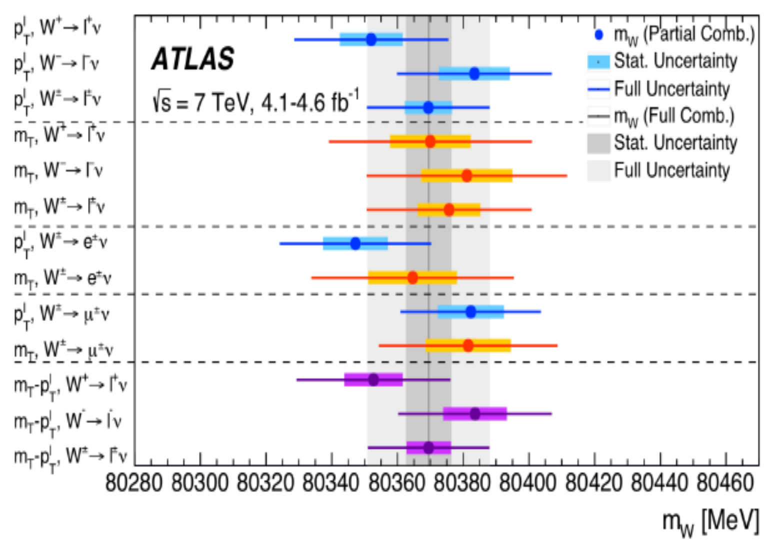
p_T^ℓ Clean energy measurement, but more sensitive to the modelling of the W transverse momentum

m_T Less sensitive to modelling but more difficult from to reconstruct (based on the missing transverse energy.

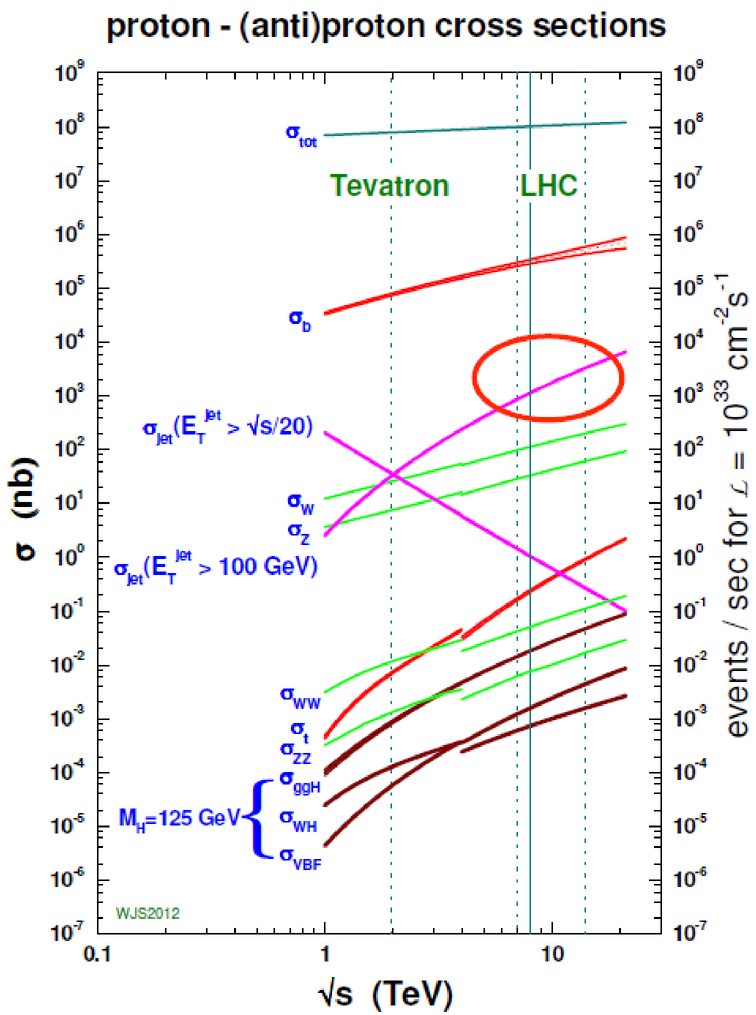
$$m_T = \sqrt{2p_T^\ell p_T^{miss}(1 - cos\Delta\phi)}$$

Categories are defined by the charge of the reconstructed lepton, its flavor (electron or muon) and its pseudo rapidity.

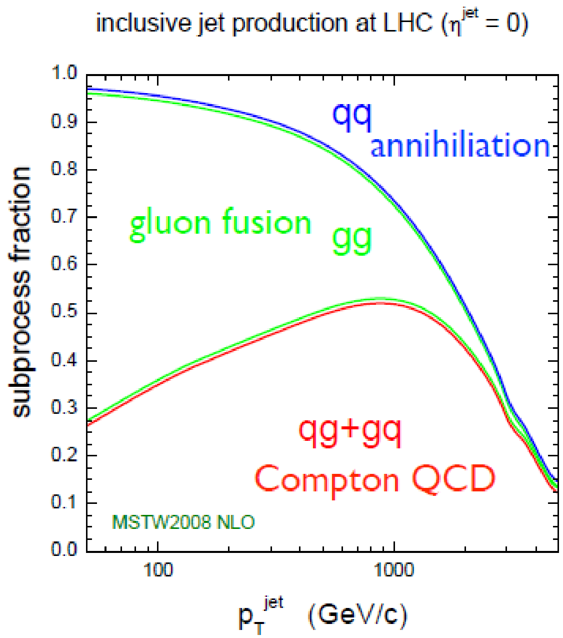
$$m_W = \begin{array}{l} 80369.5 \pm 18.5 MeV \\ (\pm 6.8\,(Stat) \\ \pm 10.6\,(Exp.\,Sys.) \\ \pm 13.6\,(Mod.\,Sys.)\,MeV) \end{array}$$



Jet physics

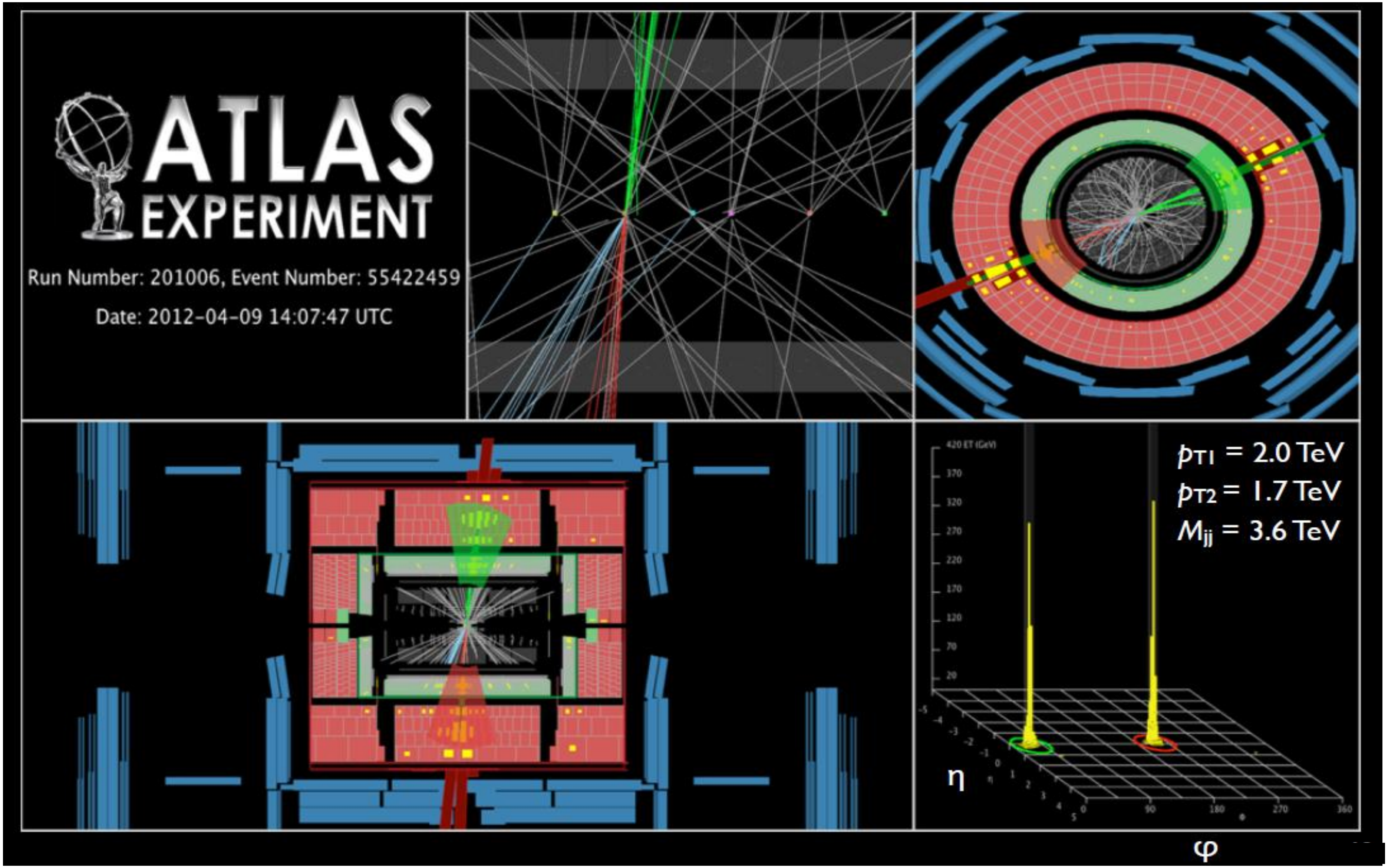


99% of events at the LHC contain at least one jet with $E_T^{jet} > 20$ GeV

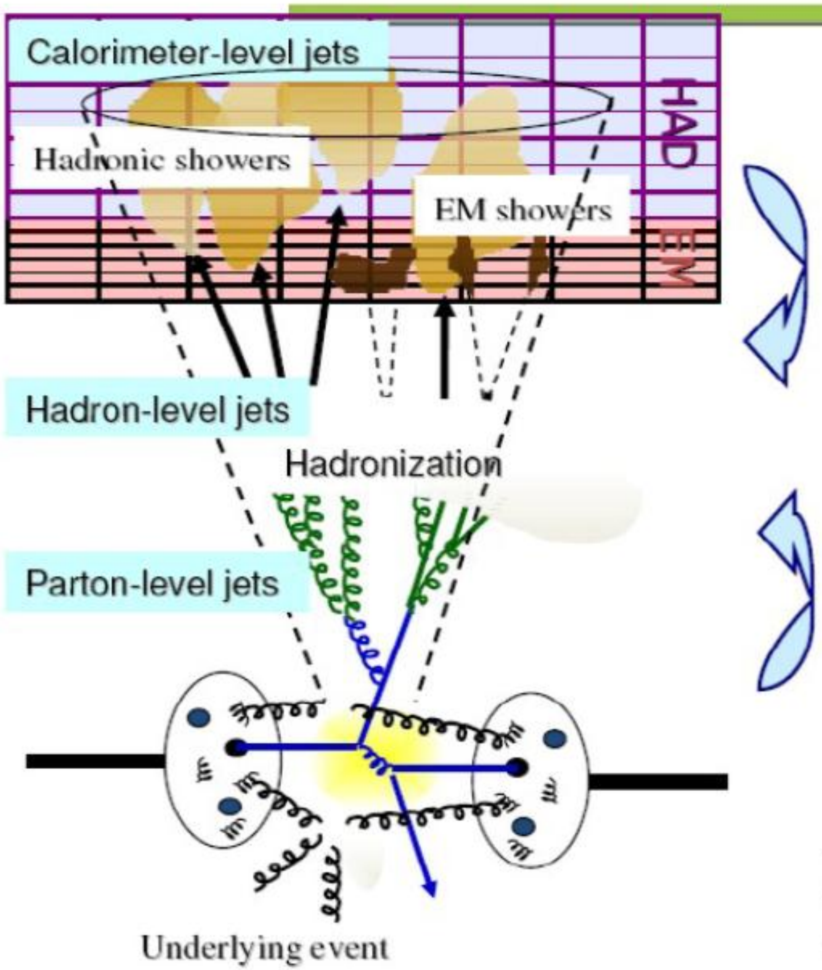


- Understand quark-gluon content of proton up to highest energies
- Perform Rutherford analysis at quark level and constrain quark compositeness

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

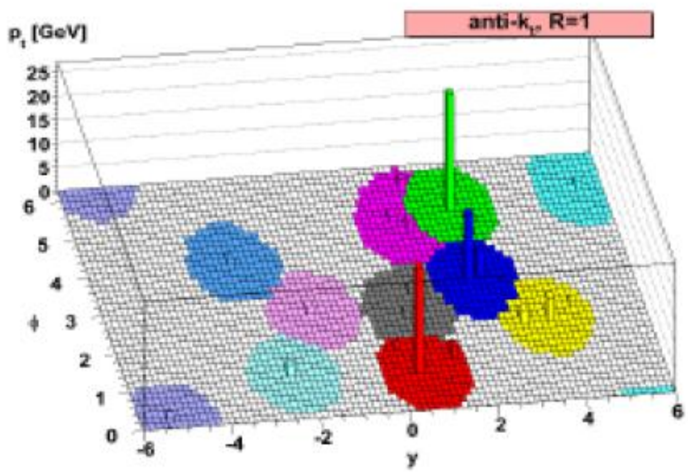
Jet reconstruction

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

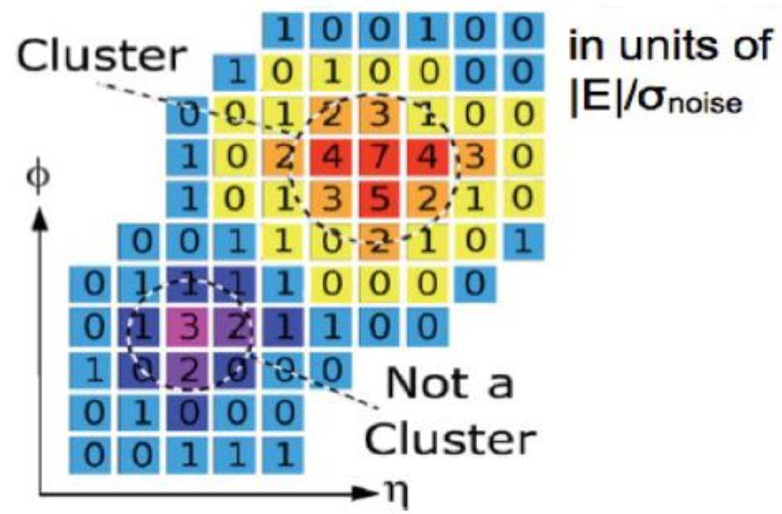
Energy deposits → noise-suppressed 3D clusters:
exploit transverse and longitudinal calorimeter segmentation

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

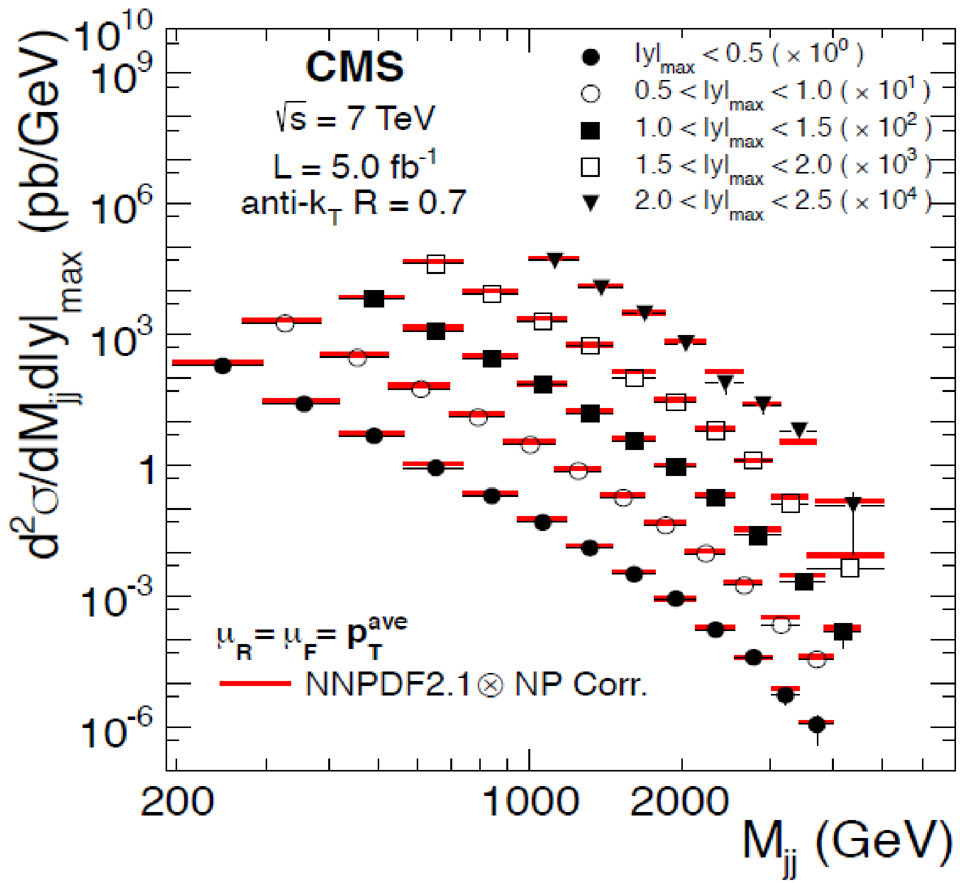


[Cacciari, Salam, Soyez JHEP 0804:063,2008]



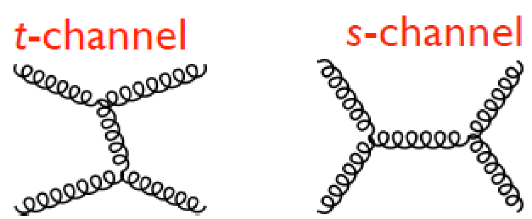
Di-jet cross-section

As a function of di-jet invariant mass in bins of rapidity (up to y_{max} = 2.5)

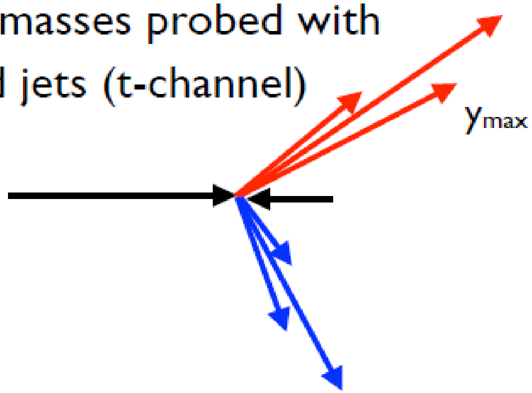


Excellent agreement between NLO theory prediction and data over eight orders of magnitude

Probing di-jet masses up to 4 TeV



Higher masses probed with forward jets (t-channel)



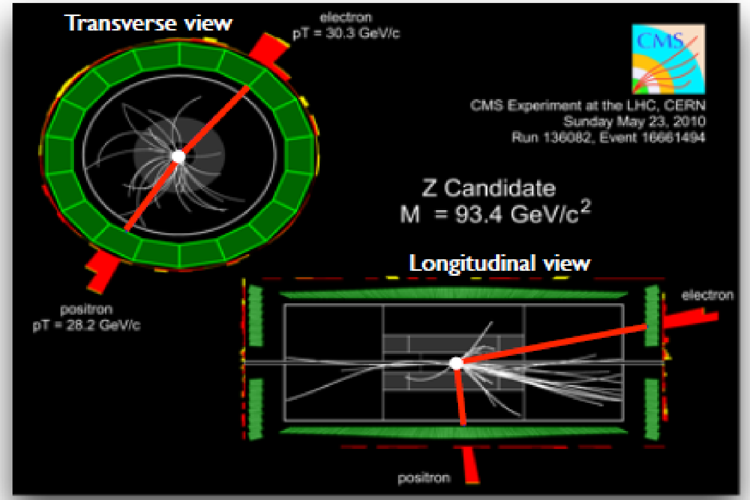
$2 \to 2$ process

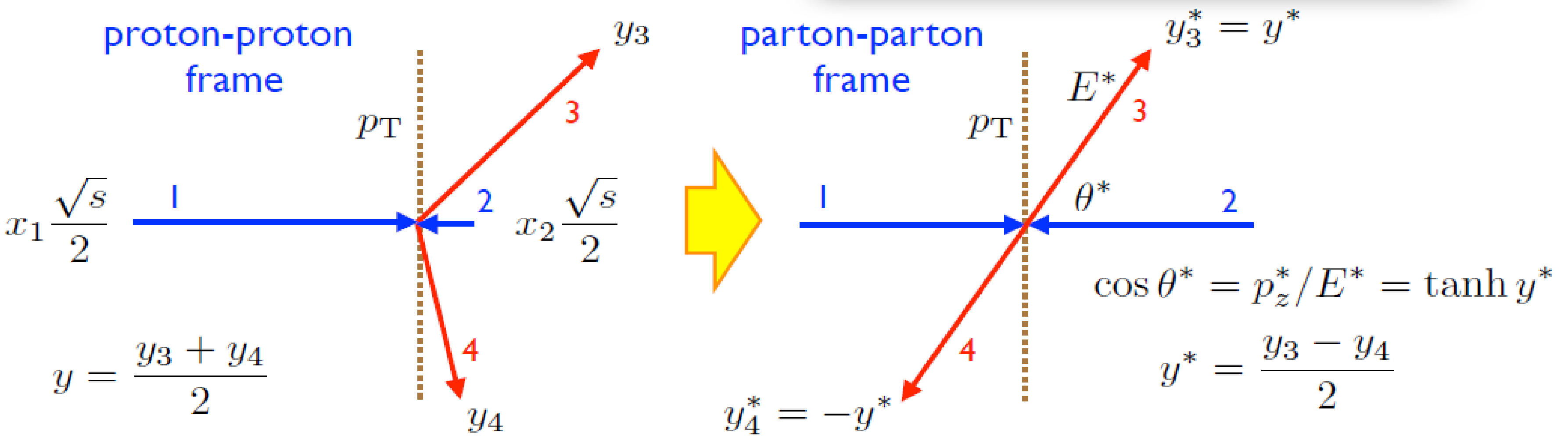
$$p_1 + p_2 \;\to\; p_3 + p_4$$

incoming partons (along beam axis) — outgoing particles (assumed massless)

From p_T, y_3 and y_4 extract:

- mass and rapidity of the 3+4 pair
- (hence x_1 and x_2)
- CoM scattering angle





$$M = 2 p_T \cosh \frac{y_3 - y_4}{2}$$

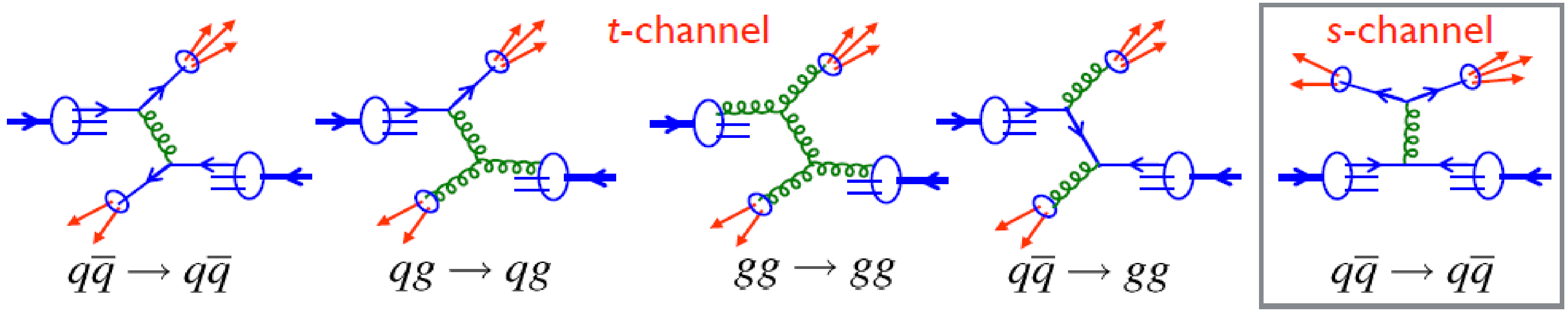
$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

$$\cos\theta^* = \tanh \frac{y_3 - y_4}{2}$$

The difference in rapidity determines the centre of mass scattering angle

Quark Compositeness?

Most important subprocesses via exchange of a massless vector boson in the *t*-channel

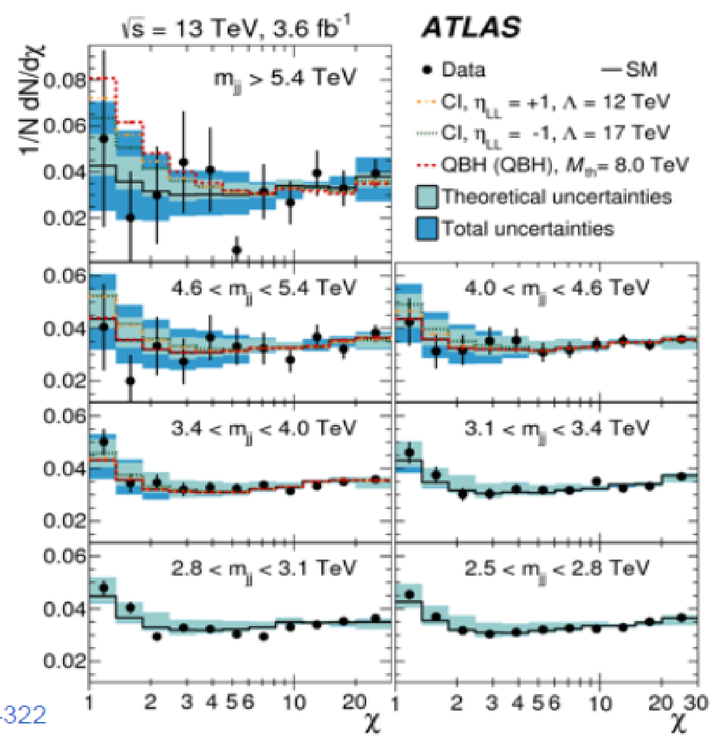


Rutherford at quark level $\quad \frac{d\hat{\sigma}}{d\cos\theta^*} \sim \frac{1}{\sin^4(\theta^*/2)}$

Variable $\quad \chi = \frac{1+\cos\theta^*}{1-\cos\theta^*} = e^{|y_3-y_4|}$

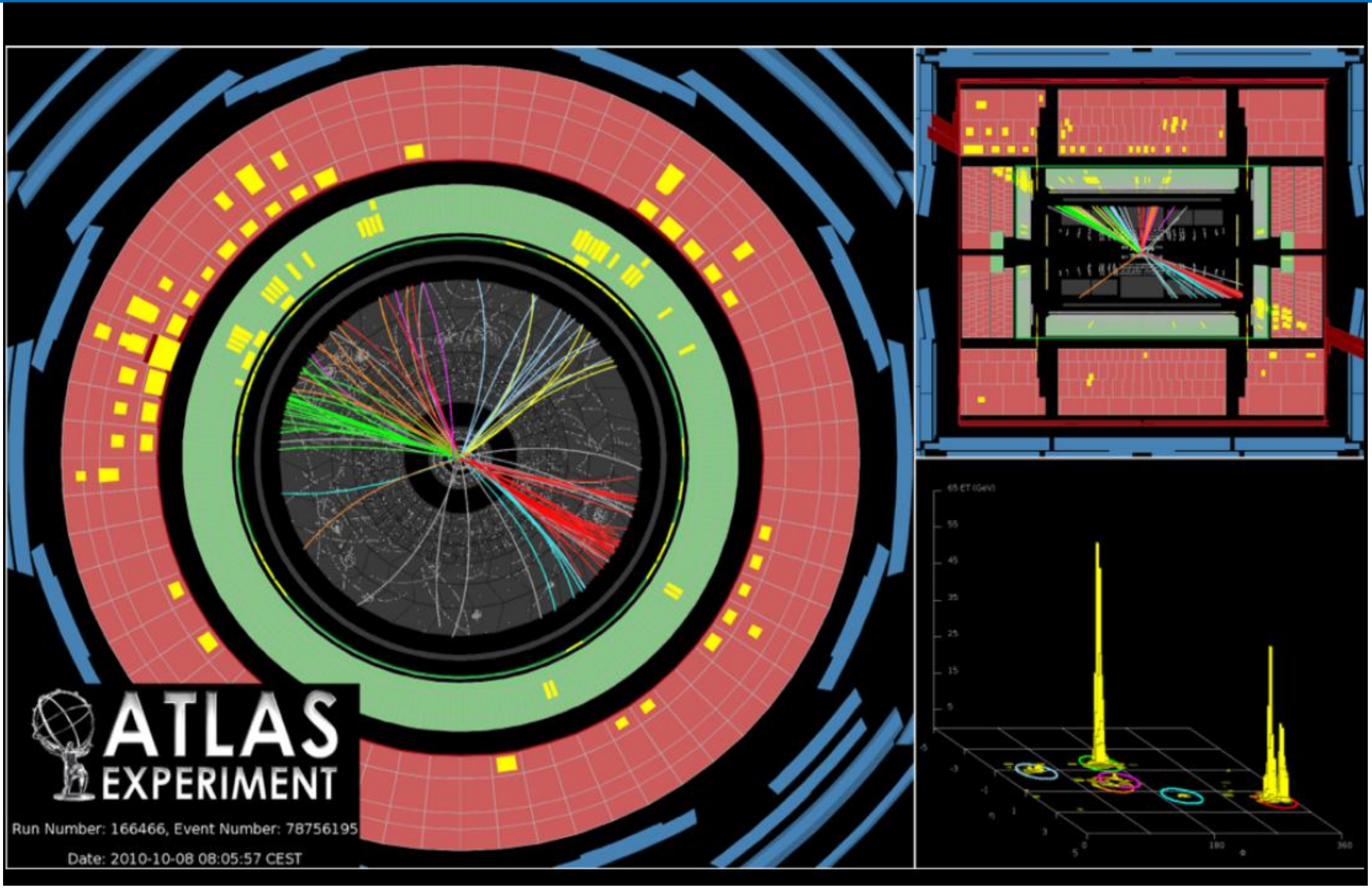
For pointlike quark: $\frac{d\hat{\sigma}}{d\chi} \sim \text{cst}$ at small angle

No evidence for quark/gluon compositeness from angular distributions



PLB 754 (2016) 302-322

Three jets



ATLAS
EXPERIMENT
Run Number: 166466, Event Number: 78756195
Date: 2010-10-08 08:05:57 CEST

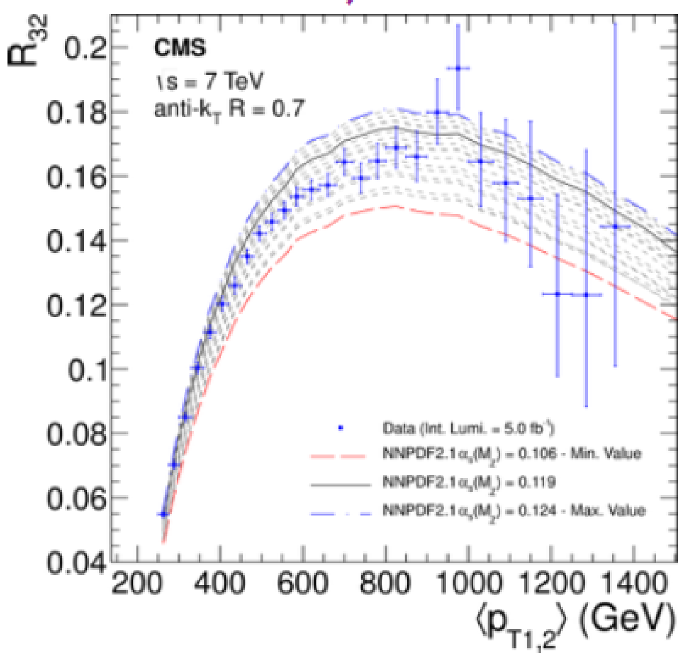
Constraints on Strong Coupling

Constraints on α_s from several jet analyses

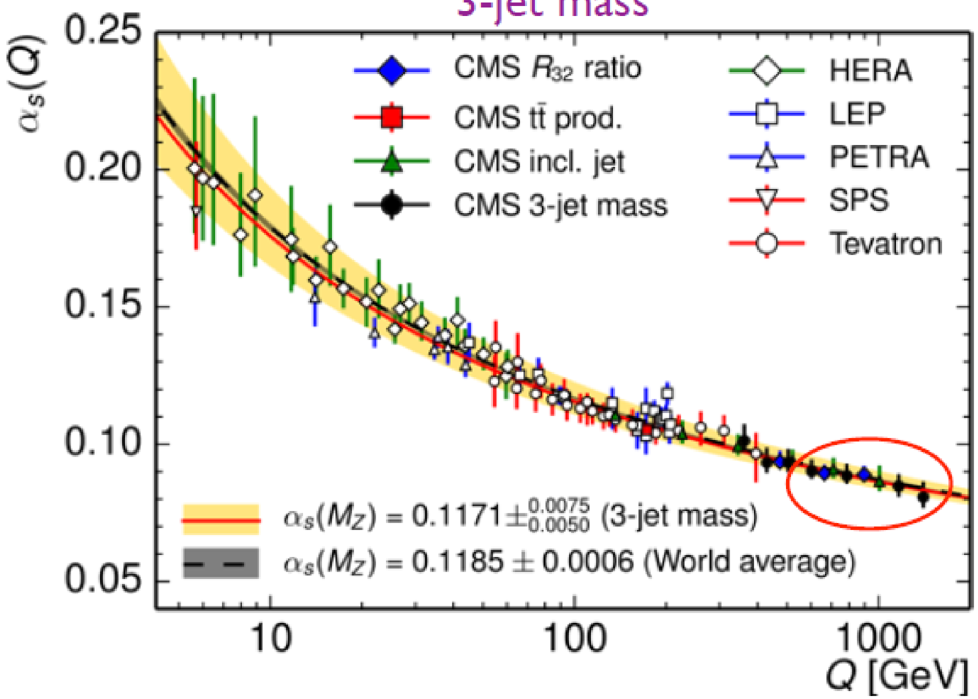
- inclusive jet production
- ratio 3-jets to 2-jets
- 3-jet mass spectrum

Uncertainties usually dominated by theory (PDFs and scales)

3 to 2 jet ratio



3-jet mass

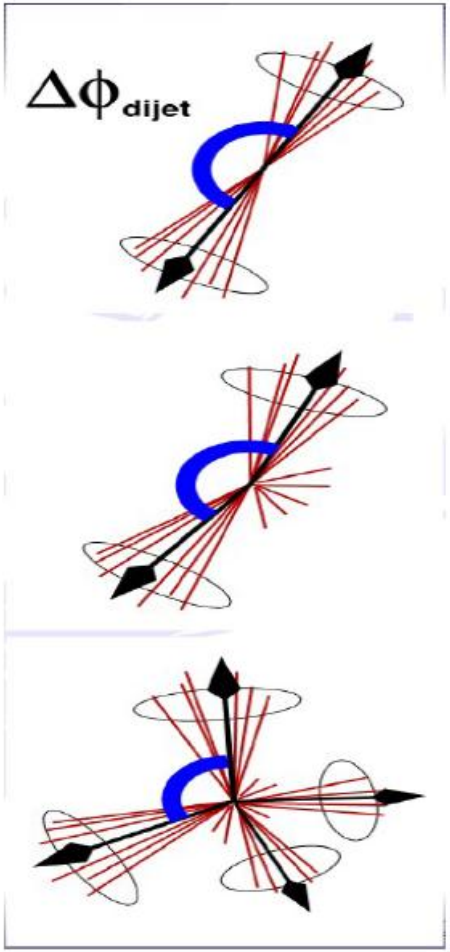


Not competitive with most precise measurements at the Z boson

- but in unprecedented range in energy (two orders of magnitude in Q!)

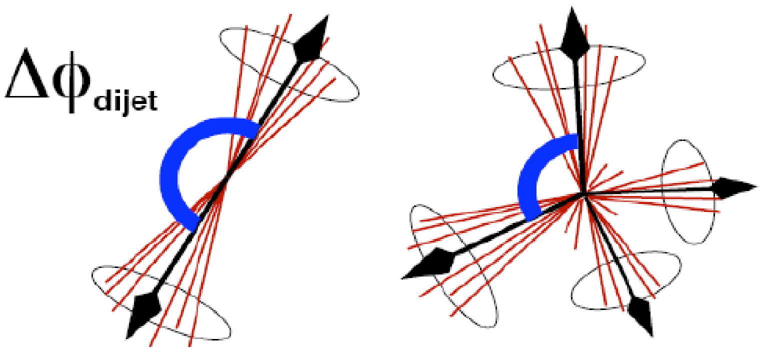
Multi-jet events

- 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

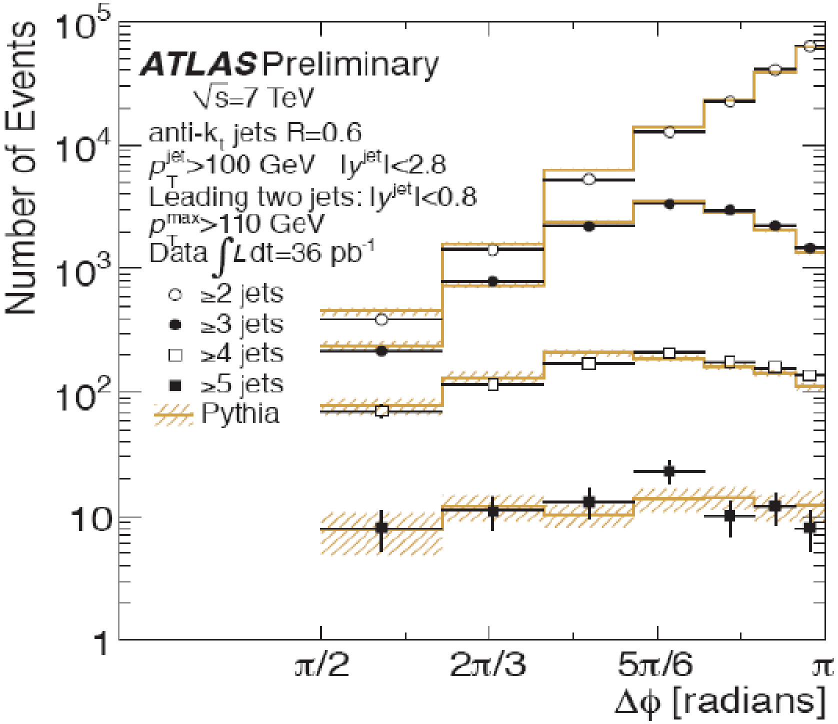


Azimuthal decorrelations

- 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.



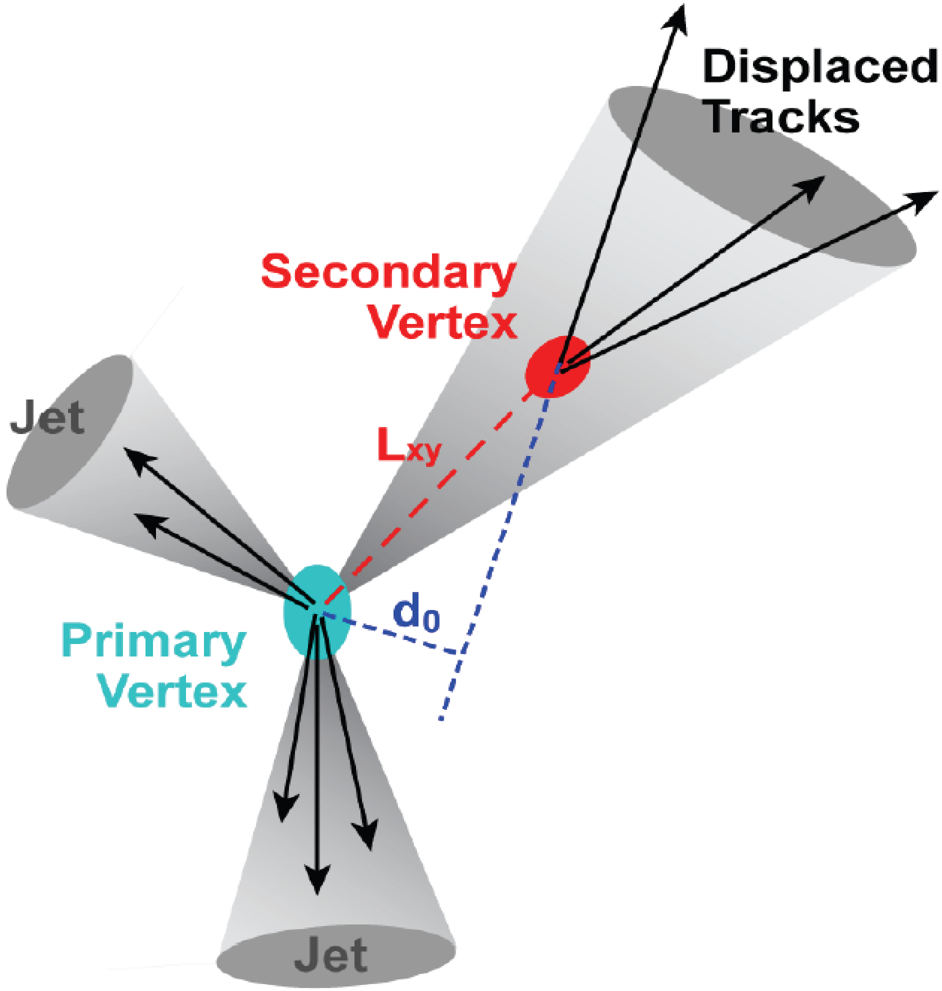
- Requiring additional jets flattens distribution.



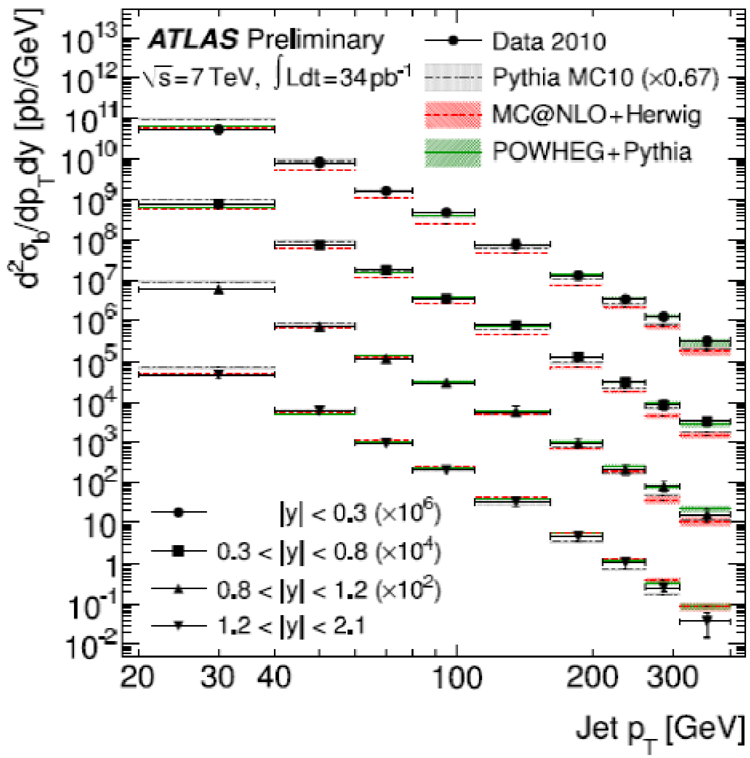
Confinement, hadronisation, jets….

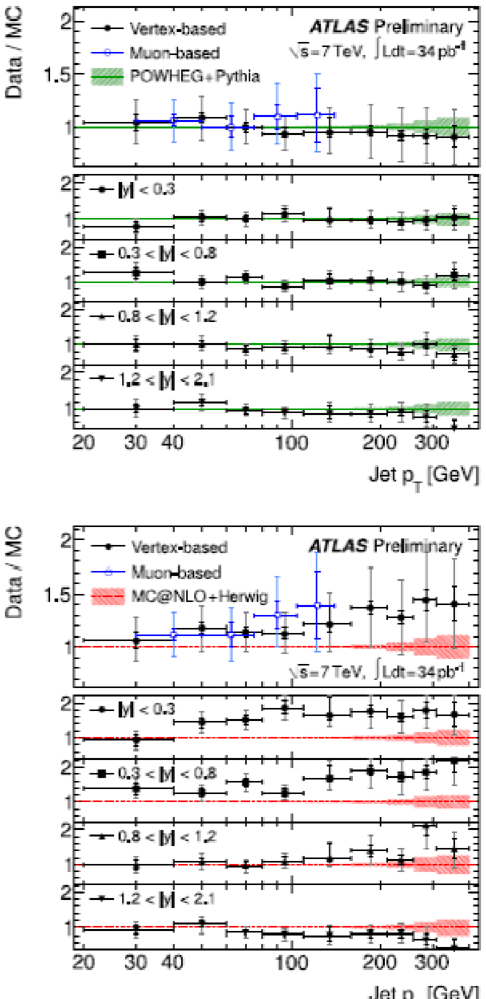
B-tagging

- 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…



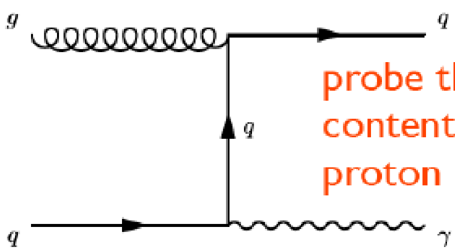
b-jet cross-sections





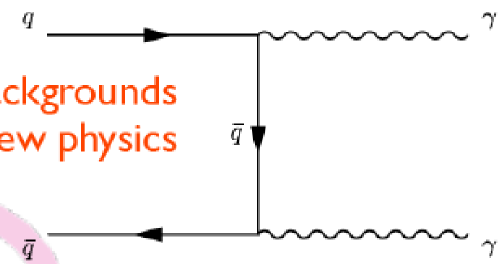
- Good agreement with Powheg+PYTHIA
- MC@NLO+Herwig predicts too few central jets, too many forward jets

Why measure prompt photons

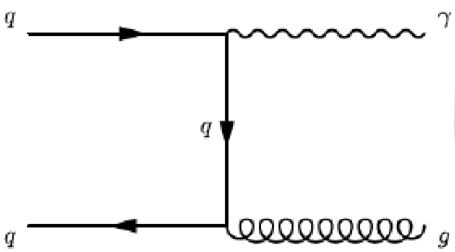


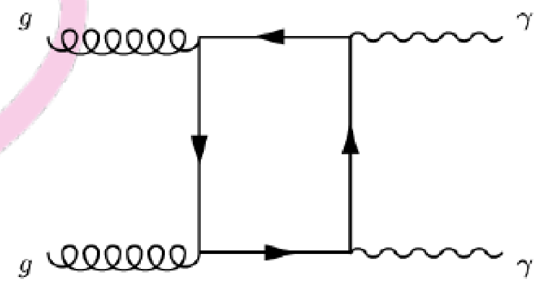
probe the gluon content of the proton

QCD backgrounds to new physics



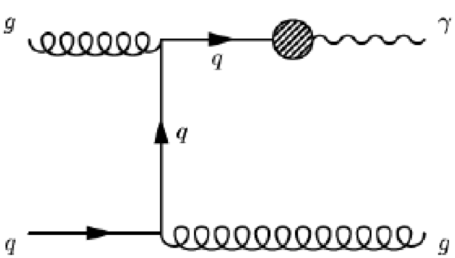
test NLO *p*QCD predictions using a measurement without jets



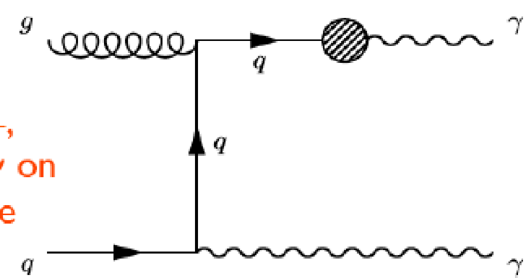


resummation

k_T factorisation

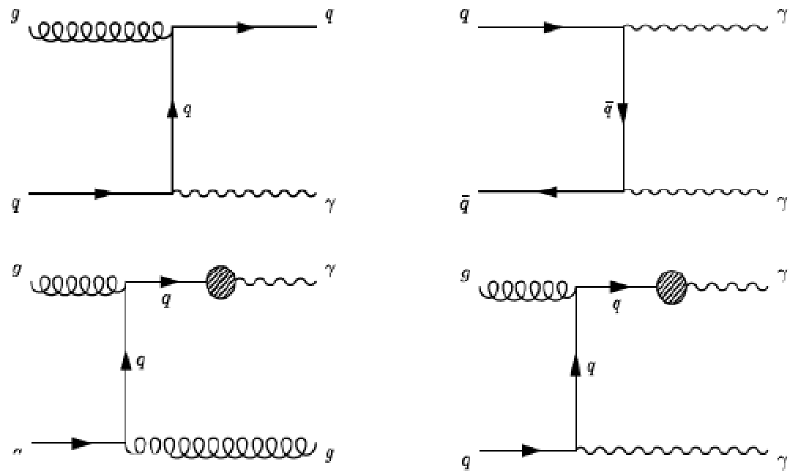


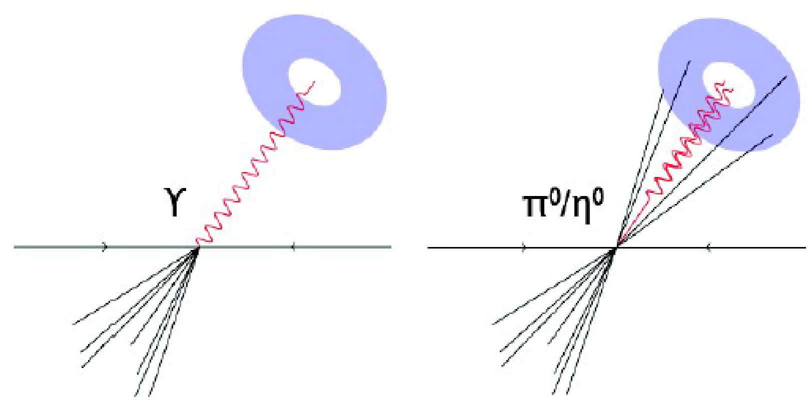
fragmentation important at low E_T, suppressed by isolation cut. MCs rely on fragmentation function to compute



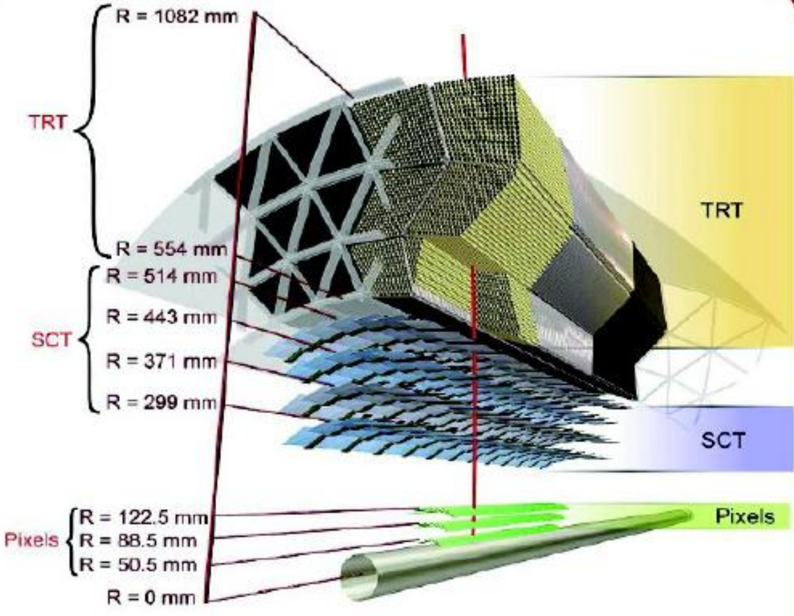
Prompt and isolated photons

- 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

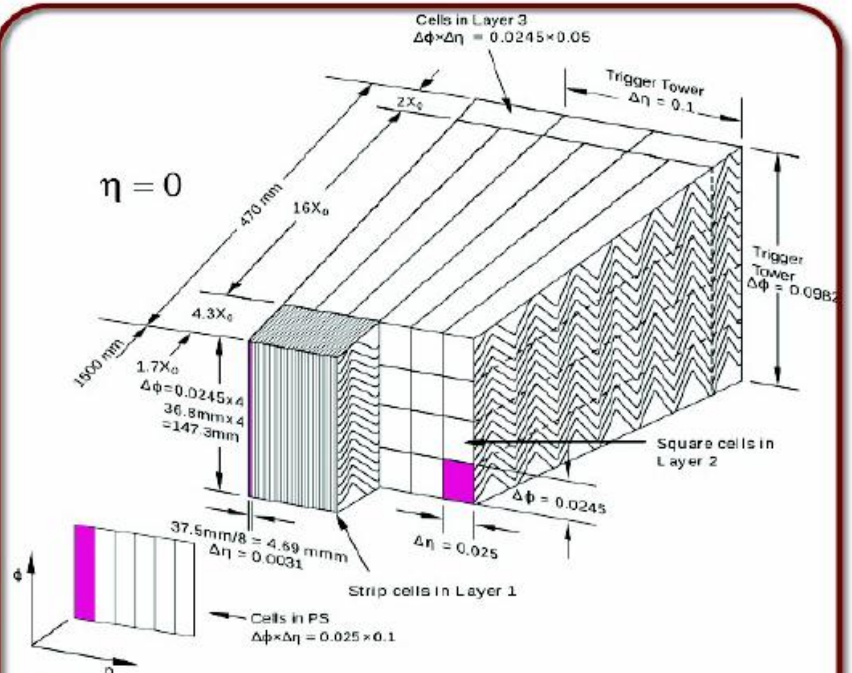




Measuring photons with ATLAS

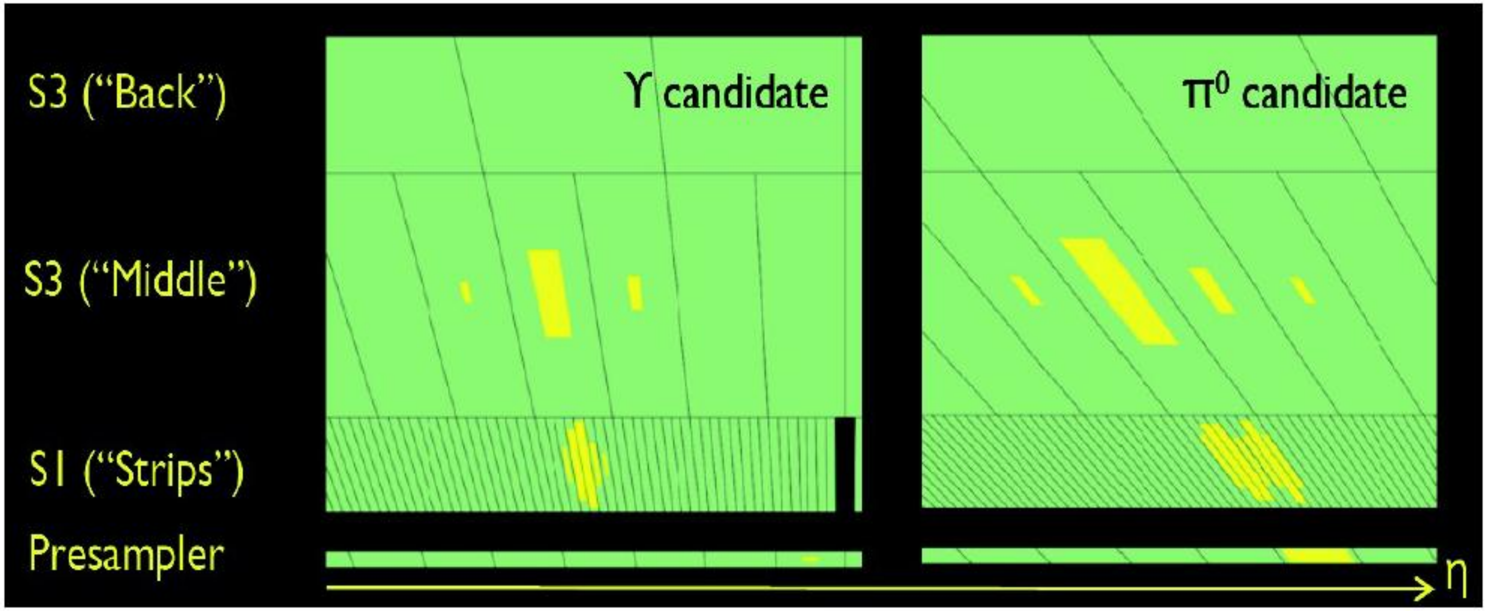


- Inner detector
  - ✓ track charged particles
  - ✓ measure transition radiation
  - ✓ e/γ discrimination
  - ✓ γ conversion reconstruction

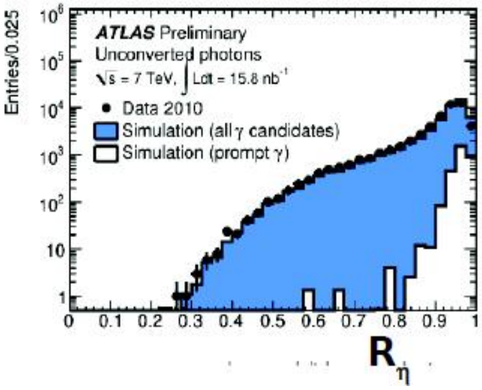


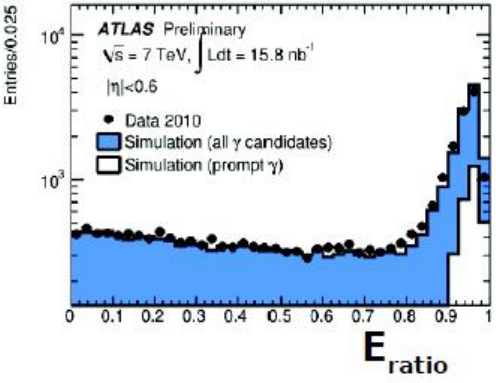
- Pb-LAr EM calorimeter
  - ✓ η/φ/longitudinal segmentation
  - ✓ fine granularity in 1st layer up to η<2.37
  - ✓ γ energy and direction
  - ✓ γ/π⁰ separation (EM shower moments)

Photon identification



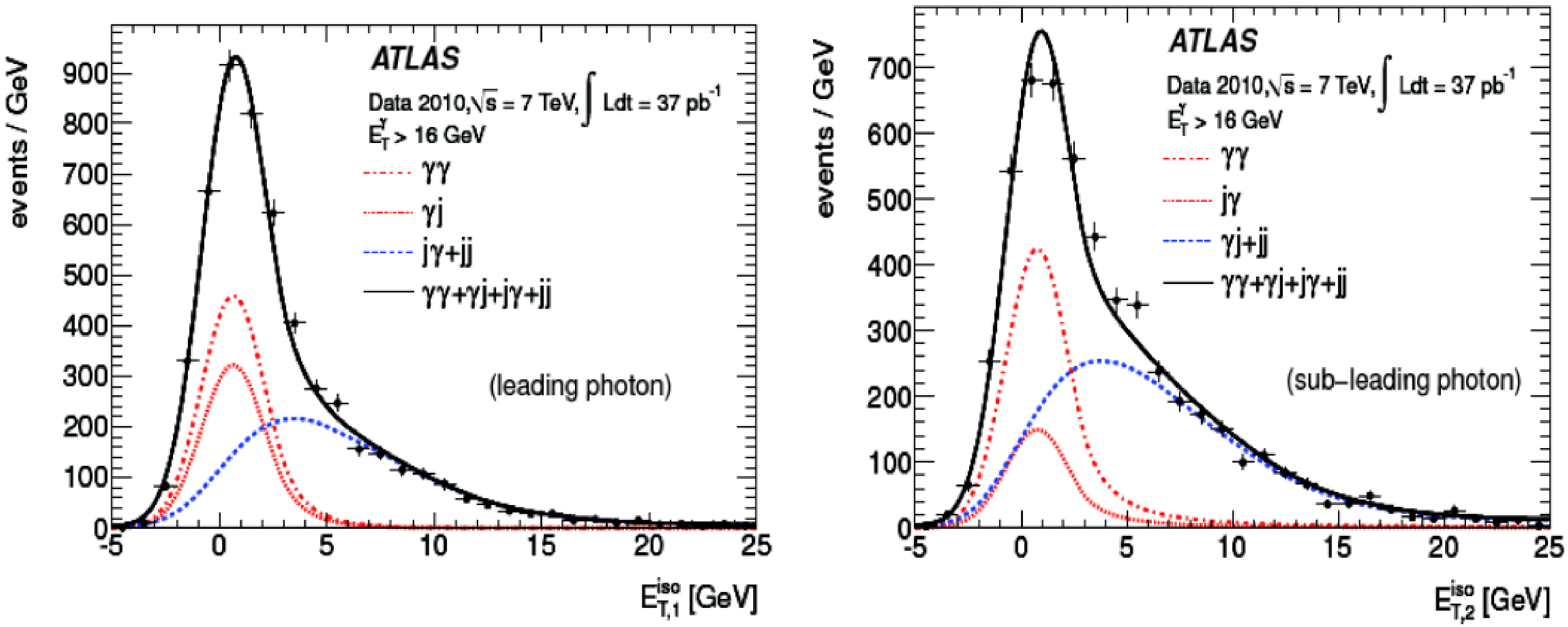
- loose and tight selection
- optimised separately for unconverted and converted photons



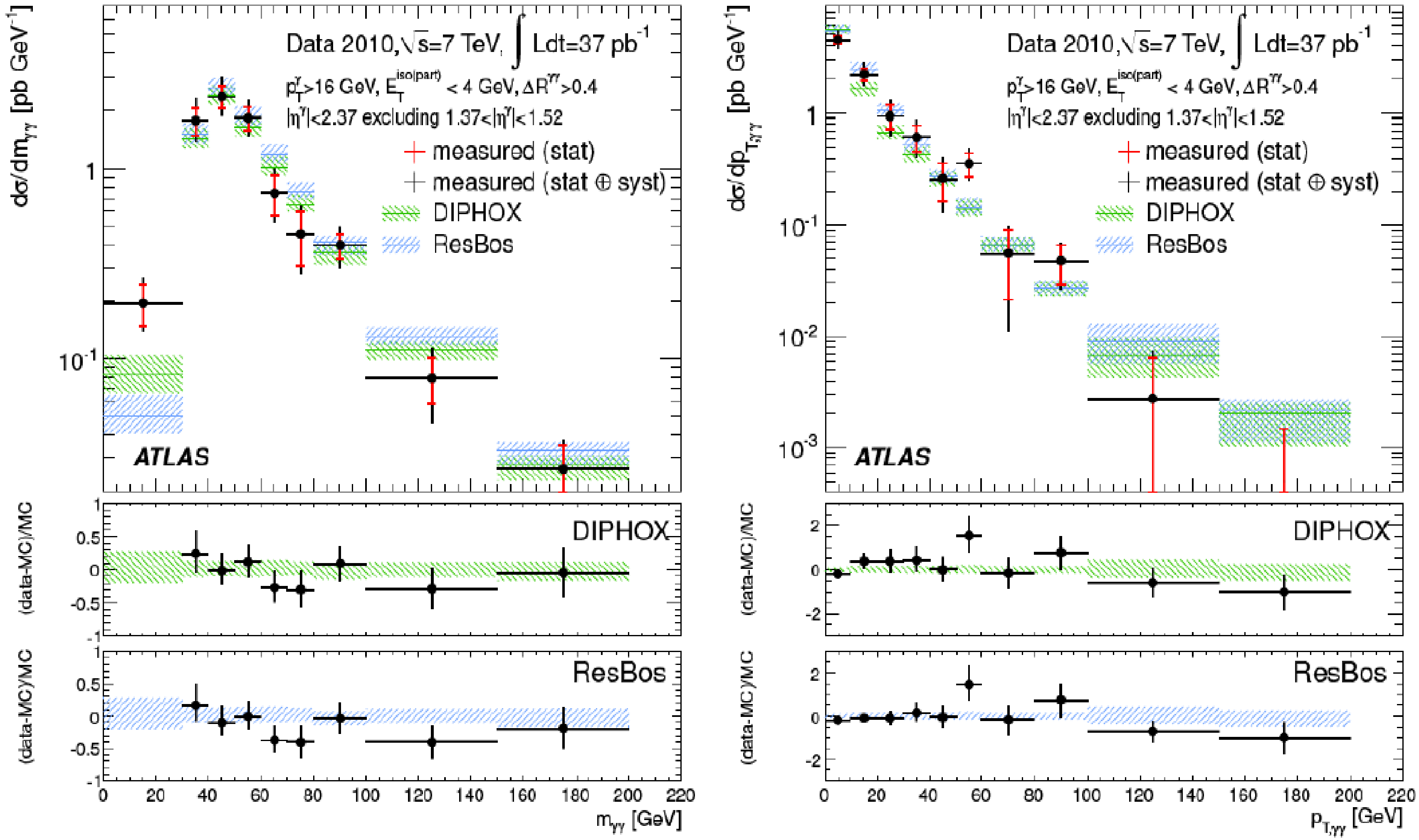


Photon isolation and background estimate

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



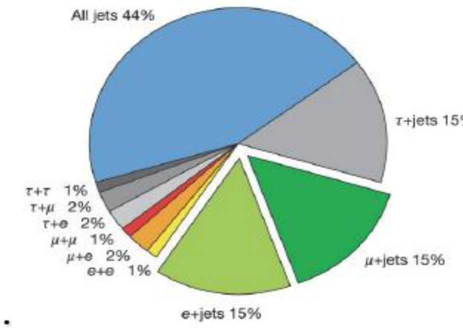
Isolated di-photon cross-section

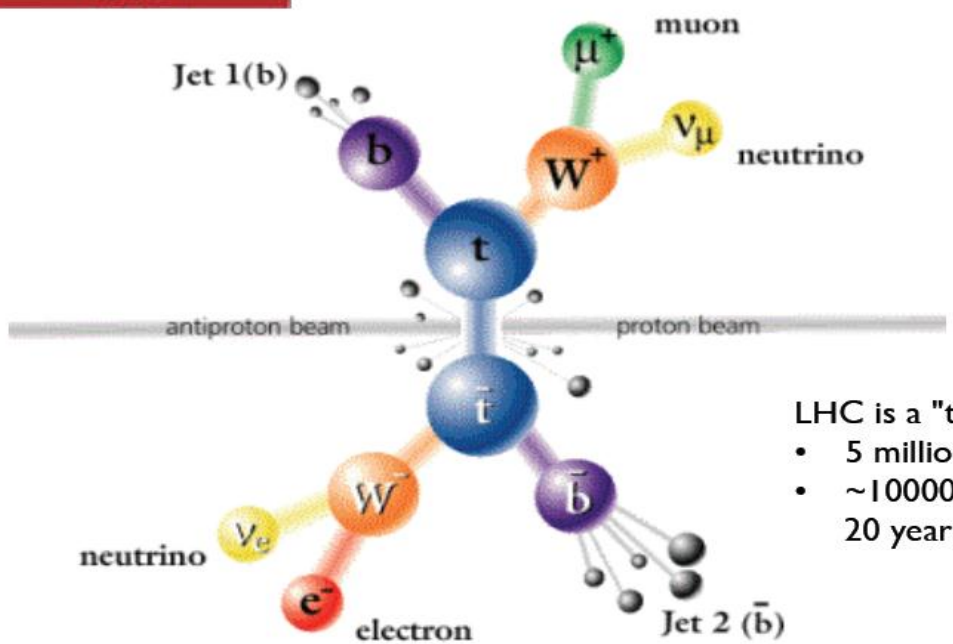


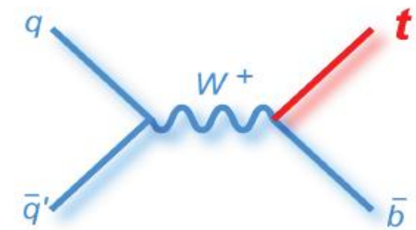
Complicated topologies….

top quark

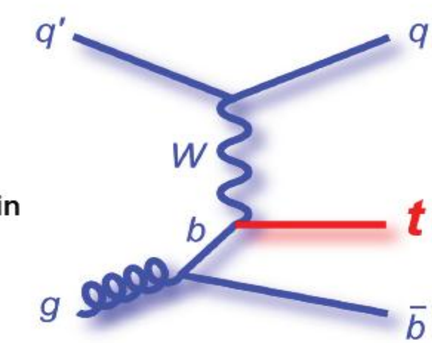
- Top quark has a mean lifetime of 5×10^{-25} s, shorter than time scale at which QCD acts: no time to hadronize!
  - ✓ It decays as $t \to Wb$
- Events with top quarks are very rich in (b) jets…





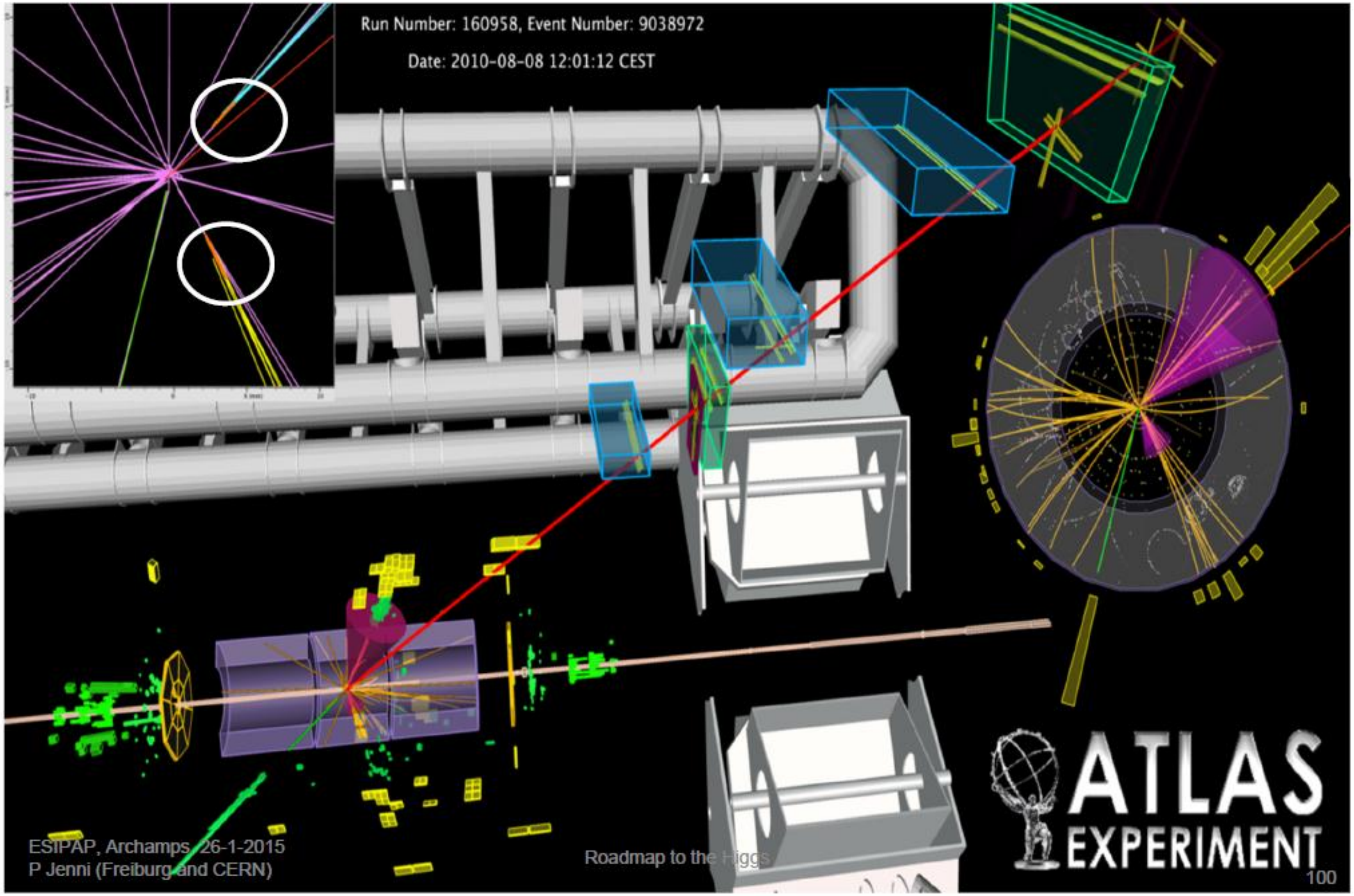


LHC is a "top factory"!
- 5 millions of tt pairs
- ~100000 in Tevatron in 20 years

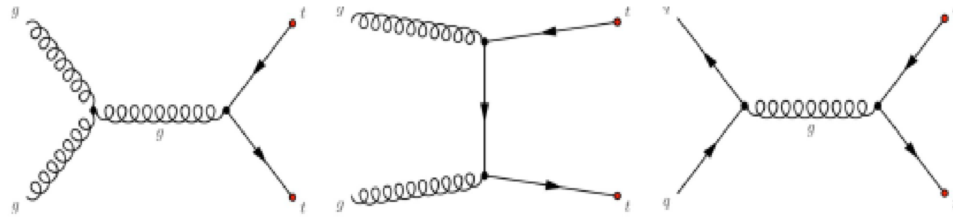


$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss



Fundamentals of top-quark physics



- Most massive fundamental particle in the SM

→ its Mass / Yukawa is a free parameter: need to measure it

- Mean lifetime ~5x10^{-25}s << 1/Λ_{QCD} ~10^{-23}s

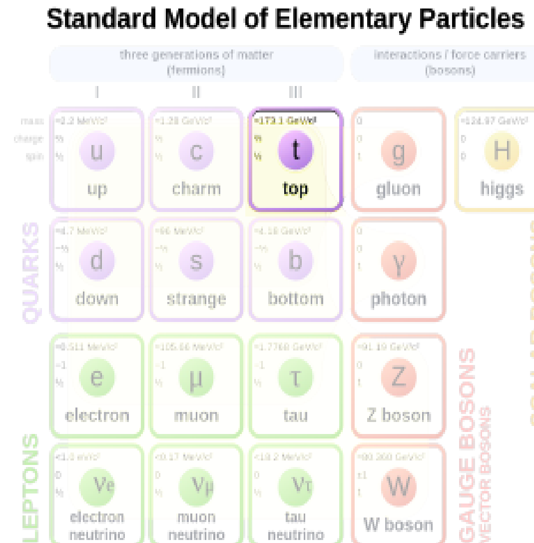
→ the only "bare quark"

- BR(t→Wb) ~ 100%

→ unique experimental signature

- Abundant production at the LHC, O(100M) pairs

→ **"standard candle"**, very useful for calibrations



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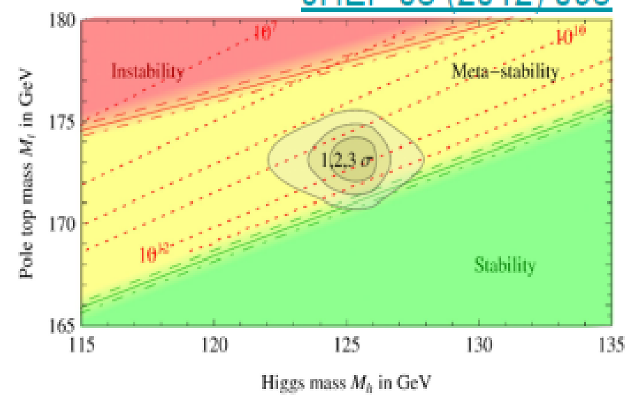
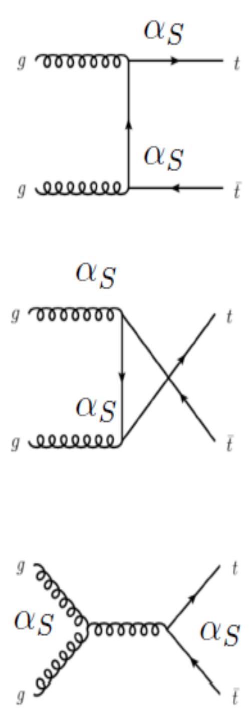
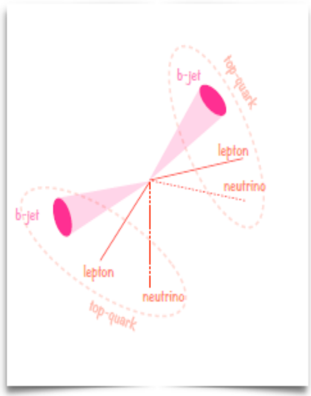


Top pair production cross-section

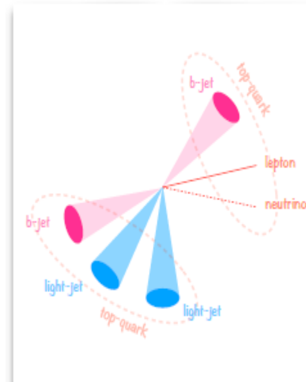
Main production diagrams
At tree level leading order
$O(\alpha_S^2)$





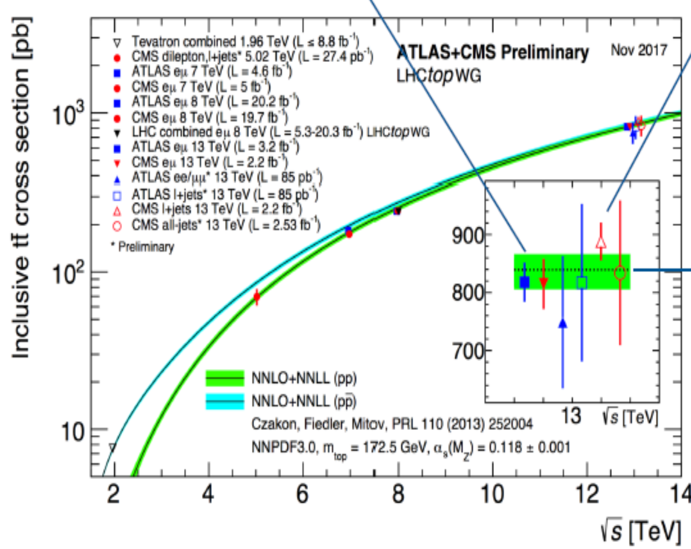
Di-lepton topology:

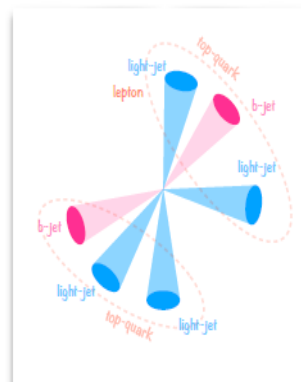
Precise determination of cross section in the different flavour electron-muon channel in particular. Excellent signal to background ratio. Lower stats (4%).



Semi-leptonic topology:

Best compromise between statistics (30%) and signal to background ratio.





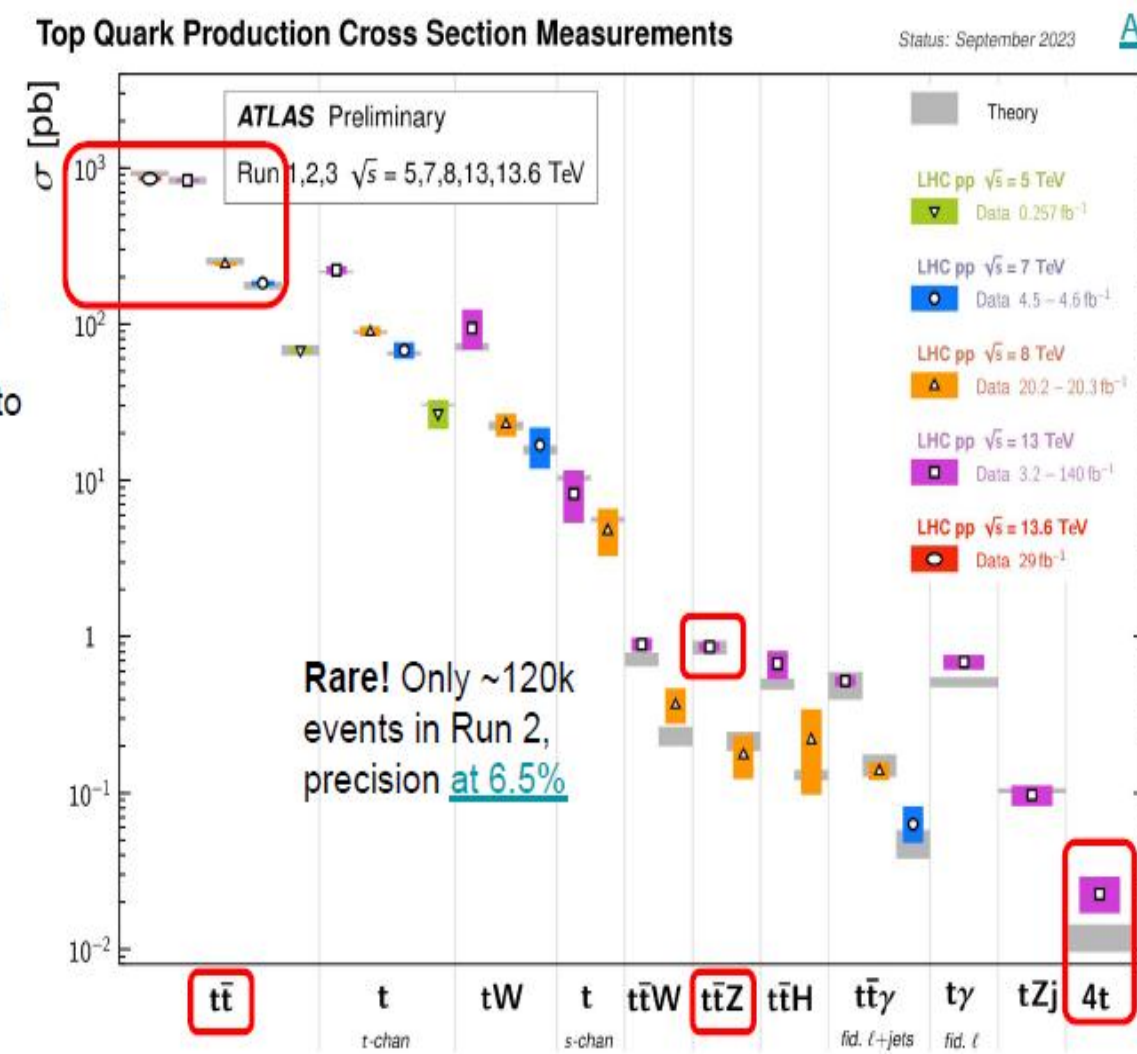
Full hadronic topology:

Largest stats (50%) but larger multi-jet background and large combinatorial.

Range of top-quark physics

Abundant production!

O(100M) events in Run 2
Precision down to [1.8%]



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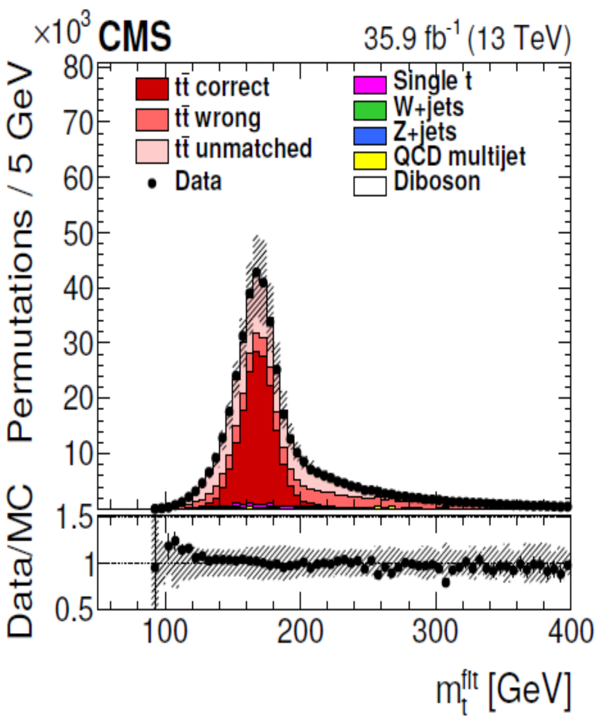
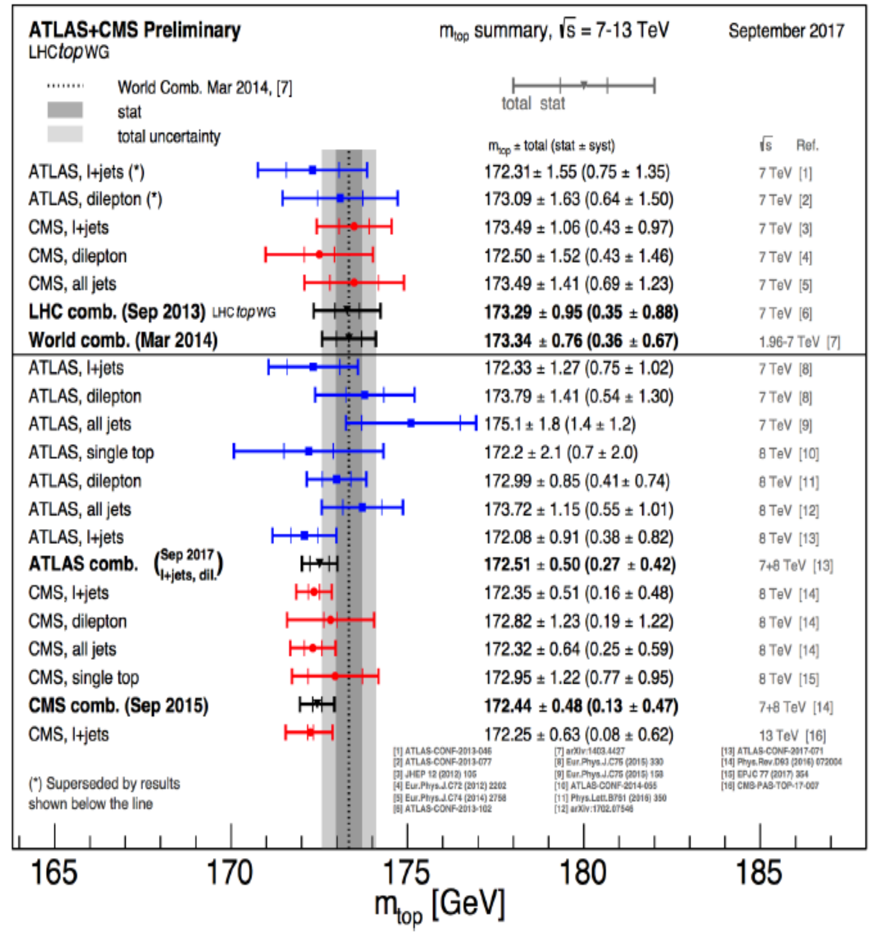
Extremely challenging!
Only ~3k events, precision ~25%

Top quark mass measurement (2017)

Direct measurements made using template fit to the reconstructed mass spectrum.



$$172.34 \pm 0.20\,(\mathrm{stat} + \mathrm{JSF}) \pm 0.76\,(\mathrm{syst})\ \mathrm{GeV}$$



Top quark mass measurement (2026)

172.52 ± 0.14 (stat) ± 0.30 (syst) GeV

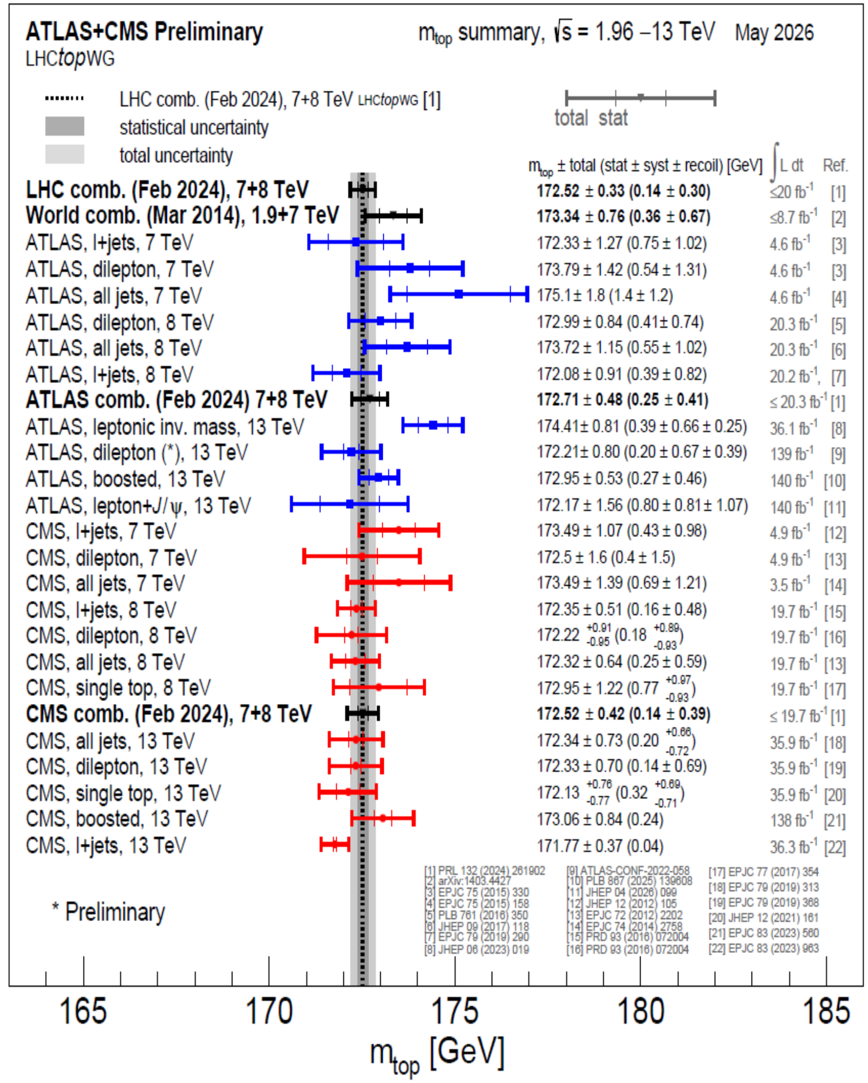
Total uncertainty of 0.33 GeV (**< 2 permil!**)

31% improvement on most precise input

Excellent compatibility: χ^2=7.5, p(χ^2)=0.91

Most precise m_{top} measurement to date

Consistency checked with per-channel combinations



Electroweak measurements (2023)