Standard Model Measurements at the Energy Frontier

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About myself

- Zhijun Liang
  - Experimental physicist at IHEP CAS
  - 2006-2010: PhD thesis in ATLAS experimental at LHC
  - 2012-2013: Convener for electroweak Physics in ATLAS
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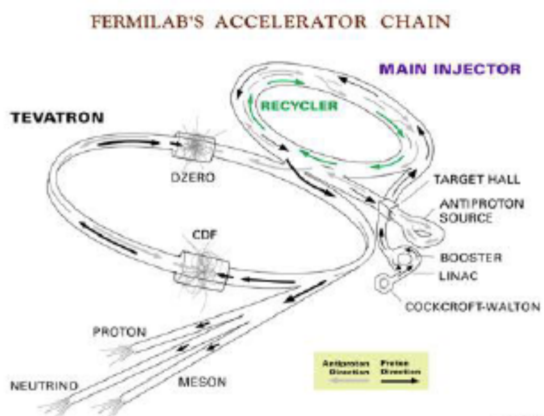
Outline

- How a SM measurement is performed.
- SM Measurement
  - QCD
  - Electroweak
  - Top

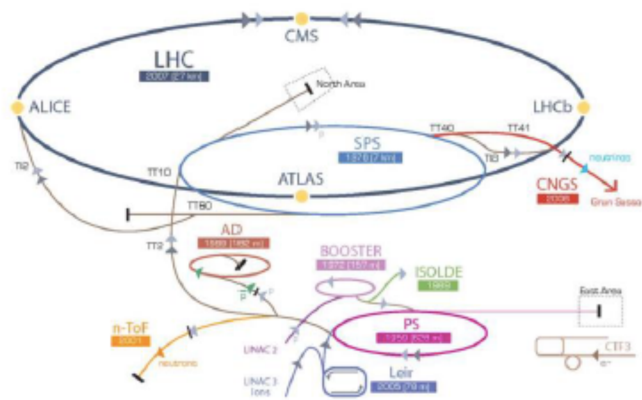
TeV Hadron Colliders

Tevatron @ Fermilab



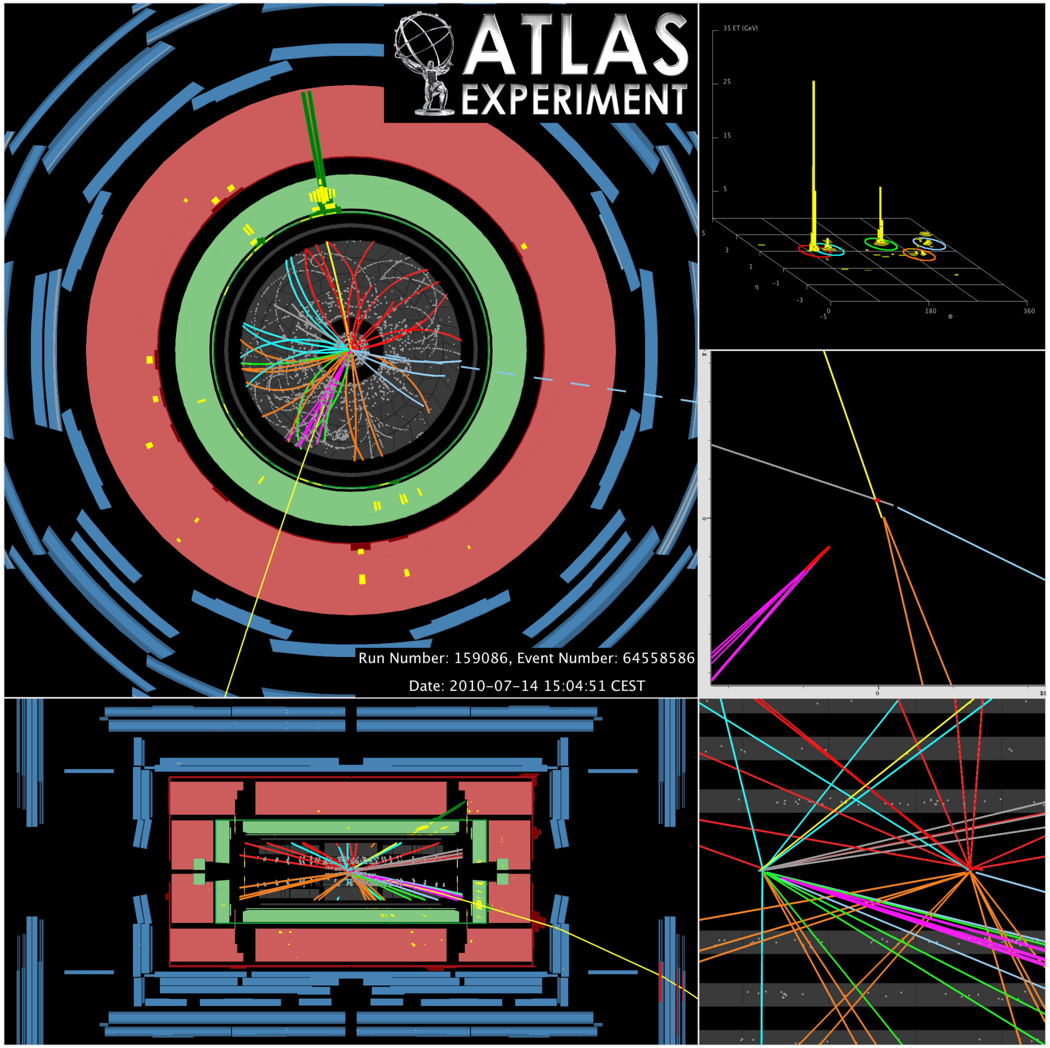
A ppbar collider
√s = 1.96 TeV
(shut down in Sep. 2011)

Large Hadron Collider (LHC) @ CERN



A pp collider
√s = 7-8 TeV
(ramped up to 13 TeV this year)

Proton interactions: complex events



More than 1000 particles!

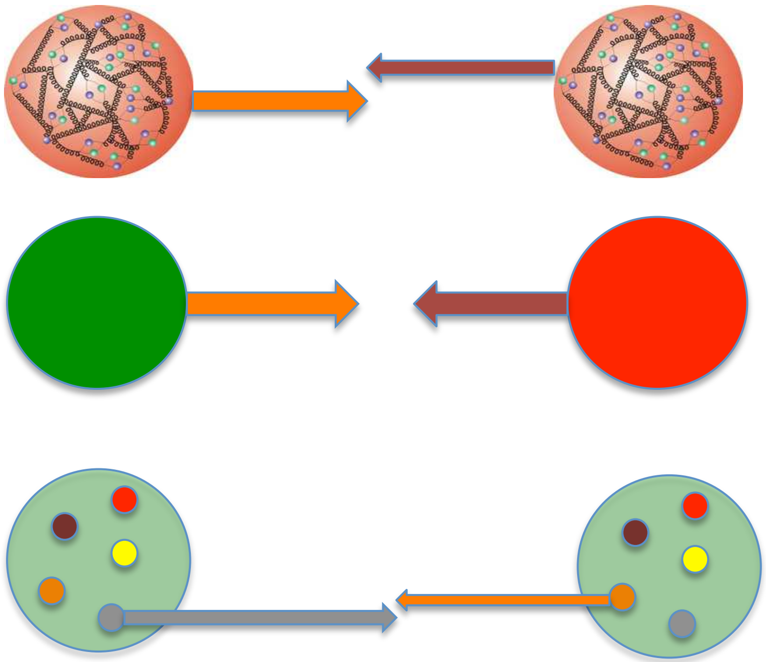
Only fraction interesting

Experimenters task:
- Identify those
- Classify events

Reveals picture of space - time of 10^{-19} m

Are partons composite?

Rutherford all over again ….



pp – interaction @ Q ≈ 0.1 GeV

qq – interaction @ Q ≈ 10 GeV

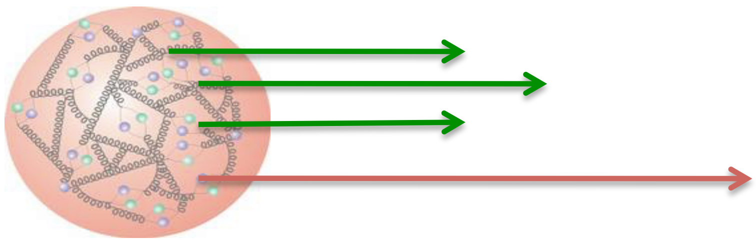
interaction of subconstituents ?
@ Q ≈ 1000 GeV ?

$$\mathcal{L}_{CI} = \frac{g^2}{\mathbf{\Lambda^2}} \eta_{LL} (\bar{\psi}_L \gamma^\mu \psi_L)(\bar{\psi}_L \gamma_\mu \psi_L) + (RR, LR)$$

$$\sigma_{ff} = \mid \mathcal{M}_{SM} \mid^2 + \mathbf{2} \frac{\mathbf{1}}{\mathbf{\Lambda^2}} \mathcal{RE}(\mathcal{M}_{\mathbf{SM}} \cdot \mathcal{M}_{\mathbf{CI}}) + \frac{1}{\Lambda^4} \mid \mathcal{M}_{CI} \mid^2$$

Add-on 1: Parton distribution function

Parton energy: only fraction x of proton energy
Statistical distribution: parton distribution function (pdf) F_f



$$\mathbf{x = E_{parton}/E_{proton}} \quad \text{for } \mathbf{E \to \infty}$$

$$\Rightarrow \mathbf{M_{scatter}} = \sqrt{\mathbf{x_A \cdot x_B}} \cdot \mathbf{E_{pp}}$$

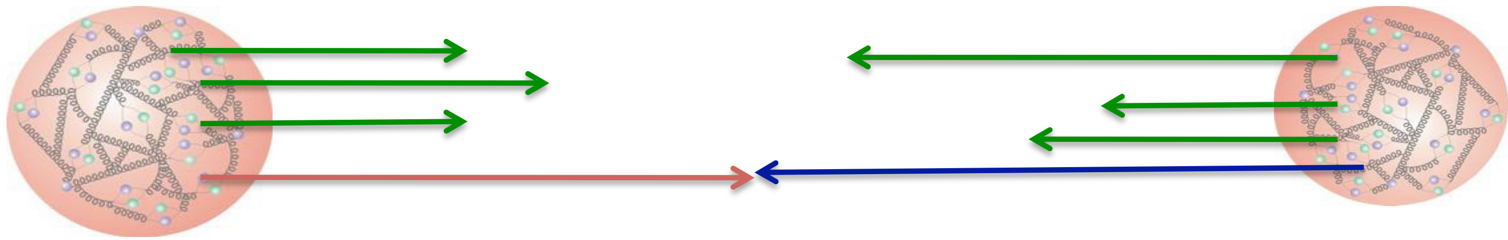
$F_f(x)$ depends on
- kind of parton f
- Q^2

For X-section: all combinations (x_1, x_2) ➔ M contribute
Example:
M = 0.3 TeV from (x_1=0.2, x_2=0.2),(0.25, 0.16), (0.4, 0.1), ...

$$\int_0^1 \mathrm{dx_1} \int_0^1 \mathrm{dx_2} \sum_f \mathbf{F_f(x_1) F_{\bar{f}}(x_2)} \sigma(\mathbf{q_1(x_1P) + q_2(x_2P) \to t\bar{t}})$$

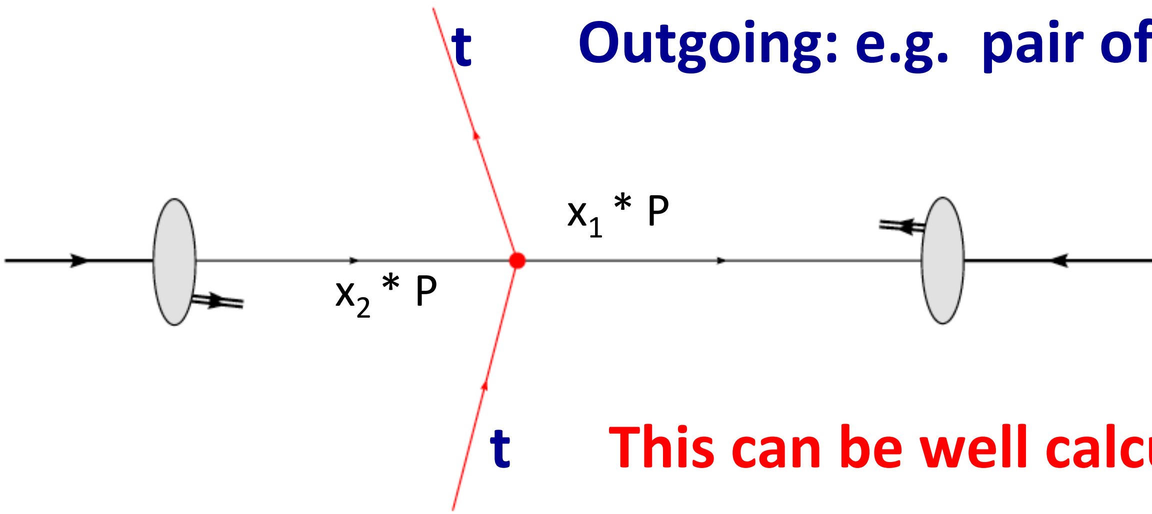
hard scatter: two in → two out
e.g. gluon-gluon → top-antitop

From Peter Mättig



Incoming: gluons of momenta $p_{1,}\ p_2$

Outgoing: e.g. pair of top / anti-top quarks



This can be well calculated

$$\sigma(g_1(p_1) + g_2(p_2) \to t\bar{t})$$

Standard Model tests

From Peter Mättig

$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

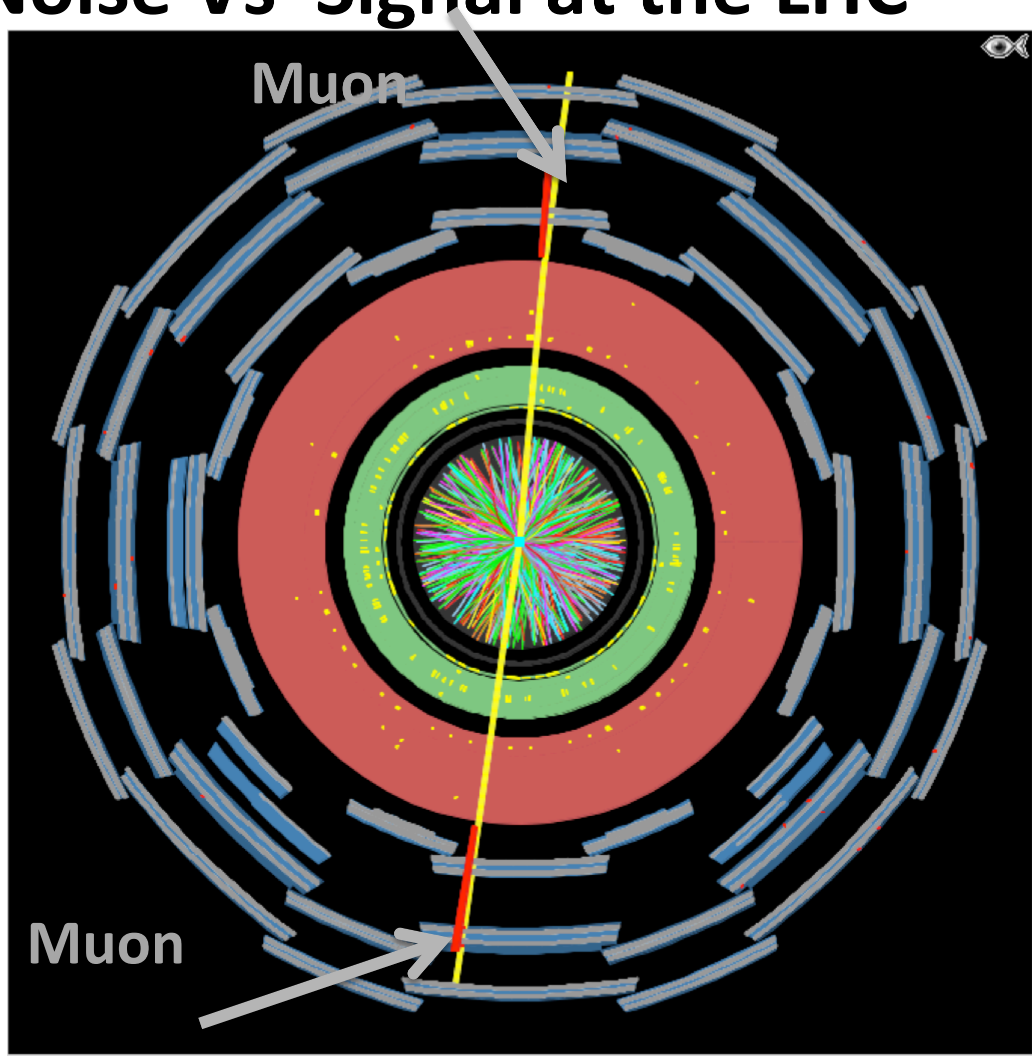
$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1}) \mathbf{F_{\bar{f}}}(\mathbf{x_2}) \sigma(\mathbf{q_1}(\mathbf{x_1 P}) + \mathbf{q_2}(\mathbf{x_2 P}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathbf{Rest})$$

pdfs **Hard scatter** **Underlying event**

Three contributions only mildly related ('factorisation') but lead to higher uncertainties

underlying event Vs hard process

Noise Vs Signal at the LHC



Noise: homogeneous distribution of low momentum hadrons: ‘underlying event’

Signal hard process: two high energetic muons

Understand and ‘subtract’ noise

Energy is not everything

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

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

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

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

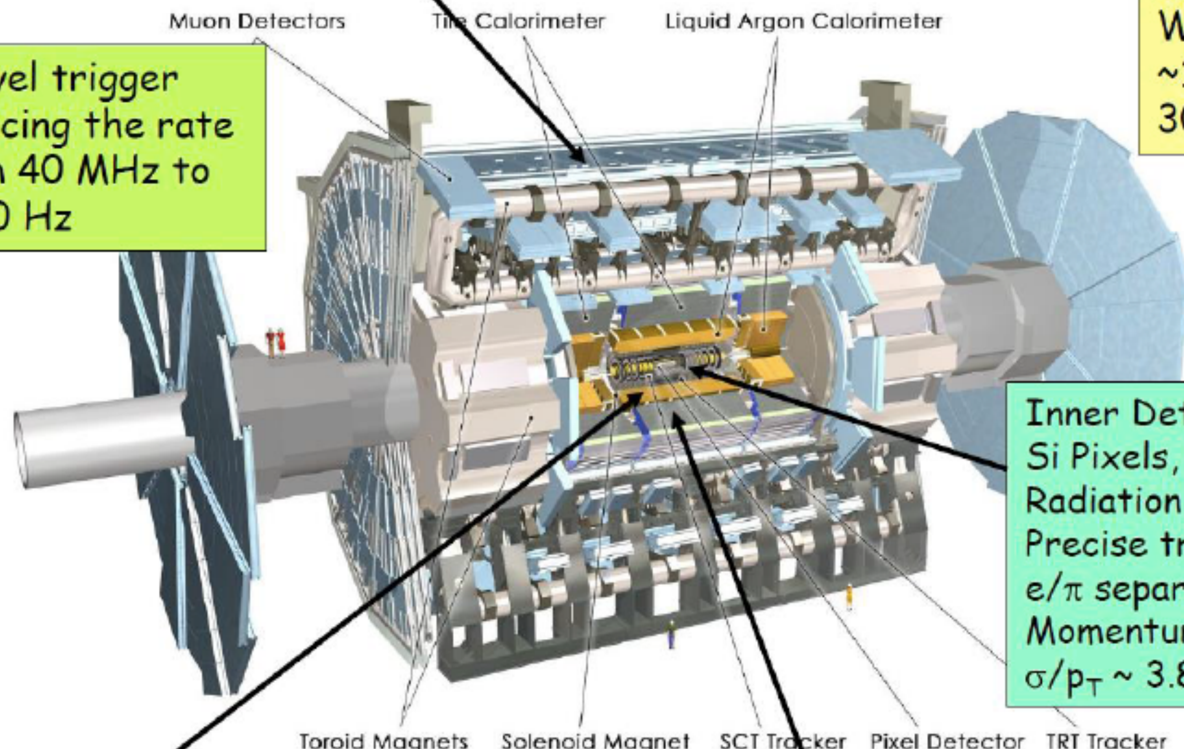
→ *1-day data taking at LHC would take 20 days at Tevatron, letting alone the big energy difference.*

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

ATLAS detector @ LHC

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

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



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

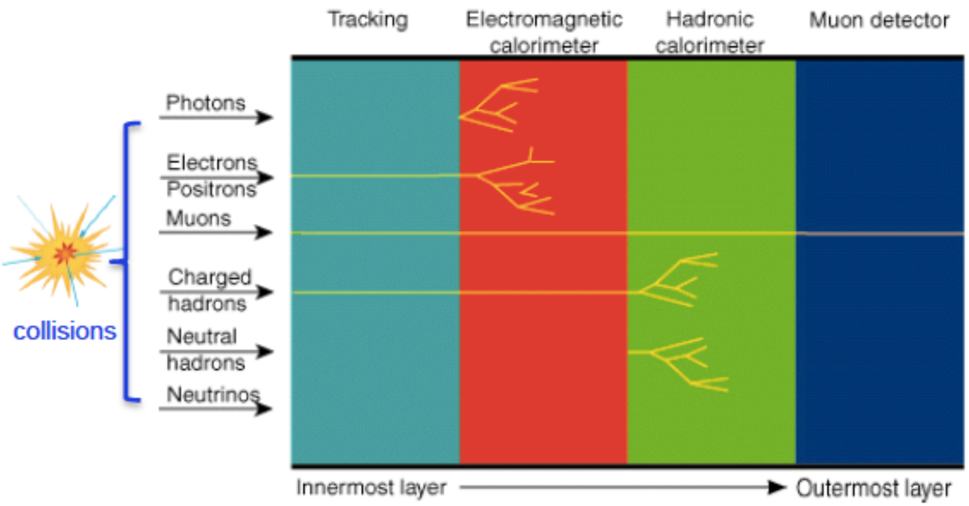
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)

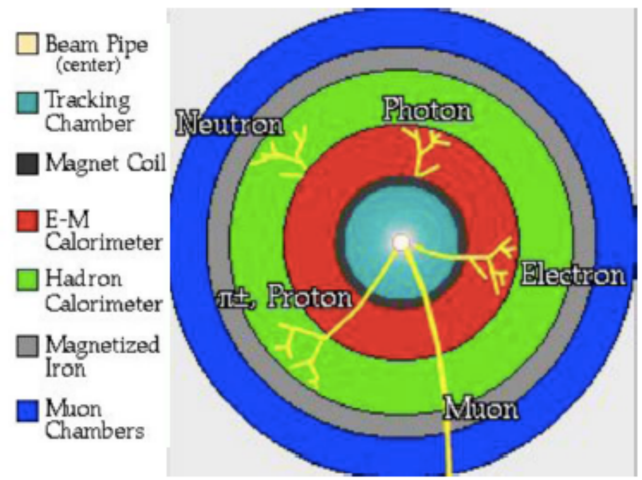
Particle detector

Cameras at high energy experiments

General particle detection principles in modern high energy experiments



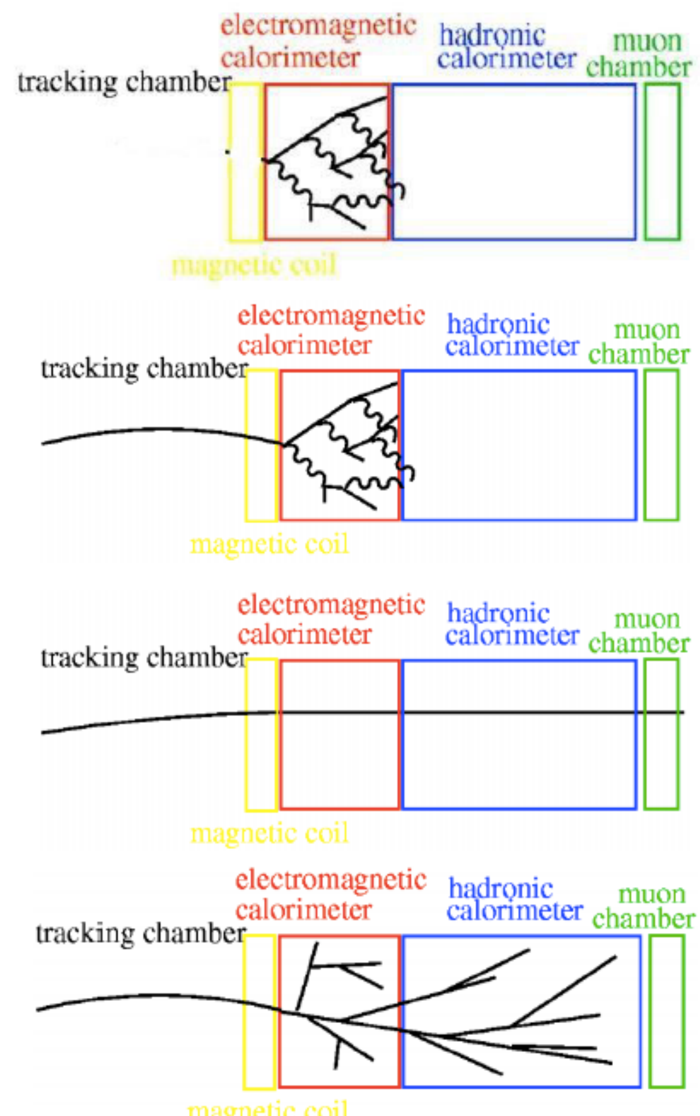
A General purpose detector



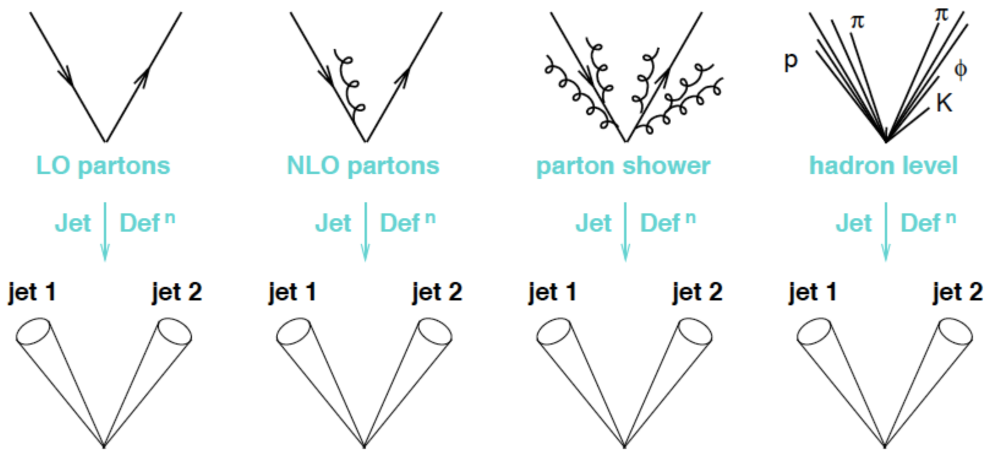
- Exploit distinguishing characteristics of different particles in interactions with matter
  - EM ionization, EM showering, hadronic showering …
- Employ multiple sub-detectors with different detection capabilities in a layer-by-layer structure.
- Achieve eventual detection goal (sensitive to all final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

Particle detector

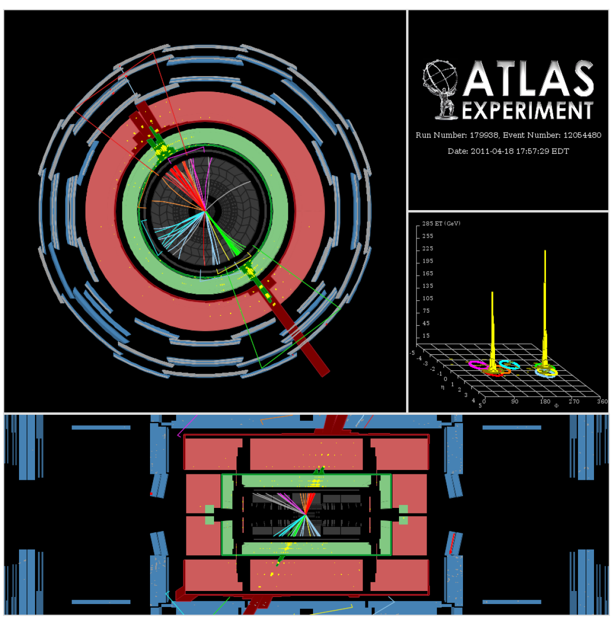
- Photons
  - A compact electromagnetic cluster
  - No track matched
- Electrons
  - A compact electromagnetic cluster
  - Matched to a track
- Muons
  - hits in muon chambers
  - Matched to a track
- Taus
  - Clusters in both electromagnetic and hadronic calorimeters
  - Matched to one or three tracks



How to find a jet ?



Unambiguous connection to underlying partons ➔ Comparison to theory



Anyway ….. how many jets?
'broadness' of jets arbitrary
➔ jet multiplicity depends on choice
➔ defined according to physics

Predefine how broad a jet should be!

Standard jet finding at LHC: ‚Anti – kt'

$$d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

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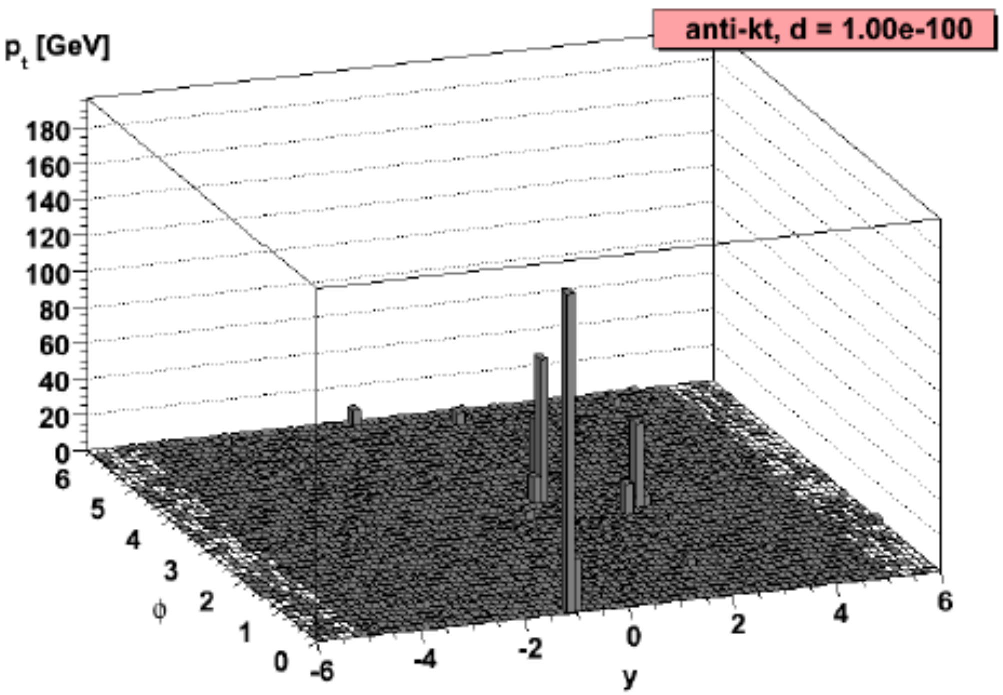

Select hard particles as ‚seeds' for jets: favoured by $\min(p_t^{-2})$

Hard particles separated in space are disctinct seeds: large ΔR_{ij}

‚cut off' given by d_{ij} (steered by R)

Standard jet finding at LHC: ‚Anti – kt‘

$$d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

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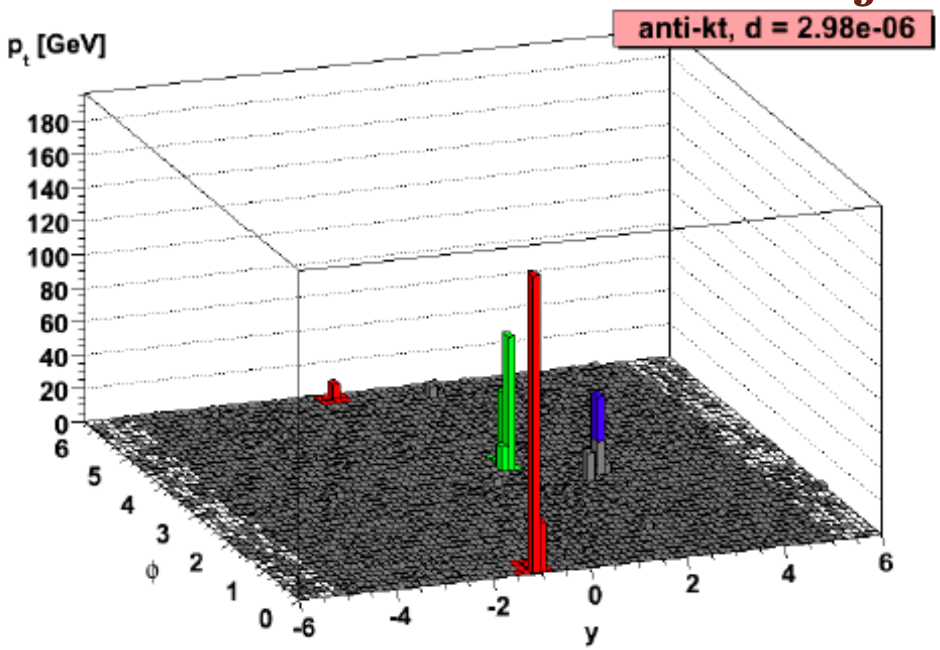


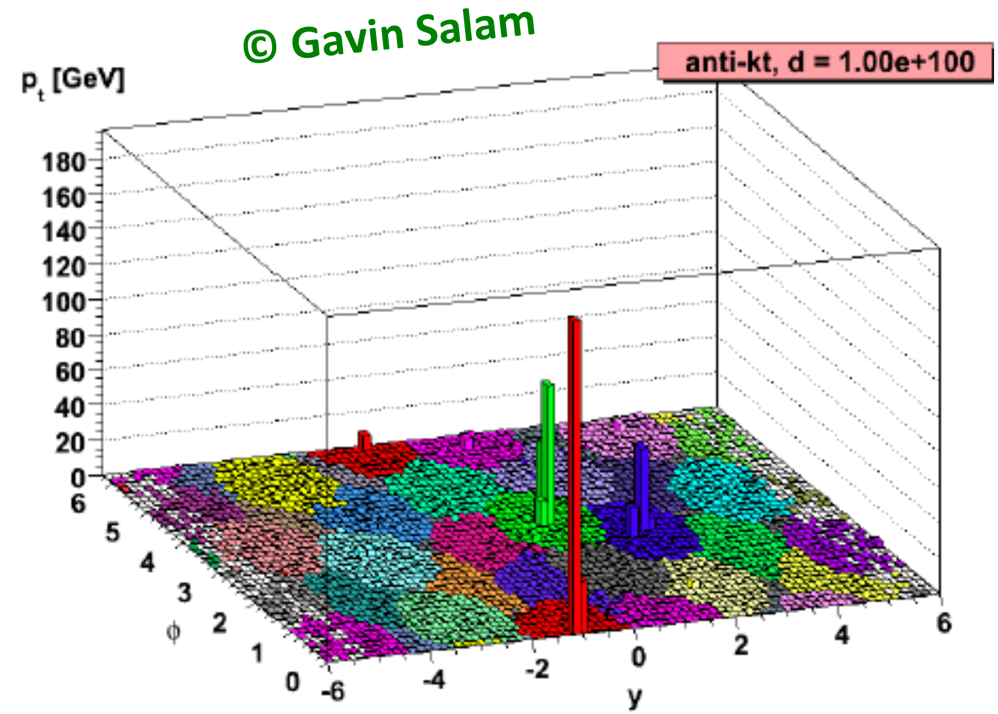
Gradual d_{ij} increase:

Associate close by particles: mostly soft ones in neighbourhood

(if no hard ones close by)

Continue until R_{max} reached

The final jets



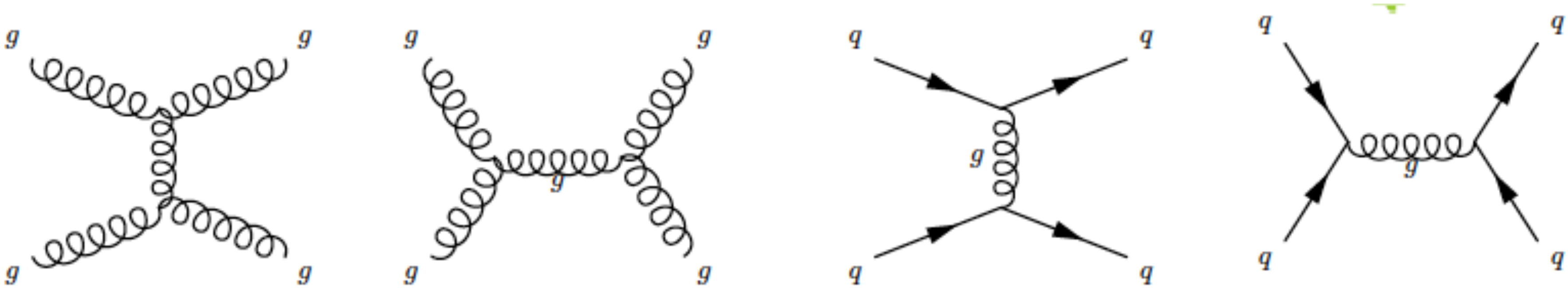
All particles assigned to jets

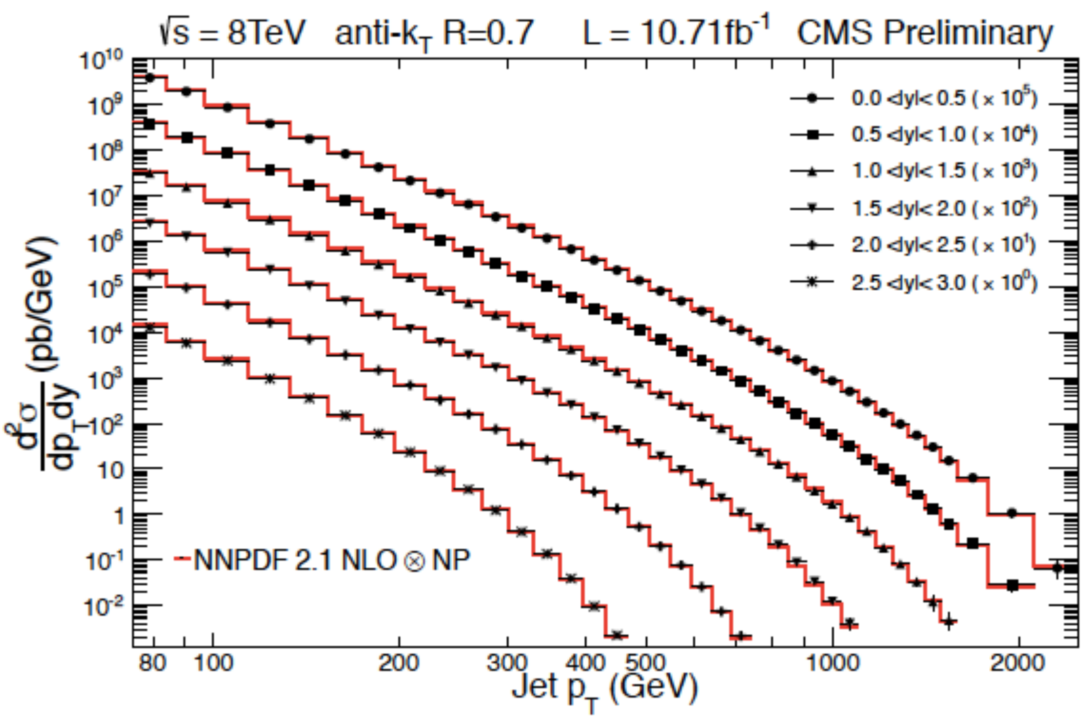
Close to circular in space good for experimental corrections

Note: special treatment of particles close to beam

Typical $\Delta R \approx$ 0.4 – 0.6

Jet cross section





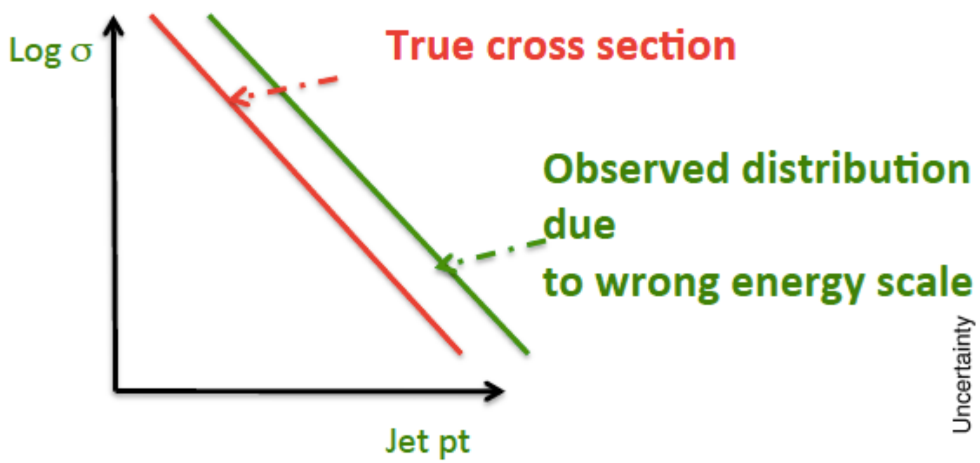
Excellent agreement theory <-> data

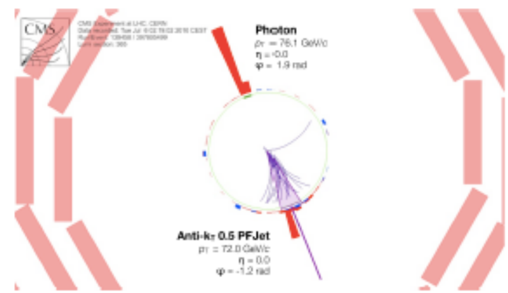
over huge range in phase space: 10 orders of magnitude

Jet p_T up to 2 TeV

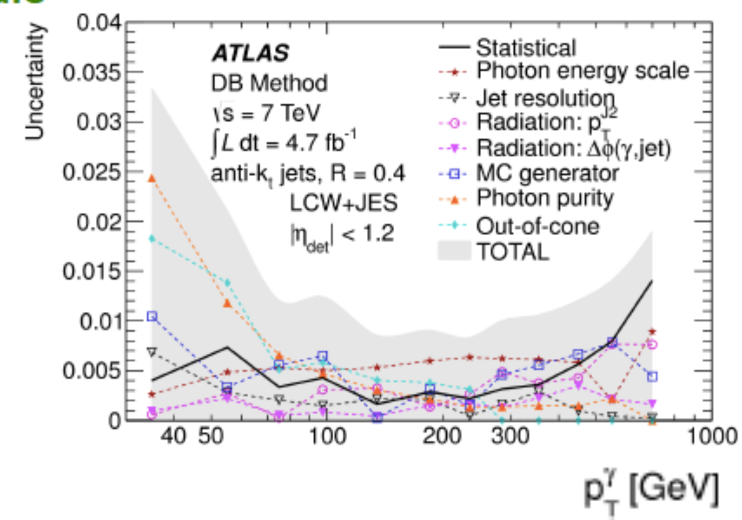
Jet energy scale systematics

- Jet energy determined from calorimeter (+ tracking information)
  How well is scale known? Jet energy scale (JES) uncertainty
  ➔ Effects on X-section magnified by steep slope
  Calibration: γ + jets data with p_T balance



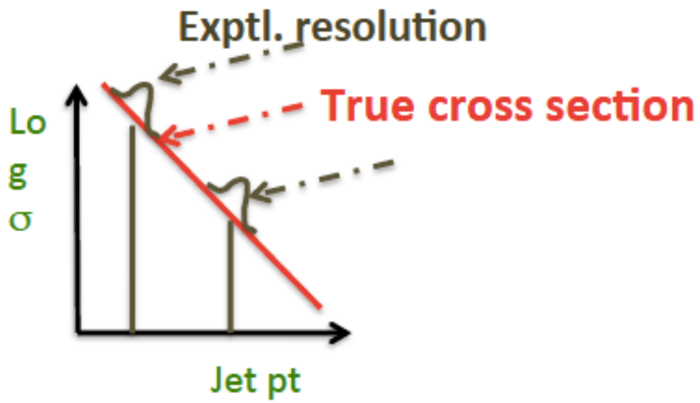


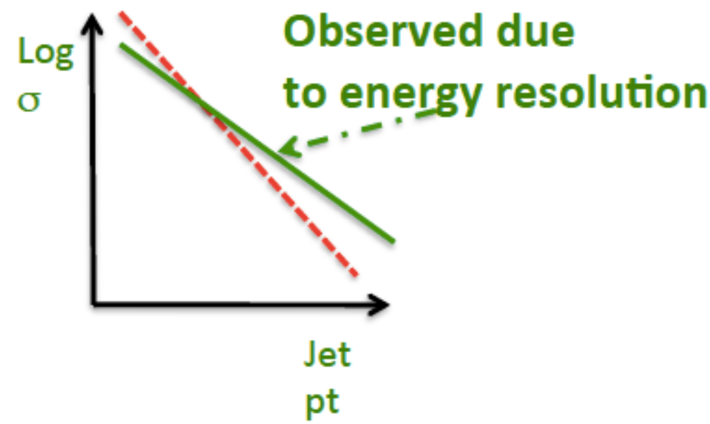
Jet energy scale known to 1 – 3%!
3% at low p_T: jet/photon id
2% at high p_T: statistics

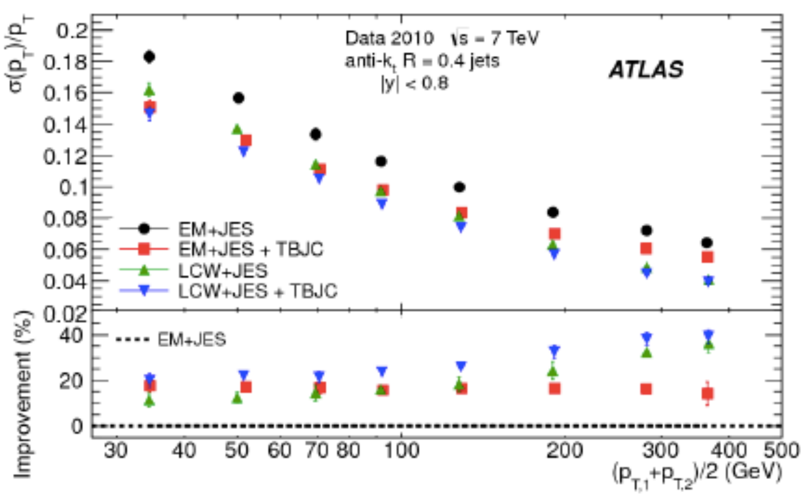


Jet energy resolution systematics

sensitivity of measured cross section to energy resolution



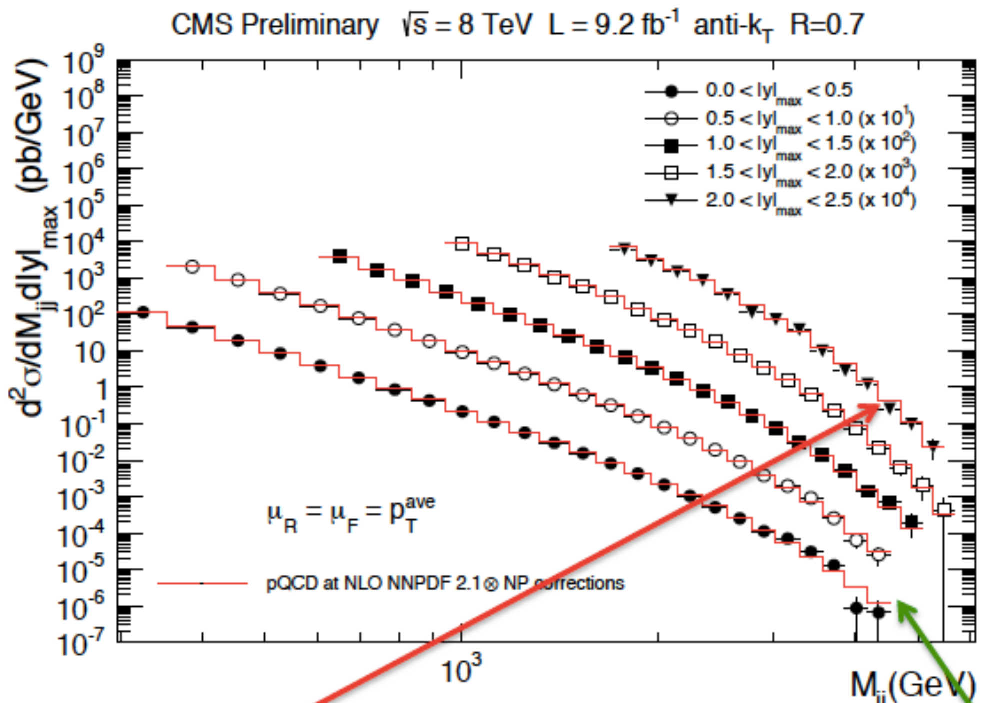




Use p_T balance in 2 – jet events

From Peter Mättig

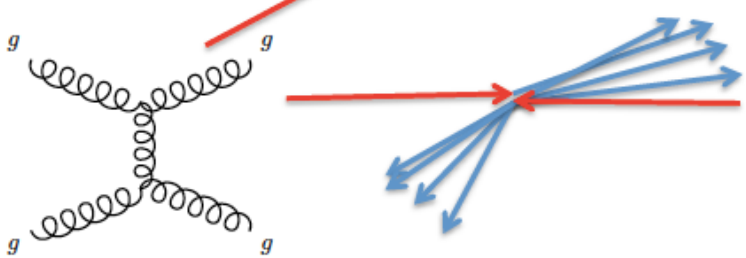
Dijet mass measurement

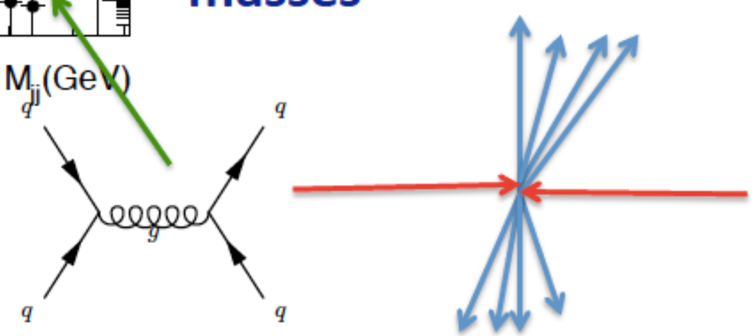


Excellent agreement theory <-> data

Probing masses up to 5 TeV!

Forward jets yield higher masses



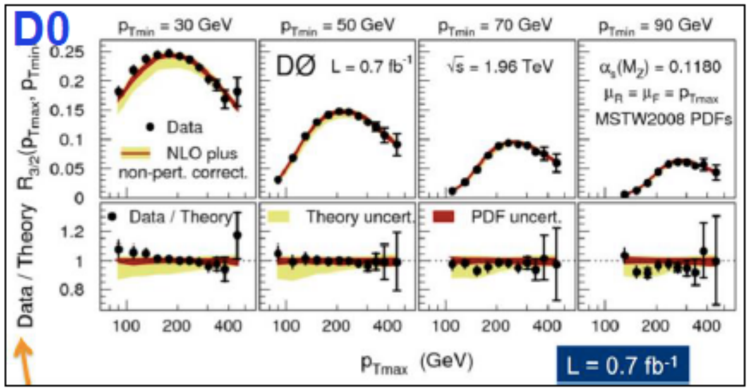


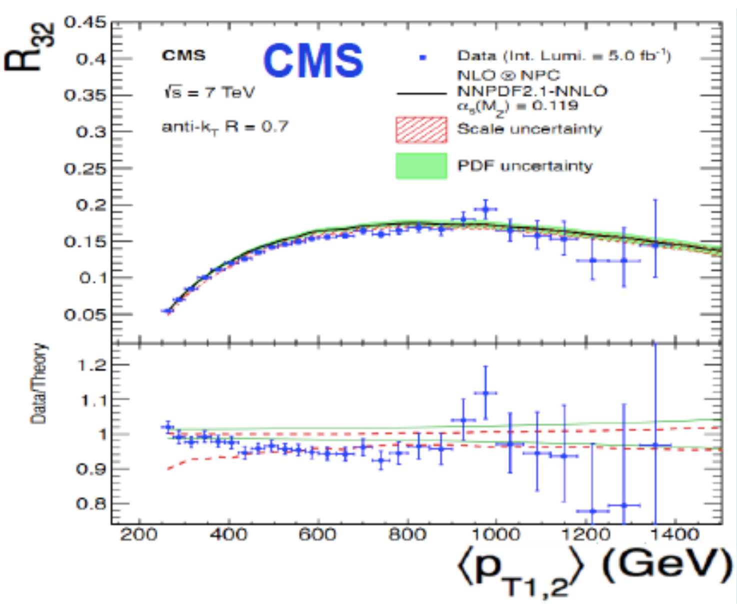
t – channel: fwd direction

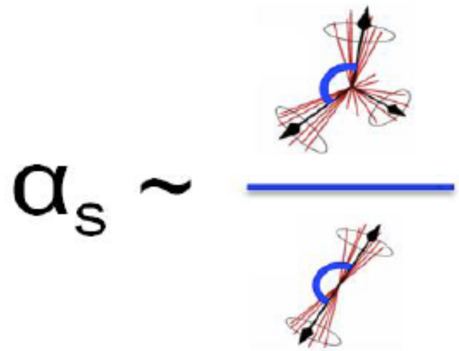
s – channel: centrally

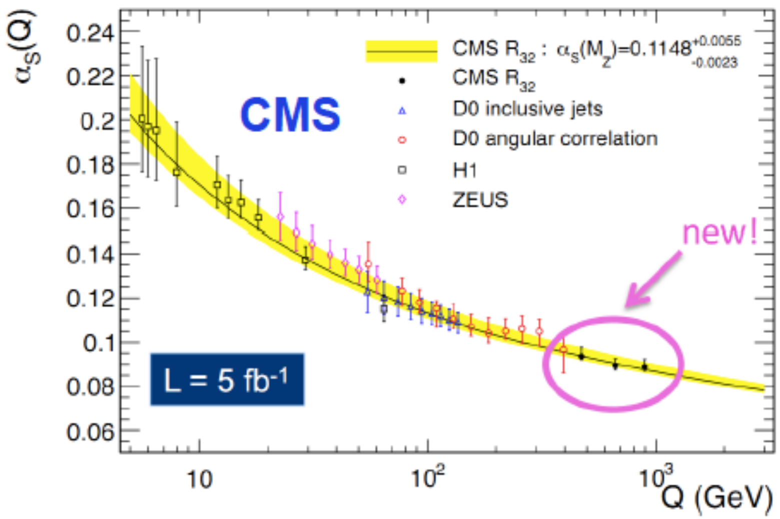
Alphas_S measurement

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







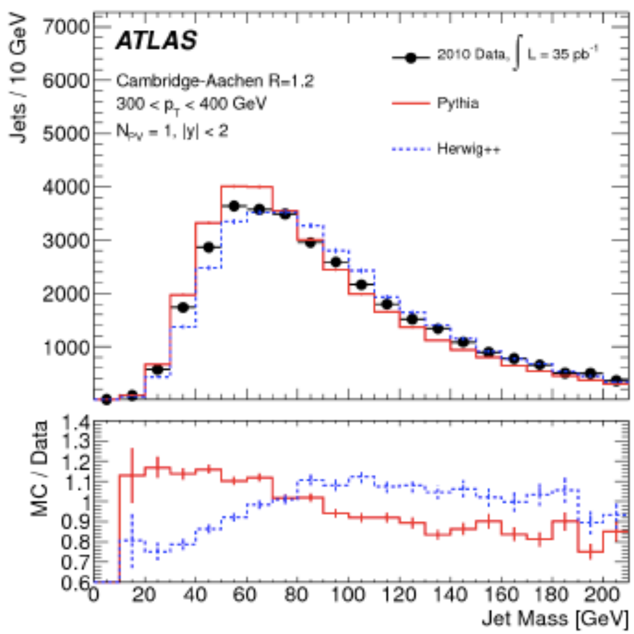


- α_s measurement extended to much higher energy scales
- Test of α_s running

High pT jets : jet substructure

High p_T jets: important to explore TeV scale physics

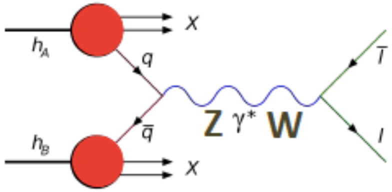
Several partons merge into a single jet



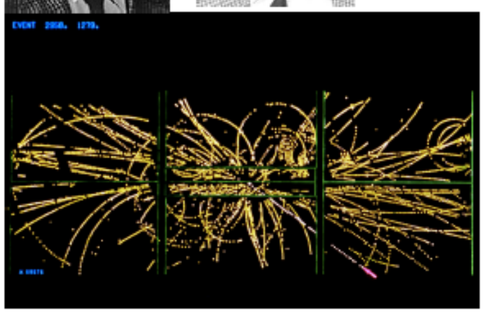
I.e. single jet has higher mass
Measure mass of high p_T jet:

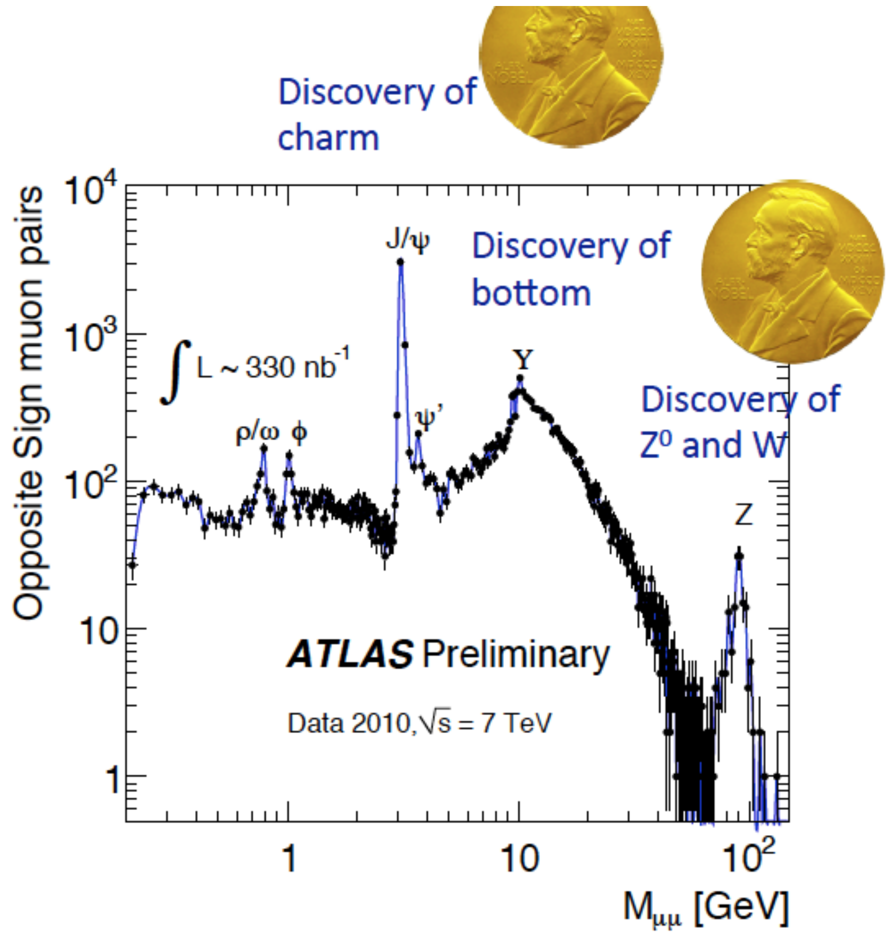
Globally: models agree with expectation
..... But details differ!

W/Z production



W/Z: CERN's first nobel prize
new accelerator technology





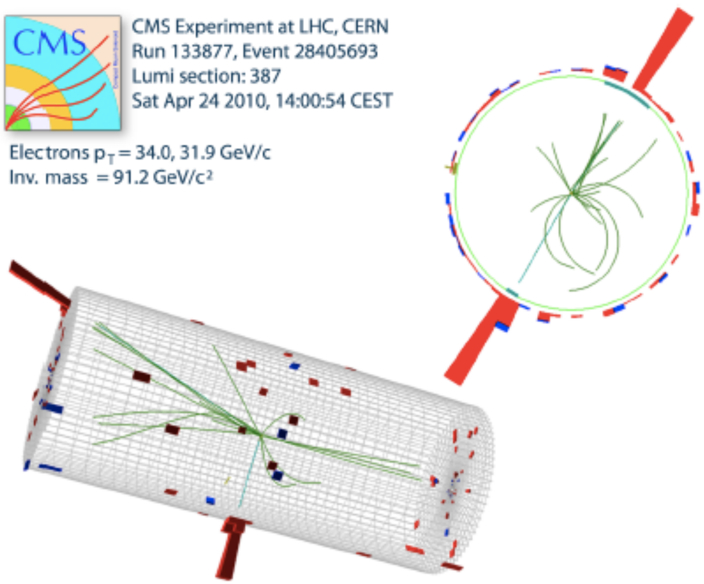
Why study W/Z ?

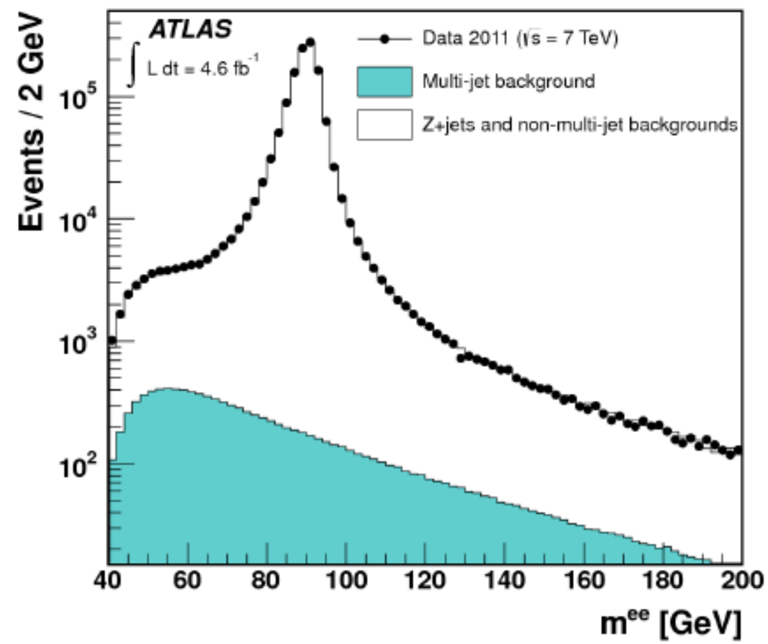
- Good testing ground for QCD
- Test and constraint of PDFs
- Detector calibration
- Simulation tuning and validation
- Important background to searches

Z production

Detectable Z decays e^+e^-, $\mu^+\mu^-$, ($\tau^+\tau^-$)

Just 3% of Z's decay in (each) lepton pair





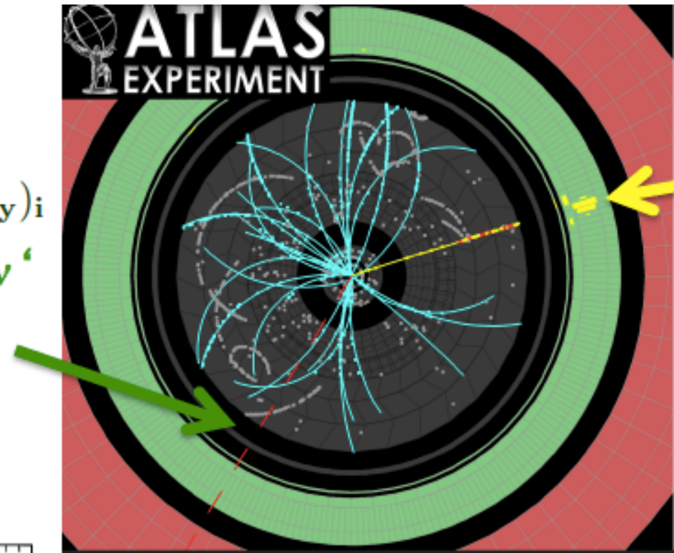
Super – clean signal 1 million Z^0s/1fb^{-1}

A lot of physics! Important calibration tool

W production

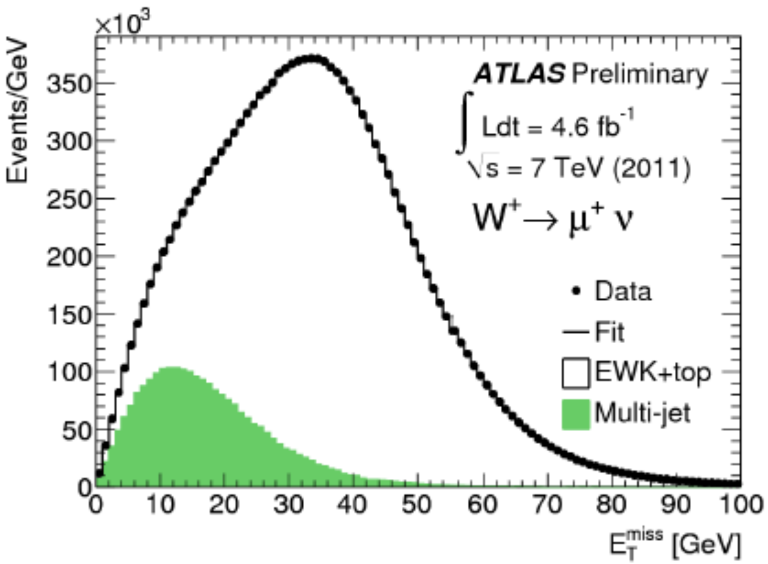
From Peter Mättig

11% decay into lν (each)



$$\mathrm{MET_x} = -\sum(\mathrm{p_x})_i, \quad \mathrm{MET_y} = -\sum(\mathrm{p_y})_i$$

Unbalanced transverse momentum = ‚ν‘



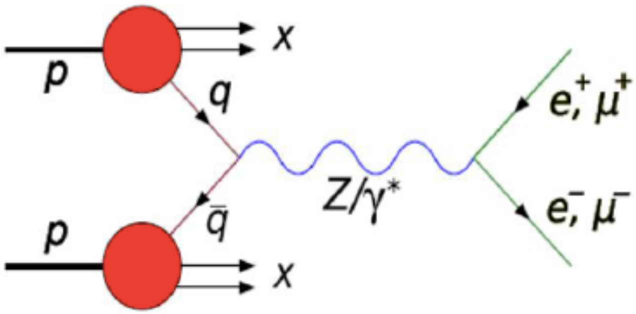
Fairly clean signal, but no mass peak

Cross section ~ 10x higher than for Z^0

Example : Performing a Z->ll measurement

- **What to measure**

pp→Z→ll production cross section

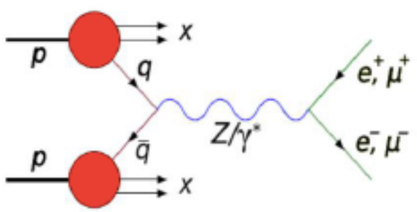


$$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to \ell\ell)$$

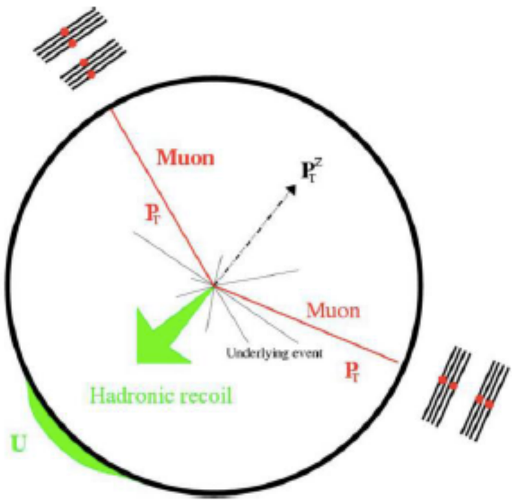
- **How to measure**

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

Event selection and trigger



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



- Event selection criteria are devised accordingly to retain pp→Z→ll signal and reject background as much as possible
  - Triggers: e_E_T_15, mu_p_T_18
  - Lepton ID: “combined” muons, “medium” electron
  - p_T>20 GeV, $|\eta|$<2.4 and $\sum p_T^{ID}/p_T < 0.2$
  - $|m_{ll} - m_Z| < 25$ GeV

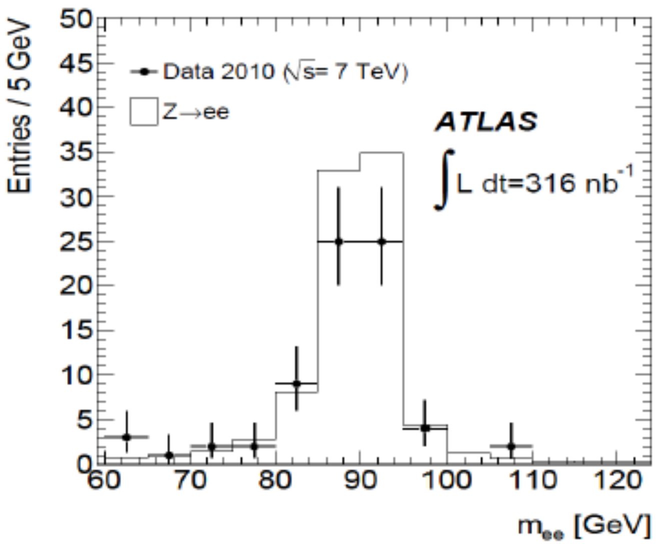
$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times \int L dt}$$

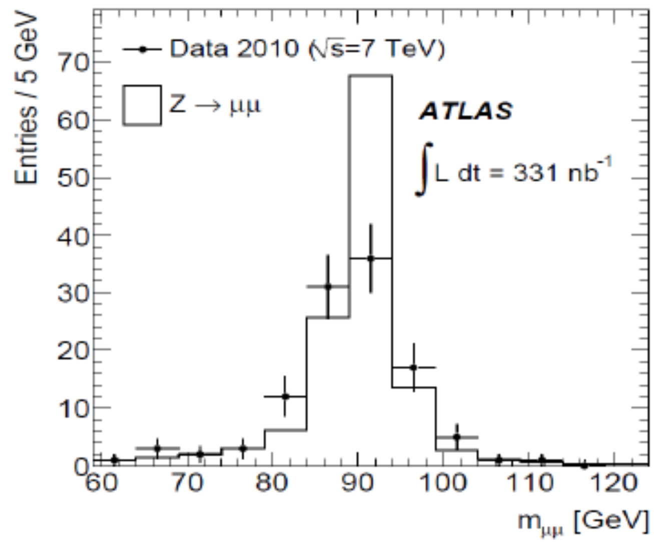
Integrated luminosity, $\int L dt$, depends on the data sample being used

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

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

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





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

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

Acceptance, A, is estimated using simulation

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

N_{all} : total number of simulated events

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

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

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

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

N_{bkg} is estimated using simulation or data driven approaches.

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

Cross Section

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

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

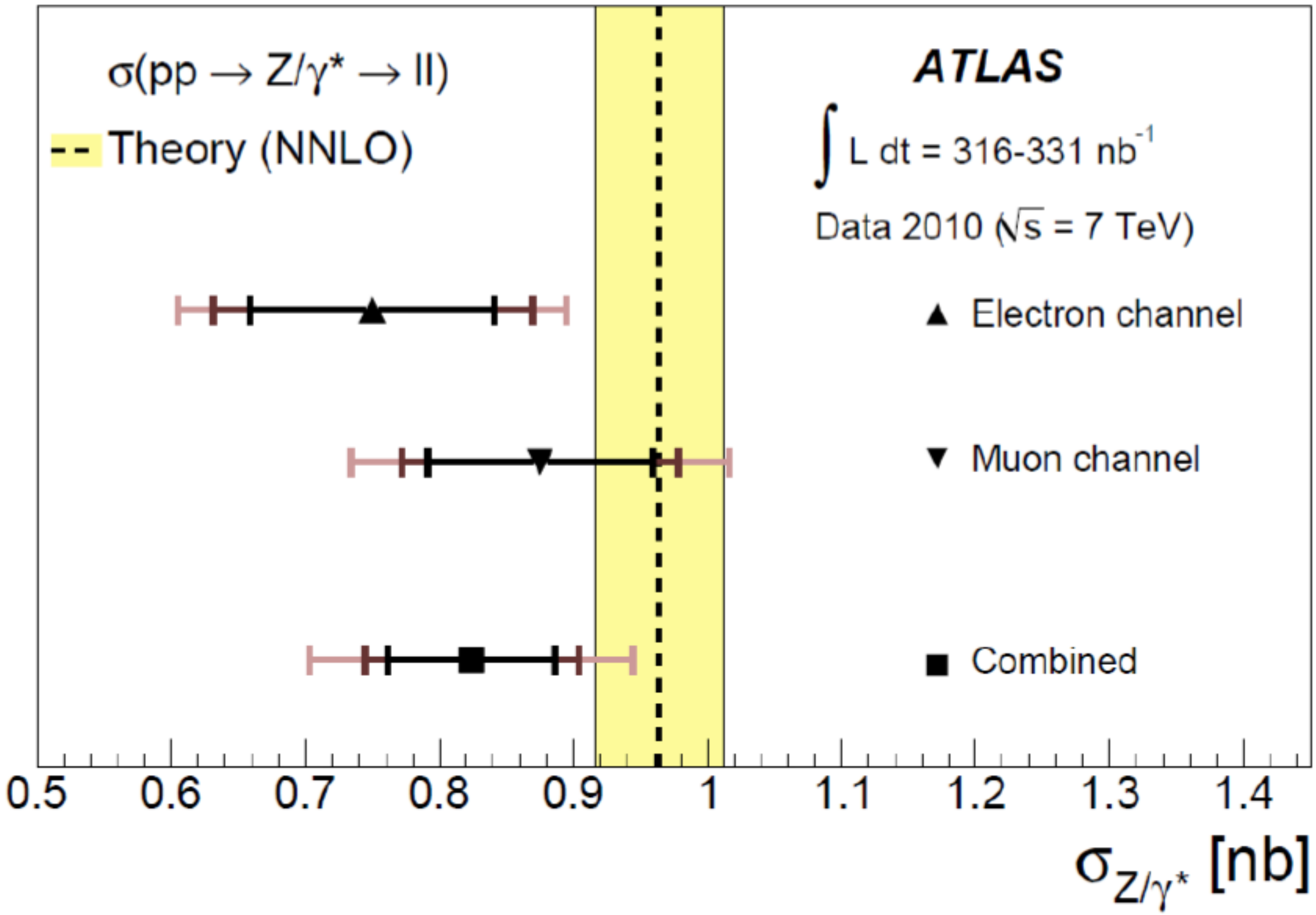
- But is this all? No! Any results without uncertainties make no sense! We need to estimate uncertainties on the measured cross section, particularly, the systematic uncertainties.

Uncertainties

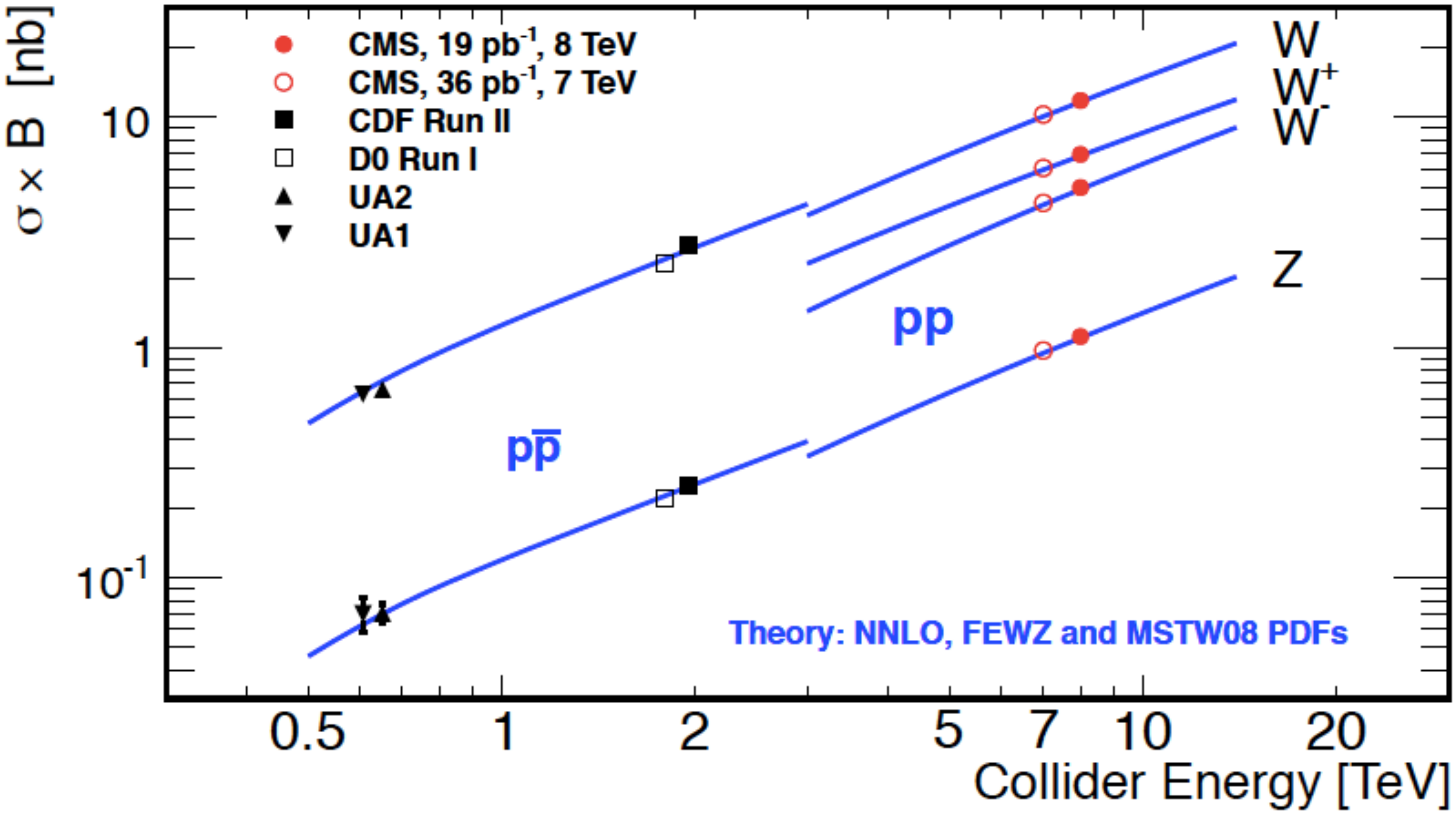
- Statistic uncertainty : δN_{obs}
  - Comes from N_{obs} that follows a Possion distribution. Quite trivial.
- Systematic uncertainties (represent our lack of knowledge, need to be assessed on every aspect of the measurement)
  - Uncertainty on A : δA
  - Uncertainty on L : δL
  - Uncertainty on N_{bkg}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

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

Final Results



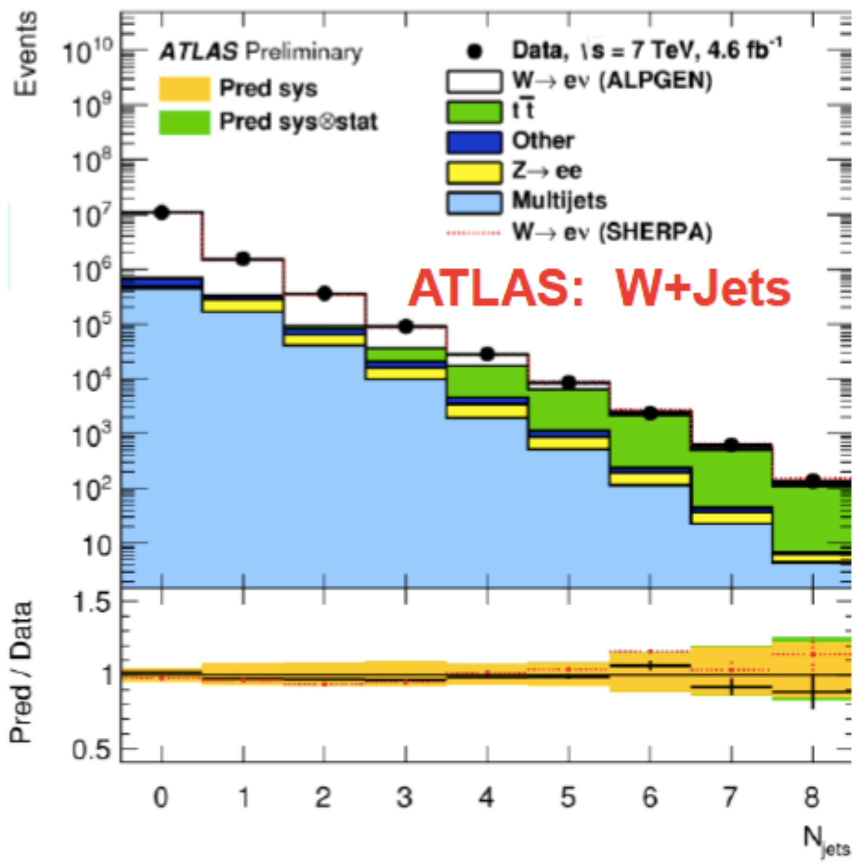
W/Z cross section

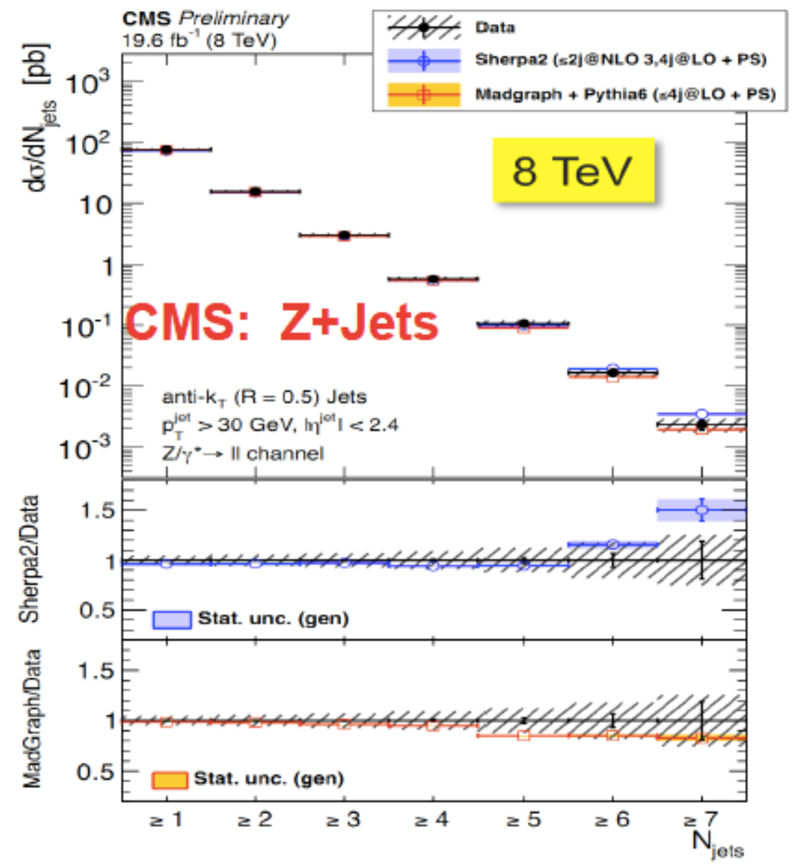


Note different cross sections for W^{+} and W^{-} at LHC

W/Z + jets production

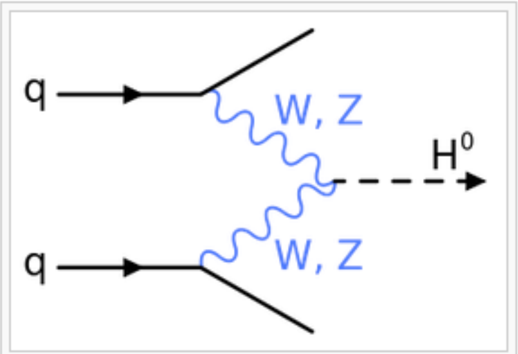
- Can be “neatly” tagged by W/Z.
- Very important testing ground for pQCD



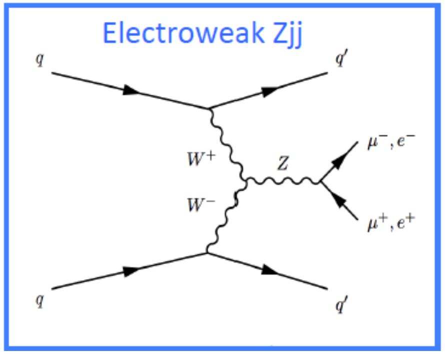


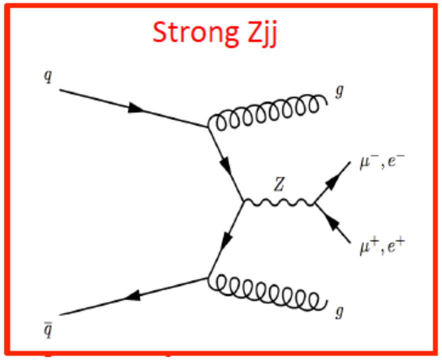
- Good description of data with N_{jets} up to 8, “deeply” testing QCD.
- A lot more derivative measurements performed: pT(j), $\Delta\phi$(j,j), Δy(j,j), M(j,j), Wj/Zj ratio, (n+1)jets/njets ratio …

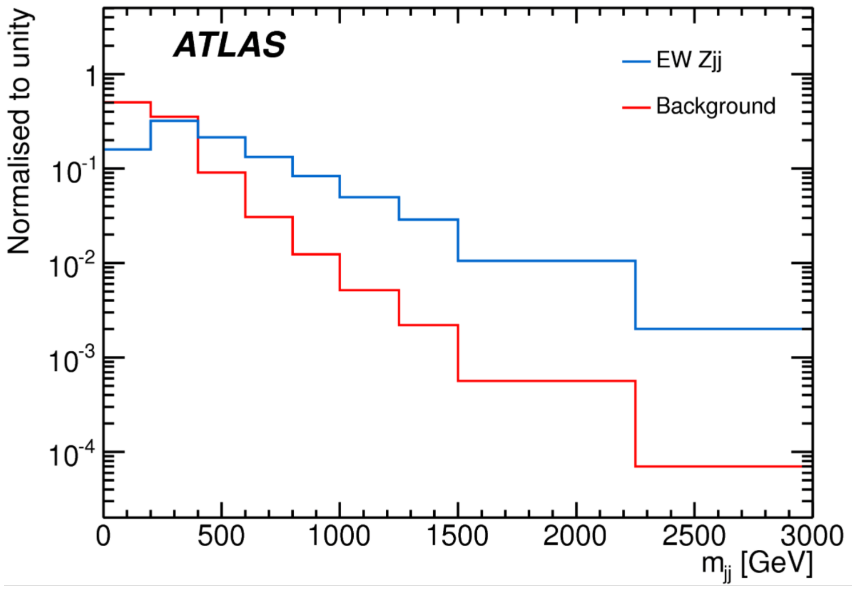
VBF Z



- Two main Higgs production mechai
  - Gluon-gluon fusion
  - Vector boson fusion (VBF)
  - Important to confirm VBF production mechanism in VBF Z+2jets channel







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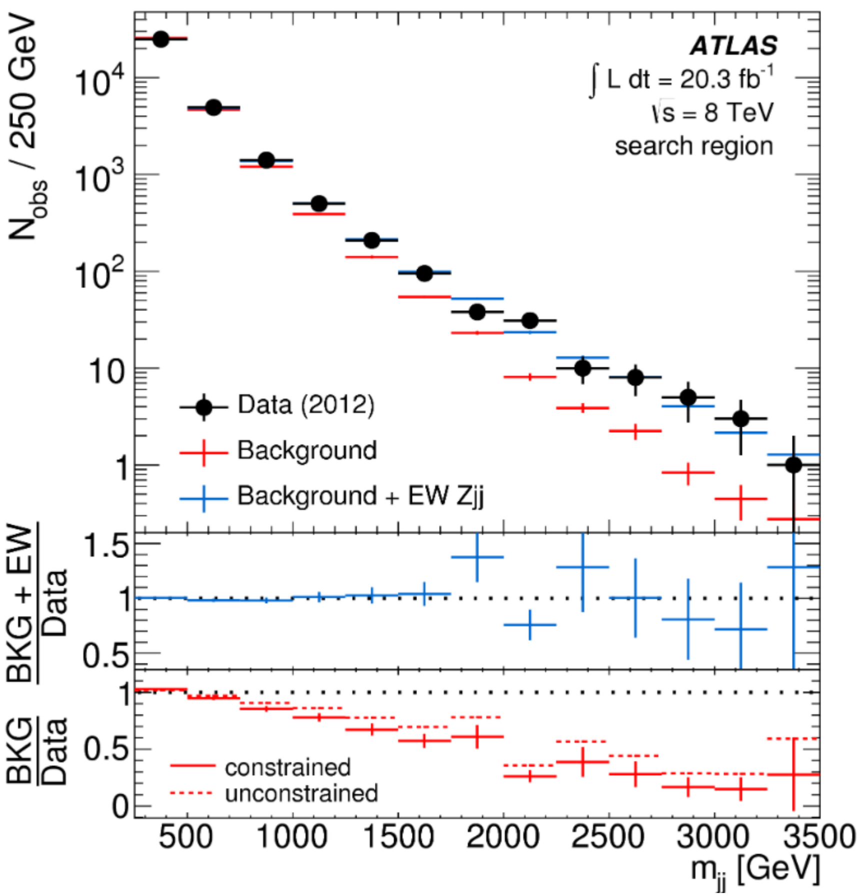
VBF Z (ATLAS)

Object selections:
- two electron/muon
- two high-p_T forward jets

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

Background-only hypothesis
Rejected at greater than
5σ significance



	Electron+muon
Data	32186
MC predicted N_{bkg}	$32600 \pm 2600\ ^{+3400}_{-4000}$
MC predicted N_{EW}	$1333 \pm 50 \pm 40$
Fitted N_{bkg}	$30530 \pm 216 \pm 40$
Fitted N_{EW}	$1657 \pm 134 \pm 40$

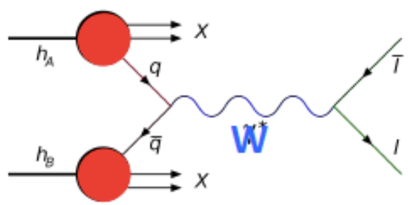
Measured EWK Zjj cross section

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

Powheg Box predictions at
next-to-leading-order (NLO) accuracy
in perturbative QCD

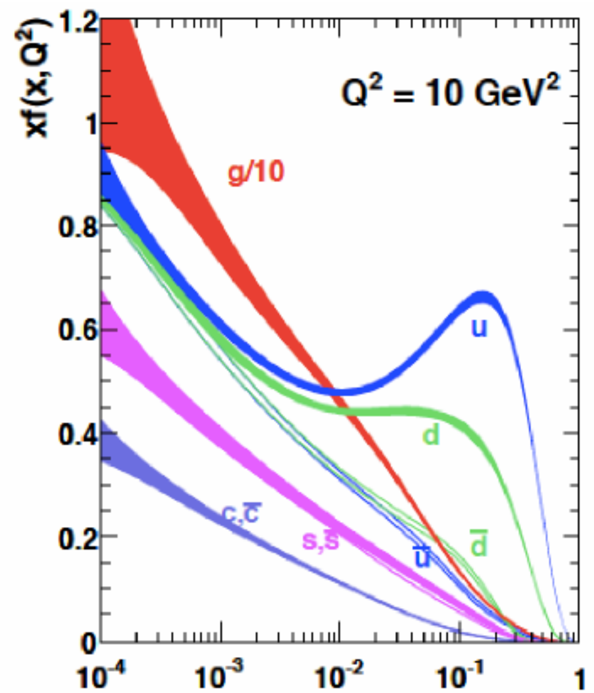
$$46.1 \pm 0.2\,(\mathrm{stat})\ ^{+0.3}_{-0.2}\,(\mathrm{scale}) \pm 0.8\,(\mathrm{PDF}) \pm 0.5\,(\mathrm{model})\ \mathrm{fb},$$

Parton distribution function and W production



Production of W^+, W^- slightly different

$$u\bar{d} \rightarrow W^+ \rightarrow \mu^+\bar{\nu}_\mu$$
$$\bar{u}d \rightarrow W^- \rightarrow \mu^-\nu_\mu$$



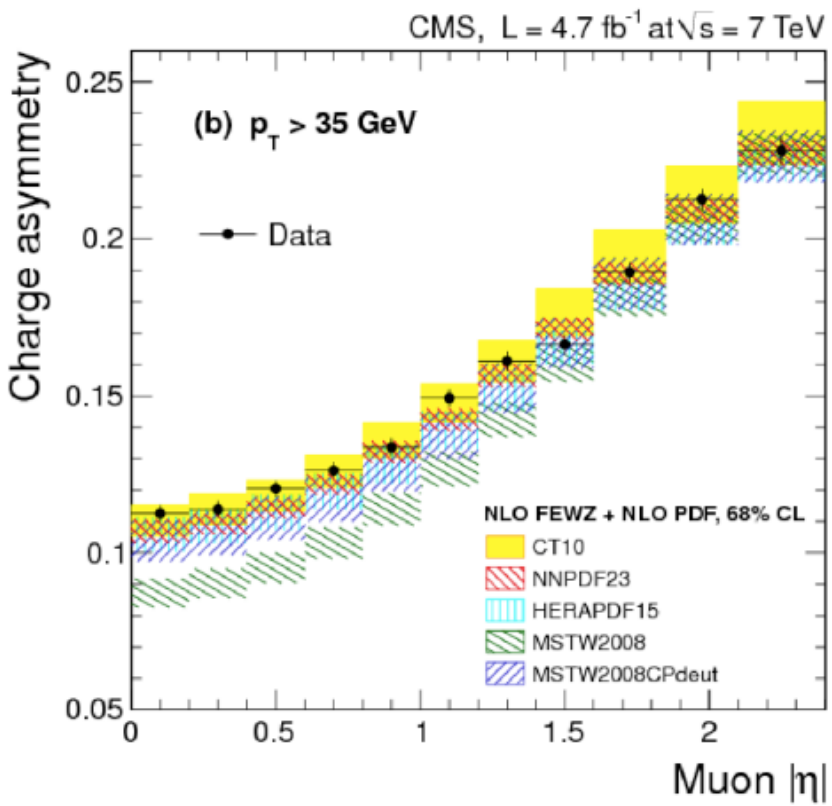
More valence u than d quarks in proton (at high x)

Sensitivity to different quark content
➔ constraint for parton distribution function

W^+ Vs W^- production

From Peter Mättig

$$\mathbf{A}_\mu = \frac{\mathbf{N}_{\mu^+}(|\eta|) - \mathbf{N}_{\mu^-}(|\eta|)}{\mathbf{N}_{\mu^+}(|\eta|) + \mathbf{N}_{\mu^-}(|\eta|)}$$



Valence quarks have high x!
Sea quarks small x
➔ high η W - bosons

Note different predictions by pdfs

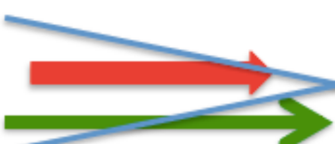
Weak particle looking into mirror

Fundamental (classical) symmetry:
left = right
Laws of physics the same if

$$(x,y,z) \rightarrow (-x,-y,-z)$$

Ok for quantum mechanics:
strong & electromagnetic interactions
But not for weak interactions!
Fermions: only one spin direction

Spin direction
Flight direction

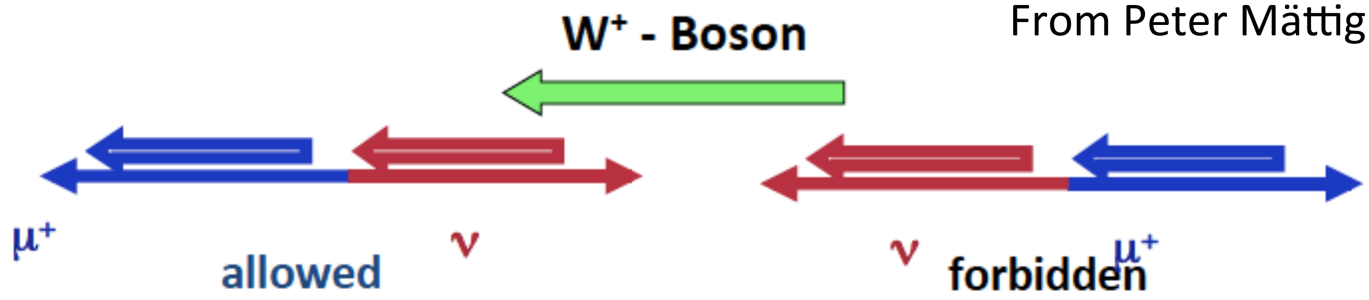


~~Spin direction~~
~~Flight direction~~

Polarisation of W

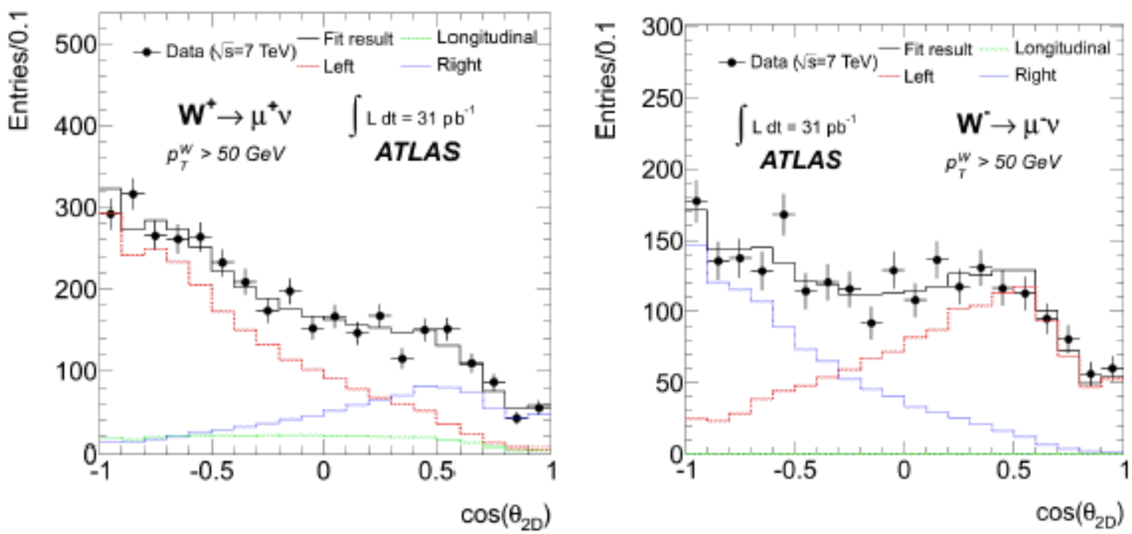
From Peter Mättig

Assume W spin direction



Basic property of weak interaction

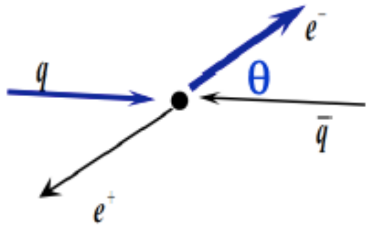
➔ μ⁺ along spin. of W⁺, μ⁻ opposite to spin of W⁻



Flight direction of μ
➔ W polarisation

Polarisation of W an important tool for top, Higgs etc. physics

Z forward and backward asymmetry

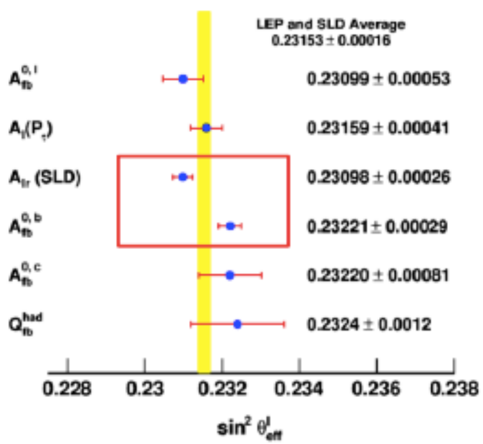


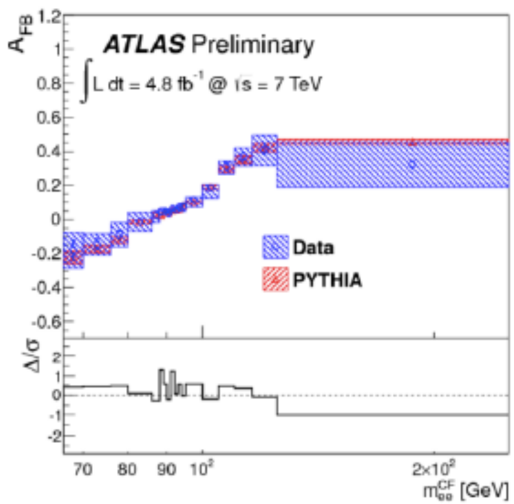
→ **cosθ > 0: forward**
cosθ < 0: backward →

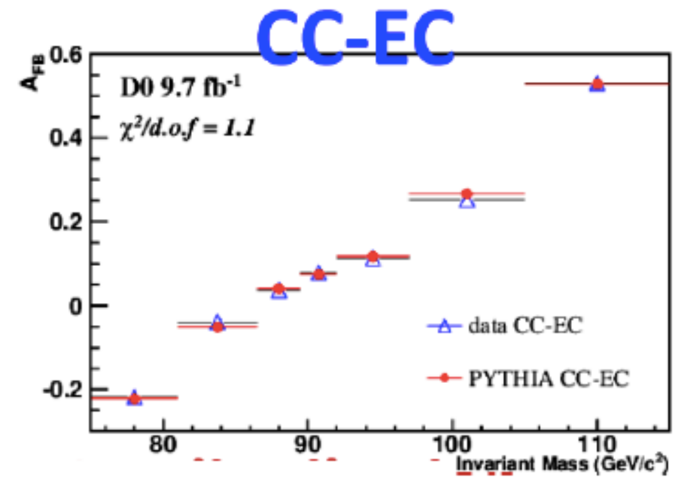
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

→ $\sin^2\theta^{eff}_W$

Why so interesting?





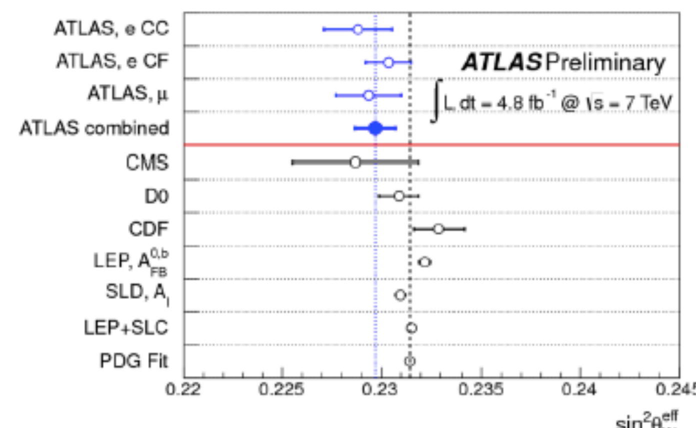


D0: $\sin^2\theta^l_{eff} = 0.23146 \pm 0.00047$

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

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

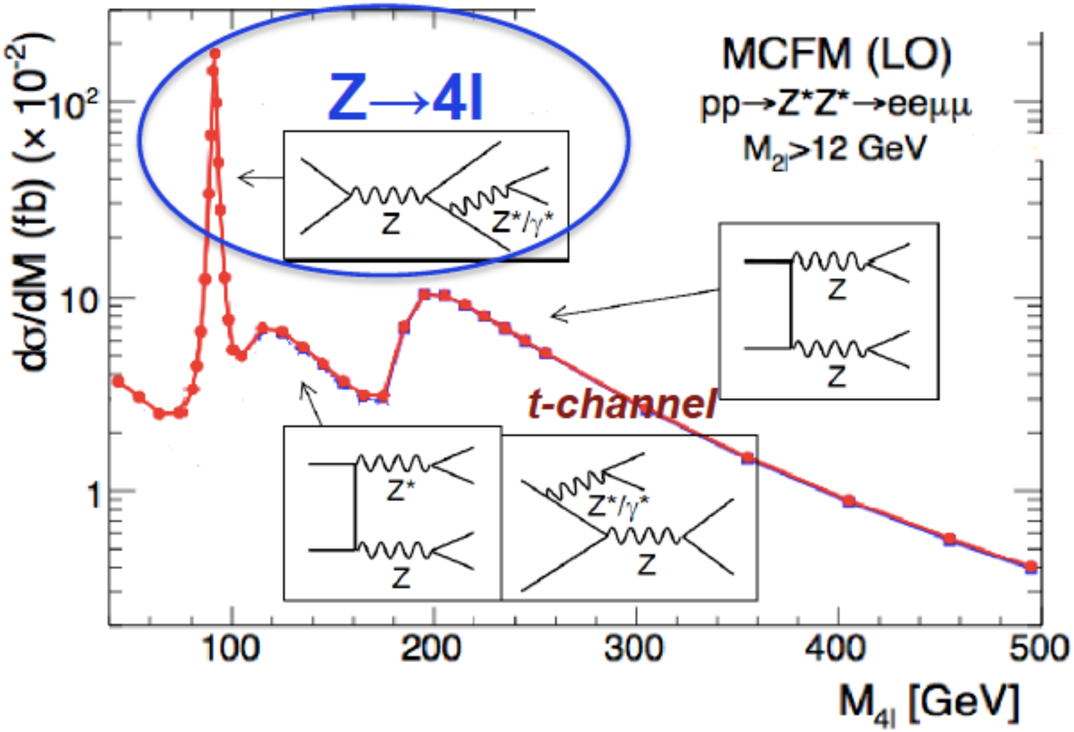
Weak mixing angle, $\sin^2\vartheta^{eff}_W$, a very important electroweak parameter to measure

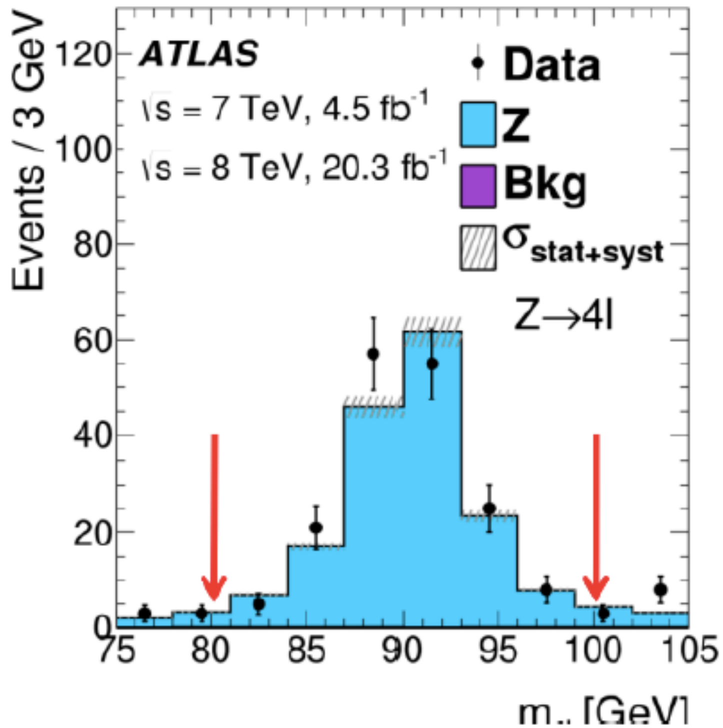


(D0 and CDF not updated yet)

Z→4l

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





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

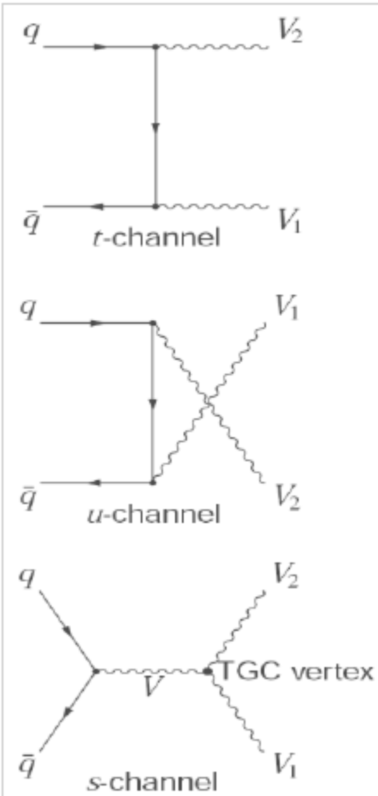
SM (NLO, 8 TeV): $\sigma_{Z\to 4\ell} = 104.8 \pm 2.5$ fb

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

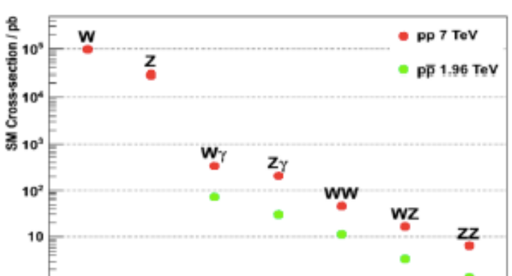
SM expectation: $(3.33 \pm 0.01)\times 10^{-6}$

First measurement of its kind at 8TeV

Diboson production



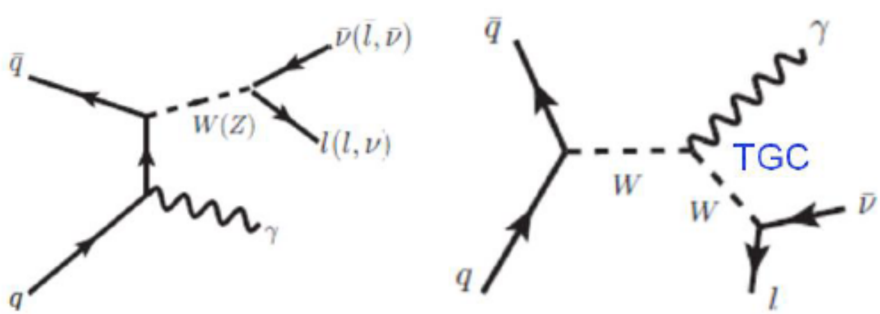
- Unique test of the electroweak sector of the SM
  - Triple gauge couplings (vector-boson self-couplings) are fundamental prediction resulting from the non-Abelian structure of the Electroweak gauge symmetry group of SU(2)*U(1), and are completely fixed in the SM.
  - Anomalous triple gauge couplings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



Wγ, Zγ, WW, WZ, ZZ

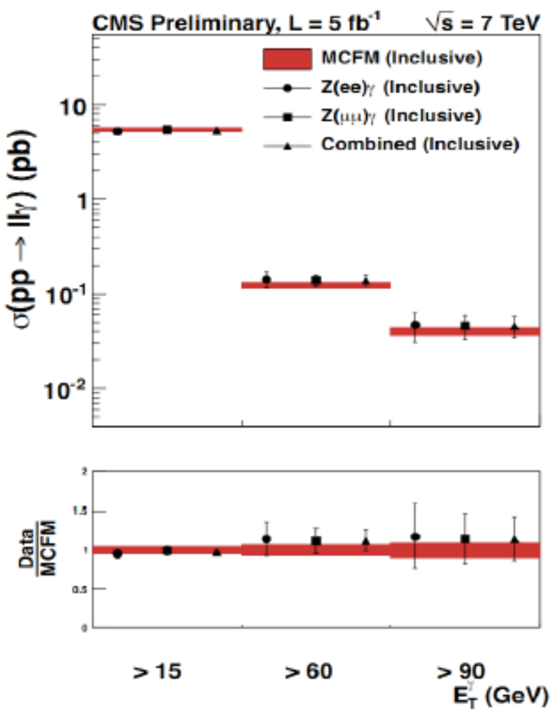
(W and Z are selected in a similar way to the previous "QCD" W/Z selections).

W/Z+gamma production

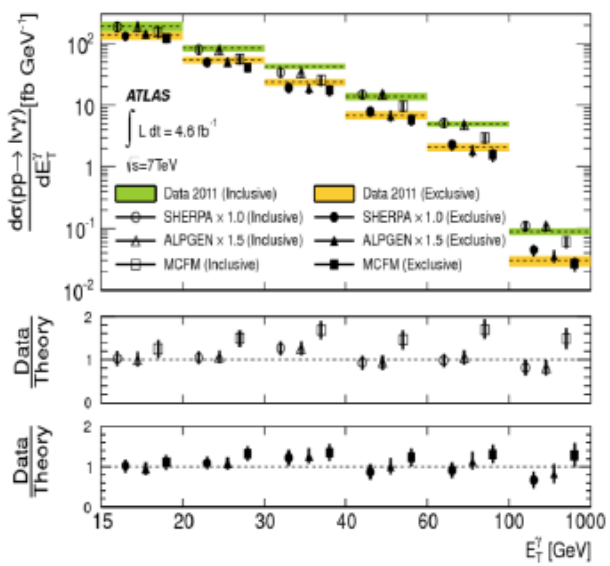


- Wγ → lνγ and Zγ → llγ
  - W/Z + isolated photon, $E_T(\gamma)$ > 15 GeV
  - Δ R(l,γ) > 0.7 (suppress FSR)
  - Background: W/Z/γ+jets
- Zγ → ννγ
  - Missing transverse energy + isolated photon
  - $E_T(\gamma)$ > 100 GeV (ATLAS)
  - $E_T(\gamma)$ > 145 GeV (CMS)
  - Background: W, Wγ, γ+jets

Zγ cross section



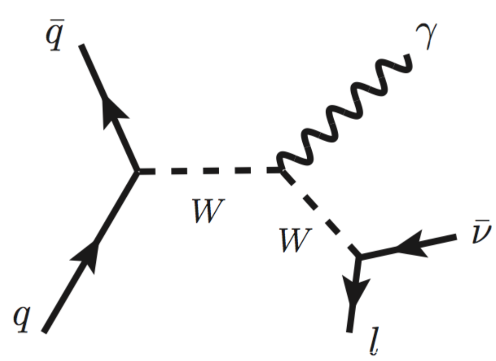
Wγ cross section

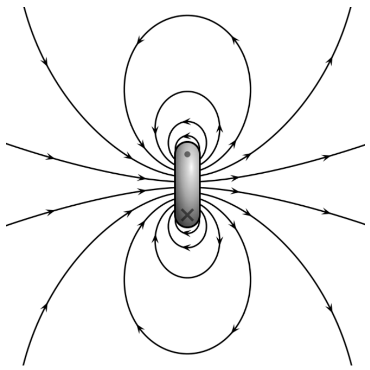


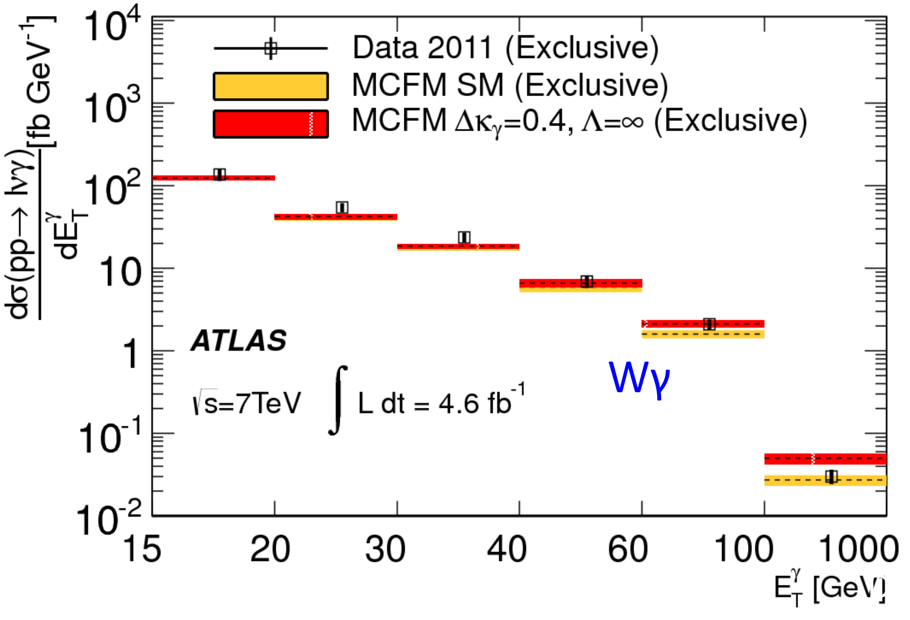
- Wγ: Data agrees with MCFM NLO prediction in low E_T, but overshoots the prediction in high E_T.
- Zγ: Data agrees MCFM NLO prediction for exclusive (no jets)

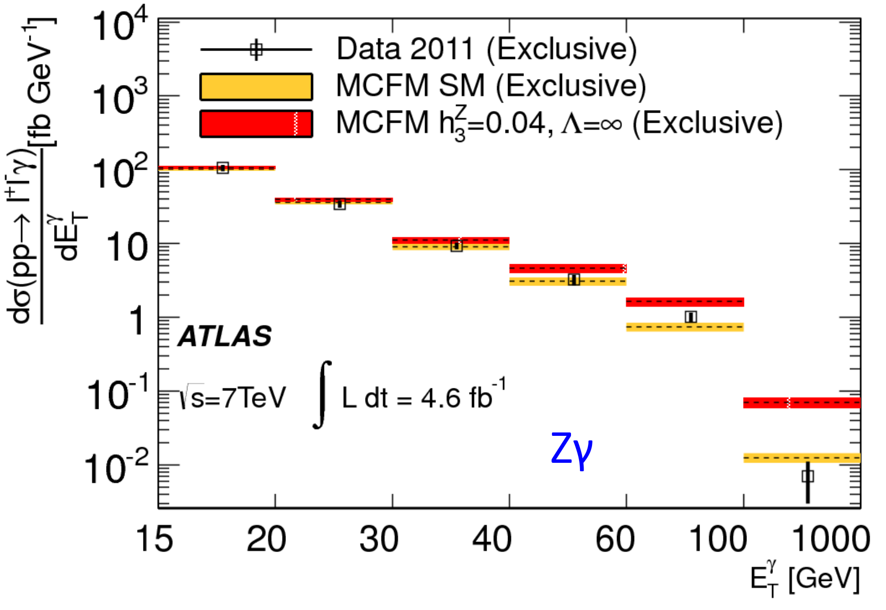
Triple Gauge Couplings

- The s-channel diagrams contain the triple gauge coupling vertex
  - probe magnetic dipole moment of W/Z boson
- aTGCs modify the event kinematics
  - Effects of aTGCs increase with *s*ˆ





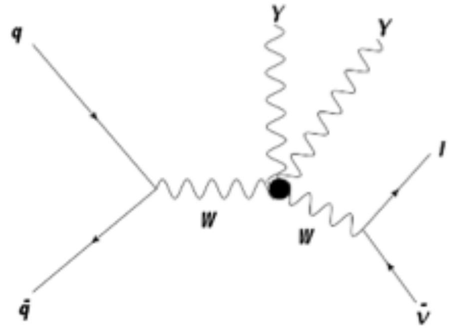


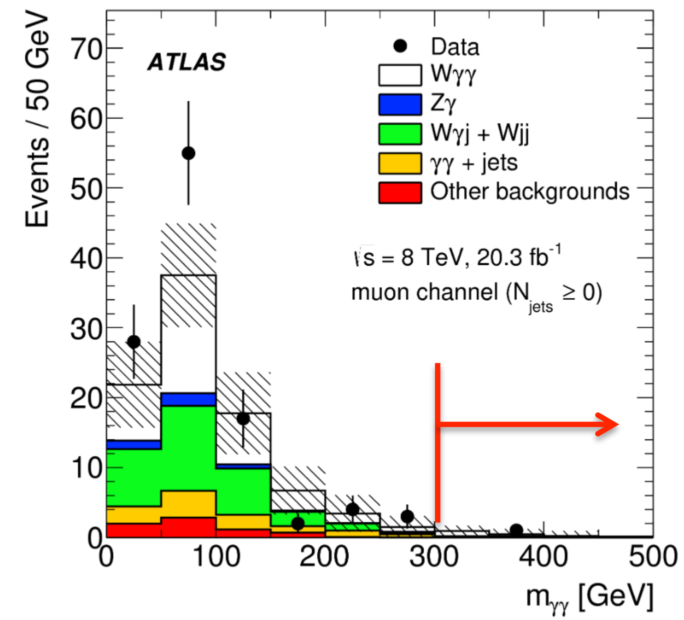


Wγγ (ATLAS)

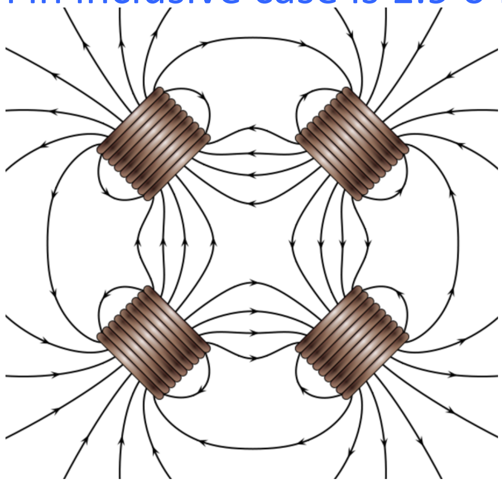
arXiv:1503.03243

- Wγγ process is sensitive to WWγγ QGCs Vertex.
  - Probe Quadrupole moment
- Other contributions from:
  - ISR photons
  - FSR photons
  - Photon from TGC vertex
  - Photon from jet fragmentation





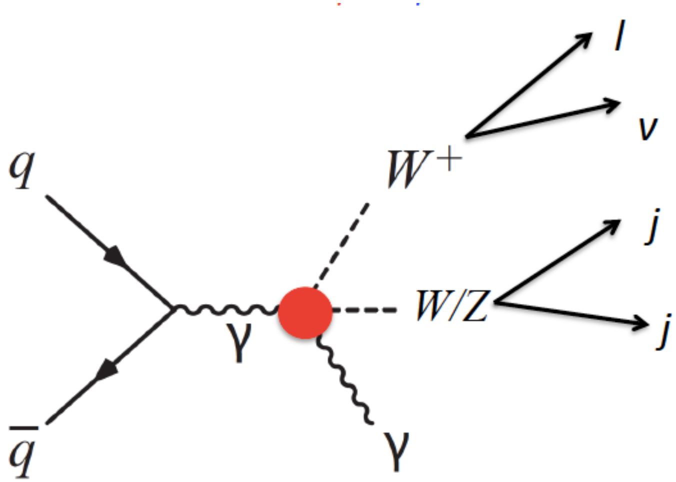
- MCFM is used for NLO Wγγ SM predicted cross section.
  - The measured cross section in inclusive case is 1.9 σ higher than predictions

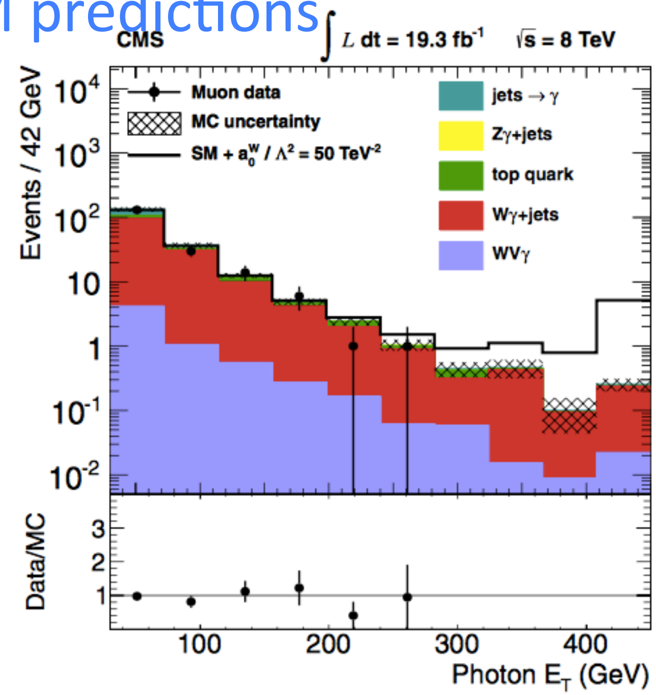


WVγ (CMS)

Phys. Rev. D 90, 032008 (2014)

- The selected data events is dominated by Wγ+jets
  - not enough signal statistics for measurements
- 95% CL cross section upper limit is set at 311 fb
  - The limit is 3.4 times larger than SM predictions





Event selection highlight

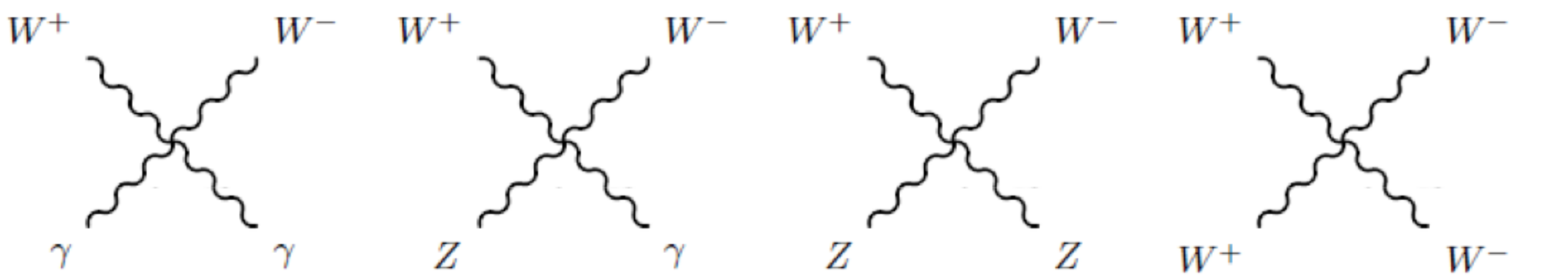
- ❑ One good lepton
- ❑ One good photon
- ❑ Two high pT jets
- ❑ 70GeV <Mjj<100GeV

Major BG in WVγ

Wγ+jets
WV +jet , jet fake as γ
Multijets

Quartic Gauge Boson Couplings

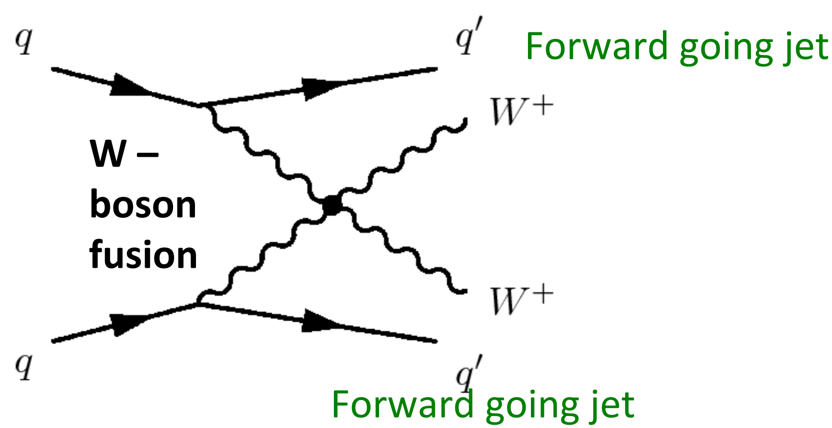
- Reminder of **Quartic Gauge Boson Couplings (QGCs)**
  - SM model predicts gauge boson self coupling
    - Four gauge boson vertex:
      - WWγγ , WWZγ , WWWW, WWZZ, …

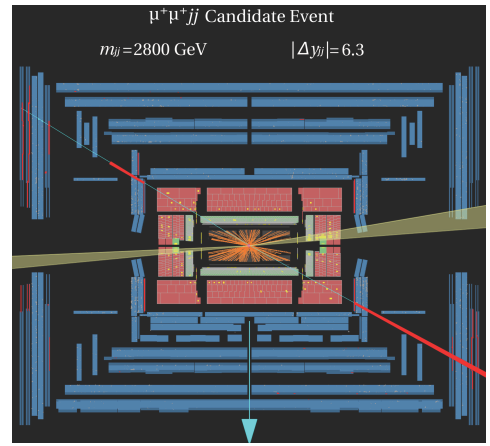


  - QGCs can be studied in
    - Tri-boson processes
    - Vector boson scattering processes
    - Exclusive γγ->WW process

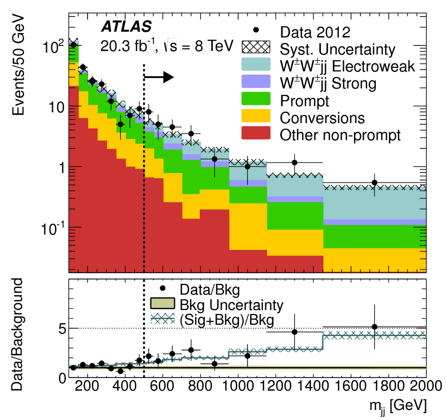
Special interest: W pairs from VBF

1960s: event rate for $W_L W_L$ ➔ $W_L W_L$ explodes at 1.2 TeV
Higgs boson should cure this: theory works fine



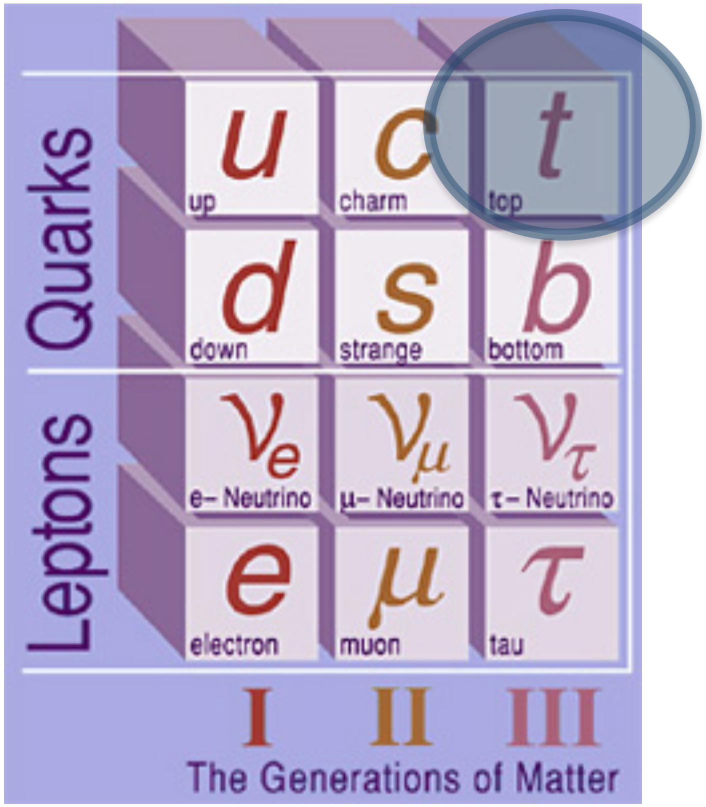


Require
high jj mass
+
high |Δy|



Expected background: 16.9
Expected WWjj: 15.2
Observed nb. Events: 34
➔ Evidence for VBF

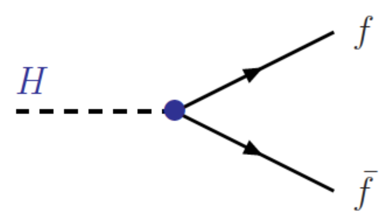
The mysterious top quark



Top quark: no internal structure but heavy as a gold atom

$$\mathrm{M_t = 173.3 \pm 1.1GeV}$$

i.e. coupling strength to Standard Model Higgs Boson



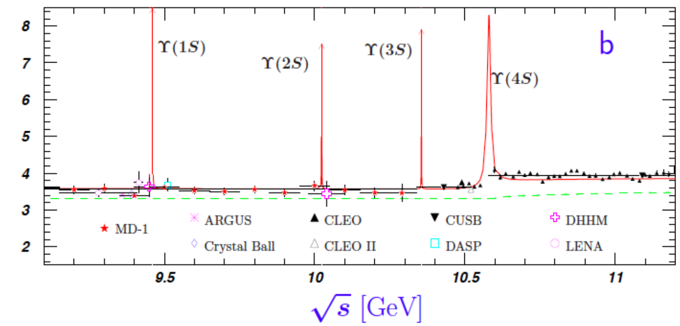
$$\mathbf{m_t} = \frac{\lambda_t \cdot \mathbf{v}}{\sqrt{2}}$$

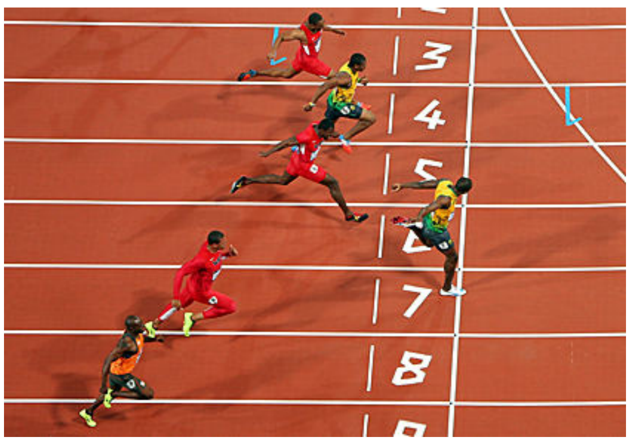
➔ λ_t = 0.996±0.006

Suggests a special role of top quark?

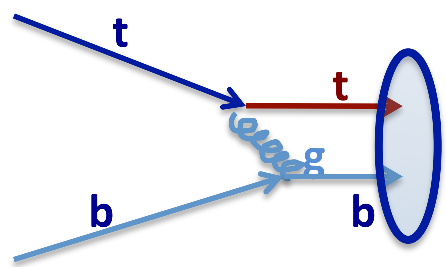
Phenomenology of heavy top

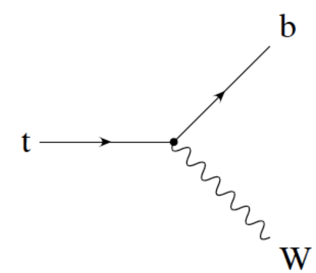
For lighter quarks:
strong interaction >> weak interactions
➔ colour neutral hadrons





competing interactions:
who's faster?



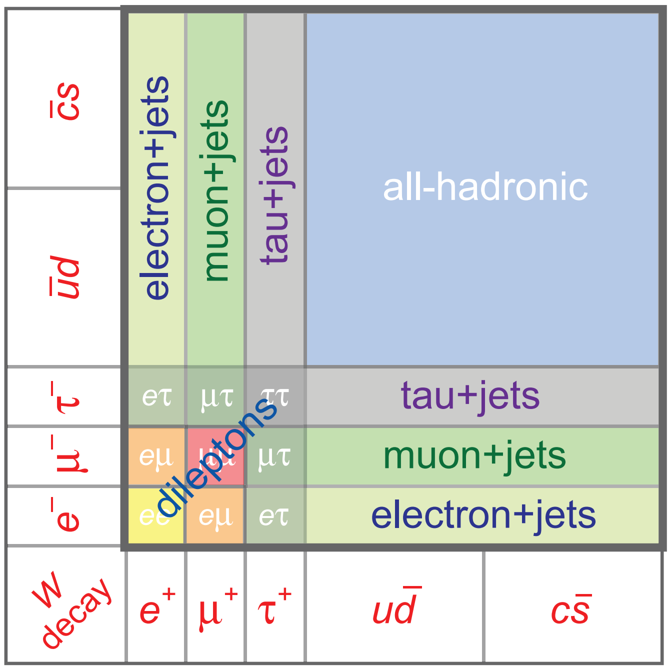


For top quark: strong interaction < weak interactions
➔top quarks decay before hadrons formed, 'free quark'

Phenomenology of heavy top

Decay properties of top quark unambigously predicted by SM
Decay fractions largely determined by fractions of W – decay

Top Pair Decay Channels



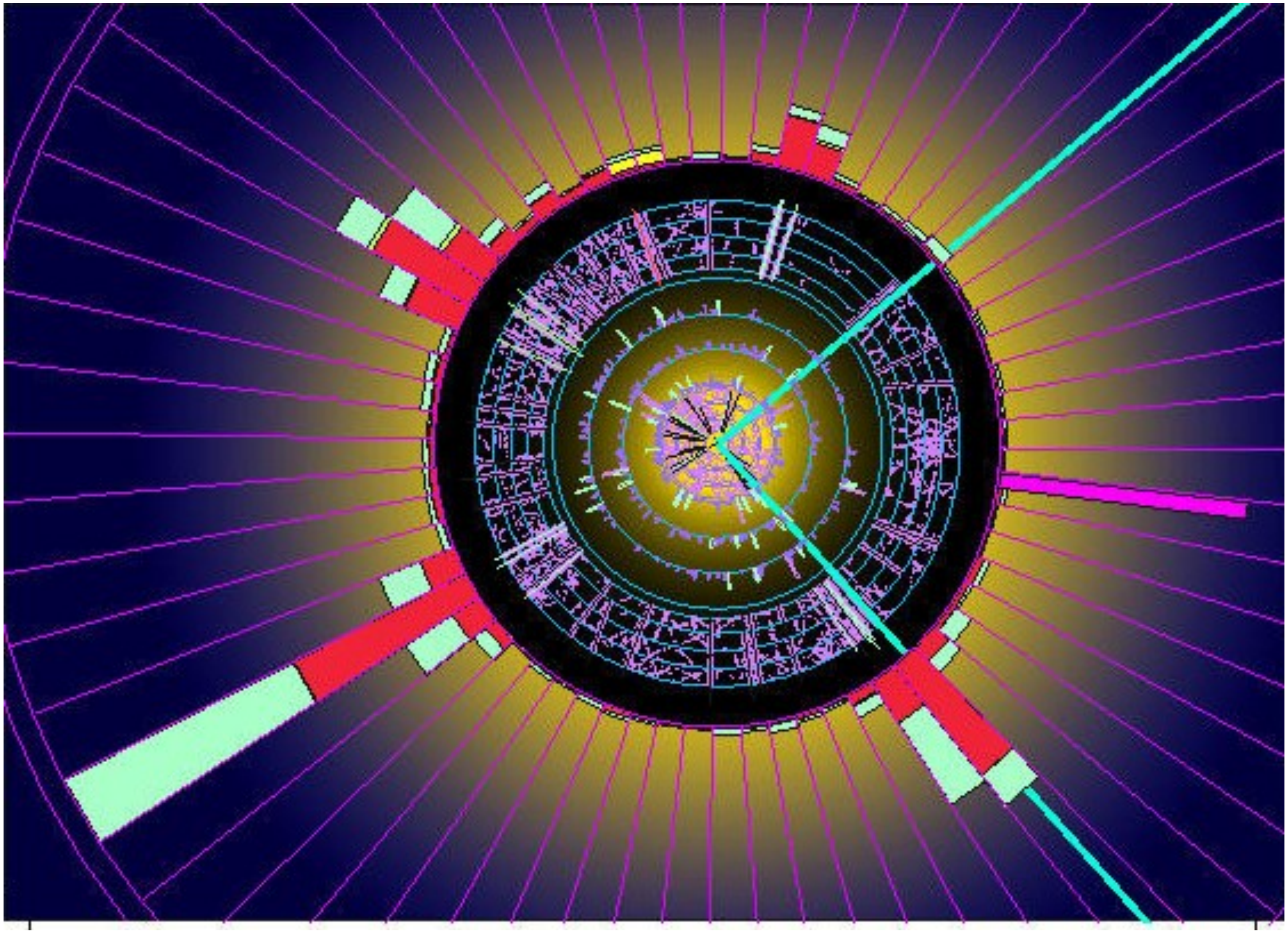
tt ➔ (only) 6 quarks
largest fraction, very high background

tt ➔ 4 quarks, charged lepton, neutrino
Some 30% ‚usable', low background
FAVOURED channel

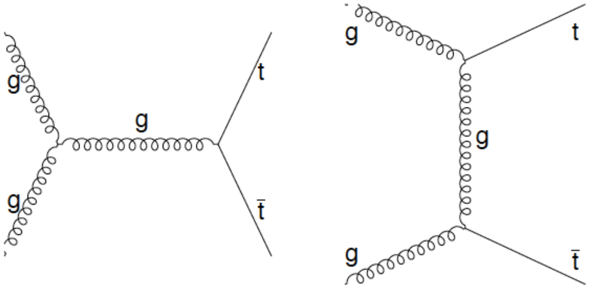
tt ➔ 2 quarks, 2 charged l, 2 neutrinos
Only 5% ‚usable', very low background, difficult to reconstruct

99.1% of all top quarks decay into a bottom quark!

A semileptonic $t\bar{t}$ event



$t\bar{t}$ Cross Section



Test of QCD with massive quarks

Measure coupling strength $gt\bar{t}$

Event selection
- 4 high p_T jets
- isolated electron/muon
- missing transverse energy

$$\sigma_{t\bar{t}} = \frac{N_{measured} - N_{background}}{\epsilon \mathcal{L}}$$

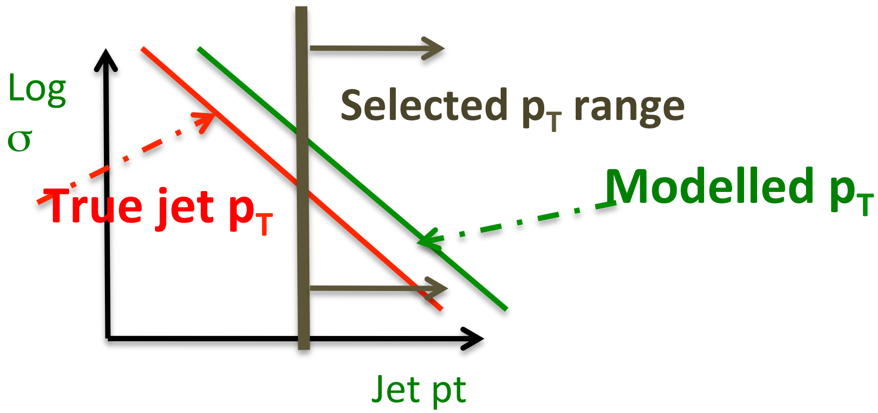
What fraction of $t\bar{t}$ events are retained after selection

Luminosity:
How many proton collisions?

Cross section determination

Experimental precision depends on how well
- background, efficiency, luminosity can be controlled

Key issue determine efficiency



Largest uncertainties:
- modelling of top
- parton distribution fct.
- Background yield
- Jet energy scale
- selection efficiencies e, μ

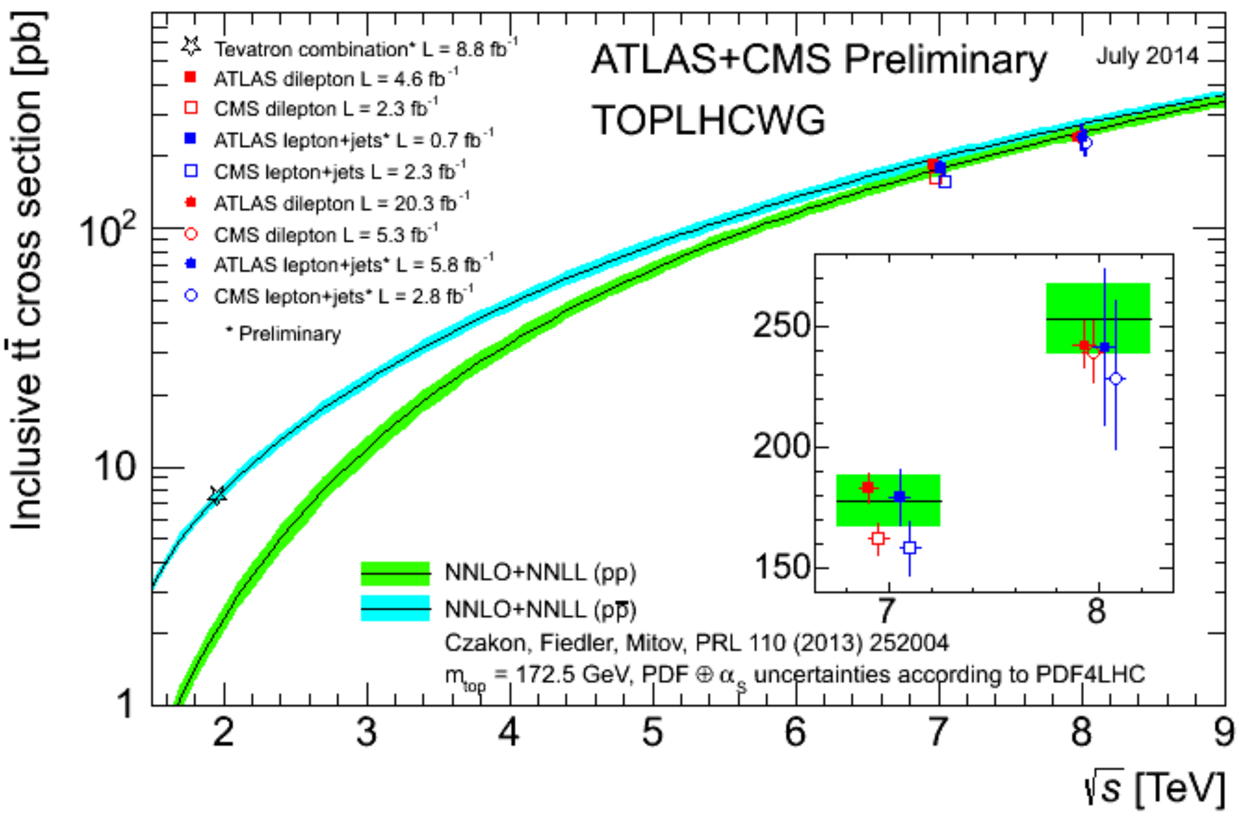
Experimental uncertainty	~ 2.3%	Total uncertainty 4.3%
Luminosity uncertainty	~ 3.1 %	
Beam energy	~ 1.7 %	

Improvement by factor 2 – 3 within a year!

Cross section measuremnt

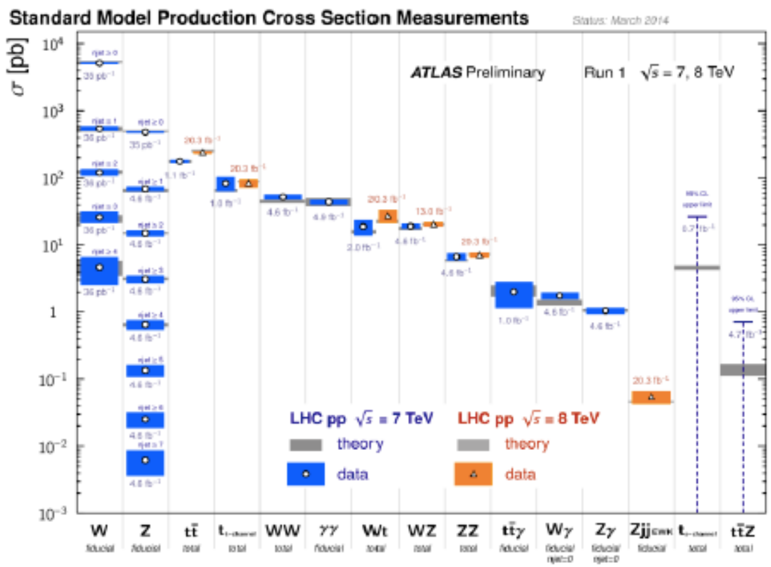
Theoretical uncertainty <5 % (significant improvement last 10y)

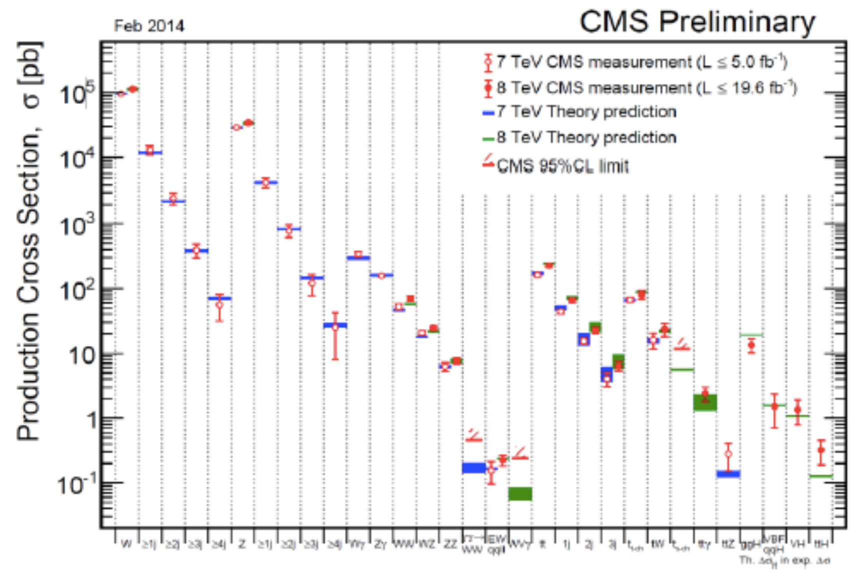
Theory & experiment uncertainty about equal



Very good agreement between data and expectation

Summary





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

SM measurements are just important