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Standard Model @ Hadron Colliders
II. Electroweak (gauge bosons)

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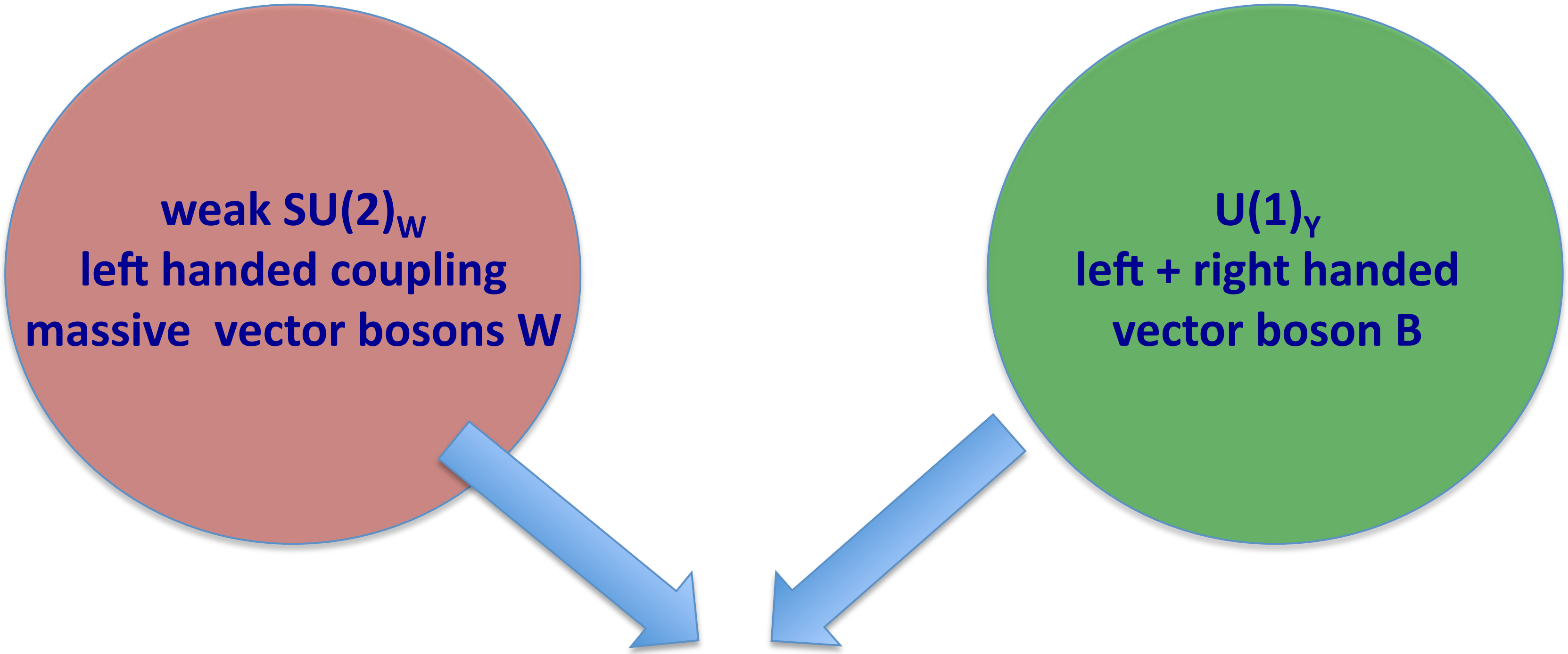
Electroweak facts



weak SU(2)$_W$
left handed coupling
massive vector bosons W

U(1)$_Y$
left + right handed
vector boson B

Interactions mix ➔ physical particles γ, Z^0

$$\mathbf{A}_\mu = \mathbf{B}_\mu \cdot \cos\theta_\mathbf{w} + \mathbf{W}^\mathbf{3}_\mu \cdot \sin\theta_\mathbf{w}$$

$$\mathbf{Z}_\mu = -\mathbf{B}_\mu \cdot \sin\theta_\mathbf{w} + \mathbf{W}^\mathbf{3}_\mu \cdot \cos\theta_\mathbf{w}$$

Electroweak facts II

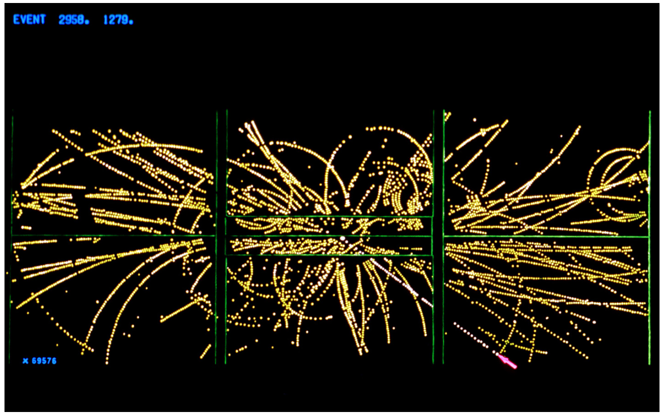
Unambiguous predictions of all measurements in terms of mass of Z^0 boson or mixing angle θ_w

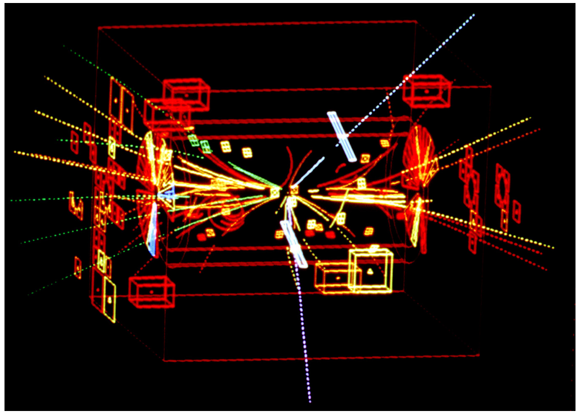
$$\begin{aligned} \alpha_{em} &= 1/137.03599976(50) \\ G_\mu &= 1.16639(1) \cdot 10^{-5} \quad \mathrm{GeV}^{-2} \\ M_Z &= 91.1882(22) \quad \mathrm{GeV} \end{aligned}$$

Can all measurements be consistently explained with these?

➔NO! Sensitive to Quantum fluctuation of unknown (top – quark and) Higgs boson

W/Z highlights of CERN

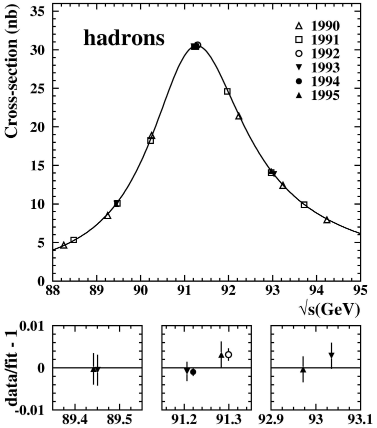




Discovery (1983)

Carlo Rubbia
Simon van der Meer

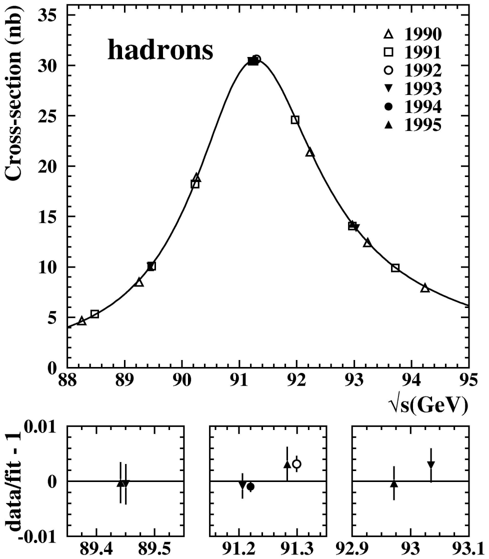
Precision measurements in 1990s



M_Z Precision 10^{-5} !
All decays precisely measured

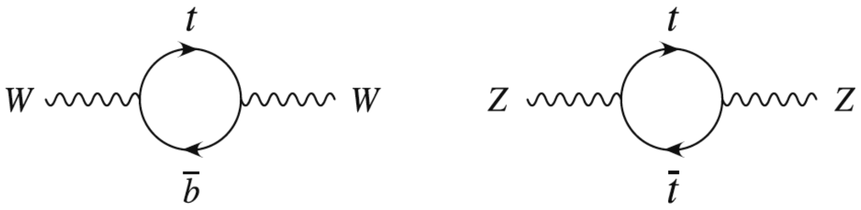
M_W precision 80.378(33) GeV
All decays precisely measured

Radiative corrections = quantum fluctuations



Measuring at mass of 91 GeV
➔sensitivity to several 100 GeV

Quantum fluctuation!



Changes mass and couplings of Z^0, $W^\pm$
(at the percent level ➔ high precision experiment & theory)

Confronting theory with data

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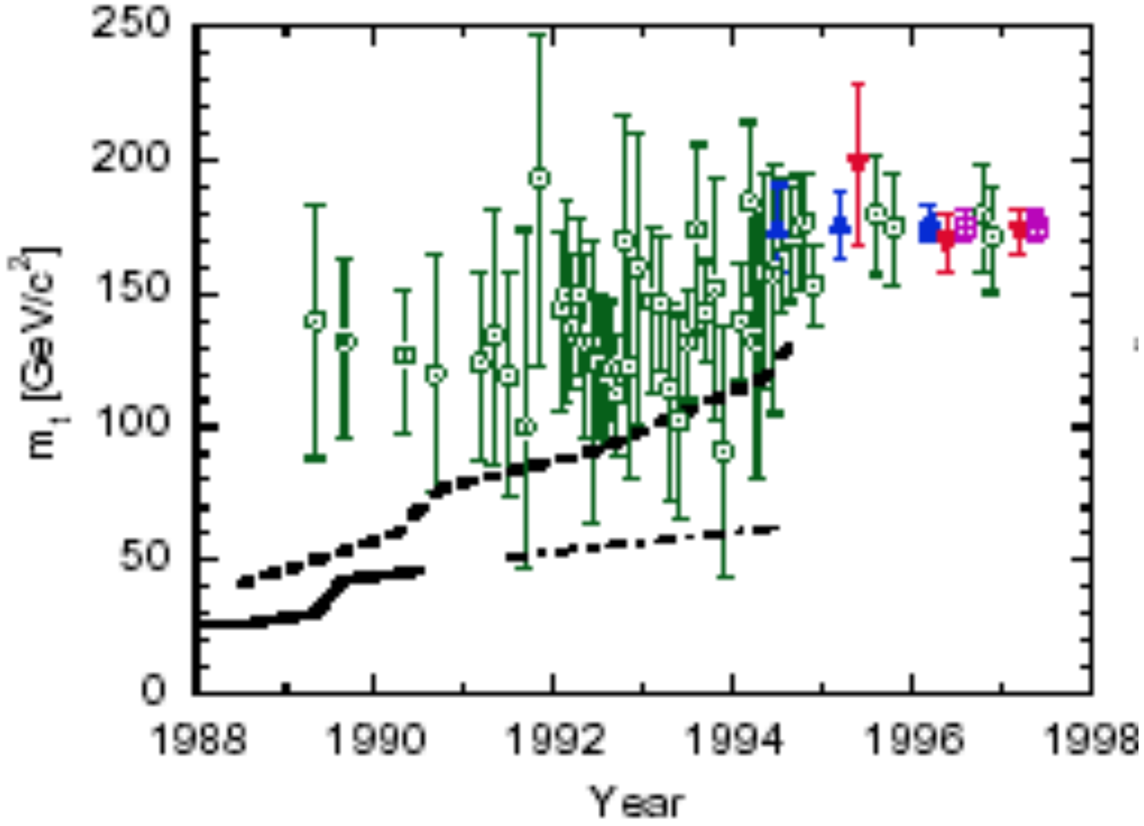
Top mass → from quantum fluctuation to reality

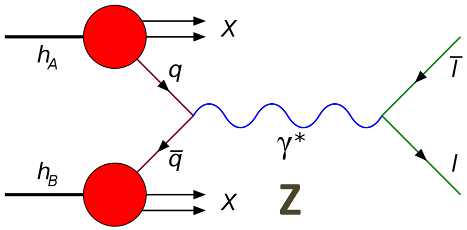


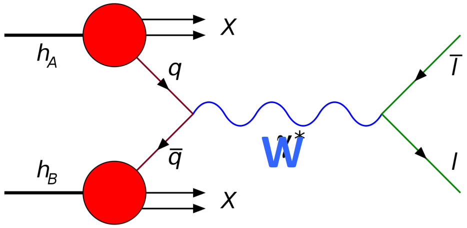
Fit with M_{top} free parameter: consistent with top observation

Electroweak Physics @ Had Colliders

- Understand W/Z production (+jets):
  background for searches Beyond Standard Model
  and QCD test/parton distribution functions
- Measure M_W (and M_{top})
- Test 3 – Boson couplings at high energies

Production of Z Bosons: Drell - Yan

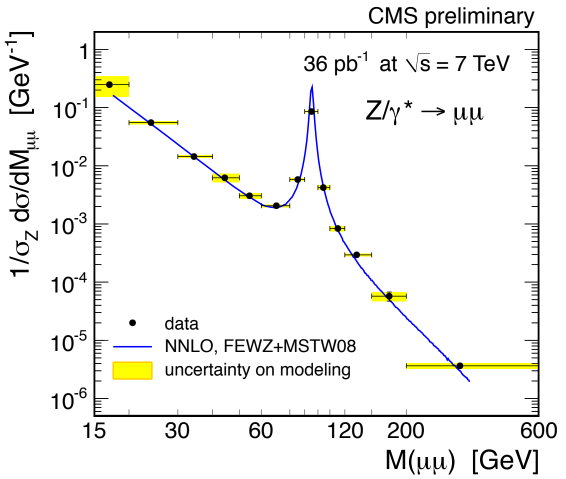


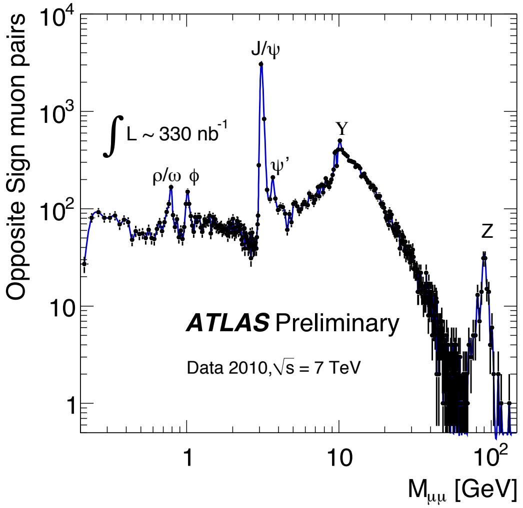


Steeply falling X-section

with a lot of structures

$$\sigma \propto \frac{1}{M^2} \times \mathcal{L}_{q\bar{q}}$$

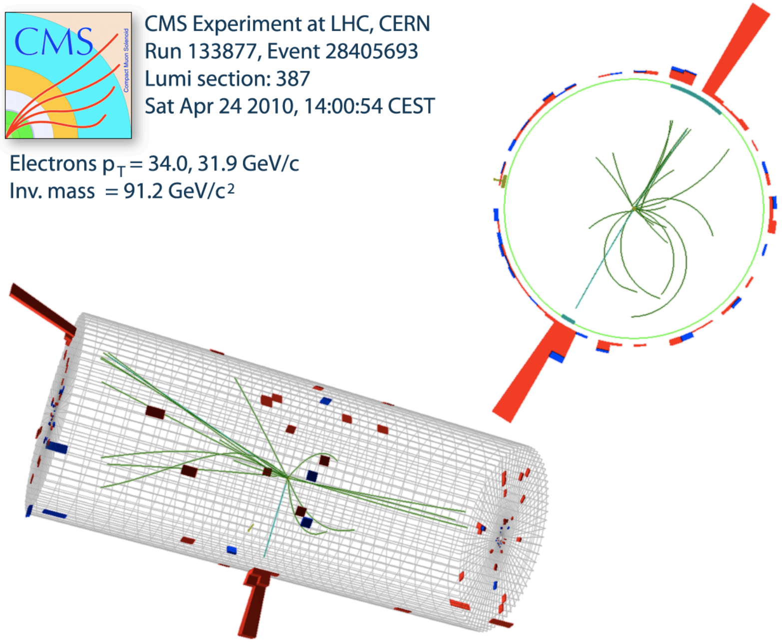


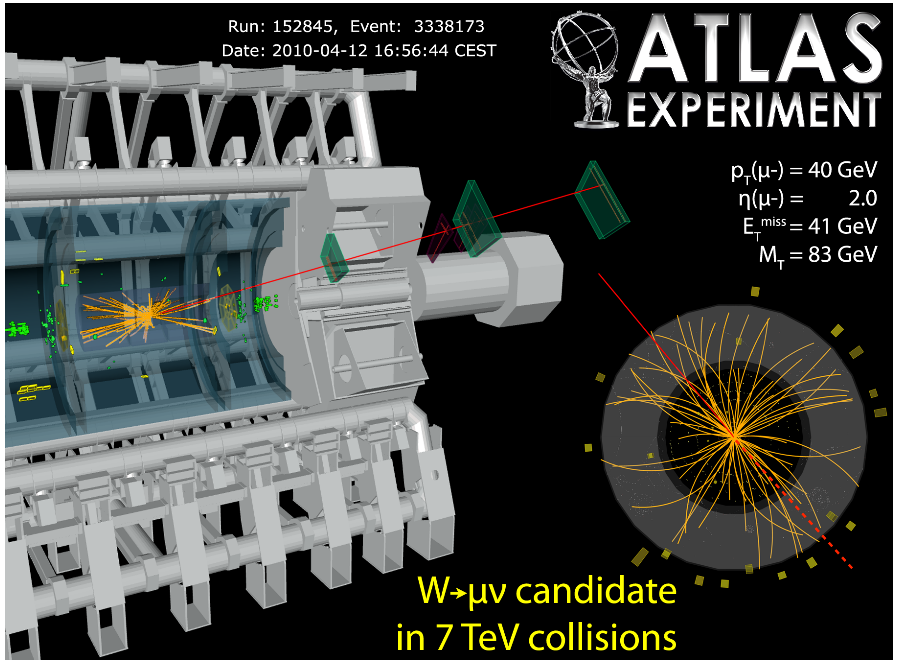


Decays of the W/Z^0

In general: W, Z decay into e, μ, τ, ν and quarks

Experimentally most visible @ LHC: decays into e, μ





W→μν candidate
in 7 TeV collisions

Branching ratios of

2*3% and **2*11%**

Z^0 reconstruction at the LHC

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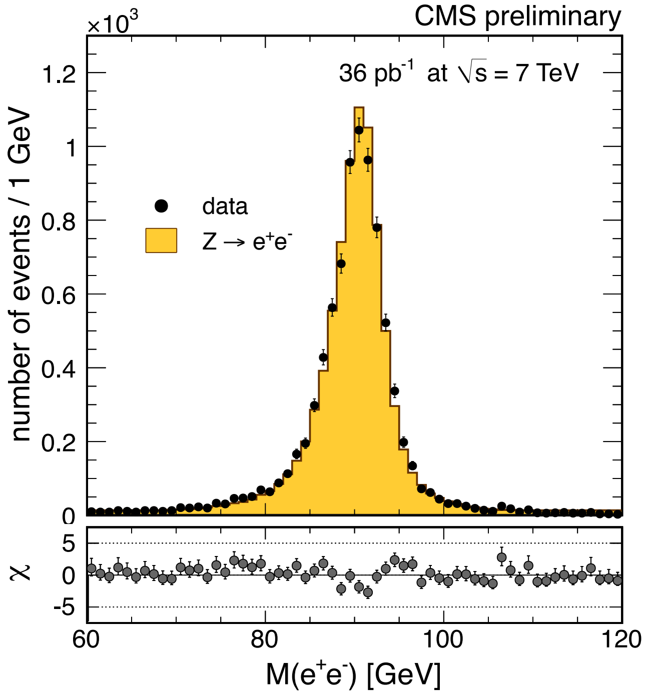
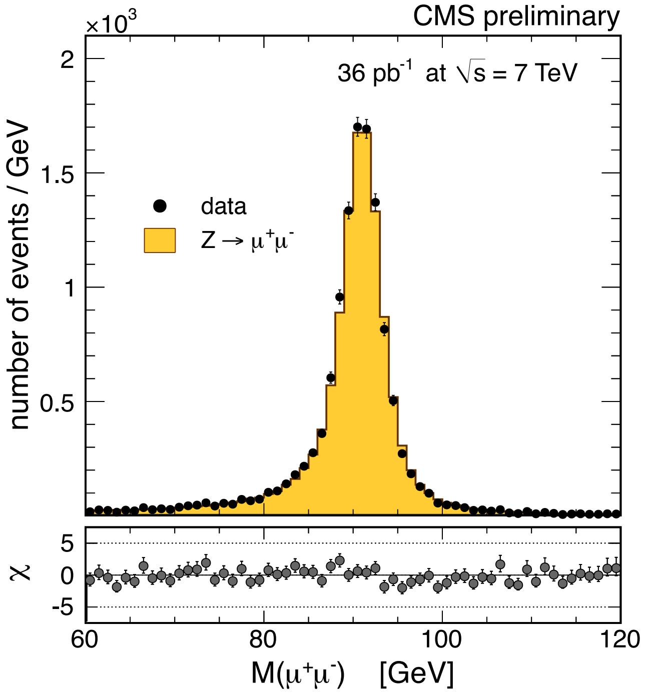




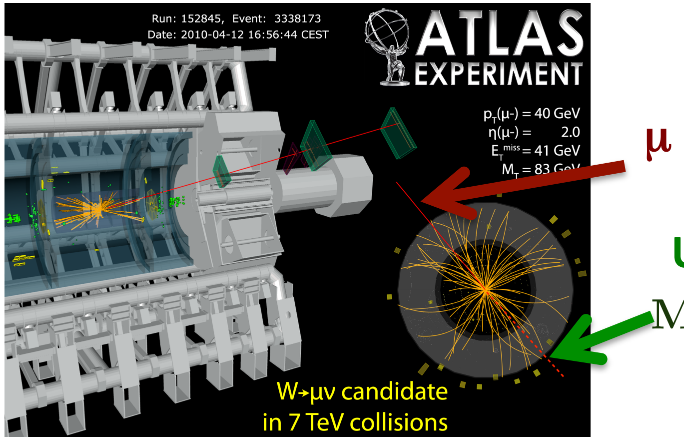
A clear, almost background – free signal

1 fb^{-1} mean some 1 million Z^0s

A lot of physics!

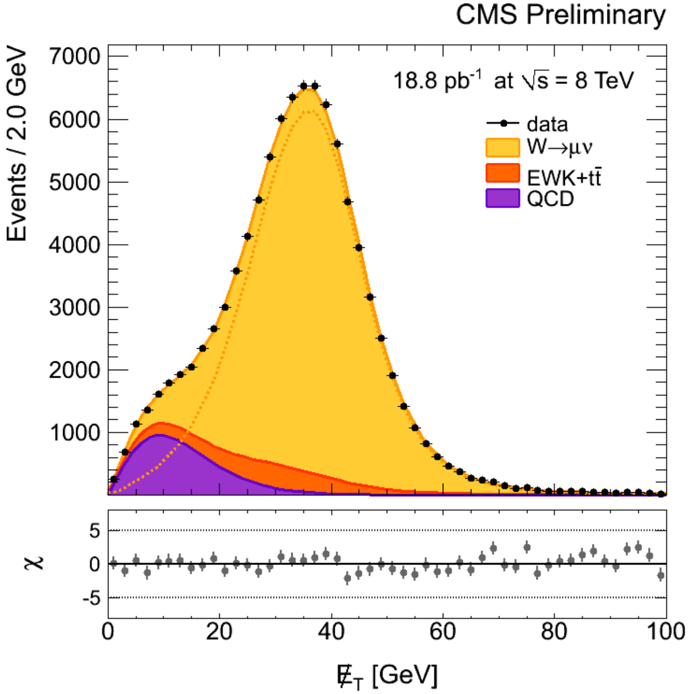
A lot for detectors: calibration of electromagnetic calorimeter

W reconstruction at the LHC



Unbalanced transverse momentum = ,ν‘

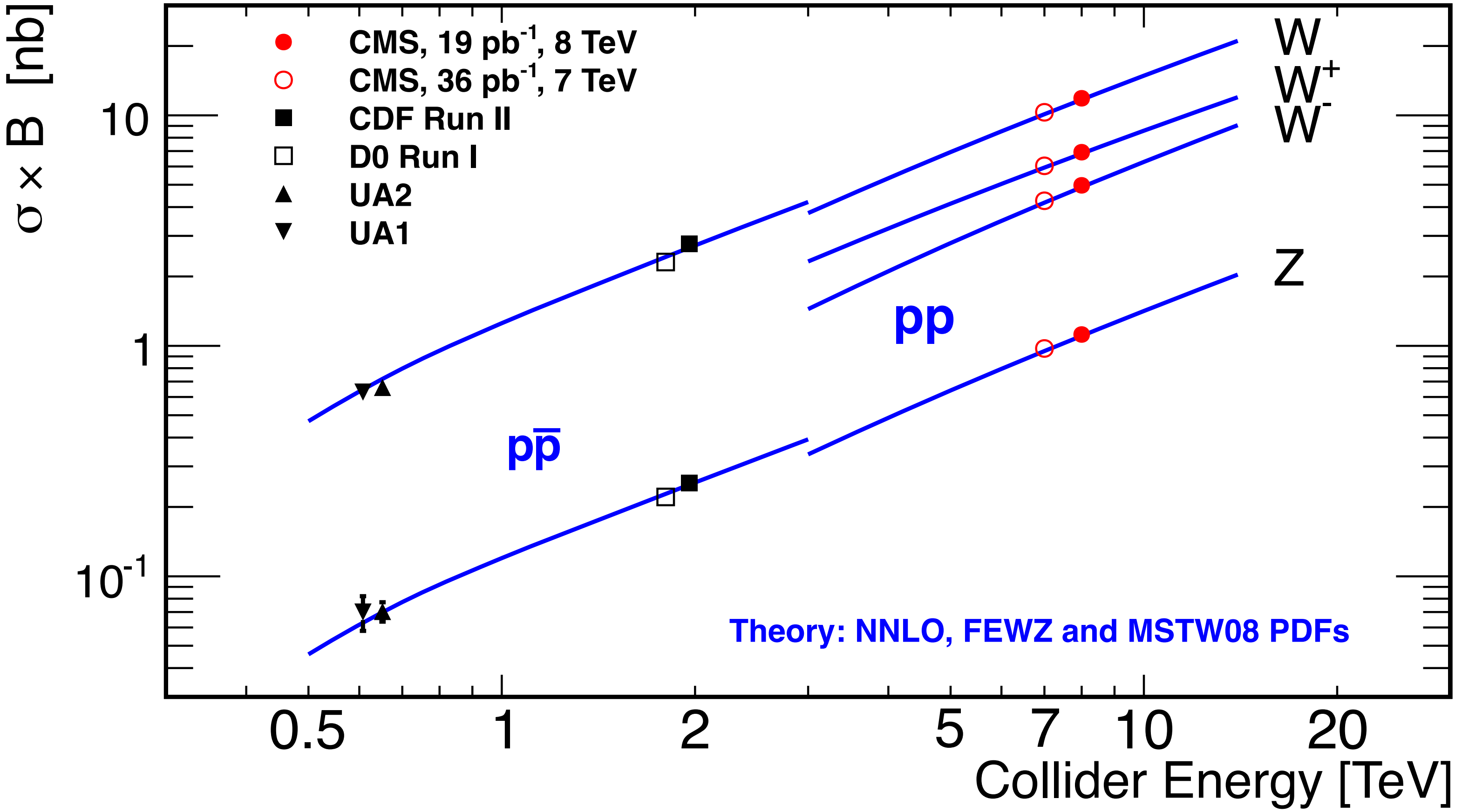
$$\mathrm{MET_x} = -\sum(\mathrm{p_x})_\mathrm{i}, \quad \mathrm{MET_y} = -\sum(\mathrm{p_y})_\mathrm{i}$$



Missing transverse momentum
not only due to ν
- mismeasurements
- additional jets/underlying ev.

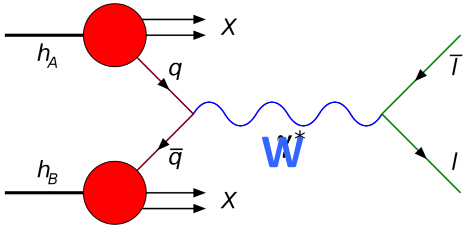
Cross section ~ 10x higher than for Z^0

W/Z Cross section



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

Production of W± Bosons



Drell – Yan process (leading order)

Very similar to Z – boson production
But different initial quarks (different flavour!!), e.g.

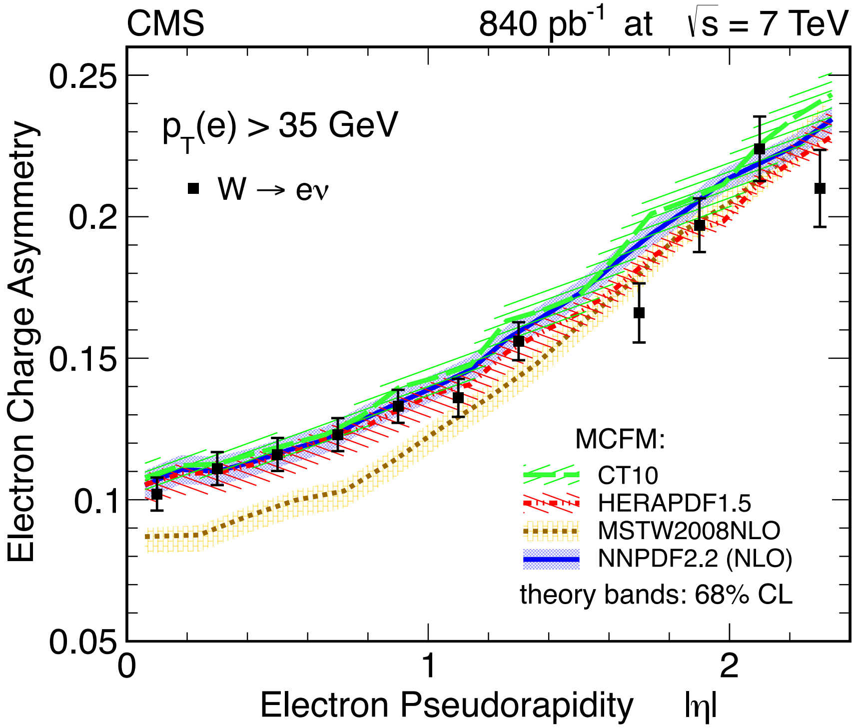
$$\mathbf{u\bar{d}} \;\rightarrow\; \mathbf{W}^{+} \;\rightarrow\; \mu^{+}\bar{\nu}_{\mu}$$

$$\mathbf{\bar{u}d} \;\rightarrow\; \mathbf{W}^{-} \;\rightarrow\; \mu^{-}\nu_{\mu}$$

Sensitivity to different quark content in proton
➔ important calibration point for parton distribution function

W^+ vs. W^- production

$$A_\mu = \frac{N_{\mu^+}(|\eta|) - N_{\mu^-}(|\eta|)}{N_{\mu^+}(|\eta|) + N_{\mu^-}(|\eta|)}$$



Note different predictions by pdfs

LHC: pp – collider:

2 valence up quarks

1 valence down quark

➔more W^+ than W^-

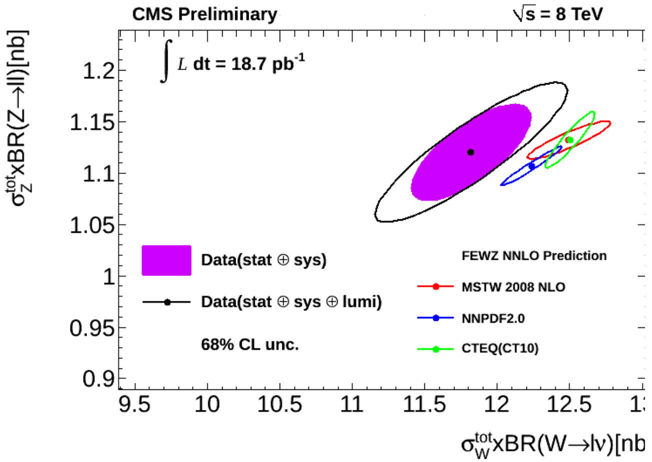
Sea quark **Valence quark**

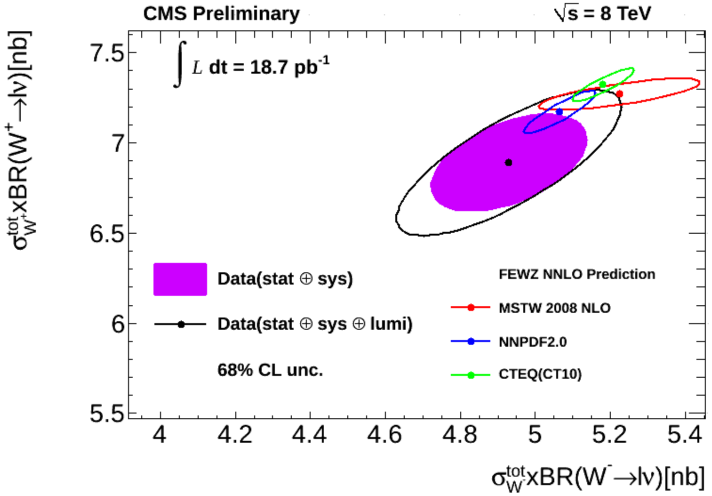
Valence quarks have high x!

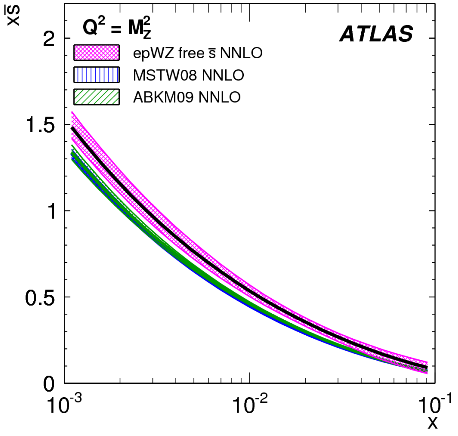
Sea quarks small x

➔ high η W - bosons

Comparing W/Z with pdfs

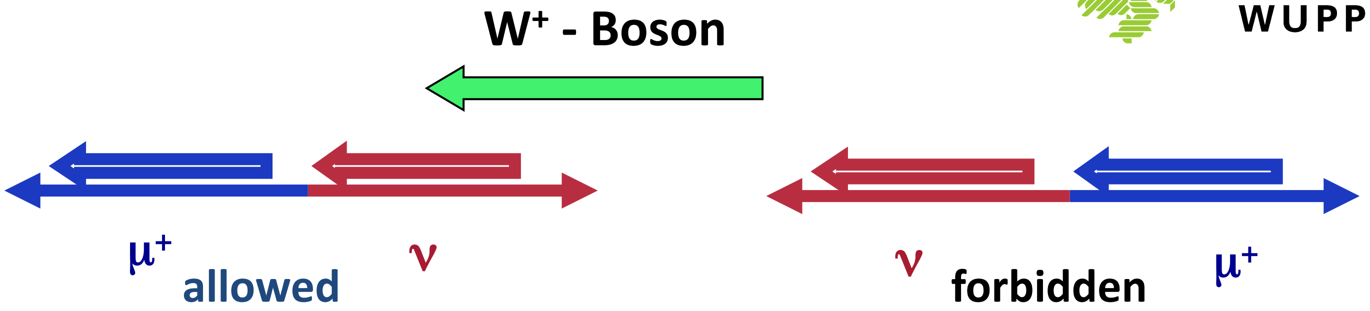






W & Z measurements significantly constrain pdfs for quarks

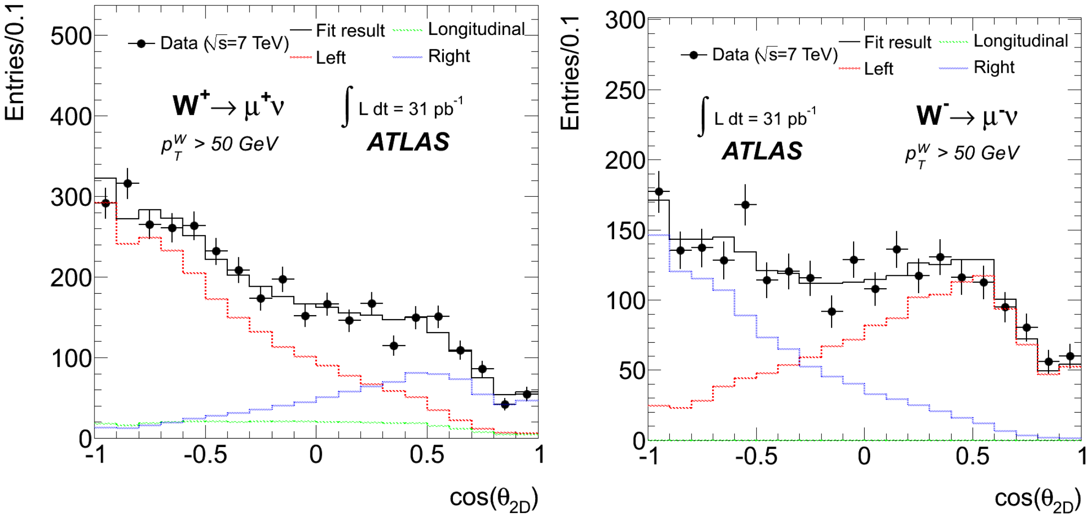
Polarisation of W



W^+ - Boson

μ^+ allowed ν

ν forbidden μ^+



Basic property of weak interaction

➔μ^+ along spin. of W^+

➔μ^- opposite to spin of W^-

Note: experimental selection and reconstruction dilutes effect

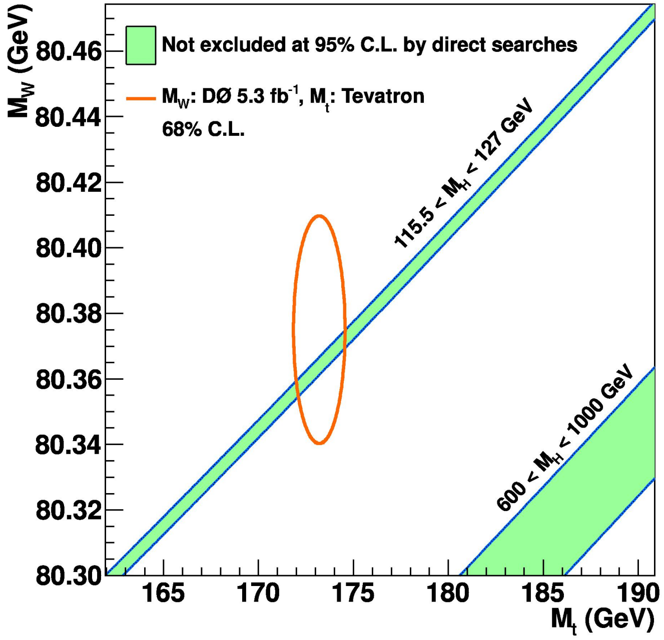
The W mass

Fundamental parameter of the Standard Model

$$G_\mu = \sqrt{2} \cdot \frac{g^2}{8 \cdot M_W^2} = \frac{\pi\alpha}{\sqrt{2}} \frac{1}{M_W^2 \cdot \sin^2\theta_W}$$

G_μ given by lifetime of μ
➔ yields prediction for M_W

Radiative corrections
➔sensitivity to mass of
Higgs boson



Precise measurement @ LEP:
80.376 ± 0.033 GeV

Mass determination at hadron coll.

Determination with electron/muon and neutrino

$$\mathbf{M_W = (E_l + E_\nu)^2 - (\tilde{p}_l + \tilde{p}_\nu)^2}$$

But:

- **How well is the energy scale e/μ known?**
- **... and what is the energy and direction of ν?**

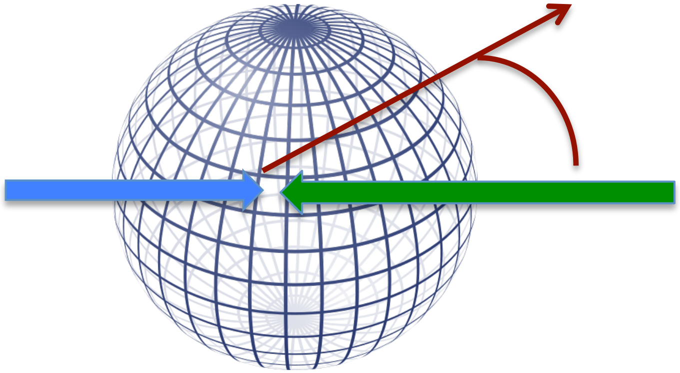
- **Use well known M_Z to calibrate energy scale**
- **consider only transverse momentum of ν**
  identify with ‚missing transverse energy'

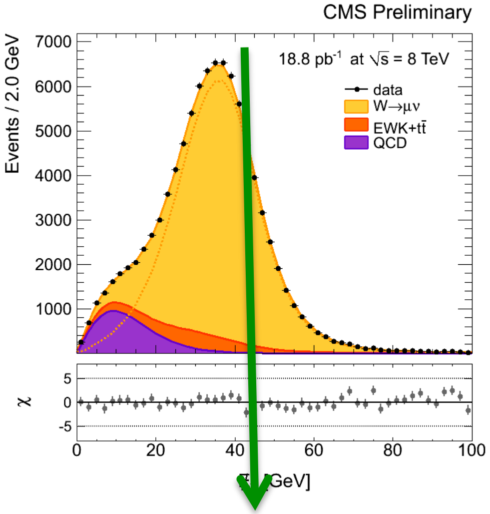
$$\mathbf{M_W^2 = (E_l + E_\nu)^2 - (\tilde{p}_l + \tilde{p}_\nu)^2 > (E_l + MET)^2 - (\tilde{p}_l + \widetilde{MET})^2}$$

W mass at hadron coll.

Reflects phase space in spherical decay:
Largest if decay perpendicular to flight direction

$$\mathbf{p_T(e)} = \frac{\mathbf{m_W}}{\mathbf{2}} \sin\theta^*, \quad \theta^*$$ **angle wrt beam in W rest system**





- **max $p_T = M_W/2$**

Sharp fall - off

Jacobian peak

Relation mass ⇔ transverse momentum

$$p_T = \frac{1}{2} M_W \cdot \sin\theta^* \quad \Rightarrow \quad \cos\theta^* = \sqrt{1 - 4 \cdot p_T^2 / M_W^2}$$

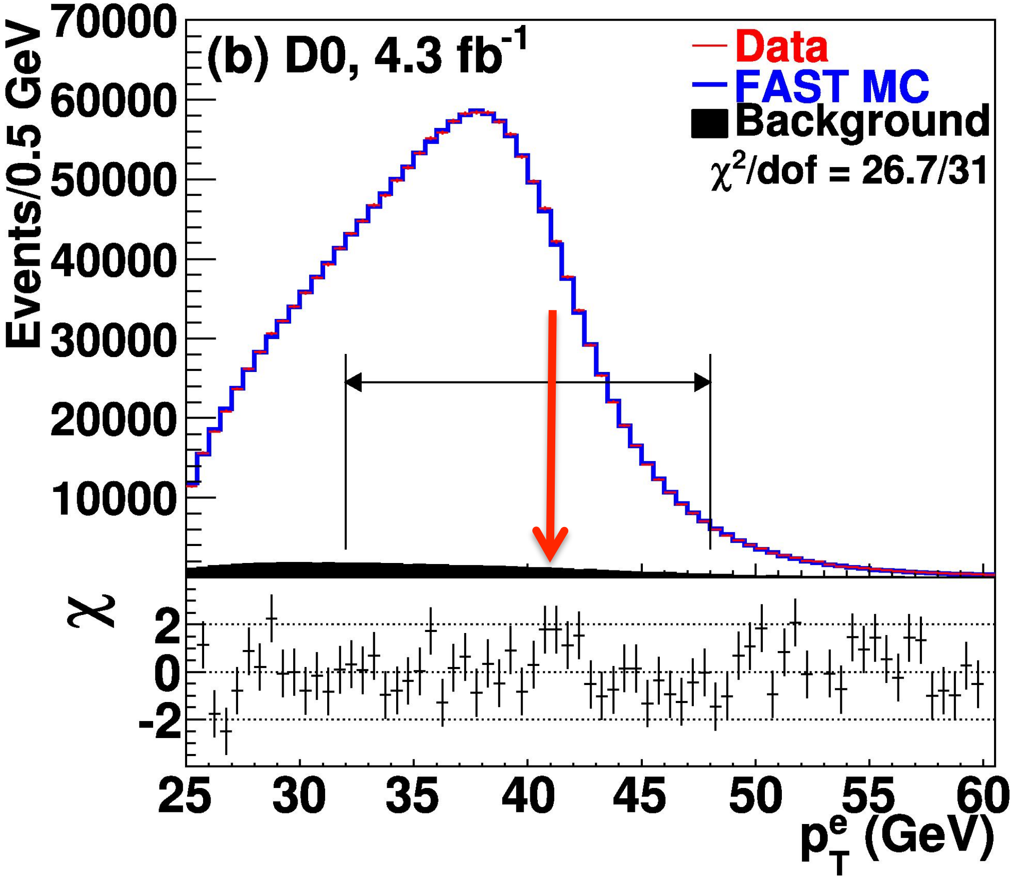
Cross section section → pole at $p_T = M_W/2$

$$\frac{d\sigma}{dp_T^2} = = \frac{d\sigma}{d\cos\theta^*} \frac{2/M_W}{\sqrt{M_W^2 - 4 \cdot p_T^2}}$$

damped by natural width of W - boson

$$\frac{d\sigma}{dM_{e\nu}dp_T^2} \propto \frac{\Gamma_W M_W}{(M_{e\nu}^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \frac{1}{M_{e\nu}^2 \sqrt{1 - 4p_T^2/M_{e\nu}^2}} \frac{d\sigma}{d\cos\theta^*}$$

Reality: Jacobian peak smeared out



Fast drop around $M_W/2$ but smeared out

- W – boson: Γ ~ 2 GeV
- QCD effects
- detector distortions

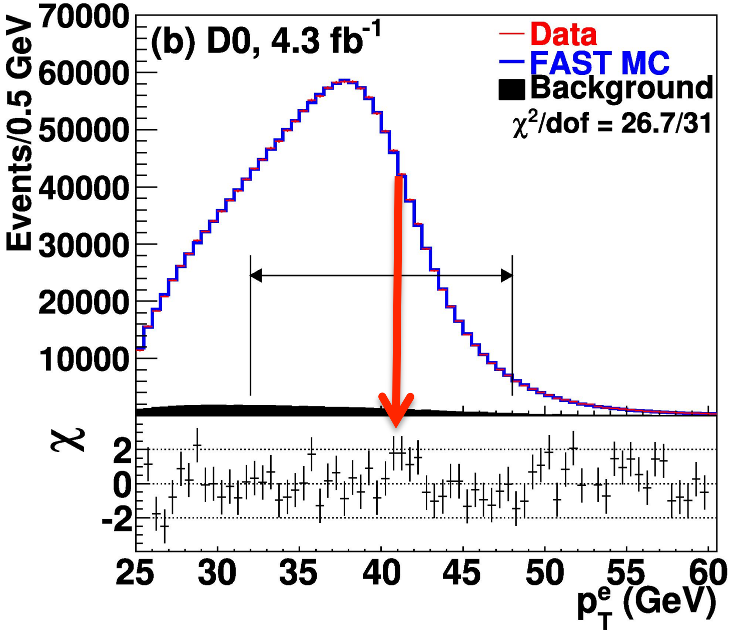
Experimental challenge: Keep systematic uncertainties under control

➔ exploit similarity Z/W

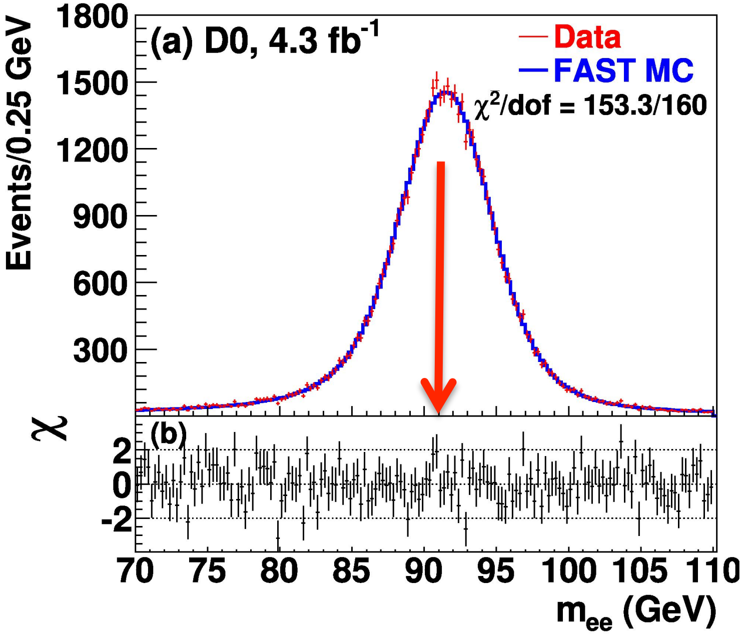
$M_W = 80.342 \pm 0.014$ GeV

Source of uncertainty: energy scale

How well does one know the ‚true‘ energy ?

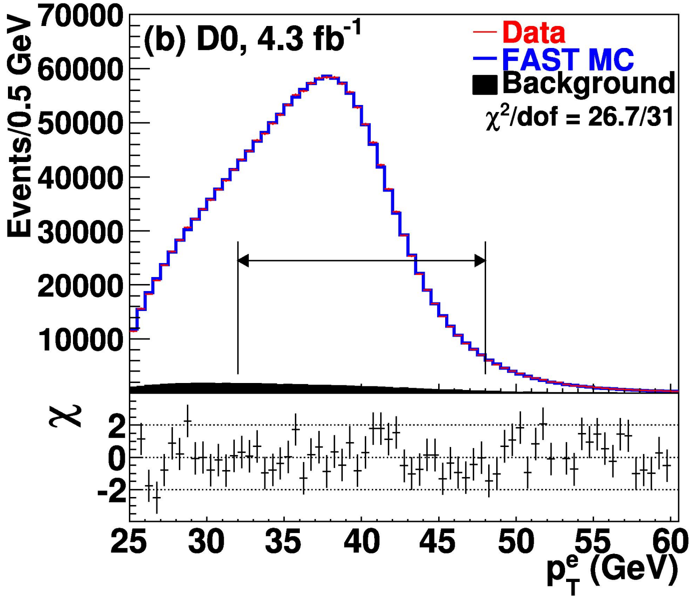


Measure Z^0: calibrate such that
M_Z = 91.1882 GeV



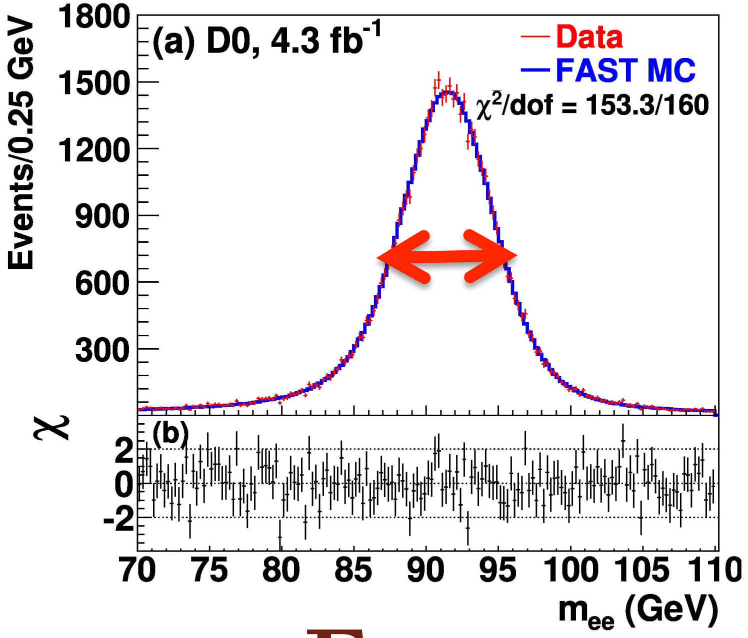
Z^0 measurement: excellent control of energy scale

Source of uncertainty: energy resolution



Measure Z^0 width:

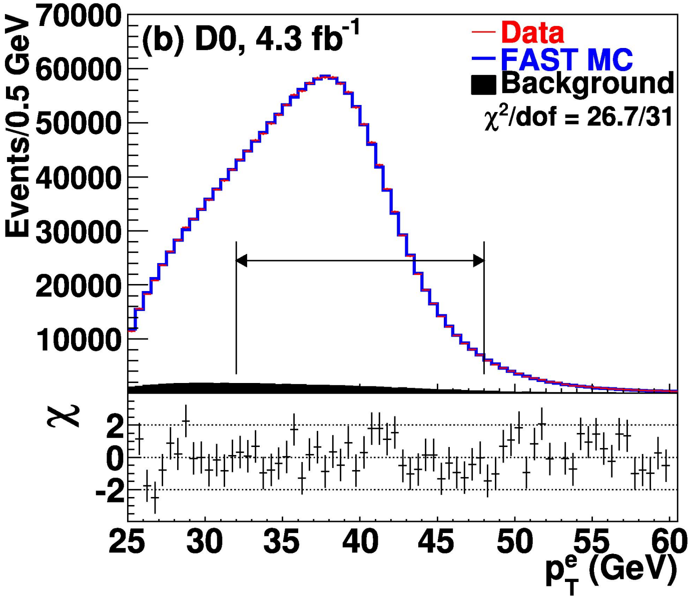
natural Γ_Z = 2.4952 GeV

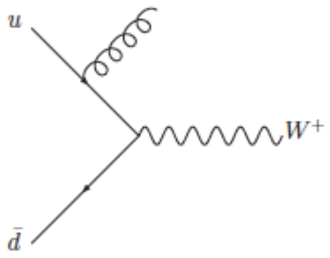


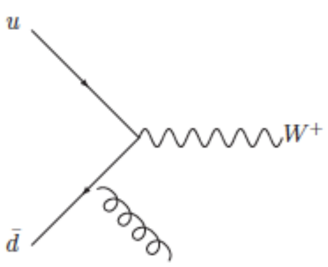
Z^0 measurement: excellent control of energy resolution

$$\sigma_{\text{observed}} = \sigma_{\text{detector}} \oplus \Gamma_{\text{Z}}$$

Source of uncertainty: p_T of W - boson







p_T(W) ~ p_T (Z)

But different couplings, (small) sensitivity to pdfs

Again: Z^0 measurement provides excellent knowledge of QCD distortions

Two other methods

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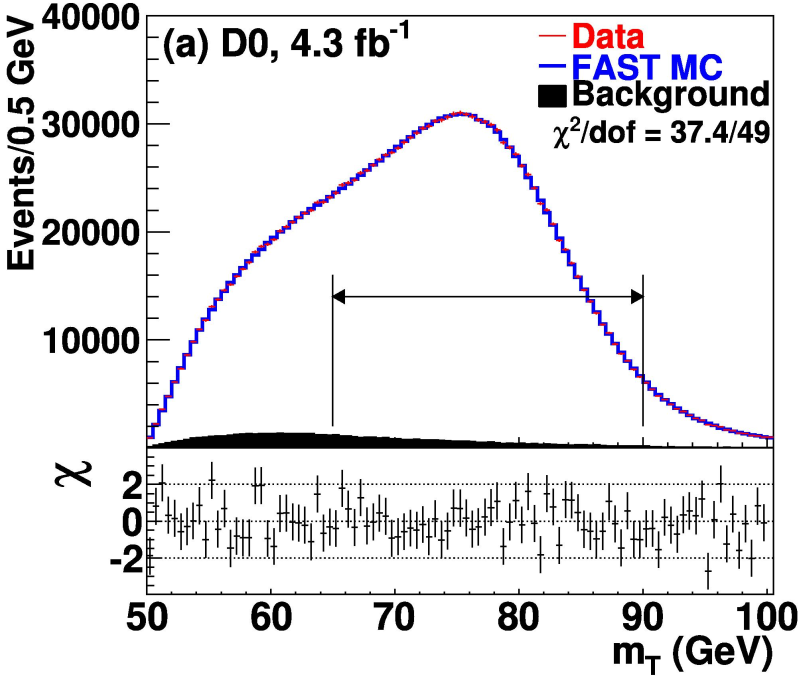
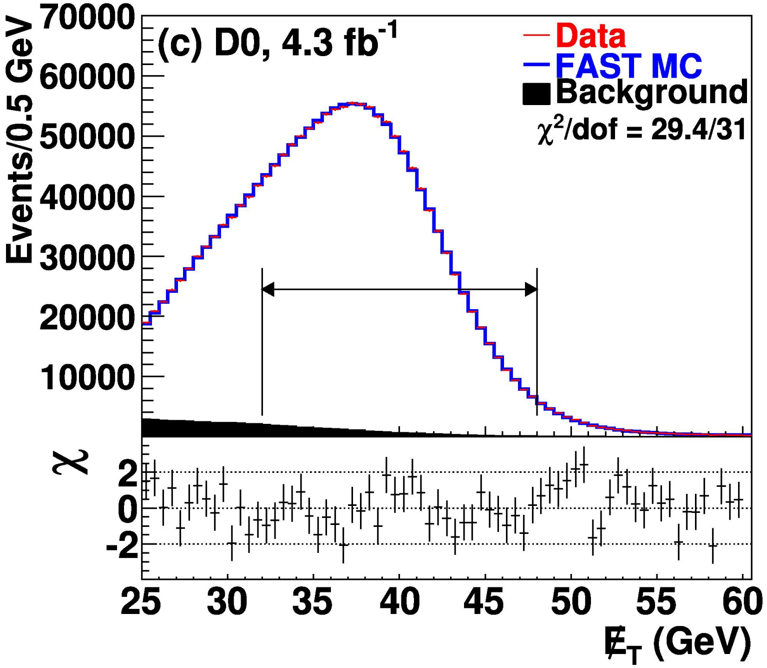


80.371±0.013



80.355±0.015

Knowing the shape & scale ➔ M_W

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Models used to estimate the transfer Z ➔ W

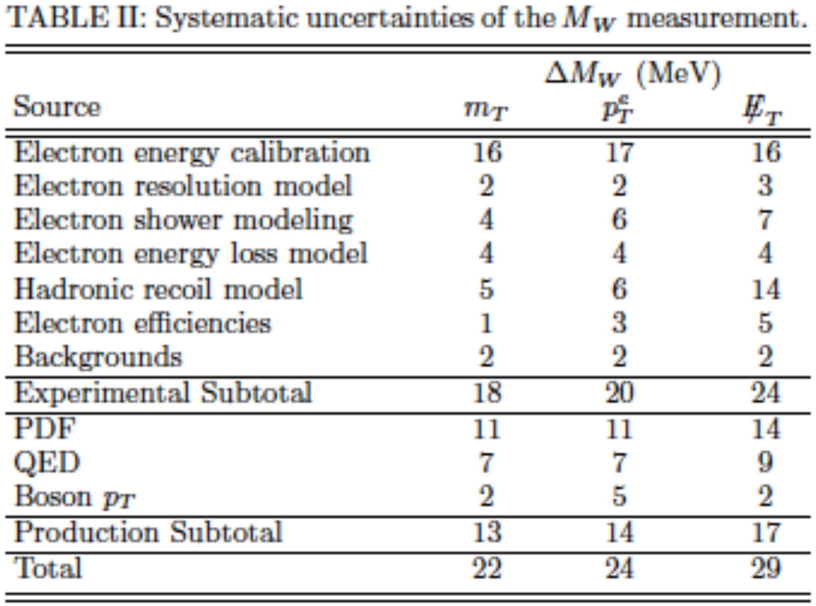

TABLE II: Systematic uncertainties of the M_W measurement.

Source	ΔM_W (MeV) m_T	 p_T^e	 $\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental Subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production Subtotal	13	14	17
Total	22	24	29

Note:
Measurements are to ~ 74% correlated

D0 measurement $M_W = 80.375 \pm 0.023$ GeV

W mass result

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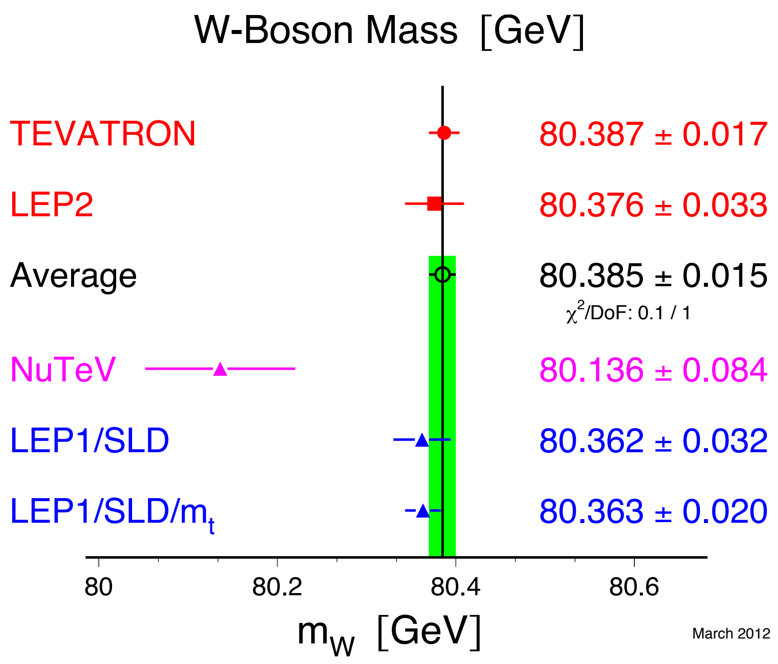
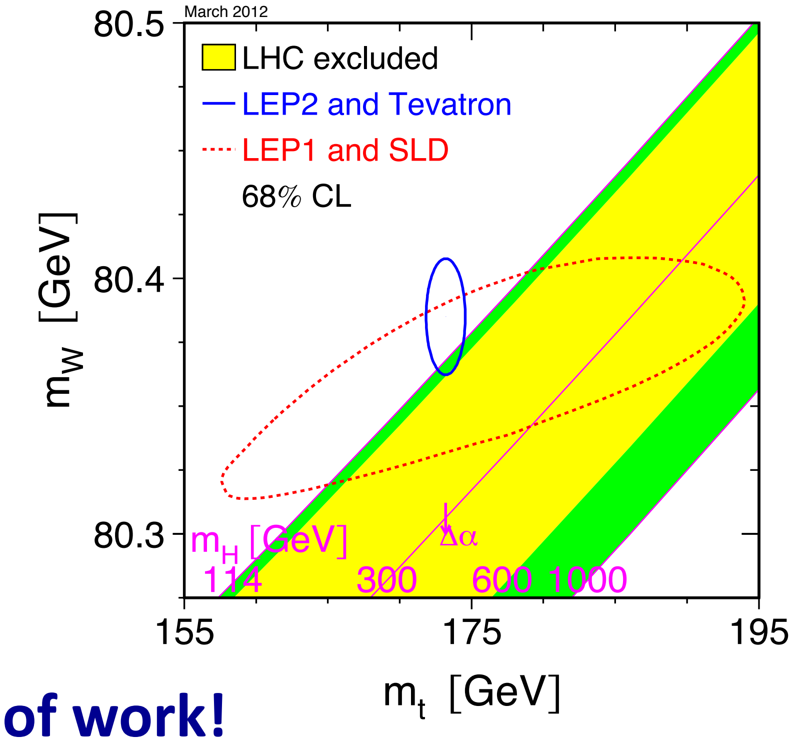
D0 measurement same precision as previous world average





A huge achievement after 20 years of work!

High precision possible at proton colliders

Strong constraint on Standard Model Higgs: mass ‚known‘

Drell – Yan at TeV scale: ee, μμ

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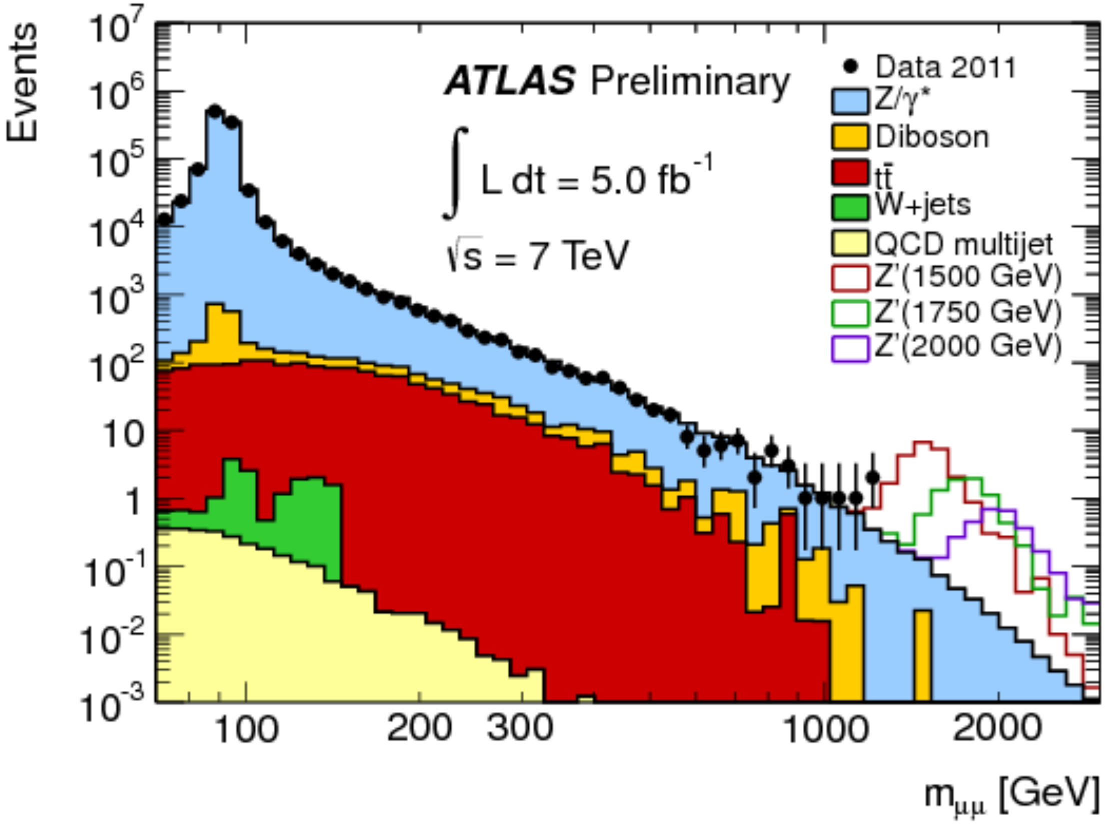

Search for deviations from Drell – Yan prediction

Many models predict ‚excited Z‘

No resonance structure found:
$M_{Z'}$ > 2 TeV (depending on model for new physics)

Drell – Yan at the TeV scale: μν

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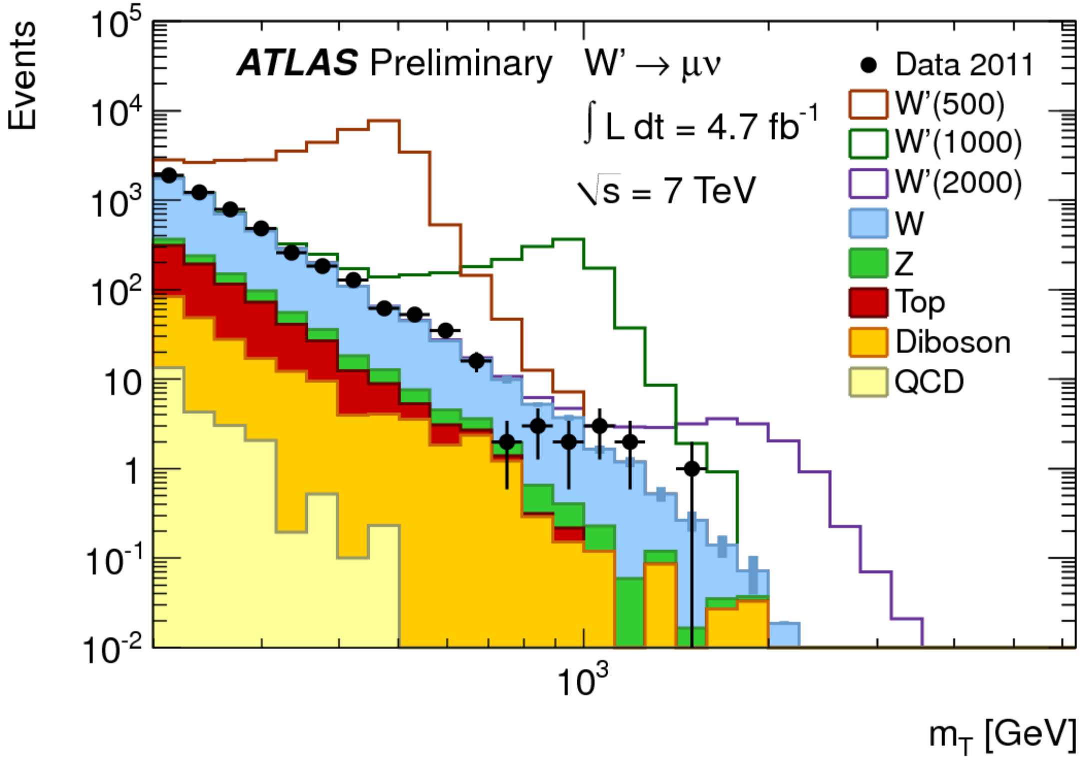
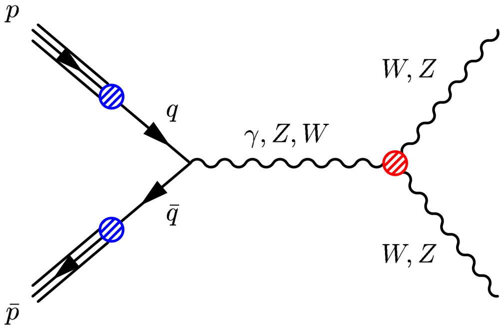


Search for deviations from Drell – Yan prediction

Many models predict ‚excited W‘

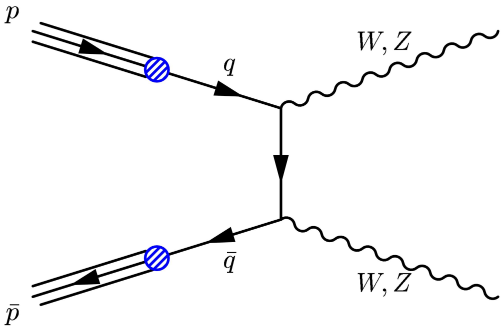
No resonance structure found:
$M_{Z'}$ > 2.5 TeV (depending on model for new physics)

Looking for TGVs (Triple Gauge Boson Vertices)



Vector Boson self interaction due to electrically and weakly charged bosons

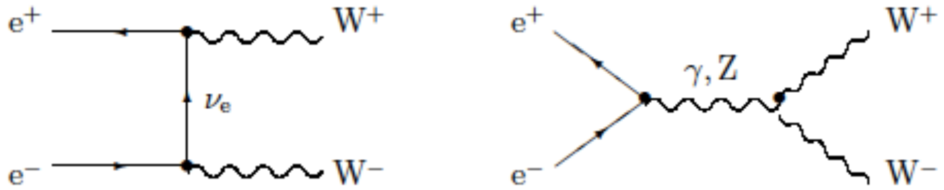
Boson pairs also due to quark exchange

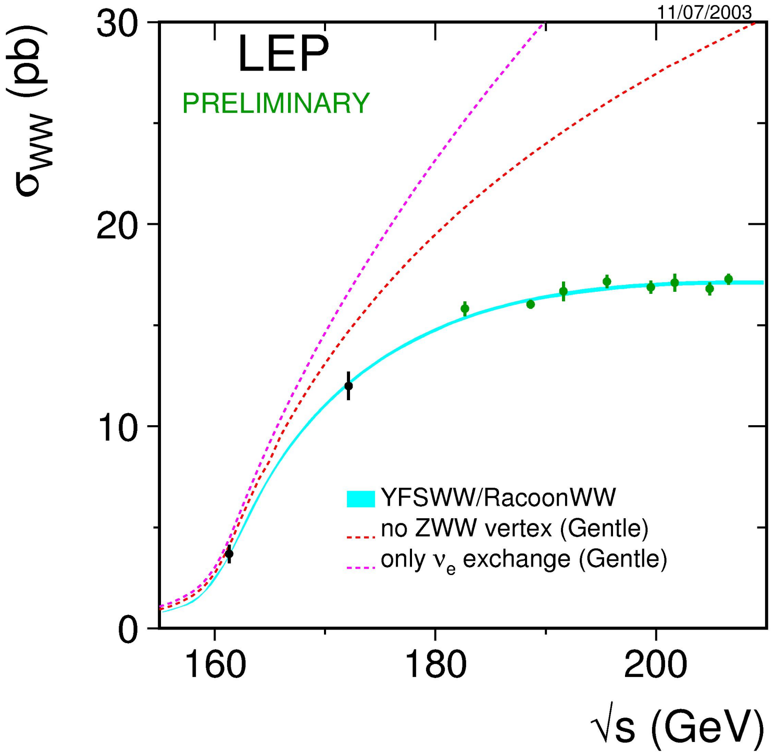


Theoretically NEEDED to cancel Divergencies

Intricate relation of quark/boson couplings

Gauge Boson production in e^+e^-





Without Z^0: cross section infinite

Early motivation to introduce Z^0

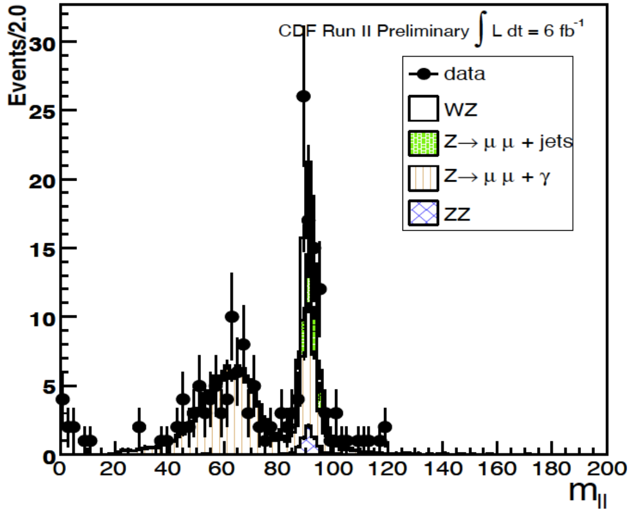
(N.B. general & succesfull recipe: postulate new particles to avoid infinities)

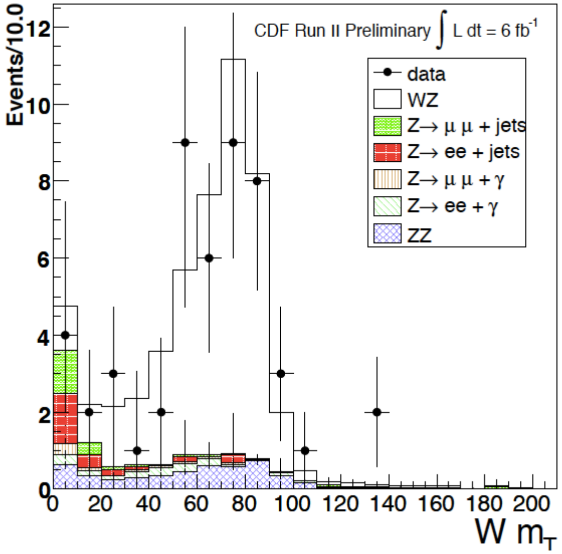
pp – colliders: selecting ZW events

Select events with
three hard leptons + missing E_T

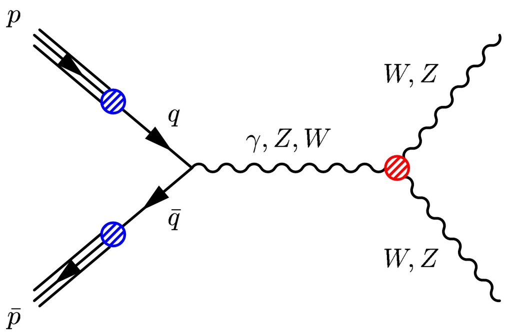
Step 1: select
$Z^0 \rightarrow e^+e^-, \mu^+\mu^-$

Step 2: in residual event
look for mass of
lepton & MET





But are couplings as predicted?



$$\frac{\mathcal{L}_{WWZ}}{g_{WWZ}} = i\left[g_1^Z(W_{\mu\nu}^\dagger W^\mu Z^\nu - W_{\mu\nu}W^{\dagger\mu}Z^\nu) + \kappa^Z W_\mu^\dagger W_\nu Z^{\mu\nu} + \frac{\lambda}{m_W^2}W_{\rho\mu}^\dagger W_\nu^\mu Z^{\nu\rho}\right]$$

Modify g_1, κ, λ and see if prediction agrees with data

- Potential deviations of g_1, λ grow with M^2_{WW}

- Potential deviations of κ grow with M_{WW}

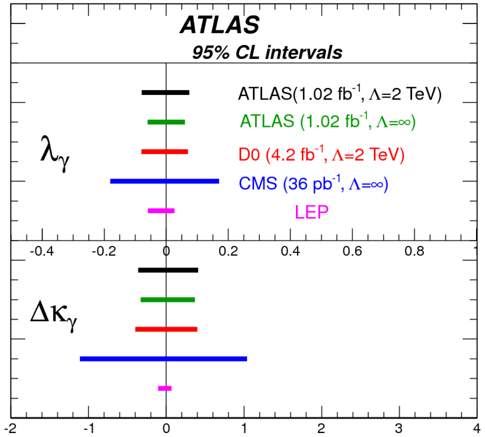
High mass reach at hadron colliders:

special sensitivity to g_1, λ

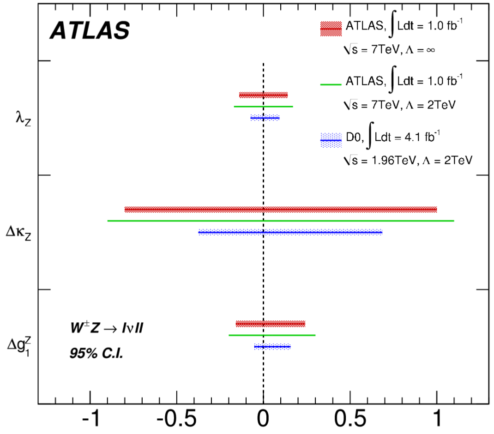
Test at hadron collider

Look at various final states

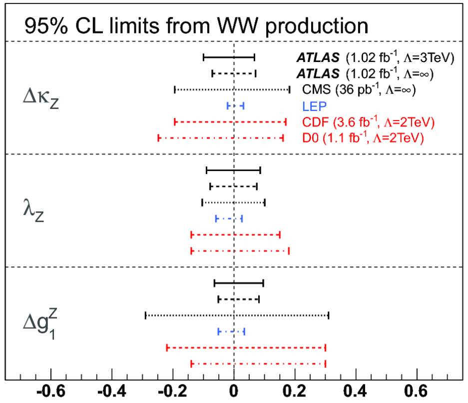
W+γ



W+Z



W+W



LHC experiments starting to become competative!

No deviations observed: strong support for gauge theories

Physics with W, Z @ hadron colliders

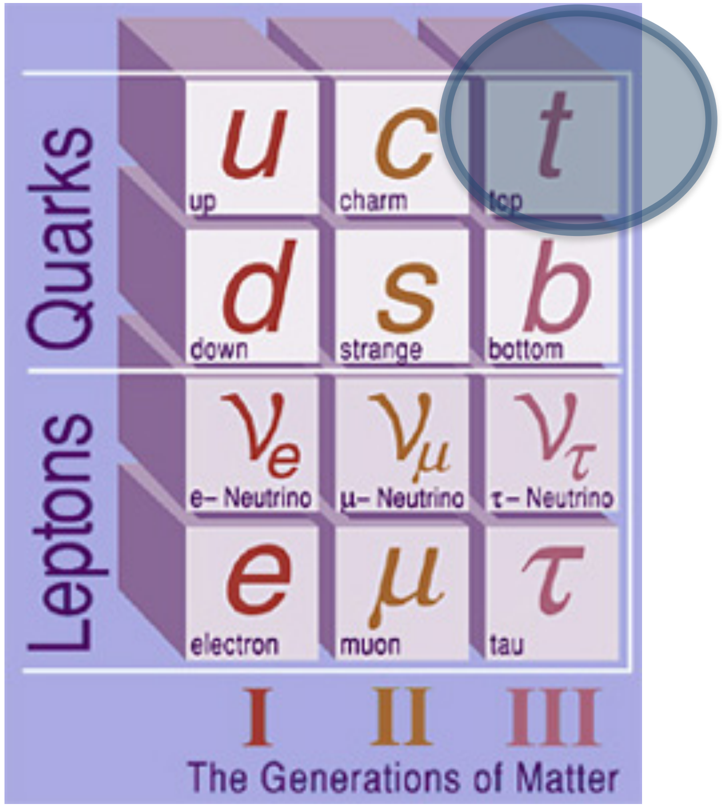
- Millions of Z^0 and $W^\pm$ at the LHC
- Precise tool to constrain parton distribution functions
- Precision measurement of fundamental M_W
- Three – Boson coupling probed to highest energies

Standard Model @ Hadron Colliders
III. Top Quark

P.Mättig

Bergische Universität Wuppertal

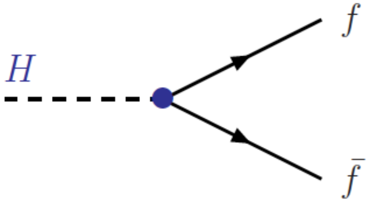
The mysterious top quark



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

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

i.e. coupling strength to Standard Model Higgs Boson



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

➔ $\lambda_t = 0.996 \pm 0.006$

Does the top quark have a special role in particle physics?

A brief history of the top quark

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Known to exist since 1973

Phenomenological prejudice: around 15 GeV

(N.B. (ss) = 1 GeV, (cc) = 3.1 GeV, (bb) = 9.4 GeV, (tt) = 30 GeV ?????? …….)

(Partly) motivating aim for several accelerators:

e^+e^-: PETRA/PEP, TRISTAN, LEP, …. pp: SppS

No signature found!

Observed in 1995 at Tevatron

Up to now a few thousand tt events

LHC currently produces ~ 50000 tt events/day

When default energy/luminosity reached: close to 1M/day

A brief history of the top quark II

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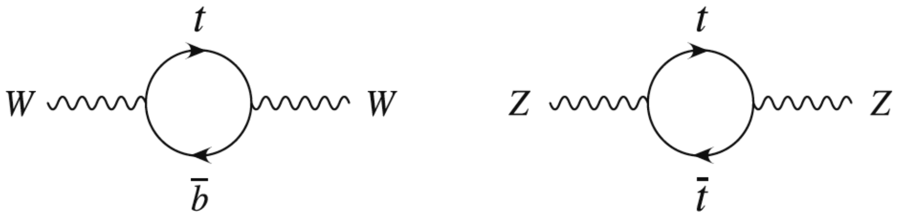
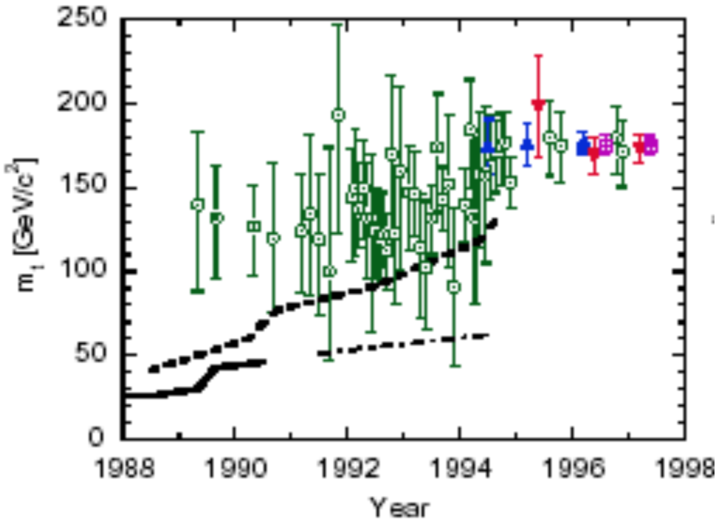
Electroweak quantum fluctuations at percent level: top must be very heavy



Precision measurements & theory in 1994

$$\mathrm{M_t} = 178.8 \pm 20\mathrm{GeV}$$



Phenomenology of heavy top

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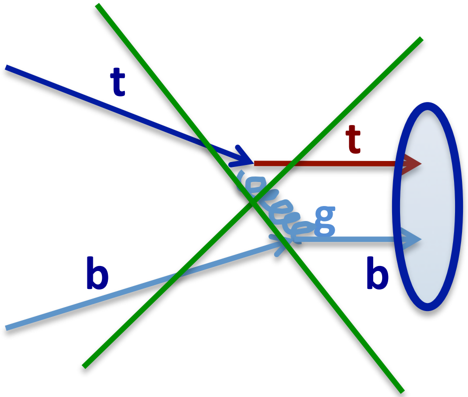
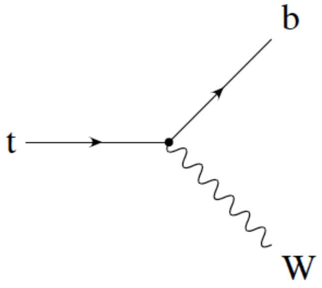
competing interactions:





For lighter quarks: strong interaction >> weak interactions

➔ colour neutral hadrons

For top quark: strong interaction < weak interactions

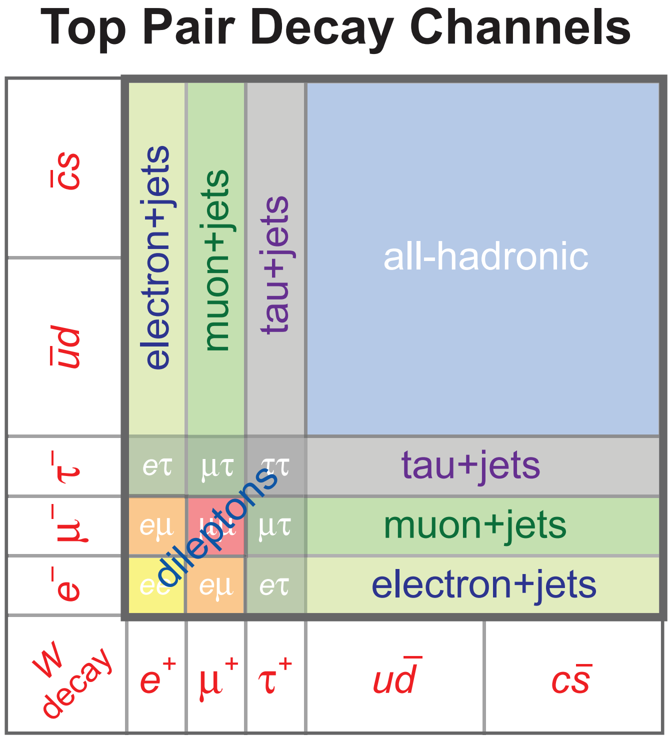
➔ no top hadrons! ‚free quark‘

top quarks decay before hadrons formed

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

Phenomenology of heavy top

Decay properties of top quark unambigously predicted by SM



Top Pair Decay Channels

$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	eτ	μτ	ττ	tau+jets	
μ^-	eμ	μμ	μτ	muon+jets	
e^-	ee	eμ	eτ	electron+jets	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

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

Decay fractions largely determined by fractions of W - decay

A semileptonic tt event

Is the top quark a normal fermion?

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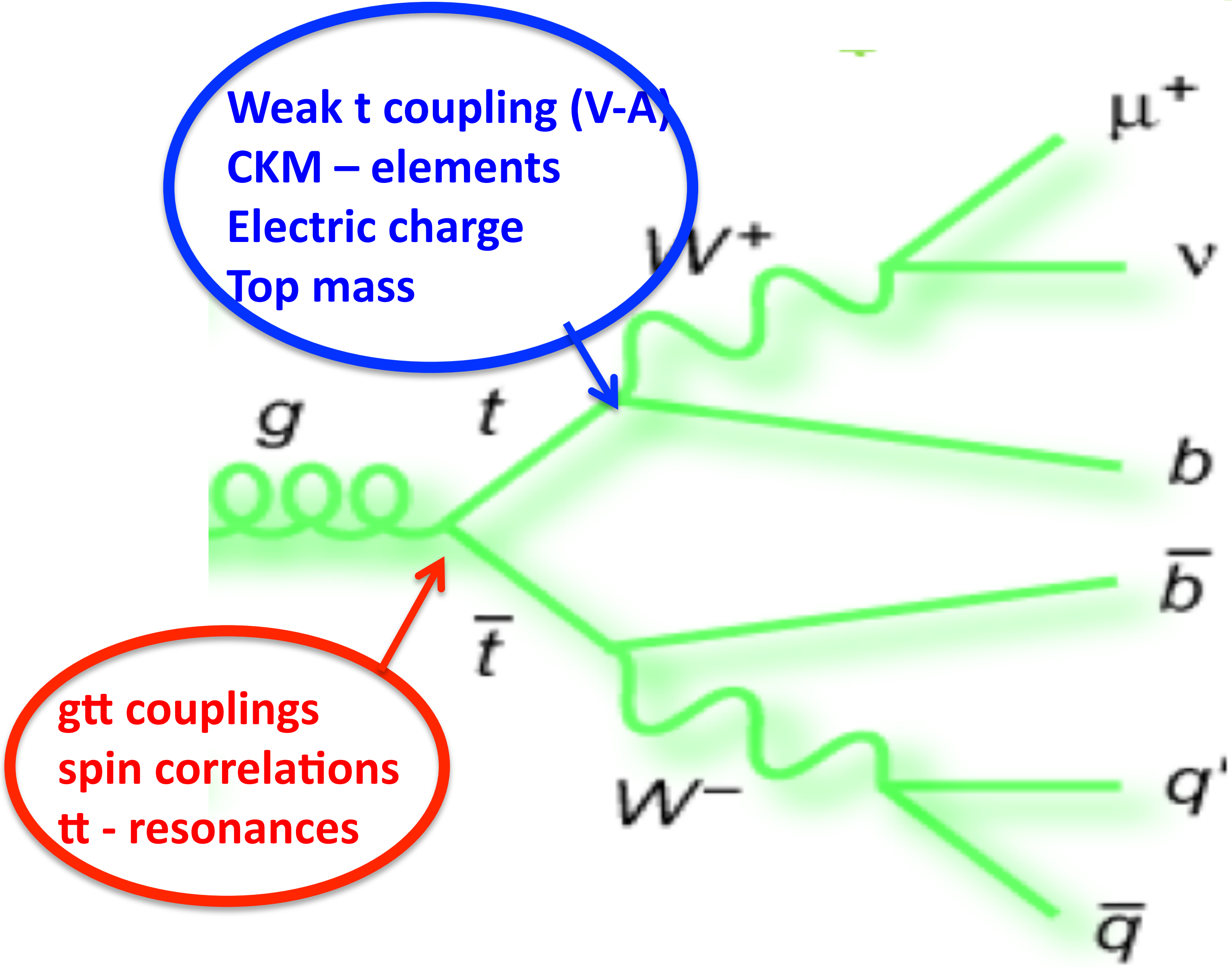

Weak t coupling (V-A)
CKM – elements
Electric charge
Top mass

gtt couplings
spin correlations
tt - resonances

How to measure tt cross section

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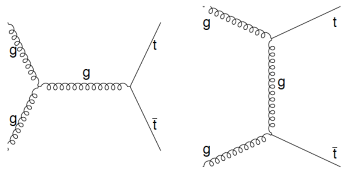
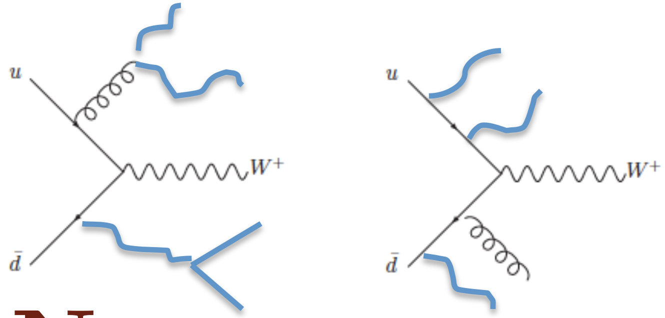


(Why should we?):
Sensitive to gluon –tt couplings
Test of QCD with massive quarks



Select events:
- 4 jets with p_T> 25 GeV
- isolated electron,muon p_T>20 GeV
- missing transverse energy > 20 GeV

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

What fraction of tt
events are retained
after selection

Luminosity:
How many proton-
collisions?

Cross section determination

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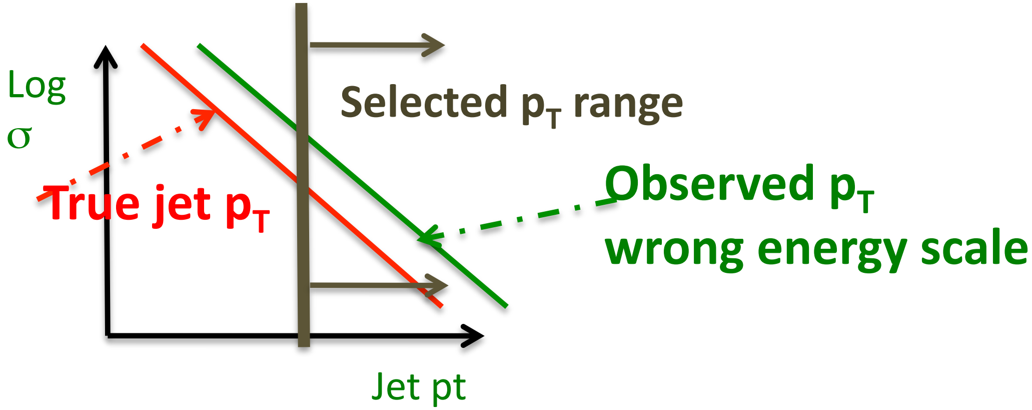
Experimental precision depends on how well
- background, efficiency, luminosity can be controlled

Key issue determine efficiency



Largest uncertainties:
- Jet energy scale
- bottom identification
- Background yield
- Jets from QCD
- selection efficiency
  e, μ, ...

Experimental uncertainty ~ 9%
Luminosity uncertainty ~ 4.4 %

Cross section measuremnt

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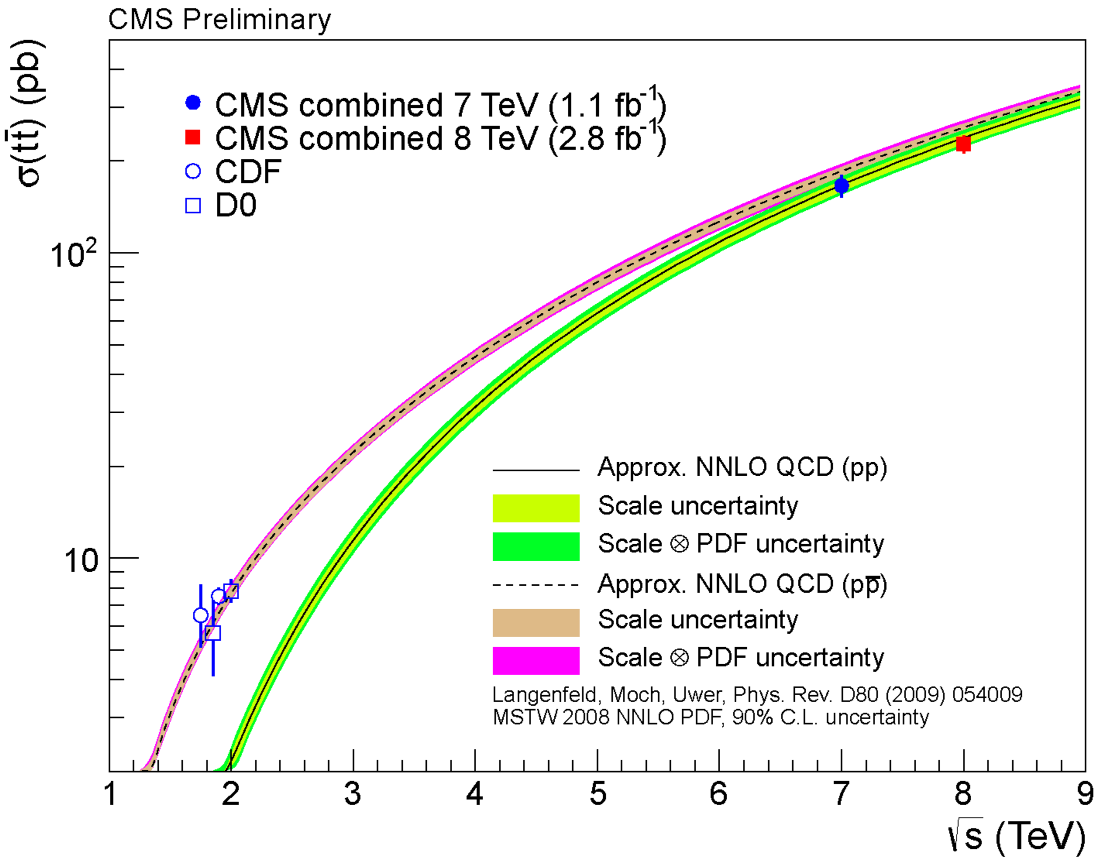

Theoretical uncertainty 7-10% partly NNLO

Theory & experiment uncertainty about equal

Very good agreement between data and expectation

Mass of the top quark

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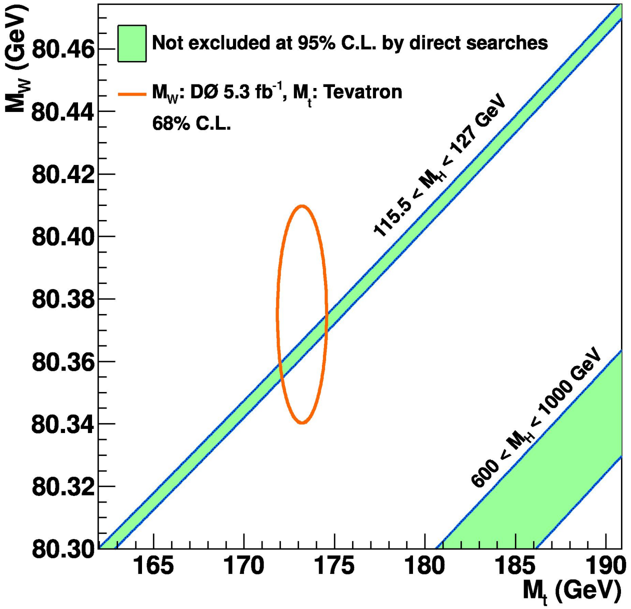
A fundamental parameter of the Standard Model



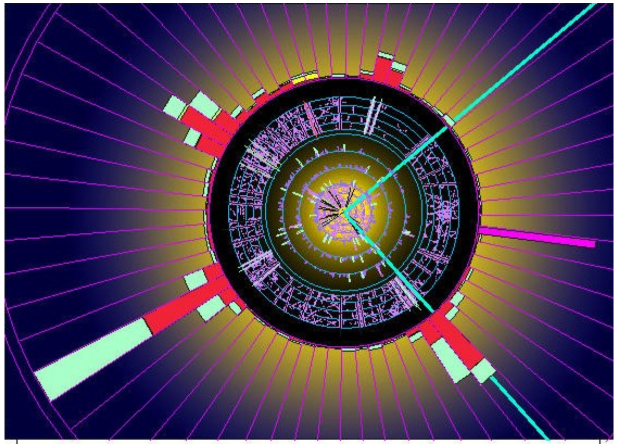
A broad spectrum of decays and methods

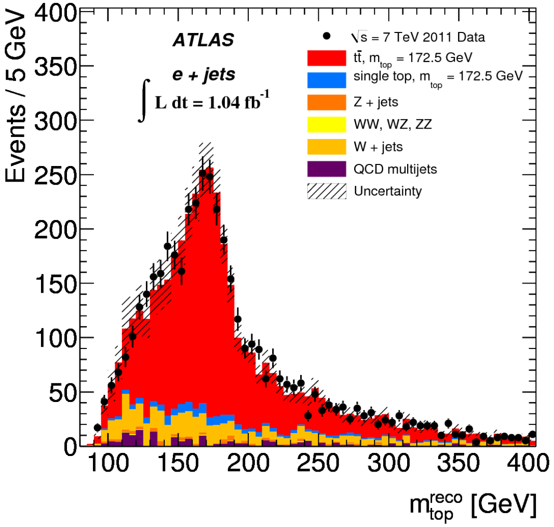
Note: first time a quark mass can be measured directly

(Lighter quarks to be inferred indirectly from hadron masses)

Top mass from l+jet decays

Favoured topology: $t\bar{t}$ ➔ 4 Jets (2 b –jets) + e/μ + ν





$$\mathrm{M}^2 = \Big(\sum_{\mathrm{jet\ i}} \mathrm{E}_{\mathrm{jet\ i}} + \mathrm{E}_{\mathrm{l}} + \mathrm{E}_{\nu}\Big)^2 - \Big(\sum_{\mathrm{jeti}} \tilde{\mathrm{p}}_{\mathrm{jeti}} + \tilde{\mathrm{p}}_{\mathrm{l}} + \tilde{\mathrm{p}}_{\nu}\Big)^2$$

The problems:

- How to get the z – component of ν
- Out of 4 (or more) jets: which jet belongs to which top?
- What is the energy scale of jets (and electrons)

Problem 1: $p_z(\nu)$

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Constraint from W - mass

$$\mathbf{M_W^2 = (E_l + E_\nu)^2 - (p_x(l) + p_x(\nu))^2 - (p_y(l) + p_y(\nu))^2 - (p_z(l) + p_z(\nu))^2}$$

$$\mathbf{E_\nu = \sqrt{p_x^2(\nu) + p_y^2(\nu) + p_z^2(\nu)}}$$

Note: ν – mass completely negligible

Quadratic equation ➔ 2 solutions
physics: in 70% the solution with smaller p_z correct

Problem 2: which jets?

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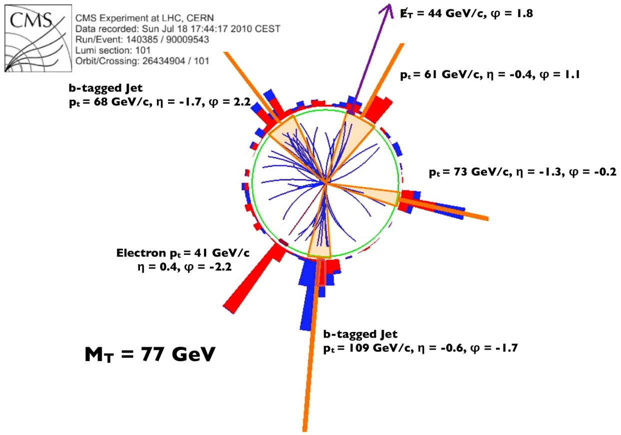


Two facettes:

- **if more than 4 jets (initial state rad.)**
  mostly jets with highest p_T
- **if exactly 4 jets: which belongs to**
  which top quark?

4 jets ➔ 4 possible assigments

$(j_A j_B J_C / j_D,\quad j_A j_B j_D / j_C,\quad ....)$

Note: if b – jets identified, reduced to 2 possibilities

Important constraints

- **mass (jjj) = mass(jlν) (= M_t)**
- **mass (jj) = M_W**

Problem 3: jet energy scale

Measure signals in calorimeter ➔ derive jet energy

Implies uncertainty!

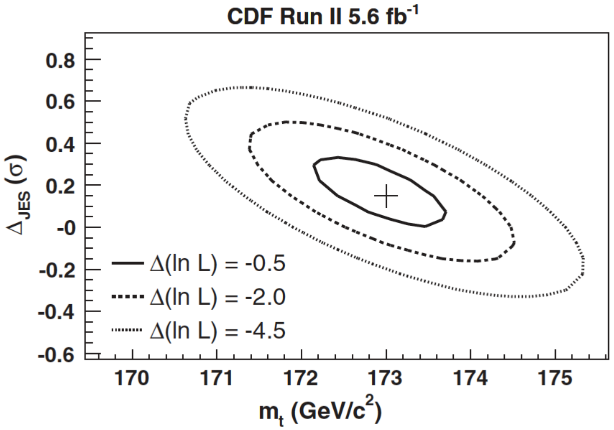
➔ relates directly to top mass

$$M^2 = \left(\sum_{\text{jet } i} E_{\text{jet } i} + E_l + E_\nu\right)^2 - \left(\sum_{\text{jet}i} \tilde{p}_{\text{jet}i} + \tilde{p}_l + \tilde{p}_\nu\right)^2$$

Top – quarks offer ‚self calibration‘

M(jj) has to be equal M_W

➔ change JES such that fulfilled

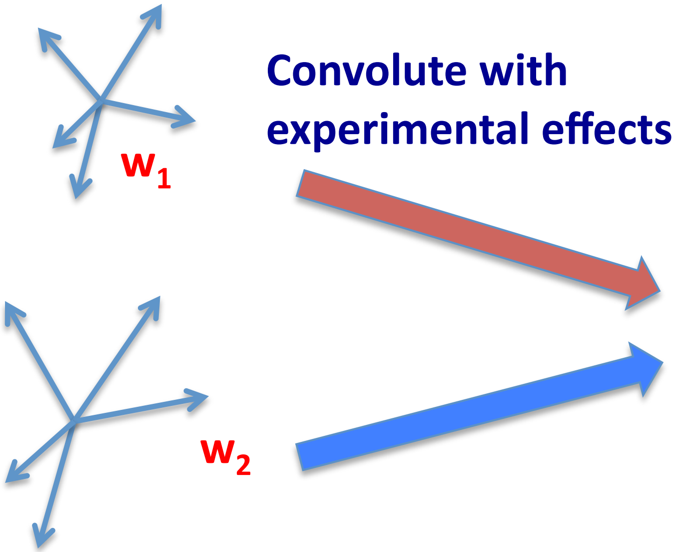


Still the (slightly) dominant uncertainty of M_t

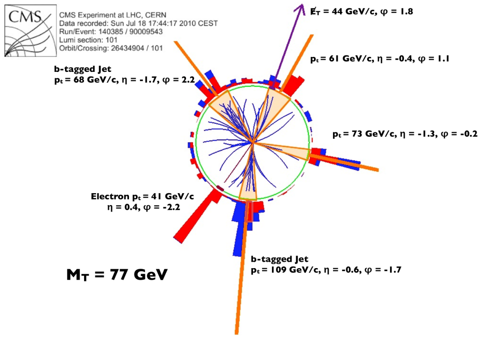
Use all information

Theoretical pred with M_1(top)

Theoretical pred with M_2(top)



Convolute with experimental effects



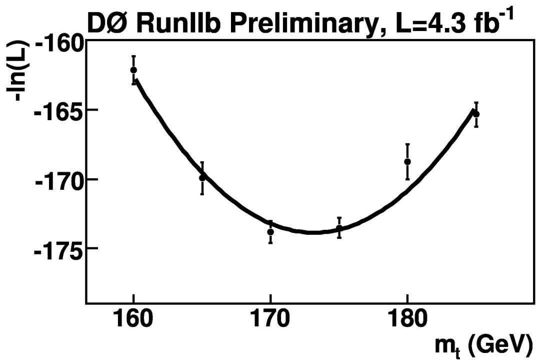
Sum over all events and find combine weights

$$\mathrm{W(M_1(top)) = w_A \cdot w_B \cdot w_C \cdot \ldots\ldots = \Pi w_i} \Longrightarrow \mathcal{L}(\mathrm{M_1(top)})$$

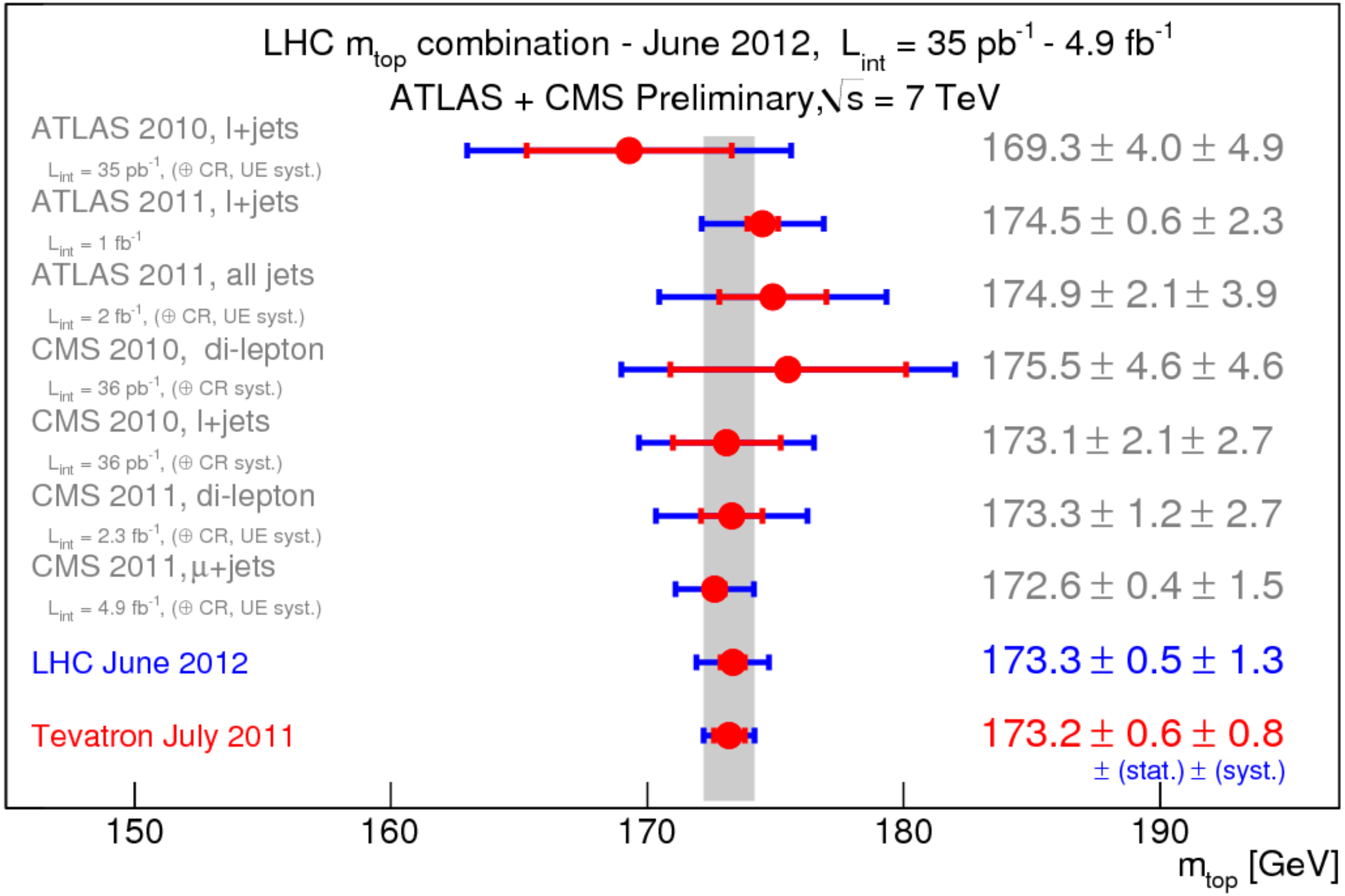
$$\mathrm{W(M_2(top)) = w_A \cdot w_B \cdot w_C \cdot \ldots\ldots = \Pi w_i} \Longrightarrow \mathcal{L}(\mathrm{M_2(top)})$$

……

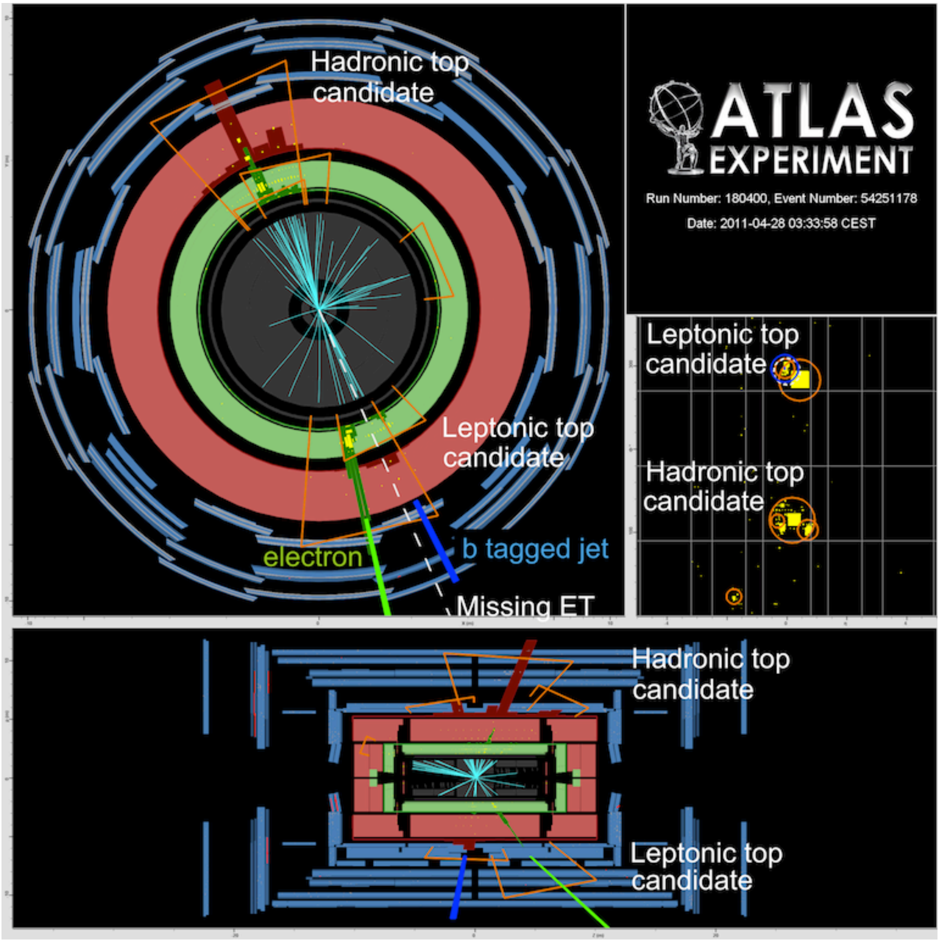
Find M(top) with maximum weight



Measurements of M_{top}



Production properties: e.g. M_{tt}



N.B. High p_T top quarks: jets merge! ‚Boosted Top Quarks'

New algorithms required

Searching for a tt - resonance

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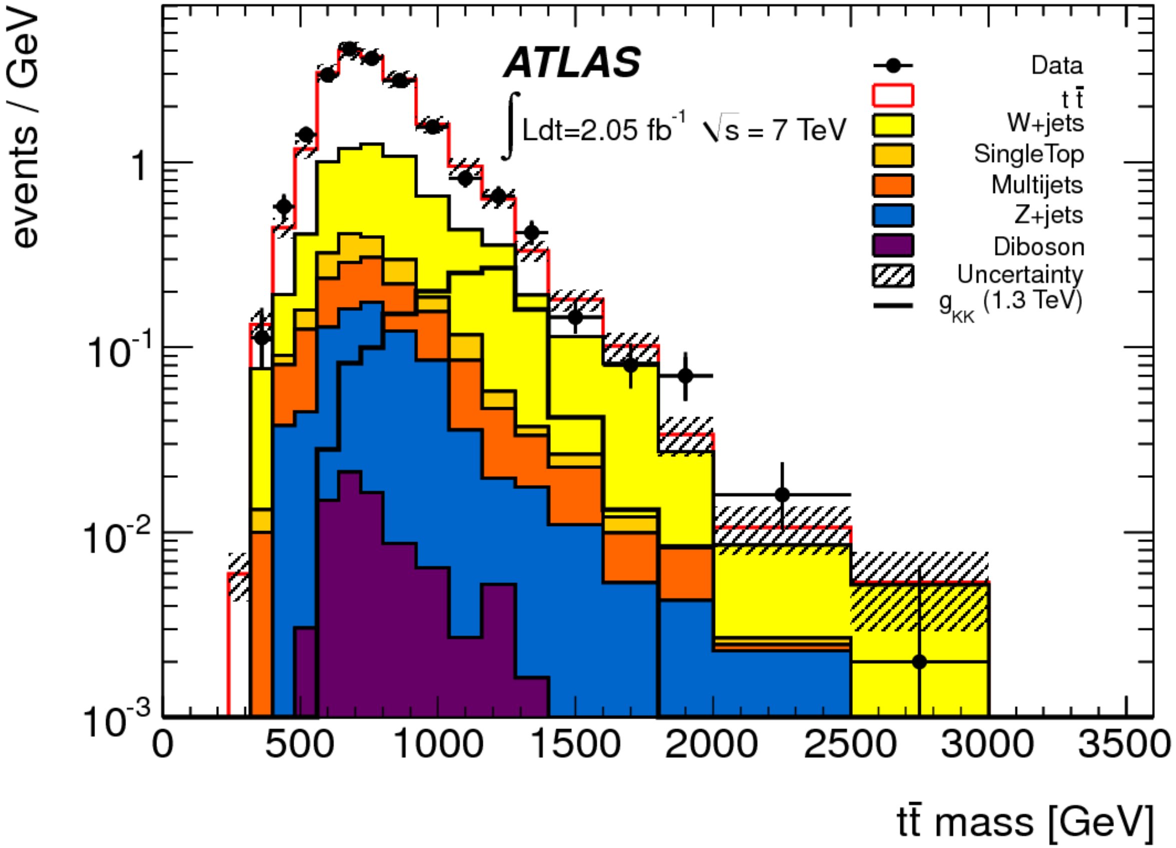

Postulated in many BSM scenarios

➔ at this stage no new particle observed

Back - up

Production of top quarks

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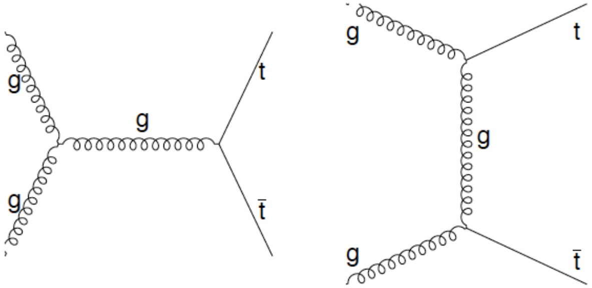
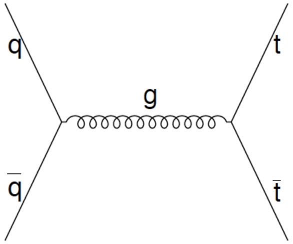
What x required for top production?

$$\sqrt{x_1 \cdot x_2} \geq \frac{2 \cdot M_t}{E_{pp}} \left\{ \begin{array}{l} \text{0.18 at Tevatron} \\ \\ \text{0.05 at LHC (0.025 @ 14 TeV)} \end{array} \right.$$

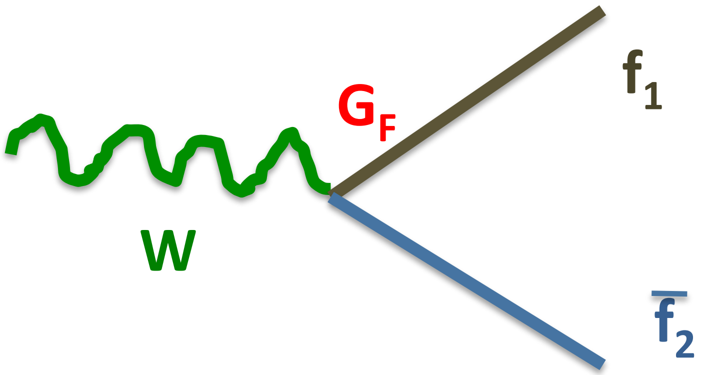


Dominant at LHC for low M_{tt}
Suppressed @ Tevatron



Relevant at LHC for high M_{tt}
Dominant @ Tevatron

Flavour universality in W decay



G_F weak coupling constant determines ‚how fast' W decays

G_F independent of f!

Decay of W the same for (at least in first order ...)

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}\underbrace{\begin{pmatrix}u\\ d\end{pmatrix}_{\mathbf{blue}}\begin{pmatrix}u\\ d\end{pmatrix}_{\mathbf{red}}\begin{pmatrix}u\\ d\end{pmatrix}_{\mathbf{green}}}\;\cdots\cdots$$

9 possible decays

11% 11% 11% 33%

decay fraction of W