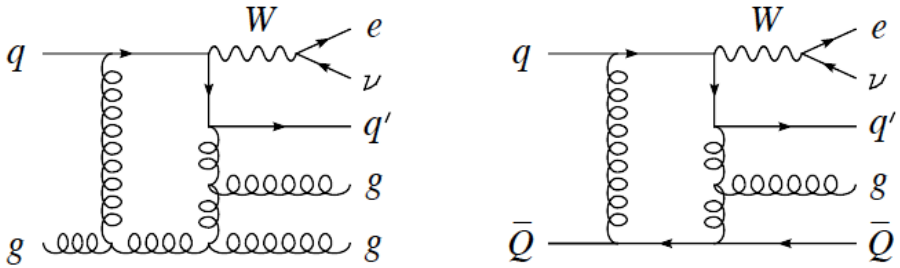
Standard Model @ Hadron Colliders
VI. W/Z + Jets (cont)

W/Z + Jets



Example: W + 3 Jets

A QCD process theoretically quite well understood
Important background for many BSM/Higgs processes

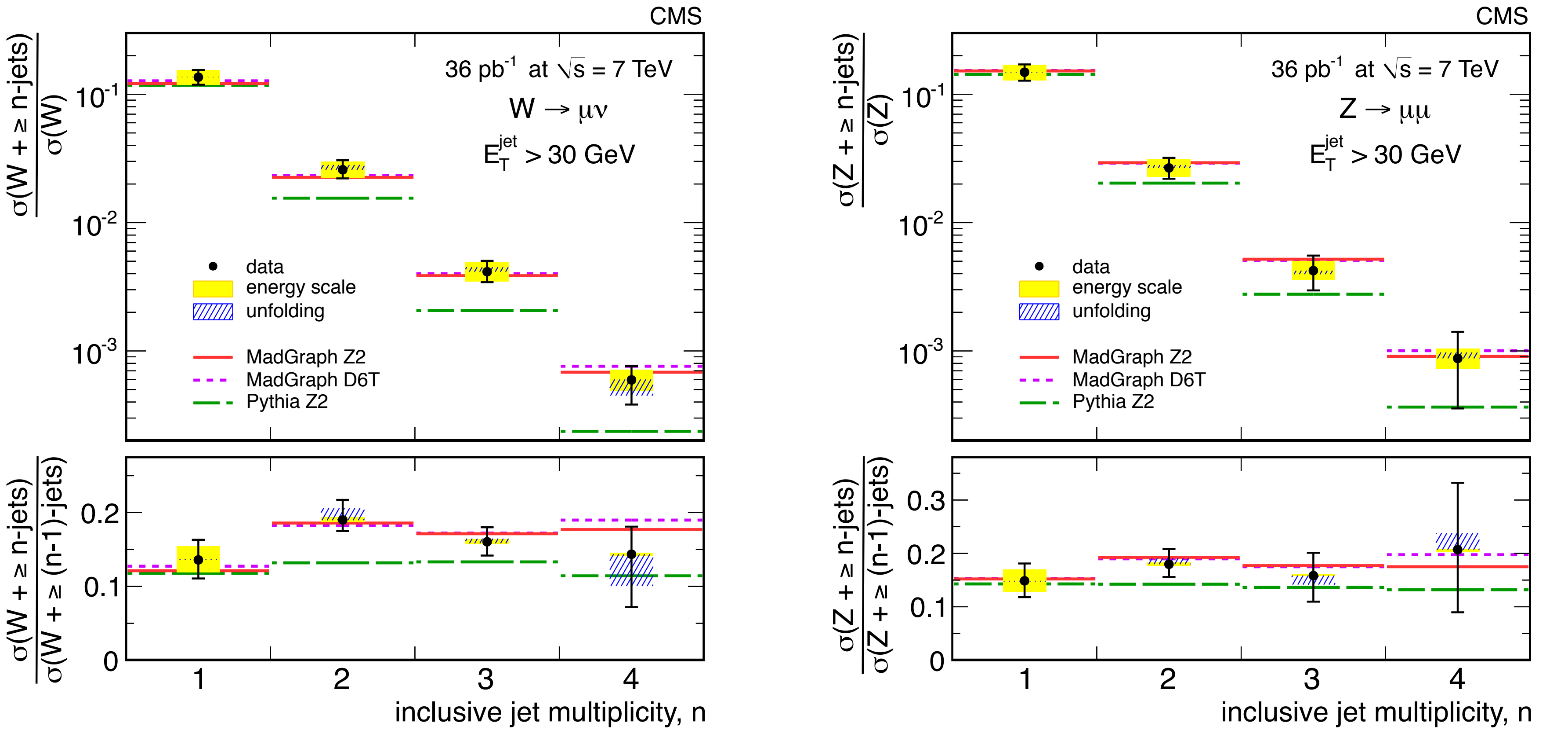
- Z & W + jets should have the same topology
- Simple minded approach

$$\mathbf{R(n)} = \frac{\sigma(\mathbf{V} + (\mathbf{n}+\mathbf{1})\ \text{jets})}{\sigma(\mathbf{V} + \mathbf{n}\ \text{jets})} = \alpha_{\mathbf{s}} = \text{constant}$$

‚Berends – Giele' scaling

Can be tested for the first time with high statistics and many jets

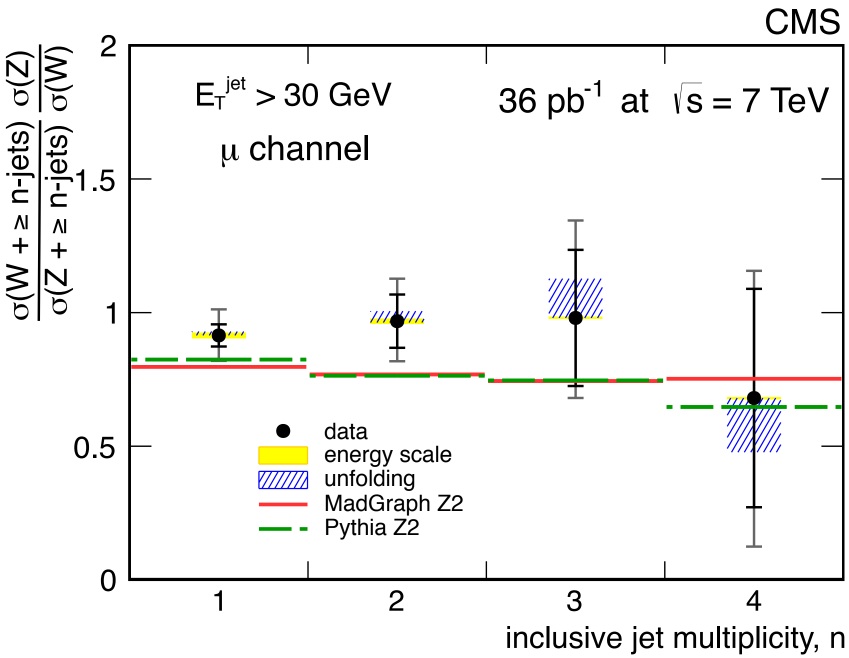
W/Z + Jets

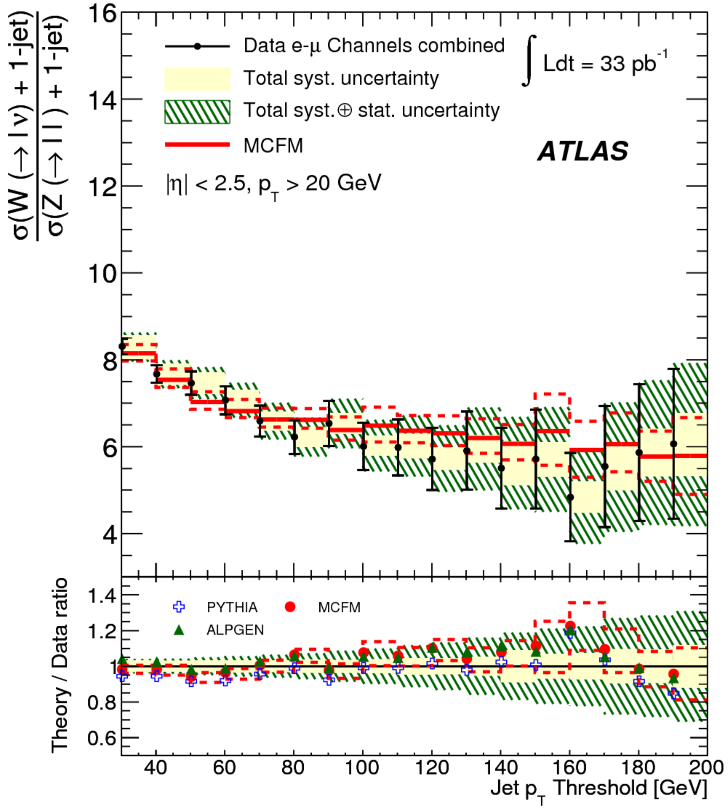


Test of Berends – Giele:

Fairly well confirmed, note model dependence

W/Z + Jets





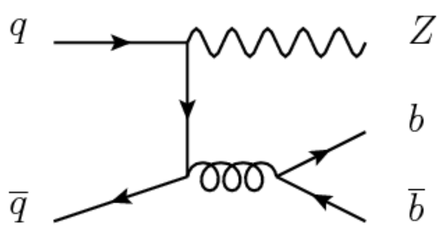
Z and W production fairly equal dependence in jet multiplicity

However, Z jets have harder p_T spectrum

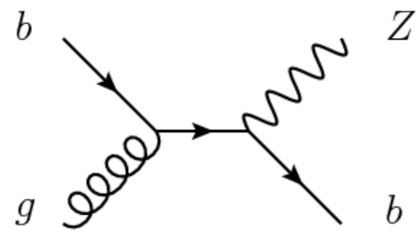
Note: some deficiencies of simulation?

W/Z + bottom Jets

BERGISCHE UNIVERSITÄT WUPPERTAL



Similar for W/Z



Much larger Zbb cplg. than Wcb

The virtue of measuring these processes:

- understand background for processed like top pairs, V+H(bb)
- Potential for measuring (charm) + (bottom) pdf

CMS measurement (within cuts)

σ(Z+b+X) = 5.84± 0.08 (stat.)± 0.72 (syst.)$^{+0.25}_{-0.44}$(theory) pb

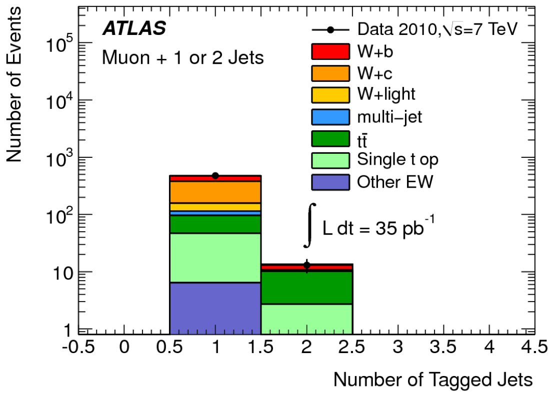
σ(Z+bb+X)= 0.37± 0.02 (stat.)± 0.07 (syst.)±0.02(theory) pb

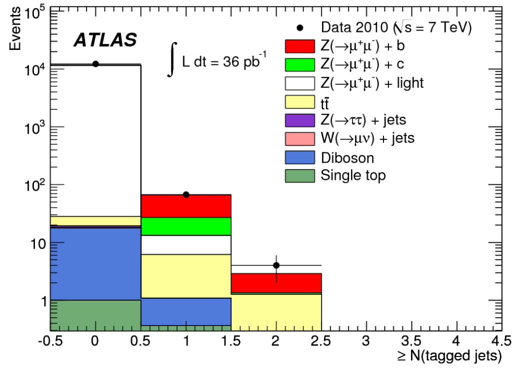
Matrix element calculations in agreement

cp. Inclusive Z – production ~ 1 nb

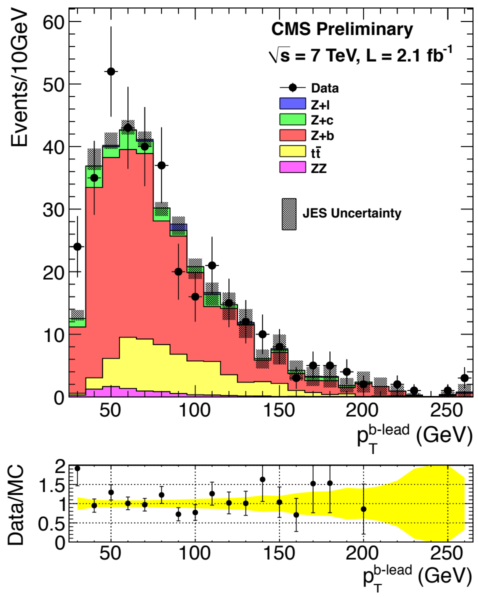
BERGISCHE UNIVERSITÄT WUPPERTAL

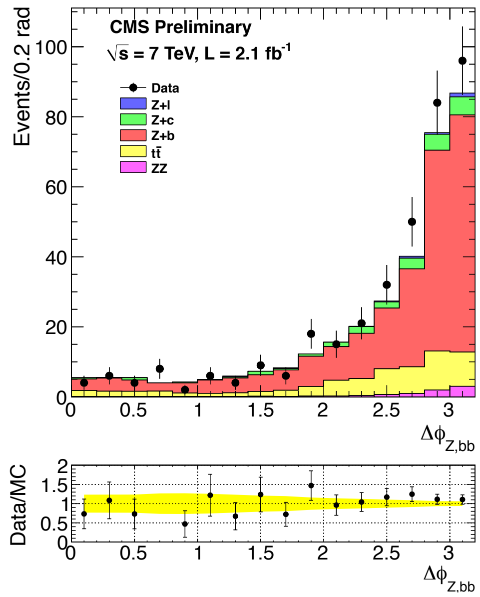
W vs. Z + bottom Jets





Fraction of bottom larger in Z^0 events

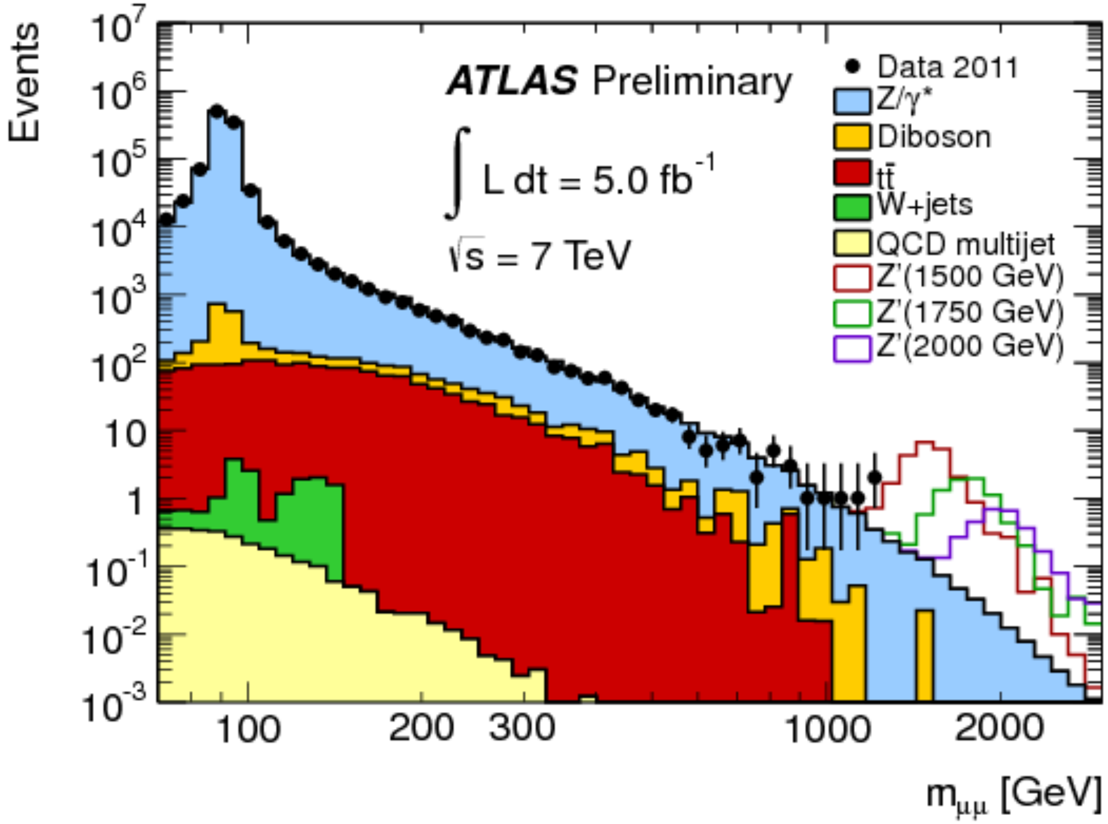




Properties of b – system in Z^0 events agree with expectation

Drell – Yan at TeV scale: ee, μμ

BERGISCHE UNIVERSITÄT WUPPERTAL



Search for deviations from Drell – Yan prediction

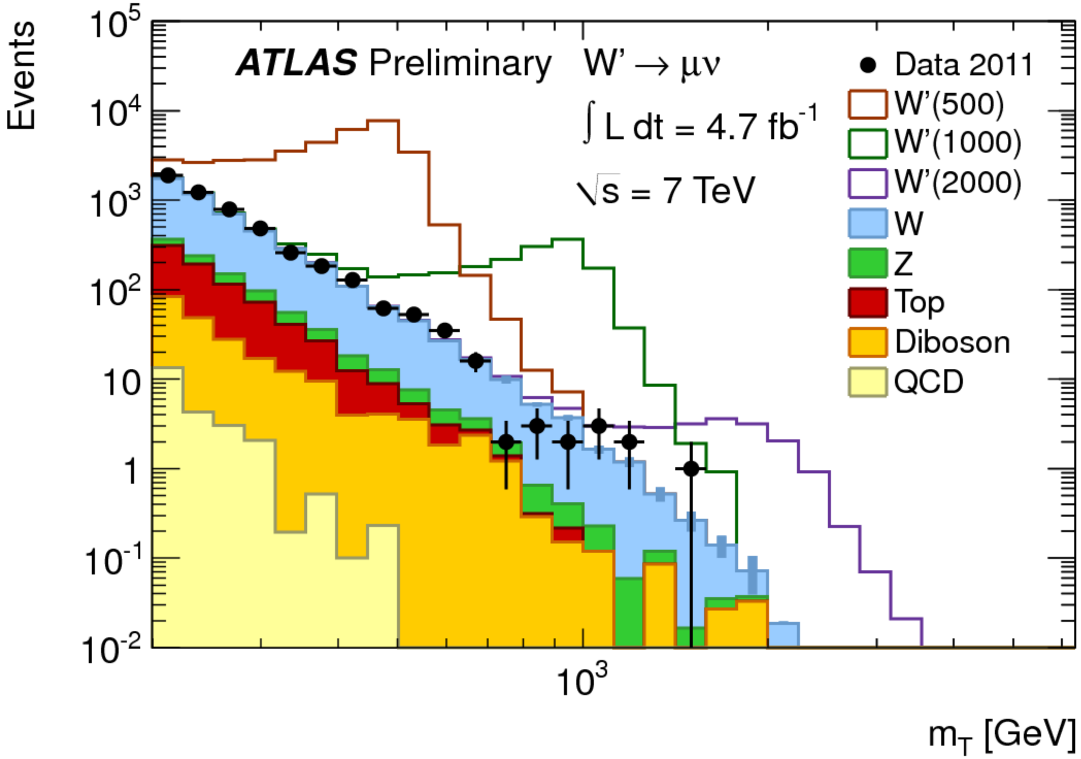
Many models predict ‚excited Z'

No resonance structure found:

$M_{Z'} > 2$ TeV (depending on model for new physics)

Note: could also be used to probe (qqll) compositeness

Drell – Yan at the TeV scale: $\mu\nu$



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)

BERGISCHE UNIVERSITÄT WUPPERTAL

Standard Model @ Hadron Colliders
VII. Electroweak effects with W/Z

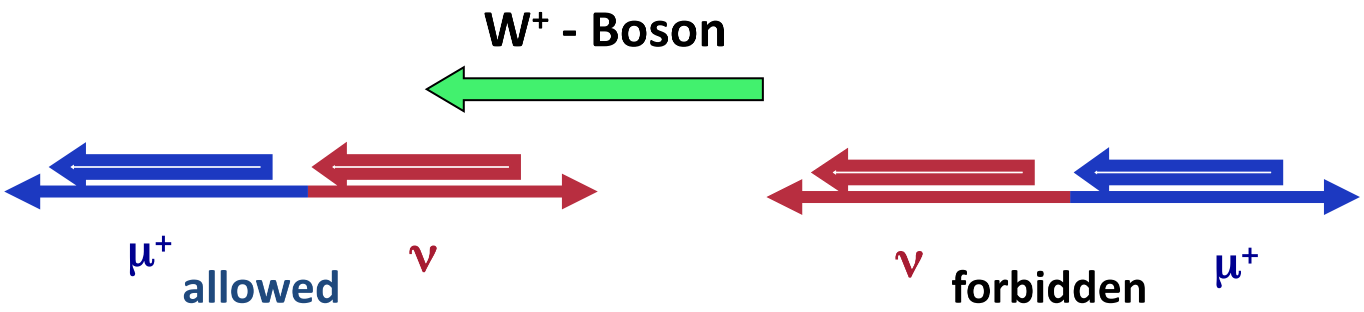
Polarisation of W

BERGISCHE UNIVERSITÄT WUPPERTAL

Assume production of W^+ by valence u – quark:

Spin of W^+ opposite to flight direction

Decay of W^+ - Boson



Flight direction of μ^+ opposite to incoming valence quark

Decay angles for W – helicity states:

$$\mathbf{W_{\pm}} : \quad \mathbf{3/8} \cdot (\mathbf{1} \mp \cos\theta^*)^{\mathbf{2}} \qquad \mathbf{W_L} : \quad \mathbf{3/4} \cdot \sin^{\mathbf{2}}\theta^*$$

At LHC

BERGISCHE UNIVERSITÄT WUPPERTAL

High y: u – quark valence quarks → W Spin against flight direction
Central y: u – quark sea quarks → Both W helicities

Additional modifications due to QCD effects → high p_T also W_{Long}

$$\frac{d\sigma}{d(p_T^W)^2 dy_W \, d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma^u}{d(p_T^W)^2 dy_W} \times \Big[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big] \quad (1)$$

↑ ↑

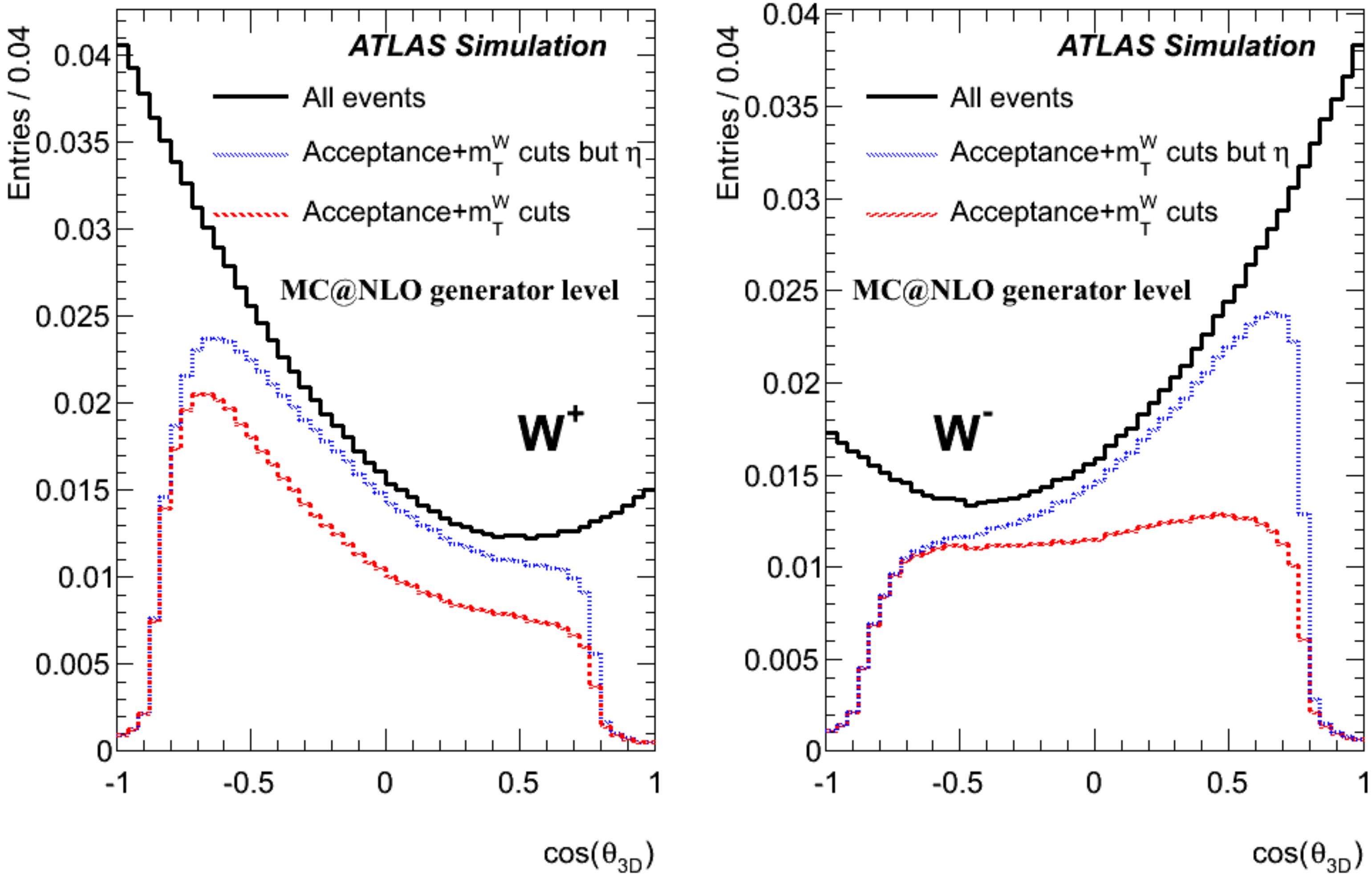
Note dependence on production properties

Compress into helicity components

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_{3D}} = \frac{3}{8}f_L(1-\cos\theta_{3D})^2 + \frac{3}{8}f_R(1+\cos\theta_{3D})^2 + \frac{3}{4}f_0\sin^2\theta_{3D}$$

Detector effects

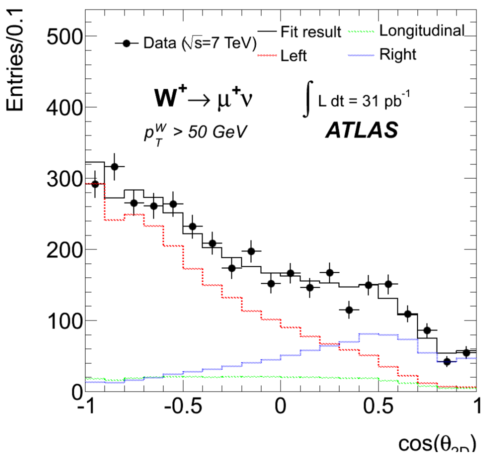
BERGISCHE UNIVERSITÄT WUPPERTAL

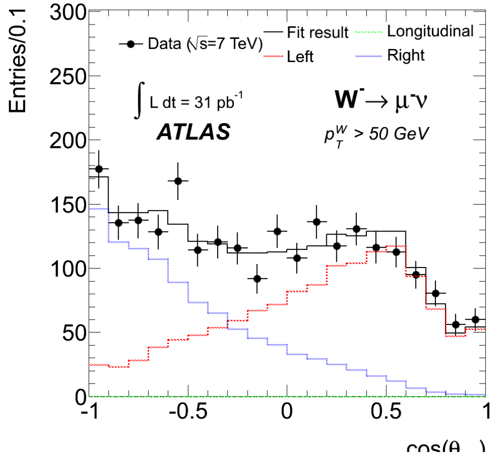


Measurement of W polarisation

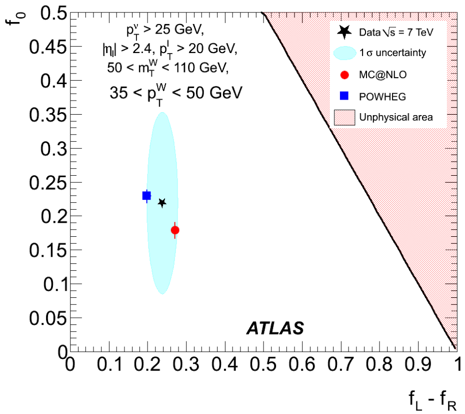
BERGISCHE UNIVERSITÄT WUPPERTAL

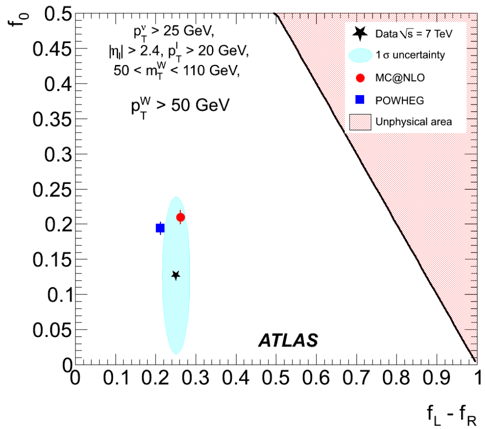
Measurement 2D angle instead of 3D





Expected differences between W^+ and W^-





Good agreement with NLO simulation

W – helicity important ingredient for other measurements

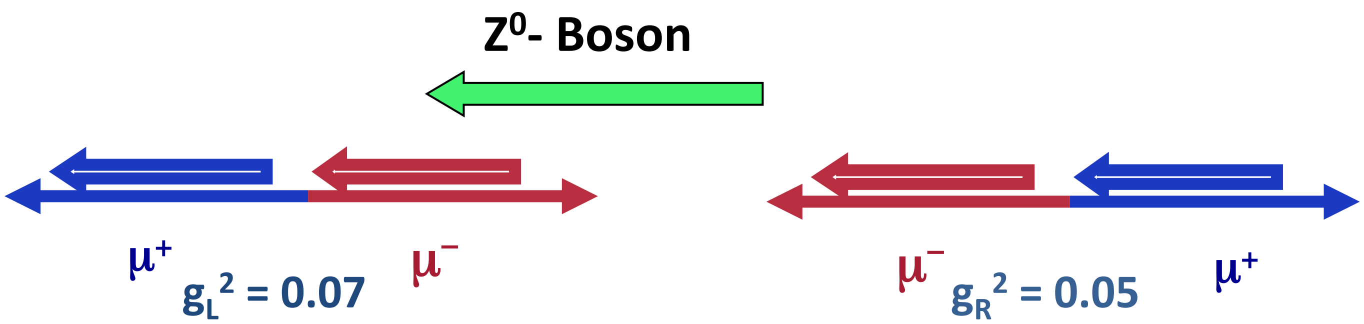
Polarisation of Z^0

BERGISCHE UNIVERSITÄT WUPPERTAL

Assume production of Z^0 by valence u – quark:

‚preference' for left handed Z^0

Decay of Z^0- Boson



‚slight' preference for μ^- in up – quark direction

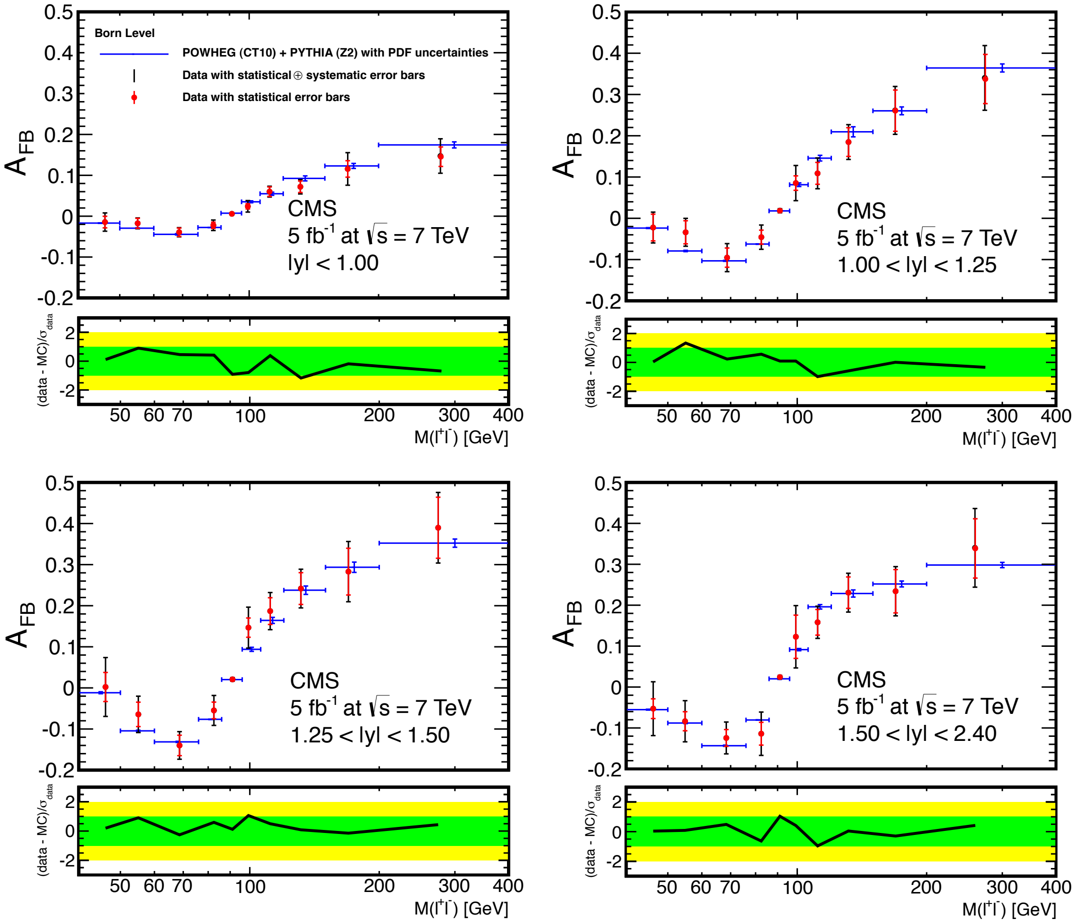
Forward – Backward Asymmetry @ Z^0

BERGISCHE UNIVERSITÄT WUPPERTAL

Central rapidity range: no clearly defined u/d direction
➔ ‚low' asymmetry

Valence quarks at high y
➔ ‚high' asymmetry

Less precise than LEP
Sensitivity to higher masses
➔ additional sensitivity to new resonances



The W mass

BERGISCHE UNIVERSITÄT WUPPERTAL

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

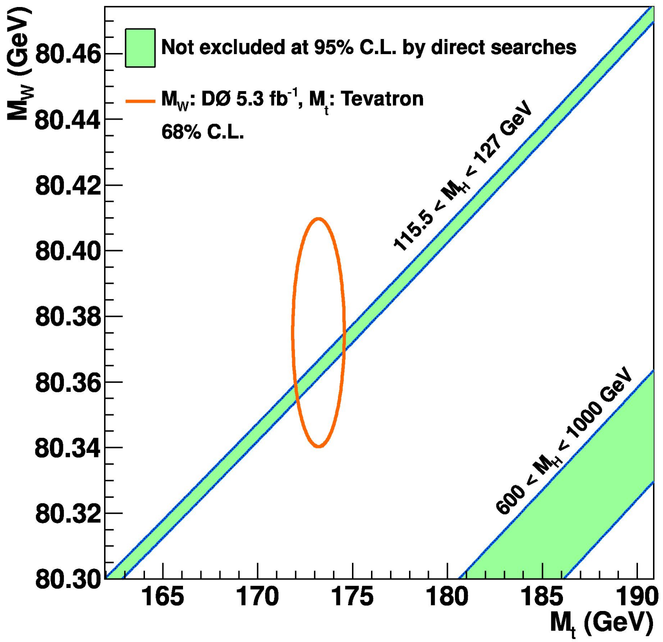
Radiative corrections Δr

➔ sensitivity to mass of Higgs boson

Precise measurement @ LEP:

80.376 ± 0.033 GeV

$$G_\mu = \frac{\pi\alpha}{\sqrt{2}} \frac{1}{M_W^2 \sin\theta_W} \frac{1}{1 - \Delta r}$$



Mass determination at hadron coll.

BERGISCHE UNIVERSITÄT WUPPERTAL

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?**

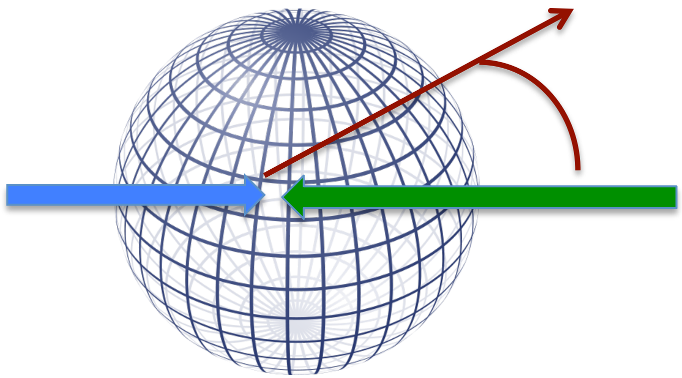
- **Use well known M_Z to calibrate energy scale**
- **consider only transverse momentum of ν identify with ‚missing transverse energy'**

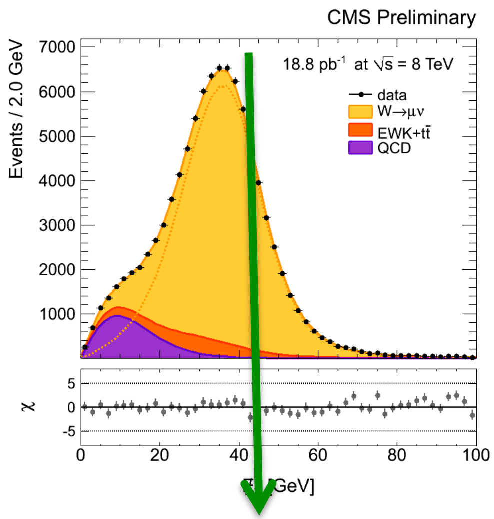
$$\mathbf{M_W^2 = (E_l + E_\nu)^2 - (\tilde{p}_l + \tilde{p}_\nu)^2 > (E_l + MET)^2 - (\tilde{p}_l + M\tilde{E}T)^2}$$

W mass at hadron coll.

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

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





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

Sharp edge

Jacobian peak

BERGISCHE UNIVERSITÄT WUPPERTAL

Relation mass ⇔ lepton transverse momentum

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

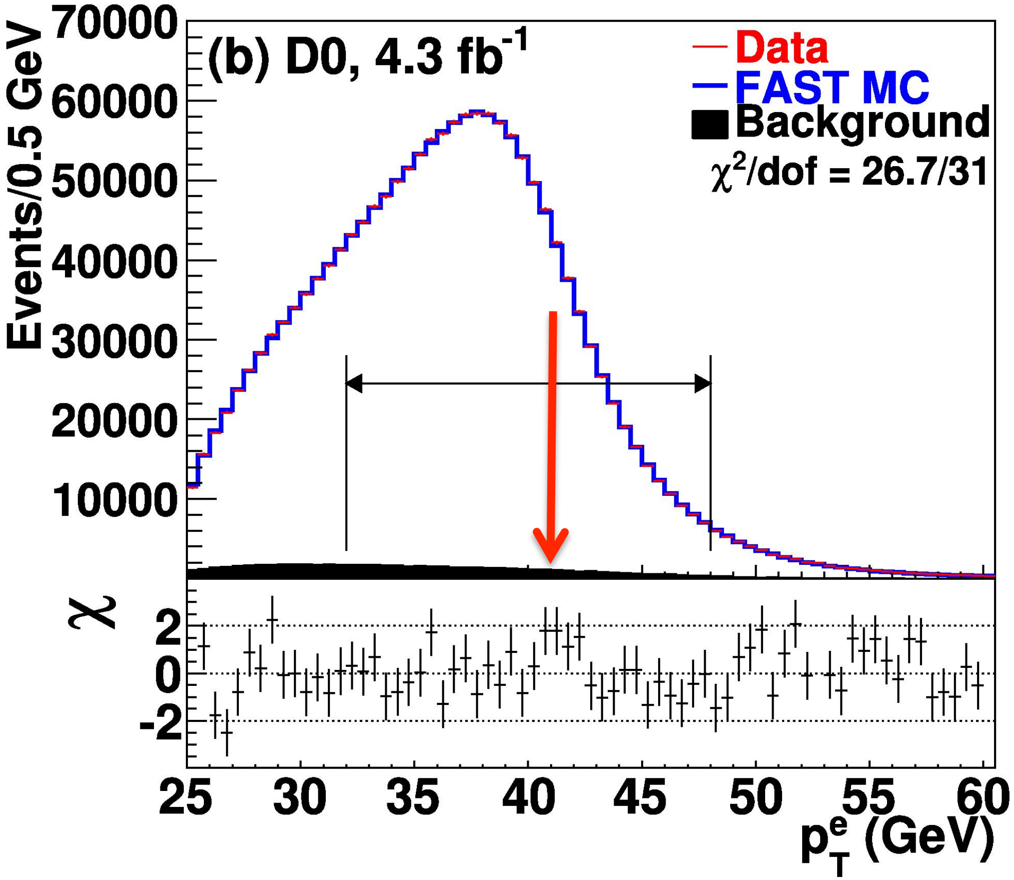
Cross section section → pole at $p_T = M_w/2$

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

damped by natural width of W - boson

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

Reality: Jacobian peak smeared out



M_W = 80.342±0.014 GeV

Fast drop around $M_W/2$ but smeared out

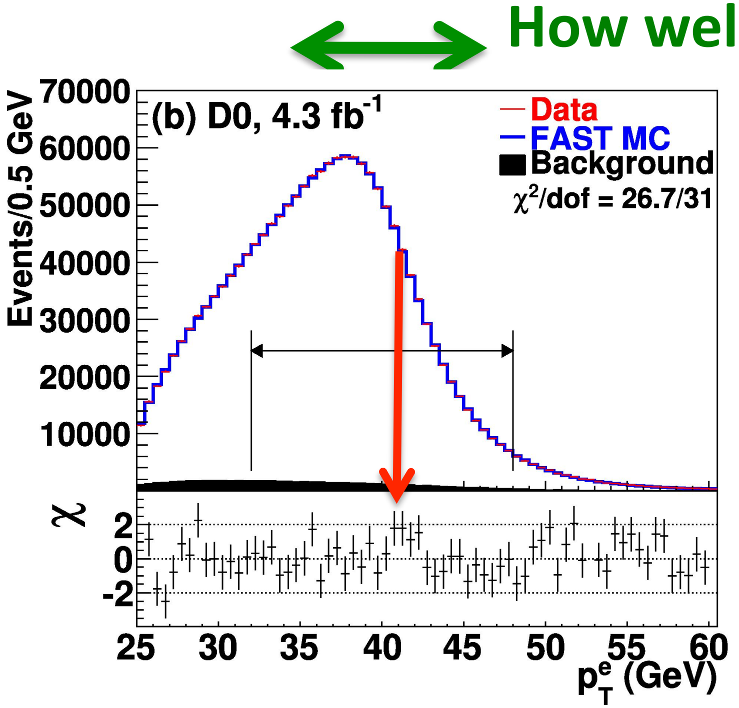
- W – boson: Γ ~ 2 GeV
- QCD effects
- detector distortions

Experimental challenge:
Keep systematic uncertainties under control

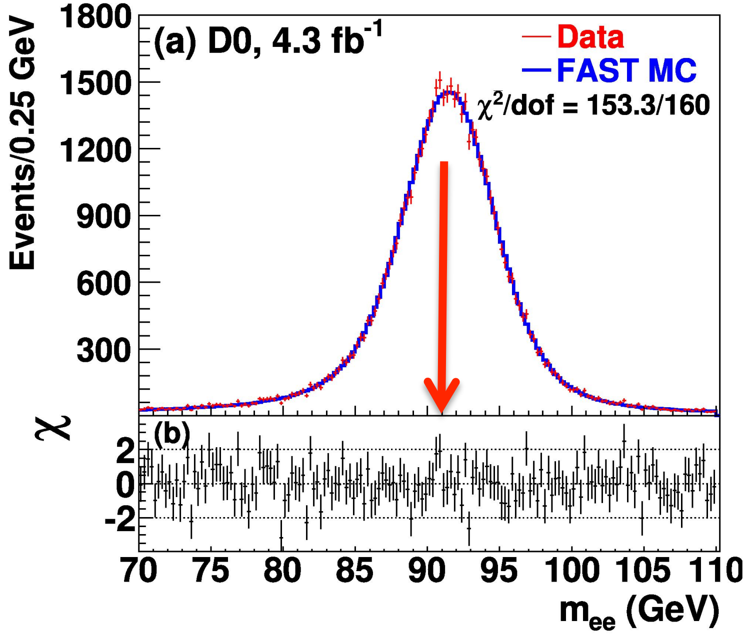
➔ exploit similarity Z/W

Source of uncertainty: energy scale

How well does one know the ‚true‘ energy ?



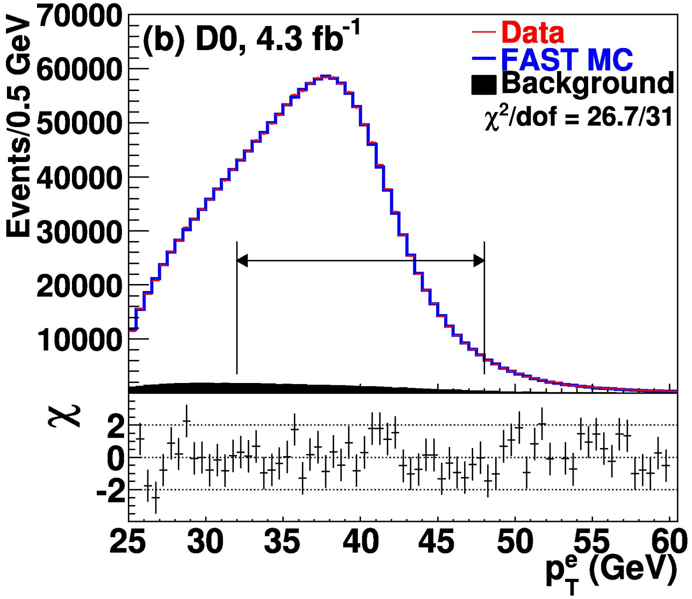
Measure Z^0: calibrate such that M_Z = 91.1882 GeV



Z^0 measurement: excellent control of energy scale

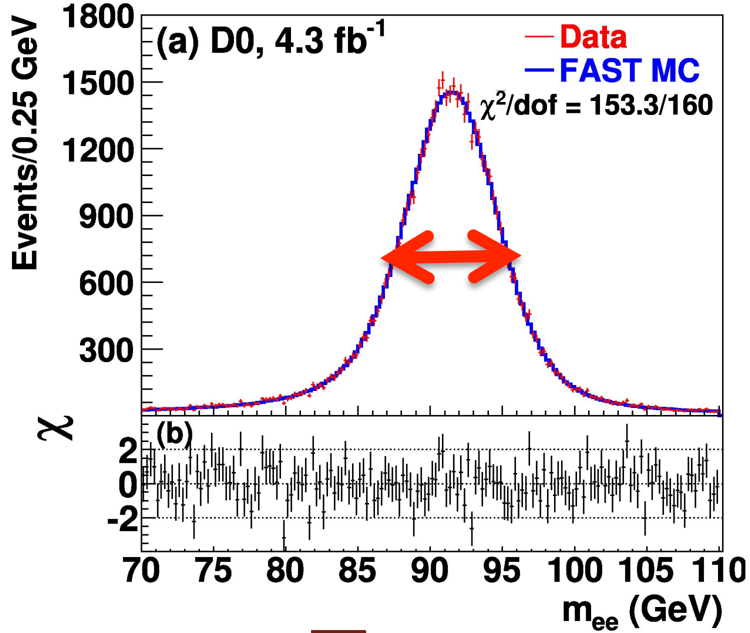
Source of uncertainty: energy resolution

BERGISCHE
UNIVERSITÄT
WUPPERTAL



Measure Z^0 width:

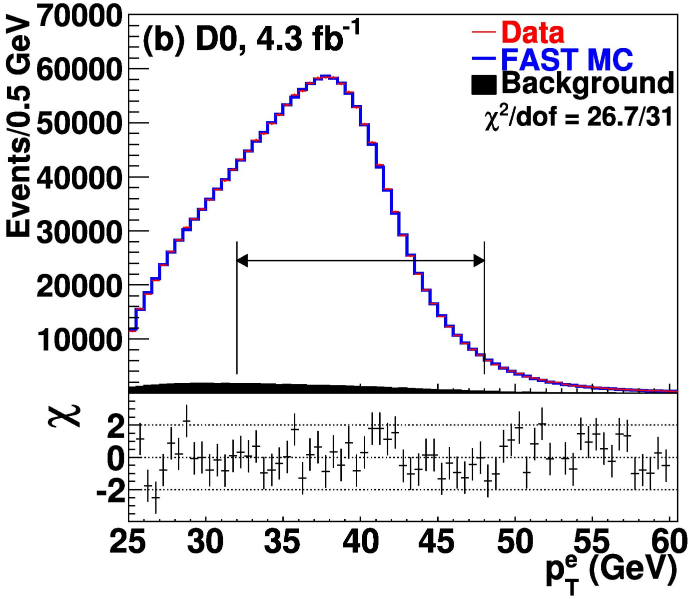
natural Γ_Z = 2.4952 GeV

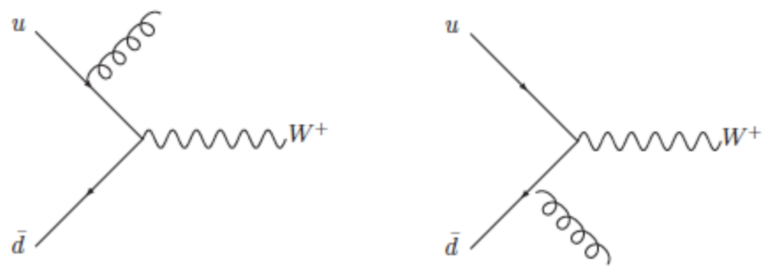


Z^0 measurement: excellent control of energy resolution

$$\sigma_{\rm observed} = \sigma_{\rm detector} \oplus \Gamma_Z$$

Source of uncertainty: p_T of W - boson





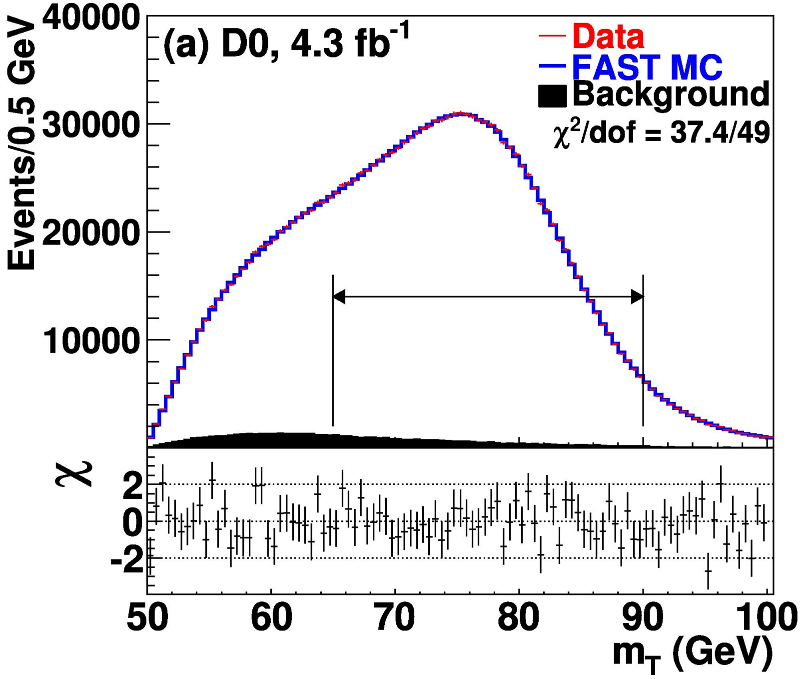
$p_T(W) \sim p_T(Z)$

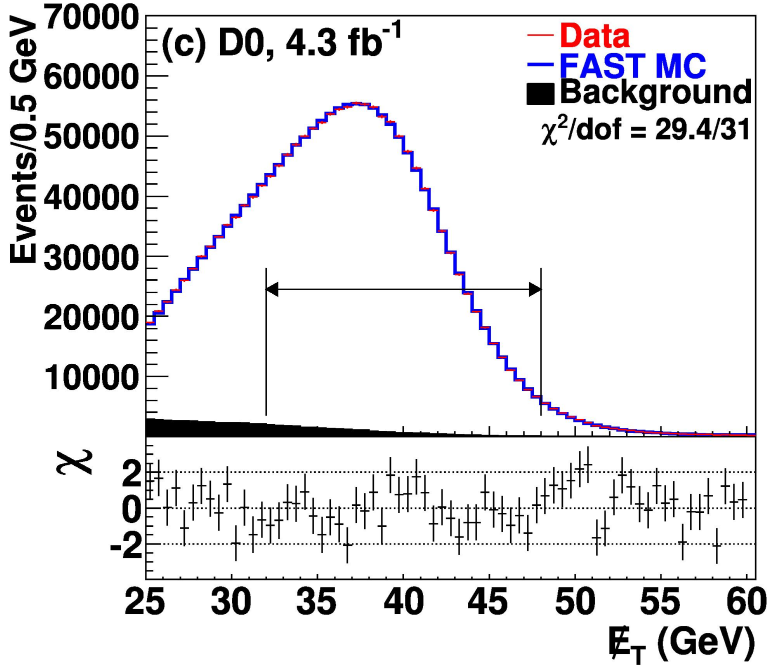
But different couplings, (small) sensitivity to pdfs

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

Two other methods

BERGISCHE UNIVERSITÄT WUPPERTAL





80.371±0.013

80.355±0.015

Knowing the shape & scale ➔ M_W

BERGISCHE UNIVERSITÄT WUPPERTAL

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

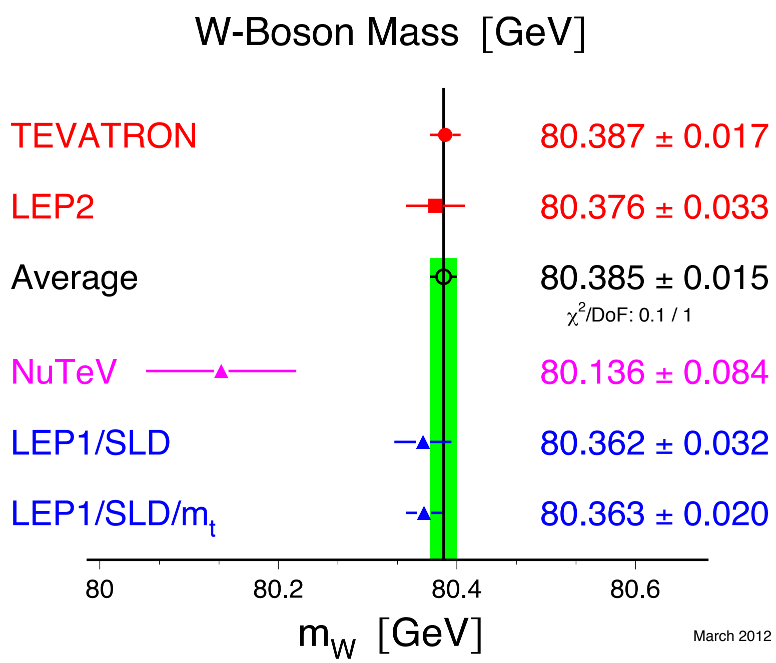
Note:
Measurements are to ~ 74% correlated

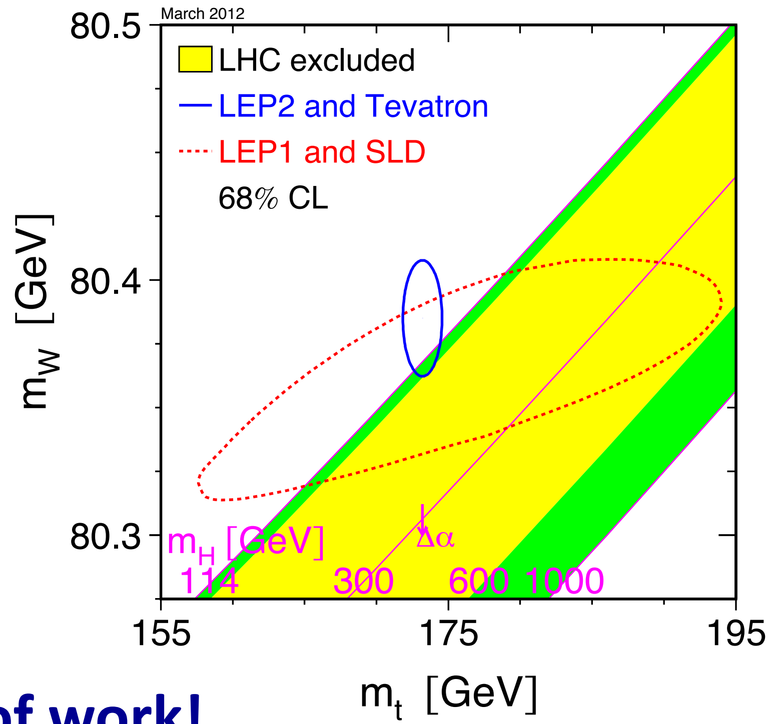
D0 measurement M_W = 80.375 ± 0.023 GeV

W mass result

BERGISCHE UNIVERSITÄT WUPPERTAL

D0 measurement same precision as previous world average





A huge achievement after 20 years of work!

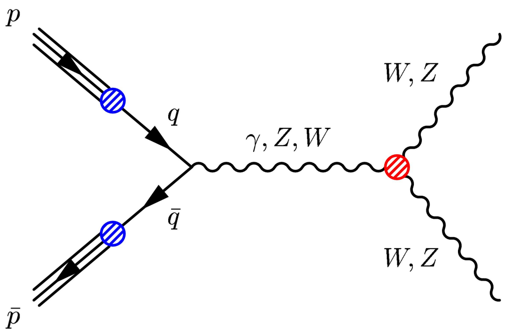
High precision possible at proton colliders

Strong constraint on Standard Model Higgs: mass ‚known'

BERGISCHE
UNIVERSITÄT
WUPPERTAL

Standard Model @ Hadron Colliders
VIII. Triple Gauge Coupling

Looking for TGVs (Triple Gauge Boson Vertices)

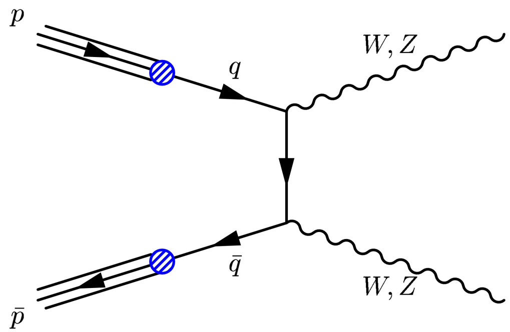


Vector Boson self interaction due to electrically and weakly charged bosons

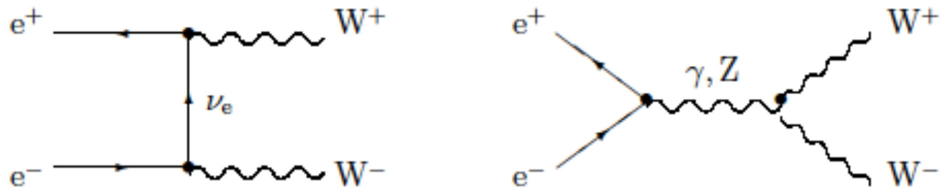
Note connection to EWSB:
$W_L W_L \rightarrow W_L W_L$ scattering leads to unitarity problem ~ 1 TeV ➔ regularised by Higgs

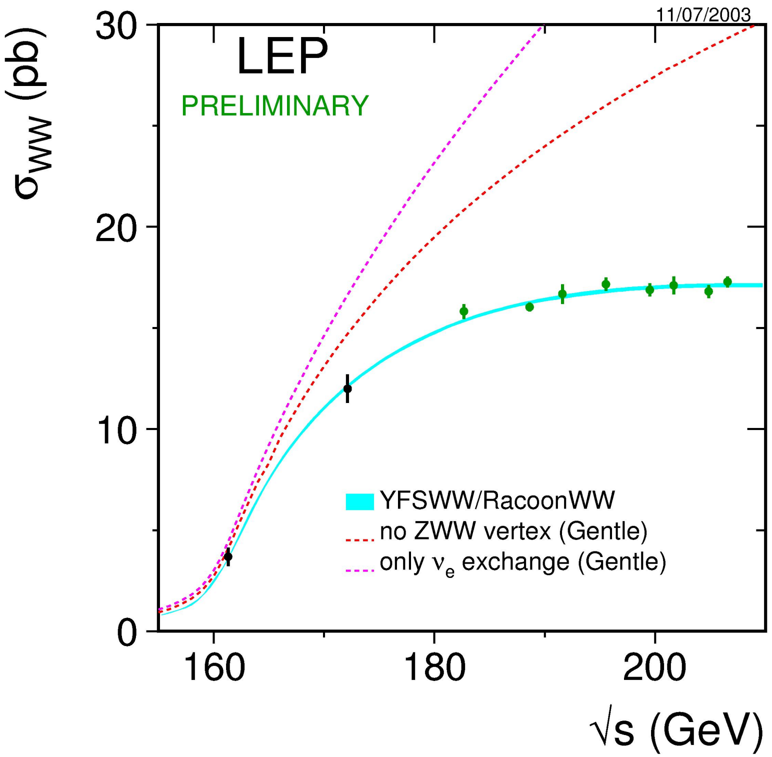
Boson pairs also due to quark exchange

Intricate relation of quark/boson couplings



Gauge Boson production in e^+e^-





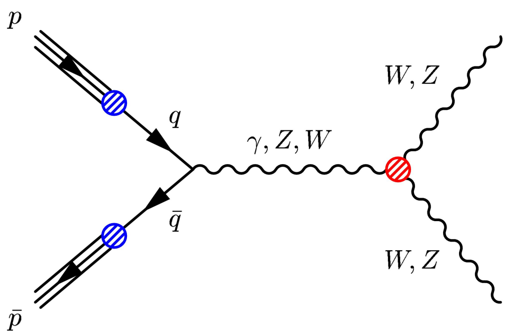
Without Z^0: cross section infinite

Early motivation to introduce Z^0

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

But are couplings as predicted?

BERGISCHE UNIVERSITÄT WUPPERTAL



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

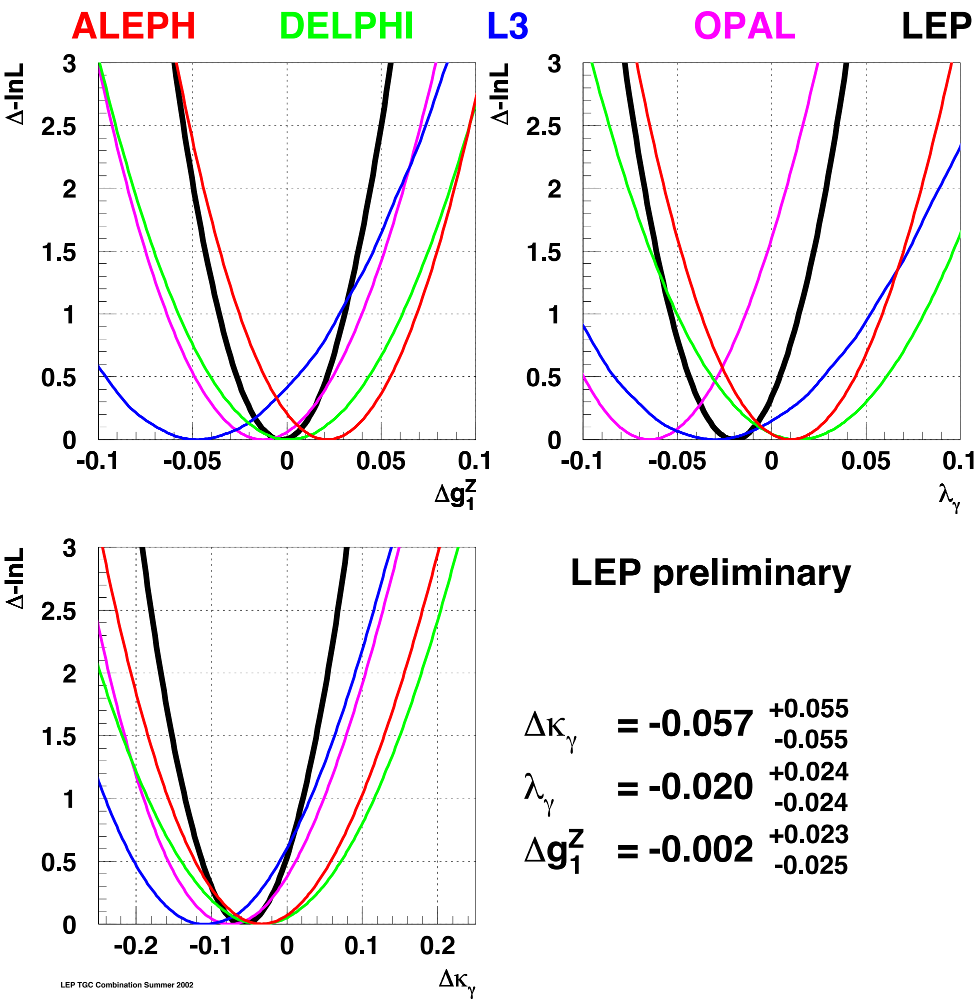
Modify g_1, κ, λ and see if prediction agrees with data

- 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

LEP legacy



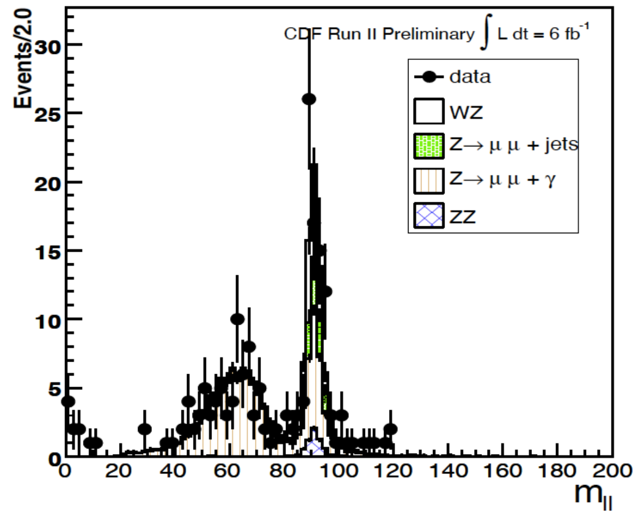
Note:
in $e^+e^- \rightarrow W^+W^-$
no discrimination between
γ and Z coupling!

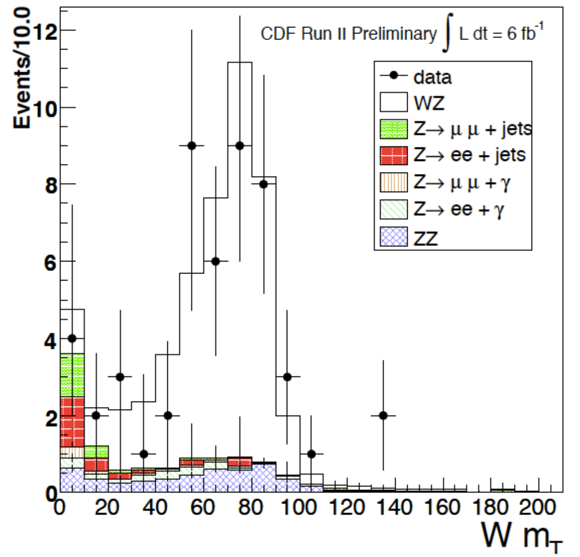
pp – colliders: selecting ZW events

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



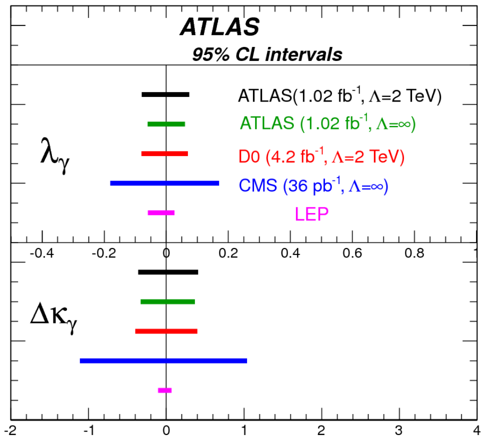


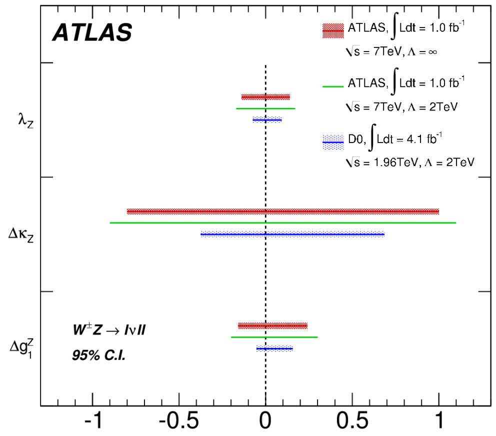
Test at hadron collider

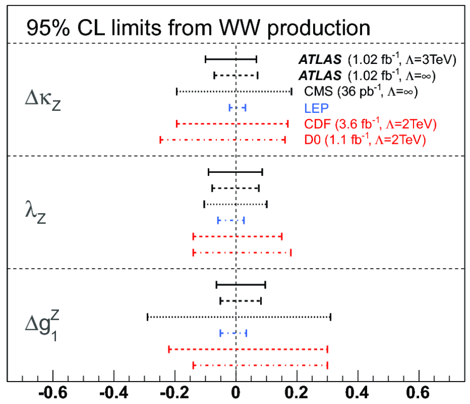
BERGISCHE UNIVERSITÄT WUPPERTAL

Look at various final states

W+γ | **W+Z** | **W+W**







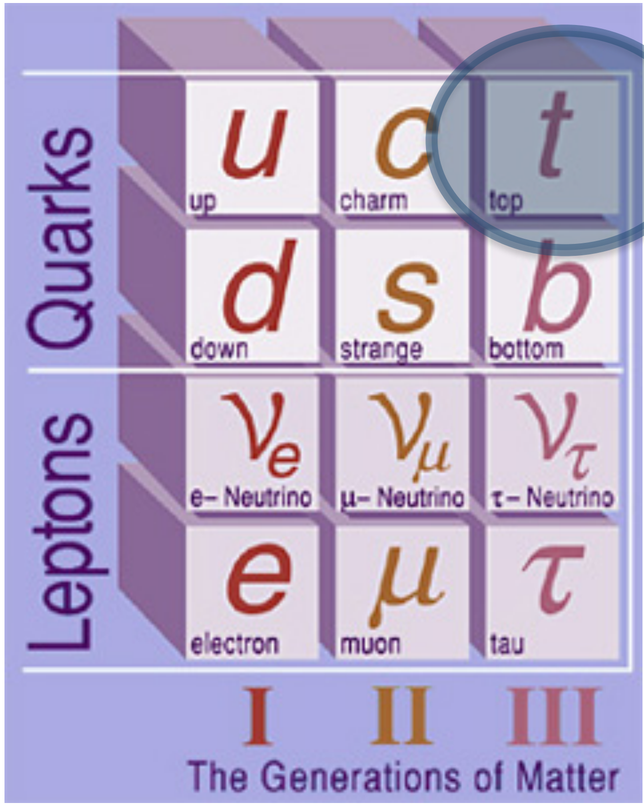
LHC experiments starting to become competative!

No deviations observed: strong support for gauge theories

BERGISCHE UNIVERSITÄT WUPPERTAL

Standard Model @ Hadron Colliders
IX. Top Quark: general statements

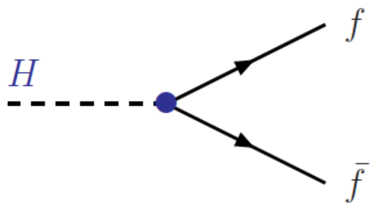
The mysterious (?) top quark



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

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

i.e. coupling strength to Standard Model Higgs Boson



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

➔ $\lambda_t = 0.996 \pm 0.006$

Natural coupling .....and all other fermions are ‚unnatural'?
Does the top quark have a special role in particle physics?

A brief history of the top quark

BERGISCHE UNIVERSITÄT WUPPERTAL

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

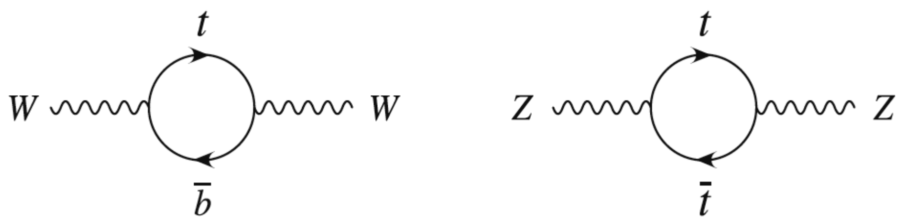
LHC currently produces ~ 50000 tt events/day

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

A brief history of the top quark II

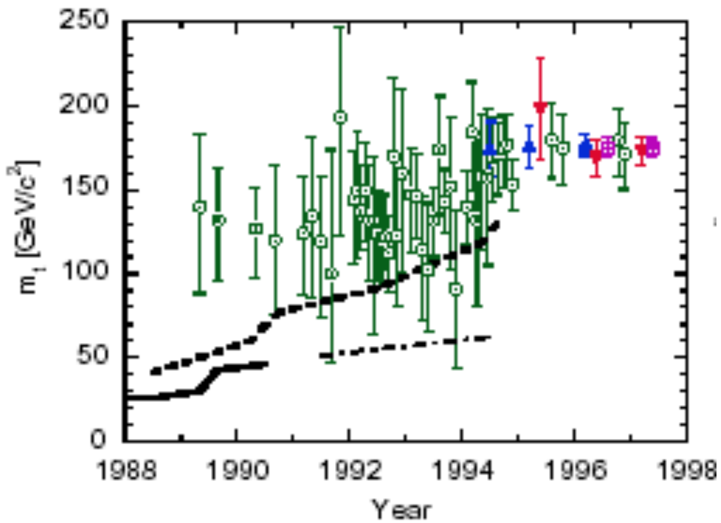
BERGISCHE
UNIVERSITÄT
WUPPERTAL

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



Precision measurements & theory in 1994

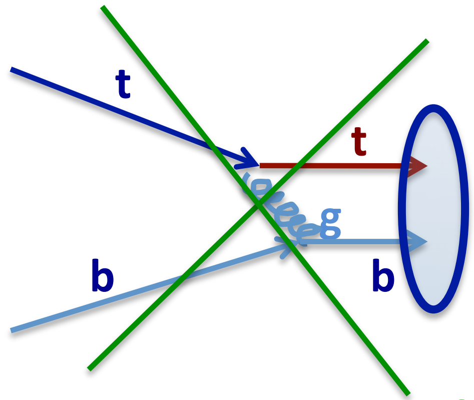
$$M_t = 178.8 \pm 20 GeV$$

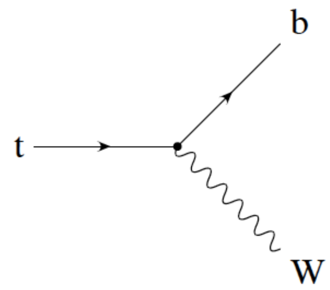


Phenomenology of heavy top

BERGISCHE UNIVERSITÄT WUPPERTAL

competing interactions:





For lighter quarks: strong interaction >> weak interactions

➔ colour neutral hadrons

For top quark: strong interaction < weak interactions

➔ no top hadrons! ‚free quark'

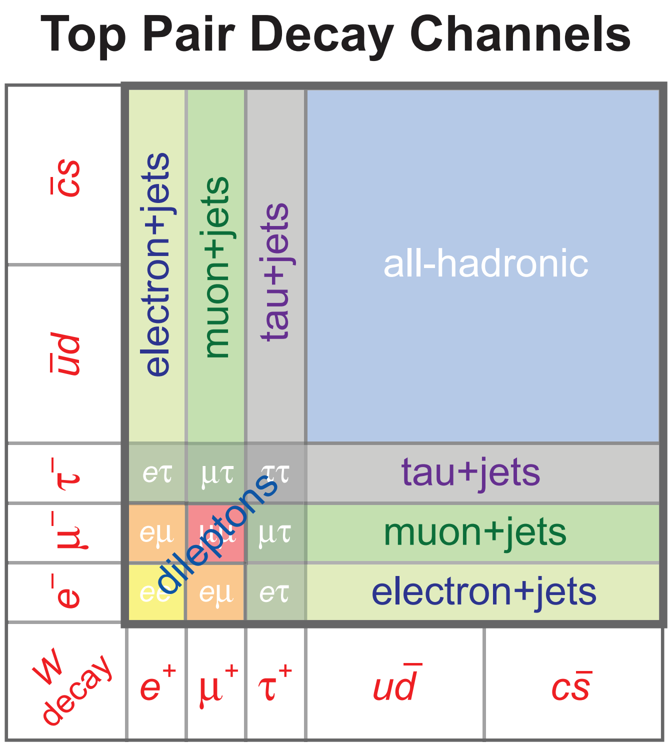
top quarks decay before hadrons formed

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

Phenomenology of heavy top

BERGISCHE UNIVERSITÄT WUPPERTAL

Decay properties of top quark unambigously predicted by SM



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

Channels and measurements

BERGISCHE UNIVERSITÄT WUPPERTAL

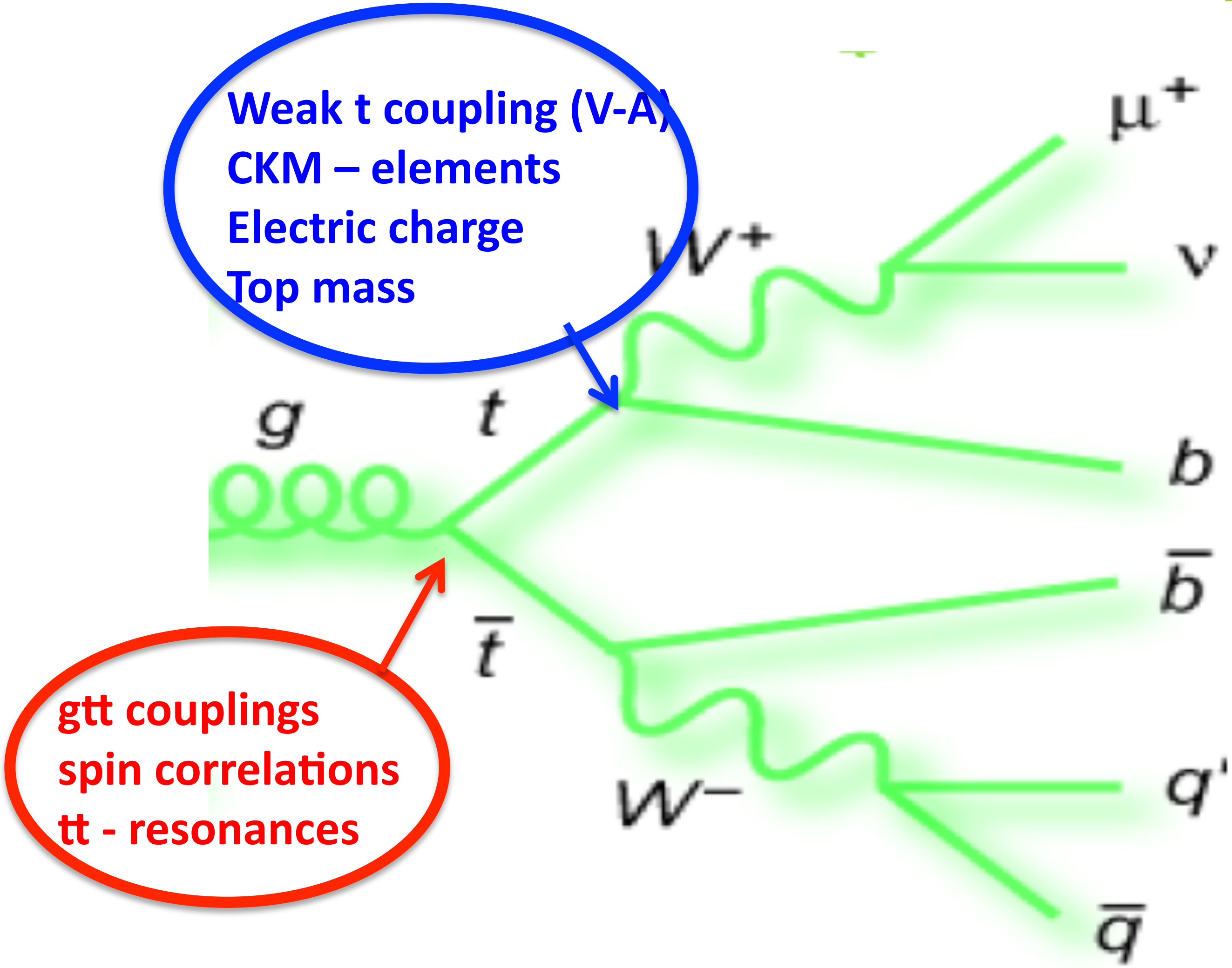
Observable	t --> b lν	t -->b qq
Charge sign	yes	difficult
momentum	with constraint	yes
Helicity	yes	no
mass	with constraint	yes

Most analyses can be performed with both decay types, however, clear differences in expected performance

A semileptonic tt event

Is the top quark a normal fermion?

BERGISCHE UNIVERSITÄT WUPPERTAL



BERGISCHE UNIVERSITÄT WUPPERTAL

Standard Model @ Hadron Colliders
X. Top Quark: production

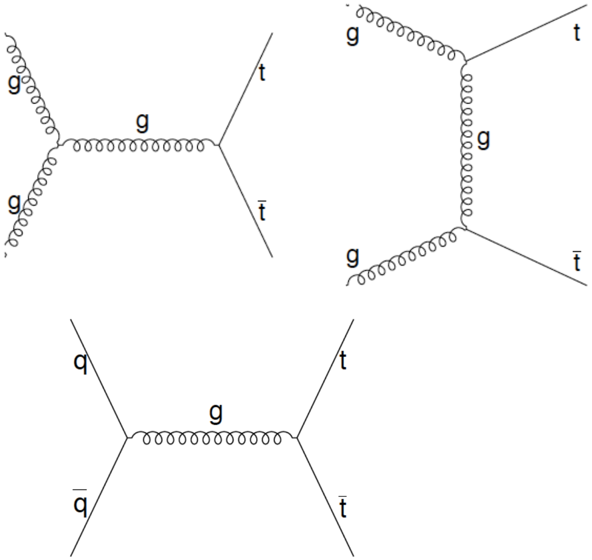
Production of top quarks

BERGISCHE
UNIVERSITÄT
WUPPERTAL

What x required for top production?

$$\sqrt{x_1 \cdot x_2} \geq \frac{2 \cdot M_t}{E_{pp}}$$

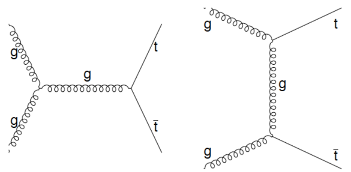
- 0.18 at Tevatron
- 0.05 at LHC (0.025 @ 14 TeV)



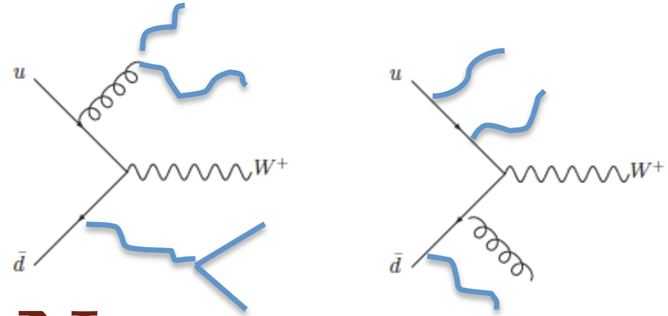
Dominant at LHC for low M_{tt}
Suppressed @ Tevatron

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

How to measure tt cross section



(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

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

What fraction of tt events are retained after selection

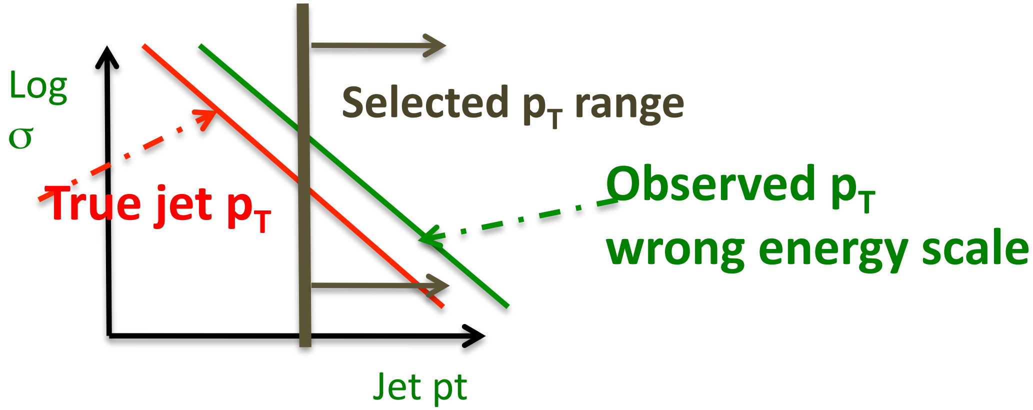
Luminosity:
How many proton-collisions?

Cross section determination

BERGISCHE UNIVERSITÄT WUPPERTAL

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 %

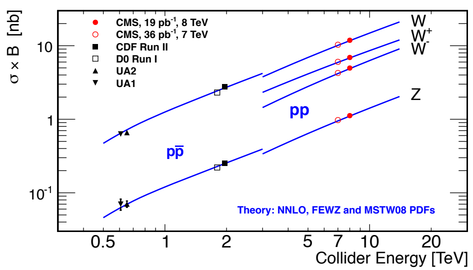
Background estimatation

Dominant background: W + 4 jets ➔ same final objects

- assume QCD generators to be correct, i.e templates
- data driven method (ATLAS):

  tt – events: same number of W^+, W^-

  W+jets method: more W^+ than W^-



$$(N_{W^+} + N_{W^-})^{exp} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(N_{W^+} - N_{W^-})^{data}$$

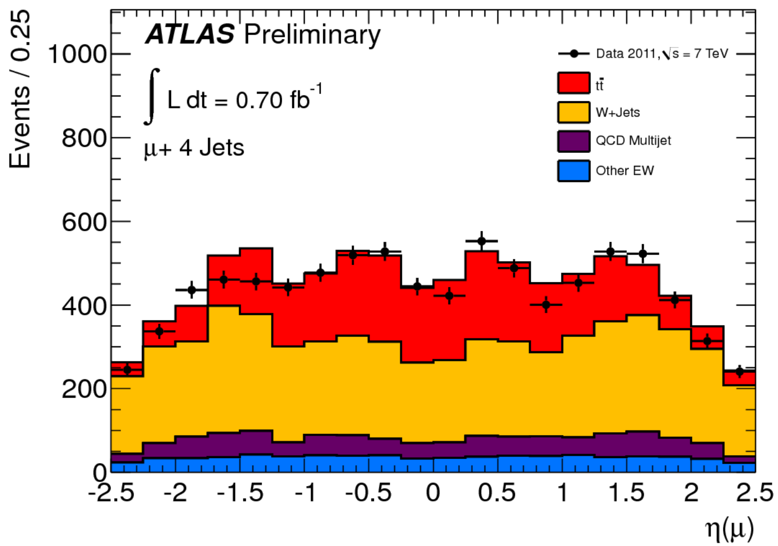
$r_{MC} = N_{W+}/N_{W-}$

➔Further step: estimate W+b(b)+2 jets fraction based on bottom tagging in W+2jets → extrapolated to 4 jets via MC

Other background: QCD with b→ lepton with high $x_{Feynman}$

Estimate from ‚non – isolated' leptons

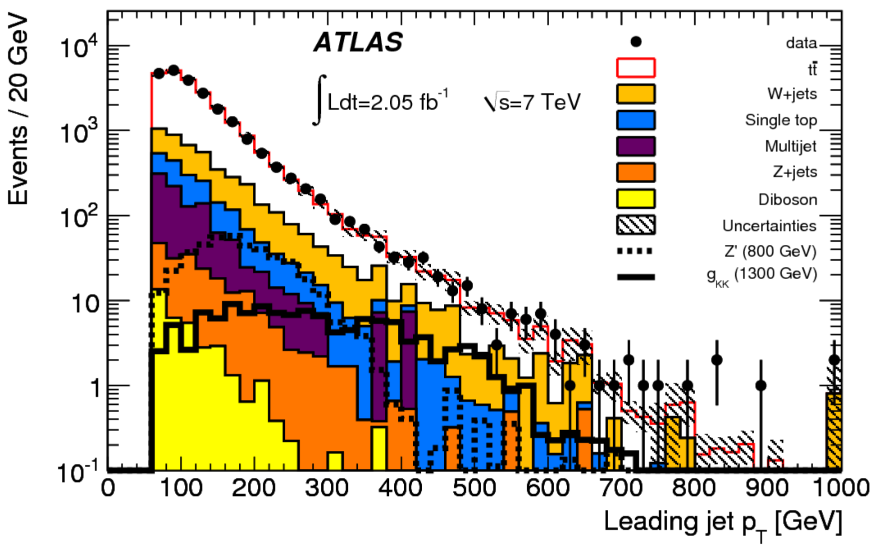
Background in semileptonic tt



Contribution to sample no b – tag

S/B ~ 1/3

W+Jets/tt ~ 1.4



Contribution to sample with b – tag

S/B ~ 4

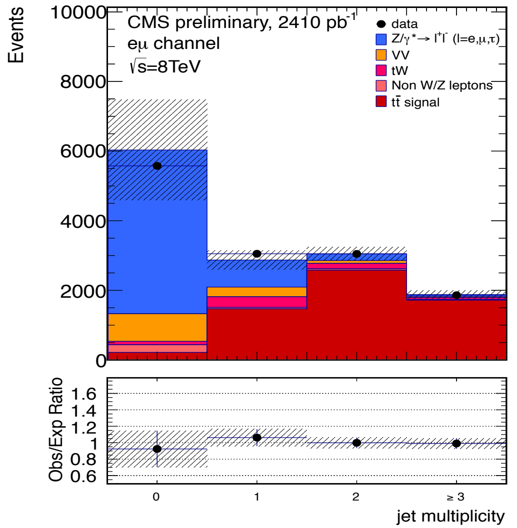
W+Jets/tt ~ 0.15

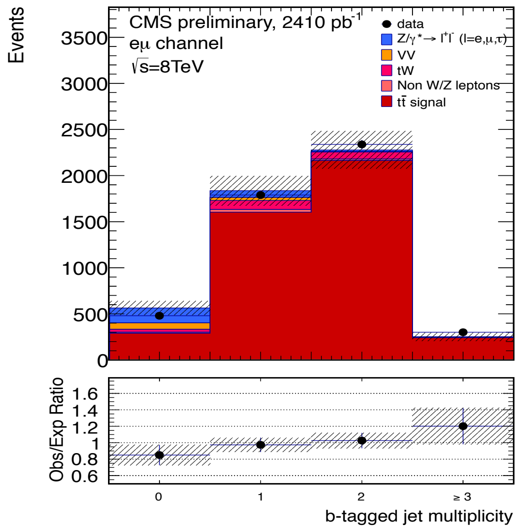
price: somewhat reduced statistics

Wb+jets more uncertain

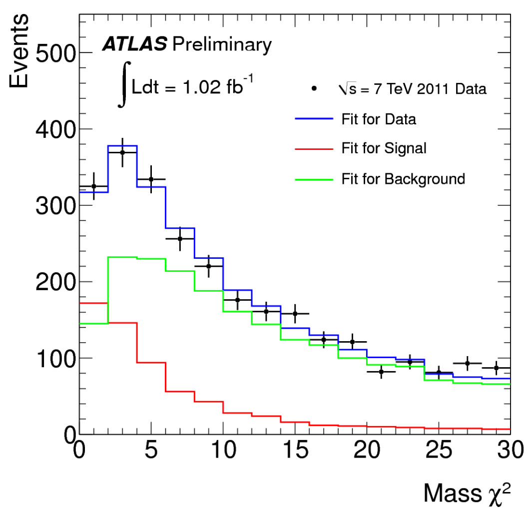
Dileptons + fully hadronic

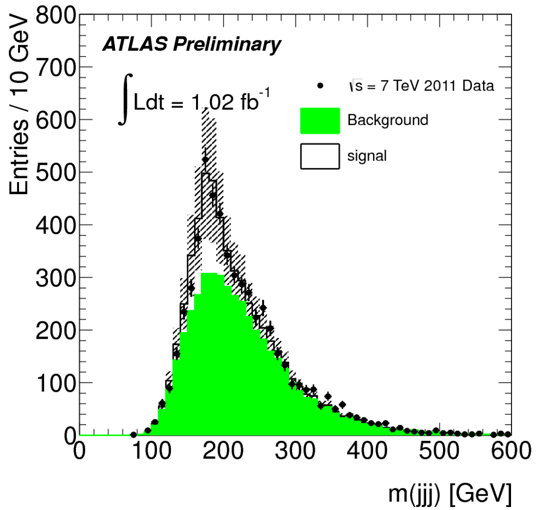
BERGISCHE UNIVERSITÄT WUPPERTAL





Dileptonic:
Very pure tt – sample
Note: for X-section
no need to use any
other property
... But loss in statistics

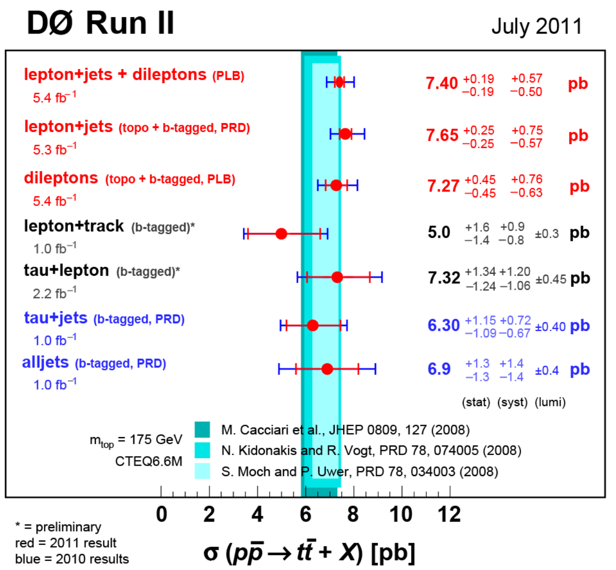


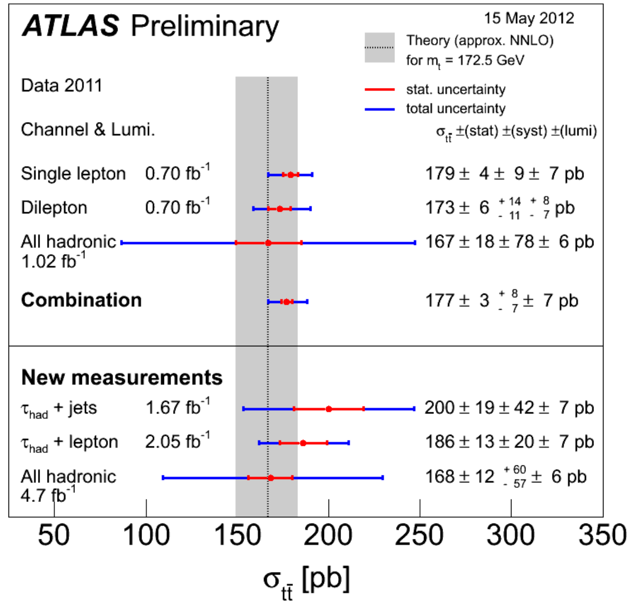


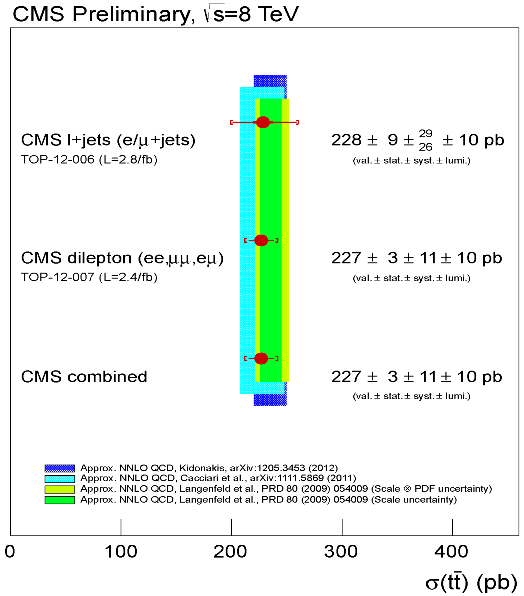
Fully hadronic:
Huge QCD background
Advantage: M(t), M(W)
➔ Kinematic fit

Summary of Xsection

BERGISCHE UNIVERSITÄT WUPPERTAL





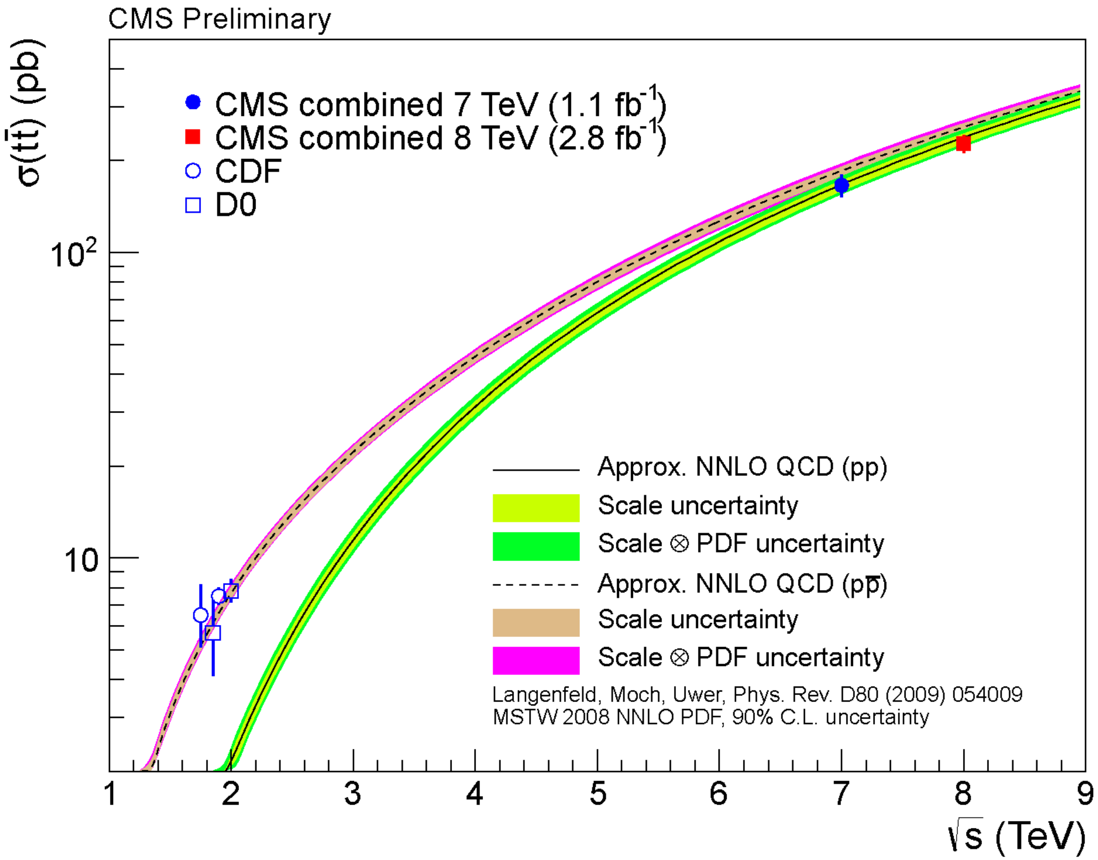


Dileptonic and semi-leptonic measurements similar precision

All hadronic larger errors

Experiments have smaller uncertainty than theoretical calculation

Cross section measurement



Theoretical uncertainty 7-10% partly NNLO

Theory & experiment uncertainty about equal

Very good agreement between data and expectation