CTEQ/MCnet School 2016

Electroweak Boson Production at the LHC

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

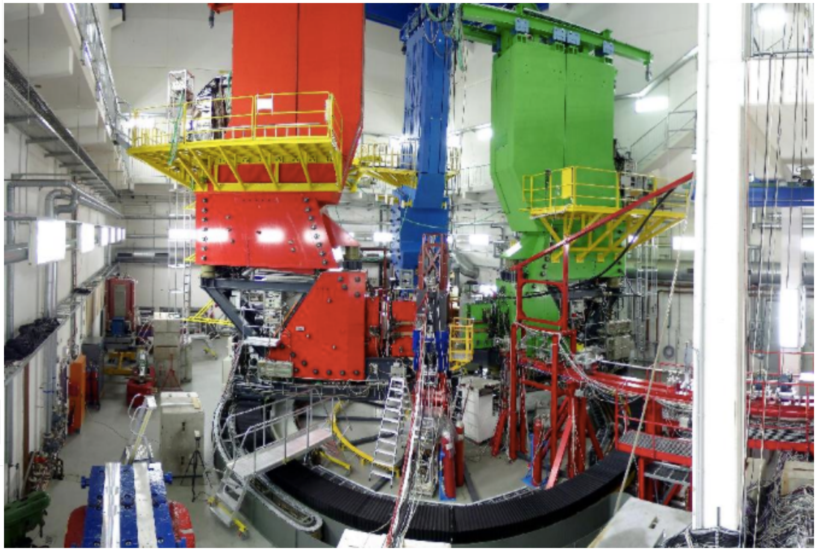
- Experimental Basics
- Some Theory and Generators
- Single W and Z Boson Production
- QCD Angular Coefficients
- Vector-Bosons and Jets
- Multibosons
- Electroweak Precision Measurements
- Conclusion

Some Facts about Mainz

- Mainz is small town, but **capital of Rhineland-Palatinate**
  - Next to the river Rhine (with some quite nice castles)
  - **20 Minutes from Frankfurt International Airport**
- Founded by **romans 2K years** ago
  - The cathedral is only 1000 years old (and burnt down several times)
- Time-Magazine's **man of the millennium**: Johannes Gutenberg, who invented the printing press in Mainz

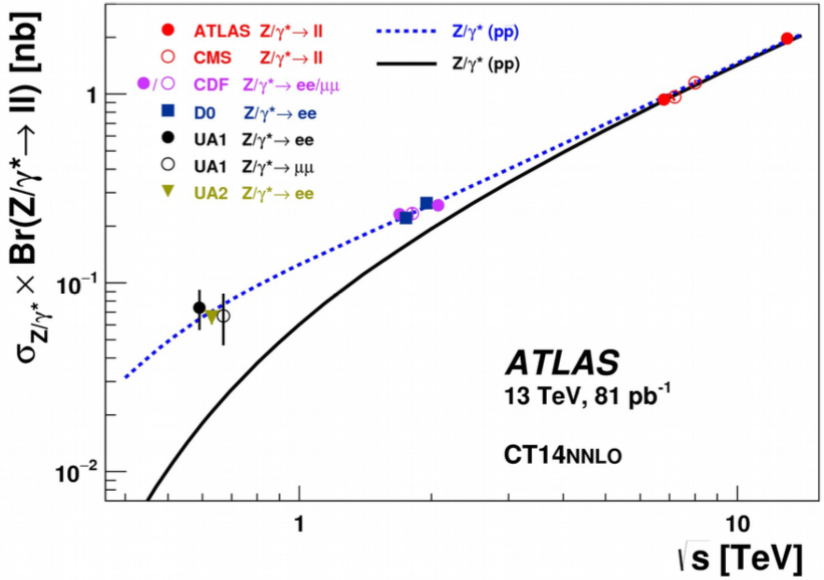
Johannes Gutenberg University

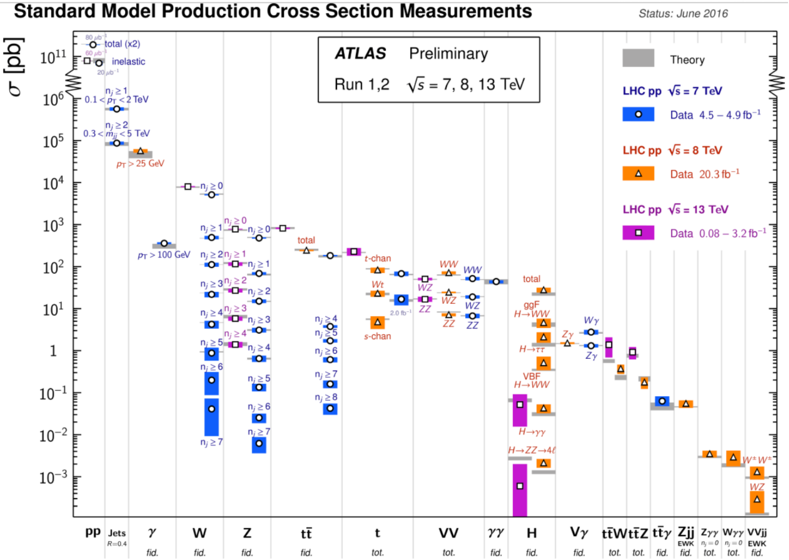
- **Founded in 1477** and reopened by the French occupation forces in 1946
- 37.000 students for all subjects (bachelor, master, PhD)
- German cluster of excellence PRISMA for fundamental physics
  - Own **electron accelerator MAMI** and research reactor
  - 60 professors and research groups: **ATLAS, IceCube, Xenon, SOX, NA62, JUNO, ALPS, …**



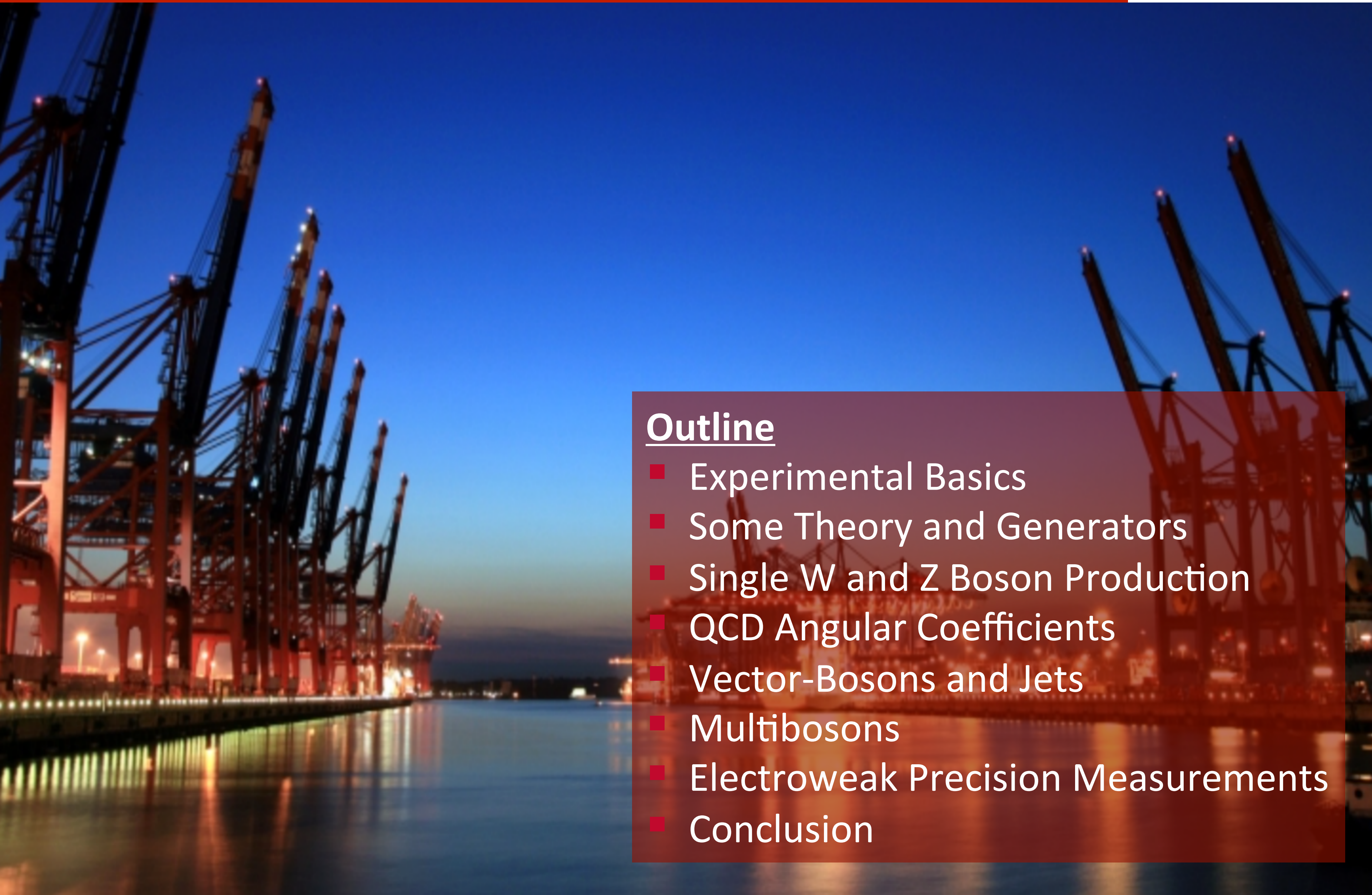
Why W and Z Bosons at the LHC?

- Testing perturbative QCD calculations to highest precision
- Testing the gauge-structure of the Electroweak Sector
  - looking for BSM
- Precision measurements of EW observables to test the SM
- Background processes to lots of “new physics searches”
- Lecture is based on two articles:
  - arXiv:1405.1160
  - arXiv:1406.7731





Experimental Basics



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Experimental Cross-Section Formula

- Theoretical Cross-Section formula
  - Integrate PDF’s and parton-level cross-section

$$\sigma_{p_A p_B \to n} = \sum_q \int dx_a dx_b \int f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \times$$
$$\times [\hat{\sigma}_0 + \alpha_s(\mu_R^2)\hat{\sigma}_1 + \ldots .]_{ab \to n},$$

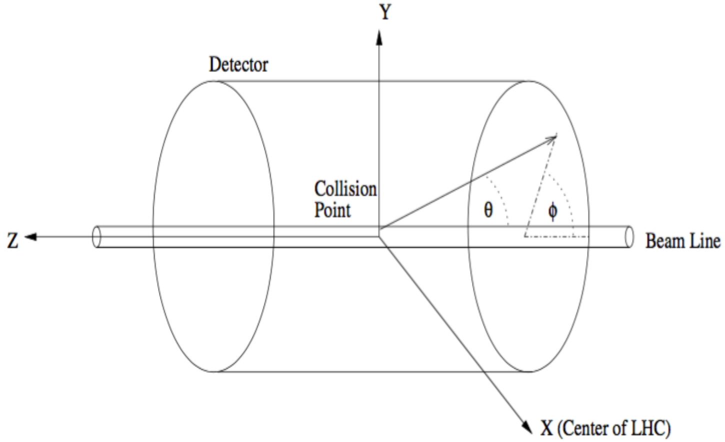
- Experimental formula: Count number of signal events and devide by the integrated luminosity (∫Ldt) of the data-set
  - Need to correct for background events B
  - Branching Ratio
  - Event selected efficiency ε=A·C
    - Acceptance A
    - Detector Correction C

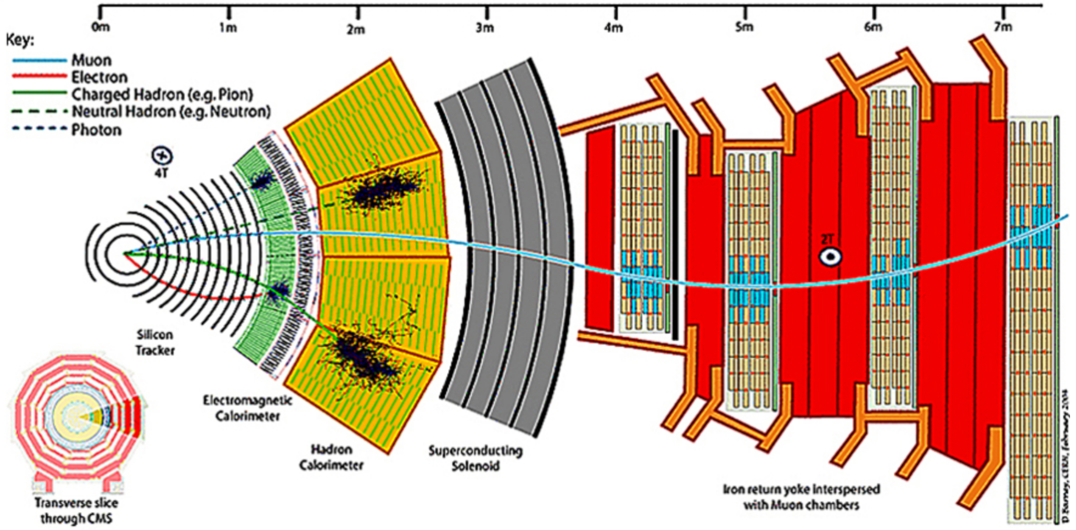
$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times C \times \mathcal{L}_{int}}$$

$$C = \frac{N_{\mathrm{MC}}^{\mathrm{reco.}}}{N_{\mathrm{MC}}^{\mathrm{gen,\ fiducial}}} \times \frac{\epsilon^{\mathrm{data}}}{\epsilon^{\mathrm{MC}}}$$

$$A = \frac{N_{\mathrm{MC}}^{\mathrm{gen,\ fiducial}}}{N_{\mathrm{MC}}^{\mathrm{gen,\ total}}}$$

What can we measure?





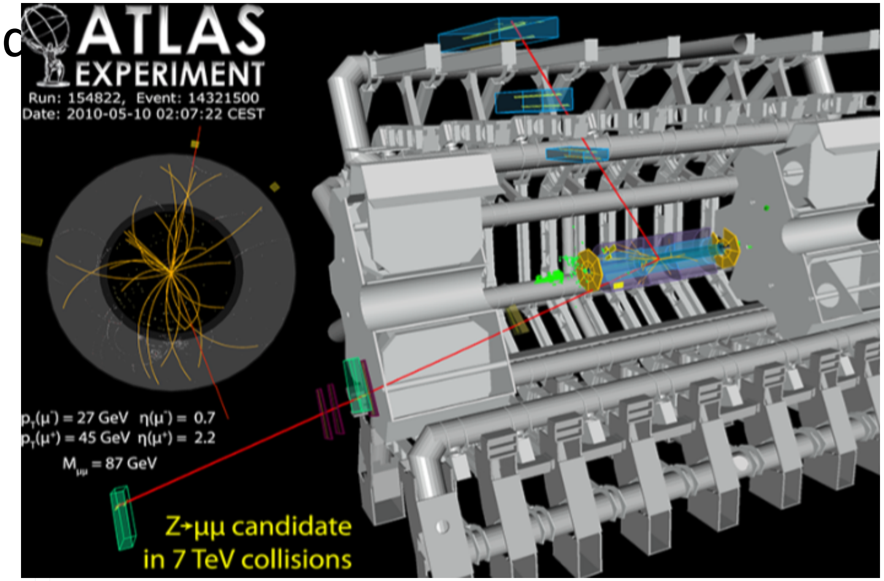
- For each proton-proton colission we try to record all stable particles

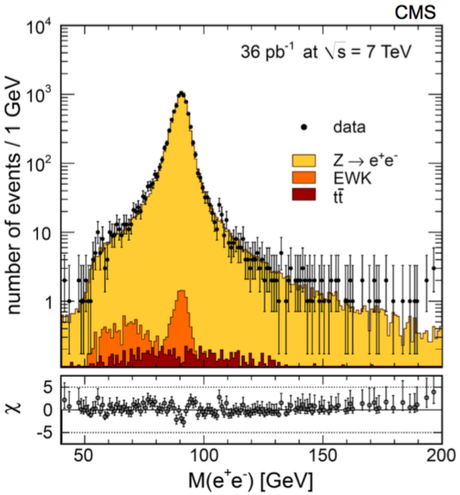
- 4-vector (p_x,p_y,p_z,E) or (p_T,η,Φ,m) and charge of electrons and muons
  - Pseudo-rapidity: $\eta = -\ln(\tan(\theta/2))$
- 4-vector information of jets: Quark-, gluon- jets, b-, c-quarks, Tau's

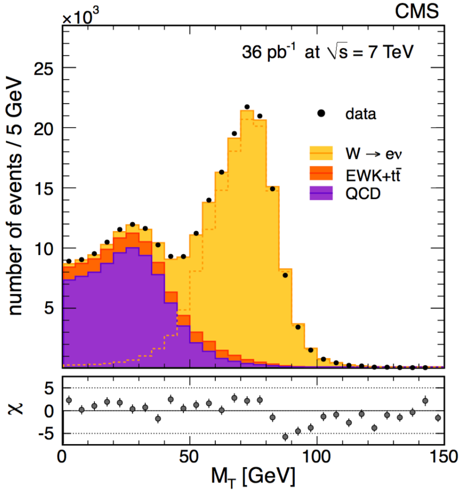
- Missing transverse energy as a measure of the neutrino p_T in the transverse plane

Signal Selection

- Only leptonic decay channels of Z and W boson can be selected
  - otherwise: large multijet bkg
  - $W\rightarrow e\nu$, $W\rightarrow \mu\nu$, $Z\rightarrow \mu\mu$, $Z\rightarrow ee$,
- Typical Z boson selection
  - 2 opposite charged leptons
  - Isolated and $p_T>20$ GeV
  - In detector volume: $|\eta|<2.5$
  - $60<m_{ll}<120$ GeV
- Typical W boson selection
  - 1 isolated lepton
  - $p_T>20$ GeV
  - $E_T^{Miss}>20$ GeV
  - $m_T>40$ GeV

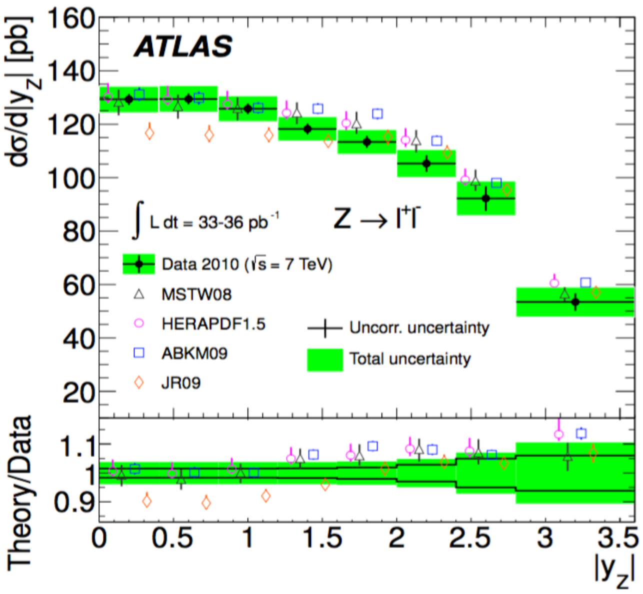




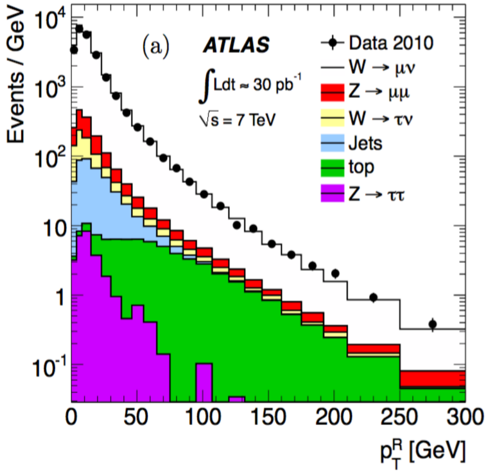


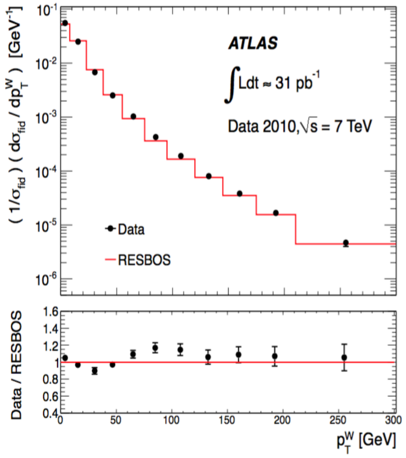
Fiducial?, Differential?, Unfolding?

- **Fiducial Cross-Section:** This is the cross-section which we actually measure within our detector
  - $\sigma_{\text{fid}} = \sigma_{\text{incl.}} \cdot A$
  - Little impact of theory unc.



- **Differential Cross-Section:** Sometimes we want to know the cross-section in dependence of an observable,
  - e.g.: $d\sigma/dy$, $d\sigma/d\eta$, $d\sigma/dp_T$
  - Measure cross-section in bins





- **Unfolding:** We transform a measured distribution to the "truth" distribution

Some Theory and Generators

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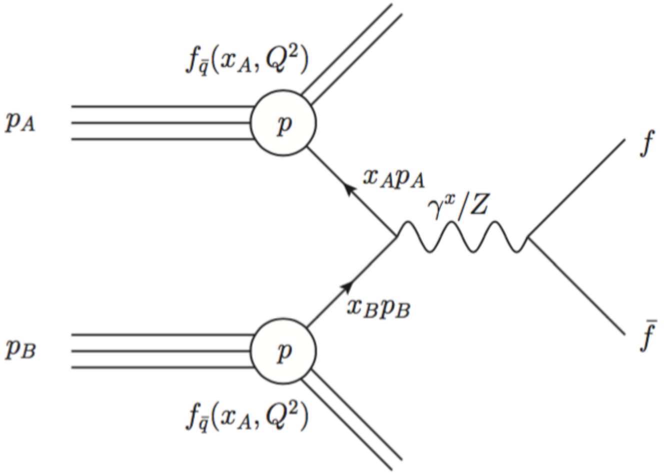
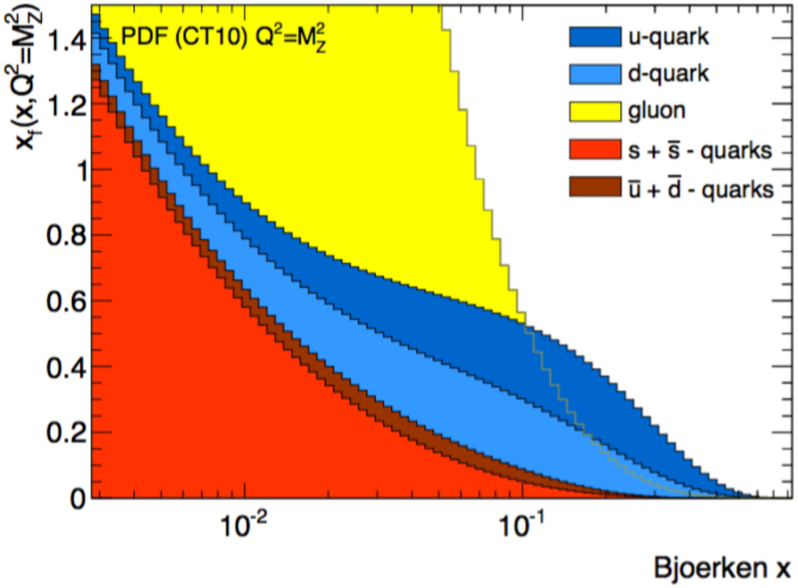
Tree-Level Diagrams

- Z/W Boson Production:
    - Quark + Antiquark annihilation
    - Two valence quarks at Tevatron
    - One valence and one see-quark at LHC

- Typical Björken x-value
    - 0.001-0.1

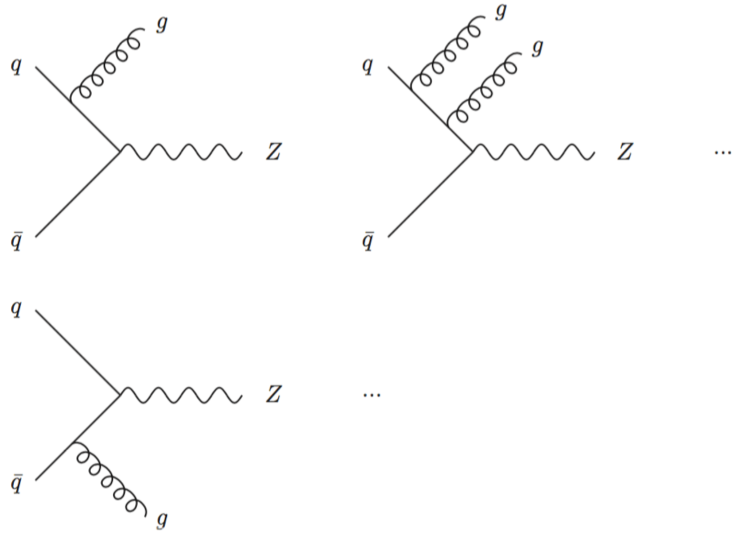
- Rapidity to Boson is correlated with Björkeb x-value
    - Small rapidities $x_1 \approx x_2$
    - High rapidities $x_1>>x_2$, $x_2<<x_1$

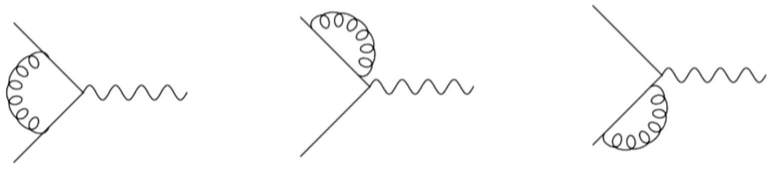


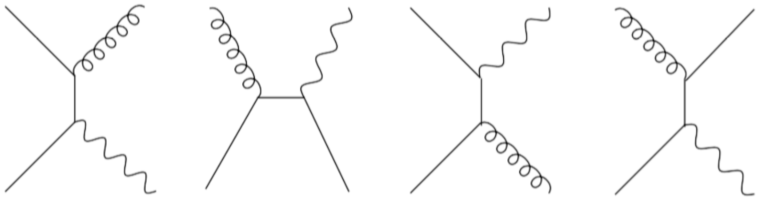


Parton Shower, NLO and Matching

- Quarks in the initial state can radiate gluons: ISR
  - Lead to transverse momentum of vector bosons
  - Described by Parton Shower Models (lots of free parameters to tune)
- Available since several years: procedures to match PS with NLO diagrams (i.e. No double counting)
- Resummation: Summing up all gluon emmissions to all orders





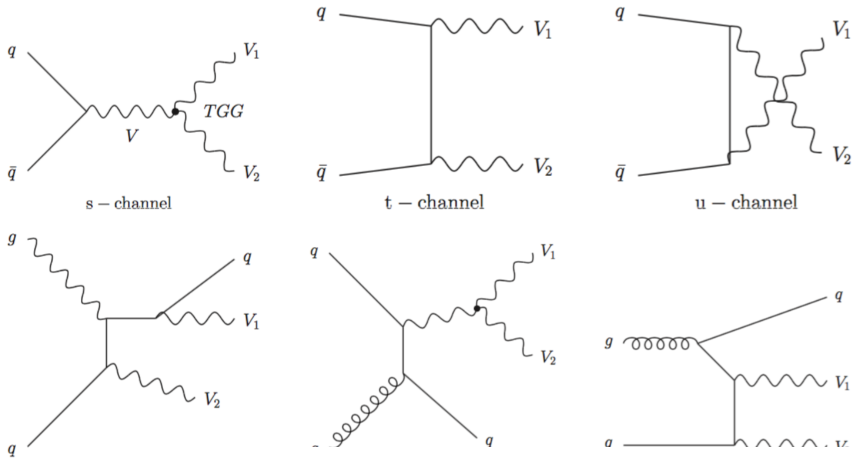


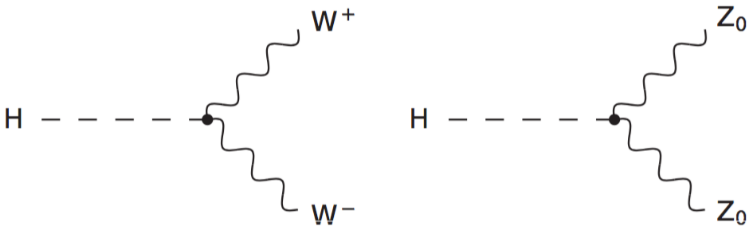
DiBoson Production

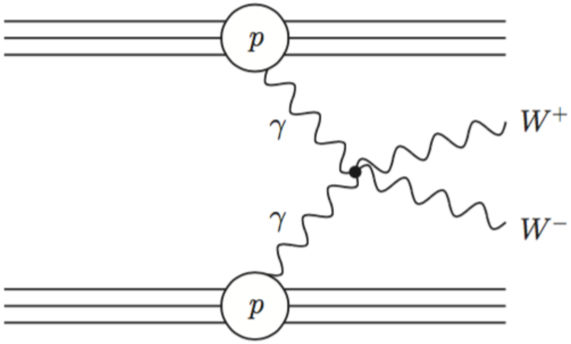
- Production of single boson production has little to do with the Electroweak-Sector of the SM

- The Electroweak sector (SU(2)xU(1)) predicts self-interactions of vector bosons
  - Triple-Gauge Couplings
  - Quadratic-Gauge Couplings

- Measuring Di-boson/Multi-boson final states tests the gauge-structure of the electroweak sector
  - Deviations of the measured cross-sections would indicate new physics





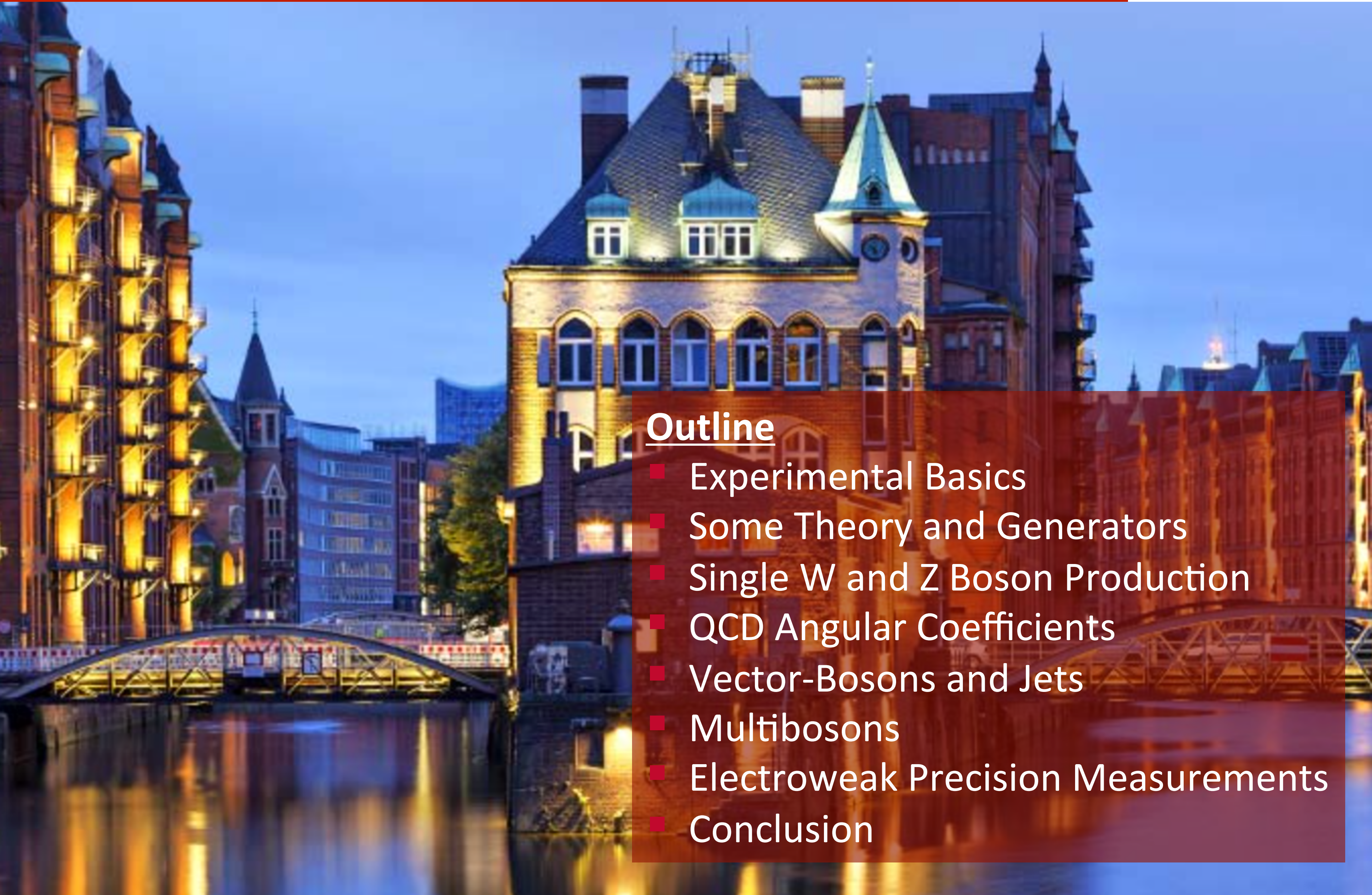


Overview of Generators

- Most generators do a good job in basic distributions
- No generator can do everything to highest precision
  - Enormous progress in recent years: NLO/NNLO revolution
  - But: Lots of future work needed

Program	Matrix-Element $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha_s)$	Full Event Generator Generator	Merging/Matching	Functionality w.r.t. W /Z and diboson production
Pythia	LO	yes	matrix-element correction for first branching	inclusive production
Herwig	LO	yes	matrix-element correction for hardest branching	inclusive production
MC@NLO	NLO	yes (interface to Herwig)	PS matching	inclusive production
aMC@NLO	NLO	yes (interface to Herwig)	PS matching	inclusive production
PowhegBox	NLO	yes (interface to Pythia or Herwig)	PS matching	inclusive production
Alpgen	LO	no (but interface to Pythia/Herwig)	MLM (all parton multiplicities)	W /Z +Jets (incl. large. multipl.)
MadGraph	LO	no (but interface to Pythia)	n.a. (all parton multiplicities)	W /Z +Jets (incl. large multipl.)
Sherpa	LO	yes	CKKW (all parton multiplicities)	W /Z +Jets (incl. large multipl.)
BlackHat-Sherpa	NLO	no (only parton level)	n.a.	W /Z +Jets (incl. large multipl.)
ResBos	Resummation	no (only boson kinematics)	n.a.	p_T spectrum of W /Z bosons
MCFM	NLO	no (only parton level)	n.a.	NLO corrections to integral rates and shapes
Fewz	NNLO	no (only boson kinematics)	n.a.	NNLO corrections to integral rates and shapes

Single W and Z Boson Production



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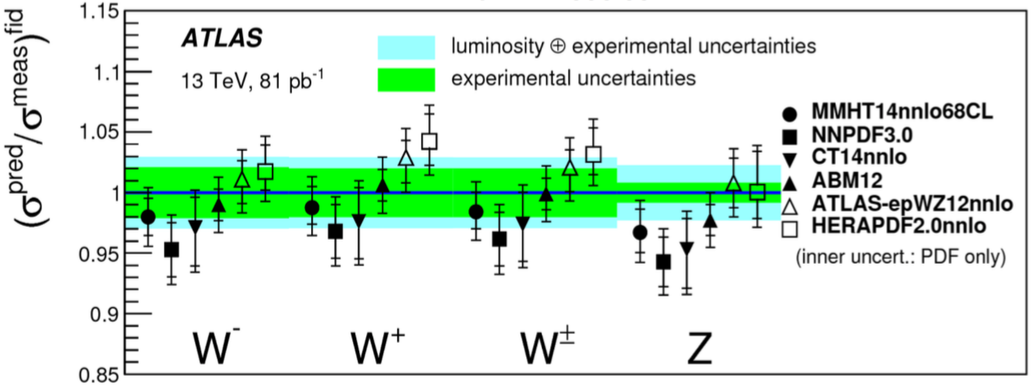
Inclusive Cross Section Results

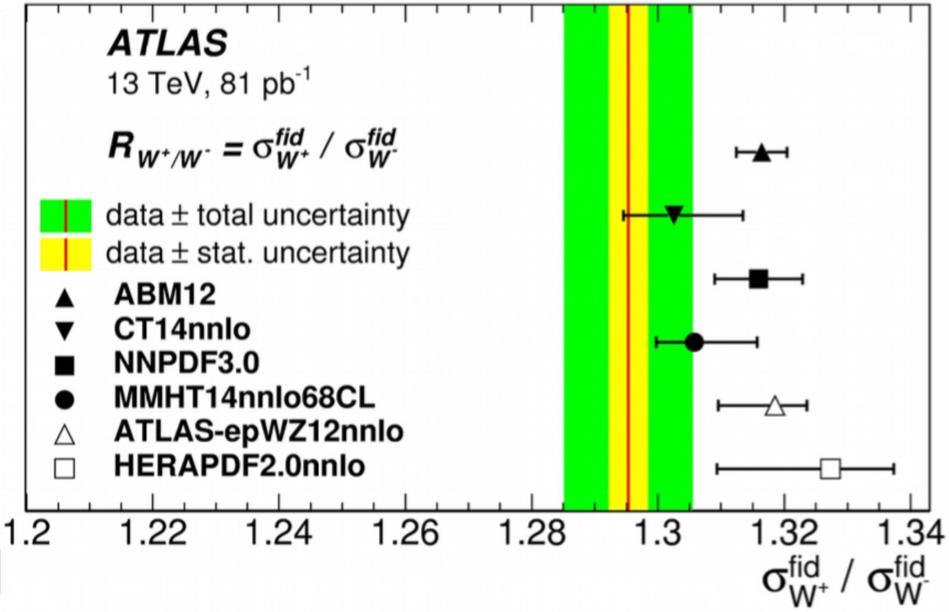
- In principle just counting, correcting for backgrounds and losses and dividing by integrated luminosity
  - Typically limited by luminosity uncertainty (1.5-2%)

- Idea: Use cross-section ratios to get more precise
  - Most systematics cancel!

- We already see here a large dependence on the PDF-sets used

arXiv:1603.09222



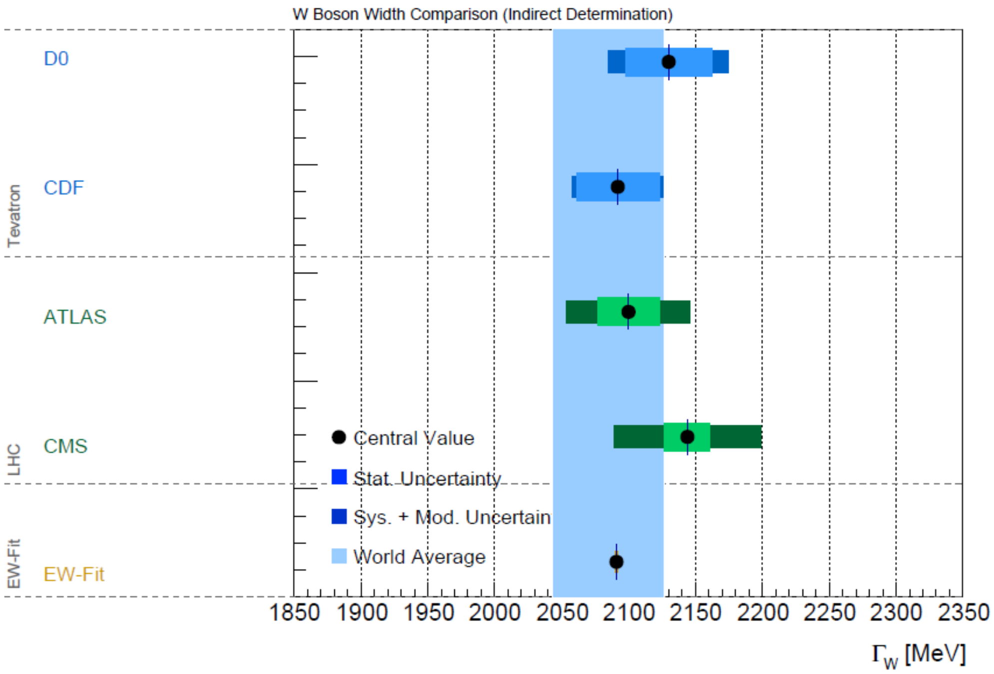


W Boson Width

- Idea: Predict inclusive cross-section of W and Z bosons
  - We know the Z boson branching ratio
  - We can predict the leptonic BR of the W boson with SM

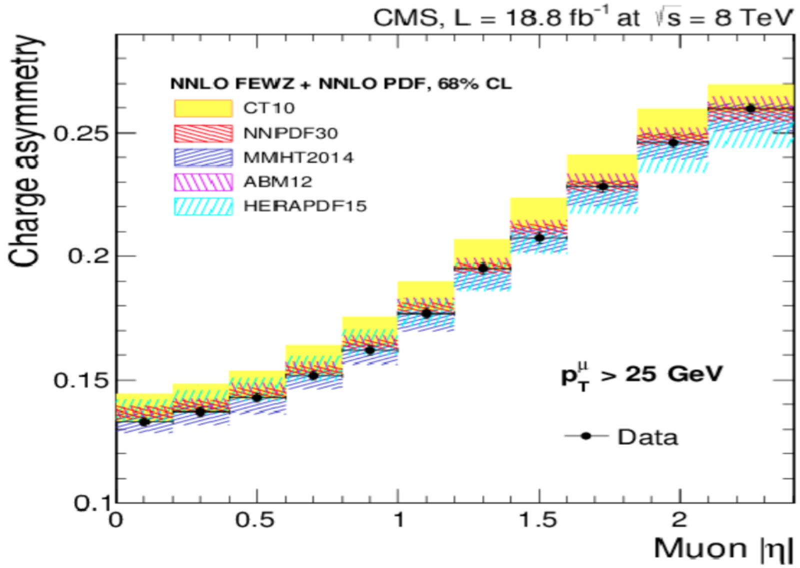
$$R_{lep} = \frac{\sigma_W}{\sigma_Z} \cdot \frac{\Gamma_{W^\pm \to l^\pm \nu}}{\Gamma_W} \cdot \frac{\Gamma_Z}{\Gamma_{Z \to l^+ l^-}}.$$

- Just measure the W and Z boson cross-section in the leptonic decay channels and derive the W boson width



Rapidity Dependence

- Rapidity is correlated to Björken-x
- Z boson rapidity can be directly reconstructed
  - Measure cross-section in dependence of y_Z
- W boson rapidity unkown due to neutrino
  - Use rapidity of the charges decay-lepton instead
  - Different production of W^+ and W^-, i.e. measure charge asymmetry vs. η



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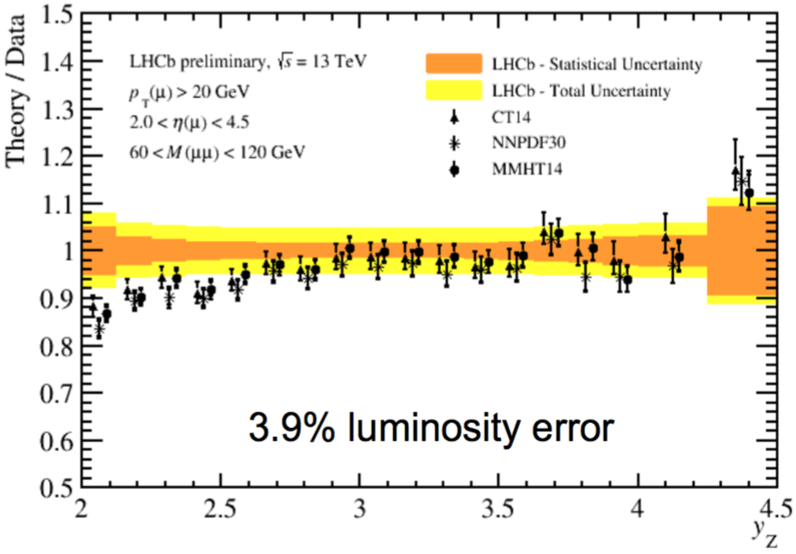
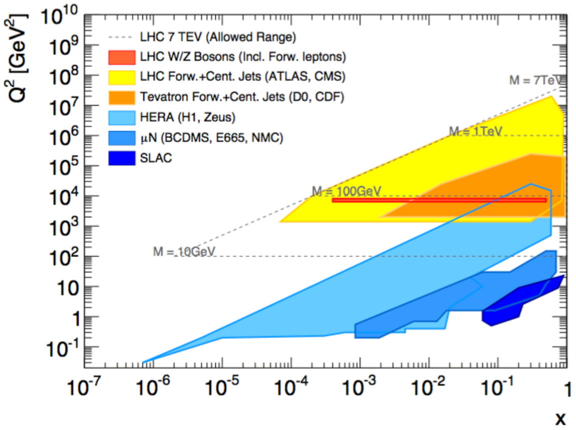
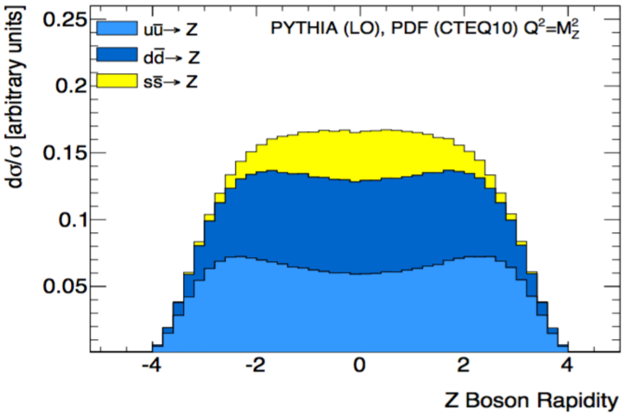


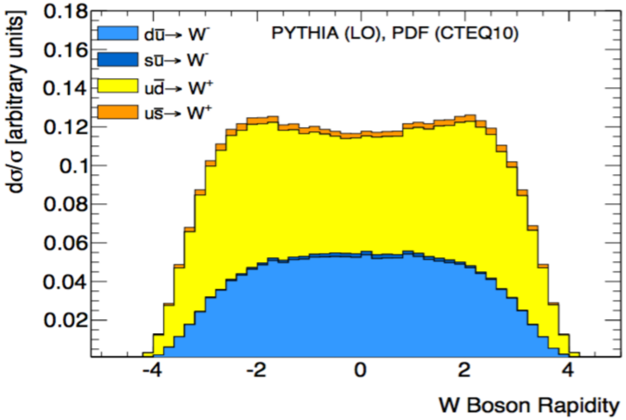
3.9% luminosity error

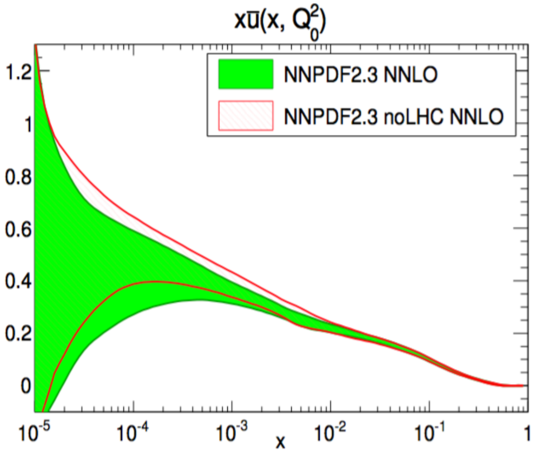
PDF Fitting

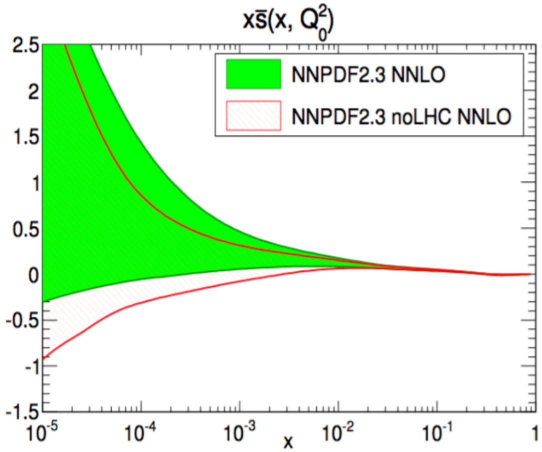
- Idea: Use all available W/Z boson production cross-sections
  - Use NNLO?-predictions of cross-sections
  - Adjust descriptions of PDFs so that they fit the data

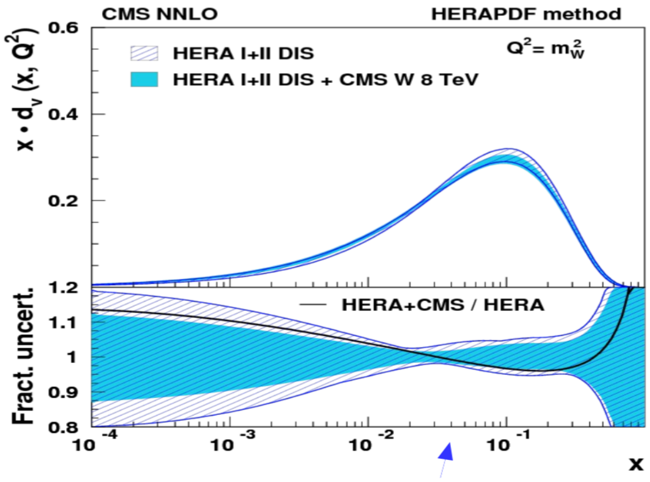






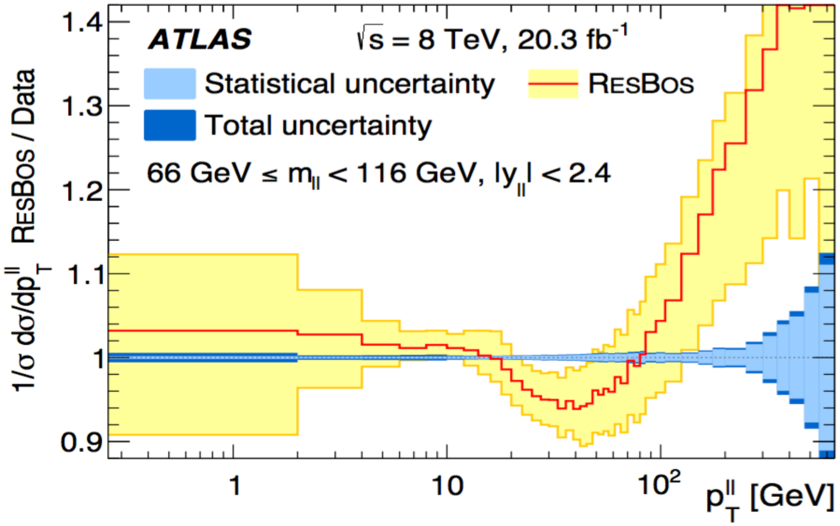


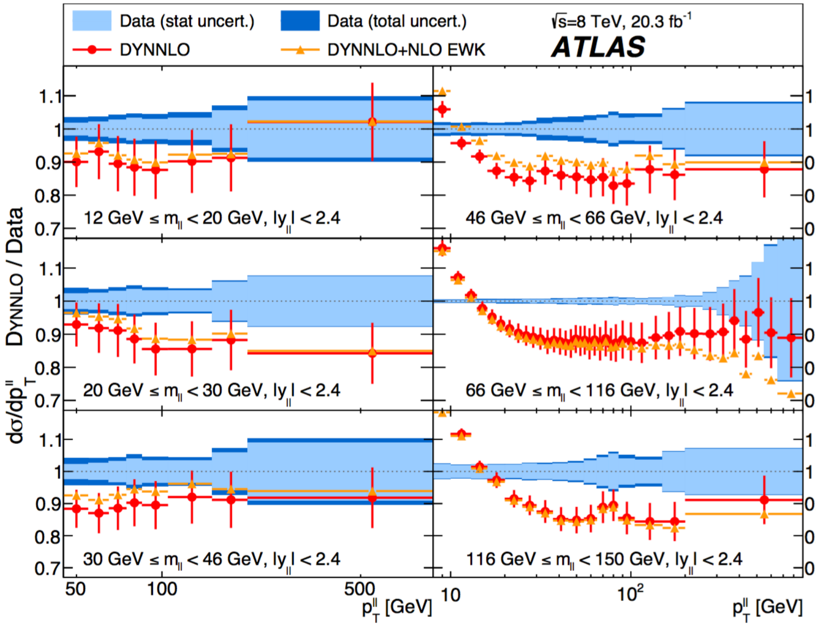




Z Boson Transverse Momentum

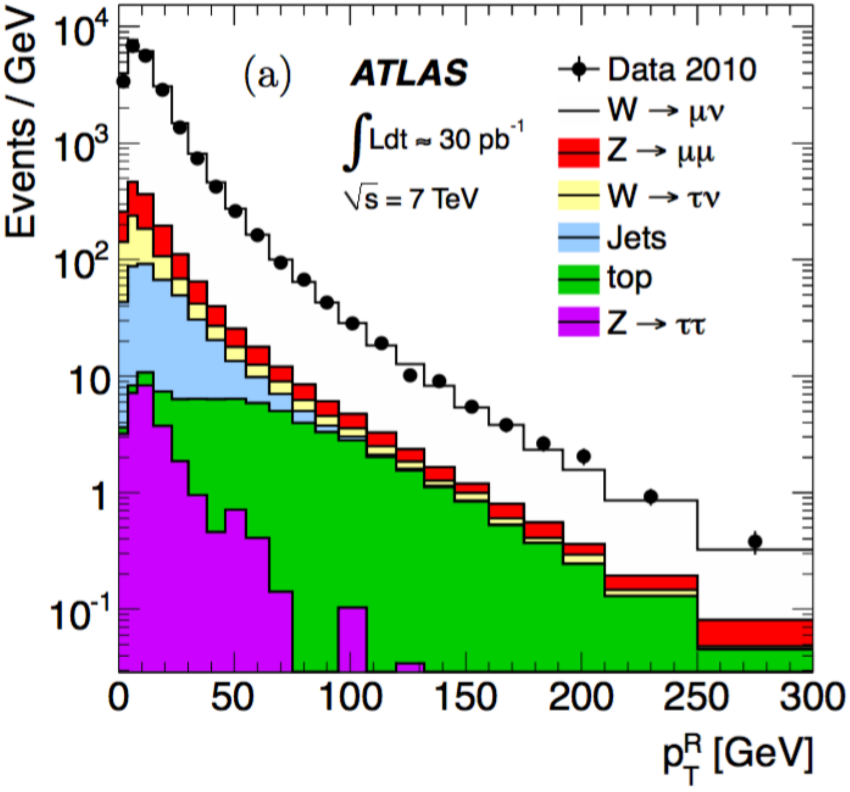
- Can be directly reconstructed by the 4-vectors of the two decay leptons
  - Very precise measurement
- Tests in some sense all what goes on in the initial state
  - PS-models, NLO corrections, Resummation, ...
- Three regimes to be tested
  - Low energy $p_T(V) \approx k_T$
  - $k_T < p_T(V) < m_V/2$
  - $m_V/2 < p_T(V)$

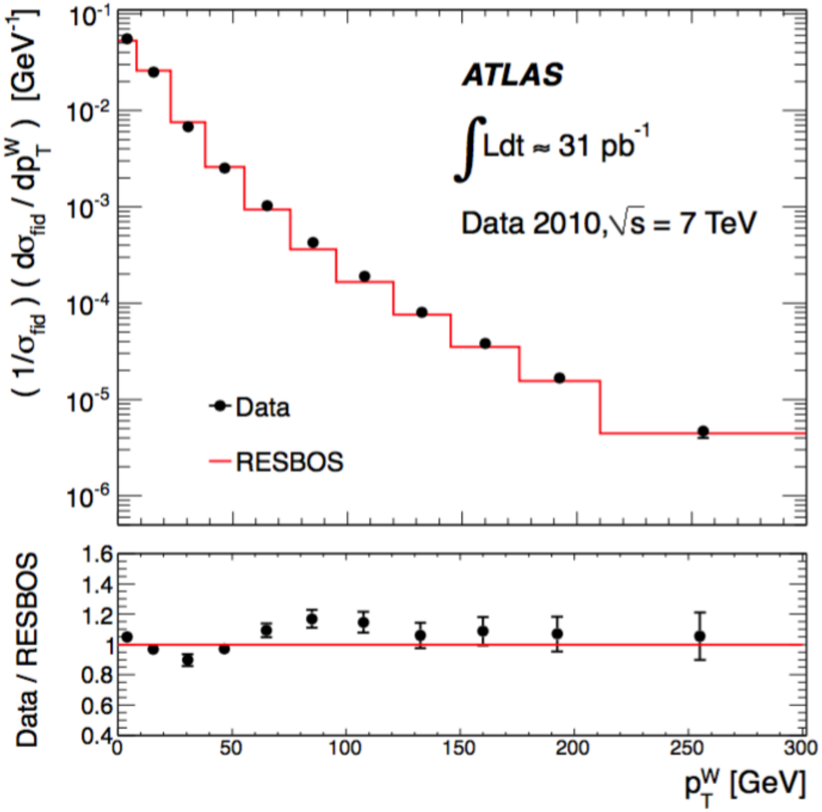




W Boson Transverse Momentum

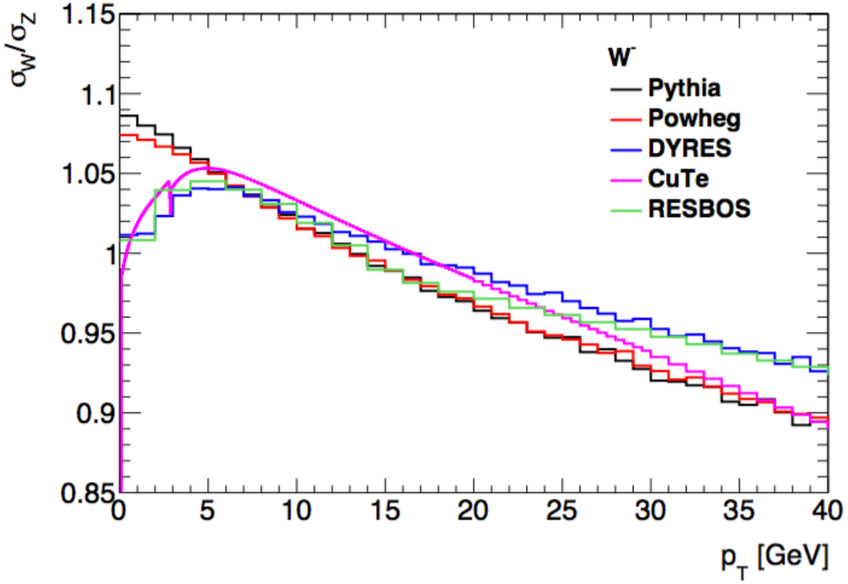
- We can’t reconstruct the neutrino, i.e. we can’t directly access pT(W)
  - Idea: Measure hadronic recoil, i.e. all the ‘hadronic stuff’ which balances the pT(W)
  - Problem: very imprecise, i.e. we expect large uncertainties

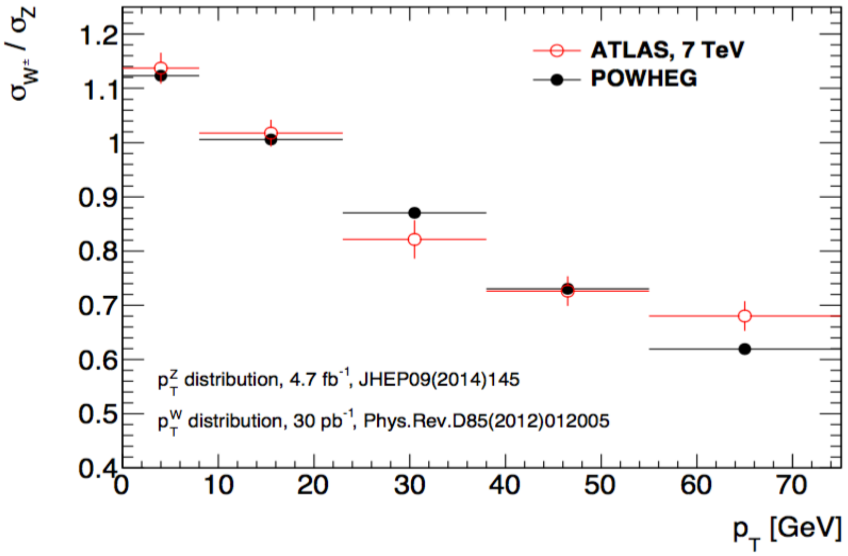




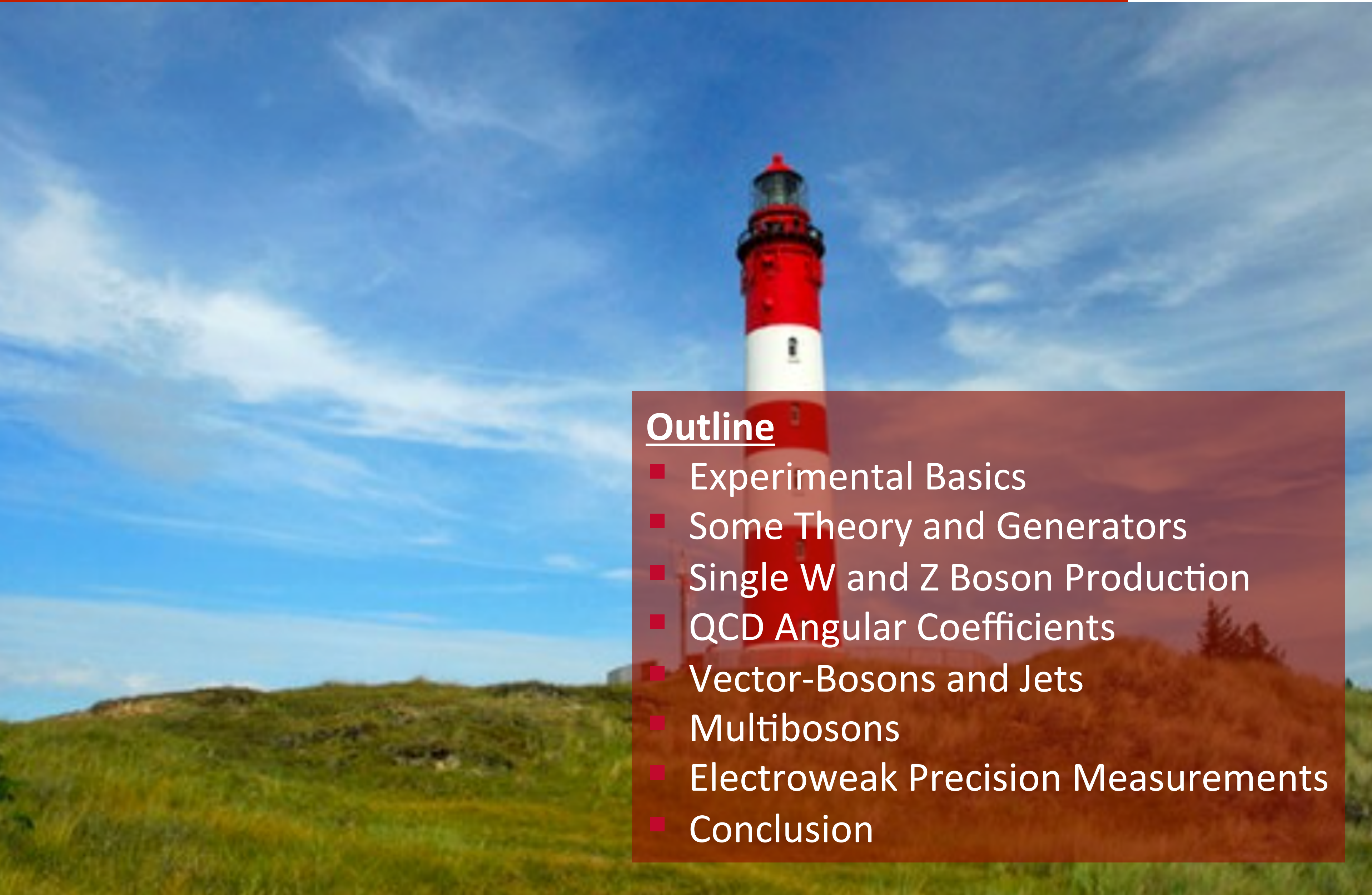
What do Generators predict?

- We can tune our generators to the measured pT(W) and pT(Z) spectrum,
  - Or: compare the ratio of these two predictions
- Theory of pT(W) and pT(Z) should be very similar
  - Apart from heavy-quark contributions
- Different generators, predict different behaviours
  - Data favours PS models, i.e. There is some work to be done





QCD Angular Coefficients



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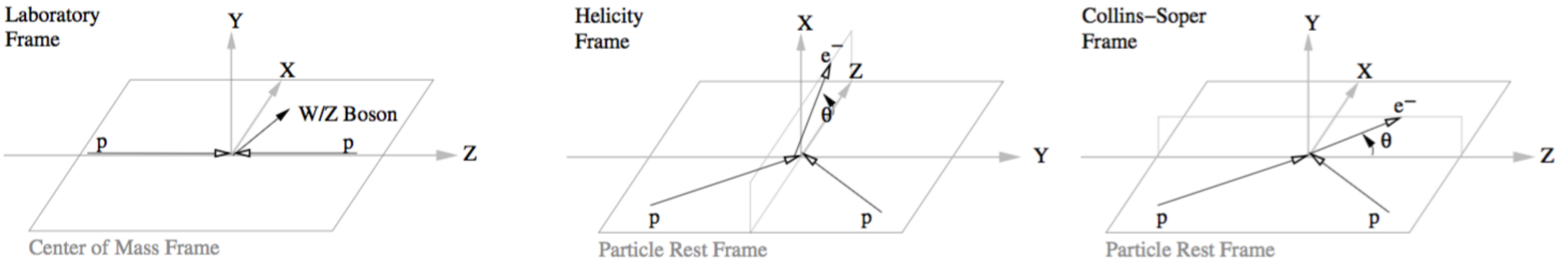
What are angular coefficients

- The general form of the differential cross-section of the Drell-Yan proces can be decomposed as a sum of harmonics in the Collin Soper Frame

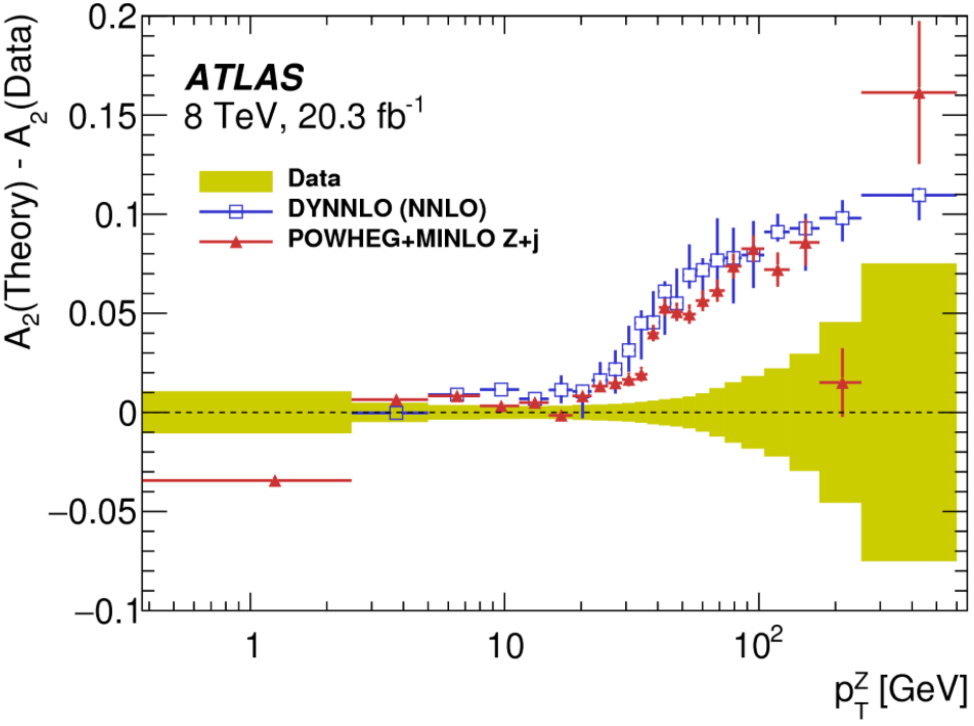
- Usually θ w.r.t incoming parton
    - Unknown in proton-proton
    - Define frame, which "reduces uncertainty": CS-Frame (a rest-frame of vector boson)

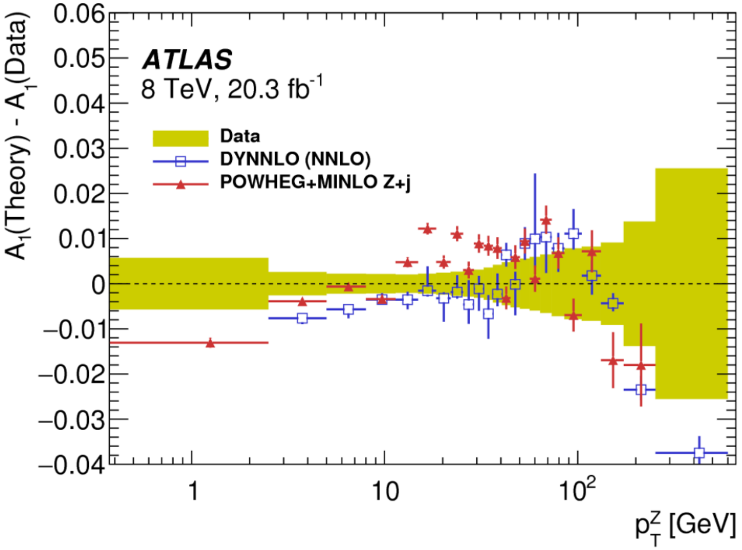
$$\begin{aligned}\frac{d\sigma}{dp_T^2 dy d\cos\theta d\phi} = \frac{d\sigma_{unpol}}{dp_T^2 dy} \cdot \Big(& (1+\cos^2\theta) \\ & +A_0 \frac{1}{2}(1-3\cos^2(\theta)) \\ & +A_1 \sin(2\theta)\cos(\phi) \\ & +A_2 \frac{1}{2}\sin^2(\theta)\cos(2\phi) \\ & +A_3 \sin(\theta)\cos(\phi) \\ & +A_4 (\cos\theta) \\ & +A_5 \sin^2(\theta)\sin(2\phi) \\ & +A_6 \sin(2\theta)\sin(\phi) \\ & +A_7 \sin(\theta)\sin(\phi)\Big),\end{aligned}$$

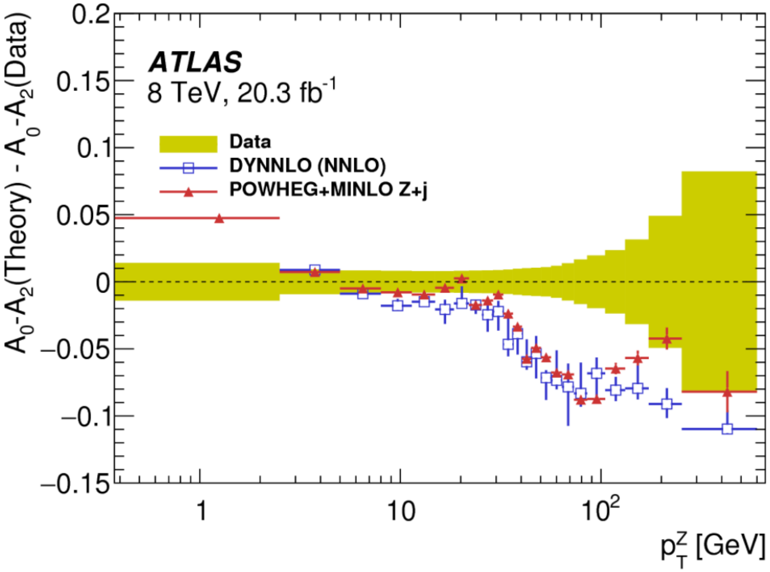


Results from ATLAS

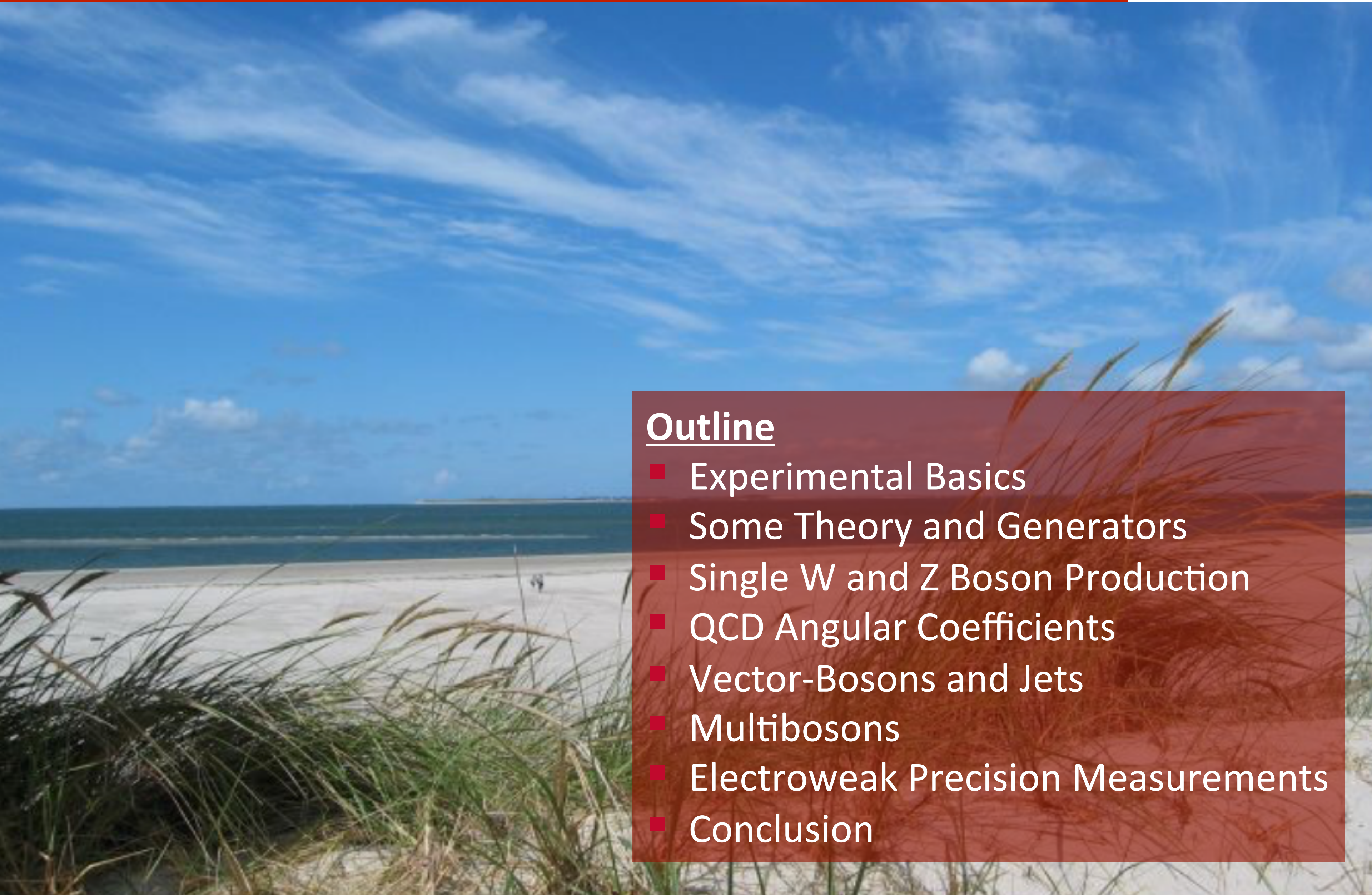
- Precise measurement based on full 2012 data-set at 8 TeV
  - Forward folding used for analysis







Vector Boson and Jets



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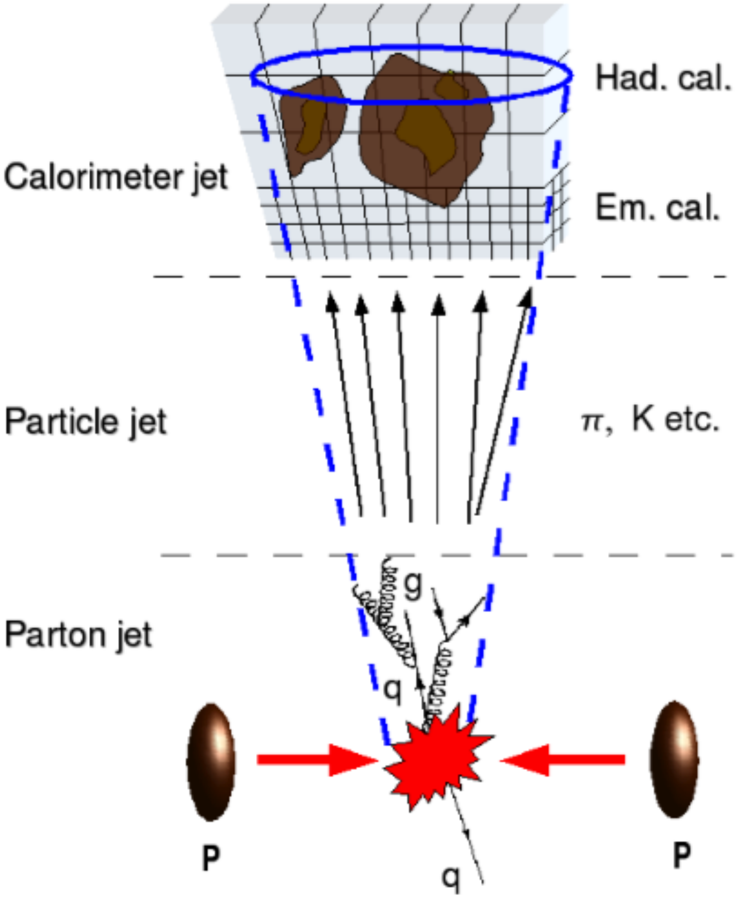
How to reconstruct Jets?

- At a very basic level: Look for energy clusters with a certain size in the calorimeter (actually little bit more complicated to get things ir-safe)
  - Variable: Cone-size of this cluster

- Experimental problem: What is the measured energy scale?
  - Rule of thump: jet-energy scale is very imprecise compared to energy scale of leptons

- Theoretical 'problem': Need also define jets on generator level, as we cannot unfold to final-state parton level



Number of Jets

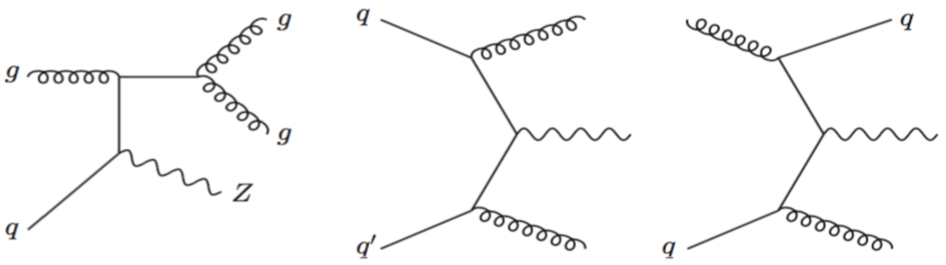
- Several generators predict N-Jet final states on tree-level

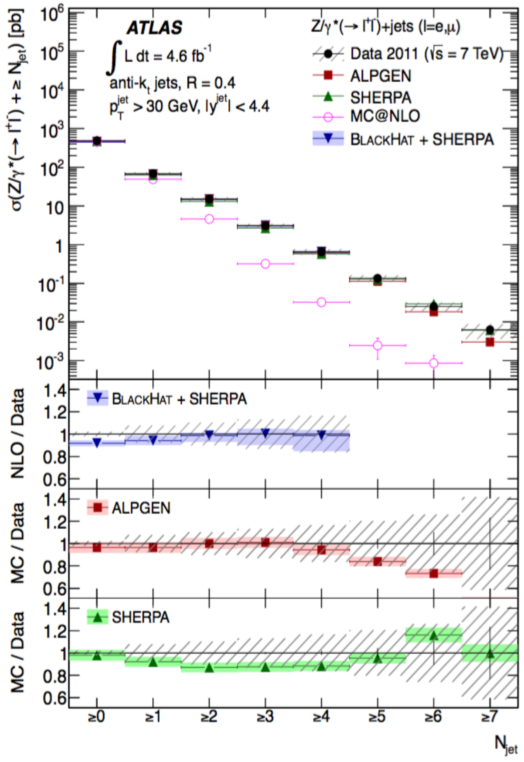
- Probability that an additional parton is governed by a Poisson distribution
    - leading-order term for a V+n-jet final state

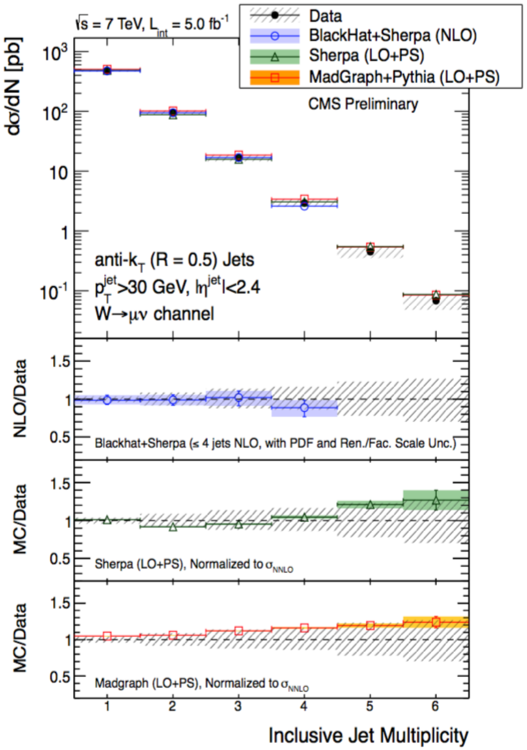
$$\sigma^{LO}_{V+n-jet} \sim \frac{\bar{n}e^{-\bar{n}}}{n!}\sigma_{tot}$$

- At hadron colliders: Experimentally observed V+n-jet final state, has the form of

$$\sigma^{LO}_{V+n-jet} \sim \sigma_0 e^{-an} \qquad \frac{\sigma_{n+1}}{\sigma_n} = e^{-a}$$

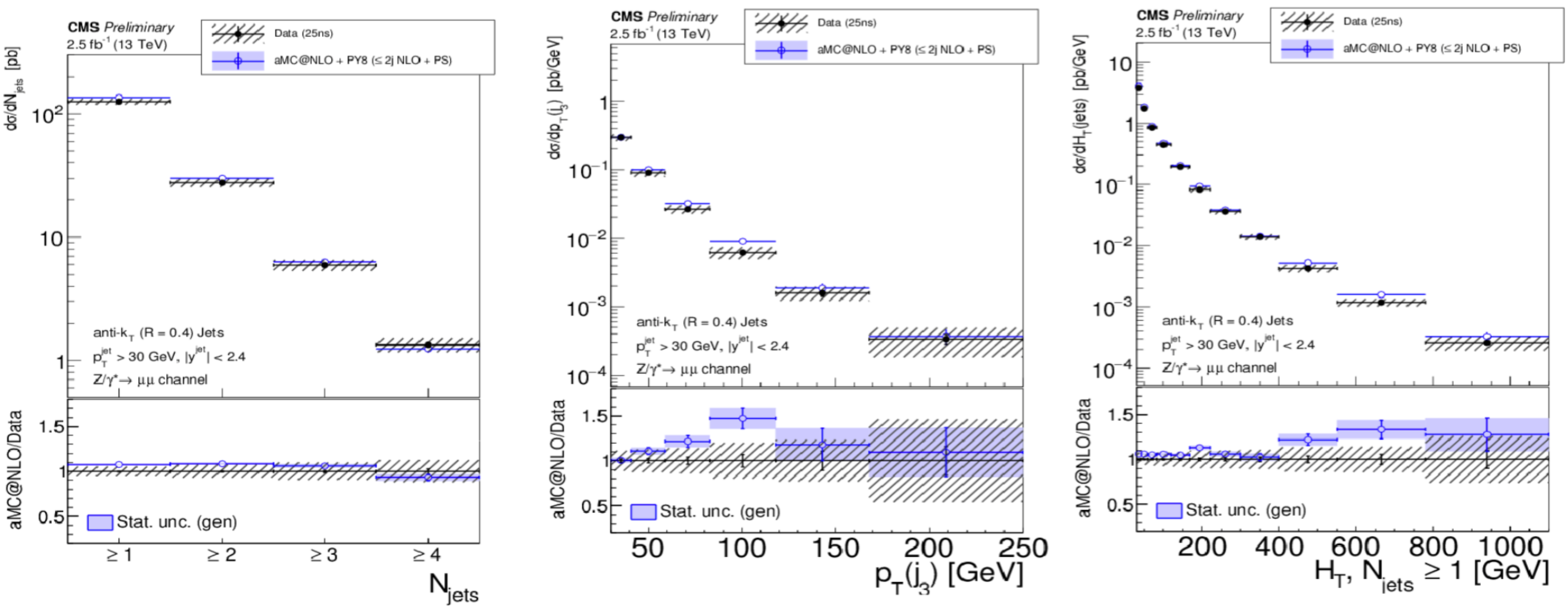






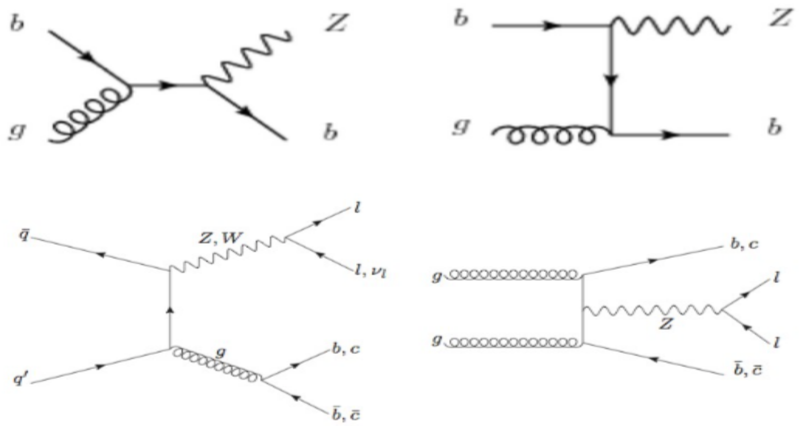
Further Observables

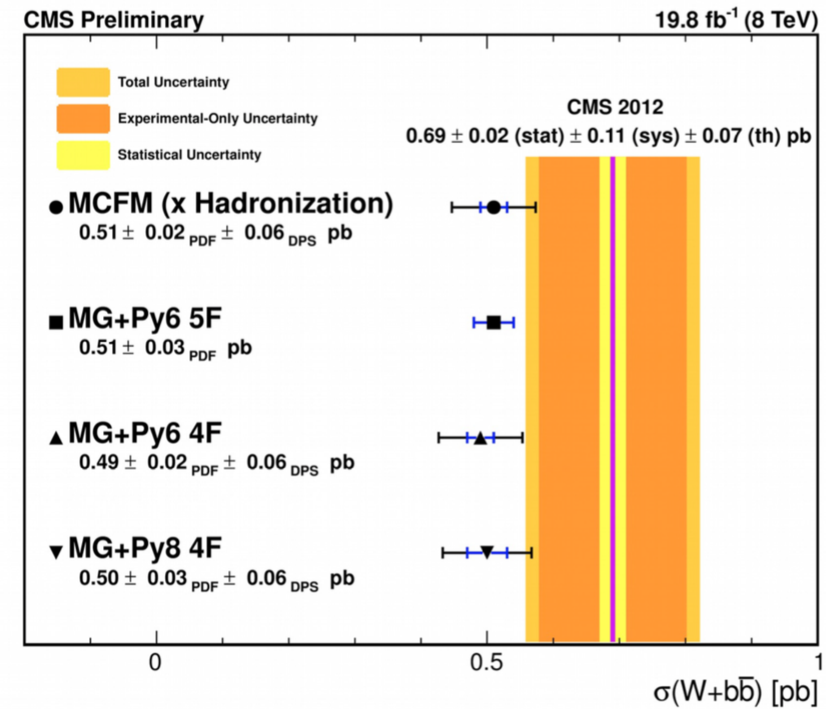
- We can test more than the number of jets:
  - transverse momentum distribution of jets
  - their angular dependencies
  - H_T: Scalar sum of all jet energies (typically used as value of μ-scales)
    - Sensitive to missing HO corrections / BSM

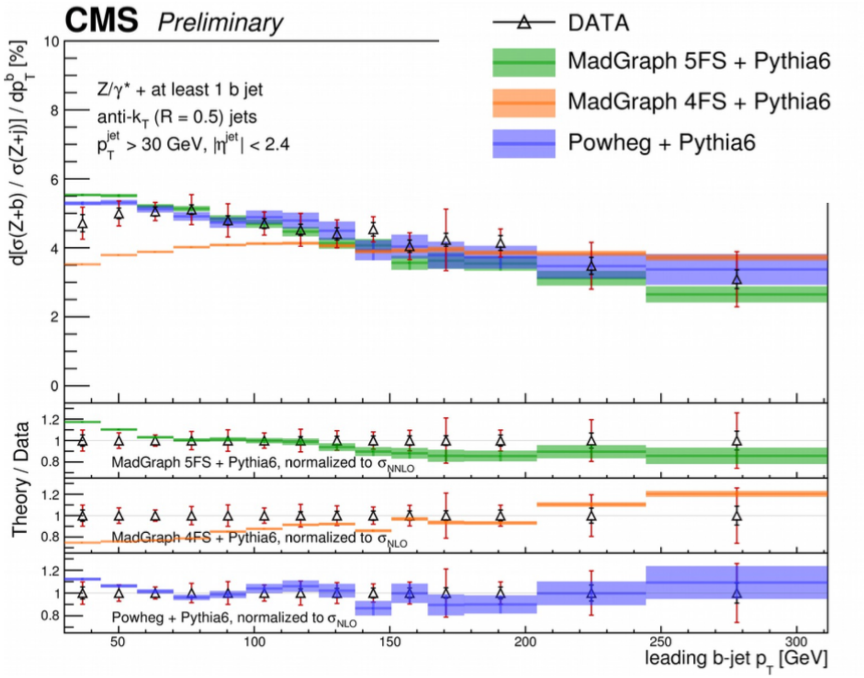


Heavy Quarks

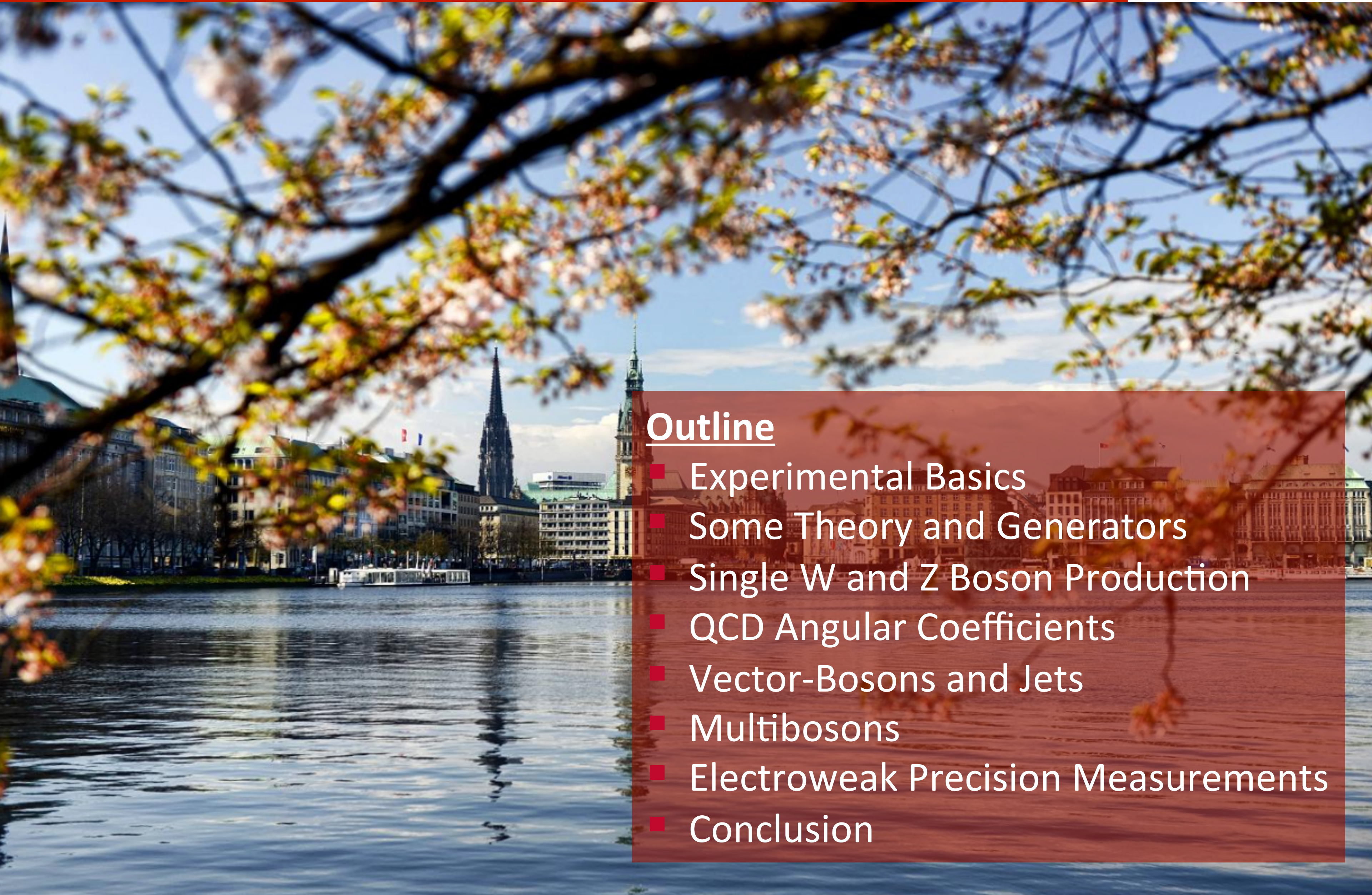
- Heavy quarks in final states in particular interesting:
  - PDF’s, Backgrounds, Calibration, BSM
- Experimentally: b- and c-jets can be identified via displaced vertices







Multibosons



Outline

- Experimental Basics
- Some Theory and Generators
- Single W and Z Boson Production
- QCD Angular Coefficients
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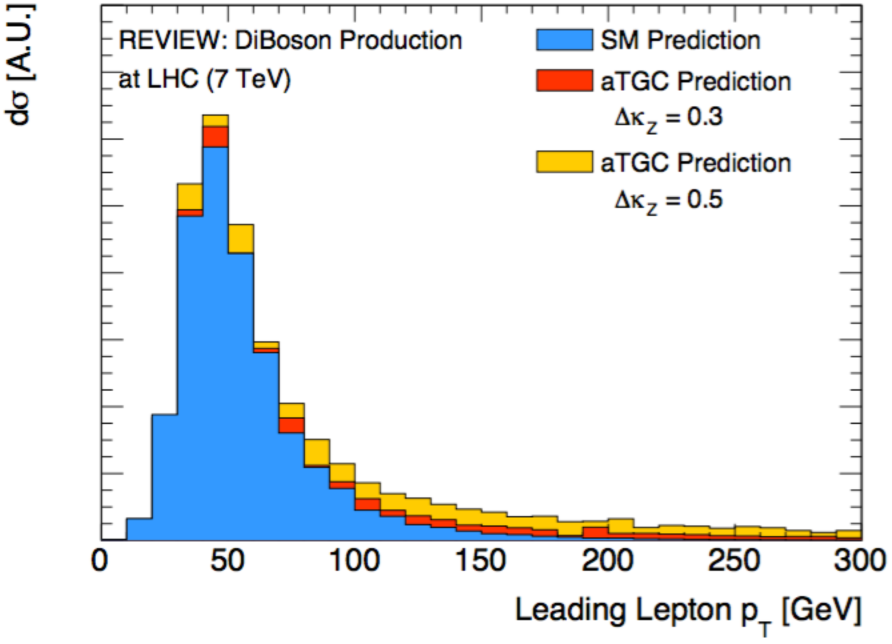
- Multibosons
- Electroweak Precision Measurements
- Conclusion

Triple Gauge Couplings and BSM

- Most general gauge invariant Lagrangian that describes the trilinear interaction of electroweak gauge boson

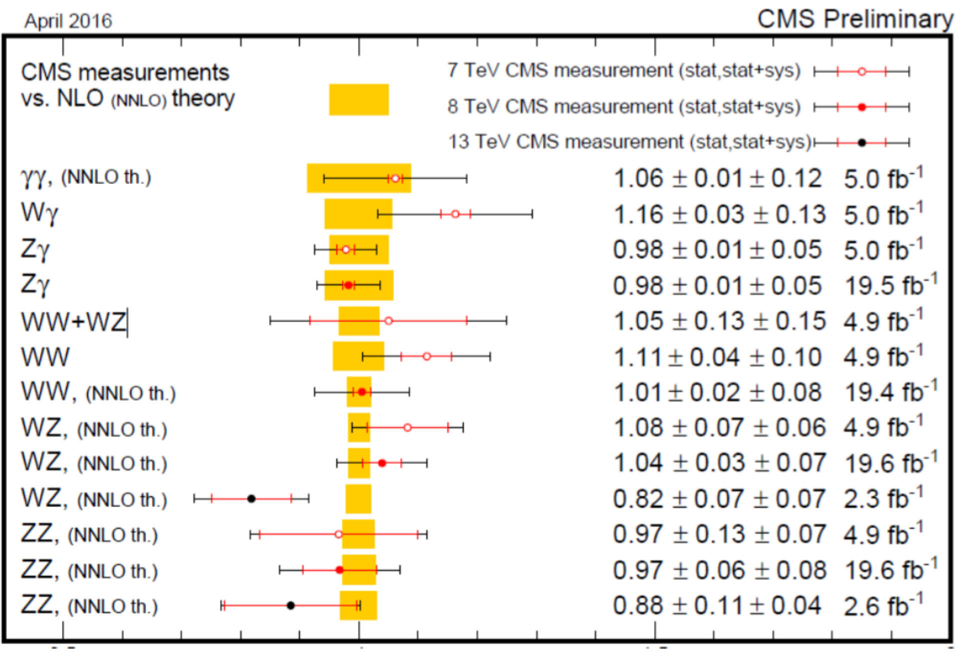
$$\begin{aligned} i\mathscr{L}_{WWV}/g_{WWV} = {} & [1+\Delta g_V^1]V^\mu(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) \\ & +[1+\Delta\kappa_V]W^+_\mu W^-_\nu V^{\mu\nu} \\ & +\frac{\lambda_V}{m_W^2}V^{\mu\nu}W^{+\alpha}_\nu W^-_{\alpha\mu} \\ & +ig_V^4 W^-_\mu W^+_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) \\ & +ig_V^5\varepsilon_{\mu\nu\alpha\beta}[(\partial^\alpha W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\alpha W^{+\nu})]V^\beta \\ & -\frac{\tilde{\kappa}_V}{2}W^-_\mu W^+_\nu \varepsilon^{\mu\nu\alpha\beta}V_{\alpha\beta} \\ & -\frac{\tilde{\lambda}_V}{2m_W^2}W^-_{\rho\nu}W^{+\mu}_\nu \varepsilon^{\nu\rho\alpha\beta}V_{\alpha\beta}, \end{aligned}$$

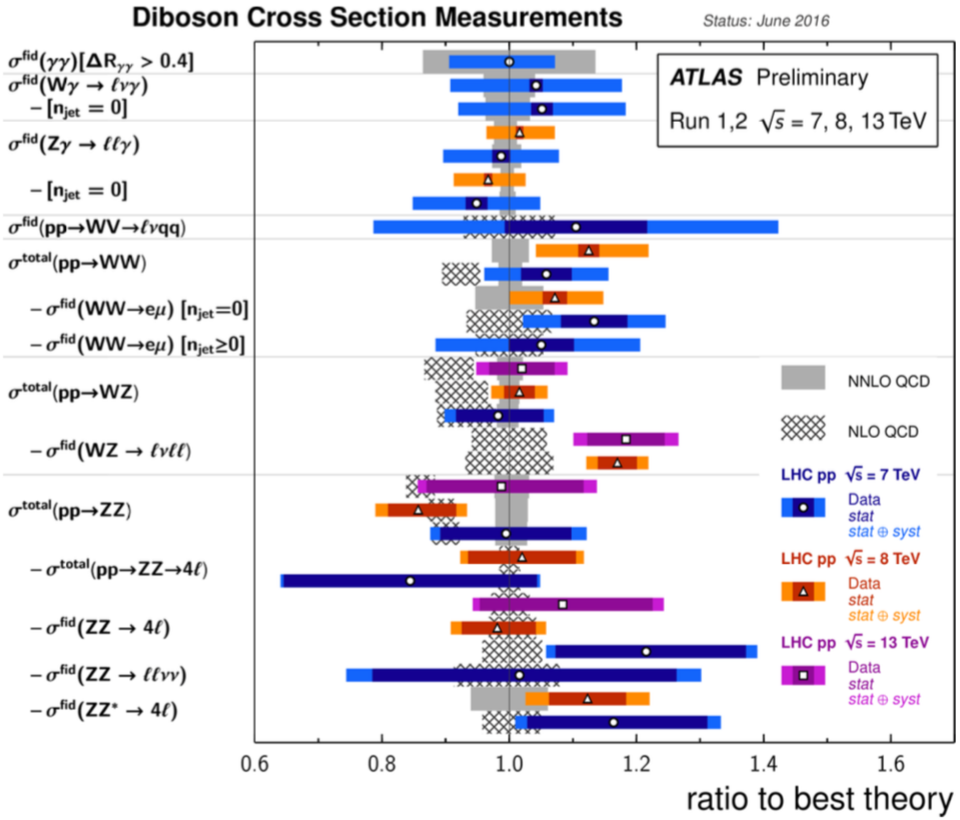
- Anomalous couplings are described by seven parameters for each of the WWV vertices: Δg_{V1} , $\Delta\kappa_V$, λ_V, g_{V4} , g_{V5} , $\tilde{\kappa}_V$ and $\tilde{\lambda}_V$.
  - All aTGCs are equal to zero in the SM.
- Non-zero aTGC's lead to increase cross-sections
  - Harder p_T spectra of decay products



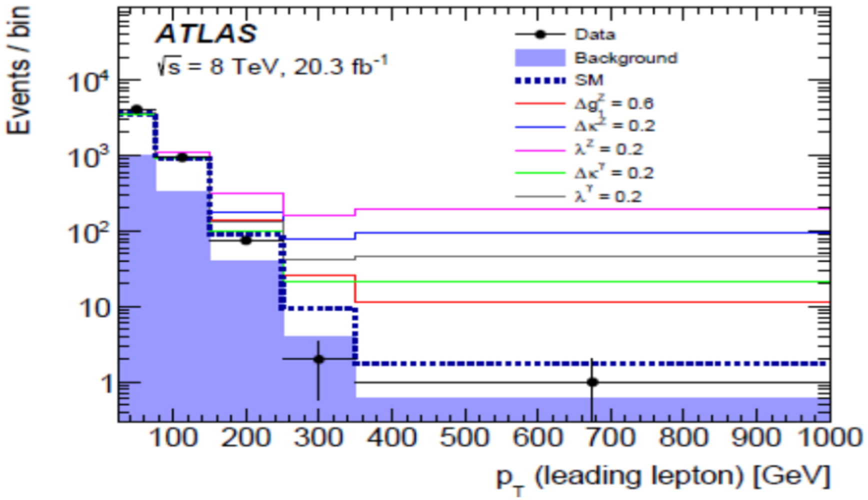
Results on DiBoson Cross-Sections

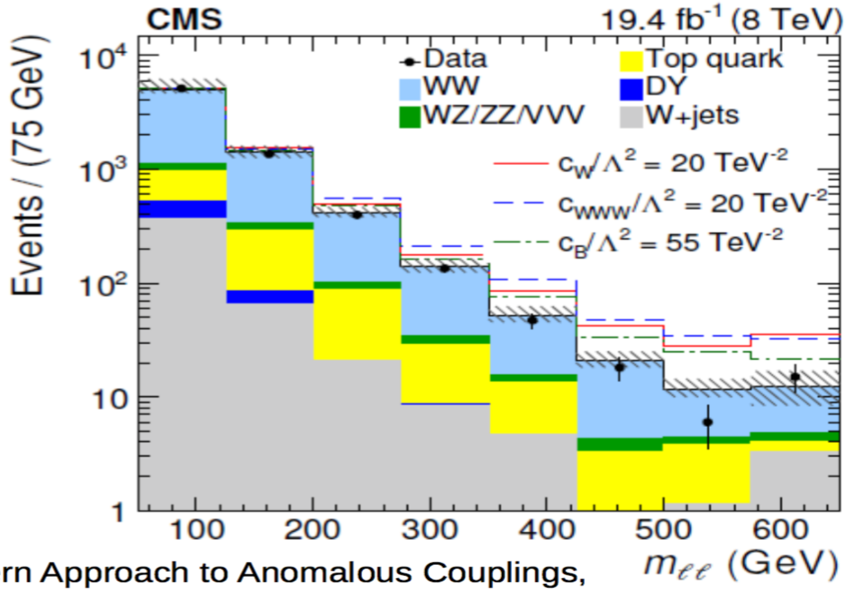
- Note (large!) difference between NNLO and NLO predictions
- Again: Very good agreement between predictions and measurements
  - “Complementary deviations” in ATLAS and CMS
  - Let’s go differentially



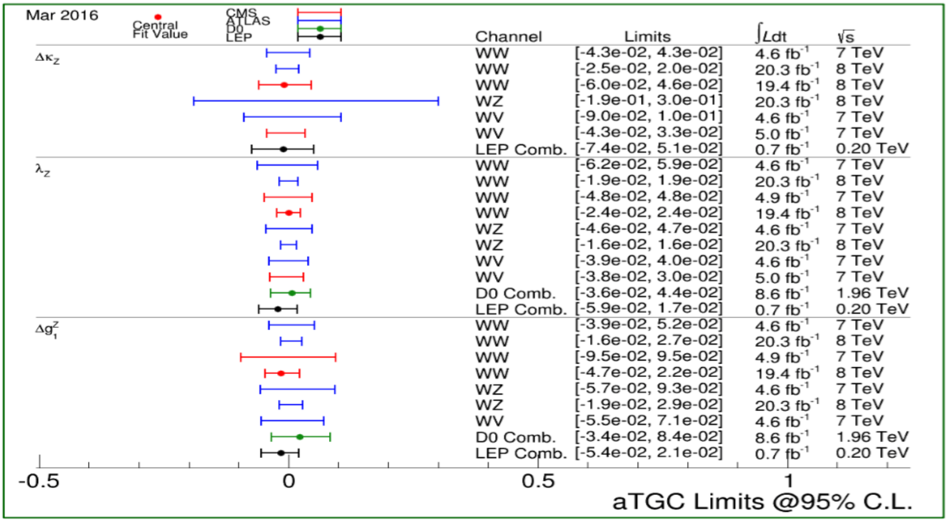


Limits on aTGCs

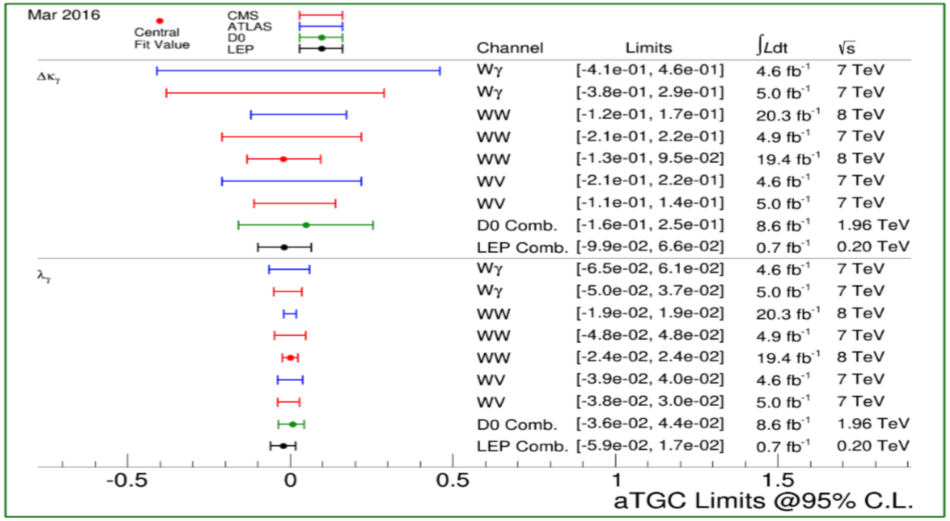




EFT Scenario (C. Degrandeet al., Effective Field Theory: A Modern Approach to Anomalous Couplings, Annals Phys. 335 (2013) 21–32, arXiv:1205.4231 [hep-ph]).



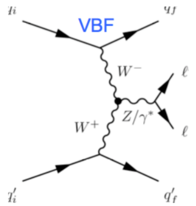
	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WW	[-6.0e-02, 4.6e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-1.9e-01, 3.0e-01]	20.3 fb^{-1}	8 TeV
	WV	[-9.0e-02, 1.0e-01]	4.6 fb^{-1}	7 TeV
	WV	[-4.3e-02, 3.3e-02]	5.0 fb^{-1}	7 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.6e-02, 1.6e-02]	20.3 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.9e-02, 2.9e-02]	20.3 fb^{-1}	8 TeV
	WV	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV



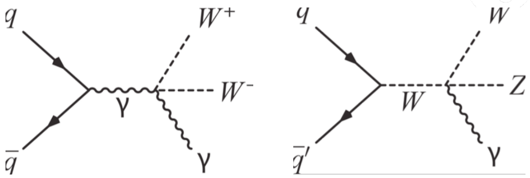
	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$\Delta\kappa_\gamma$	Wγ	[-4.1e-01, 4.6e-01]	4.6 fb^{-1}	7 TeV
	Wγ	[-3.8e-01, 2.9e-01]	5.0 fb^{-1}	7 TeV
	WW	[-1.2e-01, 1.7e-01]	20.3 fb^{-1}	8 TeV
	WW	[-2.1e-01, 2.2e-01]	4.9 fb^{-1}	7 TeV
	WW	[-1.3e-01, 9.5e-02]	19.4 fb^{-1}	8 TeV
	WV	[-2.1e-01, 2.2e-01]	4.6 fb^{-1}	7 TeV
	WV	[-1.1e-01, 1.4e-01]	5.0 fb^{-1}	7 TeV
	D0 Comb.	[-1.6e-01, 2.5e-01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb^{-1}	0.20 TeV
λ_γ	Wγ	[-6.5e-02, 6.1e-02]	4.6 fb^{-1}	7 TeV
	Wγ	[-5.0e-02, 3.7e-02]	5.0 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV

Vector Boson Fusion, aQGC, …

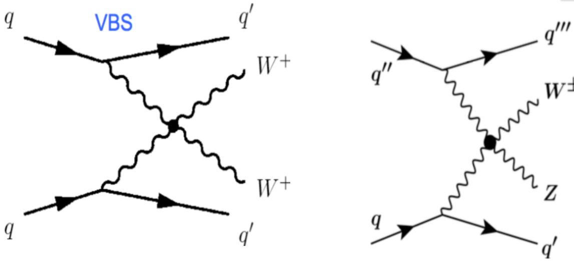
- We can test the gauge-structure of the EW-Sector even in more:
  - Vector boson Fusion

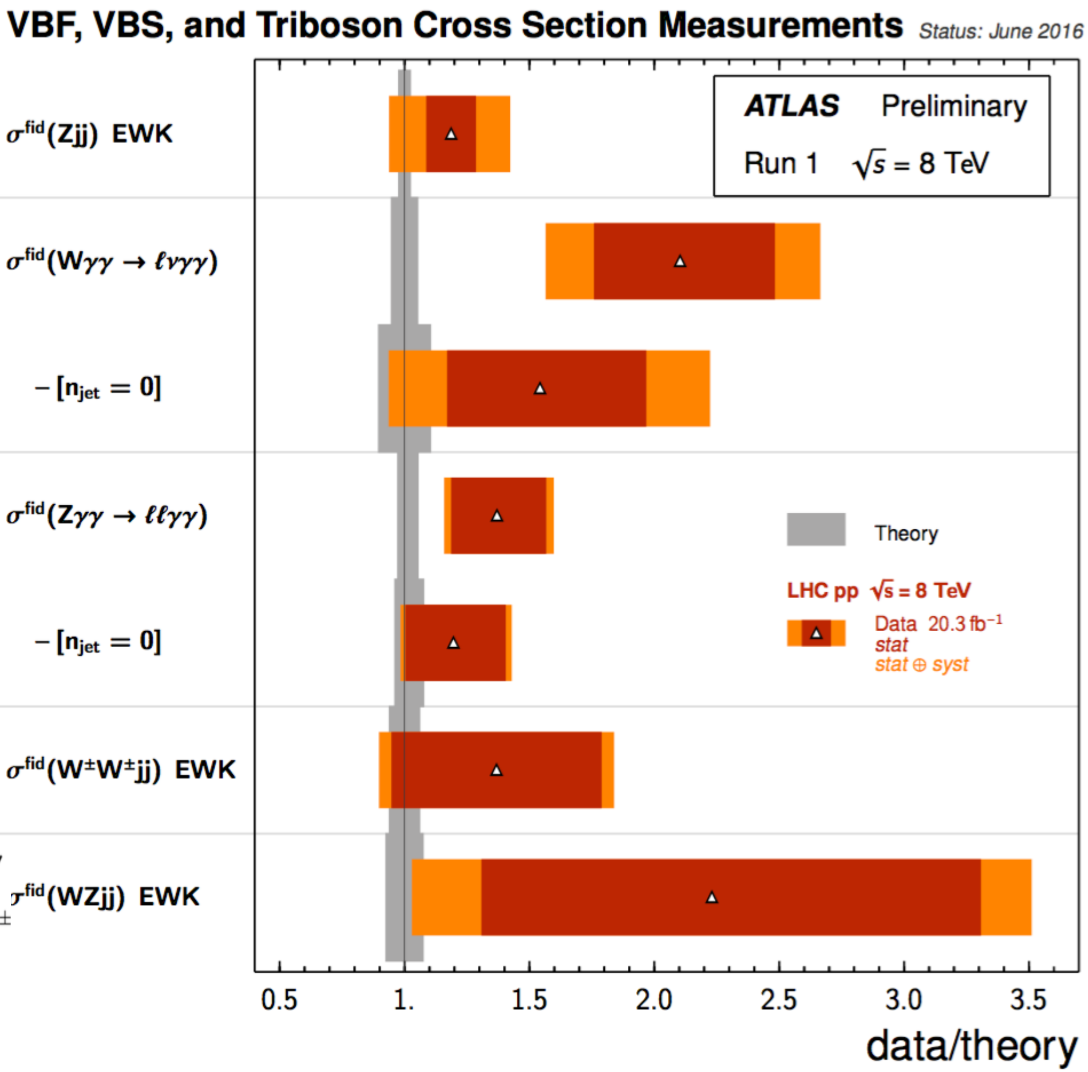


  - Tribosons

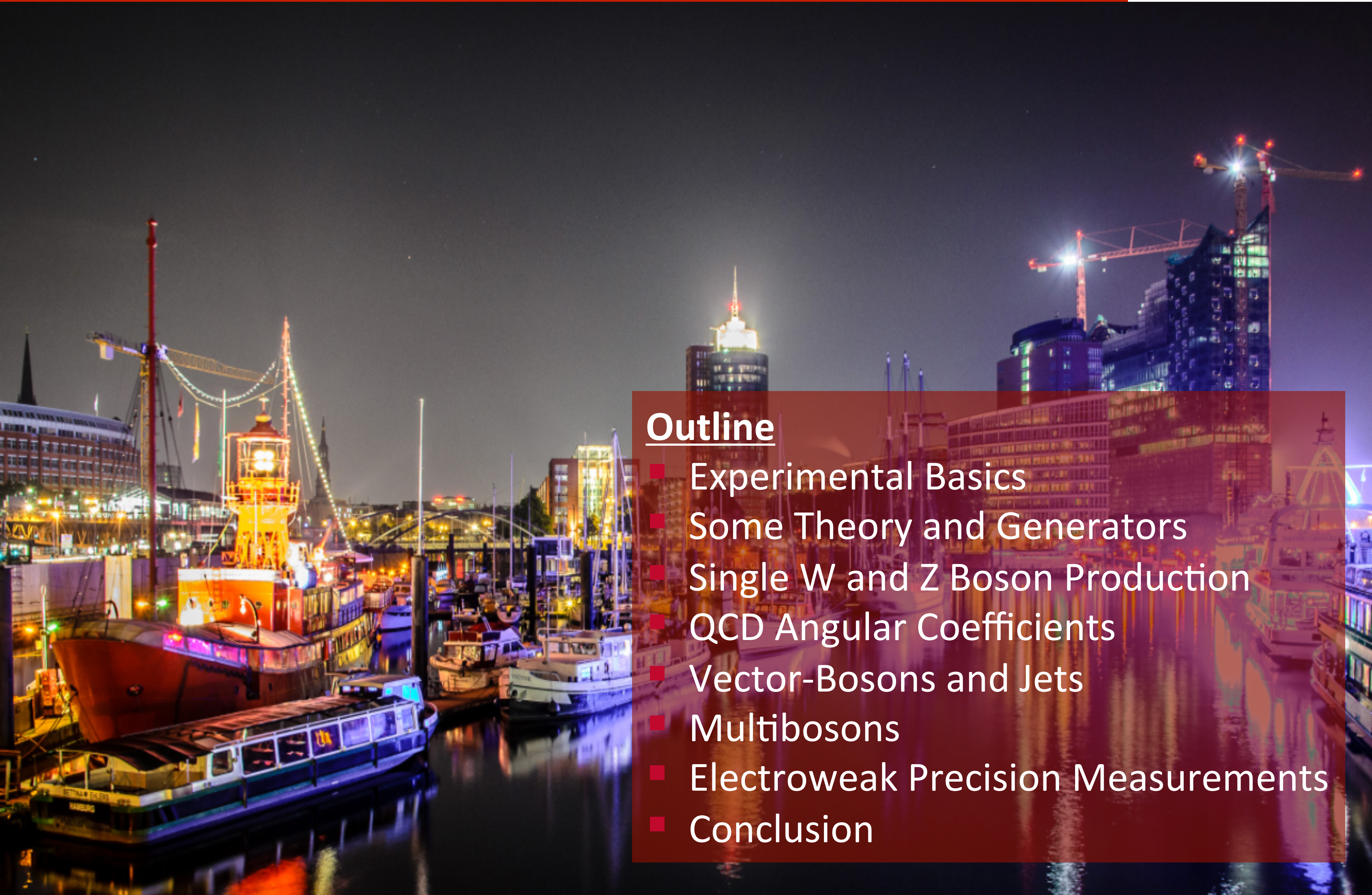


  - VBoson Scattering





Electroweak Precision Measurements



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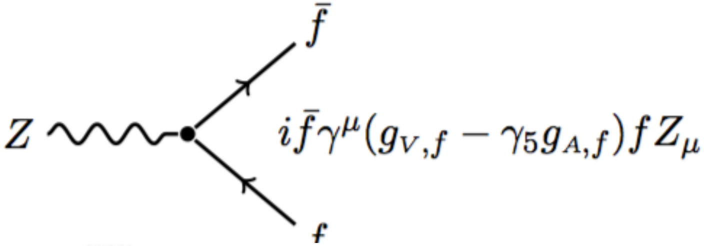
Summary of the Electroweak Sector

- The electroweak sector of the Standard Model has five parameters
  - α_{em}
  - G_F
  - m_W
  - m_Z
  - $\sin^2\theta_W$
  - (+ m_H for the scalar sector)

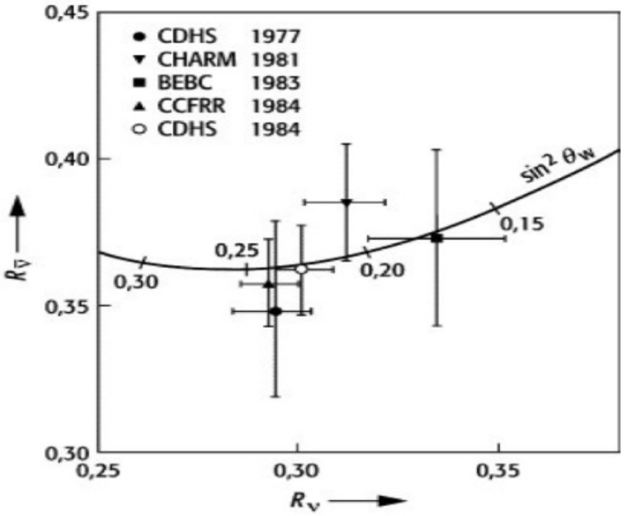


$$i\bar{f}\gamma^\mu(g_{V,f} - \gamma_5 g_{A,f})fZ_\mu$$

- However, they are not independent, but related by theory

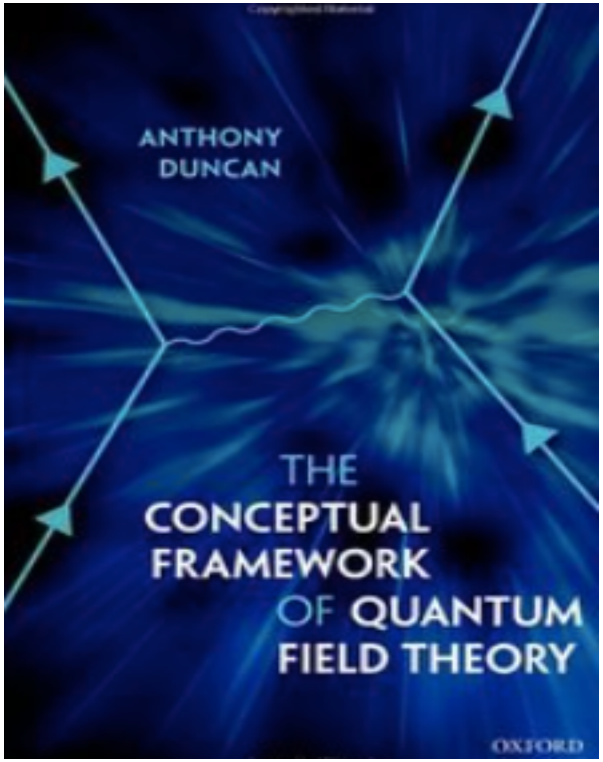
$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \qquad M_W^2\sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$

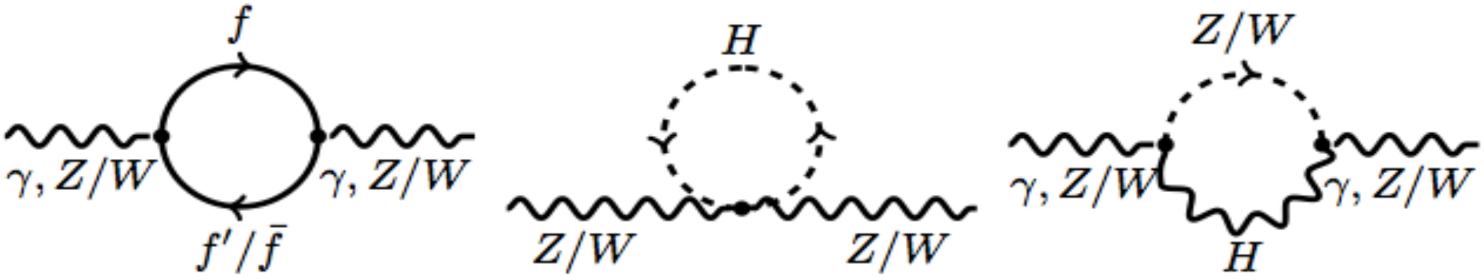
- Consequence: Predictive power of the SM



Radiative Corrections

- Lets test the **predictive power** and insert the measured values of m_Z and $\sin^2\theta_W$ predict m_W
  - m_W^{tree} = (79.964±0.005) GeV
- Lets compare with the measurement:
  - $m_W^{measured}$ = (80.385±0.015) GeV
- What went wrong?
  - Tree level relations are not sufficient
  - **radiative corrections are needed**





Radiative Corrections

- The impact of corrections stored in **EW form factors** helps to define effective coupling at Z-pole

- The relation between SM parameters appear with **quadratic dependence on m_{top}, logarithmic dependence on M_H**

- Idea of electroweak fits
  - Measure many different observables in the experiment
  - Calculate the relations between all observables in SM
  - **Probe the consistency of the SM / Predict observables**

$$\sin^2\theta^f_{\text{eff}} = \kappa^f_Z \sin^2\theta_W$$

$$g_{V,f} = \sqrt{\rho^f_Z}\,(I^f_3 - 2Q^f \sin^2\theta^f_{\text{eff}})$$

$$g_{A,f} = \sqrt{\rho^f_Z}\, I^f_3$$

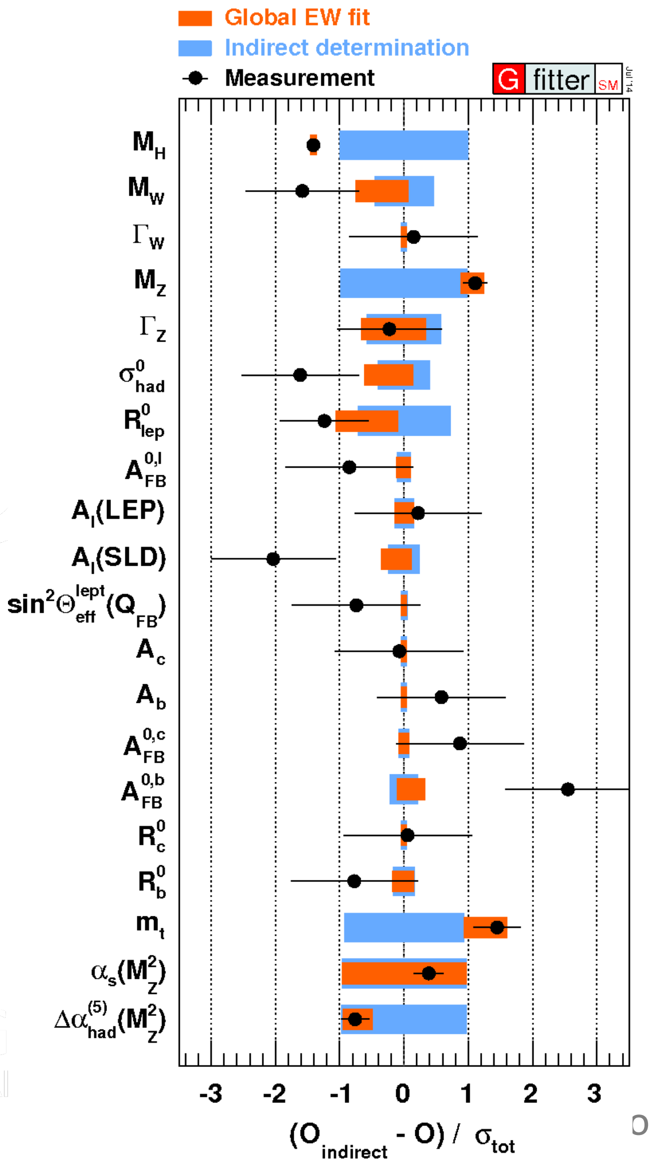
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

$$M_W\left(\ln(M_H), m_t^2, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M_Z^2), \alpha_s(M_Z^2)\right)$$

$$\sin^2\theta^f_{\text{eff}}\left(\ln(M_H), M_H, m_t^2, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M_Z^2), \alpha_s(M_Z^2)\right)$$

Input to the Global Electroweak Fit

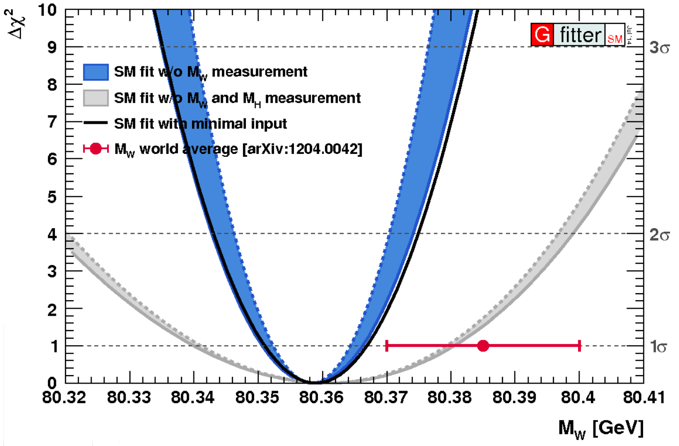
- Input for the gobal electroweak fit mostly from
  - LEP: Z boson observables
  - Tevatron: W boson, top quark mass
  - LHC: **Higgs Boson, top quark mass (see dedicated top-session**)
- Note: improvement on **m_H precision** leaves fit unchanged
- Improvement on m_{top} will be **limited by theoretical uncertainty** on pole-mass definition
- Largest discrepancy between A_l(SLD) and $A_{FB}^{0,b}$, both sensitive to $\sin^2\theta_W$

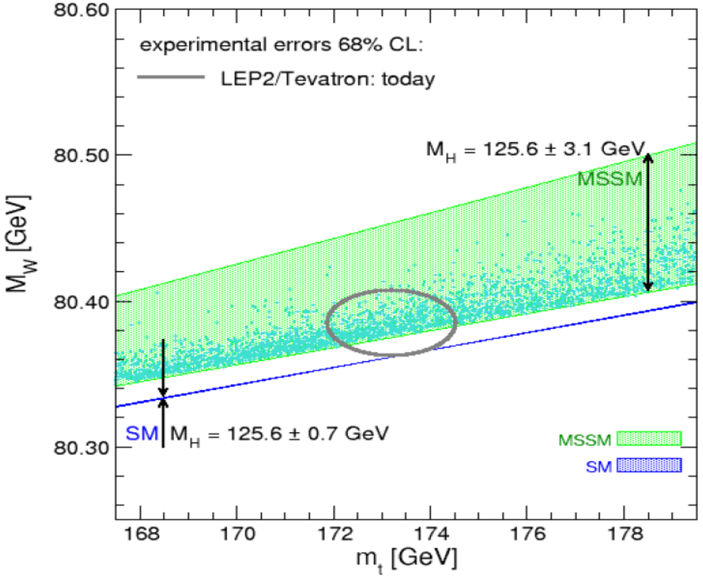


on]

What we need: m_W, m_{top}, $\sin^2\theta_W$

- “Simple” thing: Test consistency of the Standard Model
  - Current **p-value = 0.22**
  - In order to match the m_{top} precision, we would need $\Delta m_W < 5$ MeV
    - Side-Note: also **no Γ_W measurement** at LHC yet
- Electroweak precision measurements are **sensitive to several new physics scenarios**, e.g. SUSY
  - Radiative correction depends on mass splitting (Δm^2) between squarks in SU(2) doublet
  - Precision on m_W could significantly limit the allowed MSSM space



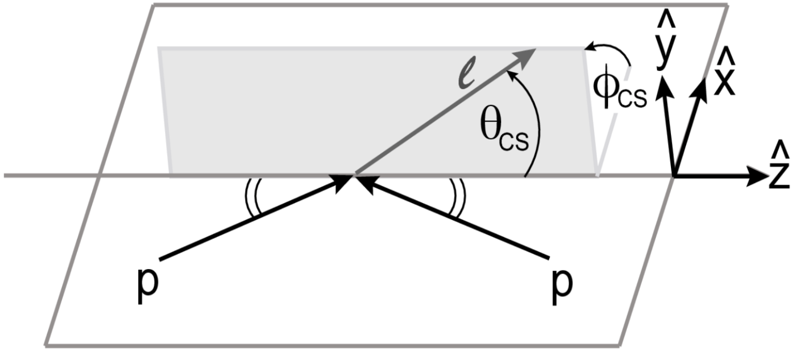


[S. Heinemeyer et. al. arXiv:1311.1663]

How to measure $\sin^2\theta_W^{\mathrm{eff}}$?

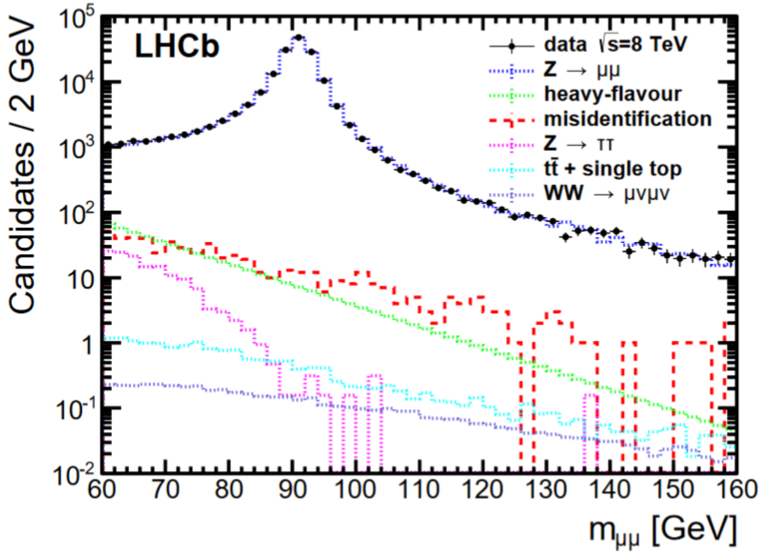
- **Forward-Backward Asymmetry**
  - Z couplings differ for left- and right-handed fermions
  - **Define A_{FB}** in Collin-Soper Frame
    - Defined w.r.t. to incoming quark and outgoing lepton

$$A_{\mathrm{FB}} = \frac{N_{\cos\theta^*_{\mathrm{CS}}\geq 0} - N_{\cos\theta^*_{\mathrm{CS}}<0}}{N_{\cos\theta^*_{\mathrm{CS}}\geq 0} + N_{\cos\theta^*_{\mathrm{CS}}<0}}$$



- A_{FB} linked to the weak mixing angle, via the relation

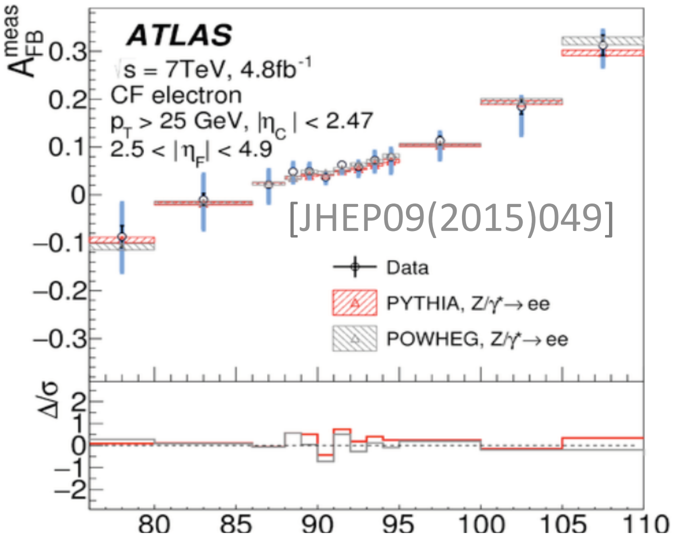
$$A_{FB} = \frac{16}{3}\cdot\frac{(1-4|Q_f|\sin^2\theta_W)}{1+(1-4|Q_f|\sin^2\theta_W)^2}\cdot\frac{(1-4|Q_{f'}|\sin^2\theta_W)}{1+(1-4|Q_{f'}|\sin^2\theta_W)^2}$$



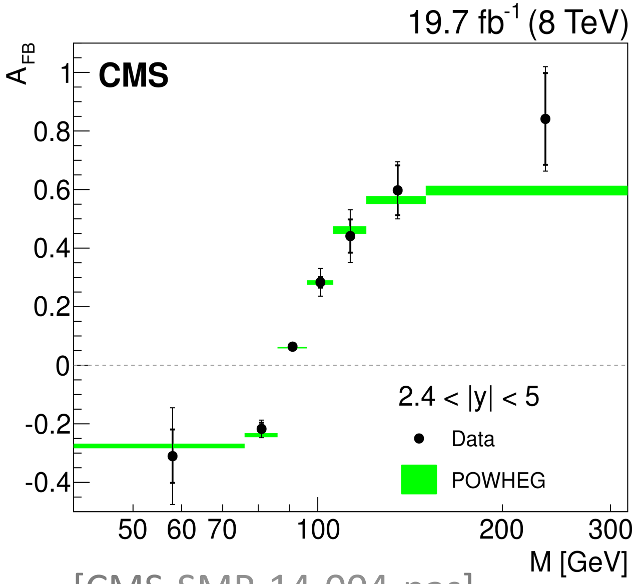
[LHCb arXiv1509.07645]

Results from the LHC

- LHC-Challenge: **where is the quark?**
  - Misidentified quark-direction results in dilution of A_{FB}
  - Forward Z events have smallest dilution effects! LHCb!
- A_{FB} measured as a function of $m_{\mu\mu}$ (LHCb) and $m_{\mu\mu}/m_{ee}$ (ATLAS/CMS)
- **Measurement approach**
  - Use template fitting to extract $\sin^2\theta_W$
  - Alternative: Publish unfolded measurement of A_{FB} and decouple extraction of $\sin^2\theta_W$



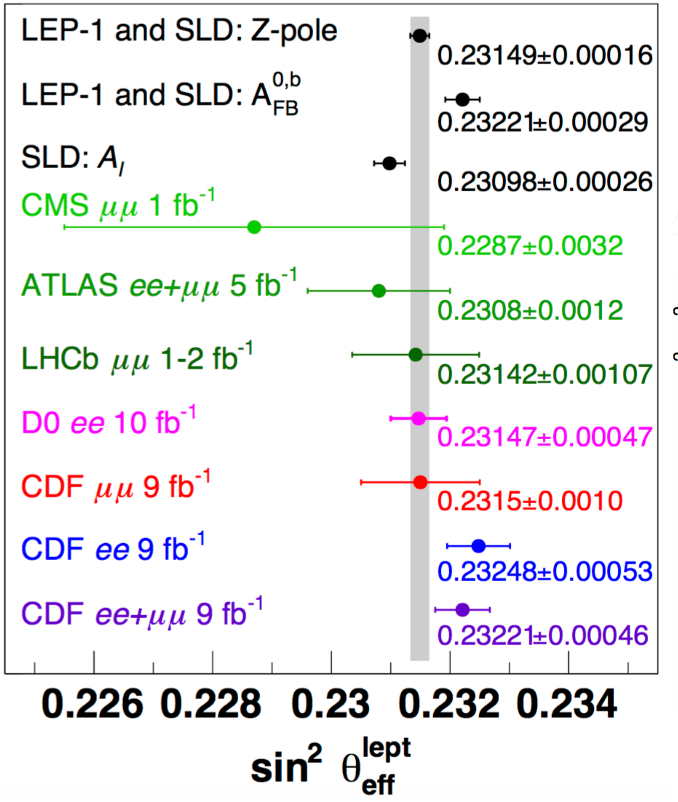
[JHEP09(2015)049]

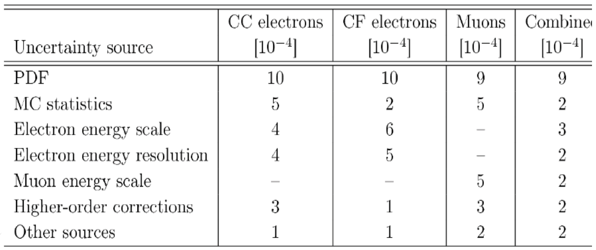


[CMS-SMP-14-004-pas]

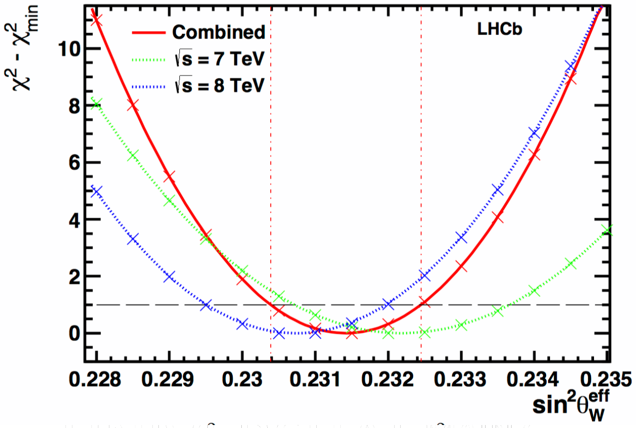
Overview and Reachable Precision

- Dominating uncertainties **due to PDFs**
- LEP and SLD measurement still most precise measurement
  - new CDF measurement gets close to solve discrepancy
  - **Profiling during $\sin^2\theta_W$ fit** might be able to improve PDF uncertainties

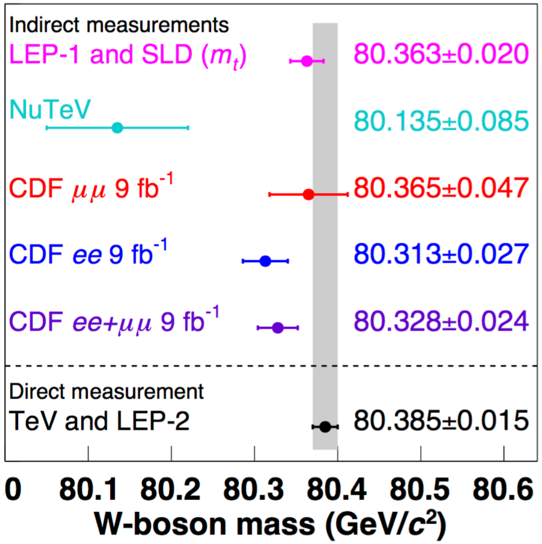




Uncertainty source	CC electrons $[10^{-4}]$	CF electrons $[10^{-4}]$	Muons $[10^{-4}]$	Combine $[10^{-4}]$
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2



[LHCb arXiv1509.07645]



[CDF arXiv:1605.02719]

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

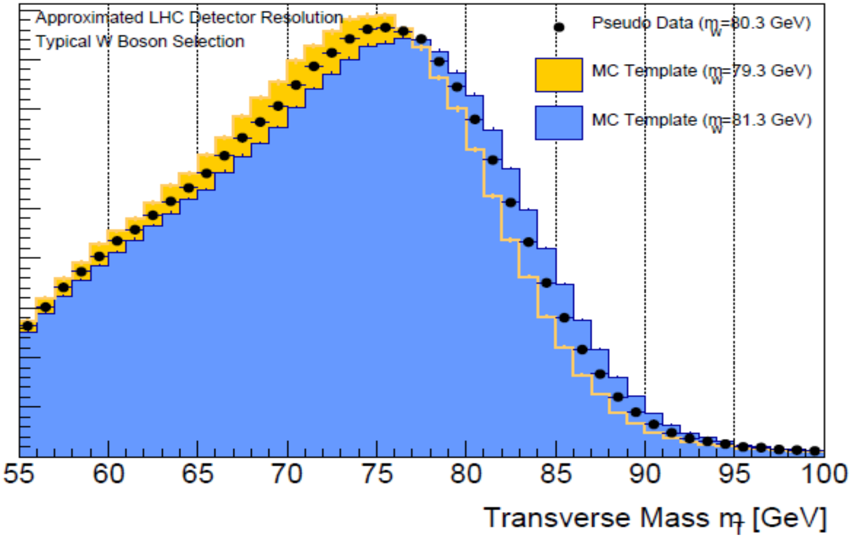
How to measure W boson mass?

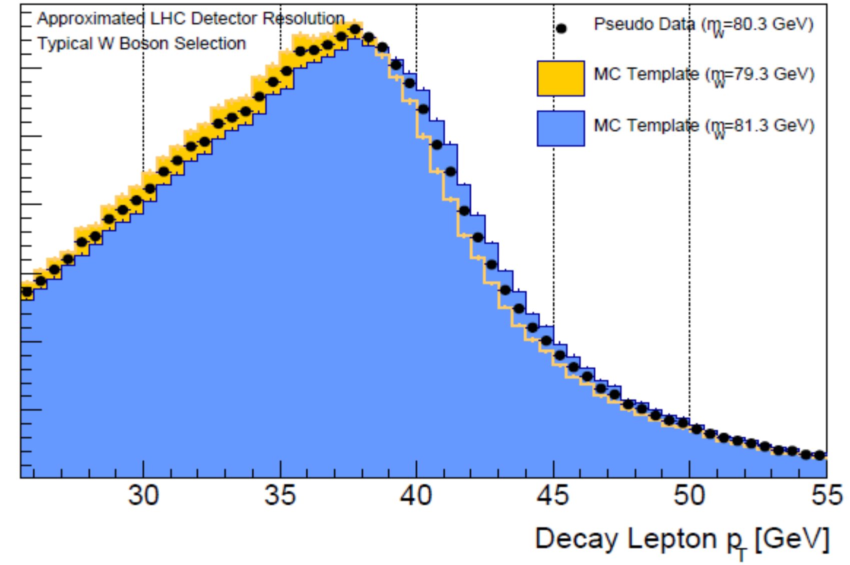
- Basic approach to measure W boson mass is a template fit

- Relevant observables
    - **Lepton transverse momentum**
    - **Transverse mass**
    - (missing transverse energy)

- Relies on perfect understanding of
    - Detector response
    - Physics modelling

- Expect different physics modelling effects for W^+, W^- and different rapidities





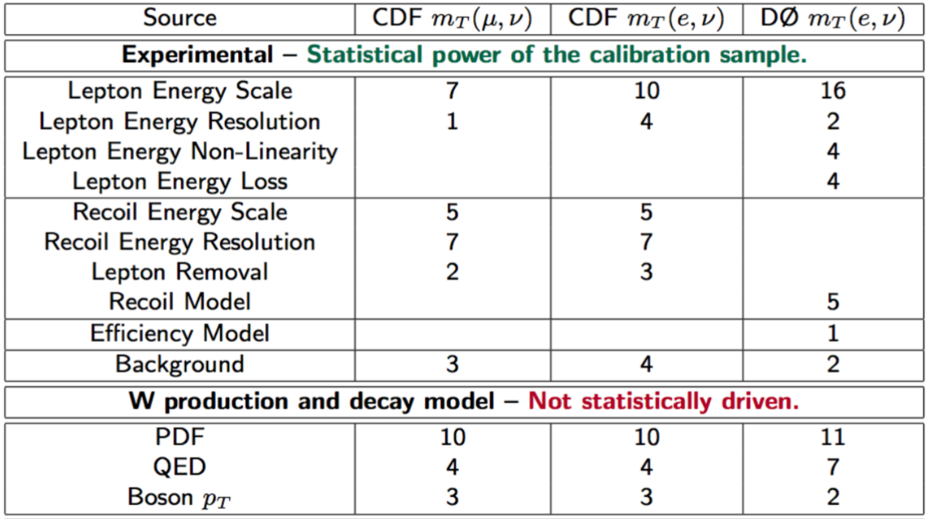
Latest Results from CDF and D0

- **Proton / anti-proton** collisions reduce impact of heavy quarks
  - No differences between W^+/W^-
  - Simplier extrapolation from Z to W
  - Low pile-up

- CDF measurement in e/mu channel
  - Only 20% of data-set used
  - Calibration via J/Psi, Upsilon and Z

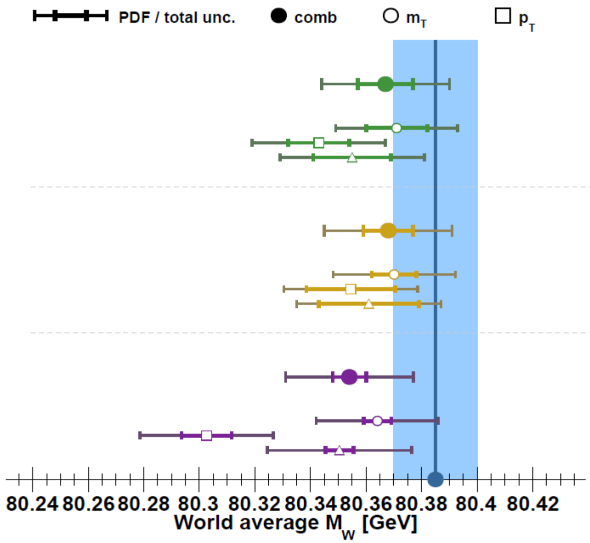
- D0 uses only electron channel
  - Acceptance up to η<1.0
  - Parameterized simulation

- D0 started a **first effort** to allow for an easy reavaluation of m_W with new PDF-sets



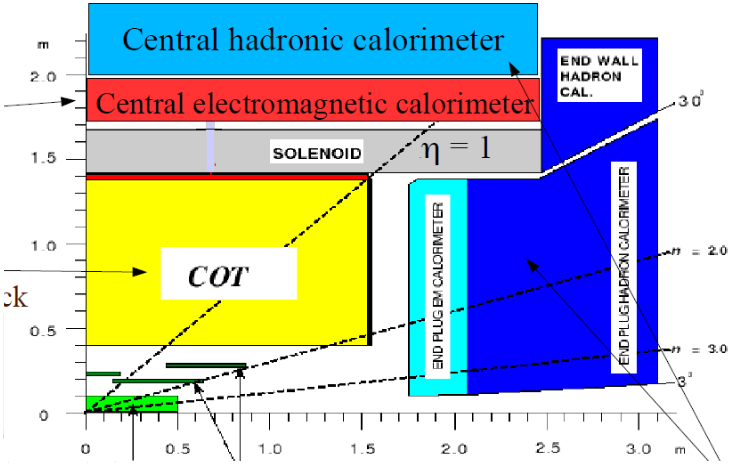
Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

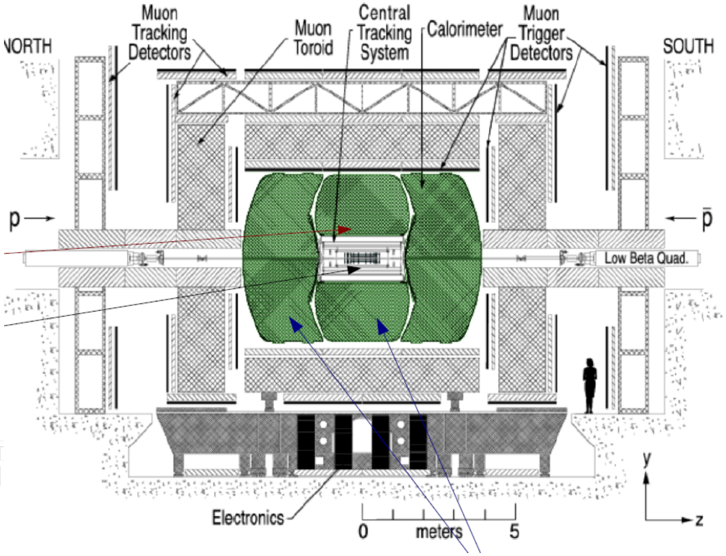
[Phys.Rev. D88 (2013)]



Possible Updates

- Factor 2-5 more statistics available
- Newer PDF sets, *e.g.* CT10W include more recent data
    - Dominant sources of W mass uncertainty are the *d*-valence and *d*-*u* degrees of freedom
    - Inclusion of all **LHC results on W^+, W^- and Z will also help to improve Tevatron** measurements
- Improvement in theoretical predictions of p_T(W/Z) needed in order to accommodate measured p_T(W/Z) spectra at Tevatron/LHC



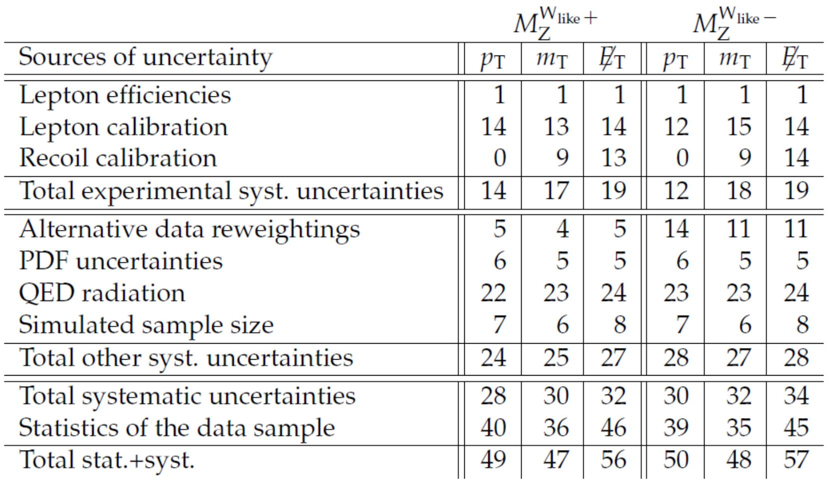


LHC: Still Testing with Z Bosons

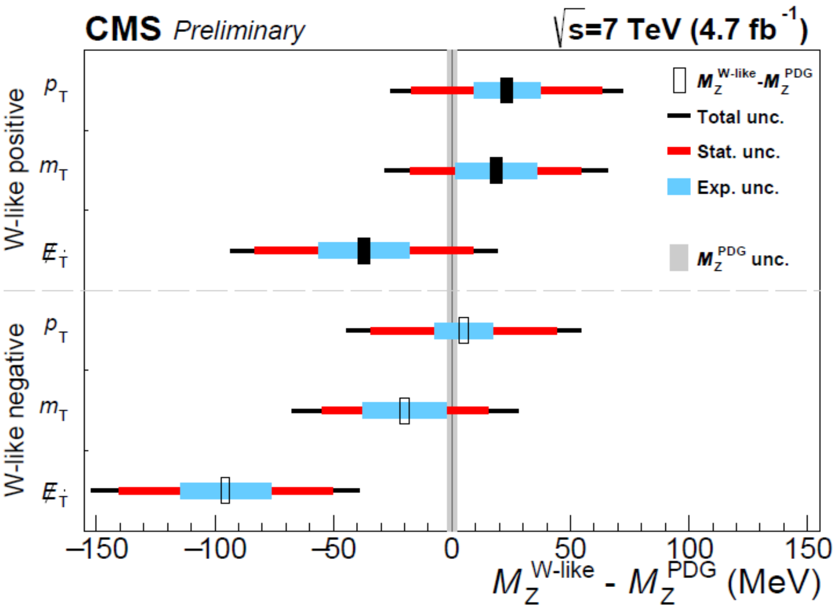
- The **full detector response calibration** of the m_W measurement can be tested to a large extend by „remeasureing“ the Z boson mass, mimicing the W
  - Turn one decay lepton in a pseudo neutrino

- CMS note using 7 TeV data
  - Validation of muon calibration
  - Statistically dominated (More in Nenad‘s talk)

- Model **uncertainties cannot** be easily transfered from Z to W
  - Also **some detector systematics** have to be treated carefully



	$M_Z^{\mathrm{W\,like}\,+}$			$M_Z^{\mathrm{W\,like}\,-}$		
Sources of uncertainty	p_T	m_T	$\not{E}_T$	p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57



[CMS PAS SMP-14-007]

Conclusions

- Experiments reach ultimate precision frontier in cross-section measurements: Often uncertainty in differential cross-sections below 0.5%
- NNLO revolution ongoing – lots of work on the theory side left
- First electroweak precision measurements at the LHC are about to come