Electroweak Precision Measurements: Status and Prospects

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The SM

$$\mathcal{L} = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{Yang-Mills}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$\mathcal{L}_{\text{Dirac}} = \bar{L}_i i\gamma^\mu \mathcal{D}_\mu L_i + \bar{e}_{Ri} i\gamma^\mu \mathcal{D}_\mu e_{Ri} + \bar{Q}_i i\gamma^\mu \mathcal{D}_\mu Q_i + \bar{u}_{Ri} i\gamma^\mu \mathcal{D}_\mu u_{Ri} + \bar{d}_{Ri} i\gamma^\mu \mathcal{D}_\mu d_{Ri}$$

$$\mathcal{L}_{\text{Yang-Mills}} = -\frac{1}{2}\,\mathrm{Tr}\left(G_{\mu\nu}G^{\mu\nu}\right) - \frac{1}{2}\,\mathrm{Tr}\left(W_{\mu\nu}W^{\mu\nu}\right) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{L}_{\text{Higgs}} = \mathcal{D}_\mu \phi^\dagger \mathcal{D}^\mu \phi + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger\phi)^2$$

$$\mathcal{L}_{\text{Yukawa}} = -\Lambda^e_{ij}\bar{L}_i \phi e_{Rj} - \Lambda^d_{ij}\bar{Q}_i \phi d_{Rj} - \Lambda^u_{ij}\bar{Q}_i \tilde{\phi} u_{Rj} + \text{c.c.}$$

- Electroweak sector (including Higgs):
  - 4 (independent) free parameters, for example:
    - α_{EM}, G_F, m_H, m_W

Parameters of the EW Sector

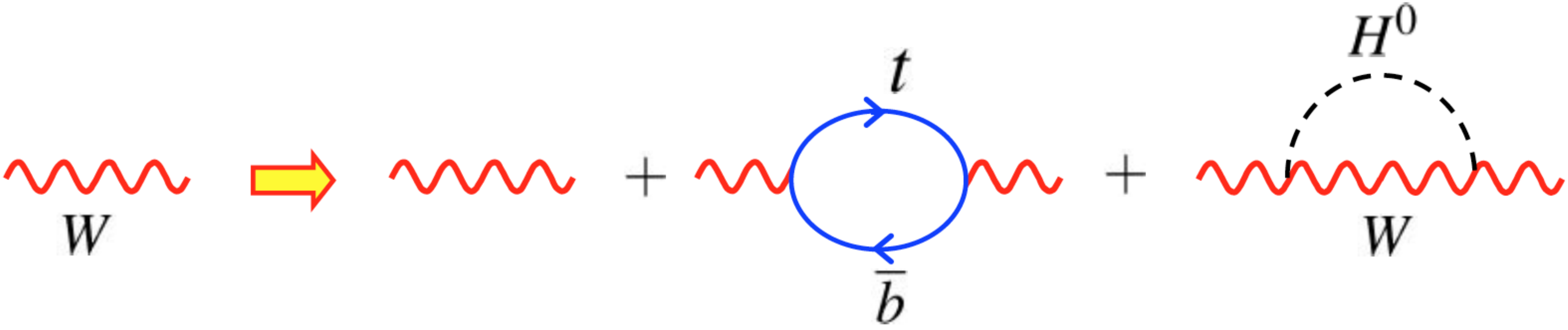
- The electroweak sector has more parameters
  - Weak mixing angle θ_W
  - M_Z
  - M_W
  - α_{EM} and G_F

- They are not independent, but related. For example (tree-level):

$$m_W = m_Z \cos\theta_W \qquad m_W = \left(\frac{\pi\alpha}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_W}$$

Parameters of the EW Sector

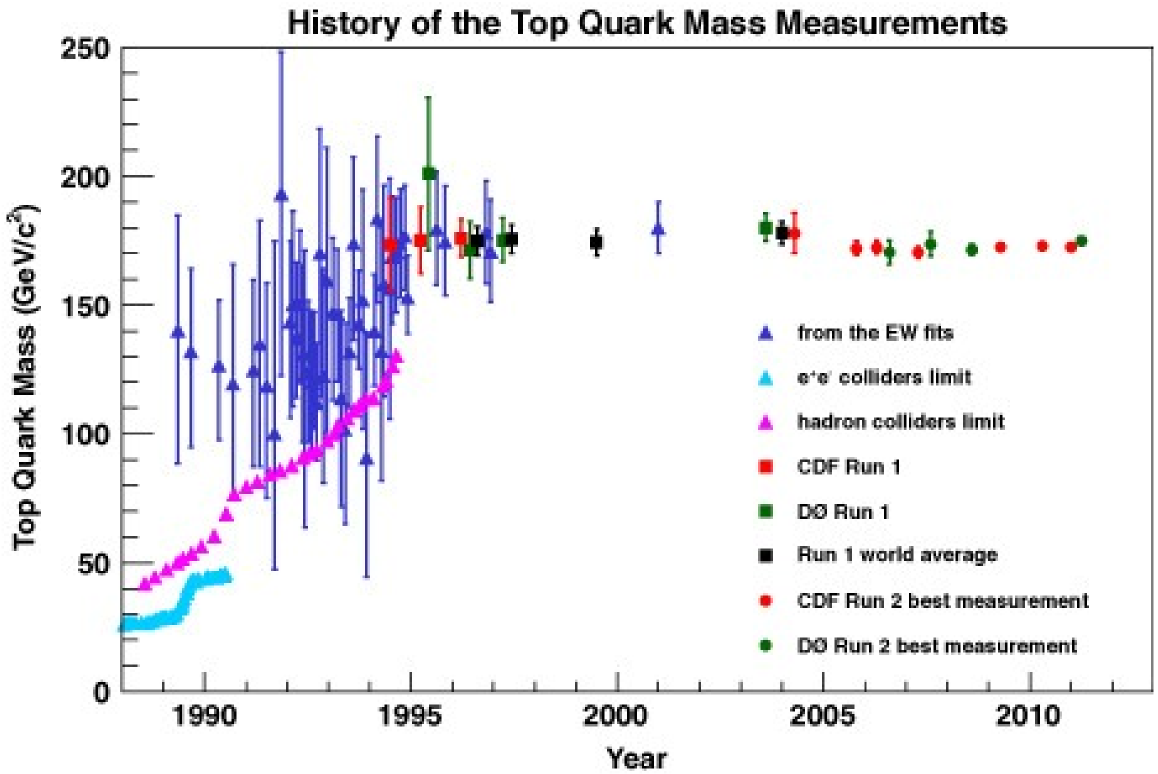
- Also m_t: related to m_W, via loops



  - Physical W mass:
    - Quadratically dependent on m_t
    - Logarithmically on m_H
- Set with smallest errors (besides free parameters: Higgs mass; mixings and fermion masses):
  - Z mass, α_{EM} and G_F

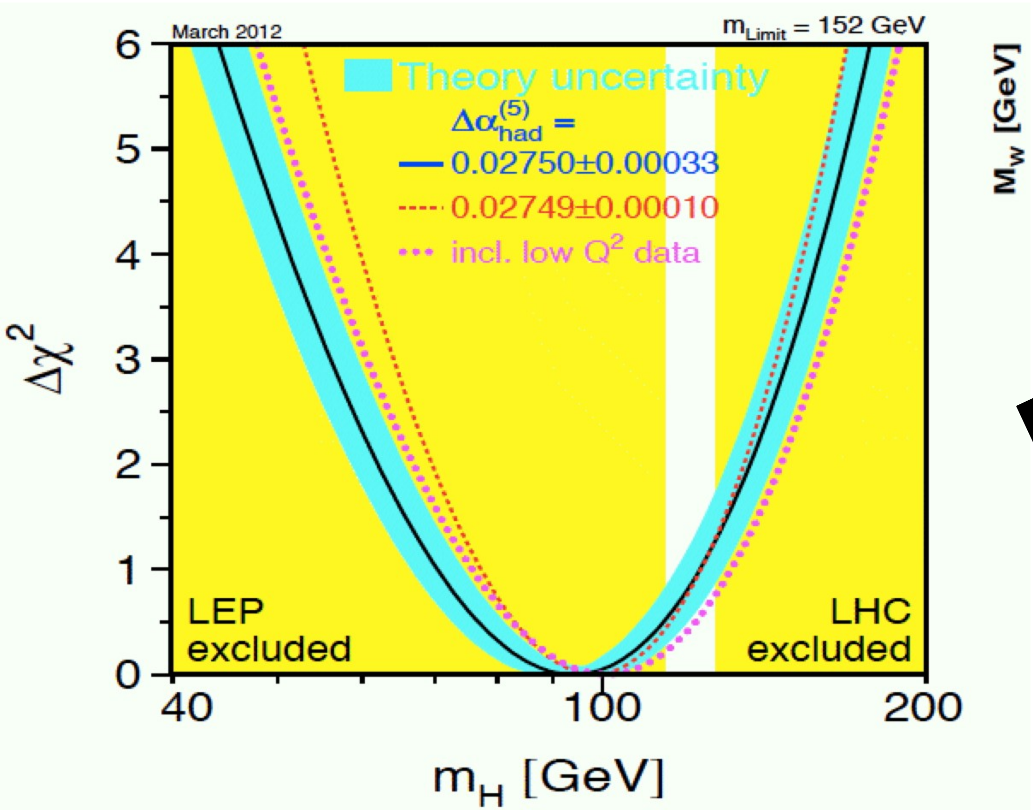
EW fits

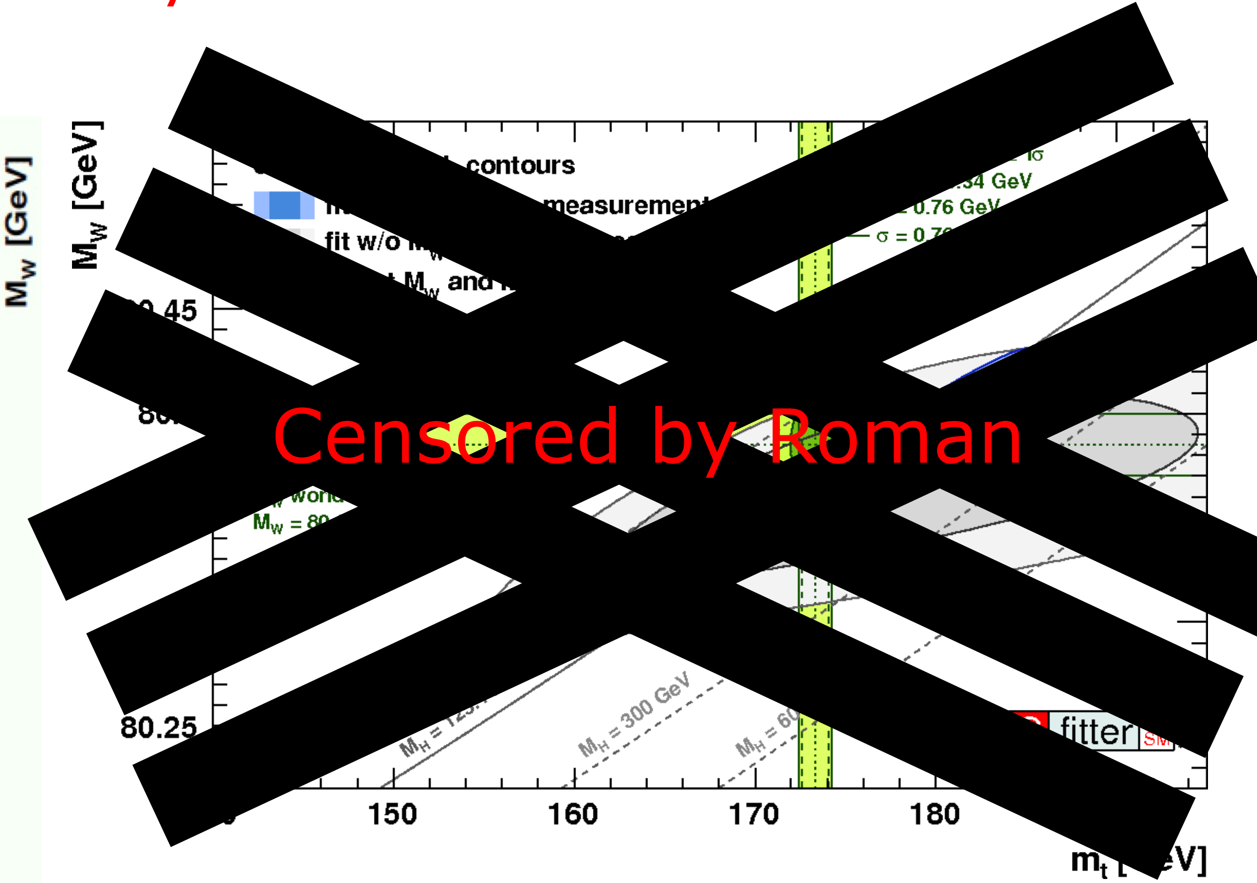
- Electroweak fits:
  - Measure as many observables as possible
    $\rightarrow$ use the relations to probe consistency of the SM
    - Or predict new parameters. E.g. top mass: predicted from EW fits way before its discovery



M_t and m_H

- Constraints on m_H: from EW fits
- Now: EW sector of the SM over-constrained
  → from predictions to consistency checks of the SM
  - More in Roman's talk





Content

- In this talk: concentrate on measurements and prospects of
  - The weak mixing angle
  - The W boson mass
  - The top mass

From LEP to LHC!

- Some more top (just because it's top!)

- Conclusion

The Z boson

and

The weak mixing angle

Weak Mixing Angle

- Electroweak unification: $U(1)_Y xSU(2)_L$
    - Y: hypercharge; with $Y=2(Q-I_3)$
  - Fields: B for $U(1)_Y$; W^0, W^1, W^2 for $SU(2)_L$
  - Linear combination of W^1 and W^2 yield $W^{\pm}$
  - To obtain photon and Z boson:

$$\begin{pmatrix}\gamma \\ Z\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B \\ W^0\end{pmatrix}$$

- θ_W: weak mixing angle

$\rightarrow$ coupling of the weak and electromagnetic interaction are related

$$\tan\theta_W = \frac{g'}{g}$$

  - With g', g: coupling constant for $U(1)_Y$ and $SU(2)_L$ respectively

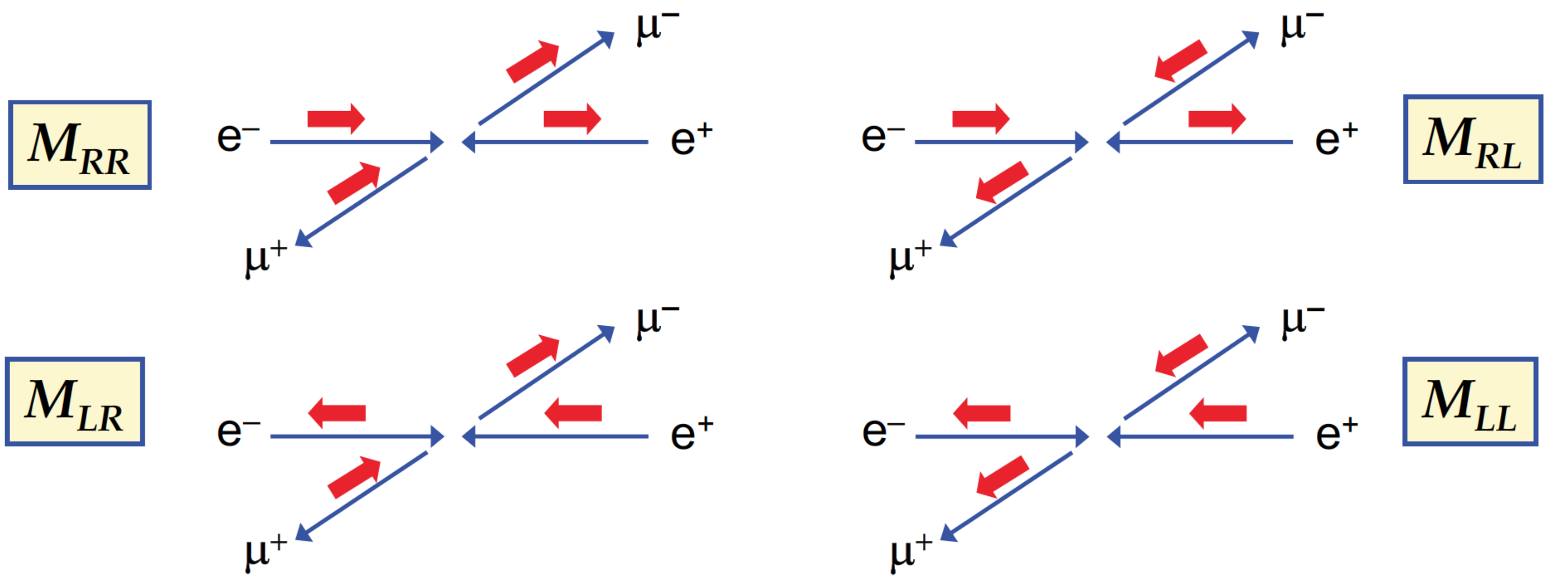
Weak Mixing Angle and Couplings

- Z boson: couples to left and right handed fermions
- Couplings:

$$c_L = I_3 - Q \sin^2\theta_W$$

$$c_R = -Q \sin^2\theta_W$$

- Look for example at $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ (e.g. at LEP):
    - Possible spin states:

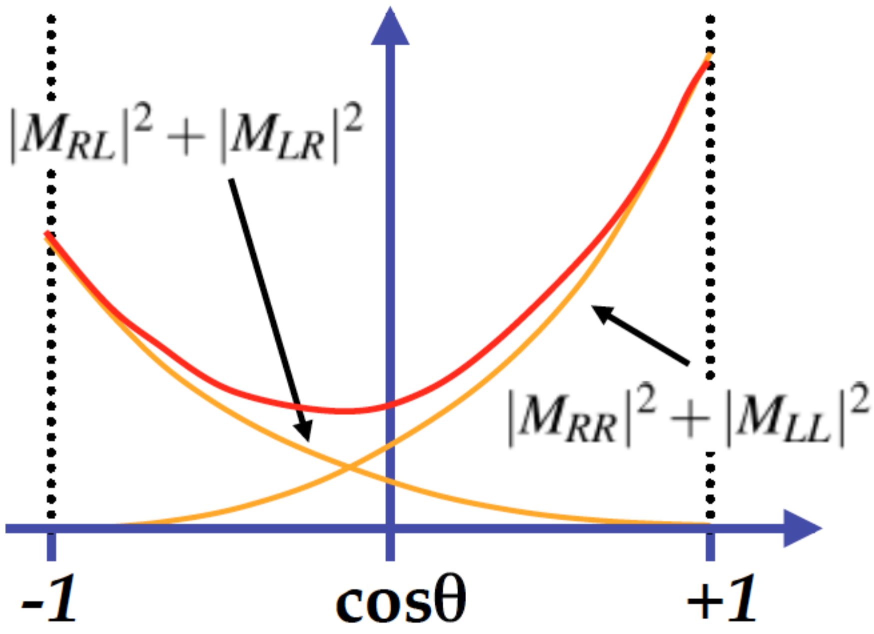


Weak Mixing Angle and Asymmetry

- Differential cross section as function of polar angle θ: depends on the contributions of the different matrix elements

- Extract asymmetry of cross section forward and backward in θ:

$$A^{l}_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



$\rightarrow$ related to coupling strengths: e.g. for $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$

$$A_{FB} = \frac{3}{4}\left[\frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2}\right]\left[\frac{(c_L^\mu)^2 - (c_R^\mu)^2}{(c_L^\mu)^2 + (c_R^\mu)^2}\right]$$

$\rightarrow$ enables extraction of $\sin^2\theta_W$

Effective Weak Mixing Angle

- A few "complications": Theoretically
- The effective weak mixing angle

$$sin^2\theta_{eff}^{f} = \left(1 - \frac{M_W^2}{M_Z^2}\right)(1 + \Delta\kappa)$$

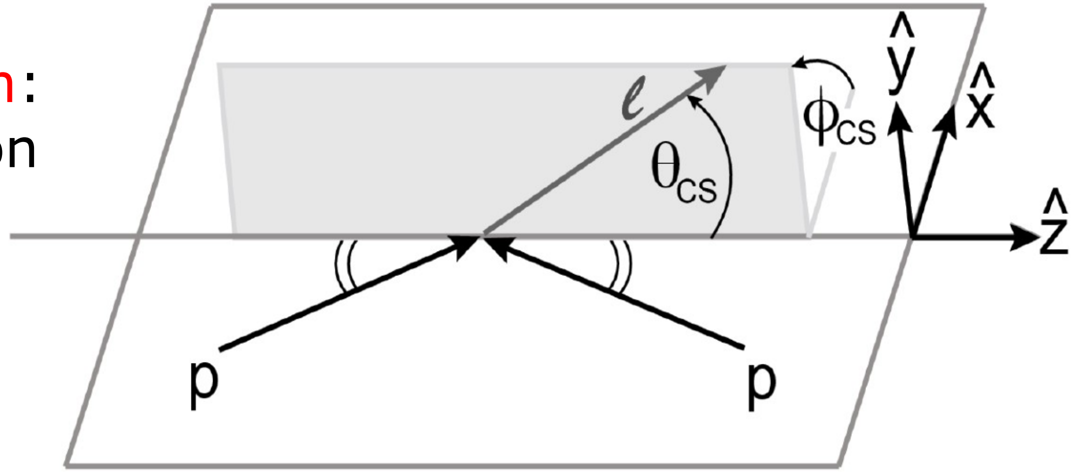
f: fermion

  - Contributions from radiative corrections ($\Delta\kappa$)
    $\rightarrow$ absorbed in an effective coupling
    - $\sin^2\theta_W$ can be extracted from $\sin^2\theta_{eff}$ using electroweak radiative-correction form factors
      $\rightarrow$ more in Roman's talk
- Extraction of $\sin^2\theta_W$:

$$sin^2\theta_{eff}^{lept} = \Re[\kappa_e(M_Z^2)]\, sin^2\theta_W$$

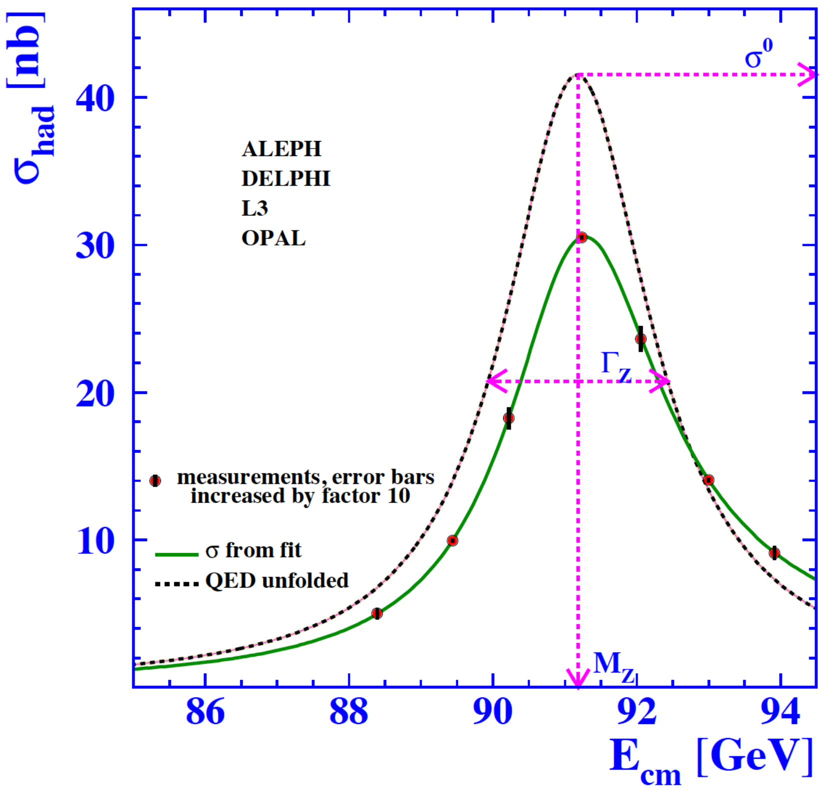
Weak Mixing Angle at Hadron Colliders

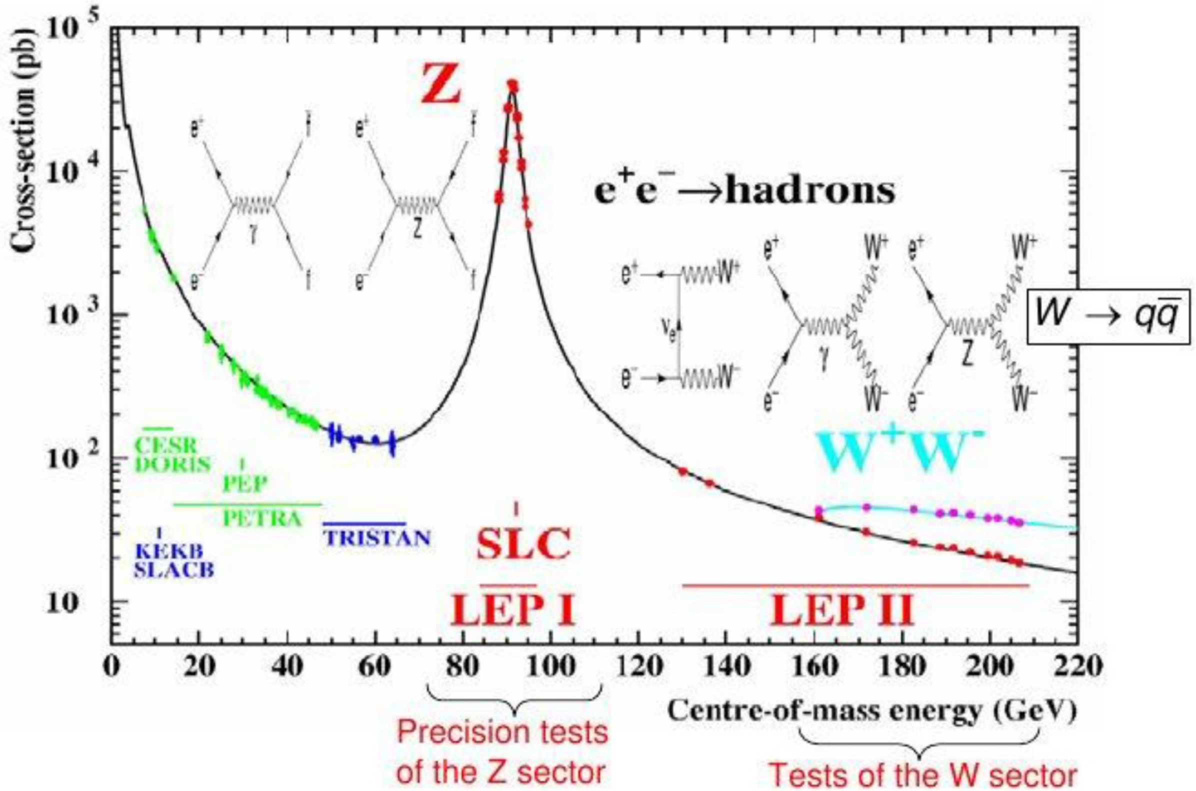
- A few "complications": Experimentally (@hadron colliders)
- Angle θ: usage of Collins-Soper frame
  - Reduces impact of the unknown four-momentum of the incoming (anti)quark
  - Boost along beam z axis to zero momentum vector of lepton pair, followed by boost along transverse component of lepton-pair momentum
- In pp: direction of quark?
  - Use boost direction of the system: assumed to be the quark direction
    - Dilution effects



Weak Mixing Angle: LEP and SLD

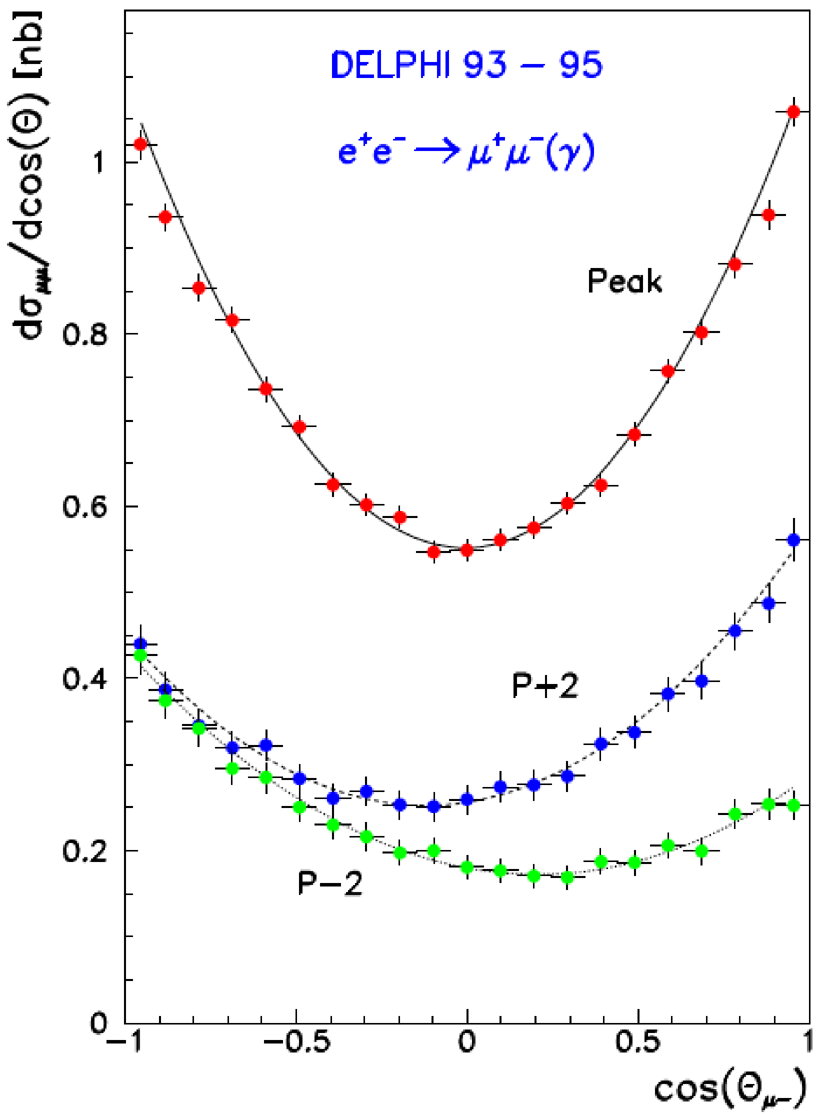
- LEP: measurements at the Z pole
  - Direction of incoming electron and positron: known
  - Very precise measurements possible
    - Also of other quantities! M_Z, Γ_Z, #neutrinos





Weak Mixing Angle: LEP and SLD

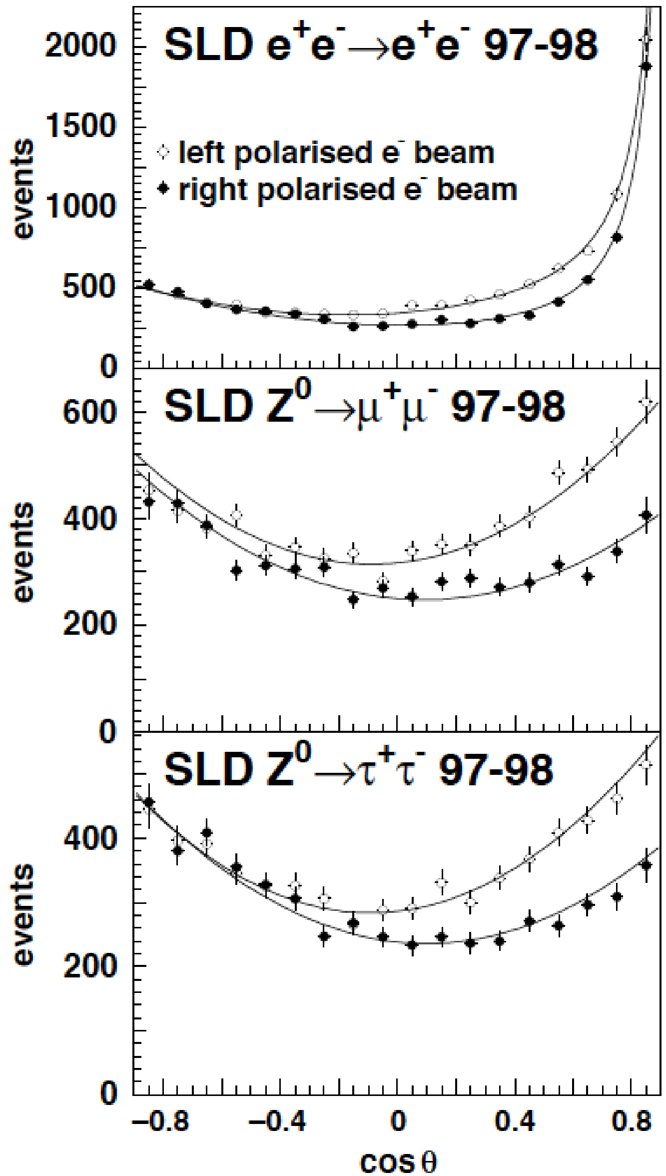
- LEP: measurements at the Z pole
  - Direction of incoming electron and positron: known
  - Very precise measurements possible
- LEP: forward backward asymmetry



Phys.Rept.427:257-454,2006

Weak Mixing Angle: LEP and SLD

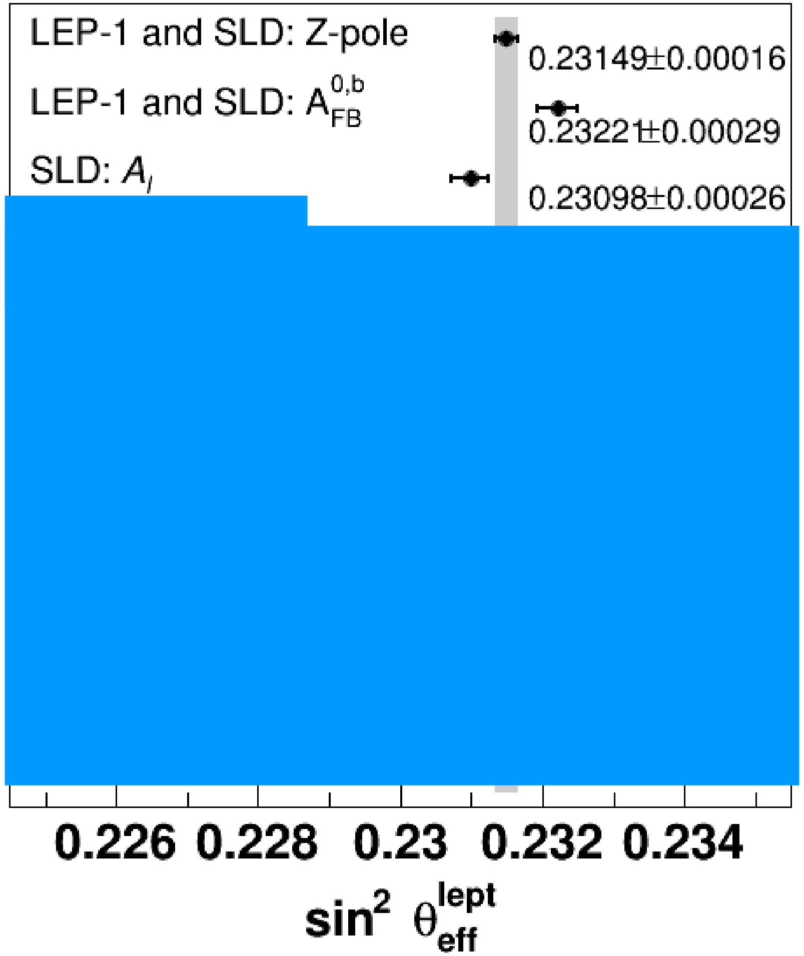
- SLD: measure left-right asymmetry
  - Usage of polarized beams!



Phys.Rept.427:257-454,2006

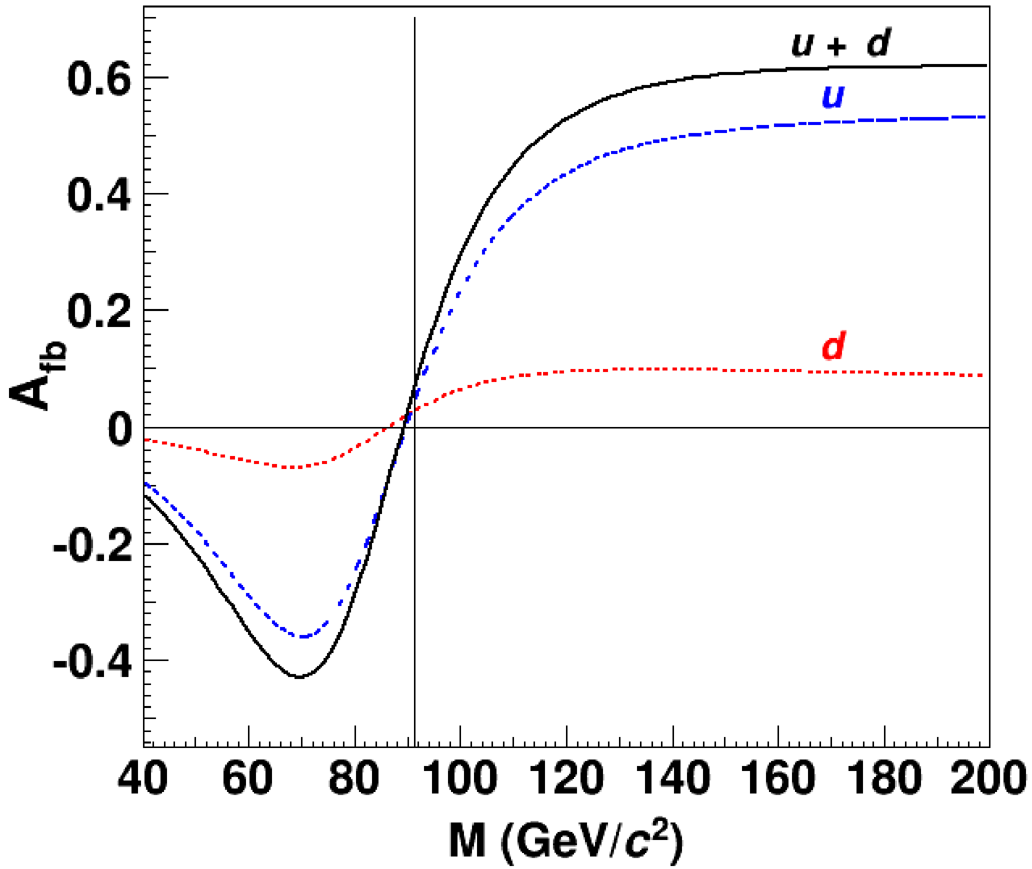
Weak Mixing Angle: LEP and SLD

- LEP and SLD: very precise measurements!
  - Not yet reached by LHC and Tevatron precisions
  - Issue: A_{FB} measurements using b-jets and SLD left-right asymmetry: discrepancy by 3.2 S.D.s



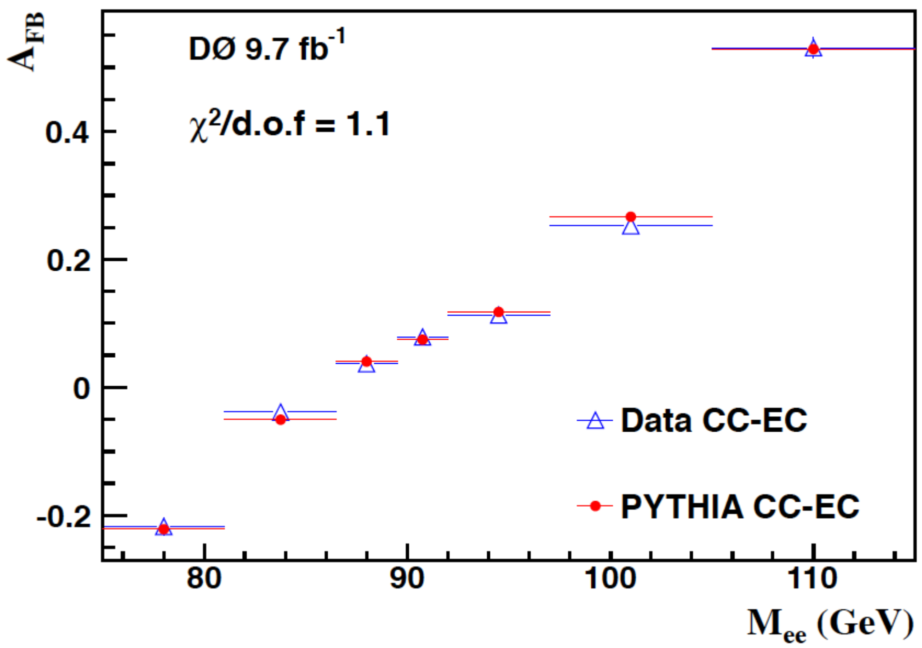
Measurements at the Tevatron

- Measurements by CDF and D0
  - $q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$ and $\mu^+\mu^-$
    - D0: only e^+e^- so far
  - Using full Tevatron data sample!
- Assume (anti)quark direction: (anti)proton direction
  - Measure asymmetry using Collins-Soper frame
    - As function of invariant m_{ll} mass
    - At Z pole: asymmetry related to $\sin^2\theta_W$
    - Away from Z pole: asymmetry dominated by γ^*-Z interference $\rightarrow$ sensitive to PDFs

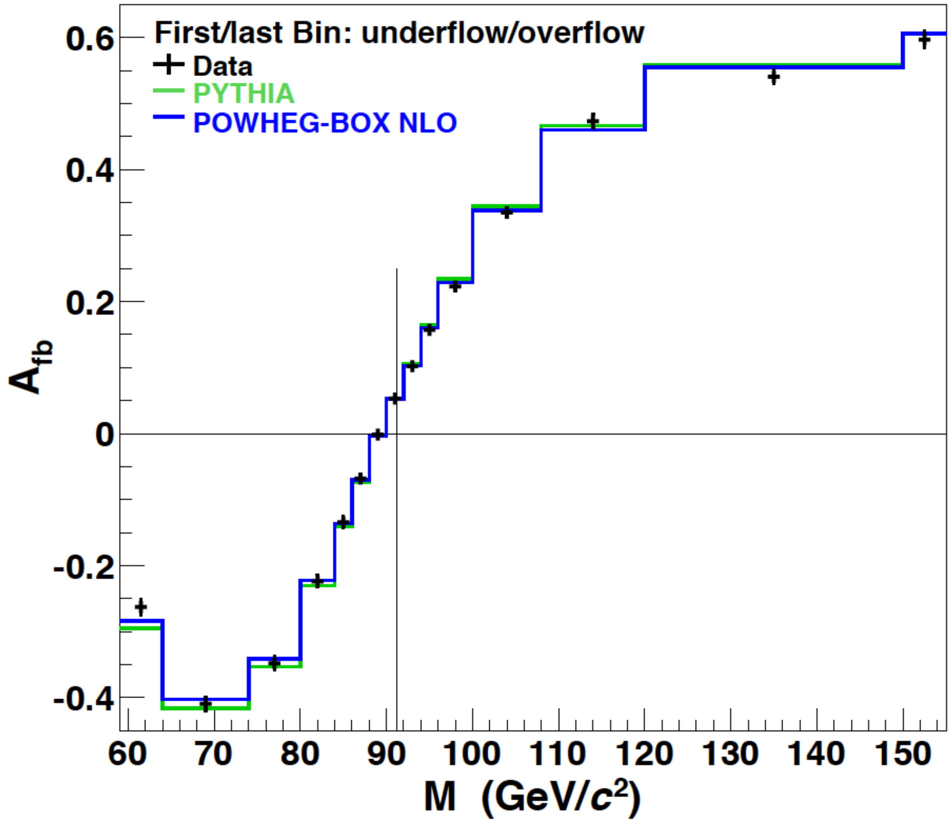


Measurements at the Tevatron

- D0: measurement using central and forward electrons
  - Extraction of $\sin^2\theta_{eff}$ using templates
- CDF: correction of A_{FB} for detector effects
- Measurements statistics-limited



Phys. Rev. Lett. 115, 041801 (2015)



Phys.Rev. D93 (2016)

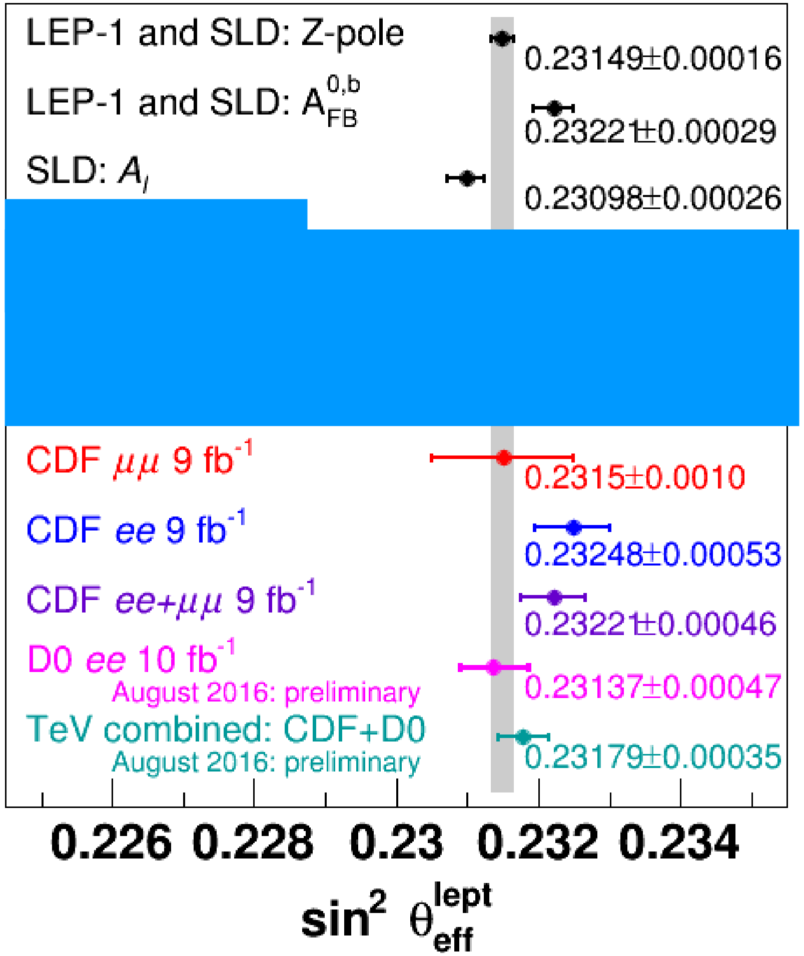
Tevatron Combination

- New combination: D0 and CDF result!
  - Using BLUE method
  - Main systematic uncertainty: PDFs

	Uncertainties on $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$		
Source	CDF Inputs	D0 Inputs	CDF and D0 Combination
Statistics	± 0.00043	± 0.00043	± 0.00030
Uncorrelated	± 0.00007	± 0.00008	± 0.00005
Correction		± 0.00005	± 0.00003
NNPDF PDF	± 0.00016	± 0.00017	± 0.00017

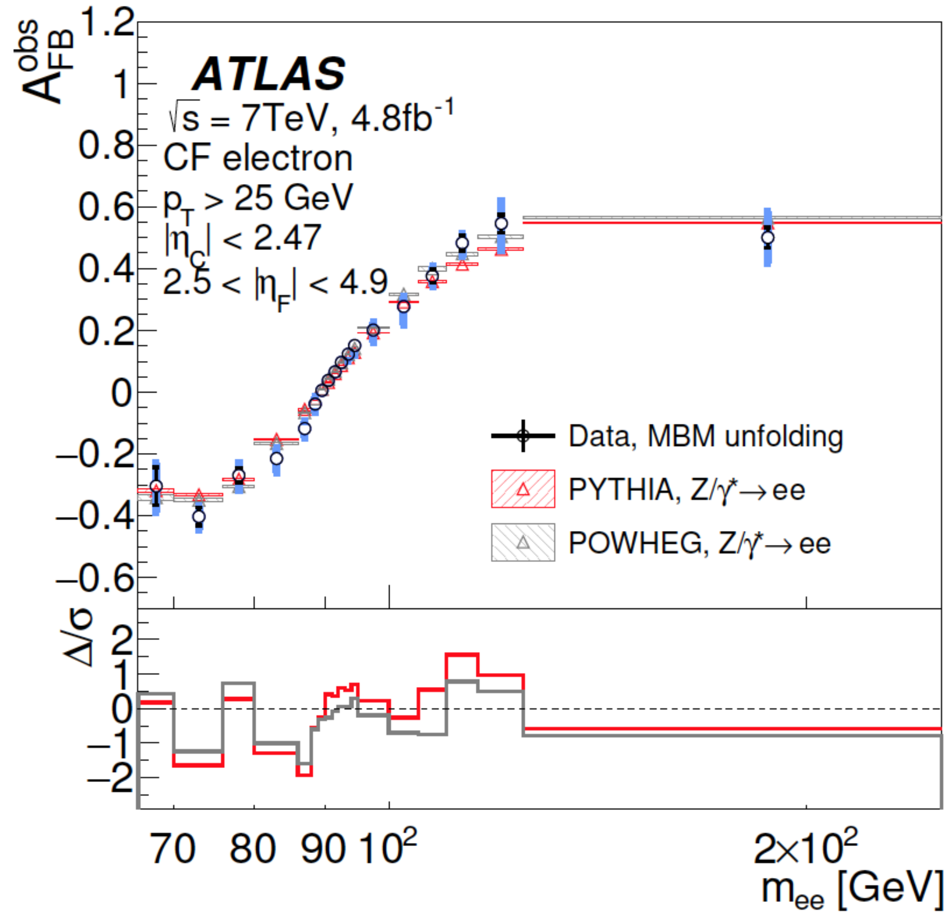
Tevatron Combination

- New combination: D0 and CDF result!
  - Using BLUE method
- Results consistent with LEP and SLD measurements



LHC: ATLAS and CMS

- Further challenge compared to Tevatron: quark direction unknown!
  - Use of boost direction of the system
    - Dilution! → the higher the boost, the more clear the quark direction
- ATLAS and CMS: measurement of asymmetry for electrons and muons (electrons: only ATLAS so far)
  - Using 7 TeV data sample



JHEP09(2015)049

(b)

LHC: ATLAS

- ATLAS: Largest uncertainties: PDF

	$\sin^2\theta_{\text{eff}}^{\text{lept}}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\text{stat.}) \pm 0.0007(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2308 \pm 0.0012$

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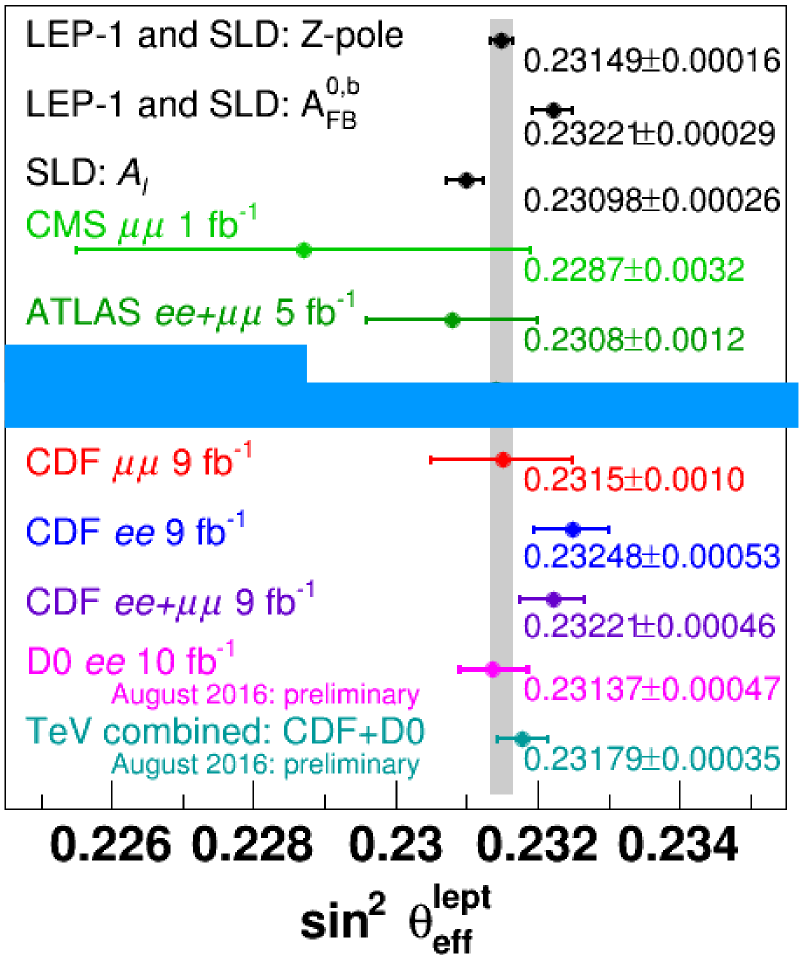
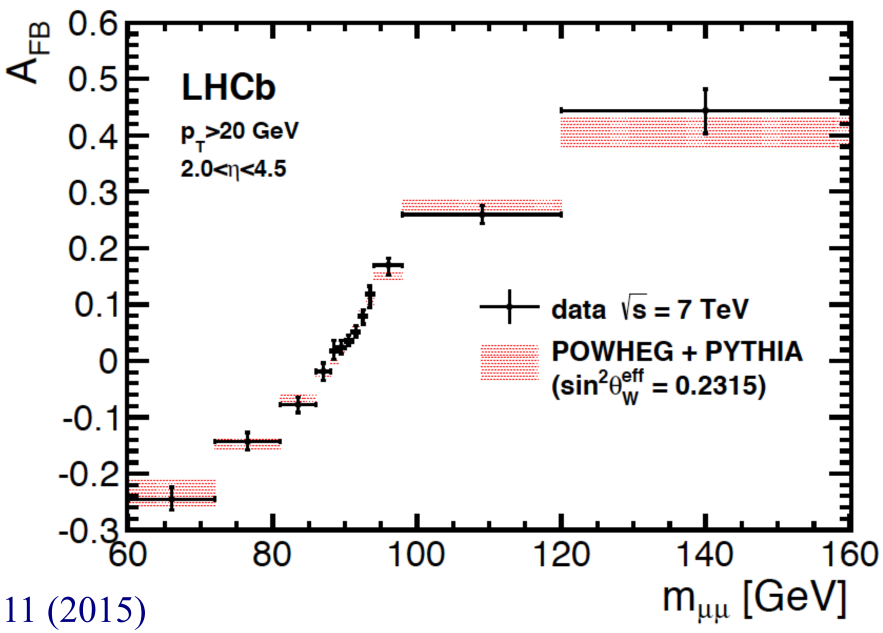
LHC: ATLAS and CMS

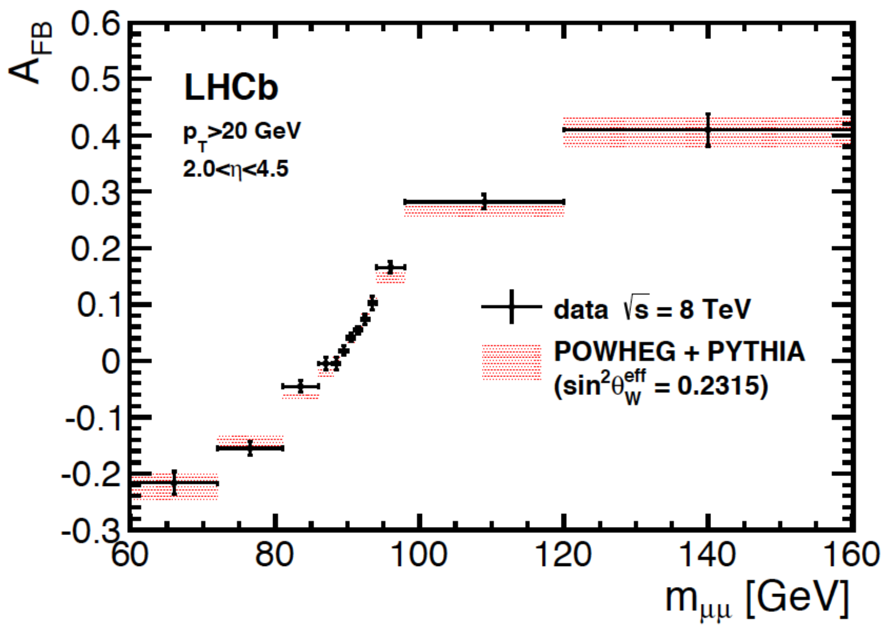
- Results for $\sin^2\theta_{eff}$



LHC: LHCb

- New result: use LHCb!
  - Forward direction: sensitivity of A_{FB} to $\sin^2\theta_{eff}$ greater for larger rapidities of Z boson!
  - In LHCb acceptance region: assignment of forward and backward decays: correct 90% of the time!
- Use di-muon events; 7 and 8 TeV data sample





J. High Energy Phys.11 (2015)

LHCb

- Most precise result from pp collider to date
- Largest uncertainty: statistics
  - Largest systematics: from PDFs

Uncertainty	average $\Delta\lvert A_{FB}^{pred}\rvert$
PDF	0.0062
scale	0.0040
α_s	0.0030
FSR	0.0016

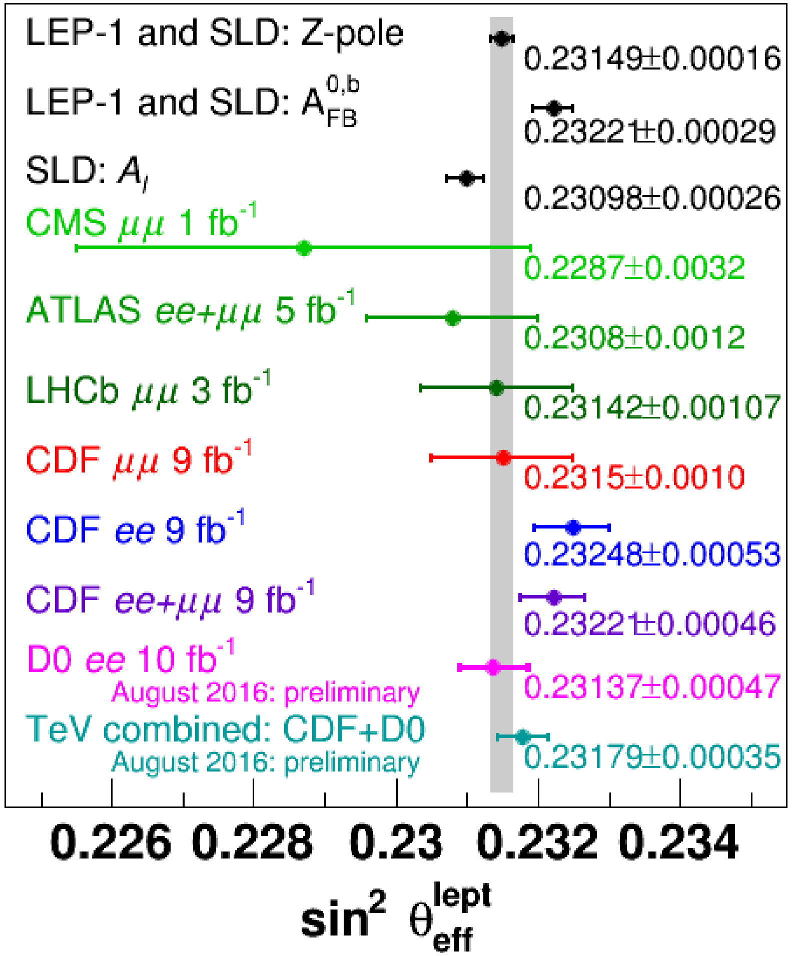
- Result: (uncertainties: stat; syst; theory)

$$\sin^2\theta_{W}^{eff} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056,$$

J. High Energy Phys.11 (2015)

The Weak mixing angle

- All collider results today:

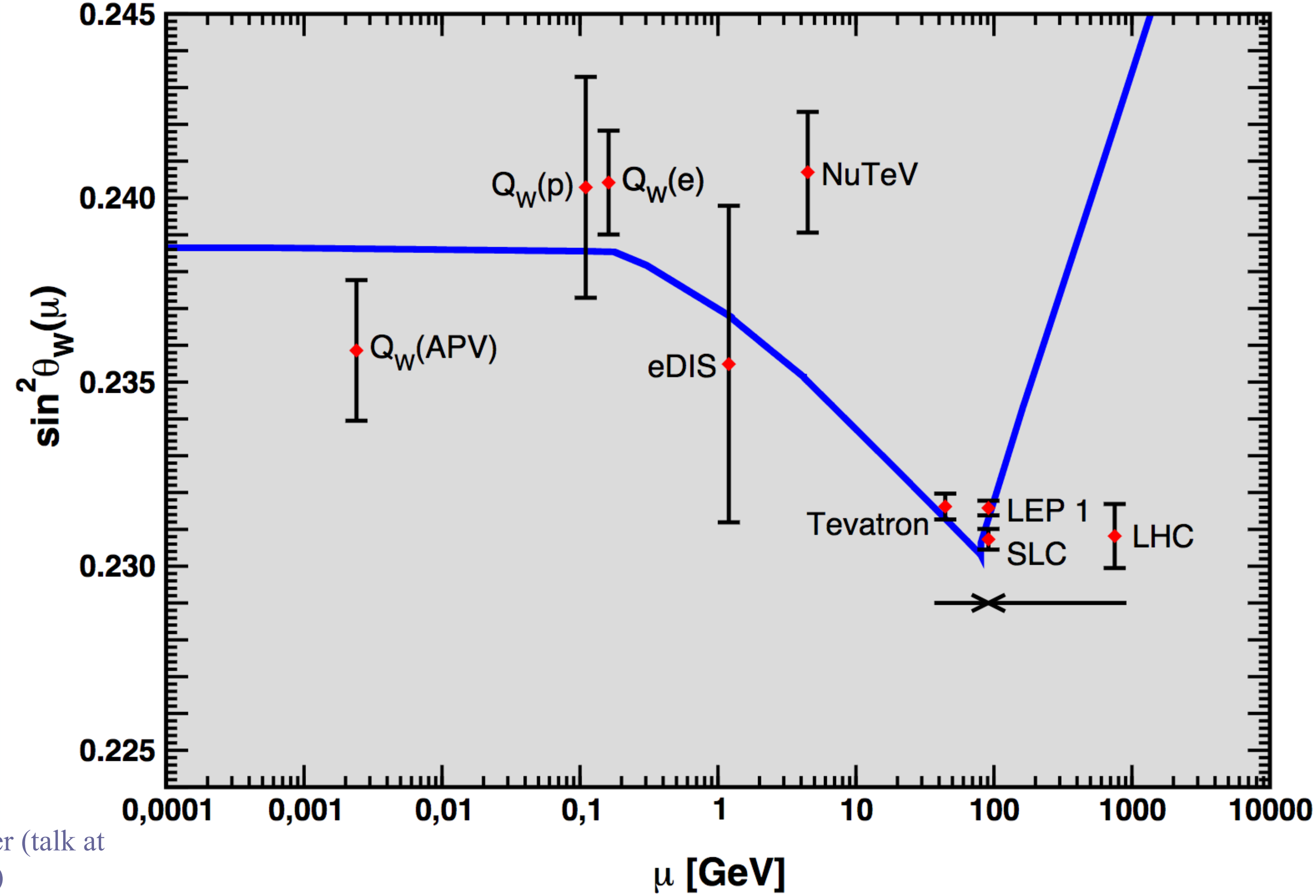


- Hard to reach LEP/SLD precision
  - Main work to do: PDFs $\longrightarrow$ profiling;
    usage of PDF dependent input

- All hadron-collider results consistent with each other and LEP+SLD average

Weak Mixing Angle

- All existing results (including low energy results) versus scale:



Taken from J. Erler (talk at PrecisionVietnam)

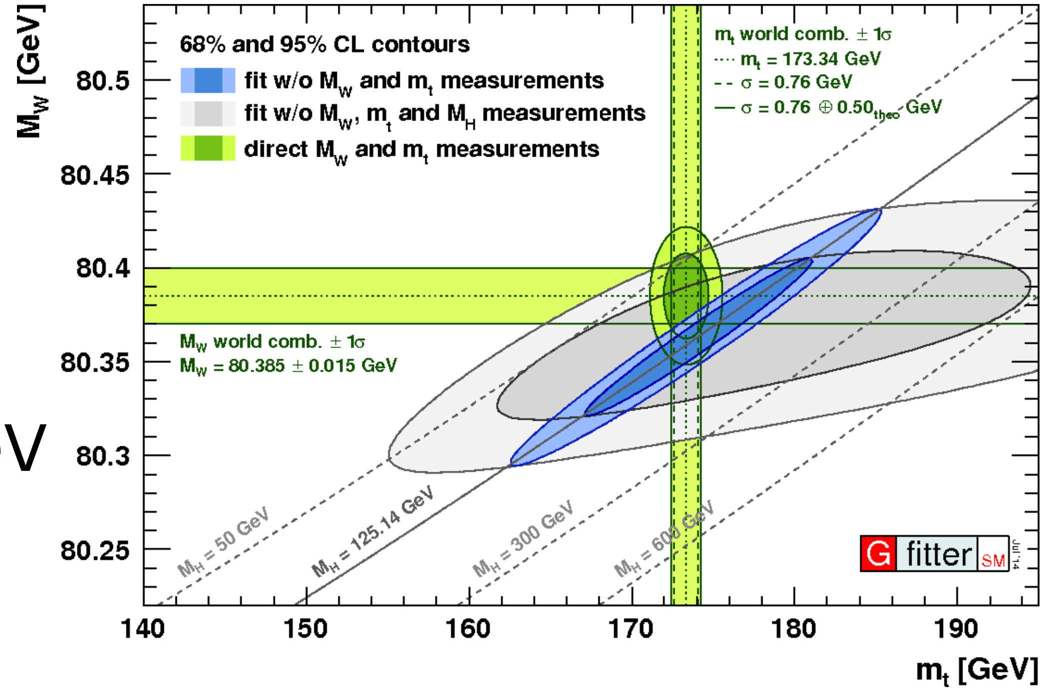
The W boson mass

The W Boson Mass

- Free parameter of the SM
  - Connected to the vacuum expectation value of electroweak symmetry breaking!
  - Physical W mass: includes loop contributions from top, Higgs, etc. → connected with top and Higgs boson mass!

→ W boson mass measurement: crucial to test consistency of the SM

→ high precision required!



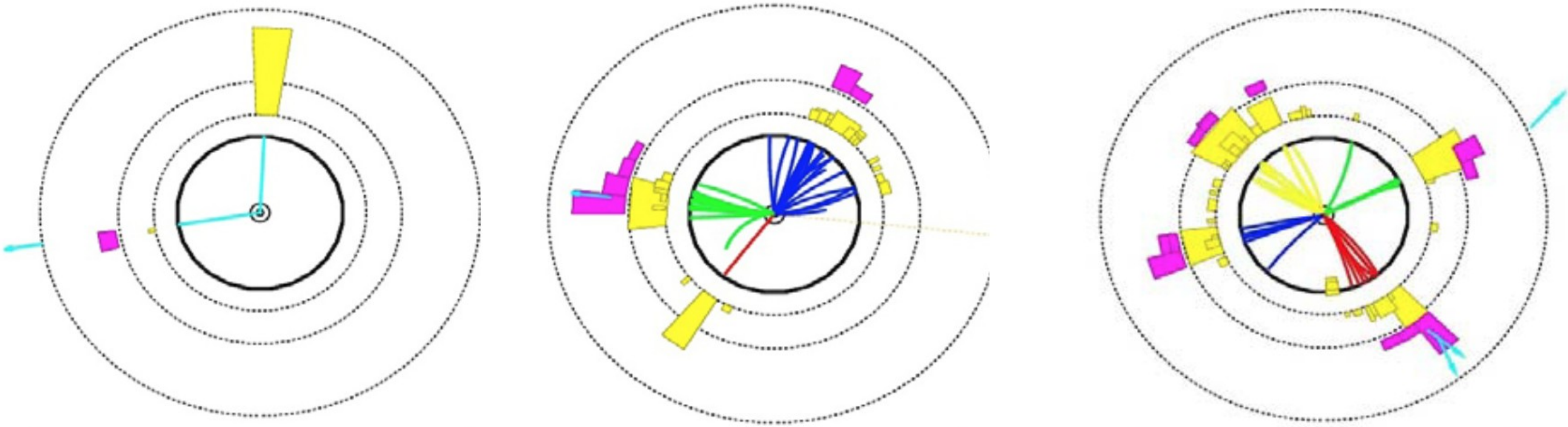
- Global EW fit: predicts Δm_W=8 MeV

→ with current uncertainties on m_H and m_t:

require precision of m_W of ~6 MeV to significantly probe the SM!

W Boson Mass at LEP

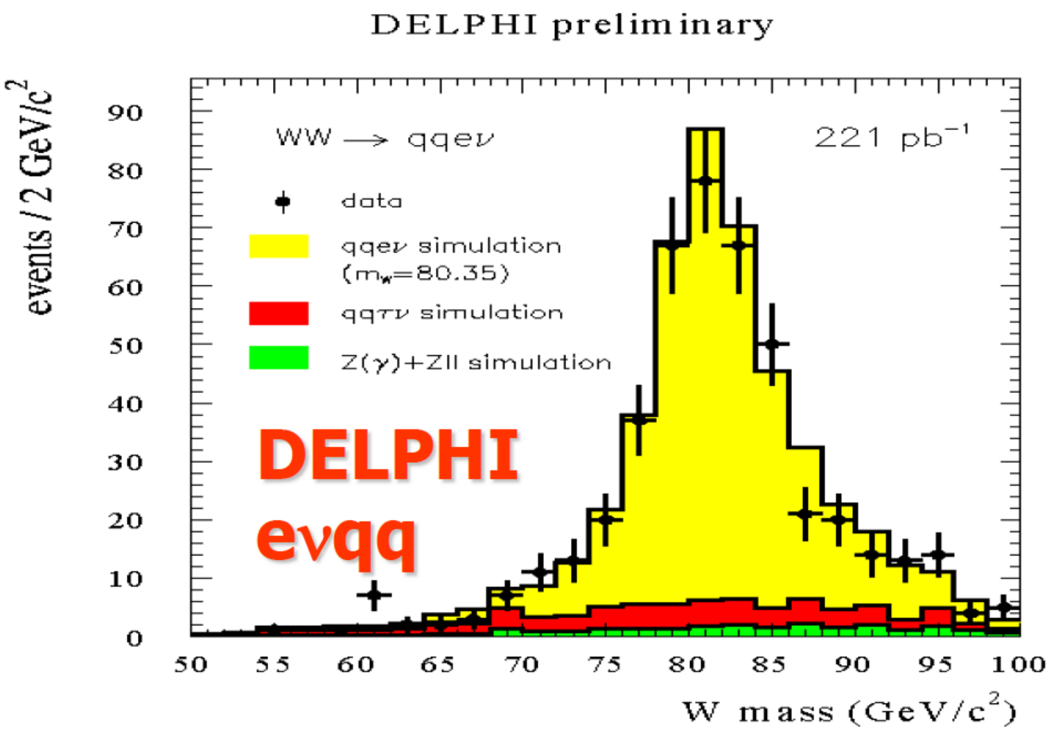
- Measurement in $e^+e^- \rightarrow W^+W^-$ production
- Each W boson can decay:
  - Leptonically: W → charged lepton+neutrino
  - Hadronically: $W \rightarrow q\bar{q}'$
- 3 different channels → reconstruction of W mass

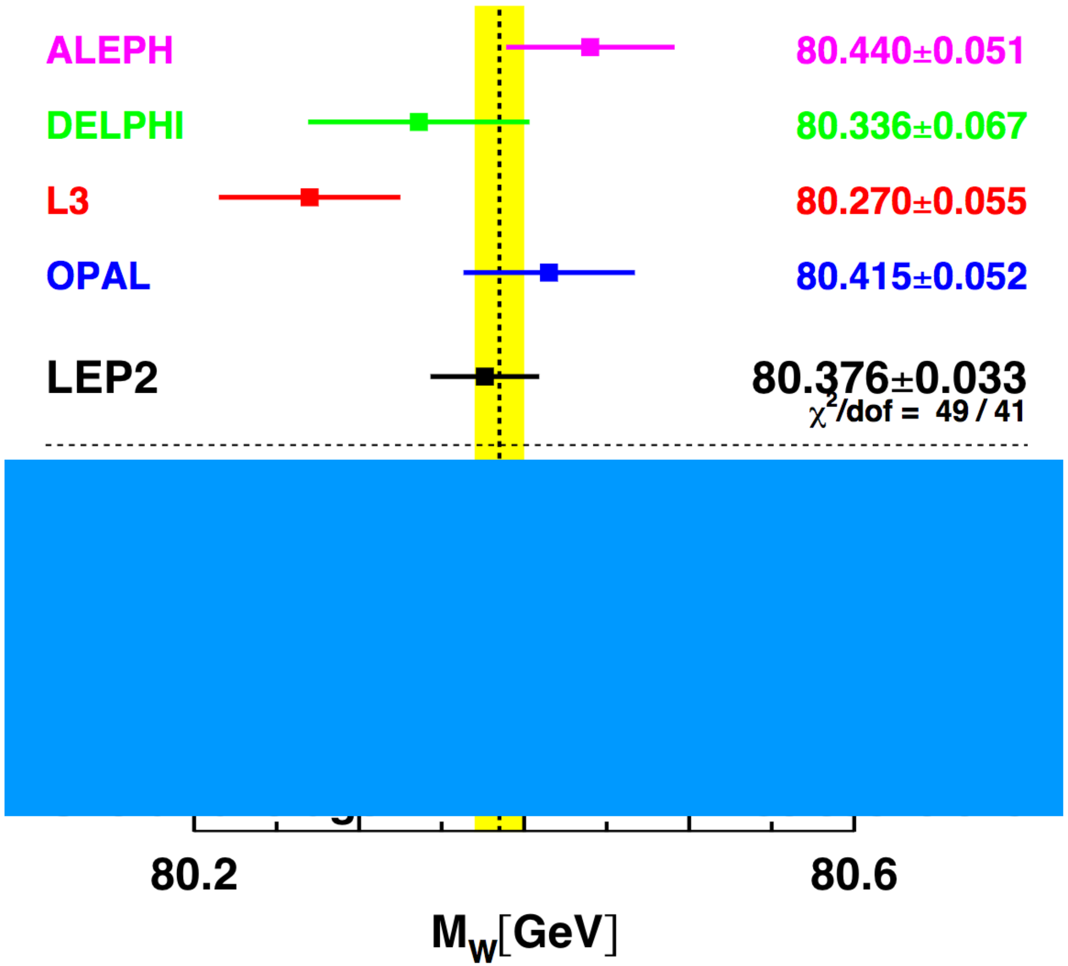


$W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ | $W^+W^- \rightarrow q\bar{q}\ell\nu$ | $W^+W^- \rightarrow q\bar{q}q\bar{q}$

W Boson Mass at LEP

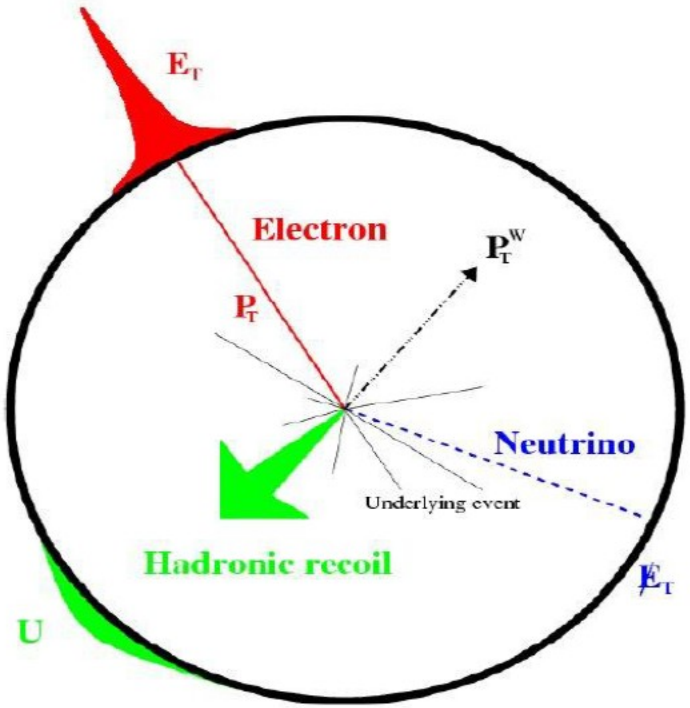
- Measurement from the position of the peak
  - Width measurement from the same distribution





The W Boson Mass at Hadron Colliders

- Hadron colliders: use $p\bar{p} \rightarrow WX$ (or $pp \rightarrow WX$)
  - X: hadronic system
  - Use signature with a charged lepton and neutrino
- Problem: initial momenta of colliding partons unknown
  $\rightarrow$ we can only get the transverse component of the neutrino from the missing transverse energy (MET)
- Trick: use the "transverse mass" for the measurement



$$m_T^2 = 2\, p_T^l\, MET\,(1 - \cos\phi)$$

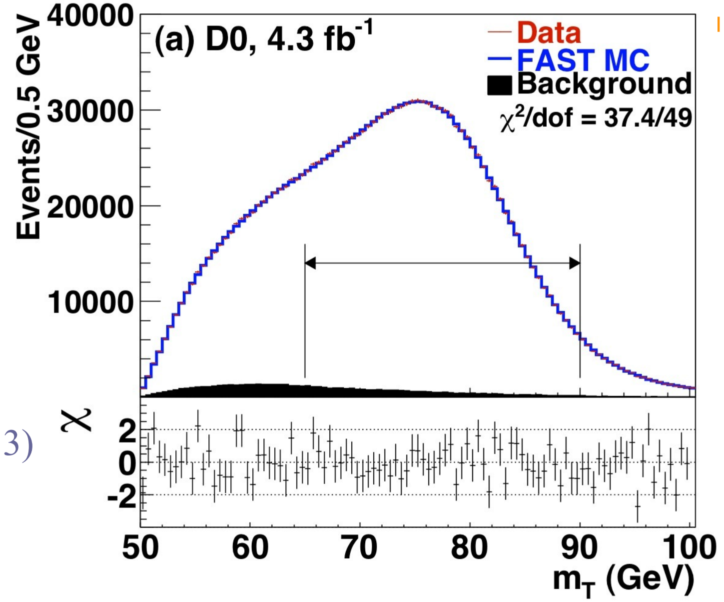
W Mass at Tevatron

- CDF and D0: measurement of W boson mass using p_T^l, MET and m_T

Systematics D0:

Source	Uncertainty (MeV)
Electron energy calibration	16
Electron resolution model	2
Electron shower modeling	4
Electron energy loss model	4
Recoil energy scale and resolution	5
Electron efficiencies	2
Backgrounds	2
Experimental subtotal	18
Parton distribution functions	11
QED radiation	7
$p_T(W)$ model	2
Production subtotal	13
Total systematic uncertainty	22
W-boson event yield	13
Total uncertainty	26

Phys. Rev. D 88, 052018 (2013)



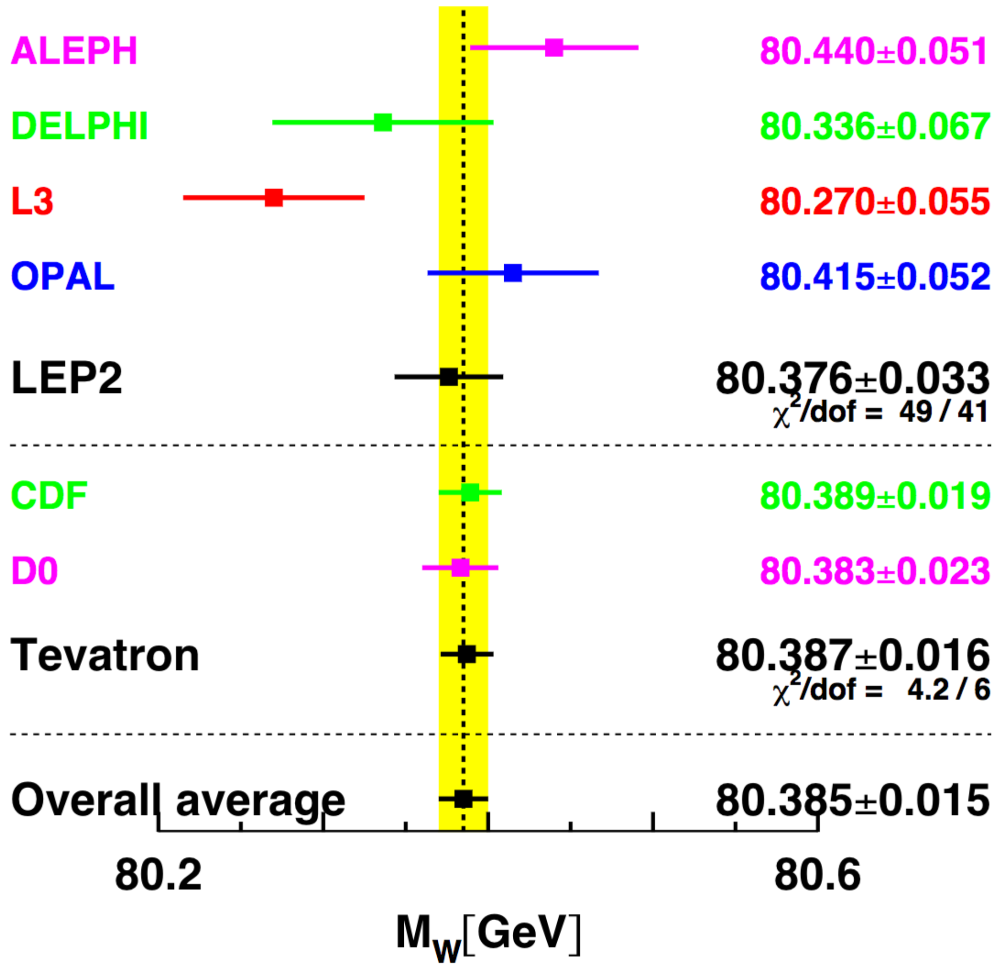
Systematics CDF:

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal from recoil	2
Backgrounds	3
Experimental subtotal	10
Parton distribution functions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson event yield	12
Total uncertainty	19

- PDFs and lepton energy calibration: limiting factors

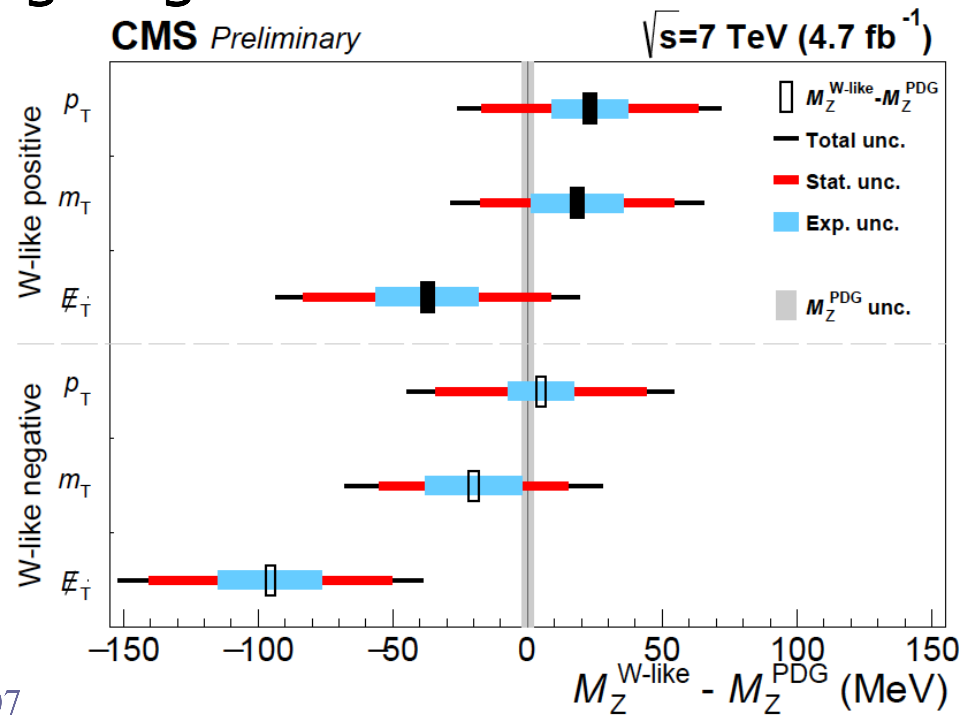
W Mass at Tevatron

- CDF and D0: Combination via BLUE
  - CDF: electron and muon channel; 2.2 fb^{-1}
  - D0: electron channel; 4.3fb^{-1}
- Still more data from Tevatron to analyse
  - Ongoing
- Limiting factor: understanding of PDFs and lepton energy scale
  - D0: electron energy scale using Z events
    → analysing full Tevatron data sample will improve this!



W Mass at LHC

- Main issues at LHC:
  - Energy calibration with pile-up!
  - PDFs: large contribution of sea quark PDFs in pp collisions
  - W^+, W^- : different physics modeling; physics modeling (e.g. p_T^W)
- ATLAS and CMS: measurements ongoing
  - CMS: Z mass measurement in "W like" Z $\rightarrow \mu\mu$
    $\rightarrow$ proof of principle
    - Expect larger uncertainties for W mass measurement: background, PDFs in W production



CMS PAS SMP-14-007

W Mass at LHC

- Various measurements will help improve precision
  - PDF-related measurements
    - W and Z cross section, W/Z ratio, W^+/W^-, Z-rapidity, W+charm
  - Improvement of physics modeling
    - Measurements of Z polarisation coefficients, Zp_T
- Snowmass report 2013: projected uncertainties for W mass measurement at LHC (ATLAS and CMS):

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}$[fb^{-1}]	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

arxiv:1310.6708

W Mass at LHC

- Various measurements will help improve precision
  - PDF-related measurements
    - W and Z cross section, W/Z ratio, W^+/W^-, Z-rapidity, W+charm
  - Improvement of physics modeling
    - Measurements of Z polarisation coefficients, Zp_T
- Proposal of W mass measurement at LHCb
  - Large rapidity region → PDF uncertainties anti-correlated with those in ATLAS and CMS measurement
  - Expect improvement of 30% when including LHCb

Eur.Phys.J. C75 (2015)

- A lot of work on theory, calibrations and PDFs required to reach goal of very precise W mass measurement!

The Top mass

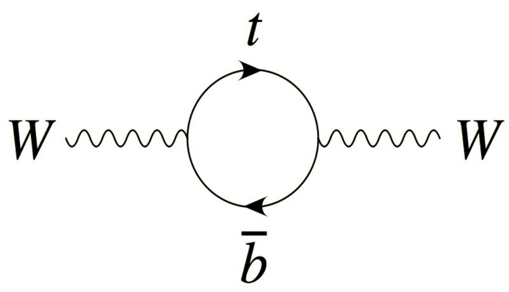
The Top Quark

- Heaviest known elementary particle:
  $m_t = \sim 173 GeV$
- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime $0.5x10^{-24}$s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson

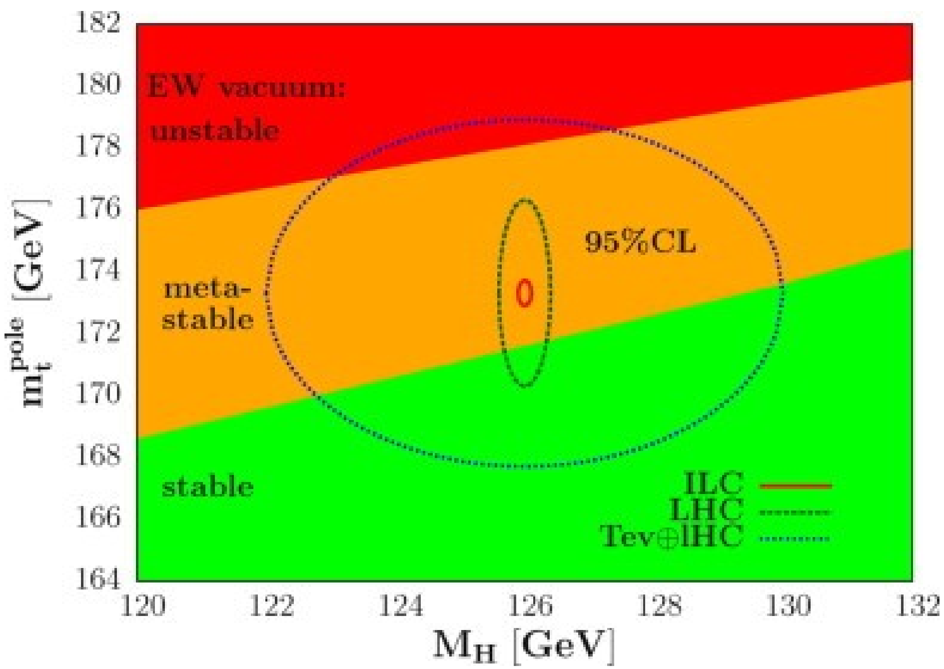
→ A lot can be learned in the top sector!

The Top Mass

- Top mass: free parameter of the SM
- important ingredient to EW fits!
  → consistency of the SM



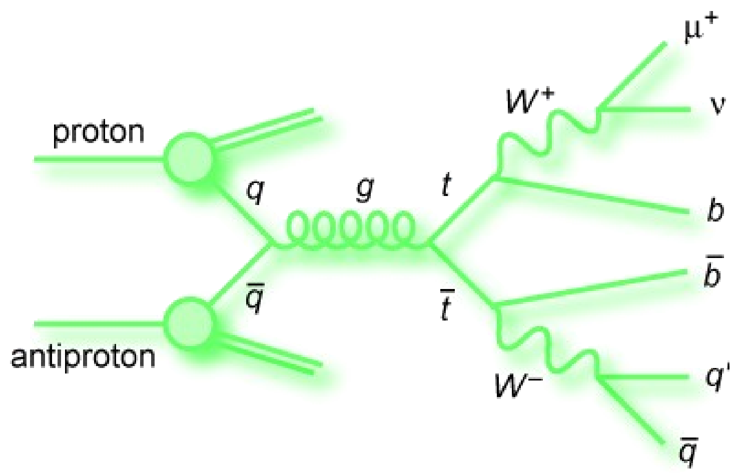
- Fate of the universe!

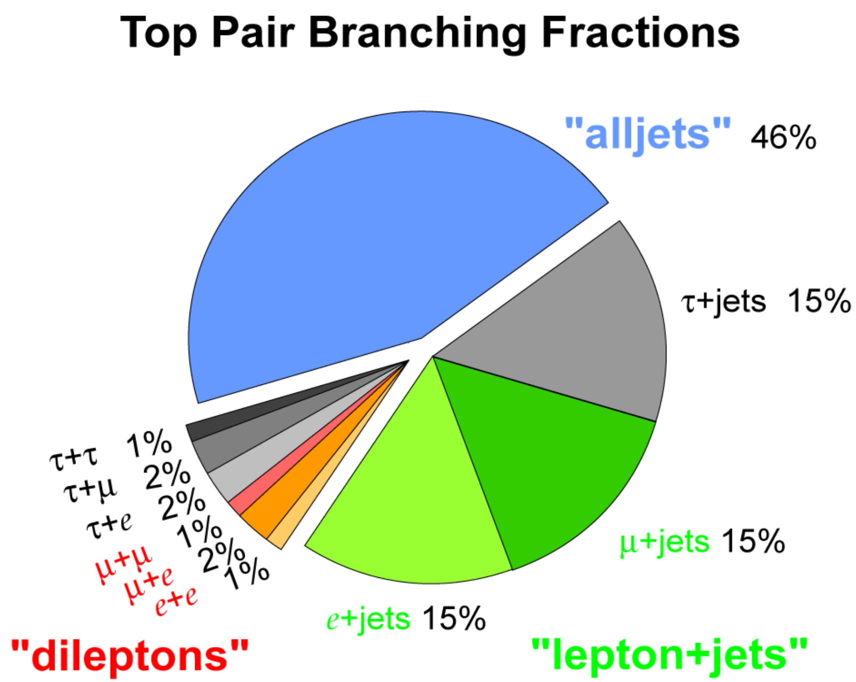


→ aim at high precision top mass measurements!

The Top Mass

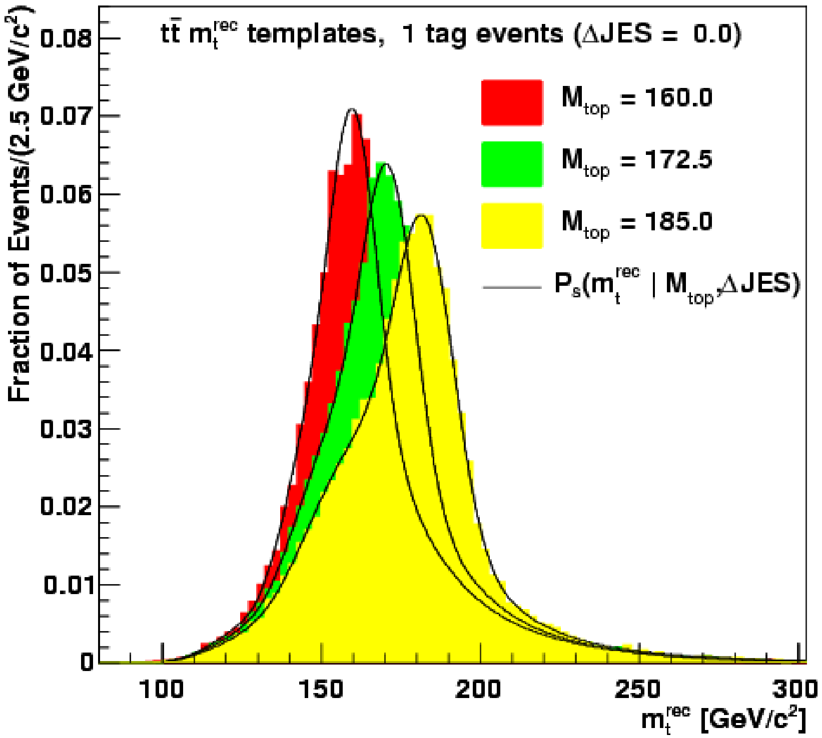
- Measurements: at Tevatron and LHC
- Measurement done with several methods:
  Template method, ideogram, matrix element, etc.
  - Allowing reach of precision not imagined before: well below 1 GeV!
- Measurements done in (almost) all final states of $t\bar{t}$

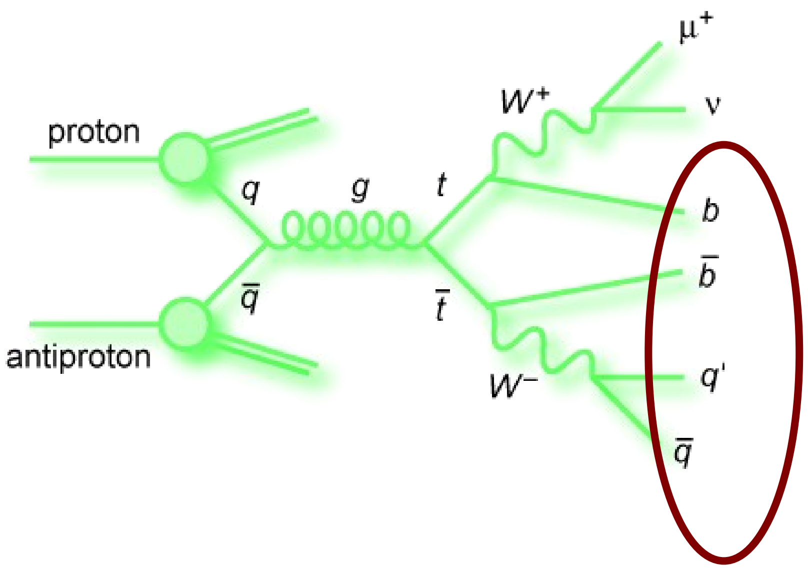




Top Quark Mass: Template Method

- Construct mass dependent template
- Compare MC for different top masses to data → "done"
- Main systematic uncertainty: Jet Energy Scale





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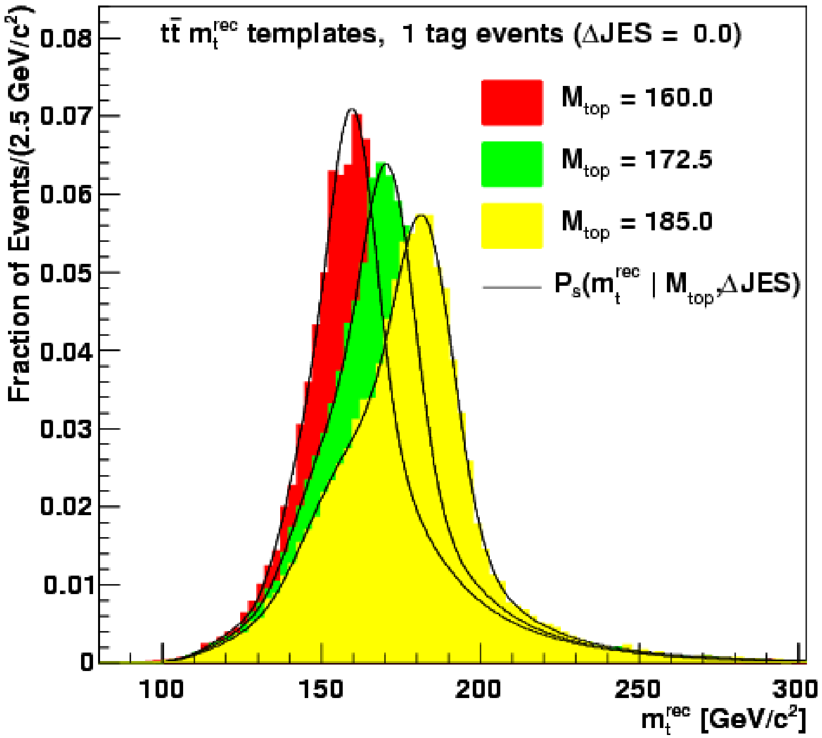

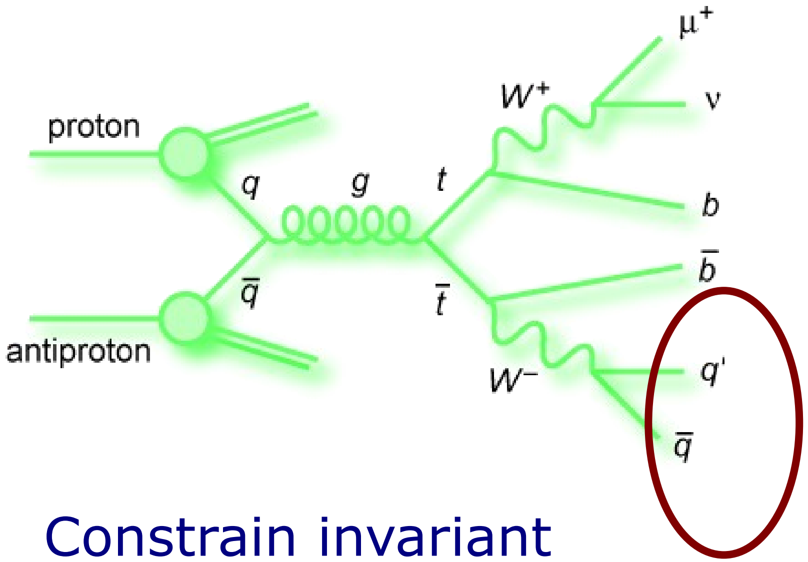

Constrain invariant mass of jets from W to known W mass

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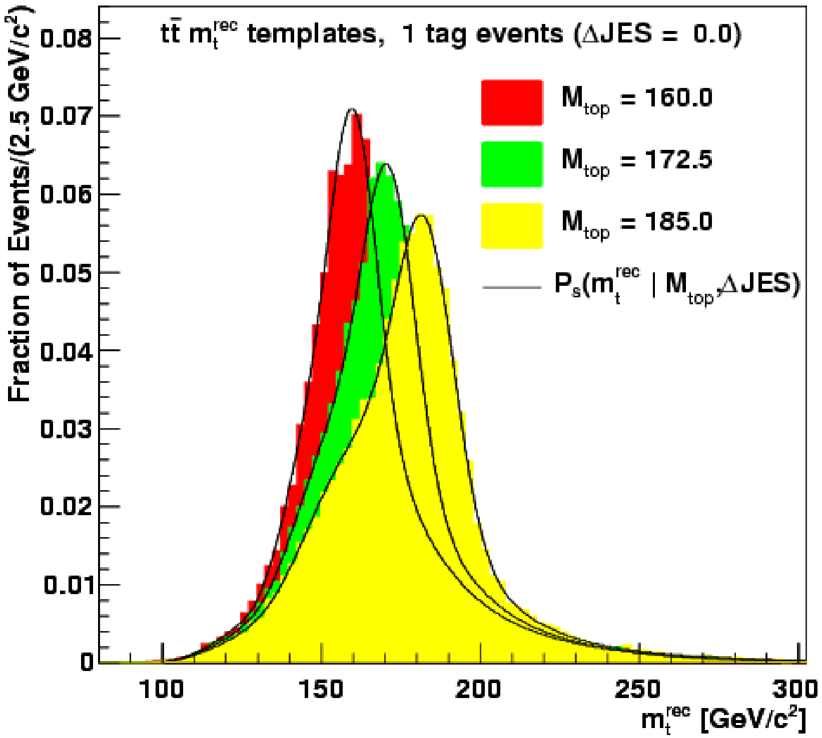
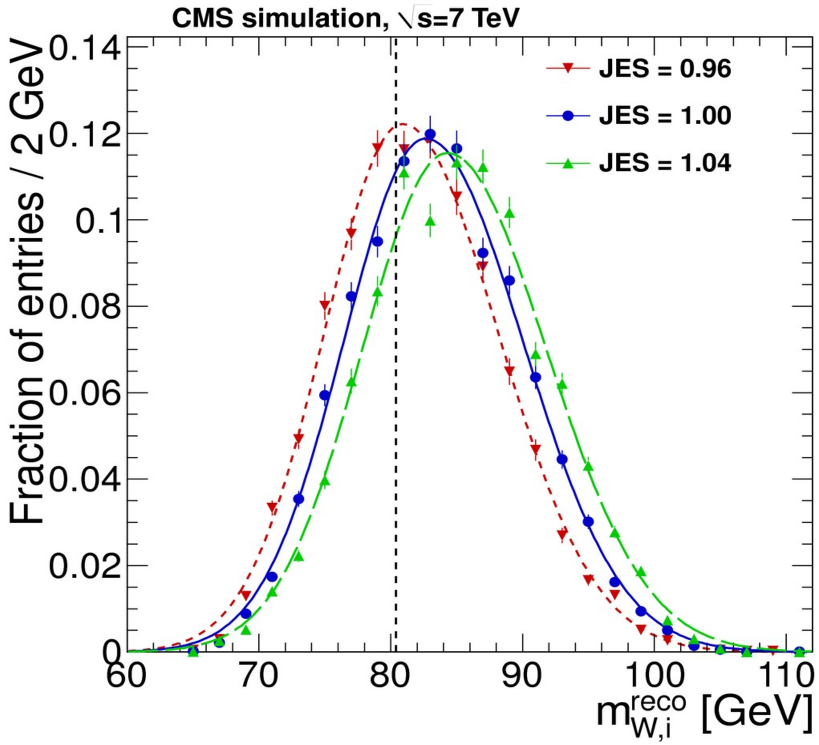
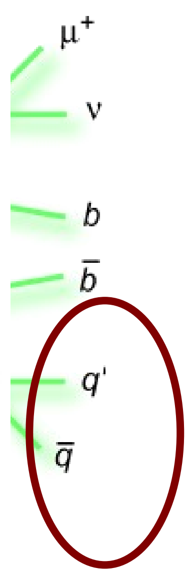


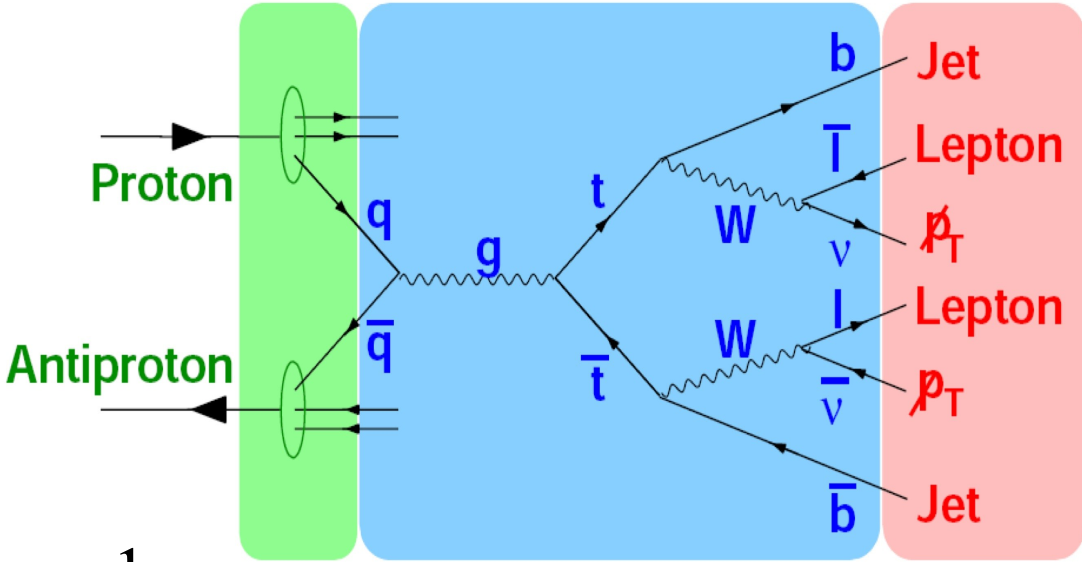




Constrain invariant mass of jets from W to known W mass

Top Quark Mass: Matrix Element Method

- Use full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass



$$P_{sig}(x;m_{top}) = \frac{1}{\sigma_{obs}} \int \sum_{flavors} dq_1 dq_2 dy\, f(q_1) f(q_2) \sigma(y;m_{top}) W(x,y)$$

PDFs

Matrix element & phase space

Transfer function: mapping of true momenta y to measured momenta x

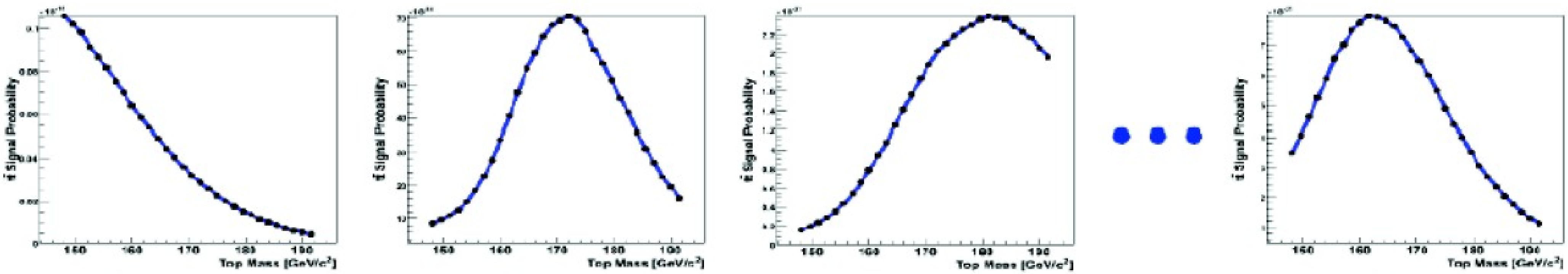
Matrix Element Method: Extraction

- In the same way as signal probabilities, calculate background probabilities $P_{bkg}(x)$
- Per-event probability:

$$P_{evt}(x, m_{top}) = f_{sig} P_{sig}(x, m_{top}) + (1 - f_{sig}) P_{bkg}(x)$$

  - f_{sig}: fraction of signal events in data sample
- Perform event-by-event likelihood:

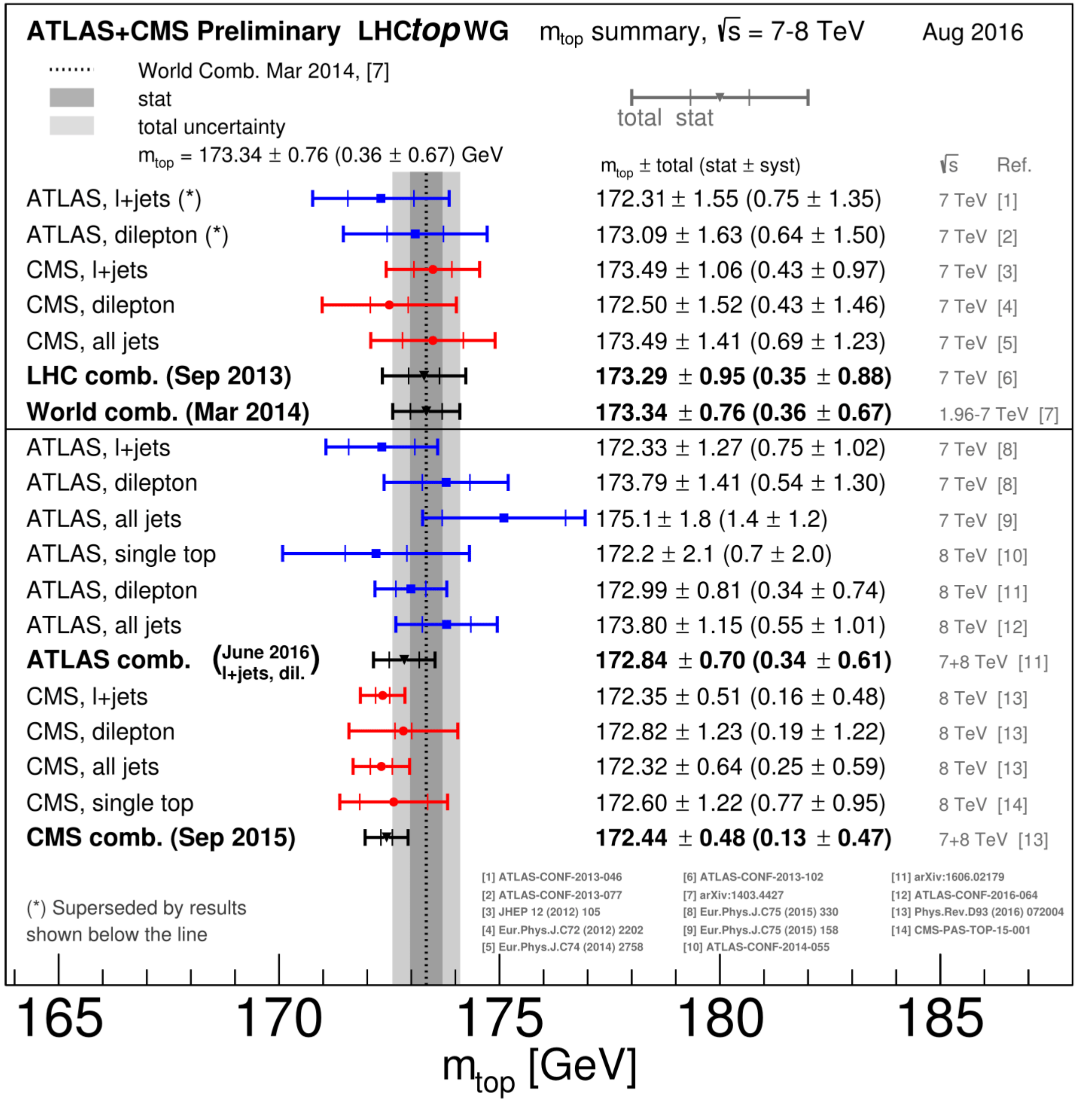
$$-\ln L(m_{top}) = -\ln \prod_i^n P_{evt}(x, m_{top})$$



Event 1 | Event 2 | Event 3 | ... | Event n

Top Mass: Status

- Many new results: → incredible precision! (CMS: 0.48 GeV)
- Limiting factors:
  - modeling
  - JES



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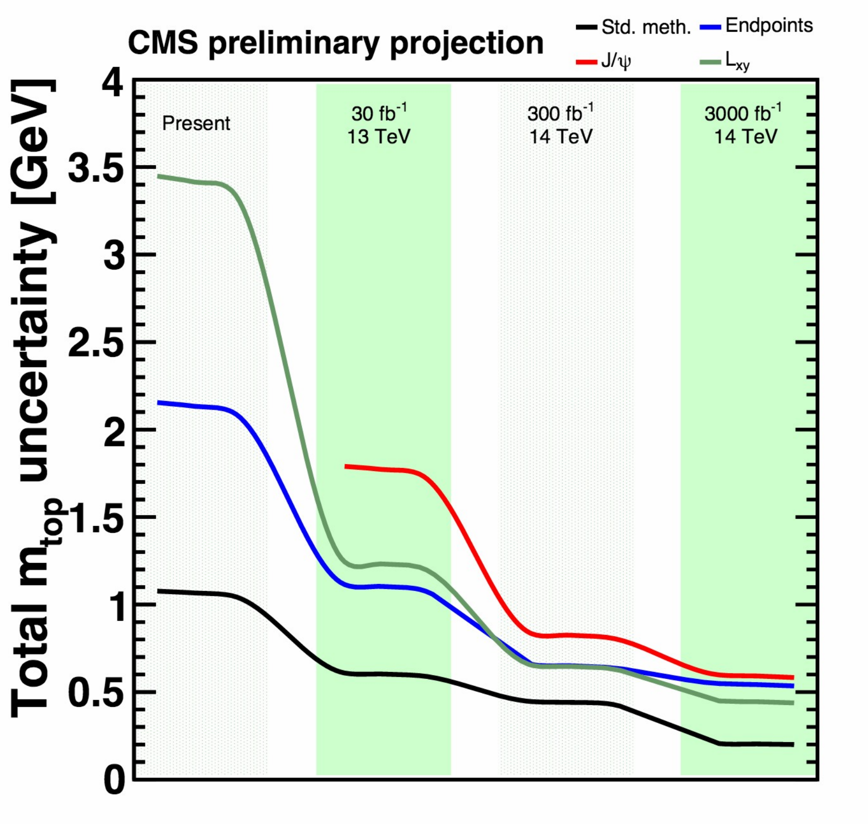
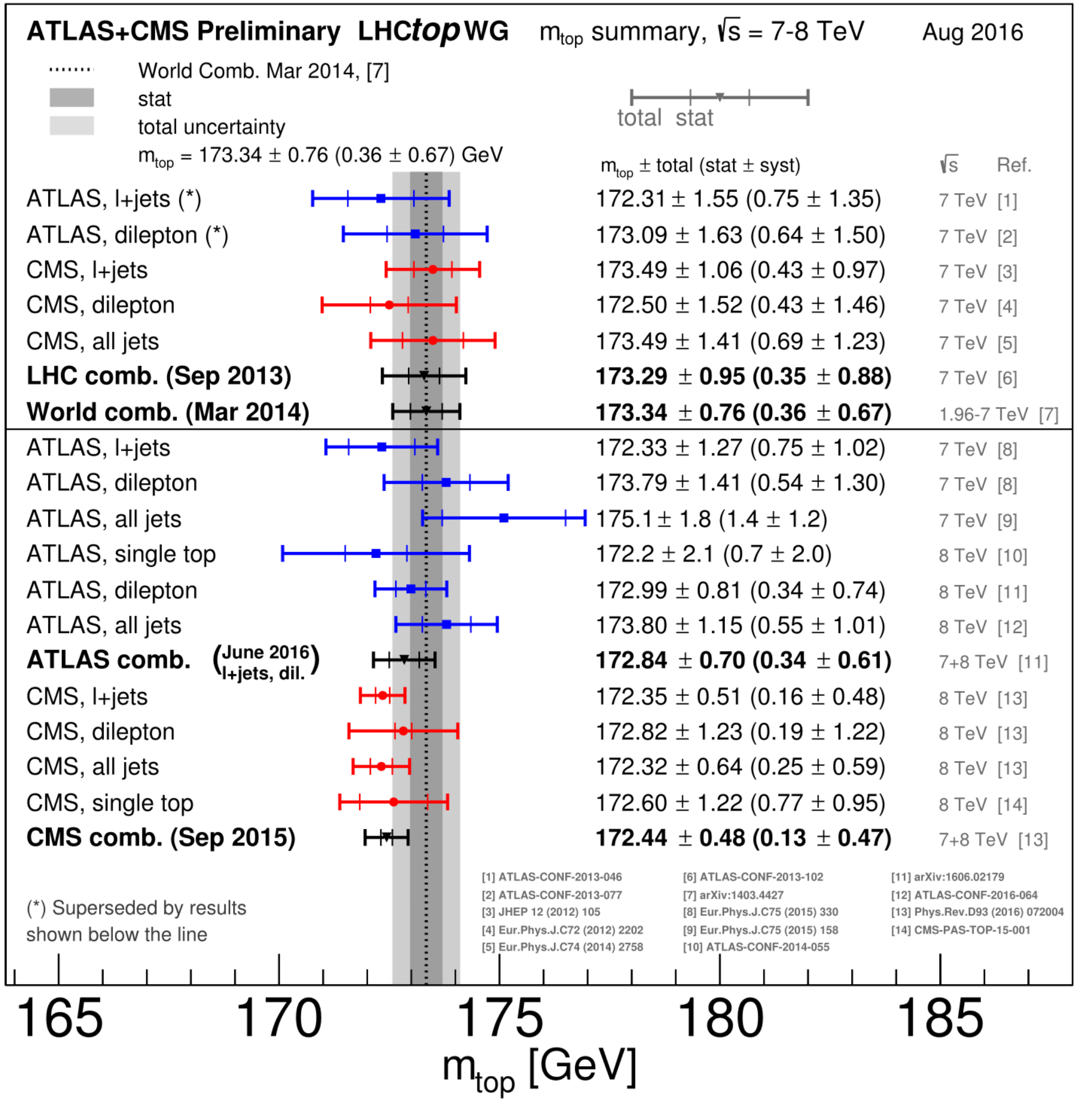
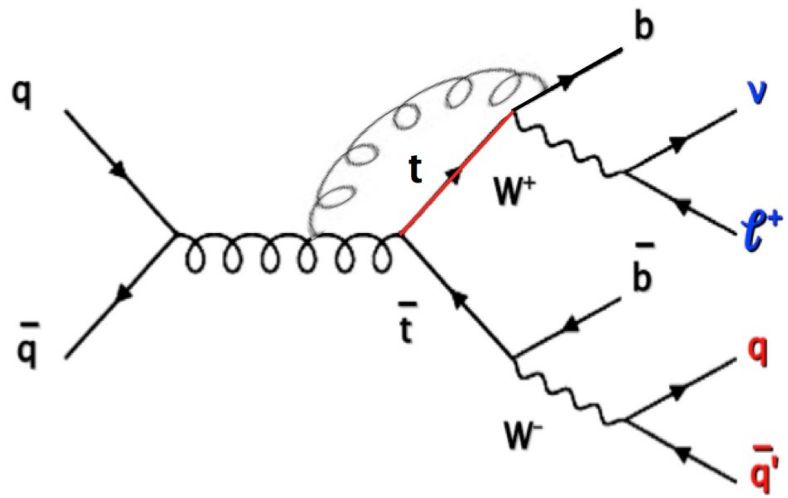




Top Quark Mass and Issues

- Constantly discussed: what is it, that we measure?
  - All direct mass measurements rely on MC for calibration
  - No clean definition of the top mass
    - e. g. contributions like this missing in MC:

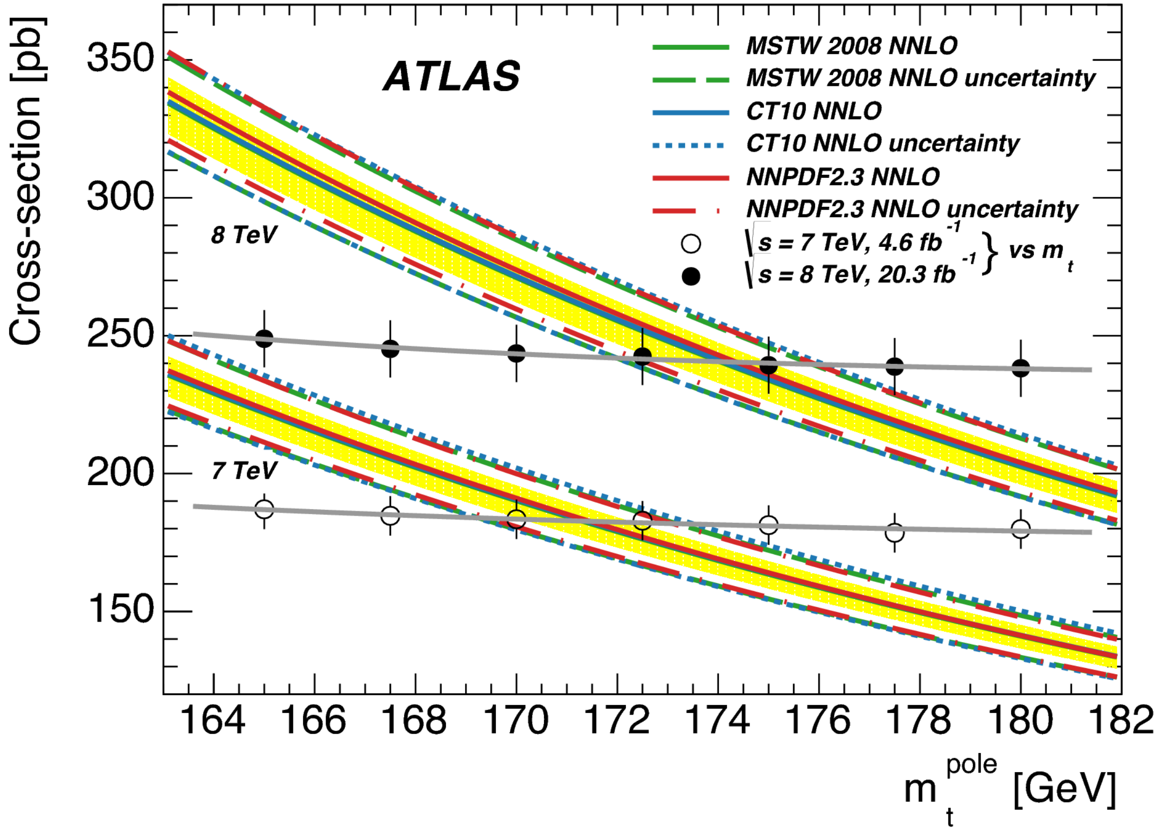


- Task mainly for theorists
  → first ideas emerging (for example "calibration")
- Experimentally: explore alternative methods

Top Quark Mass: Be aware

- Alternative method: Extract m_t from cross section measurement
  - Assuming pole or $\overline{\text{MS}}$ mass

- Unambiguous extraction of top quark mass!
  - Contra: uncertainty quite large compared to direct methods



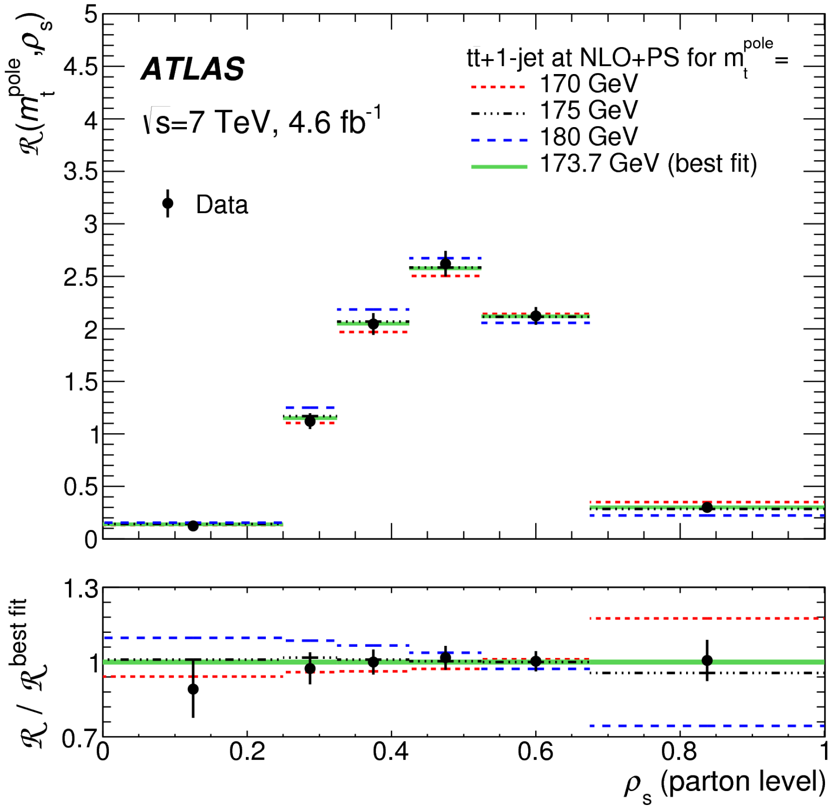
Eur.Phys.J. C74 (2014) 3109

Mass from tt̄+jets

- Extract mass from distribution in tt̄+jets events
  - Gluon radiation depends on mass of quark
  - Compare unfolded distribution to calculation → allows to uniquely define mass scheme

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s),$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}},$$

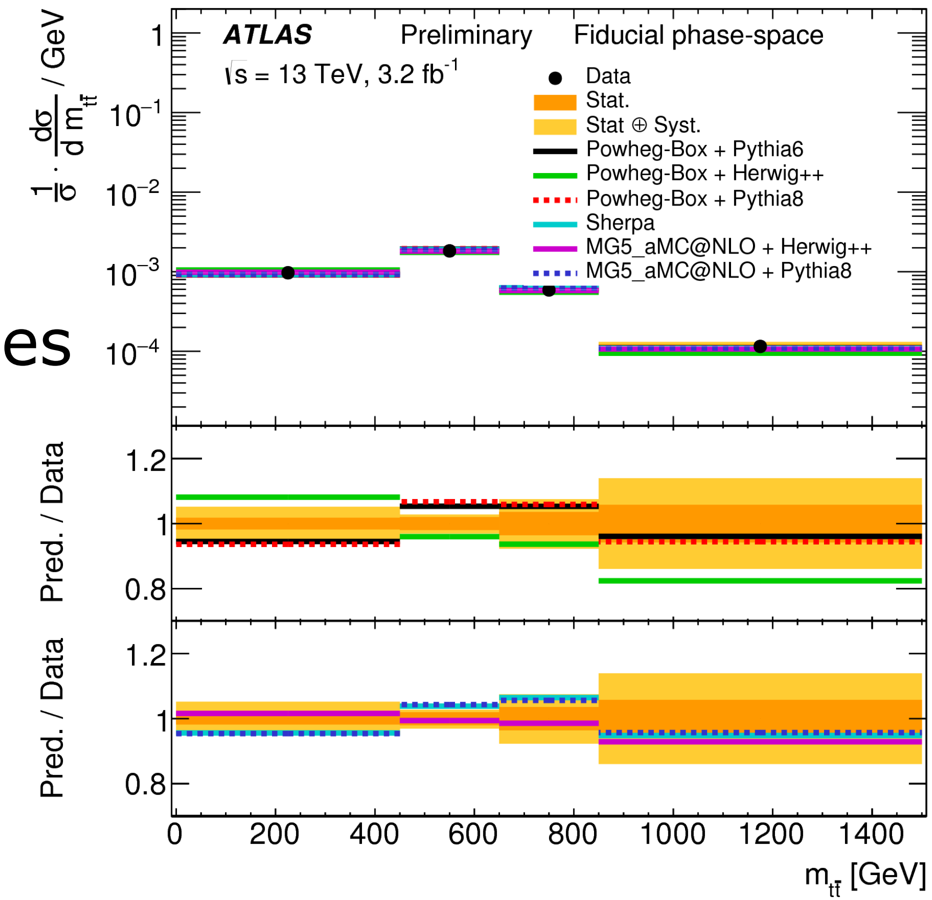


JHEP 10 (2015) 121

$$m_t^{pole} = 173.7 \pm 1.5(stat) \pm 1.4(syst)^{+1.0}_{-0.5}(theo)\, GeV$$

Top Mass: other methods and input

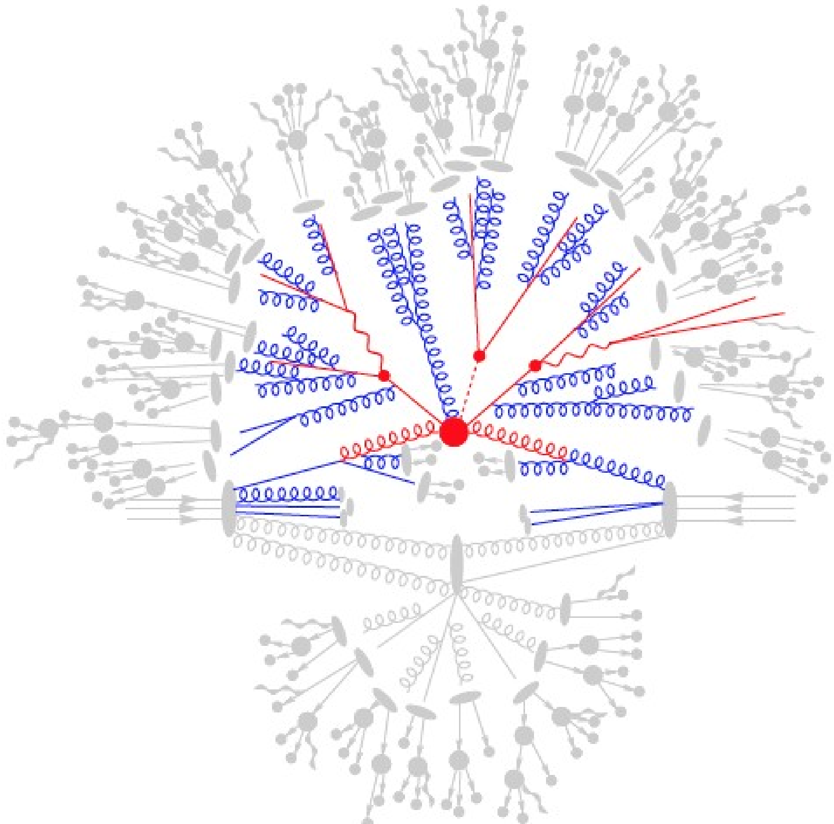
- Since systematics main limiting factor:
  - Do alternative methods
  - Reduce systematics with supporting measurements
- Alternative methods: for example track-based observables
  → minimises jet-related uncertainties
- Supporting measurements: important are differential cross section measurements
  - Get a handle of modeling systematics



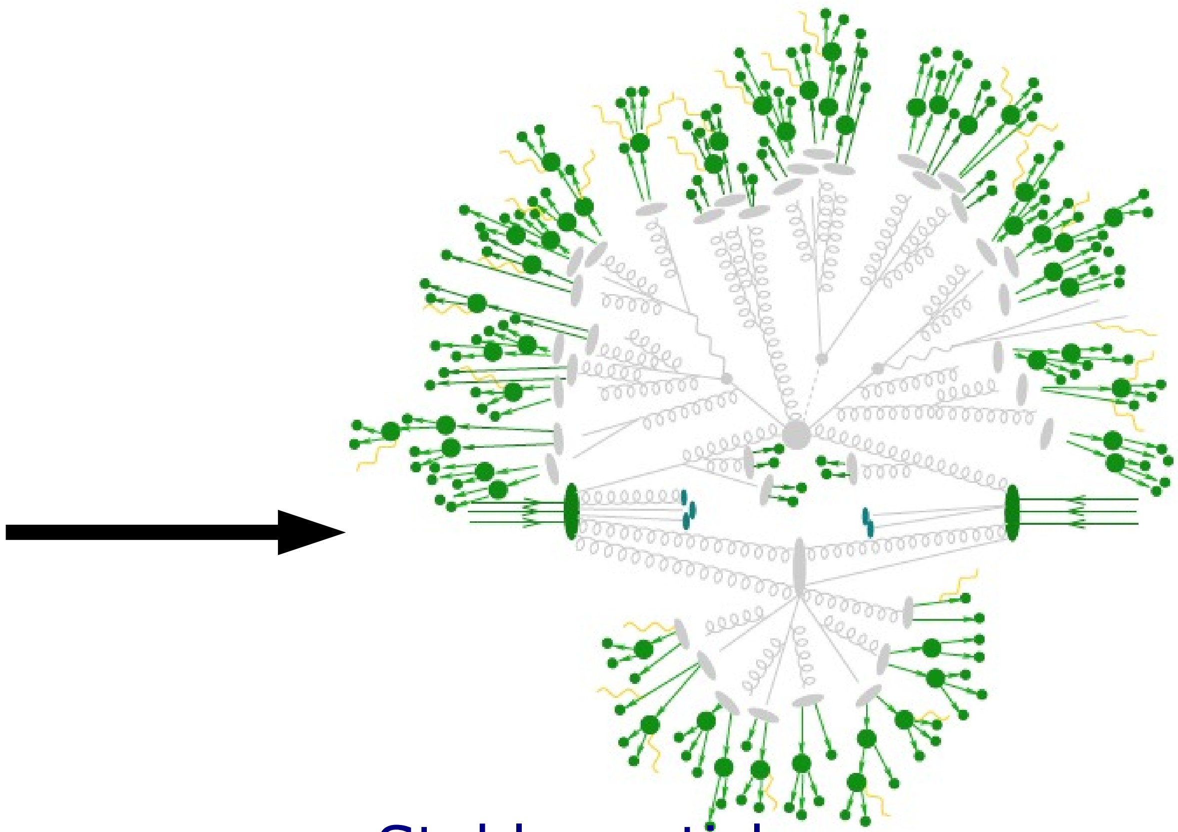
TOPQ-2016-04

Top Mass

- Important topic also for future
  - Emphasize on supporting measurements and alternative methods
- Hot Topic: differential measurements: parton versus particle level



MC generator dependencies

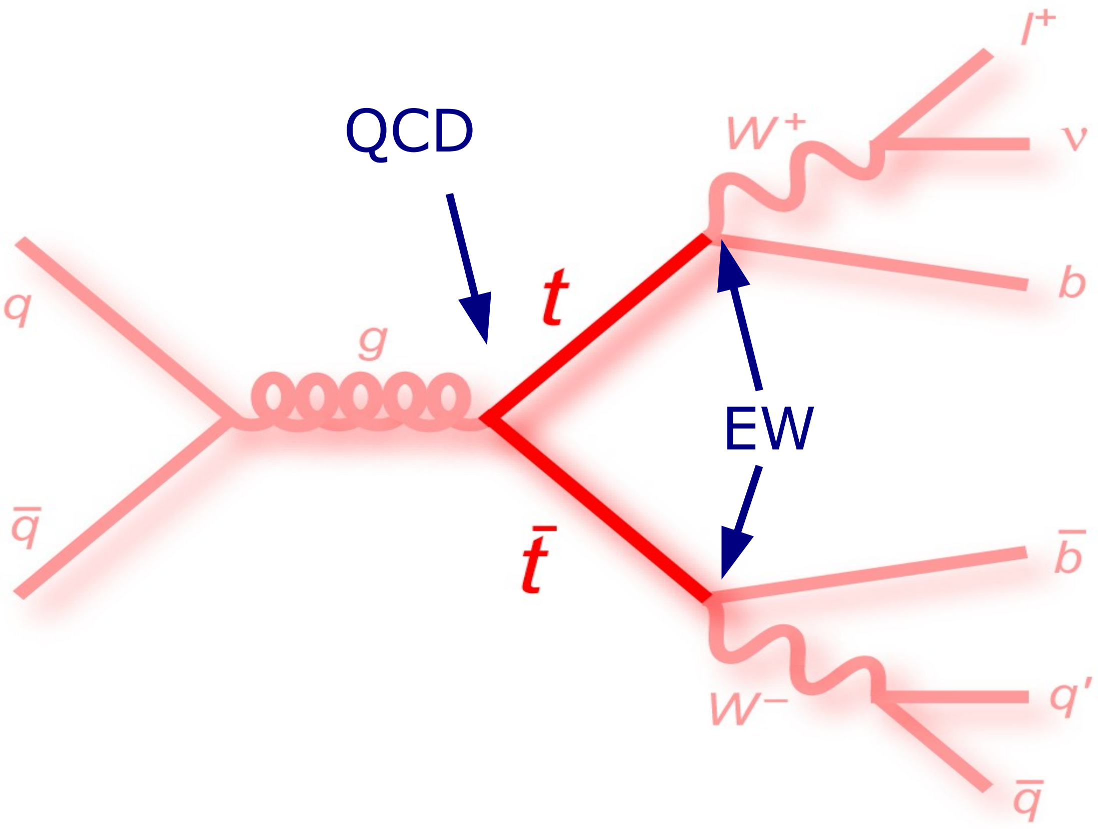


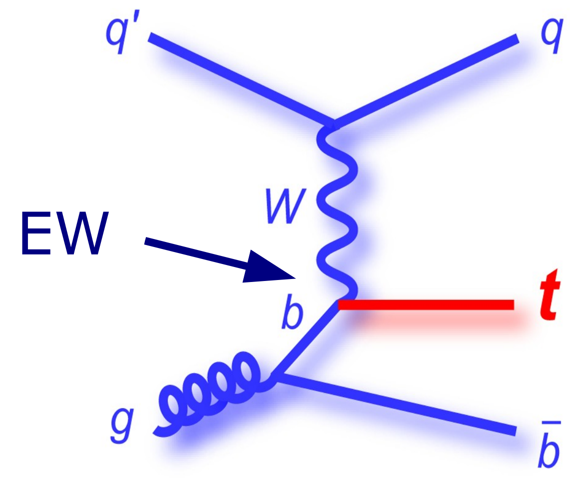
Stable particles

More Top Fun

Top Studies

- Top sector: source to test QCD and EW couplings!



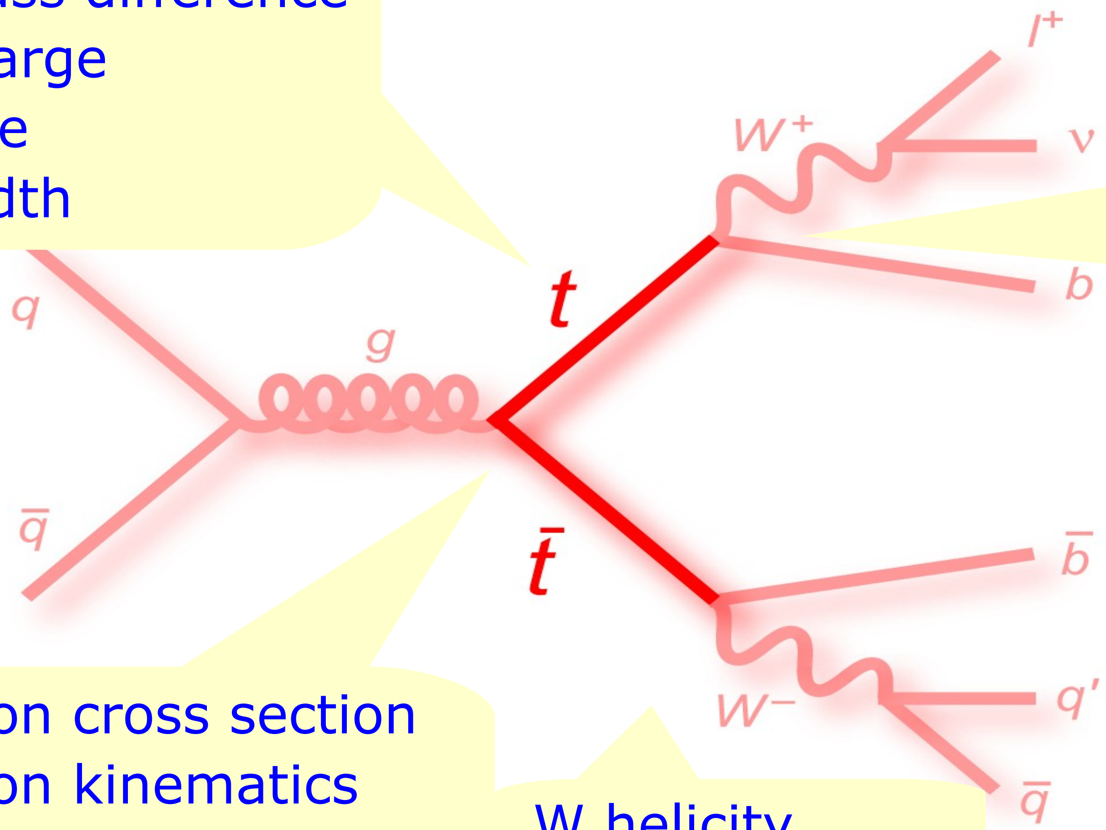


- Single top: large data samples allow more detailed studies
  - Top mass in single top
  - Differential distributions in single top

Top Studies: Overview

Top mass
Top mass difference
Top charge
Lifetime
Top width

Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays



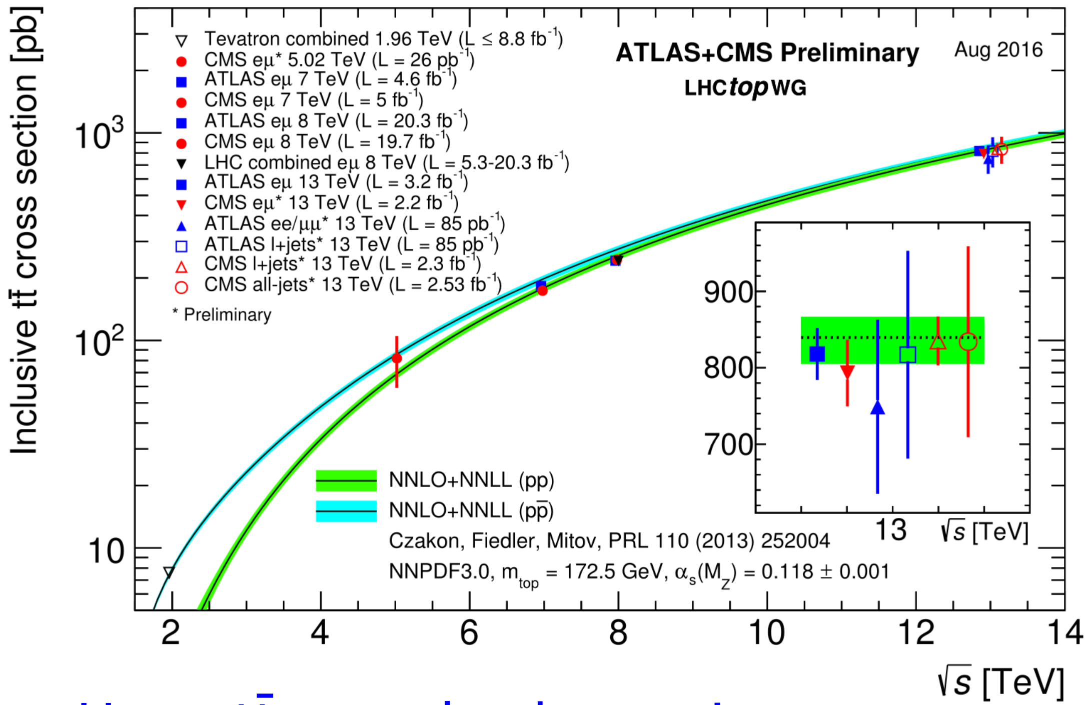
Spin correlation
Charge asymmetry
Color Flow

Production cross section
Production kinematics
Production via resonance
New particles

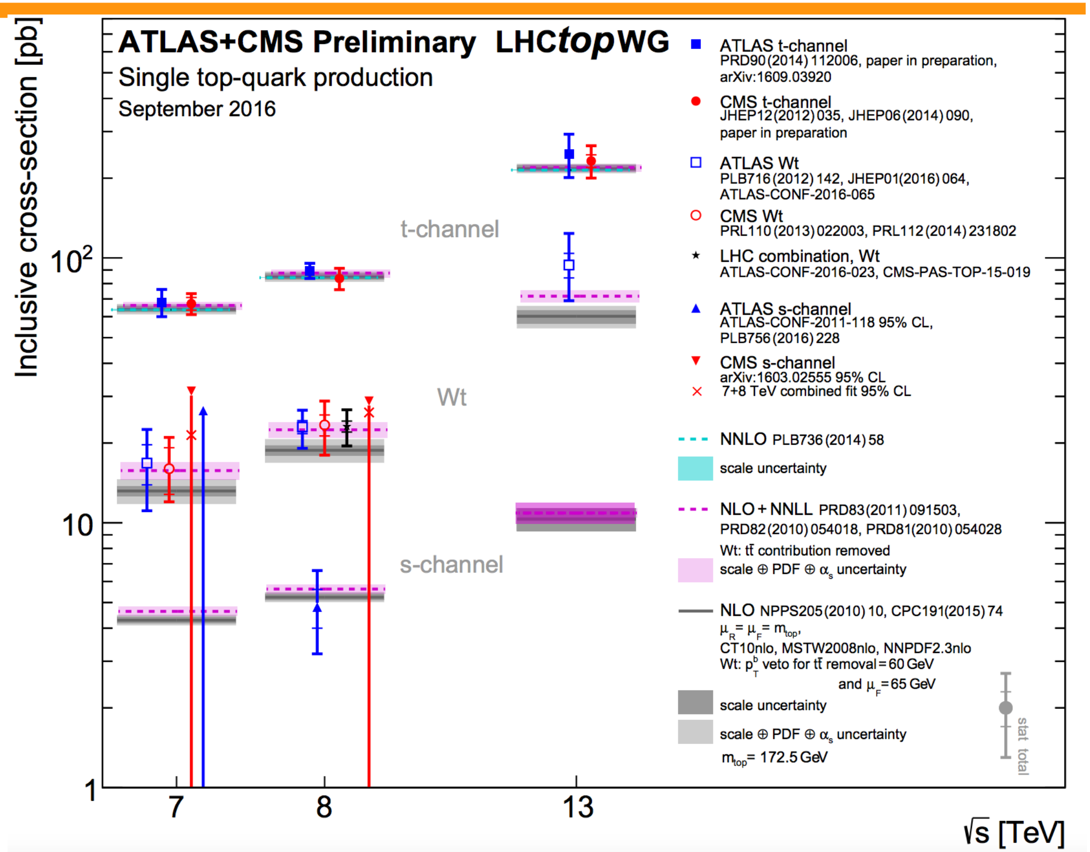
W helicity

s-, t- and Wt-channel production, properties and searches in single top events

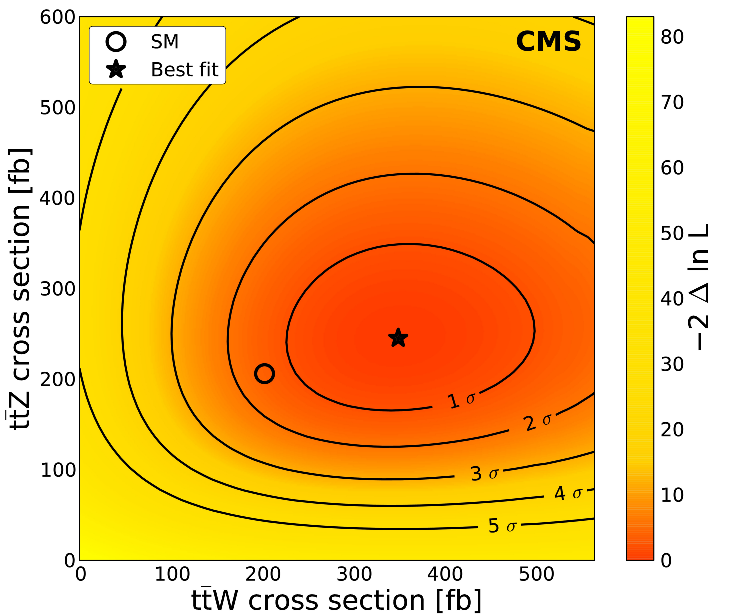
Top!



Huge $t\bar{t}$ samples becoming available → precision era



Single top: from observation to measurements



JHEP01 (2016) 096

$t\bar{t}V$ and $t\bar{t}W$ becoming accessible: direct probe of top-V coupling

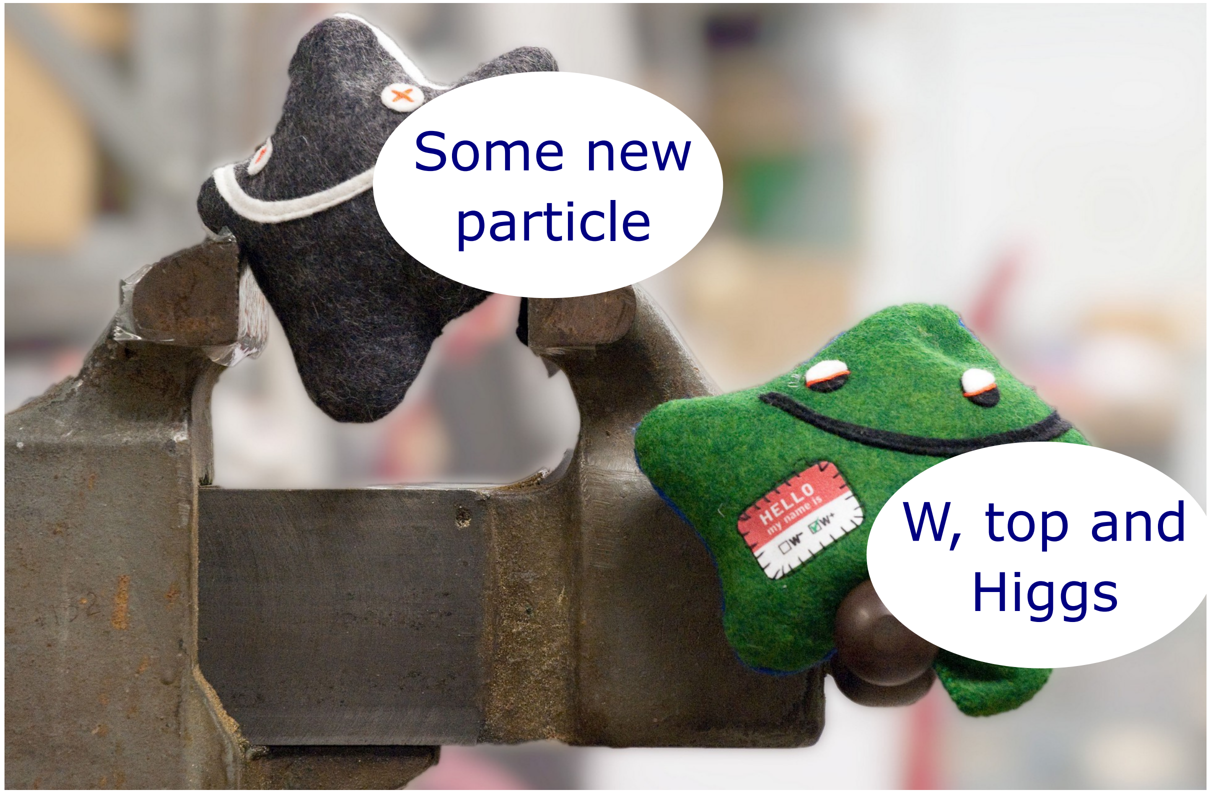
Summary

- Electroweak precision measurements: crucial to scrutinize the SM
  - Where is the new physics? → precision required!

Summary

- Electroweak precision measurements: crucial to scrutinize the SM
  - Where is the new physics? → precision required!

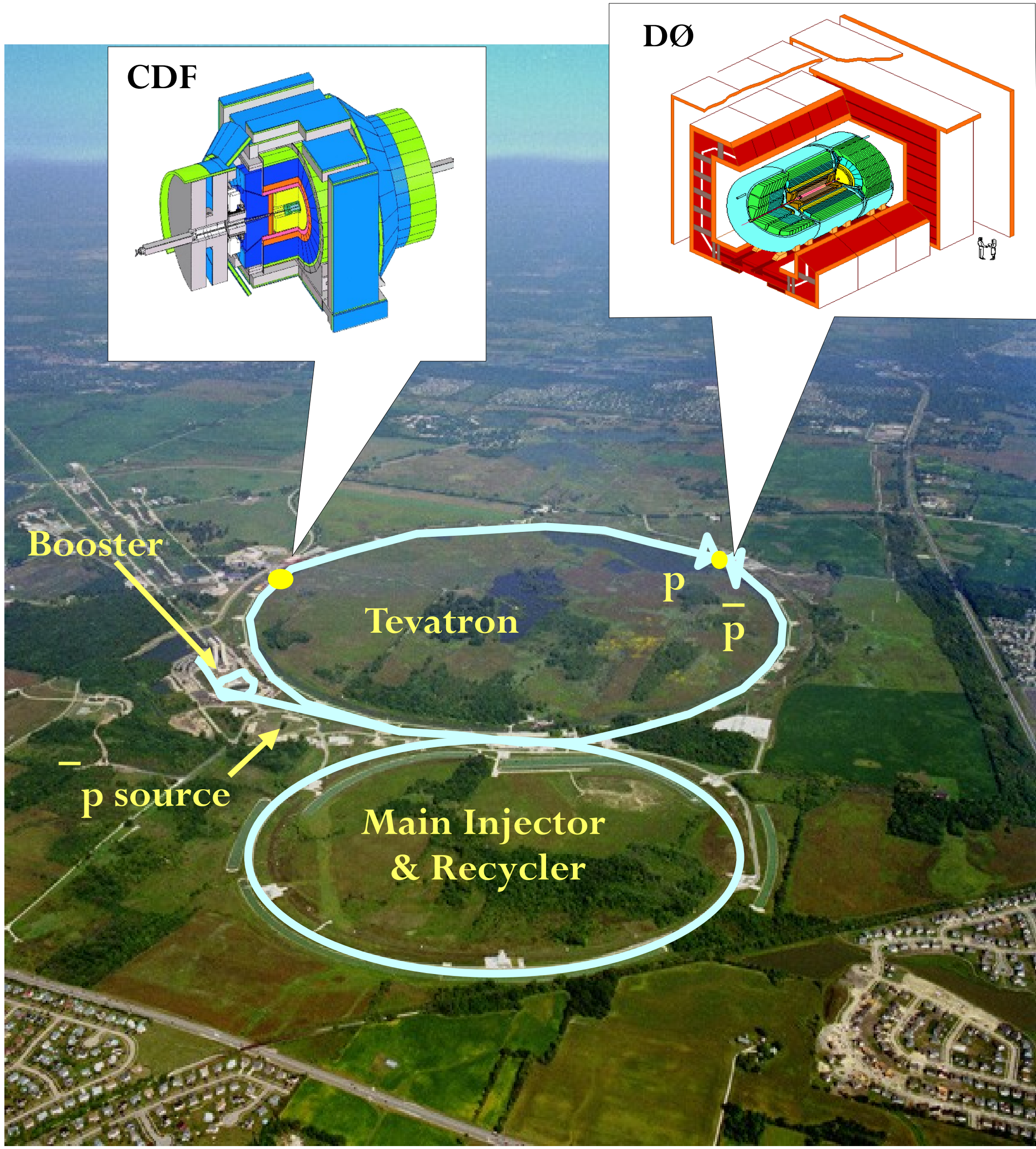
- Electroweak fits:
  relate different parameter
  in EW sector
  → consistency checks might
  reveal hints for BSM!



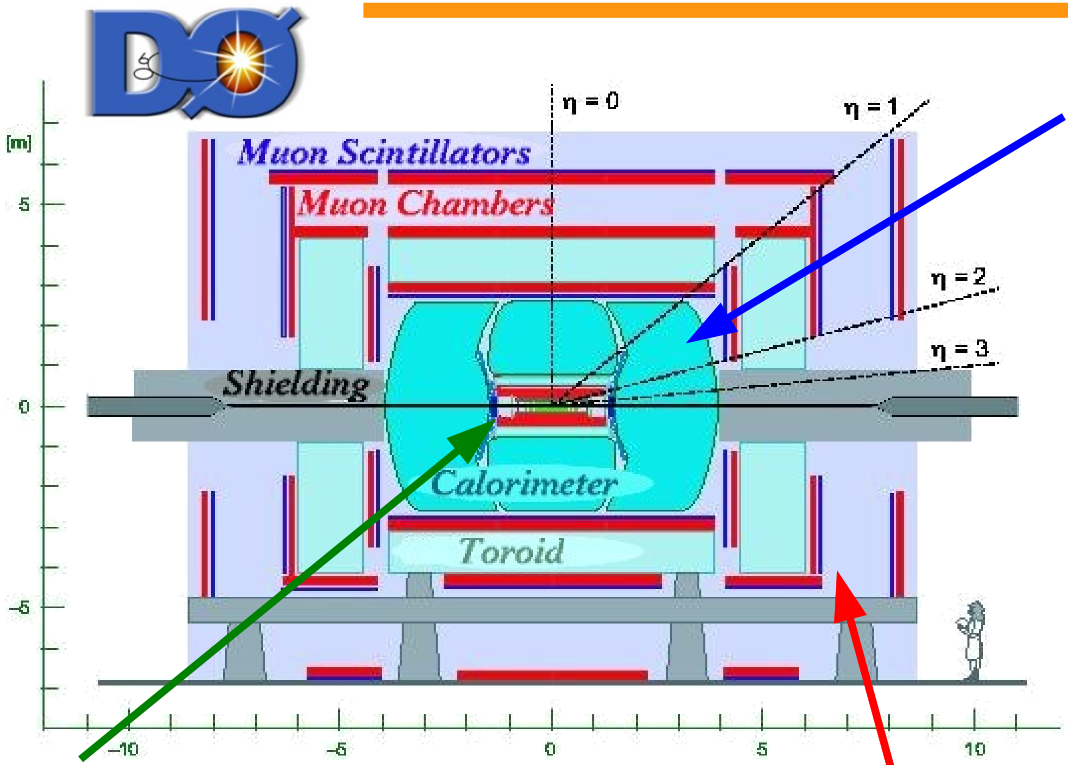
BACKUP

The Tevatron

- Tevatron at Fermilab
  - Near Chicago
- Proton Antiproton Collisions
  - Run I: 1992-1996
    - Collision energy: 1.8 TeV
  - Run II: March 2001 to 30.09.2011 (2pm)
    - Collision energy: 1.96 TeV
- Two experiments: CDF & D0



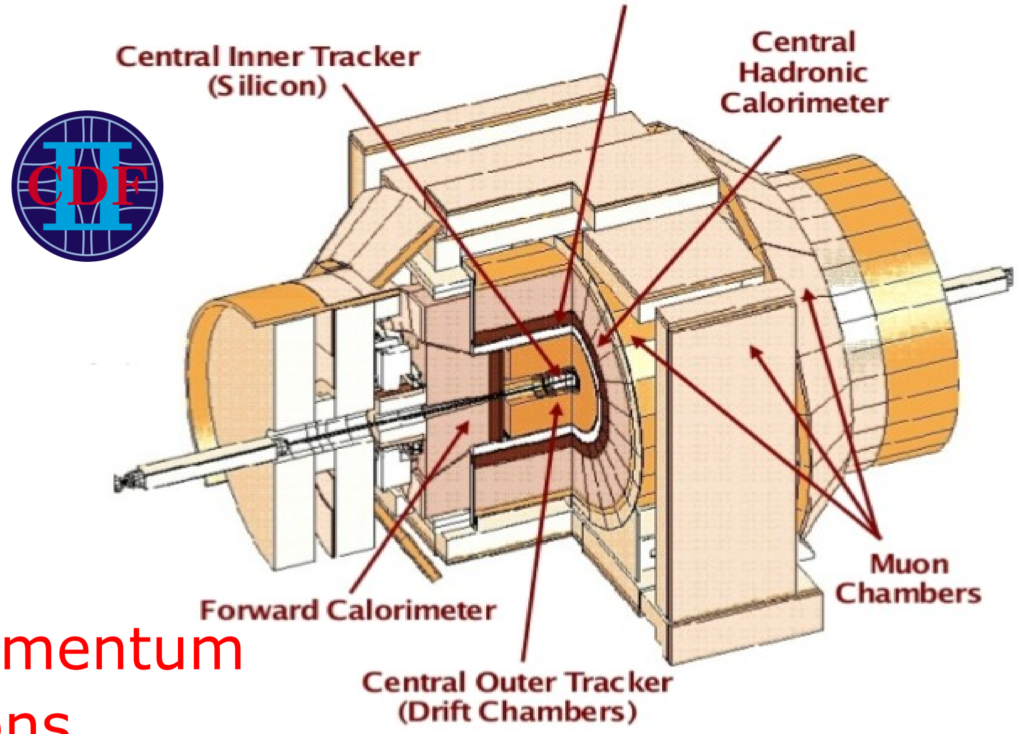
The CDF & DØ Detectors



Calorimeter:
Identification and energy measurement of jets and electrons;
tau identification

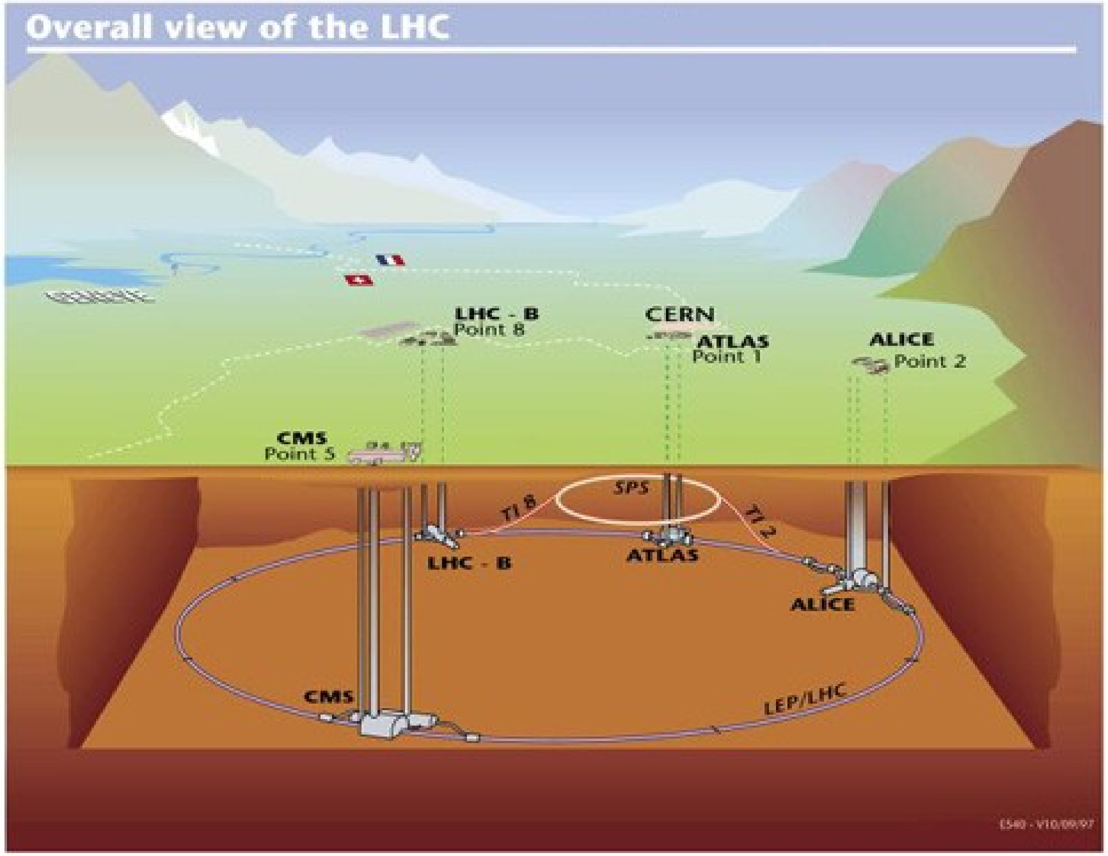
Tracker: Detection and momentum measurement for charged particles

Muon chamber:
Identification and momentum measurement of muons



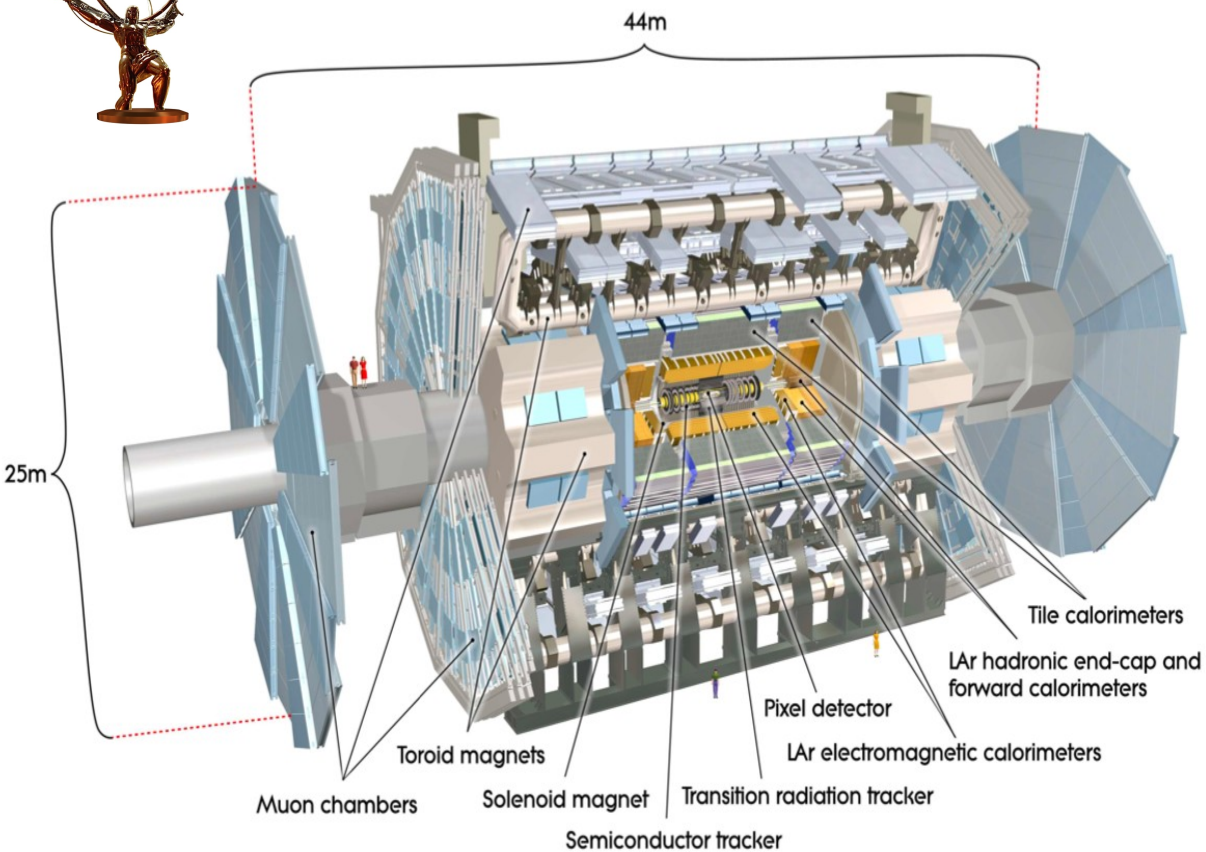
The LHC

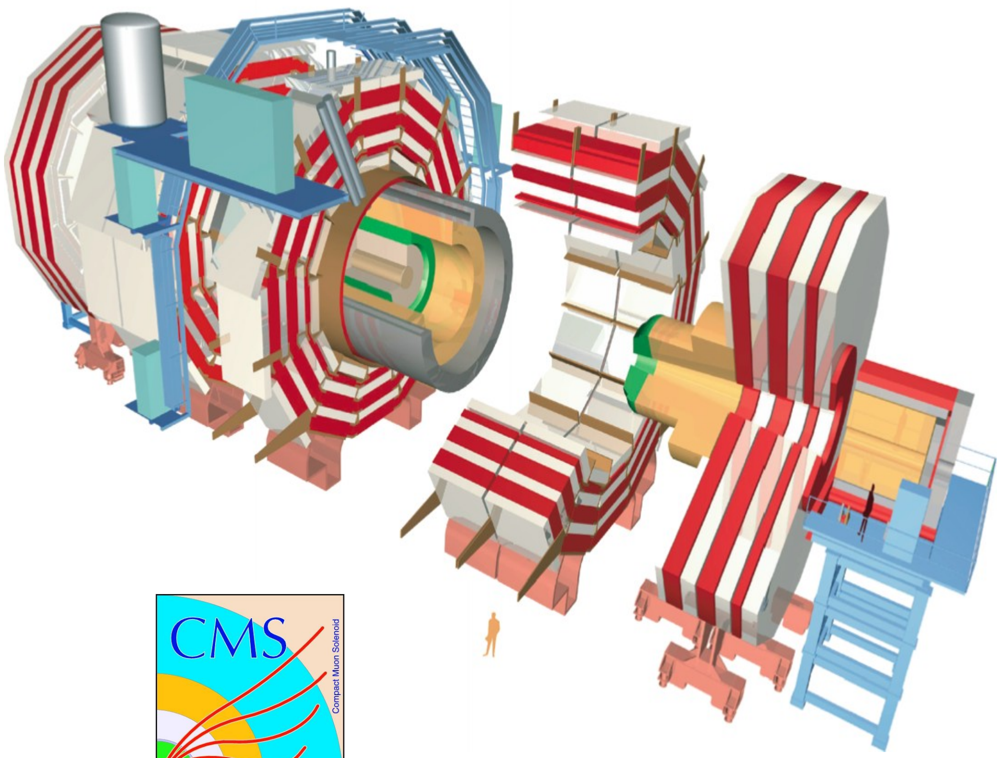
- LHC: 8 TeV Proton-Proton collisions (2011: 7 TeV)
  - Start: 2009
  - Restart: 2015 with 13 TeV
    - Later: 14 TeV



- Some LHC key data:
  - 27km ring
  - ~100m underneath surface
  - 1232 dipole magnets to keep protons in their orbit
    - Further magnets for focussing
  - Magnets get cooled to 1.9 Kelvin (-271.25 Celsius) → the LHC: coolest ring in the universe!

CMS & ATLAS Detectors





Combination Tool: BLUE Method

- For all combinations: use of BLUE method
- BLUE Method (Best Linear Unbiased Estimator):
  - Use weighted mean of all measurements y_i:

$$\hat{\theta} = \sum_i w_i y_i$$

  - The weights are set to minimize uncertainty:

$$w_i = \frac{\sum_j V_{ij}^{-1}}{\sum_k \sum_l V_{kl}^{-1}}$$

  with V: covariance matrix (of all uncertainties: statistical and all systematics)

  - Error squared on the weighted mean: $Var(\hat{\theta}) = \vec{w}^T V \vec{w}$
- For high correlations: some weights can get negative