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**‘Measure what is measurable, make  
measurable what is not so’ [Galileo]**

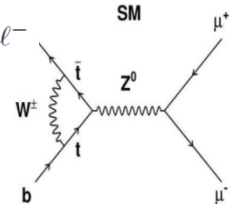
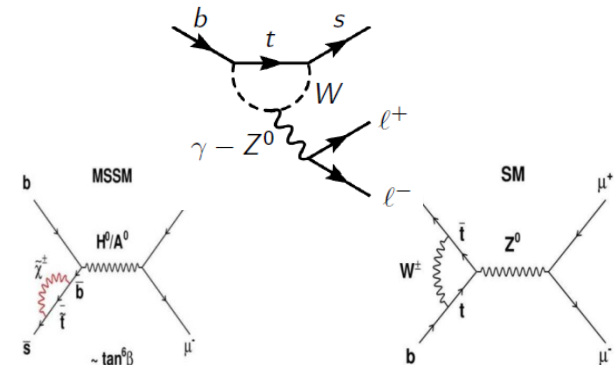
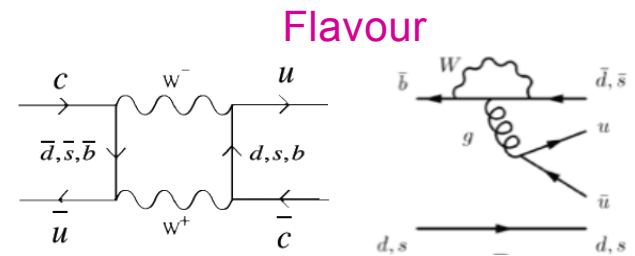
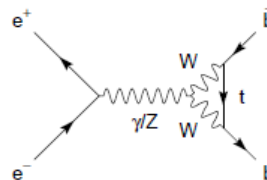
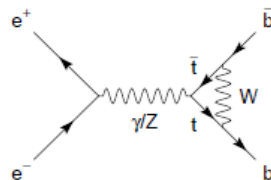
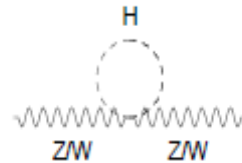
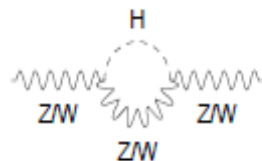
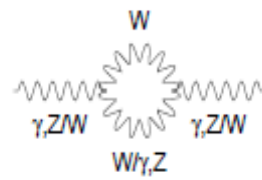
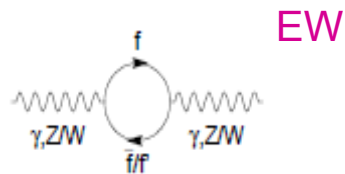
# **Prospects in heavy flavour and electroweak physics at the LHC**

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Guy Wilkinson  
University of Oxford  
LHC France 2013  
Annecy, April 2013

# Searching for New Physics through Quantum Corrections

Precision measurements in electroweak & flavour physics play the same game...

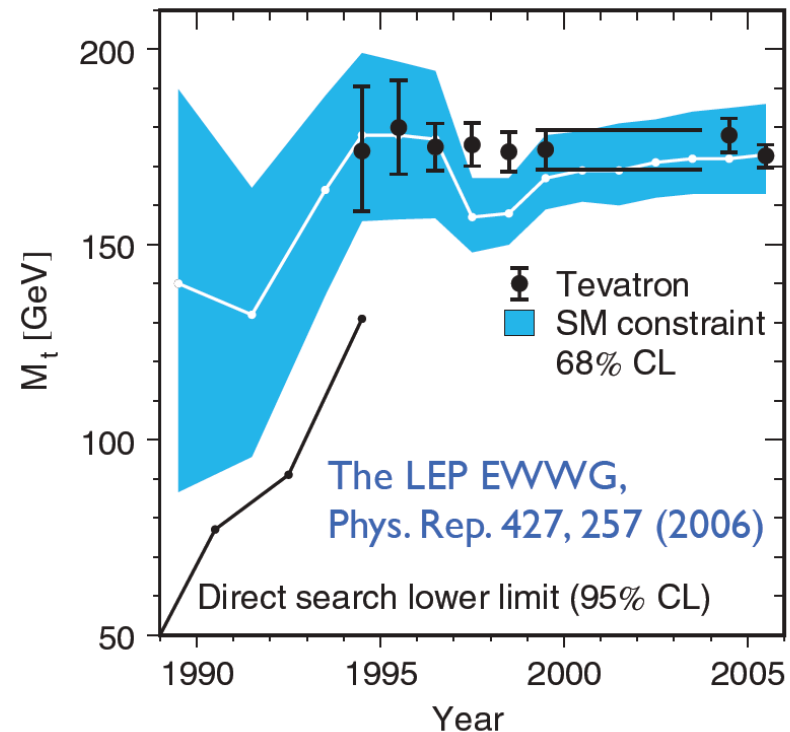


...testing the self-consistency of the SM, & looking beyond, through loop corrections.

# Precision measurements have proven track record at probing high mass scales

Example, the top quark and its mass:

- First indirect evidence of a 3<sup>rd</sup> family of quarks came from flavour physics (CP violation)
- First indication that top is heavy came from flavour physics ( $B$  mixing)
- Electroweak measurements at LEP and SLD then pinned down where the quark was eventually found



So, precision measurements are very valuable. But what precision is required?

- as precise as the prediction coming from other constraints &/or theory error
- or, sometimes as precise as you can go!

# Unwise to assume $\sim 10\%$ (or even $0.1\%$ ) is 'good enough'

Courtesy Browder  
and Soni

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"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single  $K_L \rightarrow \pi^+ \pi^-$  event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

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$$\text{BR}(K_L^0 \rightarrow \pi\pi) \sim 2 \times 10^{-3}$$

Cronin, Fitch *et al.* , 1964

# (Very) selected topics in flavour physics – status and prospects

Many, many topics in the flavour sector that the LHC will elucidate, some very important in the search for New Physics. Here are three examples:

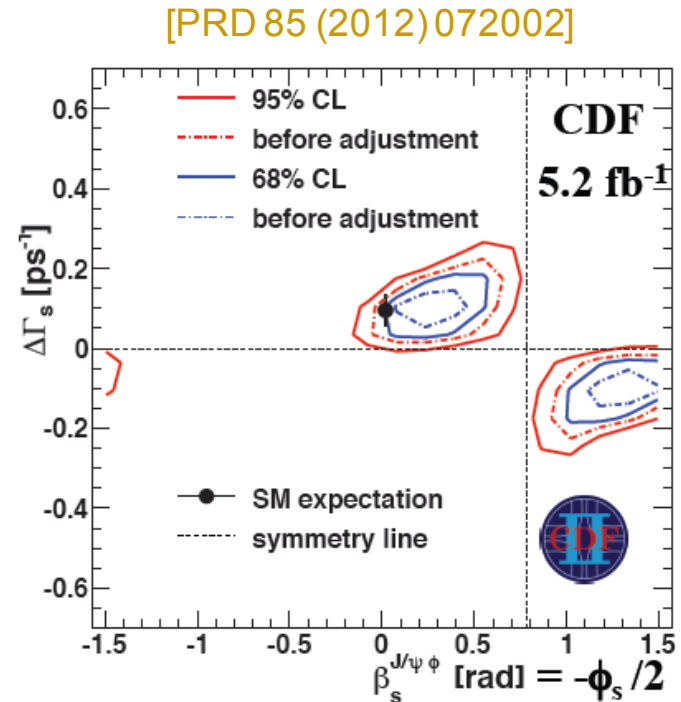
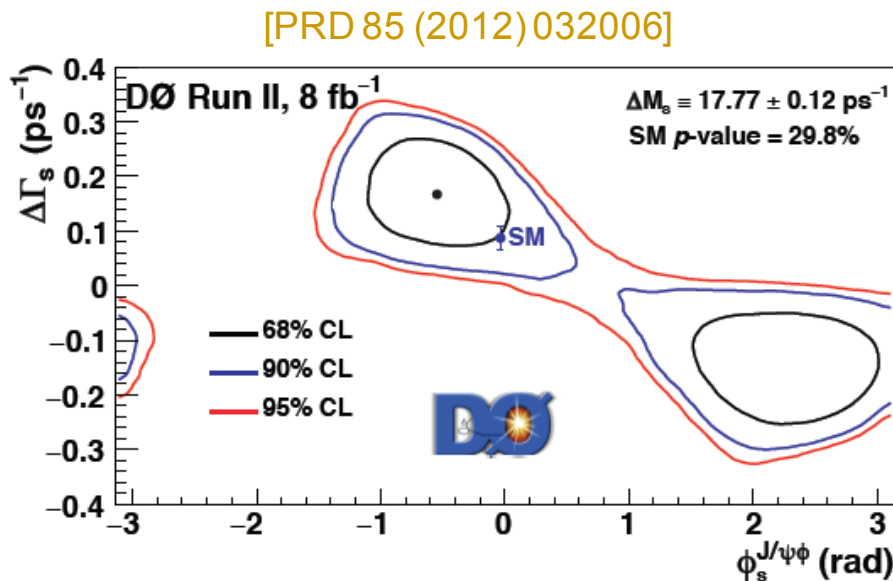
- CPV studies in the  $B_s$  system
- Precision CKM-metrology: the angle  $\gamma$
- FCNC – searching for New Physics in ‘rare decays’

ATLAS and CMS have their role to play in decays involving di-leptons, but clearly LHCb (and the LHCb upgrade) has the main responsibility.

# Mixing induced CPV in $B_s$ system

CPV phase,  $\phi_s$ , in  $B_s$  mixing-decay interference, e.g. measured in  $B_s \rightarrow J/\psi \phi$ , very small & precisely predicted in SM. Box diagram offers tempting entry point for NP!

Tevatron results were tantalising with early data and remain intriguing with final sample:

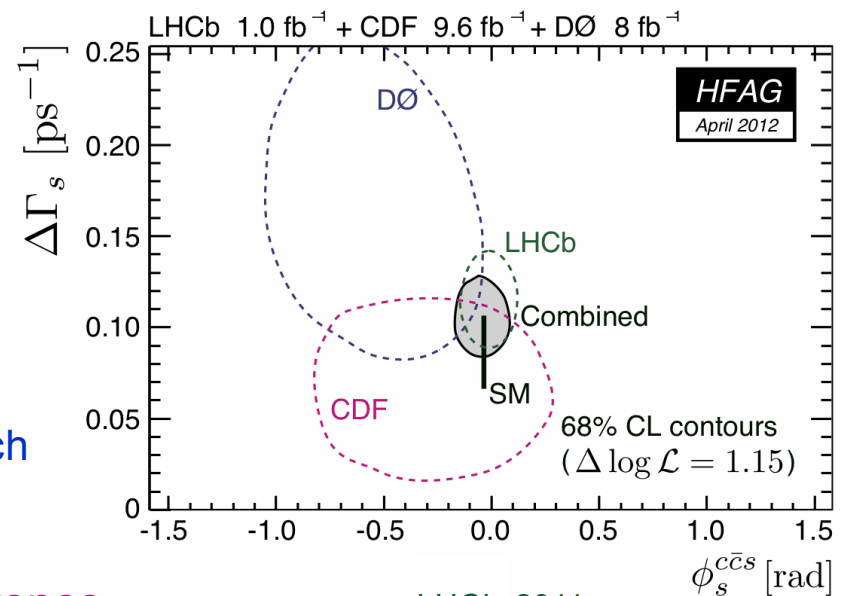
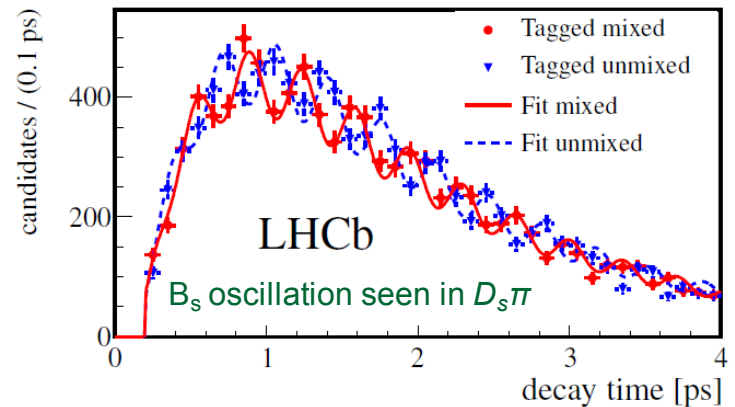
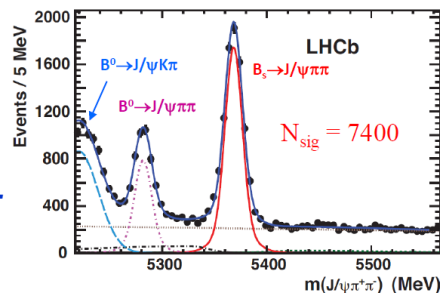


Results are consistent, & both are  $\sim 1\sigma$  away from SM. What about LHCb?

# Precision studies of $B_s$ CPV

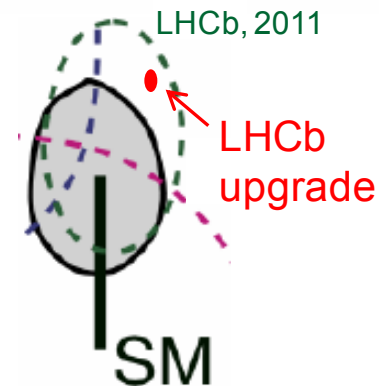
Thanks to its excellent proper-time resolution LHCb has brought clarity to the  $\phi_s$  picture:

- $B_s \rightarrow J/\psi \phi$  analysis with  $\sim 4\times$  precision of Tevatron studies [LHCb-CONF-2012-002]
- Augment this with novel analysis in complementary channel  $B_s \rightarrow J/\psi \pi\pi$  [PLB 713 (2012) 378]
- Finally, perform study looking at strong-phase change w.r.t.  $KK$  invariant mass in  $J/\psi KK$  which resolves 2-fold ambiguity [PRL 108 (2012) 241801]



No big NP effect in  $B_s$  mixing-decay interference, but essential to improve precision as  $\phi_s$  remains a priori *highly sensitive* to non-SM contributions.

Will be a key goal of the LHCb upgrade

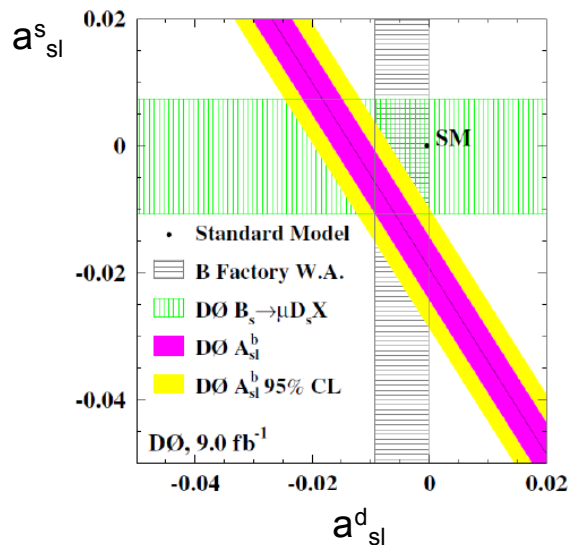
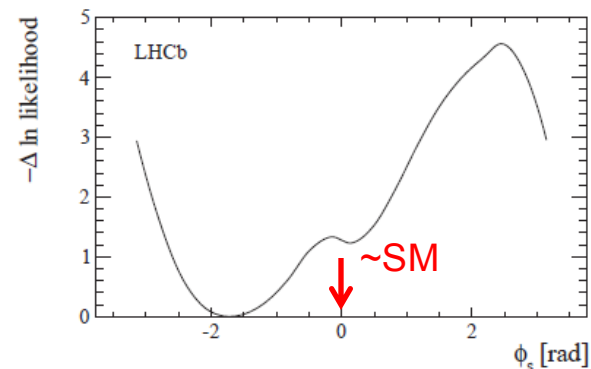
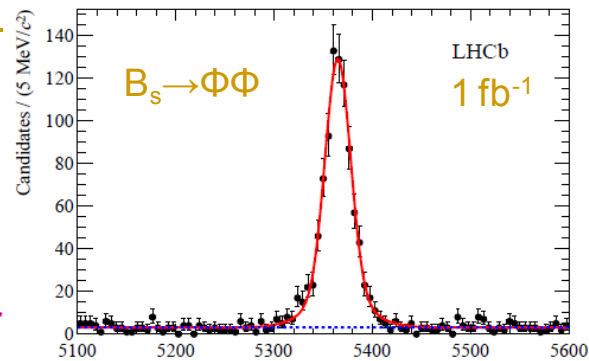


# More goals in $B_s$ CPV

Other important  $B_s$  decay modes exist in which gluonic Penguins provide an extra door for New Physics to enter

e.g.  $B_s \rightarrow \Phi\Phi$  (first time-dependent study [arXiv:1303.7127] )

Intriguingly the magnitude of central value of measured CPV phase is high (p-value with SM = 16%). Wait for 2012 update and true precision measured with upgrade



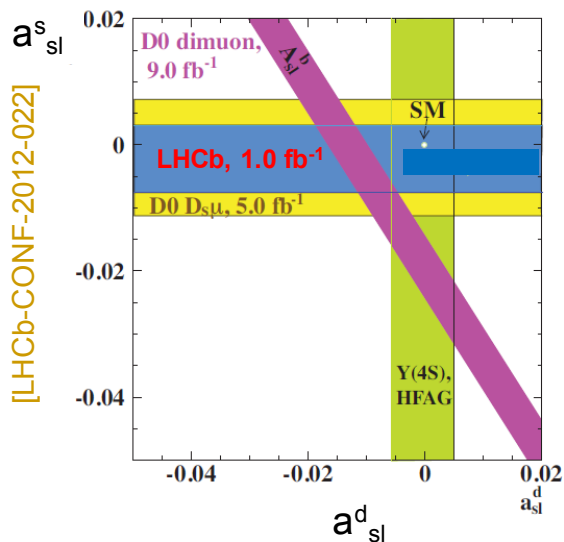
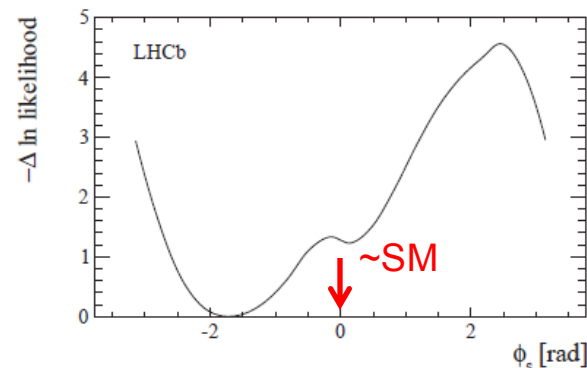
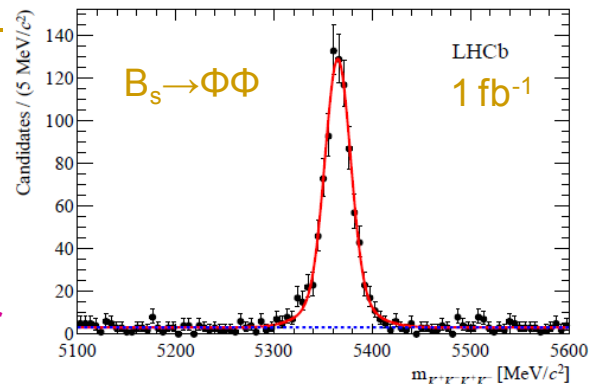
Also important is to find a resolution to the related issue (CPV in mixing) of the D0 di- $\mu$  asymmetry anomaly.

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Also important is to find a resolution to the related issue (CPV in mixing) of the D0 di- $\mu$  asymmetry anomaly.

First LHCb input appeared recently, more will come soon

# Precision CKM-metrology: the next challenge

*B*-factories (& others) have done a great job in mapping out unitarity triangle. But further progress needs improved knowledge of angle  $\gamma$  (a.k.a.  $\varphi_3$ )

Look in  $B^\pm \rightarrow DK^\pm$  decays using common mode for  $D^0$  &  $\bar{D}^0$

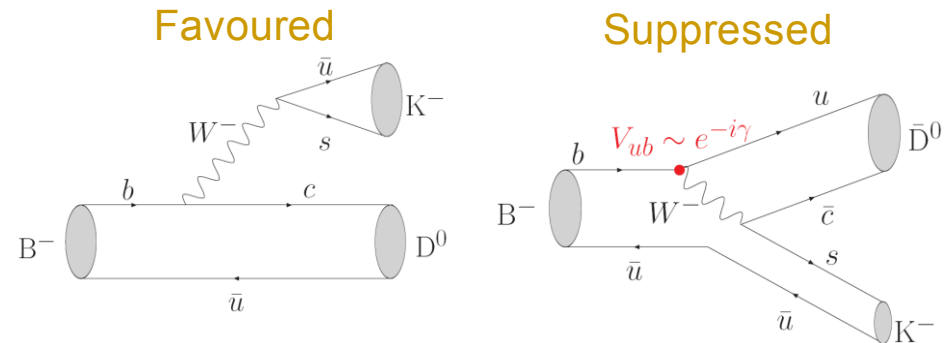
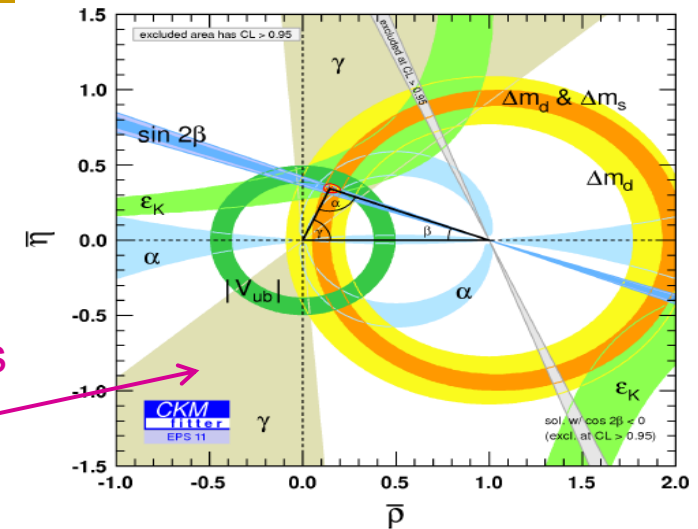
- $\gamma$  sensitive interference
- different rates for  $B^+$  &  $B^-$  (CPV!)

Many possibilities:  $K\pi$ ,  $KK$ ,  $K\pi\pi\pi$ ...

Tree-level decays: strategy very clean & yields result unpolluted by New Physics

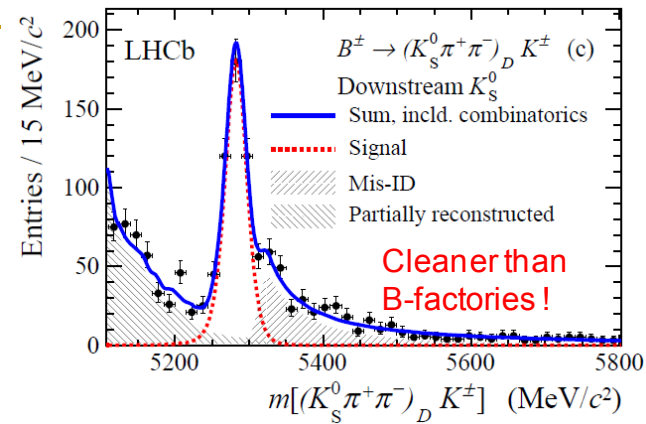
This is a good thing! Provides SM benchmark against which other loop-driven NP sensitive observables can be compared (e.g.  $\Delta m_d/\Delta m_s$ ,  $\sin 2\beta$ ,  $\gamma$  measured in  $B \rightarrow hh$ )

BaBar/Belle uncertainty  $\sim 16^\circ$  ; indirect (e.g. loops) precision  $\sim 4^\circ$  (& improving...)

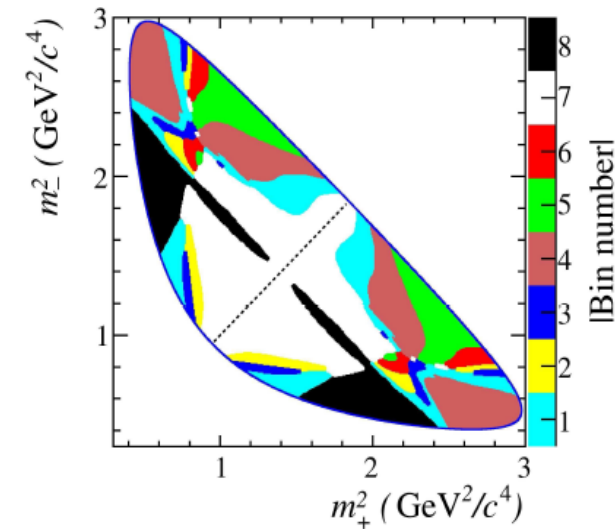
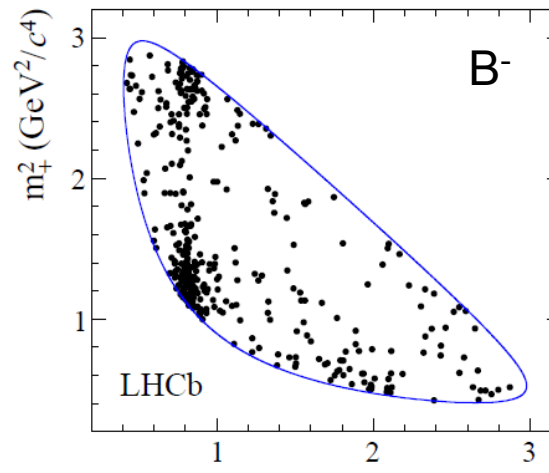
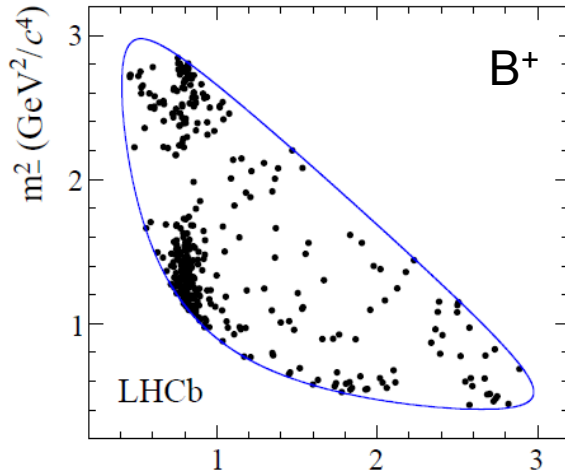


# B → DK example: multi-body decays

$B \rightarrow DK$  method can be applied to multi-body  $D$  decays such as  $D \rightarrow K_S \pi \pi$ . CPV leads to difference in  $D$  Dalitz plots for  $B^+$  and  $B^-$  decays



[LHCb, PLB 718 (2012) 43]



Data analysed in bins which have similar  $D$  decay strong-phase. To retain model independence these phases are taken from measurements of quantum-correlated  $D\bar{D}$  pairs at CLEO-c [PRD 82 (2010) 112006] - will be improved by BES-III.

Cleanliness of measurement preserved exploiting synergy of facilities !

# LHCb: current precision on $\gamma$ and future prospects

Combination of  $B \rightarrow DK$  results obtained so far with 2011 data



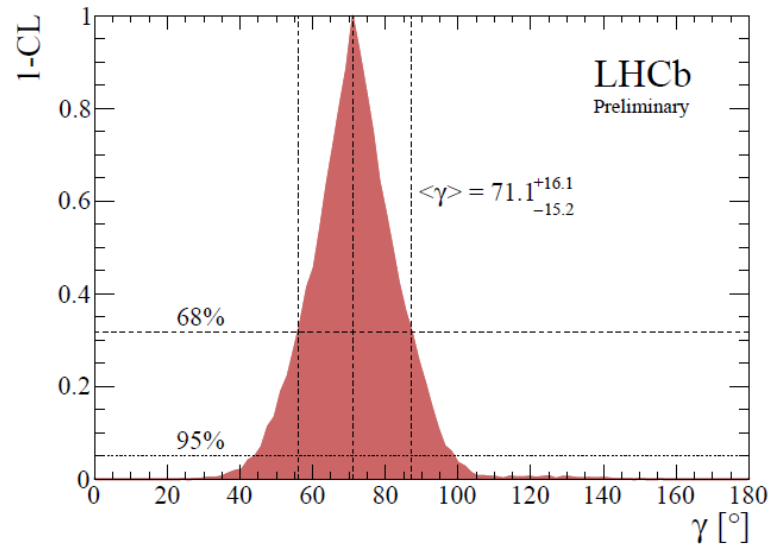
Precision of  $\sim 16^\circ$ , very similar to that obtained with full B-factory samples

Will improve steadily:

- more modes to be analysed (there are many...)
- Add 2012 and post-LS1 data (first 2012 analysis will appear next week)

Aim for  $\sim 4^\circ$  uncertainty after first stage LHCb (matches current indirect precision)

Upgrade, with improved trigger and higher lumi, will allow this to be reduced to  $\sim 1^\circ$   
→ true precision CKM-metrology !



LHCb-CONF-2012-032

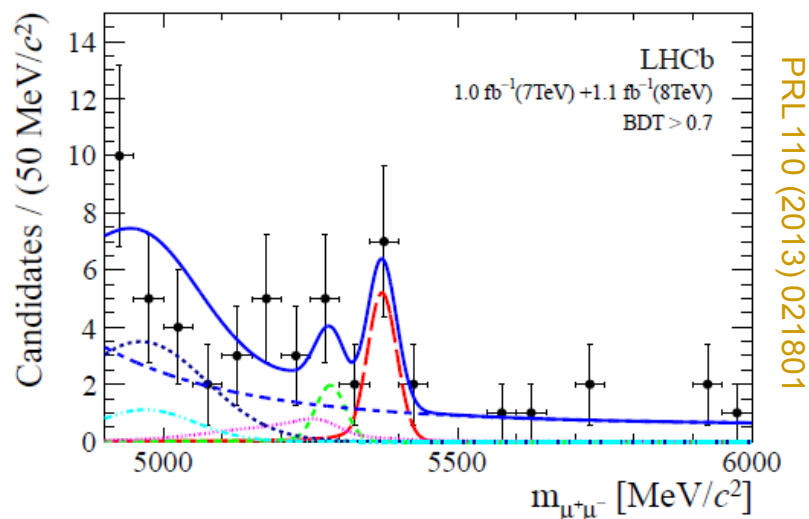
# Searching for New Physics through FCNC

Another way to probe for New Physics in the flavour sector is to study FCNC processes, especially those very rare in SM, or with rich kinematical structure

Many examples, but two seen of particular importance at start of LHC era

$$B_s \rightarrow \mu^+ \mu^-$$

Highly sensitive to NP with extended Higgs sector, especially high  $\tan\beta$  SUSY

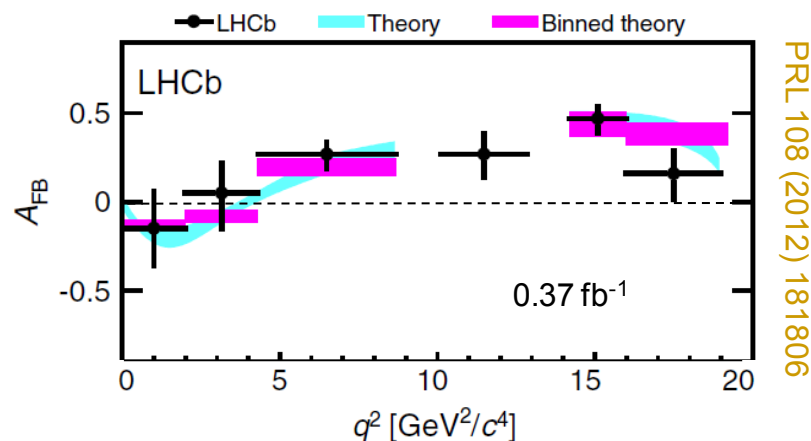


First evidence of decay, and with BR consistent with SM expectation

$$B^0 \rightarrow K^* \mu^+ \mu^-$$

Driven by electroweak Penguins, and sensitive to helicity structure of NP.

First thing to measure  $A_{\text{FB}}$  vs  $m^2(\mu\mu) (\equiv q^2)$



Asymmetry has 'textbook' behaviour !

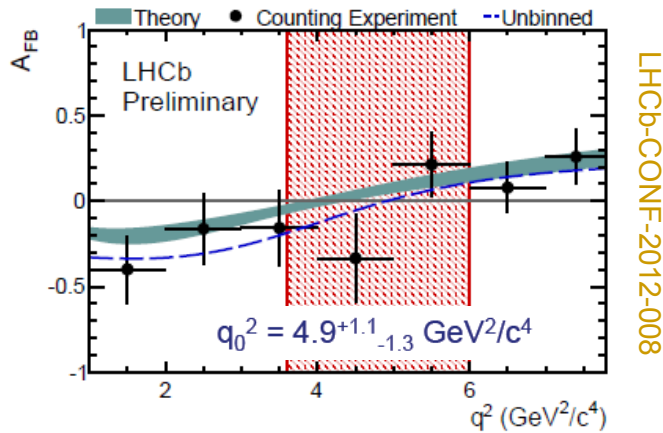
So no sign of big NP effects (the LHC story so far...), but this just the beginning

# FCNC – the tasks ahead

Bigger samples → more precise measurements & study of other observables

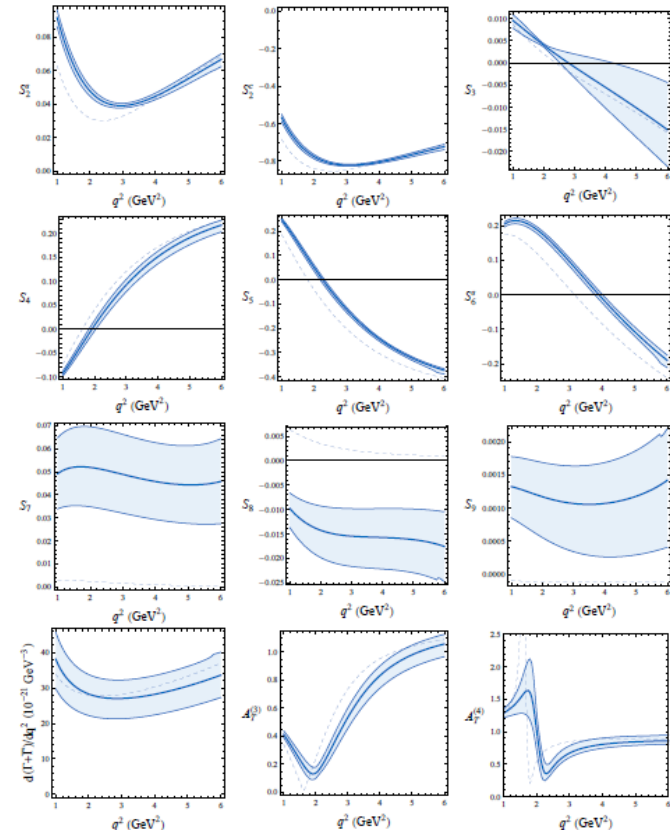
For  $B^0 \rightarrow K^* \mu^+ \mu^-$

- measure crossing point well – cleanly predicted within SM



- explore other observables, of which there are lots, many sensitive to different aspects of non-SM physics

[Altmannshofer et al., JHEP 0901 (2009) 019]

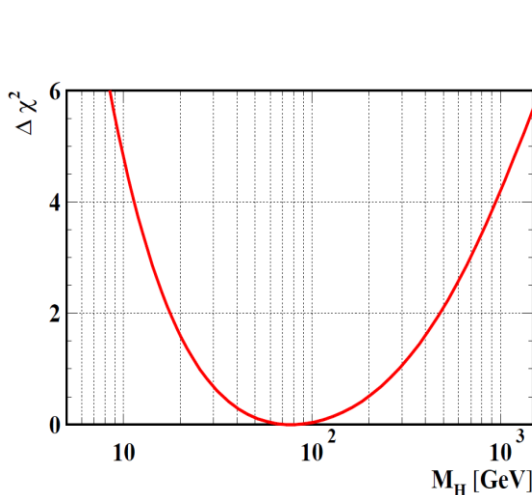


For  $B_s \rightarrow \mu^+ \mu^-$

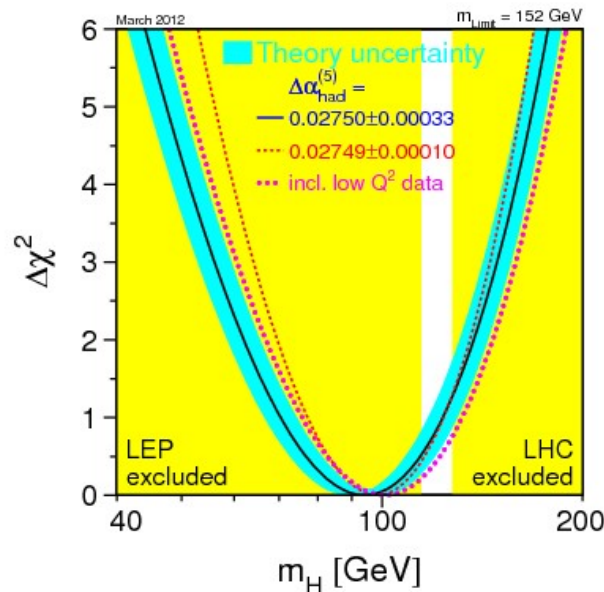
- Measure BR down to theoretical uncertainty (few  $\times 10^{-10}$ )
- Search for  $B_d^0 \rightarrow \mu^+ \mu^-$  and measure ratio w.r.t.  $B_s$  decay

# The evolving landscape of electroweak

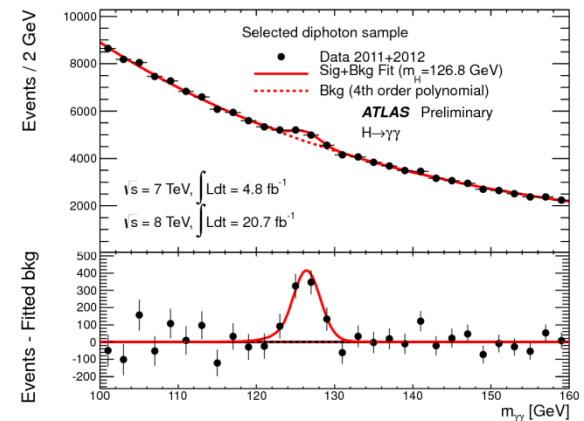
Electroweak physics took its 'great leap forward' in the 1990s (LEP1/SLD era). Last 15 years, with firstly LEP2, and then Tevatron has also seen great progress. LHC has now entered game. Discovery of 'Higgs' completes Standard Model.



1994: first attempts  
to constrain  $m_H$



Early 2012: indirect data  
insist on light Higgs

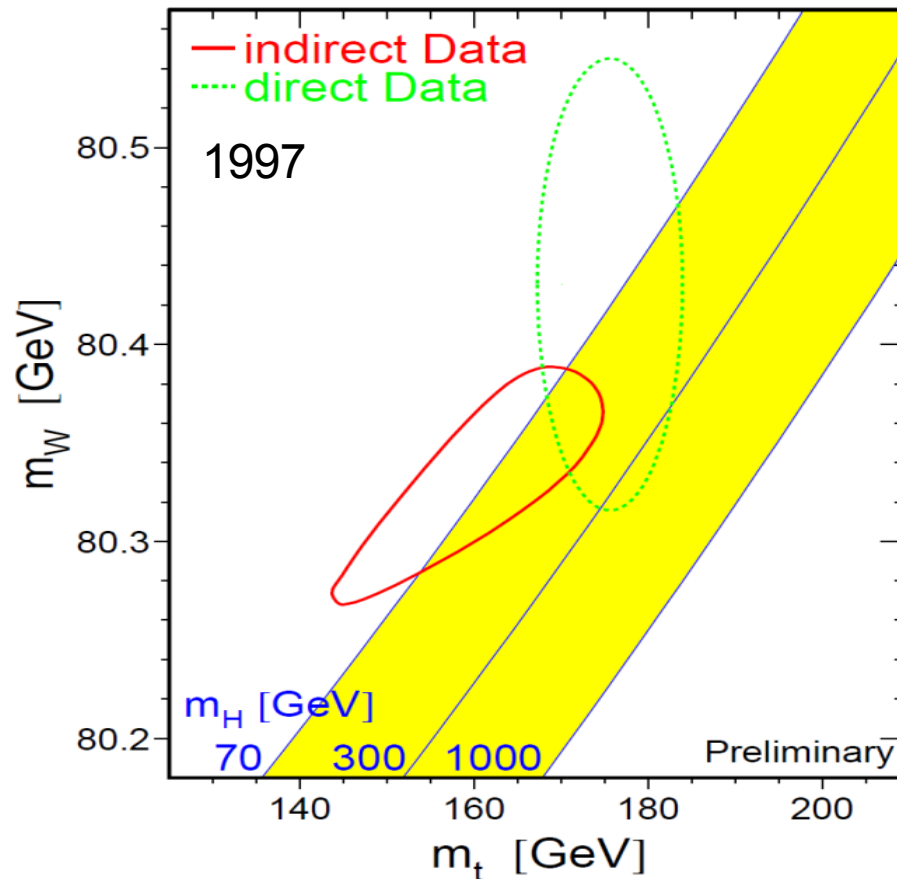


2012→: discovery, &  
first characterisation  
of properties

EW physics now must test self-consistency of SM with precision measurements

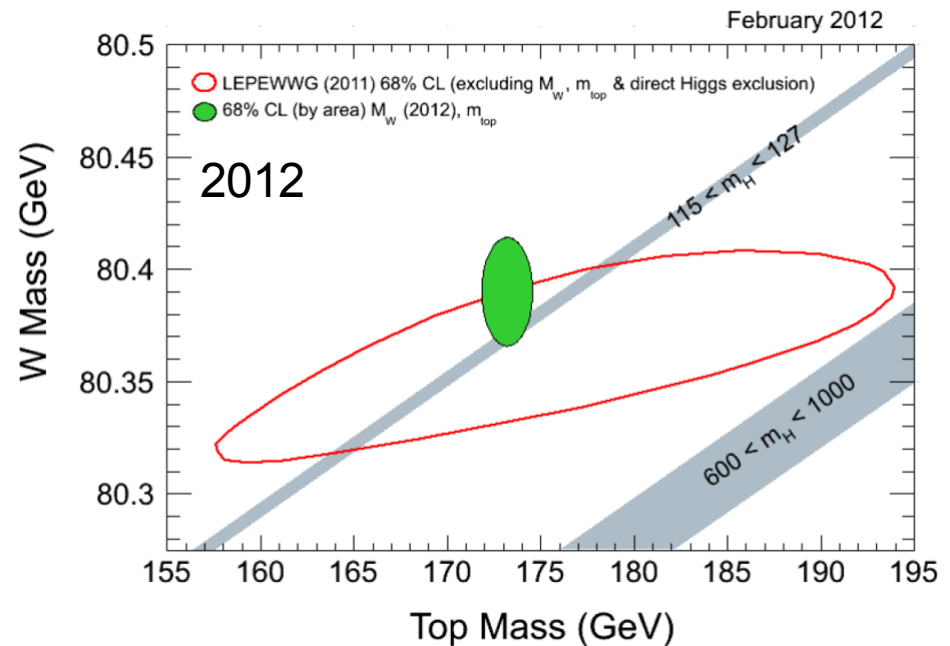
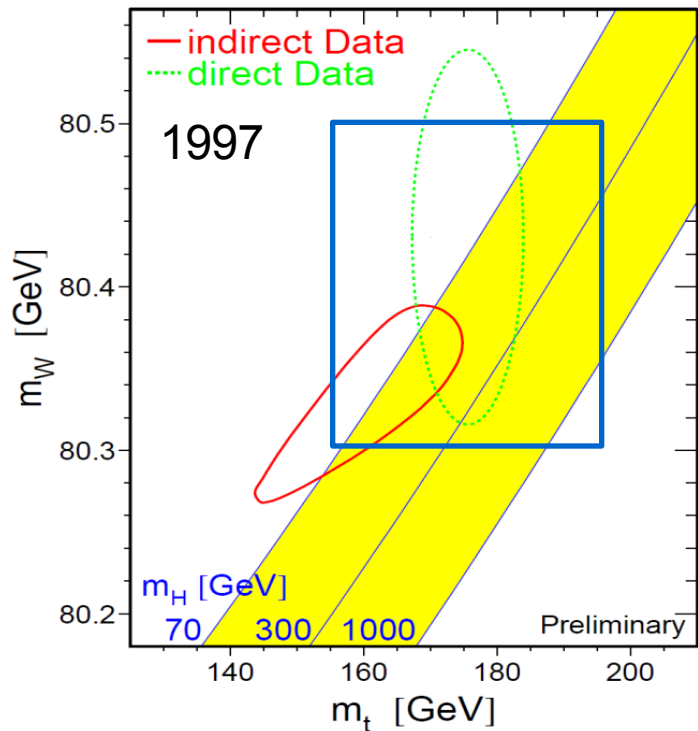
# The evolving landscape of electroweak

Self-consistency can be visualised in  $m_t$ - $m_W$  plane. Great progress in last 15 years.



# The evolving landscape of electroweak

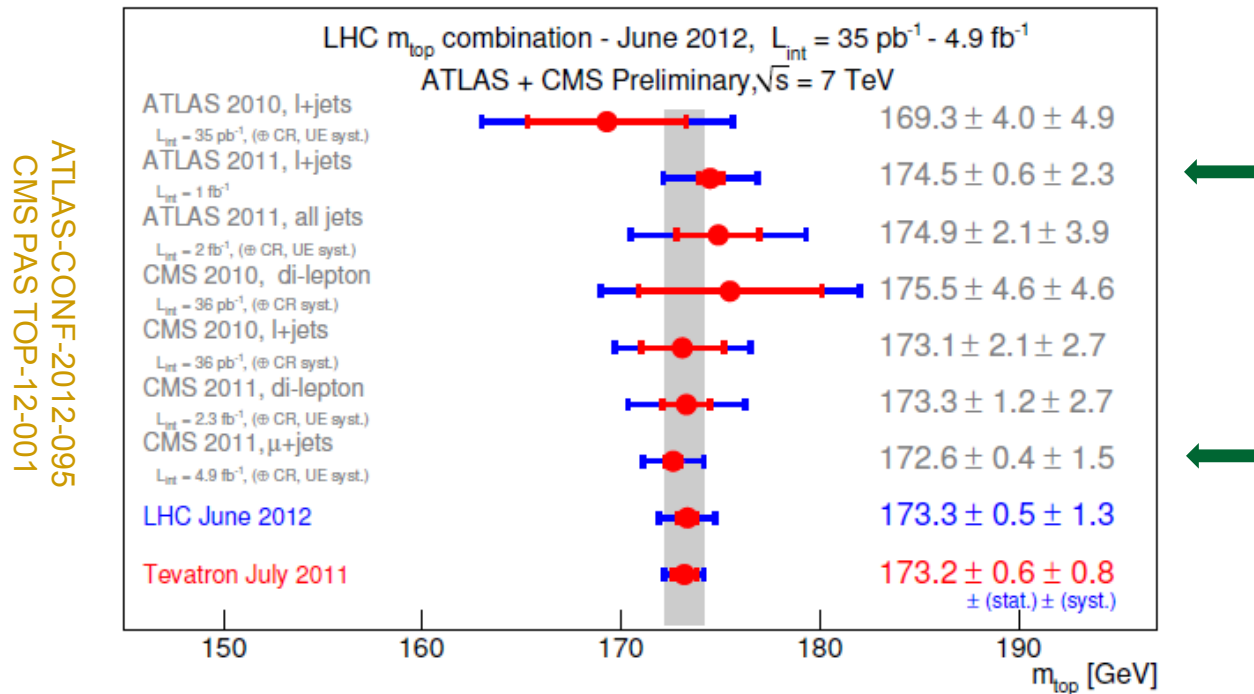
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How will our knowledge of these parameters evolve throughout LHC era ?

# $m_t$ at LHC – current status

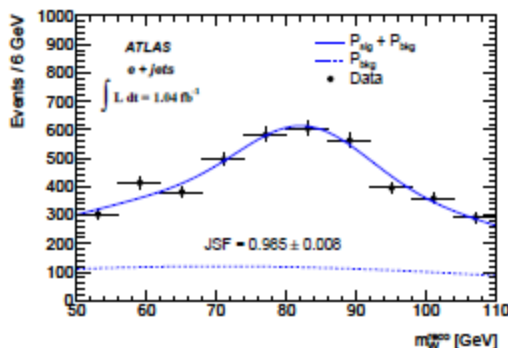
LHC has already made an impressive start to the  $m_t$  measurements campaign



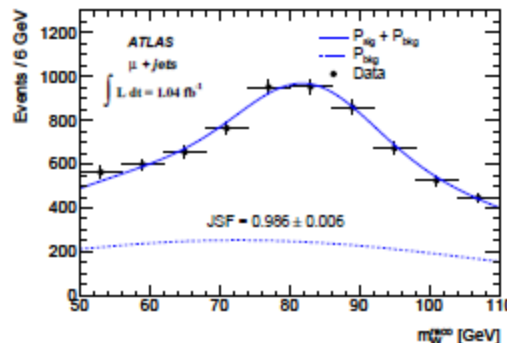
Combined precision similar to Tevatron. Average dominated by 2011 l+jets results

# 2011 lepton + jets results

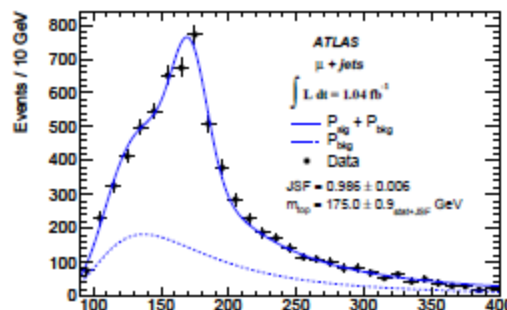
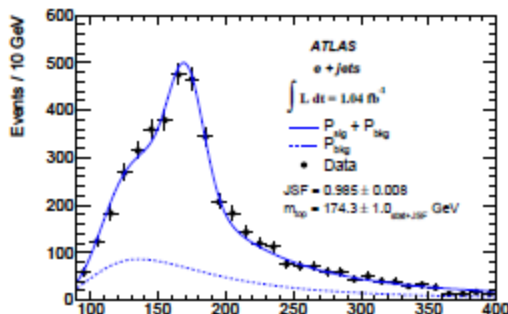
Take as an example ATLAS 1fb<sup>-1</sup> result, where final result comes from 2D fit of MC templates to Jet Energy Scale (JSF) and  $m_t$  from  $m_t^{\text{reco}}$  and  $m_W^{\text{reco}}$



e + jets



μ + jets



Measured value of $m_{\text{top}}$	174.53
Data statistics	0.61
Jet energy scale factor	0.43
Method calibration	0.07
Signal MC generator	0.33
Hadronisation	0.15
Pileup	< 0.05
Underlying event	0.59
Colour reconnection	0.55
ISR and FSR (signal only)	1.01
Proton PDF	0.10
W+jets background normalisation	0.37
W+jets background shape	0.12
QCD multijet background normalisation	0.20
QCD multijet background shape	0.27
Jet energy scale	0.66
b-jet energy scale	1.58
b-tagging efficiency and mistag rate	0.29
Jet energy resolution	0.07
Jet reconstruction efficiency	< 0.05
Missing transverse momentum	0.13
Total systematic uncertainty	2.31
Total uncertainty	2.39

Final result:  $m_{\text{top}} = 174.5 \pm 0.6_{\text{stat}} \pm 2.3_{\text{syst}} \text{ GeV}$

dominant systematics =

Similar approach pursued by CMS in JEP 12 (2012) 105

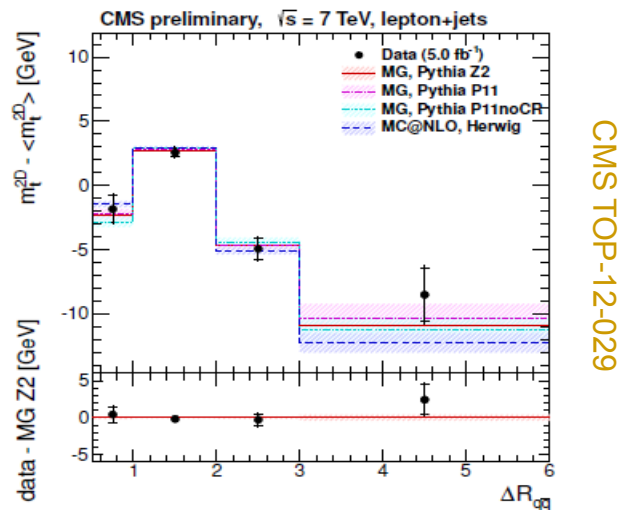
# Prospects for $m_t$

To progress requires better understanding of:

An excellent start is being made!

Studies of  $m_t$  vs kinematic variables

e.g. vs separation ( $\Delta R$ ) of light-quark jets



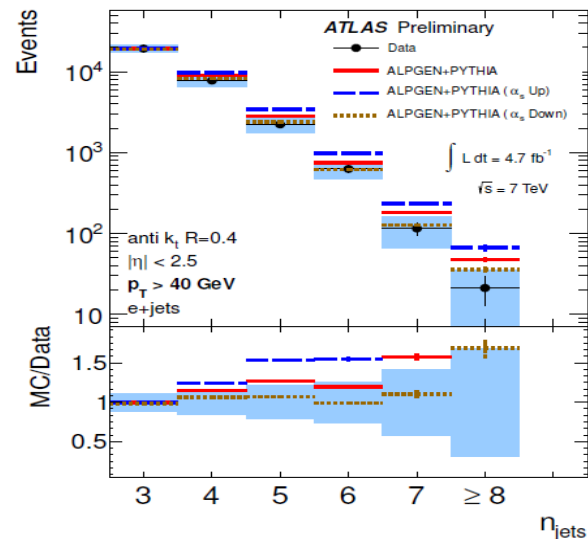
All variations well described by simulation.  
No evidence of bias from generator choice

And other methods, with very different systematics will start to enter game

- jet energy scale
- fragmentation
- ISR and FSR
- measured mass vs pole mass, colour reconnection etc

Studies of QCD radiation in  $t\bar{t}$  events

e.g.  $n_{\text{jets}}$  in  $t\bar{t}$  lepton + jets events



Some tunes unable to describe data

- lepton end-point
- $b$ -flight distance
- $m_t$  from cross-section

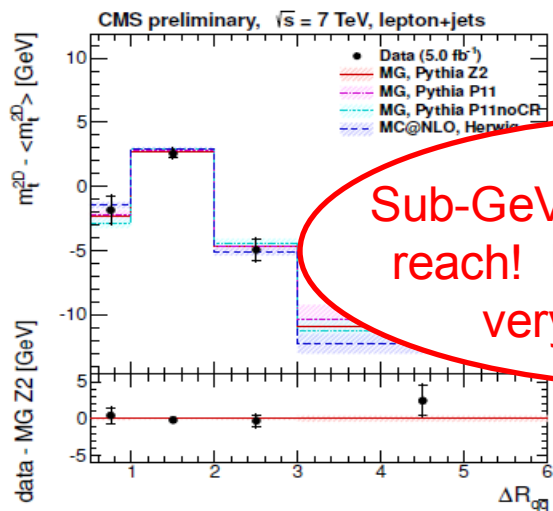
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Sub-GeV precision soon within reach! Ultimate sensitivity – very difficult to say...

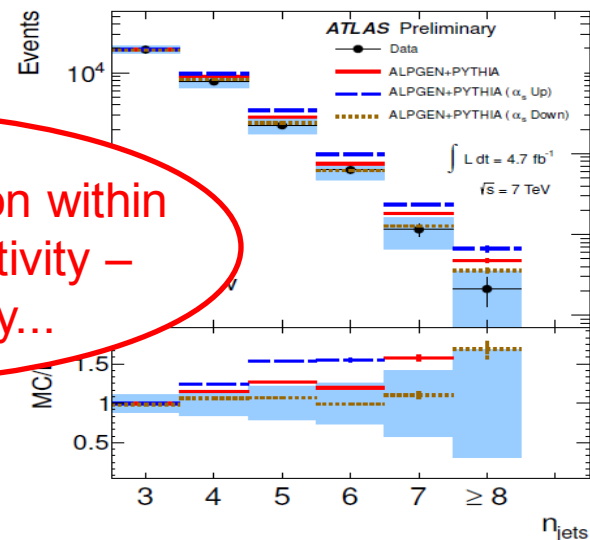
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ATL-PHYS-PUB-2013-005

# $m_W$ – state of play

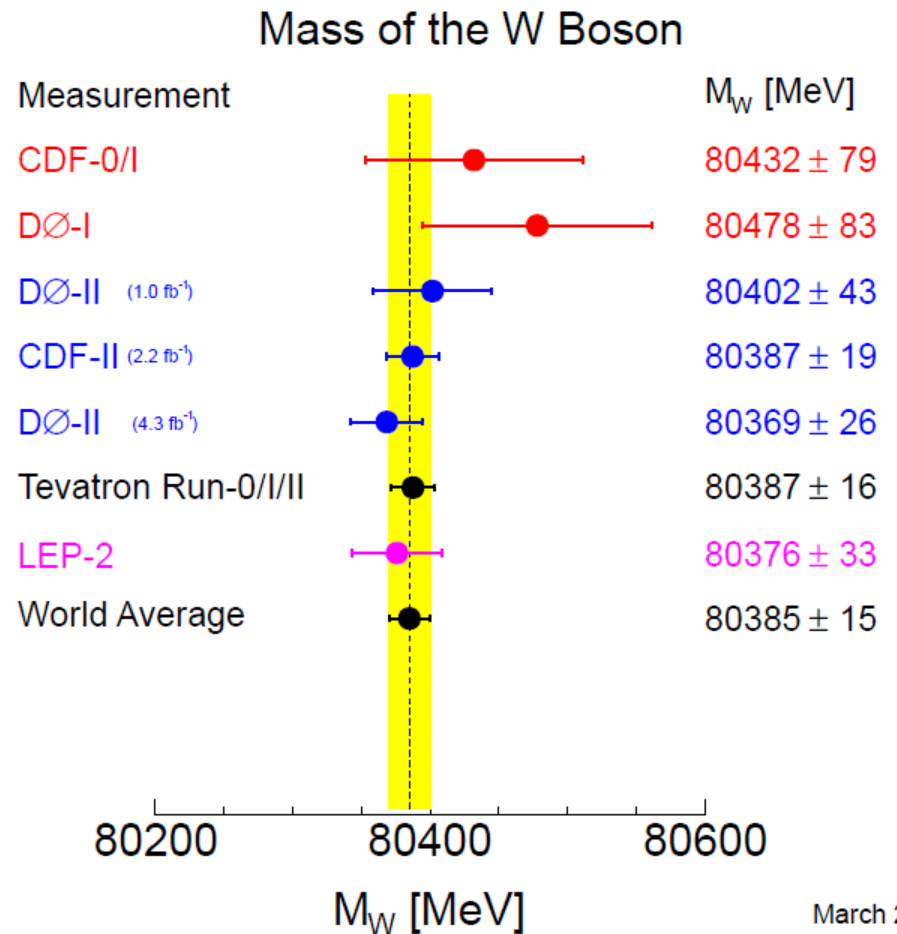
World average dominated  
by Tevatron Run-II results

Good consistency between  
LEP and Tevatron – very  
pleasing given very different  
measurement strategies

$m_W$  measurements take time:

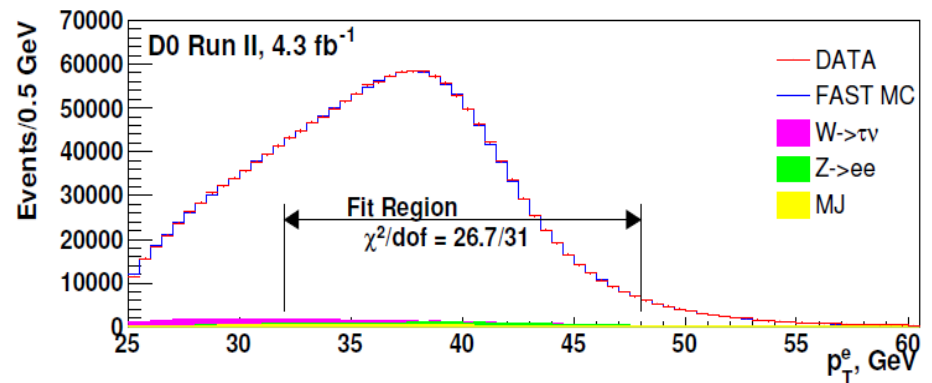
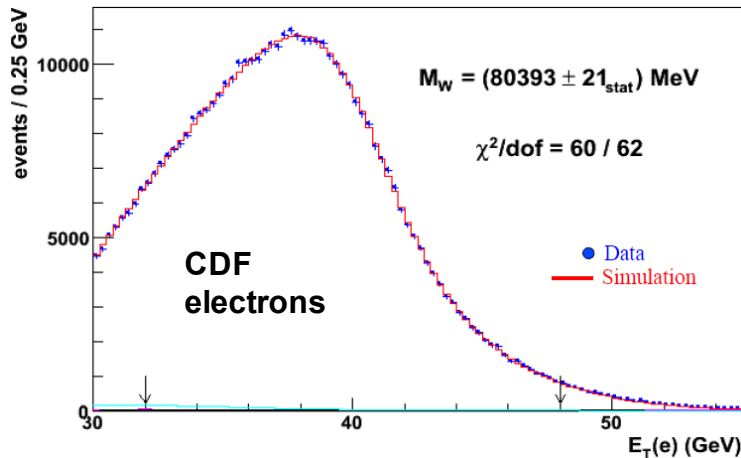
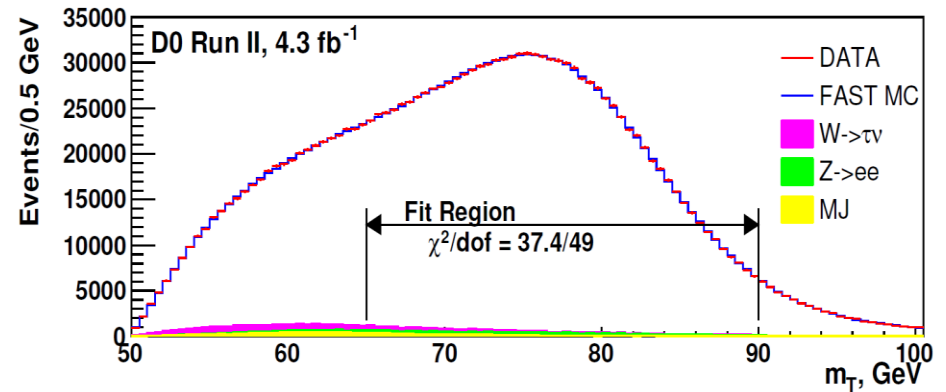
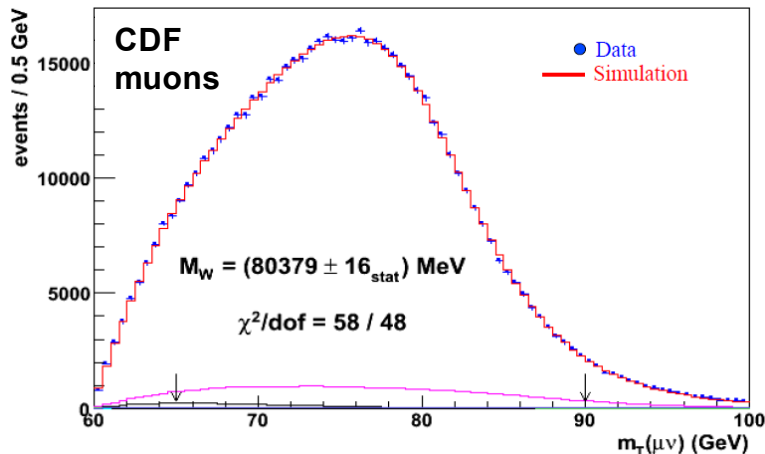
- LEP final results came  
6 years after data-taking
- Recent Tevatron results  
came last year, and they  
still have plenty of data  
left to analyse

LHC still to enter game, but plans  
underway [ATLAS-2008-070, CMS, J Phys G34 (2007) 995]  
Goal is to reach error of 5-10 MeV.



March 2012

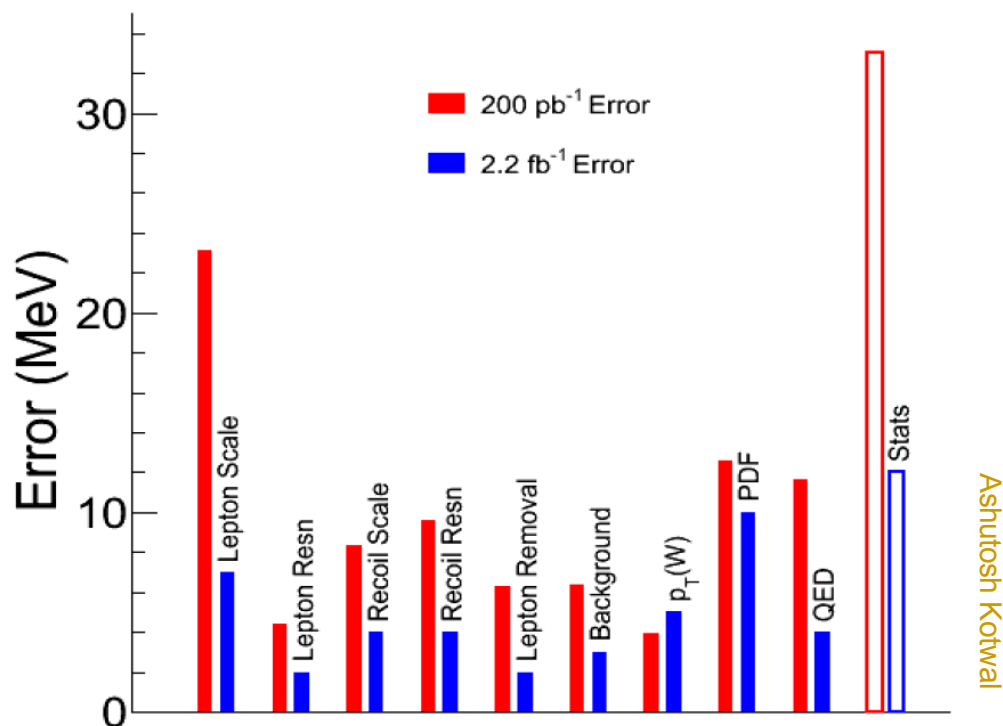
# Tevatron experience



Measurement requires excellent understanding of momentum, energy & hadronic recoil scale.  $Z^0$  decays provide invaluable control. PDF knowledge also essential.

# Improved understanding

Evolution of error budget between recent CDF measurement and earlier result

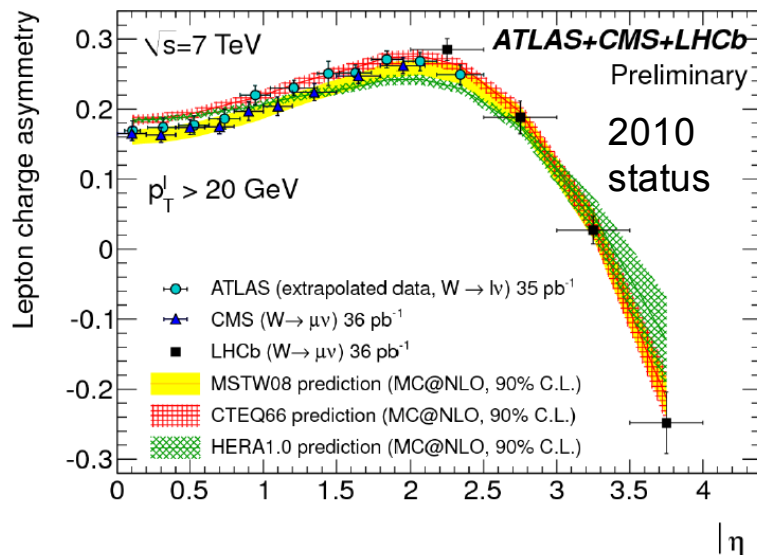


Hard work reaps rewards! PDF error now dominant. Improved understanding of this component key to further progress, both at Tevatron and the LHC.

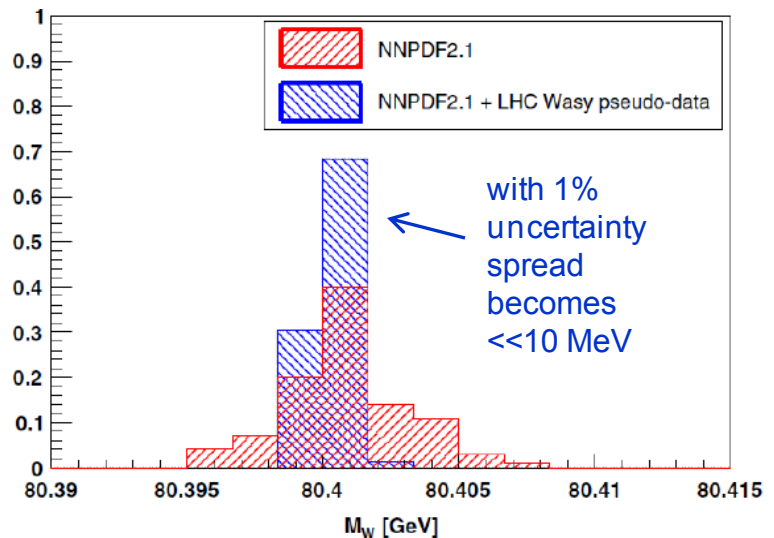
# Impact of improved PDF knowledge on $m_W$

Measurements at LHC, including W lepton charge asymmetry, Drell-Yan and Z production etc, already is allowing PDF knowledge to be improved.

e.g. toy experiments assuming 1% uncertainty on W lepton charge asymmetry



with 10x  
better  
precision



Bozzi et al., PRD 83 (2011) 113008

All this looks encouraging! But other commentators [Krasny, Dydak et al., arXiv:1004.2597] are more cautious, emphasising difficulties at LHC coming from  $pp$  initial state.

Await first results to learn more. Whatever, LHC results will help Tevatron progress.

# Summary

Precision measurements in heavy flavour physics and electroweak (and, of course, Higgs' properties – not covered here) are a vital part of LHC programme

- Very successful start in  $b$ - and  $c$ -physics  
LHCb now world-leader in most key measurements.  
No clear signs of non-SM behaviour yet seen, but the journey is barely begun, and a big step in precision is expected at LHCb-upgrade.
- Many measurements have already been made at LHC in EW sector (not discussed here), but work just beginning on  $m_t$ ,  $m_W$  (and  $\sin^2\theta_w^{\text{eff}}$ ). It will be a long road, and excellent control will be required (especially of PDFs), but prospects are good, certainly for  $m_t$  and  $m_W$ .

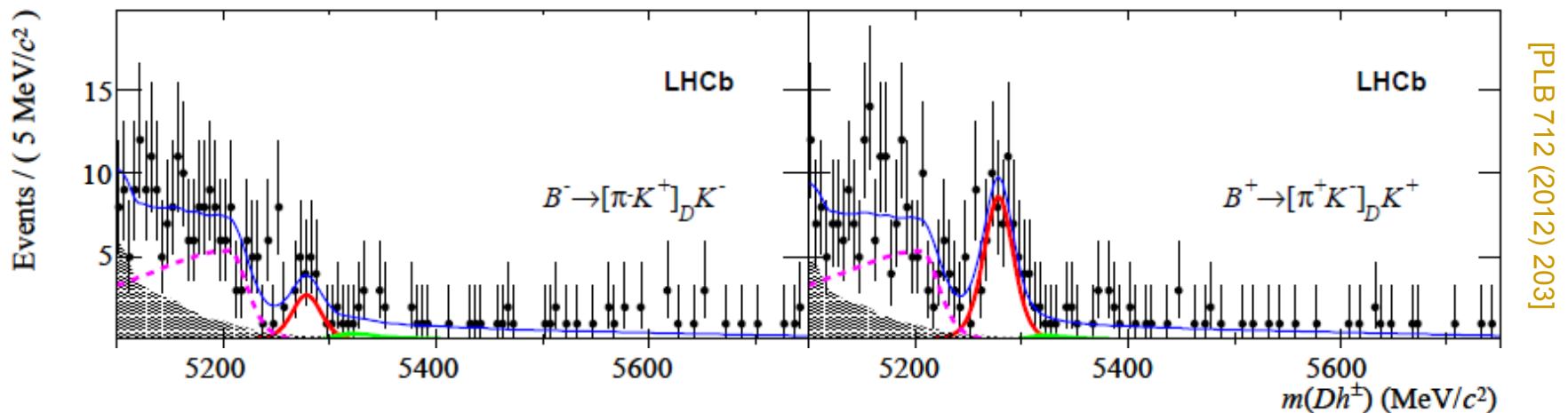
Lots to do, but these studies are mandatory for probing very high mass scales

# Backups

# CKM metrology at LHCb: playing the long game

Precise CKM metrology at LHCb, most importantly measurement of  $\gamma$ , but also improved  $\beta$  precision, will be in the long-term a critical factor in the search for NP

Important first step – first observation of the suppressed ‘ADS’ mode  $B^\pm \rightarrow (K^\mp \pi^\pm) K^\pm$   
Highly suppressed (visible BR  $\sim 10^{-7}$ ) & not seen at  $5\sigma$  with full B-factory dataset



LHCb sees mode with  $\sim 10\sigma$  stat significance. As expected, it has a very large CP asymmetry  $-0.52 \pm 0.15 \pm 0.02$  which provides critical input to LHCb  $\gamma$  measurement.

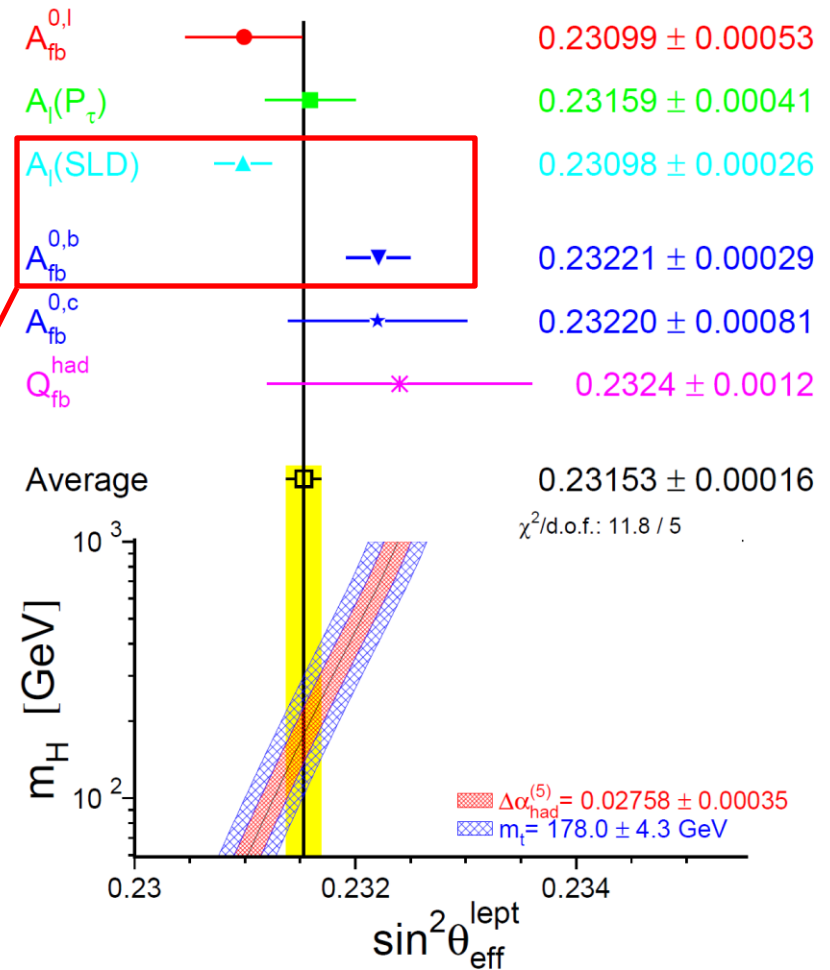
Recently joined by corresponding first observation in  $K\pi\pi\pi$  mode [arXiv:1303.4646]

# Effective weak mixing angle $\sin^2\theta_W^{\text{eff}}$

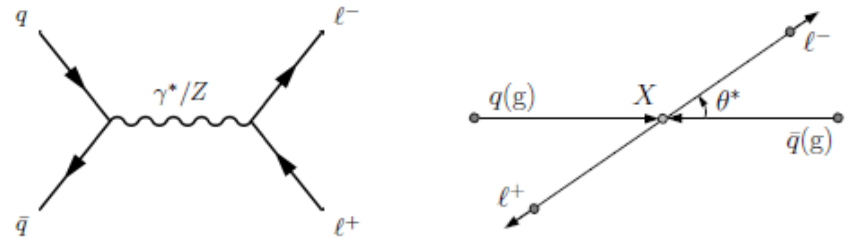
$\sin^2\theta_W^{\text{eff}}$  is a very important parameter in EW studies – a precise measurement tests self-consistency of theory

Asymmetries measured at LEP and SLD achieved precision of  $1.6 \times 10^{-4}$ , but with some intriguing internal tension between  $A_{\text{FB}}^b$  and SLD L-R asymmetry

Can LHC clarify situation and improve precision on knowledge of this parameter?



# Forward-backward $l^+l^-$ asymmetries at LHC



Dominant Drell-Yan process:

$$u\bar{u}, d\bar{d} \rightarrow \gamma^*/Z \rightarrow l^+l^-$$

Measure  $A_{FB}$ , defined w.r.t. di-lepton boost which is (usually) the direction of quark

Above (& below) Z pole: sensitivity to possible  $Z'$  contributing to Z/ $\gamma$  interference. 

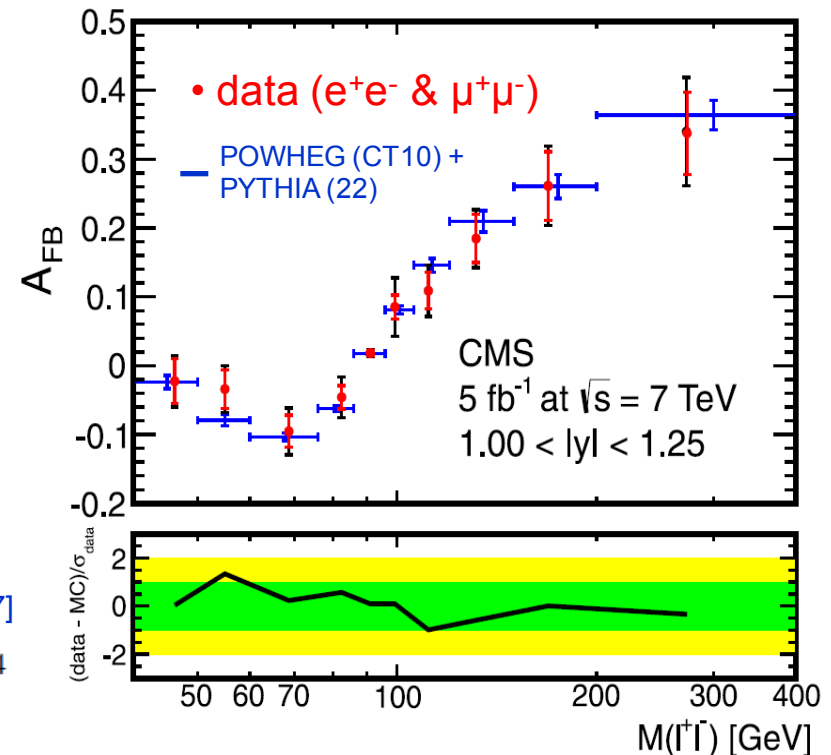
CMS 1.1 fb<sup>-1</sup>  $\mu^+\mu^-$  study [PRD 84 (2011) 112002] :

$$\sin^2 \theta_{eff} = 0.2287 \pm 0.0020 \text{ (stat.)} \pm 0.0025 \text{ (syst.)}.$$

ATLAS 100 fb<sup>-1</sup> projection [ATL-PHYS-PUB-2009-037]

$$\delta \sin^2 \theta_{eff}^{lept} = (1.5(\text{stat}) \pm 0.3(\text{exp}) \pm 2.4(\text{PDF})) \times 10^{-4}$$

Difficulty in interpreting asymmetry at LHC lies comes from dilution associated with knowledge of quark direction. Dilution  $\sim 1/\text{pseudorapidity}$ . Possibility for LHCb to contribute in its upgrade era?



CMS, PLB 718 (2013) 752

# Upgrade expectations

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb <sup>-1</sup> )	Theory uncertainty
$B_s^0$ mixing	$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$	0.10 [30]	0.025	0.008	$\sim 0.003$
	$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$	0.17 [32]	0.045	0.014	$\sim 0.01$
	$a_{sl}^s$	$6.4 \times 10^{-3}$ [63]	$0.6 \times 10^{-3}$	$0.2 \times 10^{-3}$	$0.03 \times 10^{-3}$
Gluonic penguins	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$	–	0.13	0.02	$< 0.02$
	$2\beta_s^{\text{eff}} (B^0 \rightarrow \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)$	–	0.09	0.02	$< 0.01$
	$\tau^{\text{eff}} (B_s^0 \rightarrow \phi \gamma) / \tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3 (B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0 A_{\text{FB}} (B^0 \rightarrow K^{*0} \mu^+ \mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_1 (K \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.25 [9]	0.08	0.025	$\sim 0.02$
	$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$	25 % [29]	8 %	2.5 %	$\sim 10 \%$
Higgs penguins	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$1.5 \times 10^{-9}$ [4]	$0.5 \times 10^{-9}$	$0.15 \times 10^{-9}$	$0.3 \times 10^{-9}$
	$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) / \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	–	$\sim 100 \%$	$\sim 35 \%$	$\sim 5 \%$
Unitarity triangle angles	$\gamma (B \rightarrow D^{(*)} K^{(*)})$	$\sim 10\text{--}12^\circ$ [40, 41]	$4^\circ$	$0.9^\circ$	negligible
	$\gamma (B_s^0 \rightarrow D_s K)$	–	$11^\circ$	$2.0^\circ$	negligible
	$\beta (B^0 \rightarrow J/\psi K_S^0)$	$0.8^\circ$ [63]	$0.6^\circ$	$0.2^\circ$	negligible
Charm	$A_{\text{F}}$	$2.3 \times 10^{-3}$ [63]	$0.40 \times 10^{-3}$	$0.07 \times 10^{-3}$	–
$CP$ violation	$\Delta A_{CP}$	$2.1 \times 10^{-3}$ [8]	$0.65 \times 10^{-3}$	$0.12 \times 10^{-3}$	–

# Pulls of global EW fit

