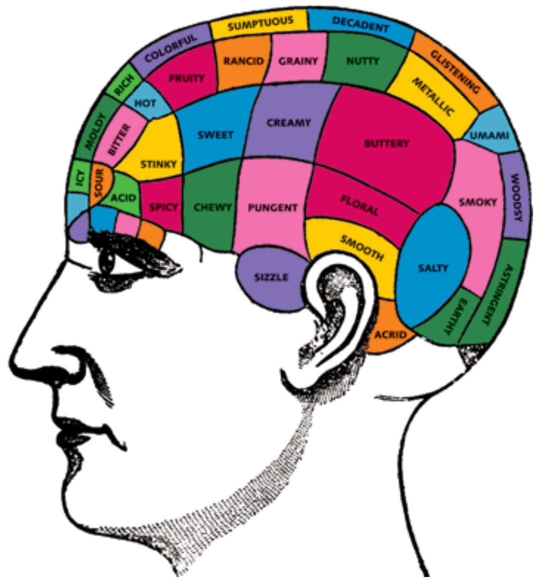

The Flavour of Higgs — EXPERIMENTAL INTRODUCTION

ANDREAS HOECKER, CERN

WEIZMANN, 23 JUNE 2014

Flavour in the SM — Charged lepton and quark flavour — Top flavour — Higgs flavour — Higgs FV — Outlook

Flavour in the SM

Flavour and *CP* violation in the Standard Model

$SU(3) \times SU(2) \times U(1)_Y$

Flavour physics fundamentally related to the Higgs mechanism, but what are implications of the Higgs boson discovery to flavour physics?

Field content and gauge charges:

$$-L_{\text{Yukawa}} = y_i^d \left(\bar{Q}_L' V_{\text{CKM}}^\dagger\right)_i \phi d_{Ri} + y_i^u \bar{Q}_{Li}' \tilde{\phi}^c u_{Ri} + y_i^\ell \bar{L}_i \phi \ell_{Ri} + \text{h.c.}$$

+ possible D=5 terms related to neutrino masses

Three terms in renormalisable part of Largrangian: freedom in field definition used to move flavour changing currents from Higgs to gauge bosons after EW symmetry breaking

- Only charged flavour-changing current
- Only physical degree of freedom: neutral Higgs boson, no FCNC associated with it
- Seems there is little direct impact of Higgs discovery (known mass) on flavour physics

Flavour and *CP* violation in the Standard Model

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Flavour physics and *CP* violation naturally embedded into predictive SM

- What is the origin of the observed flavour hierarchies?
- Did we see everything? If not, why not?

Flavour and *CP* violation in the Standard Model

The gauge hierarchy flavour problem

SM expected to be valid only below some scale Λ

$$L_{SM} = L_{\dim 4} - \frac{\Lambda^2}{2}\phi^\dagger\phi + \sum_i \frac{1}{\Lambda^2}\left(\bar{q}q\bar{q}q\right)_i + \ldots$$

- Scalar mass term is only dimensionful parameter in renormalisable part of L_{SM}
- This sets the EW scale
- Scalar mass term receives large quantum corrections if there is another scale Λ
- Electroweak physics requires $\Lambda \le M_W / g \approx$ few hundred GeV
- But flavour physics restricts the scale of dimension-6 $\Delta F = 2$ operators to

$$\Lambda > 10^{4-5}\ \text{TeV}\ (\bar{s}d)(\bar{s}d) \qquad \Lambda > 10^{3,2}\ \text{TeV}\ (\bar{b}d,s)(\bar{b}d,s)$$

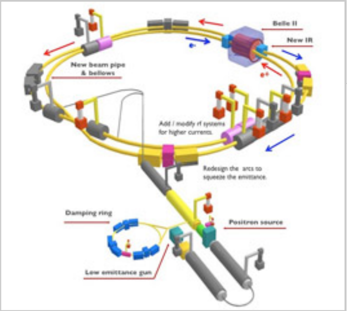
[eg: Isidori-Nir-Perez, 1002.0900]

unless it is special (weak coupling, loop suppression, CKM-like suppressions)
Generic scale far beyond reach of LHC!

Difficult to construct natural models, *if* naturalness is a good concept

Flavour and *CP* violation in the Standard Model

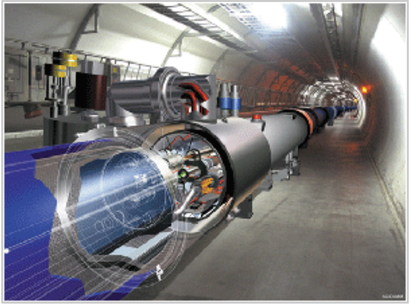
Experimental probes



A) The usual suspects

- Kaon and *B*-meson precision measurements at e^+e^- factories
- Rare decay and *CP* violation studies
- Measurements at hadron colliders (most notably LHCb, but also ATLAS, CMS, CDF, D0) cover B_s physics, loop ("penguin") phenomena, precise γ measurements, charm physics

B) New channels in LHC era

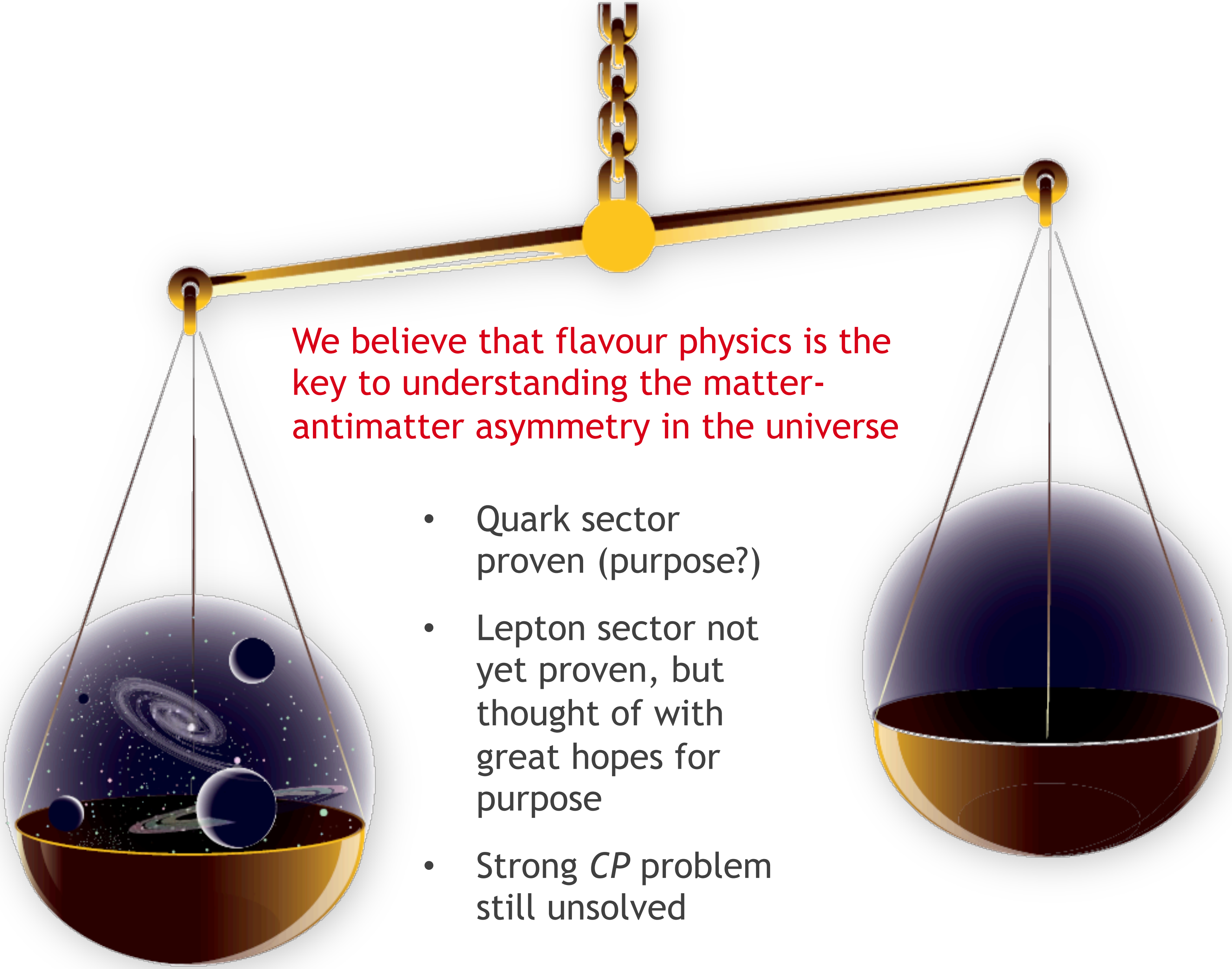


- Top flavour (ATLAS, CMS, Tevatron)
- Higgs flavour measurements (mainly ATLAS, CMS)
- Search for direct production of new fermions (ATLAS, CMS)

Relation between *direct* and *indirect* searches via BSM physics only
Specific models needed

Some experimental highlights of **quark** flavour physics

“Classical” flavour physics



We believe that flavour physics is the key to understanding the matter-antimatter asymmetry in the universe

- Quark sector proven (purpose?)
- Lepton sector not yet proven, but thought of with great hopes for purpose
- Strong *CP* problem still unsolved

Flavour Physics

SM consists of up to 24 elementary matter particles and 3 forces with **total of 26 parameters**

Fermions

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$ *6 Leptons* ℓ

6 Quarks q $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$

Bosons

Photon γ *Electro-magnetic force*

3 weak bosons $W^\pm$ Z^0 *Weak force*

8 Gluons $8 \times g$ *Strong force*

Higgs boson H^0 *Higgs field breaks electroweak symmetry and generates boson and fermion masses*

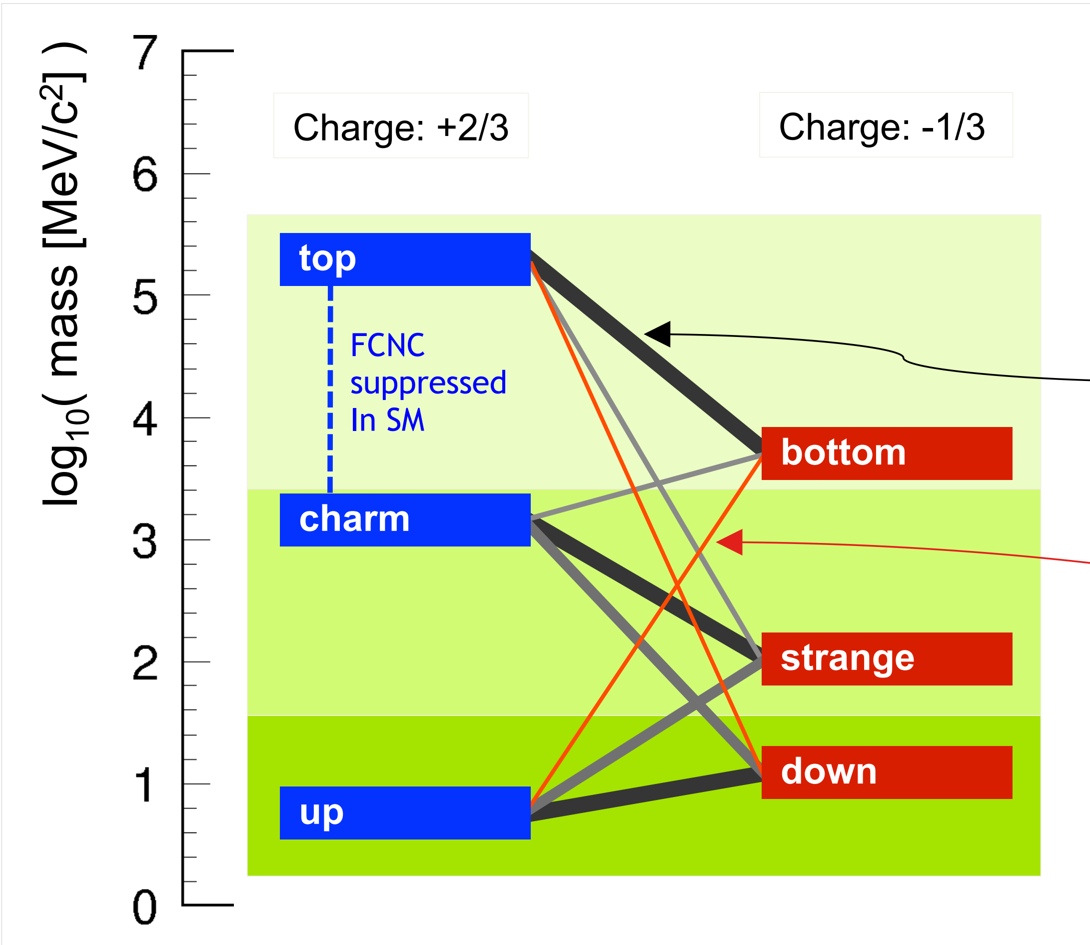
- 3 gauge couplings
- 2 Higgs sector parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 6 lepton masses
- 3 lepton mixing angles + 1 phase (+ 2 Majorana phases?)

22 of the 26 parameters related to flavour – some may appear tuned…

Quark Flavour Physics

Came a long way since the discovery of strange particles by Rochester, Butler in 1946/47

Unitary 3-generation quark mixing matrix – small CPV, top has ~unity Yukawa coupling



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \circ \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Flavour-changing transition by charged weak current

(boldness indicates transition probability $\propto |V_{ij}|$)

Smallest couplings are complex → ***CP* violation**

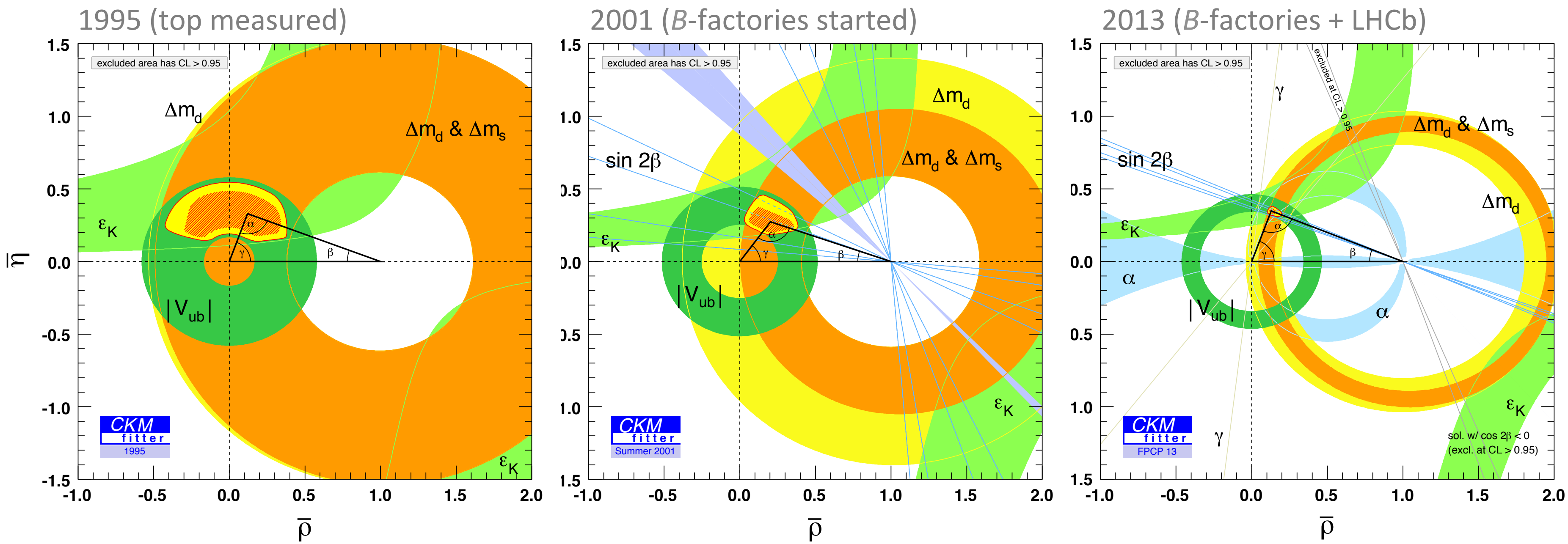
(phase $\delta \sim 70$ degrees; accident as not responsible for baryogenesis?)

Quark Flavour Physics

Came a long way since the discovery of strange particles by Rochester, Butler in 1946/47

[ckmfitter.in2p3.fr]

Quark mixing matrix consistent with **three-generation unitarity**



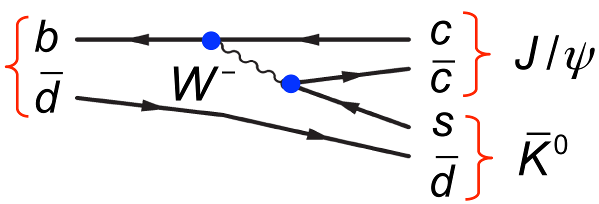
- Several anomalies appeared and disappeared or became implausible
  (eg, CPV in "penguin" decays, $B \to \tau\nu$, di-muon asymmetry A^s_{SL}, $|V_{ub}|$ discrepancy?)
- Precision constraints led to Minimal Flavour Violation (MFV) paradigm for new physics
- Many more measurements available in quark-flavour sector…

Quark Flavour Physics

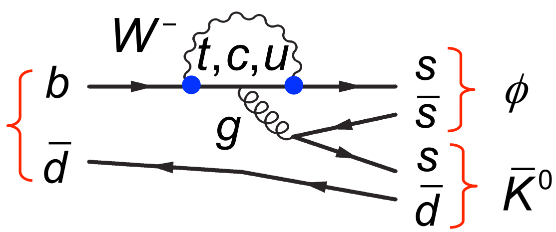
Some hope to find hints for new physics in “Penguin modes”

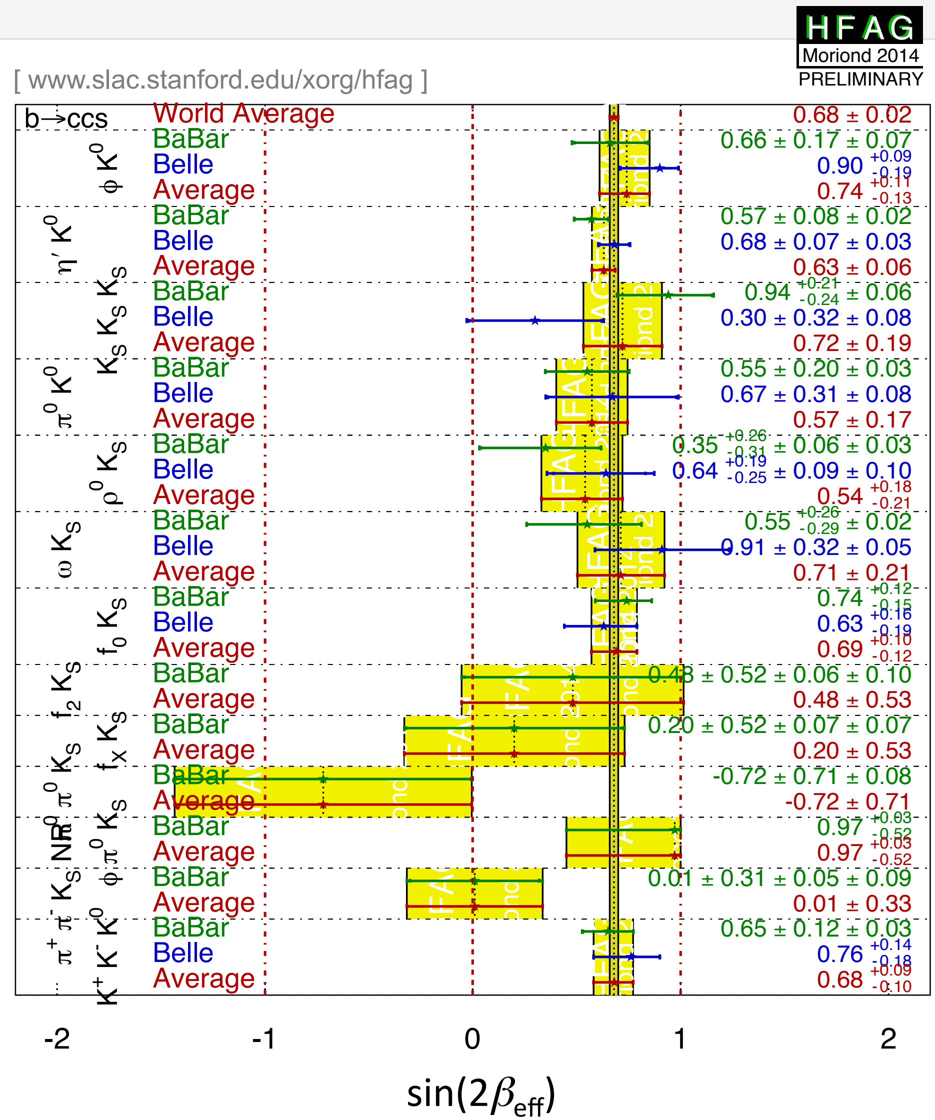
Sensitive to same (or similar) CKM angle as $B^0 \rightarrow J/\psi\, K_s$

Tree transition:



“Penguin” transition:

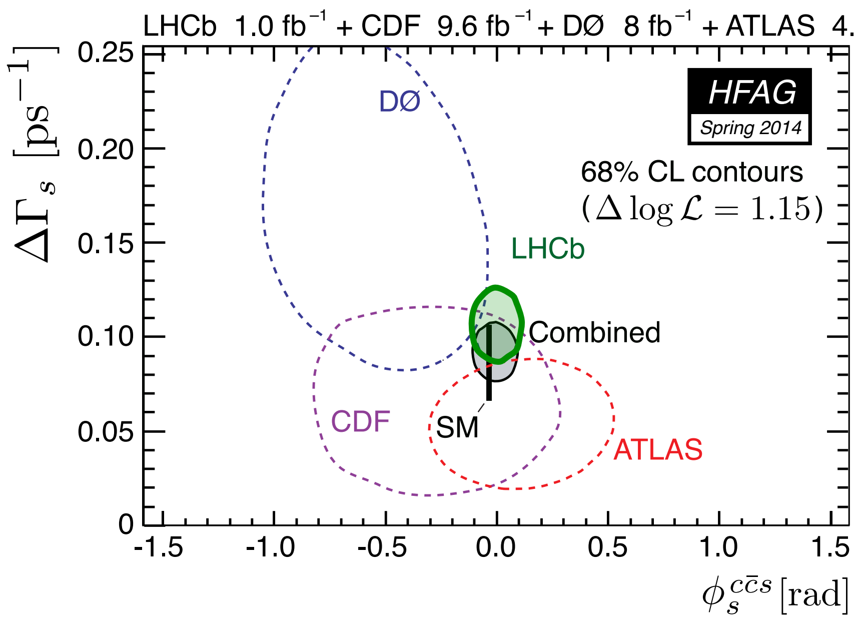


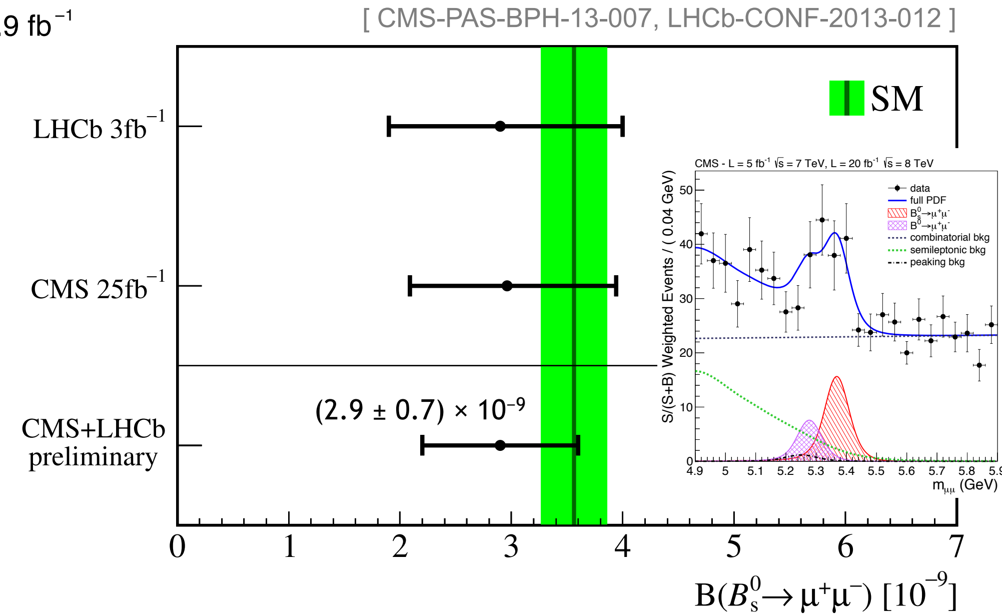


Quark Flavour Physics

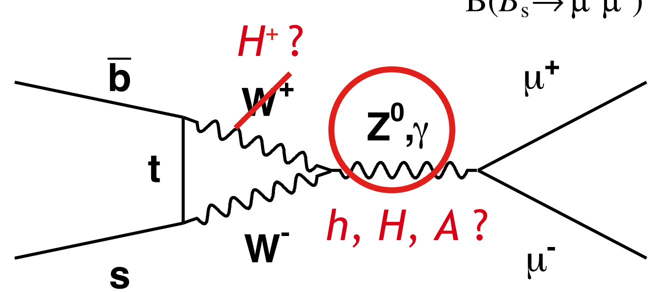
LHC enters the game: B_s physics — *CP* violation and rare decays

The most expected flavour measurements at LHC: phase ϕ_s and $B_s \to \mu\mu$





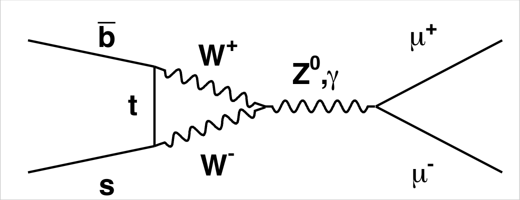
- $\phi_s = -2\beta_s = 0.00 \pm 0.07$ [HFAG, SM: -0.036 ± 0.002]
- BTW: LHCb also measured $\sin(2\beta_{\psi Ks})$: $0.73 \pm 0.07 \pm 0.04$ [*B*-factories WA: 0.665 ± 0.024]

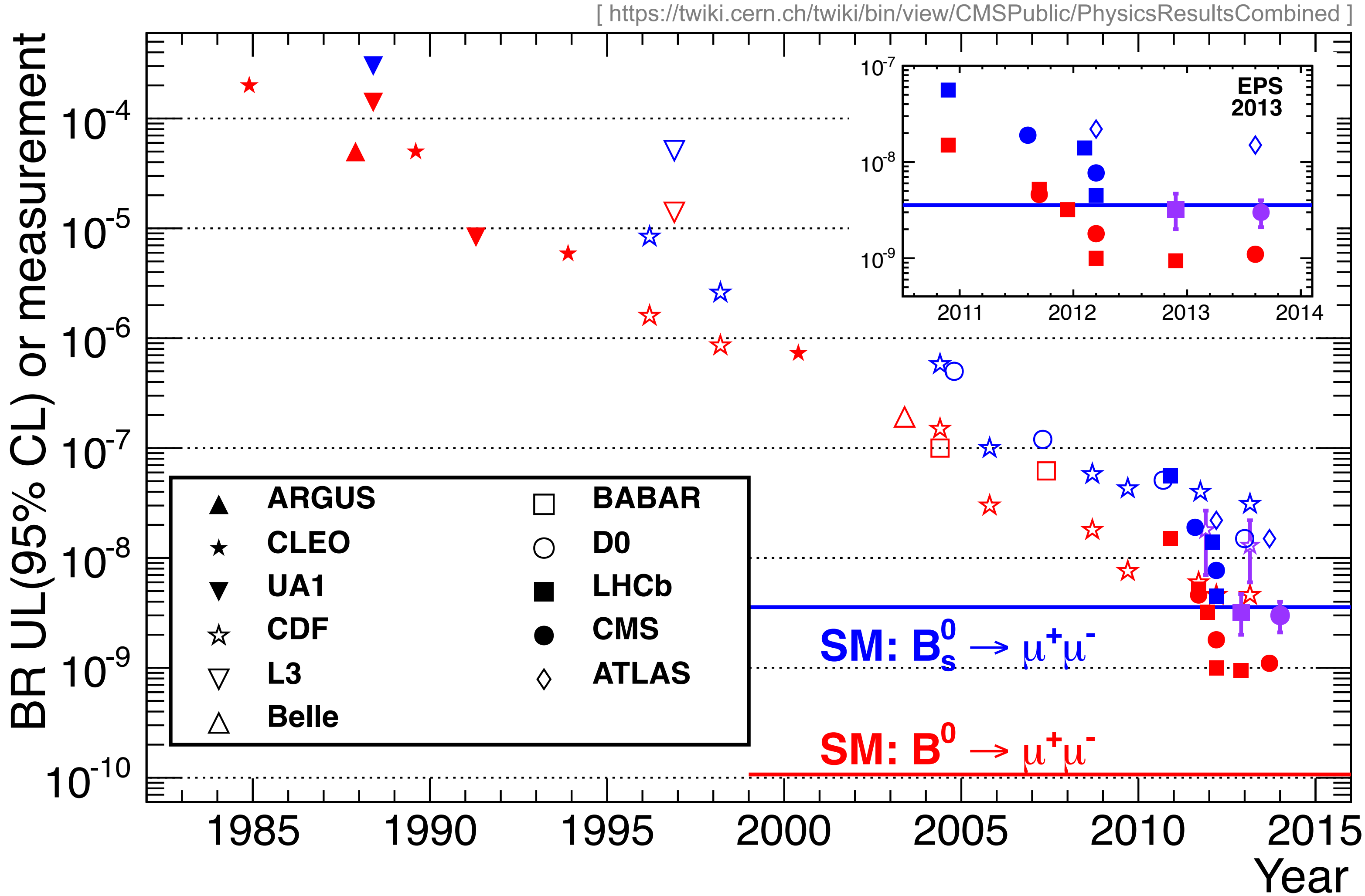


Penguin SM diagram, adds to box
Helicity-suppressed in SM
Flavour probe of EW and Higgs sector

Quark Flavour Physics

$B_s \to \mu\mu$ history



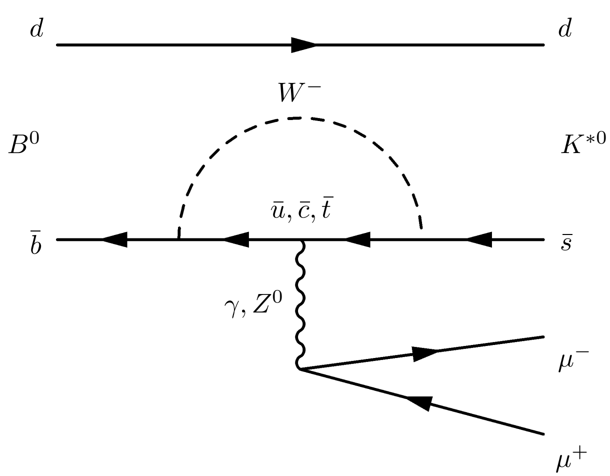


Quark Flavour Physics

Electroweak penguin decays (FCNC)

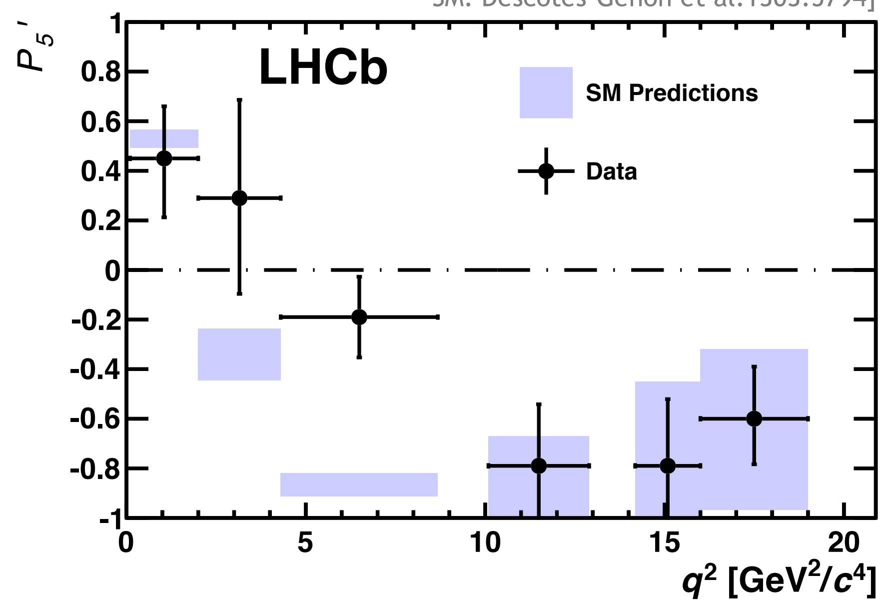
Anomaly in LHCb $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

$P_{4/5}$' : form-factor independent angular observable, theoretically clean at large recoil (low $q^2 = m^2_{\mu\mu}$)



$$H_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1...10} \left(C_i(\mu)\cdot O_i(\mu) + C_i'(\mu)\cdot O_i'(\mu) \right)$$

[LHCb: 1308.1707, 3 fb^{-1} announced to come soon
SM: Déscotes-Genon et al.1303.5794]



- Fluctuation in P_5' (local 3.7σ, global 2.8σ)? Non-perturbative effect (Λ/m_b)?
- New physics in C_9 Wilson coefficient (NNLO)? [C_7: $b \to s\gamma$, C_{10}: $B \to \mu\mu$ are constrained]

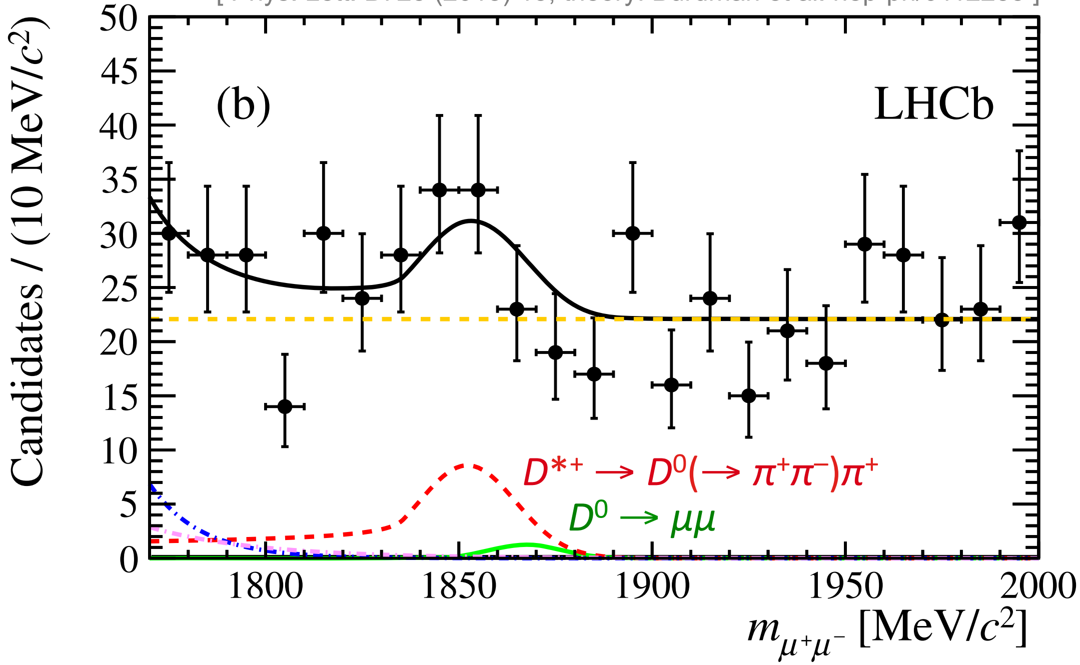
Quark Flavour Physics

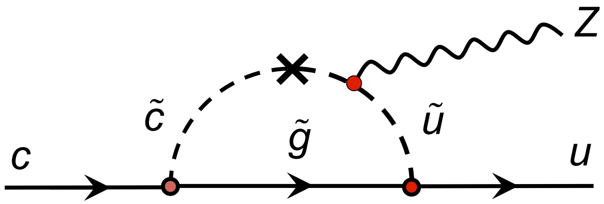
Rare charm decays

Very rare FCNC decay $D^0 \to \mu\mu$ also searched for

(Short distance: $BR_{SM} \sim 10^{-18}$, GIM & helicity suppressed, possible long-distance enhancement)

[Phys. Lett. B725 (2013) 15, theory: Burdman et al. hep-ph/0112235]



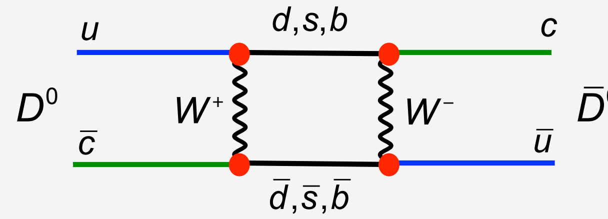


FCNC $c \to u$ transition in SUSY

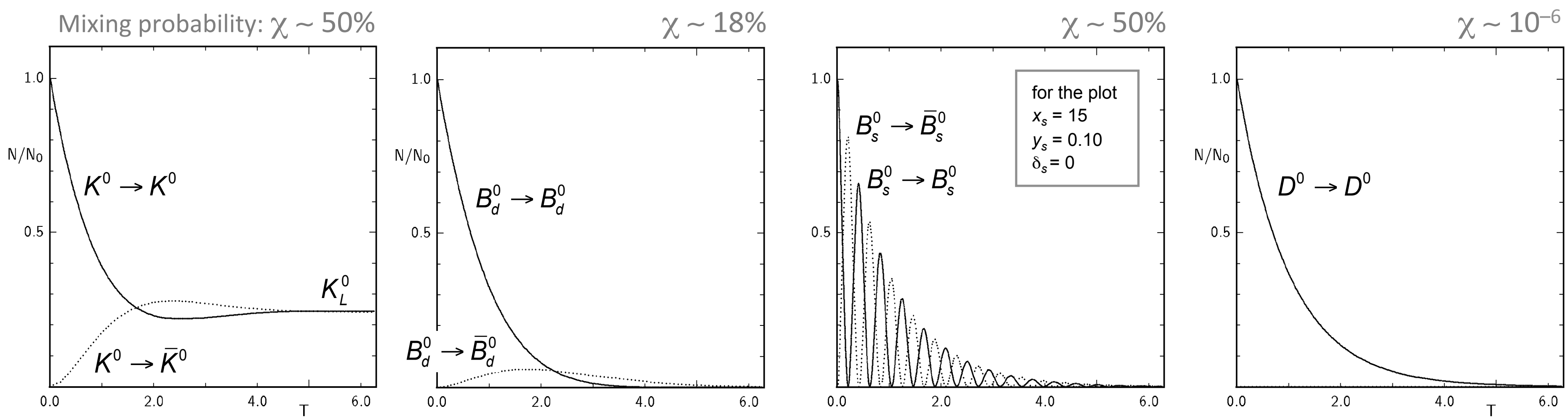
- BR($D^0 \to \mu\mu$) < 6.2 · 10^{-9}

Quark Flavour Physics

Charm mixing

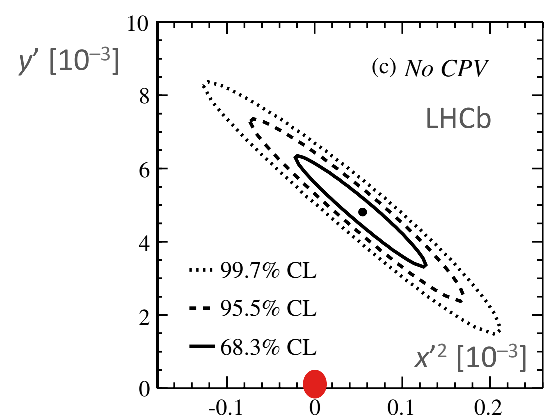


Neutral charm mesons mix much slower than neutral *K* and *B* mesons



- Charm mixing discovered in 2007 by *B*-factories, huge statistics & tiny effect → high precision measurement
- Confirmed and improved in 2012+2013 by LHCb, CDF
- No indication of *CP* violation (in agreement with SM)
- Direct *CPV*: $\Delta A_{CP}(D^0 \to K^+K^-) - \Delta A_{CP}(D^0 \to \pi^+\pi^-)$ $= -0.82 \pm 0.21 \pm 0.11$ % (3.5σ) → **$+0.14 \pm 0.16 \pm 0.08$ %**

[PRL 108,111602 (2012) → 1405.2797, May 2014]



Direct CP violation

CPV is direct if the partial decay-width of a particle into a final state differs from the width of the corresponding antiparticle into the CP-conjugate final state

Direct CPV is expected in the SM, but usually small as it requires interference amplitudes with strong and weak phase difference

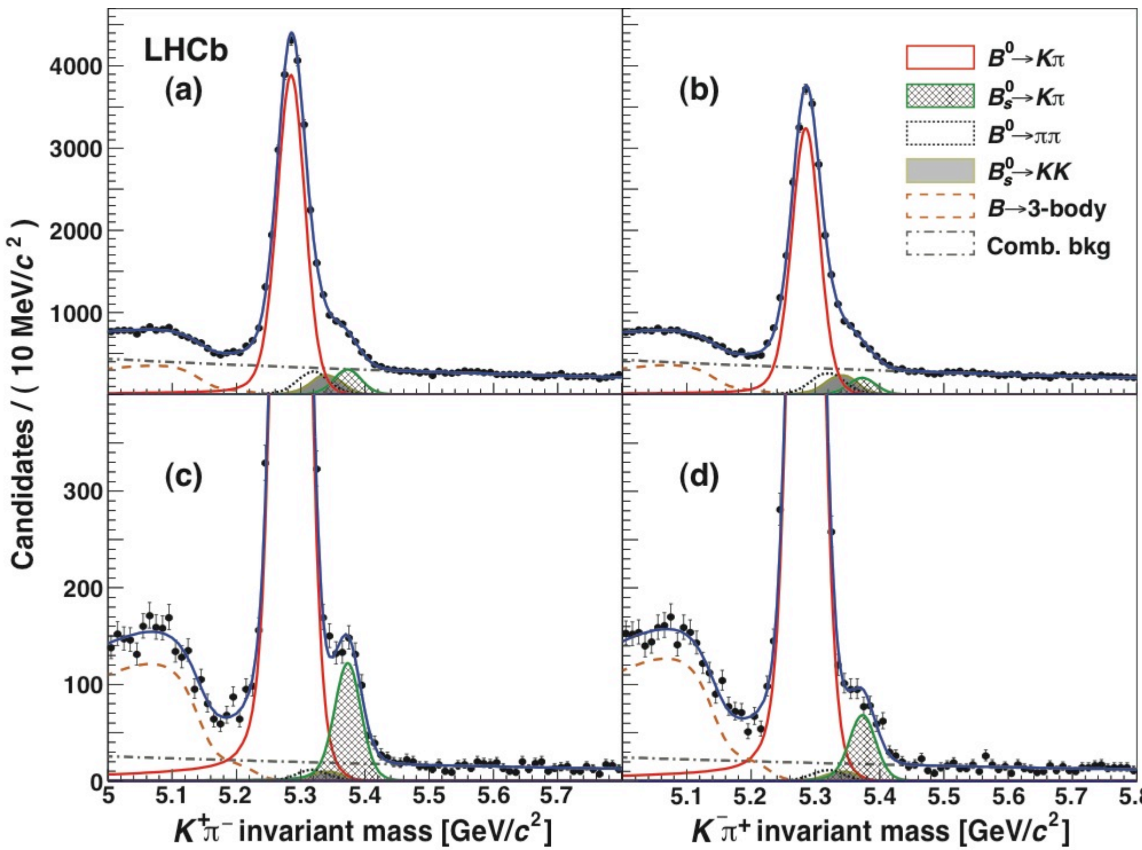
First observed in $K^0 \to \pi\pi$ system (NA48 & KTeV, 1999): $\mathrm{Re}(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \cdot 10^{-3}$

Later in $B^0 \to K^+\pi^-$ system (BABAR, Belle, 2004): $A_{K\pi} = -0.082 \pm 0.006$

And (!) in $B_s \to K^-\pi^+$ system (LHCb 2013): $A^s_{K\pi} = 0.27 \pm 0.04$

Although the existence of direct CPV is no surprise in the SM, its quantitative prediction is hard…

[LHCb: 1304.6173]

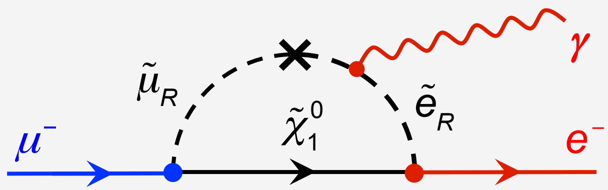


Some experimental highlights of **charged lepton** flavour physics

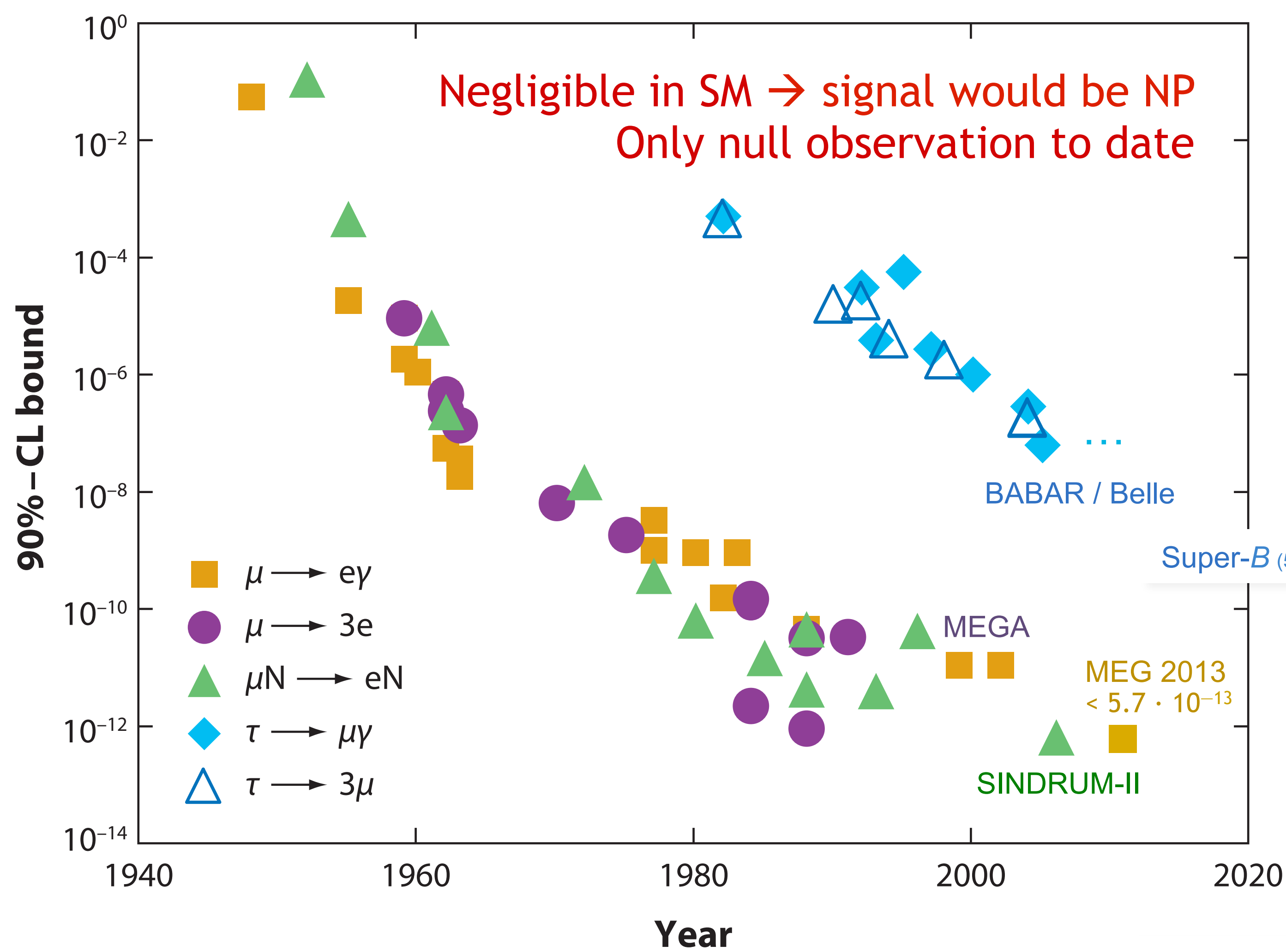
“Classical” flavour physics

Lepton Flavour Physics

Charged lepton sector: LFV



Marciano et al., Annu. Rev. Nucl. Part. Sci.58, 315 (2008)



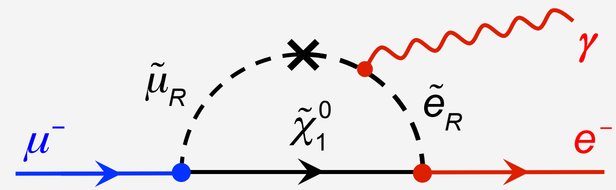
Super-*B* (50 ab^{-1})

Spectacular perspective !

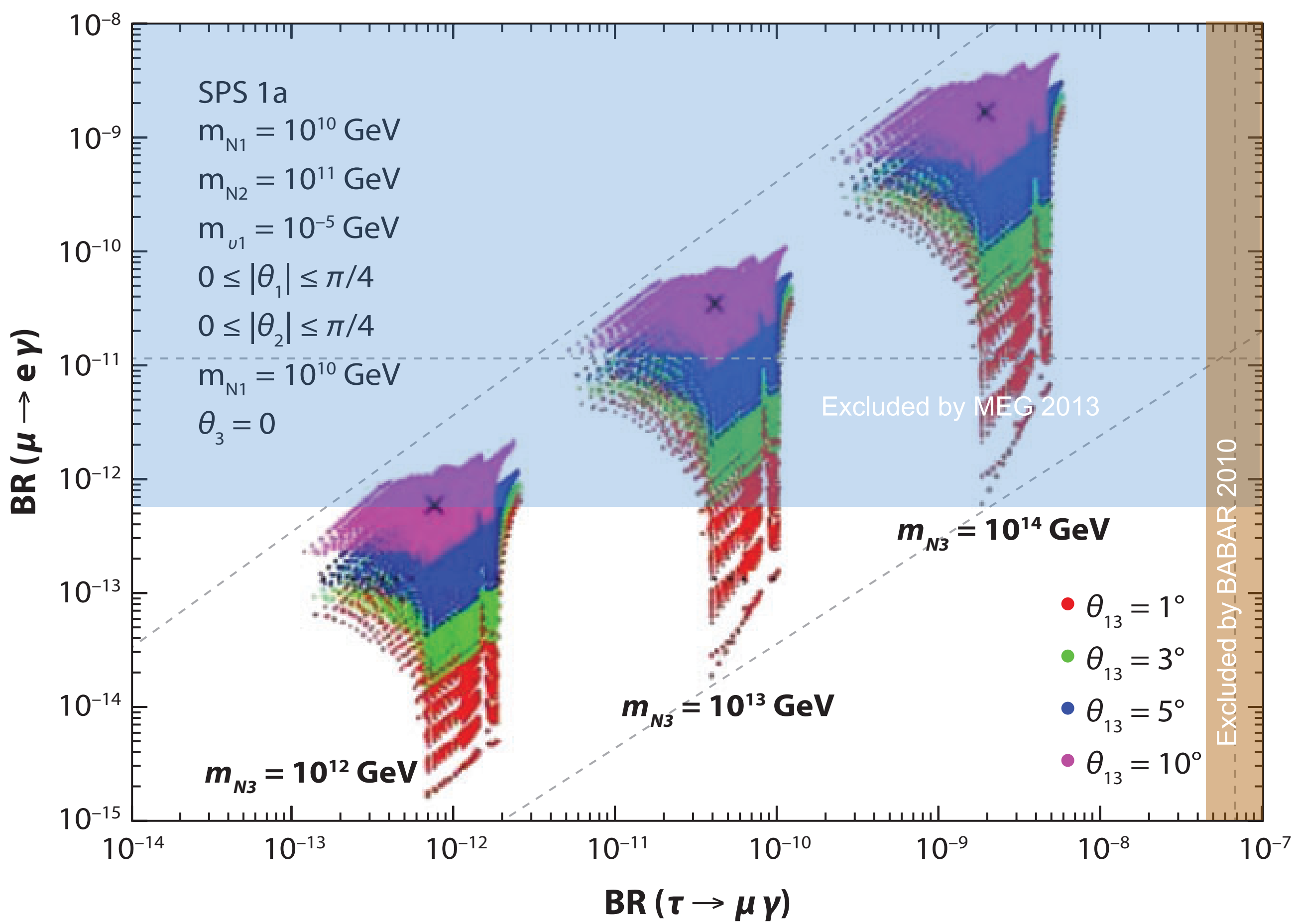
Mu2e / COMET

Lepton Flavour Physics

Charged lepton sector: LFV



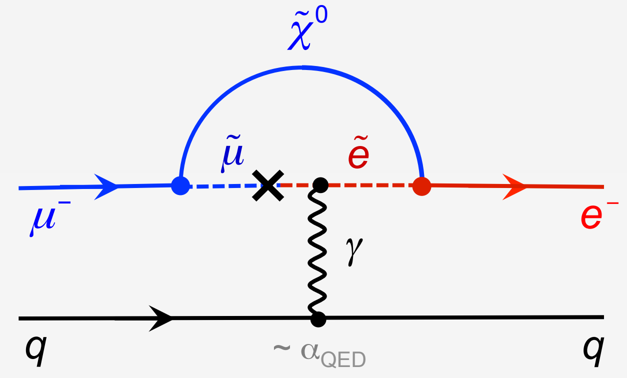
Antusch et al.. JHEP 11, 90 (2006)



CMSSM model point with 3 massive RH N for various $m(N_3)$ and θ_{13}

Lepton Flavour Physics

Charged lepton sector: LFV



Neutrinoless conversion: $\mu^- N \rightarrow e^- N$

Principle:

1. Stopped muon captured by atom
2. There: **decay** or **capture** or ***μ*–*e* conversion**
3. Conversion gives single, distinctive monoenergetic electron (104.96 / 95.56 MeV for Al / Au)

New physics sensitivity compared to $\mu \rightarrow e\gamma$ for generic dipole dominance models ~390 times lower for Al target

→ $\mathrm{BR}(\mu \rightarrow e\gamma) < 10^{-13}$ requires $R_{\mu e}(\mathrm{Al}) < 3\times10^{-16}$

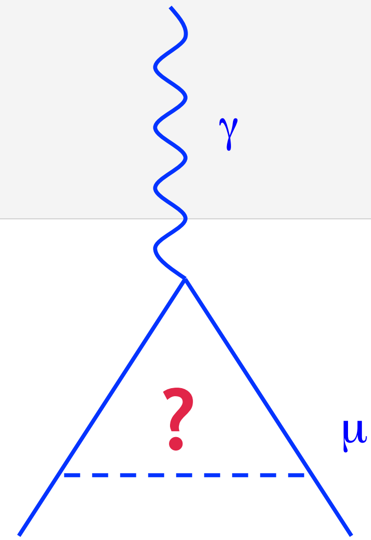
Forthcoming experiments: Mu2e @ FNAL, COMET @ J-PARC

Goal: sensitivity down to $\sim 2\times10^{-17}$ with data-taking by 2018

[Requires 5×10^{19} muons – approaching #grains of sand on earth… (R. Bernstein, Pittsburgh 2011)]

Lepton Flavour Physics

Muon anomalous magnetic moment

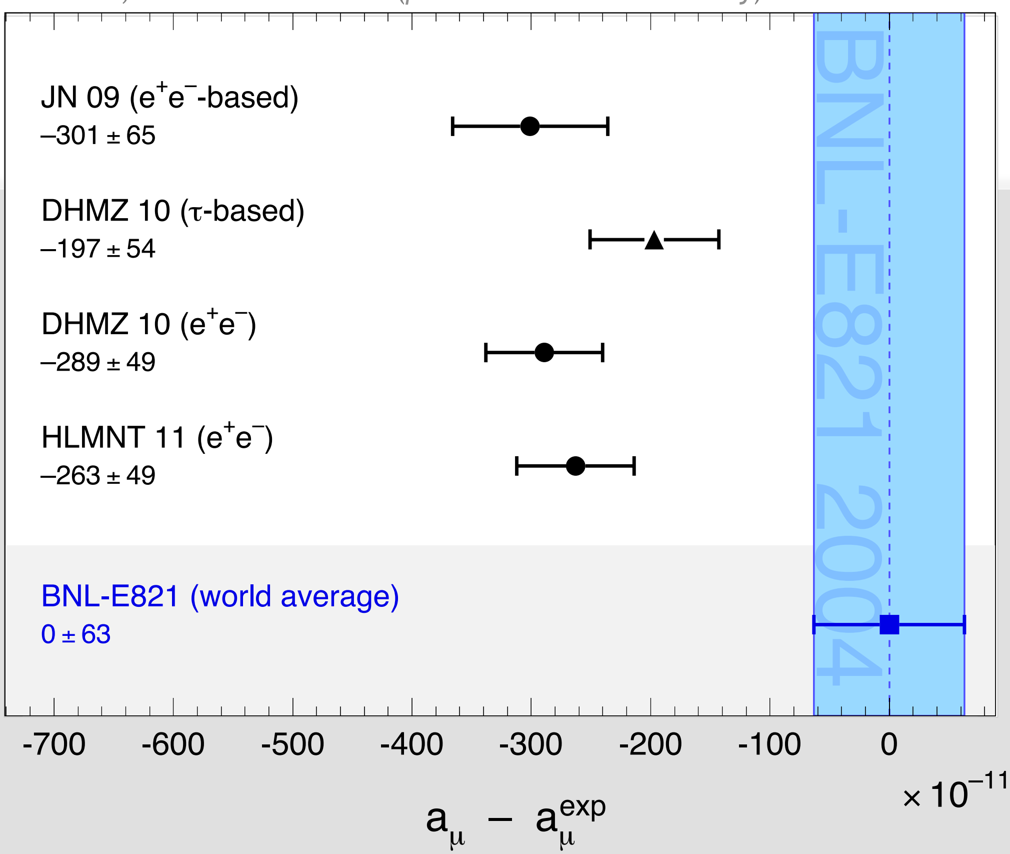


BNL E821 (2006): $a_\mu^{exp} = 11\,659\,180.3 \pm 0.1_{EW} \pm \mathbf{4.2}_{\textbf{LO-had}} \pm \mathbf{2.6}_{\textbf{NLO-had}}$

SM (DHMZ e-based): $a_\mu^{exp} = 11\,659\,209.1 \pm 5.4_{stat} \pm 3.3_{syst}$

[in units of 10^{-10}]

PDG 2013, Status: summer 2013 (*published results shown only*)



Difference: experiment – SM

$a_\mu^{exp} - a_\mu^{SM} = (28.8 \pm 8.0) \times 10^{-10}$

- ➡ 3.6 "standard deviations" (e^+e^-)
- ➡ 2.4 "standard deviations" (τ)

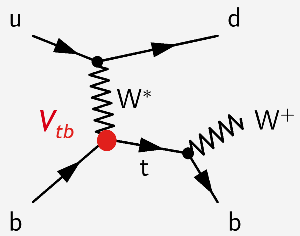
Some experimental highlights of **top** flavour physics

Top entering the scene with Tevatron and LHC

Top has O(1) coupling to Higgs ($y_t = \sqrt{2}m_t/\upsilon \approx 1$), profound effect on EW and flavour physics

Top Flavour Physics

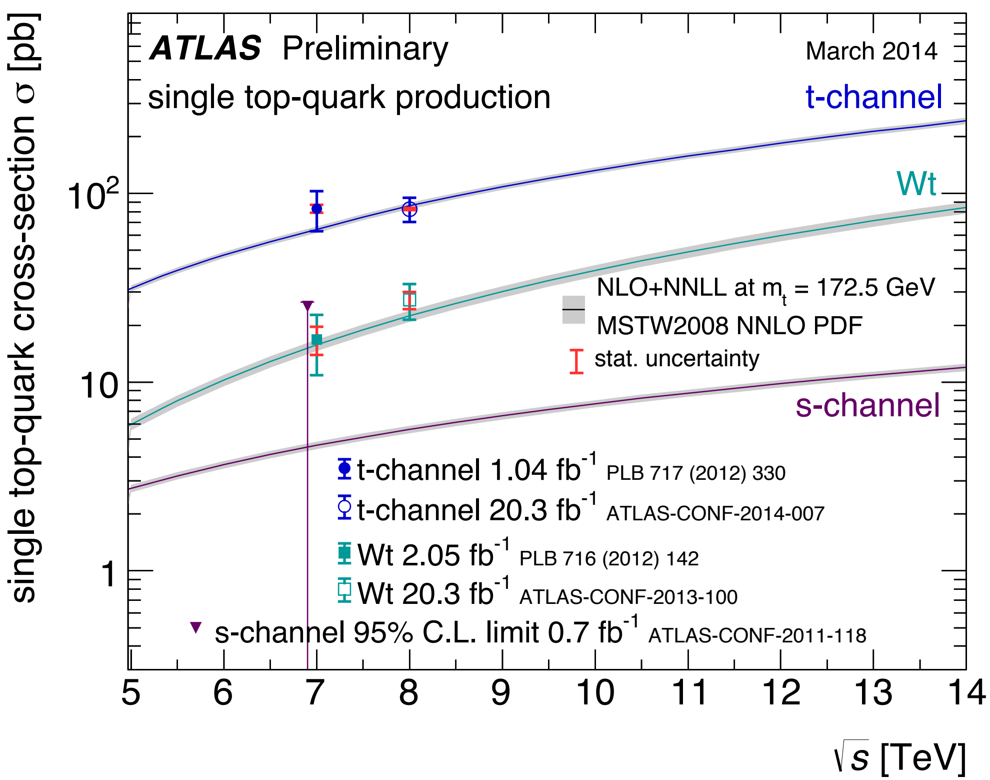
Electroweak top production



Measurements of $|V_{tb}|$ via single top production as test of CKM unitarity

(Precision, however, far below that of *B*-meson mixing)

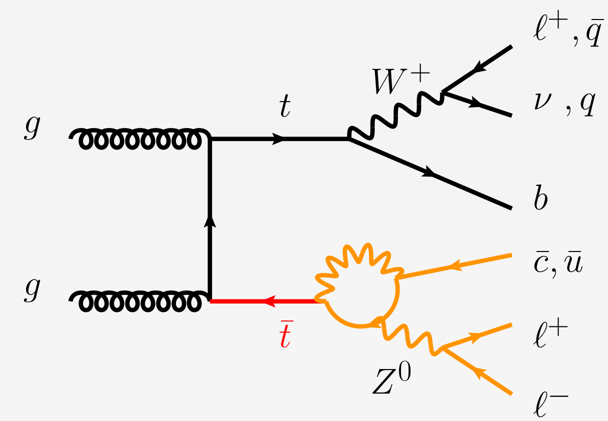
$|V_{tb}| = 0.998 \pm 0.038_{exp} \pm 0.016_{theo}$ [CMS: 1403.7366] | CKM unitarity: $1-|V_{tb}| = (8.80 \pm 0.36)\cdot 10^{-4}$



All cross sections in agreement with SM, no unitarity break down

Top Flavour Physics

FCNC in top decay



FCNC top decays are suppressed in SM

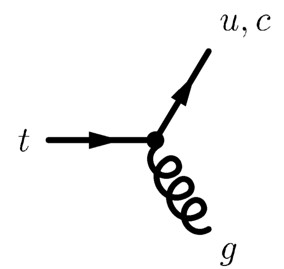
(Only at loop level, there CKM suppressed: BR($t \to cZ$) ~ 10^{-14})

- Current limit (CMS): BR($t \to cZ$) < 0.21% [CMS: 1208.0957, 7 TeV]
- Prospective (CMS):

[CMS PAS FTR-13-016]

$\mathcal{B}(t \to Zq)$	19.5 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	$< 0.10\%$	$< 0.027\%$	$< 0.010\%$
1 σ range	0.06 – 0.13%	0.018 – 0.038%	0.007 – 0.014%
2 σ range	0.05 – 0.20%	0.013 – 0.051%	0.005 – 0.020%

- Other FCNC processes involve, eg, *qg* coupling: $qg \to t \to W(\to l\nu)b$ (additional jet veto)

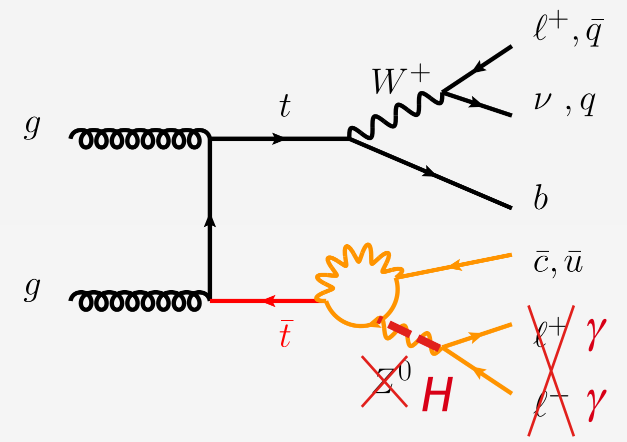


ATLAS limit: BR($t \to cg$) < 0.027 % at 95% CL

[ATLAS: 1203.0529, 7 TeV]

Top Flavour Physics

FCNC in top decay

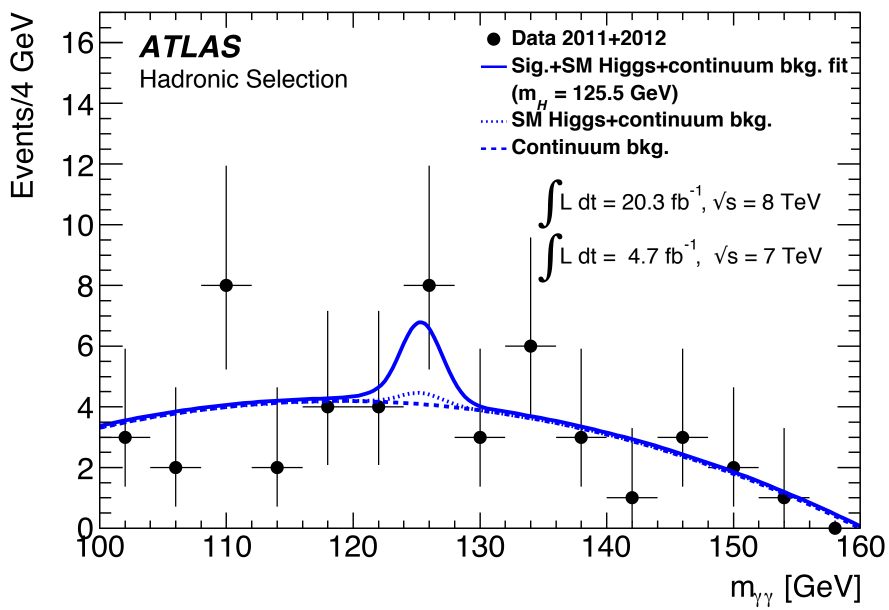


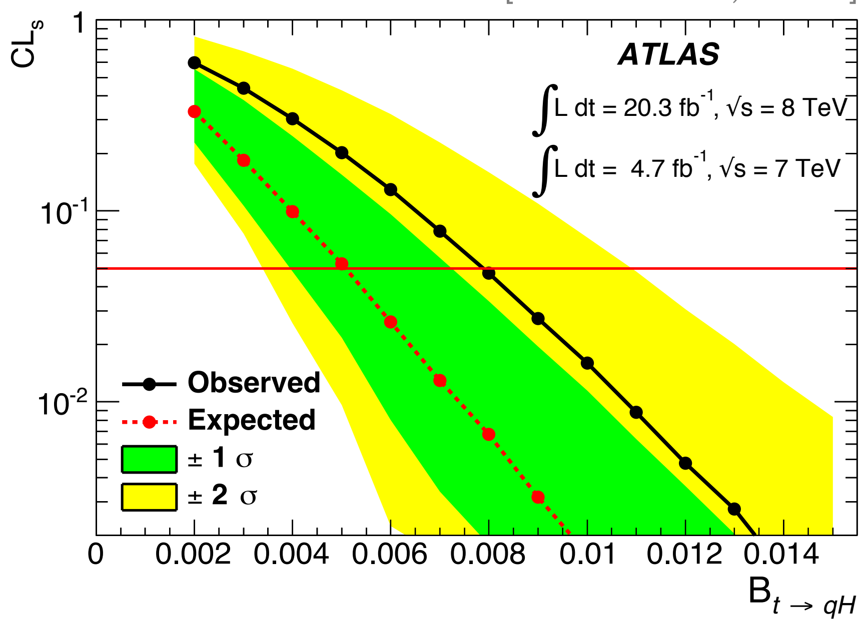
FCNC top decays are suppressed in SM

(Only at loop level, there CKM suppressed: BR($t \to cH$) ~ $3 \cdot 10^{-15}$)

- Search in $t \to qH(\to \gamma\gamma)$ channel

[ATLAS: 1403.6293, 7+8 TeV]

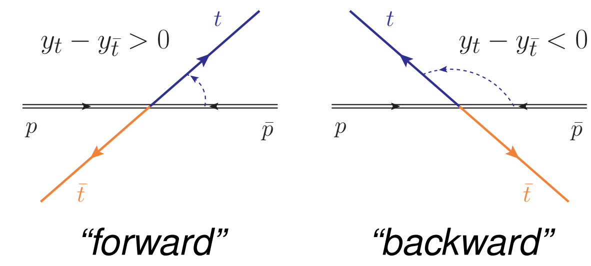




- Branching fraction limit: BR($t \to qH$) ~ (assumed) BR($t \to cH$) < 0.79 % at 95% CL
- CMS combined multilepton + diphoton to: BR($t \to cH$) < 0.56 % at 95% CL [CMS-PAS-HIG-13-034]

Top Flavour Physics

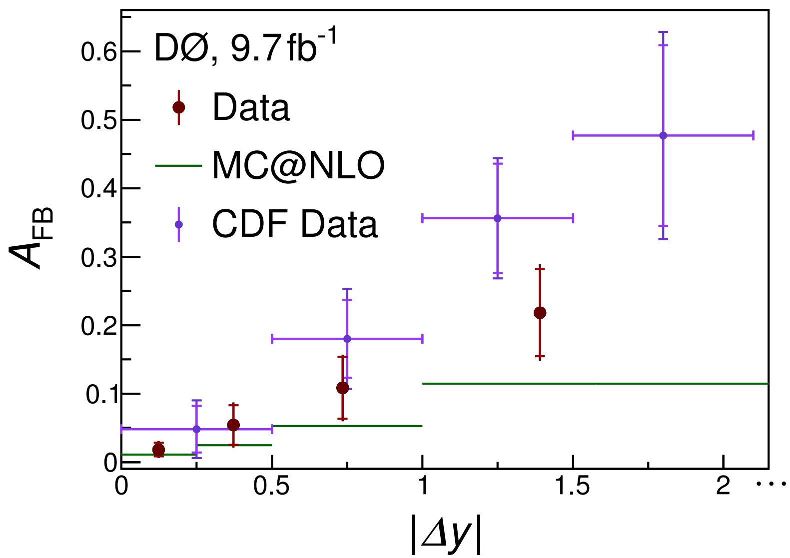
$A_{FB} = (N(\Delta y_{tt} > 0) - N(\Delta y_{tt} < 0))\ /\ \Sigma$

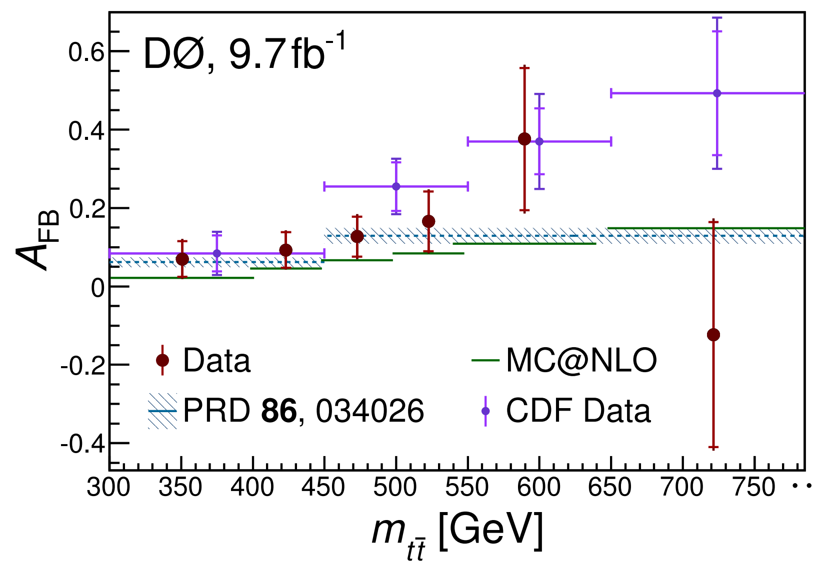


Top-antitop forward-backward asymmetry at Tevatron

(A_{FB} = 0 at LO, but asymmetry in SM at NLO)

- NLO QCD +EW: A_{FB} = +(5.0–8.8)% (δ_{NNLO} ~ ±2%) [Bernreuther-Si, PRD 86, 034026 (2012)]
- CDF: A_{FB} = +(16.4 ± 4.5)% on 9.4 fb^{-1} [CDF, PRD 87, 092002 (2013)]
- D0 (2011): A_{FB} = +(19.6 ± 6.5)% on 5.4 fb^{-1} [D0, PRD 84, 112005 (2011)]
- D0 (newest): A_{FB} = +(10.6 ± 3.0)% on 9.7 fb^{-1} [D0, 1405.0421 (May 2014)]





Not conclusive…

Theory progress would require NNLO calculation

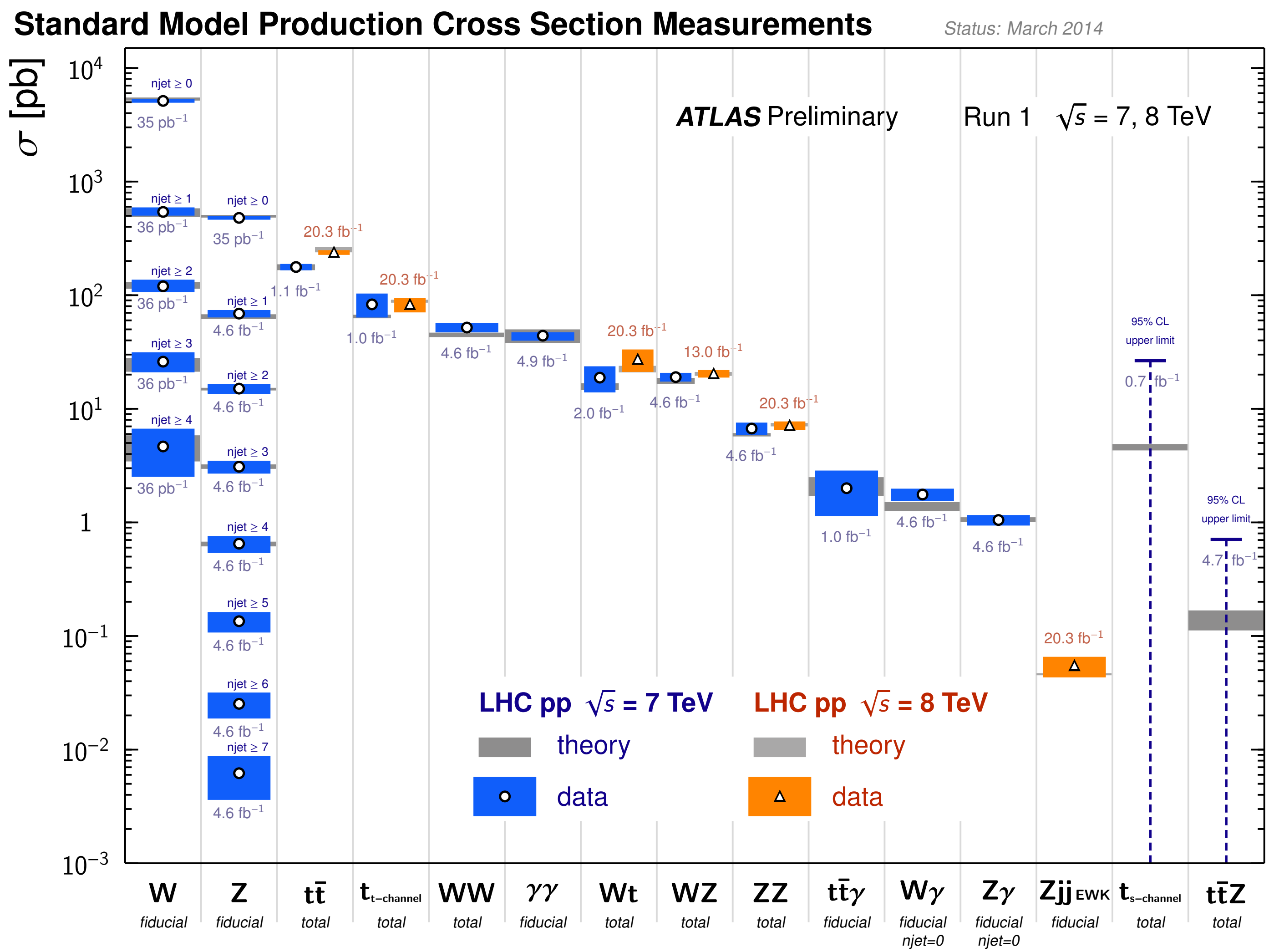
Higgs boson flavour physics

What do the data tell us about the flavour structure of the Higgs ?
Brief review of H → di-fermion decays, but production also sensitive to flavour

Higgs and Flavour Physics

The non-Higgs SM at the LHC — impressive understanding

[CombinedSummaryPlots/SM]



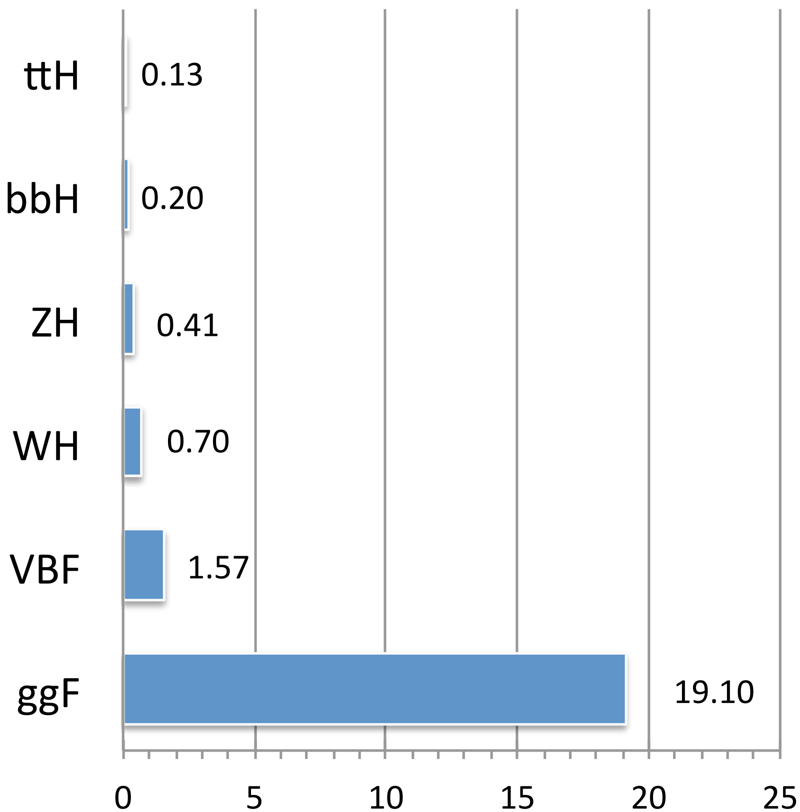
Higgs and Flavour Physics

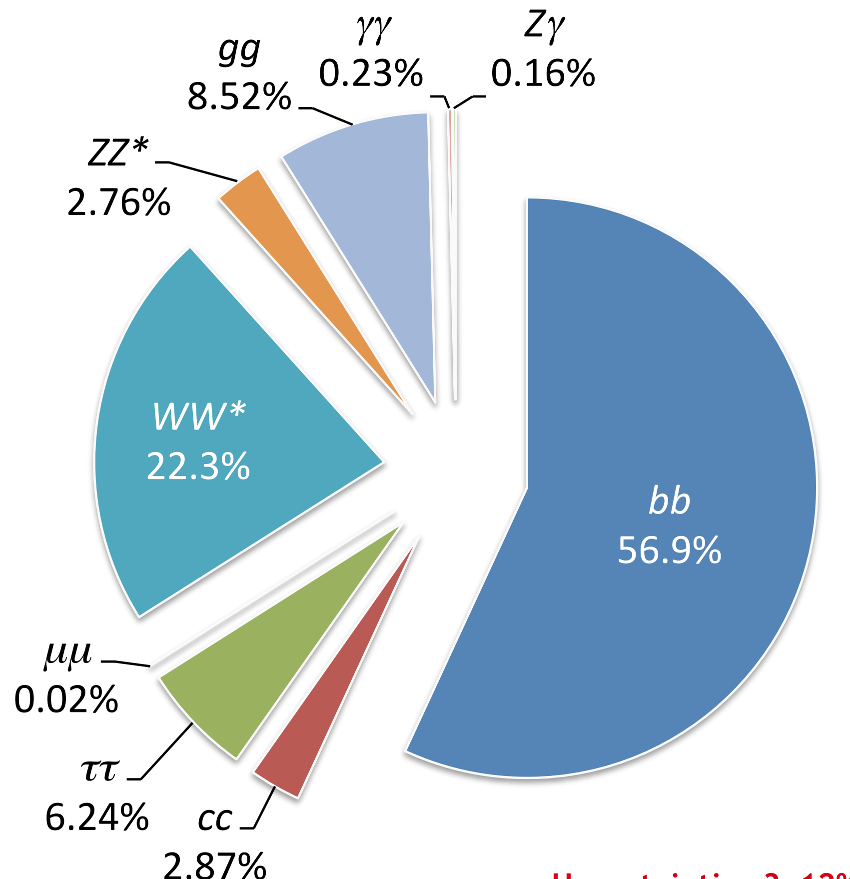
125.5 GeV Higgs boson — SM properties

[LHCPhysics/CrossSections]

Cross sections and branching fractions precisely predicted (m_H = 125.5 GeV)

$pp \to H$ cross sections at 8 TeV [pb]





Uncertainties 3~12%

Higgs and Flavour Physics

Higgs mass

SM predictions can (so far) live without a precision m_H measurement, but as experimentalists we want to do the best possible job

- Recent final Run-1 result be ATLAS after improvement of detector material description and recalibration using all SM candles (Z, W, J/ψ, Υ)

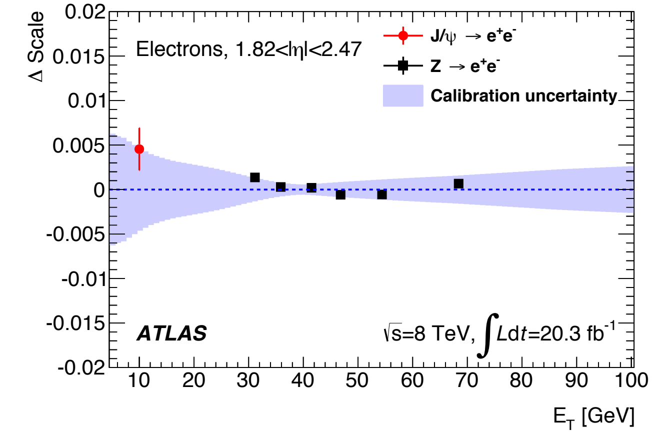
Table 5: Summary of Higgs boson mass measurements.

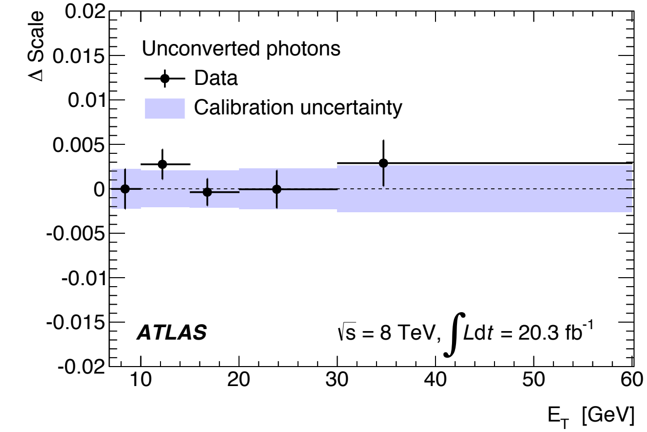
Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

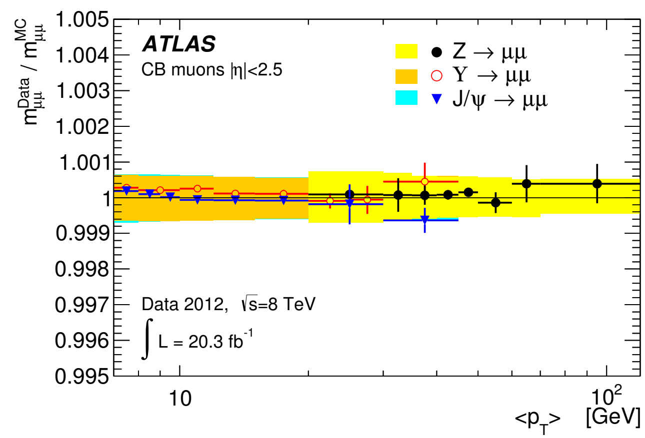
[ATLAS: 1406.3827]

- Compatible in value and uncertainty with CMS result from 4-lepton channel: [CMS: 1312.5353]

$$125.6 \pm 0.4_{stat} \pm 0.2_{syst}\ \text{GeV}$$







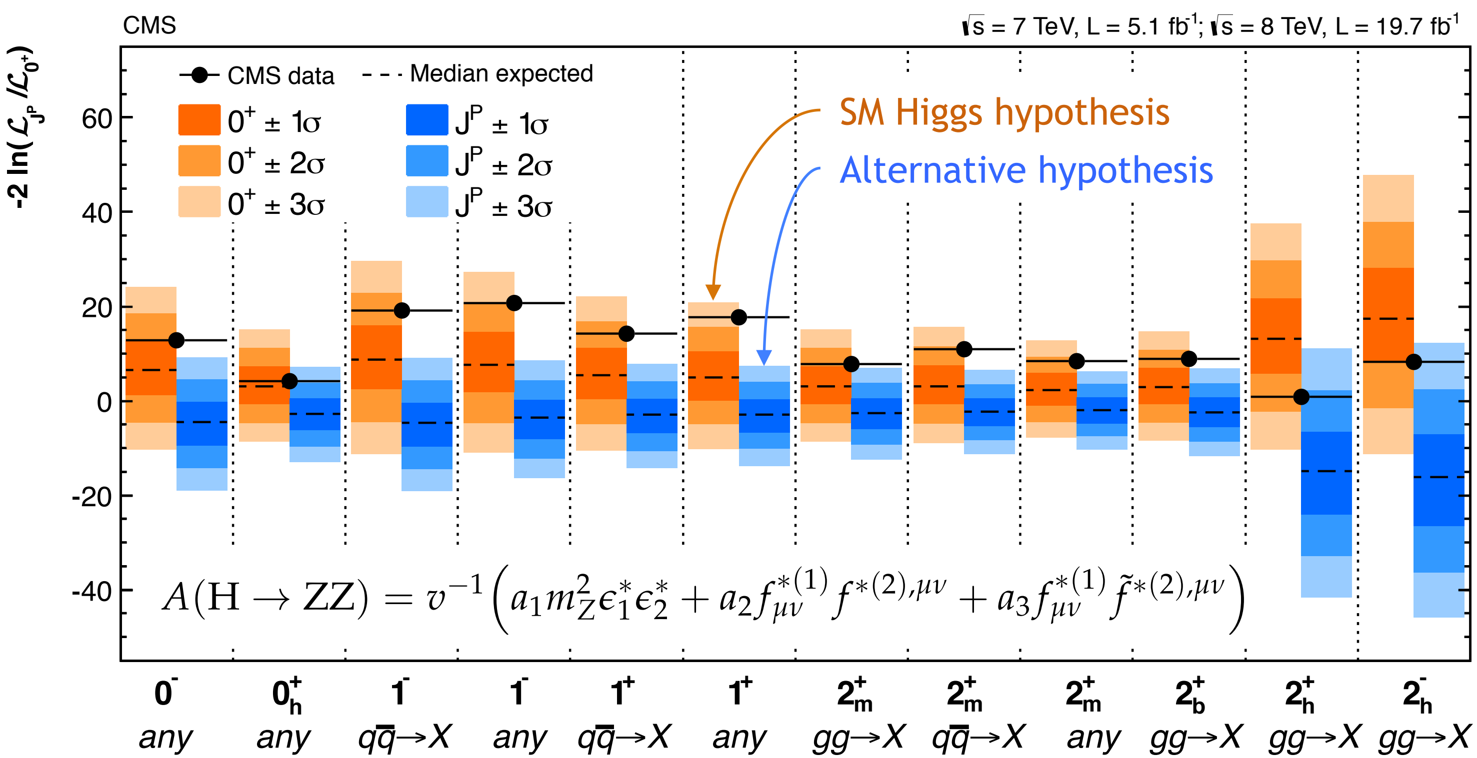
Higgs and Flavour Physics

Higgs spin and *CP* — Higgs boson appears to be SM-like: $J^P = 0^+$

[CMS: 1312.5353]

From most powerful spin/*CP* analyser: *H* → 4-lepton

- 0^- excluded at 3.6σ; *CP*-odd fraction in decay amplitude: $f_{a3} < 0.51$ (95% CL)
- Spin-1, 2 hypotheses excluded >> 95% CL

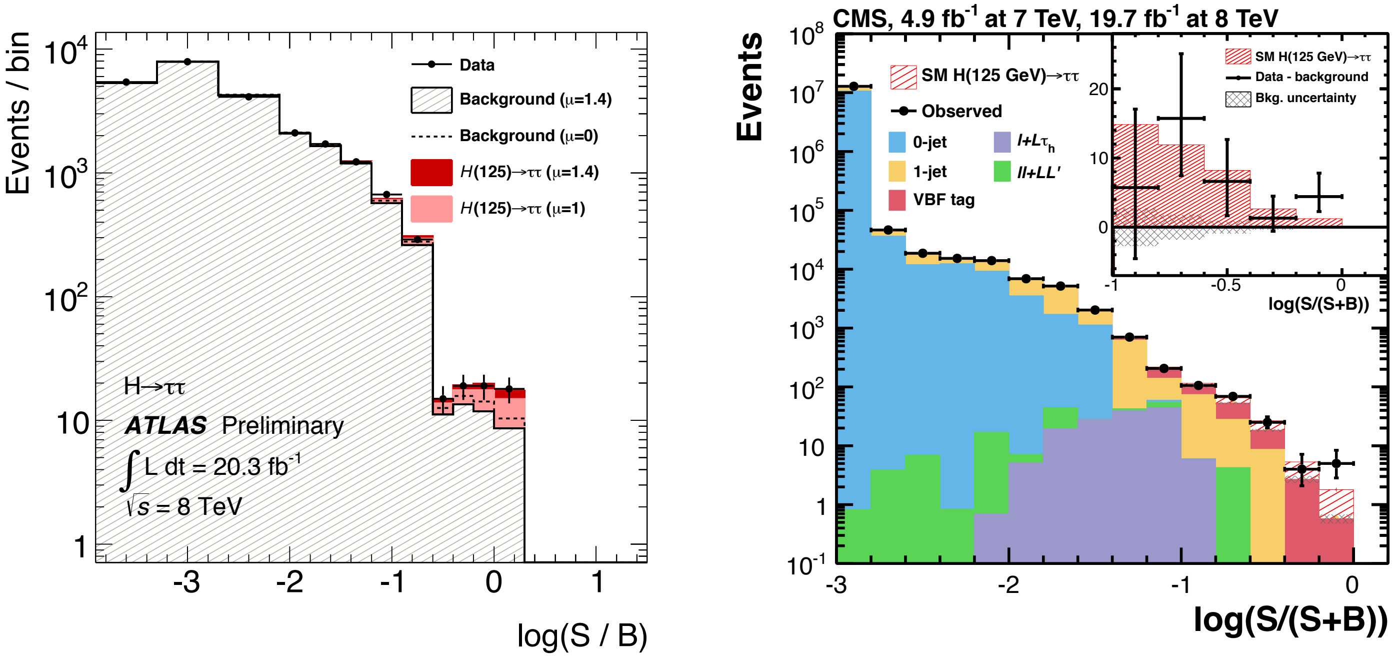


Discrimination is based on 2D PDFs (D_{bkg}, D_{JP})

[ATLAS-CONF-2013-108, CMS: 1401.5041]

Higgs to fermion analyses all very challenging (or too low BR)

- Di-tau reconstructed in all lep/had topologies and jets: 0, 1 (boosted or not), 2 (VBF, VH)
- BDT-based tau identification, Higgs discrimination based on $m_{\tau\tau}$
- Likelihood-based calculator to estimate $m_{\tau\tau}$, $\sigma(m_{\tau\tau})$ = 13% ~ 20%, best for boosted τ
- Background dominated by $Z \to \tau\tau$ (use "τ embedded" $Z \to \mu\mu$), also top & fakes important



At 125 GeV:

ATLAS (8 TeV): $\mu = 1.4^{+0.5}_{-0.4}$ (4.1 σ)

CMS (7+8 TeV): $\mu = 0.78 \pm 0.27$ (3.4 σ)

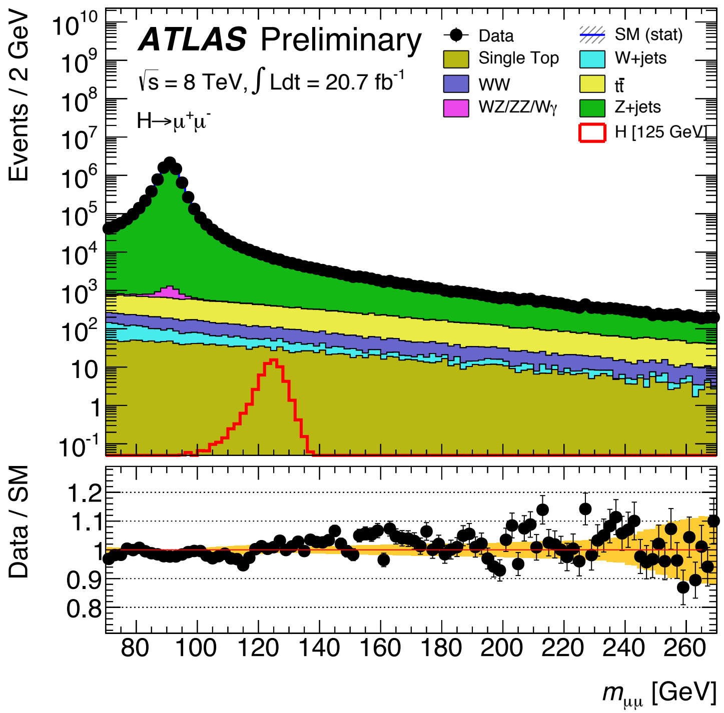
Higgs and Flavour Physics

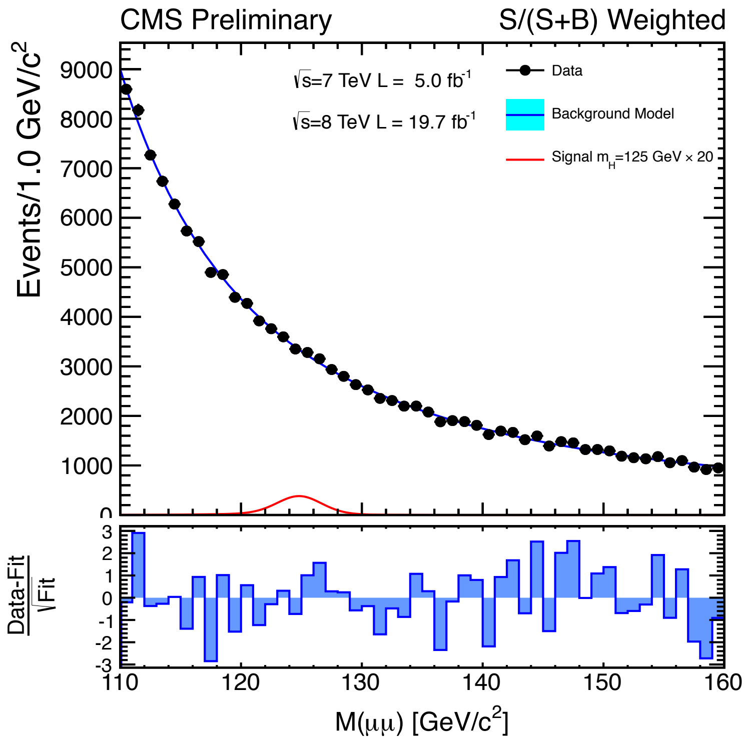
SM Higgs to fermions — $\mu\mu$

[ATLAS-CONF-2013-010, CMS-PAS-HIG-13-007]

Low branching fraction (ten times smaller than $\gamma\gamma$), mainly data-driven fit akin to $H \to \gamma\gamma$

- Slight complication due to sum of dominant DY and sub-dominant tt, WW backgrounds
- Separation of jet (gluon fusion, VBF), and S/B (central, non-central) categories





At 125 GeV:

ATLAS (8 TeV):
μ < 9.8 (8.2 exp.) (95% CL)

CMS (7+8 TeV):
μ < 7.4 (5.1 exp.) (95% CL)

Digression

Upper limit on $H \to \mu\mu$ is sufficient to exclude universal Higgs coupling to leptons

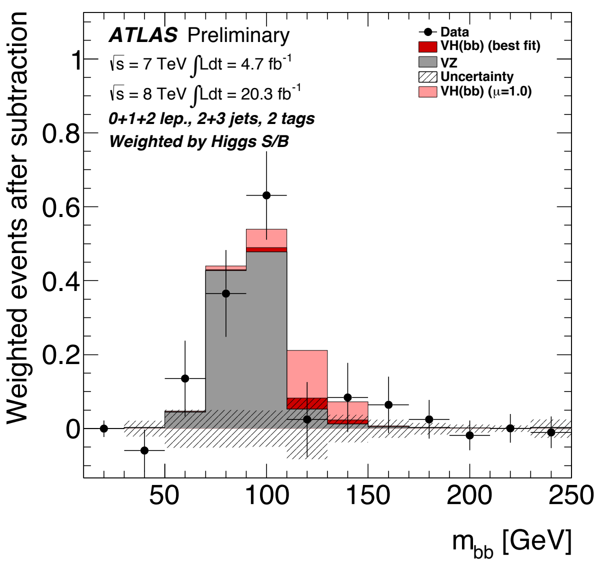
- Poor man's LHC averages (don't quote me!): $\mu_{\tau\tau} = 0.94 \pm 0.23$ together with $\mu_{\mu\mu} < 7.4$ (95% CL)
- $\mu_{\mu\mu} / \mu_{\tau\tau} < \approx 15$, but for universal couplings would expect: $\mu_{\mu\mu} / \mu_{\tau\tau} = (m_\tau / m_\mu)^2 \approx 282$

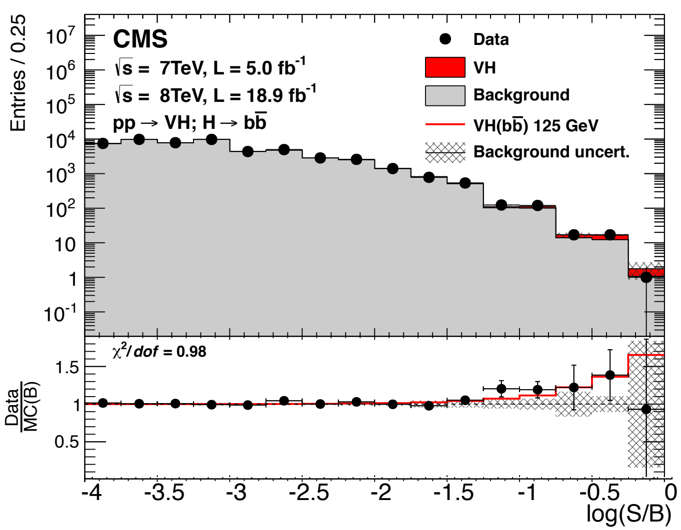
Higgs and Flavour Physics

SM Higgs to fermions — $W(\rightarrow l(\text{CMS: } \tau_{had})\nu)/Z(\rightarrow ll,\nu\nu) + H(\rightarrow bb)$

Large branching fraction, but very challenging channel due to large backgrounds

- Require 2 b-tags and distinguish 0, 1, 2 lepton channels, where 0-lepton uses E_T^{miss} trigger
- Higgs discrimination based on m_{bb}, resolution of ~16%, improved by including muons
- Categories in $p_T(V)$ & jets + topol. and kin. variables (reduced background for boosted Higgs)
- CMS uses classification BDT and MV regression to improve $m(bb)$ resolution
- Dominant backgrounds (form CRs): 0L: Zbb, tt, some Wbb; 1L: tt, Wbb; 2L: Zbb, some tt
- Dominant systematics: tt modeling, c-tag efficiency, multijet (1L), signal acceptance





At 125 GeV:

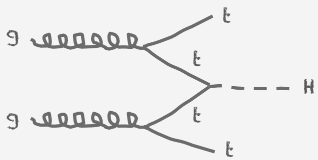
ATLAS (7+8 TeV):
$\mu = 0.2 \pm 0.6$
$\mu < 1.5$ (1.4 exp.)

CMS (7+8 TeV):
$\mu = 1.0 \pm 0.5$
$\mu < 1.9$ (1.0 exp.)

$bb + \tau\tau$ combined:
A: $\mu = 1.09 \pm 0.34$ (3.7σ)
C: $\mu = 0.83 \pm 0.24$ (3.8σ)

Higgs and Flavour Physics

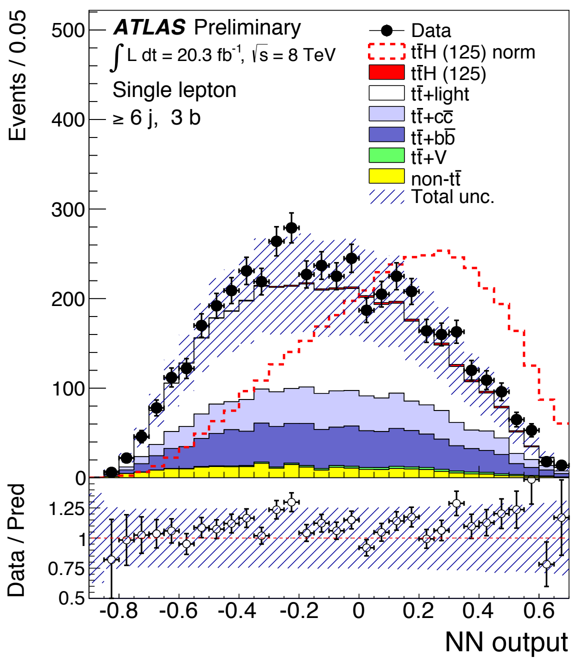
SM Higgs to fermions — $tt + H(\rightarrow bb)$: direct test of y_t



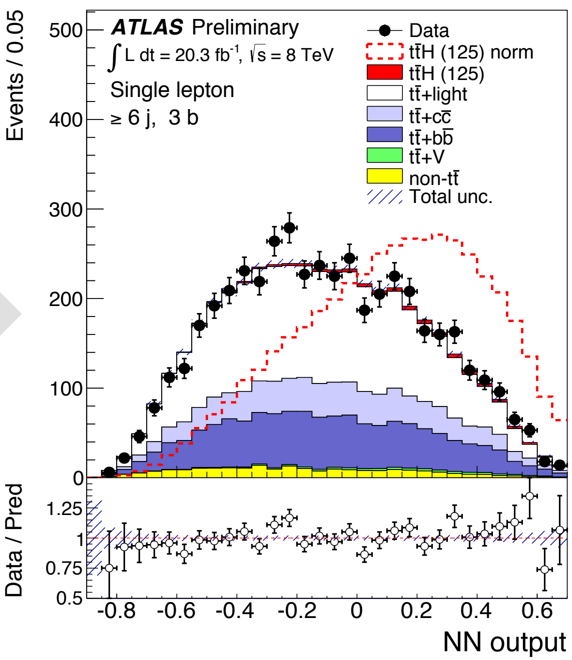
[ATLAS-CONF-2014-011, CMS: 1303.0763]

Challenging channel, requires constraining model uncertainties from data

- Reconstruct in 1, 2 lepton channels (fully had. channel in principle also accessible, *b*-jet triggers)
- Categories in jets (2–6) and *b*-tags (2–4), MVAs (NN) used for signal extraction
- Main backgrounds: *tt+bb*, *tt+cc*, *tt*+light
- Global fit of all categories allows to constrain backgrounds and nuisance parameters



After fit



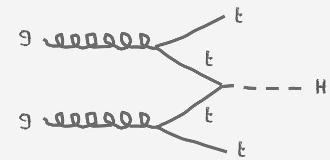
At 125 GeV:

ATLAS (8 TeV):
$\mu = 1.7 \pm 1.4$
$\mu < 4.1$ (2.6 exp.) (95% CL)

CMS (7+8 TeV):
$\mu < 5.8$ (5.2 exp.) (95% CL)

Higgs and Flavour Physics

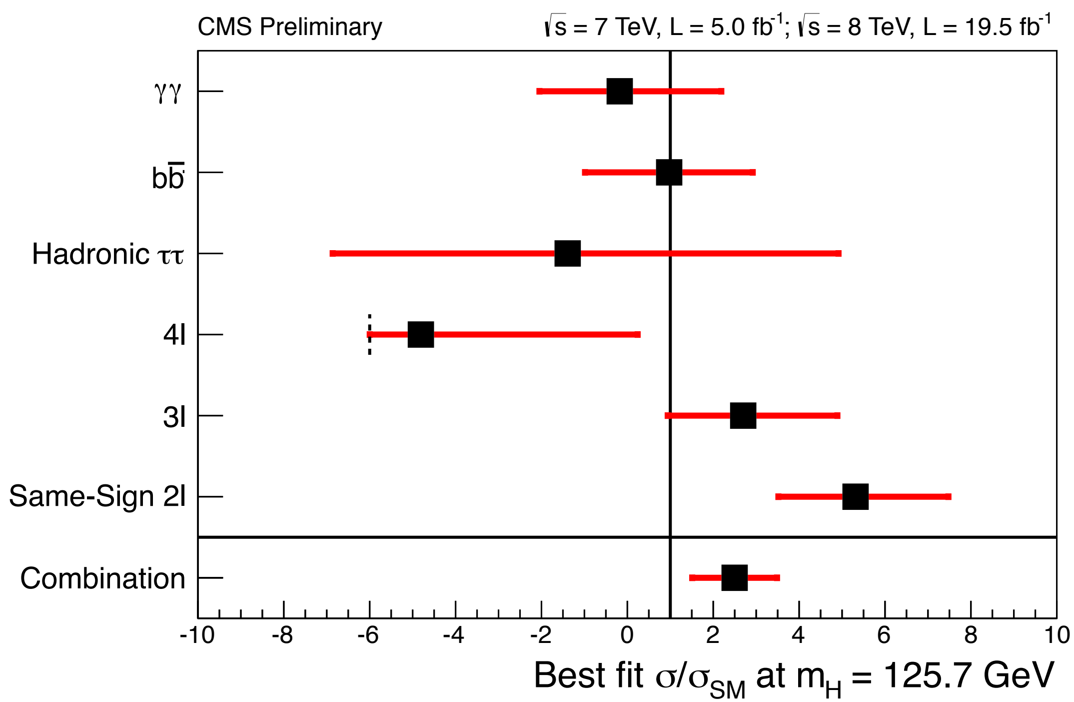
SM Higgs to fermions — *tt* + *H*



[CMSPublic/ttHCombinationTWiki]

CMS produced preliminary *tt* + *H*(→ *bb*, $\tau\tau$, *multilepton*, $\gamma\gamma$) combination

- *bb*, multilepton (incl. same-sign leptons) provide best expected sensitivity



ttH Channel	$\mu = \sigma/\sigma_{SM}$ (m_H = 125.7 GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

~2.7σ significance

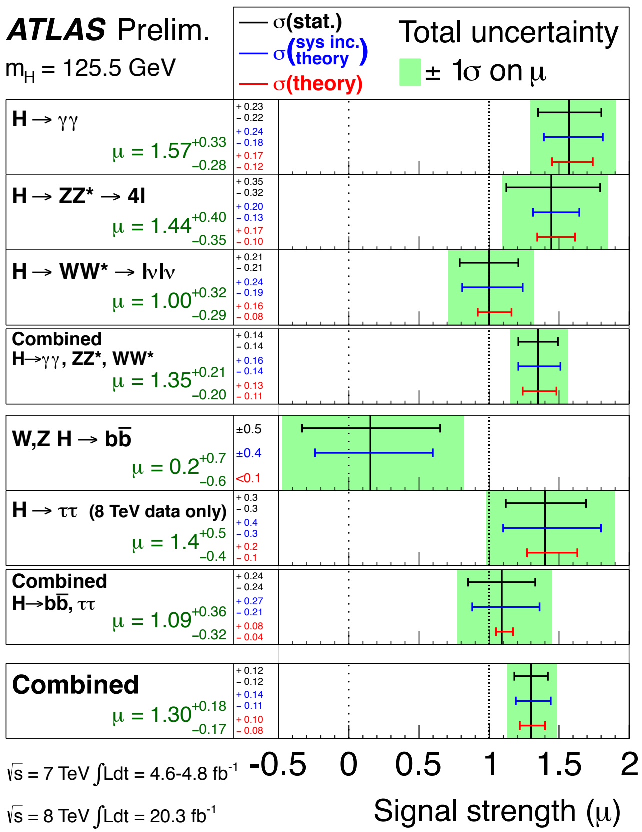
Higgs and Flavour Physics

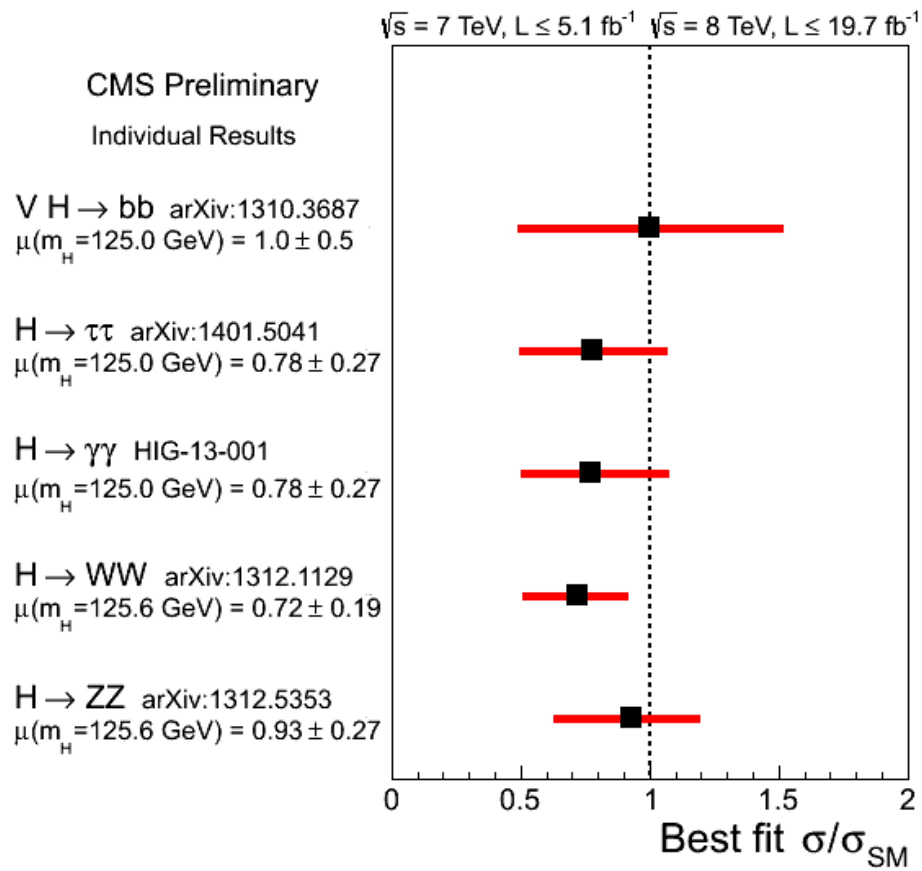
Higgs couplings — the big picture: agreement with SM

[ATLAS-CONF-2014-009, CMS: CMSPublic/PhysicsResultsHIG]

Combination of all Higgs production and decay channels (updates expected soon)

7% compatibility with μ = 1
4.6σ VBF significance



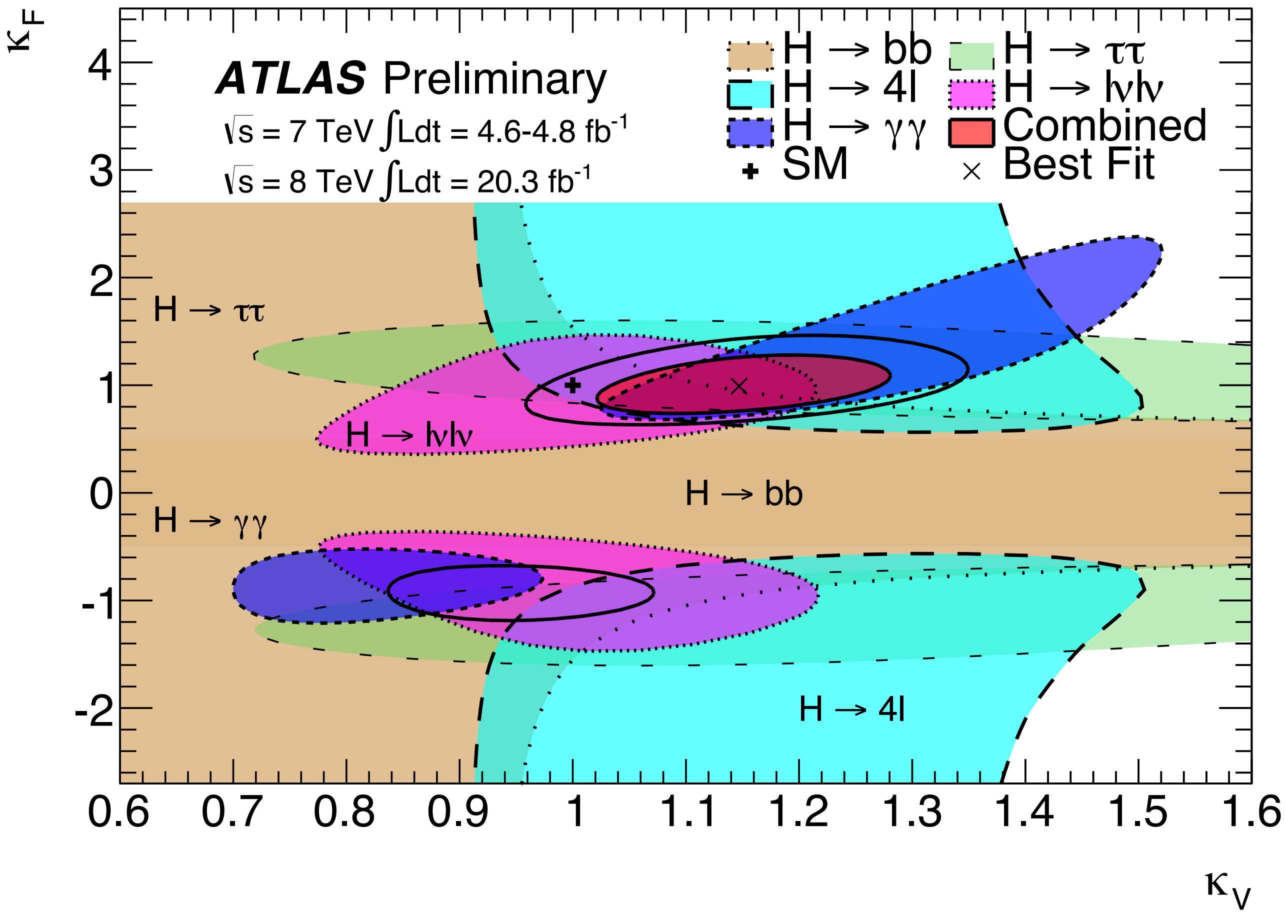


Higgs and Flavour Physics

Higgs couplings — the big picture: agreement with SM

[ATLAS-CONF-2014-009]

Fits of effective LO couplings: $\kappa_F = \kappa_{t,b,\tau,g}$ vs. $\kappa_V = \kappa_{W,Z} > 0|_{\text{convention}}$, where $\kappa_\gamma(\kappa_F, \kappa_V)$



Sensitivity to relative sign between κ_F and κ_V from destructive interference between W and top loops in $H \to \gamma\gamma$ decay:

$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 - 0.66 \cdot \kappa_W \kappa_t + 0.07 \cdot \kappa_t^2$$

$\boldsymbol{\kappa_F = 0.99\,^{+0.17}_{-0.15}}$

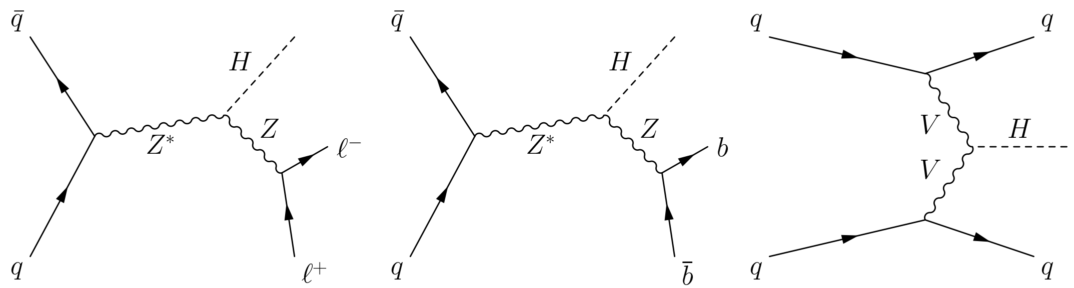
$\boldsymbol{\kappa_V = 1.15 \pm 0.08}$

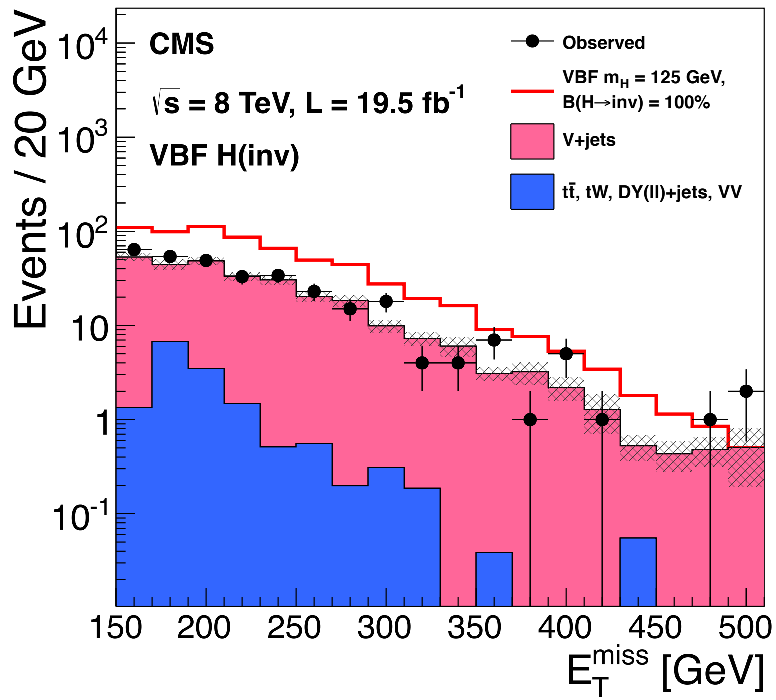
Higgs and Flavour Physics

BSM Higgs decays to invisible particles: $H \to \chi\chi$ (DM)

[ATLAS: 1402.3244, CMS: 1404.1344]

Powerful experimental methods to detect invisible decays of the Higgs





No experiment finds significant excess

Assuming SM production rates 95% CL upper limits on BR($H \to$ invisible) can be set

ATLAS: BR < 0.75, $ZH(\to ll)$

CMS: BR < 0.58, combining ZH + VBF

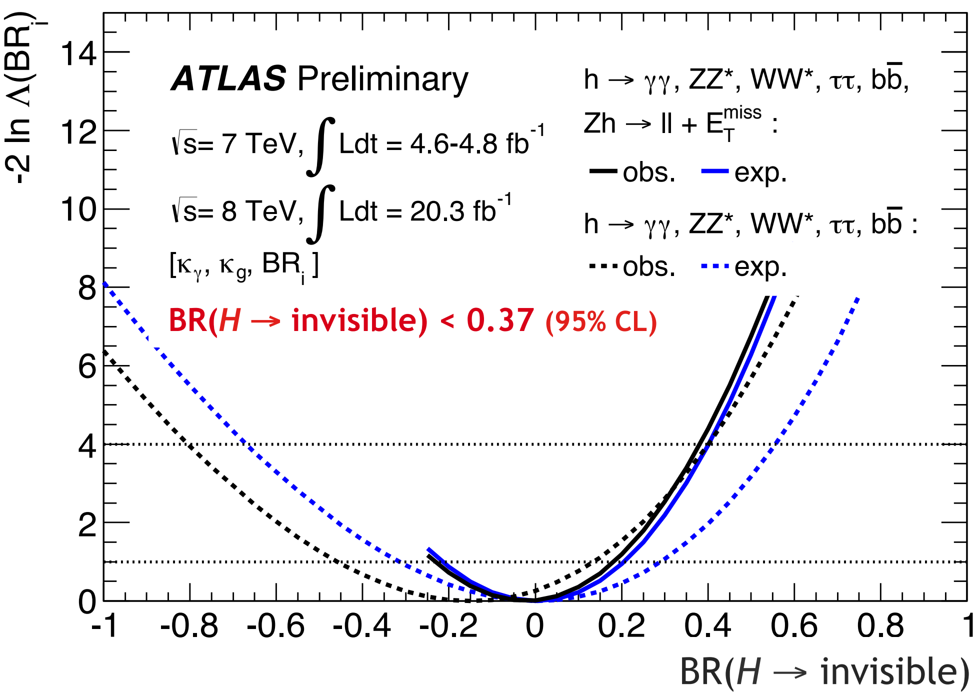
Higgs and Flavour Physics

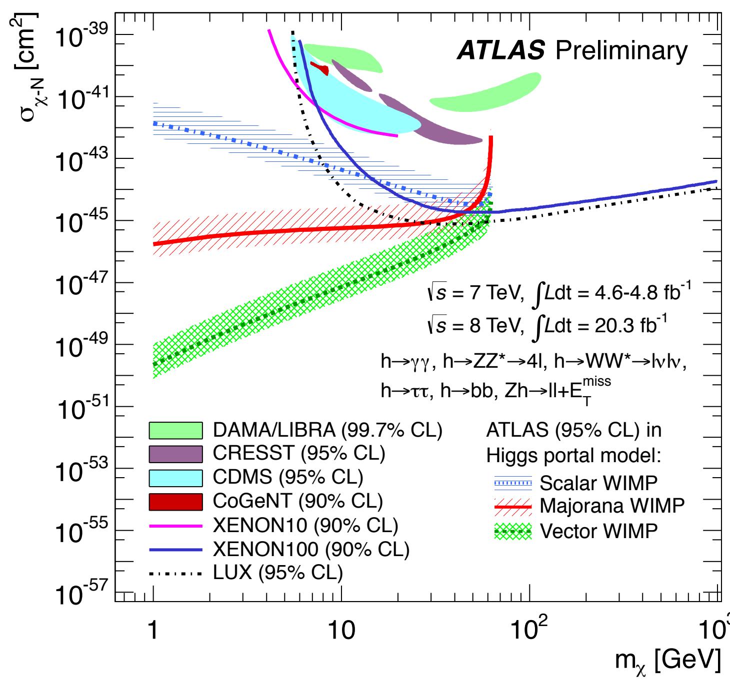
BSM Higgs decays to invisible particles: $H \to \chi\chi$ (DM)

[ATLAS-CONF-2014-010, CMS: 1404.1344]

Within "Higgs portal" models, these direct searches can be combined in a model-dependent way with the global Higgs coupling fit achieving a stronger constraint

- Assume SM-like tree Higgs couplings, but allow new physics in $H \to \gamma\gamma$, gg loop couplings
- Comparison of limits with direct DM searches assuming EFT validity



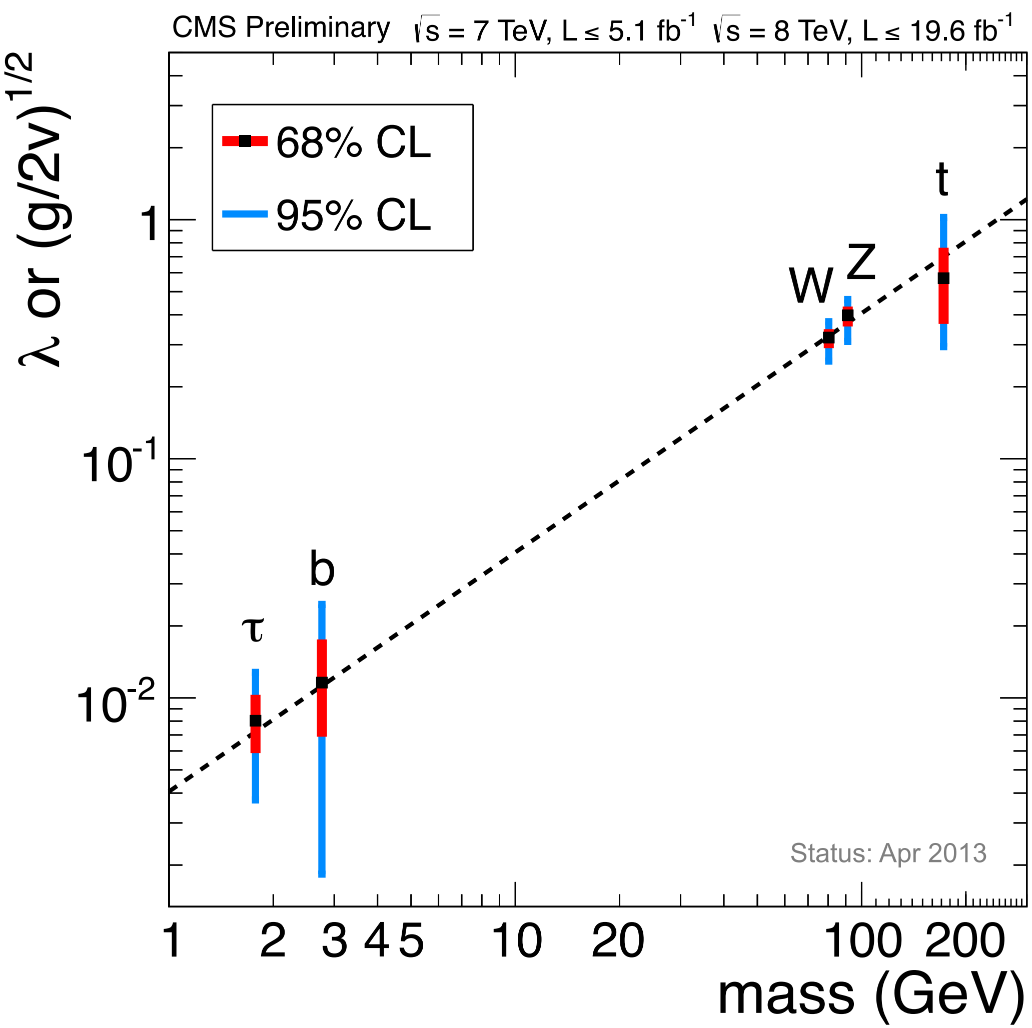


Higgs and Flavour Physics

Let's recapitulate…

[CMS-PAS-HIG-13-005]

Great measurements — the overall picture is as expected in the SM



Charged Higgs boson flavour physics

As an example for flavour-related BSM Higgs physics (much more exists!)

BSM Higgs zoo

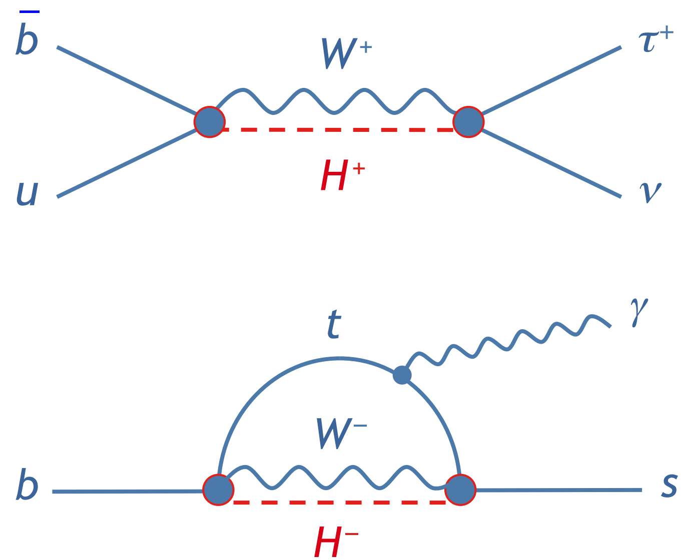
[Will Davey, LHCP 2014]

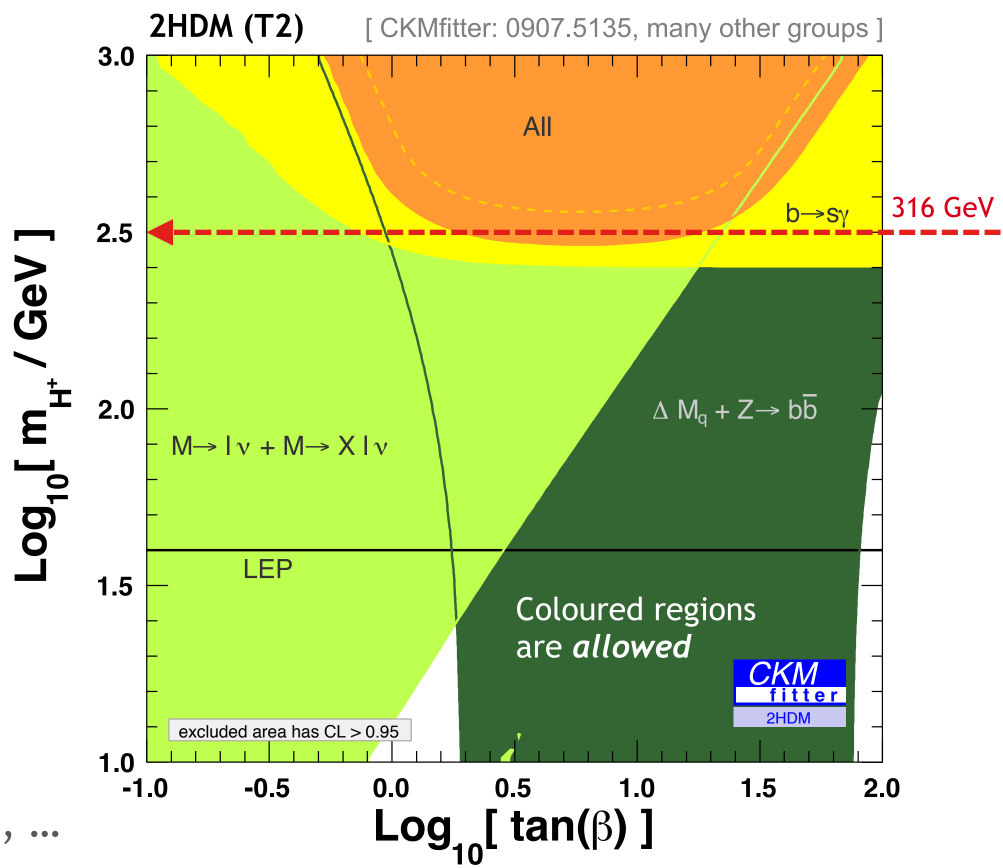
BSM Higgs and Flavour Physics

In BSM models, a charged Higgs boson would compete with *W* current

In principle, any tree or loop processes mediated by *W* and involving heavy fermions may receive charged Higgs contributions → modification of SM flavour

Examples:





Many others: R_b, $B \to D^{(*)}\tau\nu$, rare leptonic kaon and tau decays, neutral meson mixing, …

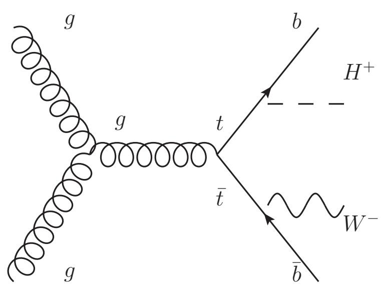
BSM Higgs and Flavour Physics

Direct charged Higgs searches at the LHC

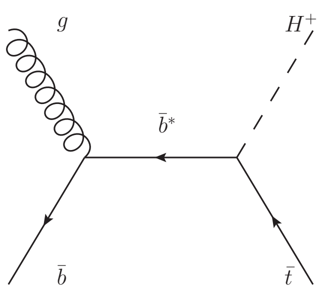
[ATLAS-CONF-2013-090, CMS: 1205.5736]

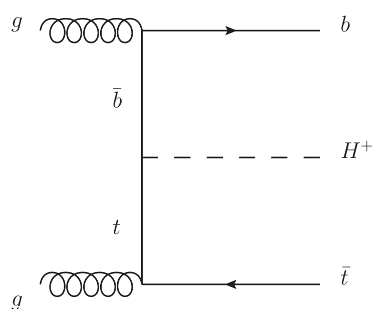
Distinguish direct searches in light / heavy H^+

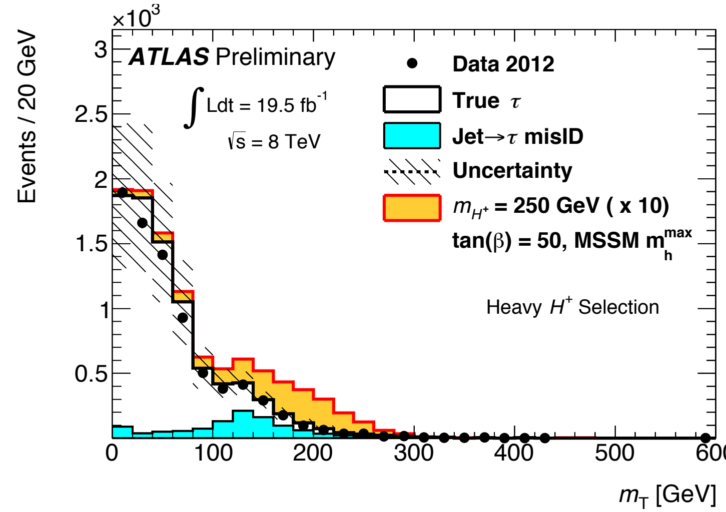
- Light charged Higgs ($m_{H+} < m_{top}$): $t \to bH^+$
  (BR decreases with m_{H+} and rises with $\tan\beta$)

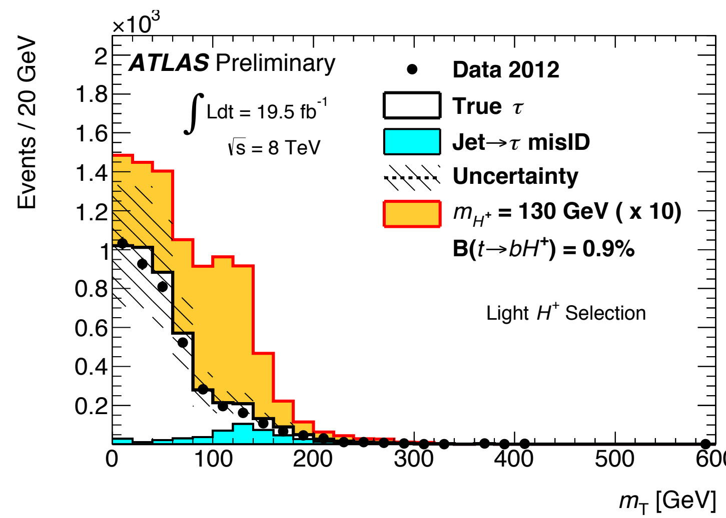


- Heavy charged Higgs ($m_{H+} > m_{top}$):
  $gb \to tH^+$ (4FS), $gg \to tbH^+$ (5FS)







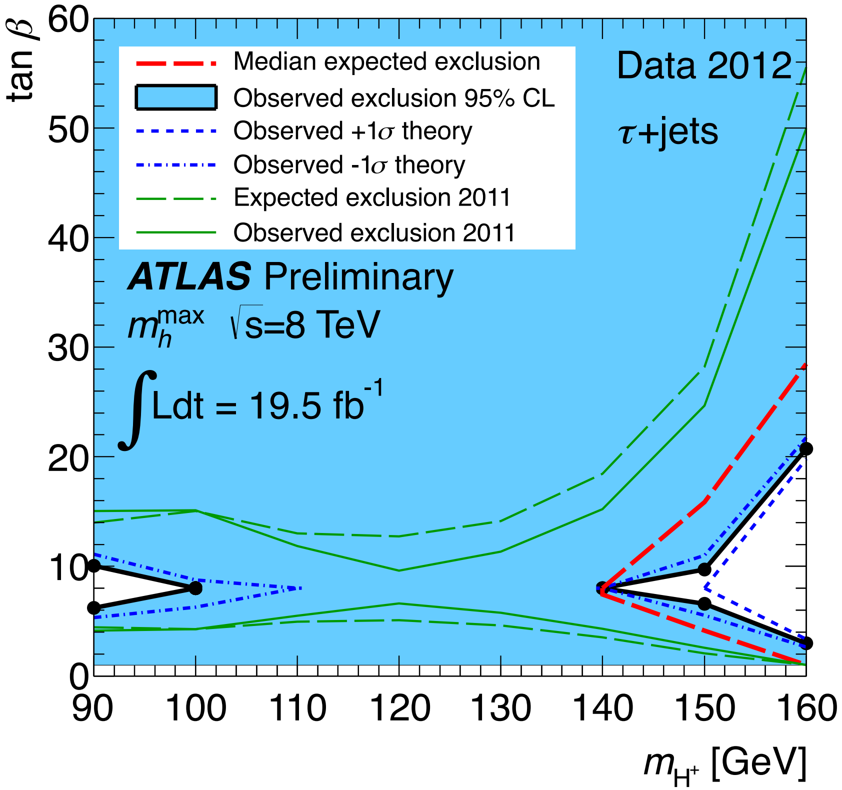


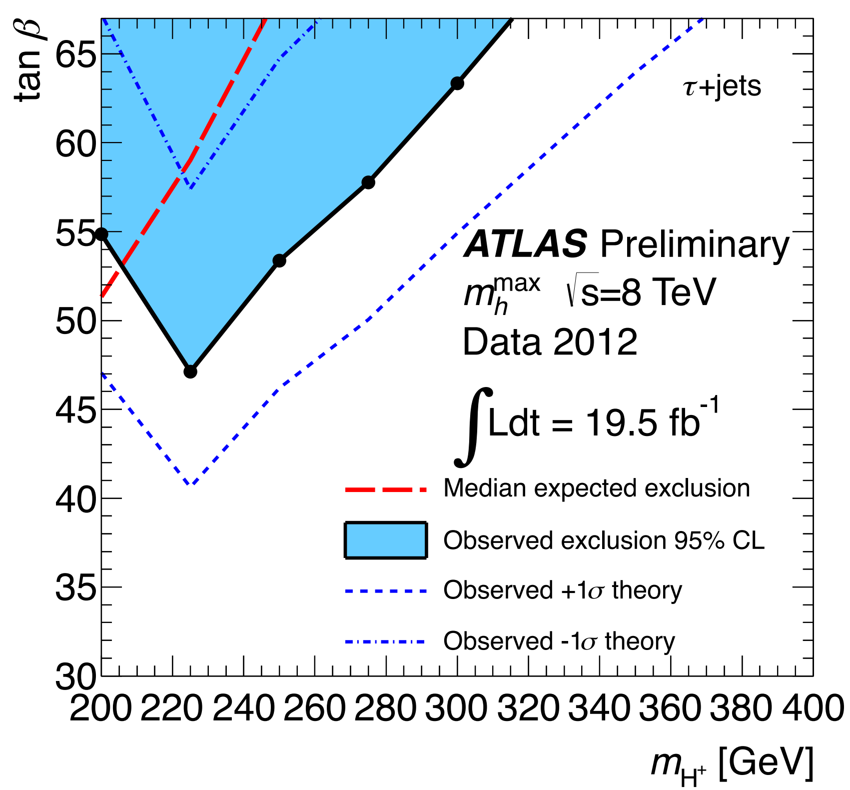
BSM Higgs and Flavour Physics

Direct charged Higgs searches at the LHC

[ATLAS-CONF-2013-090, CMS: 1205.5736]

Interpreting the limits obtained in the (so-called) MSSM m_h^{max} scenario, one finds:





→ Little room left for light H^+, much room for heavy H^+ (expts. also search for $H^+ \rightarrow tb$)

Higgs boson flavour physics

Pulling it together — constraining BSM Higgs-LFV Yukawa terms

Higgs and Flavour Physics

Lepton flavour violating Higgs couplings

[Yotam Soreq: LHCP 2014, Harnik-Kopp-Zupan: 1209.1397]

In L_{Yukawa} we had assumed the SM and removed flavour-violating terms in Y^l

Though in all generality it would look like this:

Limits from LF measurements

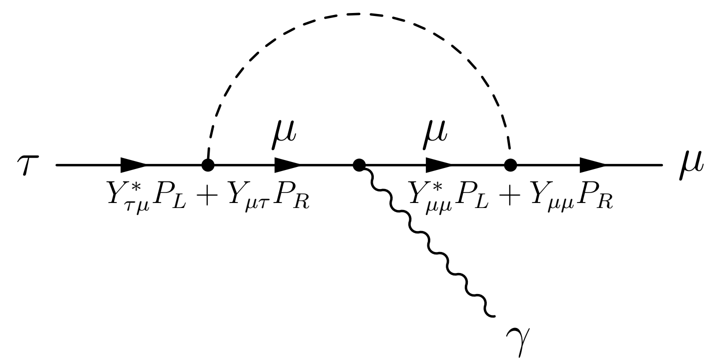
Upper limits (LHC)

$$Y^\ell = \begin{pmatrix} y_e & y_{e\mu} & y_{e\tau} \\ y_{\mu e} & y_\mu & y_{\mu\tau} \\ y_{\tau e} & y_{\tau\mu} & y_\tau \end{pmatrix}$$

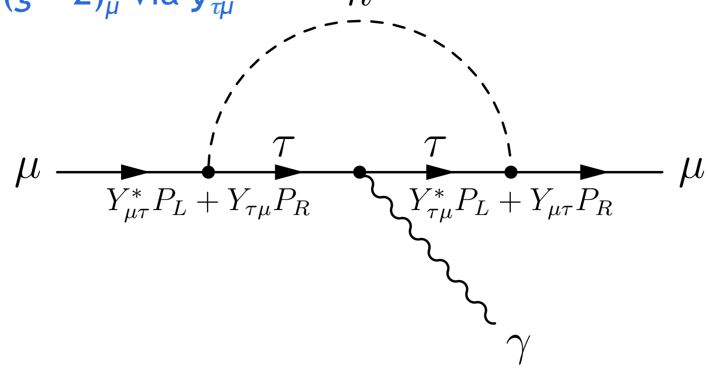
$H \to \tau\tau$ ($\sim m_\tau / \upsilon$) measured (LHC)

D=5 penguin diagrams:

$\tau \to \mu\gamma$ LFV via $y_{\tau\mu}$



$(g-2)_\mu$ via $y_{\tau\mu}$



Many more: $\mu \to e$ conversion, electron EDM (limits on complex couplings), muonium oscillation, …

Higgs and Flavour Physics

Lepton flavour violating Higgs couplings

In L_{Yukawa} we had assumed the SM and removed flavour-violating terms in Y^l

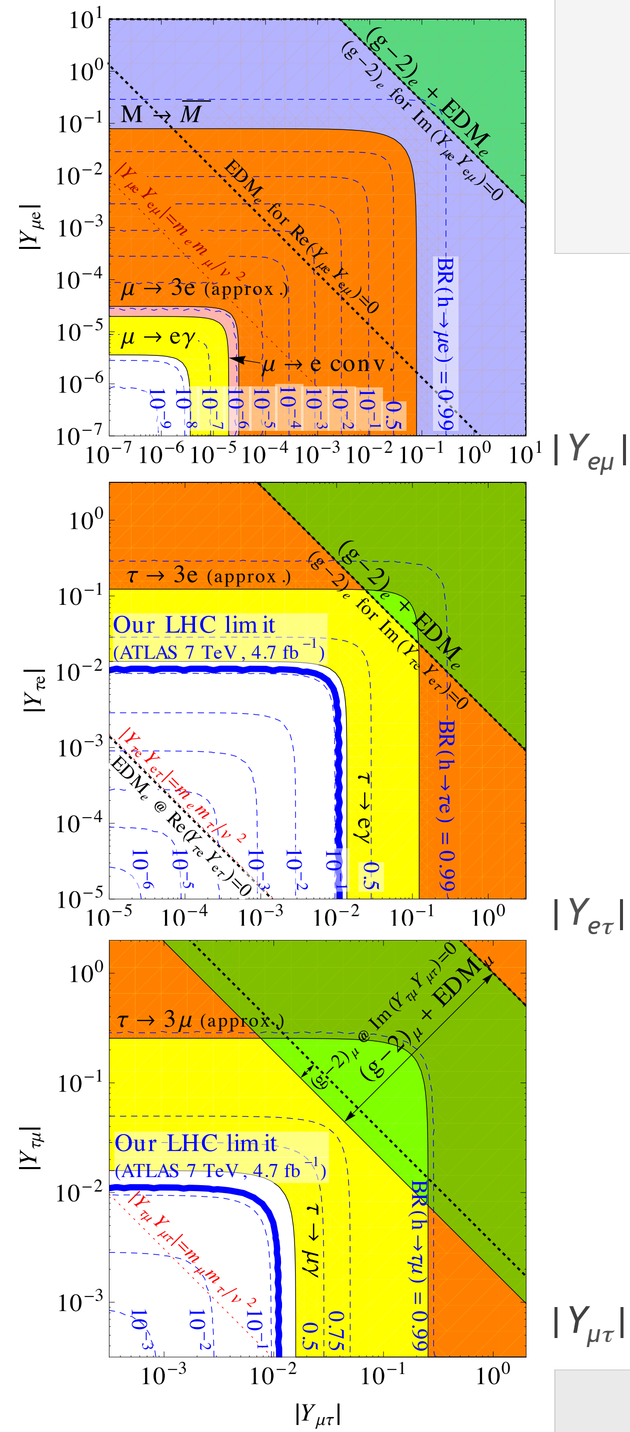
Though in all generality it would look like this:

Limits from LF measurements

Upper limits (LHC)

$$Y^{\ell} = \begin{pmatrix} y_e & y_{e\mu} & y_{e\tau} \\ y_{\mu e} & y_{\mu} & y_{\mu\tau} \\ y_{\tau e} & y_{\tau\mu} & y_{\tau} \end{pmatrix}$$

$H \to \tau\tau$ measured (LHC)



[Yotam Soreq: LHCP 2014, Harnik-Kopp-Zupan: 1209.1397]

Higgs and Flavour Physics

Quark flavour violating Higgs couplings

[Yotam Soreq: LHCP 2014, Harnik-Kopp-Zupan: 1209.1397]

Diagonal elements of Yukawa matrix from Higgs-to-quark-pair couplings

$$Y^d = \begin{pmatrix} y_d & y_{ds} & y_{db} \\ y_{sd} & y_s & y_{sb} \\ y_{bd} & y_{bs} & y_b \end{pmatrix}$$

$H \to bb$ to be measured (LHC)

$$Y^\ell = \begin{pmatrix} y_u & y_{uc} & y_{ut} \\ y_{cu} & y_c & y_{ct} \\ y_{tu} & y_{tc} & y_t \end{pmatrix}$$

Limits from $t \to qH$ and single-top production (LHC)

ttH to be measured (LHC)

$$\sqrt{|y_{tq}|^2 + |y_{qt}|^2} < 0.17$$

[ATLAS: 1403.6293]

Also limit on Im($ut \cdot tu$) from neutron EDM

Higgs and Flavour Physics

Quark flavour violating Higgs couplings

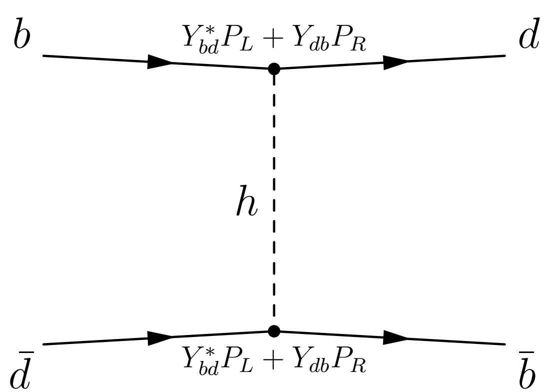
[Yotam Soreq: LHCP 2014, Harnik-Kopp-Zupan: 1209.1397]

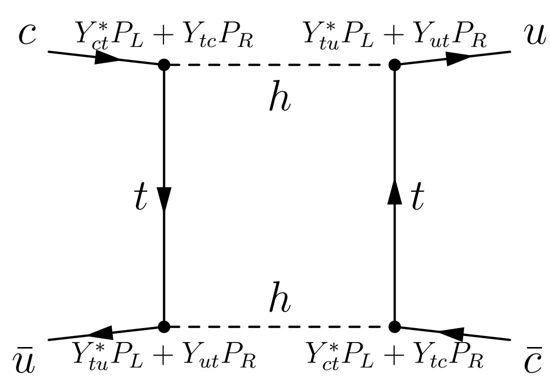
Tight limits (10^{-6} … 10^{-12}) on off-diagonal elements from neutral meson mixing

$$Y^d = \begin{pmatrix} y_d & y_{ds} & y_{db} \\ y_{sd} & y_s & y_{sb} \\ y_{bd} & y_{bs} & y_b \end{pmatrix} \qquad Y^\ell = \begin{pmatrix} y_u & y_{uc} & y_{ut} \\ y_{cu} & y_c & y_{ct} \\ y_{tu} & y_{tc} & y_t \end{pmatrix}$$

Limits on Re/Im $(sd)^2$, $(ds)^2$ from K^0–$\overline{K}^0$ mixing,
on $|db(s)|^2$, $|bd(s)|^2$ from $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing

Limits on $|uc|^2$, $|cu|^2$ from D^0–$\overline{D}^0$ mixing



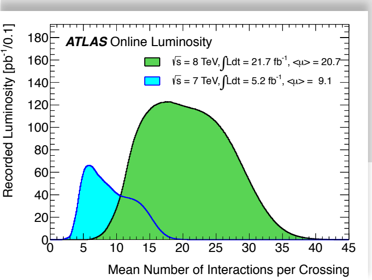


Examples of flavour violating diagrams contributing to neutral meson mixing [1209.1397]

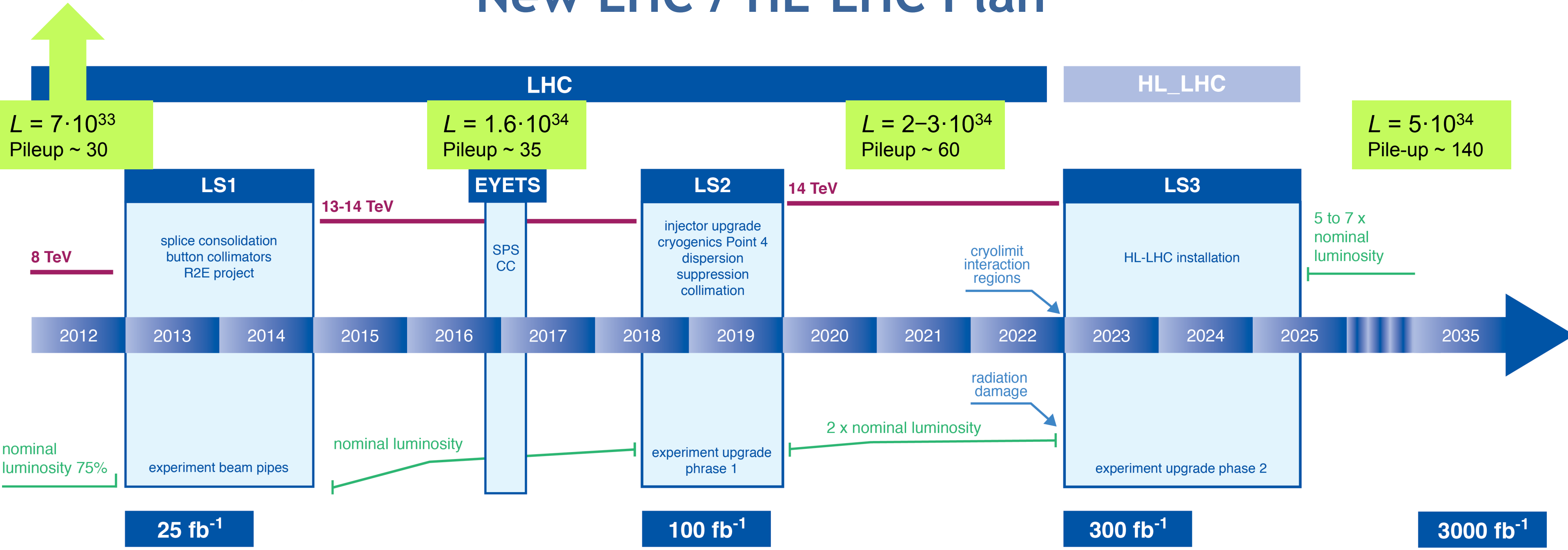
Higgs @ Run-2 and the HL-LHC

Fabiola Gianotti at LHCP 2014:

Full exploitation of LHC project with HL-LHC (√s = 14 TeV, 3000 fb⁻¹) is MANDATORY
(Europe's top priority per European Strategy, US highest-priority near-term large project per P5)



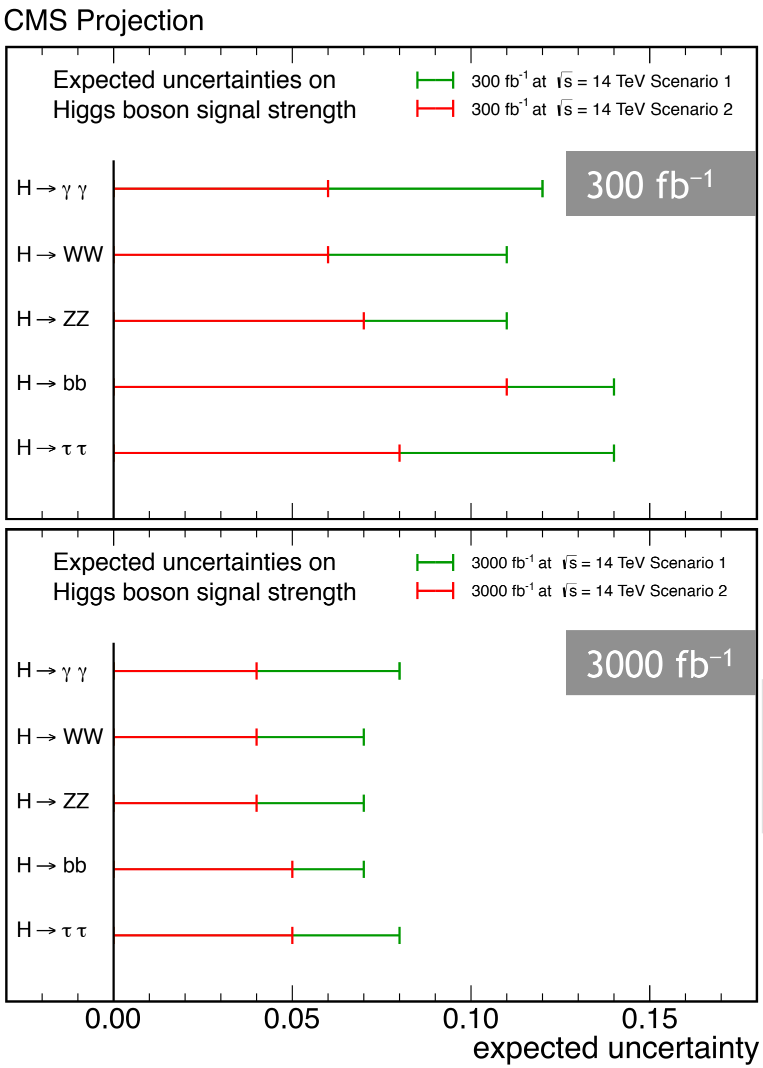
New LHC / HL-LHC Plan



Higgs @ Run-2 and the HL-LHC

Extrapolations of signal strength measurements

[CMS: 1307.7135]



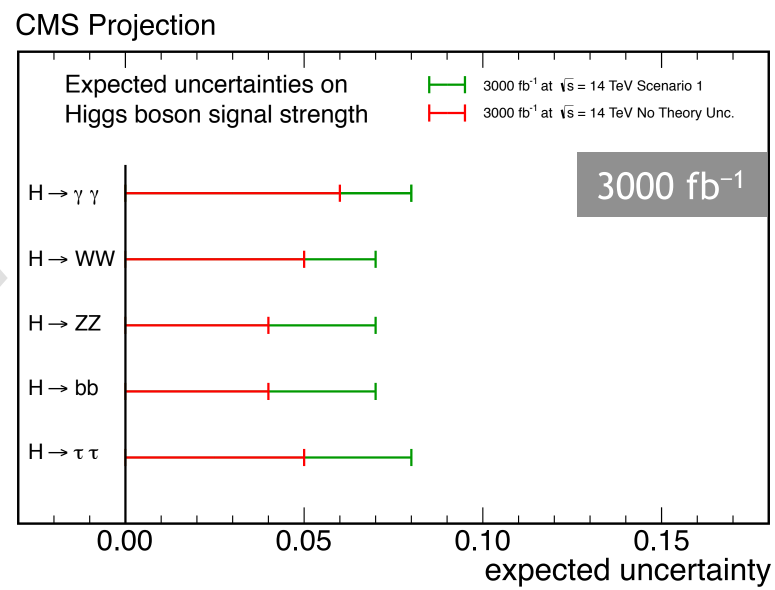
Scenario 1 (pessimistic):

Systematic uncertainties as today

Scenario 2 (optimistic):

Experimental uncertainties as $1/\sqrt{L}$, theory halved

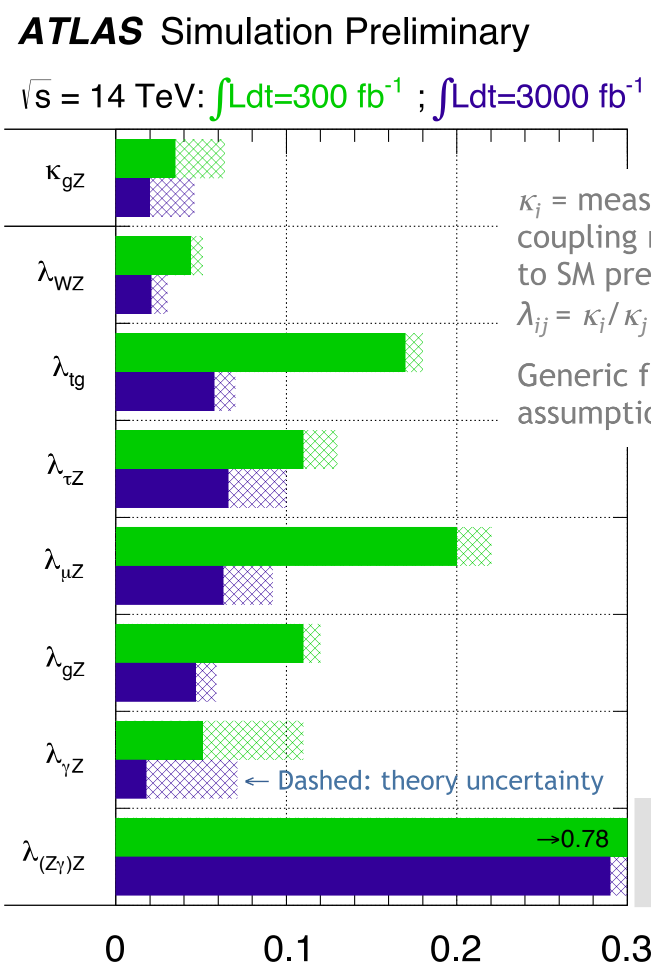
Without theory errors



Higgs @ Run-2 and the HL-LHC

Extrapolations of coupling measurements

[ATLAS: ATL-PHYS-PUB-2013-014, ATL-PHYS-PUB-2014-006]



$\Delta\lambda_{XY}=\Delta\left(\frac{\kappa_X}{\kappa_Y}\right)$

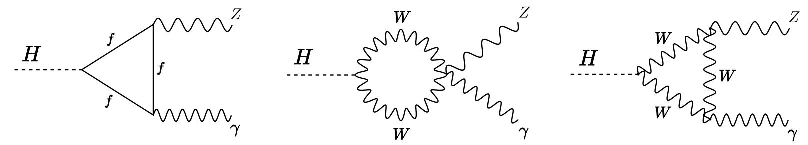
κ_i = measured coupling normalized to SM prediction

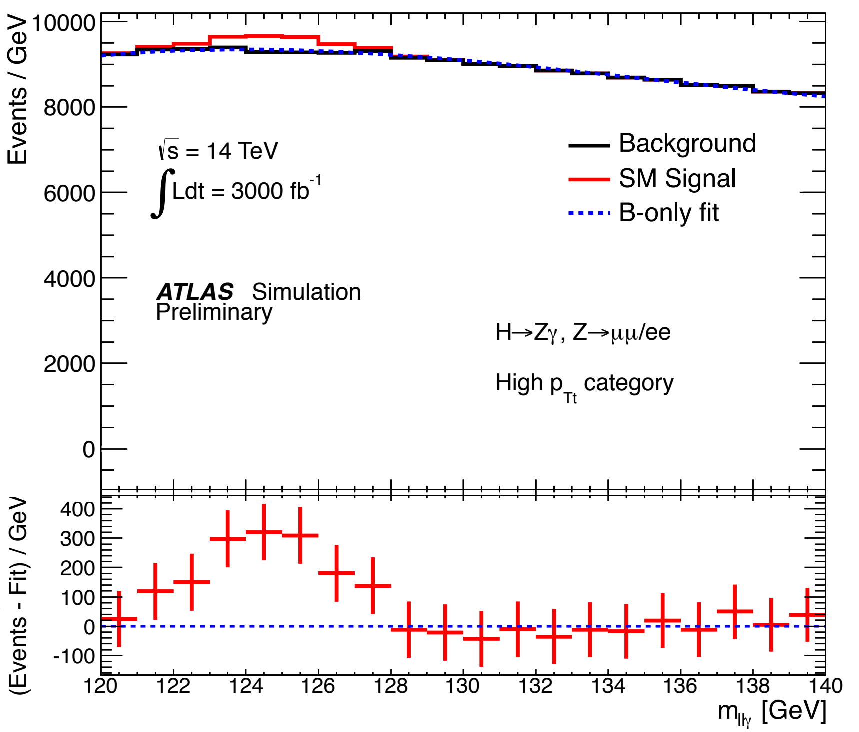
$\lambda_{ij} = \kappa_i / \kappa_j$

Generic fit without assumptions

Improved in new study

New ATLAS HL-LHC study on $pp \rightarrow H \rightarrow Z\gamma$



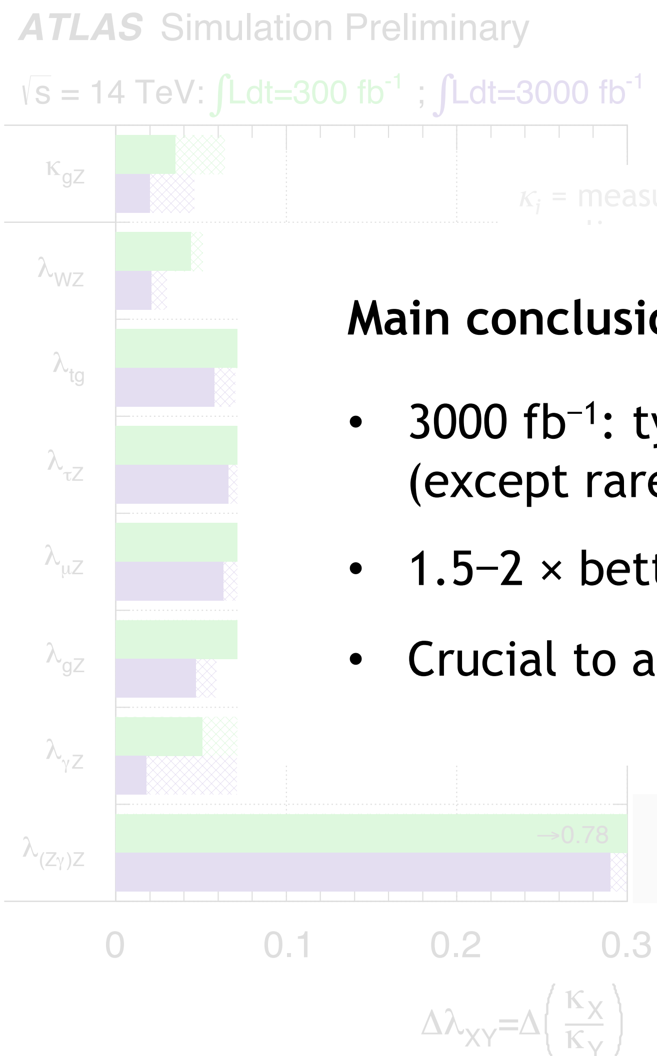


Expect: 3.9σ (2.3σ) with 3000 (300) fb^{-1}

Higgs @ Run-2 and the HL-LHC

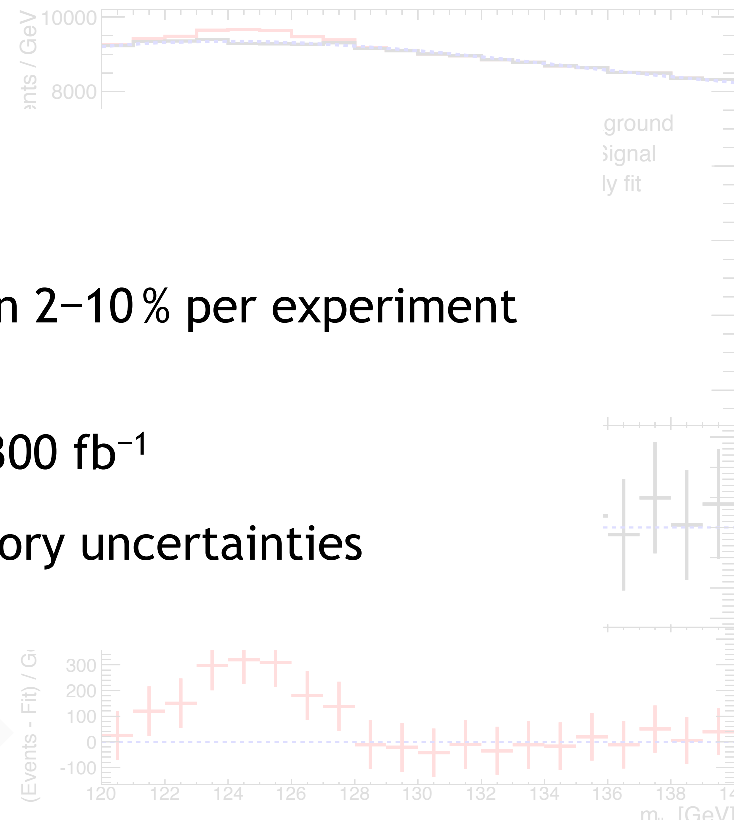
Extrapolations of coupling measurements

[ATLAS: ATL-PHYS-PUB-2013-014, ATL-PHYS-PUB-2014-006]



Improved in new study

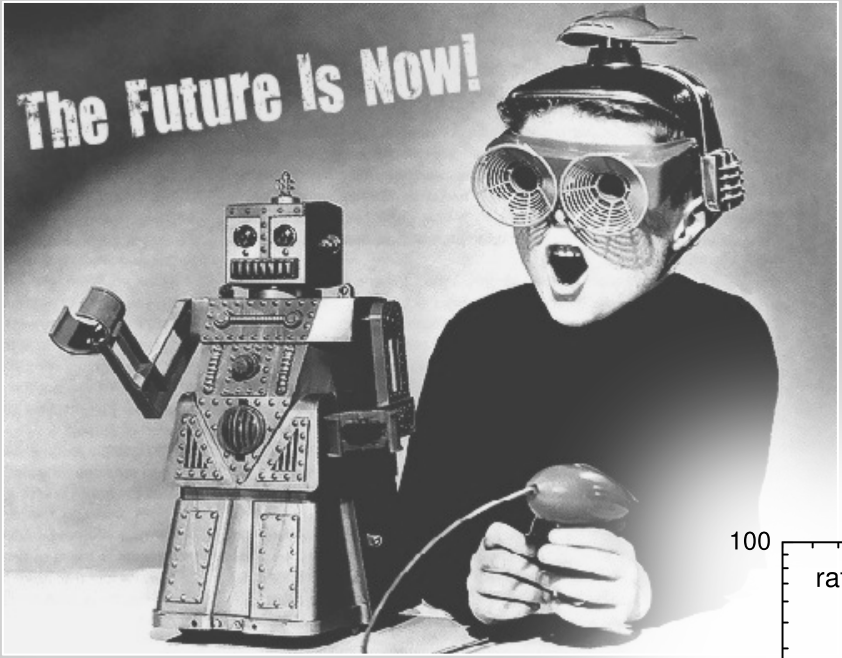
New ATLAS study on $pp \to H \to Z\gamma$

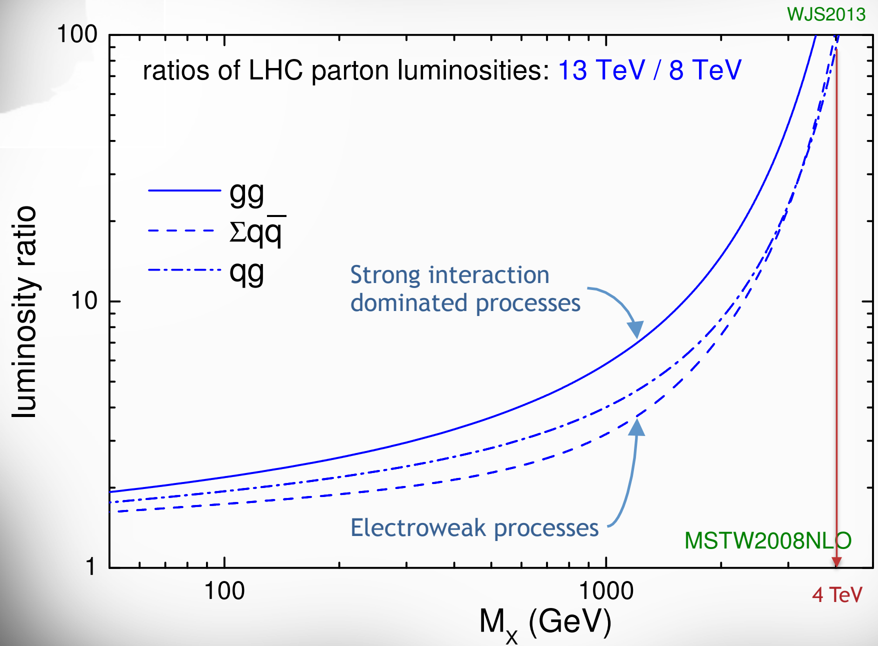


Expect: 3.9σ (2.3σ) with 3000 (300) fb^{-1}

Main conclusions:

- 3000 fb^{-1}: typical precision 2–10 % per experiment (except rare modes)
- 1.5–2 × better than with 300 fb^{-1}
- Crucial to also reduce theory uncertainties

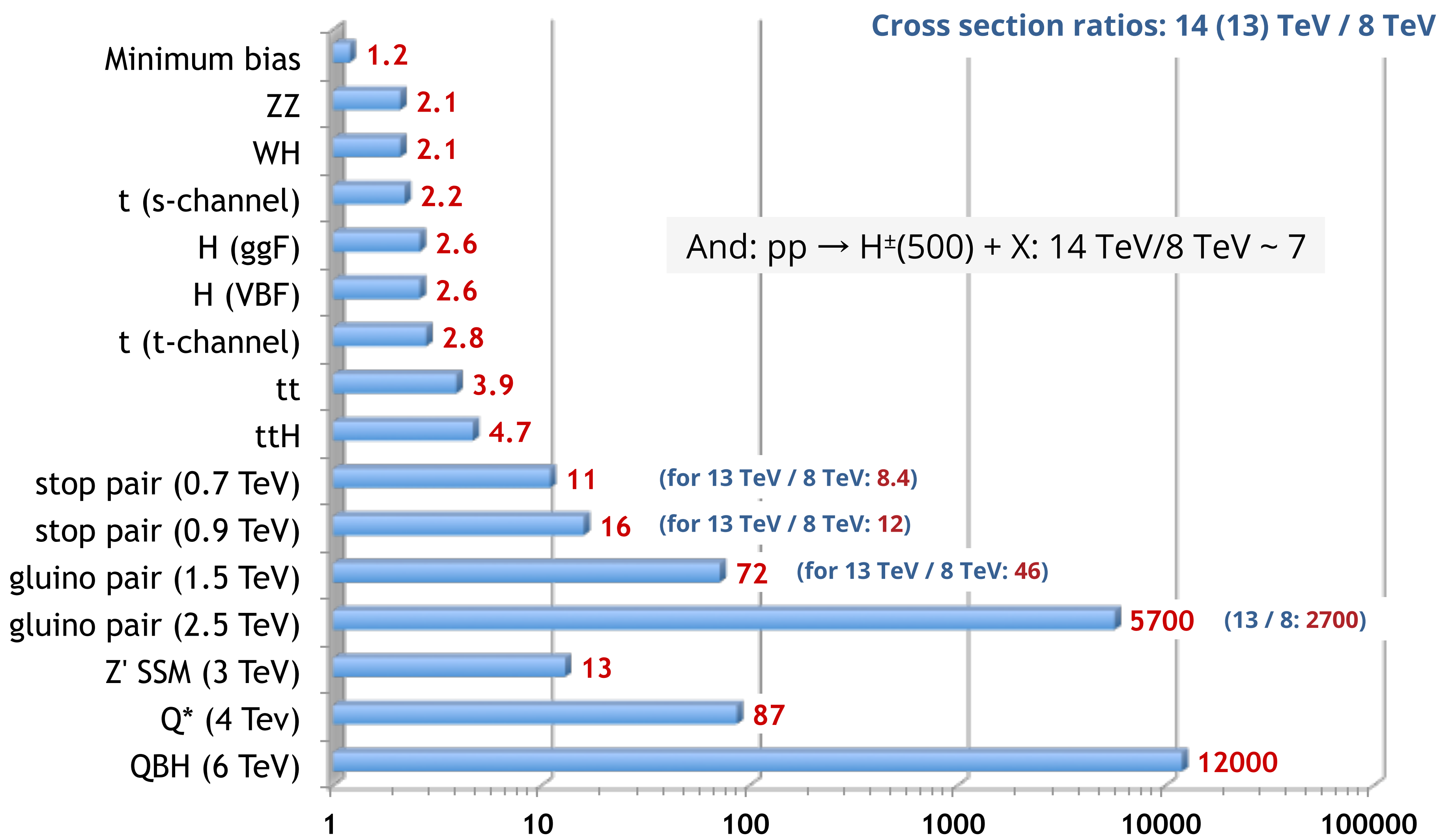

The Future Is Now!


WJS2013
ratios of LHC parton luminosities: 13 TeV / 8 TeV
gg
Σqq̄
qg
Strong interaction dominated processes
Electroweak processes
MSTW2008NLO
luminosity ratio
100
10
1
100
1000
4 TeV
M_X (GeV)

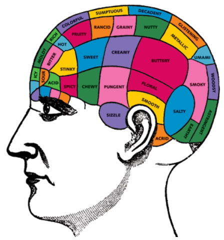
Cross section ratios

Hugely increased potential for discovery of heavy particles at 13~14 TeV

But life can become harder for states lighter than tt



Conclusions



- Flavour physics is precisely predicted in the SM and allows experimentalists to study a large variety of very different phenomena, some reaching out to very high mass scales
- The LHC added crucial new areas: precision Higgs, top and B_s physics
- Mined from all sides flavour physics appears ever more SM like
- Matching the picture that emerges from the LHC Run-1 new physics searches
- Success of CKM paradigm is puzzling in light of EW hierarchy problem
- In lack of guidance from new physics, flavour physics must remain as broad as possible and constraints from it become even more important
- New tools are ahead: LHC Run 2, HL-LHC, Super-KEKB/Belle-2, NA62, KOTO, Mu2e, new g-2, and more

Spare slides …

Constraints on flavour violating Higgs couplings to quarks (left) and leptons (right)

[Harnik-Kopp-Zupan: 1209.1397]

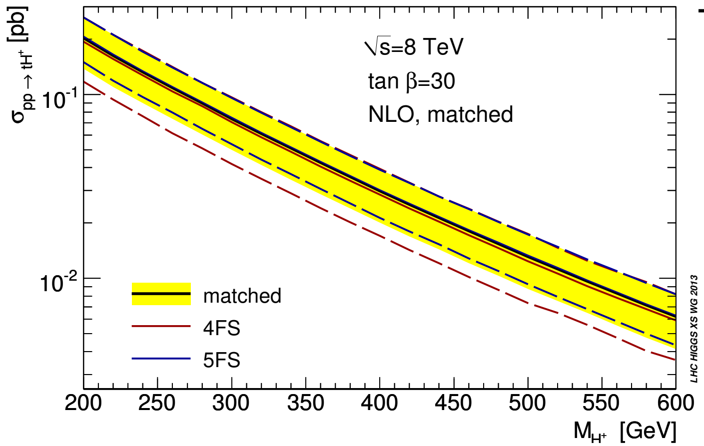
Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [48]	$\lvert Y_{ut}Y_{ct}\rvert$, $\lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert$, $\lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 4.6 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y_{e\mu}^*\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau}Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau}Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu}Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau}Y_{e\tau}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

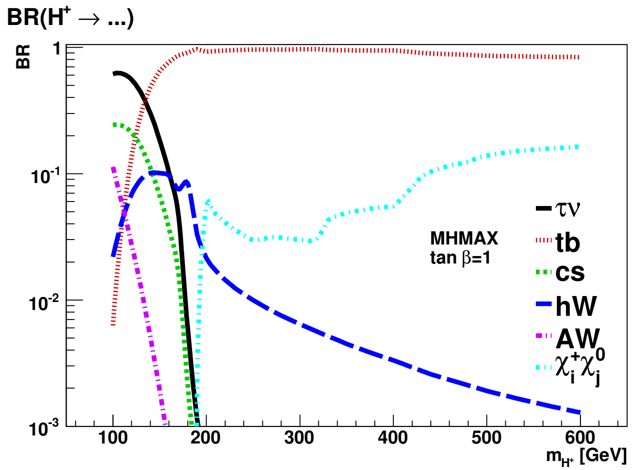
BSM Higgs and Flavour Physics

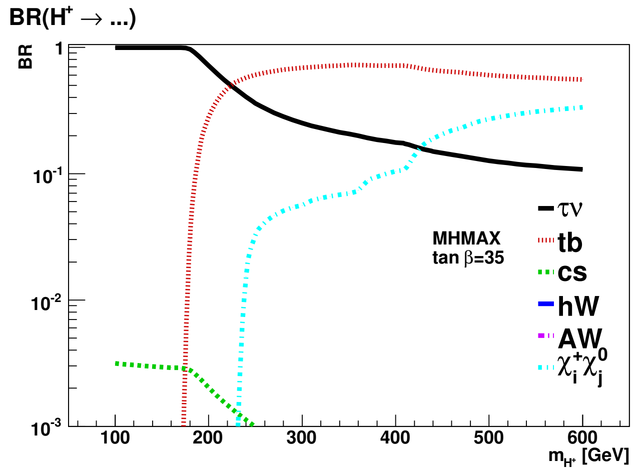
Direct charged Higgs searches at the LHC

Cross section and branching fractions for charged Higgs



Type-II 2HDM





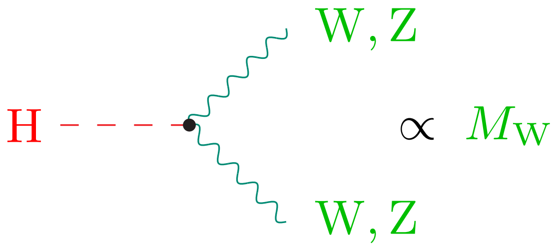
MSSM

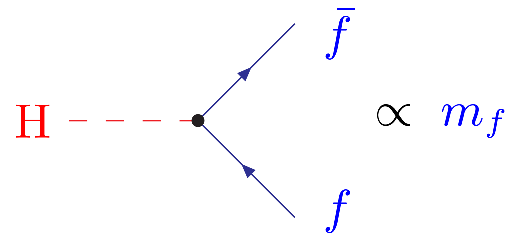
m_h^{max} scenario

[Stefan Dittmaier, LHCP 2014]

Higgs processes at the LHC

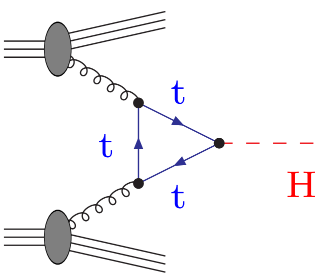
Higgs bosons couple proportional to particle masses:

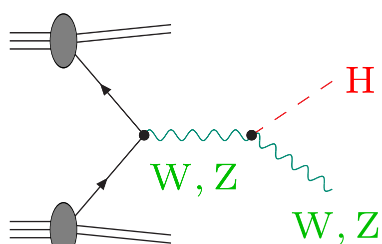


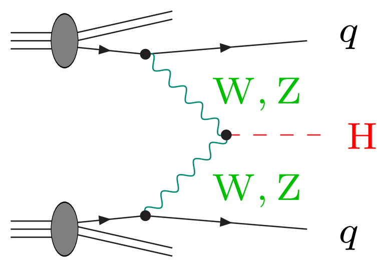


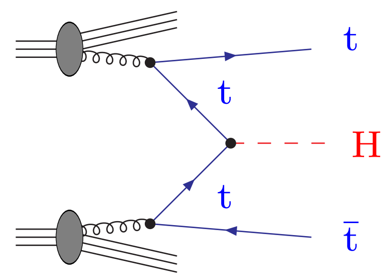
$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):









Decay channels of the Higgs boson: