Recent highlights from LHCb

Pheno Conference, May 5-7, 2014, Pittsburgh, PA

Steven Blusk

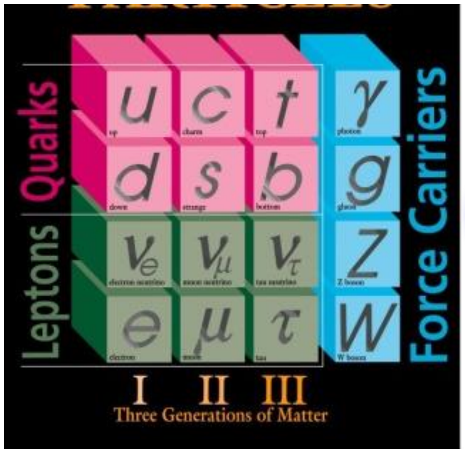
Syracuse University

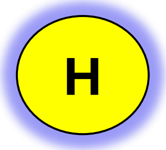
on behalf of the LHCb collaboration

A triump of the last 50-60 years

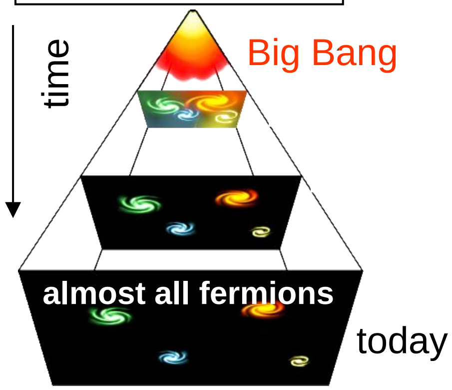
But the must be incomplete

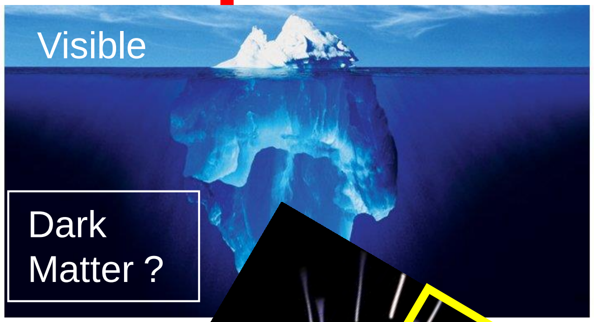
The “Complete” Standard Model



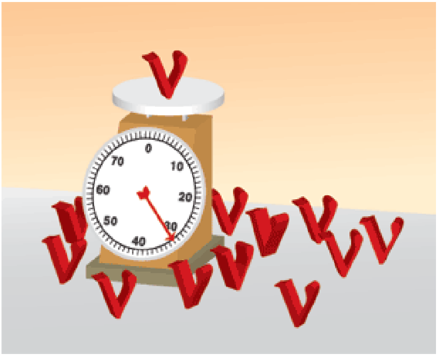


Baryogensis ?





Dark Matter ?

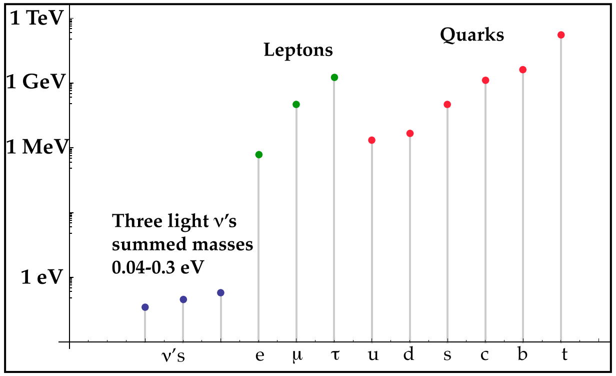


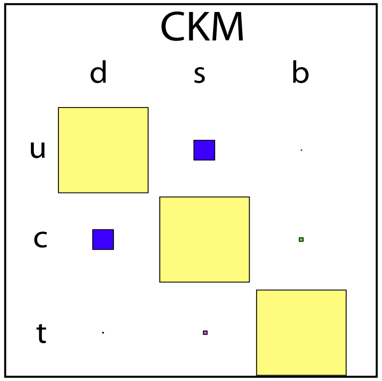
Neutrinos mass! Dirac? Majorana? CPV, Leptogenesis

GUT?
How does gravity fit in?

Hierarchy problem ?
$M_H << M_{Planck}$

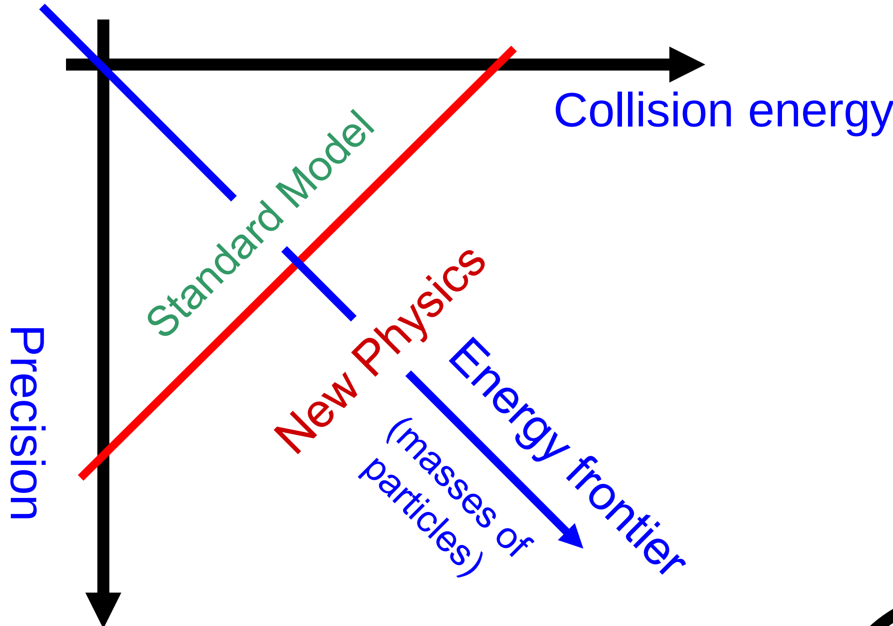
Hierarchy of masses and mixing in quark and lepton sectors



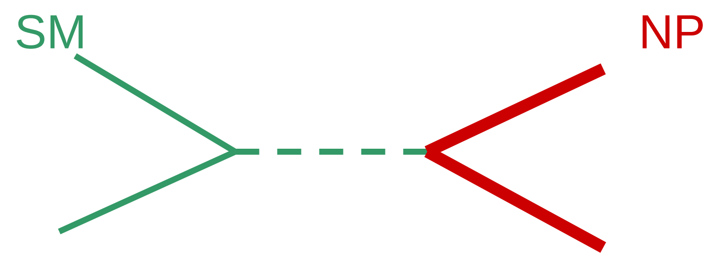


12 orders of magnitude differences not explained

NP at accelerator-based experiments

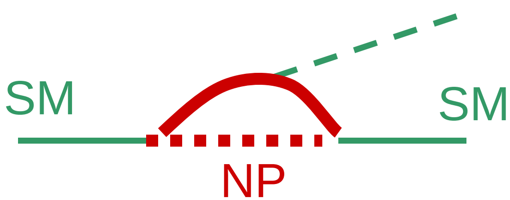


Tree diagrams, for example



Generally need $E_{beam} > M_{NP}$

Loop diagrams, for example



$$L_{eff} = L_{SM} + \frac{c_i}{\Lambda_i^2} O_i$$

For low energy observables, we will likely need precision!

Higgs – CKM connection

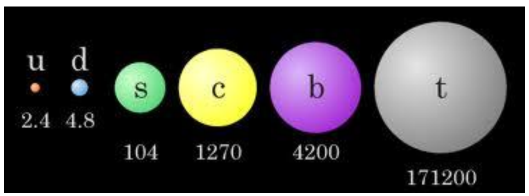
down-type, up-type, Charged ℓ

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}^i_L\phi D^j_R + Y_u^{ij}\bar{Q}^i_L\tilde{\phi}U^j_R + Y_e^{ij}\bar{L}^i_L\phi E^j_R + \text{h.c.}$$

ϕ = Higgs doublet

diagonalize

quark (and lepton) masses



CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim$$

$$d' = V_{ud}d + V_{us}s + V_{ub}b$$
$$s' = V_{us}d + V_{cs}s + V_{cb}b$$
$$b' = V_{td}d + V_{ts}s + V_{tb}b$$

Origin of fermion mass and flavor/CKM-physics intimately connected

CKM matrix

- Quark flavor transitions in SM
- Complex phase, η → CPV
- **Problem**:
  CPV in CKM 10^9 too small for BAU.
  - NP phases needed
  - Precision tests of CKM imperative

Wolfenstein parameterization

$$\mathbf{V} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

$$\boldsymbol{\delta}\mathbf{V} = \begin{pmatrix} 0 & 0 & 0 \\ -iA^2\lambda^5\eta & 0 & 0 \\ A\lambda^5(\rho+i\eta)/2 & -A\lambda^4(1/2-\rho-i\eta) & 0 \end{pmatrix}$$

- **Magnitudes** probed using rates, e.g. $|V_{td(s)}|$ with $B_{(s)}$ mixing.
- **Phases** probed using CPV asymmetries

Uncovering New Physics using b's

Kobayashi & Maskawa
Nobel Prize 2008

Two main lines of attack

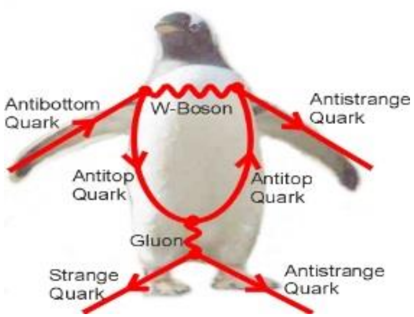
Deviations in observables from SM predictions
(requires 'theoretically clean' SM prediction)

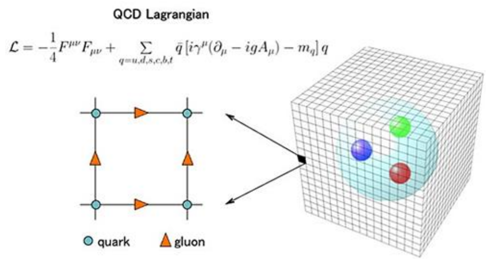
- Rare/forbidden decays
  E.g. $B_s \rightarrow \mu^+\mu^-$,..
- CPV in certain modes
  E.g. $\sin(2\beta_s)_{J/\psi\phi}$, $B_s \rightarrow D_s \ell \nu$, …
- Angular observables
  E.g. A_{FB} in $K^*\mu\mu$, ..
- …

Comparison of observables insensitive to and sensitive to **New Physics**.

Trees: γ, V_{ub}

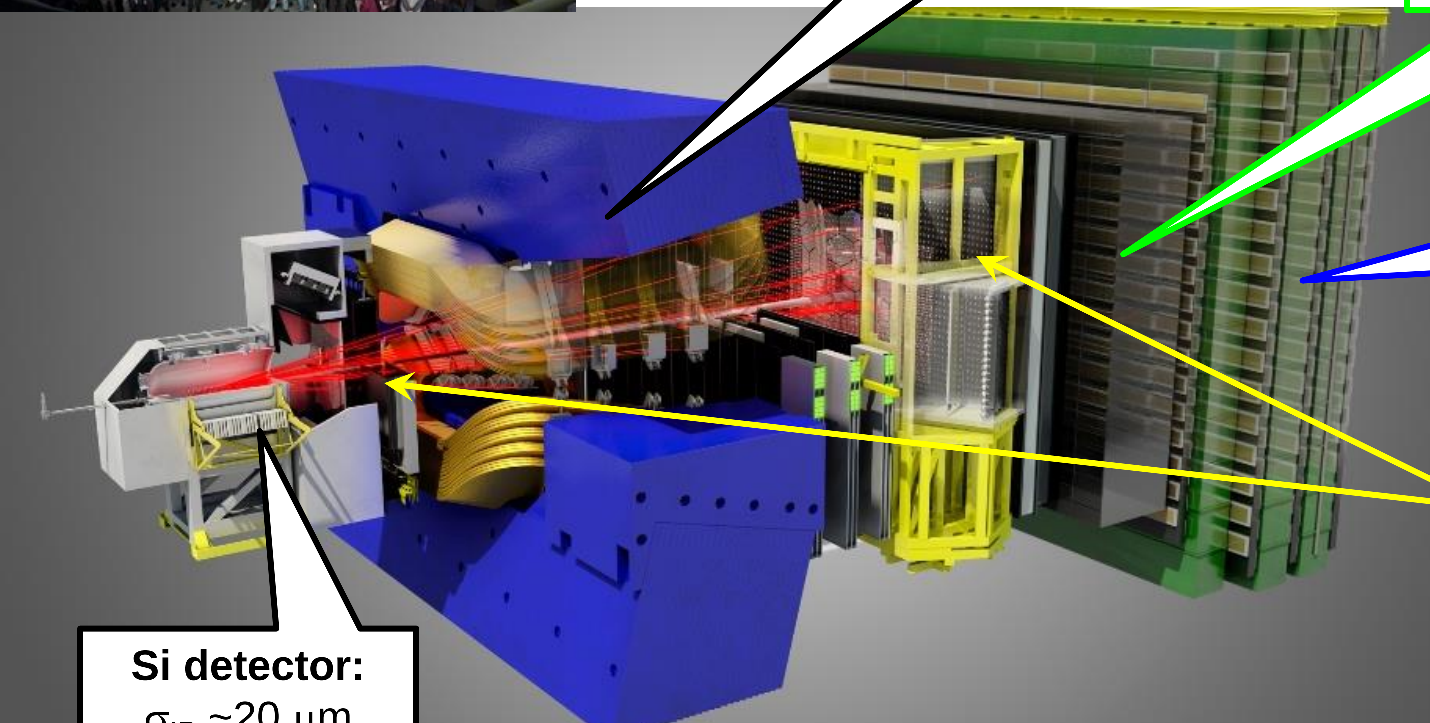
Loops



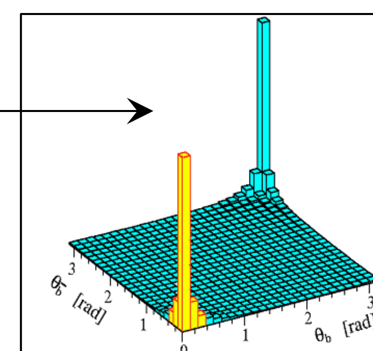


- Many measurements ~free from theory uncertainty
- Sometimes, need input from theory (usually QCD-related) to go from m'ment → underlying parameters

LHCb detector: Key aspects

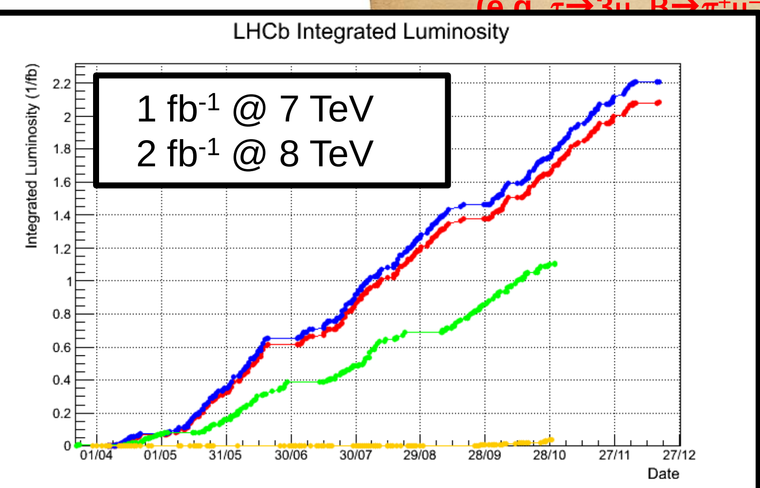


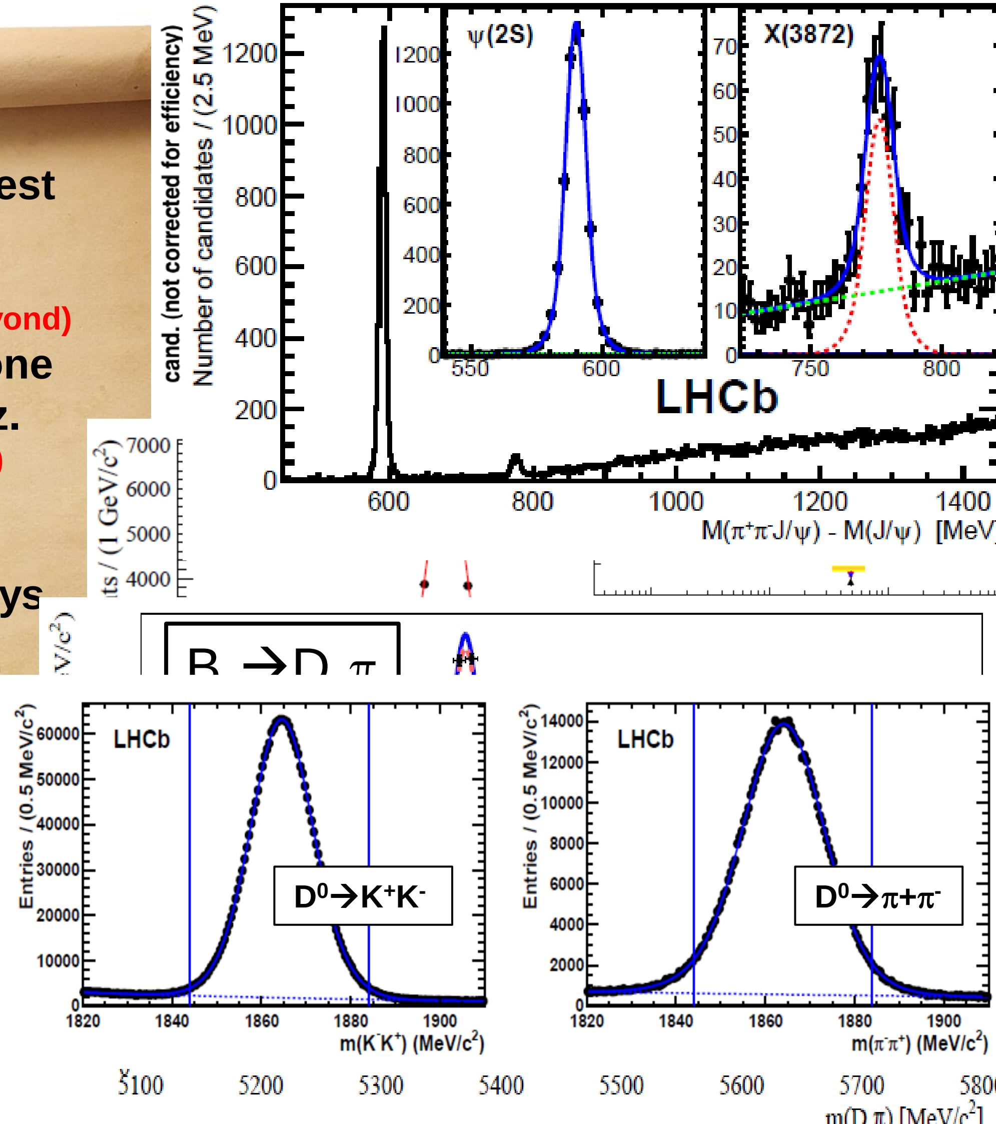
- ❑ Large $b\bar{b}$ xs in forward region (~50,000 b / sec into LHCb).
- ❑ Precision vertexing, excellent PID – crucial for b,c physics
- ❑ High BW trigger (~4kHz to tape ~ 10X CMS, ATLAS)
- ❑ Fully hadronic b triggers (in addition to μ, $\mu\mu$, etc)
- ❑ **LHCb is a GPD: If it's in our acceptance, we can trigger on it!**



LHCb Physics menu

- All b-decays of interest
  (B$^{-,0}$, B$_s$, B$_c$, b baryons..)
- Di-muon decays
  (Drell-Yan, ψ,Υ,.. Z^0 and beyond)
- As much charm as one can fit into a few kHz.
  (CPV, lifetimes, mixing, etc)
- W/Z + jets,c,b
  (Production, PDFs …)
- Rare/forbidden decays
  (e.g. $\tau \to 3\mu$, $B \to \pi^+\mu^-\mu^-$ …)
- … X, Y, Z'
- … avy ex…
- … sive/di…





Can only scratch the surface here … many more analyses in parallel sessions
~ apologies ~

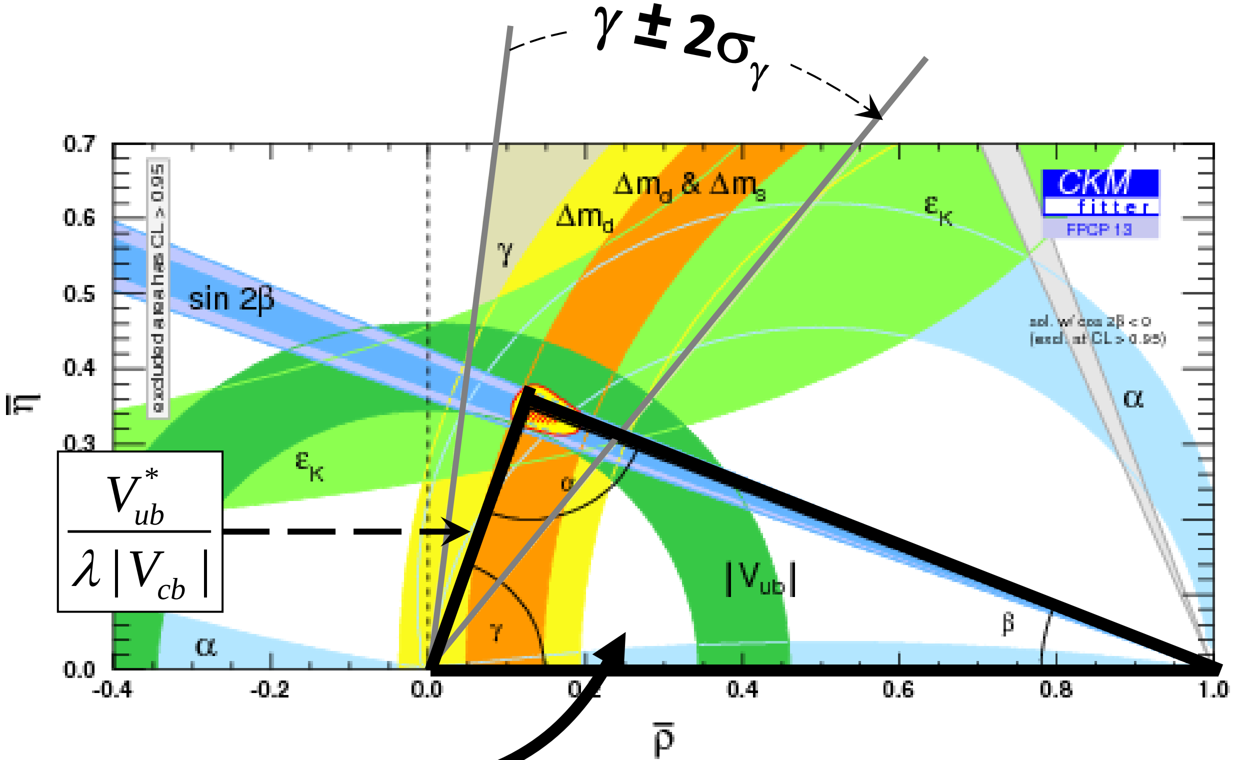
TREES

UT & determination of the Weak Phase γ

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$\frac{V_{ub}^{*}}{\lambda |V_{cb}|}$$

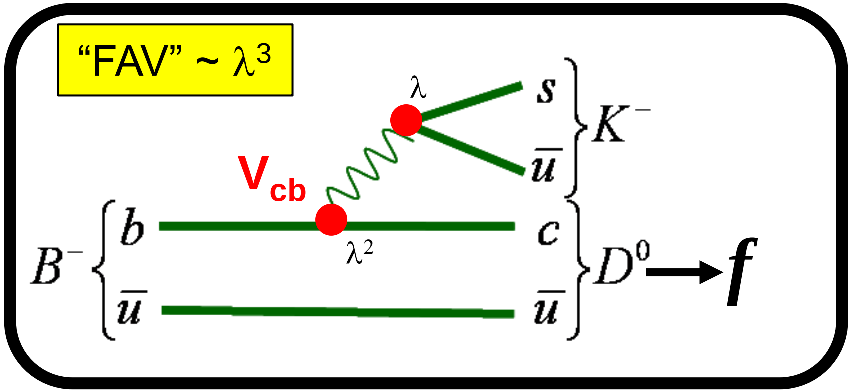


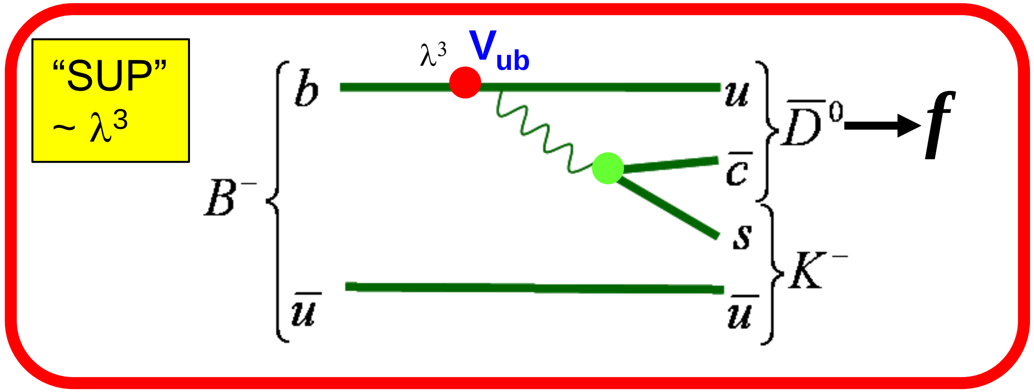
- Together with $|V_{ub}|$ pins apex of UT using processes that should be **free from NP** !
- Least precisely measured angle in UT

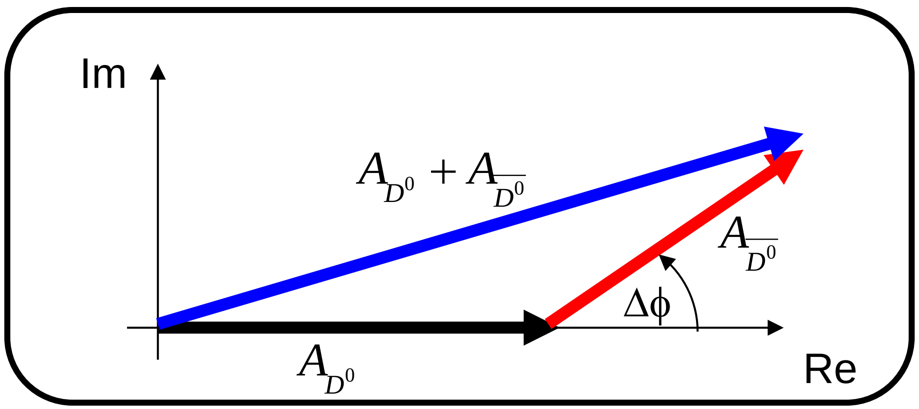
γ using trees

See talk by Charlotte Wallace

- ❑ Exploit interference between b→c and b→u transitions





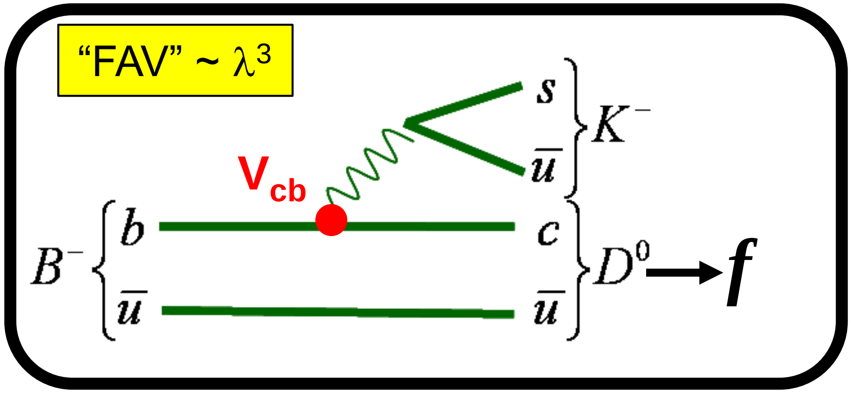


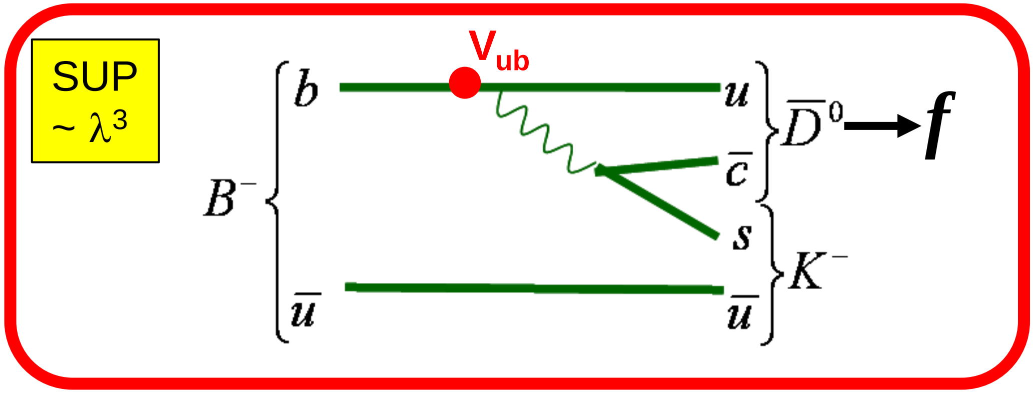
$$\Gamma = \left|A_{D^0}\right|^2 \left(1 + r_B^2 + 2 r_B \cos(\Delta\varphi)\right) \qquad r_B e^{i\Delta\varphi} = A_{\bar{D}^0} / A_{D^0}$$

- ❑ **Several methods, depending on D^0 final state**
  - ❑ **ADS**: f = $K^+\pi^-$, **GLW:** CP eigenstates e.g. K^+K^-, $\pi^+\pi^-$.
  - ❑ **GGSZ:** Multi-body, e.g. f = $D^0 \rightarrow K_s\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $K_sK\pi$…
- ❑ **Many modes being pursued for best precision on γ.**
- ❑ **B→hh′(h″) also probes γ …loop contributions → sensitive to NP!**

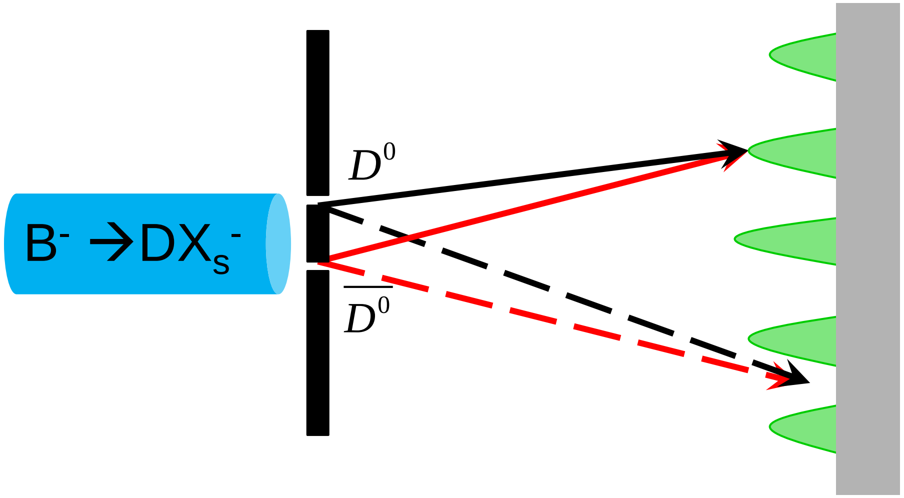
γ using trees

- Exploit interference between b→c and b→u transitions





- For final states accessible to both D^0,$\overline{D}^0$, these 2 diagrams interfere.



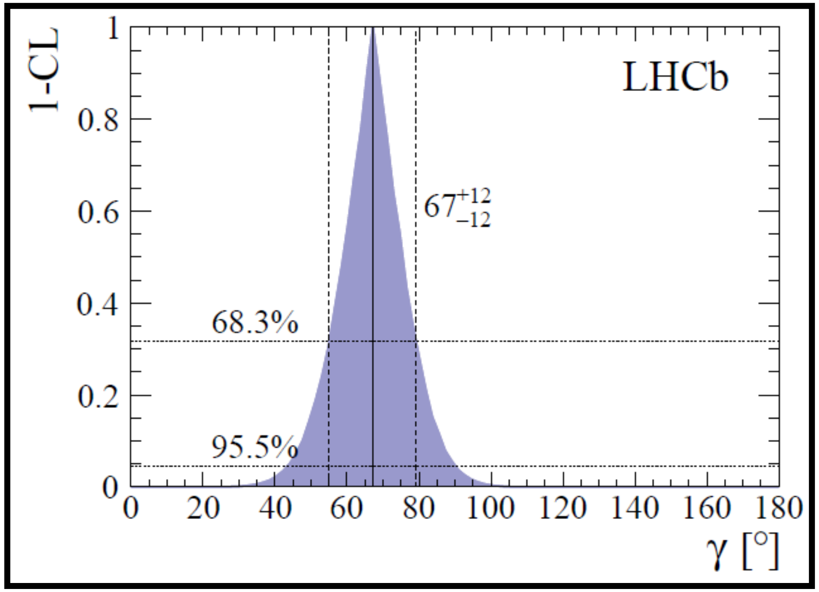
$$\Gamma = \left|A_{D^0}\right|^2 \left(1 + r_B^2 + 2 r_B \cos(\Delta\varphi)\right)$$
$$r_B e^{i\Delta\varphi} = A_{\overline{D}^0} / A_{D^0}$$

Depending on the relative phase
- Constructive interference
- Destructive interference
- Or somewhere in between

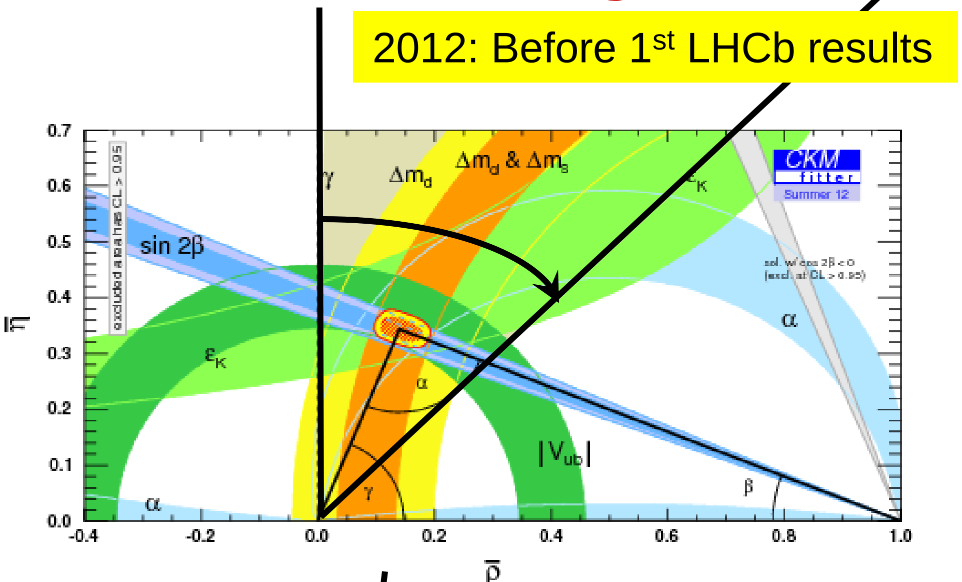
γ: ADS/GLW, GGSZ Summary

Combined ADS, GLW (1 fb^{-1})
GGSZ (3 fb^{-1})

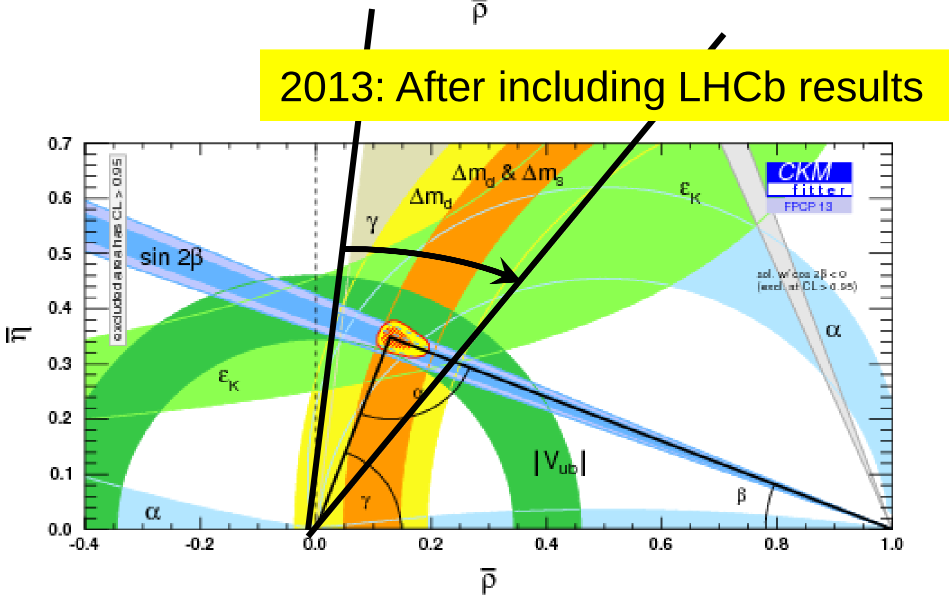
PLB 726, 151 (2013), arXiv:1305.2050



2012: Before 1st LHCb results

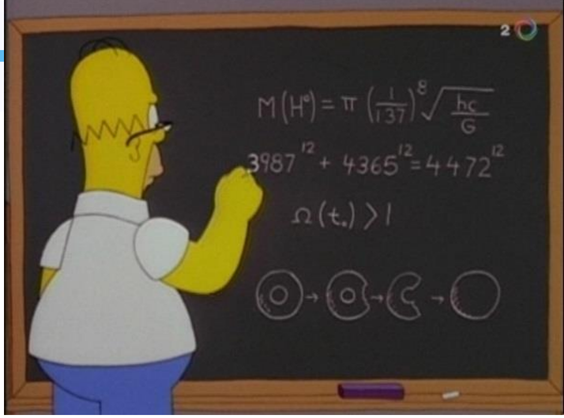


2013: After including LHCb results

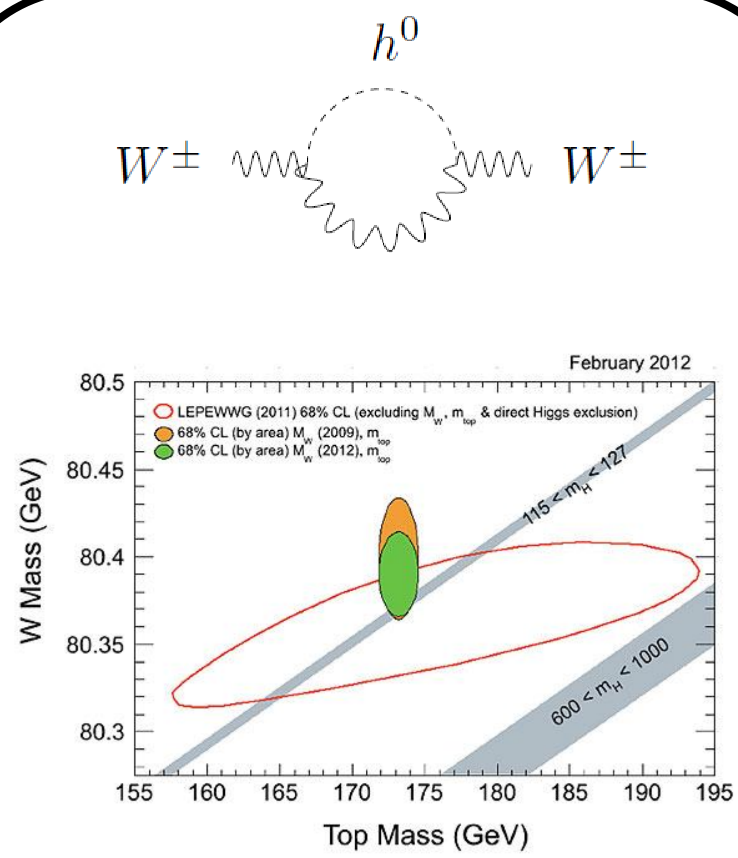


By 2018, expect σ_γ~4° !

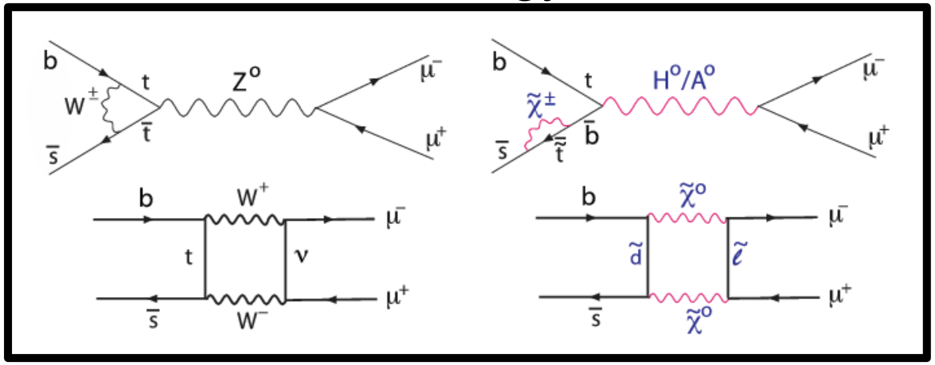
Loops: NP sensitive

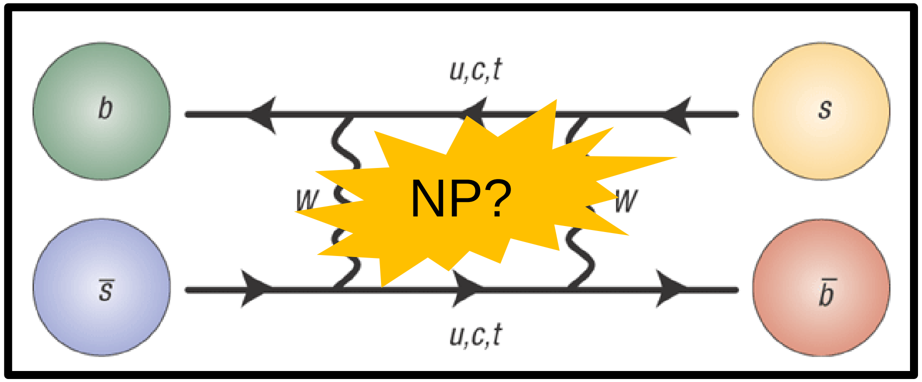


At the highest of energies



…and in low energy observables

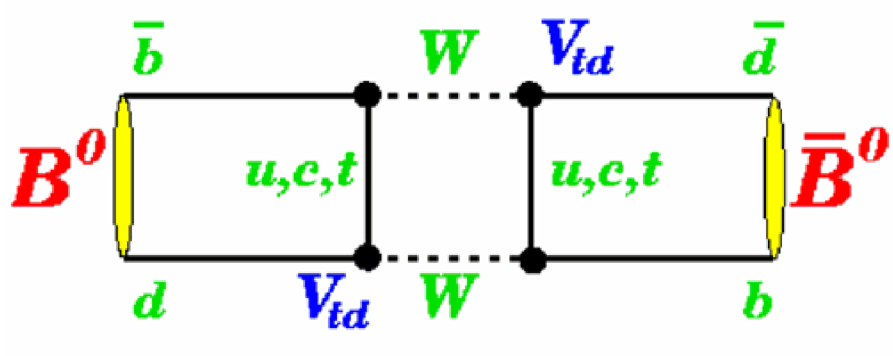




Probing large mass scales through quantum loops has a proven track record.

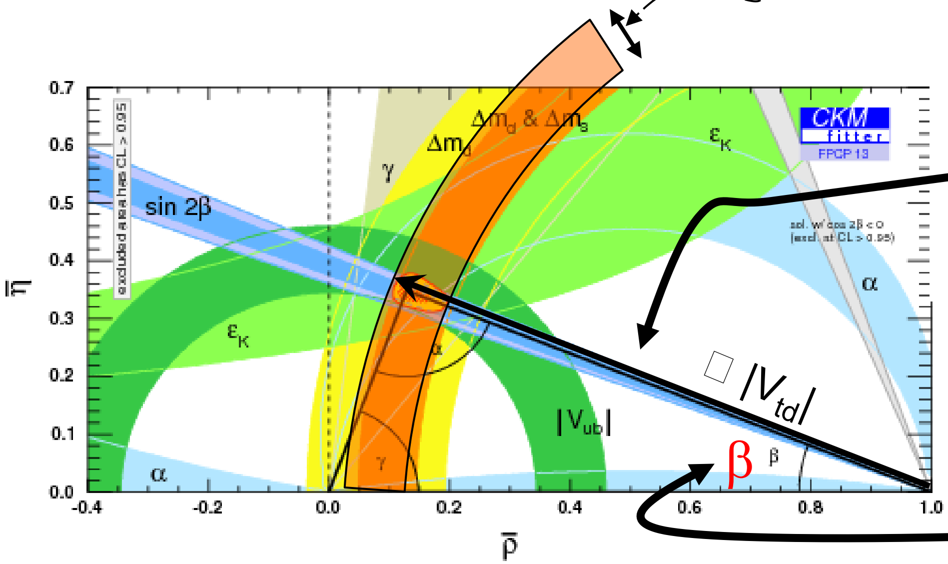
This is more evident now than ever !

B mixing & Indirect CPV



$$H = \begin{pmatrix} m_0 & M_{12} \\ M_{12}^* & m_0 \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

- Mixing due to 2nd order weak transition, M_{12}, Γ_{12} □ 0
- NP could contribute to M_{12} ($m >> m_B$)
- Imperative to measure amplitude and phase of M_{12} precisely!
  - Theoretical input (lattice) CRUCIAL here to shrink this band



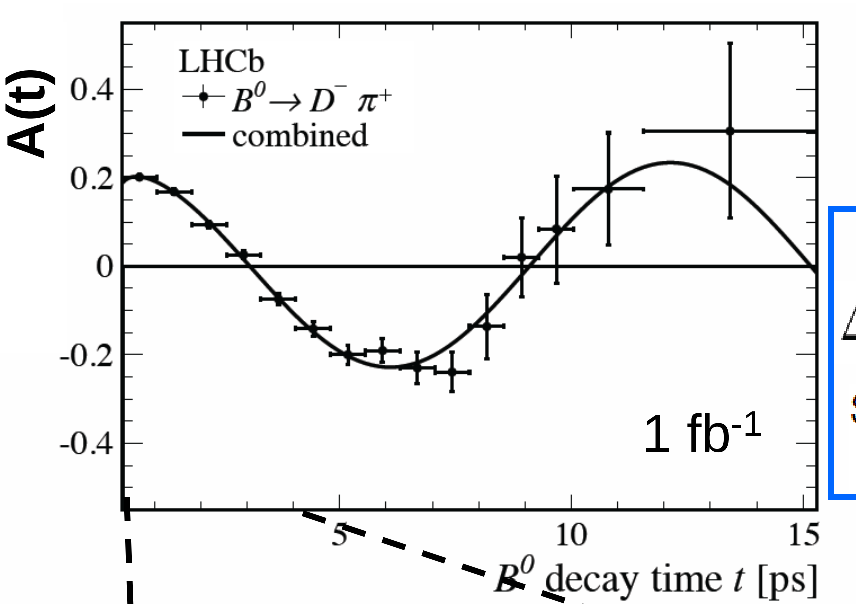
- Measure oscillation frequency
  $\Delta m \sim 2|M_{12}|$ □ $|V_{td}|$
- Phase of M_{12} (or V_{td}) obtained via TD CPV.

$$A(t) = \frac{\Gamma(f_{CP}) - \bar{\Gamma}(f_{CP})}{\Gamma(f_{CP}) + \bar{\Gamma}(f_{CP})} \propto \sin(2\beta)\sin(\Delta m t)$$

- V_{td} and $\sin(2\beta)$ also measure apex using NP-sensitive processes!

Amplitude of $B^0_{(s)}$ - $\overline{B}^0_{(s)}$ mixing

See talk by Mirco Dorigo

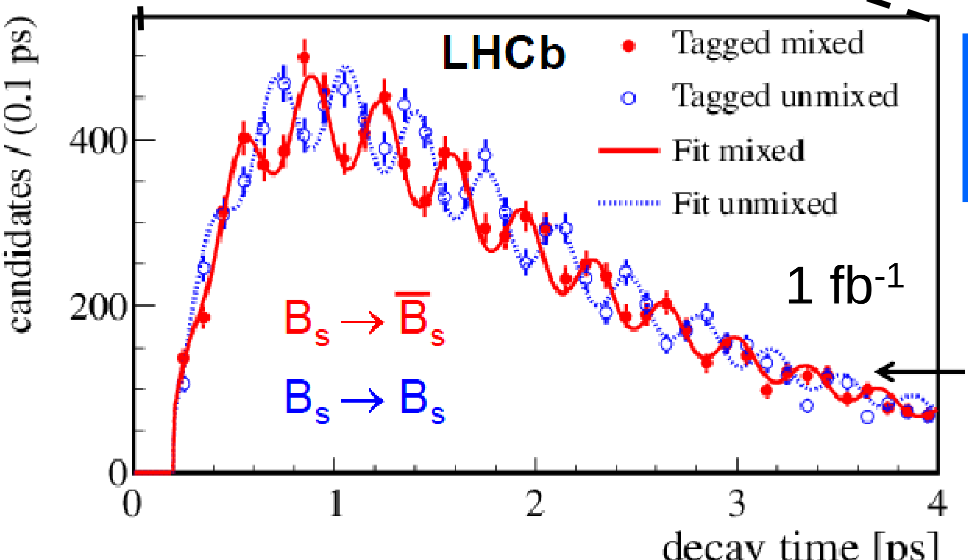


LHCb Phys.Lett. B719, 318 (2013)

Δm_d = 0.5156 ± 0.0051 (stat) ± 0.0033 (syst) ps^{-1}

Single best measurement by BELLE

$\Delta m_d = 0.511 \pm 0.005 \pm 0.006\,\text{ps}^{-1}$



New J. Phys. 15 (2013) 053021

Δm_s = 17.768 ± 0.023 ± 0.006 ps^{-1}

(B_s oscillates ~35X faster than B^0!)

CDF, PRL 97, 242003 (2006)

$$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$$

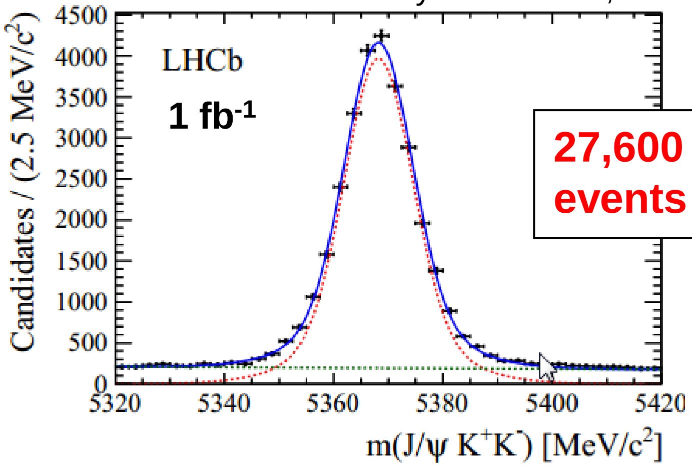
Phase of B_s-$\bar{B}_s$ mixing (ϕ_s)

See talk by Mirco Dorigo

$$A(t) = \frac{\Gamma(f_{CP}) - \bar{\Gamma}(f_{CP})}{\Gamma(f_{CP}) + \bar{\Gamma}(f_{CP})} \propto \sin\phi_s \sin(\Delta m_s t)$$

$B_s \rightarrow J/\psi\ \phi\ \ (\phi \rightarrow K^+K^-)$

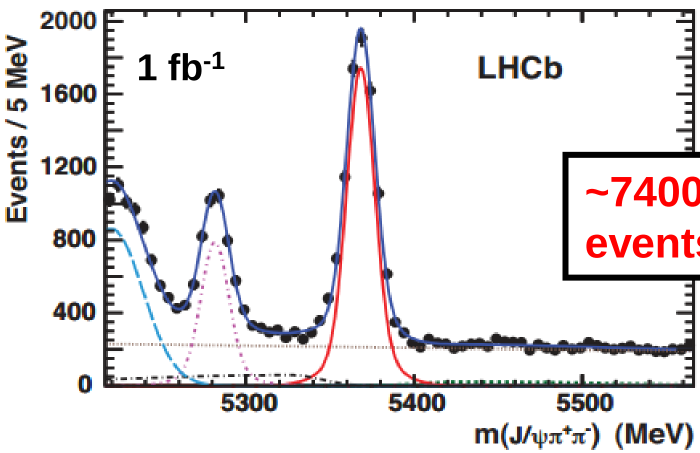
Phys. Rev. D 87, 112010 (2013)



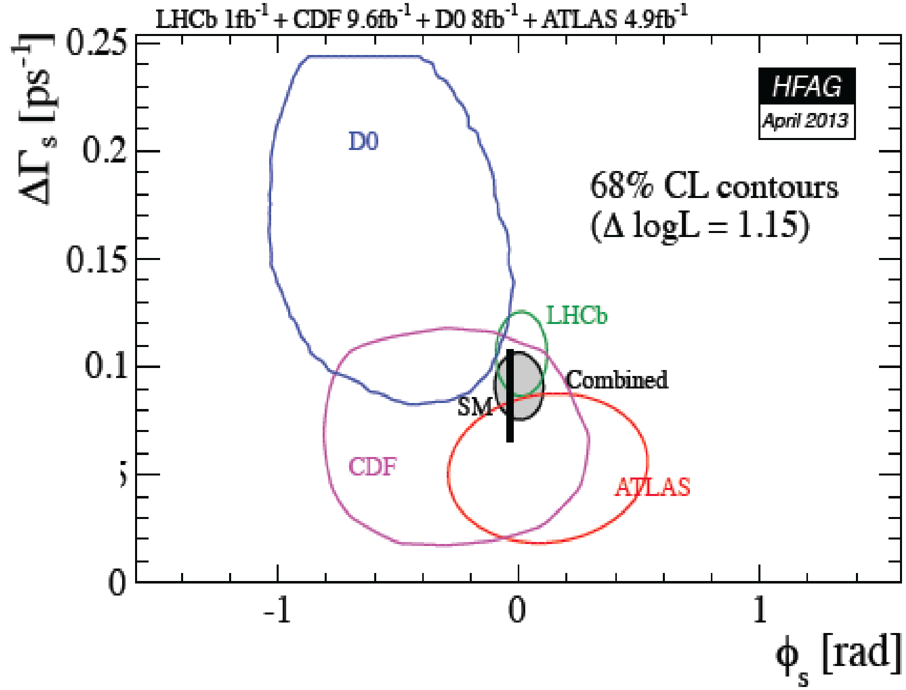
27,600 events

$B_s \rightarrow J/\psi\pi^+\pi^-$

PLB 713, 378 (2012)



~7400 events



$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07\ \text{(stat)} \pm 0.01\ \text{(syst)}\ \text{rad},\\
\Gamma_s &= 0.661 \pm 0.004\ \text{(stat)} \pm 0.006\ \text{(syst)}\ \text{ps}^{-1},\\
\Delta\Gamma_s &= 0.106 \pm 0.011\ \text{(stat)} \pm 0.007\ \text{(syst)}\ \text{ps}^{-1}.
\end{aligned}$$

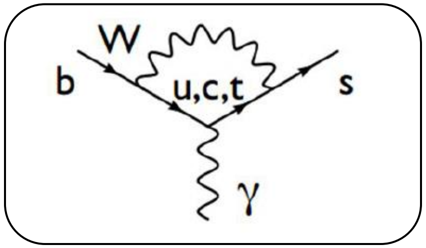
- Large improvement in precision on ϕ_s
  - → **Tight constraints on NP, but O(20%) NP contributions not ruled out.**
  - → **$B_s \rightarrow J/\psi\pi\pi$ 3 fb^{-1} update in Mirco's talk**

NP in penguins

$B^- \rightarrow (K^-\pi^+\pi^-)\,\gamma$

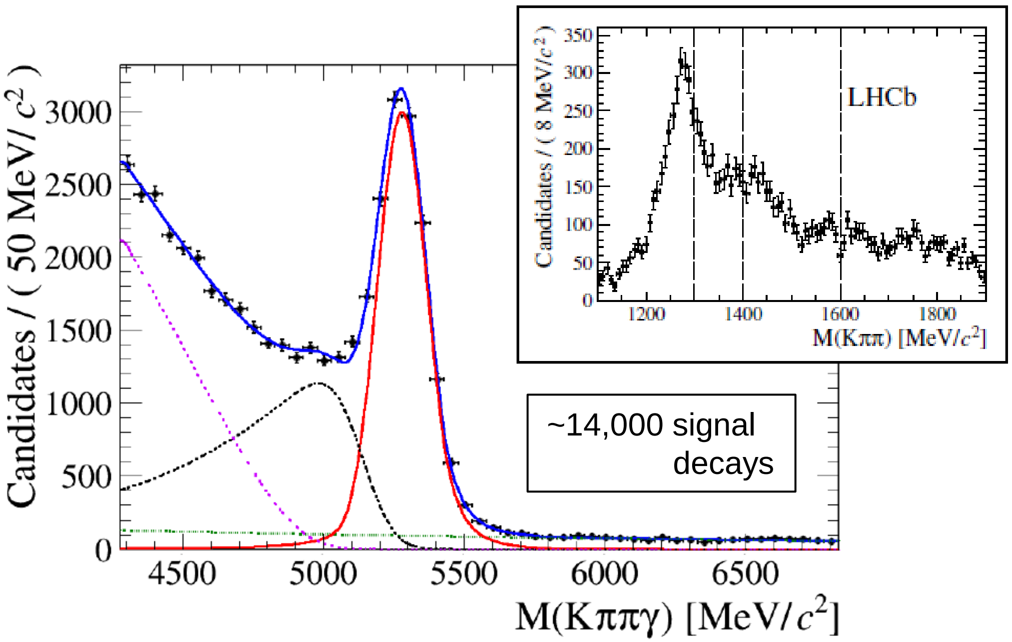
See talk by Mostafa Hoballah

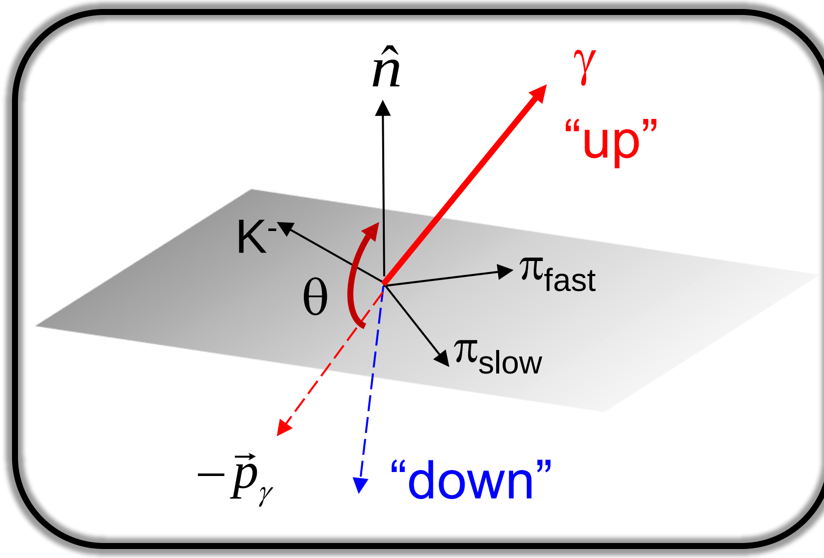
arXiv:1402.6852, **3 fb^{-1}**



- Excellent place to search for NP
- In SM, photon is ~100% LH (due to V-A)
- NP can lead to a RH component

Gronau et al, PRL 88, 051802 (2002)
Kou, et al, PRD83, 094007 (2011)





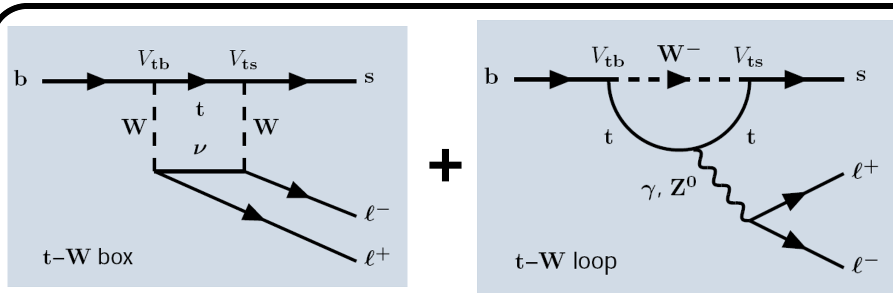
$$A_{ud} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}$$

- **1st observation of photon polarization**.
- Theory input needed to determine the photon polarization.
- A_{ud} proportional to photon polarization

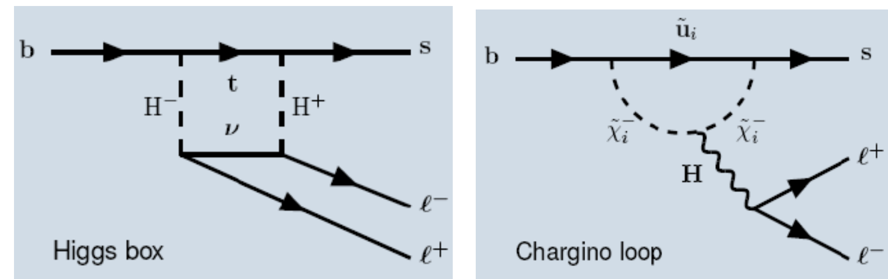
$B^0 \to K^{*0}\mu^+\mu^-$

See talk by Peter Griffith

Standard Model



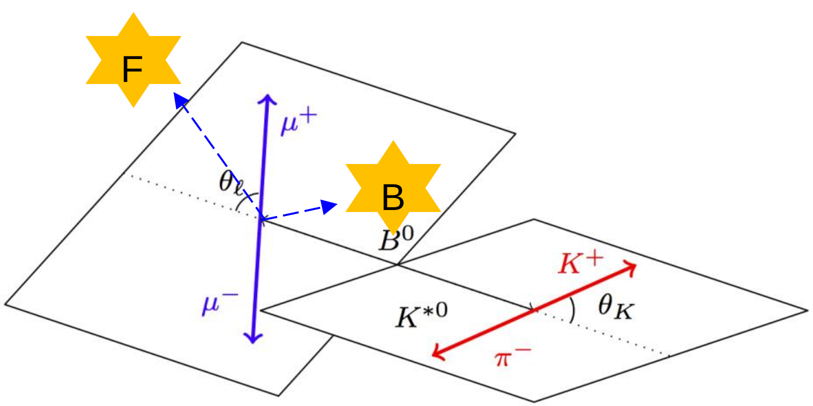
Possible NP (SUSY) contributions



- NP diagrams can interfere with SM diagrams → impacts angular observables
- Differential decay rate

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2}=\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K+F_\mathrm{L}\cos^2\theta_K+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos2\theta_\ell$$
$$-F_\mathrm{L}\cos^2\theta_K\cos2\theta_\ell+S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi$$
$$+S_4\sin2\theta_K\sin2\theta_\ell\cos\phi+S_5\sin2\theta_K\sin\theta_\ell\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_\ell+S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin2\theta_K\sin2\theta_\ell\sin\phi+S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big],$$

- F_L and S_i depend on Wilson coefficients (high mass scales)
  → Sensitive to NP
- Construct observables that minimize dependence on form factors



$$A_{FB}(q^2)=\frac{3}{4}S_6=\frac{N_F-N_B}{N_F+N_B}$$

$F_L(q^2)=K^{*0}$ longitudinal polarization fraction

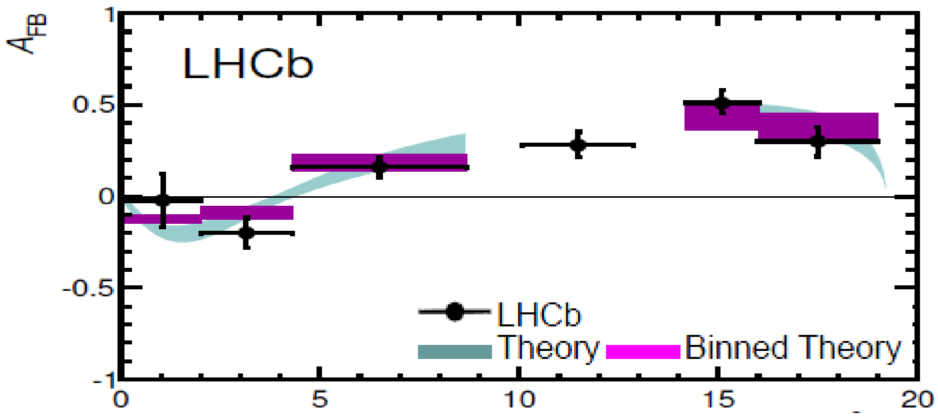
$$P'_{4,5,6,8}(q^2)=\frac{S_{4,5,7,8}(q^2)}{\sqrt{F_L(1-F_L)}}$$

$$A_I=\frac{\Gamma(B^0\to K^{(*)0}\mu^+\mu^-)-\Gamma(B^+\to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0\to K^{(*)0}\mu^+\mu^-)+\Gamma(B^+\to K^{(*)+}\mu^+\mu^-)}$$

$B^0 \to K^{*0}\mu^+\mu^-$

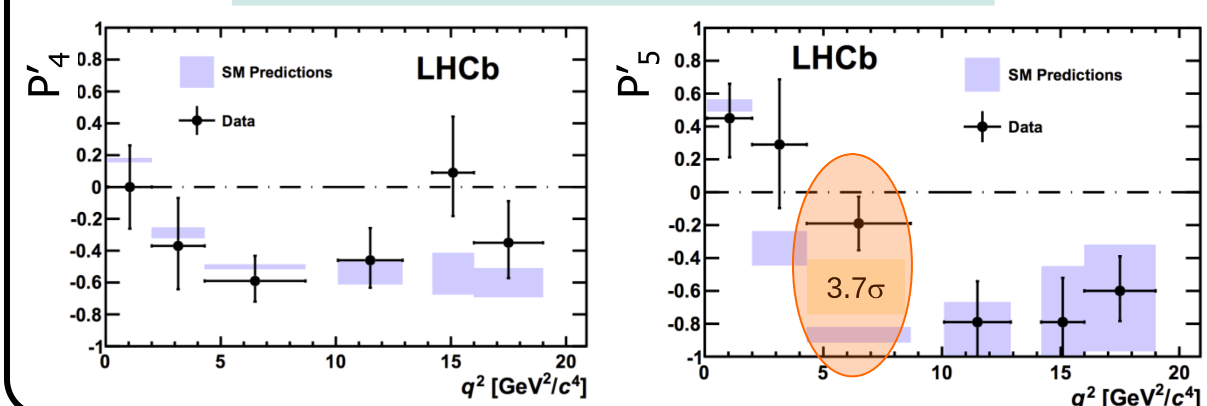
See talk by Peter Griffith

LHCb, JHEP 08, 131 (2013), 1 fb^{-1}

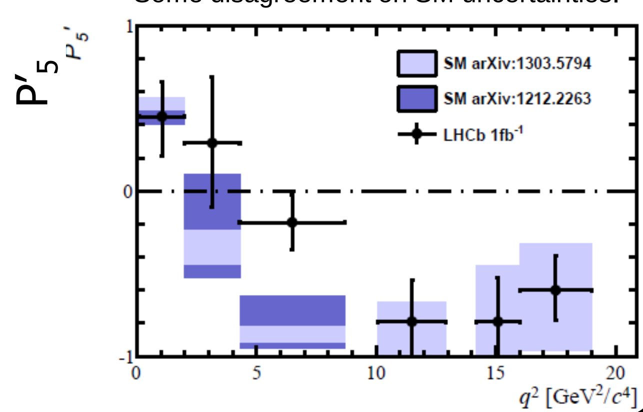


- A_{FB} dependence and zero-crossing point in agreement with SM → stay tuned for 3 fb^{-1}.

LHCb, PRL 111 (2013) 191801, arXiv:1308.1707, **1 fb^{-1}**
SM prediction: Descotes et al, arXiv:1303.5794



Reanalysis of SM by Jäger & Camalich et. al. arXiv:1212.2263…
Some disagreement on SM uncertainties.

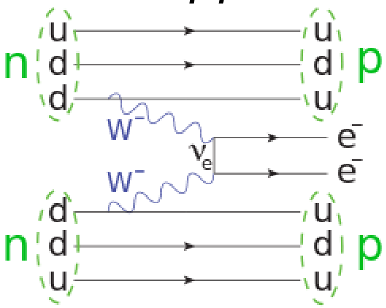


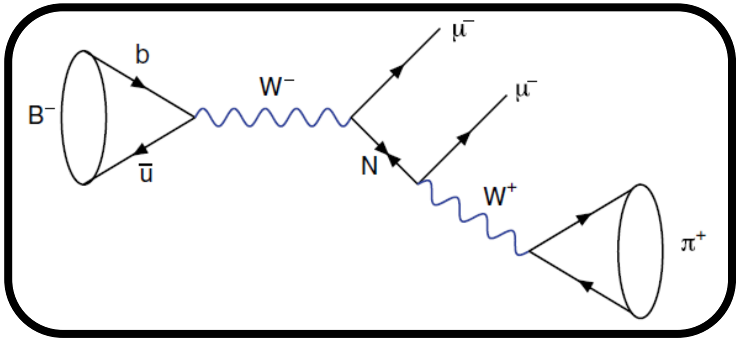
LFV - Majorana neutrino search $B^- \to \pi^+\mu^-\mu^-$

See talk by Nicole Skidmore

Phys. Rev. Lett. 112 (2014) 131802

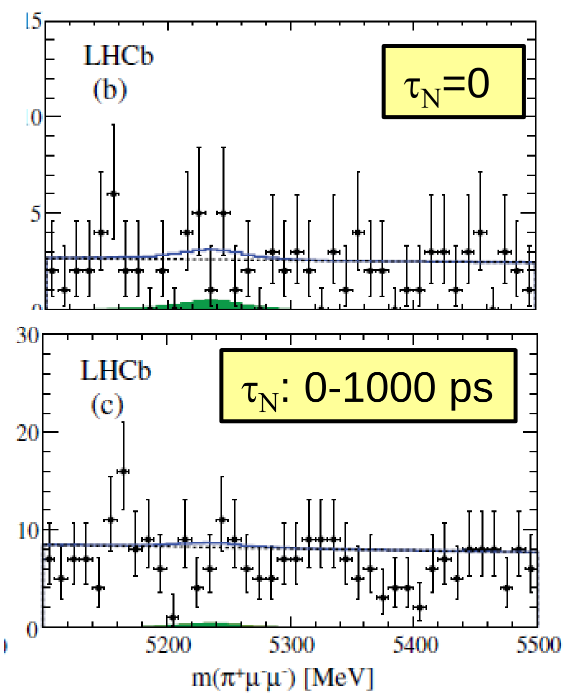
0νββ





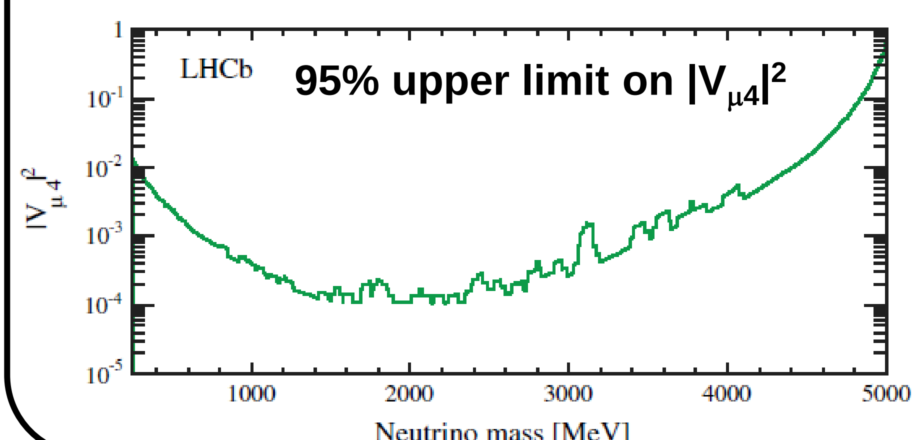
- ❑ Majorana terms in $\mathcal{L}$ elegant solution for small m_ν.
- ❑ Majorana neutrino can be on or off-shell.
- ❑ **If found, would be a major discovery!**

- ❑ Two searches: zero lifetime and long lifetime $B \to \mu^- N$, $N \to \pi^+\mu^-$
- ❑ Set limits on BF, and coupling strength, $|V_{\mu 4}|$ of 4th generation N to muons



$$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) = \frac{G_F^4 f_B^2 f_\pi^2 m_B^5}{128\pi^2\hbar}|V_{ub}V_{ud}|^2\tau_B \times \left(1 - \frac{m_N^2}{m_B^2}\right)\frac{m_N}{\Gamma_N}|V_{\mu 4}|^4,$$

Atre et al arXiv:0901.3589



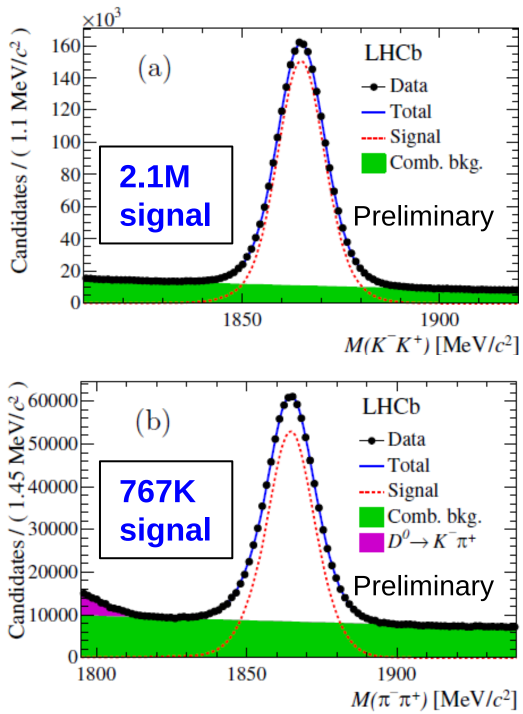
Direct CP Violation in charm

See talk by Adam Davis

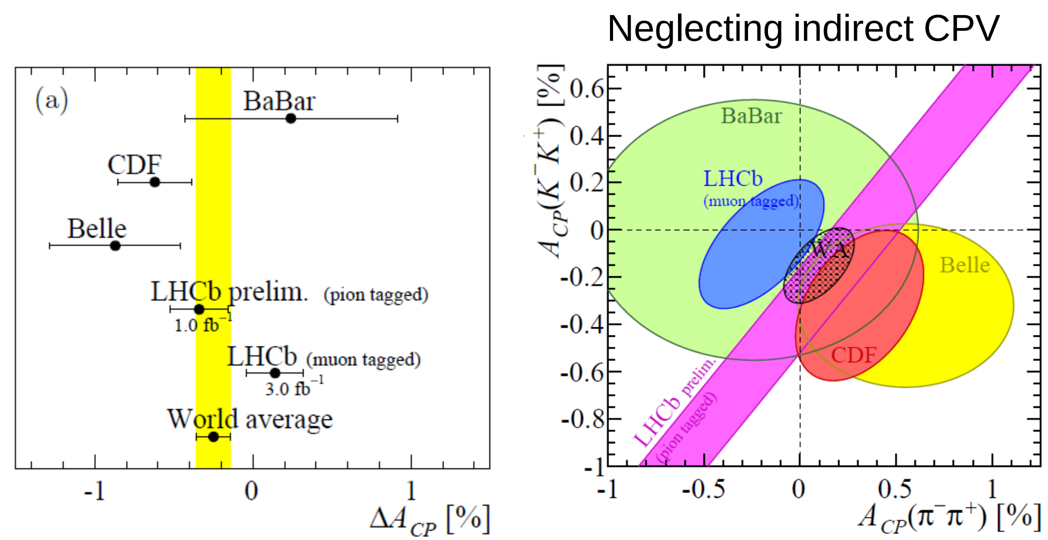
- In SM, strongly suppressed: ~**10^{-3}**
  - Long distance effects hard to calculate, **but difficult to get > few x 10^{-3}**.
  - $O(10^{-2})$ CP asymmetry would be a strong indicator of NP
- Here, use D^0's tagged in **SL $B \rightarrow D^0 X \mu\nu$ decays** (full 3 fb^{-1} data set)

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

  - Reduced systematics
  - Mixing-induced CPV cancels, leaving only direct CPV

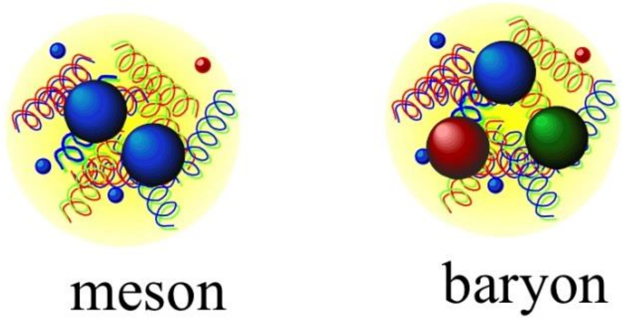


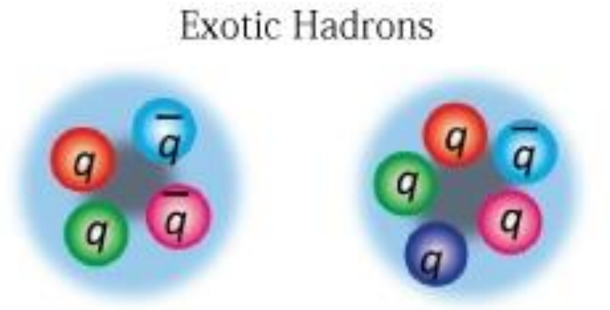
LHCb-PAPER-2014-013, in preparation -- Preliminary



Punchline: **Direct CPV looking more in line with SM expectations**

Probing QCD





- ❑ Understanding QCD → better SM predictions
- ❑ SM backgrounds / engineering measurements
- ❑ Exotic states

Here, just a few selected topics

- ❑ Λ_b baryon production
- ❑ Lifetimes
- ❑ B_c
- ❑ $Z(4430)^+$

Λ_b production, $B(\Lambda_b \to \Lambda_c \pi)$

See talk by Jim McCarthy

LHCb-PAPER-2014-002, in preparation

- Probes production and hadronization processes.
- $BF(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$ provides a normalization mode for other Λ_b^0 BF measurements.

Current WA: $\left(5.7^{+4.0}_{-2.6}\right) \times 10^{-3}$ ☹

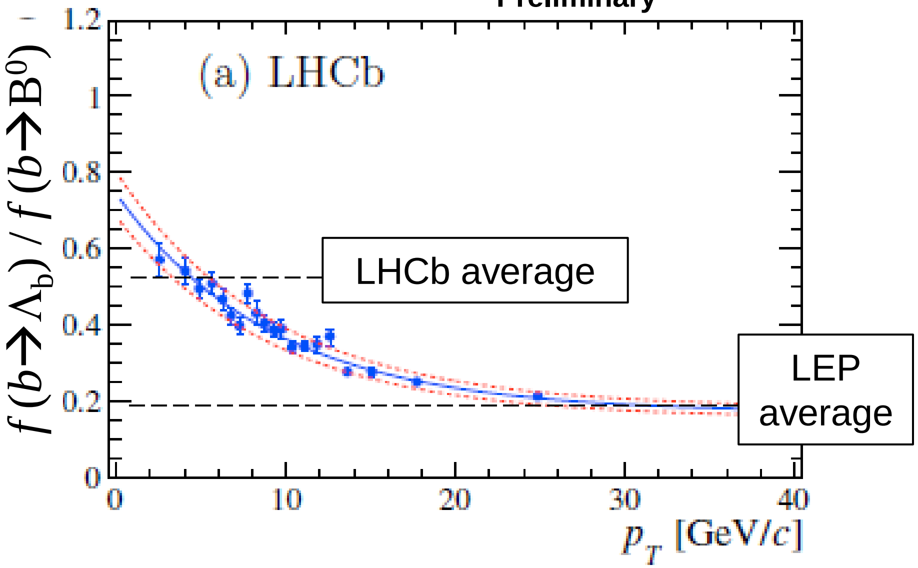
- **Key input:** Use $f_{\Lambda b}/f_d$ from semileptonic analysis (PRD 85, 03208, 2011)

$$\frac{N_{cor}\left(\Lambda_b^0 \to \Lambda_c^+ \pi^-\right)}{N_{cor}\left(B^0 \to D^- \pi^+\right)} = \frac{f_{\Lambda_b^0}}{f_d} \cdot \frac{\mathbf{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)}{B(B^0 \to D^- \pi^+)} \cdot \frac{B(\Lambda_c^+ \to pK^- \pi^+)}{B(D^- \to K^+ \pi^- \pi^-)}$$

$$\frac{N_{cor}\left(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu\right)}{N_{cor}\left(B^0 \to D^- \mu^+ \nu_\mu\right)} = \frac{f_{\Lambda_b^0}}{f_d} \cdot \frac{B(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}{B(B^0 \to D^- \mu^+ \nu_\mu)} \cdot \frac{B(\Lambda_c^+ \to pK^- \pi^+)}{B(D^- \to K^+ \pi^- \pi^-)}$$

- (blue) $\Gamma_{s\ell}(\Lambda_b^0)/\Gamma_{s\ell}(B^0) = 1 + O(0.01)$ (HQET)
- (green) Common
- (red) To be determined in this analysis
- Dominant systematic on Λ_c BF cancels out !

Preliminary



$$B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = (4.46 \pm 0.36) \times 10^{-3}$$

- **Dramatic improvement!**
- Λ_b production varies by ~2X over p_T range

Lifetimes

See talk by Adrian Pritchard

- **Lifetimes of b-hadrons provide an important test of OPE (important theor. tool)**
  - Prediction: Lifetimes of b-hadrons same to LO in $1/m_b$ expansion
  - Differences arise at $O(1/m_b^2)$

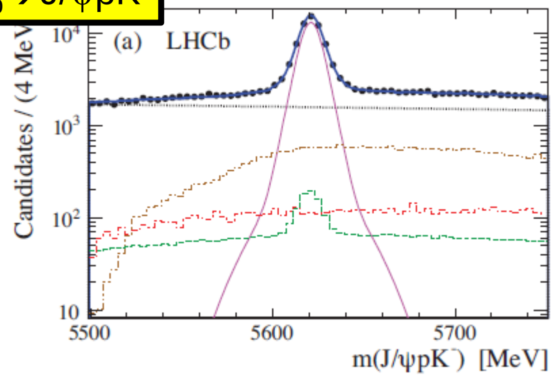
Λ_b^0 lifetime

- Longstanding puzzle as to why expt value: $\tau(\Lambda_b) / \tau(B^0) \sim 0.8$
- More recent calculations give 0.88 ± 0.05

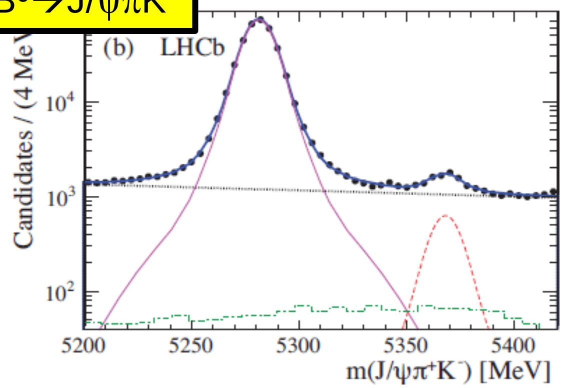
Tarantino, hep-ph/0310241
Gabbiani et al hep-ph/0407004
Neubert et al, hep-ph/9603202
Uraltsev, hep-ph/9602324
UKQCD, hep-lat/9906031
H.-Y. Cheng, hep-ph/9602265

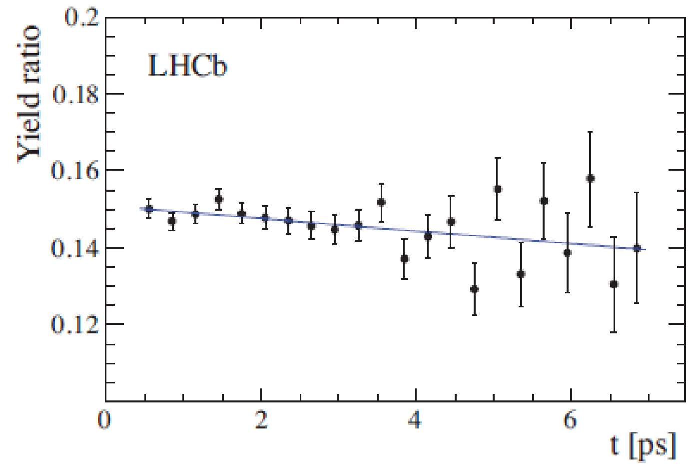
arXiv:1602.6242

$\Lambda_b \to J/\psi pK$



$B^0 \to J/\psi \pi K$





$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.974 \pm 0.006 \pm 0.004 \; (\Lambda_b^0 \to J/\psi\, pK)$$

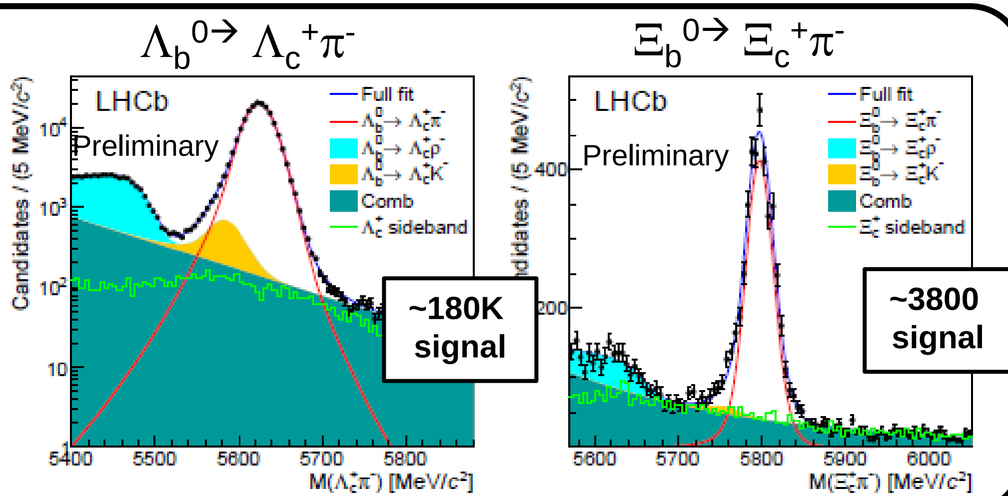
$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.929 \pm 0.018 \pm 0.004 \; (\Lambda_b^0 \to J/\psi \Lambda)$$

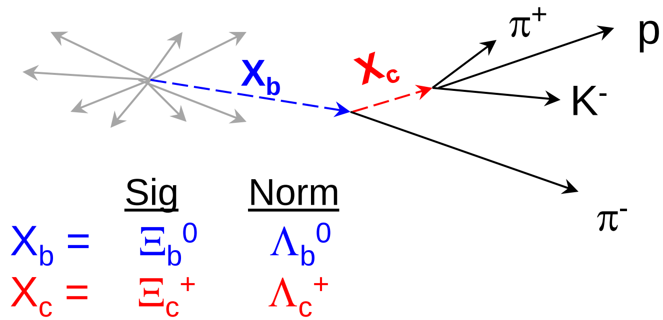
Ξ_b^0 mass & lifetime

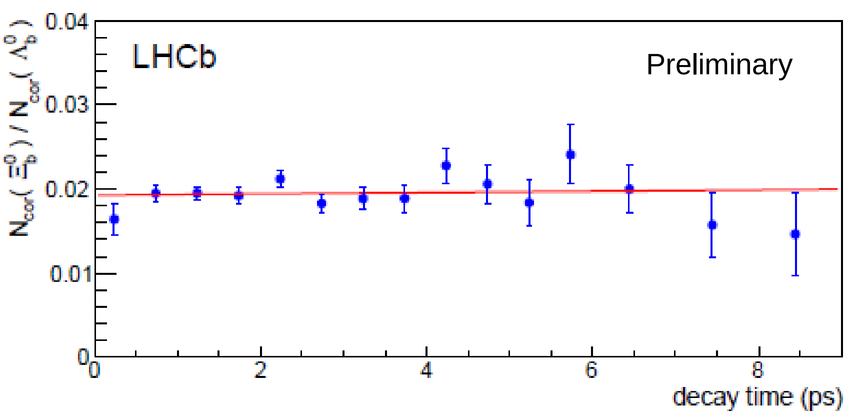
See talk by Jim McCarthy

LHCb-PAPER-2014-021, in preparation

- **First measurement of the Ξ_b^0 lifetime!**







$$\frac{\tau_{\Xi_b^0}}{\tau_{\Lambda_b^0}} = 1.006 \pm 0.018\,(\text{stat}) \pm 0.010\,(\text{syst}),$$

Preliminary

$$\tau_{\Xi_b^0} = 1.477 \pm 0.026\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.013\,(\Lambda_b^0)\ \text{ps},$$

$$M(\Xi_b^-) - M(\Lambda_b^0) = 172.44 \pm 0.39(\text{stat}) \pm 0.17\,(\text{syst})\ \text{MeV}/c^2,$$
$$M(\Xi_b^0) = 5791.80 \pm 0.39(\text{stat}) \pm 0.17\,(\text{syst}) \pm 0.26\,(\Lambda_b^0)\ \text{MeV}/c^2,$$

~x5 improvement in mass

Lifetimes in CP eigenstates

See talks by Adrian Pritchard & Jessica Prisciandaro

- In SM, CP eigenstates, f_{CP}, are nearly mass eigenstates, in which case:

$$\tau_{B_s \to f_{CP}} \approx \tau_{B_s^0} \left(1 + \frac{A_{\Delta\Gamma_s}^{f_{CP}} \Delta\Gamma_s}{2\Gamma_s} \right)$$

R. Fleischer et al, arXiv:1011.1096, arXiv:0705.1121, arXiv: 1109.5115

$$A_{\Delta\Gamma} = -\eta_{CP}\sqrt{1 - C_f^2}\cos(\varphi_s + \Delta\phi_f)$$

→ ≈ +1 for CP odd

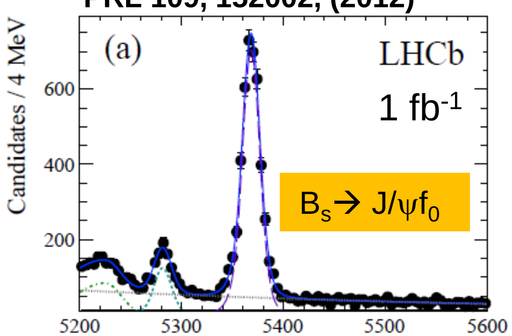
→ ≈ -1 for CP even

- **Effective lifetimes probe $\Delta\Gamma_s$ vs ϕ_s plane**

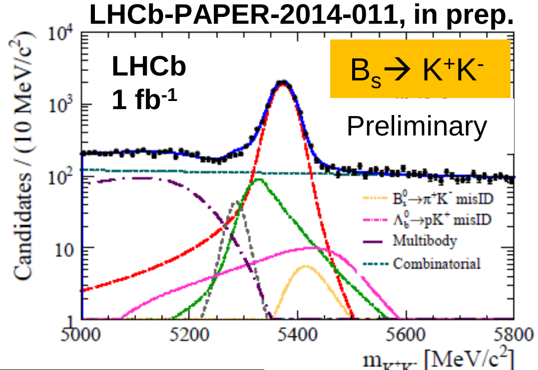
Several recent measurements

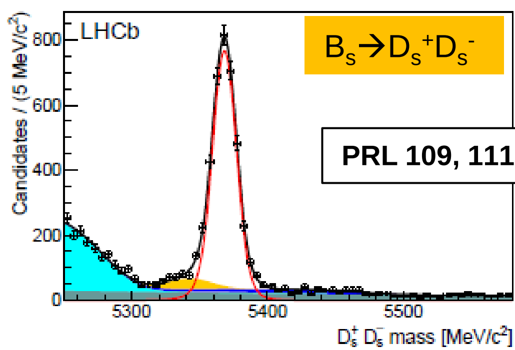
- $B_s \to J/\psi f_0$ (CP odd)
- $B_s \to D_s^+ D_s^-$ (CP even)
- $B_s \to K^+K^-$ (CP odd)
- $B_s \to J/\psi K_s$ (CP odd)

PRL 109, 152002, (2012)



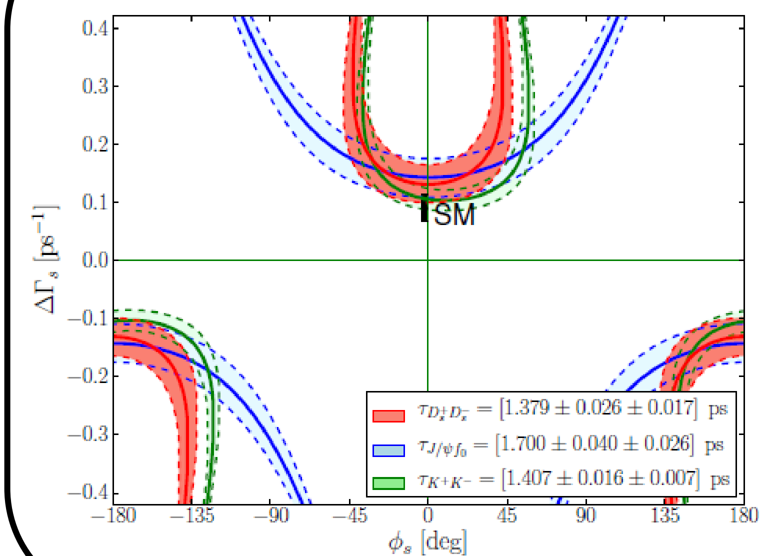
LHCb-PAPER-2014-011, in prep.





PRL 109, 111802, (2014)

Consistent with SM



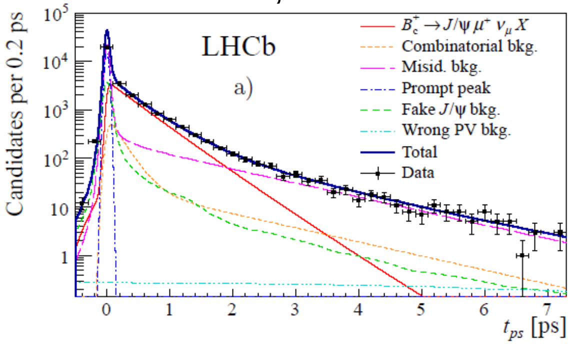
B_c physics

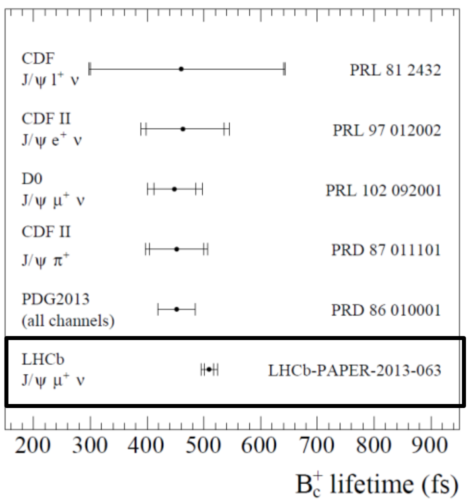
See talk by Jacco de Vries

- The B_c is the only observed weakly decaying B meson with two heavy quarks.
  - Both b and c contribute to total width
- Mass, lifetime and BFs allow for testing of QCD-inspired models [wide range of predictions for $\tau(B_c)$]

$B_c \to J/\psi\mu\nu$ lifetime

arXiv:1401.6932, 2 fb^{-1}



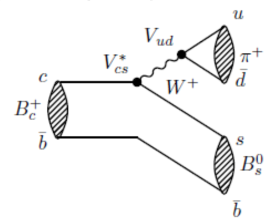


$$\tau(B_c) = 509 \pm 8 \pm 12 \text{ fs}$$

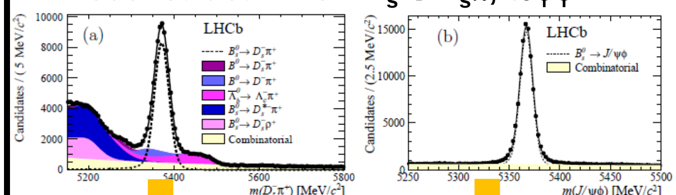
$B_c \to B_s\pi$ - 1[st] observation

PRL 111, 181801 (2013), , 1 fb^{-1}

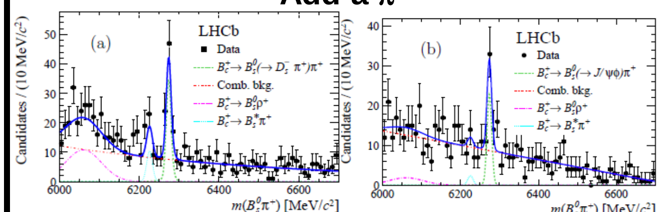
- All previous observations used $\psi \to \mu\mu$ (decay of b quark). Here, $c \to s$!



- Reconstruct ~175K $B_s \to D_s\pi$, $J/\psi\phi$



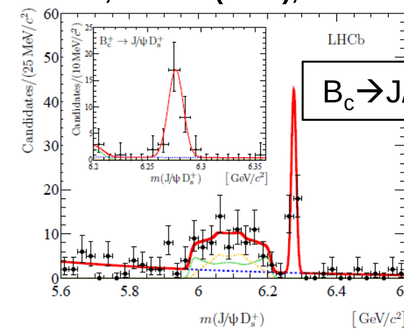
Add a π^-



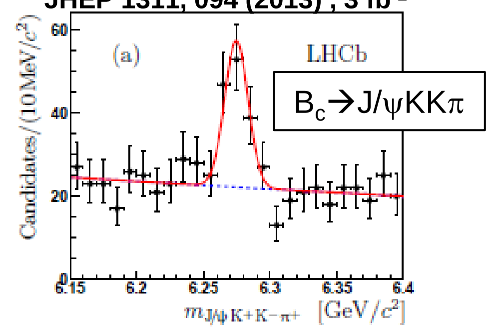
$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times B(B_c^+ \to B_s^0\pi^-) = (2.37 \pm 0.31 \pm 0.11^{+0.17}_{-0.13}) \times 10^{-3}$$

New decay modes

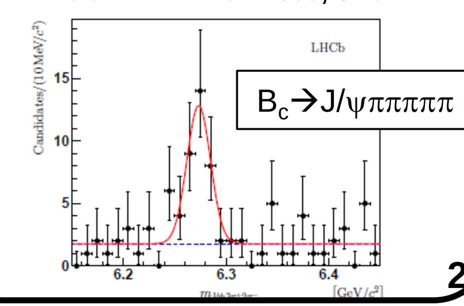
PRD 87, 112012 (2013), 3 fb^{-1}



JHEP 1311, 094 (2013) , 3 fb^{-1}



LHCb-PAPER-2014-009, 3 fb^{-1}



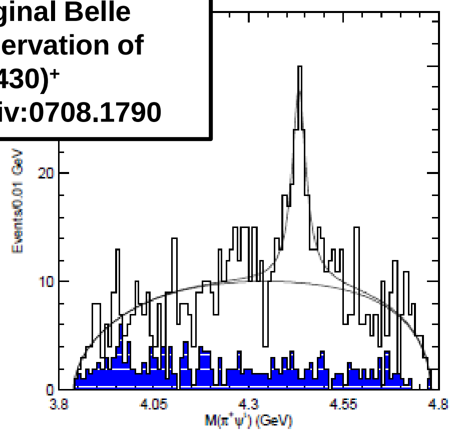
$Z(4430)^+$

See talks by Maddalena Frosini

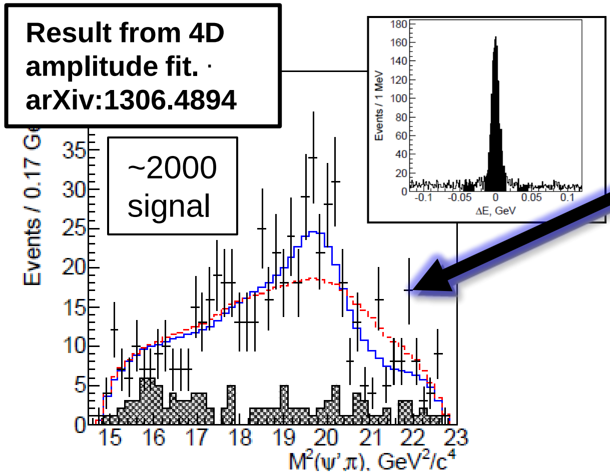
arXiv:1404.1903

- **In 2007, Belle reports a structure in the $\psi'\pi^+$ mass spectrum in $B\to(\psi'\pi^+)K$ decays.**
  - Not a conventional $q\bar{q}$ state → Tetraquark a natural explanation
  - In 2013, they report results using full 4D amplitude analysis
  - Observation @5.2σ; favors $J^P=1^+$, but <5σ wrt 0^-, 1^-, 2^-.

Original Belle observation of $Z(4430)^+$ arXiv:0708.1790



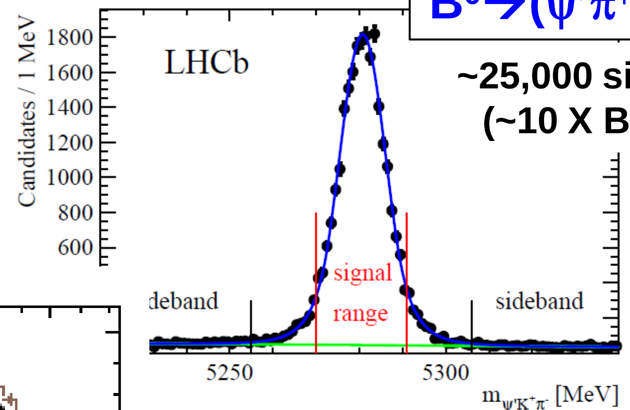
Result from 4D amplitude fit. arXiv:1306.4894



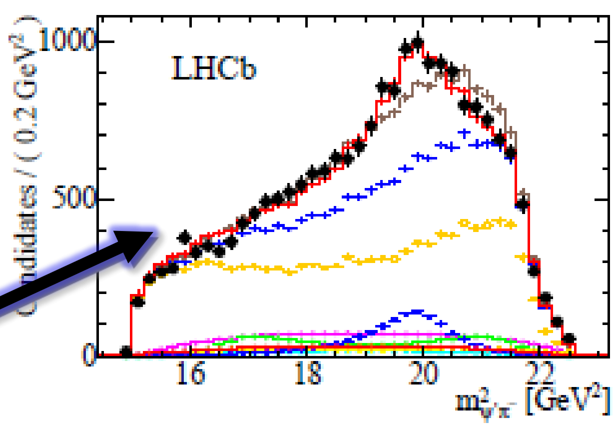
~2000 signal

- LHCb also performs 4D analysis

$B^0\to(\psi'\pi^+)K^-$



~25,000 signal (~10 X Belle)



- **$Z(4430)^+$ confirmed and 1^+ assignment >9σ wrt other J^P.**
- **Improved precision on resonance parameters**
- **Tetraquark? Molecule? Open question.**

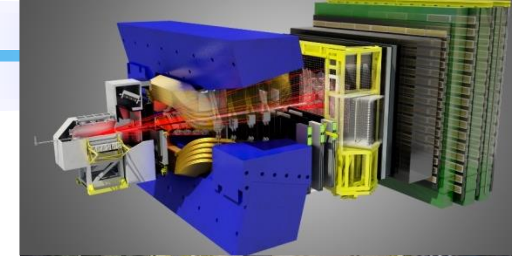
Many topics
which I didn't have time to highlight

- **Quarkonia:** Maddalena Frosini
  - J/ψ, ψ' polarization, χ_c, Υ production
- **QCD measurements in the forward region:** Marco Meissner
  - Particle production spectra, charm, energy flow in forward region.

- **Plus many other results in the parallel sessions!**

Please check them out!

Summary



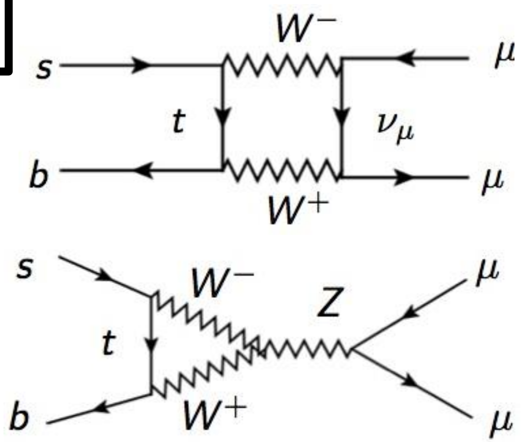
- **LHCb has a very broad physics program**
  - Main goal is to expose & elucidate NP through quantum loops
  - Many analyses provide critical input for understanding QCD, which is sometimes required to translate measurement → underlying parameters
- **Many analyses being updated to full 3 fb^{-1} (available soon)**
- **Should have ~5-6 fb^{-1} more at 13 TeV by ~2018**
  - Signal samples should increase by ~4X over existing samples.
- **Despite improve precision, many key measurements will be statistically limited.**
- **2018-2019 → LHCb upgrade!**
  - **Increase $\mathcal{L}_{inst}$ ~ 5X to ~2x10^{33} cm^{-2}s^{-1} (already exceeded by LHC in 2011!)**
  - **Read out full detector at 40 MHz**
  - **Fully software-based trigger for optimal selection**
  - **Detector upgrades**

~Fini~

$BR(B_s \to \mu^+\mu^-)$

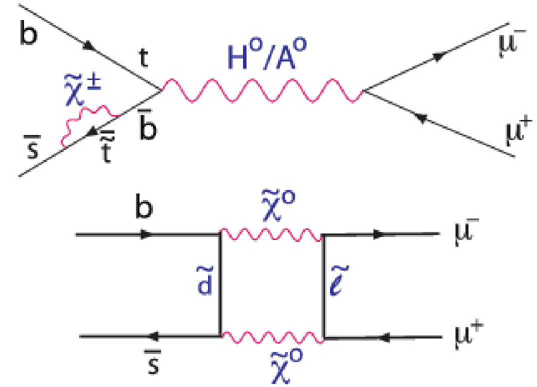
See talk by Peter Griffith

SM



$BR_{SM}(B_S \to \mu^+\mu^-) = (3.5 \pm 0.2) \times 10^{-9}$

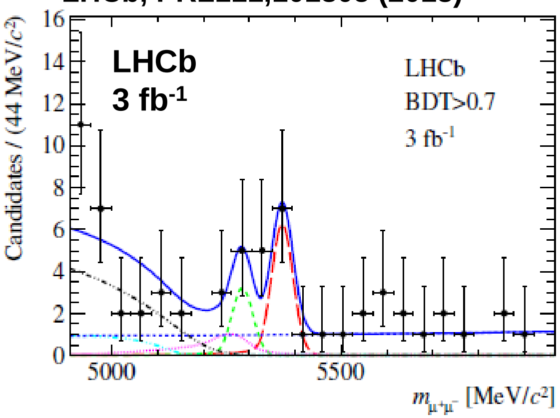
NP: E.g. SUSY



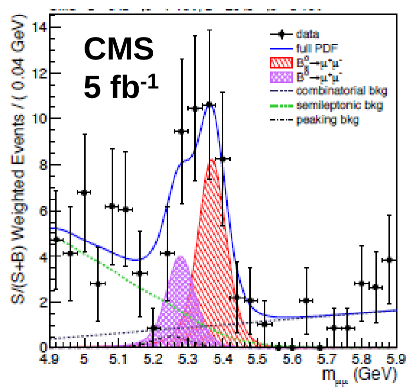
Could be strongly enhanced ~ $\tan^6\beta$

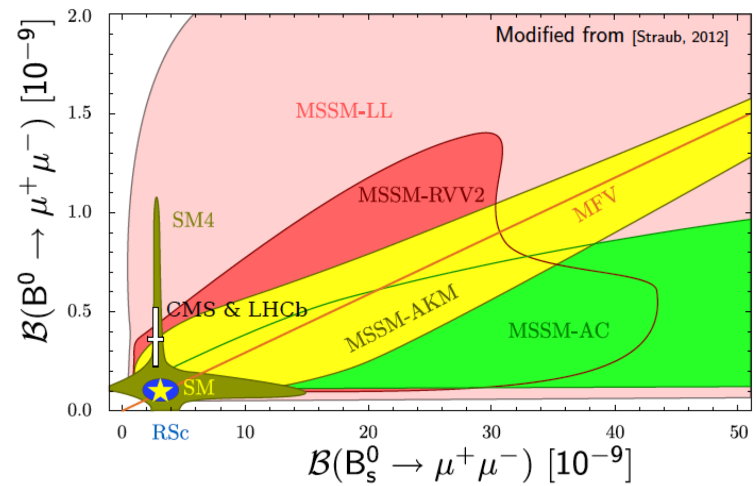
In some models, negative interference with the SM.

LHCb, PRL111,101805 (2013)



CMS, PRL111,101804 (2013)





❑ **Large swath of NP models' parameter space eliminated with these measurements..**