Highlights in Flavour Physics.

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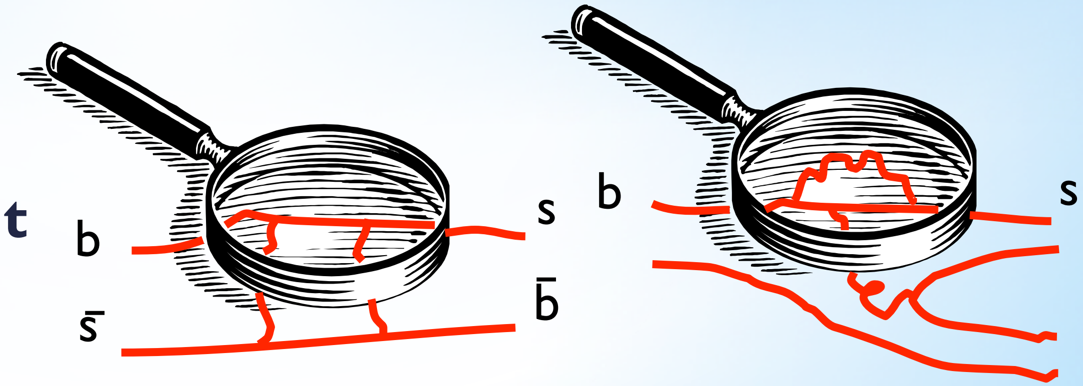


With my gratitude to the speakers at the summer 2015 physics conferences for their (unknowingly) help with the slides

Indirect Searches for NP

If the **energy** of the particle collisions is high enough, we can discover NP detecting the production of "real" new particles.

If the **precision** of the measurements is high enough, we can discover NP due to the effect of "virtual" new particles in quantum loops.

But not all loops are equal… In **"non-broken" gauge theories** like QED or QCD the "decoupling theorem" (Phys. Rev. D11 (1975) 2856) makes sure that the contributions of **heavy ($M>q^2$) new particles are not relevant**.

In broken gauge theories, like in the weak interactions, radiative corrections are usually proportional to Δm^2 (i.e. size of the isospin breaking). Larger effects of NP through quantum loops expected in third family.

Flavour is not a symmetry of the SM. In general, NP will introduce sizeable effects in flavour changing processes and modify the Yukawa interactions.

Indirect Searches for NP

Moreover, through the study of **the interference of different quantum paths** one can access not only to the magnitude of the couplings of NP, but also to their phase (for instance, by measuring CP asymmetries).

Within the SM, **only weak interactions through the Yukawa mechanism** can produce a non-zero CP asymmetry. It is indeed a big mystery why there is no CP violation observed in strong interactions (axions?).

Therefore, precision measurements of FCNC can reveal NP that may be **well above the TeV scale**, or can provide key information on the **couplings and phases** of these new particles if they are visible at the TeV scale.

Direct and indirect searches *are both needed and equally important, complementing each other.*

Status of Searches for NP

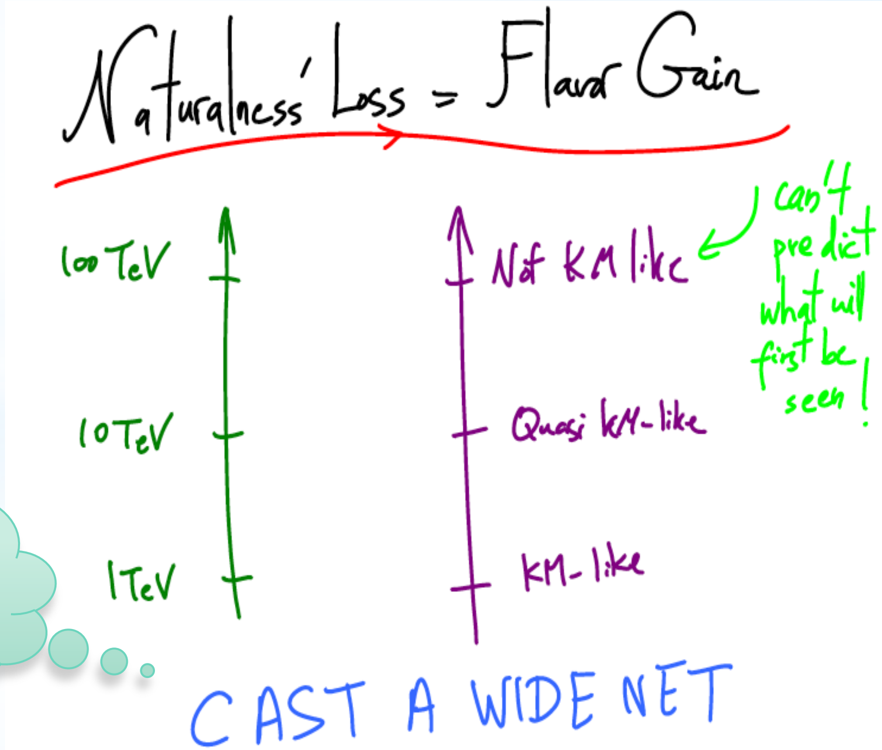
So far, no significant signs for NP from direct searches at the LHC. A Scalar Boson has been found with a mass of ~125 GeV/c^2 compatible with the SM Higgs.

Expectations were that *"naturally"* the masses of the new particles need to be light in order to reduce the *"fine tuning"* in the scalar sector. Theory departments were (still are?) full of advocates of supersymmetric particles appearing at the TeV energy scale.

However, the absence of NP effects observed in flavour physics, even before LHC, implies some level of *"tuning"* in the flavour sector → **NP FLAVOUR PROBLEM**

"Non-natural" solution:
→ Minimal Flavour Violation (MFV).

As we push the energy scale of NP higher, the NP FLAVOUR PROBLEM is reduced, hypothesis like MFV look less likely → **chances to see NP in flavour physics have, in fact, increased!**



N.Arkani-Hamed, Intensity Frontier Workshop (Nov 2011, Washington)

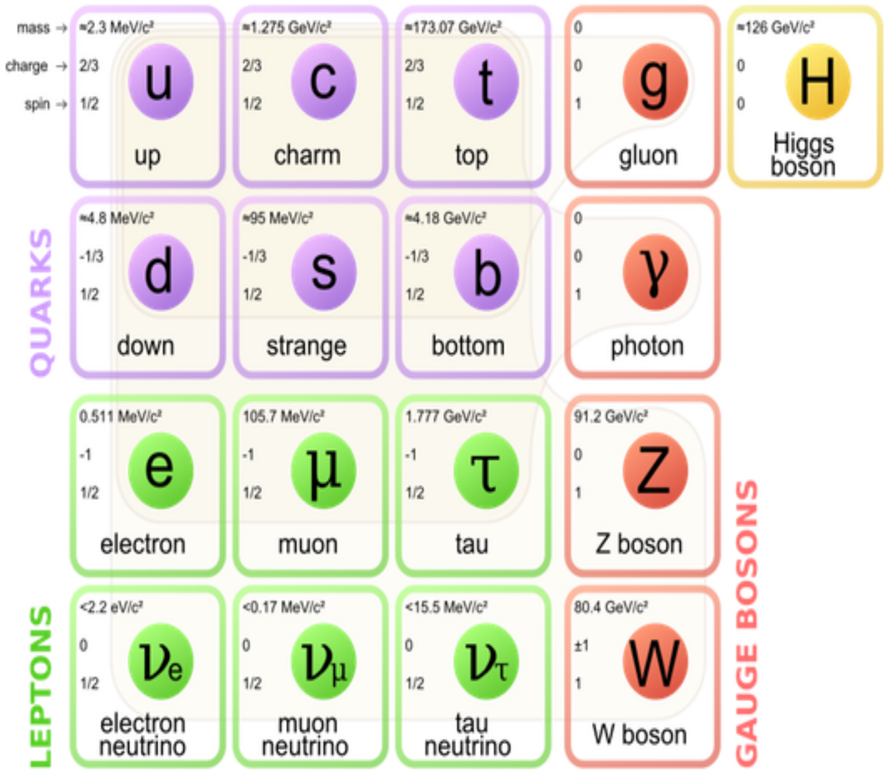
Flavour in the SM

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i)$$

The **gauge component** is the **"elegant" part**. There is **no distinction between different generations** and has a **huge degree of symmetry.** We only need to know α, θ_W, M_W and α_s and everything is determined by the local gauge symmetry group: $\mathbf{SU(3)_C x SU(2)_L x U(1)_Y}$.

The **Higgs component**, however, **breaks the flavour symmetry**. It is the **origin of the flavour structure** of the model. It is also the component that is **not stable to quantum corrections.** To describe this part we need a total of **14 parameters!**

The origin of masses and mixings, together with the origin of family replications is the most pressing problem of the SM →
SM flavour problem



The Standard Model of elementary particles

Flavour in the SM: Yukawa Mechanism in the quark sector.

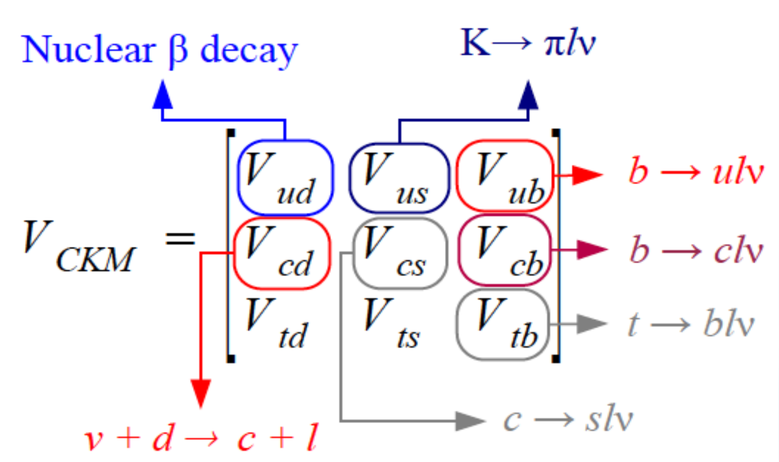
$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}^i_L\phi D^j_R + Y_u^{ij}\bar{Q}^i_L\tilde{\phi}U^j_R + Y_e^{ij}\bar{L}^i_L\phi E^j_R + \text{h.c.}$$

$$\lambda_d = \text{diag}(y_d, y_s, y_b)\ , \quad \lambda_u = \text{diag}(y_u, y_c, y_t)\ , \qquad y_q = \frac{m_q}{v}\ .$$

$$Y_d = \lambda_d\ , \qquad Y_u = V^\dagger \lambda_u\ ,$$

The quark flavour structure within the SM is described by 6 couplings and 4 CKM parameters. In practice, it is convenient to move the CKM matrix from the Yukawa sector to the weak current sector. Nevertheless, in the SM quarks are allowed to change flavour as a consequence of the Higgs mechanism to generate quark masses.

Using **Wolfenstein** parameterization (A, λ, ρ, η):



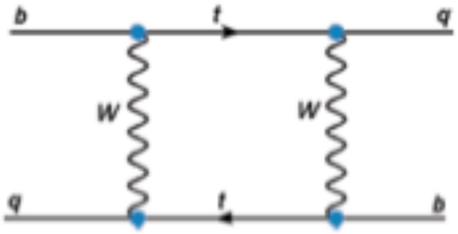
CKM

$$V = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+A\lambda^4/2(1-2(\rho+i\eta)) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^5)$$

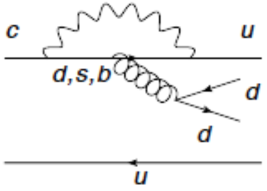
A = 0.80±0.02
λ = 0.225±0.001

$\lambda = \sin\theta_c \approx V_{us}$ measured precisely in K semileptonic decays. Notice that all **V_{ij} couplings** can be accessed experimentally using **tree-level decays**, with the **exception of V_{td} and V_{ts}**

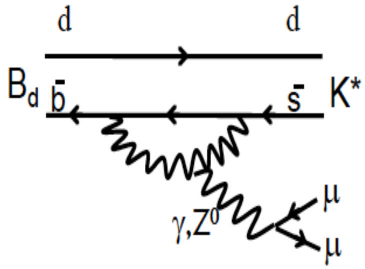
FCNC: Quark loops zoology



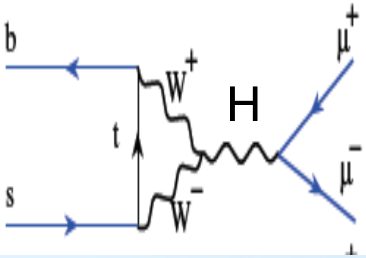
ΔF=2 box



QCD Penguin



EW Penguin



Higgs Penguin

Map of Quark FCNC transitions and type of loop processes:

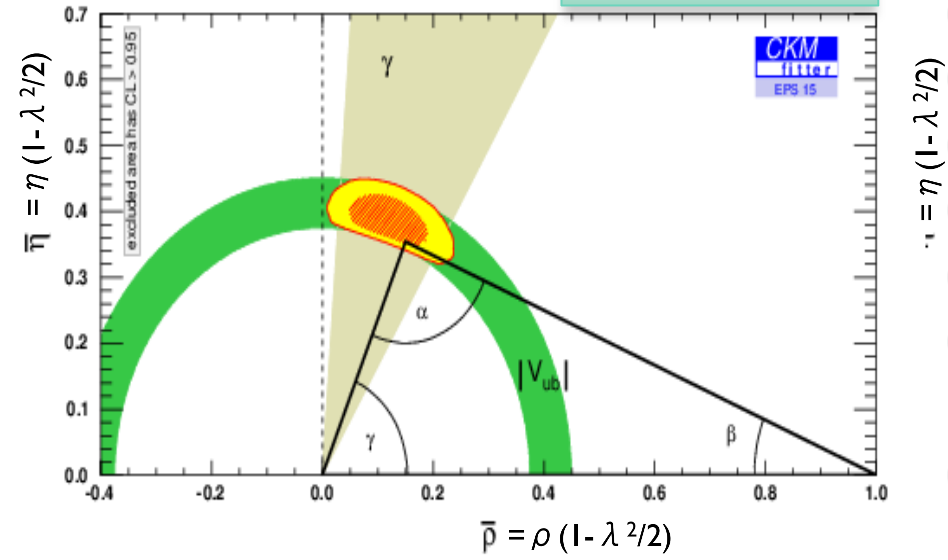
	b→s ($\|V_{tb}V_{ts}\| \alpha\, \lambda^2$)	**b→d ($\|V_{tb}V_{td}\| \alpha\, \lambda^3$)**	**s→d ($\|V_{ts}V_{td}\| \alpha\, \lambda^5$)**	**c→u ($\|V_{cb}V_{ub}\| \alpha\, \lambda^5$)**
ΔF=2 box	ΔM_{Bs}, $A_{CP}(B_s \to J/\Psi\,\Phi)$	ΔM_B, $A_{CP}(B \to J/\Psi K)$	ΔM_K, ε_K	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s\gamma$	$A_{CP}(B \to hhh)$, $B \to X\gamma$	$K \to \pi^0 ll$, ε'/ε	$\Delta a_{CP}(D \to hh)$
EW Penguin	$B \to K^{(*)}ll$, $B \to X_s\gamma$	$B \to \pi ll$, $B \to X\gamma$	$K \to \pi^0 ll$, $K^\pm \to \pi^\pm \nu\nu$	$D \to X_u ll$
Higgs Penguin	$B_s \to \mu\mu$	$B \to \mu\mu$	$K \to \mu\mu$	$D \to \mu\mu$

Tree vs loop measurements

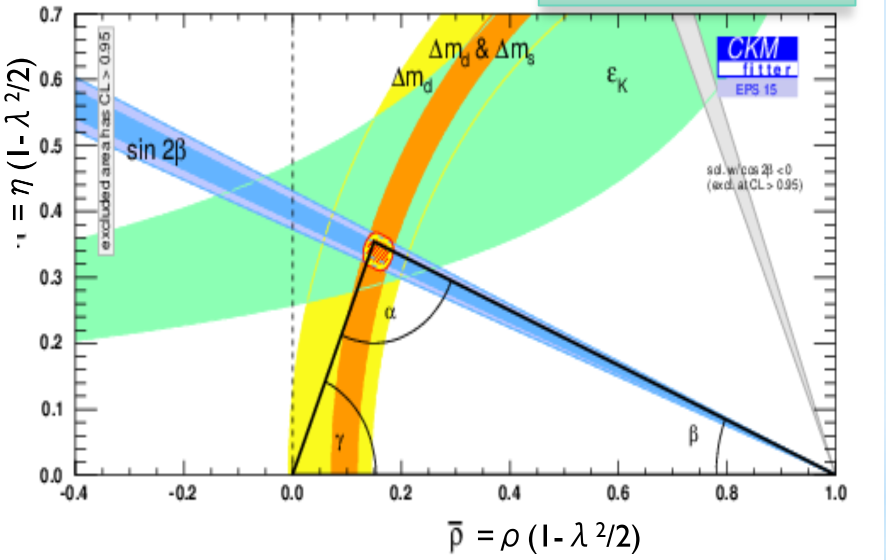
(A, λ, ρ, η) are not predicted by the SM. **They need to be measured!**

If we assume NP enters only (mainly) at loop level, it is interesting to compare the determination of the parameters (ρ, η) from processes dominated by tree diagrams (**V_{ub}, V_{cb}, γ,…**) with the ones from loop diagrams (**ΔM_d & ΔM_s, β, ε_K, …**).

Tree measurements



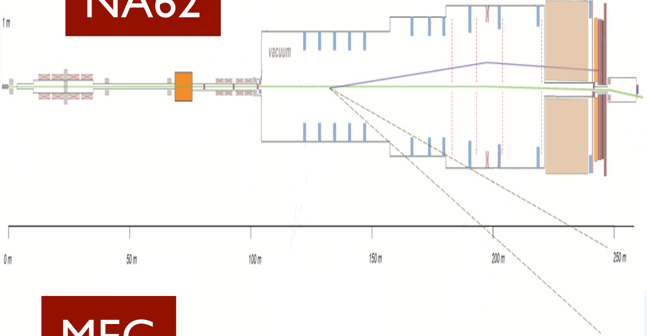
Loop measurements

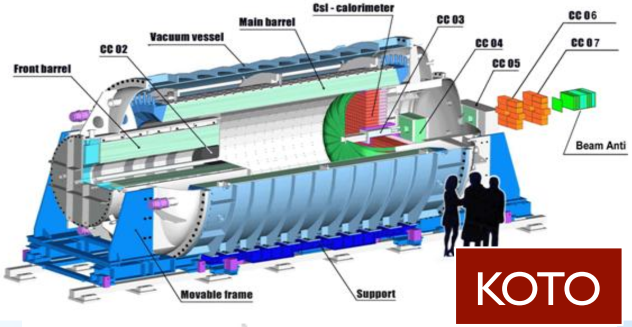


Need to improve the precision of the measurements at tree level to (dis-)prove the existence of NP contributions in loops.

Experimental Facilities

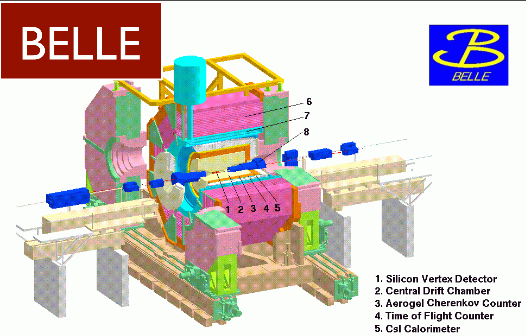
NA62





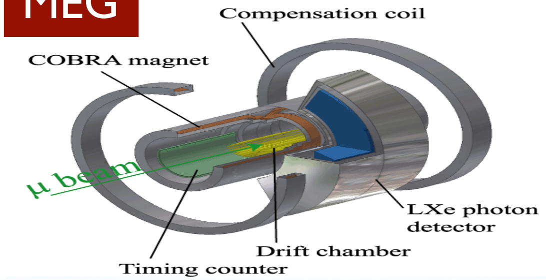
KOTO

BELLE

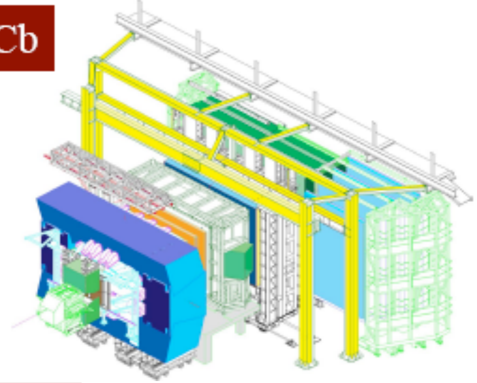


1. Silicon Vertex Detector
2. Central Drift Chamber
3. Aerogel Cherenkov Counter
4. Time of Flight Counter
5. CsI Calorimeter
6. KLM Detector
7. Superconducting Solenoid
8. Superconducting Final Focussing System

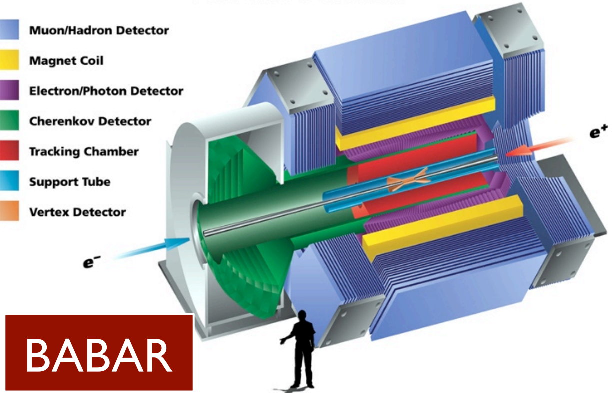
MEG



LHCb

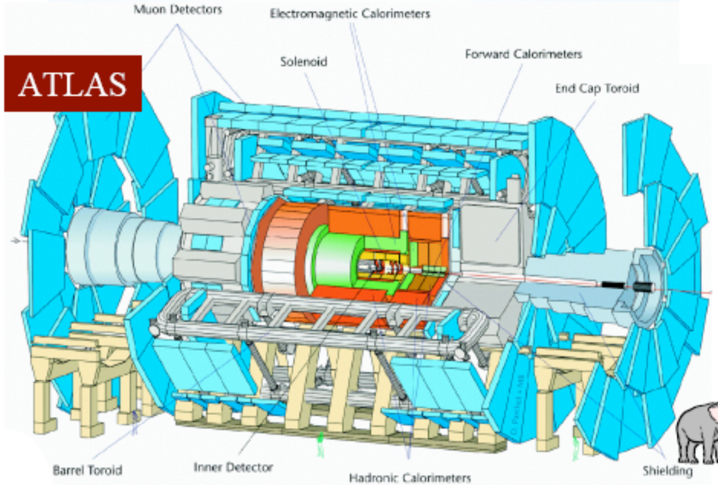


BABAR Detector

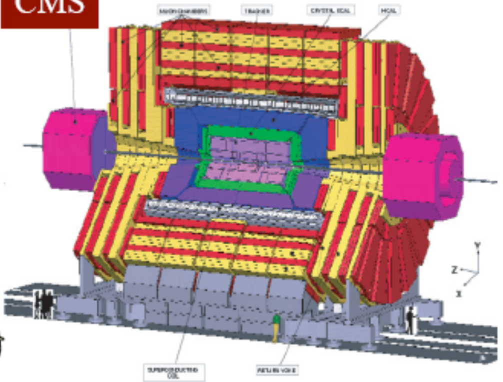


BABAR

ATLAS



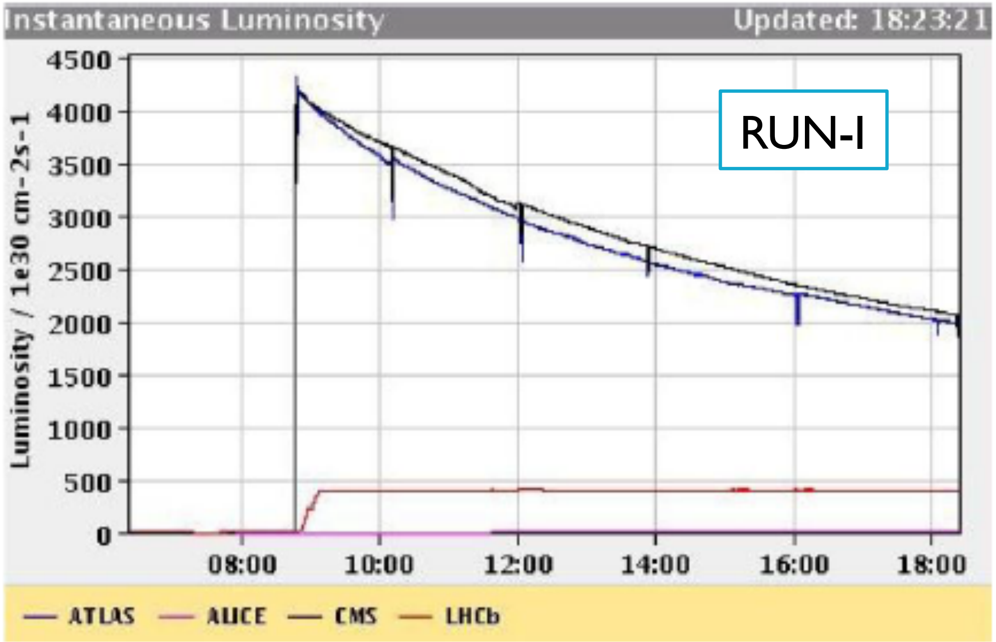
CMS



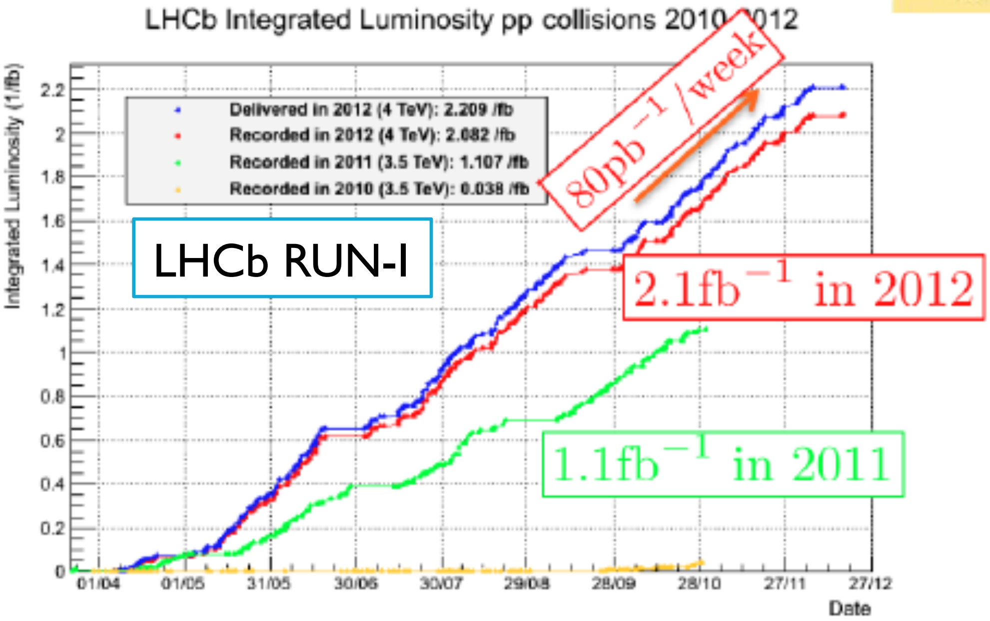
LHC is working like a dream!

In 2012 LHC delivered routinely peak luminosities of 4x10^{33}/cm^{2}/sec at **8 TeV**, for a total of 23 fb^{-1} to **ATLAS&CMS** (6 fb^{-1} in 2011 at **7 TeV**).

After 2013-2014 LS-I, in 2015 LHC is commissioning RUN-II. Intensity is ramping up, so far ~3.5x10^{33}/cm^{2}/sec at **13 TeV**, for a total so far of ~2 fb^{-1} to **ATLAS&CMS.**



RUN-I



LHCb RUN-I

LHCb took data at a constant luminosity 4x10^{32}/cm^{2}/sec during RUN-I thanks to luminosity leveling, for a total of 2.2 fb^{-1} at **8 TeV** delivered (1.2 fb^{-1} in 2011 at **7 TeV**).

RUN-II so far has delivered ~0.2 fb^{-1} to LHCb.

LHCb average number of visible pp collisions per bunch crossing ~2 at RUN-I, while for ATLAS/CMS is ~20.

LHC vs e^+e^- flavour factories

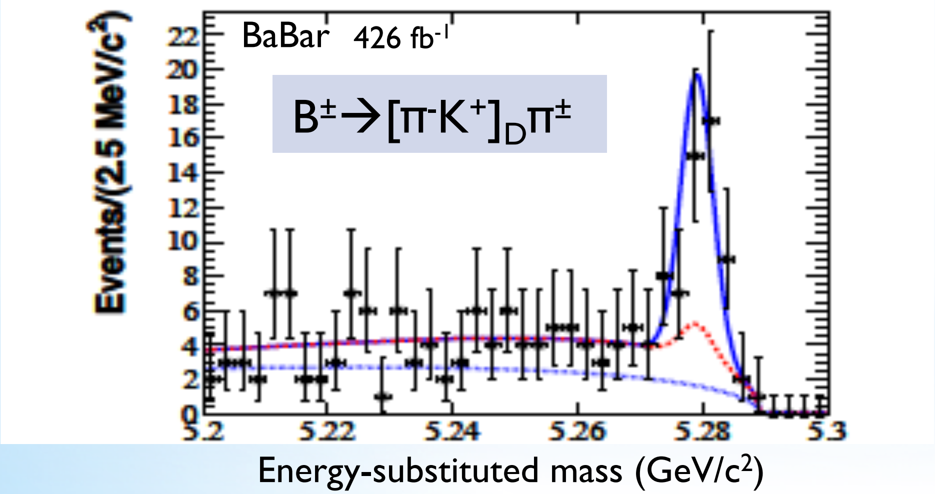
The bb x-section was measured by LHCb at 7/8 TeV to be: 3×10^{11} fb (PLB 694 (2010) 209, JHEP 06 (2013) 064) and recently at 13 TeV to be: 5×10^{11} fb (LHCb-PAPER-2015-037). The cc x-section ~20 times higher! (Nuclear Physics B 871 (2013) 1).

σ_{bb}(LHC)~5×10^5 σ_{bb}(Y(4S)) , **Luminosity rate(LHCb)~10^{-2} B-factories**

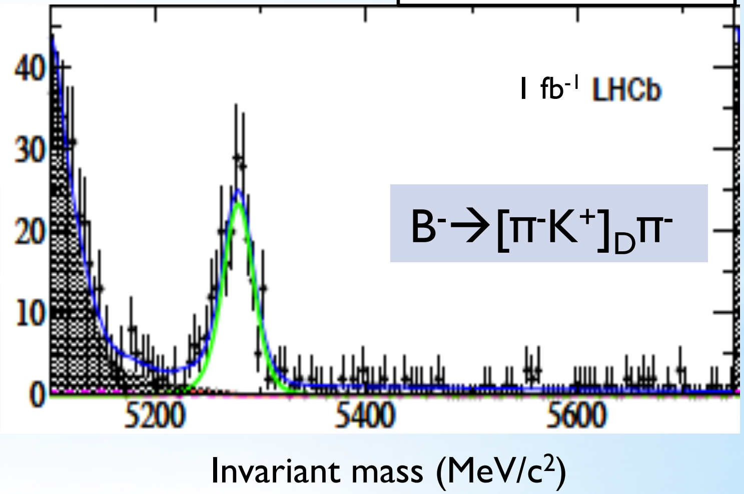
About 40% of the b-quarks produced at the LHC fragments into $B^\pm$ and another 40% into B^0, while 10% fragments into B_s and 10% into baryons. However at the LHC, the two b-quarks are produced incoherently → extra dilution factor in the tagging of B^0.

Detector resolution at hadron colliders compensate for the lack of beam energy constraint. In addition, larger boost helps to fight the background.

Phys. Rev. D82:072006 (2010)



Phys. Lett. B712 (2012)



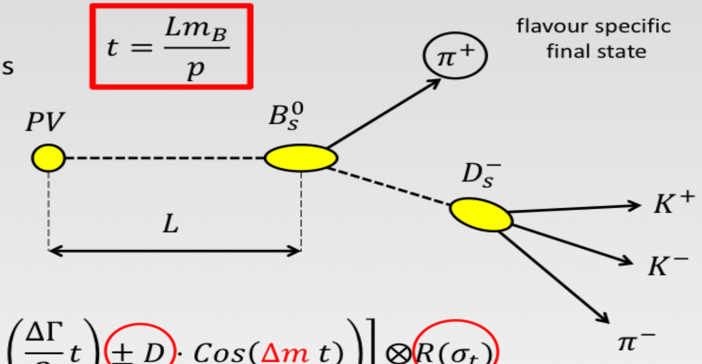
Rule of thumb:

<u>1 fb^{-1} at LHCb is equivalent to 1 ab^{-1} at the e^+e^- B-factories before tagging.</u>

…and the LHCb performance is up to it!

Need decay time dependent analysis

$$t = \frac{Lm_B}{p}$$

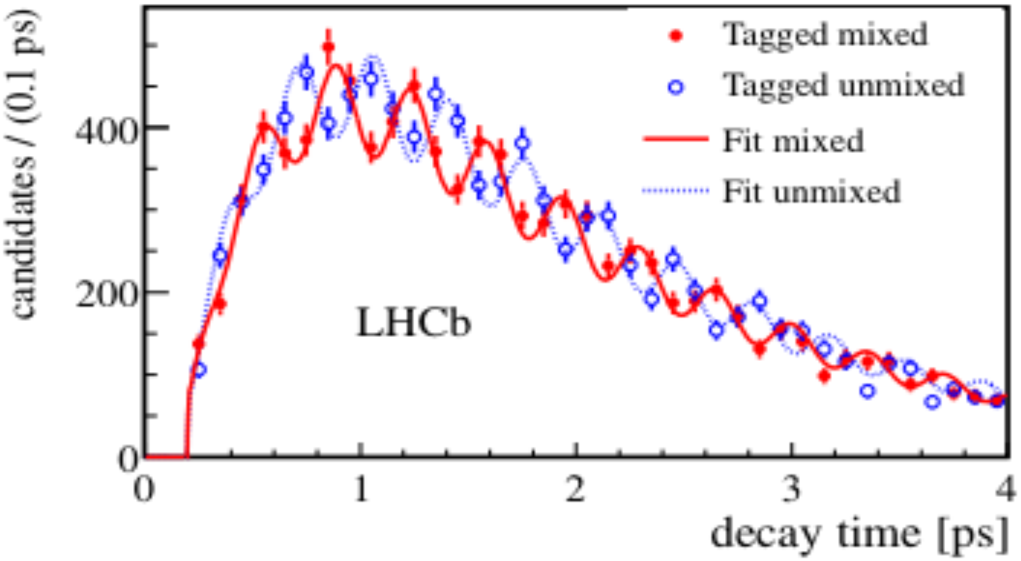


Decay time PDF:

$$PDF \propto \left[e^{-\Gamma t}\cdot\left(Cosh\left(\frac{\Delta\Gamma}{2}t\right) \pm D \cdot Cos(\Delta m\; t)\right)\right] \otimes R(\sigma_t)$$

Production flavour from tagging algorithms $D = (1-2\omega_{mistag})$

Need excellent decay time resolution



$B_s \rightarrow D_s^- [K^-K^+\pi^-]\pi^+$

Hadron trigger **~34k candidates per fb^{-1}**

Proper time resolution ~ **44 fs**
(to be compared with $2\pi^{-1}\,\Delta m_s^{-1}$~350 fs)

Effective tagging efficiency **~3.5%, D ~ 0.3**

New J. Phys. (2013) 053021

Δm_s = 17.768±0.023±0.006 ps^{-1}

$B^0 \rightarrow D^{(*)-}\,\mu^+\nu\,X$

Muon trigger **~1M candidates per fb^{-1}**

Effective tagging efficiency **~2.5%**

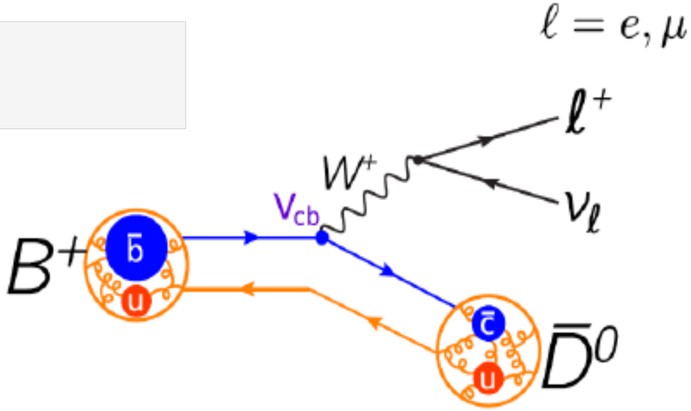
LHCb-CONF-2015-003

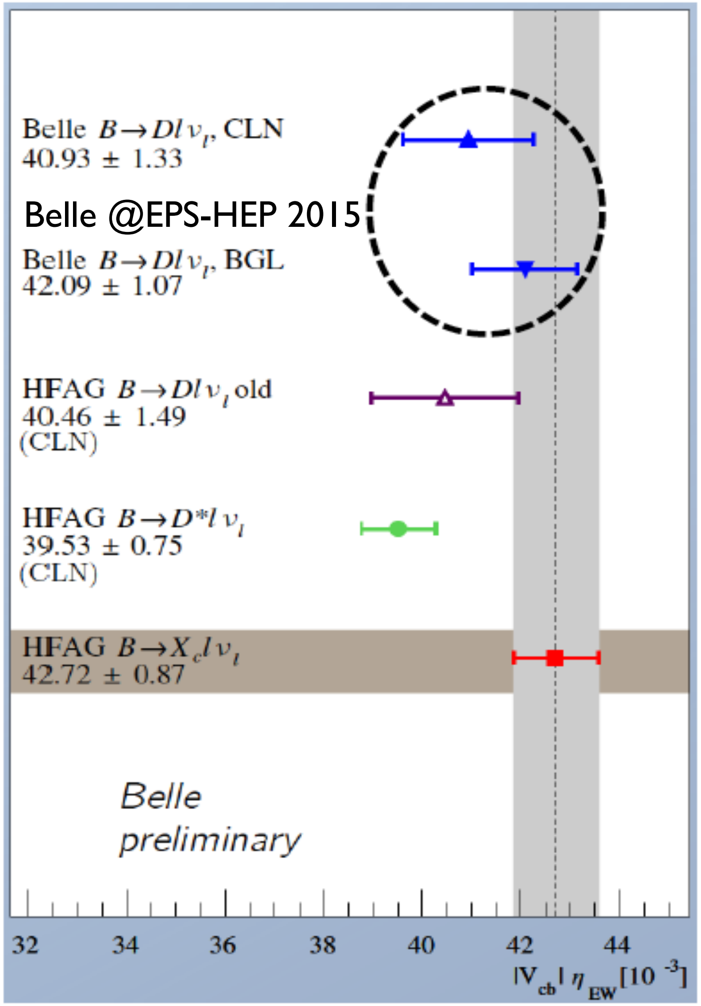
Δm_d = 503.6±2.0±1.3 ns^{-1}

Precision measurements at hadron colliders are becoming routine!

Tree Level Measurements:
V_{ub} , V_{cb} ,
arg(V_{ub}) ,…

V_{cb} and V_{ub} updates





$|V_{ub}|$ and $|V_{cb}|$ are measured in semileptonic $B^\pm$ and B_d decays using inclusive and exclusive methods. For quite some time both methods seem to disagree.

New inclusive determination of **$|V_{cb}|$** including $O(\alpha_s \Lambda^2_{QCD}/m^2_b)$, gives:

$|V_{cb}|$ (inclusive)= $(42.21\pm0.78)\times10^{-3}$

arXiv:1411.6560

Which seems to agree with the most recent determination from Belle using $B\to Dl\nu$ exclusive decays:

$|V_{cb}|$ ($B\to D$ excl.)= $(42.09\pm1.07)\times10^{-3}$

Belle@EPS-HEP 2015

However, there is still some tension (~3σ) with the determination using $B\to D^*l\nu$ exclusive decays.

The uncertainty in **$|V_{cb}|$** is one of the most important uncertainties in the SM predictions of very rare decays like: $B_s\to\mu^+\mu^-$ or $K^+\to\pi^+\nu\nu$.

See W. Sutcliffe and S. Meinel talks for more details.

V_{cb} and V_{ub} updates

New exclusive determination of $|V_{ub}|$ using new lattice form factors for B→πlν from FNAL/MILC:

$|V_{ub}|$ (B→π excl.) = $(3.72\pm0.16)\times10^{-3}$

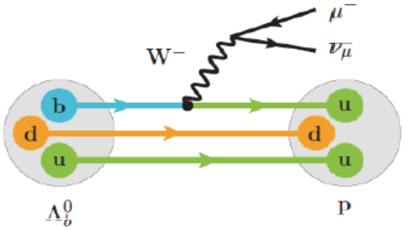
arXiv:1503.07839

seems to be in better agreement with the average from the inclusive method:

$|V_{ub}|$ (inclusive) = $(4.45\pm0.36)\times10^{-3}$

Average from CKMfitter

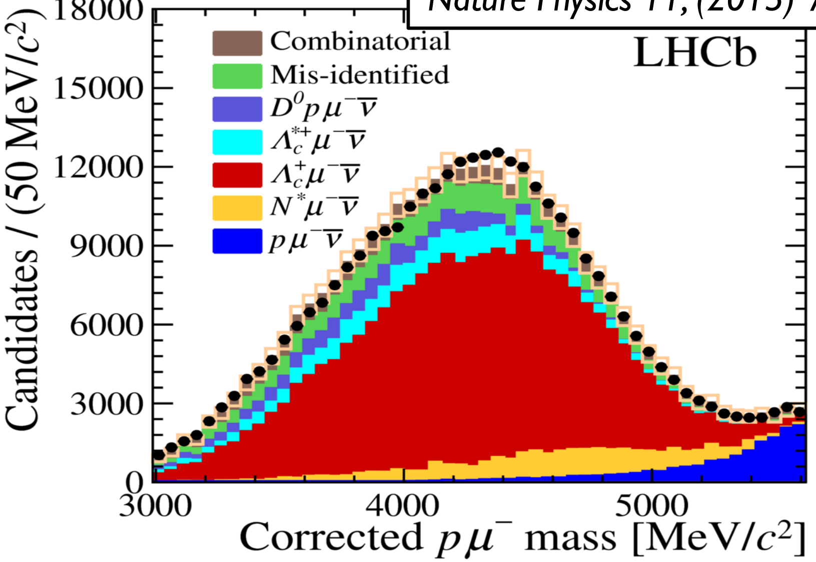
The decay $\Lambda_b \to p\mu\nu$ is the analogue to $B\to\pi\mu\nu$, with the advantage that protons are a cleaner experimental signature. LHCb has measured the ratio:

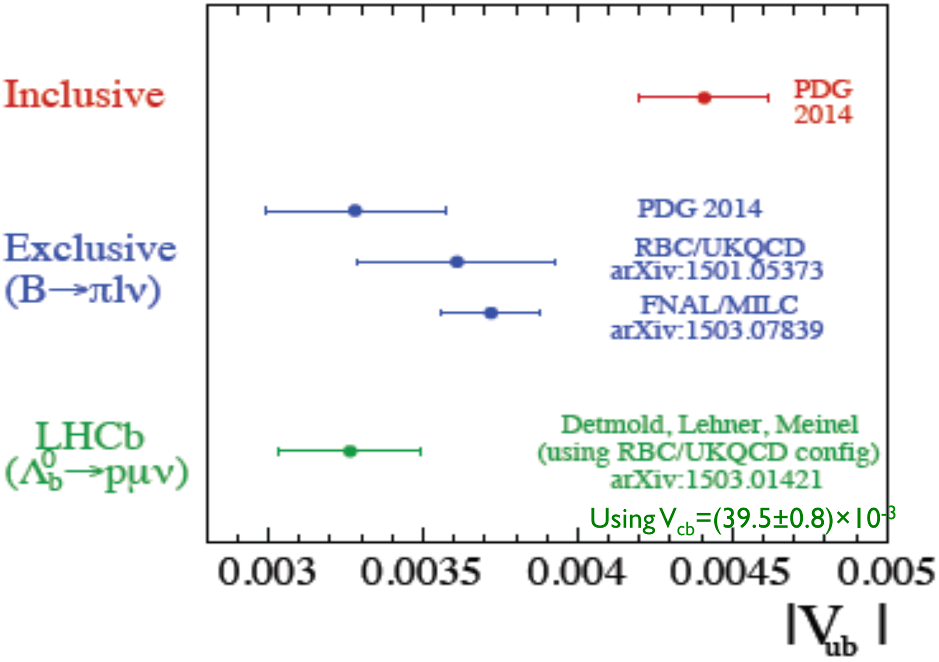


$$\frac{\mathcal{B}(\Lambda_b^0\to p\mu\nu)_{q^2>15\,\mathrm{GeV}}}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\mu\nu)_{q^2>7\,\mathrm{GeV}}} = (1.00\pm0.04\pm0.08)\%$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083\pm0.004\pm0.004$$

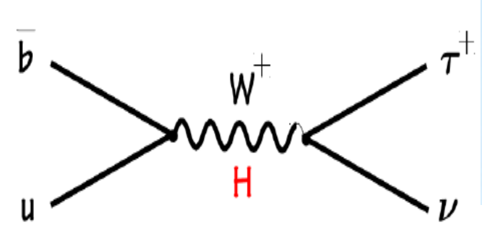
Nature Physics 11, (2015) 743





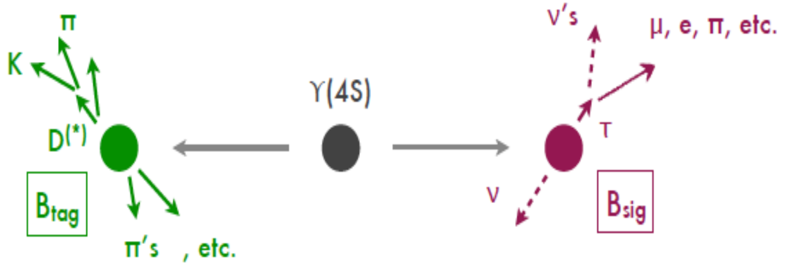
Using $V_{cb}=(39.5\pm0.8)\times10^{-3}$

NP in tree decays involving taus?



See C. Rosenfeld talk for more details.

Belle improved **new semileptonic** tagging result is in good agreement with Belle hadronic tagging and with the CKM fit (using average value of $V_{ub} = (3.71 \pm 0.07) \times 10^{-3}$).

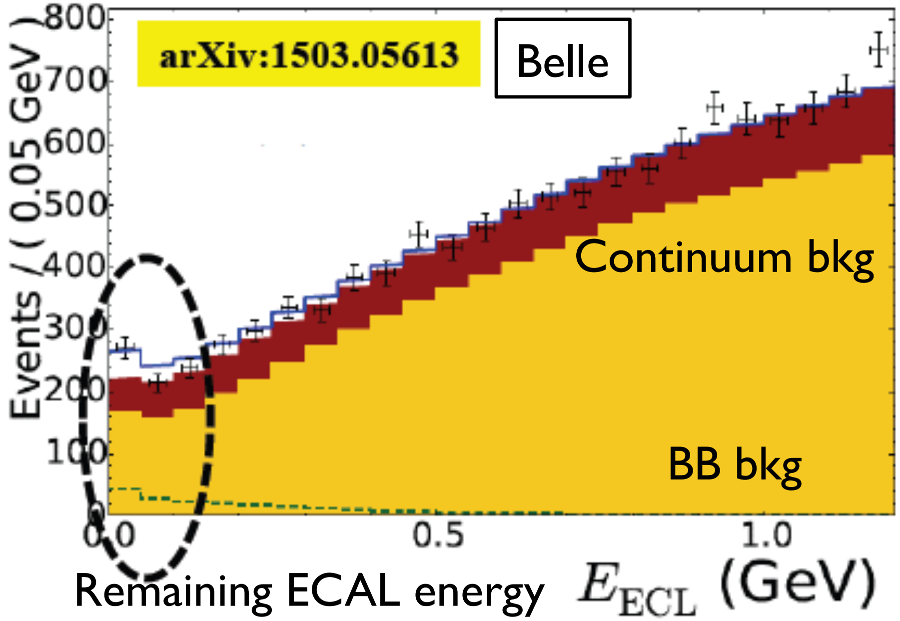


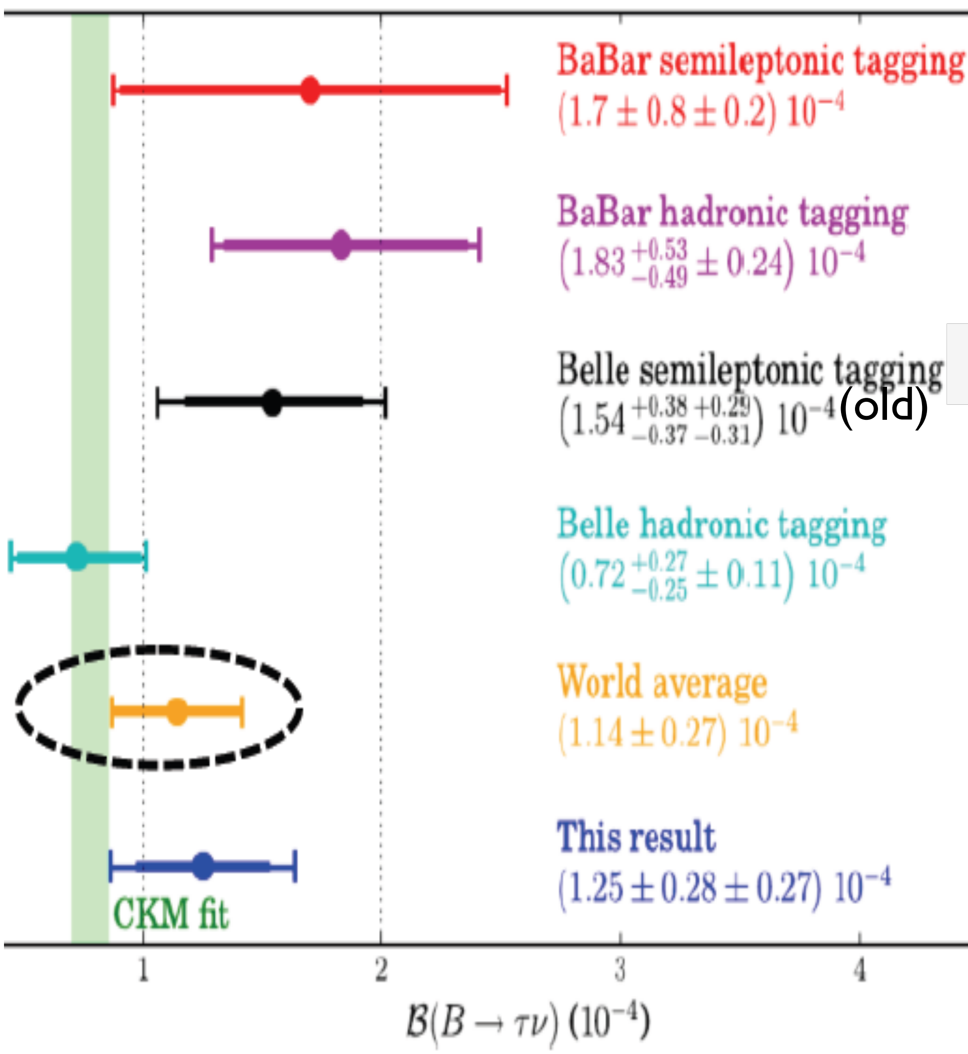
B_{tag} reconstructed from

- hadronic decays $B \to D^{(*)}\pi$, etc.,
- semileptonic decays $B \to D^{(*)} l \nu$.

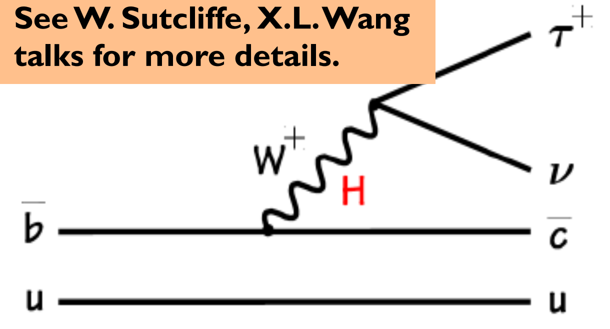
B_{sig} extracted by using

- extra energy ("E_{ECL}" or "E_{extra}"),
- missing mass squared ("M_{miss}^2").



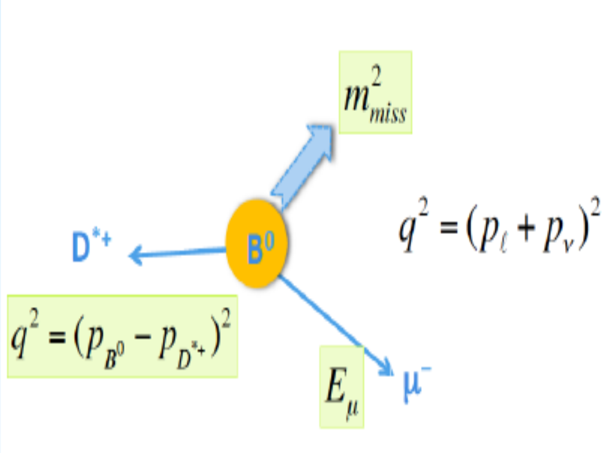


See W. Sutcliffe, X.L. Wang talks for more details.



NP in tree decays involving taus?

New results on **R(D$^{(*)}$)** from **Belle** and **R(D*)** from **LHCb** seem to confirm earlier results from BaBar.

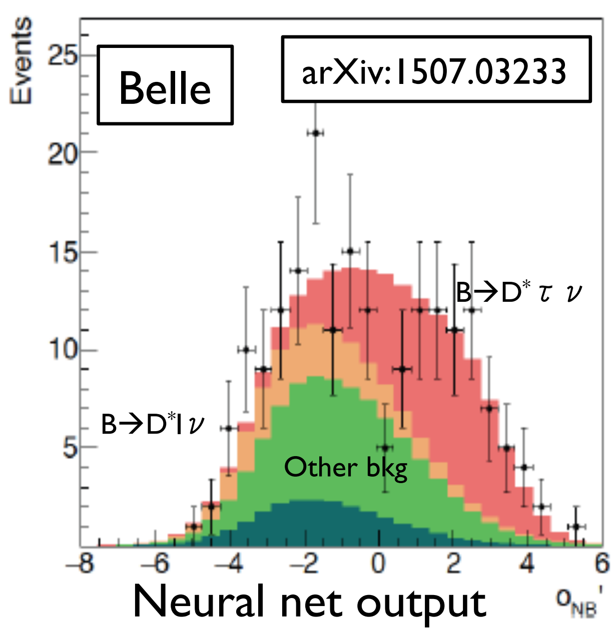


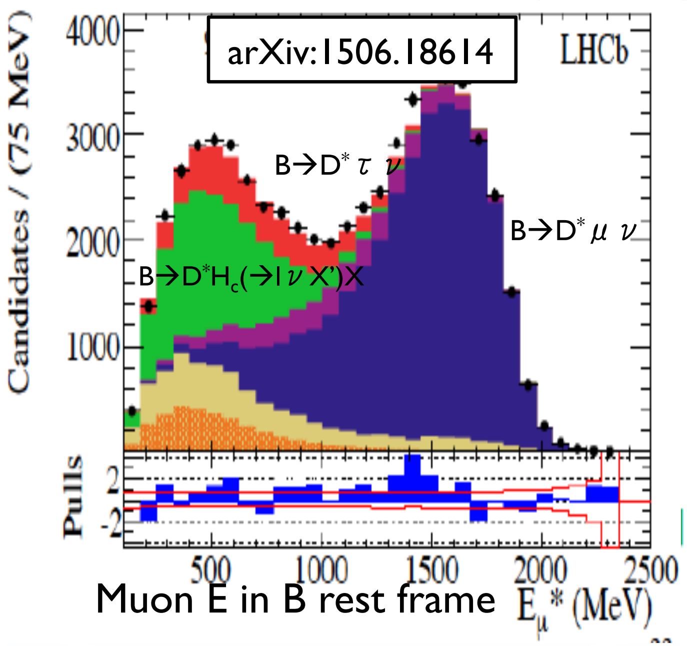
$$R(D) = \frac{\mathcal{B}(B \to D\tau^+\nu_\tau)}{\mathcal{B}(B \to D\ell^+\nu_\ell)}$$

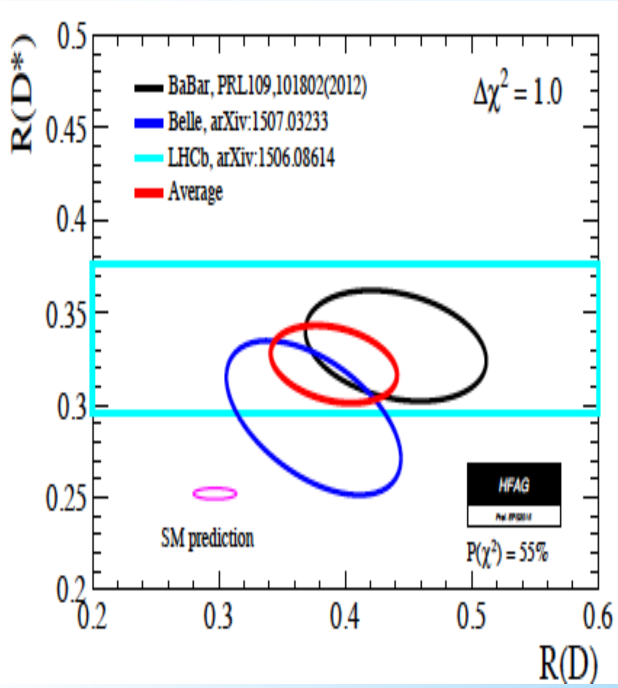
$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau^+\nu_\tau)}{\mathcal{B}(B \to D^*\ell^+\nu_\ell)}$$

Combination:
R(D*)=0.322±0.018±0.012
R(D)=0.391±0.041±0.028

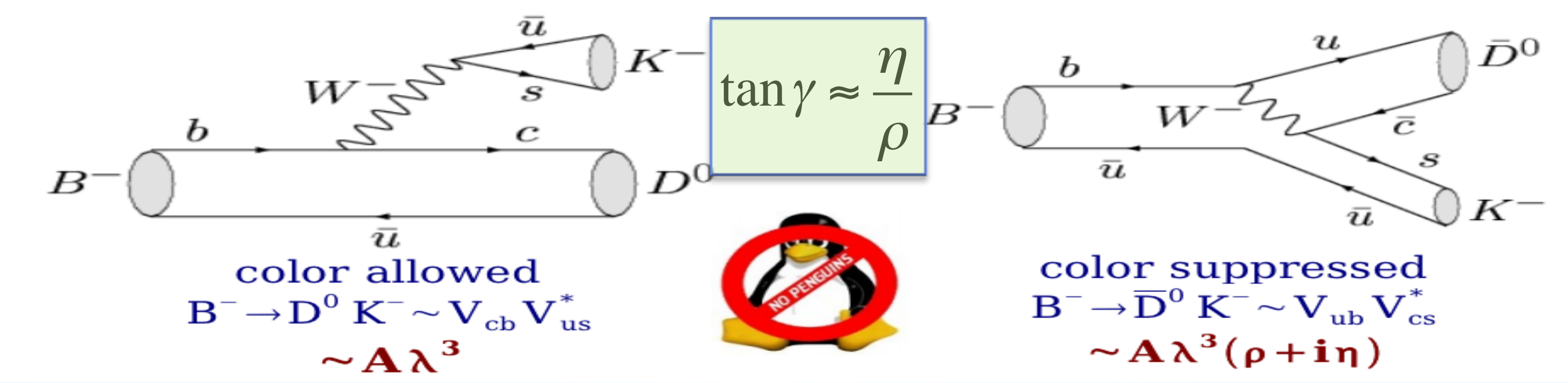
Should we take seriously a (28±7)% increase in b→c τ ν ?







V_{ub} phase (γ): No change since CKM 2014



$$\tan\gamma \approx \frac{\eta}{\rho}$$

color allowed

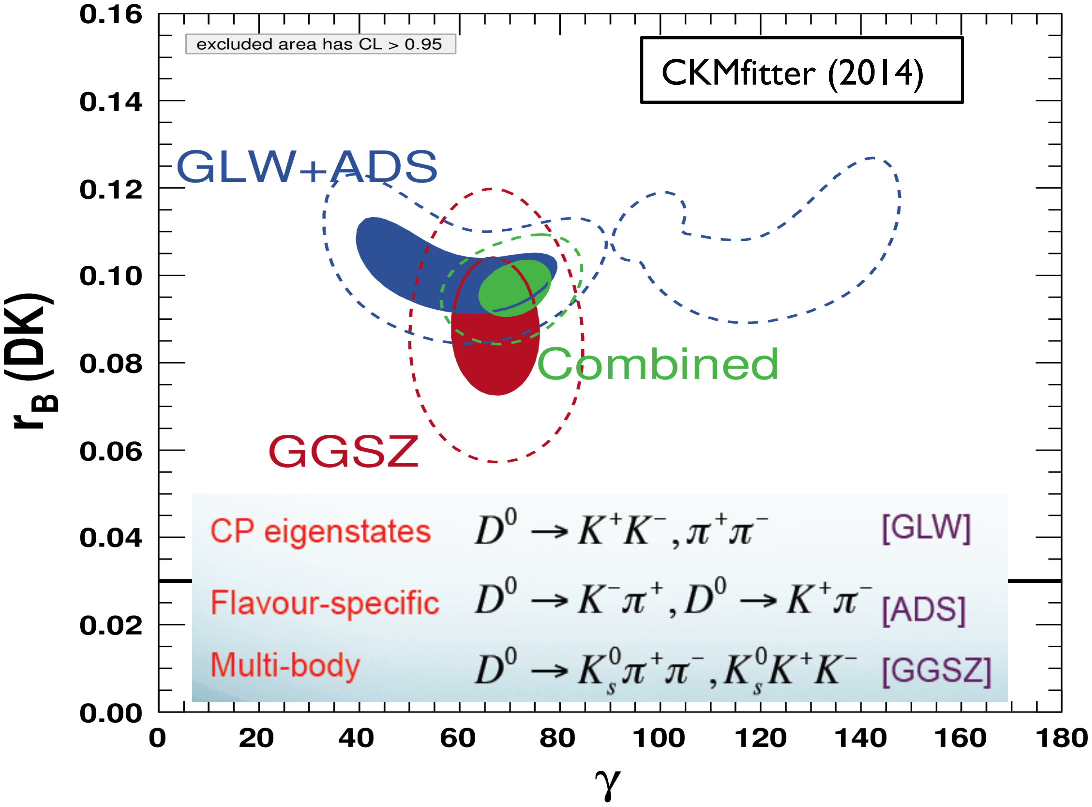
$B^- \to D^0 K^- \sim V_{cb} V^*_{us}$

$\sim A\lambda^3$

color suppressed

$B^- \to \bar{D}^0 K^- \sim V_{ub} V^*_{cs}$

$\sim A\lambda^3(\rho + i\eta)$



$$\gamma = (73.2^{+6.3}_{-7.0})^\circ$$

$$r_B = (0.097 \pm 0.006)$$

$$\delta_B = (125.4^{+7.0}_{-7.8})^\circ$$

To be compared with the CKM fit indirect determination:

γ (CKM fit)=$(66.9^{+1.0}_{-3.7})^\circ$

ΔF=2 Box Measurements

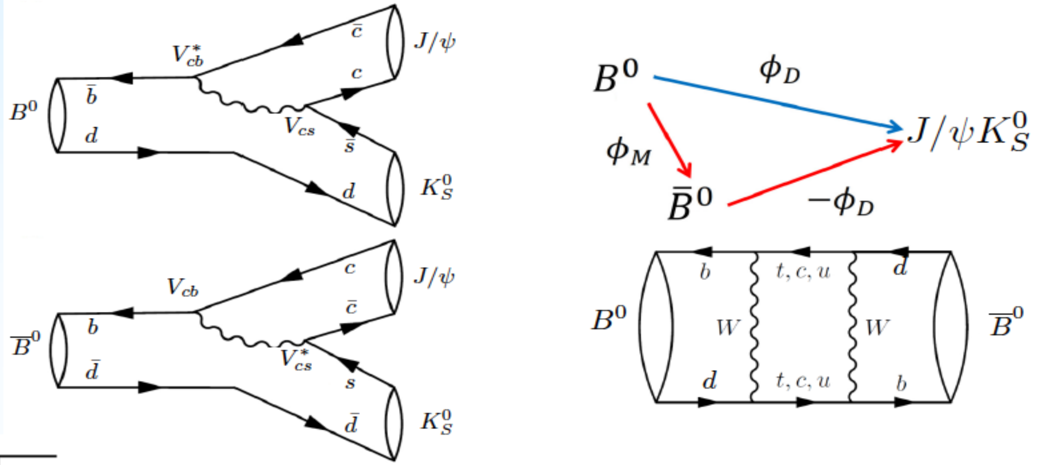
ΔF=2 box in b→d transitions: CP asymmetries in $B_s \to J/\Psi K_s$

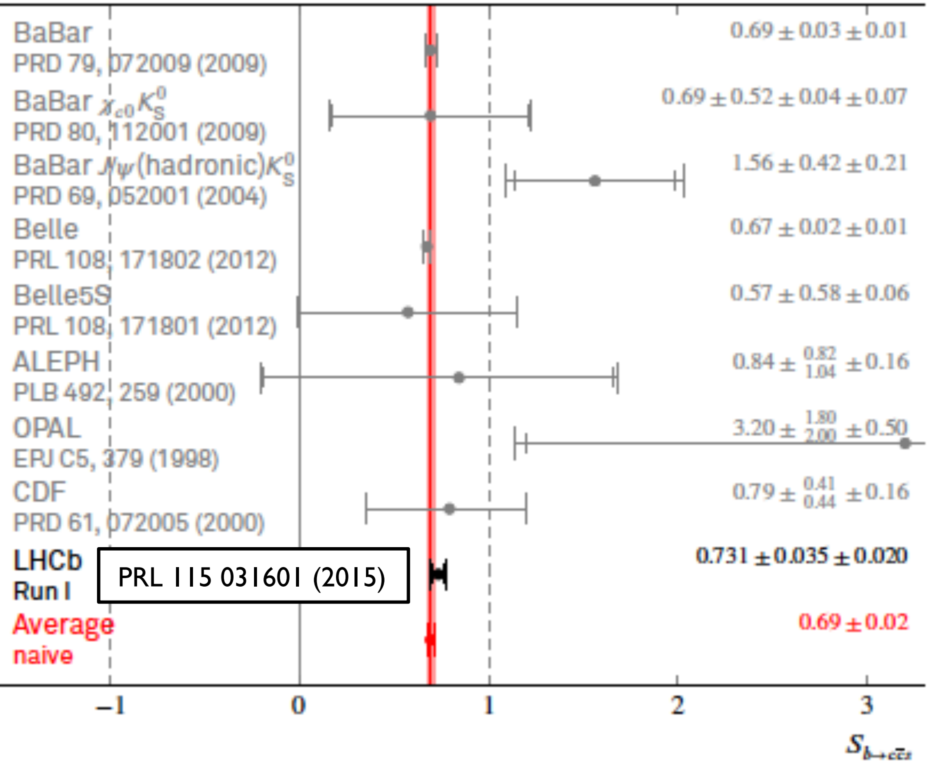
$$\tan\beta \approx \frac{\eta}{1-\rho}\left(1-\frac{\lambda^2}{2}\right)$$

If we assume the SM, **B-factories** have measured the phase of V_{td} better than 4% from b→d transitions in box diagrams. In fact, the measurement is a precise measurement of (β + ϕ_{bd}^{NP}).

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$2\beta = \phi = \phi_M - 2\phi_D$$





PRL 115 031601 (2015)

New precise result from LHCb using all RUN-I data (3 fb^{-1}) in agreement with B-factories and similar precision. Systematic uncertainty expected to decrease with statistics!

sin(2β) (LHCb) = 0.731±0.035±0.020

Average (BABAR+Belle+LHCb): **β = (24.3±0.8)°**

To be compared with the indirect determination using "tree level measurements": **β = (26.9±1.5)°**

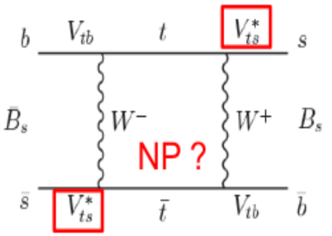
ϕ_{bd}^{NP} can be as large as O(5°) and still be consistent!

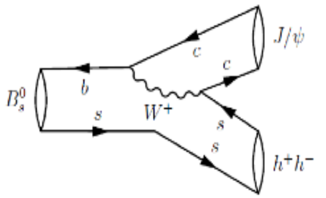
Δ F=2 box in b→s transitions: CP asymmetries in B_s→J/Ψ Φ

$$\boxed{\phi_s \approx -2\eta\lambda^2}$$

Angular analysis is needed in **B_s→J/Ψ Φ** decays, to disentangle statistically the CP-even and CP-odd components.

LHCb includes also **B_s→J/Ψ ππ** and even **B_s→$D^+_s D^-_s$.** New **ATLAS** and **CMS** analyses have also measured φ_s in B_s→J/Ψ Φ with full RUN-1 statistics.

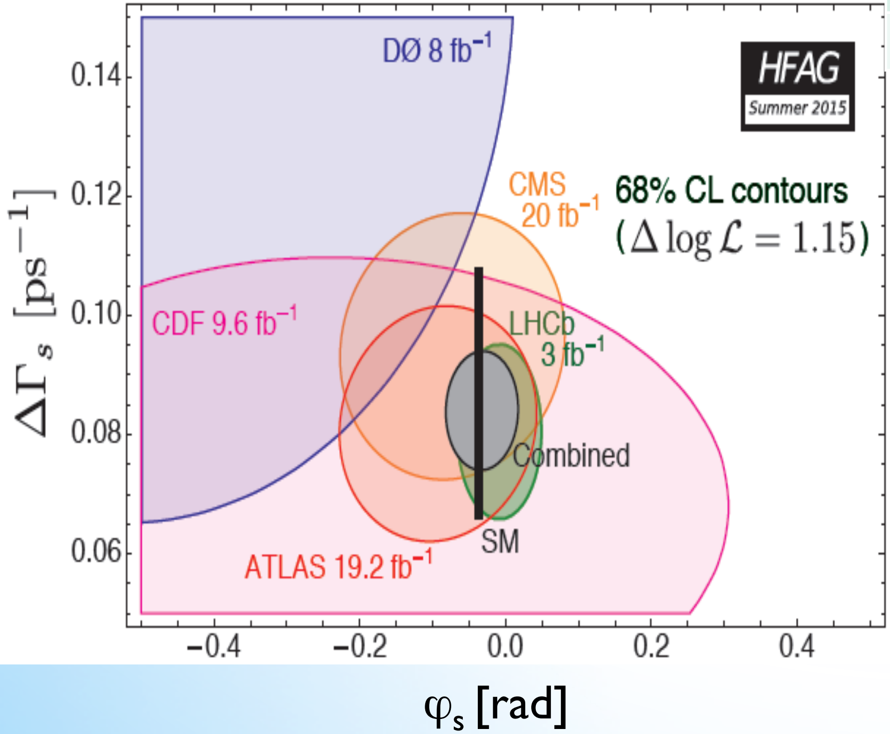




+ small penguin pollution

$$\phi_D^{SM} = -2\arg(V_{cs}V^*_{cb}) \approx 0$$

B_s→J/Ψ Φ	ATLAS @EPS-HEP 2015	CMS @EPS-HEP 2015	LHCb PRL114 041801(2015)
Luminosity (fb^{-1})	19	20	3
Effective tagging (%)	1.5	1.3	3.7
Φ_s[mrad]	-94±83±33	-75±97±31	-58±49±6
$\Delta\Gamma_s$[fs^{-1}]	82±11±7	95±13±7	80.5±9.1±3.3



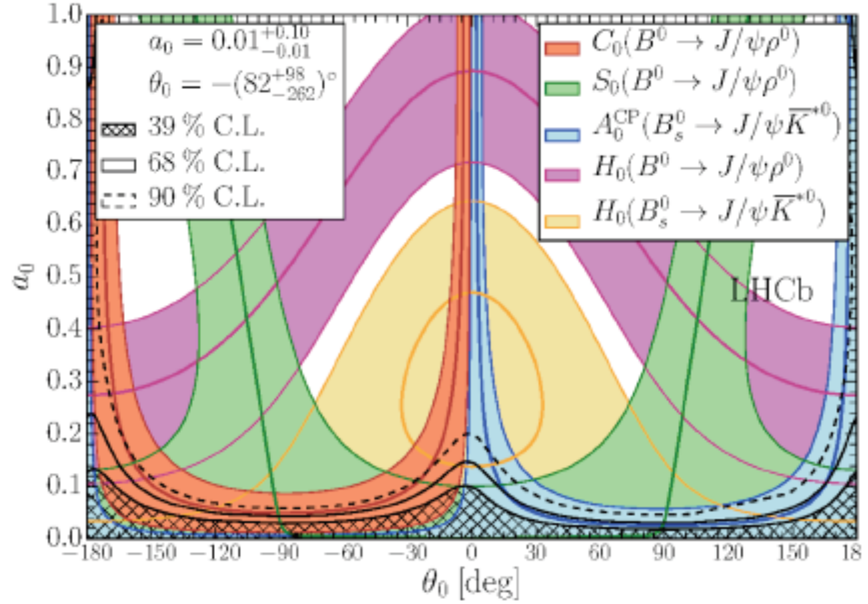
Combining all measurements:

$$\boxed{\varphi_s = (-34\pm33)\text{mrad} = (-2.01\pm1.89)°}$$

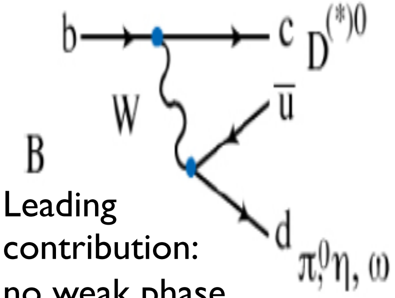
to be compared with φ_s **= (-2.1±0.1)°** using “tree level measurements”. Although, there has been **impressive progress** since the initial measurements at CDF/D0, the uncertainty needs to be further reduced for a meaningful comparison.

Penguin Contributions to Δ F=2 b→d,s transitions

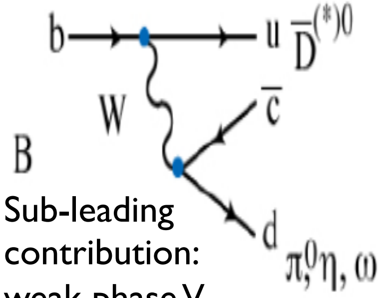
$$\boxed{\phi_q^{meas} = \phi_q + \Delta\phi_{penguin} + \Delta\phi_{BSM}}$$



$B^0 \to D^{(*)0} h^0$, $h^0 = \pi^0, \eta, \omega$



Leading contribution: no weak phase



Sub-leading contribution: weak phase V_{ub}

Measure $\Delta\phi_{penguin}$ in processes where penguin decays are not suppressed.

$$A \sim (1-\lambda^2/2)\, A'_{(i)} \left[1 + \varepsilon a'_{(i)}\, e^{i\theta'_{(i)}} e^{i\gamma}\right]$$

New results from LHCb, fit for |A'/A| to limit sensitivity to hadronic uncertainties, assuming:

$$\left|A'_i/A_i\right|\left(B_s^0 \to J/\psi\overline{K}^{*0}\right) = \left|A'_i/A_i\right|\left(B_d^0 \to J/\psi\rho^0\right)$$

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,{}^{+0.004}_{-0.009} \text{ rad}$$

$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014} \pm 0.008 \text{ rad}$$

$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014} \pm 0.008 \text{ rad}$$

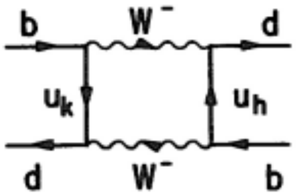
arXiv:1509.00400

Alternatively look for penguin free ($b \to c\bar{u}d$) measurements, $\Delta\phi_{penguin} \sim 0$. BaBar (0.5 ab^{-1}) and Belle (1 ab^{-1}) have combined forces to achieve:

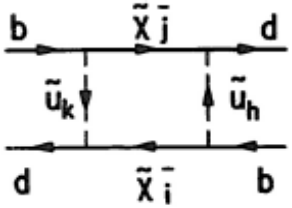
Sin(2 β) (no-penguin) = 0.66±0.10±0.06

arXiv:1505.04147

Δ F=2 box in b→q transitions



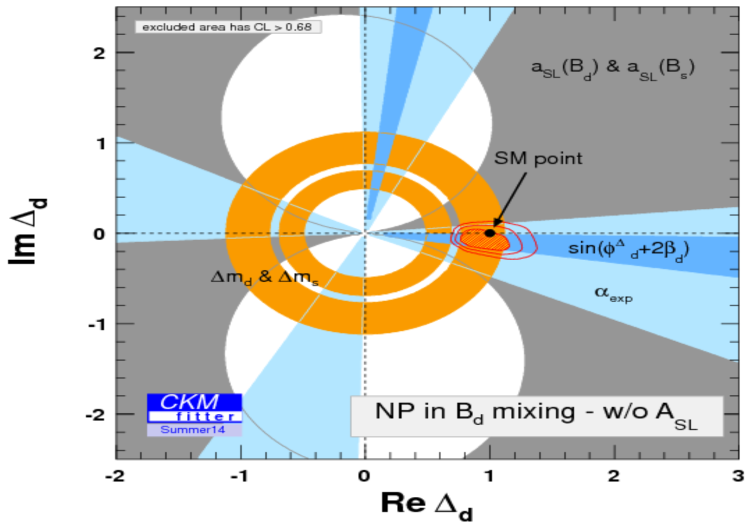
SM: $\frac{C_{\rm SM}}{m_W^2}$



NP: $\frac{C_{\rm NP}}{\Lambda^2}$

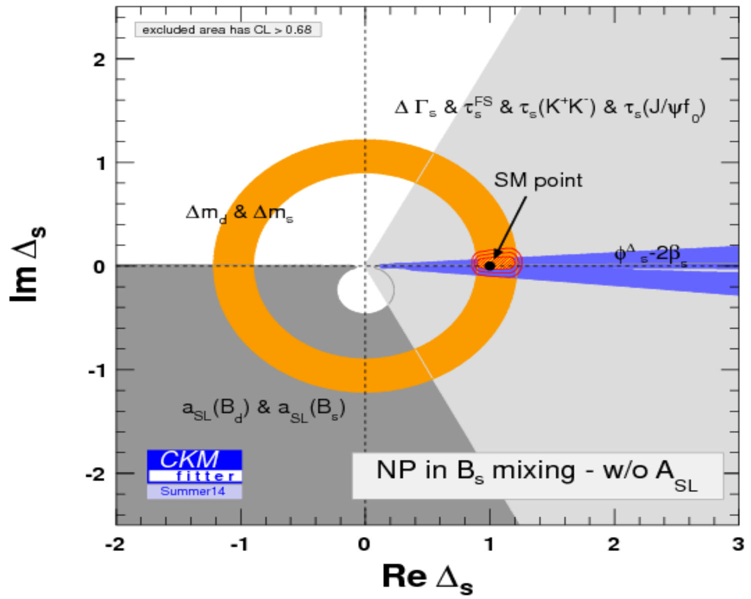
$$\boxed{\left\langle B_q^0 \middle| M_{12}^{SM+NP} \middle| \bar{B}_q^0 \right\rangle \equiv \Delta_q^{NP} \cdot \left\langle B_q^0 \middle| M_{12}^{SM} \middle| \bar{B}_q^0 \right\rangle}$$

$$\boxed{\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i\ Im(\Delta_q) = |\Delta_q| e^{i\phi_q^{\Delta}}}$$



No significant evidence of NP in B_d or B_s mixing . Remember that what is named SM prediction in these plots, is in fact the determination from other measurements (tree level).

New φ^{Δ}_q in box diagrams constrained @95%CL to be <7° (<5°) for $B_d(B_s)$.



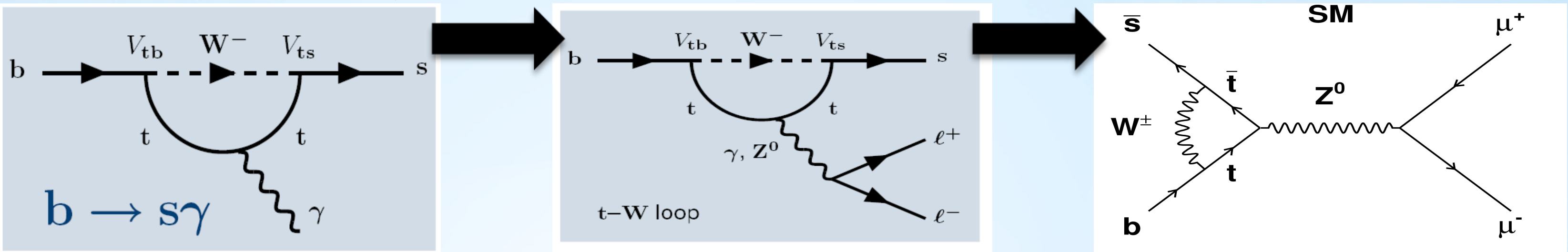
Need to increase precision to disentangle NP phases of few degrees in B_d and B_s mixing

ΔF=1 EW Penguins

Three impersonations of the EW penguin

α_{QED} suppression

helicity suppression



SM

BSM

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i C_i O_i$$

Coupling Strength C_i = Wilson coefficient
→ Sensitive to New Physics

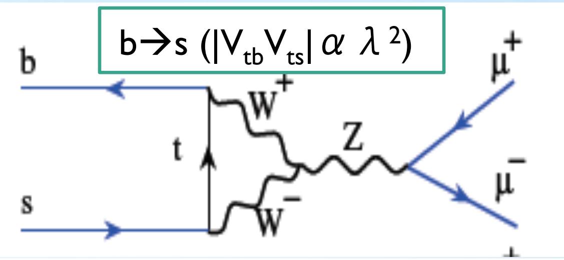
See E. Lunghi talk for more details.

i = 1, 2	Tree
i = 3-6, 8	Gluon penguin
i = 7	Photon penguin
i = 9, 10	Electroweak penguin
i = S, P	Scalar/Pseudoscalar penguin

$B_s \rightarrow \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	Large theory uncertainties O(20%)	$(3.5\pm0.4)\cdot10^{-5}$ Nuclear Physics B 867 1-18 (2013)	**γ polarization**
$B_d \rightarrow K^{*}\mu^{+}\mu^{-}$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu (\gamma_5) \ell$		$(1.16\pm0.19)\cdot10^{-6}$ JHEP 07 133 (2012)	**angular distributions**
$B_s \rightarrow \mu^{+}\mu^{-}$	$\mathcal{O}_{S(P)} \sim \bar{s}_L b_R \bar{\ell} (\gamma_5) \ell$	$(3.66\pm0.23)\cdot10^{-9}$ helicity suppressed	$(2.8^{+0.7}_{-0.6})\cdot10^{-9}$ Nature 522, 68-72 (2015)	**BR**

ΔF=1 Higgs penguins in b→d,s transitions

The pure leptonic decays of **K,D and B** mesons are a particular interesting case of EW penguin. The **helicity suppression** of the vector(-axial) terms, makes these decays particularly sensitive to new (pseudo-)scalar interactions →**Higgs penguins!**

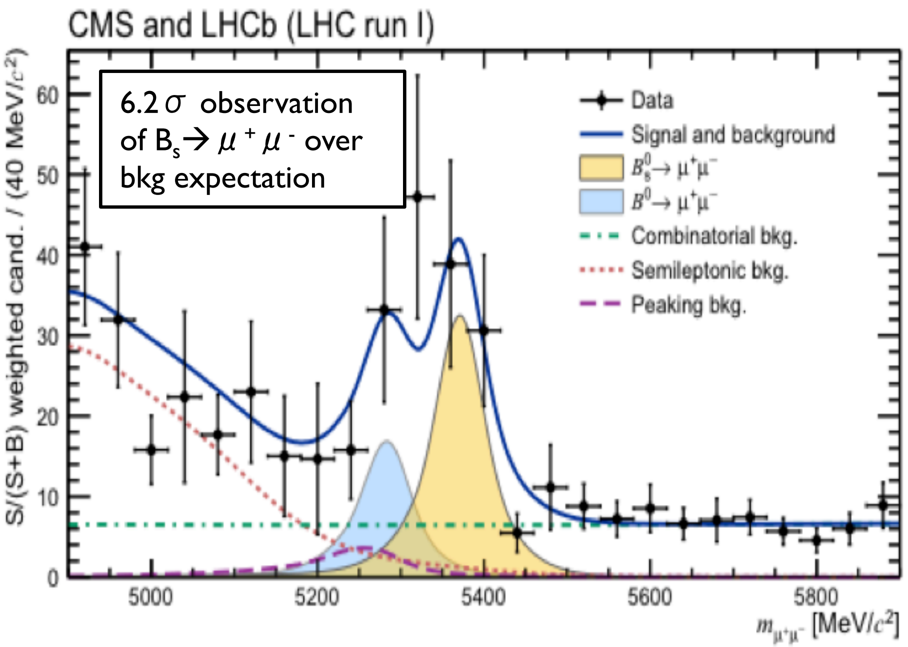


b→s ($|V_{tb}V_{ts}| \alpha \lambda^2$)

$$BR(B_q\to\mu^+\mu^-)=\frac{G_F^2\alpha^2}{64\pi^3\sin^4\theta_W}|V_{tb}^*V_{tq}|^2\,\tau_{Bq}M_{Bq}^3f_{Bq}^2\sqrt{1-\frac{4m_\mu^2}{M_{Bq}^2}}\times$$

$$\times\left\{M_{Bq}^2\left(1-\frac{4m_\mu^2}{M_{Bq}^2}\right)\left(\frac{C_S-\cancel{\mu_q}C_S'}{1+\cancel{\mu_q}}\right)^2+\left[M_{Bq}\left(\frac{C_P-\cancel{\mu_q}C_P'}{1+\cancel{\mu_q}}\right)+\overset{\sim 0.04}{\boxed{\frac{2m_\mu}{M_{Bq}}}}(C_A-C_A')\right]^2\right\}$$

with $\mu_q = m_q/m_b \ll 1$ and $m_\mu/m_B \ll 1$. Hence if $C_{S,P}$ (NP) >> $(2m_\mu/m_B) \times C_A$ ~0.2 the scalar contribution dominates.



CMS and LHCb (LHC run I)

6.2σ observation of $B_s\to\mu^+\mu^-$ over bkg expectation

These decays are well predicted theoretically, and experimentally are exceptionally clean.

Within the SM, PRL 112 (2014) 101801

$BR_{SM}(B_s\to\mu\,\mu) = (3.66\pm0.23)\times10^{-9}$
$BR_{SM}(B_d\to\mu\,\mu) = (1.06\pm0.09)\times10^{-10}$

New combined values from **CMS** and **LHCb:**

$BR(B_s\to\mu\,\mu) = (2.8^{+0.7}_{-0.6})\times10^{-9}$ (35% syst.)
$BR(B_d\to\mu\,\mu) = (3.9^{+1.6}_{-1.4})\times10^{-10}$ (18% syst.)

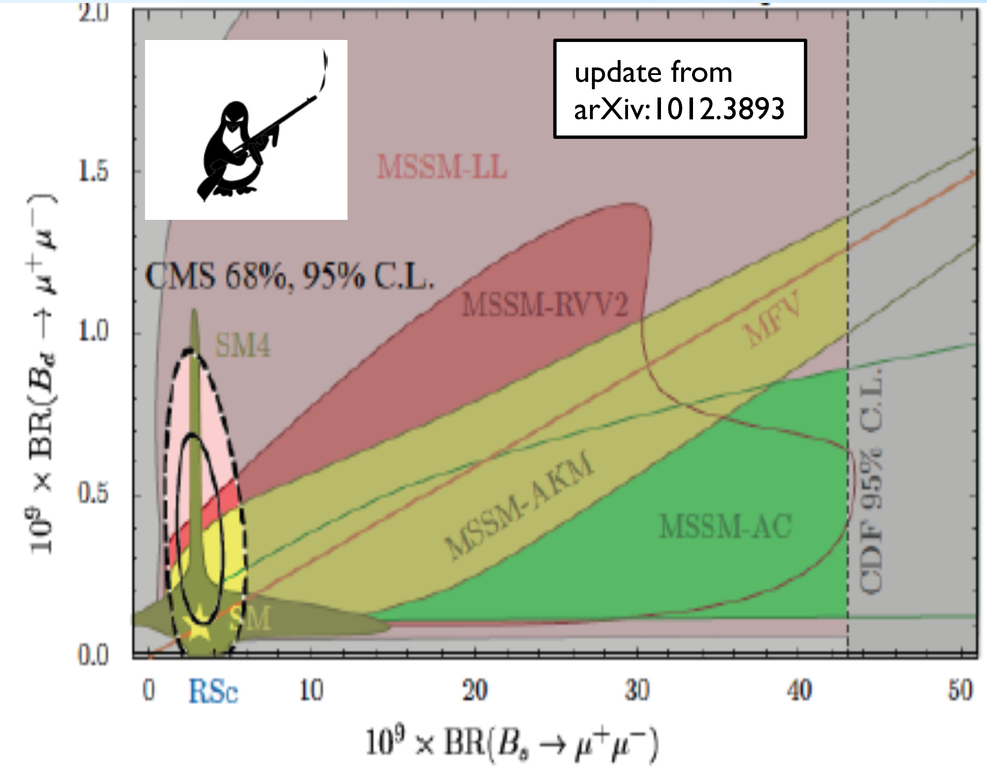
Compatible with SM at -1.2σ (+2.2σ) for B_s (B_d)

Nature 522, 68-72 (2015)

Δ F=1 Higgs penguins in b→s,d transitions: Implications

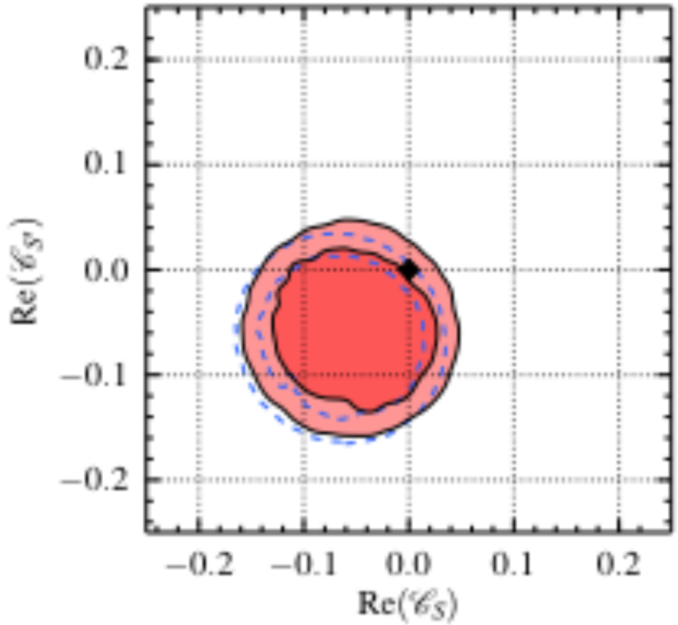
Latest results on $B_s \to \mu^+\mu^-$ strongly constrains the parameter space for many NP models, complementing direct searches from ATLAS/CMS.

In particular, large tan β with light pseudo-scalar Higgs in CMSSM is strongly disfavored.



update from arXiv:1012.3893

arXiv:1508.01526

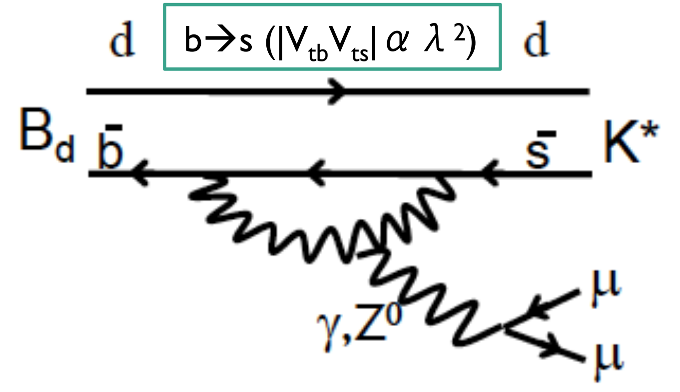


The precision achieved now is such that $B_{(s)} \to \mu^+\mu^-$ constrains on C_S are strong enough such that we cannot longer neglect C_{10} from the SM (Z, γ) penguin and potential NP contributions.

Need to include all observable into the global fit.

∆F=1 EW penguins in b→s transitions: B→K$^*\mu^+\mu^-$ angular analysis

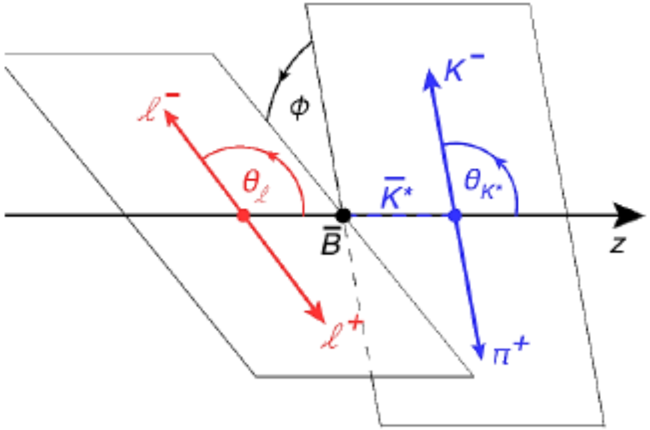
B→K$^*\mu^+\mu^-$ is the golden mode to test new vector(-axial) couplings in b→s transitions.



K*→Kπ is self tagged, hence angular analysis ideal to test helicity structure.

Sensitivity to C_7, C_9 and C_{10} and their primed counterparts. This analysis is bound to be **one of the stronger constraints** in models for NP with future statistics.

$$\begin{aligned}\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K + \boxed{F_{\mathrm{L}}}\cos^2\theta_K\\
&+\tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_l\\
&\boxed{-F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_l + \boxed{S_3}\sin^2\theta_K\sin^2\theta_l\cos 2\phi\\
&\boxed{+S_4}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi\\
&+\tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_l + \boxed{S_7}\sin 2\theta_K\sin\theta_l\sin\phi\\
&\boxed{+S_8}\sin 2\theta_K\sin 2\theta_l\sin\phi + \boxed{S_9}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]\end{aligned}$$



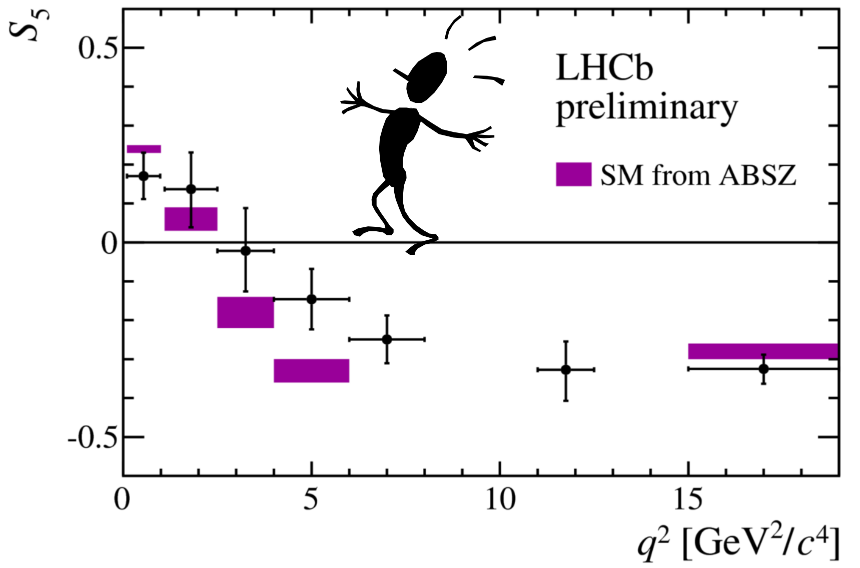
Results from **B-factories and CDF** very much limited by the statistical uncertainty. **LHCb, ATLAS and CMS** already have the largest sample (~2500 candidates) after RUN-I.

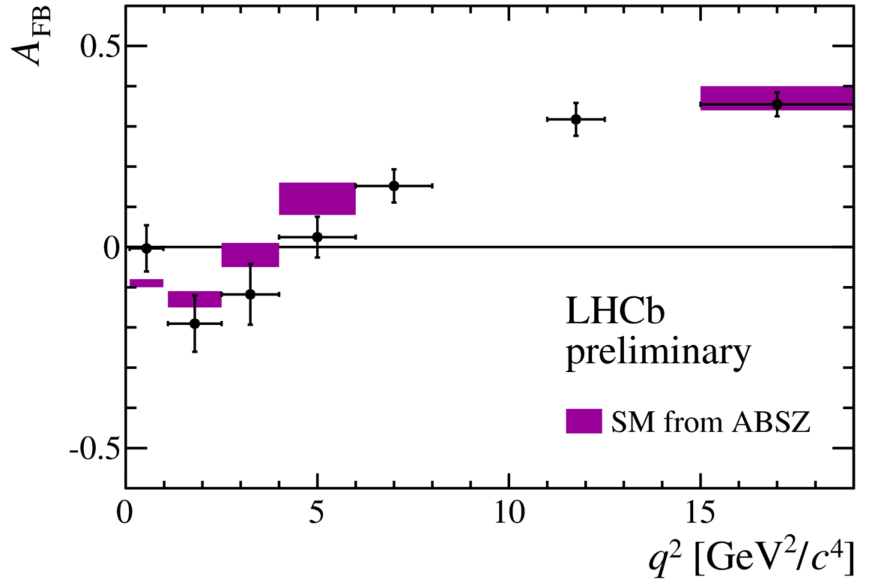
LHCb B→K* $\mu^+\mu^-$ full angular analysis

See F. Wilson talk for more details.

LHCb-CONF-2015-002

SM: Aoife Bharucha, Straub, Zwicky, arXiv:1503.05534





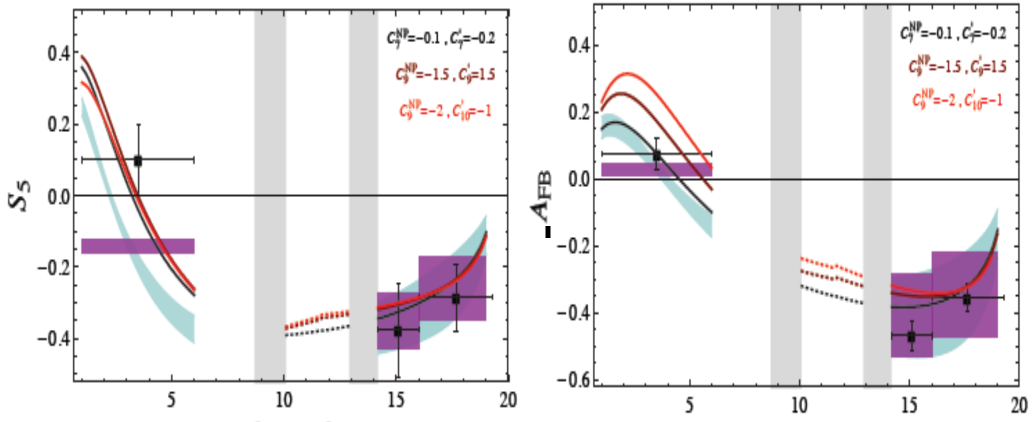
« Tour de force » full angular analysis performed for the first time by **LHCb** using RUN-I data.

Most of the measurements are in good agreement with the expectations, with only some hints for deviations for the CP-averaged measurements of S_5 and A_{FB}.

$S_5 \sin 2\theta_K \sin\theta_l \cos\phi$

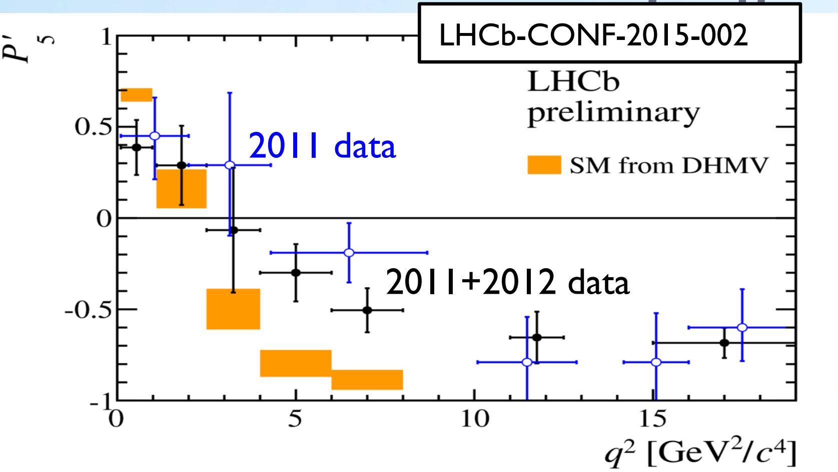
$\frac{4}{3}A_{\rm FB}\sin^2\theta_K\cos\theta_l$

	sens. at low q^2	sens. at high q^2
F_L	$C_{7,9}, C'_{9,10}$	$C'_{9,10}$
$A_{\rm FB}$	C_7, C_9	$C_{9,10}, C'_{9,10}$
S_3	$C'_{7,10}$	$C'_{9,10}$
S_4	$C_{7,10}, C'_{7,10}$	$C'_{9,10}$
S_5	$C_{7,9}, C'_{7,9,10}$	$C_9, C'_{9,10}$

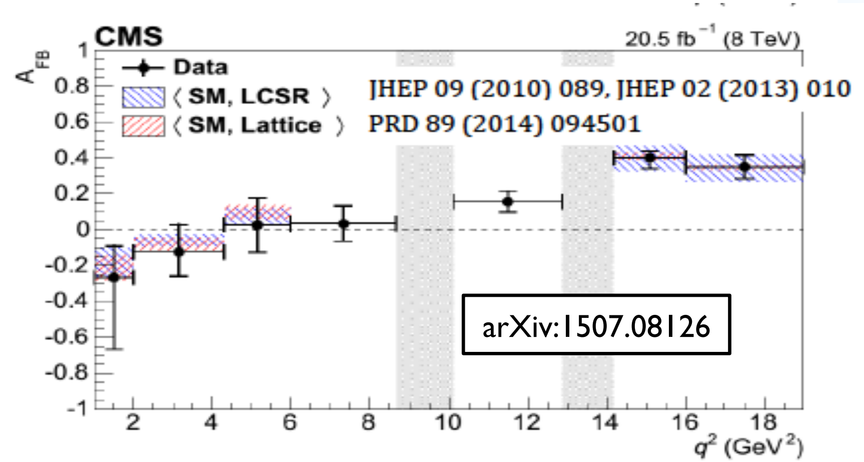


arXiv:1308.1501

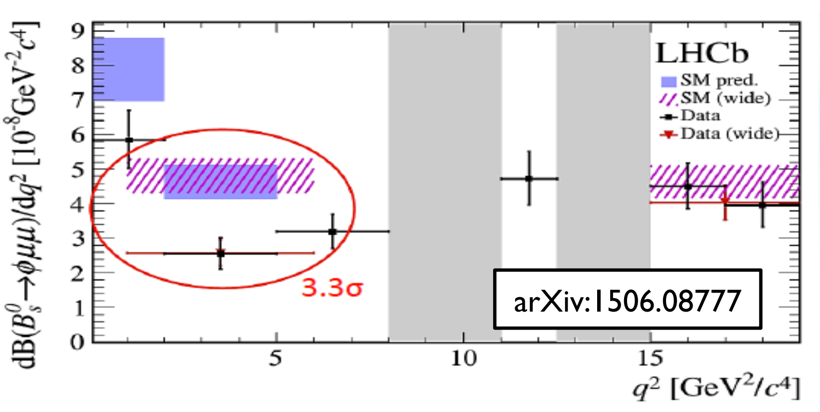
ΔF=1 EW penguins in b→s transitions: Other measurements.



LHCb-CONF-2015-002



arXiv:1507.08126



arXiv:1506.08777

SM (wide): Altmannshofer, Straub, arXiv:1411.3161

2012 LHCb data does not contradict the hints observed with 2011 on P'$_5$.

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

CMS measurements using all RUN-I data, using 1-D projections, don't contradict neither LHCb nor the SM predictions.

LHCb measurements using **B$_s$→Φ μ μ** angular distribution in agreement with SM. However discrepancies in the **BR at low q^2.**

Many other **new EW penguin measurements**:

Branching Ratio

$B^{0,+} \to K^{0,+,*+}\mu^+\mu^-$	(LHCb, Mar 14)
$B^0 \to K^{*0}\mu^+\mu^-$	(CMS, Jul 15)
$B_s^0 \to \phi\,\mu^+\mu^-$	(LHCb, Jun 15)
$B^+ \to \pi^+\mu^+\mu^-$	(LHCb, Sep 15)
$\Lambda_b^0 \to \Lambda\,\mu^+\mu^-$	(LHCb, Mar 15)
$B_{(s)}^0 \to \mu^+\mu^-$	(CMS+LHCb, Jun 15)

Lepton universality

$B^+ \to K^+l^+l^-$	(LHCb, Jun 14)

CP asymmetry

$B^+ \to \pi^+\mu^+\mu^-$	(LHCb, Sep 15)

Isospin asymmetry

$B^{0,+} \to K^{0,+,*+}\mu^+\mu^-$	(LHCb, Mar 14)

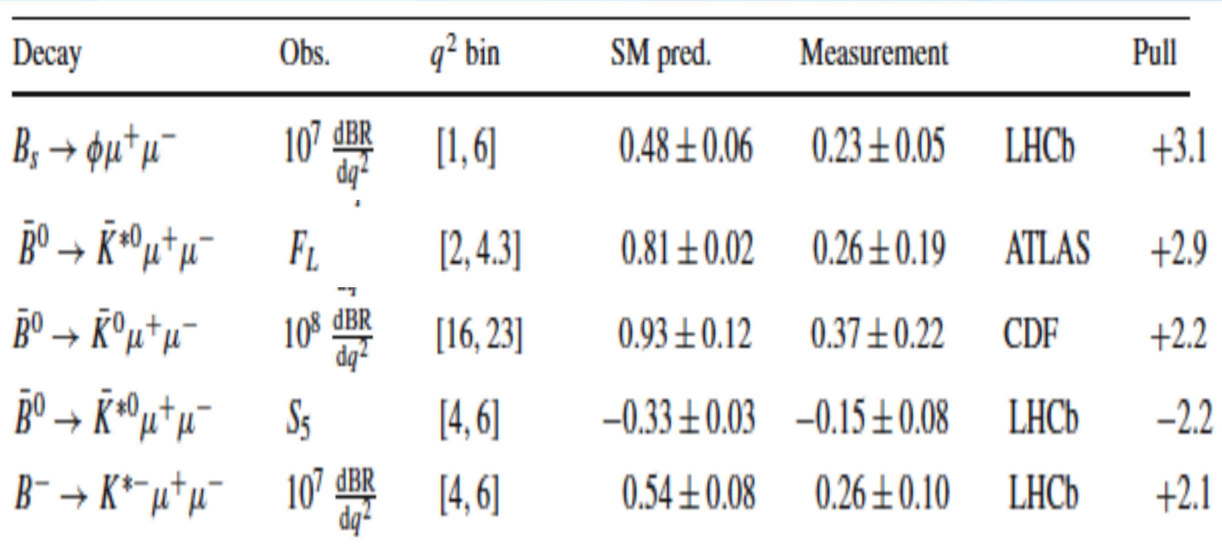
Angular

$B^0 \to K^{*0}l^+l^-$	(LHCb, Jan 15 LHCb, Mar 15 CMS, Jul 15 BaBar, Aug 15)
$B^+ \to K^{*+}l^+l^-$	(BaBar, Aug 15)
$B_s^0 \to \phi\,\mu^+\mu^-$	(LHCb, Jun 15)
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$	(LHCb, Mar 15)

Δ F=1 EW penguins in b→s transitions: Implications

The overall fit of b→sμ μ meassurements assuming the SM has a p-value of ~1%.

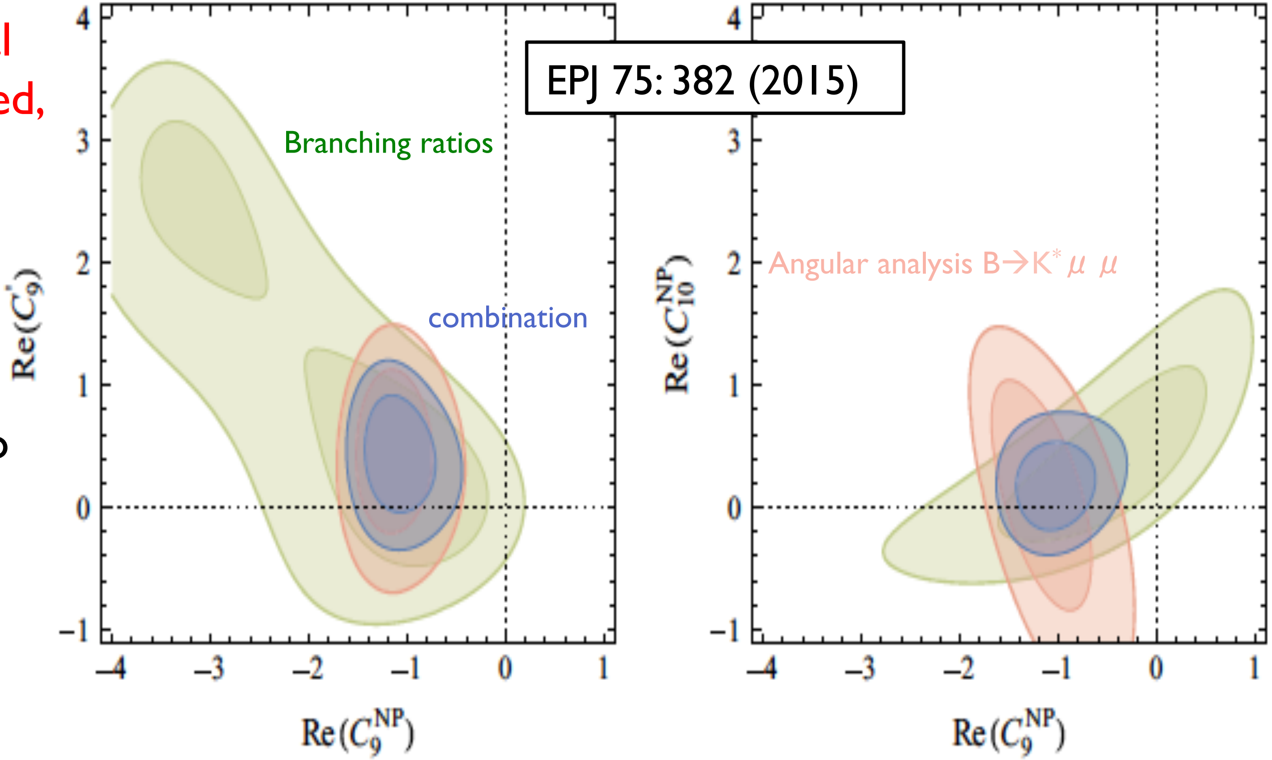
Few measurements have a pull larger than 2σ



Decay	Obs.	q^2 bin	SM pred.	Measurement		Pull
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[1, 6]	0.48 ± 0.06	0.23 ± 0.05	LHCb	+3.1
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	[2, 4.3]	0.81 ± 0.02	0.26 ± 0.19	ATLAS	+2.9
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	[16, 23]	0.93 ± 0.12	0.37 ± 0.22	CDF	+2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	[4, 6]	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	−2.2
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[4, 6]	0.54 ± 0.08	0.26 ± 0.10	LHCb	+2.1

While it could very well be that theoretical and/or experimental uncertainties are underestimated, it is also a fact that allowing for non-SM Wilson coefficients improves the p-value.

For instance, allowing **C_9^{NP}~-0.25×C_9^{SM}** improves to p~11%.



EPJ 75: 382 (2015)

See F. Wilson talk for more details.

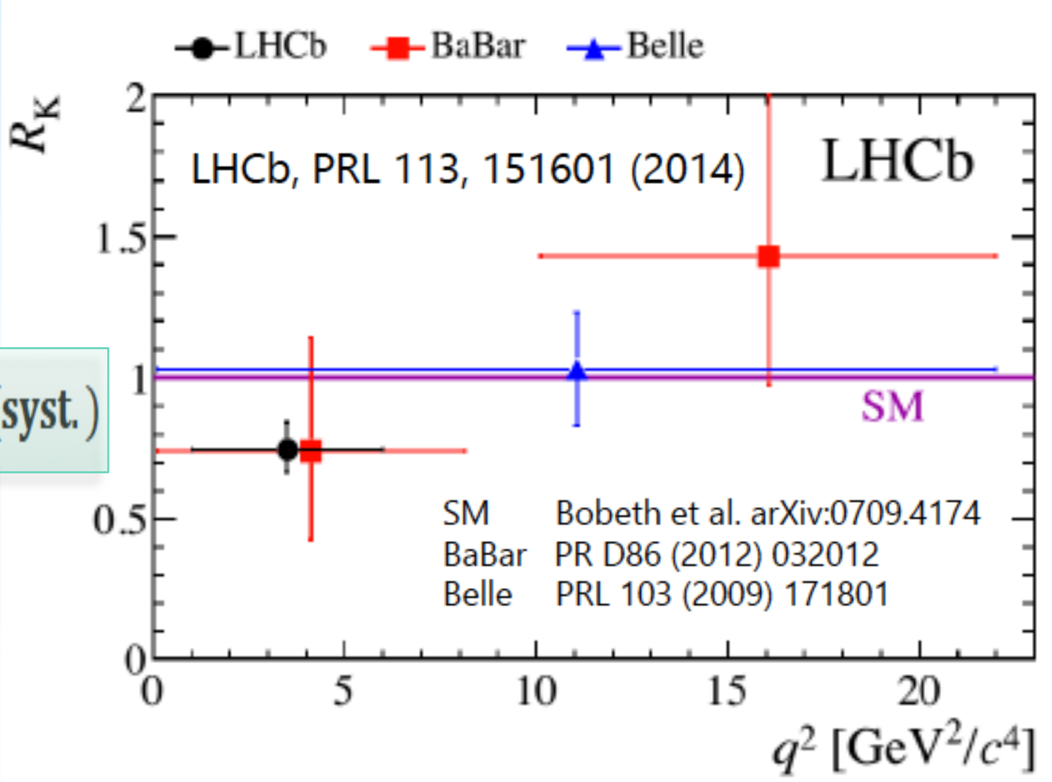
Lepton Flavour Universality in EW penguins

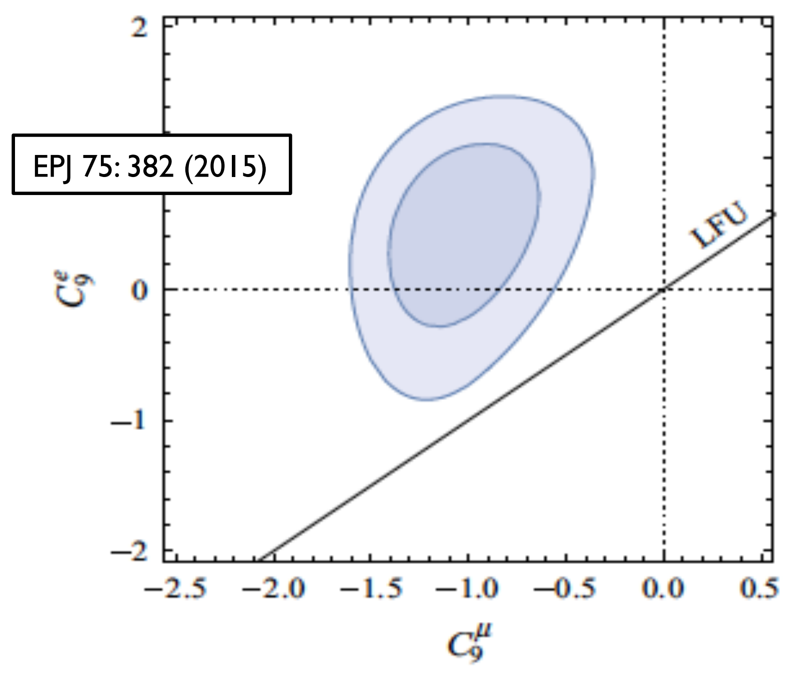
If we include now b→see transitions, we can get rid of theoretical uncertainties using ratios and test LFU.

Recent LHCb measurement of $\mathbf{R_K}$:

$$R_K = \frac{BR(B_u^+ \to K^+\mu^+\mu^-)}{BR(B_u^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.})$$

Shows a discrepancy (2.6 σ) with the SM prediction, (R_K^{SM}=1.00).





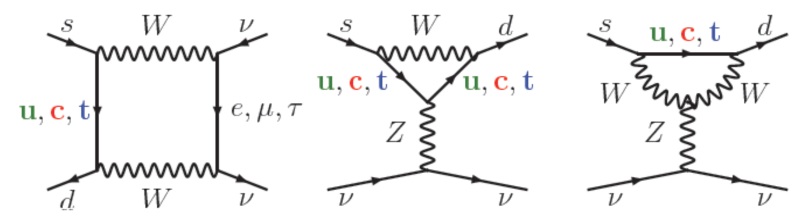
EPJ 75: 382 (2015)

B± → K±ee agrees with SM. A global fit, hence, shows C_9^e ~ SM while C_9^μ ~ non-SM.

It will be interesting to see other ratios of EW penguins with electrons and muons.

s→d ($|V_{ts}V_{td}| \alpha \lambda^5$)

ΔF=1 EW penguins in s→d transitions: $K^{(+)}\to\pi^{(+)}\nu\nu$

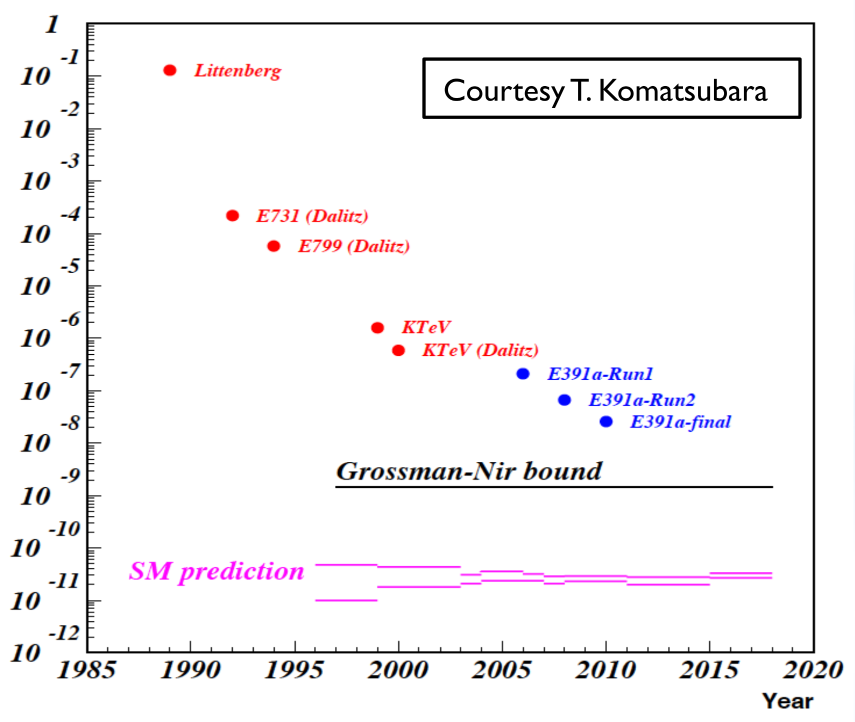


$K^+\to\pi^+\nu\nu$ and $K\to\pi^0\nu\nu$ are certainly the "cleanest" Kaon decays (not long distance pollution affecting lepton modes, dominated by a single operator) and provide sensitivity to $|V_{td}|$.

$BR_{TH}(K^+\to\pi^+\nu\nu) = (7.81\pm0.75\pm0.29)\times10^{-11}$
$BR_{TH}(K^0\to\pi^0\nu\nu) = (2.43\pm0.39\pm0.06)\times10^{-11}$

BNL upgraded E949 observed
7 $K^+\to\pi^+\nu\nu$ candidates → **$BR=(17\pm11)\times10^{-11}$**

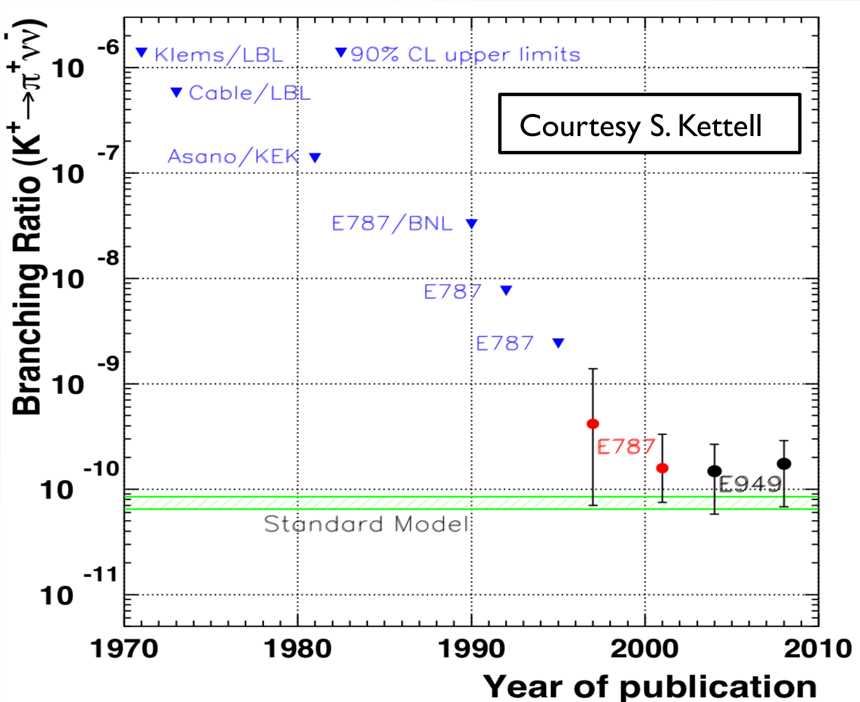
KEK E391 achieved a limit of → **$BR<2.6\times10^{-8}$ @90% C.L.**



Courtesy T. Komatsubara

NA62 physics run started in 2015. Aim to measure **$BR_{TH}(K^+\to\pi^+\nu\nu)$** with 10% precision. Expect S_{SM}~45 , B<10 per year. **Commissioning so far going well.**

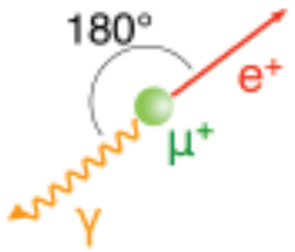
KOTO aims to have a first observation of the decay **$BR_{TH}(K^0\to\pi^0\nu\nu)$.** Took a short run (100h) at 10% nominal intensity. Similar s.e.s. than E391 already, but need to improve bkg (**halo neutrons**).

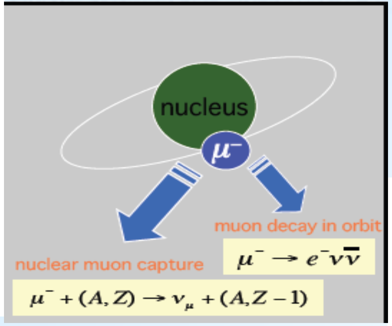


Courtesy S. Kettell

Charged Lepton Flavour Violation

CLFV: Muon Decays





$\mu^- \to e^- \nu \bar{\nu}$

$\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)$

MEG at PSI using 3.6x10^{14} stopped muons collected in 2009-2011 has the best limit on:

BR(μ →eγ)<5.7x10^{-13} @90%C.L. *(expected 7.7x10^{-13})*

PRL 110, 201801 (2013)

Twice more data available from 2012-2013.
Final results expected end of 2015?

Expects to increase x10 sensitivity with upgraded detector (2016-2019). Difficult to improve with this technique due to accidental backgrounds, which should increase with beam intensity.

$$N_{\rm acc} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T,$$

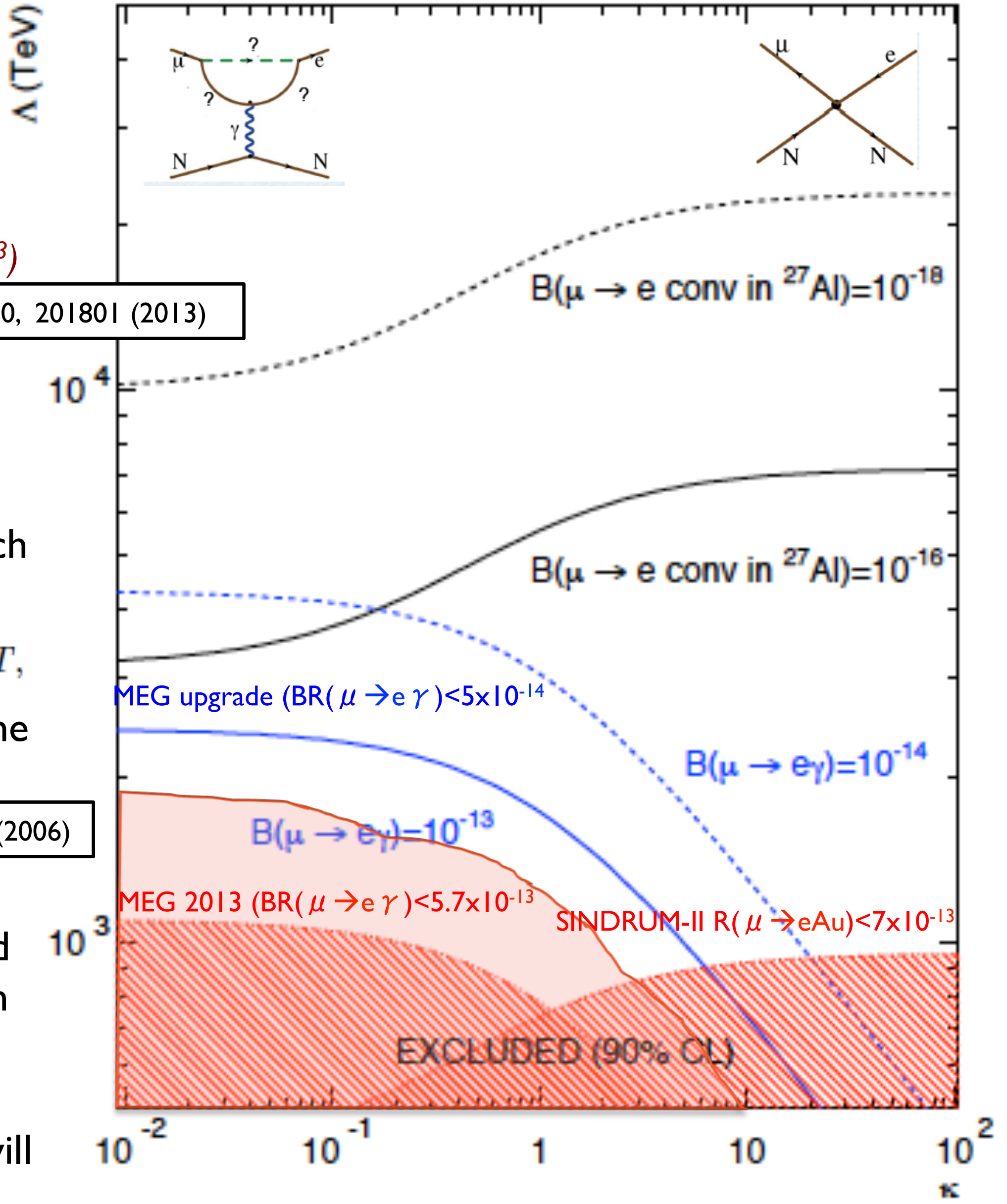
SINDRUM-II at PSI with O(10^8) μ^-/sec and time between pulses <20ns achieved:

R(μ →e Au) <7x10^{-13} @90% C.L.

EPJ 47, 2, p337 (2006)

Mu2e at the **booster** will use O(10^{10}) μ^-/sec and time between pulses ~1700ns, and expect to reach R(μ →e Al) <7x10^{-17} @90% C.L.
In a similar time scale, and with similar beam parameters, **COMET-II** at **JPARC's main ring** will reach similar sensitivities.

Modified from A.Gouvea and P.Vogel, arXiv:1303.4097



CLFV: τ Decays

In principle τ are more sensitive than μ since mass typically decreases suppression (>500), and is sensitive to BSM scalar sector. However, rates at e^+e^- B-factories are ~2×10^9 τ per ab^{-1}. On the other hand the enormous charm production at the LHC increases the τ production rate ($D_s \rightarrow \tau\nu$) by 10^5, but unavoidable with a less efficient analysis.

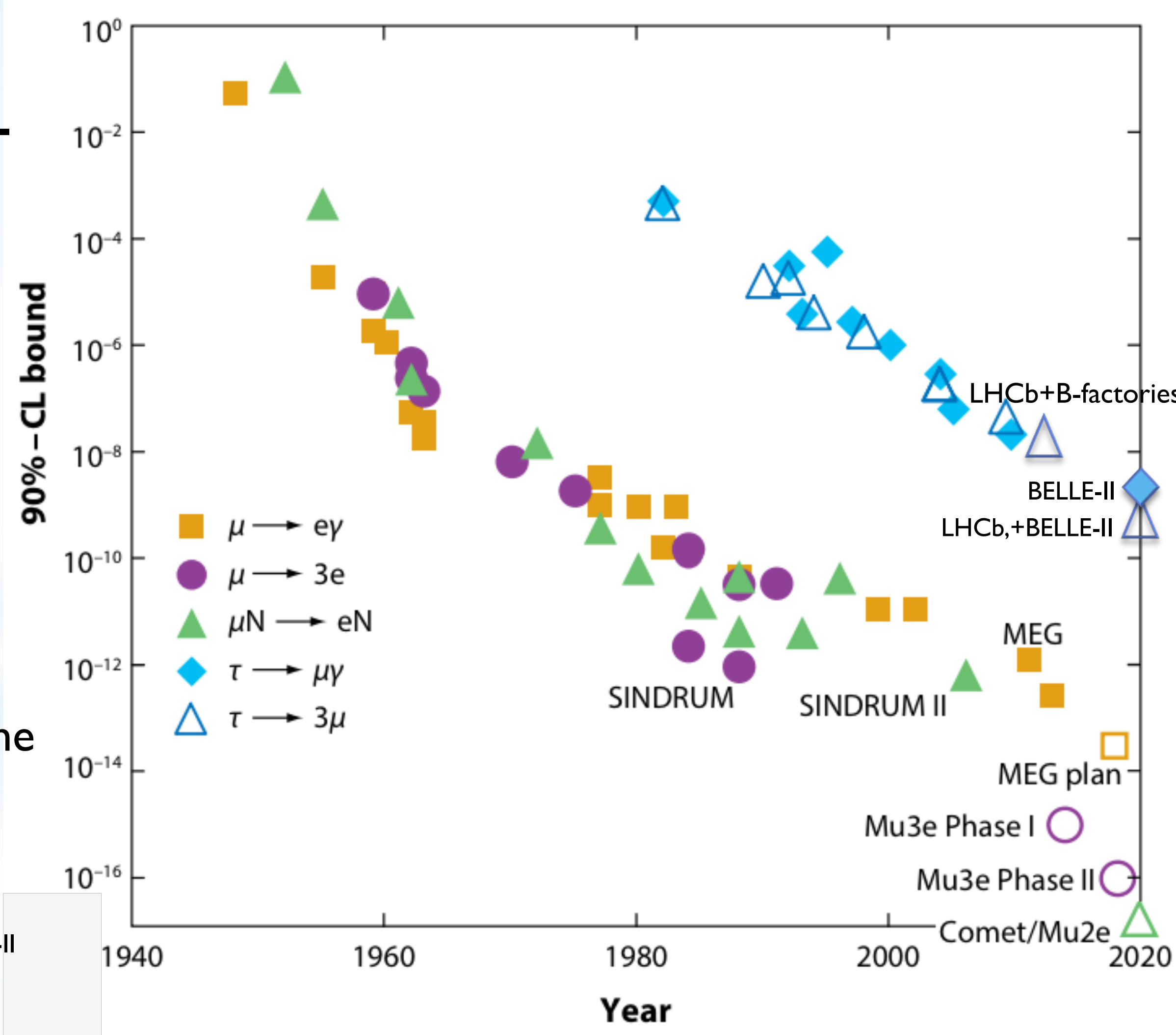
Best limits on $\tau \rightarrow \mu\mu\mu$ and $\tau \rightarrow \mu\gamma$ using ~1.4×10^9 τ at the **B-factories** are $O(10^{-8})$. **LHCb** has reached similar sensitivities for $\tau \rightarrow \mu\mu\mu$ using 2×10^{11} τ. The new HFAG average is:

$BR(\tau \rightarrow \mu\gamma)$ $<5\times10^{-8}$ @90%C.L.
$BR(\tau \rightarrow \mu\mu\mu) <1.2\times10^{-8}$ @90%C.L.

arXiv:1412.7515

BELLE-II expects to increase x50 the statistics, and the **LHCb upgrade** x30. Depending on how the bkg will scale:

$BR(\tau \rightarrow \mu\gamma)$<**(1-7)x10**$^{-9}$ from BELLE-II
$BR(\tau \rightarrow \mu\mu\mu)$<**(1-10)x10**$^{-10}$ from LHCb+BELLE-II



Conclusions

Messages to take home

Interest in precision flavour measurements is stronger than ever. In some sense it would have been very "unnatural" to find NP at the LHC RUN-I from direct searches with the same SM CKM flavour structure. I'm afraid this also applies for RUN-II.

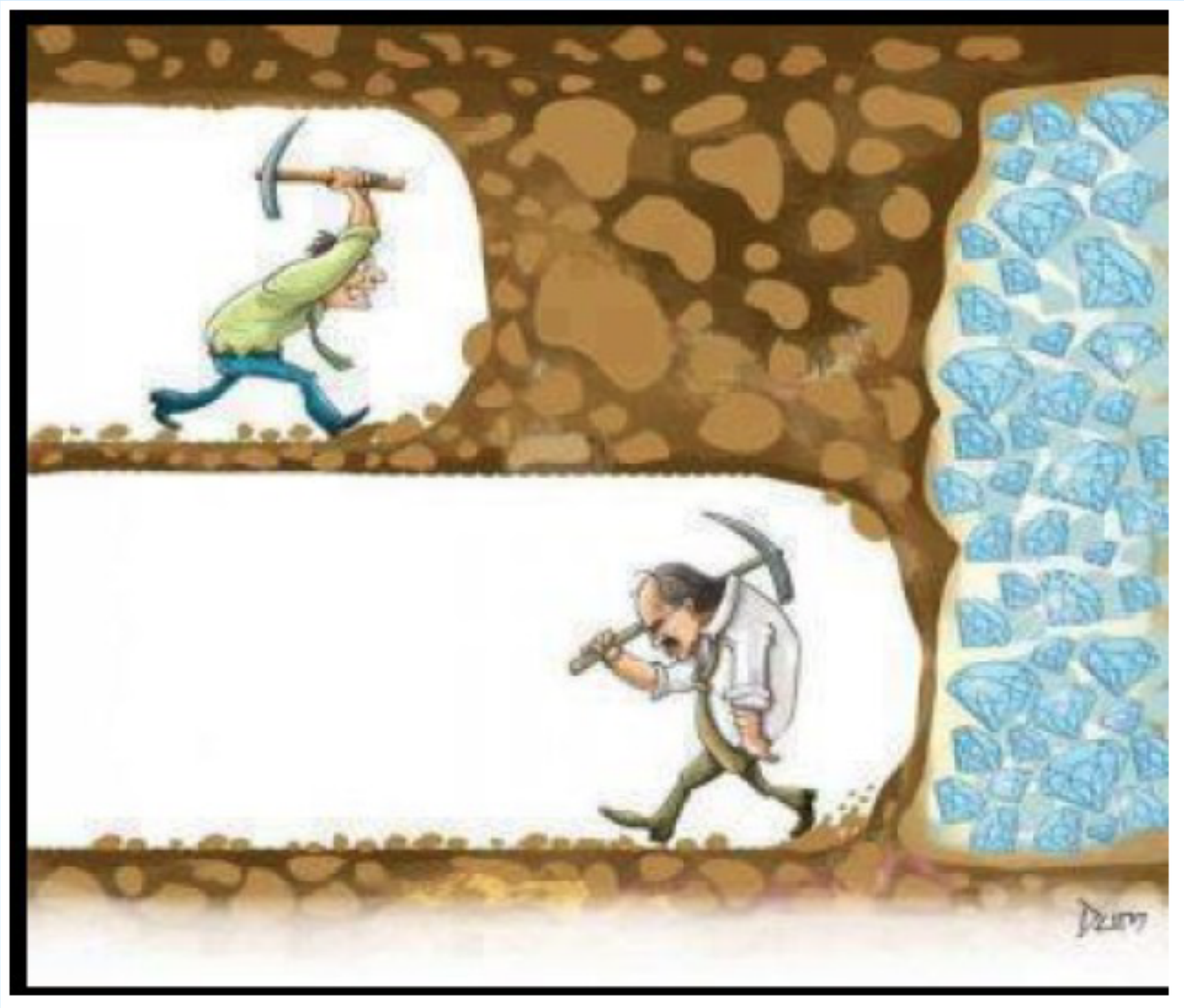
There are few interesting anomalies to be followed up, but in general the agreement with the SM is excellent → large NP contributions, O(SM), ruled out in most of quark flavour transitions. This is not the case for lepton flavour violation processes.

There is a priory as many good reasons to find NP by measuring precisely the couplings of the new scalar boson, as by precision measurements in the flavour sector!

The search has just started. In the next decade, the LHCb upgrade plans to collect ~50 fb^{-1} with a factor ~2 increase in bb and cc cross-section. ATLAS/CMS plan to collect ~300 fb^{-1} and Belle-II plans to collect ~50 ab^{-1}. NA62 and KOTO have started taking data. Very interesting results in **CLFV** specific experiments (MEG, Mu2e, COMET, Mu3e,…) in the next decade or so.

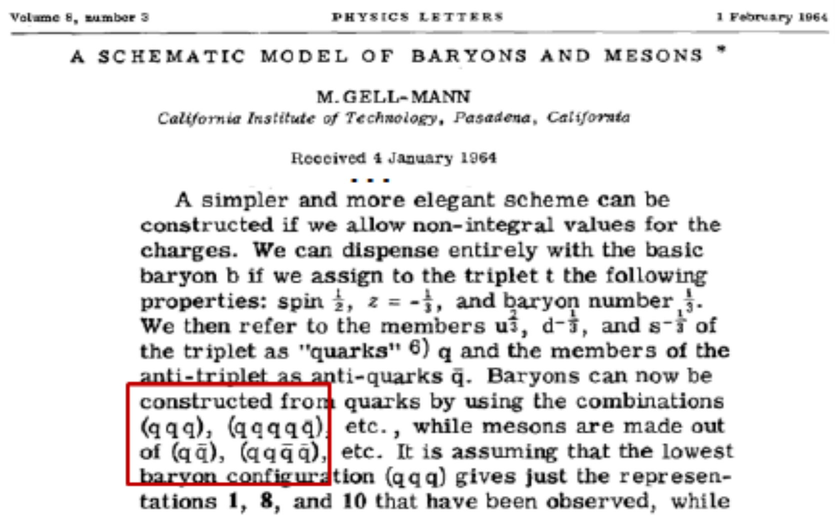
We don't know yet what is the scale of NP→ cast a wide net!

Don’t give up yet!



Backup

(Parenthesis) Quark confinement in the SM



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

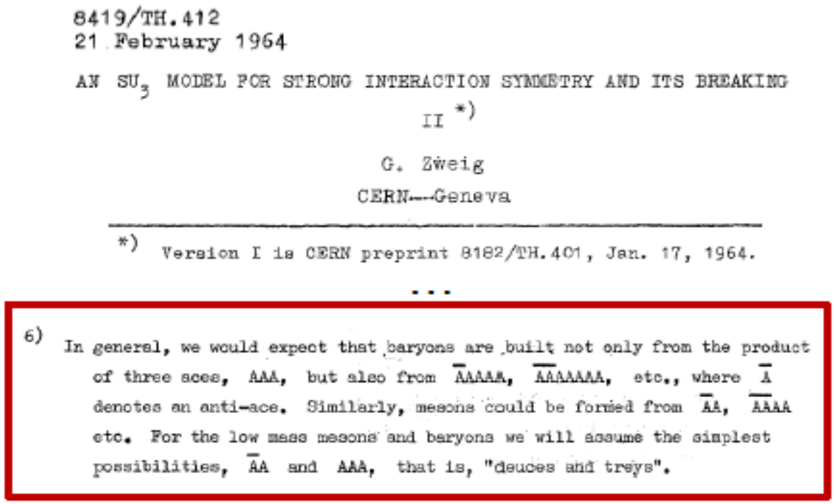
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

. . .

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig
CERN---Geneva

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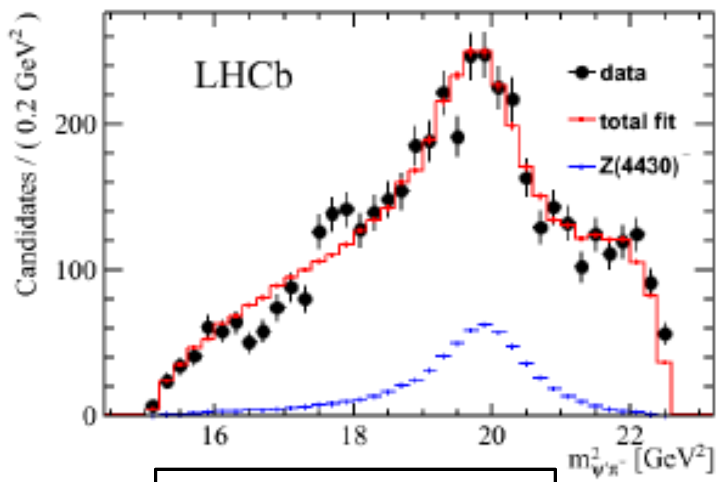
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

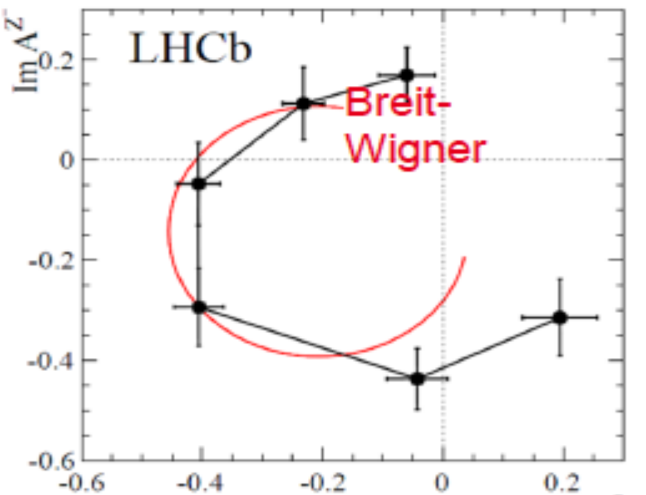
. . .

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\overline{A}AAAA$, $\overline{AA}AAAAA$, etc., where $\overline{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\overline{A}A$, $\overline{AA}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\overline{A}A$ and AAA, that is, "deuces and treys".

Several observations of charmonium and bottomonium like states compatible with tetraquarks. For example, the Z(4430) is a c cbar d ubar state observed by Belle in 2007 and confirmed by LHCb in 2014 in $B^0 \rightarrow \psi' \pi^- K^+$.

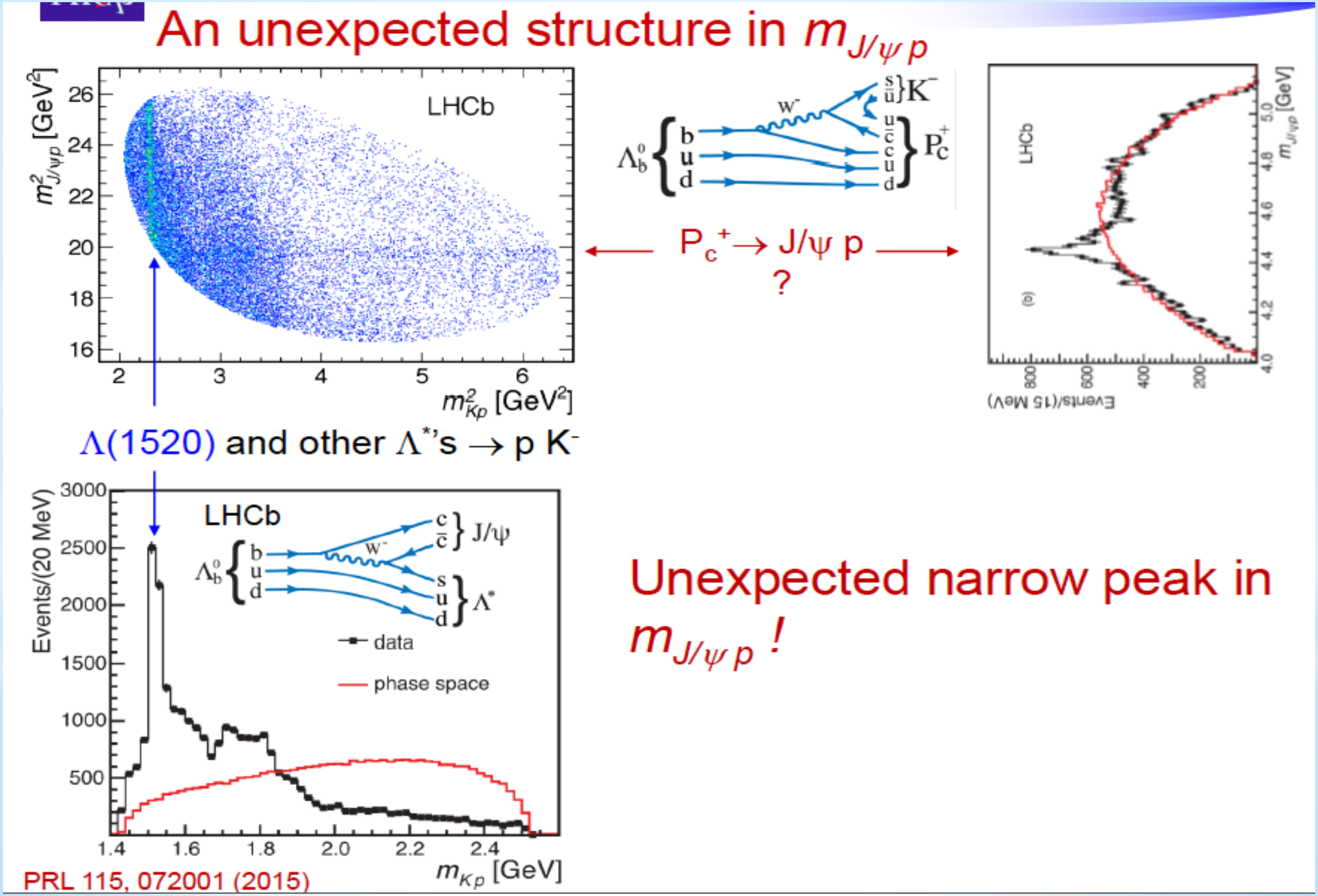


PRL 112, 222002 (2014)



PRL 112, 222002 (2014)

(Parenthesis) What about Pentaquarks?



An unexpected structure in $m_{J/\psi p}$

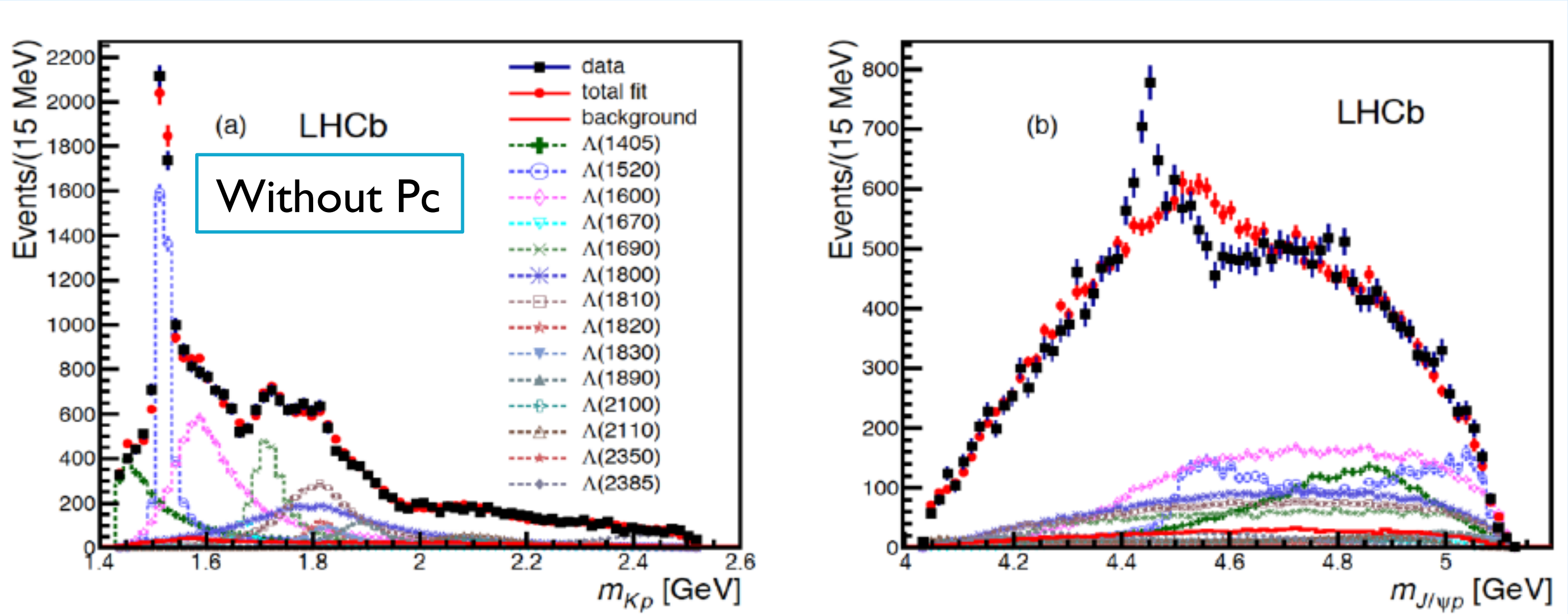
$P_c^+ \to J/\psi\, p$
?

Λ(1520) and other Λ*'s → p K$^-$

Unexpected narrow peak in $m_{J/\psi p}$!

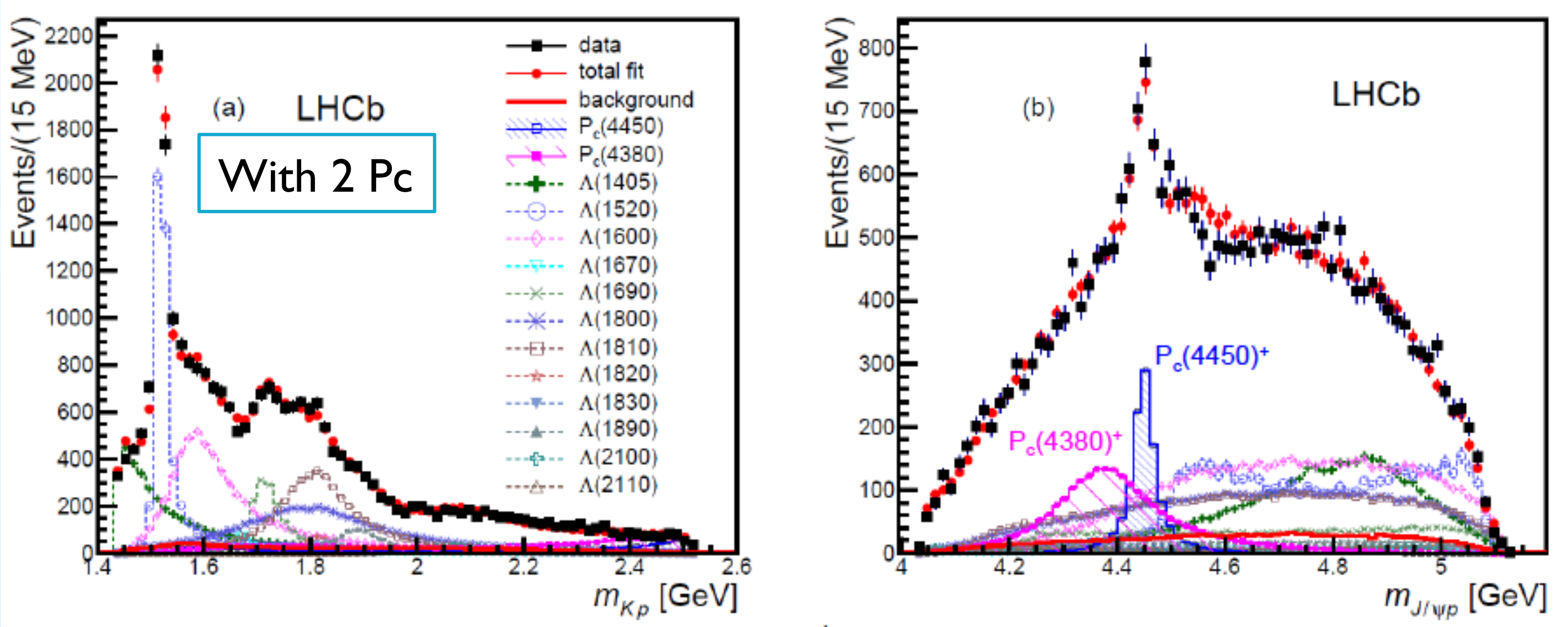
PRL 115, 072001 (2015)

(Parenthesis) What about Pentaquarks?



Without Pc

PRL 115, 072001 (2015)



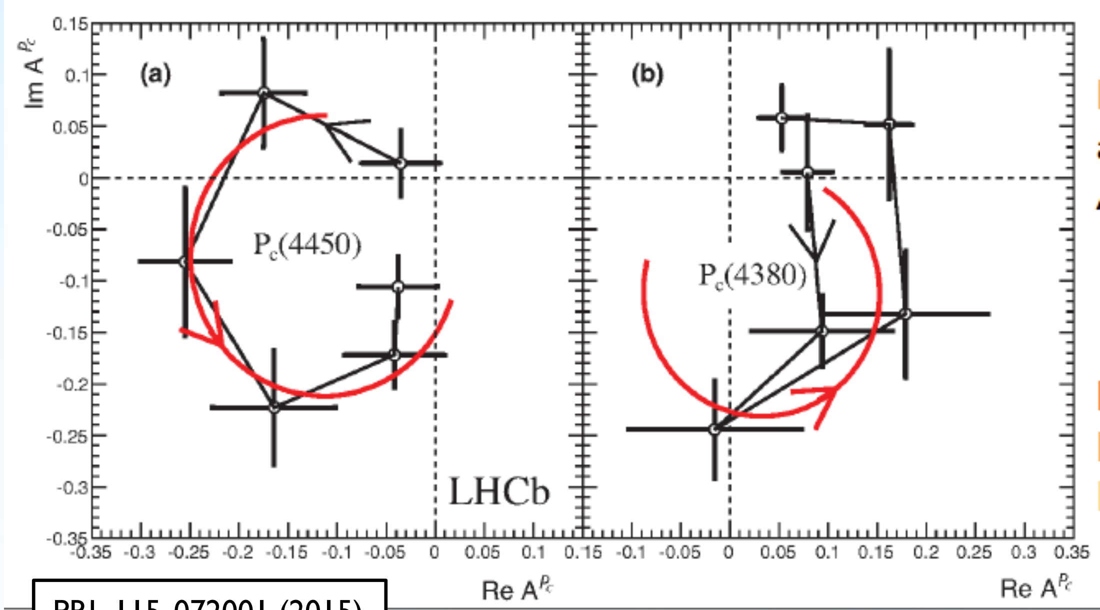
With 2 Pc

(Parenthesis) What about Pentaquarks?

Overwhelming evidence for resonant states that **cannot be explained by interferences** from existing resonances.

Full amplitude analysis, i.e. not only an invariant mass « bump ».

Nature of these states is **unknown.** More sensitive studies are needed.



PRL 115, 072001 (2015)