Experimental Results on Flavor Physics

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On Behalf of LHCb Collaboration

Presenting also results from BaBar and Belle

Workshop on High Energy Physics Phenomenology
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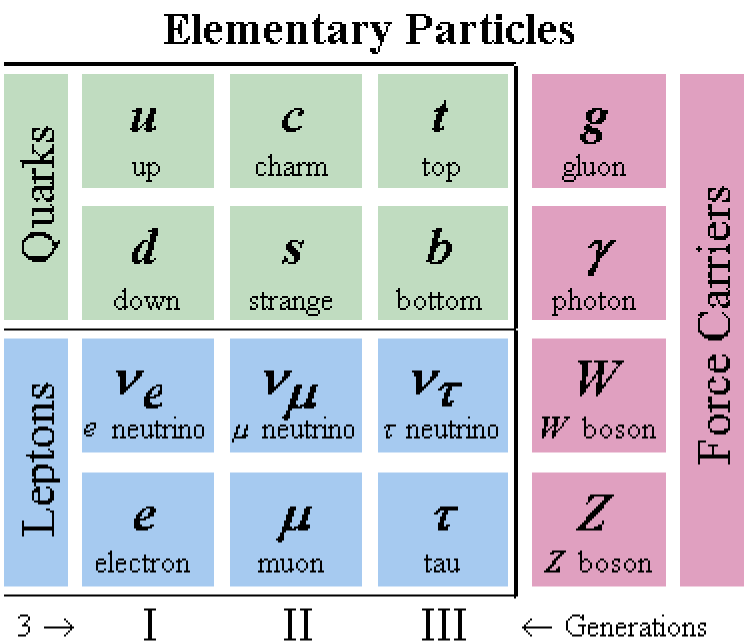
Outline

- Motivation for studying flavor physics
- CP violation and CKM physics
  - Sin(2β) in $B \to J/\psi K_s$ [Bfact+LHCb]
  - Sin(2β) in $\overline{B} \to D_{CP}^{(*)} h^0$ [Bfact]
  - Δm_d [LHCb]
  - |Vub/Vcb| from $\Lambda_b \to p\mu\nu$ [LHCb]
- Rare Decays
  - $B_{(s)} \to \mu^+\mu^-$ BF combination (CMS LHCb)
  - B->K* $\mu^+\mu^-$ and $\phi\mu^+\mu^-$ angular analysis (LHCb)
- Universality
  - R_K in $B \to K l^+ l^-$ (LHCb)
  - R_D e R_{D^*} in $B \to D^* \tau\nu$ (BaBar, Belle, LHCb)

Motivation for studying flavor physics

- In the Standard model the Yukawa couplings of the Higgs boson to the fermions determine the quark mixing matrix
- 10 out of 19 of the free parameters of the model are the masses and the mixing parameters of the quarks. Their study gives us fundamental informations. But there are also some fundamental open questions
- Why are there 3 generations?



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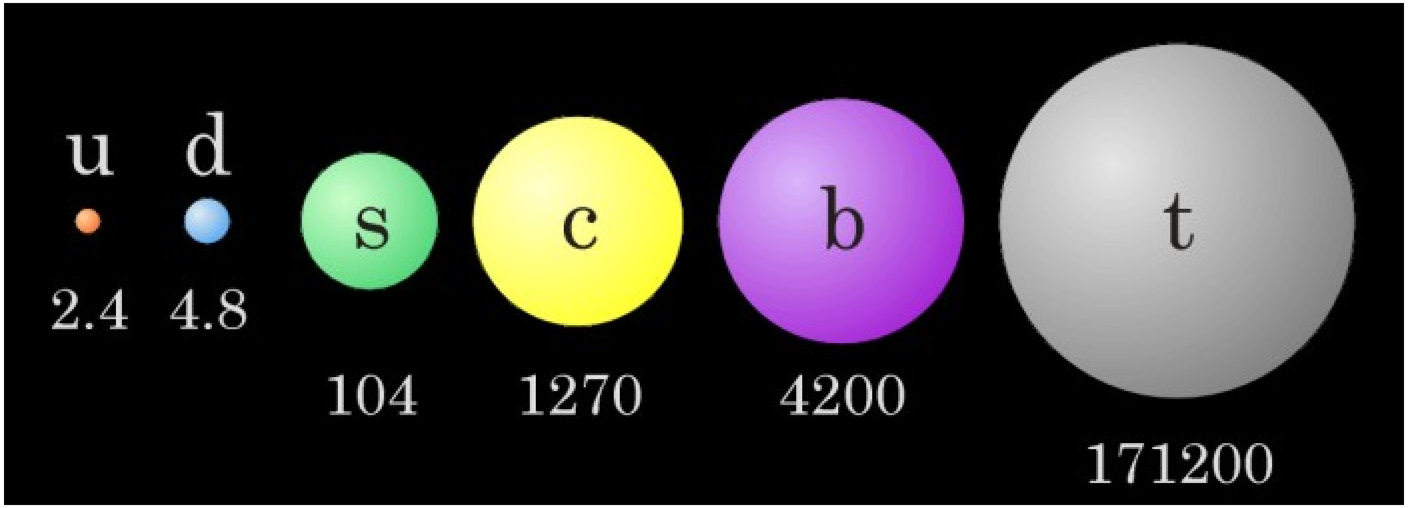
- Why there is a striking hierarchy in the quark masses? Why the Higgs mass is at the EW scale?



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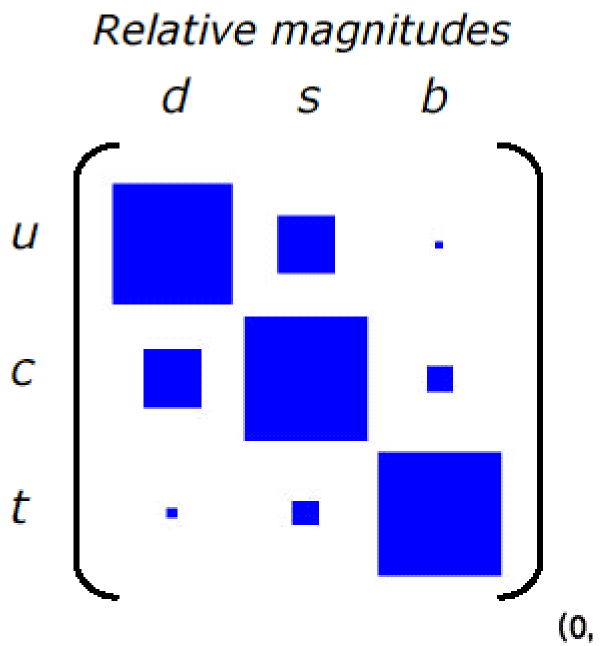

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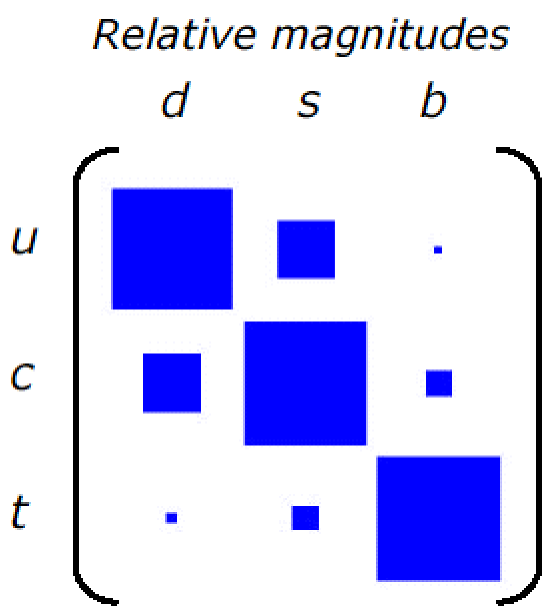
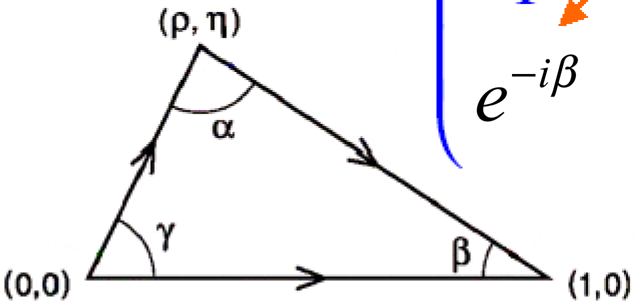
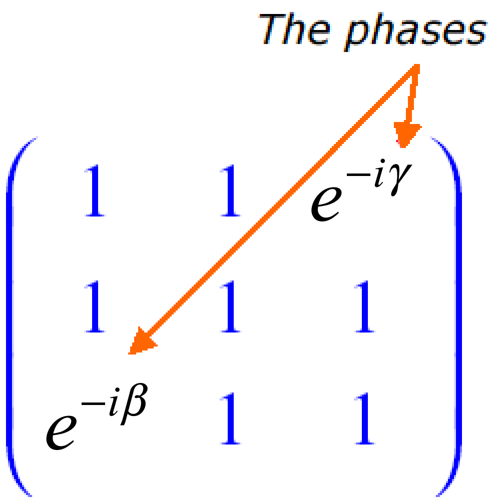
- Why is there a large matter anti matter asymmetry in the universe?

CP Violation

- Baryon asymmetry requires large CP violation $\frac{\Delta n_B^{expected}}{n_\gamma} = 10^{-17}$ while $\Delta \frac{n_B}{n_\gamma} = 10^{-9}$
- In the standard model CP violation is described in by a single weak phase in the quark mixing (CKM) matrix

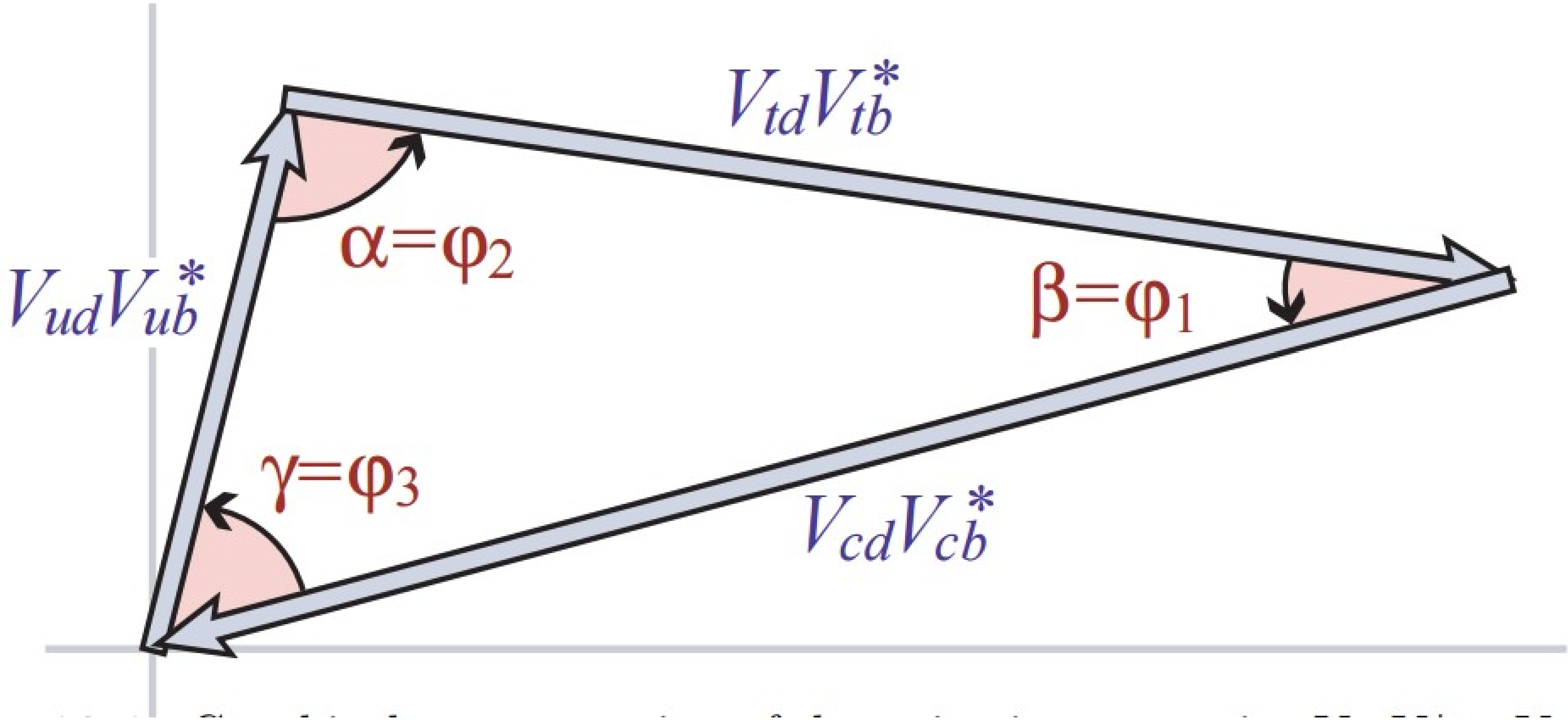






The Unitarity triangle

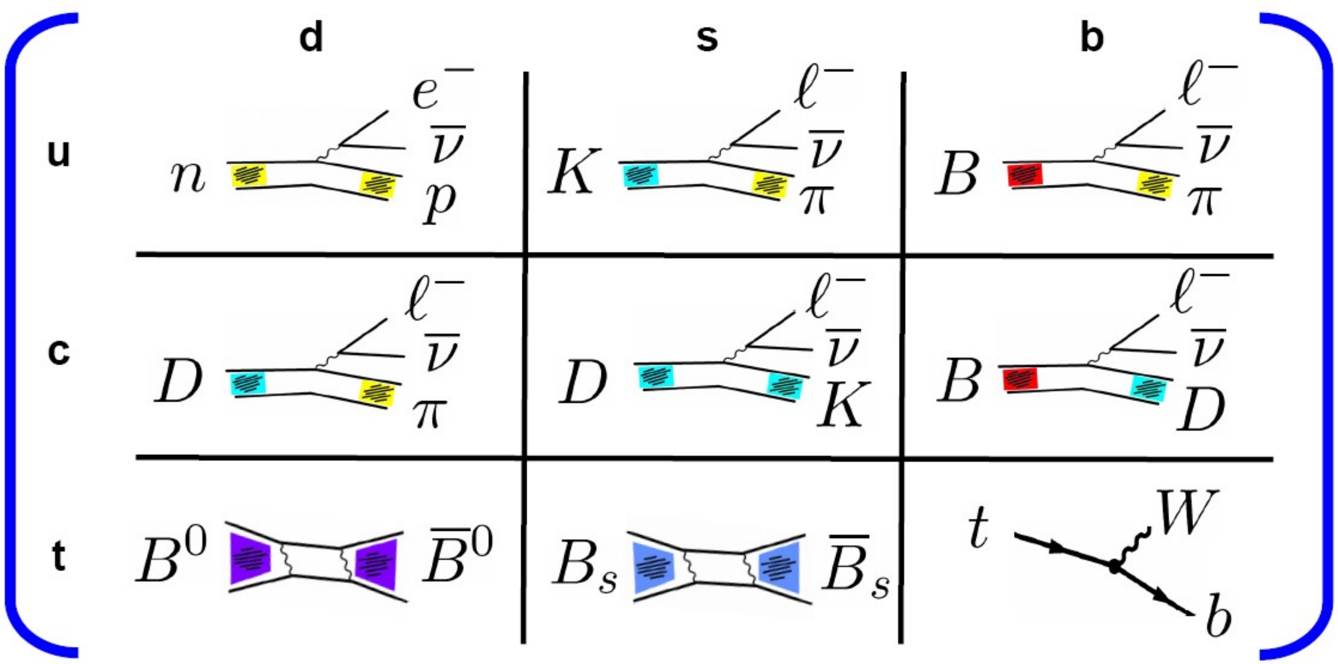
- The unitarity of the matrix can be represented as a triangle relation between its elements
- Measuring angles and sides of the triangle and over-constrains the model => consistency checks



CKM Matrix elements

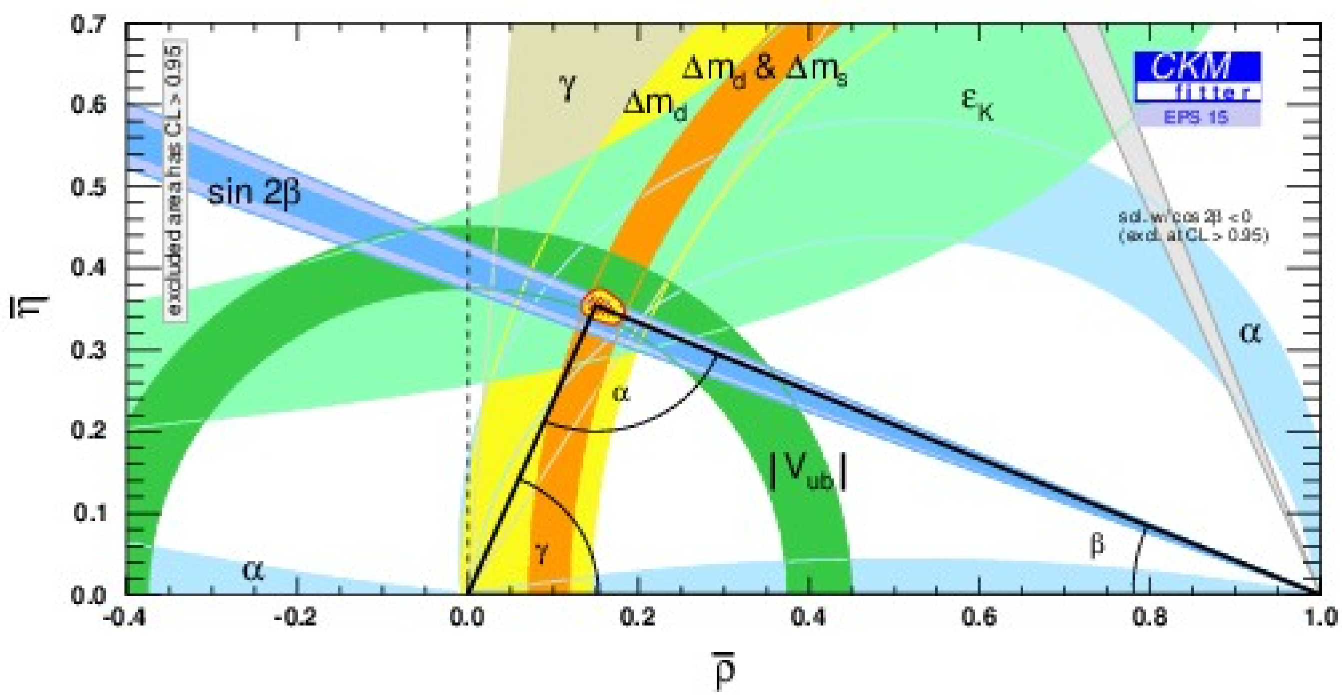
- How can the sides and angles of the triangle be measured?
- Quarks can change flavor only trough charged current interactions proportional to elements of the CKM matrix
- Interference effects between amplitudes give us informations on the angles and sides

V =



The Unitarity triangle

- The CKM mechanism is extremely successful in describing the observed pattern of decays, mixing and CP violation



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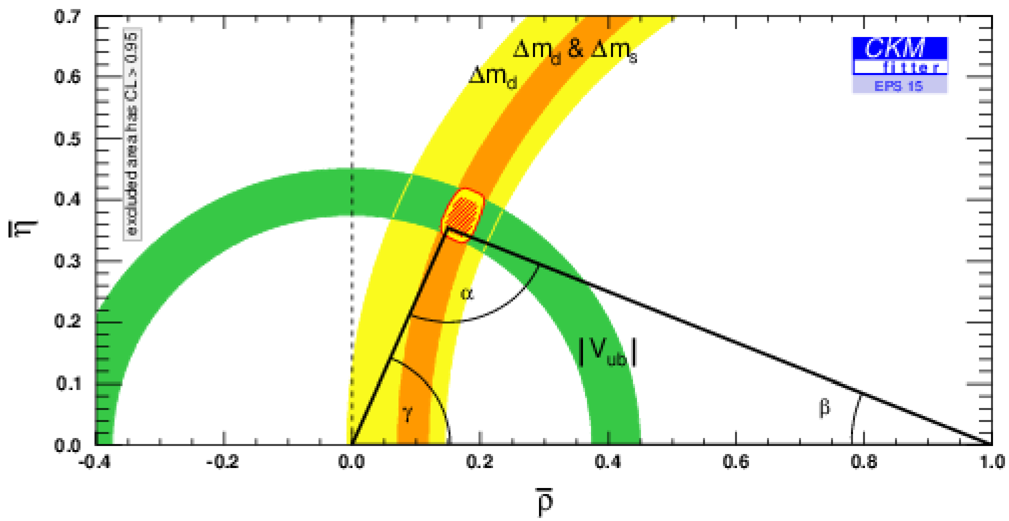
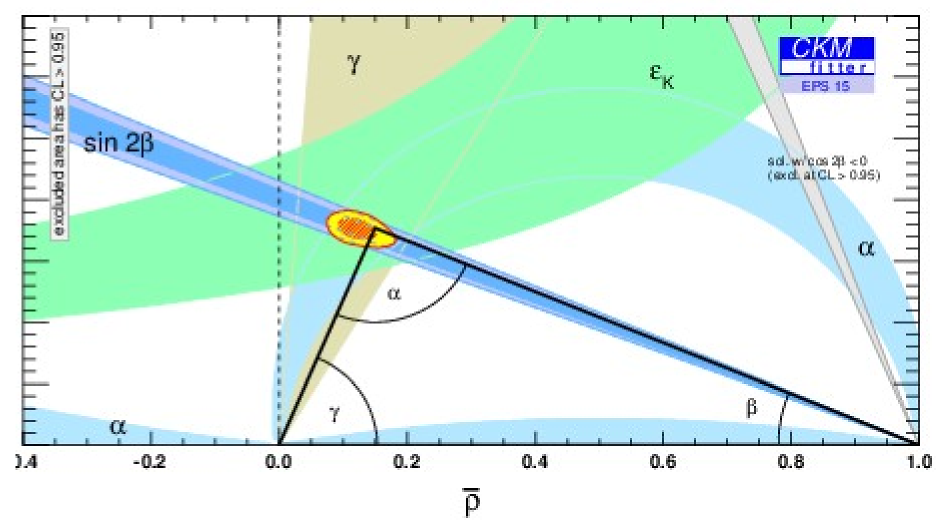
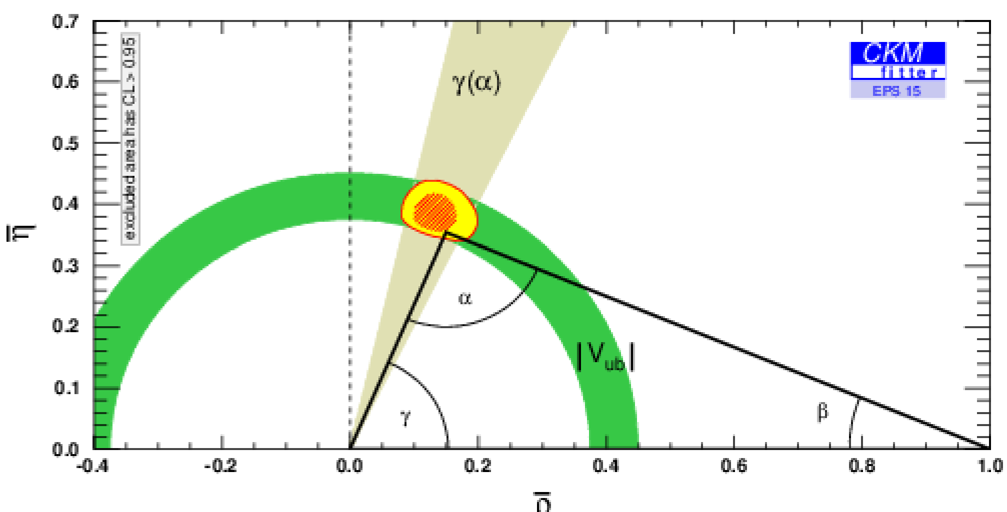


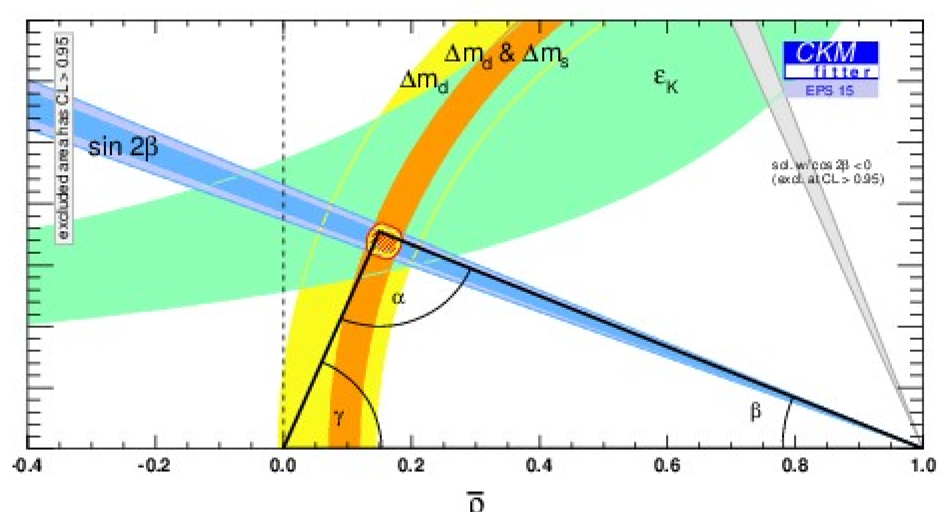
CP conserving



CP violating



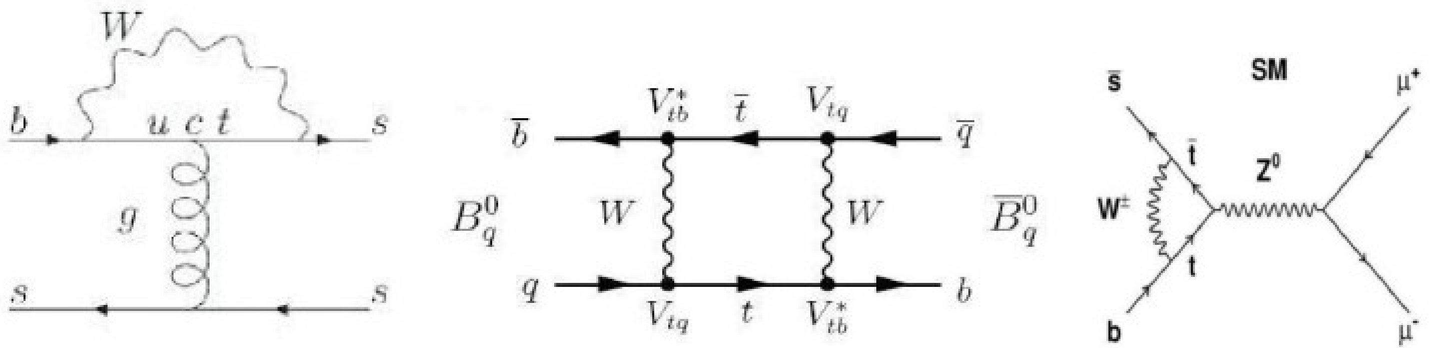
tree



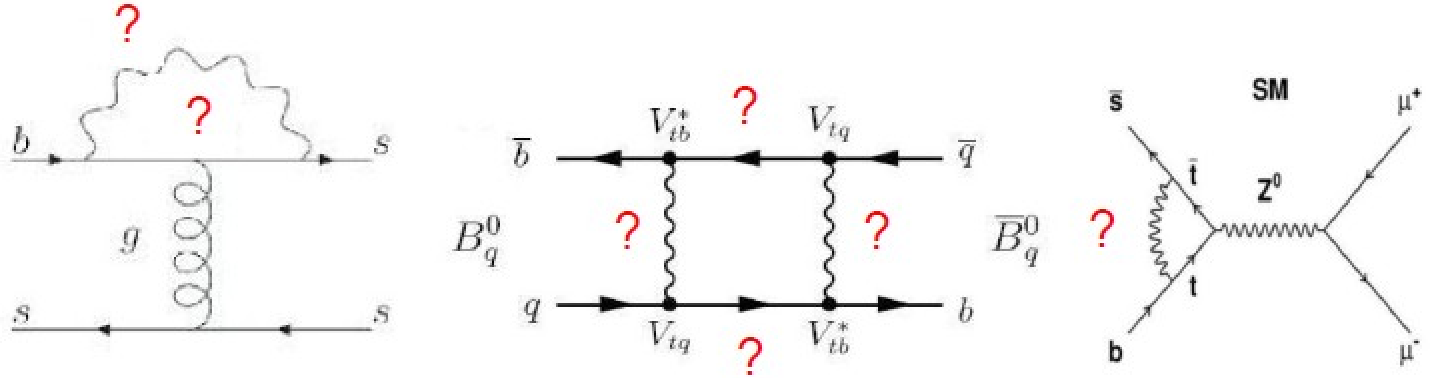
loop

Rare Decays

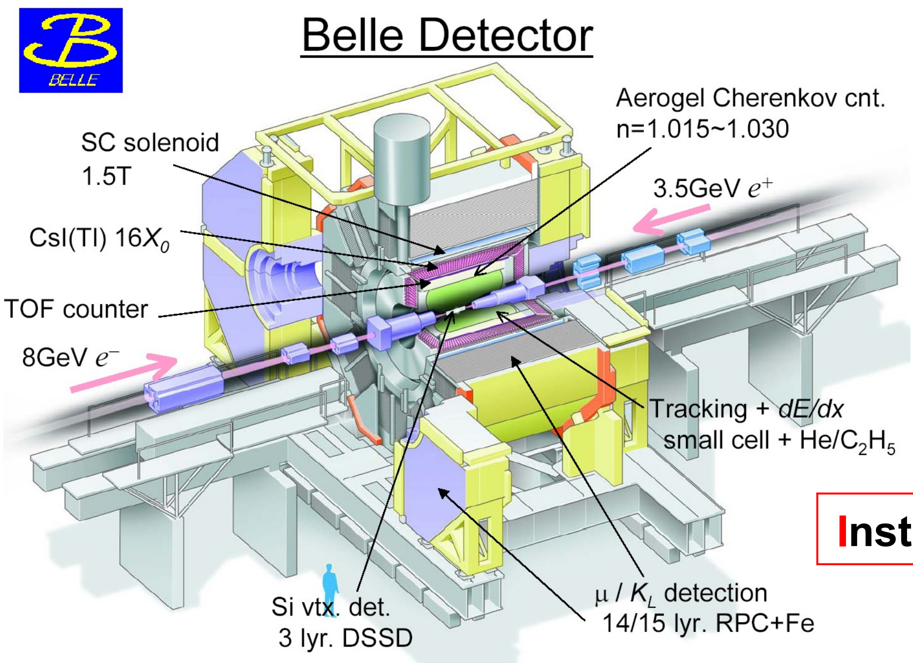
- In tree decays however new physics effects are loop suppressed
- Flavor changing neutral currents are already highly suppressed in the SM

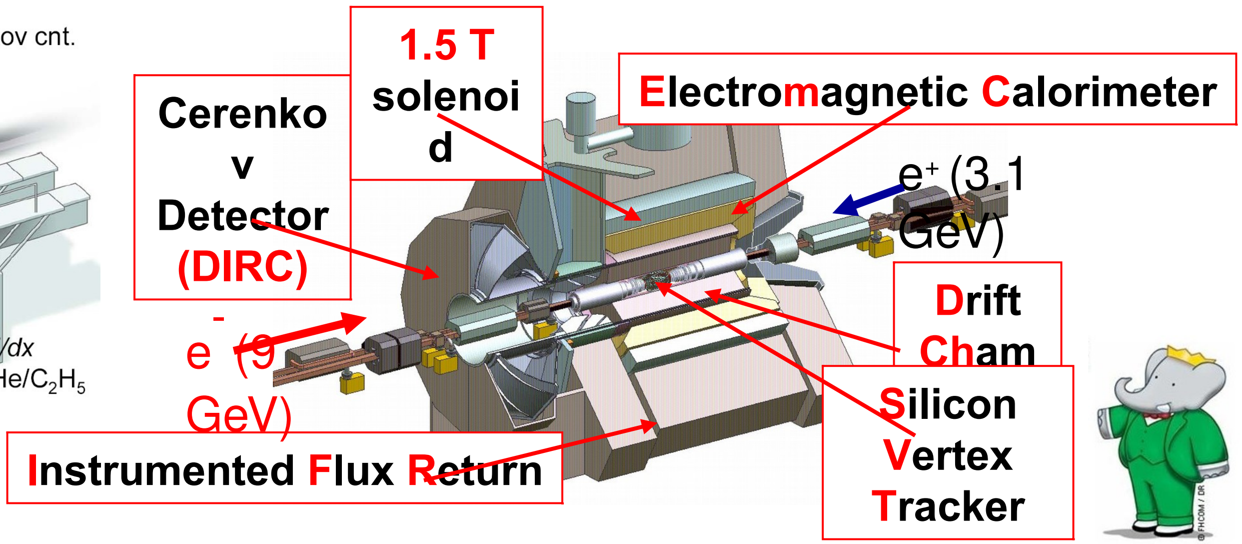


- Therefore new intermediate particles can appear in the loops giving un-suppressed contributions=> clean signatures of New Physics
- In addition they can probe higher energy scales inaccessible with direct searches



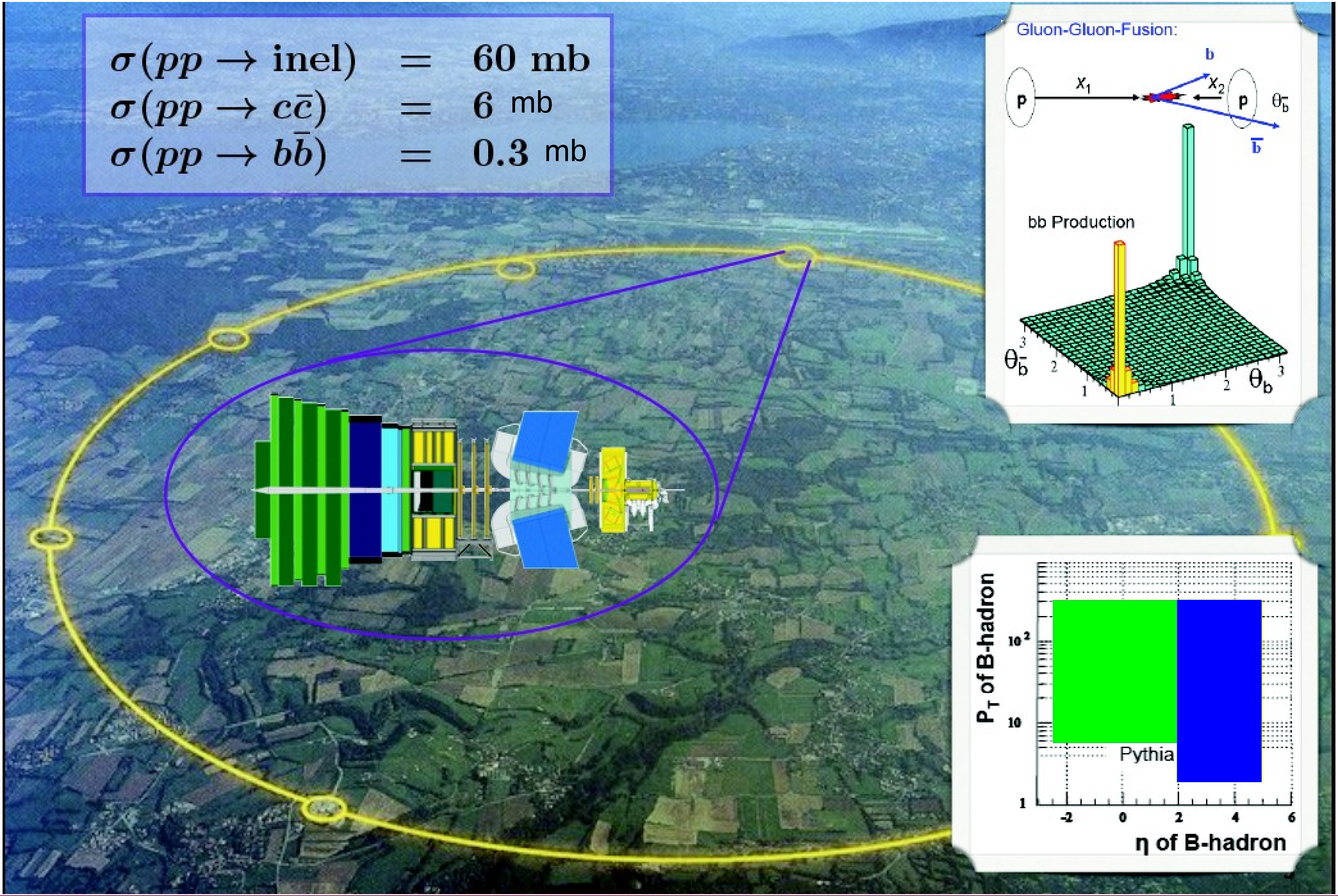
- Bfactories provide a clean environment to measure CKM parameters and rare decays
- $B\bar{B}$ pairs are produce at threshold from the Y(4S) resonance
- $s(b\bar{b})$~1.1nb and $s(q\bar{q})$~3nb
  - Almost hermetic detector, highly efficient trigger



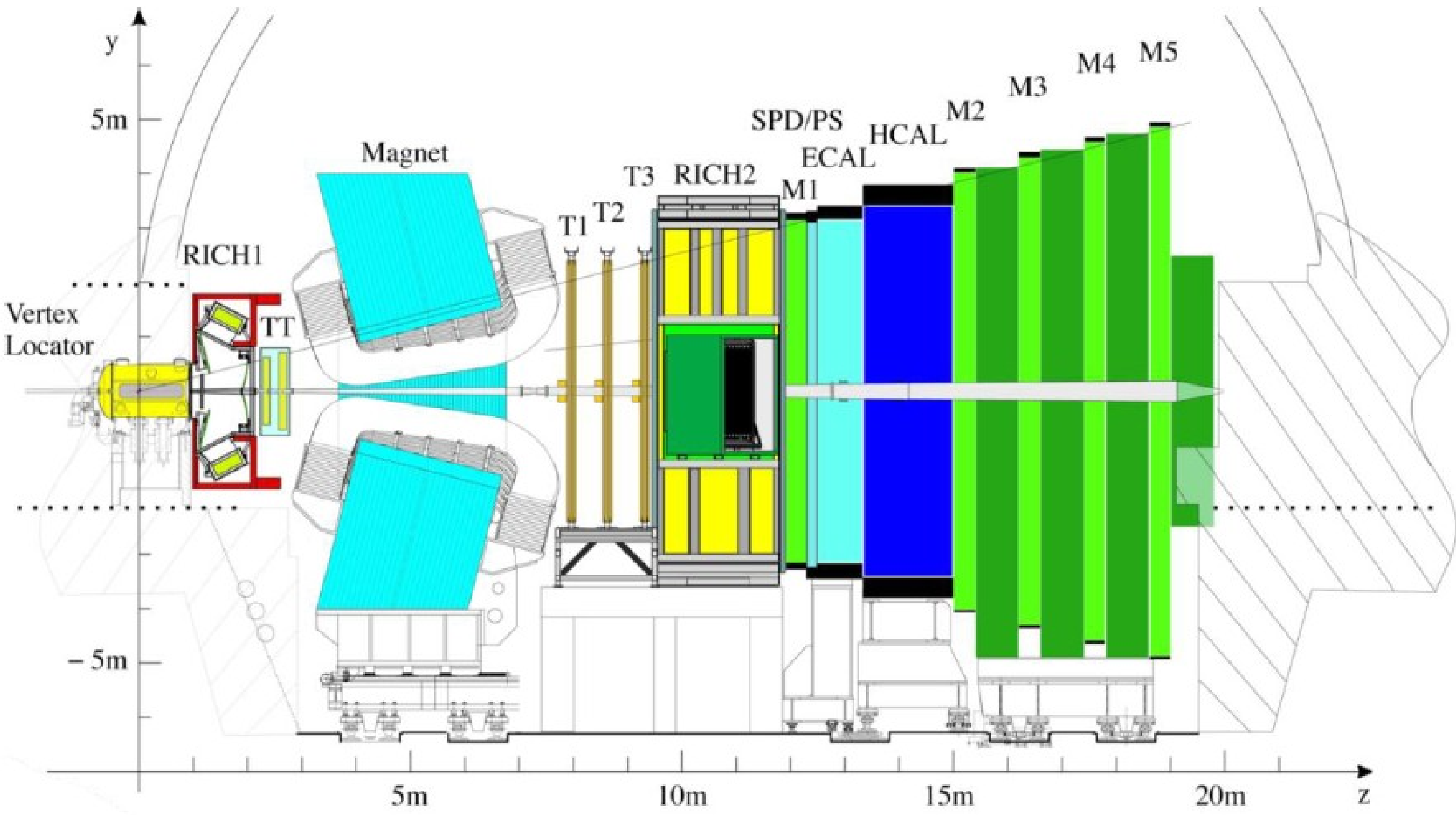


The LHCb experiment

$$\sigma(pp \to \text{inel}) = 60 \text{ mb}$$
$$\sigma(pp \to c\bar{c}) = 6 \text{ mb}$$
$$\sigma(pp \to b\bar{b}) = 0.3 \text{ mb}$$

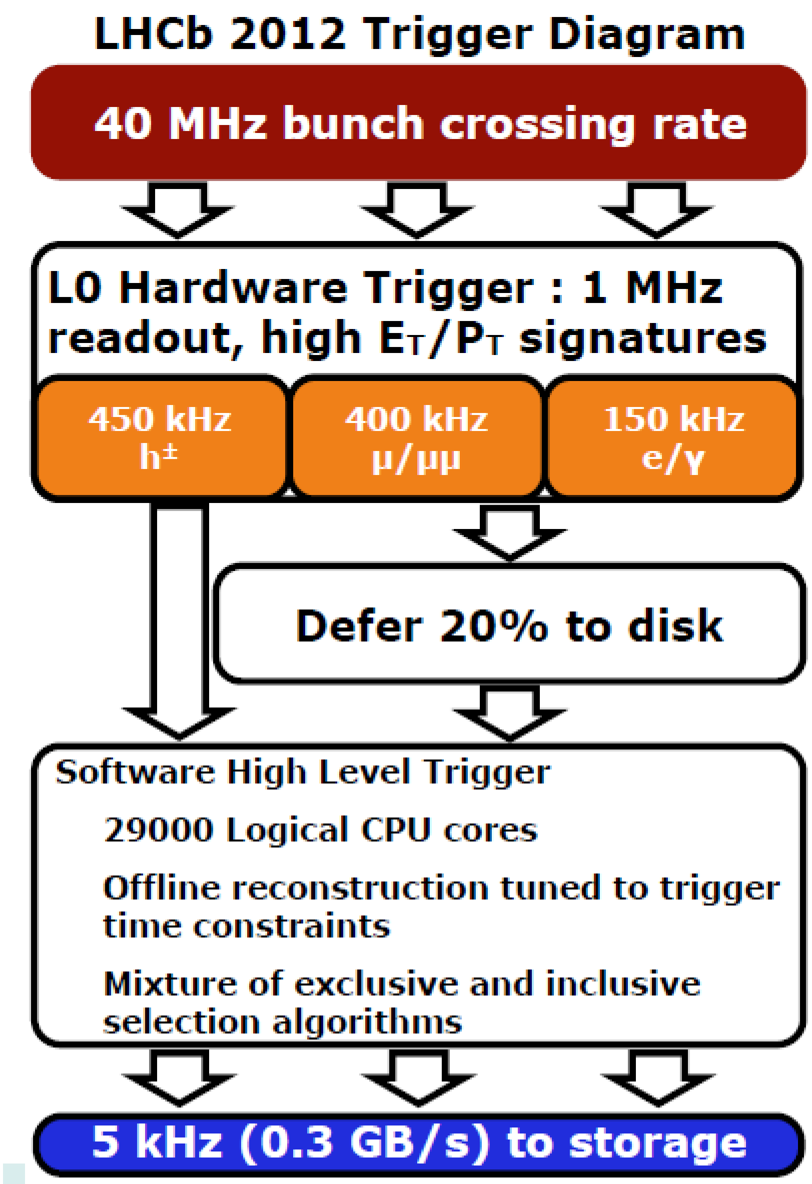


A Forward spectrometer for flavor physics



- Requirements:
  - Vertex resolution to resolve Bs oscillations
  - Excellent PID for flavor tagging and bkg rejection in rare decays
  - Momentum resolution to separate B/Bs, D/Ds

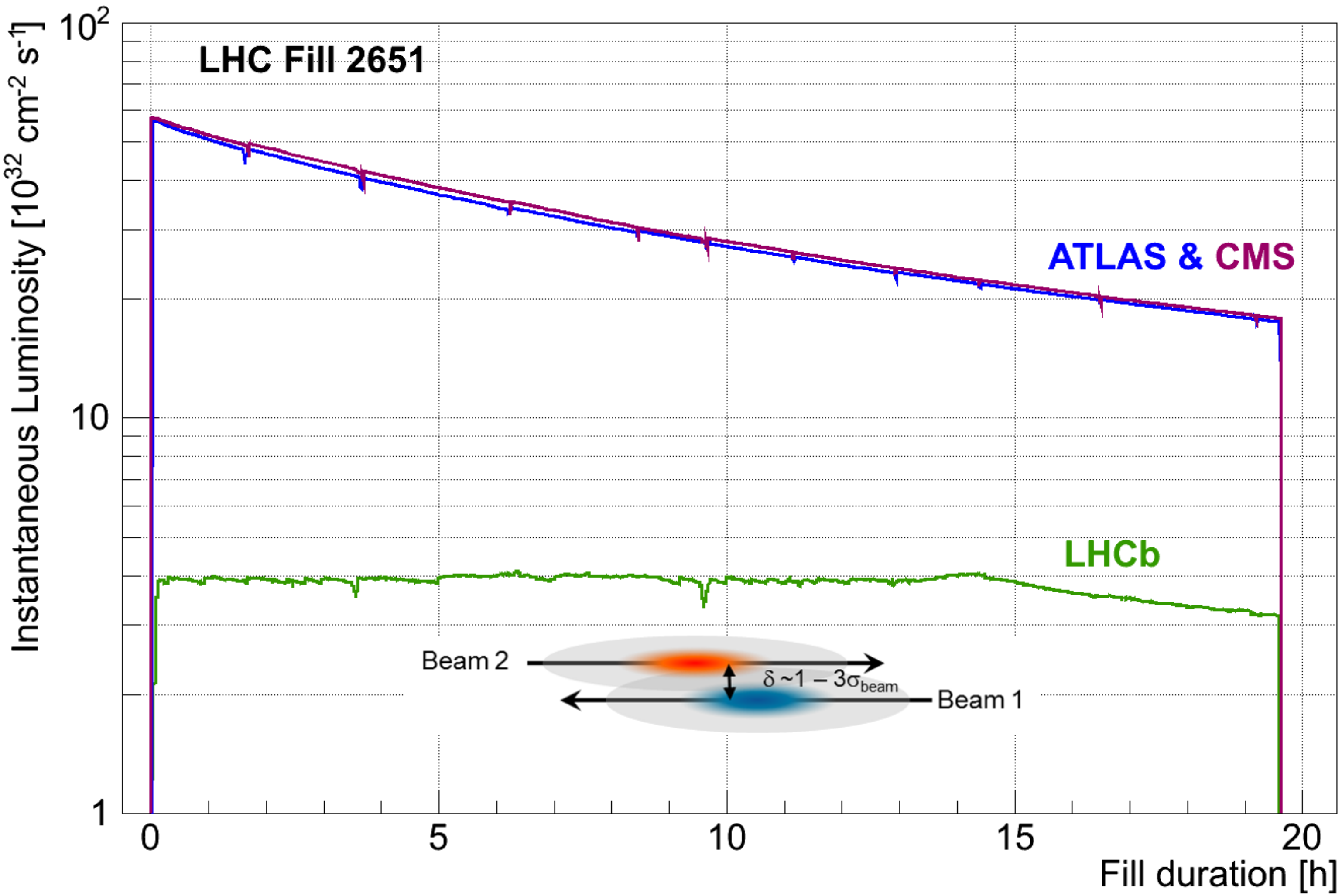
LHCb trigger



- High efficiency for manageable rates
- Background
  - Minimum bias
  - Other B and D decays
- Trigger variables
  - High pt tracks
  - High impact parameter and displaced vertices
- Upgraded in Run II
  - Perform real-time detector calibrations and alignment
  - Full offline-like event selection
  - Turbo stream (5kHz)

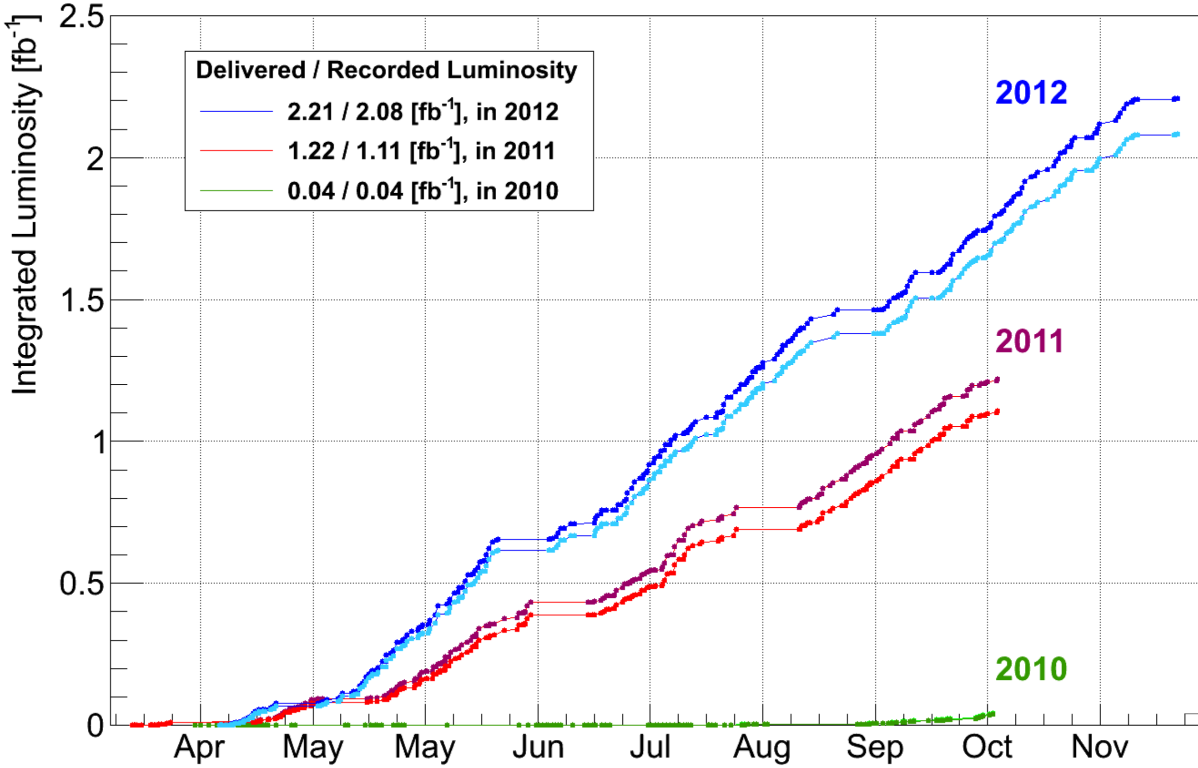
LHCb luminosity

- LHCb tracking/PID sensitive to pileup and occupancy
- Reduce luminosity by displacing the beams from head-on collisions

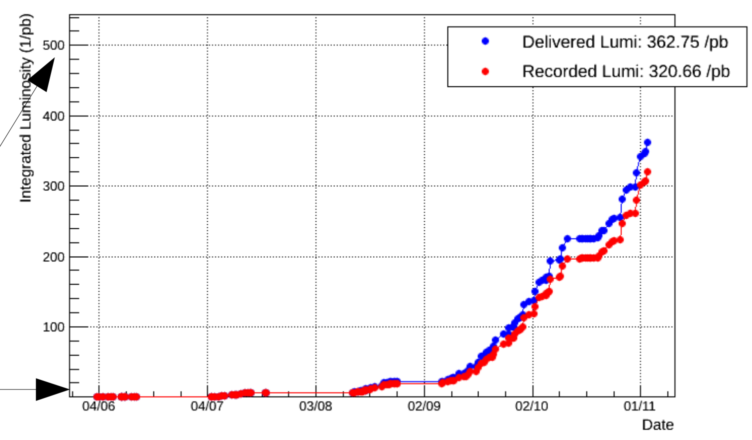


LHCb data

- LHC run 1 went from 2010 to 2012, during which LHCb collected 3 fb-1 of data (this corresponds to ~3 x 10[11] b anti-b pairs being produced within LHCb).



2015 delivered/recorded data

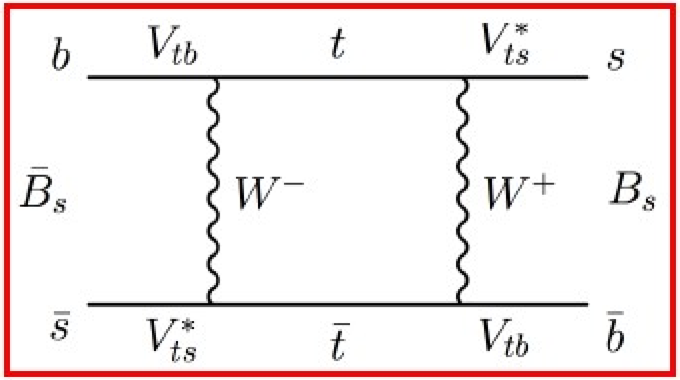


- Run 2 started after a 2 year shutdown, necessary to upgrade LHC energy.

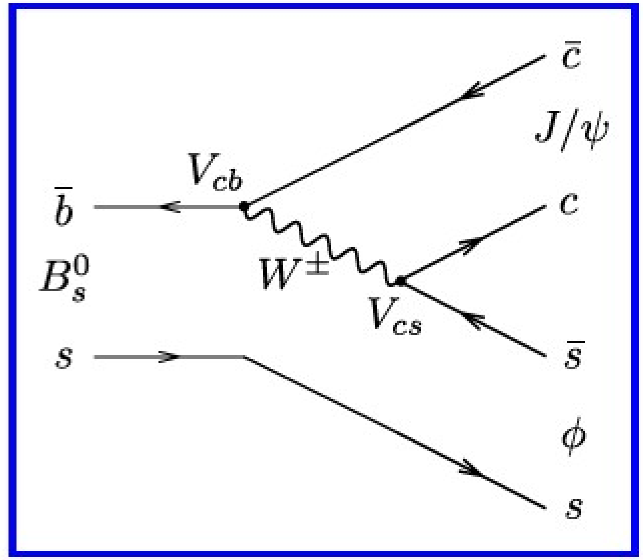
- Will continue to end of 2018 –we aim to increase our beauty sample by x3 or more

Sin(2β) with $B \rightarrow J/\psi\ K_s$

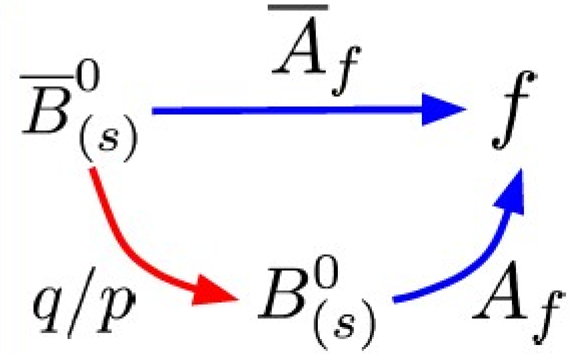
How to observe CP violation



$$\phi_{mix} = 2\arg(\mathrm{V_{tb}V^*_{ts}})$$



$$\phi_{dec} = \arg(\mathrm{V_{cb}V^*_{cs}})$$



$$|\lambda_f| \equiv \left|\frac{q}{p}\frac{A_f}{\overline{A}_f}\right| \approx 1$$

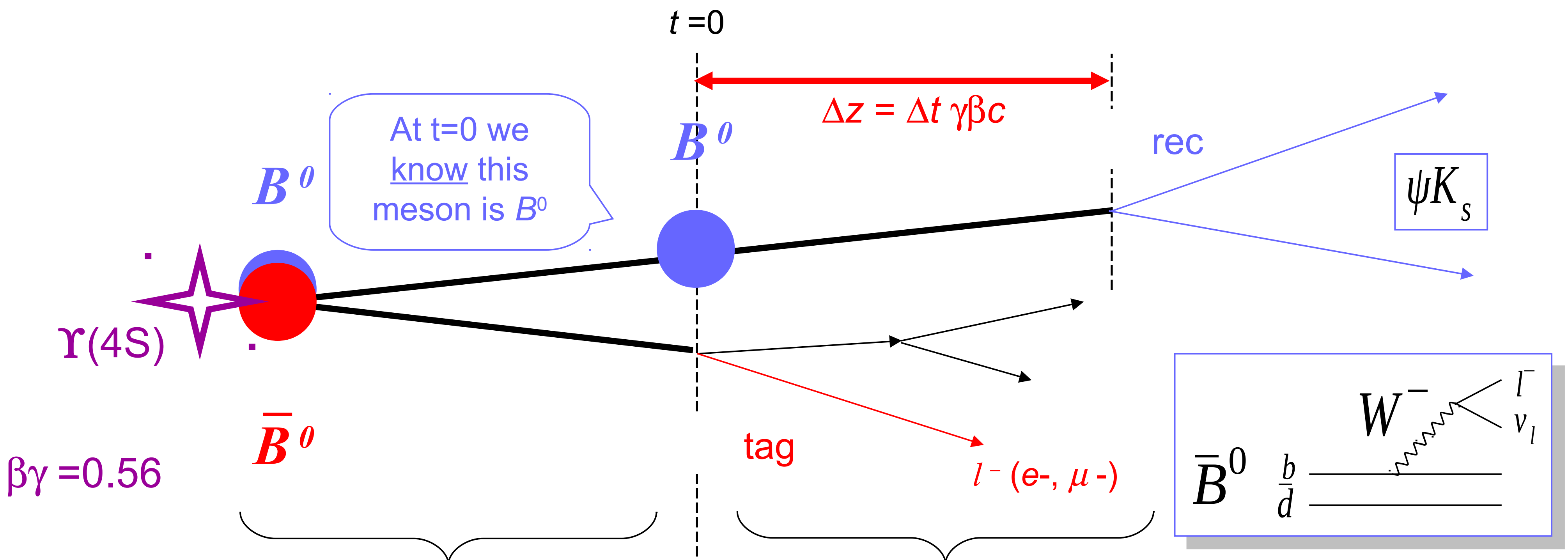
$$A_f = |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)},$$
$$\overline{A}_{\overline{f}} = |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)}.$$

$$A_{CP}(t) \equiv \frac{\Gamma_{B^0\to f} - \Gamma_{\overline{B}^0\to f}}{\Gamma_{B^0\to f} + \Gamma_{\overline{B}^0\to f}} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)}$$

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$
$$S_f \equiv \frac{2\sin\phi_{d,s}}{1+|\lambda_f|^2}$$
$$A_{\Delta\Gamma} \equiv -\frac{2\cos\phi_{d,s}}{1+|\lambda_f|^2}$$

Measurement of time dependent rates at Bfactories

- Time dependent CP violation measured employing entanglement of initial states to know the flavor of the B at the reference time t=0



The two mesons oscillate coherently : at any given time, if one is a B^0 the other is necessarily a $\bar{B}^0$

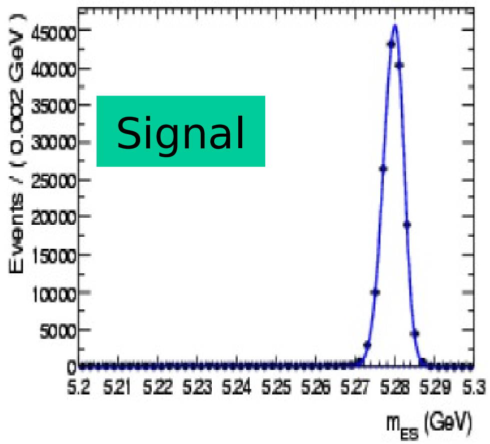
In this example, the tag-side meson decays first.
It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson :
$l^- = B^0$ $l^+ = \bar{B}^0$.
Kaon tags also used.

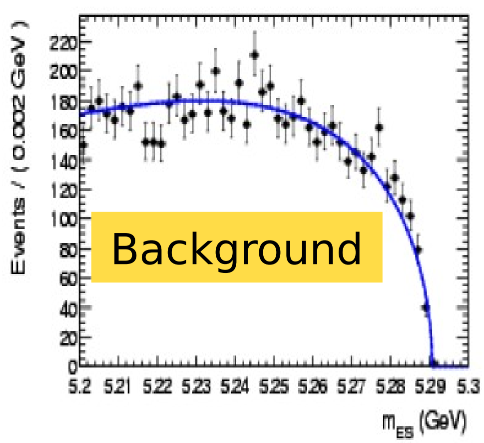
Δt picoseconds later, the B^0 (or perhaps it is now a $\bar{B}^0$) decays.

Key analysis techniques at B-Factores

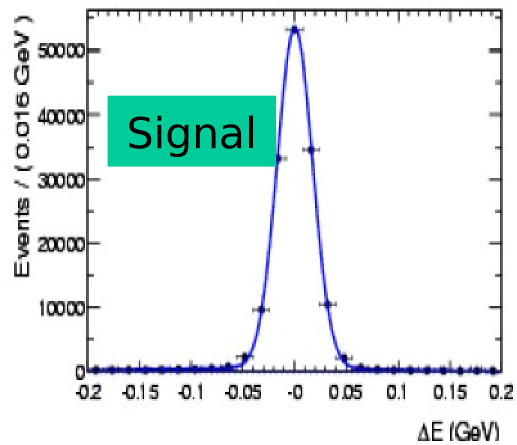
Threshold kinematics: the initial energy of the Y(4S) system is known, and therefore the approximate energy and magnitude of momentum of each B

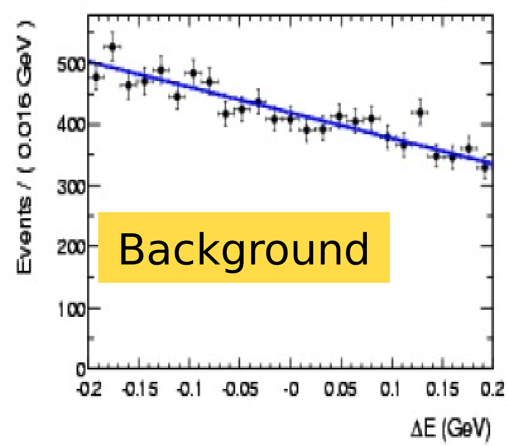
$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$



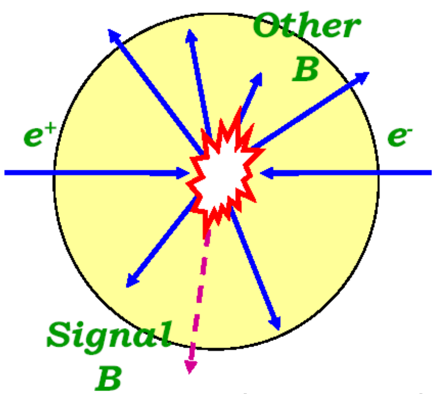


$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

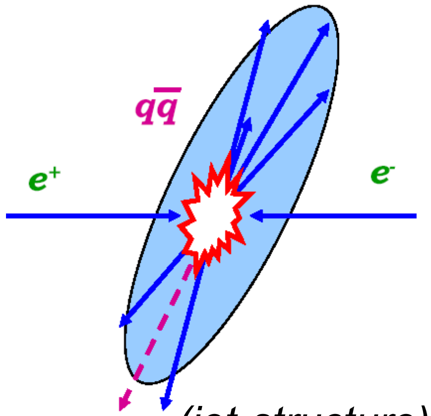




Event topology

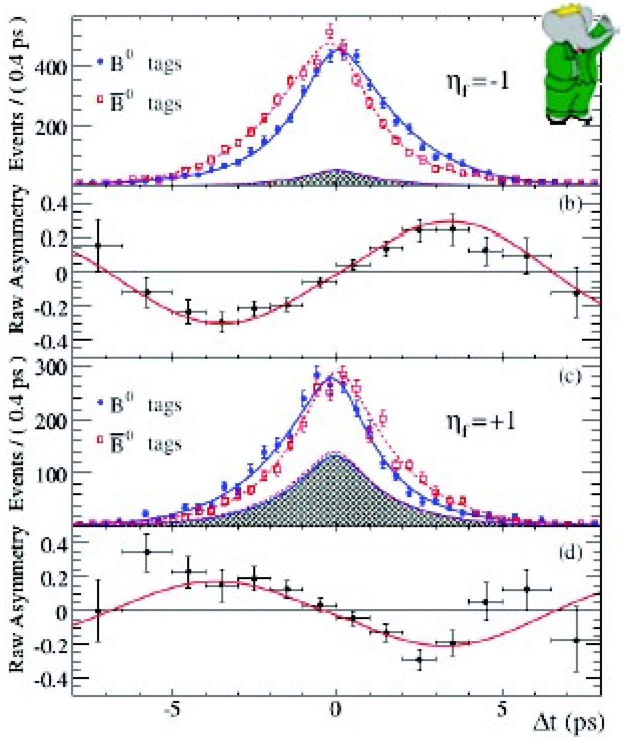


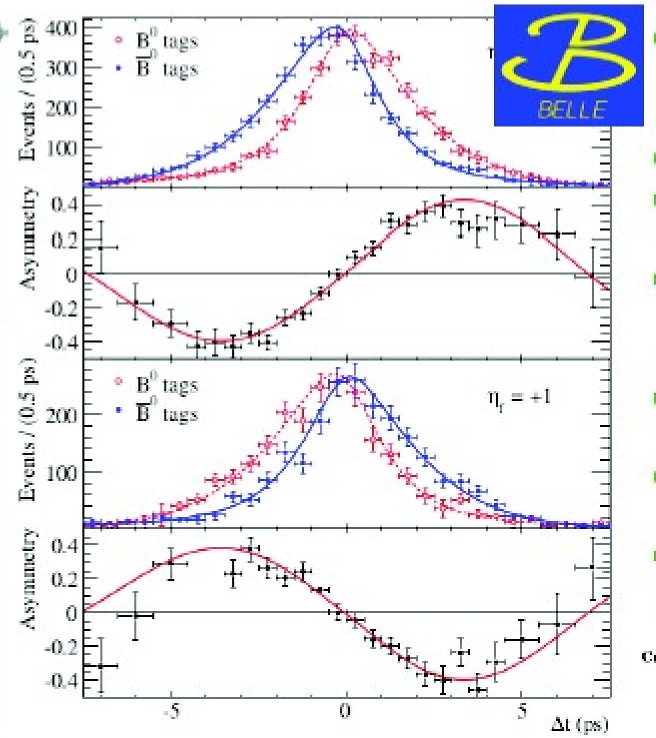
(spherical)

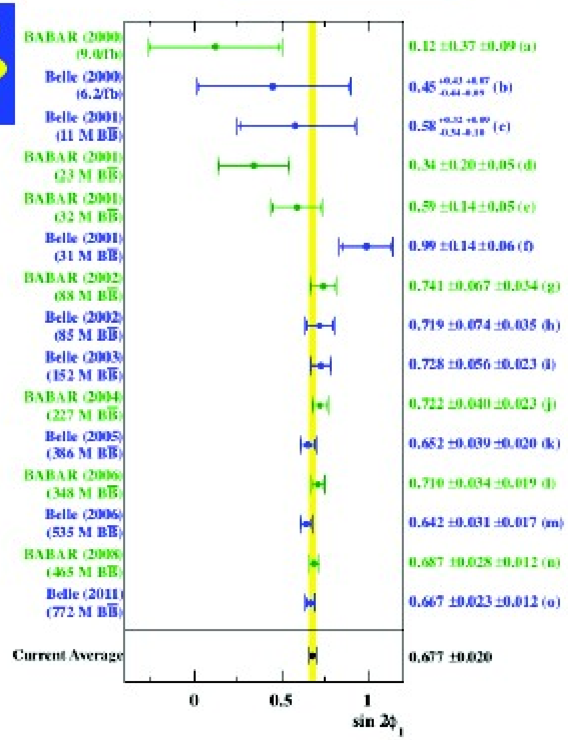


(jet-structure)

[Eur. Phys. J. C74 (2014) 3026, arXiv:1406.6311]

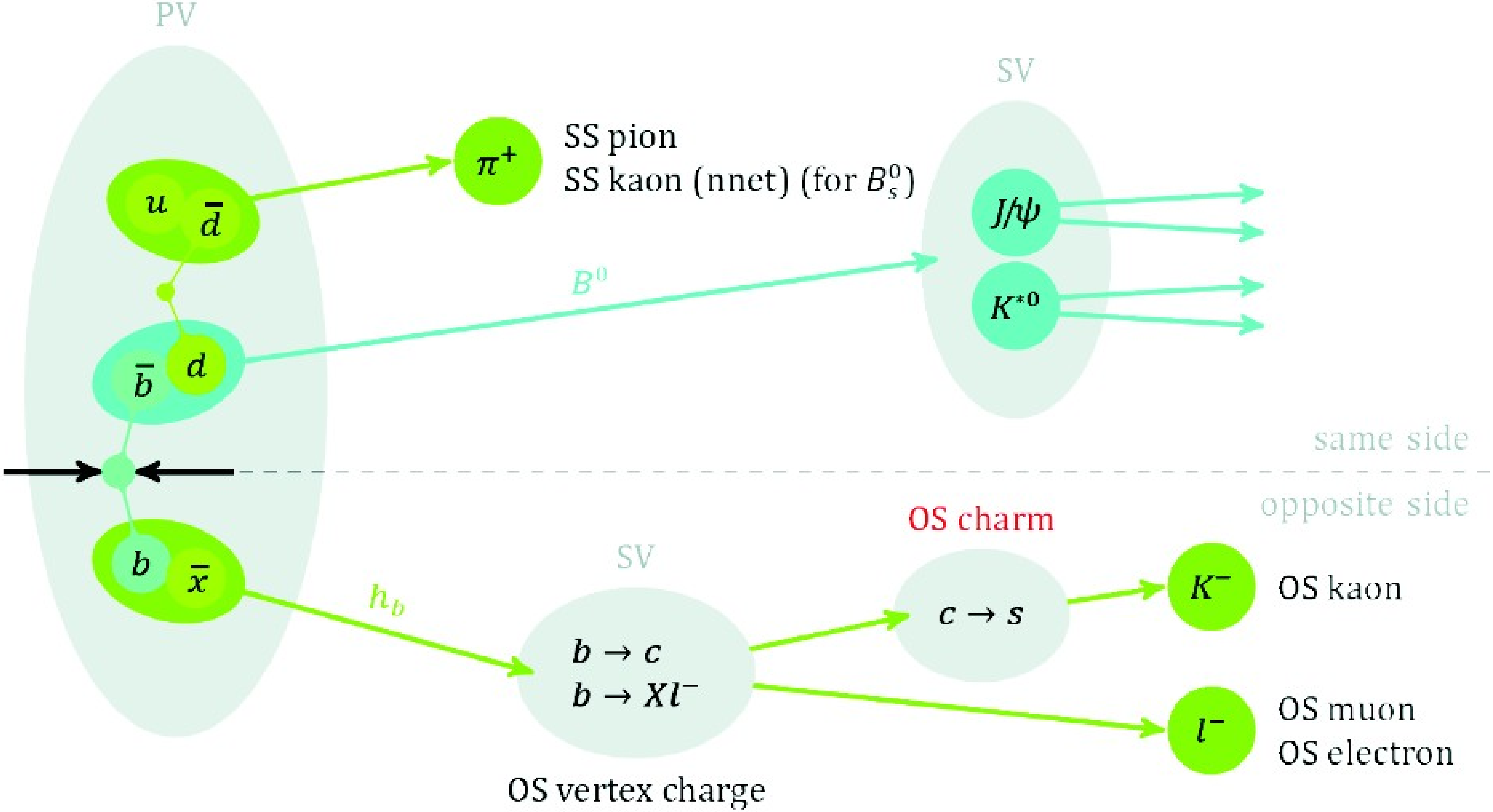






- BaBar:
  - $-\eta_f S_f$ = 0.687 ± 0.028 ± 0.012 [PRD 79, 072009 (2009)]
  - C_f = 0.024 ± 0.020 ± 0.016
- Belle:
  - $-\eta_f S_f$ = 0.667 ± 0.023 ± 0.012 [PRL 108, 171802 (2012)]
  - C_f = 0.006 ± 0.016 ± 0.012.

TD CPV at the LHC: flavor tagging

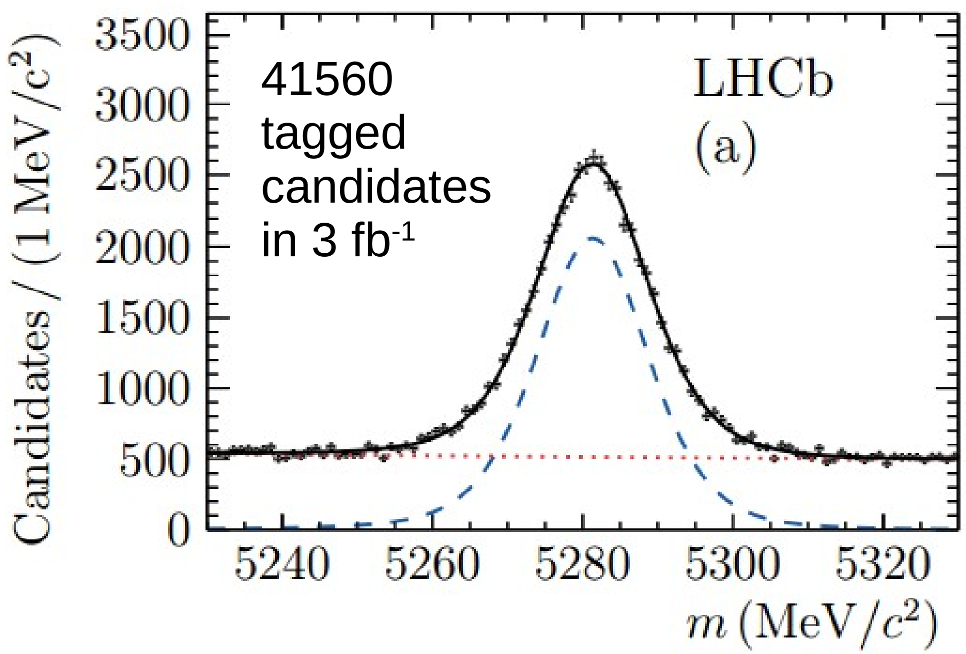


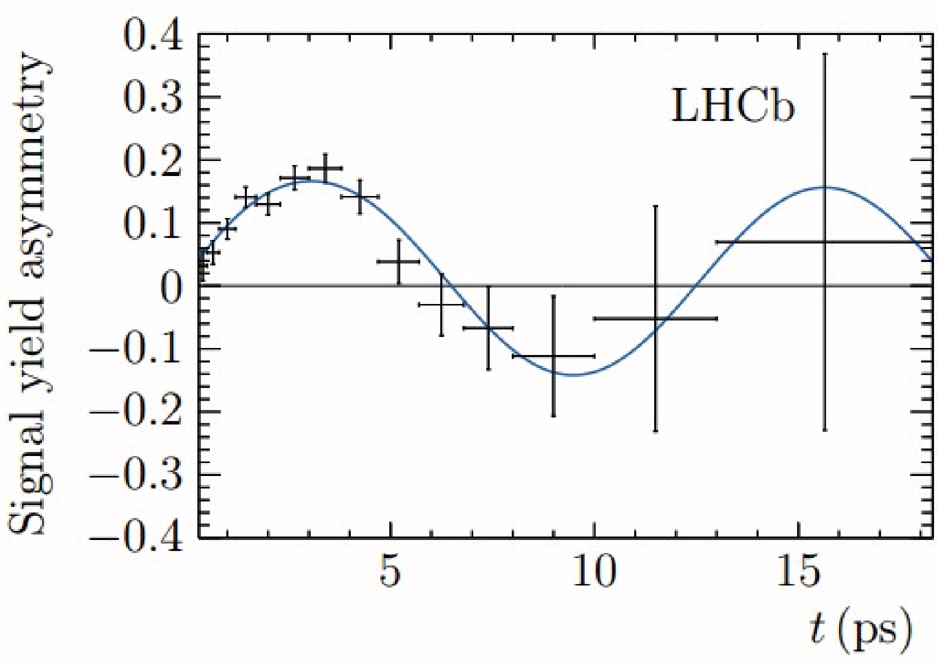
- OS tagging obtained similarly to BFactories, however
- no correlation between the evolution of the two B hadrons => intrinsic dilution => intrinsically small effective tagging efficiency

Sin(2β) in B→J/Ψ Ks at LHCb

[Phys. Rev. Lett. 115 031601 (2015)]

- Tagging using OS tagger
- Inclusion of SS pion tagger → eff=2.4% → 3%
  - Calibrated using B→ J/Ψ K^{*0}
- Time dependence of acceptance determined from data at small times (trigger effects) and MC for large times (reconstruction effects)
- $-\eta_f S_f = 0.731 \pm 0.035 \pm 0.020$,
- $C_f = -0.038 \pm 0.032 \pm 0.005$,





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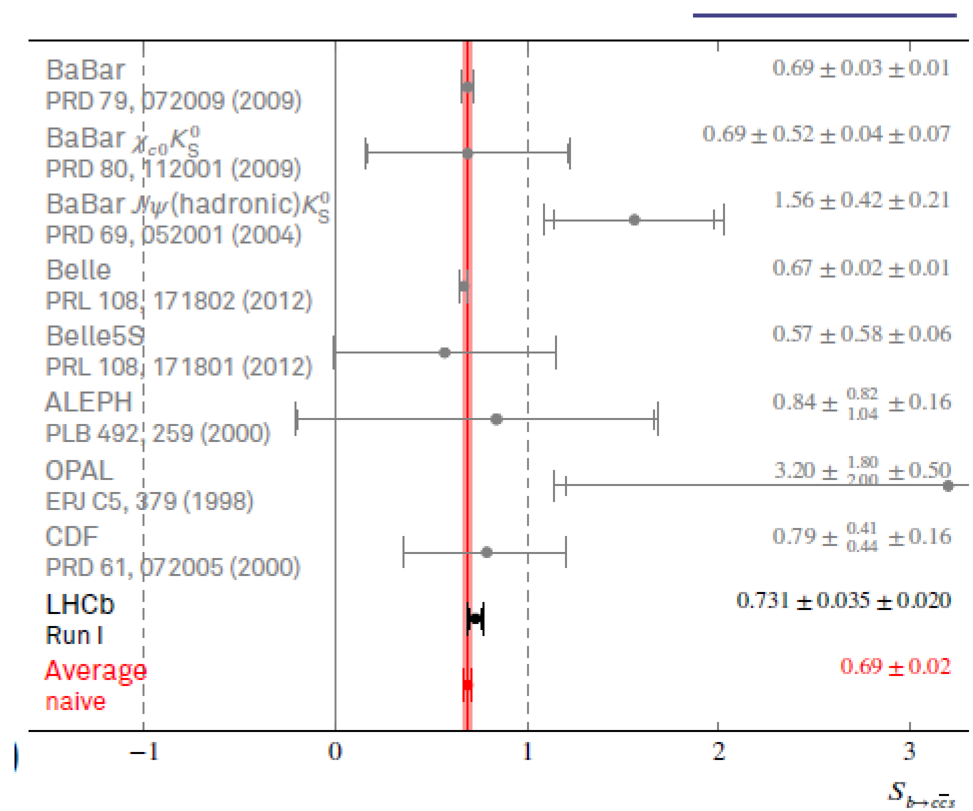
- Tagging using OS tagger
- Inclusion of SS pion tagger → eff=2.4% → 3%
  - Calibrated using B→ J/Ψ K*⁰
- Time dependence of acceptance determined from data at small times (trigger effects) and MC for large times (reconstruction effects),
- Now competitive with B-Factories
- B-Factories still better precision

$$S^{LHCb}=0.731\pm0.035\pm0.020,$$
$$S^{BaBar}=0.663\pm0.039\pm0.012,$$
$$S^{BELLE}=0.670\pm0.029\pm0.013$$

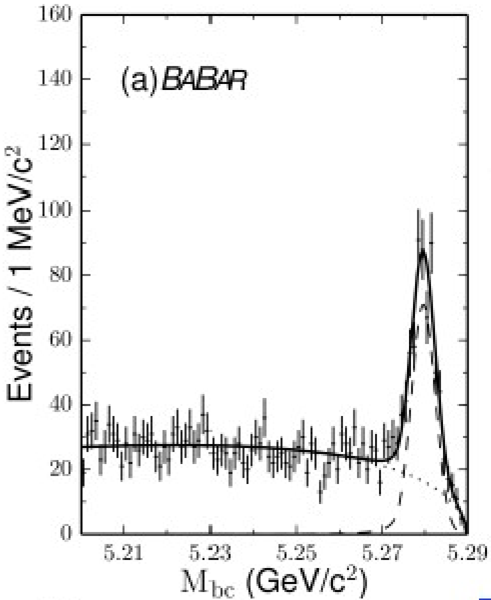


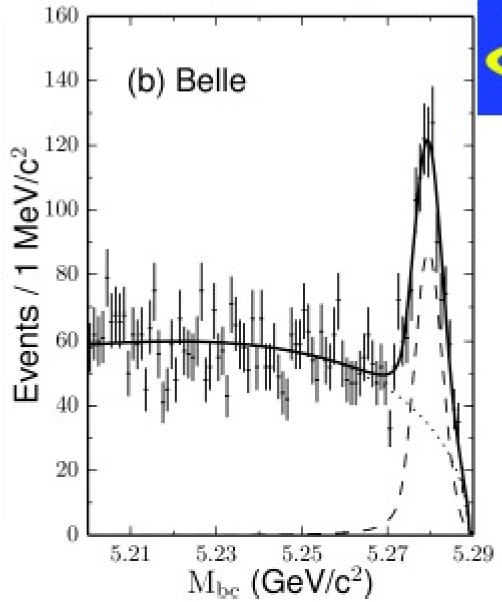
Sin(2β) in $\bar{B}\to D_{CP}^{(*)}h^0$ with BaBar and Belle

PRL 115, 121604 (2015)

- $\bar{B}\to D^{(*)}h^0$ decays proceed mainly trough tree amplitudes $q\to c\bar{u}d$
- If D decays to CP eigenstate K^+K^-, $K_S\pi^0$, $K_S\omega$ with $h^0=\pi^0, \eta, \omega$ then time dependent CP violation can occur via interference with oscillation
- Penguin free measurement of sin(2β) that can be used as a reference for mising induced CP violation in penguin mediated $b\to s$ B meson decays
- First combined fit to BaBar and Belle data (1.243 10^9 $B\bar{B}$ pairs)
-

	BaBar	Belle
$\bar{B}^0 \to D^{(*)}_{CP} h^0$ total	508 ± 31	757 ± 44





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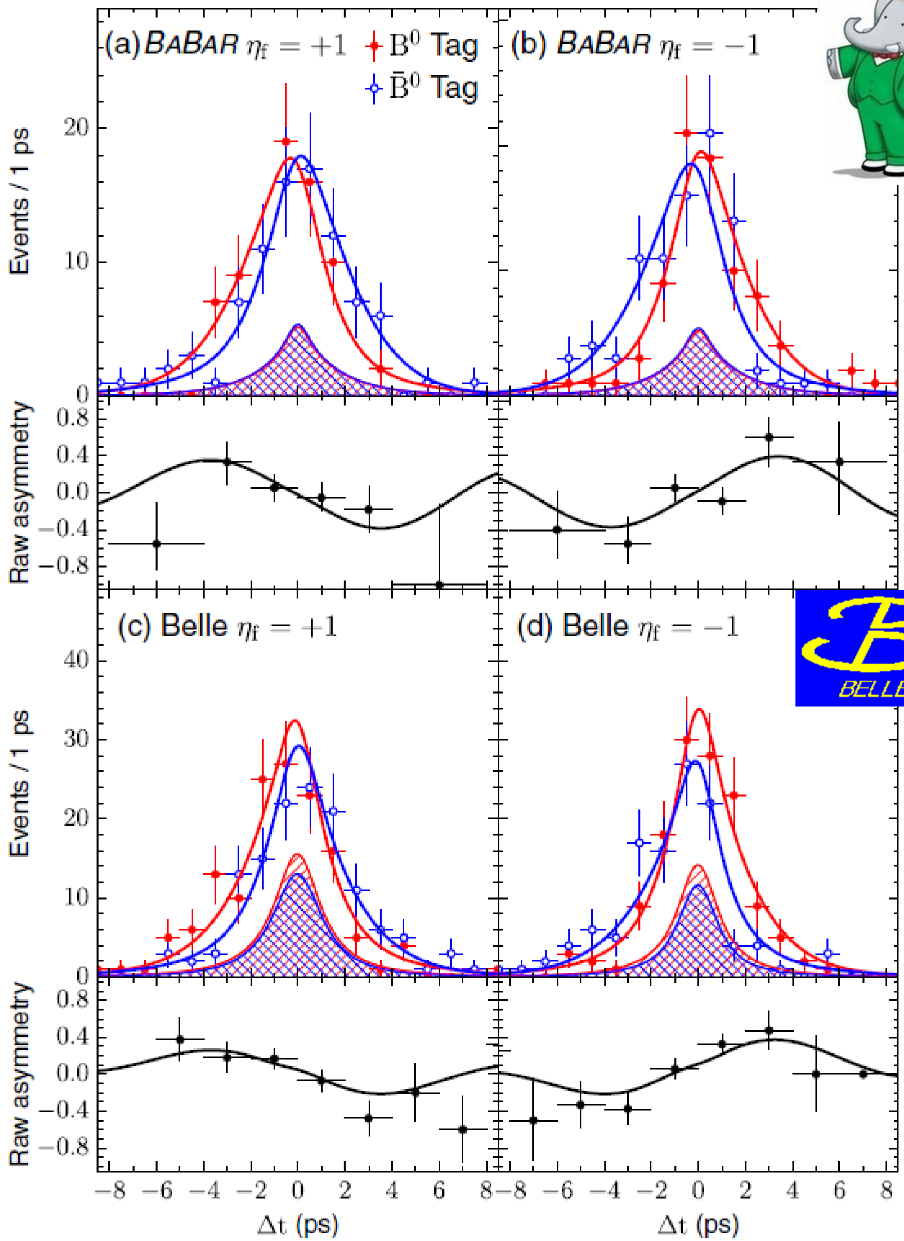
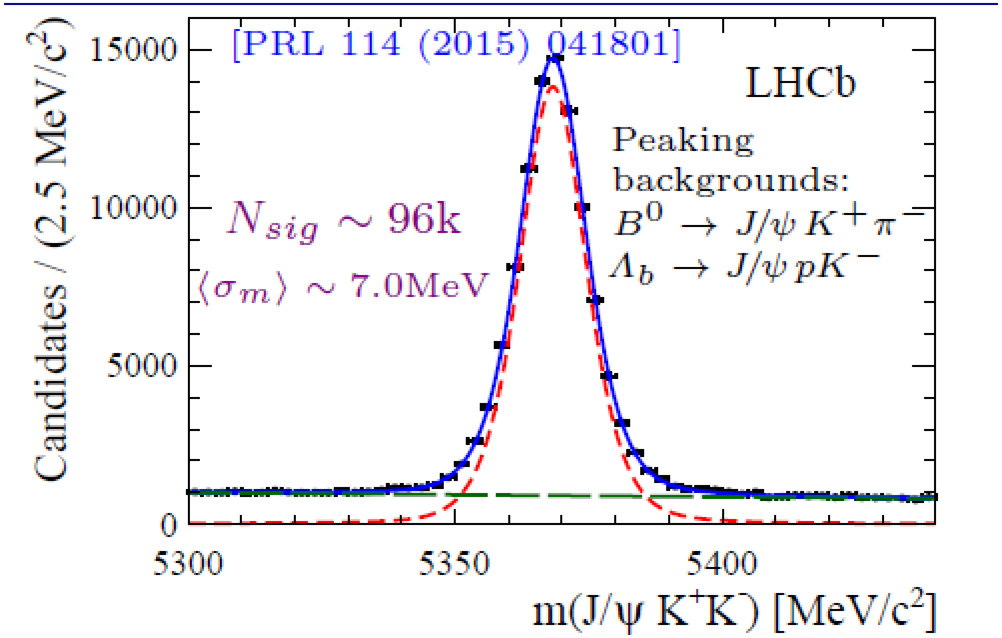
- Penguin free measurement of sin(2β) that can be used as a reference for mising induced CP violation in penguin mediated b→s B meson decays
- First combined fit to BaBar and Belle data (1.243 10^9 $B\bar{B}$ pairs)
- $$-\eta_f S = +0.66 \pm 0.10(\mathrm{stat}) \pm 0.06(\mathrm{syst}),$$
  $$C = -0.02 \pm 0.07(\mathrm{stat}) \pm 0.03(\mathrm{syst}).$$

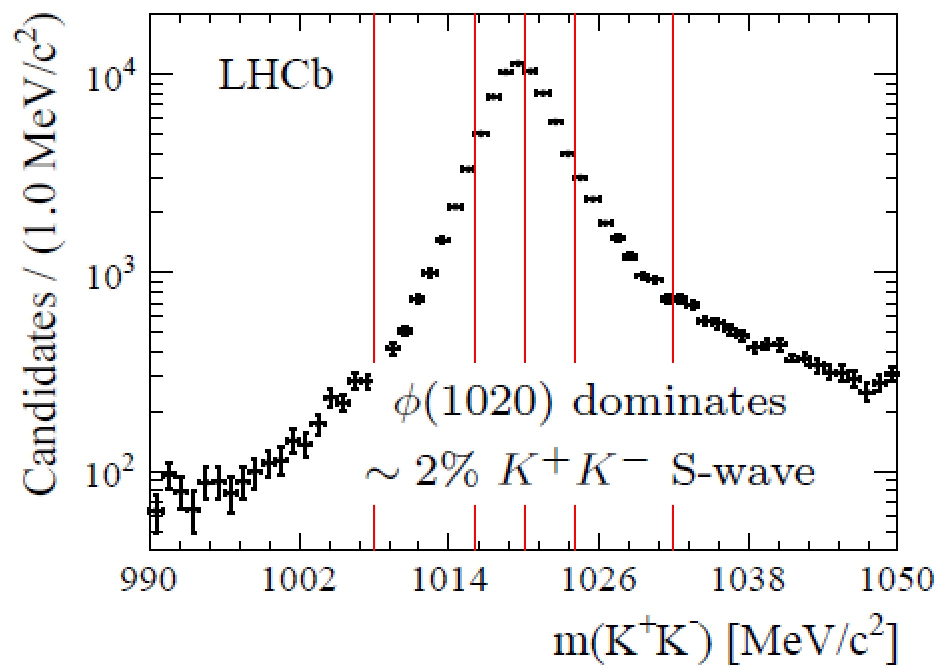


ϕ_s from $B_s^0 \to J/\psi\phi$

- $J/\psi \to \mu^+\mu^-$
- $\Phi \to K^+K^-$
- $B_s^0 \to J/\psi\,\varphi$ is $P \to VV$ decays so use angular information to disentangle CP -odd and CP -even components.
- Measure φ_s, Δm_s, Γ_s, $\Delta\Gamma_s$, $|\lambda_f|$ at the same time
- Precise determination of lifetime params

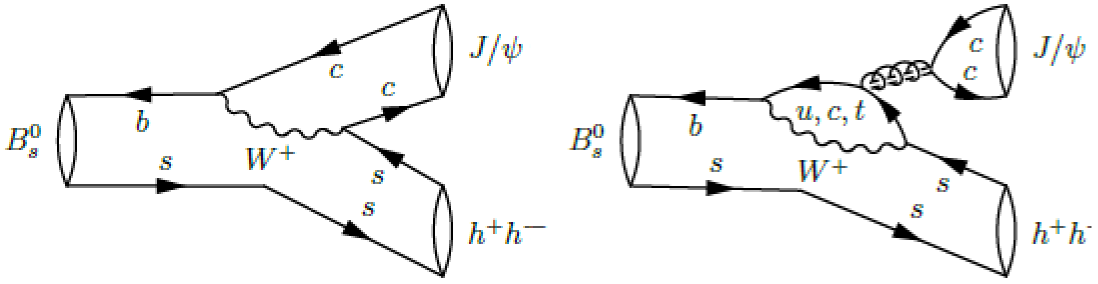
ϕ_s	$-0.058 \pm 0.049 \pm 0.006$ rad
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Γ_s	$0.6603 \pm 0.0027 \pm 0.0015$ ps^{-1}
$\Delta\Gamma_s$	$0.0805 \pm 0.0091 \pm 0.0032$ ps^{-1}
Δm_s	$17.711\ ^{+0.055}_{-0.057} \pm 0.011$ ps^{-1}





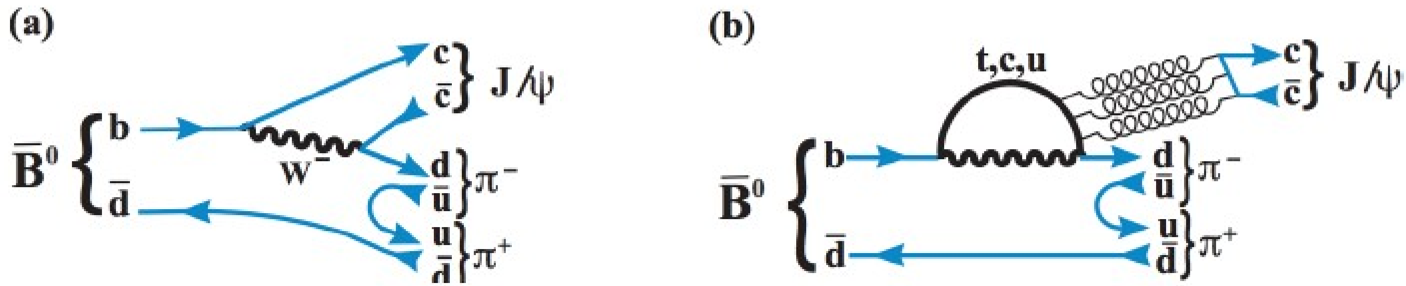
Controlling penguin pollution

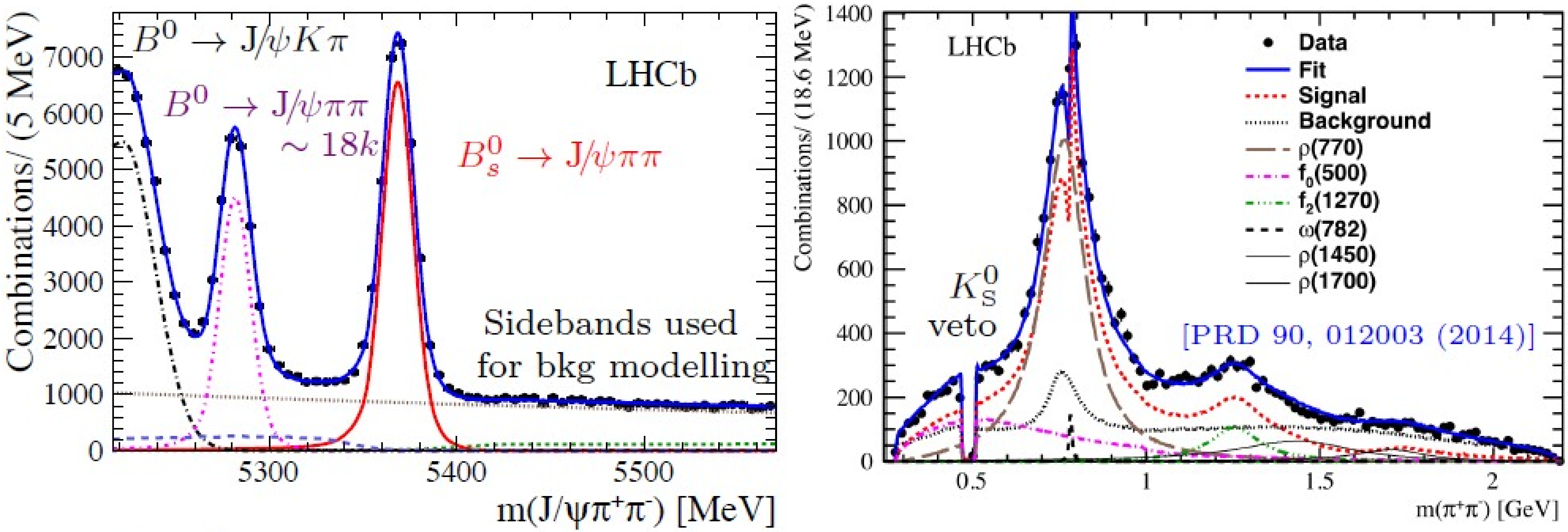
- Measured cp violating phase could be shifted due to a penguin amplitude with different weak phase
  - $\Phi_q^{measured} = \phi_q + \delta^{penguin} + \delta^{NP}$



- => measure using decays where penguin/tree ratio is not suppressed.
  - Use SU(3)-favour relations to link B°s and B° (broken at 20-30% level).

Penguin pollution: $B^0 \to J/\psi\pi^+\pi^-$ PLB 742 (2015) 38-49





- Use $\rho^0(770)$ component to measure:

$$\phi_d^{\text{eff}} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ,\ \alpha_{CP} \equiv \frac{1-|\lambda_f|}{1+|\lambda_f|} = (-32 \pm 28^{+9}_{-7}) \times 10^{-3}$$

$$\Rightarrow \Delta\phi_d = (-0.9 \pm 9.7^{+2.8}_{-6.3})^\circ$$ (equivalent to $0.016 \pm 0.169^{+0.049}_{-0.110}$ rad)

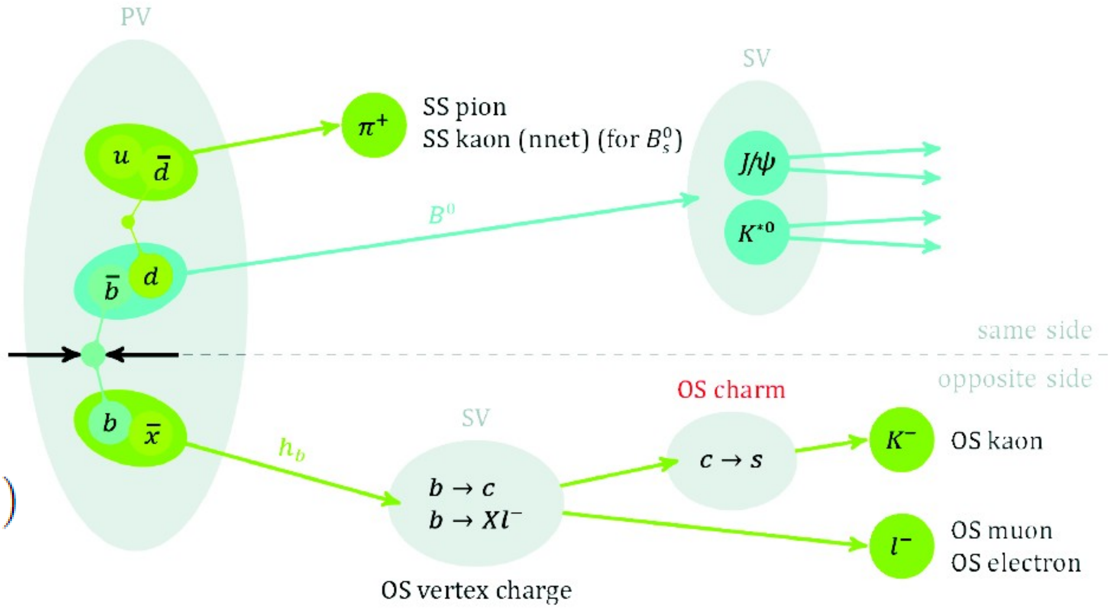
Not covering γ and α

Δm_d

B mixing frequency measurement

LHCb-CONF-2015-003

- Using as signal $B \to D^{(*)}\mu\nu$ to determine the decay vertex and the flavor of the B at the decay point is possible to precisely determine the B mixing frequency

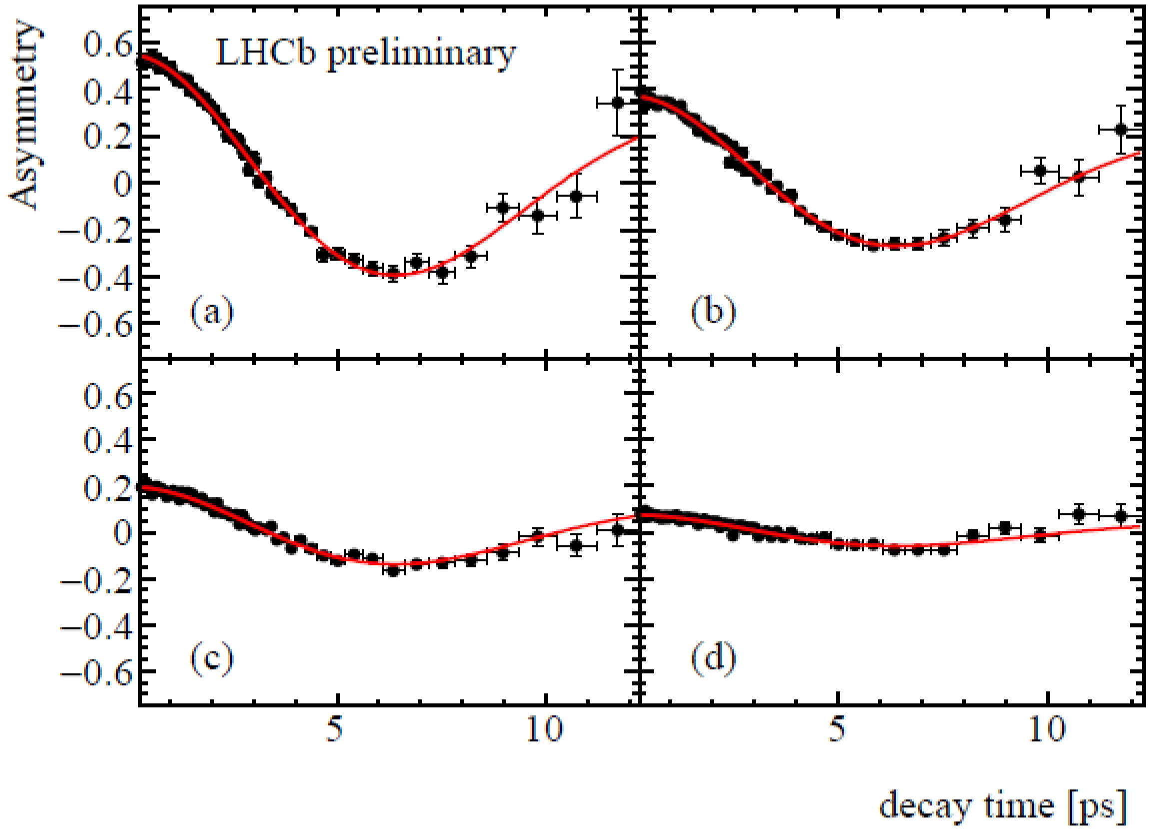


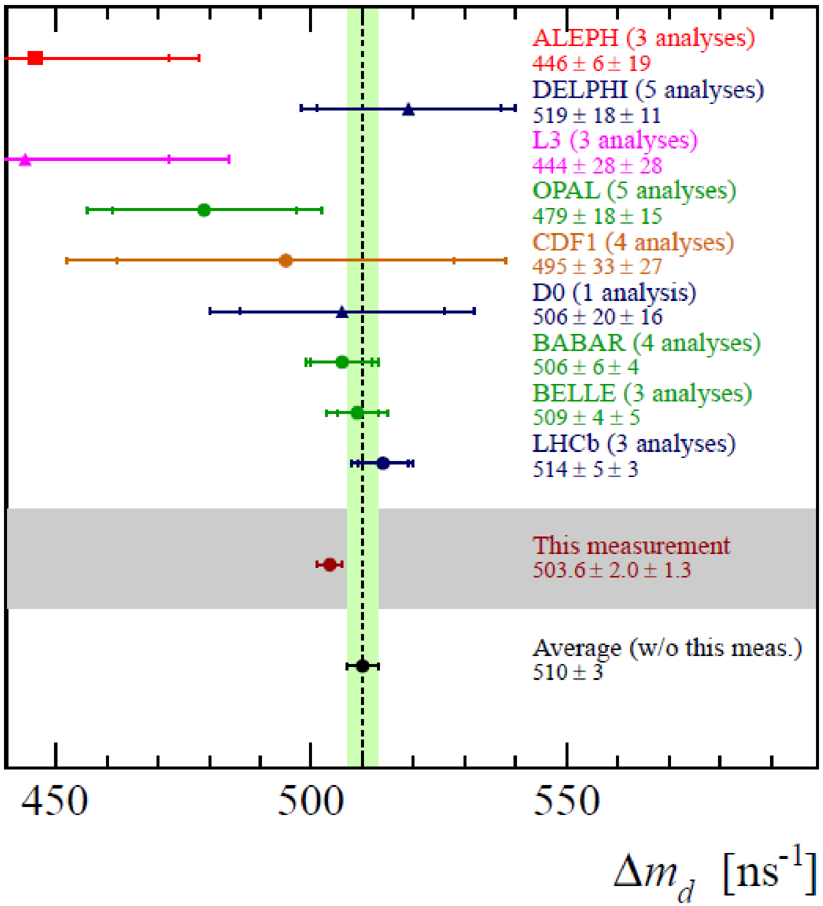
$$A(t) = \frac{N^{\rm unmix}(t) - N^{\rm mix}(t)}{N^{\rm unmix}(t) + N^{\rm mix}(t)} = \cos(\Delta m_d t)$$

- Ptag=$\varepsilon_{tag}(1-2w)^2$=2.4%
- Dominant background from $B \to D^{(*)}\mu\nu X$ rejected with BDT
- B momentum cannot be measured due to the neutrinos=> use factor $k=p_{reco}/p_{true}$ to correct the time $t=k_{av}(M)\, l\, M_{PDG}/p_{reco}$
- It introduces an additional resolution function in the decay time distribution

$$P_{sig}(t)=T(t)\otimes R(t)\otimes F(k)\cdot A(t)$$

B mixing result





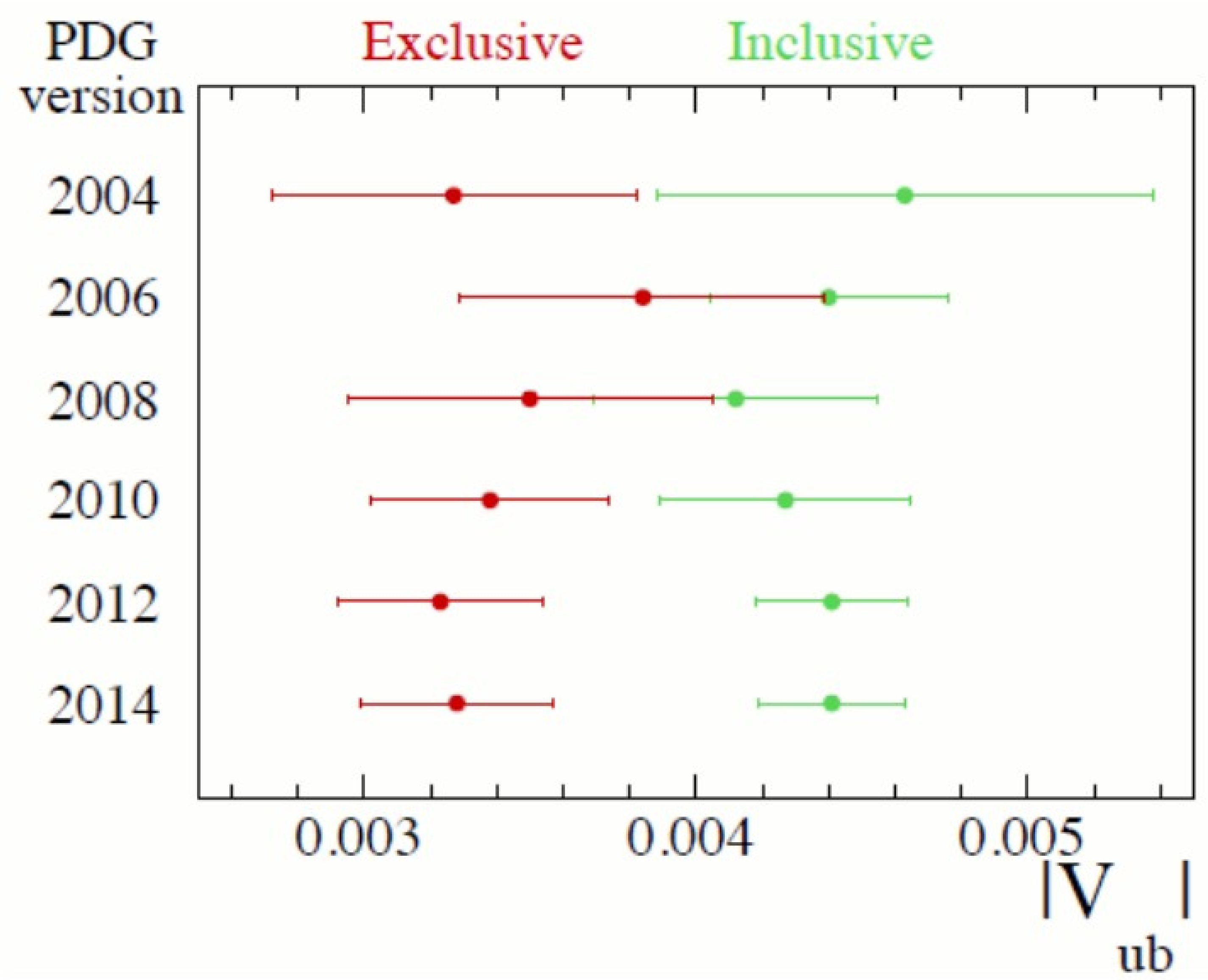
$$\Delta m_d = 503.6 \pm 2.0(stat) \pm 1.3(sys)\, GeV/c^2$$

Most precise single measurement

$\Lambda_b \rightarrow p\mu\nu$

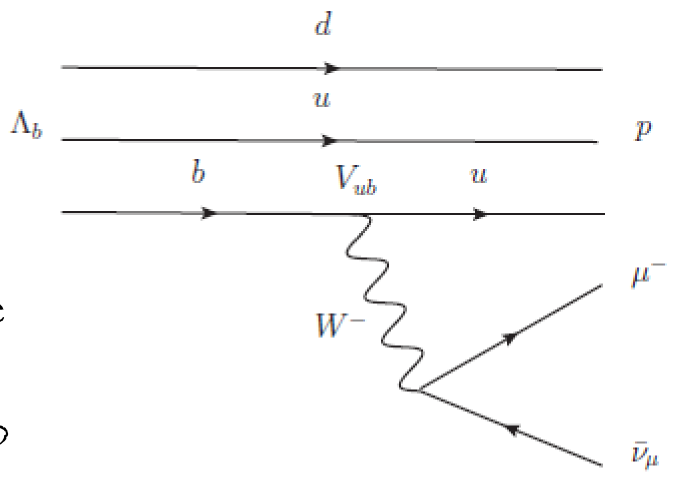
V_{ub}

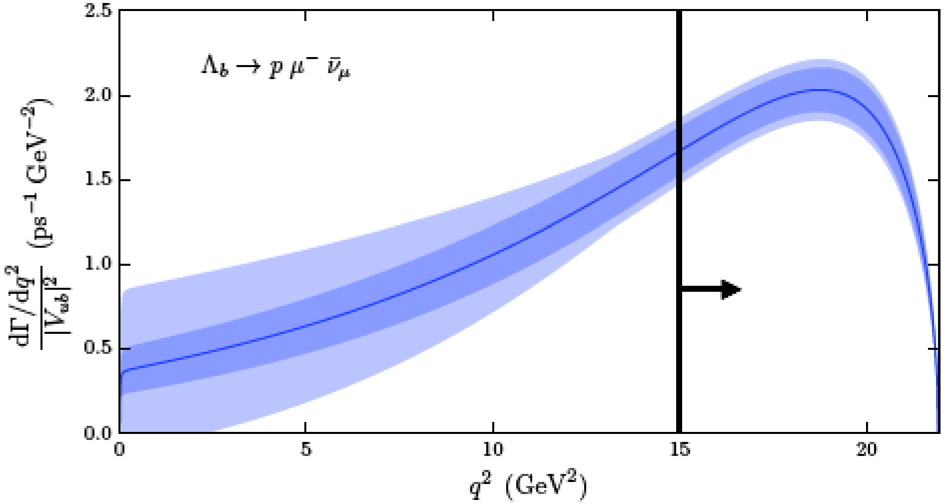
- Long standing issue with V_{ub}

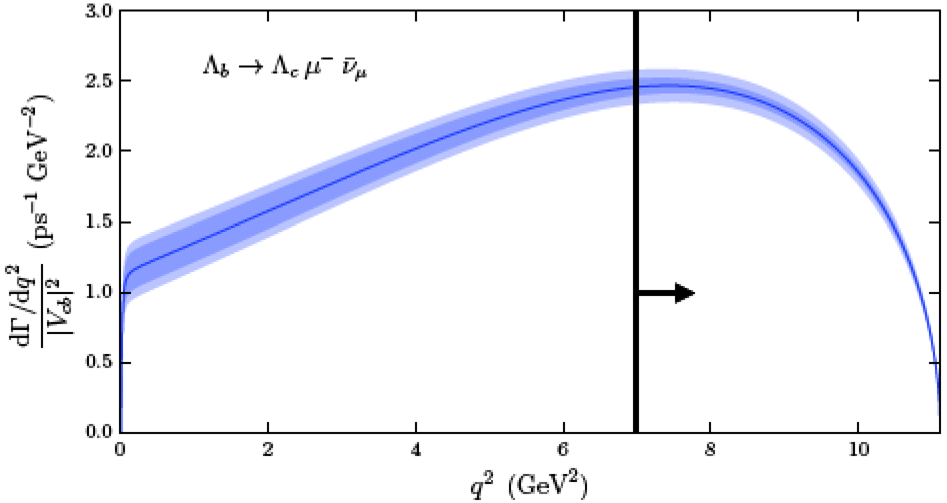


V_{ub}/V_{cb} from $\Lambda_b \to p\,\mu\,\nu$

- Vub measured at B-Factories using BF($B \to \pi l \nu$)
- $\Lambda_b \to p\, l\, \nu$ is the baryonic version of $B \to \pi l \nu$
- Measure the BF only in high q^2 region where lattice calculation is known precisely → uncertainty on Vub ~ 5%

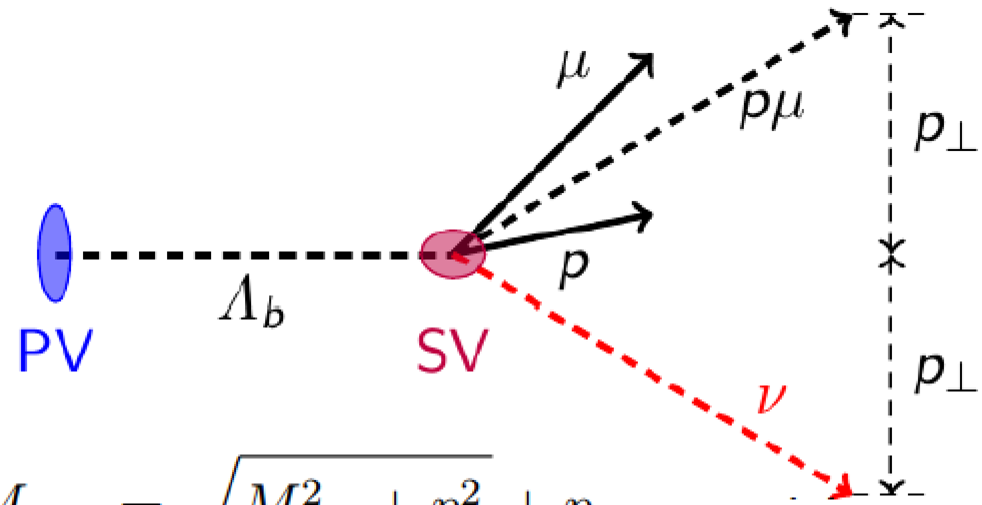




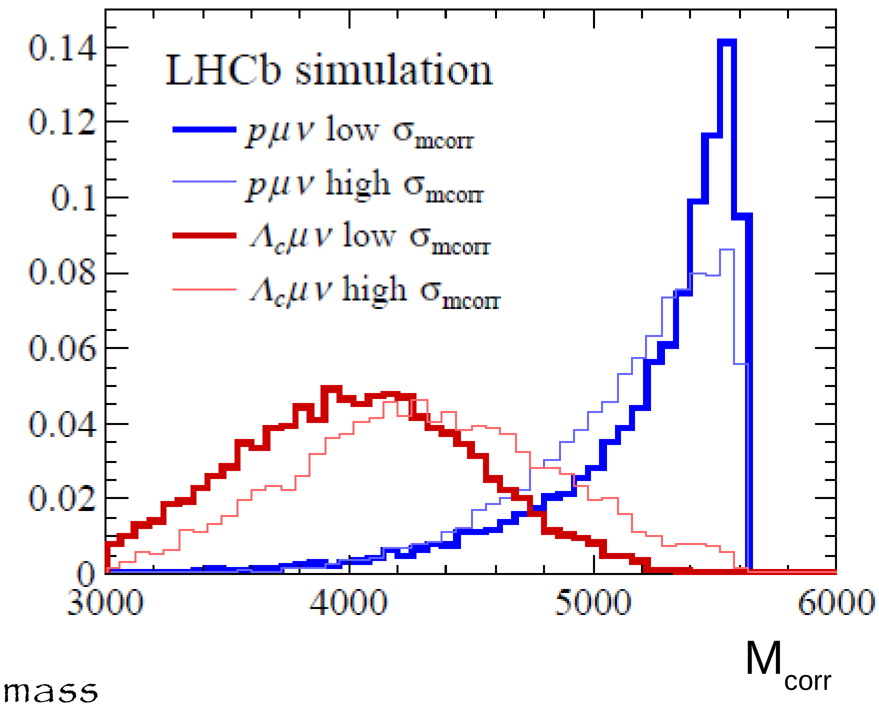


W. Detmold, C. Lehner and S. Meinel: arxiv:1503.01421(hep-lat)

$\Lambda_b \to p\,\mu\,\nu$ reconstruction at LHCb



$$M_{corr} = \sqrt{M^2_{X\mu} + p_T^2} + p_T$$



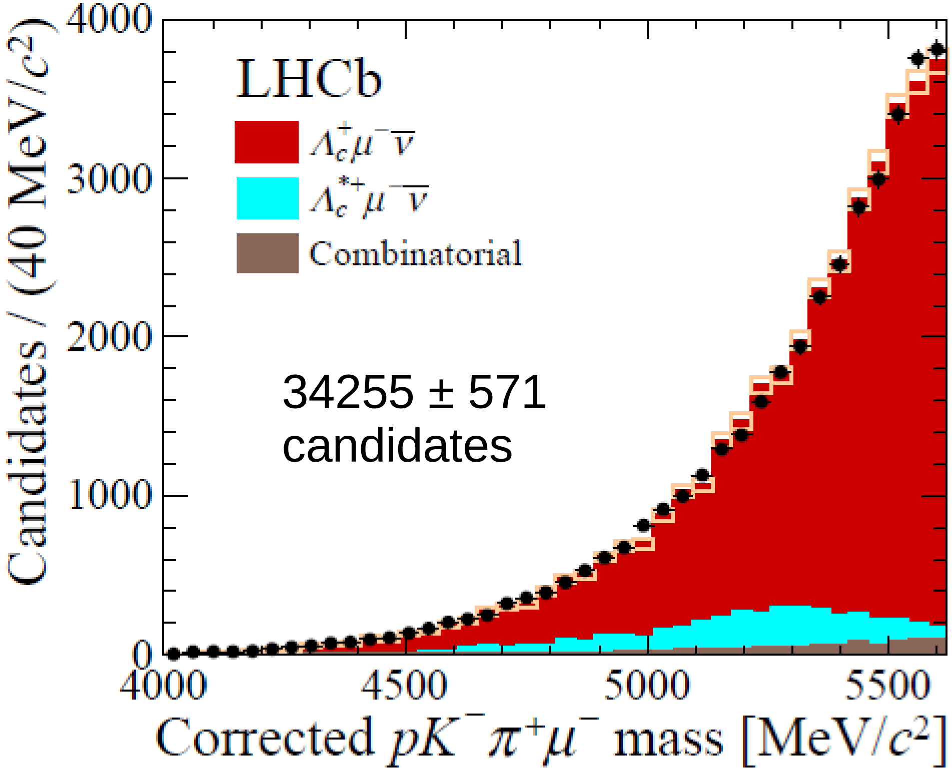
- Signal yield extracted from a fit to the corrected mass
  - Exploits the knowledge of the direction of the B
  - Is the minimum mass of the system assuming a massless neutrino
  - The resolution can be improved cutting on the computer error on M_{corr}
  - Selection mostly cut-based, a part from BDT used to isolate against background with additional charged tracks that were not reconstructed

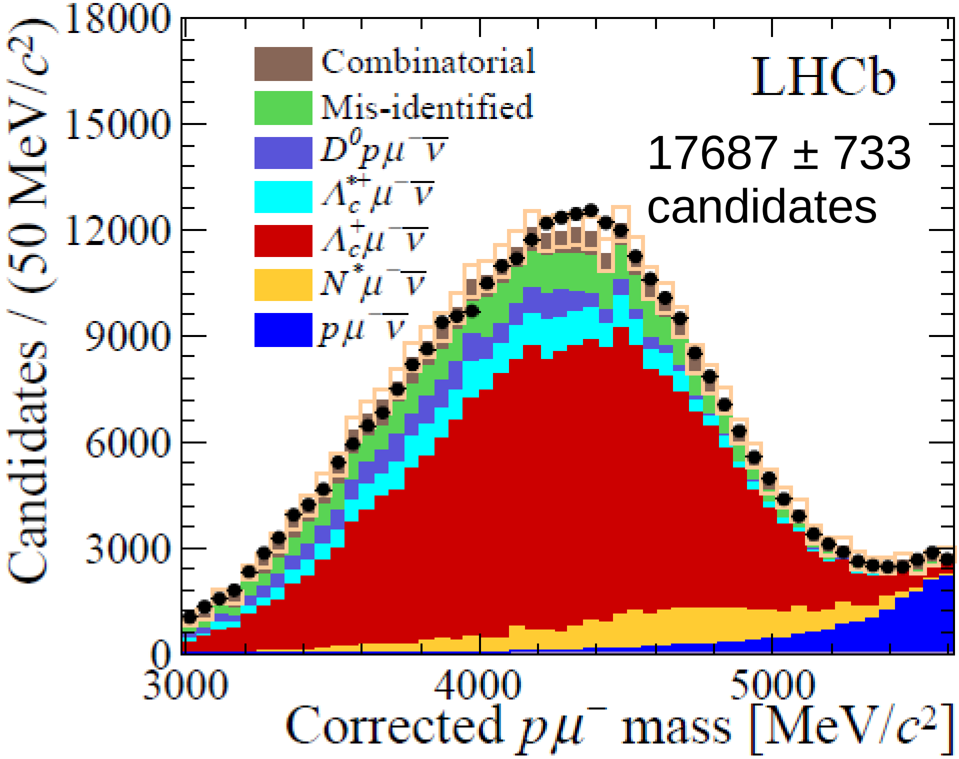
Normalization and signal fit

- Use $\Lambda_b \rightarrow \Lambda_c \mu\nu$ at high q^2 as normalization channel

Lattice calculations from Meinel et al.: arxiv:1503.01421(hep-lat)

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{G(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{G(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

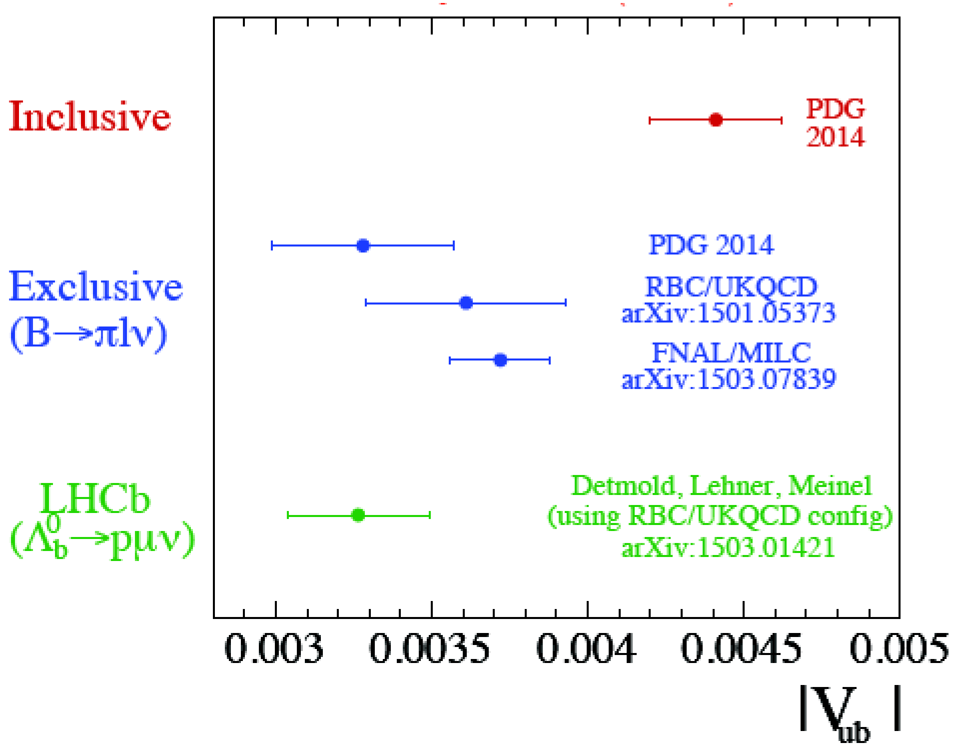


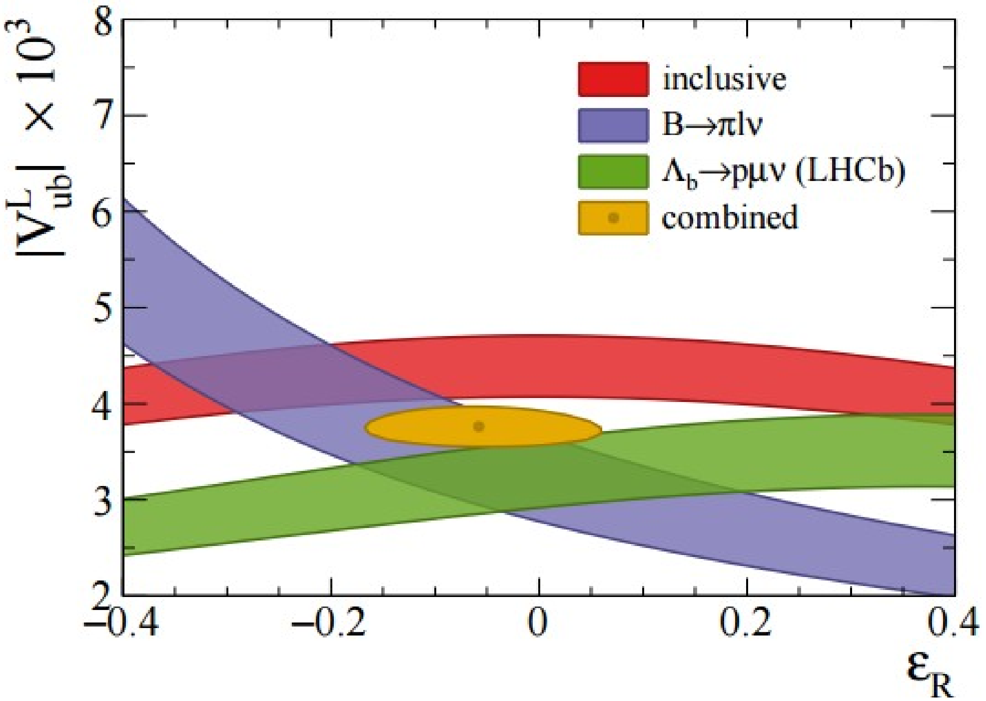


- Largest background from $\Lambda_b \rightarrow \Lambda_c \mu\nu$

- Most signal like background $\Lambda_b \rightarrow N^* \mu\nu$

$|V_{ub}/V_{cb}|$ result





- Largest experimental systematic: ~5% external measurement of BF($\Lambda c \to pK\pi$)

  Then trigger , tracking and selection efficiency : ~3% each

- V_{ub}=3.27 ± 0.15(exp) ± 0.16(theory) ± 0.06($|V_{cb}|$)
- Confirms discrepancy between inclusive and exclusive
- Inconsistent with a significant right handed current

Prospects on Sides and angles

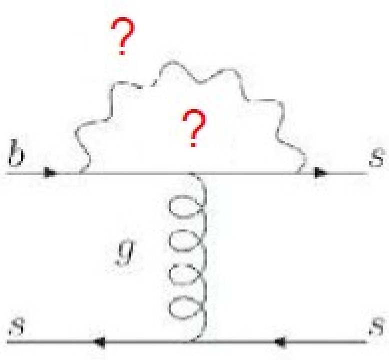
- LHCb reached comparable sensitivity to B-Factories on β
  - Keep under control penguin contributions becomes important
- Both β and γ are statistically limited
  - There is a margin do better by improving the tagging
- |Vub/Vcb| can also be improved
  - Lattice calculations
  - External input $B(\Lambda c \rightarrow pK\pi)$
  - New decays, eg $Bs \rightarrow K\mu\nu$
- Also precision on Δm_d , Δm_s can be improved by improving lattice calculations

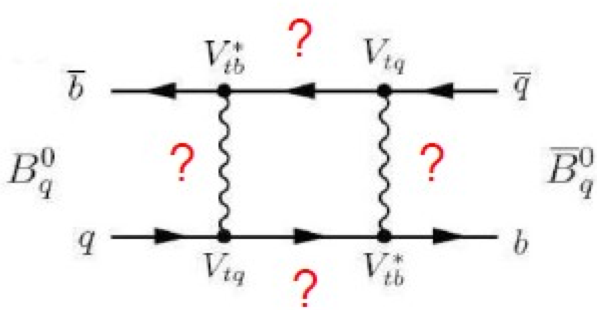
Rare Decays

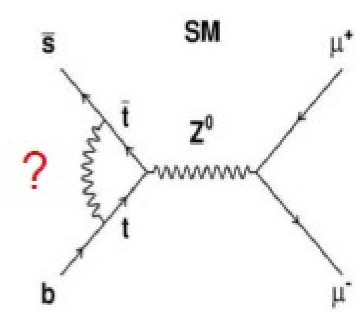
Rare Decays

- In tree decays new physics effects are loop suppressed
- Flavor changing neutral currents are naturally highly suppressed in SM

- New intermediate particles can appear in the loops giving a contribution not suppressed with respect to the standard model => clean signatures of New Physics



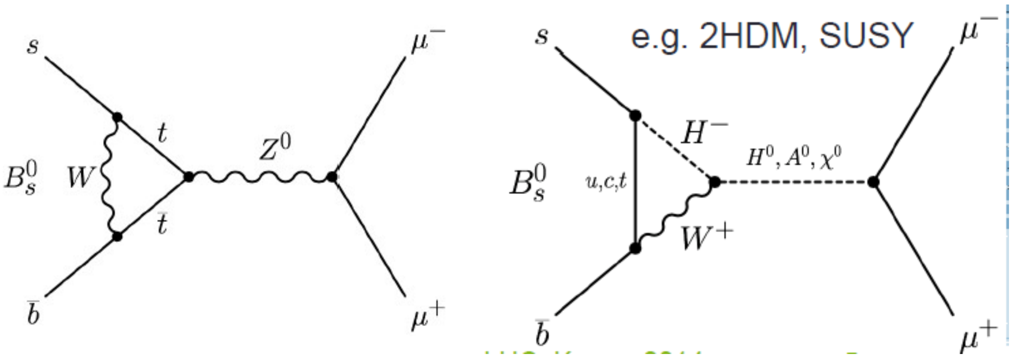


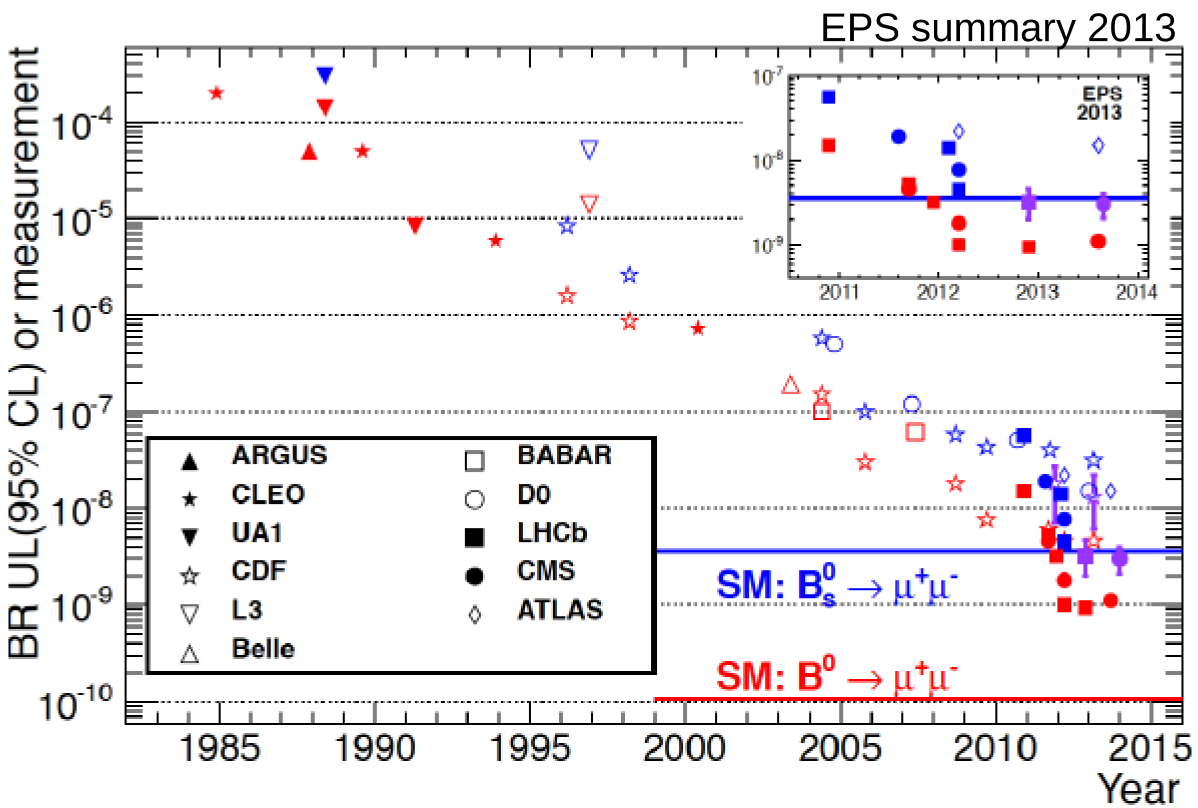


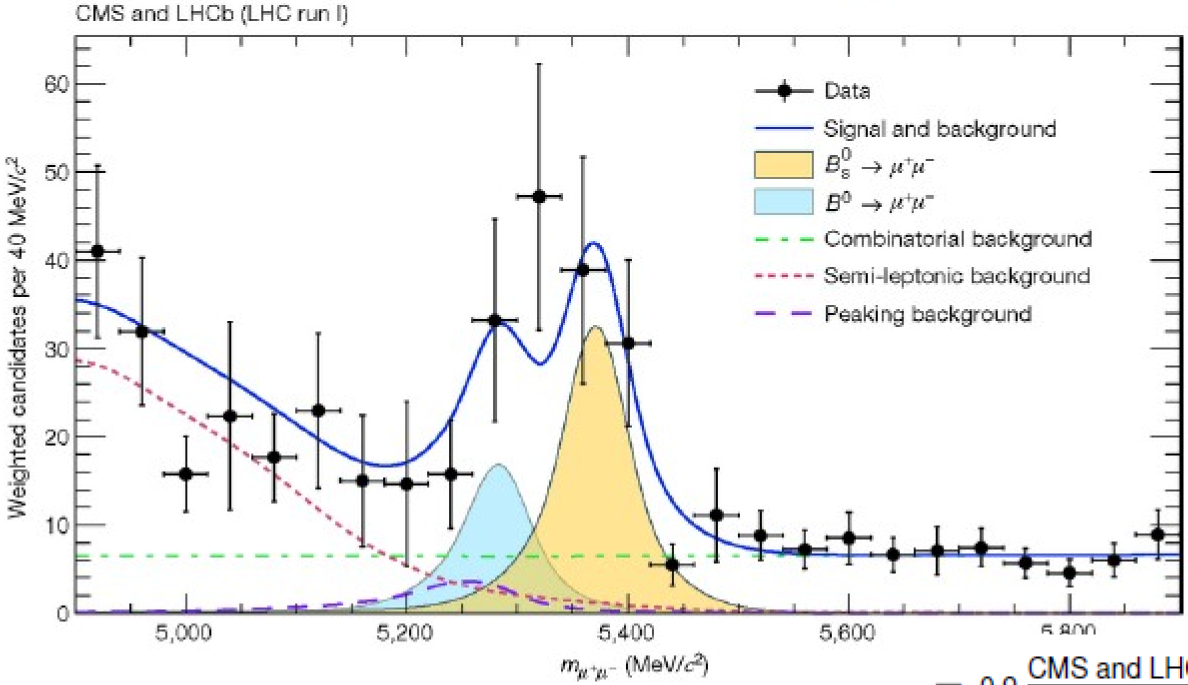
$B_s \to \mu\mu$ BF combination (CMS LHCb)

Nature 522 (2015) 68

- Very rare FCNC process with additional suppression due to CKM and helicity
- New physics contributions not necessarily suppressed
- Long history of search



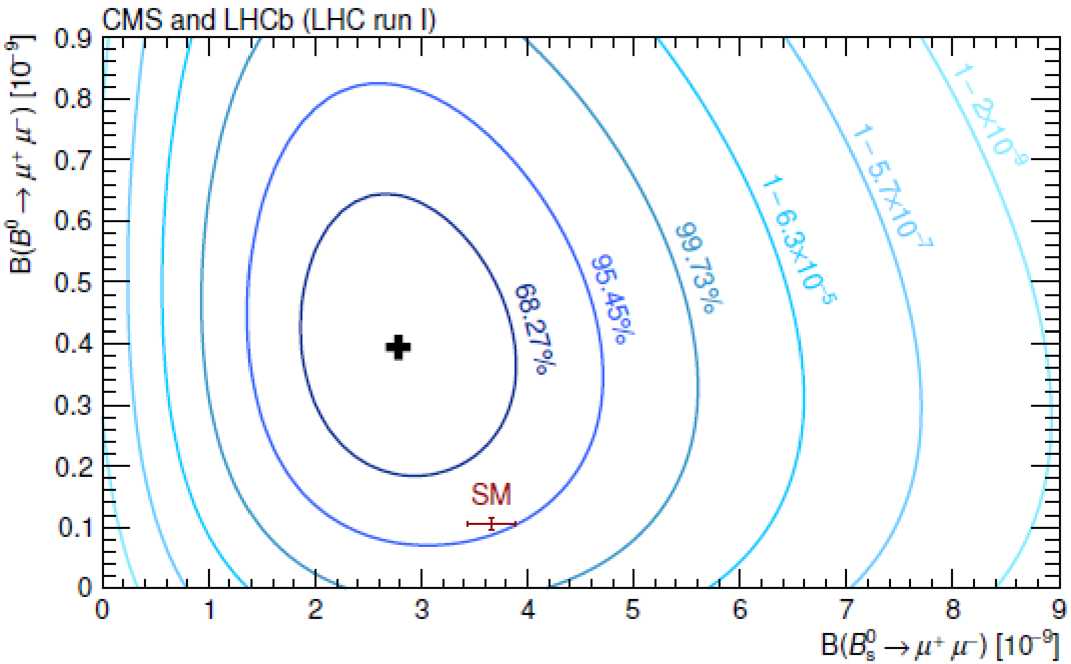




- First observation of $B_s \to \mu\mu$ and first evidence of the $B_d \to \mu\mu$ decay
- Compatible with the SM
- Strong constraints on new (pseudo) scalar couplings

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$
$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right)_{\rm SM} = 3.66 \pm 0.23 \times 10^{-9}$$

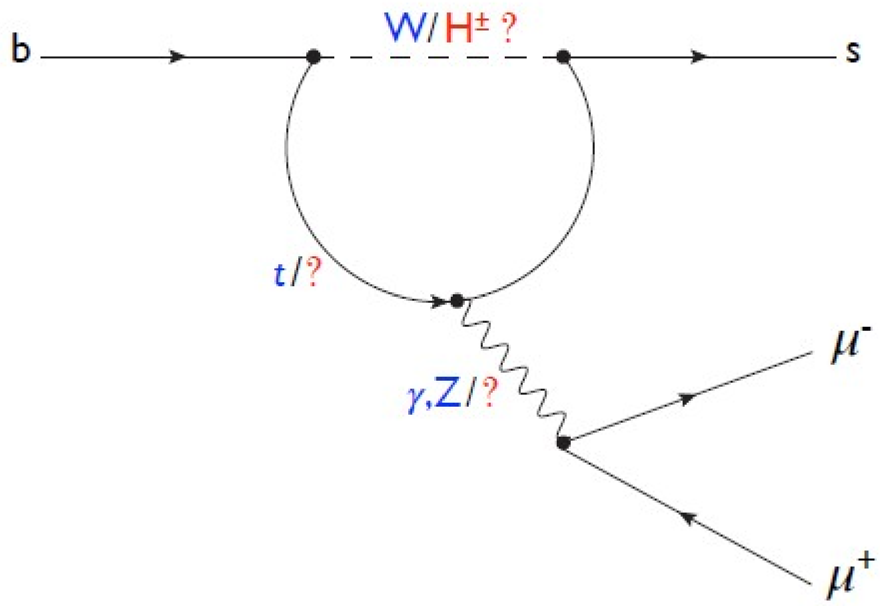
$$\mathcal{B}\left(B_d^0 \to \mu^+\mu^-\right) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$
$$\mathcal{B}\left(B_d^0 \to \mu^+\mu^-\right)_{\rm SM} = 1.06 \pm 0.09 \times 10^{-10}$$



$B \rightarrow K^*\mu^+\mu^-$, $B \rightarrow \phi\mu^+\mu^-$ full angular analysis

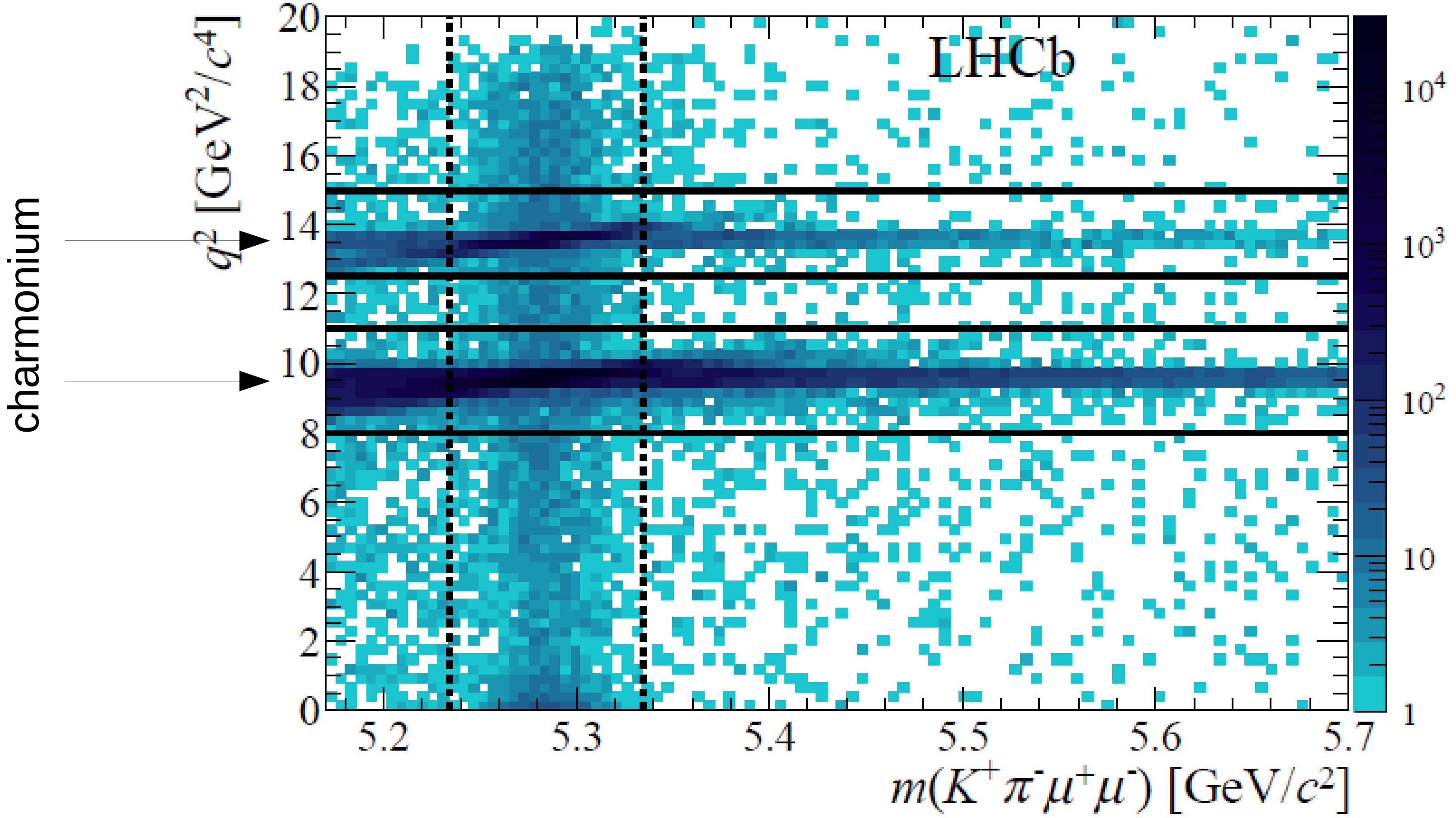
$B \to K^* \mu^+\mu^-$ EW penguin

- New particles may appear in the loop and give contribution not suppressed w.r.t. SM one
- Many observables: angular distributions, decay rates, asymmetries



Signal

- Peaking background from charmonium→ $\mu^-\mu^+$ resonances: veto using PID and kinematic variables
- Combinatorial background reduced using BDT
- $q^2=m^2_{\mu\mu}$



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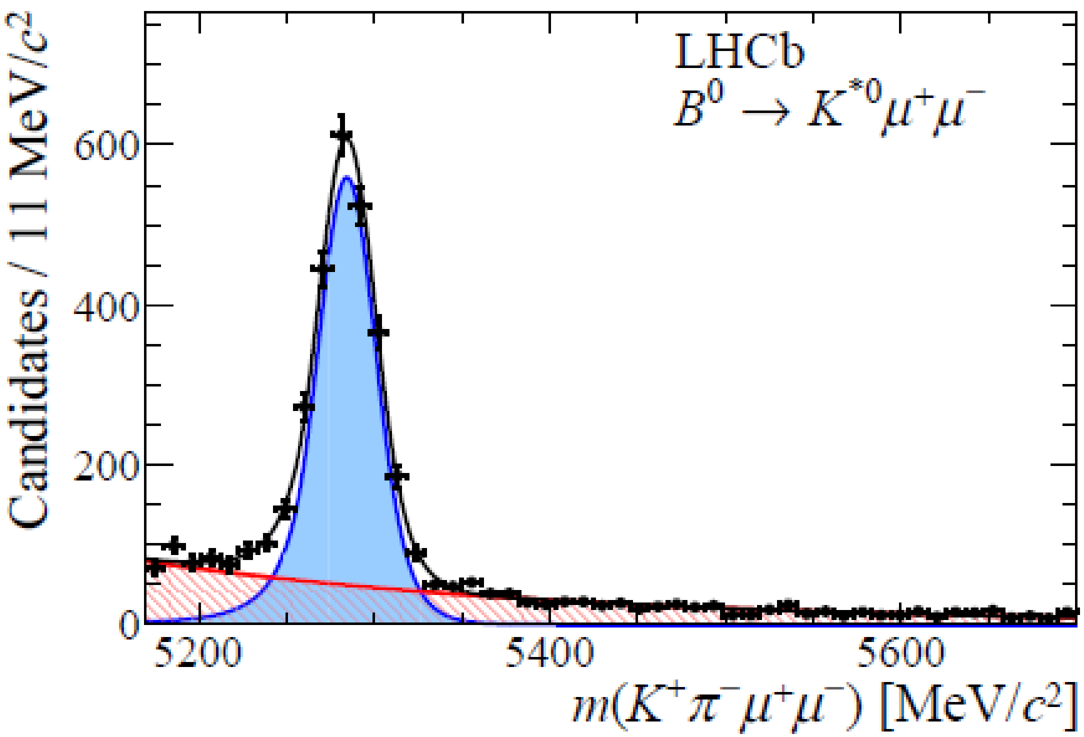


Angular variables

LHCB-PAPER-2015-051

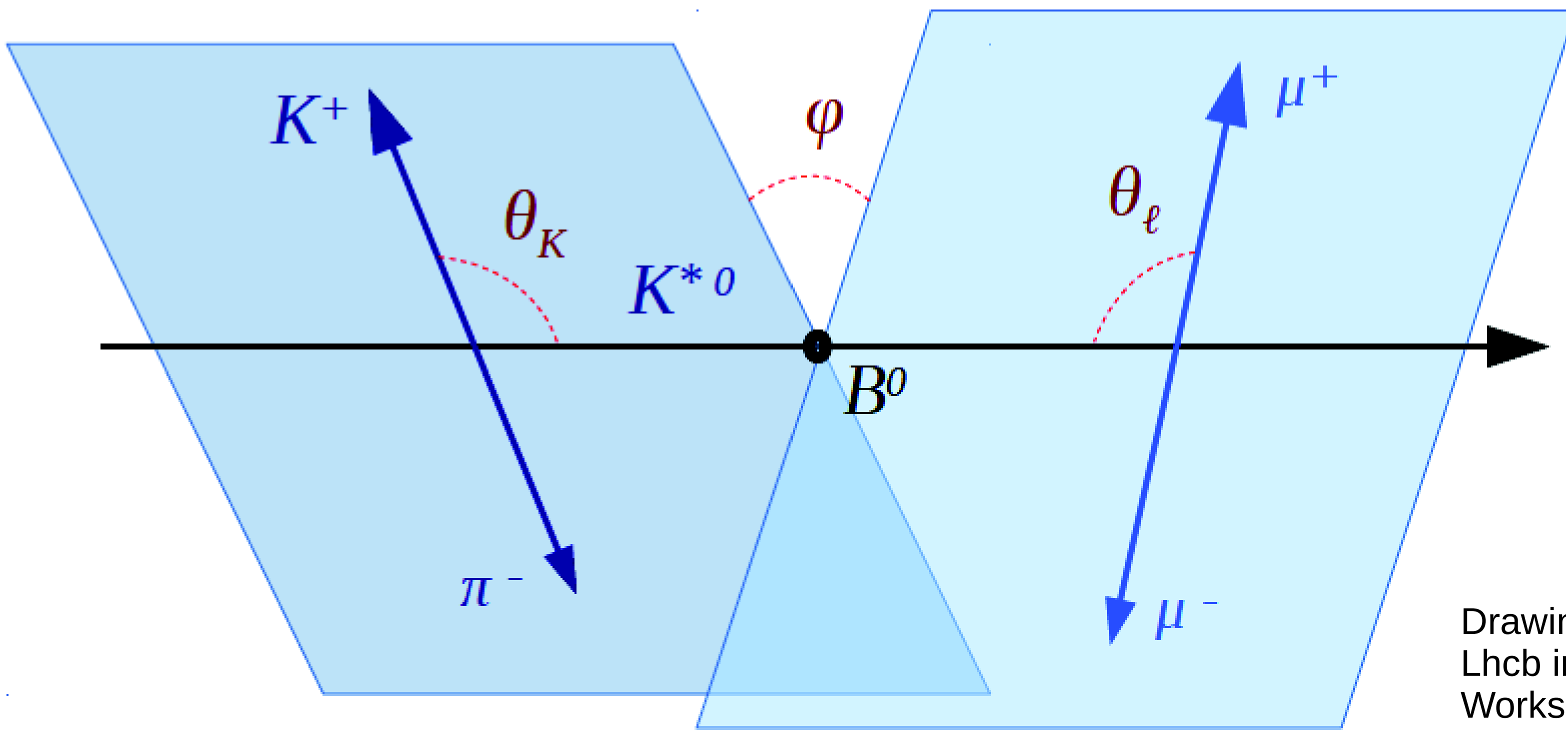
- System fully described by q² and three angles $\vec{\Omega} = (\cos\theta_l, \cos\theta_k, \phi)$

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_j I_j(q^2) f_j(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_j \bar{I}_j(q^2) f_j(\vec{\Omega})$$

$$S_j = (I_j + \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

$$A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$



Drawing by S.Cunliffe
Lhcb implications
Workshop 2015

Angular variables

LHCB-PAPER-2015-051

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$$A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

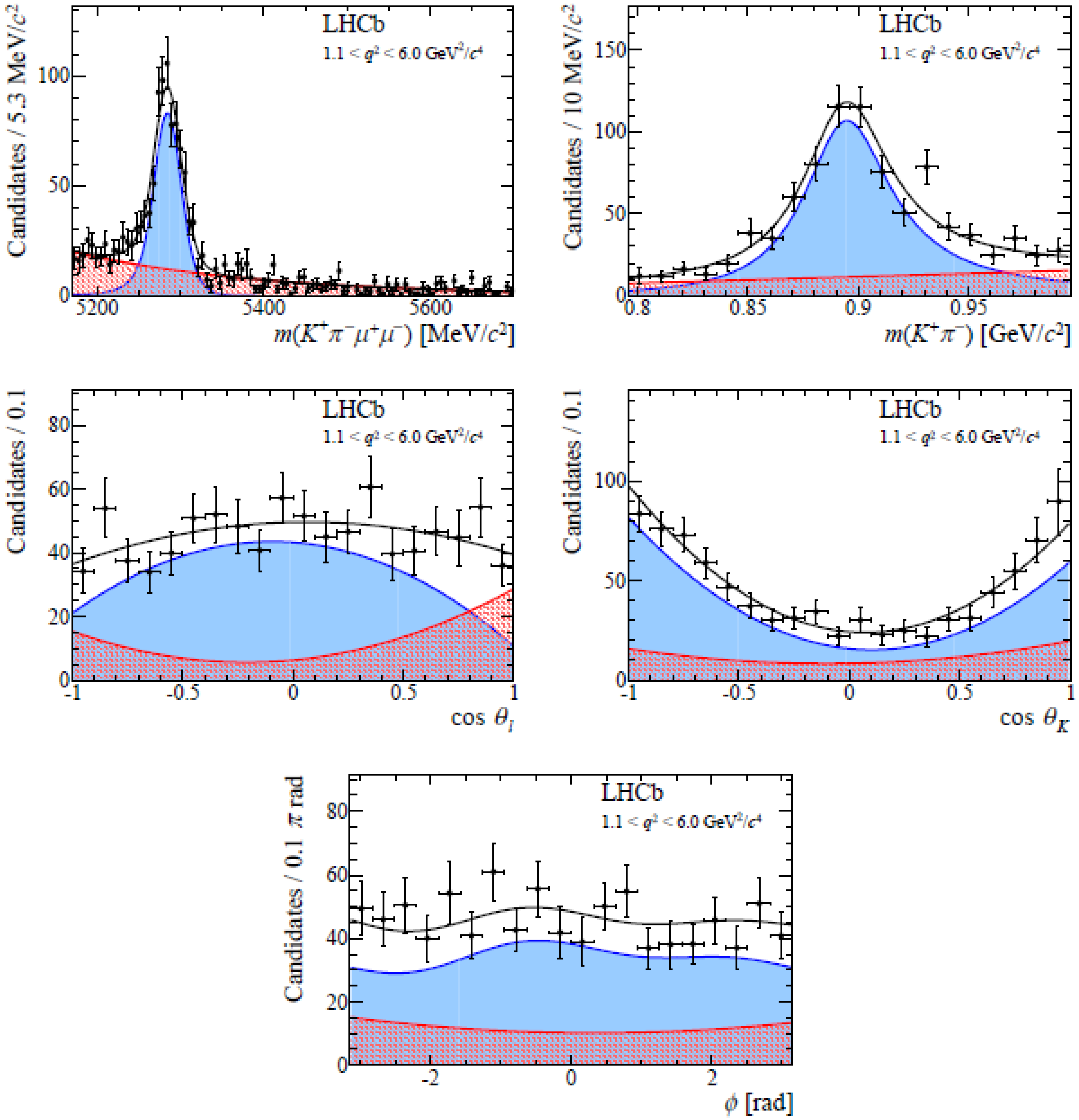
- Full set of Sj and Aj never measured before ⇐ New
- Clever combinations have reduced dependence on form factors

$$P'_{4,5} = S_{4,5} / \sqrt{F_L(1 - F_L)}$$

- Account for S-wave Kπ component which can help separate vector from scalar by fitting simultaneously the $m_{K\pi}$
- Correct for dependence of efficiency as a function of angles

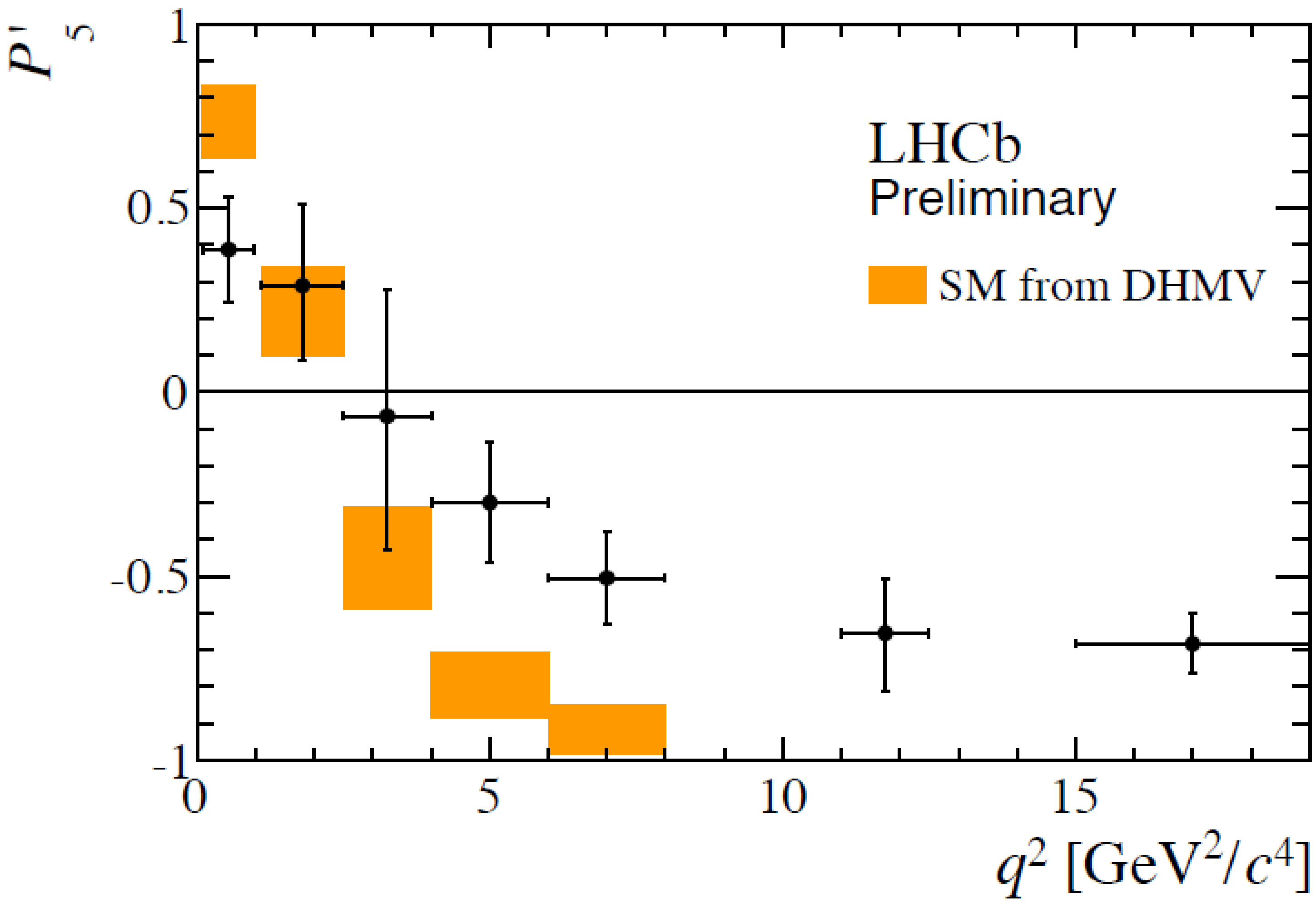
ML fit of angular distributions and masses

LHCB-PAPER-2015-051



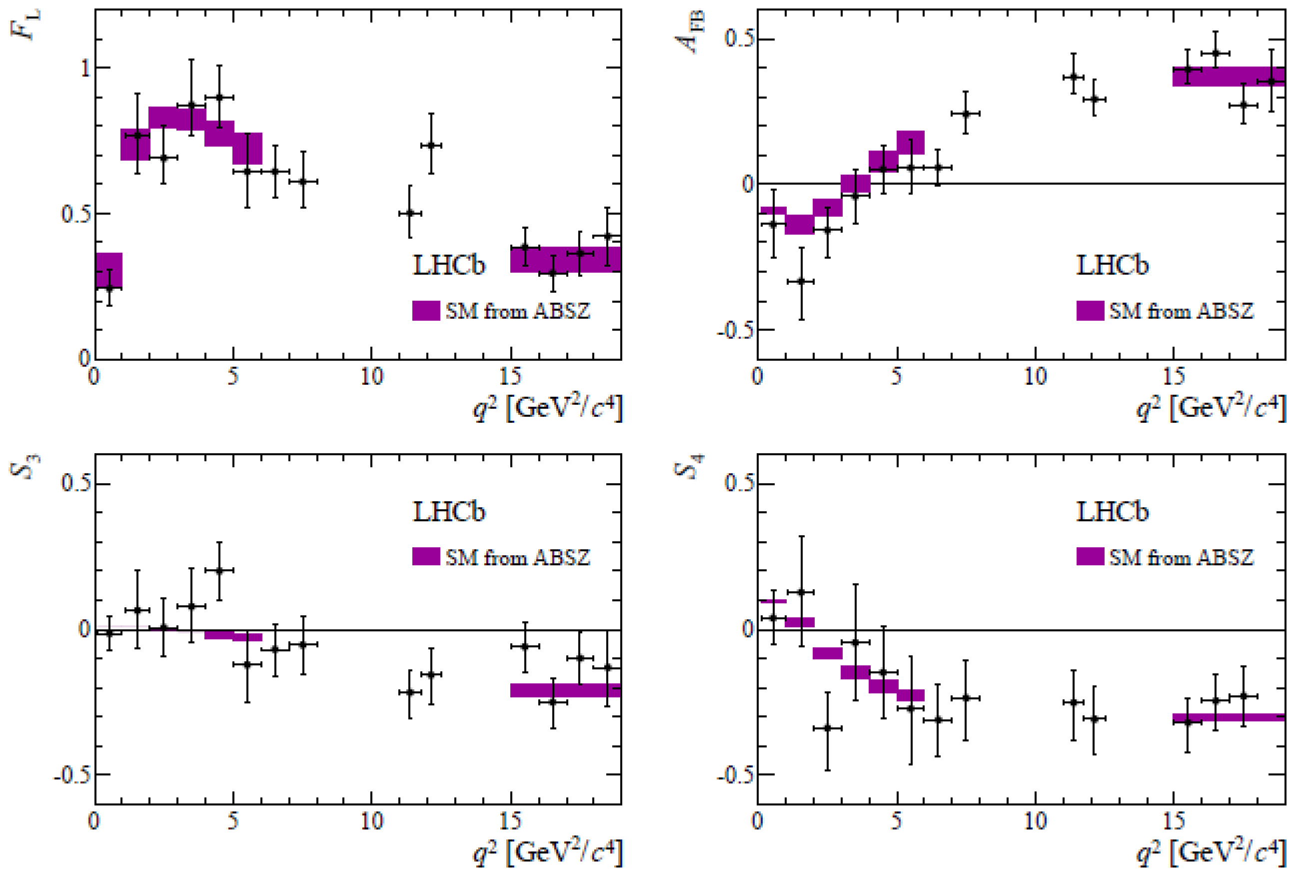
ML fit results

- Inconsistency with SM remains, the level of the inconsistency evaluated using the complete set of observables



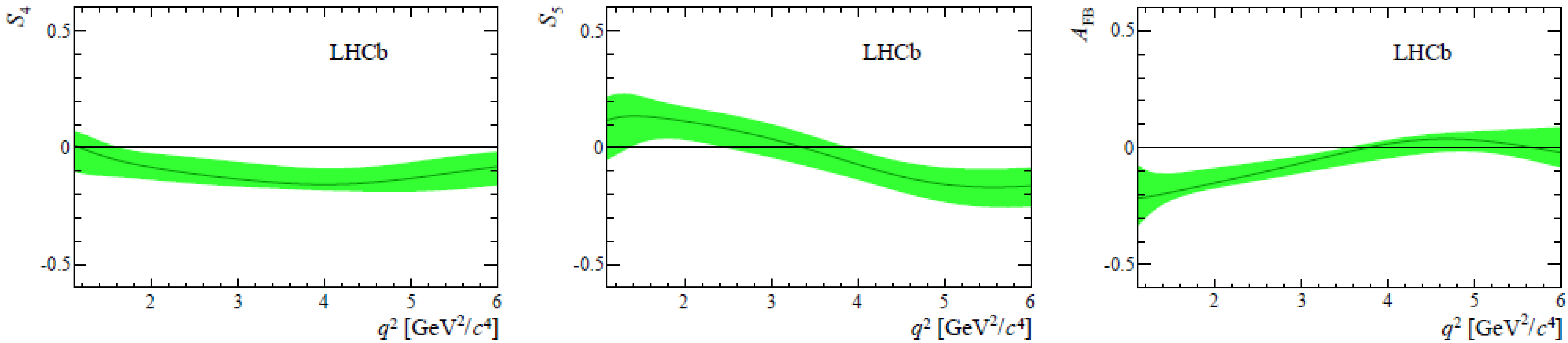
Moments

- Two other methods used to fit the parameters of the angular distributions
- Moments
  - Compute spherical moments of angular distribution and extract coefficients of spherical harmonics



Amplitudes

- Two other methods used to fit the parameters of the angular distributions
- Amplitues ⇦ New
  - Fit directly the amplitudes making the assumption $\mathcal{A}(q^2) = \alpha + \beta q^2 + \frac{\gamma}{q^2}$



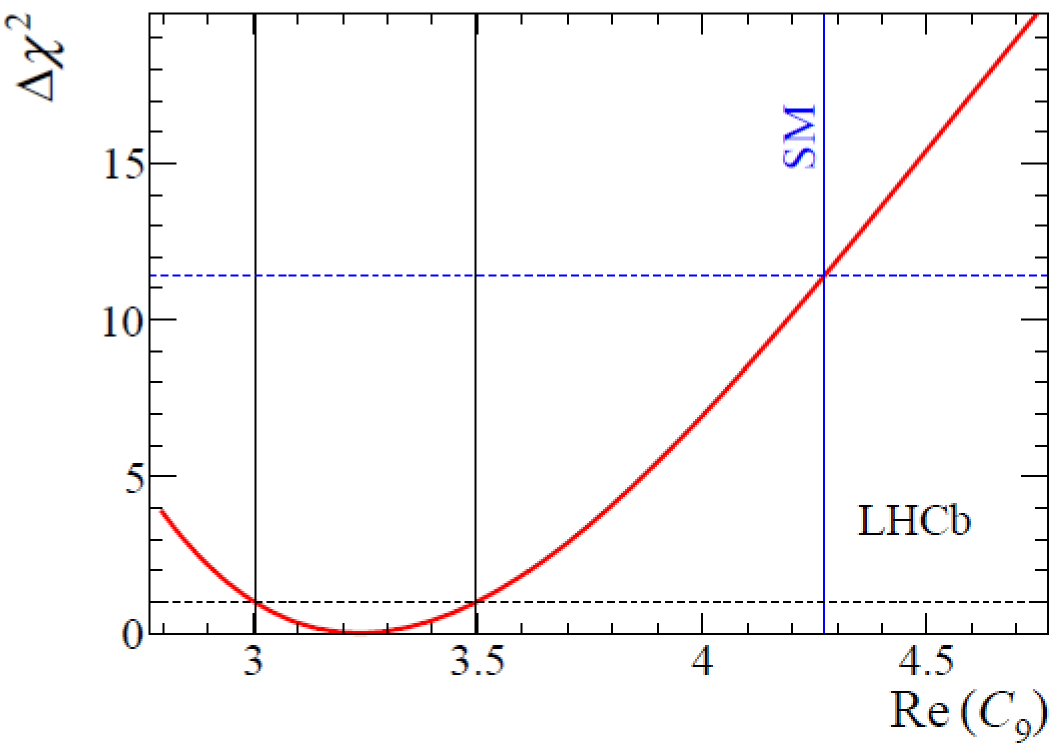
- Extract directly the zero crossing points of the observables

$$q_0^2(S_4) < 2.65\,\text{GeV}^2/c^4 \text{ at } 95\% \text{ confidence level (C.L.)},$$
$$q_0^2(S_5) \in [2.49, 3.95]\,\text{GeV}^2/c^4 \text{ at } 68\% \text{ C.L.},$$
$$q_0^2(A_{\rm FB}) \in [3.40, 4.87]\,\text{GeV}^2/c^4 \text{ at } 68\% \text{ C.L.}.$$

⇦ New

Compatibility with SM

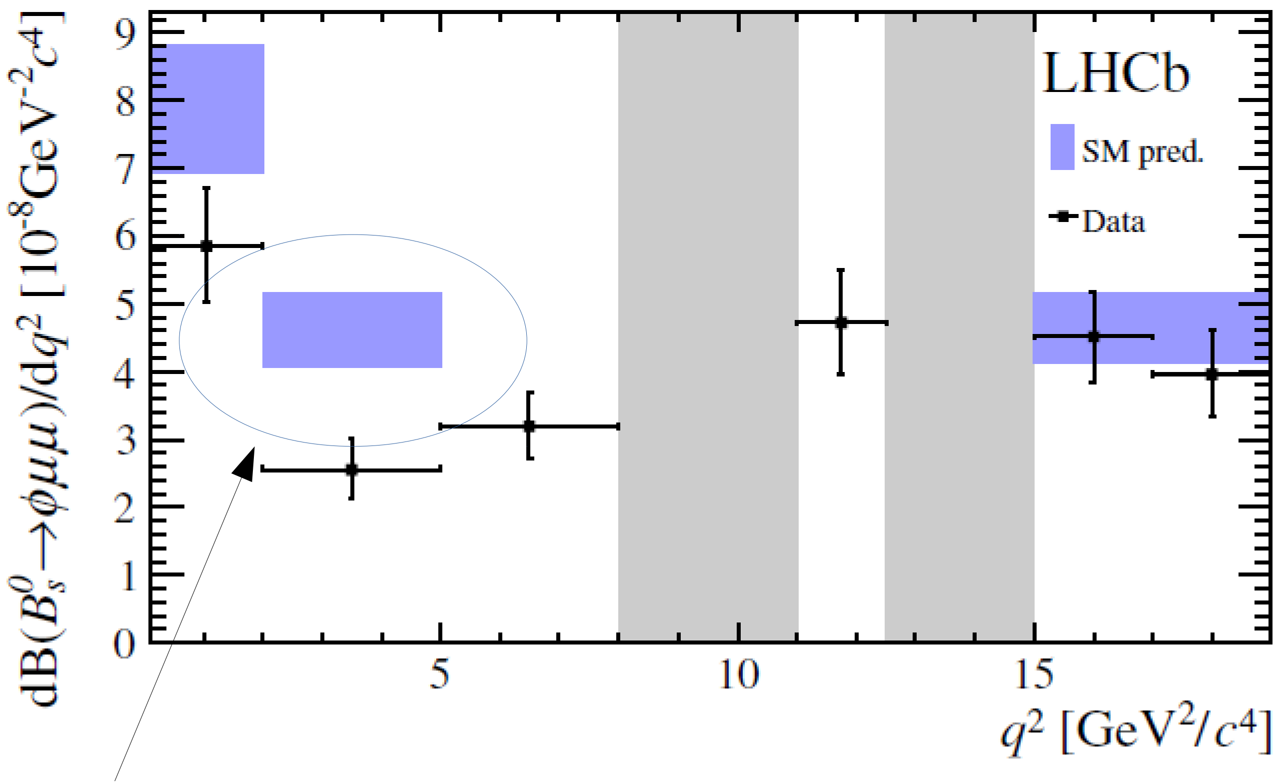
- A χ^2 fit for $Re(C_9)$ is performed to the CP-averaged angular observables F_L, A_{FB} and S3-S9 obtained from the likelihood fit to the data
- No additional effective couplings tested
- Compatibility with SM is 3.4 σ
- A fit to the moments gives consistent results but less precise



$B_s \to \phi\mu^+\mu^-$

- Differential branching fraction and full angular analysis

$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7},$$



3.3 σ inconsistency with SM

$B_s \to \phi\mu^+\mu^-$

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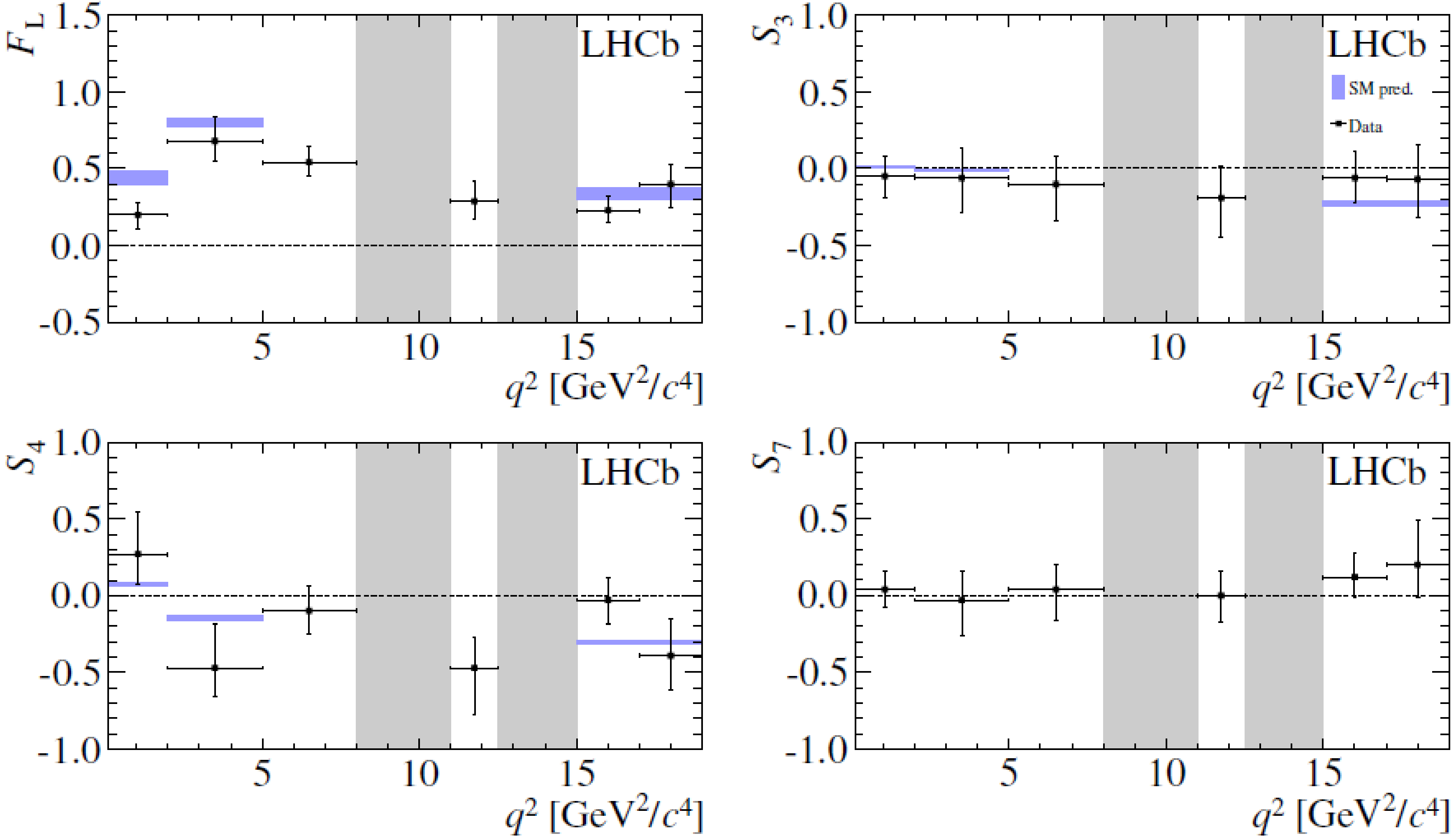
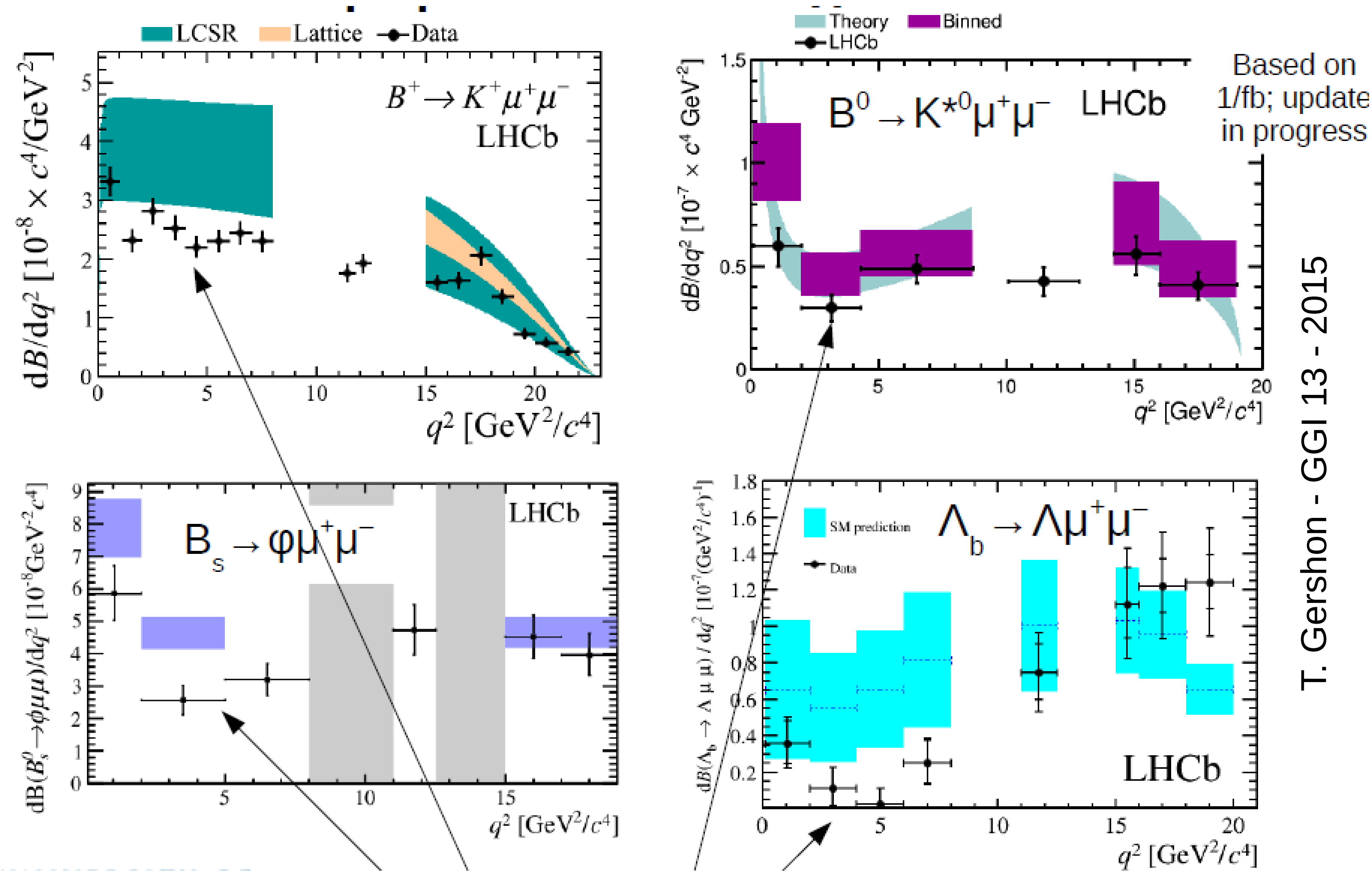


$b \to s\mu^+\mu^-$ brancing fractions



Common trend to be below SM prediction at low q^2

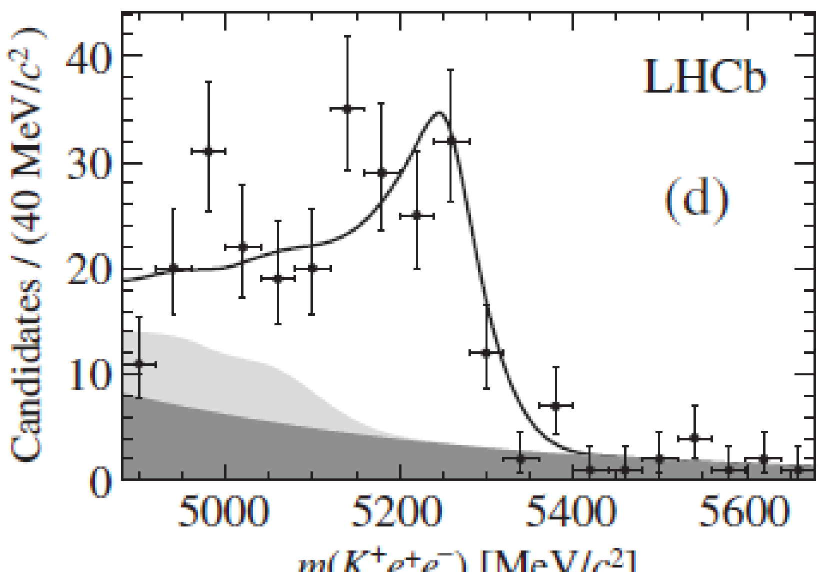
Lepton universality in $B^+ \to K^+ ll$

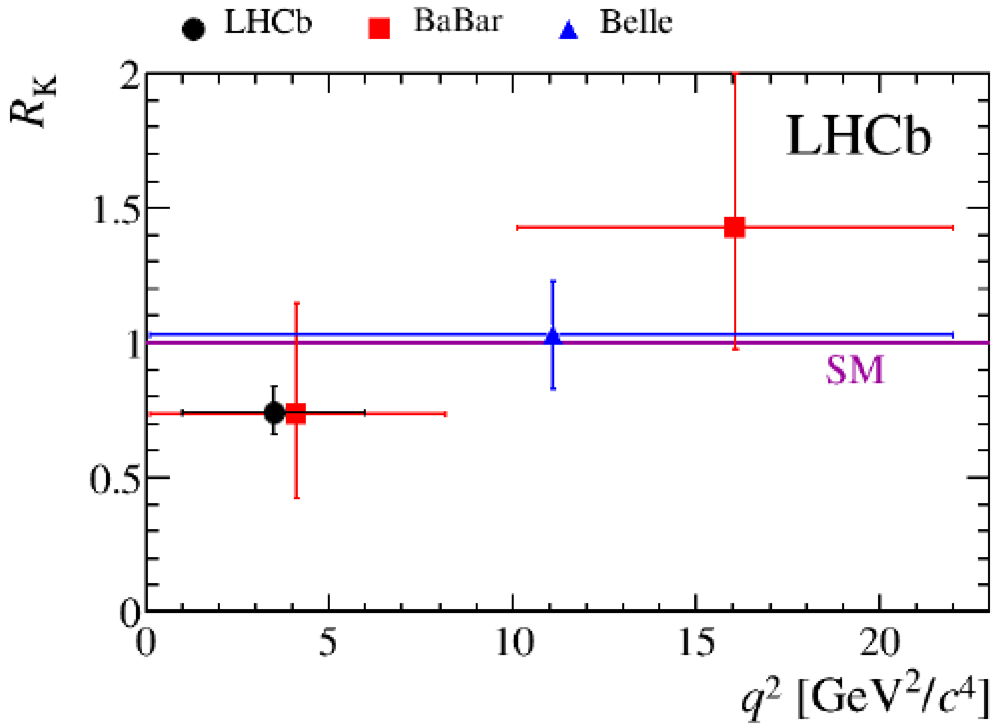
R_K in $B^+ \to K^+ ll$

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right) \times \left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right),$$

- Normalize the BF to the $B^+ \to K^+ J/\psi$ to cancel systematic effects mainly due to the different energy loss (see tail a low energy)
- R_K measure in $1<q^2<6$ GeV^2/c^4 is 3σ from SM prediction

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst}).$$





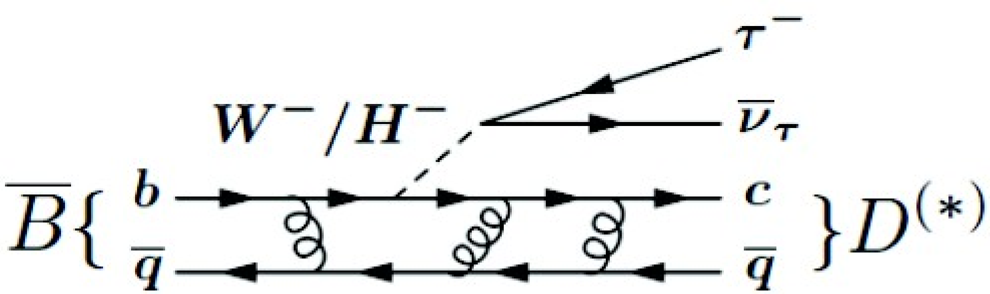
Rare decays prospects

- Moving away from discovery and towards precision era
  - for $B_s \rightarrow \mu\mu$
- Full angular analysis of $b \rightarrow s\mu\mu$ shows several interesting 3σ BSM effects
  - Ongoing effort to control hadronic uncertainties
- More decay modes to be studied to explore the full potential
- Combine all available informations with global fits to effective couplings (Wilson coefficients)
- $b \rightarrow d\mu\mu$ is becoming also interesting

$B \rightarrow D^{(*)}\tau\nu$

New physics in semileptonic decay channels

- Semileptonic decay channels are used to extract CKM matrix elements with good precision because of the factorization of the hadronic leptonic current
- In addition charged lepton universality assures that decays to e, μ and τ should differ only in phase space and helicity suppression
- Many extensions of the SM instead predict a difference between lepton flavors, for instance a charged Higgs type II THDM would couple predominantly to decays into τ leptons

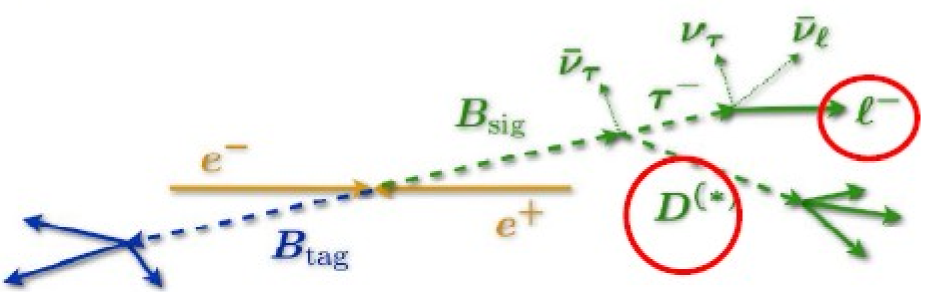


RD e RD* in $B \to D^{(*)}\tau\nu$: BaBar

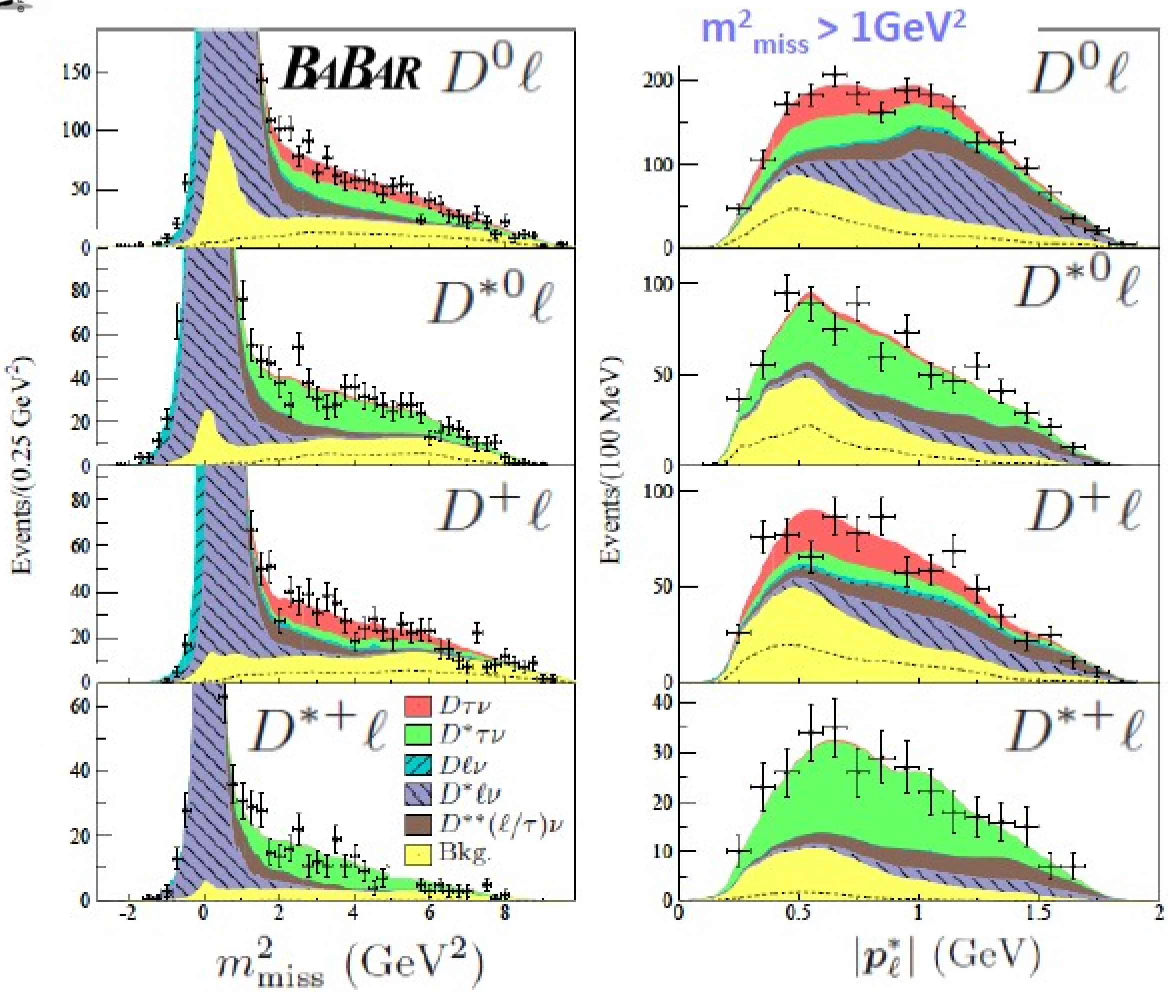
- Can access both RD and RD*
- Signal reconstructed in $\tau \to l\bar{\nu}_l\nu_\tau$
- Normalization has same topology as signal
  - Is also largest background
- Uncertainties cancel in the ratio
  - $D^{(*)}$reconstruction, PID, Tracking
  - |Vcb|, form factors
- B_{tag} fully reconstructed into hadrons
  - Allows to reconstruct charge and momentum of signal B
- Everything else should come from the signal B
  - Not possible at hadron colliders

$$R(D) = \frac{BF(B \to D\,\tau\,\nu_\tau)}{BF(B \to D\,l\,\nu_l)_{l=e,\mu}}$$

$$R(D^*) = \frac{BF(B \to D^*\,\tau\,\nu_\tau)}{BF(B \to D^*\,l\,\nu_l)_{l=e,\mu}}$$

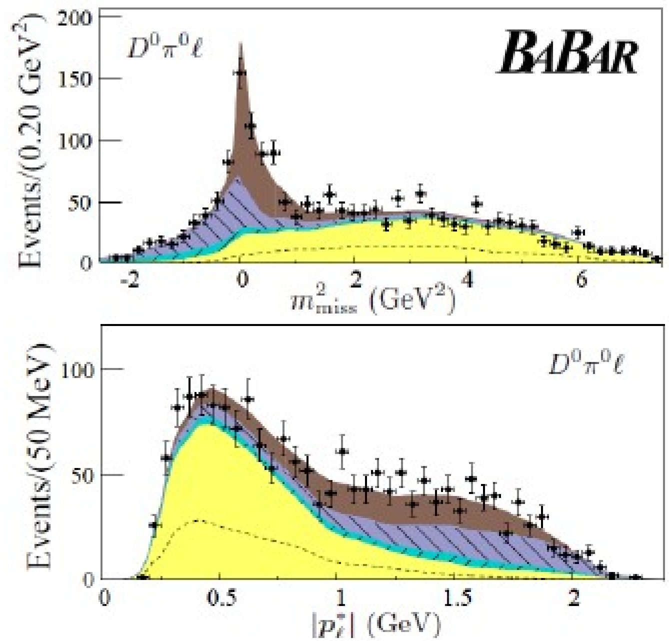


RD e RD* BaBar results



$$m^2_{miss} = (P_{e^+e^-} - P_{Btag} - P_l - P_{D^{(*)}})^2$$

- Main sist. related to D** bkg fixed on control sample



- 4 signal samples (D°,D⁺,D*°,D*⁺)lν
- 4 control samples (D°,D⁺,D*°,D*⁺)π°lν to derive D** lν background.

Isospin constrained results:

$$R(D) = 0.440 \pm 0.058 \pm 0.042$$

$$R(D*) = 0.332 \pm 0.024 \pm 0.018$$

Significance >8 σ

BaBar implications for a Type II 2HDM

PRL109,101802(2012)
PRD88,072012(2013)

- Type II 2HDM can describe the higgs sector in the MSSM
- Differential decay rates

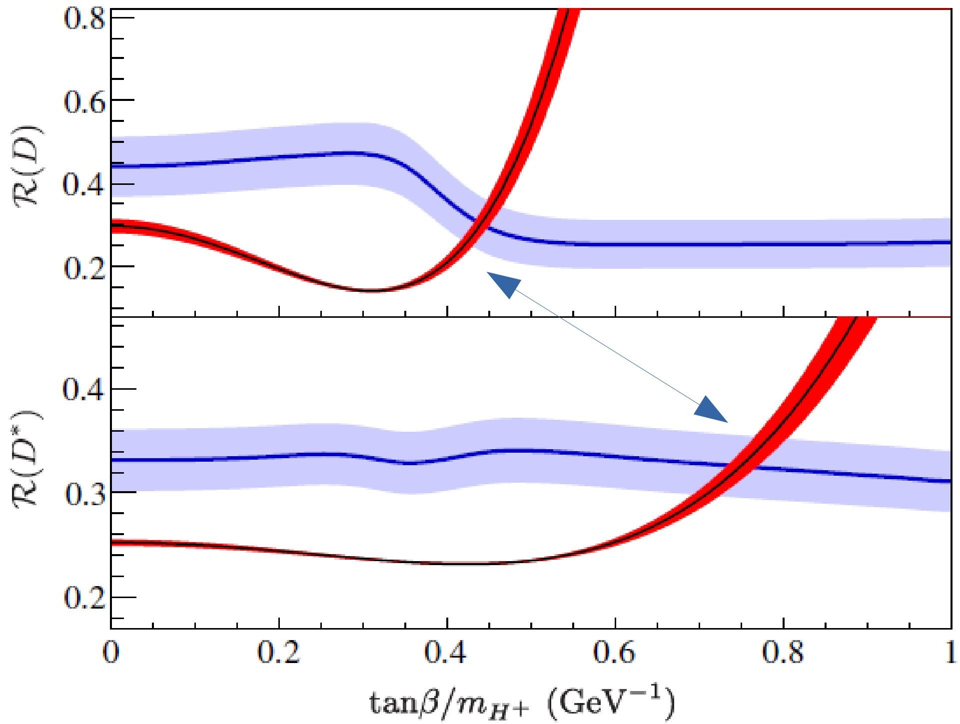
$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\boldsymbol{p}^*_{D^{(*)}}| q^2}{96\pi^3 m_B^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2 \Big[(|H_+|^2 + |H_-|^2 + |H_0|^2)\left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2}|H_s|^2\Big],$$

are modified by a charged higgs

$$H_s^{\rm 2HDM} \approx H_s^{\rm SM} \times \left(1 + (S_R \pm S_L)\frac{q^2}{m_\tau(m_b \mp m_c)}\right).$$

in a q^2 dependent manner

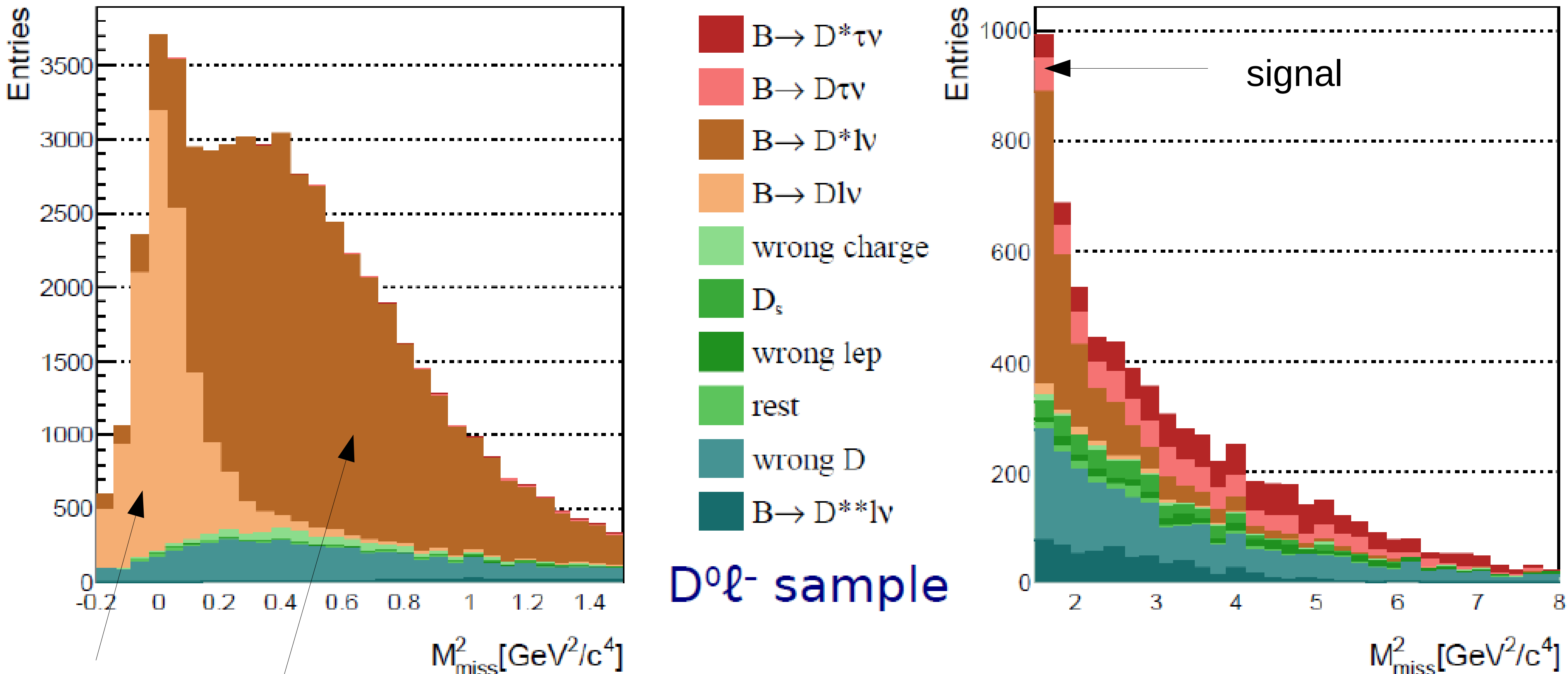
- Consider different values of $\tan\beta/m_{H+}$: generate new signal shapes and measure $R(D^{(*)})$, compare with SM prediction
- Result is incompatible with 2HDM



RD* in B→D$^{(*)}\tau\nu$: Belle

arXiv:1507.03233

- New result this summer with more sophisticated analysis
- Divide the sample in low m_{miss} to fit normalization sample and cross feed and high m_{miss} to extract signal from NN



normalization

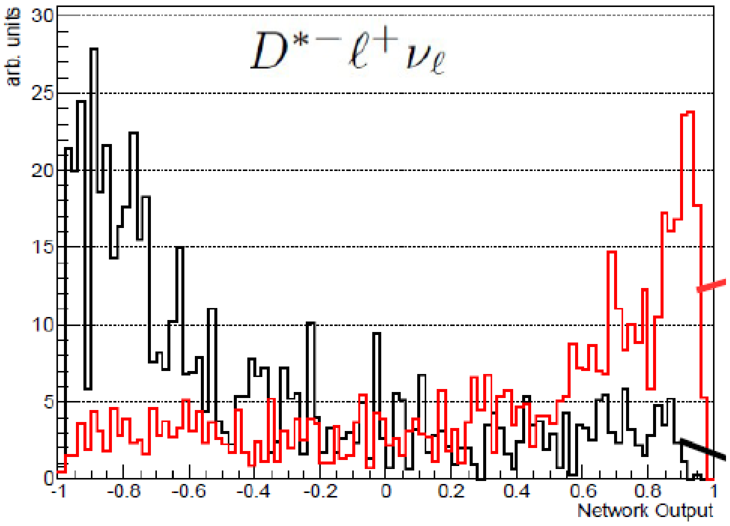
Cross feed

o) Signal cross feed, wrong charge and combinatorial
  - constrained or measured from sidebands
o) D** yield free parameter of the fit

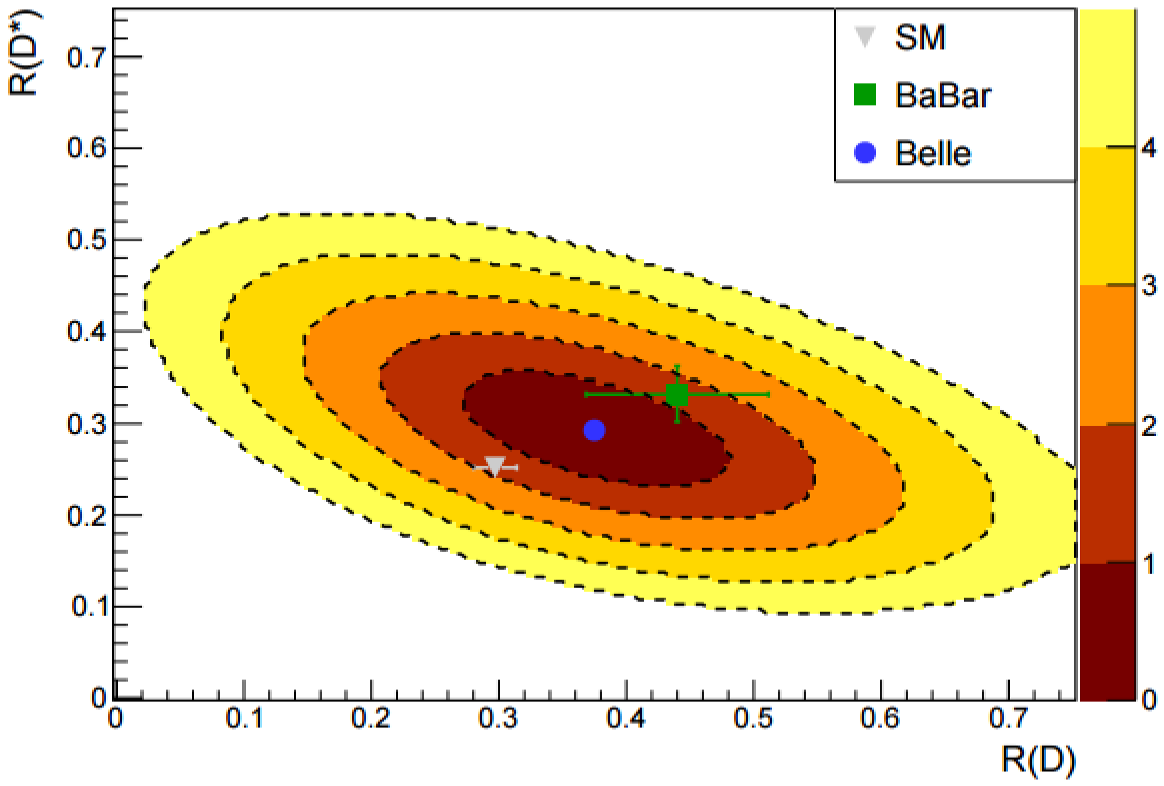
RD* in $B \to D^{(*)}\tau\nu$: Belle

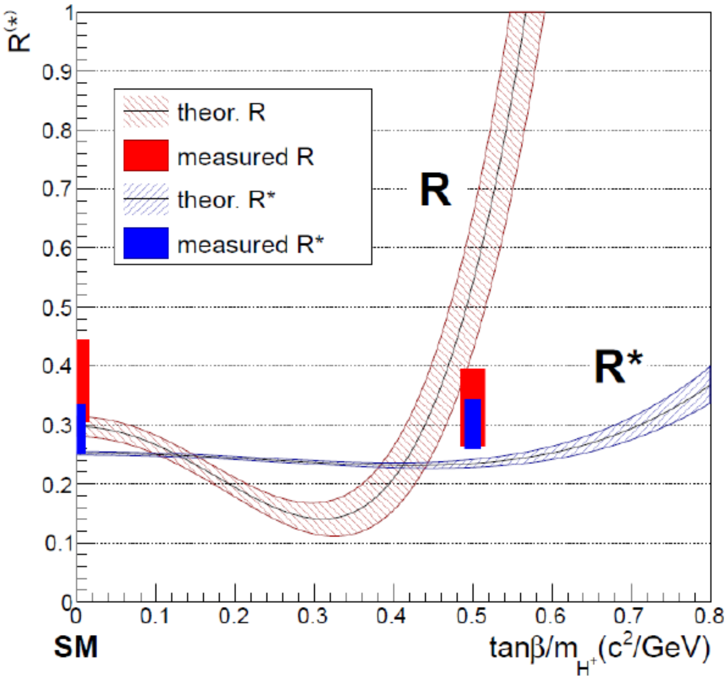
- Result is compatible with both BaBar and SM
- Repeat analysis for 2HDM type II with $\tan\beta/m_{H+} = 0.5 c^2/GeV$

Neural network signal and background



T.Kuhr FPCP 2015

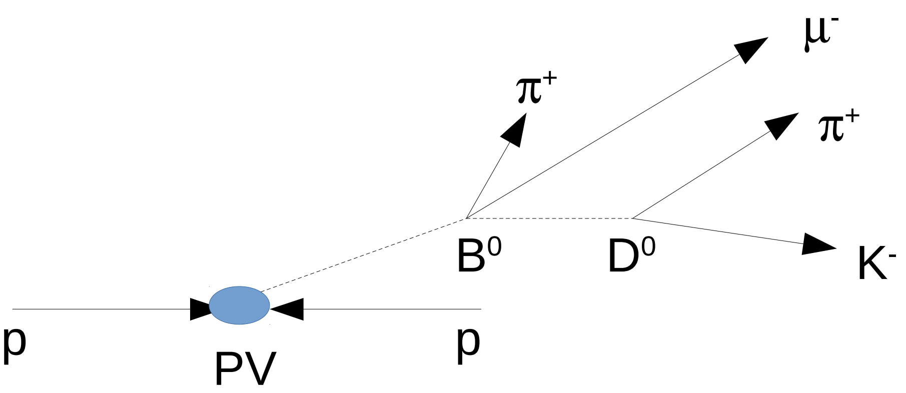




RD* in B→D*τν: LHCb Phys.Rev.Lett. 115 (2015) 11

- Trigger on the charm component
- Selection of signal exploiting excellent secondary vertex reconstruction and muon identification
- τ reconstruction efficiency 77.6% of the μ normalization mode
- B meson rest frame is not known: determine B direction from PV and B vertex
  - Approximate B boost along the beam direction with boost of the visible system

$$p_z(B^0) = \frac{m_{B^0}}{m(D^*\mu)} p_z(D^*\mu)$$

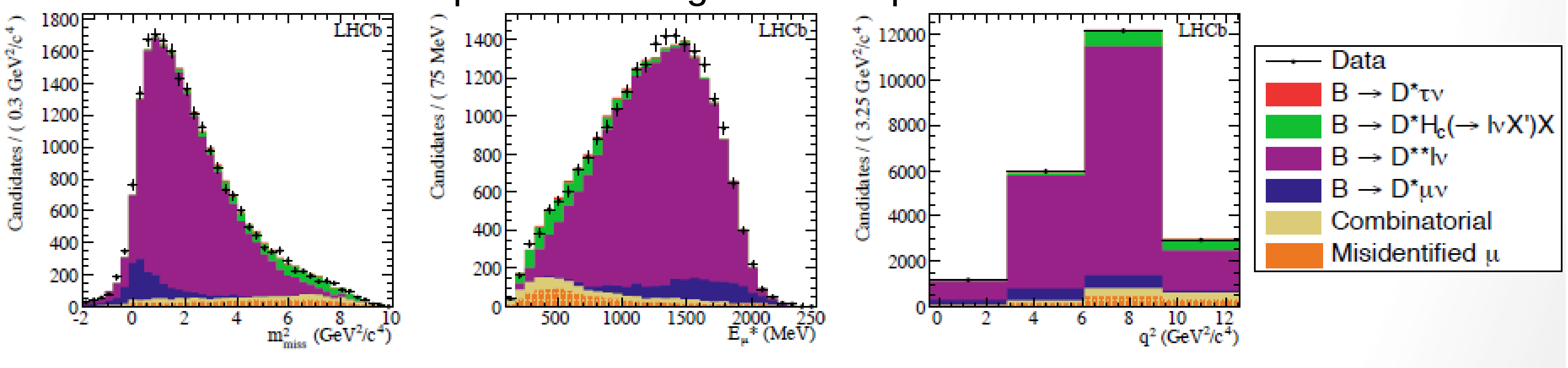


Backgrounds and signal fit

Phys.Rev.Lett. 115 (2015) 11

- ML fit to m^2_{miss}, E_μ, q^2 distributions with 3D templates representing signal, normalization and background sources
- Largest backgrounds from partially reconstructed semileptonic decays
  - $B \to D^{**} \mu^- \nu$
    - Known resonances modeled using template from MC, validated on $D^{*+}\mu^-\pi^+$
    - Higher charm states models using ISGW2

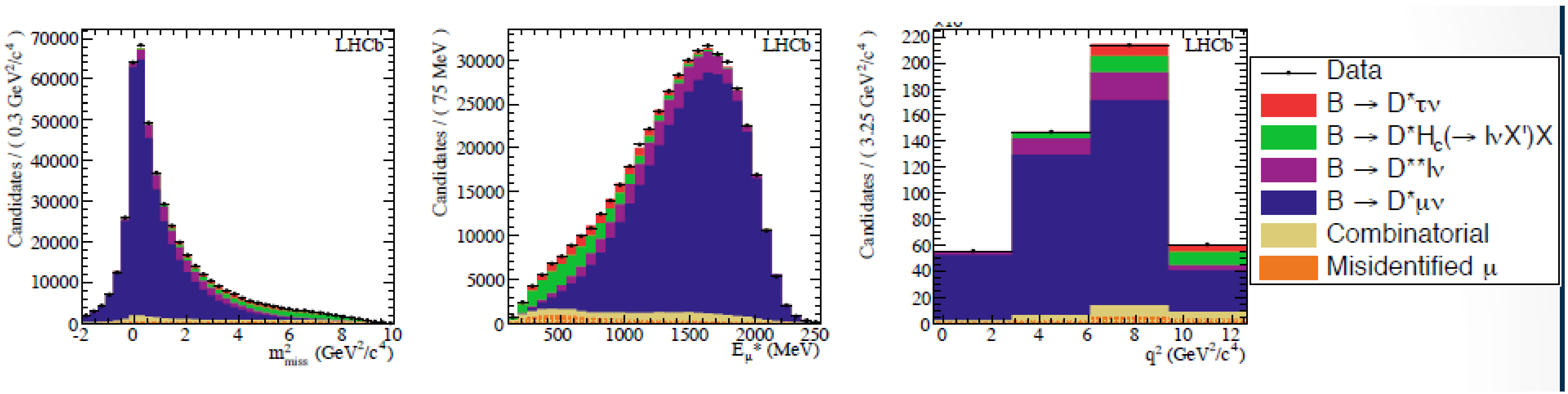
Fit to the control sample with background templates



Signal fit result

Phys.Rev.Lett. 115 (2015) 11

- Semileptonic decays of a second charm hadron in the event represent a significant source of background
- Empirical corrections to the templates extracted from fits to $D^{*-}\mu^{-}K^{\pm}$ control sample
- Muon misidentification and combinatorial also modeled with control samples



Fit in 4 q² bins

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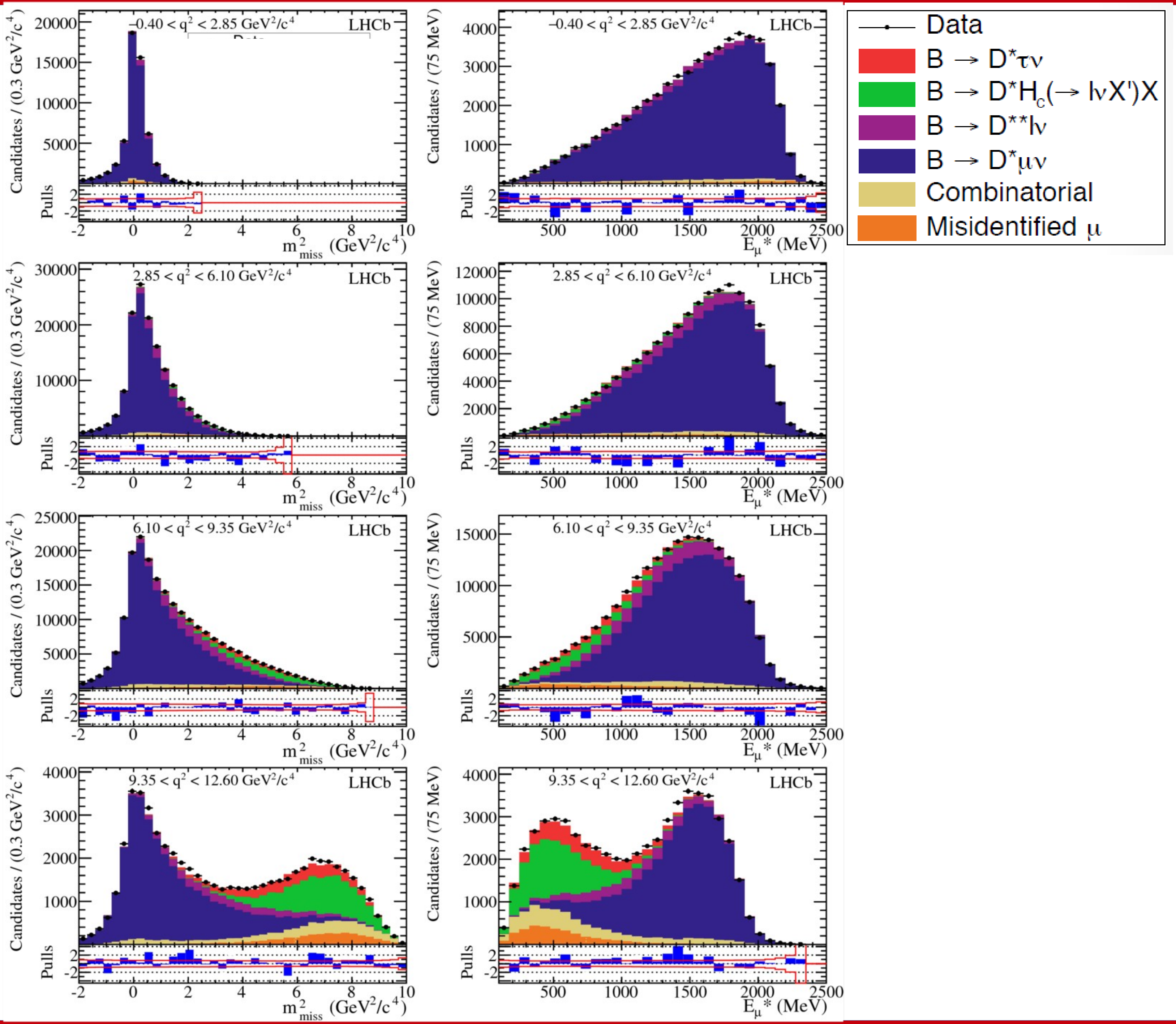
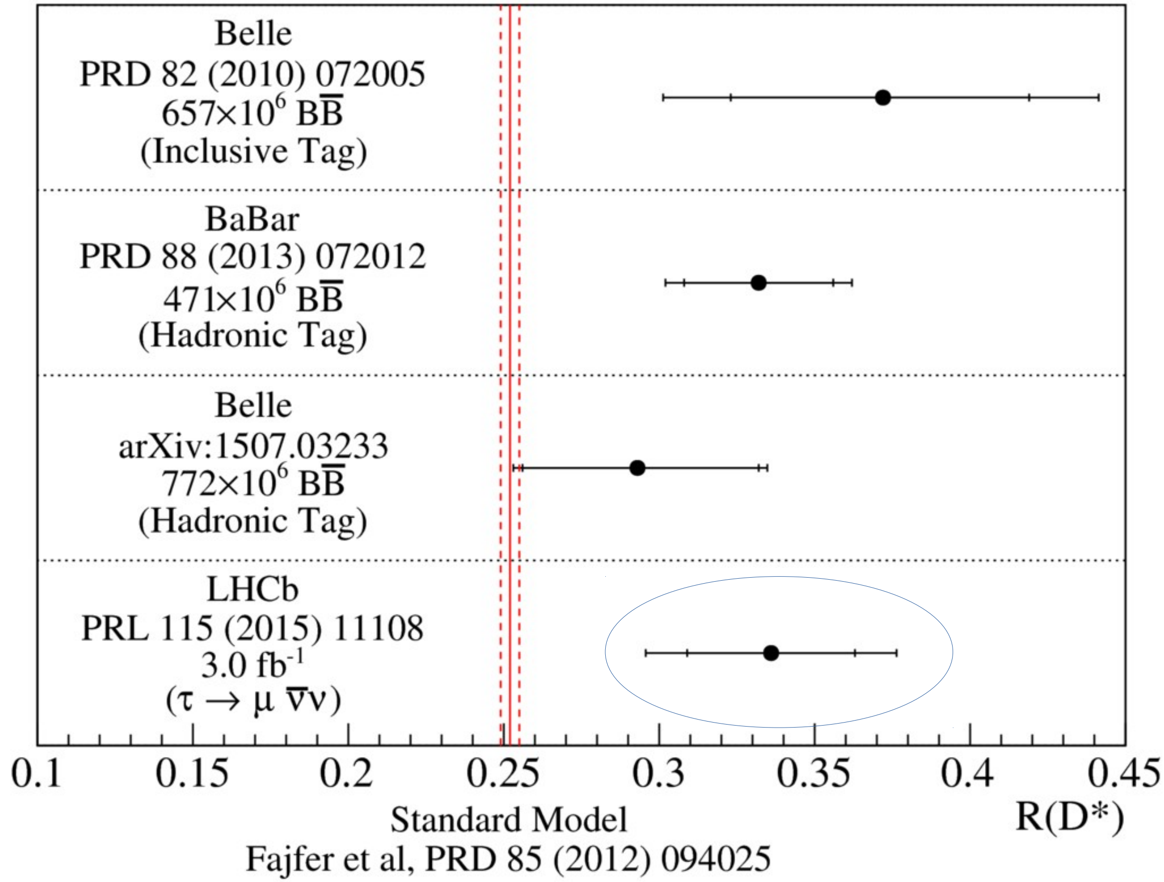


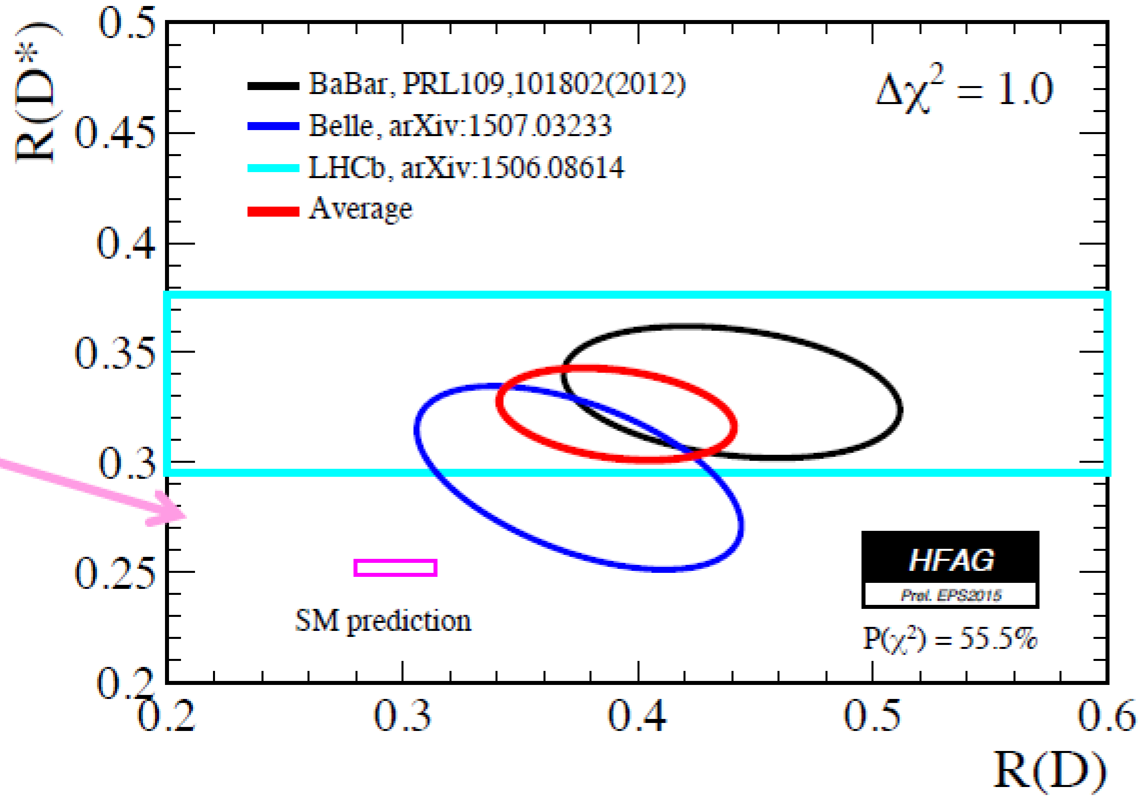
Result

- $R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$
- In agreement with previous measurement
- 2.1 σ higher than SM



 Phys.Rev.Lett. 115 (2015) 11

M. Calvi
EPS 2015



SM predictions

R(D*)=0.252 ±0.003

*PRD **85** (2012) 094025*

R(D) =0.297 ±0.017

*PRD **78** (2008) 014003*

HFAG average

$R(D^*) = 0.322 \pm 0.018 \pm 0.012$

$R(D) = 0.391 \pm 0.041 \pm 0.028$

Corr (D,D*)= − 0.29

- Difference with the SM predictions at 3.9 σ level.

Lepton Universality prospects

- Expand the physics program searching for other modes
  - Measure a ration similar to Rk($B \to K\mu^+\mu^-/B \to K e^+e^-$) in decays to K^*,ϕ,Λ,etc
  - Expand $D\tau\nu$ to D^*,D_s, Λ_c
  - Search for lepton number violation $B \to \tau\nu$, $K\tau\nu$, $Ke\nu$ etc.
    - Mostly Belle-II

Conclusions

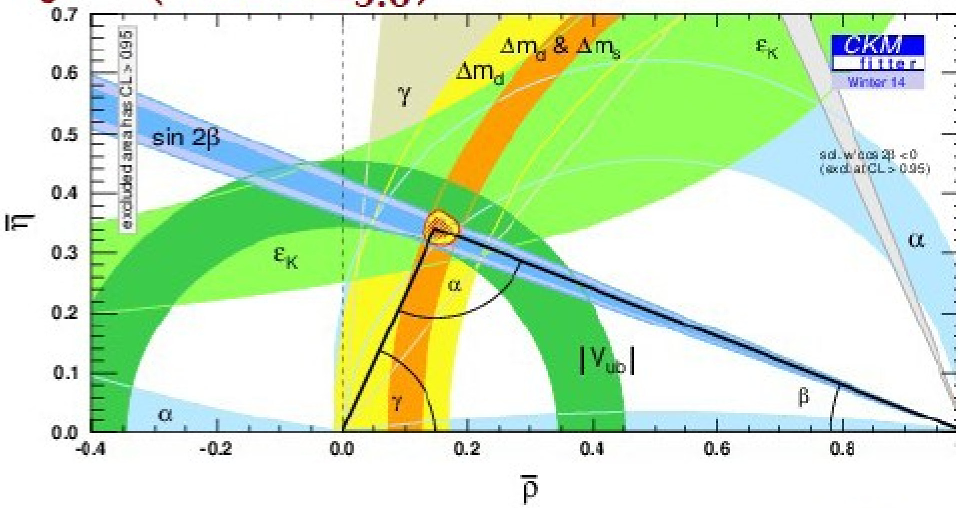
- Many recent exciting results
- Sides and Angles
  - Reached high precision and consistency
  - There is margin to improve sensitivity on both β and γ, $|Vub/Vcb|$, Δm_d, Δm_s with more statistics (Belle II, LHCb upgrade)
- Rare decays
  - Hints of deviations fromSM pointing in the same direction?
  - Is there a way to explain the observed pattern of deviations
- Lepton universality
  - Inconsistencies with 2HDM Type II confirmed
  - measurements pointing toward a bigger coupling to taus and electrons w.r.t. muons
    - puzzling
  - Need to improve experimental sensitivity: more decay channels and more data

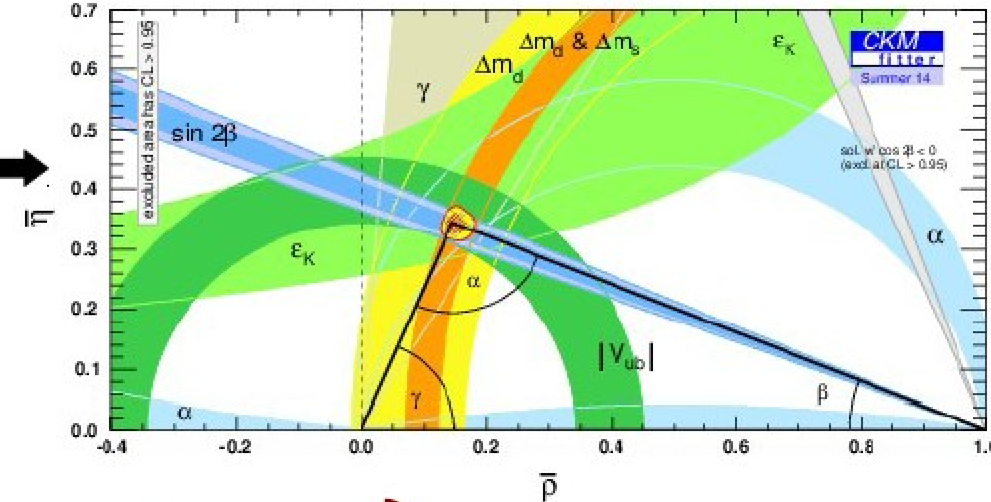
Backup

γ determination

Trablesi, FPCP 2015

$\gamma = (70.0\ ^{+7.7}_{-9.0})^\circ$





mostly from charged $B \to D^{(*)}K$:

$\gamma_{BaBar} = (70 \pm 18)^\circ$

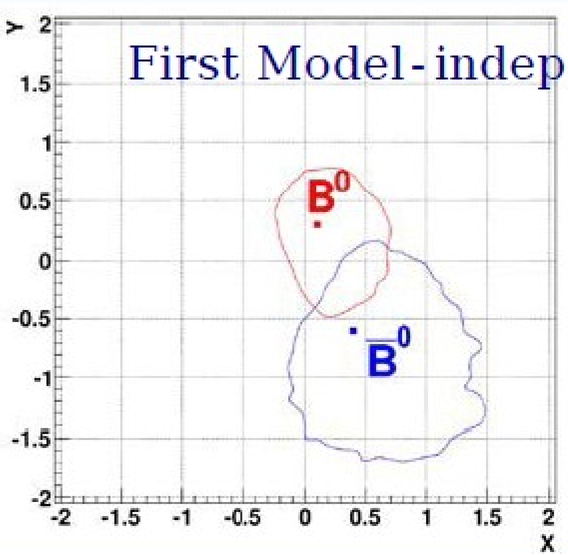
$\gamma_{Belle} = (73\ ^{+13}_{-15})^\circ$

$\gamma_{LHCb} = (75 \pm 9)^\circ$

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

$r_B = 0.0970 \pm 0.0063$

from neutral $B \to DK^*$: [Markus Rohrken]



First Model-independent GGSZ by Belle [arXiv:1505.07550]

$$r_S^2 = \frac{\int A^2_{b\to u}(p)dp}{\int A^2_{b\to c}(p)dp}$$

$r_S < 0.87$ at 68% CL

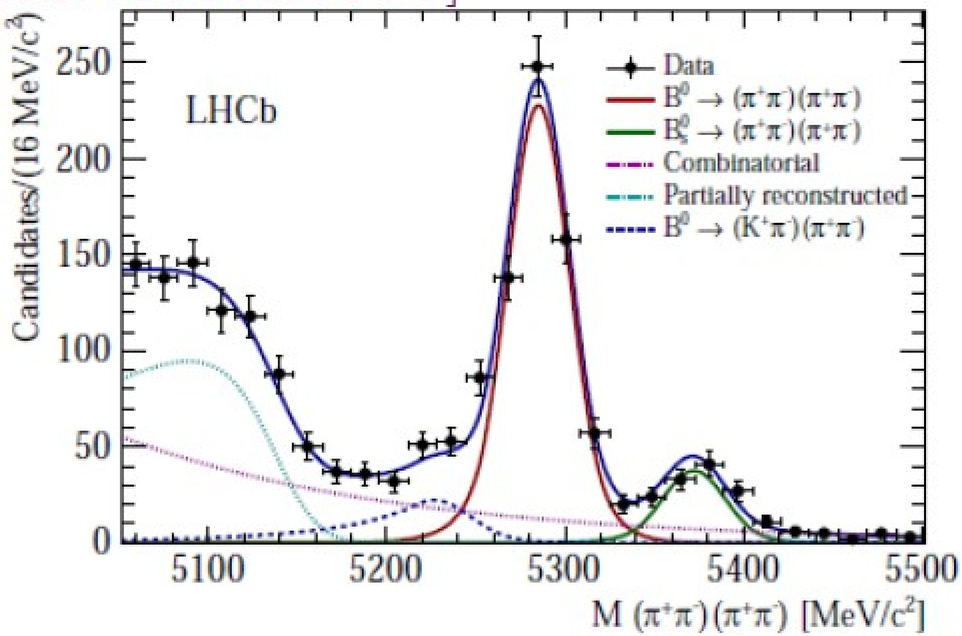
GLW+ADS by LHCb [arXiv:1407.8136]

$r_S = 0.236\ ^{+0.043}_{-0.052}$

$B\to\rho^0\rho^0$ and α determination

Trablesi, FPCP 2015

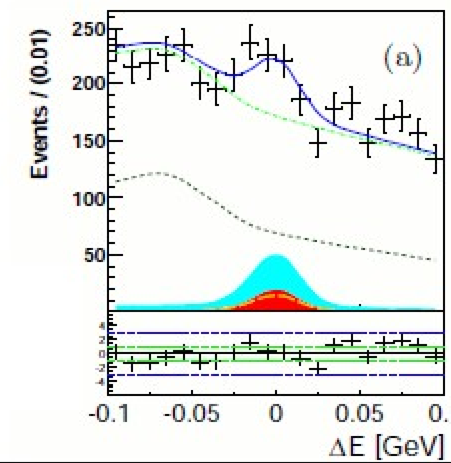
[arXiv:1503.07770]



BR of $B\to\rho^0\rho^0$

[PRD 89 (2014) 072008]

772M $B\bar{B}$



Decay mode	Signal yields 2011	Signal yields 2012
$B^0\to(\pi^+\pi^-)(\pi^+\pi^-)$	$185\pm15\pm4$	$449\pm24\pm\ 7$
$B^0\to(K^+\pi^-)(\pi^+\pi^-)$	$1610\pm42\pm5$	$3478\pm62\pm10$
$B^0\to(K^+K^-)(K^+\pi^-)$	$1513\pm40\pm8$	$3602\pm62\pm10$
$B_s^0\to(\pi^+\pi^-)(\pi^+\pi^-)$	$30\pm\ 7\pm1$	$71\pm11\pm\ 1$
$B_s^0\to(K^-\pi^+)(\pi^+\pi^-)$	$40\pm10\pm3$	$96\pm14\pm\ 6$
$B_s^0\to(K^+K^-)(K^-\pi^+)$	$42\pm10\pm3$	$66\pm13\pm\ 4$

$\Rightarrow$ 600 signal $4\pi^\pm$ events

$\mathcal{B}(B\to\rho^0\rho^0) = (0.94\pm0.17\pm0.09\pm0.06)\times10^{-6}$

$f_L = 0.745\ ^{+0.048}_{-0.058}\pm0.034$

angular analysis