CP violation in charged current decays

Abhijit Mathad, CERN

Challenges in Semileptonic B Decays

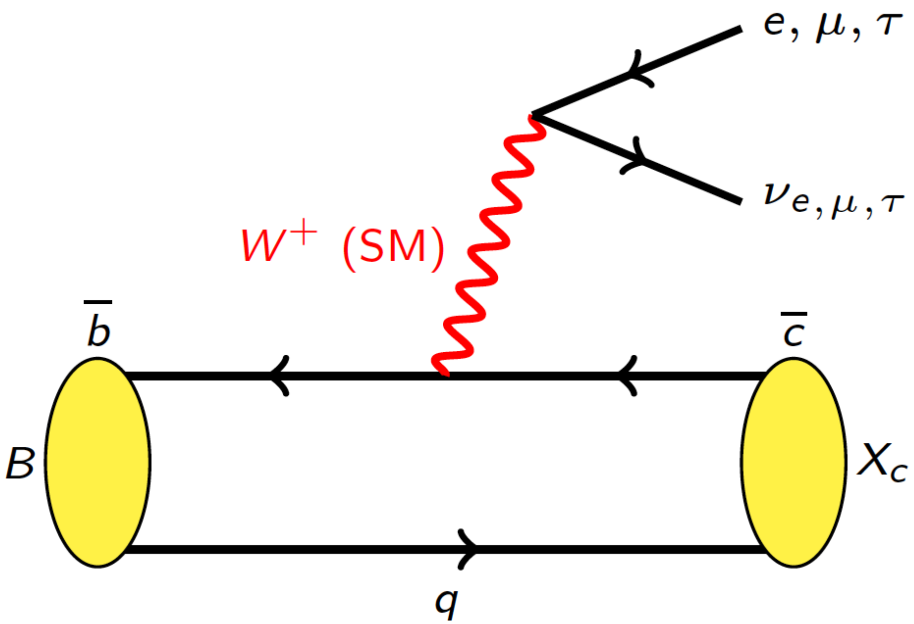
Vienna, Austria

Road most travelled (to new physics)

Vub, Vcb, LFU and angular analysis.

Road most travelled : The good

Abundant signal allowing
for high precision.

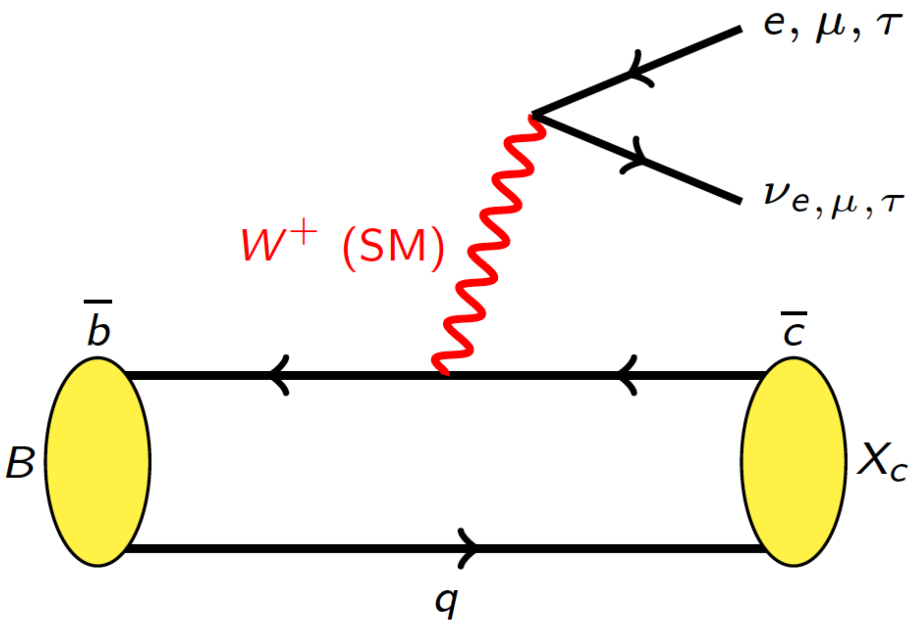


Good control over
theoretical uncertainties.

Road most travelled : The good, the bad

Abundant signal allowing for high precision.

Missing neutrinos



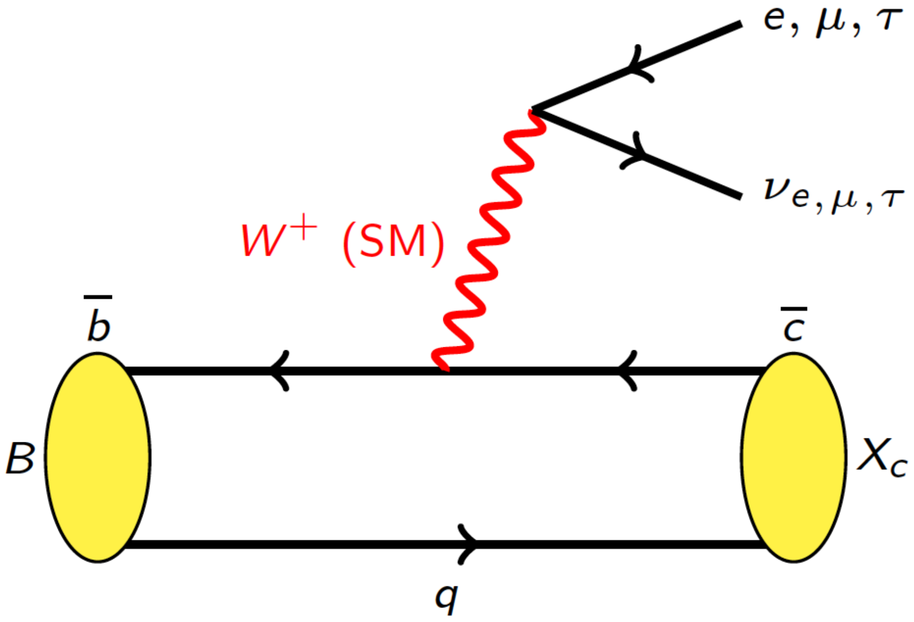
Good control over theoretical uncertainties.

Large and perfectly calibrated simulation samples

Road most travelled : The good, the bad and the "ugly"

Abundant signal allowing for high precision.

Missing neutrinos



Require good knowledge bkg

(Most time-consuming part)

Good control over theoretical uncertainties.

Large and perfectly calibrated simulation samples

Road most travelled : The good, the bad and the "ugly"

Conduct analyses not so sensitive to this, yet provide smoking-gun signal to NP?

Require good knowledge bkg

(Most time-consuming part)

Road less travelled (to new physics)

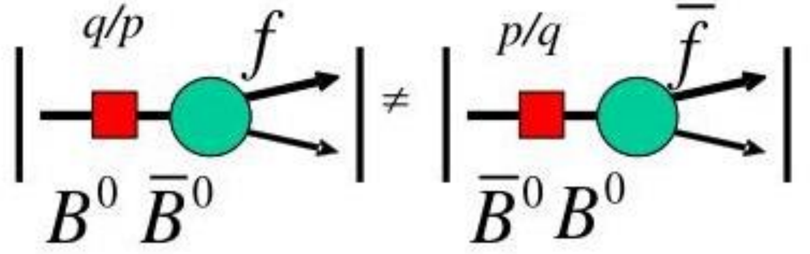
Tests of CKM unitarity, LFU and angular analysis.

CP violation

Types of CP violation

* Not covered CPV
in interference

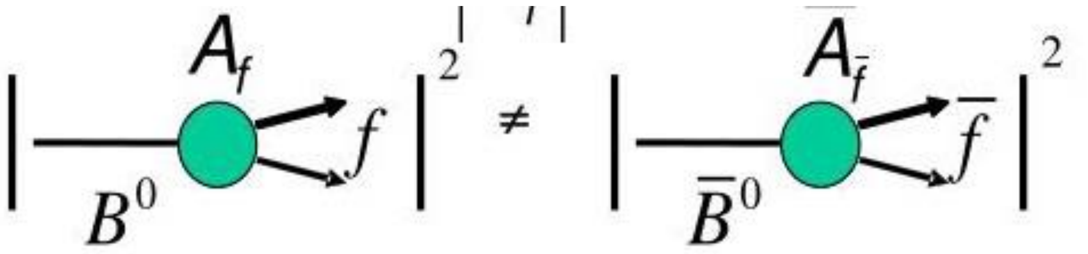
CPV in mixing



$$P(B^0 \rightarrow \overline{B^0}) \neq P(\overline{B^0} \rightarrow B^0)$$

Measurement of a_{sl}^{q} and prospects

CPV in decay



$$P(\overline{B} \rightarrow \bar{f}) \neq P(B \rightarrow f)$$

- Direct CPV in $B \rightarrow D^{**} l\nu$
- Triple product asymmetries in $B \rightarrow D^{*} l\nu$

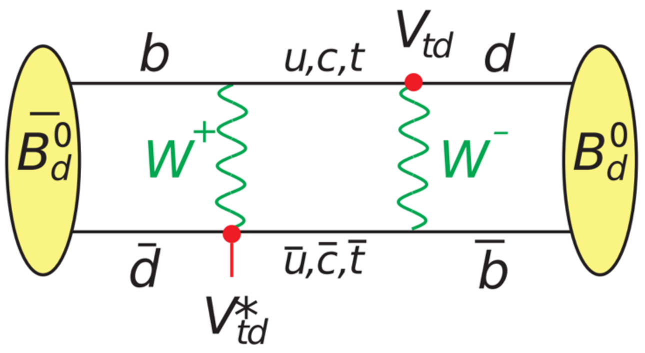
Measurement of a_{sl}^{q} and prospects

CPV in mixing

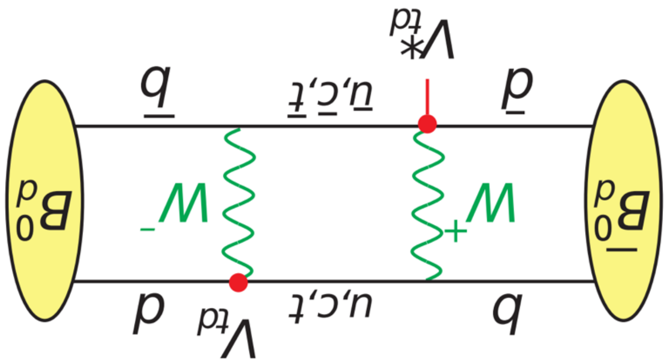
[M. Grabalso thesis]

CPV in mixing

$$a_{\rm sl} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\overline{B} \to f) + \Gamma(B \to \bar{f})} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_{12}$$



$\neq$



New physics sensitive in the loop.

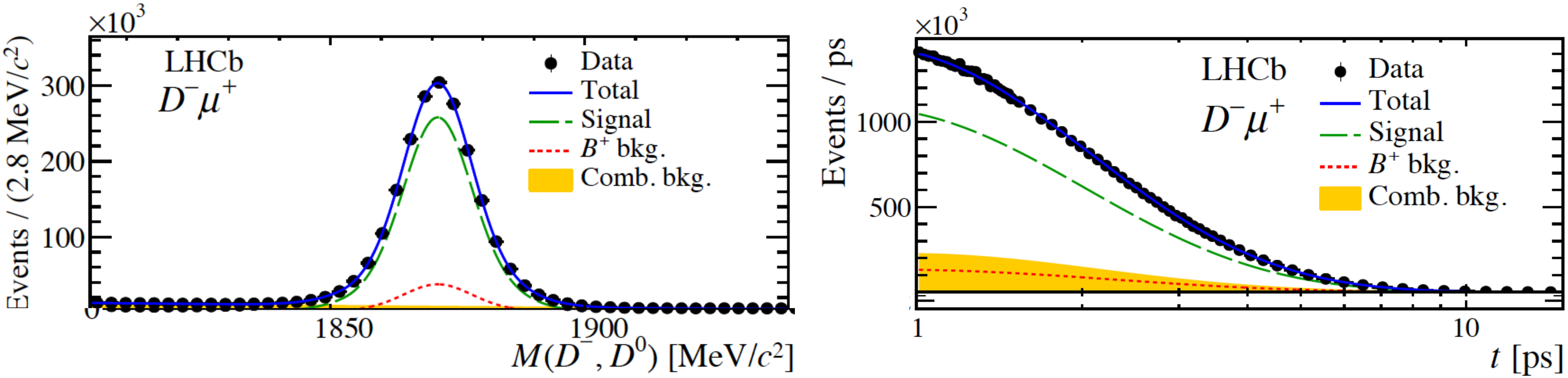
Explore the flavour-specific decays $B^0 \to D^{(*)-}\mu^+X$ and $B^0_s \to D^{(*)-}\mu^+X$ i.e. μ charge identifies B flavour at decay.

Explore asymmetry in untagged decays i.e. no need to determine the B flavour at production.

a_{sl}^{d}: Fit to for B^0 and $\bar{B}^0$ samples

2D fit to charm mass and decay time for B^0 and $\bar{B}^0$ simultaneously
Apply corrections to decay time (acceptance, resolution and missing energy)

$$P(\eta_{flav}, t) \propto \left[P(\eta_{flav}, t_{true})\right. \otimes R(t - t_{true})\left.\right] \otimes F(k) \otimes \epsilon(t)$$



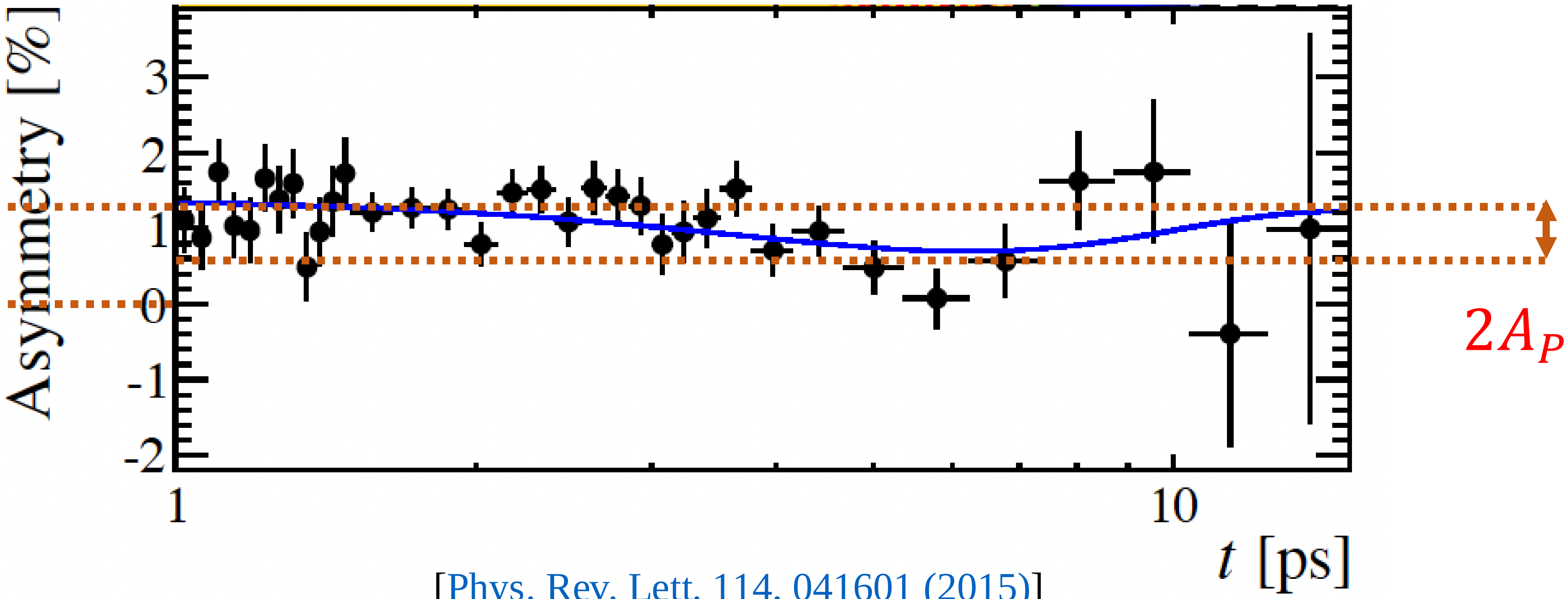
[Phys. Rev. Lett. 114, 041601 (2015)]

a_{sl}^{d} extractions

Nuissance asymmetries (covered later)

$$A_{raw} = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} = \frac{a_{sl}}{2}\,(1 - \cos(\Delta m t)) + [A_D + A_P \cos(\Delta m t)]$$

$A_D + A_P$

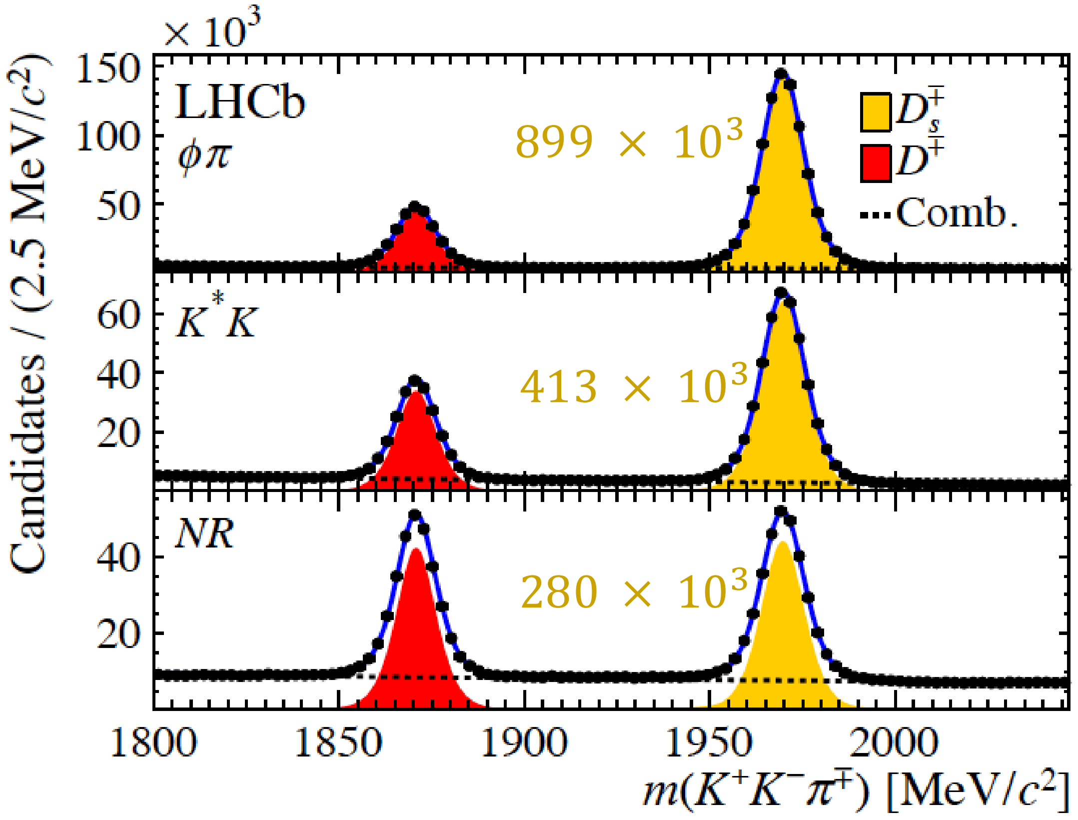


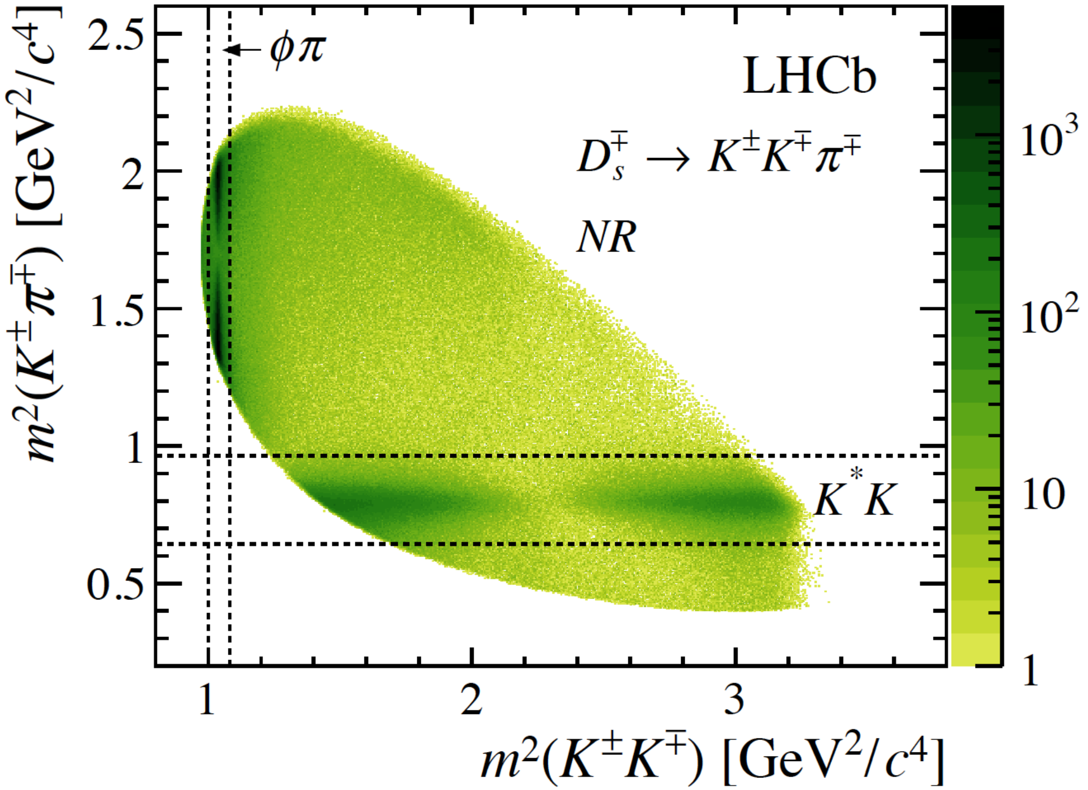
$2A_P - a_{sl}$

[Phys. Rev. Lett. 114, 041601 (2015)]

a_{sl}^{s}: Fit to for B_s^0 and $\bar{B}_s{}^0$ samples

Fit charm mass for B_s^0 and $\bar{B}_s^0$ decays simultaneously.
Three measurements of varying bkg in $D_s \to K^+K^-\pi^-$ Dalitz plot.





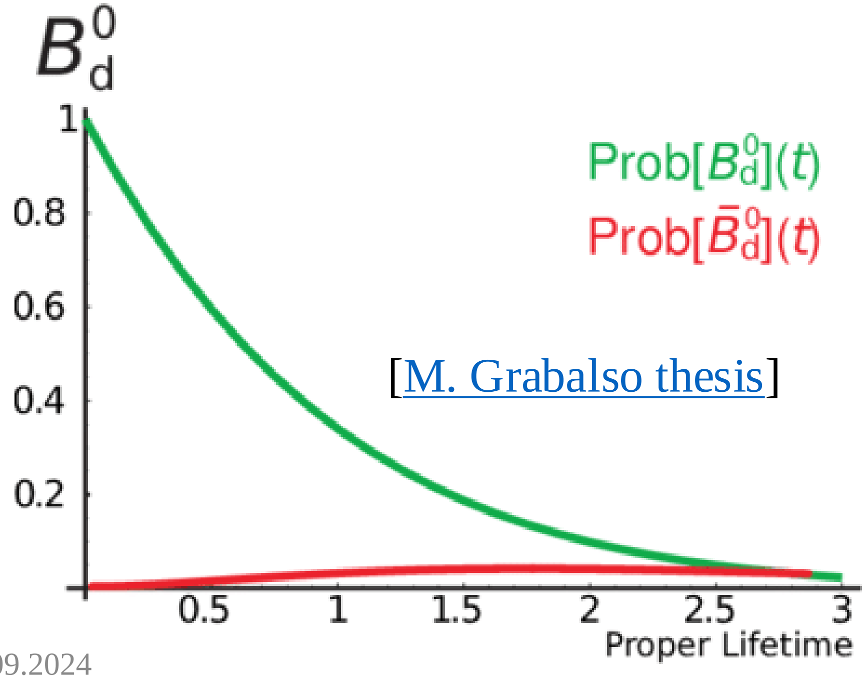
[Phys. Rev. Lett. 117, 061803 (2016)]

a_{sl}^{s} with fast oscillations

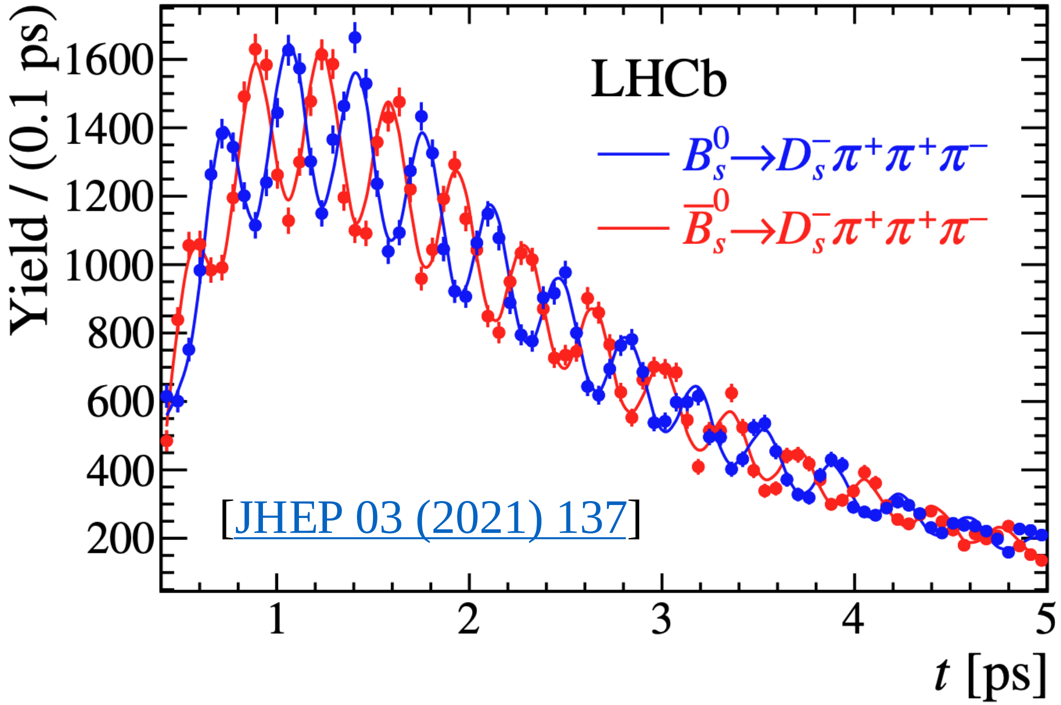
Nuissance asymmetries (covered later)

$$\int A_{raw}(t)dt = \frac{a_{sl}}{2}\left(1 - \int \cos(\Delta m t)dt\right) + [A_D + A_P \int \cos(\Delta m t)dt]$$

Due to fast B_s^0 integral is almost zero $O(10^{-3})$.



[M. Grabalso thesis]



[JHEP 03 (2021) 137]

a_{sl}^{s} with bkg asymmetries

Nuissance asymmetries (covered later)

$$A_{raw} = \frac{a_{sl}}{2}\left(1 - \sum_{i\in bkg} f_i\right) + [A_D + \sum_{i\in bkg} f_i\, A_P^i]$$

Bkg decays

$B^+ \to D^{(*)0} D_s^{(*)+} X$
$B^0 \to D^0 D_s^{(*)+} X$
$B^0 \to D^- D_s^{(*)+} X$
$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$
$\Lambda_b^0 \to \Lambda_c^+ D_s^{(*)+} X$
$B^- \to D_s^+ K^- \mu^- \nu X$
$\overline{B}^0 \to D_s^+ K_S^0 \mu^- \nu X$

$$\sum_{i\in bkg} f_i = (18 \pm 6)\%$$

$$\sum_{i\in bkg} f_i\, A_P^i = -0.045 \pm 0.033)\%$$

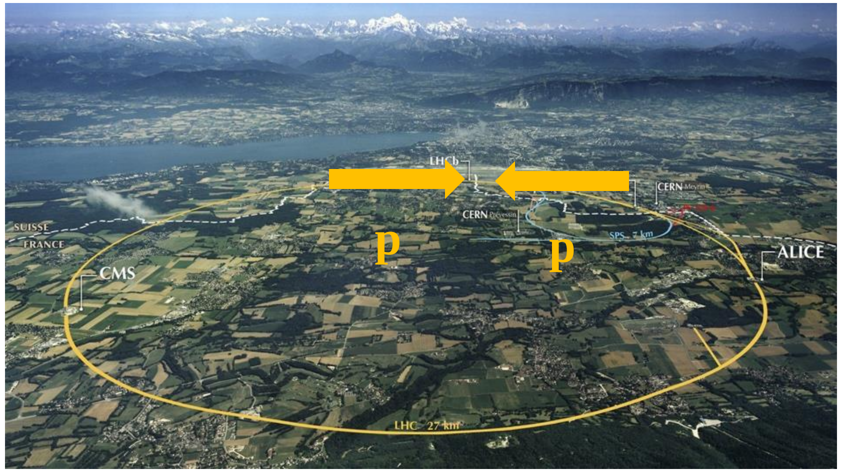
[Phys. Rev. Lett. 117, 061803 (2016)]

Nuisance asymmetries

$$A_{raw} = \frac{a_{sl}}{2}\,(1 - \cos(\Delta m t)) + [A_D + A_P \cos(\Delta m t)]$$

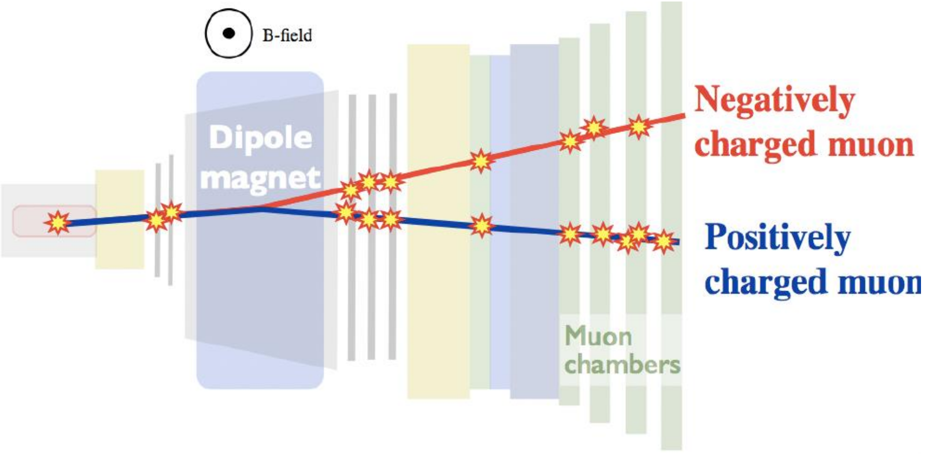
Production asymmetry

$$A_P = \frac{\sigma(pp \to B\,X) - \sigma(pp \to \bar{B}X)}{\sigma(pp \to B\,X) + \sigma(pp \to \bar{B}X)}$$



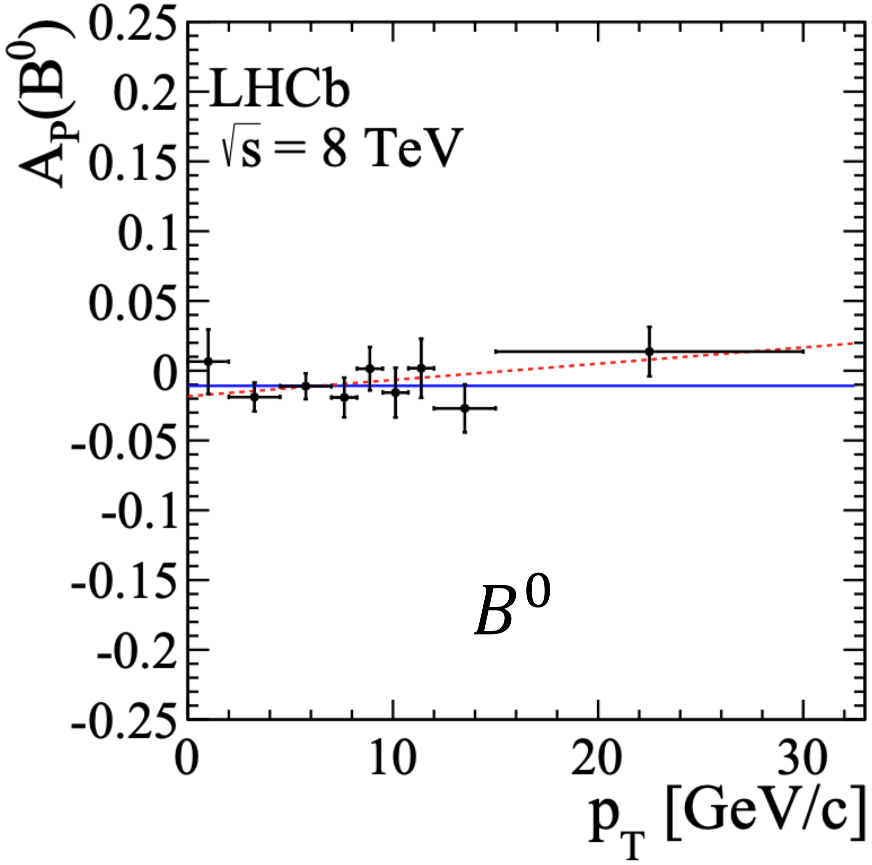
Detection asymmetry

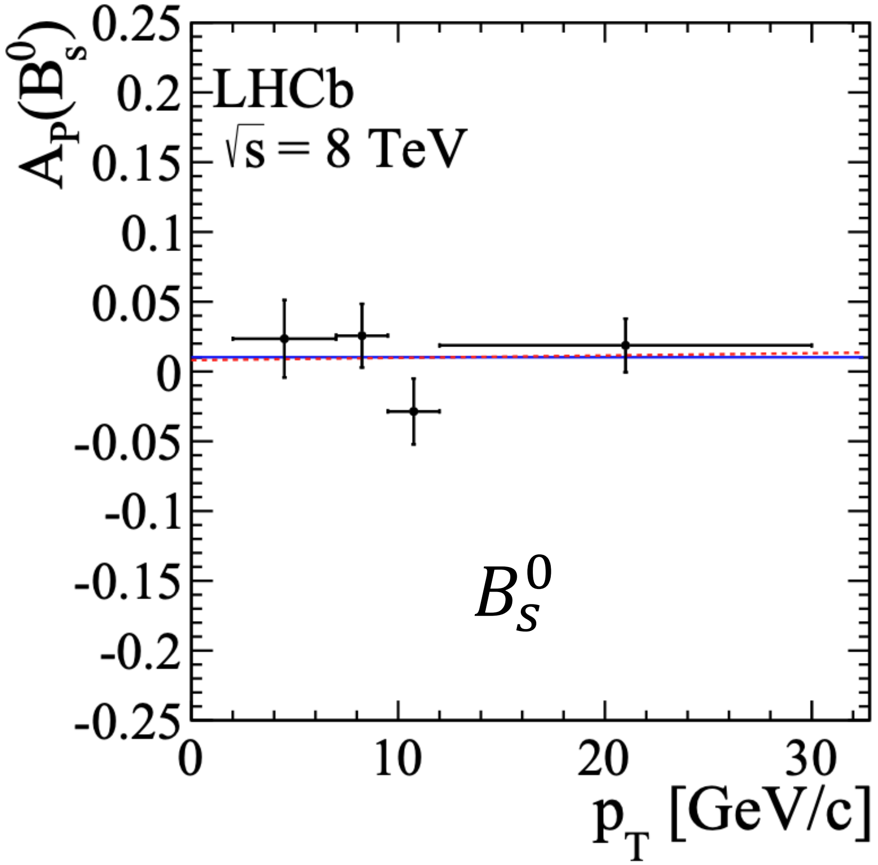
$$A_D = \frac{\epsilon\,(B \to f) - \epsilon(\bar{B} \to f)}{\epsilon\,(B \to f) + \epsilon(\bar{B} \to f)}$$



Production asymmetry

Measured for all B species as function of p_T and η.





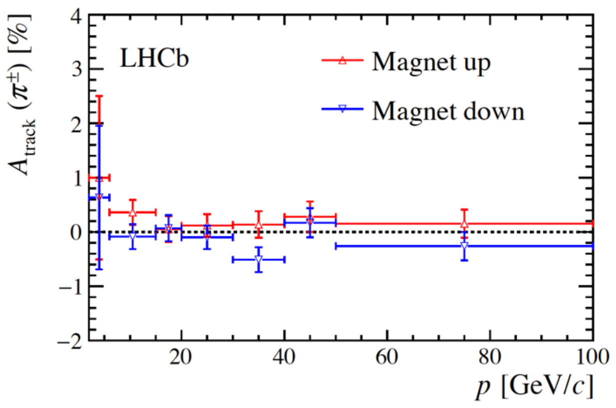
[Phys. Lett. B739 (2014) 218, Phys. Lett. B 774 (2017) 139-158]

Detection asymmetry

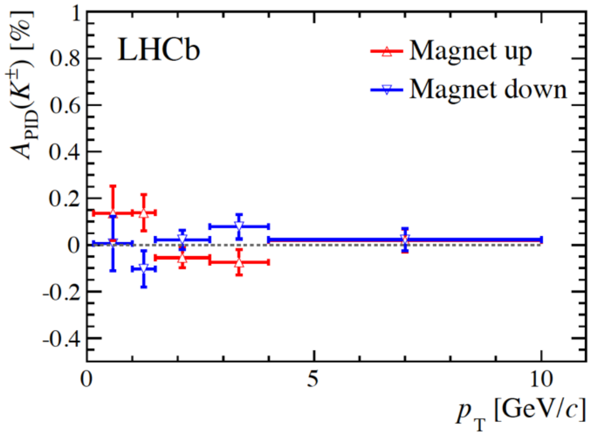
[Phys. Rev. Lett. 117, 061803 (2016)]

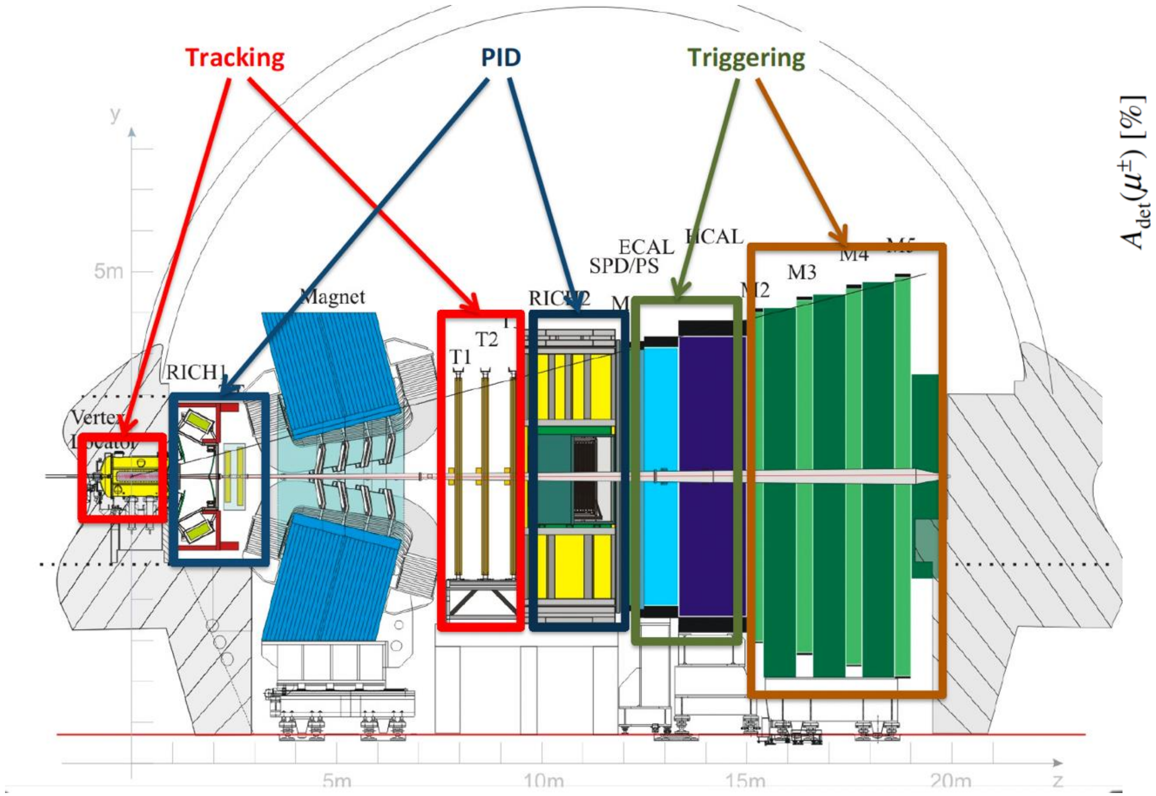
[Talk by Jacco Devries]

Pion track asymmetry

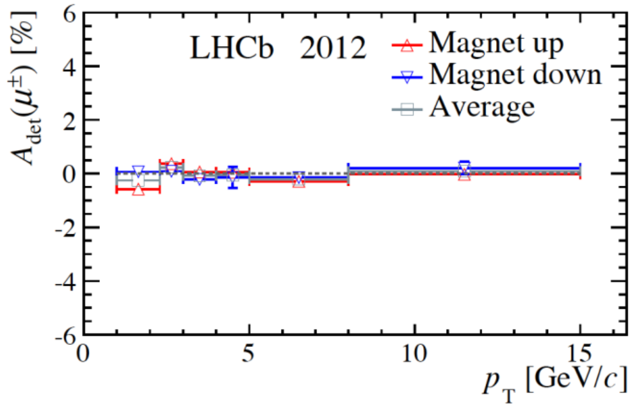


Kaon PID asymmetry





Muon trigger asymmetry



Well established data-driven methods to evaluate these effects!

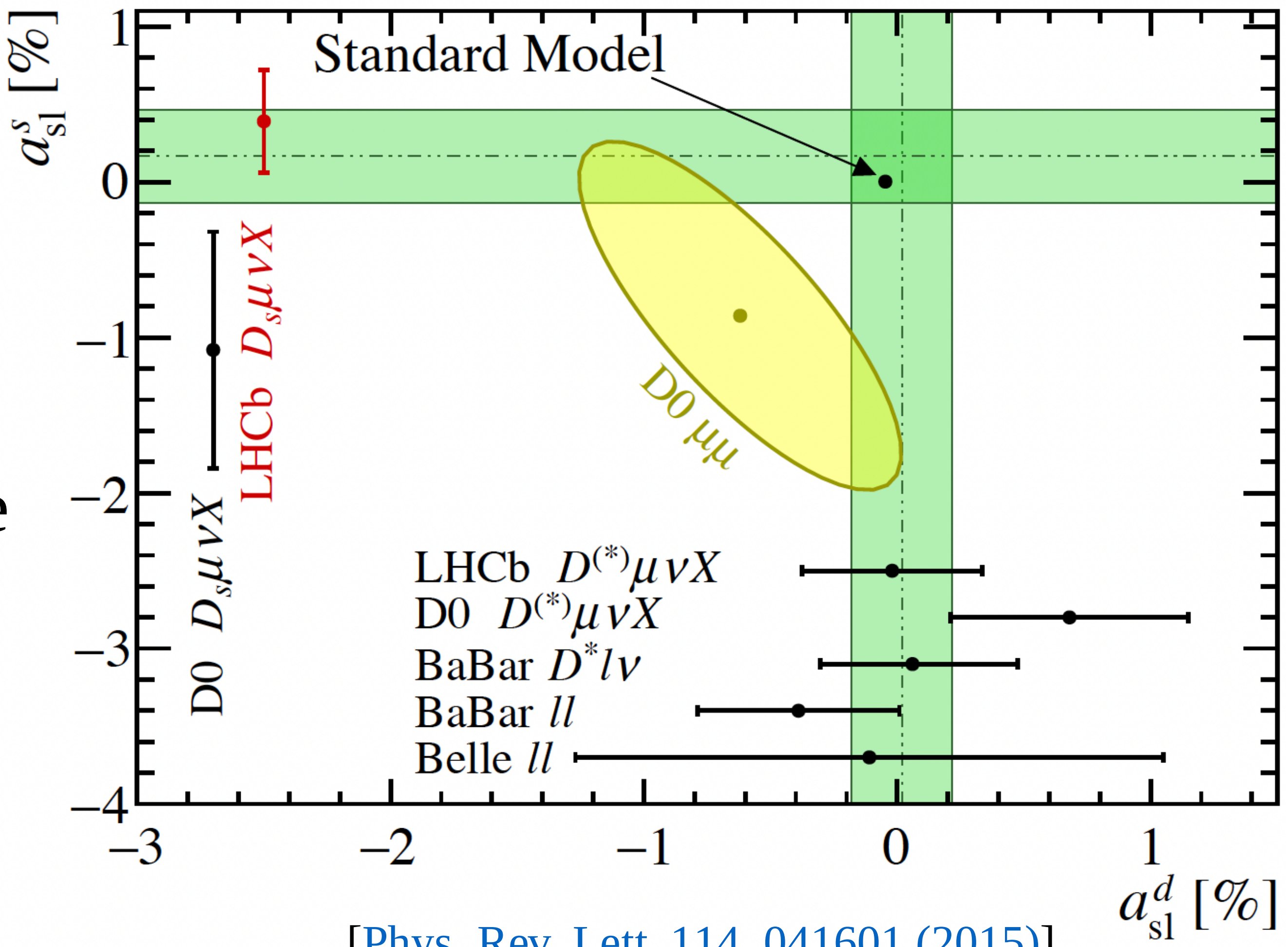
a_{sl}^d and a_{sl}^s

- Both results use LHCb Run I data.

$$a_{sl}^d = (-0.02 \pm 0.19 \pm 0.30)\ \%$$

$$a_{sl}^s = (0.39 \pm 0.26 \pm 0.20)\ \%$$

- Nuisance asymmetries dominate systematics but scale with sample size.
- Full Run 2 updates in-progress:
  - 50% reduction in σ_{stat}.
  - 30% reduction in σ_{syst}.



[Phys. Rev. Lett. 114, 041601 (2015)]

[Phys. Rev. Lett. 117, 061803 (2016)]

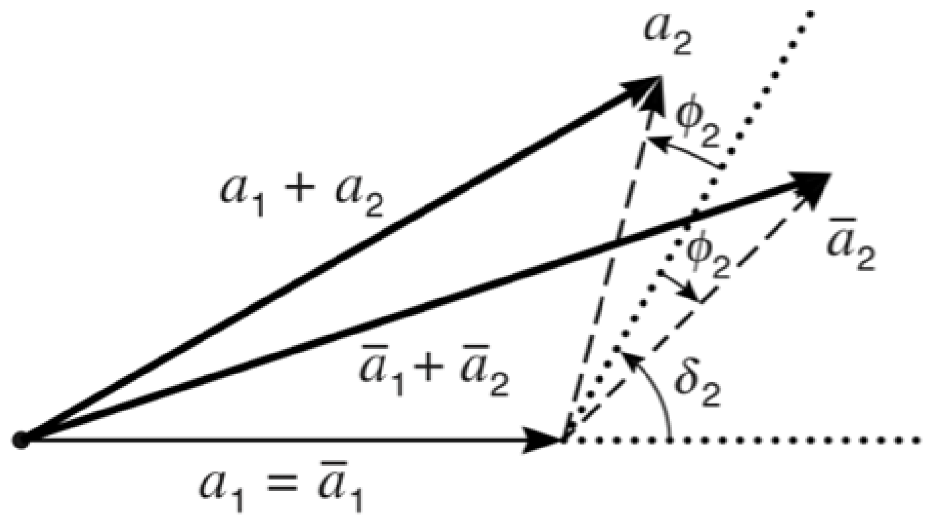
New physics induced CPV in decay

CPV in decay

Direct CP asymmetry (CP-odd):

$$A_{CP}^{dir} \propto \sin(\Delta\phi)\, \sin(\Delta\delta)$$

Requires $\Delta\phi \neq 0$ and $\Delta\delta \neq 0$.



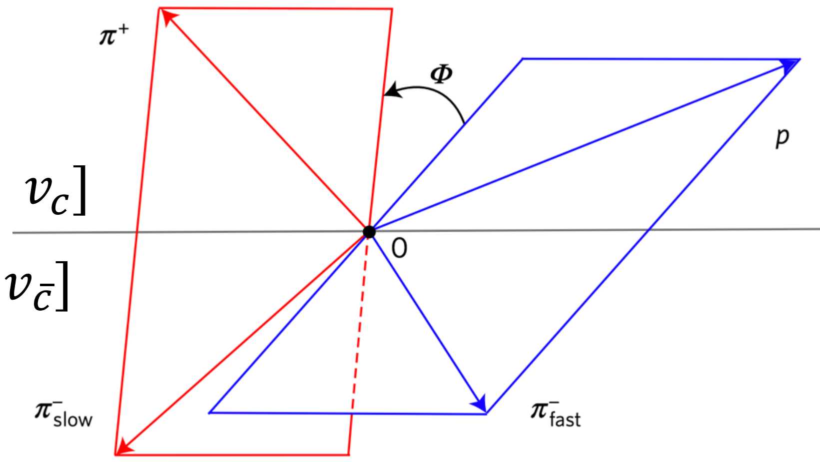
Triple Product asymmetry (T-odd):

$$A_{T-odd} \propto \sin(\Delta\phi)\, \cos(\Delta\delta)$$

Maximal when $\Delta\delta = 0$

$$A_{T-odd} = v_a . [v_b \times v_c]$$

$$\bar{A}_{T-odd} = v_{\bar{a}} . [v_{\bar{b}} \times v_{\bar{c}}]$$



Which specific decay channels?

Direct CP asymmetry (CP-odd):

$$A_{CP}^{dir} \propto \sin(\Delta\phi)\,\sin(\Delta\delta)$$

Requires $\Delta\phi \neq 0$ and $\Delta\delta \neq 0$.

[Y Grossman et al]

SL decays with excited charm(less) states

Mesons: $B^- \to D^{**0}\, l^- \nu$ and $B^- \to (\pi^+\pi^-)\, l^-\nu$.
Baryons: $\Lambda_b^0 \to \Lambda_c^{*+} l^- \nu$ and $\Lambda_b \to N^* l^- \nu$)

Triple Product asymmetry (T-odd):

$$A_{T-odd} \propto \sin(\Delta\phi)\,\cos(\Delta\delta)$$

Maximal when $\Delta\delta = 0$

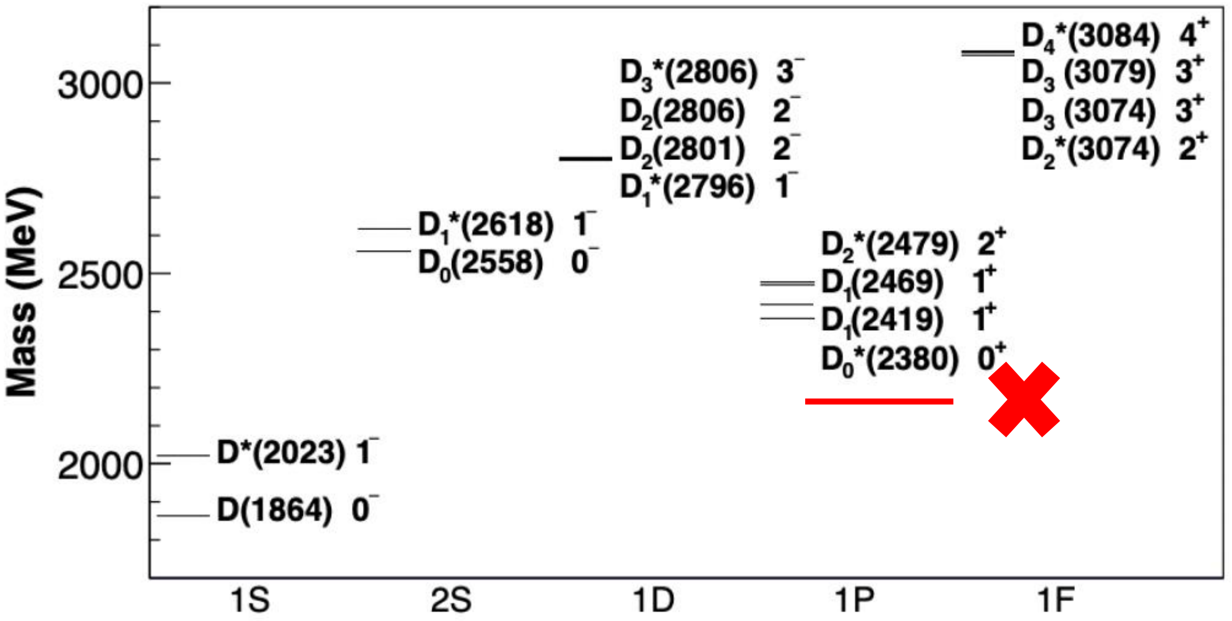
[D London et al]

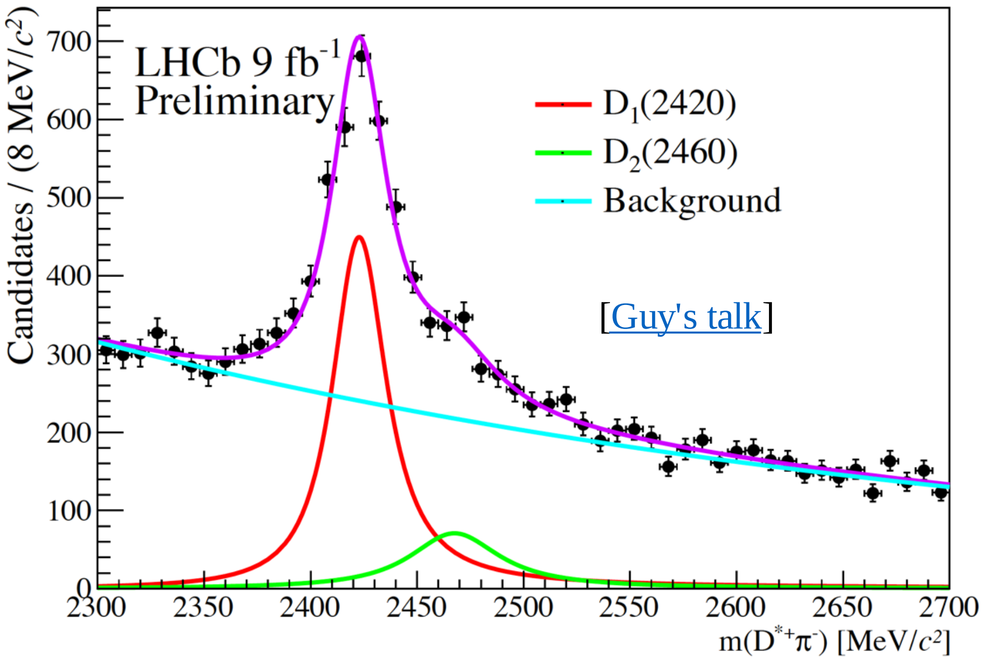
SL decays with charm(less) states

Mesons: $B^0 \to D^{(*)+}\, l^- \nu$ and $B^0 \to \pi^+\, l^- \nu$,
Baryons: $\Lambda_b^0 \to \Lambda_c^+ l^- \nu$ and $\Lambda_b \to p l^- \nu$)

A_{CP}^{dir} : Strong phase in $B^- \to D^{**}\tau\nu$

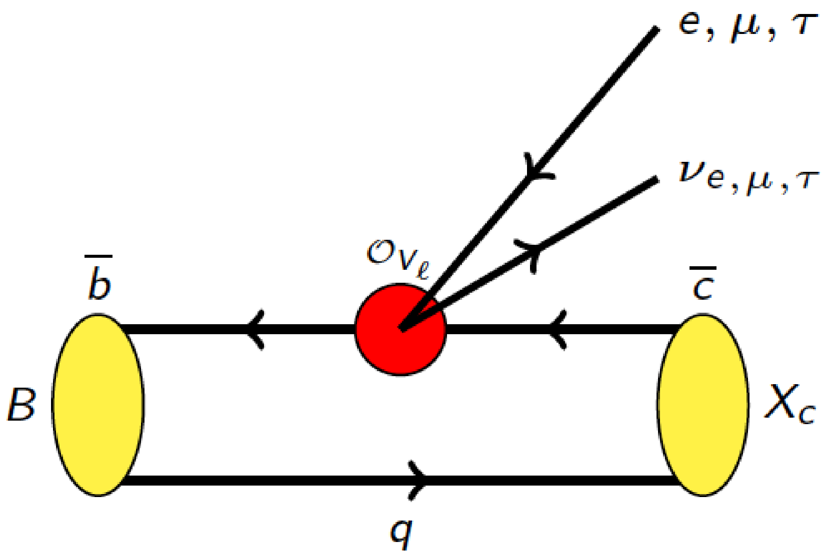
Predicted spectrum of $c\bar{u}$ resonances





Various $c\bar{u}$ resonances with same J^P interfer to give strong phase $\Delta\delta$.

A_{CP}^{dir} : Weak phase in $B^- \to D^{**}\tau\nu$



$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\Big\{\Big[(1 + g_L)\bar{c}\gamma^\mu P_L b + g_R\,\bar{c}\gamma^\mu P_R b\Big]\bar{\ell}\gamma_\mu P_L \nu_\ell + \Big[g_S\,\bar{c}b + g_P\,\bar{c}\gamma^5 b\Big]\bar{\ell}P_L\nu_\ell + g_T\,\bar{c}\sigma^{\mu\nu}P_L b\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell + h.c.\Big\}$$

[Vlad's talk]

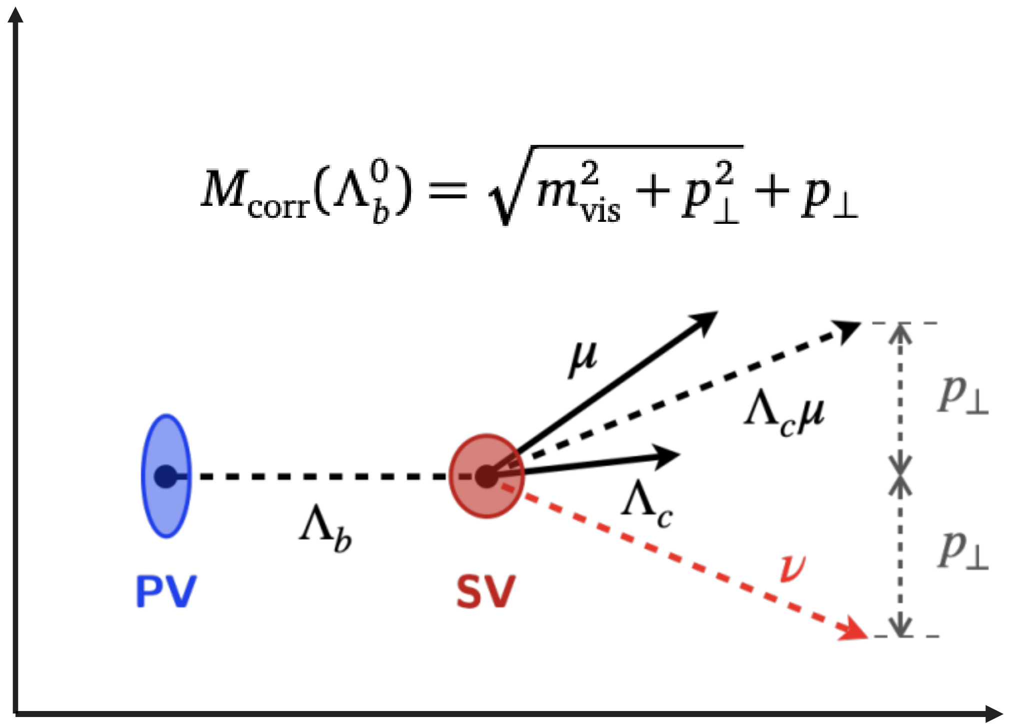
New physics with different Lorentz structures give rise to weak phase $\Delta\phi$.

A_{CP}^{dir} : Problems and Solutions

Problem 1

- Large uncertainties in BFs by B-factories [1,2,3] and now LHCb [Guy's talk].
- Form factors not–so well known [F. Bernlochner et al].

→ Investigate observables insensitive to these effects e.g. corrected mass.



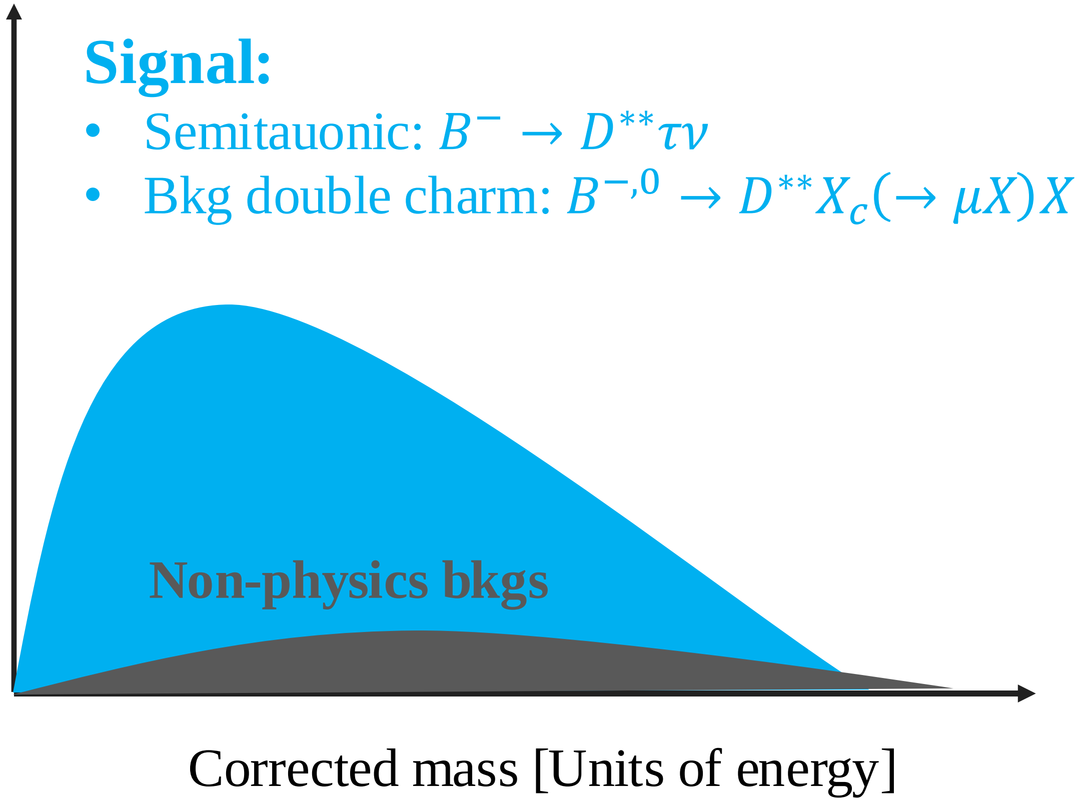
Corrected mass [Units of energy]

A_{CP}^{dir} : Problems and Solutions

Problem 2

➢Hard to disentangle $B^- \to D^{**}\tau\nu$ from bkgs.

→ Don't, bkg's don't exhibit no CP violation (highly suppressed).

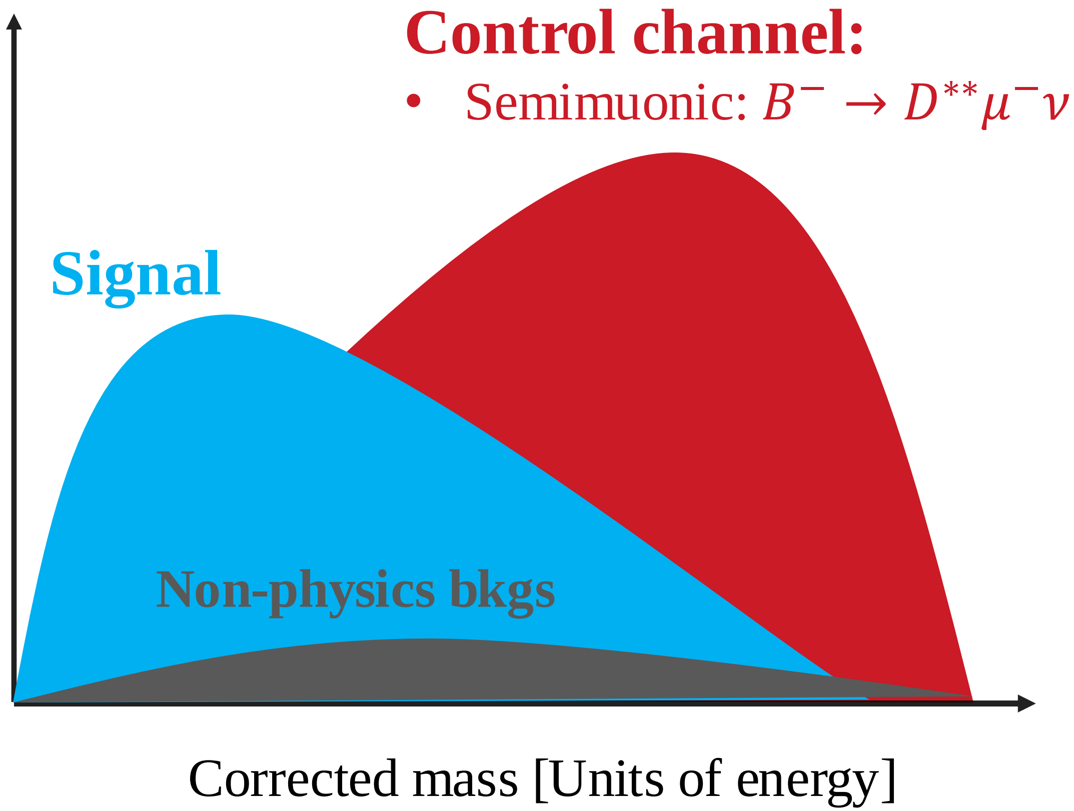


A_{CP}^{dir} : Problems and Solutions

Problem 3

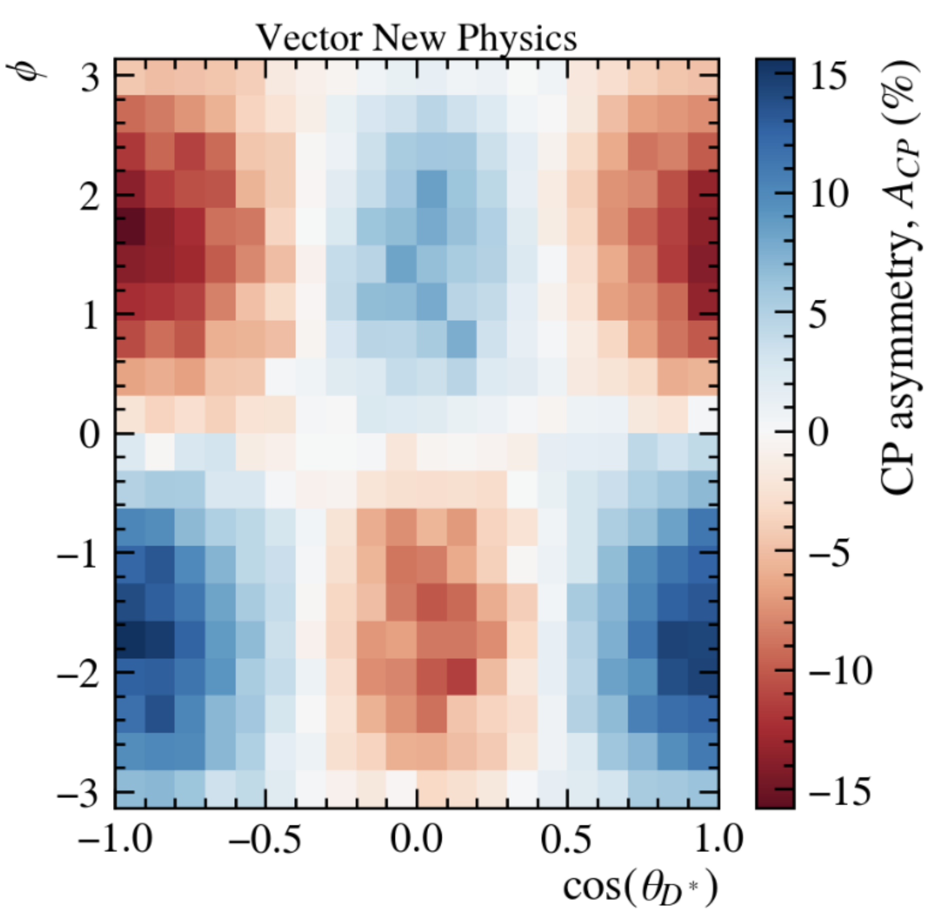
➢Require control over nuisance asymmetries.

→ Use control channel with same initial and final state to cancel the nuisance asymmetries.



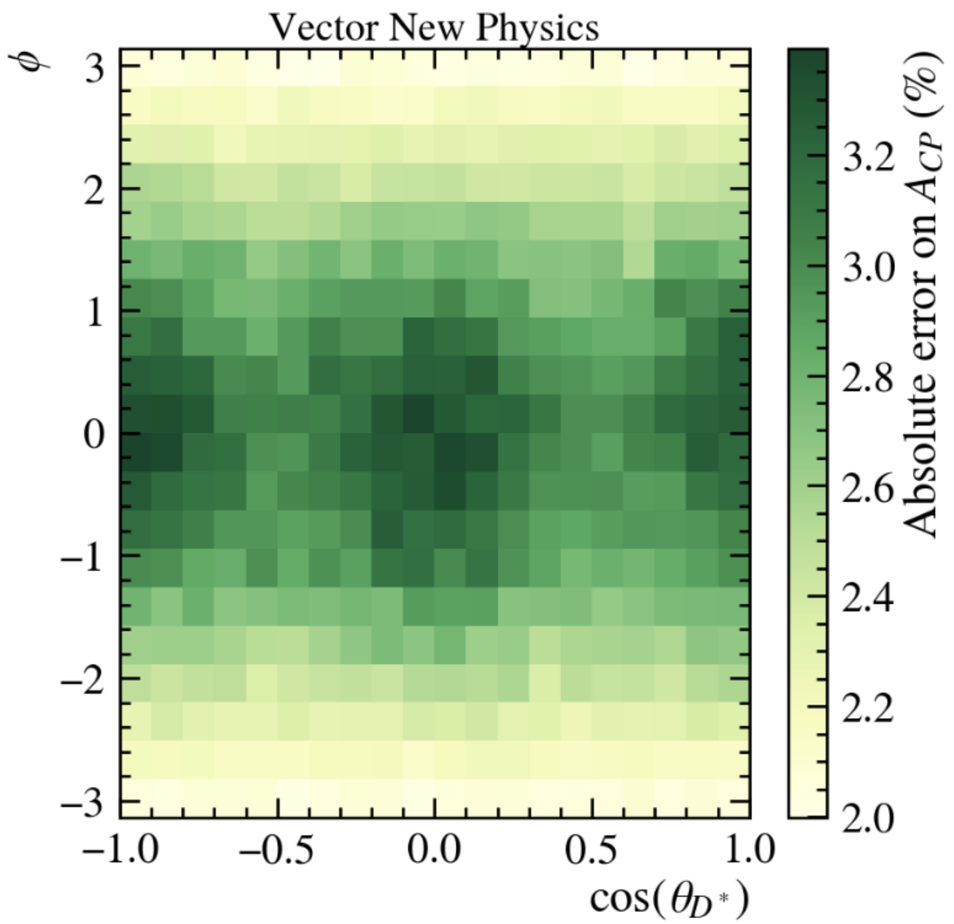
Measure $\Delta A_{CP}^{dir} = A_{raw}^{control} - A_{raw}^{signal}$ in phase space bins.

(Preliminary) Sensitivity to ΔA_{CP}^{dir}



$|g_{V_R}| = 0.8\,(1+i)$

D_1 and D_2^* included.



- With Run 2 and Run 3 data expect around 300k events (0.1% sel. Eff).
- **$\Delta A_{CP} \neq 0$ would be a smoking gun signal for NP!**

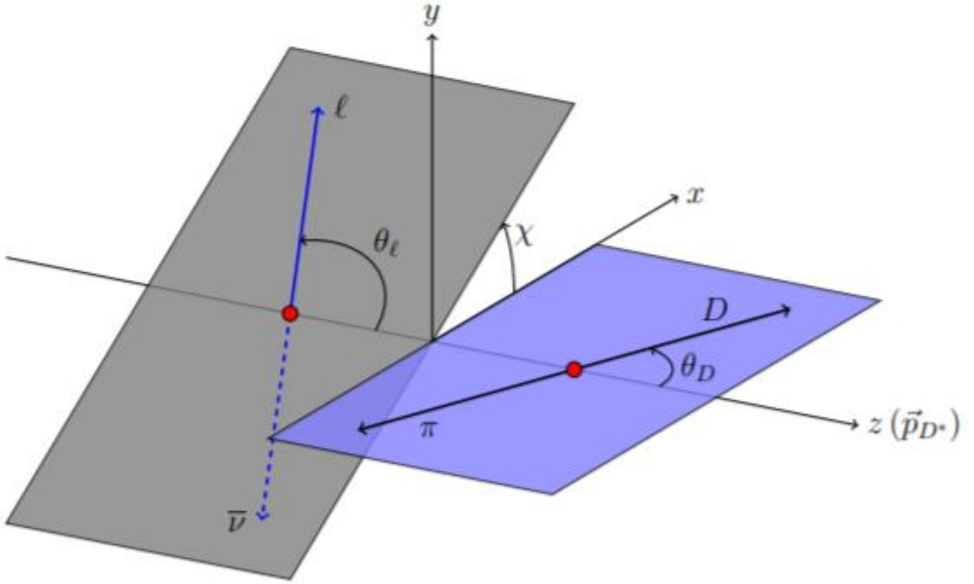
Triple products (TP) in $B^0 \to D^{*-}\mu\nu$

[D London et al]

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta^*\, d\chi} = \frac{3}{8\pi}\frac{G_F^2|V_{cb}|^2(q^2-m_\ell^2)^2|p_{D^*}|}{2^8\pi^3 m_B^2 q^2} \times \mathcal{B}(D^*\to D\pi)\left(N_1 + \frac{m_\ell}{\sqrt{q^2}}N_2 + \frac{m_\ell^2}{q^2}N_3\right)$$

Interested only in terms $Im(A_i A_j^*)$

Amplitude term	Coupling	Angular function
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta_D \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$2\sin^2\theta_\ell \sin^2\theta_D \sin 2\chi$
$\mathrm{Im}(\mathcal{A}_{SP} \mathcal{A}_{\perp,T}^*)$	$\mathrm{Im}(g_P g_T^*)$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta_D \sin\chi$



Angular terms $Im(A_i A_j^*)$ non-zero in two cases:

- Rel. strong phase only → fake CPV signal (≡ 0 in both SM and NP for these decays.)
- **Rel. weak phase only → true CPV signal (≡ 0 in SM but ≠ 0 in NP).**

Triple products (TP) in $B^0 \to D^{*-}\mu\nu$

[A Poluektov and Vlad Dedu]

$$P_{\text{tot}}(\Omega) = P_{\text{even}}(\Omega) + P_{\text{odd}}(\Omega)$$

$$P_{\text{odd}}(\Omega) = P^{(1)}_{\text{odd}} \sin\chi + P^{(2)}_{\text{odd}} \sin 2\chi$$

$$\Omega = (q^2, \theta_D, \theta_\ell, \chi)$$

Extract the two angular functions ($P^{(1)}_{odd}$ and $P^{(2)}_{odd}$) from total PDF

Unbinned true observables

$$P^{(1)}_{\text{odd}} = \frac{1}{\pi}\int_{-\pi}^{\pi} P_{\text{tot}}(\Omega)\sin\chi d\chi$$

$$P^{(2)}_{\text{odd}} = \frac{1}{\pi}\int_{-\pi}^{\pi} P_{\text{tot}}(\Omega)\sin 2\chi d\chi$$

$\rightarrow$

Binned reconstructed observables

$$A^{(1)}_i = \frac{N_{\text{bins}}}{N_{\text{signal}}}\sum_{n=1}^{N_i}\sin\chi_n \simeq \mathrm{Im}(g_R)\, A^{(1)}_{RH,i} + \mathrm{Im}(g_P g_T^*)\, A^{(1)}_{PT,i}$$

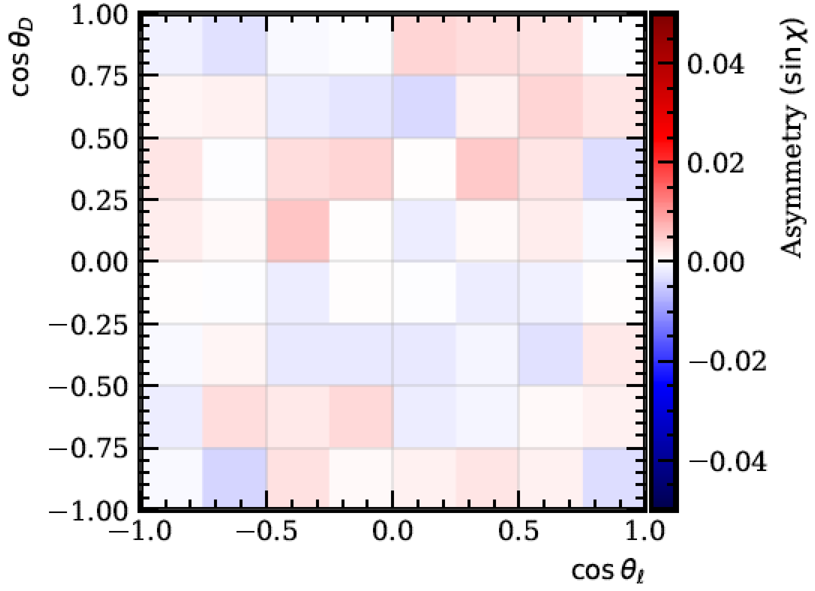
$$A^{(2)}_i = \frac{N_{\text{bins}}}{N_{\text{signal}}}\sum_{n=1}^{N_i}\sin 2\chi_n \simeq \mathrm{Im}(g_R)\, A^{(2)}_{RH,i}$$

Sum all N_i events in i^{th} bin of $[q^2, \cos(\theta_D), \cos(\theta_l)]$

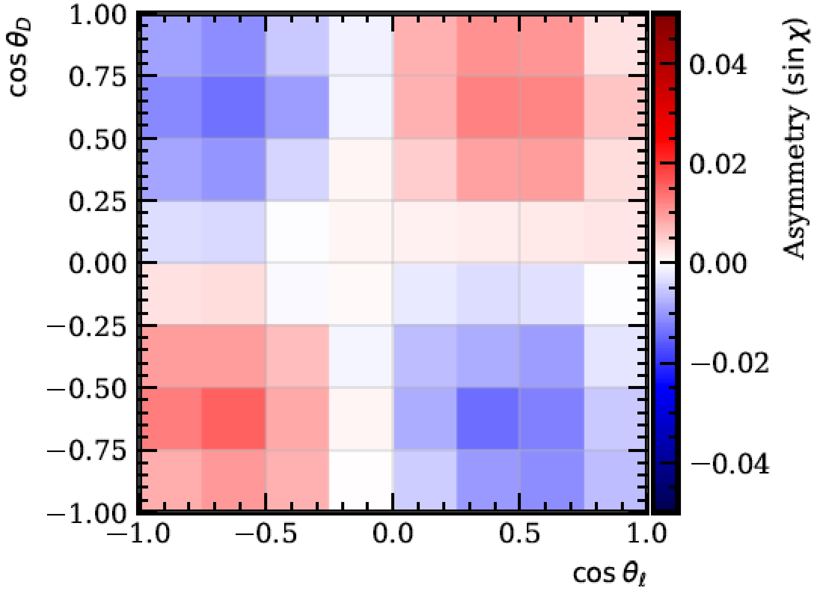
TP: Asymmetries in $B^0 \to D^{*-}\mu\nu$

Trend in one of the two functions: $A^{(1)}$ [A Poluektov and Vlad Dedu]

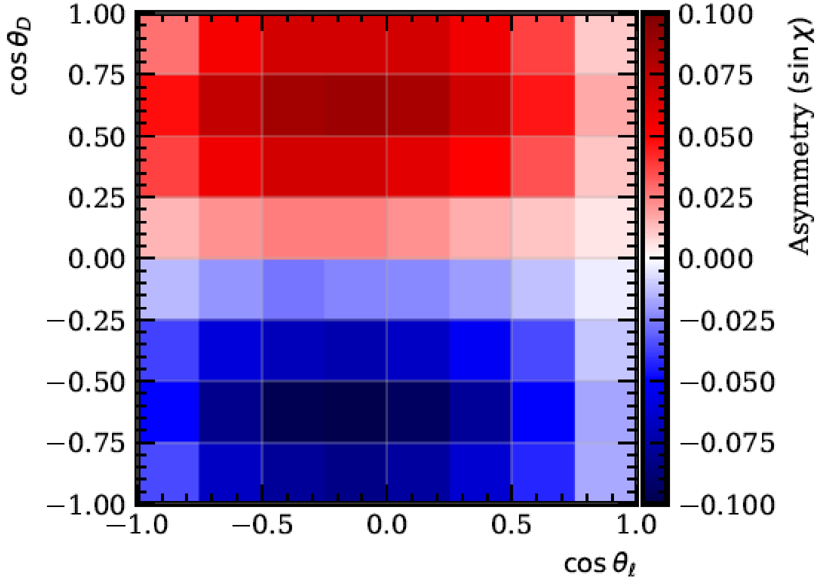
SM



NP: $g_R = 0.1i$



NP: $g_P g_T^* = 0.1i$



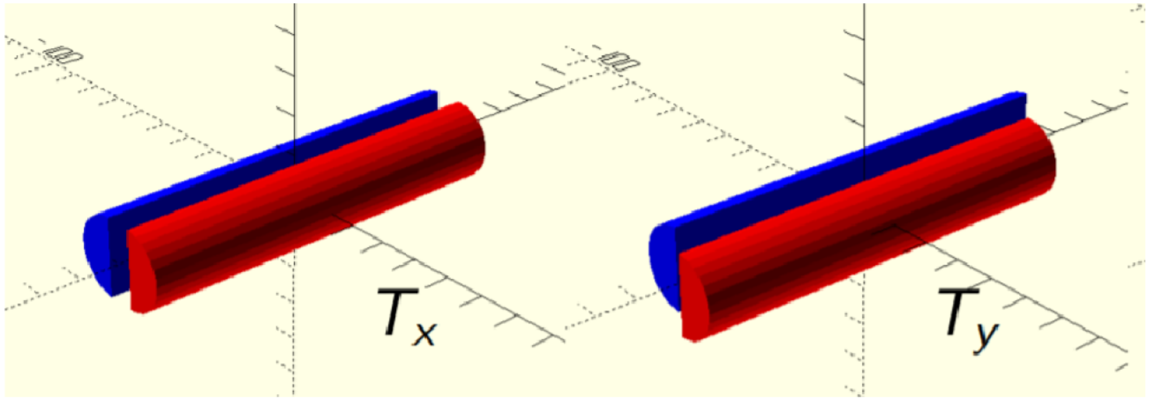
Clear trends when weak phase is non-zero

TP: Fit and systematics

[A Poluektov and Vlad Dedu]

$$\chi^2_{\text{corr}} = \sum_i \sum_{a,b=1,2} \Delta A_i^{(a)} \left(\Sigma_i^{-1}\right)^{(ab)} \Delta A_i^{(b)}$$

- Perform χ^2 fit considering correlation b/w $\sin(\chi)$ and $\sin(2\chi)$.
- Signal and bkg discrimination from 3D fit: q^2, m^2_{miss} and E^*_μ.
- Systematics:
  - CP asymmetry: Non-physics bkg.
  - Instrumental effects (e.g., tracking system misalignment)
  - Non-uniform reconstruction efficiency.



Misalignment of velo modules → Bias in vertex position → Bias in $\sin(\chi)$

TP: Expected sensitivity in $B^0 \to D^{*-}\mu\nu$

- Triple-product-like CP asymmetries (and P asymmetries) probed.
- Run 2 data provides sensitivity to $Im(g_R)$ and $Im(g_P g_T^*)$.
- Dominant systematic is due to detector misalignments.
- Future work to extend this $B^0 \to D^{*-}\tau\nu$.

[A Poluektov and Vlad Dedu and Vlad's thesis]

Assigned systematic	Δ Im(g_R)	Δ Im($g_P g_T^*$)
Misid	0.85×10^{-3}	2.45×10^{-4}
Fake D^* comb	0.40×10^{-3}	0.70×10^{-4}
True D^* comb	1.45×10^{-3}	1.98×10^{-4}
T_y 2 µm misalignment	4.16×10^{-3}	4.33×10^{-4}
Control sample	2.78×10^{-3}	6.12×10^{-4}
Total	$\mathbf{5.82 \times 10^{-3}}$	$\mathbf{0.92 \times 10^{-3}}$

***CP* asymmetries:**

$$\mathrm{Im}(g_R) = (X.XX \pm 0.51\ (\mathrm{stat.}) \pm 0.58\ (\mathrm{syst.}))\%,$$
$$\mathrm{Im}(g_P g_T^*) = (X.XX \pm 0.13\ (\mathrm{stat.}) \pm 0.09\ (\mathrm{syst.}))\%.$$

Central values are blinded.

Summary and conclusions

- CP symmetry in SL decays offers powerful null tests of the SM.
- Signal and bkg separation in LFU is replaced by established methods for handling nuisance asymmetries in CPV.
- Full Run 2 updates on CPV in mixing (a_{sl}) with SL decays on the way.
- Prospects to explore direct CPV in $B \rightarrow D^{**}\tau\nu$ decays with Run II and III data.
- Triple-product-like CP asymmetries in $B \rightarrow D^{*}\mu\nu$ studied including systematic effects.
- **Exciting new precision tests with SL decays ahead!**

Backup

a_{ls}^{s} bkg fractions

Mode	$\mathcal{B}$ [%]	$\mathcal{B}(c \to \mu)$ [%]	$\varepsilon_{\text{sig}}/\varepsilon_{\text{bkg}}$	$f_{\text{bkg}}/f_{\text{sig}}$ [%]	A_{bkg} [%]
$B^+ \to D^{(*)0} D_s^{(*)+} X$	7.9 ± 1.4	6.5 ± 0.1	4.34	5.8 ± 1.1	-0.6 ± 0.6
$B^0 \to D^0 D_s^{(*)+} X$	5.7 ± 1.2	6.5 ± 0.1	4.08	4.4 ± 1.0	-0.18 ± 0.13
$B^0 \to D^- D_s^{(*)+} X$	4.6 ± 1.2	16.1 ± 0.3	6.41	5.6 ± 1.5	-0.18 ± 0.13
$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$	4.5 ± 1.4	8.1 ± 0.4	3.68	1.0 ± 0.3	–
$\Lambda_b^0 \to \Lambda_c^+ D_s^{(*)+} X$	$10.3^{+2.1}_{-1.8}$	4.5 ± 1.7	4.51	3.0 ± 1.4	$+0.5 \pm 0.8$
$B^- \to D_s^+ K^- \mu^- \nu X$	0.061 ± 0.010	–	2.43	1.3 ± 0.2	0.6 ± 0.6
$\overline{B}^0 \to D_s^+ K_S^0 \mu^- \nu X$	0.061 ± 0.010	–	2.89	1.1 ± 0.2	0.18 ± 0.13

a_{sl} systematics

a_{sl}^{d}

Source of uncertainty	a_{sl}^{d}	A_{P}(7 TeV)	A_{P}(8 TeV)
Detection asymmetry	0.26	0.20	0.14
B^{+} background	0.13	0.06	0.06
Λ_b^0 background	0.07	0.03	0.03
B_s^0 background	0.03	0.01	0.01
Combinatorial D background	0.03	–	–
k-factor distribution	0.03	0.01	0.01
Decay-time acceptance	0.03	0.07	0.07
Knowledge of Δm_d	0.02	0.01	0.01
Quadratic sum	0.30	0.22	0.17

a_{sl}^{s}

Source	Value	Stat. uncert.	Syst. uncert.	
A_{raw}	0.11	0.09	0.02	
$-A_{\text{track}}(K^+K^-)$	0.01	0.00	0.03	
$-A_{\text{track}}(\pi^-\mu^+)$	0.01	0.05	0.04	
$-A_{\text{PID}}$	-0.01	0.02	0.03	
$-A_{\text{trig}}$(hardware)	0.03	0.02	0.02	
$-A_{\text{trig}}$(software)	0.00	0.01	0.02	
$-f_{\text{bkg}}\ A_{\text{bkg}}$	0.02	–	0.03	+
$(1-f_{\text{bkg}})a_{\text{sl}}^{s}/2$	0.16	0.11	0.08	
$2/(1-f_{\text{bkg}})$	2.45	–	0.18	×
a_{sl}^{s}	0.39	0.26	0.20	