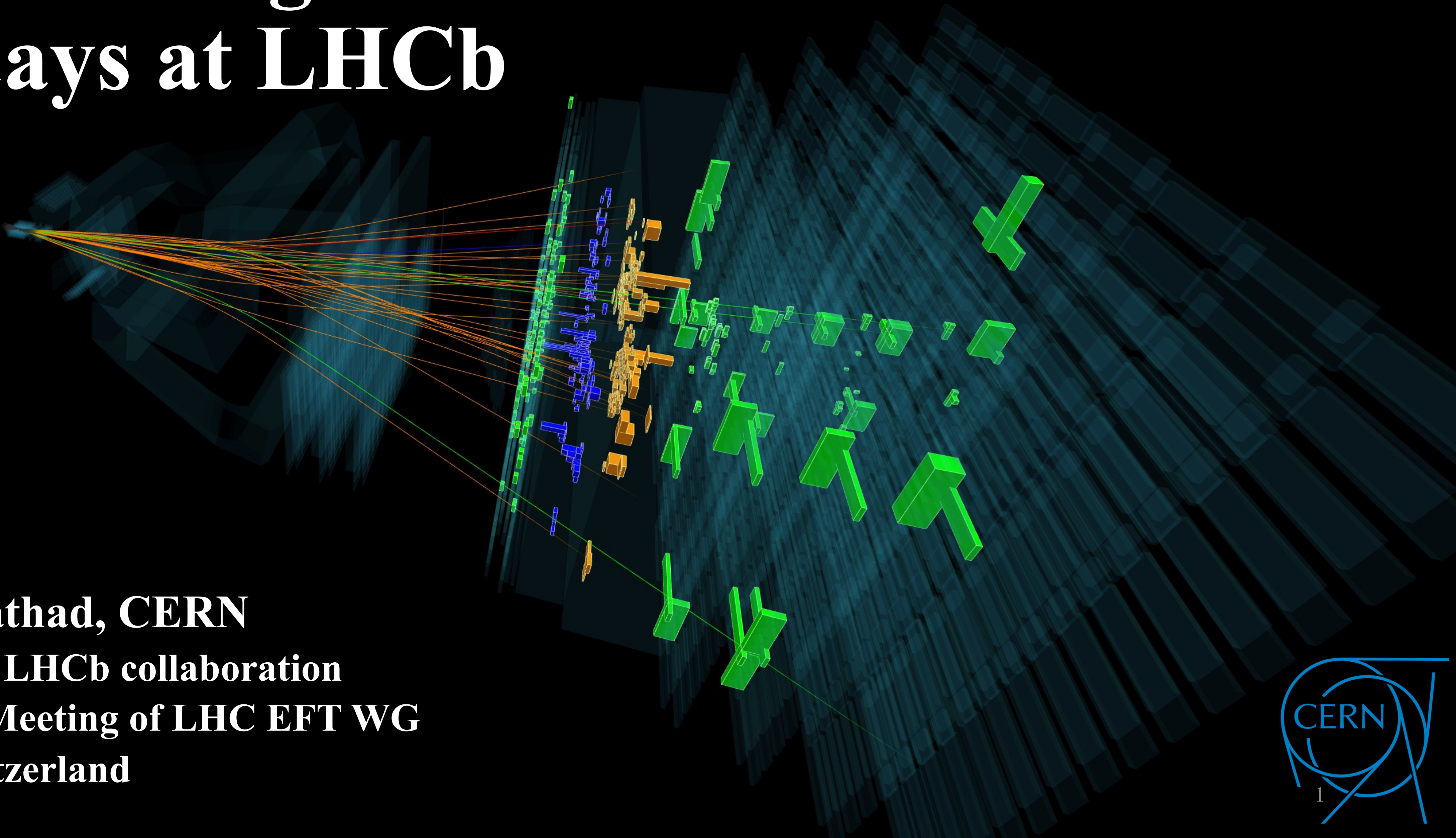
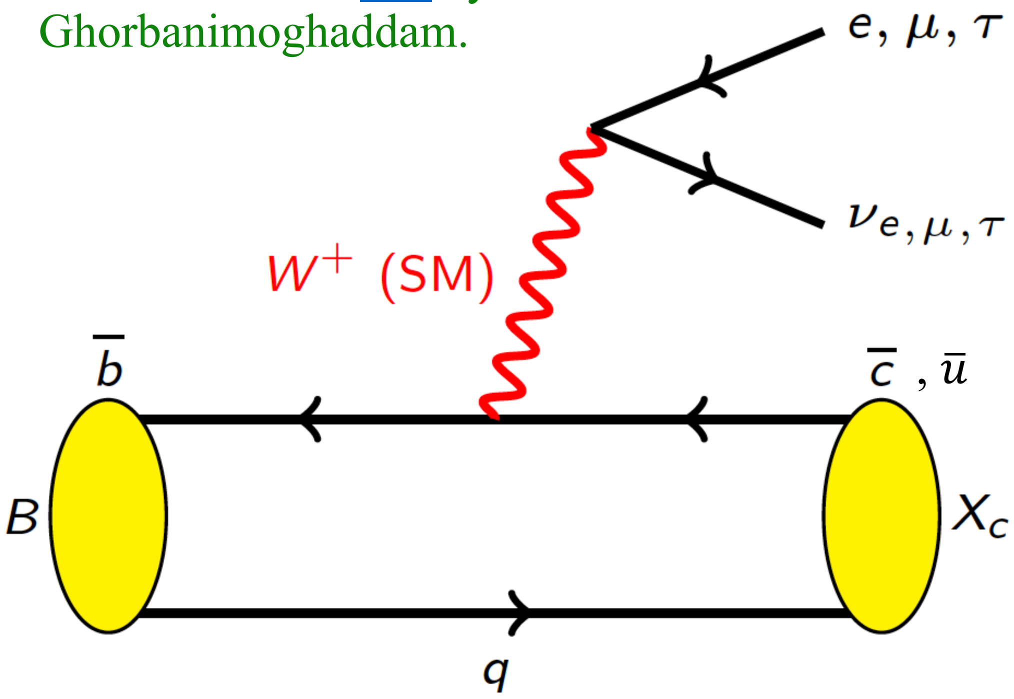
# EFT in charged current B decays at LHCb



**Abhijit Mathad, CERN**
**On behalf of LHCb collaboration**
**8th General Meeting of LHC EFT WG**
**Geneva, Switzerland**

# Paradise for SM precision tests

For neutral current: See talk by Zahra Ghorbanimoghaddam.

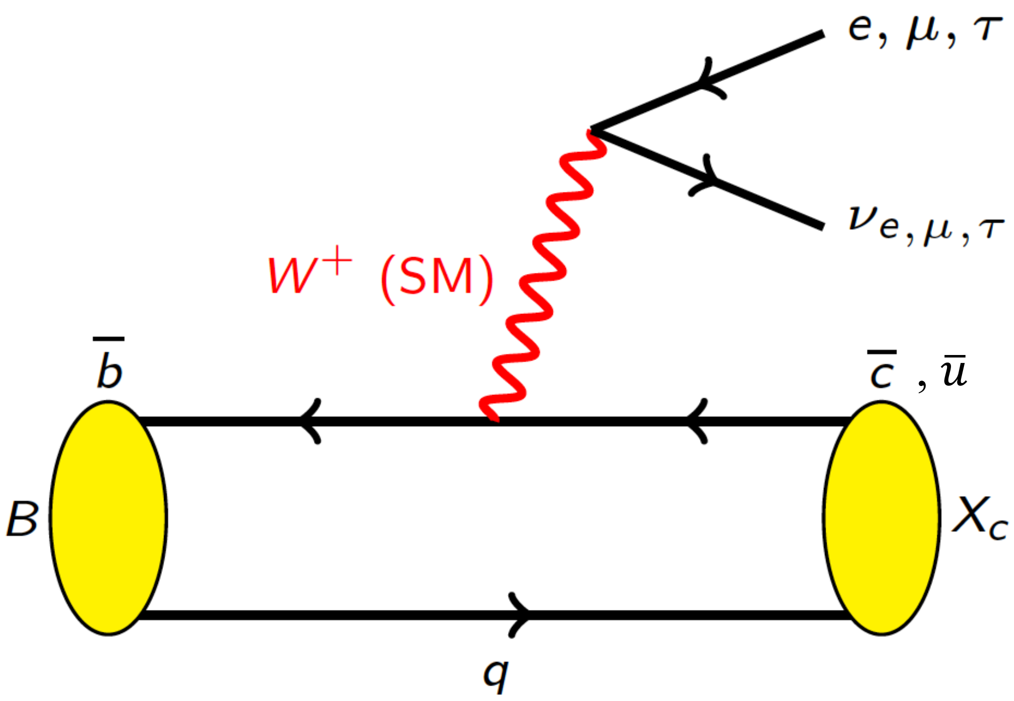



Charged current: BF~ few %.

**Probing indirectly energy regions ~ 10 TeV.**

Tree level decays perfect holiday destination?

# Trouble in paradise



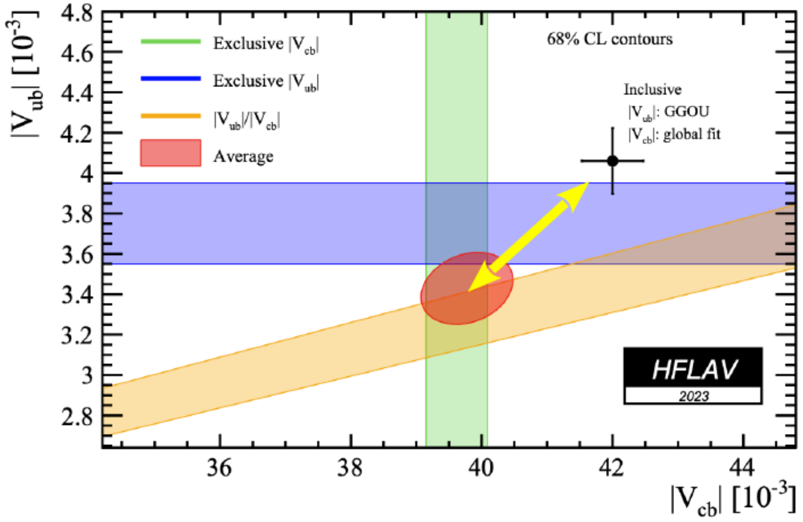


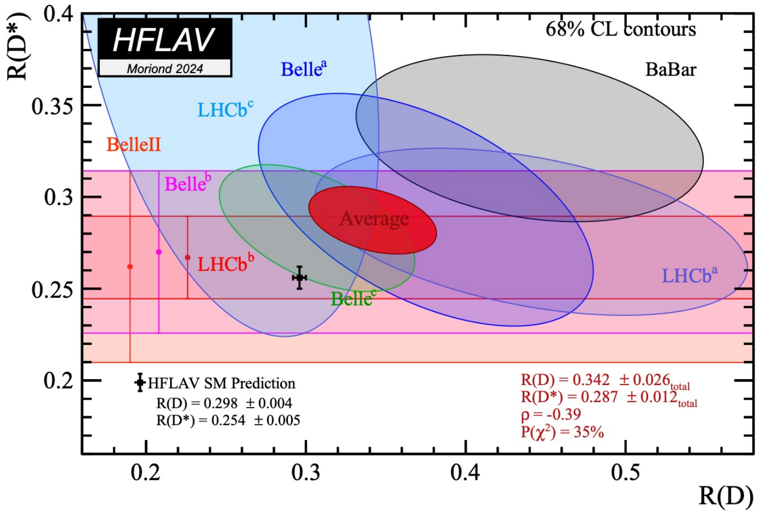
Charged current: BF~ few %.

**Probing indirectly energy regions ~ 10 TeV.**

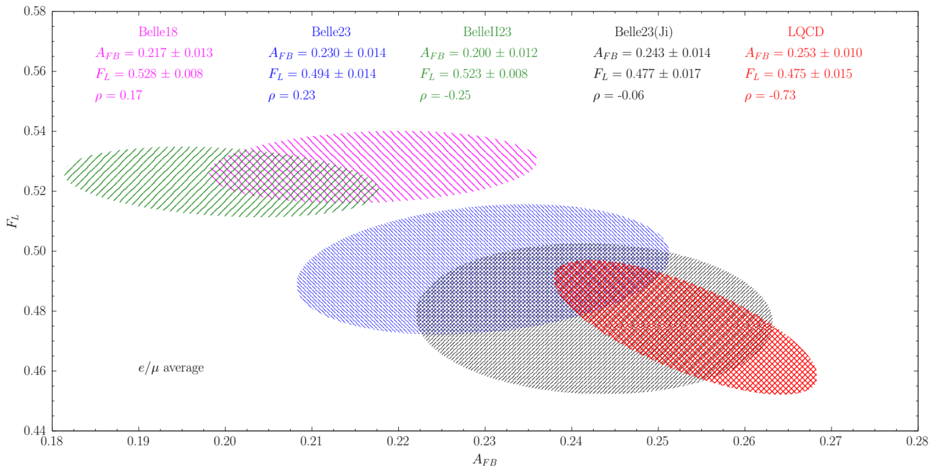
An island full of trouble…

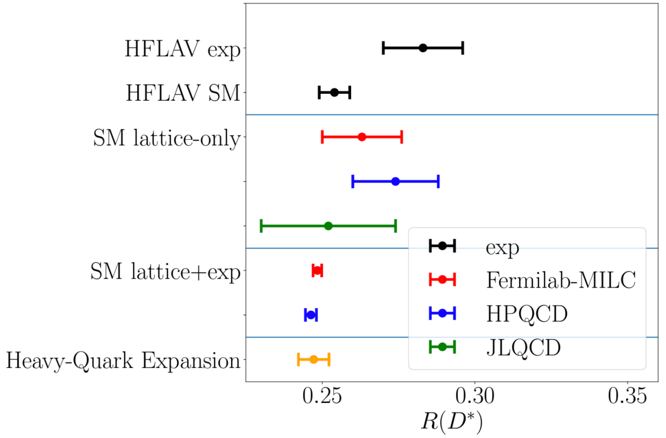
# Trouble in paradise



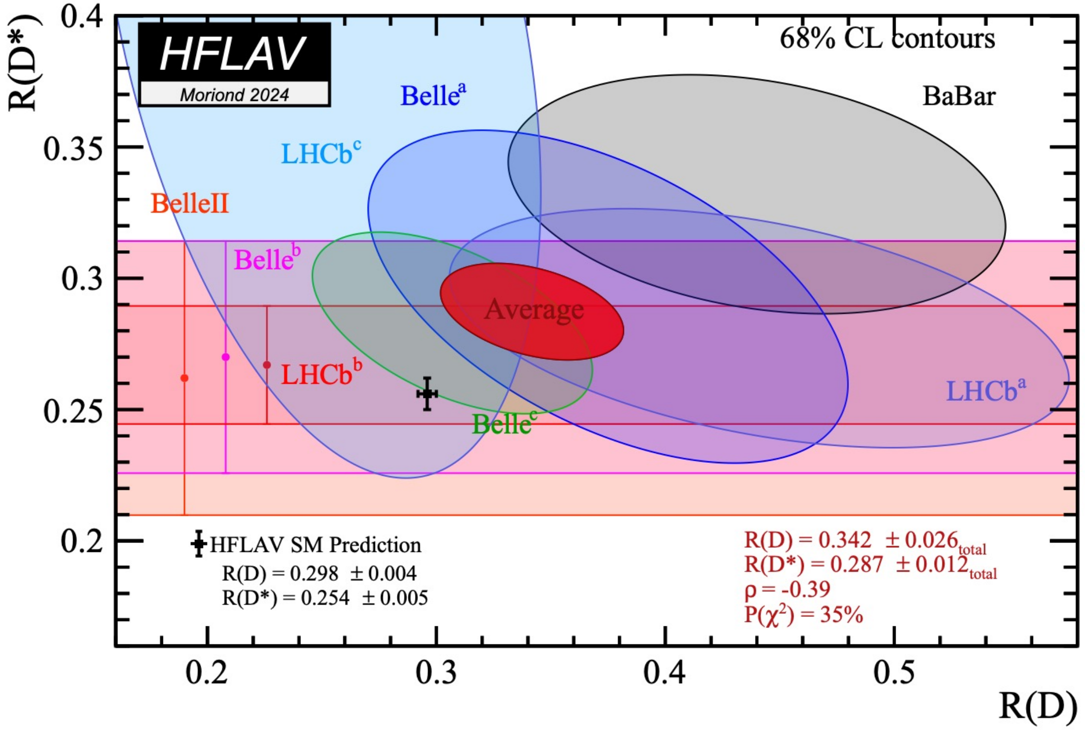

**Many descrepencies exist…**



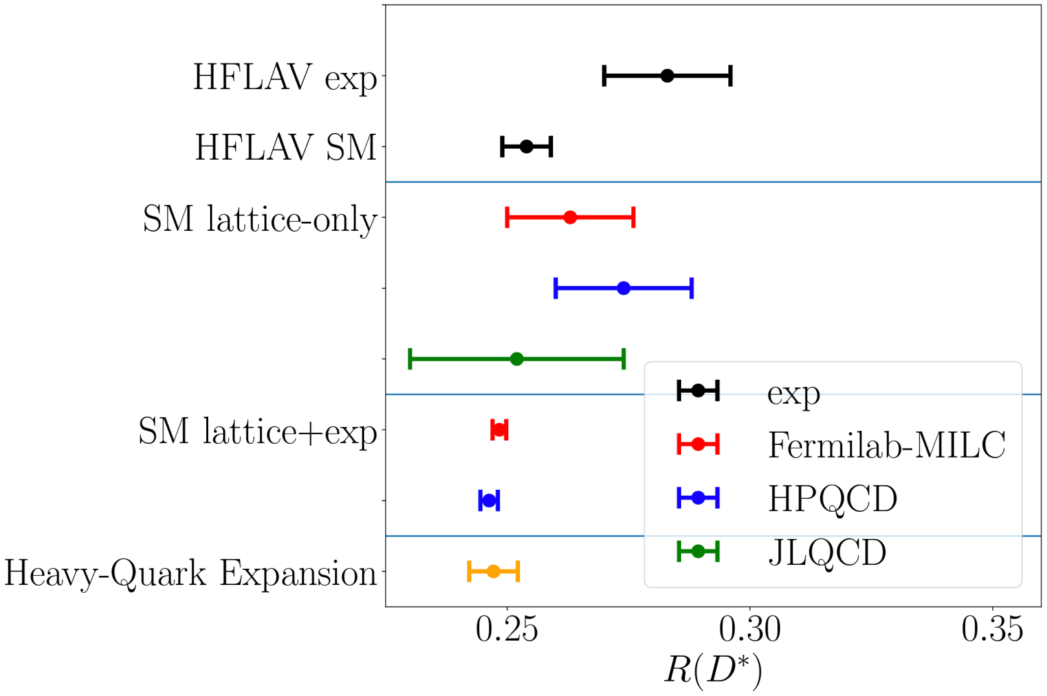
# Trouble involving 3rd gen leptons ($b \to c\tau\nu$)

LFU trouble (exp): ~ $3\sigma$ tension




LFU trouble (theory)

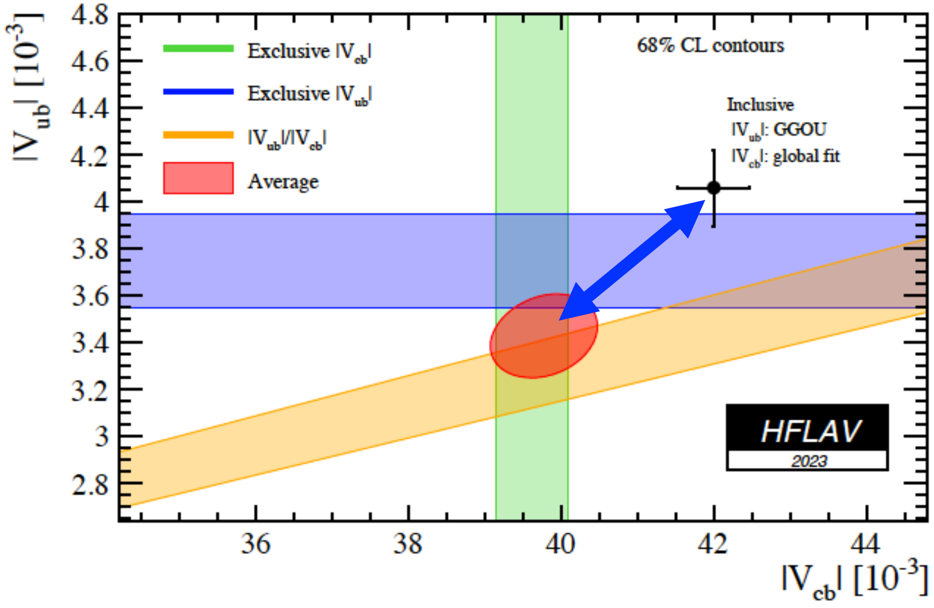
[Talk by Judd Harrison]




**NP? Can indep. measurements beyond simple BF ratio confirm/refute it?**

# All good with the lighter leptons $b \to xl\nu$? **No**

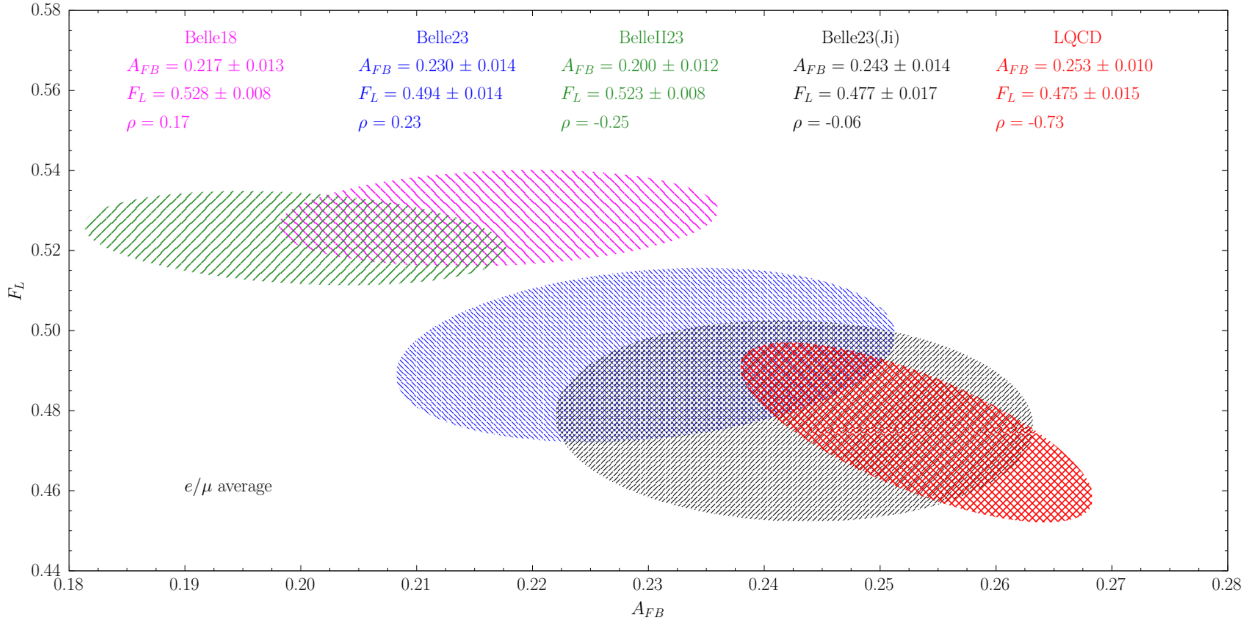
## Long standing tension ~ 3 $\sigma$




***CKM***: $V_{xb}$ **obtained via inclusive (e.g.** $B \to X_c l\nu$**) do not match exclusive (e.g.** $B \to D^* l\nu$**).**

## $A_{FB}$ Vs longitudinal polarisation of $D^*$

[Talk by Guido Martinelli]




**Differential distribution b/w experiments and LQCD don't agree!**

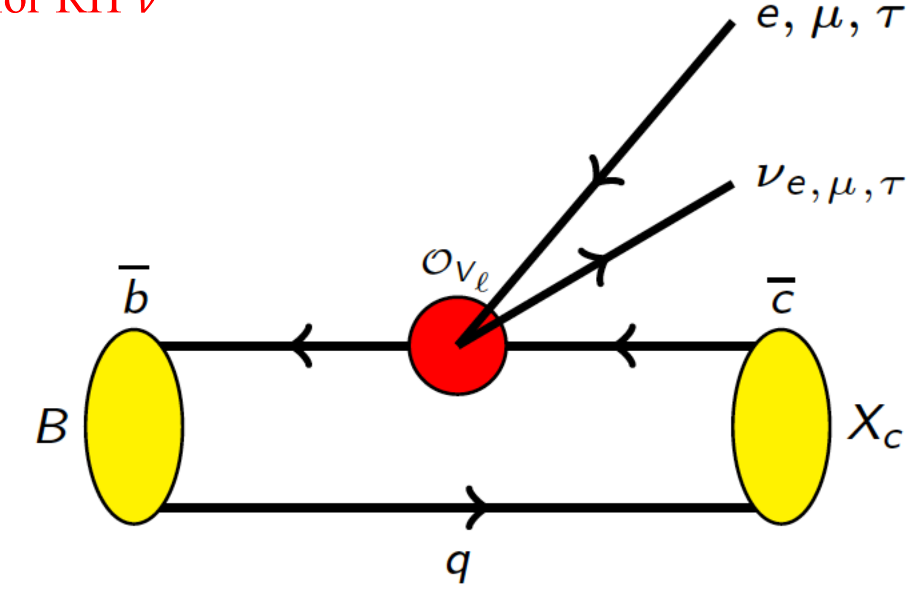
**At what level can New Physics (NP) affect the interactions with light leptons?**

# Effective Hamiltonian $b \to cl\nu$

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[ (1 + C_{V_L}) \mathcal{O}_{C_{V_L}} + C_{V_R} \mathcal{O}_{C_{V_R}} + C_{S_L} \mathcal{O}_{C_{S_L}} + C_{S_R} \mathcal{O}_{C_{S_R}} + C_{T_L} \mathcal{O}_{C_{T_L}} \right] + h.c.$$

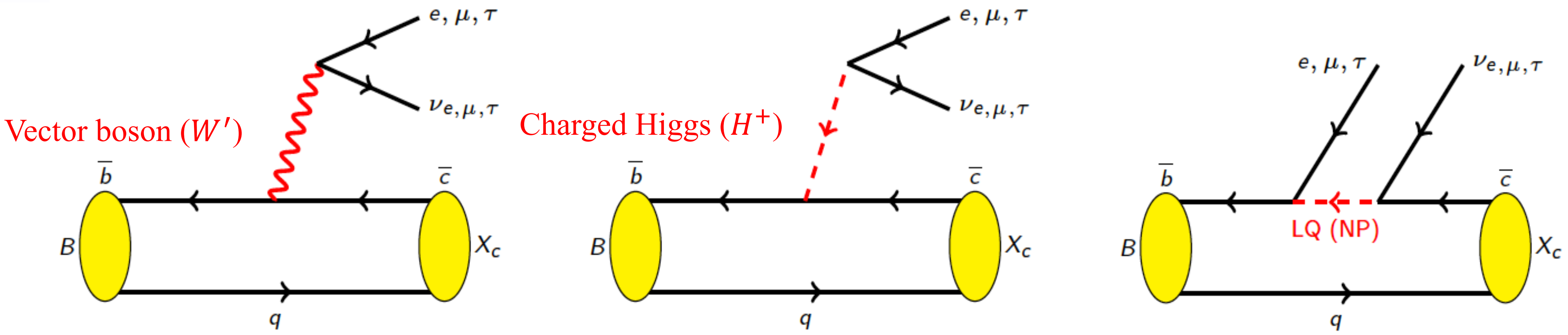
*Assuming left-handed $\nu$. Five more for RH $\nu$

| | | |
|---|---|---|
| **SM vector left-handed** | $\mathcal{O}_{C_{V_L}}$ | $= \bar{c}_L \gamma^\mu b_L \, \bar{\ell}_L \gamma_\mu \nu_L \,,$ |
| NP Vector right-handed | $\mathcal{O}_{C_{V_R}}$ | $= \bar{c}_R \gamma^\mu b_R \, \bar{\ell}_L \gamma_\mu \nu_L \,,$ |
| NP Scalar left-handed | $\mathcal{O}_{C_{S_L}}$ | $= \bar{c}_R b_L \, \bar{\ell}_R \nu_L \,,$ |
| NP Scalar right-handed | $\mathcal{O}_{C_{S_R}}$ | $= \bar{c}_L b_R \, \bar{\ell}_R \nu_L \,,$ |
| NP Tensor left-handed | $\mathcal{O}_{C_{T_L}}$ | $= \bar{c}_R \sigma^{\mu\nu} b_L \, \bar{\ell}_R \sigma_{\mu\nu} \nu_L$ |




**Need to disentangle short distance (WCs) from long distance (hadronic form factor)!**

# What New Physics models?

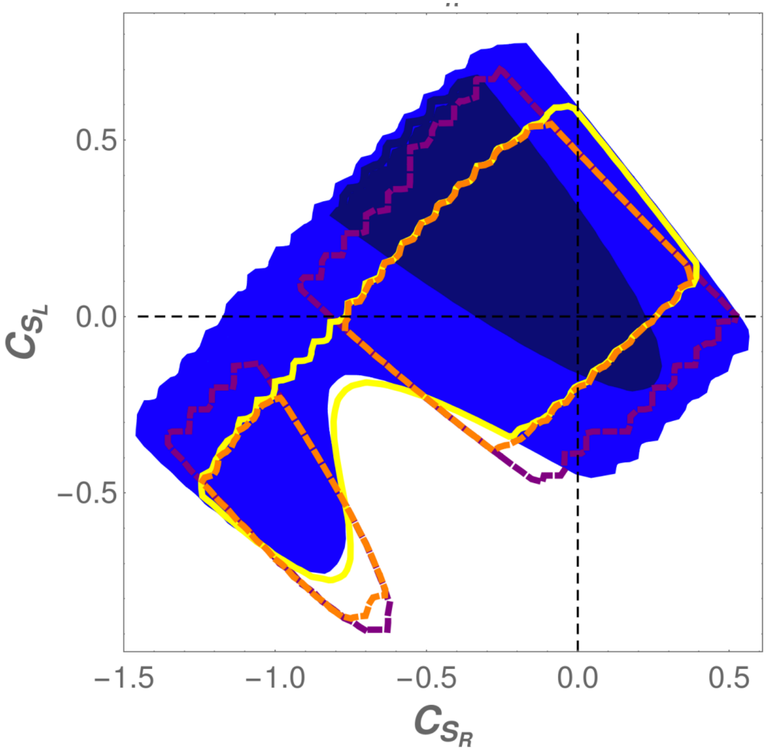



| Model | $C_{V_L}$ | $C_{V_R}$ | $C_{S_R}$ | $C_{S_L}$ | $C_T$ | $C_{S_L} = 4C_T$ | $C_{S_L} = -4C_T$ |
|---|---|---|---|---|---|---|---|
| Vector-like singlet | × | | | | | | |
| Vector-like doublet | | × | | | | | |
| $W'$ | × | | | | | | |
| $H^{\pm}$ | | | × | × | | | |
| $S_1$ | × | | | | | | × |
| $R_2$ | | | | | | × | |
| $S_3$ | × | | | | | | |
| $U_1$ | × | | × | | | | |
| $V_2$ | | | × | | | | |
| $U_3$ | × | | | | | | |

**Note: No single NP model can give rise to tensor alone!**

# Current bounds from global fits

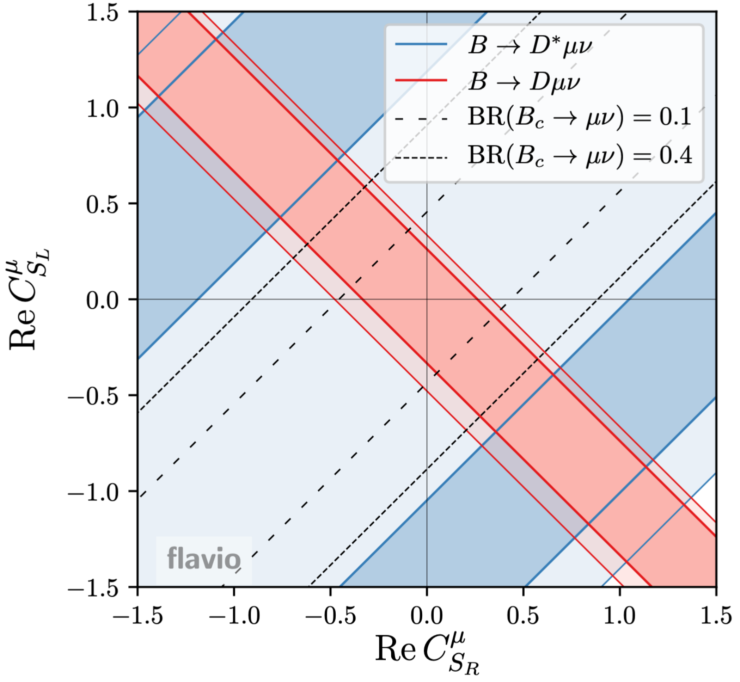
### $b \to c\tau\nu$



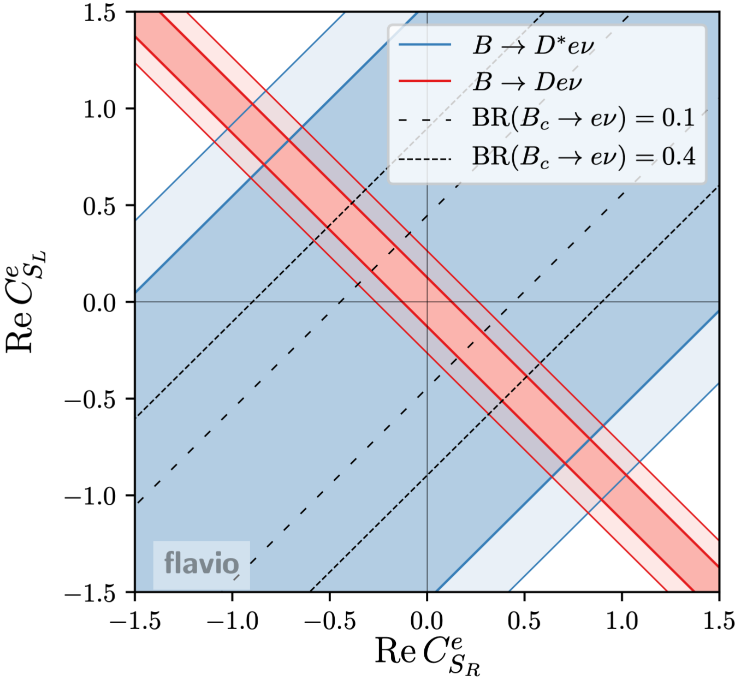

[KEK-TH-2464, JHEP 09 (2019) 103]

**Loose bounds on NP!**

### $b \to c\mu\nu$




### $b \to ce\nu$




**Darker band: 68% CL**
**Lighter band: 95% CL**

[M. Jung, D. Straub]

**NP can affect light leptons at per mille level!**

# Challenges at LHC

Reconstructing B rest frame with missing neutrinos


Model independence

Degradation in resolution

Large calibrated simulation samples

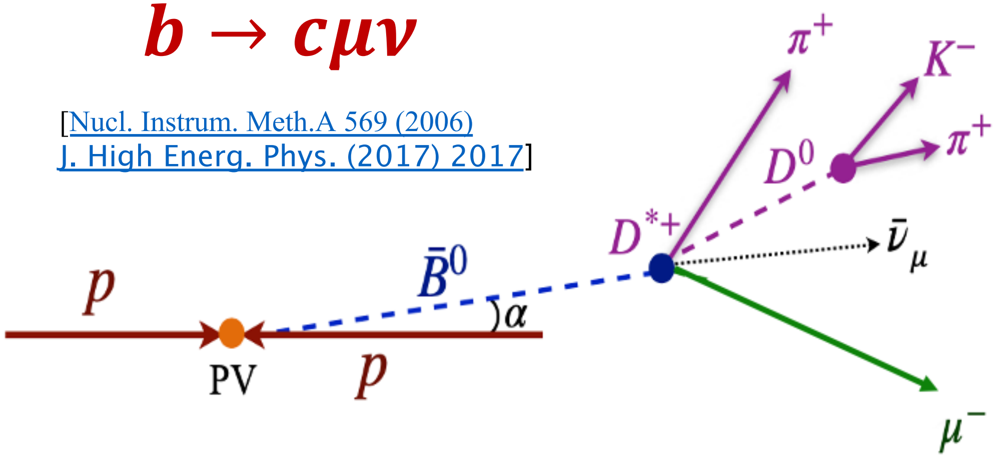
Signal & bkg discremination

Large varied bkg knowledge required

# Challenges at LHC: B rest frame reconstruction

**$b \to c\mu\nu$**

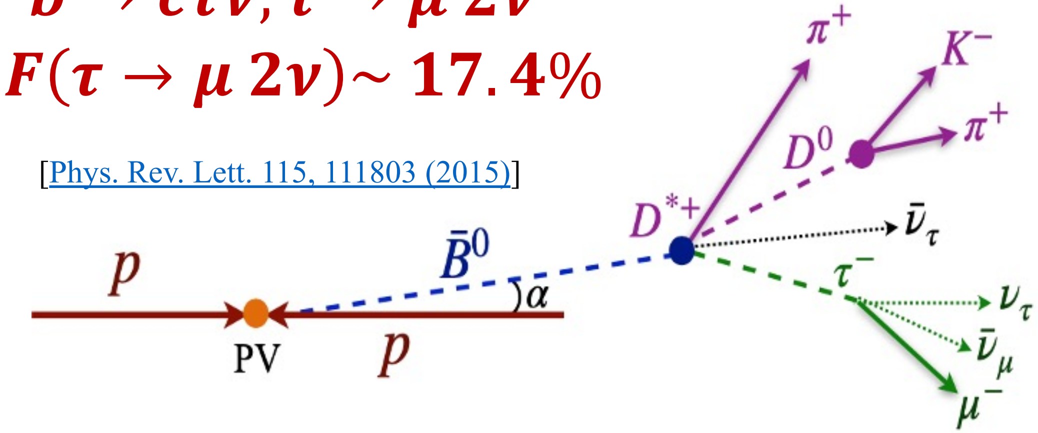
[Nucl. Instrum. Meth.A 569 (2006)
J. High Energ. Phys. (2017) 2017]




B mom. reconstructed with **quadratic ambiguity**

**$b \to c\tau\nu; \tau \to \mu\, 2\nu$**
**$BF(\tau \to \mu\, 2\nu) \sim 17.4\%$**

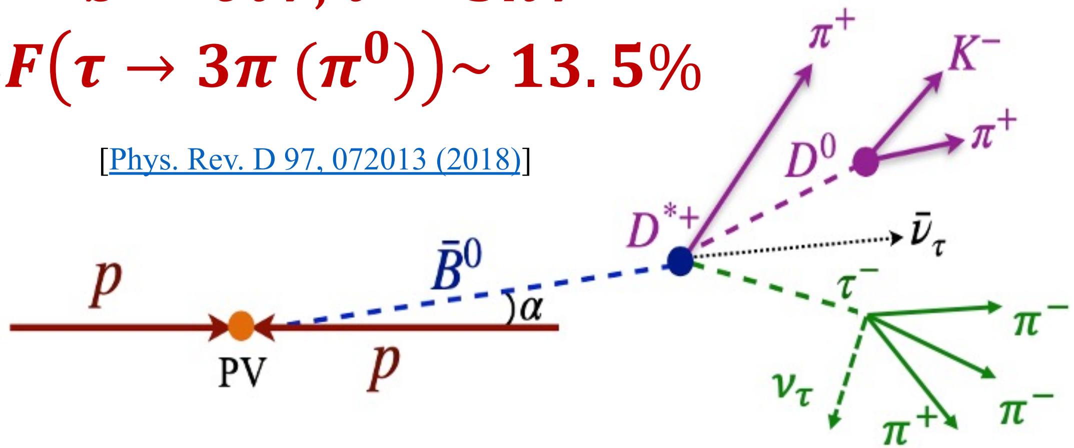
[Phys. Rev. Lett. 115, 111803 (2015)]




B mom. reconstructed with **rest frame approx.: $p_B^{\parallel} \propto p_{vis}^{\parallel}$**

**$b \to c\tau\nu; \tau \to 3\pi\nu$**
**$BF(\tau \to 3\pi\, (\pi^0)) \sim 13.5\%$**

[Phys. Rev. D 97, 072013 (2018)]



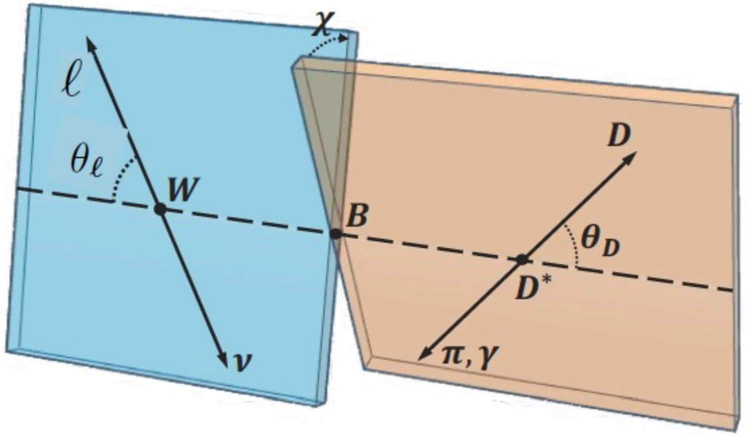

B mom. reconstructed upto **two quadratic ambiguities** (4 solutions).

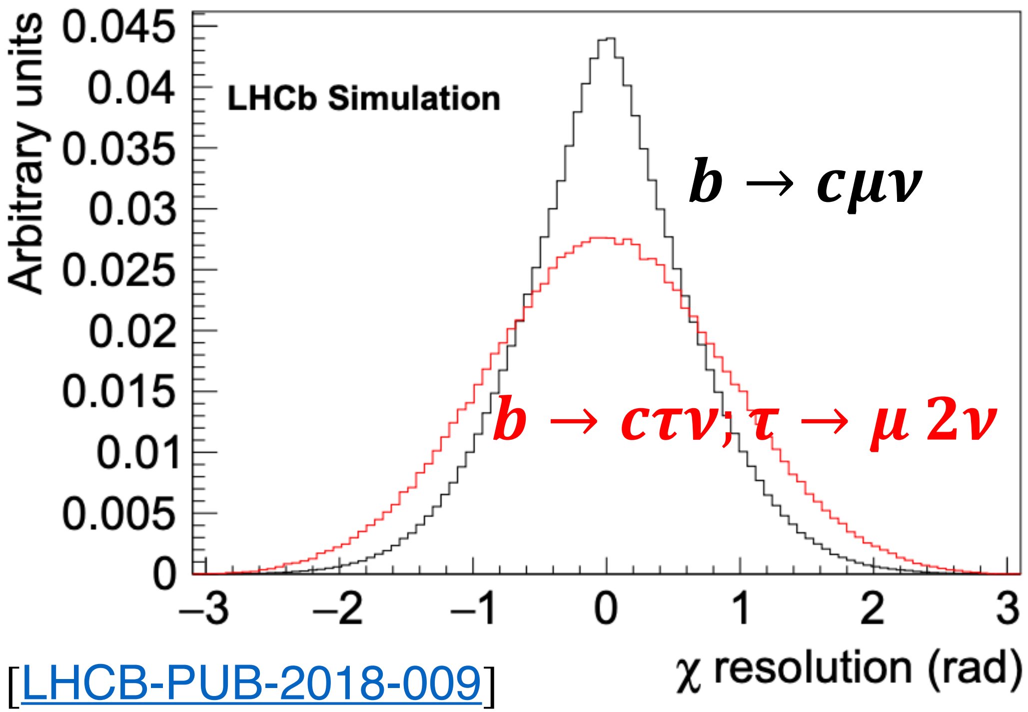
**Use ML techniques (e.g. Gaussian Process regression) to break the ambiguities.**

# Challenges at LHC: Resolution degradation

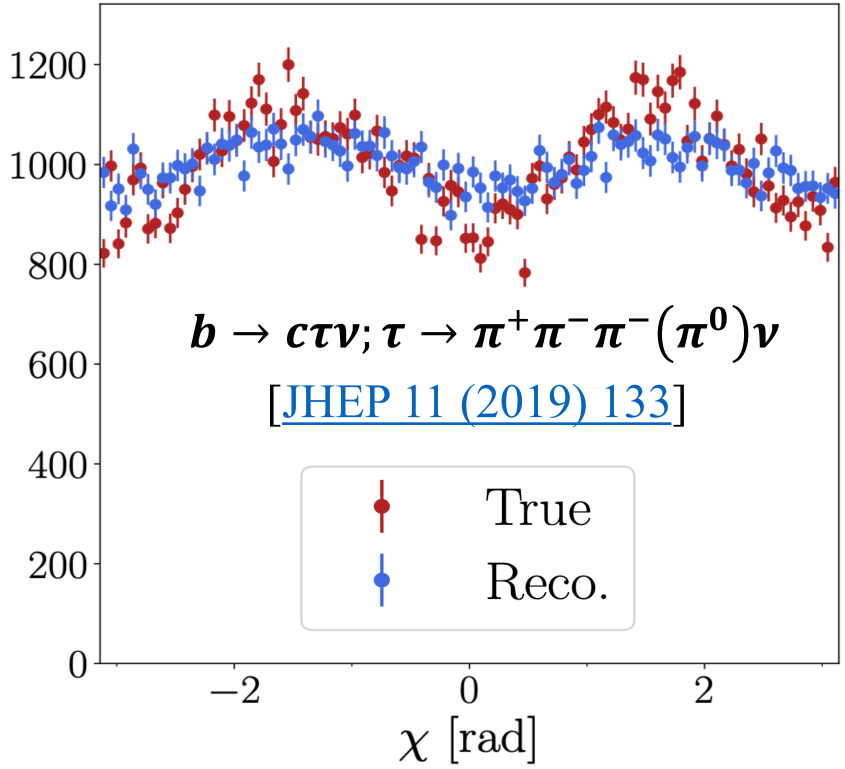
**Muonic tau**: Large yield but worse resolution.

**Hadronic tau:** Good resolution lower reco. efficiency



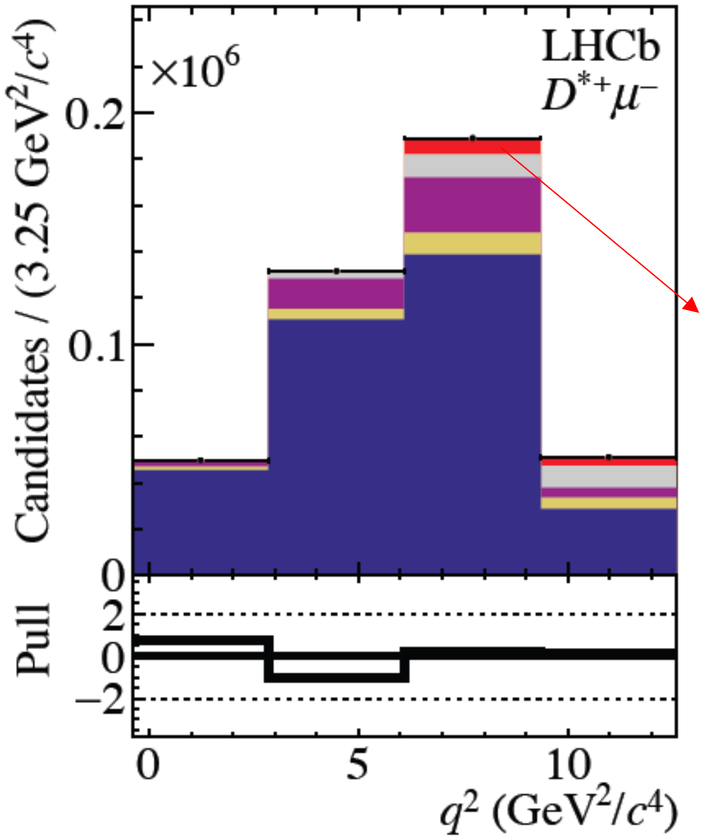




[LHCB-PUB-2018-009]



# Challenges at LHC: Large backgrounds

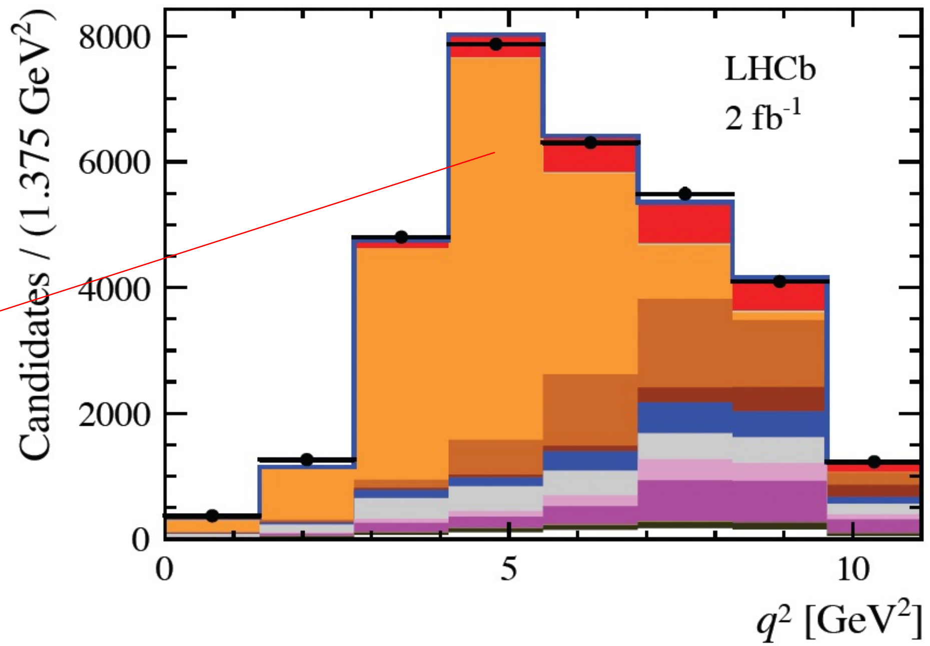
$b \to c\tau\nu; \tau \to \mu\, 2\nu$




[Phys. Rev. Lett. 131 (2023) 111802]

Our signal!
Requires excellent control over the backgrounds!

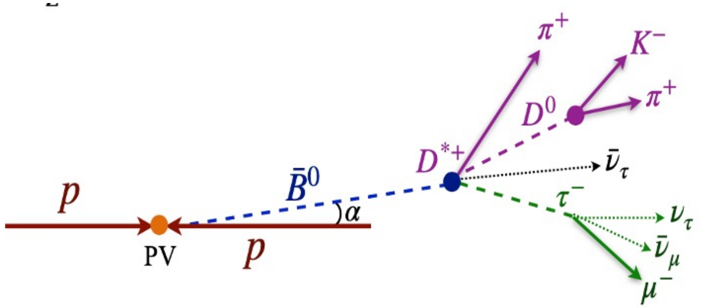
$b \to c\tau\nu; \tau \to \pi^+\pi^-\pi^-(\pi^0)\nu$



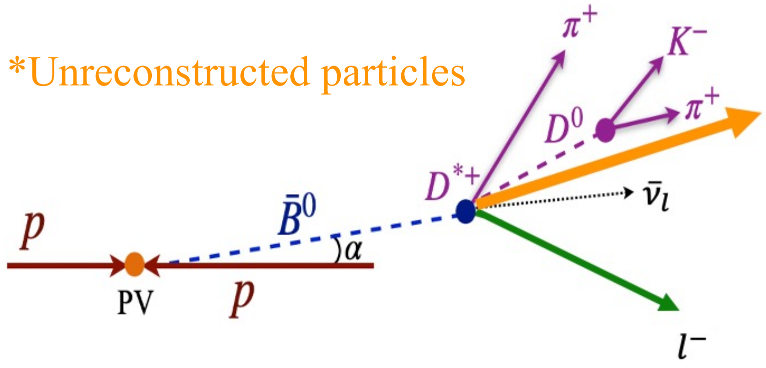

[Phys. Rev. D108 (2023) 012018]

# Challenges at LHC: Which bkgs for muonic $\tau$?

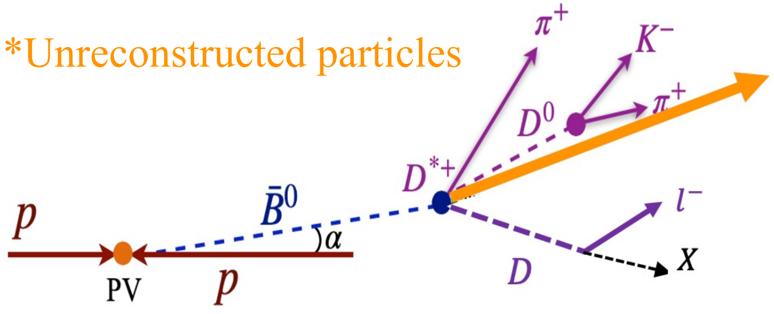
**Signal:**
$\bar{B} \to D^{*}\tau^{-}\nu$



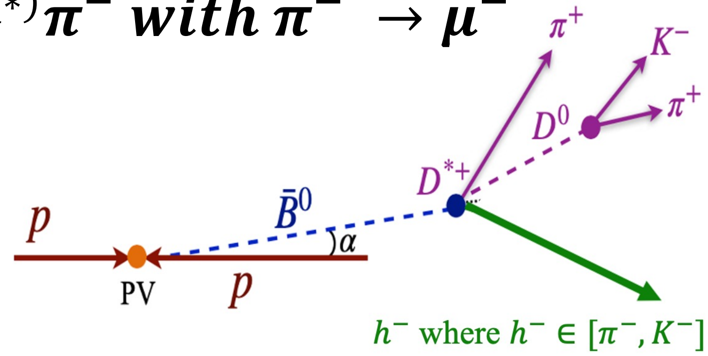

**Feed down bkg:**
$\bar{B} \to D^{**}(\to D^{(*)}\pi^{-})\, l^{-}\nu$




**Double charm bkg:**
$\bar{B} \to D^{(*)}D(\to l^{-}X)K$



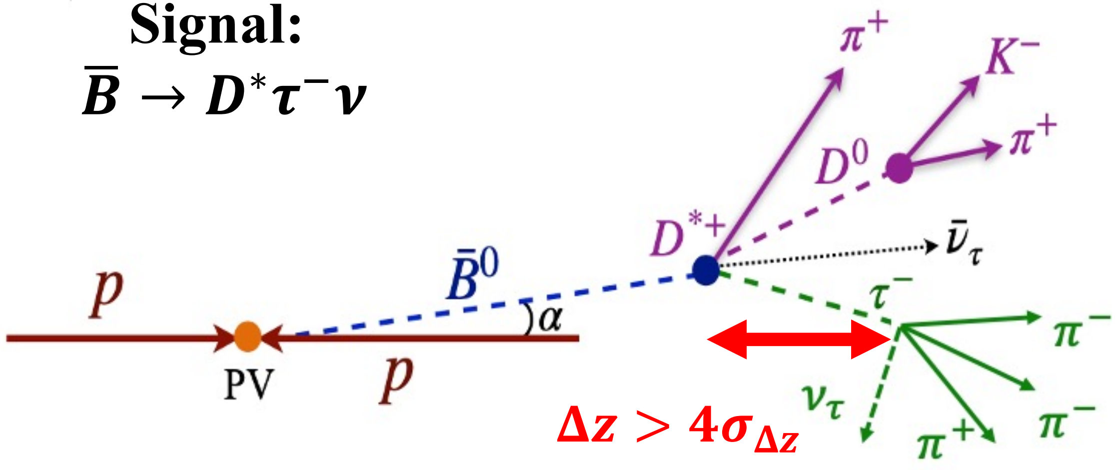

**MisID bkg:**
$\bar{B} \to D^{(*)}\pi^{-}\ with\ \pi^{-} \to \mu^{-}$



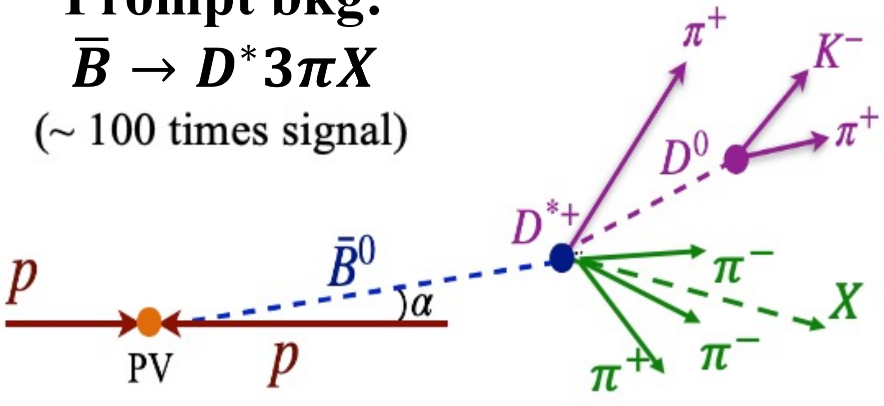

- Reduce bkg from isolation and particle ID.
- Residual bkg knowledge via data-driven studies!

# Challenges at LHC: Which bkgs for hadronic $\tau$?

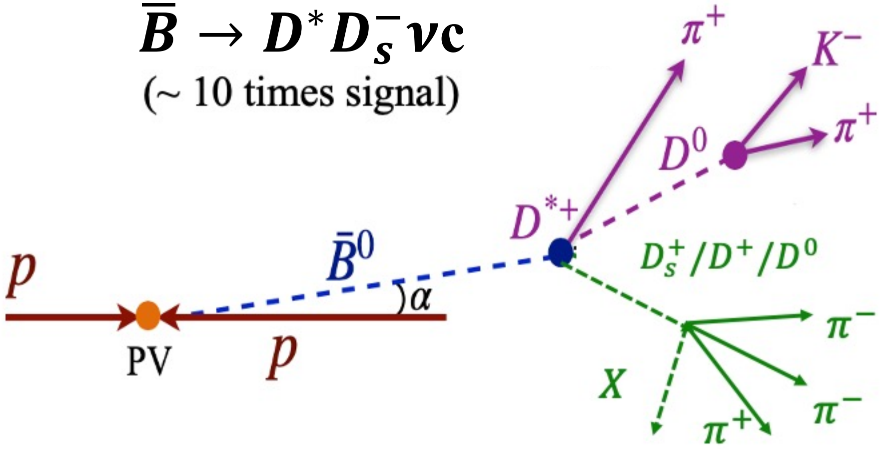
**Signal:**
$\bar{B} \to D^{*}\tau^{-}\nu$




**Prompt bkg:**
$\bar{B} \to D^{*}3\pi X$
(~ 100 times signal)



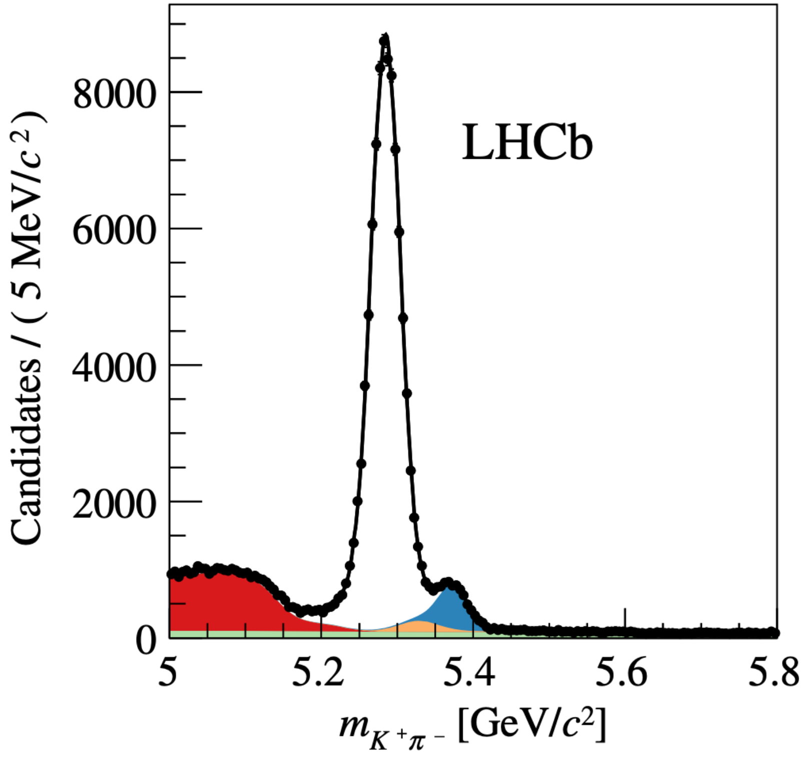

**Double charm:**
$\bar{B} \to D^{*}D_s^{-}\nu c$
(~ 10 times signal)




- Reduce prompt bkg where $\tau^-$ vertex downstream of B.
- Residual bkg knowledge via data-driven studies!

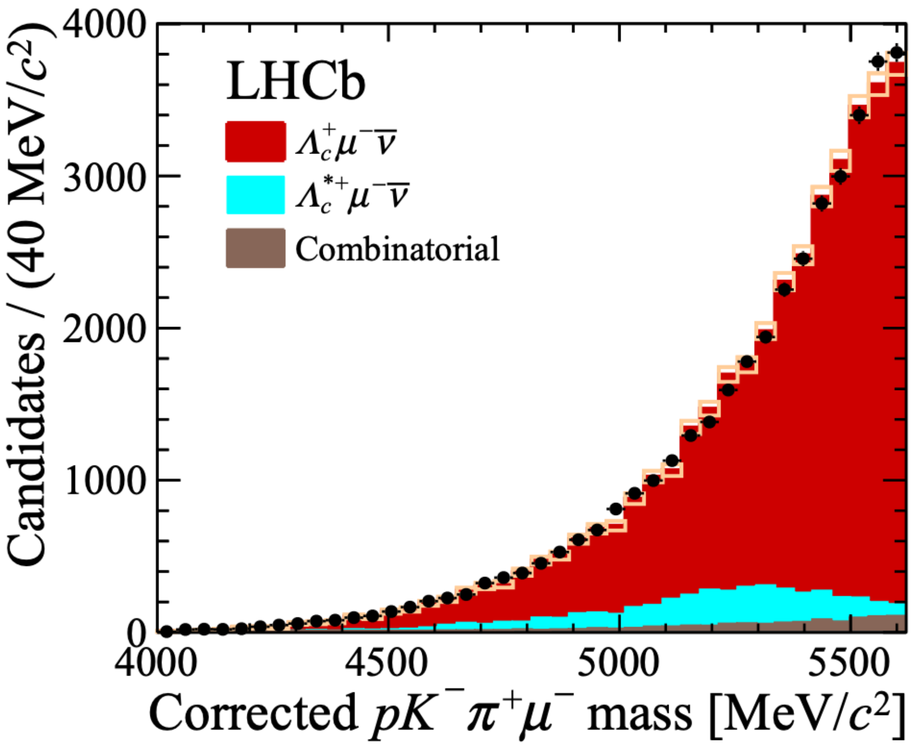
# Challenges at LHC: Signal & bkg discrimination

[Phys. Rev. D 98 (2018) 032004]




Beautiful peaks for fully reconstructed B decays!

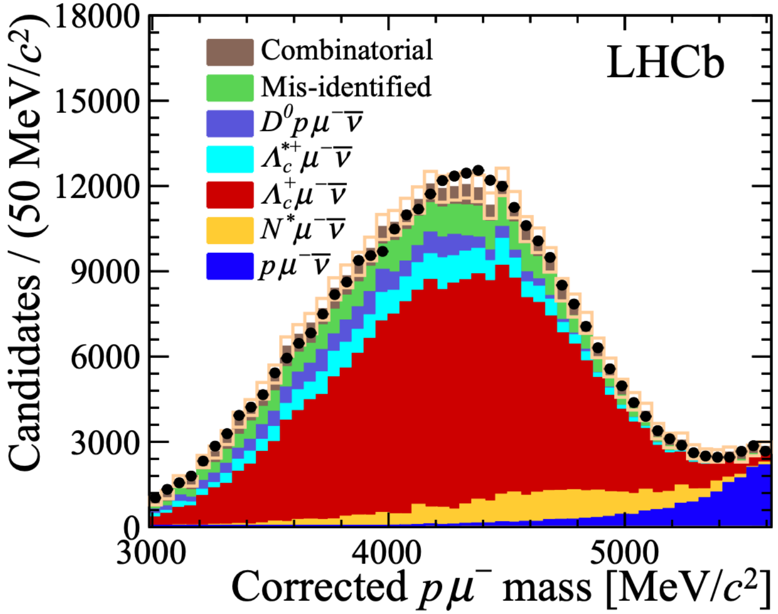
[Nature Phys. 11 (2015) 743-747]




No peaks, continuum distributions with missing neutrinos!

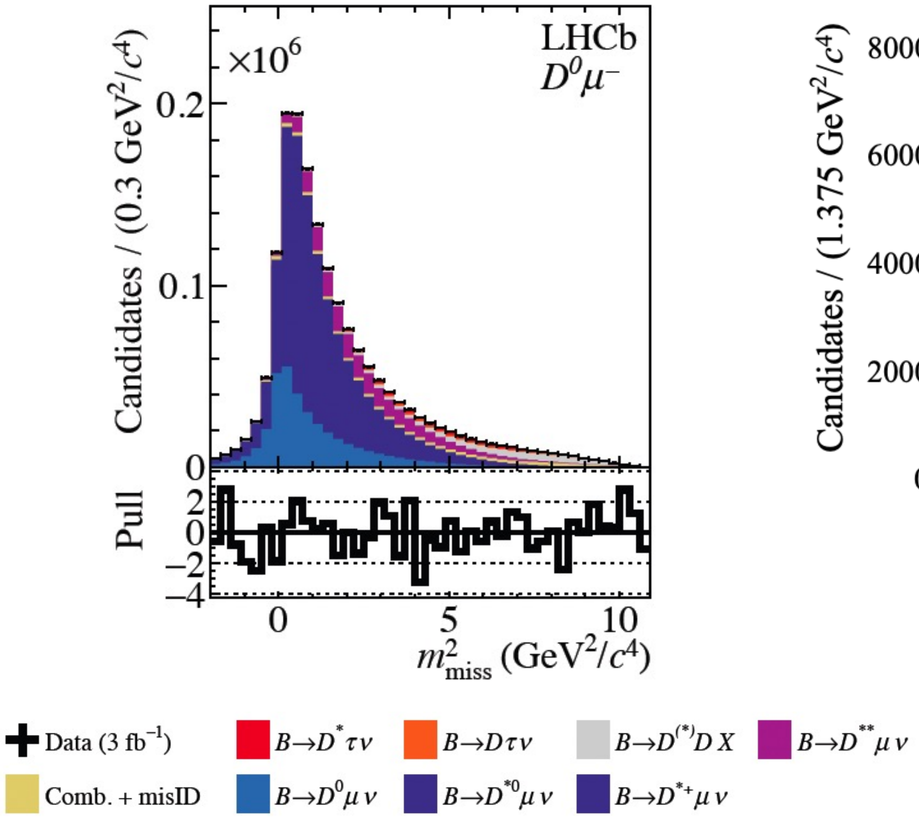
# Challenges at LHC: Signal & bkg discrimination

| $b \to cl\nu$; *light leptons* | $b \to c\tau\nu$; *Muonic* $\tau$ | $b \to c\tau\nu$; *Hadronic* $\tau$ |
| --- | --- | --- |

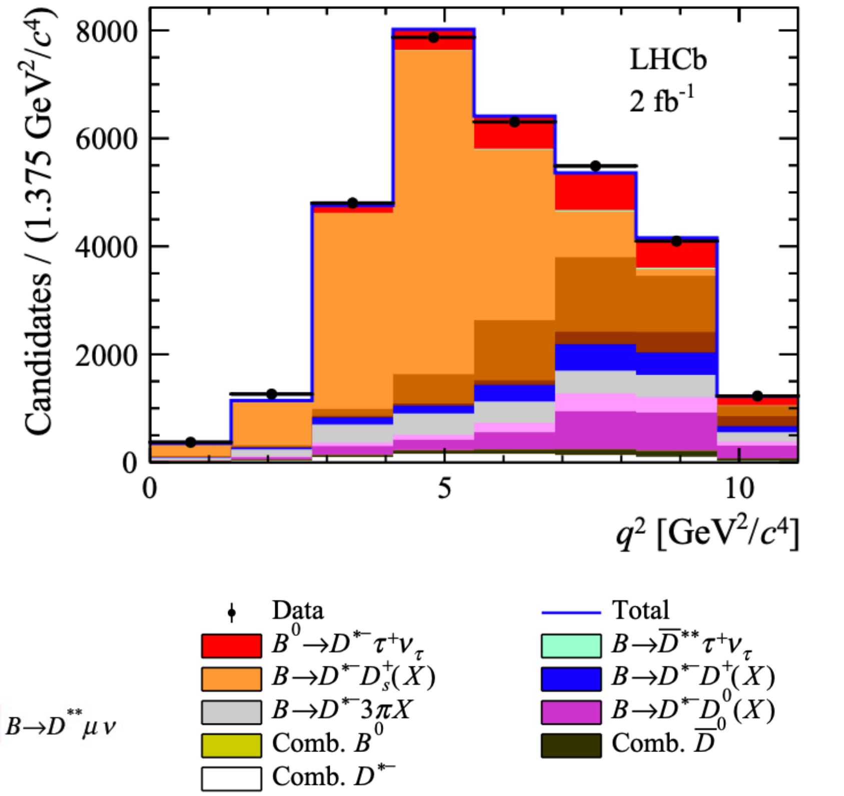



$$m_{\text{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$

**1D fit to corrected mass fits in phase space bins**




**3D template fit to $q^2$, $m^2_{miss}$ and $E_l^*$.**




**3D fit to $q^2$, anti-$D_s^+$ BDT output and $\tau$ lifetime.**

# Analysis covered

- **$D^*$ polarisation in $B \to D^*\tau\nu$**
- **Angular coefficients with $B \to D^*\tau\nu$**
- **Wilson coefficients with $B \to D^*\tau\nu$**
- **CP-odd observables with $B \to D^*\mu\nu$**
- **Angular analysis of $\Lambda_b \to \Lambda_c\mu\nu$**

# $D^*$ polarization in $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_l$

[LHCb-PAPER-2023-020]
(Accepted by PRD)

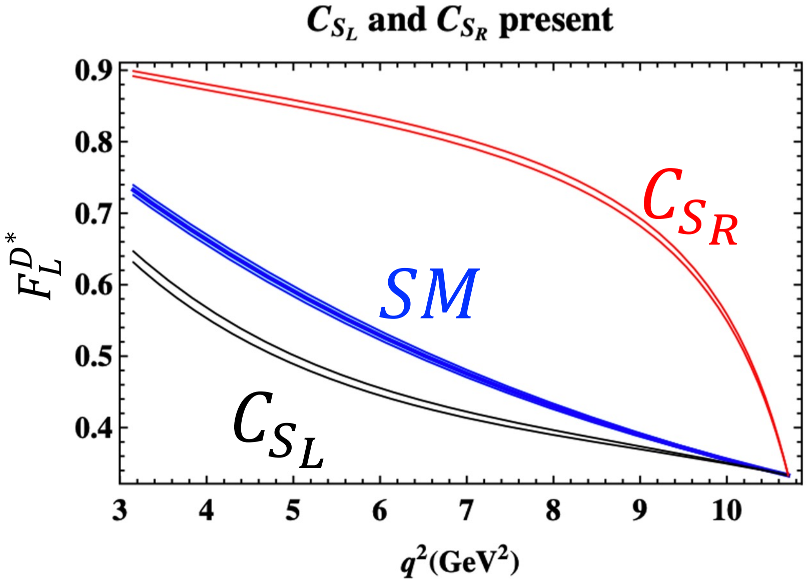
[Phys. Rev. D 95 (2017) 115038]

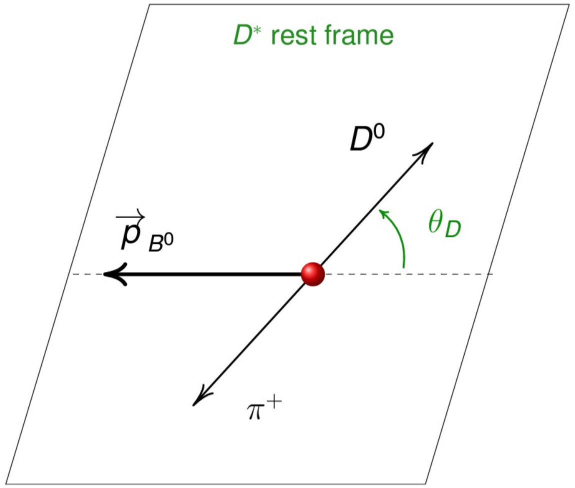
- Use Run 1 ( 3 $fb^{-1}$) and partial Run 2 (2 $fb^{-1}$).
- NP can strongly affect $F_L^{D^*}(q^2)$ even if LFU ratios align with SM predictions.

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

$a_{\theta_D} \propto N_{unpolarised}$ $c_{\theta_D} \propto N_{polarised}$

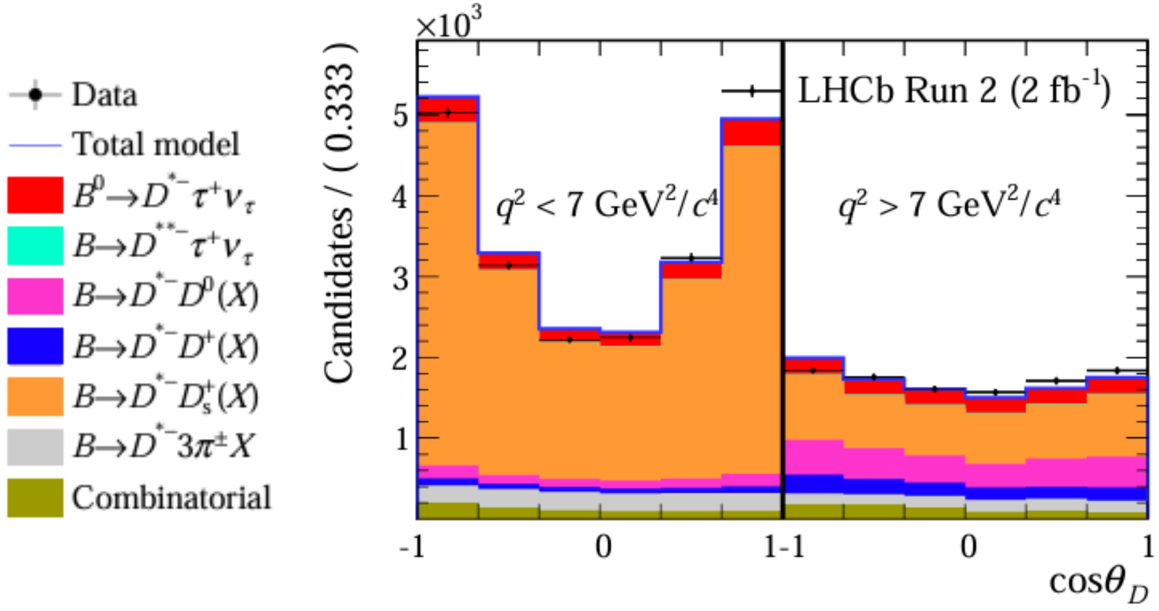


# Fit for $F_L^{D^*}$

[LHCb-PAPER-2023-020]
(Accepted by PRD)

- ➢Measure $F_L^{D^*}$ in two $q^2$ bins: $\lessgtr 7\ GeV^2$.
- ➢Data-driven correction to the $\cos(\theta_D)$ for double charm ($\bar{B}^0 \to D^{*+} D\ (\to 3\pi^{\pm})\ X$).
- ➢4D template fit to $q^2$, $\cos(\theta_D)$, anti-$D_s^+$ BDT output and $\tau$ lifetime.



# $F_L^{D^*}$ results

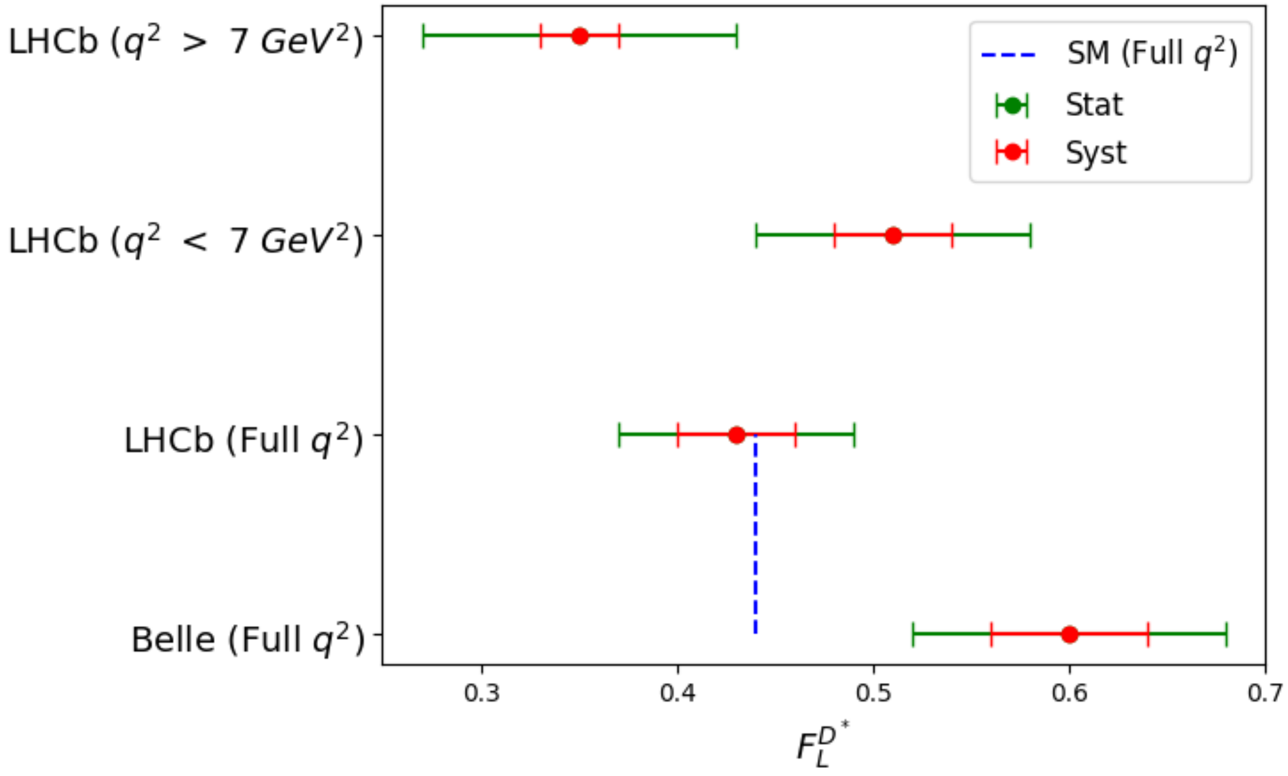
[LHCb-PAPER-2023-020]
(Accepted by PRD)

| | |
|---|---|
| $q^2 < 7\,\mathrm{GeV}^2/c^4$ : | $0.51 \pm 0.07(stat) \pm 0.03(syst)$ |
| $q^2 > 7\,\mathrm{GeV}^2/c^4$ : | $0.35 \pm 0.08(stat) \pm 0.02(syst)$ |
| $q^2$ whole range : | $0.43 \pm 0.06(stat) \pm 0.03(syst)$ |

→ Compatible with both SM and previous Belle measurement

**Major systematics**

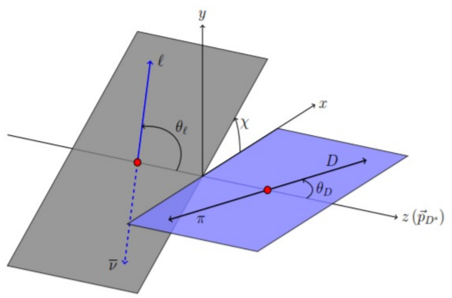
- Simulation sample size and modelling signal and bkg.

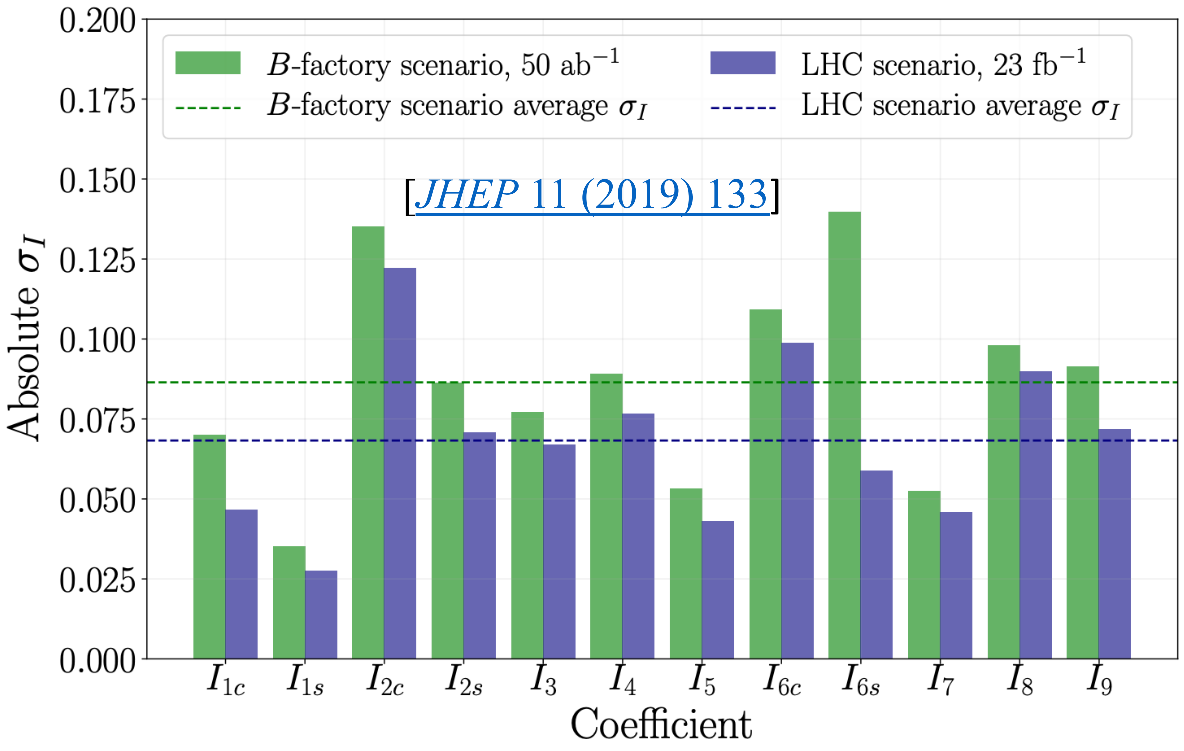


# Angular coefficients in $B \to D^* l\nu$

Fit for 12 angular coefficients which are model-independent and integrated over $q^2$

$$\frac{d^4\Gamma}{dq^2\, d(\cos\theta_D)\, d(\cos\theta_L)\, d\chi} \propto I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L + [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L + [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D + [I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D + [I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D\,,$$



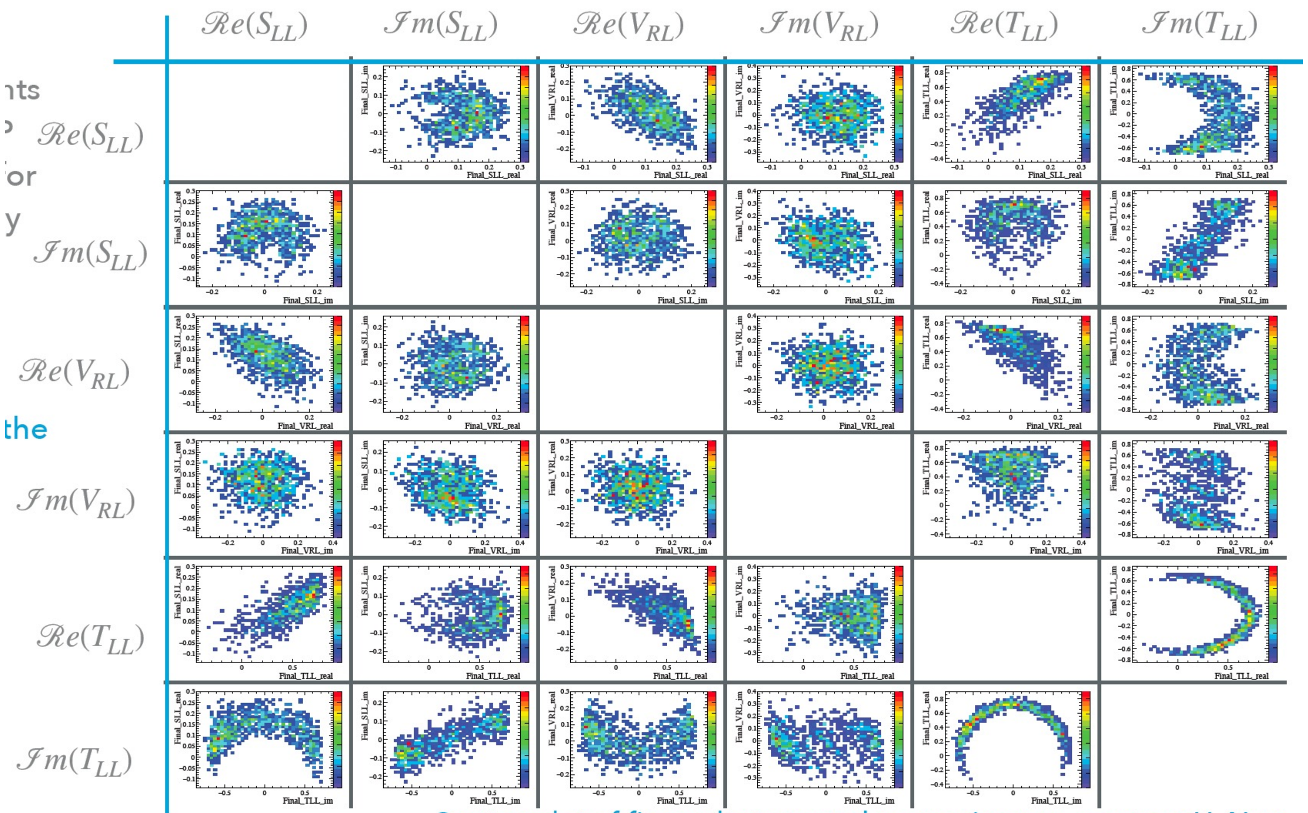



**Ongoing analysis with $B \to D^*\mu(e)\nu$ (to be published next year) and plans with $B \to D^*\tau\nu$!**

# Wilson coefficients in $B \to D^* l\nu$

[Talk](#) by Lucia Grillo
Results of toy fits.

- Another model-independent approach is to fit for WC directly.
- Template fit to 5D distributions (3 angles, dilepton spectrum and missing mass).
- Simulations are weighted to NP scenario at each minimisation step using [HAMMER](#).
- Hadronic form factor parameters also fitted simultaneously in three different parametrisations.




Scatter plot of fit results to pseudo-experiments, courtesy H. Nur

**Ongoing analysis with $B \to D^*\mu\nu$ (to be published next year) and plans with $B \to D^*\tau\nu$!**

# CP-odd observables in $B^0 \to D^{*-}\mu\nu$ [D London et al]

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

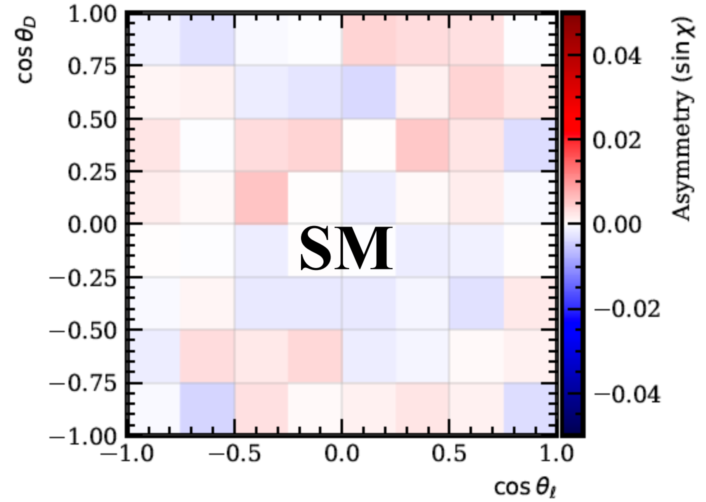
$$P_{\rm odd}(\Omega) = P_{\rm odd}^{(1)} \sin\chi + P_{\rm odd}^{(2)} \sin 2\chi$$

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

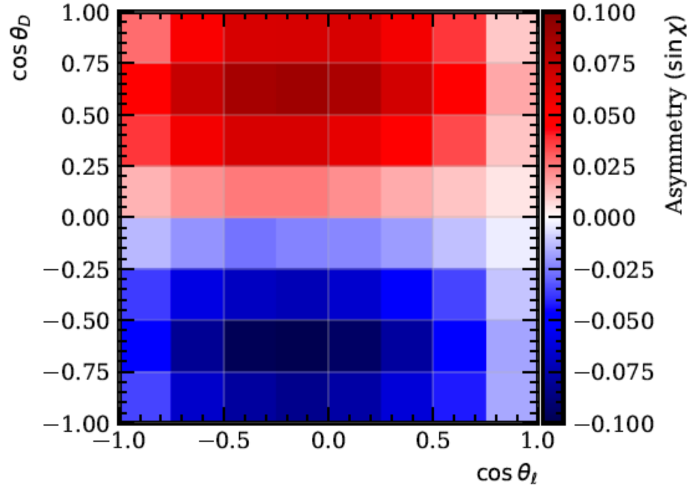
| Amplitude term | Coupling | Angular function |
|---|---|---|
| $\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$ | $\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$ | $-\sqrt{2}\sin 2\theta_\ell \sin 2\theta_D \sin\chi$ |
| $\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$ | $\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$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

$Im(A_i A_j^*)$ non-zero when:

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




$g_P g_T^* = 0.1i$



# CP-odd sensitivity in $B^0 \to D^{*-}\mu\nu$

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

**$CP$ asymmetries:**

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

**Central values are blinded.**

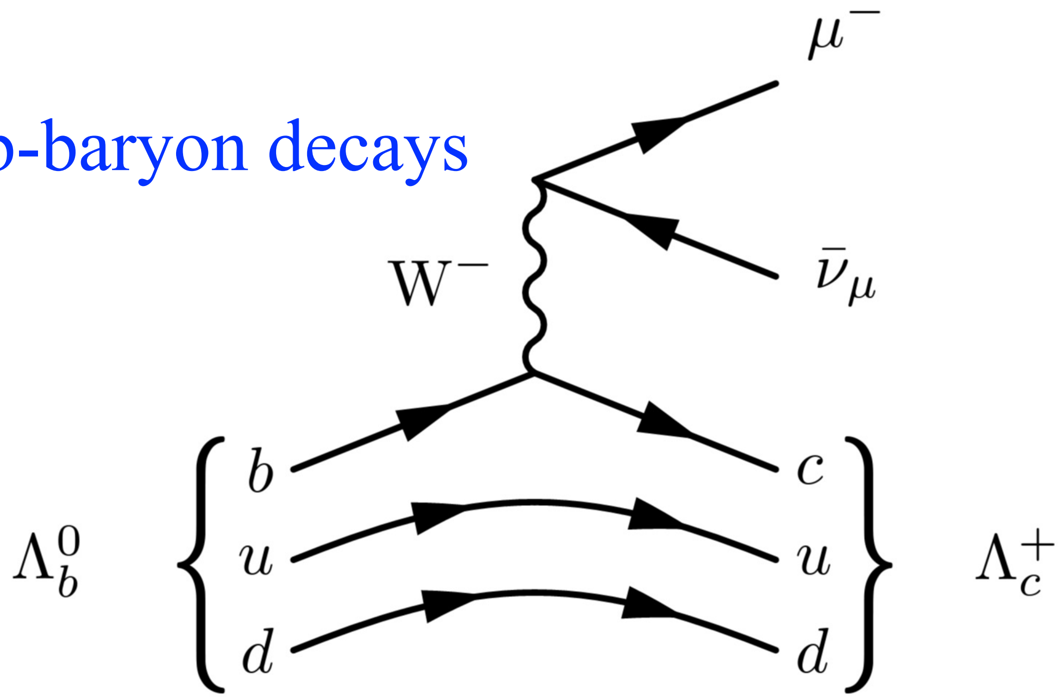
| Assigned systematic | $\Delta\ \mathrm{Im}(g_R)$ | $\Delta\ \mathrm{Im}(g_P g_T^*)$ |
|---|---|---|
| Misid | $0.85 \times 10^{-3}$ | $2.45 \times 10^{-4}$ |
| Fake $D^*$ comb | $0.40 \times 10^{-3}$ | $0.70 \times 10^{-4}$ |
| True $D^*$ comb | $1.45 \times 10^{-3}$ | $1.98 \times 10^{-4}$ |
| $T_y$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

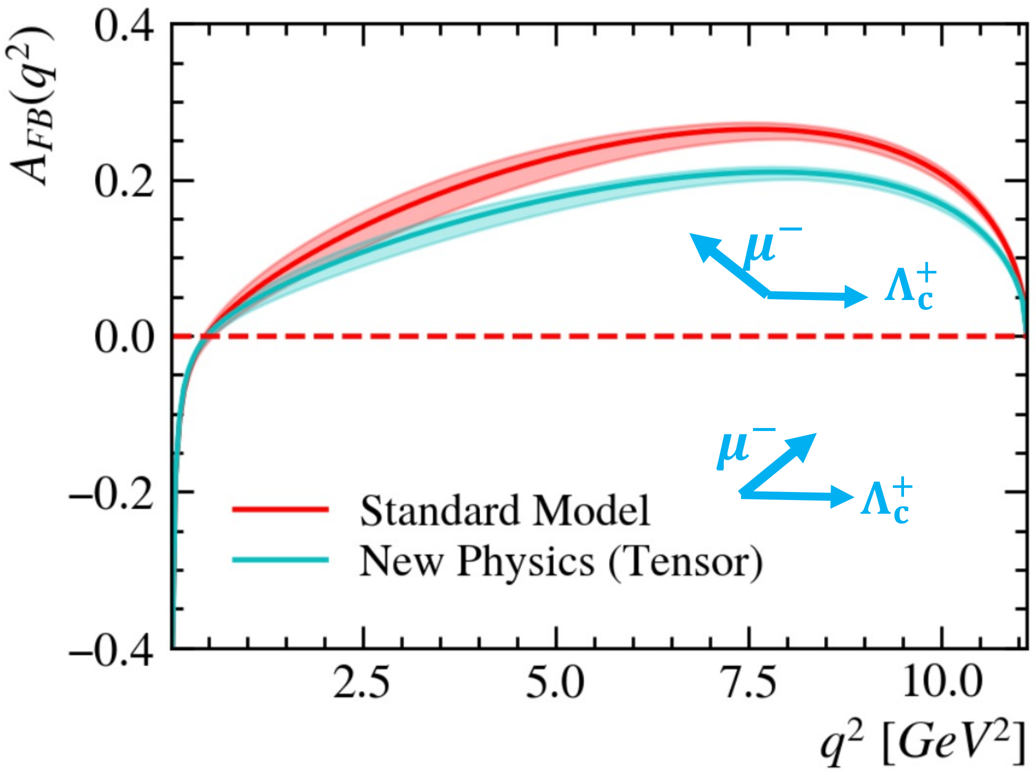
**Dominant syst due to detector misalignments.**

**Ongoing analysis planned to be published next year!**

# b-baryons

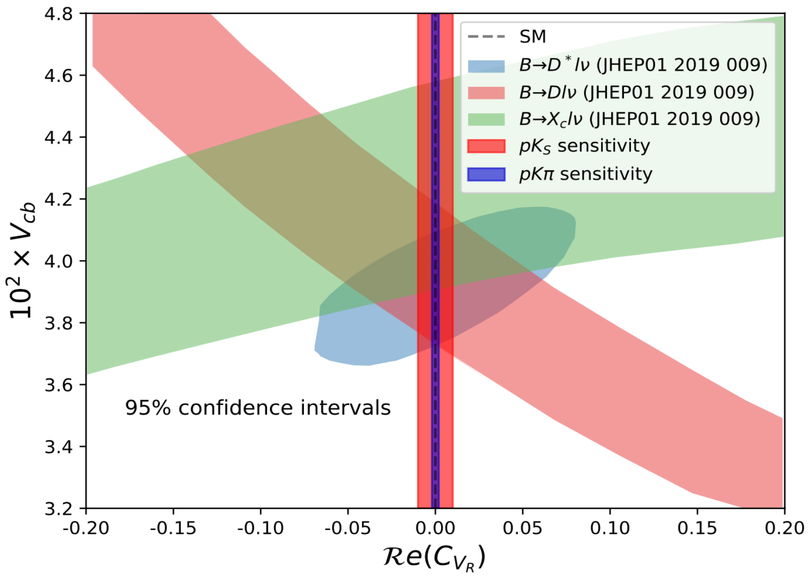
b-baryon decays

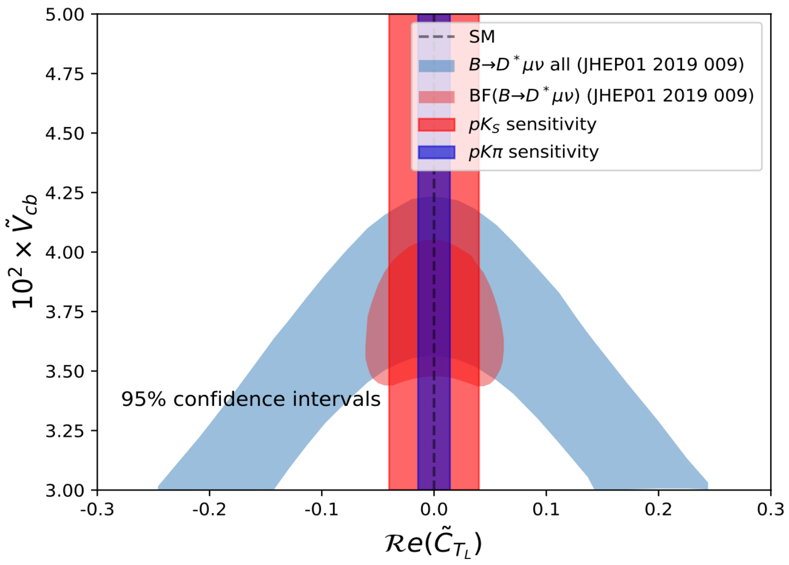



- ➢ 57k $\Lambda_b$'s per sec at LHCb in Run 3 @ peak luminosity!
- ➢ Different **spin structure**: Sensitive to different Lorentz operators compared to pseudo scalar decays.

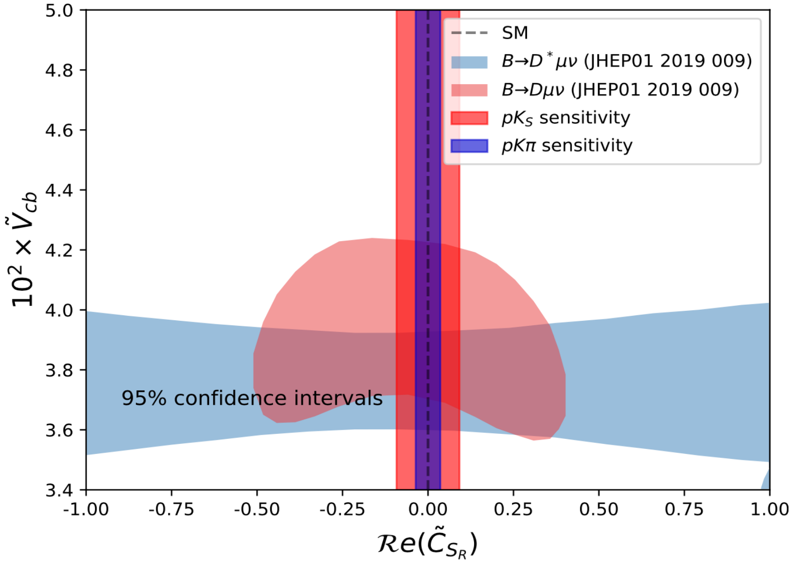
# Sensitivity on WC with $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$

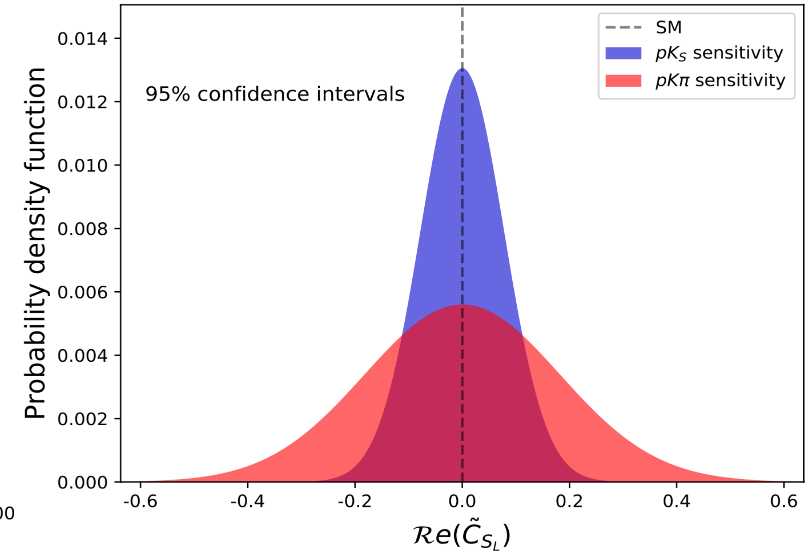



[JHEP 12 (2019) 148]

Model efficiency and resolution on $q^2$ and angular observable explicitly and publish data differential distributions.




**Planned to be published next year!**

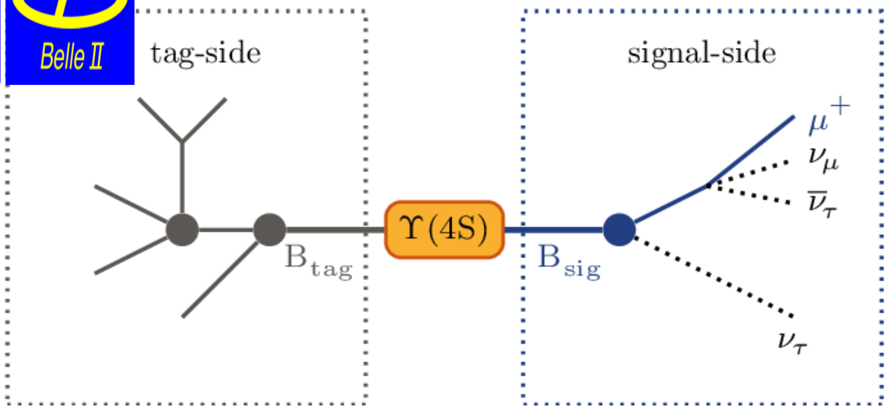
# Summary and conclusions

- Presented the EFT framework in $b \to c\, l\, \nu$ decays.
- Presented the various challenged related to these measurements.
- Discussed recently published result on $D^*$ polarisation in $B \to D^* \tau \nu$.
- Angular analysis of light leptons to come soon.
- Angular analysis with $\tau$ leptons are ongoing.
- Many other analysis with $b \to u\, l\, \nu$ ongoing but not discussed here.
- **Exciting new precision tests with SL decays ahead!**

# Summary and conclusions

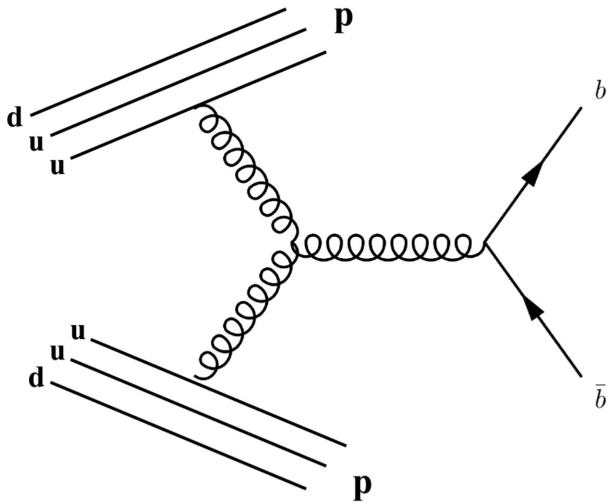
# Competing facilities

US + Japan




- **Electron-positron** colliders.
- $\boldsymbol{O}(\mathbf{10^9})$ $B^{0/+}$ mesons produced.
- b-mesons produced with **fixed CoM.**
- **B rest frame reconstructed with high precision** even with missing neutrinos.

Switzerland



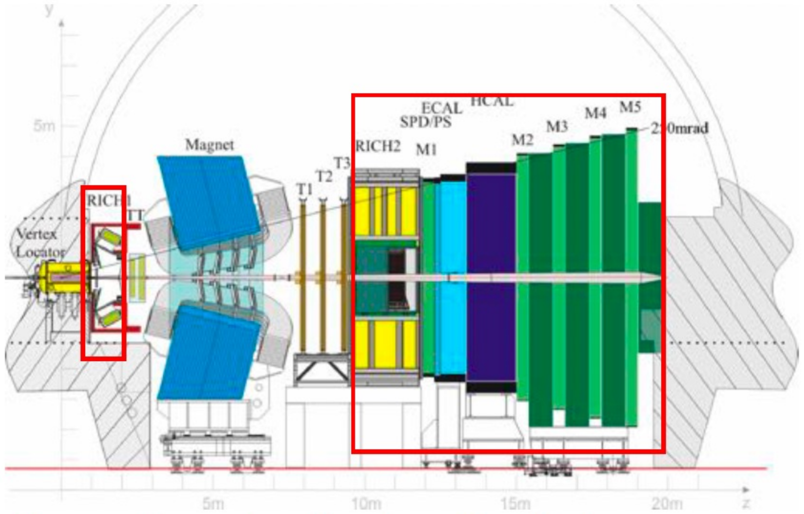

- **Proton-proton** colliders.
- $\boldsymbol{O}(\mathbf{10^{12}})$ $B_{(s)}^{0/+}, \Lambda_b, \Xi_b$ hadrons produced.
- Produced predominantly via **gluon fusion**.
- B rest frame approximated: Thanks for **highly boosted B** and **good separation from primary vertex**.

# Challenges at LHC: Large simulation samples

- Limited simulation sample size often form dominant systematic. **But why?**
- **Data:**
    - In Run 3, a signal event ($B \to D^*\tau\nu$) occurs every $1.7 \times 10^7$ bunch crossings.
    - These many bunch crossings occur at LHC every **0.6 seconds**.
- **MC:** Compare this to time taken to simulate a signal event ~ **1 – 2 min**.
- **Need fast simulation techniques!**

**E.g. Tracker only MC**

Turn off parts of the detector response (shower development, photon propagation in RICH).




Speed up by factor 8, disk space down by 40%

# Contraints on $b \to c\tau\nu$

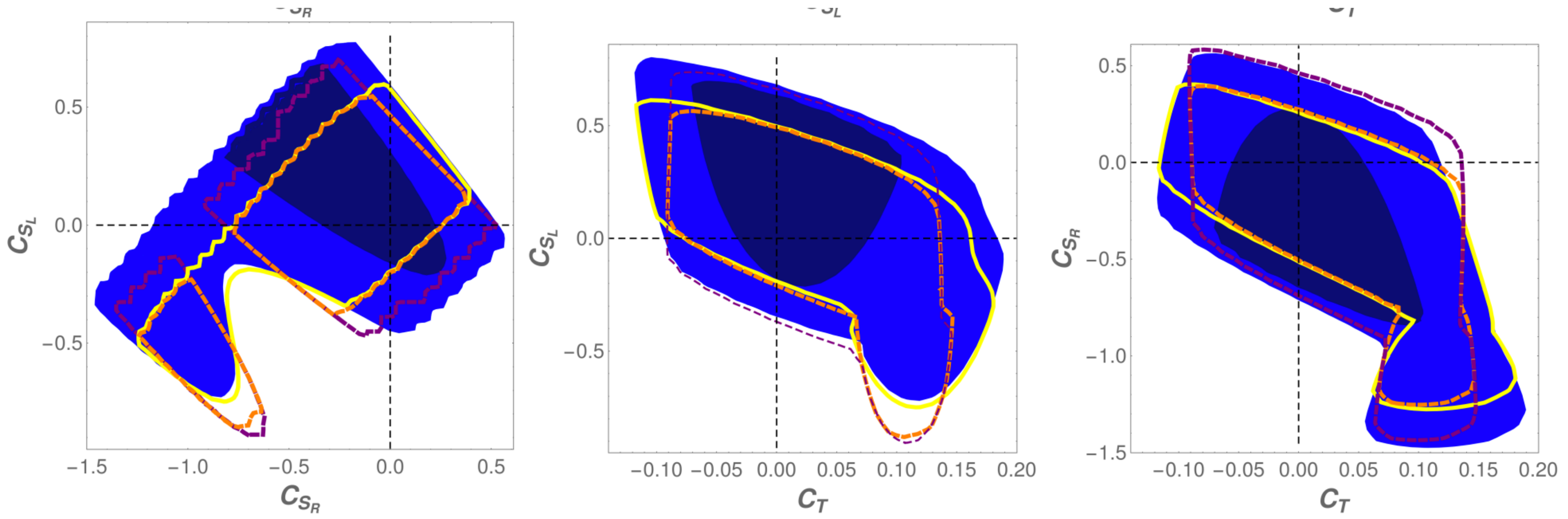



Figure 3: Allowed regions for all possible combinations of two Wilson coefficients for different scenarios: Blue areas (lighter 95% and darker 68% CL) show the minima without $F_L^{D^*}$ and with $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 30\%$. The yellow lines display how the 95% CL bounds change when $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$. The dashed lines show the effect of adding the observable $F_L^{D^*}$ for both $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 30\%$ (purple) and for $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$ (orange).

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

[A Poluektov and Vlad Dedu]

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

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

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

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

**Unbinned true observables**

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

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

$\rightarrow$

**Binned reconstructed observables**

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

$$A_i^{(2)} = \frac{N_{\rm bins}}{N_{\rm signal}} \sum_{n=1}^{N_i} \sin 2\chi_n \simeq \mathrm{Im}(g_R)\, A_{RH,i}^{(2)}$$

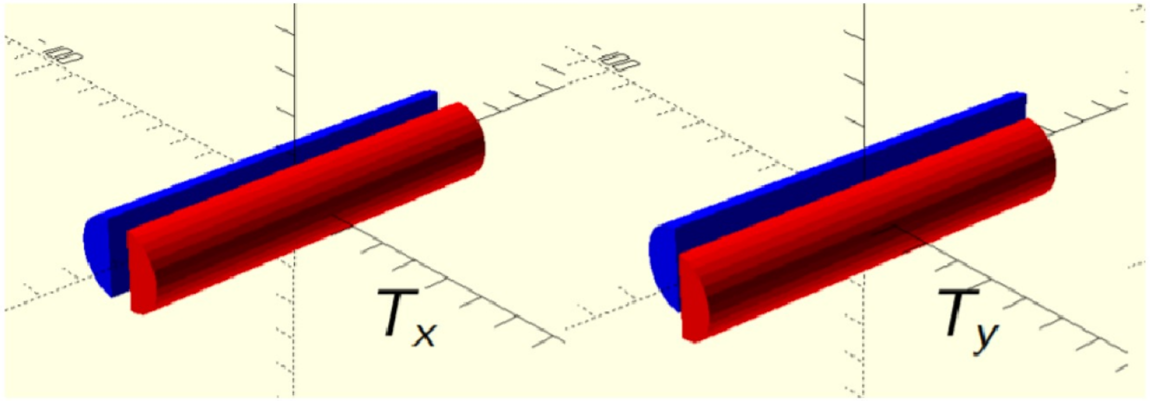
Sum all $N_i$ events in $i^{th}$ bin of $[q^2, \cos(\theta_D), \cos(\theta_l)]$

# TP: Fit and systematics

[A Poluektov and Vlad Dedu]

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

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




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