Search for $B^+ \to K^+\tau^+\tau^-$ with LHCb

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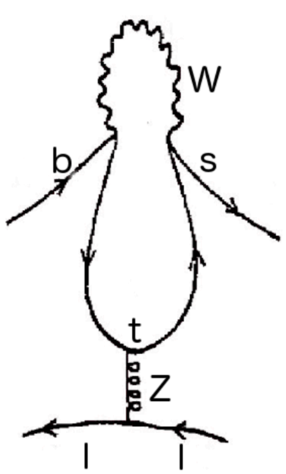
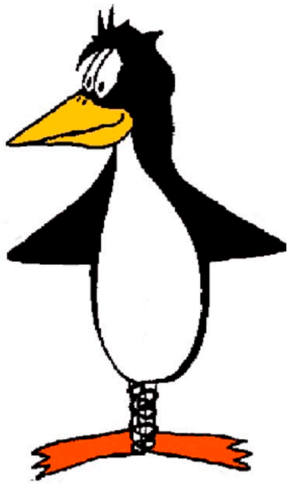
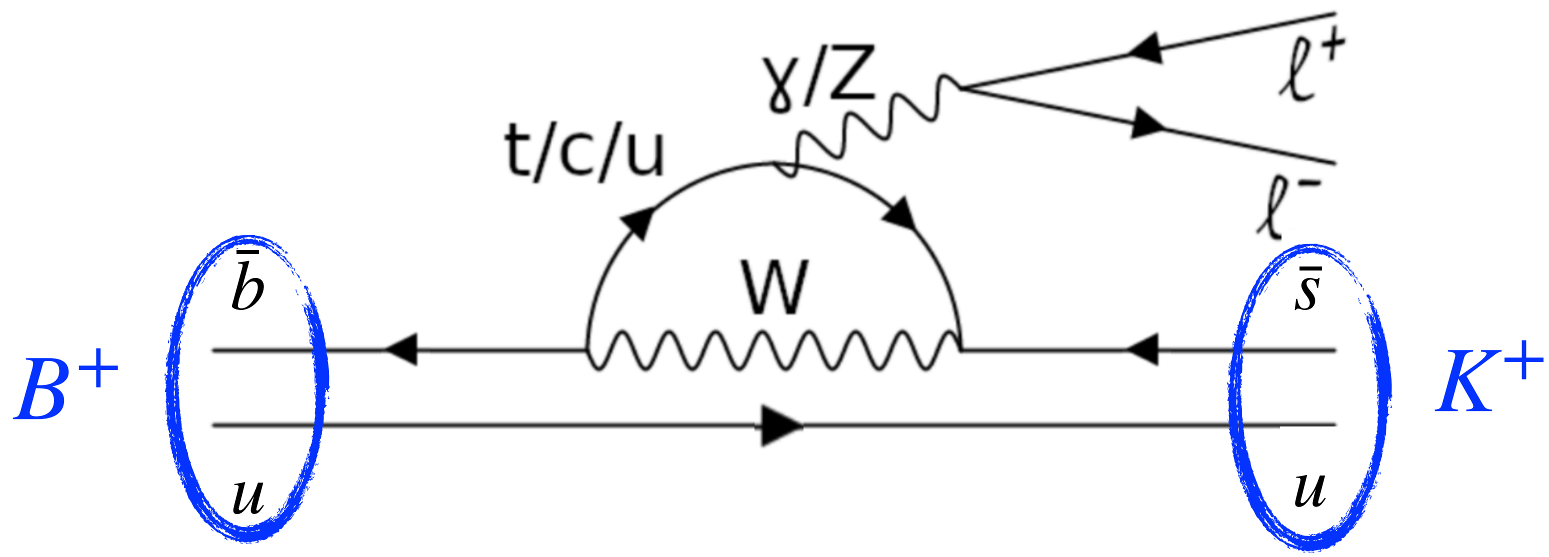
Joint annual meeting of SPS and OPG in Basel
05/09/2023





The $B^+ \to K^+\tau^+\tau^-$ decay

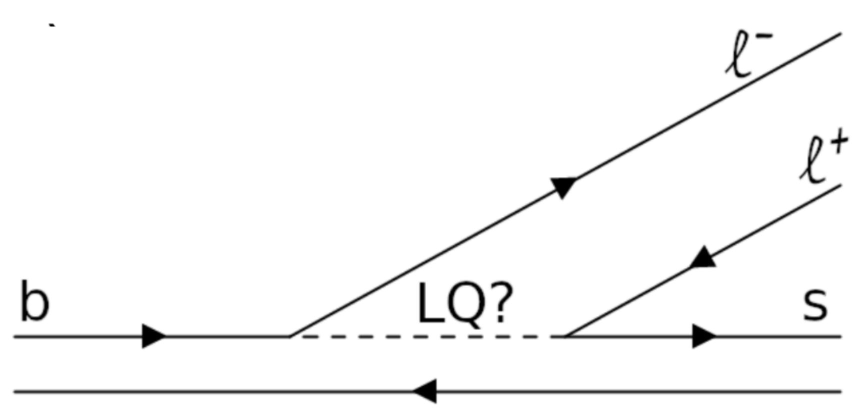
Leading order Feynman diagram in the SM

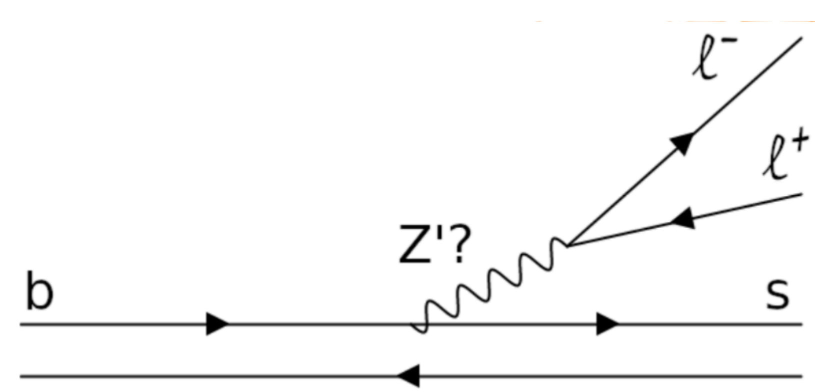


- $b \to sll$ transitions can only proceed at loop level in the SM
- leading order penguin diagram is CKM suppressed ($|V_{ts}V_{tb}| \approx 10^{-2}$)

$$\mathscr{B}(B^+ \to K^+\tau^+\tau^-)_{SM}^{q^2\in[15,22]} = (1.22 \pm 0.10) \times 10^{-7}$$ Phys. Rev. D 93, 034005 (2016)

Possible NP contributions



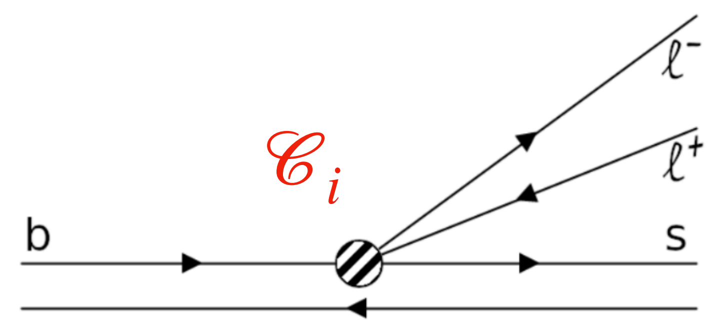


$b \to sll$ in weak effective theory

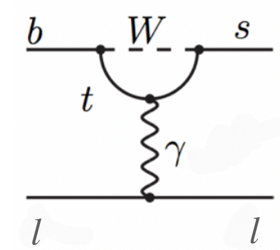
$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Wilson coefficients $\mathcal{C}_i$: $E \gg m_b \approx 4$ GeV

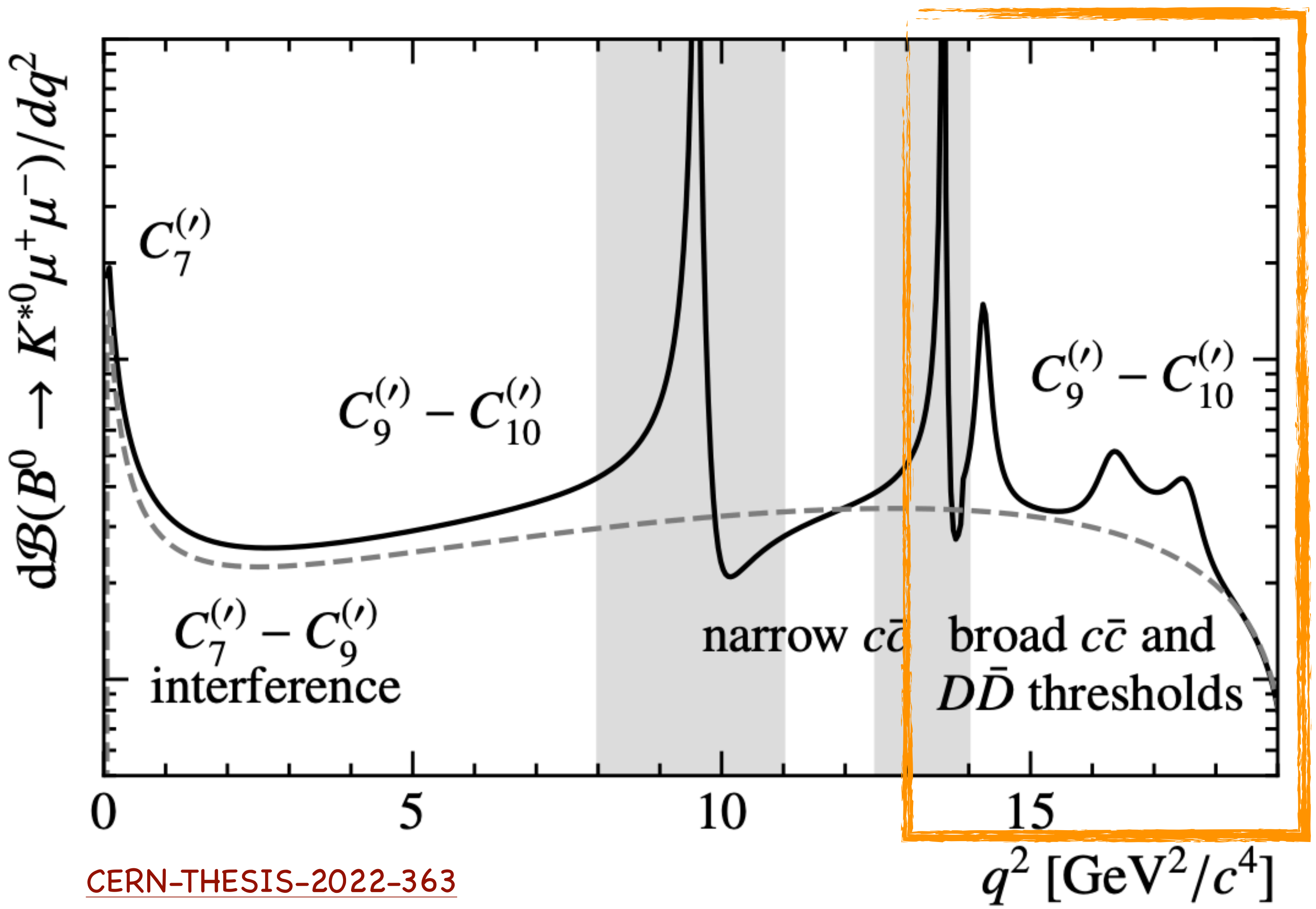
Local operators $\mathcal{O}_i$: $E \lesssim m_b \approx 4$ GeV



$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{g^2}(\bar{s}\sigma_{\mu\nu}P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$$



$$\frac{d\mathcal{B}}{dq^2} \propto | < K^+ l^+ l^- | \mathcal{H}_{eff} | B^+ > |^2$$



$4m_\tau^2 \approx 13$ GeV²

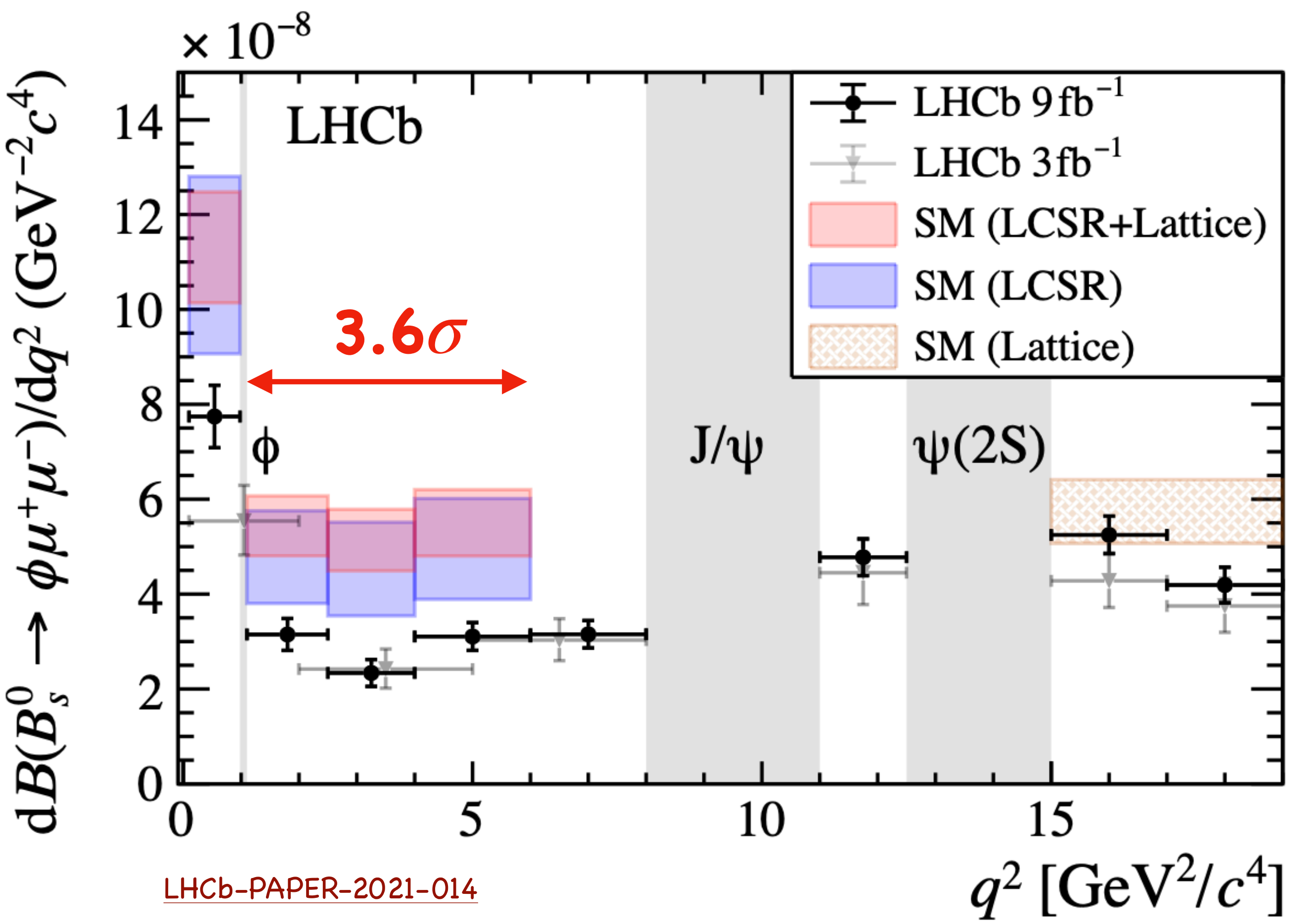
CERN-THESIS-2022-363

Flavour anomalies

A set of deviations between the SM predictions and experimental results has been found in several semileptonic B decays

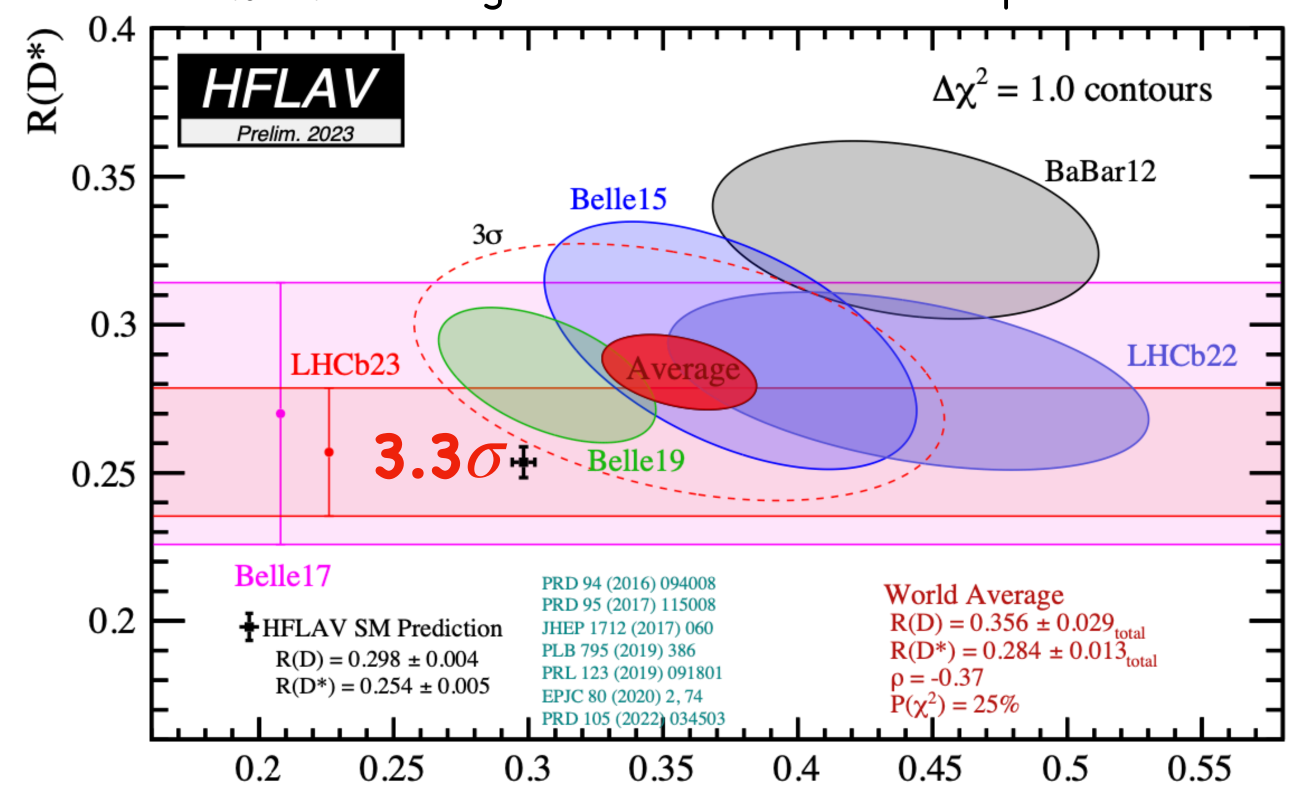
$b \to sll$ (**loop** level)

$b \to c l \bar{\nu}$ (**tree** level)



LHCb-PAPER-2021-014

Global fit using results from different experiments:



Preliminary average of R(D) and R(D*) for Summer 2023

$$R_{D^{(*)}} = \frac{\mathscr{B}(\bar{B}^0 \to D^{(*)0}\tau^-\bar{\nu}_\tau)}{\mathscr{B}(\bar{B}^0 \to D^{(*)0}\mu^-\bar{\nu}_\mu)}$$

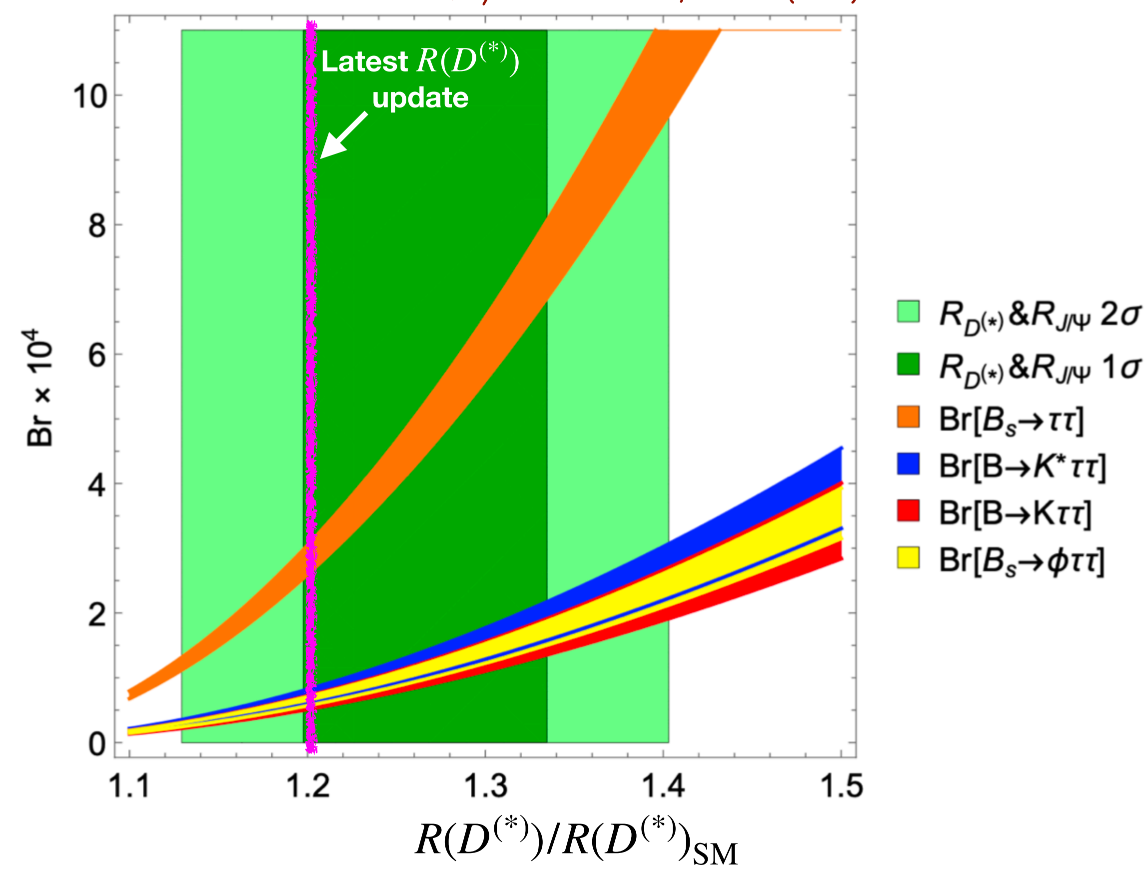
Expected enhancements on $\mathscr{B}(B \to X\tau\tau)$

EFT analyses predict that NP in $R(D^{(*)})$ and $b \to s\tau\tau$ are correlated:

$$\mathscr{B}(B \to X\tau^+\tau^-) \propto \Delta^2, \text{ where } \Delta \propto \sqrt{\frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}}} - 1$$

$\Longrightarrow$ Enhancement of $\mathscr{B}(B^+ \to X\tau^+\tau^-)$ of up to **3 orders of magnitude** wrt SM is possible

Phys. Rev. Lett. 120, 181802 (2018)



$\mathscr{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ @ 90% CL (Phys. Rev. Lett. 118, 031802 BaBar 2017)

$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ @ 90% CL (Phys. Rev. D 108, L011102, Belle 2023)

$\mathscr{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ @ 95% CL (Phys. Rev. Lett. 118, 251802, LHCb 2017)

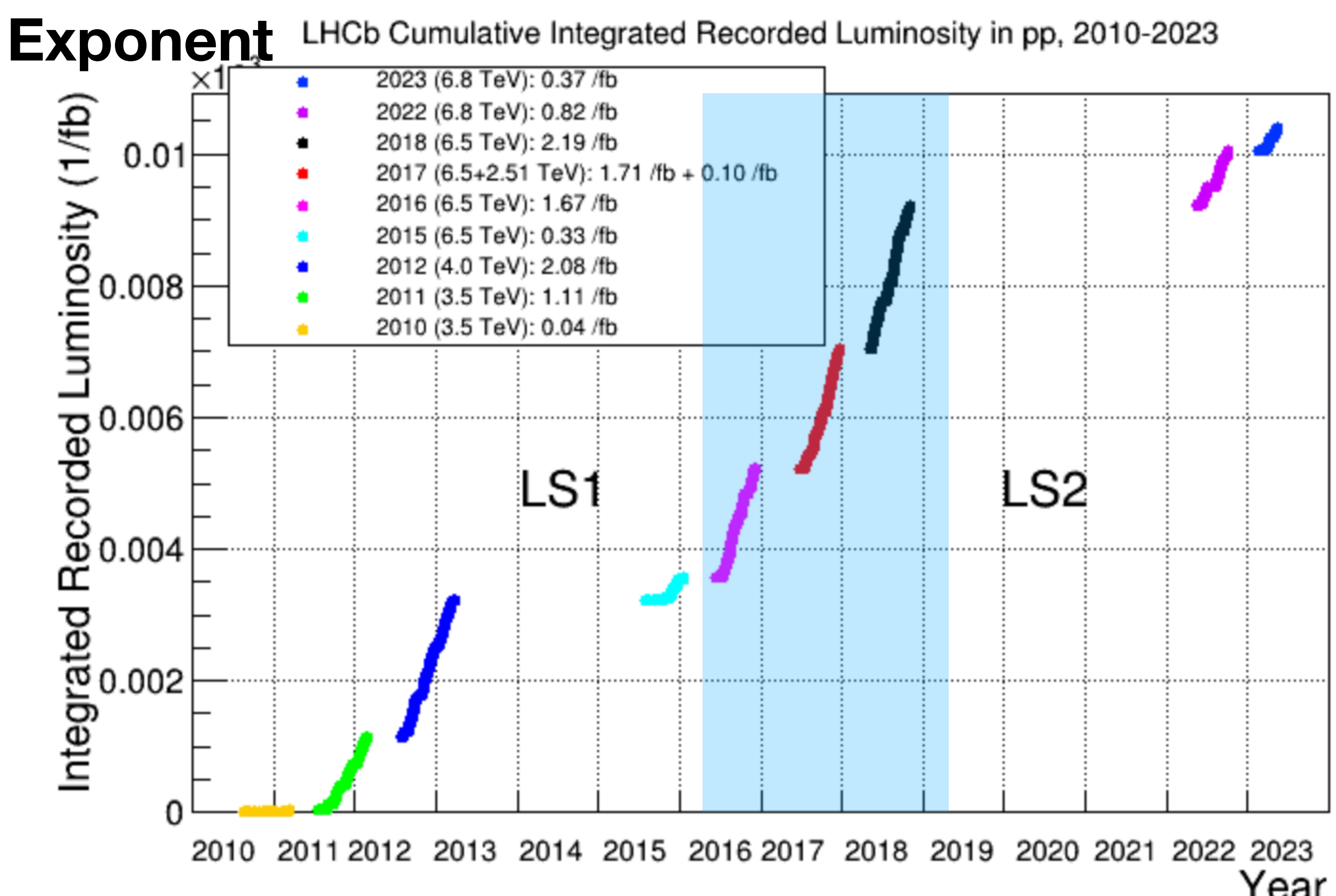
Currently ongoing @LHCb:

- Update of $B^0_{(s)} \to \tau^+\tau^-$ with Run2 data
- First analyses of $B^0 \to K^{*0}\tau^+\tau^-$ (on review) and $B^+ \to K^+\tau^+\tau^-$

Can we do better?

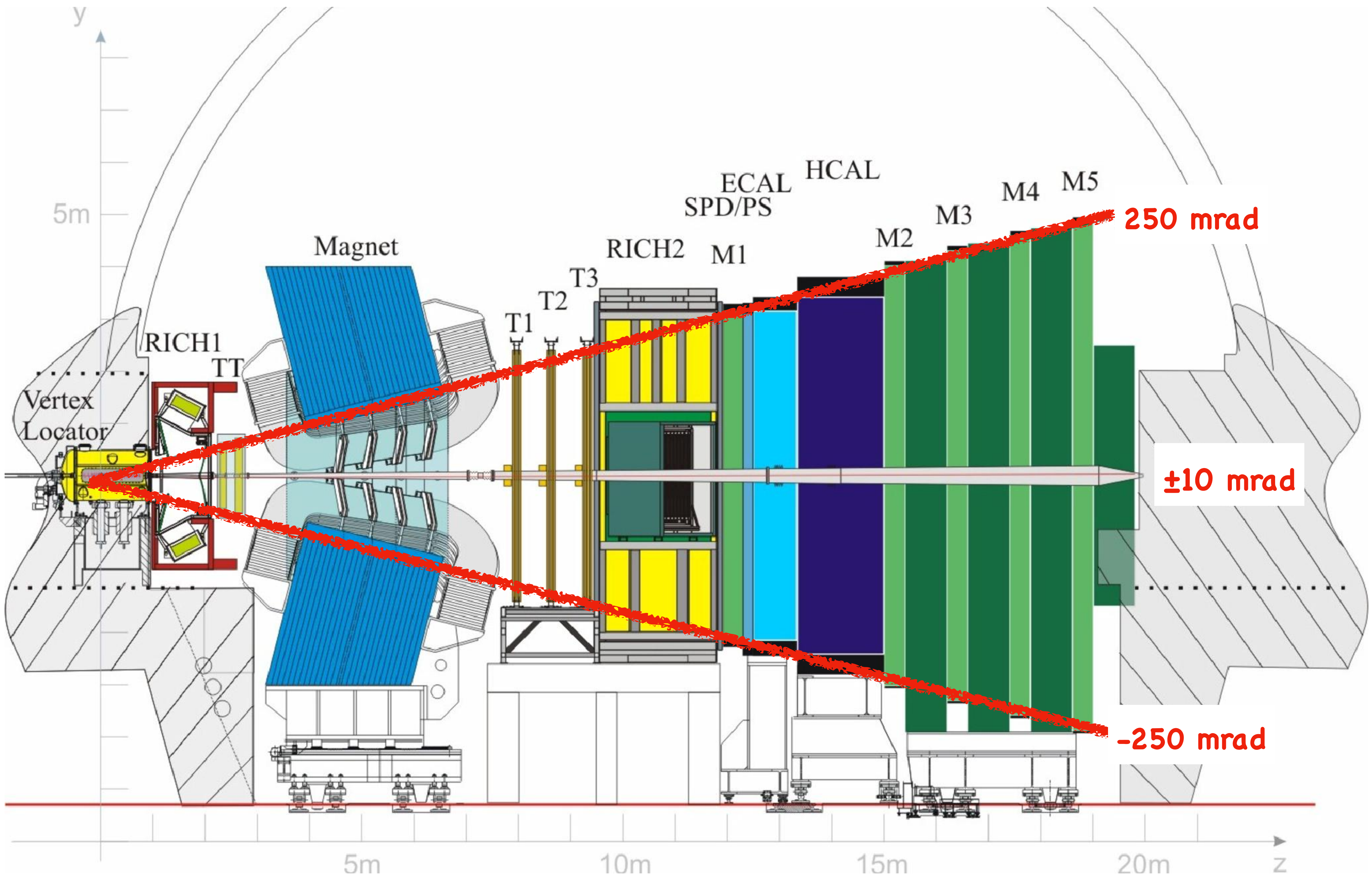
Datasets and trigger

- 2016-**2018** LHCb data (L~6 fb^{-1})
  - **Right-sign (RS) data**: $B^+ \to K^+\tau^+\tau^-$ (signal model)
  - **Wrong-sign (WS) data**: $K^+\tau^+\tau^+$ or $K^-\tau^+\tau^+$ (mimics combinatorial background)
- Simulated samples of signal and specific types of background
- We rely on a hadronic trigger (hardware) and we require 1 or 2 tracks in the final state (software)



LHCb Cumulative Integrated Luminosity

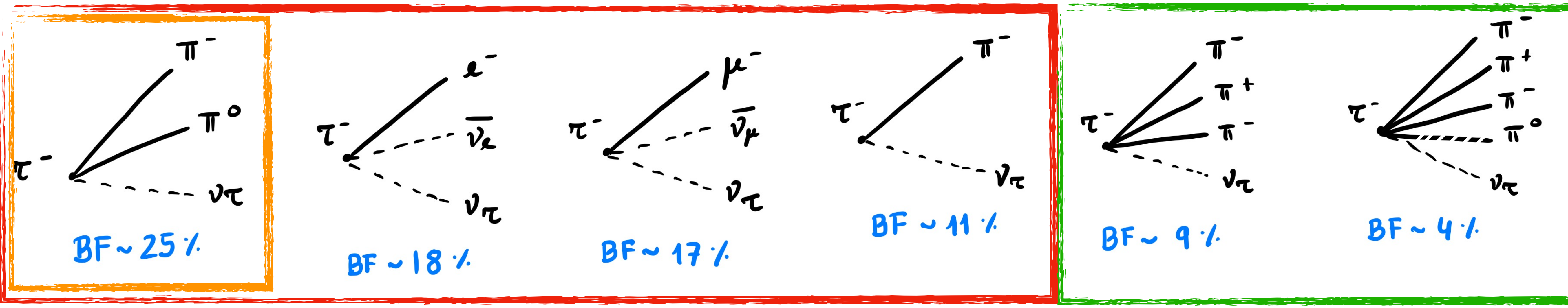
The LHCb detector



The LHCb detector is not fully hermetic $\Longrightarrow$ we cannot reconstruct all the particles in an event (we do not know the total $\vec{p}_T^{miss}$)

Reconstruction of $B^+ \to K^+\tau^+\tau^-$

The τ lepton has a **short lifetime** (~0.3 ps in proper frame) and it is observed to travel ~1 mm before it decays



Low efficiency of π^0 reconstruction @ LHCb

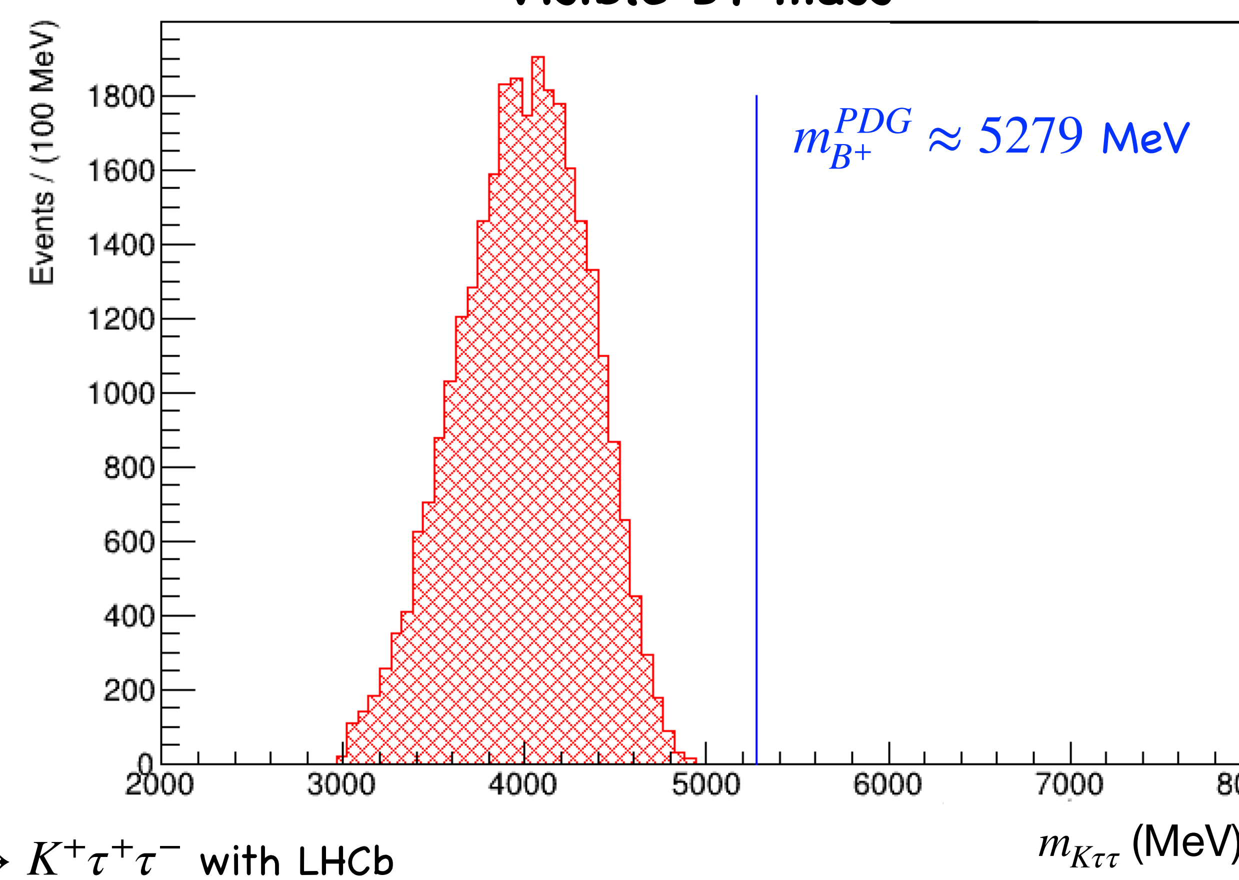
Do not allow to reconstruct the τ decay vertex

The τ leptons are reconstructed in their decay $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

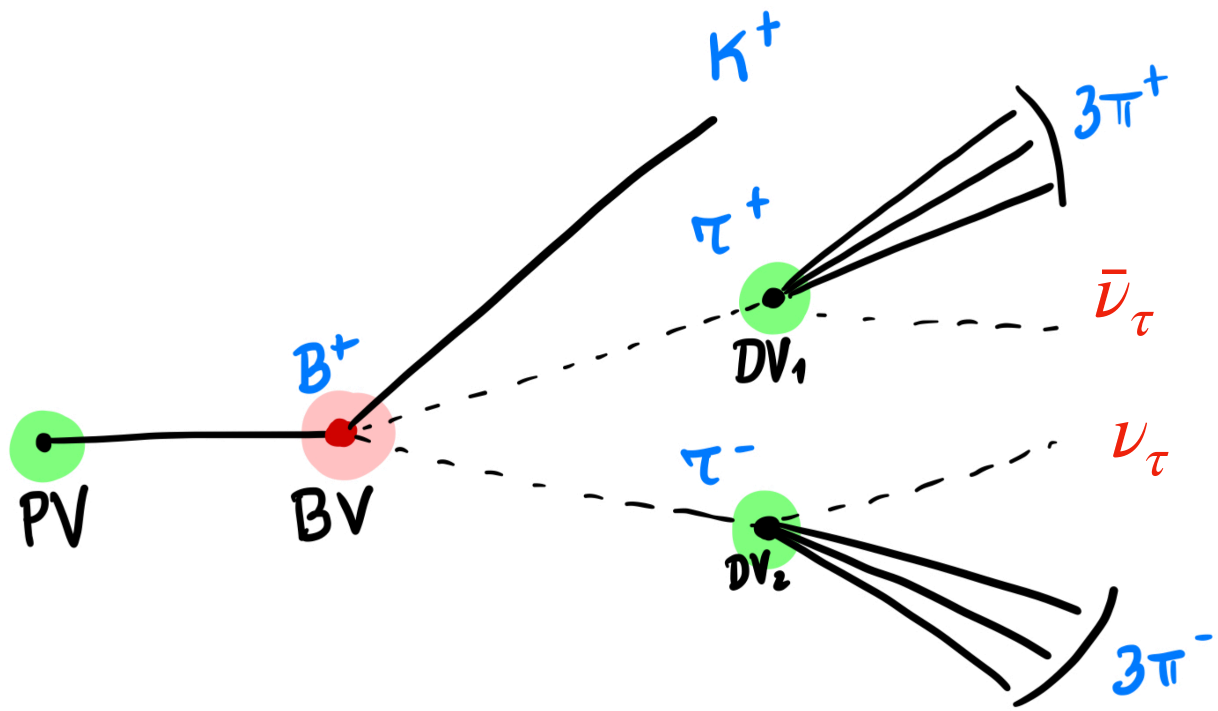
$\tau^+ \to a_1(1260)^+\bar{\nu}, a_1(1260)^+ \to \rho^0\pi^+, \rho^0 \to \pi^+\pi^-$

The neutrinos in the final state are not reconstructible at LHCb

Visible B+ mass



Least-squares decay fit



m_{B^+} **analytical reconstruction**

- We have 23 unknown parameters
- We can apply 24 constraints to analytically write m_{B^+} in terms of measured quantities

- The analytical result is used as an **initial input to a least-squares fit** of the decay
- Constraints are expressed as χ^2 contributions

$$\chi^2 = (m - h(x))^T R (m - h(x))$$

Residual — $(m - h(x))$

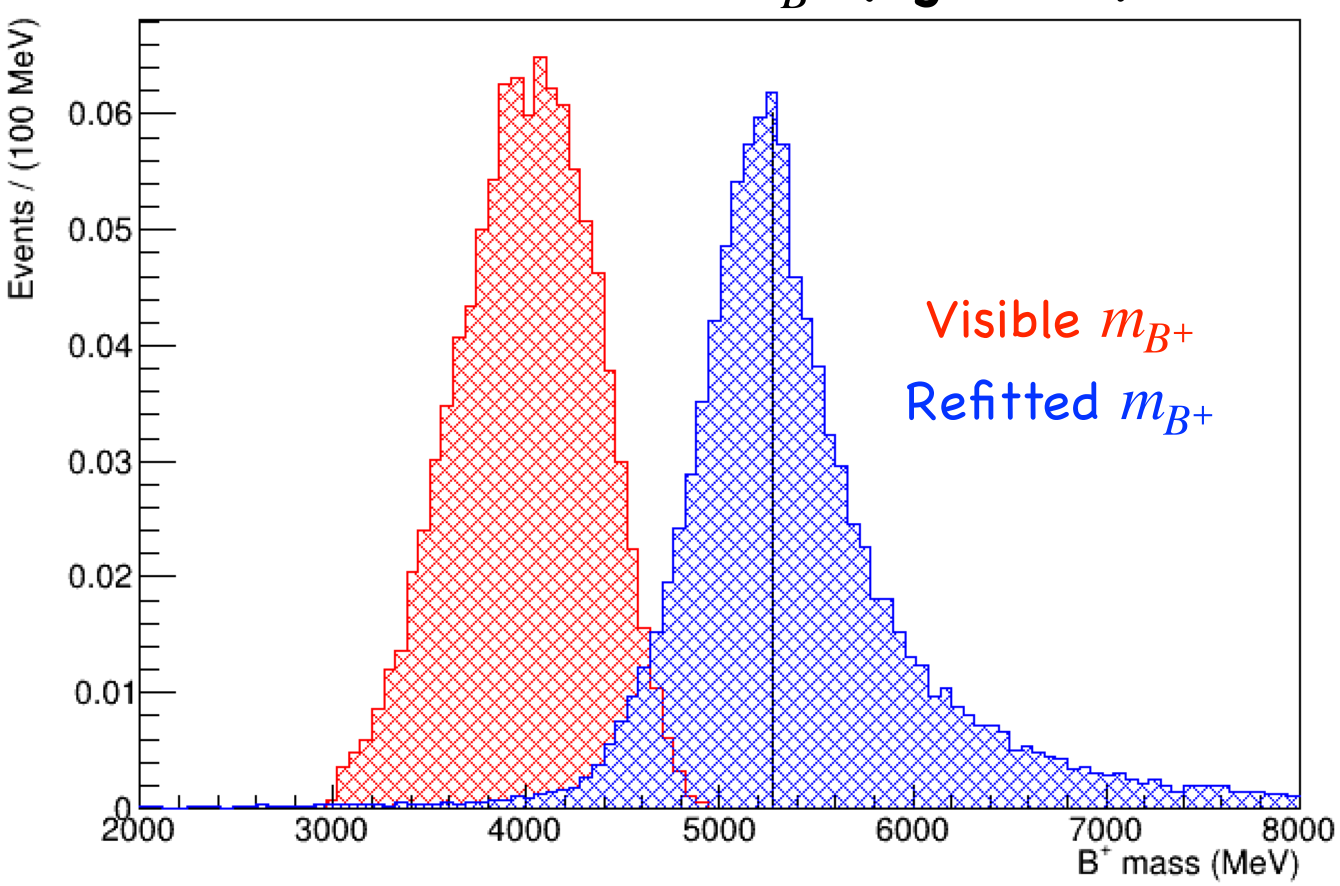
Uncertainty in the residual — R

measurement — m

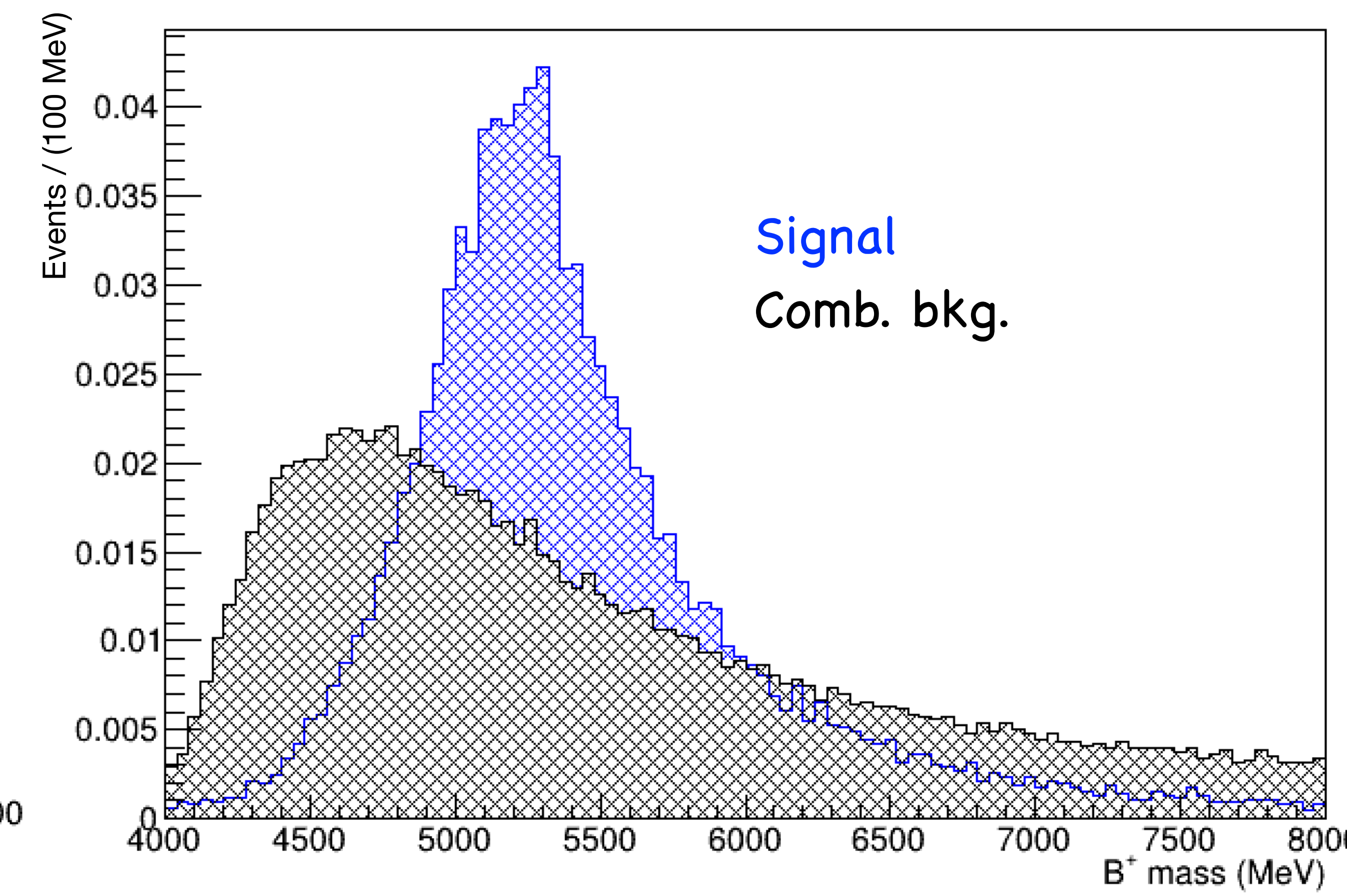
measurement model — $h(x)$

Refitted m_{B^+}

Reconstructed m_{B^+} (signal MC)



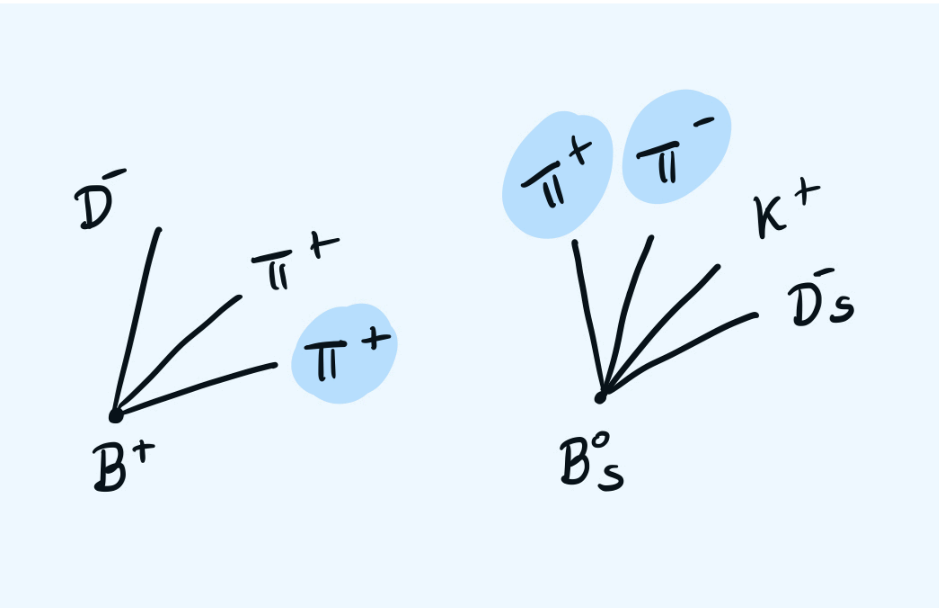
Signal vs comb. bkg. m_{B^+} comparison



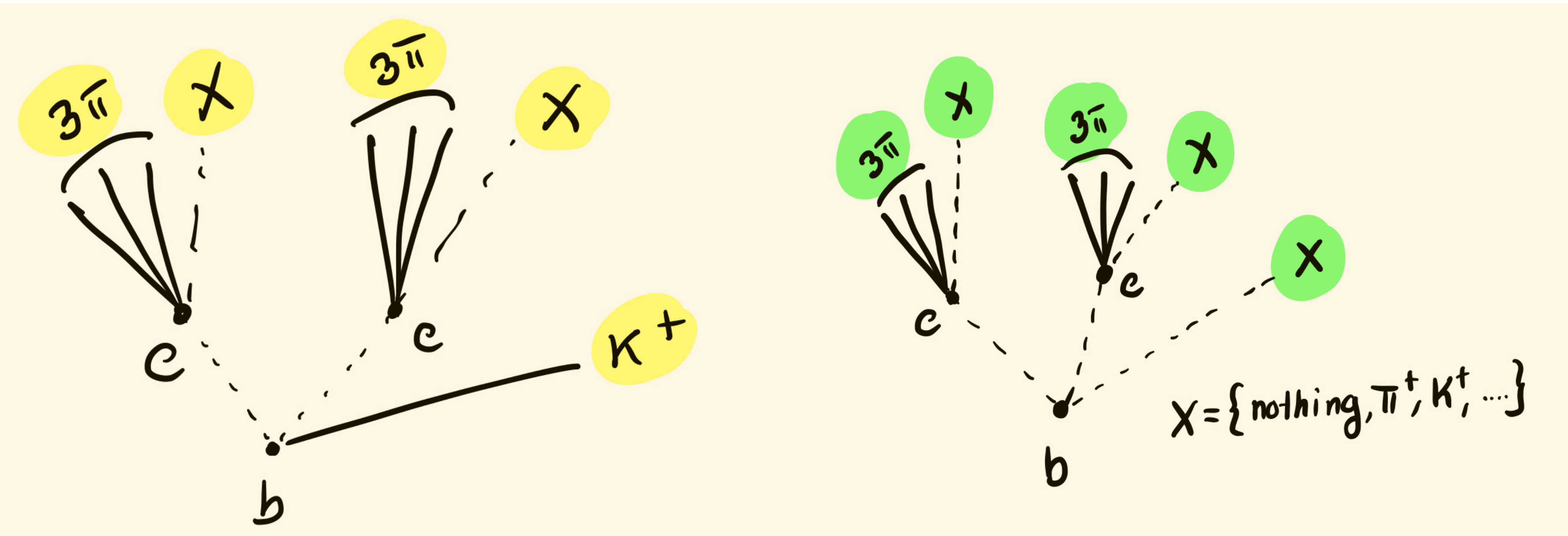
Refitted m_{B^+} distribution has resolution **~280 MeV**

Backgrounds

Combinatorial background

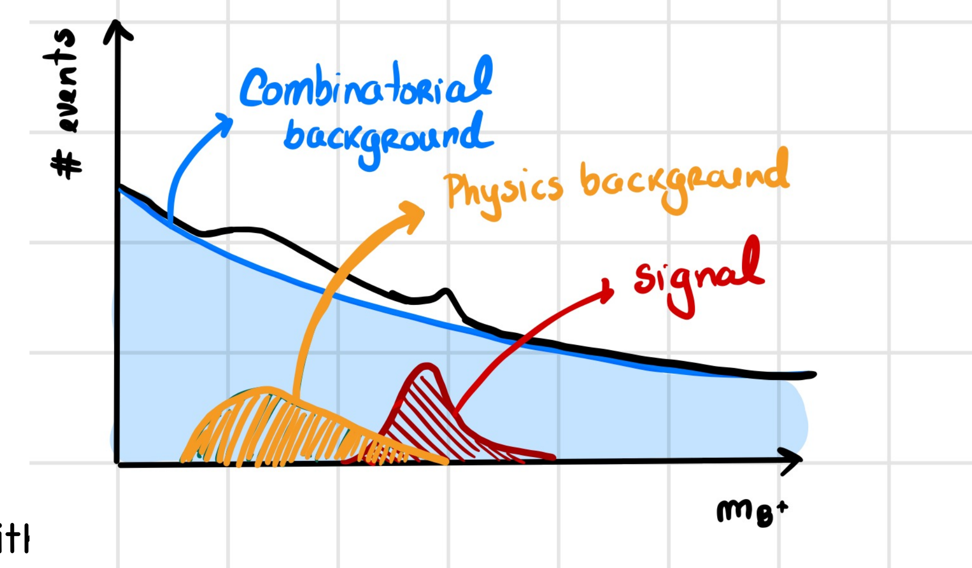


Physics backgrounds

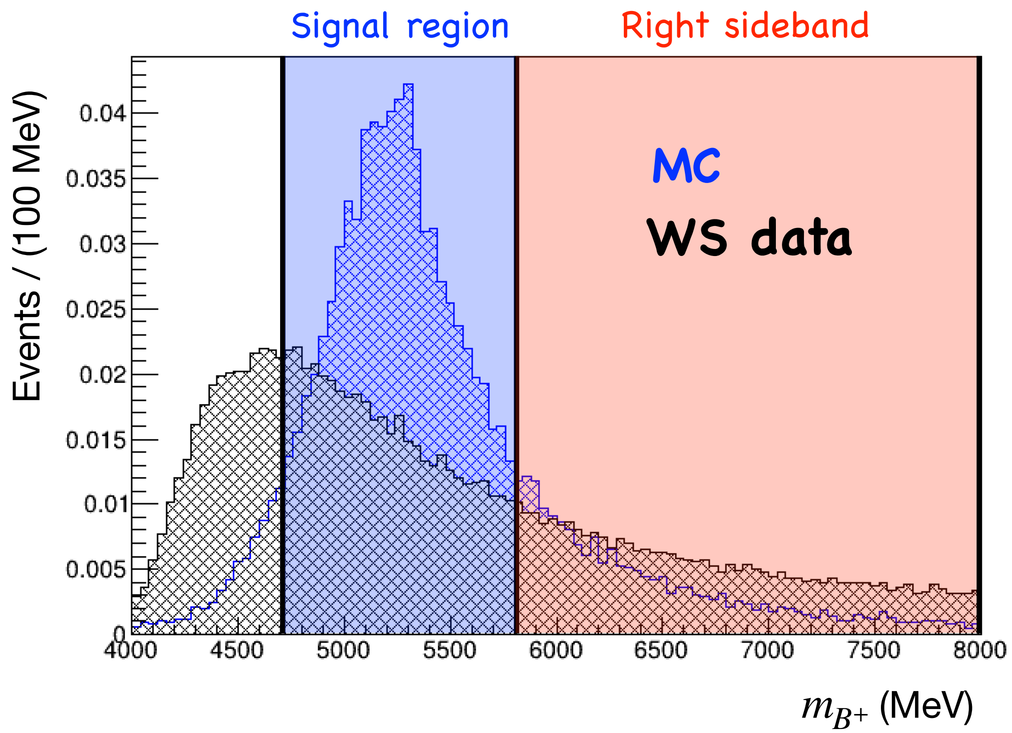


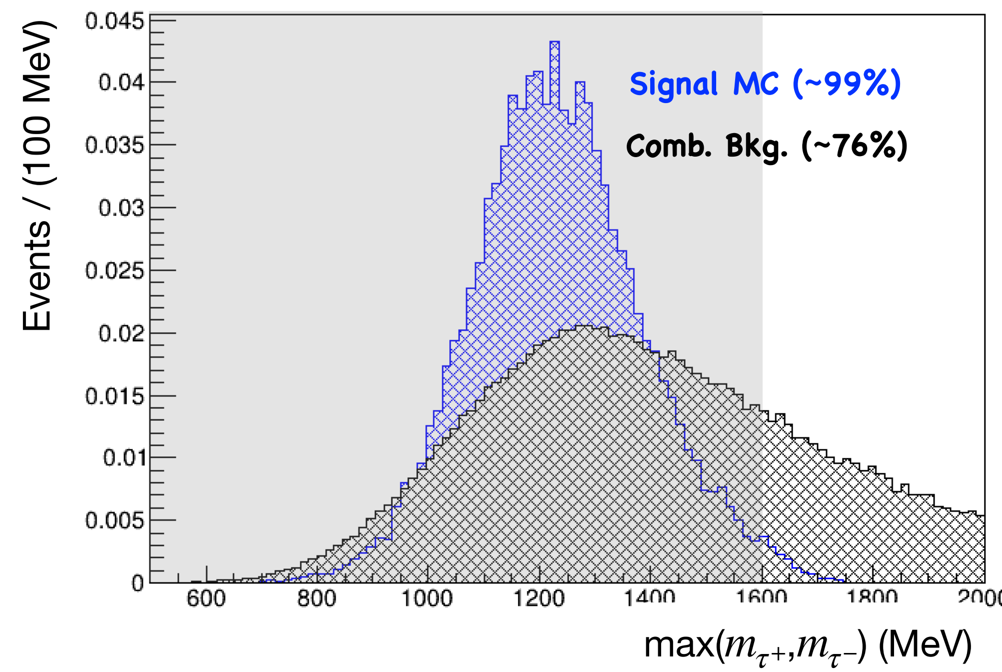
- To simulate the physics backgrounds correctly **we benefit from new BESIII results**:
  - charm -> $3\pi X$ branching fraction measurements) (arXiv:2301.03214 (2023), Phys. Rev. D 108, 032001 (2023))
  - Amplitude analyses of the Dalitz structure of charm decays (Phys. Rev. D 95, 072010 (2017), Phys. Rev. D 100, 072008 (2019), JHEP07 (2022) 051)

- Some backgrounds will be **irreducible**; these will be modelled and constrained in the final mass fit

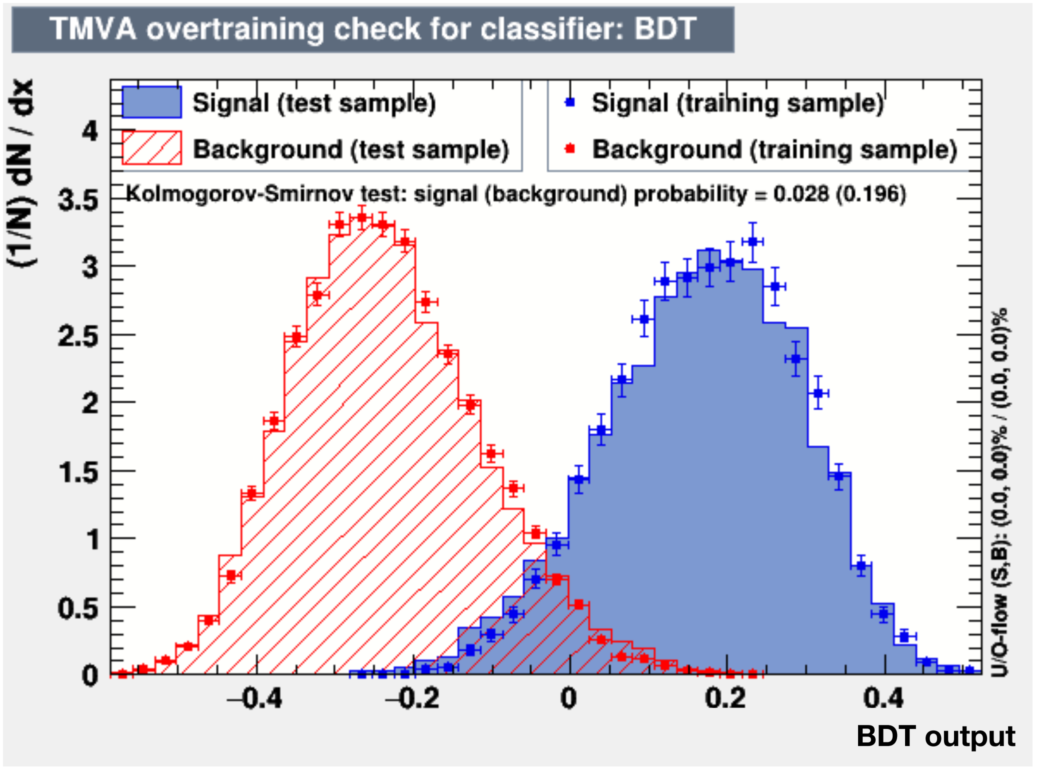


Selection requirements





- Rectangular selections
- Boosted Decision Tree (BDT)
- Signal proxy: 3pi3pi MC in signal region
- (Comb.) background proxy: WS data in signal region
- Input variables: kinematic, geometric, isolation

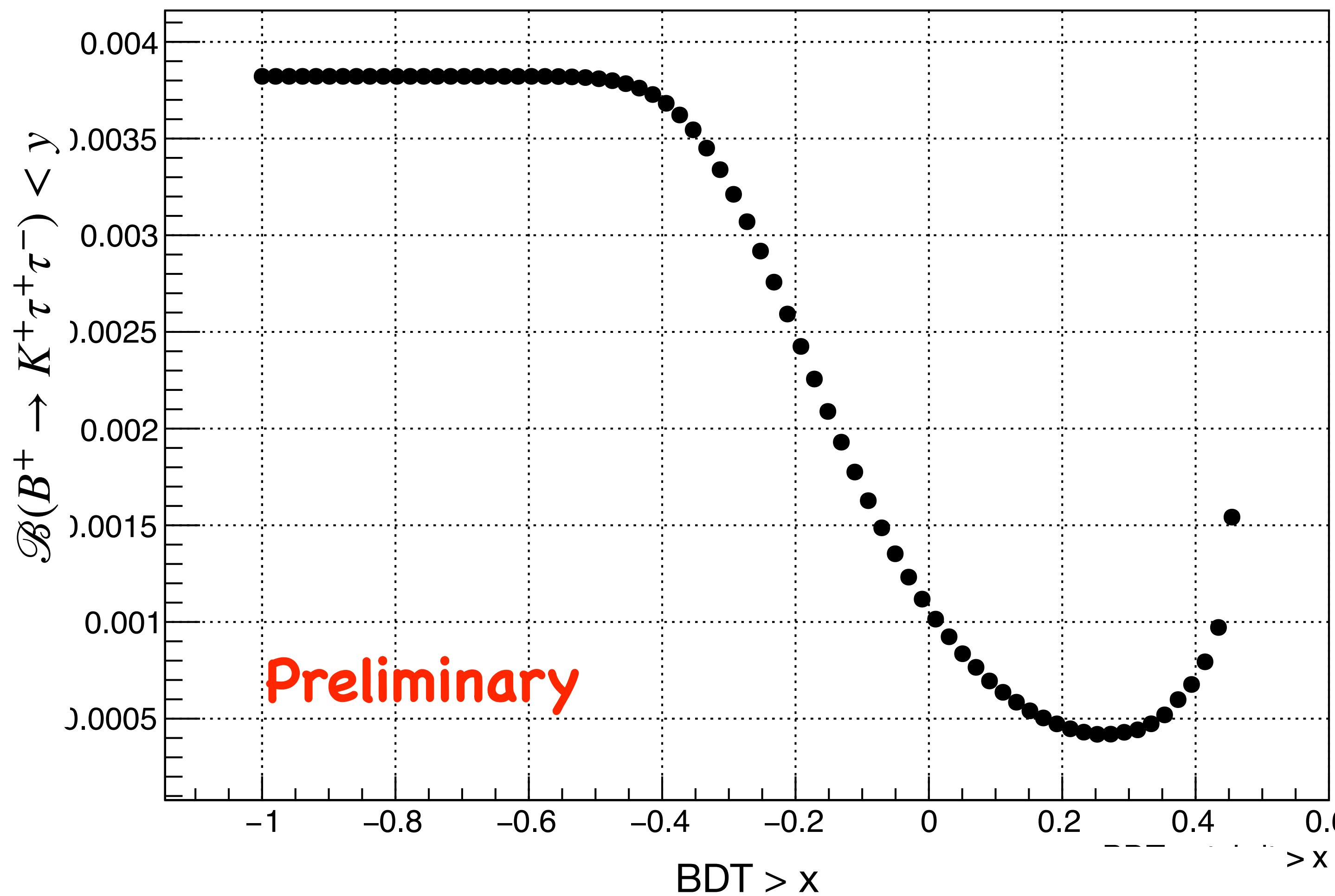


Estimate of sensitivity to $\mathscr{B}(B^+ \to K^+\tau^+\tau^-)$

$$\mathscr{B}(B^+ \to K^+\tau^+\tau^-) = \frac{1}{L\sigma_{B^+}\epsilon_S} \frac{S}{[\mathscr{B}(\tau \to 3\pi\nu) + \mathscr{B}(\tau \to 3\pi\pi^0\nu)]^2}$$

Caveats:

- We still need to include physics backgrounds
- We assume that WS data describes well the comb. bkg. in the RS data



The cut **BDT > 0.25** provides the best sensitivity:

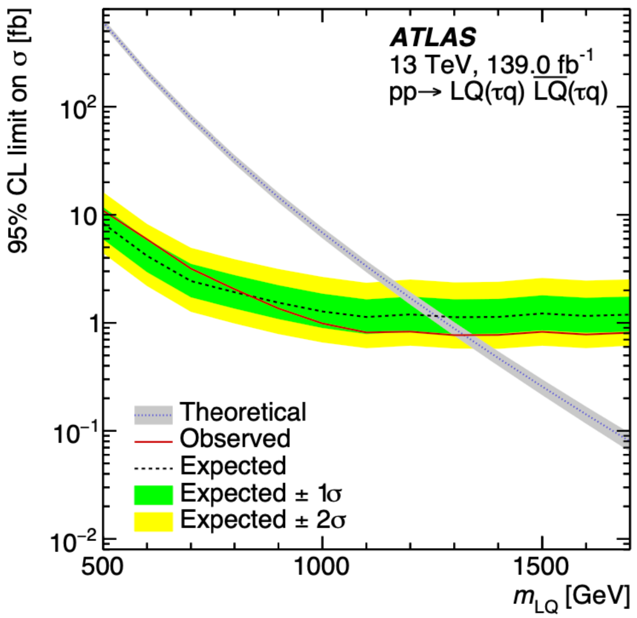
$$\mathscr{B}(B^+ \to K^+\tau^+\tau^-) < 4.2 \times 10^{-4} \text{ @ 95\% CL}$$

Next steps

- Improve selections (2 stage BDT)
- Study abundance of different physics backgrounds
- Develop mass fit
- Reconstruct and measure normalisation channel ($B^+ \to D^+D^-K^+$)
- Currently we are exploring a different approach to the decay fit to see if we can improve the m_{B^+} distribution even further

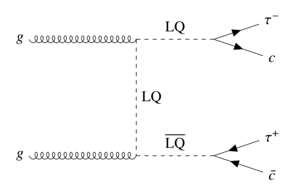
Future of $b \to s\tau\tau$

Searches for NP @ ATLAS and CMS:



JHEP06 (2023) 199

ATLAS 2023 paper excludes LQs with masses < 1.3 TeV @ 95% C.L

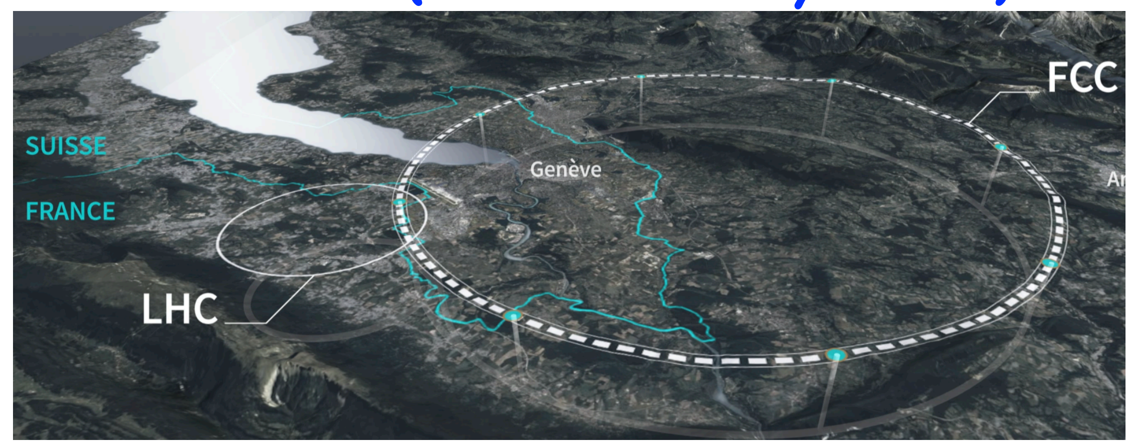


Upgraded detectors:

*LHCb will take x10 **more data** by 2035 (LHCb upgrade II)

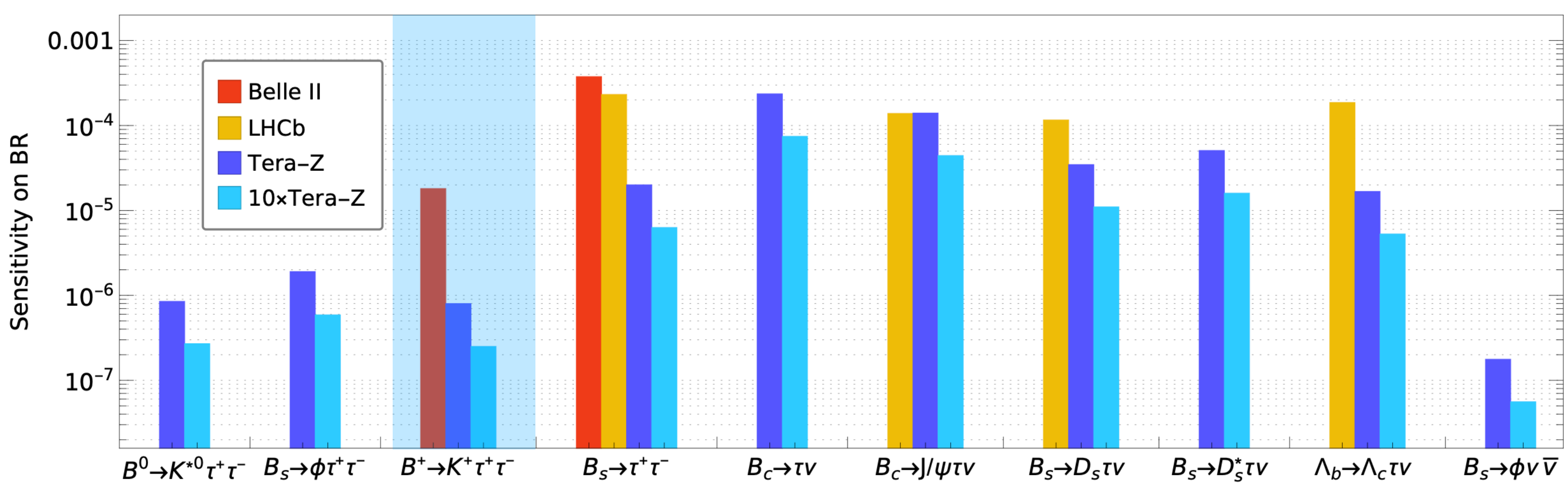
*Belle2 will take x50 **more data** than its predecessor by 2031 (@ 50 ab^{-1})

New colliders like FCC (FCC-ee in early 2040s):



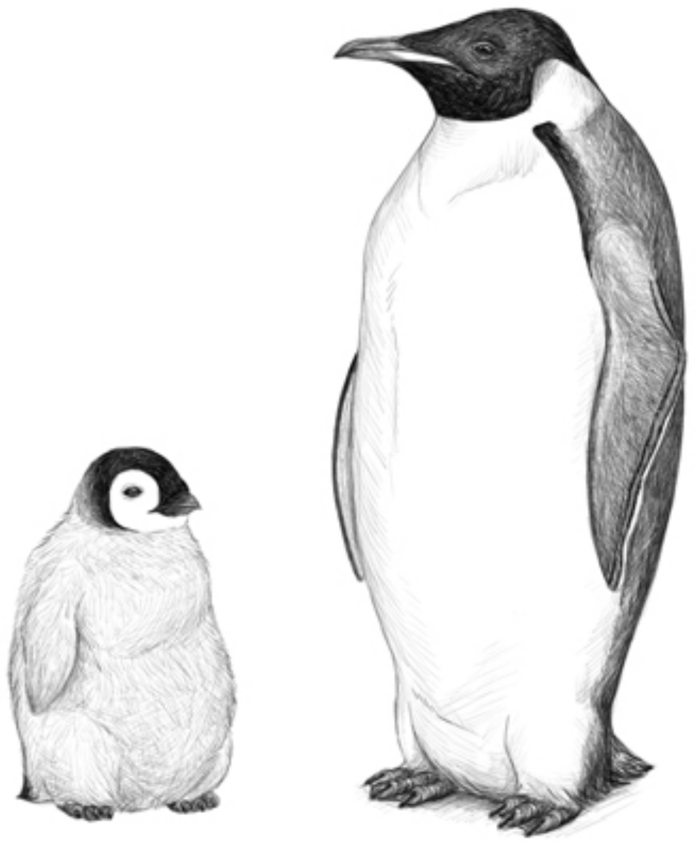
*Will **increase the CM energy** of collisions by x6 - x25 wrt to the current LHC

Sensitivity to $b \to s\tau\tau$ branching fractions will approach SM level (~10^{-7}) at future colliders



arXiv:2212.02433 (2022)

Thank you!



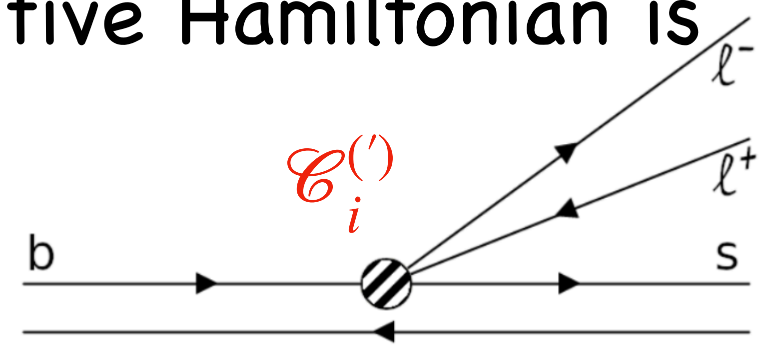
The u-quark loop contribution in Fig. 2.1 a) is doubly Cabibbo suppressed since $V_{ub}V_{us}^* \approx 0.0007 \ll V_{tb}V_{ts}^* \approx 0.04$ and can be neglected. With this approximation and using the unitarity of the CKM matrix, $V_{ub}V_{us}^* + V_{cb}V_{cs}^* + V_{tb}V_{ts}^* = 0$, the t-quark and c-quark contributions are related by $V_{tb}V_{ts}^* = -V_{cb}V_{cs}^*$. The effective Hamiltonian can then be written as

$$
\begin{aligned}
10^7 \times \mathrm{Br}(B \to K^*\tau^+\tau^-)^{[15,19]} = {} & (0.98 + 0.38C_9^{\mathrm{NP}} - 0.14C_{10}^{\mathrm{NP}} - 0.30C_{9'} + 0.12C_{10'} - 0.08C_9^{\mathrm{NP}}C_{9'} \\
& - 0.03C_{10}^{\mathrm{NP}}C_{10'} + 0.05C_9^{\mathrm{NP2}} + 0.02C_{10}^{\mathrm{NP2}} + 0.05C_{9'}^2 + 0.02C_{10'}^2) \\
& \pm (0.09 + 0.03C_9^{\mathrm{NP}} - 0.01C_{10}^{\mathrm{NP}} - 0.03C_{9'} - 0.01C_9^{\mathrm{NP}}C_{9'} \\
& - 0.01C_{9'}C_{10'} + 0.01C_{9'}^2 - 0.01C_{10'}^2),
\end{aligned}
$$

$b \to sll$ in weak effective theory

At the b mass scale $m_b \approx 4$ GeV, the effective Hamiltonian is

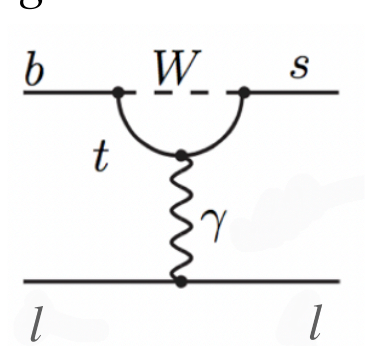
$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i \mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i' \mathcal{O}_i'$$

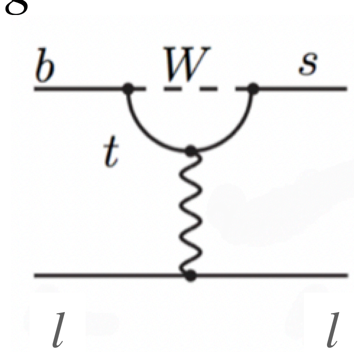


Wilson coefficients ($\mathcal{C}_i^{(\prime)}$): are the coupling constants of the local interactions; contain information about the high-energy degrees of freedom: W,Z (~80 GeV), top (170 GeV) NP particles (~1-100 TeV?)

Local operators ($\mathcal{O}_i^{(\prime)}$): encode information about the low-energy degrees of freedom ($\lesssim m_b$): all leptons, photon, all quarks except top

$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{g^2}(\bar{s}\sigma_{\mu\nu}P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu) \qquad \mathcal{O}_{10}^{(\prime)} = \frac{e^2}{g^2}(\bar{s}\sigma_{\mu\nu}P_{L(R)}b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$$





New physics can:

- alter the value of the Wilson coefficients $\mathcal{C}_i^{(\prime)}$
- add new local operators $\mathcal{O}_i^{(\prime)}$

$B \to Kll$ decay rate (enlarge plot)

$$\mathcal{M}(B \to Kll) = < Kll | \mathcal{H}_{eff} | B > \text{ (decay amplitude)}$$

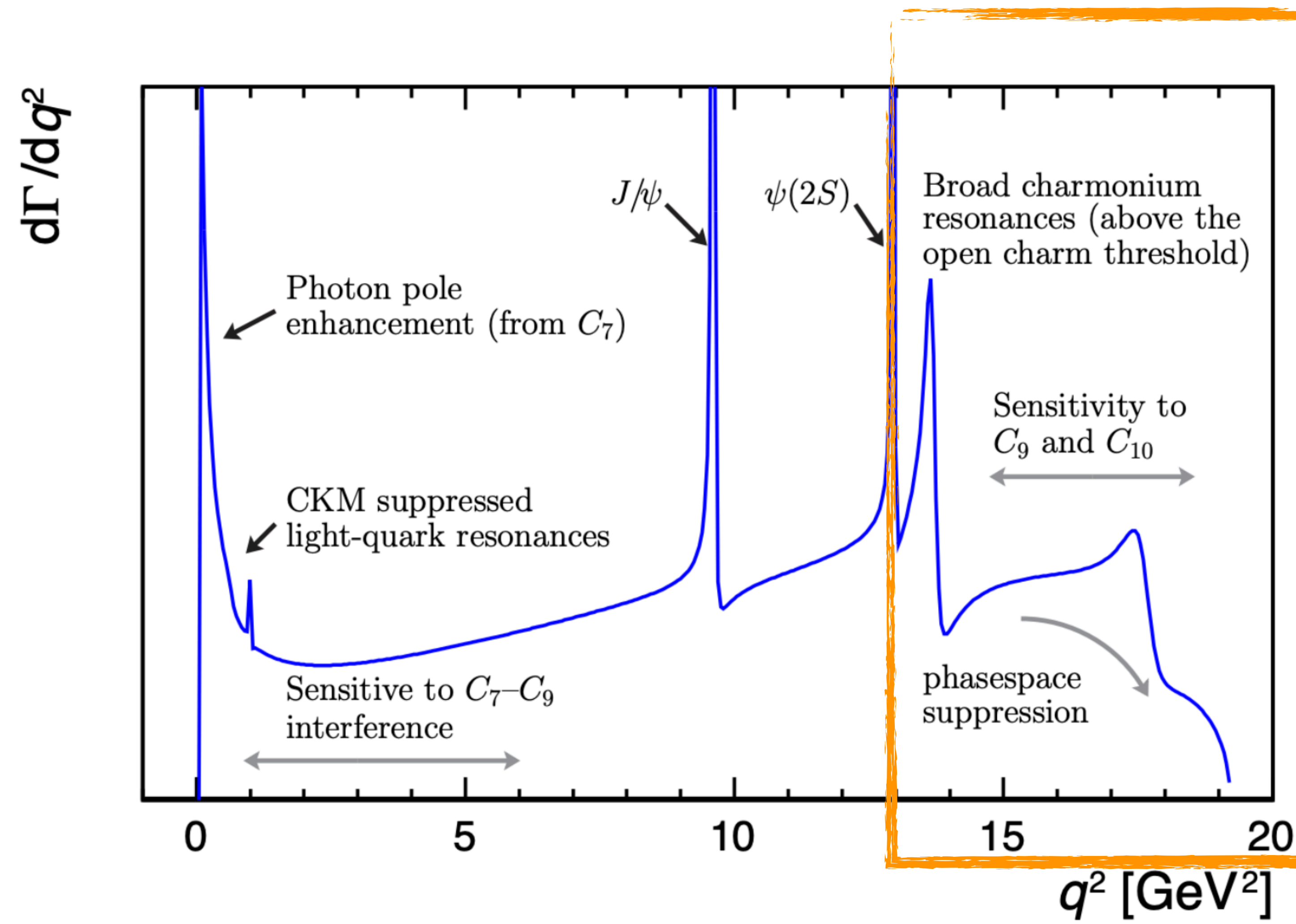
$$\frac{d\Gamma}{dq^2} \propto |\mathcal{M}(B \to Kll)|^2 \text{ (decay rate)}$$

$$\mathcal{B}(B \to Kll) = \frac{\Gamma(B \to Kll)}{\Gamma(B)} \text{ (branching fraction)}$$

For $b \to s\tau\tau$ decays only the q^2 region above the $\psi(2S)$ resonance is available due to kinematics ($4m_\tau^2 \approx 13$ GeV²)

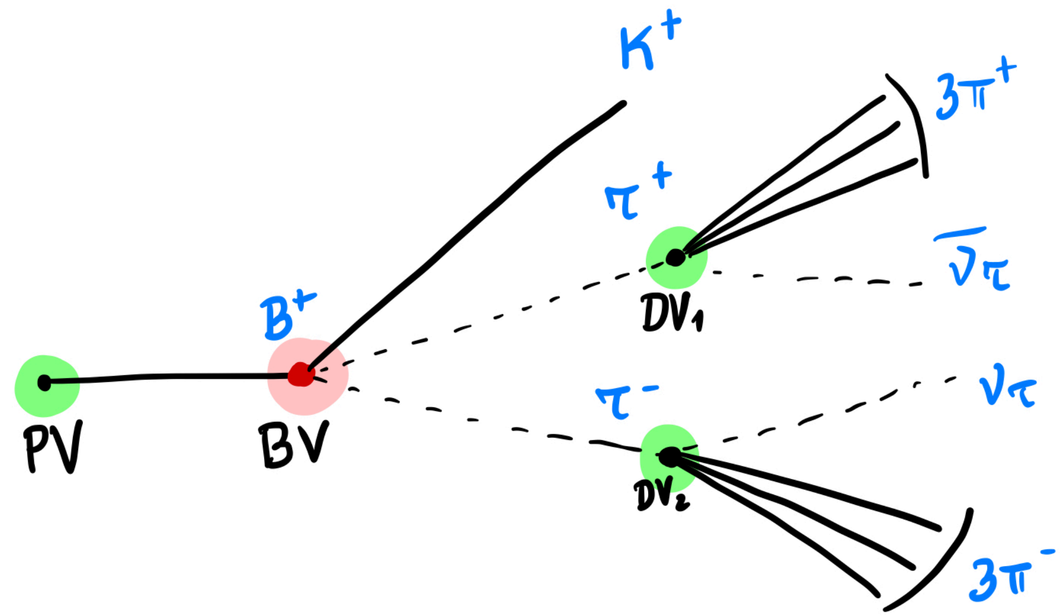
- The **Wilson coefficients** $\mathcal{C}_i^{(\prime)}$ are computed using perturbation theory
- The **matrix elements** $< Kll | \mathcal{O}_i^{(i)} | B >$ are written in terms of **form factors**, which are computed with non-perturbative methods (lattice QCD, LCSRs...)

Source of large theory errors



q^2 is the di-lepton invariant mass squared

B^+ mass analytical reconstruction



- **23 known parameters**:
  - primary vertex (PV)
  - τ^+, τ^- decay vertices
  - $(3\pi)^+$, $(3\pi)^-$, K^+ 4-momenta
  - Reference point on K^+ trajectory
- **23 unknown parameters:**
  - B^+ decay vertex (BV)
  - B^+, τ^+, τ^-, $\bar{\nu}_\tau$, ν_τ 4-momenta

24 constraints:

- B^+ decay vertex must lie in K^+ trajectory **(2)**
- 4-momentum conservation in each decay vertex **(4x3=12)**
- Tau mass constraint **(2)**
- Neutrino mass constraint **(2)**
- $\vec{p}_{\tau 1} \parallel \overrightarrow{DV_1} - \overrightarrow{BV}$ **(2)**
- $\vec{p}_{\tau 2} \parallel \overrightarrow{DV_2} - \overrightarrow{BV}$ **(2)**
- $\vec{p}_B \parallel \overrightarrow{BV} - \overrightarrow{PV}$ **(2)**

Constraints are used in a kinematic fitter ->

Decay Tree Fitter (DTF)

- Is a kinematic fitter that **performs a least-squares fit to the whole decay chain simultaneously to obtain better estimates for the track parameters**
- We used a **modified** version of DTF in which we included the neutrinos in the final state
- The unknown kinematics is initialised using the results of the analytical calculations

$$\boldsymbol{x} = \{x_1, y_1, z_1, \theta_1, p_{x1}, p_{y1}, p_{z1}, E_1, ..., x_n, y_n, z_n, \theta_n, p_{xn}, p_{yn}, p_{zn}, E_n, \}$$

($\theta = l/|\vec{p}|$, l is the decay length)

- Constraints are expressed as χ^2 contributions:

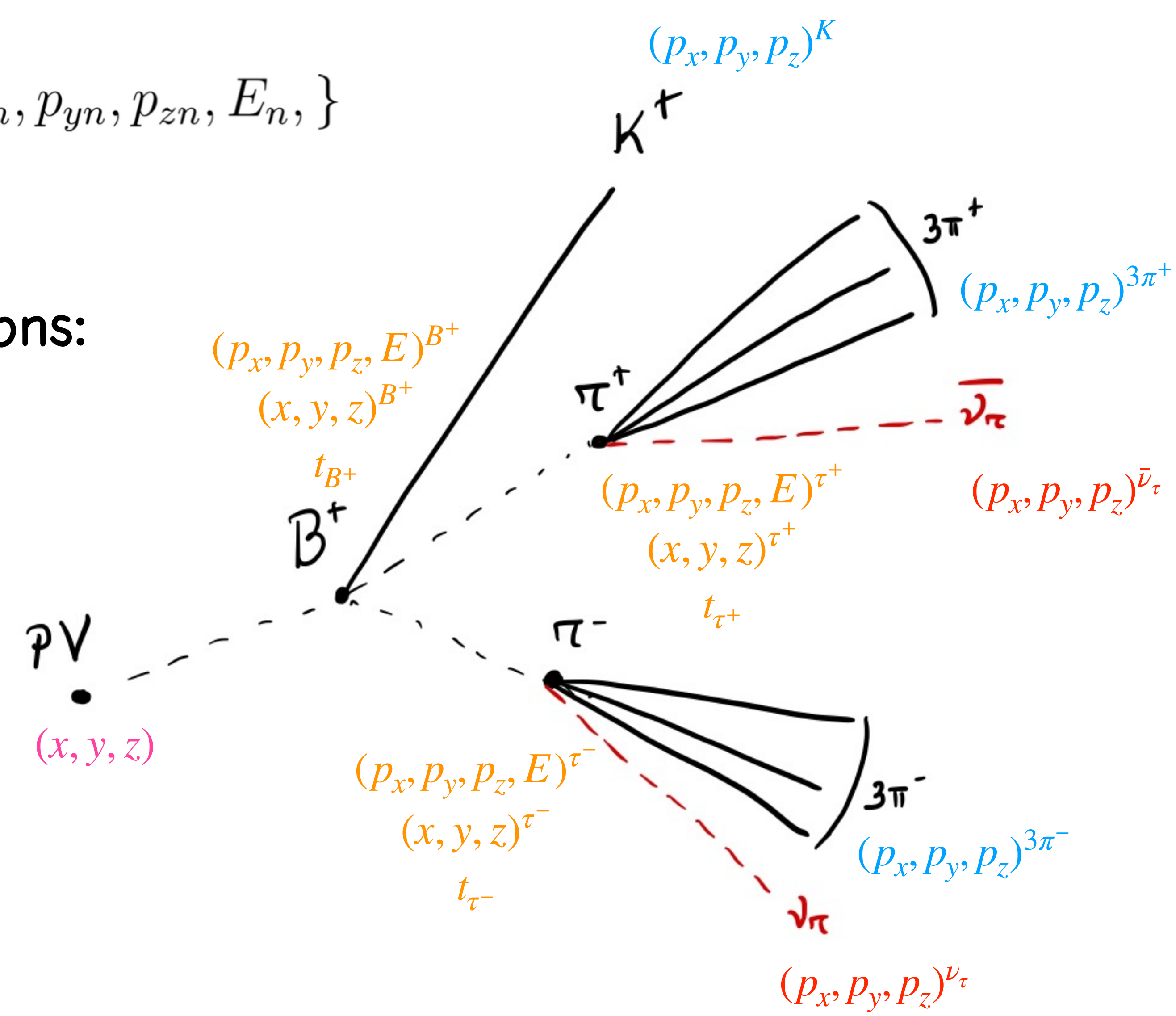
$$\chi_k^{2(i)} = (r_k^{k-1(i)})^T (R_k^{k-1(i)})^{-1} (r_k^{k-1(i)})$$

Residual — Uncertainty in the residual

$$r_k^{k-1} = m_k - h_k(x_{k-1})$$

measurement — measurement model

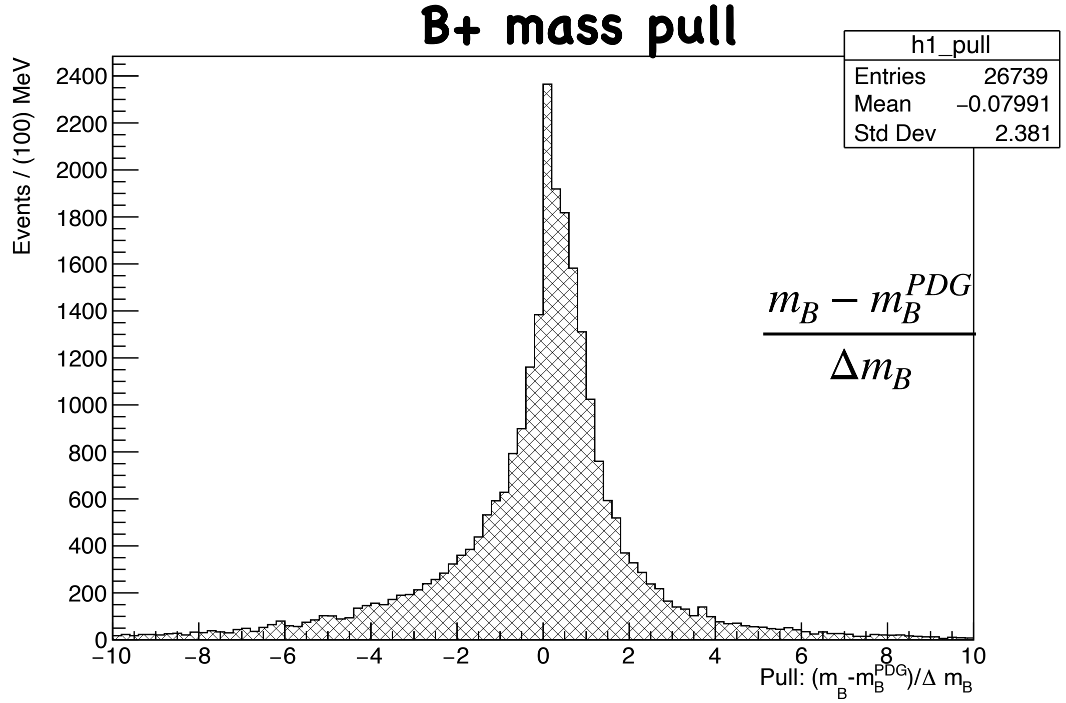
Needs to be inverted when updated $x_k^i \rightarrow x_k^{i+1}$



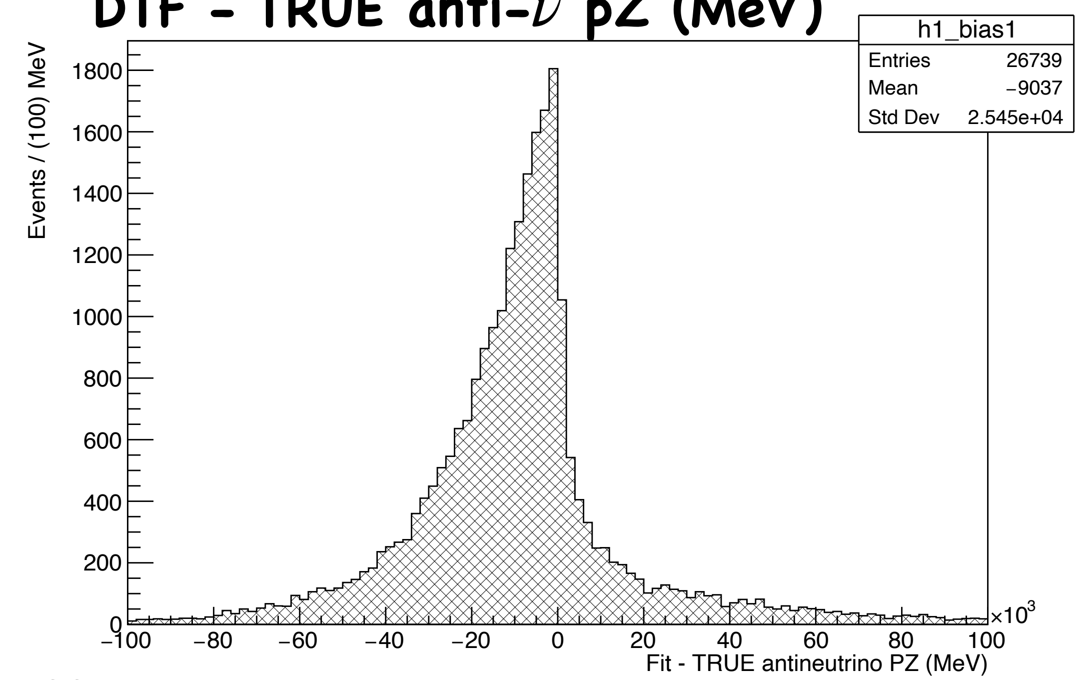
DTF issues in B2Ktautau analysis

- DTF is a very robust tool which is widely used in LHCb in many different analyses
- However, it is not ideal to deal with **decays with missing particles in the final state**
- We observe biases in some variables and the τ mass constraint is not applied exactly:

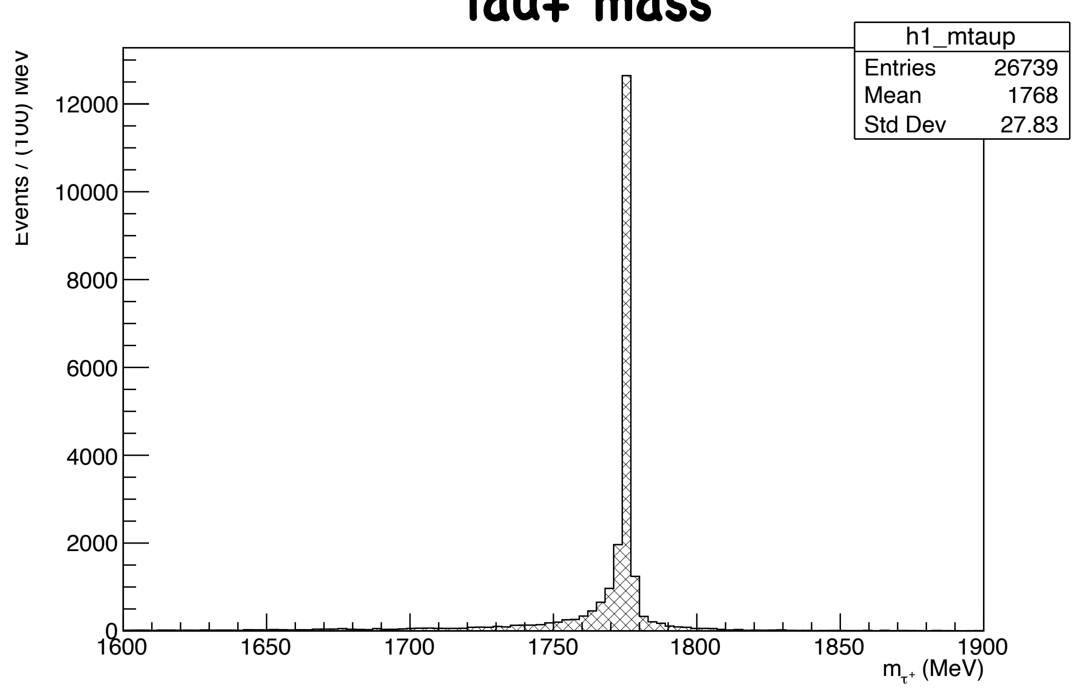
B+ mass pull



DTF - TRUE anti-ν pZ (MeV)



tau+ mass



Standalone fitter

- We define the χ^2

$$\chi^2 = (m - h(x))^T W (m - h(x))$$

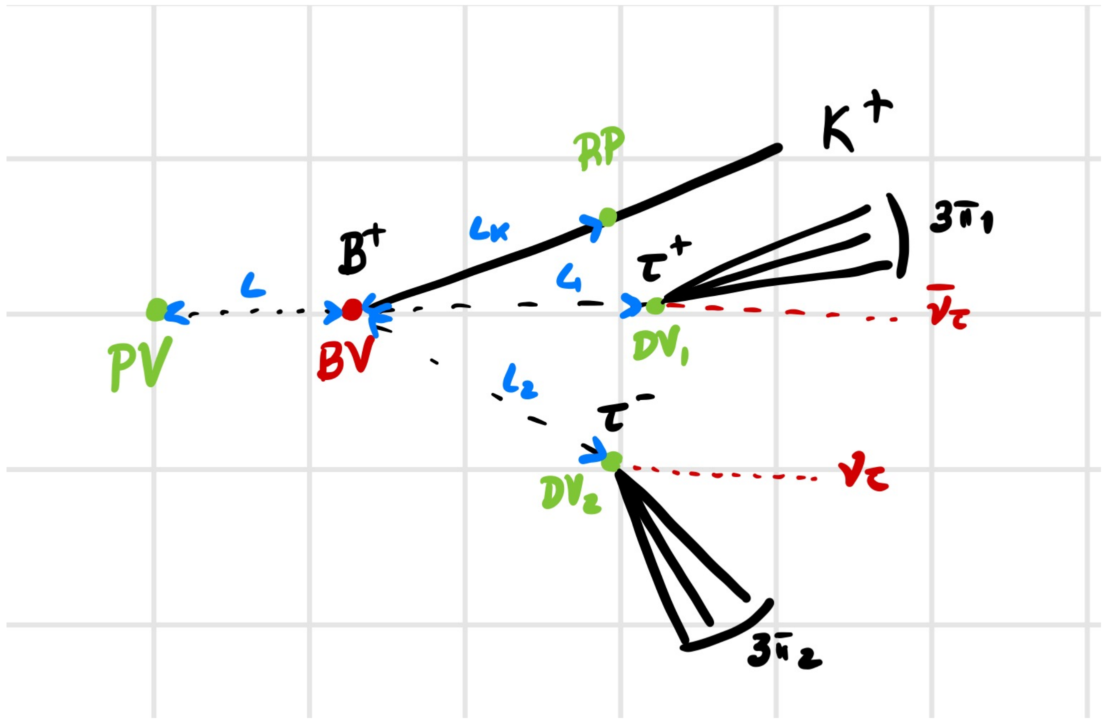
- m is a 23-D vector containing the **known** parameters

$$m = (PV, DV_1, \vec{p}_{3\pi 1}, m^2_{3\pi 1}, DV_2, \vec{p}_{3\pi 2}, m^2_{3\pi 2}, RP_T, \vec{p}_{6\pi K}, m^2_{6\pi K})$$

- $W = V^{-1}$ is the **weights** matrix (V is the 23x23 covariance matrix of m)
- x is a 23-D vector containing the **unknown** parameters

$$x = (BV, \vec{p}_B, m^2_B, \vec{p}_{\tau 1}, \vec{p}_{\nu 1}, \vec{p}_{\tau 2}, \vec{p}_{\nu 2}, L_1, L_2, L, L_K)$$

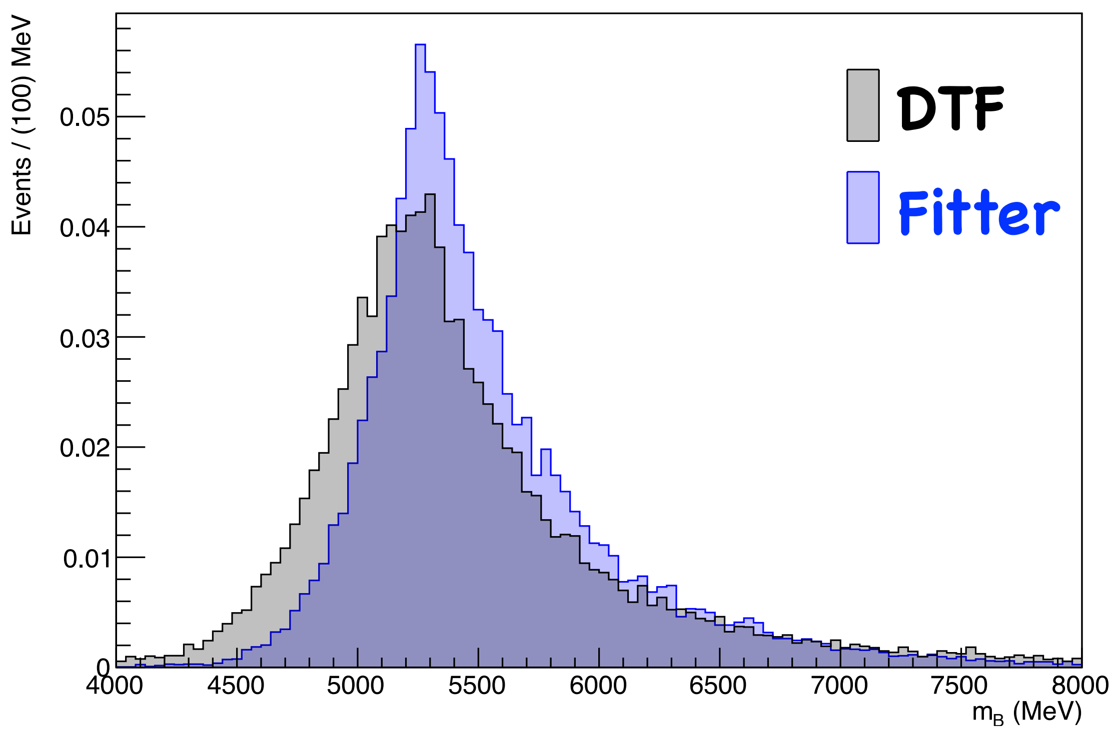
- $h(x)$ is the estimate of m based on x obtained by applying the **24 model constraints**



Standalone fitter: comparison w/ DTF

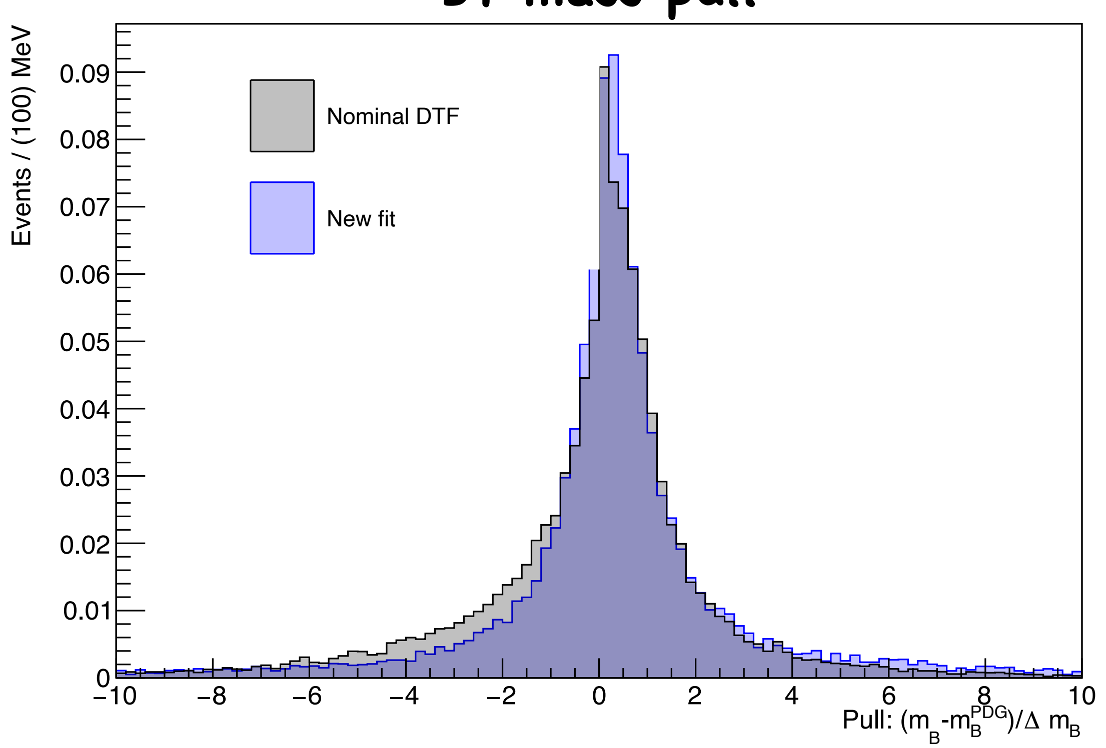
- Only events that pass the χ^2 minimisation successfully are considered

B+ mass

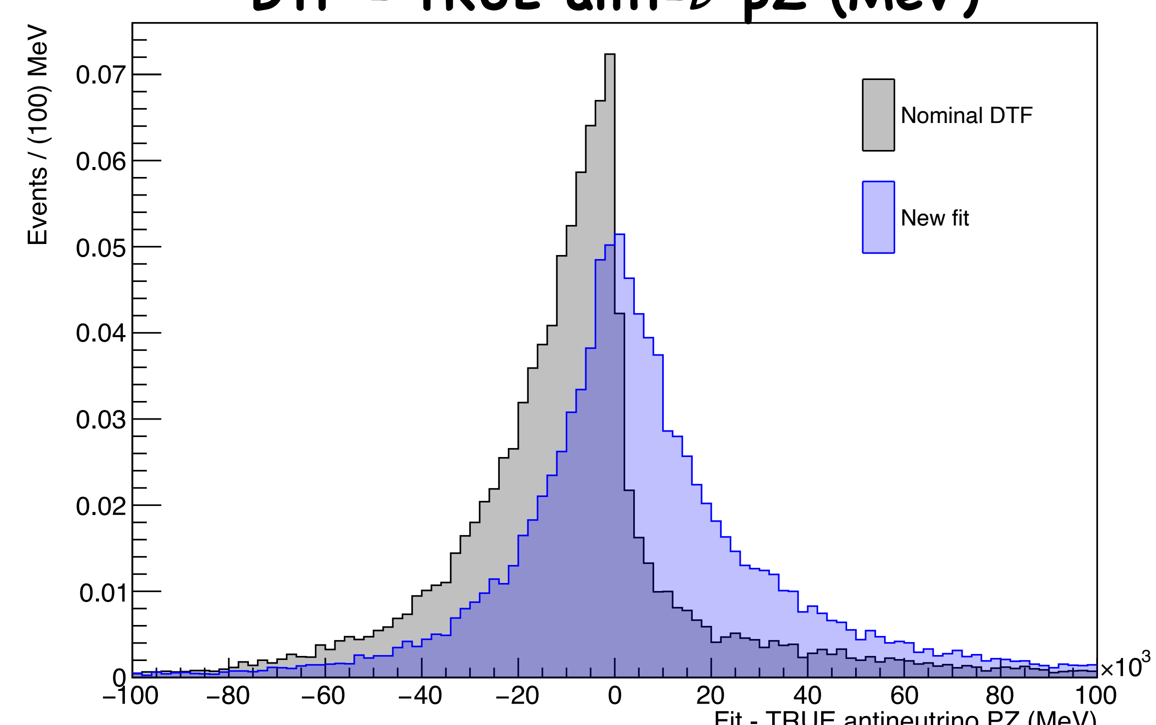


	DTF	Fitter
Passing rate	97%	91%
B mass resolution	288.7 MeV	203.8 MeV
B mass peak	5300 MeV	5260 MeV

B+ mass pull



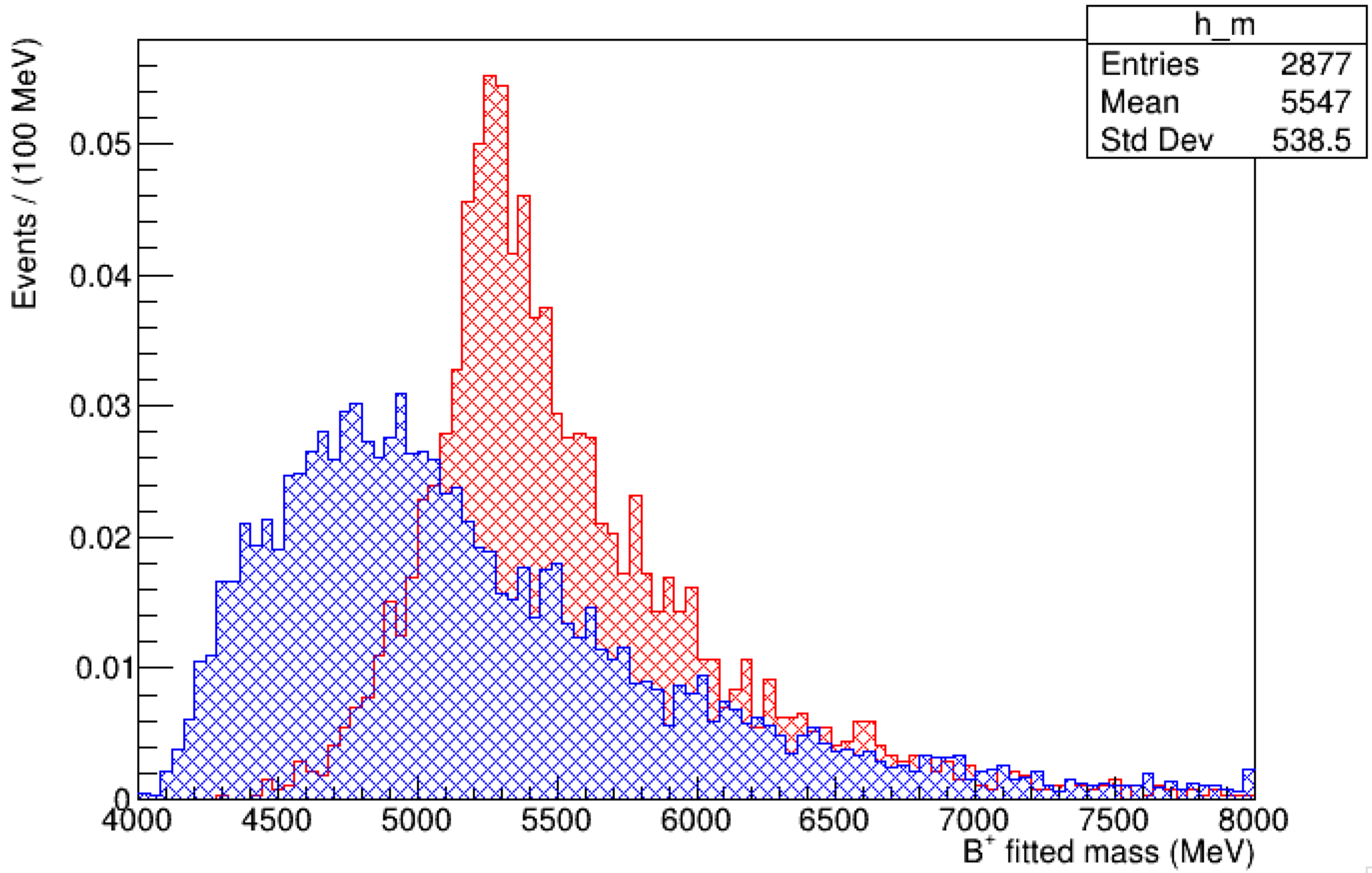
DTF - TRUE anti-ν pZ (MeV)



Standalone fitter: data vs MC B+ mass

I use 10K data events and 3186 Mc events (all components)

~80% of data passes fitter / ~90% of MC passes fitter



Pre-BDT efficiencies

MC acceptance

	MagUp	MagDown	Total (average)
2016	$5.33 \pm 0.01\,\%$	$5.34 \pm 0.01\,\%$	$5.335 \pm 0.007\,\%$
2017	$5.31 \pm 0.01\%$	$5.32 \pm 0.01\%$	$5.315 \pm 0.007\%$
2018	$5.35 \pm 0.01\,\%$	$5.31 \pm 0.01\,\%$	$5.330 \pm 0.007\,\%$

MC stripping

	MagUp	MagDown	Total (average)
2016	$1.259 \pm 0.007\,\%$	$1.254 \pm 0.007\,\%$	$1.256 \pm 0.005\,\%$
2017	$1.281 \pm 0.005\%$	$1.286 \pm 0.005\%$	$1.283 \pm 0.004\%$
2018	$1.024 \pm 0.004\,\%$	$1.033 \pm 0.004\,\%$	$1.028 \pm 0.003\,\%$

MC reco (truth-matched reco / gen)

Year	3pi3pi	3pi3pipi0	3pi3pi2pi0	Total
2016	a	a	a	a
2017	a	a	a	a
2018	61.0 ± 0.4 %	62.5 ± 0.4 %	62.4 ± 0.9 %	61.7 ± 0.2 %

Trigger

Year	MC	RS data	WS data
2016	a	a	a
2017	a	a	a
2018	34.5 ± 0.2 %	55.5 ± 0.1 %	48.5 ± 0.1 %

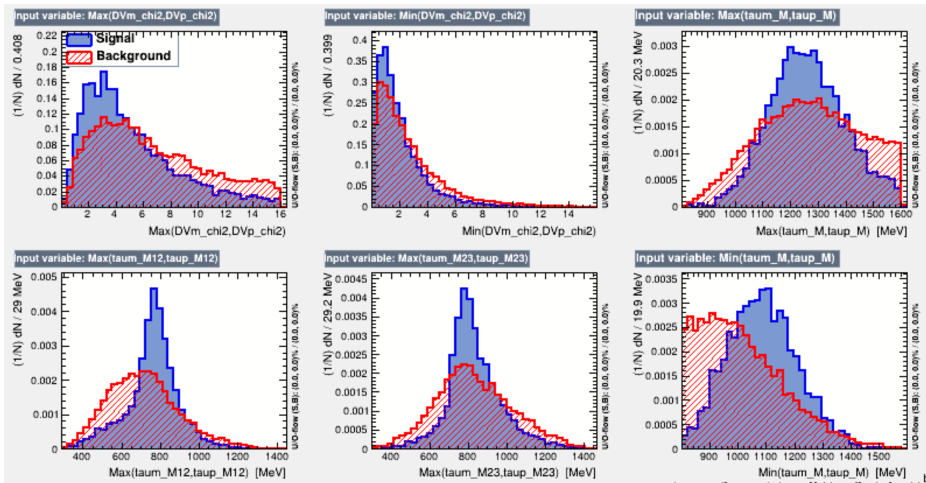
Pass DTF

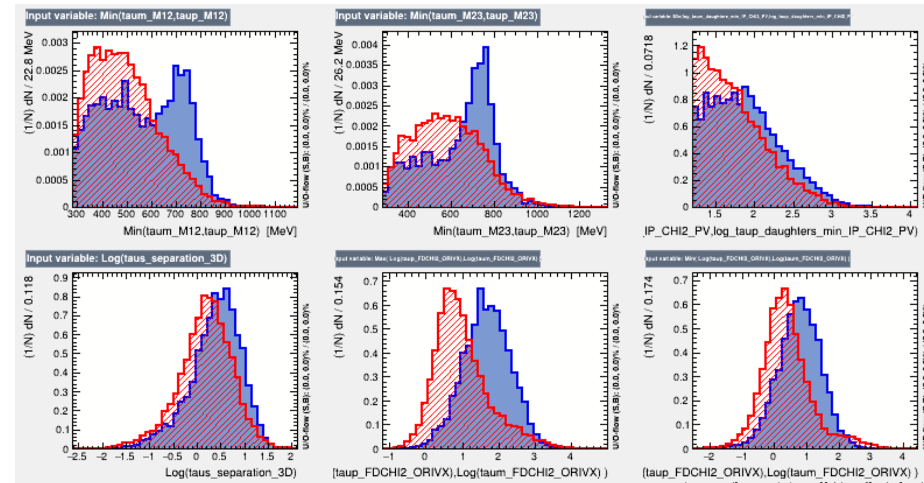
Year	MC	RS data	WS data
2016	a	a	a
2017	a	a	a
2018	96.8 ± 0.7 %	96.4 ± 0.2 %	96.1 ± 0.2 %

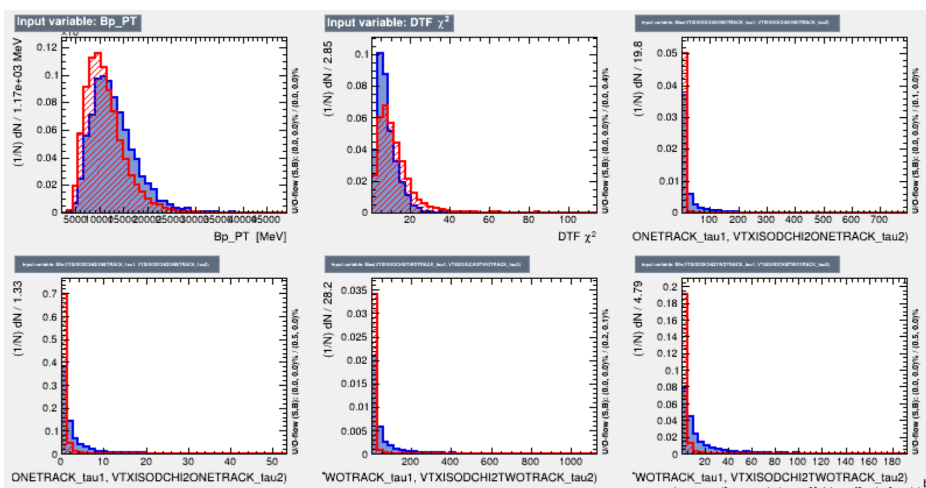
Rectangular cuts

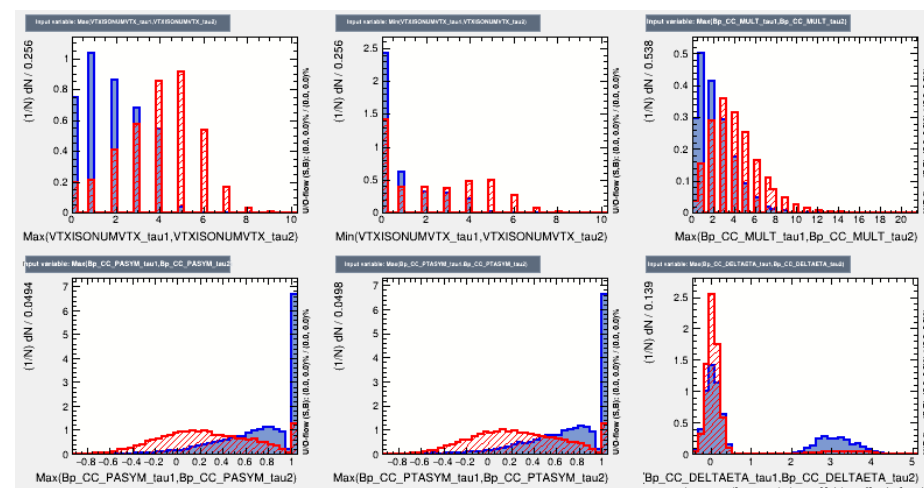
Year	MC	RS data	WS data
2016	a	a	a
2017	a	a	a
2018	87.0 ± 0.7 %	36.2 ± 0.1 %	37.0 ± 0.1 %

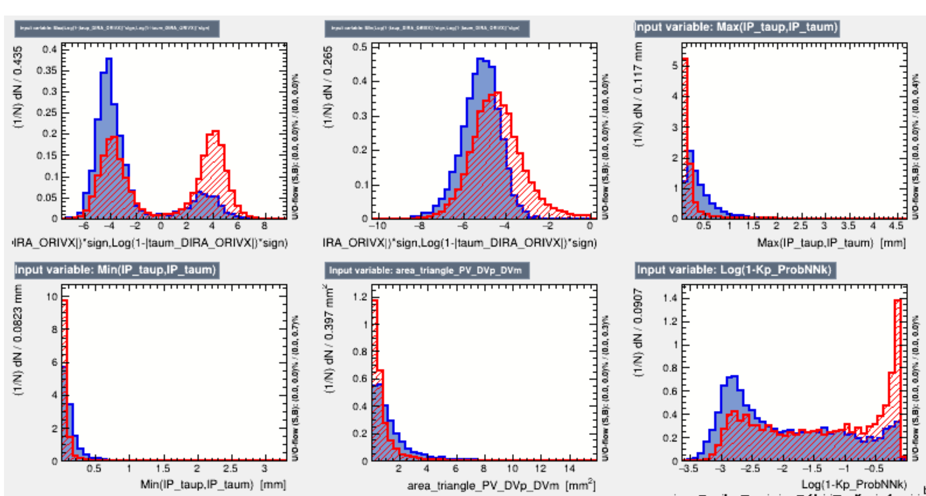
BDT input variables

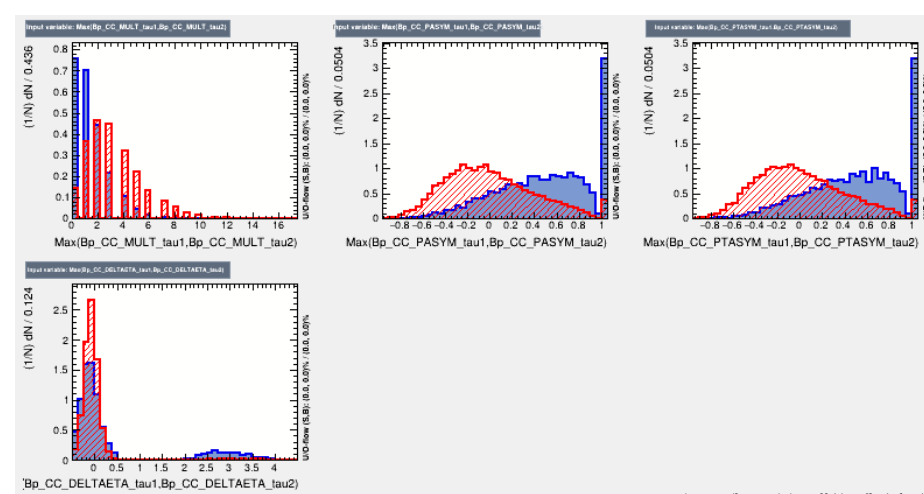




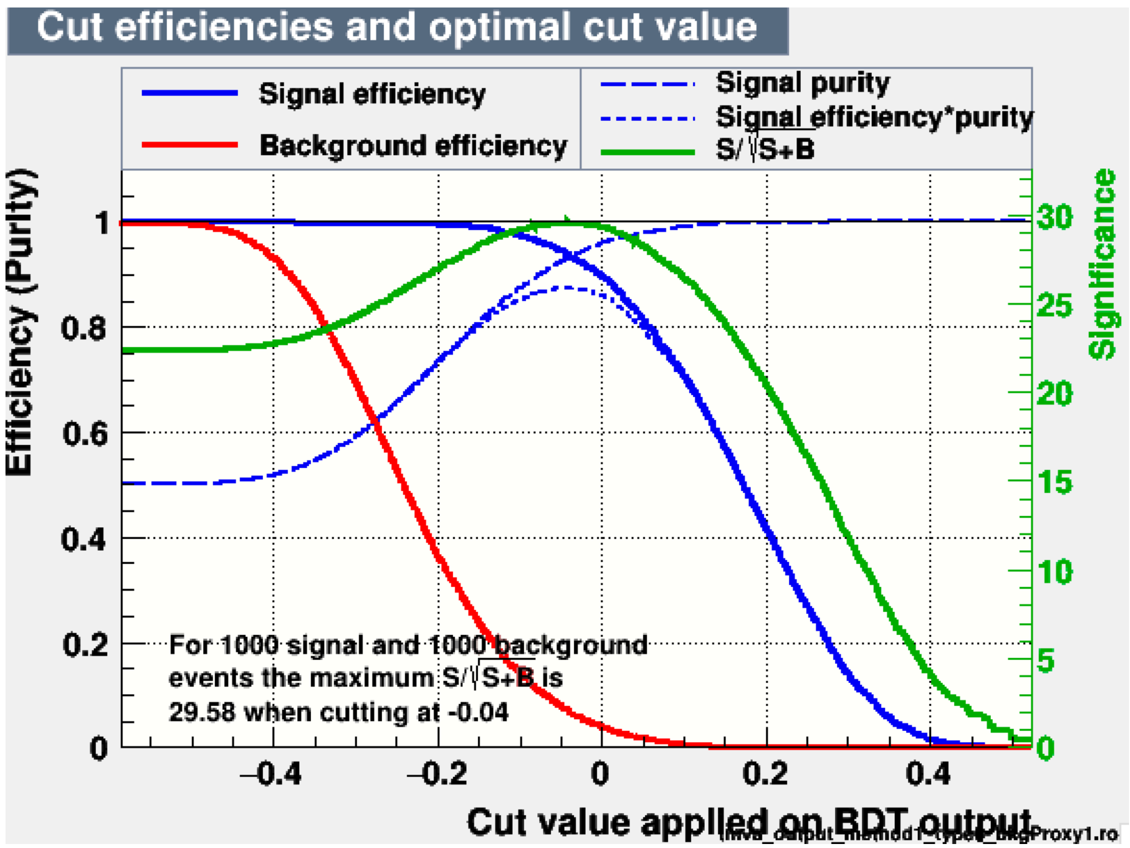




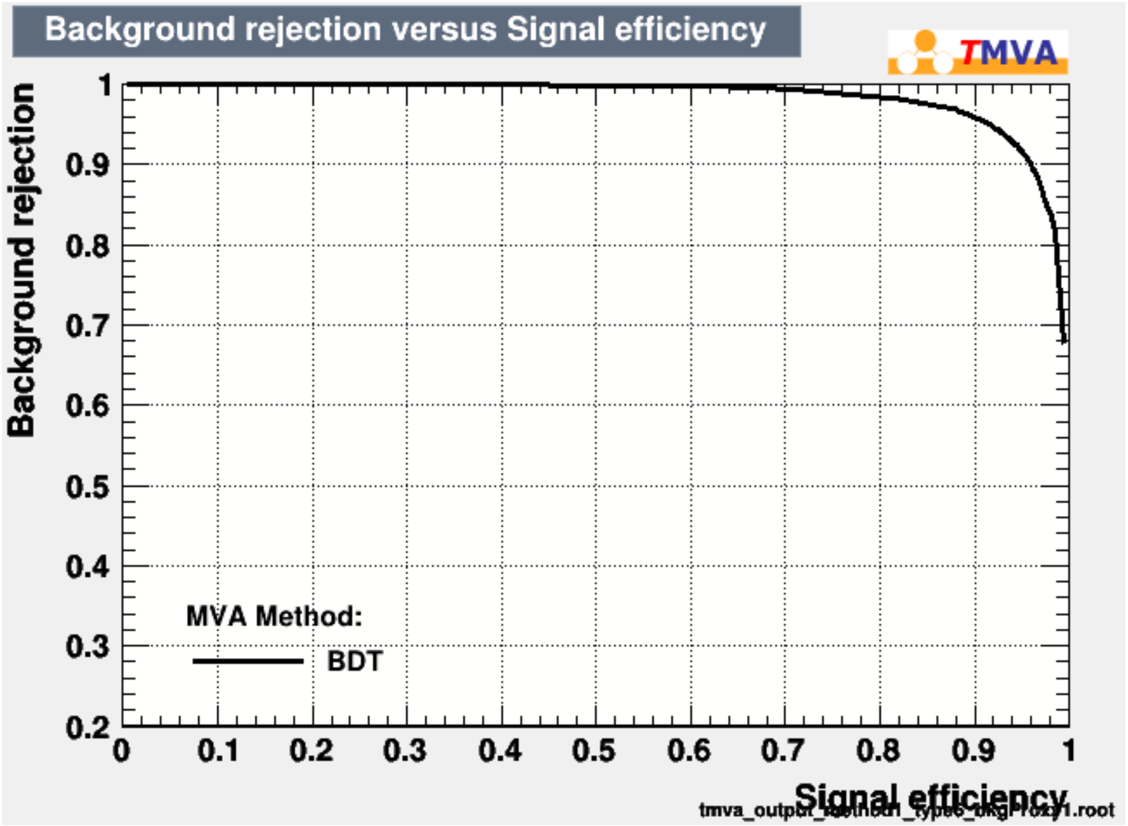




BDT metrics

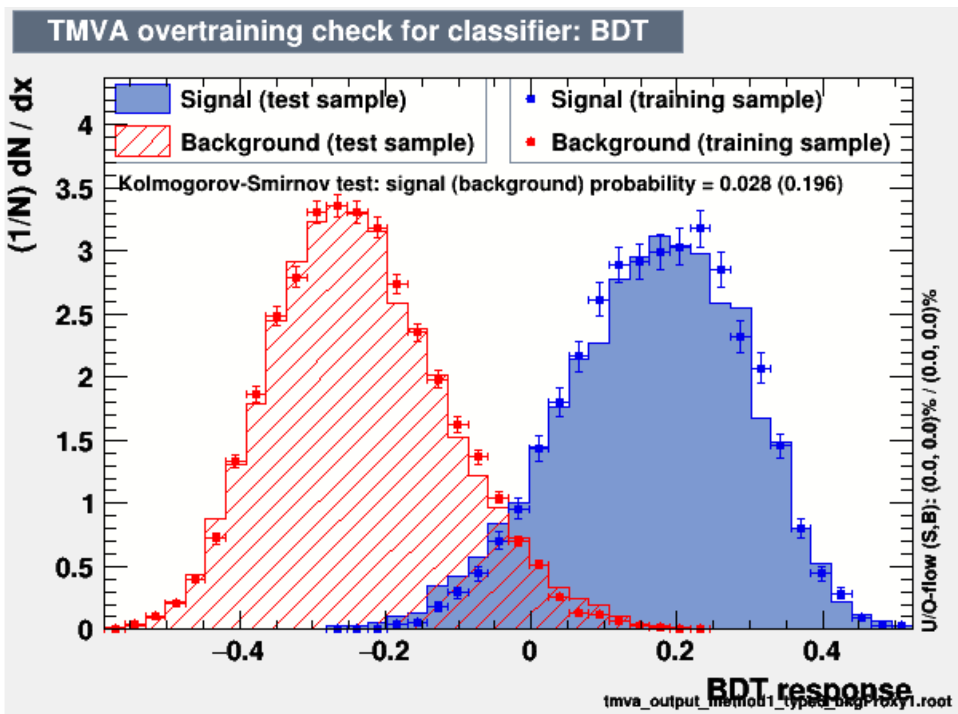


Cut efficiencies and optimal cut value
Signal efficiency
Background efficiency
Signal purity
Signal efficiency*purity
S/√S+B
Efficiency (Purity)
Significance
For 1000 signal and 1000 background events the maximum S/√S+B is 29.58 when cutting at -0.04
Cut value applied on BDT output

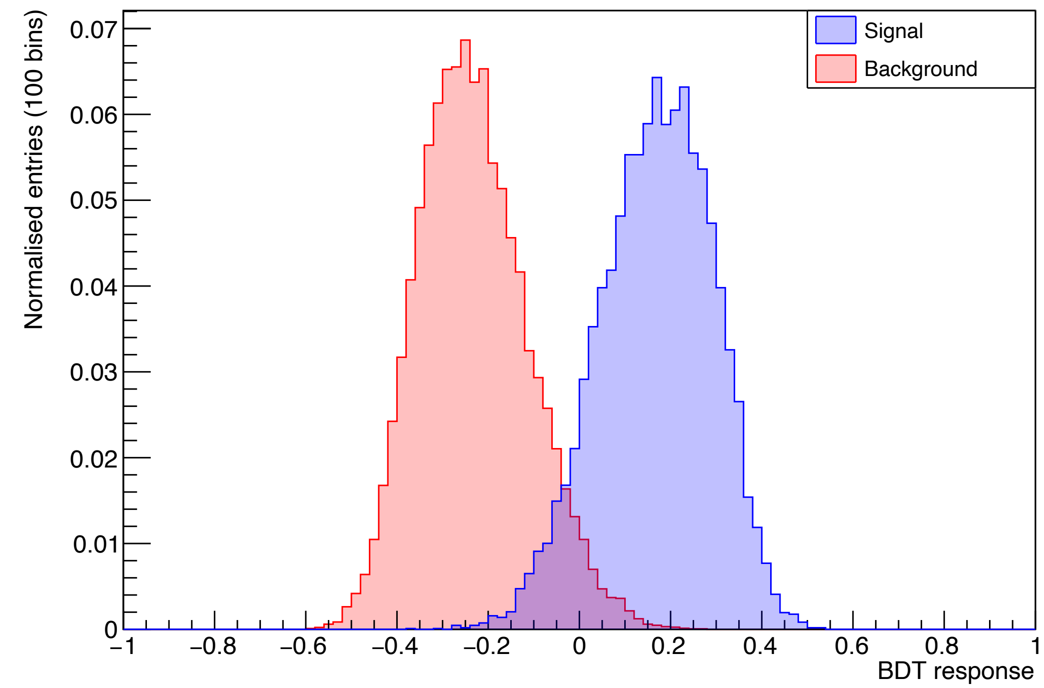


Background rejection versus Signal efficiency
TMVA
Background rejection
MVA Method:
BDT
Signal efficiency

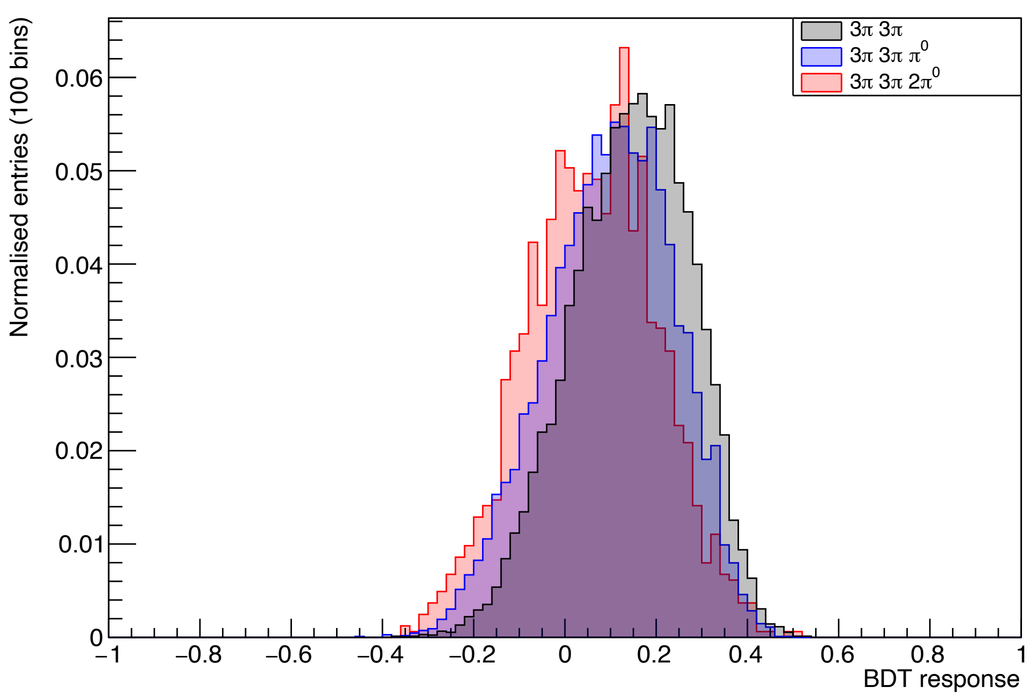
BDT response



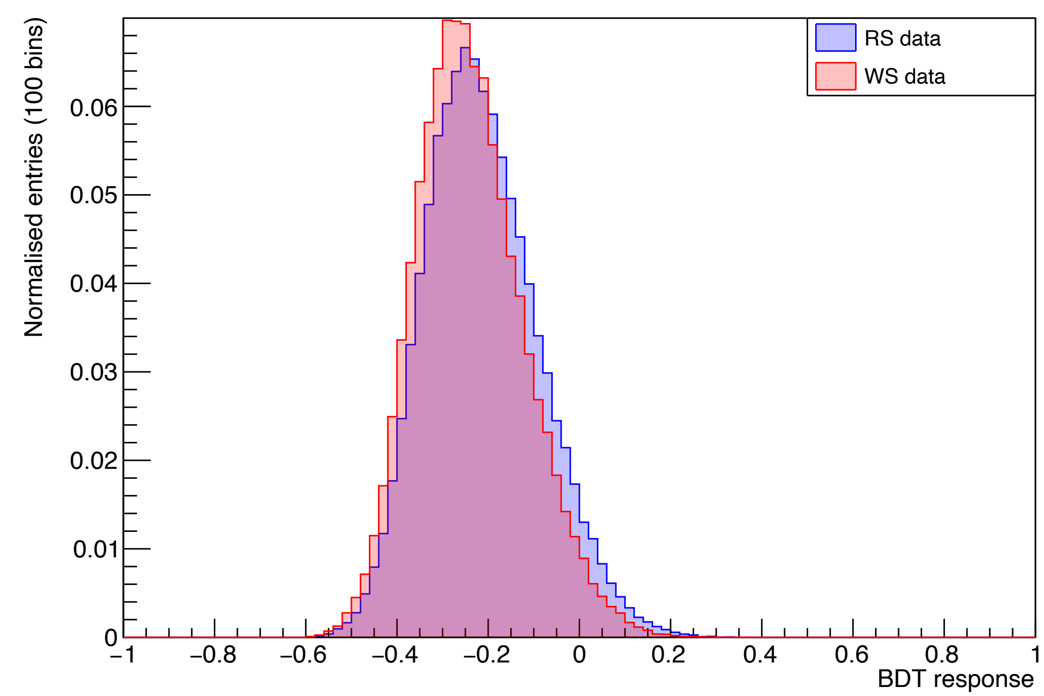
(truthMatch)+passDTF+cuts+trigger+others



truthMatch+passDTF+trigger+others



passDTF+trigger+others



Sensitivity estimate (2018)

$$\mathcal{B}(B^+ \to K^+\tau^+\tau^-) = \frac{1}{L\sigma\epsilon_S} \frac{S}{[\mathcal{B}(\tau \to 3\pi\nu) + \mathcal{B}(\tau \to 3\pi\pi^0\nu)]^2}$$

- L -> luminosity of the subset of data we are using (2018)
- $\sigma = 2 \times f_u \times \sigma(pp \to b\bar{b})$, $\sigma(pp \to b\bar{b}X) \approx 560\mu$b (LHCb), $f_u \approx 0.412$
- $\mathcal{B}(\tau \to 3\pi\nu) = (9.31 \pm 0.05)\,\%$, $\mathcal{B}(\tau \to 3\pi\pi^0\nu) = (4.62 \pm 0.05)\,\%$ (PDG)
- $\epsilon_S = \epsilon_S^{\text{pre-BDT}} \times \epsilon_S^{\text{BDT}}$

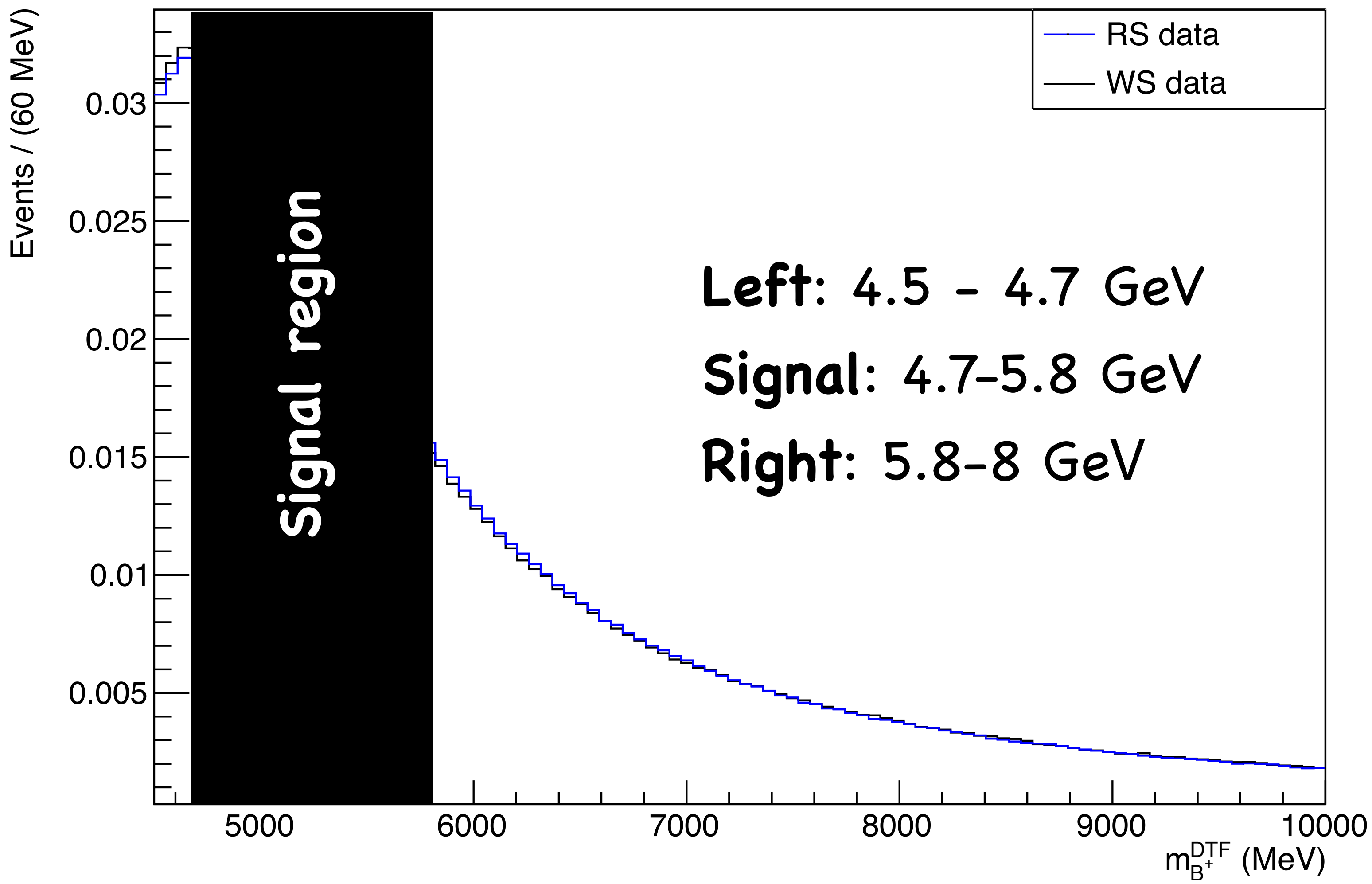
S -> 95% C.L. upper limit on the signal yield in RS data

Figure of merit: $\frac{S}{\sqrt{S+B}} = 1.64$, where $B = B^{\text{pre-BDT}} \times \epsilon_B^{BDT}$

$B^{\text{pre-BDT}}$ is the background yield in RS data **before** the BDT cut

Background yield in data before BDT cut

RS vs WS DTF B+ mass after pre-BDT cuts



- We **blind** the signal region (4.7-5.8 GeV) in the RS data
- RS and WS shapes agree very well before BDT cut
- **Assumption**: they also agree well after BDT cut

$$N_{signal}^{RS} = \frac{N_{right}^{RS}}{N_{RS}^{WS}} \times N_{signal}^{WS}$$

$$B^{\text{pre-BDT}} = 2492110 \pm 1579$$

(Evaluated on the signal region)

BDT efficiency and yields