



université
PARIS-SACLAY

LPNHE
PARIS



iJC Lab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis

Aix*Marseille
université



Search for rare B decays with τ in the final state at LHCb and Belle II

J. Cerasoli, G. de Marino, S. Watanuki, S. G. Weber

OUTLINE

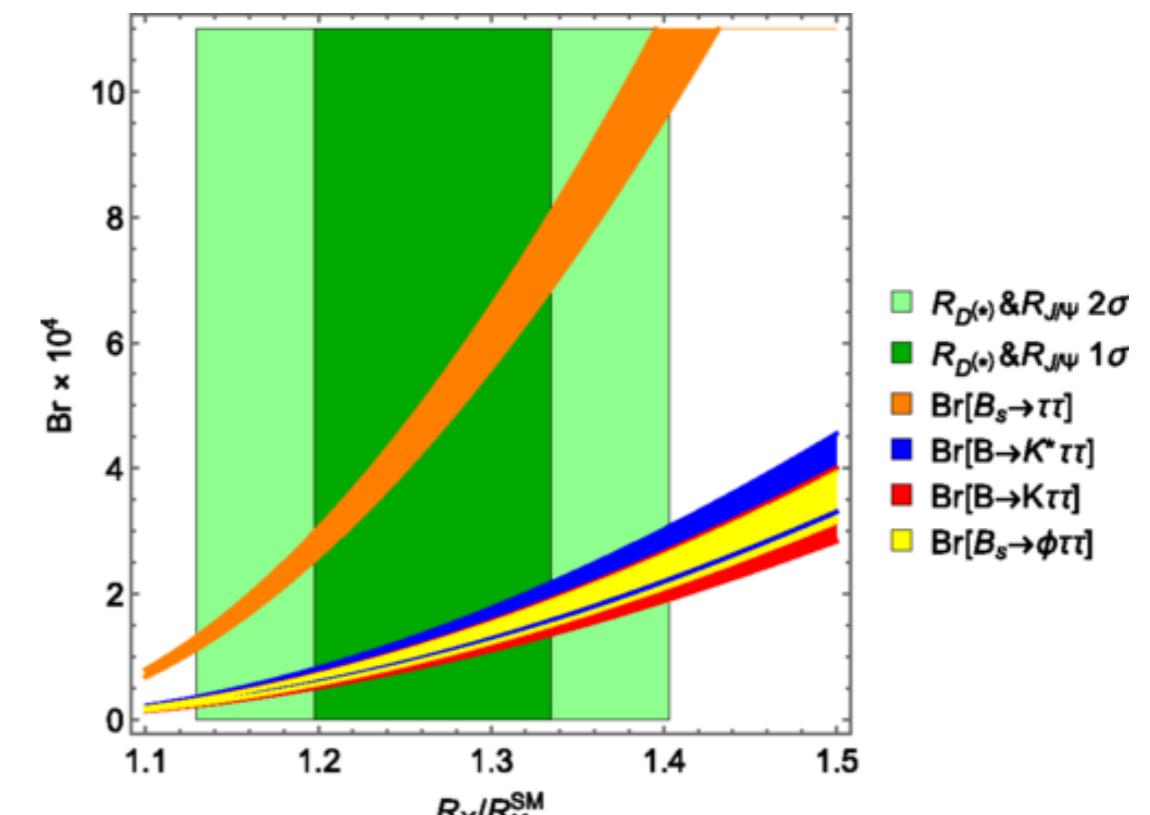
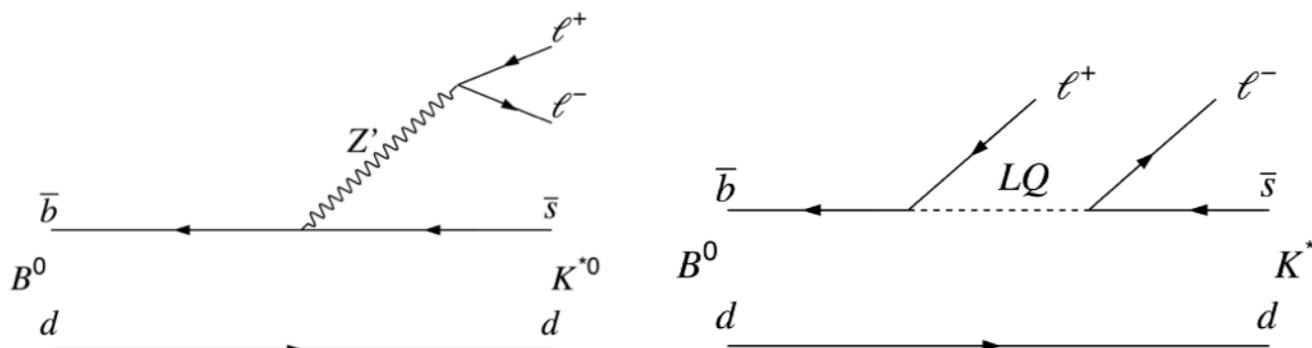
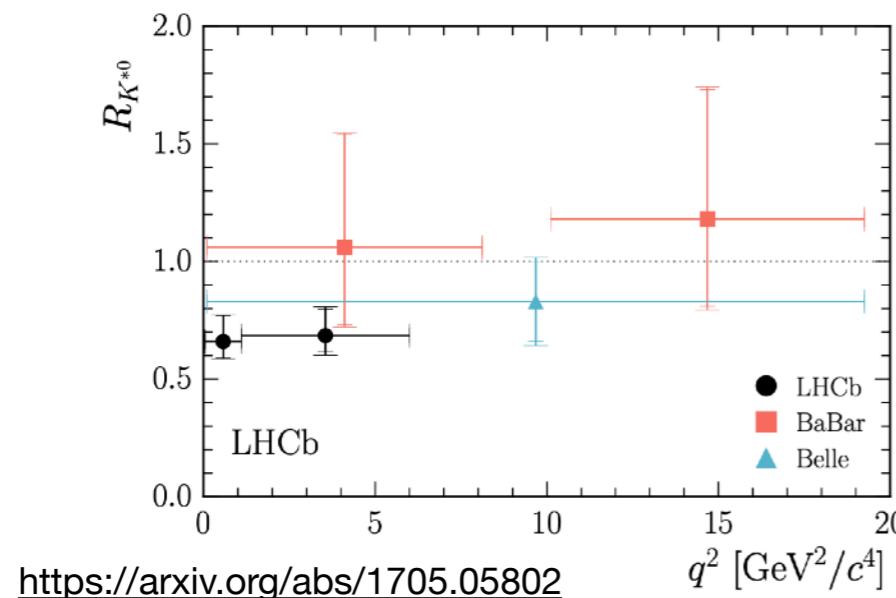
- Introduction and motivation
- LHCb experiment
- Belle II experiment
- LHCb and Belle II: overview

The analyses

- $B^0 \rightarrow K^{*0} \tau\tau$
- $B^0 \rightarrow K^{*0} \tau\mu$
- $B^+ \rightarrow K^+ \tau l$
- Conclusion, plans

INTRODUCTION AND MOTIVATION

- Rare tau lepton modes are largely unexplored, and interest in these modes is growing in the HEP community
- Lots of room for beyond the SM effects (leptoquarks, Z' bosons, ...) that could be coupled mainly to the 3rd generation, which could bring to **Lepton Flavor (Universality) violation**
- Several hints of new physics ($R_{K^{(*)}}$, $R_{D^{(*)}}$, ...): BR could be sensitive to the presence of **new physics particles entering the loops** and be enhanced up to thousands times the SM predictions

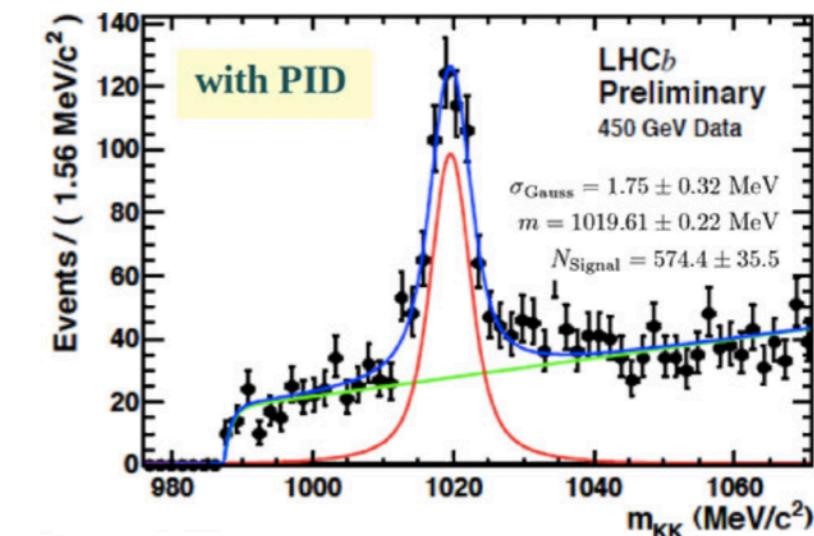
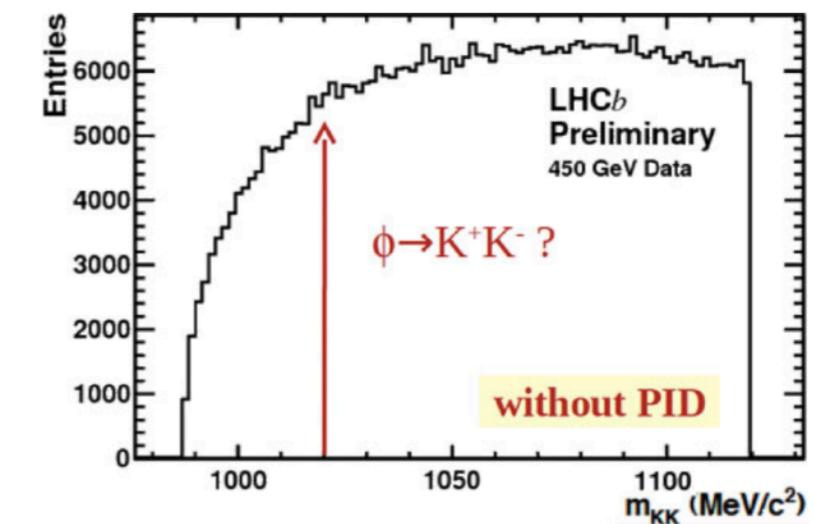
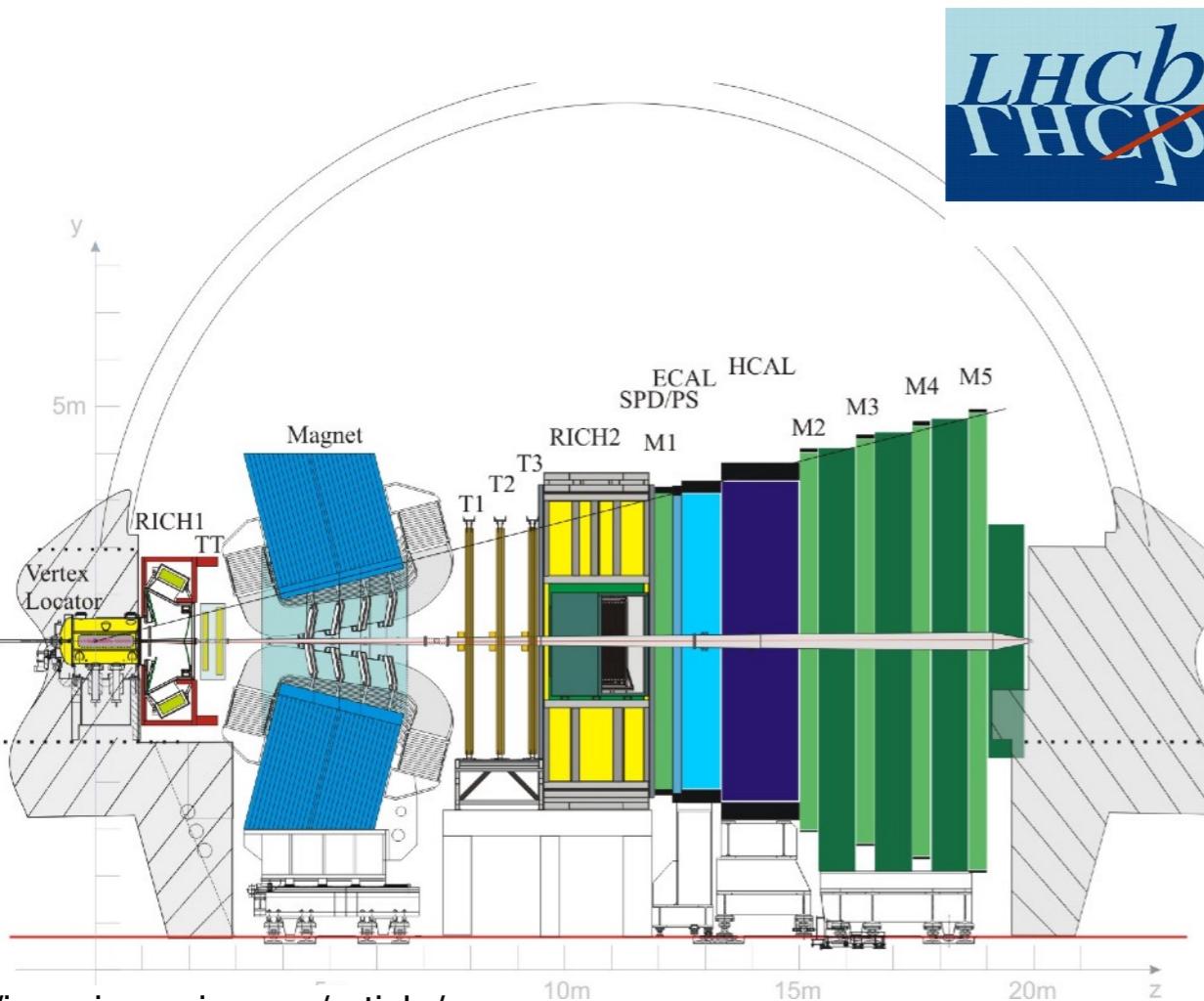
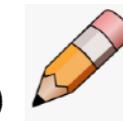


B. Capdevila et al. Dec 2017
<https://arxiv.org/abs/1712.01919v1>

- **Lepton Flavor violating modes:** the (accidental) conservation of leptonic number for each family could be violated ($B_s \rightarrow \tau \mu$, $B^0 \rightarrow K^* \tau \mu$, ...)
- **$b \rightarrow s l^+ l^-$ quark level transition modes:** highly suppressed in the SM, could be enhanced due to the presence of new physics ($B^0 \rightarrow K^* \tau \tau$, $B^+ \rightarrow K^+ \tau \tau$, ...)

THE LHCb DETECTOR

- Precision experiment to study CP violation in B hadron decays
General purpose experiment optimized for detecting beauty and charm hadrons (B^0 , B_s , B_c , ...)
- Peculiar features for rare B decays studies:
 - Vertex Locator (VELO): Precise **measurement of displaced vertex positions** ($\sim 13\mu\text{m}$ vertex resolution in transverse plane, $\sim 70\mu\text{m}$ along beam axis)
 - RICH detectors: **identification of charged hadrons** via Cherenkov effect (over $\sim 2\text{-}100$ GeV range)
 - Tracking system: good momentum resolution ($\sim 0.8\%$ for 100 GeV particles)
 - Muon stations: **muon identification** and trigger



THE BELLE II EXPERIMENT

World Record Luminosity

$$\mathcal{L}_{\text{peak}} = 2.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ (June 15th)}$$

Currents ~0.7A (LER)/0.6 A (HER)

Belle II: a multi-purpose detector installed at the IP of the B-Factory **SuperKEKB**.
Location: KEK Laboratory - Tsukuba, Japan

Ensure equal/better performance (tracking, vertexing, PID, calorimeter resolution) in a harsher environment (higher trigger rate: 0.5 kHz → 30 kHz)

Nano beam scheme

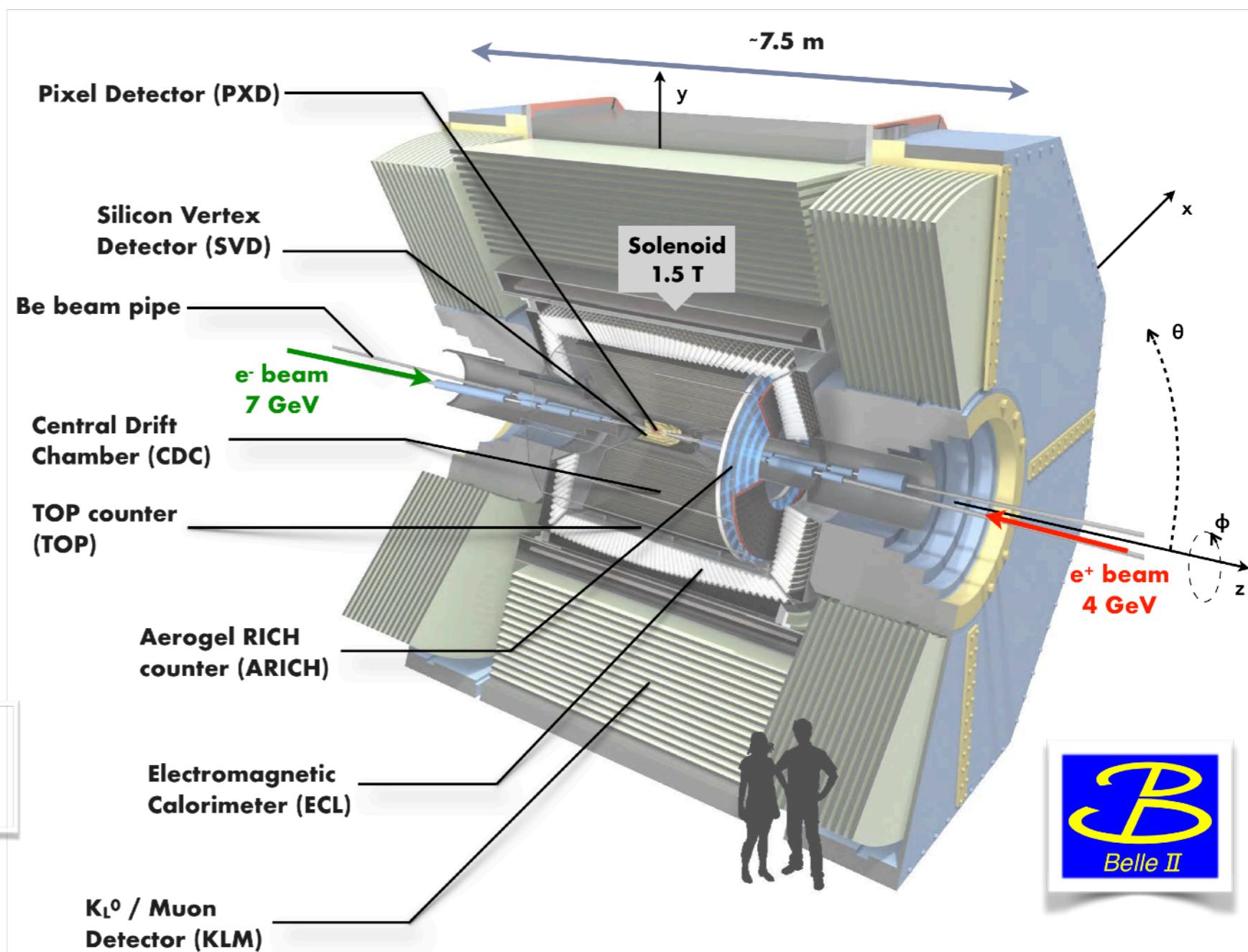
$$\mathcal{L} = \frac{\gamma_{\pm}}{2\pi r_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left(\frac{I_{\pm} \xi_{y\pm}}{\beta_y^*} \right) \left(\frac{R_L}{R_{\xi_{y\pm}}} \right)$$

5.9 mm (KEKB) → 0.3 mm (SuperKEKB)

Collected 74 fb⁻¹ so far
→ Rediscoveries, first 2 papers

Goal: $\mathcal{L}_{\text{int}} = 50 \text{ ab}^{-1}$ (2019 - 2031)

(Belle @ KEKB: $\mathcal{L}_{\text{int}} = 1.05 \text{ ab}^{-1}$ [1999-2010])

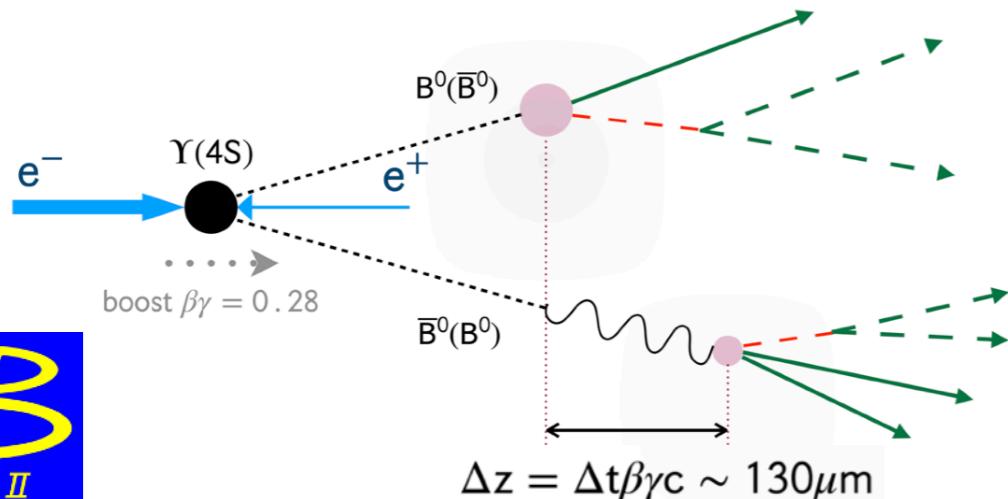


LHCb VS BELLE II, DIFFERENT APPROACH, SAME GOAL: SEARCH FOR RARE B DECAYS

Belle II

$$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

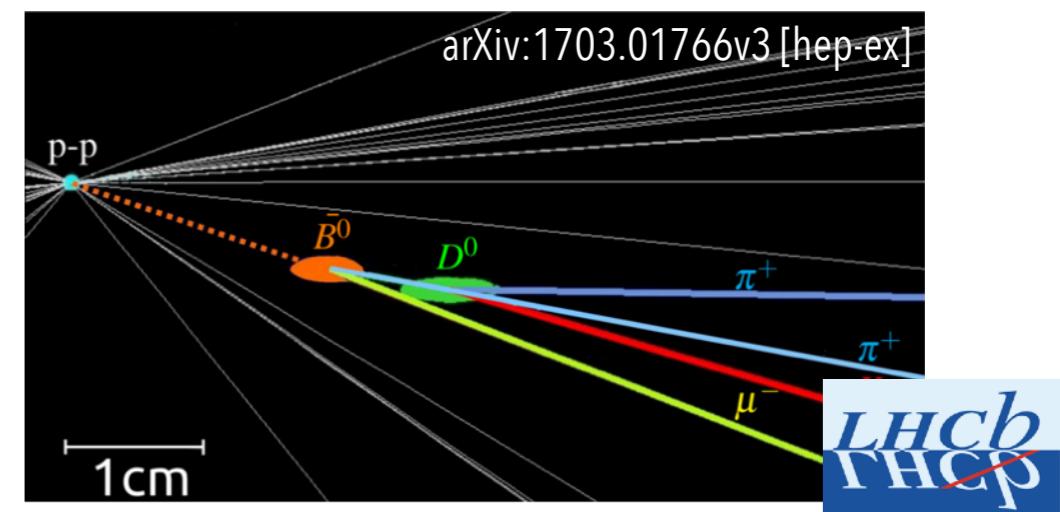
- $\sigma_{b\bar{b}} \sim 1 \text{ nb}$
- $\sigma_{b\bar{b}}/\sigma_{\text{tot}} \sim 1/4$
- 3D momentum conservation
- Clean environment - low background
 - Efficient detection of neutrals ($\gamma, \pi^0, K_s^0 \dots$), low multiplicity processes (dark sector)
- Electrons reconstruction ~ muon reconstruction
- **B meson decay lengths: hundreds of μm (Closer to the IP)**



LHCb

$$pp \rightarrow B\bar{B}X$$

- $\sigma_{b\bar{b}} \sim \text{hundreds of } \mu\text{b} >> \sigma_{b\bar{b}}(\text{Belle II})$.
- Not just $B^{+/0}$: B_s, B_c, Λ_b - beyond $\Upsilon(4S)$ energy
- $\sigma_{b\bar{b}}/\sigma_{\text{tot}} \sim 10^{-2}$
 - Lower trigger efficiencies
- p_t momentum conservation
- **B meson decay lengths: mm**
 - Good sensitivity and signal/background for modes with muons and charged final states using vertexing



$B^0 \rightarrow K^* \tau^+ \tau^-$ ANALYSIS

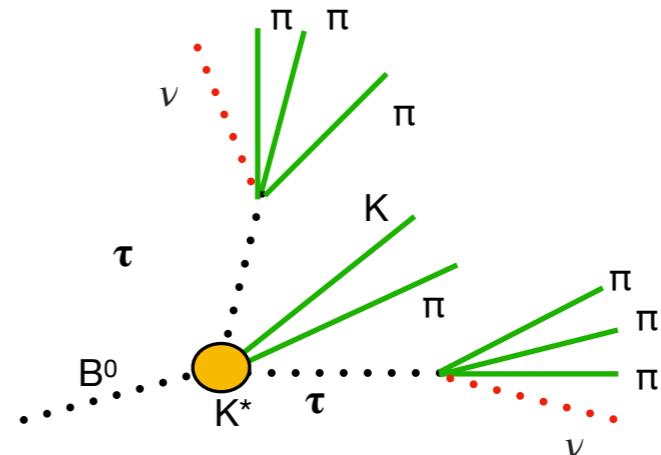
J. Cerasoli, J.Cogan, G.Mancinelli
Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

- Goal: perform the study **using full LHCb dataset** (9.1 fb^{-1}):

$$B \rightarrow K^* (\rightarrow K^- \pi^+) \tau^+ (\rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau) \tau^- (\rightarrow \pi^+ \pi^- \pi^- \nu_\tau)$$

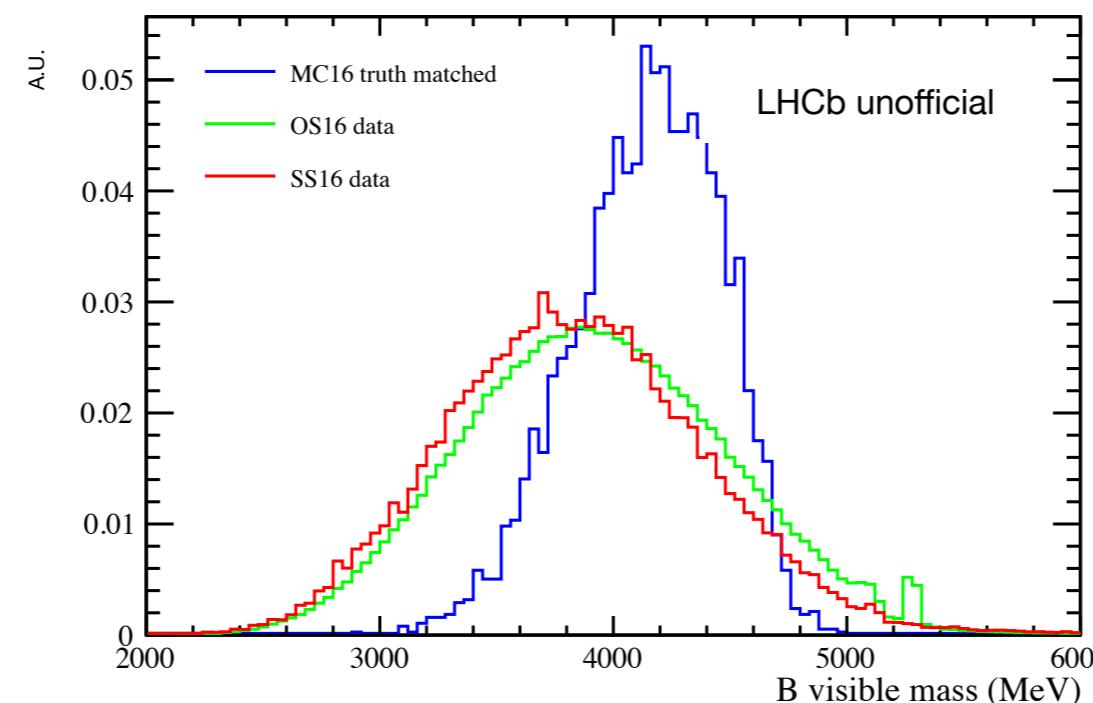
$$BR(K^* \rightarrow K^- \pi^+) \sim 100 \%$$

$$BR(\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau) = 9.31 \pm 0.05 \%$$



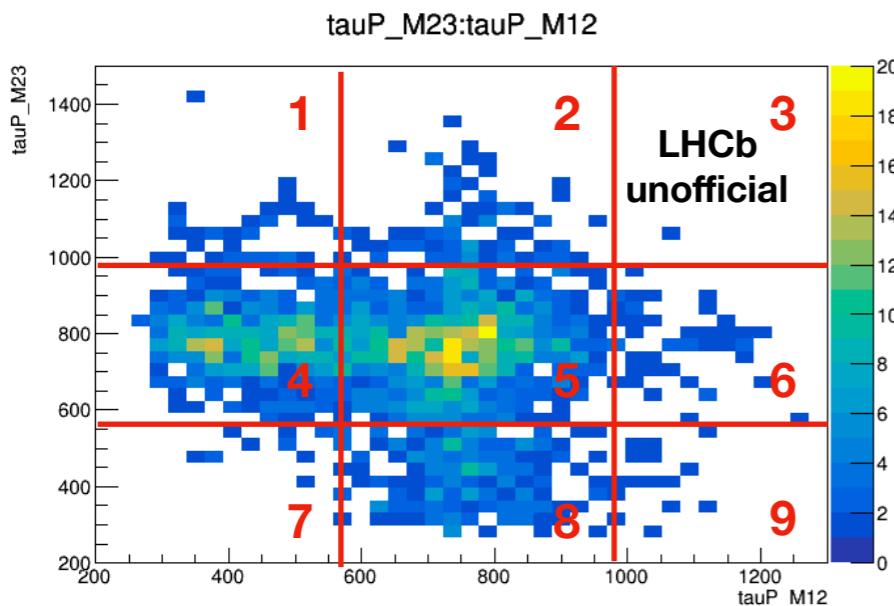
- Very challenging analysis:

- High event multiplicity:** ~ 10 candidates per event on average after trigger requirements
- Two neutrinos in the final state:** LHCb has not full solid angle coverage, can not reconstruct missing energy
- B mass can not be used to fit:** Visible and analytically reconstructed B mass (computed applying tau mass constraints) have poor discriminating power. The **fit is performed on the output of a BDT** (similar to $B_s \rightarrow \tau \tau$)
- There is no obvious background template which provides a good description of the BDT distribution in the signal region**



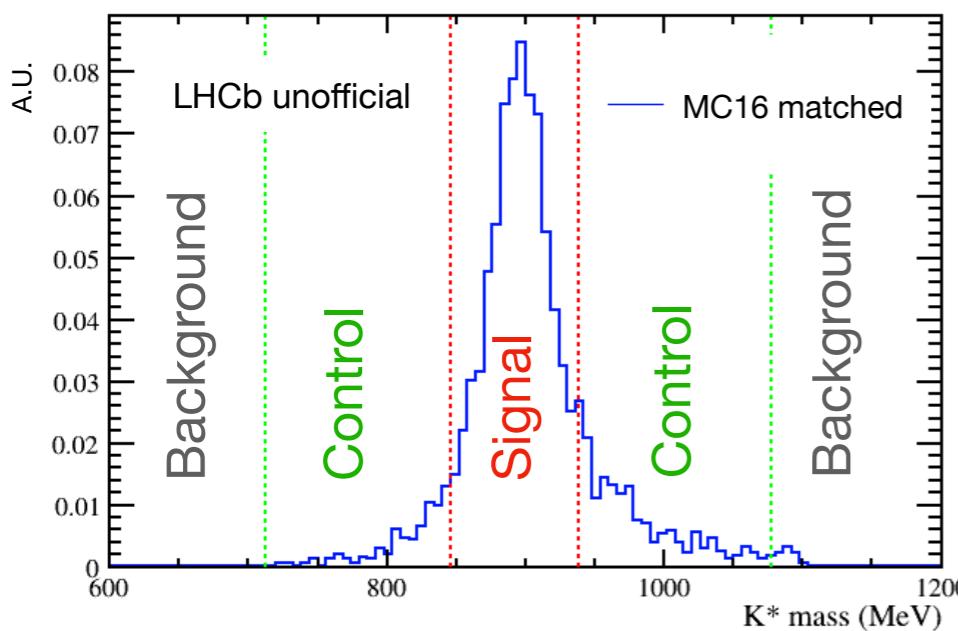
BACKGROUND TEMPLATE

- Background template from tau Dalitz plane:



- A “Dalitz-like” plane is defined for each tau decaying into pions (similar to $B_s \rightarrow \tau^+ \tau^-$ analysis)
- “Cross” shape due to the tau decay into rho meson and a pion
- Fit to data is performed selecting events with **both taus in box 5**
- Other boxes used as proxy for background
- Background template does not provide a good description of data in the signal region**
- Low efficiency: ~13 % events in box 5**

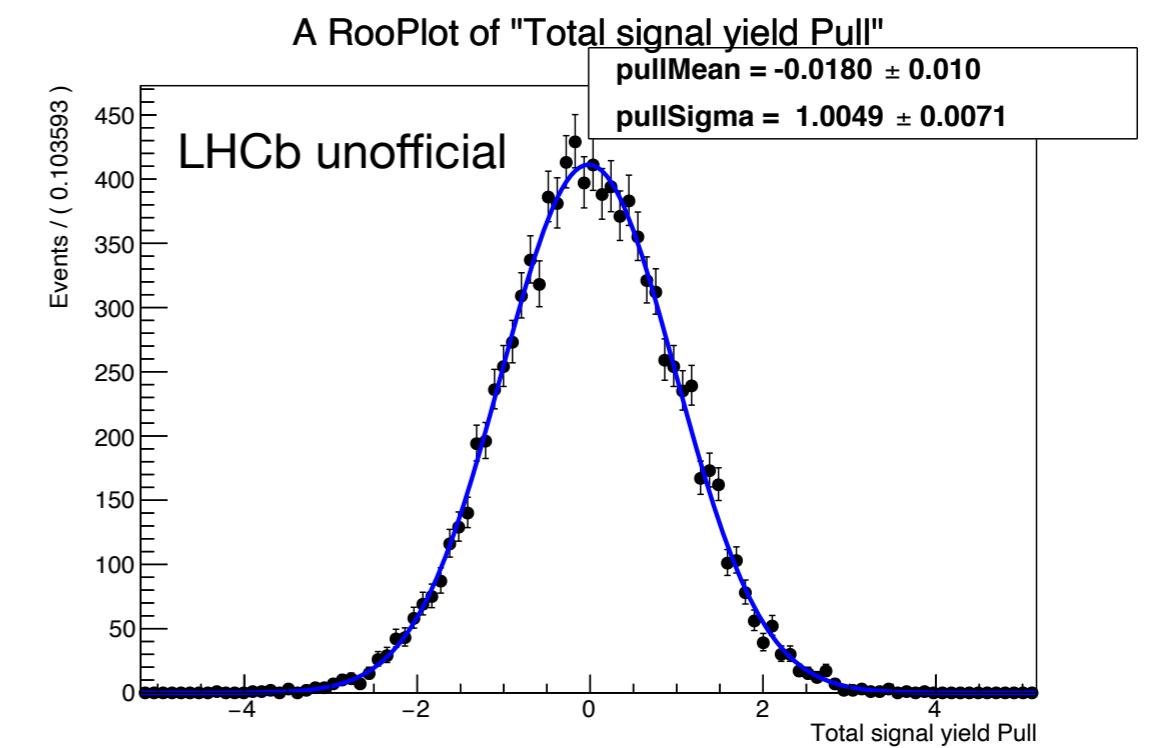
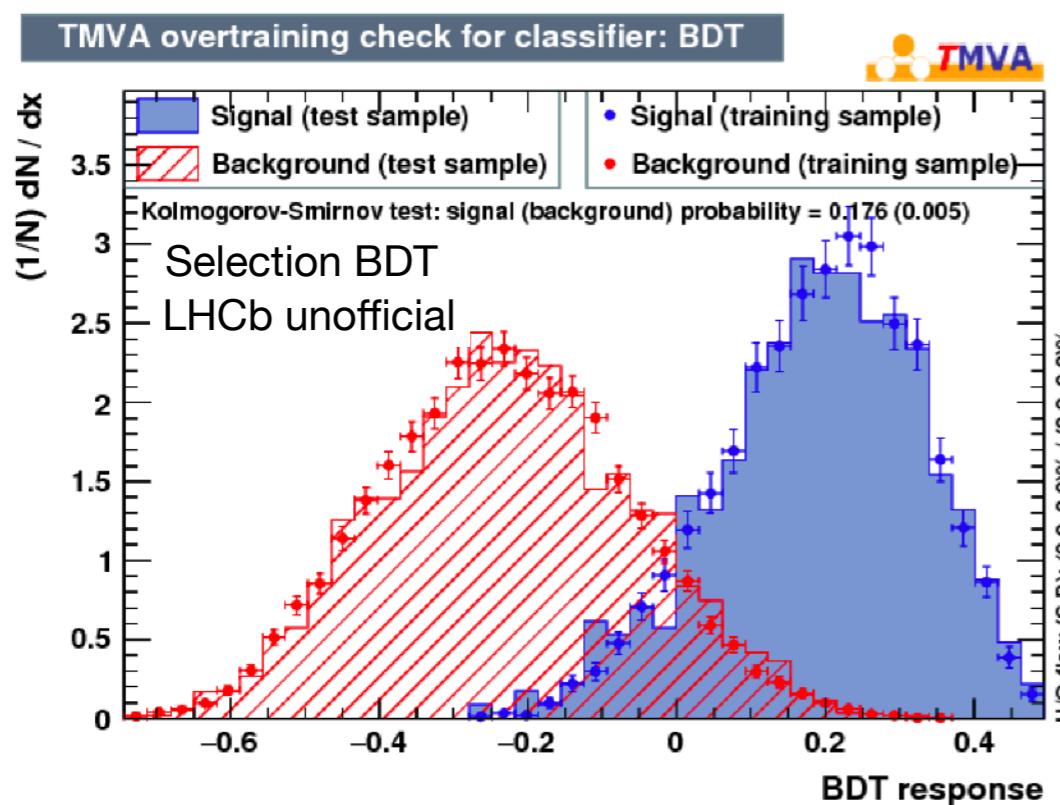
- Background template from K^* mass distribution:



- Fit is done selecting events close to the K^* mass peak, ~ 75% efficiency on signal**
- Data from background regions are used as background proxy for BDT training
- Control regions are used to get background template in the fit
- The **background template provides good description of BDT distribution** in signal region if there's **no correlation with K^* mass for the variables used in the BDT**

ANALYSIS STRATEGY

- **Loose cut-based preselection** on isolation variables: quantify the probability of a track in proximity of the signal candidate to form a different decay chain together with tracks belonging to the signal candidate chain itself
- A **selection BDT** is used to cut away most of the background. It is trained on:
 - Fully matched and reconstructed **signal MC events**
 - **Data from K^{*} mass background regions**
- After the selection **the fit BDT is trained**
- **Simultaneous binned maximum likelihood fit** to get the total number of signal events in signal region
- A normalization channel to avoid introduction of uncertainty related to luminosity and cross-section measurements (used for data-MC comparison as well) $B^0 \rightarrow D^+ (\rightarrow \pi^+\pi^+K^-)$ $D_s^- (\rightarrow K^+K^-\pi^+)$
- **Cross-check:** The analysis has been repeated using **same-sign data** (both tau's are required to have the same charge), fit BDT in good agreement between signal and control region



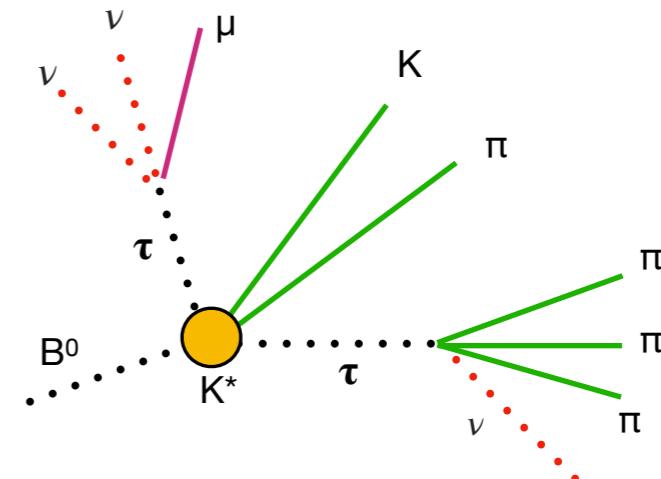
THE SEMILEPTONIC FINAL STATE

- A second final state has been investigated:

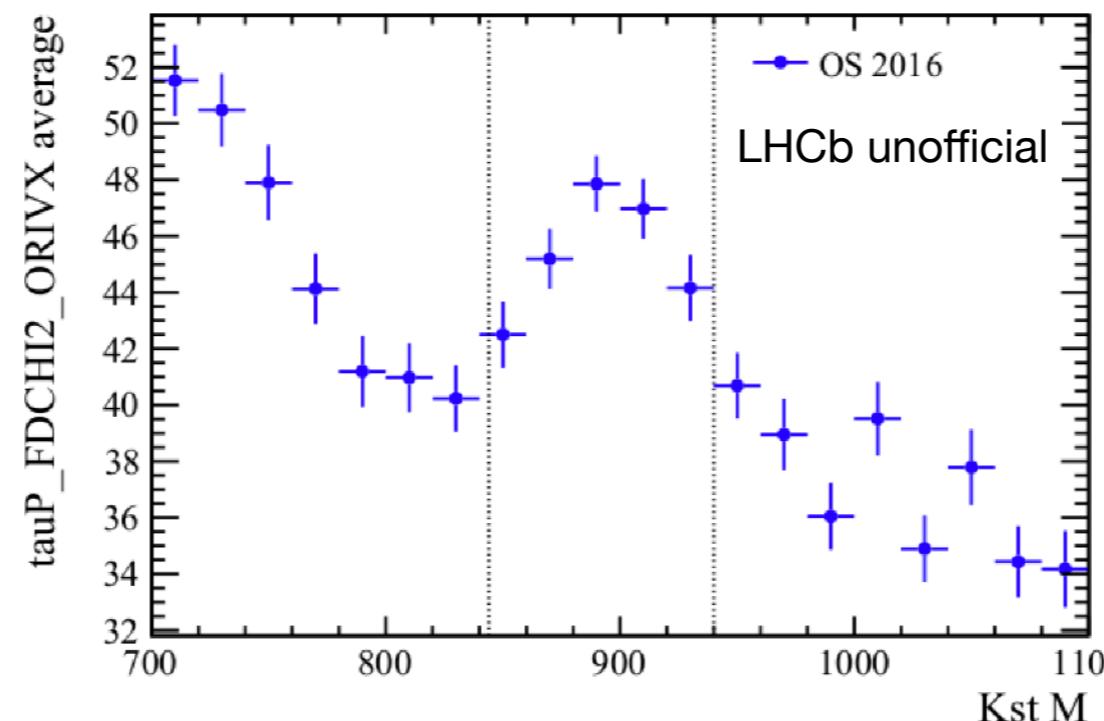
$$B \rightarrow K^* (\rightarrow K^-\pi^+) \tau^+ (\rightarrow \pi^+\pi^+\pi^-\bar{\nu}_\tau) \tau^- (\rightarrow \mu^-\bar{\nu}_\mu\nu_\tau)$$

$$BR(K^* \rightarrow K^-\pi^+) \sim 100 \%$$

$$BR(\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau) = 17.39 \pm 0.04 \%$$



- Similar difficulties as for the hadronic final state: **high event multiplicity, poor mass discriminating power, ...**
- More background** due to semi-leptonic decays
- None of the two strategies succeeded** in order to find a background template for the fit: in particular the K^* mass shows much more correlation with other variables
- We are now focusing mainly on the hadronic final state



$B^0 \rightarrow K^* \tau^\pm \mu^\mp$ ANALYSIS

F. Polci, S. G. Weber
LPNHE Paris

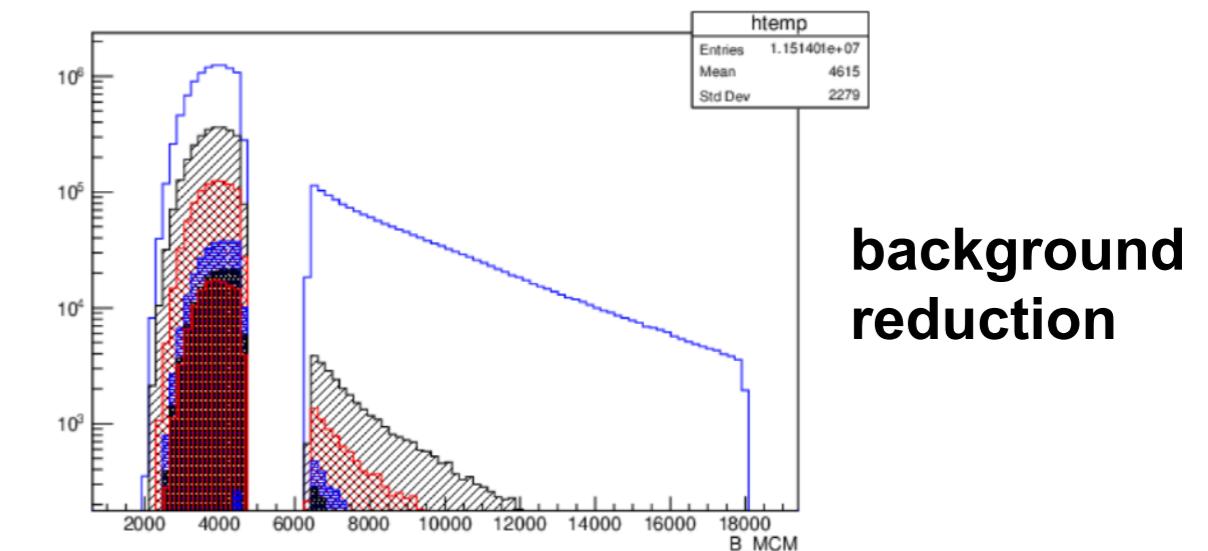
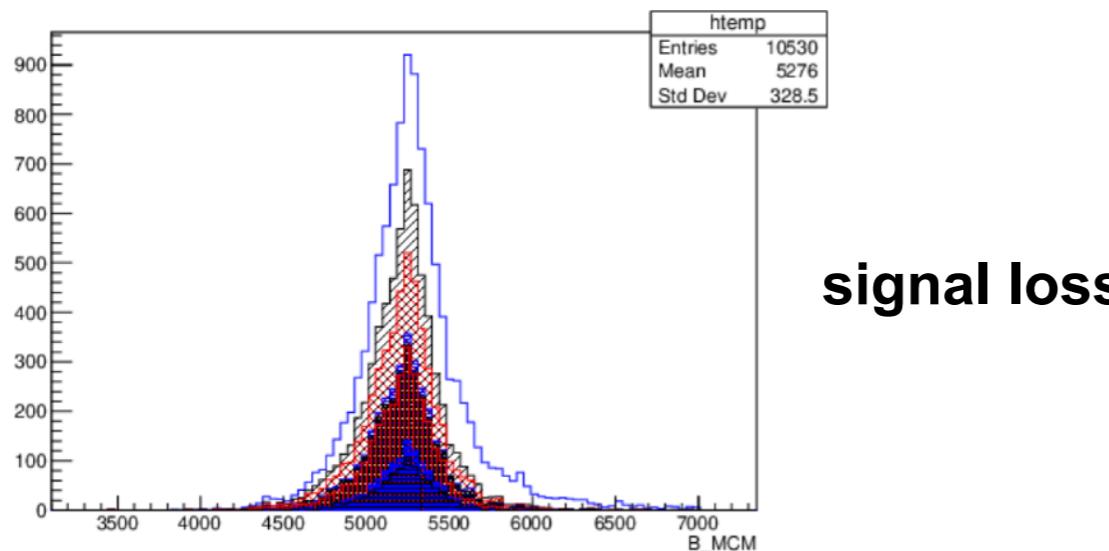
- Decay channel: $B \rightarrow K^* (\rightarrow K^- \pi^+) \tau^\mp (\rightarrow \pi^\mp \pi^\mp \pi^\pm \nu_\tau) \tau^- \mu^\pm$
- Also sensitive to, but not optimized for, to $\tau^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp \pi^0 \nu_\tau$
- Using full LHCb dataset ($\sim 9 \text{ fb}^{-1}$)
- Analysis split in two different configurations, depending on relative charge of K and τ (different backgrounds and different signal in case of NP)
- **Blind Analysis:** signal region not investigated until analysis strategy is frozen
- Mass reconstruction: have to correct for missing energy of neutrino
→ “Minimally corrected mass”:

$$MCM = \sqrt{P_T^2 + MM^2} + P_T \quad MM: \text{measured mass}$$

- Normalized to $B^0 \rightarrow D^+ (\rightarrow \pi^+ \pi^+ K^-) D_s^- (\rightarrow K^+ K^- \pi^+)$
+ Similar decay topology
- no μ in final state → have to use hadron trigger, increases systematic uncertainties

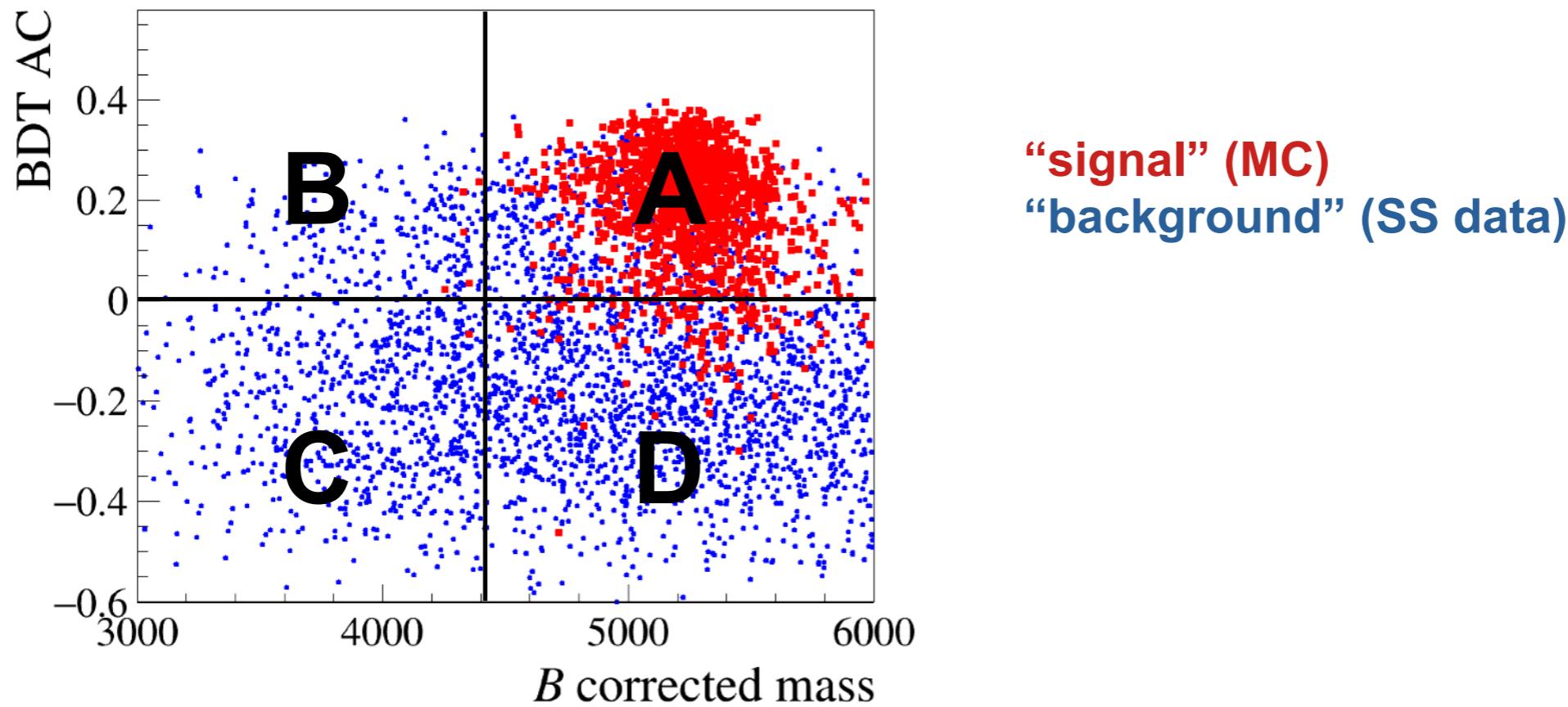
ANALYSIS DETAILS

- Usage of three Multivariate selection steps using:
 - **Topological variables** (flight distances, secondary vertices) against *combinatorial background*
 - **Kinematic variables** of τ daughters (min, max p_T , invariant masses) against *background from D decays*
 - **Isolation variables** (tracks compatible with vertices, $\Delta\chi^2$ when adding more tracks) against *partially reconstructed backgrounds*
 - k-Folding procedures to avoid biases and overtraining
- Mass vetoes against particles from D decays



BACKGROUND ESTIMATION

- Estimate background counts under signal from “ABCD” method:
- 2D plane: corrected mass vs anti-combinatorial-BDT output



- Signal expected in region A, background yield estimated from yields in B, C, D:

$$A_{\text{bkg, est}} = B^*C/D$$

- Alternative: fit method under investigation

BELLE / BELLE II $b \rightarrow s\tau^+\tau^-$ STATUS

- Belle experiment has not analysed data for $b \rightarrow s\tau^+\tau^-$ yet and Belle II will improve significantly on the measurement of $B \rightarrow K\tau^+\tau^-$ decay.
- Belle II will collect $\sim 1 \text{ ab}^{-1}$ before 2022 long shutdown → surpass BaBar and Belle.
- **One τ in the final state** → the τ can be reconstructed in hadronic B tagged events: the tau 4-momentum can be determined from p_B , p_K and p_l . These clear signatures allow to set upper limits of the **order of 10^{-6}** .
- **Final states with two τ 's** → the tag-B meson is needed. That way tau leptons can be reconstructed in single prong decays. Even with improved reconstruction, observation of the $\mathcal{B}_{\text{SM}}(B \rightarrow K\tau\tau) \sim 10^{-7}$ is unlikely. Expected upper limits are of **order 10^{-5}** .

Observables	Expected sensitivities		Current limits
	Belle 0.71 ab^{-1}	Belle II 50 ab^{-1}	
$b.r.(B^+ \rightarrow K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 2.0	< 225
$b.r.(B^+ \rightarrow K^+\tau^\pm e^\mp) \cdot 10^6$	-	< 2.1	< 30
$b.r.(B^+ \rightarrow K^+\tau^\pm \mu^\mp) \cdot 10^6$	-	< 3.3	< 48
			< 39

[arXiv:1808.10567]

@ BaBar - 424 fb⁻¹
arXiv:1204.2852v2 [hep-ex]

@ LHCb - 9 fb⁻¹
JHEP 06 (2020) 129

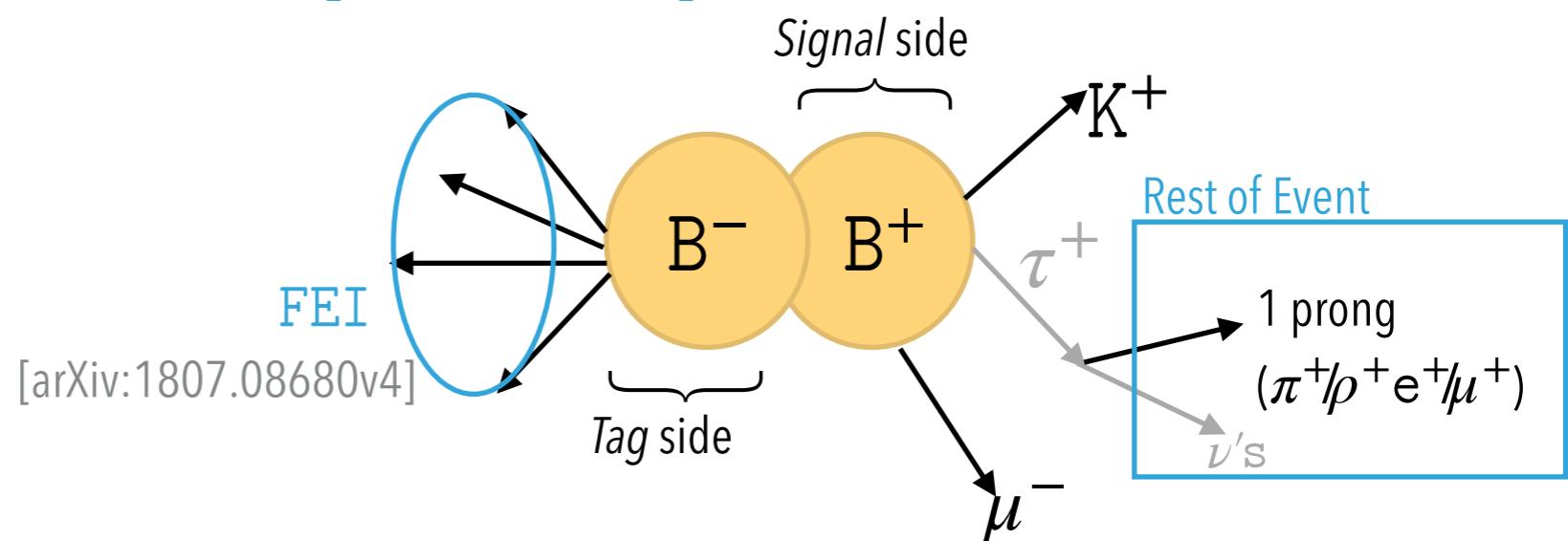
$B^+ \rightarrow K^+\tau^+\mu^-$

$\text{Br } (B \rightarrow K\tau^+\tau^-)_{\text{SM}}^{[15,22]} = (1.20 \pm 0.12) \times 10^{-7}$

$B^+ \rightarrow K^+\tau^+\mu^-$ SEARCH WITH BELLE DATA [0.71 ab⁻¹]

THE STRATEGY

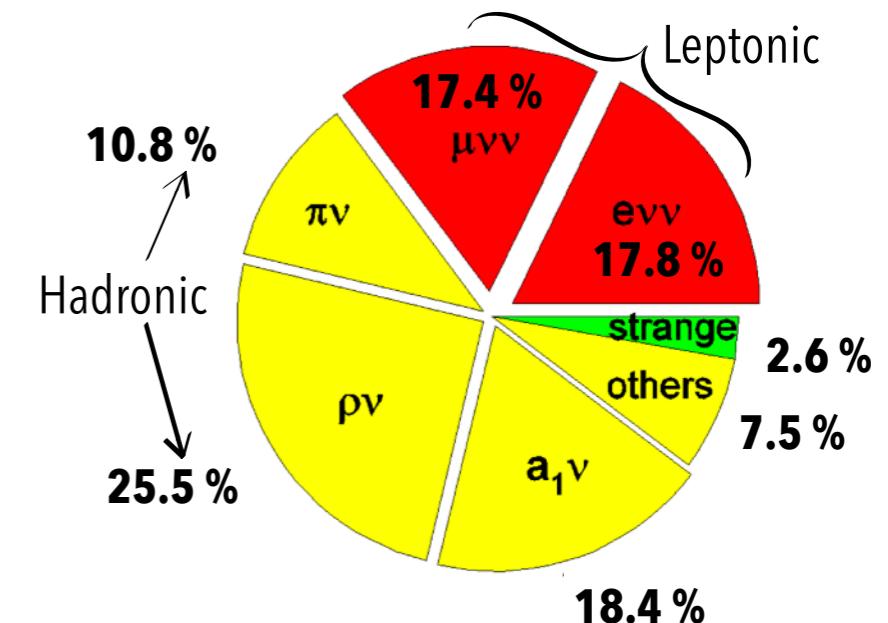
- Tag side reconstruction
- Tau mass calculation
- BG suppression
- Fit to the tau mass
- BR upper limit



Tag side reconstruction:

Full Event Interpretation

- Embedded in basf2 (Belle II Analysis Software Framework), can be used on Belle data
- >200 BDTs reconstructing 10k B decays
- Hadronic FEI:
 - Pros: Exact knowledge of B through reconstruction of many exclusive modes
 - Cons: Low tagging efficiency



Tau mass

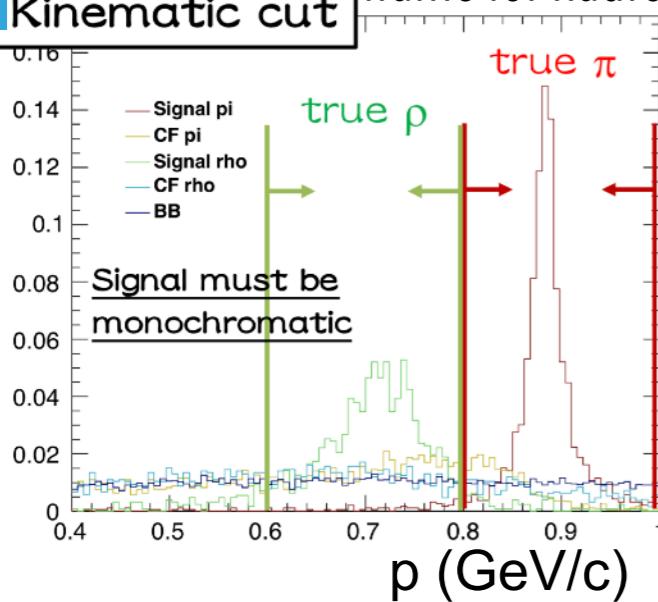
$$m_\tau^2 = m_B^2 + m_{K\mu}^2 - 2(E_{beam}^* E_{K\mu}^* - |\vec{p}_{B_{sig}}^*| |\vec{p}_{K\mu}^*| \cos \theta)$$

E_{beam}^* $\sqrt{(E_{beam}^*)^2 - m_B^2}$ θ angle between $\vec{p}_{B_{sig}}^*$ ($= -\vec{p}_{B_{tag}}^*$) and $\vec{p}_{K\mu}^*$

BACKGROUND SUPPRESSION

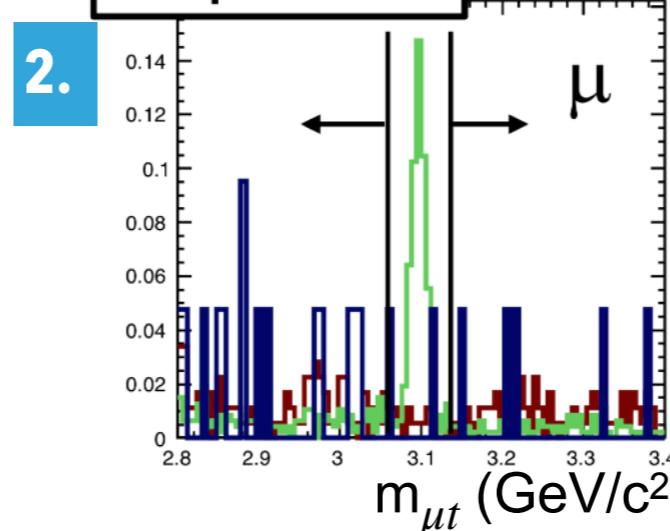
τ prong momentum at τ rest
frame for hadronic modes

1. Kinematic cut

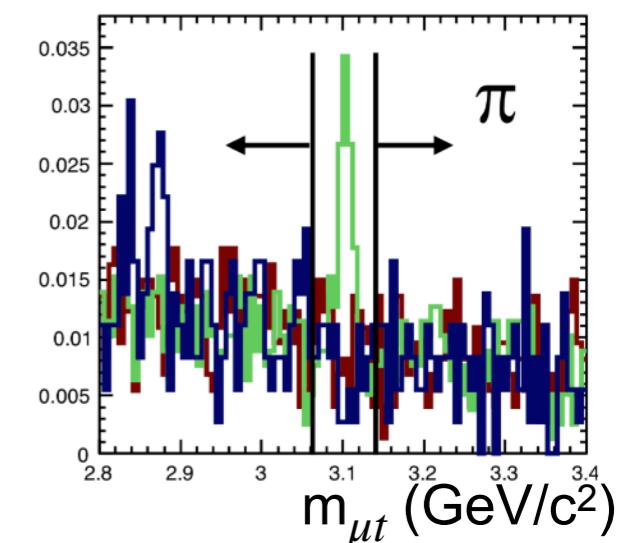


2. J/ ψ veto

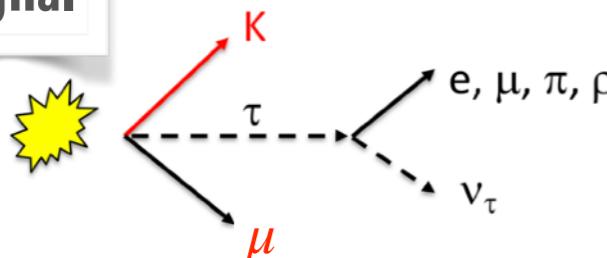
2.



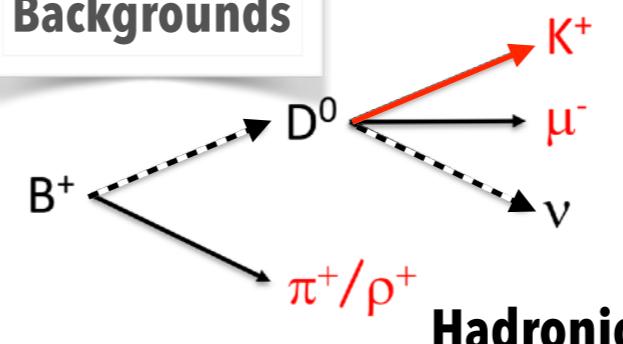
Invariant mass of primary μ and τ prong



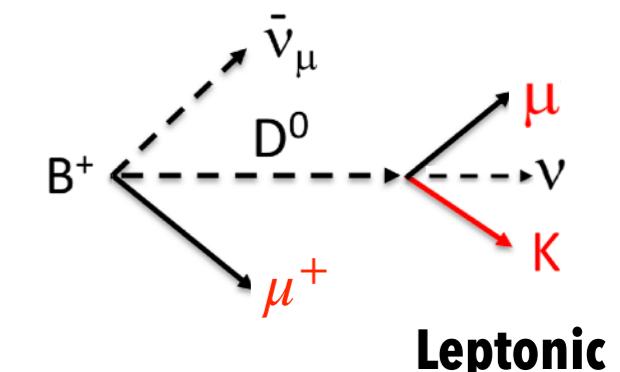
Signal



Backgrounds



Hadronic



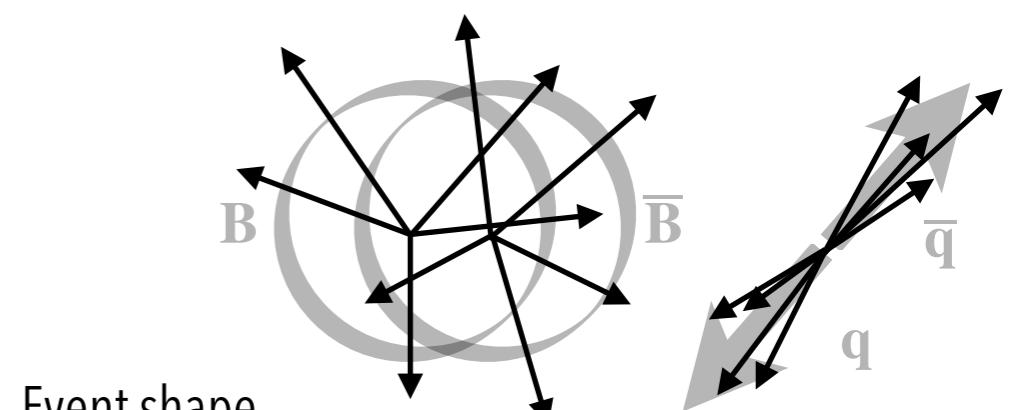
Bkg suppression through two dedicated FBDTs

3. B \bar{B}

- E(ECL), #(ECL clusters)
- muon-ID
- Distance between primary kaon and muon

4. q \bar{q}

- CleoConeThrust
- R₂
- θ_B



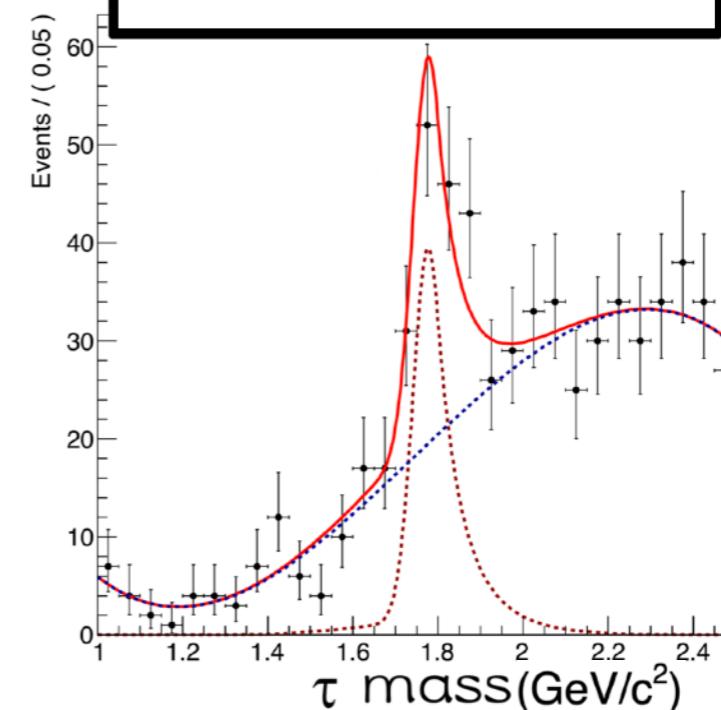
(q = u, d, s, c)

FITTING PROCEDURE AND LIMIT EXTRACTION

Fitting

- Signal: CBS+Gaussian
- Background: 3rd order Chebyshev polynomial
 - Only $B\bar{B}$ bg left
- Signal shapes fixed from MC
- Floating background pdf parameters

1 pseudo experiment with
b.r. = 5×10^{-5} for illustration

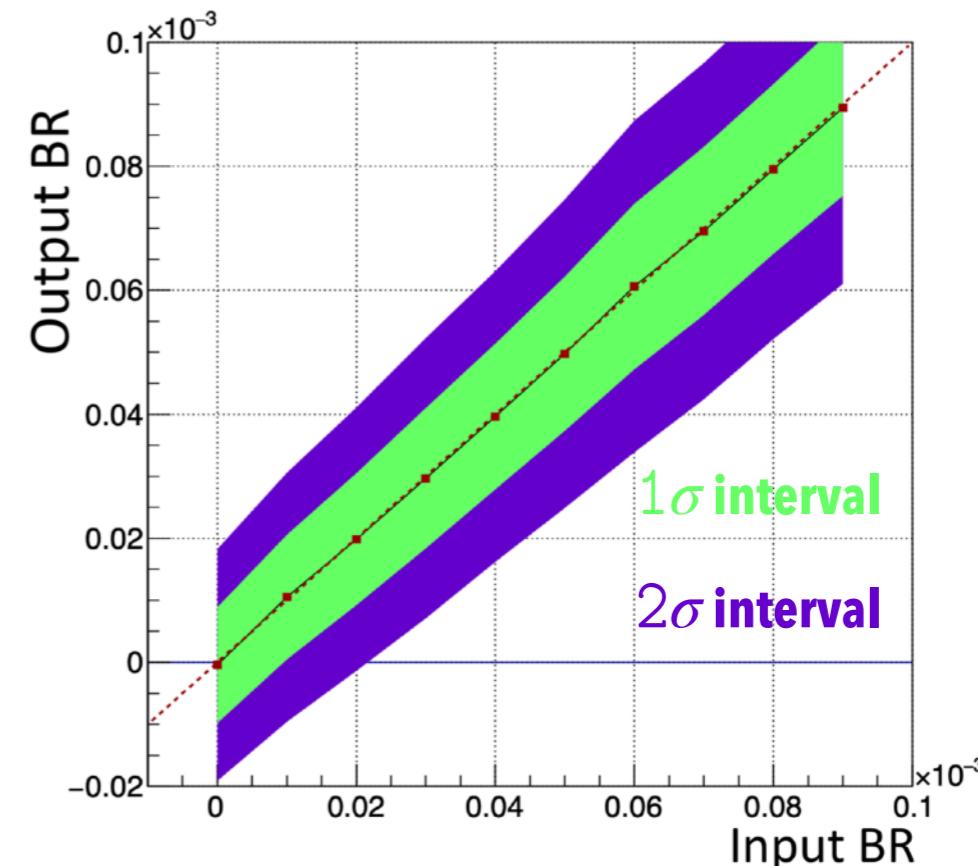


Toy-MCstudy

The procedure is repeated for several input B.R. assumptions
→ No bias found

For zero $B^+ \rightarrow K^+ \tau^+ \mu^-$ events
 $\sim 1.8 \times 10^{-5}$ U.L @ 95% C.L

Stat. Error only!

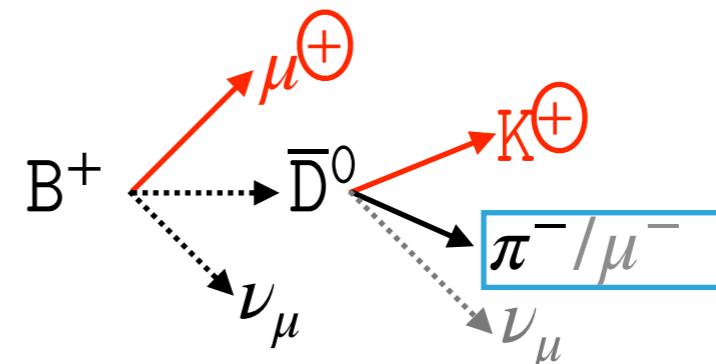


$B^+ \rightarrow K^+ \mu^+ \tau^-$: SS VS OS

- So far the OS mode was presented

The SS mode has a higher background due to semileptonic B decays; the Cabibbo-favored decays of the D meson lead the K to have predominantly the same charge as the μ $\rightarrow D^0$ veto for μ, π, ρ modes needed

OS \Leftrightarrow 'Opposite sign' between K and μ
SS \Leftrightarrow 'Same sign' between K and μ



- Candidate control samples
 - OS: $B^0 \rightarrow J/\psi K_S$
 - SS: $B^+ \rightarrow D^- \pi^+ \pi^-$



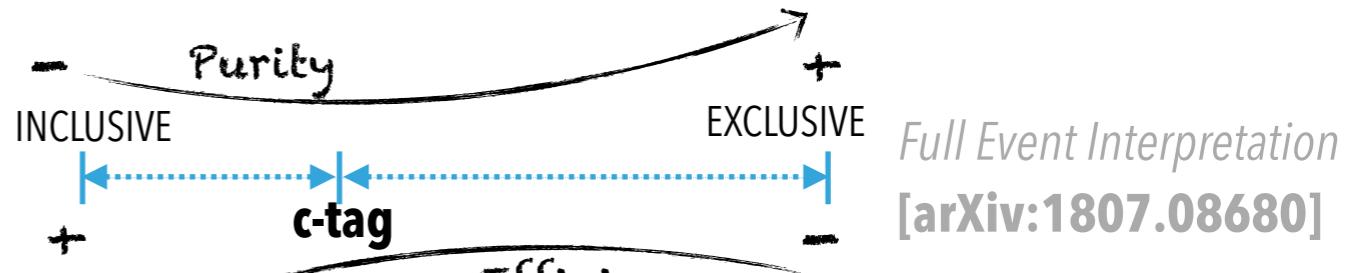
To-do

- Complete also $B^+ \rightarrow K^+ \tau e$
- Control samples for $B^+ \rightarrow K^+ \tau e / \mu$ (SS and OS)

C-TAG: THE IDEA

- c-tag as a semi-inclusive, intermediate tagging method

$B^+ \rightarrow \mu^+ \nu_\mu$ search
[arXiv:1911.03186]



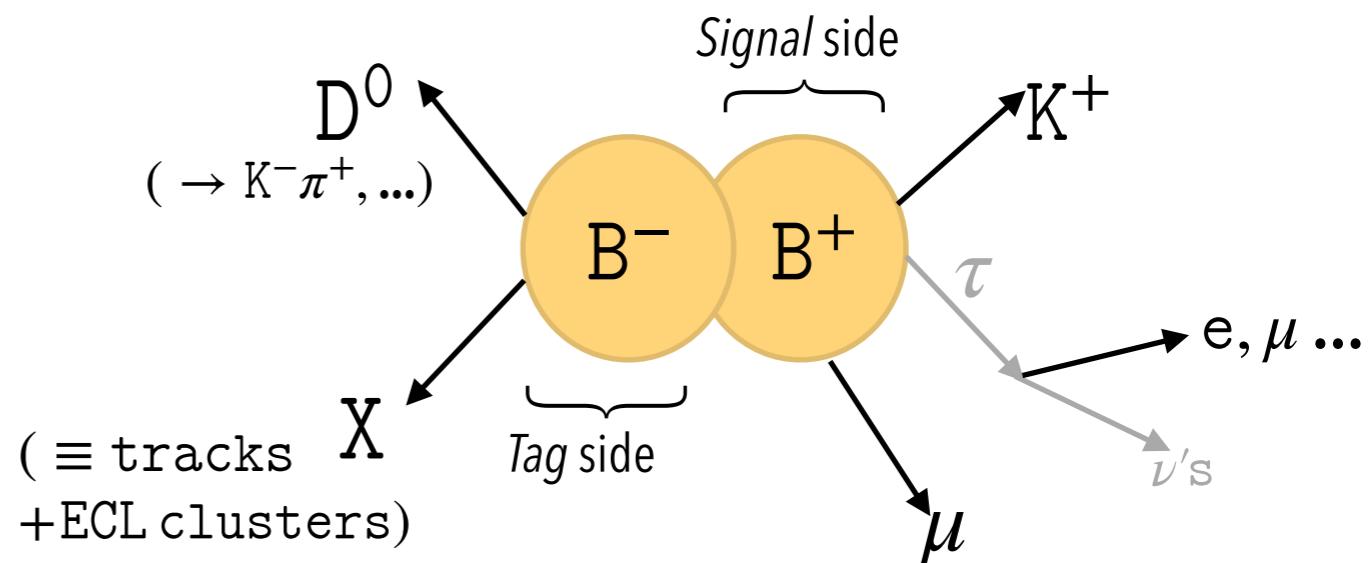
Full Event Interpretation
[arXiv:1807.08680]

- Exploit the high B.R. of $B^+ \rightarrow \bar{D}^0 X$
→ Access to ~80% of charged B decays

	$B^+ \rightarrow$	$B^0 \rightarrow$
$D^0 X$	$(8.6 \pm 0.7)\%$	$(8.1 \pm 1.5)\%$
$\bar{D}^0 X$	$(79 \pm 4)\%$	$(47.4 \pm 2.8)\%$
$D^+ X$	$(2.5 \pm 0.5)\%$	$(< 3.9)\%$
$D^- X$	$(9.9 \pm 1.2)\%$	$(36.9 \pm 3.3)\%$
$D_s^+ X$	$(7.9 \pm 1.4)\%$	$(10 \pm 2)\%$
$D_s^- X$	$(1.10 \pm 0.40)\%$	$(< 2.6)\%$
$\Lambda_c^+ X$	$(2 \pm 1)\%$	$(< 3.1)\%$
$\Lambda_c^- X$	$(3 \pm 1)\%$	$(5.0 \pm 2.0)\%$

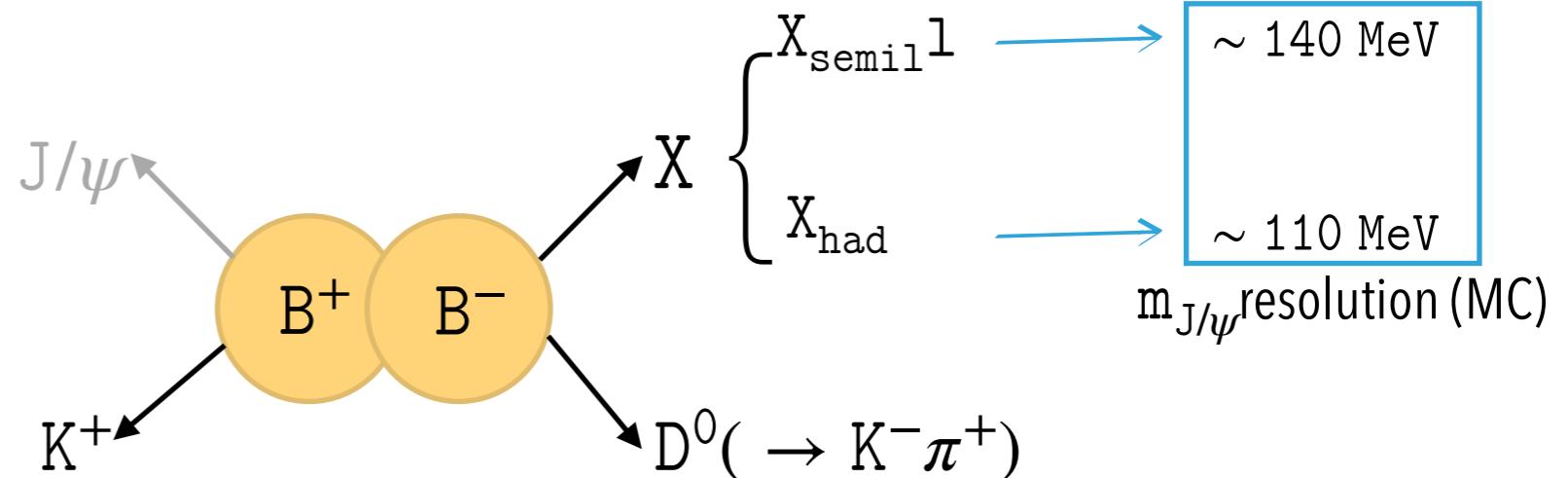
- Application in $B \rightarrow K\tau l$ analysis, where the topology with $K + \mu$ may allow looser reconstruction in B_{tag} side

- 1) D^0 is reconstructed
- 2) Primary K and μ , and τ decay prong are chosen
- 3) " $D^0 + \text{inclusive } X$ " provide the tag side B momentum



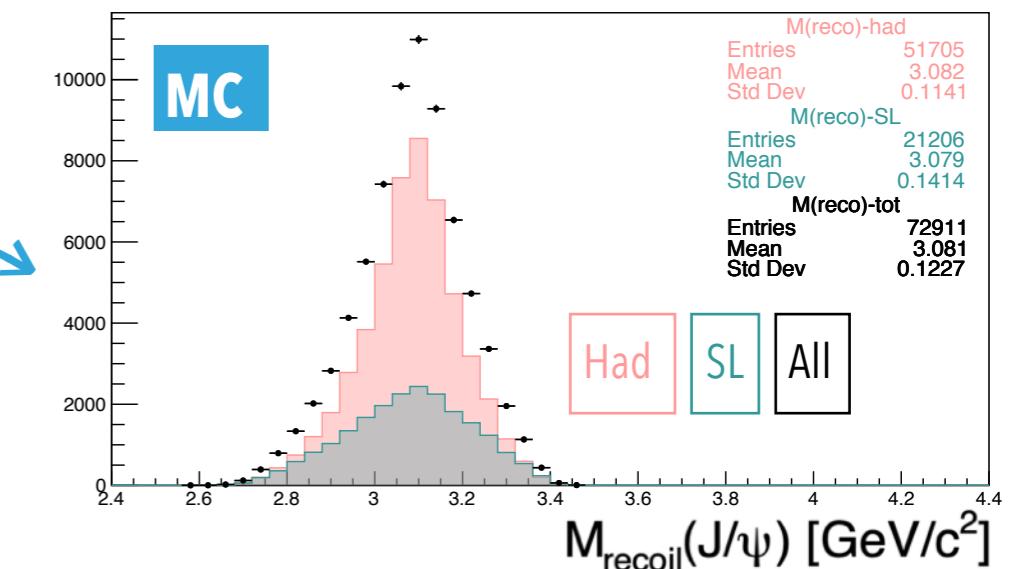
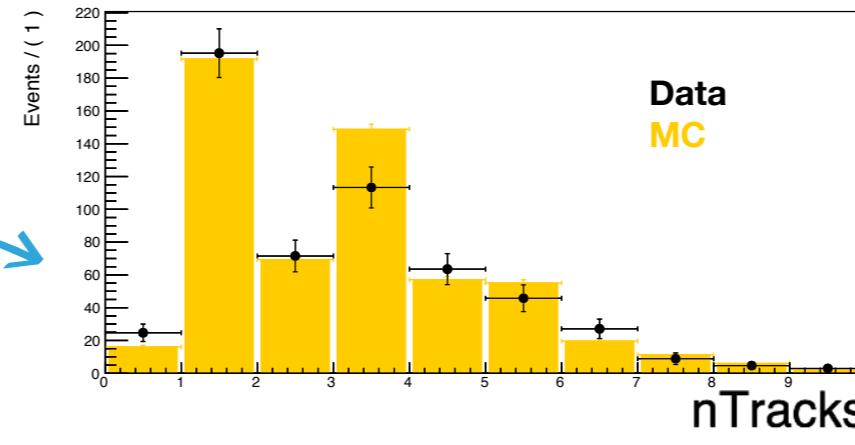
C-TAG: THE STUDY

Belle (MC / Data) & Belle II (Data)



Test the method with $J/\psi K^\pm$ as signal side:

- High purity $B^{+/-}$
- Study the properties of the tagging side
- Evaluate the resolution of the recoil $m_{J/\psi}$

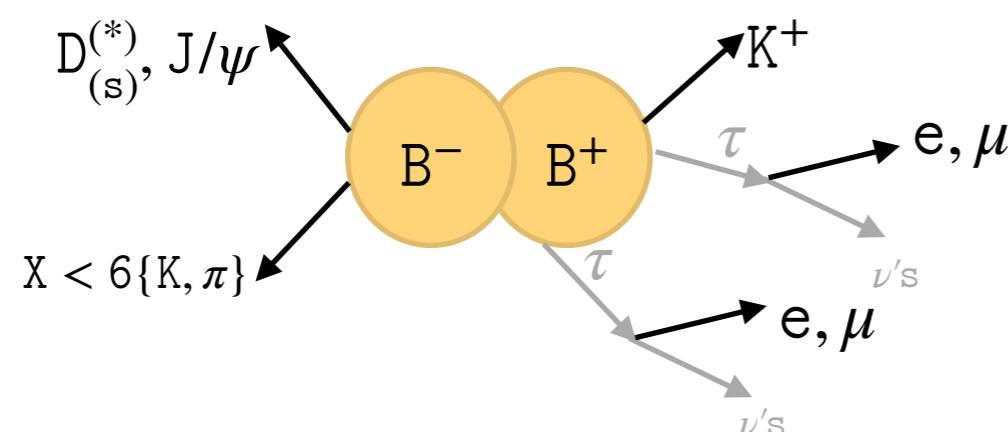


To-do

- Check the m_τ resolution with different tagging conditions
- Estimate the background level
- Explore other D^0 channels to increase the tagging efficiency

$B^+ \rightarrow K^+\tau\tau$ SEARCH - BABAR [424 fb $^{-1}$]

■ Hadronic tag



■ Leptonic τ modes

- 6 event-shape variables \rightarrow suppressing 75% of the continuum events while retaining >80% of signal and background BB MC events
- $B_{\text{sig}} \rightarrow D^{(*)} (\rightarrow K l' \bar{\nu}_{l'}) l \bar{\nu}_l$ suppression based on MLP

- Cut and count analysis:** compare observed events with expected background yield

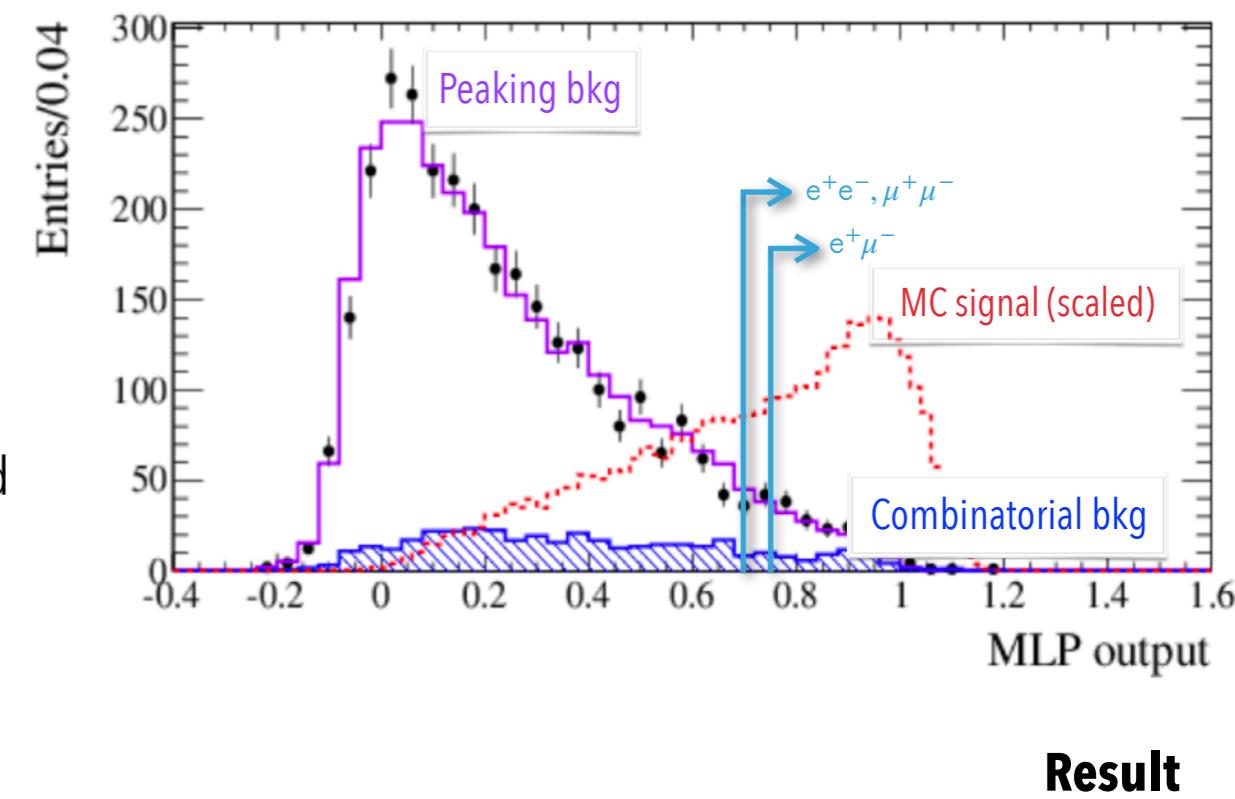
$$\mathcal{B}_i = \frac{N_{\text{obs}}^i - N_{\text{bkg}}^i}{\epsilon_{\text{sig}}^i N_{B\bar{B}}}, \quad i = (e^+e^-, \mu^+\mu^-, e^+\mu^-)$$

Selection:

- 3 tracks + PID
- $E_{\text{miss}} > 0$
- $m_{\text{ES}} > 5.27 \text{ GeV}, |\Delta E| < 0.12 \text{ GeV}$
(Sideband: $m_{\text{ES}} [5.20, 5.26] \text{ GeV}$)
- **Veto**: $J/\psi, D^0 \rightarrow K\pi (\rightarrow \mu), \gamma \rightarrow ee$

$$m_{\text{ES}} = \sqrt{E_{\text{beam}}^2 - \vec{p}_{B_{\text{tag}}}^* \cdot \vec{p}_{B_{\text{tag}}}^*}$$

$$\Delta E = E_{\text{beam}} - E_{B_{\text{tag}}}^*$$



$\mathcal{B}(B^+ \rightarrow K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ @ 90 % C.L.

CONCLUSION, PLANS

$B \rightarrow K\tau\mu$

If observed, an unambiguous proof of non standard physics.
Upper limit on the decay rate will put constraints on theoretical models.

@ Belle I/II

- Optimisation of selection and background suppression
- Simultaneous fit for each τ decay channel
- Sensitivities: Belle (ongoing) $\sim 2 \times 10^{-5}$ (stat.only),
Belle II (expected) $\sim 10^{-6}$
- In addition to $K\tau\mu$, $K\tau e$ is also being studied

@ LHCb

- Analysis well advanced but still ongoing
- All LHCb datasets included in analysis
- Selection steps and background description are being optimised
- Expected limits (Run 1+2): $2.38 \times 10^{-5} (K^+, \tau^-)$
 $3.30 \times 10^{-5} (K^+, \tau^+)$

$B \rightarrow K\tau\tau$

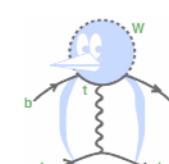
Final states with great missing energy make the search very challenging.
 \mathcal{B}_{SM} very small but possible enhancement due to NP / break of lepton universality.

@ Belle I/II

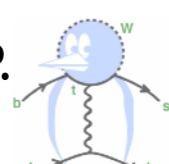
- τ reconstruction: 1-prong vs 3π (LHCb)
- hadronic FFI
- c-tag (to be tested on $K\tau\mu$)
- Expected limit @ Belle II: 2.0×10^{-5}

@ LHCb

- Selection defined and optimization ongoing
- Fit model and toy studies → no bias has been observed
- Normalization channel yield has been measured
- Next step: evaluation of the systematic uncertainties

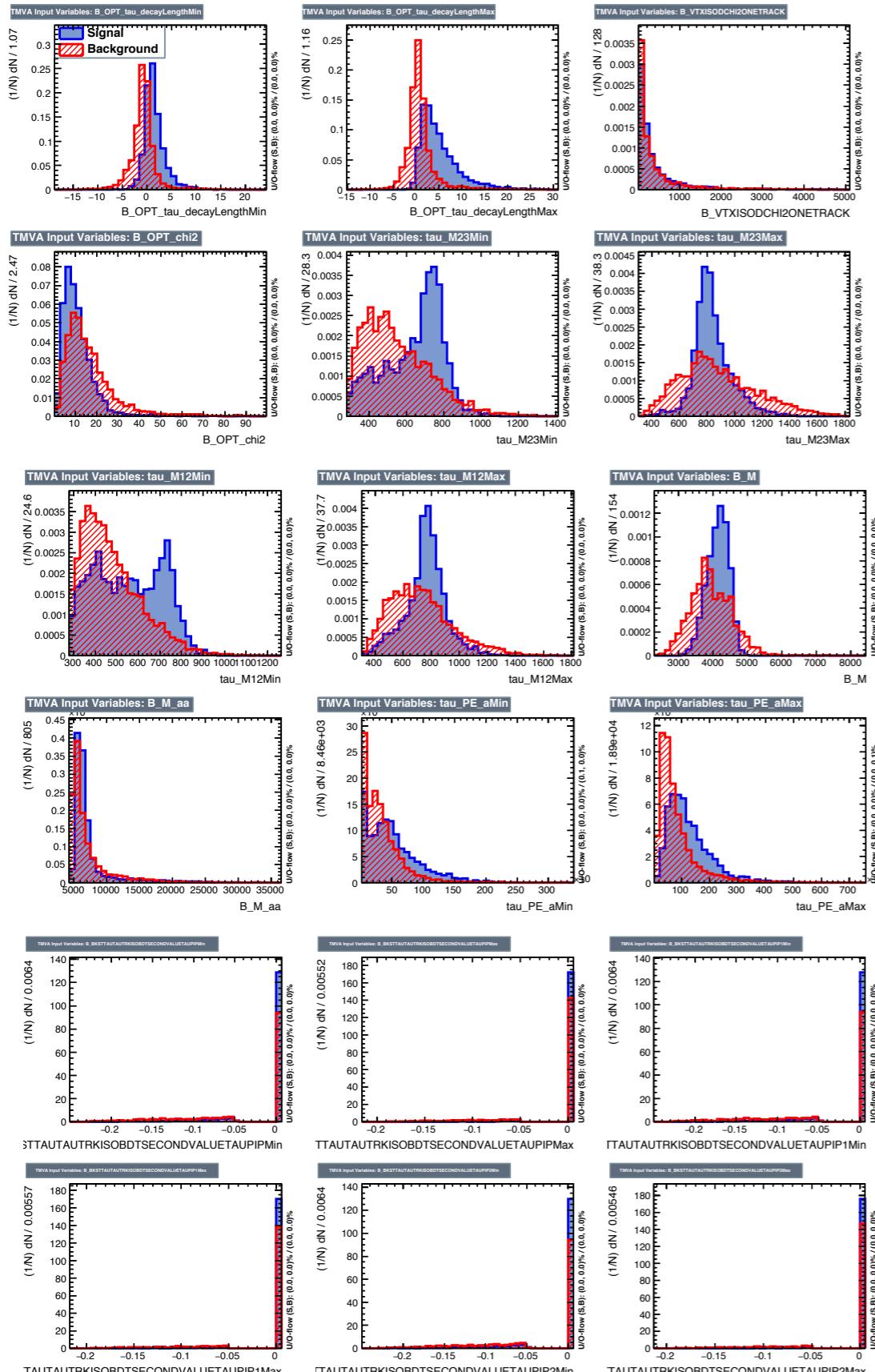


Different strategies at LHCb and Belle II: two experiments are required to establish NP.
They have some overlaps in the physics program but also unique strengths.



BACKUP

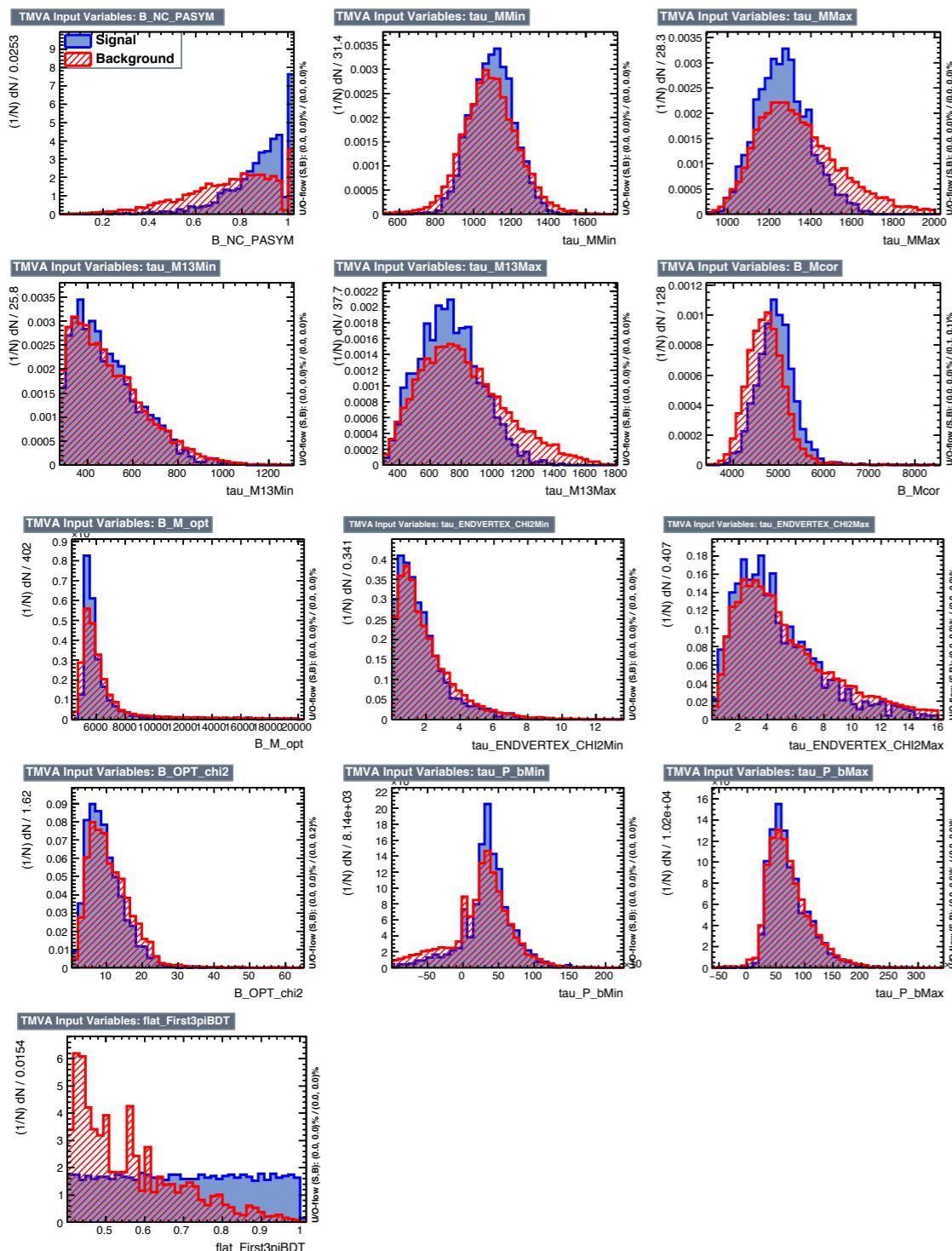
BDT1 variables



Rank : Variable

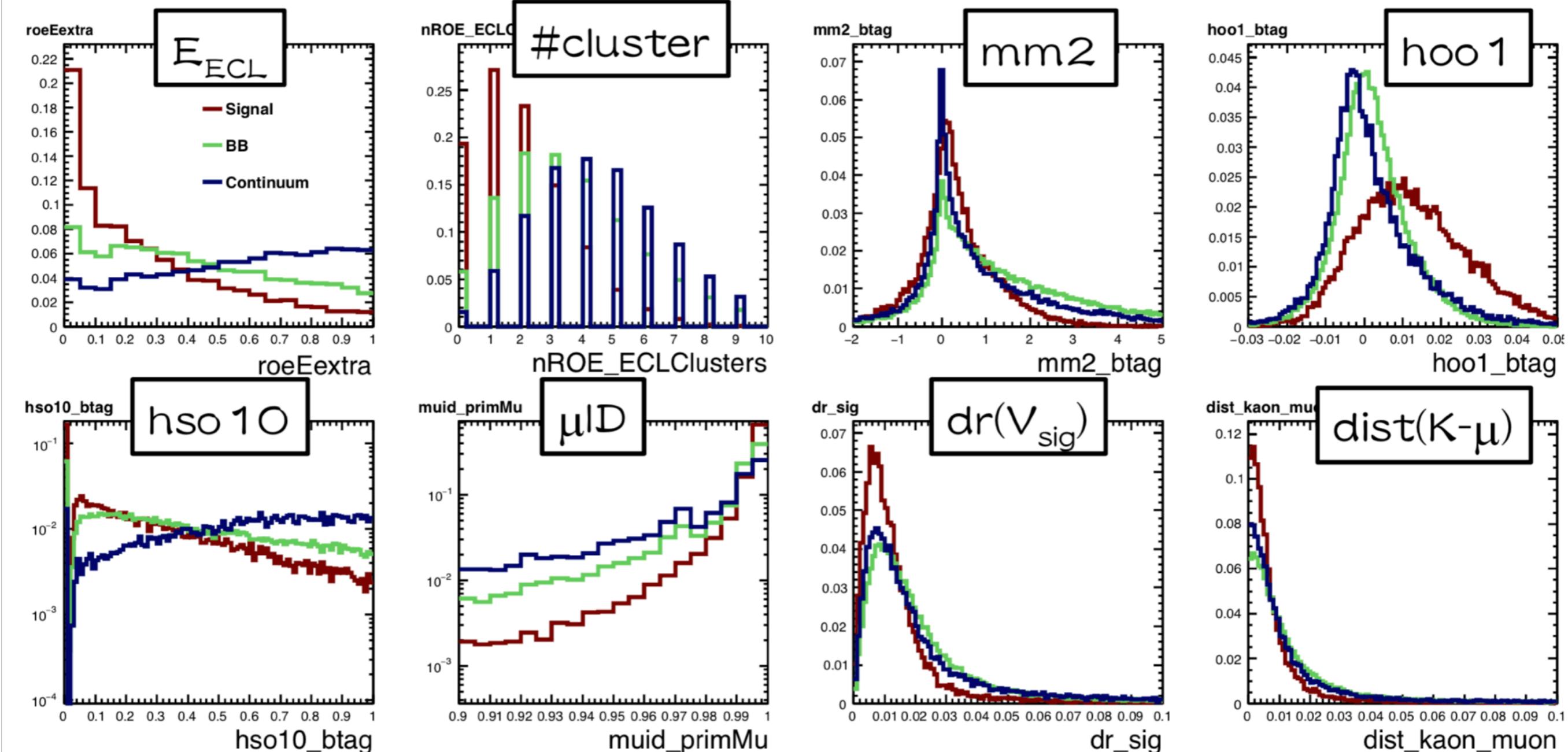
	: Separation
1 : B_OPT_tau_decayLengthMax	: 3.885e-01
2 : B_OPT_tau_decayLengthMin	: 3.122e-01
3 : B_M	: 1.943e-01
4 : tau_M23Max	: 1.764e-01
5 : tau_PE_aMax	: 1.570e-01
6 : tau_M23Min	: 1.452e-01
7 : tau_M12Max	: 1.217e-01
8 : B_M_aa	: 9.785e-02
9 : tau_M12Min	: 9.778e-02
10 : B_OPT_chi2	: 9.470e-02
11 : tau_PE_aMin	: 8.083e-02
12 : B_BKSTTAUTAUTRKISOBDTSECONDVALUETAUIP2Min	: 7.857e-02
13 : B_BKSTTAUTAUTRKISOBDTSECONDVALUETAUIPMin	: 7.777e-02
14 : B_BKSTTAUTAUTRKISOBDTSECONDVALUETAUIP1Min	: 7.661e-02
15 : B_BKSTTAUTAUTRKISOBDTSECONDVALUETAUIP1Max	: 6.703e-02
16 : B_BKSTTAUTAUTRKISOBDTSECONDVALUETAUIPMax	: 6.385e-02
17 : B_BKSTTAUTAUTRKISOBDTSECONDVALUETAUIP2Max	: 6.274e-02
18 : B_VTXISODCHI2ONETRACK	: 1.232e-02

BDT2 variables



Rank	Variable	: Separation
1	flat_First3piBDT	: 1.873e-01
2	B_NC_PASYM	: 1.476e-01
3	tau_MMax	: 7.477e-02
4	B_Mcor	: 7.383e-02
5	tau_M13Max	: 5.651e-02
6	B_M_opt	: 4.125e-02
7	tau_MMin	: 2.983e-02
8	tau_P_bMin	: 2.854e-02
9	B_OPT_chi2	: 2.024e-02
10	tau_EndVERTEX_chi2Max	: 1.617e-02
11	tau_P_bMax	: 1.197e-02
12	tau_EndVERTEX_chi2Min	: 1.136e-02
13	tau_M13Min	: 8.664e-03

BB suppression

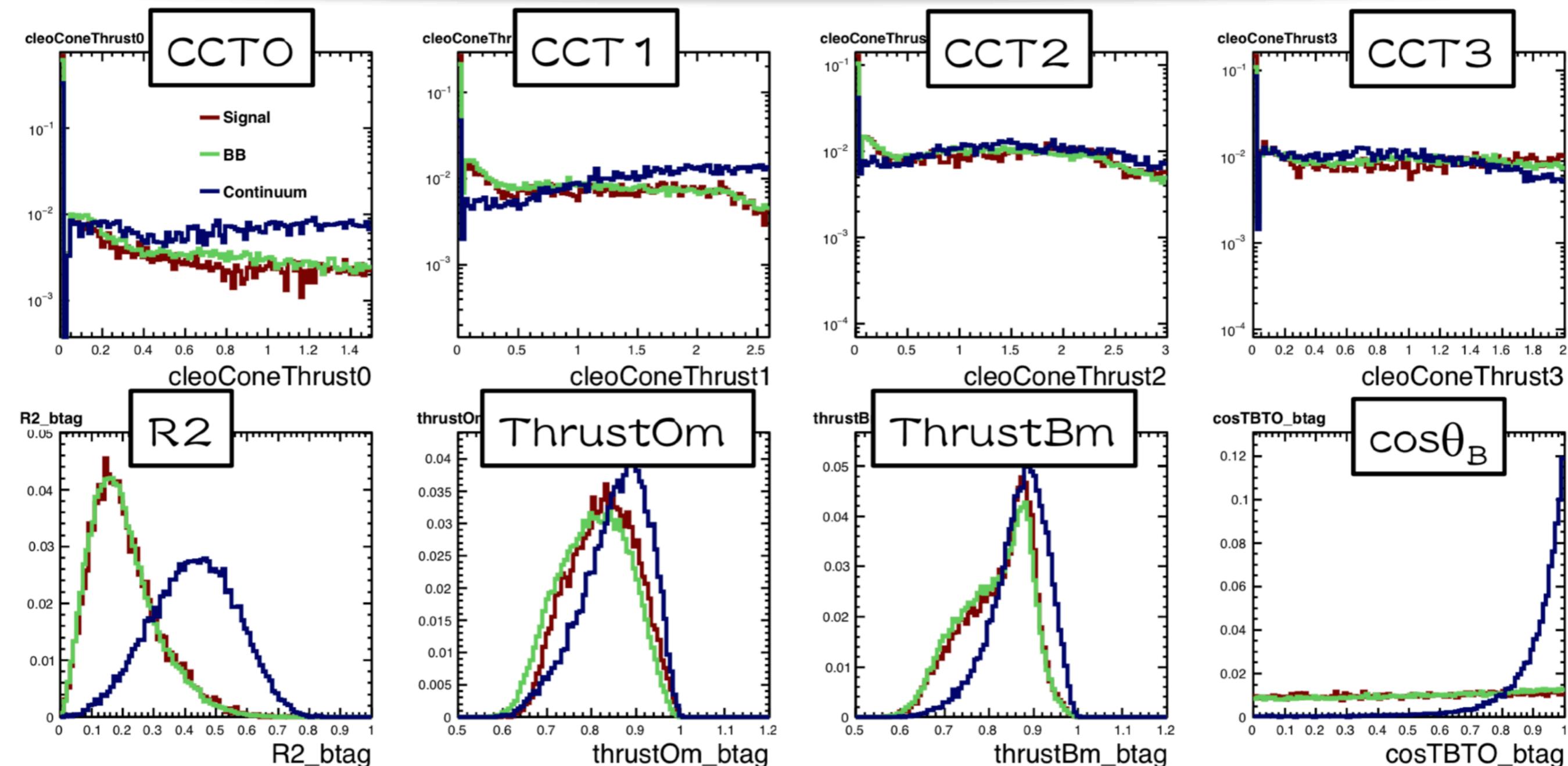


- EECL, number of ECL clusters.
- KSFW (modified Fox-Wolfram moments) input parameters.
- μ ID of primary muon.
- Distance b/w primary kaon and muon.
- etc.¹²

...and so on

[S. Watanuki - IJCLab]

qq suppression

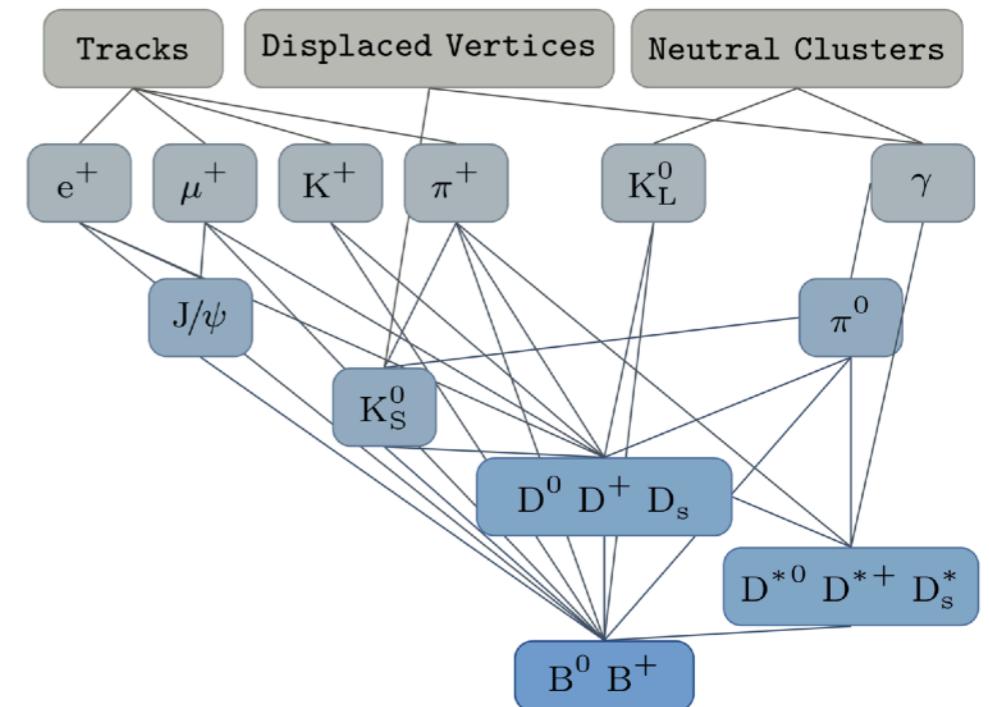
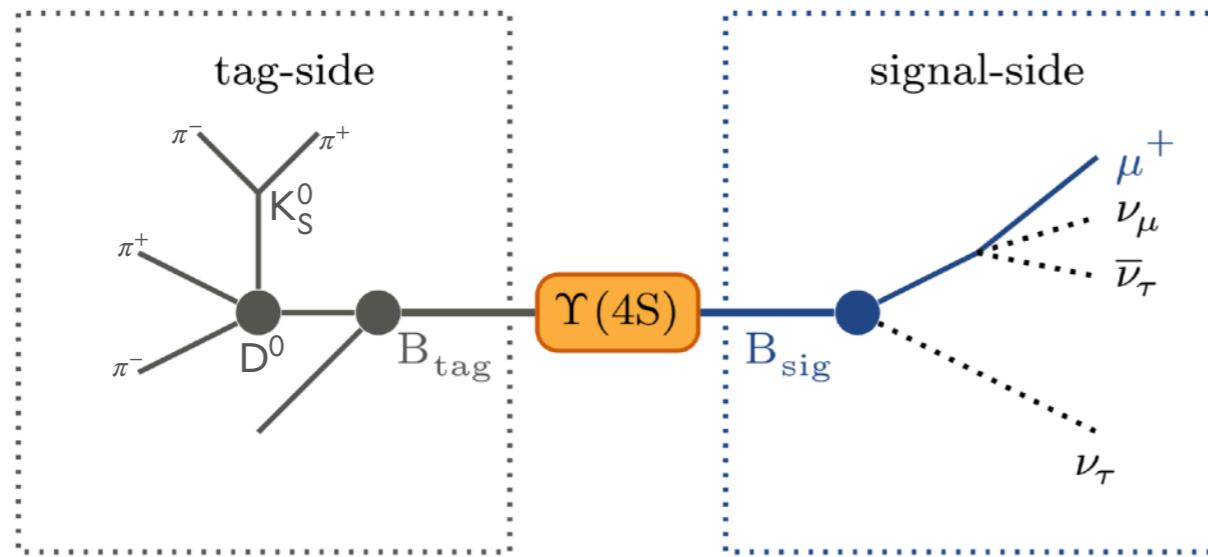


- CleoConeThrust (modified thrust information)
- R2
- $\cos\theta$
- etc.

...and so on

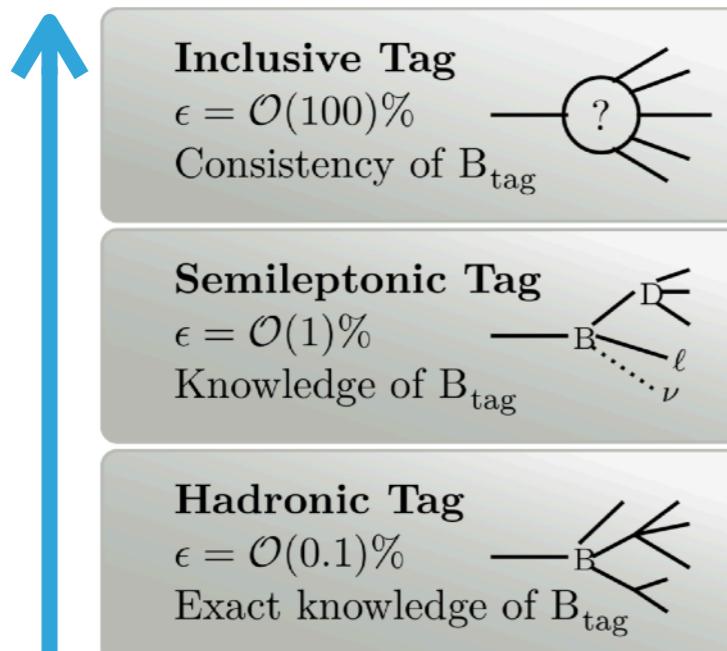
[S. Watanuki - IJCLab]

FEI



- >200 BDTs reconstructing 10k B decays
- Embedded in basf2 (Belle II Analysis Software Framework), can be used on Belle data

Efficiency



Purity

	B^\pm	B^0
Hadronic		
FEI with FR channels	0.53 %	0.33 %
FEI	0.76 %	0.46 %
FR	0.28 %	0.18 %
SER	0.4 %	0.2 %
Semileptonic		
FEI	1.80 %	2.04 %
FR	0.31 %	0.34 %
SER	0.3 %	0.6 %

SHAPE VARIABLES FOR CONTINUUM SUPPRESSION

Variables related to the B meson direction: the spin-1 $\Upsilon(4S)$ decaying into two spin-0 B mesons results in a $\sin^2 \Theta_B$ angular distribution with respect to the beam axis; in contrast for $e^+e^- \rightarrow f\bar{f}$ events, the spin-1/2 fermions f, and its two resulting jets, are distributed following a $1 + \cos^2 \Theta_B$ distribution. Using the angle Θ_B between the reconstructed momentum of the B candidate (computed in the $\Upsilon(4S)$ reference frame) and the beam axis, the variable $|\cos \Theta_B|$ allows one to discriminate between signal B decays and the B candidates from continuum background.

The **Fox-Wolfram moments**: for a collection of N particles with momenta p_i , the k-th order Fox-Wolfram moment H_k is defined as

$$H_k = \sum_{i,j}^n |\vec{p}_i| |\vec{p}_j| P_k(\cos \theta_{ij})$$

where θ_{ij} is the angle between p_i and p_j , and P_k is the k-th order Legendre polynomial. Notice that in the limit of vanishing particle masses, $H_0 = 1$; that is why the normalized ratio $R_k = H_k/H_0$ is often used, so that for events with two strongly collimated jets, R_k takes values close to zero (one) for odd (even) values of k. These sharp signatures provide a convenient discrimination between events with different topologies.

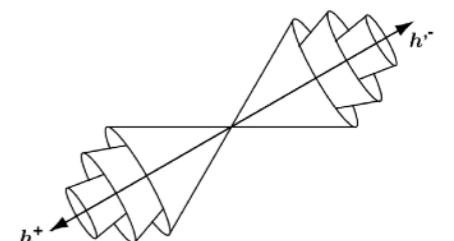
$$R_n = \frac{H_n}{H_0}$$

Thrust: for a collection of N momenta p_i ($i = 1, \dots, N$), the thrust axis T is defined as the unit vector along which their total projection is maximal; the thrust scalar T (or thrust) is a derived quantity defined as

$$T = \frac{\sum_{i=1}^N |\vec{T} \cdot \vec{p}_i|}{\sum_{i=1}^N |\vec{p}_i|}$$

For a BB event, both B mesons are produced almost at rest in the $\Upsilon(4S)$ rest frame, so their decay particles are isotropically distributed, their thrust axes are randomly distributed, and thus $|\cos \Theta_T|$ follows a uniform distribution in the range [0,1]. In contrast for $q\bar{q}$ events, the momenta of particles follow the direction of the jets in the event, and as a consequence the thrusts of both the B candidate and the ROE are strongly directional and collimated, yielding a $|\cos \Theta_T|$ distribution strongly peaked at large values.

Cleo Cones: Set of nine variables corresponding to the momentum flow around the thrust axis of the B candidate, binned in nine cones of 10° around the thrust axis as illustrated



$\Psi(2S)$ RESONANCE

$$m_\tau = (1776.82 \pm 0.16) \text{ MeV} \implies 2m_\tau \sim 3.6 \text{ GeV}$$

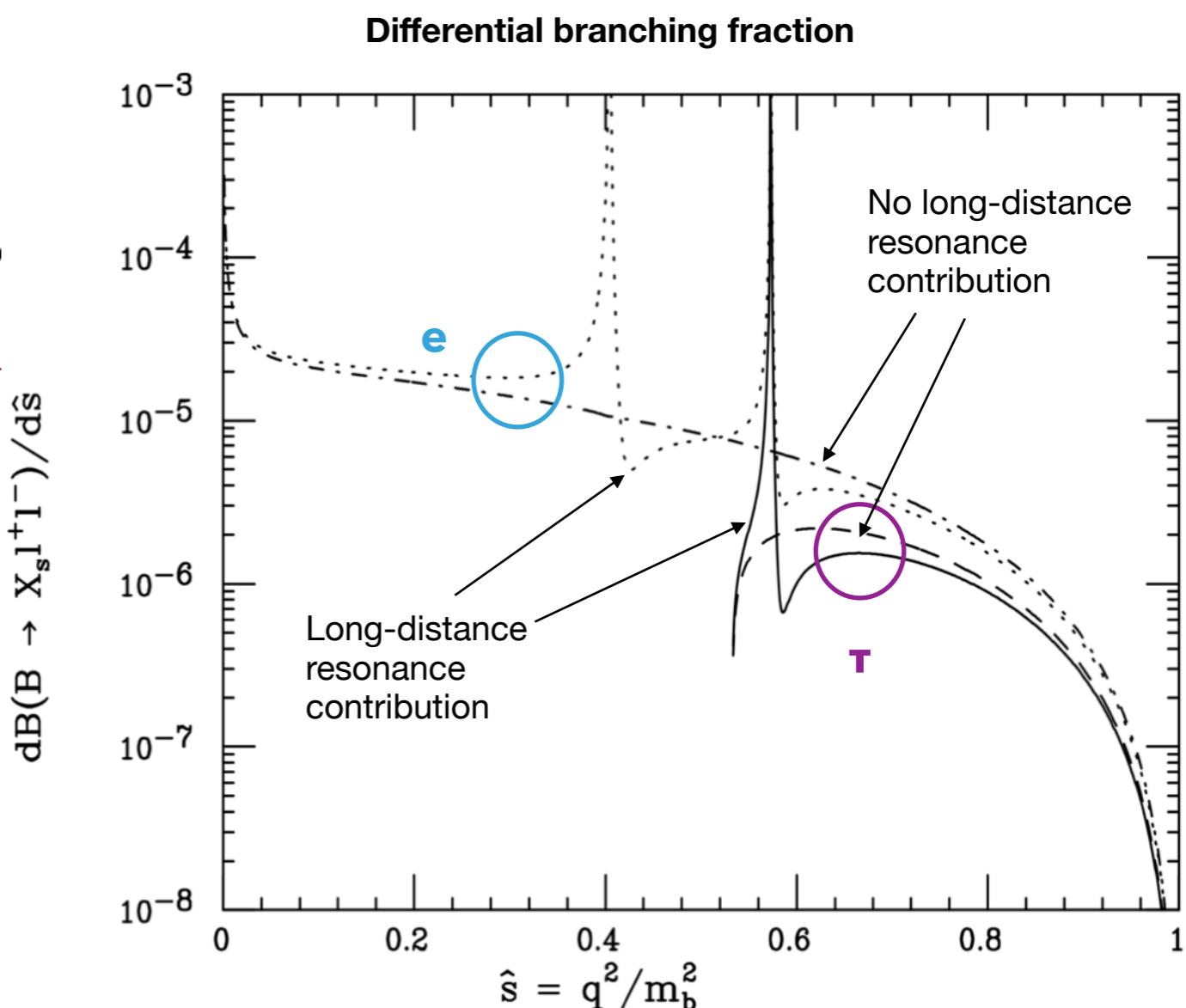
	J/ψ	$\psi(2S)$	$J^{PC} = 1^{--}$
--	----------	------------	-------------------

$$m(\text{GeV}) = \begin{cases} 3.1 & J/\psi \\ 3.7 & \psi(2S) \end{cases}$$

Cut on q^2 :

$$\begin{cases} \hat{s}_1 \text{ around } 0.56 \rightarrow \text{SM control sample} \\ \hat{s}_2 > 0.6 \end{cases}$$

$$\mathcal{B}(B^+ \rightarrow K^+ \psi(2S)(\rightarrow \tau\tau)) \sim 2 \times 10^{-6}$$



"Tau Polarization Asymmetry in $B \rightarrow X_s \tau^+ \tau^-$ " J. L. Hewett, [\[arXiv:9506289\]](#)

$$\mathcal{B}(B^+ \rightarrow K^+ \psi(2S)) = (6.39 \pm 0.33) \times 10^{-4}$$

M. Tanabashi et al. (PDG), Phys. Rev. D 98, 030001 (2018)

$$\mathcal{B}(\psi(2S) \rightarrow \tau^+ \tau^-) = (3.1 \pm 0.4) \times 10^{-3}$$

PERFORMANCE COMPARISON

		BaBar (SER)	Belle (FR)	Belle II (FEI)	
Hadronic	B^+B^-	0.4	0.28	0.53**	0.76†
Tag Eff. (%)^x	B^0B^0	0.2	0.18	0.33**	0.46†
Semil.	B^+B^-	0.3*	0.31	1.80	
Tag Eff. (%)^x	B^0B^0	0.6*	0.34	2.04	

Constructed combining an exclusive D() with a lepton

**FR had. channels

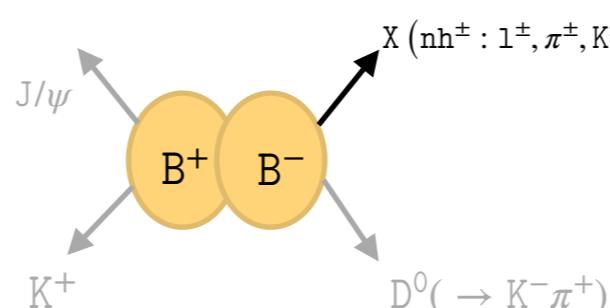
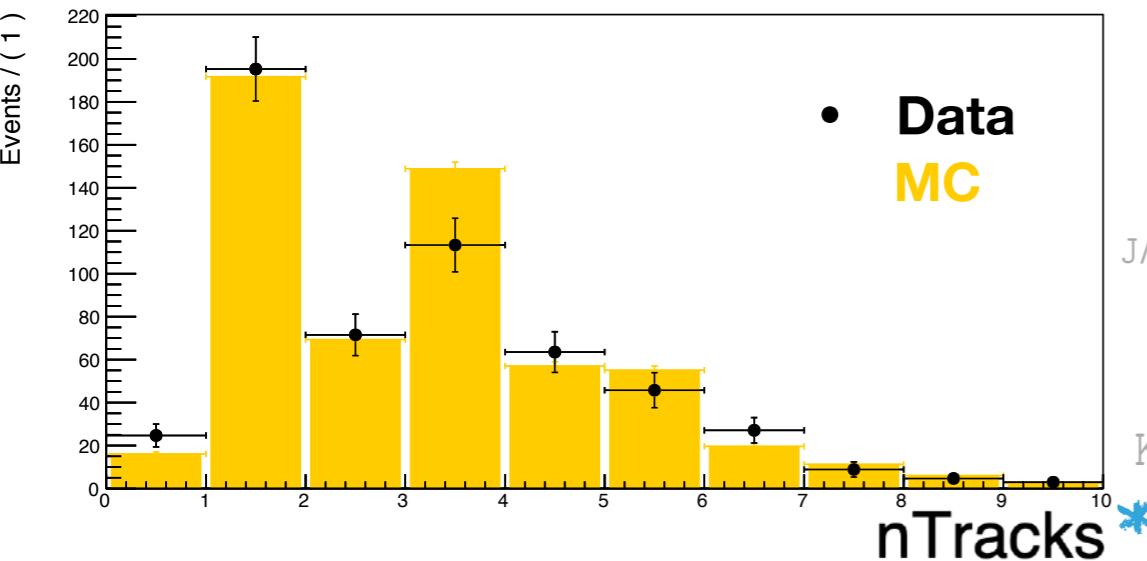
† FR + 38 more channels

^x Maximum value

Experiment	BB produced	e efficiency	$e \rightarrow \pi$ mis – ID	μ efficiency	$\mu \rightarrow \pi$ mis – ID	K efficiency	$K \rightarrow \pi$ mis – ID
Belle	772×10^6	90%	0.1%	93%	3%	85%	5%
BaBar	471×10^6	92%	0.1%	60%	1%	84%	1%

PROBE THE TAG SIDE: D^0 YIELDS AND PROPERTIES OF X

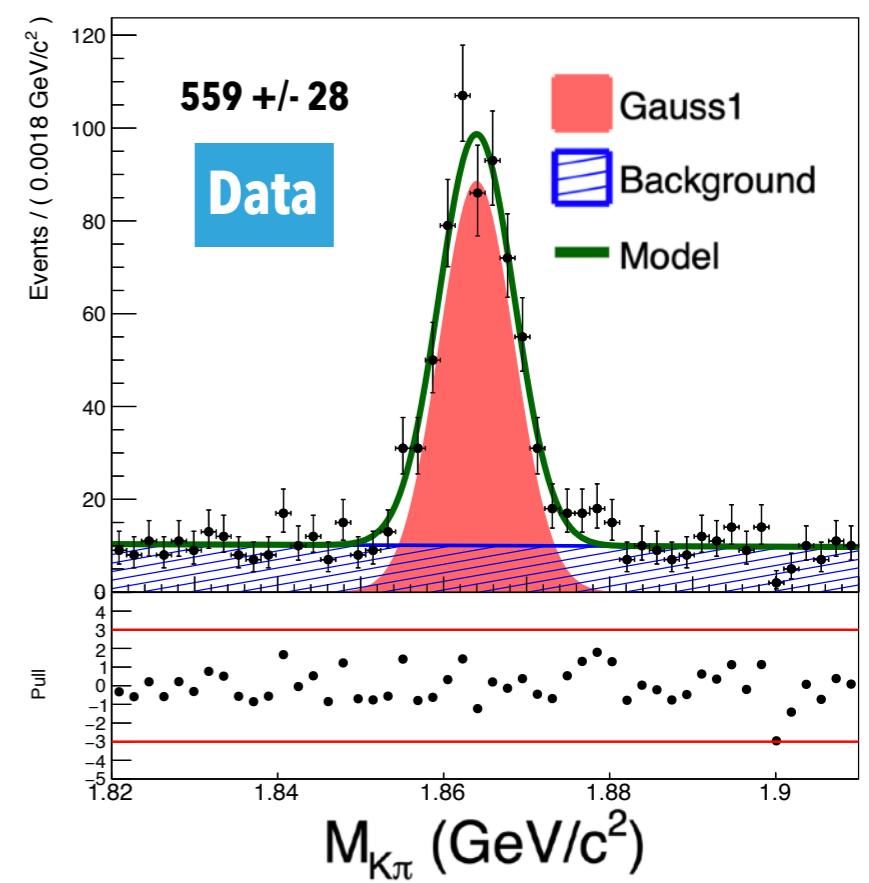
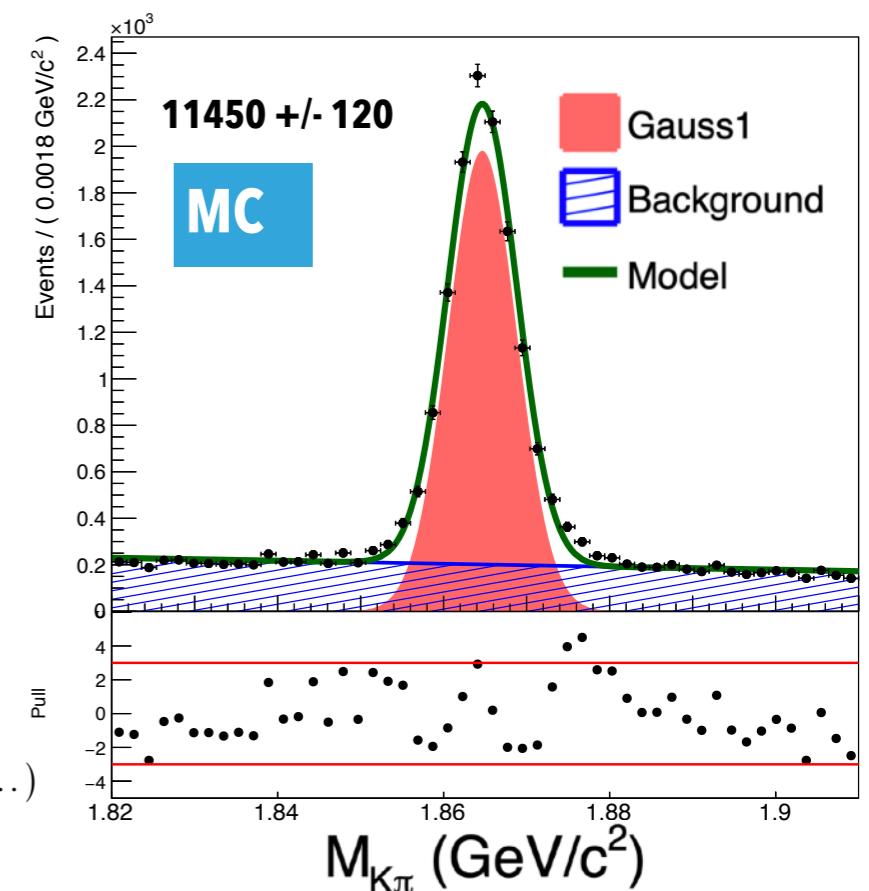
- The $M(K\pi)$ used as discriminating variable to sPlot any interesting variable in the X:
 - Companion particles (inclusively reconstructed)
 - Global variables (number of tracks*, clusters etc.)



	Bsig	$D^0(K\pi)$	Reco eff. (%)
MC	605156	11450	62
Data	31367	559	58

Tagging efficiency
~1.8% with $D^0(K\pi)$

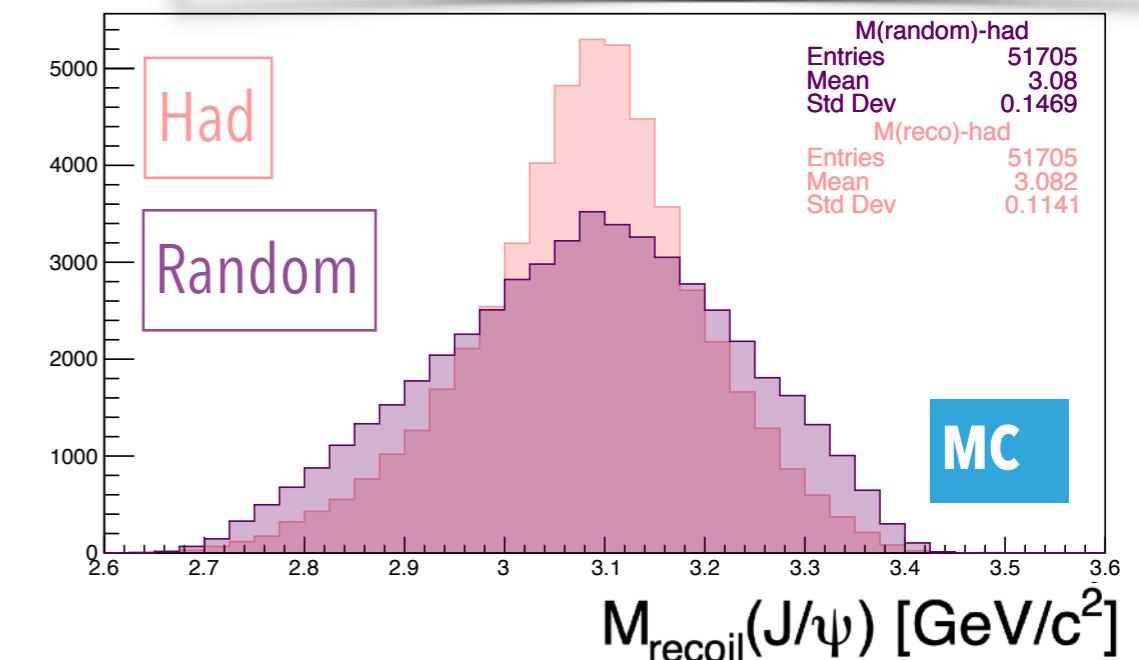
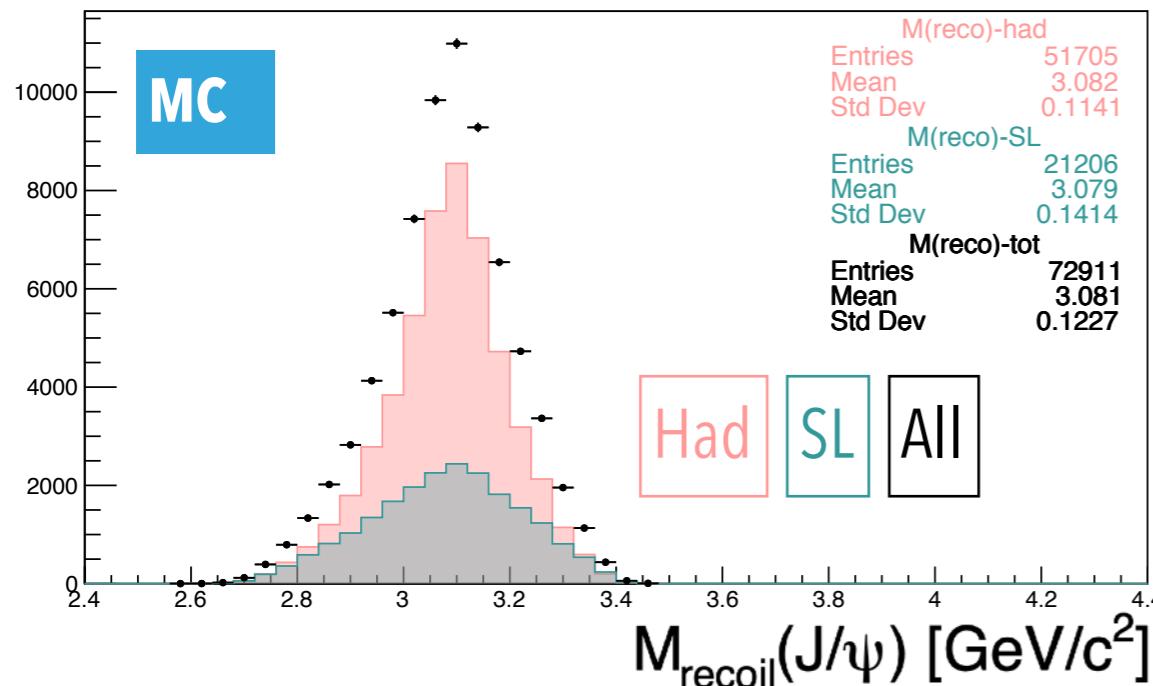
b.r.($B^+ \rightarrow \bar{D}^0 X$) \times b.r.($\bar{D}^0 \rightarrow K^+\pi^-$) $\sim 3\%$



RECOIL MASS WITH INCLUSIVE TAG

REMINDER

$$m_{J/\psi}^2 = m_B^2 + m_K^2 - 2(E_B^* E_K^* - |\vec{p}_{B_{\text{sig}}}^*| |\vec{p}_K^*| \cos \theta)$$



- J/psi recoil mass poorly sensitive to $\vec{p}_{B_{\text{tag}}}^*$ direction
- What if $\cos \theta$ is a random number uniformly distributed in (-1,1)?

does it hold also for $K\tau\mu$?

Higher sensitivity to $\vec{p}_{B_{\text{tag}}}^*$ direction,
probably due to the broader spectrum
for $p_{K\mu}^*$ with respect to p_K^*

