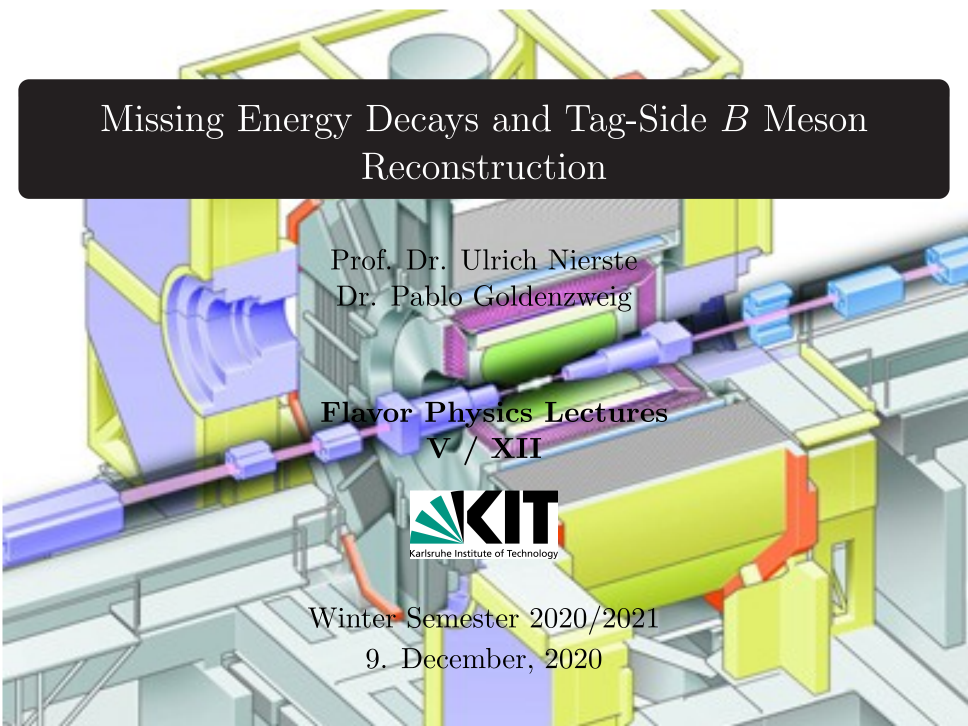

Missing Energy Decays and Tag-Side B Meson Reconstruction

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Dr. Pablo Goldenzweig

Flavor Physics Lectures
V / XII

Karlsruhe Institute of Technology

Winter Semester 2020/2021
9. December, 2020

Reading material and references

Lecture material based on several textbooks and online lectures/notes. Credits for material and figures include:

Literature

Perkins, Donald H. (2000), *Introduction to High Energy Physics*.

Griffiths, David J. (2nd edition), *Introduction to Elementary Particles*.

Stone, Sheldon (2nd edition), *B decays*.

Online Resources

Belle/BaBar Collaborations, *The Phyiscs of the B-Factories*.
http://arxiv.org/abs/1406.6311

Bona, Marcella (University of London), *CP Violation Lecture Notes*,
http://pprc.qmul.ac.uk/ bona/ulpg/cpv/

Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and CP Violation*.
http://physics.ucsd.edu/students/courses/winter2010/physics222/references/driver_houches12.pdf

Thomson, Mark (Cambridge University), *Particle Physics Lecture Handouts*,
http://www.hep.phy.cam.ac.uk/ thomson/partIIIparticles/welcome.html

Grossman, Yuval (Cornell University), *Just a Taste. Lectures on Flavor Physics*,
http://www.lepp.cornell.edu/ pt267/files/notes/FlavorNotes.pdf

Kooijman, P. & Tuning, N., *CP Violation*,
https://www.nikhef.nl/ h71/Lectures/2015/ppII-cpviolation-29012015.pdf

Recap & outline

So far, we:

- Introduced the CKM matrix and looked at ways to over-constrain the Unitary Triangle through Kaon and B-meson decays.
- Studied 3 types of CP violation and looked at experimental results for Kaon mixing, Direct CPV in the $B \to K\pi$ system, and CPV in the interference between mixing and decay in $B \to J/\psi K_S^0$
- Talked about e^+e^- B factories and how we produce and reconstruct B-mesons

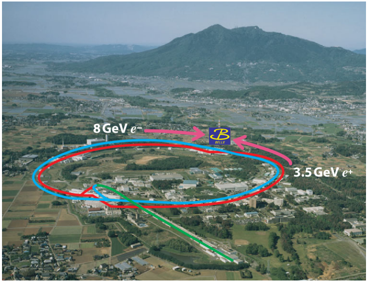
Today, we'll:

- Learn how we can reconstruct B-mesons which decay to final-states containing neutrinos.
- Study some of these leptonic and semi-leptonic decays in detail.

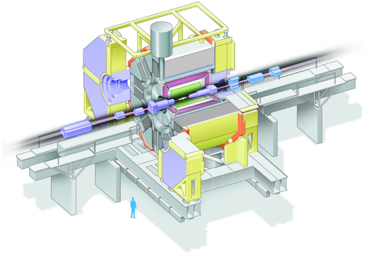
The Belle Experiment

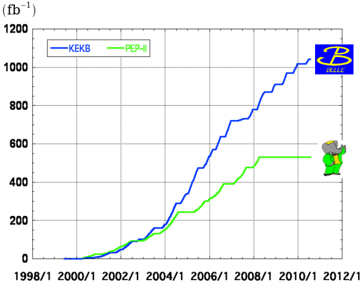
The KEKB accelerator

- Asymmetric e^+e^- collider
- Mainly operates at the $\Upsilon(4S)$ resonance



The Belle detector



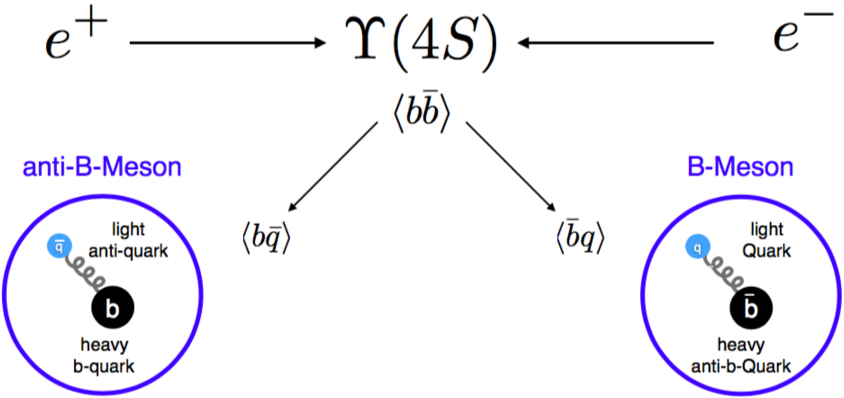


Final data sample

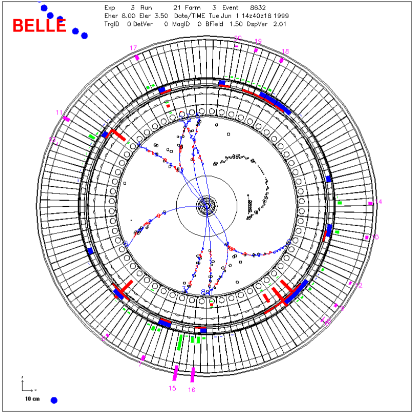
- $711 fb^{-1}$ $\Upsilon(4S)$ resonance
- $121 fb^{-1}$ $\Upsilon(5S)$ resonance

e^+e^- collisions at the $\Upsilon(4S)$

$$\sqrt{s} = 10.58\,\text{GeV}$$

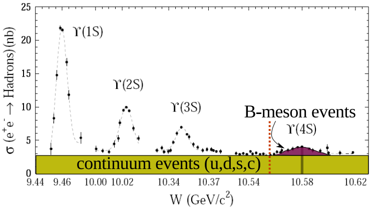


Typical hadronic event

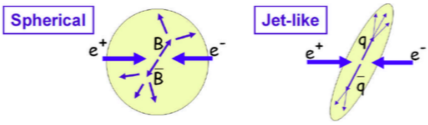


- Few tracks and clusters
- Nothing produced in addition to the $\Upsilon(4S)$
- High reconstruction efficiency
- Very good particle identification

Signal B reconstruction

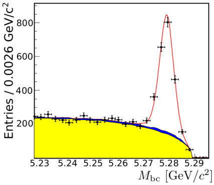


Different event topologies



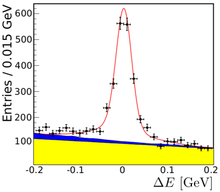
B-mesons Continuum

Example signal-side reconstruction



Beam constrained mass

$M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2}$



Energy difference

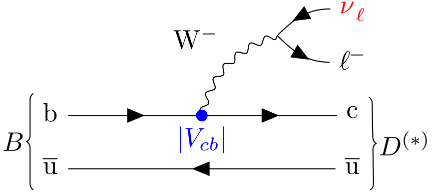
$\Delta E \equiv E_B - E_{\text{Beam}}$

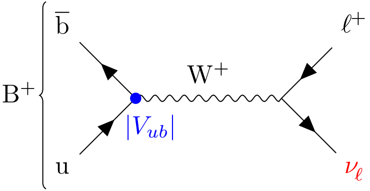
$B^0 \to \eta' K_S^0$

- $B\bar{B}$
- $e^+e^- \to q\bar{q}$

But what happens when we cannot *fully* reconstruct the signal-side due to neutrinos in the final state?

Several key B decay channels for measuring CKM elements contain neutrinos in the final state: $\overline{B} \to D^{(*)}\ell\overline{\nu}_\ell$, $B^+ \to \ell^+\nu_\ell$





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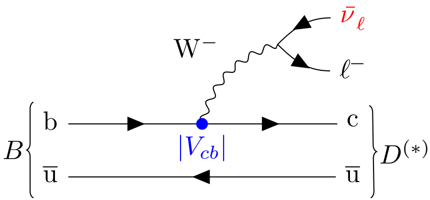
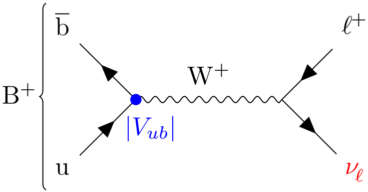
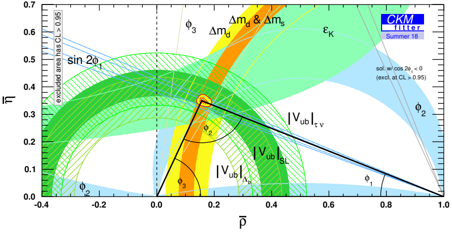




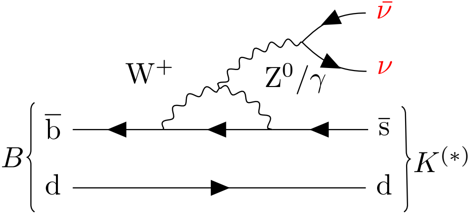


← $|V_{ub}|$ from inclusive and exclusive semileptonic B decays.

← $|V_{ub}|$ from $B^+ \to \tau^+\nu_\tau$.

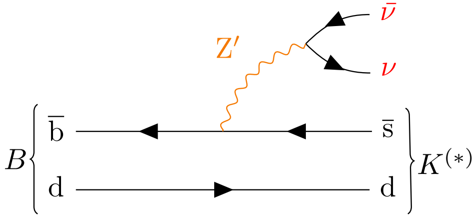
← $|V_{ub}|/|V_{cb}|$ from Λ_b decays.

$B \to K^{(*)} \nu \bar{\nu}$



Flavor changing neutral current (FCNC) decays

$B \to K^{(*)} \nu \bar{\nu}$



New Physics scenario

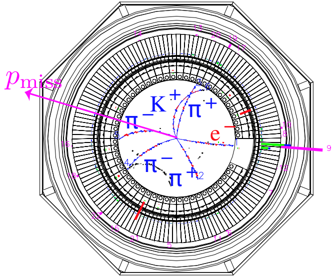
Take advantage of experimental setup of B-factories:

- **$B\overline{B}$ pairs are produced without any additional particles;**
- **Detectors enclose the interaction region almost hermetically;**
- **Collision energy (initial state) is precisely known:**

$$p_{e^+} + p_{e^-} = p_B + p_{\overline{B}}.$$

The Full Reconstruction method (KIT 2011)

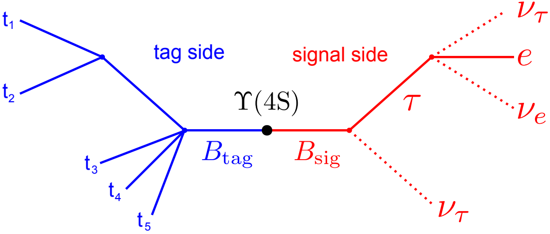
Typical B factory event



$B^+_{tag} \to \bar{D}^0\pi^+\pi^+\pi^-$
$\hookrightarrow K^+\pi^-$

$B^-_{sig} \to \tau^-\bar{\nu}_\tau$
$\hookrightarrow e^-\bar{\nu}_e\nu_\tau$

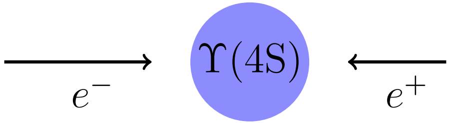
Tag- and signal-side of the full reconstruction



- Reconstruct B_{tag}
  - Suppresses the $e^+e^- \to q\bar{q}$ continuum background
  - Signal B momentum is known: $p(B_{\text{sig}}) = p(\text{beam}) - \text{p(B}_{\text{tag}})$
- Check if the remaining particles in the detector are consistent with signal signature

Event Reconstruction

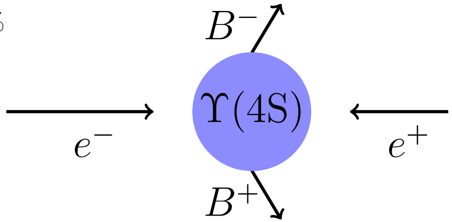
– Collide e^+ and e^- at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.



Event Reconstruction

– Collide e^+ and e^- at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.

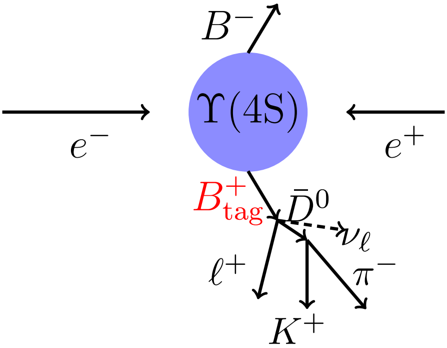
  $\Upsilon(4S)$ decays to B^+B^- and $B^0\bar{B}^0$ 96% of the time.



Event Reconstruction

- Collide e^+ and e^- at $\sqrt{s} = 10.58$ GeV to create Υ(4S) resonance.

  Υ(4S) decays to B^+B^- and $B^0\bar{B}^0$ 96% of the time.
- Reconstruct one B meson as tag-side (B_{tag}) in semileptonic or hadronic channels.



Event Reconstruction

- Collide e^+ and e^- at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.

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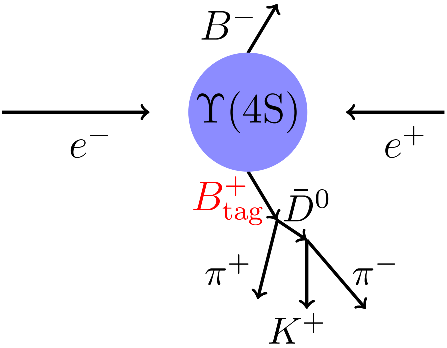
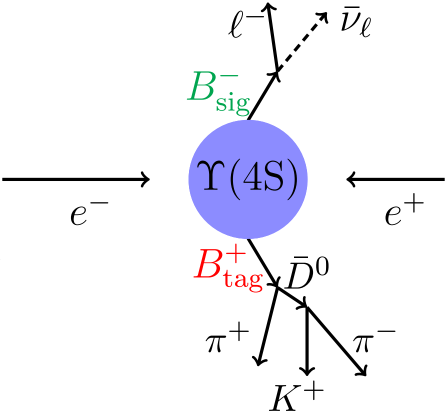


Event Reconstruction

- Collide e^+ and e^- at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.

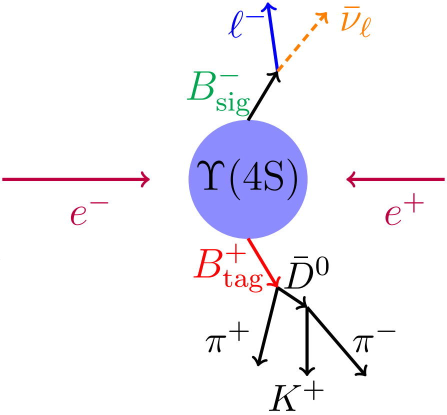
  $\Upsilon(4S)$ decays to B^+B^- and $B^0\bar{B}^0$ 96% of the time.
- Reconstruct one B meson as tag-side (B_{tag}) in semileptonic or hadronic channels.
- Study remaining B meson as signal (B_{sig}).



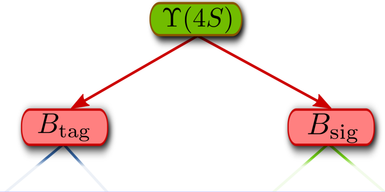
Event Reconstruction

- Collide e^+ and e^- at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.

  $\Upsilon(4S)$ decays to B^+B^- and $B^0\bar{B}^0$ 96% of the time.
- Reconstruct one B meson as tag-side (B_{tag}) in semileptonic or hadronic channels.
- Study remaining B meson as signal (B_{sig}).
- Flavour constraints:
  $B^+_{\text{tag}} \Rightarrow B^-_{\text{sig}}$
  Kinematic constraints:
  $p_{\bar{\nu}_\ell} = p_{e^+e^-} - p_{\ell^-} - p_{B^+}$



Which tag-side reconstruction?



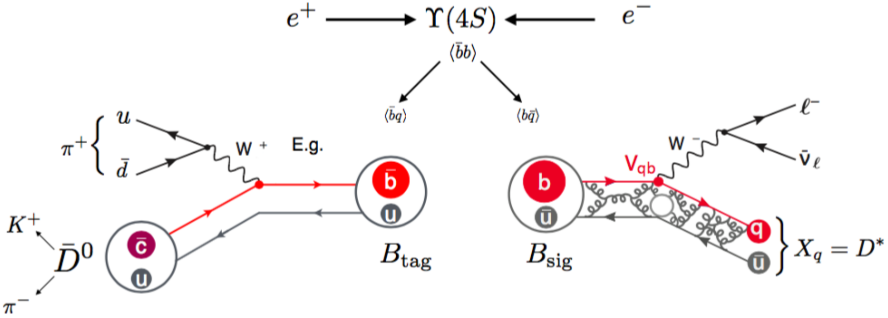
Tagging techniques

Purity →

← Efficiency

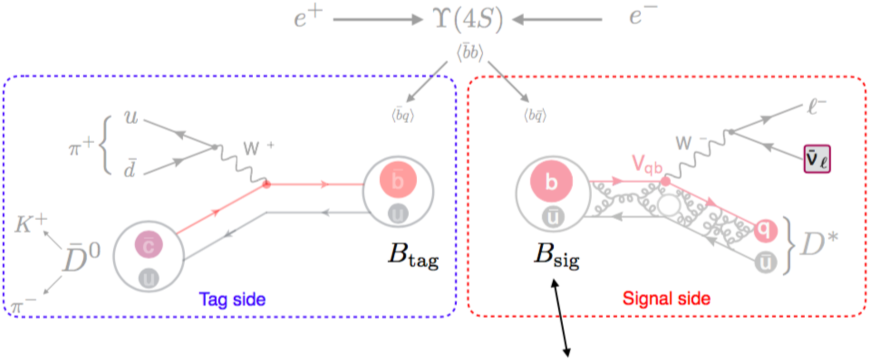
Inclusive	**Semileptonic**	**Hadronic**
$B \to$ anything	$B \to D^{(*)}\ell\nu_\ell$	$B \to$ hadrons
$\epsilon \approx \mathcal{O}(2\%)$	$\epsilon \approx \mathcal{O}(0.2\%)$	$\epsilon \approx \mathcal{O}(0.1\%)$
Very large statistics; Also very large background	High reconstruction efficiency; Less information about B_{tag} due to neutrino	Cleaner sample Knowledge of $p(B_{\text{sig}})$; Lower tagging efficiency

B_{tag} reconstruction using hadronic modes



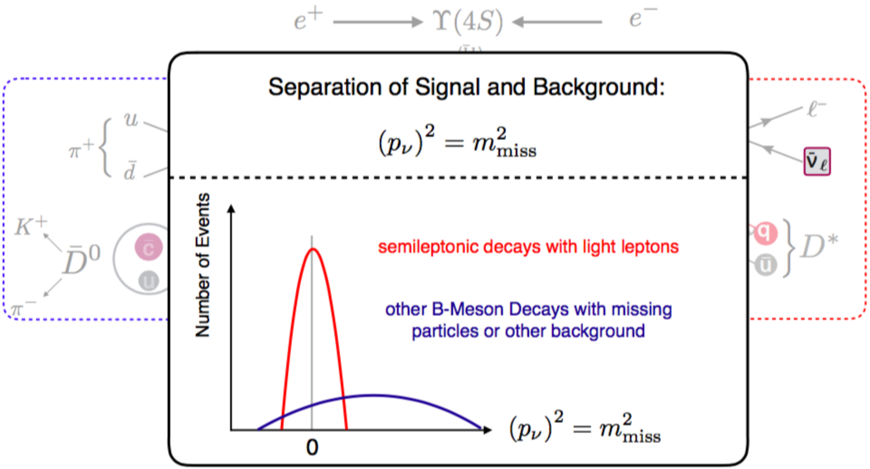
Complete reconstruction using
hadronic modes

Missing momentum



$$p_{\text{miss}} = p_\nu = (\overbrace{p_{e^+e^-} - p_{\text{tag}}}^{p_{B_{\text{sig}}}} - p_{X_q} - p_\ell)$$

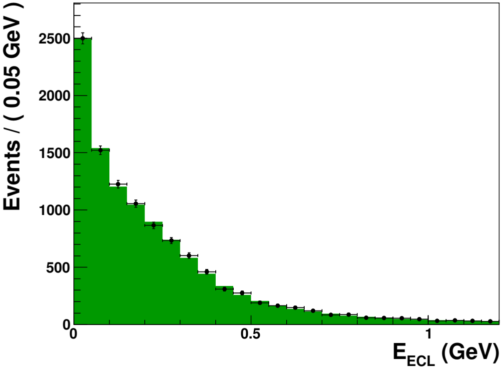
Missing mass



Extra energy in the calorimeter

Sum of energies of neutral clusters not associated with reconstructed particles:

$$E_{ECL} = \sum E_{\text{Calor.}} - (\sum E_{\text{tag}} + \sum E_{\text{sig}})$$



Along with M^2_{miss}, the signal yield can be extracted by fitting this distribution of Extra Energy in the Calorimeter

(Semi-)leptonic decays

$B \to \tau\nu$

$B \to \ell\nu\gamma$

$B \to D^{(*)}\ell\nu$

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

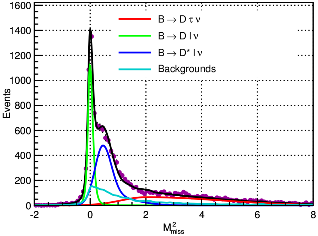
$B \to h\nu\nu$

$B \to \nu\nu$

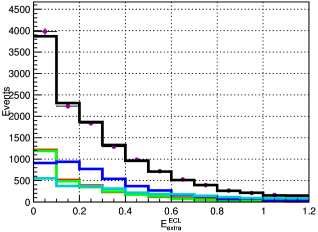
Inclusive searches

$B \to K + X_{c\bar{c}}$

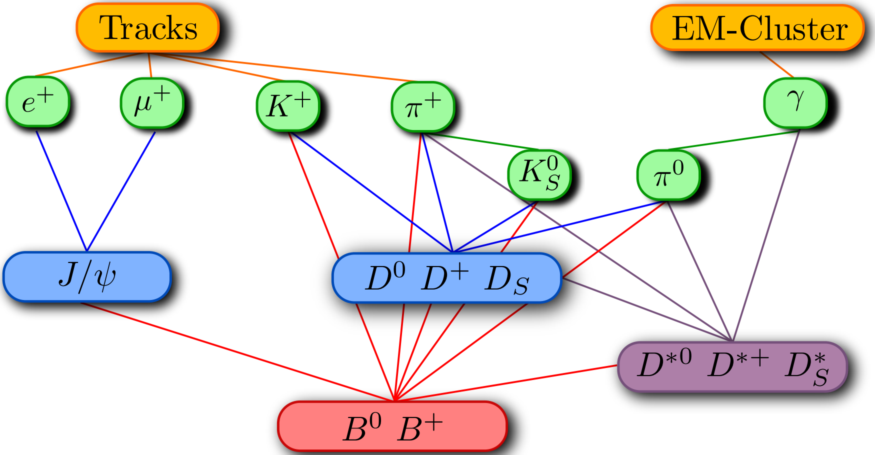
Monte Carlo Simulation:



$M^2_{\text{miss}} = ((p_{\text{beam}}) - p_{\text{tag}} - p_{\text{visible signal}})^2/c^2$



Hierarchical B_{tag} reconstruction

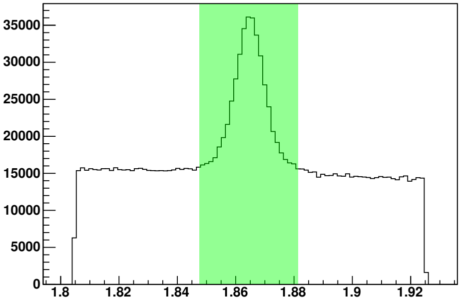


Exemplary reconstruction of a hadronic B_{tag}

$$B^+ \to D^0 \pi^+ \pi^+ \pi^-$$

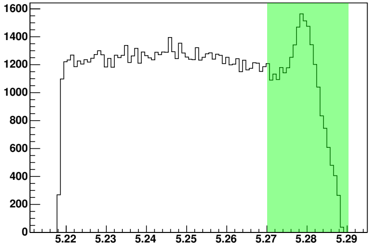
First step

- Reconstruction of D^0 meson (exemplary $\bar{D}^0 \to K^+ \pi^-$)
- Specific cuts on Particle ID
- Cut on D^0 mass

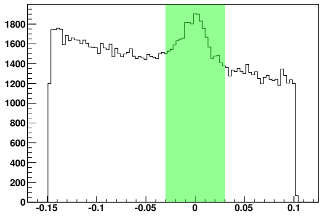


Mass of the D^0 meson

Exemplary reconstruction of a hadronic B_{tag}



M_{bc} of the B^+ meson



ΔE of the B^+ meson

B reconstruction: Important variables

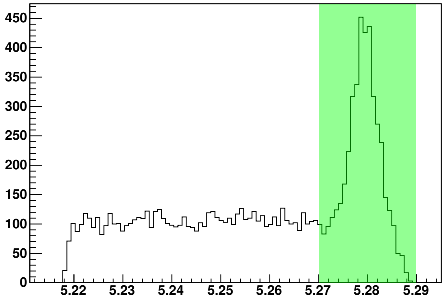
$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2}$$

$$\Delta E \equiv E_{B\text{-meson}} - E_{\text{Beam}}$$

Often necessary: Improvement of significance

Usage of multivariate techniques.

Exemplary reconstruction of a hadronic B_{tag}



M_{bc} of the B^+ meson

Typical variables:

Vertex fit information;

Kinematic Variables;

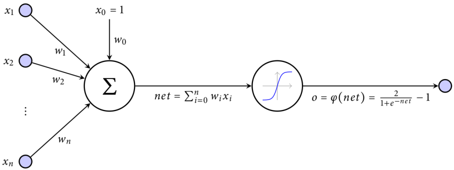
Particle ID information;

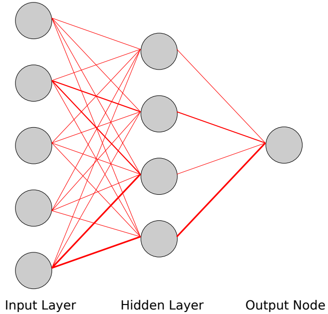
M_{bc} or ΔE.

Full Reconstruction:
This procedure is performed for hundreds of different channels.

NeuroBayes

Multivariate analysis software combining a **Neural** Network with sophisticated pre-processing

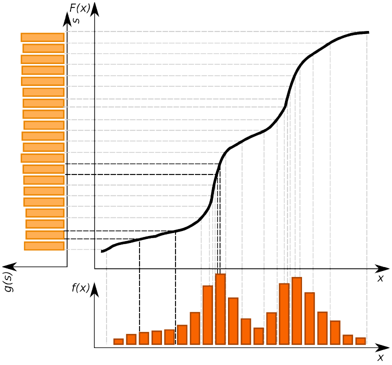




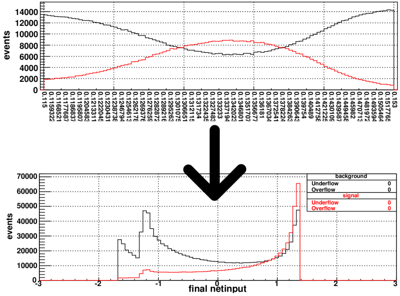
The output of the Network can be interpreted as **Bayesian** probability

NeuroBayes: pre-processing (I)

Input variables are flattened

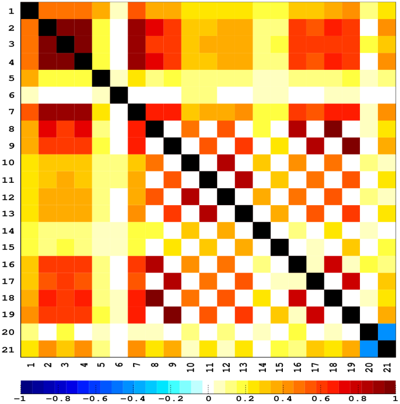


Purity is taken and transformed to have mean 0 and width 1.



NeuroBayes: pre-processing (II)

Input variables are decorrelated



Pre-processing:

- Speeds up the training process;
- Facilitates the weight finding;
- Increases the robustness of the algorithm.

Probability

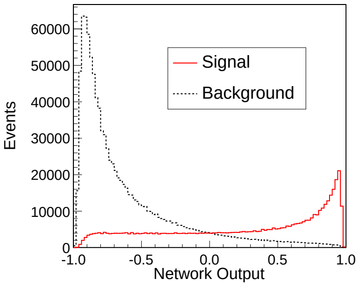
S/B in training is the same as on data

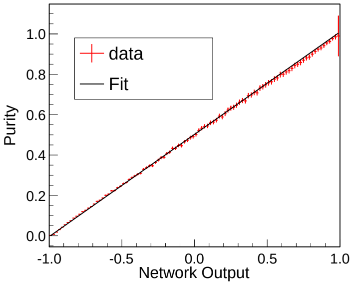
(Output of NeuroBayes+1)/2 is the signal probability by construction.

S/B in training is not the same as on data

- It is often necessary to artificially enhance the signal component for the training.
- The output can be corrected:

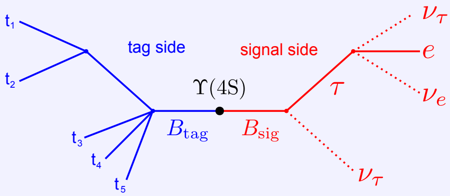
$$o_p = \frac{1}{1 + (\frac{1}{o_t} - 1)\frac{P_p(B)}{P_p(S)}\frac{P_t(S)}{P_t(B)}}$$





Efficiency and purity (I)

Two premises



The more **correct** tag side B mesons, the more signal side B mesons are available for analysis.

$\Rightarrow$ ***Need for good efficiency***

The more **incorrect** tag side B mesons, the more background pollutes the signal side.

$\Rightarrow$ ***Need for good purity***

Efficiency and purity (II)

In simple terms, one has to decide …

For the B_{tag} Channels

Maximisation of Efficiency	Maximisation of Purity
Many channels for B_{tag} reconstruction	Exclusion of “dirty” channels.

For eventual cuts

Maximisation of Efficiency	Maximisation of Purity
Loose or no cuts	Tight, pure cuts

The quality of the compromise depends on the variables that are used to distinguish signal from background.

Hadronic B_{tag} channels (I)

Channel			$\mathcal{BR}$	Channel			$\mathcal{BR}$
B^+	$\rightarrow$	$\bar{D}^0\pi^+$	0.484%	B^0	$\rightarrow$	$D^-\pi^+$	0.268%
B^+	$\rightarrow$	$\bar{D}^0\pi^+\pi^0$	1.340%	B^0	$\rightarrow$	$D^-\pi^+\pi^0$	0.760%
B^+	$\rightarrow$	$\bar{D}^0\pi^+\pi^+\pi^-$	1.100%	B^0	$\rightarrow$	$D^-\pi^+\pi^+\pi^-$	0.800%
B^+	$\rightarrow$	$D_S^+\bar{D}^0$	1.000%	B^0	$\rightarrow$	$\bar{D}^0\pi^0$	0.026%
B^+	$\rightarrow$	$\bar{D}^{0*}\pi^+$	0.519%	B^0	$\rightarrow$	$D_S^+D^-$	0.720%
B^+	$\rightarrow$	$\bar{D}^{0*}\pi^+\pi^0$	0.980%	B^0	$\rightarrow$	$D^{*-}\pi^+$	0.276%
B^+	$\rightarrow$	$\bar{D}^{0*}\pi^+\pi^+\pi^-$	1.030%	B^0	$\rightarrow$	$D^{*-}\pi^+\pi^0$	1.500%
B^+	$\rightarrow$	$\bar{D}^{0*}\pi^+\pi^+\pi^-\pi^0$	1.800%	B^0	$\rightarrow$	$D^{*-}\pi^+\pi^+\pi^-$	0.700%
B^+	$\rightarrow$	$D_S^{+*}\bar{D}^0$	0.760%	B^0	$\rightarrow$	$D^{*-}\pi^+\pi^+\pi^-\pi^0$	1.760%
B^+	$\rightarrow$	$D_S^+\bar{D}^{0*}$	0.820%	B^0	$\rightarrow$	$D_S^{+*}D^-$	0.740%
B^+	$\rightarrow$	$D_S^{+*}\bar{D}^{0*}$	1.710%	B^0	$\rightarrow$	$D_S^+D^{*-}$	0.800%
B^+	$\rightarrow$	$\bar{D}^0K^+$	0.037%	B^0	$\rightarrow$	$D_S^{+*}D^{*-}$	1.770%
B^+	$\rightarrow$	$D^-\pi^+\pi^+$	0.107%	B^0	$\rightarrow$	$J/\psi K_S^0$	0.087%
B^+	$\rightarrow$	$J/\psi K^+$	0.101%	B^0	$\rightarrow$	$J/\psi K^+\pi^-$	0.120%
B^+	$\rightarrow$	$J/\psi K^+\pi^+\pi^-$	0.107%	B^0	$\rightarrow$	$J/\psi K_S^0\pi^+\pi^-$	0.100%
B^+	$\rightarrow$	$J/\psi K^+\pi^0$	0.047%				
B^+	$\rightarrow$	$J/\psi K_S^0\pi^+$	0.094%				

Hadronic B_{tag} channels (II)

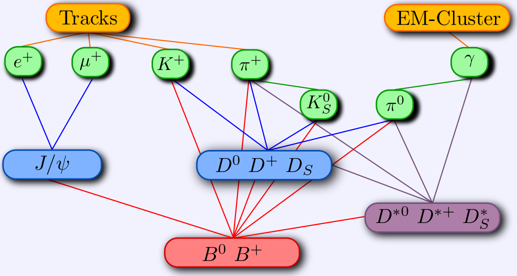
Channel			$\mathcal{BR}$	Channel			$\mathcal{BR}$
D^0	$\to$	$K^-\pi^+$	3.89%	D^+	$\to$	$K^-\pi^+\pi^+$	9.40%
D^0	$\to$	$K^-\pi^+\pi^+\pi^-$	8.09%	D^+	$\to$	$K_S^0\pi^+$	1.49%
D^0	$\to$	$K^-\pi^+\pi^0$	6.90%	D^+	$\to$	$K_S^0\pi^+\pi^0$	6.90%
D^0	$\to$	$\pi^+\pi^-$	0.14%	D^+	$\to$	$K^-\pi^+\pi^+\pi^0$	6.08%
D^0	$\to$	$\pi^+\pi^-\pi^0$	1.44%	D^+	$\to$	$K_S^0\pi^+\pi^+\pi^-$	3.10%
D^0	$\to$	$K_S^0\pi^0$	1.22%	D^+	$\to$	$K^+K^-\pi^+$	0.98%
D^0	$\to$	$K_S^0\pi^+\pi^-$	2.94%	D^+	$\to$	$K^+K^-\pi^+\pi^0$	1.50%
D^0	$\to$	$K_S^0\pi^+\pi^-\pi^0$	5.40%	D^{+*}	$\to$	$D^0\pi^+$	67.70%
D^0	$\to$	K^+K^-	0.39%	D^{+*}	$\to$	$D^+\pi^0$	30.70%
D^0	$\to$	$K^+K^-K_S^0$	0.47%				
D^{0*}	$\to$	$D^0\pi^0$	61.9%	D^{0*}	$\to$	$D^0\gamma$	38.10%
D_S^+	$\to$	$K^+K_S^0$	1.49%	D_S^+	$\to$	$K^+K^-\pi^+\pi^+\pi^-$	0.88%
D_S^+	$\to$	$K^+\pi^+\pi^-$	0.69%	D_S^+	$\to$	$\pi^+\pi^+\pi^-$	1.10%
D_S^+	$\to$	$K^+K^-\pi^+$	5.50%	D_S^{+*}	$\to$	$D_S^+\gamma$	94.20%
D_S^+	$\to$	$K^+K^-\pi^+\pi^0$	5.60%	J/ψ	$\to$	e^-e^+	5.94%
D_S^+	$\to$	$K^+K_S^0\pi^+\pi^-$	0.96%	J/ψ	$\to$	$\mu^-\mu^+$	5.93%
D_S^+	$\to$	$K^-K_S^0\pi^+\pi^+$	1.64%				

Total hadronic B_{tag} channels

Channels		$\mathcal{BR}$	Channels		$\mathcal{BR}$	Channels		$\mathcal{BR}$
D^+	7	29.4%	D^{*+}	2	98.4%	B^+	17	12.0%
D^0	10	37.9%	D^{*0}	2	100.0%	B^0	15	10.4%
D_S^+	8	17.9%	D_S^{*+}	1	94.2%			
J/Ψ	2	11.9%						

Reconstruction of **1104 exclusive decay channels**

Hierarchical Reconstruction



Intermediate cuts

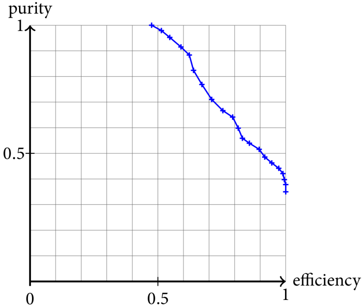
With an equivalent of **1104 decay channels** with up to 12 final state particles, intermediate cuts are absolutely necessary.

Maximisation of Efficiency

Efficient, loose cuts. Or even somehow no cuts at all?

Maximisation of Purity

Pure, tight cuts.



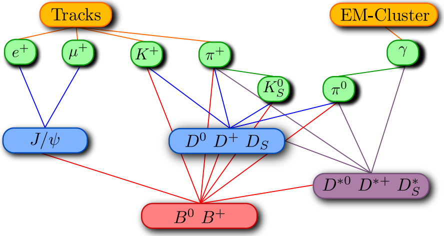
Intermediate cuts

How to make the smartest cuts possible?

How do you compare $D^0 \to K^-\pi^+$ to $D^0 \to K_S^0\pi^+\pi^-\pi^0$?

Even worse: The cut depends on the next level: The D^0 meson in $B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$ should get a different cut than in $B^+ \to \bar{D}^0\pi^+$.

Solution: Multiply the signal probability (given by the NeuroBayes training) of all children and use that to cut.



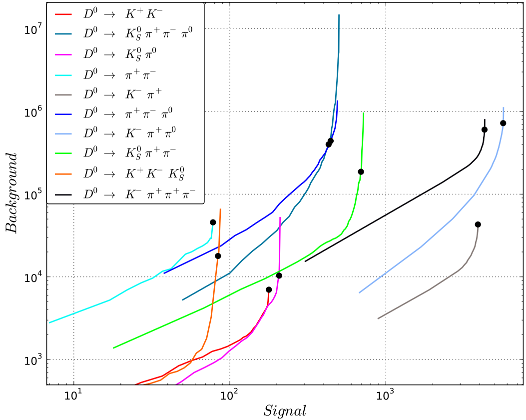
Cut decisions are postponed to a later level

Not only the reconstruction is **hierarchical**, but also the **information flow**.

Cut choice

Cut on the product of the **signal probabilities (= NeuroBayes outputs)** of the children.

The cuts are determined for all D^0 modes simultaneously: Required that the additional amount of bkgd. that would have to be taken into the sample to gain one additional signal event was the same for all D^0 modes.



Choose a cut to have roughly the same slope for all curves.

This slope corresponds to the number of candidates.

Very soft cuts, usage of probability product on next level.

Trade-off:
Efficiency ↔ Purity and CPU time.

Results

What is the result of the Full Reconstruction?

A collection of B_{tag} candidates

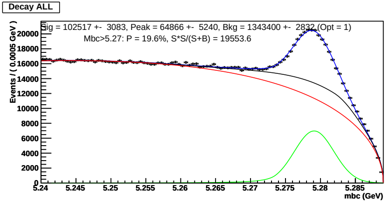
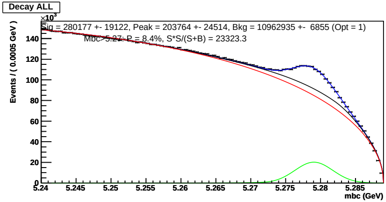
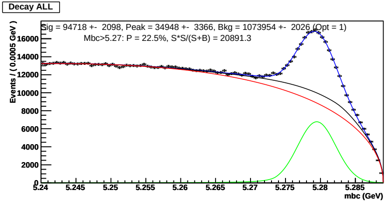
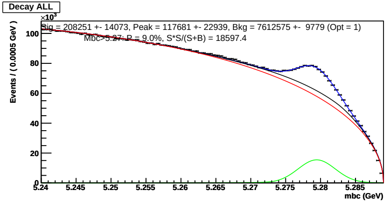
Visualisation of results: beam constrained mass M_{bc}

$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2}$$

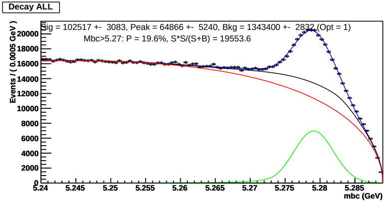
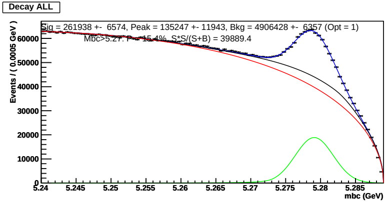
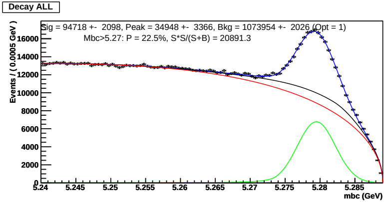
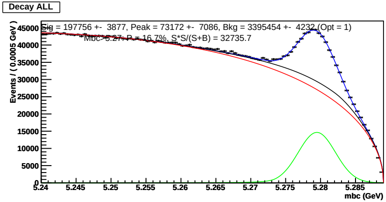
Any basis for comparison?

Yes! The cut-based predecessor to this Full Reconstruction.

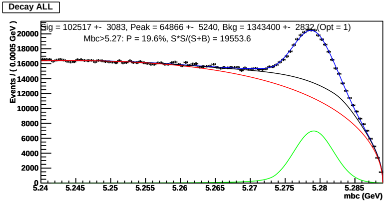
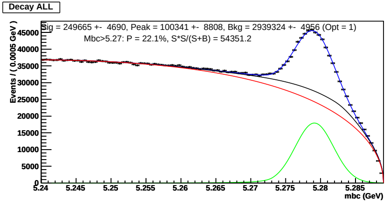
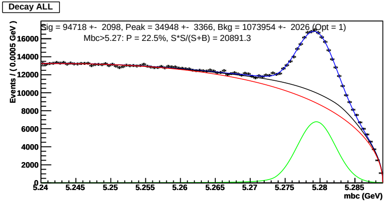
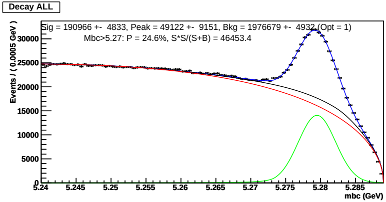
Adjusting cut on NeuroBayes output

	Cut-based predecessor	NeuroBayes Full Reconstruction
B^+		
	sig: 103,000 **bg: 1,300,000** pur: 19.6 %	**sig: 280,000** **bg: 11,000,000** pur: 8.4 %
B^0		
	sig: 95,000 **bg: 1,100,000** pur: 22.5 %	**sig: 209,000** **bg: 7,600,000** pur: 9.0 %

Adjusting cut on NeuroBayes output

	Cut-based predecessor	NeuroBayes Full Reconstruction
B^+		
	sig: 103,000 **bg: 1,300,000** pur: 19.6 %	**sig:262,000** **bg: 4,900,000** pur: 15.4 %
B^0		
	sig: 95,000 **bg: 1,100,000** pur: 22.5 %	**sig:198,000** **bg: 3,400,000** pur: 16.7 %

Adjusting cut on NeuroBayes output

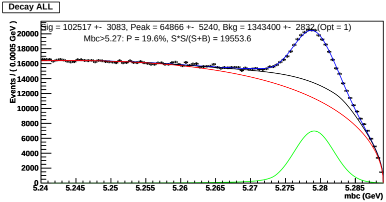
	Cut-based predecessor	NeuroBayes Full Reconstruction
B^+		
	sig: 103,000 **bg: 1,300,000** pur: 19.6 %	**sig: 250,000** **bg: 2,900,000** pur: 22.1 %
B^0		
	sig: 95,000 **bg: 1,100,000** pur: 22.5 %	**sig: 191,000** **bg: 2,000,000** pur: 24.6 %

Adjusting cut on NeuroBayes output

	Cut-based predecessor	NeuroBayes Full Reconstruction

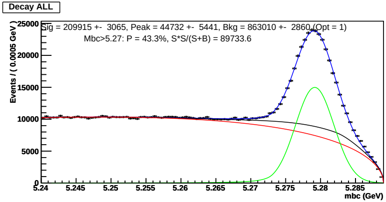
B^+

Cut-based predecessor



sig: 103,000 **bg: 1,300,000** pur: 19.6 %

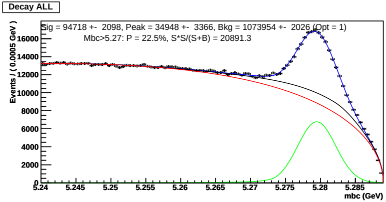
NeuroBayes Full Reconstruction



sig: 210,000 **bg: 860,000** pur: 43.3 %

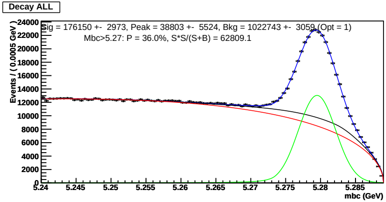
B^0

Cut-based predecessor



sig: 95,000 **bg: 1,100,000** pur: 22.5 %

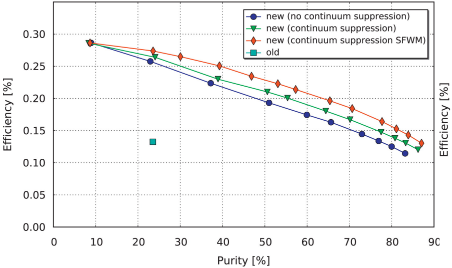
NeuroBayes Full Reconstruction



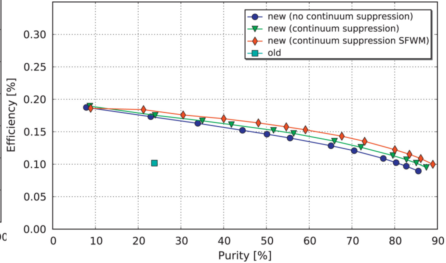
sig: 176,000 **bg: 1,000,000** pur: 36.0 %

Purity-Efficiency of B_{tag} Sample

2.1 Million B^+_{tag} mesons

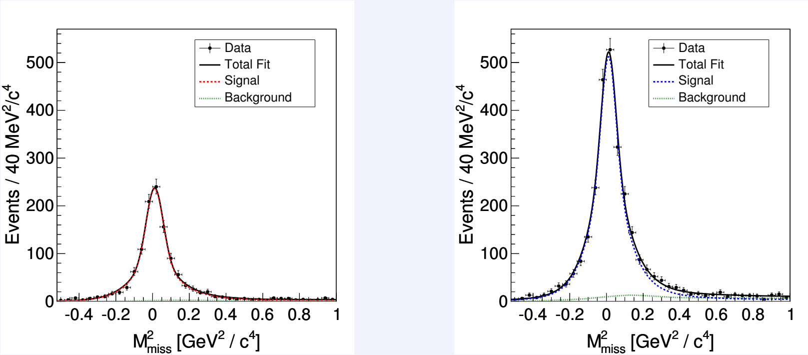


1.4 Million B^0_{tag} mesons



Reconstruct $\sim 2x$ the number of events from the *same dataset*.
Equivalent to running the Belle experiment for several additional years!

Exemplary signal side reconstruction: $B^0 \to D^{*-} l^+ \nu_l$



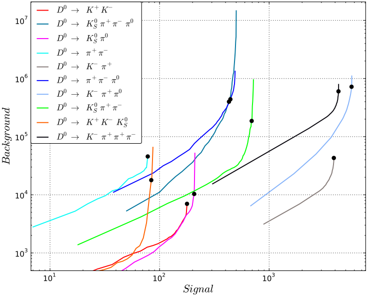
Comparison between the cut based **(left)** and the NeuroBayes **(right)** Full Reconstruction.

Reduced channels

The question has popped up:

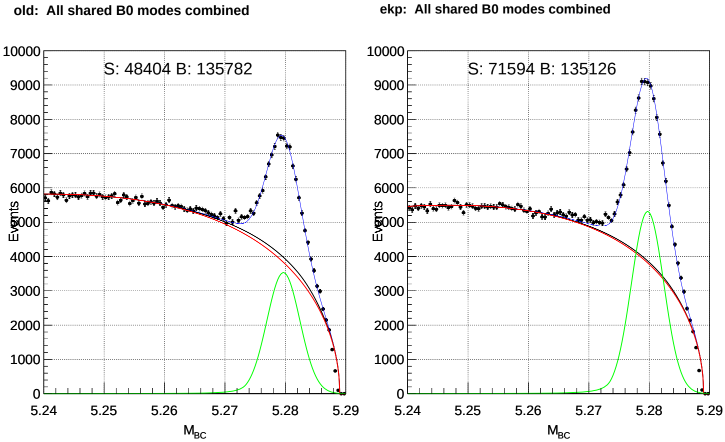
> *"How much of the improvement is due to new channels and how much due to NeuroBayes?"*

Hard to answer, as the two aspects are connected.



Approximation: Only use channels that are common to both Full Reconstructions.

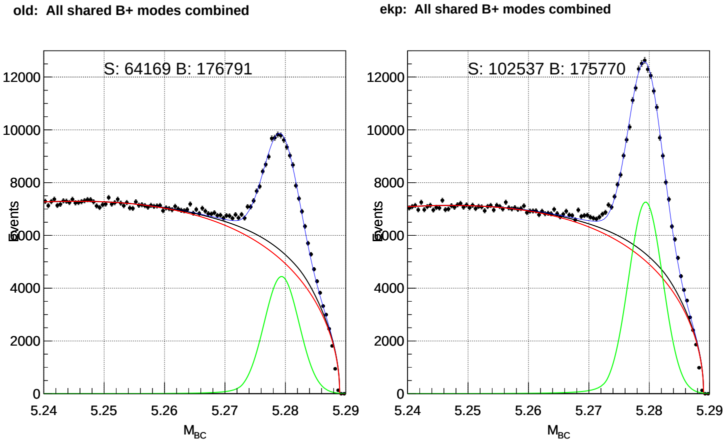
Reduced channels: B^0



Still a factor ~ 1.5 improvement

Tag side for only common channels for the cut based **(left)** and the NeuroBayes **(right)** Full Reconstruction.

Reduced channels: B^+



Still a factor ~ 1.6 improvement

Tag side for only common channels for the cut based **(left)** and the NeuroBayes **(right)** Full Reconstruction.

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A hierarchical NeuroBayes-based algorithm for full reconstruction of B mesons at B factories

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ABSTRACT

We describe a new B-meson full reconstruction algorithm designed for the Belle experiment at the B-factory KEKB, an asymmetric e^+e^- collider that collected a data sample of 771.6×10^6 $B\bar{B}$ pairs during its running time. To maximize the number of reconstructed B decay channels, it utilizes a hierarchical reconstruction procedure and probabilistic calculus instead of classical selection cuts. The multivariate analysis package NeuroBayes was used extensively to hold the balance between highest possible efficiency, robustness and acceptable consumption of CPU time.

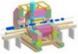
In total, 1104 exclusive decay channels were reconstructed, employing 71 neural networks

http://www.sciencedirect.com/science/article/pii/S0168900211011193

Summer 2015 results from Belle

BELLE

Belle Collaboration



Belle is an experiment at the KEK B-factory. Its goal is to study the origin of CP violation.

[一般向 (日本語)| Introduction (English)]

Belle members only

KEK [English]

KEKB

SuperKEKB

Belle II

"The Physics of B Factories" Book

jointly accomplished by Belle & BaBar !

European Physics Journal C, 74:3026 (arXiv:1406.6311)

[KEK Press Release (English , Japanese)]

Physics achievements from the Belle experiment

Prog. Theor. Exp. Phys. (PTEP) 2012, 04D001 (arXiv:1212.5342)

New Energy Scan of Exotic Resonance Channels

$h_b(mP)\ \pi^+\pi^-$ [Presented at LP2015 (Belle-CONF-1503 arXiv:1508.06562)]

$\Upsilon(nS)\ \pi^+\pi^-$ [submitted to journal (arXiv:1501.01137)]

$B \to D^{(*)}\tau\nu$ with Hadronic-tag with Full data

[To appear in Phys. Rev. D (arXiv:1507.03233),
presented at FPCP 2015 (slides)]
[Scientific American article]

First Joint Analysis of Belle and BaBar

Observation of $B^0 \to D^{(*)}{}_{CP}\ h^0$ Time-dependent CPV

[KEK Press Release (Japanese , English),
Phys. Rev. Lett. 115, 121604 (2015) (arXiv:1505.04147)]

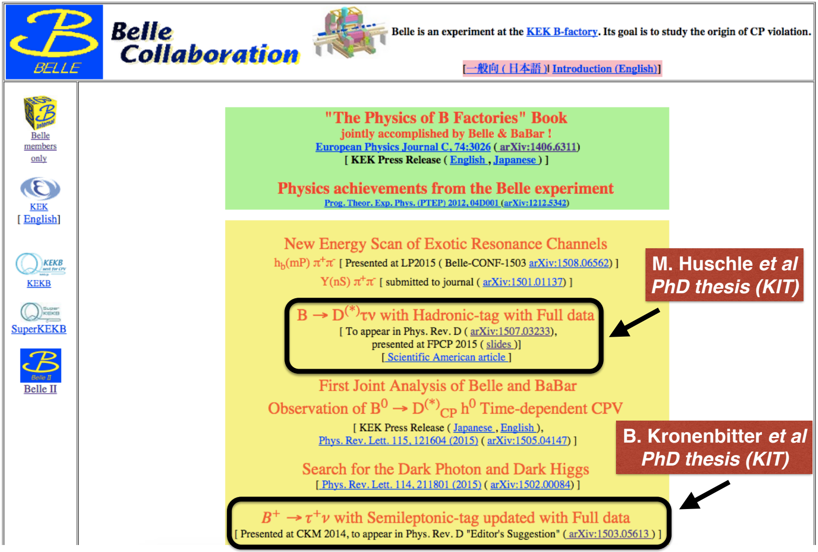
Search for the Dark Photon and Dark Higgs

[Phys. Rev. Lett. 114, 211801 (2015) (arXiv:1502.00084)]

$B^+ \to \tau^+\nu$ with Semileptonic-tag updated with Full data

[Presented at CKM 2014, to appear in Phys. Rev. D "Editor's Suggestion" (arXiv:1503.05613)]

Summer 2015 results from Belle @KIT



Belle Collaboration

Belle is an experiment at the KEK B-factory. Its goal is to study the origin of CP violation.

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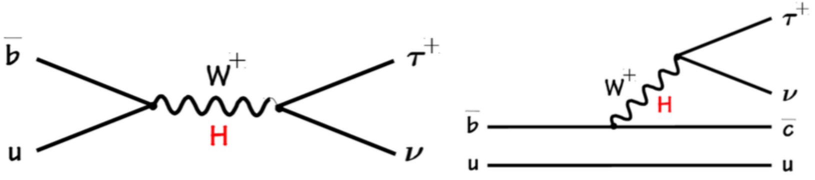
M. Huschle *et al* *PhD thesis (KIT)*

B. Kronenbitter *et al* *PhD thesis (KIT)*

(Semi)leptonic tree level decays

Why study these decays?

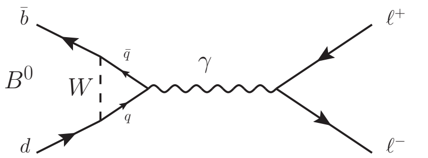
- Precision test of the quark-flavor sector of the Standard Model (SM)
  $\Rightarrow$ ***Measure elements of the CKM matrix.***
- Provide complementary information to test and validate QCD calculations.
- Indirectly probe New Physics
  $\Rightarrow$ ***Charged Higgs boson appearing in place of the W***



Complementarity with searches at the energy frontier.

Purely leptonic B decays

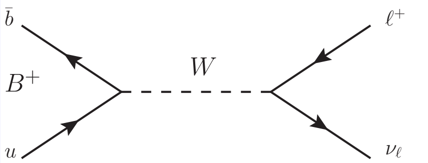
Leptonic B^0 decays



- $B^0 \to \tau^+\tau^-$ from B factories and LHCb.
- $B^0_{(s)} \to \mu^+\mu^-$ from LHC experiments
  $B^0_s \to \mu^+\mu^- = (3.1 \pm 0.7) \times 10^{-9}$.

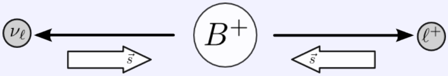
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\text{CKMfit}} = (1.1 \pm 0.1) \times 10^{-10}$$

Leptonic B^+ decays



- Only measurable at B factories.
- Measurement of $B^+ \to \tau^+\nu_\tau$ with $> 3\sigma$.
- Upper limit on $\mathcal{B}(B^+ \to \mu^+\nu_\mu)$ decays by Belle.
  New result just unblinded at KIT!

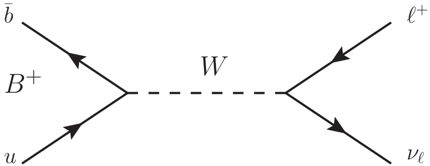
Helicity suppression



$$\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\text{CKMfit}} = \left(0.847^{+0.041}_{-0.029}\right) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \mu^+\nu_\mu)_{\text{CKMfit}} = \left(0.381^{+0.021}_{-0.013}\right) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to e^+\nu_e)_{\text{CKMfit}} = \left(0.891^{+0.049}_{-0.031}\right) \times 10^{-11}$$

- Pure $B^+ \to \ell^+\nu$ decay is helicity suppressed.
- B meson has spin 0 and decays into particle and antiparticle with opposite spin. $\Rightarrow$ *Both particles are almost exclusively right- or left-handed.*
- A heavier lepton has a lower momentum and thus a bigger coupling to the weak current.

$B \to \ell\nu$ decays



In the SM, annihilation process mediated by $W^\pm$

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell)_{\mathrm{SM}} = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$\mathcal{B}(l=\tau) > \mathcal{B}(l=\mu) > \mathcal{B}(l=e)$

$\mathcal{O}(10^{-4})$ $\mathcal{O}(10^{-6})$ $\mathcal{O}(10^{-11})$

f_B: B meson decay constant. *Can be calculated from Lattice QCD.*

V_{ub}: CKM matrix element. *Can be measured from $b \to ul\nu$ decays.*

Both can also be obtained from a CKM global fit.

In a type-II two-Higgs-doublet model

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\mathrm{SM}} \times \left|1 - \frac{\tan^2\beta}{m_{H^\pm}^2} m_B^2\right|^2$$

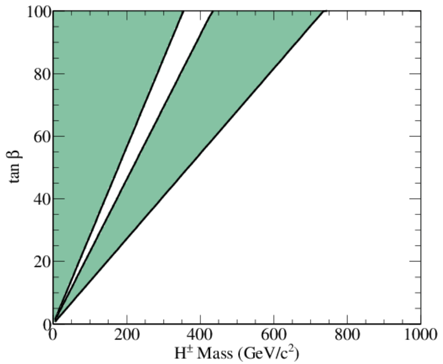
Constraint on NP from $B^+ \to \tau^+ \nu_\tau$

The result of $\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ can be used to constrain the parameter space for new physics models. If we exclude the entire space, then we can rule out the model.

For the type-II two-Higgs-doublet model:

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{\mathrm{SM}} \times \left| 1 - \frac{\tan^2 \beta}{m_{H^\pm}^2} m_B^2 \right|^2$$

Exclusion possible:



Belle 2012
95% C.L. excluded

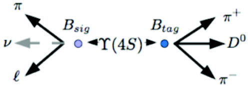
Recall the trade-off between diff. B_{tag}

Hadronic tag: $B \to D^* X$, where X some hadronic state

Cleaner sample

Knowledge of $p(B_{\text{sig}})$

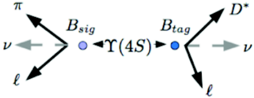
Lower tagging efficiency



Semileptonic tag: $B \to D^{(*)} \ell \nu$

Higher reconstruction efficiency

Less information about B_{tag} due to neutrino



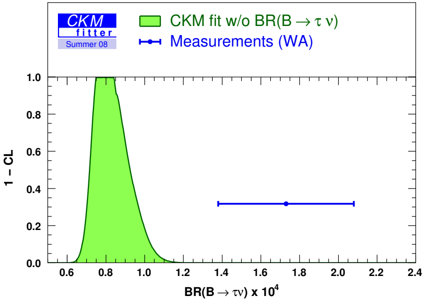
$B^+ \to \tau^+\nu_\tau$: Tension with the SM (2008)

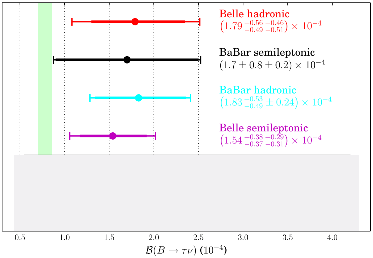
- Combining $B^+ \to \tau^+\nu_\tau$ hadronic and semileptonic measurements from Belle and BaBar, a tension emerged for V_{ub} from $B^+ \to \tau^+\nu_\tau$ vs. CKM full triangle fit.

  Discrepancy of 2.8σ with CKM fit prediction

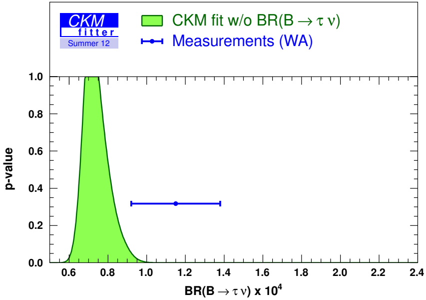
- Is $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ too high?

  Could New Physics be causing this?



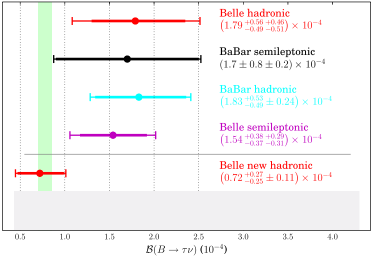


$B^+ \to \tau^+ \nu_\tau$: Tension eased (2012)



- New Belle measurement with **improved hadronic tag using NeuroBayes** and improved tracking on full dataset.
- More consistent result with CKM fit predictions.

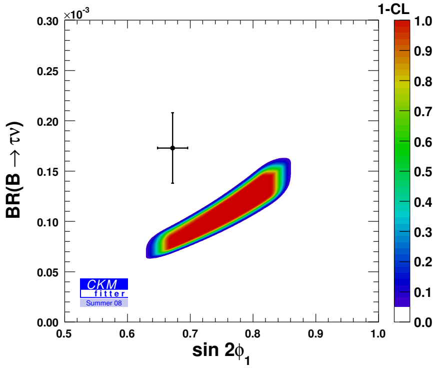
Can we do even better?



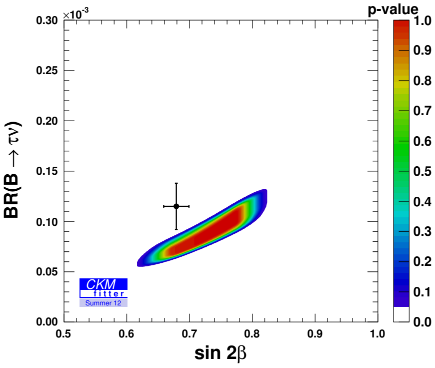
Comparison with $\sin 2\beta$

- Recall our measurement of $\sin 2\beta$ with $B \to J/\psi K_S^0$ and co.
- Here we can see how a deviation of $\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ can be compared with the average of $\sin 2\beta$ measurements, *to look for deviations from SM expectations.*

2008



2012



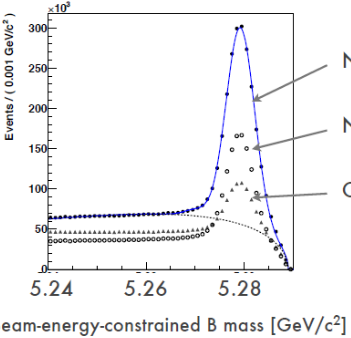
$B^+ \to \tau^+\nu_\tau$ measurement in 2012

What went into the 2012 update?

- Improved hadronic tag:

NIMA 654, 432 (2011)

  - Add decay modes (B→Dπππ, etc.) which have several final-state particles.
  - Use NeuroBayes package for a better separation with backgrounds.



New tag on full data (reprocessed)

New tag on previous data

Classical tag on previous data

× 1.8 (data increase)

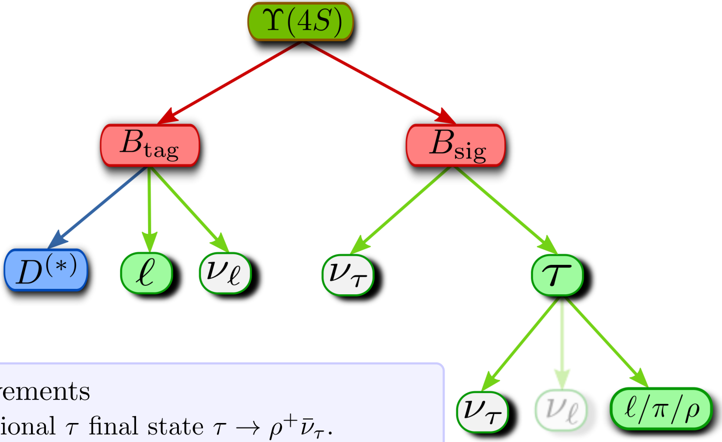
× 1.7 (tag improvement)

Purity also improved.

3.0 times larger tagged events in total

(Efficiency slightly larger if signal side is B→τν.)

New $B^+ \to \tau^+\nu_\tau$ measurement in 2015



Improvements

- Additional τ final state $\tau \to \rho^+\bar{\nu}_\tau$.
- Inclusion of 2nd variable in signal extraction:
  visible momentum of the τ candidate in the centre-of-mass frame.

Signal vs. background MC

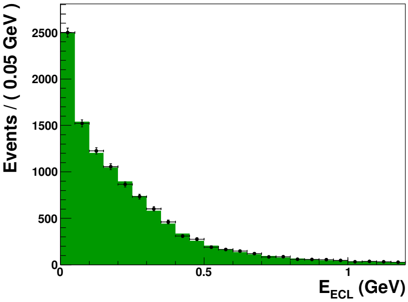
Kinematic information missing; used information for signal extraction:

$\boldsymbol{E}_{\mathbf{ECL}}$: sum of energy deposition not used in the reconstruction

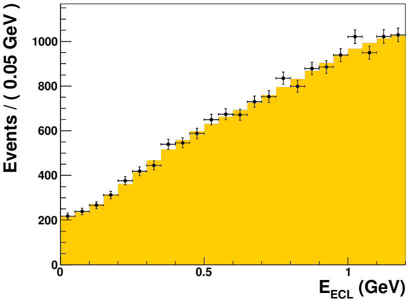
$\boldsymbol{p}^*_{\mathrm{sig}}$: momentum of signal particle

$\boldsymbol{E}_{\mathbf{ECL}}$

Signal:



$\boldsymbol{b} \rightarrow \boldsymbol{c}$ background:



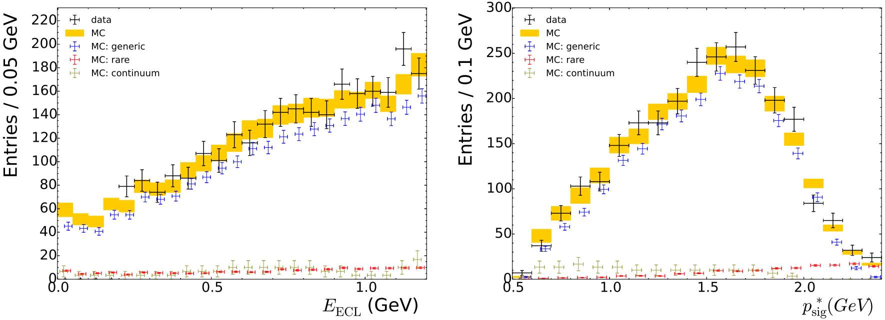
Validation before signal extraction

Before looking at the signal region, ($E_{ECL} < 0.2$ GeV), we look at a region where we expect no signal (called the "sideband" region, here $E_{ECL} > 0.2$ GeV) and compare our **MC expectation** with that of real **data**.

Recall our signal signature:

1 charged track consistent to be e or μ

No additional activity in the calorimeter



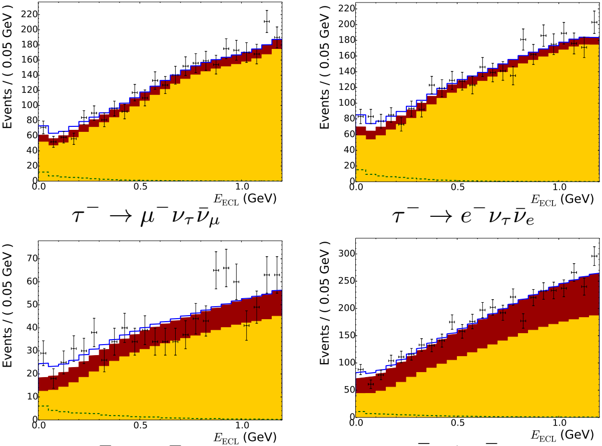
Example: E_{ECL} sideband

New measurement of $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$

$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ fitted simultaneously in all τ decay channels
Constrained by relative reconstruction efficiency

Efficiency:

	$\epsilon(10^{-3})$
$\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$	0.5
$\tau^- \to e^-\nu_\tau\bar{\nu}_e$	0.7
$\tau^- \to \pi^-\nu_\tau$	0.4
$\tau^- \to \rho^-\nu_\tau$	0.7
Total	2.3



$\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$; $\tau^- \to e^-\nu_\tau\bar{\nu}_e$; $\tau^- \to \pi^-\nu_\tau$; $\tau^- \to \rho^-\nu_\tau$

■: Signal
■: B background
■: Continuum background

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$$

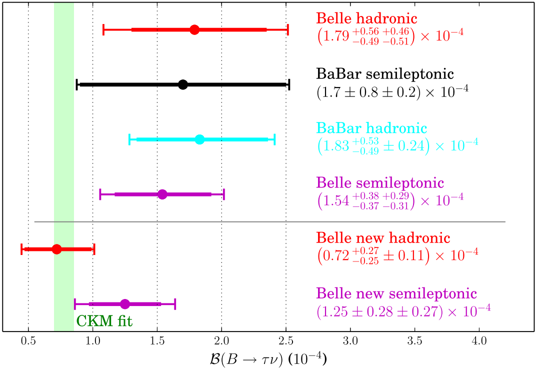
All $B^+ \to \tau^+ \nu_\tau$ measurements

Results of new semileptonic-tag measurement (3.8σ)

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$$

Combination with new hadronic-tag measurement (4.6σ)

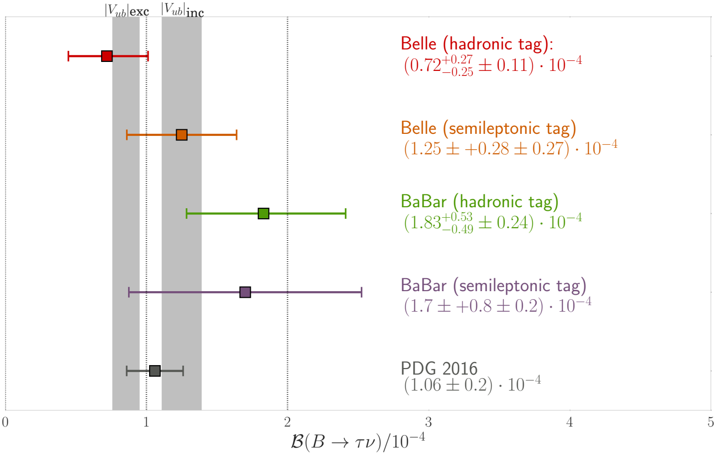
$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (0.91 \pm 0.19 \pm 0.11) \times 10^{-4}$$



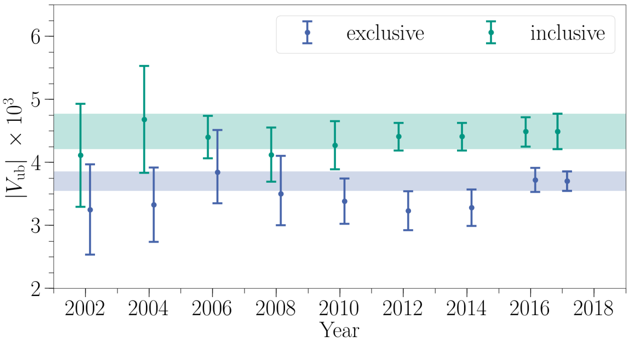
Consistent with the SM expectation based on a global fit using other inputs

$|V_{ub}|_{\text{Exc}}$ vs. $|V_{ub}|_{\text{Inc}}$, and $B^+ \to \tau^+\nu_\tau$

Only including new Belle hadronic and semileptonic $B^+ \to \tau^+\nu_\tau$ results:

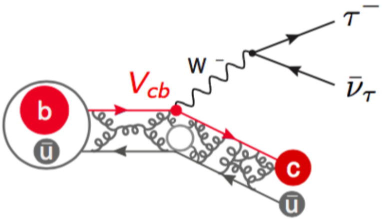


Other Avenues to Measure $|V_{ub}|$

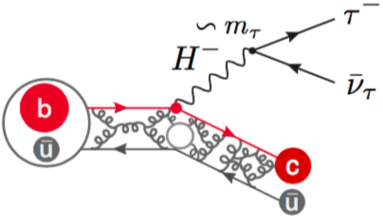


- Full or partial decay width of the inclusive $B \to X_u l\nu$ decay:
  - Full: High $\mathcal{B}$ and $< 5\%$ theo. uncertainty, *but large contamination from CKM-favored $B \to X_c l\nu$.*
  - Partial: Easier to measure by demanding a high p_l, *but theoretical calculation more challenging.*
- Exclusive measurement of the $B \to \pi l\nu$ decay:
  - Experimentaly clean, *but lower $\mathcal{B}$ and requires theo. input for form factors.*

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



Decay in the Standard Model

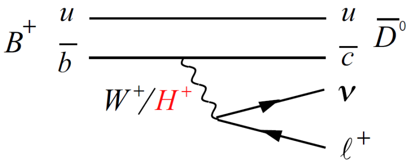


Decay with New Physics
e.g. with charged Higgs boson

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)}$$

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

- Process with 3rd generation quarks and leptons.
- New Physics could change $\boldsymbol{\mathcal{B}}$ and $\boldsymbol{\tau}$ polarization.
- Effect could be different for D and D^*.



Large mass of τ adds sensitivity to additional helicity amplitude.

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cb}|^2|p|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_{t0}|^2\right]$$

A charged Higgs (2HDM type II) of spin 0 couples to the τ and will only affect H_{t0}:

$$H_{t0}^{\mathrm{2HDM}} = H_{t0}^{\mathrm{SM}} \times \left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2}\frac{q^2}{1 \mp m_c^2/m_b^2}\right)$$

This could enhance or decrease the ratios $R(D^*)$ depending on $\frac{\tan^2\beta}{m_{H^\pm}^2}$

3.4σ deviation from SM observed by BaBar, 2HDM type II excluded

No 2HDM type II? (says BaBar data)

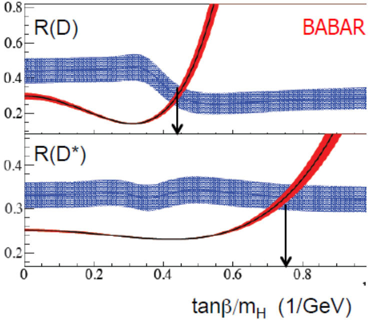
- A charged Higgs (2HDM type II) of spin 0 couples to the τ and will only affect H_t

$$H_t^{2HDM} = H_t^{SM} \times \left(1 - \frac{\tan^2\beta}{m_{H\pm}^2} \frac{q^2}{1 \mp m_c/m_b}\right)$$

- for $D\tau\nu$
+ for $D^*\tau\nu$

This could enhance or decrease the ratios R(D*) depending on $\tan\beta/m_H$

- We estimate the effect of 2DHM, accounting for difference in efficiency, and its uncertainty
- The data match 2DHM Type II at
  - $\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)
  - $\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)
- However, the combination of R(D) and R(D*) excludes the Type II 2HDM in the full $\tan\beta$-m_H parameter space with a probability of >99.8%, provided M_H>10GeV !



Principle of the measurement

Measure the ratios ($\ell = e$ or μ):

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

and check for deviations from SM prediction:

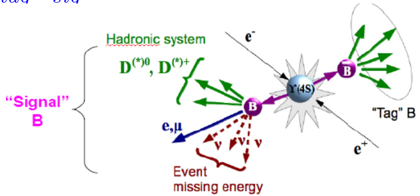
$$R(D)|_{\rm SM} = 0.293 \pm 0.017, \quad R(D^*)|_{\rm SM} = 0.252 \pm 0.003.$$

τ reconstructed only using leptonic decays, $\tau \to \ell\nu_\tau\nu_\ell$:

- so that $\overline{B} \to D^{(*)}\tau\nu$ (signal) and $\overline{B} \to D^{(*)}\ell\nu$ (normalization) are identified by the same particles in the final state.
- leads to cancellation of dependence on FF and CKM matrix element, and on various sources of uncertainty in the ratios $R(D^{(*)})$.

Full reconstruction of $e^+e^- \to \Upsilon(4S) \to B_{tag}B_{sig}$ events:

- Improved hadronic B_{tag} reconstruction using NeuroBayes.
- Constrain charge, flavour as well as (E,p) of B_{sig}.



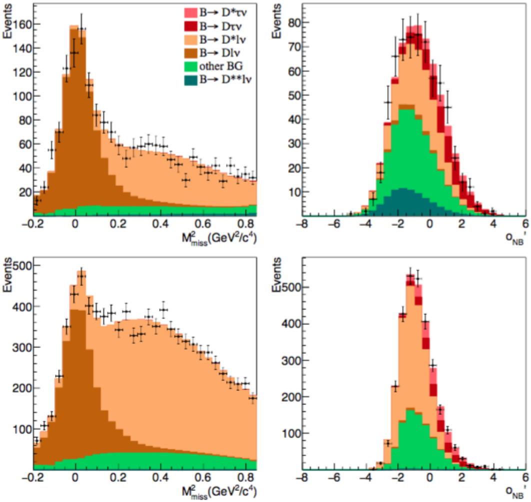
2015 Belle hadronic tag result

Fit Strategy

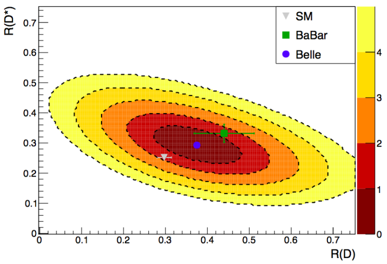
$\mathbf{M^2_{miss} < 0.85}$ (left)
$B \to D^{(*)} l \nu$ $(l = e, \mu)$ dominated
$\Rightarrow$ *fit* M^2_{miss} *for bkgd normalization*

$\mathbf{M^2_{miss} > 0.85}$ (right)
$B \to D^{(*)} \tau \nu$ enhanced
$\Rightarrow$ *fit fit neural-net variable* o'_{NB}

$D^+ l^-$ (top)
$D^0 l^-$ (bottom)

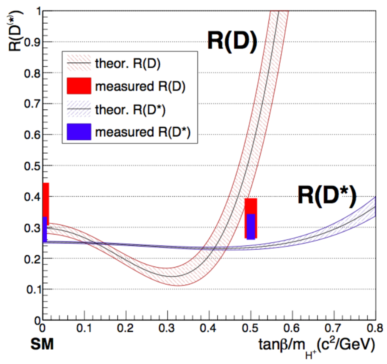


$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$



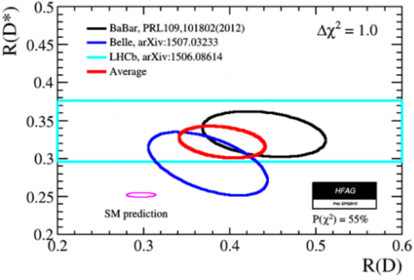
Result lies between the SM prediction and BaBar result

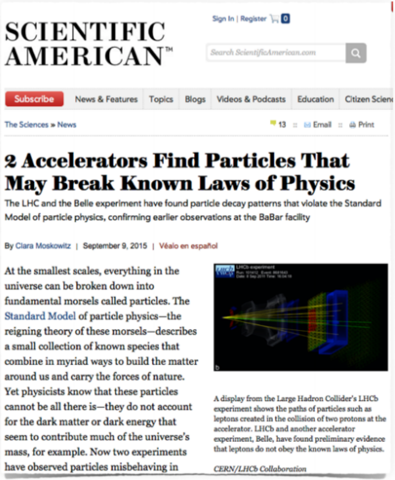
Fit is repeated with PDF generated for type II 2HDM with $\tan\beta/m_H = 0.5$ GeV^{-1}



Compatible with type II 2HDM around $\tan\beta/m_H = 0.5$ GeV^{-1}

Including 1st LHCb result in 2015





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2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español

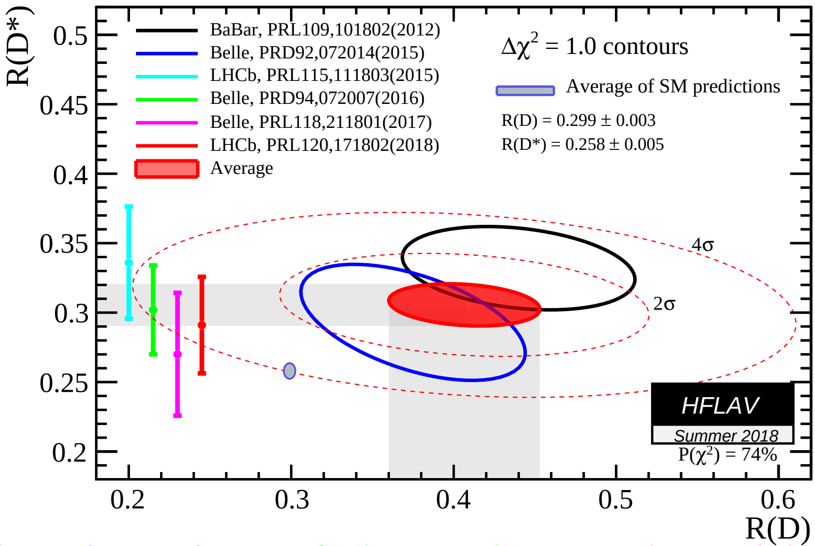
At the smallest scales, everything in the universe can be broken down into fundamental morsels called particles. The Standard Model of particle physics—the reigning theory of these morsels—describes a small collection of known species that combine in myriad ways to build the matter around us and carry the forces of nature. Yet physicists know that these particles cannot be all there is—they do not account for the dark matter or dark energy that seem to contribute much of the universe's mass, for example. Now two experiments have observed particles misbehaving in

A display from the Large Hadron Collider's LHCb experiment shows the paths of particles such as leptons created in the collision of two protons at the accelerator. LHCb and another accelerator experiment, Belle, have found preliminary evidence that leptons do not obey the known laws of physics.

CERN/LHCb Collaboration

3.9σ deviation from the SM

Summer 2018 status

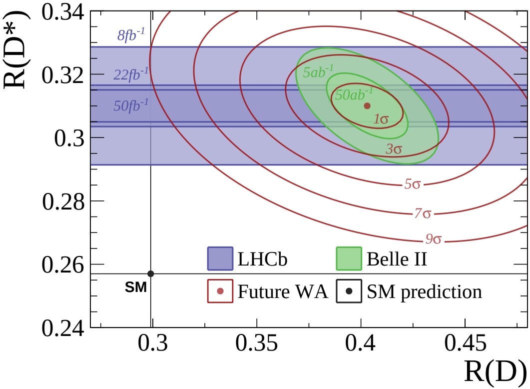


Belle: Hadronic tag, leptonic τ Semileptonic tag, leptonic τ Hadronic tag, hadronic τ

BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

$\overline{B} \to D^{(*)}\tau\overline{\nu}$ with Belle II & LHCb arXiv:1709.10308

Measurement	SM prediction	Current World Average	Current Uncertainty	Projected Uncertainty[1]				
				Belle II		LHCb		
				$5ab^{-1}$	$50ab^{-1}$	$8fb^{-1}$	$22fb^{-1}$	$50fb^{-1}$
				2020	2024	2019	2024	2030
$R(D)$	(0.299 ± 0.003)	$(0.403 \pm 0.040 \pm 0.024)$	11.6%	5.6%	3.2%	-	-	-
$R(D^*)$	(0.257 ± 0.003)	$(0.310 \pm 0.015 \pm 0.008)$	5.5%	3.2%	2.2%	3.6%	2.1%	1.6%



Currently re-analyzing the KIT Belle measurement *with the Belle 2 Full Event Interpretation (improved tag-side recombination algorithm).*

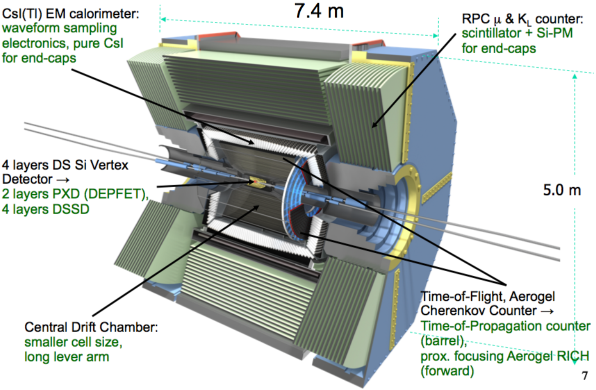
[1] *Projected uncertainties not including improvements in detectors and algorithms.*

Belle II detector

Upgrade for SuperKEKB and Belle II to achieve 40x peak $\mathcal{L}$ under 20x BG.
Accumulate 50 ab^{-1} of data in 10 years of running

Targeted improvements:

- *Increase hermiticity.*
- *Increase K_S^0 efficiency.*
- *Improve IP and secondary vertex resolution.*
- *Improve K/π separation.*
- *Improve π^0 efficiency.*
- *Add PID in endcaps.*
- *Add μ ID in endcaps.*

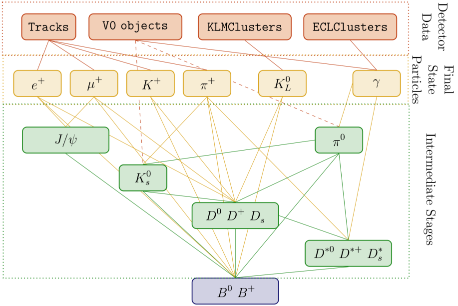


To be reviewed in detail in future lectures

Tag-side reconstruction at Belle II

New Full Event Interpretation (FEI) algorithm for tag-side reconstruction

- $\mathcal{O}(10000)$ decay chains.
- 2 modes of operation:
  - Generic tag-side training;
  - *Signal-specific* training.
- Made possible due to speed-optimized training algorithms, full automation, and use of parellelization on all levels.
- Fully applicable in Belle and Belle II analyses in the Belle II software framework.
- Use of DNNs are a possible avenue for improvement.



Maximum tag-side ε on MC

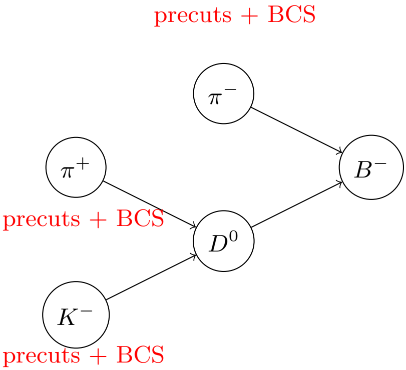
Tag	FR[1]	FEI Belle	FEI Belle II
Hadronic B^+	0.28%	0.76%	0.66%
Hadronic B^0	0.18%	0.46%	0.38%
SL B^+	0.67%	1.80%	1.45%
SL B^0	0.63%	2.04%	1.94%

[1] Belle Full Reconstruction algorithm.

arXiv:1807.08680

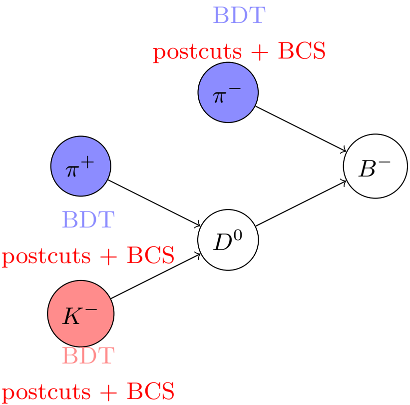
The Algorithm

– Particle candidates assigned from tracks and clusters after precuts + Best Candidate Selection (BCS).



The Algorithm

- Particle candidates assigned from tracks and clusters after precuts + Best Candidate Selection (BCS).
- For each particle, a BDT is trained/applied and post cuts + BCS are made.



The Algorithm

- Particle candidates assigned from tracks and clusters after precuts + Best Candidate Selection (BCS).
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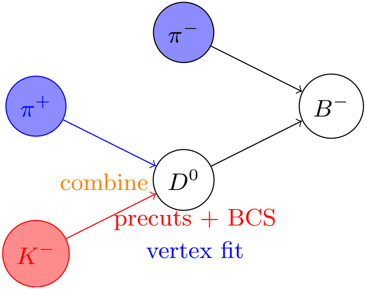
- Stable particles are combined to reconstruct decays of intermediate particles. After precuts + BCS a vertex fit is performed.



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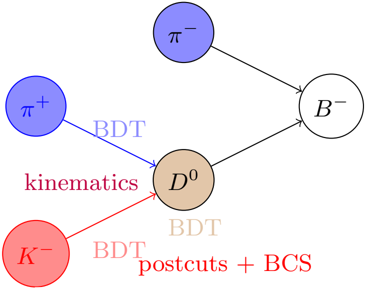

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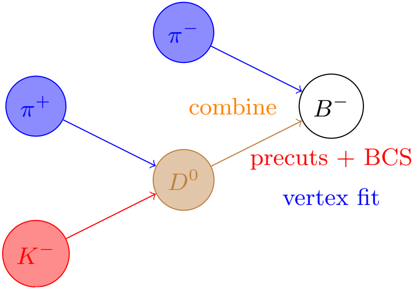

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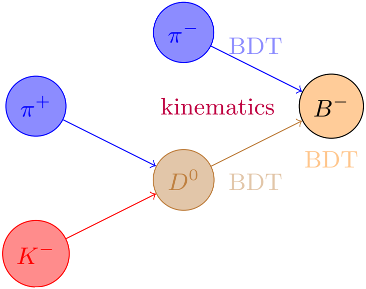
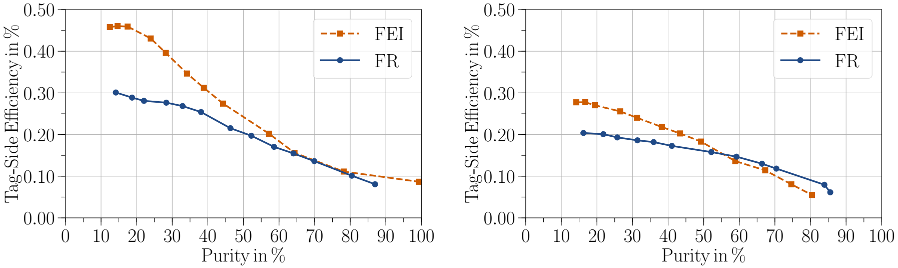
- B classifier takes daughter classifiers and kinematics as inputs.



FEI on Belle data

ROC of charged (left) and neutral (right) B_{tag} mesons extracted from a fit of m_{bc} on Belle data in the Belle II software framework.



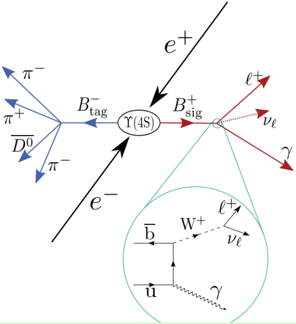
Sizeable increase in reconstruction efficiency.

Can now perform analyses with converted Belle data in the Belle II software framework with a larger dataset, thanks to more B mesons recombined with the FEI.

First B2BII FEI Analysis: $B^+ \to \ell^+ \nu \gamma$

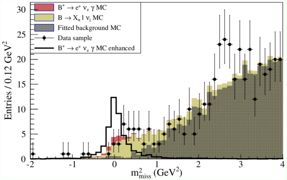
- Photon lifts helicity suppression, thus enhancing the weak decay amplitude.
- Photon emission needs an approximation from heavy quark theory where $E_\gamma > 1$ GeV is required.
- Branching fraction depends on the first inverse moment λ_B^{-1} of the B meson LCDA Φ_B in the high-energy limit:
  - Theoretical calculation challenging: $\frac{1}{\lambda_B} = \int_0^\infty d\omega \frac{\Phi_B(\omega)}{\omega}$.
  - Important parameter for several non-leptonic B meson decays, Nucl. Phys. B591 (2000) 313-418

    including $K\pi$ decays and the $K\pi$ CP-Puzzle. The Belle 2 Physics Book
  - QCD factorization expectation for value of $\lambda_B = 200$ MeV. EPJ C (2011) 71:1818



- Worlds best limits set by Belle (90% CL): $\lambda_B > 238$MeV

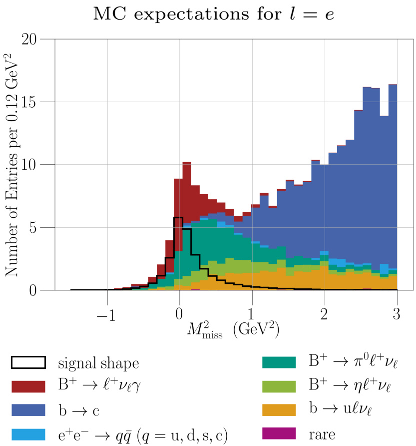
  $\mathcal{B}\left(B^+ \to e^+(\mu^+)\nu\gamma\right) < 6.1(3.4) \times 10^{-6}$



A. Heller, PG, M. Heck, T. Kuhr *et al.* (Belle), PRD **91** 112009 (2015)

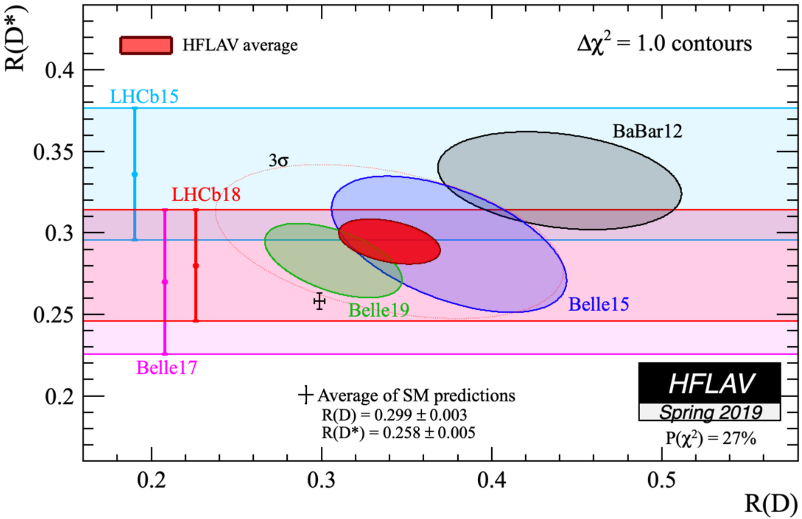
First results presented at CKM18 in Sept.

- Significant improvement in tag-side recombination efficiency with the FEI.
- Signal-specific FEI calibration performed for the first time.
- Both MC studies assume a partial branching fraction of $\Delta\mathcal{B}\left(B^+ \to \ell^+\nu_\ell\gamma\right) = 5 \cdot 10^{-6}$, to enable a comparison of the expected yields with the different analysis frameworks.



	$B^+ \to e^+\nu_e\gamma$	$B^+ \to \mu^+\nu_\mu\gamma$	Combined
$N_{\rm New}$	24.8	25.7	50.5
$N_{\rm Published}$	8.0	8.7	16.5

Second Belle FEI analysis: Belle19



Belle: Hadronic tag, leptonic τ Semileptonic tag, leptonic τ Hadronic tag, hadronic τ

BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

Extra reading

A hierarchical NeuroBayes-based algorithm for full reconstruction of B mesons at B factories, Nucl. Instrum. Meth. A654: 432 (2011)

The Full Event Interpretation – An exclusive tagging algorithm for the Belle II experiment.

Measurement of the branching fraction of $B^+ \to \tau^+ \nu_\tau$ decays with the semileptonic tagging method

Scientific American article (Slide 59).