Radiative decays from LHCb to Belle II

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Outline

1. Framework: Radiative b-decays
2. Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb
3. TDCPV analysis of $B^0 \to K_s\pi^+\pi^-\gamma$ at Belle
4. Conclusions

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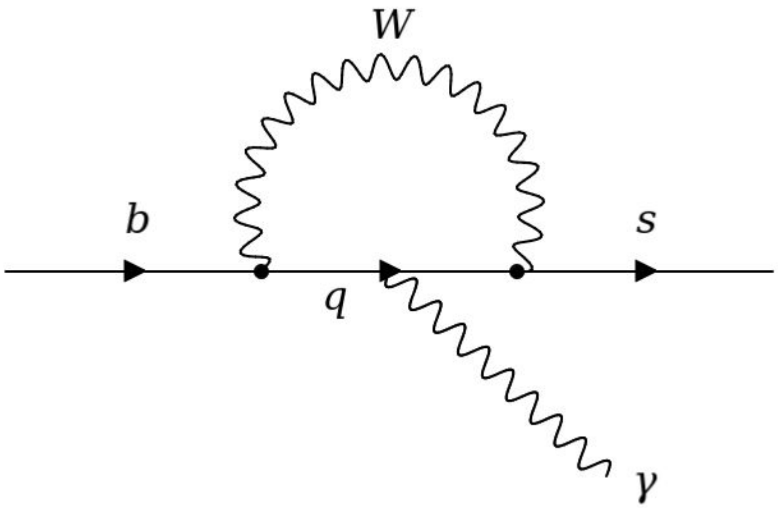
But, why are they interesting?



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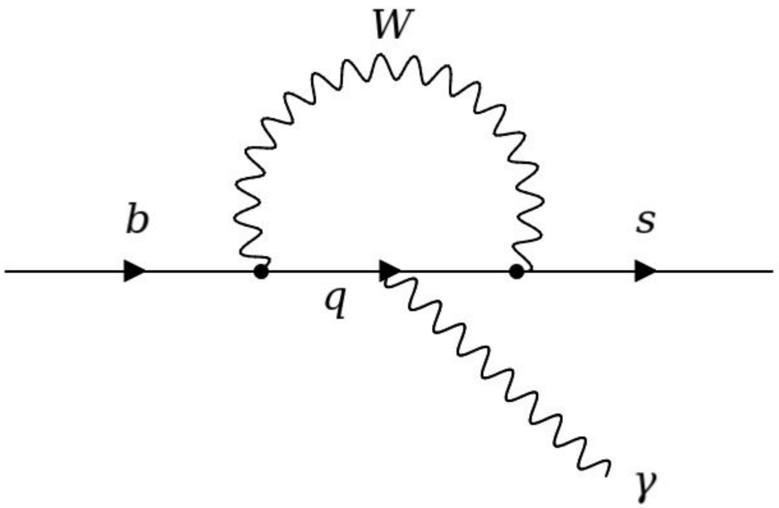

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- Transitions highly suppressed by the SM.
  - GIM mechanism
  - CKM Hierarchy

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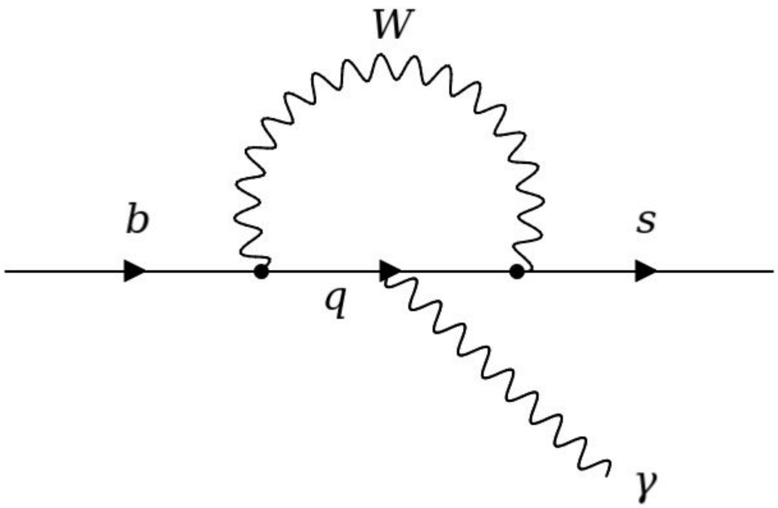

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- Transitions highly suppressed by the SM.
- Observables very sensitive to beyond SM physics.
  - Branching ratios
  - **CP asymmetries**
  - **Photon polarization**

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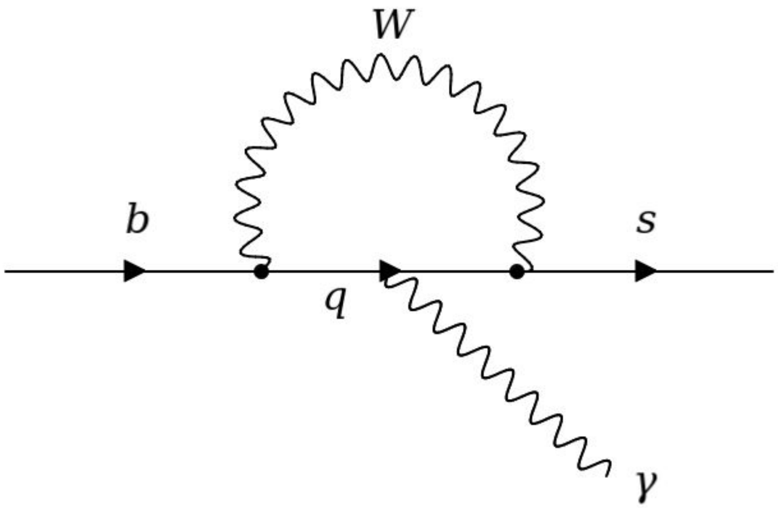

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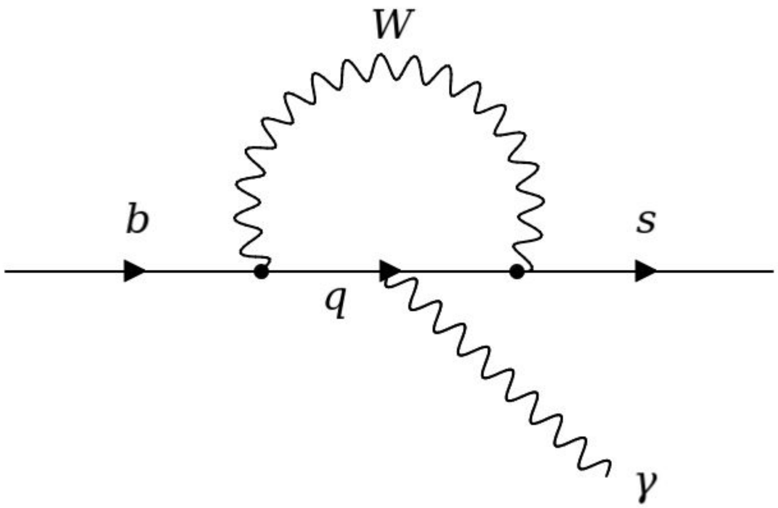

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- Probe NP at higher energy scales.

Test the SM through precision measurements.

Theoretical framework

These transitions can be described by effective field theory using the operation product expansion.

$$\mathcal{H}_{eff} \sim V_{CKM} \sum_i \mathcal{C}_i \mathcal{O}_i$$

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At leading order:

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \left(\mathcal{C}_7 \mathcal{O}_7 + \mathcal{C}_7' \mathcal{O}_7' \right)$$

Electromagnetic operators: $\mathcal{O}_7, \mathcal{O}_7'$ (long-distance)

Wilson coefficients: $\mathcal{C}_7, \mathcal{C}_7'$ (short-distance)

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In the SM the electroweak interaction only couples to left-handed quarks.

New Physics models can enhance right-handed currents, making these transitions very sensitive.

Photon polarization

The SM has a clean prediction of the photon polarization:

$$\alpha_\gamma = \frac{N(\gamma_L) - N(\gamma_R)}{N(\gamma_L) + N(\gamma_R)} = \frac{1 - |r|^2}{1 + |r|^2} \approx 1 \qquad |r| = \frac{\mathcal{C}_7'}{\mathcal{C}_7} \sim 0$$

How to measure it?

- CP asymmetries
- Angular distribution:
  - Hard in b-meson decays.
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Measurement of the photon polarization in $\Lambda_b \to \Lambda\gamma$ (LHCb)

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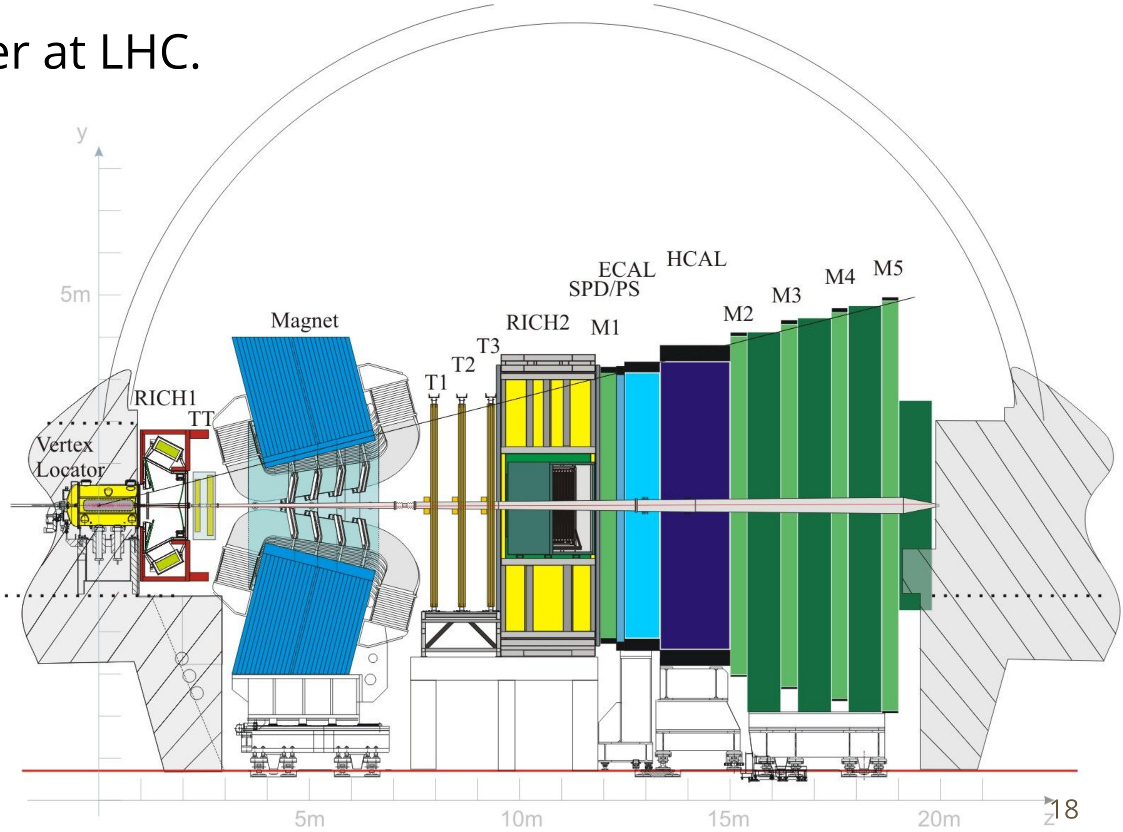
The LHCb experiment

Single-arm forward spectrometer at LHC.

- bb cross-section: ~10^5 nb
- Small efficiencies (acc., reco.)
- All kind of b-hadrons

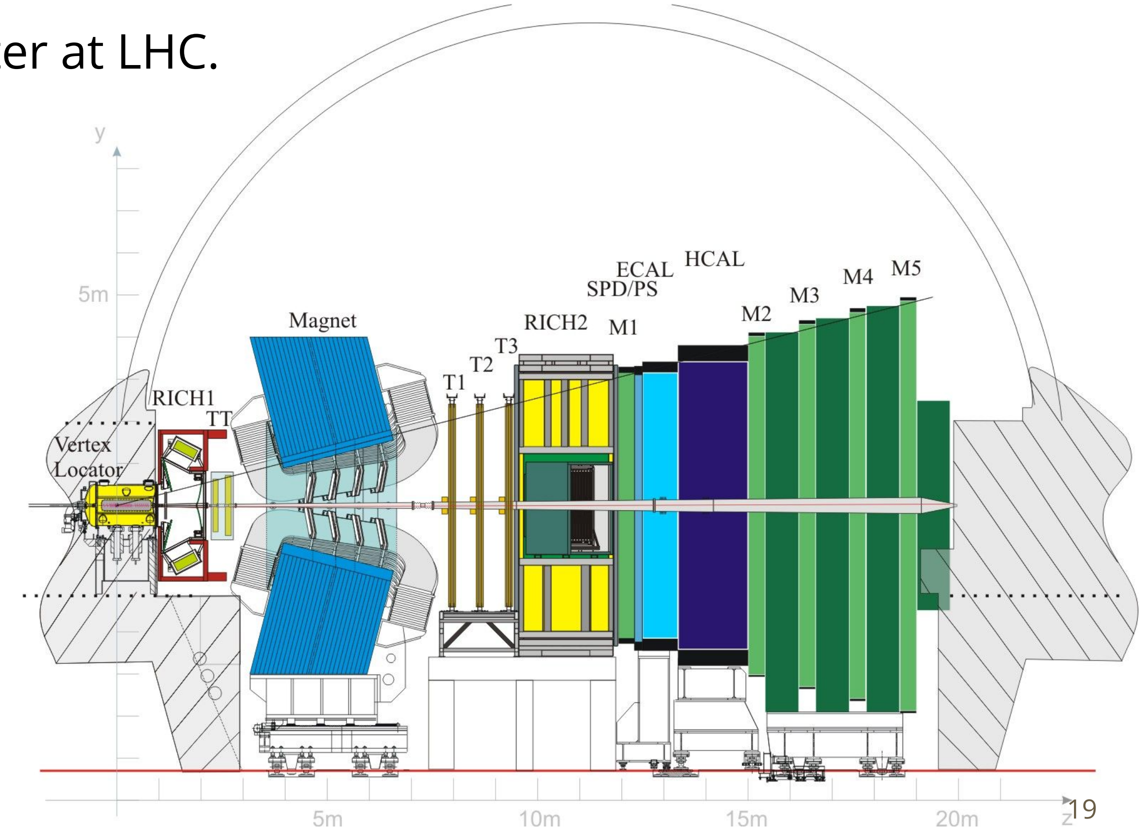
  $B^0,\ B_s,\ \Lambda_b,\ \Xi_b$
- B-hadrons boosted



The LHCb experiment

Single-arm forward spectrometer at LHC.

- Momentum resolution
  - 0.4 - 0.6% at 5-100 GeV.
- Kaon ID eff: 95%
  - 5% $\pi \to$ K miss-ID.
- E resolution for photons:
  - 1% + 10%/√E(GeV)



The $\Lambda_b \to \Lambda\gamma$ decay

Cannot be measured in B-factories (BaBar/Belle).

Currently only LHC has access to this kind of decays.

Observation by the LHCb experiment using 2016 data. [Phys. Rev. Lett. 123, 031801]

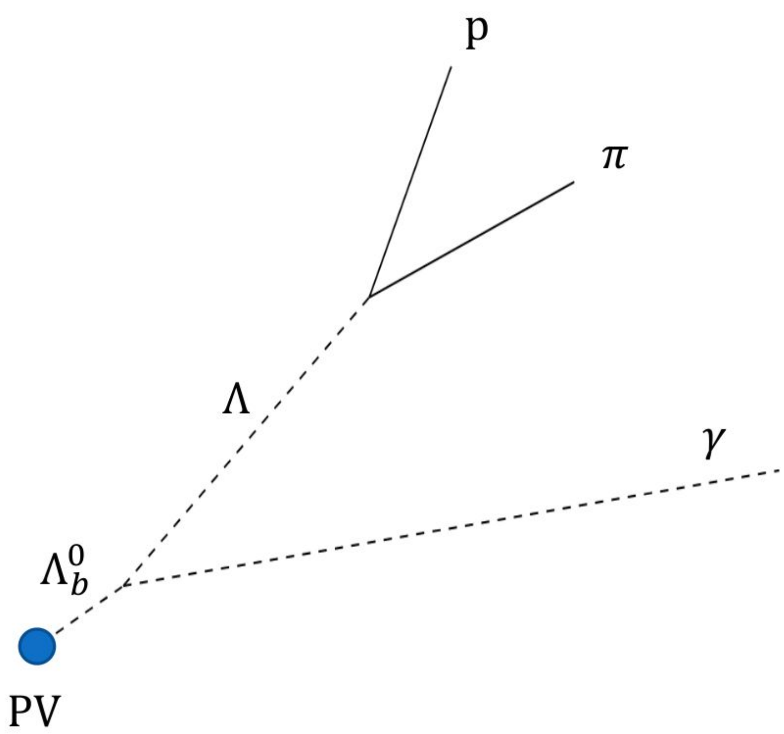
$$\mathcal{B}(\Lambda_b \to \Lambda\gamma) = (7.1 \pm 1.7) \times 10^{-6}$$

Exploits the weak decay of the Λ.

$$\Lambda_b \to \Lambda\gamma$$
$$\Lambda \to p\pi$$

The $\Lambda_b \rightarrow \Lambda\gamma$ decay

Very challenging to measure:



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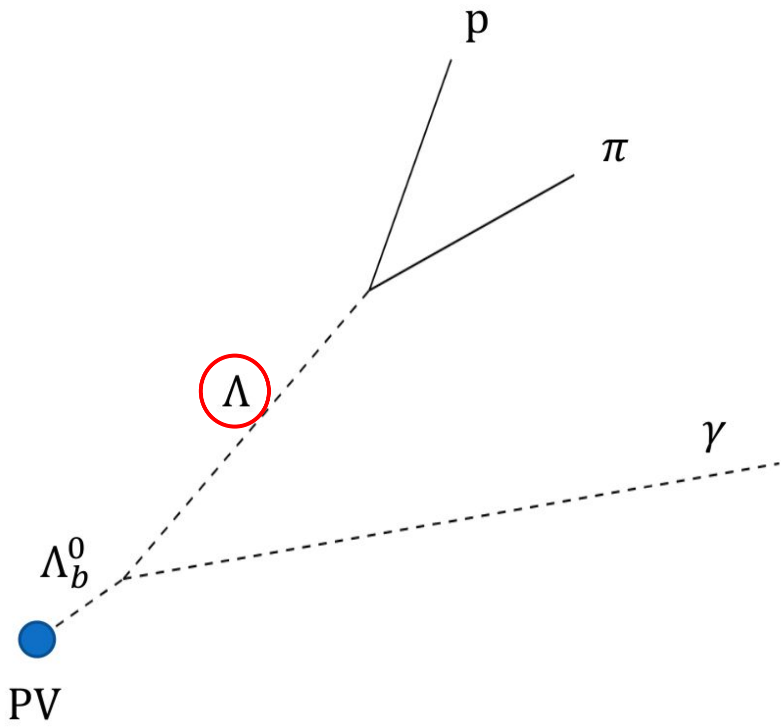

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Very challenging to measure:

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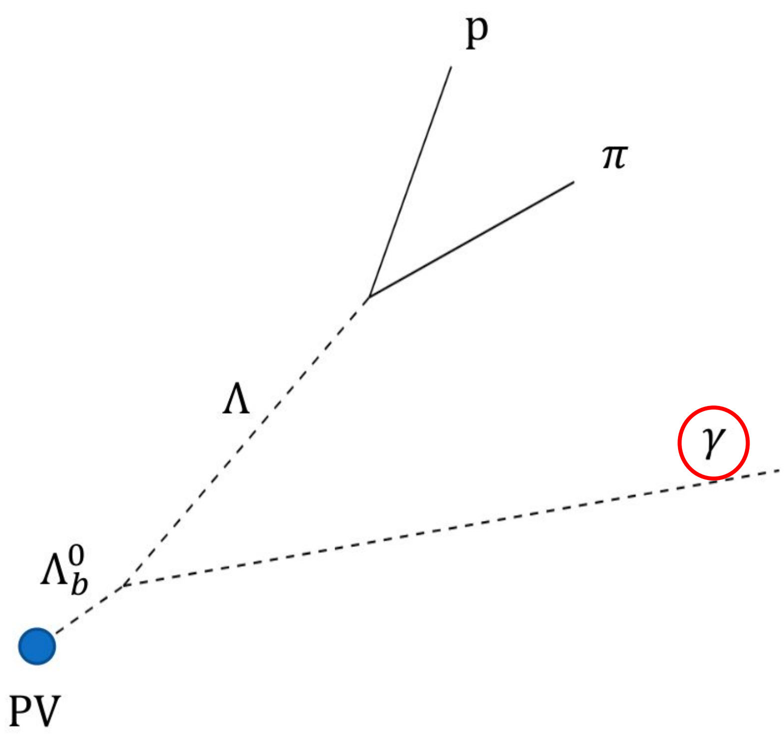
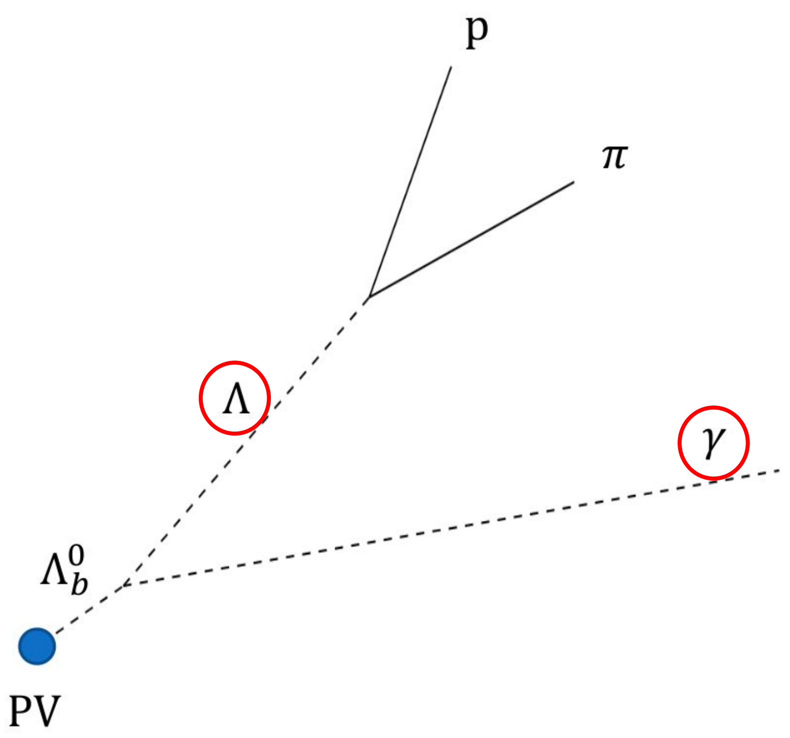


The $\Lambda_b \to \Lambda\gamma$ decay

Very challenging to measure:

- Λ is long lived.
- No photon direction in LHCb.
- No Λ_b vertex (SV).

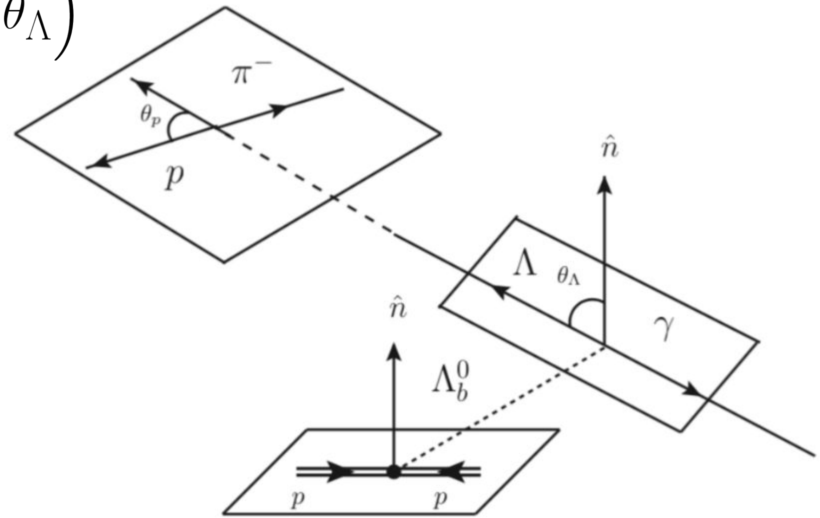
  Both Λ, γ leave no hits in tracking detectors.



The $\Lambda_b \to \Lambda\gamma$ decay

But, has direct access to α_γ via angular distribution

$$\frac{d\Gamma}{d(\cos\theta_p, \cos\theta_\Lambda)} \propto 1 - \alpha_\Lambda P_{\Lambda_b} \cos\theta_p \cos\theta_\Lambda \\ -\alpha_\gamma \left(\alpha_\Lambda \cos\theta_p - P_{\Lambda_b} \cos\theta_\Lambda \right)$$



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Integrating over the angles:

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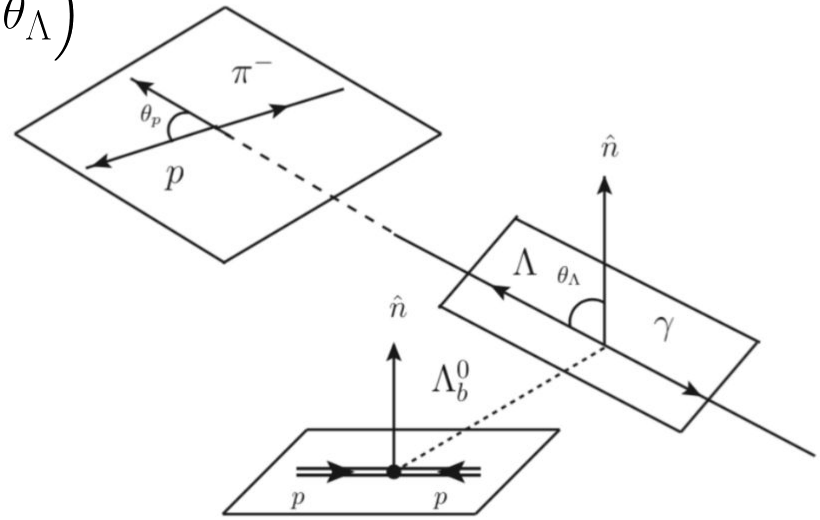

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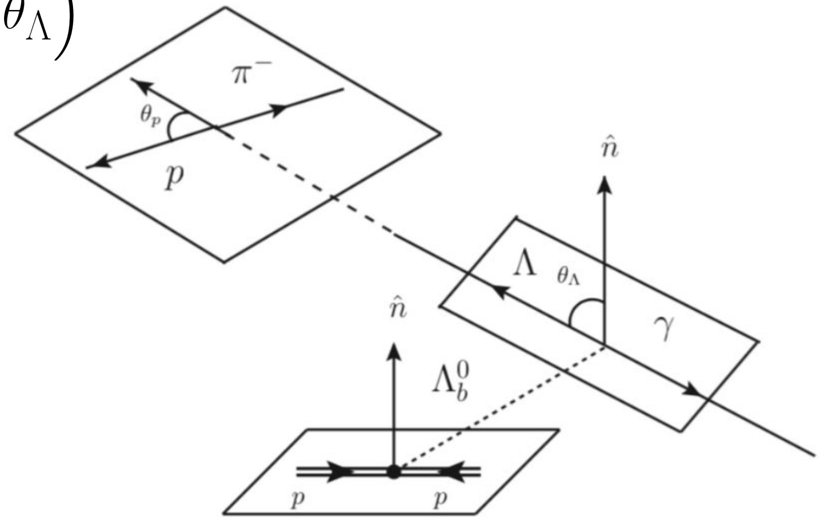

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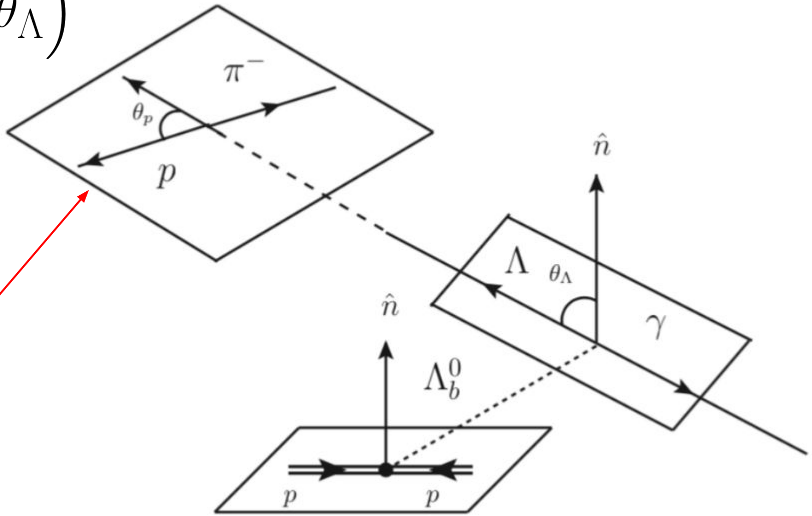

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Reconstruction and online selection

Run 2 data

2016, 2017, 2018

How do we reconstruct such a tricky decay?

a) Λ is long lived.

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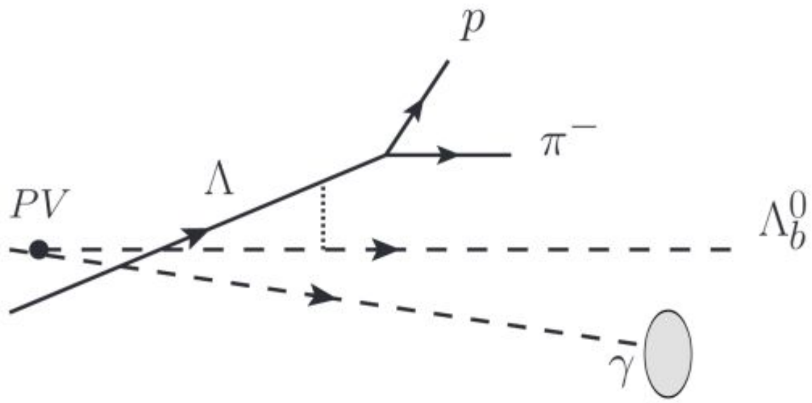
c) No Λ, γ tracks



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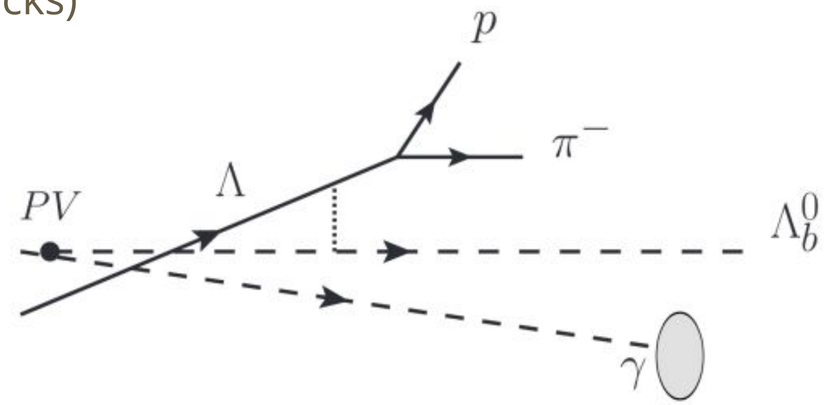

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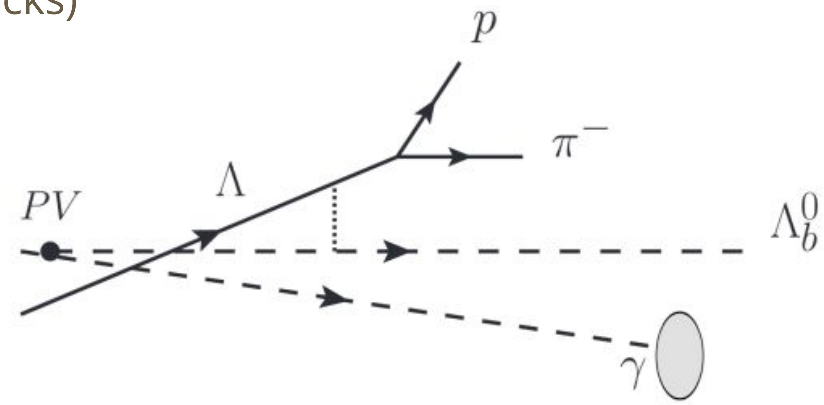

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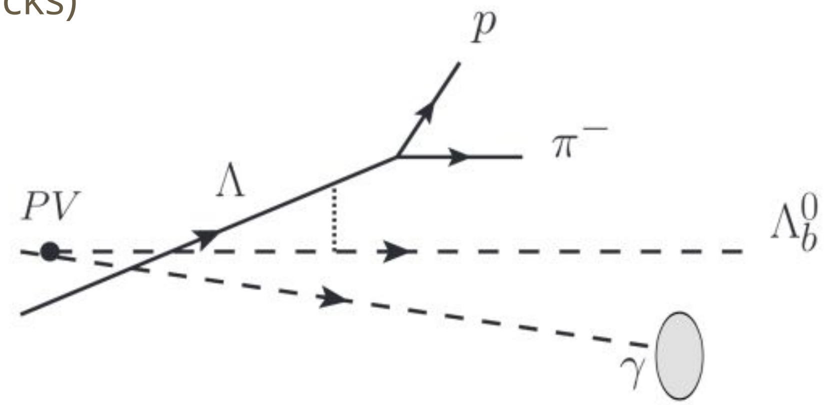
   Do not reconstruct SV, direct sum of Λ and γ momentum



Online selection

Run 2 data

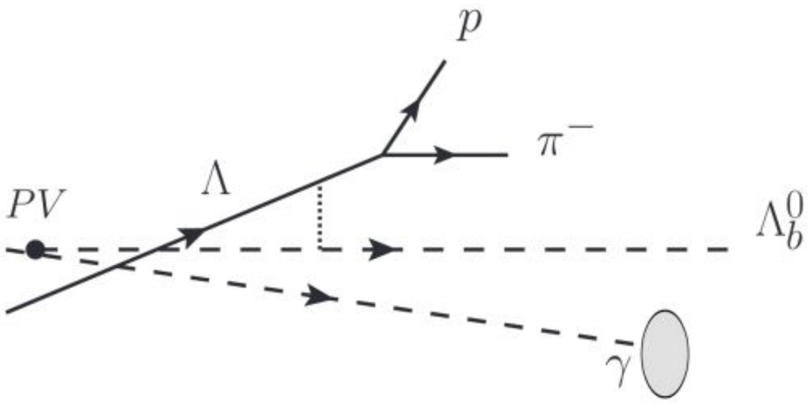
2016, 2017, 2018

Online selection:

1) Large transverse energy photon

2) A charged track with high transverse momenta and large impact parameter

3) Specific selection



Offline selection

Goal: Further separate signal from background candidates.

Based on simulated signal events.

- Loose selection.
- Multivariate Analysis: Boosted Decision Tree (BDT).

But, need to make sure **simulation** and **data** are in **agreement**.

- Kinematics of mother particles are usually mismodeled (Λ_b)

  Correct for these discrepancies using control channels ($\Lambda_b \to pK\, J/\psi$)

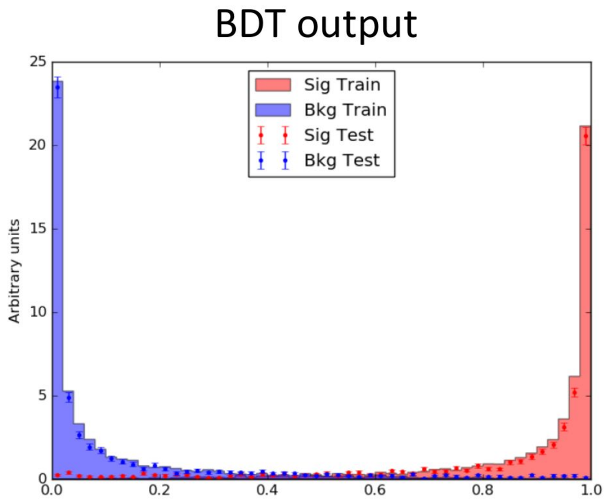
Multivariate classifier: BDT

Disentangle signal from combinatorial background.

- Simulation as signal.
- Data sidebands as background.
- Use kinematic and geometric variables
- 2-fold technique and tests for biases

How do we define a the best output?

F.o.M based on pseudo-experiments maximizing the sensitivity to the photon polarization (α_γ)



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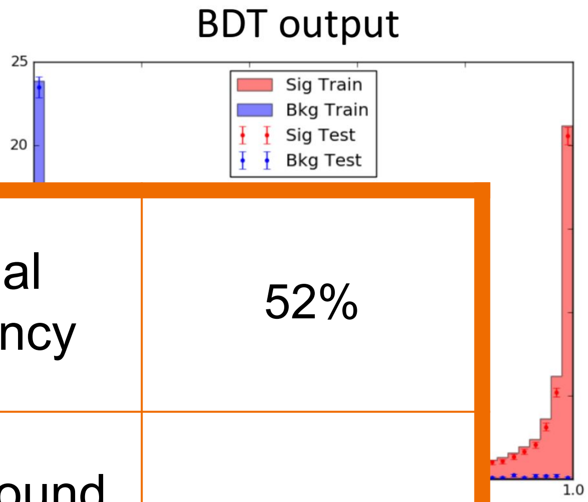

Signal efficiency	52%
Background rejection	99.2%

Strategy

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- Effects on θ_p: acceptance and resolution.
- Extract α_γ: fit $\cos\theta_p$.
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Yield extraction: Modeling

Extract yields using an invariant mass fit to Λ_b in data.

Three components:

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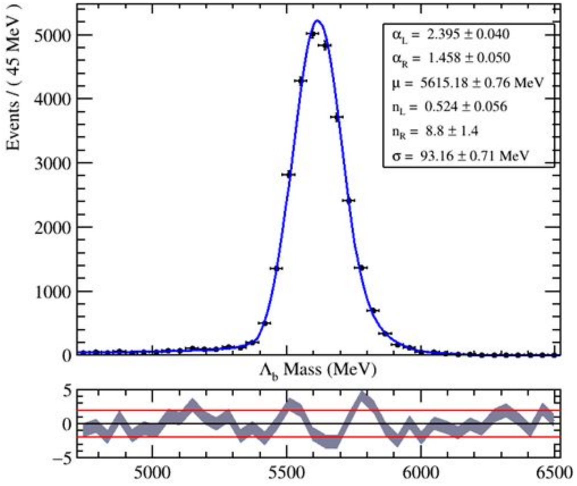
Three components:

- Signal
  - ➔ Simulated events.
  - ➔ Double sided Crystal Ball



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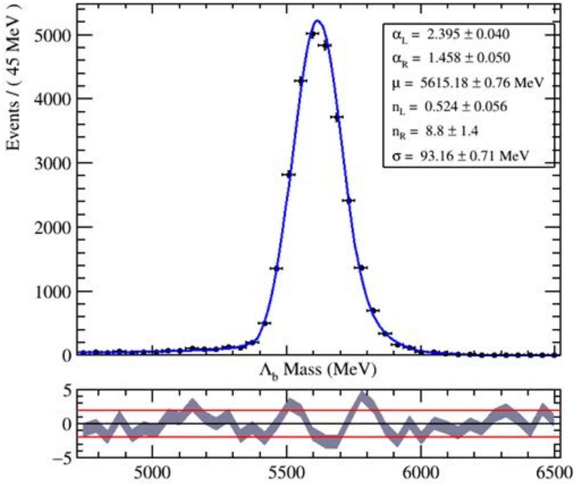
  - ➔ Simulated events.
  - ➔ Double sided Crystal Ball
- Combinatorial
  - ➔ Data from side bands.
  - ➔ Exponential



Yield extraction: Modeling

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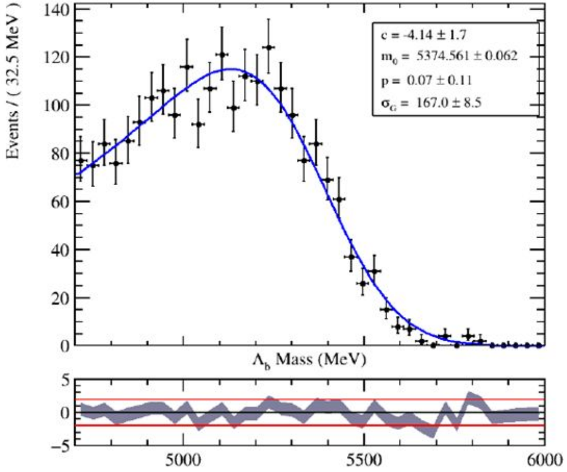
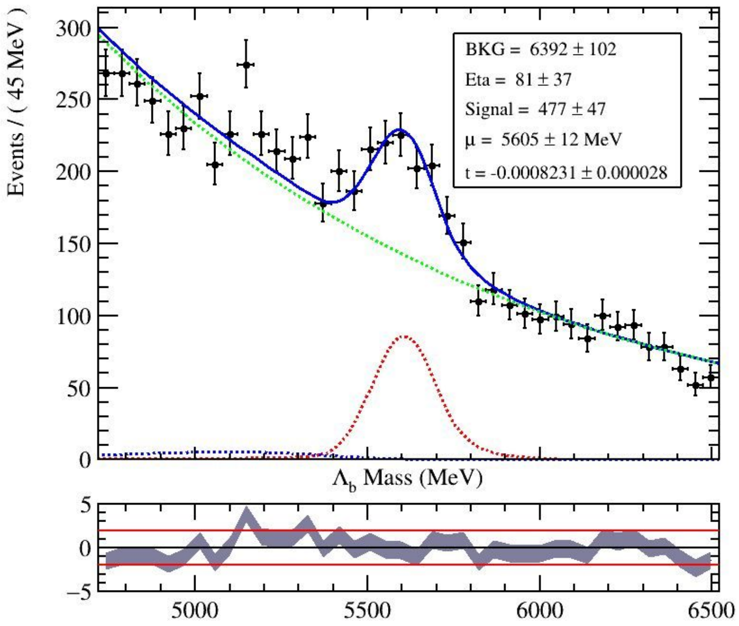
Three components:

- Partially reconstructed background
    - ➔ $\Lambda_b \rightarrow \Lambda\,\eta$ ($\eta \rightarrow \gamma\gamma$)
    - ➔ Simulated events
    - ➔ Convolution: Argus x Gaussian



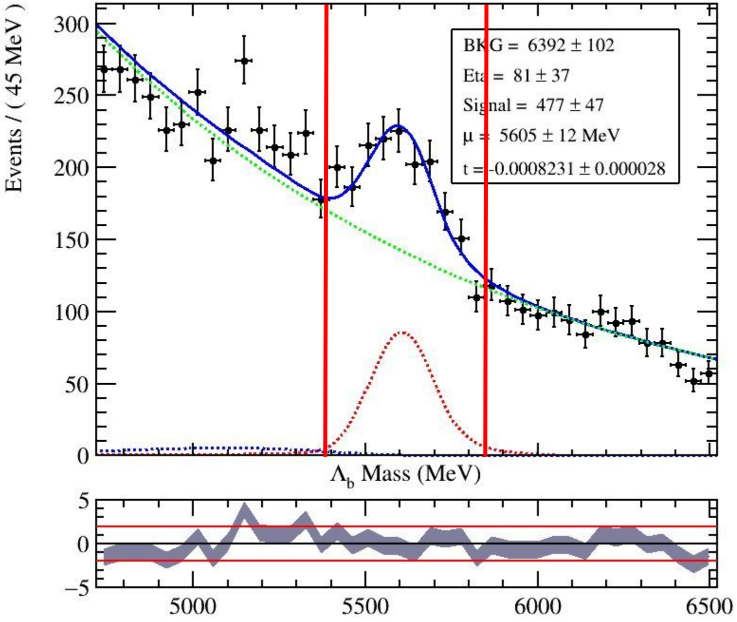
Invariant mass fit



Invariant mass fit

Mass window centered around Λ_b mass

$N^{2.5\sigma}_{sig}$	444 ± 44
$N^{2.5\sigma}_{comb}$	1460 ± 23
$N^{2.5\sigma}_{\Lambda_b^0 \to \Lambda\eta}$	10 ± 4



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Angle θ_p effects: Resolution

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Simulation samples also reproduce detector response:

$$\text{Resolution} = \theta_p^{measured} - \theta_p^{gen}$$

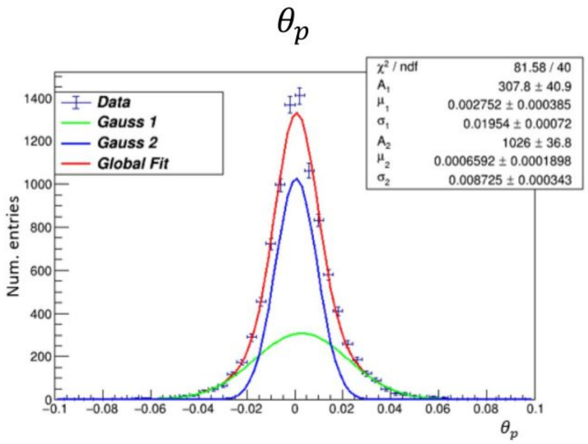
Computed in four bins of $\cos\theta_p$.

Model: double-Gaussian.

Parameters:

$$\mu_1, \mu_2 \sim 0$$
$$\sigma_1, \sigma_2 \sim O(1\%)$$

Angular pseudo-experiments:
Resolution not relevant



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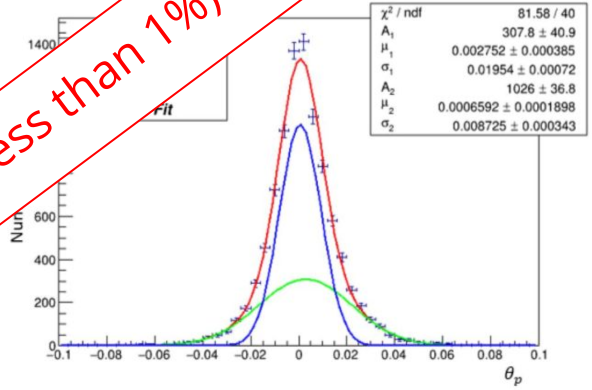
Angular pseud… :

Resolution not r…

Negligible (less than 1%)



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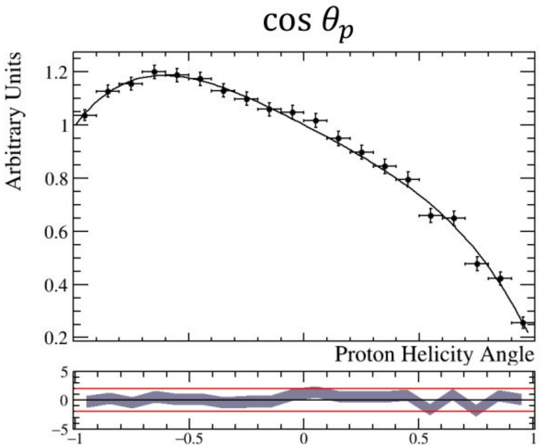
Measured θ_p distribution after selection divided by theoretical θ_p distribution.

Extracted from simulation samples.

Model: 4th order polynomial

Angular pseudo-experiments:
Important effect

Agreement between simulation and data cross-checked using $\Lambda_b^0 \to \Lambda\, J/\psi$



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Non-negligible

➔ Need modeling

➔ Need control channel

Angular pseud

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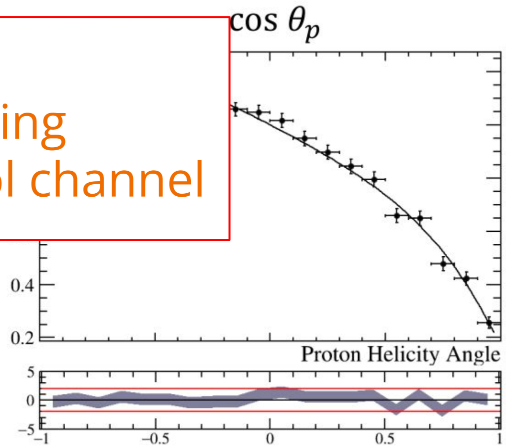

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Angular fit

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Yields: S, B

Angular fit

$$\Gamma(\alpha_\gamma;\theta_p) = \frac{S}{S+B}\left[\boxed{\Gamma_{\mathrm{sig}}(\alpha_\gamma;\theta_p)}\cdot A(\theta_p)\right] + \frac{B}{S+B}\left[\Gamma_{\mathrm{bkg}}(\theta_p)\right]$$

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Signal shape:

$$\frac{d\Gamma}{d(\cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$

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Yields: S, B

Acceptance: A(θ_p)

Signal shape:

$$\frac{d\Gamma}{d(\cos\theta_p)} \propto 1 - \alpha_\gamma\alpha_\Lambda \cos\theta_p$$

Background shape

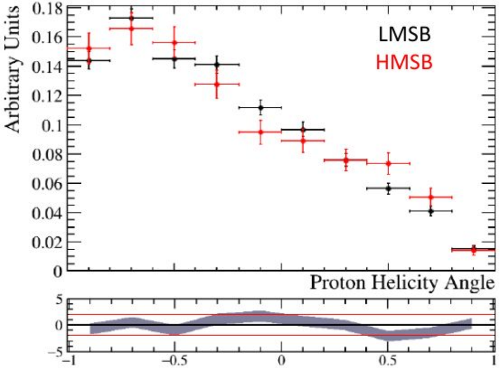
Missing

Angular fit: Background

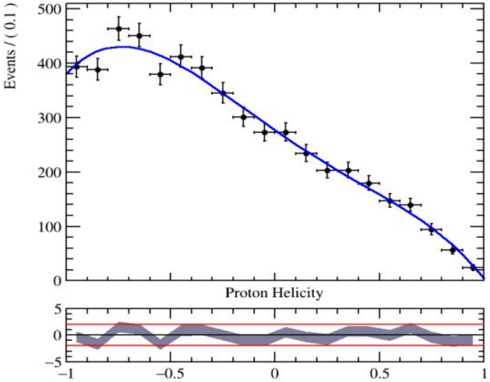
Background shape from data:
- Low mass side band (LMSB)
- High mass side band (HMSB)

Model: 4^{th} order polynomial.

$\cos\theta_p$



$\cos\theta_p$



$\Lambda_b^0 \to \Lambda\eta$ **background** candidates:

- No theory prediction.
- Very small contribution.
- Compatibility between HMSB and LMSB.

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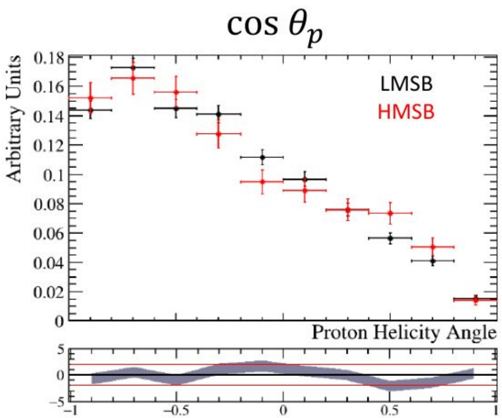
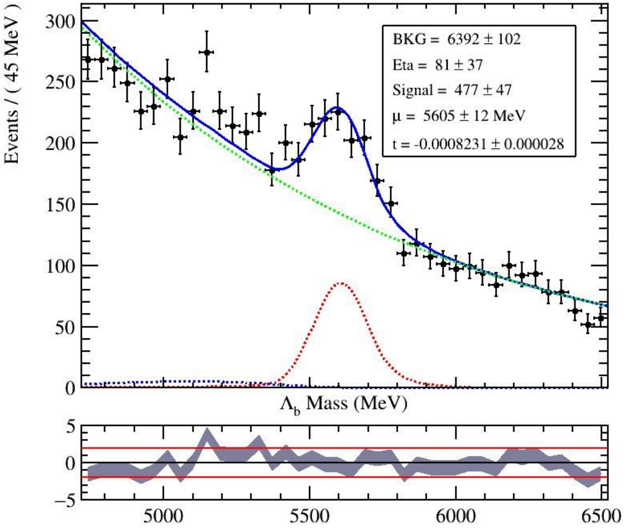




$\Lambda_b^0 \rightarrow \Lambda\eta$ **background** candidates:

- No theory prediction.
- Very small contribution.
- Compatibility between HMSB and LMSB.

Angular fit: Validation

Validate: Pseudo-experiments (20000)

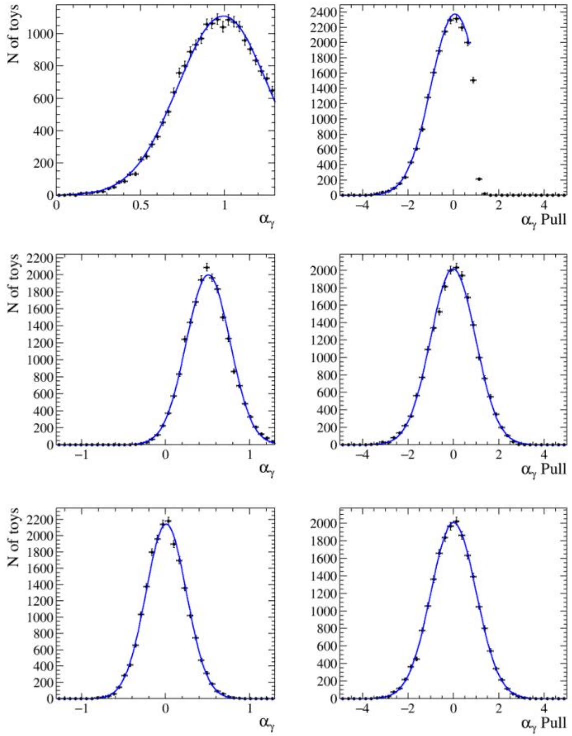
Generate $\alpha_\gamma = 0, 0.5,\ 1$

Pull asymmetric behavior when $\alpha_\gamma \to 1$.

$$\frac{d\Gamma}{d(\cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$

Negative p.d.f at $\boldsymbol{\alpha_\gamma > \left|\frac{1}{\alpha_\Lambda}\right| \sim 1.326}$

Validation with a cut-off.

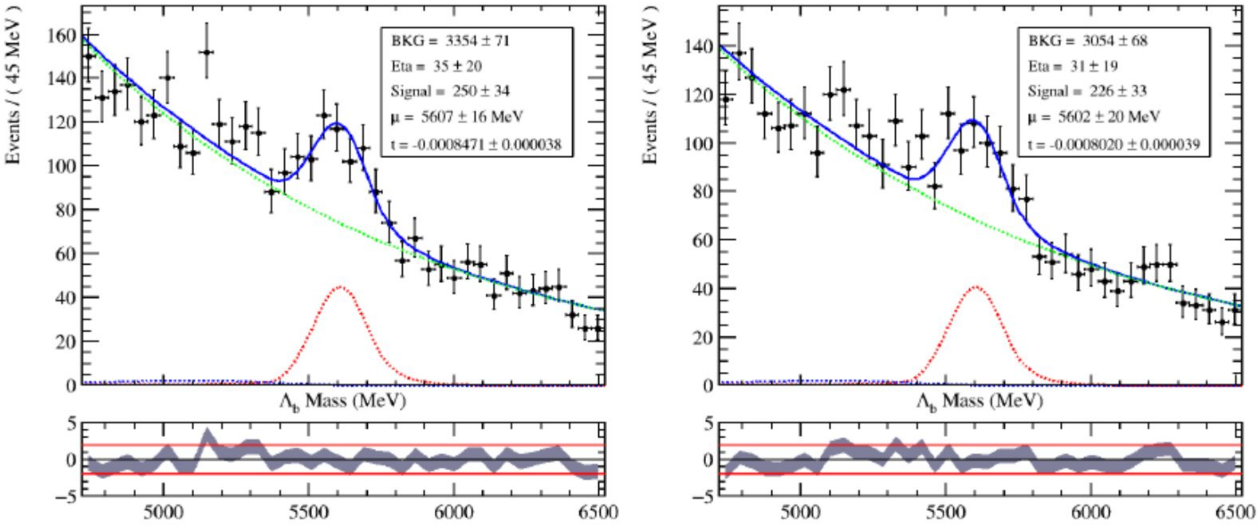


Tagged measurement

Same price, a tagged measurement:

The charge of the proton tag the decay

$\Lambda_b^0 \to \Lambda\gamma$ $\overline{\Lambda}_b^0 \to \overline{\Lambda}\gamma$



Systematic uncertainties

Systematics are computed using pseudo-experiments.

Main sources:

- Acceptance and background shape
- Yield extraction
- α_Λ uncertainty

Systematics

Acceptance	MC limited size	0.040
	Model	0.005
	Kin. weights	0.037
Background	Data limited size	0.114
	Model	0.014
Yields		0.035
α_Λ		0.023
Total		0.134

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Systematic uncertainties: Tagged

Systematics are computed using pseudo-experiments.

Main sources:

- Acceptance and background shape
- Yield extraction
- α_Λ uncertainty

Main systematic from background size.

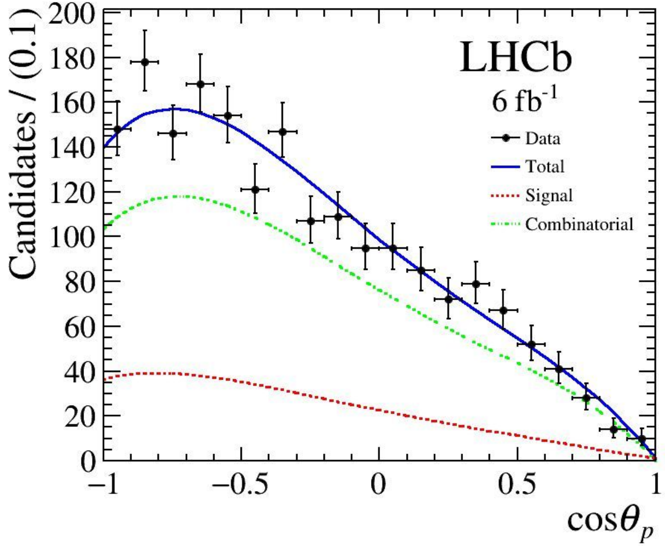
Dominated by the statistical uncertainty.

Tagged sample, more of the same

Systematic source		α_γ^- (part)	α_γ^+ (anti)
Acceptance	MC limited size	0.038	0.047
	Model	0.023	0.024
Background	Data limited size	0.128	0.107
	Model	0.125	0.105
Yields		0.035	0.035
α_Λ		0.076	0.062
Total correlated		0.133	0.117
Total uncorrelated		0.152	0.129
Total		0.202	0.174

Results

$$\alpha_\gamma = 0.82 \pm 0.23$$



Results: tagged

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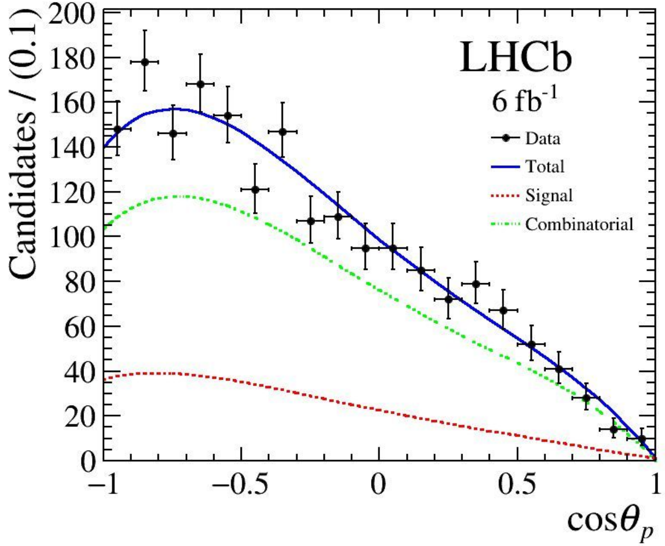
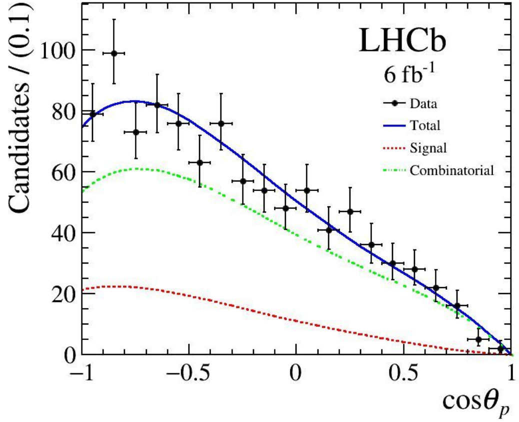


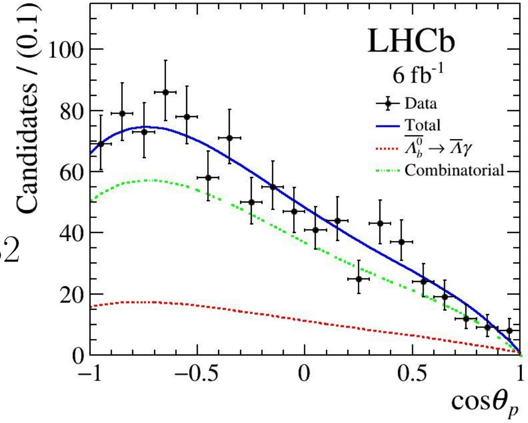
$$\Lambda_b \to \Lambda\gamma$$

$$\alpha_\gamma^- = 1.26 \pm 0.42$$



$$\overline{\Lambda}_b \to \overline{\Lambda}\gamma$$

$$\alpha_\gamma^+ = -0.55 \pm 0.32$$



Strategy

- Reconstruct and select events.
- Extract signal and background yields
- Effects on θ_{p}: acceptance.
- Extract α_{γ}: fit $\cos\theta_{\mathrm{p}}$.
- **Interpretation of the results.**

Physical interpretation

Photon polarization is physically bounded between -1 and 1.

Need to translate the result of the fit to a physical measurement, use Feldman-Cousins technique.

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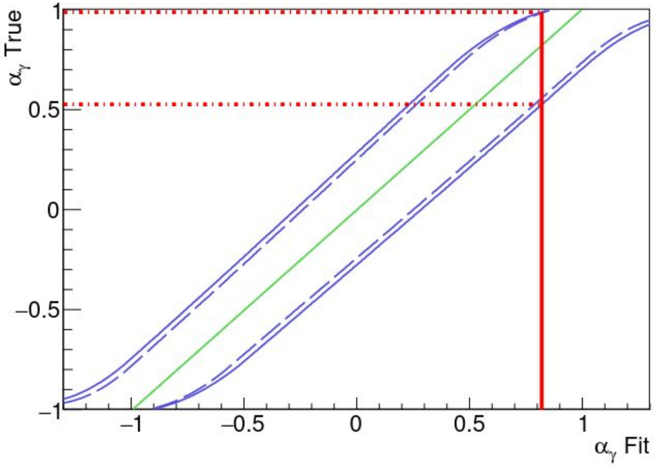
Measurement

$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})\,^{+0.04}_{-0.13}\,(\text{syst.})$$

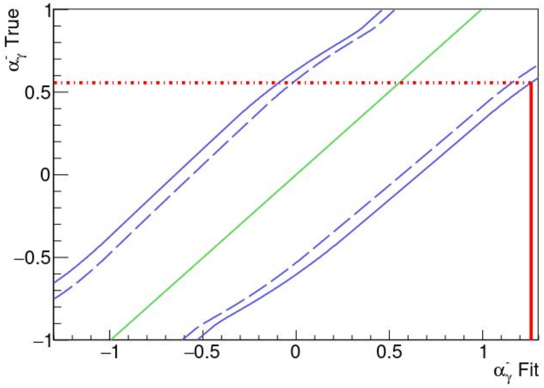


Physical interpretation: tagged

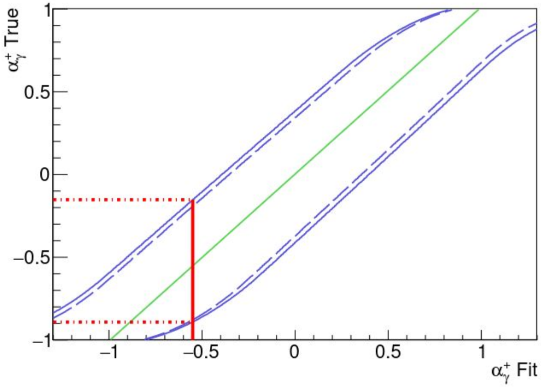
Photon polarization is physically bounded between -1 and 1.

Need to translate the result of the fit to a physical measurement, use Feldman-Cousins technique.

$\alpha_\gamma^- > 0.56\ (0.44)$ at 90% (95%)



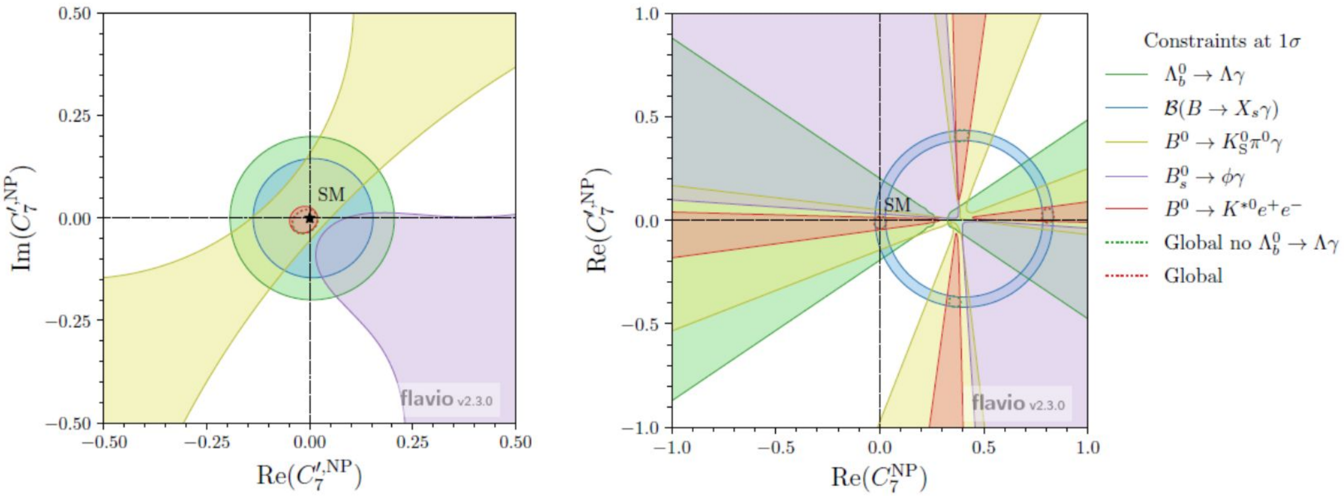
$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33}\ (stat.)\ {}^{+0.16}_{-0.09}\ (syst.)$



Constraints

The Photon polarization places additional constraints to the Wilson coefficients

$$\alpha_\gamma = \frac{N(\gamma_L) - N(\gamma_R)}{N(\gamma_L) + N(\gamma_R)} = \frac{1-|r|^2}{1+|r|^2} \qquad |r| = \frac{\mathcal{C}_7'}{\mathcal{C}_7}$$



Outline

1. Framework: Radiative b-decays
2. Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb
3. **TDCPV analysis of $B^0 \to K_s \pi^+ \pi^- \gamma$ at Belle**
4. Conclusions

Observable: Time-dependent CP asymmetry

TDCP asymmetry is sensitive to the photon polarization.

➔ Interference of the amplitudes of B decaying into a CP eigenstate emerging as a result of the B oscillation.

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$$
\begin{aligned}
\mathcal{A}_{CP} &= \frac{\Gamma\left(B_{tag=\overline{B}}(\Delta t) \to f_{CP}\right) - \Gamma\left(B_{tag=B}(\Delta t) \to f_{CP}\right)}{\Gamma\left(B_{tag=\overline{B}}(\Delta t) \to f_{CP}\right) + \Gamma\left(B_{tag=B}(\Delta t) \to f_{CP}\right)} \\
&= S \cdot \sin\left(\Delta m_d \Delta t\right) - C \cdot \cos\left(\Delta m_d \Delta t\right)
\end{aligned}
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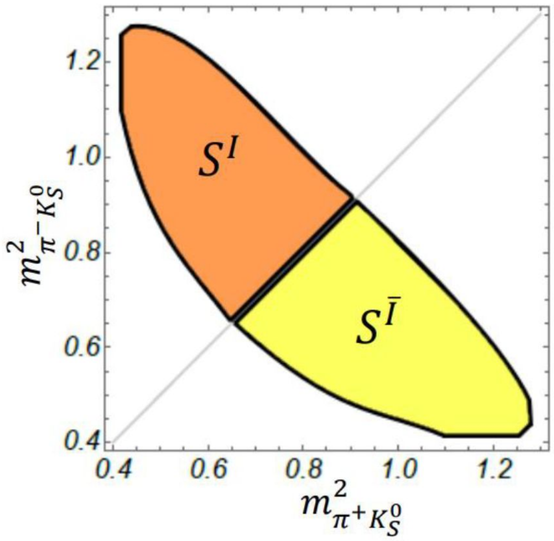
TDCPV analysis of $B^0 \to K_s \rho\gamma \to K_s \pi^+\pi^-\gamma$ (Belle & Belle II)

Constraints on Wilson coefficient: C_7

Split the m(πK_s) phase-space to measure S-parameter and new constraints on the Wilson coefficients [JHEP 09 (2019) 034].



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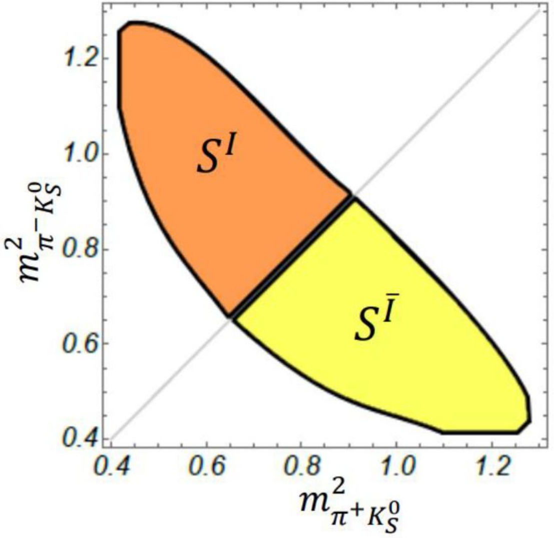

Two new observables: $$S^+ = S^I + S^{\bar{I}}$$ $$S^- = S^I - S^{\bar{I}}$$

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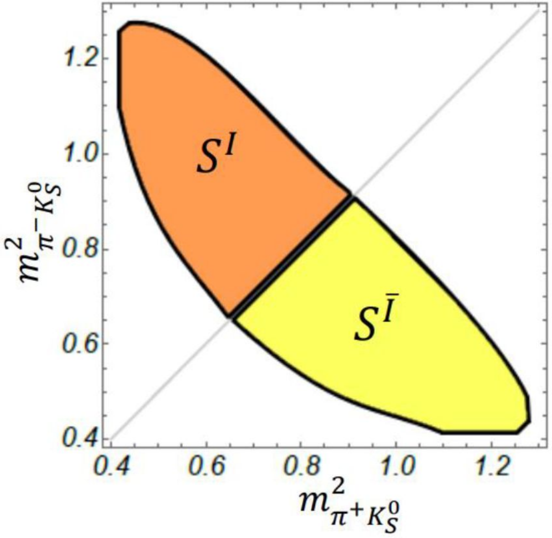

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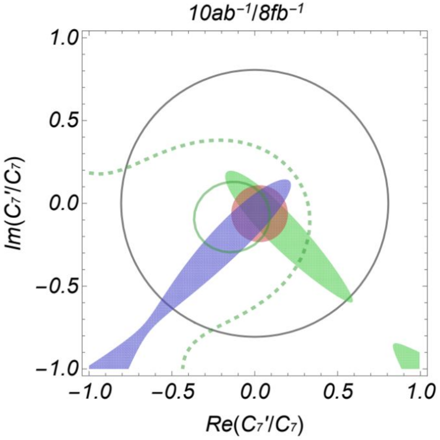
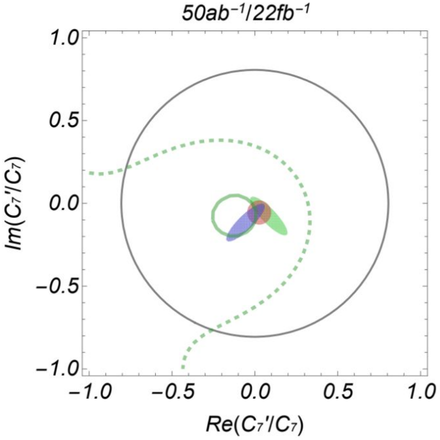
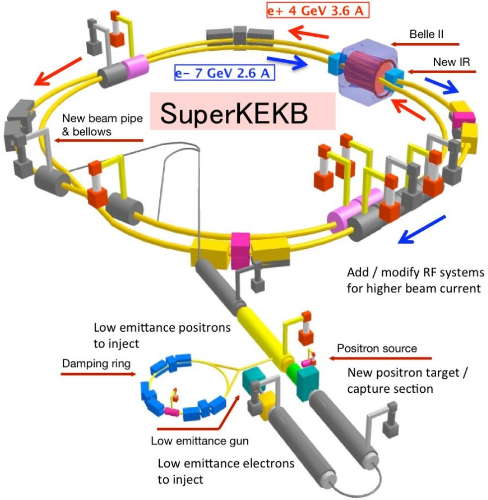


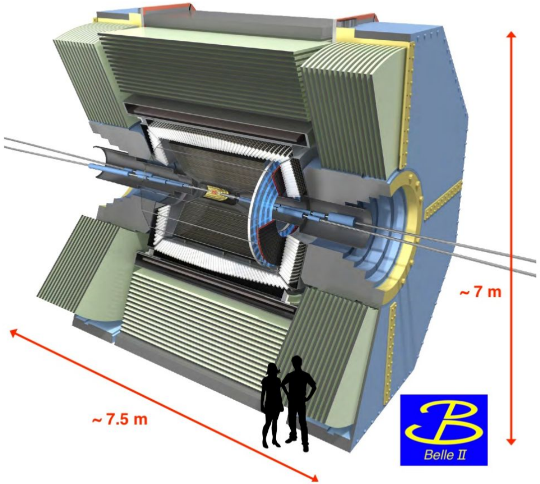


SuperKEKB and Belle II

SuperKEKB: e^--e^+ collider - Y(4S)

- World Record peak instantaneous luminosity. $4.7 \times 10^{\mathbf{34}}\ \mathrm{cm^{-2}s^{-1}}$
- Recorded $427\mathrm{fb}^{-1}$ (BaBar)
- New run started this week after LS2.

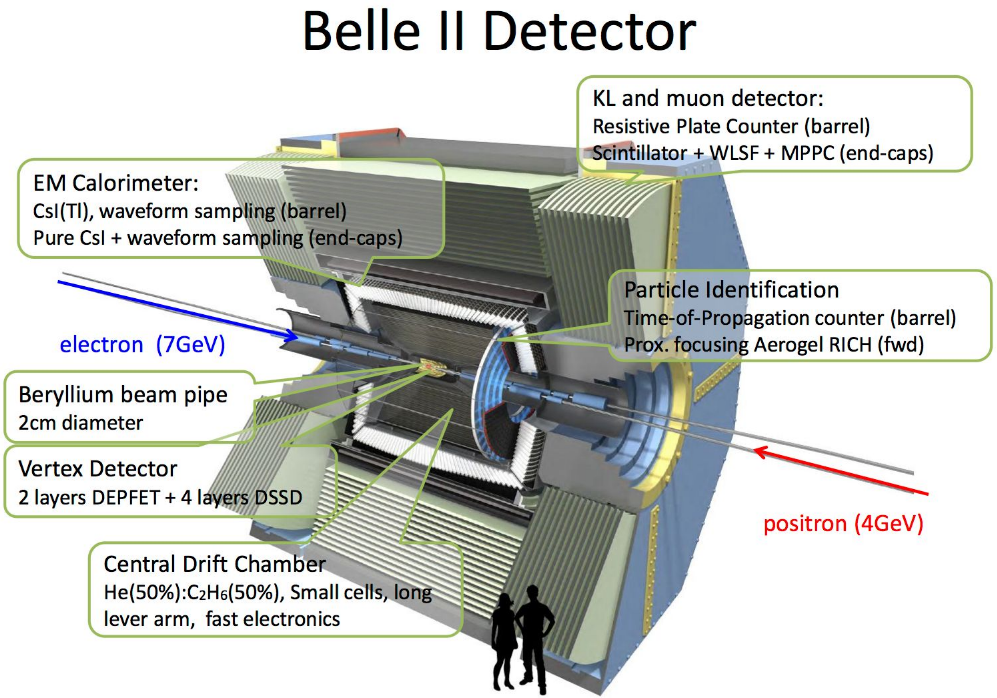




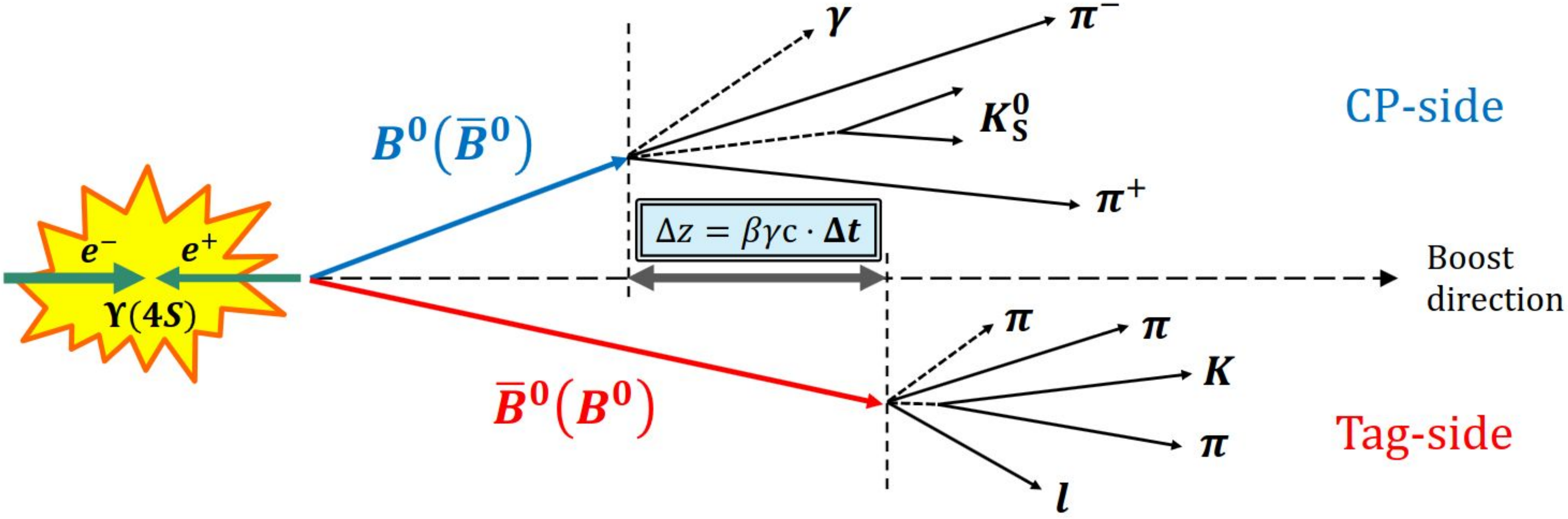
The Belle II detector

General purpose spectrometer:

- bb cross-section: ~1 nb
- Hermetic, clean collisions
- Mostly B, B^+
  Inclusive analysis, tau decays, ...
- Excellent tagging power
- Good reconstruction of neutrals



Event Reconstruction

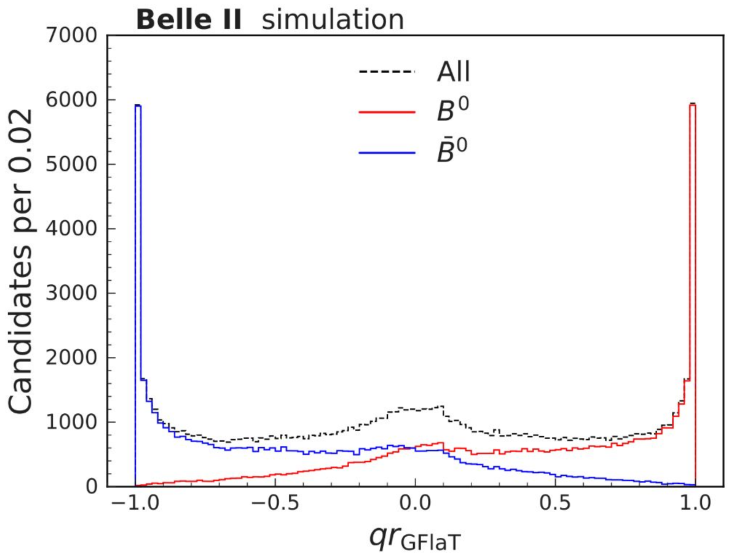


Flavor tagger

B flavor is estimated BDT + Graph Neuronal Network (GNN) based on several flavor estimators (p_t, N leptons, etc ...)

Flavor tagger output parameters

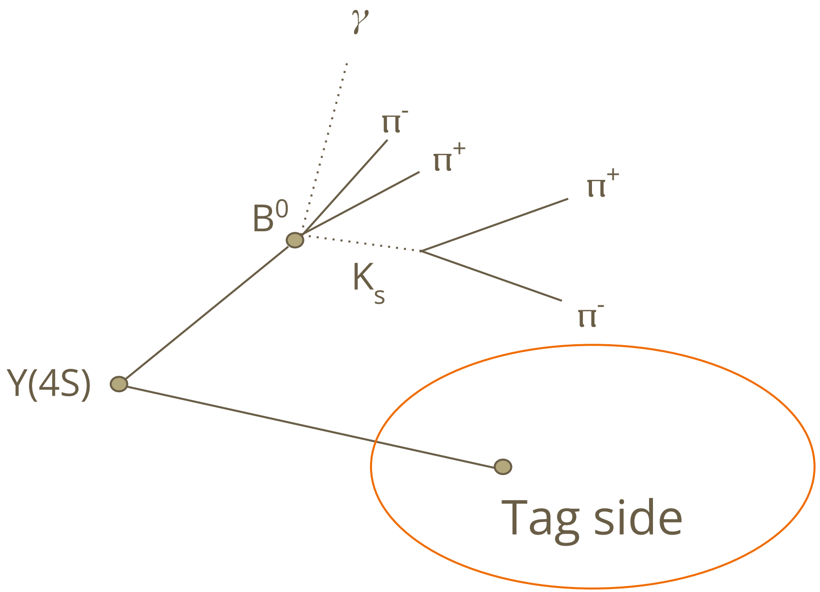
- Tag-B flavor: q=±1
- Confidence factor: r= 1-2w
- Mistag fraction: w



Overall 37% effective tagging power

Reconstruction and selection

Reconstruct the CP side first then the tag side with the Rest of the Event

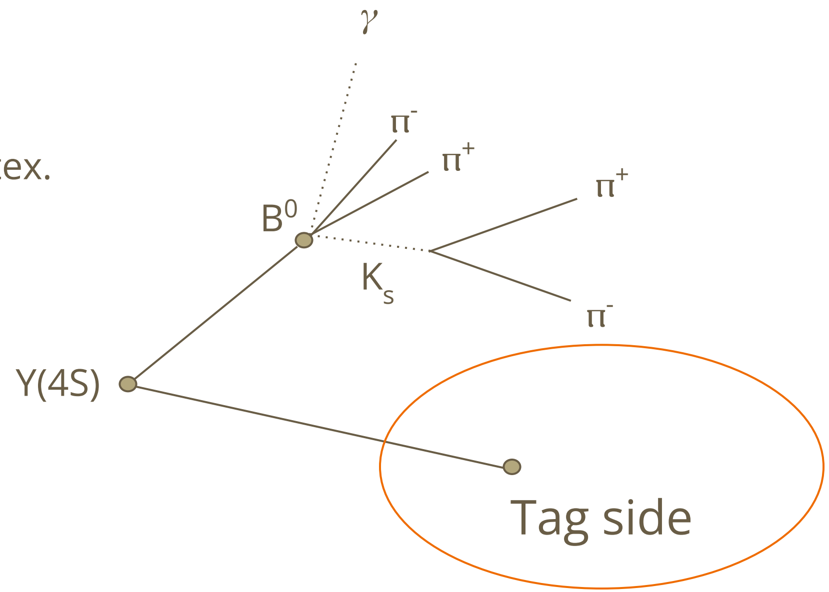


Reconstruction and selection

Reconstruct the CP side first then the tag side with the Rest of the Event

Pions:

- Small requirements on the p_t and PID.
- Prompt pions used to reconstruct the B vertex.
- Mass compatible with a ρ(770).
- MVA: K_s goodness.



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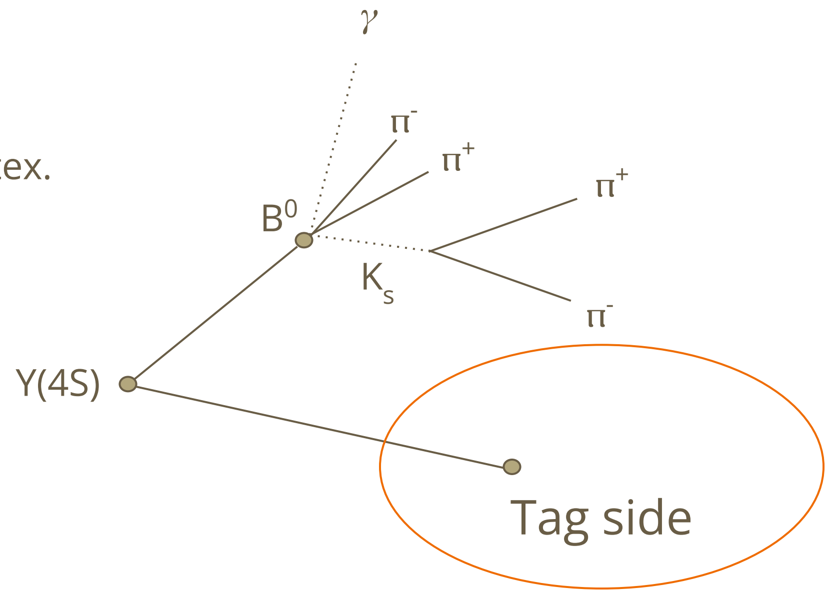
Photon:

- Energy requirement 1.4 - 4 GeV
- π^0 PID rejection.



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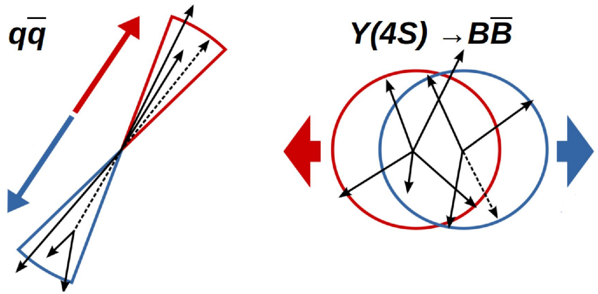

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- Energy requirement 1.4 - 4 GeV
- π^0 PID rejection.

Continuum is the dominant background. MVA trained using event-shape.

Fit strategy

Tridimensional, simultaneous maximum likelihood fit with four components.

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3-dimensions:

- $M_{bc} = \sqrt{{E_{\mathrm{beam}}/2}^2 - {p_{\mathrm{B}}^{*}}^2}$
- $\Delta E = E_{\mathrm{B}}^{*} - \sqrt{s}/2$
- ΔT (S,C)

Fit strategy

Tridimensional, simultaneous maximum likelihood fit with four components.

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Simultaneous:

- Two flavor tagging bins

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- ΔT (S,C)

Simultaneous:

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4 components:

1. Signal
2. Self cross-feed
3. Continuum
4. Combinatorial B physical background

Modeling

Models for M_{bc} and ΔE are extracted from simulated samples.

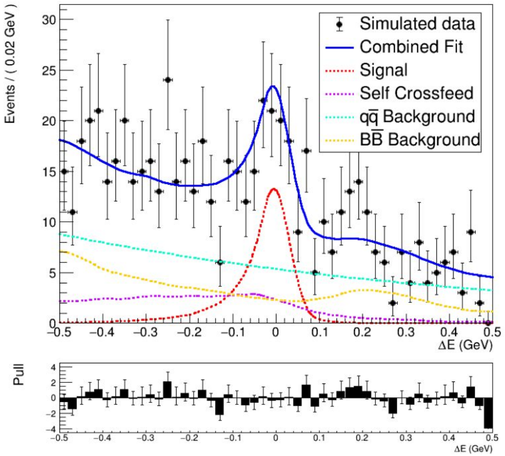
ΔE

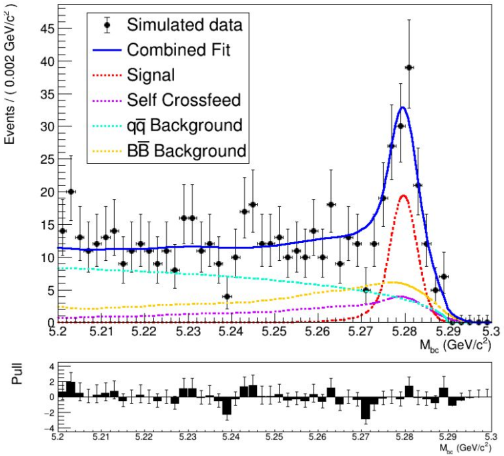
Signal: DSCB

SCF: Chev(2)+Gauss

qq: Exponential

BB: Exp+Gauss





M_{bc}

Signal: Crystal Ball

SCF: Argus+Gauss

qq: Argus

BB: Argus + Gauss

Signal Δt modeling

$$\mathcal{T}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B}(1 - q\Delta w + q\mu(1 - 2w)$$
$$+ [q(1 - 2w) + \mu(1 - q\Delta w)]\,[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)] \otimes \mathcal{R}_{\Delta t}$$

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Flavor tagger parameters: q, μ, w, Δw

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CP parameters: S, C

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Resolution: Finite precision of the detector in measuring the vertex position

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Flavor tagger parameters: q, μ, w, Δw

CP parameters: S, C

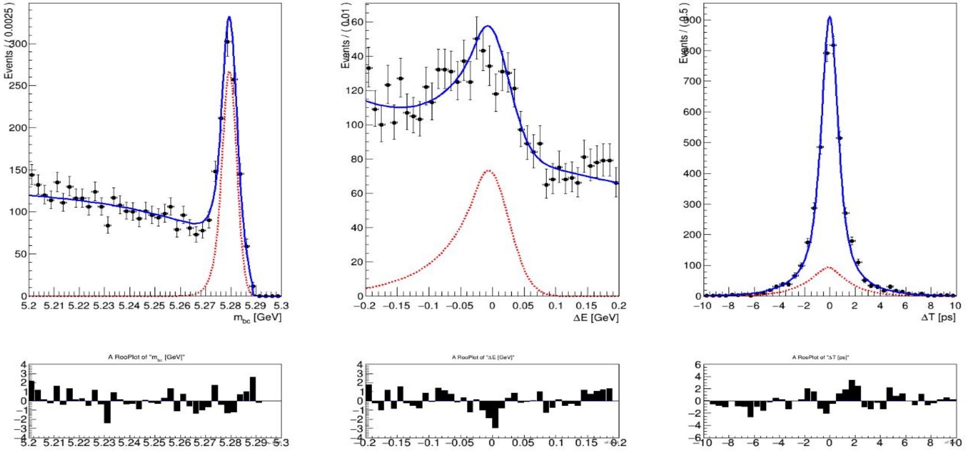
Resolution: Finite precision of the detector in measuring the vertex position

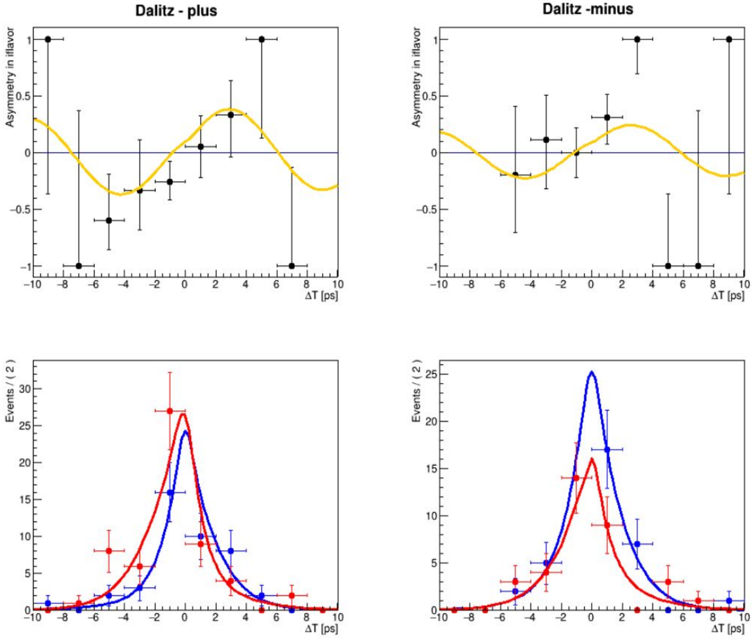
$$\mathcal{R}(\delta\Delta t;\sigma) = (1 - f_{\mathrm{OL}})\mathcal{R}_{\mathrm{core}}(\delta\Delta t;\sigma) + f_{\mathrm{OL}}\mathcal{R}_{\mathrm{OL}}(\delta\Delta t;\sigma)$$

$$\begin{aligned}\mathcal{R}_{\mathrm{core}}(\delta\Delta t;\sigma) = &(1 - f_{\mathrm{tail}}) \cdot G(\delta\Delta t; \mu_{\mathrm{main}}\cdot\sigma, s_{\mathrm{main}}\cdot\sigma)\\ &+ (1 - f_{\mathrm{exp}}) \cdot f_{\mathrm{tail}} \cdot G(\delta\Delta t; \mu_{\mathrm{tail}}\cdot\sigma, s_{\mathrm{tail}}\cdot\sigma)\\ &+ f_{\mathrm{tail}} \cdot f_{\mathrm{exp}} \cdot G(\delta\Delta t; \mu_{\mathrm{tail}}\cdot\sigma, s_{\mathrm{tail}}\cdot\sigma)\\ &\quad\otimes \big((1 - f_{\mathrm{R}})\exp_{-}(\delta\Delta t/c\cdot\sigma) + f_{\mathrm{R}}\exp_{+}(-\delta\Delta t/c\cdot\sigma)\big)\end{aligned}$$

Validation

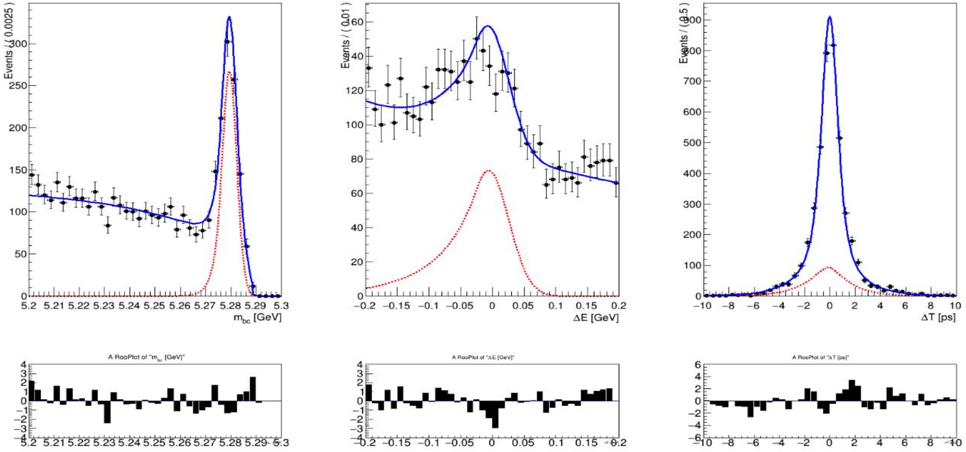
Fit strategy is validated using pseudo-experiments

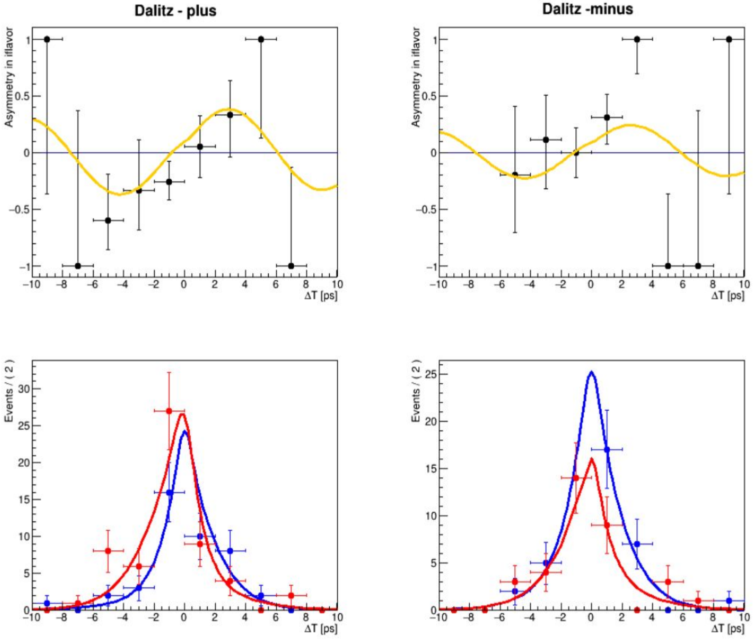




Validation

Fit strategy is validated using pseudo-experiments





$$\sigma_S \sim 0.11$$
$$\sigma_C \sim 0.09$$

Tests: B lifetime and S-linearity

Outline

1. Framework: Radiative b-decays
2. Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb
3. TDCPV analysis of $B^0 \to K_s\pi^+\pi^-\gamma$ at Belle
4. **Conclusions**

Conclusions

- ➔ Radiative b-decays are very powerful to perform precision measurements of the SM.

- ➔ LHCb and Belle II are complementary and able to tackle different approaches to the measurement of C_7, C_7'.
  - Radiative b-baryon decays are complementary to b-meson measurements.
  - New constraints to C_7, C_7' using TDCPV asymmetry.

Thank you