

Angular analysis of $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

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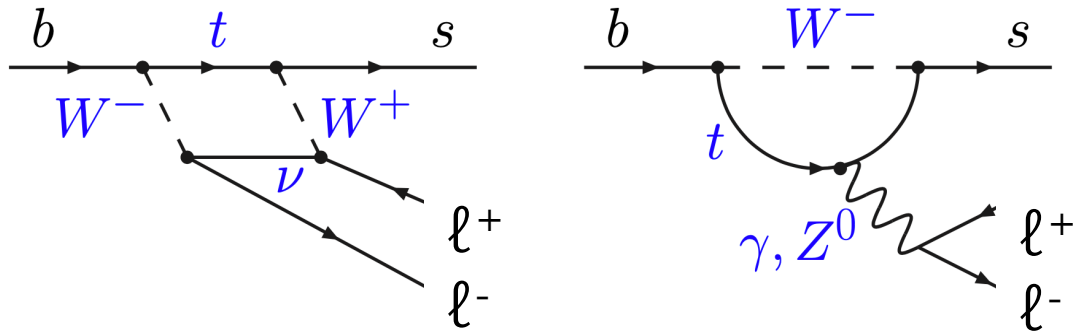
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IN2P3/CNRS & Université Paris-Saclay

- Why and how ?
- Current status

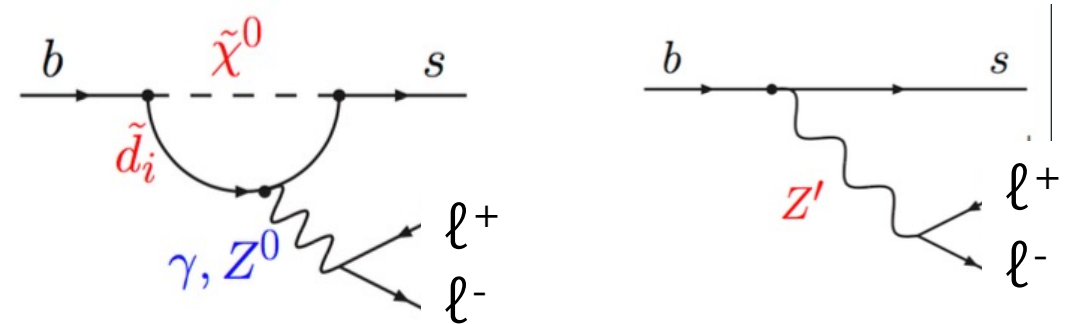
Why ?

$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ is a FCNC $\rightarrow$ rare and ideal to search for signs of physics originating from Beyond Standard Model (New Physics)

SM



New Physics (examples)



Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+ \ell^-)$

How NP would manifest ?

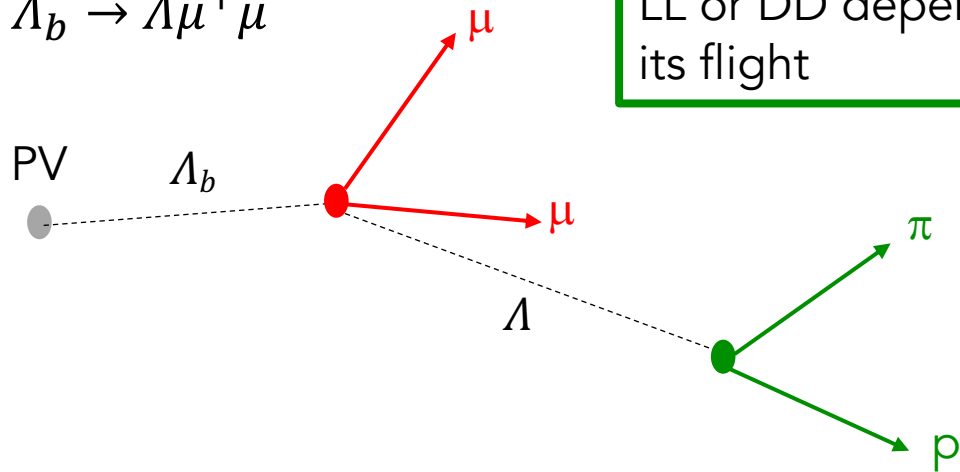
- Modification of the decay rates ($\uparrow$ or $\downarrow$)
- **Modification of the angular distributions**
- New sources of CP violation

Potentially different for $b \rightarrow s \mu^+ \mu^-$ and $b \rightarrow s e^+ e^-$

How: characteristics of the decay

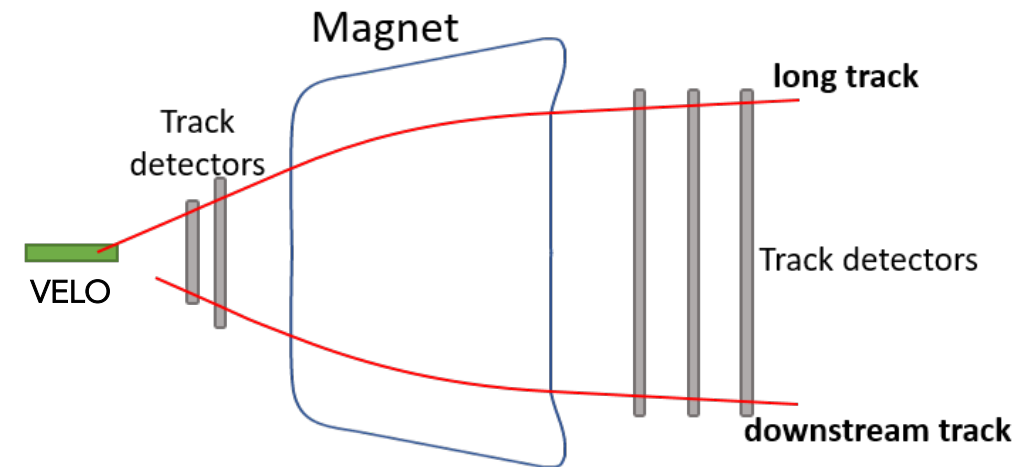
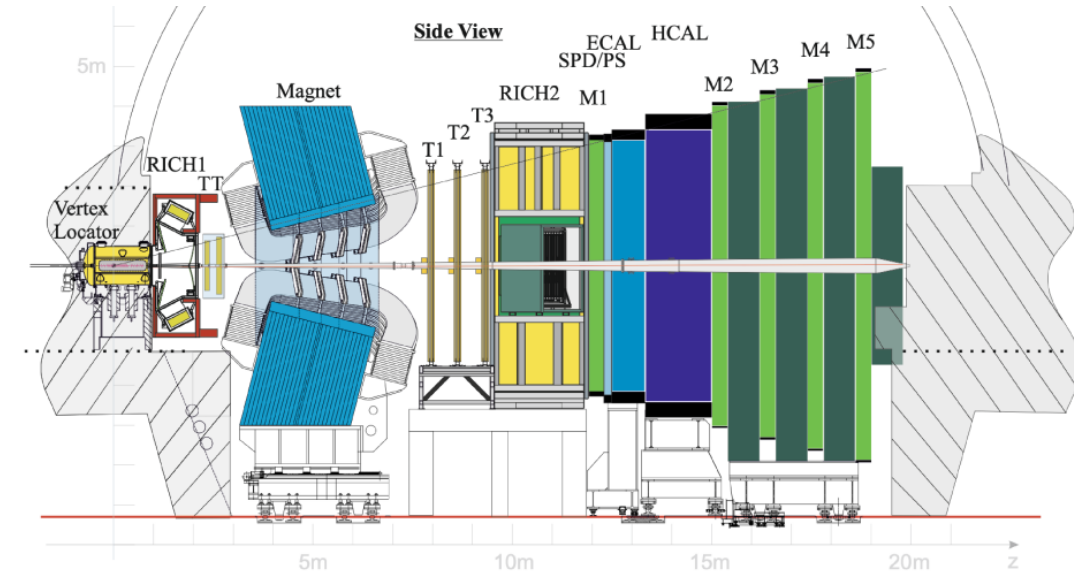
- Unique to LHCb
- The simplest $b \rightarrow s$ LL decay for b -baryon.

$$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$$



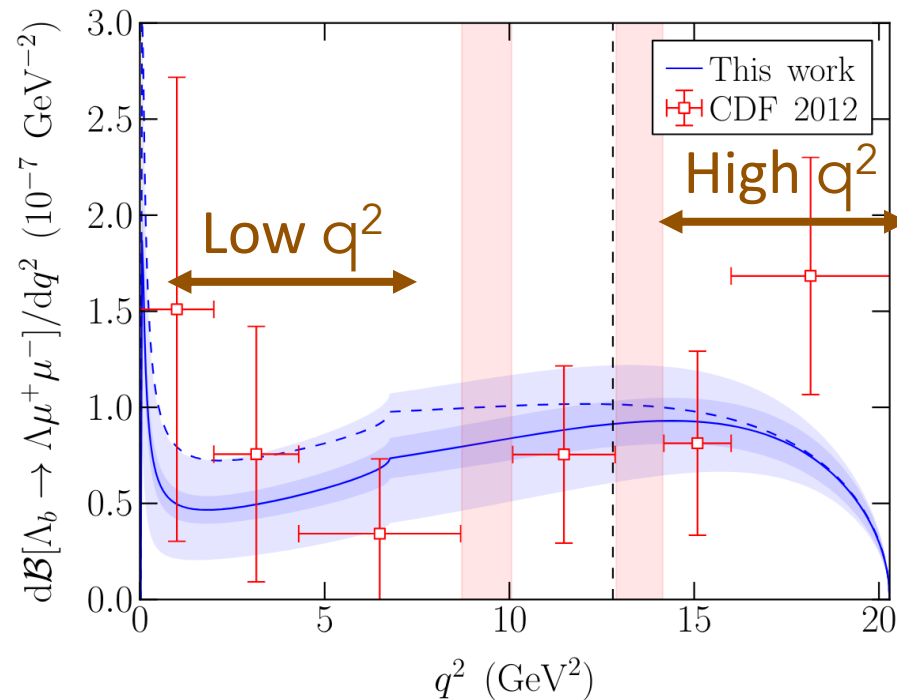
Λ can be reconstructed as LL or DD depending on its flight

- Use of $\Lambda_b \rightarrow \Lambda J/\psi$ ($\rightarrow \mu^+ \mu^-$) (more abundant, tree level) as control channel



How: data sample, regions

- Full Run1 + Run2 (2011-2018) statistics (9 fb^{-1})
- Several q^2 ($= m(\mu^+\mu^-)^2$) regions



Currently focussing on the high q^2

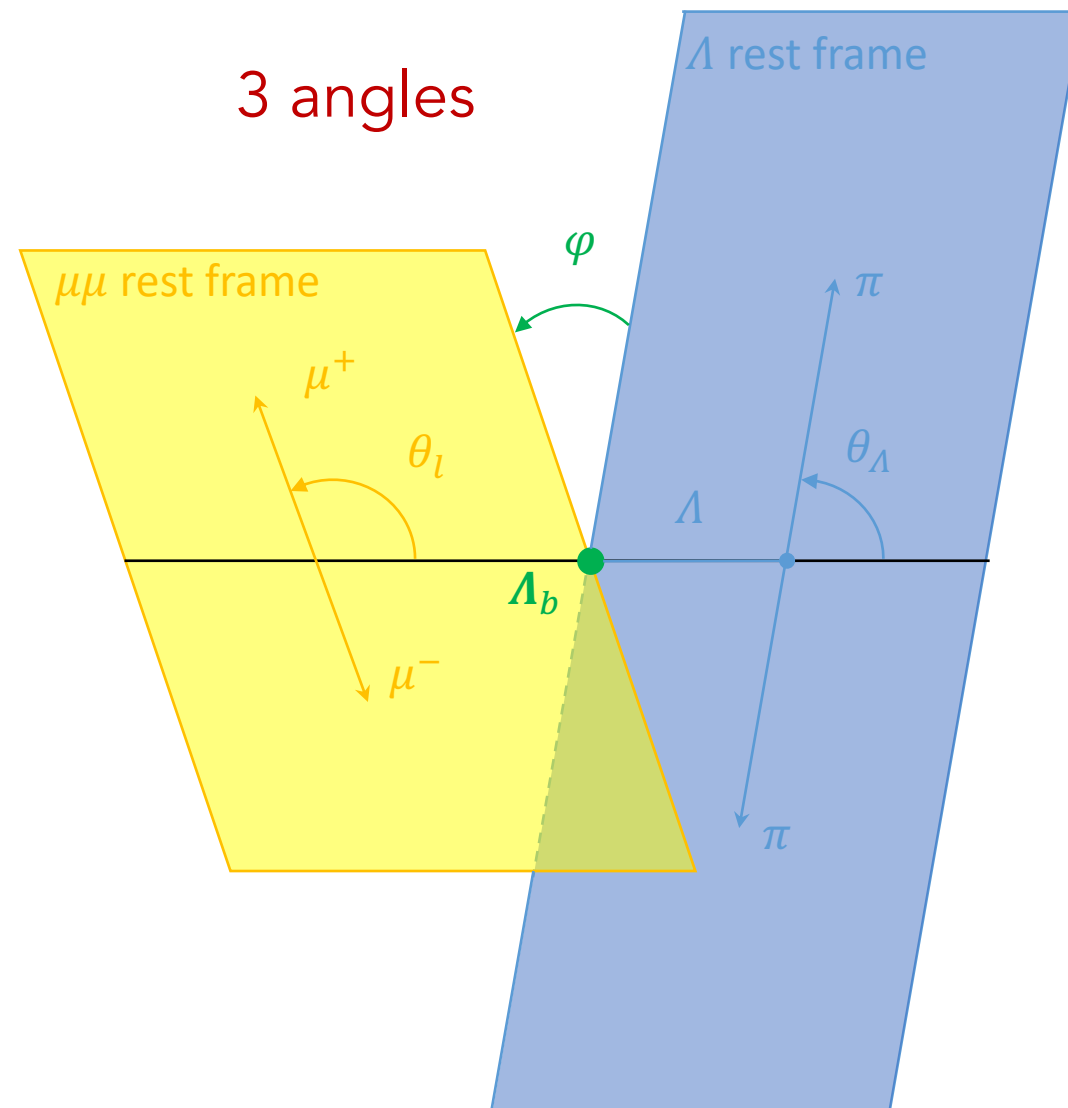
- resonant $\Lambda_b \rightarrow \Lambda J/\psi \ (\rightarrow \mu^+\mu^-)$ control mode

How: angles

- The full angular distribution for an unpolarised Λ_b is described by:

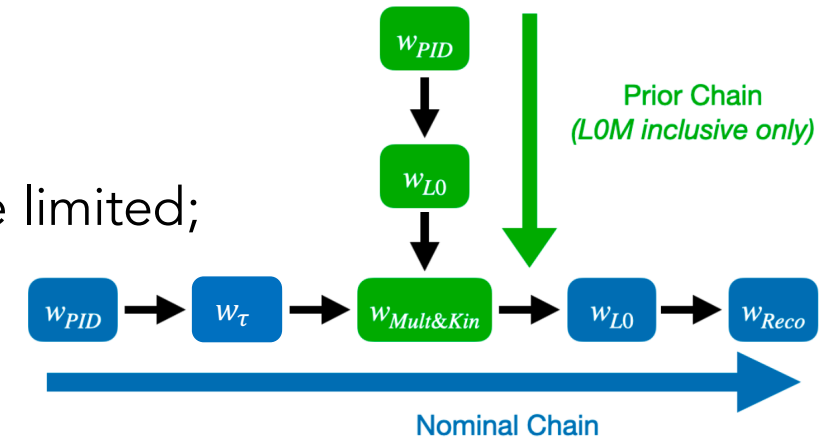
$$\begin{aligned} K(q^2, \varphi, \cos\theta_l, \cos\theta_\Lambda) &= \frac{8\pi}{3} \frac{d^4\Gamma}{dq^2 d\varphi d\cos\theta_l d\cos\theta_\Lambda} = \\ &= (\mathbf{K}_{1ss}\sin^2\theta_l + (1 - 2\mathbf{K}_{1ss})\cos^2\theta_l + \mathbf{K}_{1c}\cos\theta_l) \\ &+ (\mathbf{K}_{2ss}\sin^2\theta_l + \mathbf{K}_{2cc}\cos^2\theta_l + \mathbf{K}_{2c}\cos\theta_l)\cos\theta_\Lambda \\ &+ (\mathbf{K}_{3sc}\sin\theta_l \cos\theta_l + \mathbf{K}_{3s}\sin\theta_l)\sin\theta_\Lambda \sin\varphi \\ &+ (\mathbf{K}_{4sc}\sin\theta_l \cos\theta_l + \mathbf{K}_{4s}\sin\theta_l)\sin\theta_\Lambda \cos\varphi \end{aligned}$$

- The analysis aims to measure the 9 angular observables $\mathbf{K}_i$



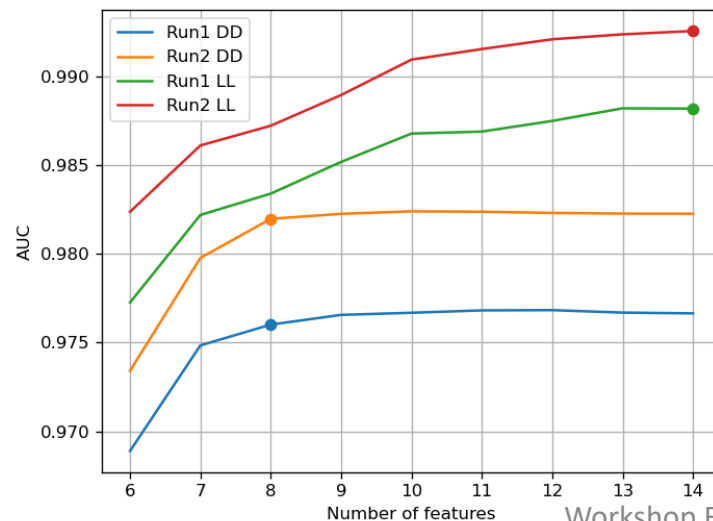
Current status: analysis chain

- Trigger lines and preselection fixed (see backup)
- MC is corrected following the R_X strategy:
 - Muon PID (w_{PID})
 - Tracking and HLT: no corrections made, impact expected to be limited;
 - Λ_b^0 lifetime: correct using $w_\tau = \exp(-t/\tau_{\text{measured}})/\exp(-t/\tau_{\text{sim}})$;
 - Multiplicity and kinematics: corrections made for true Λ_b^0 , p , p_T , η and nTracks using sWeighted $\Lambda_b^0 \rightarrow \Lambda J/\psi(\rightarrow \mu^+ \mu^-)$ decays;
 - Reconstruction: corrections made for Λ_b^0 , p , p_T and η using $\Lambda_b^0 \rightarrow \Lambda J/\psi(\rightarrow \mu^+ \mu^-)$ candidates after MVA and tight mass window cut.
- Combinatorial background rejected by a BDT



Current status: MVA model

- Gradient Boosted Trees
- Signal: reweighted $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ MC
- Background: data side bands $5800 < M(\Lambda_b) < 6300$
- k-folding used for training MVA models (k=5)
- hyperparameters (max tree depth, number of individual trees) optimized
- Recursive removal of the least discriminating variables



Workshop France Ukraine Octobre 2026

MVA features

For LL only

$$\log(P_t(\Lambda_b))$$

$$\tau(\Lambda_b)$$

$$\chi^2_{\tau}(\Lambda_b)$$

$$\chi^2_{DV}(\Lambda_b)$$

$$\chi^2_{DTF}/ndof(\Lambda_b)$$

$$\cos^{-1}(DIRA(\Lambda_b))$$

$$\log(P_t(\Lambda))$$

$$\tau(\Lambda)$$

$$Z_{DV}(\Lambda)$$

$$\min [\chi^2_{IP}(\mu^+), \chi^2_{IP}(\mu^-)]$$

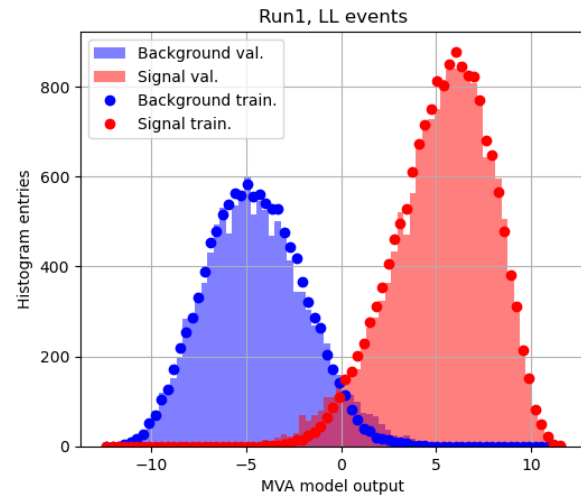
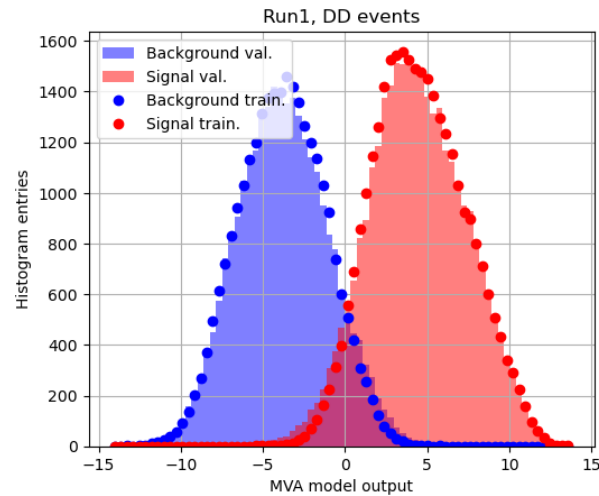
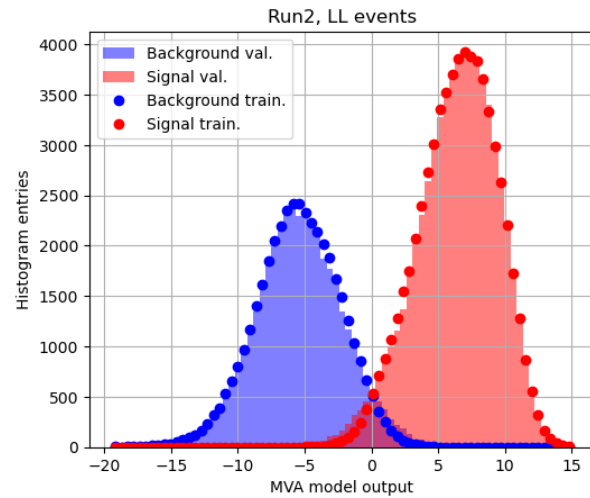
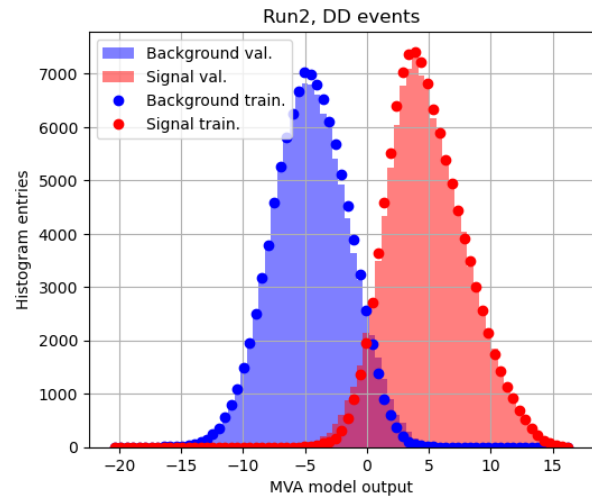
$$\min [\log(\chi^2_{IP}(p)), \log(\chi^2_{IP}(\pi))]$$

$$\log(P_t(\pi))$$

$$\log(P(p))$$

$$\chi^2_{FD}(\Lambda)$$

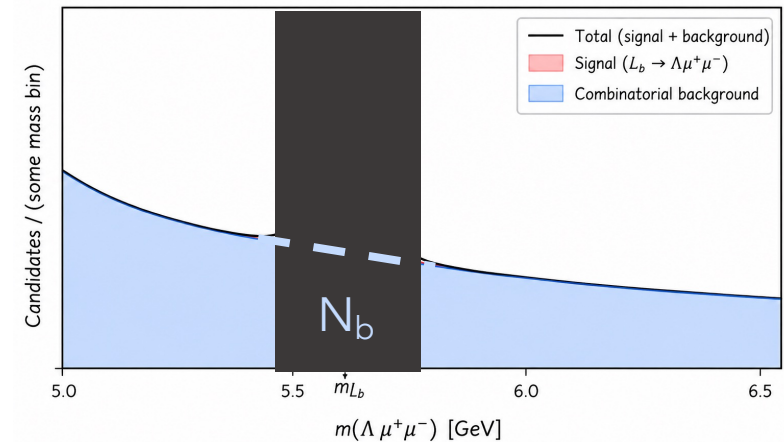
Current status: MVA cut optimization



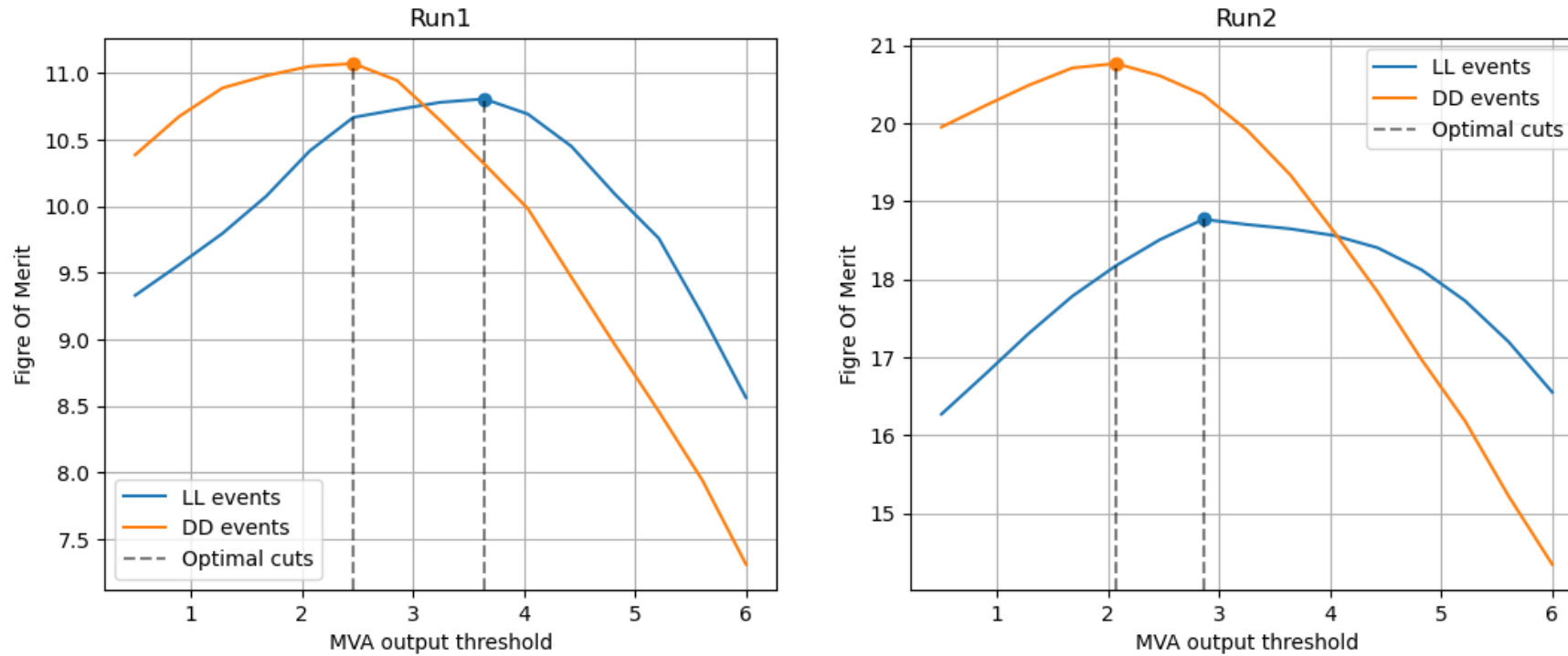
From data

$$FOM = \frac{N_s}{\sqrt{N_b + N_s}}$$

$$N_s = Y_{J/\psi} \frac{\varepsilon_{rare}}{\varepsilon_{J/\psi}} \frac{\mathcal{B}(\Lambda_b \rightarrow \Lambda \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b \rightarrow \Lambda J/\psi) \mathcal{B}(J/\psi \rightarrow \mu^- \mu^+)}$$



Current status: FOM and signal yields



The figure of merit was calculated for different MVA cuts to find the optimal value.

Current status: angular fit

4D (mass + 3 angles) simultaneous fit of four categories (2 Runs $\times$ 2 track types).

Mass

- $\Lambda\mu\mu$ invariant mass from MC with free shift of the peak and scale for the width
- Exponential mass-background slopes are floating but shared for the same track types.

Angles

- Signal: $K(\vec{\Omega}) \times \varepsilon(\vec{\Omega}) = K(\vec{\Omega}) \times \varepsilon_{\Lambda}(\cos\theta_{\Lambda}) \times \varepsilon_{\ell}(\cos\theta_{\ell}) \times \varepsilon_{\varphi}(\varphi)$. Acceptance ε is modeled using Legendre (for $\cos\theta_{\Lambda}$ or $\cos\theta_{\ell}$) or Fourier (for $\cos\varphi$) series, with coefficients fitted using PHSP Monte Carlo.
- Background: $B(\vec{\Omega}) = B_{\Lambda}(\cos\theta_{\Lambda}) \times B_{\ell}(\cos\theta_{\ell}) \times B_{\varphi}(\varphi)$. Legendre and Fourier polynomials.
- The angular background parameters are floating and shared between all categories.
- The 9 K_i are shared between all categories.

Current status: angular fit

4D (mass + 3 angles) simultaneous fit of four categories (2 Runs $\times$ 2 track types).

Mass

- $\Lambda\mu\mu$ invariant mass from MC with free shift of the peak and scale for the width
- Exponential mass-background slopes are floating but shared for the same track types.

On data the analysis is blinded for the angles
but not for the invariant mass

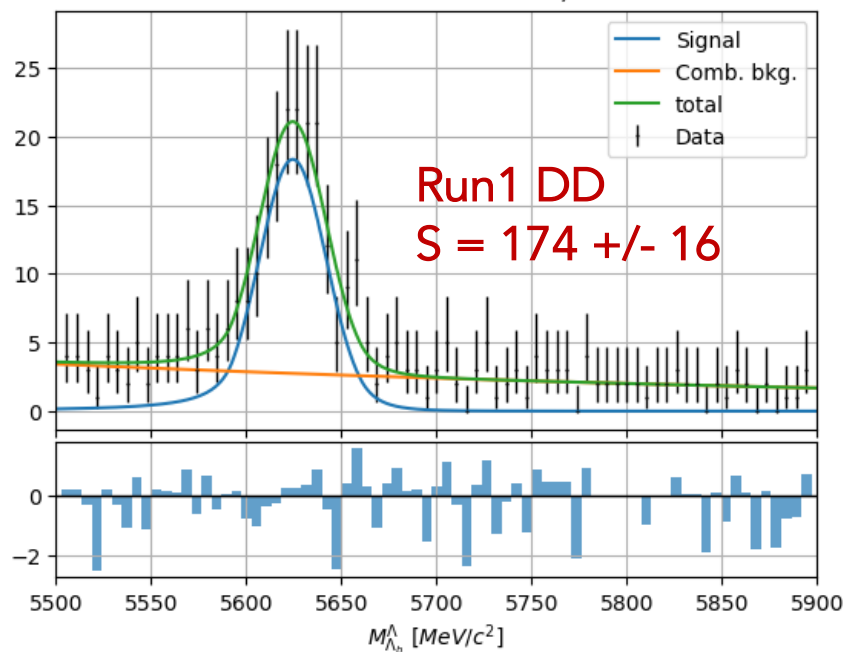
Angles

- Signal: $\Lambda\mu\mu$ invariant mass ε is modeled with 9 coefficients fitted using PHSP Monte Carlo.
- Background: $B(\vec{\Omega}) = B_{\Lambda}(\cos\theta_{\Lambda}) \times B_{\ell}(\cos\theta_{\ell}) \times B_{\varphi}(\varphi)$. Legendre polynomials.
- The angular background parameters are floating and shared between all categories.
- The 9 K_i are shared between all categories.

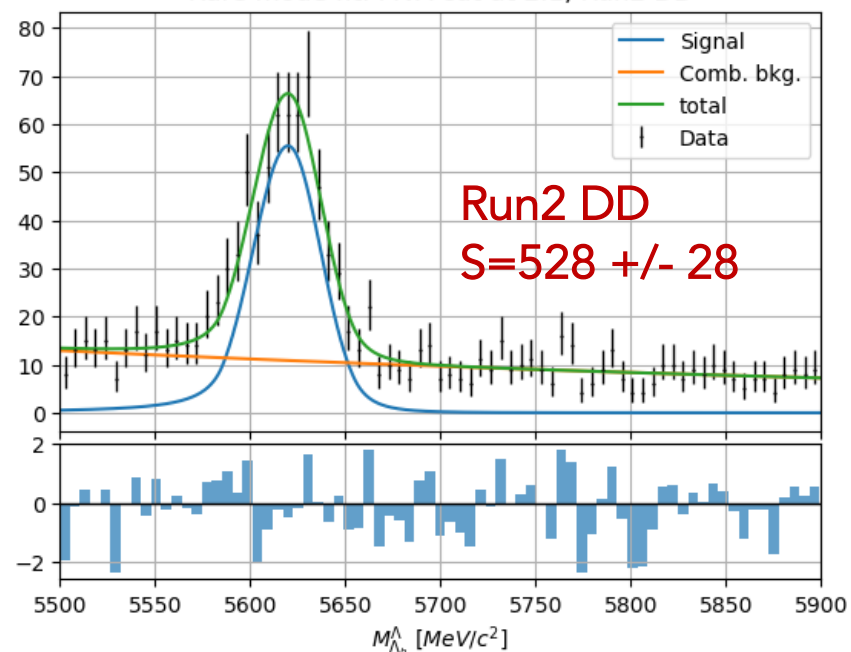
Data fits

~ 1100 signal events

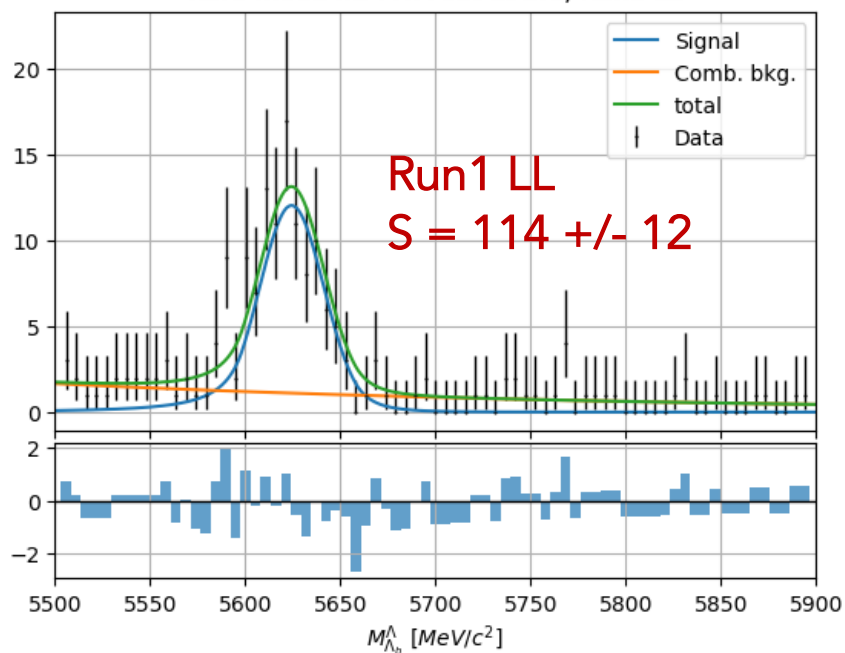
Rare mode fit. MVA cut at 2.1, Run1 DD



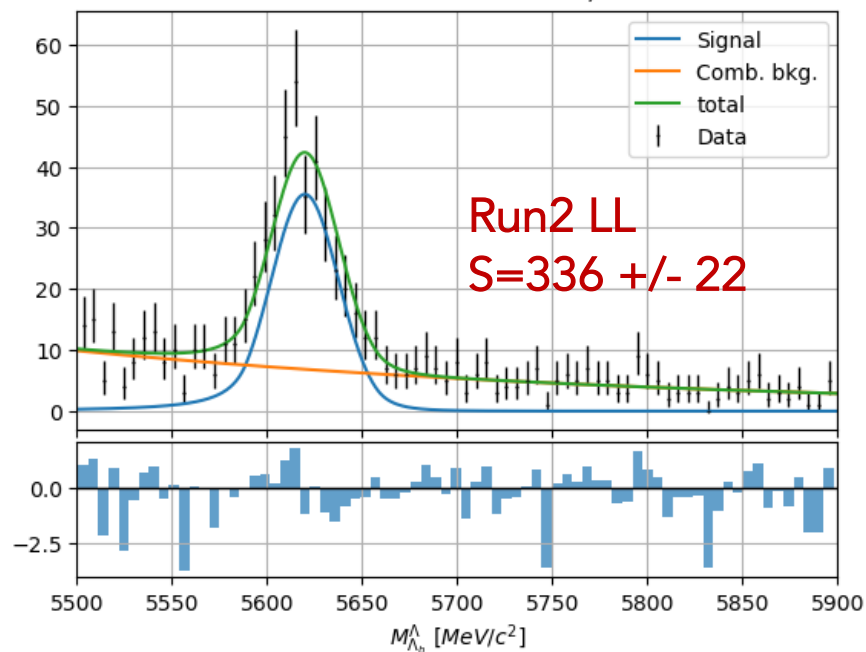
Rare mode fit. MVA cut at 2.1, Run2 DD



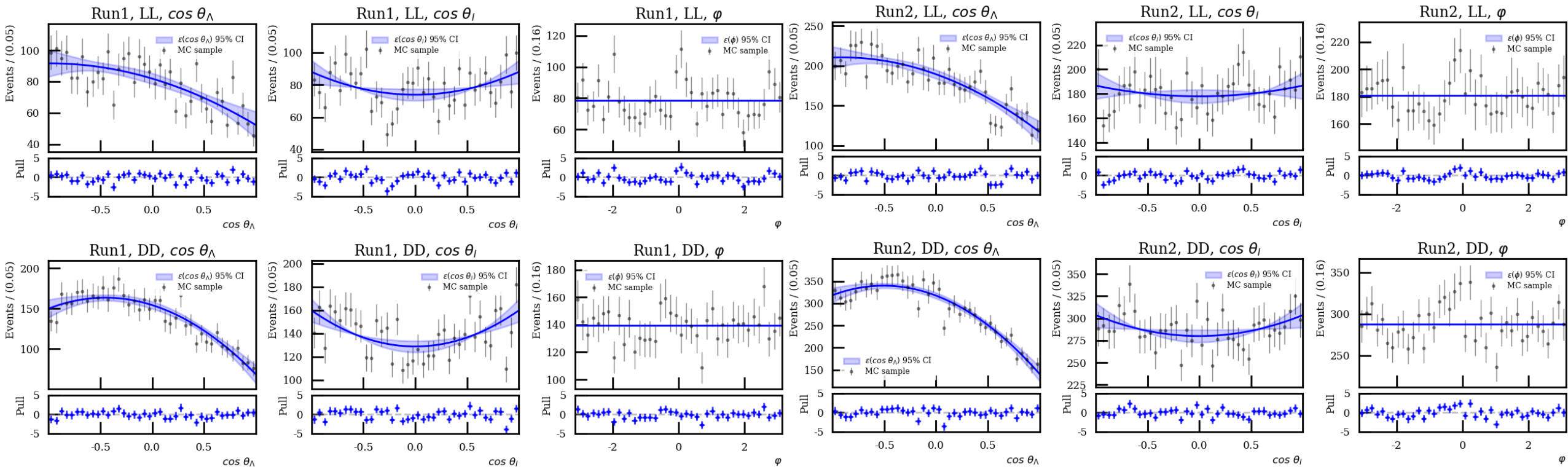
Rare mode fit. MVA cut at 3.6, Run1 LL



Rare mode fit. MVA cut at 2.9, Run2 LL



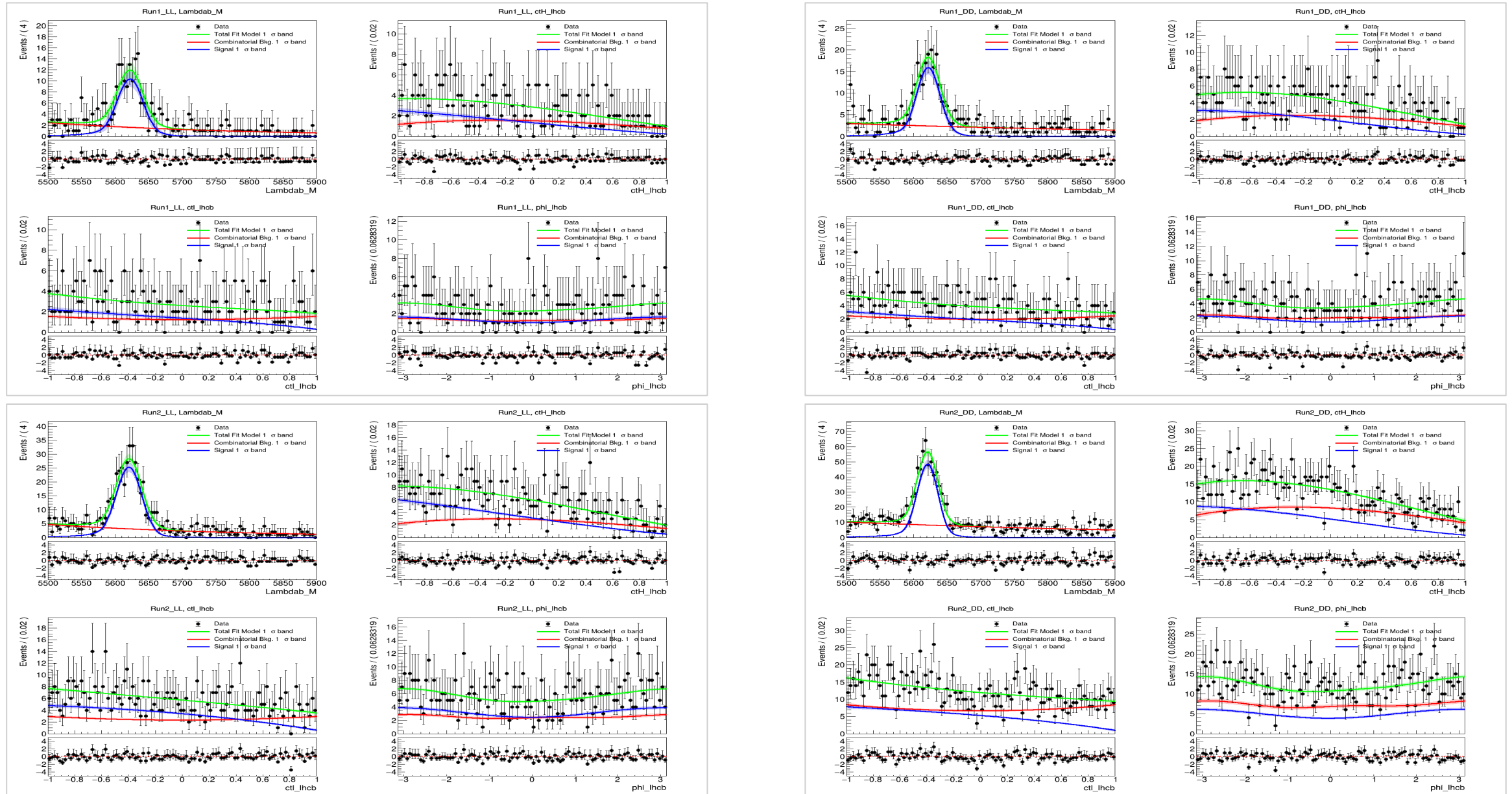
Current status: acceptance



Current status: toys

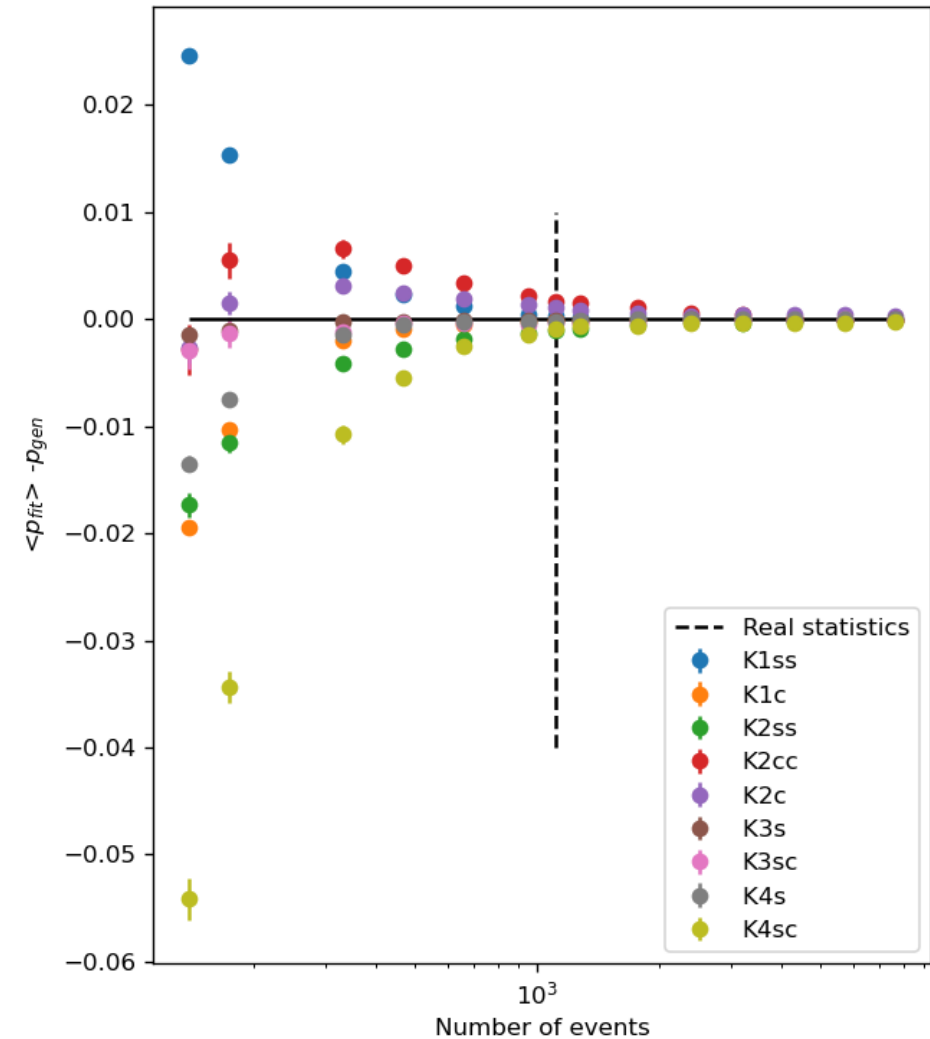
- Pseudo-experiments are used to validate the final fit strategy, identify potential biases in the fit, and to show that the fitting model is able to correctly describe the data.
- 10k toys, mimicking data, were generated:
 - Mass parameters (peak, exponential slope) as estimated from a mass fit on data
 - Angular background estimated on the sidebands data
 - For the angular signal, the SM EOS values for K observables were used.
 - Signal and background yields are estimated during the mass fit and distributed with a Poisson distribution during the generation of the pseudo-data.

Current status: one random toy

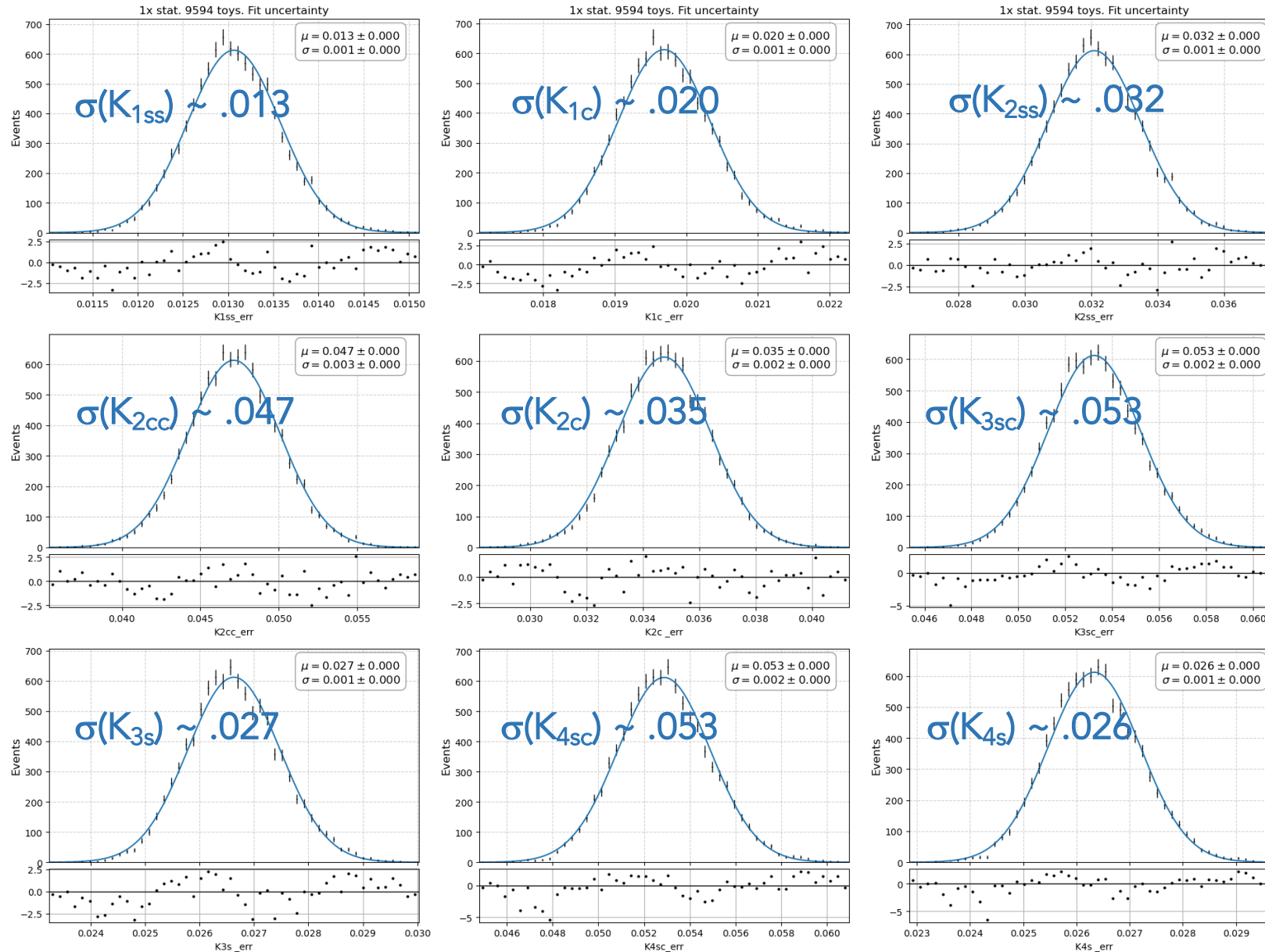


Current status: biases

- The results of the toys study show the existence of intrinsic biases for some of the K_i parameters
- The biases are caused by the limited statistics and diminish with an increasing number of events.
- For our sample, they remain at maximum of the order of 15% of the statistical uncertainties



Current status: expected precision



Summary and what's next

- Finalize the high- q^2 study and document it
- Repeat on the low- q^2 region about 440 signal events expected
- Enter into working group review and publish !

back-up slides

Preselections

- Bu2LLK_mmLine used for striping.
- Trigger selections and simple cuts were applied.
- Preselections are the same for DD and LL track types

Trigger level	Lines Run 1	Lines Run 2
L0	Muon	Muon
HLT1	TrackAllL0 TrackMuon	TrackMVA TrackMuonMVA TwoTrackMVA
HLT2	Topo2BodyBBDT TopoMu2BodyBBDT Topo3BodyBBDT TopoMu3BodyBBDT DiMuonDetached DiMuonDetachedHeavy	Topo2Body TopoMu2Body TopoMuMu2Body Topo3Body TopoMu3Body TopoMuMu3Body DiMuonDetached DiMuonDetachedHeavy

Description	Cut
Λ mass	$ \Lambda - 1116 \text{ MeV}/c^2 < 8$
Fiducial	$0 < \tau(\Lambda) < 2 \text{ ns}$ $\text{DIRA}(\Lambda) > 0$ $\chi^2_{FD}(\Lambda) > 0$ $0 < Z_{DV}(\Lambda) < 2300 \text{ mm}$
Lepton Acceptance	hasRich InAccMuon
Leptons	$3000 \text{ MeV}/c < P < 200000 \text{ MeV}/c$ $P_t > 800 \text{ MeV}/c$
PID	ProbNNmu> 0.2

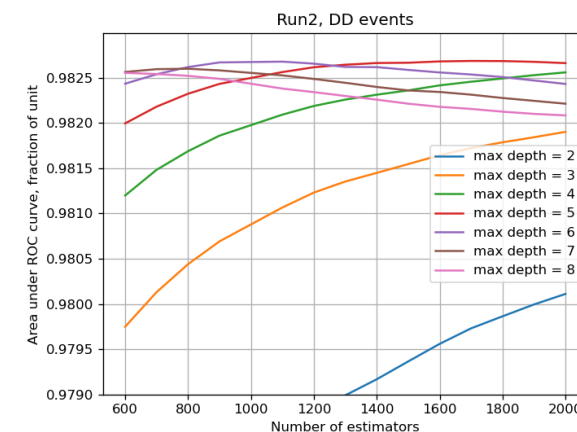
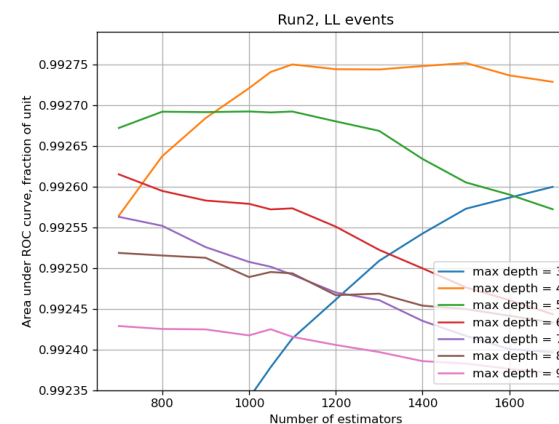
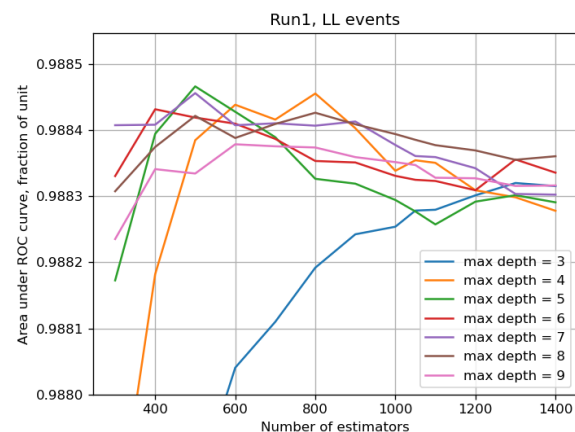
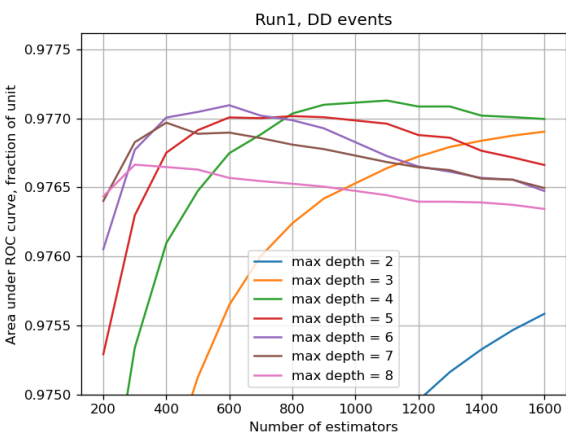
MVA hyperparameters optimization

- The gradient-boosted trees with different hyperparameters were trained to select the best set of hyperparameters. The following parameters were scanned:

- max tree depth
- number of individual trees

Optimal values

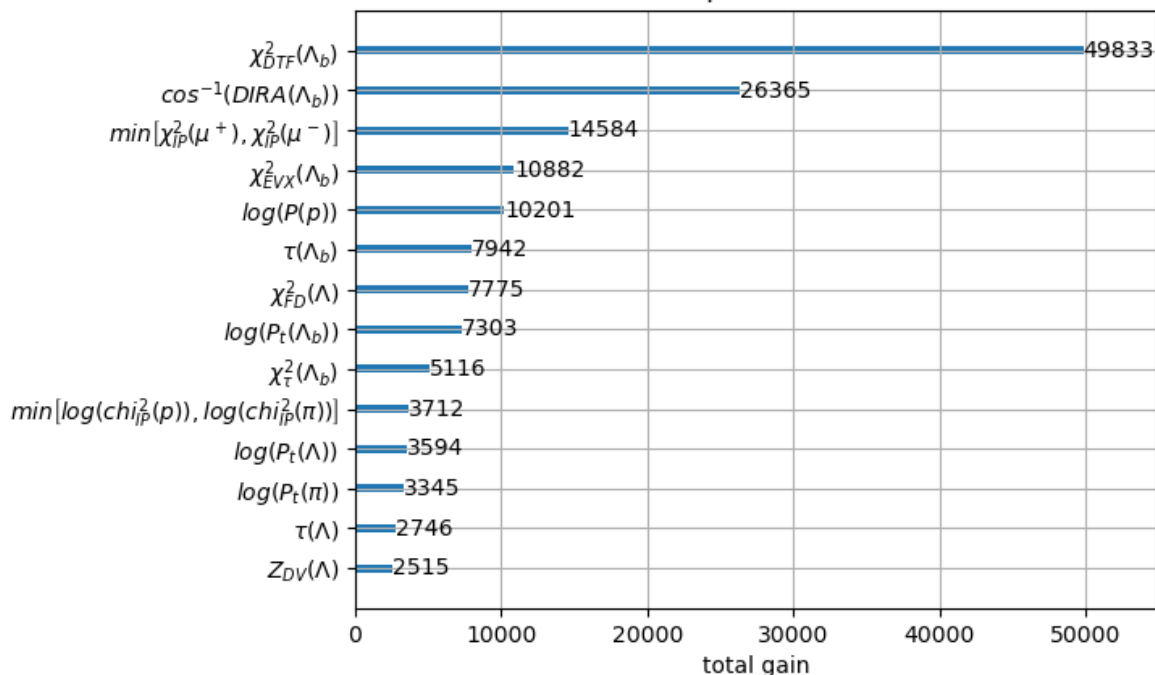
Run, tracks type	Run 1, LL	Run 1, DD	Run 2, LL	Run 2, DD
Max tree depth	4	4	4	5
Max number of trees	600	1100	1500	1800



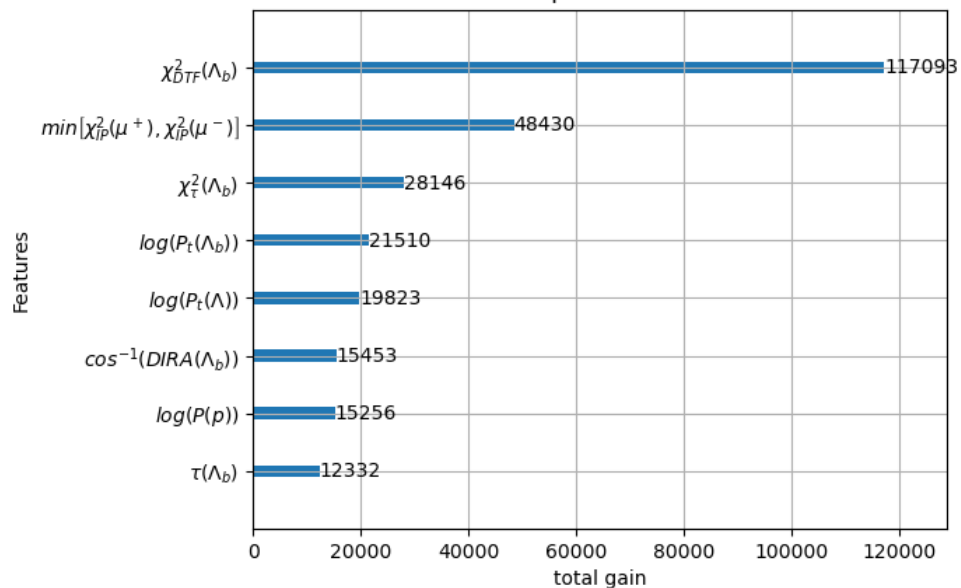
Metrics evaluated on validation data

Features

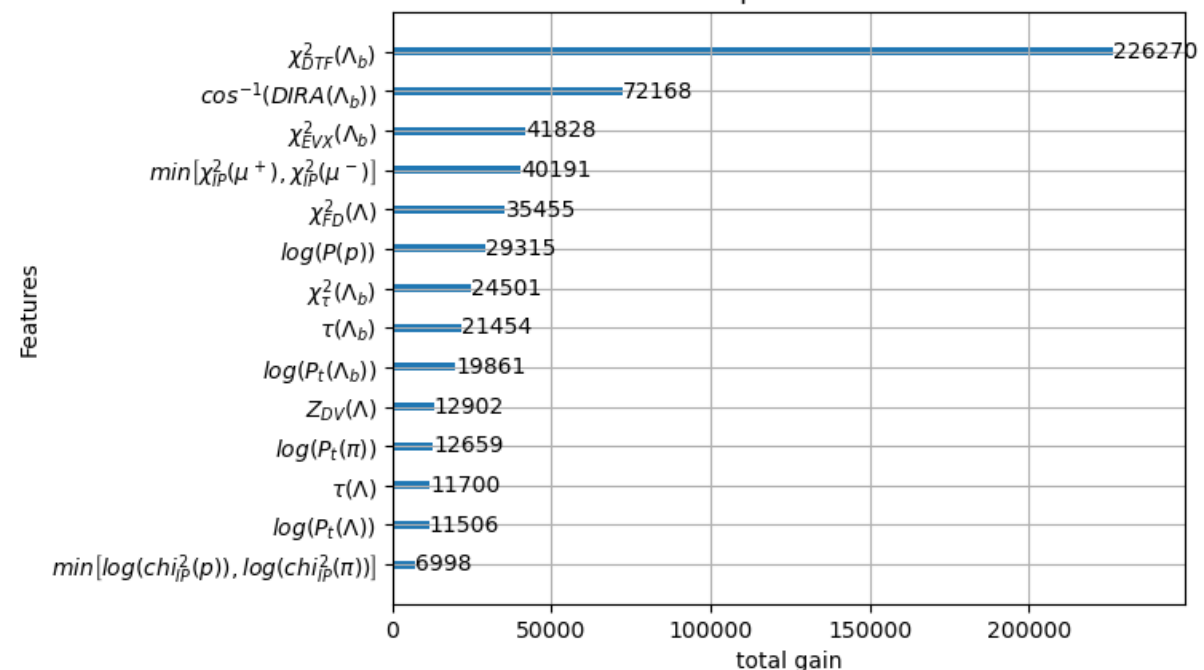
Feature importance. Run1 LL



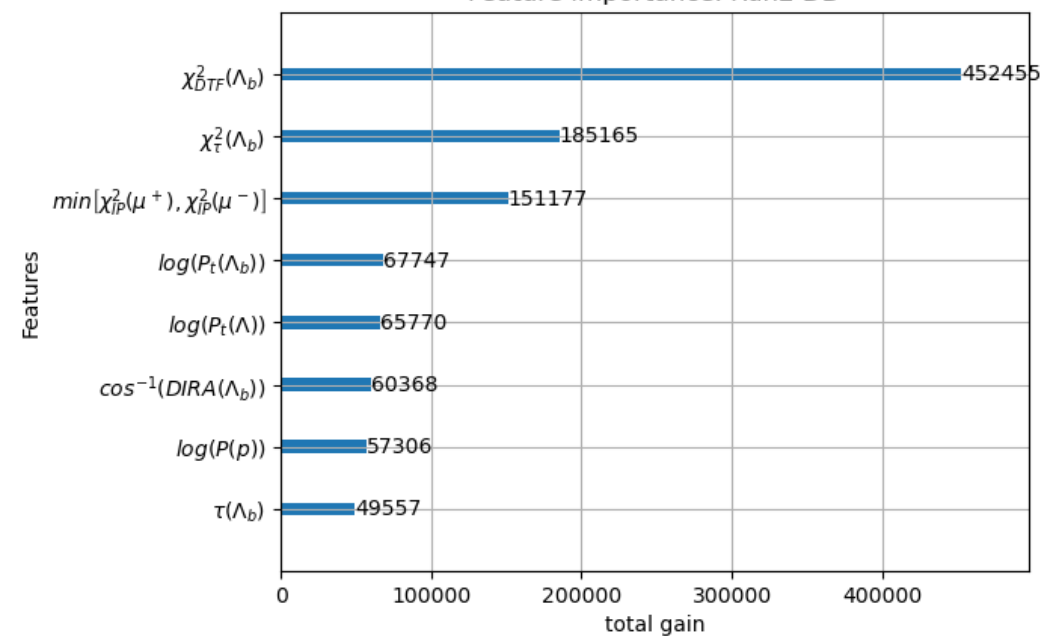
Feature importance. Run1 DD



Feature importance. Run2 LL

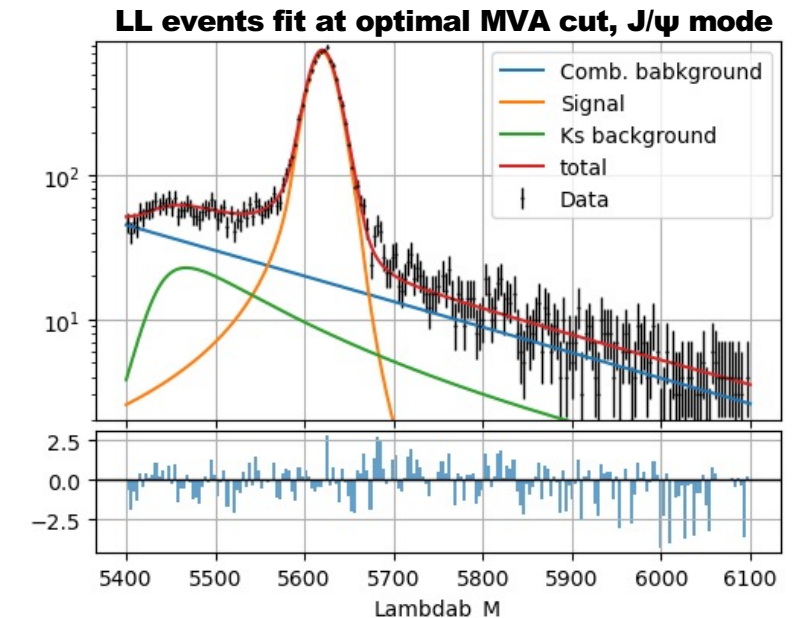
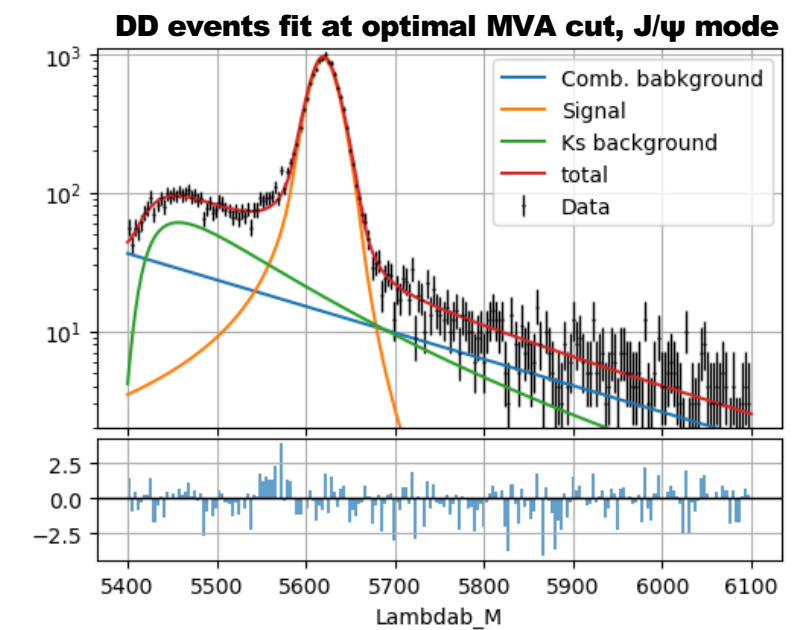


Feature importance. Run2 DD



Λ_b mass fit

- Fitting signal with DECB. Tail parameters and the ratio between sigmas are prefitted on MC.
- The combinatorial background is fitted with an exponential distribution.
- Misidentification background:
 - $B^0 \rightarrow \mu^+ \mu^-$ ($K_S \rightarrow \pi^+ \pi^-$)
 - One of the pions is misidentified as proton, and because of this, entire event considered to be Λ_b event
 - Misidentification background is fitted with Johnson SU function (ad hoc solution)
 - Misidentification background is too small to be visible in rare mode, but not negligible in resonant mode.



Variable	Run 1		Run 2	
	LL	DD	LL	DD
Calculated signal yield	133 ± 40	162 ± 49	456 ± 137	594 ± 178
Fitted signal yield	114 ± 12	174 ± 16	336 ± 22	528 ± 28
FOM (calculated)	10,8	11,0	18,8	20,8