Direct measurement of electromagnetic dipole moments of strange baryons at LHCb

Giorgia Tonani on behalf of Milano, Valencia, UCAS and CERN groups

Strong2020 workshop

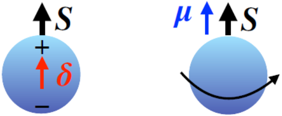
23rd June, 2022

Electromagnetic dipole moments: definition

Static property of particles
In a quantum system:

- Electric dipole moment (EDM)

$$\boldsymbol{\delta} = d\mu_B \frac{\mathbf{P}}{2}$$



- Magnetic dipole moment (MDM)

$$\boldsymbol{\mu} = g\mu_B \frac{\mathbf{P}}{2}$$

with d gyroelectric factor, g gyromagnetic factor,
$\mu_B = e\hbar/(2mc)$ particle magneton
$\mathbf{P} = 2 < \mathbf{S} > /\hbar$ the spin polarization vector, with **S** spin operator

Electromagnetic dipole moments: physics motivation

$$H = -\boldsymbol{\delta} \cdot \boldsymbol{E} \;\; -\boldsymbol{\mu} \cdot \boldsymbol{B}$$

$$\xrightarrow{P,\,T} \quad H = +\boldsymbol{\delta} \cdot \boldsymbol{E} \;\; -\boldsymbol{\mu} \cdot \boldsymbol{B}$$

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[1] Phys. Lett. B291 (1992) 293

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- MDM measurement → experimental test of low-energy QCD models, related to non-perturbative QCD dynamics + sensitive to internal baryon dynamics

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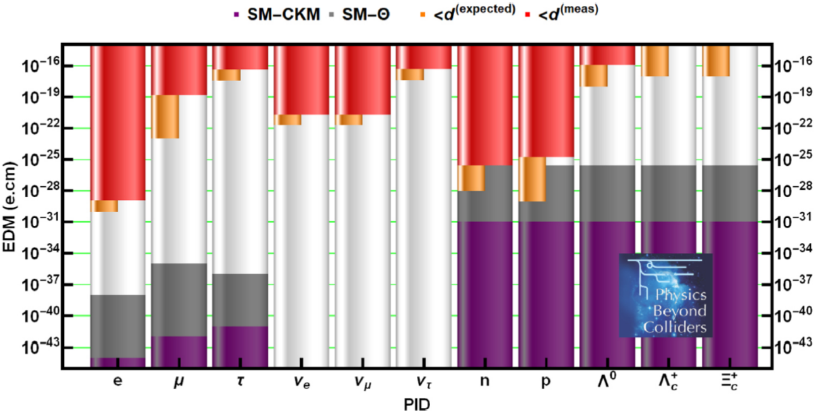
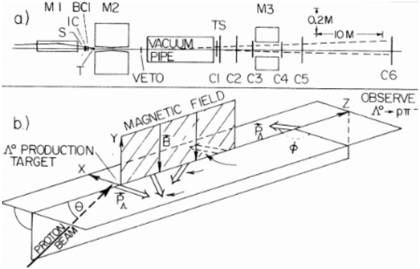
Electromagnetic dipole moments: state of the art

Wordwide effort to search EDMs, we focus on Λ baryons



J. Phys. G: Nucl. Part. Phys. **47** (2020) 010501

Λ EDM/MDM: state of the art



Measurement performed at Fermilab with p-Be fixed-target experiment:

- 300 GeV protons
- strong Λ production
- low Λ polarization ≈ 9%

- Λ EDM current upper limit: $< 1.5 \times 10^{-16} e\,\mathrm{cm}$ at 95% of confidence level (PRD 23, 814 (1981))

- Λ MDM current value: $(0.6138 \pm 0.0047)\ \mu_N$ (PRL 41, 1348 (1978))

- No $\bar{\Lambda}$ polarization → not possible to measure $\bar{\Lambda}$ MDM

Electromagnetic dipole moments: experimental method

Spin polarization vector precession in the magnetic field (usually used for tracking purposes)

Electromagnetic dipole moments: experimental method

Spin polarization vector precession in the magnetic field (usually used for tracking purposes)

Simple example: assuming initial polarization $\vec{P}_0 = (0, 0, P_0)$ and magnetic field $\vec{B} = (0, B_y, 0) \rightarrow$ final polarization

$$\vec{P}_f = (-P_0 \sin\Phi, -P_0 \frac{d\beta}{g} \sin\Phi, P_0 \cos\Phi), \qquad (1)$$

with $\Phi \propto g \int_0^l \vec{B} dl'$ ($\approx \pi/4$ with LHCb dipole magnet)

Electromagnetic dipole moments: experimental method

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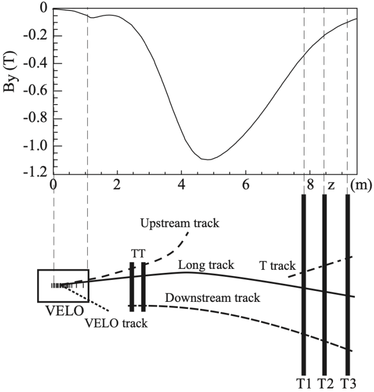
EDM/MDM $\Leftrightarrow \mathrm{P}_{f\,y}$, $\Phi \Leftrightarrow \vec{P}_f$, $\vec{P}_0$ measurement

Electromagnetic dipole moments: experimental method

Main ingredients:

- Source of polarized Λ baryons: weak decays (large longitudinal polarization, due to P violation)
- Magnetic field $\vec{B}$: LHCb dipole magnet
- Detector: LHCb



[a]

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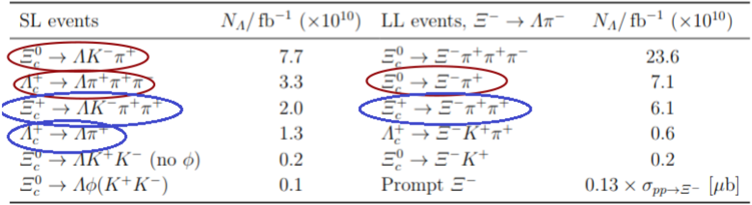
[a] Int. J. Mod. Phys. 634 A30 (2015)

Source of polarized Λ baryons



SL events	$N_\Lambda/\mathrm{fb}^{-1}$ $(\times 10^{10})$	LL events, $\Xi^- \to \Lambda\pi^-$	$N_\Lambda/\mathrm{fb}^{-1}$ $(\times 10^{10})$
$\Xi_c^0 \to \Lambda K^- \pi^+$	7.7	$\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-$	23.6
$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$	3.3	$\Xi_c^0 \to \Xi^- \pi^+$	7.1
$\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+$	2.0	$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$	6.1
$\Lambda_c^+ \to \Lambda \pi^+$	1.3	$\Lambda_c^+ \to \Xi^- K^+ \pi^+$	0.6
$\Xi_c^0 \to \Lambda K^+ K^-$ (no ϕ)	0.2	$\Xi_c^0 \to \Xi^- K^+$	0.2
$\Xi_c^0 \to \Lambda \phi (K^+ K^-)$	0.1	Prompt Ξ^-	$0.13 \times \sigma_{pp\to\Xi^-}$ [μb]

[2]

- $\Xi_c^0 \to \Xi^- \pi^- \pi^+ \pi^+$: excluded, not dedicated trigger available, low efficiency

Another decay considered:

- $\Lambda_b^0 \to J/\psi\,\Lambda$: 100% Λ polarisation measured by LHCb collaboration [3], high trigger efficiency in $J/\psi \to \mu^+\mu^-$ decay

Prompt Λs not an option: not polarized at LHC (PRD 91 3, 2015)

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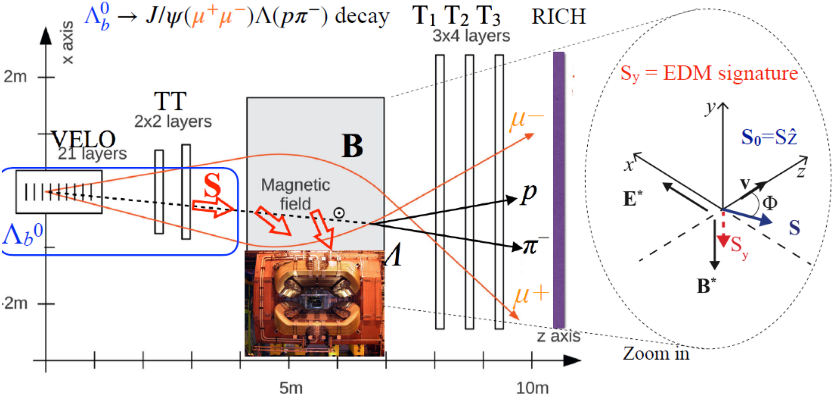
[2] EPJC **77**, 181, 2017

[3] JHEP, **2020**, 110, 2020

Electromagnetic dipole moments: experimental method

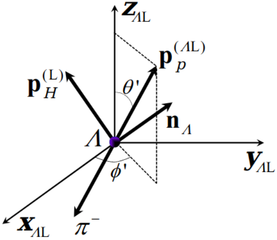
We focus on Λ baryons: $\tau \approx 10^{-10}s$, p ≈ 50 GeV/c → L ≈ 5 m
Λ baryons spin precession in the LHCb magnetic field



initial polarization $\mathbf{P}_0$:
upstream the magnet

final polarization $\mathbf{P}_f$:
downstream the magnet

Λ polarization measurement



Λ decay theoretical angular distribution in Λ helicity frame ($\frac{1}{2} \to \frac{1}{2}\ 0$):

$$\frac{d\Gamma}{d\Omega}(\cos\theta_p, \phi_p, \vec{P}) \propto 1+\alpha P_x \sin\theta_p \cos\phi_p+\alpha P_y \sin\theta_p \sin\phi_p+\alpha P_z \cos\theta_p, \quad (2)$$

Λ decay ($\to p\pi^-$) asymmetry parameter $\alpha = 0.732 \pm 0.014$ [4].

Experimental distribution: theoretical one to be corrected with efficiency and background contribution

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[4] PDG, Prog.Theor.Exp.Phys. **2020**

Introduction

Experimental method

Status of EDM/MDM measurement

- Polarization upstream the magnet $\mathbf{P}_0$
- Polarization downstream the magnet $\mathbf{P}_f$

Conclusions

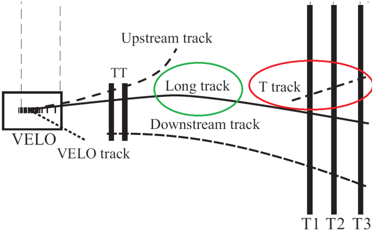
Current status of Λ polarization measurement

Polarization upstream the magnet $\mathbf{P}_0$:

- Ongoing analysis: $\Xi_c^0 \to \Lambda K^- \pi^+$, $\Lambda_c^+ \to \Lambda \pi^- \pi^+ \pi^+$ and $\Xi_c^0 \to \Xi^- (\to \Lambda \pi^-) \pi^+$
- $\Lambda_b^0 \to J/\psi\, \Lambda$: 100% initial Λ polarization

Polarization downstream the magnet $\mathbf{P}_f$:

- Most challenging part, never performed a physics measurement with T tracks in LHCb
- Reconstruction feasibility demonstrated with $\Lambda_b^0 \to J/\psi\, \Lambda$ decay (LHCb-DP-2022-001 paper in review by LHCb)



Introduction

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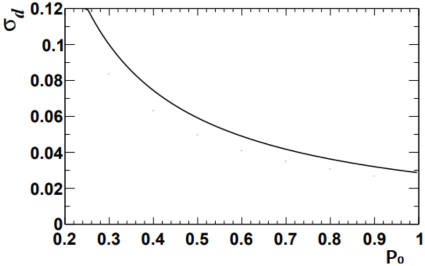
Initial polarization and EDM/MDM sensitivity

We are interested in as large as possible initial polarization $\mathbf{P}_0$, sensitivity saturates close to 100%

$$\vec{\delta} = d\mu_B \vec{P}/2 \qquad \sigma_d \propto 1/P_0$$



[5]

Same behaviour for MDM

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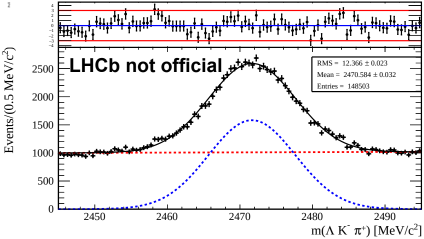
[5] EPJC **77**, 181, 2017

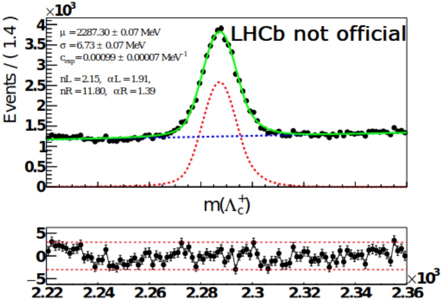
Ongoing analysis: $\Xi_c^0 \to \Lambda K^- \pi^+$ and $\Lambda_c^+ \to \Lambda \pi^- \pi^+ \pi^+$ selection

$\Xi_c^0 \to \Lambda K^- \pi^+$



60k signal candidates, 50% purity, 2015+2016+2017 dataset

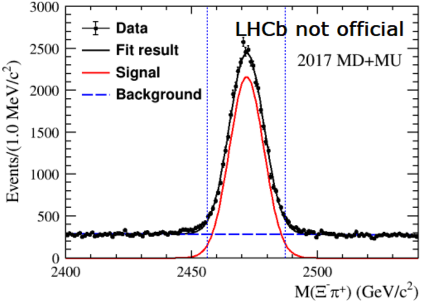
$\Lambda_c^+ \to \Lambda \pi^- \pi^+ \pi^+$



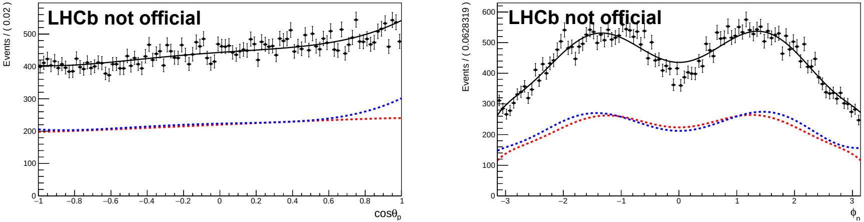
23k signal candidates, 54% purity, 2016 dataset

Ongoing analysis: $\Xi_c^+ \to \Xi^-(\to \Lambda\pi^-)\pi^+$ selection

- Ongoing study, selection is completed (36 k, 80% purity)
- Higher purity, lower background than previous decays
- Preliminarily measured higher Λ polarization than previous decays due to two-body decay topology (see next slide)



Preliminary angular fit in $\Xi_c^0 \to \Lambda K^- \pi^+$ decays integrated over the phase space



Signal: red, Bkg: blue

$|\vec{P}_\Lambda| \approx 0.15$ ($|\vec{P}_\Lambda| \approx 0.25$ in $\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$) → Low polarization with respect to other weak decays (e.g. $\Lambda_b^0 \to J/\psi\,\Lambda \quad |\vec{P}_\Lambda| \approx 1$)

→ Conclusion: in multi-body decays resonances interfere and a polarization dilution is introduced [6] → better to consider two-body weak decays for the first EDM/MDM measurement

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[6] PRC 95 (2017)

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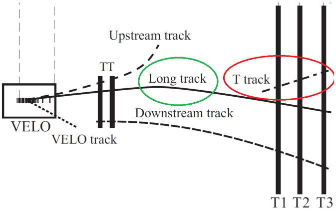
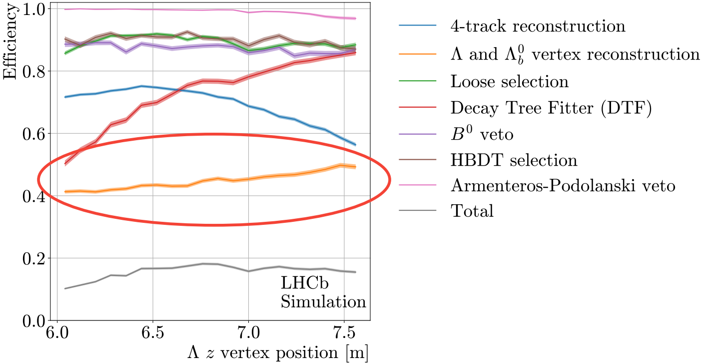
Main challenges to measure the polarization downstream the magnet

Challenging reconstruction of Λ baryons decaying downstream the magnet, using T tracks:

- momentum resolution of 20-30% (0.5-1% Long tracks) → crucial to apply kinematic constraints to improve it
- long propagation distances → need RungeKutta extrapolator (cubic interpolation for Long tracks)
- vertex reconstruction resolution of 10-50 cm ($\approx 100\ \mu$m for Long tracks)

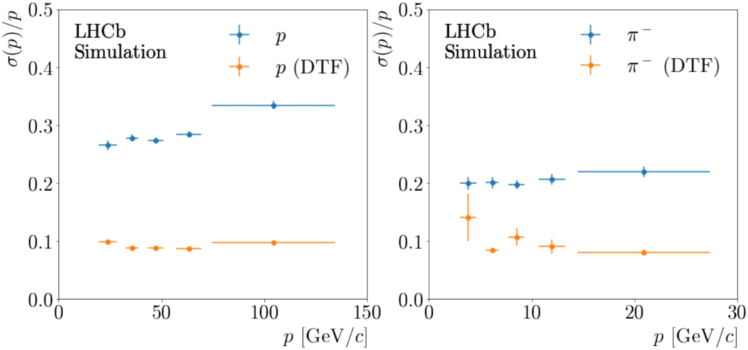


$\Lambda_b^0 \to J/\Psi\Lambda$ reconstruction efficiency



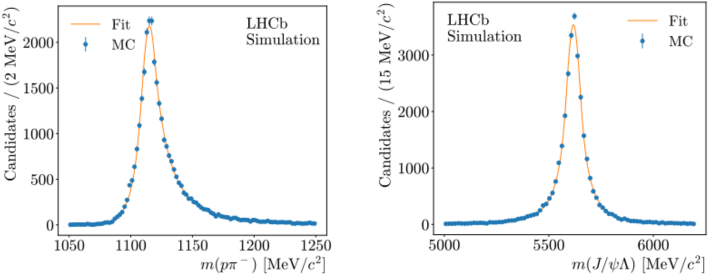
Bottleneck is the vertex reconstruction efficiency for Λ and Λ_b^0 $\to$ dedicated studies to improve it are ongoing

$\Lambda_b^0 \to J/\Psi\Lambda$ reconstruction resolutions



- Low integrated magnetic field in T track region → large bending radius, poor momentum resolution
- Instead of bottom-up reconstruction of the decay, fit entire decay chain simultaneously with DecayTreeFitter tool
- Momentum resolution improvement using DecayTreeFitter with primary vertex, J/Ψ and Λ invariant mass constraints

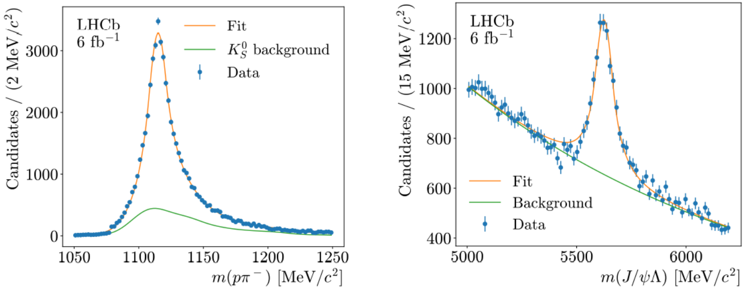
$\Lambda_b^0 \to J/\Psi\Lambda$ reconstruction: performance on simulation



Invariant mass fit with double-tailed Crystal Ball

Core invariant mass resolution of 6.8 $\pm$ 3 MeV/c^2 for Λ and 37$\pm$ 1 MeV/c^2 for Λ_b

$\Lambda_b^0 \to J/\Psi\Lambda$ reconstruction: performance on data



Invariant mass fit with double-tailed Crystal Ball.
Background in the m(pπ^-) distribution parameterised using a template determined from simulation.
Background in m($J/\Psi\Lambda$) parametrised with exponential pdf.

Samples of about 6140 $\Lambda_b^0 \to J/\Psi\Lambda$ signal events are reconstructed. Core mass resolutions of 7.7 ± 0.4 and 41 ± 2 MeV/c^2 for Λ and Λ_b^0 respectively

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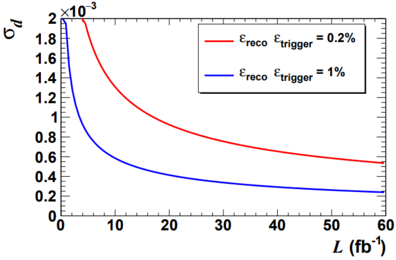
Sensitivity studies



[7]

- Current limit Λ EDM: Fermilab, 1981, fixed target experiment
  Λ EDM $< 1.5 \times 10^{-16}$ ecm, with 95% C.L.
- Expected improvement Λ EDM: LHCb project, sensitivity reachable $\approx 1.3 \times 10^{-18} ecm$ with Run 1, 2 data

- Current measured value Λ MDM:
  $0.613 \pm 0.004\ \mu_N$
- Expected improvement Λ MDM:
  sensitivity reachable $\approx 10^{-4} \mu_N$ with Run 1, 2 data

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[7] EPJC **77**, 181, 2017

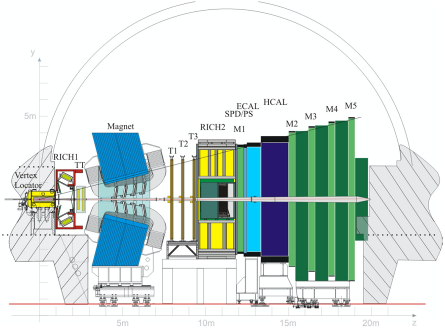
Next steps

- proof-of-principle measurements of Λ dipole moments using $\Lambda_b^0 \to J/\Psi\Lambda$ decays (data already available Run 1+2)

- Addition of Cherenchov detector info (RICH2) to improve momenta resolution for T tracks (under investigation)

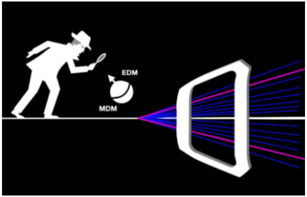
- Custom vertex fitting to increase the efficiency

- Optimization of trigger selection for Run3



Conclusions

- EDM and MDM measurement are sensitive to physics in and beyond the Standard Model



- Λ Polarization measurement ongoing in $\Xi_c^0 \to \Lambda K^- \pi^+$, $\Lambda_c^+ \to \Lambda \pi^- \pi^+ \pi^+$ and $\Xi_c^0 \to \Xi^-(\to \Lambda \pi^-)\pi^+$ decays
  - Demonstrated feasibility of reconstruction of Λ baryons decaying downstream the magnet using $\Lambda_b^0 \to J/\Psi \Lambda$ decays between 6 and 7.6 m from the IP (in LHCb collaboration review)
  - EDM and MDM measurement method is feasible in LHCb, no showstopper identified

EMDMs, we are looking for you!

Keep in touch!

- See you at the SELDOM Workshop in Gargnano del Garda 26-28 September 2022 (agenda will be published here soon: ▸ Agenda)
- Online: ▸ SELDOM-web-page
- On Twitter: ▸ SELDOM-Twitter

Backup

Event selection overview

Run 2 data (6 fb^{-1}) + MC simulated signal

- Online di-muon trigger: detached $J/\Psi \to \mu^+\mu^-$
- Reconstruction: vertex with PV and mass constraints
- Selections applied:
  - loose selection based on kinematic variables
  - threshold cut on HBDT classifier output
  - Veto on physical background (Λ_b^0 or B^0)
  - Armenteros-Podolanski (AP) plot