Search for Rare b to Open-Charm Two-Body Decays of Baryons at LHCb

Promotionsverteidigung

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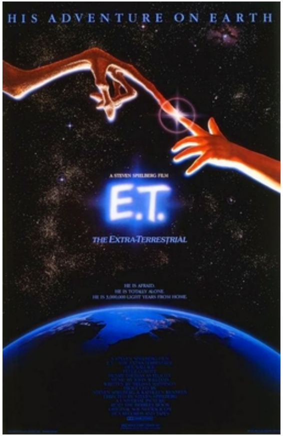
Introduction

What if? Consider communication with an alien…

- → Before flying by we want to know: is alien world made out of **anti-matter***?
- → Can we propose an experiment to find out?



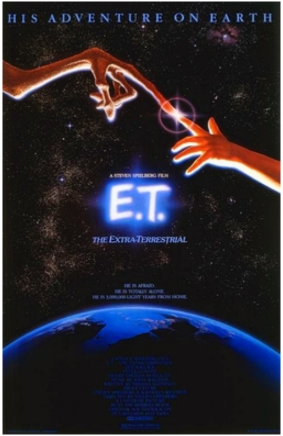
(Image: John Alvin, (c) 1982 Universal Studios)

**cf.* fermions: if ψ obeys $(i\not{\partial} - m)\psi = 0$, then $(\mathrm{CP}\ \psi)$ is also a solution (**C**harge and **P**arity inverted)

Introduction

What if? Consider communication with an alien…

- → Before flying by we want to know: is alien world made out of **anti-matter***?
- → Can we propose an experiment to find out?
- → Where not to look for: QED, QCD (neither **C**harge (C), nor **P**arity (P), nor **T**ime reversal (T) symmetry is broken here
- → What about weak interaction?
  - → P violation measured with Wu-Experiment!
  - → …but asymmetry cancels exactly when using anti-matter
  - → **Is definition of anti-matter ambiguous?**



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* *cf.* fermions: if ψ obeys $(\mathrm{i}\partial\!\!\!/ - m)\psi = 0$, then $(\mathrm{CP}\,\psi)$ is also a solution (**C**harge and **P**arity inverted)

On the other hand…

- Baryon asymmetry of the Universe:

$$\mathcal{O}(\eta_{\text{cosm}}) = \mathcal{O}\left(\frac{n_B - n_{\overline{B}}}{n_\gamma}\right) \sim 10^{-10} \neq 0,$$

  with $n_{B,\overline{B},\gamma}$ = number of baryons, anti-baryons and photons

- Universe is filled with matter (rather than anti-matter*)
- Standard Model of Cosmology: Big Bang produces $n_B = n_{\overline{B}}$ (**CP invariant**)
- Evolution: QED and QCD are **CP invariant**

* *i.e.*, most likely alien world is made out of matter as well

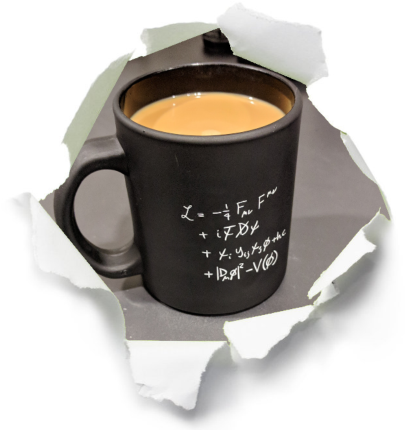
Introduction

Can we explain $\mathcal{O}(\eta_{\text{cosm}})$?

- → **No!** We fail to describe one of the most obvious property of our Universe!

Can we (at least) describe some CP violating processes?

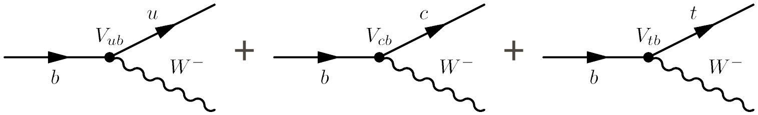
- → Yes! The Standard Model of Particle Physics contains a CP violating sector (weak interaction)
- → However, it does not predict the right order of magnitude of η_{cosm} !



Introduction

- Diagonalizing Yukawa matrices* leads to **quark mass eigenstates** q, but skews **quark flavor eigenstates** q'

$$\mathcal{J}^{\mu}_{cc} \supset (\overline{u'},\, \overline{c'},\, \overline{t'})\, \gamma^{\mu} \frac{1-\gamma^5}{2} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \quad \longrightarrow \quad (\overline{u},\, \overline{c},\, \overline{t})\, \gamma^{\mu} \frac{1-\gamma^5}{2} V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- This introduces the non-trivial transformation matrix V_{CKM} for quarks (CKM matrix)
- V_{CKM} is a **unitary** 3×3 matrix (CP violation *in* complex phases)

* *cf.* Higgs mechanism

State-of-the-art

What we know

- → We understand CP violation (CPV) on quark level in the framework of the Standard Model (SM)
- → CPV is predicted and confirmed with high confidence for **mesons*** at particle accelerators

What we don't know

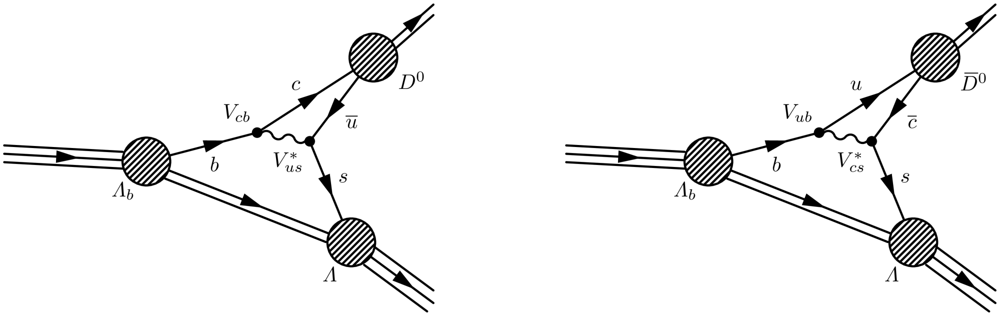
- → Absence of anti-**baryons*** is a large scale CPV which we cannot explain
- → (strong CPV, neutrino CPV, Sakharov conditions, ...)

Idea of this analysis

- → Establish (yet unknown) **baryon** decay which can be used (in the future) to measure CPV parameter of the SM

*meson / anti-meson: $(q\overline{q})$, baryon: (qqq), anti-baryon: $(\overline{qqq})$

The decay $\Lambda_b \to D^0 \Lambda$



- Perfectly suited for LHCb
- CKM angle: $\gamma + \mathcal{O}(\lambda^4)$ (without CPV in D^0 system)
- CPV in $\Lambda_b \to D^0/\overline{D}^0 \Lambda$ and
  - $D^0/\overline{D}^0 \to K^+\pi^-$ (CPV but Cabibbo suppressed, **future prospect**)
  - $D^0/\overline{D}^0 \to K^+K^- / \pi^+\pi^-$ (CPV but Cabibbo suppressed, **future prospect**)
  - $D^0 \to K^-\pi^+$ (no CPV but Cabibbo favored, **this analysis**)

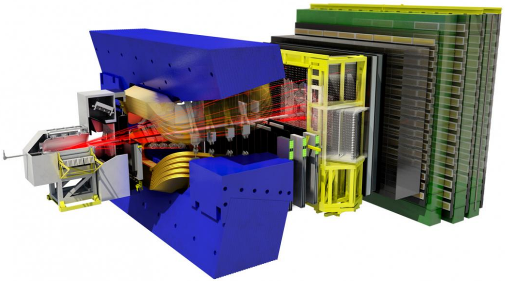
Large Hadron Collider

(Symbolic image, picture taken at CERN site)

- World's largest and highest-energy particle accelerator
- Built by CERN
- Collides proton beams with $\sqrt{s} = 13$ TeV
- b baryon factory (Λ_b is lightest b baryon)

LHCb Experiment

"LHCb is an experiment set up to explore what happened after the Big Bang that allowed matter to survive and build the Universe we inhabit today"



- One of the four major experiments at the LHC
- Dataset: $6\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$

Multipurpose detector, *e.g.*:

- Excellent vertex resolution
- Powerful particle identification

Outline

Why / What?

- Pave the way to measure CPV in decays of baryons at colliders
- Prose: search for the decays

$$\Lambda_b/\Xi_b^0 \to [K^-\pi^+]_{D^0}\,[p\pi^-]_{\Lambda}$$

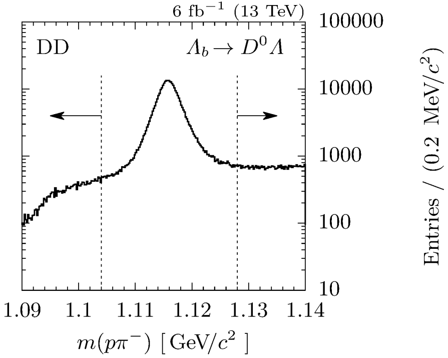
How?

- (Data calibration and pre-processing†)
- Classification of data as *signal* and *background* using MVA*
- (Study various physical backgrounds†)
- Count signal events with fit and estimate stat. significances*
- Estimate branching ratios $\mathcal{B}(\Lambda_b \to D^0\Lambda)/\mathcal{B}(\Lambda_b \to D^0 p\pi^-)^\dagger$ and $\mathcal{B}(\Xi_b^0 \to D^0\Lambda)/\mathcal{B}(\Lambda_b \to D^0\Lambda)^*$

†not discussed here, *partially discussed here

How to find genuine decays? —Example $\Lambda \to p\pi^-$

- Create Λ candidates: $\{\Lambda\} := \{p\} \otimes \{\pi^-\}$
- Use inv. mass $m(\Lambda)^\star \stackrel{?}{=} m(p\pi^-)$ as proxy
- Separate components:
  1. Combinatorial background
     (random track combinations)
  2. physical background
     (*e.g.*, $K_S \to \pi^+\pi^-$)
  3. genuine $\Lambda \to p\pi^-$ decays



(*PDG: $m(\Lambda) \approx 1.117\,\mathrm{GeV}/c^2$)

Technical detail: only (weak) Cabibbo suppressed decays possible for Λ

- *long* lifetime
- some Λ decay outside (inside) of first detector element: refer to as **DD** (**LL**)
- different detector response, separate analysis necessary

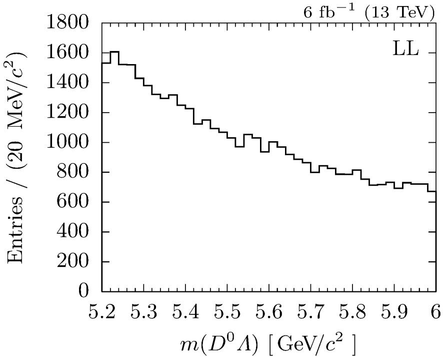
Do the same for $\Lambda_b/\Xi_b^0 \to D^0 \Lambda$?

i.e., $\{\Lambda_b/\Xi_b^0\} := \underbrace{\{K^-\} \otimes \{\pi^+\}}_{\{D^0\}} \otimes \underbrace{\{p\} \otimes \{\pi^-\}}_{\{\Lambda\}}$

Searching for $\Lambda_b/\Xi_b^0 \to D^0\Lambda$

No signal visible!

- Background (at this stage) mainly combinatorial
- Need to increase
  - purity of $\{D^0\}$
  - purity of $\{\Lambda\}$
  - filter $\{D^0\} \otimes \{\Lambda\}$ for $\Lambda_b/\Xi_b^0 \to D^0\Lambda$ decays by constraining physical properties
- (Carefully analyse physical backgrounds†)



(PDG: $m(\Lambda_b) \approx 5.620\,\mathrm{GeV}/c^2$,
PDG: $m(\Xi_b^0) \approx 5.792\,\mathrm{GeV}/c^2$)

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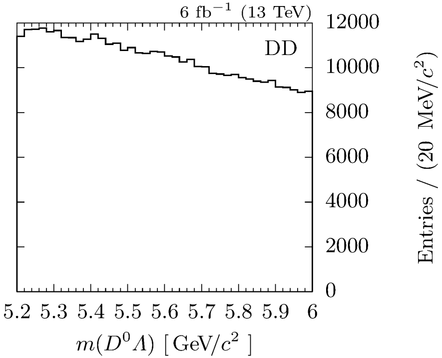

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Searching for $\Lambda_b/\Xi_b^0 \to D^0\Lambda$

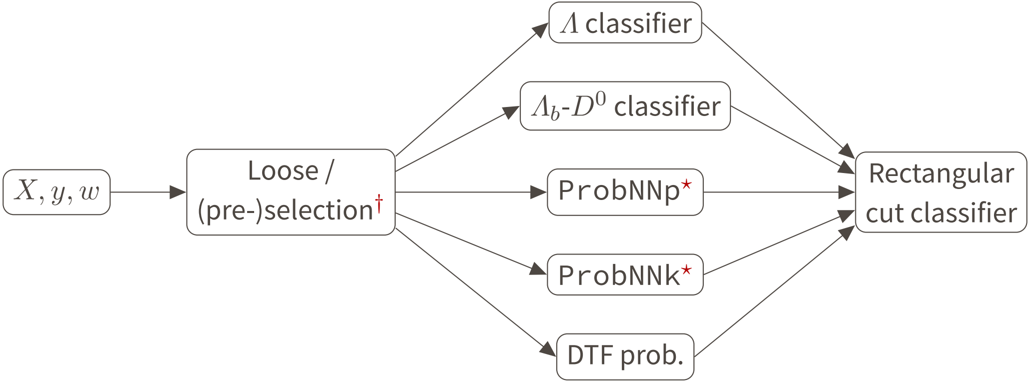
Use ML to rescue! Classification problem

- Separate ***signal*** (genuine $\Lambda_b/\Xi_b^0 \to D^0\Lambda$)
- ...from (combinatorial) ***background***
- Labels?
  - use MC simulated decays for class *signal*†
  - use recorded data from sidebands for class *background*

(Image: R. Diepenheim on thenounproject.com)

† calibration needed (not discussed here)

MVA methodoloy

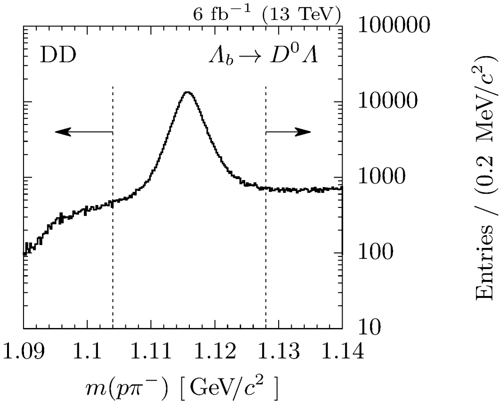


Training: classify m data $X \in \mathbb{R}^{m \times n}$ with n features using labels $y \in \{\text{sig., bkg.}\}^m$ and calibration factors† $w \in \mathbb{R}^m$ with $\mathcal{O}(m) = 10k, n = 18$

⋆ pre-trained shallow NN

Example: Λ classifier

- 5 features of $\{\Lambda\}$:
  1. transverse momentum
  2. angle between momentum and connecting line between pp-IA point (PV) and Λ decay vertex
  3. χ^2 improvement of PV with Λ track
  4. fit prob. of decay vertex
  5. significance of flight distance
- Separate classifiers for LL and DD
- Optimize hyper-parameters of 5 classifiers using grid search w.r.t. ROC-AUC* value



* Prob. that clf. will rank randomly chosen *sig.* instance higher than randomly chosen *bkg.* one

Example: Λ classifier

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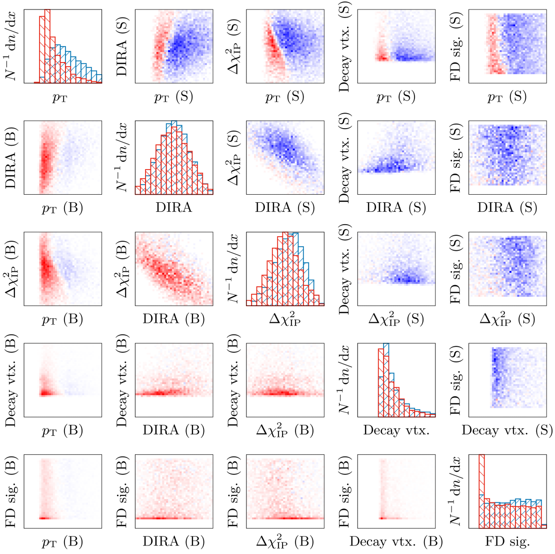

(track type **DD**)

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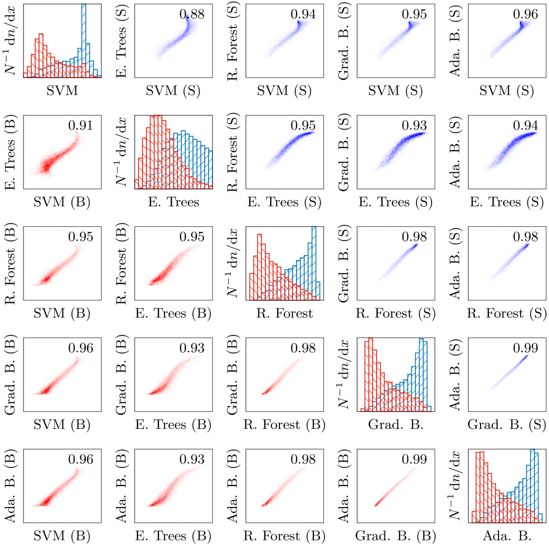

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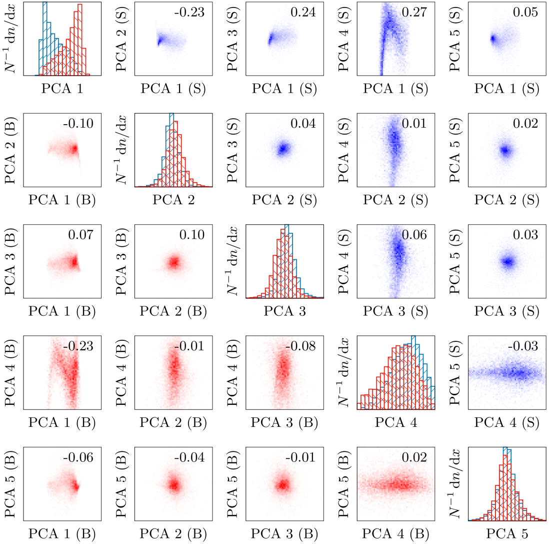

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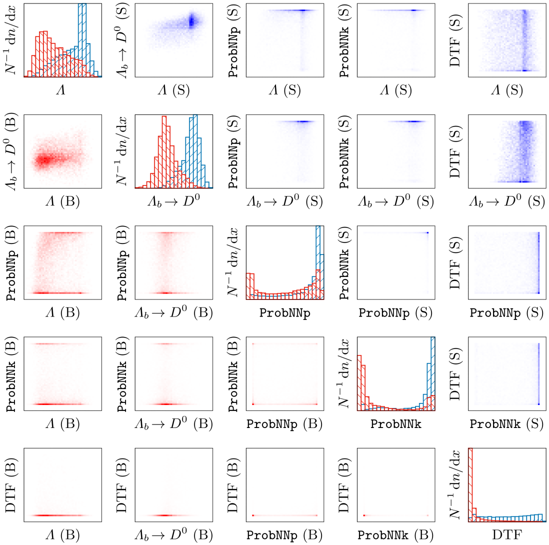
Fusion of high level classifiers



(track type DD)

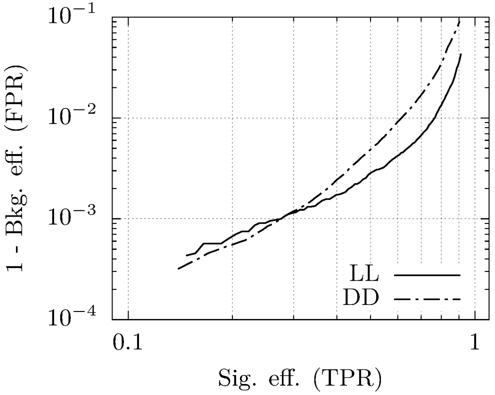
Fusion of high level classifiers

- → Optimize rectangular cut classifier (to avoid MC fidelity issues†)
- → …using classifier outputs as features
  1. Λ classifier
  2. Λ_b-D^0 classifier
  3. `ProbNNp`
  4. `ProbNNk`
  5. Decay tree fit
- → (Compare rect. cut clf. eff. against decision tree†)

Classifier fusion

Optimize rect. cut clf.

- Minimize FPR* at given TPR**
- Numerically noisy: use simulated annealing for finding minimum
- Set thresholds at TPR $\approx 50\,\%$ (LL) and TPR $\approx 30\,\%$ (DD)
- (Refine *optimal* TPR with in a second, tight max. step only using Λ/Λ_b-D^0 classifiers†)



*FPR: false positive rate, *i.e.*, genuine bkg. predicted as sig.
**TPR: true positive rate, *i.e.*, genuine sig. predicted as sig.

Classifier fusion

Optimize rect. cut clf.

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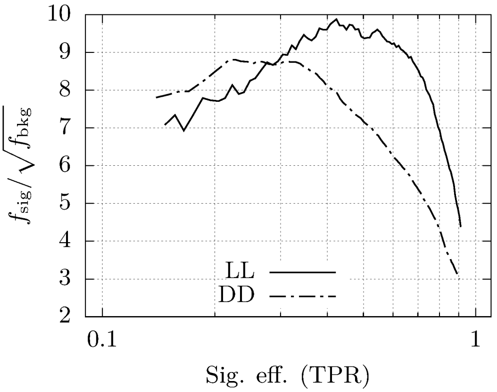

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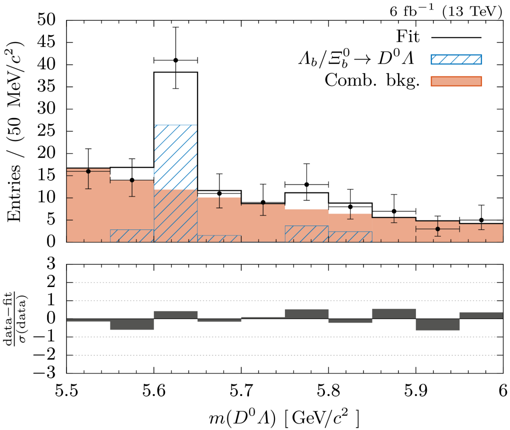
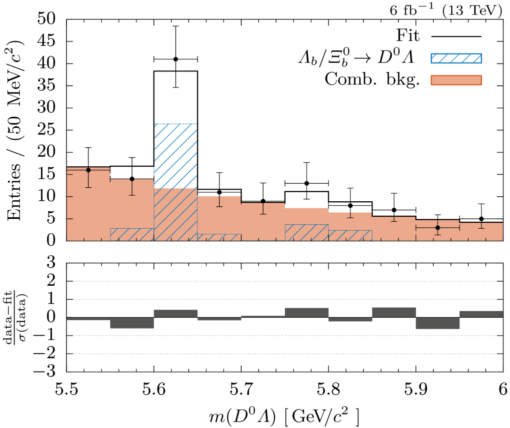
Fit invariant mass



Result: $n(\Lambda_b) = 31(7)$ and $n(\Xi_b^0) = 6(4)$
(only stat. uncertainty given)

- Fit remaining 260 signal candidates (rec. data)
- Simultaneously fit rec. and MC sim. data of both track types (6 samples)
  - 23 parameters
  - most of them shared between at least two samples
- Vary fit model to check for systematic error
  - change parametrization
  - change inv. mass range
  - … (8 variations in total†)

Fit invariant mass



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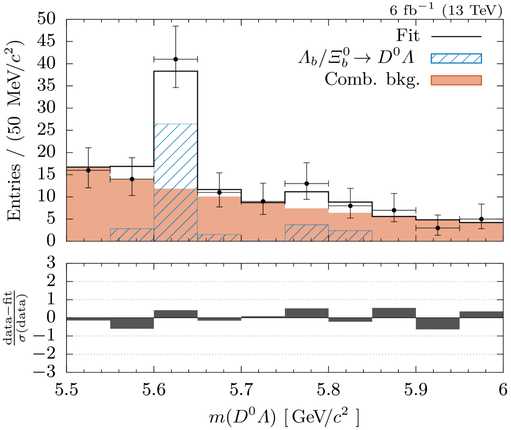
Sanity checks

→ (Bias of estimated yields†)

→ (Validity of (stat.) error estimates†)

Fit invariant mass



Result: $n(\Lambda_b) = 31(7)$ and $n(\Xi_b^0) = 6(4)$
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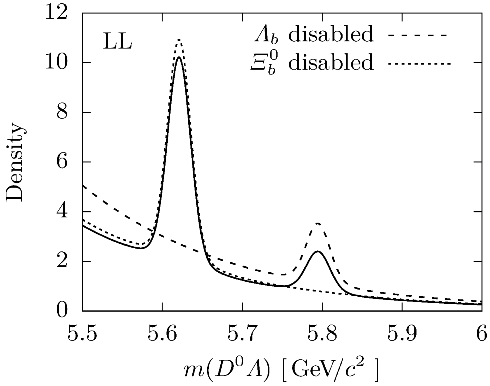
Stat. significance of yields

- Fix all parameters from MC sim.
- Run fit twice
  - $\mathcal{L}$ for signal comp. **enabled**
  - $\mathcal{L}$ for signal comp. **disabled**
- Stat. sign. given by $\sqrt{-2\Delta\ln\mathcal{L}}$

Statistical significance of yields

Wilks theorem

- Here: if sample size tends to infinity $2\Delta\ln\mathcal{L}$ tends to a χ^2-distribution with one DoF
- Hence: stat. significance of rej. null hypothesis *no signal* is $\sqrt{-2\Delta\ln\mathcal{L}}$
- Test assumption with pseudo experiment (*Toy MC*)
  - sample Toy MC from fitted PDF w/o signal component
  - run fit twice (w/ and w/o signal component)



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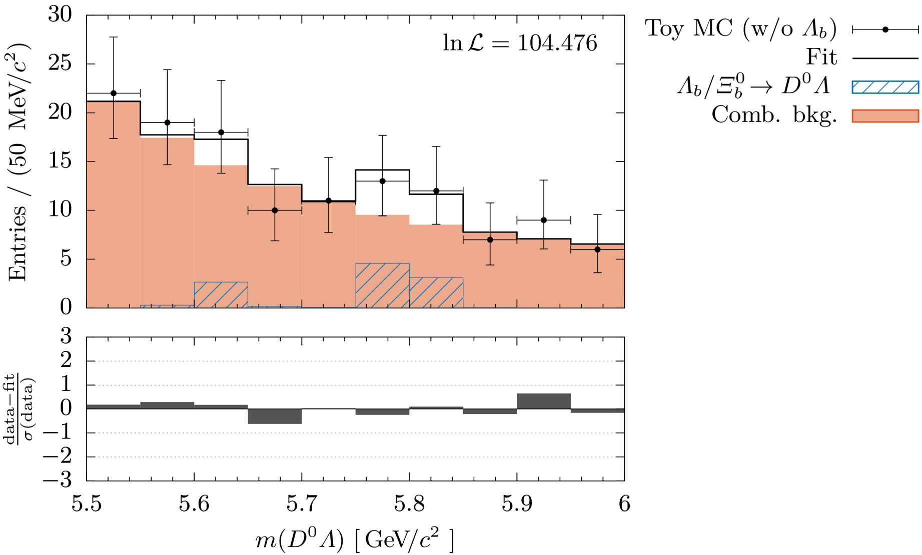

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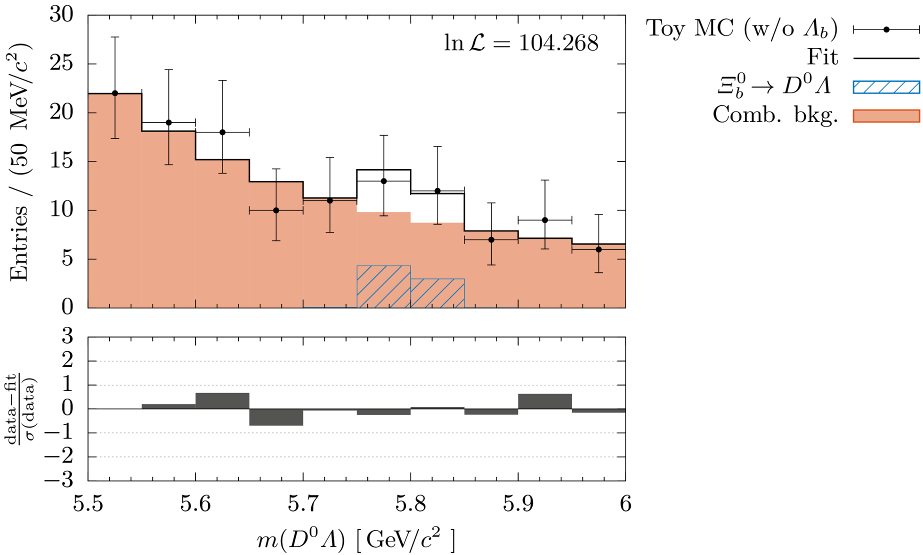

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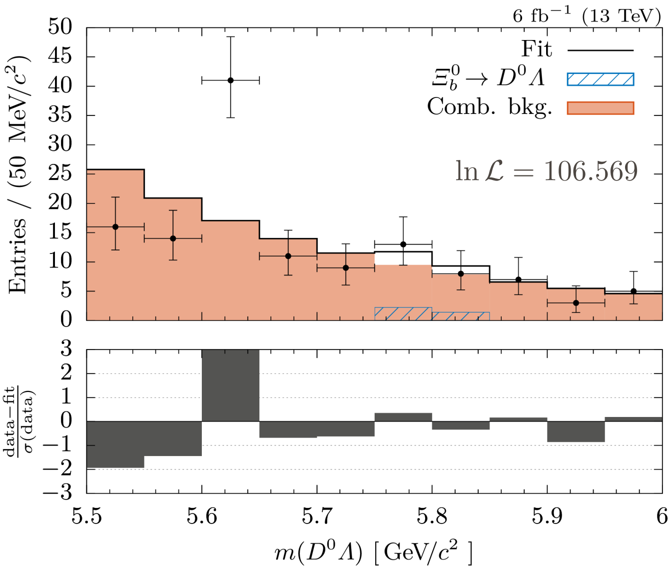

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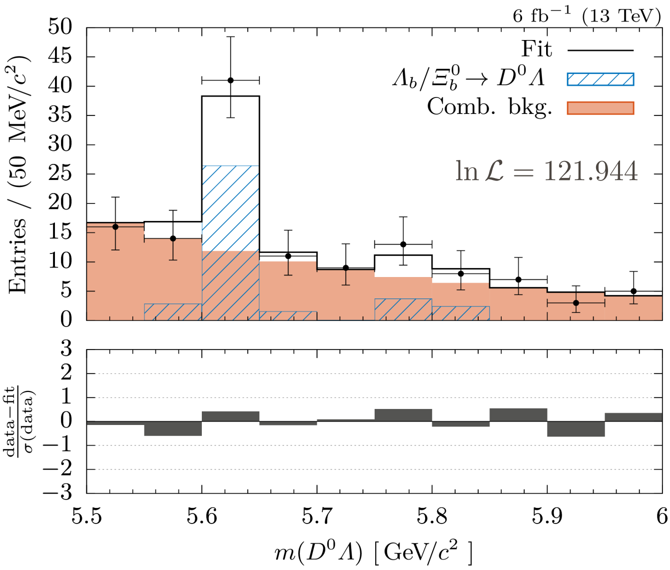

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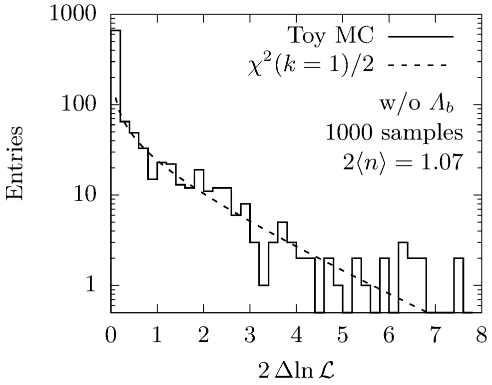


Wilks theorem

- → Distribution of $\Delta\ln\mathcal{L}$ indeed follows a χ^2-distribution with 1 DoF
- → Wilks theorem is applicable!

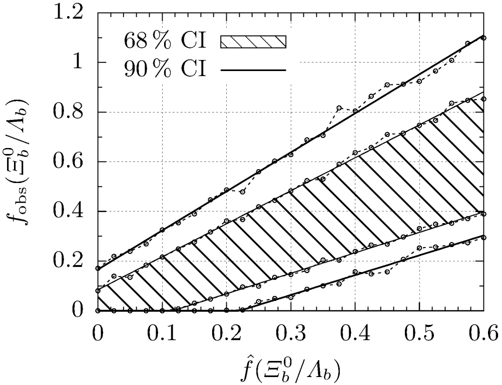
Estimated **yield significances**: **5.5** for $\Lambda_b \to D^0\Lambda$ and **1.8** for $\Xi_b^0 \to D^0\Lambda$

Bayesian CIs

- (Different likelihood scans assuming flat prior[†])

Frequentist CIs

- Toy MC: draw random events from fitted PDF and vary Ξ_b^0/Λ_b ratio (400 fits for each $\hat{f}(\Xi_b^0/\Lambda_b)$)
- CI from interval in $\hat{f}(\Xi_b^0/\Lambda_b)$ at $f_{\text{obs}}(\Xi_b^0/\Lambda_b) = 0.20(15)$
- Construct CIs in $f_{\text{obs}}(\Xi_b^0/\Lambda_b)$ by
  - **central method**
  - shortest method



(central in f_{obs})

Branching Ratios —Example $f(\Xi_b^0/\Lambda_b)$

Bayesian CIs

- (Different likelihood scans assuming flat prior[†])

Frequentist CIs

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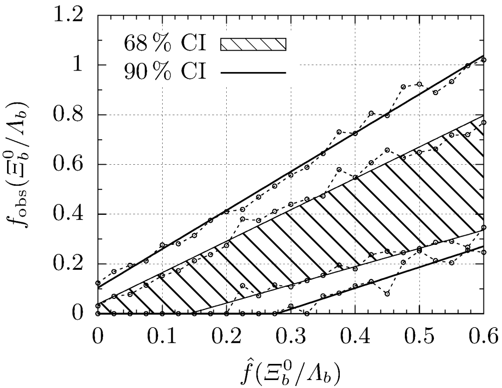
  - **shortest method**



(shortest in f_{obs})

Results / Outlook

Search for new decays

- $\Lambda_b \to D^0 \Lambda$ with a stat. sign. of 5.5 σ (discovery)
- $\Xi_b^0 \to D^0 \Lambda$ with a stat. sign. of 1.8 σ

Measurement of branching fractions / ratios

- $\mathcal{B}(\Lambda_b \to D^0 \Lambda) = (9.9 \pm 2.3_{\text{stat}} \pm 1.6_{\text{sys}} \pm 1.1_{\text{ext}}) \times 10^{-6}$
- $\frac{f_{\Xi_b^0}}{f_{\Lambda_b}} \times \frac{\mathcal{B}(\Xi_b^0 \to D^0 \Lambda)}{\mathcal{B}(\Lambda_b \to D^0 \Lambda)} < 0.5 \quad (\text{CL} = 95\,\%)$

Outlook

- Collect $\sim$ 20x more data (in reach within next LHC runs)
- Benchmark SM by measuring CPV parameter γ using suppressed D^0 decays

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Thank you for your attention

BACKUP

The CKM matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - \mathrm{i}\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - \mathrm{i}\eta) & -A\lambda^2 & 1 \end{pmatrix}}_{\text{cf. Wolfenstein: Phys. Rev. Lett. 51 (1945), 21}} + \mathcal{O}(\lambda^3)$$

$$\lambda \approx .23, A \approx .81, \rho \approx .14, \eta \approx .35$$

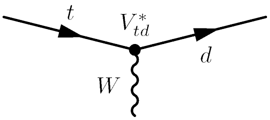
- One non-trivial complex phase, encoded in matrix elements
  - V_{ub} and V_{td} (up to $\mathcal{O}(\lambda^2)$)
  - V_{cd}, V_{cs} and V_{ts} (up to $\mathcal{O}(\lambda^6)$)
- CP violation if and only if $\eta \neq 0$

CP violation (?)

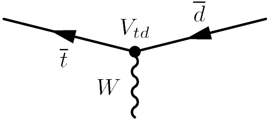
- If $\eta \neq 0$ some V_{ij} carry a complex phase (*weak* phase)
  - amplitude: $\mathcal{A}(t \to dW^{+}) \sim V_{td}^{*}$
  - amplitude: $\bar{\mathcal{A}}(\bar{t} \to \bar{d}W^{-}) \sim V_{td}$
  - CPV since $\mathcal{A} \neq \bar{\mathcal{A}}$ (?)

… not quite

- Amplitude $\mathcal{A}$ is not observable …
- … but branching fraction $\mathcal{B} \sim |\mathcal{A}|^2$ is
  - CPV needs at least two interfering decay modes with …
  - … one **CP odd** and one **CP even** phase



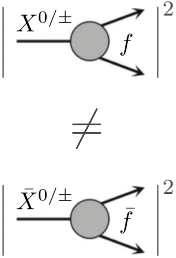
$t \to dW^{+}$



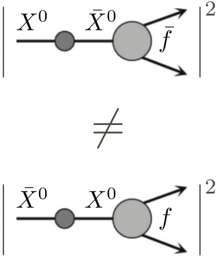
$\bar{t} \to dW^{-}$

Types of CPV

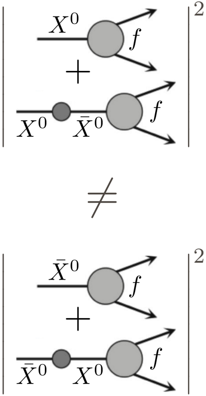
(1) Direct CPV



(2) CPV in mixing



(3) CPV in interference of mixing and decay



(Images: *CP Violation*, I. I. Bigi and A. I. Sanda)

- CP odd: from CKM matrix
- CP even:
  - (1): strong phase difference between both amplitudes (*e.g.*, *tree* and *penguin*)
  - (2), (3): $\pi/2$ (**constant!**)

The CKM Matrix

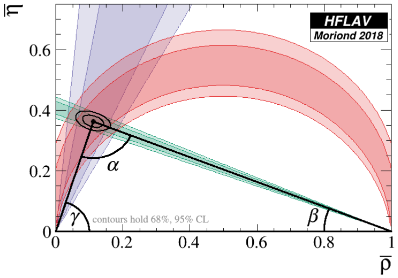
Another parametrization – Prog. Part. Nucl. Phys. 47 (2001)

$$V_{\text{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{+i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{+i\phi_2} & |V_{tb}| \end{pmatrix}$$

$$\begin{aligned} \gamma &\equiv \tilde{\gamma} - \phi_4, & \phi_2 &\approx \eta\lambda^2 \\ \beta &\equiv \tilde{\beta} + \phi_4, & \phi_4 &\approx \eta A^2\lambda^4 \\ \alpha &\equiv \pi - \beta - \gamma, & \phi_6 &\approx \eta A^4\lambda^6 \\ \beta_s &\equiv \phi_s \equiv \phi_2 + \phi_6 \end{aligned}$$

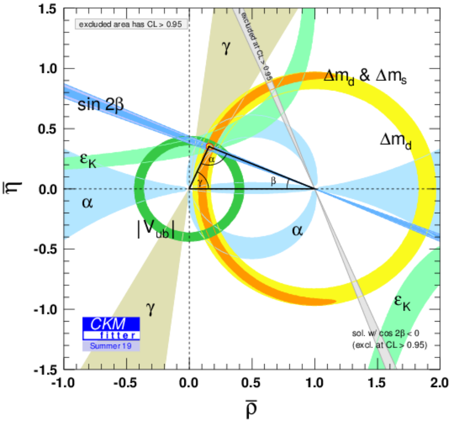
- From unitarity: 6 triangles
  - $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - … 4 more
- Angles $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$ and $\phi_{2,4,6}$ **depend on phase convention** (*i.e.*, not observable)
- Phases of products $V_{ij}V_{kl}V_{il}^*V_{kj}^*$ are **invariant** and **observable** (*e.g.*, α, β, γ, …)

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Probing the SM by Overconstraining

- **Motivation:**
  - We utterly fail explaining CPV on cosmological scale!
  - Is the CKM matrix the only source of CPV?
  - Is the SM incomplete / are there more particles?
- **Strategy:**
  - Overconstrain CKM triangles by measuring
    - sides – *e.g.*, $|V_{td}V_{tb}^*|$
    - angles – *e.g.*, $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$
  - Is $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$ tiny? ($\mathcal{O}(\lambda^2)$)



Any deviation would point towards **new physics**, *e.g.*, 4th quark family?

Branching ratios