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Searching for New Physics with rare charm decays at LHCb

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Introduction and Outline

Brief presentation

I am about to finish the PhD in Cagliari, within the LHCb group.
The main activities I was involved in are:

- Upgrade of readout system and readout electronics,
- Maintanace of GEM detectors,
- Radiation hardness test of readout electronics,
- Data analysis on rare charm decays.

Outline

- Theoretical introduction
- LHCb experiment
- Status of the $D^0 \to h^+h^-\mu^+\mu^-$ $(h = K, \pi)$ angular analysis
- Other rare charm measurements from LHCb
- Conclusions

Why flavour physics?

- Several open questions in Standard Model comes from flavour sector, i.e.
  - Why three generations of quarks/leptons?
  - Origin of the mass hierarchy for different flavours;
  - Explanation of the matter – antimatter asymmetry in the universe.

- The Standard Model (SM) is an effective theory at low energy

$$\mathcal{H} = \mathcal{H}_{SM} + \alpha \sum_i C_i^{NP}(\mu)\,\mathcal{O}_i(\mu)$$

New couplings (Wilson coeff.) — New operators

- Effects of new particles or interactions can be probed with high precision measurements at low energy in flavour processes (*indirect search*)

$$\mathcal{A}_{i\to j} = \mathcal{A}_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_{NP}}{\Lambda^2} \right]$$

New Physics (NP) scale

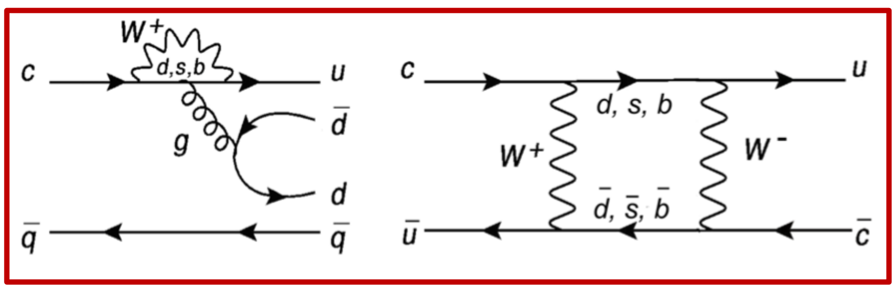
Why rare decays?

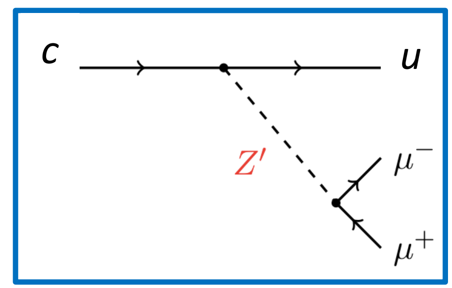
- Very small rate (branching fractions) because highly suppressed in the SM, excellent laboratories to probe NP effects

$$\mathcal{A}_{i\to j} = \mathcal{A}_0 \left[\underbrace{\frac{c_{SM}}{M_W^2}}_{\sim 0} + \frac{c_{NP}}{\Lambda^2} \right]$$

- Flavour changing neutral current (FCNC) processes, as $c \to u$, are possible only at high order in the SM. Branching fraction $< 10^{-9}$

SM



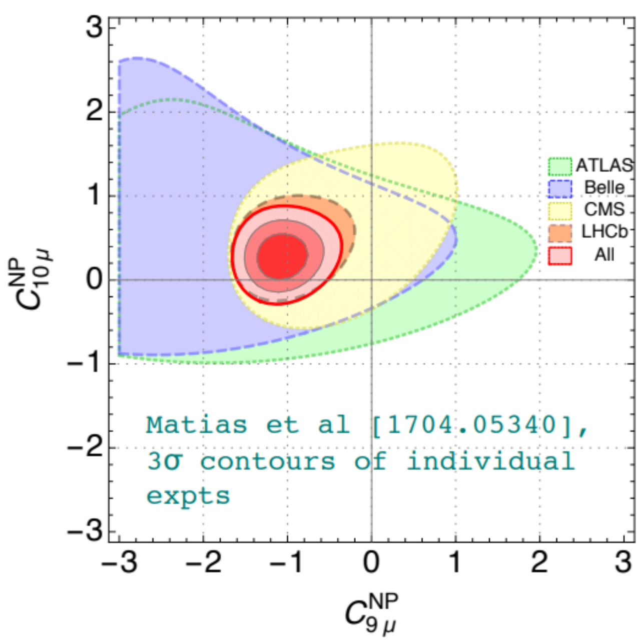


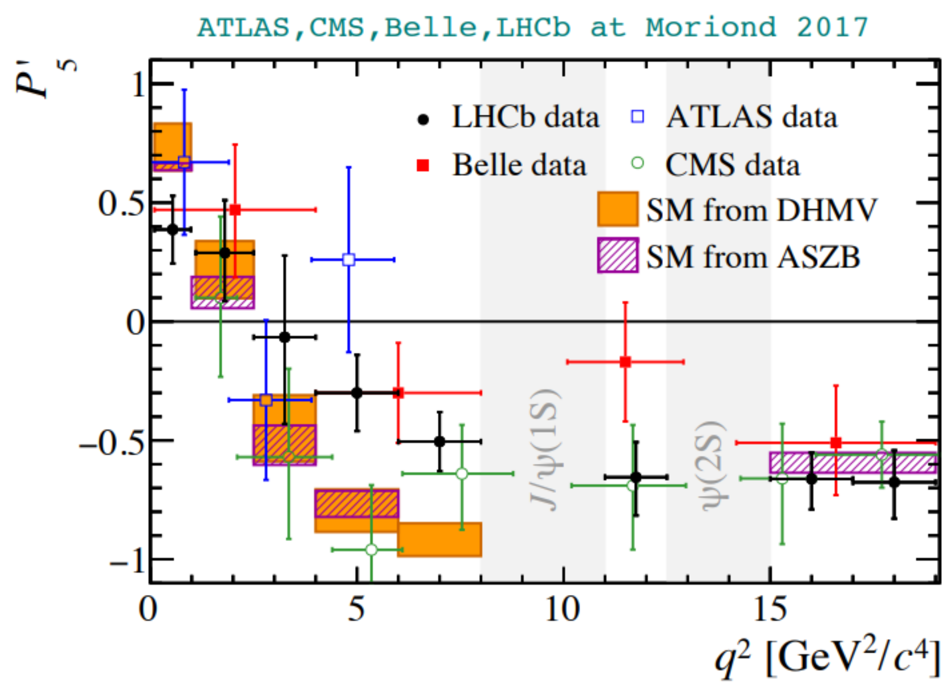
NP

- Two main effects from NP
  - enhancing branching fractions,
  - **modifying angular distributions.**

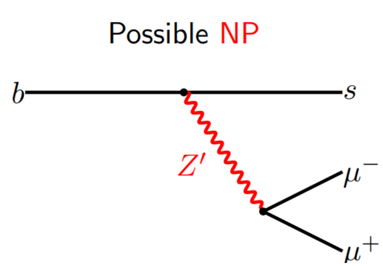
Interesting results from B physics

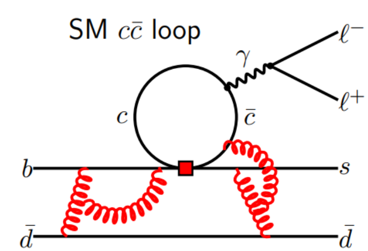
- Angular analysis of the rare decay $B^0 \to K^{*0}\mu^+\mu^-$.
  The angular coefficient P_5' (exp. observable) shows an interesting anomaly.
- Global fits show deviation for the Wilson coefficient C_9, tension at level of $4-5\,\sigma$





- Several attempts to interpret the data:
  - New boson Z' , leptoquarks, etc.
  - SM loop of $c\bar{c}$ can mimic corrections to C_9.



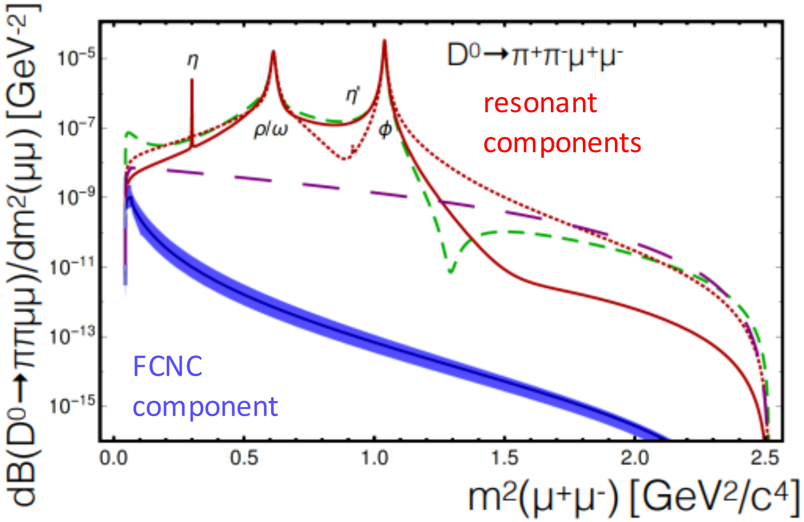


Why shall we use charm decays?

- **Promising**, some NP models predict large enhancements for branching fractions and angular observables [PRD 83 114006 (2011)] [PRD 98 035041 (2018)]
- **Unique probe of NP** in the up-type quark sector, complementary to B and K systems; No angular study in rare charm decays so far.
- **Challenging**, non-perturbative SM dynamics (resonance states) dominate the decay rate, hiding FCNC processes → large theoretical uncertainties,
  → Studies on angular distribution are more sensitive to NP.

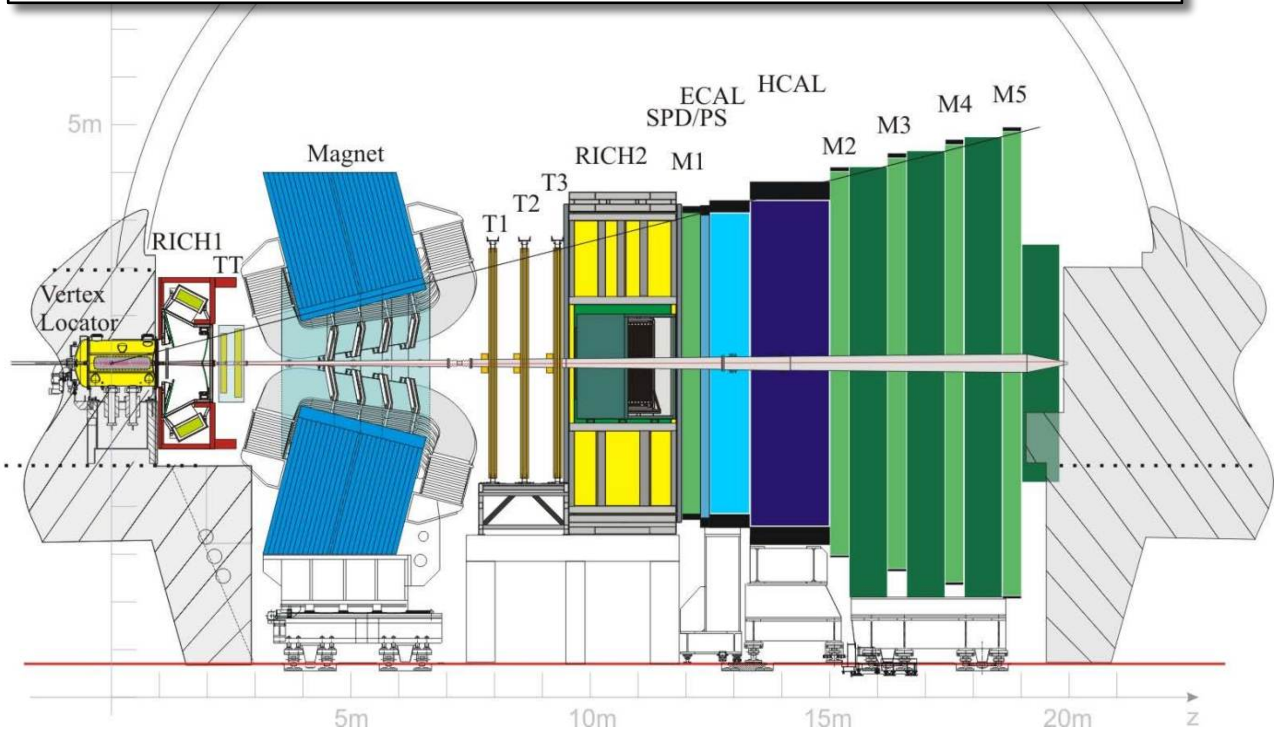
model	A_{FB}
Leptoquark models	$\lesssim 8 \times 10^{-1}$
Little Higgs model	$\lesssim \mathcal{O}(5 \times 10^{-3})$
Minimal SUSY SM	$\lesssim \mathcal{O}(10^{-1})$
Up vector-like quark singlet	$\lesssim 10^{-3}$
SM	~ 0

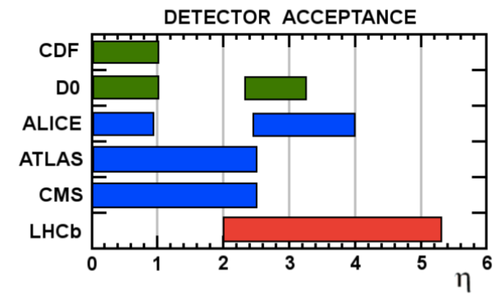
[PRD 98 035041 (2018)]

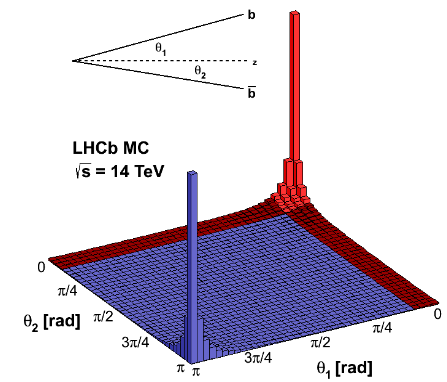


LHCb experiment

Single-arm forward spectrometer, optimized to study c- and b-hadrons physics ($2 < \eta < 5$)







Huge sample of $c\bar{c}$
$N(c\bar{c}) \sim 8 \cdot 10^{12}$
(RunI+RunII)

Performance:

- Momentum resolution: 0.35% (at 5 GeV/c) – 0.55% (at 100 GeV/c)
- Mass resolution: 10–25 MeV/c^2
- Impact parameter resolution: 20 μm for high-p_T tracks
- Excellent particle ID: two RICH detectors and Muon stations ($\epsilon(\mu) \approx 97\%$, $\epsilon_{misID}(\pi \to \mu) \approx 3\%$))

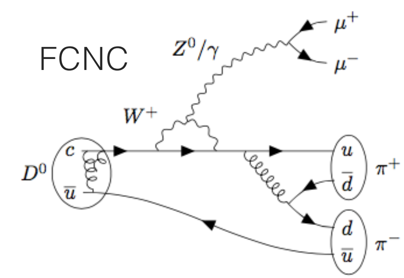
$D^0 \to h^+h^-\mu^+\mu^-$ ($h = K, \pi$) decays

- Final state observed by LHCb: the rarest charm decay observed, compatible with SM. [PRL 119(2017)181805] [JHEP 04(2013)135]

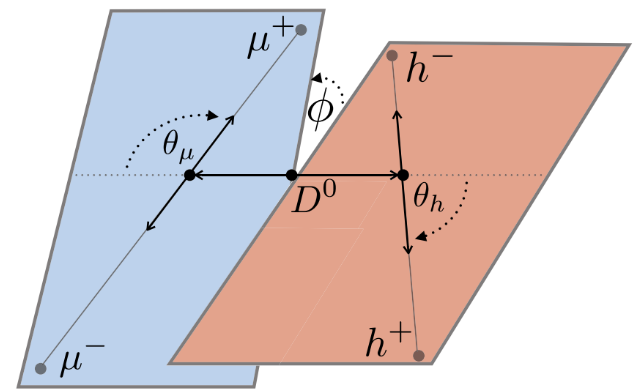
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \cdot 10^{-7}$$

$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \cdot 10^{-7}$$

FCNC



- Dominated by non-perturbative resonant dynamics, several possible resonant states.



- Four-body decay = 5-dimensional phase space, $m(h^+h^-)$, $m(\mu^+\mu^-)$, $\cos(\theta_\mu)$, $\cos(\theta_h)$, ϕ

- Full angular parametrization

$$d^5\Gamma = \frac{1}{2\pi}\left[\sum_{i=1}^{9} c_i(\theta_\mu, \phi) I_i(q^2, p^2, \theta_h)\right] \cdot dq^2 dp^2 d(\cos\theta_\mu) d(\cos\theta_h) d\phi$$

known 2-D function of angles
→ orthogonal angular basis

9 angular coefficients to be measured

$I_{5,\dots,9}$ are ~null in the SM

Analysis goal

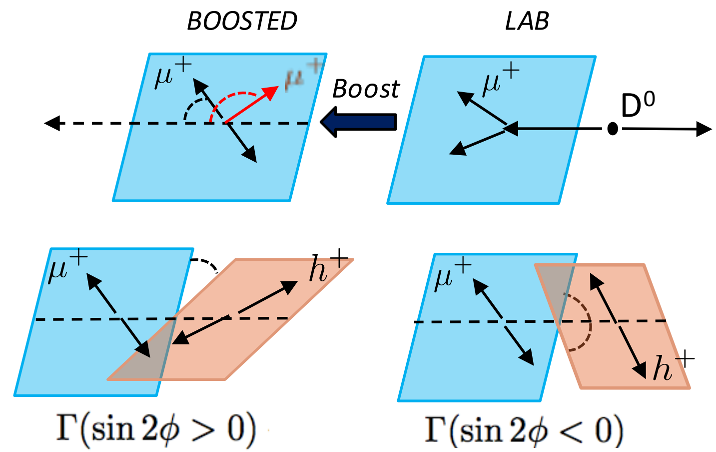
1. Measure the angular coefficients as function of $q^2 = m^2(\mu^+\mu^-)$ with full Run II sample (2015-2018). Two times more statistics w.r.t previous analysis. [PRL 121 (2018) 091801]
2. Inclusion of Run I dataset (2011-2012) → three times more statistics.

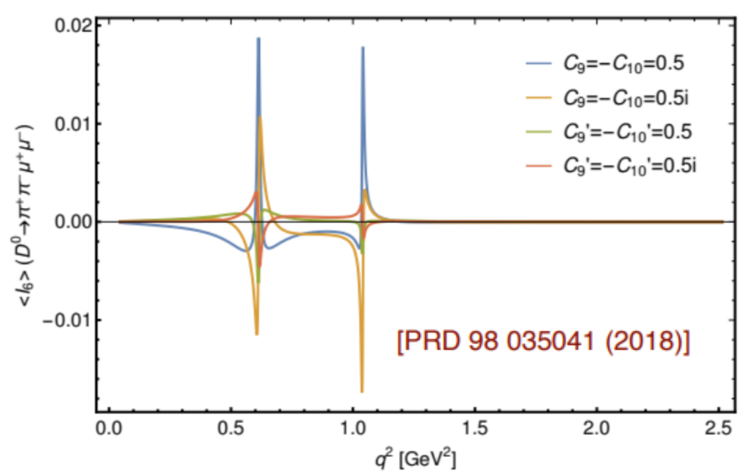
- Some coefficients are related to angular asymmetries

$$A_{FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)} \propto \langle I_6 \rangle$$

$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)} \propto \langle I_9 \rangle$$

$$A_{\phi} = \frac{\Gamma(\sin \phi > 0) - \Gamma(\sin \phi < 0)}{\Gamma(\sin \phi > 0) + \Gamma(\sin \phi < 0)} \propto \langle I_7 \rangle.$$



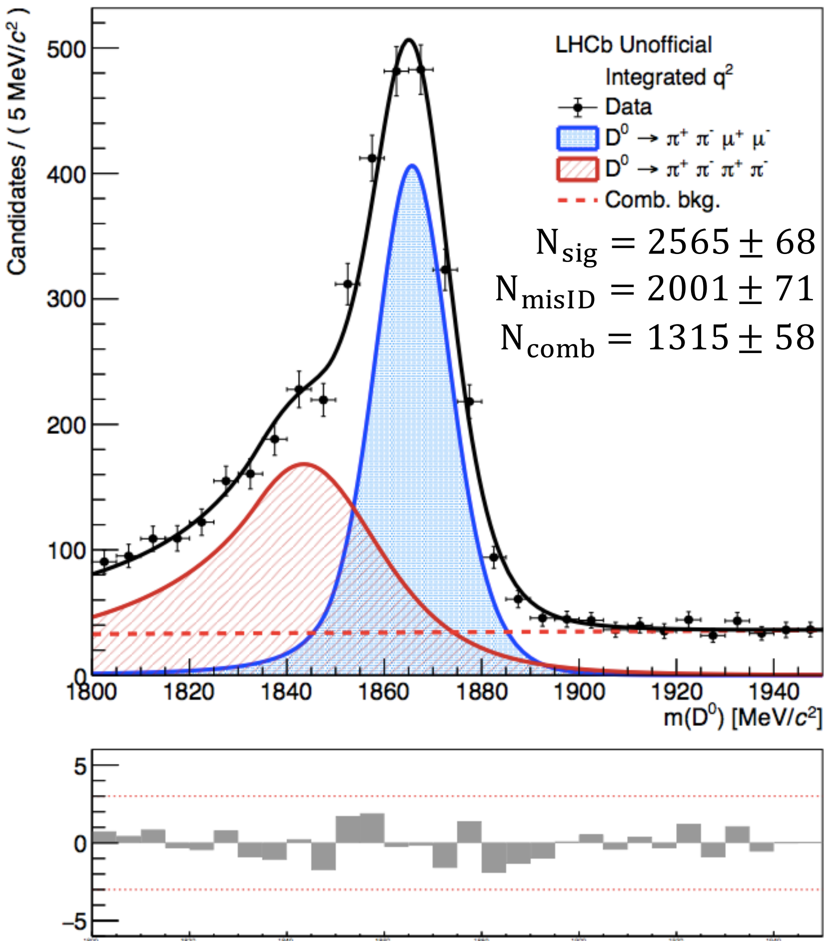


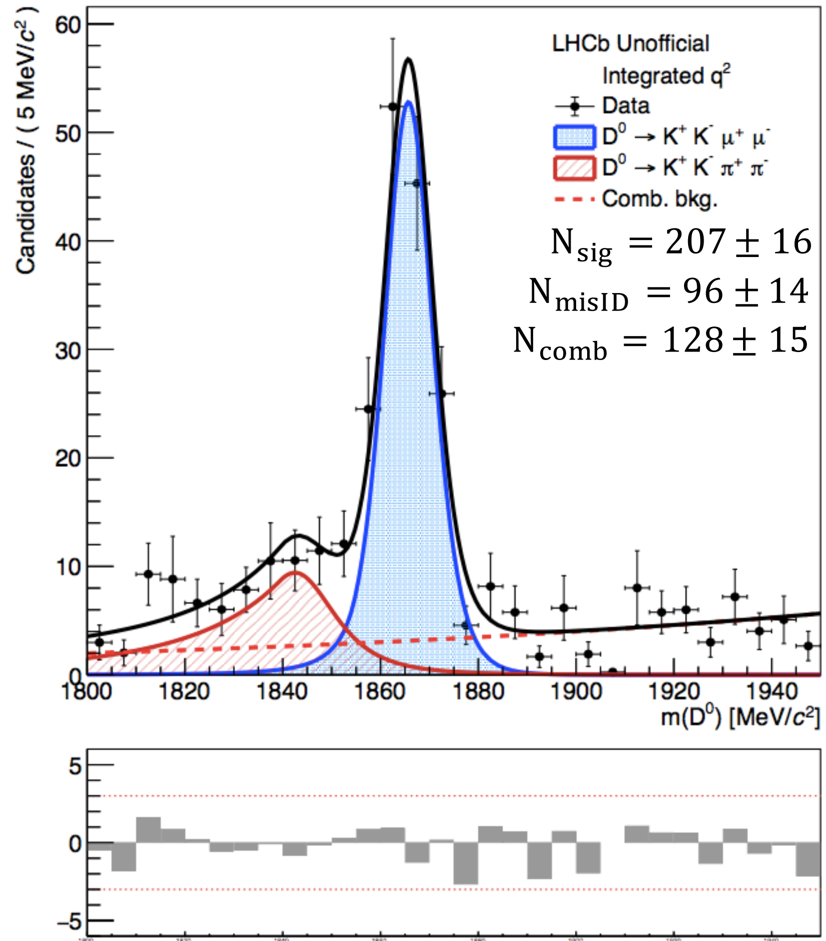
- Possibility to make the CP asymmetry measurement

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

D^0 invariant mass fit

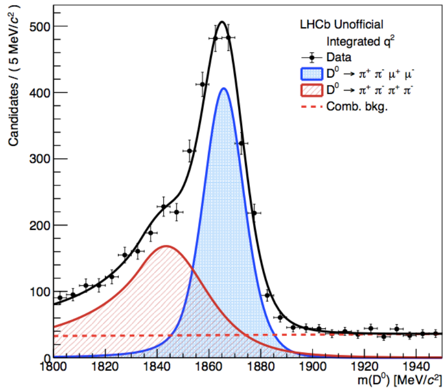
- After reconstruction and D^0 decays selection we are able to observe the signal. Two sources of background: combinatorial and doubly misidentified $D^0 \to h^+ h^- \pi^+ \pi^-$
- More than two times more statistics with respect to the 2011-2016 data set





Background subtraction

- The angular distributions are polluted by the two background components



Statistical background subtraction

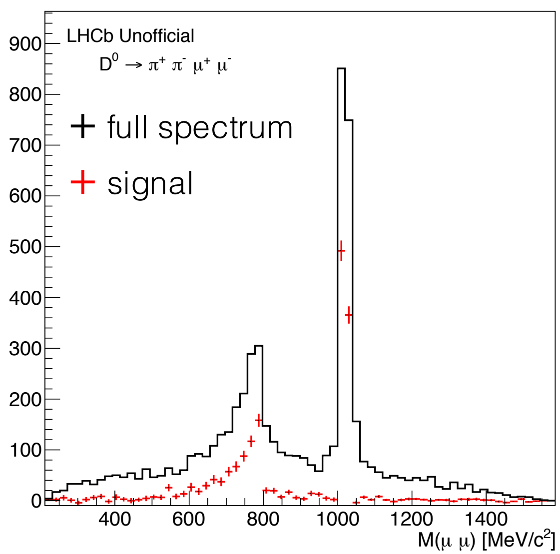
arXiv:physics/0402083v3

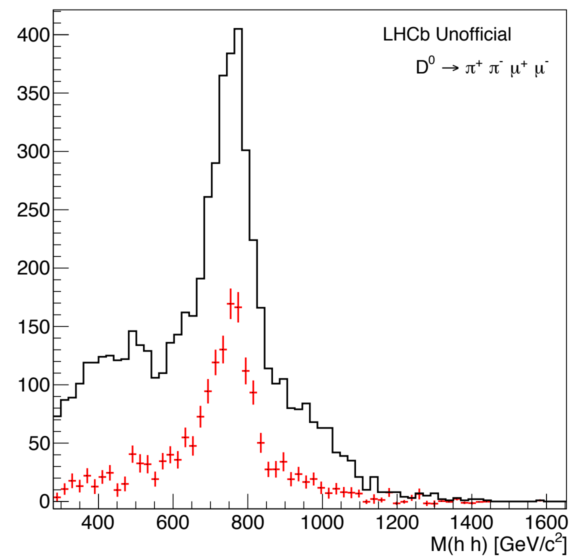
For each D^0 candidate *i* 3 weights are defined:

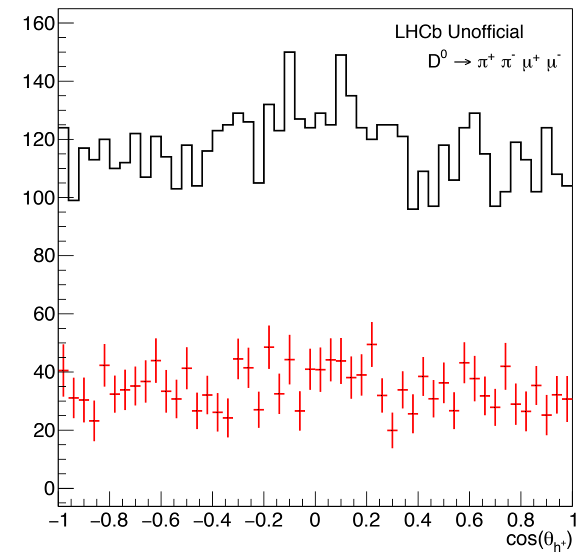
- $\mathrm{w}^{\mathrm{i}}_{\mathrm{sig}}$
- $\mathrm{w}^{\mathrm{i}}_{\mathrm{misID}}$
- $\mathrm{w}^{\mathrm{i}}_{\mathrm{comb}}$

$$\mathrm{w}^{\mathrm{i}}_{\mathrm{sig}}+\mathrm{w}^{\mathrm{i}}_{\mathrm{misID}}+\mathrm{w}^{\mathrm{i}}_{\mathrm{comb}} = 1$$

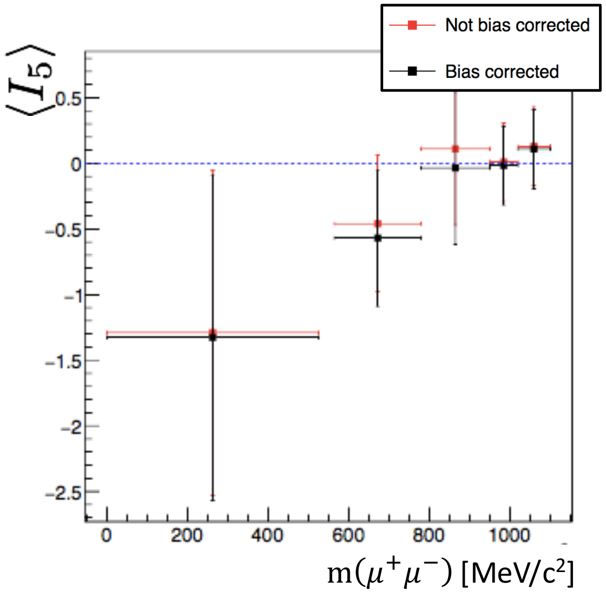
- Example of background subtraction on the three phase-space variables, not used in the angular fit: $\mathrm{m}(h^+h^-), \mathrm{m}(\mu^+\mu^-), \cos(\theta_\pi)$

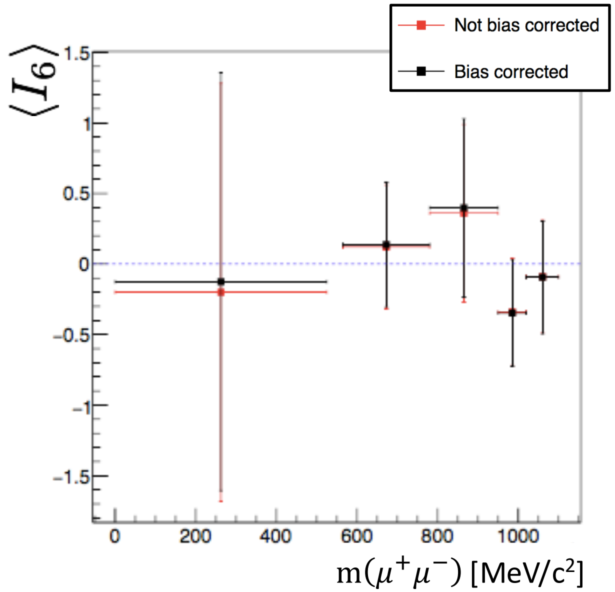


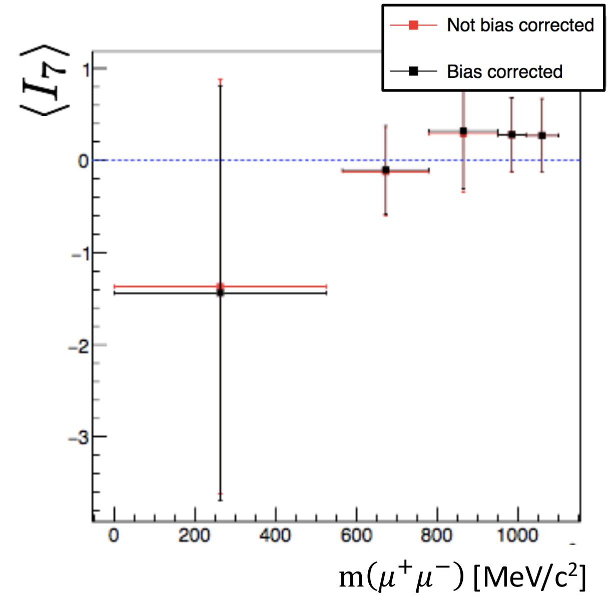




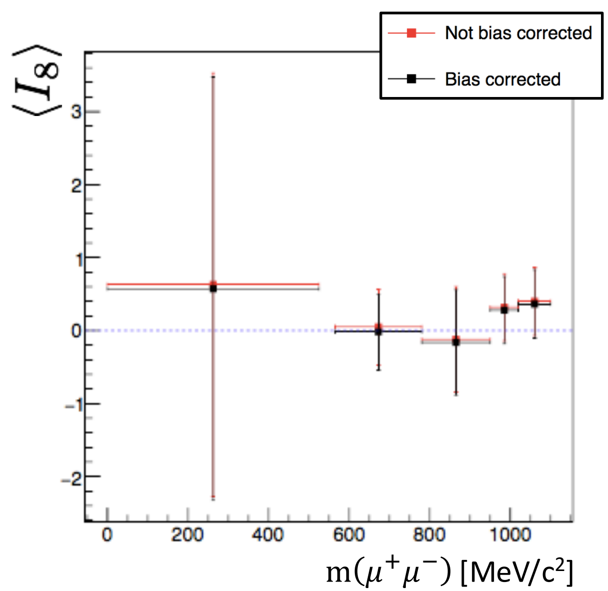
Angular fit validation: SM null test results

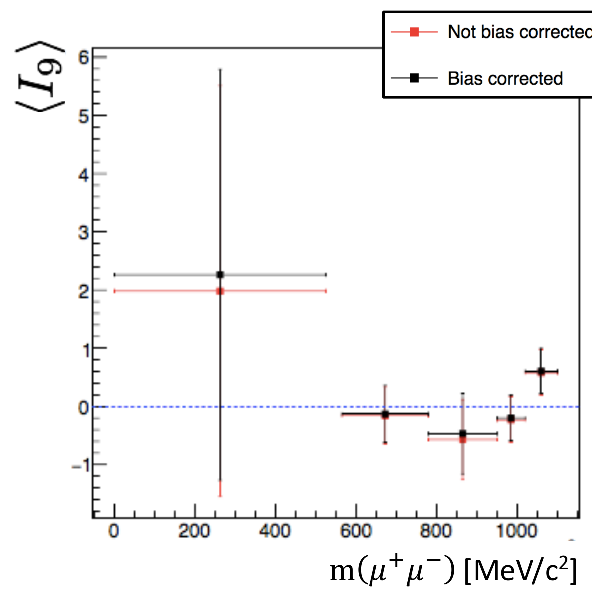






- Pseudo-experiments have been developed to simulate the SM null test on $\langle I_{5,\ldots,9} \rangle$
- The coefficients show values not significantly different from zero using SM contributions only.





Other measurements from LHCb

- Search for $\Lambda_c^+ \to p\mu^+\mu^-$

  Upper limit on non-resonant component

  $$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 9.6 \times 10^{-8} \quad 95\%\ \mathrm{CL}$$

  ~1000× better than previous result from BaBar [PRD 84 (2011) 072006]
  and first observation in the ρ/ω region of the dimuon spectrum.
  Ongoing with Run II data.

- Search for $D^0 \to \mu^+\mu^-$

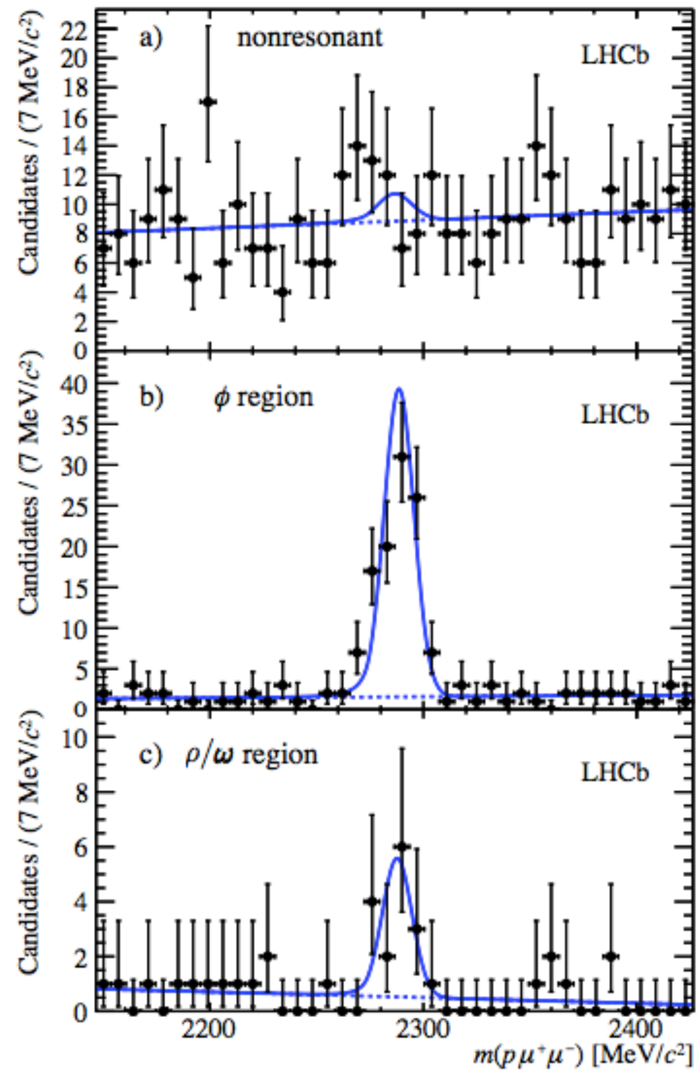
  Current limit by LHCb with 0.9 fb^{-1} of 2011 dataset [PLB (2013) 725]

  $$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2(7.6) \times 10^{-9} \text{ at } 90\%\ (95\%)\ \mathrm{CL}.$$

  Ongoing with Run II data.

- Other analyses currently ongoing:
  - Search for $\mathrm{D}_{(s)}^+ \to \mathrm{h}^+\mathrm{l}^+\mathrm{l}^-$
  - Radiative decays $\mathrm{D}^0 \to \{\rho, \phi\}\gamma$
  - Search for $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-\mathrm{e}^+\mathrm{e}^-$

$\Lambda_c^+ \to p\mu^+\mu^-$



Conclusions

About this analysis

- Angular analysis in a well advanced status,
- Dominated by statistical uncertainty,
- This will be the first angular analysis in a rare charm decay, lot of interest from theorists.
- Most of the C++11 code developed using Hydra libraries, a framework for data analysis in parallel platforms (GPU)

HYDRA
Multithreaded Data Analysis Framework

https://github.com/MultithreadCorner/Hydra

Rare charm decays

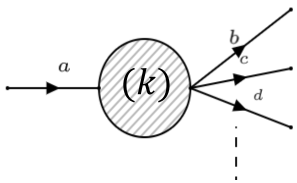
- Progress over the years, LHCb leading in the field,
- Started to probe SM regimes, rates $\sim 10^{-8}$,
- Started to look also into final states with electrons,
- Expected some results in radiative decays, measured recently by Belle, PRL 118, 051801 (2017), A_{CP} precision ~ 2%-15%.

Backup slides

Angular fit validation: amplitude model

- Amplitude model for the $D^0 \to \pi^+\pi^-\mu^+\mu^-$

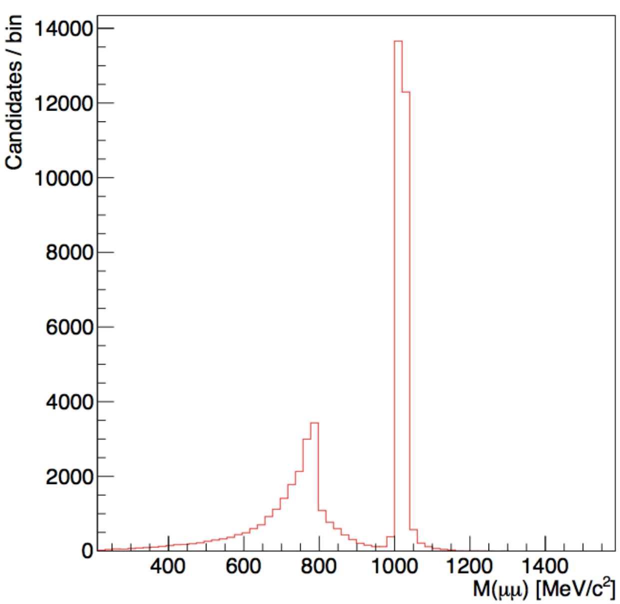
$$W_{if} = \frac{2\pi}{\hbar}|M_{if}|^2\frac{dN}{dE_f}$$

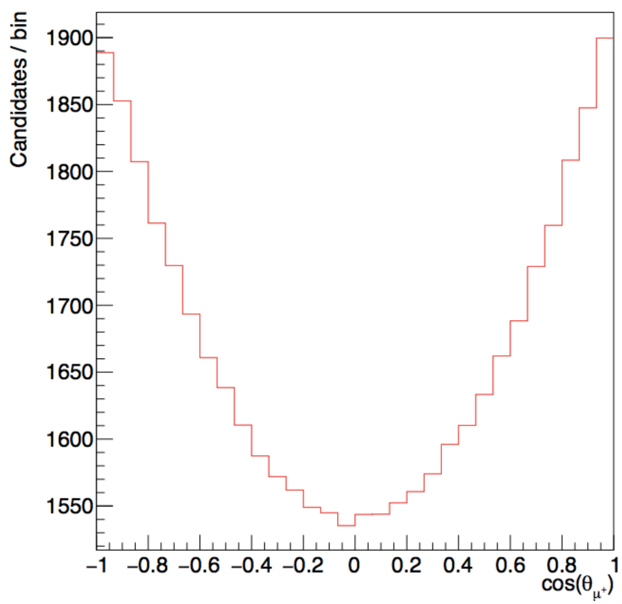
$M_{if}^{(k)} =$  $=$ [4-body non resonant] $+ \sum_j$ [Resonant state]$_j$

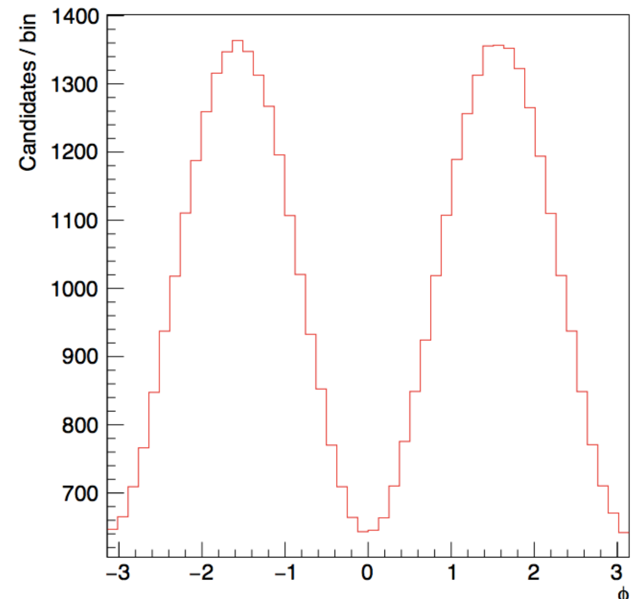
4-body non resonant ~ 0

- Three configurations are considered: $D^0 \to \rho\,\rho\,,\ D^0 \to \rho\,\phi,\ D^0 \to a_1^{\pm}\pi^{\mp}$

- Generated distributions using the amplitude model





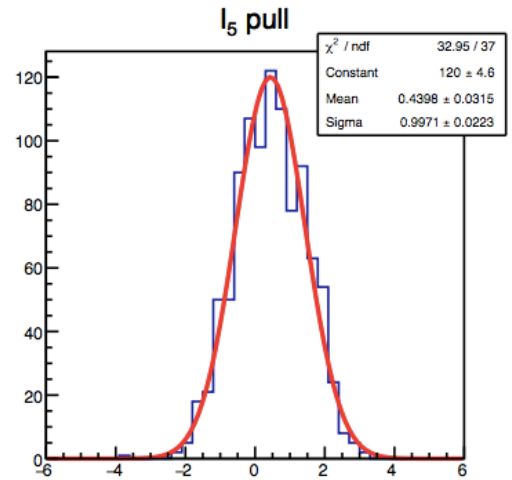


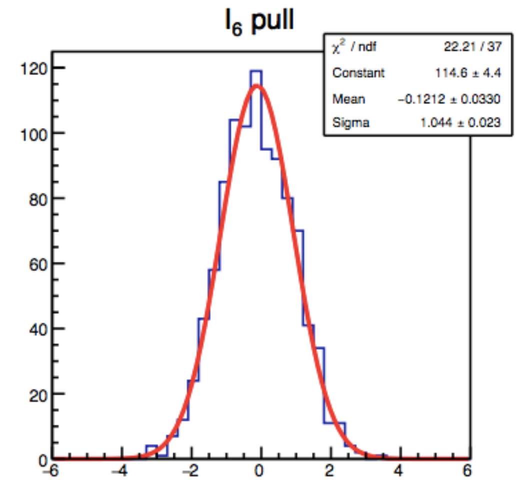
Angular fit validation: pseudo-experiments

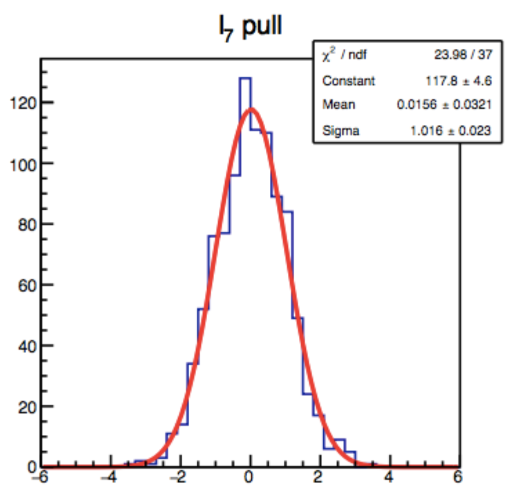
- Pull distributions after 1000 pseudo-experiments
- Gaussian with σ compatible with 1, mean values show small biases

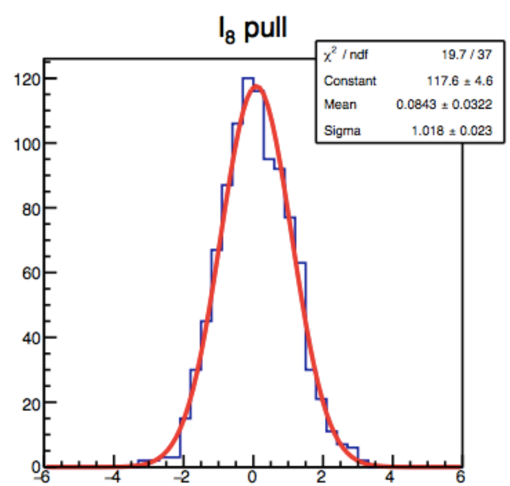
$$\text{pull}_i = \frac{I_i^{\text{fit}} - I_i^{\text{gen}}}{\sigma_{I_i}}$$

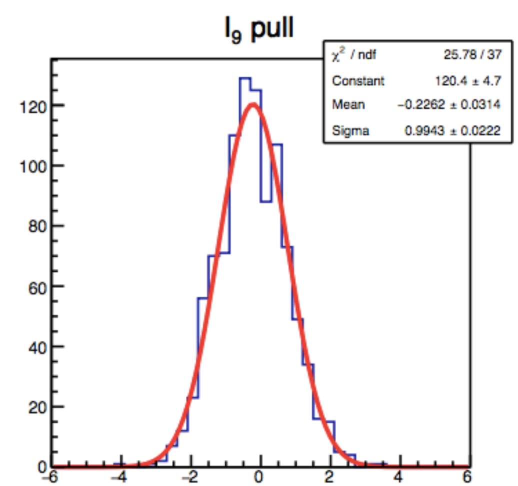
$$\text{bias}_{I_i} = \langle \text{pull} \rangle_{I_i}$$





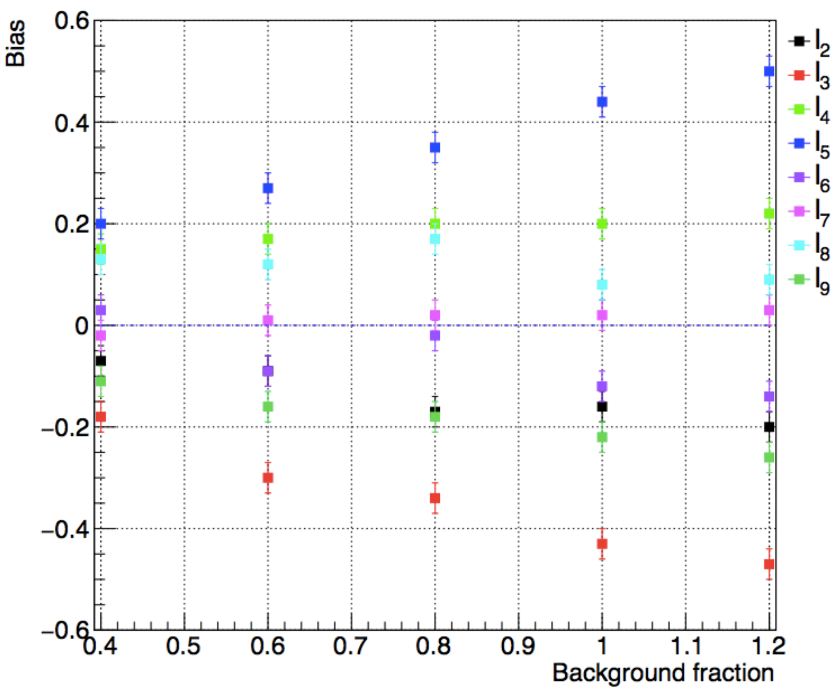


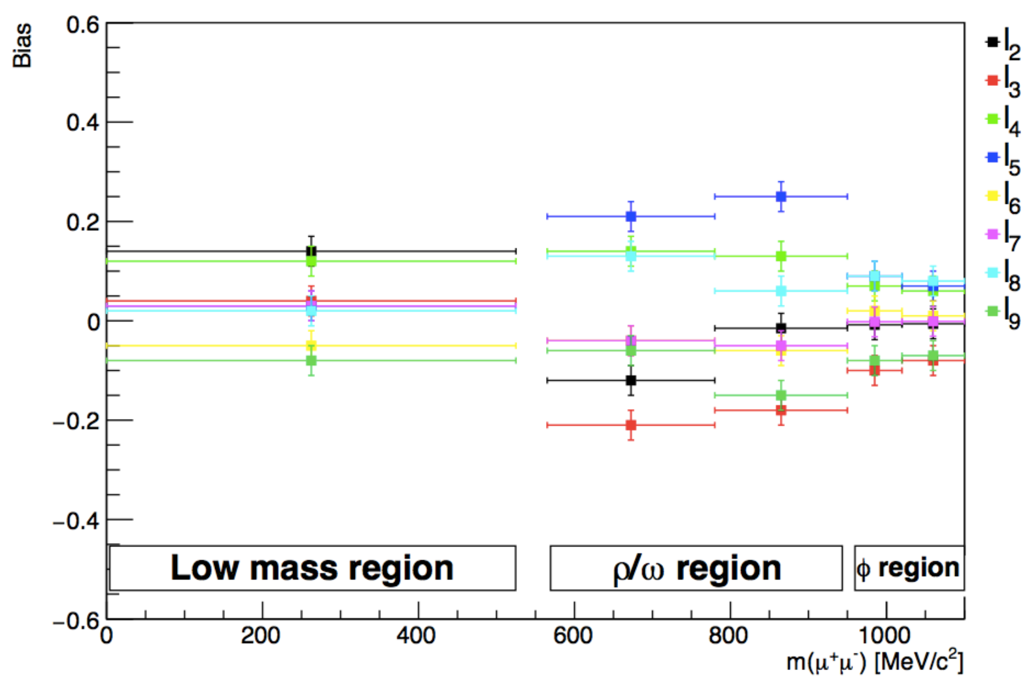




Angular fit validation: pseudo-experiments

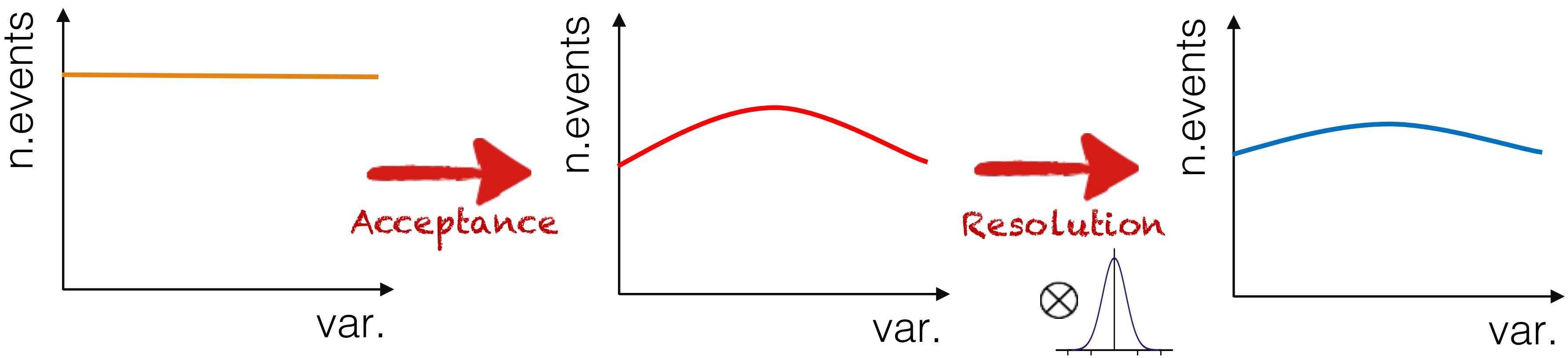
- The biases do not exceed 0.5 σ_{I_i}
- For some coefficient the bias increases as a function of the background pollution
- Possibility to change the D^0 selection to further reduce the background fraction



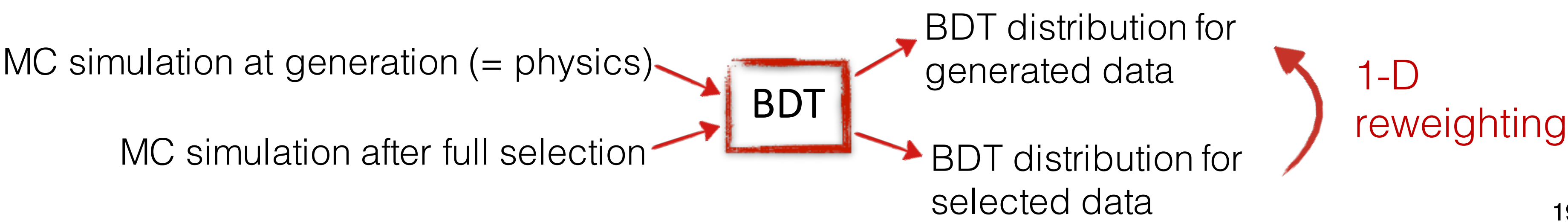


Phase-space dependent efficiency

- Detector acceptance, reconstruction and selection can introduce efficiency and resolution effects as a function of the phase space region.

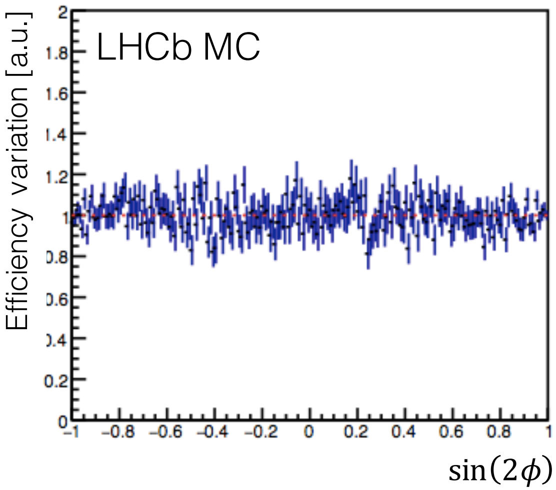


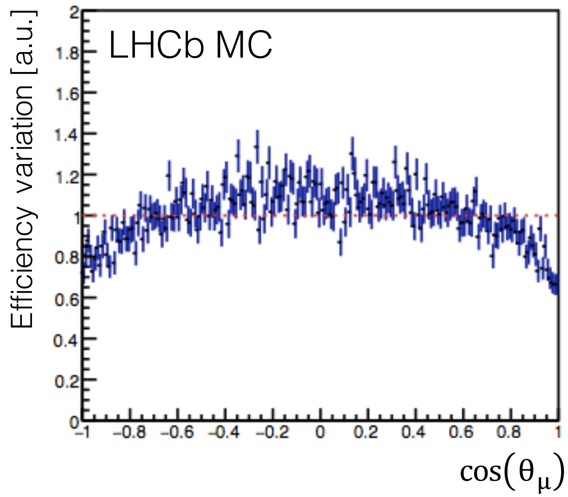
- In order to get the correct angular distributions we have to correct for these effects in the **5-D** phase space → reweight selected data
- A reweighter BDT is used to reduce the problem to **1-D** reweighting

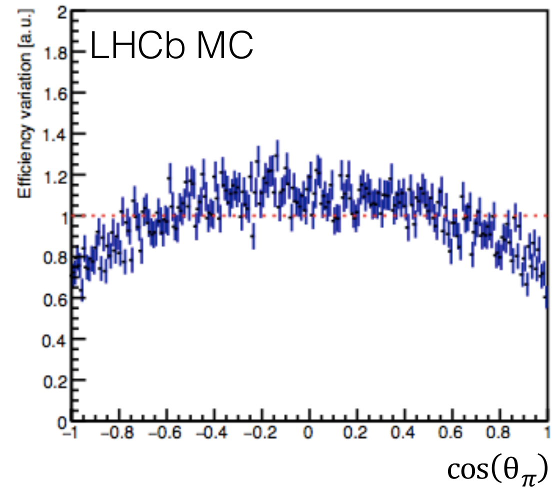


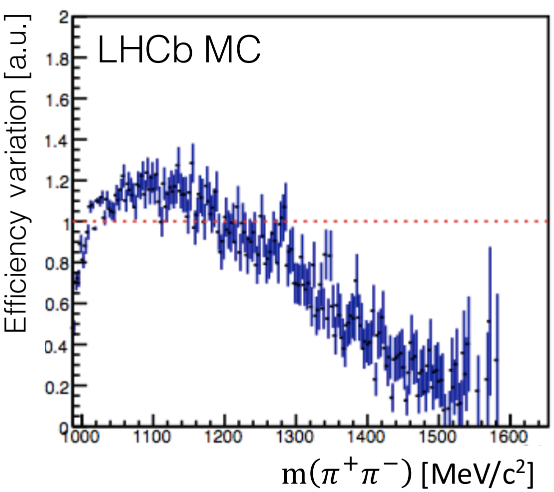
Phase-space dependent efficiency

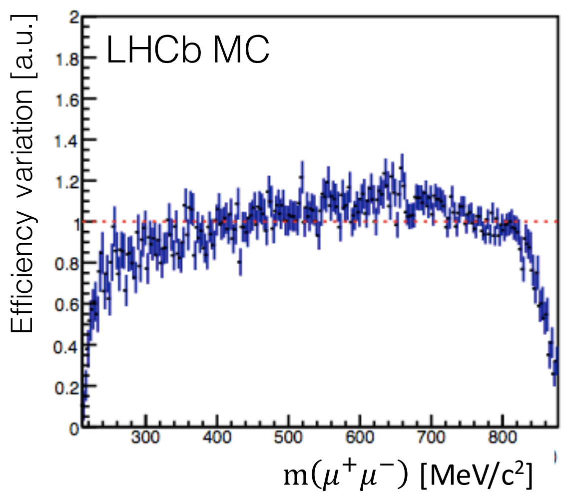
- Projections of the phase-space dependent efficiency for $D^0 \to \pi^+\pi^-\mu^+\mu^-$



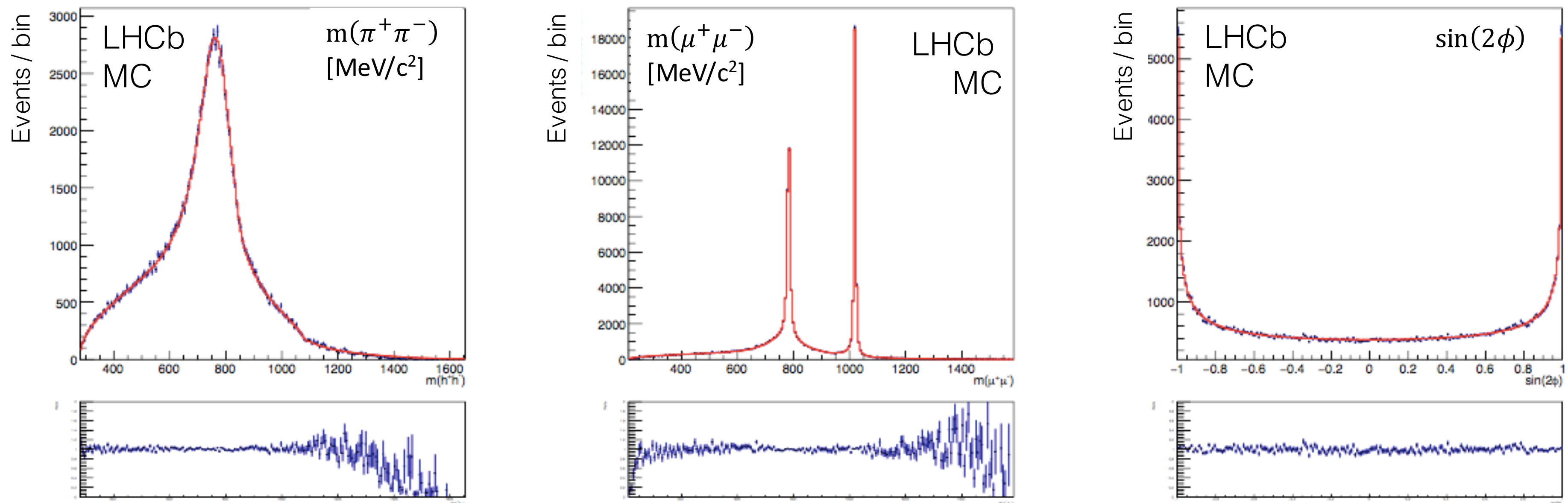


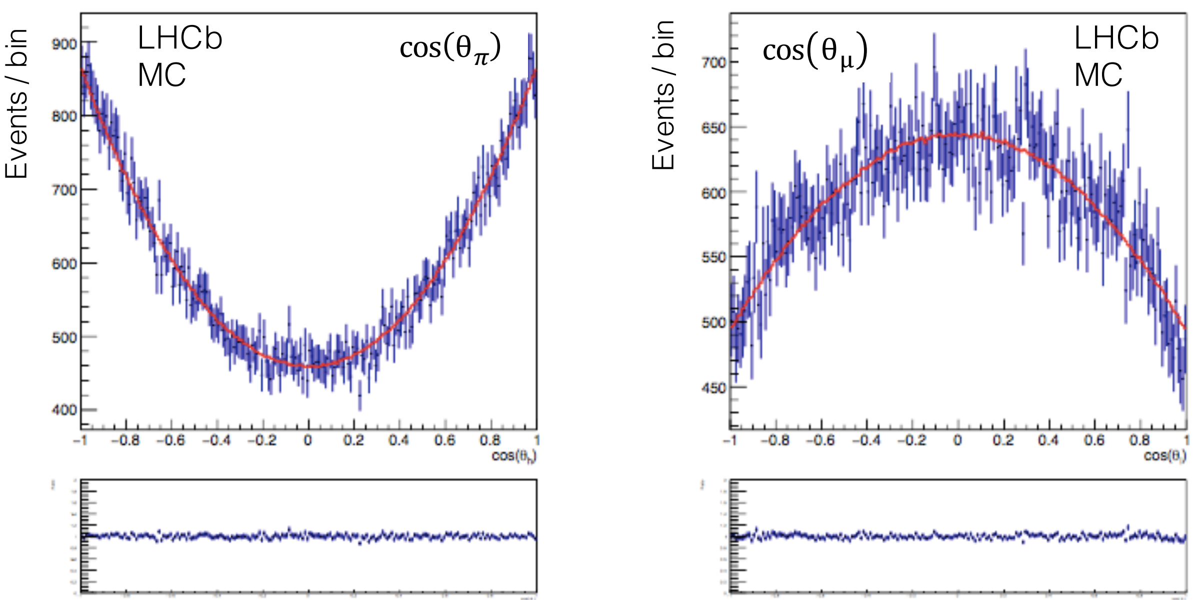


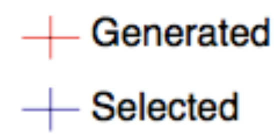




Phase-space dependent efficiency





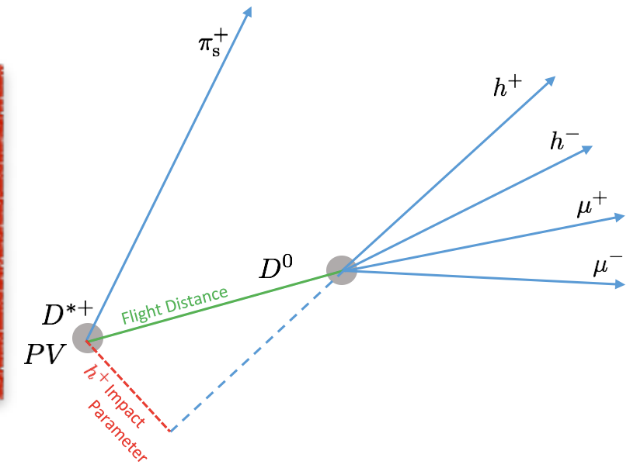


Simulated phase-space variable distributions for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ after the reweighting

Analysis strategy

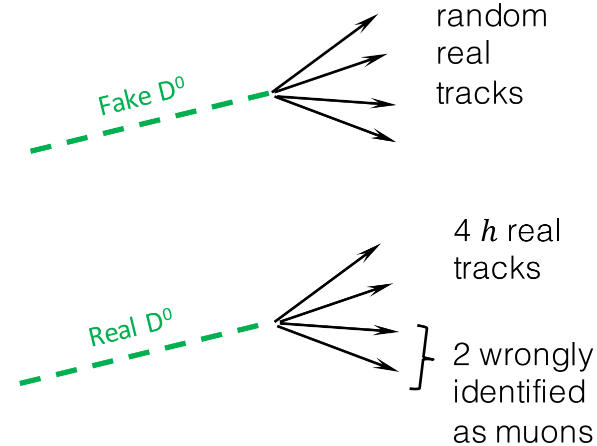
Preliminary data Selection

- Select $\mathrm{D^0}$ and $\overline{\mathrm{D}}^0$ from the decay $D^{*\pm} \to D^0 \pi_S^{\pm}$
  It allows to use the observable $\Delta M = m(D^{*+}) - m(D^0)$
- Required good quality of vertices and daughter tracks, required Particle Identification of hadrons and muons.



Background rejection

- Multivariate classifier against combinatorial background,
- muon PID cut against doubly misidentified $\mathrm{D^0} \to 4\,\pi$

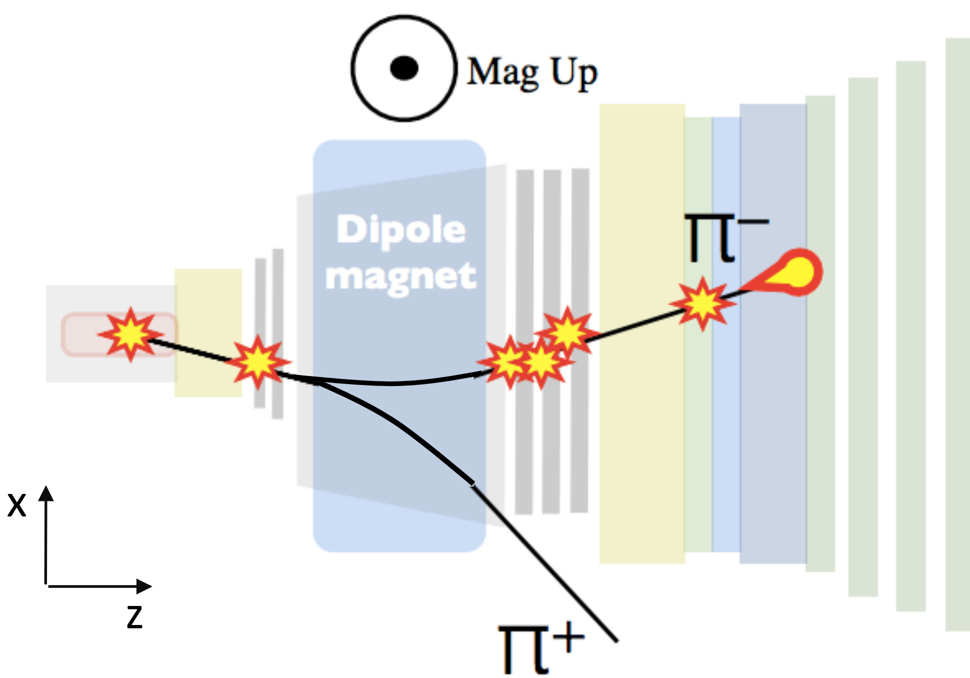


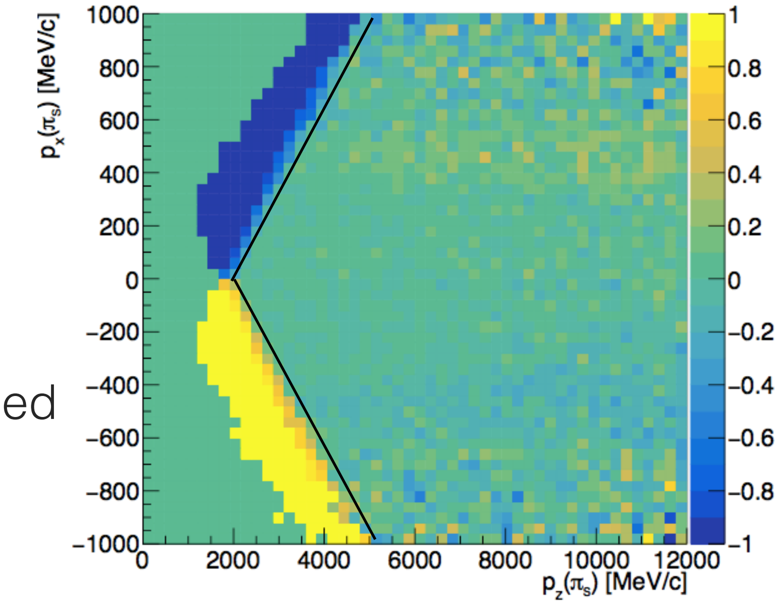
Angular coefficients measurements

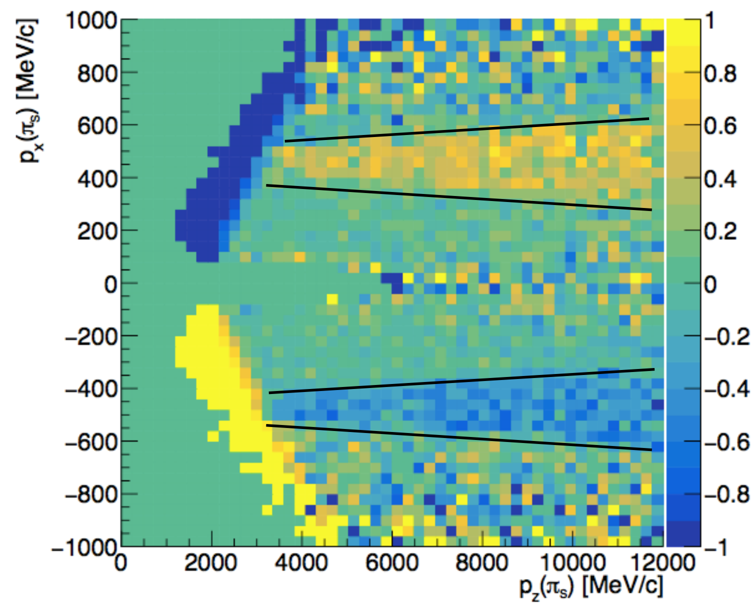
- Fit on invariant mass $\mathrm{m}(h^+ h^- \mu^+ \mu^-)$
- Fit on angular distributions background subtracted
- Correction for phase-space-dependent efficiencies

Soft pion charge asymmetry

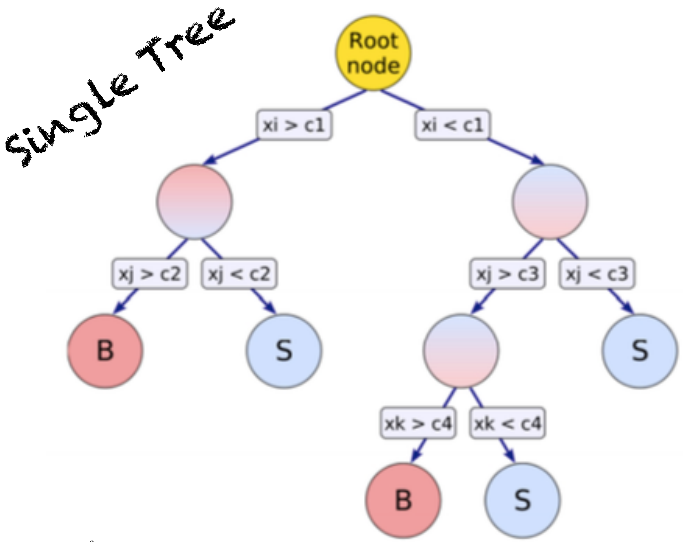
- For specific regions of phase space, the soft pion of a given charge is bent outside the detector acceptance
- The asymmetry can introduce higher-order effects in D^0 angular distributions
- The involved phase space regions are excluded



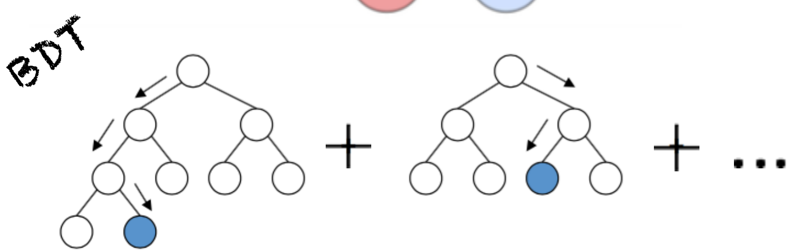


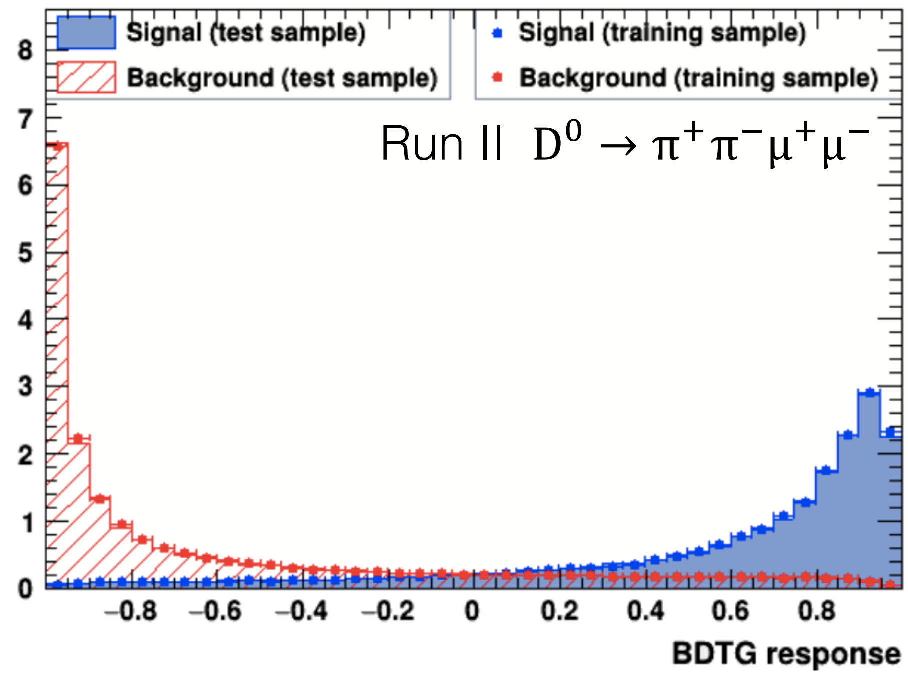


Reduce the combinatorial background

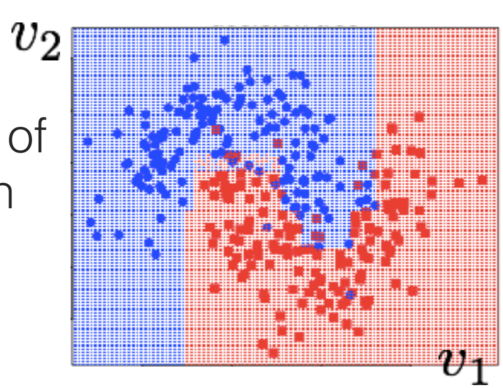


- Multivariate statistical method (machine learning) to classify signal and background
- Decision Tree: sequential nested cuts on given variables (kinematical and geometrical)
- Boosted Decision Tree: single output using many trees

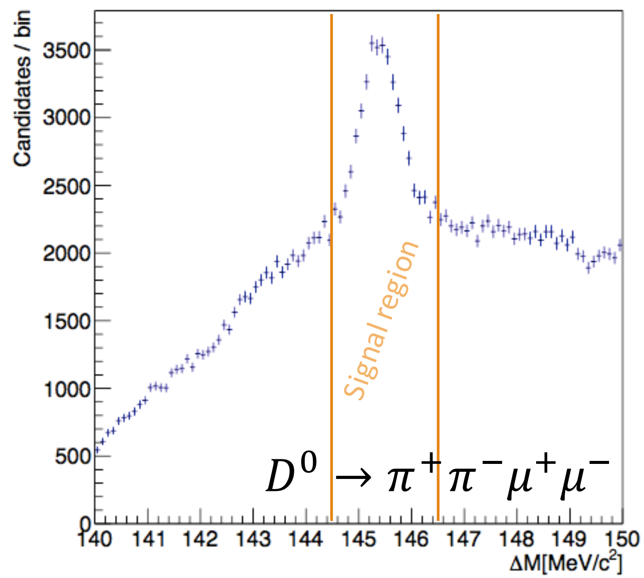


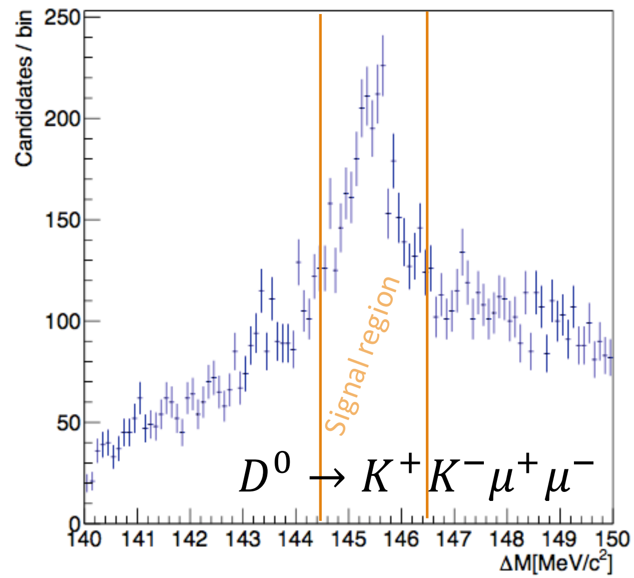


An example of classification using two variables

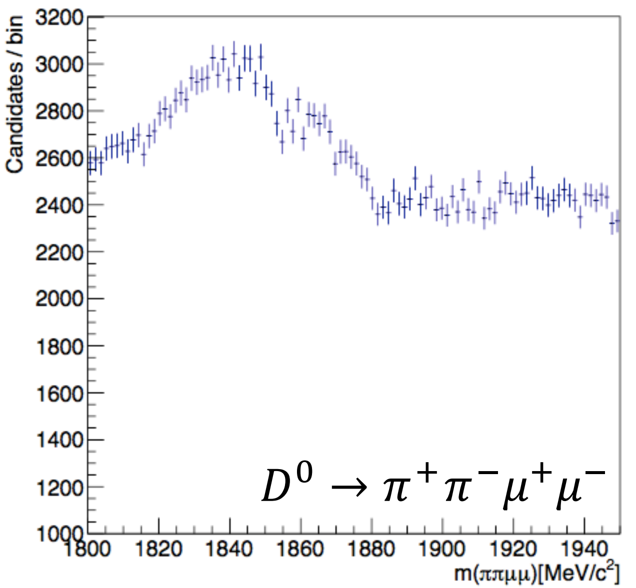


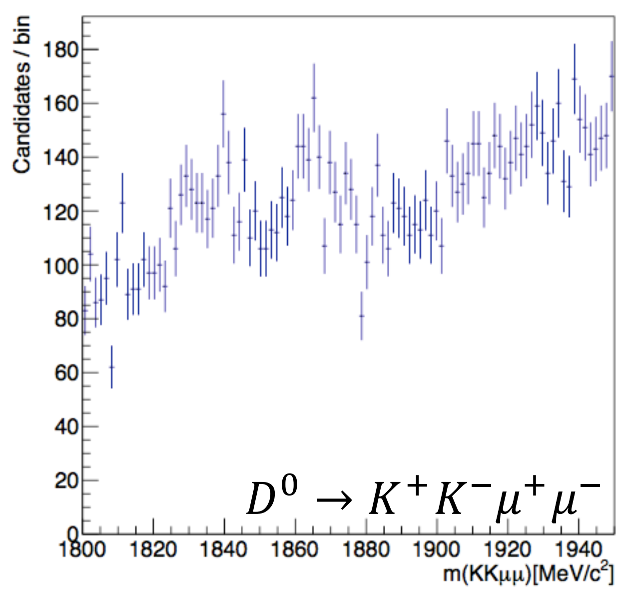
Run II data after the pre-selection





Cut on the variable $\Delta m = m(D^0\pi_s) - m(D^0)$ to suppress the combinatorial background





Signal $m(D^0)$ distribution hidden by the backgrounds

Angular fit development

- Angular distribution parametrization

$$d^5\Gamma = \frac{1}{2\pi}\left[\sum_{i=1}^{9} c_i(\theta_\mu,\phi) I_i(q^2,p^2,\theta_h)\right] \cdot dq^2 dp^2 d(\cos\theta_\mu) d(\cos\theta_h) d\phi$$

Angular basis:
known function of angles

Angular coefficients to be measured in bins of q^2

$I_{5,\ldots,9}$ are ~null in the SM

- Since we are not interested in the normalization but in the distribution shape only the first coefficient can be fixed in the fit. Equivalent to redefine $I'_i \propto I_i/I_1$

$$pdf = 1 + \frac{1}{2\pi}\sum_{i=2}^{9} c_i(\theta_\mu,\phi)\ \langle I'_i\rangle(q^2)$$

To fit in the 2-D space $\cos(\theta_\mu) - \phi$

- The SM null test for $\langle I_{5,\ldots,9}\rangle$ are not affected by the rescaling

Angular fit validation: pseudo-experiments

- Before perform the fit on real data we must validate the procedure;
- A complete pseudo-experiment chain has been developed
  1. Simple amplitude model to generate and emulate a realistic angular distribution of the signal, add the efficiency effect,
  2. Adding the real background (misID and combinatorial) from Run II DATA,
  3. Correct for the efficiency effect,
  4. Perform the D^0 mass fit and sWeights,
  5. Perform the angular fit on the background subtracted distribution, Get the coefficient $\langle I_i' \rangle (q^2)$

Repeat 1000 times

- The pseudo-experiments allow to study possible bias in the fit

$$\text{pull}_i = \frac{I_i^{\text{fit}} - I_i^{\text{gen}}}{\sigma_{I_i}}$$

Pulls have to be distributed as normal distributions

Future prospects

- Analysis in a well advanced status, selection completed,
- Angular fit validated by a complet set of pseudo-experiment chains,
- The fit returns correctly null values for $\langle I_{5,\ldots,9} \rangle$ corresponding to SM terms,
- Biases due to background and low statistics are well controlled,
- Dominated by statistical uncertainty,
- This will be the first angular analysis in a rare charm decay, lot of interest from theorists.

Future steps

- Check selection and investigate systematic sources
- Check MC-Data agreement
- Perform the measurement on real data

Angular basis

$$c_1 = 1, \;\; c_2 = \cos 2\theta_\mu, \;\; c_3 = \sin^2\theta_\mu \cos 2\phi, \;\; c_4 = \sin 2\theta_\mu \cos\phi, \;\; c_5 = \sin\theta_\mu \cos\phi,$$

$$c_6 = \cos\theta_\mu, \;\; c_7 = \sin\theta_\mu \sin\phi, \;\; c_8 = \sin 2\theta_\mu \sin\phi, \;\; c_9 = \sin^2\theta_\mu \sin 2\phi.$$

Hypathia PDF

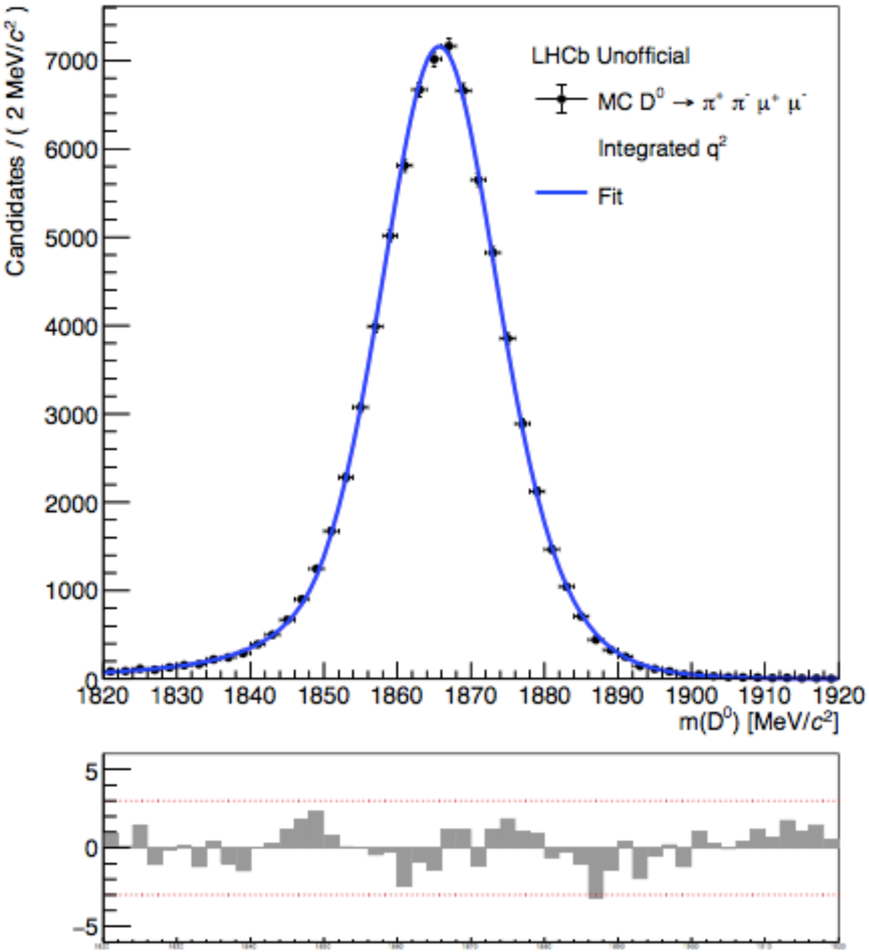
$$I(m;\, \mu, \sigma, \lambda,\xi, \beta, a, n) \propto \begin{cases} A/(B+m-\mu) & \text{if } m-\mu < -a\sigma, \\ ((m-\mu)^2+\delta^2)^{\frac{1}{2}\lambda-\frac{1}{4}}\, e^{\beta(m-\mu)}\, K_{\lambda-\frac{1}{2}}(\alpha\sqrt{(m-\mu)^2+\delta^2}) & \text{otherwise.} \end{cases}$$

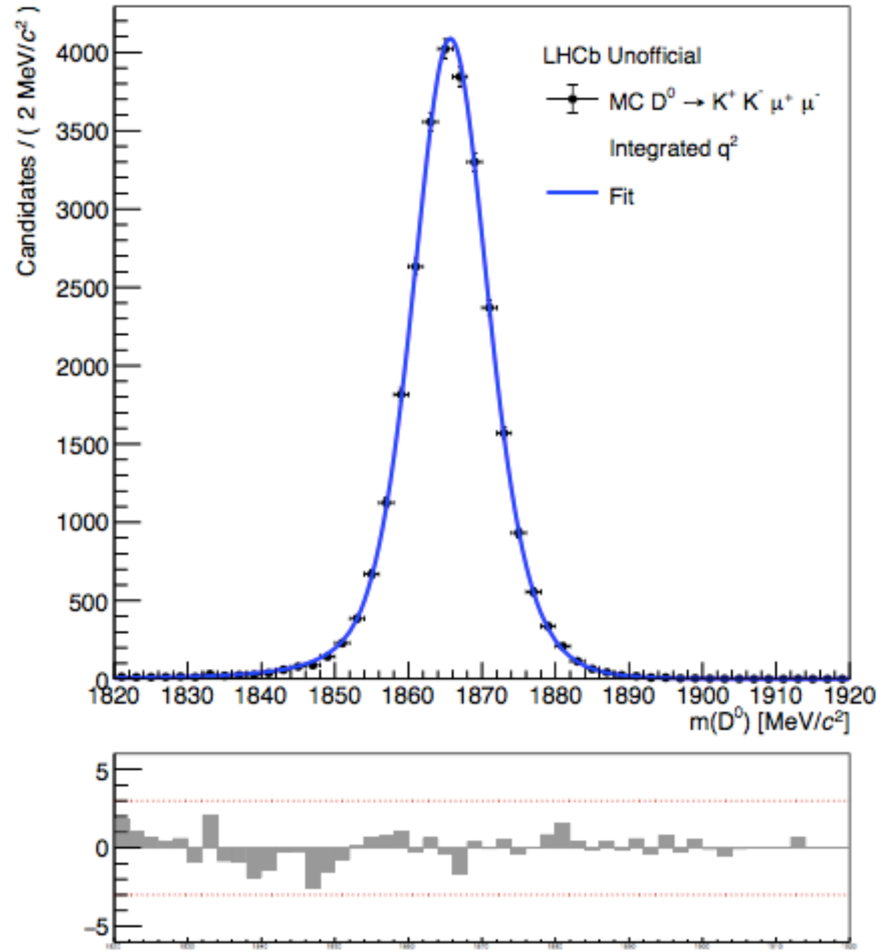
where K_ν is the modified Bessel function of the second kind, the parameter δ and α are defined as

$$\delta = \sigma\sqrt{\xi K_\lambda(\xi)/K_{\lambda+1}(\xi)},$$
$$\alpha = \sigma\sqrt{\xi K_{\lambda+1}(\xi)/K_\lambda(\xi)}/\sigma,$$

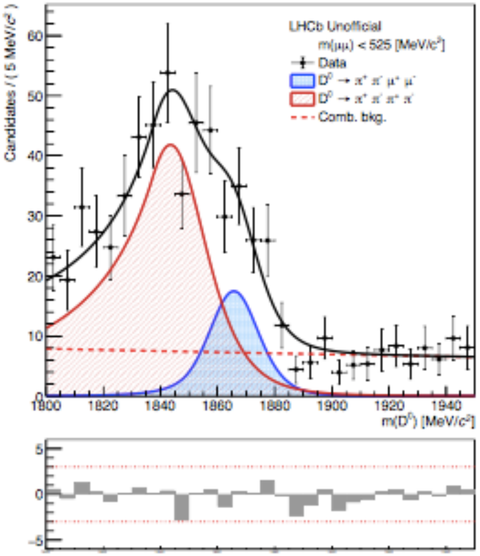
and the parameters A and B are obtained by imposing continuity and differentiability on the connection point $m = \mu - a\sigma$. The parameters μ describes the most probable values for the distribution core, while σ describes the mass resolution.

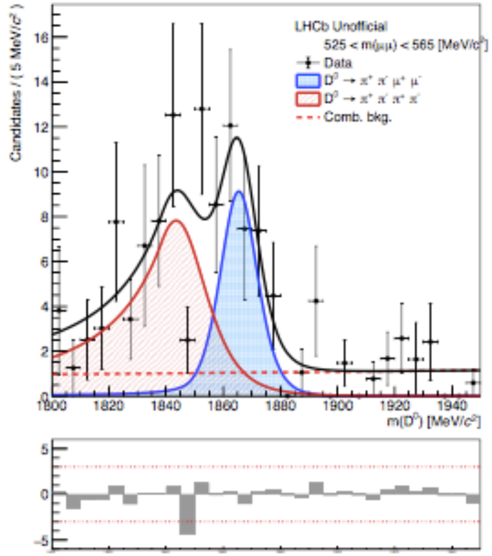
Signal shape from MC

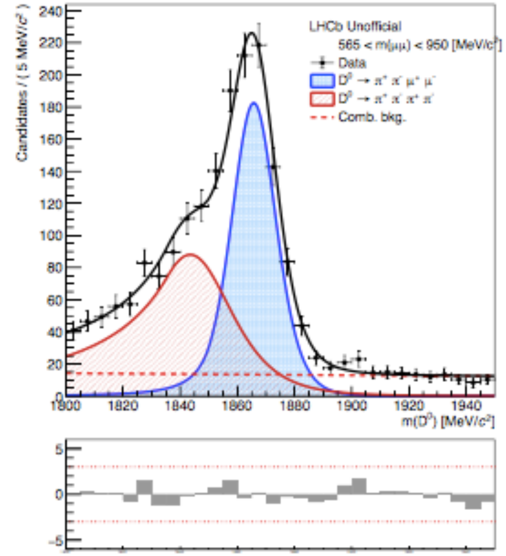


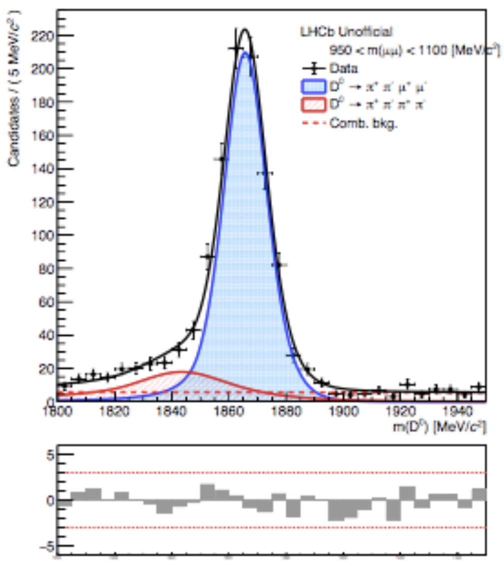


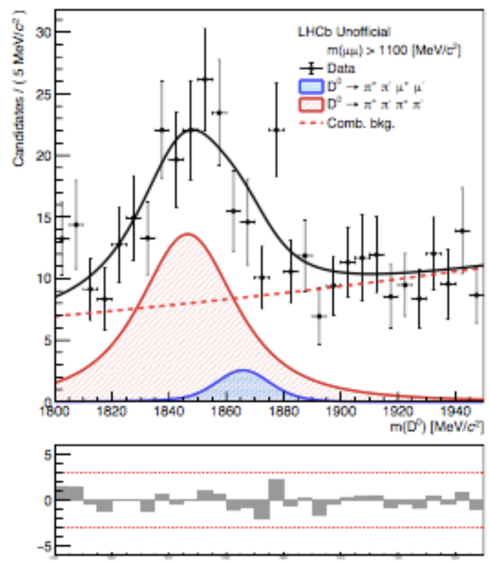
Fit on q^2 bins



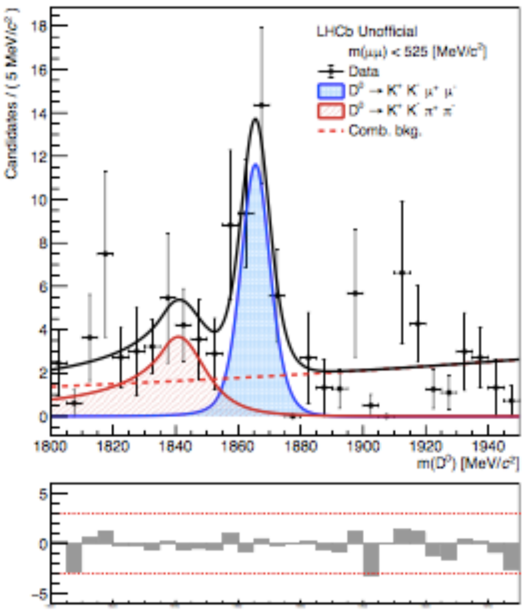


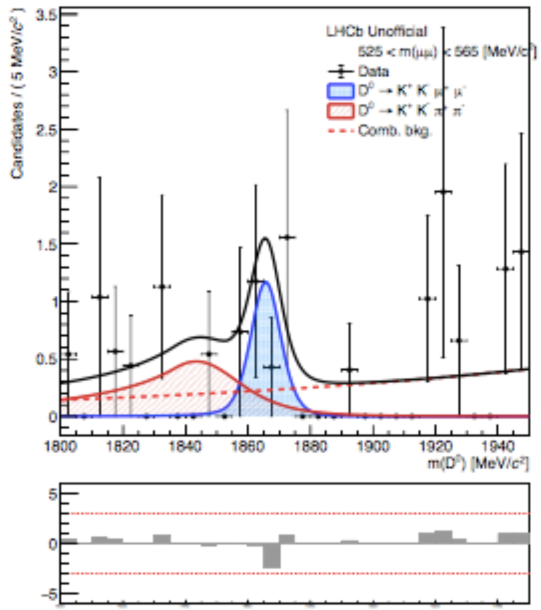


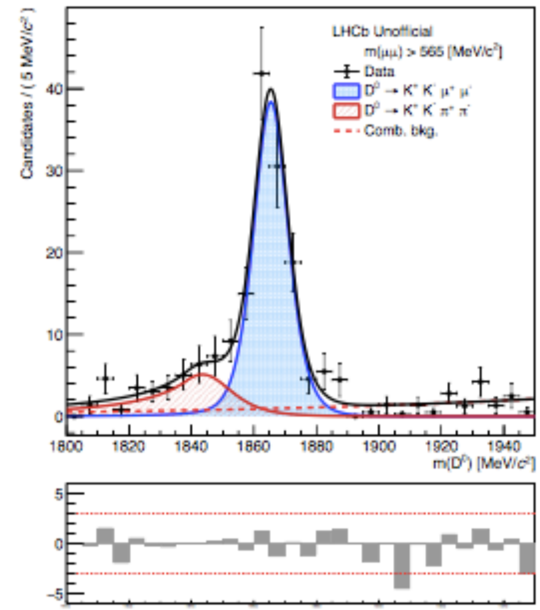




Fit on q^2 bins



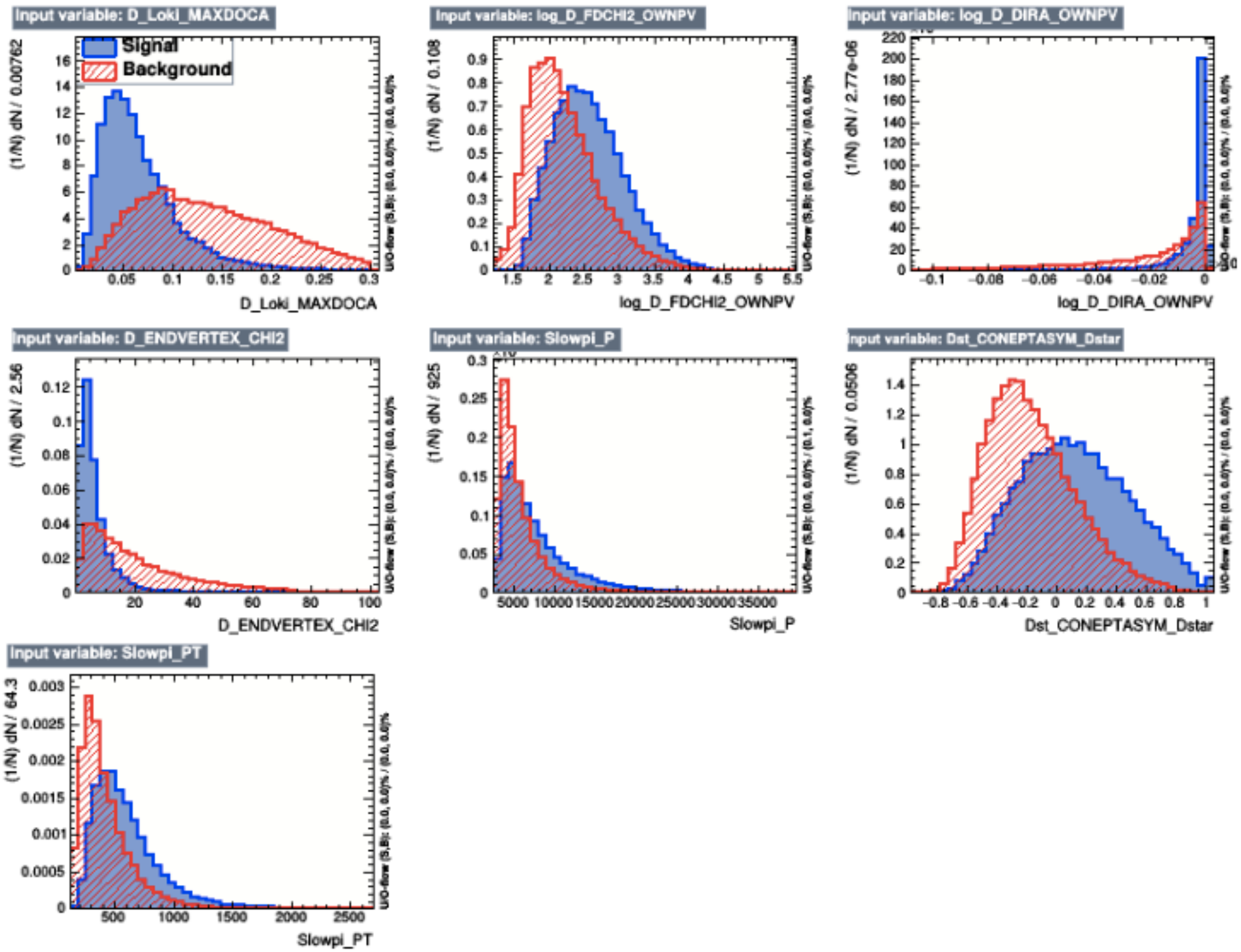




BDT input variables

- largest distance of closest approach of the D^0 daughters (D^0 **MAXDOCA**),
- logarithm of the D^0 χ^2_{FD}, $\log \chi^2_{\mathrm{FD}}(D^0)$,
- logarithm of the cosine of D^0 pointing angle, $\log \mathrm{DIRA}(D^0)$,
- χ^2_{vertex} of the D^0 decay,
- momentum of the π^+_{s}, $p(\pi^+_{\mathrm{s}})$,
- transverse momentum of the π^+_{s}, $p_{\mathrm{T}}(\pi^+_{\mathrm{s}})$,
- the D^*-cone p_{T} asymmetry.

BDT input variables

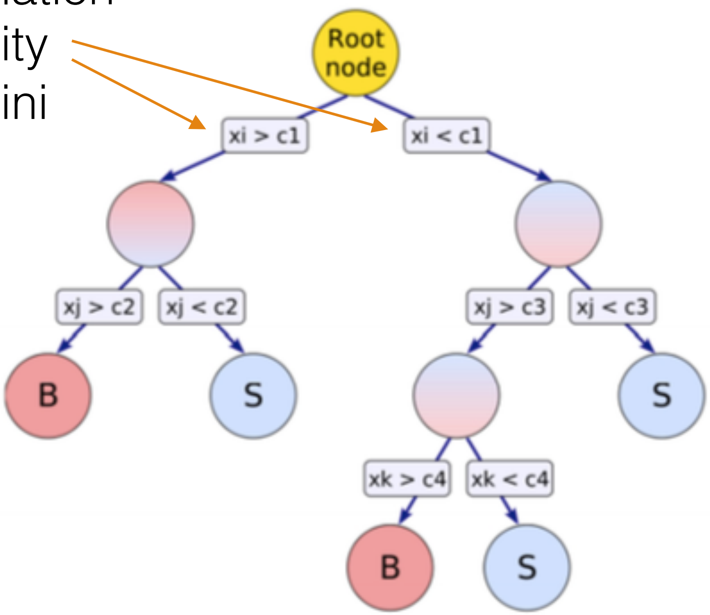


Boosted Decision Tree

- Advanced statistical method for events classification
- Simultaneous selection using many variables, taking into account all the correlations,
- Training sample using signal simulation and backgroud data

Single output variable – best signal-background separation

Calculation of purity and gini Index



- Decision tree: sequential nested cuts
- Boosting: reweighting of events misidentified in the previous tree, and grow of a next
- Output variable as a "majority vote": how many tree classify the candidate as backgroud/signal?

Trigger HLT2 selection

Particle	Variable	Requirement	
μ	p	$>$	$3\,\mathrm{GeV}/c$
	p_T	$>$	$300\,\mathrm{MeV}/c$
	Track χ^2/dof	$<$	5
	Impact-parameter χ^2	$>$	2
$\mu^+\mu^-$ combination	DOCA	$<$	$0.1\,\mathrm{mm}$
	$\sum p_T$	$>$	$0.\,\mathrm{MeV}/c$
	$\mathrm{M}(\sum p^\mu)$	$<$	$2100\,\mathrm{MeV}/c^2$
	PV		all from same
Dimuon object	Flight-distance χ^2	$>$	9
	Flight-distance	$>$	$0\,\mathrm{mm}$
	$M_{corrected}$	$<$	$3500\,\mathrm{MeV}/c^2$
$h^\pm$	p	$>$	$3\,\mathrm{GeV}/c$
	p_T	$>$	$300\,\mathrm{MeV}/c$
	Track χ^2/dof	$<$	5
	Impact-parameter χ^2	$>$	0
$(\mu^+\mu^-)h^+h^-$ combination	MIN DOCA	$<$	$0.1\,\mathrm{mm}$
	MAX DOCA	$<$	$0.2\,\mathrm{mm}$
	$\sum p_T$	$>$	$3\,\mathrm{GeV}/c$
	$\sum \sqrt{\chi^2_{IP}}$	$>$	12
	PV		all from same
D^0	m	$>$	$1800\,\mathrm{MeV}/c^2$
		$<$	$1950\,\mathrm{MeV}/c^2$
	DIRA	$>$	0.9999
	Vertex χ^2/dof	$<$	15
	Impact-parameter χ^2	$<$	25
	$M_{corrected}$	$<$	$3500\,\mathrm{MeV}/c^2$

Stripping Selection

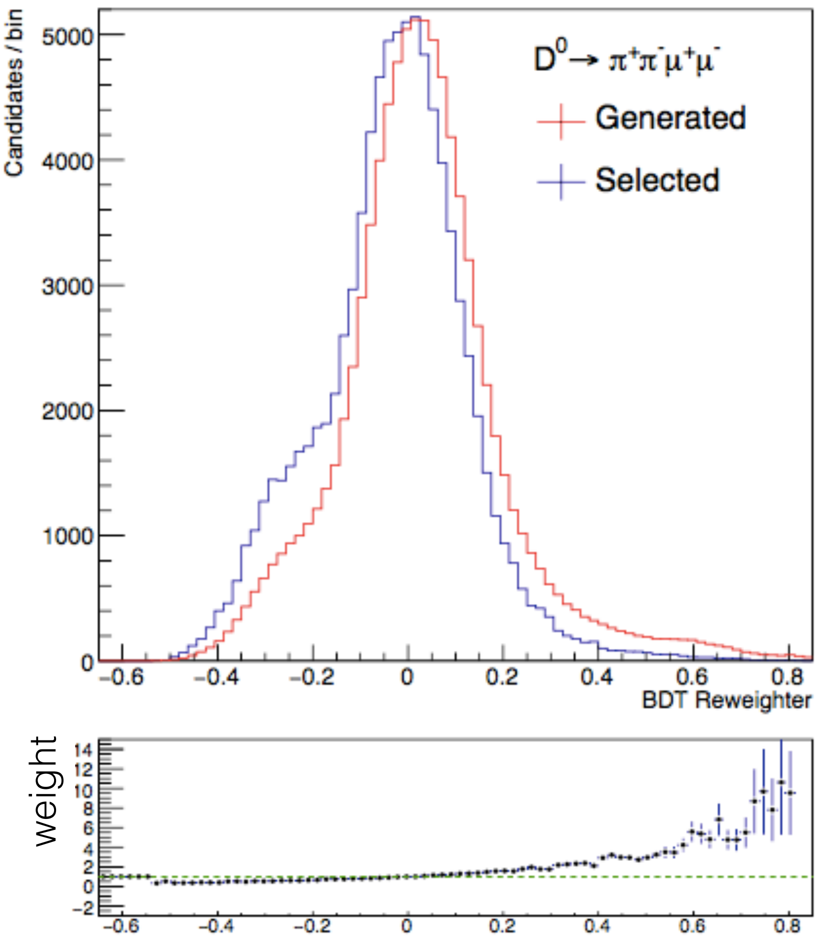
Particle	Variable	Requirement	
K,π,μ	p	$>$	$3\,\mathrm{GeV}/c$
	p_T	$>$	$300\,\mathrm{MeV}/c$
	Impact-parameter χ^2	$>$	3
	Track χ^2/dof	$<$	3
μ	`isMuon`		True
K	DLL_K	$>$	-5
D^0	p	$>$	$3\,\mathrm{GeV}/c$
	p_T	$>$	$2\,\mathrm{GeV}/c$
	m	$>$	$m_{\mathrm{PDG}} - 100\,\mathrm{MeV}/c^2$
		$<$	$m_{\mathrm{PDG}} + 100\,\mathrm{MeV}/c^2$
	Vertex χ^2/dof	$<$	20
	Flight-distance χ^2	$>$	30
	Impact-parameter χ^2	$<$	36
	Cosine of the direction angle (a.k.a. DIRA)	$>$	0.9998
	Largest distance of closest approach of daughters (a.k.a. MAXDOCA)	$<$	0.3 mm
	Impact-parameter χ^2 of at least one of the daughters	$>$	9
D^*	p_T	$>$	$2\,\mathrm{GeV}/c$
	Vertex χ^2/dof	$<$	20
	Distance of closest approach of daughters (a.k.a. DOCA)	$<$	0.3 mm
	Δm	$>$	$137.4\,\mathrm{MeV}/c^2$
		$<$	$163.4\,\mathrm{MeV}/c^2$
π_s	p_T	$>$	$120\,\mathrm{MeV}/c$
	Track χ^2/dof	$<$	3
	Number of primary vertices	$\geq$	1

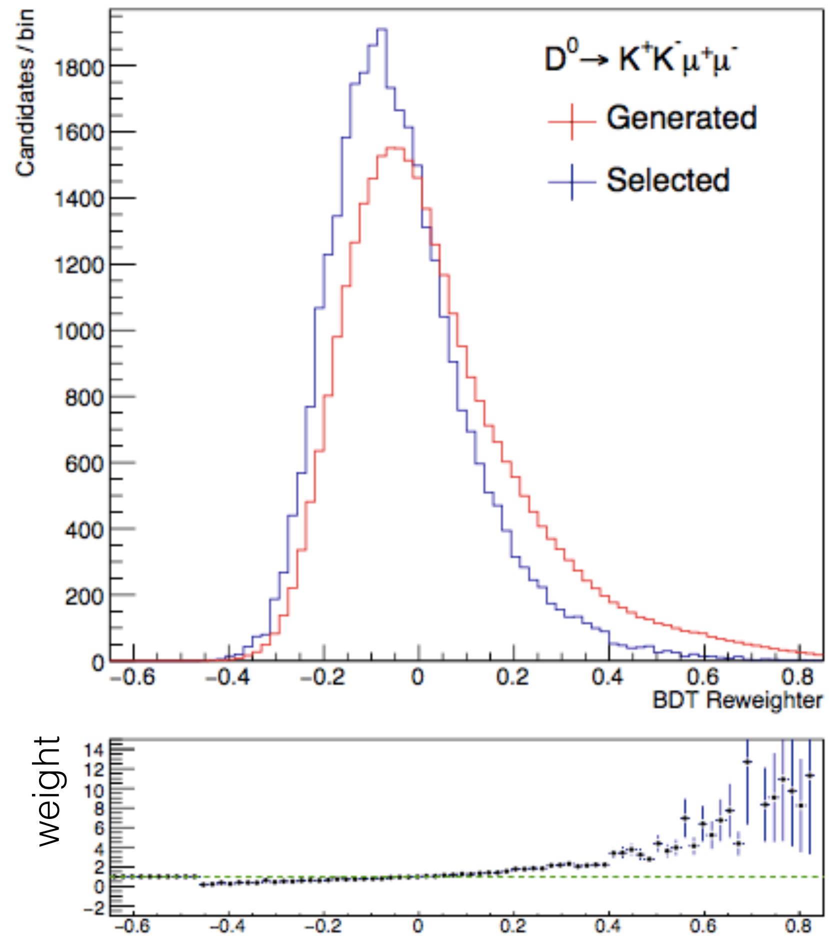
Preselection

particle	Variable	$D^0 \to K^+K^-\mu^+\mu^-$	$D^0 \to \pi^+\pi^-\mu^+\mu^-$
K, π, μ	TRACKGhostProb	< 0.3	< 0.3
π_s	TRACKGhostProb	< 0.05	< 0.05
μ	MuonNShared	$= 0$	$= 0$
π	ProbNNpi		> 0.2
K	ProbNNK	> 0.2	
D^0	IPχ^2	< 25	< 25
D^{*+}	Δm	$> 144.5\,\mathrm{MeV}/c^2$	$> 144.5\,\mathrm{MeV}/c^2$
		$< 146.5\,\mathrm{MeV}/c^2$	$< 146.5\,\mathrm{MeV}/c^2$

Phase-space dependent efficiency

- Output of the reweighter BDT and the corresponding weight





Sensitivity to asymmetries - $\pi^+\pi^-$ mode

- Simultaneous fit splitting dataset by a random tag,
- Same shapes and selection assumed,
- Asymmetry A as shared parameter.

$$N^+ = \frac{N_{tot}}{2}(1 + A)$$

$$N^- = \frac{N_{tot}}{2}(1 - A)$$

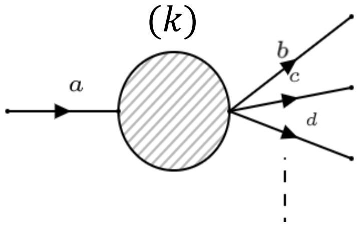
Channel		$m(\mu^+\mu^-)$ MeV/c^2	ΔA
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	full range		2.5%
	low mass	< 525	20%
	η	$525 - 565$	20%
	ρ/ω (left)	$565 - 780$	5.1%
	ρ/ω (right)	$780 - 950$	7.3%
	ρ/ω (full)	$565 - 950$	4.3%
	ϕ (left)	$950 - 1020$	4.5%
	ϕ (right)	$1020 - 1100$	4.0%
	ϕ (full)	$950 - 1100$	3.1%
	high mass	> 1100	–
$D^0 \to K^+K^-\mu^+\mu^-$	full range		7.5%
	low mass	< 525	18%
	η	$525 - 565$	–
	high mass	> 565	8%

Amplitude Analysis feasibility

1. Build a model of the full amplitude M_{if} in order to include all the possibile contributions,
2. Add contributions, according to their possibility to interfere,
3. Fit the model in the 5-dimensional phase-space,
4. Determine asymmetries for each component.

$$W_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \frac{dN}{dE_f}$$

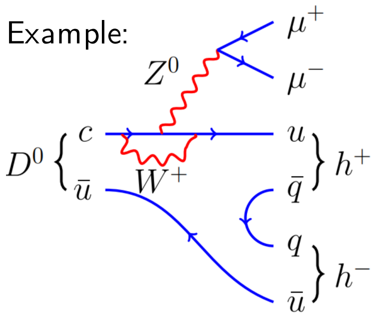
$M_{if}^{(k)} =$



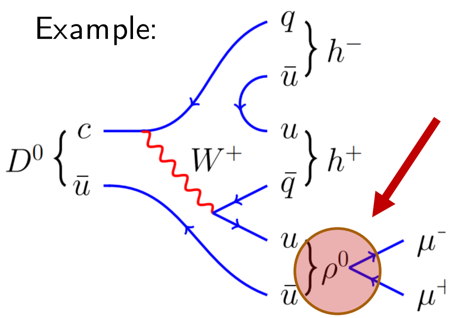
$=$ $a_0 e^{i\delta_0}$ [Non Resonant (short distance)] $+ \sum_j$ $a_j e^{i\delta_j} \mathcal{A}_j$ [Resonances (long distance)]$_j$

Coherent sum of contributions which can produce the same final states and can interfere.

Example:



Example:



$$\left|M_{if}^{final}\right|^2 = |\langle i|U|f\rangle|^2 = \sum_k \left|M_{if}^{(k)}\right|^2$$ Final Incoherent sum

Amplitude Analysis feasibility

- Impossible to build the amplitude from first principles.
- Phenomenological approach needed. A decay amplitude for a process $\boldsymbol{a} \rightarrow \boldsymbol{b}\ \boldsymbol{c}$ can be modelled in the helicity formalism and isobar model as:

$$\mathcal{A}(a \rightarrow b\ c) = \mathbf{A}_{\lambda_b,\lambda_c} \mathbf{D}^{\mathbf{J}^a}_{\mathbf{s}^a,\Delta\lambda_a}(\phi_\mathbf{b}, \theta_\mathbf{b}, -\phi_\mathbf{b})$$

Dynamical factor

Wigner-D-function contains the angular distribution

$$A_{\lambda_b,\lambda_c} = (coef) \cdot B_{L_a}(p_a, d) \left(\frac{p_a}{m_a}\right)^{L_a} \cdot BW(m, m_a, \Gamma_a)$$

- Blatt-Weisskopf form factors
- Breit-Wigner lineshape or its generalizations

- For now we are studying the model only for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$

J^P	$\pi\pi$ resonances	$\mu\mu$ resonances
0^+	$f_0(980)$, $f_0(500)$, $f_0(1370)$	
0^-		η
1^-	$\rho(770)$, $\omega(782)$, $\rho(1450)$	$\rho(770)$, $\omega(782)$, $\phi(1020)$
2^+	$f_2(1270)$	

Amplitude Analysis feasibility

- Only some combinations of specific J^P are allowed, due to angular momentum and parity conservation.
  For example (only lower J and L):
  - $D^0 \to 0^+0^-$ S-wave: $f_0(980)\eta$, $f_0(500)\eta$, $f_0(1370)\eta$
  - $D^0 \to 1^-0^-$ P-wave: $(\rho-\omega)\,\eta$, $\rho(1450)\,\eta$
  - $D^0 \to 1^-1^-$ P-wave: $(\rho-\omega)(\rho-\omega)$, $(\rho-\omega)\,\phi$ → *Most important*

- For two resonances production (first topology) the single contribution can be written as:

$$A^{R_1,R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}} = \sqrt{\frac{(2s_{R_1}+1)(2s_{R_2}+1)}{(4\pi)^2}} \sum_{\lambda_{R_1}} d^{J_{R_2}}_{\lambda_{R_1},\lambda_{\mu^+}-\lambda_{\mu^-}}(\theta_{\mu^+})\, d^{J_{R_1}}_{\lambda_{R_1},0}(\theta_{\pi^+})\, e^{-i\,\lambda_{R_1}\phi}\, A^{R_1}_{0,0}\, A^{R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}}$$

0^+0^-: $$A^{R_1,R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}} = \frac{1}{4\pi} A^{R_1}_{0,0}\, A^{R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}}$$

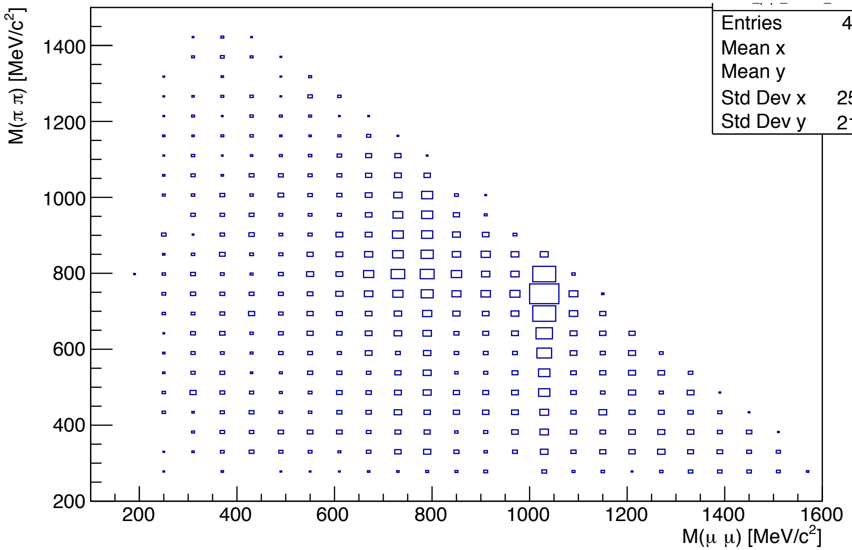
1^-0^-: $$A^{R_1,R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}} = \frac{\sqrt{3}}{4\pi} \sum_{\lambda_{R_1}} d^{1}_{\lambda_{R_1},0}(\theta_{\pi^+})\, e^{-i\,\lambda_{R_1}\phi}\, A^{R_1}_{0,0}\, A^{R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}}$$

1^-1^-: $$A^{R_1,R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}} = \frac{\sqrt{3}}{4\pi} \sum_{\lambda_{R_1}} d^{1}_{\lambda_{R_1},\Delta\lambda_{\mu}}(\theta_{\mu^+})\, d^{1}_{\lambda_{R_1},0}(\theta_{\pi^+})\, e^{-i\,\lambda_{R_1}\phi}\, A^{R_1}_{0,0}\, A^{R_2}_{\lambda_{\mu^+},\lambda_{\mu^-}}$$

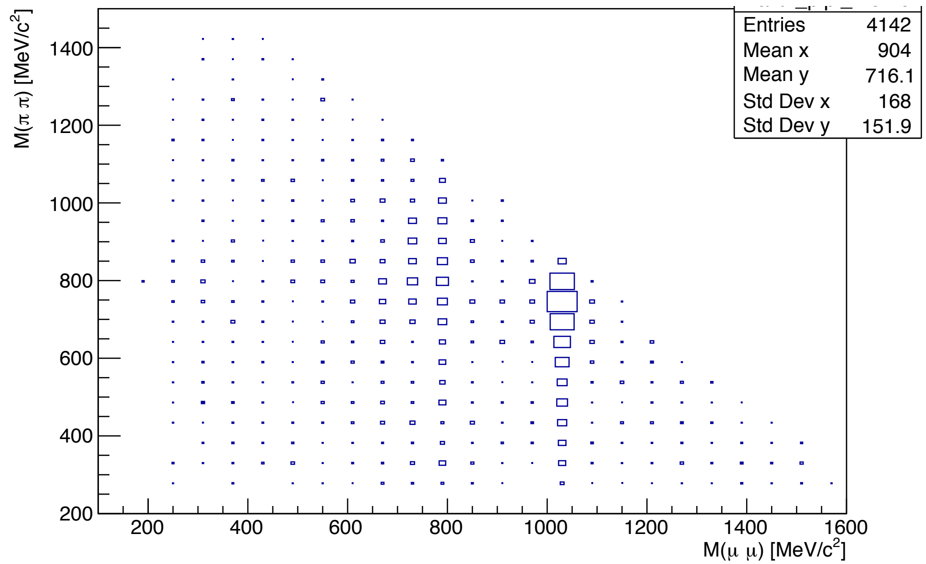
Background subtracted distributions

- First look at 2017 data phase-space slice in $\{m(\mu\mu), m(\pi\pi)\}$ plane after sWeights,
- Important note: in this slice the phase-space-only distribution is not flat!

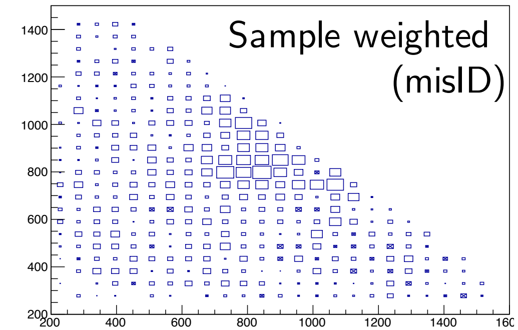
Full sample unweighted



Sample weighted (signal)



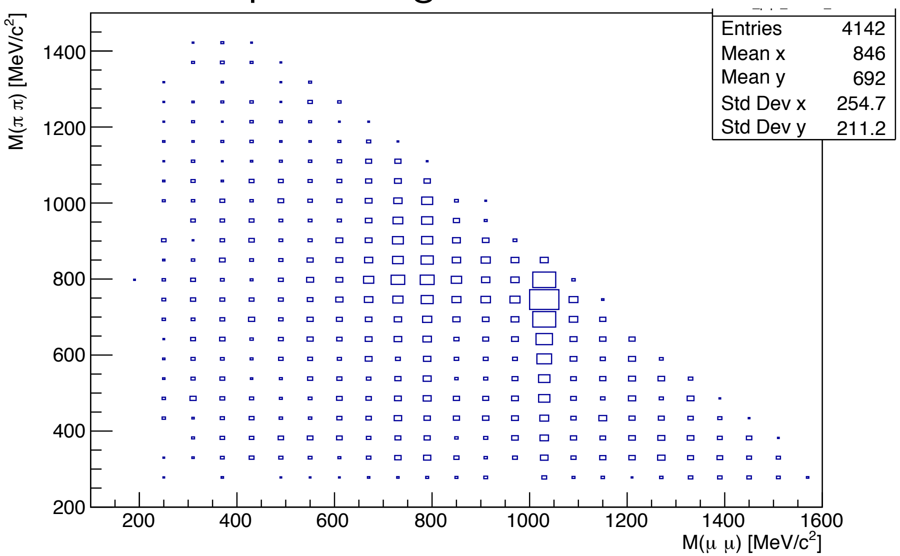
- MisID background populate the whole $m(\mu\mu) - m(\pi\pi)$ plane: evident contribution $(\rho - \omega)$ $(\rho - \omega)$



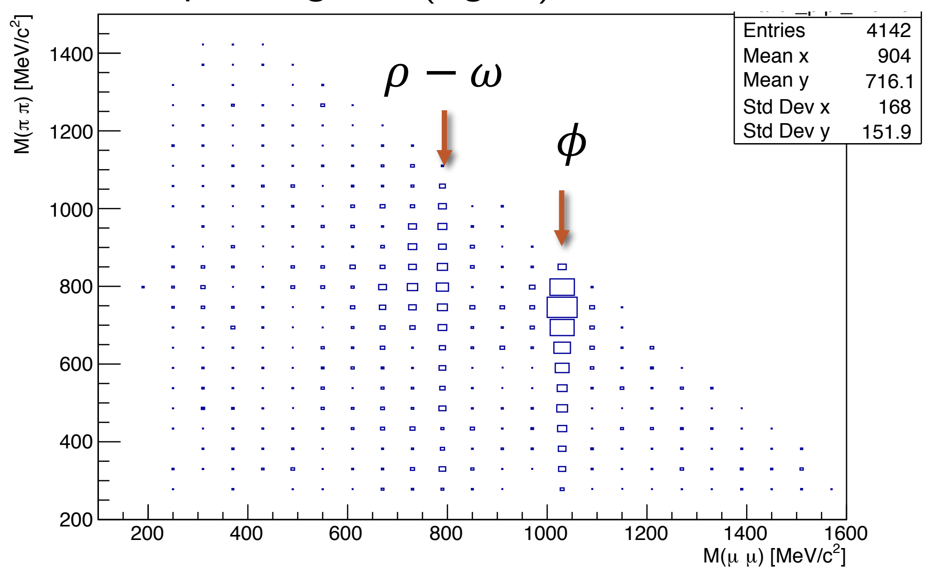
Background subtracted distributions

- First look at 2017 data phase-space slice in $\{m(\mu\mu), m(\pi\pi)\}$ plane after sWeights,
- Important note: in this slice the phase-space-only distribution is not flat!

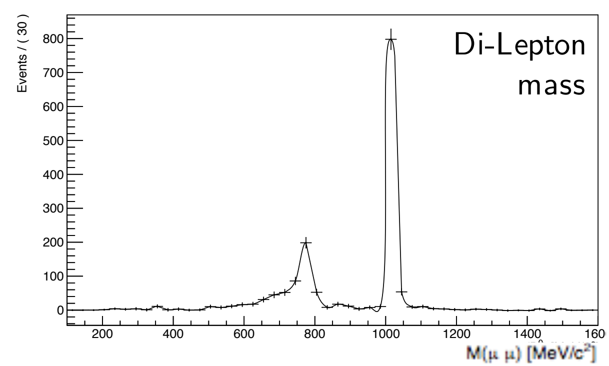
Full sample unweighted



Sample weighted (signal)



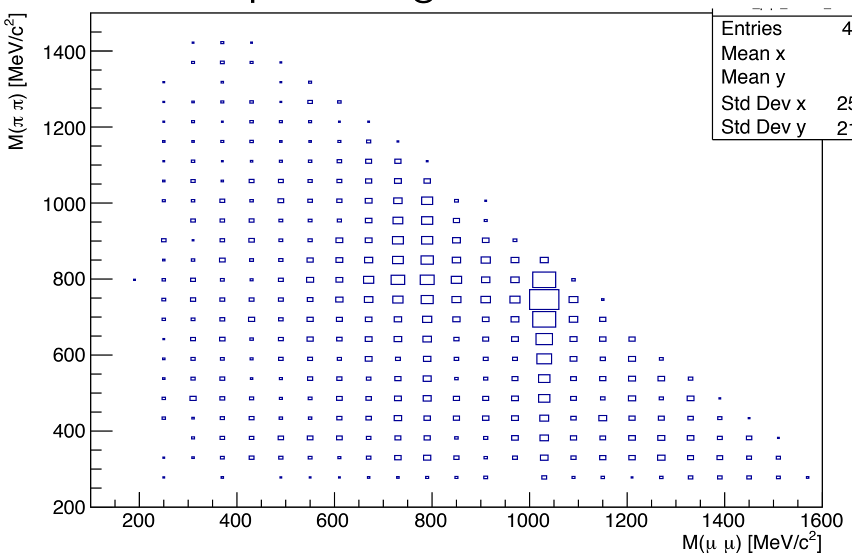
- MisID background populates the whole $m(\mu\mu) - m(\pi\pi)$ plane: evident contribution $(\rho - \omega)$ $(\rho - \omega)$
- Clear evidence of ϕ and $\rho - \omega$ contributions in $m(\mu\mu)$, as expected



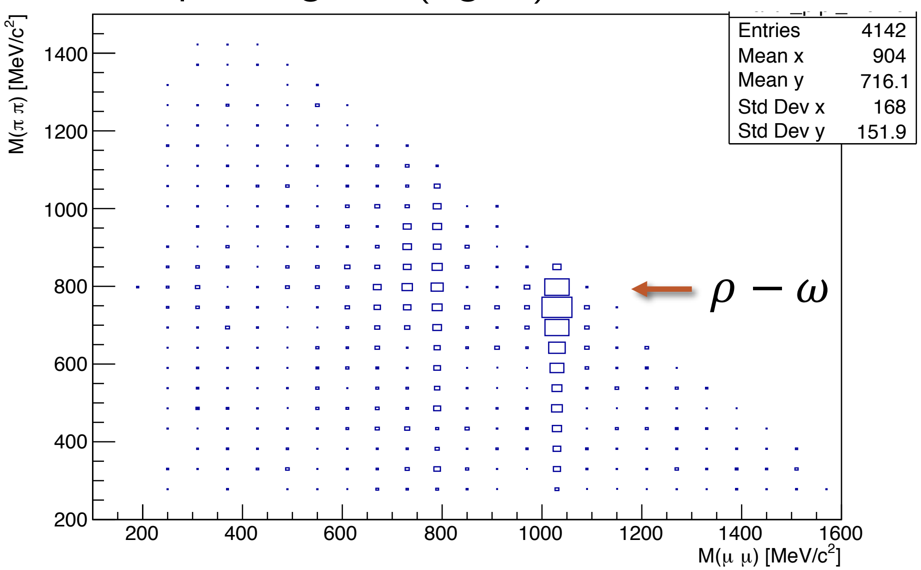
Background subtracted distributions

- First look at 2017 data phase-space slice in $\{m(\mu\mu), m(\pi\pi)\}$ plane after sWeights,
- Important note: in this slice the phase-space-only distribution is not flat!

Full sample unweighted



Sample weighted (signal)



- MisID background populates the whole $m(\mu\mu) - m(\pi\pi)$ plane: evident contribution $(\rho - \omega)$ $(\rho - \omega)$
- Clear evidence of ϕ and $\rho - \omega$ contributions in $m(\mu\mu)$, as expected
- Evidence of $\rho - \omega$ contributions in $m(\pi\pi)$, as expected. Interference patterns will be clearer with the full statistics.