Λ_b Polarization Measurement at ATLAS

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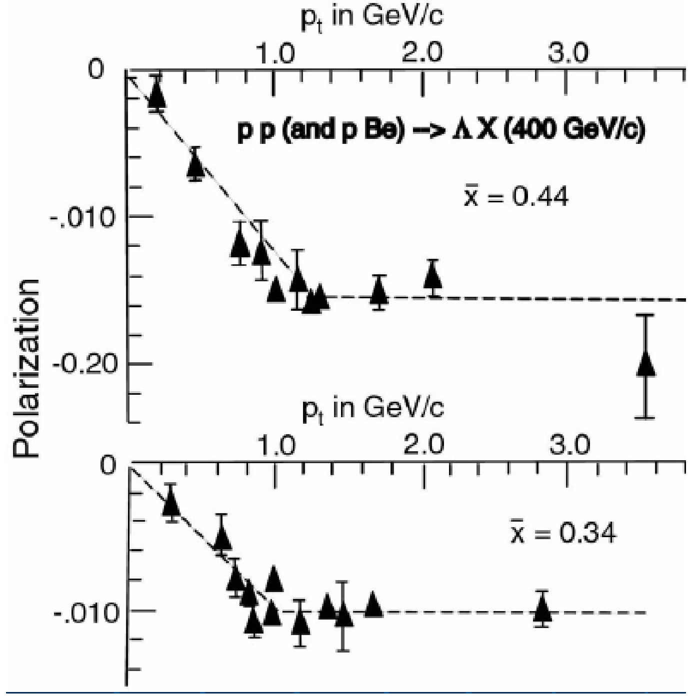
Λ_b Production at LHC

- Due to the parity conservation in the strong interactions, at LHC Λ_b can be produced with polarization orthogonal to the production plane

- ***... but why polarization ?***
  - Large number of unanswered questions about the role of spin in production of hyperons at high energies which we wish to explore
    - Λ hyperon (uds)
      - Why is the polarization is so large ?
      - Why is the shape so unusual ?
    - Λ_b hyperon (udb)
      - Are the mechanisms of Λ and Λ_b polarization different ?
      - Are the s and b production mechanisms similar ?
      - Does the polarization depend on quark mass?



K. Heller, Procedings of the 9th International Symposium on High Energy Physics, Bonn (1990)

Λ_b Decay

- The considered decay, $\Lambda_b \to J/\psi(\mu\mu)\ \Lambda(p\pi)$, is characterizes by 4 helicity amplitudes and the asymmetry parameter α_b caused by the parity non conservation of the weak interactions
- $1/2 \to 1/2 + 1$

$$a_+ = A(1/2,0)$$
$$a_- = A(-1/2,0)$$
$$b_+ = A(-1/2,-1)$$
$$b_- = A(1/2,1)$$

$$\alpha_b = \frac{|a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2}{|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2}$$

- helicity amplitudes and asymmetry parameter α_b not yet measured
- they can, in principle, be predicted using PQCD, and thus be a tool to test theoretical models and to search for new physics
- Other interesting studies for this decay channel
  - Lifetime of Λ_b hyperon
  - CP violation in baryons

Λ_b in ATLAS

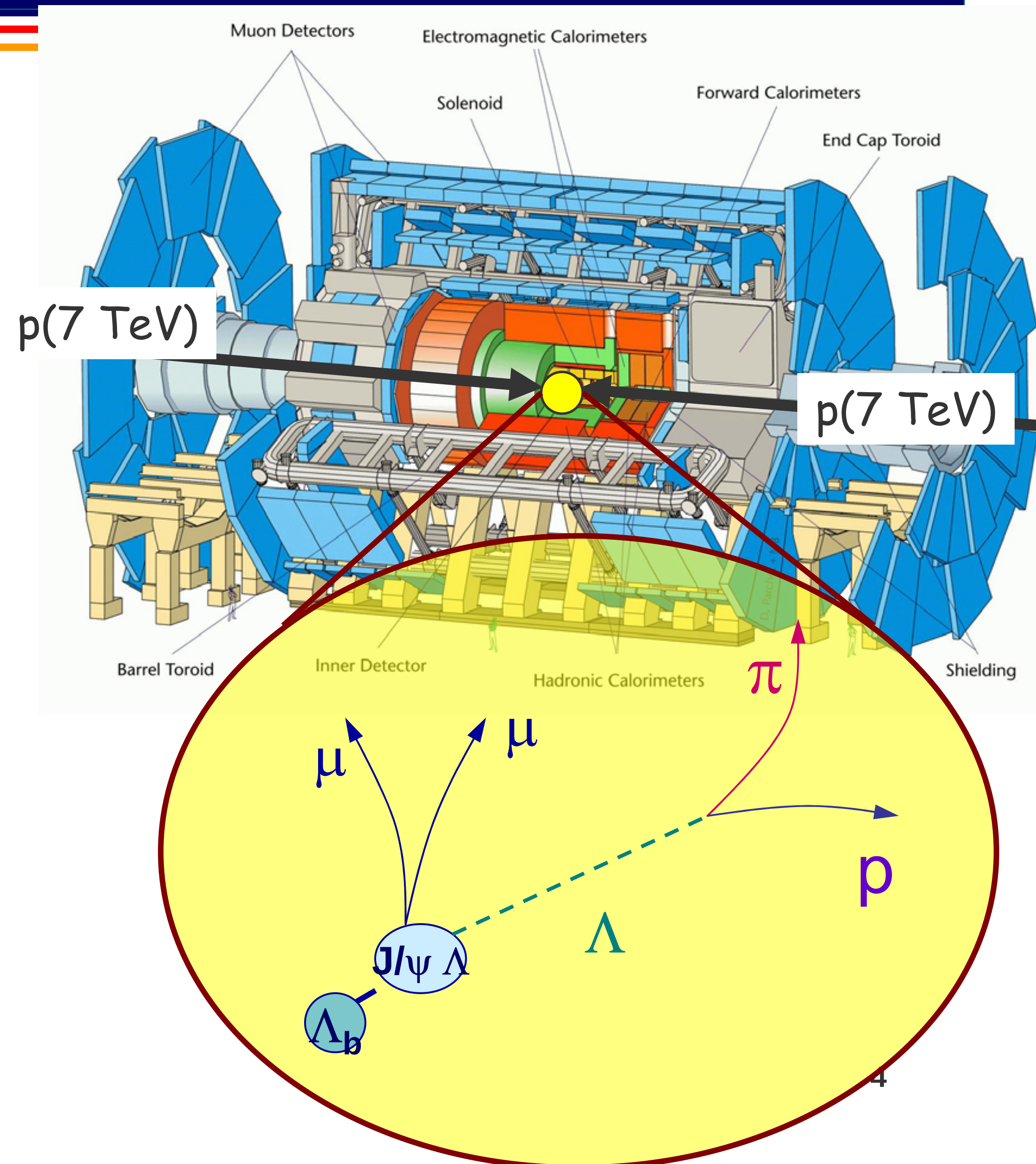
- For Low luminosity operations

L= 10^{33} cm^{-2} s^{-1}

  - $\int$ L= 10fb $^{-1}$ → O(10^{12}) Λ_b per year

- In the first 3 years O(10^5) Λ_b→ J/ψ ($\mu^+\mu^-$) Λ (πp) (ATLAS TDR estimation)

- The world's biggest sample so far is ~ O(10^2) Λ_b →J/ψ (μ μ) Λ (π p)

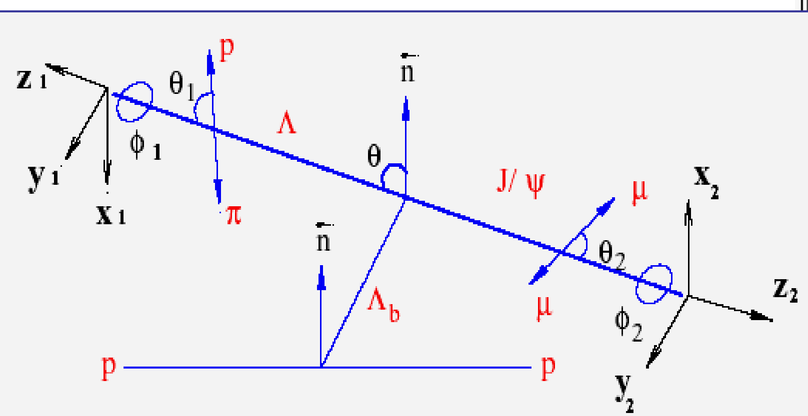


Measurement of $\Lambda_b \to J/\psi\ \Lambda$

The Λ_b polarization (P_b) and decay parameters can be determined from the angular distributions p.d.f. of the cascade decay

$$w(\Omega, \Omega_1, \Omega_2) = \frac{1}{(4\pi)^3} \sum_{i=0}^{i=19} f_{1i} f_{2i}(P_b, \alpha_\Lambda) F_i(\theta, \theta_1, \theta_2, \phi_1, \phi_2)$$

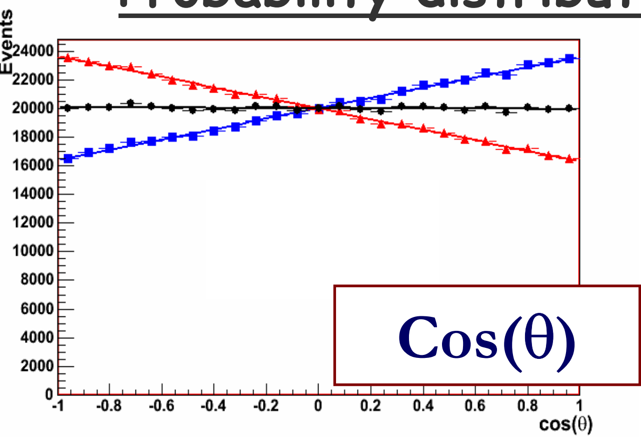
$\Lambda_b \to J/\psi(\mu\mu)\Lambda(\pi p)$ p.d.f. depends on 5 angles + 6 parameters of 4 complex helicity amplitudes and polarization P_b (→ 7 unknowns).

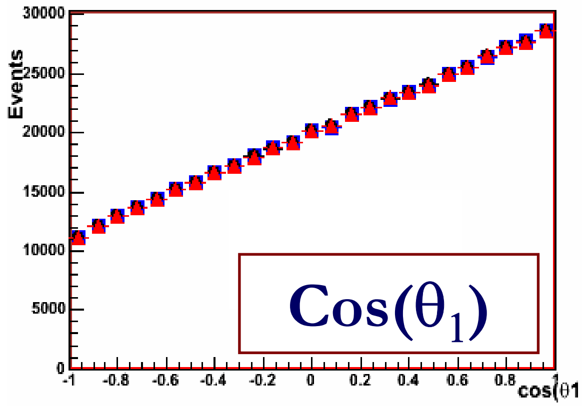


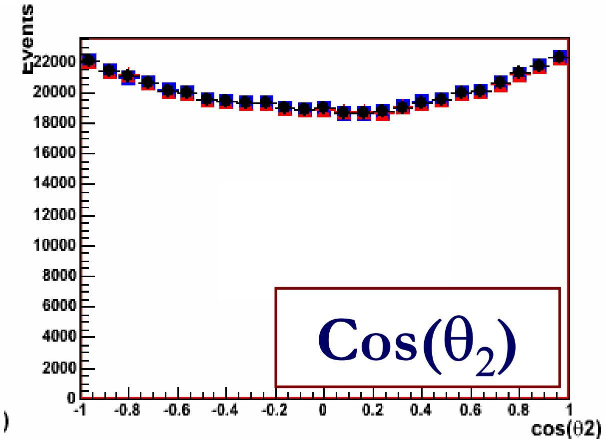
i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
1	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	P_b	$\cos\theta$
2	$a_+a_+^* - a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\cos\theta_1$
3	$a_+a_+^* + a_-a_-^* - b_+b_+^* - b_-b_-^*$	$P_b\alpha_\Lambda$	$\cos\theta\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	1	$d_{00}^2(\theta_2)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P_b	$d_{00}^2(\theta_2)\cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$d_{00}^2(\theta_2)\cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P_b\alpha_\Lambda$	$d_{00}^2(\theta_2)\cos\theta\cos\theta_1$
8	$-3Re(a_+a_-^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos\phi_1$
9	$3Im(a_+a_-^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin\phi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2 cos(\phi_1+2\phi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2 sin(\phi_1+2\phi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\cos\phi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\sin\phi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P_b\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1+\phi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P_b\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1+\phi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P_b	$\sin\theta\sin\theta_2\cos\theta_2\cos\phi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P_b	$\sin\theta\sin\theta_2\cos\theta_2\sin\phi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1+\phi_2)$
19	$-\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1+\phi_2)$

What angular distributions do we expect?

Probability distributions:



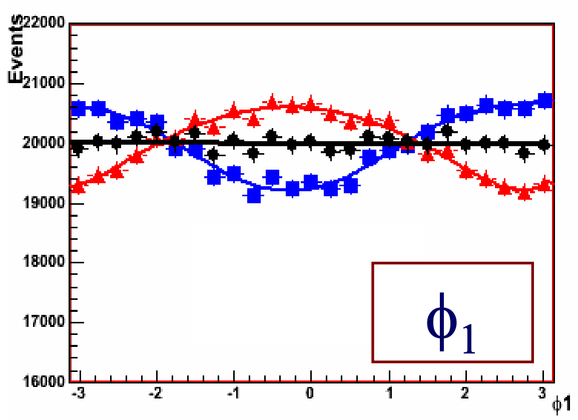


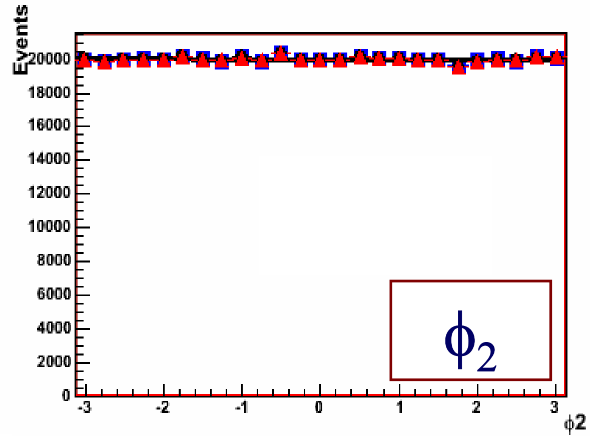


P = 0%

P = -40%

P = 40%





A Model for Λ_b Decay

- The general amplitude for the decay $\Lambda_b \rightarrow \Lambda\, J/\psi$ is given by:

$$M = \bar{\Lambda}(p_\Lambda)\varepsilon^*_\mu(p_{J/\psi})\left[A_1\gamma^\mu\gamma_5 + A_2\frac{p^\mu_{\Lambda_b}}{m_{\Lambda_b}}\gamma_5 + B_1\gamma^\mu + B_2\frac{p^\mu_{\Lambda_b}}{m_{\Lambda_b}}\right]\Lambda_b(p_{\Lambda_b}),$$

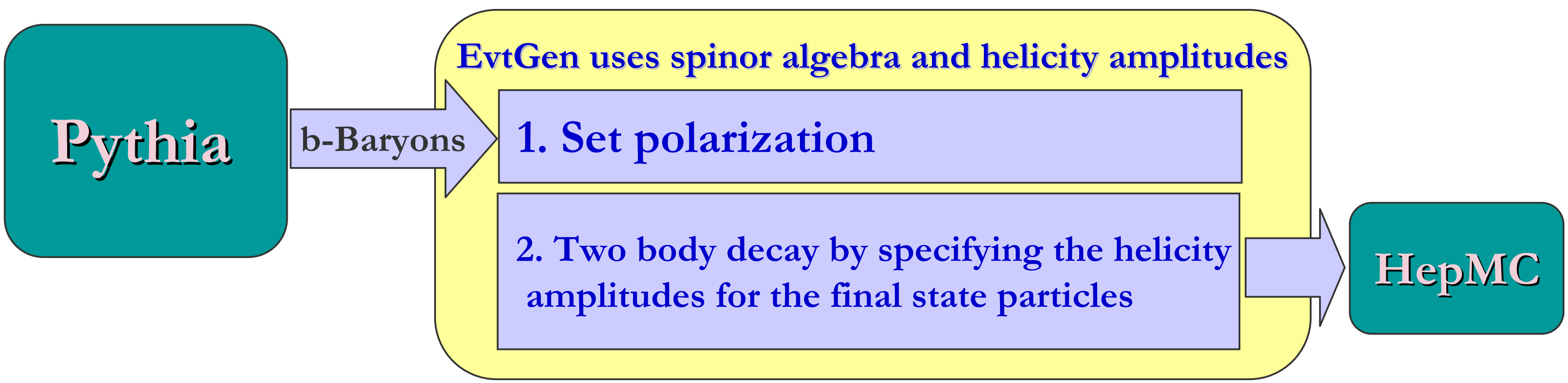
- ε_μ^* - polarization vector of the vector meson (J/ψ)
- A_1, A_2, B_1, B_2 - complex decay amplitudes are calculable within the framework of PQCD models using factorization theorems (*Phys. Rev. D65:074030, 2002, hep-ph/0112145*)
- Helicity amplitudes related to A_1, A_2, B_1, B_2:

$a_+ = -0.0176 - 0.4290i$
$a_- = 0.0867 + 0.2454i$
$b_+ = -0.0810 - 0.2837i$
$b_- = 0.0296 + 0.8124i$

$$\alpha_b = -0.457$$

Generation of Polarized Λ_b

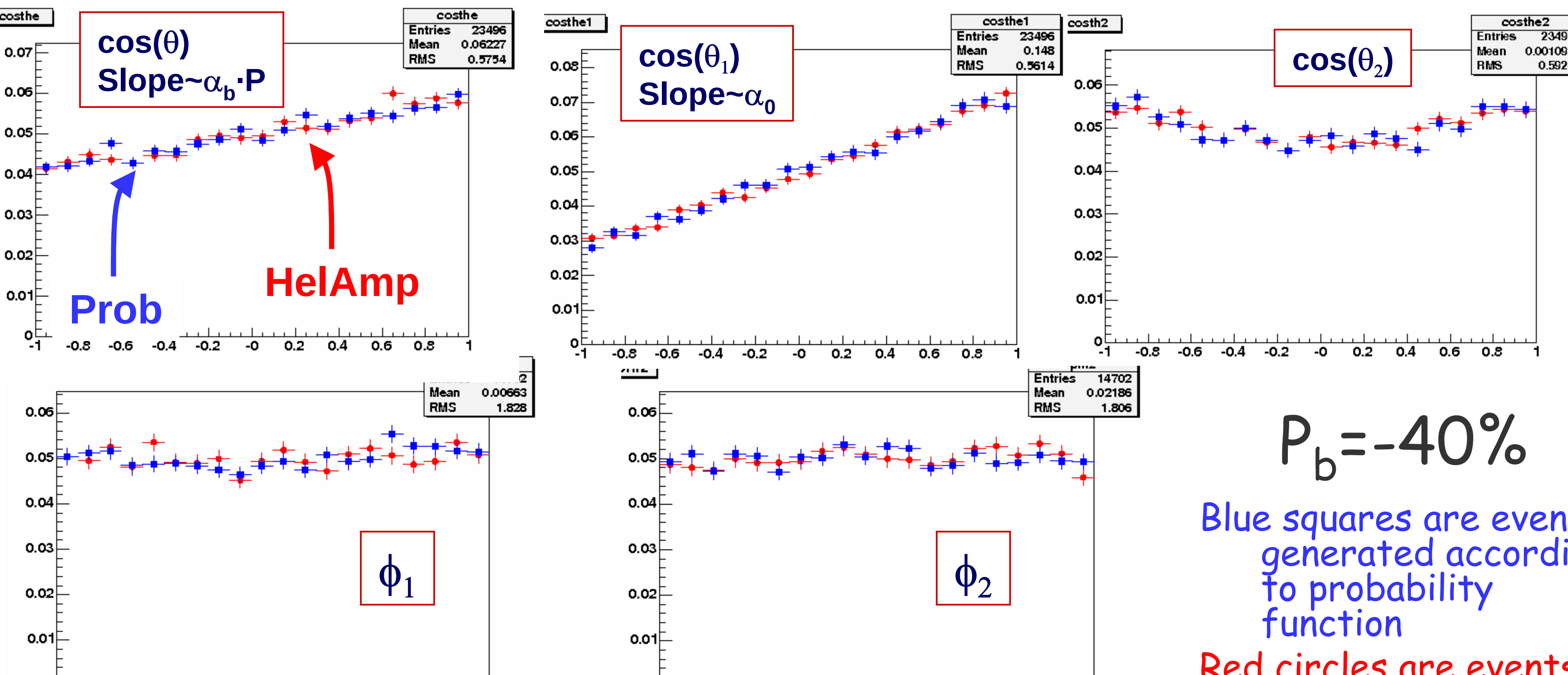
- In order to study the feasibility of measuring Λ_b polarization in ATLAS we have developed a way to make polarized Λ_b in EvtGen
- EvtGen: originally written in BaBar and CLEO, now also in MC/LCG project
  - package providing a framework for implementation of processes relevant to B physics
  - uses spinor algebra and helicity amplitudes
    - it's possible to set the polarization of the particle before the particle is decayed
    - .. and obtain the correct angular distributions



First ever adaptation of EvtGen as a generator of polarized baryons

EvtGen Cross Check

- 5 angular distributions are generated using both the probability function and using the full amplitude feature in EvtGen



Very good agreement between the angular distributions generated with EvtGen and the probability density function!

P_b=-40%

Blue squares are events generated according to probability function

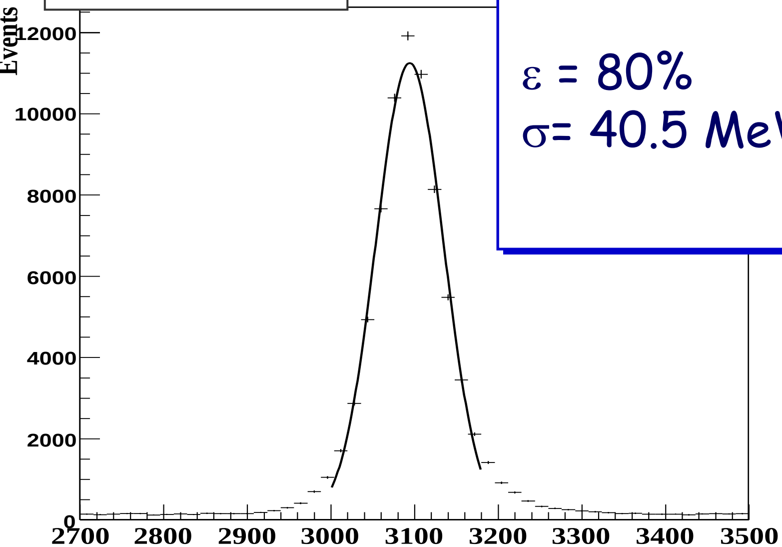
Red circles are events generated with helicity amplitudes in EvtGen

Data Simulation, Reconstruction and Analysis

- Events generated with Pythia/EvtGen
  - several input models
  - Production cuts:
    - $p_T(\mu_1) > 2.5GeV$, $p_T(\mu_2) > 4.0GeV$,
    - $p_T(\pi/p) > 0.5$ GeV, $|\eta| < 2.7$
- Full simulation in ATLAS detector with Geant4
- Recostruction
  - Dedicated algorithm for low p_T muons developed
    - Better efficiency for J/ψ identification
  - Inner Detector tracking and vertexing algorithms for Λ and Λ_b identification
  - Angular distributions determination
- Analysis
  - MC toy for "fast" predictions
  - Maximum Likehood method to measure P_b and Λ_b decay parameters

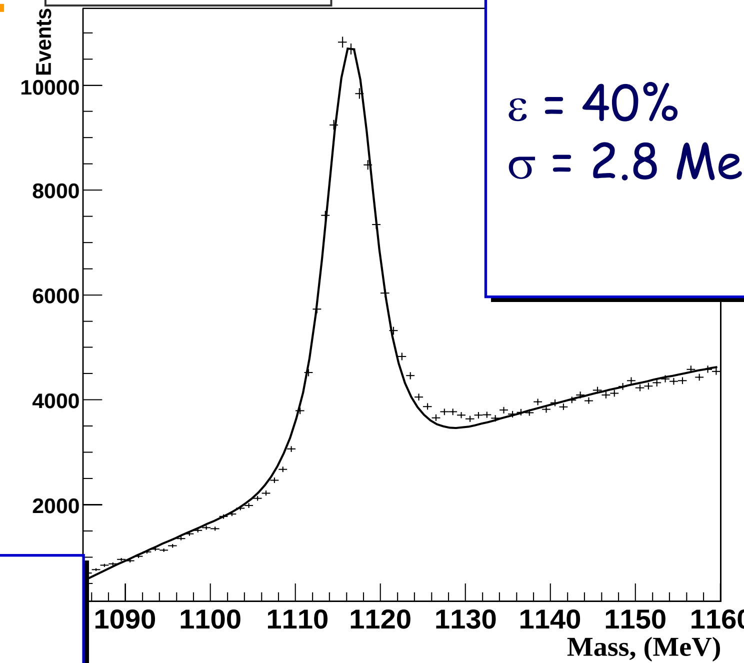
Event Reconstruction

J/ψ mass



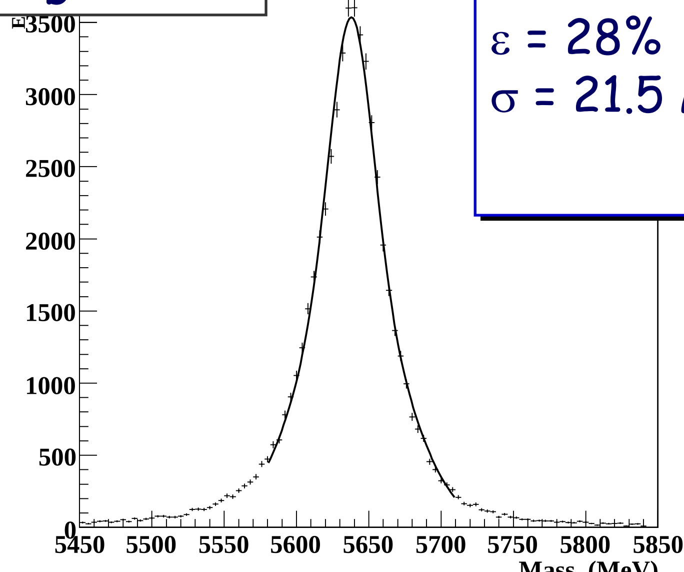
ε = 80%
σ= 40.5 MeV

Λ mass



ε = 40%
σ = 2.8 MeV

Λ_b mass

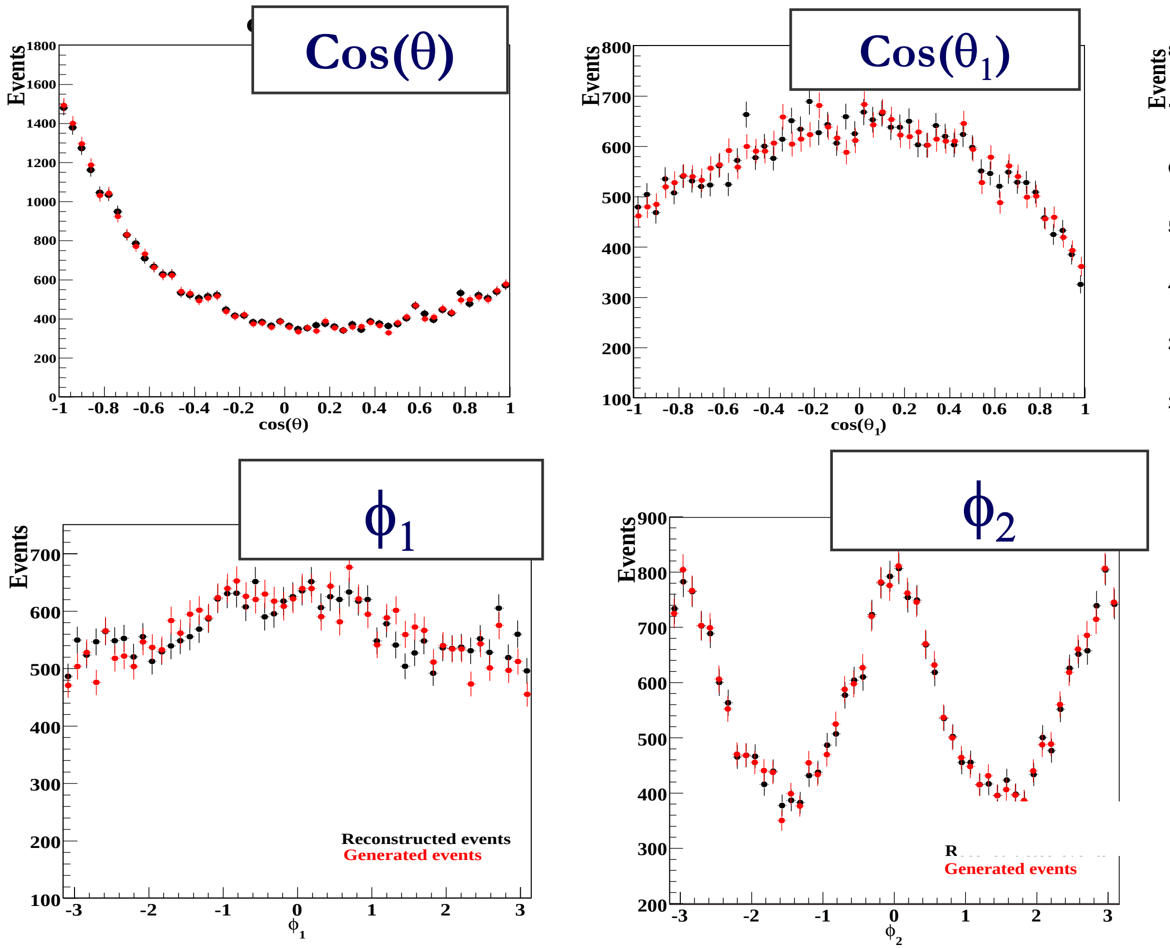


ε = 28%
σ = 21.5 MeV

ε = rec efficiency
σ from Gaussian fits

Angular distributions in ATLAS detector

ATLAS acceptance modifies the angular distributions and increases the difficulty of the measurement



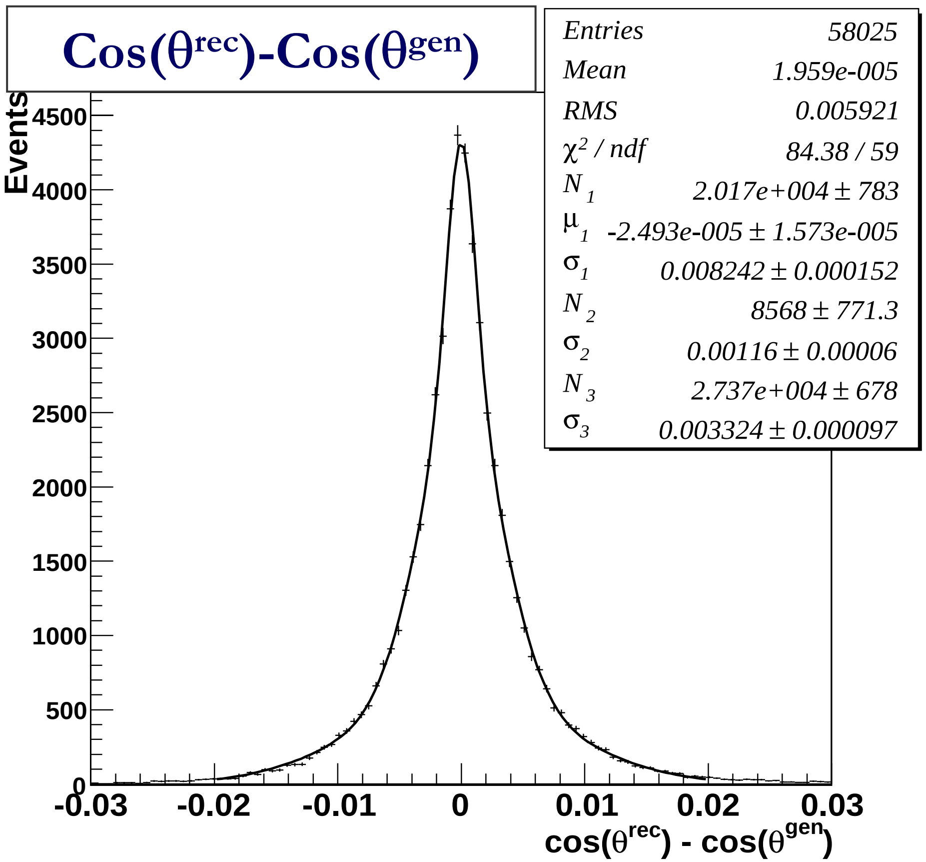
P=-100%

Reconstructed angle

vs

Generated angle

Angular Resolutions



Angles	Gaussian fit σ (mrad)
cosθ	2
$\cos\theta_1$	21
ϕ1	32
$\cos\theta_2$	3
ϕ_2	13

Maximum Likelihood Results

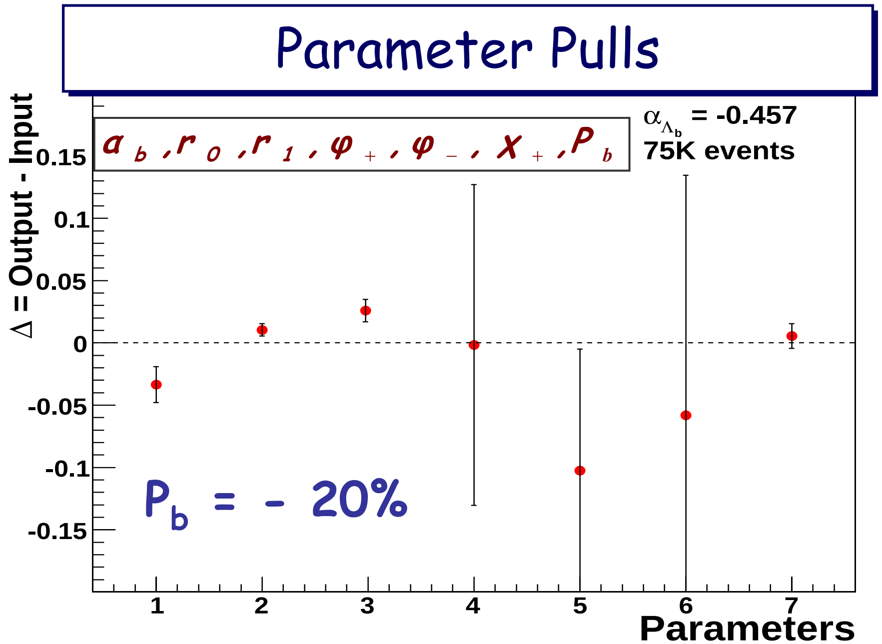
- In the problem we have 9 parameters: P and four complex amplitudes

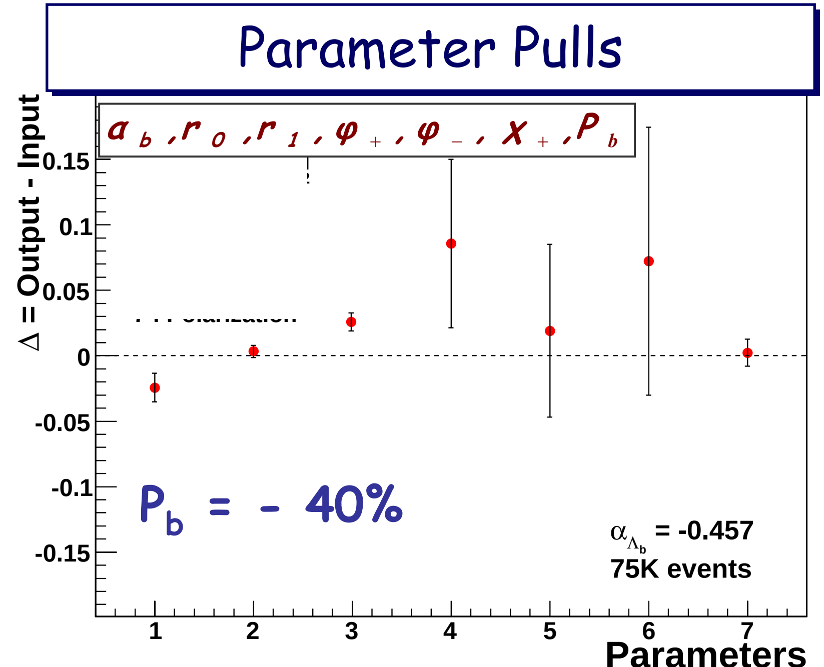
$$a_+ = |a_+| e^{i\alpha_+}, a_- = |a_-| e^{i\alpha_-}, b_+ = |b_+| e^{i\beta_+}, b_- = |b_-| e^{i\beta_-}$$

- The normalization + global phase constraint → 7 independent parameters

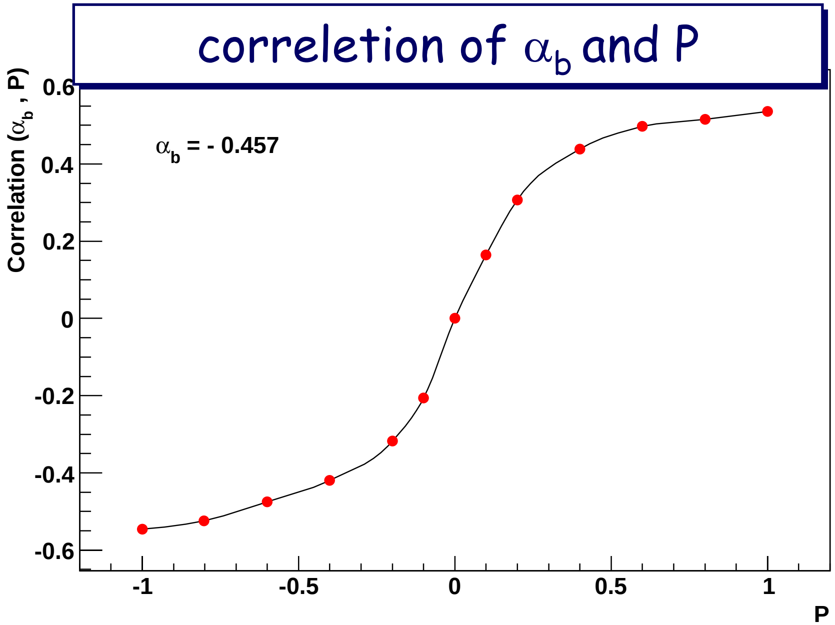
$$\alpha_b ; r_0 = |a_+|^2 + |a_-|^2 ; r_1 = |a_+|^2 - |a_-|^2 ; \varphi_+ = \alpha_+ - \beta_- ; \varphi_- = \alpha_- - \beta_- ; \chi_+ = \beta_+ - \beta_- ; P_b$$

- The ML results (Toy MC sample + angular resolution from reconstruction + detector acceptance)
  - only statistical uncertainties are shown

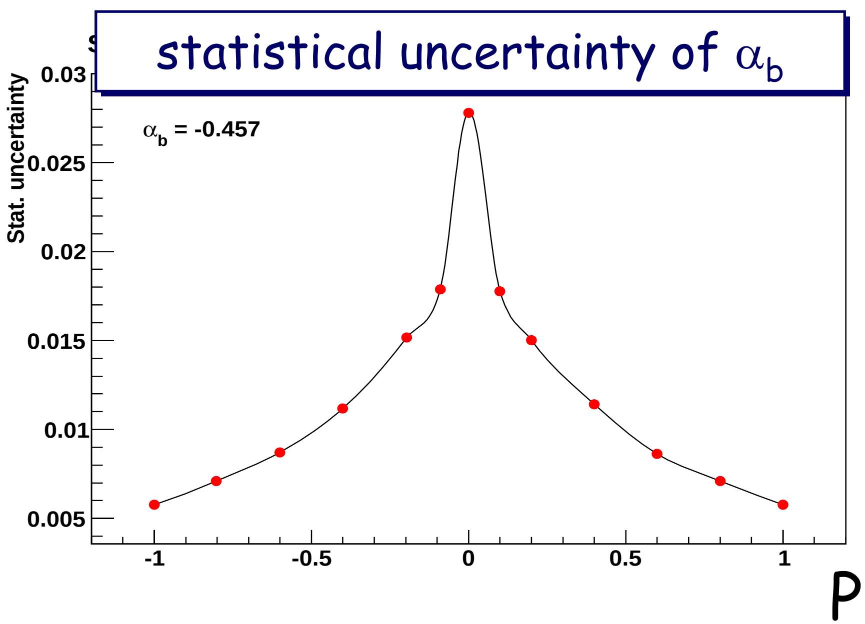


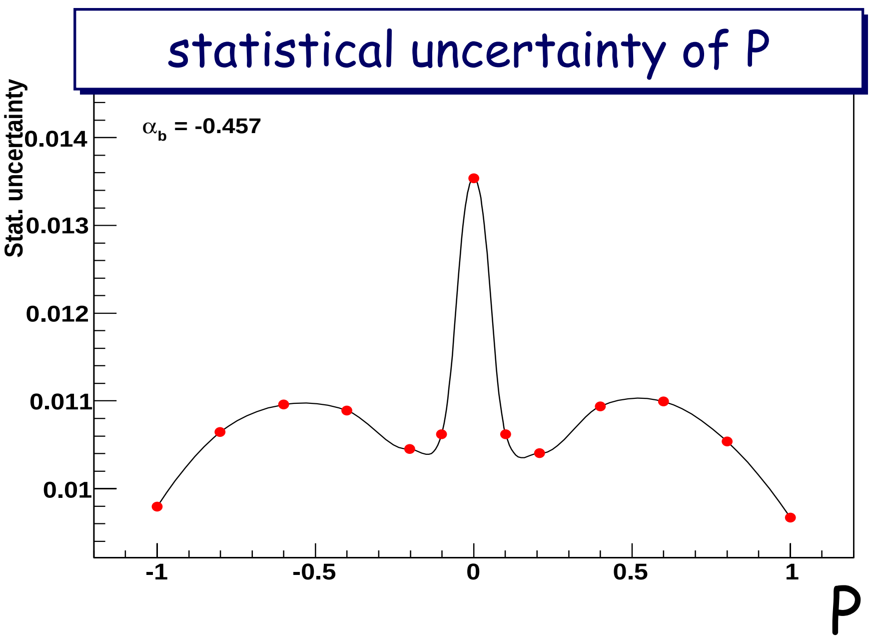


- **Decoupling P and α_b**
  - $\alpha_b P\cos(\theta)$ – dominant term
  - The 5 angle method allows to decouple P and α_b.



- **Estimating the statistical uncertainties**
  1) α_b can be measured with good precision even if P~0.
  2) Small uncertainty (P), even for P~0.





Summary and Outlook

- We have done an extensive study of the feasibility of measuring Λ_b parameters in ATLAS:
  - Generator model in EvtGen for producing polarized Λ_b in ATLAS
  - Λ_b reconstruction from their decay into Λ's and J/ψ
  - Polarization and amplitudes extraction from the decay angles
  - Effects of angular resolution on the determination of the parameters
  - Correlations between α_b and polarization

- Future plans
  - make background studies
  - continue to develop likelihood fitting procedures
  - incorporate trigger in analysis
  - make Lifetime feasibility studies
  - develop plans for CP studies

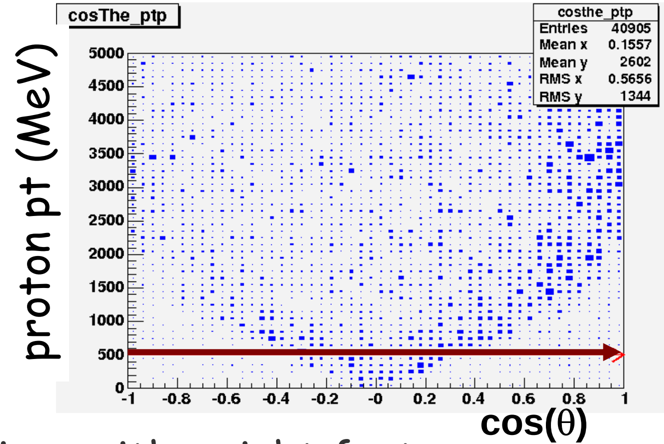
Back-up Slides

Acceptance Effects

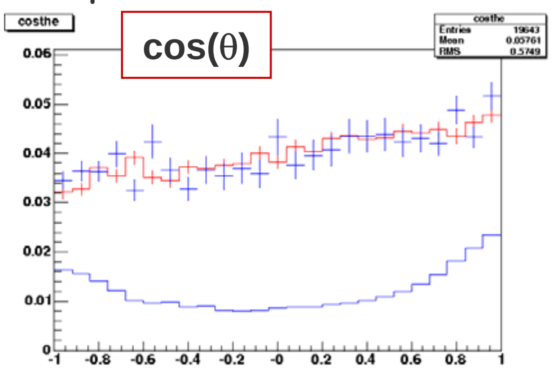
Cuts @ Generator Level:

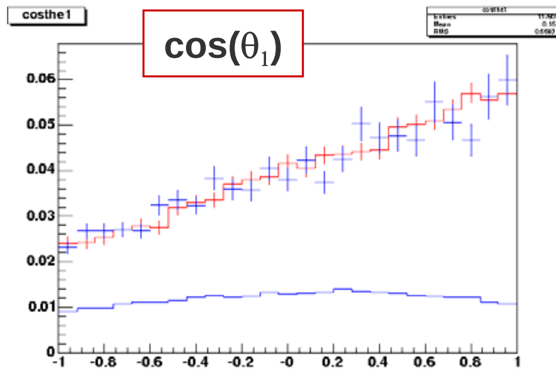
- $p_T(p,\pi)>0.5$ GeV
- $p_T(\mu)>2.5, 4$ GeV
- $|\eta|<2.7$

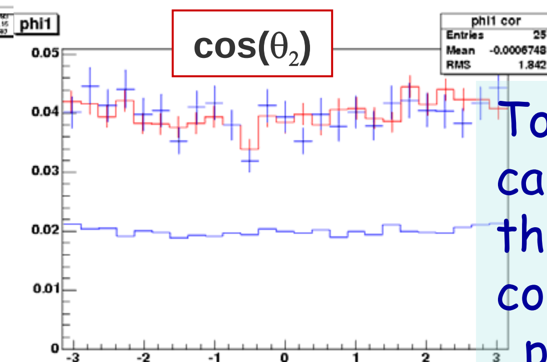
ATLAS acceptance modifies the angular distributions

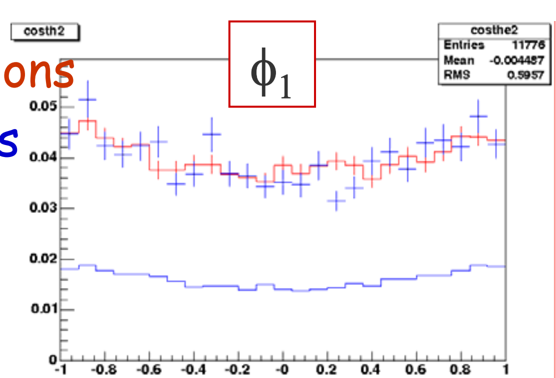


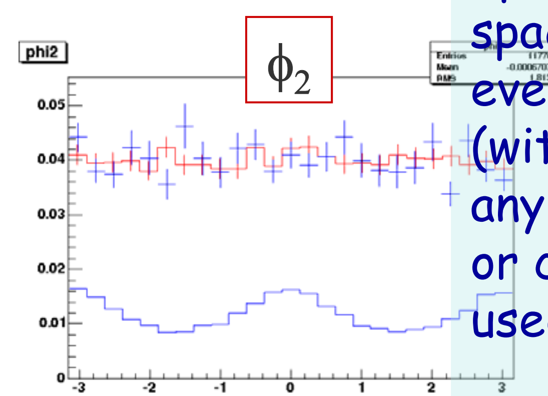
It's possible to correct distorted angular distributions with weight factors











generated distributions

generated after cuts

after corrections

To calculate the corrections, phase space events (without any model or cuts) are used

Maximum Likelihood (ML) Method

ML Mehod :

$$w(\Omega, \Omega_1, \Omega_2) = \frac{1}{(4\pi)^3} \sum_{i=0}^{i=19} f_{1i} f_{2i}(P_b, \alpha_\Lambda) F_i(\theta, \theta_1, \theta_2, \phi_1, \phi_2)$$

$$w_{obs}(\vec{\theta}', \vec{A}, \vec{\alpha}) = \frac{\int w(\vec{\theta}, \vec{A}, \vec{\alpha}) T(\vec{\theta}, \vec{\theta}') d\vec{\theta}}{\int\int w(\vec{\theta}, \vec{A}, \vec{\alpha}) T(\vec{\theta}, \vec{\theta}') d\vec{\theta} d\vec{\theta}'}$$

θ': Measured angles
θ : Generated angles

where:

$$\vec{\theta} = \begin{pmatrix} \theta \\ \theta_1 \\ \phi_1 \\ \theta_2 \\ \phi_2 \end{pmatrix}, \vec{A} = \begin{pmatrix} a^+ \\ a^- \\ b^+ \\ b^- \end{pmatrix}, \vec{\alpha} = \begin{pmatrix} \alpha_\Lambda \\ P \end{pmatrix}$$

$$T(\vec{\theta}, \vec{\theta}') = \varepsilon(\vec{\theta}, \vec{\theta}') R(\vec{\theta}, \vec{\theta}')$$

***R(θ,θ')* is the resolution**
***ε(θ,θ')* is the acceptance correction**

Acceptance correction normalization : $\int F_i(\vec{\theta}) \varepsilon(\vec{\theta}) d\vec{\theta}$

i=0...19

Backgrounds

- Dominated by J/ψ from b-hadrons + Λ from heavier hadrons and fragmentation
- fake μ and combinatorial background found negligible in similar topologies ($B^0 \to J/\psi\ K_s$)
- real J/ψ from cascade decay estimated at percent level (ex. $\Xi_b^{-,0} \to \Xi^{-,0}\ J/\psi \to \Lambda\ \pi^{-,0}\ J/\psi$)
- $B^0 \to J/\psi\ K_s$ where a proton mass is given to a p rejected with mass constraints
- for non direct Λ_b from Σ_b; try to reconstruct Σ_b to reduce the diluition of polarization