Polarized radiative Λ_b decays at LHCb

SPS meeting - Lausanne Feb. 13, 2006

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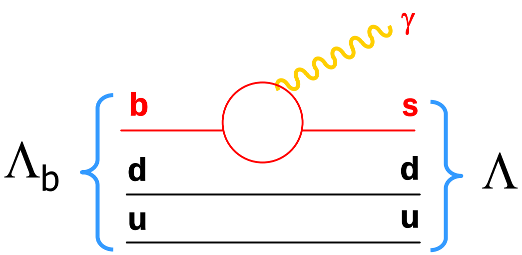
Outline

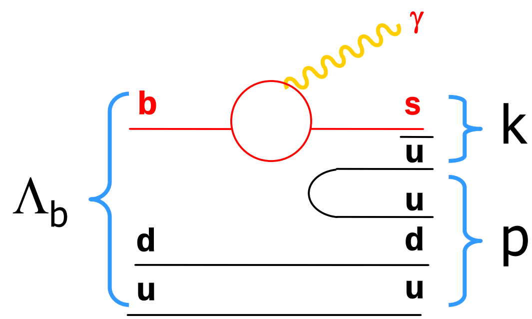
- Theoretical motivations
- Angular distributions
- Observables
- Λ_b production at LHC
- Selection of $\Lambda_b \to \Lambda(x)\,\gamma$ events at LHCb
- Status and perspectives

Theoretical motivations

- $\Lambda_b \to \Lambda(1115)\,\gamma$
  - $\to p\,\pi$



- $\Lambda_b \to \Lambda(X)\,\gamma$
  - $\to p\,k$



- Electromagnetic penguin $b \to s\,\gamma$
- Effective Hamiltonian at LO in α_s:

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb}\, [C_7 Q_7 + C_7' Q_7']$$

left ($C_7 Q_7$) right ($C_7' Q_7'$)

- Wilson coefficients C_7, C_7'
- BR($B \to X_s\,\gamma$) constrains $|C_7|^2 + |C_7'|^2$

Observables for $\Lambda_b \to \Lambda(1115)\,\gamma$

- Forward-backward angular asymmetries (with respect to Λ_b momentum) :

$$A_\gamma = -\frac{P_B}{2}\,\frac{1-|r|^2}{1+|r|^2} \qquad A_p = -\frac{\alpha_p}{2}\,\frac{1-|r|^2}{1+|r|^2}$$

  - P_B = Λ_b polarization
  - α_p = weak decay parameter

constrain

sensitive to NP →

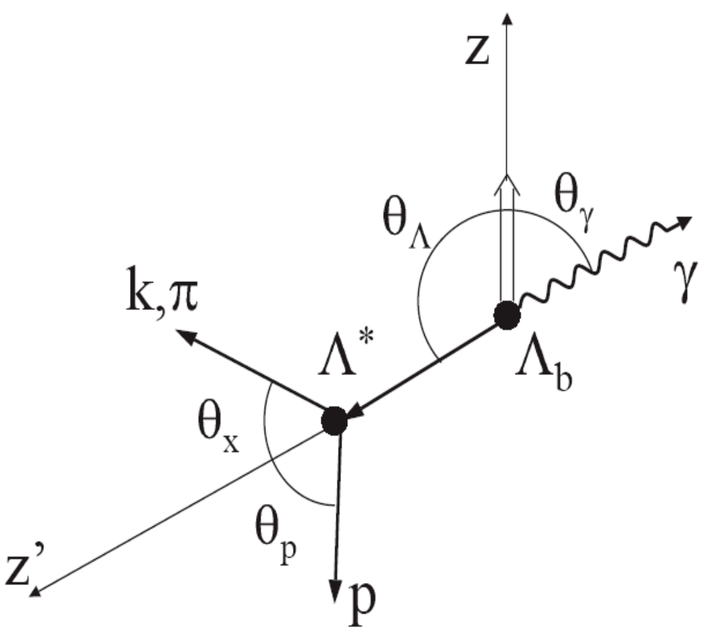
$$r = \frac{C_7'}{C_7} \overset{SM}{=} \frac{m_s}{m_b}$$

- 2 indipendent measurements for r, or
- Λ_b polarization measurement:
  - a discrepancy with the value measured in semileptonic $\Lambda_b \to \Lambda_c\, l\, \nu\, X$ decays would indicate the presence of non-standard right-handed $b \to c$ currents
- Direct CP violation at NLO: $\mathcal{O}(1\%)$ in SM but $\leq$10% if NP!
  - r probes the ratio of CP even contributions to NLO Hamiltonian

Hiller, Kagan, Phys Rev D65, 404 (2001)

Helicity formalism for $\Lambda_b \to \Lambda(px)\,\gamma$

- From the experimental point of view the decay $\Lambda_b \to \Lambda(1115)\,\gamma$ is quite hard to observe ($c\tau$ = 7.89 cm)
- Can we increase the statistics by using heavier Λ resonances?
- Need angular distributions → helicity formalism



Jacob, *Wick*, Ann Phys 7, 404 (1959)

- Λ_b polarization $$P_B = \frac{\rho_{++} - \rho_{--}}{\rho_{++} + \rho_{--}}$$
  - Polarization density matrix :

$$\begin{pmatrix} \rho_{++} & \rho_{+-} \\ \rho_{-+} & \rho_{--} \end{pmatrix}$$

+ → ½
- → -½

- Helicity amplitudes
  - $\Lambda_b \to \Lambda(X)\,\gamma$ $\quad C(\lambda_\Lambda, \lambda_\gamma)$
  - $\Lambda(X) \to px$ $\quad E(\lambda_p)$

Results : $J_\Lambda = 1/2$

Angular distributions

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_B \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_p \cos\theta_p$$

Photon asymmetry

$$\alpha_\gamma = \frac{|C_{\frac{1}{2}}|^2 - |C_{-\frac{1}{2}}|^2}{|C_{\frac{1}{2}}|^2 + |C_{-\frac{1}{2}}|^2}$$

Proton asymmetry

$$\alpha_p = \frac{|E_{\frac{1}{2}}|^2 - |E_{-\frac{1}{2}}|^2}{|E_{\frac{1}{2}}|^2 + |E_{-\frac{1}{2}}|^2}$$

- $\alpha_p = 0.642$ $\Lambda \rightarrow p\pi$
- $\alpha_p = 0$ $\Lambda(X) \rightarrow pk$ (P cons)
- $\alpha_\gamma \sim -1$ in SM

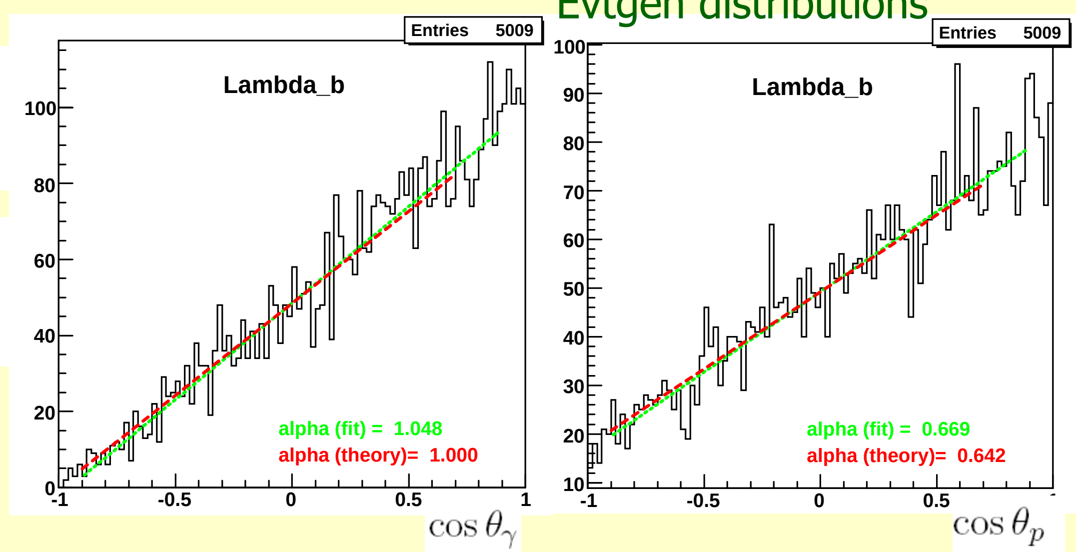
Asymmetries

$$A_\gamma = -\frac{P_B}{2}\frac{1-|r|^2}{1+|r|^2} = -\frac{1}{2}\alpha_\gamma P_B$$

$$A_p = -\frac{\alpha_p}{2}\frac{1-|r|^2}{1+|r|^2} = -\frac{1}{2}\alpha_\gamma \alpha_p$$

↑ HQET ↑ Helicity formalism

Evtgen distributions



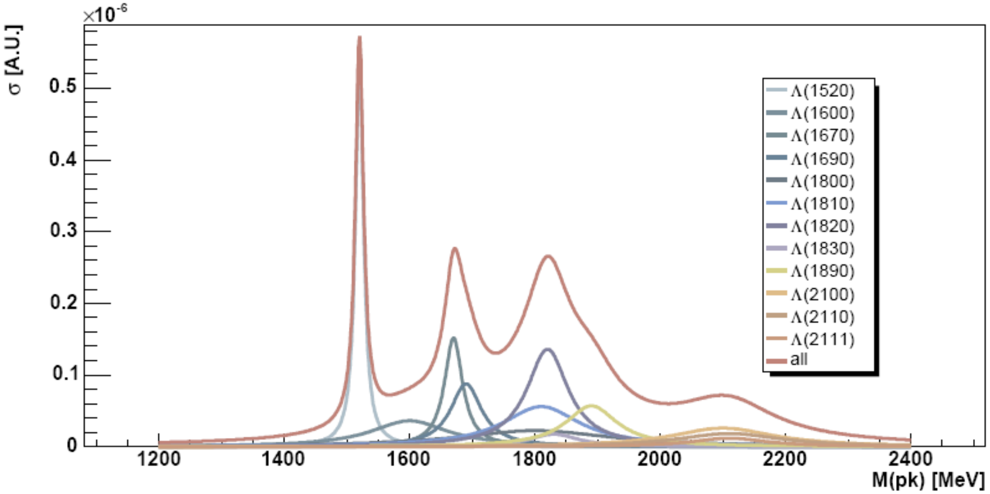
Λ(X) baryons

- $J_\Lambda > 1/2$
  - more helicity amplitudes!!
  - no theoretical calculations for hadronic matrix elements

Particle	$L_{I \cdot 2J}$	Γ	Status	$N\bar{K}$	$\Sigma\pi$
$\Lambda(1405)$	S_{01}	50 MeV	****	-	100%
$\Lambda(1520)$	D_{03}	15.6 MeV	****	45%	42%
$\Lambda(1600)$	P_{01}	150 MeV	***	15-30%	10-60%
$\Lambda(1670)$	S_{01}	35 MeV	****	20-30%	25-55%
$\Lambda(1690)$	D_{03}	60 MeV	****	20-30%	20-40%
$\Lambda(1800)$	S_{01}	300 MeV	***	25-40%	seen
$\Lambda(1810)$	P_{01}	150 MeV	***	20-50%	10-40%
$\Lambda(1820)$	F_{05}	80 MeV	****	55-65%	8-14%
$\Lambda(1830)$	D_{05}	95 MeV	****	3-10%	35-75%
$\Lambda(1890)$	P_{03}	100 MeV	****	20-35%	3-10%
$\Lambda(2000)$	???	120 MeV	*	???	???
$\Lambda(2020)$	F_{07}	130 MeV	*	???	???
$\Lambda(2100)$	G_{07}	200 MeV	****	25-35%	5%
$\Lambda(2110)$	F_{05}	200 MeV	***	5-25%	10-40%
$\Lambda(2325)$	D_{03}	170 MeV	*	???	???
$\Lambda(2100)$	H_{09}	150 MeV	***	12%	10%

PDG 2004

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, BR, *etc.* are not very well determined
**	Evidence of existence is fair.
*	Evidence of existence is poor.



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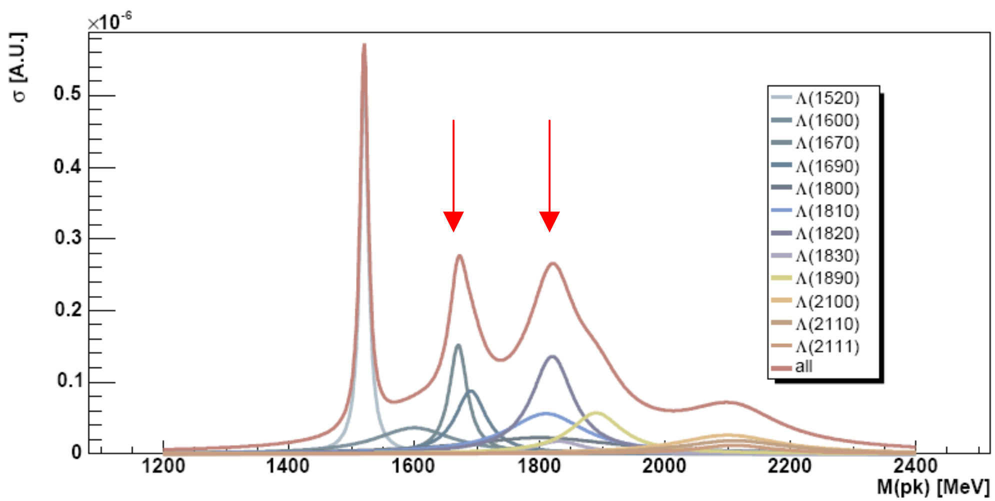

Λ(X) baryons

$\Lambda_b \to \Lambda(1115)\,\gamma$ $\Lambda_b \to \Lambda(1670)\,\gamma$

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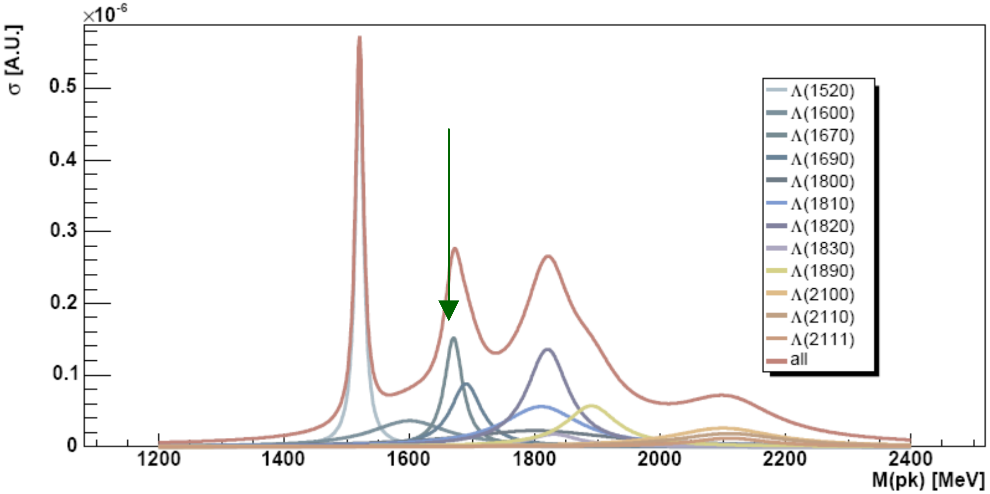
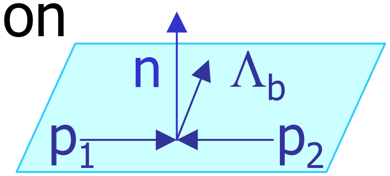


Λ_b production at LHC:

- $b\bar{b}$ cross section in pp collision = 500 μb

LHC intro: K. Vervink talk

- ~10% of produced bb hadronize in B hadrons
- Λ_b dominates (~90%)
- Λ_b produced with transversal polarization



$$P_B = < \vec{S}_{\Lambda_b} \cdot \vec{n} >$$

  - Predictions are P_B ~ 20%

Ajaltouni, Conte, Leitner, "Λ_b into Λ-vector decays", Phys Lett B, 614 (2005)

  - ATLAS plans to measure it with a statistical precision better than 1%

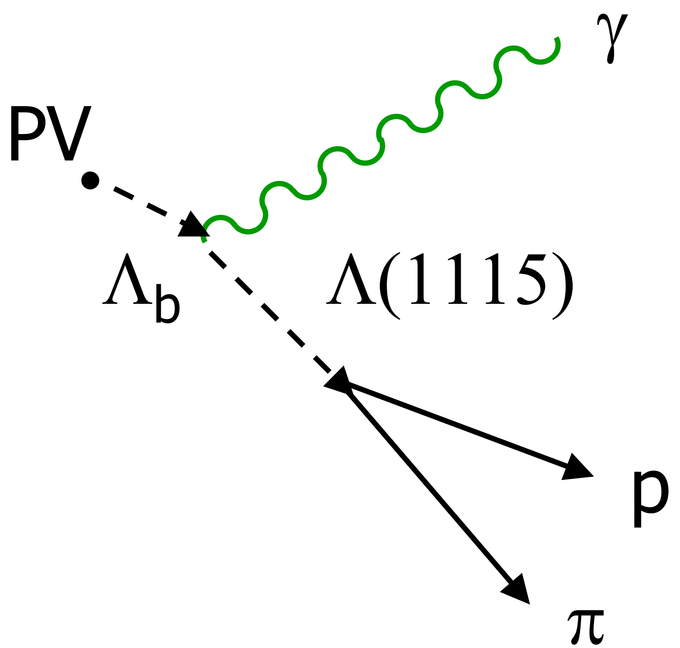
Feasibility of Beauty Baryon Polarization Measurement in $\Lambda_b \rightarrow J/\Psi \, \Lambda$ decay channel by ATLAS – Atlas note

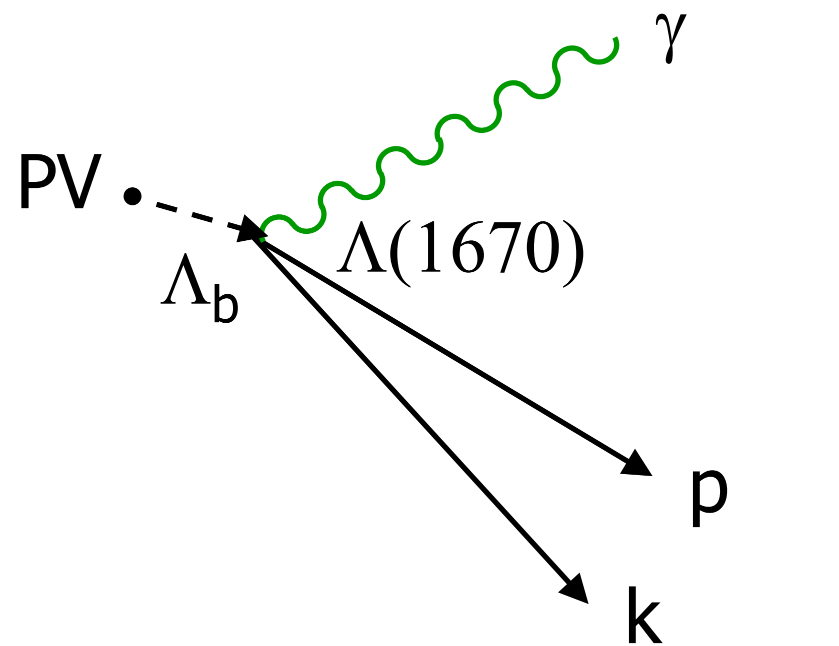
- BR ($\Lambda_b \rightarrow \Lambda(1115)\,\gamma$) = $4.15 \cdot 10^{-5}$
- BR ($\Lambda_b \rightarrow \Lambda(1670)\,\gamma$) = $0.70 \cdot 10^{-5}$

Calculations based on Hiller (2001)+PDG2004

Event reconstruction at LHCb

$\Lambda_b \to (\Lambda(1115) \to p\pi)\gamma$ $\Lambda_b \to (\Lambda(1670) \to pk)\gamma$



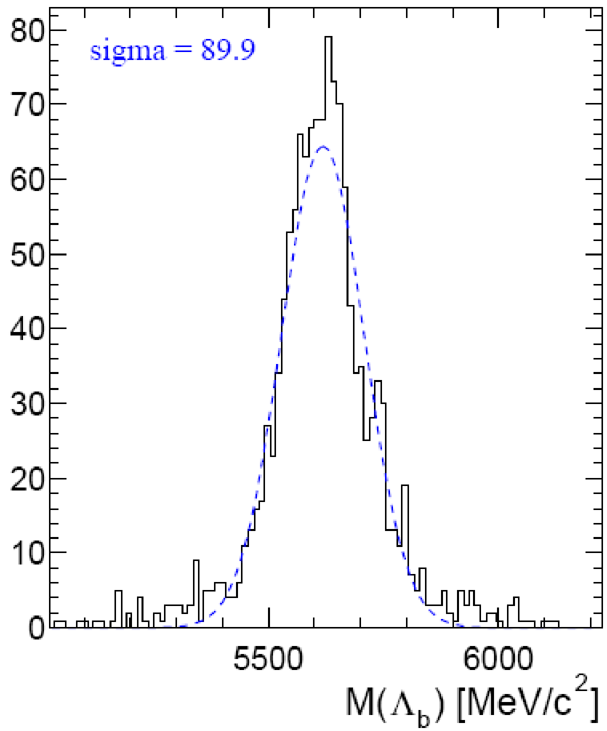


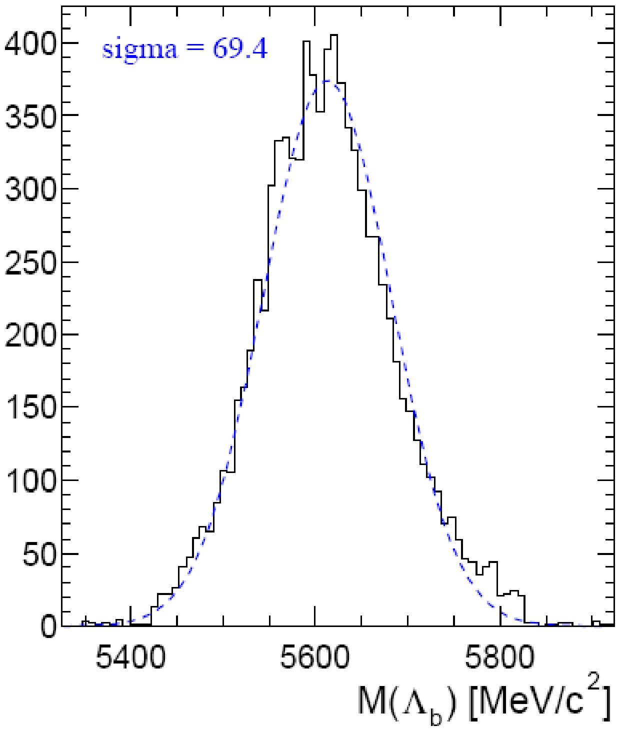
- PT, IPS (with respect to all primaries) cuts on final states
- Mass window = 4σ for resonances with intrinsic width
- Λ_b primary vertex: smallest IPS
- Cut values chosen to kill bb background events while maintaining higher possible efficiency on signal

LHCb intro: K. Vervink talk

Mass resolution plots

$\Lambda_b \to (\Lambda(1115) \to p\pi)\gamma$ $\Lambda_b \to (\Lambda(1670) \to pk)\gamma$





$B_{s,d} \to \phi/K^* \gamma$, σ = 64 MeV (LHCb Reoptimization TDR)

Event yields

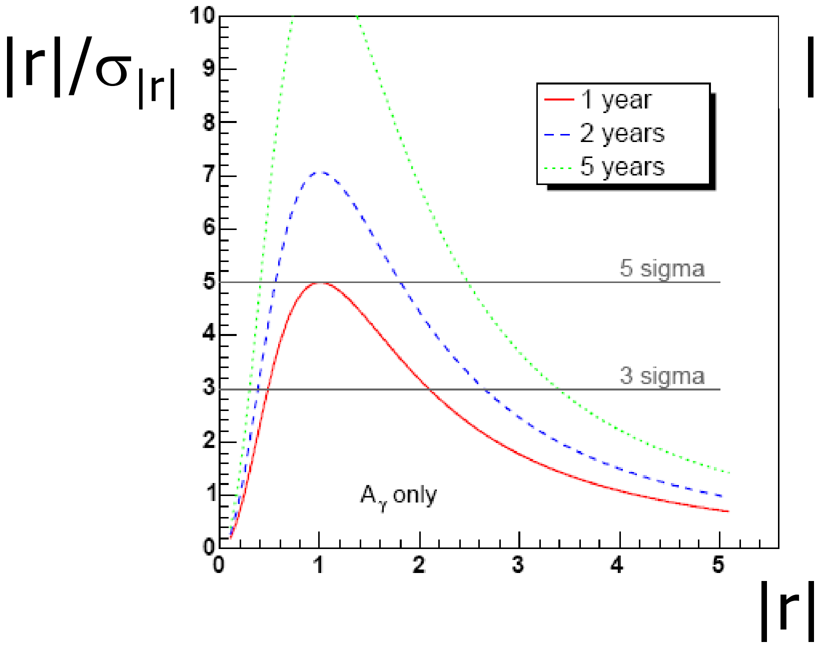
$$S_{\text{year}} = N_{\Lambda_b} \times \mathcal{BR}_{\text{vis}} \times \epsilon_{\text{tot}}$$

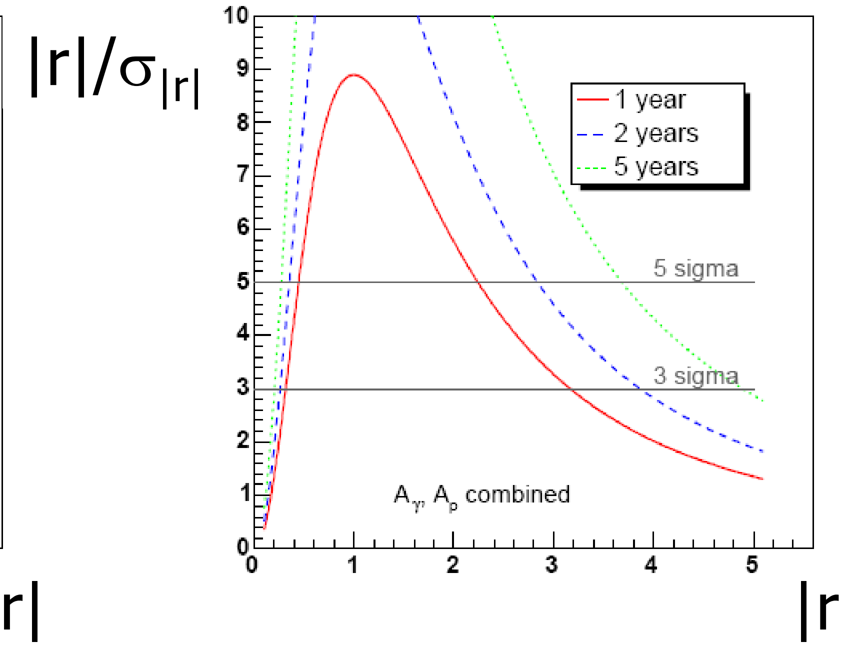
- $\Lambda_b \rightarrow \Lambda(1115)\,\gamma$
  - ε_{tot} = 0.011 %
  - S_{year} = 724
  - 0 events selected in 40M bb inclusive evts
  - B/S < 50 @ 90 % CL

- $\Lambda_b \rightarrow \Lambda(1670)\,\gamma$
  - ε_{tot} = 0.225 %
  - S_{year} = 2515
  - 0 events selected in 40M bb inclusive evts
  - B/S < 18 @ 90 % CL

Conclusions

$\Lambda_b \to (\Lambda(1670) \to pk)\gamma$ $\Lambda_b \to (\Lambda(1115) \to p\pi)\gamma$

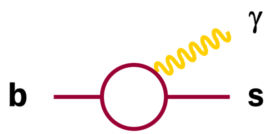




- Significance plots obtained using expected event yield
- no resolution effects taken into account yet
  - work in progress
- most promising: $\Lambda_b \to \Lambda(1115)\, \gamma$

Backup slides

LO Effective hamiltonian $b \to s\gamma$



OPE (Operator Product expansion):

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[C_7 Q_7 + C_7' Q_7' \right]$$

- Electromagnetic dipole operators:

$$Q_7 = \frac{e}{8\pi^2} m_b \bar{s} \sigma_{\mu\nu} R b F^{\mu\nu}$$

$$Q_7' = \frac{e}{8\pi^2} m_b \bar{s} \sigma_{\mu\nu} L b F^{\mu\nu}$$

$R \equiv 1 + \gamma_5$ $L \equiv 1 - \gamma_5$

- Wilson coefficients :

C_7, C_7'

left (→ C_7) right (→ C_7')

- BR($B \to X_s \gamma$) constrains $|C_7|^2 + |C_7'|^2$

NLO Effective hamiltonian b→sγ

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (DQ_7 + D'Q_7')$$

- Wilson coefficients:

$$D = C_7^{(0)} + \frac{\alpha_s}{4\pi}(C_7^{(1)} + C_2^{(0)} k_2 + C_8^{(0)} k_8)$$

$$D' = C_7'^{(0)} + \frac{\alpha_s}{4\pi}(C_7'^{(1)} + C_8'^{(0)} k_8)$$

- CP violation in C_7, C_8
- Direct CP violation: interference between the weak and strong phases in the decay amplitudes
  - $\mathcal{O}$(1%) in SM
  - ~10% if NP!

$$a_{CP}^{\Lambda_b} \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

Observables at NLO

- Angular asymmetries:

$\Lambda_b \rightarrow$ $$\mathcal{A}^{\gamma} = -\frac{P_{\Lambda_b}}{2}\frac{1-|r^{\rm eff}|^2}{1+|r^{\rm eff}|^2}, \qquad \mathcal{A}_{\theta_p} = -\frac{\alpha}{2}\frac{1-|r^{\rm eff}|^2}{1+|r^{\rm eff}|^2}$$

$\overline{\Lambda}_b \rightarrow$ $$\bar{\mathcal{A}}^{\gamma} = -\frac{P_{\Lambda_b}}{2}\frac{1-|\bar{r}^{\rm eff}|^2}{1+|\bar{r}^{\rm eff}|^2}, \qquad \bar{\mathcal{A}}_{\theta_p} = -\frac{\alpha}{2}\frac{1-|\bar{r}^{\rm eff}|^2}{1+|\bar{r}^{\rm eff}|^2}$$

  - where :

$$r^{\rm eff} \equiv D'/D, \qquad \bar{r}^{\rm eff} \equiv \bar{D}'/\bar{D}.$$

← probe chirality

- Ratio of CP even quantities:

$$r_{av} \equiv \sqrt{\frac{|D'|^{2+}}{|D|^{2+}}}$$

← sensitive to NP

  - Expected small in SM ~ m_s/ m_b

Hiller et al., Phys Rev D65, 404 (2001)

BR ($\Lambda_b \to \Lambda(x)\,\gamma$)

Hiller et al., Phys Rev D65, 404 (2001)

$$\mathcal{B}(\Lambda_b \to \Lambda\gamma) = \tau(\Lambda_b)\,|C_7|^2(1+|r|^2)\,\frac{\alpha G_F^2 |V_{tb}V_{ts}^*|^2}{32\pi^4} m_{\Lambda_b}^3 m_b^2 \left(1-\frac{m_\Lambda^2}{m_{\Lambda_b}^2}\right)^3 |F(0)|^2$$

Dependance on m_Λ

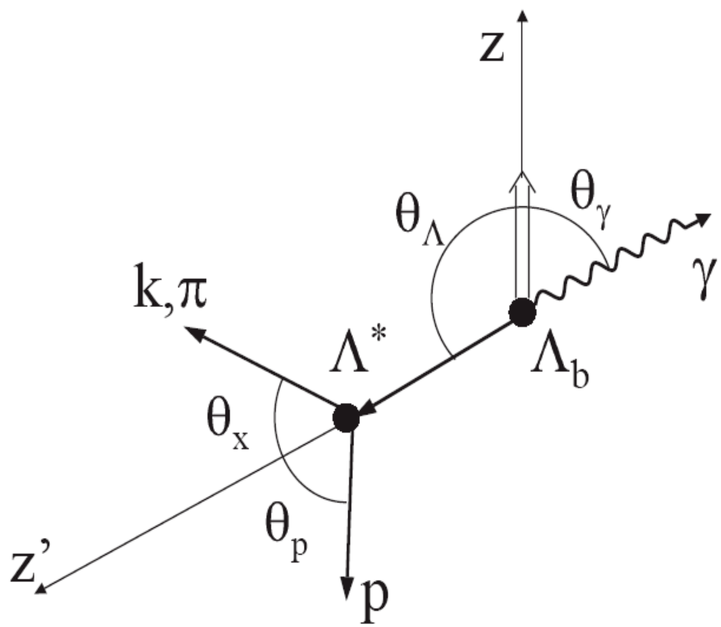
⇩

- BR ($\Lambda_b \to \Lambda(1115)\,\gamma$) = 4.15 · 10^{-5}
- BR ($\Lambda_b \to \Lambda(1520)\,\gamma$) = 1.30 · 10^{-5}
- BR ($\Lambda_b \to \Lambda(1600)\,\gamma$) = 0.65 · 10^{-5}
- BR ($\Lambda_b \to \Lambda(1670)\,\gamma$) = 0.70 · 10^{-5}
- …

- HQET, LEET → form factors,
- SM values for C_7, C_7'
- PDG 2004 values for $\Lambda(x) \to NK$

➡ BR ~ $10^{-5} \div 10^{-6}$

Helicity formalism for $\Lambda_b \to \Lambda(px)\,\gamma$



	J	M	λ
Λ_b	1/2	±1/2	
Λ	s_Λ	M_Λ	M_Λ
γ	1	±1	±1
p	1/2	±1/2	±1/2
x	0	0	0

- z : spin quantization axis
  - parallel to Λ_b spin
- z' : parallel to Λ momentum
- $(\theta_\Lambda,\phi_\Lambda)$ and $(\theta_\gamma,\phi_\gamma)$
  - Λ_b rest frame
- (θ_p,ϕ_p) and (θ_x,ϕ_x)
  - Λ rest frame
  - x = k,π
  - ϕ the same in both frames

Jacob, Wick, Ann Phys 7, 404 (1959)

Decay probability for $\Lambda_b \rightarrow \Lambda(px)\,\gamma$

- Λ_b polarization
  - Polarization density matrix : $\begin{pmatrix} \rho_{++} & \rho_{+-} \\ \rho_{-+} & \rho_{--} \end{pmatrix}$

+ $\rightarrow$ ½
- $\rightarrow$ -½

No correlation production/decays $\Rightarrow$ $\rho_{mm'} = \delta_{mm'}\rho_{mm'}$

C,E helicity amplitudes

- If P $\rightarrow$ $E(\lambda_p) = \pm E(-\lambda_p)$

- Amplitude probability :

$$A = \sum_{\lambda_\Lambda} D^{s_\Lambda *}_{\lambda_\Lambda,\lambda_p}(\phi_p,\theta_p,-\phi_p)\,D^{J*}_{M,\lambda_\Lambda-\lambda_\gamma}(\phi_\Lambda,\theta_\Lambda,-\phi_\Lambda)\,C(\lambda_\Lambda,\lambda_\gamma)\,E(\lambda_p)$$

- Decay probability : $w = \sum_{M,\lambda_\gamma,\lambda_p} \rho_{MM}|A|^2$

We don't measure the final helicities

Jacob, Wick, Ann Phys 7, 404 (1959)

Results : $J_\Lambda = 1/2$

- γ helicity can only assume the values ±1
- only 2 helicity states are possible:

$$(\lambda_\Lambda, \lambda_\gamma) \;=\; (1/2, 1) \Longrightarrow \lambda_f = \; -1/2$$

$$(\lambda_\Lambda, \lambda_\gamma) \;=\; (-1/2, -1) \Longrightarrow \lambda_f = \; +1/2$$

- Decay probability:

$$w_{\frac{1}{2}} \;\propto\; 1 - \alpha_p \cos\theta_p P_B \cos\theta_\Lambda + \alpha_\gamma(-\alpha_p \cos\theta_p + P_B \cos\theta_\Lambda)$$

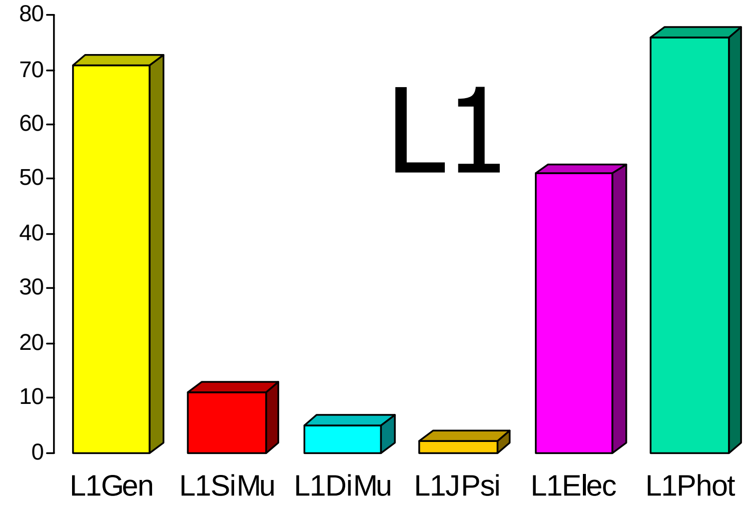
Results : $J_\Lambda = 3/2$

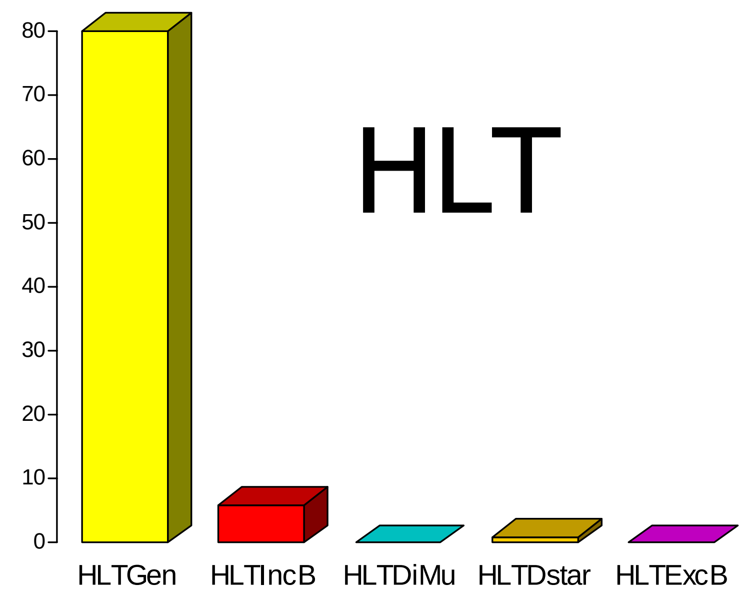
- Λ helicity can now assume the values: ±1/2, ±3/2
  - 4 helicity amplitudes!!
  - no theoretical calculations
- Decay probability:

$$
\begin{aligned}
w \;\propto\;& 3\{1 + P_B \cos\theta_\Lambda\}\{|C_{\frac{3}{2},1}|^2 + |C_{-\frac{3}{2},-1}|^2\} \sin^2\frac{\theta_p}{2}\cos^2\frac{\theta_p}{2} + \\
&+\{1 - P_B \cos\theta_\Lambda\}\{|C_{\frac{1}{2},1}|^2 + |C_{-\frac{1}{2},-1}|^2\}\{|d^{\frac{3}{2}}_{\frac{1}{2},\frac{1}{2}}(\theta_p)|^2 + |d^{\frac{3}{2}}_{\frac{1}{2},-\frac{1}{2}}(\theta_p)|^2\} + \\
&+\sqrt{3}\sin\theta_\Lambda \left[\mathrm{Re}\{C_{\frac{3}{2},1}C_{\frac{1}{2},1}\}e^{i(\phi_\Lambda+\phi_p)} + \mathrm{Re}\{C_{-\frac{3}{2},-1}C_{\pm\frac{1}{2},-1}\}e^{-i(\phi_\Lambda+\phi_p)}\right] \sin\theta_p\cos\theta_p
\end{aligned}
$$

Trigger for $\Lambda_b \to \Lambda(1115)\,\gamma$

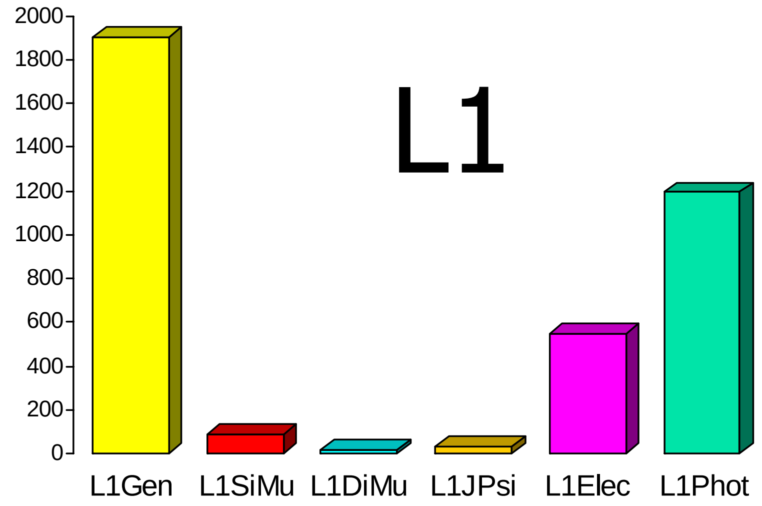
- Trigger breakdown:
  - $\varepsilon_{L0/sel}$ = 0.75
  - $\varepsilon_{L1/L0}$ = 0.30
  - $\varepsilon_{HLTgen/L1}$ = 0.54
  - $\varepsilon_{HLTgen/HLT}$ = 0.09

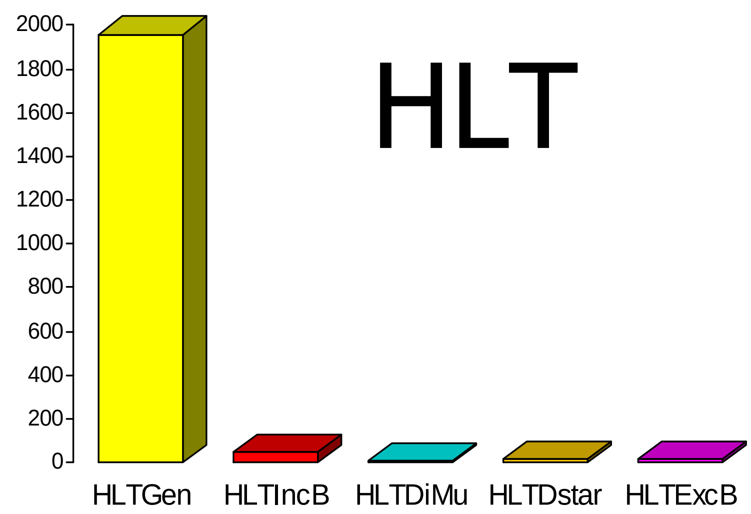




Trigger for $\Lambda_b \rightarrow \Lambda(1670)\ \gamma$

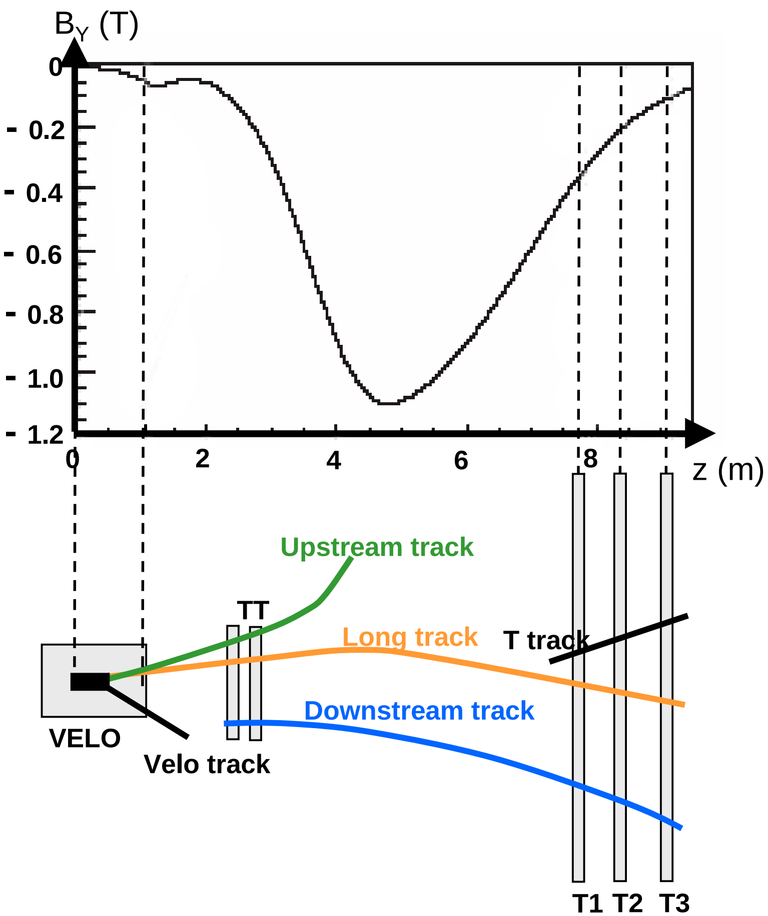
- Trigger breakdown:
  - $\varepsilon_{L0/sel}$ = 0.71
  - $\varepsilon_{L1/L0}$ = 0.63
  - $\varepsilon_{HLTgen/L1}$ = 0.80
  - $\varepsilon_{HLTgen/HLT}$ = 0.04



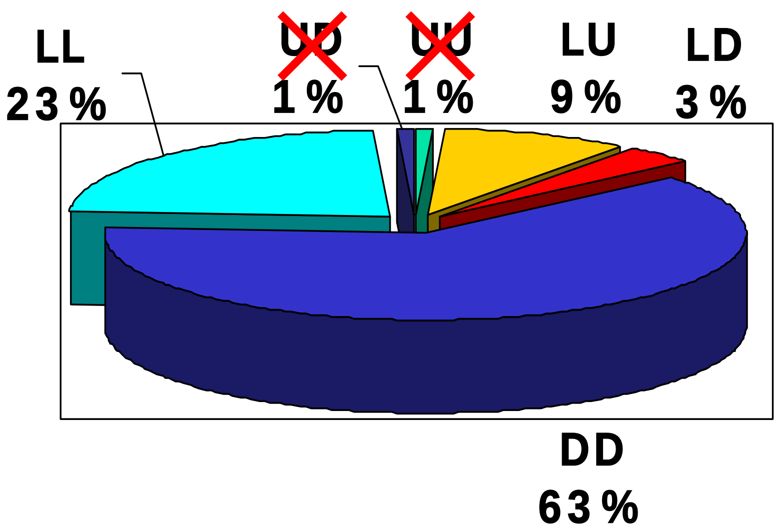


$\Lambda(1115) \rightarrow p\ \pi$

- $c\tau$ = 7.89 cm
- About 14% of Λ interact before decay or decay after LHCb spectrometer $\rightarrow$ lost
  - 305000 (generated) $\rightarrow$ 262464 (DoI)



Λ candidates (associated to MC truth)



Charged tracks selection (Λ(1115))

p:

LONG	UP	DOWN
DLL p-π > 6	DLL p-π > 6	DLL p-π > 10
DLL p-k > 4	DLL p-k > 0	DLL p-k > 8
PT > 1400 MeV	PT > 500 MeV	PT > 2000 MeV
sIPS > 4	sIPS > 3	sIPS > 4

π:

LONG	UP	DOWN
PT > 250 MeV	PT > 200 MeV	PT > 300 MeV
sIPS > 4	sIPS > 3	sIPS > 4

- Hard DLL and PT cuts on protons to suppress background
- Slow momentum pions

Λ(1115) selection

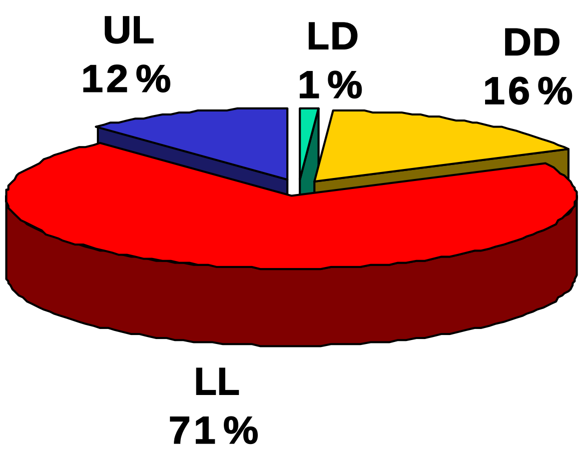
LL
- $\chi^2 < 6$
- $\Delta m < 6$ MeV
- PT > 500 MeV
- sIPS > 4
- FS > 4

UL
- $\chi^2 < 3$
- $\Delta m < 27$ MeV
- PT > 500 MeV
- sIPS > 4
- FS > 4

DD
- $\chi^2 < 2$
- $\Delta m < 11$ MeV
- PT > 2000 MeV
- sIPS > 3
- FD > 300 mm

LD
- $\chi^2 < 2$
- $\Delta m < 6$ MeV
- PT > 1500 MeV

1624 selected Λ



$\Lambda_b \rightarrow (\Lambda(1115) \rightarrow p\ \pi)\ \gamma$

Λ_b selection

LL
- PT > 500 MeV
- $\chi^2 < 2$
- $\Delta m < 350$ MeV
- $\theta(\Lambda_b) < 0.15$

UL
- PT > 500 MeV
- $\chi^2 < 2$
- $\Delta m < 350$ MeV
- $\theta(\Lambda_b) < 0.15$

DD
- PT > 2000 MeV
- $\chi^2 < 1$
- $\Delta m < 400$ MeV
- $\theta(\Lambda_b) < 0.15$

LD
- PT > 1000 MeV
- $\chi^2 < 2$
- $\Delta m < 400$ MeV
- $\theta(\Lambda_b) < 0.15$

γ selection

- PT > 3200 MeV/c
  - PT > 3800 MeV/c for UL combinations
- PT (in Λ_b direction) $\in$ [2200, 3000] MeV/c

Efficiencies for $\Lambda_b \rightarrow \Lambda(1115)\,\gamma$

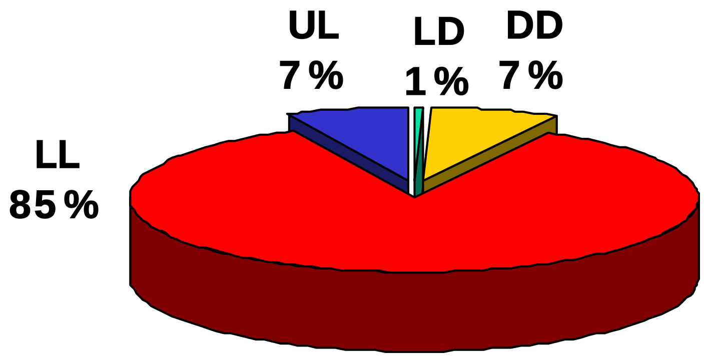
- $\varepsilon_{tot} = \varepsilon_{det} \times \varepsilon_{rec/det} \times \varepsilon_{sel/rec} \times \varepsilon_{trg/sel} = 0.011\ \%$

  - $\varepsilon_{det} = 0.009$
  - $\varepsilon_{rec/det} = 0.78$
  - $\varepsilon_{sel/rec} = 0.07$
  - $\varepsilon_{trg/sel} = \varepsilon_{L0/sel} \times \varepsilon_{L1/L0} \times \varepsilon_{HLTgen/L1} = 0.2$

  - no events selected in 39M bb incl

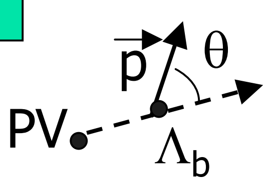
- Yield = 724 / year
- B/S < 50 @ 90 % CL

- $\Lambda(1115)$ after selection



$\Lambda_b \to \Lambda(1670)\,\gamma$ selection

- Protons:
  - Only Long tracks
  - DLL p-π > 5
  - DLL p-K > 0
    - Exclusive DLL selection
  - PT > 600 MeV
  - sIPS > 3
- Kaons:
  - Only Long tracks
  - DLL K-π > 5
  - DLL K-p > 0
    - Exclusive DLL selection
  - PT > 600 MeV
  - sIPS > 3
- γ :
  - PT > 2600 MeV
  - 1600 MeV < PT (in Λ_b direction) < 2800 MeV
- $\Lambda(1670)$:
  - $\chi^2 < 6$, $\Delta m < 100$ MeV
  - PT > 1500 MeV
  - sIPS > 4
- Λ_b :
  - $\Delta m < 200$ MeV
  - FS > 2;
  - PT > 2000 MeV
  - $\theta(\Lambda_b) < 0.01$



Efficiencies for $\Lambda_b \to \Lambda(1670)\ \gamma$

- Phase space (PHSP)
  - ε_{tot} = 0.225 %
  - Annual yield: 2515
- long. pol
  - ε_{tot} = 0.224 %
  - Annual yield: 2507
- trans. pol
  - ε_{tot} = 0.228 %
  - Annual yield: 2553

TDR, after L0 x L1

$B_s \to \phi\ \gamma$, ε_{tot} = 0.220 %
$B_d \to K^*\ \gamma$, ε_{tot} = 0.156 %

- no events selected in 39M bb incl.
  - B/S = 18.2 @ 90% CL