Search for CP violation in the $B_s - \overline{B}_s$ system with LHCb

DPF 2011, Brown University, Providence

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On behalf of the LHCb collaboration

Aug. 10 2011

Outline

LHCb

- Search for New Physics at LHCb
- LHCb detector

$B_s \rightarrow J/\psi\,\varphi$

- CP violating phase ϕ_s
- Ingredients for ϕ_s measurement
- Selection
- Proper time resolution and acceptance
- Angular analysis (including angular acceptance)
- Tagging
- Mixing: Δm_s
- ϕ_s Results

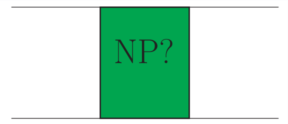
Other channels

- $B_s \rightarrow J/\psi f_0$
- $B_s \rightarrow \varphi\varphi$, $B_s \rightarrow K^* \overline{K^*}$
- $B_s \rightarrow K^+ K^-$

Search for New Physics at LHCb

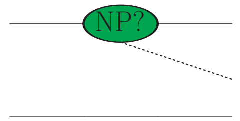
- Search for New Physics (NP) in LHCb by making precision measurements in loop-mediated processes
- Indirect search for NP via
  - Rare decays
  - CP violation

Box diagrams



- $B_s \to J/\psi\,\varphi$
- $B_s \to J/\psi f_0$

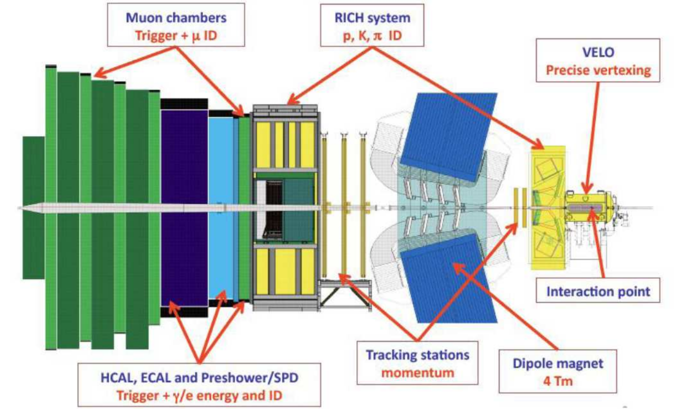
Penguin diagrams



- $B_s \to \varphi\varphi$
- $B_s \to K^* \overline{K^*}$
- $B_s \to J/\psi \overline{K^*}$

The LHCb detector

- LHCb is one of the 4 large LHC experiments
- Single arm forward spectrometer: $1.9 < \eta < 4.9$
- Dedicated to heavy flavour physics:
- Dimensions: 20 m x 10 m x 10 m



Muon chambers
Trigger + μ ID

RICH system
p, K, π ID

VELO
Precise vertexing

Interaction point

HCAL, ECAL and Preshower/SPD
Trigger + γ/e energy and ID

Tracking stations
momentum

Dipole magnet
4 Tm

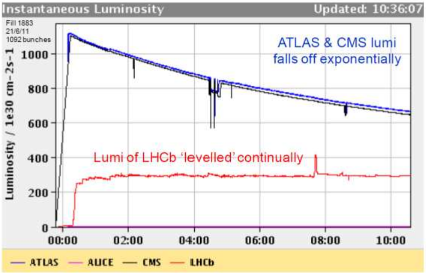
LHCb performance

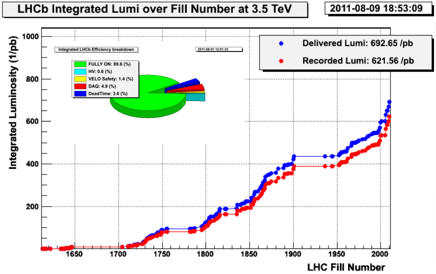
Lumi levelling

- LHCb reconstruction and trigger efficiency sensitive to pile-up
- LHC beams displaced at LHCb interaction point
- Lumi levelling: Beam displacement reduced during fill

Integrated luminosity

- 2010: $\sim 37\,\mathrm{pb}^{-1}$: Results in this talk are from this dataset
- 2011: $\sim 620\,\mathrm{pb}^{-1}$
- On schedule for $1\,\mathrm{fb}^{-1}$ at the end of 2011





CP violating phase ϕ_s in $B_s \to J/\psi\,\varphi$

- Final state $J/\psi\,\varphi$ accessible to both B_s and $\overline{B}_s$: Interference between decays with and without mixing
- Interference measured through weak phase ϕ_s:
  - ϕ_s is the sum of mixing phase and decay phase

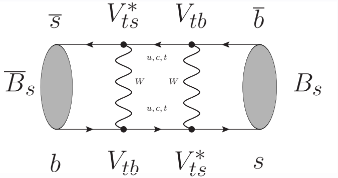
$$\begin{tikzcd}
B_s^0 \arrow[rr, "\phi_D"] \arrow[dr, bend right, "\phi_M"'] & & J/\psi\phi \\
& \bar{B}_s^0 \arrow[ur, bend right, "-\phi_D"'] &
\end{tikzcd}$$

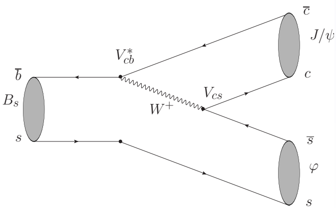
Mixing phase:

- $\phi_M^{SM} = \arg\,(V_{tb}V_{ts}^*)^2 = -2\,\beta_s$

Decay phase

- $\phi_{c\bar{c}s}^{SM} = \arg(V_{cb}V_{cs}^*) \approx 0$ $+$ small penguin contribution





- $\phi_s^{SM} = -2\,\beta_s \approx -0.04$

CP violating phase ϕ_s in $B_s \to J/\psi\,\varphi$

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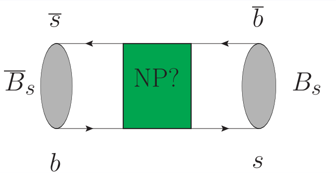
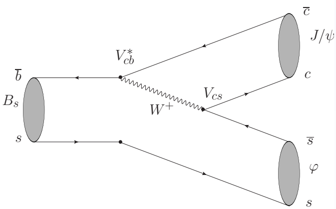




- New Physics (NP) models could enhance ϕ_s
- $\phi_s \to \phi_s^{SM} + \Delta\phi^{NP}$
- ϕ_s weakly constrained by experiments
- Tevatron results show hints for SM deviation

How to measure ϕ_s?

CP assymetry

- If the final state is a CP eigenstate with eigenvalue η_f, the CP assymetry is defined as

$$A_{CP} \equiv \frac{N(\overline{B} \to f) - N(B \to f)}{N(\overline{B} \to f) + N(B \to f)} \sim \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- Δm_s is the $B_s - \overline{B}_s$ mixing frequency

Requirements to measure A_{CP}

- Need tagging information
- Need to disentangle CP even and CP odd states with angular analysis
- Detector effects dilute the CP assymetry:
  - Proper time resolution (σ_t)
  - Mistag probability (ω)

$$A_{CP} \sim (1-2\omega)\exp(-0.5\Delta m_s^2\sigma_t^2)\,\eta_f\,\sin\phi_s\,\sin(\Delta m_s t)$$

- Strength of LHCb: good proper time resolution and tagging power

Ingredients for the ϕ_s analysis at LHCb

Selection and lifetime measurements

- Define common $J/\psi X$ selection
- Measure lifetimes $J/\psi X$ channels

Angular analysis to disentangle different CP eigenstates

- Control channel $B_d \to J/\psi K^*$

Tagging and mixing

- Determine the initial flavour of the B meson
- Measure mixing frequency Δm_s

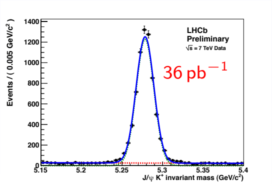
ϕ_s measurement

- Physics parameters:
  $(\Gamma, \Delta\Gamma(=\Gamma_L - \Gamma_H), |A_0|^2, |A_\parallel|^2, |A_S|^2, \delta_\parallel, \delta_\perp, \delta_S, \phi_s, \Delta m_s)$
- Observables: $(t, m_B, \cos\psi, \cos\theta, \phi, q, \omega)$
- Simultaneous fit to all observables

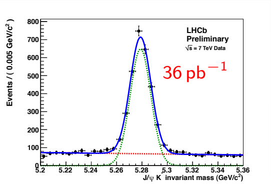
Selection

- Similar selection for all $J/\psi X$ channels
  - Cuts on kinematical, track and vertex quality variables
- In the fit we cut at $t > 0.3\,\text{ps}$ to suppress prompt background
- Good mass resolutions, low background levels
- Trigger
  - Single and Dimuon triggers without IP cut: proper time unbiased

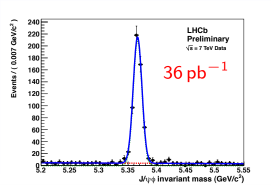
$B^+ \to J/\psi\, K^+$
$N_{\text{sig}} = 6741 \pm 85$
$\sigma_m = 10.7\,\text{MeV}$



$B_d \to J/\psi\, K^*$
$N_{\text{sig}} = 2668 \pm 58$
$\sigma_m = 8\,\text{MeV}$



$B_s \to J/\psi\, \varphi$
$N_{\text{sig}} = 570 \pm 24$
$\sigma_m = 7\,\text{MeV}$

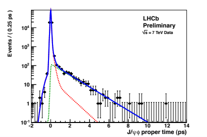


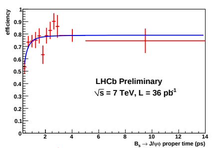
LHCb preliminary: *LHCb-Conf-2011-01*

Lifetime measurements

- All channels fitted with single exponential
- Proper time resolution model from prompt events:
  - Triple Gaussian: effective resolution $< \sigma_t > = 50\,\mathrm{fs}$
- Add events from proper time biased trigger lines
  - Determine proper time acceptance from overlap between unbiased and biased events

LHCb preliminary: *LHCb-Conf-2011-01*

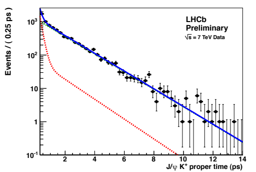




$B^+ \rightarrow J/\psi\, K^+$

LHCb: $\tau = 1.689 \pm 0.022 \pm 0.047$

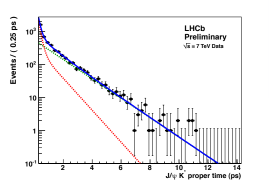
PDG: $\tau = 1.638 \pm 0.011$



$B_d \rightarrow J/\psi\, K^*$

LHCb: $\tau = 1.512 \pm 0.032 \pm 0.042$

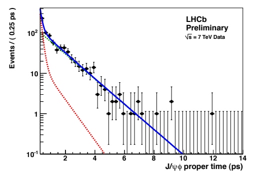
PDG: $\tau = 1.525 \pm 0.009$



$B_s \rightarrow J/\psi\, \varphi$

LHCb: $\tau = 1.447 \pm 0.064 \pm 0.056$

PDG: $\tau = 1.477 \pm 0.046$



Angular analysis

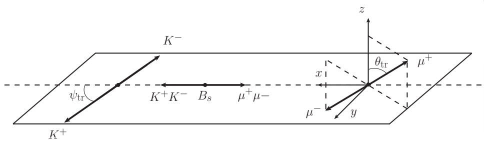
Spin states

- B_s is spin 0, decays to J/ψ (spin 1) and φ (spin 1)
- Different orbital angular momentum configurations from spin conservation
- $B_s \rightarrow J/\psi\,\varphi$ is admixture of CP even and odd states
  - $\mathrm{CP}|J/\psi\,\varphi\rangle = (-1)^L|J/\psi\,\varphi\rangle$
- $L = 0$ and $L = 2$ states are CP even, $L = 1$ is CP odd

Transversity basis

Three transversity amplitudes

- CP even: $A_{\|}$ and A_0, CP odd: $A_{\perp}$
- Use transversity angular distributions (ψ, θ, ϕ) to statistically disentangle CP even and CP odd components



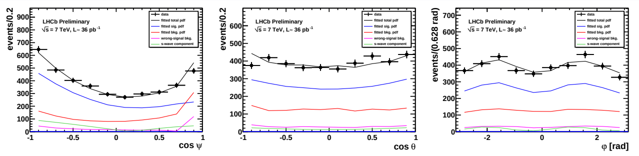
Angular analysis: Control channel $B_d \rightarrow J/\psi K^*$

Angular acceptance correction

- Correct for angular acceptance using MC
- Angular acceptance due to p_T cuts (implicit or explicit)

Results

- Projections on transversity angles



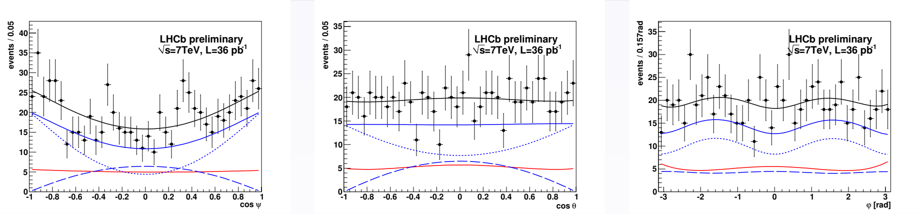
- $K\pi$ S-wave component included ($5\% \pm 2\%$)

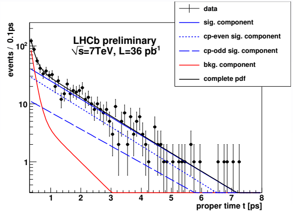
Parameter	LHCb: result ± stat. ± syst.	BaBar: result ± stat. ± syst.
$\lvert A_{\parallel}\rvert^2$	$0.252 \pm 0.020 \pm 0.016$	$0.211 \pm 0.010 \pm 0.006$
$\lvert A_{\perp}\rvert^2$	$0.178 \pm 0.022 \pm 0.017$	$0.233 \pm 0.010 \pm 0.005$
$\delta_{\parallel}$	$-2.87 \pm 0.11 \pm 0.10$	$-2.93 \pm 0.08 \pm 0.04$
$\delta_{\perp}$	$3.02 \pm 0.10 \pm 0.07$	$2.91 \pm 0.05 \pm 0.03$

LHCb preliminary: *LHCb-Conf-2011-02* BaBar: *hep-ex/0607081v1*

$\Delta\Gamma$ from untagged $B_s \to J/\psi\,\varphi$ analysis

- $\Delta\Gamma = \Gamma_L - \Gamma_H$ (lifetimes of the light and heavy B_s states)
    - $B_{s,L} = p|B_s\rangle + q|\overline{B_s}\rangle \quad , \quad B_{s,H} = p|B_s\rangle - q|\overline{B_s}\rangle$
- Fit $B_s \to J/\psi\,\varphi$ events without tagging information
- Set $\phi_s = 0$





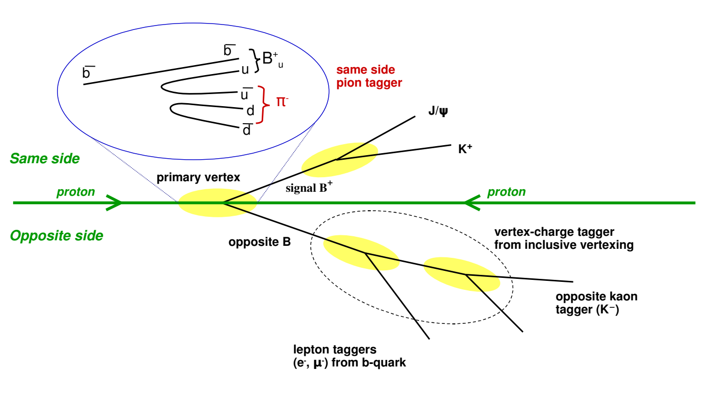
LHCb preliminary: *LHCb-Conf-2011-02*

Parameter	result ± stat. ± syst.
Γ (ps^{-1})	$0.679 \pm 0.036 \pm 0.027$
$\Delta\Gamma$ (ps^{-1})	$0.077 \pm 0.119 \pm 0.021$
$\|A_0\|^2$	$0.528 \pm 0.040 \pm 0.028$
$\|A_\perp\|^2$	$0.263 \pm 0.056 \pm 0.014$
$\delta_\parallel$	$3.14 \pm 0.52 \pm 0.13$

CDF ($5.2\,\mathrm{fb}^{-1}$): $\Delta\Gamma = 0.075 \pm 0.035 \pm 0.010$ ps^{-1}
(CDF/ANAL/BOTTOM/PUBLIC/10206)

Tagging

- To measure mixing parameters such as Δm_s one needs information on the flavor of the produced B meson
- Indicated by tag decision $q = \pm 1$, with per-event mistag probability ω_i
- Two types: Opposite Side Tagger (OS) and Same Side Tagger (SS)



Tagging power

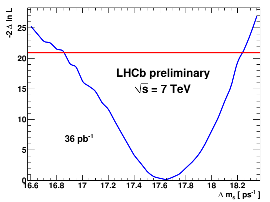
- Sensitivity of a CP asymmetry directly related to the effective tagging power $\epsilon_{\mathrm{eff}} = \epsilon_{\mathrm{tag}} D^2 = \epsilon_{\mathrm{tag}}(1-2\omega)^2$
- Tagging power represents the effective statistical reduction of the sample size

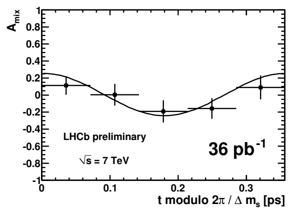
- With 2010 statistics, SS tagger not calibrated yet
- Use OS tagger only!
- For $B_s \to J/\psi\,\varphi$: $\omega_{\mathrm{eff}} = 32\% \pm 2\%$
- Tagging power $\epsilon D^2 = 2.2\% \pm 0.5\%$
- Will improve when including SS tagger!

Δm_s measurement

- 4 decays:
  - $B_s \rightarrow D_s(\varphi\pi)\pi$ (515 ± 25)
  - $B_s \rightarrow D_s(K^*K)\pi$ (338 ± 27)
  - $B_s \rightarrow D_s(KK\pi)\pi$ (283 ± 27)
  - $B_s \rightarrow D_s(KK\pi)3\pi$ (245 ± 46)
- 2D (t, m) unbinned simultaneous fit to 4 samples
- LHCb preliminary: $\Delta m_s = 17.63 \pm 0.11\ (\text{stat.}) \pm 0.04\ (\text{syst.})\ \text{ps}^{-1}$

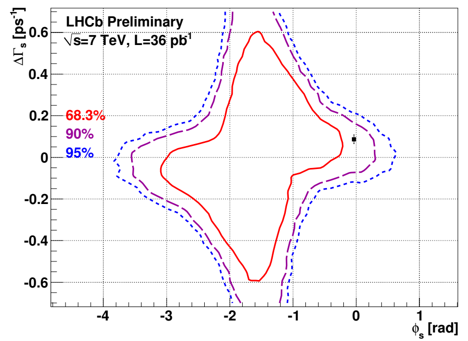
  (*LHCb-Conf-2011-05*)
  - CDF: $\Delta m_s = 17.77 \pm 0.10\ (\text{stat.}) \pm 0.07\ (\text{syst.})\ \text{ps}^{-1}$ (*hep-ex/0609040v1*)





ϕ_s results

- No meaningful point estimates with 2010 statistics
- Confidence contours with Feldman-Cousins method
- Systematic effects much smaller than statistical effects



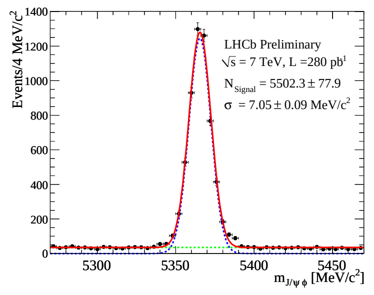
$\phi_s \in [-2.7, -0.5]$ at 68 % CL
SM p-value: 22% ($\sim$1.2σ)

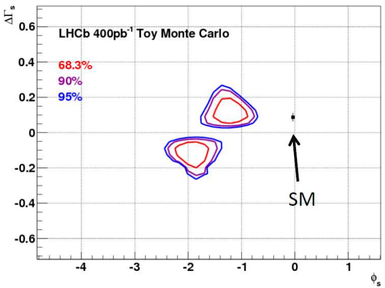
LHCb preliminary: *LHCb-Conf-2011-06*

ϕ_s prospects

- Analysis for 10 times more data being refereed as we speak
- Between 350 and 400 pb^{-1}
- Preview for 280 pb^{-1} below

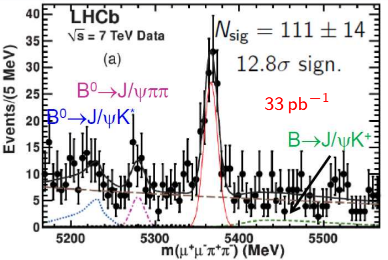
- Toy with 2010 fit results as input, assuming identical LHCb performance
- Expect world best measurement soon!





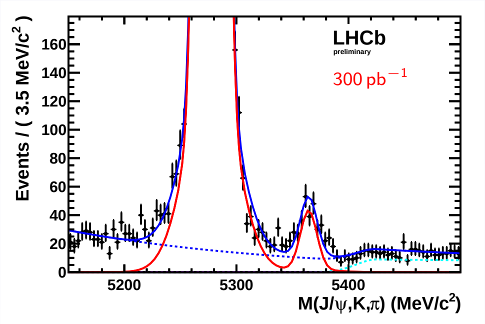
Other channels: ϕ_s from $B_s \rightarrow J/\psi f_0$

- $f_0(980)$ is a bound $s\bar{s}$ state, just like φ
- Smaller BR than $B_s \rightarrow J/\psi\,\varphi$
- Big advantage: $J/\psi f_0$ is a CP odd eigenstate, not an admixture as in $B_s \rightarrow J/\psi\,\varphi$
- No angular analysis needed!
- ϕ_s measurement in $B_s \rightarrow J/\psi f_0$ soon, first observation: *(arXiv:1102.0206v2)*



$$R_{f_0/\varphi} = \frac{\Gamma(B_s \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+\pi^-))}{\Gamma(B_s \rightarrow J/\psi\varphi, \varphi \rightarrow K^+K^-))} = 0.252^{+0.046+0.027}_{-0.032-0.033}$$

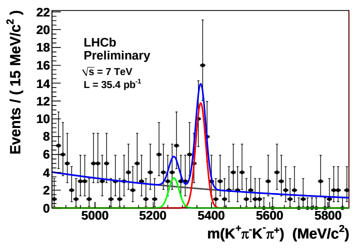
Evidence for $B_s \to J/\psi \overline{K^*}$



- Can help control penguin contributions in $B_s \to J/\psi\,\varphi$
- See for example Faller, Fleischer and Mannel: arXiv:0810.4248v1
- For 36 pb^{-1}: $\mathcal{B}(B_s \to J/\psi \overline{K^*}) = (3.5^{+1.1}_{-1.0}(\mathrm{stat.}) \pm 0.9(\mathrm{syst.})) \times 10^{-5}$
- Assuming that all $K\pi$ pairs in the B_s mass peak originate from K^*'s

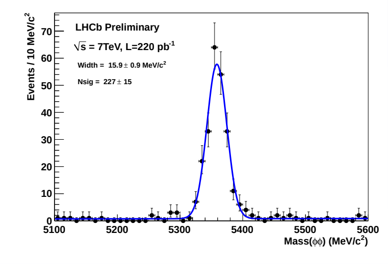
LHCb preliminary: *LHCb-Conf-2011-25*

Penguin decay $B_s \to K^* \overline{K^*}$: first observation



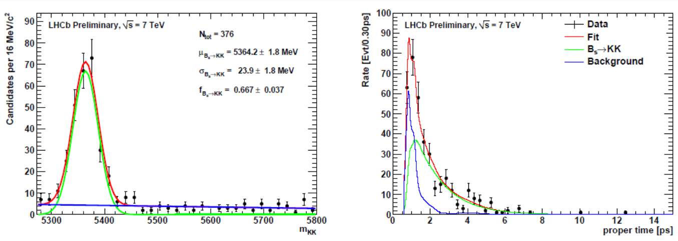
LHCb preliminary: *LHCb-Conf-2011-19*

- $\mathcal{B}(B_s \to K^* \overline{K^*}) = (1.95 \pm 0.47(\text{stat.}) \pm 0.51(\text{syst.}) \pm 0.29(f_d/f_s)) \times 10^{-5}$
- In SM: decay phase cancels mixing phase
- Sensitive to NP that could affect box diagrams in a different way than penguin diagrams
- Similar to $B_s \to \varphi\varphi$



Lifetime measurement in $B_s \rightarrow K^+K^-$

- Also dominated by penguins
- Can constrain NP contributions to $\Delta\Gamma$ and ϕ_s
- Two independent measurements:
  - Absolute measurement
  - Measurement relative to B_d lifetime



- Combined result: $\tau_{B_s} = 1.440 \pm 0.096(\text{stat.}) \pm 0.010(\text{syst.})$ ps
- See Paul Sail's talk on Friday

LHCb-Conf-2011-18

Conclusions

- Great performance of LHC and LHCb in 2010 and first half of 2011
- Many ingredients for the ϕ_s measured with first 36 pb^{-1}:
  - Lifetimes in $B \to J/\psi X$
  - Polarization amplitudes in control channel $B_d \to J/\psi K^*$
  - $\Delta\Gamma$ from untagged $B_s \to J/\psi\,\varphi$ analysis
  - Δm_s from $B_s \to D_s\pi$ events
- ϕ_s measurement with $\sim 400\,\mathrm{pb}^{-1}$ of data will be presented very soon
- Aim for world's best measurement at the end of this year

- First observations of $B_s \to J/\psi f_0$ and $B_s \to K^*\overline{K^*}$
- Evidence for $B_s \to J/\psi\overline{K^*}$
- Lifetime measurement in $B_s \to K^+K^-$

- Very exciting times!

Backup

$B_s \to J/\psi\,\varphi$ time-dependent functions

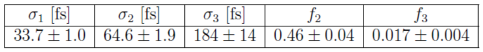
$$
\begin{aligned}
A_1 &= |a_0|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_2 &= |a_{||}|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_3 &= |a_{\perp}|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_4 &= |a_{||}||a_{\perp}|e^{-t/\tau}[-\cos(\delta_{\perp} - \delta_{||})\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_{\perp} - \delta_{||})\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_{\perp} - \delta_{||})\cos(\Delta m t)] \\
A_5 &= |a_0||a_{||}|e^{-t/\tau}\cos(\delta_{||} - \delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_6 &= |a_0||a_{\perp}|e^{-t/\tau}[-\cos(\delta_{\perp} - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_{\perp} - \delta_0)\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_{\perp} - \delta_0)\cos(\Delta m t)] \\
A_7 &= |a_S|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t] \\
A_8 &= |a_S||a_{||}|e^{-t/\tau}[-\sin(\delta_{||} - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_{||} - \delta_S)\cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_{||} - \delta_S)\cos(\Delta m t)] \\
A_9 &= |a_S||a_{\perp}|e^{-t/\tau}\sin(\delta_{\perp} - \delta_S)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_{10} &= |a_S||a_0|e^{-t/\tau}[-\sin(\delta_0 - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0 - \delta_S)\cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_0 - \delta_S)\cos(\Delta m t)]
\end{aligned}
$$

		$\cosh\left(\frac{\Delta\Gamma}{2}t\right)$	$q_T \cos(\Delta m t)$	$\sinh\left(\frac{\Delta\Gamma}{2}t\right)$	$q_T \sin(\Delta m t)$
$\|\mathcal{A}_0(t)\|^2$	$\frac{\|a_0\|^2 e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
$\|\mathcal{A}_{\|\|}(t)\|^2$	$\frac{\|a_{\|\|}\|^2 e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
$\|\mathcal{A}_{\perp}(t)\|^2$	$\frac{\|a_{\perp}\|^2 e^{-t/\tau}}{1+q_T C}$	1	C	$+D$	$+S$
$\Im(\mathcal{A}_{\|\|}^*(t)\mathcal{A}_{\perp}(t))$	$\frac{\Re(a_{\|\|}^* a_{\perp})e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$
	$\frac{\Im(a_{\|\|}^* a_{\perp})e^{-t/\tau}}{1+q_T C}$	C	1	0	0
$\Im(\mathcal{A}_0^*(t)\mathcal{A}_{\perp}(t))$	$\frac{\Re(a_0^* a_{\perp})e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$
	$\frac{\Im(a_0^* a_{\perp})e^{-t/\tau}}{1+q_T C}$	C	1	0	0
$\Re(\mathcal{A}_0^*(t)\mathcal{A}_{\|\|}(t))$	$\frac{\Re(a_0^* a_{\|\|})e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
	$\frac{\Im(a_0^* a_{\|\|})e^{-t/\tau}}{1+q_T C}$	0	0	0	0
$\|\mathcal{A}_S(t)\|^2$	$\frac{\|a_S\|^2 e^{-t/\tau}}{1+q_T C}$	1	C	D	S
$\Im(\mathcal{A}_S^*(t)\mathcal{A}_{\perp}(t))$	$\frac{\Re(a_S^* a_{\perp})e^{-t/\tau}}{1+q_T C}$	0	0	0	0
	$\frac{\Im(a_S^* a_{\perp})e^{-t/\tau}}{1+q_T C}$	1	C	D	S
$\Re(\mathcal{A}_S^*(t)\mathcal{A}_0(t))$	$\frac{\Re(a_S^* a_0)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
	$\frac{\Im(a_S^* a_0)e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$
$\Re(\mathcal{A}_S^*(t)\mathcal{A}_{\|\|}(t))$	$\frac{\Re(a_S^* a_{\|\|})e^{-t/\tau}}{1+q_T C}$	C	1	0	0
	$\frac{\Im(a_S^* a_{\|\|})e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$

$B_s \rightarrow J/\psi\,\varphi$ angular functions

amplitudes	Angular function
$\lvert a_0\rvert^2$	$2\cos^2\psi\left(1-\sin^2\theta\cos^2\phi\right)$
$\lvert a_{\parallel}\rvert^2$	$\sin^2\psi\left(1-\sin^2\theta\sin^2\phi\right)$
$\lvert a_{\perp}\rvert^2$	$\sin^2\psi\sin^2\theta$
$\Im(a_{\parallel}\,a_{\perp})$	$-\sin^2\psi\sin 2\theta\sin\phi$
$\Re(a_0\,a_{\parallel})$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
$\Im(a_0\,a_{\perp})$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
$\lvert a_S(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
$\Re(a_S^*(t)a_{\parallel}(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
$\Im(a_S^*(t)a_{\perp}(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
$\Re(a_S^*(t)a_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

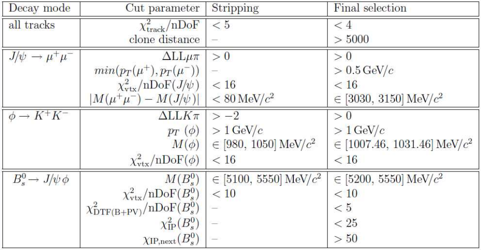
Proper time resolution



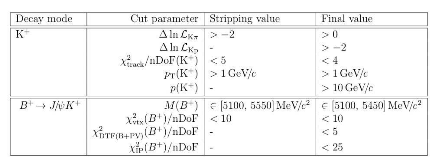
σ_1 [fs]	σ_2 [fs]	σ_3 [fs]	f_2	f_3
33.7 ± 1.0	64.6 ± 1.9	184 ± 14	0.46 ± 0.04	0.017 ± 0.004

- Dilution from Gaussian proper time
- $D = \exp\left(-\Delta m_s^2 \sigma_t^2/2\right)$
- $D = (1 - 0.46 - 0.017)\exp(-0.5 * 17.8^2 * 0.0337^2) + 0.46\exp(-0.5 * 17.8^2 * 0.0646^2) + 0.017 * \exp(-0.5 * 17.8^2 * 0.184^2) = 0.674$
- Converting back to effective proper time resolution
- $< \sigma_t > =$50 fs^{-1}

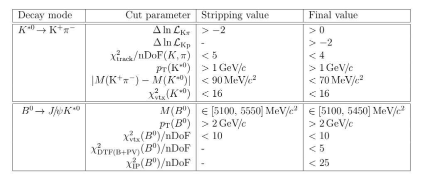
Selection details



Decay mode	Cut parameter	Stripping	Final selection
all tracks	$\chi^2_{\text{track}}/\text{nDoF}$	< 5	< 4
	clone distance	–	> 5000
$J/\psi \to \mu^+\mu^-$	$\Delta\text{LL}\mu\pi$	> 0	> 0
	$min(p_T(\mu^+), p_T(\mu^-))$	–	$> 0.5\,\text{GeV}/c$
	$\chi^2_{\text{vtx}}/\text{nDoF}(J/\psi)$	< 16	< 16
	$\lvert M(\mu^+\mu^-) - M(J/\psi)\rvert$	$< 80\,\text{MeV}/c^2$	$\in [3030,\ 3150]\,\text{MeV}/c^2$
$\phi \to K^+K^-$	$\Delta\text{LL}K\pi$	> -2	> 0
	$p_T\ (\phi)$	$> 1\,\text{GeV}/c$	$> 1\,\text{GeV}/c$
	$M(\phi)$	$\in [980,\ 1050]\,\text{MeV}/c^2$	$\in [1007.46,\ 1031.46]\,\text{MeV}/c^2$
	$\chi^2_{\text{vtx}}/\text{nDoF}(\phi)$	< 16	< 16
$B^0_s \to J/\psi\,\phi$	$M(B^0_s)$	$\in [5100,\ 5550]\,\text{MeV}/c^2$	$\in [5200,\ 5550]\,\text{MeV}/c^2$
	$\chi^2_{\text{vtx}}/\text{nDoF}(B^0_s)$	< 10	< 10
	$\chi^2_{\text{DTF(B+PV)}}/\text{nDoF}(B^0_s)$	–	< 5
	$\chi^2_{\text{IP}}(B^0_s)$	–	< 25
	$\chi_{\text{IP,next}}(B^0_s)$	–	> 50



Decay mode	Cut parameter	Stripping value	Final value
K^+	$\Delta\ln\mathcal{L}_{\text{K}\pi}$	> -2	> 0
	$\Delta\ln\mathcal{L}_{\text{Kp}}$	-	> -2
	$\chi^2_{\text{track}}/\text{nDoF}(\text{K}^+)$	< 5	< 4
	$p_{\text{T}}(\text{K}^+)$	$> 1\,\text{GeV}/c$	$> 1\,\text{GeV}/c$
	$p(\text{K}^+)$	-	$> 10\,\text{GeV}/c$
$B^+ \to J/\psi K^+$	$M(B^+)$	$\in [5100,\ 5550]\,\text{MeV}/c^2$	$\in [5100,\ 5450]\,\text{MeV}/c^2$
	$\chi^2_{\text{vtx}}(B^+)/\text{nDoF}$	< 10	< 10
	$\chi^2_{\text{DTF(B+PV)}}(B^+)/\text{nDoF}$	-	< 5
	$\chi^2_{\text{IP}}(B^+)/\text{nDoF}$	-	< 25



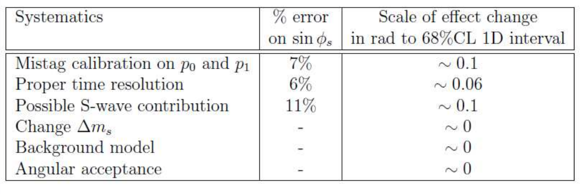
Decay mode	Cut parameter	Stripping value	Final value
$K^{*0} \to \text{K}^+\pi^-$	$\Delta\ln\mathcal{L}_{\text{K}\pi}$	> -2	> 0
	$\Delta\ln\mathcal{L}_{\text{Kp}}$	-	> -2
	$\chi^2_{\text{track}}/\text{nDoF}(K,\pi)$	< 5	< 4
	$p_{\text{T}}(\text{K}^{*0})$	$> 1\,\text{GeV}/c$	$> 1\,\text{GeV}/c$
	$\lvert M(\text{K}^+\pi^-) - M(K^{*0})\rvert$	$< 90\,\text{MeV}/c^2$	$< 70\,\text{MeV}/c^2$
	$\chi^2_{\text{vtx}}(K^{*0})$	< 16	< 16
$B^0 \to J/\psi K^{*0}$	$M(B^0)$	$\in [5100,\ 5550]\,\text{MeV}/c^2$	$\in [5100,\ 5450]\,\text{MeV}/c^2$
	$p_{\text{T}}(B^0)$	$> 2\,\text{GeV}/c$	$> 2\,\text{GeV}/c$
	$\chi^2_{\text{vtx}}(B^0)/\text{nDoF}$	< 10	< 10
	$\chi^2_{\text{DTF(B+PV)}}(B^0)/\text{nDoF}$	-	< 5
	$\chi^2_{\text{IP}}(B^0)/\text{nDoF}$	-	< 25

Systematics

Main systematics

- Relative uncertainty in dilution from flavour tagging (7%)
- Proper time resolution (6%)
- Ignoring S-wave (11%)

All this does not change the contours significantly



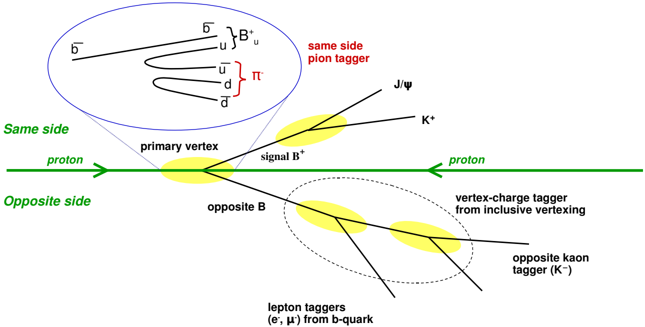
Systematics	% error on $\sin\phi_s$	Scale of effect change in rad to 68%CL 1D interval
Mistag calibration on p_0 and p_1	7%	~ 0.1
Proper time resolution	6%	~ 0.06
Possible S-wave contribution	11%	~ 0.1
Change Δm_s	-	~ 0
Background model	-	~ 0
Angular acceptance	-	~ 0

Angular acceptance

$$\epsilon = \frac{N^{\mathrm{sig}}_{\mathrm{unbiased\&\&biased}}}{N^{\mathrm{sig}}_{\mathrm{unbiased}}}$$

$$\epsilon = \frac{t_{\mathrm{unbiased}}}{t_{\mathrm{biased-only}}}$$

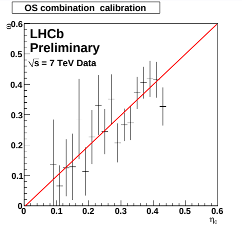
Tagging diagram



Tagging

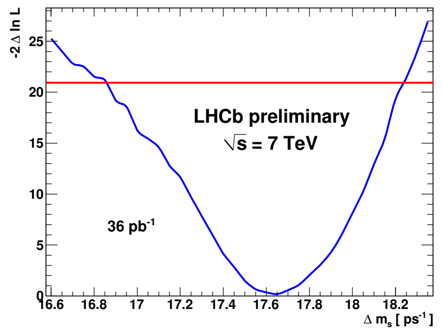
- $\epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1-2w)^2 = \epsilon_{\text{tag}} D_{eff}^2 = D^2$
- $D = \sqrt{\epsilon_{\text{tag}}}(1-2w)$
- $\frac{1}{D\sqrt{N}} = \frac{1}{D_{\text{eff}}\sqrt{N\epsilon_{\text{tag}}}} = \frac{1}{\sqrt{\epsilon_{\text{tag}}}D_{\text{eff}}\sqrt{N}}$

- Calibrate mistag probability using self-tagging decay $B^+ \rightarrow J/\psi K^+$
- $\omega_i = p_0 + p_1(\eta - <\eta>)$
- Float p_0 and p_1 within their errors in fits



LHCb-Conf-2011-03

Δm_s measurement

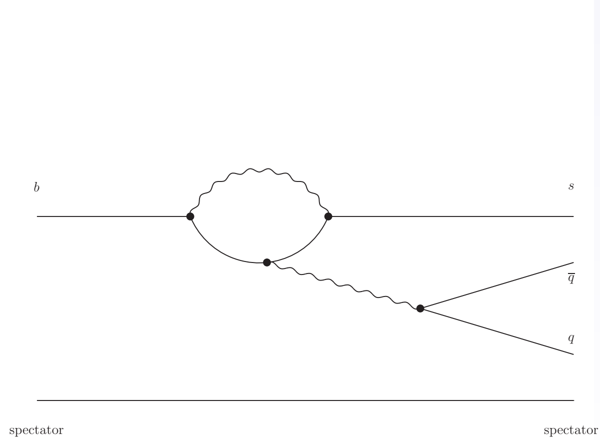


- red line is likelihood value in case of infinite Δm_s
- $-2(\ln L - \ln L_{max}) = N^2$
- N is number of σ's
- So this is $\sqrt{20.94} = 4.6\sigma$

Feldman Cousins method

- The confidence level contours are constructed using p-values of each gridpoint on the $\phi_s - \Delta\Gamma$ plane
- Fit the data twice:
  - 1) float all parameters to find the $L_{max,data}$ at gridpoint
  - 2) float all other parameters but fix ϕ_s and $\Delta\Gamma$ to the gridpoint values
- Get the difference of loglikelihood values $\Delta LL_{data} = \ln L_{max,data} - \ln L_{fix,data}$
- Generate a large number of toys at gridpoint (other parameters fixed to the one found in the second fit in first step)
- For each toy fit twice:
  - 1) floating all parameters to find $L_{max,toy}$
  - 2) float other parameters but fix ϕ_s and $\Delta\Gamma$ at gridpoint.
- Get the difference of loglikelihood values $\Delta LL_{toy} = \ln L_{max,toy} - \ln L_{fix,toy}$
- The fraction of toys having $\Delta LL_{toy} > \Delta LL_{data}$ is the p-value of the gridpoint

Penguins



Assymetry

$$A_{CP} \equiv \frac{N(\overline{B} \to f) - N(B \to f)}{N(\overline{B} \to f) + N(B \to f)} = \frac{\eta_f \sin\phi_s \sin\Delta m t}{\cosh\frac{\Delta\Gamma t}{2} + \eta_f \cos\phi_s \sinh\frac{\Delta\Gamma t}{2}}$$

$$\begin{aligned}
\Gamma_{B\to f}(t) &= |A_f|^2\,(1+|\lambda_f|^2)\,\frac{e^{-\Gamma t}}{2}\,\cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - D_f\,\sinh\frac{\Delta\Gamma t}{2} + C_f\,\cos\Delta m t - S_f\,\sin\Delta m t\right) \qquad (1)\\
\Gamma_{B\to\overline{f}}(t) &= |\overline{A}_{\overline{f}}|^2\left|\frac{q}{p}\right|^2(1+|\overline{\lambda}_{\overline{f}}|^2)\,\frac{e^{-\Gamma t}}{2}\,\cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - \overline{D}_{\overline{f}}\,\sinh\frac{\Delta\Gamma t}{2} - \overline{C}_{\overline{f}}\,\cos\Delta m t + \overline{S}_{\overline{f}}\,\sin\Delta m t\right) \qquad (2)\\
\Gamma_{\overline{B}\to f}(t) &= |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\,\frac{e^{-\Gamma t}}{2}\,\cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - D_f\,\sinh\frac{\Delta\Gamma t}{2} - C_f\,\cos\Delta m t + S_f\,\sin\Delta m t\right) \qquad (3)\\
\Gamma_{\overline{B}\to\overline{f}}(t) &= |\overline{A}_{\overline{f}}|^2\,(1+|\overline{\lambda}_{\overline{f}}|^2)\,\frac{e^{-\Gamma t}}{2}\,\cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - \overline{D}_{\overline{f}}\,\sinh\frac{\Delta\Gamma t}{2} + \overline{C}_{\overline{f}}\,\cos\Delta m t - \overline{S}_{\overline{f}}\,\sin\Delta m t\right) \qquad (4)
\end{aligned}$$

where

$$\begin{aligned}
D_f &= \frac{2\,\mathrm{Re}[\lambda_f]}{1+|\lambda_f|^2}\ , \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\ , \quad S_f = \frac{2\,\mathrm{Im}[\lambda_f]}{1+|\lambda_f|^2}\ , \\
\overline{D}_{\overline{f}} &= \frac{2\,\mathrm{Re}[\overline{\lambda}_{\overline{f}}]}{1+|\overline{\lambda}_{\overline{f}}|^2}\ , \quad \overline{C}_{\overline{f}} = \frac{1-|\overline{\lambda}_{\overline{f}}|^2}{1+|\overline{\lambda}_{\overline{f}}|^2}\ , \quad \overline{S}_{\overline{f}} = \frac{2\,\mathrm{Im}[\overline{\lambda}_{\overline{f}}]}{1+|\overline{\lambda}_{\overline{f}}|^2}\ .
\end{aligned} \qquad (5)$$

LHCb trigger

- Trigger important:
- σ_{bb} is less than 1 % of total inelastic cross section
- BR of interesting B decays $< 10^{-5}$

- *b*-hadrons long-lived:
  - Separate primary and secondary vertices
- *b*-hadrons have large mass:
  - Decay products with high p_T

- L0: Search for high p_T μ, e, γ and hadron candidates
- HLT: Software trigger
- HLT1: L0 confirmation
- HLT2: Global event resconstruction
  - Inclusive and exclusive selections

Trigger scheme