Advanced Study Institute
"Physics at LHC", LHC Praha-2003,
B Physics Day, 11/07/2003

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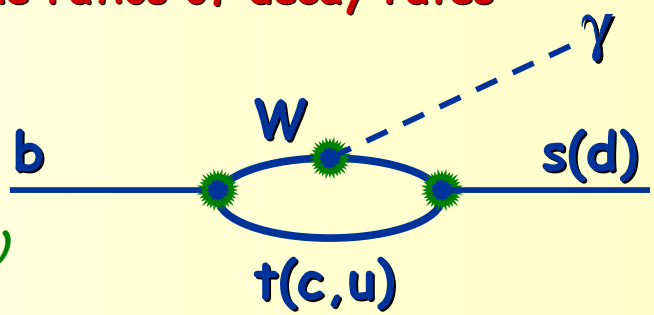
for LHCb collaboration

Study of exclusive radiative B decays with LHCb

Physics motivation

- Constraint on CKM matrix elements $|V_{td}/V_{ts}|$ from the ratios of decay rates
  $B^0 \to \rho(\omega)\gamma$ / $B^0 \to K^{*0}\gamma$
  $B_s^0 \to K^{*0}\gamma$ / $B_s^0 \to \phi\gamma$
- Search for New Physics
  - Direct CP violation
    A_{CP} < 1% in SM *(tiny u quark contribution in loop)*
    up to ~ 10% in SM extensions
    $B^0 \to K^{*0}\gamma$; $B^+ \to K^{*+}\gamma$; $B \to K^{**}\gamma$; $B_s^0 \to K^{*0}\gamma$
  - Mixing-induced CP violation
    ~0 in SM *(different γ polarizations in B^0 and $\overline{B}^0$ decays)*
    up to ~ 50% in SM extensions
    $B_s^0 \to \phi\gamma$;
    $B^0 \to K^{**0}\gamma$ with $K^{**0} \equiv \overline{K}^{**0}$, *e.g.* $K^*_0{}^0(1430) \to K^0_S \pi^+\pi^-$ *(Dalitz plot analysis of $K^0_S \pi^+\pi^-$ to extract flavour blind $K^0_S \rho^0$)*
  - Exotics, super rare decays
    $B^0_{(s)} \to l^+ l^- \gamma$, $B^0_{(s)} \to \gamma\gamma$, *etc*
- Test of QCD
  $B \to K^*\gamma$, $K^{**}\gamma$, $K n\pi \gamma$; $\Lambda_b \to \Lambda\gamma$, *etc*



Experimental overview

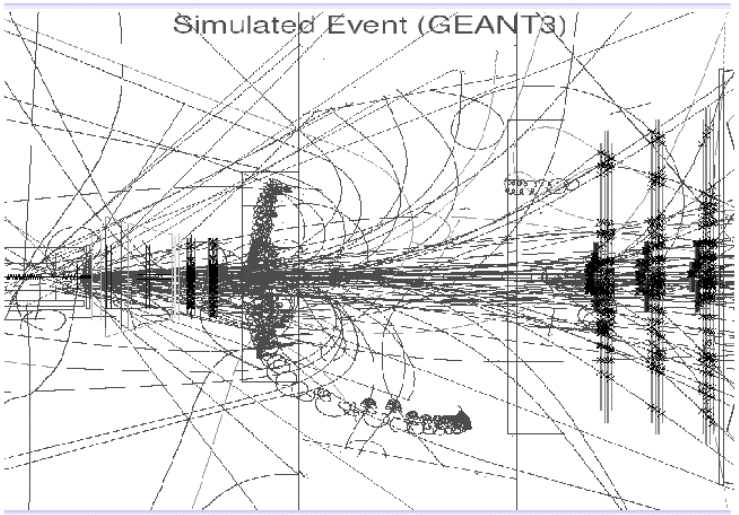
The first exclusive radiative penguin $B^0 \to K^{*0}\gamma$ was observed by CLEO in 1993

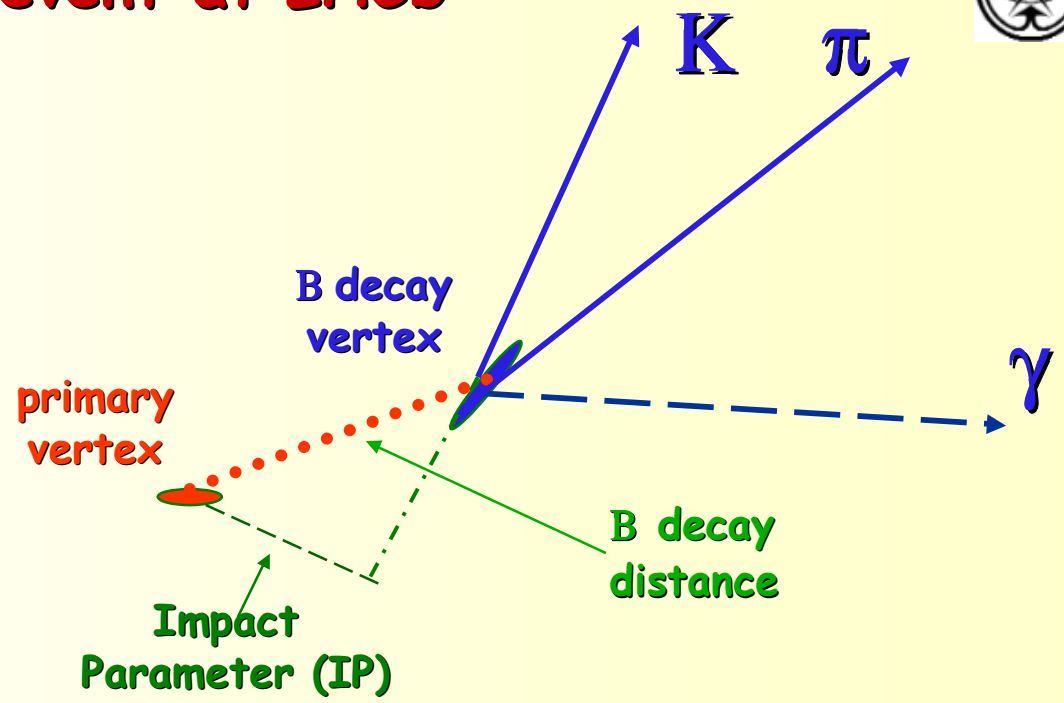
$B^0 \to K^{*0}\gamma$	$(4.3 \pm 0.4)\times10^{-5}$	PDG 2003
$B^+ \to K^{*+}\gamma$	$(3.8 \pm 0.5)\times10^{-5}$	PDG 2003
$A_{CP}(B \to K^*\gamma)$	-0.01 ± 0.07	PDG 2003
$B \to K^*_2(1430)\gamma$	$(1.3 \pm 0.5)\times10^{-5}$	PDG 2003

$B^+ \to K^+\pi^-\pi^+\gamma$; $B^+ \to K^{*0}\pi^+\gamma$; $B \to K\pi\gamma$; $B \to K\rho^0\gamma$		Belle
$B^0 \to \rho^0\gamma$; $B^+ \to \rho^+\gamma$; $B^0 \to \omega\gamma$; $B^0 \to \gamma\gamma$	Upper limit	BABAR
$B^0 \to$ barion γ	Upper limit	CLEO

Statistics at B-factories is still not sufficient for stringent test of SM in CP violation in radiative decays and for observation of $b \to d\gamma$

B $\bar{B}$ event at LHCb





- $N_{b\ hadrons} = 10^{12}$ / year
  - all types of b hadrons
- $\sigma_{bb} / \sigma_{inel} \sim 5 \times 10^{-3}$
  - high charged and neutral multiplicity
  - few primary vertices

Challenge

- **Electromagnetic penguins are indeed rare B decays**
  - inclusive Br $(b \to s\,\gamma) = (3.3 \pm 0.4) \times 10^{-4}$
  - exclusive Br are ~10-100 smaller
  - $b \to d\,\gamma$ are further suppressed by $|V_{td}/V_{ts}|^2$
  - $f(b \to \bar{B}^0_s) / f(b \to \bar{B}^0) \sim 0.26$
- **Background sources**
  - Huge combinatorial background from generic $b\,\bar{b}$ events
  - Minimum bias events
  - $B \to X\,\pi^0$ decays
    - γ / π^0 separation using different shower shape
    - for X=V polarization can be exploited

Search for CP violation

- **Direct CP violation**
  - no tag and lifetime analysis are required
  - Systematic errors are of great importance:

    fake (non-CP) asymmetries
    - different B and $\overline{B}$ production rates in pp interactions
    - detector asymmetries

    Hopefully can be calibrated with other final states

    e.g. $B^0 \to J/\psi\, K^{*0}$
- **Mixing-induced CP violation**
  - need to tag B flavour
  - proper time resolution is critical

    especially for B^0_S due to fast oscillations ($x_s > 19$) to be resolved

Can we measure radiative decays at LHCb

- $B^0 \to K^{*0}(K^+\pi^-)\,\gamma$ — Direct CP
  - Energetic γ
    - huge soft γ and π^0 background can be effectively removed
      dedicated trigger selects high E_T photons at Level 0
  - two charged tracks
    - B^0 vertex reconstruction
- $B^0_S \to \phi(K^+K^-)\,\gamma$ — B_s decay & mixing-induced CP
  - small $\Gamma_\phi \Rightarrow$ narrow $\Delta M(\phi)$ cut; small ϕ yield in B decays:
    - background conditions are more favourable
  - extremely small opening angle $\phi \to K^+K^-$
    - problem with B^0_S vertex (proper time) resolution
- $B^0 \to \omega(\pi^+\pi^-\pi^0)\,\gamma$ — $b \to d\,\gamma$
  - small $\Gamma_\omega \Rightarrow$ narrow $\Delta M(\omega)$ cut
  - problem with combinatorial background from π^0
    - in progress (not presented here)

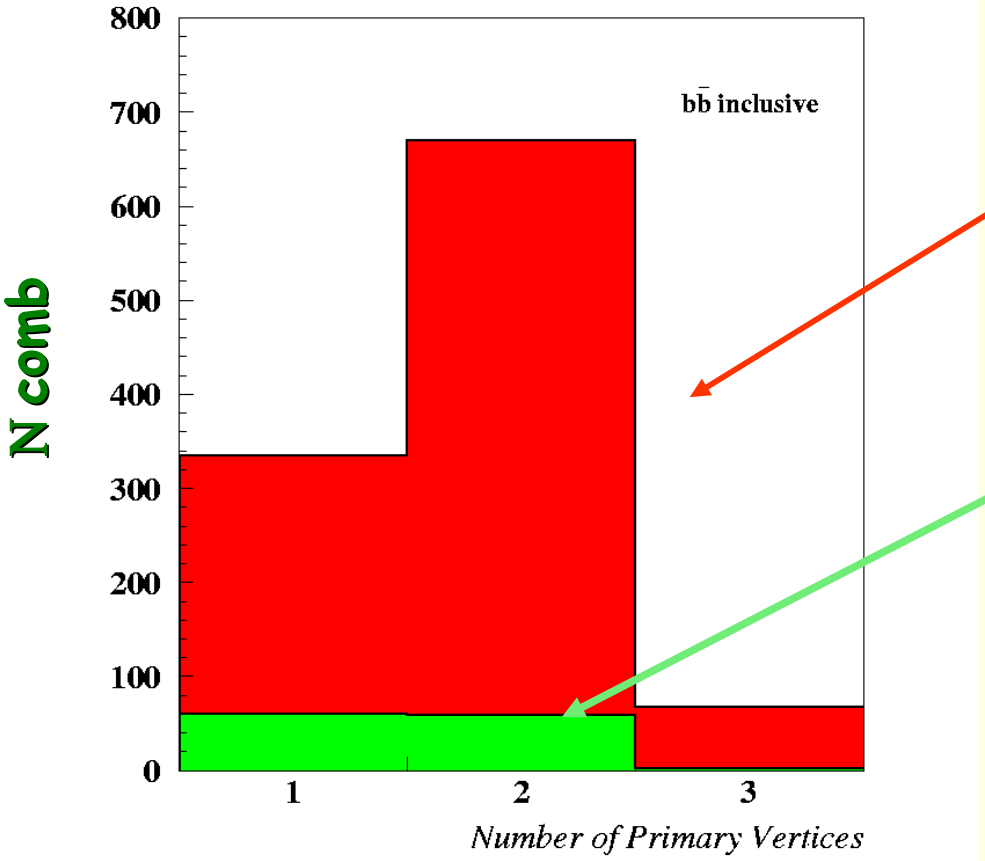
$B^0 \to K^{*0} \gamma$ reconstruction

Select $K^+ \pi^- \gamma$ combinations

- Tracks are consistent with K^+ & π^- hypothesis
- Reject K^+, π^- tracks from all primary vertices ($\chi^2_{IP} > 16$)
- $K^+ \pi^-$ produce secondary vertex ($\chi^2 < 49$)
- $|M(K^+\pi^-) - M_{PDG}(K^{*0})| < 60$ MeV/c^2
- $E_T(\gamma) > 2.8$ GeV (close to L0 trigger requirement)
- $2.2 < E^*_T(\gamma) < 2.7$ GeV
- Select primary vertex with minimum IP of B^0 candidate
- Require B^0 momentum and flight direction to be consistent ($\theta_B < 6$ mrad)
- K^{*0} helicity angle: in K^{*0} rest frame $|\cos(p_B, p_K)| < 0.7$

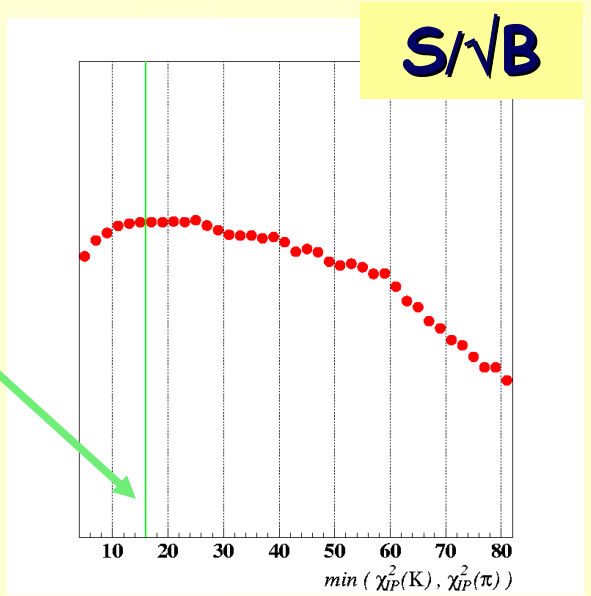
Background suppression (1)

- Require large IP of K^+, π^- to all reconstructed primary vertex ($\chi^2_{IP} > 16$)
  - suppress primary tracks
  - especially effective background suppression in events with multiple interactions

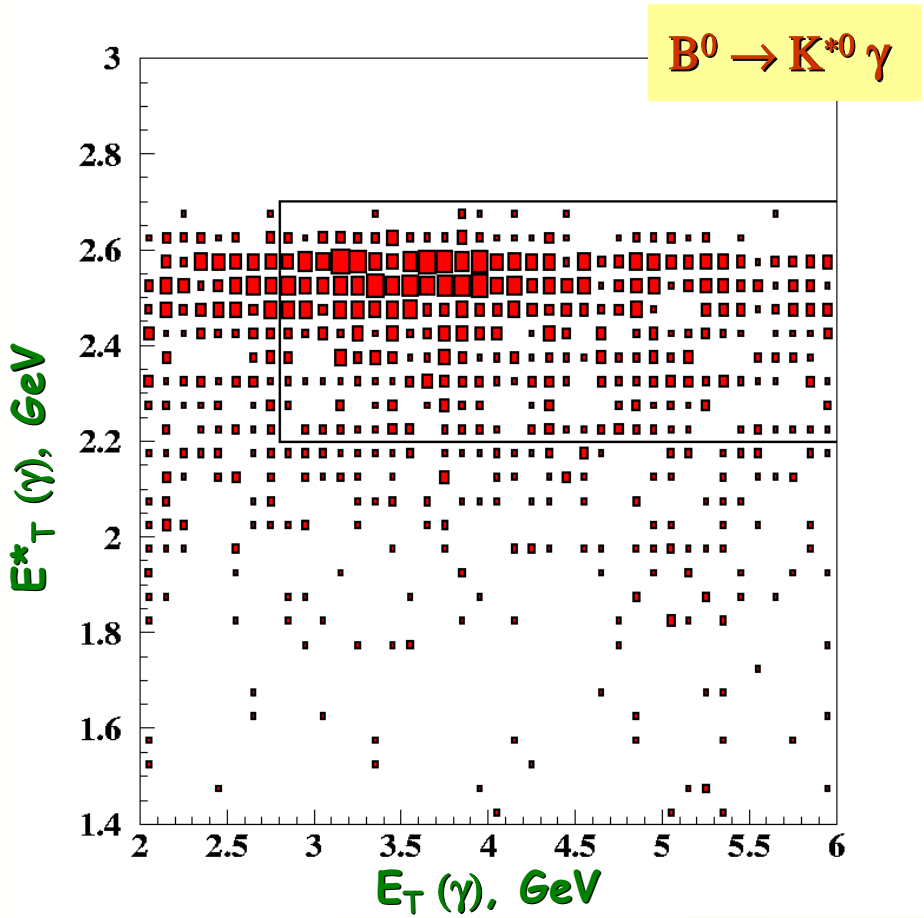


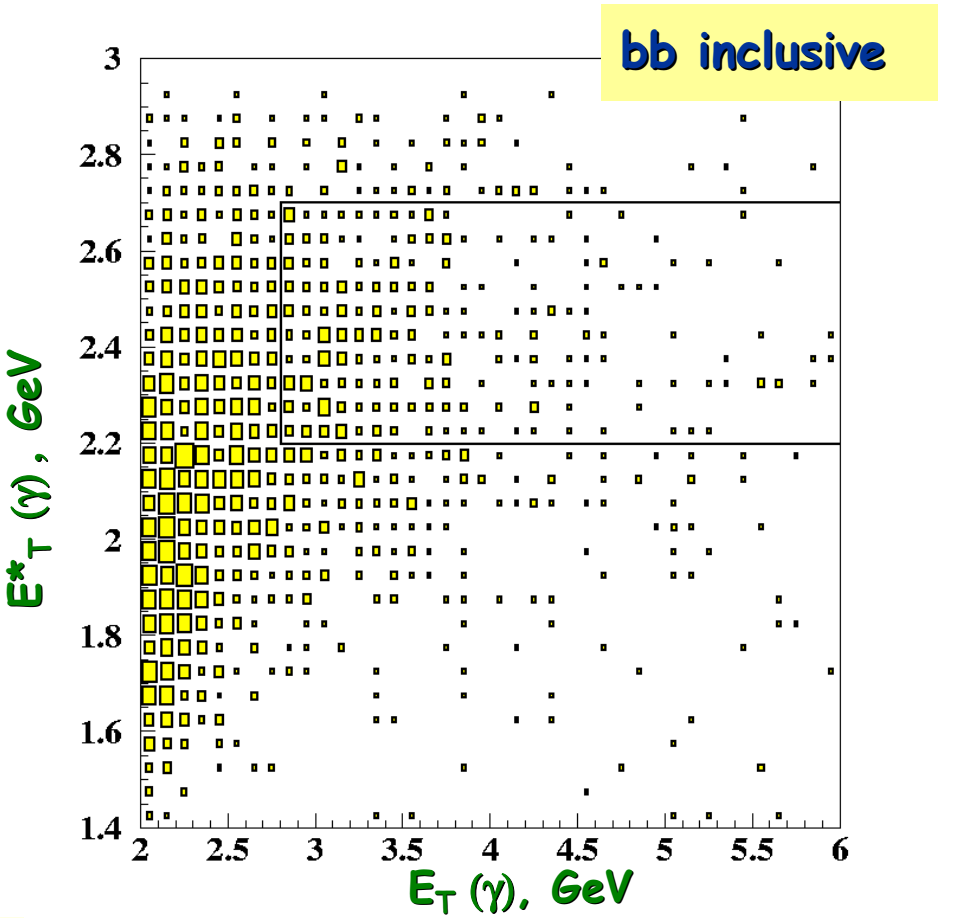
No χ^2_{IP} cut

optimized $\chi^2_{IP} > 16$



Background suppression (2)



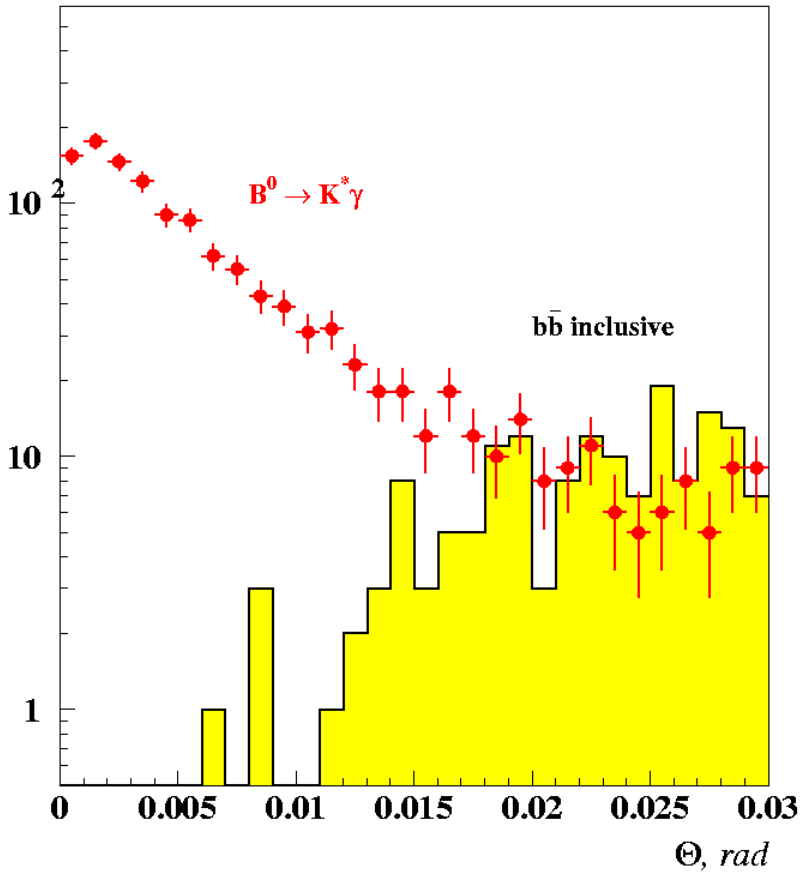


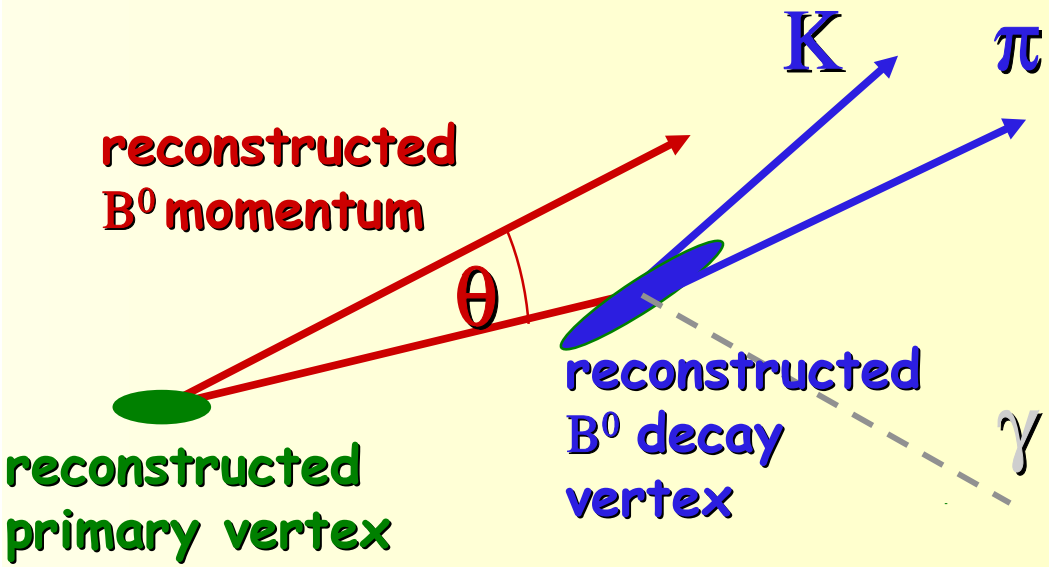
Transverse energy $E^*_T(\gamma)$ in B^0 rest frame vs $E_T(\gamma)$ in the lab frame

$E_T(\gamma) > 2.8$ GeV powerful against low energy γ and π^0

$2.2 < E^*_T(\gamma) < 2.7$ GeV rejects also soft K^{*0} candidates

Background suppression (3)





One of the most powerful cut!

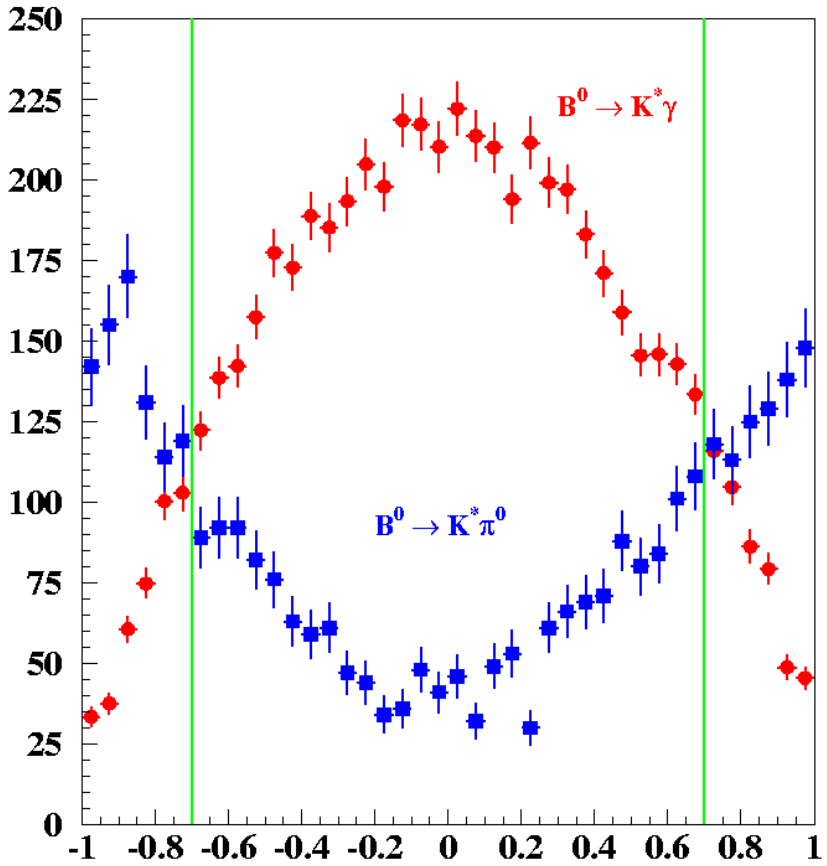
$\varepsilon_{signal} \sim 60\%$; $\varepsilon_{bb} < 1\%$

Angle θ between B^0 momentum and B^0 flight direction

- should be 0 for real B^0 candidates (smeared by $K\pi$ vertex resolution)
- randomly distributed for combinatorial background

π^0 suppression

K^{*0} helicity:
in K^{*0} rest frame cos (p_B, p_K)



Significant suppression of fast π^0 is expected after application of special algorithm for γ / π^0 separation based on shower shape
(to be implemented soon)

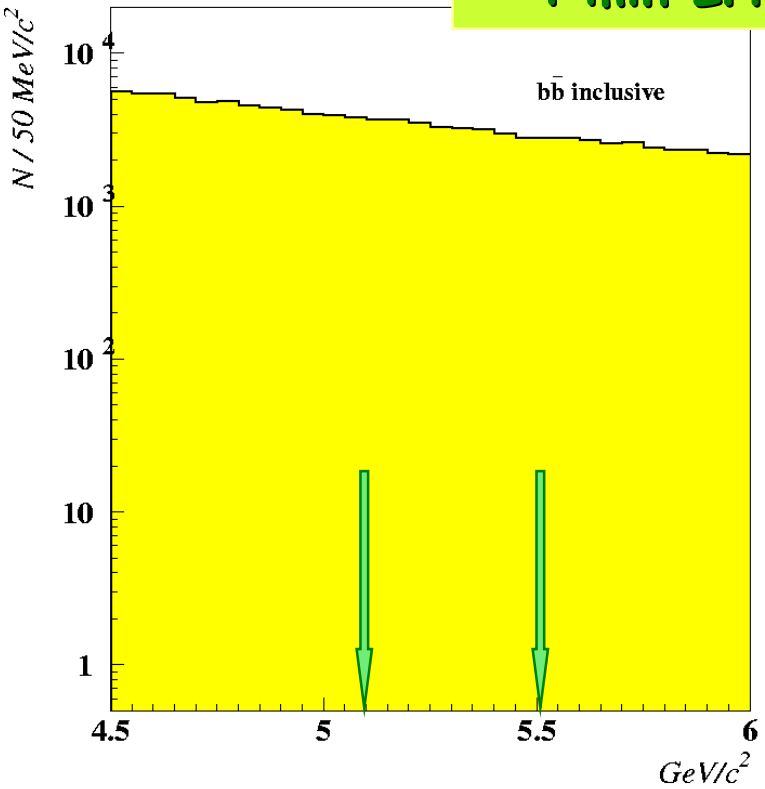
Contribution from $B^0 \to K^{*0}\pi^0$ is small and can be further suppressed exploiting K^{*0} polarization :

K^{*0} helicity states

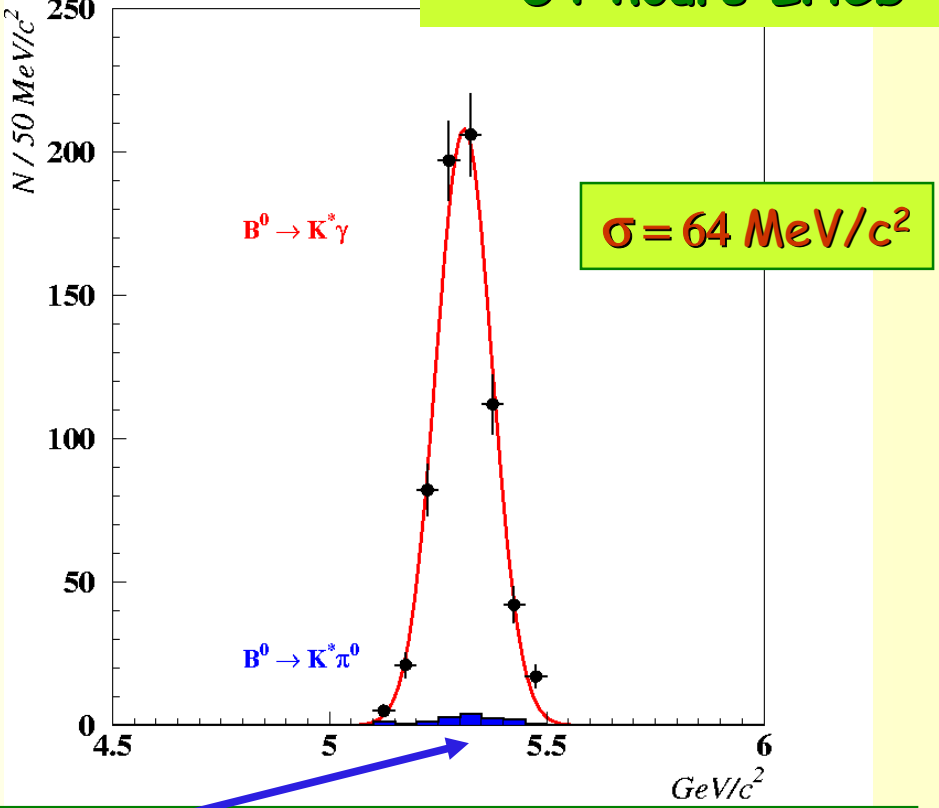
	0	$B^0 \to K^{*0}\pi^0$
+1	−1	$B^0 \to K^{*0}\gamma$

$B^0 \to K^{*0}\gamma$: signal and background summary

~ 4 min LHCb



~ 54 hours LHCb



0 events

in (4.5-6.0) GeV/c^2 mass window
after trigger and off-line selection
with all available MC statistics
~ 10.3 M events

In blue: contribution from $B^0 \to K^{*0}\pi^0$ after trigger and off-line cuts

$< 2.2\%$ of $B^0 \to K^{*0}\gamma$

Br ($B^0 \to K^{*0}\pi^0$) $< 3.6 \cdot 10^{-6}$ PDG 2003

$B^0 \to K^{*0}\gamma$: Annual yield and CP sensitivity

Efficiency, [%]				N_{year}	$\sigma(A_{CP})$
Reconstruction & acceptance	selection	trigger	total		
4.5	9.2	38	0.16	35 K	< 0.01
BACKGROUND / SIGNAL < 0.7 @ 90 % CL					
Assuming: Br ($B^0 \to K^{*0}\gamma$) = (4.3 ± 0.4) × 10^{-5} f ($\bar{b} \to B^0$) = 0.39					

$$A_{CP} = \frac{N(B^0 \to K^{*0}\gamma) - N(\bar{B}^0 \to \bar{K}^{*0}\gamma)}{N(B^0 \to K^{*0}\gamma) + N(\bar{B}^0 \to \bar{K}^{*0}\gamma)}$$

$B^0_s \to \phi\gamma$ reconstruction

Two different tasks

- **Branching ratio measurement**

  similar to $B^0 \to K^{*0}\gamma$ reconstruction:

  - Tracks are consistent with K^+ & K^- hypothesis
  - Reject K^+ , K^- tracks from all primary vertices ($\chi^2_{IP} > 4$)
  - K^+K^- produce secondary Vertex ($\chi^2 < 49$)
  - $|M(K^+K^-) - M_{PDG}(\phi)| < 10$ MeV/c^2
  - $E_T(\gamma) > 2.8$ GeV (close to LO trigger requirements)
  - $2.0 < E^*_T(\gamma) < 2.7$ GeV
  - Select primary vertex with minimum IP of B^0_s candidate
  - B^0_s momentum and flight direction to be consistent

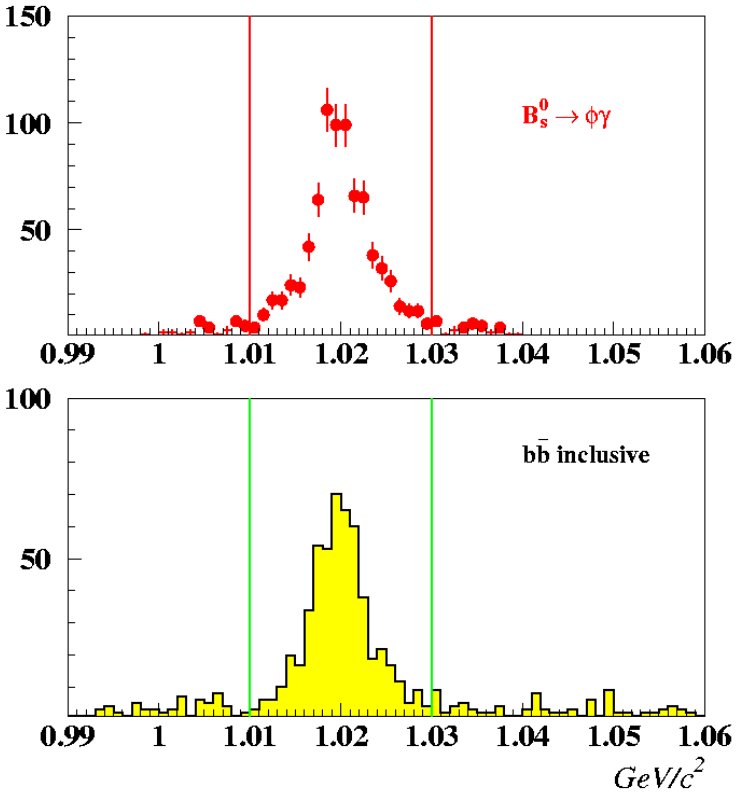
    $\theta_B < 12$ mrad (worse B^0_s vertex resolution)
  - ϕ helicity : in ϕ rest frame $|\cos(p_B, p_K)| < 0.7$

- **Search for mixing-induced CP:**

  selection to be re-optimized

$B^0_s \to \phi\gamma$: background suppression

M ($K^+ K^-$)



After LOxL1 trigger & off-line cuts

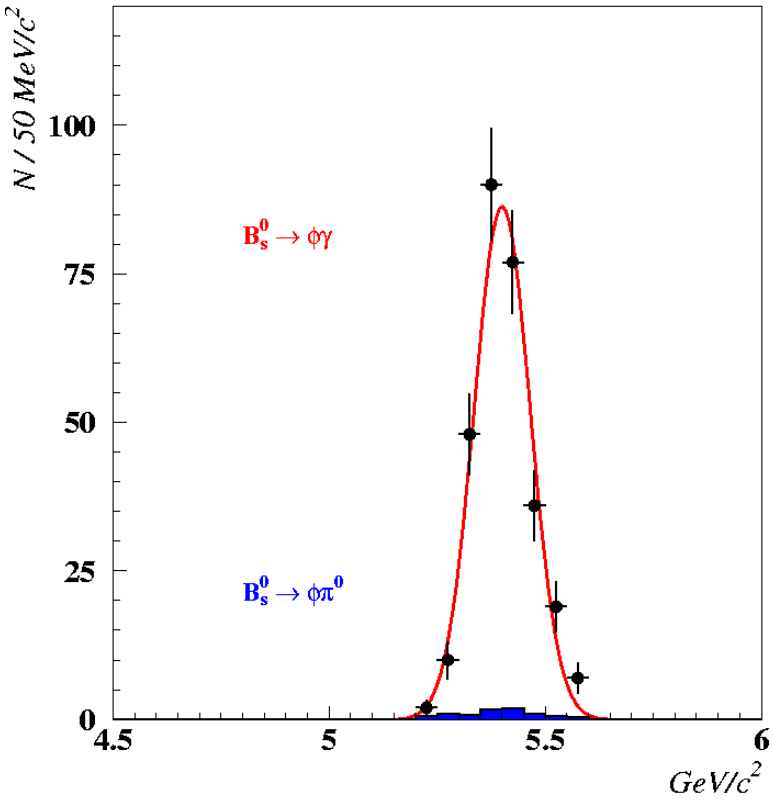
bb inclusive: 0 event
in mass window (4.5 – 6.0) GeV/c^2
from ~ 10.3 M events (~ 4 min LHCb)

$N(B^0_s \to \phi\pi^0) / N(B^0_s \to \phi\gamma) < 4\%$
assuming
$Br(B^0 \to K^{*0}\pi^0) = Br(B^0_s \to \phi\pi^0) < 3.6 \cdot 10^{-6}$

$\Gamma_\phi << \Gamma_{K^{*0}}$: narrow $\Delta M(\phi) < 10$ MeV/c^2
Background is mainly due to real ϕ
Fortunately small ϕ yield from B decays.

$B^0_s \to \phi\gamma$ after trigger and off-line cuts

~ 87 hours LHCb



$\sigma = 64$ MeV/c²

Efficiency [%]				N_{year}
reconstr. & accept.	selection	trigger	total	
4.3	15	34	0.22	9.4 K

BACKGROUND / SIGNAL < 2.4 90 % CL

limited by MC statistics, expected to be better

Assuming:

Br $(B^0_s \to \phi\gamma) = (4.3 \pm 0.4) \times 10^{-5}$

$f(\bar{b} \to B^0_s) = 0.10$

Search for mixing induced ~~CP~~ in $B^0_S \to \phi\gamma$

Main problem:

Proper time resolution is critical:

- dominated by poor $\phi \to K K$ vertex resolution $\Rightarrow$ kaons are almost collinear

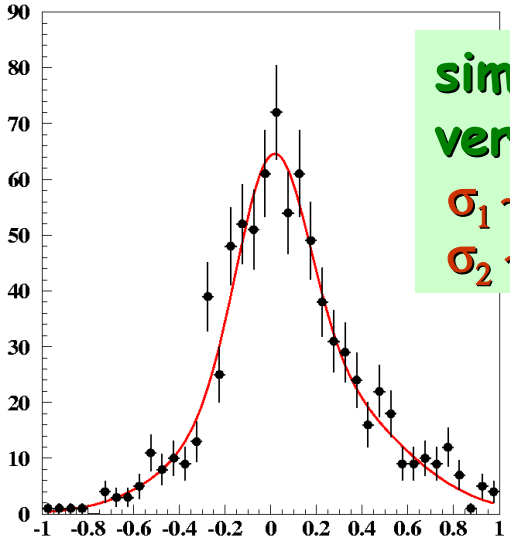
- no extra information on B^0_s vertex from γ

Improvement can be achieved:

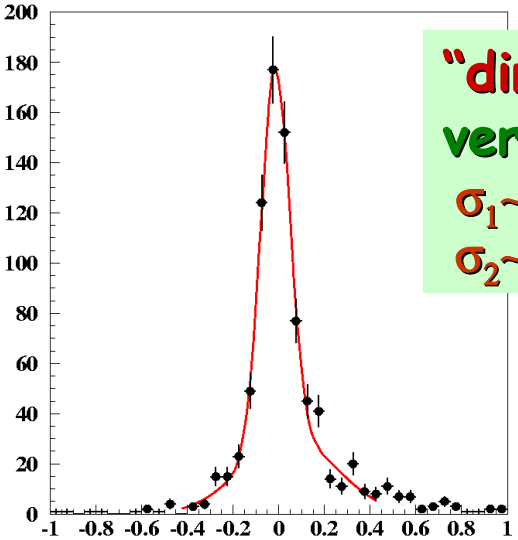
- Constrain the B^0_s flight direction to B^0_s momentum: ("direction" vertex fit)
  Improve vertex resolution by factor > 2.5

- Select kinematical region with the better vertex (proper time) resolution: (slow $\phi \Rightarrow$ larger $K K$ opening angle)

$B^0_S \to \phi\gamma$ proper time resolution



simple vertex fit
$\sigma_1 \sim 160$ fs (40%)
$\sigma_2 \sim 380$ fs(60%)

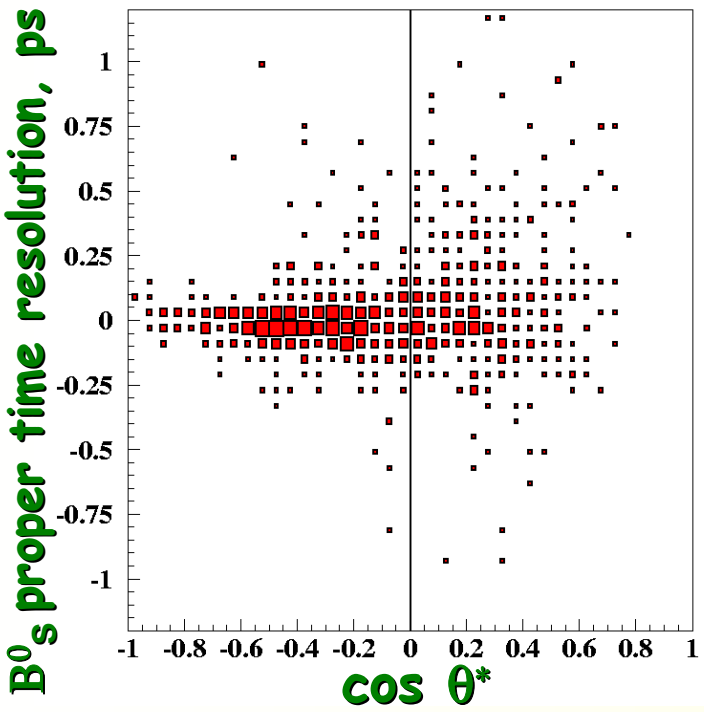


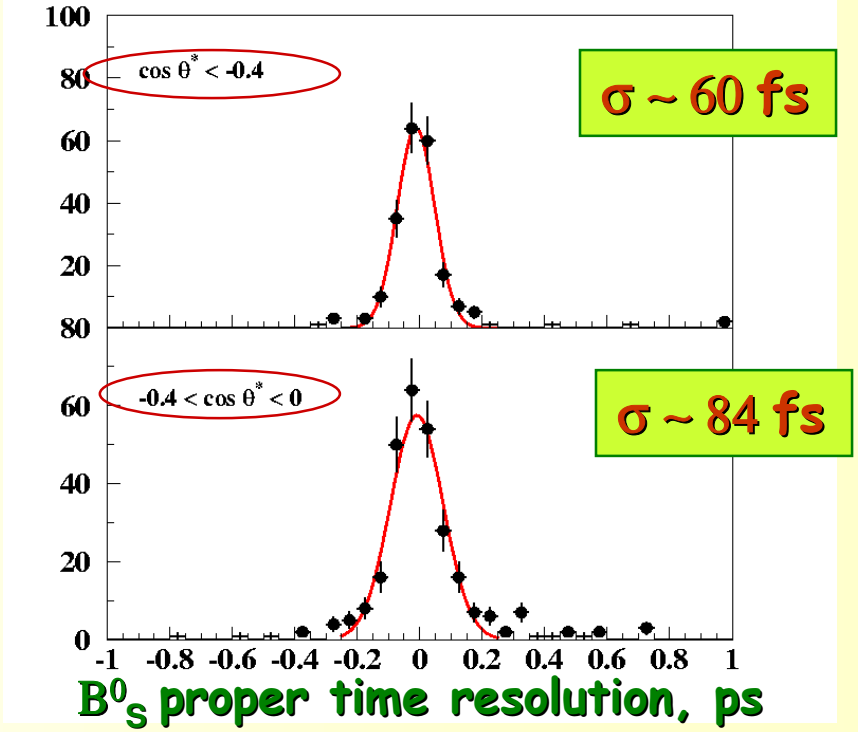
"direction" vertex fit
$\sigma_1 \sim 62$ fs (60%)
$\sigma_2 \sim 200$ fs (40%)

$B^0_s \to \phi\gamma$ lifetime resolution

cuts re-optimization for CP violation study

Decay angle θ^* (between ϕ momentum in rest frame of B^0_s and B^0_s flight direction) is convenient variable to select the kinematical region that provides the better proper time resolution





Require: $\cos\theta^* < 0$,
$E_T(\gamma) > 3.2$ GeV, tighter cut
No cut $E^*_T(\gamma)$

Achieved lifetime resolution is close to those for charged modes. Estimation of CP violation sensitivities is in progress

Conclusion

$B^0 \to K^{*0}(K^+\pi^-)\ \gamma$

- record statistical sensitivity in direct CP violation
  $\sigma(A_{CP}) < 0.01$ for one year LHCb. Stringent test of SM extensions!
- systematic errors to be studied carefully

$B^0_S \to \phi(K^+K^-)\gamma$

- precise measurement of the branching fraction
  with ~2% accuracy for one year LHCb
- For indirect CP violation B^0_S proper time resolution is critical
  - advanced fit vertex procedure and dedicated cut optimization allow to hope on reasonable sensitivity

Others channels of interest

- $B^0 \to \omega(\pi^+\pi^-\pi^0)\gamma$ — $|V_{td}/V_{ts}|$
- $B \to K^{**}\gamma$ — direct CP violation
- $B^0 \to K^{**}(1430)\,(K^0_s\rho^0)\gamma$ — mixing-induced CP violation
- $B^0 \to \mu^+\mu^-\gamma$ — why not?

under study