$B \to K^{(*)}\nu\nu$ at Belle II

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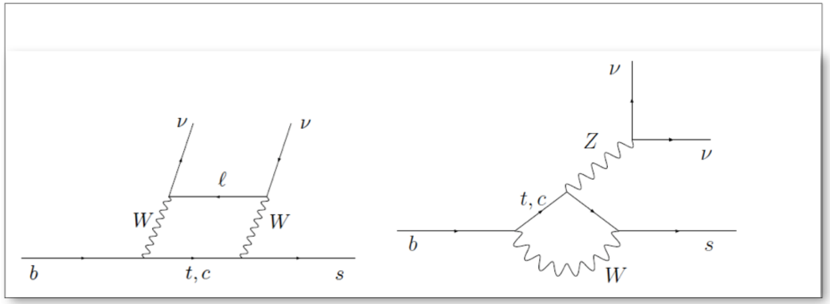
THEORETICAL AND EXPERIMENTAL STATUS

$B \to K^{(*)}\nu\nu$: theoretical motivations

- SM predictions ([1] JHEP 02 184,2015) updated in D. M. Straub, BELLE2-MEMO-2016-007([2]):

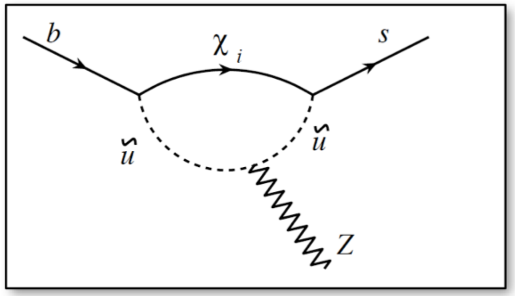
TABLE I: SM $B \to K^{(*)}\nu\bar{\nu}$ branching fractions.

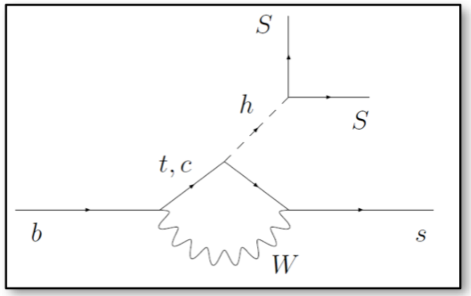
Mode	$\mathcal{B}$ $[10^{-6}]$ Ref. [2]	$\mathcal{B}$ $[10^{-6}]$ Ref. [1]
$B^+ \to K^+\nu\bar{\nu}$	$3.98 \pm 0.43 \pm 0.19$	4.68 ± 0.64
$B^0 \to K^0_S\nu\bar{\nu}$	$1.85 \pm 0.20 \pm 0.09$	2.17 ± 0.30
$B^+ \to K^{*+}\nu\bar{\nu}$	$9.91 \pm 0.93 \pm 0.54$	10.22 ± 1.19
$B^0 \to K^{*0}\nu\bar{\nu}$	$9.19 \pm 0.86 \pm 0.50$	9.48 ± 1.10

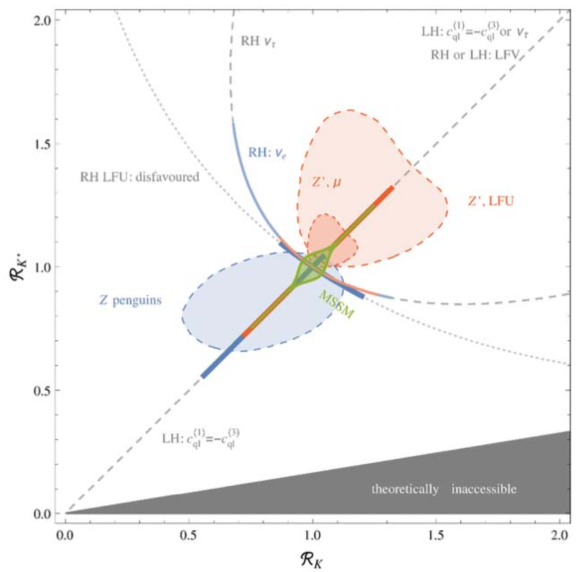


$R_{K(*)}$ = $B \to K^{(*)}\nu\nu$ BR normalized to SM expectations [JHEP 02 184,2015]

- NP effects:
  - non standard Z-couplings
  - new sources of missing energy

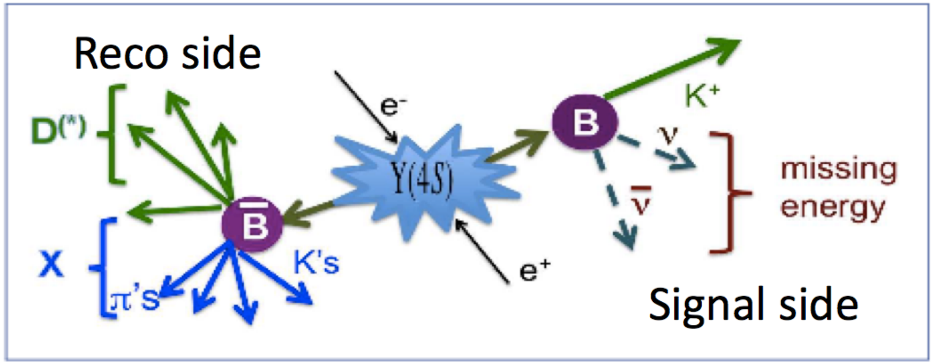






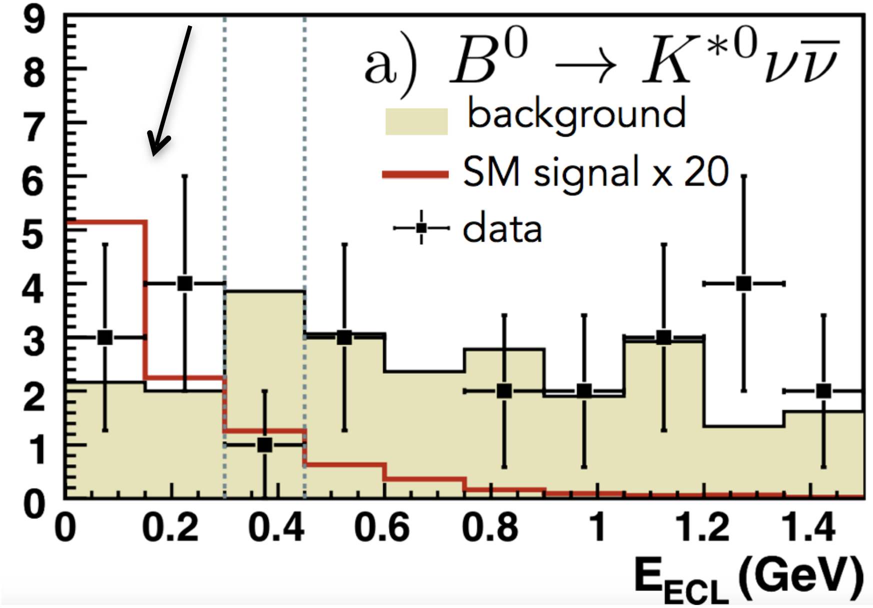
$B \rightarrow K^{(*)}\nu\nu$: experimental search (I)

- Recoil method:
  - reconstruct semileptonic or hadronic B decays on one side
  - look for K/K* + missing energy on the rest of the event (and ~ nothing else)



- Suppress qq and combinatoric BB background by using kinematic and event shape variables
- Crucial ingredients:
  - detector hermeticity and performing tracking: veto extra-tracks, low (→0) extra-energy in the calorimeter
  - particle identification: suppression of events with mis-identified K/π on both Reco and Signal sides
- Signal extraction: cut or fit to E_{ECL} distribution (extra-energy in the calorimeter)

here, signal region: E_{ECL}<300 MeV



[Belle, PRL 99 221802, 2007]

$B \to K^{(*)}\nu\nu$: experimental search (II)

- Most recent experimental results:
  - Belle search for $B \to h^{(*)}\nu\nu$; 0.711 ab^{-1} [PRD RC 87, 111103(2013)]

Mode	Upper limit
$B^+ \to K^+\nu\bar{\nu}$	$< 5.5 \times 10^{-5}$
$B^0 \to K^0_s\nu\bar{\nu}$	$< 9.7 \times 10^{-5}$
$B^+ \to K^{*+}\nu\bar{\nu}$	$< 4.0 \times 10^{-5}$
$B^0 \to K^{*0}\nu\bar{\nu}$	$< 5.5 \times 10^{-5}$

SM exp (10^{-5})
~ 1
~1

  - BaBar search for $B \to K^{(*)}\nu\nu$; 0.429 ab^{-1} [PRD 87, 112005(2013)]

$BF(B^+ \to K^+\nu\bar{\nu})$	$< 1.6 \times 10^{-5}$
$BF(B^0 \to K^0\nu\bar{\nu})$	$< 4.9 \times 10^{-5}$
$BF(B \to K\nu\bar{\nu})$	$< 1.7 \times 10^{-5}$
$BF(B^+ \to K^{*+}\nu\bar{\nu})$	$< 6.4 \times 10^{-5}$
$BF(B^0 \to K^{*0}\nu\bar{\nu})$	$< 12.0 \times 10^{-5}$
$BF(B \to K^{*}\nu\bar{\nu})$	$< 7.6 \times 10^{-5}$

SM exp (10^{-5})
~ 0.4
~ 0.2

~ a factor of 4-5 between exp and SM for K^+, K^{*+}, and K^{*0} channels

B→K(*)νν: perspectives at Belle-II

- First extrapolation in BELLE2-MEMO-2016-008, assuming:
  - similar background to Belle
  - hadronic analysis: 100% higher B_{tag} reco efficiency, 30% higher K_S reco efficiency
  - SM predictions from BELLE2-MEMO-2016-007

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\rm Backg.}$ 711 fb^{-1} Belle	$N_{\rm Sig-exp.}$ 711 fb^{-1} Belle	$N_{\rm Backg.}$ 50 ab^{-1} Belle II	$N_{\rm Sig-exp.}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	4.68	5.68	21	3.5	2960	245	20%	22%
$B^0 \to K^0_S\nu\bar{\nu}$	2.17	0.84	4	0.24	560	22	94%	94%
$B^+ \to K^{*+}\nu\bar{\nu}$	10.22	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.48	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

- What's (will be) new:
  - exp side: sensitivity study performed with Belle-II full simulation, more reliable estimates of
    - background contamination: e.g. higher pile-up reduced → discriminant power of E_{ECL} (study and optimization of ECL performances ongoing)
    - signal efficiency: lower boost → higher hermeticity (lower bkg, higher eff.), improved tracking and particle identification

MC STUDIES on $B^+ \rightarrow K^{*+} \nu\nu$

Samples & reconstruction strategy

- SIGNAL SAMPLES:
  - 1002000 evts for BGx1 configs (private production with release-00-05-03)
  - generated and reconstructed channels: $K^{*+} \rightarrow K^{+}\pi^{0}$, $K_S\pi^{+}$
- GENERIC MC SAMPLES: (MC5 production, release-00-05-03) corresponding to 500 fb^{-1}

- Reconstruction strategy:
  - Hadronic tag side reconstructed with FEI algorithm[*]
    - multivariate technique to reconstruct hadronic B decay
    - hierarchical approach: different multivariate classifier, for final state particles, intermediate particles and hadronic B candidates
    - analysis-independent training
  - dedicated clustering cleaning and PID selection wrt official Belle2 FEI (see back-up for details)
  - B_{tag} signal probability (goodness of hadronic B reconstruction) > 1%
  - Number of tracks not associated to B_{sig} nor to B_{tag} (# extra tracks) = 0
  - Best Υ candidate selected according to highest B_{tag} signal probability and K* with smallest $|m_{K^*,reco}-m_{K^*,PDG}|$

[*]https://ekp-invenio.physik.uni-karlsruhe.de/record/48602/files/EKP-2015-00001.pdf

Selection strategy

- Apply pre-selection cuts on B_{tag} kinematics:
  - $M_{bc} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$
  - $\Delta E = E^{*}_{B} - E^{*}_{beam}$

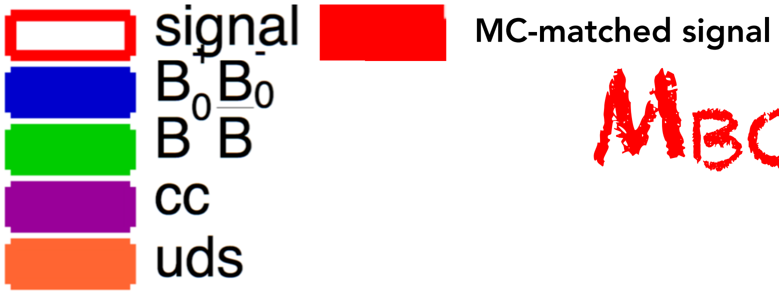
- Optimize cuts using S/sqrt(B) as figure of merit on:
  - R2: event shape variable for continuum suppression [PhysRevLett.41.1581]
  - strange meson reconstruction: m_{KS}, m_{K*}

- Apply cuts on $\cos^*\theta_{miss}$, $cp^*_{miss}+E^*_{miss}$
  - with $P^*_{MISS} = P^*_{Y4S} - P^*_{Btag} - P^*_{K*}$

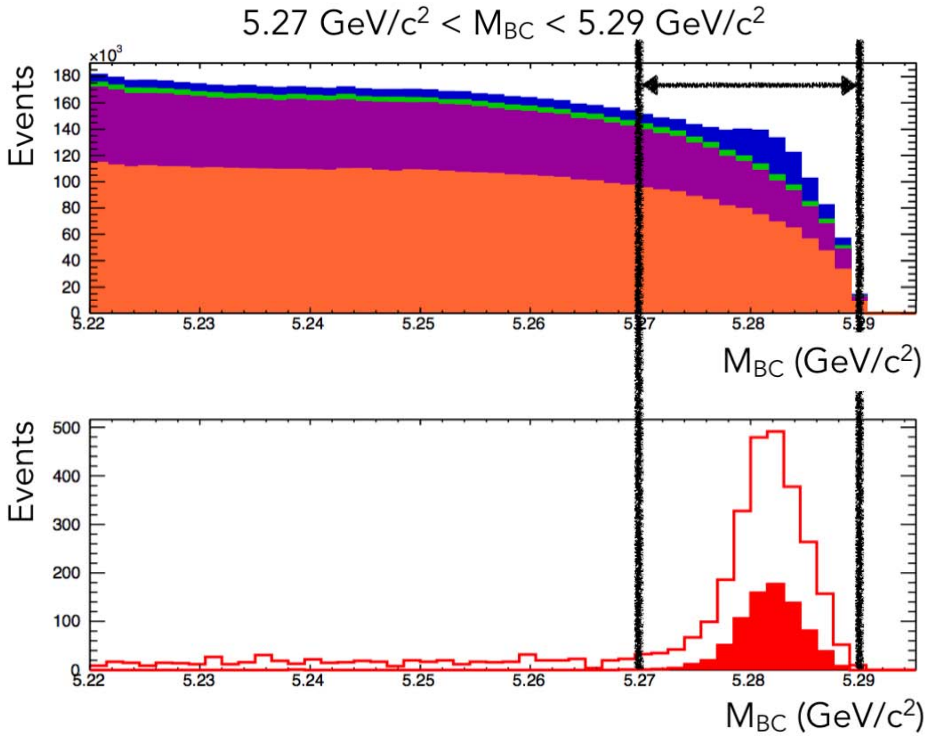
- Define a signal window on the extra energy deposited in the calorimeter, E_{ECL}, and evaluate signal efficiency and expected number of background events

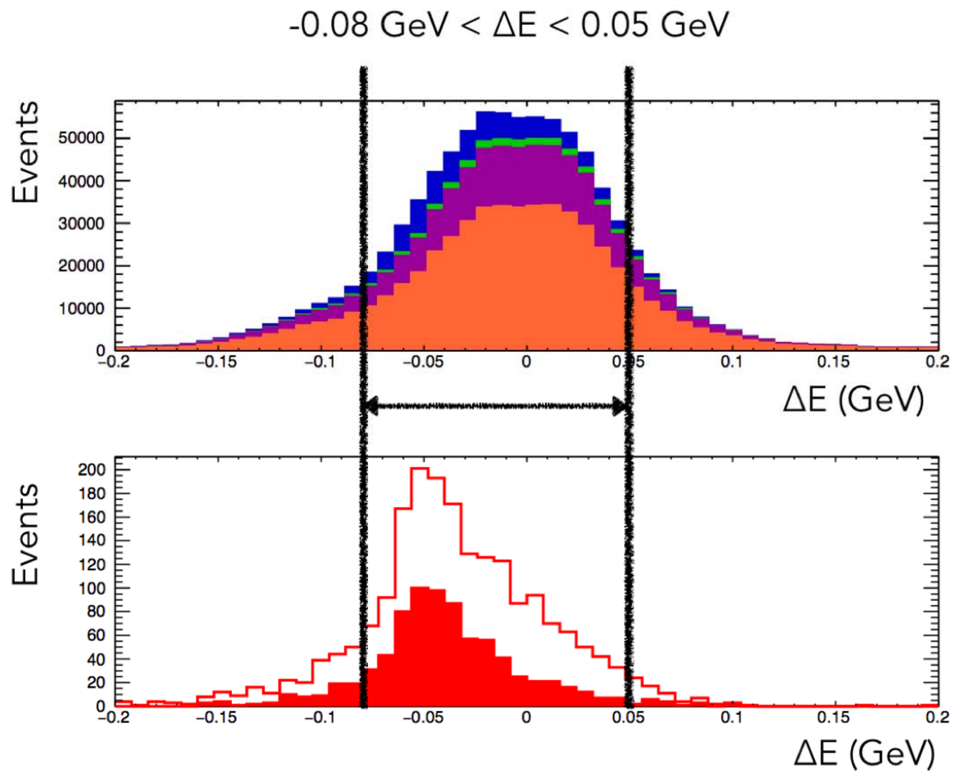
- Estimate Upper Limit @ 90% C.L. with Bayesian approach

- In all plots shown: generic yield corresponding to 500 fb^{-1}, arbitrary normalization for signal MC

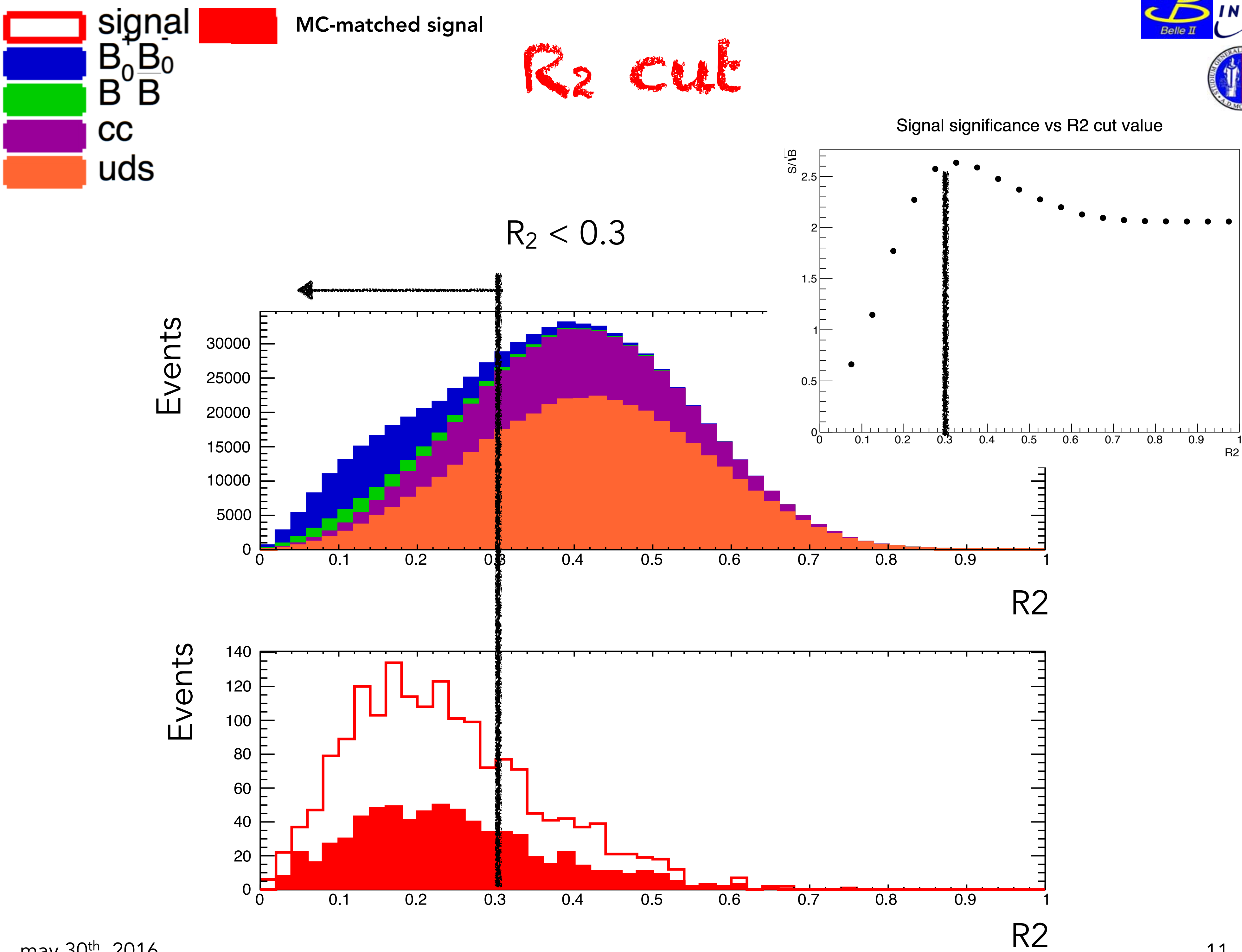

signal
MC-matched signal
B^+B^-
$B^0\bar{B}^0$
cc
uds

M_{BC} & ΔE cut

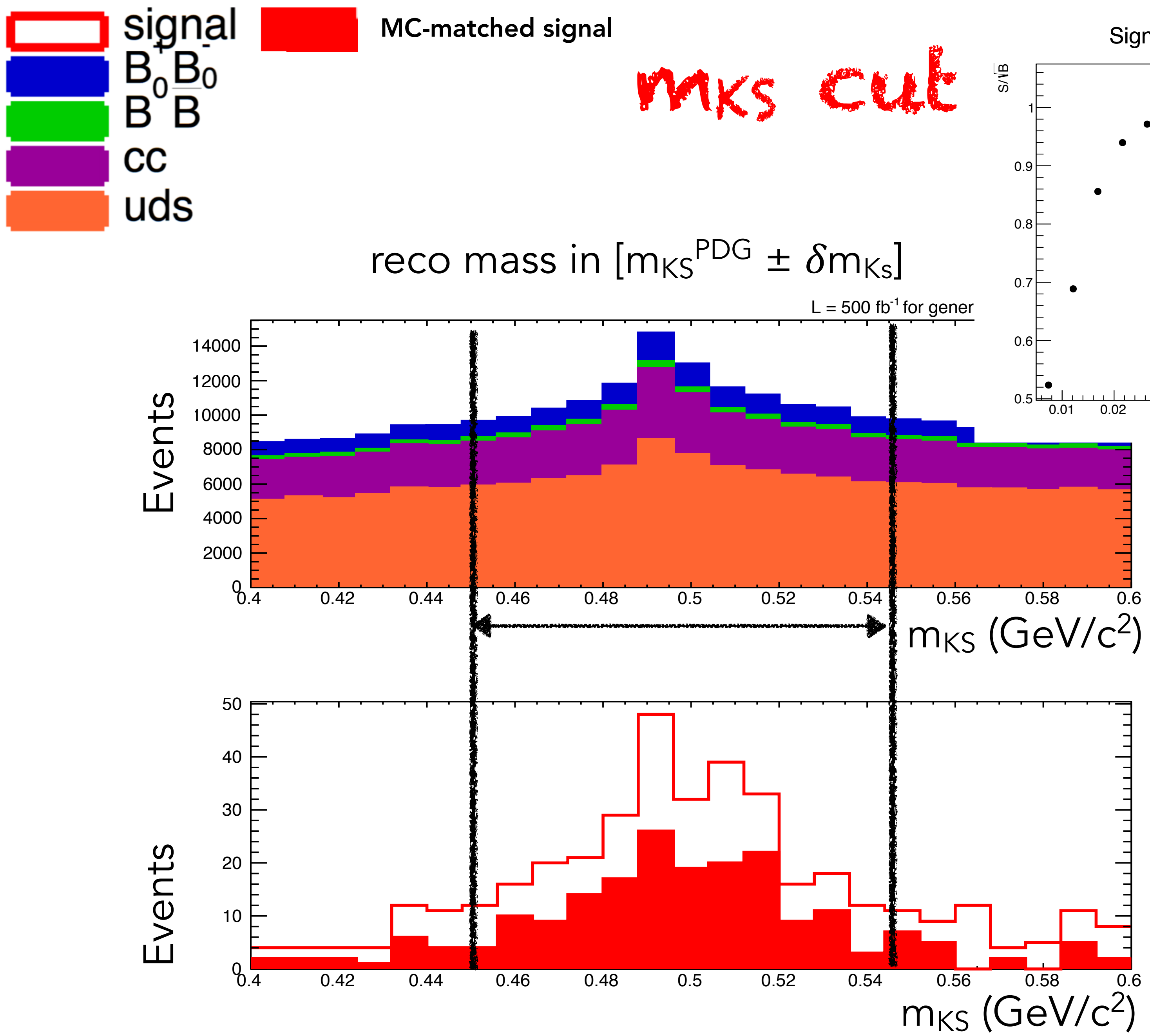

5.27 GeV/c² < M_{BC} < 5.29 GeV/c²
Events
$\times 10^3$
M_{BC} (GeV/c²)
Events
M_{BC} (GeV/c²)

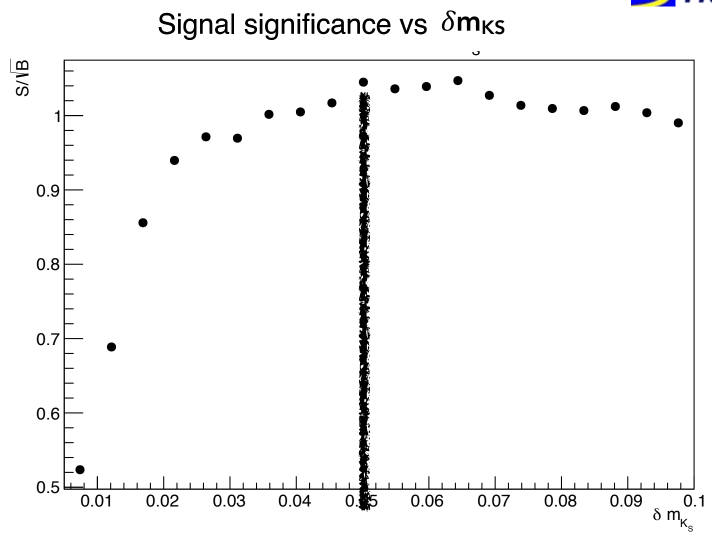

-0.08 GeV < ΔE < 0.05 GeV
Events
ΔE (GeV)
Events
ΔE (GeV)

R2 cut


signal
MC-matched signal
uds
R2 < 0.3
Events
R2
Signal significance vs R2 cut value
S/√B

m_{KS} cut





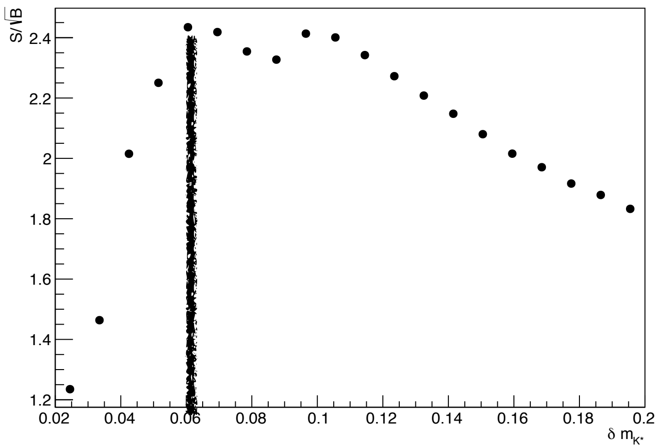
$K^{*+} \rightarrow K_S\pi^+$ only

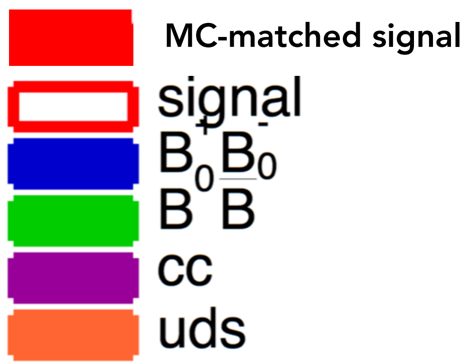
Very loose selection on K_S (no vertex fit applied), to be refined

m_{K^*} cut

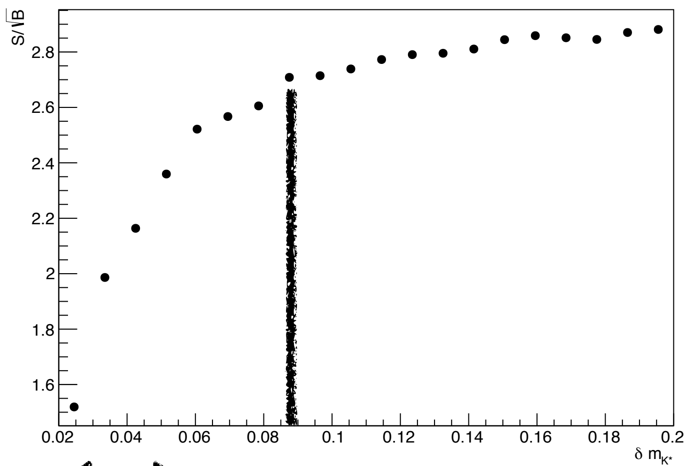
reco mass in $[m_{K^*}^{PDG} \pm \delta m_{K^*}]$

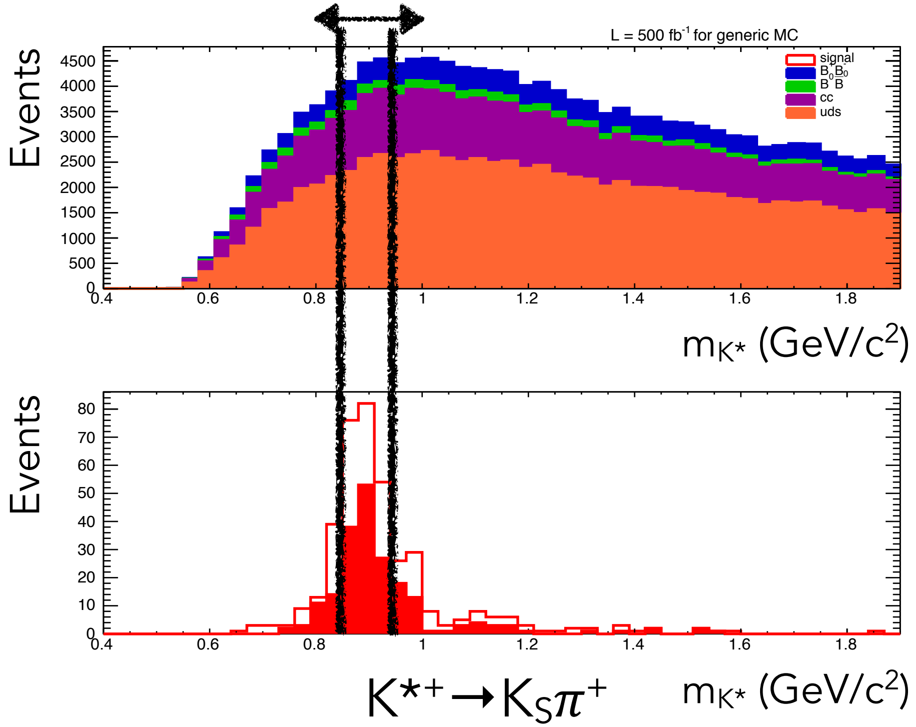
Signal significance vs δm_{K^*}



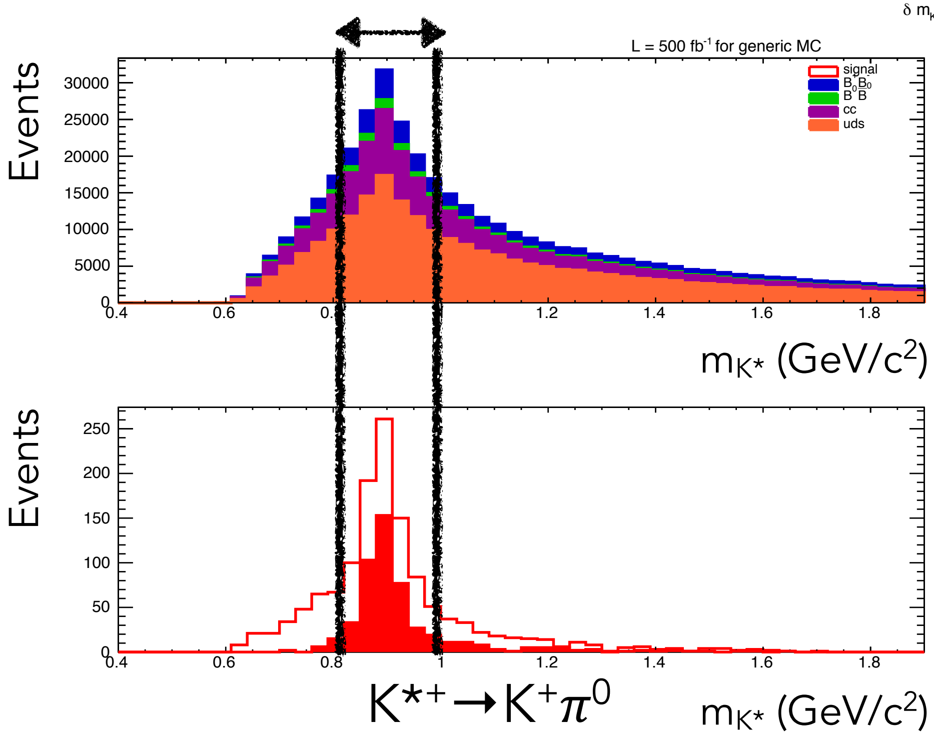


Signal significance vs δm_{K^*}





$K^{*+} \to K_S \pi^+$



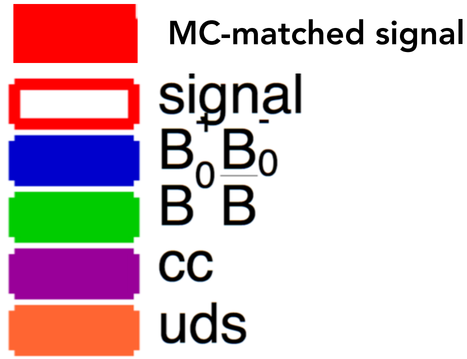
$K^{*+} \to K^+ \pi^0$

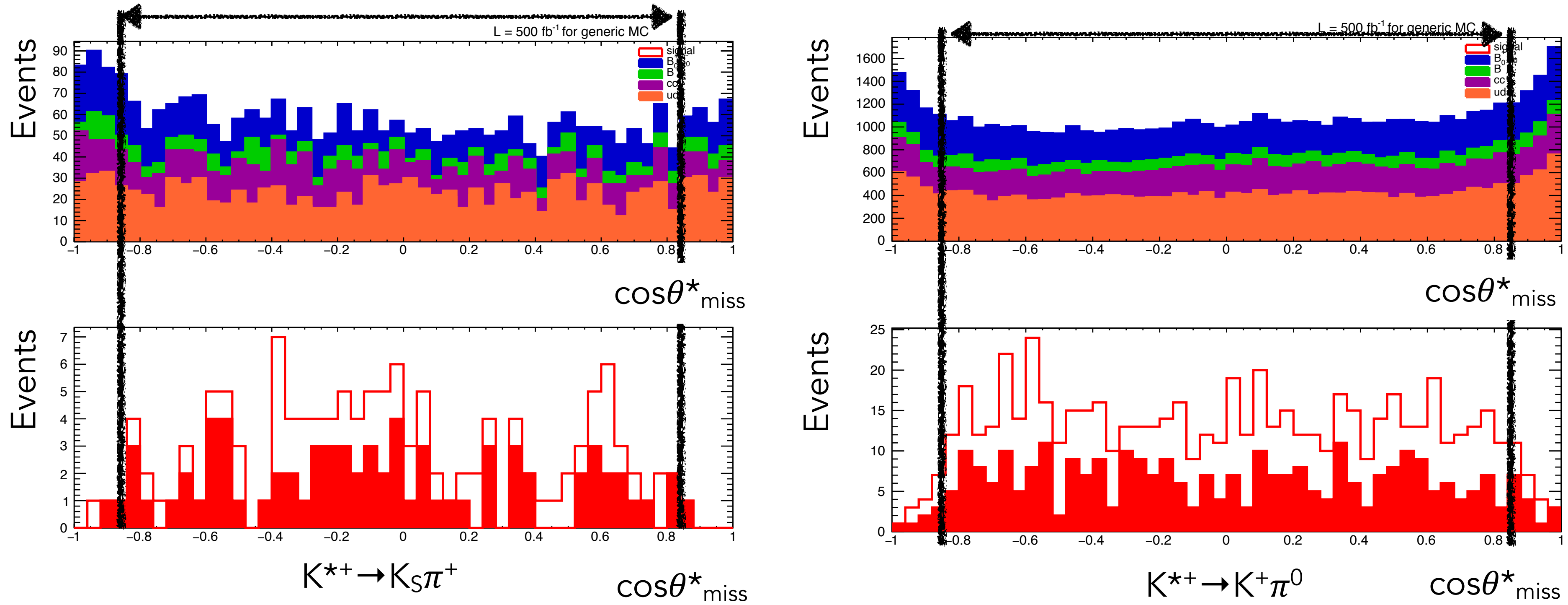
$\cos\theta^*_{miss}$ cut

- Missing momentum in CM frame:
  - $P^*_{MISS} = P^*_{Y4S} - P^*_{Btag} - P^*_{K^*}$
  - At reco level, # extra tracks = 0 is required

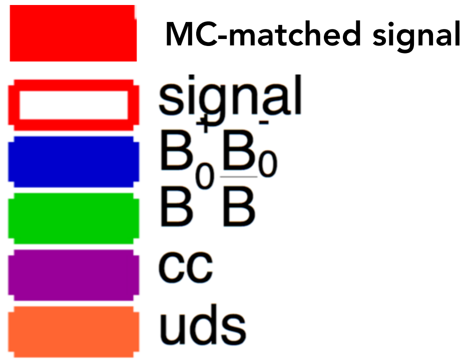
→missing momentum related to extra neutrals only

- Cut not optimized with significance scan: $\cos\theta^*_{miss} \in [-0.85, 0.85]$



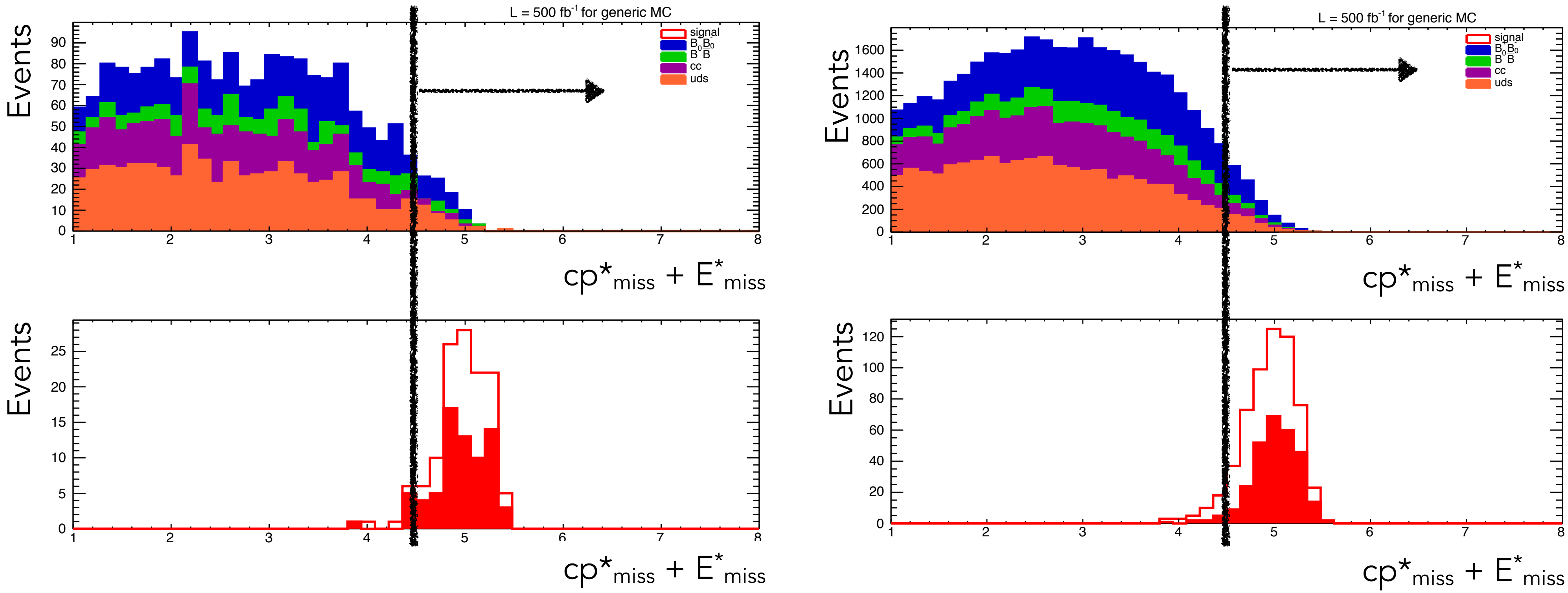


$cp^*_{miss} + E^*_{miss}$ (I)



- Cut not optimized with significance scan:

$$cp^*_{miss} + E^*_{miss} > 4.5 \text{ GeV}$$

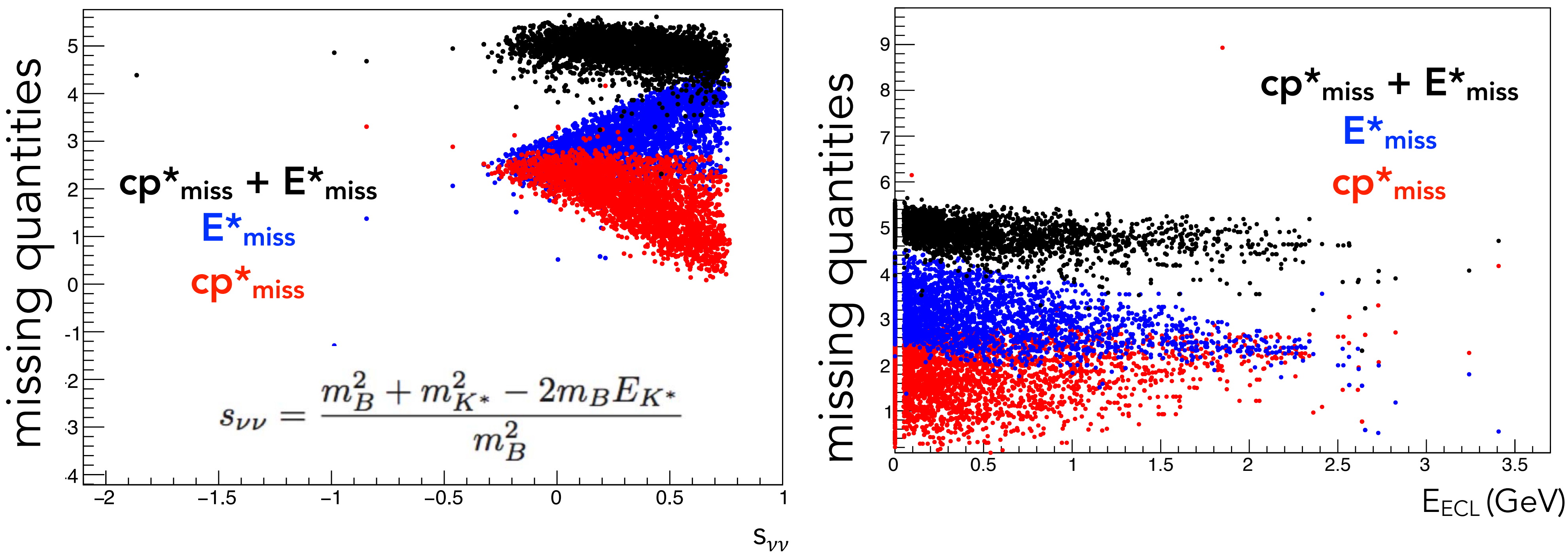


$K^{*+} \rightarrow K_S \pi^+$ $K^{*+} \rightarrow K^+ \pi^0$

cp^*_{miss} + E^*_{miss} (II)

- In order to have a model-independent analysis, variables correlated with $\nu\nu$ kinematics shouldn't be used (e.g. K* momentum)
- A 2-D fit to extra neutral energy & missing quantities can be use to extract signal and bkg yield, small correlation among the two variables is desirable

$K^{*+} \rightarrow K^+\pi^0$

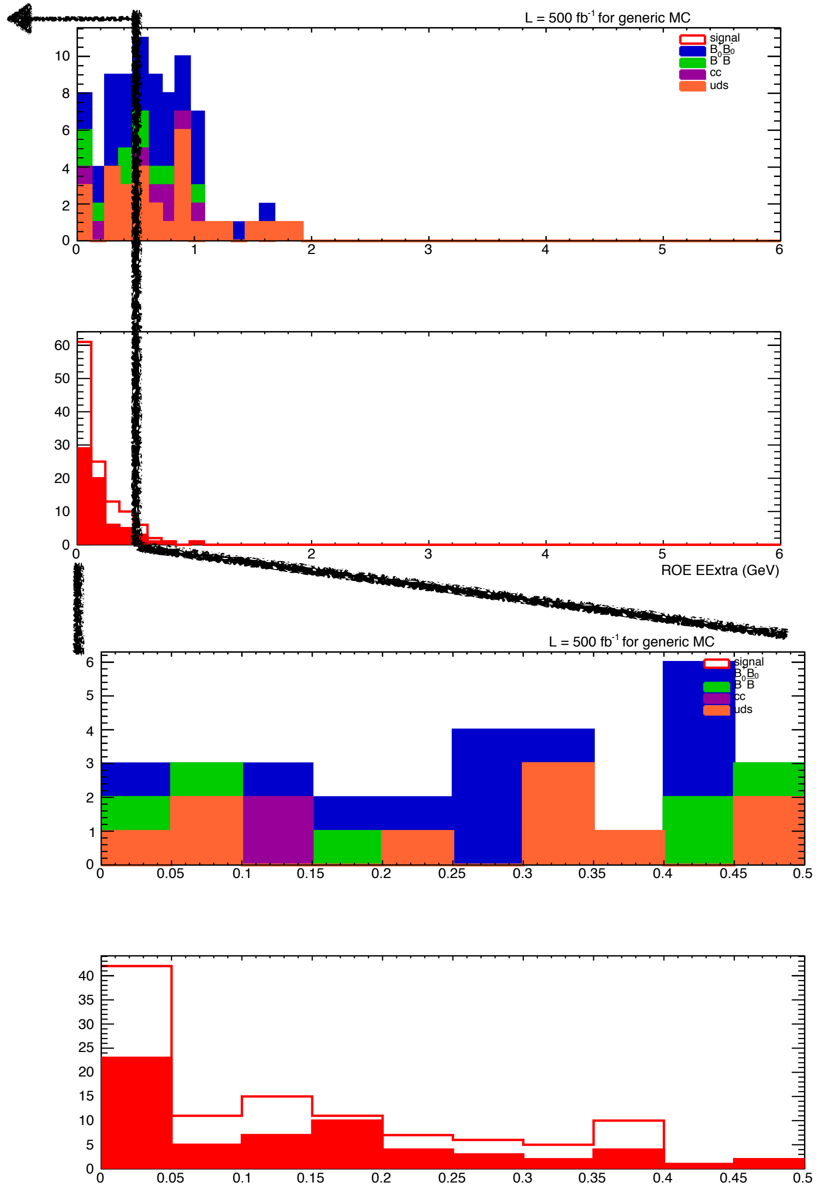


signal
$B_0\bar{B}_0$
B^+B^-
cc
uds

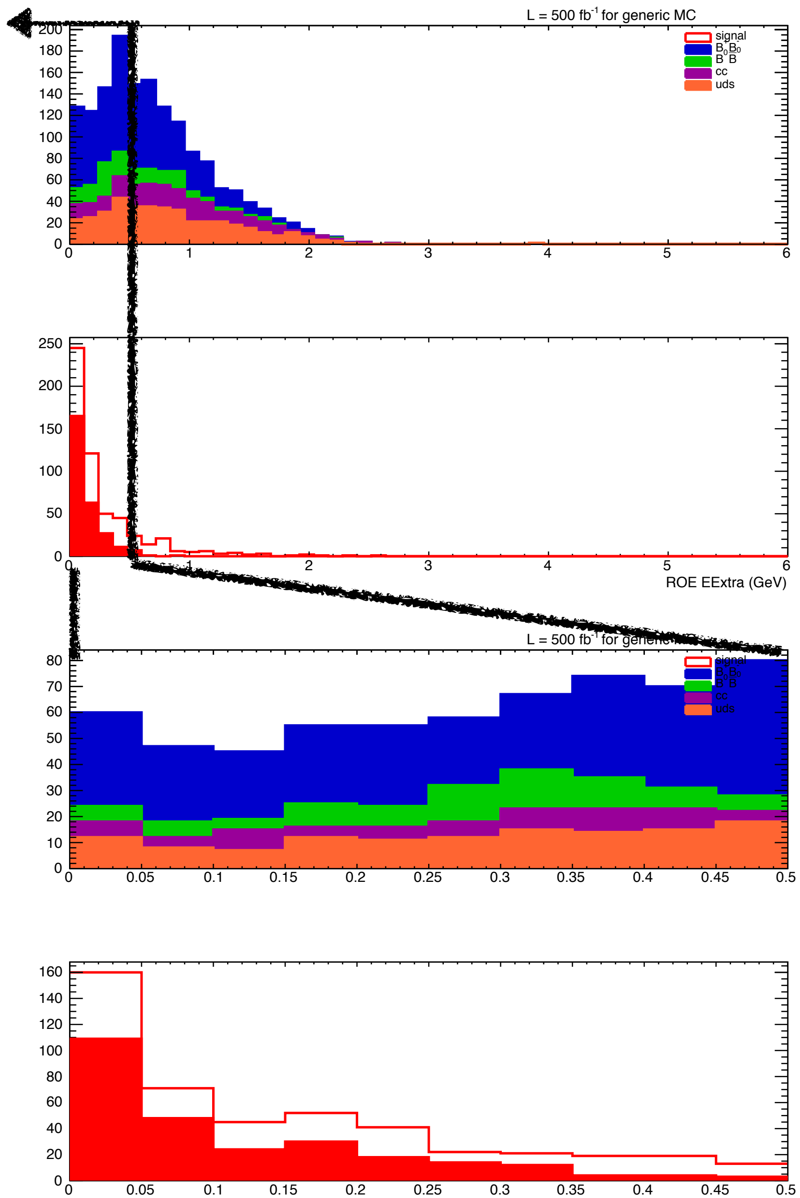
MC-matched signal

Extra neutral energy cut

Signal region: E_{ECL} <0.5 GeV



$K^{*+} \to K_S \pi^+$ E_{ECL} (GeV)



$K^{*+} \to K^+ \pi^0$ E_{ECL} (GeV)

Selection results and comparison with BaBar and Belle

	Current estimation	BaBar 2008 cut-and-count [*]	BELLE 2013 E_{extra} fit [PRD RC 87, 111103(2013)]
Lumi (fb^{-1})	500	413	711
expected background yield	$K_S\pi^+$:31 ± 6, $K^+\pi^0$: 609 ± 25	$K_S\pi^+$: 9 ± 5, $K^+\pi^0$:19 ± 9	
signal efficiency (10^{-4})	$K_S\pi^+$:1.1 ± 0.1, $K^+\pi^0$: 4.6 ± 0.2	$K_S\pi^+$: ~0.7, $K^+\pi^0$: ~1	1.47

- Statistical errors only
- Main differences between this and BaBar analysis:
  - tighter selection and reconstruction requirements (e.g. K_S and K* reconstruction)
  - no contamination from machine background in BaBar case

[*] NN fit results published for 2008 BaBar analysis (PRD 78, 072007(2008)), cut-and-count analysis in my PHD thesis

Upper limit estimation (I)

- Use Bayesian approach to estimate UL @ 90% C.L. with 500 fb^{-1}
- Inputs:
  - Uncertainties on BB yield at 1% level
  - Statistical uncertainties on signal efficiency and background estimation from this MC study
  - Systematic uncertainties on signal efficiency and background estimation from BaBar cut-and-count analysis

	Cut and Count		
K^* mode	$K^+\pi^0$	$K^0_S\pi^+$	$K^+\pi^-$
	Signal efficiency (%)		
MC statistics	3.5	4.1	3.1
Selection variables	3.4	7.0	6.0
Tracking	0.3	1.0	0.7
K^0_S reconstruction	–	2.5	–
π^0 reconstruction	3.0	–	–
Particle ID	1.5	–	1.6
Model dependence	6.7	6.8	7.2
Total	8.9	11.0	10.0
	Background yield (events)		
$N_{\rm bkg}$	9.0	4.1	2.5

- Correlation on systematic uncertainties among the two channels accounted for
- Relative systematic uncertainties on expected bkg yield at 50% level

Upper limit estimation

- At 500 fb^{-1}:
  - stat errors only: $BF(B \to K^{*+} \nu\nu) < 3.4 \times 10^{-4}$
  - stat & syst errors: $BF(B \to K^{*+} \nu\nu) < 4.4 \times 10^{-4}$
- Babar 2008 cut-and-count result (413 fb^{-1}):

$$BF(B \to K^{*+} \nu\nu) < 3.3 \times 10^{-4}$$

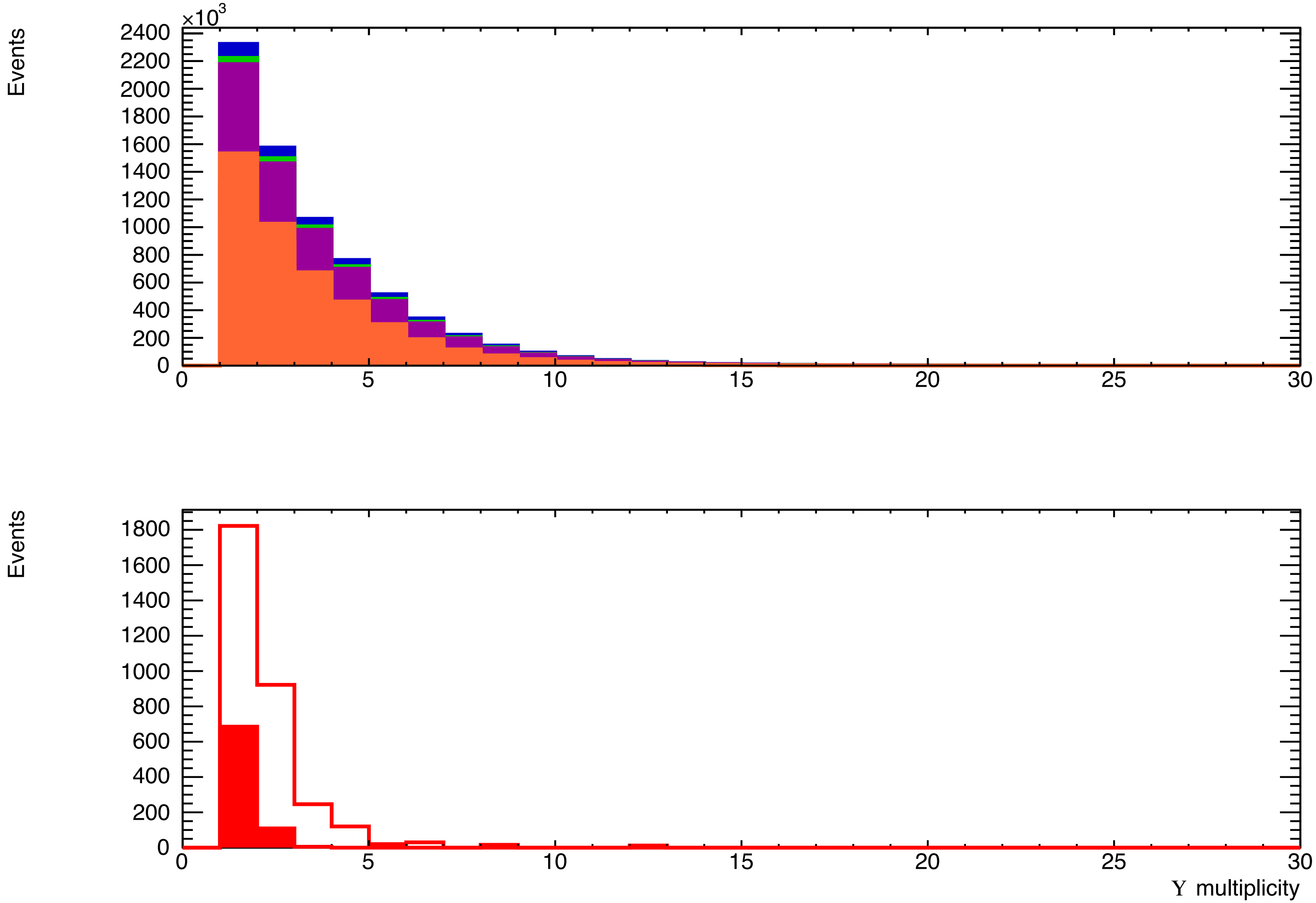
- Room for improvements:
  - refine K_S and K* reconstruction
  - refine background rejection (continuum suppression tools)
  - very conservative systematic error in background estimation applied here → fit to extract signal yield to be implemented

Conclusions

- Cut-And-Count analysis of Belle2 generic MC5 + private signal MC production performed
  - preselection on tag side variables
  - cut optimization for continuum rejection and strange meson masses
  - loose selection on missing angle, sum of missing energy and momentum and E_{ECL}
- Selection efficiencies and expected background yields estimated, Upper limit estimation at 500 fb^{-1} ~ compatible with BaBar cut-and-count
- Next steps:
  - Refinement on K_S and K^* reconstruction, and continuum rejection
  - signal yield extraction with 1-DIM (E_{extra}) or 2-DIM (E_{extra} vs cp^*_{miss}+E^*_{miss})

EXTRA SLIDES

Y multiplicity



Efficiencies in 10^{-4} units for $K^{*+} \to K^+ \pi^0$ mode

cut/sample	signal MC	B+B-	B0B0bar	ccbar	uubar	ddbar	ssbar
m_{BC}	15.6 +/-0.4	2.570 +/- 0.001	0.640 +/- 0.005	2.027 +/- 0.006	28.282 +/- 0.006	28.847 +/-0.012	23.14 +/-0.011
ΔE	13.2 +/-0.4	2.219 +/- 0.001	0.517 +/- 0.004	1.605 +/- 0.005	22.539 +/- 0.005	23.010 +/-0.011	17.95 +/- 0.01
R2	9.8 +/-0.3	1.925 +/- 0.0008	0.455 +/- 0.004	0.418 +/- 0.003	0.493 +/- 0.002	0.506 +/- 0.005	0.386 +/- 0.005
m_{K^*}	6.3 +/-0.3	0.5800 +/- 0.0005	0.176 +/- 0.002	0.181 +/- 0.002	0.184 +/- 0.002	0.193 +/- 0.003	0.148 +/- 0.003
$\cos\theta^*_{miss}$	5.9 +/-0.2	0.4695 +/- 0.0004	0.145 +/- 0.002	0.150 +/- 0.002	0.1458 +/- 0.0002	0.155 +/- 0.003	0.126 +/- 0.003
cp^*_{miss} + E^*_{miss}	5.5 +/-0.2	0.02750 +/- 0.0001	0.0061 +/- 0.0005	0.0037 +/- 0.0002	0.0029 +/- 0.0002	0.0037 +/- 0.0004	0.005 +/- 0.0005
E_{exrra}	4.6 +/-0.2	0.012608 +/- 0.00007	0.0031 +/- 0.0003	0.0009 +/- 0.0002	0.0009 +/- 0.0001	0.0009 +/- 0.0002	0.0028 +/- 0.0003
$N_{exp, bkg}$		337 +/- 18	88 +/- 9	62 +/- 8	71 +/- 8	18 +/- 4	33 +/- 6

Efficiencies in 10^{-4} units for $K^{*+} \to K_S \pi^+$ mode

cut/sample	signal MC	B+B-	B0B0bar	ccbar	uubar	ddbar	ssbar
m_{BC}	4.61 +/-0.21	10.876 +/- 0.006	0.296 +/- 0.003	1.272 +/- 0.004	1.654 +/- 0.005	1.642	1.504 +/- 0.009
ΔE	3.94 +/-0.20	9.443 +/- 0.006	0.241 +/- 0.003	1.002 +/- 0.004	1.306 +/- 0.004	1.300 +/- 0.008	1.162 +/- 0.008
R2	2.76 +/-0.17	8.310 +/- 0.006	0.218 +/- 0.003	0.247 +/- 0.002	0.282 +/- 0.002	0.281 +/- 0.004	0.222 +/- 0.003
m_{KS}	2.16 +/-0.15	4.683 +/- 0.005	0.123 +/- 0.002	0.137 +/- 0.001	0.151 +/- 0.001	0.154 +/- 0.003	0.123 +/- 0.003
m_{K^*}	1.31 +/-0.11	0.029 +/- 0.001	0.0105 +/- 0.0006	0.0010 +/- 0.0004	0.0100 +/- 0.0004	0.0103 +/- 0.0007	0.0008 +/- 0.0007
$\cos\theta^*_{miss}$	1.28 +/-0.11	0.0229 +/- 0.0009	0.0008 +/- 0.0005	0.0008 +/- 0.0004	0.0008 +/- 0.0003	0.0008 +/- 0.0006	0.0007 +/- 0.0006
cp^*_{miss} + E^*_{miss}	1.19 +/-0.11	0.0013 +/- 0.0002	0.0003 +/- 0.0001	0.00012 +/- 0.00004	0.00025 +/- 0.00006	0.0002 +/- 0.0001	0.0003 +/- 0.0001
E_{exrra}	1.10 +/-0.10	0.0005 +/- 0.0001	0.0002 +/- 0.00009	0.00003 +/- 0.00002	0.00007 +/- 0.00003	0.00010 +/- 0.00007	0.00010 +/- 0.00007
$N_{exp, bkg}$		13 +/- 4	6.0 +/- 2.4	2.0 +/- 1.4	6.0 +/- 2.4	2.0 +/- 1.4	2.0 +/- 1.4

Cluster selection & PID

PID selection

- Likelihood function based on E/p (energy loss in the calorimeter divided by particle momentum) and dE/dx (energy loss in the tracking system)
- Cut on the LR = L(particle) / (L(e) + L(mu) + L(pi))

Photon selection

- cluster cleaning (to reject photons from beam background) with cuts on photon energy, cluster timing, E9/E25 and minimum distance between the cluster and tracks in the event (separately in forward, barrel and backward detector regions)