$B \to \eta' K_s$ analysis

Belle II Physics week
29/11/2022

Stefano Lacaprara, Jakub Kandra
INFN Padova

Introduction

- Time dependent CP violation can be measured using formula:

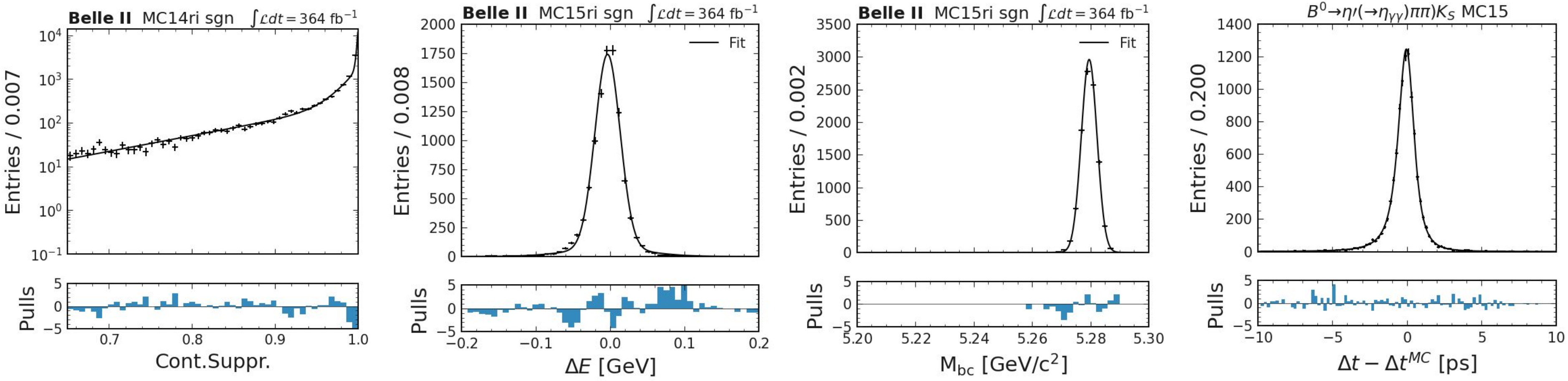
$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left(1 + q \cdot \left[\mathcal{S}_{\eta' K^0} \sin(\Delta m_d \Delta t) + \mathcal{A}_{\eta' K^0} \cos(\Delta m_d \Delta t)\right]\right)$$

$\Delta t = t_{rec} - t_{tag}$ — B^0 lifetime — tag for B mesons (+1 or -1) — mixing frequency

  - Monte Carlo predictions for fitting parameters $\mathcal{S}_{\eta' K^0} = -\xi_f \sin 2\phi_1$ and $\mathcal{A}_{\eta' K^0} = 0$, but no zero parameter can be described as difference $\Delta\mathcal{S}_{\eta' K^0} = \sin 2\phi_1^{\text{eff}} - \sin 2\phi_1$
- The difference $\Delta\mathcal{S}_{\eta' K^0}$ can be predicted from several sources:
  - SU(3)F approach limits it to the range [−0.05, 0.09]
  - QCD factorization constrains it to the range [−0.03, 0.03]
  - Other estimations
- Measurement of this difference out of the mentioned ranges could be sign of New Physics
- Previous measurements in BaBar and Belle introduce large statistical uncertainty what motivates to provide more precise measurements

Signal and signal cross feed shapes

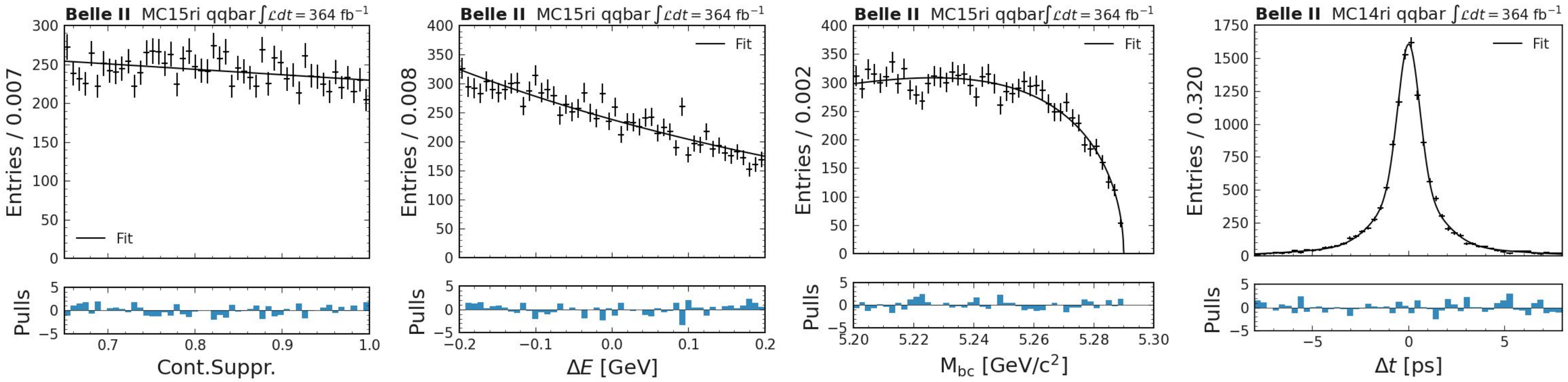
- Signal (and signal cross feed) shapes modeling:
  - $fBDT_{trans}$: Sum of three exponentials
  - m_{bc}: Double gaussian (Crystal ball)
  - ΔE: Double gaussian
  - Δt: Hadronic modeling refitted on our data (how to model signal cross feed?)



Jakub Kandra, INFN Padova

Continuum and peaking background shapes

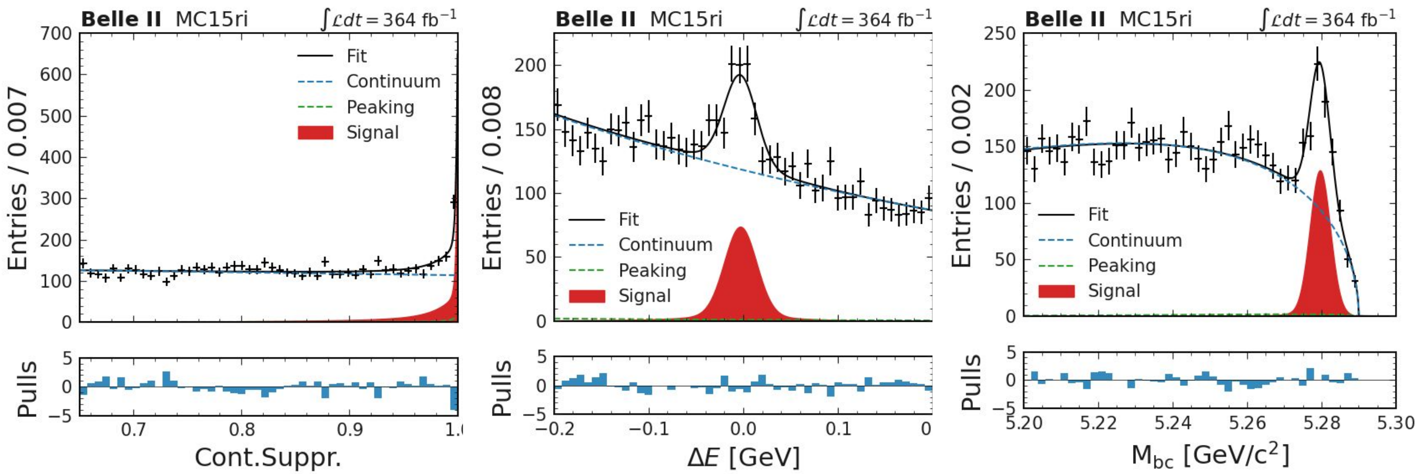
- Continuum (and peaking) background modeling:
  - $fBDT_{trans}$: Chebyshev with linear and constant and linear degrees (Double exponential)
  - m_{bc}: ArgusBG (shape parameters in back-up)
  - ΔE: Exponential (shape parameters in back-up)
  - Δt resolution: Three gaussian (how to model peaking background?)



Yield fit at 364 fb^{-1}

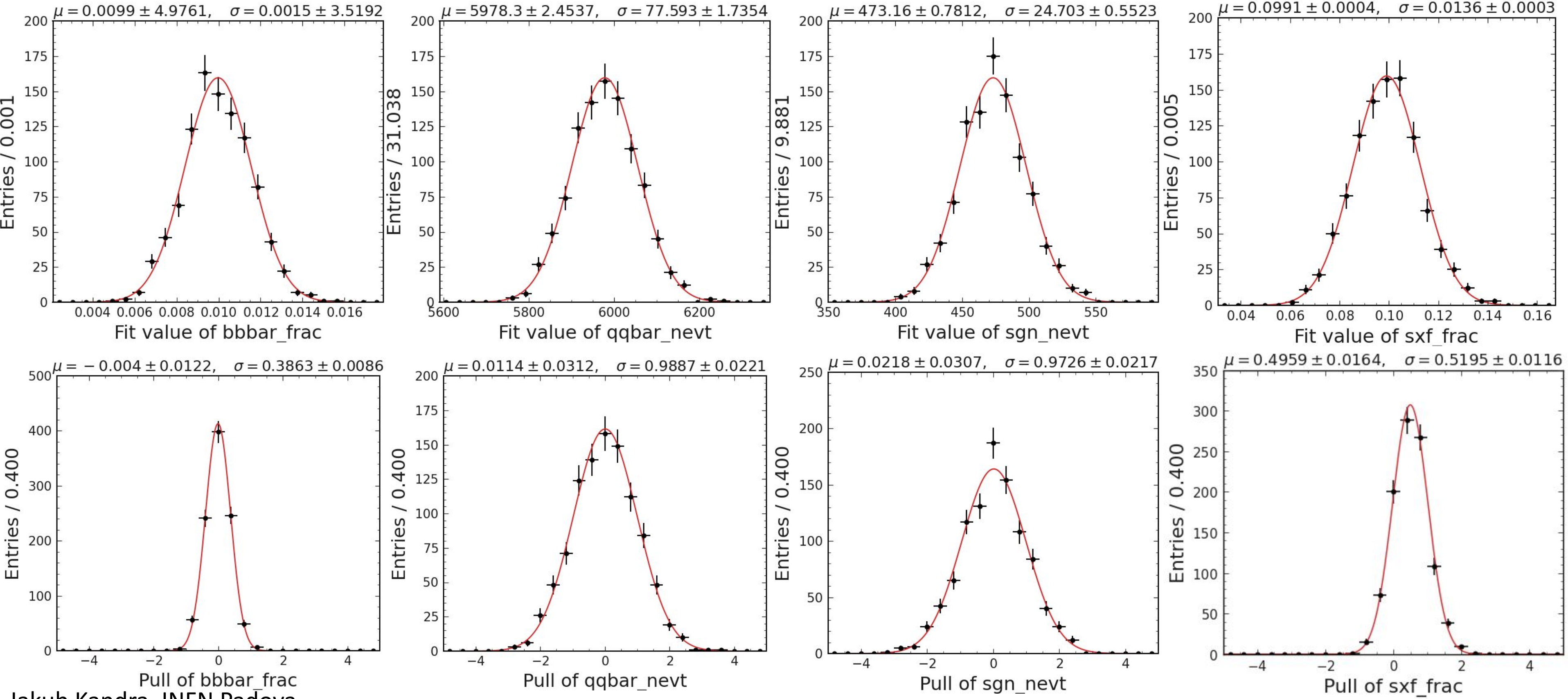
- The total fitted function is three dimensional ($fBDT_{trans} \times m_{bc} \times \Delta E$) pdf.
  - two number of events (signal and continuum) free floating and two fractions (signal cross feed and peaking) constrained to MC value with sigma equals MC statistical uncertainty
- The MC test with expected yield at current integrated luminosity (expected)
- Then we set toys as 1000 measurements:
  - Generated from total pdf
  - Sampled from datasets

Signal events
453.0 ± 25.0 (431 + 40)
Signal cross feed ratio
0.096 ± 0.026
Signal cross feed events
44.5 ± 16.0 (40)
Continuum events
5994.0 ± 78.0 (5920 + 57)
Peaking fraction
0.0089 ± 0.0041
Peaking events
53.0 ± 24.7 (57)



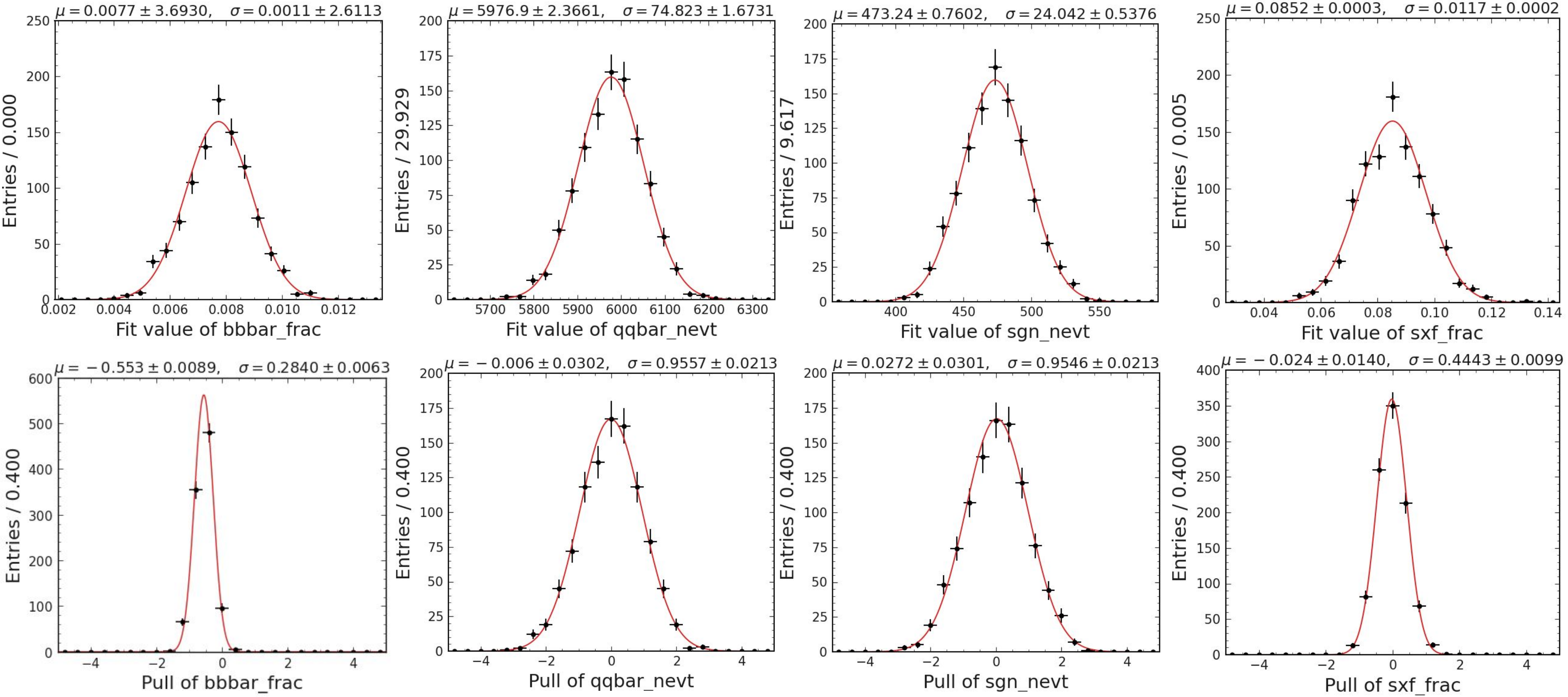
Toys generated from pdfs

- Toys demonstrate really stable fit

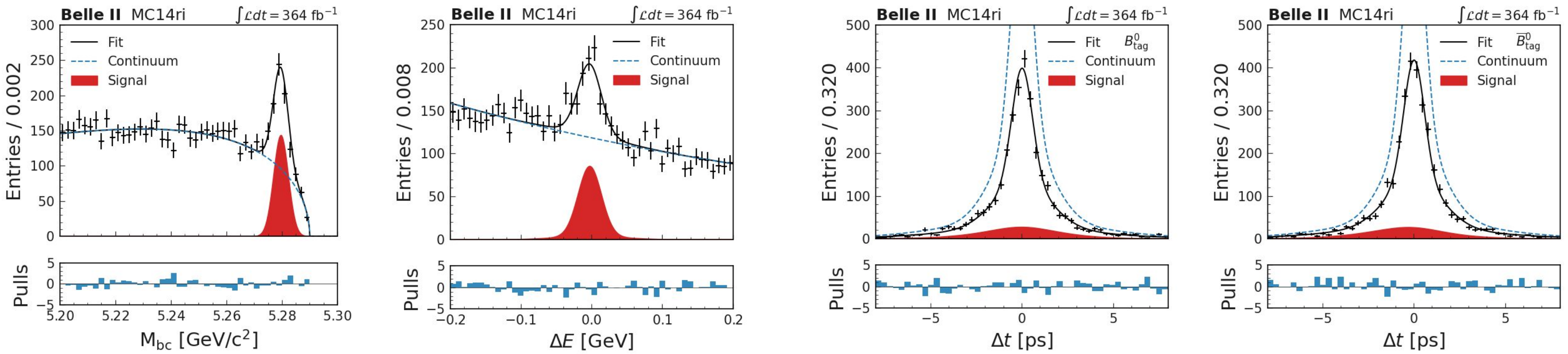


Sampled toys from datasets

- Toys demonstrate really stable fit



TD CP Violation fit (continuum + signal only)



- Fit technically working from sampled MC with L_{Data}
  - Some issue in fit component overlays for tag categories (2x normalization of pdf ?)
- Warning: very preliminary work
  - Still no SxF and BBbar
  - Still fit in qr∈[0,1]
    - With resolution from first qr bin
  - Yield for signal and continuum are ok
    - A_{CP} = 0.063 +/- 0.065 (input 0)
    - S_{CP} = 0.29 +/- 0.096 (input 0.7)

Values not to be taken seriously!
So far, just technical test

Is the B+->eta'K+ channel enough as only control channel? Or should we use anything more?

Backup

Ntuple production

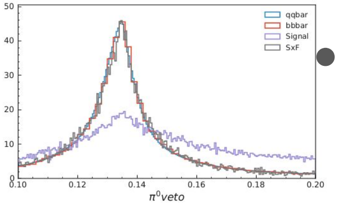
- Steering code is at:
  - https://stash.desy.de/users/lacaprar/repos/etaprime/browse/steering_files
  - Produced (so far) for All Data, MC15ri (qq-bar+taupair 1/ab), and MC15rd (exp20-26 ~700/fb)
  - As well as for signals
    - **Channel #1**:
      - $B^0 \to \eta' (\to \eta(\to \gamma\gamma)\pi^+\pi^-)K_s(\pi^+\pi^-)$
      - $B^0 \to \eta' (\to \eta(\to \gamma\gamma)\pi^+\pi^-)K_s(\pi^0\pi^0)$
      - $B^+ \to \eta' (\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^+$
    - Channel #3:
      - $B^0 \to \eta' (\to \rho(\to \pi^+\pi^-)\gamma)K_s(\pi^+\pi^-)$
      - $B^0 \to \eta' (\to \rho(\to \pi^+\pi^-)\gamma)K_s(\pi^0\pi^0)$
      - $B^+ \to \eta' (\to \rho(\to \pi^+\pi^-)\gamma)K^+$
    - Channel #2:
      - $B^0 \to \eta' (\to \eta(\to \pi^+\pi^-\pi^0)\pi^+\pi^-)K_s(\pi^+\pi^-)$
      - $B^0 \to \eta' (\to \eta(\to \pi^+\pi^-\pi^0)\pi^+\pi^-)K_s(\pi^0\pi^0)$
      - $B^+ \to \eta' (\to \eta(\to \pi^+\pi^-\pi^0)\pi^+\pi^-)K^+$

Selection η': two channels

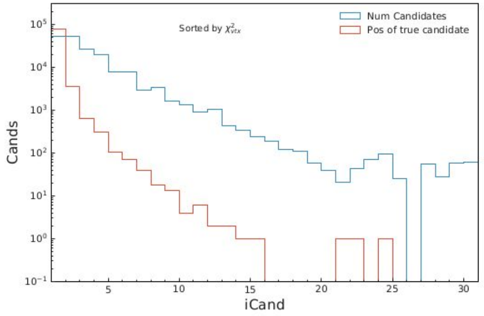
$$\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$$

- Gamma:loose
  - E_γ>150 MeV
  - $0.5 < M_{\gamma\gamma} < 0.57$ GeV/c ^{2}
- Pi:all
  - opposite charge

$$\eta' \to \rho(\to \pi^+\pi^-)\gamma$$



- Gamma:loose
  - E_γ>150 MeV
  - cos $\theta_\gamma > -0.64$
  - No pi0 veto: losing too much signal
- Pi:loose
  - $0.47 < M_{\pi+\pi-} < 1.07$ GeV/c^2
- $0.92 < M_{\eta'} < 1.0$ GeV/c ^{2}



- K:loose
  - Global PID(K) >0.1
  - cos $\theta_K > -0.5$
- K_S0:merged (V0+hh)
  - $0.49 < M_{\pi+\pi-} < 0.51$ GeV/c ^{2}
  - Vertex fit not failing
  - cos $\theta_{p,v} > 0.99$
    - (angle between momentum and vertex vector)
- **B_0** and **B^+** decay chain fitted with treeFit algo
  - Mass constraint on η, η‘,
  - NO IP vertex constraint
- Keep only one candidate per event sortex by vtx pValue

Selections

$\eta' \to \eta\pi^+\pi^-$

- $E_\gamma > 150$ MeV
- $0.5 < M_\eta < 0.57 \frac{GeV}{c^2}$
- $0.92 < M_{\eta'} < 1.0 \frac{GeV}{c^2}$

$\eta' \to \rho\gamma$

- $E_\gamma > 150$ MeV
- $\cos\theta_\gamma > -0.64$
- $0.51 < M_\rho < 1.0 \frac{GeV}{c^2}$
- $0.92 < M_{\eta'} < 1.0 \frac{GeV}{c^2}$

K

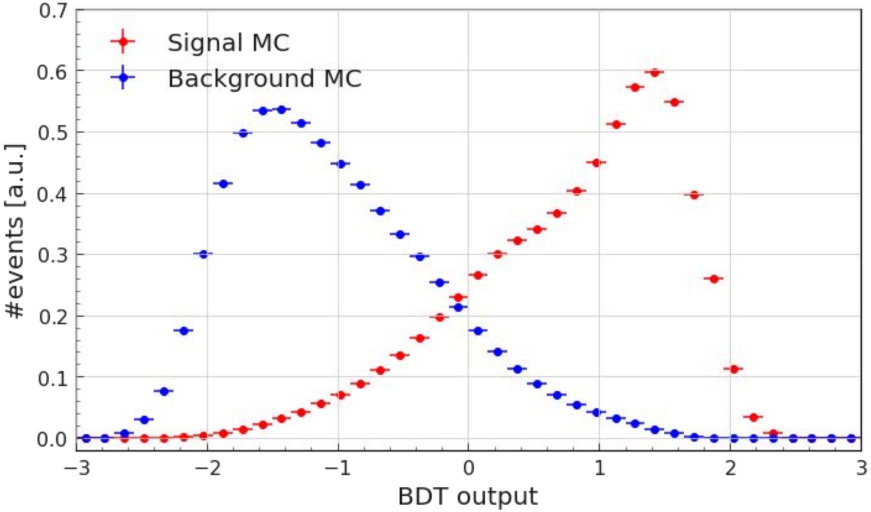
- $\cos\theta_K > -0.5$

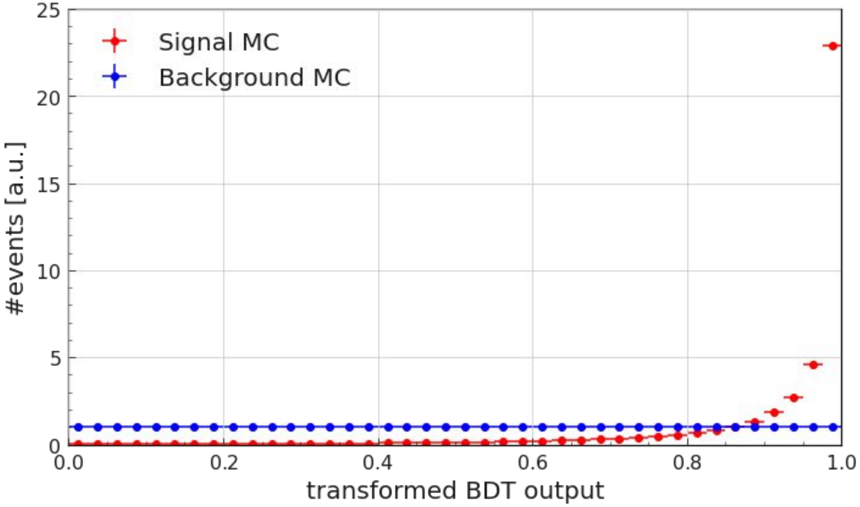
K_s^0

- $\cos\theta_{p,v} > -0.64$
- $0.49 < M_{K_s^0} < 0.51 \frac{GeV}{c^2}$

Continuum suppression modelling

- Probability integral transformation transform distributions according given empirical cumulative distribution (background), then background is flat and signal is concentrated around maximum (one)

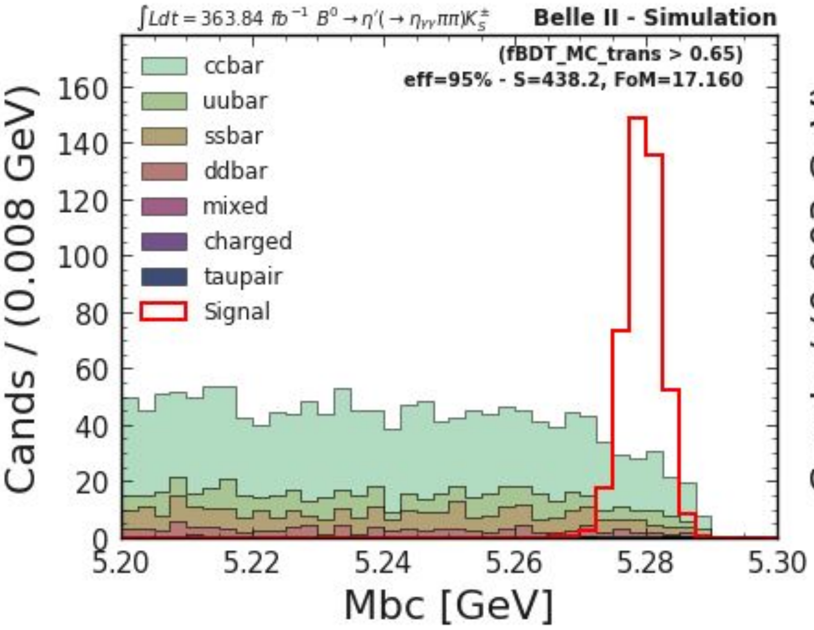


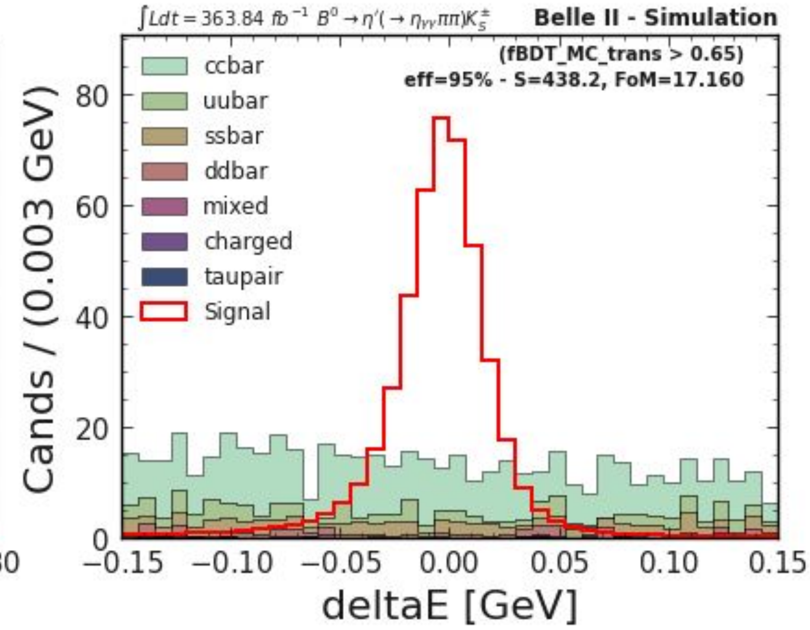



```python
# empirical cumulative distribution function
from statsmodels.distributions.empirical_distribution import ECDF
ecdf = ECDF(qq_allCh['fBDT_MC'])
qq_allCh['fBDT_MC_trans'] = ecdf(qq_allCh['fBDT_MC'])
sgn_allCh['fBDT_MC_trans'] = ecdf(sgn_allCh['fBDT_MC'])
data_allCh['fBDT_MC_trans'] = ecdf(data_allCh['fBDT_MC'])
```

The fBDT transformed cut

- To reduce amount of continuum background we apply additional cut based on the transformed fBDT:
  - The cut was selected to reduce no more than 5% of signal
  - All events with value larger than 0.65 fBDT_MC_trans have been kept

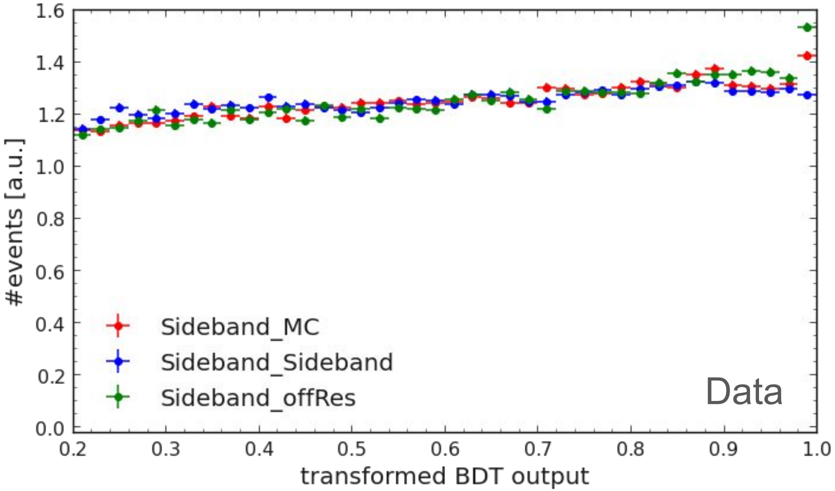


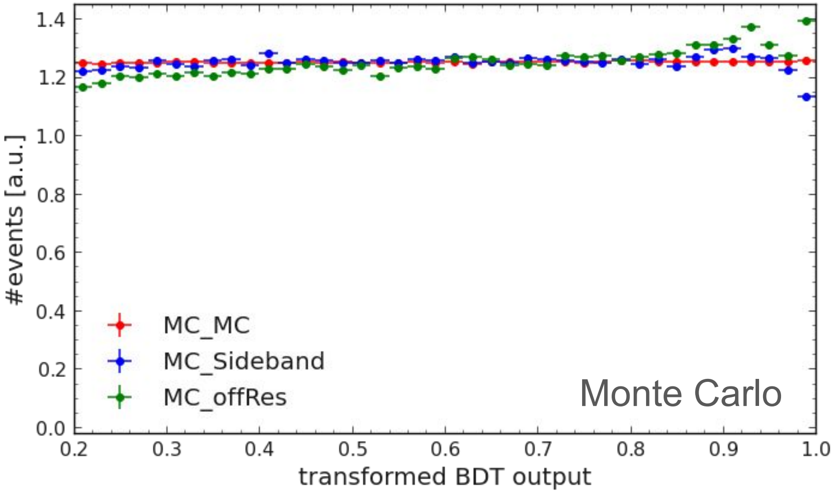


Jakub Kandra, INFN Padova

Different techniques for different datasets

- Due to different distributions in different datasets
- We decided:
  - Keep the standard MC technique of training fBDT for Monte Carlo datasets
  - Keep the technique based on the sideband for real data
- Our approach will reduce systematics uncertainty from fBDT

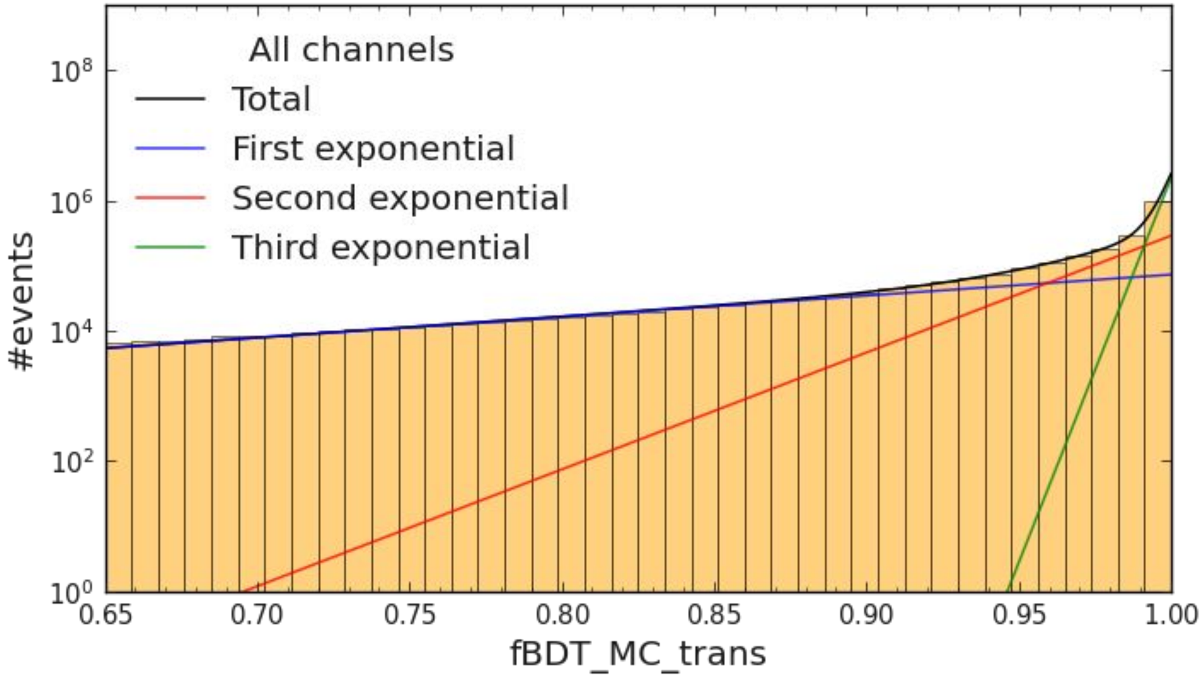




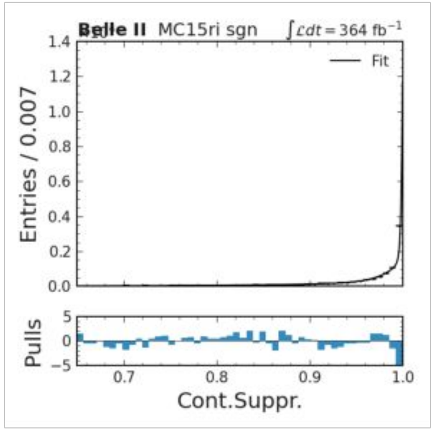
Jakub Kandra, INFN Padova

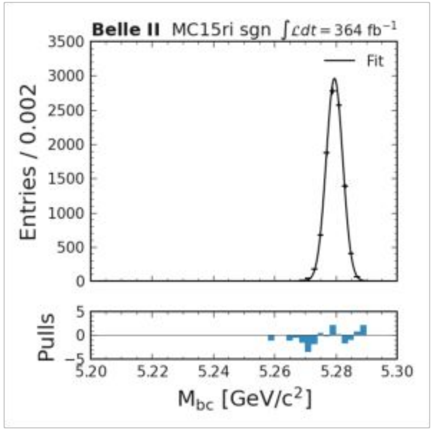
Shapes of fBDT transformed

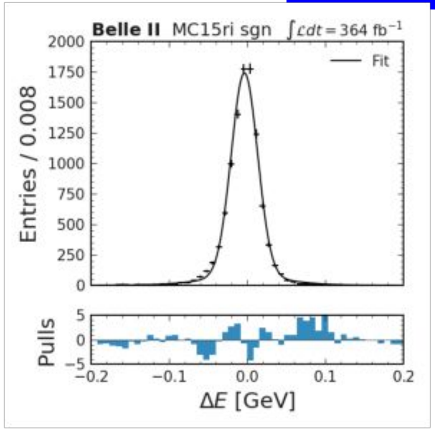
- The shape fitted on signal Monte Carlo dataset:
    - Signal: Sum of the three exponential pdfs
    - Continuum background: polynomial pdf with no larger then linear element
    - Peaking background: Sum of two exponential pdfs



Signal





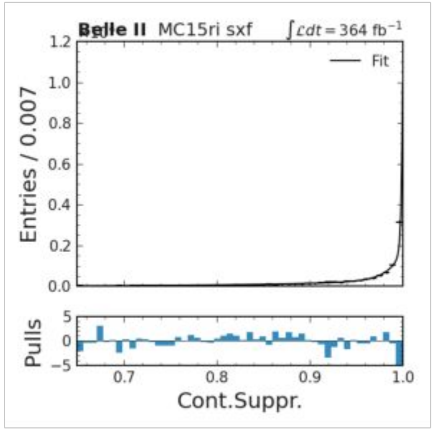


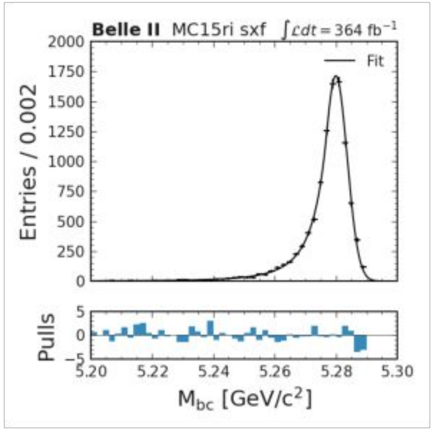
RooExponential sgn_cs_exp1
sgn_cs_exp1_a = 52.9 ± 3.2
RooExponential sgn_cs_exp2
sgn_cs_exp2_a = 704.482 ± 0.038
RooExponential sgn_cs_exp3
sgn_cs_exp3_a = 8.24 ± 0.39
Sum of pdfs called sgn_cs_exp12
sgn_cs_frac1 = 0.644 ± 0.012
sgn_cs_exp1 and sgn_cs_exp2
Sum of pdfs called sgn_cs_pdf
sgn_cs_frac2 = 0.575 ± 0.017
sgn_cs_exp12 and sgn_cs_exp3

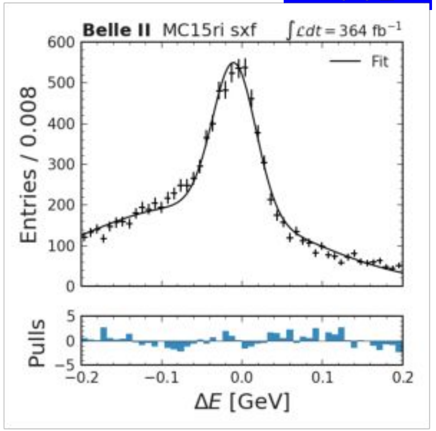
RooGaussian sgn_mbc_gs1
sgn_mbc_gs_mean = 5.279589 ± 2.7e-05
sgn_mbc_gs1_sigma = 0.002685 ± 2e-05
RooGaussian sgn_mbc_gs2
sgn_mbc_gs_mean = 5.279589 ± 2.7e-05
sgn_mbc_gs2_sigma = 0.01 ± 0.0016
Sum of pdfs called sgn_mbc_pdf
sgn_mbc_frac = 0.9965 ± 0.0012
sgn_mbc_gs1 and sgn_mbc_gs2

RooGaussian sgn_de_gs1
sgn_de_gs_mean = -0.00318 ± 0.00019
sgn_de_gs1_sigma = 0.01689 ± 0.00023
RooGaussian sgn_de_gs2
sgn_de_gs_mean = -0.00318 ± 0.00019
sgn_de_gs2_sigma = 0.0521 ± 0.0018
Sum of pdfs called sgn_de_pdf
sgn_de_frac = 0.8854 ± 0.0098
sgn_de_gs1 and sgn_de_gs2

Signal cross feed





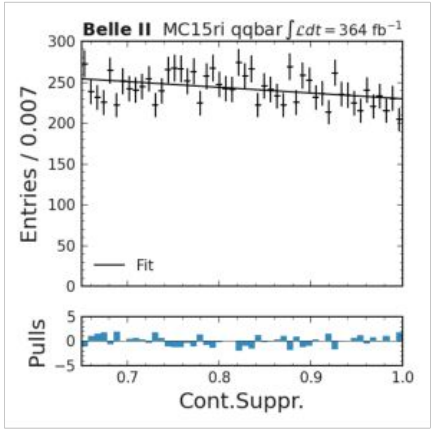


RooExponential sxf_cs_exp1
sxf_cs_exp1_a = 8.36 ± 0.29
RooExponential sxf_cs_exp2
sxf_cs_exp2_a = 704.354 ± 0.011
RooExponential sxf_cs_exp3
sxf_cs_exp3_a = 66.9 ± 4.2
Sum of pdfs called sxf_cs_exp12
sxf_cs_frac1 = 0.76 ± 0.0094
sxf_cs_exp1 and sxf_cs_exp2
Sum of pdfs called sxf_cs_pdf
sxf_cs_frac2 = 0.689 ± 0.013
sxf_cs_exp12 and sxf_cs_exp3

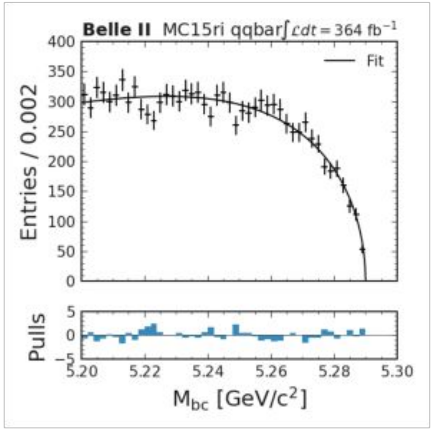
RooCrystalBall sxf_mbc_pdf
sxf_mbc_gs_mean = 5.279973 ± 7.2e-05
sxf_mbc_gs_sigma = 0.003687 ± 5.2e-05
sxf_mbc_gs_alpha = 0.809 ± 0.028
sxf_mbc_gs_n = 4.01 ± 0.26
sxf_mbc_gs_alphaR = 10000.0 ± 0.0

RooGaussian sxf_de_gs1
sxf_de_gs1_mean = -0.00932 ± 0.00085
sxf_de_gs1_sigma = 0.02673 ± 0.00099
RooGaussian sxf_de_gs2
sxf_de_gs2_mean = -0.0663 ± 0.0046
sxf_de_gs2_sigma = 0.1408 ± 0.005
Sum of pdfs called sxf_de_pdf
sxf_de_frac = 0.31 ± 0.013
sxf_de_gs1 and sxf_de_gs2

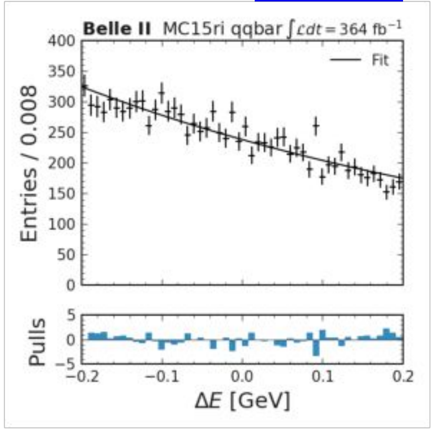
Continuum background



RooChebychev qqbar_cs_pdf
qqbar_cs_che_lin = -0.051 ± 0.016

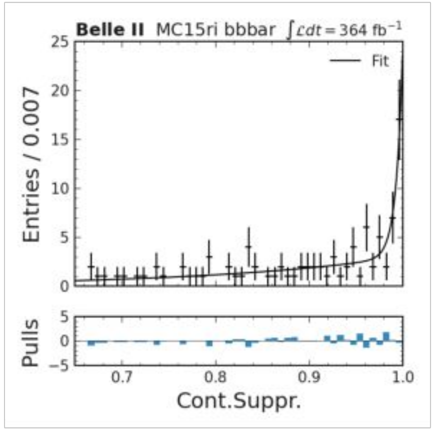


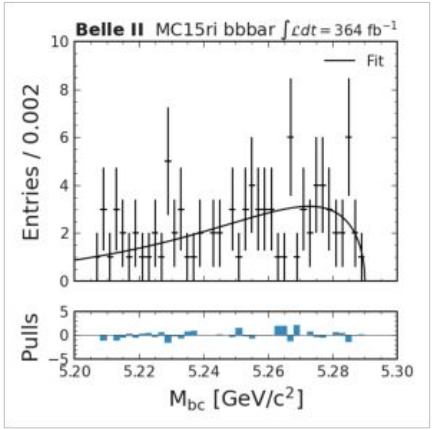
ArgusBG qqbar_mbc_pdf
qqbar_mbc_arg_k = -20.5 ± 1.0

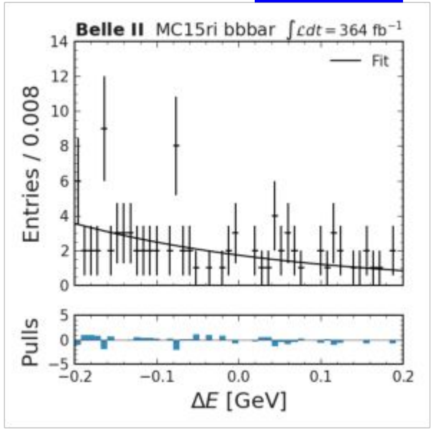


RooExponential qqbar_de_pdf
qqbar_de_arg_c = -1.548 ± 0.08

Peaking background







RooExponential bbbar_cs_exp1
bbbar_cs_exp1_a = 4.8 ± 1.5
RooExponential bbbar_cs_exp2
bbbar_cs_exp2_a = 143.0 ± 63.0
Sum of pdfs called bbbar_cs_pdf
bbbar_cs_frac = 0.781 ± 0.065
bbbar_cs_exp1 and bbbar_cs_exp2

ArgusBG bbbar_mbc_pdf
bbbar_mbc_arg_k = -76.0 ± 12.0

RooExponential bbbar_de_pdf
bbbar_de_arg_c = -3.6 ± 0.94

Yield Systematics

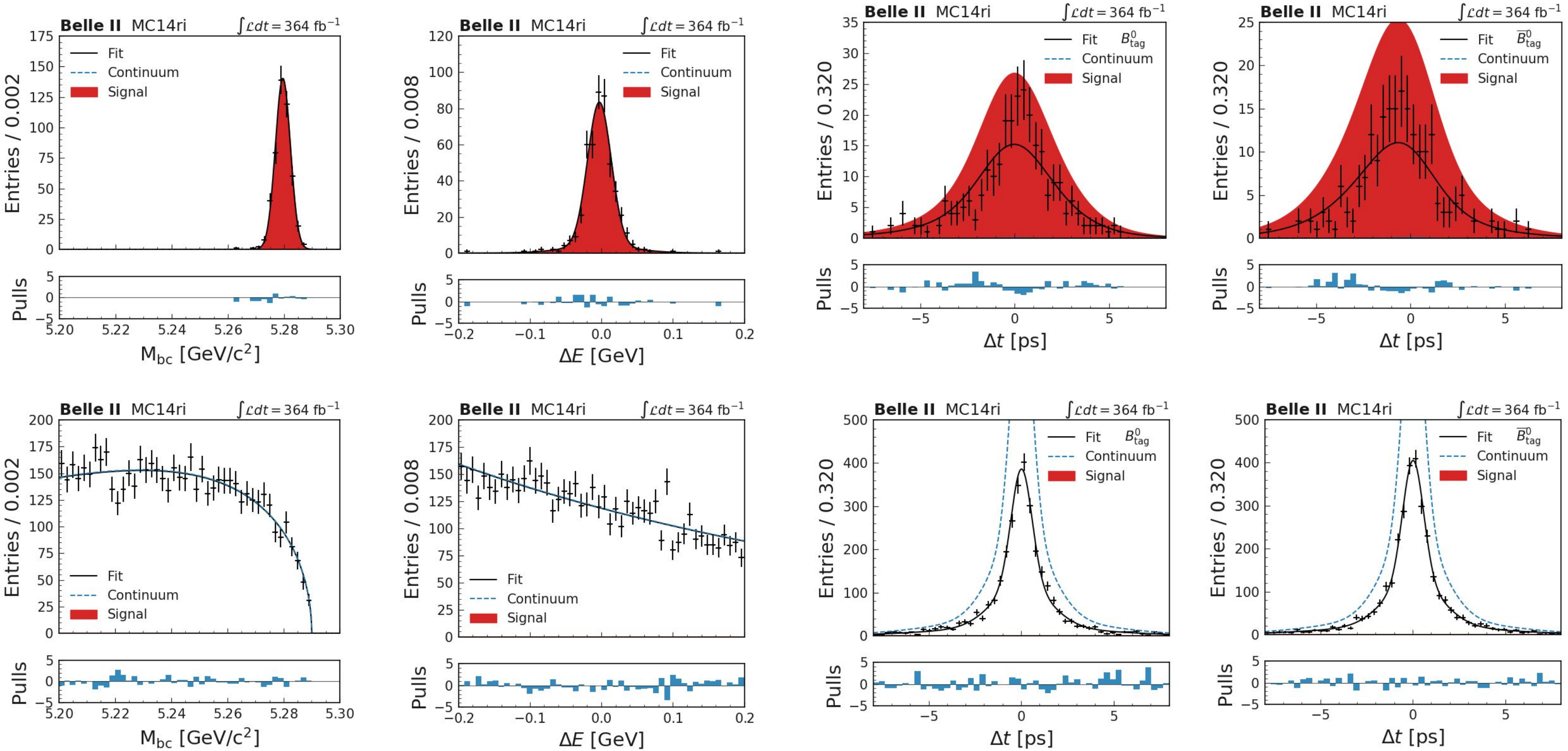
Yield systematics in arxiv paper

TABLE 2. Summary of systematics uncertainties (in %) by category and channel.

Channel	$B^{\pm} \to \eta' K^{\pm}$	$B^{0} \to \eta' K^{0}_{S}$	$B^{\pm} \to \eta' K^{\pm}$	$B^{0} \to \eta' K^{0}_{S}$
Source	$\eta' \to \eta\pi^{+}\pi^{-}$		$\eta' \to \rho\gamma$	
Tracking efficiency	2.1	2.8	2.1	2.8
Photon efficiency	0.5	0.5	0.5	0.5
K^{0}_{S} efficiency	-	4.5	-	4.5
$\pi^{\pm}$ PID	-	-	2.4	2.4
$K^{\pm}$ PID	2.5	-	2.5	-
~~Cont. supp. modelling~~	~~5.0~~	~~1.0~~	~~5.5~~	~~2.3~~
SxF fraction	2.6	1.8	5.9	3.2
N($B\bar{B}$)	1.4			
Total	6.6	5.9	9.1	7.2

Removed by using Data side band for modelling

Signal/Background only TDCPV fit



TDCPV systematics

From: JHEP 1410 (2014) 165 Belle

772×10^6 BBar pairs

Source	$S_{\eta' K^0}$	$\mathcal{A}_{\eta' K^0}$
Vertexing	±0.014	±0.033
Δt resolution	±0.025	±0.006
$\eta' K^0_S$ signal fraction	±0.013	±0.006
$\eta' K^0_L$ signal fraction	±0.005	±0.004
Background Δt PDF	±0.001	< 0.001
Physics parameters	±0.001	< 0.001
Flavor tagging	±0.003	±0.003
Possible fit bias	±0.001	±0.001
Tag-side interference	±0.001	±0.020
Total	±0.032	±0.040

- Vertexing:
  - They are estimated by varying several algorithm conditions and repeating the final fit.
    - In particular, selection on h (reduced χ^2) and σ_z
    - IP constraint varied
    - Mis-alignment
- Dt resolution:
  - Varies parameters of DT resolution (using tatami)
- Signal fraction:
  - Varying parameter of pdf
- Tag-side (A_{CP}):
  - Toys MC with varied signal DT distribution

TDCPV systematics

From: PRD 79 (2009) 052003 BaBar w/ 467 × 10^6 BB pairs

Source	$S_{\eta' K^0_S}$	$C_{\eta' K^0_S}$
Variation of PDF parameters	0.006	0.009
Bias correction	0.006	0.005
Interference from DCSD on tag side	0.001	0.015
$B\overline{B}$ background	0.009	0.005
Signal Δt parameters from $B_{\rm flav}$	0.009	0.015
SVT alignment	0.002	0.003
Beam-spot position and size	0.002	0.001
Vertexing method	-	-
Self-crossfeed	0.004	0.001
Total	0.016	0.024

- Pdf parameters
  - Toys MC varying pdf params
- Bias
  - From toys MC
- BB-background
  - Varied +/-20%
- B_{flav}
  - Varies B→charmless CP parameters within uncert for BB background
- Self-crossfeed:
  - Toy MC w/ and w/o SxF
- Interference
  - ~same as Belle