Search for the decay $B_s^0 \to \pi^0\pi^0$ at Belle

XXV DAE-BRNS High Energy Physics symposium 2022
IISER Mohali

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(*on behalf of the Belle collaboration*)
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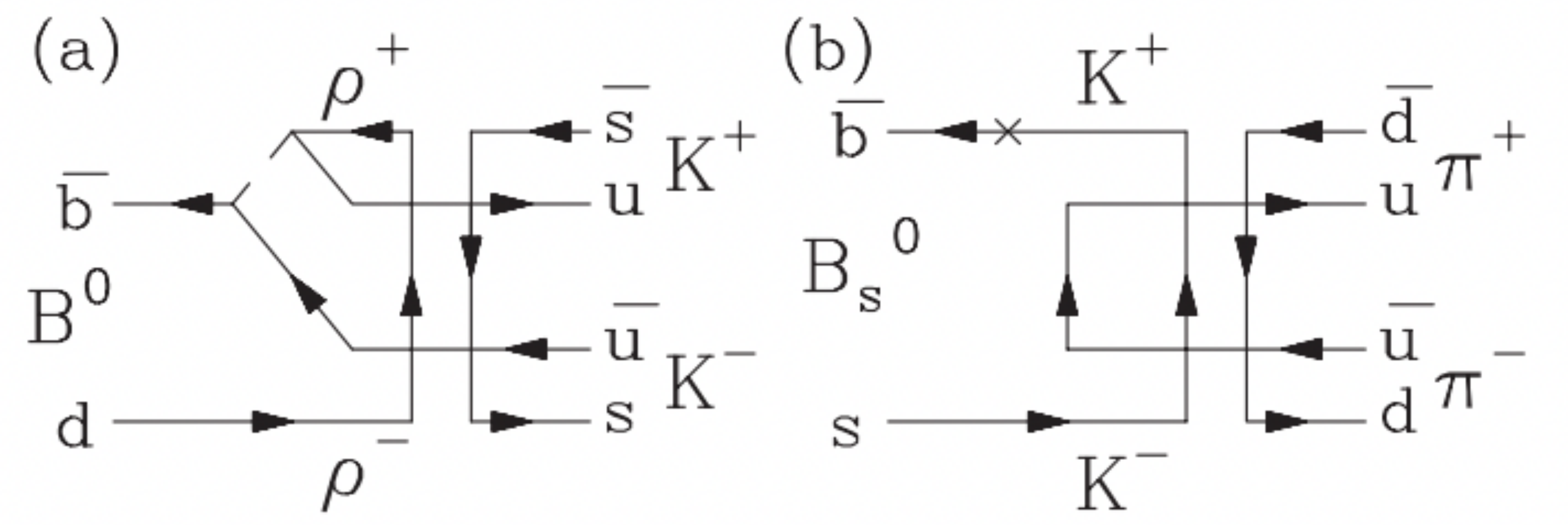
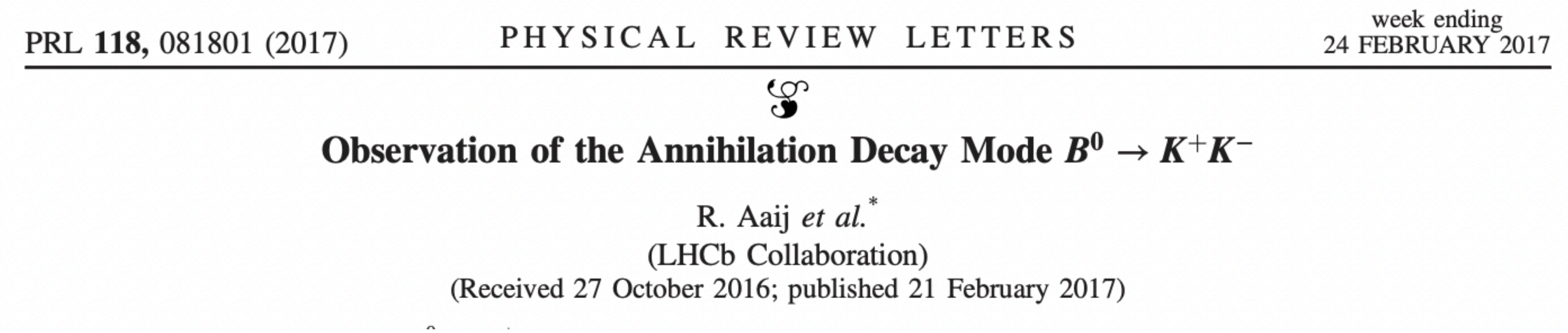
Motivation for studying *weak annihilation* rare decays in B_s^0 mesons

- Heavy flavored hadrons decaying via "weak annihilation" Feynman diagrams are suppressed within the SM ($\mathcal{O}(\lambda^n \frac{f_B}{m_B})$)
- In the last decade, study of these decays have gained impetus both theoretically and experimentally (LHCb/Belle)
- Their predicted branching fraction ($\mathscr{B}$) lies in the range of $10^{-6} - 10^{-8}$ **PRD 91, 344 014011 (2015)**
- However, owing to rescattering effects their $\mathscr{B}$ can be enchanced upto a maximum of the order of 100 **PRL 78, 21 (1997)**
- Pure annihilation diagrams are an excellent probe to investigate new physics (NP) **PRD 87, 036008 (2013)**
- Additionally, weak annihilation B_s^0 decays can be used to extract γ angle of the CKM matrix **PLB 459 (1999)**



Rescattering effect


PRL **118,** 081801 (2017) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2017

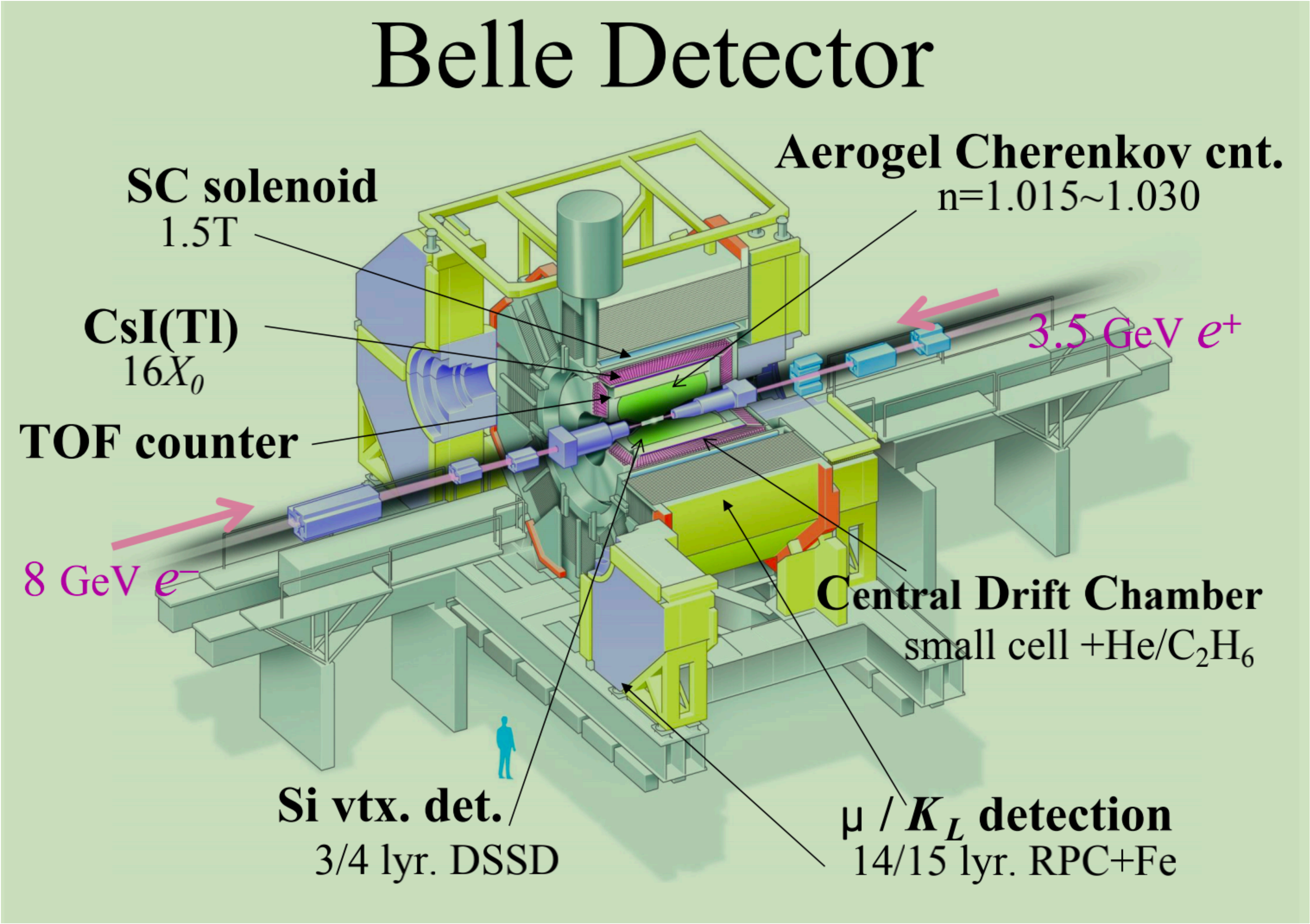
Observation of the Annihilation Decay Mode $B^0 \to K^+K^-$

R. Aaij *et al.**
(LHCb Collaboration)
(Received 27 October 2016; published 21 February 2017)

Significant deviation between experiment and theory in the decay channel, $B_s^0 \to \pi^+\pi^-$ **PLB 740 (2015)**

The Belle detector

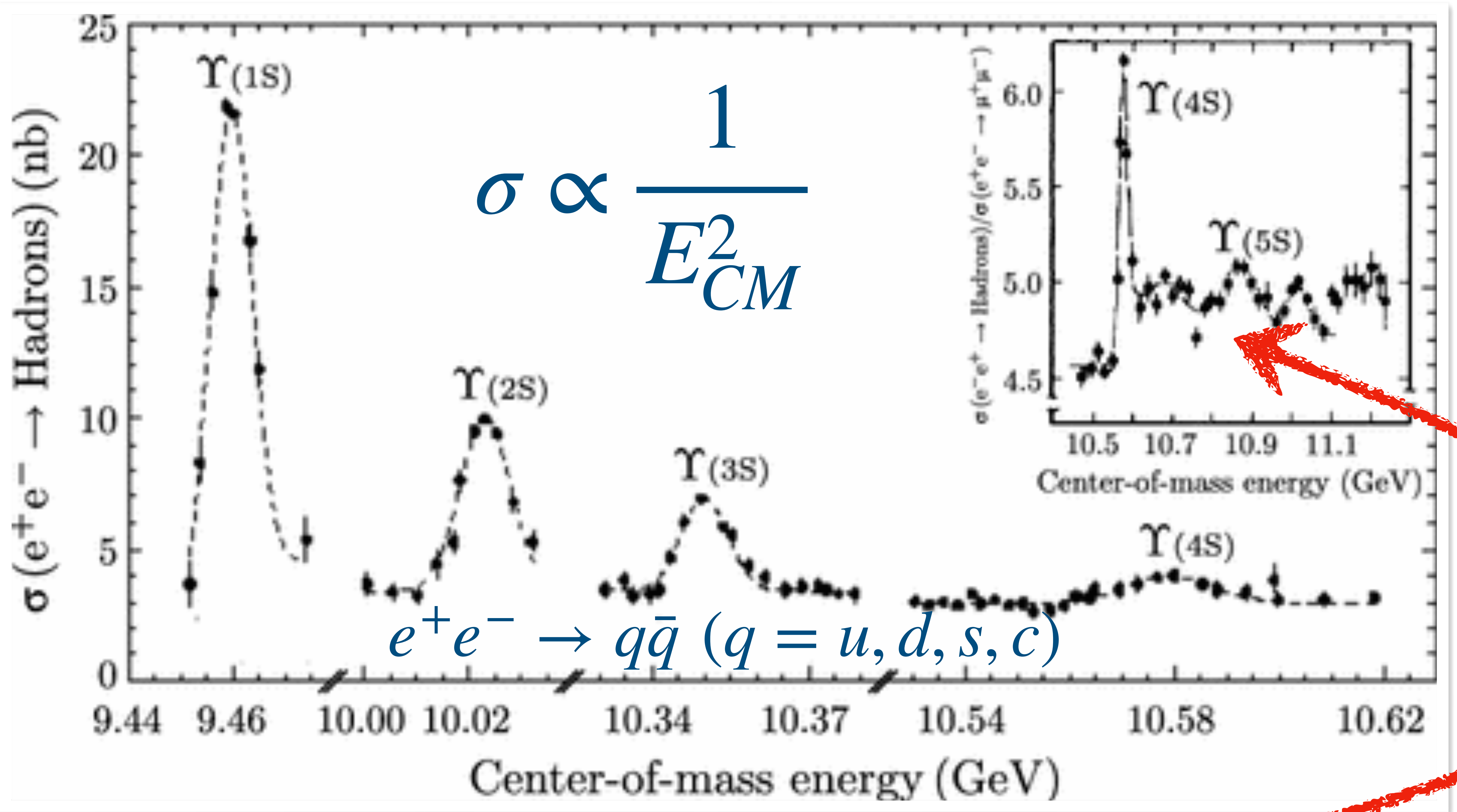
NIM A **479** 117 (2003) / PTEP **2012** 04D001 (2012)



- General purpose 4π hermetic detector
- Asymmetric in energy to provide Lorentz boost to B mesons required for CPV studies

- SVD : Vertex reconstruction of B mesons
- CDC : Measure momentum of charged tracks
- TOF/ACC : Particle identification together with CDC
- ECL : Measure energy deposition of charged and neutral particles
- KLM : Identification of K_L and μ

Production of B_s^0 mesons near $\Upsilon(5S)$ resonance



$$\sigma \propto \frac{1}{E_{CM}^2}$$

$$e^+e^- \to q\bar{q}\ (q = u, d, s, c)$$

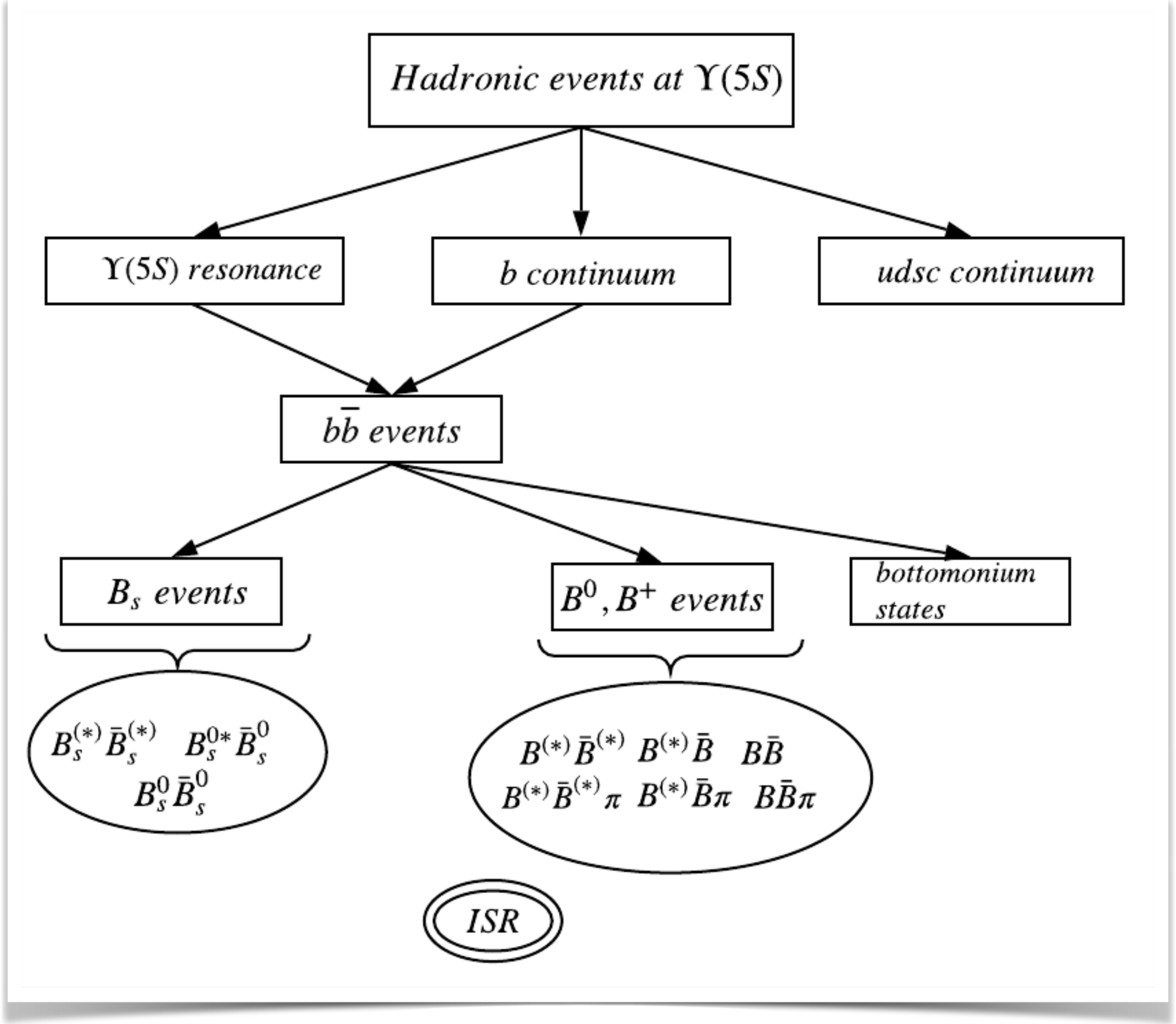
$$E_{CM} = \sqrt{s} = 10.86\ (\text{GeV})$$

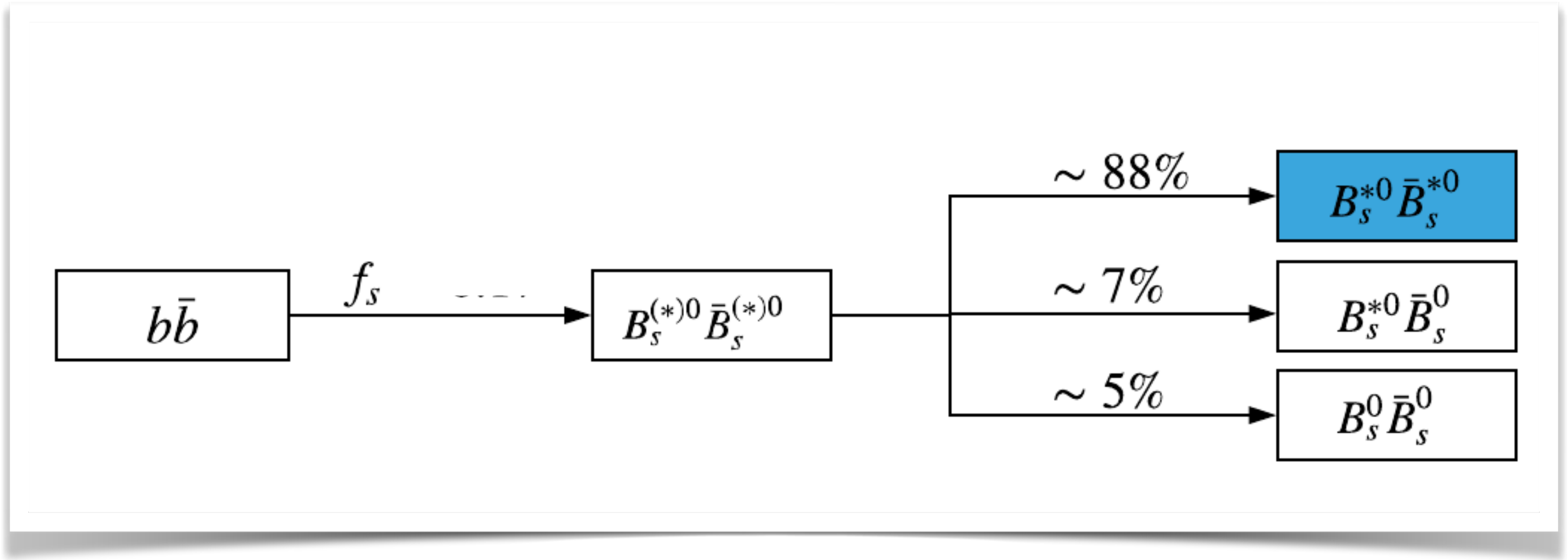
$$\mathscr{L} = 121.4\ \text{fb}^{-1}$$

$$\sigma_{b\bar{b}}^{\Upsilon(5S)} = (0.340\ \pm\ 0.016)\ \text{nb}$$

$$f_s = 0.201\ \pm 0.031$$

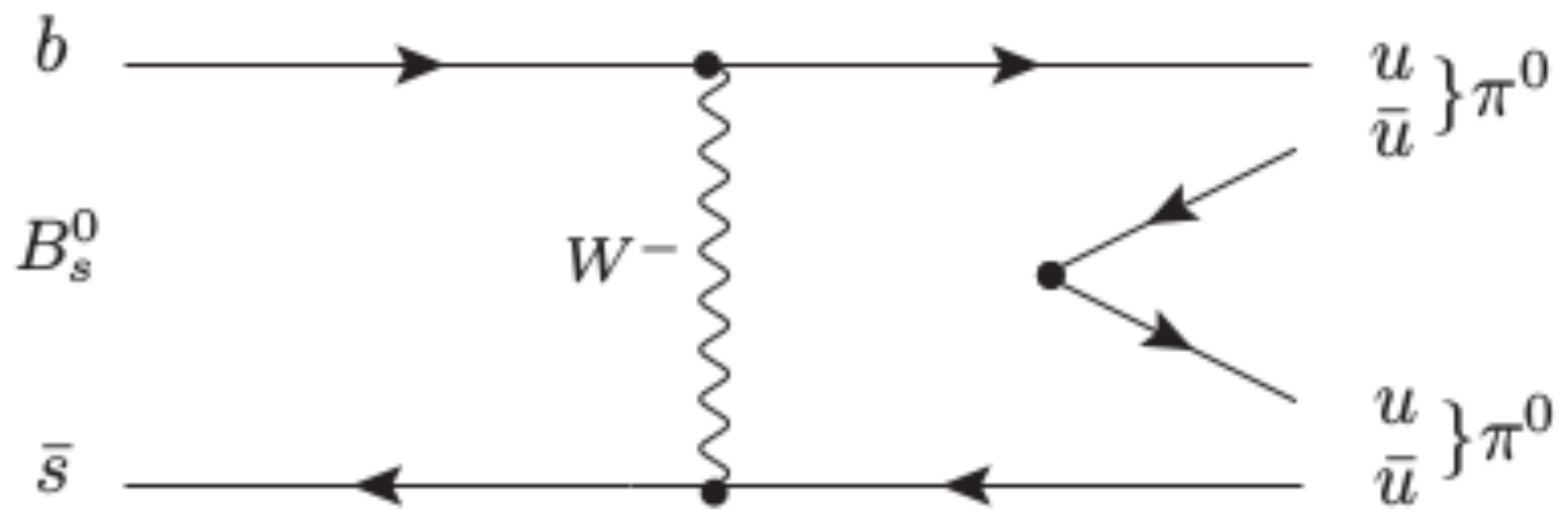
$$N_{B_s^0\bar{B}_s^0} = \mathscr{L} \cdot \sigma_{b\bar{b}}^{\Upsilon(5S)} \cdot f_s = (8.30\ \pm 1.34) \times 10^6\ \text{pairs}$$



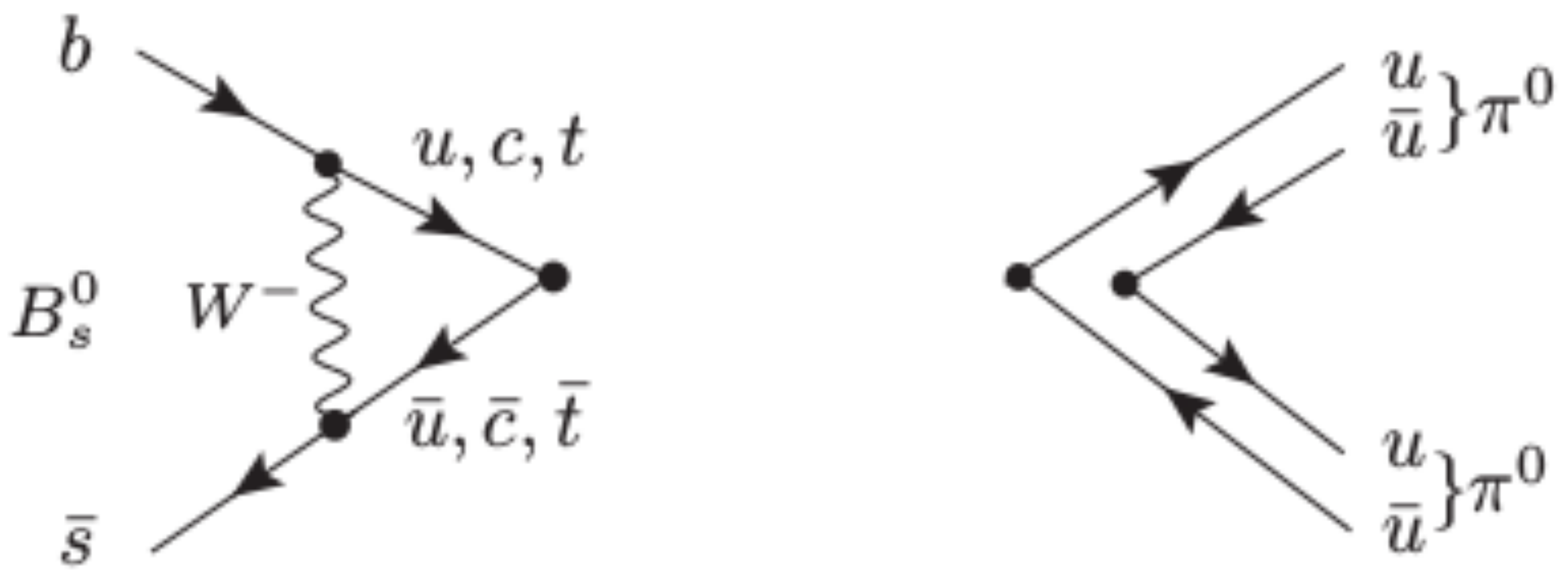


Outline / Analysis strategy

- It is a neutral, charmless, non-leptonic, strangeness non-conserving rare decay channel.
- Within the Standard Model (SM), it proceeds via W-exchange and 'penguin'-annihilation topological diagrams.



W-exchange



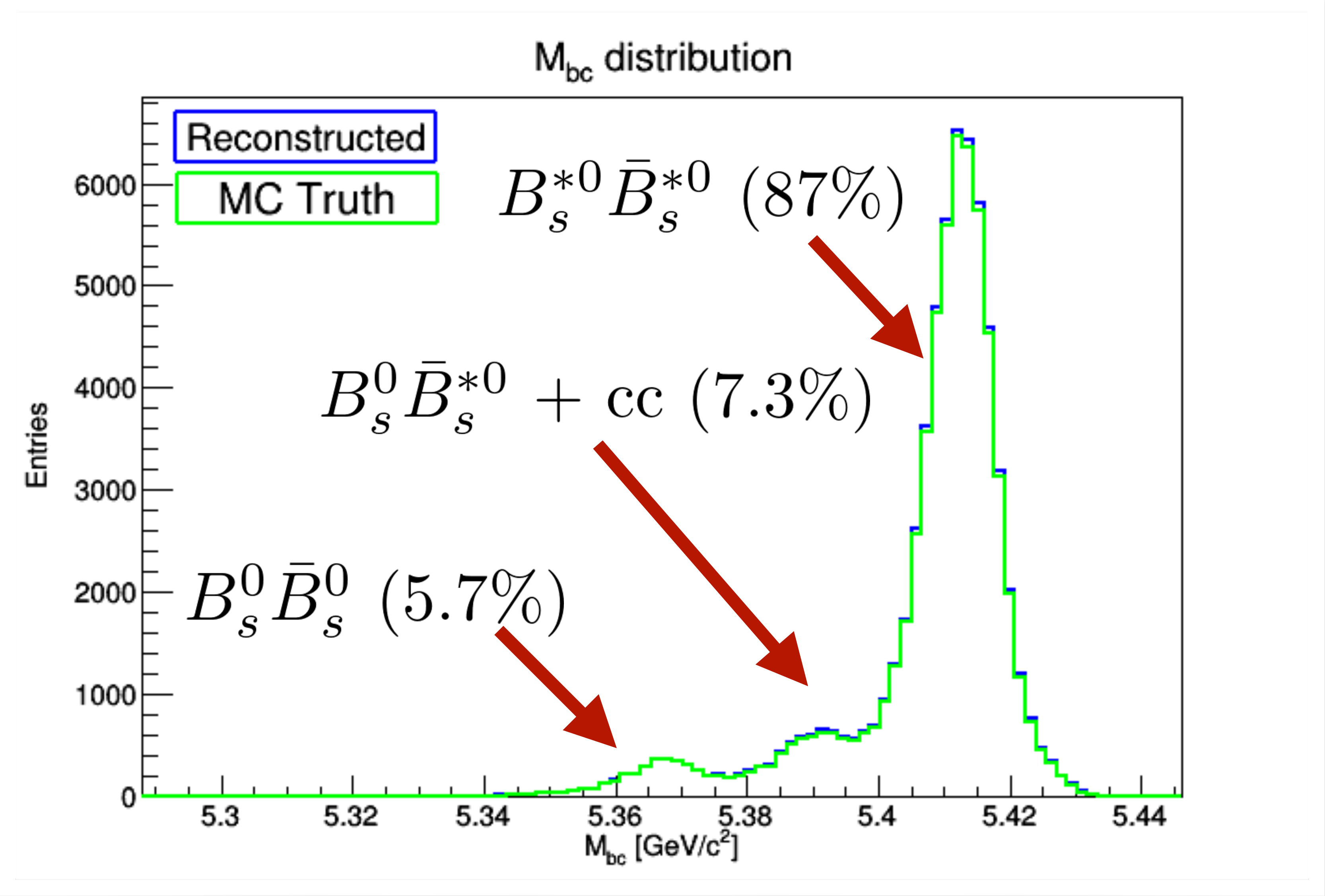
'Penguin' annihilation

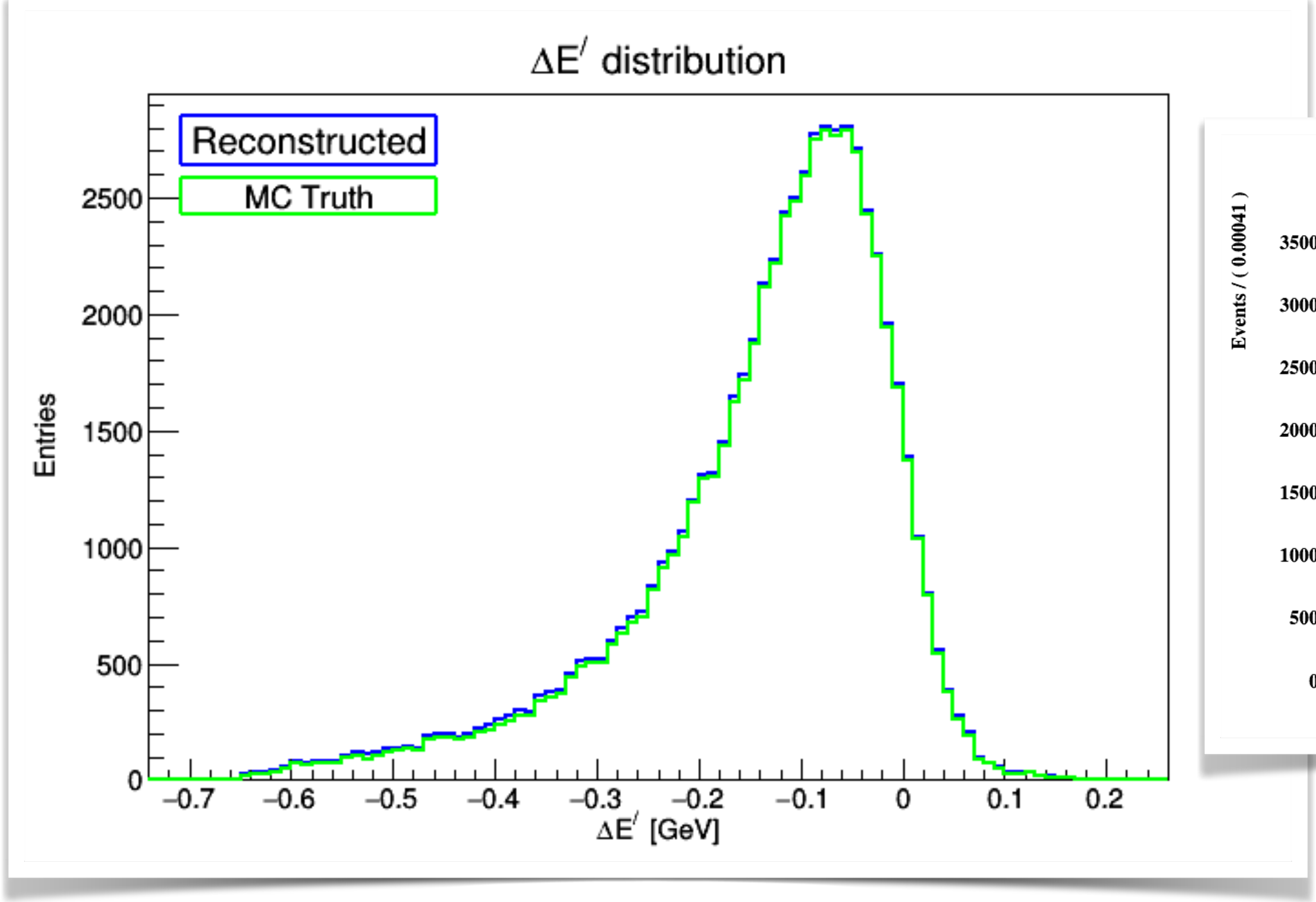
Quantity	Flavor SU(3)	pQCD	QCDF
$\mathcal{B}$ (10^{-6})	0.40 ± 0.27	0.28 ± 0.09	0.13 ± 0.05

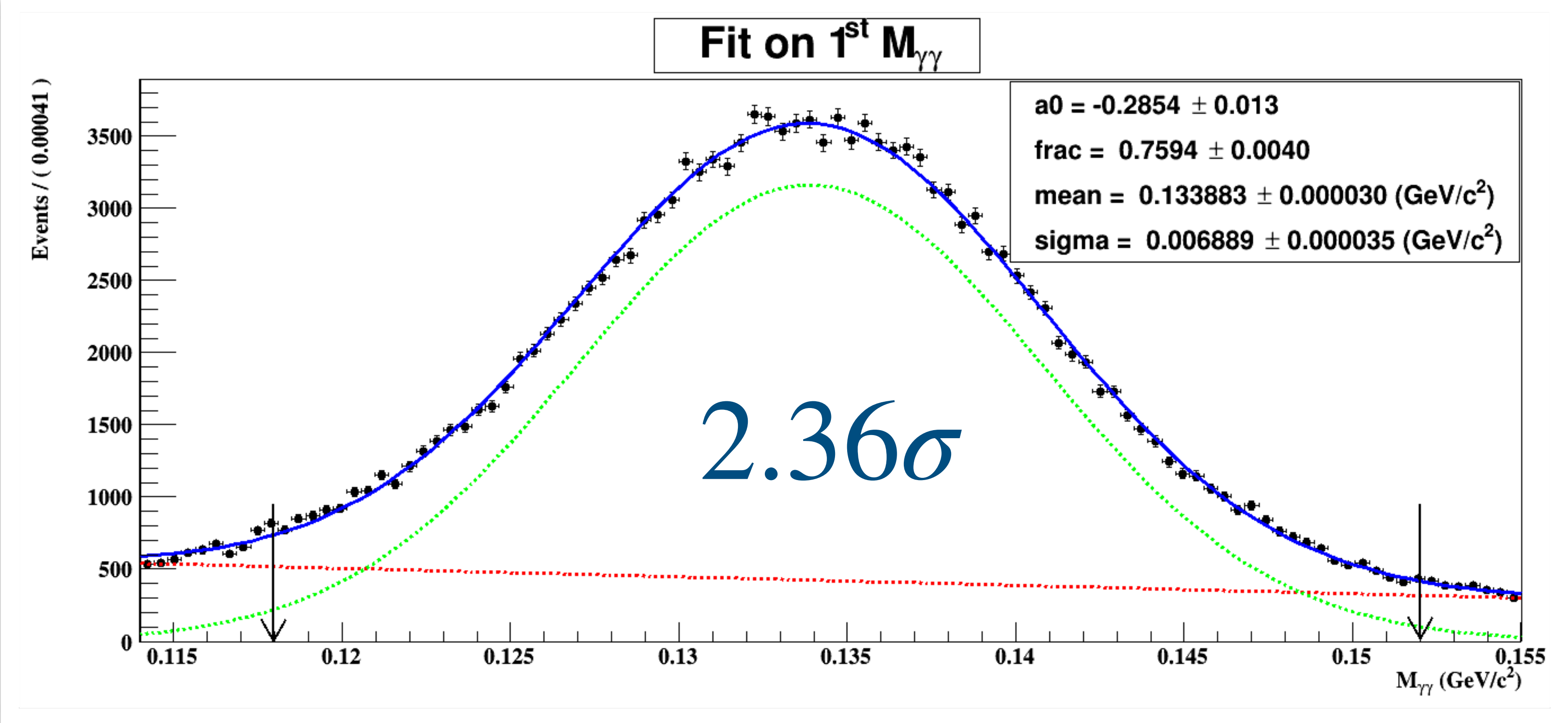
Phys. Rev. D 91, 344 014011 (2015)

- Previously searched by L3 experiment in 1995 by producing B_s^0 from 3 million Z decays **PLB 363, 127 (1995)**
- Did not find any significant signal yield and hence put an UL on the $\mathcal{B}$ of less than 2.1×10^{-4} at 90% CL
- First search at Belle with 121.4 fb^{-1} of data collected at $\Upsilon(5S)$ resonance.

Signal MC study







MCtruth : Correctly reconstructed signal candidates

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^{*2} - p_{B_s^0}^{*2}}$$

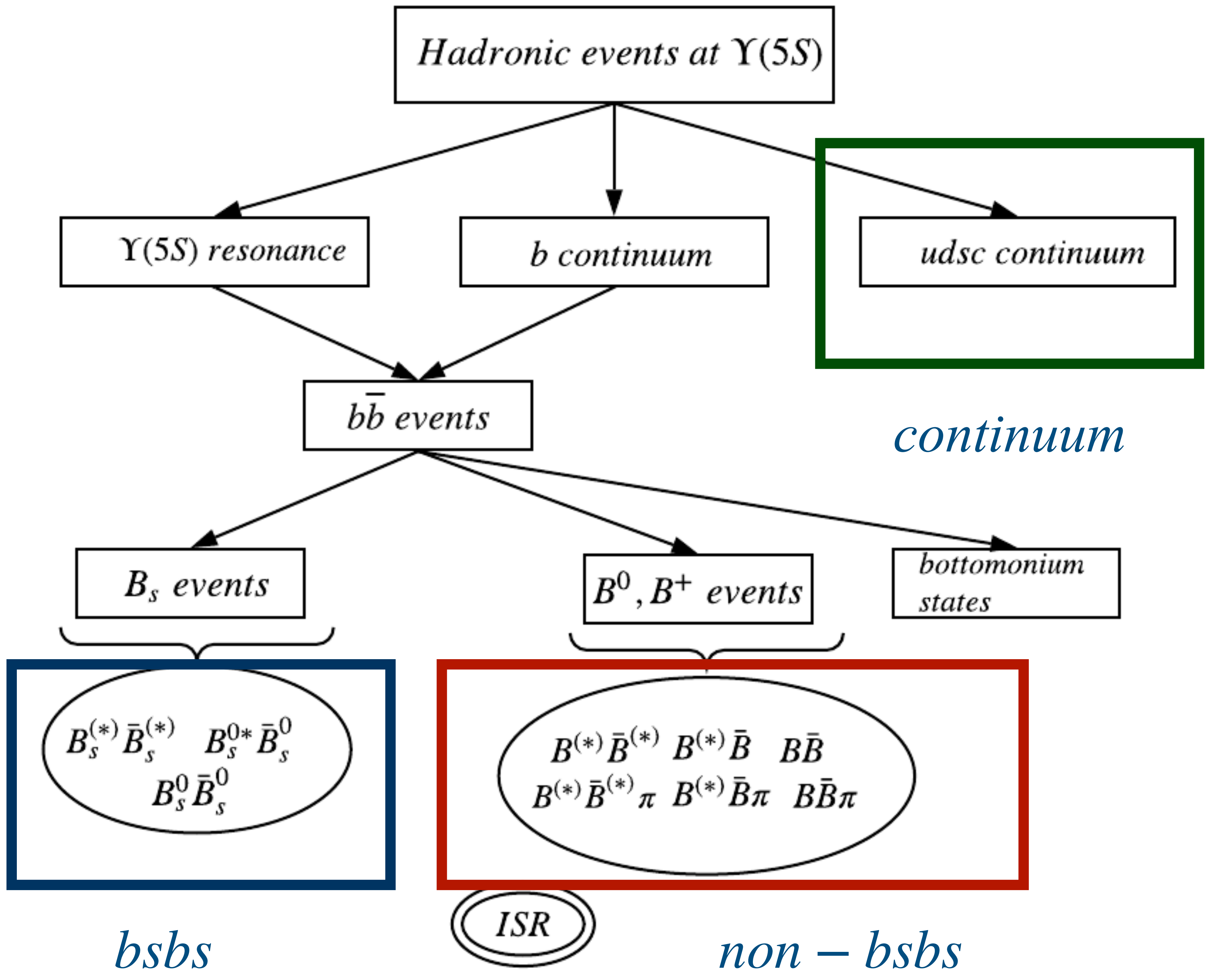
$$\Delta E' = E^*_{B_s^0} - E^*_{\text{beam}} + M_{\text{bc}} - M_{B_S^0}$$

- $\Delta E'$ has a greater mass dependency than M_{bc}
- $\Delta E'$ provides greater discrimination than M_{bc}
- For correctly reconstructed signal candidates, $\Delta E'$ should peak around zero(0)
- However, neutrals in the final state cause shower leakage in the ECL crystals which elongates the tail of the distribution

$$E_{\text{CM}} = \sqrt{s} = 10.86 \text{ (GeV)}$$

$$E^*_{\text{beam}} = E_{\text{CM}}/2 = E^*_{B_s^0}$$

Background MC study

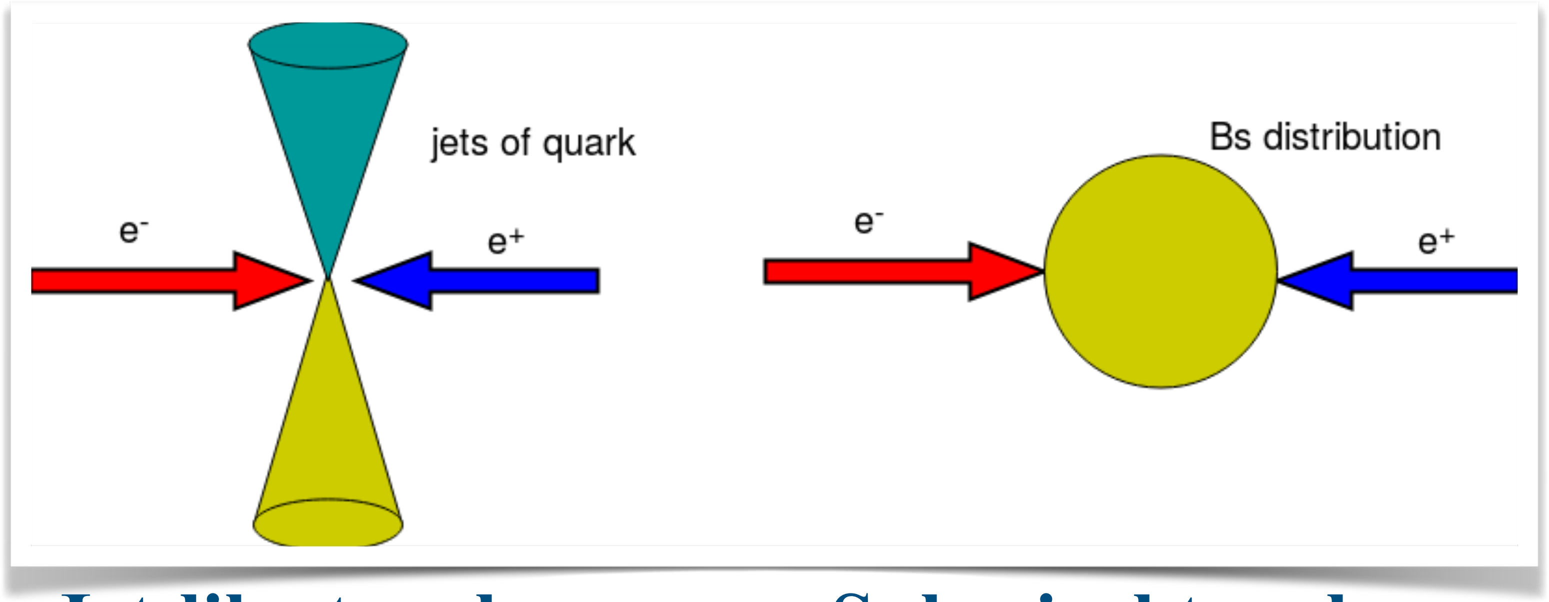


Background MC statistics = $6 \times 121.4\ \mathrm{fb}^{-1}$

Bsbs and non-bsbs backgrounds do not survive the selection criteria

Continuum is the dominant background !

$\propto 1 + cos^2\theta$ $\propto sin^2\theta$



Jet-like topology **Spherical topology**

Event shape distributions

Phys. Rev. Lett. 41, (1978)

3 mom. of i[th] and j[th] FSP

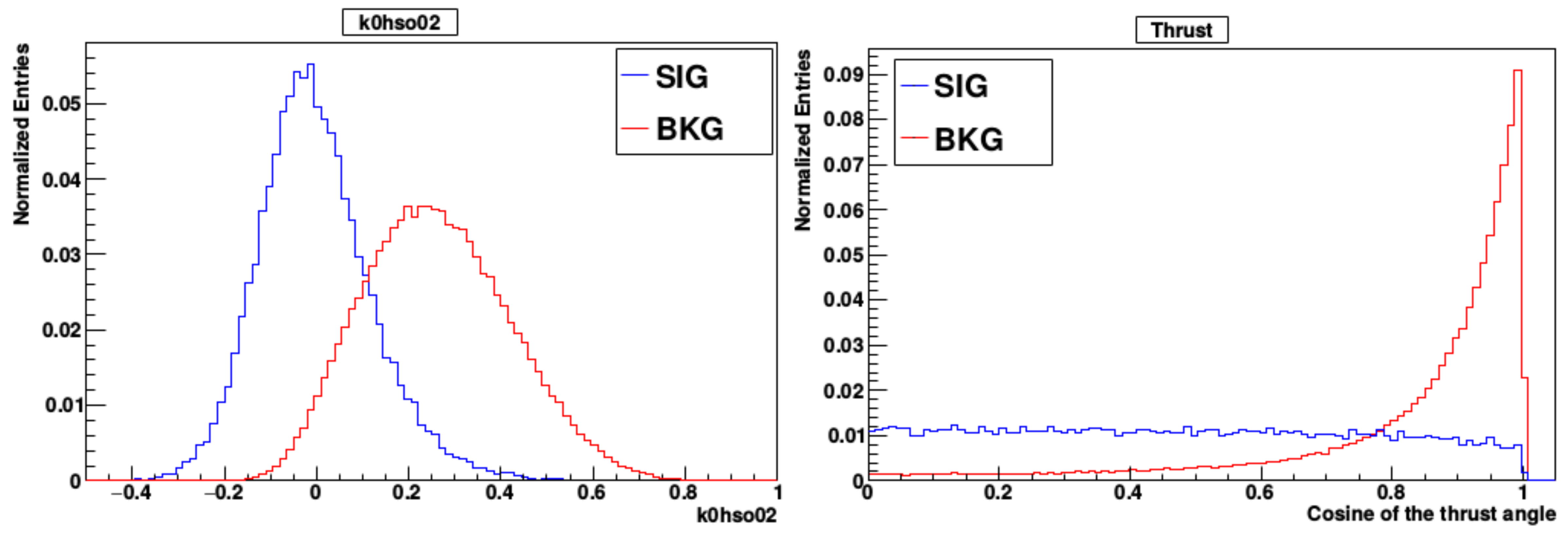
$$\mathrm{H}_l = \sum_{i,j}^{N} \frac{|\bar{P}_i|\ |\bar{P}_j|}{s} P_l(cos\theta_{i,j})$$

Associated Legendre's Polynomial

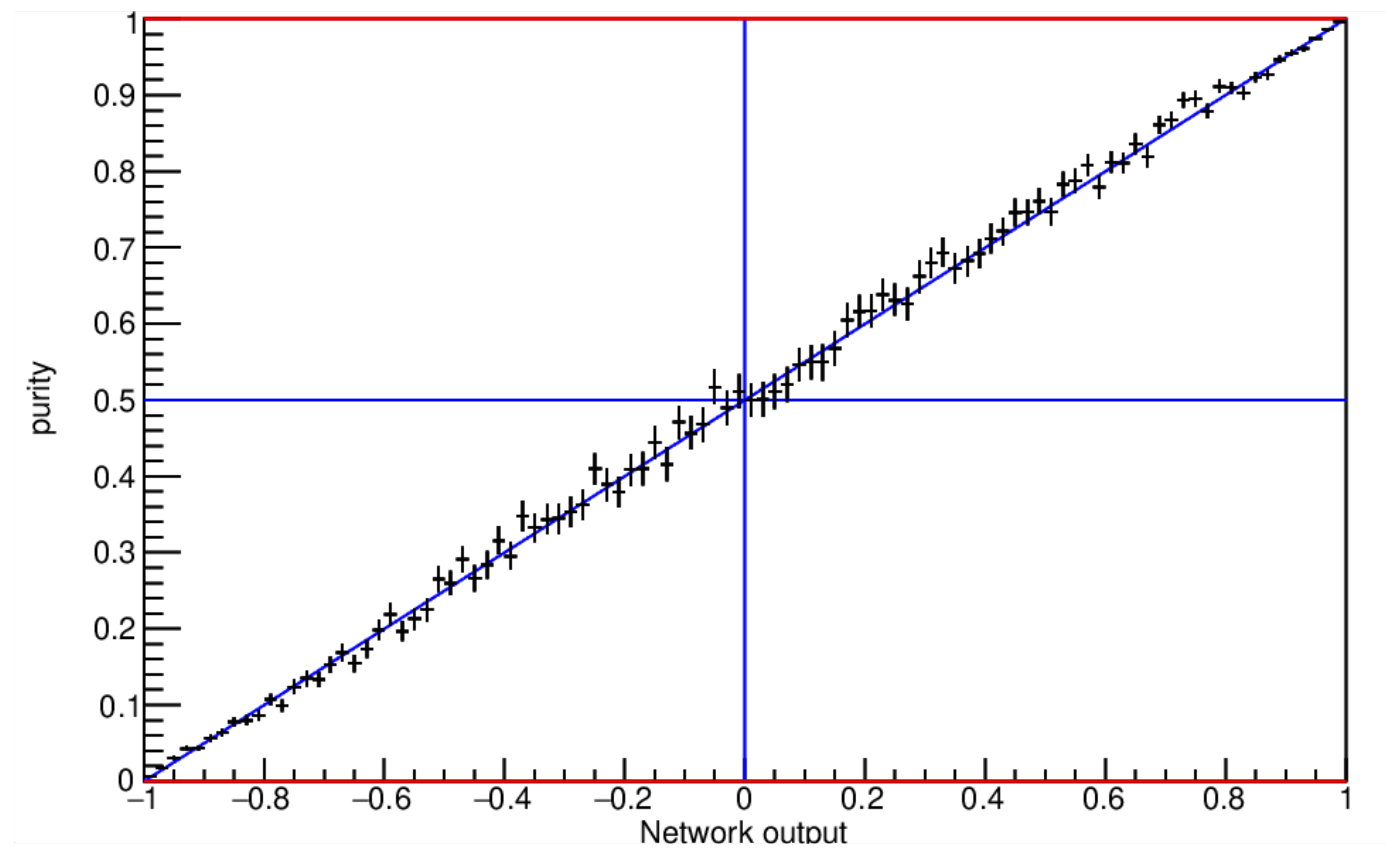
Fox-Wolfram moments

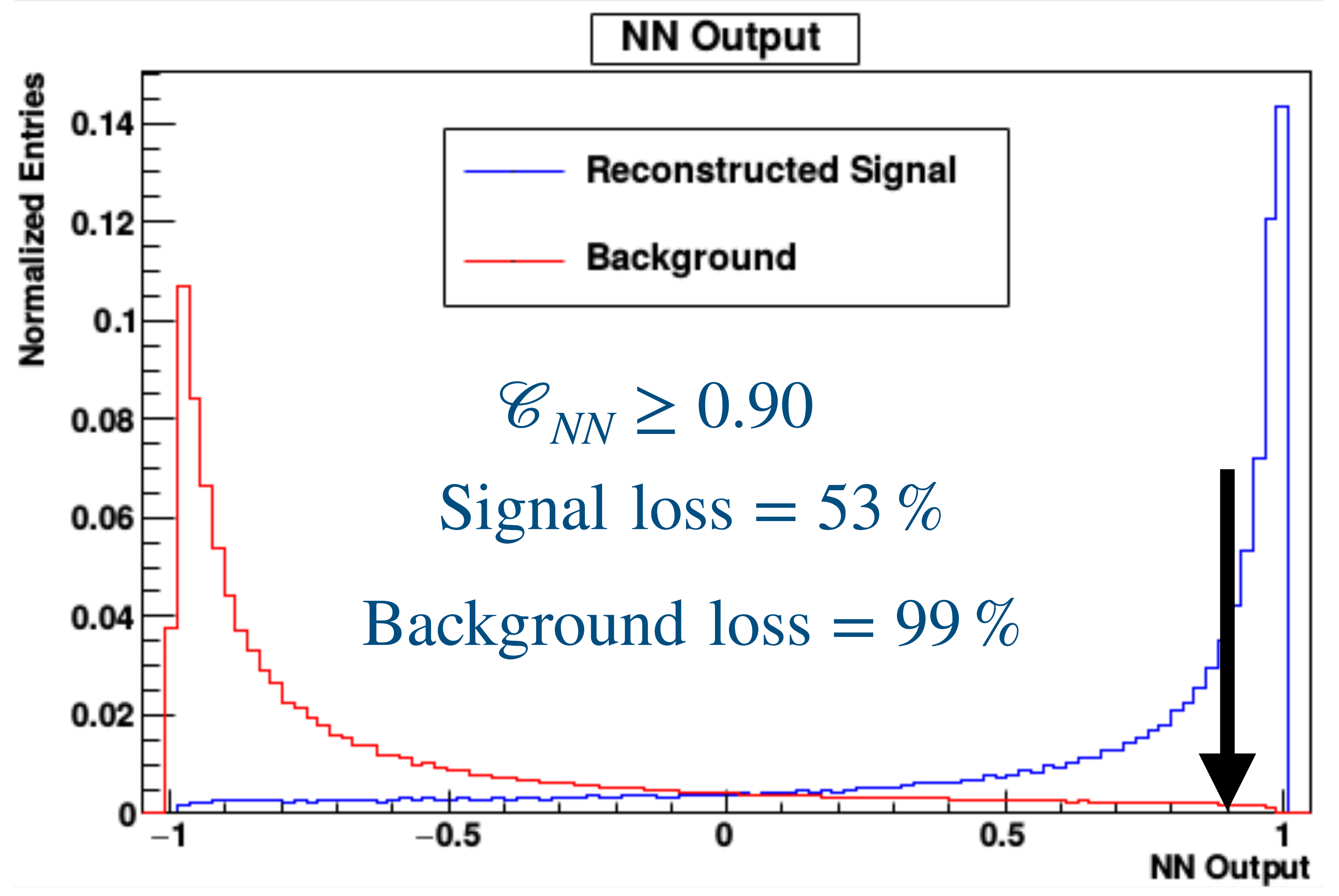
Continuum Suppression: Neural Network

16 mFW moments + thrust angle are given as inputs to neural network



(a) Plot of event shape variable (b) Plot of thrust angle





$\mathscr{C}_{NN} \geq 0.90$

Signal loss = 53 %

Background loss = 99 %

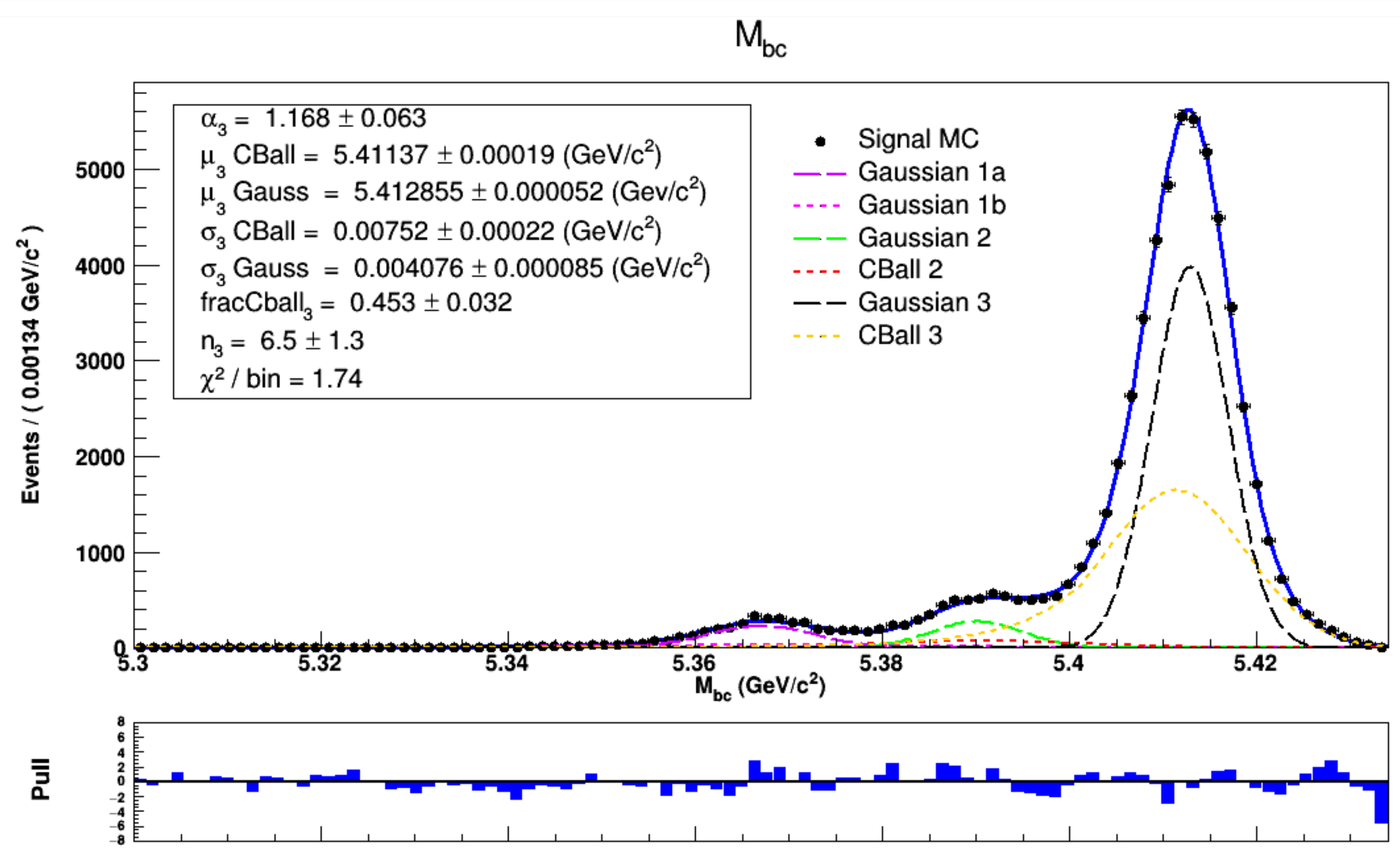
Neural network is used to classify the signal and the background !

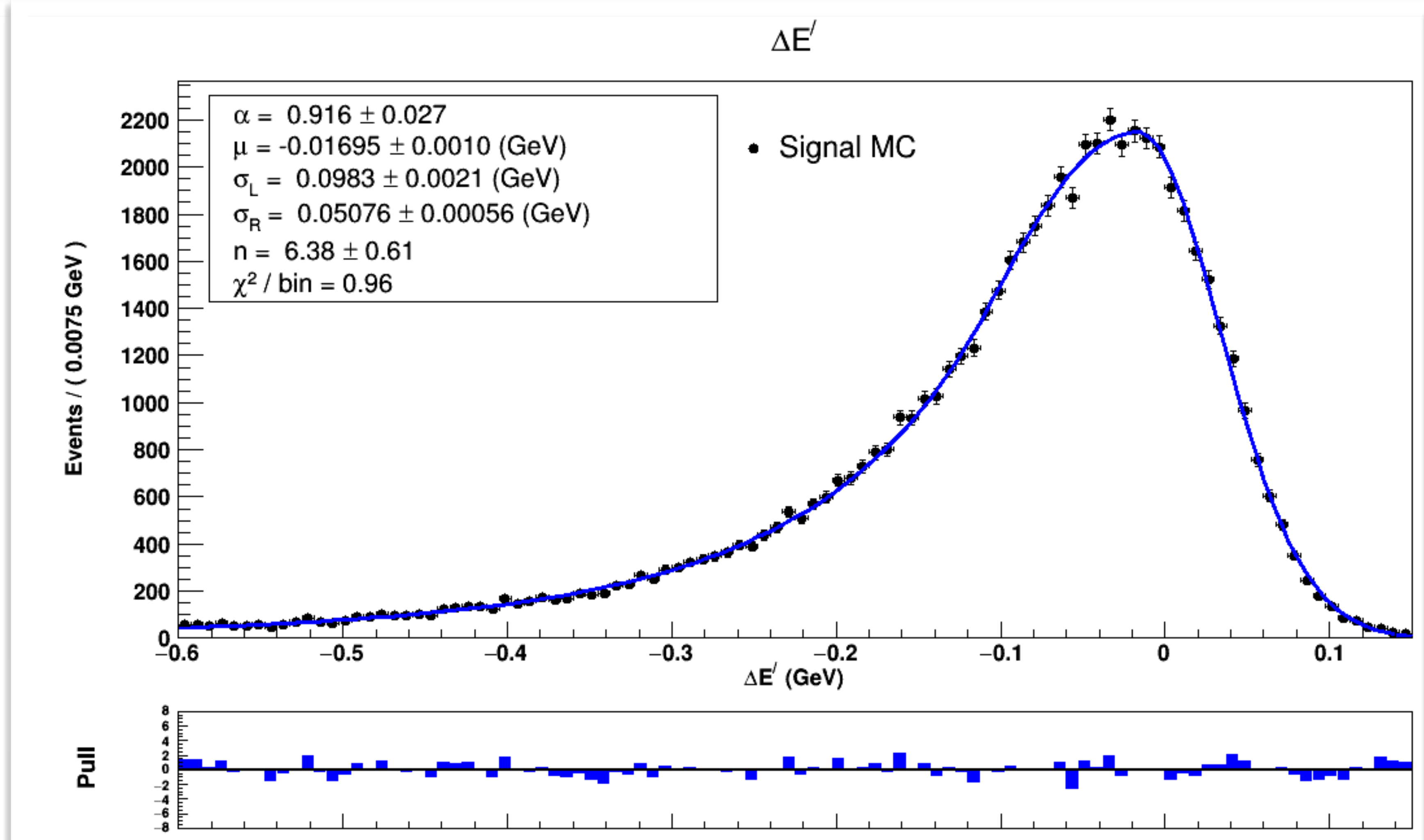
NN output is transformed for easier parametrization

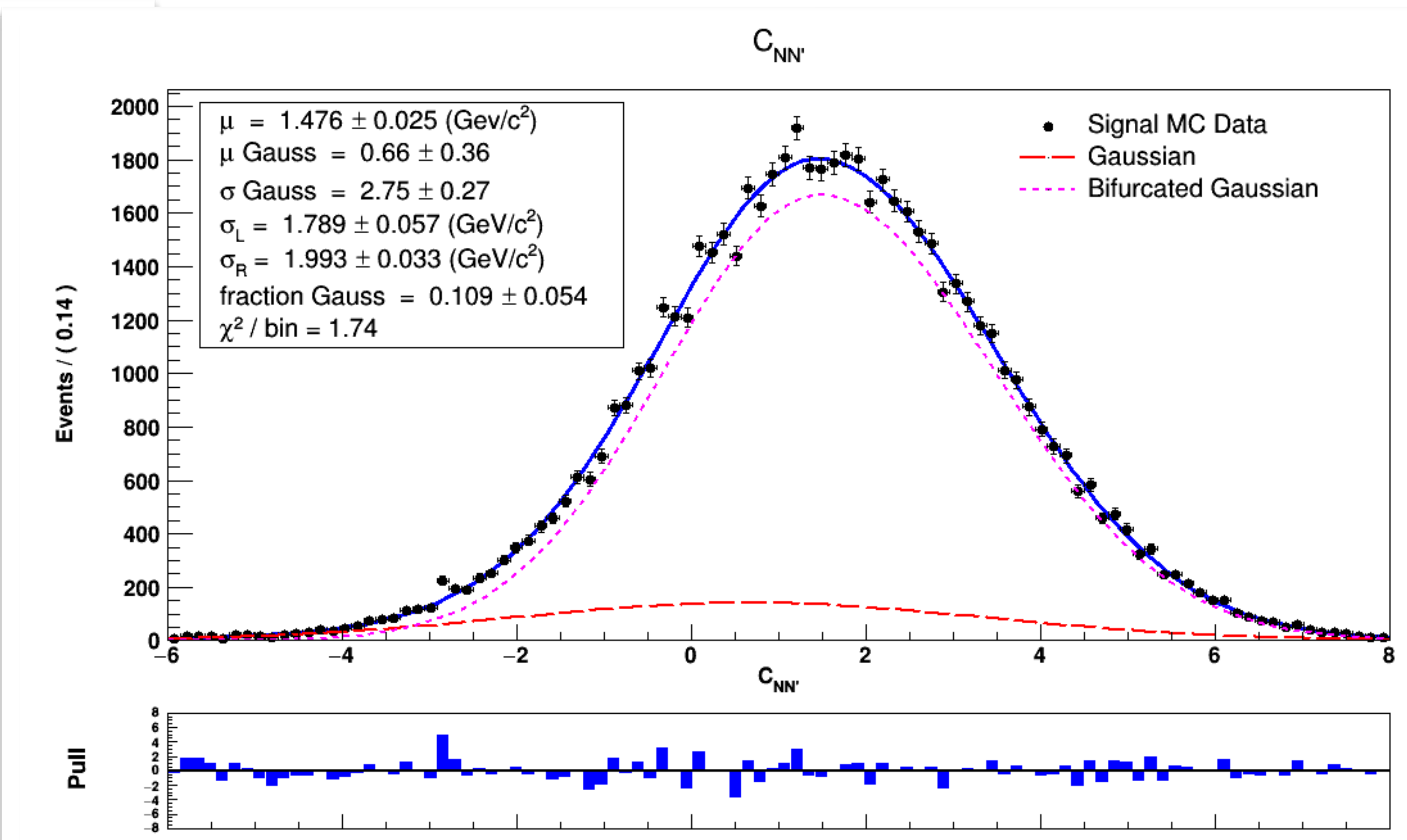
$$\mathscr{C}'_{NN} = log\left(\frac{\mathscr{C}_{NN} - \mathscr{C}_{NN(min)}}{\mathscr{C}_{NN(max)} - \mathscr{C}_{NN}}\right)$$

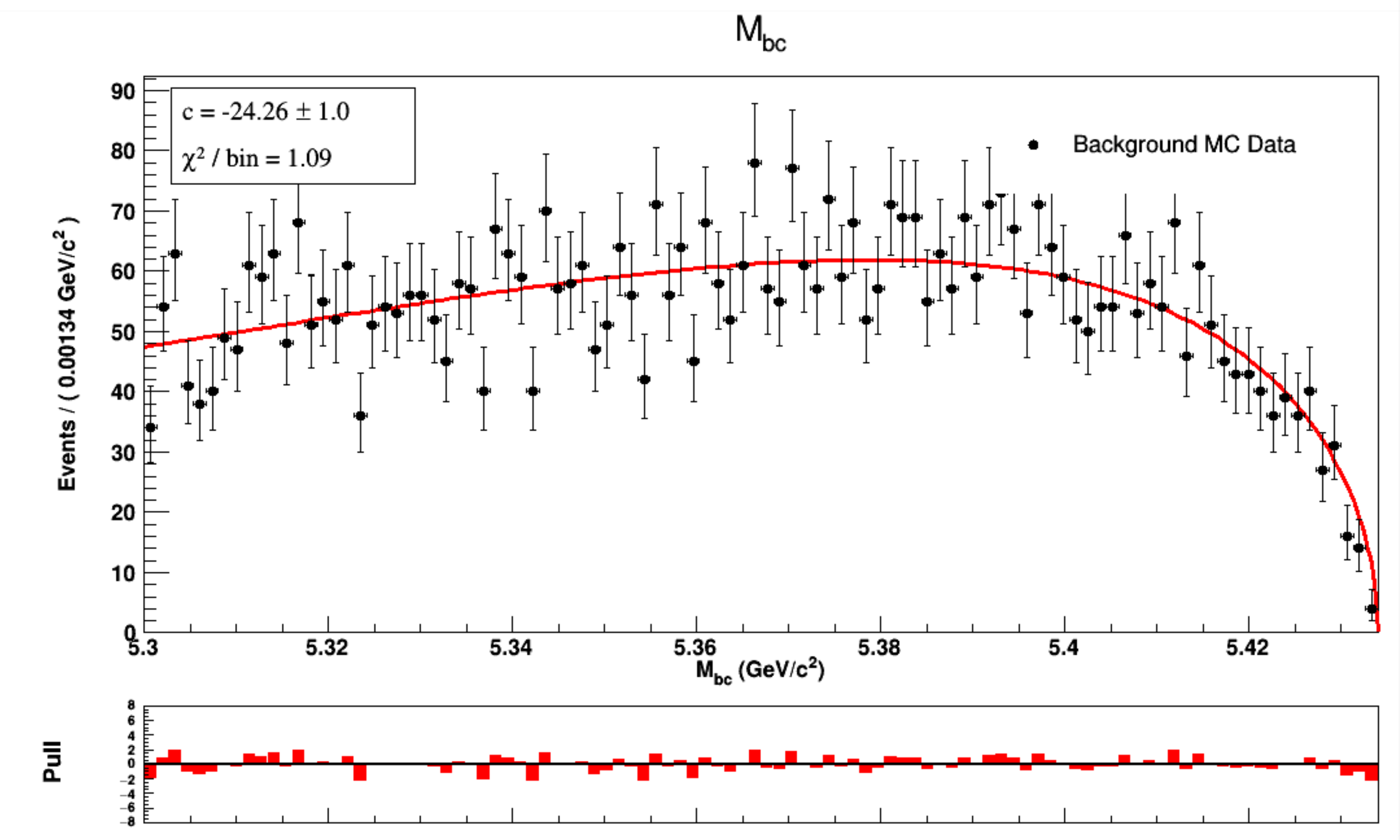
$$\mathscr{C}_{\mathrm{NN(min)}} = 0.90,\ \mathscr{C}_{\mathrm{NN(max)}} = 0.99$$

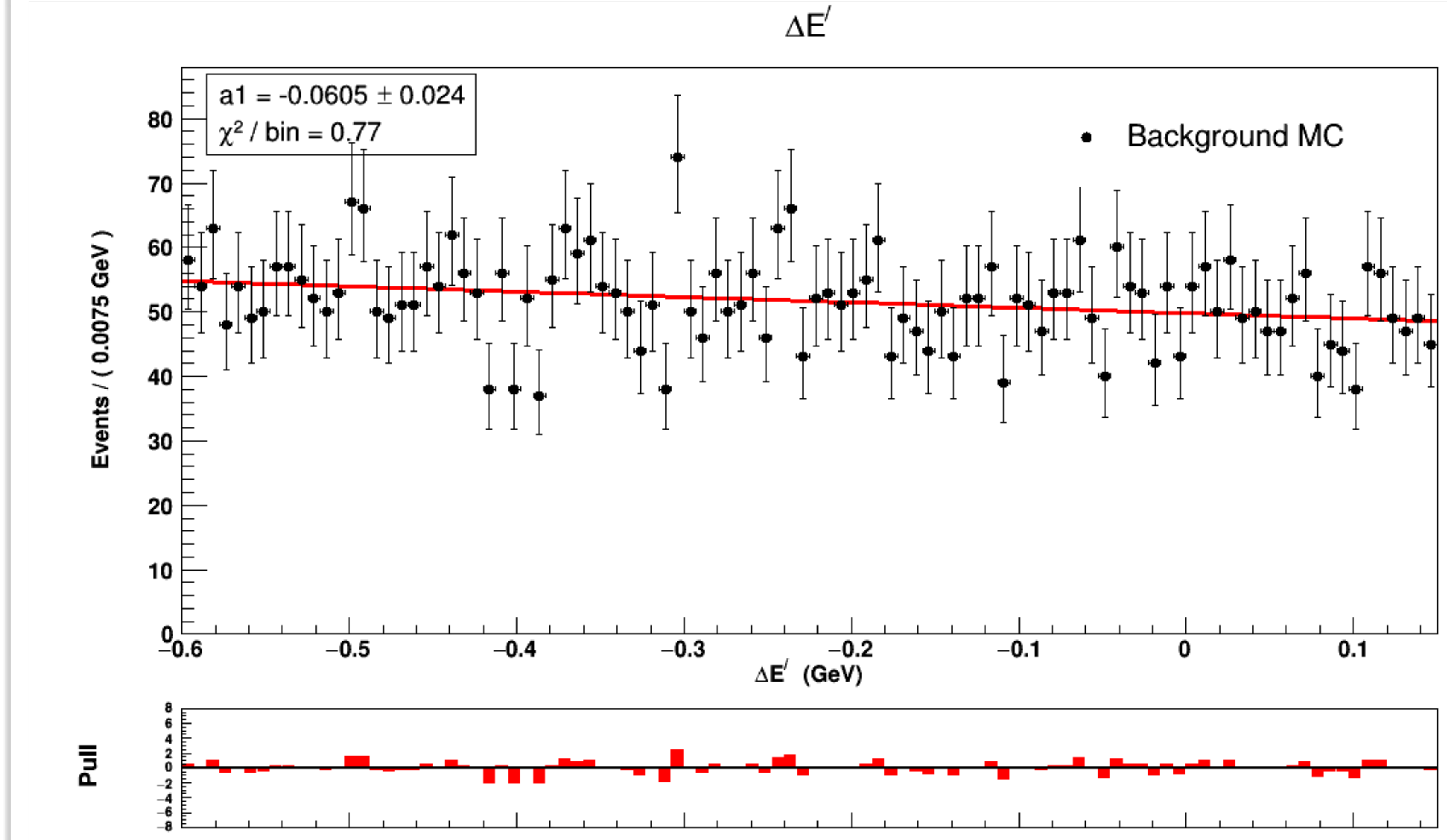
1D PDF parametrizations

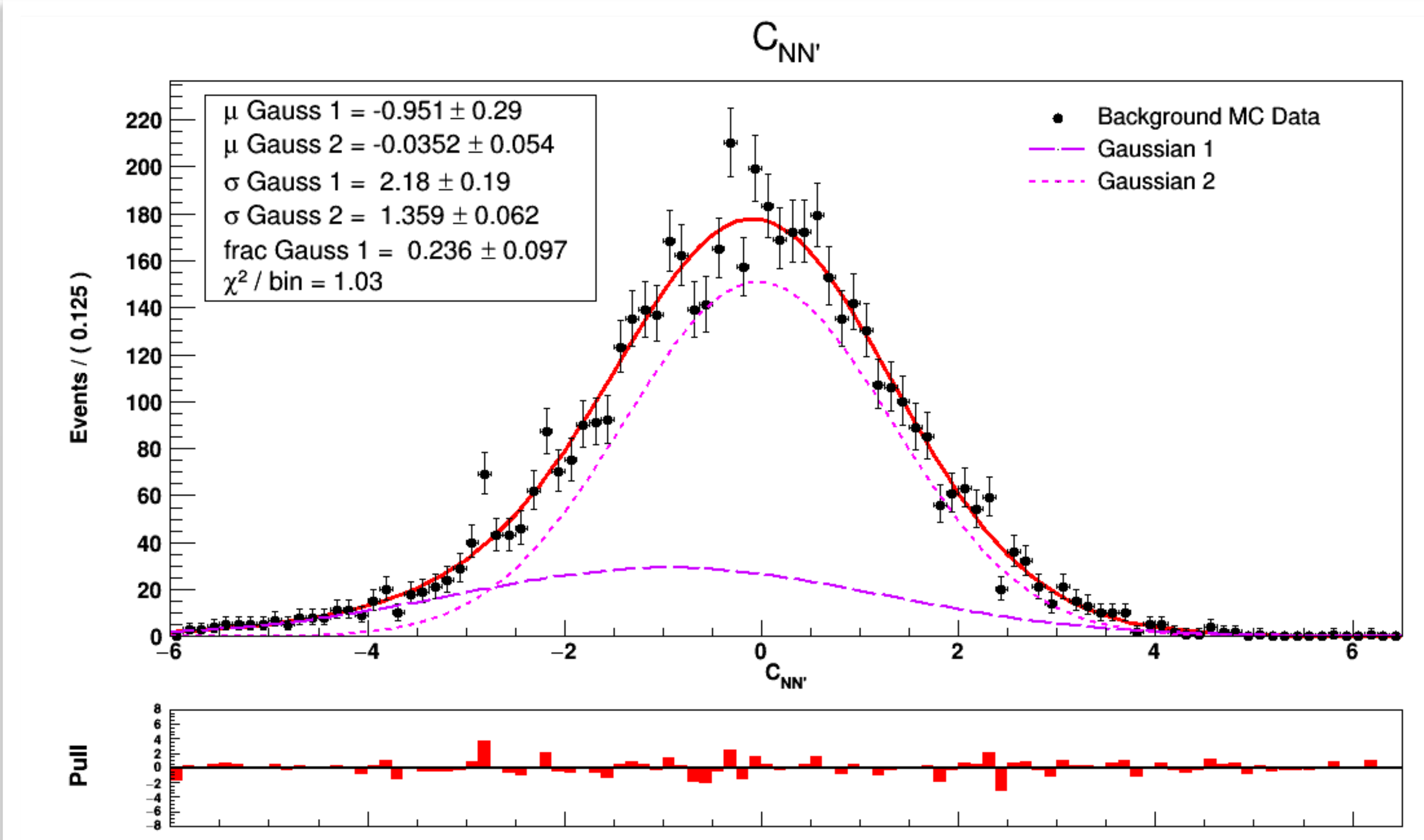








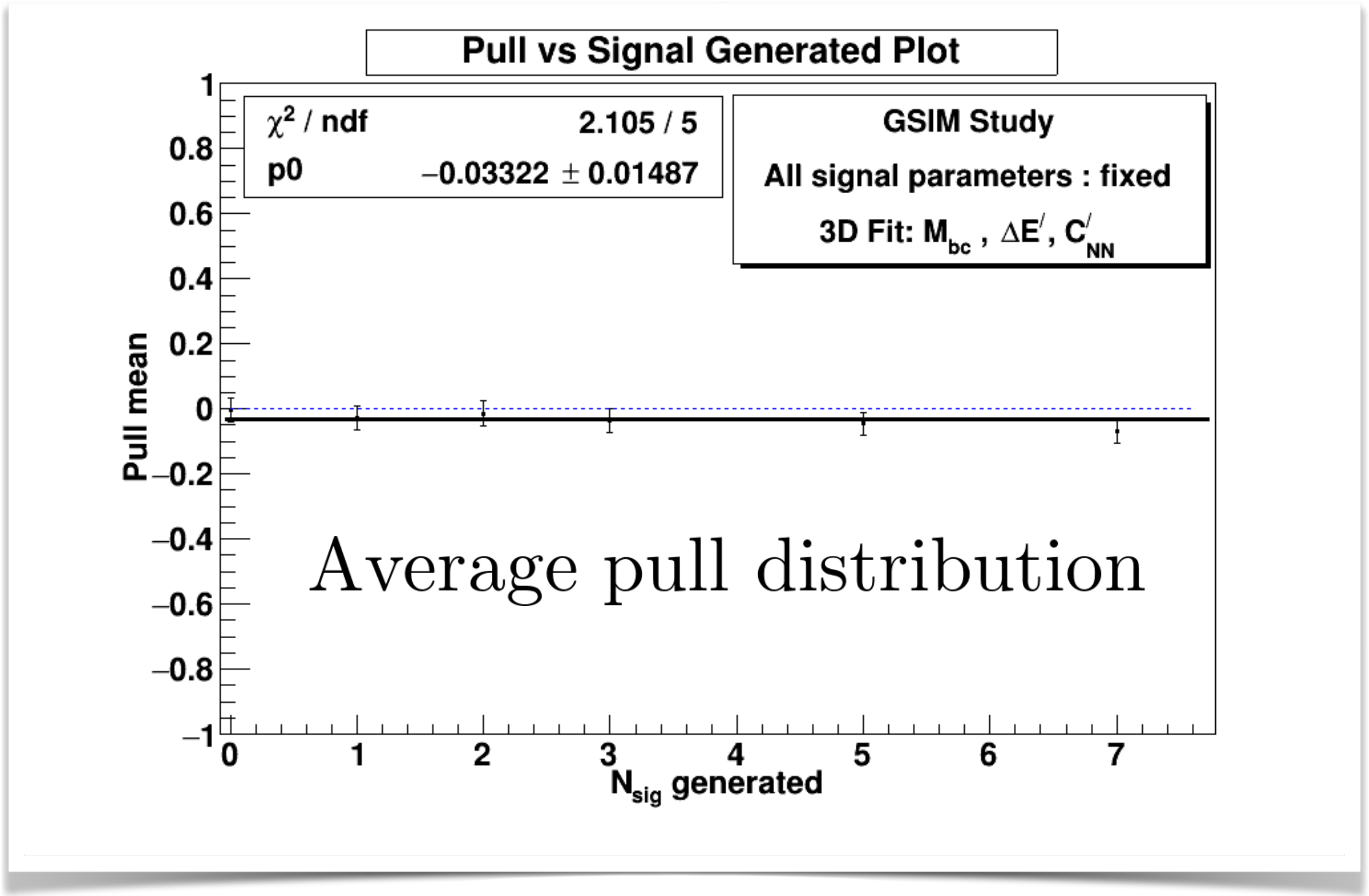




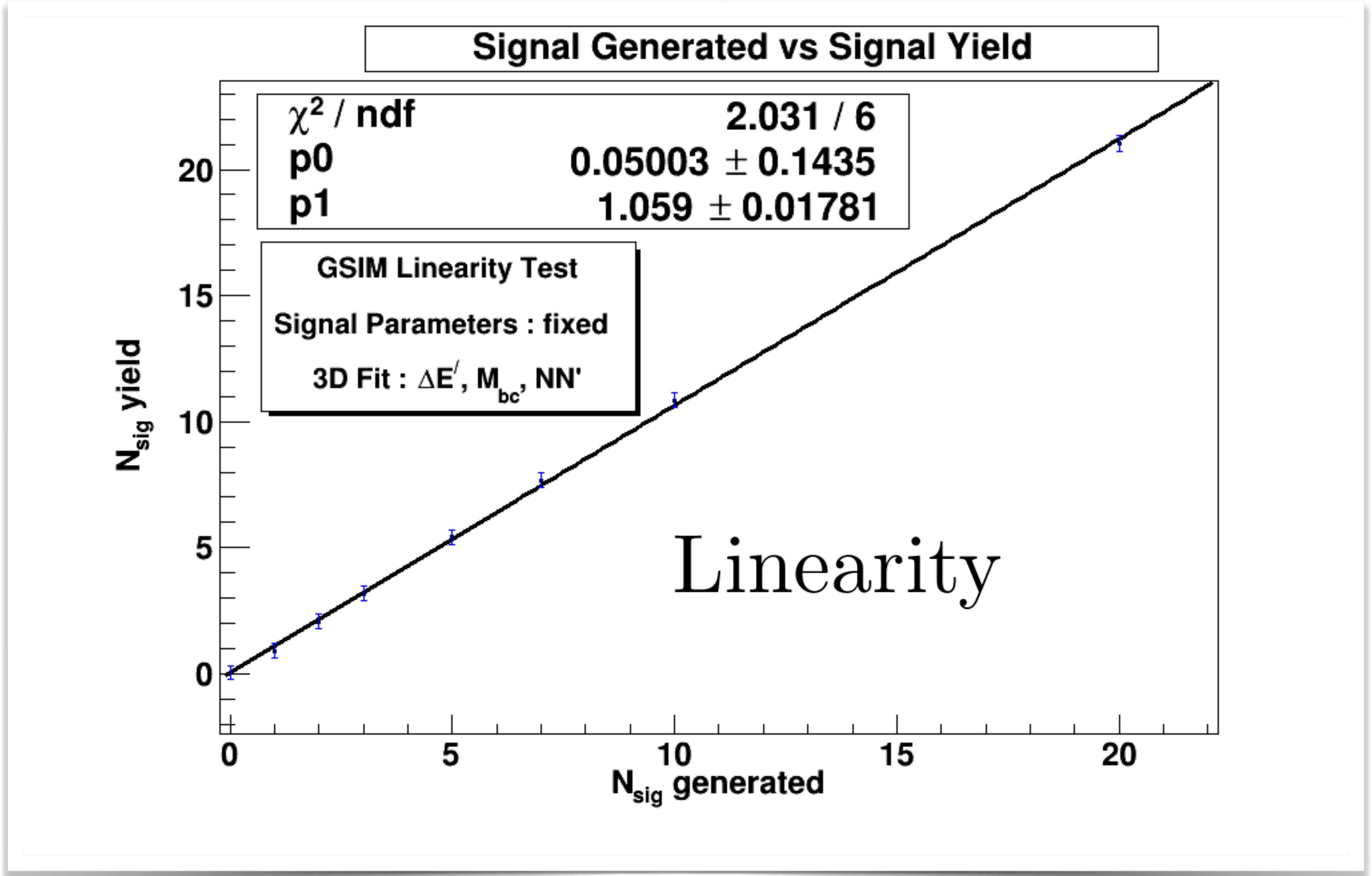
Linear correlations among the fit variables are negligible

Fit model : $3D(M_{bc} \times \Delta E' \times \mathscr{C}'_{NN})$

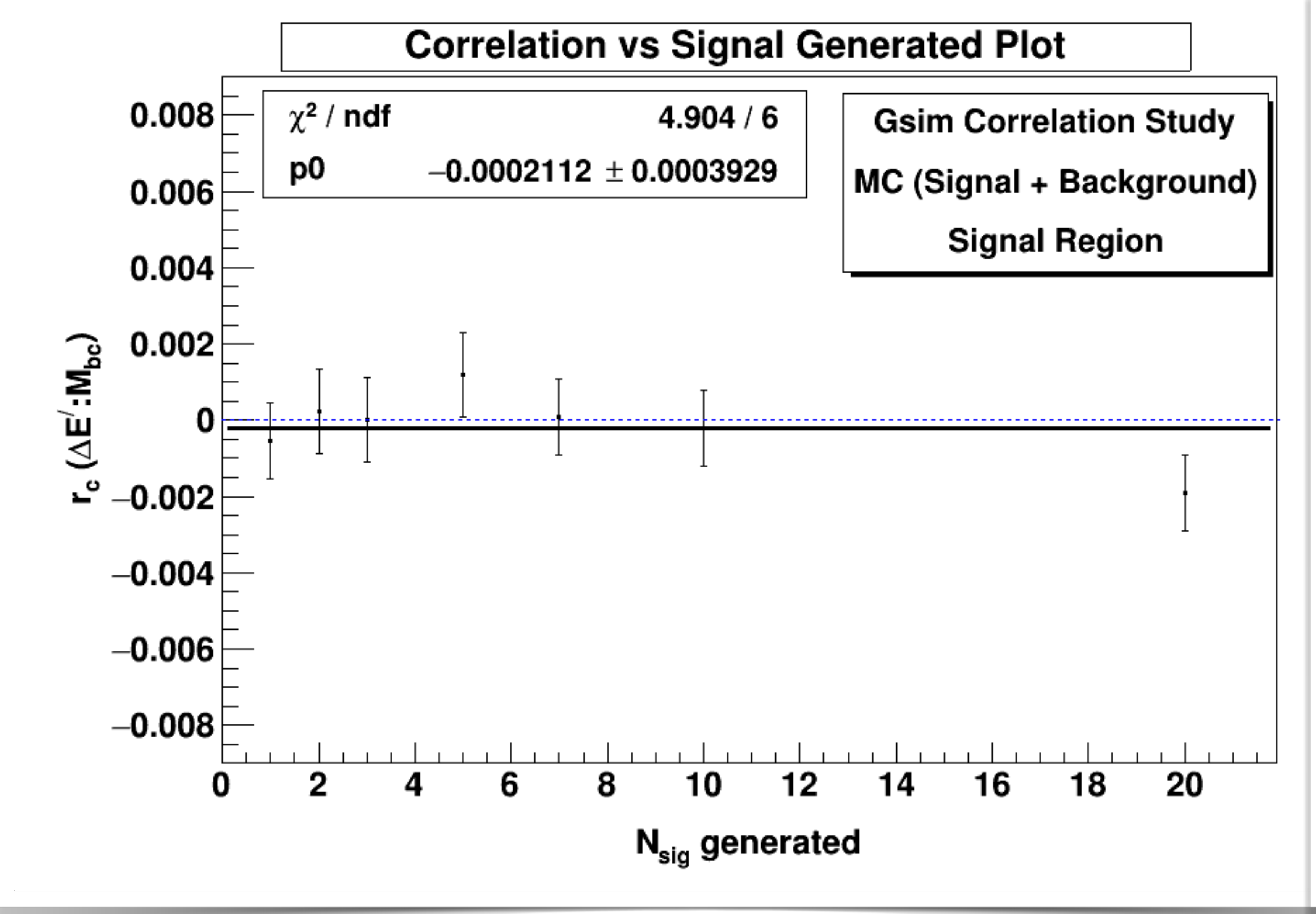
Ensemble study : Fit bias, linearity and correlations

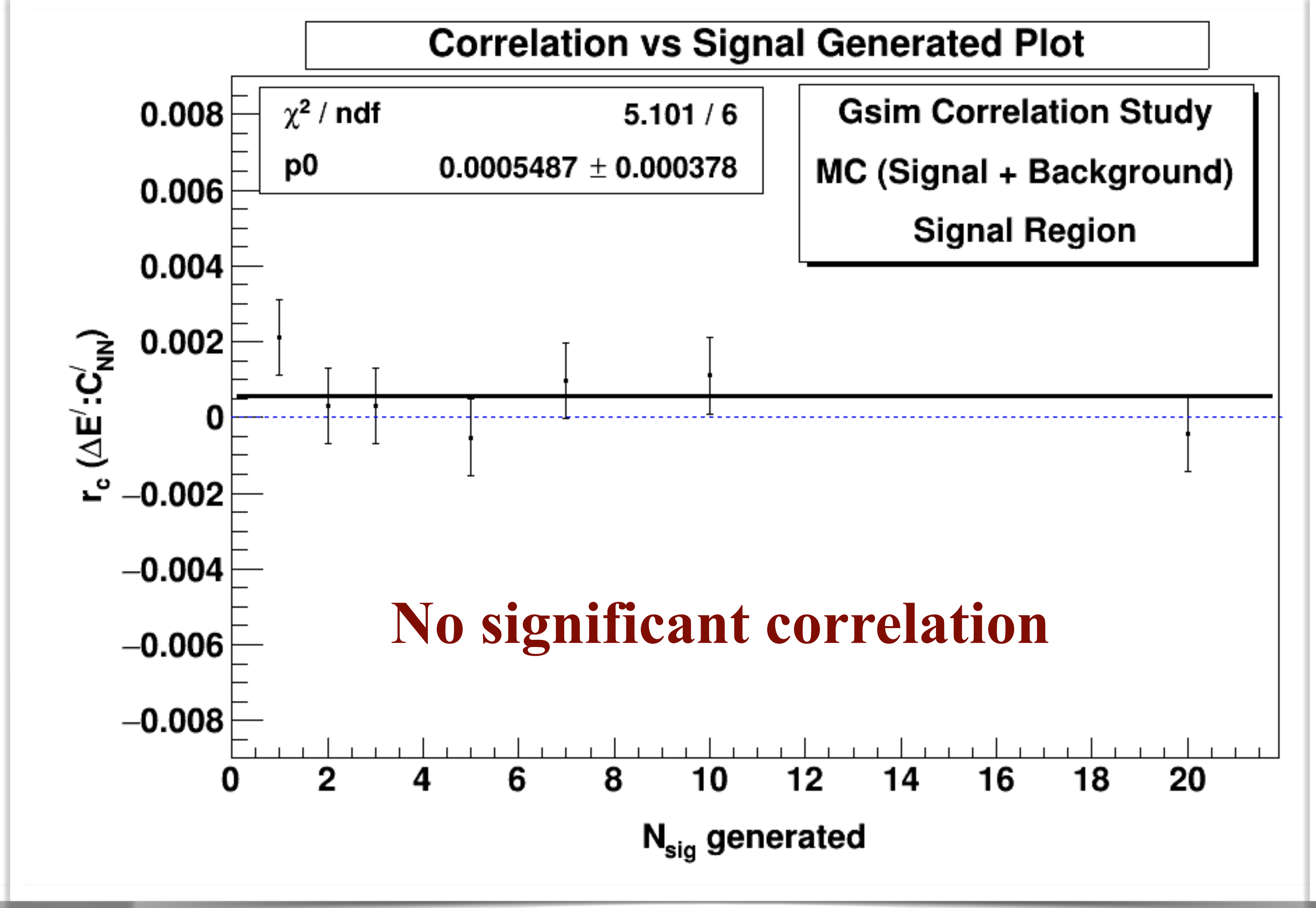


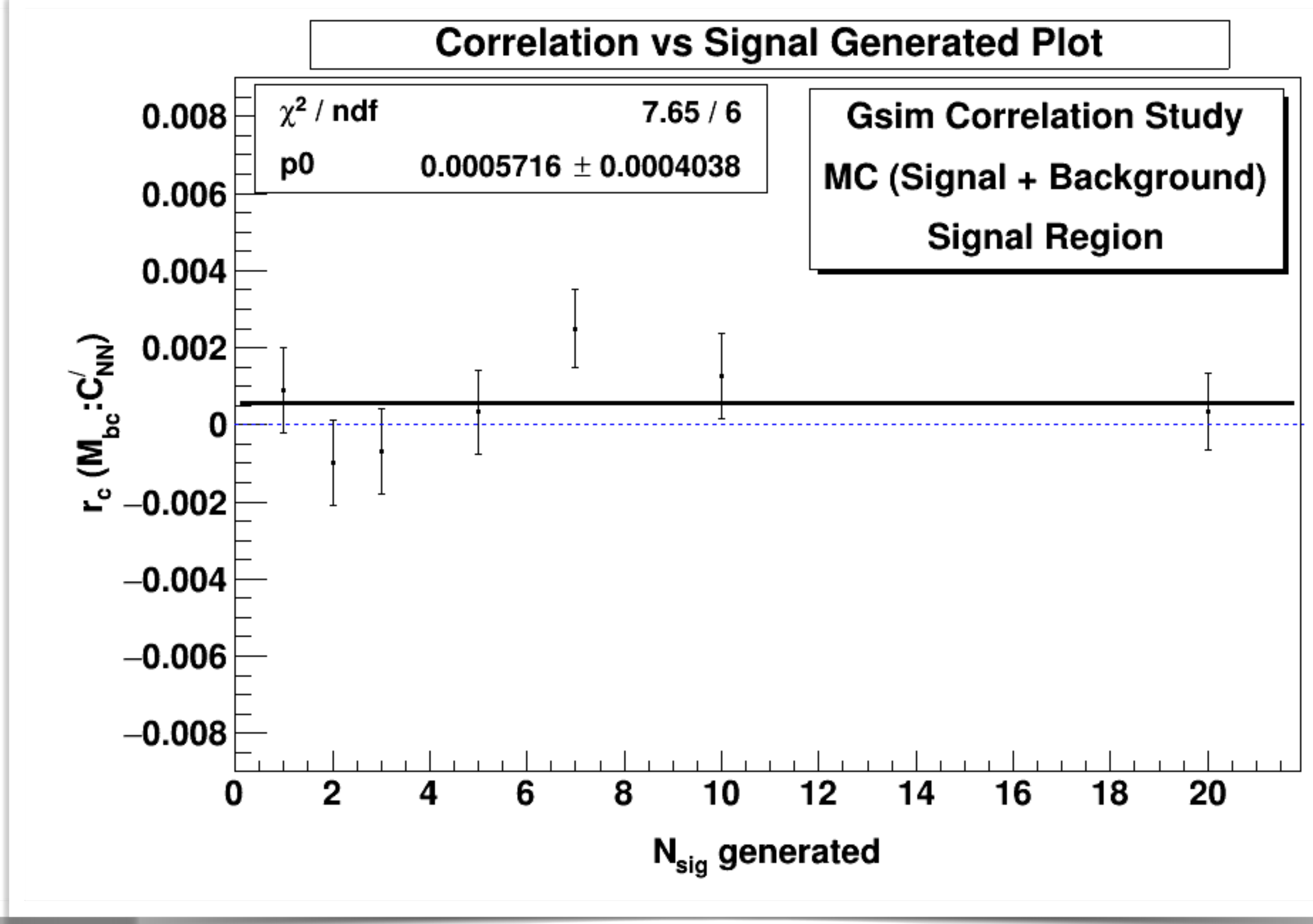
Fit bias = -3.3%



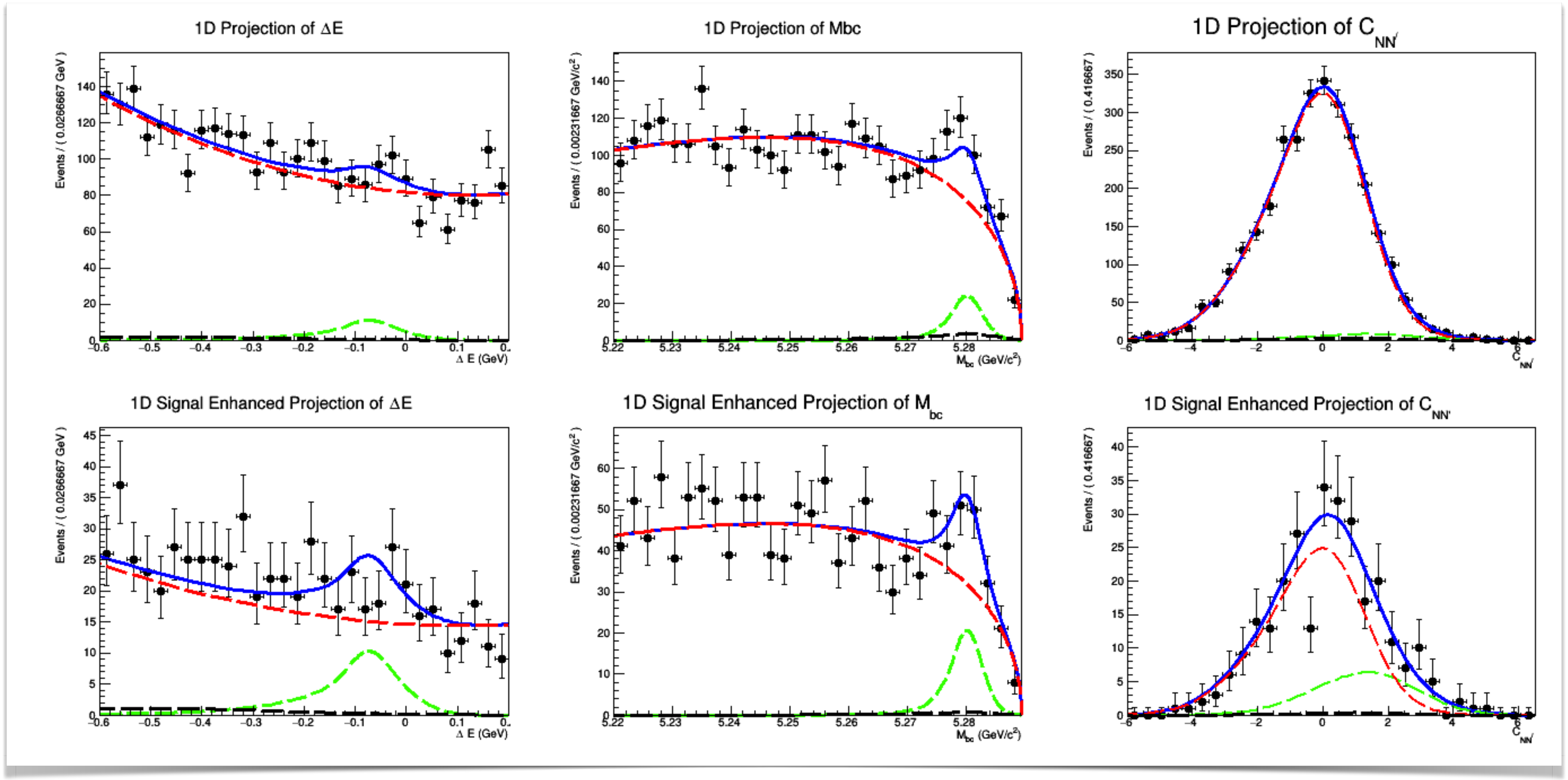
Average correlation distributions for MC (signal + background)







Control sample : $B_d^0 \to \pi^0\pi^0$ (similar final state)



Misreconstruction
Signal region = 0.8%

Candidate region
$-0.6 < \Delta E(GeV) < 0.2$
$5.22 < M_{bc}(GeV/c^2) < 5.29$

Signal region
$-0.23 < \Delta E(GeV) < 0.15$
$5.27 < M_{bc}(GeV/c^2) < 5.29$

- Reconstruction efficiency, $\epsilon = 11.16\%$
- Expected signal yield = 91 (SVD2 data only)

$N^{sig}_{yield} = 80 \pm 14$

BF (PDG) = $(1.59 \pm 0.26) \times 10^{-6}$ [1.17 - 2.01]

BF (Belle) = $(1.31 \pm 0.19(stat.)) \times 10^{-6}$ [0.74 - 1.88]

BF = $(1.18 \pm 0.21(stat.)) \times 10^{-6}$ (within 1.6σ [PDG], 1σ [Belle])

Summary of MC study for $B_s^0 \to \pi^0\pi^0$

Discussion	Remarks
Event generation and simulation	$B_s^{*0}\bar{B}_s^{*0}$, $B_s^{*0}\bar{B}_s^0 + cc$ and $B_s^0\bar{B}_s^0$ 100k signal events for each expt. @ $121.4(fb)^{-1}$ of real data at $\Upsilon(5S)$ resonance
Selection criteria	$0.118 < M(\gamma\gamma)(GeV/c^2) < 0.152$ $E_\gamma > 0.050(0.100)(GeV)$ in barrel (endcaps) $-0.6 < \Delta E' < 0.15$, $M_{bc} > 5.30$ in GeV units, $\mathcal{C}'_{NN} > 0.90$
Signal reconstruction efficiency	12.69%
Multiple candidates	10.4%(7.4%) in candidate (signal) region
BCS criteria	$\chi^2(B_s^0) = \chi^2_{min}(\pi^0) + \chi^2_{min}(\pi^0)$ Overall BCS efficiency = 96%
Misreconstruction fraction	1.7%(1.2%) in candidate (signal) region
Background MC study	continuum is the only surviving background (expect 862 @ $121.4(\text{fb})^{-1}$)
Correlation among fit variables ($\Delta E'$, M_{bc}, $\mathcal{C}'_{NN}$)	Negligibe (1D PDF parametrizations can be done)
Perform 3D UML fit	Extract signal in real data
Control sample study	The $\mathcal{B}(B^0 \to \pi^0\pi^0)$ is obtained within 1σ of the previous Belle result.
Ensemble study	Fit is linear and is found to have insignificant correlation among the fit variables We will assign -3.3% as a source of systematic uncertainty coming from the fit bias.

BCS : Best Candidate Selection

$$\chi^2 = \frac{(M_{rec} - M_{PDG})^2}{\sigma^2}$$

Results for $B_s^0 \to \pi^0\pi^0$

Signal enhanced projections : Signal region selection criteria has been applied for each of the distributions for the other two variables.

- Data equivalent to luminosity of 121.4 fb^{-1}
- Signal and background yields are obtained from 3D fit to M_{bc}, $\Delta E'$, $\mathscr{C}'_{NN}$

Type	MC	Data	Region
Signal	1	5.7 ± 5.8	Candidate
Background (continuum)	862	989 ± 32	Candidate
	327	338 ± 19	Signal
UL (90% CL)	$< 6.6 \times 10^{-6}$	$< 7.7 \times 10^{-6}$	

- Solid blue : Total fit function
- Red dashed : Continuum background
- Cyan-filled : Signal

Systematic uncertainties in $B_s^0 \to \pi^0\pi^0$ analysis procedures

Source	Value (%)
Fit bias	-3.3
Fixed PDF parametrization	$^{+3.5}_{-5.2}$
Fractions of $B_s^{*0}\bar{B}_s^{(*0)}$	$^{+5.2}_{-3.5}$
Reconstruction efficiency, ϵ_{rec}	± 0.4
$\mathcal{C}'_{\rm NN}$ requirement	± 3.0
$\pi^0 \to \gamma\gamma$ selection efficiency	± 4.4
$\mathcal{B}(\pi^0 \to \gamma\gamma)$	± 0.03
$b\bar{b}$ cross-section, $\sigma_{b\bar{b}}$	± 4.7
f_s	± 15.4
Total	$^{+18.1}_{-18.4}$

Branching fraction and upper limit (UL) calculation

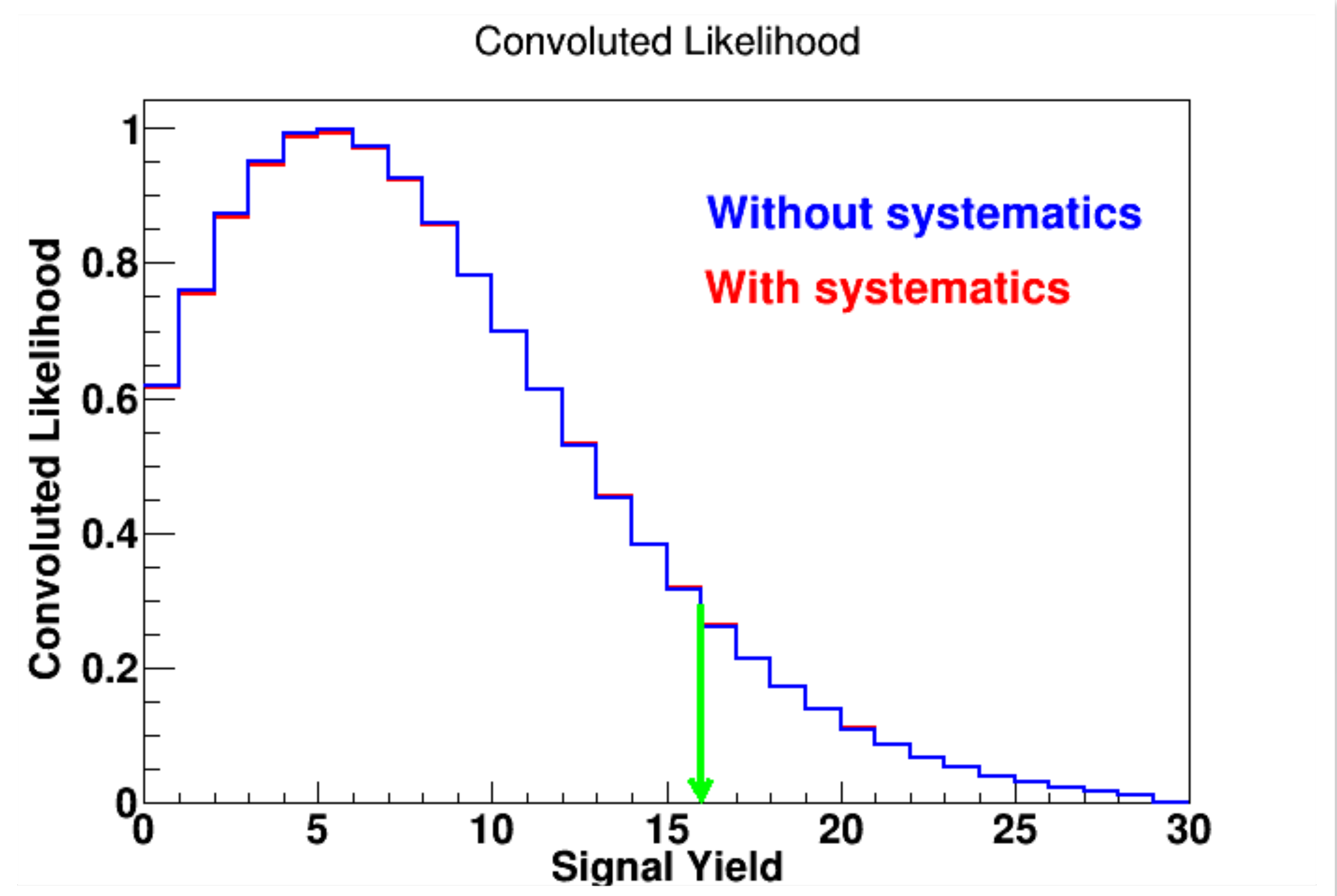
$$\mathcal{B}(B_s^0 \to \pi^0\pi^0) = \frac{N_{sig}}{N_{B_s^0\bar{B}_s^0} \times \epsilon_{rec} \times \prod_{i=1}^{2} \mathcal{B}(\pi^0 \to \gamma\gamma)} = \frac{5.7}{16.6 \times 10^6 \times 0.1269 \times 0.9766} = 2.8 \times 10^{-6}$$

$$\Delta\mathcal{B}_{\text{stat}} = \frac{\Delta N_{\text{sig}}}{N_{\text{sig}}} \times \mathcal{B} = \frac{5.8}{5.7} \times 2.8 \times 10^{-6} = 2.8 \times 10^{-6}$$

$$\mathcal{B}(B_s^0 \to \pi^0\pi^0) = (2.8 \pm 2.8(\text{stat.}) \pm 0.5(\text{syst.})) \times 10^{-6}$$

Use Bayesian approach to set UL on the branching fraction
(*assuming null or background only hypothesis*)

Significance $= 1\sigma$



Without systematics

- $\mathcal{B}(B_s^0 \to \pi^0\pi^0) < 7.3 \times 10^{-6}$@90%CL

With systematics

- $\boldsymbol{\mathcal{B}(B_s^0 \to \pi^0\pi^0) < 7.7 \times 10^{-6}}$**@90%CL**
- $\boldsymbol{f_s \times \mathcal{B}(B_s^0 \to \pi^0\pi^0) < 1.5 \times 10^{-6}}$**@90%CL**

Summary

- We have analyzed data for all the experiments to look at the results for this analysis.
- The branching fraction obtained after un-blinding is $(2.8 \pm 2.8\ (\text{stat.}) \pm 0.5\ (\text{syst.})) \times 10^{-6}$.
- In absence of any significant signal yield, we use the Bayesian approach to estimate the upper limit on the branching fraction.
- The upper limit on the branching fraction at 90% confidence level is calculated to be less than 7.7×10^{-6}. This is an improvement by a magnitude of twenty seven(27) from the previous upper limit set by L3 experiment ($< 2.1 \times 10^{-4}$ at 90% CL).
- The manuscript is ready for journal submission. **(Belle publication council)**

Some recent B_s^0 publications from Belle (2021 - 2022)

- **Search for the decay $B_s^0 \to \eta' K_s^0$**, T. Pang, V. Savinov et al. , PRD 106, 051123 (2022)
- **Search for the decay $B_s^0 \to \eta\eta$**, B. Bhuyan, K. J. Nath, J. Borah et al. , PRD 105, 012007 (2022)
- **Search for the decay $B_s^0 \to \eta'\eta$**, N. K. Nisar, V. Savinov et al. , PRD 104, L031101 (2021)
- **Search for $B_s^0 \to \eta' X_{s\bar{s}}$ at Belle using a semi-inclusive method**, S. Dubey, T. E. Browder et al., PRD 104, 012007 (2021)

Thank You

Additional slides

$$\mathscr{L} = SU_c(3) \times SU_L(2) \times U_Y(1)$$

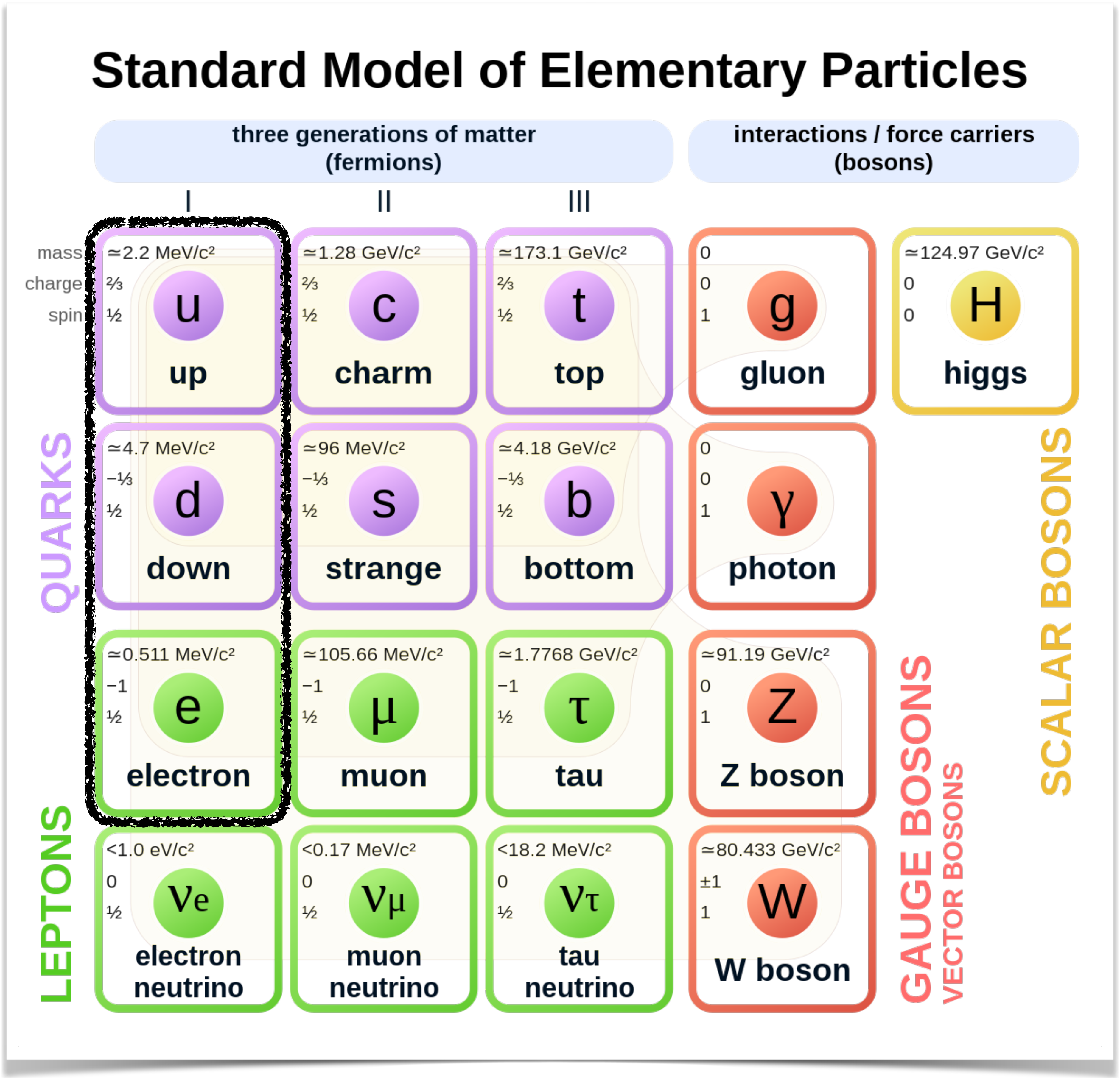
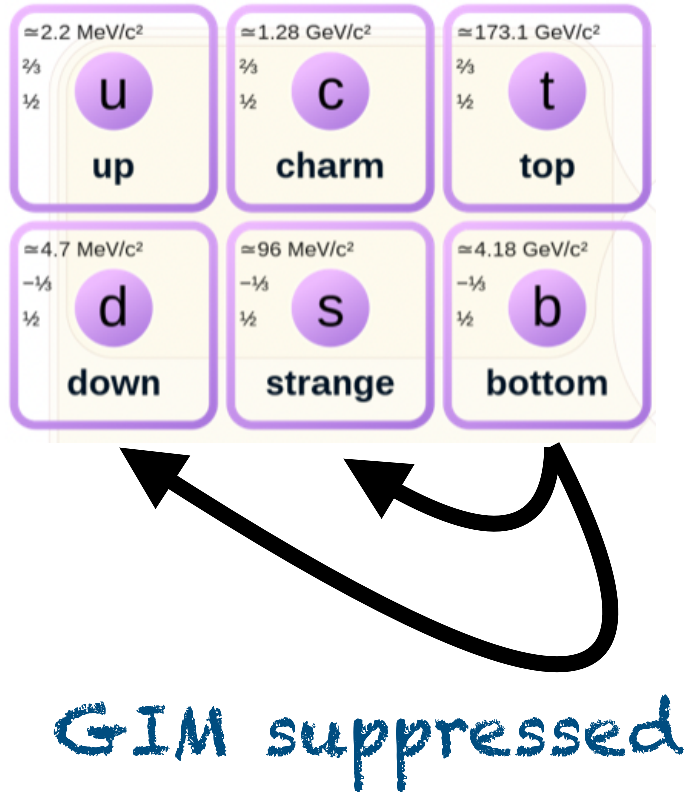
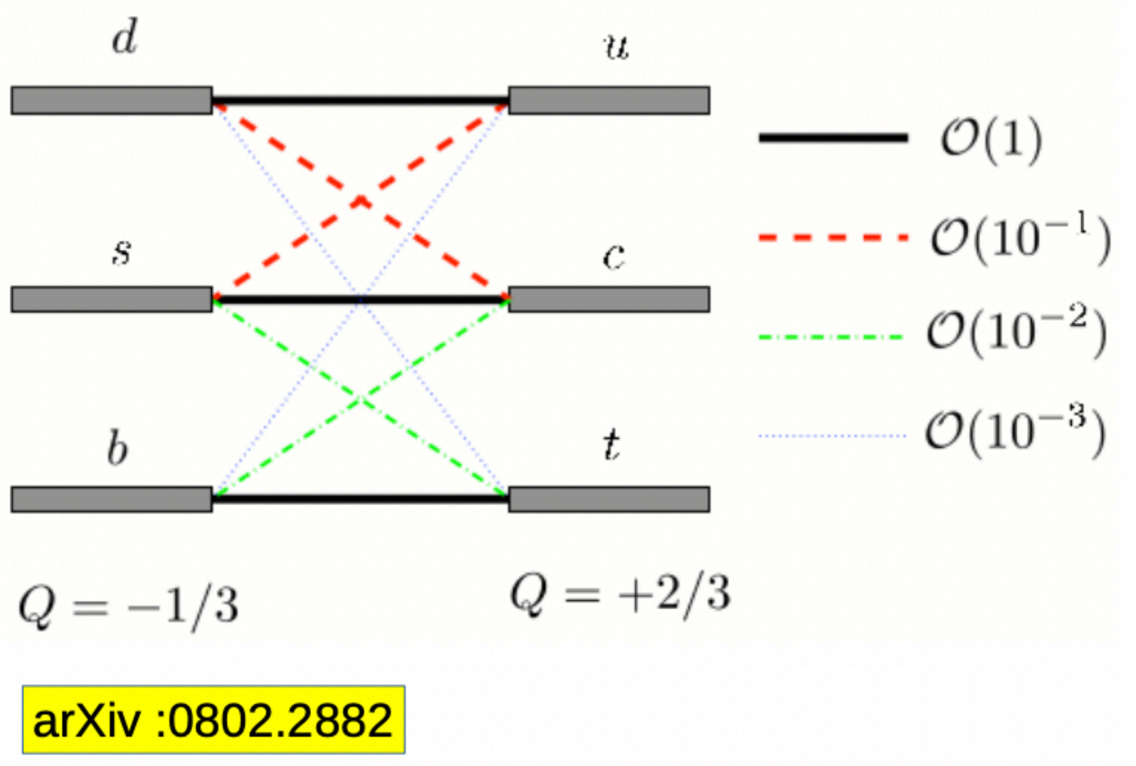


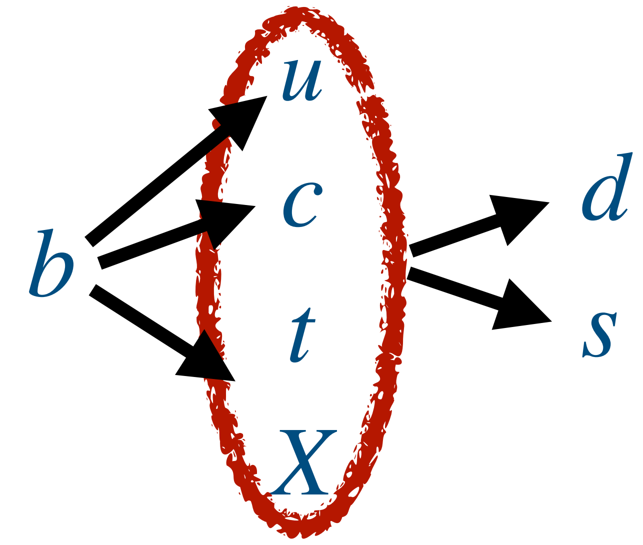
Image Courtsey : Wikipedia

- Mesons are bound states of quark-antiquark pairs held together by strong interactions
- B mesons are composed of a bottom quark and any of the other four anti-b quarks giving, $B^+(\bar{b}u)$, $B_c^+(\bar{b}c)$, $B^0(\bar{b}d)$, $B_s^0(\bar{b}s)$
- At Belle, $B^+(\bar{b}u)$, $B^0(\bar{b}d)$, $B_s^0(\bar{b}s)$ are well studied with topics ranging from searches for rare decay modes, CP violation measurements, CKM matrix elements determination, Lepton Flavor Universality tests (LFU) and many other interesting aspects of flavor physics.

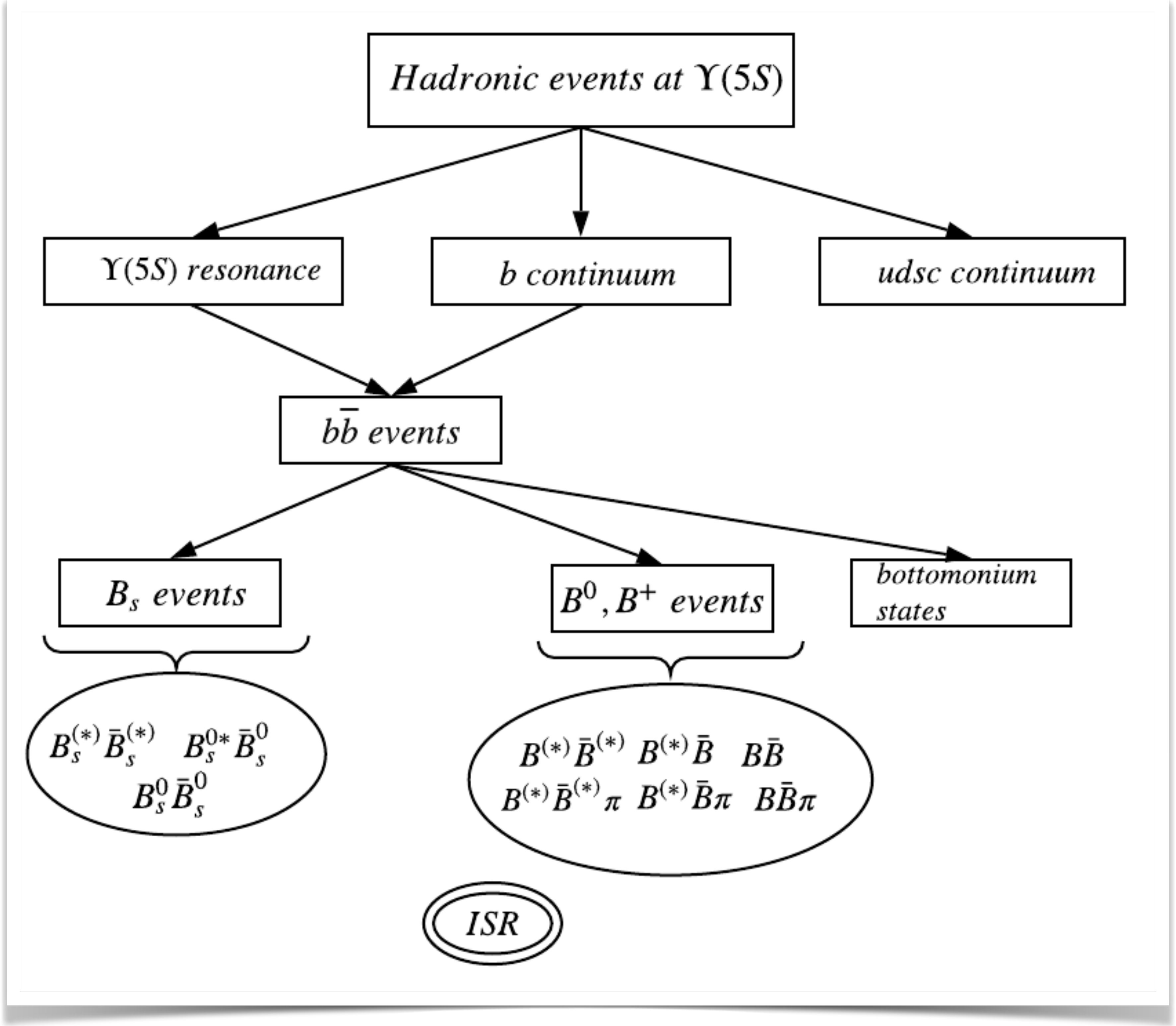
- Decays which do not transit via usual $b \to c$ transitions are rare







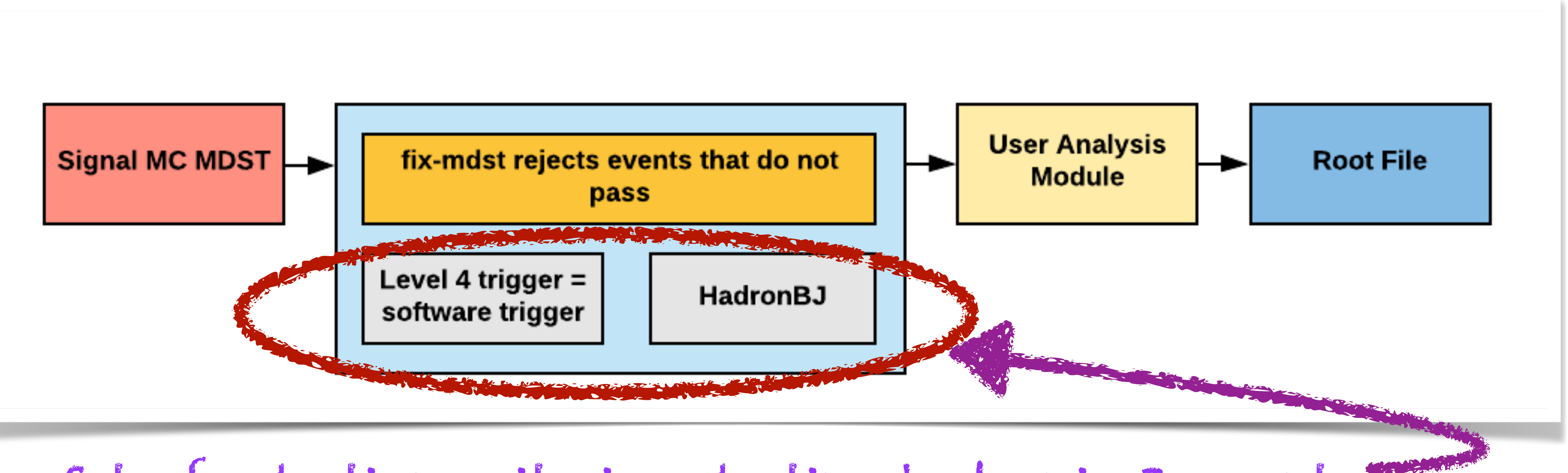
Event generation and event selection



Decay process	Physics models
$\Upsilon(5S) \to B_s^{*0}\bar{B}_s^{*0}$	N-body phase space
$\Upsilon(5S) \to B_s^{*0}\bar{B}_s^{0}$ + cc	N-body phase space
$\Upsilon(5S) \to B_s^{0}\bar{B}_s^{0}$	Vector to scalar scalar
$B_s^{*0} \to B_s^0\gamma$	Vector to scalar photon p-wave
$B_s^0 \to \pi^0\pi^0$	N-body phase space
$\pi^0 \to \gamma\gamma$	N-body phase space

EvtGen (generation)

GEANT (simulation)



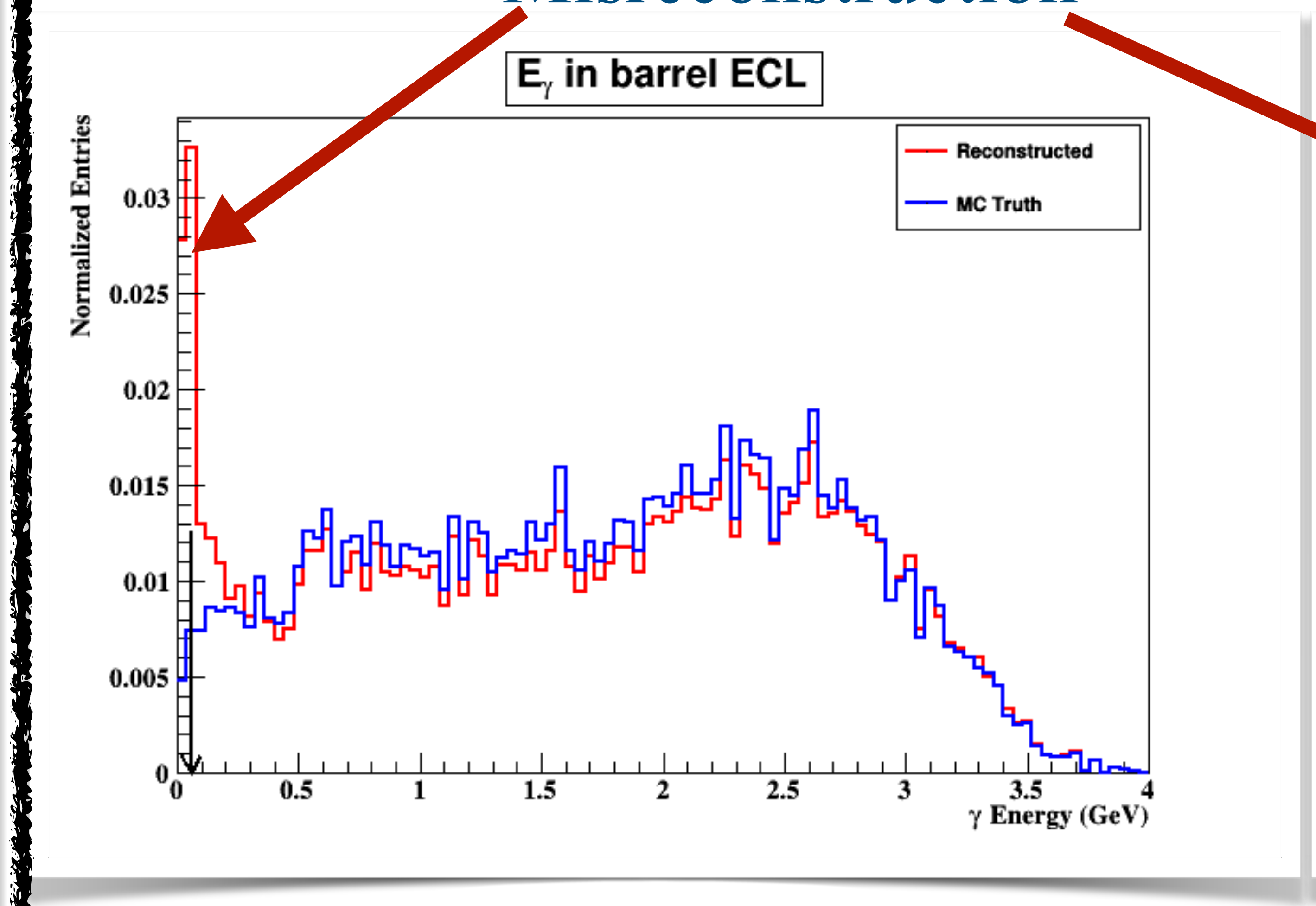
Set of selection criteria selecting hadronic B_s events

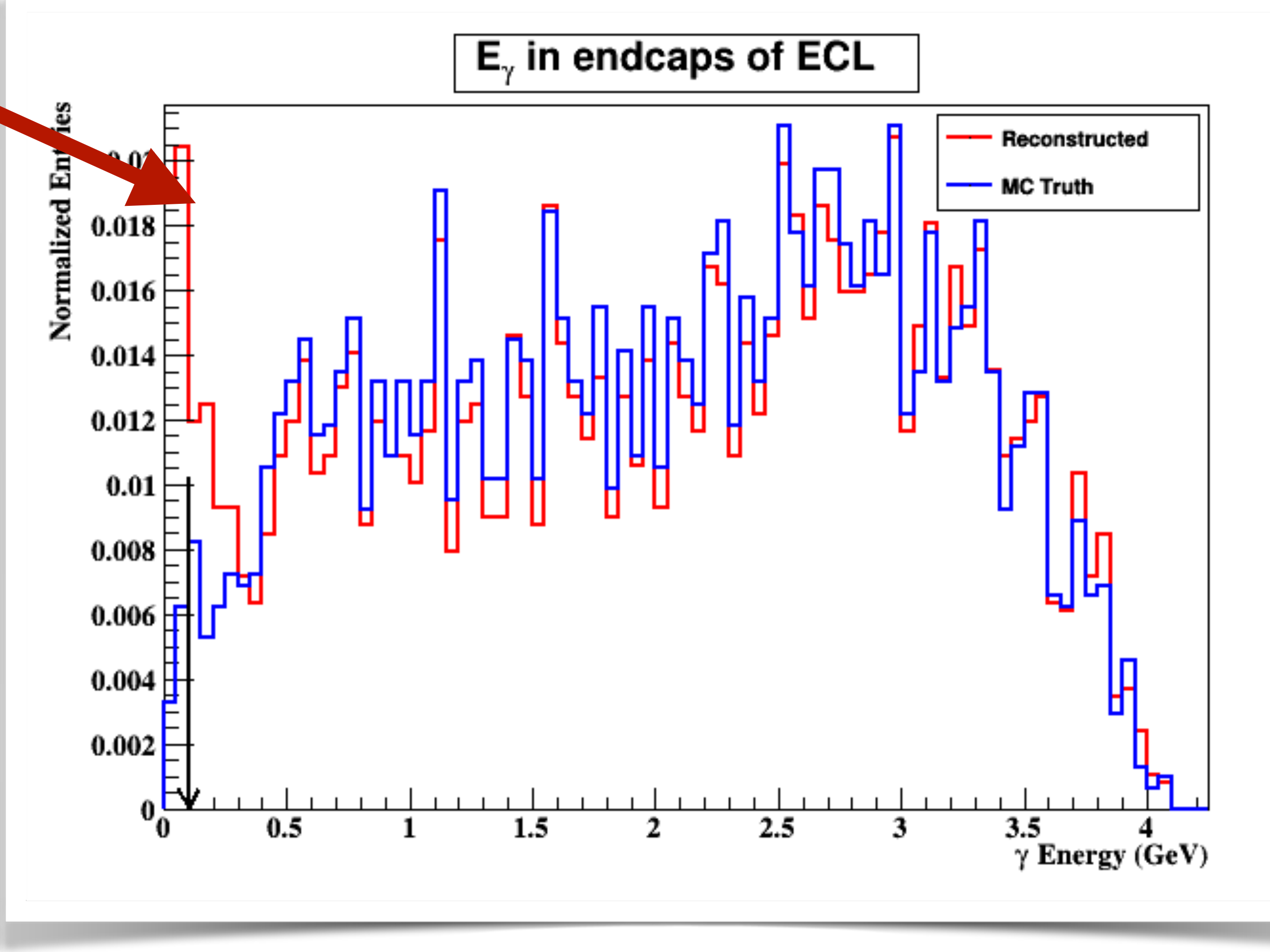
- A large sample of signal MC events are generated and simulated for experiments dedicated to Υ(5S) resonance.
- They are then scaled to their corresponding luminosities.
- Background MC study is performed with statistics which is six times the integrated luminosity of data collected at Υ(5S) resonance.

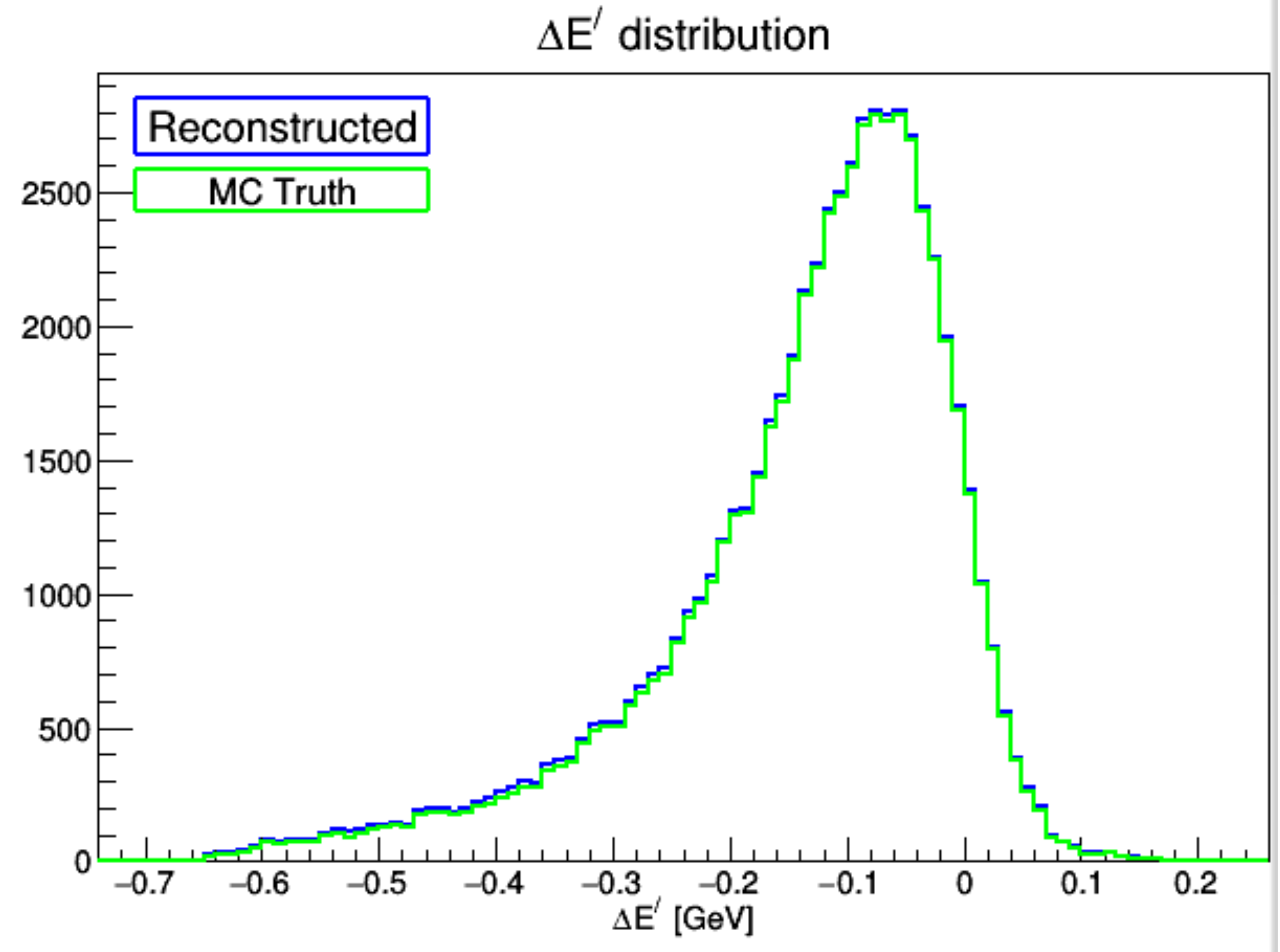
Signal MC study

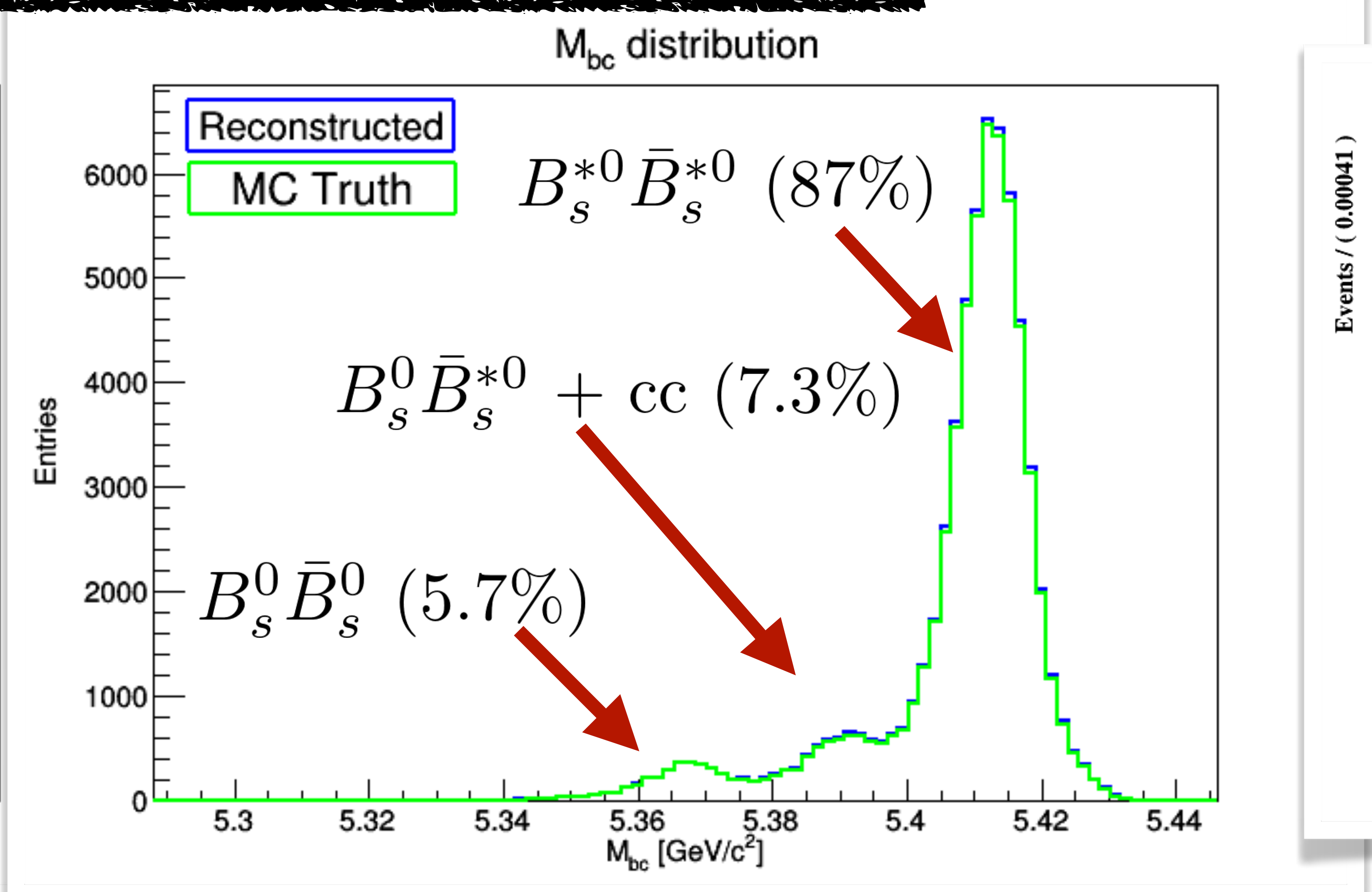
Variables	Selection Criteria	Remarks
Photon ID	$! = 911$ (MC only)	off-time QED effects
$M_{\gamma\gamma}$	$0.118 < M_{\gamma\gamma} < 0.152\ (GeV/c^2)$	2.36σ
E_γ	$0.050\ (0.100)\ GeV$ barrel(endcaps)	remove beam backgrounds
M_{bc}	$M_{bc} > 5.30\ GeV/c^2$	$M_{bc} = \sqrt{E^{*2}_{\text{beam}} - p^{*2}_B}$
$\Delta E'$	$-0.6 < \Delta E' < 0.15\ (GeV)$	$\Delta E' = \Delta E + M_{bc} - M(B^0_s)$ $\Delta E = E^*_B - E^*_{\text{beam}}$
$\mathcal{C}'_{NN}$	$\mathcal{C}'_{NN} > 0.90$	remove continuum

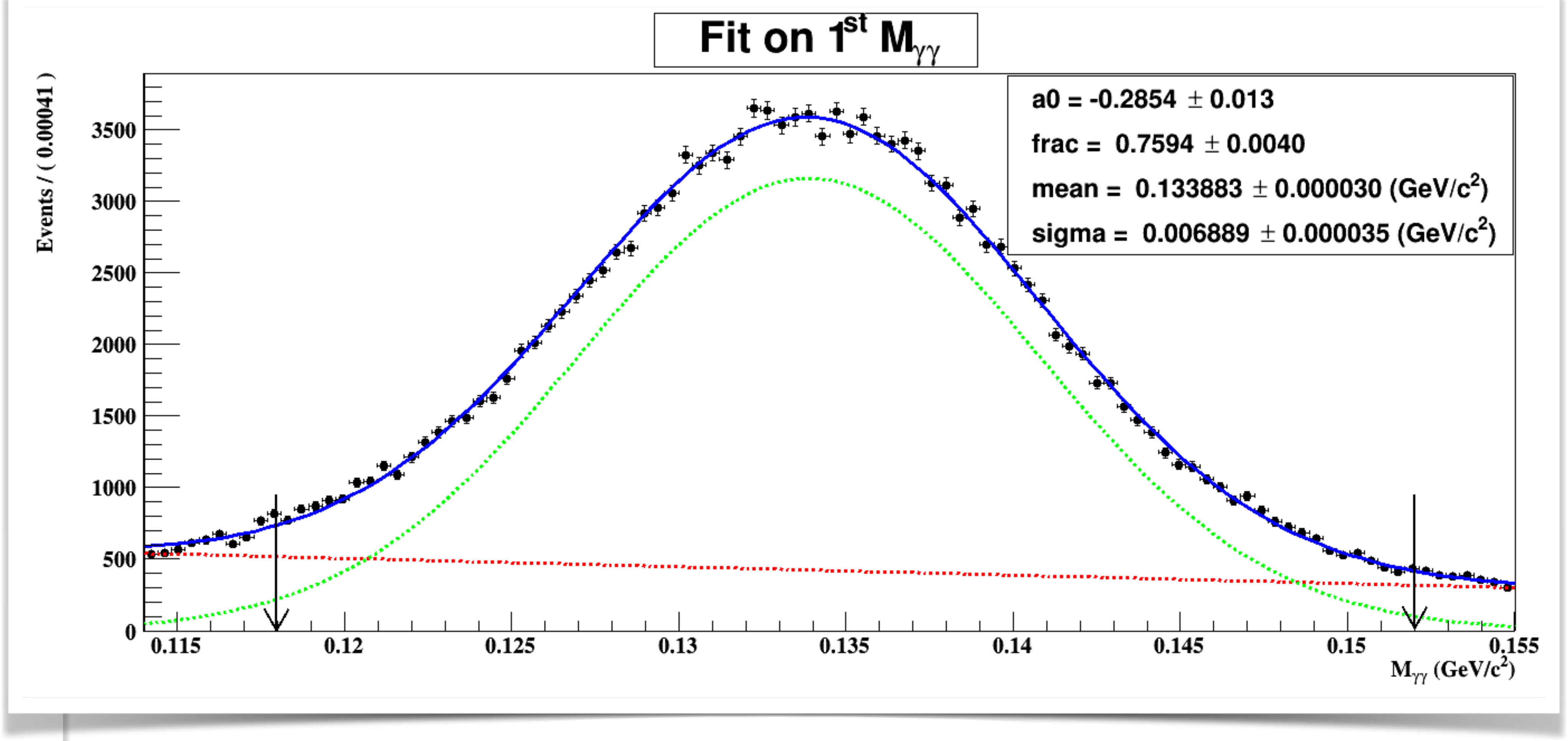
Misreconstruction





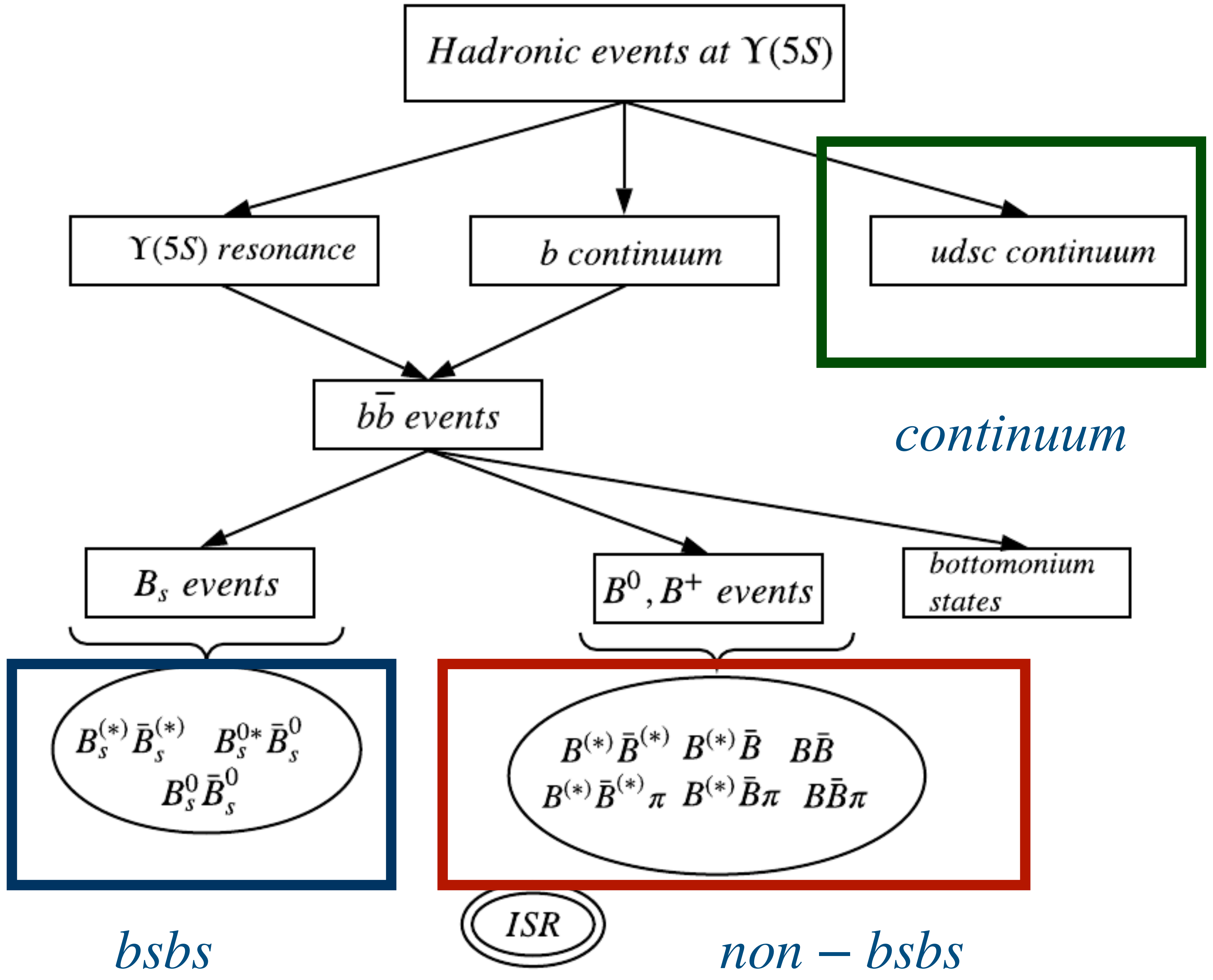


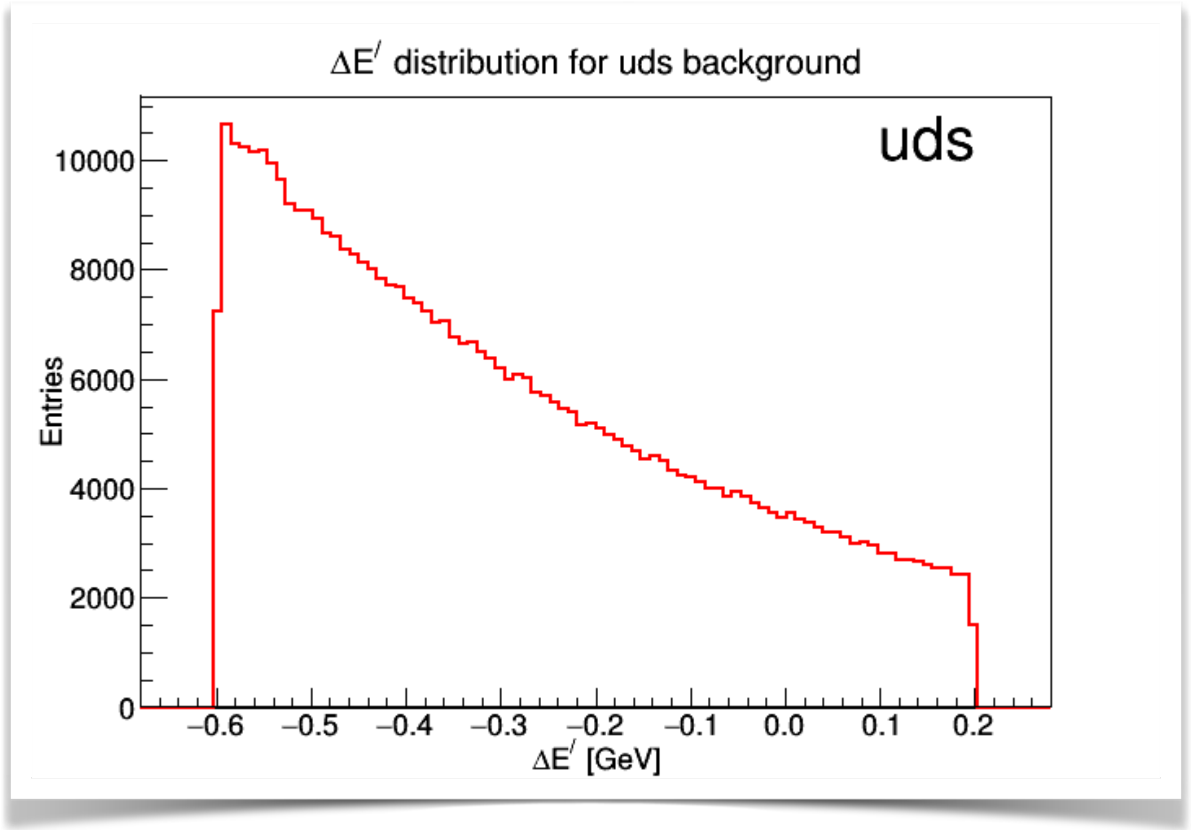


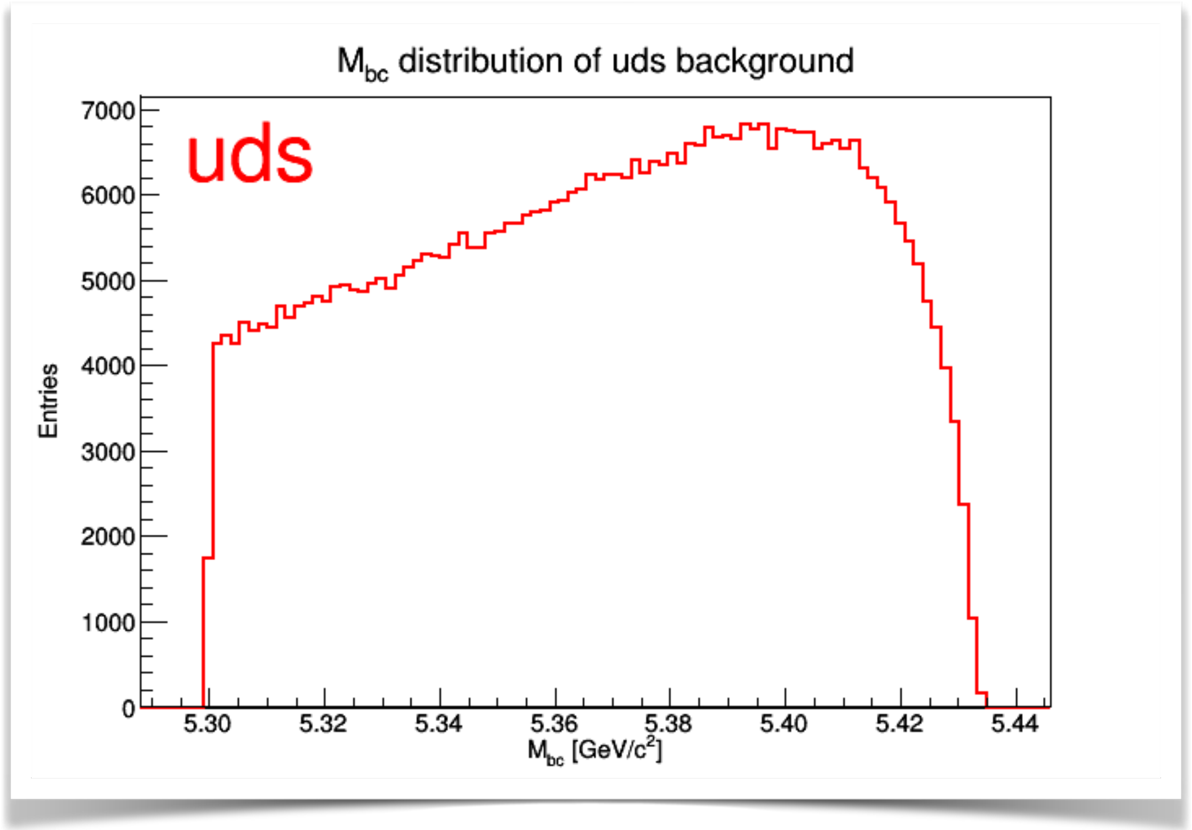


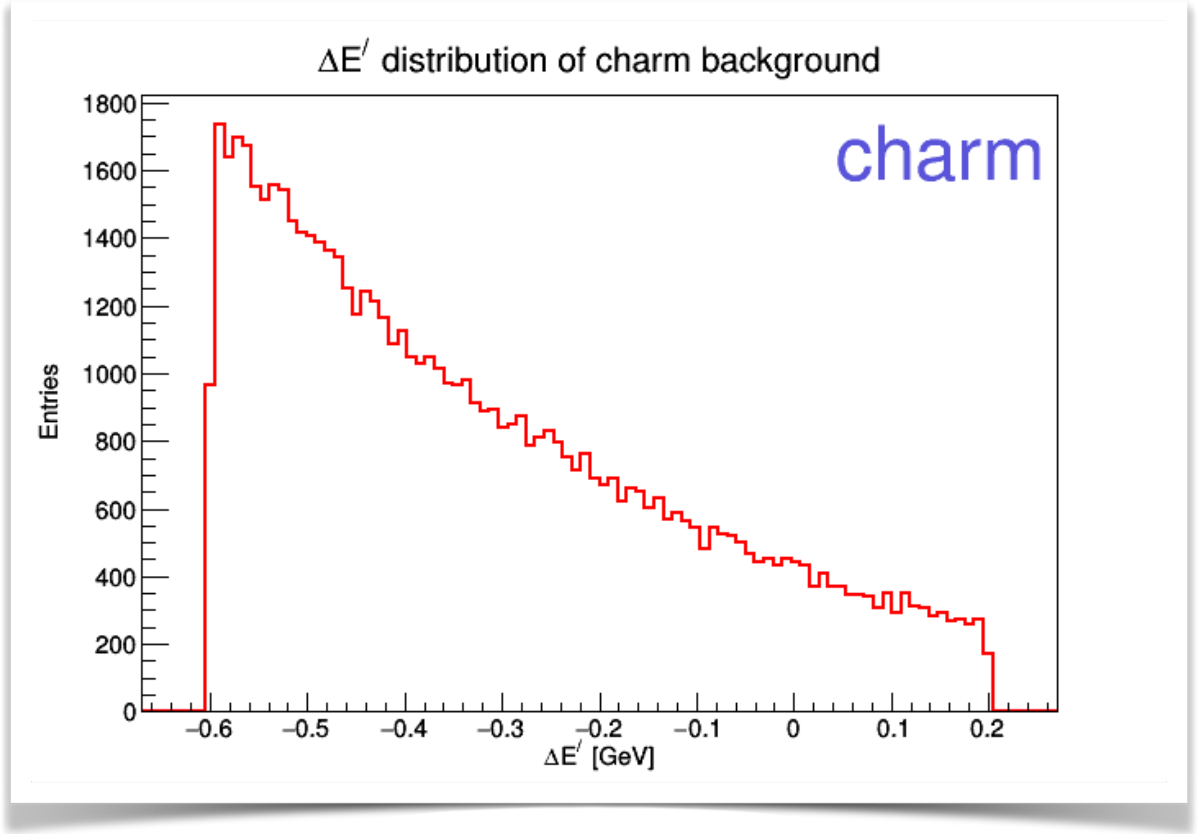
MCtruth : Correctly reconstructed signal candidates

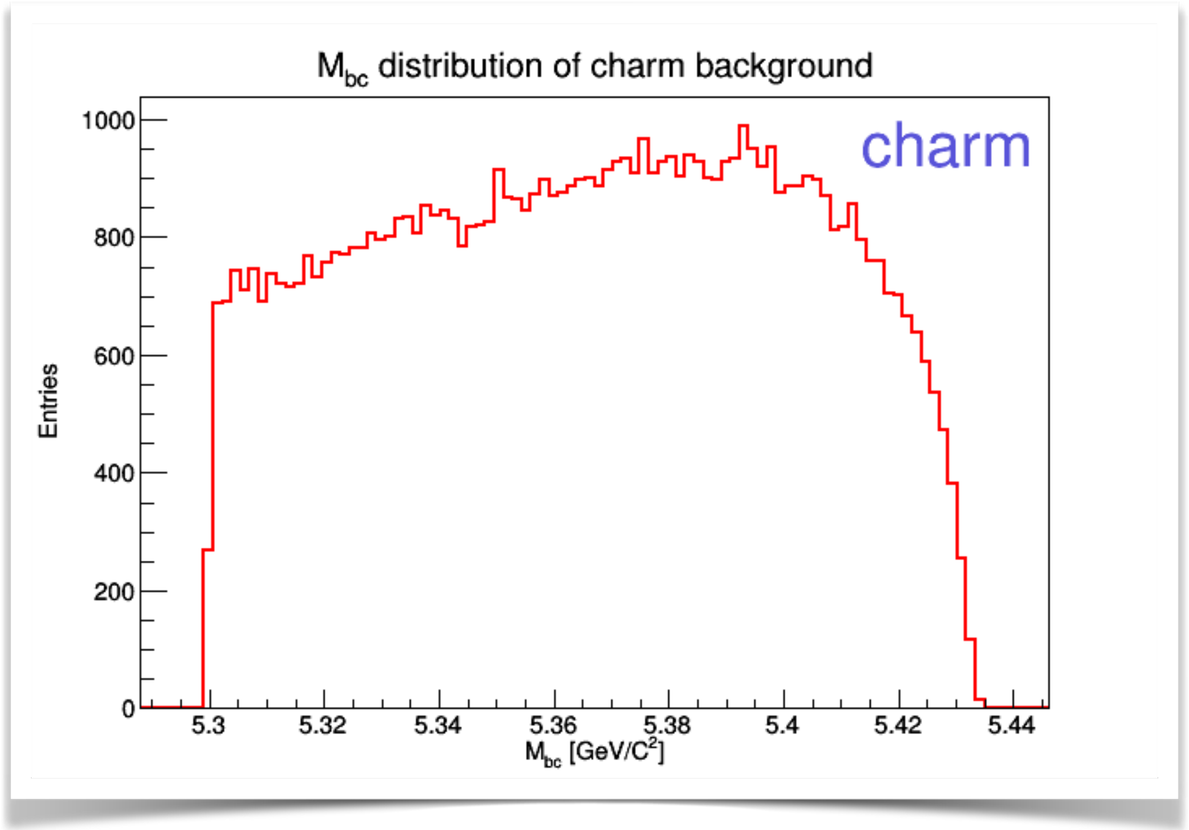
Background MC study









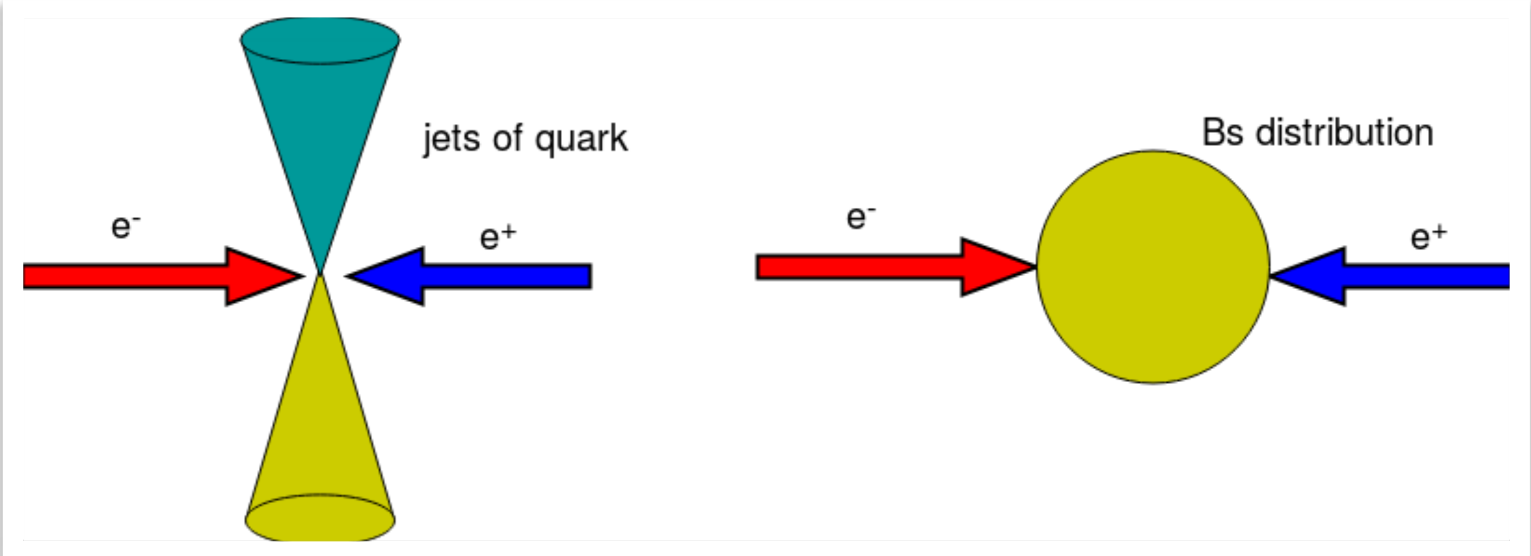


Background MC statistics $= 6 \times 121.4\ \text{fb}^{-1}$

Continuum is the dominant background !

Continuum Suppression

$\propto 1 + cos^2\theta$ $\propto sin^2\theta$



Jet-like topology **Spherical topology**

Event shape distributions

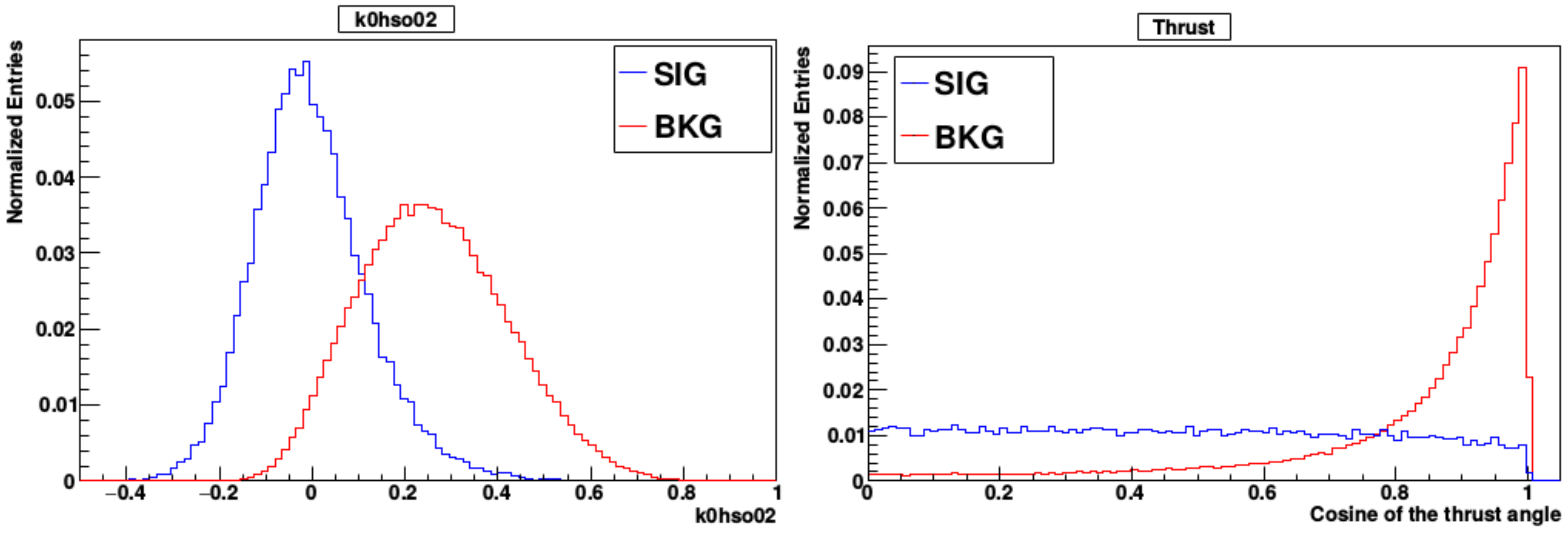
Phys. Rev. Lett. 41, (1978)

3 mom. of i^th and j^th FSP

$$H_l = \sum_{i,j}^{N} \frac{|\bar{P}_i|\ |\bar{P}_j|}{s} P_l(cos\theta_{i,j})$$

Associated Legendre's Polynomial

Fox-Wolfram moments



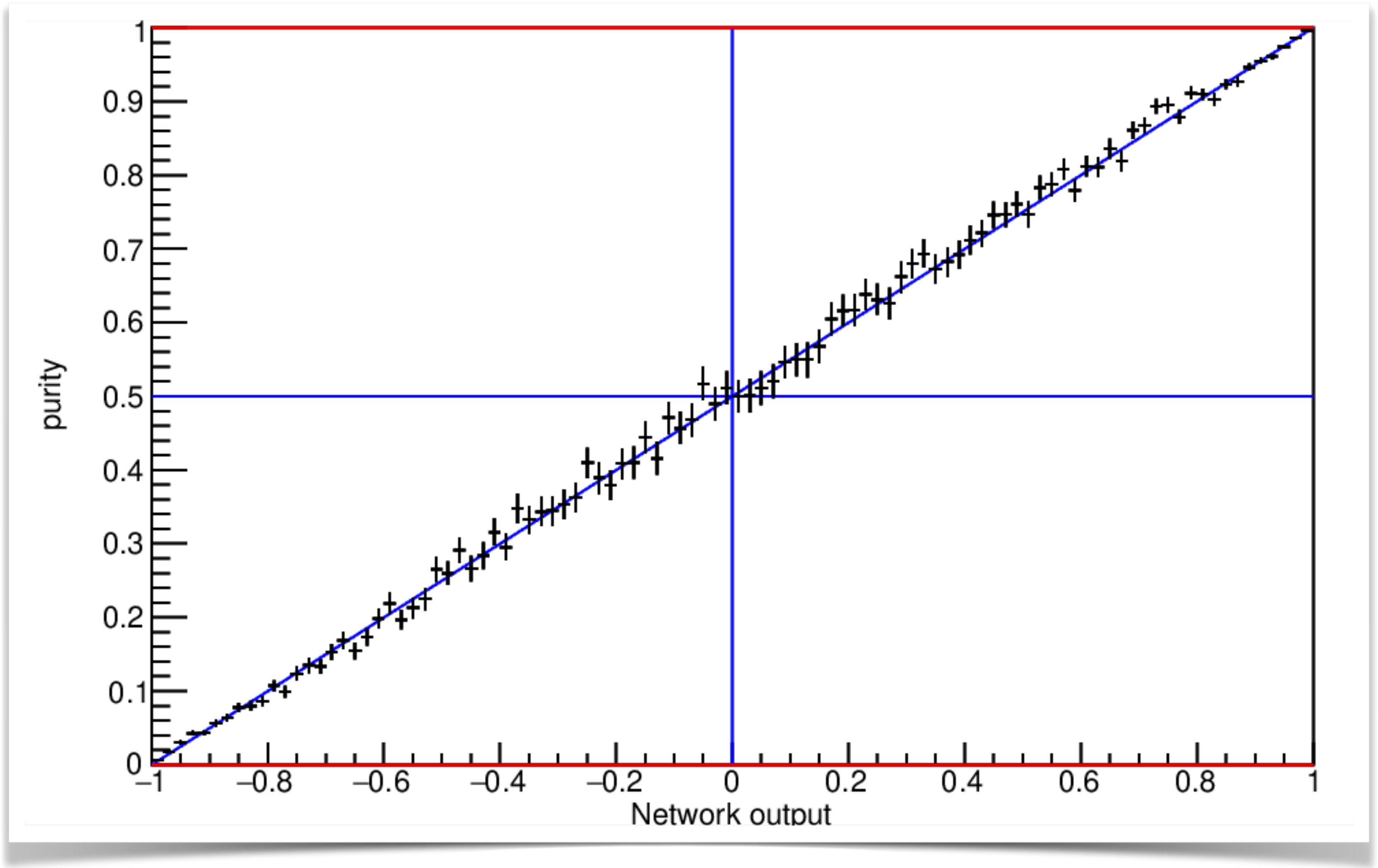
(a) Plot of event shape variable (b) Plot of thrust angle

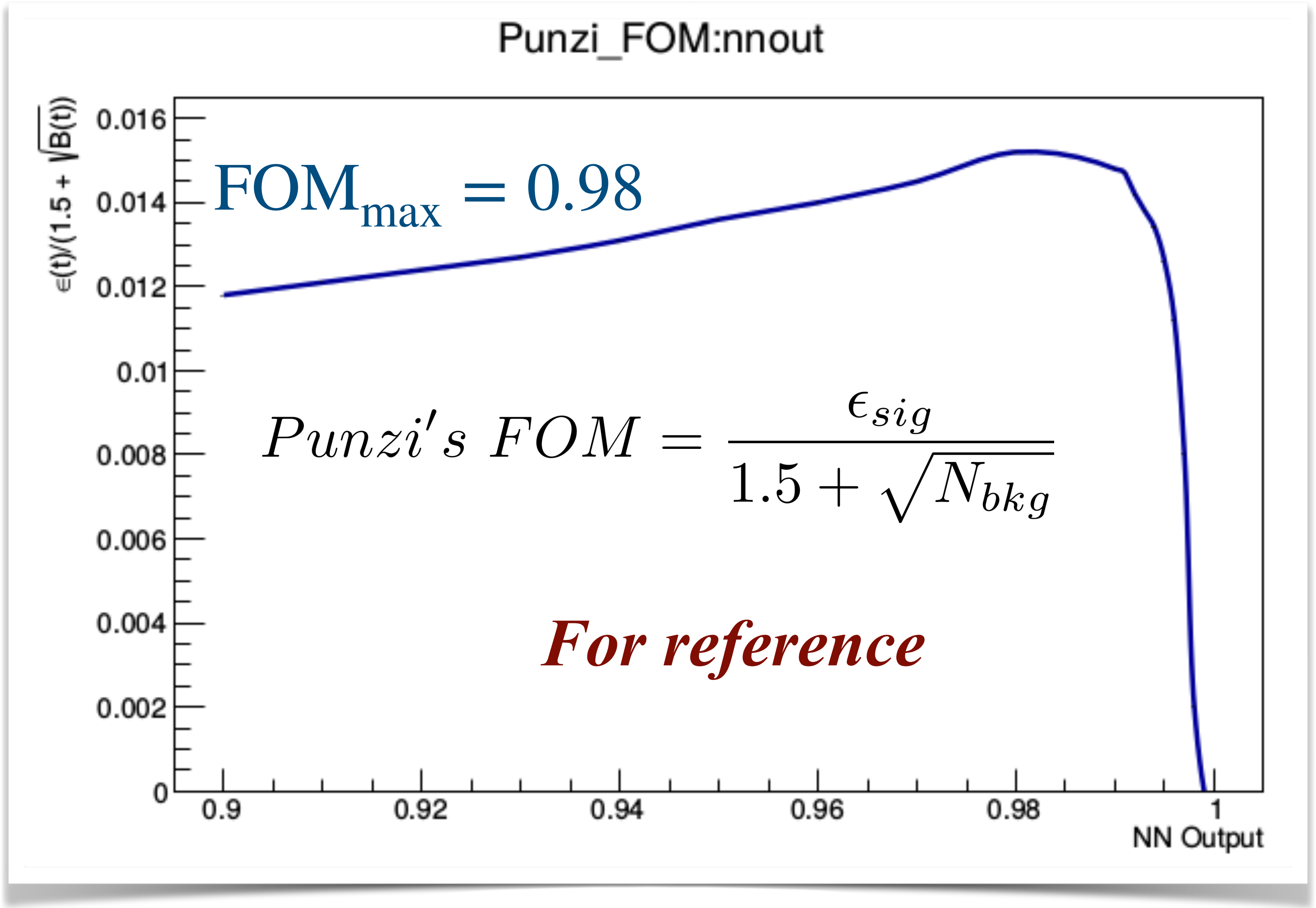
- 16 modified Fox-Wolfram (mFW) moments are used to differentiate between signal and continuum
- Thrust axis : Axis along which there is a maximum projection of the 3-mom of the final state particles
- Thrust angle : Angle between the signal thrust axis and the ROE (Rest-of-event) thrust axis.

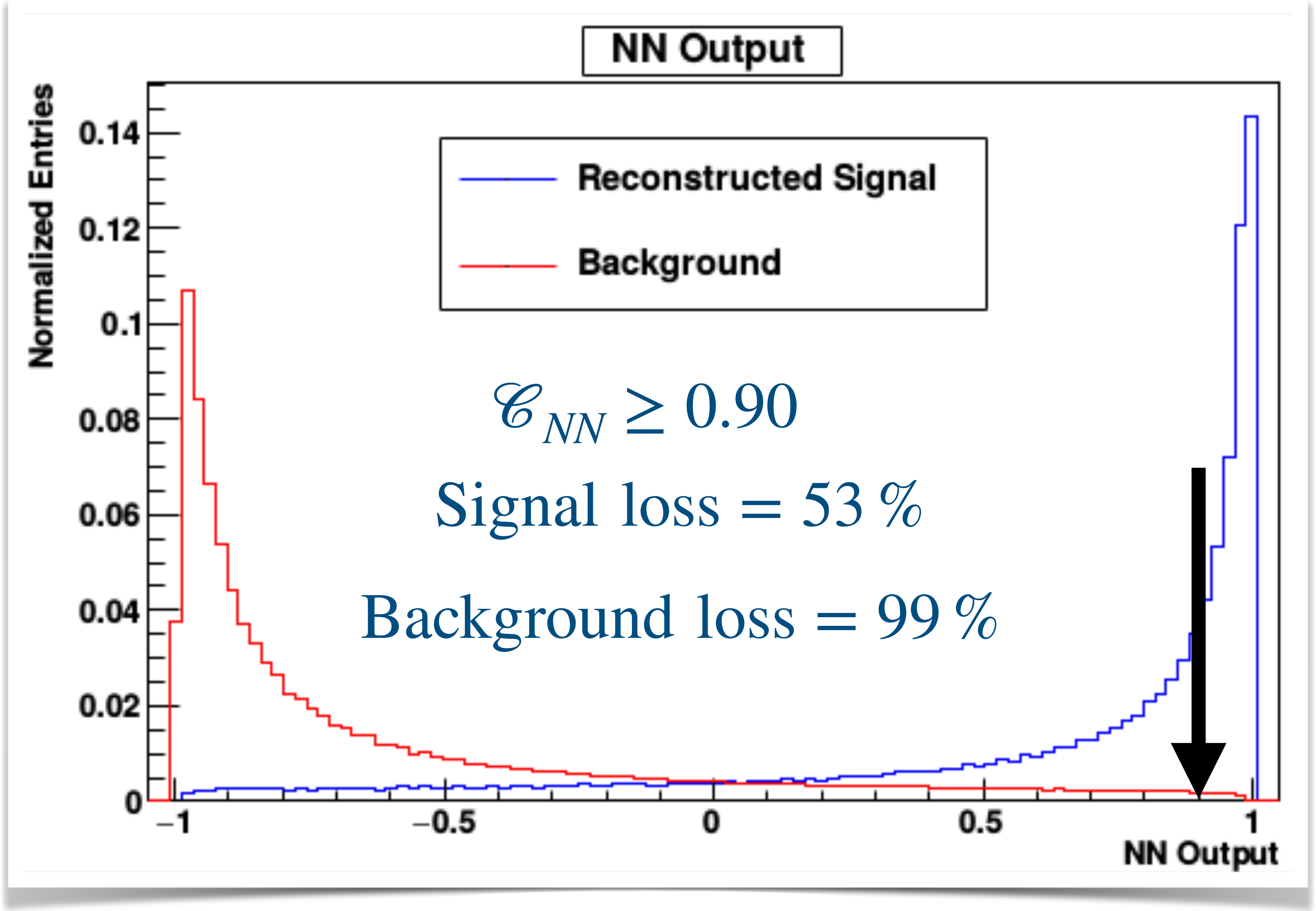
Neural network is used to classify the signal and the background !

16 mFW moments + thrust angle are given as inputs to neural network

Neural Network (NN) output

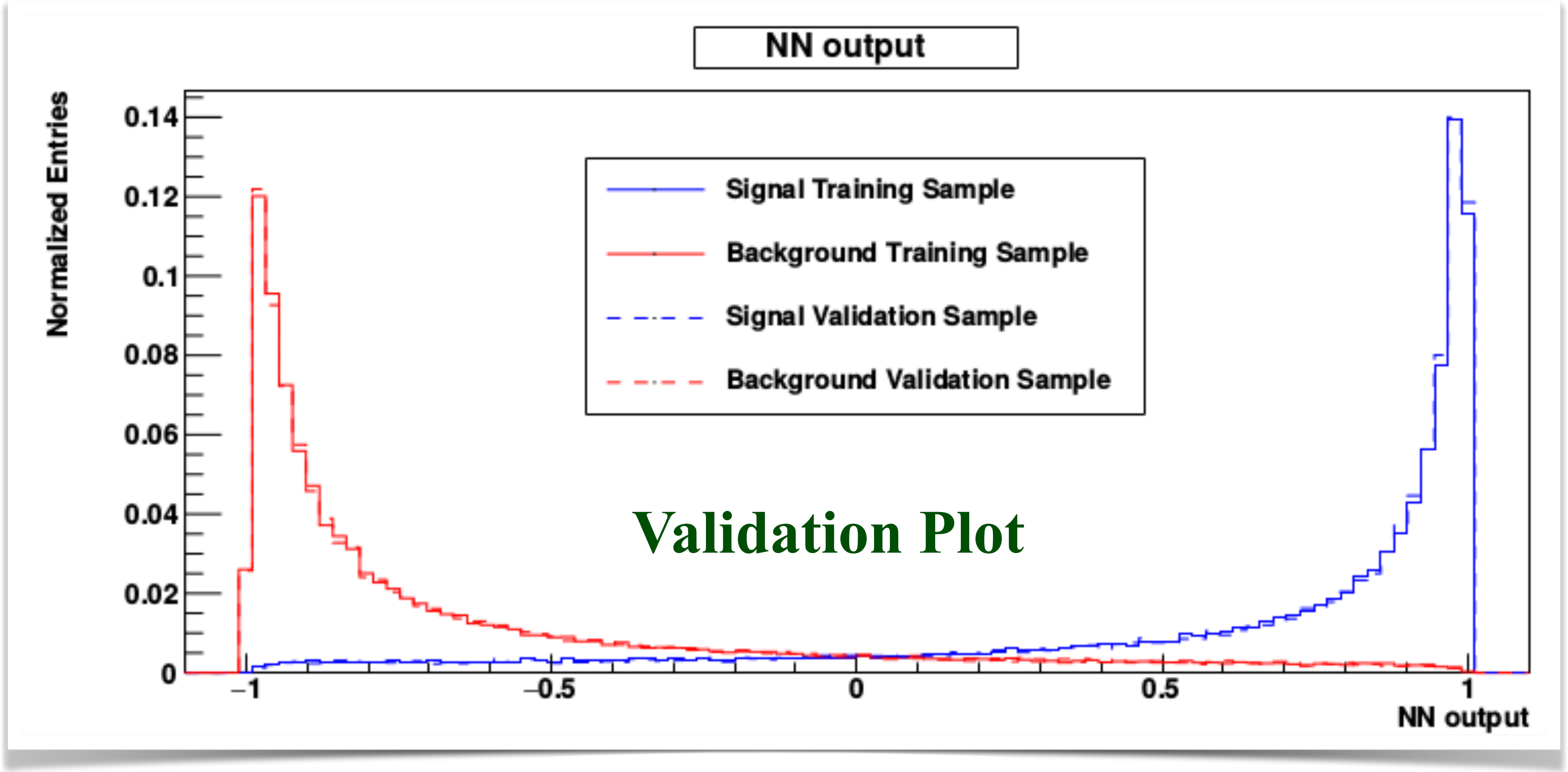






NN output is transformed for easier parametrization

$$\mathscr{C}'_{NN} = log\left(\frac{\mathscr{C}_{NN} - \mathscr{C}_{NN(min)}}{\mathscr{C}_{NN(max)} - \mathscr{C}_{NN}}\right)$$



Modified FW moments   PRD **66** 092002 (2002)

$$h_l^{so} = \sum_{i,j} p_i p_j P_l(\cos\theta_{ij}),$$

$$h_l^{oo} = \sum_{j,k} p_j p_k P_l(\cos\theta_{jk}),$$

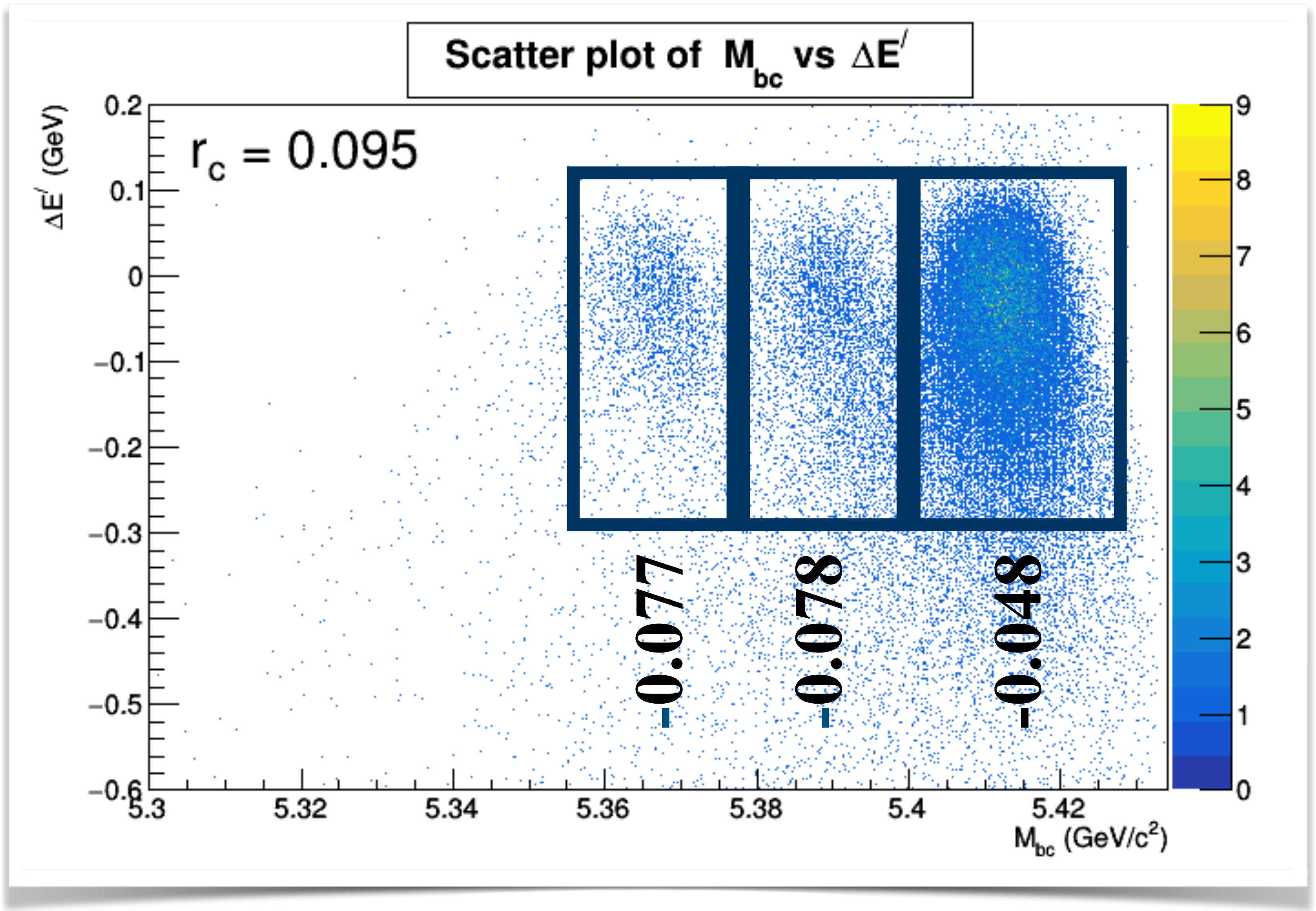
where i enumerates B *signal* candidate particles (s particles) and j and k enumerate the *remaining* particles in the event (o particles); p_i is the ith particle's momentum, and $P_l(\cos\theta_{ij})$ is the lth Legendre polynomial of the angle θ_{ij} between particles i and j. The h_l^{so} terms contain information on the correlation between the B candidate direction and the direction of the rest of the event. The odd h_l^{oo} terms partially reconstruct the kinematics of the other B in the event while the even terms quantify the sphericity of the other side of the event. We create a six-variable Fisher discriminant called the super Fox-Wolfram defined as

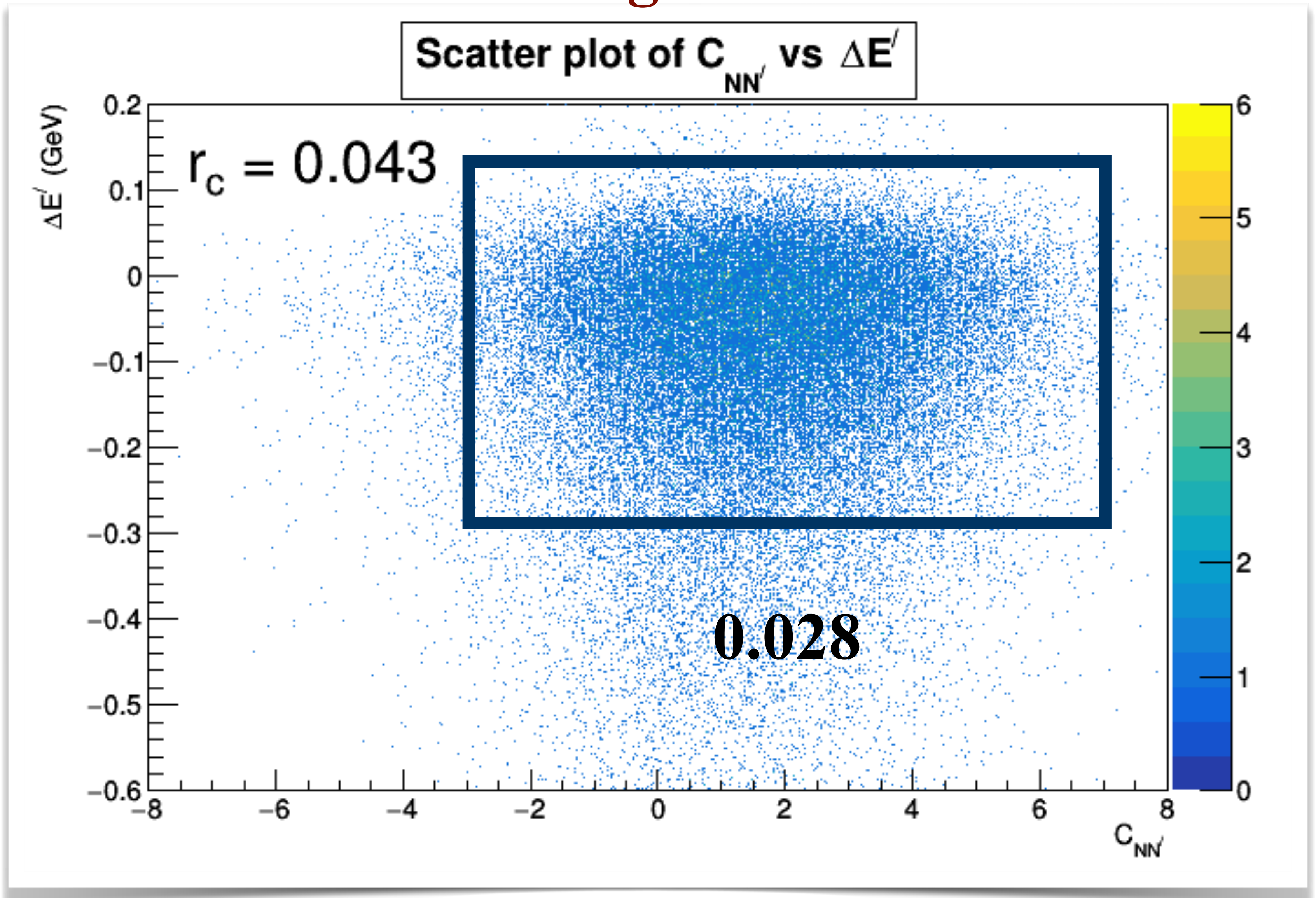
$$SFW = \sum_{l=2,4} \alpha_l \left(\frac{h_l^{so}}{h_0^{so}}\right) + \sum_{l=1-4} \beta_l \left(\frac{h_l^{oo}}{h_0^{oo}}\right),$$

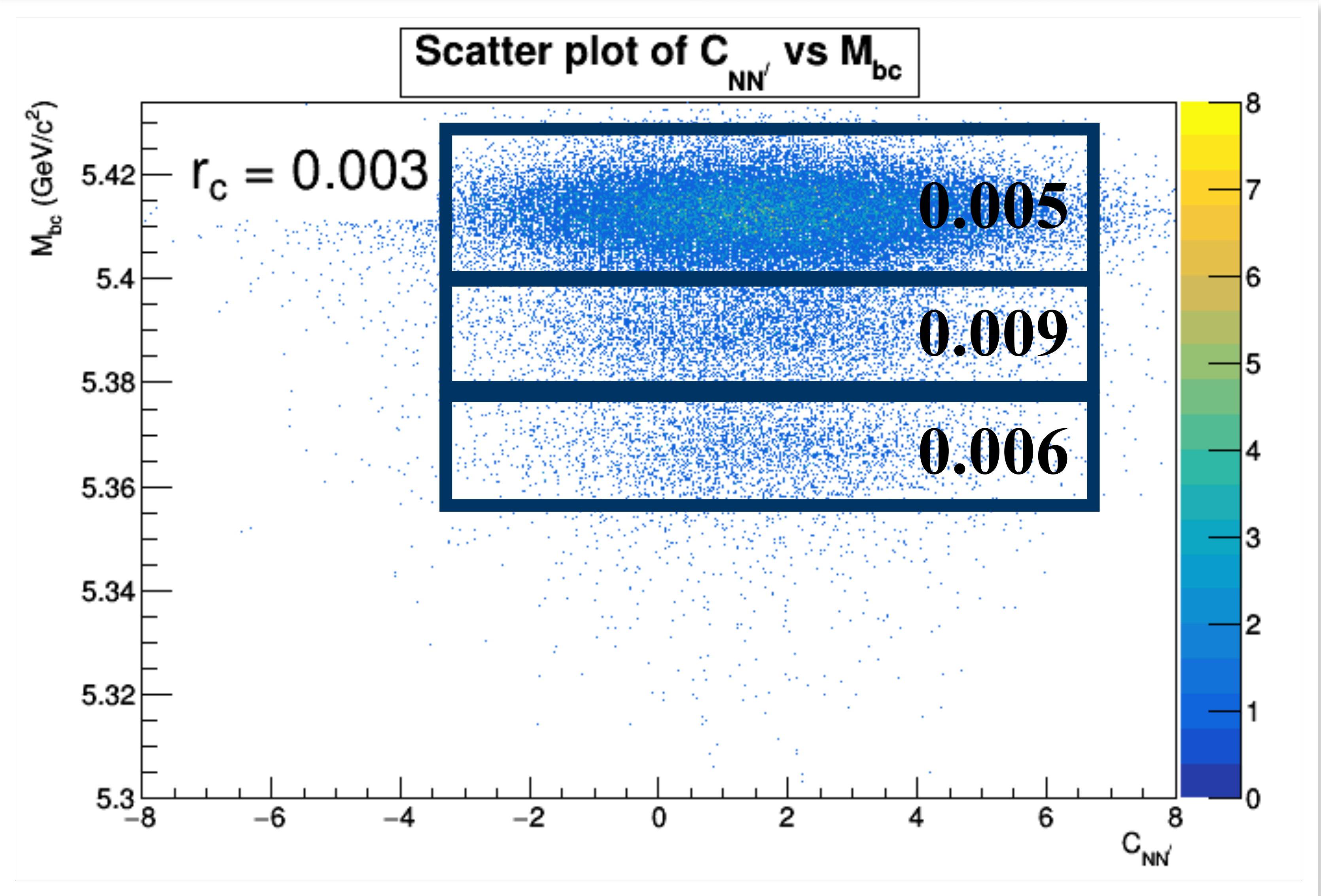
where α_l and β_l are the Fisher coefficients.

Correlation among the fit variables (Linear correlation coefficients)

Signal MC

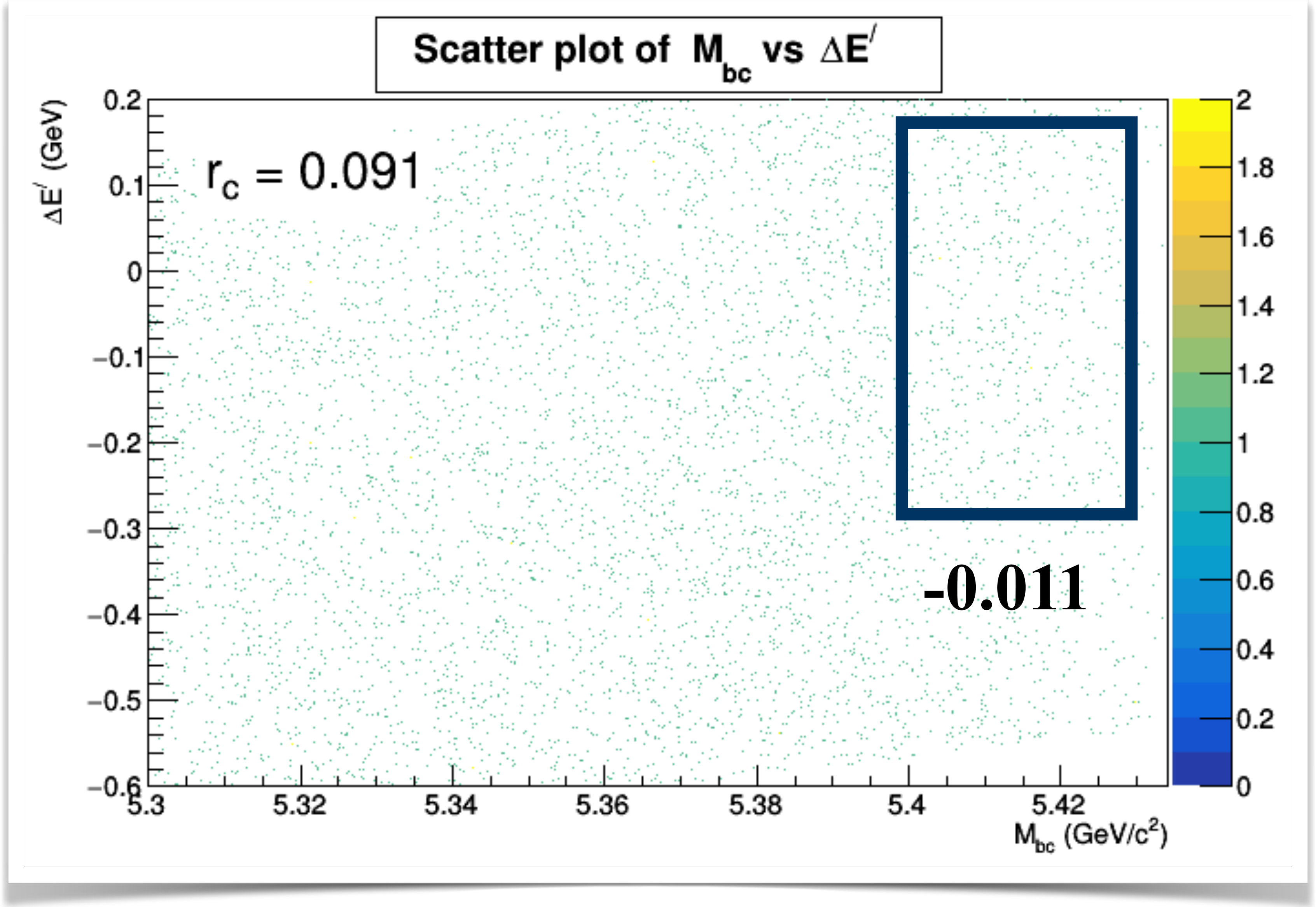


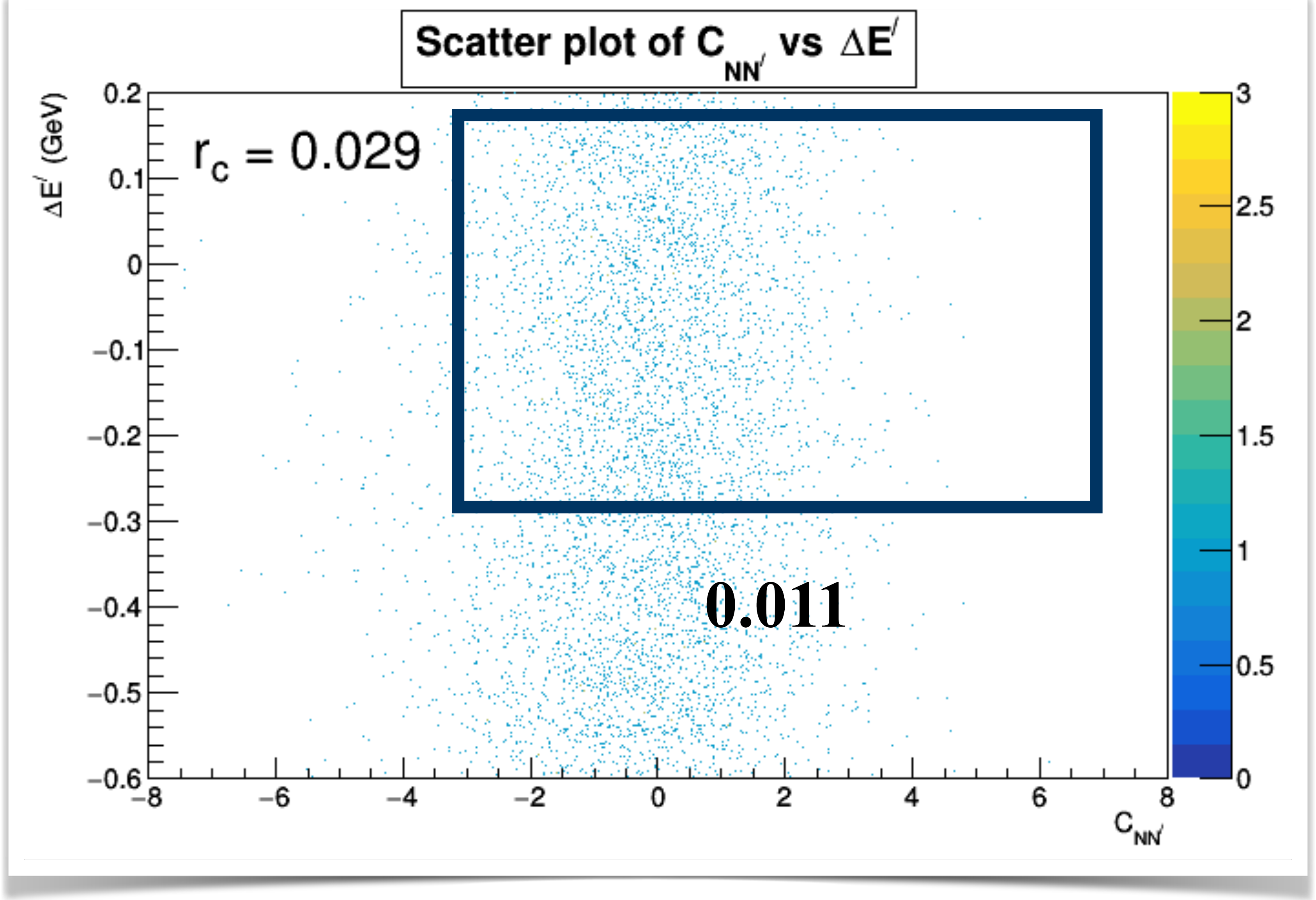


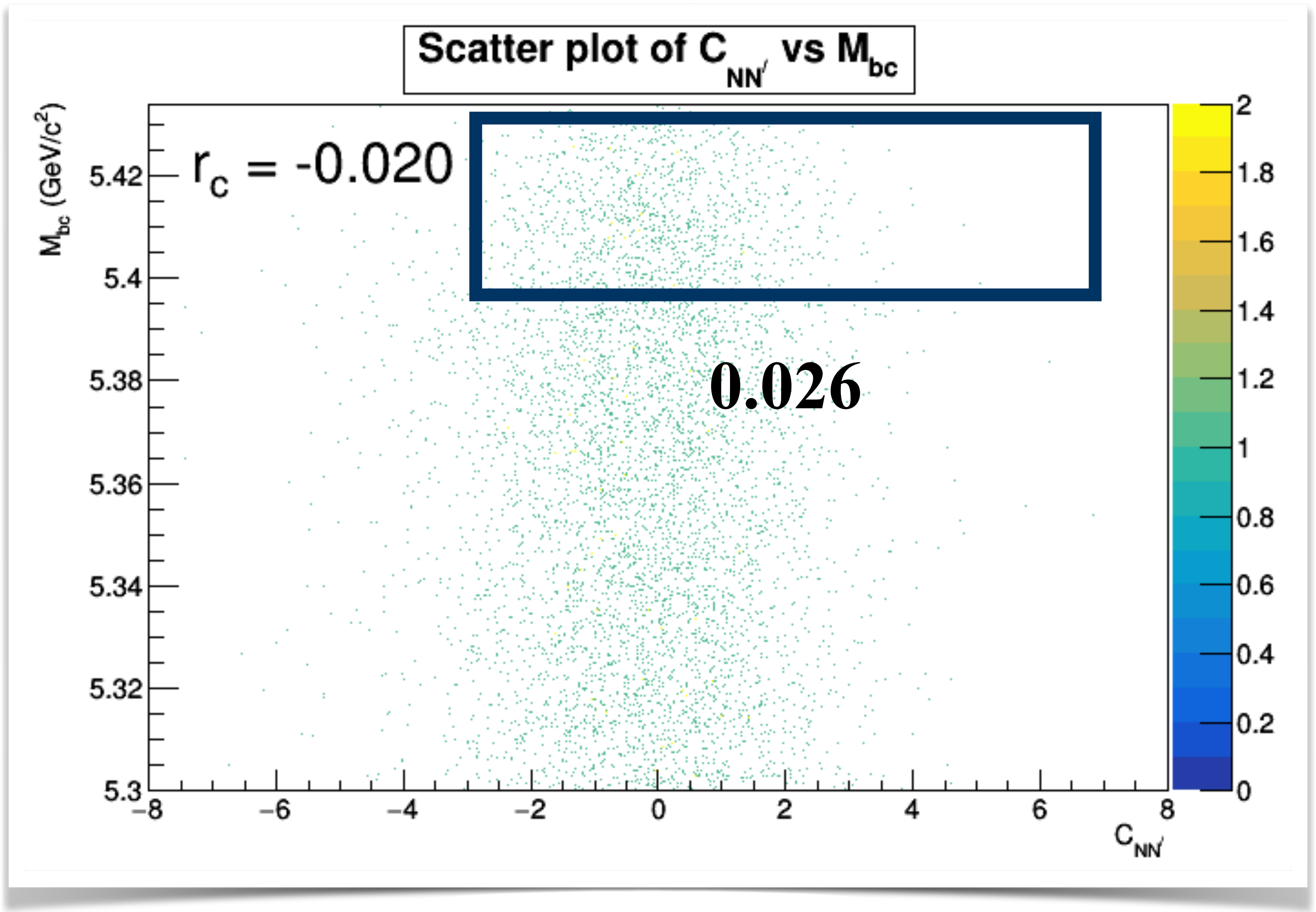


Background MC

No significant correlations are observed







Control Sample Study: $B_d^0 \to \pi^0\pi^0$

Target Sample

Variables	Selection Criteria
Photon ID	$! = 911$ (MC only)
$M_{\gamma\gamma}$	$0.118 < M_{\gamma\gamma} < 0.152\ (GeV/c^2)$
E_γ	$0.050\ (0.100)\ GeV$ barrel(endcaps)
$\Delta E'$	$-0.6 < \Delta E' < 0.15\ (GeV)$
M_{bc}	$M_{bc} > 5.30\ GeV/c^2$
$\mathcal{C}'_{NN}$	$\mathcal{C}'_{NN} > 0.90$

Control Sample (MC)

Variables	Selection Criteria
Photon ID	$! = 911$ (MC only)
$M_{\gamma\gamma}$	$0.118 < M_{\gamma\gamma} < 0.152\ (GeV/c^2)$
E_γ	$0.050\ (0.100)\ GeV$ barrel(endcaps)
$\Delta E'$	$-0.6 < \Delta E' < 0.20\ (GeV)$
M_{bc}	$M_{bc} > 5.22\ GeV/c^2$
$\mathcal{C}'_{NN}$	$\mathcal{C}'_{NN} > 0.90$

Control Sample (Data)

Variables	Selection Criteria
ECL timing	$9000 - 11000\ ns$
$M_{\gamma\gamma}$	$0.118 < M_{\gamma\gamma} < 0.152\ (GeV/c^2)$
E_γ	$0.050\ (0.100)\ GeV$ barrel(endcaps)
$\Delta E'$	$-0.6 < \Delta E' < 0.20\ (GeV)$
M_{bc}	$M_{bc} > 5.22\ GeV/c^2$
$\mathcal{C}'_{NN}$	$\mathcal{C}'_{NN} > 0.90$

- PDG Branching Fraction (BF) $= (1.59 \pm 0.26) \times 10^{-6}$
- Previous Belle result, BF $= (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$
- Reconstruction efficiency, $\epsilon = 11.16\%$
- Expected signal yield @ 619×10^6 $B\bar{B}$ pairs (SVD2) $= 91$
- Use $3D$ unbinned maximum liklihood fit to extract signal from data

MC sample	Experiment	Remarks
Signal	55	100,000 scaled to expt.55 luminosity
$e^+e^- \to q\bar{q}, (q \to u,\ d,\ s\ c)$	55	$6\times$ real data
$\Upsilon(4S) \to B^+B^-$	37, 41, 43, 55	$10\times$ real data
$\Upsilon(4S) \to B^0\bar{B}^0$	37, 41, 43, 55	$10\times$ real data
$b \to u$ (charged)	37, 41, 43, 55	$50\times$ real data
$b \to u$ (mixed)	37, 41, 43, 55	$50\times$ real data

Our aim is to test the analysis procedure using the control sample

1D PDF parametrizations: $B_d^0 \to \pi^0\pi^0$

Cut-flow table

Variables	Selection Criteria	Truth Matched	Signal	uds	charm	bsbs	nonbsbs	Background
M_{bc} (GeV/c^2)	$M_{bc} > 5.30$	147751	157279	1452869	239717	49	1757	1694392
$\Delta E'$ (GeV)	$-0.60 < \Delta E' < 0.15$	146274 (1%)	154134 (2%)	894766 (38%)	140889 (41%)	1 (83%)	770 (56%)	1036433 (39%)
E_γ (GeV)	$E_\gamma > 0.05(0.1)$ Barrel(Fwd/Bwd)	140716 (3.8%)	144732 (6.1%)	831577 (7%)	131537 (6.6%)	1 (12.5%)	705 (8.4%)	963826 (7%)
$M_{\gamma\gamma}$ (GeV/c^2)	$0.118 < M_{\gamma\gamma} < 0.152$	131007 (6.9%)	135470 (6.4%)	771407 (7.2%)	120707 (8.2%)	0 (28%)	653 (7.3%)	892772 (7.3%)
NN Output	$\mathcal{C}_{NN} > 0.90$	62359 (52%)	63477 (53%)	4439 (99%)	723 (99%)	–	0 (100%)	5169 (99%)

Table 7: Cut-flow table. The figures in the parenthesis indicates percentage loss. The backgrounds are considered for six streams.

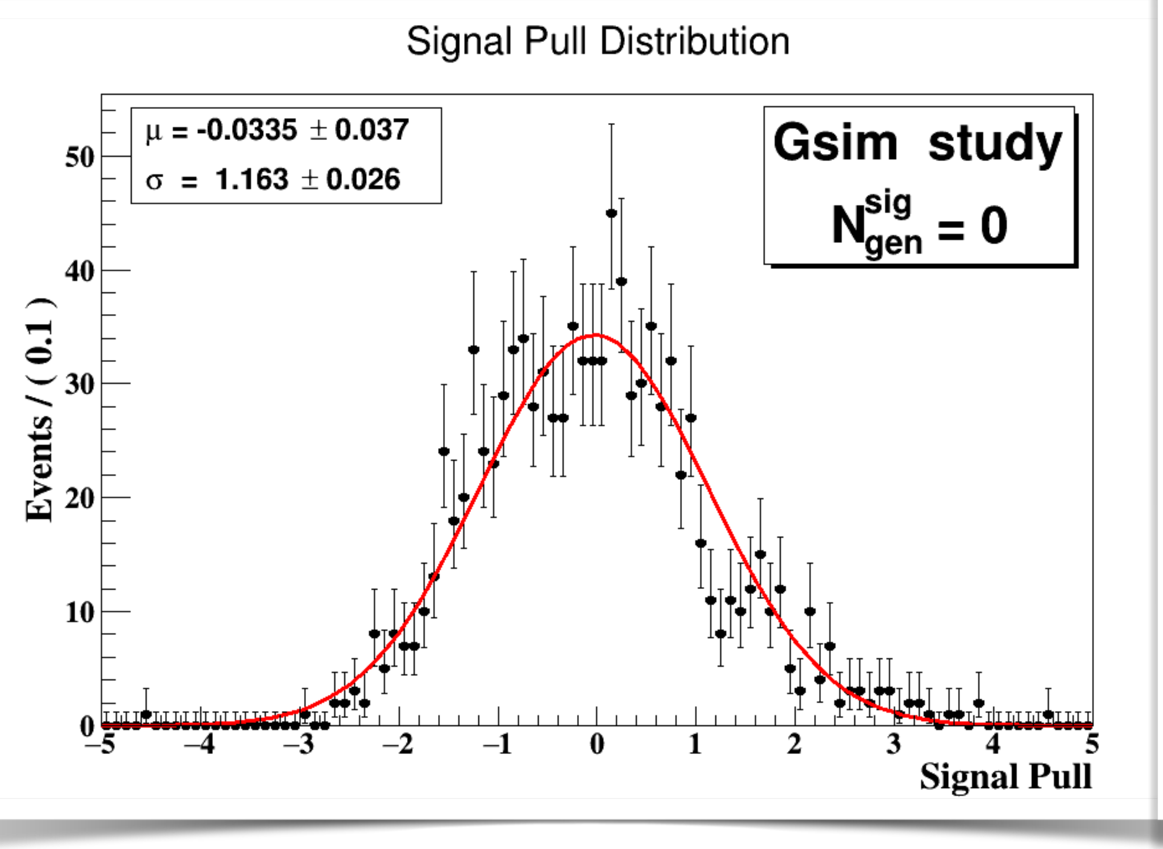
Rare B_s^0 decays

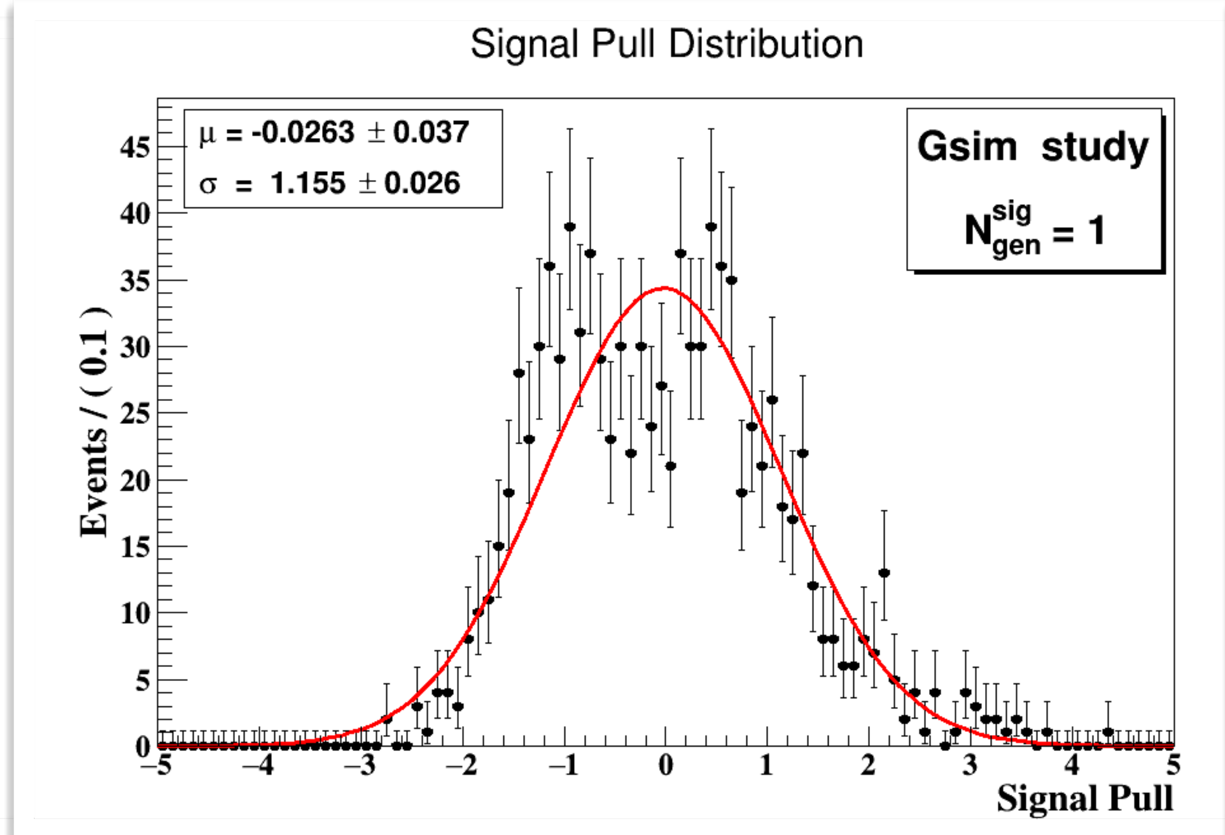
Serial No.	Decay channel	DECAY.DEC $\mathcal{B}(10^{-5})$	PDG $\mathcal{B}(10^{-5})$	Remarks $\mathcal{B}(10^{-5})$
1	$B_s \to \rho^+\rho-$	–	–	0.1(Theory)
2	$B_s \to \eta\pi^0$	–	–	0.012(Theory)
3	$B_s \to \bar{K}_S^0\pi^0$	0.02	–	0.23(Theory)
4	$B_s \to \bar{K}_S^0 K_S^0$	0.79	1.76	Re-generated
5	$B_s \to K^*(892)^+K^-$	–	1.9	–
6	$B_s \to K^*(892)^+\pi^-$	–	0.29	–
7	$B_s \to K_2^*(1430)^+K^-$	–	1.0	–
8	$B_s \to K_0^*(1430)^+K^-$	–	3.1	–
9	$B_s \to K_0^*(1430)^+\bar{K}^0$	–	3.3	–
10	$B_s \to K_0^{*0}(892)\bar{K}^0$	–	2.0	–
11	$B_s \to K_S^0\bar{K}^{*0}(892)$	–	1.6	–
12	$B_s \to K^{*0}(892)\bar{K}^{*0}(892)$	–	1.11	–
13	$B_s \to K_S^0\pi^+\pi^-$	–	0.95	–
14	$B_s \to K_S^0K^+\pi^-$	–	0.84	–
15	$B_s \to K_S^0K^+K-$	–	0.13	–

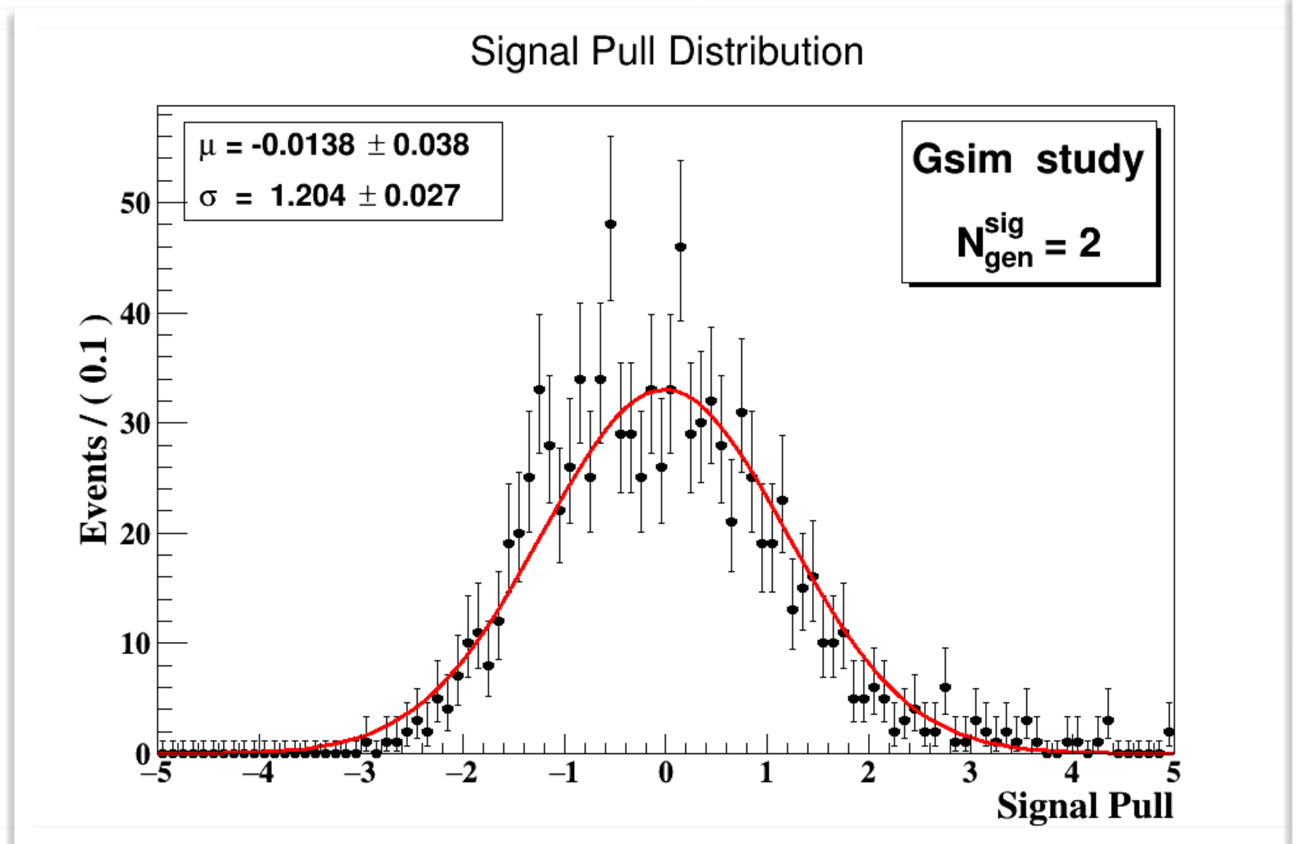
Table 9: List of decay channels considered for rare MC B_s background study.

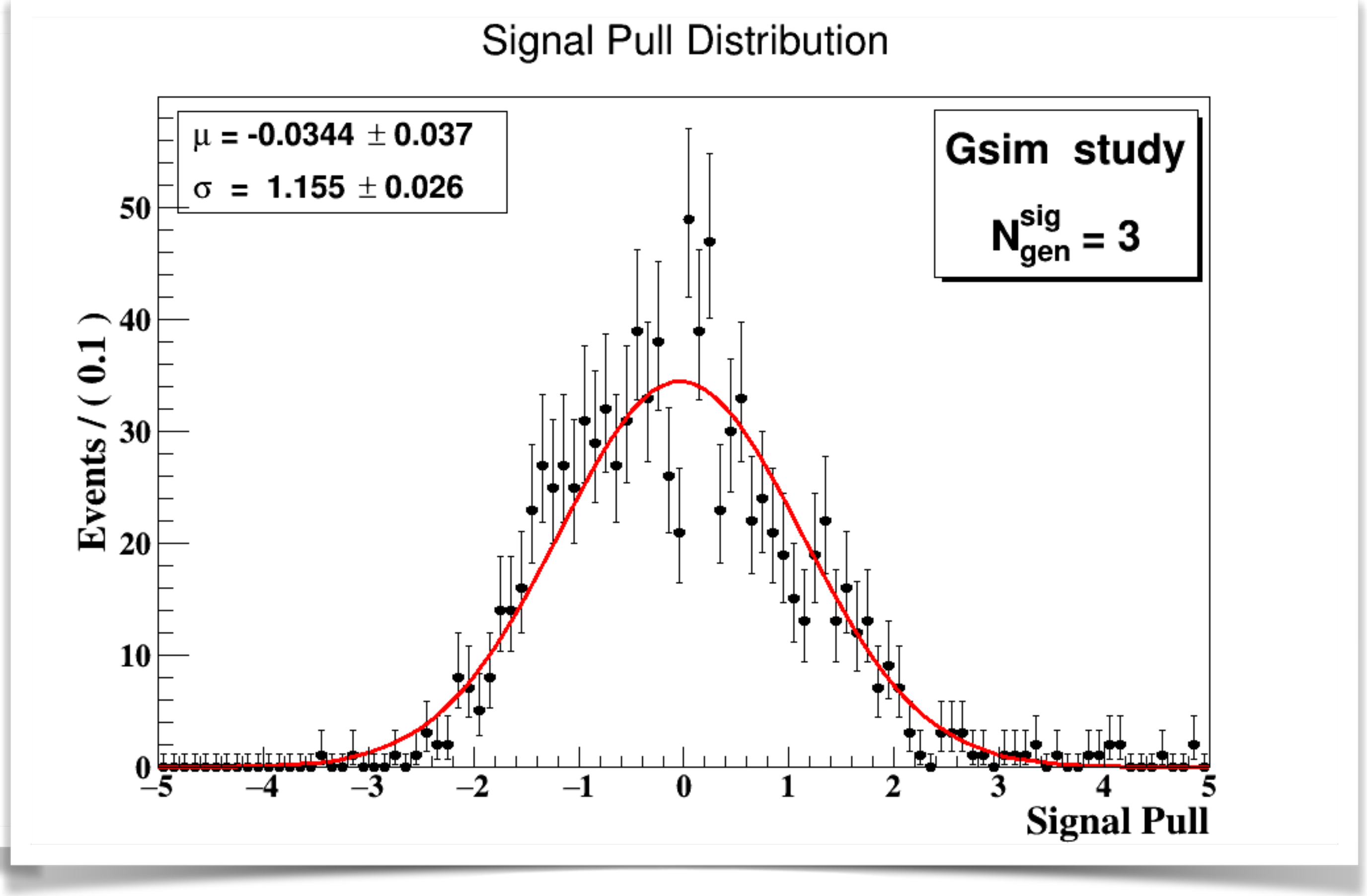
Expt. No.	Luminosity $(\text{fb})^{-1}$	Events generated	Events passed	Decay channel	$\mathcal{B}$ $(10)^{-5}$	Expected events @ $\Upsilon(5S)$
53	21.513	100000	2	$B_s \to \rho^+\rho^-$	0.1	0.000032
			1	$B_s \to \bar{K}_S^0\pi^0$	0.23	0.00038
67	27.22	100000	2	$B_s \to \rho^+\rho^-$	0.1	0.000032
			1	$B_s \to \bar{K}_S^0\pi^0$	0.23	0.00038
69	47.830	100000	5	$B_s \to \rho^+\rho^-$	0.1	0.000083
			3	$B_s \to \bar{K}_S^0\pi^0$	0.23	0.0011
71	22.938	100000	2	$B_s \to \rho^+\rho^-$	0.1	0.000032
			1	$B_s \to \bar{K}_S^0\pi^0$	0.23	0.00038

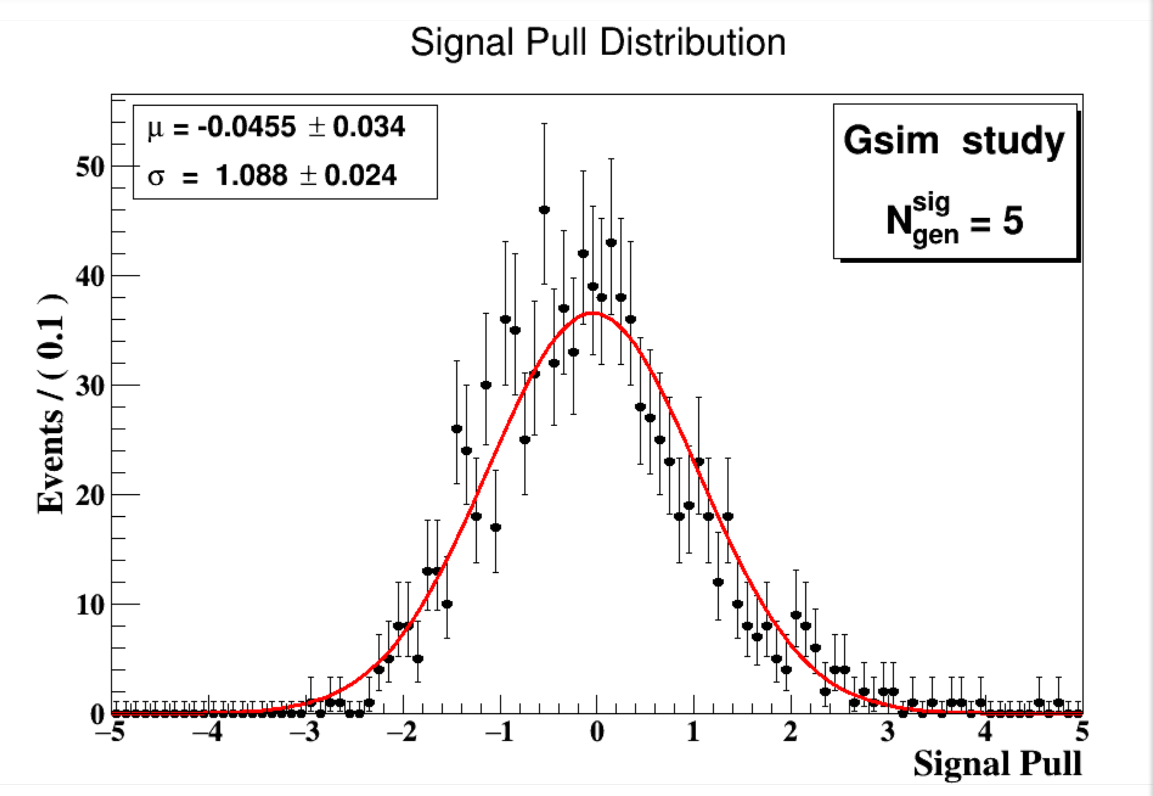
Ensemble study (Pull distributions) : $B_s^0 \to \pi^0\pi^0$

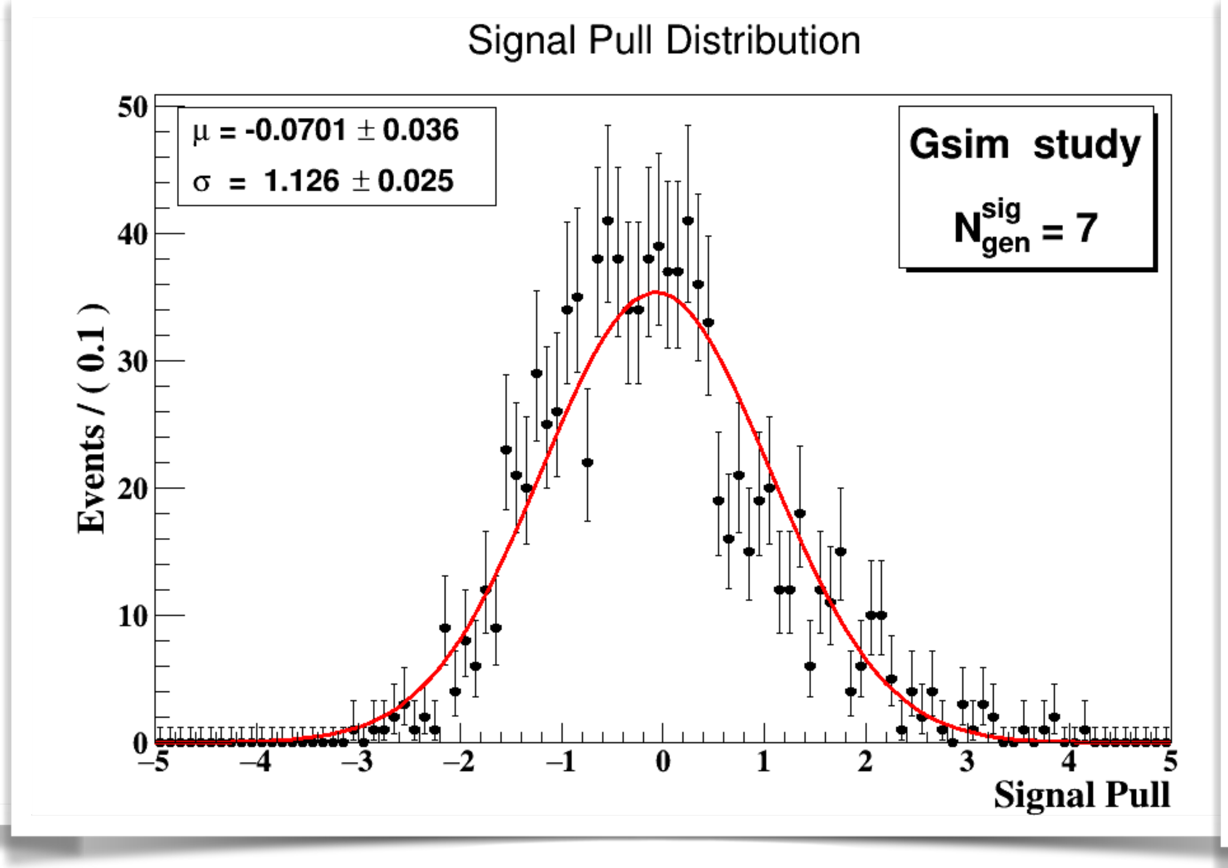


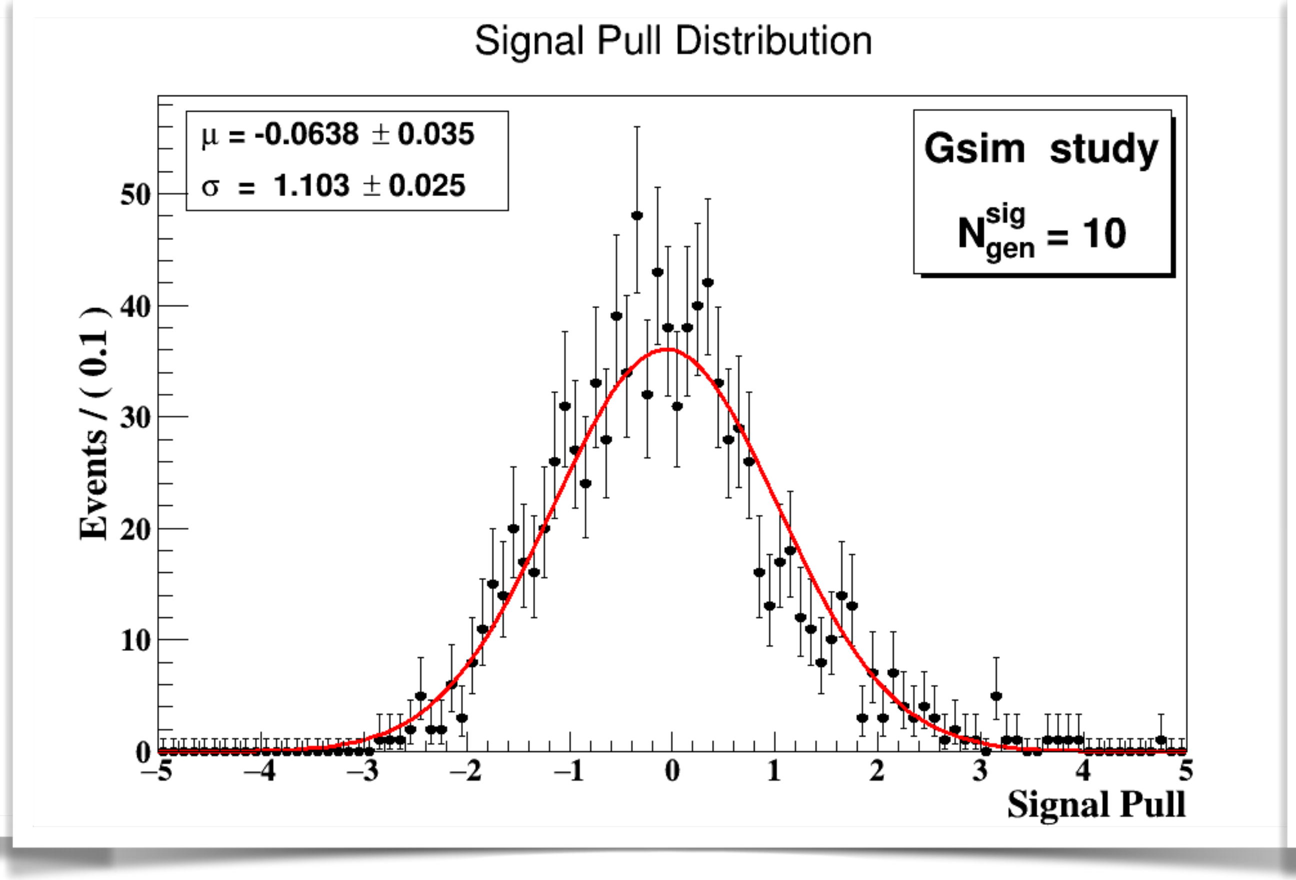


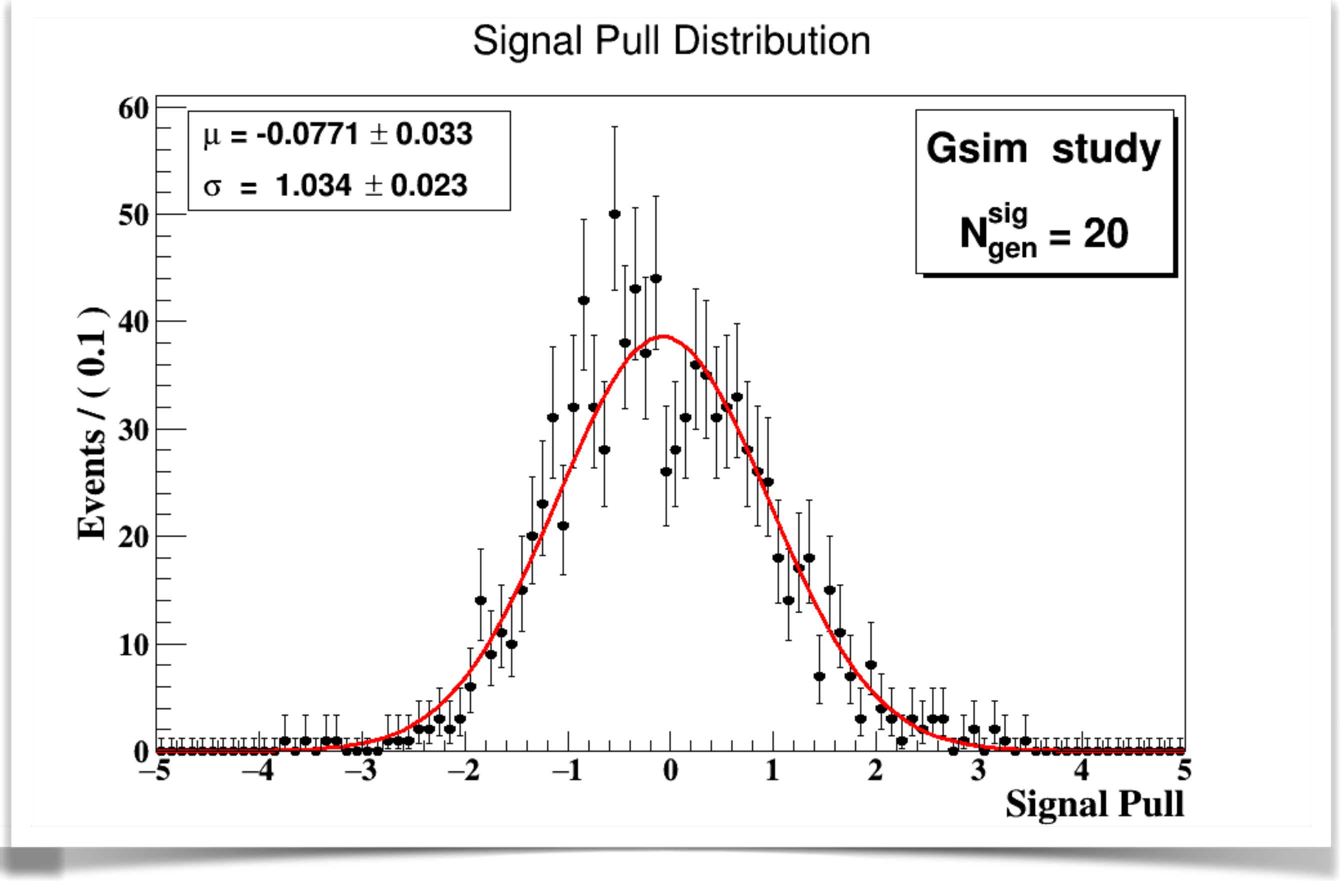






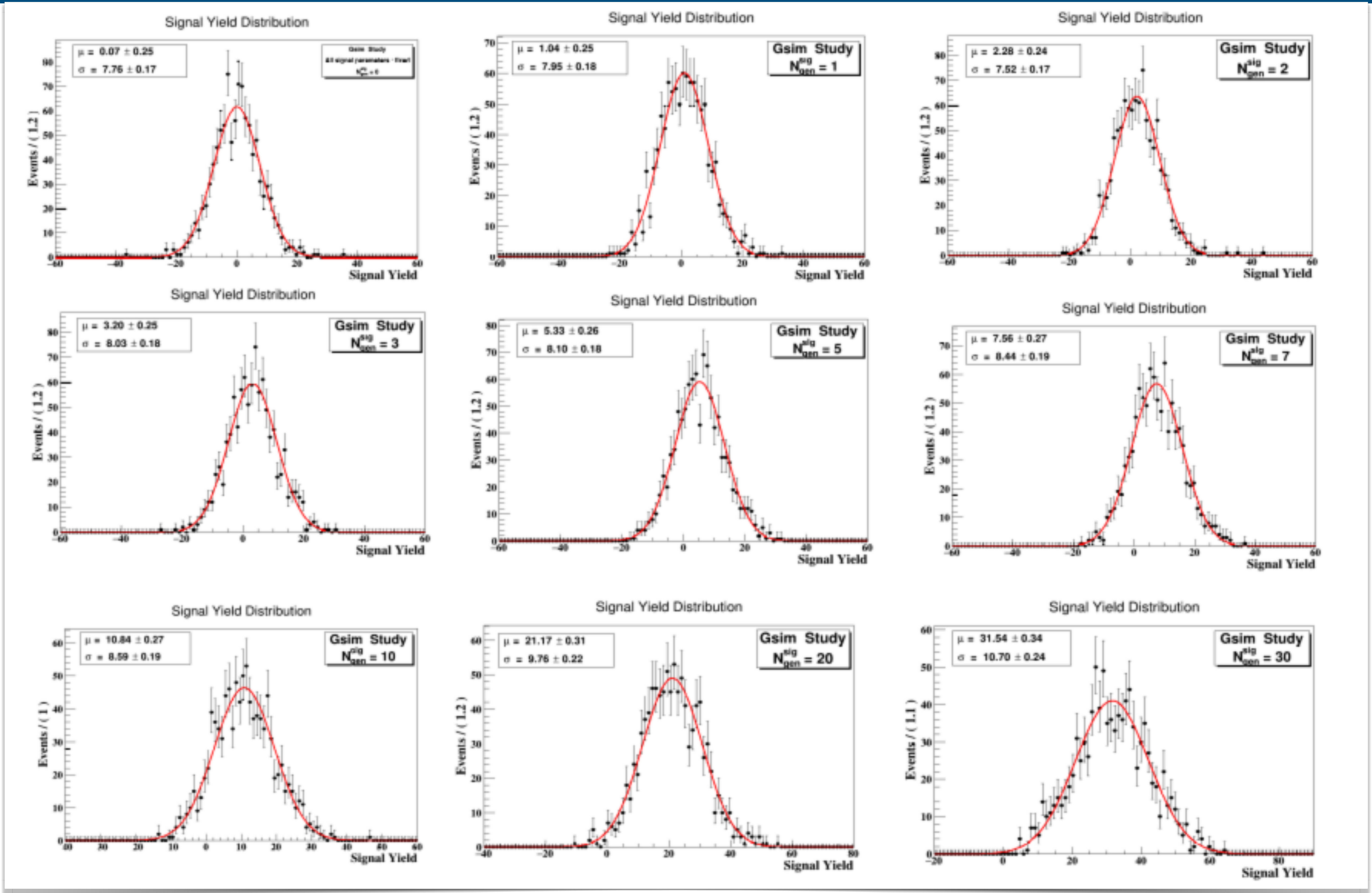




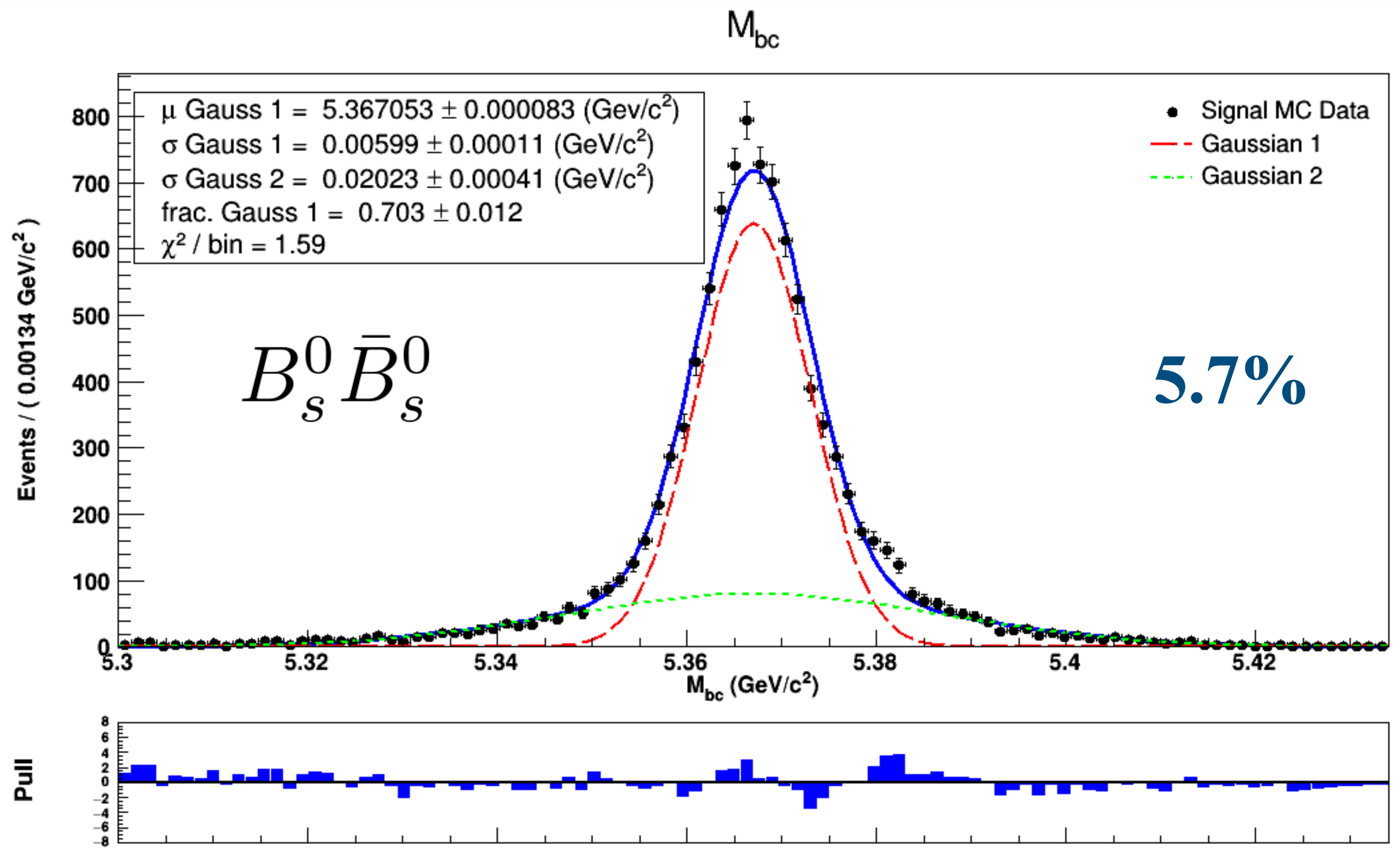


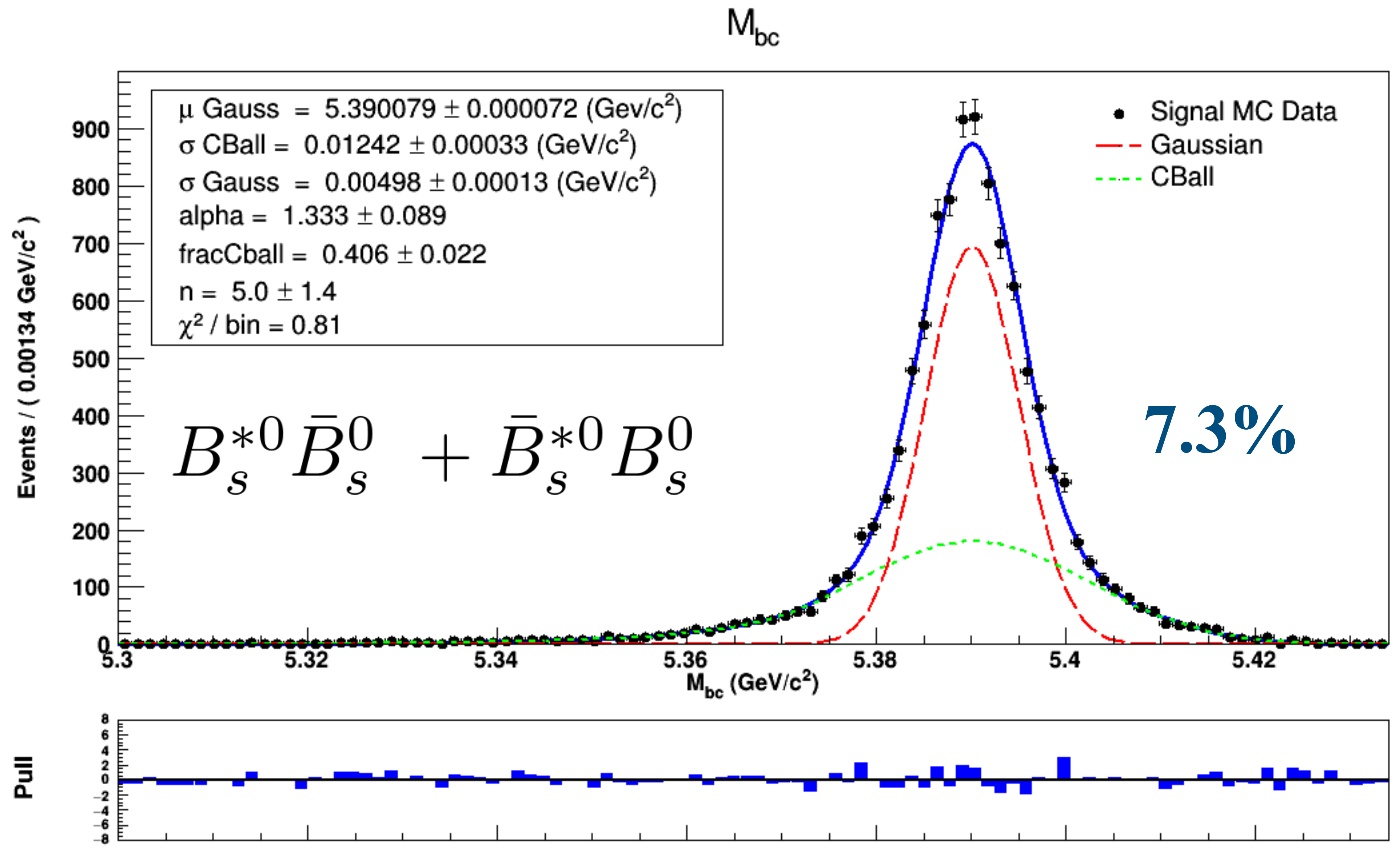
All signal parameters and background ARGUS end point is fixed
All other background parameters are floated

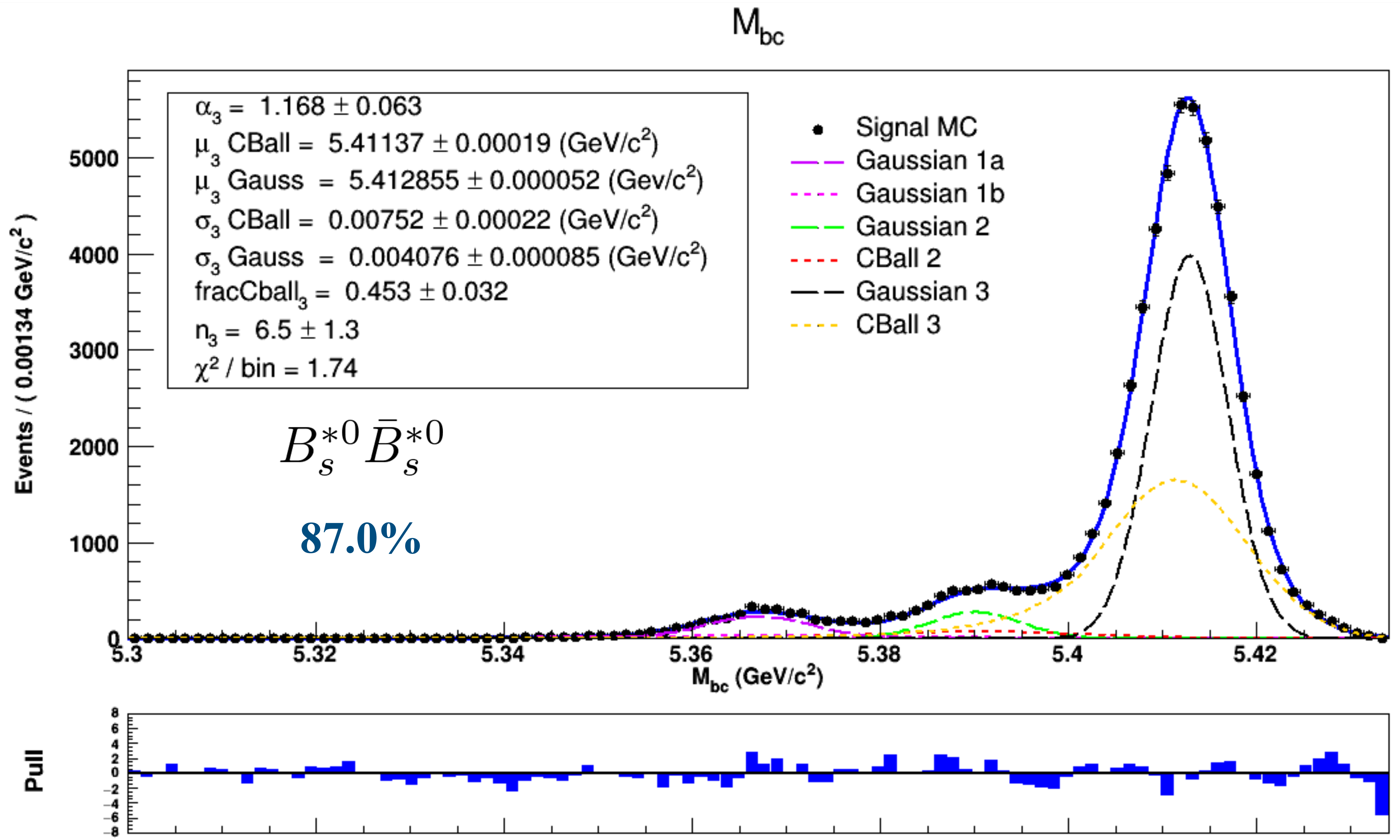
Yield distributions from ensemble study



Addition of three production channels : 1D PDF parametrizations





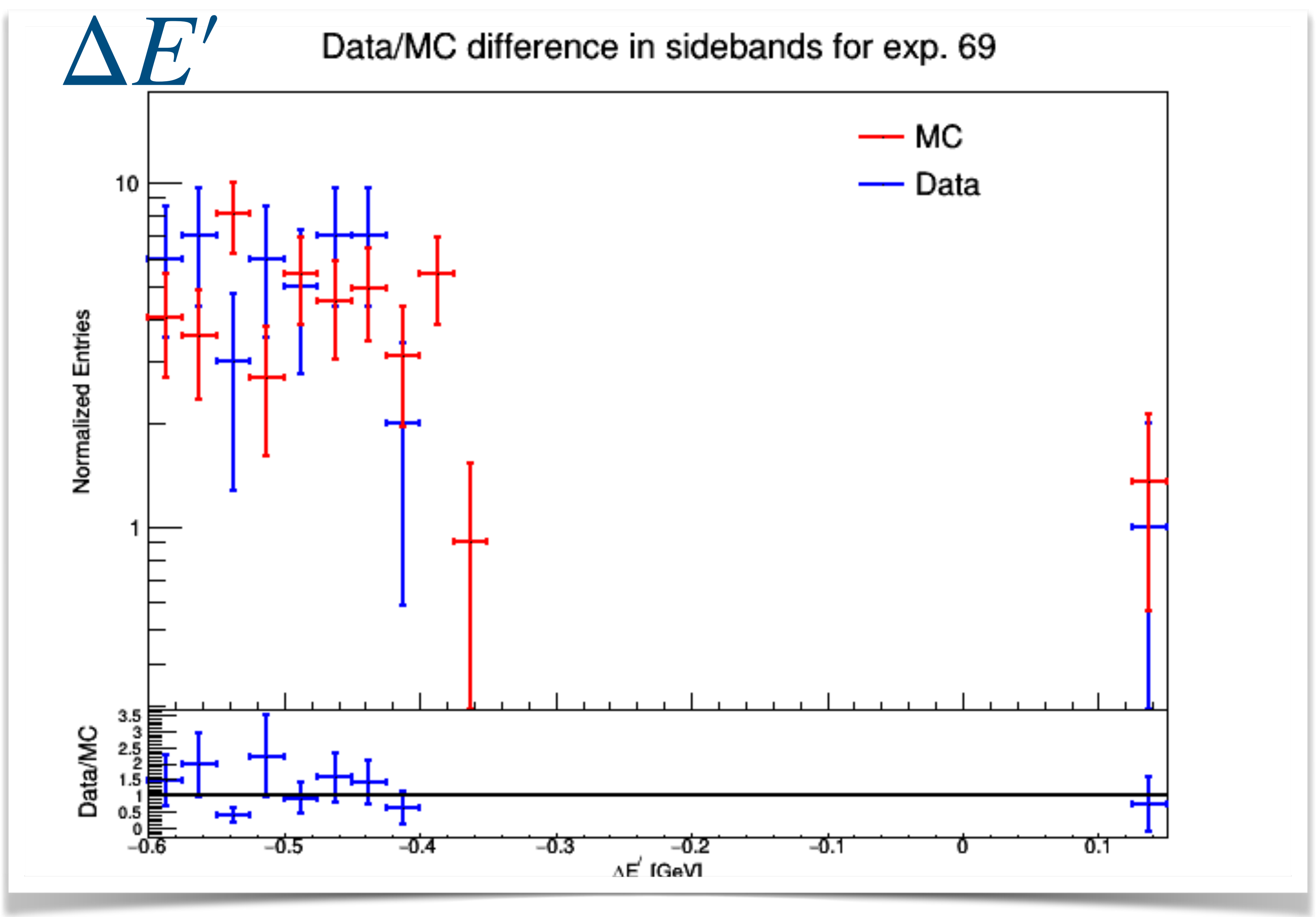


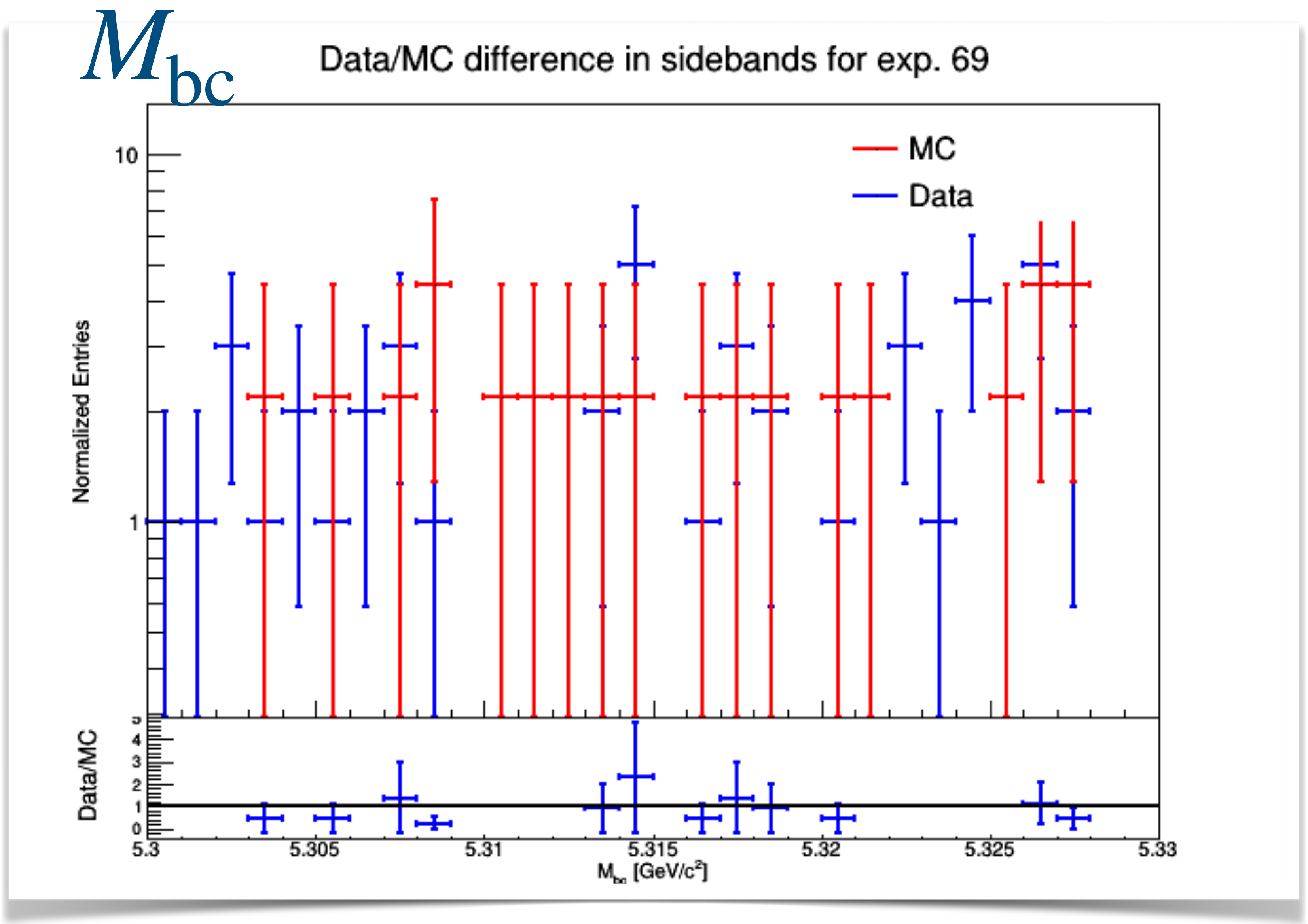
Channel	Fraction
$B_s^* \bar{B}_s^*$	0.870 ± 0.017
$B_s^* \bar{B}_s + cc$	0.073 ± 0.014

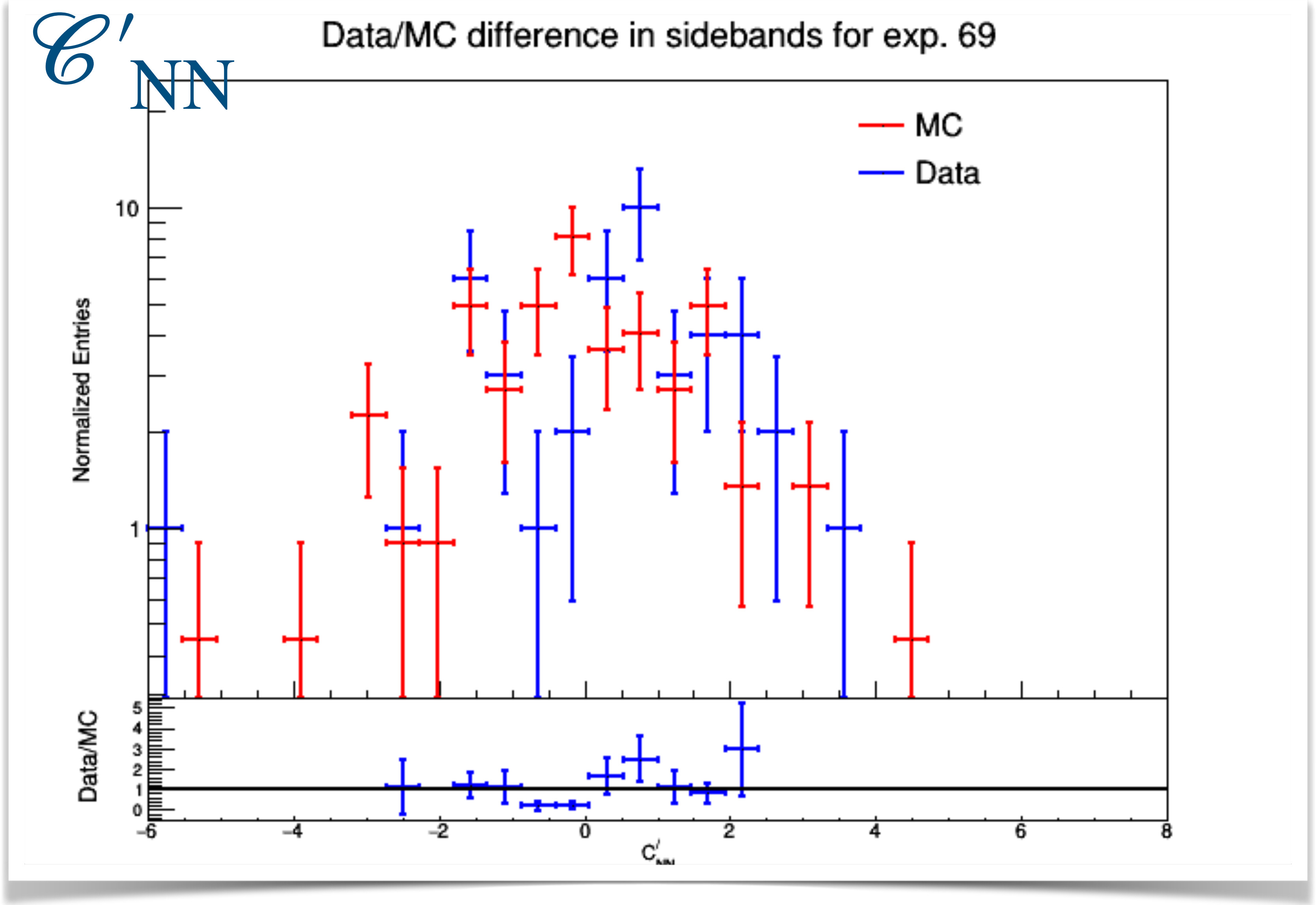
The production fractions are fixed in the final fit

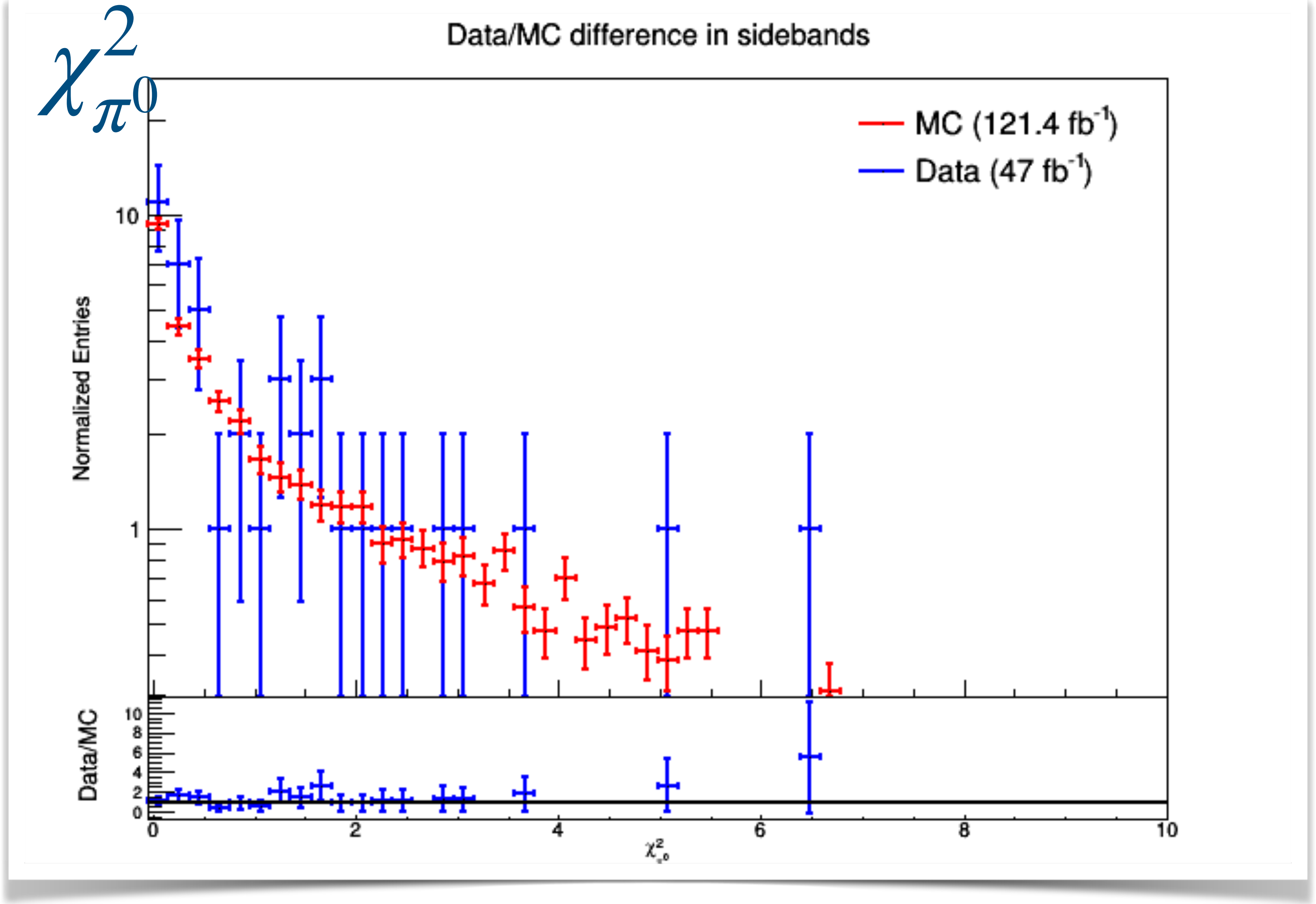
PRD.87.031101

Data sideband/MC cross-check









Systematic uncertainty due to PDF parametrization and NN selection criterion

Sl. No	Variable	Channel	PDF	Parameters	Parameter Values	Yield (-1σ)	Yield	Yield $(+1\sigma)$
1			G1	μ	5.367053 ± 0.000083	5.7	5.7	5.7
2	M_{bc} (GeV/c^2)	$B_s^0 \bar{B}_s^0$		σ	0.00599 ± 0.00011	5.7	5.7	5.7
3				fraction	0.703 ± 0.012	5.7	5.7	5.7
4			G2	σ	0.02023 ± 0.00041	5.7	5.7	5.7
5		$B_s^0 \bar{B}_s^0$		fraction	0.057 ± 0.022	5.6	5.7	5.7
	Uncertainty						$^{+0.0}_{-0.1}$	
6			G	μ	5.390079 ± 0.000072	5.7	5.7	5.7
7				σ	0.00498 ± 0.00013	5.7	5.7	5.7
8	M_{bc} (GeV/c^2)	$B_s^0 \bar{B}_s^{*0}$ + cc		σ	0.01242 ± 0.00033	5.7	5.7	5.7
9			CB	α	1.333 ± 0.089	5.7	5.7	5.7
10				n	5.0 ± 1.4	5.7	5.7	5.7
11				fraction	0.406 ± 0.022	5.7	5.7	5.7
12		$B_s^0 \bar{B}_s^{*0} + cc$		fraction	0.073 ± 0.014	5.6	5.7	5.8
	Uncertainty						$^{+0.1}_{-0.1}$	
13			G	μ	5.41283 ± 0.000051	5.6	5.7	5.8
14				σ	0.00411 ± 0.000083	5.6	5.7	5.7
15				μ	5.41136 ± 0.00020	5.7	5.7	5.7
16	M_{bc} (GeV/c^2)	$B_s^{*0} \bar{B}_s^{*0}$		σ	0.00766 ± 0.00023	5.6	5.7	5.7
17			CB	α	1.134 ± 0.068	5.7	5.7	5.6
18				n	7.8 ± 2.1	5.7	5.7	5.7
19				fraction	0.437 ± 0.031	5.6	5.7	5.8
20		$B_s^{*0} \bar{B}_s^{*0}$		fraction	0.87 ± 0.017	5.6	5.7	5.4
	Uncertainty						$^{+0.4}_{-0.2}$	
21		all (background)	ARGUS	m (end-point)	5.434 ± 0.000095	5.8	5.7	5.8
	Uncertainty						$^{+0.1}_{-0.1}$	
22				μ	-0.01695 ± 0.0010	5.6	5.7	5.7
23				σ_L	0.0983 ± 0.0021	5.6	5.7	5.7
24	$\Delta E'$ (GeV)	all	ACB	σ_R	0.0507 ± 0.00056	5.6	5.7	5.7
25				α	0.916 ± 0.027	5.7	5.7	5.7
26				n	6.38 ± 0.61	5.7	5.7	5.7
	Uncertainty						$^{+0.0}_{-0.2}$	
27				μ	1.475 ± 0.025	5.7	5.7	5.6
28			BG	σ_L	1.792 ± 0.054	5.6	5.7	5.8
29	$\mathcal{C}'_{NN}$	all		σ_R	1.992 ± 0.032	5.7	5.7	5.7
30				μ	0.66 ± 0.33	5.7	5.7	5.6
31			G	σ	2.77 ± 0.27	5.7	5.7	5.7
32				fraction	0.106 ± 0.049	5.6	5.7	5.8
	Uncertainty						$^{+0.2}_{-0.1}$	
	Total Uncertainty						$\mathbf{^{+0.5}_{-0.3}}$	

Type	Selection Criterion	Yield	$\epsilon_{\text{Data}}/\epsilon_{\text{MC}}$	R
Data	Without $\mathcal{C}'_{NN}$ cut	85023 ± 292	0.011 ± 0.00035	
	With $\mathcal{C}'_{NN} > 0.90$	989 ± 31		
				1.100 ± 0.050
MC	Without $\mathcal{C}'_{NN}$ cut	86320 ± 294	0.010 ± 0.00033	
	With $\mathcal{C}'_{NN} > 0.90$	862 ± 29		

Bayesian approach to calculate the upper limit on the branching fraction

21.3 Upper limit on the branching fraction

The process of obtaining the upper limit (UL) is enumerated below (following the reference [20]),

1. Construct the profile likelihood, $-2ln\lambda = ln(\mathcal{L}_0) - ln(\mathcal{L}_{max})$ where, $\mathcal{L}_0$ and $\mathcal{L}_{max}$ are the plain likelihoods considering background only(no signal) hypothesis and maximum value obtained from the 3D fit, respectively.

2. Convolute the plain likelihood, λ with a Gaussian distribution of width equal to the total systematic uncertainty estimated from the analysis. We find the total systematic uncertainty associated with the procedures adopted for signal extraction to be $^{+18.1}_{-18.4}\%$.

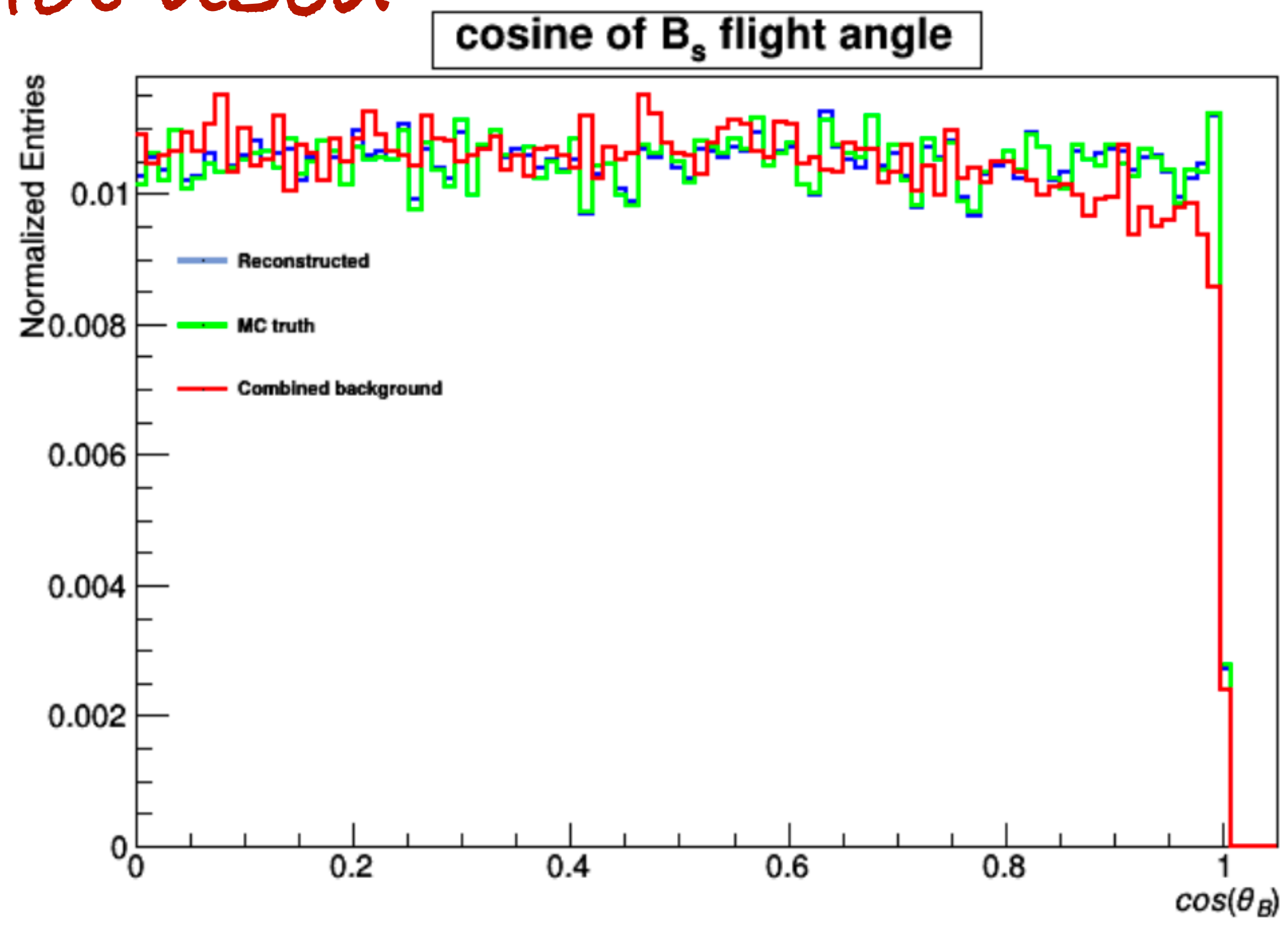
3. Integrate the convoluted plain likelihood upto 90% of its area to estimate the 90% confidence level (CL) UL. Figure (47) shows the convoluted likelihood obtained from real data.

Data/MC correction factors (control sample)

Variable	Parameter	Data	Signal MC	Difference/Ratio	Comment
$\Delta E\ GeV$	μ	-0.02017 ± 0.0041	-0.01927 ± 0.0030	-0.0009 ± 0.0051	Floated
	σ_L	0.1013 ± 0.0083	0.0900 ± 0.0051	1.1256 ± 0.1115	Floated
	μ (Common)	5.27990 ± 0.00065	5.27977 ± 0.00038	0.00013 ± 0.00075	Floated
$M_{bc}\ GeV/c^2$	σ (CBall)	0.00320 ± 0.00038	0.00317 ± 0.00013	1.00946 ± 0.11994	Floated
	σ (Gaussian)	0.00362 ± 0.00039	0.0035 ± 0.0002	1.0342 ± 0.12612	Floated

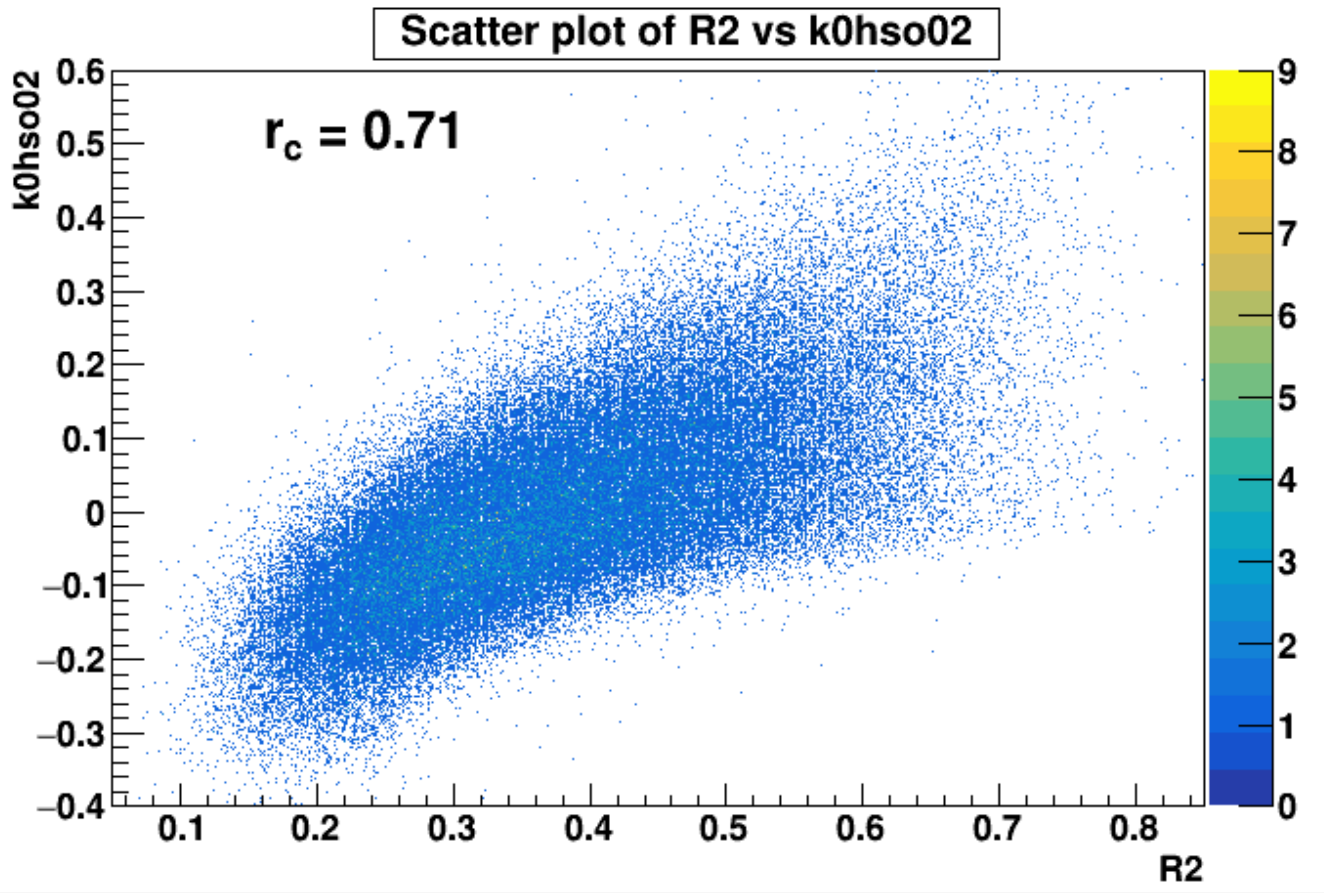
Inputs to the NN

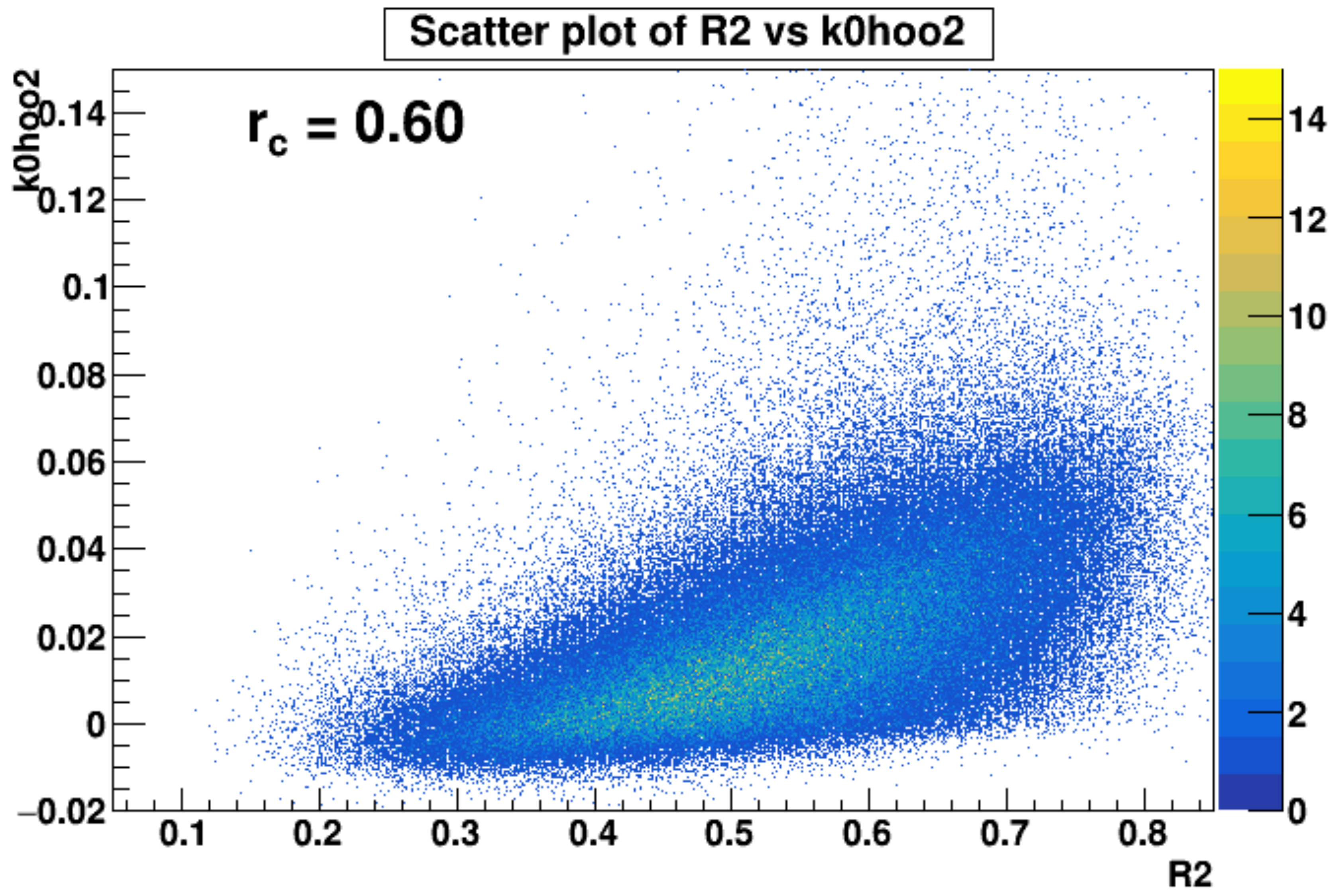
Not used



Physics of the B-factories

decay vertex. The ΔZ variable is not applicable for the decay modes with only photons in the final state, for instance $B^0 \to \pi^0\pi^0$. It is possible to use photon conversions to obtain the B vertex in a future super flavor factory. The





Variable	Correlation coefficients	
	M_{bc}	$\Delta E'$
k0et	0.0150	0.0816
k0mm2	−0.0048	−0.0997
k0hoo0	−0.0065	0.0790
k0hoo1	0.003	0.005
k0hoo2	0.0144	0.0237
k0hoo3	−0.0022	0.0008
k0hoo4	0.0071	0.0067
k0hso00	0.0123	0.0692
k0hso02	−0.0033	0.0019
k0hso04	−0.0076	−0.0115
k0hso10	−0.0083	−0.0075
k0hso12	−0.0385	−0.0469
k0hso14	−0.0452	−0.0622
k0hso20	−0.0196	0.0171
kohso22	−0.0426	−0.0536
kohso24	−0.0051	−0.0038
thrust	−0.0112	−0.0147