

Integrated luminosity recovery using machine learning

A new strategy for luminosity determination

based on learning of event migrations within the instrumented acceptance

I. Bozovic, VINCA, Uni. Belgrade
co-author: I. Vidakovic

Overview

Introduction to luminosity measurement

- Process (Small Angle Bhabha Scattering)
- Physics effects (ISR, FSR, BS, EMD of initial and final states)

Luminosity recovery

- Learning about migrations
- Preliminary luminosity precision

$\mathcal{L}$ measurement – Small Angle Bhabha Scattering

$$N = \mathcal{L} \cdot \sigma \cdot \varepsilon$$

$$\Delta\mathcal{L}/\mathcal{L} = (\Delta N/N) \oplus (\Delta\varepsilon/\varepsilon) \oplus (\Delta\sigma/\sigma)$$

N – Bhabha experimental count

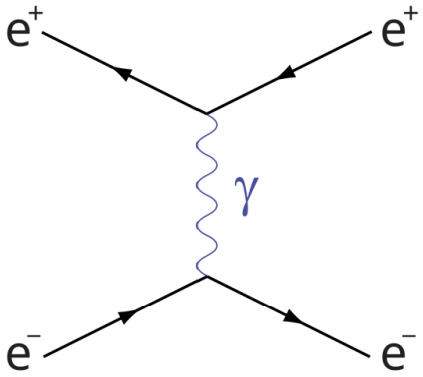
σ – theoretical cross-section

ε – total efficiency

ΔN – statistical ⊕ systematic uncertainty of the count (statistical $<10^{-4}$)

Δσ – theoretical uncertainty (typically $\Delta\sigma/\sigma \sim 10^{-4}$)

Δε – selection efficiency (i.e. one rely on E, ϑ, φ measurement) ⊕ reconstruction efficiency



QED, t-channel photon exchange (s-channel Z + Z-γ interference typically at ≥ 100 mrad)

$$\frac{\sigma_{s\text{-channel}}}{\sigma_{\text{total}}} \sim 10^{-3}$$

Bhabha (BHLUMI) theoretical precision: 5×10^{-4}

What was included:

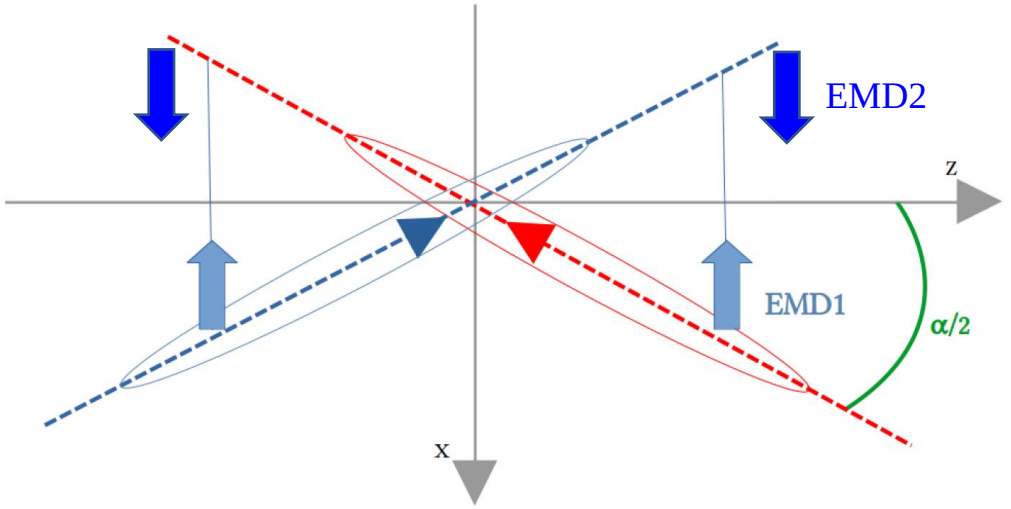
- ❑ Complete O(α) corrections
- ❑ Maximize control over multiple photon radiation
- ❑ Vacuum polarization effects

- ❑ Dominant uncertainties:
- ❑ Missing (some) sub-leading $O(\alpha^2)$ terms
- ❑ Hadronic vacuum polarization ($\gamma^* \to q\bar{q} \to \gamma^*$)

Physics effects: Radiative + Deflective

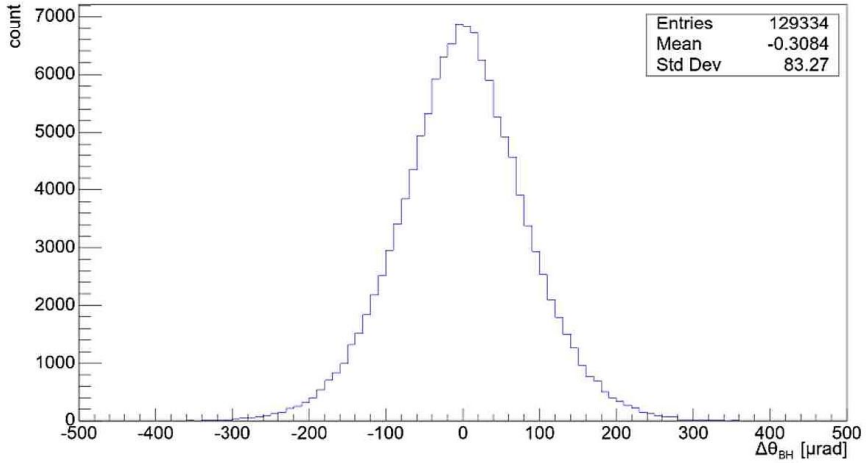
ISR – Initial State Radiation
FSR – Final State Radiation
BS – Beamstrahlung

Bremsstrahlung-like processes charge particle radiates due to (de)acceleration



EMD1 – EM deflection of the initial state
EMD2 – EM deflection of the final state

Collective field of the opposite charge bunches



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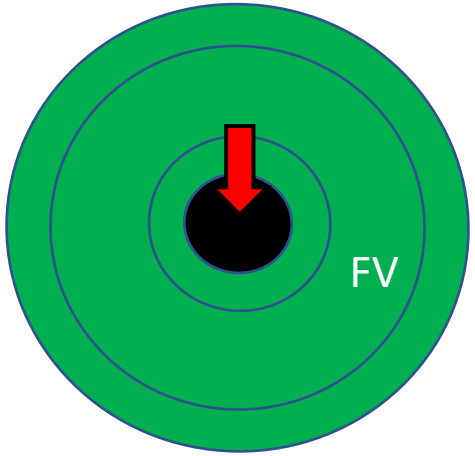
FV [53-79] mrad	$\Delta\mathcal{L}_{\rm int}/\mathcal{L}_{\rm int}$	$\Delta\theta_{\rm BH}$ [μrad]
EMD2	3.4 ‰	47.1
ISR+FSR	3.6 ‰	52.6
ISR+FSR+BS	3.8 ‰	52.9

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EMD1 does not bias Bhabha polar angle
EMD2 introduces focusing towards z-axis
Radiative effects cause additional migrations

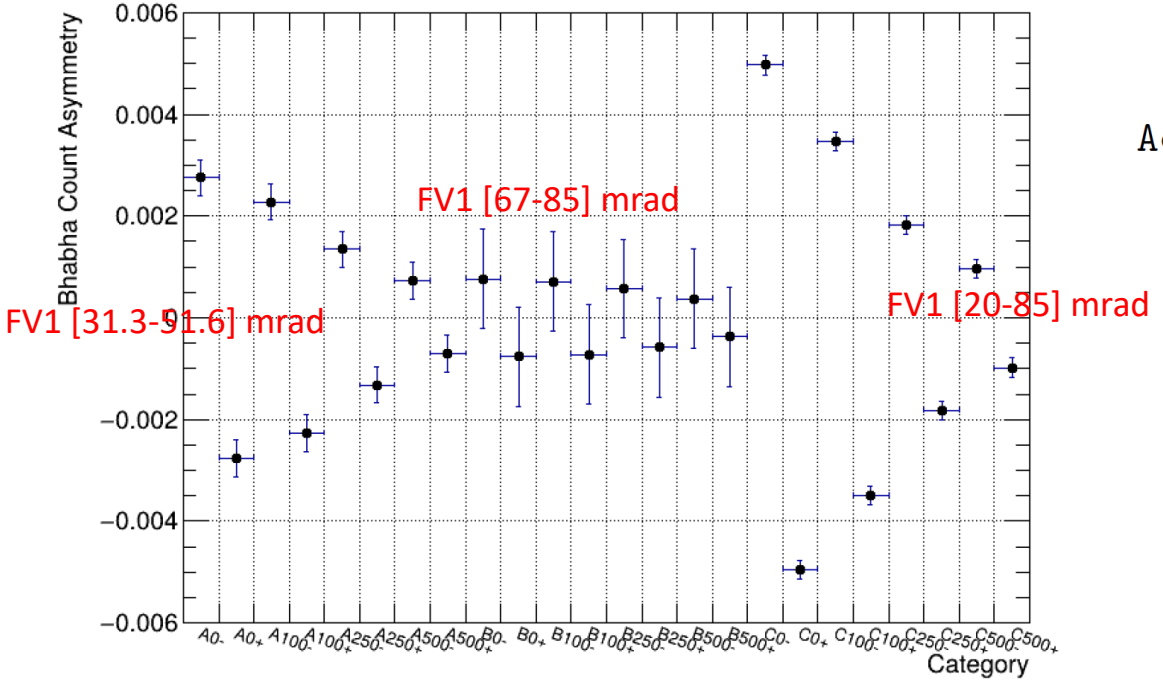
Luminosity corrections – observable based

STATE-OF-THE-ART: DEFINE OBSERVABLE sensitive to EM deflective effects (asymmetry, acolinearity), FIND CORRECTION IN SIMULATION-CALIBRATE, CHECK STABILITY



ILC: Use z-vertex reconstruction with certain precision σ to define asymmetry:

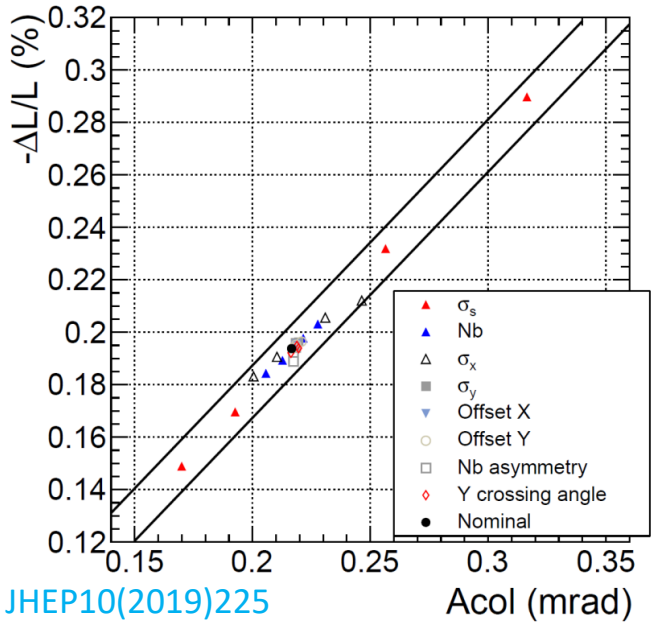
$$A_{\pm}^{\sigma[\mu m]} = \frac{N_{+z} - N_{-z}}{N_{+z} + N_{-z}}$$



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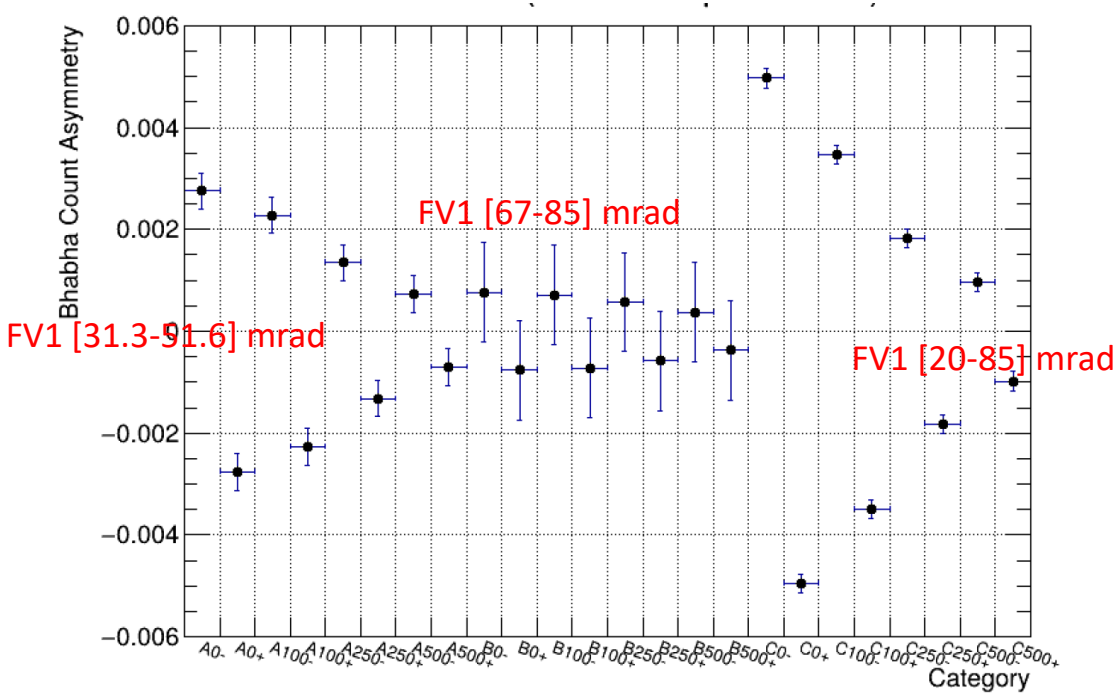
FCCee: Use reconstructed polar angle in the luminometer:

$$\texttt{Acol} = \left\langle \Delta\theta^{+-} \right\rangle_{|\phi^-|>\pi/2} - \left\langle \Delta\theta^{+-} \right\rangle_{|\phi^-|<\pi/2} \qquad \Delta\theta^{+-} = \theta^- - \theta^+$$

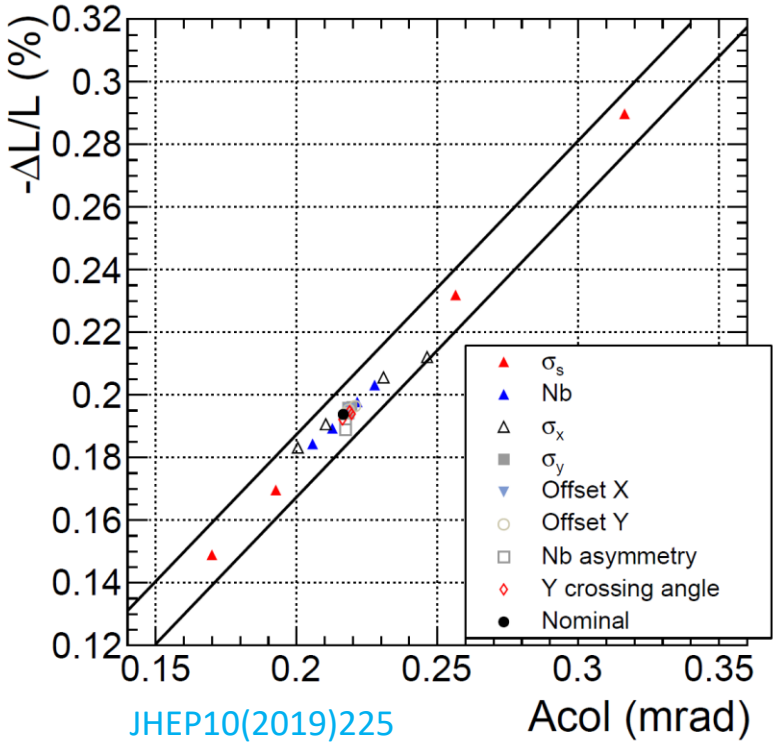


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Luminosity corrections – observable based



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Several common features:

- Always **use FV to measure luminosity**
- Compress physical information into **single observable**
- **Get the luminosity correction** from simulation

Limitations:

- Statistical sensitivity (region, fit)
- Calibration (modeling) introduces systematic uncertainty
- Information outside FV can not be recovered

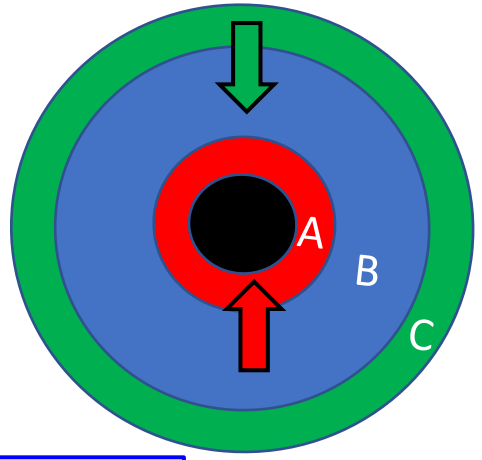
Changing paradigm

1. Let's measure luminosity – not derive corrections
2. Do it in a fraction of FV using the rest of the instrumented region to track event migrations
3. Use ML (more than one observable) to fully benefit from event kinematics

SIMULATION (53-83) mrad
FV: (53-79) mrad
PHYSICAL ACCEPTANCE: (30-105) mrad

THREE AREAS, $\mathcal{L}$ is measured in B:

A. INNER [53-60) mrad
B. CENTRAL [60-78] mrad
C. OUTER (78-83] mrad



MEASURE $\mathcal{L}_{int}$ IN CENTRAL (AREA B)

$N = N(B \rightarrow B) + N(B \rightarrow A,C)$

$N_{exp}(B) - N(A,C \rightarrow B)$

Simulation ~ 6 million events in FV
(~3 min of run at the Z-pole, ~ 40 s with the updated luminosity):
BHLUMI (ISR+FSR)
GP++ (EMD1,2)

BDTG TRAINING, FV: MULTIPLE VARIABLES

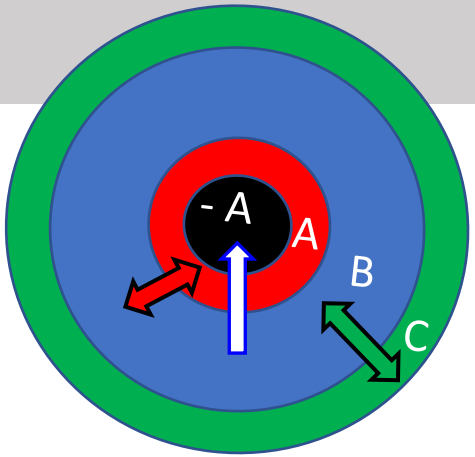
1. Effective collision energy $s' = (P_+ + P_-)^2$
2. Acolinearity π - *arc cos*$((\mathbf{e}_{p-}, \mathbf{e}_{p+})$
3. Acoplanarity *arc cos*$((\mathbf{e}_{p-},\mathbf{e}_z)\cdot(\mathbf{e}_{p+},\mathbf{e}_z))$;
4. $|\phi_- - \phi_+|$
5. $|\theta_+ - \theta_-|$
6. Mean polar angle $(\theta_+ + \theta_-)/2$
7. Energy difference $|E_1 - E_2|/(E_1 + E_2)$
8. E_{e-}, E_{e+}, θ_+, θ_-
9. p^-_z, p^+_z

Learning about migrations

Let us see how migrations look like to and from B

MEASURE $\mathcal{L}_{int}$ IN CENTRAL (AREA B)

N = N(B →B) + N(B→A,C)



True count in B (simulation): 2 802 035

l = 1 N(B→A, C)	l = 2 N(B→B)	l = 3 N(B→A,C)		l = 4 N(B→A, C)	unrecoverable	exp. count N(A,C →B)
e^+: B → A e^-: B → A	e^+: B → B e^-: B → B	e^-: B → A e^+: B → B e^-: B → B e^+: B → A	e^-: B → C e^+: B → B e^-: B → B e^+: B → C	e^-: B → C e^+: B → A e^-: B → A e^+: B → C --- e^+: B → C e^-: B → C	e^-: B → -A e^+: B → B e^-: B → B e^+: B → -A	event excess in B
2132	N_0: 2 777 532	20 211	2094	1, 11	54	N_1:5041

unrecoverable: 54
~1.9 · 10^{-5}

N_1: N(B→A,C) =24 499

N_2: N(A,C →B) = 5041

N_{exp}(B) = 2 782 573
= N_0+ N_1

- Due to radiative processes and EM deflection, original Bhabha events to be found in the measurement region B (true count) migrate both in and outside B;
- With the current definition of B, fraction of lost events from FV (unrecoverable) is 1.9 ·10^{-5}
- Fraction (l=4) of migrations N(B→A, C) is negligible (4.3 ·10^{-6}); **Overall lost 2.3 ·10^{-5}**

Learning about migrations

Classifier implementation to determine N_0=N(B→B) = 2 777 532

How to: calibrate event probability after the training phase

BDT1, measures (l=2)

Training:1 388 766 events

l=2 vs. N_{exp}(B) ⟹ signal event probability per BDT_{out} bin

Application: N_{exp}(B)

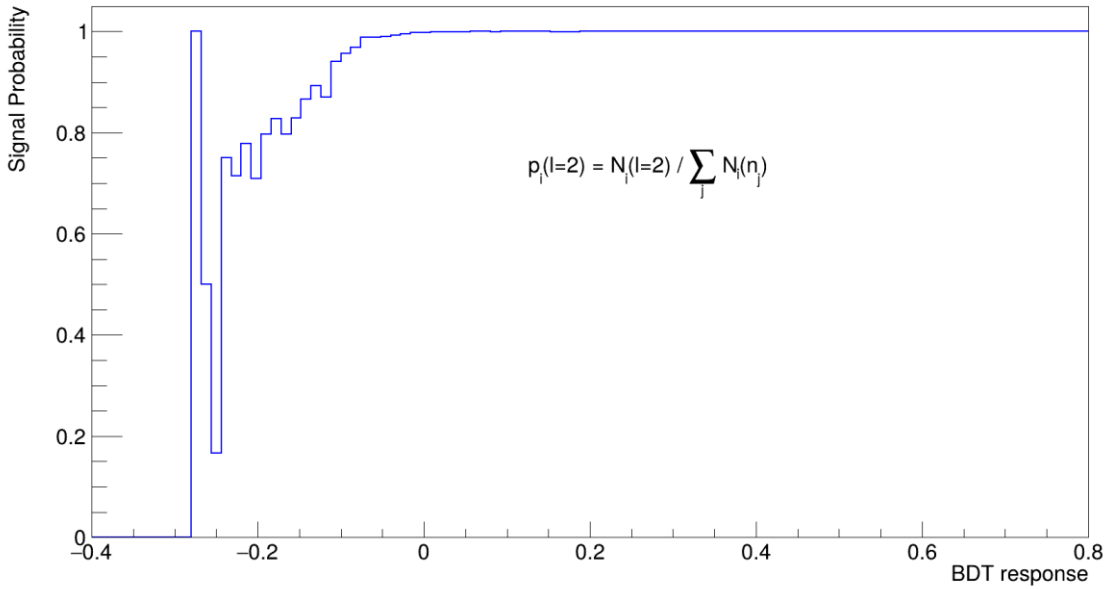
Result: Multiplying BDT_out in application/experiment with signal probability obtained in the training

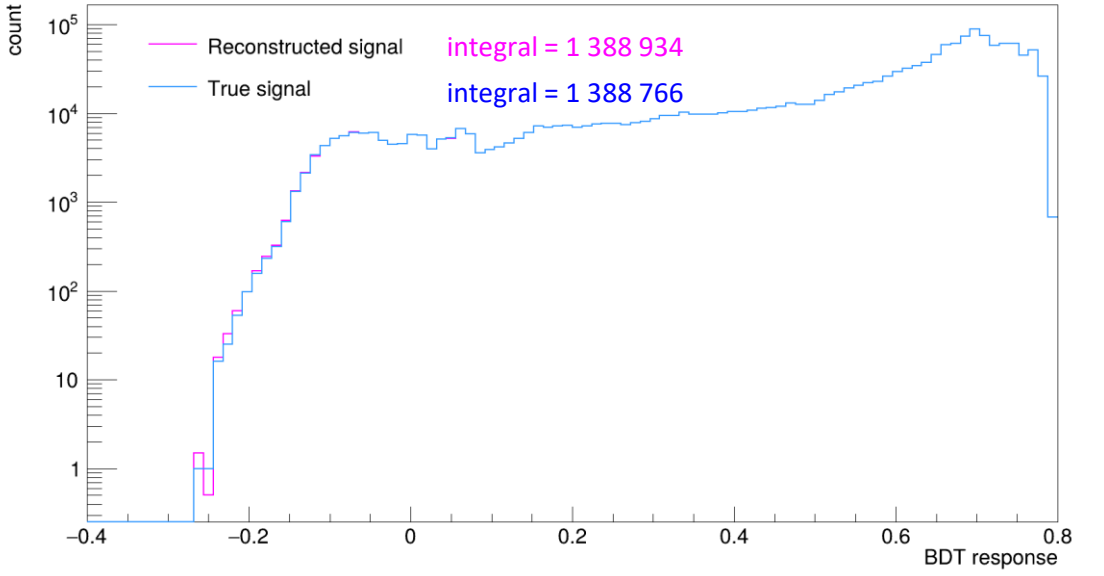
Signal is recovered as N_{rec}= 1388934

N(B→B) = 2·N_{rec}= 2777868

ΔN=N_{rec}-N_0= 336

Relative statistical precision is: **$1.2 \cdot 10^{-4}$;**





Learning about migrations

l = 1	l = 3	
N(B→A, C)	N(B→A,C)	
e^+: B → A e^-: B → A	e^-: B → A e^+: B → B e^-: B → B e^+: B → A	e^-: B → C e^+: B → B e^-: B → B e^+: B → C
2132	20 211	2094

BDT1, measures (l=2)
Training: l=2 vs. N_{exp}(B) → signal event probability
Application: N_{exp}(B)
Result: **N(B→B)**



WE NEED TO DO NEXT l=3

BDT3 (B→A)
Training: [l=3, (B→A)] vs. N_{exp}(1inB1inA)
Application: N_{exp}(1inB1inA)
BDT4 (B→C)
Training: [l=3, (B→C)] vs. N_{exp}(1inB1inC)
Application: N_{exp}(1inB1inC)

WE NEED TO DO NEXT l=1

BDT2, measures (l=1)
Training: l=1 vs. N_{exp}(A)
Application: N_{exp}(A)



NEXT STEPS

We have **recovered true events remaining in the counting region with a relative precision of 1.2 10^{-4}**

Lost or unrecoverable events: **2.3 10^{-5}**

N(B→A,C) : To keep luminosity error < $2 \cdot 10^{-4}$ l=1 and l=3 have to be recovered with the relative precision of ~ 6.5 10^{-3} (~158 events over 24437)

Discussion on uncertainties (to be checked)

NEXT STEPS

1. STATISTICAL TEST for BDT1
a. Repeat training and application on independent random samples
b. Perform ~ 150 pseudo-experiments to establish bias and dissipation → understand the limit of precision and room for improvement (statistical 'floor' for Poisson-distributed background is ~$2.5 \cdot 10^{-5}$, a factor 4.8 w.r.t. the current precision)

2. BEAM PARAMETER VARIATIONS
- See what happens if beams in application/experiment are not nominal (±5% variations)

3. EXPERIMENTAL REALITY
- Detector performance
- Background to Bhabha

SUMMARY

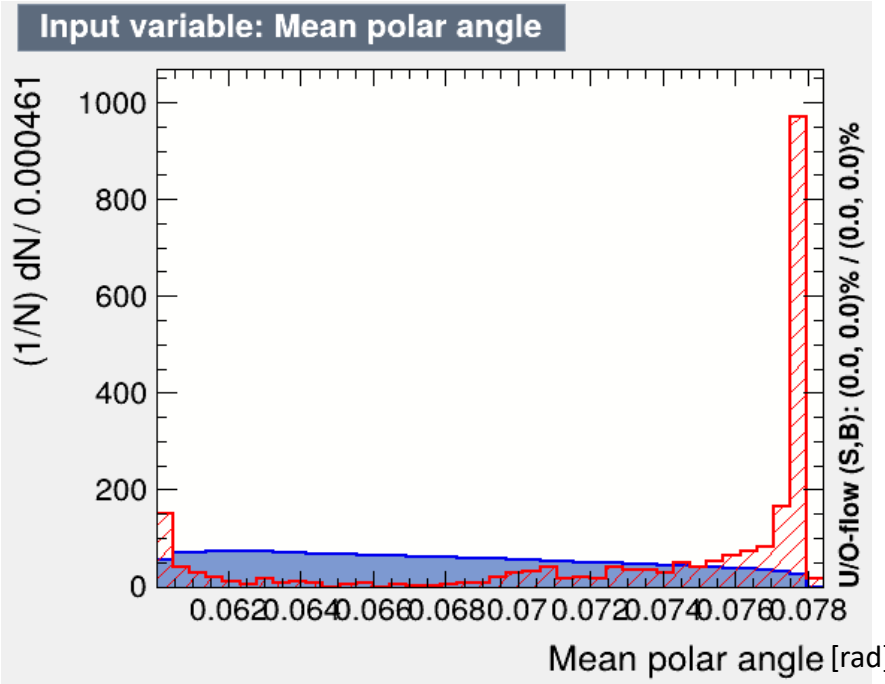
- ML-BASED METHOD IS ESTABLISHED TO MEASURE TRUE BHABHA COUNT IN THE PRESENCE OF RADIATIVE AND DEFLECTION EFFECTS INSTEAD OF DERIVING LUMINOSITY CORRECTION
- LUMINOSITY IS MEASURED IN A SEGMENT OF FV, WHILE THE REST OF INTESTRUMENTED REGION IS USED TO STUDY AND QUANTIFY EVENT MIGRATIONS
- MULTI-CLASSIFIER METHOD ESTIMATES THE TRUE NUMBER OF EVENTS MIGRATING TO AND FROM THE MEASURING REGION

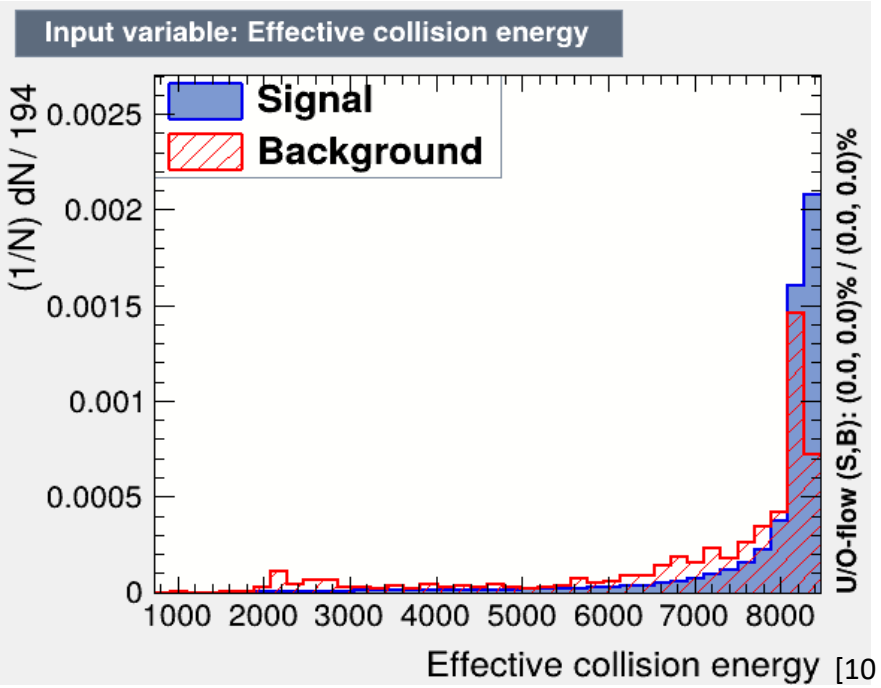
- **WE HAVE DEMONSTRATED THE APPLICABILITY OF ML-BASED METHOD FOR LUMINOSITY MEASUREMENT**
- **PRECISE RECOVERY OF NON-MIGRATING BHABHA IN THE MEASURING REGION WITH THE RELATIVE UNCERTAINTY OF $1.2 \cdot 10^{-4}$**
- **IRREDUCIBLE LOSSES ARE $2.3 \cdot 10^{-5}$**

- STATISTICAL TESTS ARE IDENTIFIED TO UNDERSTAND PRECISION LIMITS (ROOM FOR IMPROVEMENT)
- REALISTIC CONDITIONS SHOULD BE CONSIDERED AT SOME POINT (STABILITY TO BEAM PARAMETER VARIATIONS DETECTOR RESPONSE, BACKGROUND)

BACKUP

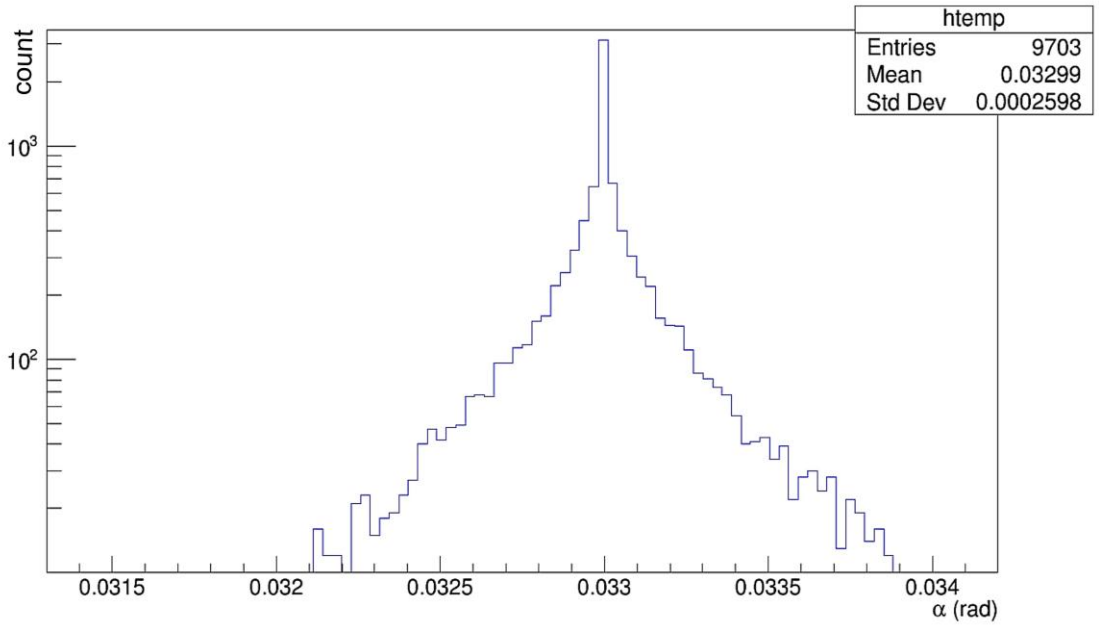
BDT1 variables





EMD1

Crossing angle determination from di-muon production at the Z^0 pole, in ~70 pb^{-1} of integrated luminosity.



Standard error gives 260 μrad/√Nμμ
10^6 events takes < 1 min

Progress of Theoretical and Experimental Physics, ptag137 (2026)

