Photon efficiency calibration with $e^+e^- \to \mu^+\mu^-\gamma_{\mathrm{ISR}}$ in release-08

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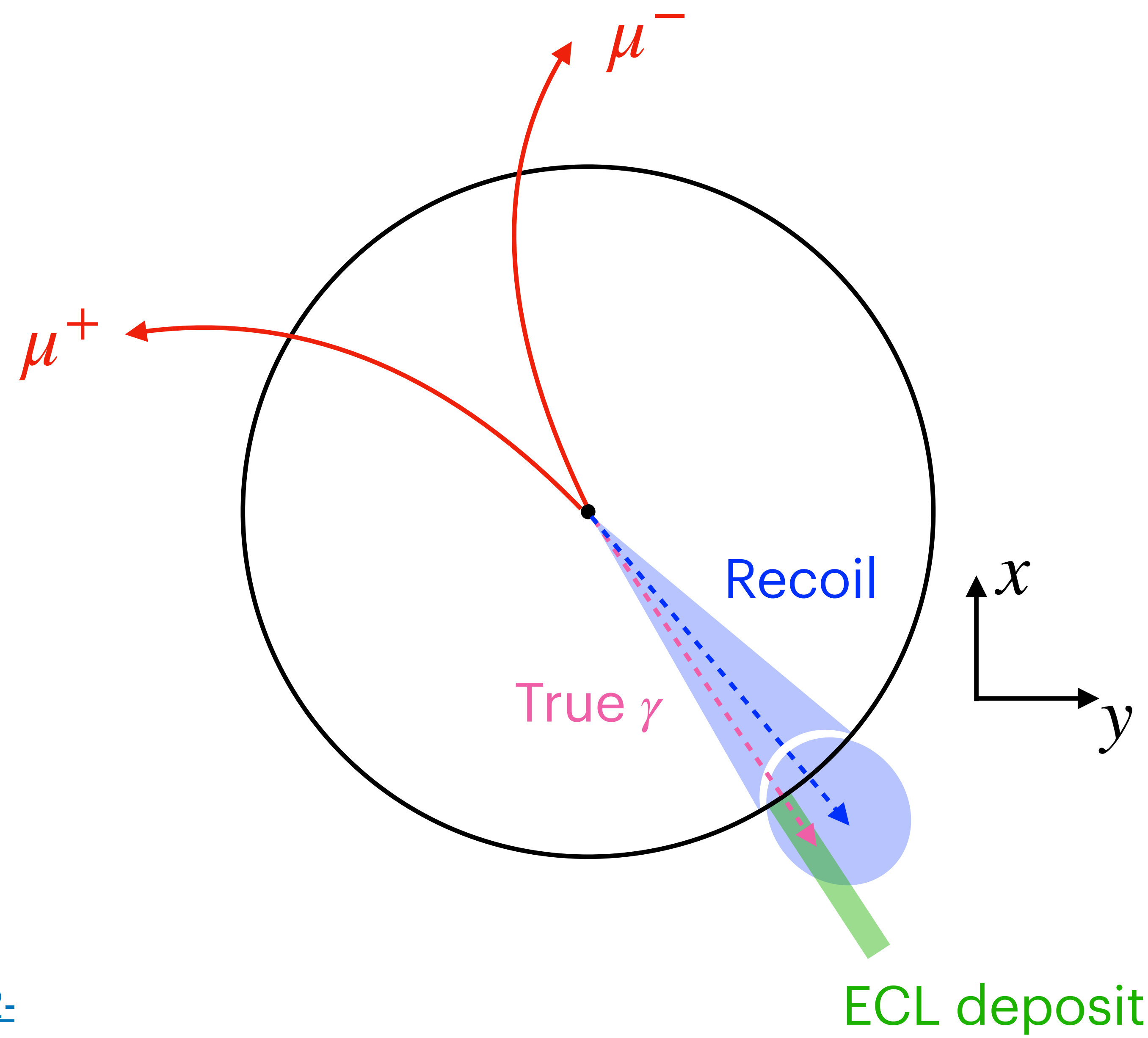
Overview

Obtain data/MC photon efficiency calibrations in bins of p and θ.

Reconstruct $\mu^+\mu^-$ recoil in $e^+e^- \to \mu^+\mu^-\gamma_{\mathrm{ISR}}$ and search for corresponding photon in cone.

Take over from Henrikas/Lu: use and improve existing code (https://docs.belle2.org/files/471/BELLE2-NOTE-TE-2024-002-V2/1/BELLE2-NOTE-TE-2024-002-V2.pdf).



$$\text{Efficiency} = \frac{\text{ECL deposits (inside the cone)}}{\text{Recoils}}$$

Previous presentations:
https://indico.belle2.org/event/15002/contributions/92009/attachments/33854/50144/neutrals_17_04_25_v3.pdf
https://indico.belle2.org/event/15715/contributions/95327/attachments/35357/52420/neutrals_03_07_25_vF.pdf
https://indico.belle2.org/event/15714/contributions/96207/attachments/35708/53043/neutrals_24_07_25_vF.pdf

Changes/improvements wrt previous analysis

Produce two separate sets of corrections:

– KLM-based corrections (nominal), with new selection on muon PID to avoid systematics related to ECL data/MC discrepancies (Sebastiano);

– ECL-based corrections, similar to previous analysis with some improvements (Kylian) — compare as validation.

Main improvements:

– new selections: add track-based trigger requirement, remove ECL selections on muons, add PID selection. Recoil cone now calculated using the 3D angle. Tighter requirement on m^2_{rec}, and new requirement on $E_{\mathrm{recoil}}/p_{\mathrm{recoil}}$.

– empirical beam calibration to improve recoil distributions data/MC agreement.

Samples and selection

Data: proc16 (Υ(4S)+off-res)

MC: proc16 (Υ(4S)+off-res)
all samples (also low-multiplicity)

Data: prompt (Υ(4S)+off-res)

MC: prompt (Υ(4S)+off-res)
all samples (also low-multiplicity)

Tracks: |dz| < 1.0 cm, |dr| < 1 cm,
p > 1 GeV, nCDCHits > 20, clusterE > 0.0,
$\mathscr{L}_{\mu}^{\mathrm{KLM}}/(\mathscr{L}_{\mu}^{\mathrm{KLM}} + \mathscr{L}_{\pi}^{\mathrm{KLM}} + \mathscr{L}_{e}^{\mathrm{KLM}}) > 0.5$.

$\mu\mu$ system: $|m_{\mathrm{rec}}^2| < 0.15$ GeV, $p_{\mathrm{rec}} > 0.2$ GeV,
$0.19 < p_{\mathrm{rec}}^{\theta} < 2.95$, $0.85 < E_{\mathrm{recoil}}/p_{\mathrm{recoil}} < 1.15$.

ECL clusters: $0.21 < \theta_{\gamma} < 2.75$, $E_{\gamma} > 0.05$,
$0.5 < E_{\gamma}/p_{\mathrm{rec}} < 1.2$, |timing| < 200 ns.

At least one trigger in [ffo, fyo, ff30, fy30, stt, cdcklm1, cdcklm2].

Photon in recoil cone (0.3 rad). if 2 photons found in cone, remove event.

Apply momentum scale corrections.

Remove ECL-based selections on tracks. Use KLM-only PID instead.

Beam energy calibration

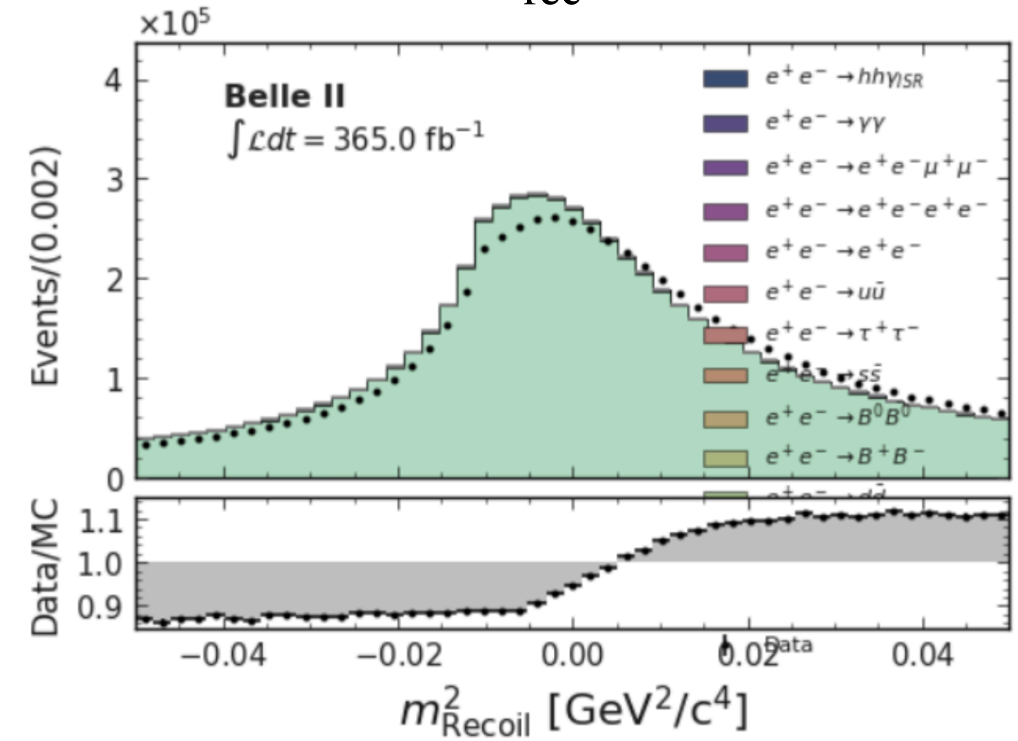
Observe large data/MC difference in $\mu\mu$ distributions. Two options:
1) apply very loose selection (as in previous analysis)
2) correct discrepancy and apply tighter selection

Disagreement (shift and fudge) observed also in $\mu\mu$ invariant mass.

Could be due to muon momentum scale or beam parameters.

Calculate empirical correction (beam mass shift) to correct for discrepancy:

Example of m^2_{rec} peak in Proc16:



$E_i = E_{LER} + E_{HER}$ = beam energy in the lab frame

$$E_i^{\mathrm{mod}} = \sqrt{|\vec{p}_i|^2 + (m_i + \Delta m)^2}$$

with $m_i = \sqrt{E_i^2 - |\vec{p}_i|^2}$

$$E^{\mathrm{mod}}_{\mathrm{Recoil}} = E_i^{\mathrm{mod}} - E_{\mu 1} - E_{\mu 2}$$

$$\vec{p}^{\,\mathrm{mod}}_{\mathrm{Recoil}} = \vec{p}_i - \vec{p}_{\mu 1} - \vec{p}_{\mu 2} = \vec{p}_{\mathrm{Recoil}}$$

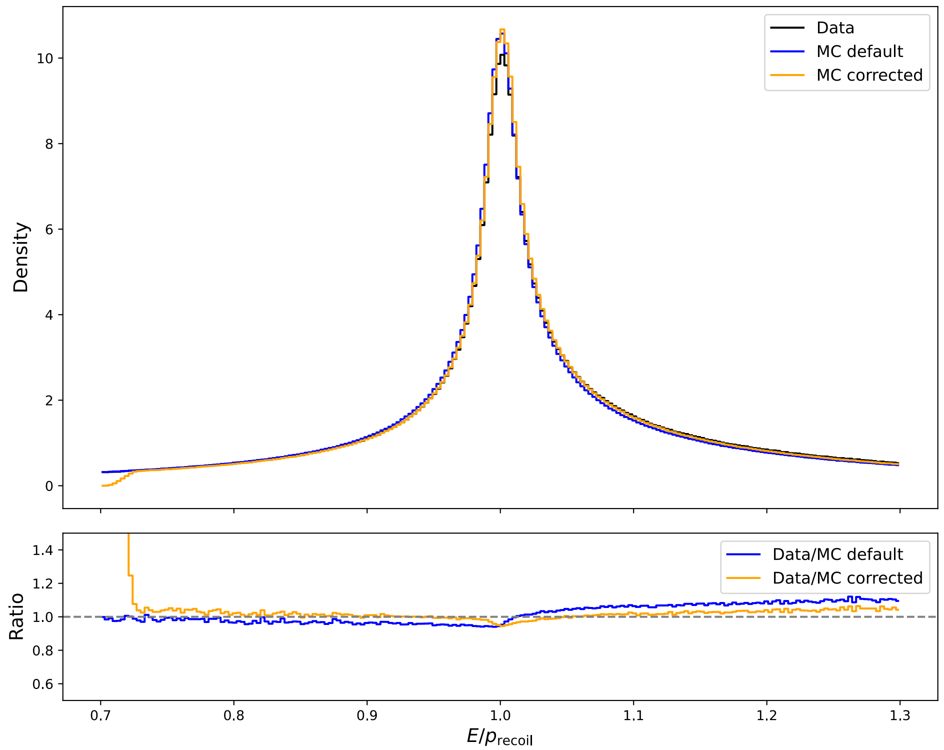
Beam calibration modifies beam and recoil energy, not momenta.

Beam energy calibration

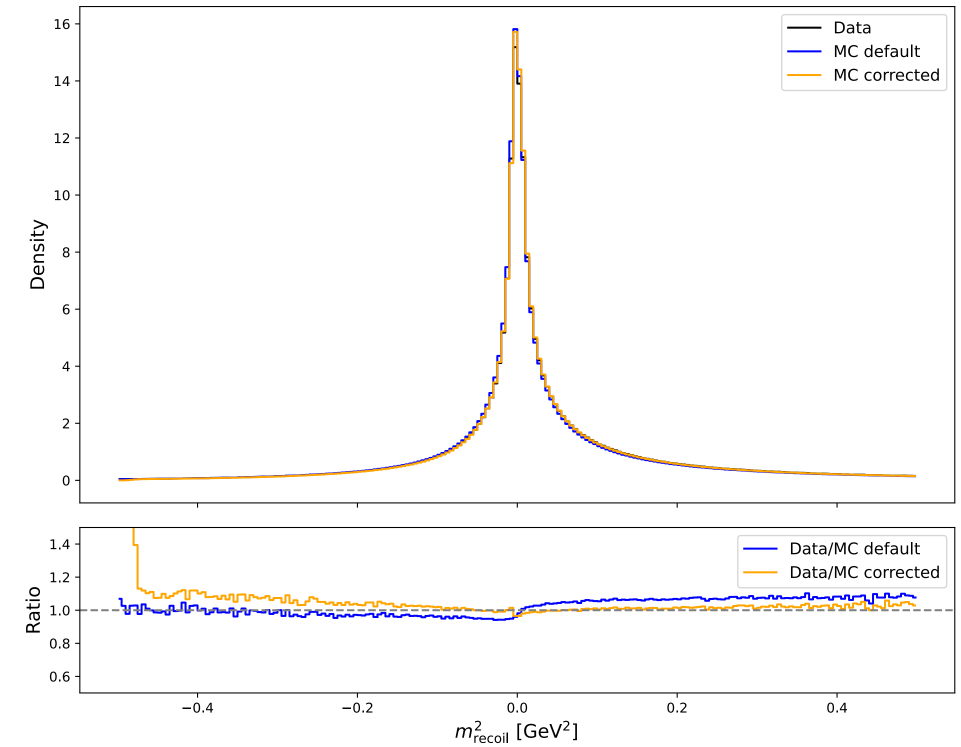
Scan Δm values and minimize (m^2_{rec} and $E_{\text{recoil}}/p_{\text{recoil}}$) Kolmogorov Smirnov data/MC distances in 80% central quantile — to avoid tail effects.

Repeat for each experiment.

Experiment	**Type**	**Beam Mass Shift [MeV/c^2]**
12	$\Upsilon(4S)$	+2.50
12	Off-resonance	+4.10
14	$\Upsilon(4S)$	+2.60
16	$\Upsilon(4S)$	+2.50
17	$\Upsilon(4S)$	+2.60
18	$\Upsilon(4S)$	+2.60
18	Off-resonance	+11.50
20	$\Upsilon(4S)$	+2.50
22	$\Upsilon(4S)$	+2.50
24	$\Upsilon(4S)$	+2.50
25	Off-resonance	+2.10
26	$\Upsilon(4S)$	+2.90
30	$\Upsilon(4S)$	+2.20
31	Off-resonance	+1.90
32	Off-resonance	+1.70
33	$\Upsilon(4S)$	+2.30
35	$\Upsilon(4S)$	+2.40



$E_{\text{recoil}}/p_{\text{recoil}}$



m^2_{rec}

Improved agreement. Systematic will be smaller.

Choose $\mu\mu$ recoil selections

Obtain true cone efficiency for various selections. Choose selections based on it.

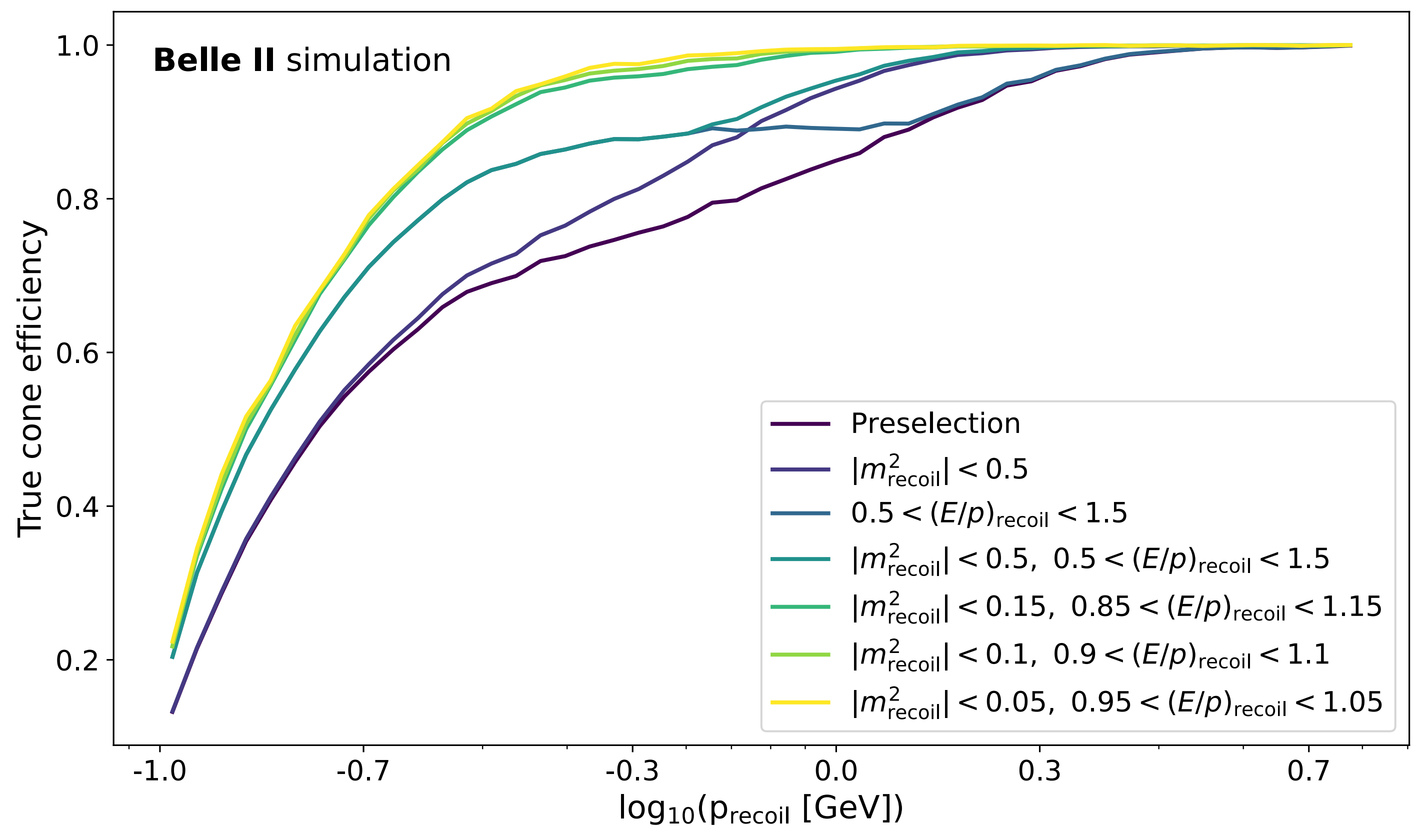
$\varepsilon_{\rm cone}^{\rm MC}$ (number of MC photons in MC recoil)

= 1 → measure absolute γ efficiency

< 1 if multi $\gamma_{\rm ISR}$ or muon track resolution smearing

Tight selections on $m_{\rm rec}^2$ and $E_{\rm recoil}/p_{\rm recoil}$ → higher $\varepsilon_{\rm cone}^{\rm MC}$.

Too tight selections: large systematic and no improvement.



Choose selection $|m_{\rm rec}^2|$ < 0.15 GeV, 0.85<$E_{\rm recoil}/p_{\rm recoil}$<1.15

PID corrections

Apply PID to each muon: $\mathscr{L}_{\mu}^{\mathrm{KLM}}/(\mathscr{L}_{\mu}^{\mathrm{KLM}}+\mathscr{L}_{\pi}^{\mathrm{KLM}}+\mathscr{L}_{e}^{\mathrm{KLM}}) > 0.5.$

Use systematic framework to get data/MC corrections (using the same $e^+e^- \to \mu^+\mu^-\gamma_{\mathrm{ISR}}$ events).

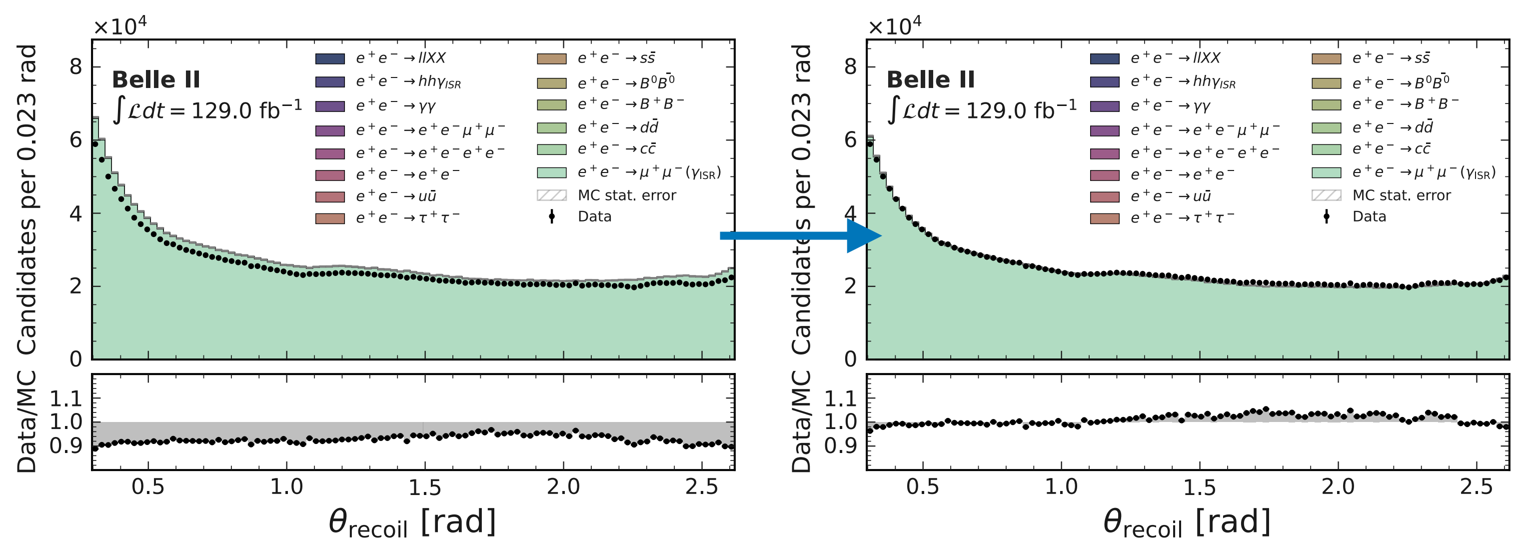
Custom binning to take into account high μ momenta.

PID corrections improve data/MC normalization. Small uncertainties.

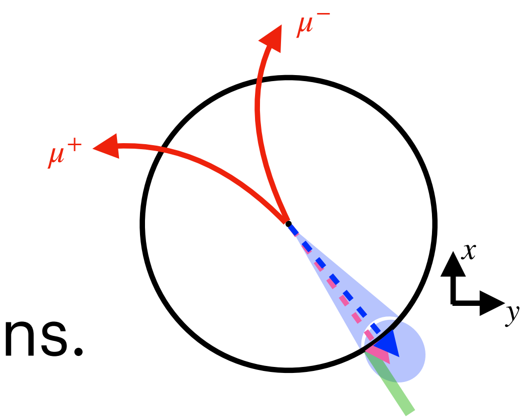
Prompt $\Upsilon(4S)$ corrections

mu ratio table for cut "trinaryKLMID(mu,pi,e) > 0.5"

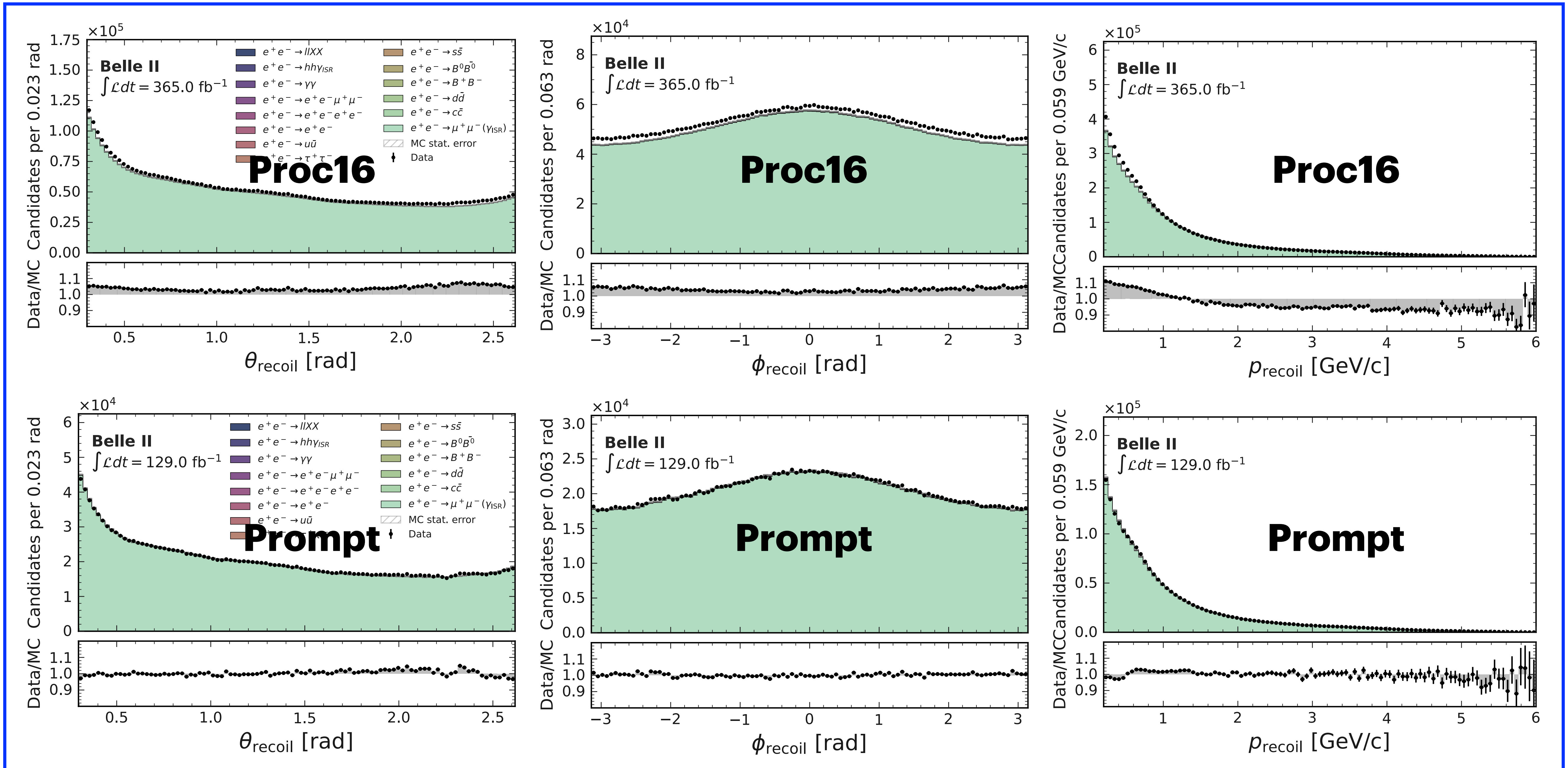
p bins \ cosTheta bins	-0.866 – -0.682	-0.682 – -0.4226	-0.4226 – -0.1045	-0.1045 – 0.225	0.225 – 0.5	0.5 – 0.766	0.766 – 0.8829	0.8829 – 0.9563
1.0 – 1.5	0.94±0.00	0.96±0.00	0.96±0.00	0.96±0.00	0.96±0.00	0.97±0.00	0.95±0.00	[illegible]
1.5 – 2.0	0.95±0.00	0.97±0.00	0.96±0.00	0.96±0.00	0.97±0.00	0.97±0.00	0.97±0.00	0.92±0.01
2.0 – 2.5	0.98±0.00	0.97±0.00	0.96±0.00	0.96±0.00	0.97±0.00	0.97±0.00	0.99±0.00	0.95±0.00
2.5 – 3.0	0.98±0.00	0.97±0.00	0.96±0.00	0.96±0.00	0.97±0.00	0.97±0.00	0.99±0.00	0.99±0.00
3.0 – 3.5	0.99±0.00	0.98±0.00	0.96±0.00	0.97±0.00	0.97±0.00	0.97±0.00	0.99±0.00	0.99±0.00
3.5 – 3.8	0.99±0.00	0.97±0.00	0.97±0.00	0.97±0.00	0.98±0.00	0.97±0.00	0.99±0.00	0.99±0.00
3.8 – 4.1	0.99±0.00	0.95±0.00	0.96±0.00	0.97±0.00	0.98±0.00	0.98±0.00	0.99±0.00	0.99±0.00
4.1 – 4.4	0.98±0.00	0.96±0.00	0.96±0.00	0.97±0.00	0.98±0.00	0.98±0.00	0.99±0.00	0.99±0.00
4.4 – 4.7	0.98±0.00	0.97±0.00	0.95±0.00	0.97±0.00	0.98±0.00	0.98±0.00	0.99±0.00	0.99±0.00
4.7 – 5.0	0.89±0.07	0.94±0.01	0.95±0.00	0.96±0.00	0.98±0.00	0.98±0.00	0.99±0.00	1.00±0.00
5.0 – 5.3	0.97±0.14	0.71±0.24	0.96±0.00	0.97±0.00	0.97±0.00	0.98±0.00	0.99±0.00	1.00±0.00
5.3 – 5.6	0.14±0.94	0.00±nan	0.92±0.07	0.97±0.00	0.97±0.00	0.97±0.00	1.00±0.00	1.00±0.00
5.6 – 5.9	0.62±0.70		0.00±nan	0.97±0.01	0.97±0.00	0.96±0.00	0.98±0.00	1.00±0.00
5.9 – 6.2	0.67±0.76			0.64±0.23	0.97±0.00	0.95±0.00	0.95±0.00	1.00±0.00
6.2 – 6.5	0.00±nan			0.50±0.71	0.97±0.04	0.91±0.00	0.85±0.00	1.01±0.00
6.5 – 7.0	0.42±0.55			0.00±nan	1.00±0.00	0.74±0.00	0.89±0.00	1.00±0.00



Data/MC comparisons

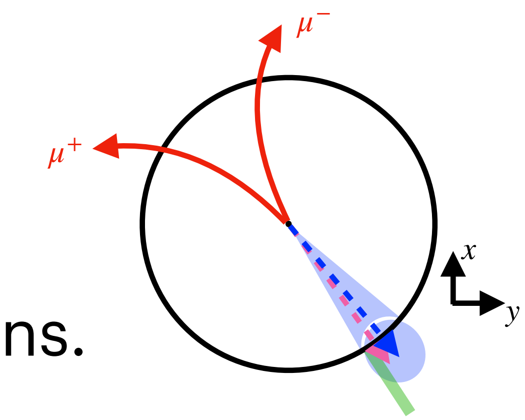


Compare data/MC distributions of selected recoils after PID corrections.

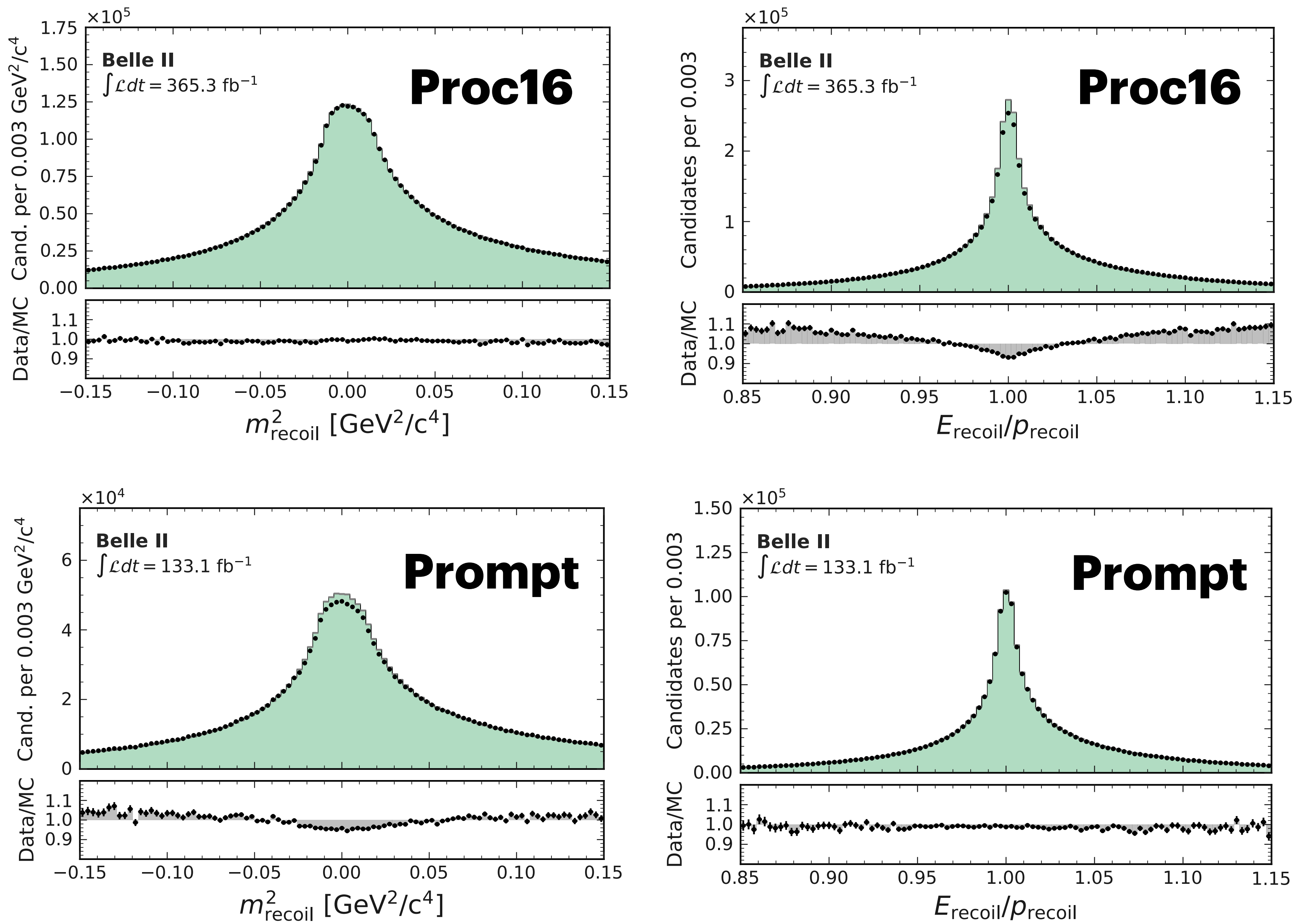


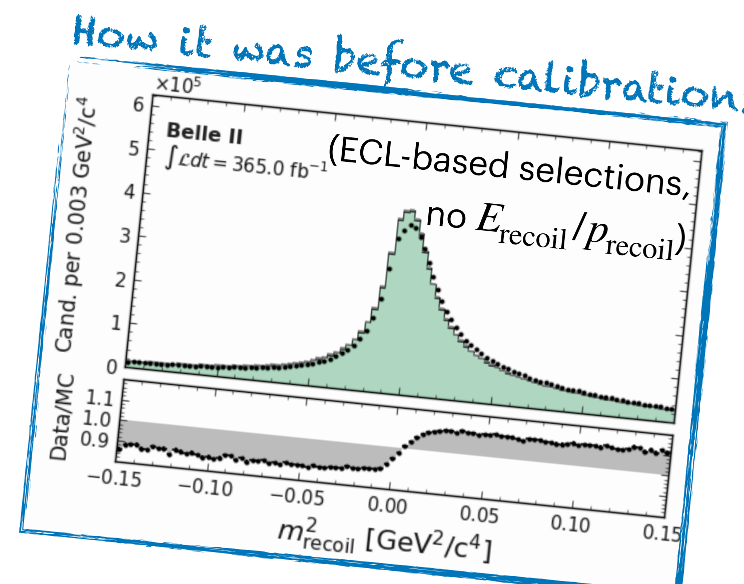
Small normalization issue in Proc16.
Tried to remove trigger selection, but no improvement.

Data/MC comparisons



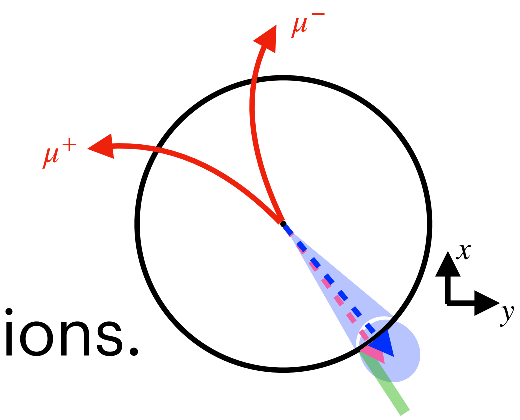
Compare data/MC distributions of selected recoils after PID corrections.



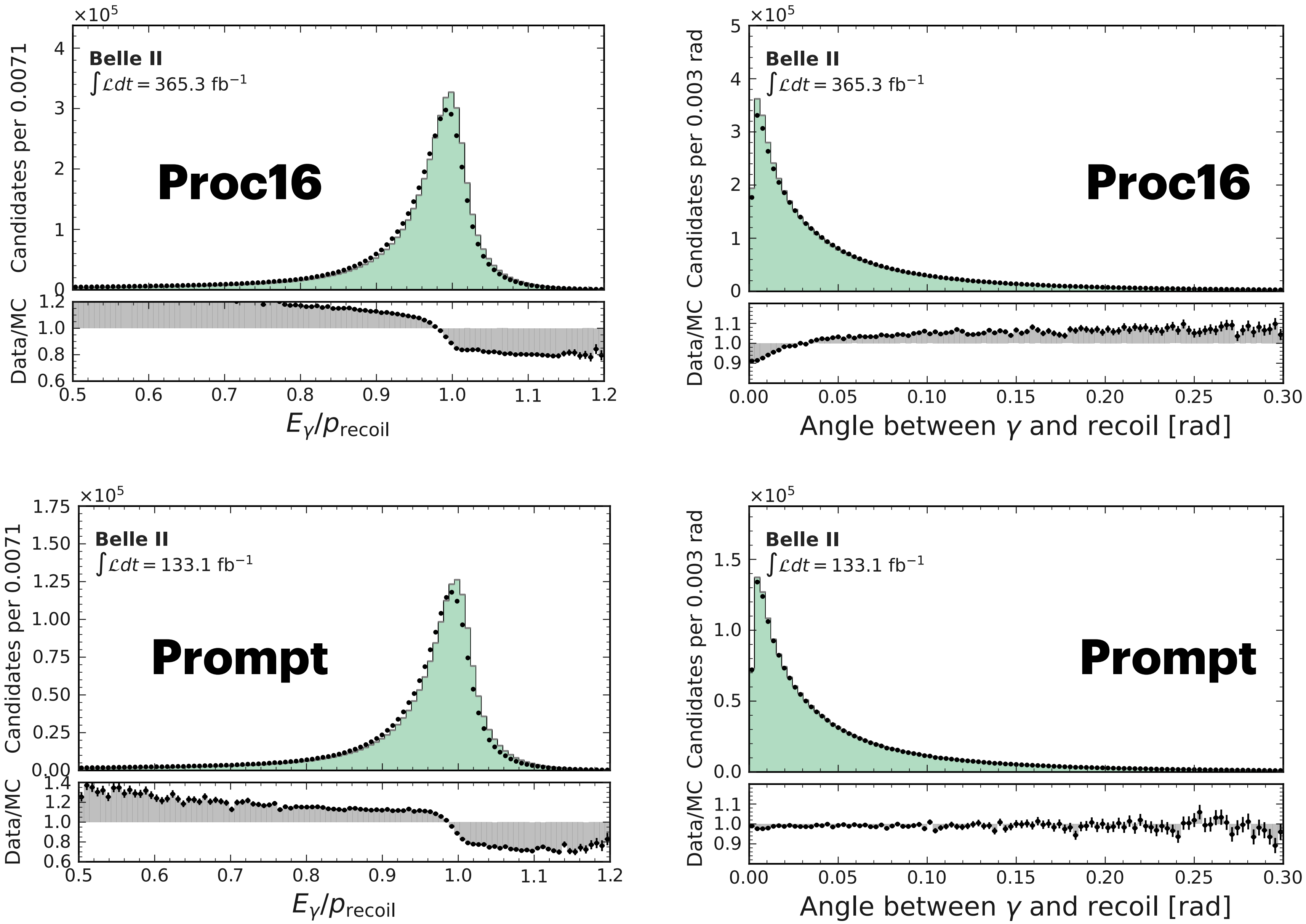


Small normalization issue in Proc16.
After beam calibration, much better data/MC agreement.

Data/MC comparisons



Compare data/MC distributions of matched photons after PID corrections.



Small normalization issue in Proc16.

Large discrepancy in $E_\gamma/p_{\text{recoil}}$ as in previous analyses.

Fake photons

Estimate fraction of fake photons from MC.

Overall fraction is 0.6% in both Run1 and Run2. No large deviation between experiments. Exp26 has highest fraction.

50% fake photons are electrons. 50% are beam backgrounds or hadronic splitoffs.

Experiment	Type	Fake Photon Fraction
12	$\Upsilon(4S)$	0.45%
12	Off-resonance	0.46%
14	$\Upsilon(4S)$	0.41%
16	$\Upsilon(4S)$	0.50%
17	$\Upsilon(4S)$	0.48%
18	$\Upsilon(4S)$	0.61%
18	Off-resonance	0.61%
20	$\Upsilon(4S)$	0.56%
22	$\Upsilon(4S)$	0.50%
24	$\Upsilon(4S)$	0.52%
25	Off-resonance	0.67%
26	$\Upsilon(4S)$	1.05%
30	$\Upsilon(4S)$	0.41%
31	Off-resonance	0.50%
32	Off-resonance	0.42%
33	$\Upsilon(4S)$	0.54%
35	$\Upsilon(4S)$	0.85%

Systematics

Selections efficiencies should cancel in photons/recoils ratio, but data/MC discrepancies can cause bias. Assess systematic uncertainties from cuts variations.

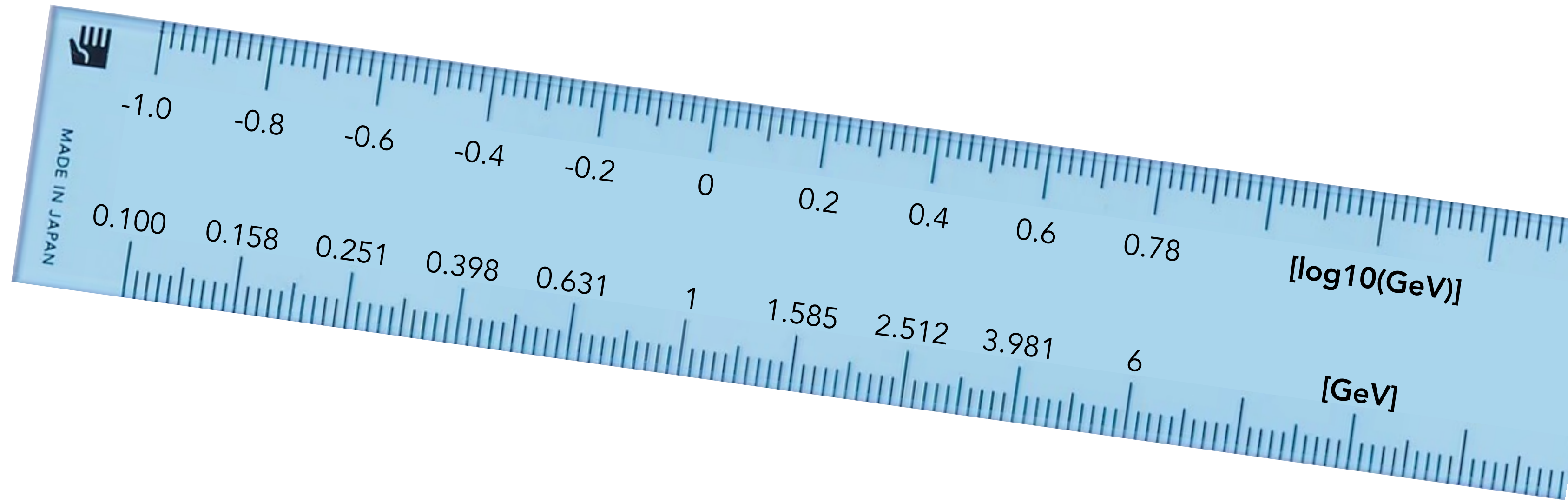
Variations are similar to previous analysis.

Largest contributions from cone selection and $E_\gamma/p_{\text{recoil}}$.

For PID: propagate uncertainties from systematic framework to photon calibrations (<0.05%).

Systematic Source	**Nominal Value**	**Variation**
Angle between muon and recoil	>0.3 rad	>0.2 rad >0.4 rad
m^2_{recoil}	[-0.15 , +0.15]	[−0.18 , +0.18] [−0.12 , +0.12]
$(E/p)_{\text{recoil}}$	[0.85,1.15]	[0.82 , 1.18] [0.88 , 1.12]
Cone around recoil	<0.3 rad	<0.35 rad <0.25 rad
$E_\gamma/p_{\text{recoil}}$	[0.5 , 1.2]	[0.4 , 1.3] [0.6 , 1.1]
MC Background Subtraction	Not applied	Applied

Systematics under control.



Results

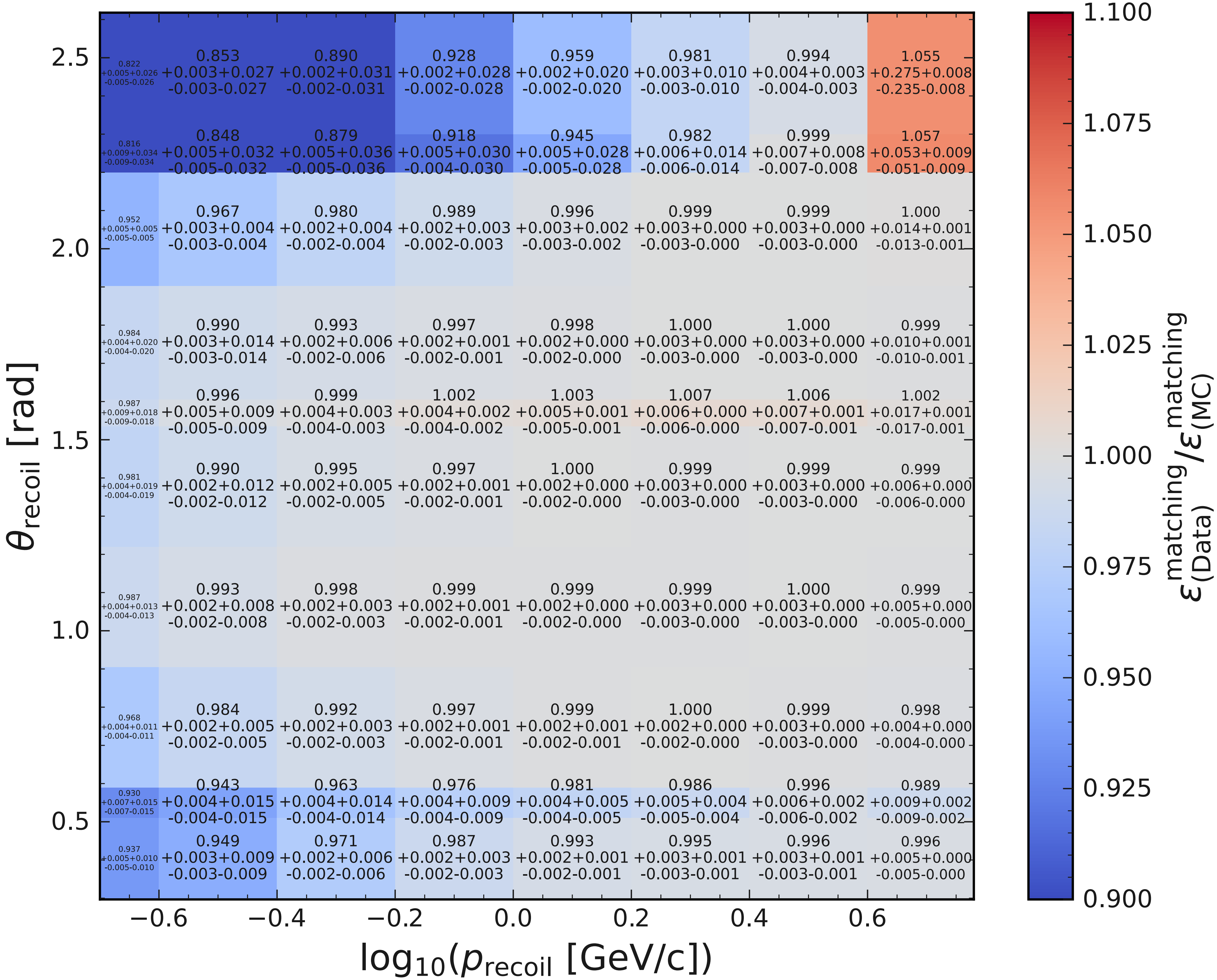
Note on binning:

p_{recoil}: 8 bins in $log_{10}(p_{\text{recoil}})$

θ_{recoil}: same binning as previous analysis

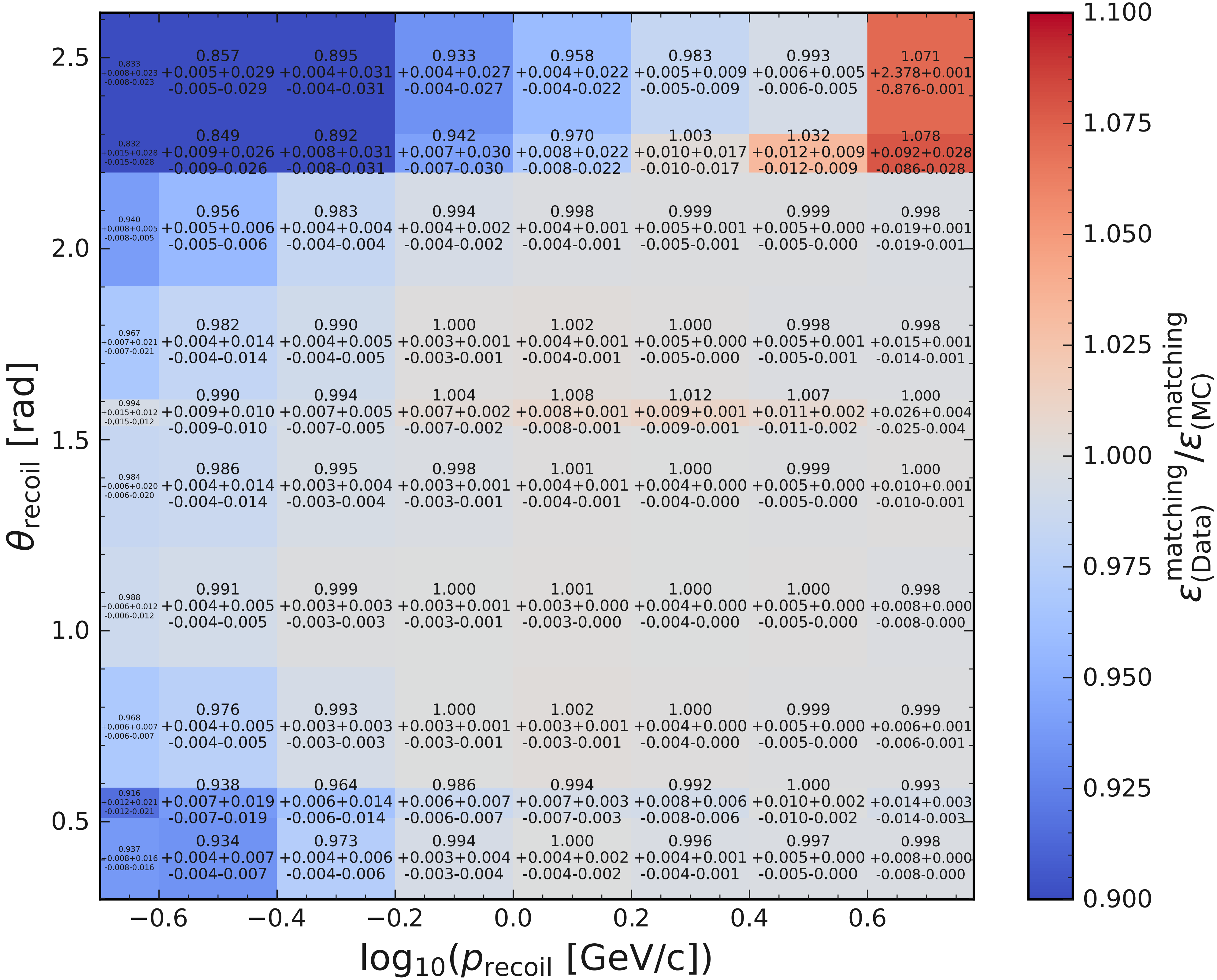
No ϕ_{recoil} bins — no dependence

Results (Proc16 *Υ(4S)* — offRes in backup)



Looks good. Large uncertainties only in few low-*p* endcaps bins.

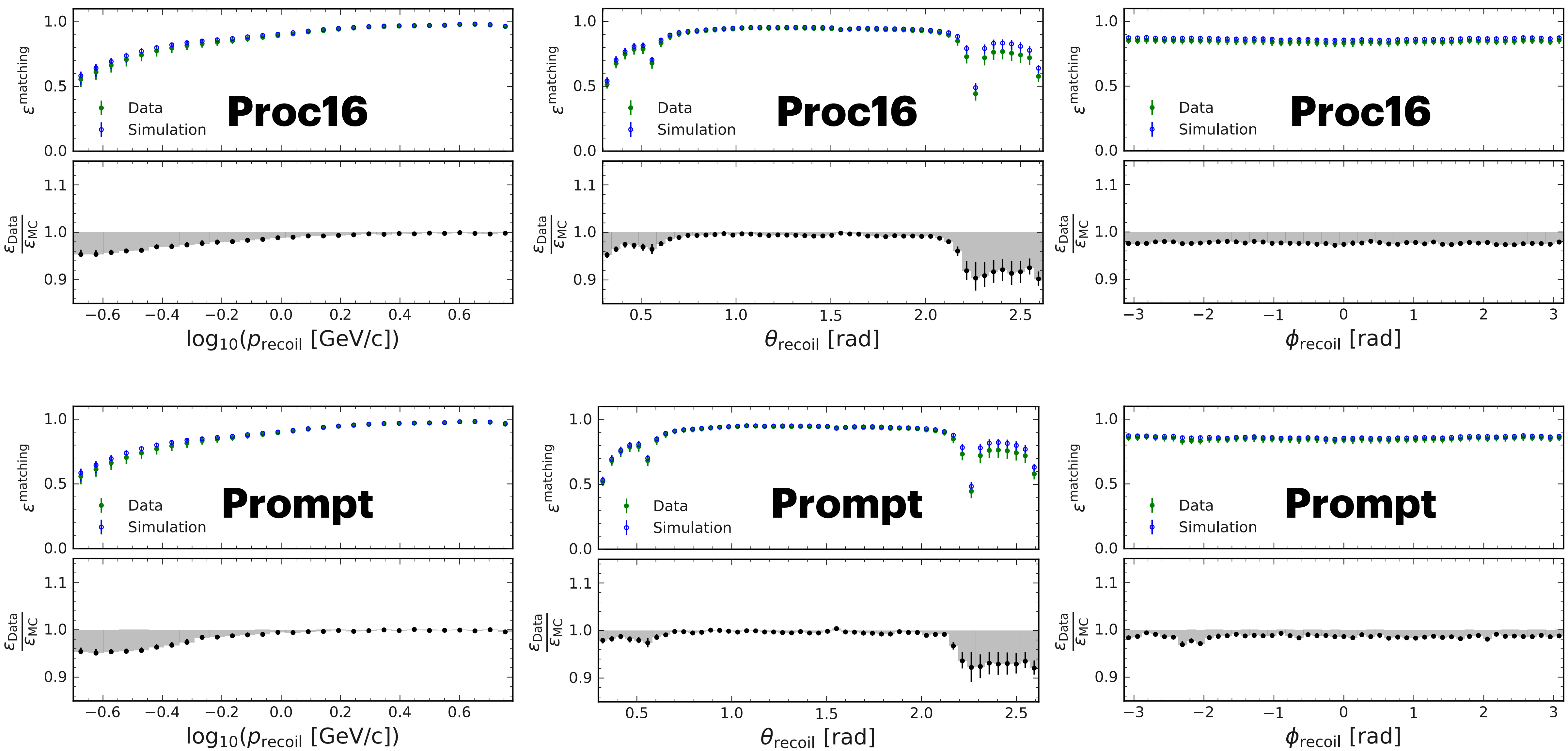
Results (Prompt *Y(4S)* — offRes in backup)



Looks good. Large uncertainties only in few low-*p* endcaps bins.

Efficiency as function of recoil observables

Check efficiency ratio as function of various recoil observables.



Large calibrations at low momentum and backward endcap.

Negligible dependence on ϕ_{recoil}.

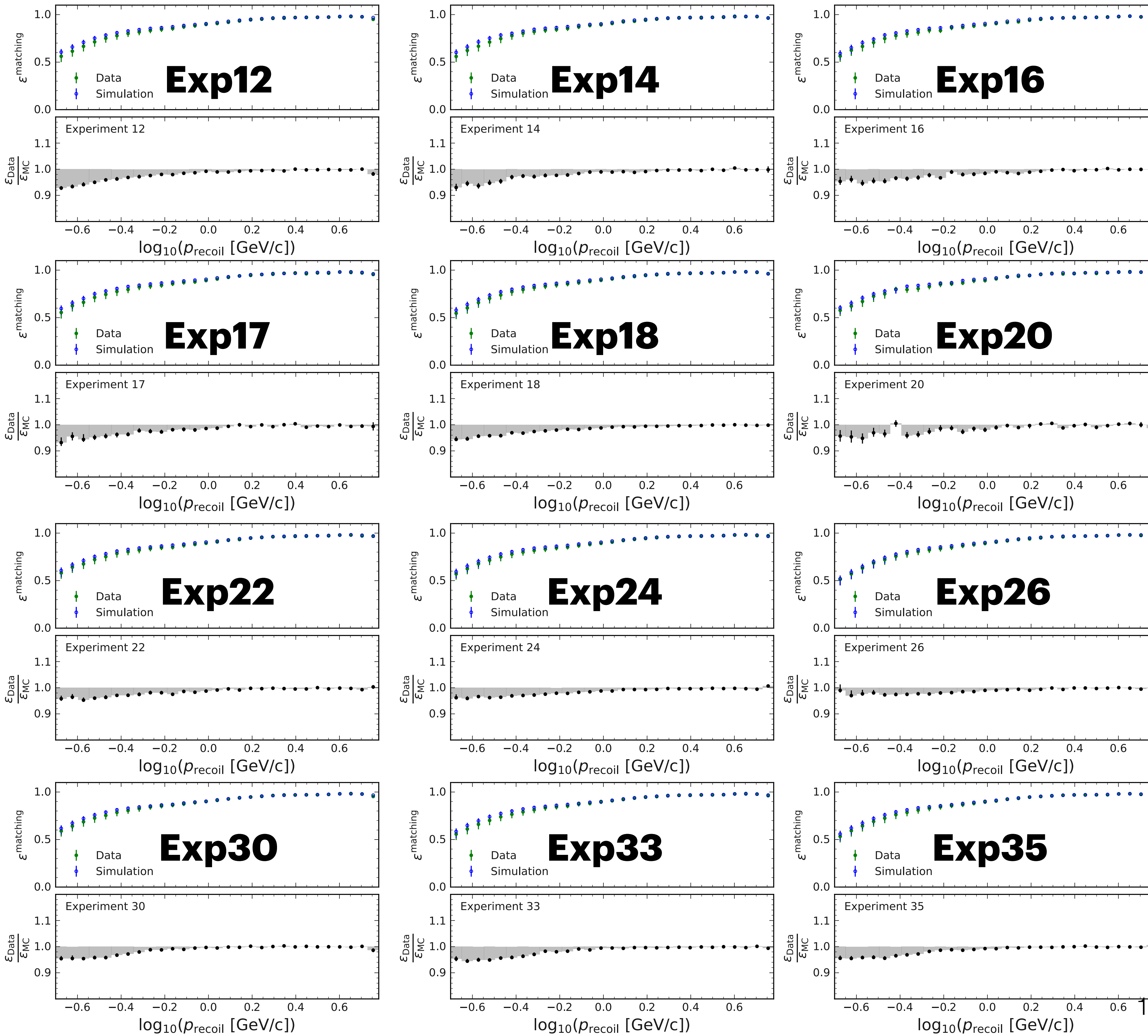
Efficiency as function experiment number

Check possible differences between experiments.

Exp26: best data-MC agreement.

Prompt calibrations smaller than Proc16.

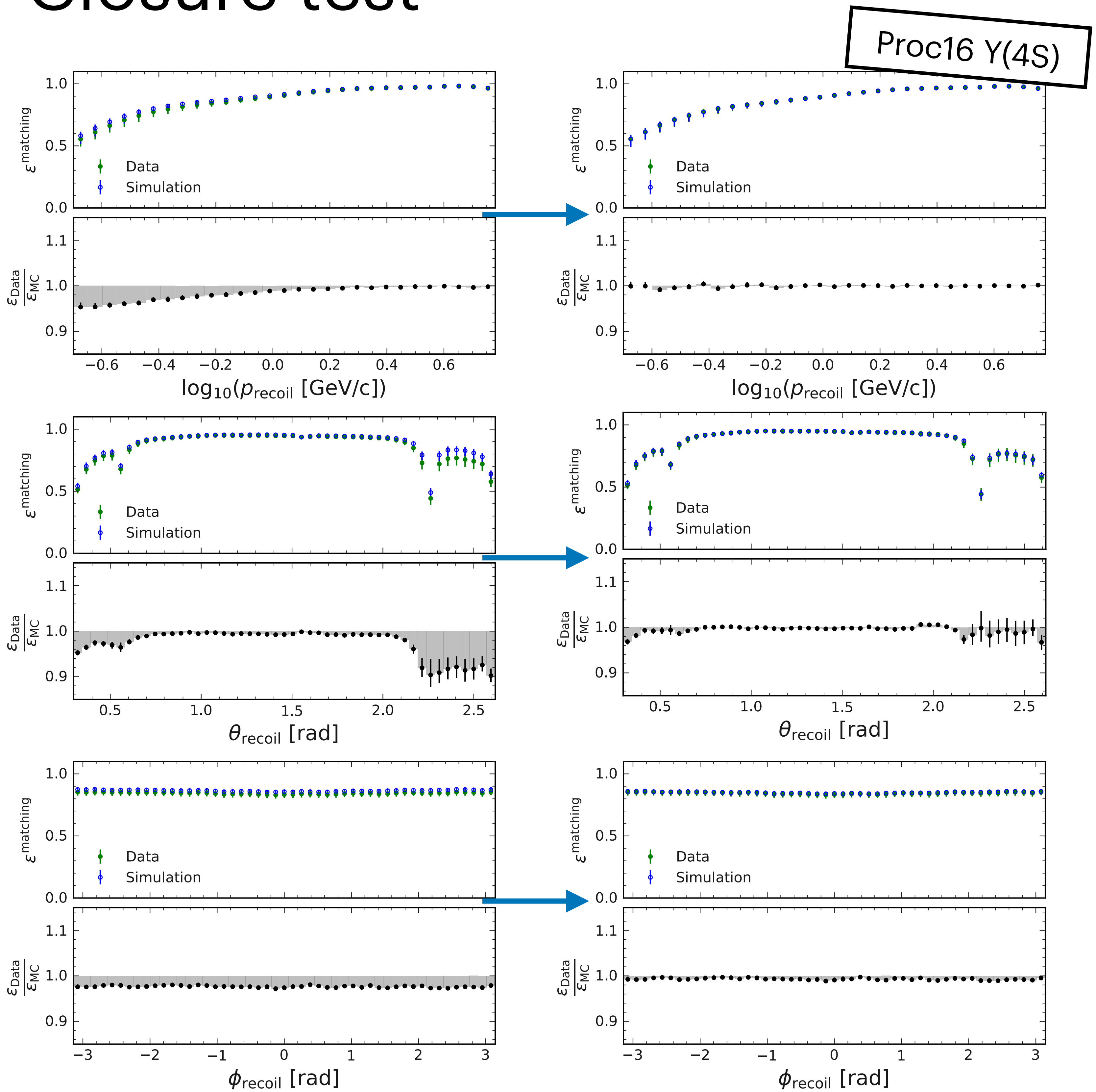
Split in Run1/Run2.



Closure test

Closure test

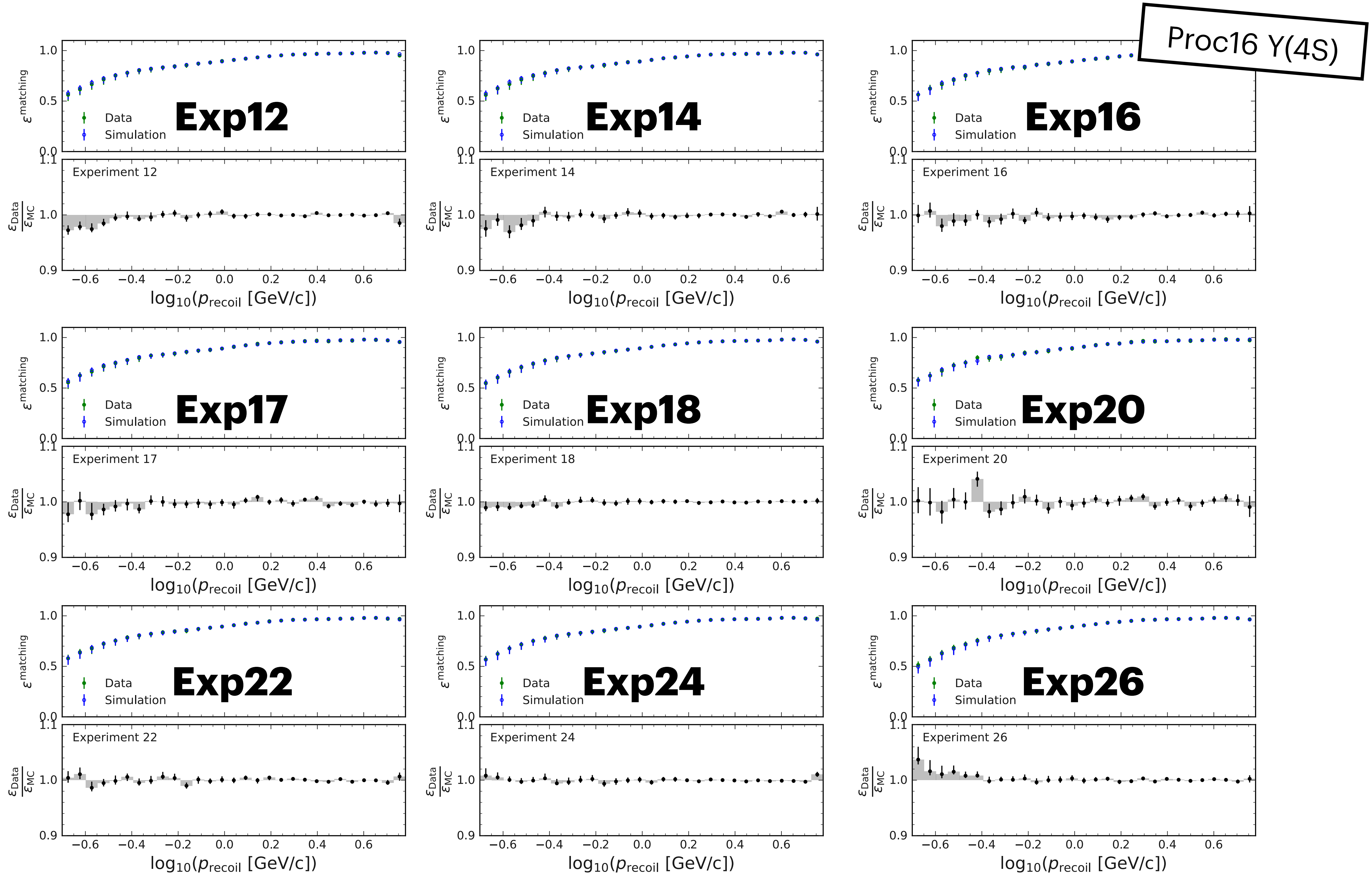
Apply photon calibrations to MC ntuples. Check data/MC efficiency ratios before/after.



Ratio after photon calibration is close to 1. Looks good.

Exp-dependence (again)

Check effect of time-integrated corrections on eff ratio for each experiment.



Look good (except Exp12 and Exp26 at low p — will have cross=check from π^0's).

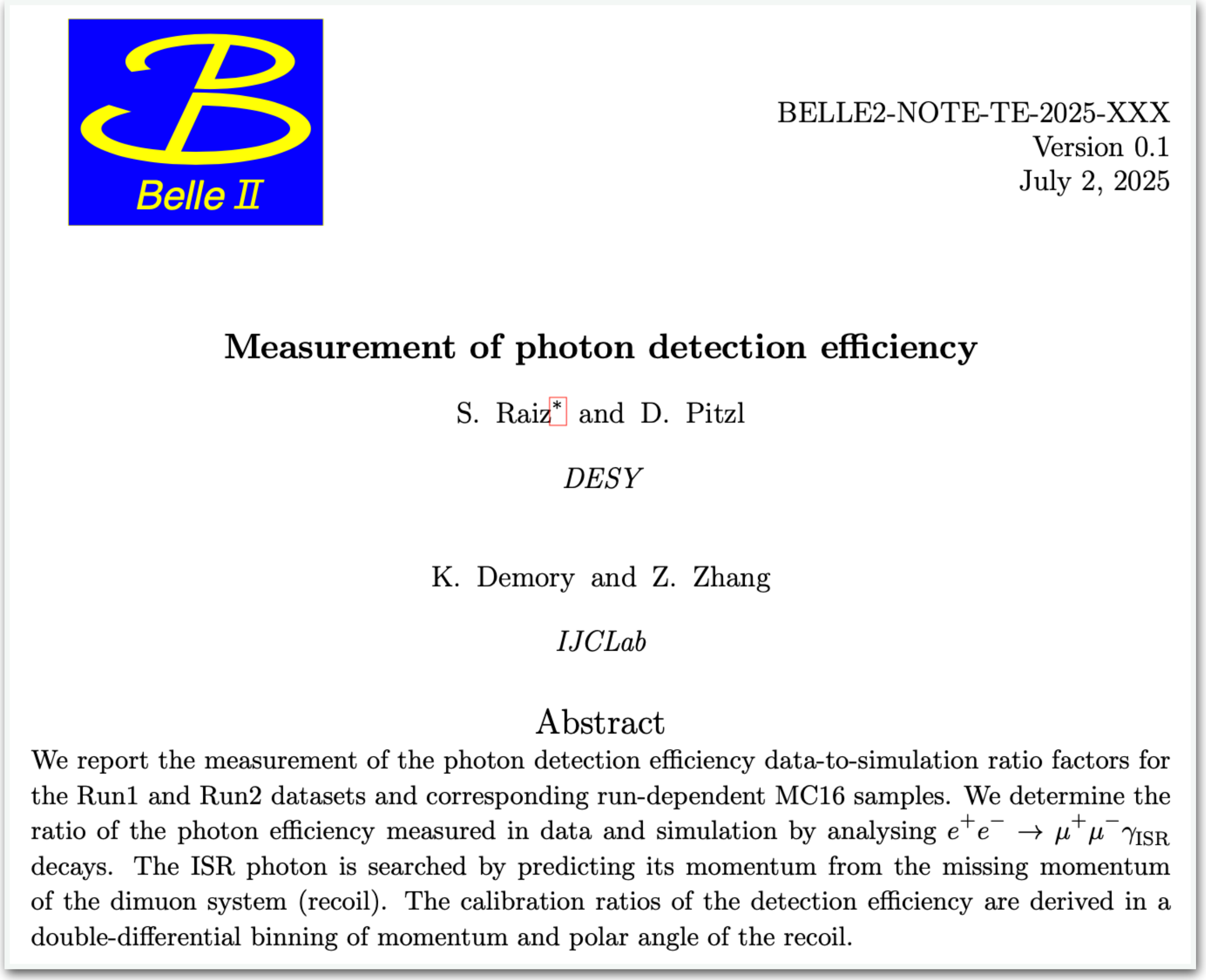
No need exp-dependent calibrations. Just split in Run1/Run2.

Summary

Obtained photon efficiency calibrations from $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$ (KLM-based selections).

Changes:
– remove ECL selections on muons, add PID selection. Use true cone efficiency to choose requirements on m^2_{rec} and E_{recoil}/p_{recoil};
– empirical beam calibration to improve recoil distributions data/MC agreement;
– new binning in $log_{10}(p_{recoil})$;
– provide only different corrections for Run1 and Run2.

Next steps:
– compare with ECL-based corrections;
– compare low-p corrections from asymmetric π^0's using τ;
– add in systematic framework;
– closure test for π^0 correction: get π^0 reconstruction efficiency correction from η decays with/without γ weights (in progress, see next Neutrals meeting on Thursday).



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Version 0.1
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Measurement of photon detection efficiency

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DESY

K. Demory and Z. Zhang

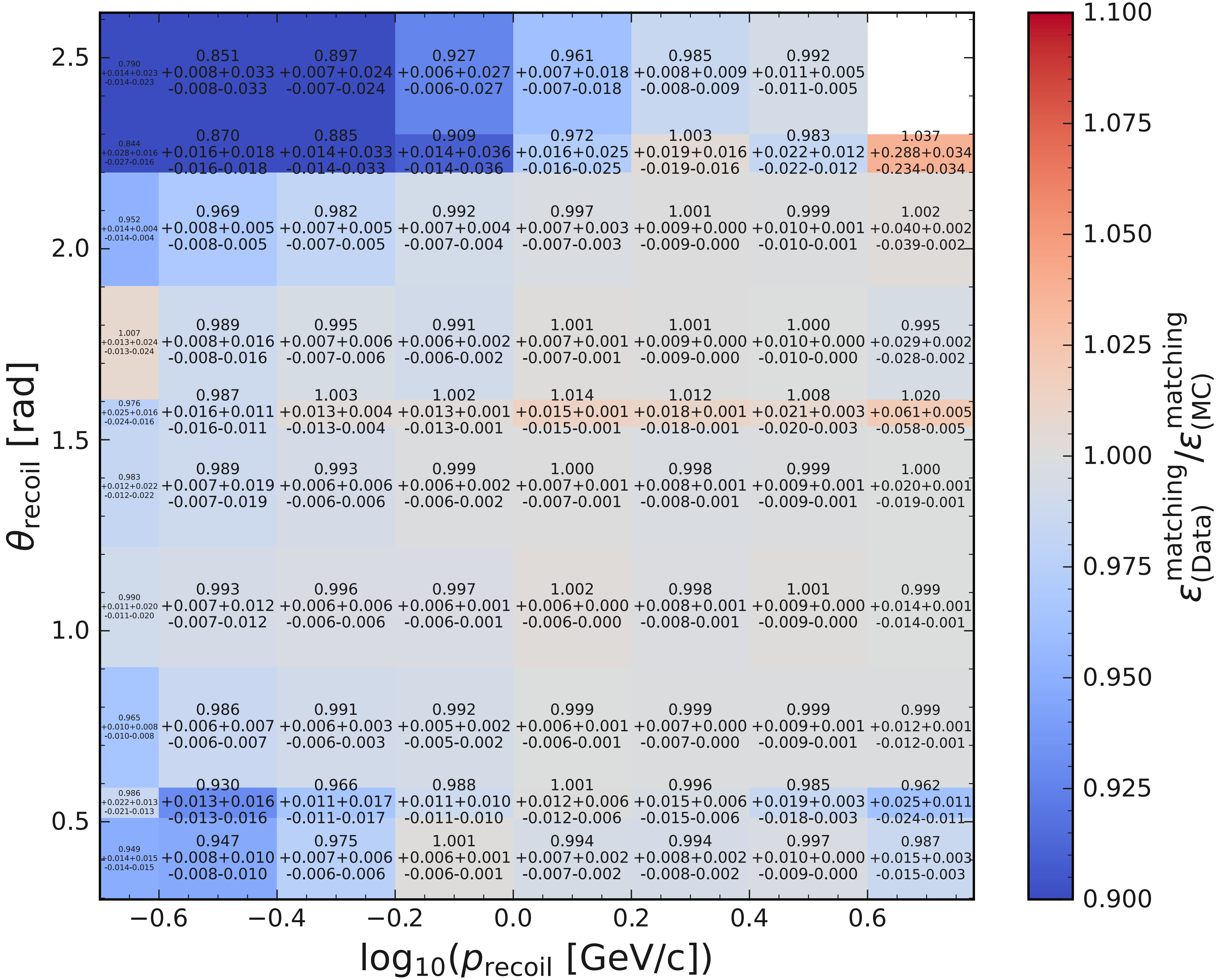
IJCLab

Abstract

We report the measurement of the photon detection efficiency data-to-simulation ratio factors for the Run1 and Run2 datasets and corresponding run-dependent MC16 samples. We determine the ratio of the photon efficiency measured in data and simulation by analysing $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$ decays. The ISR photon is searched by predicting its momentum from the missing momentum of the dimuon system (recoil). The calibration ratios of the detection efficiency are derived in a double-differential binning of momentum and polar angle of the recoil.

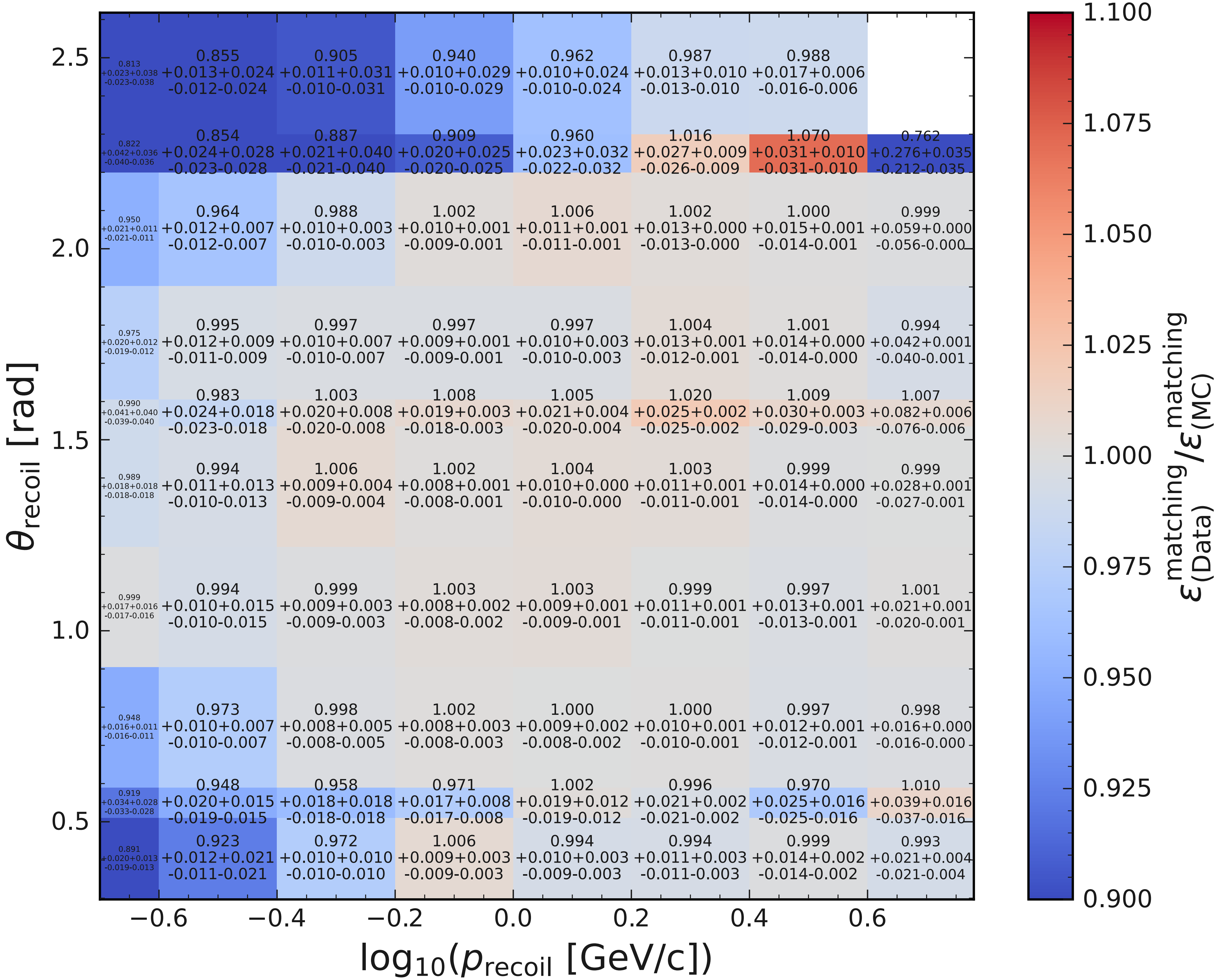
Backup

Results (Proc16 off-res)



Looks good. Large uncertainties only in few low-*p* endcaps bins.

Results (Prompt off-res)



Looks good. Large uncertainties only in few low-*p* endcaps bins.

Selection on recoil momentum

Considering looking at recoil momentum > 0.2 GeV only (as in previous analysis).

Low-energy photon efficiency corrections from asymmetric π^0 decays in τ decays.