Testing Charge Symmetry with Precision SIDIS π^+/π^- Ratios

Update on the CSV Experiment

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Argonne NATIONAL LABORATORY

Introduction

- Motivation
- Formalism
- Experiment Status
- Summary

Motivation

Charge Symmetry

What is charge symmetry?

Charge symmetry (CS) is a specific case of isospin symmetry (IS) that involves a rotation of 180° about the "2" axis in isospin space $\rightarrow e^{i\pi I_2}$

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Low energy: CS in Nuclei

Interchange protons and neutrons

- pp and nn scattering lengths are nearly the same
- $M_p \simeq M_n$ (to 1%)
- $B(^3H) \simeq B(^3He)$ (to 1%)
- Energy levels in mirror nuclei are equal (to 1%)

After electromagnetic corrections
CS respected down to $\sim 1\%$

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QCD: CS in quark distributions

$$u^p(x,Q^2) = d^n(x,Q^2)$$
$$d^p(x,Q^2) = u^n(x,Q^2)$$

Origin of CS violations:

- Electromagnetic interaction
- $\delta m = m_d - m_u$

Naively, one would expect that CSV would be of the order of $(m_d - m_u)/\langle M \rangle$
Where $\langle M \rangle$ = 0.5 - 1 GeV
$\rightarrow$ CSV effect of 1%

CS in parton distributions almost universally assumed for the past 40 years!

Motivation

- CSV measurements are important on their own as a further step in studying the inner structure of the nucleon
- The validity of charge symmetry is a necessary condition for many relations between structure functions
- Flavor symmetry violation extraction $\bar{u}(x) \neq \bar{d}(x)$ relies on the implicit assumption of charge symmetry (number of pdfs doubles)
- Charge symmetry violation could be a viable explanation for the anomalous value of the Weinberg angle extracted by NuTeV experiment
- Important to know degree of CSV when extracting parton distributions/models: unpolarized/polarized PDFs, TMDs, GPDs, GTMDs, etc.

Theory, Phenomenology, and Lattice

$$u^p(x,Q^2) \stackrel{?}{=} d^n(x,Q^2)$$
$$d^p(x,Q^2) \stackrel{?}{=} u^n(x,Q^2)$$

$$\delta u(x) = u^p(x) - d^n(x)$$
$$\delta d(x) = d^p(x) - u^n(x)$$

Based on the same twist-2 PDF from Adelaide group

- Model by Sather (PLB274(1992)433): $\delta d \sim$ 2-3% and $\delta u \sim$ 1%
- Model by Rodionov, Thomas and Londergan (Mod. PLA9(1994)1799): δd could reach up to 10% at high x

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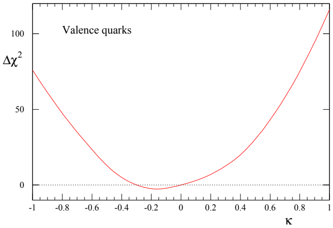

MRST group studied uncertainties in PDFs (Eur. Phys. J.35(2004)325)

- CSV parameterization $\delta u_v = -\delta d_v = \kappa(1-x)^4 x^{-0.5}(x-0.0909)$
- The form has to satisfy the normalization condition $\int dx \delta u_v(x) = \int dx \delta d_v(x) = 0$
- κ was varied in the global fit: 90% CL obtained for (-0.65 $< \kappa <$ 0.8)

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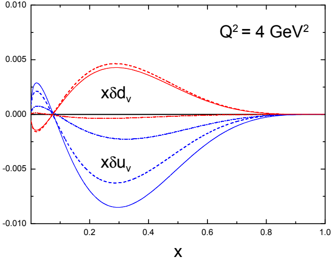

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Lattice gives the QCD contribution

Phys.Rev. D83 (2011) 051501

$$\delta u = -0.0023(6) \qquad \delta d = \quad 0.0020(3)$$

Phys.Lett. B753 (2016) 595-599

Dash-dotted, dashed and solid curves represent pure QED, pure QCD and the total

Experimental Limits

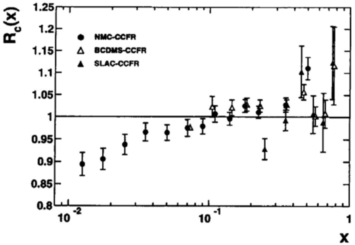
- Upper limit obtained by comparing:
  F_2^{ν} and F_2^{γ} on isoscalar targets
- F_2^{ν} by CCFR collaboration at FNAL (Fe data)
- F_2^{γ} by NMC collaboration using muons (D target)
- $0.1 \leq x \leq 0.4 \rightarrow 9\%$ upper limit for CSV effect!

$\bar{Q}(x) = \sum_{u,d,s} \left(q(x) + \bar{q}(x)\right)$

Charge Ratio

$$R_c(x) = \frac{F_2^{\gamma N_0}(x) + x\left[s^+(x) + c^+(x)\right]/6}{5\bar{F}_2^{W N_0(x)}/18}$$

$$= 1 + \frac{3\left(\delta u(x) + \delta\bar{u}(x) - \delta d(x) - \delta\bar{d}(x)\right)}{10\bar{Q}(x)}$$



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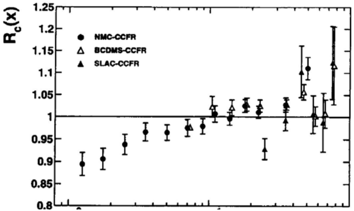

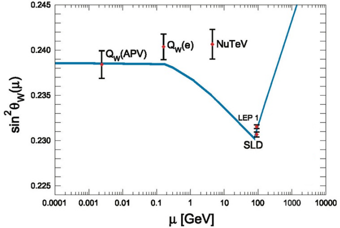

Isovector EMC effect explains the NuTeV anomaly - Cloët, Bentz, Thomas

NuTeV Anomaly + EM corrections (10%) + CSV (40%) + Iso-vector EMC (50%)
$\longrightarrow$ **No Anomaly!**

PRL 102 (2009) 252301, PLB 753 (2016)595

Formalism

Londergan, Pang and Thomas PRD54(1996)3154

$$R^D_{\text{Meas}}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)}$$

Factorization

$$N^{Nh}(x,z) = \sum_q e_q^2 q^N(x) D_q^h(z)$$

Impulse Approximation

$$N^{Dh}(x,z) = N^{ph}(x,z) + N^{nh}(x,z)$$

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$$\Delta(z) = D_u^{\pi^-}/D_u^{\pi^+}$$

$$D(z) = \frac{1-\Delta(z)}{1+\Delta(z)}$$

$$R(x,z) = \frac{5}{2} + R^D_{\text{Meas}}$$

$$A(x) = \frac{-4}{3(u_v(x)+d_v(x))}$$

$$C(x) = \delta d(x) - \delta u(x)$$

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$$\Delta_s(z) = \frac{D_s^{\pi^+}(z) + D_s^{\pi^-}(z)}{D_u^{\pi^+}(z)}$$

$A(x)$ and $B(x,z)$ are known

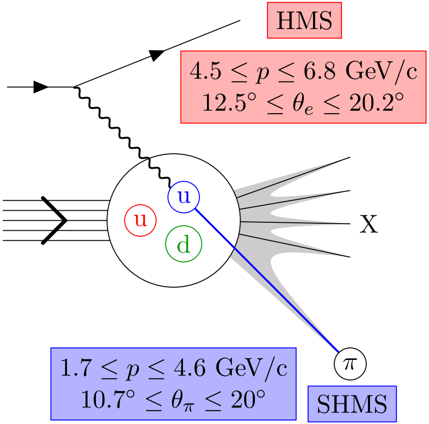
Extract simultaneously D(z) and C(x) in each Q^2 bin!

Experiment in Hall C – E12-09-002

Measurements: D$(e, e'\pi^+)$ and D$(e, e'\pi^-)$

Setup

- ~~11 GeV~~ 10.6 GeV e^- beam
- 10 cm LD_2 target
- SHMS $\rightarrow \pi^\pm$, HMS $\rightarrow e'$



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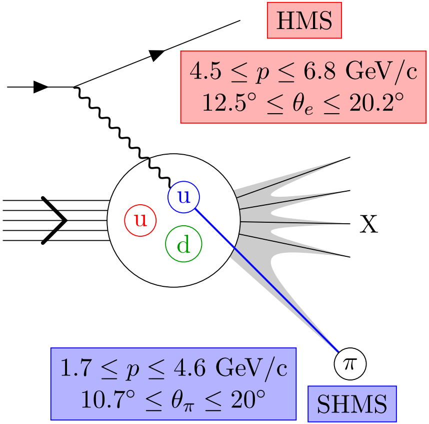
To each x setting corresponds 4 z measurements
z = 0.4, 0.5, 0.6, 0.7

$$R_Y(x,z) = Y^{D\pi^-}(x,z)/Y^{D\pi}(x,z)$$

$$\boxed{R^D_{\text{Meas}}(x,z) = \frac{4R_Y(x,z)-1}{1-R_Y(x,y)}}$$



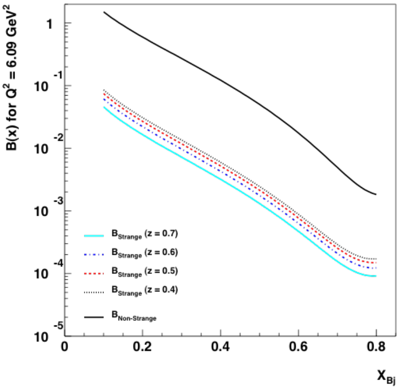
$Q^2 = 4$ GeV^2 $\rightarrow$ x = 0.35, 0.40, 0.45, 0.50
$Q^2 = 5$ GeV^2 $\rightarrow$ x = 0.45, 0.50, 0.55, 0.60
$Q^2 = 6$ GeV^2 $\rightarrow$ x = 0.50, 0.55, 0.60, 0.65 (high Q^2 extended run plan)

For each Q^2 we have 16 equations and 8 unknowns: $D(z_i)$ and $C(x_i)$

$$D(z)\ R(x,z) + A(x)C(x) = B(x,z)$$

B(x,z)

Using CTEQ6L PDFs and DSS FFs



At $x > 0.35$ strange contribution becomes negligible

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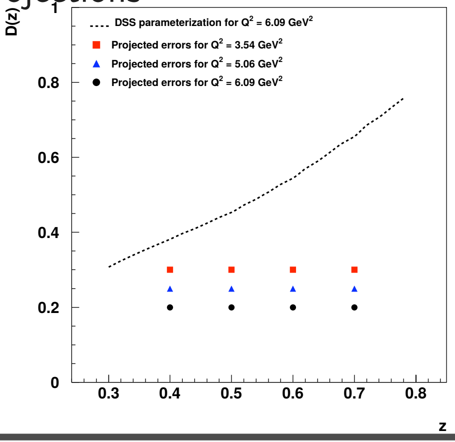
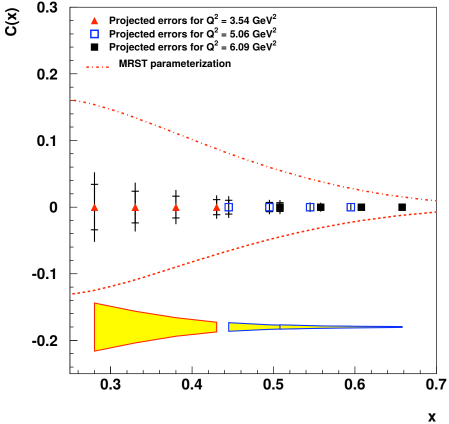
$$\Delta_s(z) = \frac{D_s^{\pi^+}(z) + D_s^{\pi^-}(z)}{D_u^{\pi^+}(z)}$$

Projections





$$D(z)\ R(x,z) + A(x)C(x) = B(x,z)$$

$$\left[\frac{1-\Delta(z)}{1+\Delta(z)}\right]\left[\frac{5}{2} + R^{D}_{\text{Meas}}\right] + \left[\frac{-4}{3(u_v(x)+d_v(x))}\right]\left[\delta d(x) - \delta u(x)\right] = \frac{5}{2} + \frac{5\left[\bar{u}(x)+\bar{d}(x)\right]}{u_v(x)+d_v(x)} + \frac{\Delta_s(z)\left[s(x)+\bar{s}(x)\right]/\left[1+\Delta(z)\right]}{u_v(x)+d_v(x)}$$

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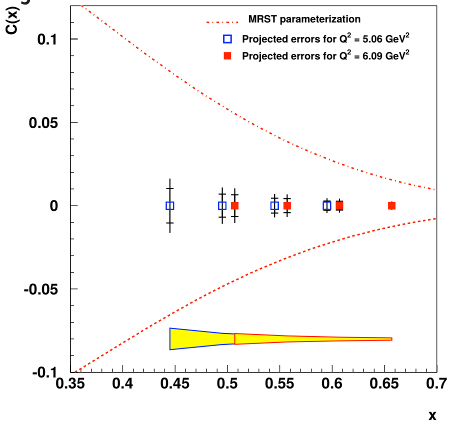

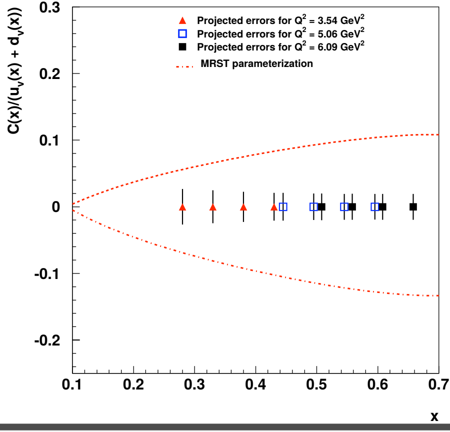

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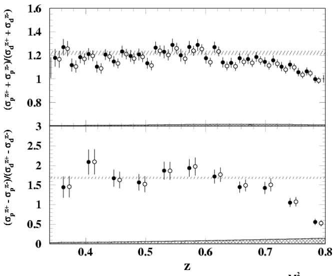
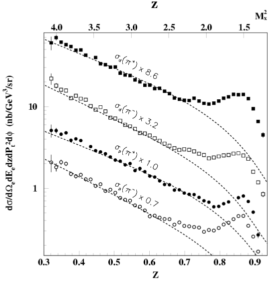
Testing factorization at 12 GeV





$$\frac{\sigma_p(\pi^+) + \sigma_p(\pi^-)}{\sigma_d(\pi^+) + \sigma_d(\pi^-)} = \frac{4u(x) + 4\bar{u}(x) + d(x) + \bar{d}(x)}{5(u(x) + d(x) + \bar{u}(x) + \bar{d}(x))}$$

$$\frac{\sigma_p(\pi^+) - \sigma_p(\pi^-)}{\sigma_d(\pi^+) - \sigma_d(\pi^-)} = \frac{4u_v(x) - d_v(x)}{3(u_v(x) + d_v(x))}$$

If factorization holds, the ratios should be independent of z

Ratio data from E-00-108 indicates this is the case up to $z \sim 0.7$.

Factorization important for JLab 12 GeV physics program.

Precise measurements of charged pion ratio off deuterium

HMS (electrons)

$4.5 \leq p \leq 6.8$ GeV/c
$12.5^\circ \leq \theta_e \leq 20.2^\circ$

- Taking 200 Hz pre-scaled singles

SHMS (pions)

$1.7 \leq p \leq 4.6$ GeV/c
$10.7^\circ \leq \theta_\pi \leq 20^\circ$

- Heavy Gas Č @ 1 atm
  $p_{\text{threshold}}\ (\pi) = 2.65$ GeV/c
  $p_{\text{threshold}}\ (\text{K}) = 9.4$ GeV/c
- Aerogel (n = 1.015)
  $p_{\text{threshold}}\ (\pi) = 0.8$ GeV/c
  $p_{\text{threshold}}\ (\text{K}) = 2.85$ GeV/c

- Hem Bhatt (MSU)
- Shuo Jia (Temple)

Fall 2018

Run from Nov. 8 through Nov. 25

Q^2	x	
4.00	0.35	*
4.00	0.45	
3.90	0.45	*
3.98	0.50	
4.75	0.45	*
5.00	0.50	
4.76	0.55	*
4.78	0.60	

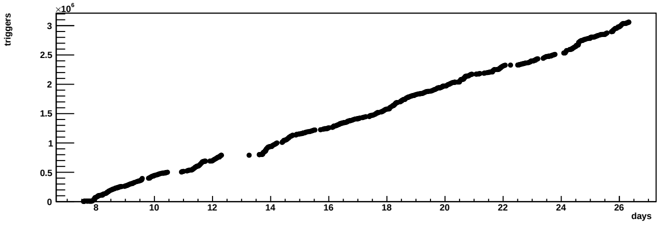
* $\rightarrow$ D+H Targets

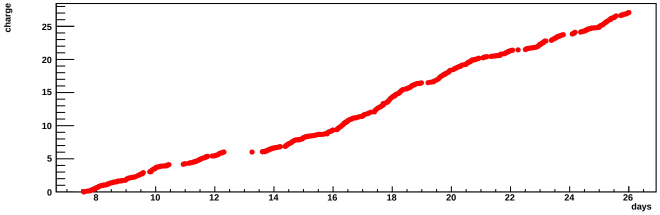
High Q^2 settings for 2019 run

Q^2	x
5.50	0.50
5.50	0.55
5.50	0.60
5.63	0.65

Each setting with 4 z measurements

z = 0.4, 0.5, 0.6, 0.7





November

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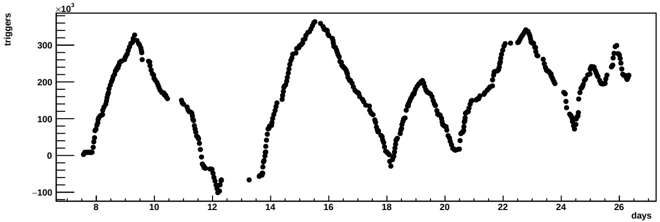

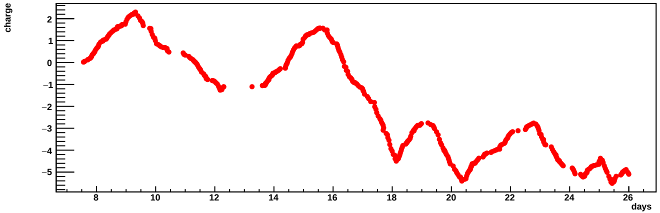

November

Outlook and Summary

- Experiment E12-09-002 will measure precision ratios of charged pion electroproduction in semi-inclusive deep inelastic scattering from deuteron
- Measurement provides direct access to CSV effects in valence PDFs for the first time.
- The goal is to measure the x-dependence of charge symmetry violating valence PDFs or to substantially improve the upper limit
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- Will run for 18 days in March 2019

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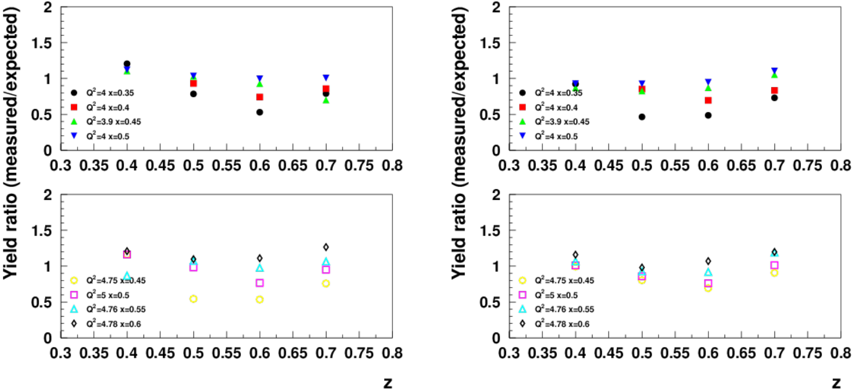
Looking forward to finishing experiment run in March – many shifts still open!

Many thanks to the hall staff for their support.

Thank you!

Backup

Predicted/Measured



Preliminary plots from Dave Gaskell

Uncertainties

$$\frac{\Delta(R^D_{\text{Meas}})}{R^D_{\text{Meas}}} = \frac{3R_Y}{(4R_Y - 1)(1 - R_Y)} \frac{\Delta(R_Y)}{R_Y}$$

Source	Pion Yield (%)	$\Delta(R_Y)/R_Y$ (%) per z bin	$\Delta(R_{meas})/R_{meas}$) (%) Per z bin
Statistics	0.7	1	2.6
Luminosity	0.3	0.3	0.8
Tracking efficiency	0.1 - 1	0.2	0.5
Dead time	< 0.1	< 0.1	< 0.3
Acceptance	1 – 2	0.1	0.3
PID efficiency	< 0.5	0.2	0.5
ρ background	0.5 – 3	0.2 – 0.7 (1.2)	0.5 – 1.8 (3)
Exclusive Rad. tail	0.2 – 1.3	0.1 – 0.6 (1.3)	0.3 – 1.5 (3)
Total systematics		0.49 – 1.02 (1.8)	1.1 0.6 – 2.4 (4)
Total uncertainty			1.1 2.6 – 3.5(4.7)

PAC Comments

PAC34 report: "cross sections are such basic tests of the understanding of SIDIS at 11 GeV kinematics that they will play a critical role in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement CLAS12 measurements in areas where the precision of spectrometer experiments is essential – in this case, precise control of the relative acceptance and efficiency for different particle charges"

The present measurements are complementary to Hall B SIDIS measurements where polarized H, D targets and large acceptance are at play E12-07-107, E12-09-007, E12-09-009,. . . and we will benefit from these measurements for a more precise determination of backgrounds such as ρ-meson production

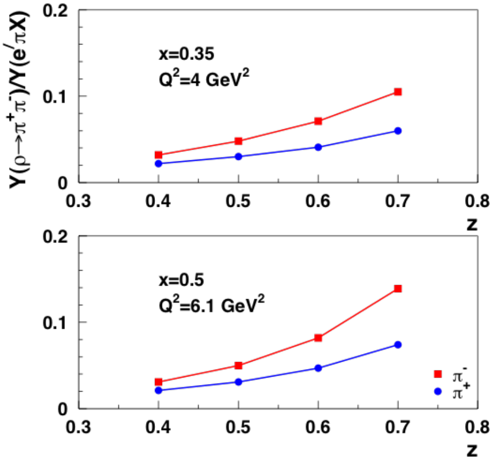
Proposal

- PAC 34
- PAC 38 Approved

Nonetheless, the cross sections are such basic tests of the understanding of SIDIS at 11 GeV kinematics that they will play a critical role in establishing the entire SIDIS program of studying the partonic structure of the nucleon.

Background

- ρ cross section from PYTHIA modified to agree with HERMES and CLAS data at lower energies
- To estimate the uncertainties on the charged pion ratio, we assume the parameterization of the cross section to be accurate to 20%
- The yield of the π^- from diffractive ρ should be identical to yield of π^+
- In general contributions are not large $< 10\%$ for $z = 0.5$.
- Uncertainty on the charged pion ratio will be reduced



Background

- Simulated using SIMC
- Radiative tail calculated using energy peaking approximation of resonance production model
- C12-09-017 is planning to model these contributions by having dedicated runs @ lower beam energy and scattered electron energy
- Estimated uncertainty due to radiative background 0.8%