中国科学技术大学
University of Science and Technology of China

STCF上超子半轻衰变过程$\Xi^- \to \Lambda e^- \bar{\nu}_e$研究

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超级陶粲装置研讨会
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Outline

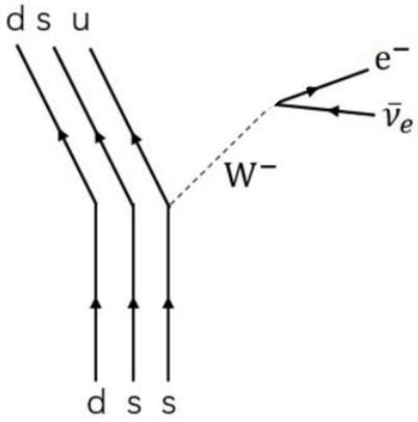
- Motivation
- Analysis strategy
- Simulated data sets
- Single tag analysis
- Double tag analysis
- Measure the Form Factors and V_{us}
- Summary

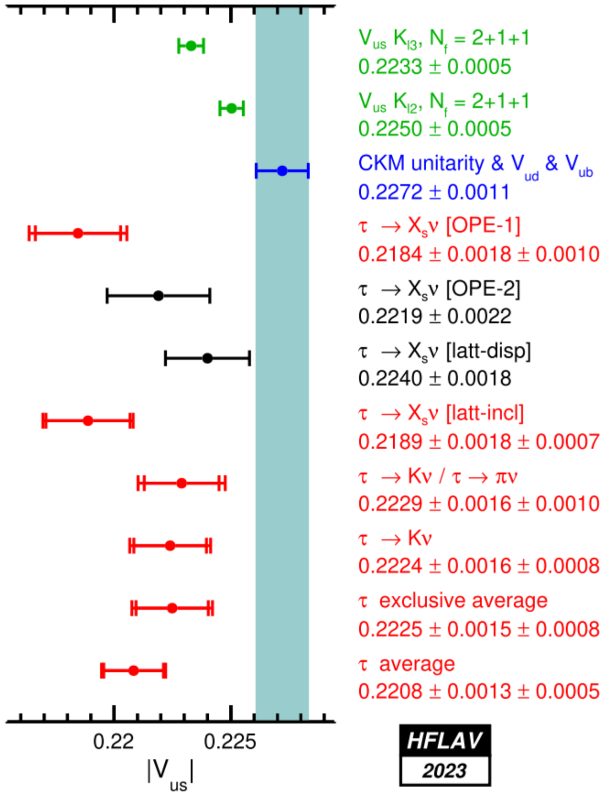
Motivation

- Determination of CKM matrix element V_{us} or Cabibbo-angle θ_c. In fact, different previous measurements of θ_c, have poor mutual agreement which is so-called "Cabibbo-angle anomaly".
- $\Xi^- \to \Lambda e^- \bar{\nu}_e$ can provide a complementary method to determine the Cabibbo angle θ_c and to test the Unitarity of the CKM matrix.
  - ✓ Determine the branching fraction
  - ✓ Determine the form factors

$$\Gamma_{e,\mathrm{SM}} \simeq \frac{G_F^2 |V_{us} f_1(0)|^2 \Delta^5}{60\pi^3} \left[\left(1 - \frac{3}{2}\delta\right) + 3\left(1 - \frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2} - 4\delta \frac{g_2(0)}{f_1(0)}\frac{g_1(0)}{f_1(0)} \right]$$

PRL 114, 161802 (2015)





Motivation

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- Study of SU3 breaking effects.
  - ✓ $g_1(0)/f_1(0)$ has intriguingly small SU3 breaking effects. Lots of phenomenology models are waiting for more experiments.
  - ✓ g_2 is 0 or not. Could be the first observation of a second-class weak-interaction current.
- Proton spin content
  - ✓ Provide complementarity to polarized deep inelastic scattering experiments for the determination of the proton spin content.

- **实验：**深度非弹性轻子-核子散射过程

$$\int_0^1 dx\ g_1^p(x,Q^2) = \left(\frac{1}{12}g_A^{(3)} + \frac{1}{36}g_A^{(8)}\right)\left\{1+\sum_{\ell\geq 1} c_{\mathrm{NS}\ell}\,\alpha_s^\ell(Q)\right\}$$
$$+\frac{1}{9}g_A^{(0)}|_{\mathrm{inv}}\left\{1+\sum_{\ell\geq 1} c_{\mathrm{S}\ell}\,\alpha_s^\ell(Q)\right\} + \mathcal{O}\left(\frac{1}{Q^2}\right) - \beta_1(Q^2)\frac{Q^2}{4M^2}.$$

Decay	Scale	$f_1(0)$	$g_1(0)$	g_1/f_1	f_2/f_1
$n \to pe^-\bar{\nu}$	V_{ud}	1	$D+F$	$F+D$	$\frac{M_n}{M_p}\frac{(\mu_p-\mu_n)}{2} = 1.855$
$\Xi^- \to \Xi^0 e^-\bar{\nu}$	V_{ud}	-1	$D-F$	$F-D$	$\frac{M_{\Xi^-}}{M_p}\frac{(\mu_p+2\mu_n)}{2} = -1.432$
$\Sigma^\pm \to \Lambda e^\pm \nu$	V_{ud}	0^{b}	$\sqrt{\frac{2}{3}}D$	$\sqrt{\frac{2}{3}}D$	$-\frac{M_{\Sigma^\pm}}{M_p}\sqrt{\frac{3}{2}}\frac{\mu_n}{2} = 1.490$
$\Sigma^- \to \Sigma^0 e^-\bar{\nu}$	V_{ud}	$\sqrt{2}$	$\sqrt{2}F$	F	$\frac{M_{\Sigma^-}}{M_p}\frac{(2\mu_p+\mu_n)}{4} = 0.534$
$\Sigma^0 \to \Sigma^+ e^-\bar{\nu}$	V_{ud}	$\sqrt{2}$	$-\sqrt{2}F$	$-F$	$\frac{M_{\Sigma^0}}{M_p}\frac{(2\mu_p+\mu_n)}{4} = 0.531$
$\Xi^0 \to \Sigma^+ e^-\bar{\nu}$	V_{us}	1	$D+F$	$F+D$	$\frac{M_{\Xi^0}}{M_p}\frac{(\mu_p-\mu_n)}{2} = 2.597$
$\Xi^- \to \Sigma^0 e^-\bar{\nu}$	V_{us}	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}(D+F)$	$F+D$	$\frac{M_{\Xi^-}}{M_p}\frac{(\mu_p-\mu_n)}{2} = 2.609$
$\Sigma^- \to ne^-\bar{\nu}$	V_{us}	-1	$D-F$	$F-D$	$\frac{M_{\Sigma^-}}{M_p}\frac{(\mu_p+2\mu_n)}{2} = -1.297$
$\Sigma^0 \to pe^-\bar{\nu}$	V_{us}	$\frac{-1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}(D-F)$	$F-D$	$\frac{M_{\Sigma^0}}{M_p}\frac{(\mu_p+2\mu_n)}{2} = -1.292$
$\Lambda \to pe^-\bar{\nu}$	V_{us}	$-\sqrt{\frac{3}{2}}$	$-\frac{1}{\sqrt{6}}(D+3F)$	$F + D/3$	$\frac{M_\Lambda}{M_p}\frac{\mu_p}{2} = 1.066$
$\Xi^- \to \Lambda e^-\bar{\nu}$	V_{us}	$\sqrt{\frac{3}{2}}$	$-\frac{1}{\sqrt{6}}(D-3F)$	$F - D/3$	$-\frac{M_{\Xi^-}}{M_p}\frac{(\mu_p+\mu_n)}{2} = 0.085$

Annu. Rev. Nucl. Part. Sci. 2003.

Motivation

- Searching for new physics

PRL 114, 161802 (2015)

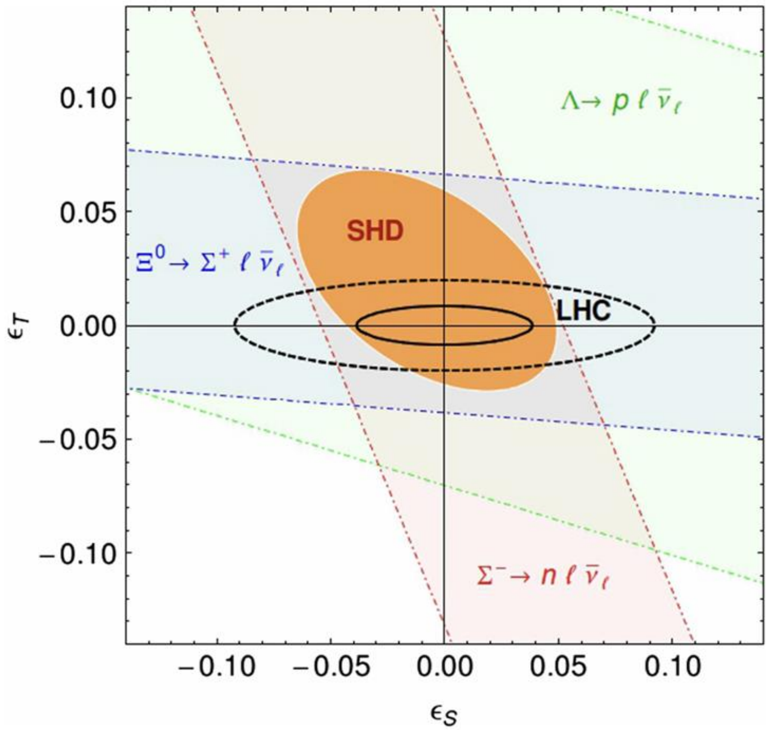
  - ✓ Provide extremely stringent constraints on the Wilson coefficients (ϵ_S, ϵ_T) of new physics.
  - ✓ Complement the search for new physics at high-energy experiments such as the LHC.

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)}.$$

$$R^{\mu e}_{\rm SM} = \sqrt{1 - \frac{m_\mu^2}{\Delta^2}}\left(1 - \frac{9}{2}\frac{m_\mu^2}{\Delta^2} - 4\frac{m_\mu^4}{\Delta^4}\right) + \frac{15}{2}\frac{m_\mu^4}{\Delta^4}\arctan{\rm h}\left(\sqrt{1 - \frac{m_\mu^2}{\Delta^2}}\right).$$

$$\frac{R^{\mu e}}{R^{\mu e}_{\rm SM}} = 1 + r_S \epsilon_S + r_T \epsilon_T,$$

	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^0 \to \Sigma^+$	$\Xi^- \to \Lambda$
$g_1(0)/f_1(0)$	0.718(15)	−0.340(17)	1.210(50)	0.250(50)
$f_S(0)/f_1(0)$	1.90(10)	2.80(14)	1.36(7)	2.25(11)
$f_T(0)/f_1(0)$	0.72	−0.28	1.22	0.22
r_S	1.60	4.1	0.56	3.7
r_T	5.2	1.7	7.2	1.1



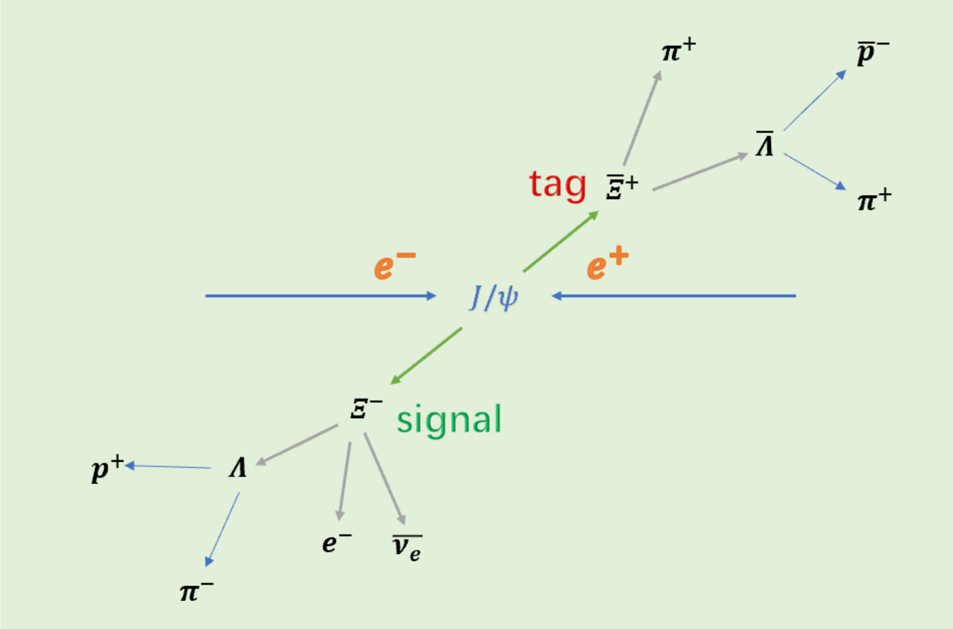
Analysis strategy

✓ **Double Tag Method:**

Double tag method can reduce several terms of systematic uncertainty.

Tag Mode: $\bar{\Xi}^+ \to \bar{\Lambda}\,\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$

Signal Mode: $\Xi^- \to \Lambda e^- \bar{\nu}_e, \Lambda \to p\pi^-$



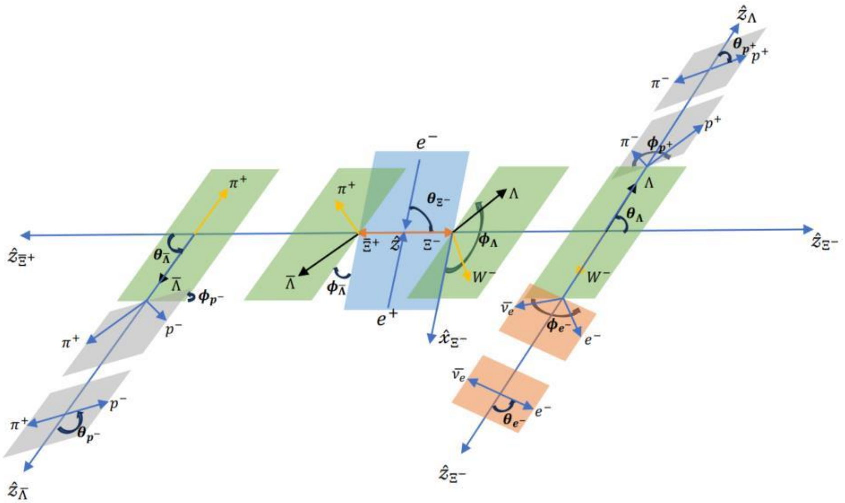
Yield of each side:

- $N_{ST} = N_{J/\psi} \times Br_{J/\psi\to\bar{\Xi}^+\Xi^-} \times Br_{\bar{\Xi}^+\to\bar{\Lambda}\,\pi^+} \times Br_{\bar{\Lambda}\to\bar{p}\pi^+} \times \varepsilon_{ST}$
- $N_{DT} = N_{J/\psi} \times Br_{J/\psi\to\bar{\Xi}^+\Xi^-} \times Br_{\bar{\Xi}^+\to\bar{\Lambda}\,\pi^+} \times Br_{\bar{\Lambda}\to\bar{p}\pi^+} \times Br_{\Xi^-\to\Lambda e^-\bar{\nu}_e} \times Br_{\Lambda\to p\pi^-} \times \varepsilon_{DT}$
- $\boldsymbol{Br_{\Xi^-\to\Lambda e^-\bar{\nu}_e} = \frac{N_{DT}}{N_{ST}} \times \frac{\varepsilon_{ST}}{\varepsilon_{DT}} \times \frac{1}{Br_{\Lambda\to p\pi^-}}}$

Simulated data sets

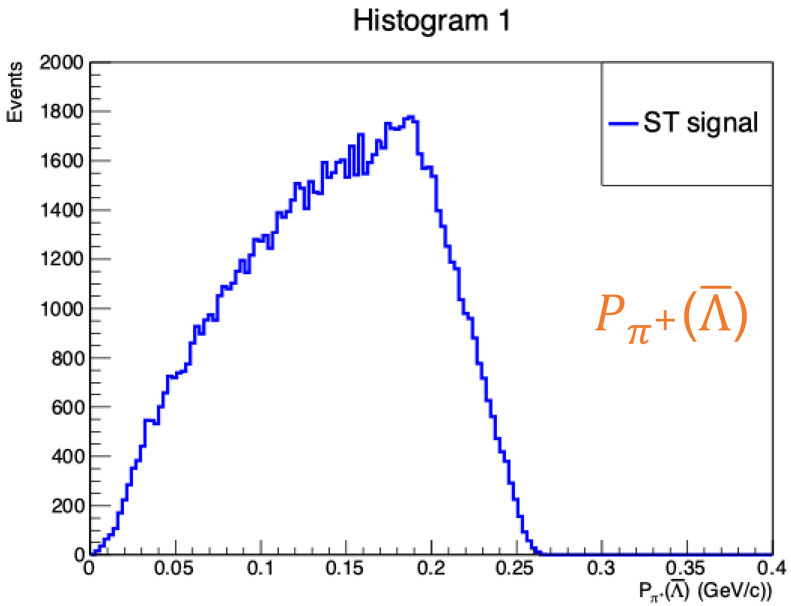
- ✓ OSCAR version: 2.6.2
- ✓ CDR J/ψ:3.4×10^{12}
- ✓ Simulated MC and dominant BKG sample: $5.0 \times 10^5 (2\times)$ and $5 \times 10^7 (0.1\times)$
- ✓ Signal MC : $e^+e^- \to J/\psi \to \bar{\Xi}^+\Xi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \Xi^- \to \Lambda e^- \bar{\nu}_e, \bar{\Lambda} \to \bar{p}\pi^+, \Lambda \to p\pi^-$
- ✓ Background MC: $e^+e^- \to J/\psi \to \bar{\Xi}^+\Xi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \Xi^- \to \Lambda\pi^-, \bar{\Lambda} \to \bar{p}\pi^+, \Lambda \to p\pi^-$

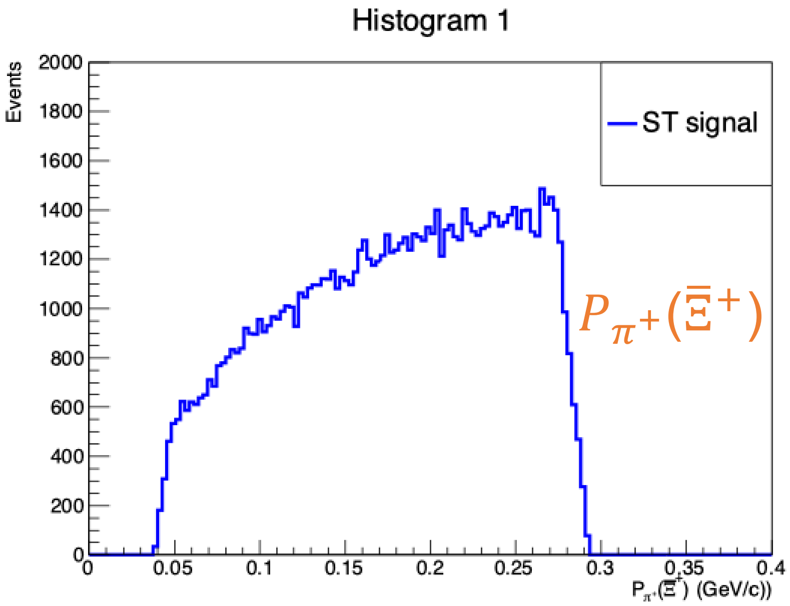
  - ST-MC: $J/\psi \to \bar{\Xi}^+(\bar{\Lambda}\pi^+(\bar{\Lambda} \to \bar{p}\pi^+))\Xi^-(anything)$
  - DT-MC: $J/\psi \to \bar{\Xi}^+(\bar{p}\pi^+\pi^+)\Xi^-(\Lambda e^-\bar{\nu}_e(\Lambda \to p\pi^-))$

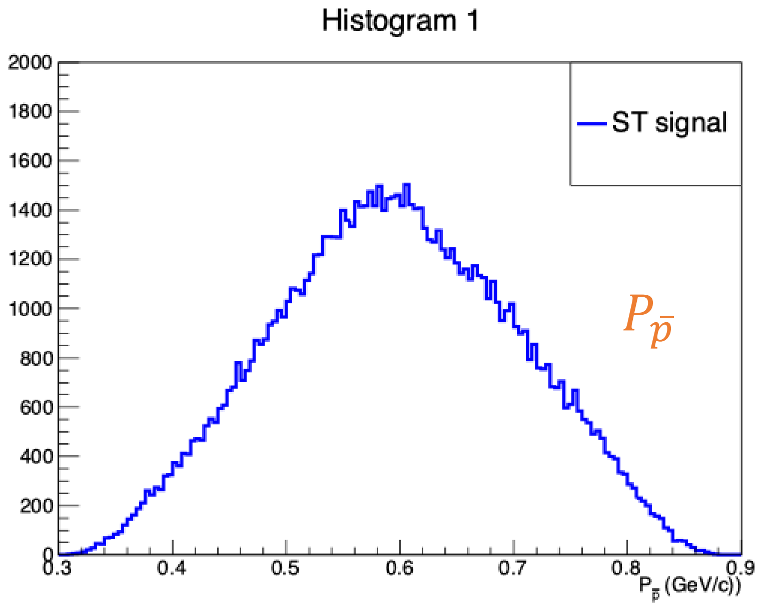


Single tag analysis

➢ ST signal MC truth information(final state particles):







- ST-MC: $J/\psi \to \bar{\Xi}^+(\bar{\Lambda}\,\pi^+(\bar{\Lambda} \to \bar{p}\pi^+))\Xi^-(anything)$

Single tag analysis

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➢ ST Event Selection

Tag Mode: $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+,\ \bar{\Lambda} \to \bar{p}\pi^+$

✓ **Good charged track :** No Vertex requirement; $|\cos\theta| < 0.94,\ N_{charge^+} \geq 2; N_{charge^-} \geq 1$

✓ **Particle ID:** For proton: $p_{\bar{p}} > 0.32 GeV/c;\ N_{\bar{p}} \geq 1$;
For pion: $p_{\pi^+} < 0.30\ GeV/c;\ N_{\pi^+} \geq 2$;

✓ **Vertex fit for $\bar{\Lambda}, \bar{\Xi}^+$:** Primary vertex fit : $\bar{p}\pi^+$ for $\bar{\Lambda}$, $\bar{\Lambda}\pi^+$ for $\bar{\Xi}^+$
Secondary vertex fit : $\bar{\Lambda}\pi^+$ and $\bar{\Xi}^+$, $\bar{\Xi}^+$ and initial vertex

Loop all the combinations, select the minimum $\chi^2 = \frac{\left(M_{\bar{p}\pi^+} - M_{\bar{\Lambda}_{PDG}}\right)^2}{\sigma^2_{\bar{\Lambda}}} + \frac{\left(M_{\bar{p}\pi^+\pi^+} - M_{\bar{p}\pi^+} + M_{\bar{\Lambda}_{PDG}} - M_{\bar{\Xi}^+{}_{PDG}}\right)^2}{\sigma^2_{\bar{\Xi}}}$

✓ **Decay length:** $L_{\bar{\Lambda}}/\sigma_{L_{\bar{\Lambda}}} > 0\ \&\&\ L_{\bar{\Xi}^+}/\sigma_{L_{\bar{\Xi}^+}} > 0$

✓ **Mass distribution :** $|M_{\bar{\Lambda}} - M_{\bar{\Lambda}_{PDG}}| < 0.006\text{GeV};\ \left|M_{\bar{p}\pi^+\pi^+} - M_{\bar{p}\pi^+} + M_{\bar{\Lambda}_{PDG}} - M_{\Xi^+_{PDG}}\right| < 0.008\text{GeV}$
$1.273 GeV < M_{recoil} < 1.363 GeV$

Single tag analysis

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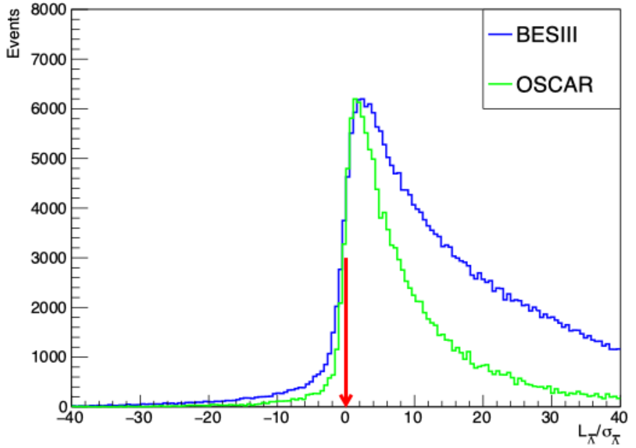
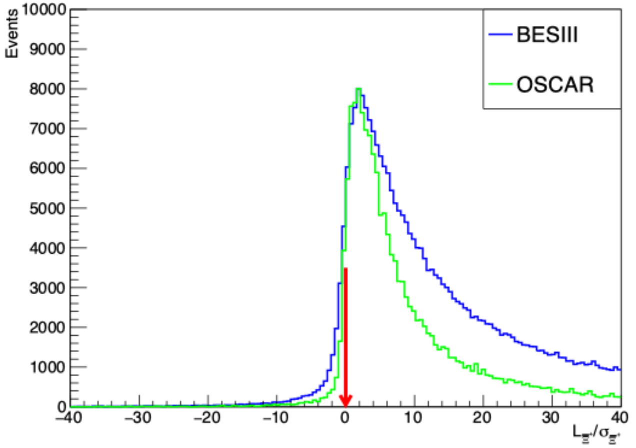
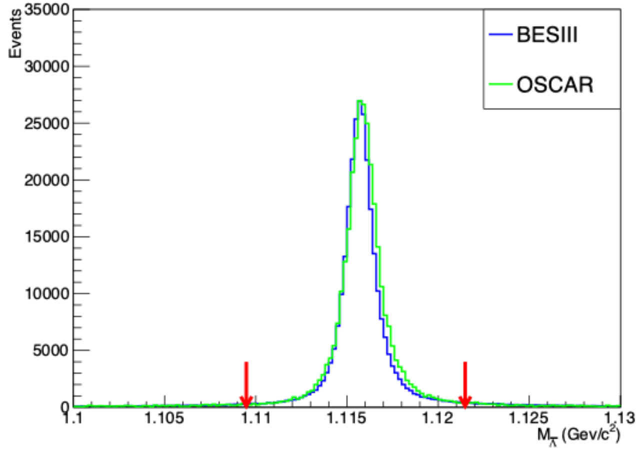
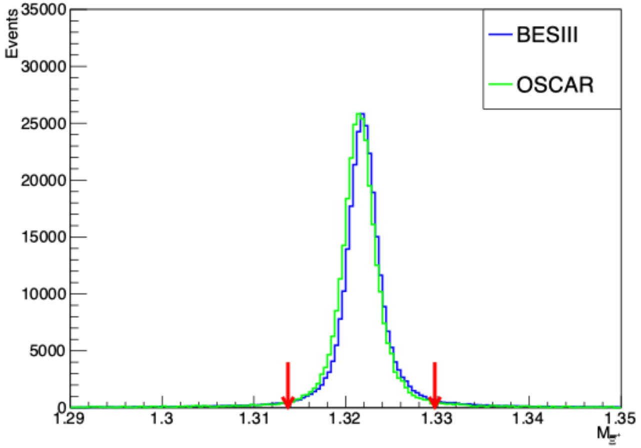
➢ ST Event Selection



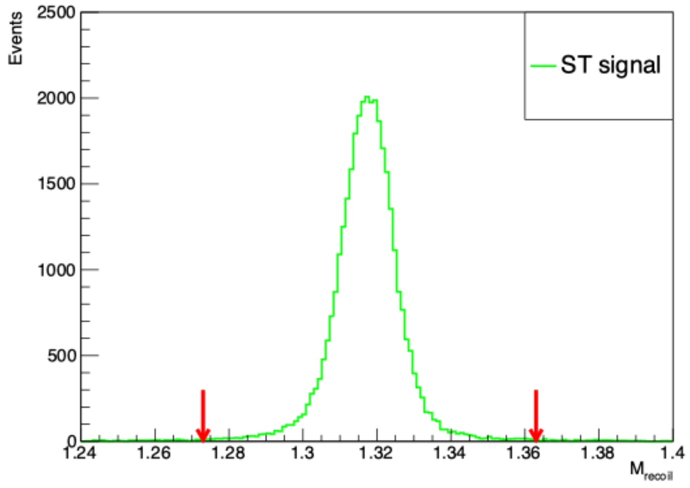






$$1.273GeV < M_{rec} < 1.363GeV$$

$$M_{recoil} = (ecms - P_{\bar{\Xi}^+}).M();$$



recoil

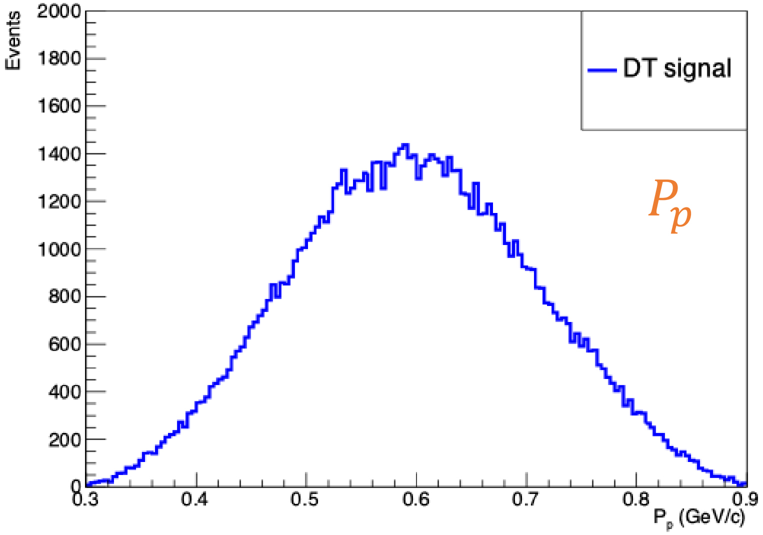
Single tag analysis

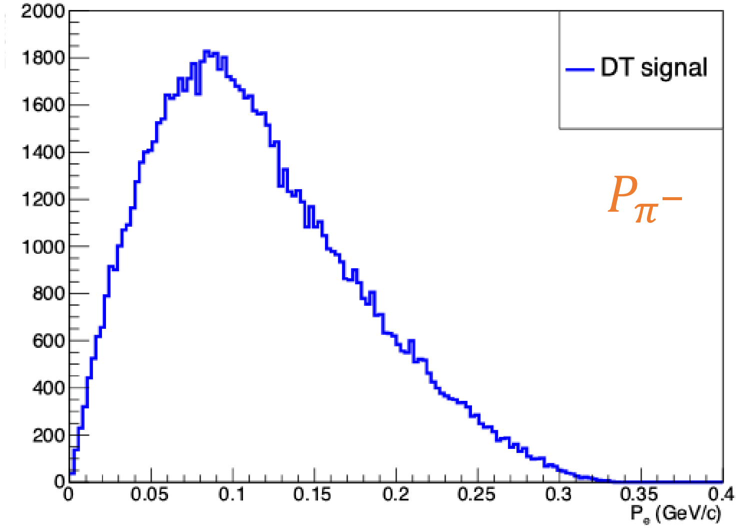
- Cut flow

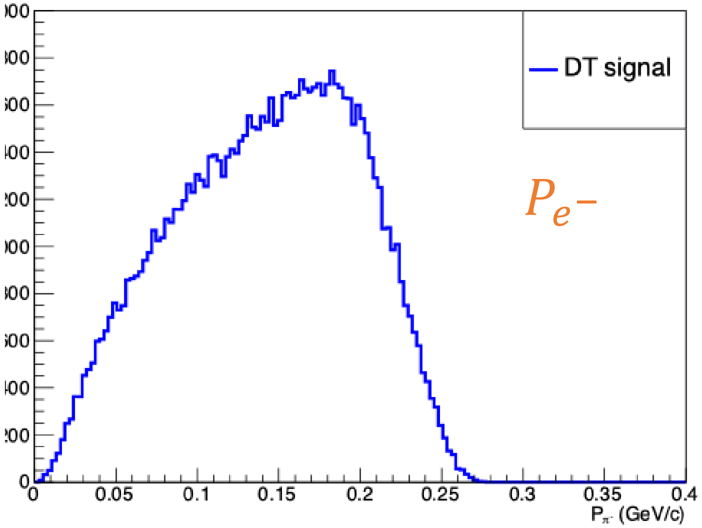
Selection Criteria	Event number	STCF		BESIII	
		Absolute Efficiency(%)	Relative Efficiency(%)	Absolute Efficiency(%)	Relative Efficiency(%)
Total Number	500000	100.00	------	100.00	------
Good charged track	480551	96.11	96.11	92.81	92.81
$N_{\bar{p}} \geq 1$	444423	88.88	92.48	80.53	86.77
$N_{\pi^+} \geq 2$	352551	70.51	79.33	54.27	67.39
$\bar{\Xi}^+$ Vertex	335150	67.03	95.06	48.01	88.47
Further cut	173603	34.72	51.80	27.27	56.80

Double tag analysis

- DT signal MC truth information(final state particles):







- DT-MC: $J/\psi \to \bar{\Xi}^+(\bar{p}\pi^+\pi^+)\Xi^-(\Lambda e^-\bar{\nu}_e(\Lambda \to p\pi^-))$

Double tag analysis

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- DT Event Selection

Signal Mode: $\Xi^- \to \Lambda e^- \bar{\nu}_e,\ \Lambda \to p\pi^-$

✓ **Particle ID:** Proton: $p_p > 0.32 GeV/c$; $N_p \geq 1$;

Pion or electron: $p/\pi^- < 0.30\ GeV/c$; $N \geq 2$

✓ **Vertex fit under the hypothesis $\Xi^- \to \Lambda e^- \bar{\nu}_e$:**

Primary vertex fit: $p\pi^-$ for Λ, Λe^- for Ξ^-. Secondary vertex fit: Λ and Ξ^-, Ξ^- and Primary Vertex.
Loop all the pairs, select combination by minimizing $|M_{p\pi^-} - M_{\Lambda_{PDG}}|$ and minimizing primary vertex fit $\chi^2_{\Lambda e^-}$ of Ξ^-
Ξ^- secondary vertex fit has also been done to get the decay length information.

✓ **Vertex fit under the hypothesis $\Xi^- \to \Lambda \pi^-$:**

Primary vertex fit: $p\pi^-$ for Λ, $\Lambda\pi^-$ for Ξ^-. Secondary vertex fit: $\Lambda\pi^-$ and Ξ^-, Ξ^- and Primary Vertex

Loop all the pairs, select the minimum $\chi^2 = = \frac{\left(M_{p+\pi^-} - M_{\Lambda_{PDG}}\right)^2}{\sigma^2_\Lambda} + \frac{\left(M_{p+\pi^-\pi^-} - M_{p+\pi^-} + M_{\Lambda_{PDG}} - M_{\Xi_{PDG}}\right)^2}{\sigma^2_\Xi}$

- $\left|M_{p\pi^-\pi^-} - M_{p\pi^-} + M_{\Lambda_{PDG}} - M_{\Xi^-_{PDG}}\right| > 0.00\mathbf{54}GeV$

✓ **Further cut**: $L_\Lambda/\sigma_{L_\Lambda} > 0$ && $L_\Xi/\sigma_{L_\Xi} > 0$; $\chi^2_{\Lambda e^-} < 20$; $|M_\Lambda - M_{\Lambda_{PDG}}| < 0.006GeV$

Double tag analysis

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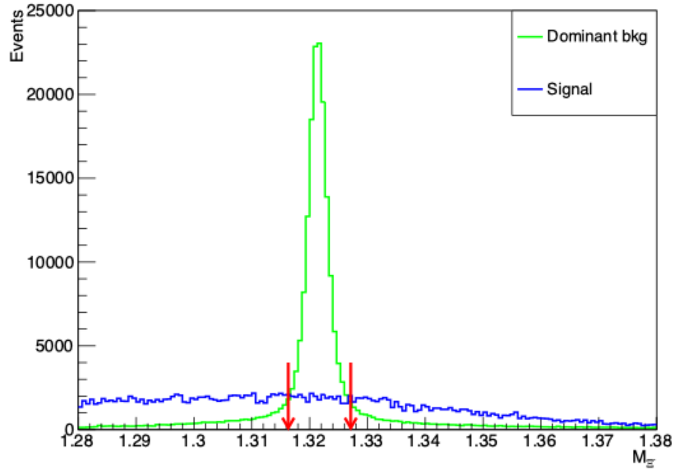
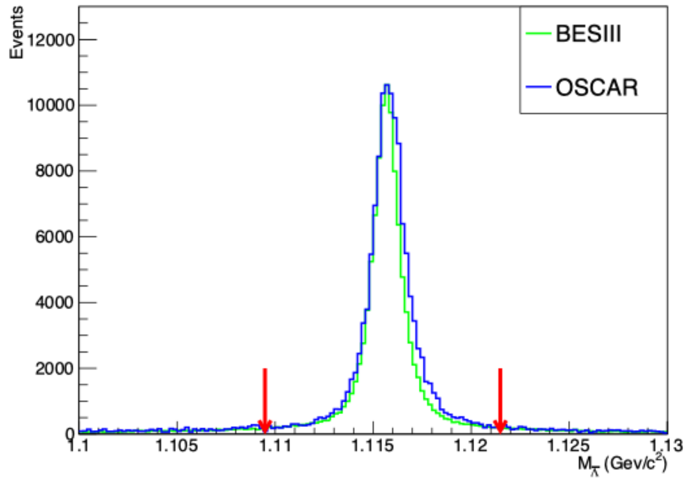
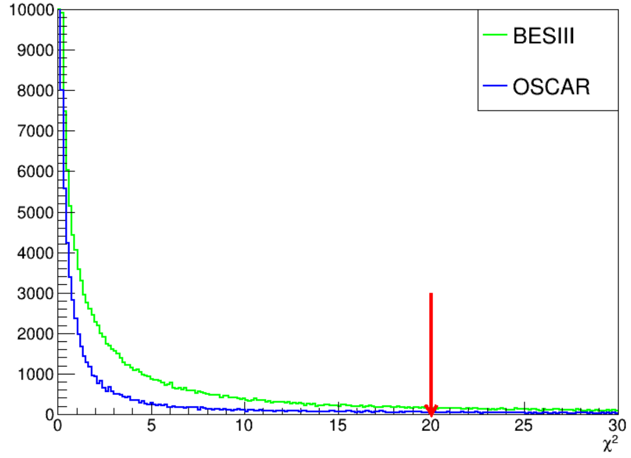
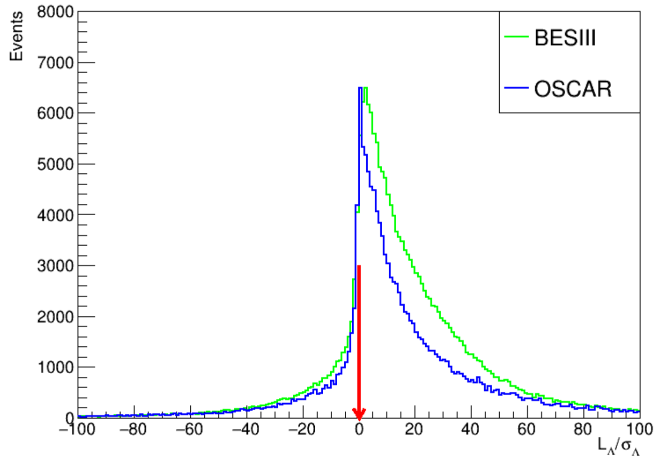
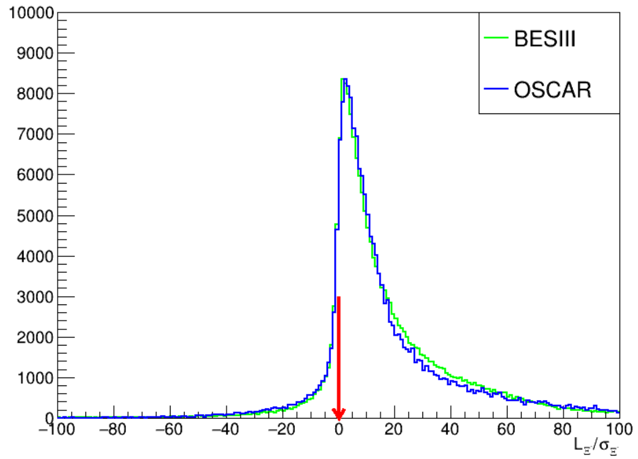
- DT Event Selection









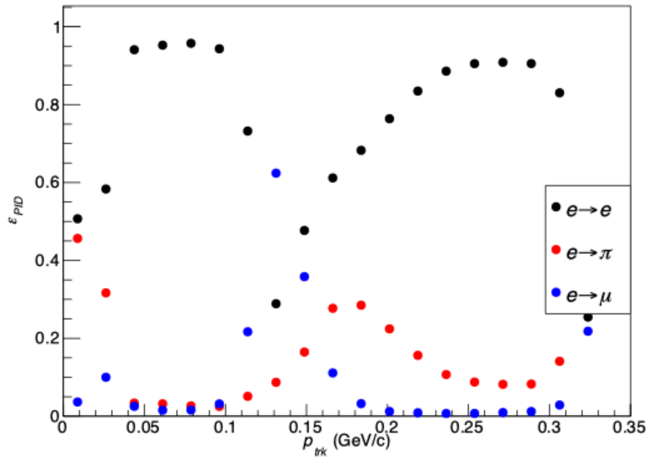


Double tag analysis

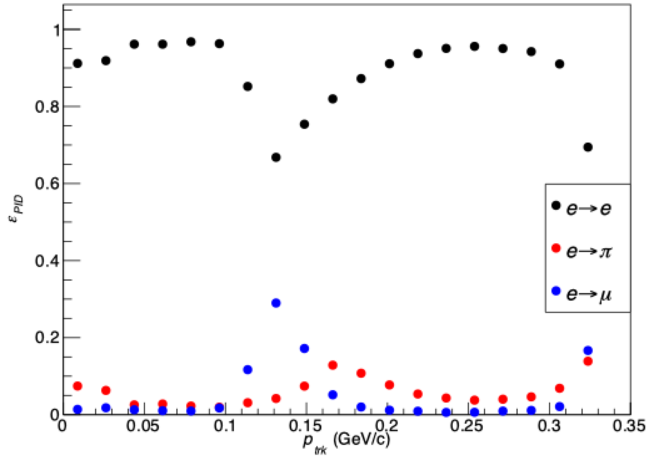
➢ Cut flow

Selection Criteria	STCF				BESIII			
	Signal		Dominant bkg		Signal		Dominant bkg	
	Absolute Eff. (%)	Relative Eff. (%)	Absolute Eff. (%)	Relative Eff. (%)	Absolute Eff. (%)	Relative Eff. (%)	Absolute Eff. (%)	Relative Eff. (%)
After DT Vertex fit	19.83	57.11	22.47	---	13.58	49.80	15.92	---
veto dominant bkg	17.55	88.50	5.92	26.35	11.99	88.29	3.05	19.16
$\frac{L_\Lambda}{\sigma_{L_\Lambda}} > 0$	13.51	76.98	3.53	59.63	9.98	83.24	2.06	67.63
$\frac{L_{\Xi^-}}{\sigma_{L_{\Xi^-}}} > 0$	10.72	79.35	1.70	84.16	8.60	86.17	1.31	63.50
χ^2<20	9.90	92.35	1.05	61.76	6.77	78.72	0.54	41.37
$\lvert M_{p^+\pi^-} - M_\Lambda^{\mathrm{PDG}} \rvert < 6MeV$	9.32	94.14	0.59	56.19	6.50	96.01	0.44	81.84
Global PID or BDT	3.99	42.81	0.00217	0.37	4.15	61.57	0.00066	0.15

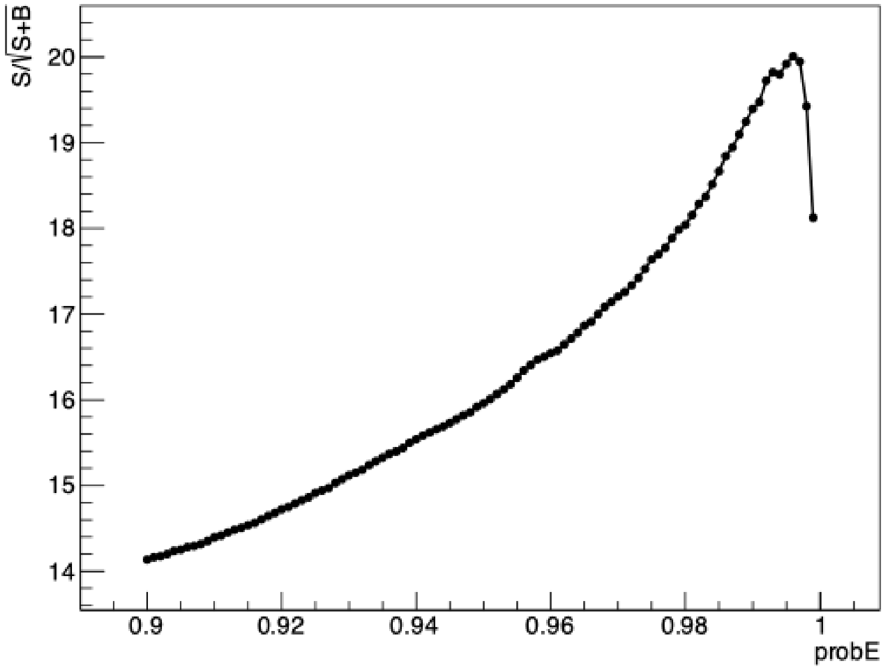
Global PID current status



Optimize



- Maximum significance at $\mathrm{Prob}(e^-) > 0.996$

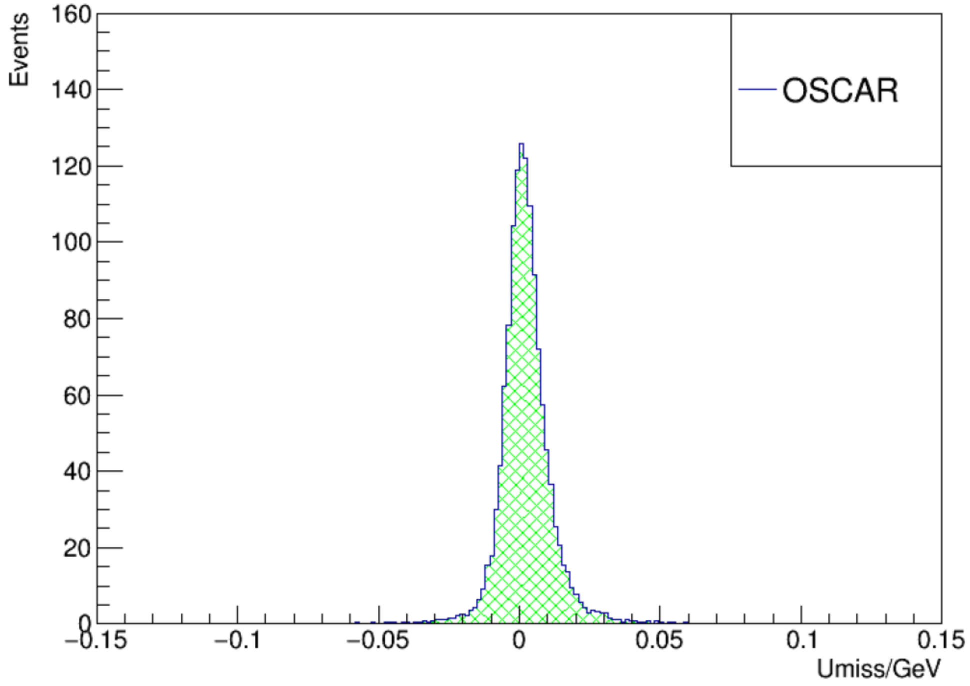


Signal		Background	
Absolute Eff. (%)	Relative Eff. (%)	Absolute Eff. (%)	Relative Eff. (%)
3.99	42.81	0.00217	0.37

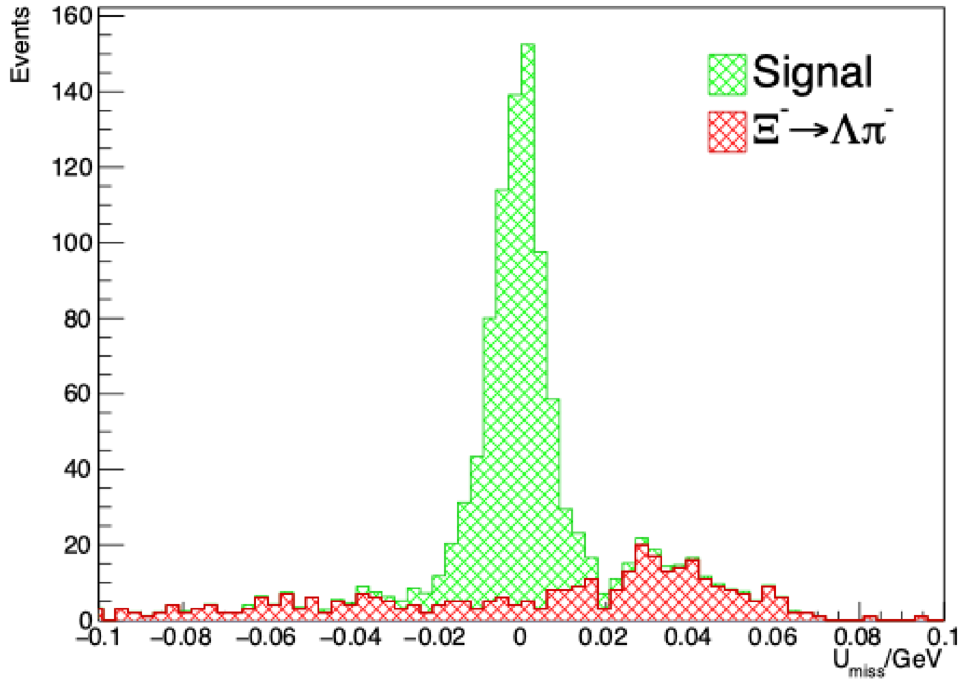
U_{miss}

$$E_\nu = E_{cm}/2 - E_\Lambda - E_e$$

$$P_\nu = P_{\Xi_{\mathrm{corr}}} - P_\Lambda - P_e$$



Comparison of the distribution of Umiss different processs



Measure the form factors

- Differential cross section:

$$\mathcal{W} \propto V_{Ph}(q^2)\left(q^2 - m_e^2 \sum_{\mu,\bar{\nu}=0}^{3} \sum_{\mu'}^{3} \sum_{\bar{\nu}'}^{3} C_{\mu\bar{\nu}} B^{\Xi^-}_{\mu\mu'} A^{\Lambda}_{\nu'0} A^{\bar{\Xi}^+}_{\bar{\nu}\bar{\nu}'} A^{\bar{\Lambda}}_{\bar{\nu}'0}\right), \qquad B_{\mu\nu} = R_{\mu\rho} b_{\rho\nu},\ A_{\mu\nu} = R_{\mu\rho} a_{\rho\nu}$$

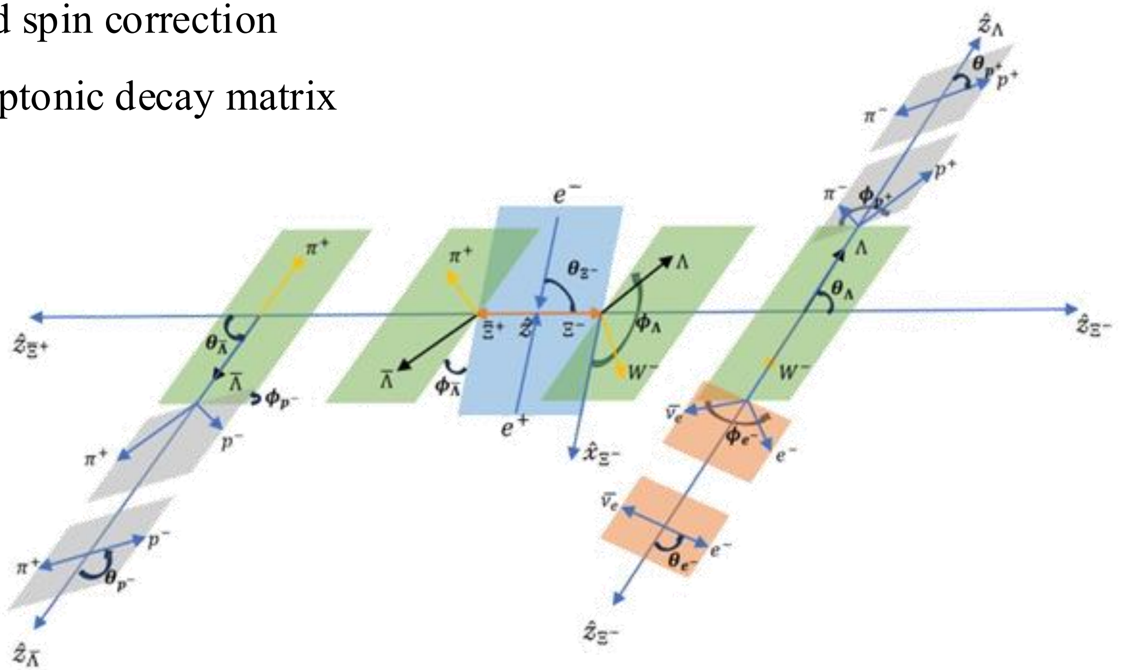
$R_{\mu\rho}$: Rotation matrix, $C_{\mu\bar{\nu}}$: Polarization and spin correction

$b_{\rho\nu}$: Semi-leptonic decay matrix, $a_{\rho\nu}$: Non-leptonic decay matrix

$$\Rightarrow \quad \mathcal{W} = \mathcal{W}(\xi, \omega)$$

Observables: $\xi = (\theta_{\Xi^-}, \theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_{\bar{p}}, \phi_{\bar{p}}, \theta_e, \phi_e, q^2)$

Fit parameters: $\omega = (\alpha_\Psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_\Lambda, g_{av}, g_w, g_{av2}, \alpha_\Lambda)$



Maximum likelihood estimation

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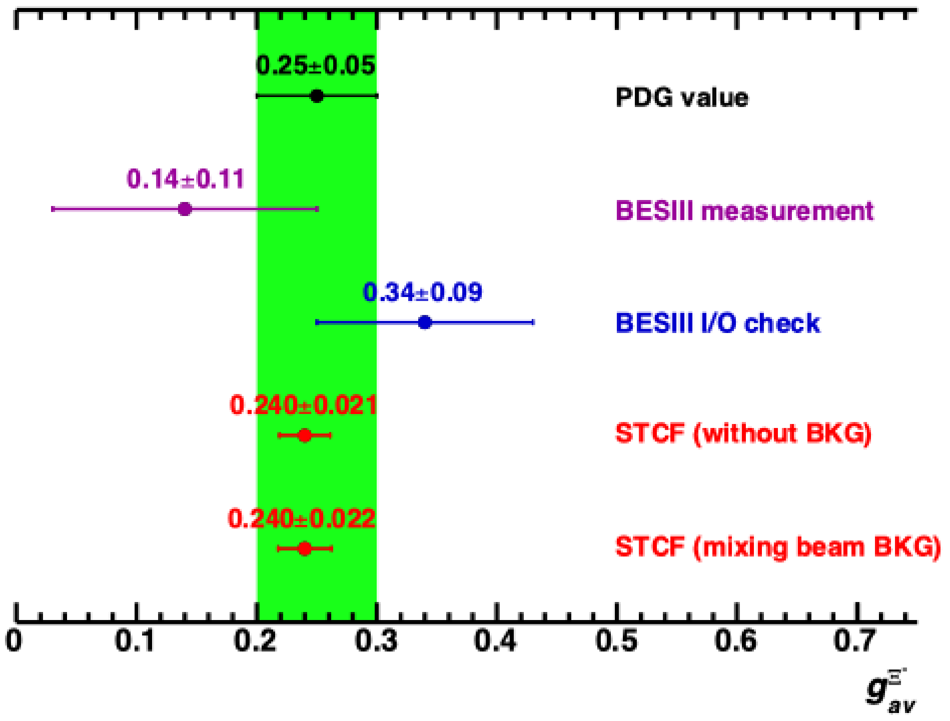
- Likelihood: $L = \prod_{n=1}^{N} \frac{\mathcal{W}(\xi_i,\omega)\,\varepsilon_i}{C}, C = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} \frac{\mathcal{W}(\xi_i,\omega)}{\mathcal{W}(\xi_i,\omega_0)}$
- Predictions:
  - Fix g_w, g_{av2}: $\Delta g_{av} \sim 0.003 \Rightarrow 36 \times$ precision
  - Float g_{av}, g_w, g_{av2}:

    $\Delta g_{av} \sim 0.007, \Delta g_w \sim 0.04, \Delta g_{av2} \sim 0.05$
- Input parameters for DIY MC sample:
  - Channel: $\Xi \to \Lambda e^- \overline{\nu}_e,\ \Lambda \to p\pi^-$

$\alpha_{J/\psi}$	$\Delta\Phi$	g_{av}	g_w	α_{Ξ^+}	ϕ_{Ξ^+}	α_Λ	$\alpha_{\bar{\Lambda}}$
0.586	1.213	0.25	0.085	0.3756	−0.012	0.7572	−0.7629



Summary and Next to do

Summary

- ✓ This work is now ready to study at the STCF under the OSCAR framework.
- ✓ Optimized the event selection of $\Xi^- \to \Lambda e^- \nu_e$
- ✓ Fitted the form factor g_{av}

Next to do

- ➢ Try to fit with the g_{av2} and g_w and further calculate V_{us}
- ➢ Prepare the note

Thanks!