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
- Simulated data sets
- Analysis strategy
- Single tag analysis
- Double tag analysis
- Summary

Motivation

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- 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

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

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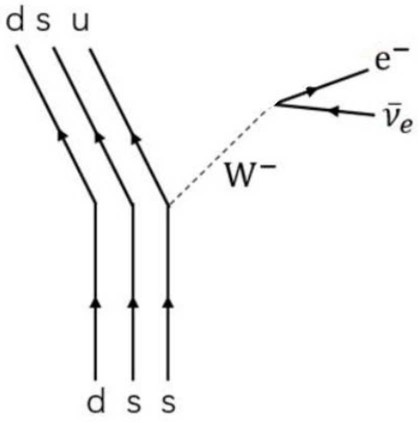

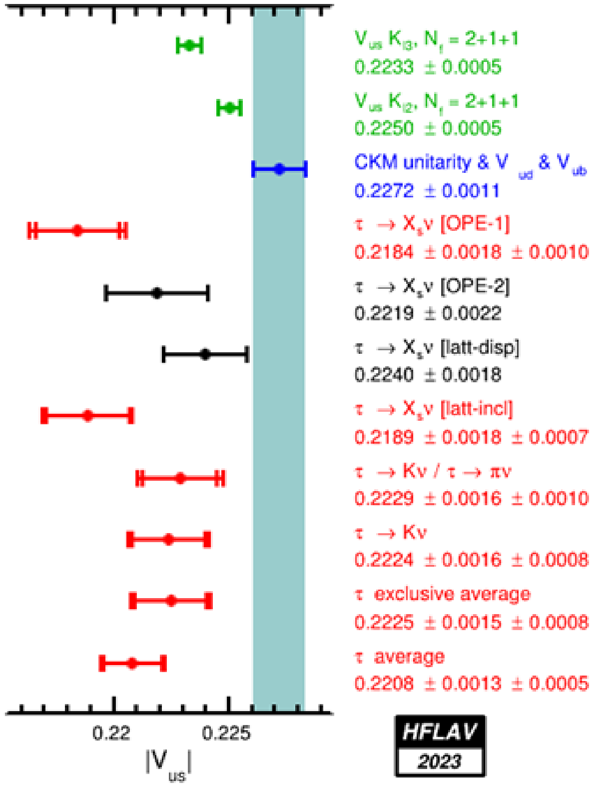

Motivation

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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 waitting 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

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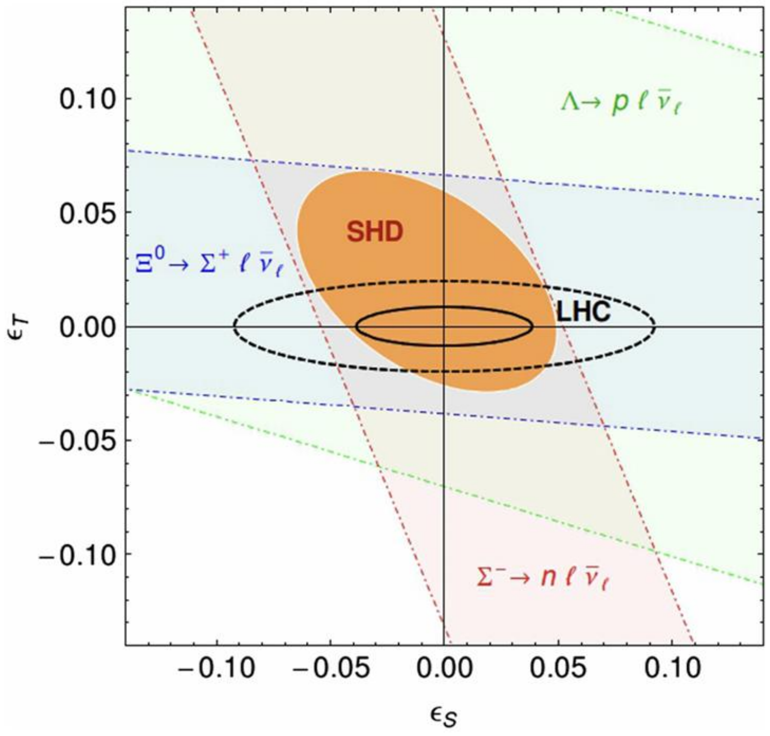
- ✓ Provide extremely stringent constraints on the Wilson coefficients (ϵ_S, ϵ_T) of new physics.
- ✓ Complement the search for new physics at high-energy experiments such as the LHC.

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

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

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

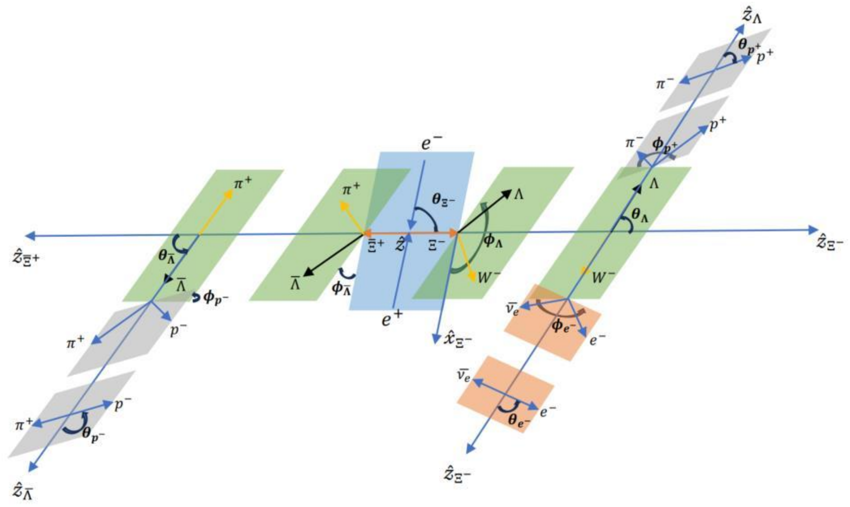
	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^0 \to \Sigma^+$	$\Xi^- \to \Lambda$
$g_1(0)/f_1(0)$	0.718(15)	−0.340(17)	1.210(50)	0.250(50)
$f_S(0)/f_1(0)$	1.90(10)	2.80(14)	1.36(7)	2.25(11)
$f_T(0)/f_1(0)$	0.72	−0.28	1.22	0.22
r_S	1.60	4.1	0.56	3.7
r_T	5.2	1.7	7.2	1.1



Simulated data sets

- ✓ OSCAR version: 2.6.2
- ✓ CDR J/ψ:3.4×10^{12}
- ✓ Simulated MC and dominant BKG sample: 2.0×10^{5}
- ✓ Signal MC : $e^{+}e^{-} \rightarrow J/\psi \rightarrow \bar{\Xi}^{+}\Xi^{-}, \bar{\Xi}^{+} \rightarrow \bar{\Lambda}\pi^{+}, \Xi^{-} \rightarrow \Lambda e^{-}\bar{\nu}_{e}, \bar{\Lambda} \rightarrow \bar{p}\pi^{+}, \Lambda \rightarrow p\pi^{-}$
- ✓ Background MC: $e^{+}e^{-} \rightarrow J/\psi \rightarrow \bar{\Xi}^{+}\Xi^{-}, \bar{\Xi}^{+} \rightarrow \bar{\Lambda}\pi^{+}, \Xi^{-} \rightarrow \Lambda\pi^{-}, \bar{\Lambda} \rightarrow \bar{p}\pi^{+}, \Lambda \rightarrow p\pi^{-}$

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



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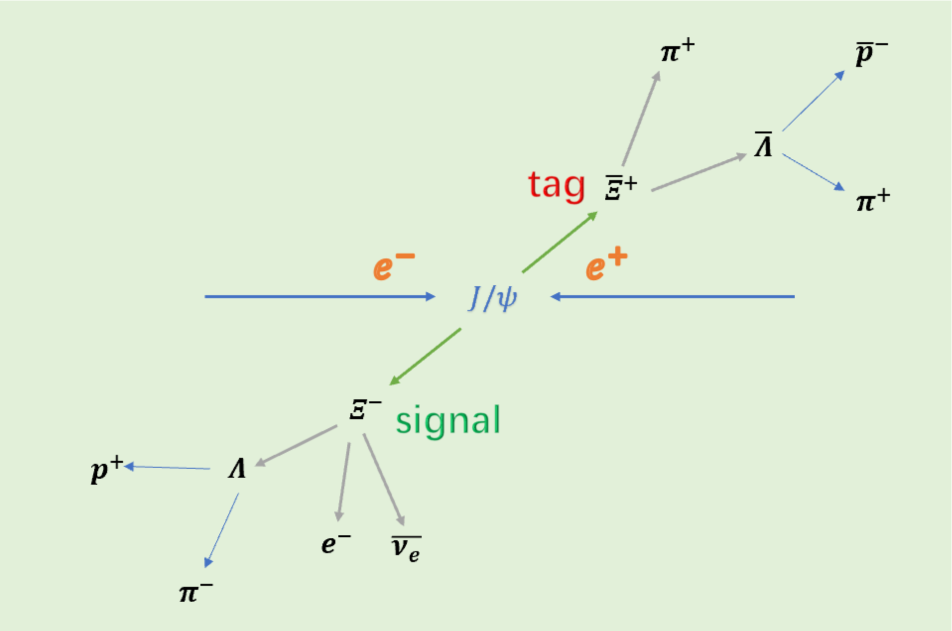
✓ **Double Tag Method:**

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

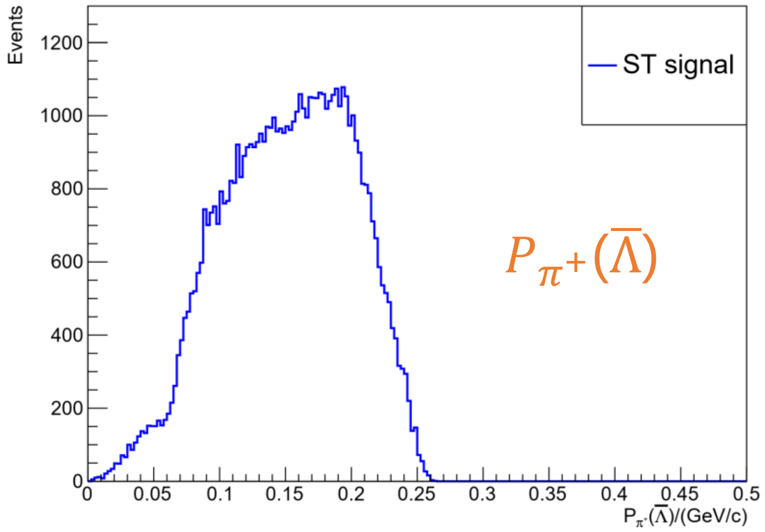


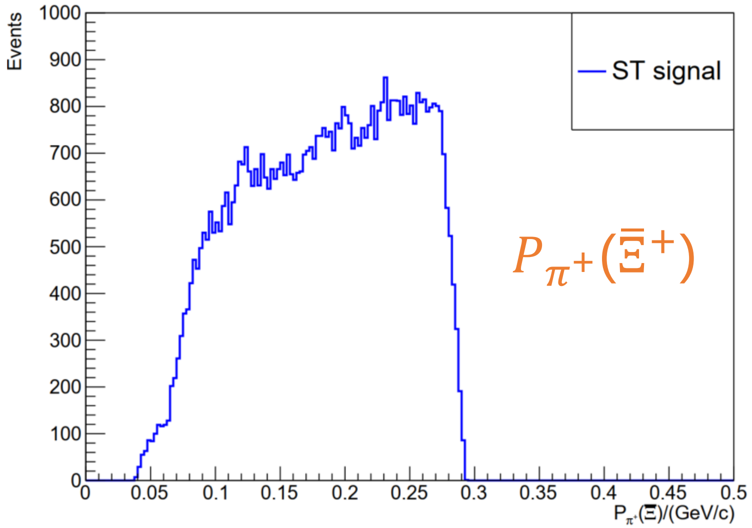
Yield of each side:

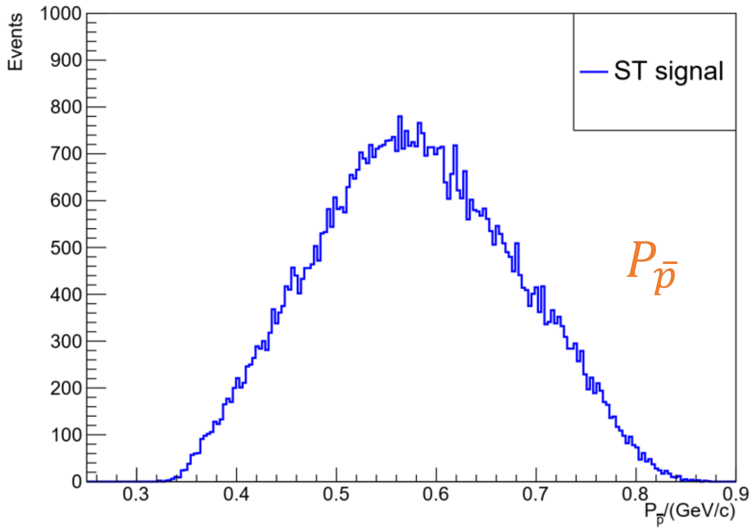
- $N_{ST} = N_{J/\psi} \times \mathrm{Br}_{J/\psi\to\bar{\Xi}^+\Xi^-} \times \mathrm{Br}_{\bar{\Xi}^+\to\bar{\Lambda}\,\pi^+} \times \mathrm{Br}_{\bar{\Lambda}\to\bar{p}\pi^+} \times \varepsilon_{ST}$
- $N_{DT} = N_{J/\psi} \times \mathrm{Br}_{J/\psi\to\bar{\Xi}^+\Xi^-} \times \mathrm{Br}_{\bar{\Xi}^+\to\bar{\Lambda}\,\pi^+}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

Single tag analysis

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







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

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; $|\cos\theta| < 0.93$, $N_{charge^+} \geq 2$; $N_{charge^-} \geq 1$

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

✓ **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

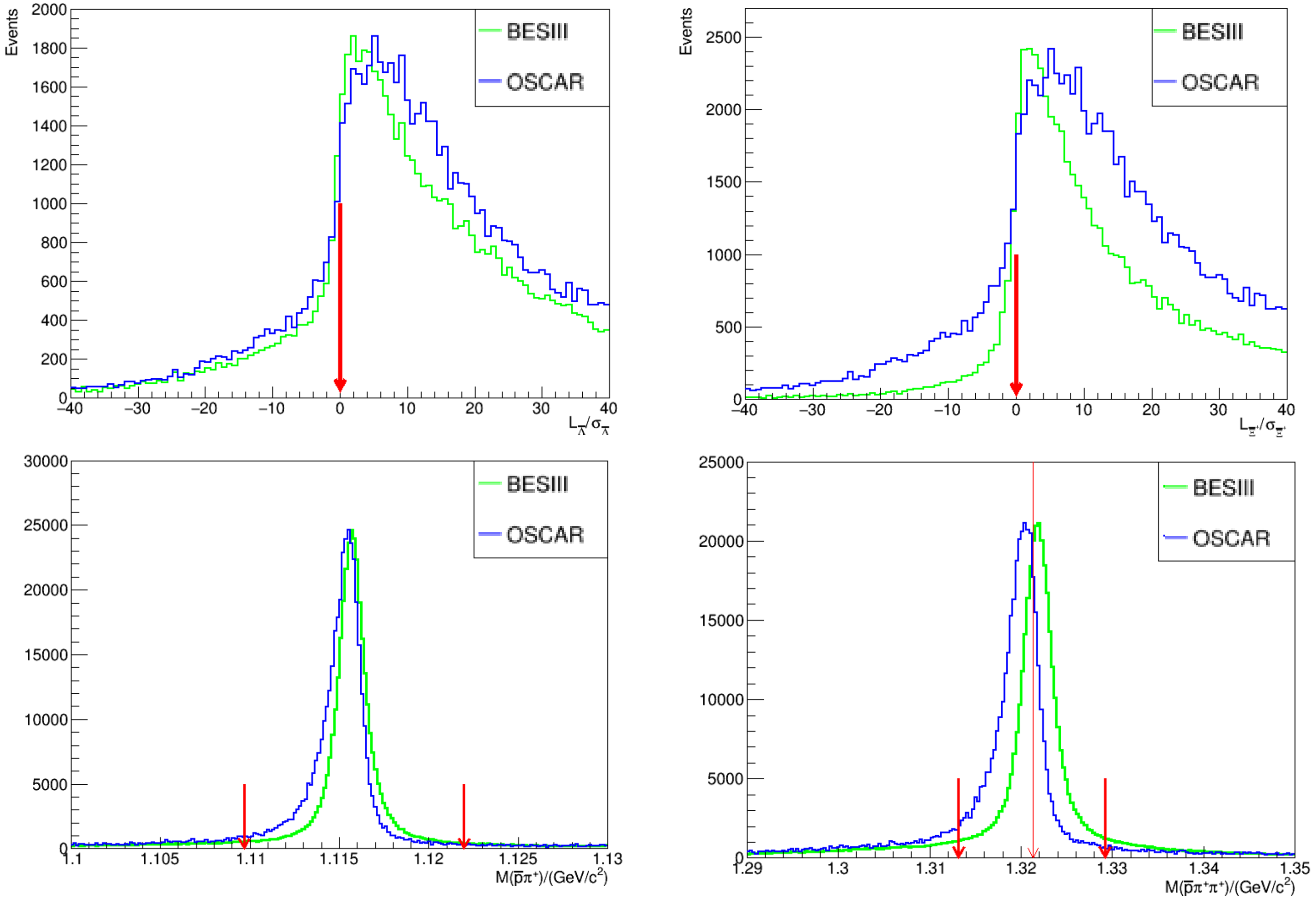
Loop all the combinations, select the minimum $\chi^2 = \frac{\left(M_{\bar{p}\pi^+} - M_{\bar{\Lambda}_{PDG}}\right)^2}{\sigma_{\bar{\Lambda}}^2} + \frac{\left(M_{\bar{p}\pi^+\pi^+} - M_{\bar{p}\pi^+} + M_{\bar{\Lambda}_{PDG}} - M_{\bar{\Xi}^+{}_{PDG}}\right)^2}{\sigma_{\bar{\Xi}}^2}$

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

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

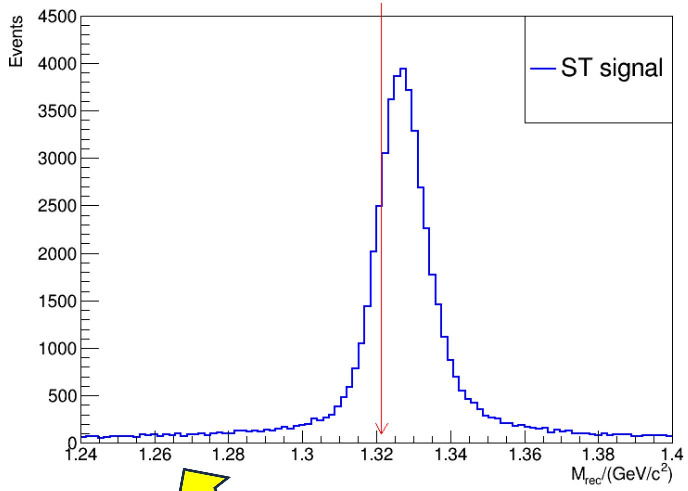
Single tag analysis

- ST Event Selection



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

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



recoil

Single tag analysis

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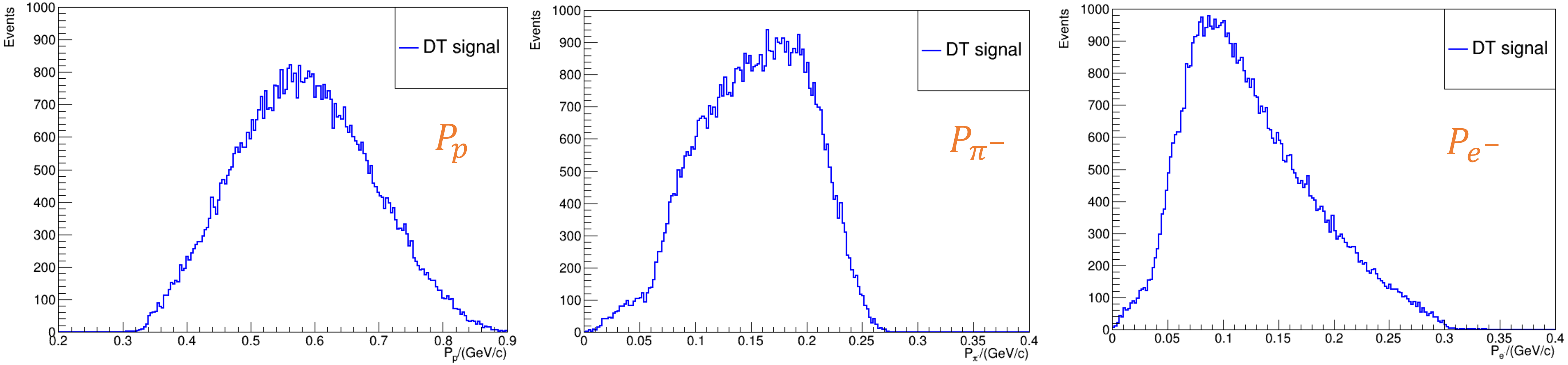
➢ Cut flow

Selection Criteria	Event number	OSCAR		BESIII	
		Absolute Efficiency(%)	Relative Efficiency(%)	Absolute Efficiency(%)	Relative Efficiency(%)
Total Number	200000	100	------	100	------
Good charged track	191889	95.94	95.94	92.81	92.81
$N_{\bar{p}} \geq 1$	179202	89.60	93.39	80.53	86.77
$N_{\pi^+} \geq 2$	137757	68.88	76.88	54.27	67.39
$\bar{\Xi}^+$ Vertex	109697	54.85	79.63	48.01	88.47
Further cut	71339	35.27	64.30	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:$p_p > 0.32 GeV/c$; $N_p \geq 1$;$Prob(p) > Prob(\pi)$ && $Prob(p) > Prob(K)$

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

✓ **Vertex fit for simulated decay $\Xi^- \to \Lambda\pi^-$ candidate:**

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 chisqure

✓ **Vertex fit for signal candidate :**

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 then minimizing primary vertex fit χ^2 of Ξ^-

✓ **Mass distribution:** Veto $\left|M_{p\pi^-\pi^-} - M_{p\pi^-} + M_{\Lambda_{PDG}} - M_{\Xi^-_{PDG}}\right| < 0.006$GeV

$|M_\Lambda - M_{\Lambda_{PDG}}| < 0.006$GeV

✓ **Further cut**: $L_\Lambda/\sigma_{L_\Lambda} > 0$ && $L_\Xi/\sigma_{L_\Xi} > 0$; $\chi^2 < 20$

Double tag analysis

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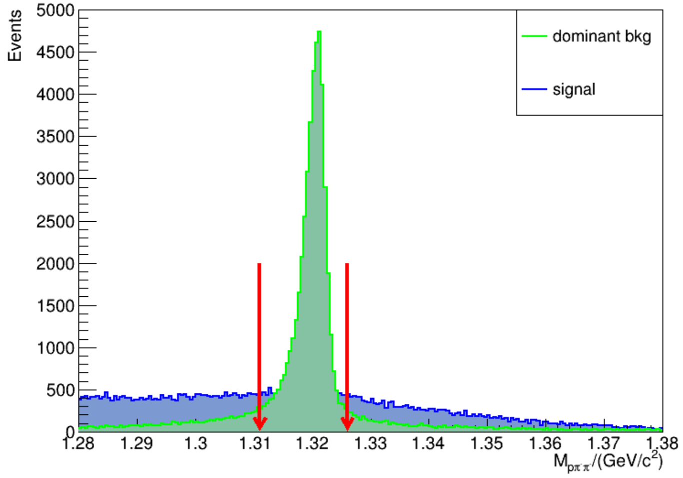
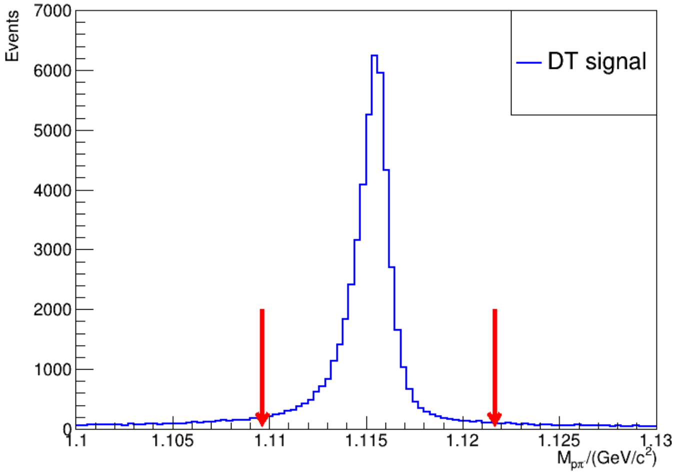
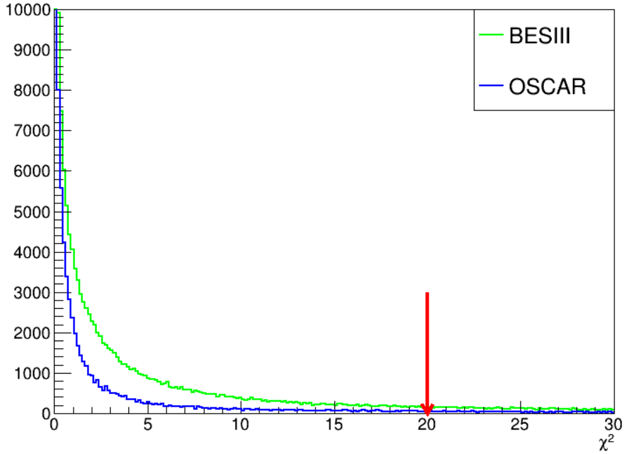
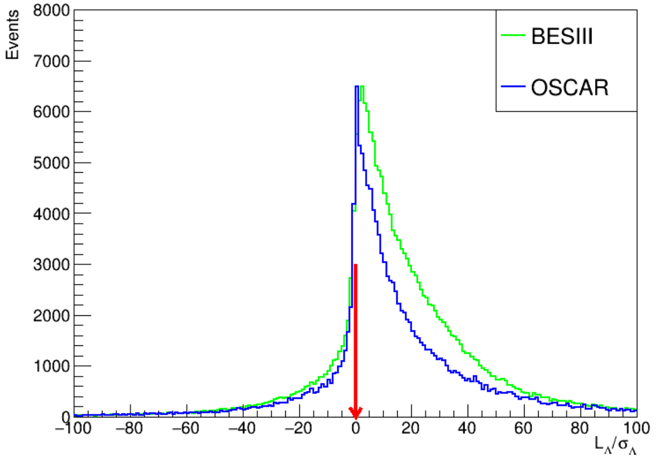
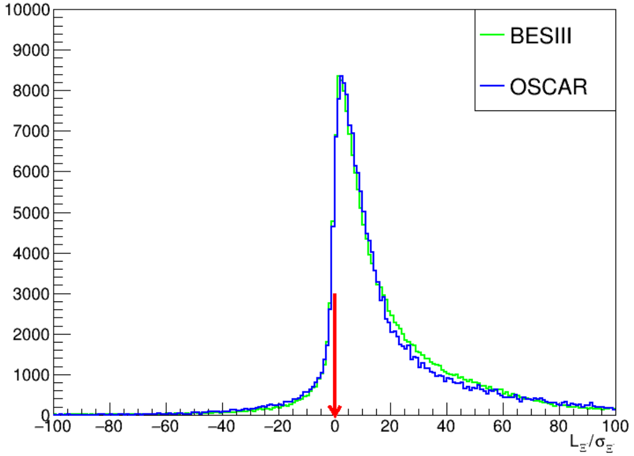
➢ DT Event Selection











Double tag analysis

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- Cut flow

Selection Criteria	OSCAR			BESIII		
	Absolute Efficiency(%) signal	Relative Efficiency(%) signal	Absolute Efficiency(%) dominant bkg	Absolute Efficiency(%) signal	Relative Efficiency(%) signal	Absolute Efficiency(%) dominant bkg
After DT Vertex fit	19.26	49.05	21.83	13.58	49.80	15.69
veto dominant bkg	15.77	81.88	5.02	11.99	88.29	2.97
$\frac{L_\Lambda}{\sigma_{L_\Lambda}} > 0$	12.64	80.15	2.14	9.98	83.24	2.39
$\frac{L_{\Xi^-}}{\sigma_{L_{\Xi^-}}} > 0$	9.59	75.87	1.01	8.60	86.17	1.26
χ^2<20	8.92	93.01	0.57	6.77	78.72	0.422
$\lvert M_{p^+\pi^-} - M_\Lambda^{\mathrm{PDG}}\rvert < 6MeV$	8.55	95.85	0.42	6.50	96.01	0.417

OSCAR : $\frac{S}{\sqrt{S+B}} \approx 27.10$

BESIII : $\frac{S}{\sqrt{S+B}} \approx 1.12$

Summary

- This work is now ready to study at the STCF under the OSCAR framework.
- Efficiency and signal-to-noise ratio have both been improved compared to BESIII. However, it is hoped that in future research and exploration, we can further improve this.
- Understanding the reasons for the deviations in the central values and the asymmetry in the distribution of the numerous reconstructed mass spectra, and exploring the next steps for resolution and improvement.

Thanks!