Search for invisible decay of K_S^0

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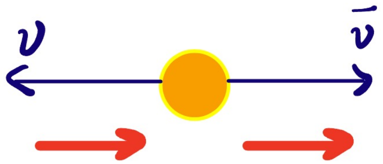
Oct 14, Wuhan (Online)

Outline

- Motivation
- Analysis strategy
- Data sets
- Event selection
- Background analysis
- Summary

SM prediction

- In SM, the rate of neutral mesons $K_S^0, K_L^0 \to \bar{\nu}\nu$ decays is predicted to be extremely small, because it's forbidden kinematically by angular momentum conservation.
- $\Gamma(M^0 \to \nu\bar{\nu}) \sim (\frac{m_\nu}{m_{M^0}})^2 \leq 10^{-16}$ PRD 91, 015004 (2015)
- Any observation of K_S^0 →invisible would signal the presence of new physics.



$K_S^0 \to \nu\bar{\nu}$

Initial state: $\vec{S} = 0$

Final state: $\vec{S} = \pm 1$

forbidden

Experimental limits

- $\Gamma_{K_L(K_S)} = \sum_i \Gamma_i(K_L(K_S) \to visible) + K_L(K_S) \to invisible$

Sum of all the possible modes of K_S^0 based on PDG

→ $\sum_i \mathrm{Br}_i(K_S \to \text{visible}) = 1.00068 \pm 0.00048$ → $\mathrm{Br}(K_S \to \text{invisible}) < 1.1 \times 10^{-4}$ (95% C.L.),

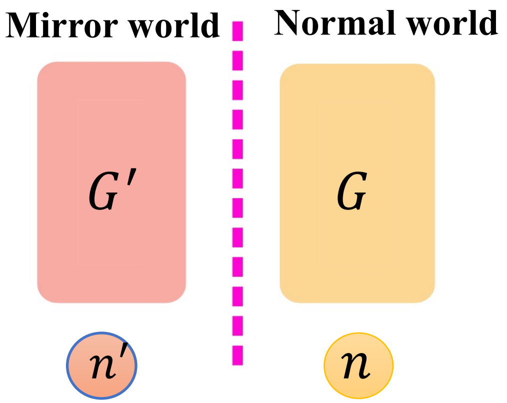
PRD 91, 015004 (2015)

Motivation

Why search K_S^0 →invisible?

Theoretical limits

arXiv:2006.10746



- **Mirror matter model** (M^3 model), assuming that there exists an almost exact mirrored copy (n') of the known ordinary particles (n) , n' can not be detected, and they can only interact with each other gravitationally.
- Consider a gauge symmetry G ⊗ G′ for the two worlds, we assume that the mirror symmetry M(G↔ G′) is spontaneously broken by the Higgs vacuum. n − n′ oscillations

➢ Invisible decay rate:

$$B_{\text{inv}} = \frac{1}{2}\sin^2(2\theta)\frac{(\Delta\tau)^2}{1+(\Delta\tau)^2}.$$

- Long lived hadrons can have relative large branching fractions, which are detectable at existing accelerator facilities

$Br(K_S^0$ →invisible)= 1.8×10^{-6}

But no direct measurement for K_S^0 → invisible decay yet!

Neutral hadrons	K_L^0	K_S^0	π^0
Life time(s)	5.12×10^{-8}	8.96×10^{-11}	8.52×10^{-17}
$\mathcal{B}_{inv}$	9.9×10^{-6}	**1.8×10^{-6}**	6×10^{-18}

Data sets

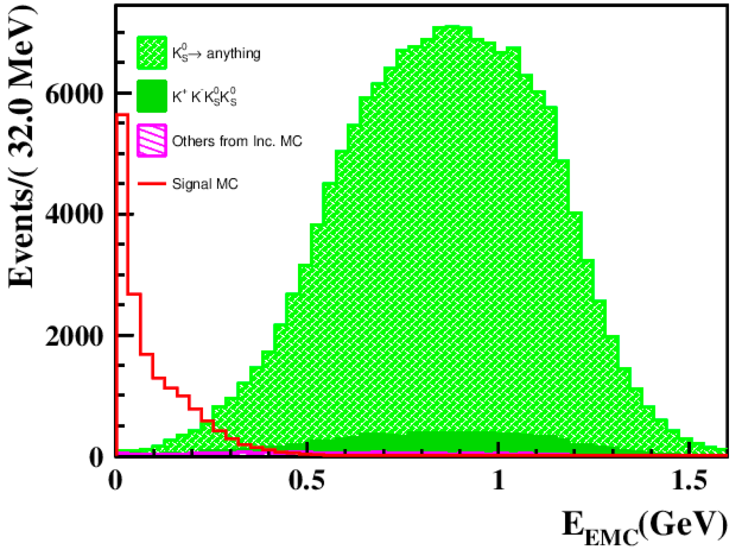
- **Boss version**: 708
- **Inclusive MC:** 10B J/ψ inclusive MC
  - Understand the potential backgrounds
  - Optimize the event selection criteria.
- **Signal MC**:
  - 600K $J/\psi \to \phi K_S^0 K_S^0, K_S^0 \to invisible$
  - Obtain the detection efficiency
- **Blind analysis**
  - Avoid analyst bias towards the physical result
  - Use MC simulation samples to determine event selection criteria.

  Open 10% of the data to verify consistency with MC samples.

  Once the analysis strategy is finalized, open all the data

- **Semi-blind data**
  - 30% data @2009
  - 10% data @2012, 2018, 2019

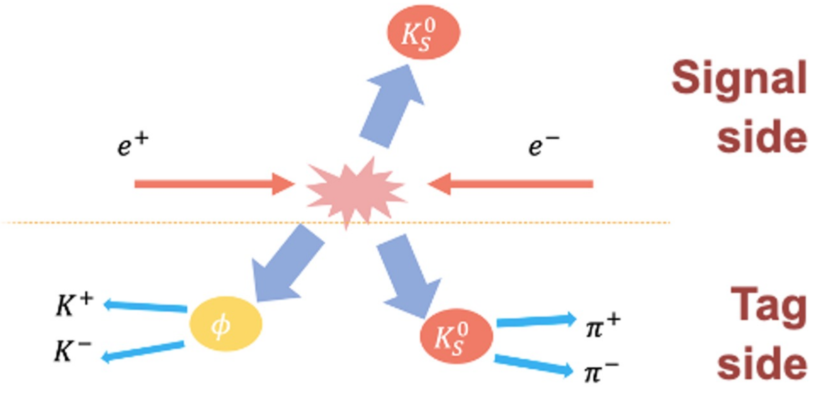
Blind analysis result



Analysis strategy

➢ Analysis strategy

- Using $J/\psi \to \phi K_S^0 K_S^0$ as tag mode
- $K_S^0 \to invisible$ is searched in the system recoil against ϕK_S^0



➢ Tag mode:

$$\Rightarrow J/\psi \to \phi K_S^0 K_S^0, \phi \to K^+K^-, K_S^0 \to \pi^+\pi^-, K_S^0 \to anything(100\%)$$

$$N_{tag} = N_{J/\psi} \times \mathcal{B}(J/\psi \to \phi K_S^0 K_S^0) \times \mathcal{B}_{inter} \times \varepsilon^{tag}$$

$$\mathcal{B}_{\text{inter}} = \mathcal{B}(\mathrm{K_S^0} \to \pi^+\pi^-) \times \mathcal{B}(\phi \to \mathrm{K^+K^-}) = 0.34$$

➢ Signal mode:

$$\Rightarrow J/\psi \to \phi K_S^0 K_S^0, \phi \to K^+K^-, K_S^0 \to \pi^+\pi^-, K_S^0 \to \text{inv}$$

$$N_{sig} = N_{J/\psi} \times \mathcal{B}(J/\psi \to \phi K_S^0 K_S^0) \times \mathcal{B}_{inter} \times \mathcal{B}(K_S^0 \to inv) \times \varepsilon^{sig}$$

$$\boxed{\mathcal{B}(K_S^0 \to inv) = \frac{N_{sig} \times \varepsilon^{tag}}{N_{tag} \times \varepsilon^{sig}}}$$

- ➢ Potential systematic uncertainty can be canceled
  - ➢ $\mathcal{B}(J/\psi \to \phi K_S^0 K_S^0)$
  - ➢ $N_{J/\psi}$
  - ➢ Intermediate branching fraction
  - ➢ Tracking, PID uncertainty of pion & kaon

Selection of tag side

➢ Good charged tracks

- Loose selection:

  $|\cos\theta| < 0.93$

  $|V_z|$<20cm

  $N^{+}_{loose} \geq 2, N^{-}_{loose} \geq 2$
- Tight selection:

  $|\cos\theta| < 0.93$

  $|V_{xy}| < 1cm; |V_Z| < 10cm$

➢ K PID (TOF +dE/dx)

$L_K > L_\pi$

➢ K_S^0 reconstruction

PID on $\pi^+\pi^-$: $L_\pi > L_K$ &$L_\pi > L_K$

2^{nd} vertex fit :L/σ_L >2

$0.486 < M_{\pi^+\pi^-} < 0.510$ GeV/ c^2

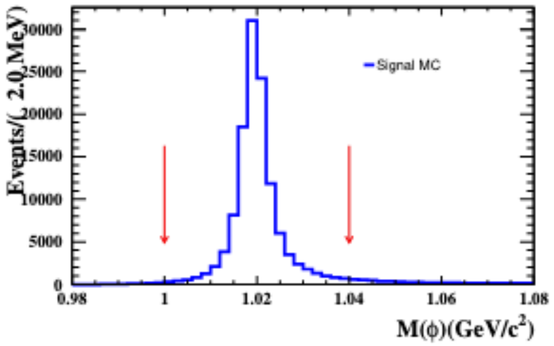
$n_{K_S^0} = 1$

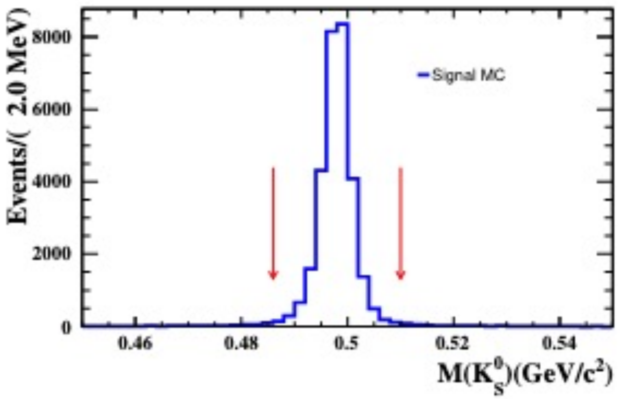
➢ Φ reconstruction

$1.00 < M_{K^+K^-} < 1.04$ GeV/ c^2

➢ Recoil side of the selected ϕK_S^0

$cos\theta_{Recoil} < 0.8$ to ensure the recoiling K_S^0 flies withing the acceptance of detector





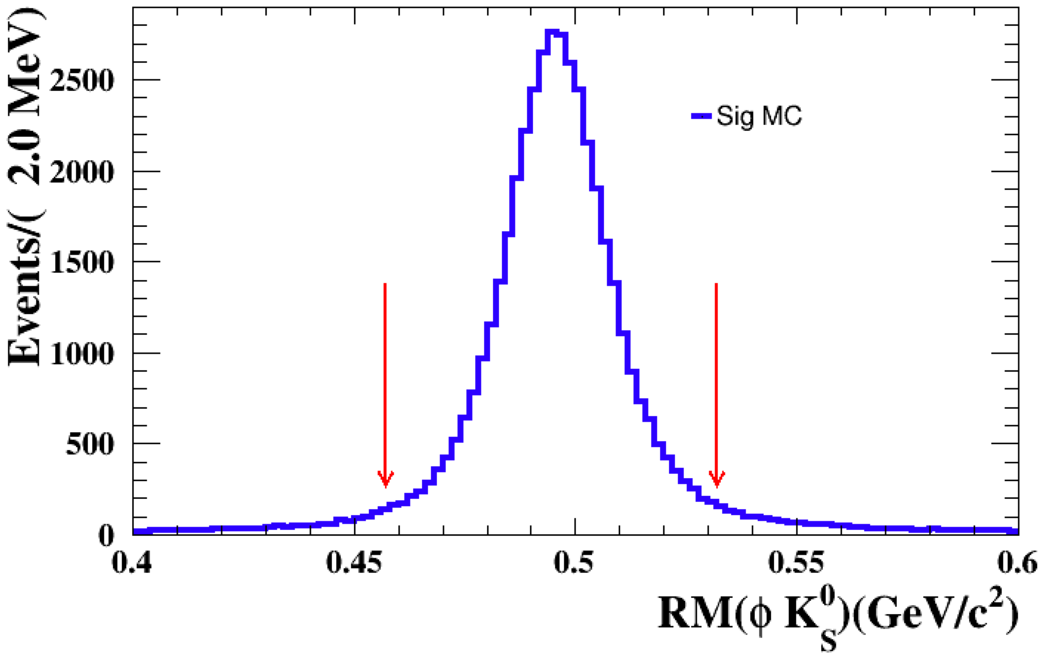
Selection of tag side

➢ Recoil mass of ϕK_S^0 system

$$E_{Recoil} = E_{beam} - E_{\phi} - E_{K_S^0}$$

$$\vec{p}_{recoil} = \vec{p}_{Lab} - \vec{p}_{K_S^0} - \vec{p}_{\phi}$$

$$RM(\phi K_S^0) = \sqrt{E_{recoil}^2 - \vec{p}_{recoil}^{\,2}}$$



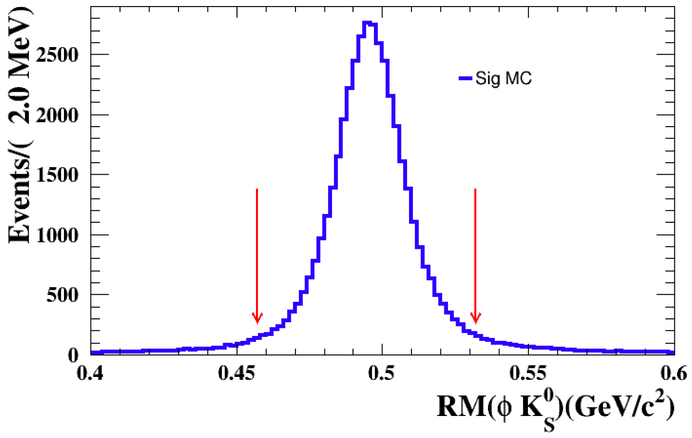
➢We require the recoil mass distribution $RM(\phi K_S^0)$ should within 40 MeV/c^2 around the nominal mass of K_S^0

➢Tag yields are determined through binned maximum likelihood fit

$\Rightarrow$ $N_{tag}{\sim}3{\times}10^4$ is expected for the semi-blind data

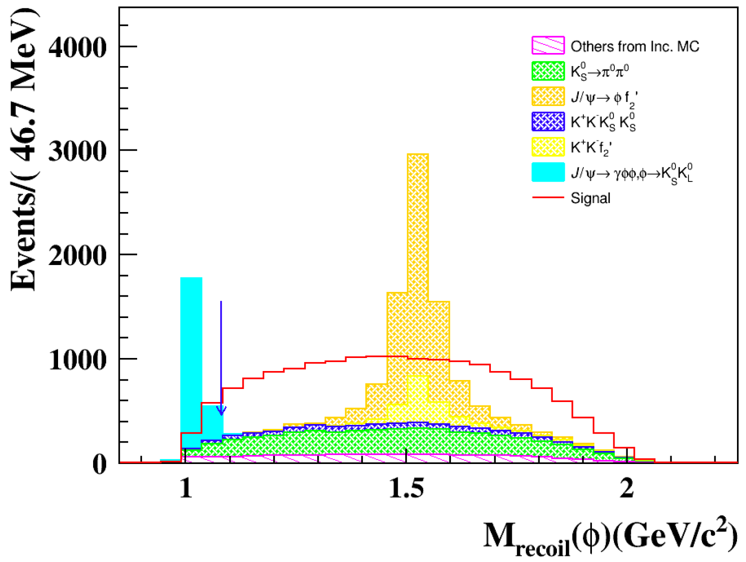
Selection of $K_S^0 \to inv$

- To select the signal candidates of the invisible K_S^0 decays, we further require:
  - ⇒Four charged tracks with net charge equals zero
  - ⇒No other charged track in the candidate events



- To suppress the backgrounds from $J/\psi \to \gamma\phi\phi, \phi \to K^+K^-, \phi \to K_S^0 K_L^0$
  - ⇒We require the recoil mass of ϕ satisfy:

$$M_{recoil}(\phi) > 1.08 \text{ GeV}/\, c^2$$



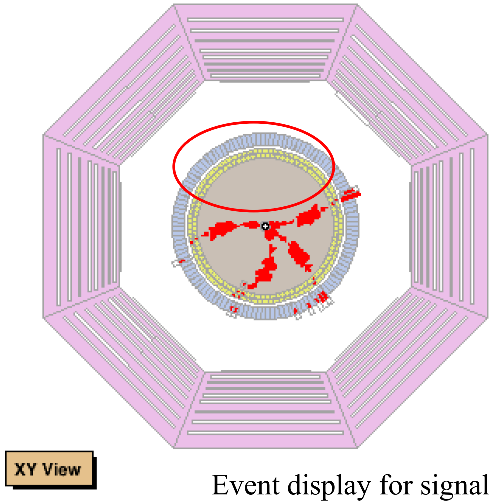
Background study

- Since the invisible K_S^0 decay will not deposit any energy in the EMC, the energy sum of all the showers (E_{EMC}) not associated with any charged tracks, can be used to distinguish signal and background
  - Good shower requirement:

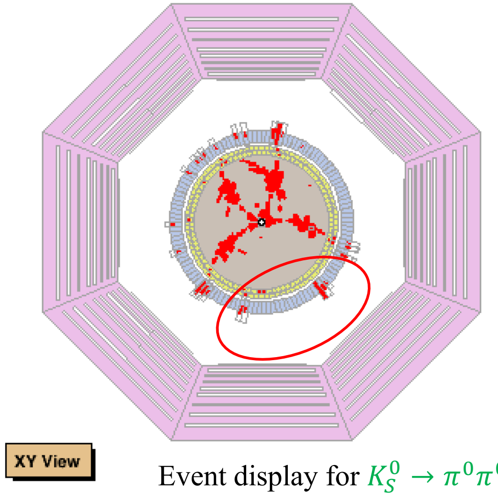
    Isolation angle $\theta > 10^{\circ}$

    $t_{TDC} \in [0, 14](\times 50\ ns)$

- Dominant background
  - ✓ $K_S^0 \to anything$
    - $J/\psi \to \phi K_S^0 K_S^0, K_S^0 \to \pi^0\pi^0$
    - $J/\psi \to \phi f_2', f_2' \to K_S^0 K_S^0, K_S^0 \to \pi^0\pi^0$
    - $J/\psi \to \phi K_S^0 K_S^0, K_S^0 \to \pi^+\pi^-$
  - ✓ Non $-\ \phi$ contribution
    - $J/\psi \to K^+K^-\ K_S^0 K_S^0$
    - $J/\psi \to K^+K^-\ K_S^0 K_L^0$
  - ✓ Continuum contribution
  - ✓ Others backgrounds



Event display for signal MC



Event display for $K_S^0 \to \pi^0\pi^0$

No.	Decay Chain	nEvt
1	$J/\psi \to \phi K_S^0 K_S^0, K_S^0 \to \pi^+\pi^-, \phi \to K^+K^-, K_S^0 \to \pi^0\pi^0,$	86668
2	$J/\psi \to \phi f_2', \phi \to K^+K^-, f_2' \to K_S^0 K_S^0, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^0\pi^0,$	29232
3	$J/\psi \to \phi K^0 \bar{K}^0, \phi \to K^+K^-, K^0 \to K_S^0, \bar{K}^0 \to K_S^0, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^0\pi^0,$	16116
4	$J/\psi \to K^+K^- K_S^0 K_S^0, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^0\pi^0,$	4457
5	$J/\psi \to K^+K^- f_2', f_2' \to K_S^0 K_S^0, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^0\pi^0,$	3270
6	$J/\psi \to \phi f_2(1270), f_2(1270) \to K_S^0 K_S^0, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^0\pi^0,$	643
7	$J/\psi \to \phi f_0(980), \phi \to K^+\bar{K}^-, f_0(980) \to K_S^0 K_S^0, \bar{K}_S \to \pi^+\pi^-, \bar{K}_S \to \pi^0\pi^0,$	634
8	$J/\psi \to \pi^+\pi^-\eta K^+K^-, \eta \to \gamma\gamma,$	62
rest	$J/\psi \to$ others (81 in total)	1834

Background study

Among the $K_S^0 \to anything$ background, $K_S^0 \to \pi^0\pi^0$ is the dominant backgrounds:

➢ Select $K_S^0 \to \pi^0\pi^0$ control samples

- Study the consistency between data and MC shape
- For further systematic uncertainty analysis.

➢ Event selections

✓Charged tracks selection

Same as the nominal analysis

✓Showers selection

Isolation angle $\theta > 10°$

$t_{TDC} \in [0, 14](\times 50\ ns)$

$n_\gamma \geq 2$

✓π^0 reconstruction

$M_{\gamma\gamma} \in [0.115, 0.150]$ GeV/ c^2

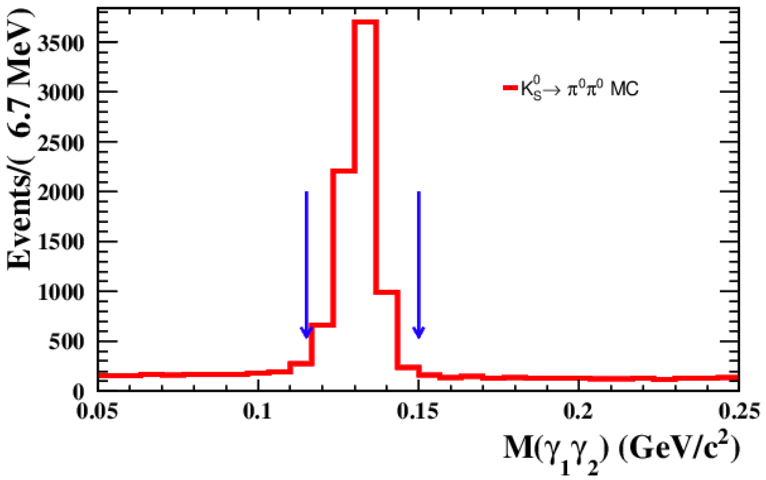
✓1C kinematic fit

Mass constraints on the missing track, $M_{Miss} = M_{\pi^0}$

Energy momentum constraints on $K^+K^-K_S^0\gamma_1\gamma_2\ track_{miss}$

$\chi^2 < 100$

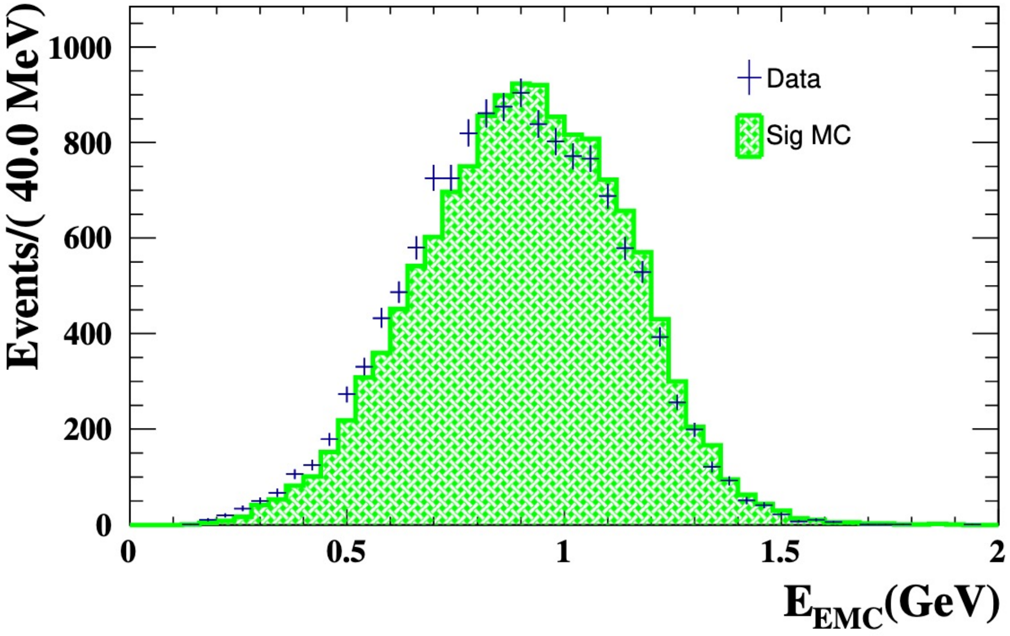
✓Apply with the same veto cuts as the nominal analysis



Background study

- The control sample with high purity is selected (~95.1%)

- The MC shape consistent with data for the control sample

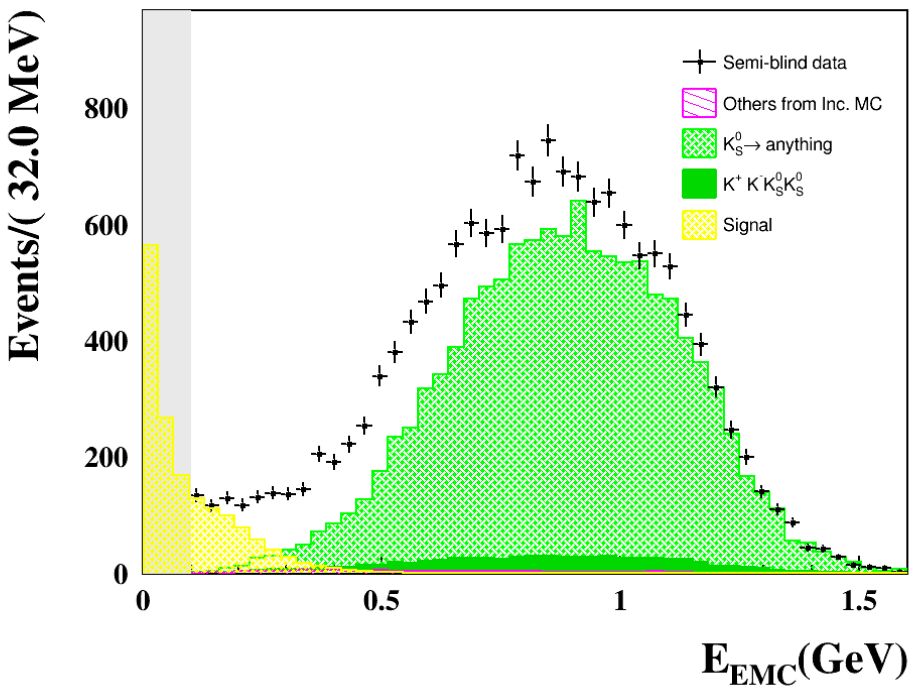


Background study

- The Non$-\phi$ contribution consists of :
  - $J/\psi \to K^+K^-K_S^0K_S^0$
  - $J/\psi \to K^+K^-K_S^0K_L^0$
- At the early stage of the analysis, a discrepancy between the data and MC is observed, particularly for the energy deposited around zero Fake signal?

➠ The components in MC, as listed in the topology, have been normalized with the PDG value

- The event display is used for checking the fake signal
  - 😫 No hint



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3	$J/\psi \to \phi K^0 \bar{K}^0, \phi \to K^+K^-, K^0 \to K_S^0, \bar{K}^0 \to K_S^0, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^0\pi^0,$	16116
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rest	$J/\psi \to$ others (81 in total)	1834

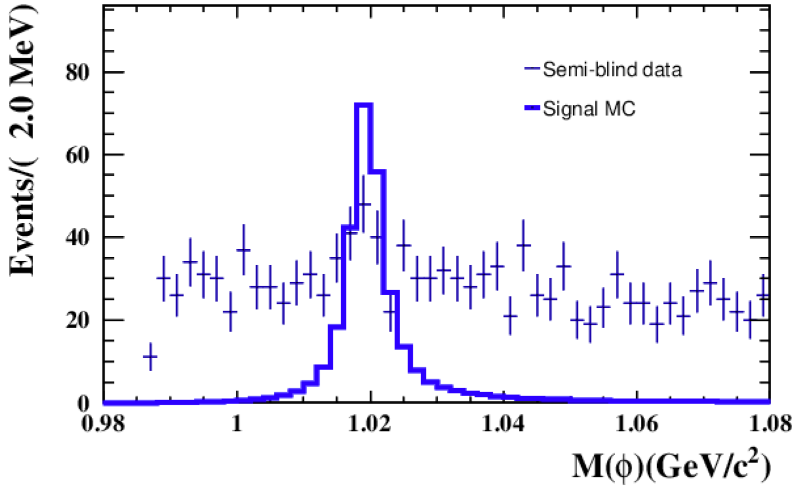
Table 3: The topology results for inclusive MC after the event selections

Background study

$J/\psi \to K^+K^-K_S^0K_L^0$

- However, we do find hint on the fake signal events on the mass distributions of $M(K^+K^-)$!
  - ✓ The peak component seems to have a flat distributions in ϕ signal region
  - $\Rightarrow K^+K^-\ K_S^0 + K_L^0$?

With $E_{EMC} < 0.1$ cuts

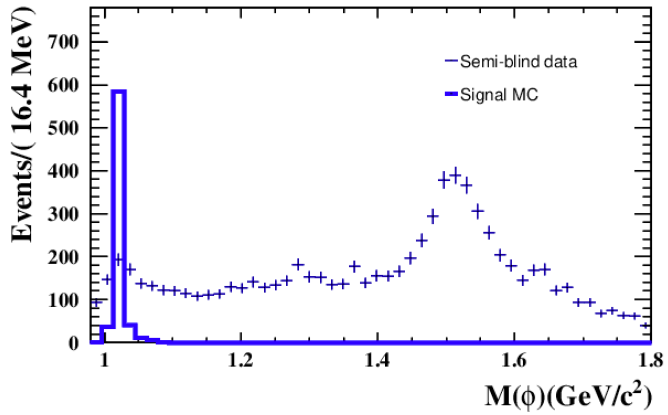


Decay Mode	Branching ratio
$J/\psi \to \pi^+\pi^-K_S^0K_L^0$	$(3.8 \pm 0.6)\times 10^{-3}$
$J/\psi \to \pi^+\pi^-K_S^0K_S^0$	$(1.68 \pm 0.19)\times 10^{-3}$
$J/\psi \to K^+K^-K_S^0K_S^0$	$(4.2 \pm 0.7)\times 10^{-4}$
$J/\psi \to K^+K^-K_S^0K_L^0$	?

$\Rightarrow$ The process $J/\psi \to K^+K^-K_S^0K_L^0$ has not been measured yet

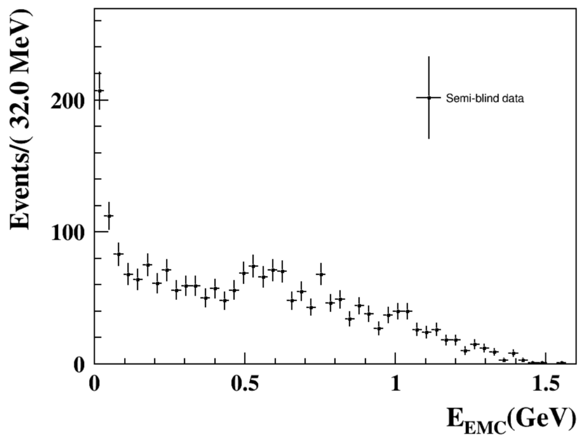
$\Rightarrow$ But we can extrapolate the BF from $J/\psi \to K^+K^-K_S^0K_S^0$, since the $K^0 \to K_S$ $/K_L$ is already known

✓ $\mathcal{B}_{expt}(J/\psi \to K^+K^-K_S^0K_L^0) = (8.4 \pm 1.4)\times 10^{-4}$

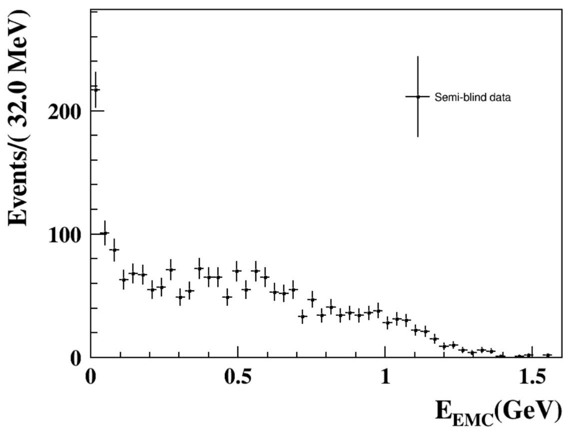


Background study

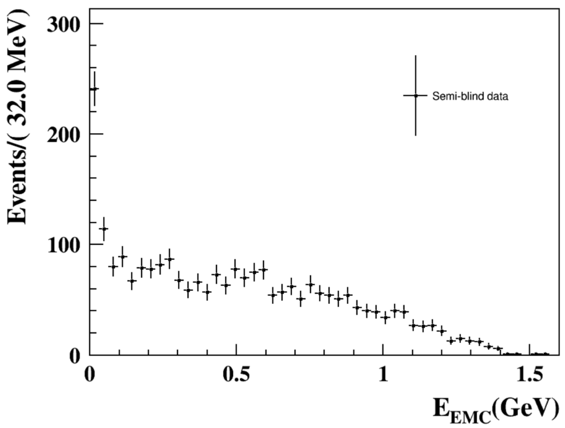
- The contribution from $K^+K^-K_S^0K_L^0$
  - ✓ Can be described by the $\mathrm{E_{EMC}}$ shape of data in the ϕ sideband region
    - ➠ Signal region : $M(K^+K^-) \in [1.0,1.04]\ \mathrm{GeV}/c^2$
    - ➠ Sideband region : $M(K^+K^-) \in [1.1,1.14]\ \mathrm{GeV}/c^2$
  - ✓ The shape of $\mathrm{E_{EMC}}$ remains stable for the alternative choice of sideband region



$M(K^+K^-) \in [1.1,1.14]$ GeV/c2



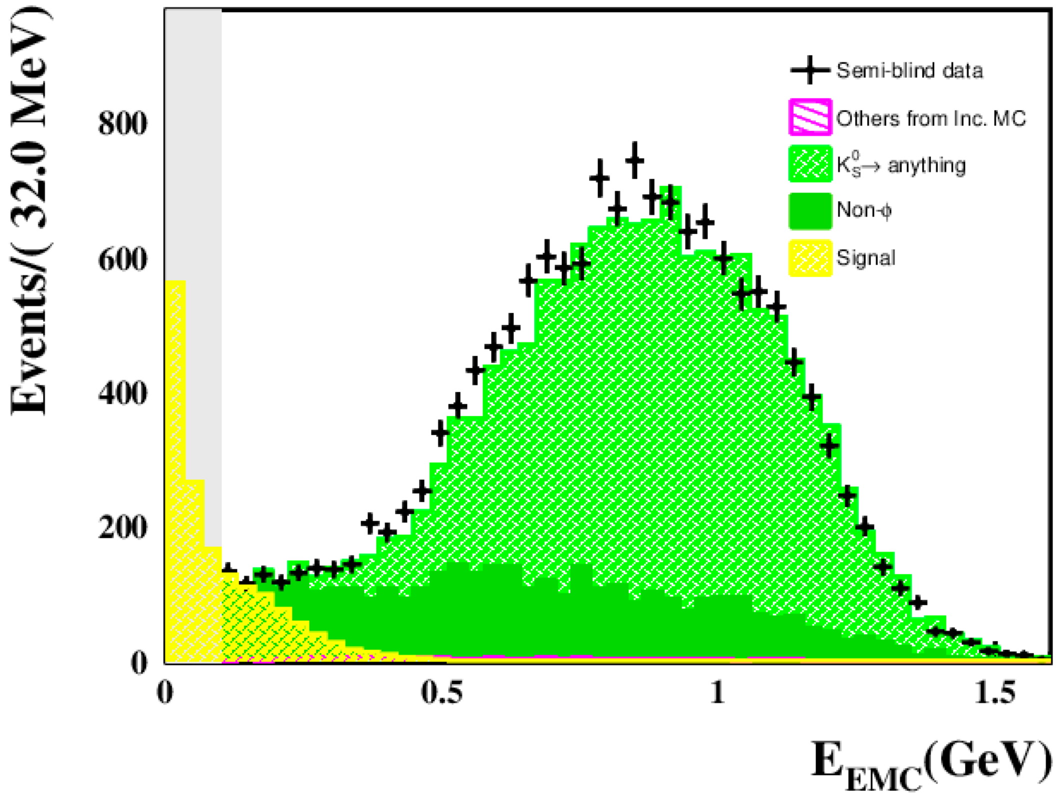
$M(K^+K^-) \in [1.14,1.18]$ GeV/c2



$M(K^+K^-) \in [1.06,1.10]$ GeV/c2

Background study

- Since the invisible K_S^0 decay will not deposit any energy in the EMC, the energy sum of all the showers (E_{EMC}) not associated with any charged tracks, can be used to distinguish signal and background
  - ✓ *Good shower* requirement
- Dominant background
  - ✓ $K_S^0 \rightarrow anything$ Normalized to PDG value
    - J/ψ→ $\phi K_S^0 K_S^0, K_S^0 \rightarrow \pi^0\pi^0$
    - J/ψ → $\phi K_S^0 K_S^0, K_S^0 \rightarrow \pi^+\pi^-$
    - J/ψ→ $\phi f_2', f_2' \rightarrow K_S^0 K_S^0$, $K_S^0 \rightarrow \pi^0\pi^0$
  - ✓ Non − ϕ contribution
    - J/ψ→ $K^+K^-\ K_S^0 K_S^0$ Normalized to PDG value
    - J/ψ→ $K^+K^-\ K_S^0 K_L^0$ ✓ Shape described by sideband region Yields normalized to expected BF
  - ✓ Continuum, estimated by data collected at $\sqrt{s}$=3.080 GeV
  - ✓ Others backgrounds Normalized to luminosity



The consistency is greatly improved

Summary

➢ We have done:

✓ Semi-blind data is opened to check the consistency between data and MC

✓ Control samples $K_S^0 \rightarrow \pi^0\pi^0$ with high purity are selected

✓ The origin of fake signals are studied

✓ The method to describe the fake signals are developed

➢ We will do next:

- ☐ Estimate the systematic uncertainty
- ☐ Estimate the Upper limit of $K_S^0 \rightarrow inv$ (The expected UL $\sim 10^{-4}$ for the semi-blind data)
- ☐ release the memo soon…

Backup

Event display