Tau to (K K pi pi) decay analysis – Reference material

Randall Sobie University of Victoria

Version 1 - January 2026

1 Motivation and review of related work

Section 1: Interest in high-multiplicity (rare) tau decays

TABLE VIII. Summary of branching fractions excluding contributions from $K_S^0 \to \pi^+\pi^-$.

Decay mode	Branching fraction
Resonant decays	
$\tau^- \to 2\pi^-\pi^+\eta\nu_\tau$ (including f_1)	$(2.25 \pm 0.07 \pm 0.12) \times 10^{-4}$
$\tau^- \to 2\pi^-\pi^+\eta\nu_\tau$ (excluding f_1)	$(0.99 \pm 0.09 \pm 0.13) \times 10^{-4}$
$\tau^- \to \pi^-2\pi^0\eta\nu_\tau$ (including f_1)	$(2.01 \pm 0.34 \pm 0.22) \times 10^{-4}$
$\tau^- \to \pi^- f_1\nu_\tau$ via $f_1 \to 2\pi^+2\pi^-$	$(5.20 \pm 0.31 \pm 0.37) \times 10^{-5}$
$\tau^- \to \pi^- f_1\nu_\tau$ via $f_1 \to \pi^+\pi^-\eta$	$(1.26 \pm 0.06 \pm 0.06) \times 10^{-4}$
$\mathcal{B}(f_1 \to 2\pi^+2\pi^-)/\mathcal{B}(f_1 \to \pi\pi\eta)$	$0.28 \pm 0.02 \pm 0.02$
$\tau^- \to 2\pi^-\pi^+\omega\nu_\tau$	$(8.4 \pm 0.4 \pm 0.6) \times 10^{-5}$
$\tau^- \to \pi^-2\pi^0\omega\nu_\tau$	$(7.3 \pm 1.2 \pm 1.2) \times 10^{-5}$
Nonresonant decays	
$\tau^- \to 3\pi^-2\pi^+\nu_\tau$ (excluding ω, f_1)	$(7.68 \pm 0.04 \pm 0.40) \times 10^{-4}$
$\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$ (excluding η, ω, f_1)	$(1.0 \pm 0.8 \pm 3.0) \times 10^{-5}$
$\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$ (excluding η, f_1)	$(16.9 \pm 0.8 \pm 4.3) \times 10^{-5}$
$\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ (excluding η, ω, f_1)	$(3.6 \pm 0.3 \pm 0.9) \times 10^{-5}$
$\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ (excluding η, f_1)	$(1.11 \pm 0.04 \pm 0.09) \times 10^{-4}$
Inclusive decays (including η, ω, f_1)	
$\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$	$(2.07 \pm 0.18 \pm 0.37) \times 10^{-4}$
$\tau^- \to 3\pi^-2\pi^+\nu_\tau$ (excluding ω)	$(8.33 \pm 0.04 \pm 0.43) \times 10^{-4}$
$\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$	$(1.65 \pm 0.05 \pm 0.09) \times 10^{-4}$
η' (958) decays (90% upper level confidence limit)	
$\tau^- \to \pi^-\pi^0\eta'(958)\nu_\tau$	$<1.2 \times 10^{-5}$
$\tau^- \to K^-\eta'(958)\nu_\tau$	$<2.4 \times 10^{-6}$
$\tau^- \to \pi^-\eta'(958)\nu_\tau$	$<4.0 \times 10^{-6}$
Kaonic decays (90% upper level confidence limit)	
$\tau^- \to K^-2\pi^-2\pi^+\nu_\tau$	$<2.4 \times 10^{-6}$
$\tau^- \to K^+3\pi^-\pi^+\nu_\tau$	$<5.0 \times 10^{-6}$
$\tau^- \to K^-K^+2\pi^-\pi^+\nu_\tau$	$<4.5 \times 10^{-7}$
$\tau^- \to K^-2\pi^-2\pi^+\pi^0\nu_\tau$	$<1.9 \times 10^{-6}$
$\tau^- \to K^+3\pi^-\pi^+\pi^0\nu_\tau$	$<8 \times 10^{-7}$

STUDY OF HIGH-MULTIPLICITY THREE-PRONG AND ...

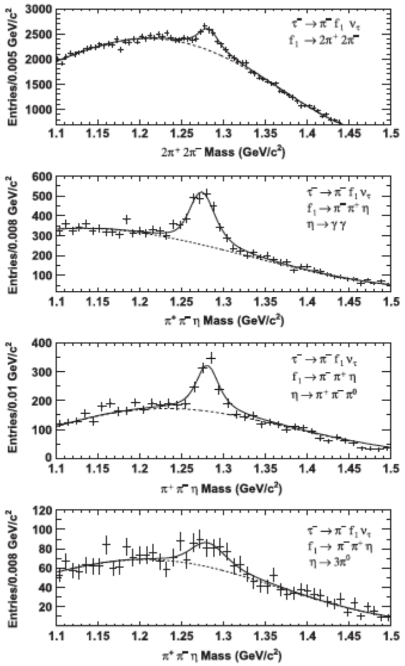


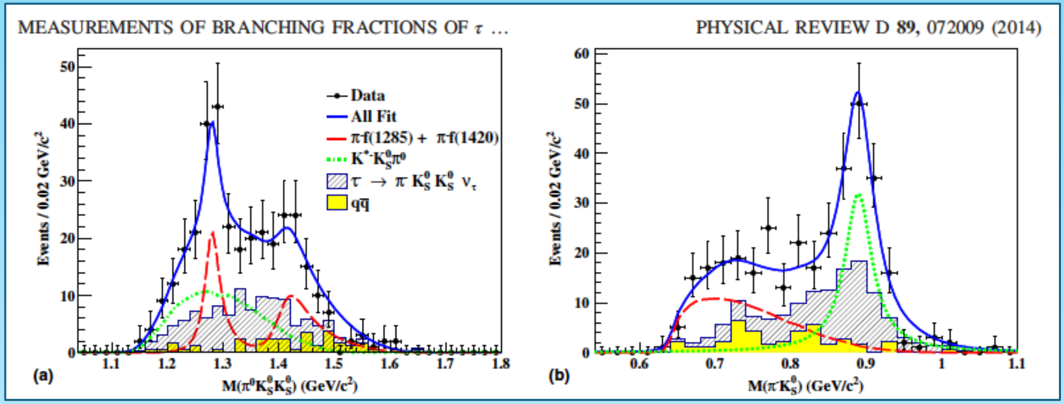
FIG. 2. The $2\pi^+2\pi^-$ and $\pi^+\pi^-\eta$ invariant mass distributions for $\tau^- \to 2\pi^-\pi^+\eta\nu_\tau$ decay candidates after all selection criteria are applied. The lower three plots are for the $\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$, and $\eta \to 3\pi^0$ decays. The solid lines represent the fit to the $f_1(1285)$ peak and background. The dashed lines show the extrapolation of the background function under the f_1 peak.

Study of high-multiplicity three-prong and five-prong tau decays at BABAR

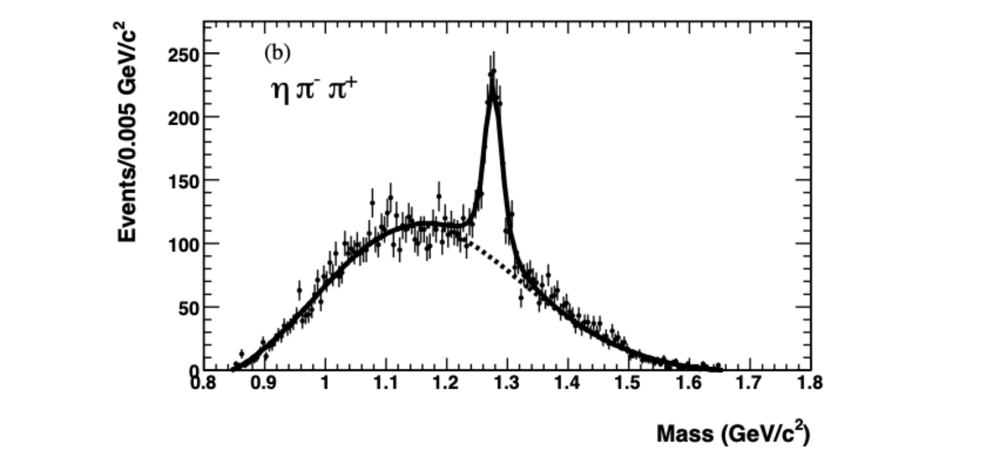
PHYSICAL REVIEW D 86, 092010 (2012)

Section 1: Belle study of the tau decay to (pi- KS KS pi0)

Belle found a signal for the f1(1285) and f1(1420) in tau decays to (pi- KS KS pi0)



Our BaBar analysis of tau decays showed clear evidence of the f1(1285) but not the f1(1420)



$f_1(1285)$ $I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1281.8 \pm 0.5$ MeV (S = 1.7)
Full width $\Gamma = 23.0 \pm 1.1$ MeV (S = 1.6)

$f_1(1285)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
4π	(32.7± 1.8) %	S=1.2	568
$\pi^0\pi^0\pi^+\pi^-$	(21.8± 1.2) %	S=1.2	566
$2\pi^+2\pi^-$	(10.9± 0.6) %	S=1.2	563
$\rho^0\pi^+\pi^-$	(10.9± 0.6) %	S=1.2	336
$\rho^0\rho^0$	seen		†
$4\pi^0$	< 7 × 10^{-4}	CL=90%	568
$\eta\pi^+\pi^-$	(35 ±15) %		479
$\eta\pi\pi$	(52.2± 1.9) %	S=1.2	482
$a_0(980)\pi$ [ignoring $a_0(980) \to K\bar{K}$]	(38 ± 4) %		238
$\eta\pi\pi$ [excluding $a_0(980)\pi$]	(14 ± 4) %		482
$K\bar{K}\pi$	(9.0± 0.4) %	S=1.1	308
$K\bar{K}^*(892)$	not seen		†

$f_1(1420)$ $I^G(J^{PC}) = 0^+(1^{++})$

See the review on "Spectroscopy of Light Meson Resonances."
Mass $m = 1428.4^{+1.5}_{-1.3}$ MeV (S = 1.8)
Full width $\Gamma = 56.7 \pm 3.3$ MeV (S = 1.3)

$f_1(1420)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\bar{K}\pi$	seen	440
$K\bar{K}^*(892)$+ c.c.	seen	167
$\eta\pi\pi$	possibly seen	574
$\phi\gamma$	seen	350

Did we miss the f1(1420)?

The PDG says the (eta pi pi) decay may be seen

Unfortunately, we do not yet have a large enough sample to study the (pi- KS KS pi0) decay.

Section 1: Isospin symmetry says (pi- K0 K0b pi0) = (pi- K+ K- pi0)

CLEO and ALEPH measurements (30% error) and no studies of the decay mechanism

$\Gamma(K^- K^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ **Γ_{107}/Γ**

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.61±0.18 OUR FIT		(Produced by HFLAV)				
0.60±0.18 OUR AVERAGE						
0.55±0.14±0.12		48	ARMS	05	CLE3	7.6 fb^{-1}, E^{ee}_{cm}=10.6 GeV
7.5 ±2.9 ±1.5			BARATE	98	ALEP	1991–1995 LEP runs

B2 should have a sample with a few thousand (pi- K- K+ pi0) decays

Never studied by BaBar or Belle with tau decays

Section 1: Rich, complicated decay structures observed in related measurements

ISR, tau, J/Psi and D-meson decays

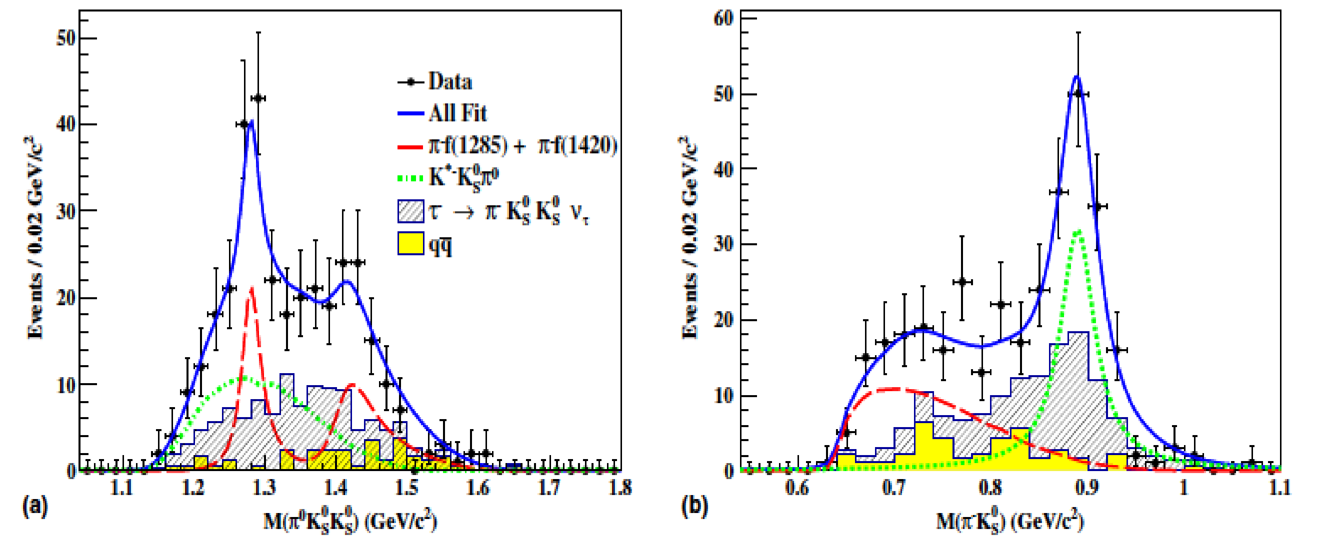
Results are very dependent on the nature of the probe or decay

Belle tau decays with KS-mesons

Observed (pi- f1(1285)), (pi- f1(1420)) and (K*-Ks pi0) final states

Belle found a signal for the f1285 and f1420 in tau decays to (pi- KS KS pi0)

MEASUREMENTS OF BRANCHING FRACTIONS OF τ ... PHYSICAL REVIEW D 89, 072009 (2014)



$$\mathcal{B}(\tau^- \to f_1(1285)\pi^-\nu_\tau)\cdot\mathcal{B}(f_1(1285)\to K_S^0K_S^0\pi^0)$$
$$= (0.68 \pm 0.13 \pm 0.07)\times 10^{-5},$$
$$\mathcal{B}(\tau^- \to f_1(1420)\pi^-\nu_\tau)\cdot\mathcal{B}(f_1(1420)\to K_S^0K_S^0\pi^0)$$
$$= (0.24 \pm 0.05 \pm 0.06)\times 10^{-5},$$
$$\mathcal{B}(\tau^- \to K^{*-}K_S^0\pi^0\nu_\tau)\cdot\mathcal{B}(K^{*-}\to K_S^0\pi^-)$$
$$= (1.08 \pm 0.14 \pm 0.15)\times 10^{-5}.$$

$$m_{f_1(1285)} = 1274 \pm 3\ \mathrm{MeV}/c^2,$$
$$\Gamma_{f_1(1285)} = 20 \pm 4\ \mathrm{MeV}/c^2,$$
$$m_{f_1(1420)} = 1425 \pm 2\ \mathrm{MeV}/c^2,$$
$$\Gamma_{f_1(1420)} = 42 \pm 19\ \mathrm{MeV}/c^2.$$
$$m_{K^{*-}} = 890 \pm 3\ \mathrm{MeV}/c^2,$$
$$\Gamma_{K^{*-}} = 48 \pm 2\ \mathrm{MeV}/c^2.$$

Section1: BES III studied the (KS KS pi0) decay from the J/PSI (Partial Wave Analysis PWA)

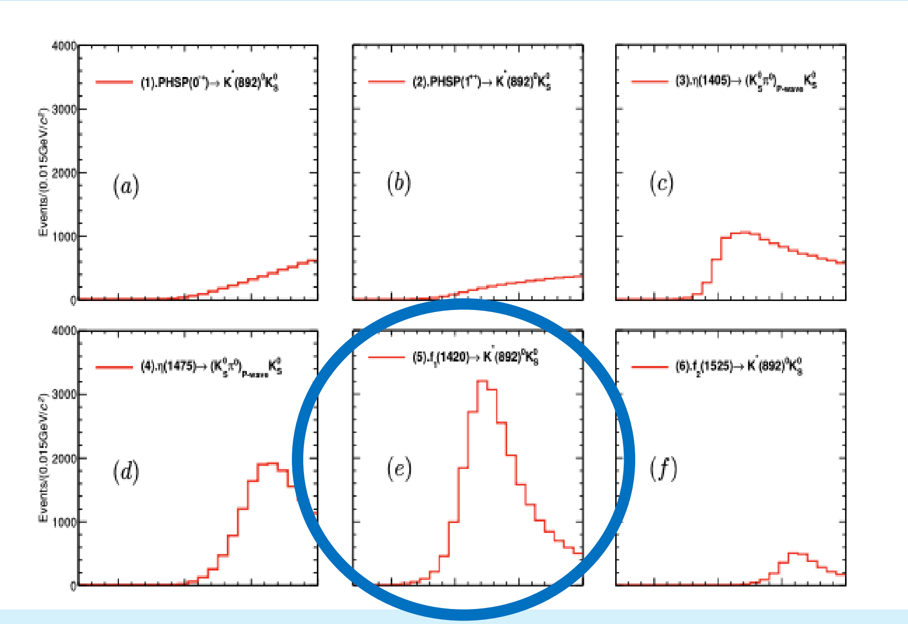
https://doi.org/10.1007/JHEP03(2023)121

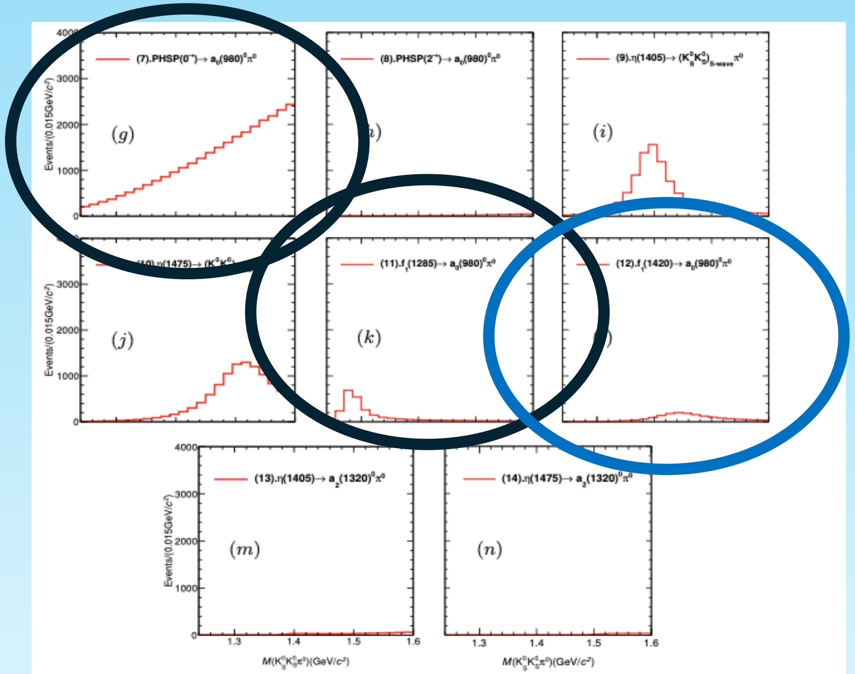
200-300K decays

Simultaneous fit to extract many parameters, of notable interest:

f1285 to the (KS KS pi0) final state via phase space and the (pi- a0(980)) final state

f1420 via (K* KS pi0) and (pi- a0) final state (significantly more (x10) f1420s than f1285s)





e 5. Invariant mass distribution of $K_S^0 K_S^0 \pi^0$ for each of the 14 individual components corre-
ing to table 3 included in the MD PWA nominal solution.

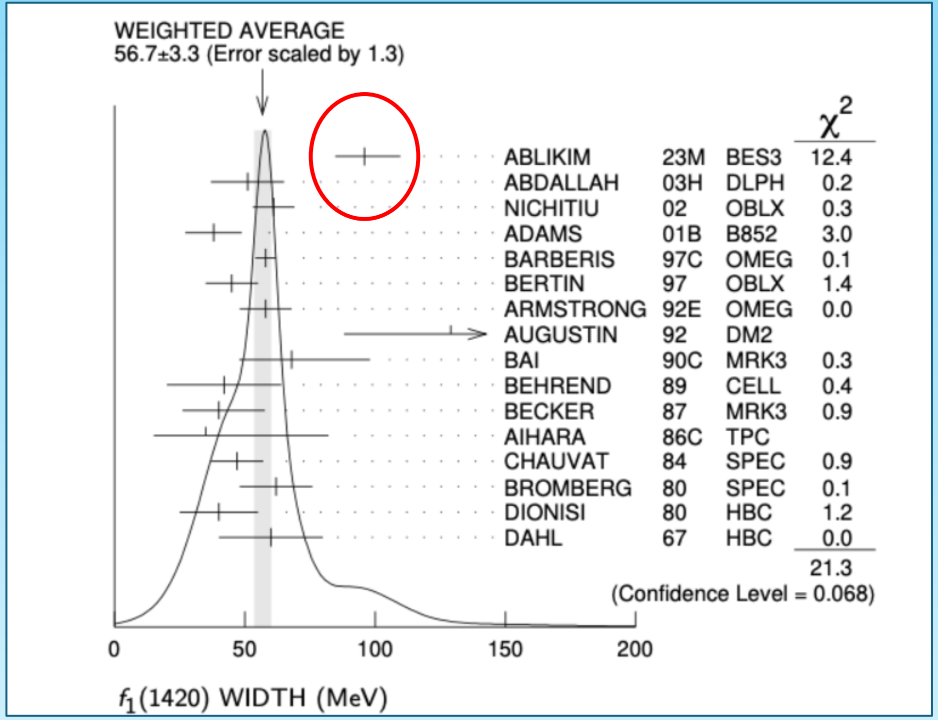
Section 1: BES III sees a much broader width for the f1420

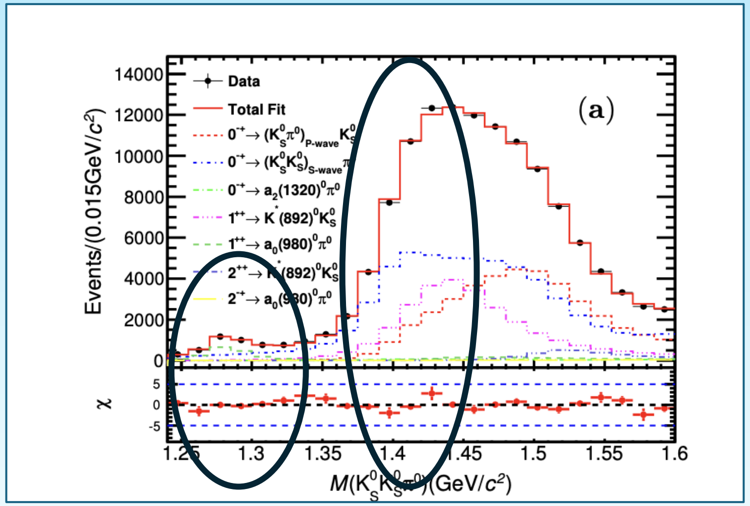
96 MeV vs 57 MeV quoted by the PDG

Belle quote f1420 decay width of (42 +/- 29) MeV

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	Decay Mode	B.F.
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$	$J/\psi \to \gamma\eta(1405) \to \gamma K^0_S(K^0_S\pi^0)_{\text{P-wave}} \to \gamma K^0_S K^0_S \pi^0$	$(5.84 \pm 0.12^{+2.03}_{-3.36}) \times 10^{-5}$
			$J/\psi \to \gamma\eta(1405) \to \gamma(K^0_S K^0_S)_{\text{S-wave}}\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(2.88 \pm 0.04^{+1.64}_{-0.38}) \times 10^{-5}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$	$J/\psi \to \gamma\eta(1475) \to \gamma K^0_S(K^0_S\pi^0)_{\text{P-wave}} \to \gamma K^0_S K^0_S \pi^0$	$(6.58 \pm 0.12^{+3.98}_{-2.82}) \times 10^{-5}$
			$J/\psi \to \gamma\eta(1475) \to \gamma(K^0_S K^0_S)_{\text{S-wave}}\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(3.99 \pm 0.09^{+0.41}_{-0.66}) \times 10^{-5}$
$f_1(1285)$	[illegible]	[illegible]$^{+5.5}_{-2.9}$	$J/\psi \to \gamma f_1(1285) \to \gamma a_0(980)^0\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(8.55 \pm 0.41^{+3.42}_{-1.04}) \times 10^{-6}$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$	$J/\psi \to \gamma f_1(1420) \to \gamma K^*(892)^0 K^0_S \to \gamma K^0_S K^0_S \pi^0$	$(7.25 \pm 0.12^{+0.73}_{-1.25}) \times 10^{-5}$
			$J/\psi \to \gamma f_1(1420) \to \gamma a_0(980)^0\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(4.62 \pm 0.36^{+2.36}_{-1.94}) \times 10^{-6}$
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{[illegible]}$	$J/\psi \to \gamma f_2(1525) \to \gamma K^*(892)^0 K^0_S \to \gamma K^0_S K^0_S \pi^0$	$(9.47 \pm 0.43^{+1.51}_{-0.66}) \times 10^{-6}$

Table 4. Masses (M), widths (Γ), branching fractions (B.F.) and significances (Sig.) of predominant components in the MD PWA solution. The first uncertainties are statistical and the second ones are systematic.





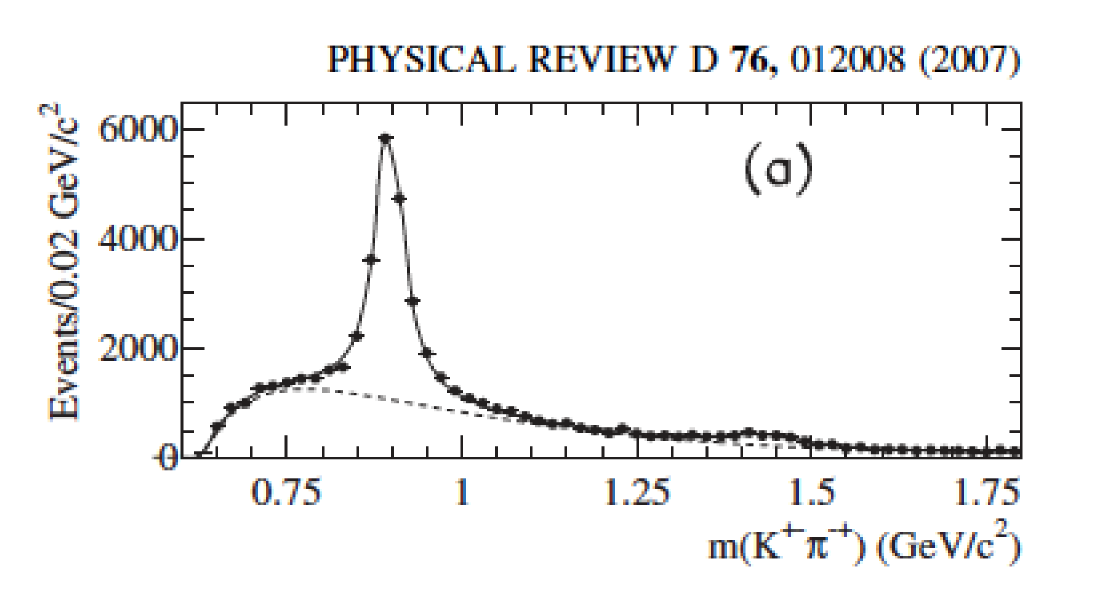
f1285 and f1420

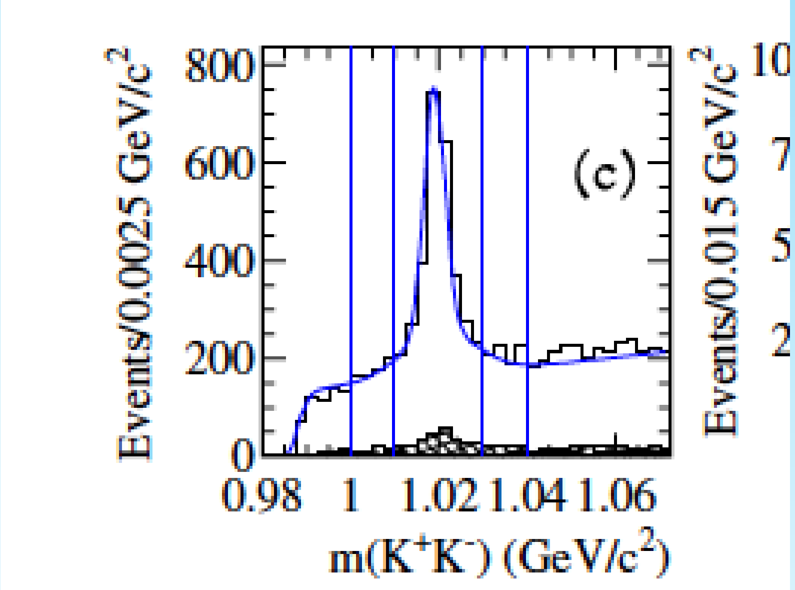
Section 1: BaBar ISR measurement

Able to study the channel to high-mass but the f1 mesons are not an allowed final state
Observe K* and phi-mesons but their reach is to much higher masses

PHYSICAL REVIEW D 76, 012008 (2007)

$e^+e^- \rightarrow K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$ and $K^+K^-K^+K^-$ cross sections measured with initial-state radiation





Section1: Possible tau final states and other measurements

Decay modes:

pi- K- K+ pi0	phase space (PS)	
pi- f1(1285)	f1285 to KKpi0 (via PS or a0)	
pi- f1(1420)	f1420 to KKpi0 (via PS or a0) and K*-K+pi0	
pi- phi pi0	PS (or via some resonance)	
K- K* pi0	K* to (pi- K+)	
pi– K*- K+	K* to (K- pi0)	via (f1420 or PS)
pi- K- K*+	K* to (K+ pi0)	via (f1420 or PS)

f1 properties

f1(1285) mass (width already measured precisely)

f1(1420) mass and BFs

Mixing amplitude of f1s (see discussion on lineshapes)

15 possible measurement plus resonance parameters and phase space contributions

2 Lineshapes (low and high mass thresholds, and interference)

Section 2: Digression into line shapes of the resonances

Note that there is no visible difference between a Breit-Wigner and Relativistic BW in this work

Assume tau decay into a final state (R X nut)

where R is a resonance that decays to a final state of particles R(N) and X are the other particles in the tau decay

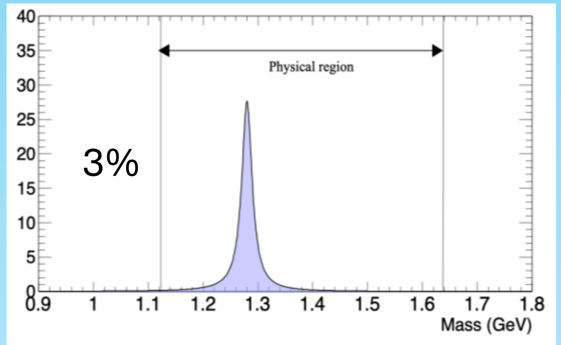
Case 1 – the mass of the R resonance M_R is <u>above</u> the sum of the masses of its decay particles Sum (M_{Ri}) but the tails of the lineshape reach into the unphysical region (well known case with analytical forms for 2-body final states)

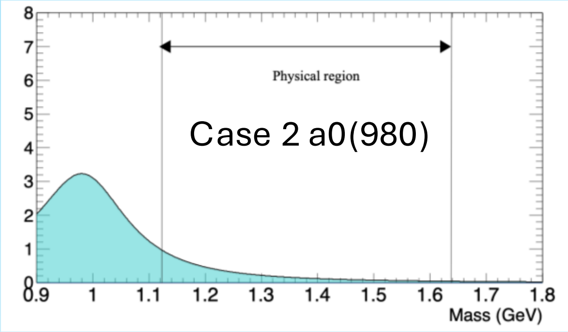
Case 2 – the mass of the R resonance M_R is <u>below</u> the sum of the masses of its decay particles Sum (M_{Ri}) where most of the lineshape lies in the unphysical region

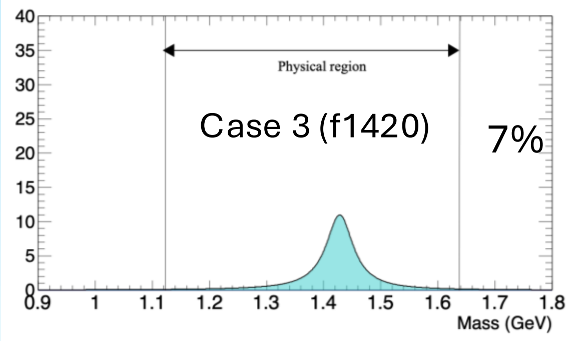
Case 3 – the mass of the R resonance M_R is <u>below</u> the tau mass less the X mass (M_{tau} - M_X) where some of the lineshape lies in the unphysical region

Case 4 – the interference between the f1285 and f1420

Case 1 (f1285)





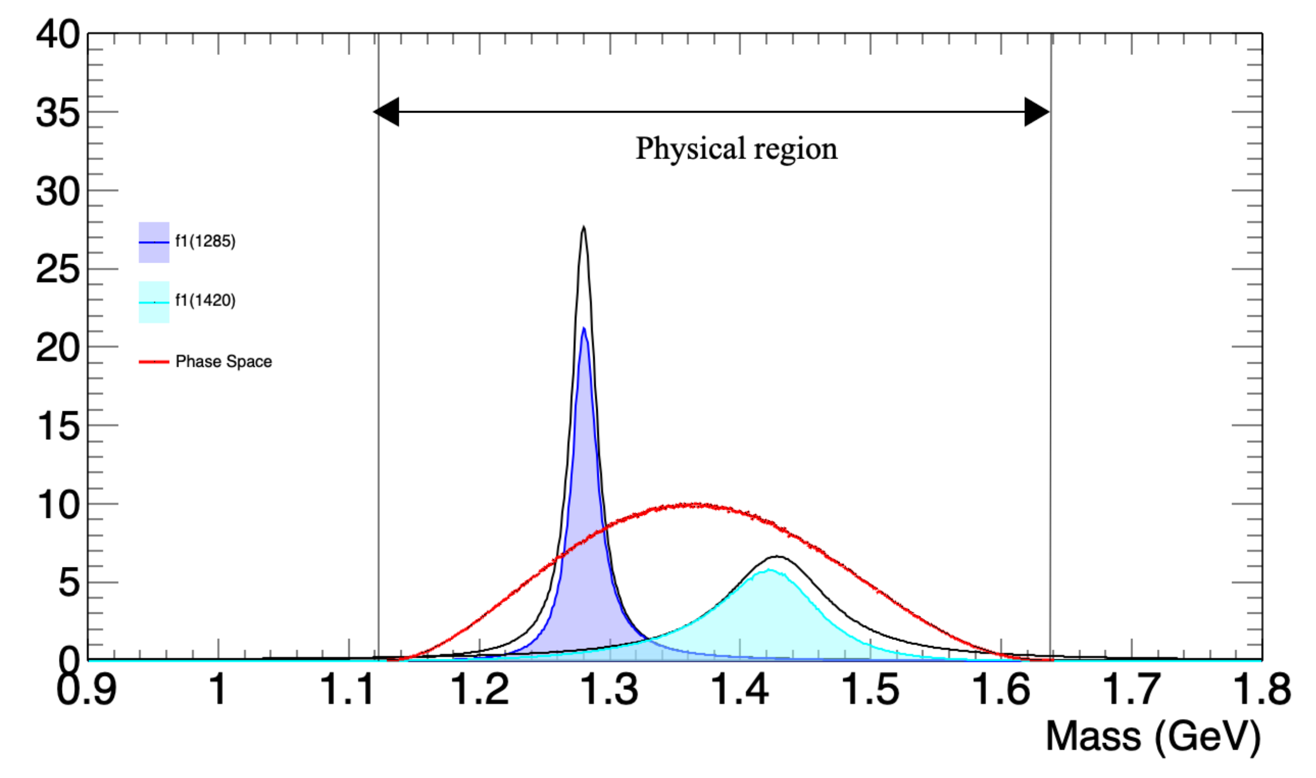


Section 2: Weight the f1285 and f1420 lineshapes by the phase space distribution

Phase space distribution generated using the ROOT function (TPhaseSpace)

Plot show the f1285 and f1420 lineshapes corrected by phase space value

The uncorrected f1285 and f1420 lineshapes are nomalized to unit area



Note that I am using a width of 58 MeV for the f1420 whereas BES-III measured a width of 96 MeV

Section 2: Compare the f1285 PS-corrected distribution with the analytical form

Screen shot from PHYSICAL REVIEW D 107, 112011 (2023)

A. Relativistic Breit-Wigner model

The relativistic Breit-Wigner lineshape function is defined as [1]

$$f_{\mathrm{BW}}(M) = \frac{m_{\mathrm{BW}} M \Gamma(M)}{(M^2 - m_{\mathrm{BW}}^2)^2 + m_{\mathrm{BW}}^2 \Gamma(M)^2}, \quad (3)$$

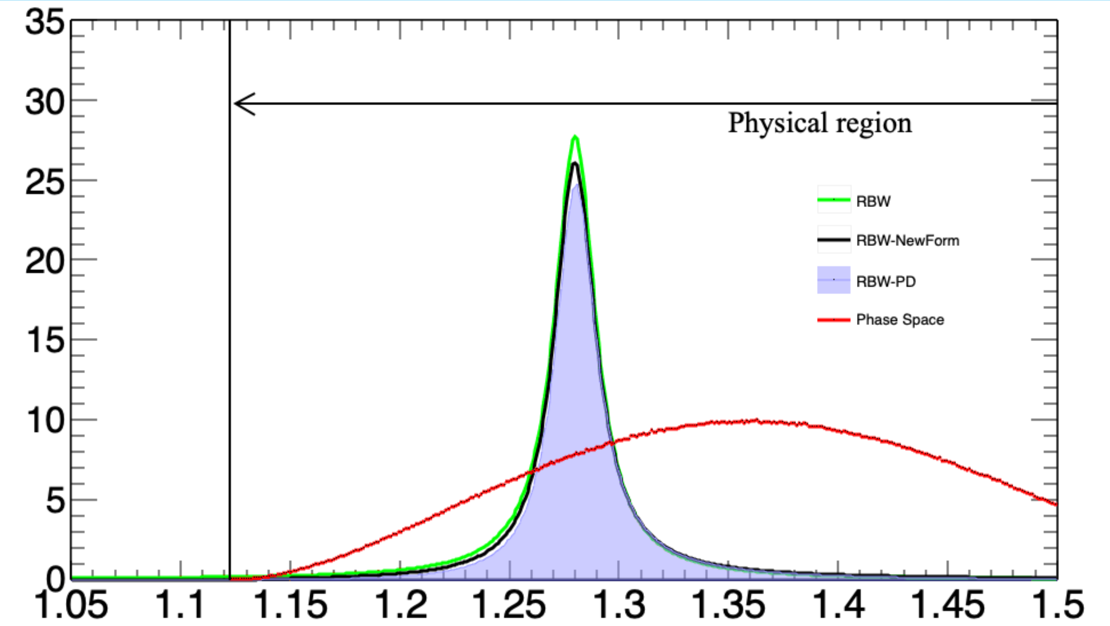
where M is the observed invariant mass, and m_{BW} is the mass of the resonance. The mass-dependent width $\Gamma(M)$ is defined as

$$\Gamma(M) = \Gamma_{\mathrm{BW}} \frac{m_{\mathrm{BW}}}{M} \left(\frac{p(M)}{p(m_{\mathrm{BW}})} \right)^{2L+1}, \quad (4)$$

where Γ_{BW} and L are the width of the resonance and the orbital angular momentum, respectively. Taking account of the closeness to the threshold, the decay is assumed to be pure S-wave ($L = 0$) with no D-wave ($L = 2$) admixture. The momentum of one of the daughters in the rest frame of $X(3872)$, $p(M)$, can be calculated as

$$p(M) = \frac{1}{2M} \sqrt{(M^2 - (m_{D^0} + m_{D^{*0}})^2)} \times \sqrt{(M^2 - (m_{D^0} - m_{D^{*0}})^2)}. \quad (5)$$

Using (Mk + Mk + Mpi) and 0 for difference term

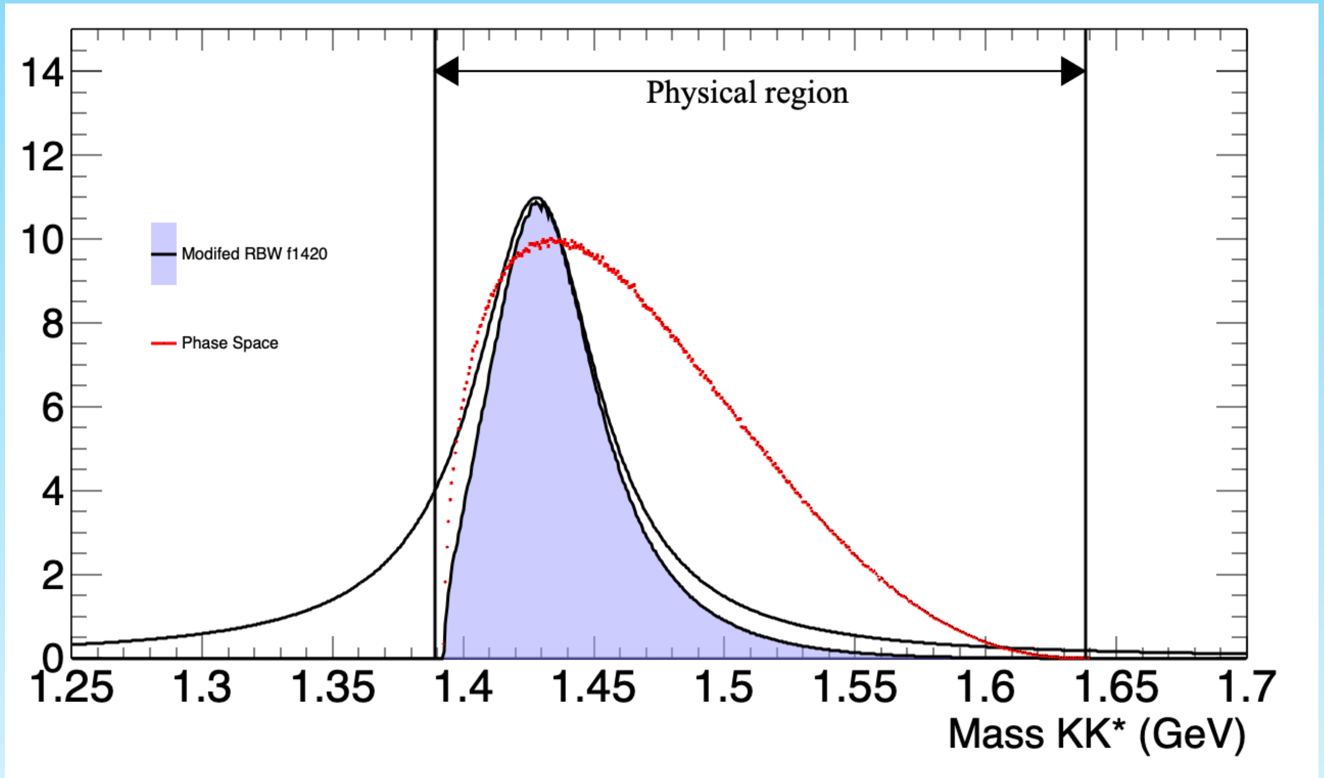


BW-PS and the BW-analytical form are similar

Need to search for analytical lineshape for 3-body decays

Section 2: Both Belle and BES-III say that the f1420 decays to a K*K final state

Plot shows RBW (black line) and RBW-PS (shaded histogram), and phase space (red)

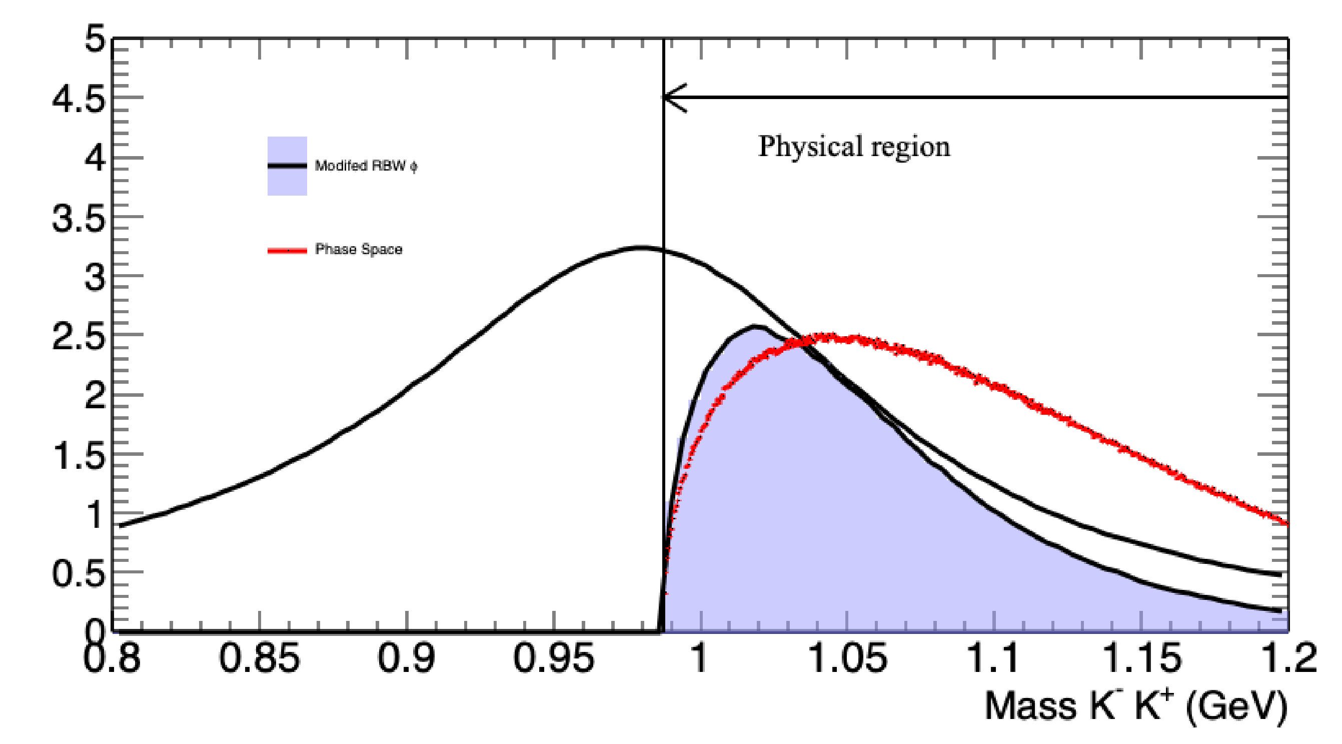


f1420 lineshape is impacted by the low and high mass kinematic limits

Section 2: Weight the a0 (980) lineshapes by the phase space distribution

PDG: a0 M = (980 +/- 20) MeV Width = 50-100 MeV
Using M=980 MeV and W = 75 MeV

Have not found an analytical form when the peak of the resonance is below the mass threshold



The a0 BW looks similar to the phase distribution if the width is higher

Section 2: Interference between the f1285 and f1420 resonances

Similar to what is observed for the rho resonances

On the ambiguity of determination of interfering resonances parameters

https://arxiv.org/pdf/1505.01509

V.M. Malyshev

V.M.Malyshev@inp.nsk.su

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Abstract

The general form of solutions for parameters of interfering Breit-Wigner resonances is found. The number of solutions is determined by the properties of roots of corresponding characteristic equation and does not exceed 2^{N-1}, where N is the number of resonances. For resonances of more complicated form, provided that their amplitudes satisfy certain conditions, for any $N \geq 2$ multiple solutions also exist.

B. Relativistic form of resonance amplitude

Let us consider more accurate dependence of the resonance amplitude on energy:

$$\sigma(E) = \frac{m_1^4 \sqrt{E^2 - 4\mu^2}^3}{E^4 \sqrt{m_1^2 - 4\mu^2}^3} \cdot \left| \frac{2m_1 a}{E^2 - m_1^2 + i\Gamma_1 m_1} + \frac{2m_2 b e^{i\psi}}{E^2 - m_2^2 + i\Gamma_2 m_2} \right|^2$$

Note that the amplitudes that interfere are only for (K- K+ pi0) final state

$$\Gamma_{KK\pi} + \Gamma_{K^*K}$$

$$\Gamma_{KK\pi} = \left| A_{KK\pi}^{1285} + A_{KK\pi}^{1420} \right|^2$$

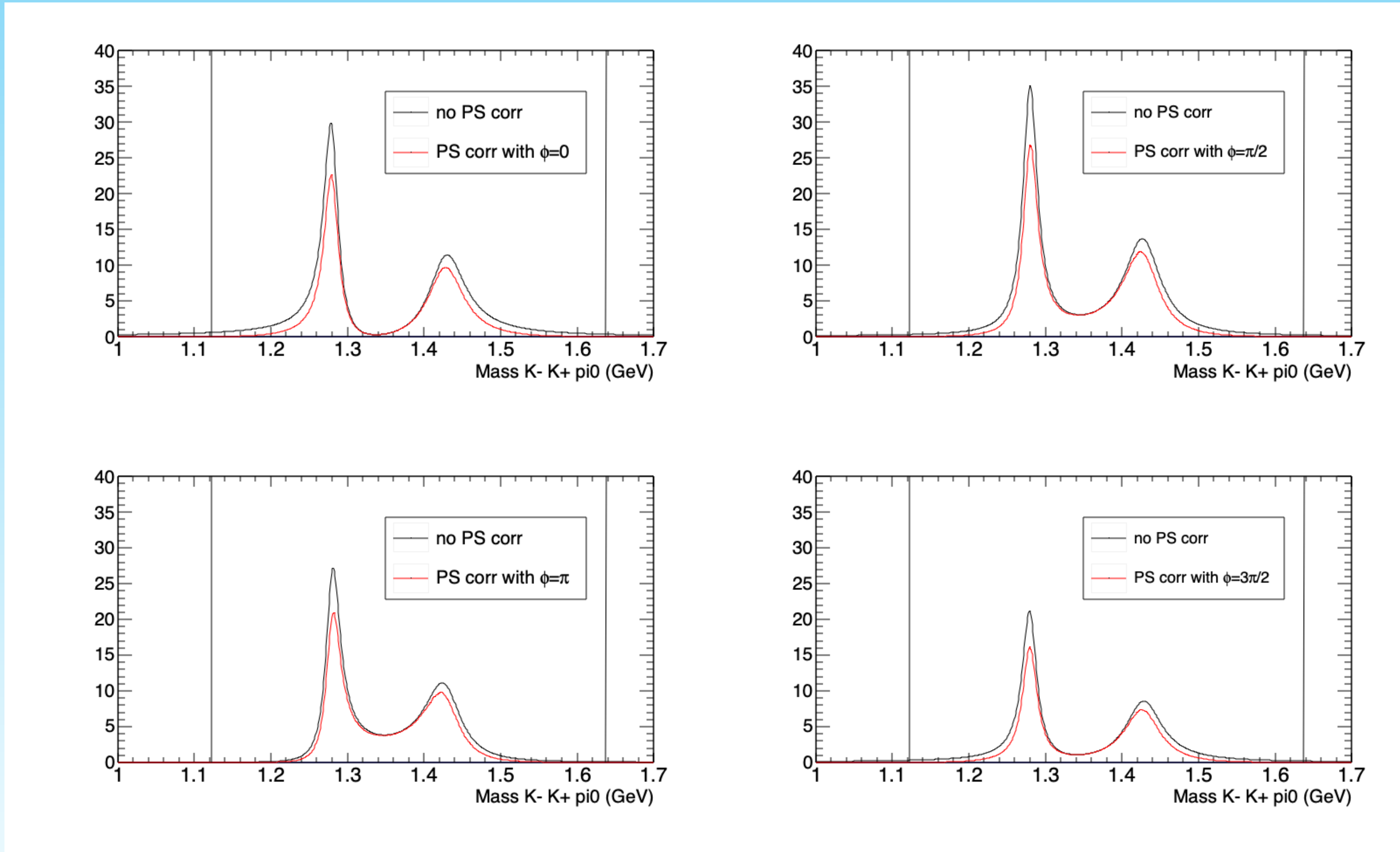
Adds a phase factor between the two amplitudes for the (KKz) decays

Belle did not include a phase angle and assumed the angle was (pi/2).

Section 2: Interference between the f1285 and f1420 resonances

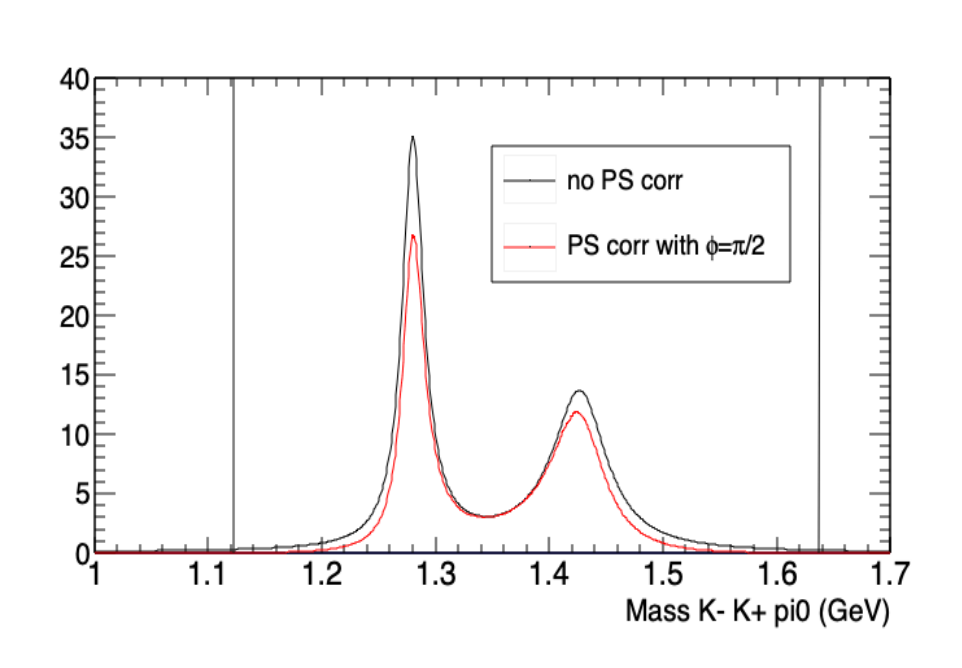
RBW (black) and RBW-PS (red) lineshapes using the PDG masses and widths for 4 phase angles

Using f1420 width of 58 MeV (PDG) BES-III measured f1420 width of 96 MeV

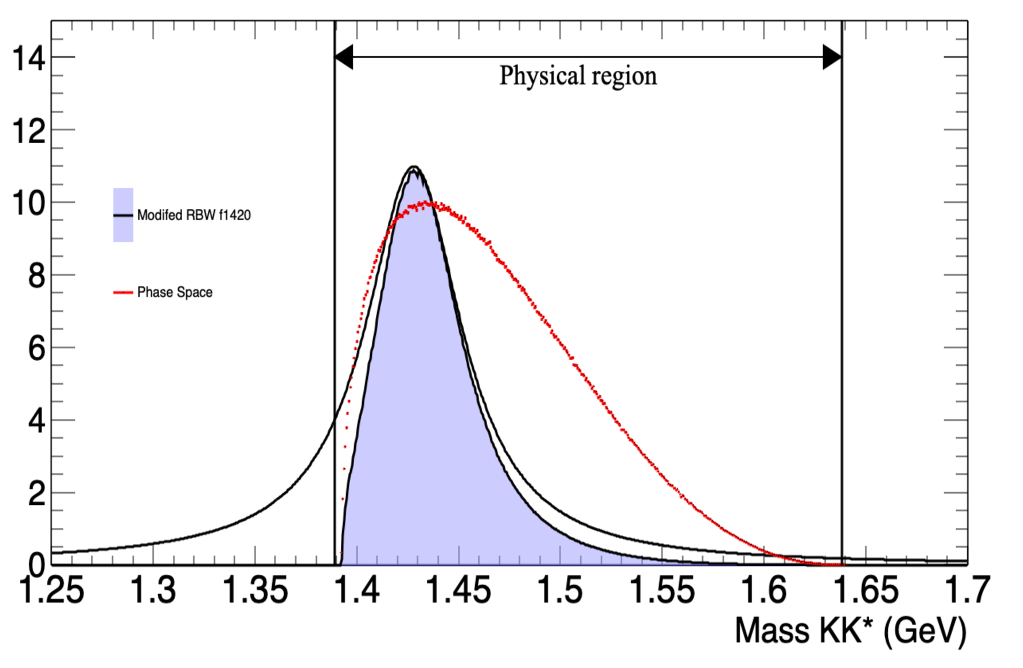


Section 2: Hence the f1 mesons lineshape is

Lineshape ~ | Amplitude_{kkz}(f1258) + Amplitude_{kkz}(f1420)$|^2$ + BW-PS_{KK}(f1420)



+



BES-III also shows a phase space component for both the (KKpi0) and (K*K) final state which would add two more terms to the lineshape

(Assume the PS contributions are negligible until necessary)

BES-III only observed the (K-K+pi0) final state via the (a0 pi0) mode

(The lineshape shown above is for the PS mode; not via the a0)

Unraveling the tau decays to the (pi- K- K+ pi0) final state

Nine mass distributions:
(tau – decay to)

pi- K- K+ pi0
K- K+
K- K+ pi0
pi- K- K+
pi- K+
K- pi0
K+ pi0
pi- pi0
pi- K+ pi0

Background from qqbar and other tau decays validated with control samples
(DONE - later in these slides)

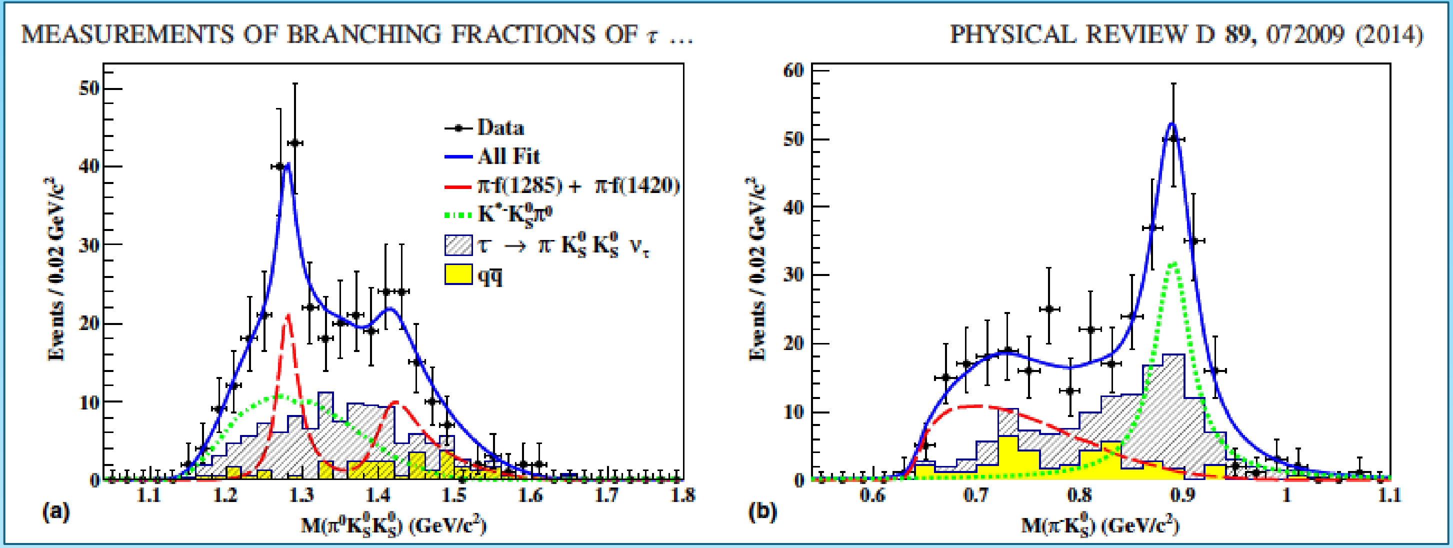
Resonant (peaking) backgrounds validated with control samples
(DONE - later in these slides)

Calibrate resonance shapes with control samples
(Ongoing finished)

Start assuming all decays are from a resonance
Ignore phase space contributions – e.g. tau to (pi- K- K+ pi0 nut)

Resonances: phi, a0(980), f1258, f1420, K*(pi-K+), K*(K+/- pi0)
Not clear whether data will yield results for all resonances

Follow the Belle method to fit the mass distributions



Belle did a simultaneous fit for the f1285, f1420 and K*K

(including contributions of resonances to other mass distributions)

Note for Belle, K* = (pi- K+)

Plan is to include: phi, a0(980) and the K* (pi-K+), (K-pi0), (K+pi0)

Will generate phase space distributions using Pythia (like Belle)

3 Data and MC Samples

Section 3: Data and MC samples I

Data (Int Lum = 568 fb-1 according to gbasf2)

Peak	/belle/collection/Data/S16_proc16_4S_skim_79000100_v2
Scan	/belle/collection/Data/S16_proc16_5S_scan_skim_79000100_v2
Offpeak	/belle/collection/Data/S16_proc16_4S_offres_skim_79000100_v2
Peak prompt	/belle/collection/Data/S16_prompt_4S_skim_79000100_v1
Offpeak prompt	/belle/collection/Data/S16_prompt_4S_offres_skim_79000100_v1

Monte Carlo

udsc	/belle/collection/MC/S16_MC16rd-proc16_4S_udsc_skim_79000100_v2
bb	/belle/collection/MC/S16_MC16rd-proc16_4S_BB_skim_79000100_v2

Monte Carlo (no/few events pass preselection)

llXX	/belle/collection/MC/S16_MC16rd-proc16_4S_llXX_skim_79000100_v2
ee	/belle/collection/MC/S16_MC16rd-proc16_4S_ee_skim_79000100_v2
mumu	/belle/collection/MC/S16_MC16rd-proc16_4S_mumu_skim_79000100_v2

Special note:

Although no ee MC events pass preselection, there is evidence for ee events in the e-tag data

Cuts applied to remove Ptag(CMS) > 4 GeV and in endcap regions when tag hemisphere has an electron track

Section 3: Data and MC samples II

Tau pair Monte Carlo

Peak	/belle/collection/MC/S16_MC16rd-proc16_4S_taupair_skim_79000100_v1
Offpeak	/belle/collection/MC/S16_MC16rd-proc16_4S_offres_taupair_skim_79000100_v1
Scan	/belle/collection/MC/S16_MC16rd-proc16_5S_scan_taupair_skim_79000100_v1

Belle II Tauola decay modes

(mode number from Table 1 BELLE2-NOTE-PH-2020-055)

pi- K- K+ pi0	(mode 23)	Tauola (0.00061)	Phase space decay (CLEO results 30% error)
pi- K- K+	(mode 103)	Tauola (0.001435)	Well understood (K- K*)
K- phi K+K-	(mode 230)	Tauola (0.000023)	Well understood
pi- f1(1285):	eta pi+ pi- (with eta to gg, pi-pi+pi0) and 2pi- 2pi+		Well understood

<u>Not included:</u>

pi- phi	PDG BR (3.4 10-5)
pi- phi pi0	(mode 118)
pi- f1(1285)	PDG BR (f1 to pi- K K) = 11%
pi- f1(1420)	PDG (f1 to pi- K Kb) seen and (f1 to K K*b) seen

Focused on a data-driven analysis (may not need signal MC samples)

No previous studies of (pi- K- K+ pi0) decay mechanism (only BF with 30% error)

Not yet sure what measurements will result (considering relative BF ratios)

Sample of (pi- K- K+ pi0) is okay for topology variables but is not useful for studying the decay mechanism.

4 Grid skim selection and lists

Section 4: Processing of the TauGeneric skim samples

Event requirements:
Standard track, photon*, pi0 lists
2-6 tracks

Tau topology requirements:
Event split into hemispheres based on thrust (total Q in event = 0)
One hemisphere has only 1 track (tag hem)
Signal hemisphere has at least two tracks (with opp Q) with KPID > 0.01 abnd N(pi0) >= 1

Photon requirements:
Following CPV analysis but refined cut to remove fake photons from hadronic interactions
(they used a hard energy cut; smoothed it out but the impact in this work is negligible as Epi0 is high)

E(photons) > 0.08 GeV
(did not need to be so low for this work; developed for the (pi- KS KS pi0) selection)

Also added (recommendation of CHearty)
gammaCuts += ' and abs(clusterTiming/clusterErrorTiming) < 2'

Last processing in September 2025 **See next slide for python-selection code**

Section 4: Grid (my-skim) requirements

```
# track lists
# Sep 10 2025 - CDC hits > 20 (from 0)
trackCuts = 'p<10'
trackCuts += ' and pt>0.1'
trackCuts += ' and nCDCHits>20'
trackCuts += ' and abs(d0)<2'
trackCuts += ' and abs(z0)<4'
ma.fillParticleList(decayString='pi-:allhem',  cut=trackCuts, path=my_path)
ma.fillParticleList(decayString='pi-:hem0',    cut=trackCuts, path=my_path)
ma.fillParticleList(decayString='pi-:hem1',    cut=trackCuts, path=my_path)

# photon lists (updated Jan 22 2024
# Feb 11 2025:  change E from 0.02 back to 0.10 (CPV selection criteria)
# Jun  4 2025:  change to 0.05 from 0.10 (and remove cleanup)
# Jun 19 2025:  energy cut to 0.08 (from 0.05) and restore a modified cleanup cut
# Jun 27 2025: added cut on significance of the cluster timing
gammaCuts = 'E>0.08'
gammaCuts += ' and clusterNHits > 1.5'
gammaCuts += ' and -0.8660 < cosTheta < 0.9563'
gammaCuts += ' and abs(clusterTiming) < 200'
gammaCuts += ' and abs(clusterTiming/clusterErrorTiming) < 2'
ma.fillParticleList(decayString='gamma:allhem',  cut=gammaCuts, path=my_path)
ma.fillParticleList(decayString='gamma:hem0',    cut=gammaCuts, path=my_path)
ma.fillParticleList(decayString='gamma:hem1',    cut=gammaCuts, path=my_path)

# apply cuts to reduce processing time (50% reduction in time) - not needed for tau Kshort skim
event_cuts = "[nParticlesInList(pi-:allhem) > 1]"
ma.applyEventCuts( event_cuts, path=my_path )

# Sep 2025 - added for pi/K NN PID
b2.conditions.prepend_globaltag('pid_nn_release06_Kpi')

# pizeros
reconstructDecay('pi0:allhem -> gamma:allhem gamma:allhem',  '0.119954<M<0.150000', 1,True, my_path)
reconstructDecay('pi0:hem0 -> gamma:allhem gamma:allhem', '0.119954<M<0.150000', 1,True, my_path)
reconstructDecay('pi0:hem1 -> gamma:allhem gamma:allhem', '0.119954<M<0.150000', 1,True, my_path)
```

Require two oppositely charged tracks to have KPID >0.01

E(photon) > 0.08 GeV could be higher as E(pi0) in (kkpz) decays is >0.5 GeV

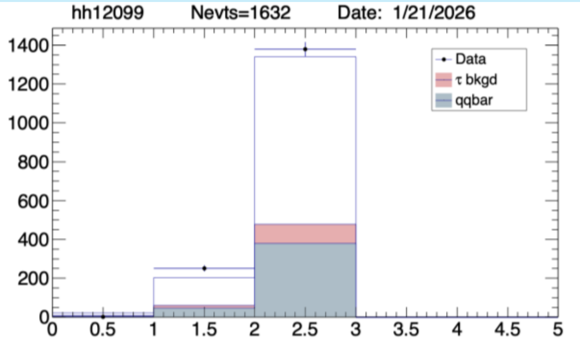
Section 4: Trigger requirements

No trigger requirements applied to data/MC in result shown
(but most data is available)

Previous study (KSKS mode) used:
lml triggers (0,1,2, 4,6,7,8,9,10) OR the hie trigger
(following the 2021 tau mass paper)

BELLE-NOTE-PH-2024-17 used
ECL- and CDC-based triggers
hie, lml0, lml1, lml2, lml4, lml6, lml7, lml8, lml9, lml10, lml12, ffy, fyo, fff and ffo
(need to reprocess the data to get these additional trigger bits)

Results applying KSKS trigger
Observed that
2 data events fail req (0.1%)
8 MC fail trigger req (0.5%)



Histogram shows
0-bin - hie/lml both fail
1-bin – one bit is set
2-bin – both bits set

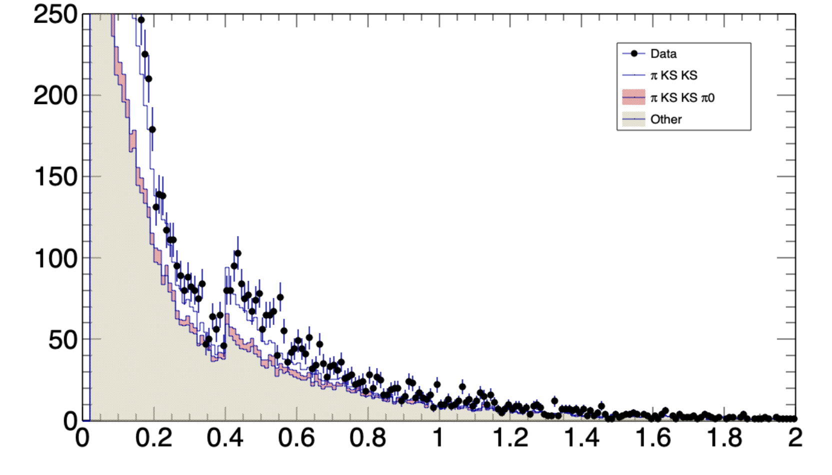
From BELLE-NOTE-PH-2024-17

Name	Base	Definition
hie	ECL	total ECL energy > 1 GeV and no ECL Bhabha veto signal
lml0	ECL	$N_{\text{cluster}} \geq 3$, one with $E_{\text{CM}} > 300$ MeV, $1 < \theta_{\text{id}} < 17 \equiv 12.4° < \theta_{\text{lab}} < 154.7°$, not an ECL Bhabha
lml1	ECL	exactly 1 cluster with $E_{\text{CM}} > 2$ GeV and $4 < \theta_{\text{id}} < 14 \equiv 32.2° < \theta_{\text{lab}} < 124.6°$
lml2	ECL	$N_{\text{cluster}} \geq 1$ with $E_{\text{CM}} > 2$ GeV, $\theta_{\text{id}} = 2, 3, 15$ or 16 $\equiv 18.5° < \theta_{\text{lab}} < 32.2°$ or $124.6° < \theta_{\text{lab}} < 139.3°$ and not an ECL Bhabha
lml4	ECL	$N_{\text{cluster}} \geq 1$ with $E_{\text{CM}} > 2$ GeV, $\theta_{\text{id}} = 1$ or $17 \equiv 12.4° < \theta_{\text{lab}} < 154.7°$ and not an ECL Bhabha
lml6	ECL	exactly one cluster with $E_{\text{CM}} \geq 1$ GeV, $4 \leq \theta_{\text{id}} \leq 15 \equiv 32.2° < \theta_{\text{lab}} < 128.7°$ and no other cluster with $E_{\text{lab}} > 300$ MeV anywhere
lml7	ECL	exactly 1 cluster with $E_{\text{CM}} > 1$ GeV, $\theta_{\text{id}} = 2, 3$ or 16 $\equiv 18.5° < \theta_{\text{lab}} < 31.9°$ or $128.7° < \theta_{\text{lab}} < 139.3°$ and no other cluster with $E_{\text{lab}} > 300$ MeV anywhere
lml8	ECL	two clusters with $170° < \Delta\phi_{\text{CM}} < 190°$ and $E_{\text{CM}} > 250$ MeV and no other cluster with $E_{\text{CM}} \geq 2$ GeV anywhere
lml9	ECL	two clusters with $170° < \Delta\phi_{\text{CM}} < 190°$ and one cluster with $E_{\text{CM}} > 250$ MeV, the other with $E_{\text{CM}} < 250$ MeV and no other cluster with $E_{\text{CM}} \geq 2$ GeV anywhere
lml10	ECL	two clusters with $160° < \Delta\phi_{\text{CM}} < 200°$ and $160° < \sum\theta_{\text{lab}} < 200°$ and no other cluster with $E_{\text{CM}} \geq 2$ GeV anywhere
lml12	ECL	$N_{\text{cluster}} \geq 3$, one with $E_{\text{CM}} \geq 500$ MeV, $2 \leq \theta_{\text{id}} \leq 16 \equiv 18.5° < \theta_{\text{lab}} < 139.3°$, not an ECL Bhabha
ffy	CDC	≥ 2 full tracks and one track reconstructed using a Neural Network
fyo	CDC	1 full track and 1 Neural Network reconstructed track, with $\Delta\phi > 90°$
fff	CDC	≥ 3 full tracks
ffo	CDC	≥ 2 full tracks, with $\Delta\phi > 90°$

TABLE X: ECL and CDC-based trigger bits definition.

Section 4: Requirement on proximity of photons to tracks

KS CPV analysis (2024) rejected photons if MinTrkDistance >40 and E>0.4 GeV

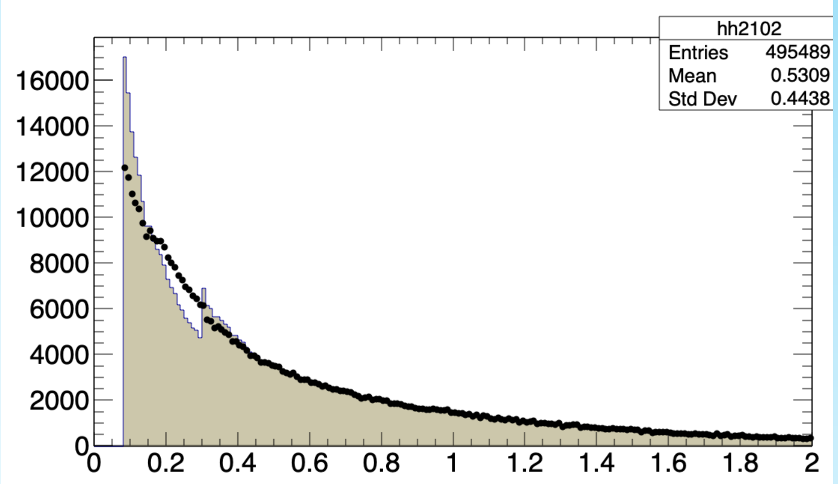


Use an exponential function (4/E) to remove sharp cut

MinTrkDistance > 4.0/Ephoton

No cut applied if Ephoton > 0.5 GeV

Photons are required to have E>0.08 GeV



Requirement developed for (pi- KS KS pi0) analysis and has minimal impact
(but eliminates a sharp cut on an energy variable)

Current selection requires:

Energy (pi0) > 0.4 GeV and the energy of the photons in the pi0 to be (Ehigh>0.2 and Elow>0.1 GeV)

5 Selection Criteria

Section 5: Select topology

Select events with a 1:3 track topology based on the thrust vector
(hence referred as "signal" and "tag" hemispheres)

- Signal hemisphere must have one pi0 — Additional requirements on pi0 applied in second likelihood
- Three tracks in signal-hem must have abs(Q) = 1 — 2 tracks with same charge as tau) and 1 with opposite charge
- General tau event requirements
  - Thrust (0.91 – 0.995)
  - Evisible (4-11) GeV

Section 5: Tag hemisphere requirements

Tag Hemisphere

- Track PID
  If (ePID>0.8 || muPID >0.8) event is considered "lepton-tag" other events are "hadron-tag" (no events rejected)

- Number of photons
  <1 (lepton-tag) <2 (hadron-tag)

- Mass of the track and photons in the tag-hem (lepton-tag) No mass requirement if no photons in tag-hem
  M(tag) < 1 GeV

- Mass of the track and photons in the tag-hem (hadron-tag)
  M(tag) < 1 GeV
  if Nphotons=2, then mass of 2-photons is consistent with a pi0 (adds tau to rho decays to selection)

- Bremsstrahlung photons in electron tag
  Identify photons that have abs(deltaTheta) < 0.02 radians and deltaPhi in (=0.025 to 0.200) radians as **brem-photons**
  Brem-photon excluded from Nphoton
  Energy of brem-photon added to electron when calculating the M(tag)

- Bhahbas in electron tag-hem
  Reject event if tag track is an electron with p(CM) < 3.8 GeV and cosTheta(lLAB)< -0.3 or >0.5
  Bhabha (ee) Monte Carlo does not show the observed excess of events in the above region

Signal Hemisphere

- Kaon track PID

  Require 2 oppositely charged tracks to have KPIDNN > 0.95

  If there are 2 same-charged tracks with KPIDNN, take the one with the highest value

  cos(theta)>0.5 of kaon tracks

- Pion track PID

  The residual track (with same charge as tau) is required to have piPIDNN>0.8

- Mass of the tracks and pi0 in the sig-hem — Use kaon or pion mass as appropriate

  M(kkpz) (1.4 – 1.76) GeV

- Likelihood to separate qqbar from tau events — See following pages

  thrust, Evisible

  Nphotons(sig), Nphotons(tag), Nphotons (sum), Ephoton(extra)

  PT (sig-hadron track), PT (tag-track)

- Likelihood to separate tau decays with a pi0 from tau decays with a fake pi0 — See following pages

  Pi0: mass, energy

  Photon1: energy, E1E1, minCD distance

  Photon2: energy, E1E1, minCD distance

Section 5: qqbar Likelihood selection – lepton tag

Use the samples after the Prelection and the pi0 LH

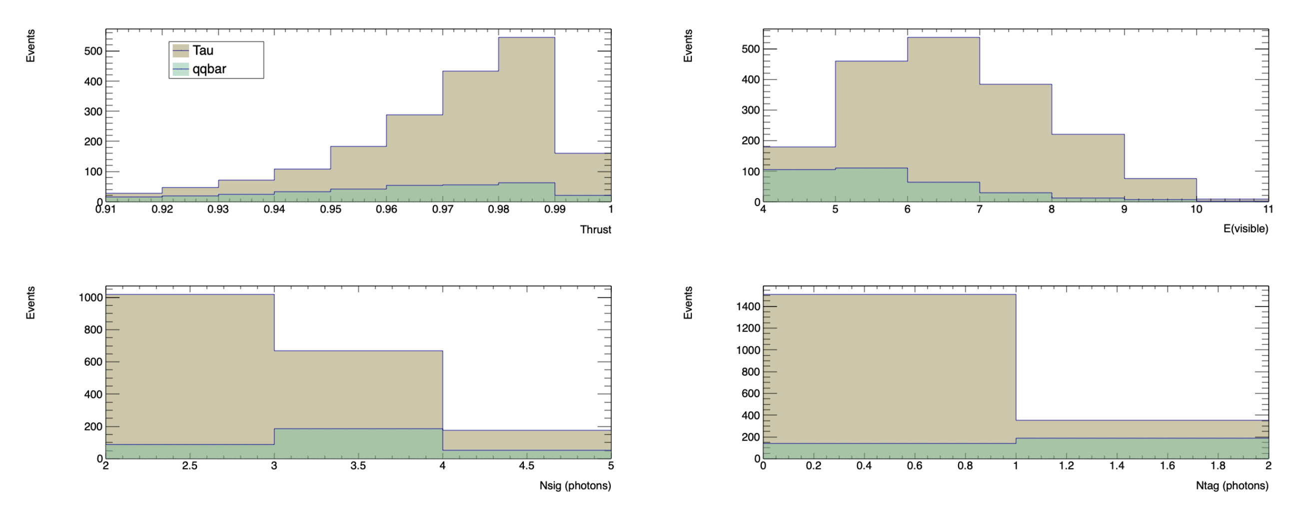
Combine all tau decays into one sample

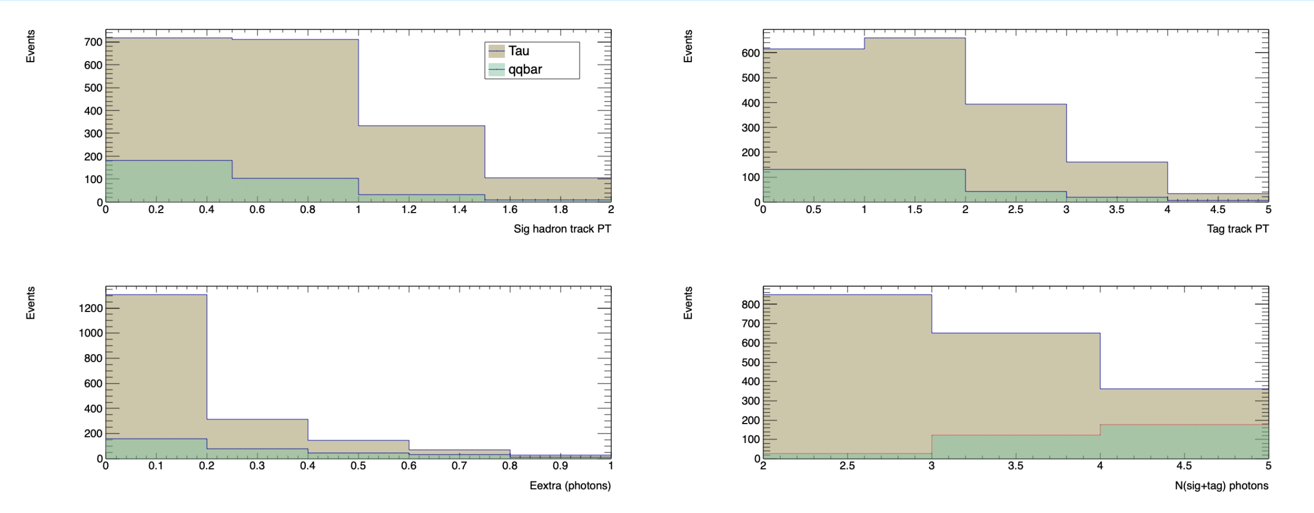
Variables:

thrust, Evisible

Nphotons(sig), Nphotons(tag), Nphotons (sum), Ephoton(extra)

PT (sig-hadron track), PT (tag-track)





For reference:

Probability of variable V having a value v_i for hypothesis H is: $P_V(v_i)$

Probablility of a set of variables having values $\vec{V}$ is: $L_H(\vec{V}) = \prod_i P_{V_i}$

Likelihoold to separate tau decays from qq is: $LH(qq) = \frac{L_{tau}}{L_{tau} + W L_{H_{qq}}}$

Likelihold to separate tau-kkpz decays from other tau decays is: $LH(kkpz) = \frac{L_{tau\text{-}kkpz}}{L_{tau\text{-}kkpz} + W L_{H_{tau\ bkgd}}}$

where *W* is constant factor that can adjust the relative contribution

Section 5: qqbar Likelihood selection – hadron tag

Made a new LH for the hadron-tag sample (different type of qqbar events – no lepton)

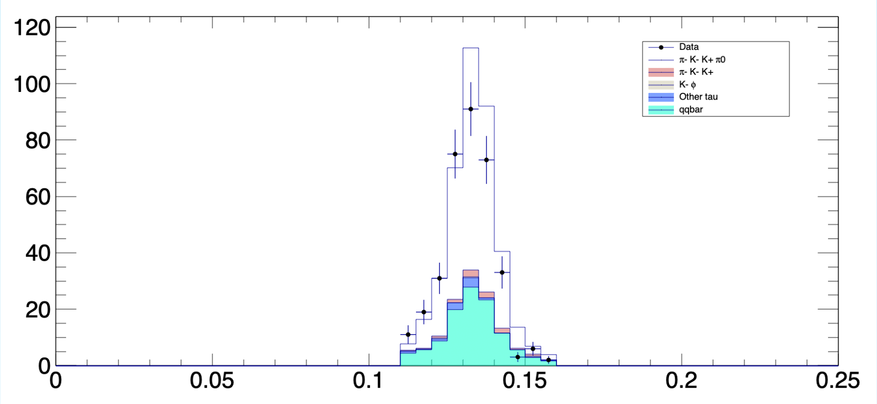
Use the samples after the Prelection and the pi0 LH

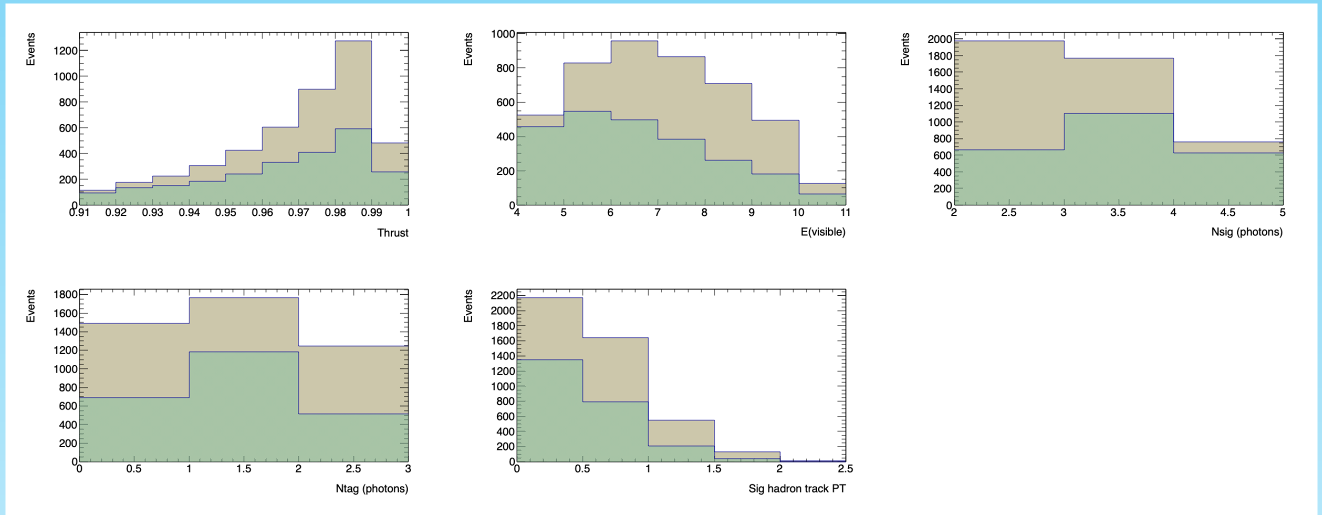
Combine all tau decays into one sample

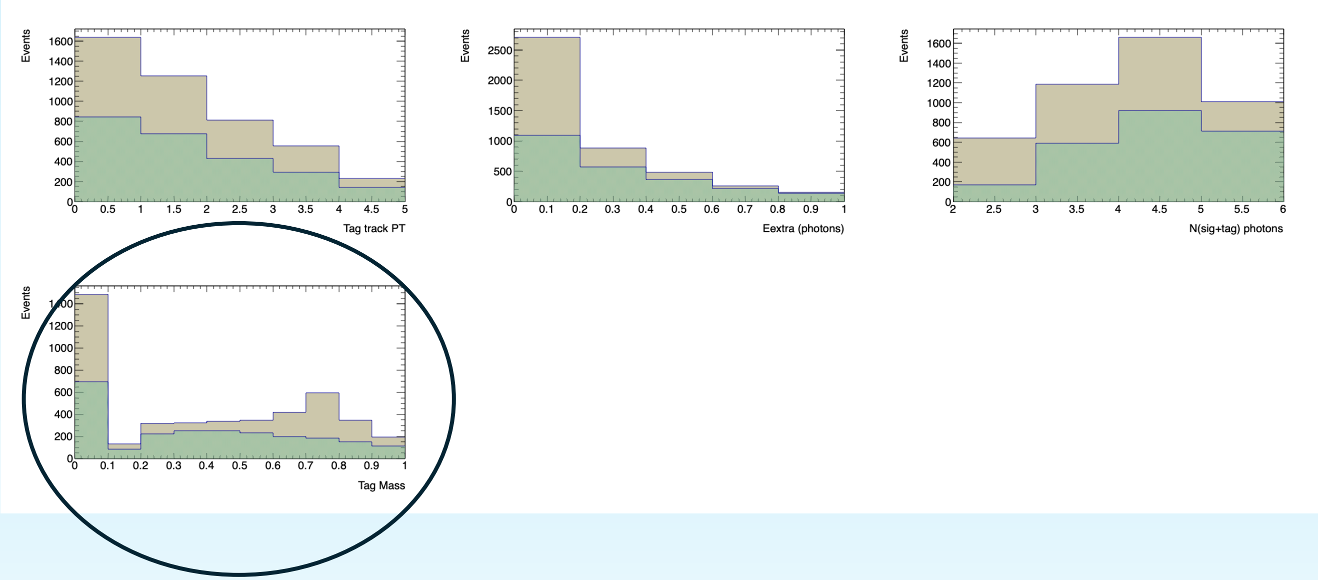
Variables:

thrust, Evisible
Nphotons(sig), Nphotons(tag), Nphotons (sum)
PT (sig-hadron track), PT (tag-track)
Ephoton(extra)
Mass of tag-track and photons in tag hemisphere

Allow hadron-tagged data to have 1 or 2 photons in the tag hemisphere but the mass of the 2 photons must be (0.11-0.16) GeV

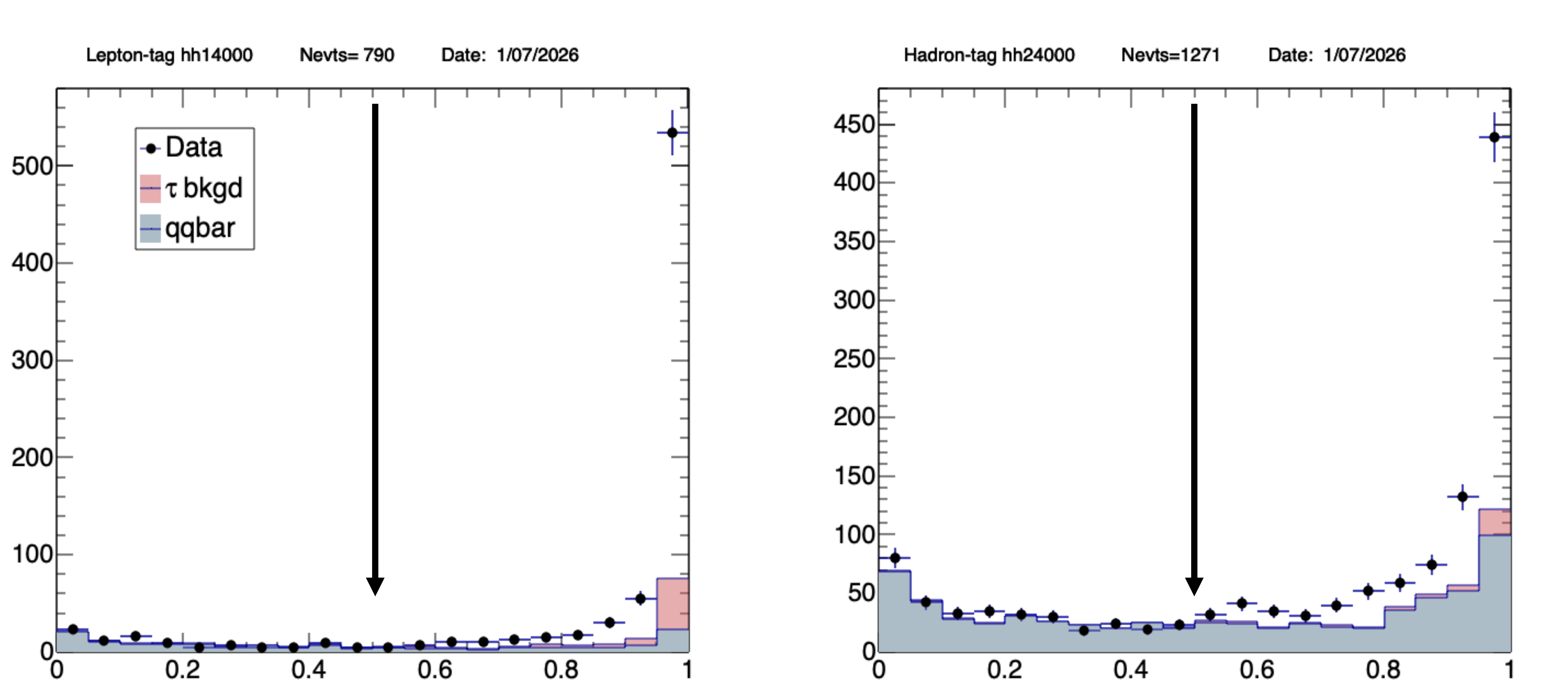






Section 5: qqbar Likelihood selection – lepton and hadron tag

Includes rescaling factor on qqbar and kkp MC samples (in next pages)



Use the samples after the Prelection and the qqLH

Combine all tau decays into one sample

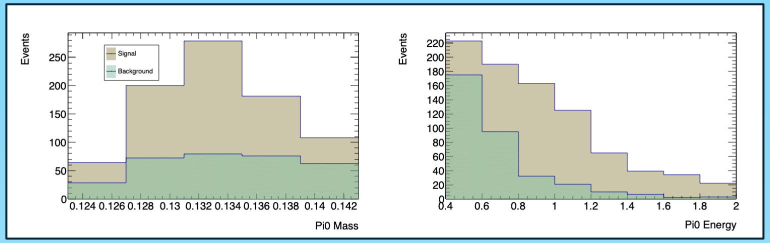
The pzLH first adds cuts to define boundaries of the pzLH where there is no signal.

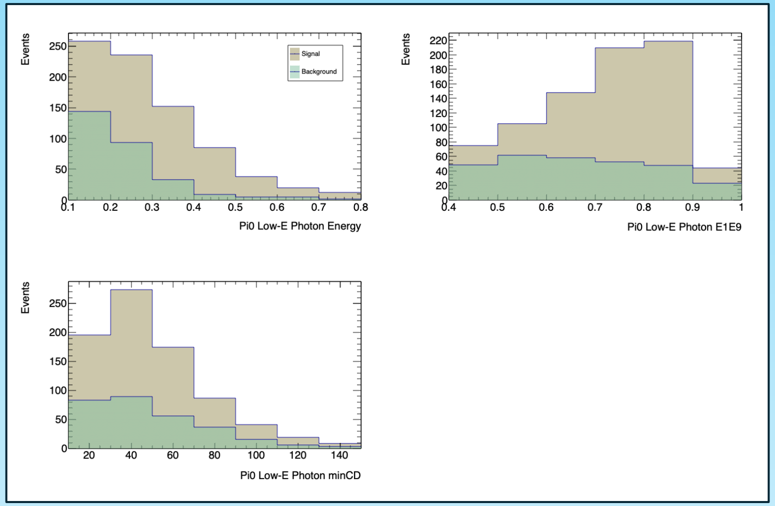
We use the excess of DATA over MC background to define (kkpz) signal

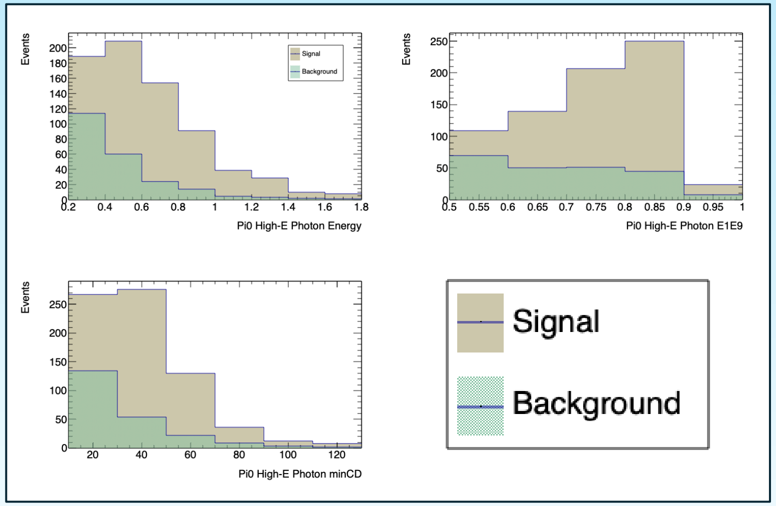
Variables:

Pi0: mass, energy
Photon1: energy, E1E1, minCD distance
Photon2: energy, E1E1, minCD distance

Signal = (pi- K- K+ pi0)
Background = other tau decays
(qqbar not included)

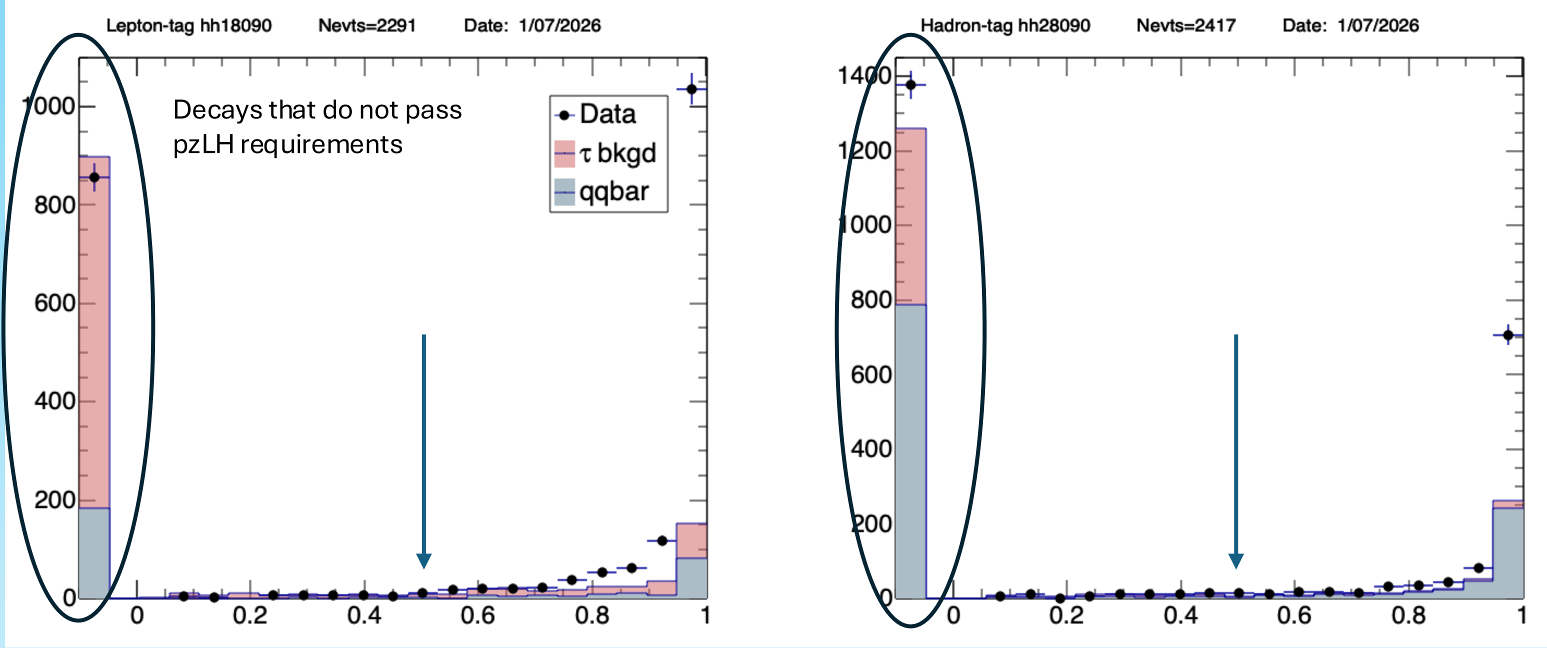






Section 5: Tau Likelihood – separate signal (pi- K- K+ pi0) from other tau decays

Non-signal tau decays are mainly pi-K-K+ with a fake pi0

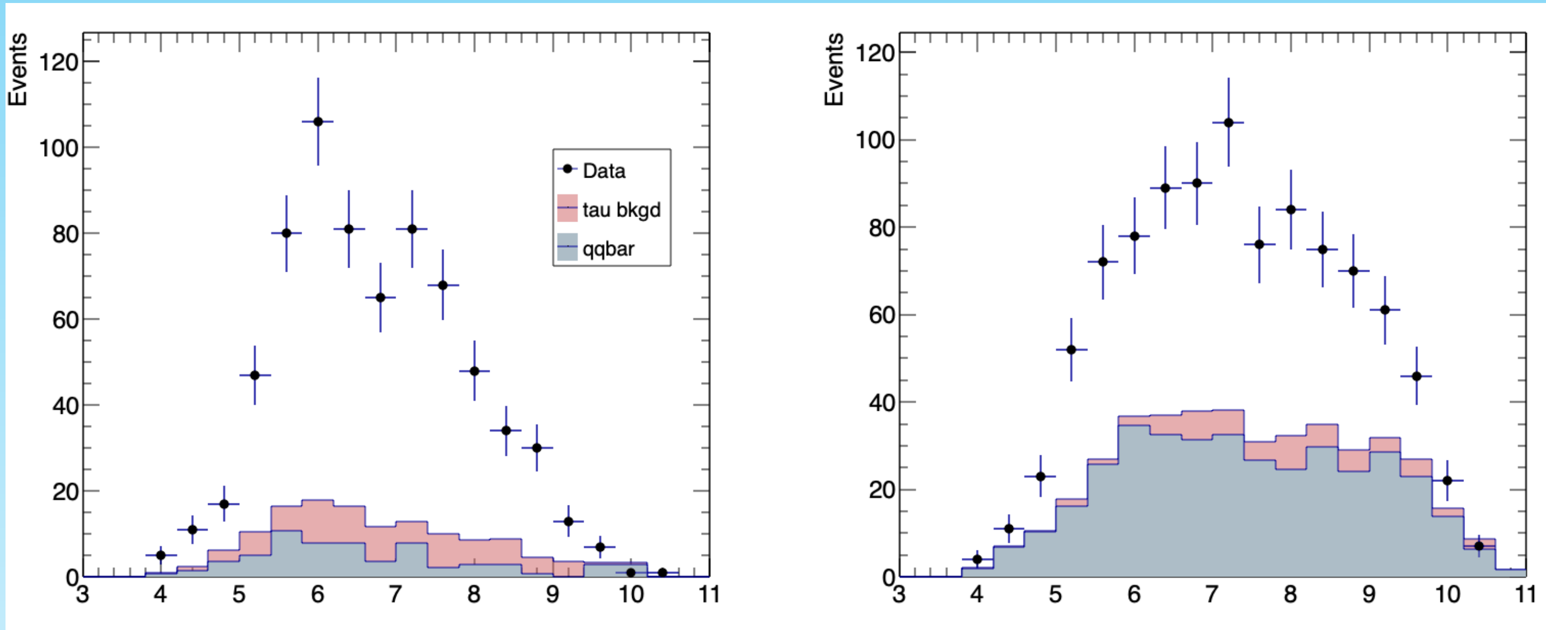


Require pzLHv2 > 0.5

Background from other tau decays is small and the impact of this requirement is minimal.

6 Selection Results

Section 6: Results after selection



MC backgrounds have been validated using D/MC control sample studies (see next section)

Lepton-tag

qqbar	9%
Tau	11%

Hadron-tag

qqbar	38%
Tau	6%

K- K+ pi-	44.4
K- phi	3.0
Other tau decays	23.1

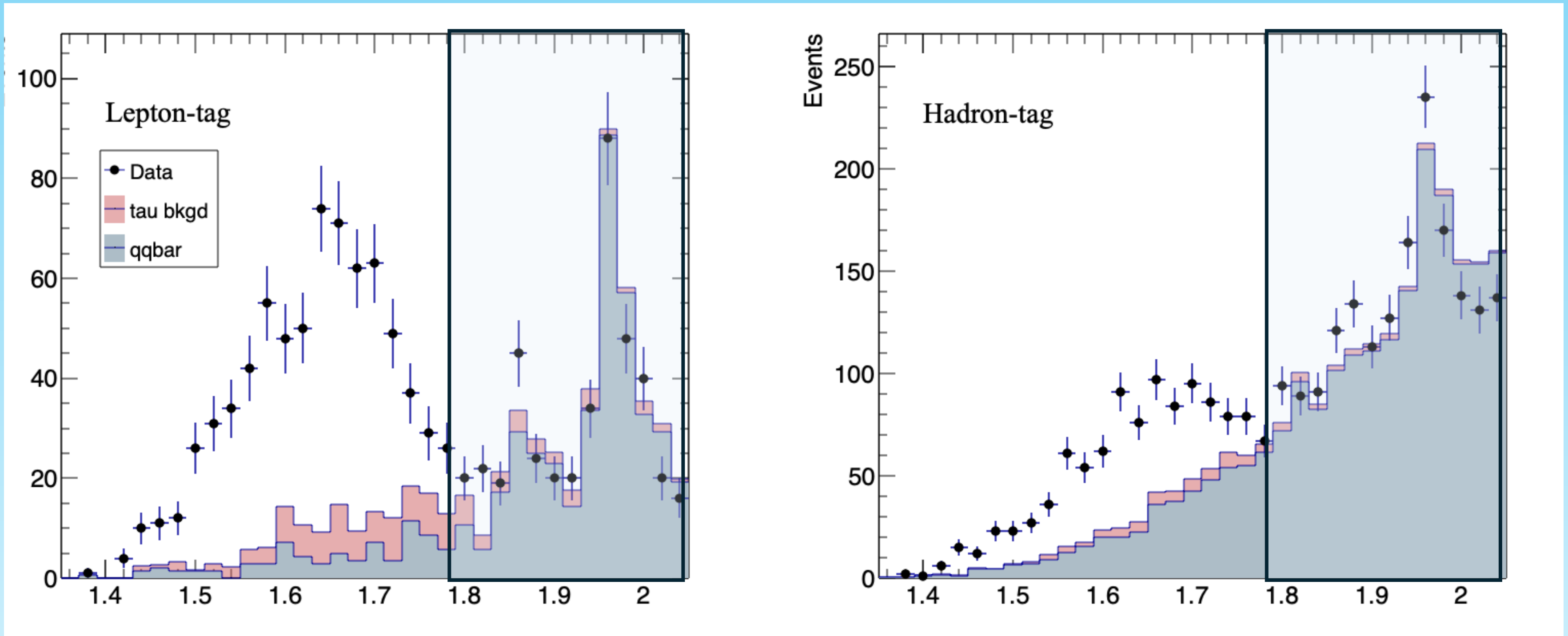
K- K+ pi-	21.6
K- phi	2.4
Other tau decays	16.7

pi- pi0	1.0
pi- pi+ pi- pi0	1.8
K- KS pi0	4.6
K- omega	5.1
pi0 2pi- K-	4.1

7 Validation of qqbar and tau backgrounds with control samples

Section 7: validate qqbar background with control samples

Mass distributions for (pi- K- K+ pi0) and (pi- K- K+)



Mass (pi- K- K+ pi0) with all selection criteria

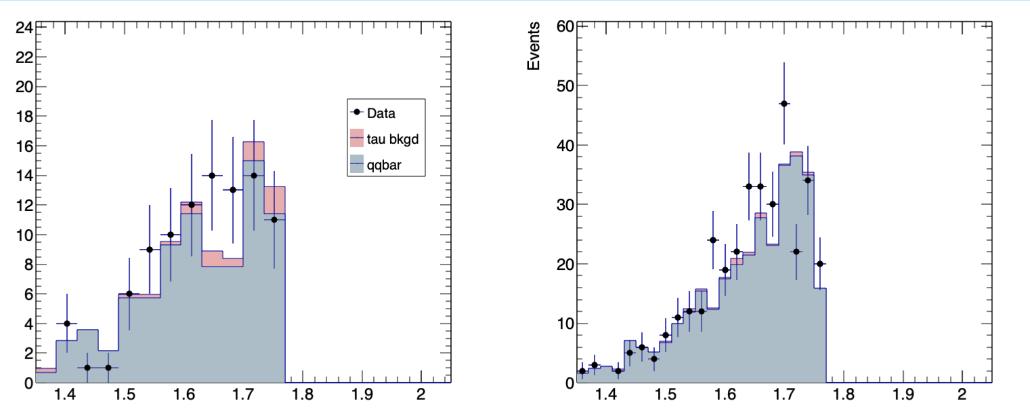
qqbar background in lepton-tag was scaled upward by 1.7

qqbar background in hadron-tag did not require a scale factor

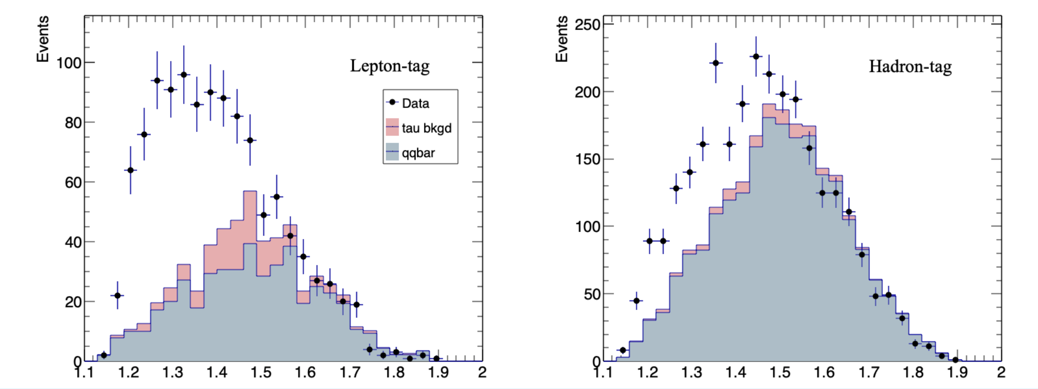
Section 7: cross check qqbar background with other distributions

Cross check of qqbar background

Further confirmation that qqbar is understood



Mass (pi- K- K+ pi0) with all selection criteria and qqLH cut reversed (lepton and hadron tag)



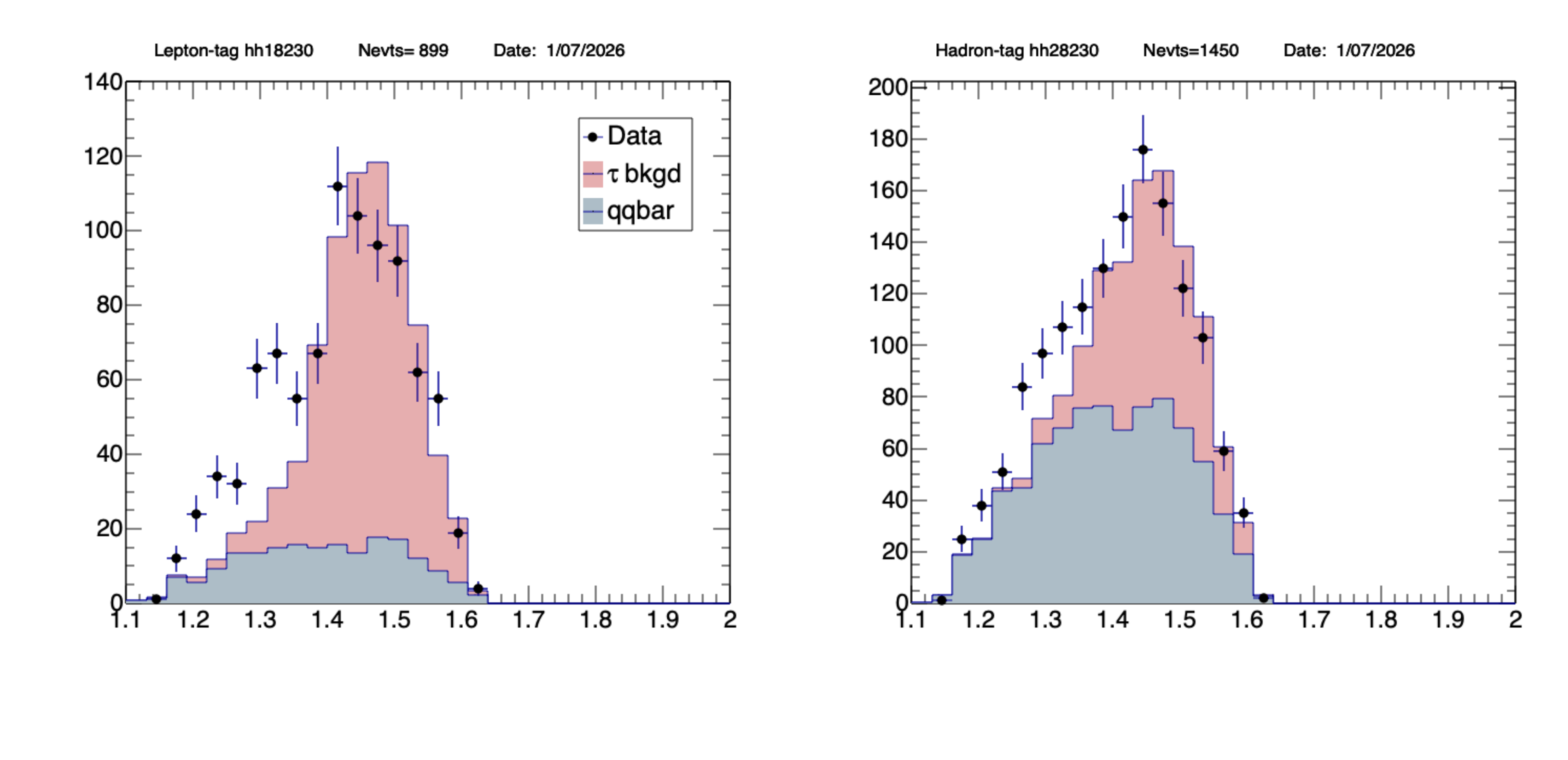
Mass (pi- K- K+) with all selection criteria and qqLH cut reversed and no cut on M(pkkz)
(lepton and hadron tag)

Section 7: Tau background – check results with control samples

All selection criteria except flip the pzLH requirement (pzLH<0.5 instead of pzLH>0.5)

Plotting the mass (pi- K- K+) for lepton and hadron tag sample (some signal in the sample)

Results indicate that tau and qqbar background are well-modelled and good to <10%
(need to determine specific error and add another check)



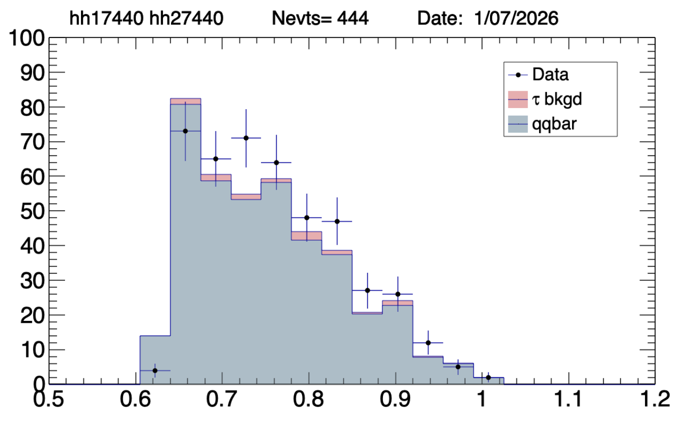
Section 8 Resonant backgrounds

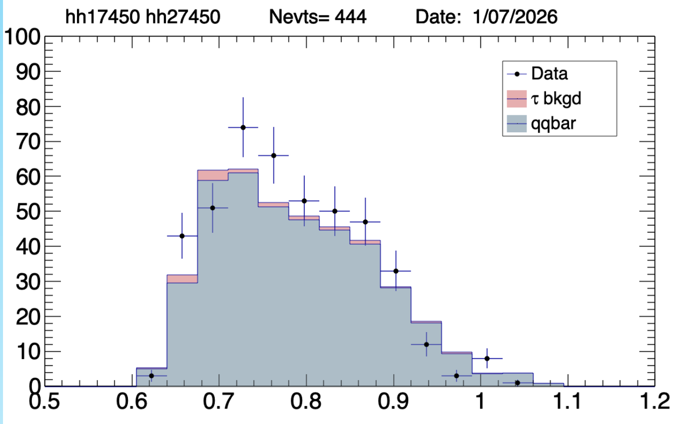
Section 8: Resonant backgrounds from qqbar events

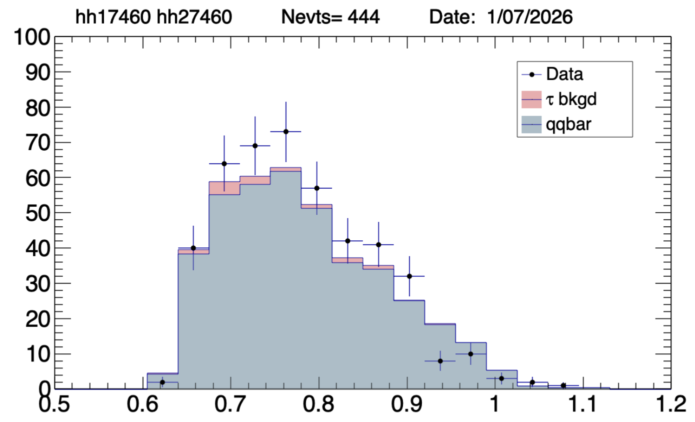
All selection criteria (both lepton and hadron tags) with qqLH cut reversed

Masses of (pi- K+), (K- pi0) and (K+ pi0) where the charge of the tau is MINUS

No evidence of K* from qqbar events

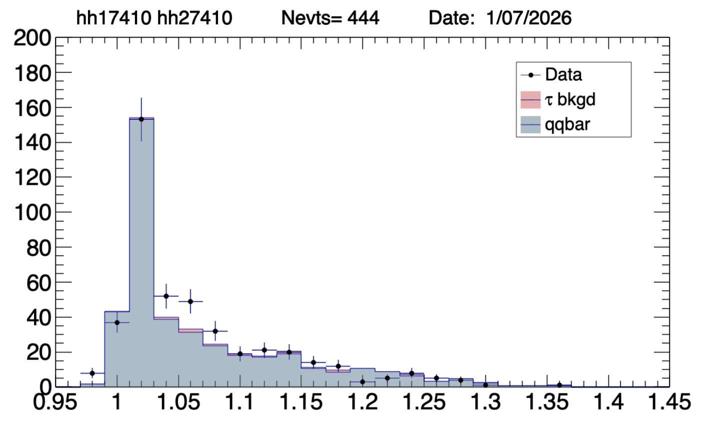


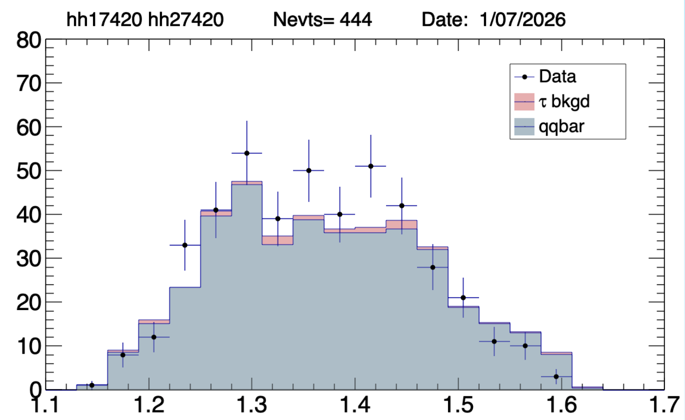




Masses of the (K-K+) and (K-K+pi0)

Evidence of the phi meson and no evidence of the f1 mesons



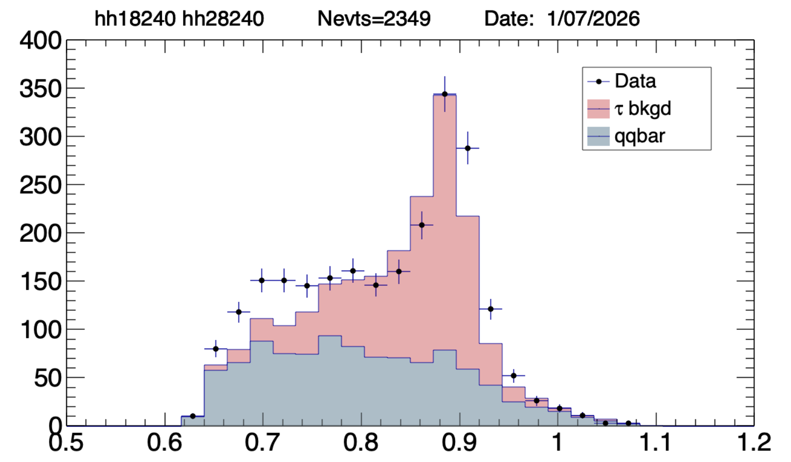


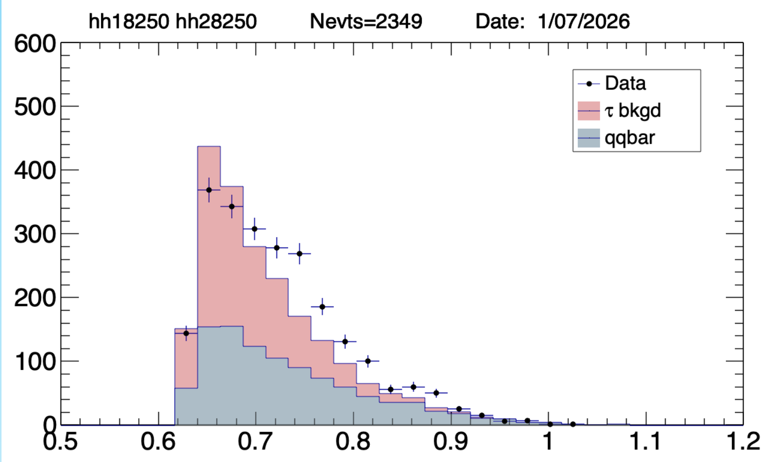
Section 8: Resonant backgrounds other tau decays

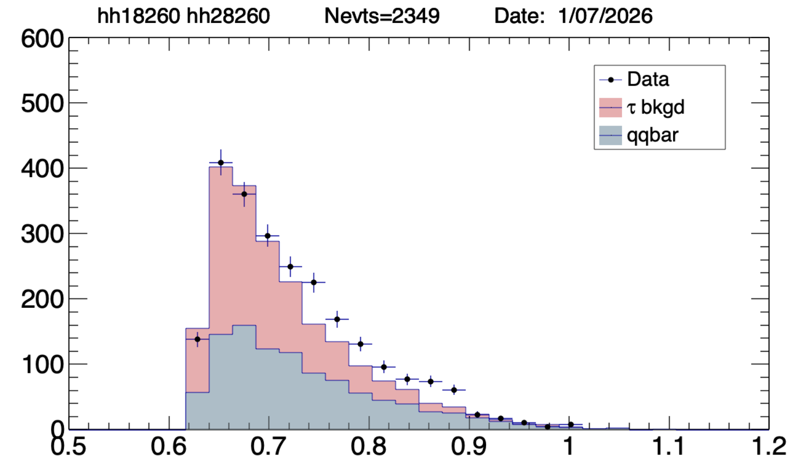
All selection criteria (both lepton and hadron tags) with qqLH cut reversed
Primary tau background is (pi- K- K+) which cannot contain an f1 meson

Masses of (pi- K+), (K- pi0) and (K+ pi0) where the charge of the tau is MINUS

K* (pi- K+) from (pi- K- K+) decays

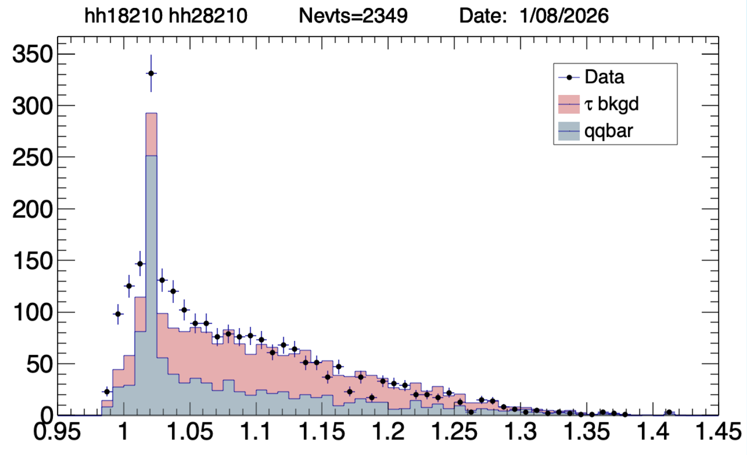






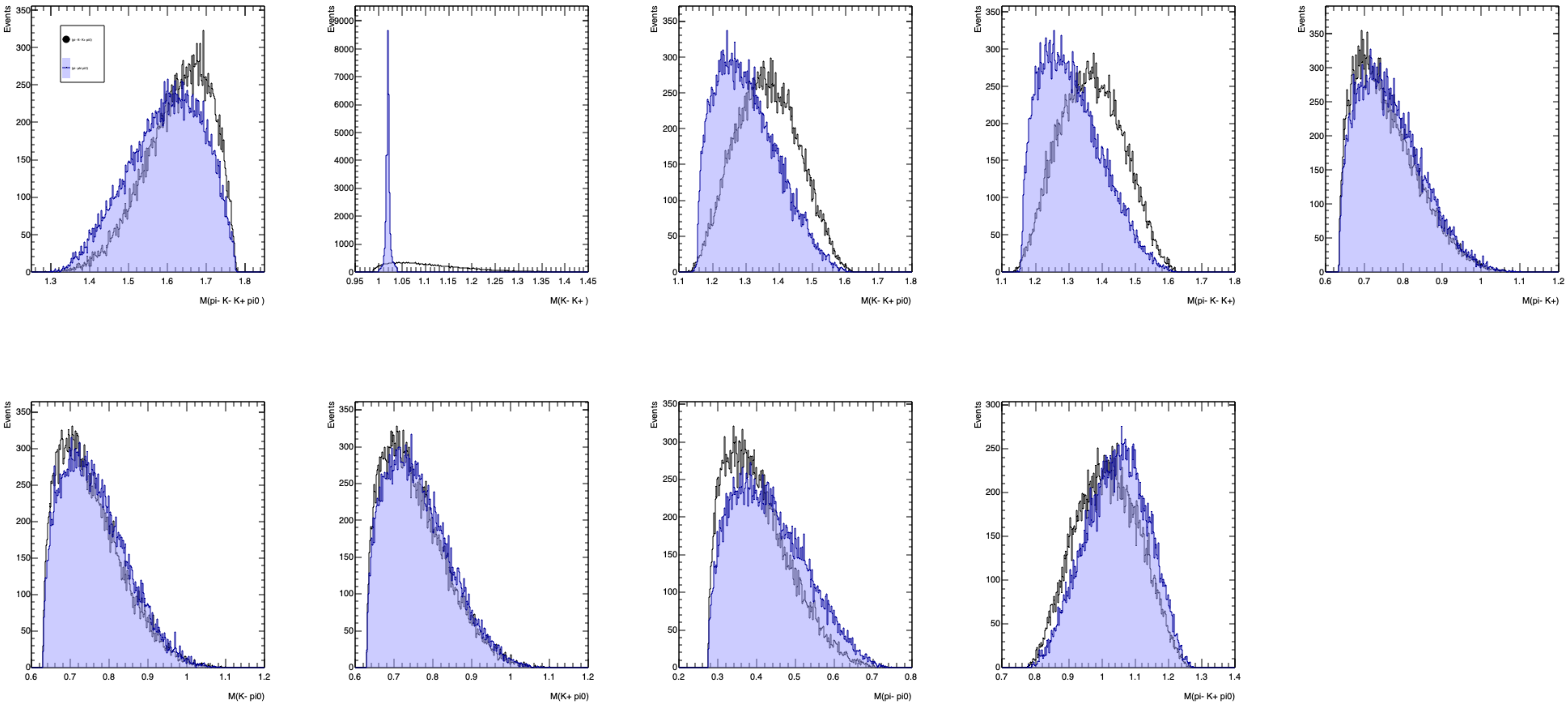
Mass of the (K-K+)

Tau decay to (pi- phi) has been observed (see PDG) – the MC predicts 8 decays. Needs further investigation.

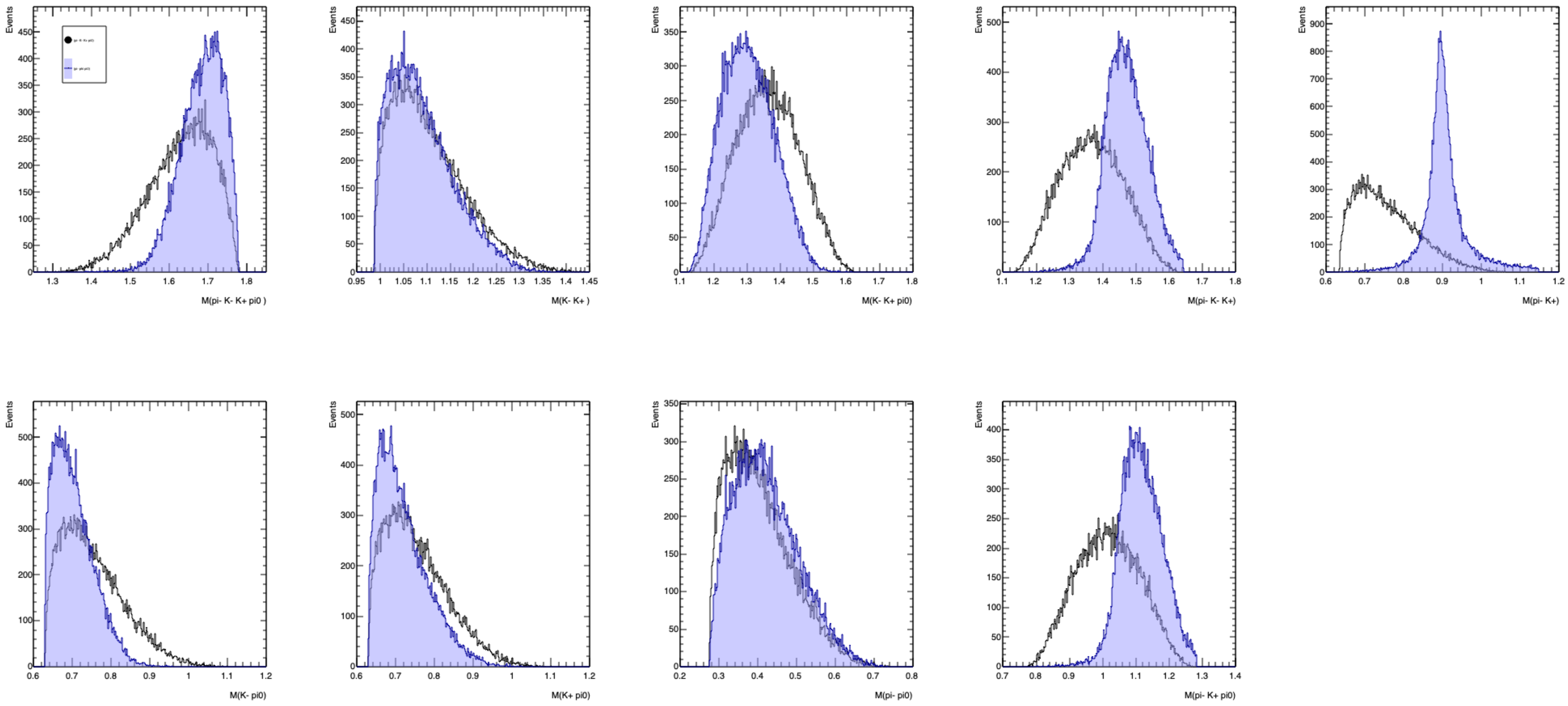


Section 9 Pythia 4-vector samples for fit studies

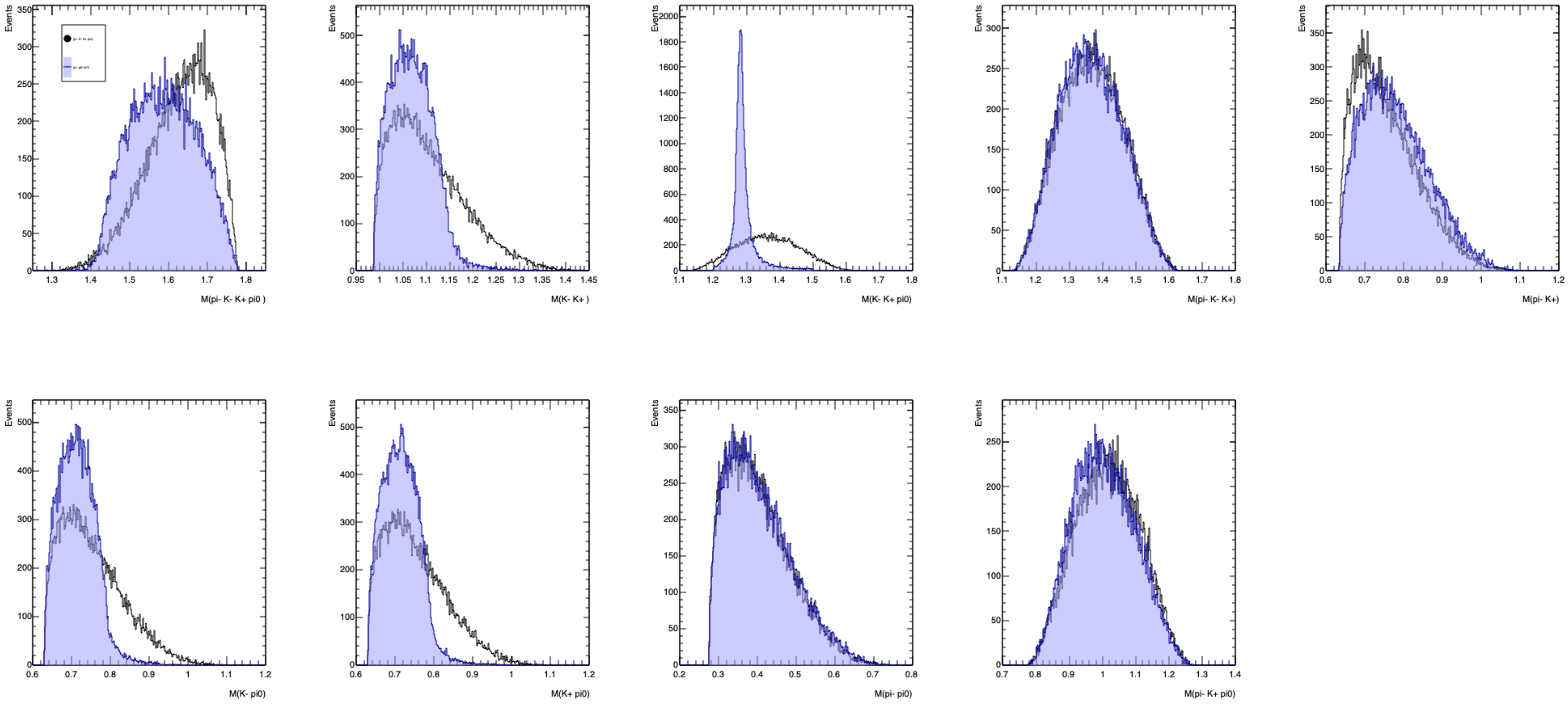
Section 9: Pythia 4vectors (no selections) PS and (pi- phi pi0)



Section 9: Pythia 4vectors (no selections) PS and (K*0 K- pi0)

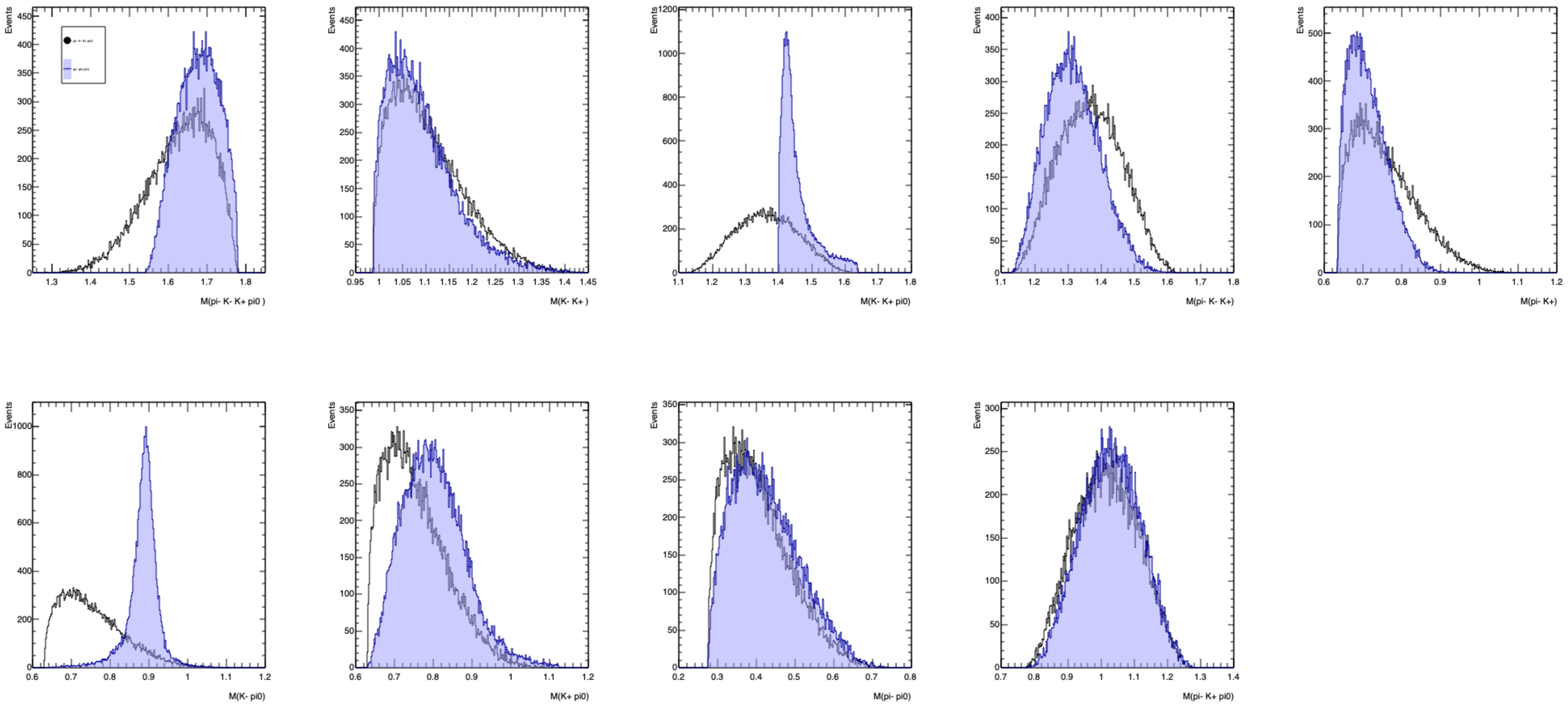


Section 9: Pythia 4vectors (no selections) PS and f1285 to (pi- K- K+)



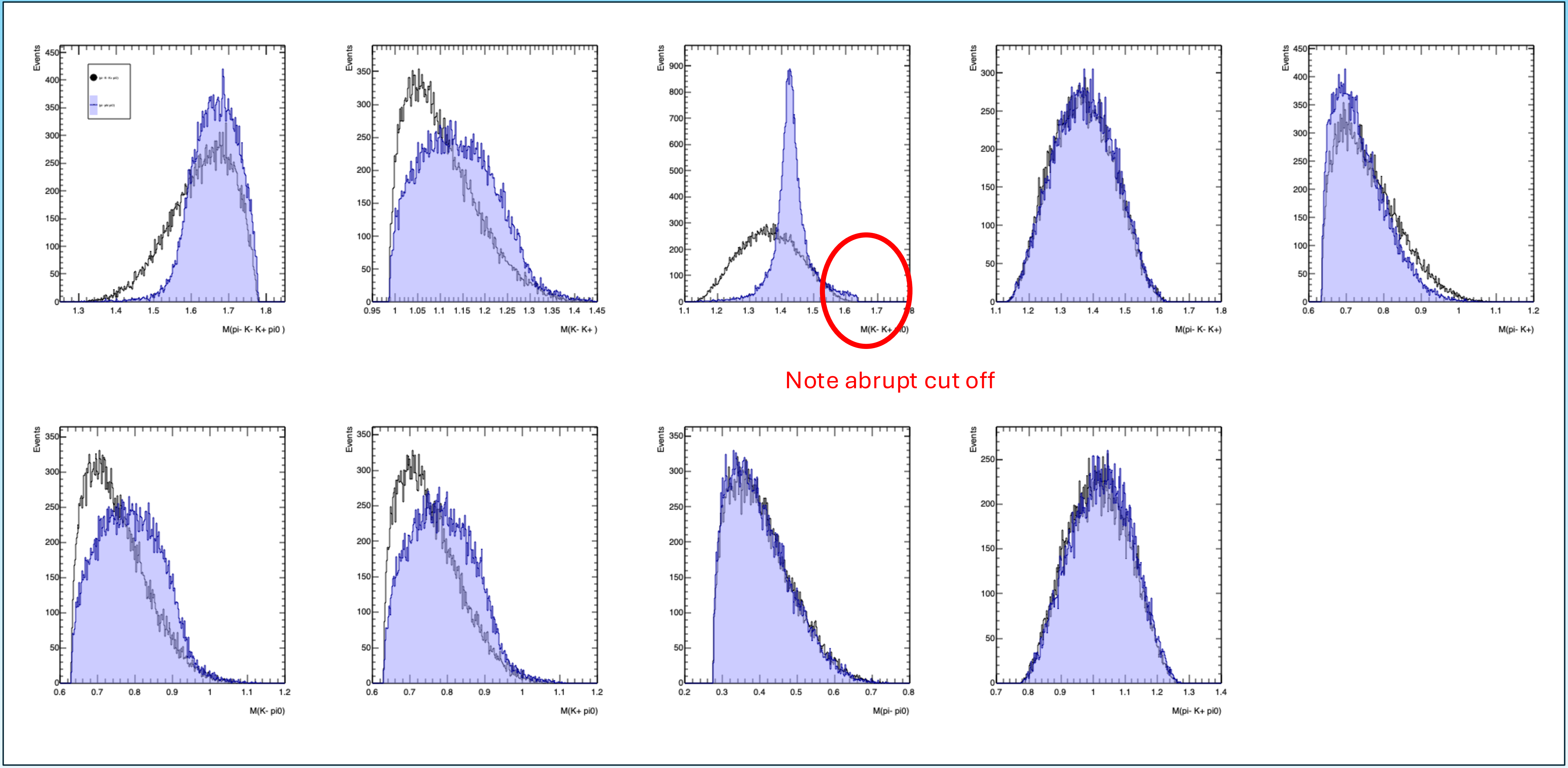
Pythia 4vectors (no selections)

PS and f1420 to a0 pi0 and a0 to K-K+

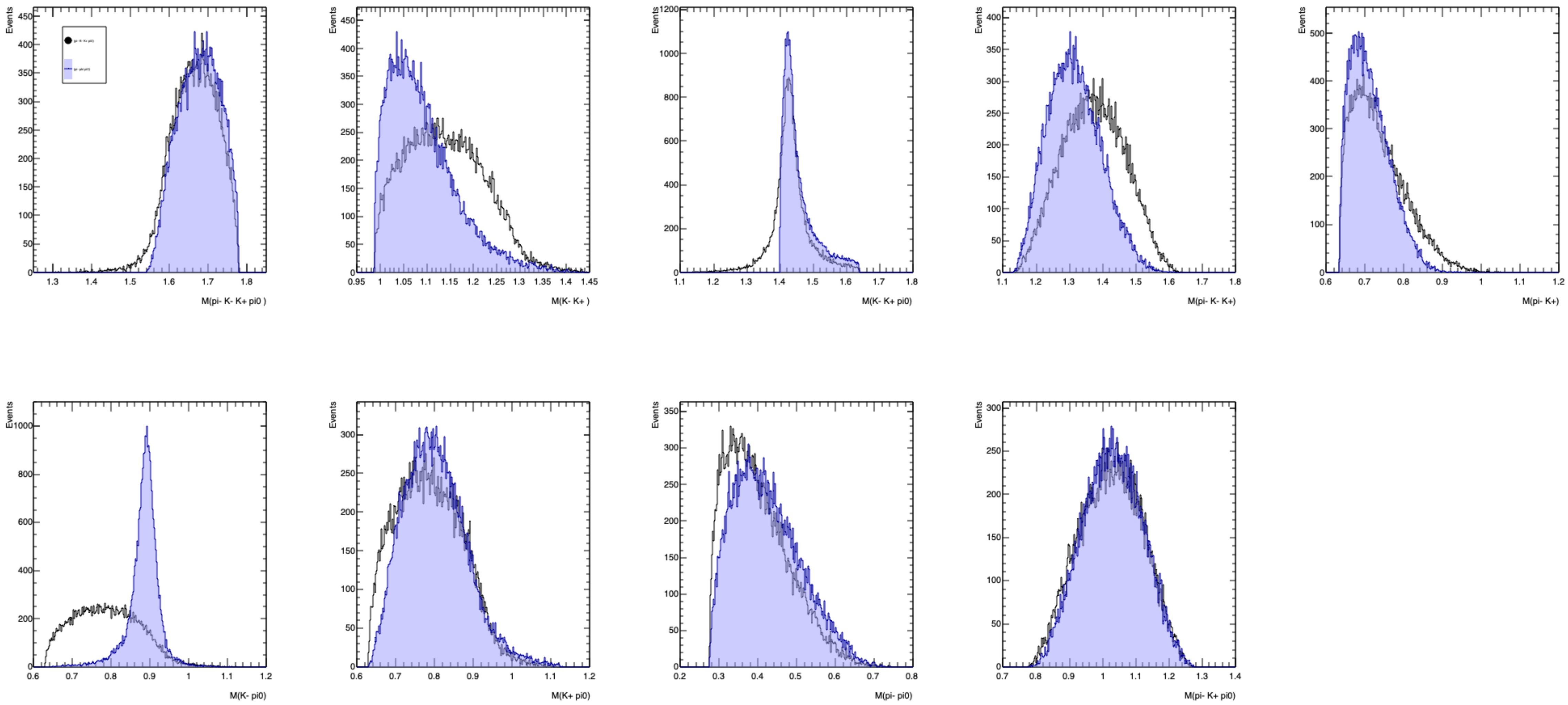


Section 9 Pythia 4vectors (no selections) PS and f1420 to (K+K- pi0)

Not the default mode for the f1420 (needed to be added)



Pythia 4vectors (no selections) Pythia8 (kkpz-kkz vs f1420-k*k)



Section 9 First test sample for development of fits

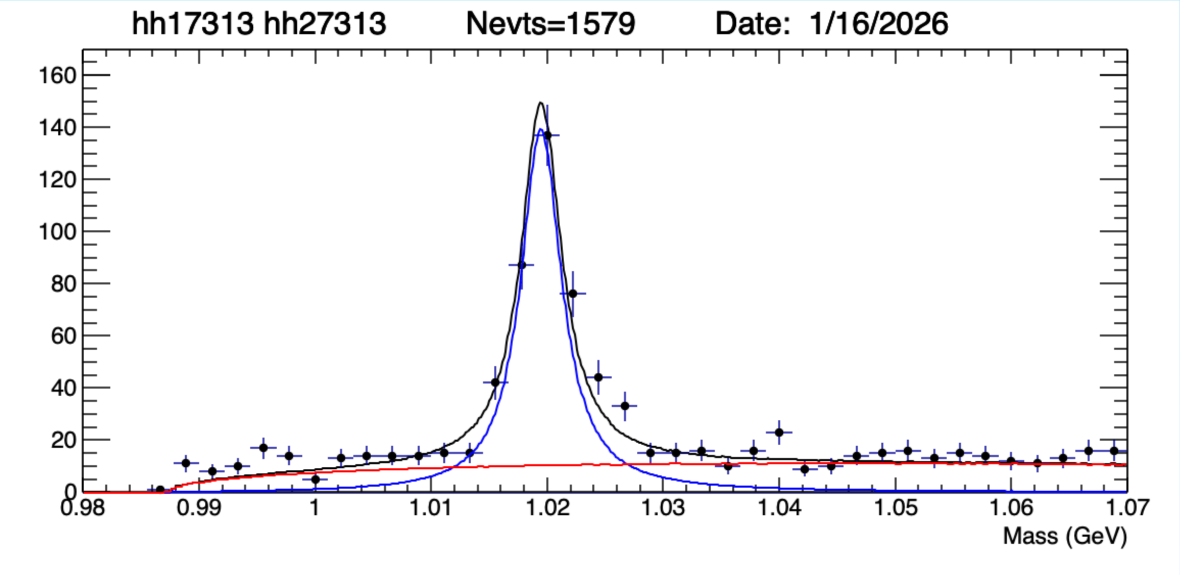
Section 10 Mass and width of phi meson with control samples

Fit phi meson with qqbar sample

(pzLHv2_nominal>0.5 && qqLHv2_ltag<0.5 && mpkkz0<2.05)

PDG phi M/W = (1.01946 and 0.00425)

Fit gives M/W consistent with the PDG values



Fixed, M-free, MW-free

NO.	NAME	VALUE	ERROR
1	p0	1.01404e-01	5.92870e-03
2	p1	1.01946e+00	fixed
3	p2	4.25000e-03	fixed
4	p3	1.12017e+00	4.78208e-02

Chisq/NDF = 93.02 for NDF 72
0.06
Area from integration : 401 +/- 23

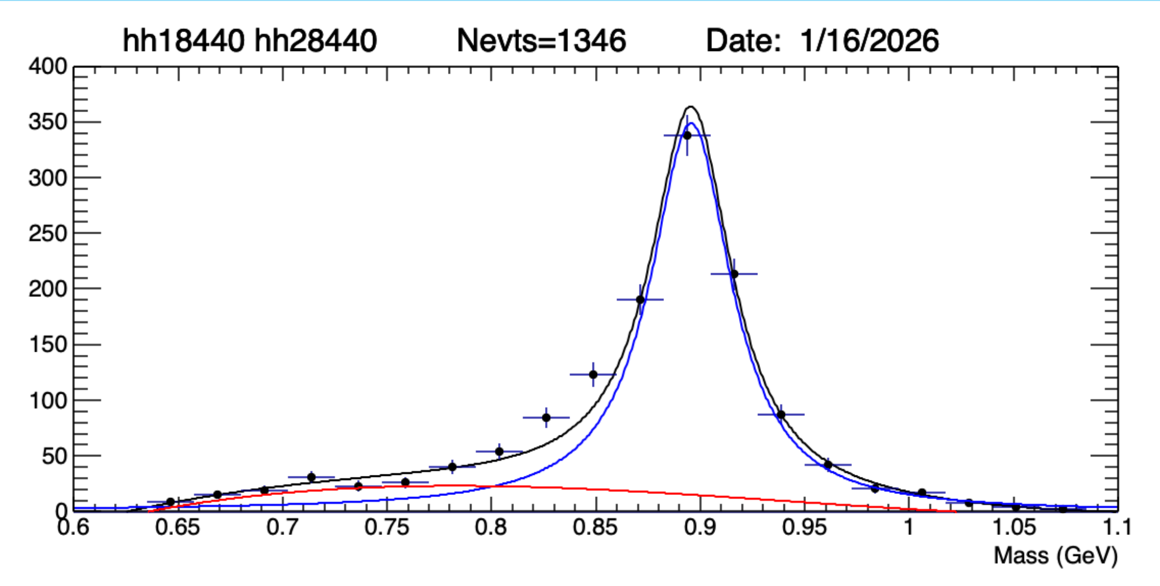
NO.	NAME	VALUE	ERROR
1	p0	1.01680e-01	5.90955e-03
2	p1	1.01986e+00	2.09899e-04
3	p2	4.25000e-03	fixed
4	p3	1.11991e+00	4.78103e-02

Chisq/NDF = 88.92 for NDF 71
0.06
Area from integration : 404 +/- 23

NO.	NAME	VALUE	ERROR
1	p0	1.05135e-01	6.51510e-03
2	p1	1.01990e+00	1.96775e-04
3	p2	4.71302e-03	3.96256e-04
4	p3	1.10346e+00	4.97742e-02

Chisq/NDF = 87.4 for NDF 70
0.06
Area from integration : 416 +/- 26

Section 10 Mass and width of K* (pi-K+) with tau control samples



NO.	NAME	VALUE	ERROR
1	p0	2.58822e+01	9.33563e-01
2	p1	8.95550e-01	fixed
3	p2	4.73000e-02	fixed
4	p3	-1.30794e+03	6.32881e+00
5	p4	4.46467e+03	1.13689e+01
6	p5	-4.88937e+03	1.09011e+01
7	p6	1.73492e+03	8.23878e+00
8	p7	0.00000e+00	fixed

Chisq/NDF = 23.8 for NDF 15
0.04
Area from integration : 1087 +/- 39

PDG parameters for K* are fine

Section 11 Pythia 4-vector fit studies

Summarize pythia decay modes — Jan 26 2026

Only decaying the tau+ (the tau- is set to decay to the (e nu nu) channel)

Tau+ to (pi+ phi pi0 nut) — **KK**

Tau+ to (pi+ f1258 nut)

f1258 to (K+ K- pi0)		**KKz**
f1258 to (a0(980) pi0)	where a0(980) to (K+ K-)	**KKz and KK**

Tau+ to (pi+ f1258 nut)

f1420 to (K+ K- pi0)		**KKz resonance**
f1420 to (a0(980) pi0)	where a0(980) to (K+ K-)	**KKz and KK**
f1420 to (K*+ K-)	where K*+ to (K+ pi0)	**KKz and Kpi0**

(assume (K*- K+) is identical to (K*+ K-)

Non-resonant modes:

Tau + to (K*0 K+ pi0 nut) **K*0 to (K- pi+)** — **K- pi+**

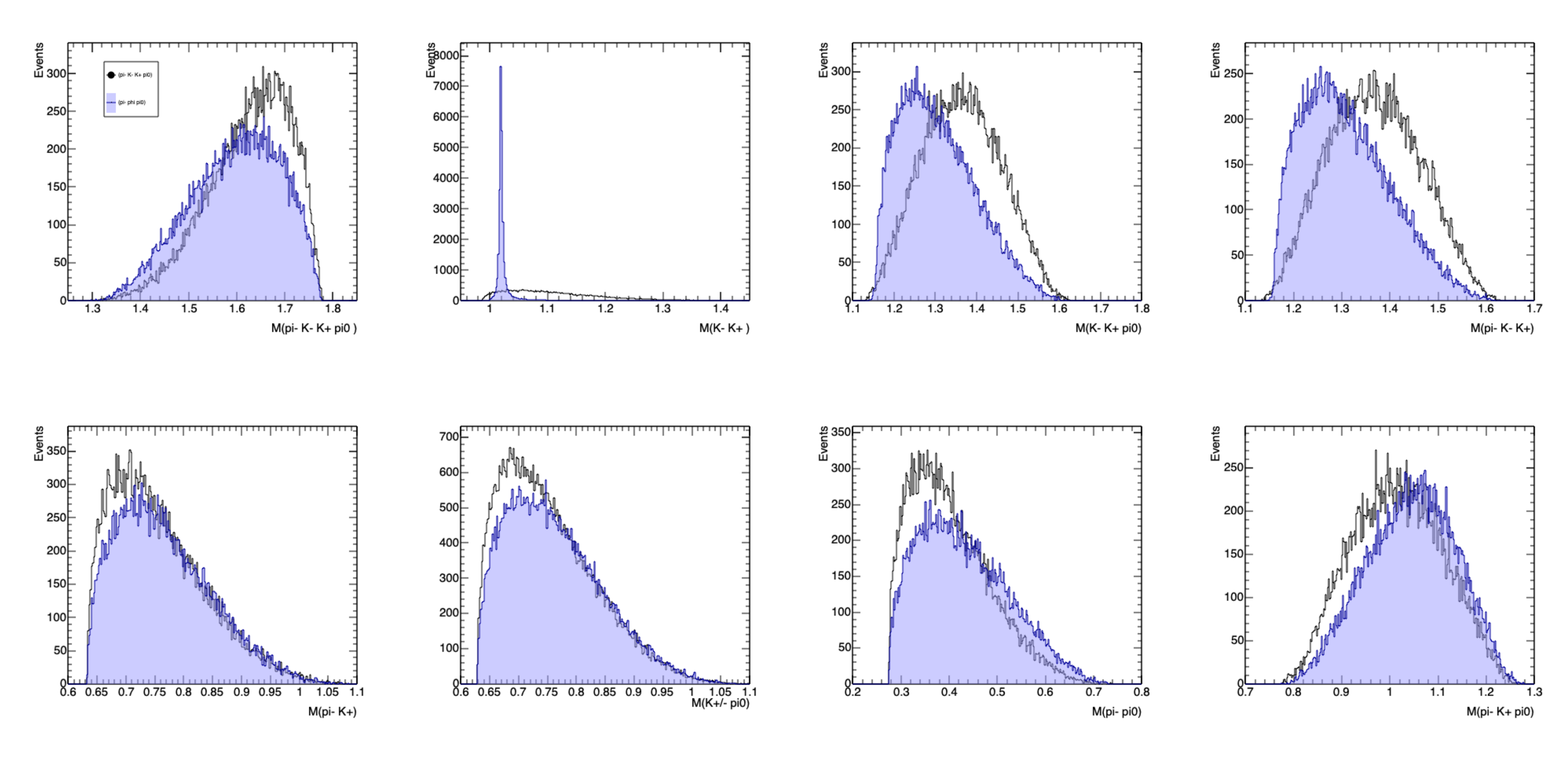
(K*0 to K+ pi- would give a different tau final state)

Tau + to (K*+ K- pi+ nut) **K*+ to (K+ pi0)** — **K+ pi0**

(assume K*-K+ pi+ nut final state is identical. - plots of (Kpi0) show both K-charges)

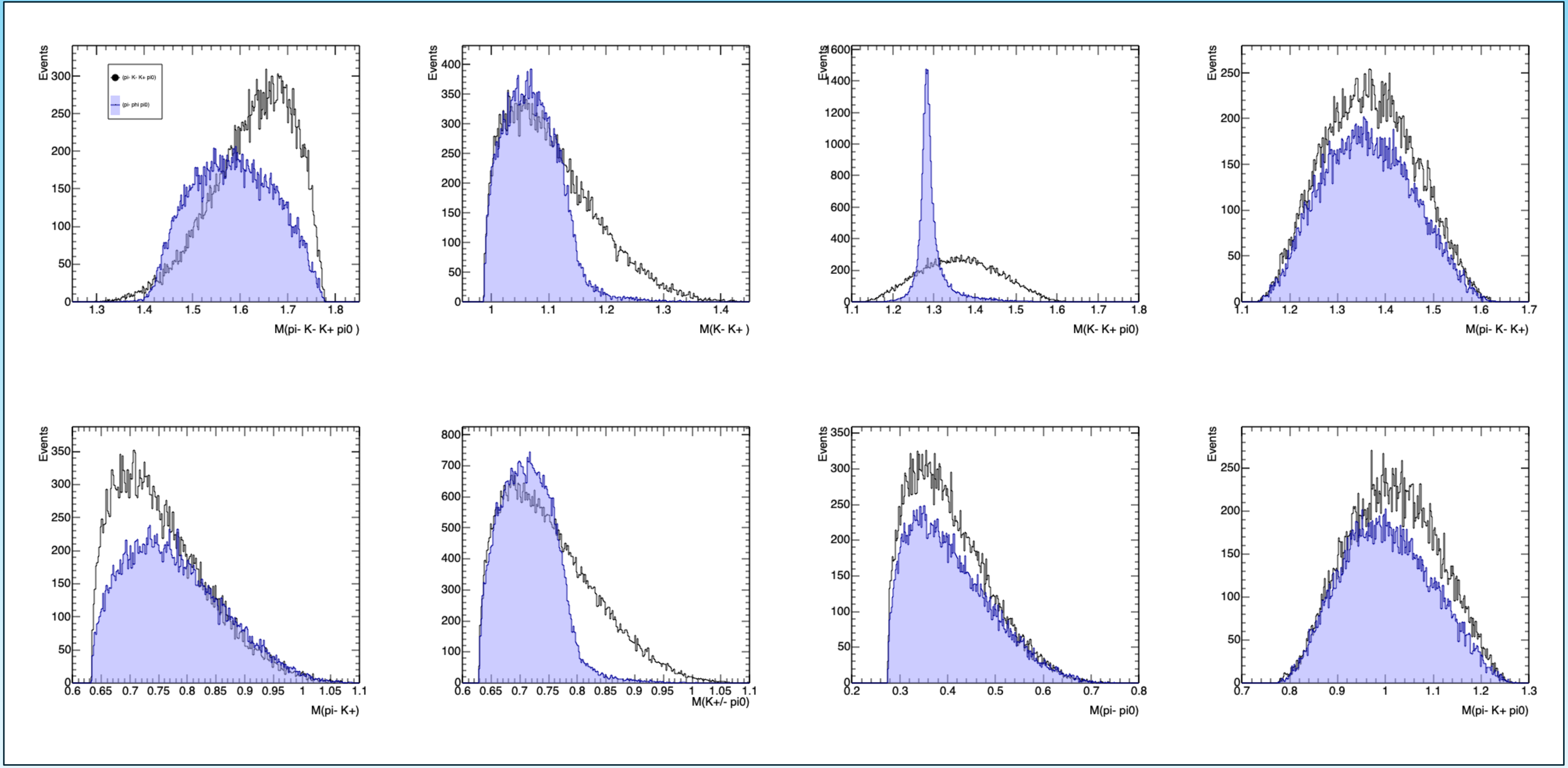
Tau+ to (pi- phi pi0) phi to (KK) Jan 26 2026

Weighted by (kkz) and (kk)



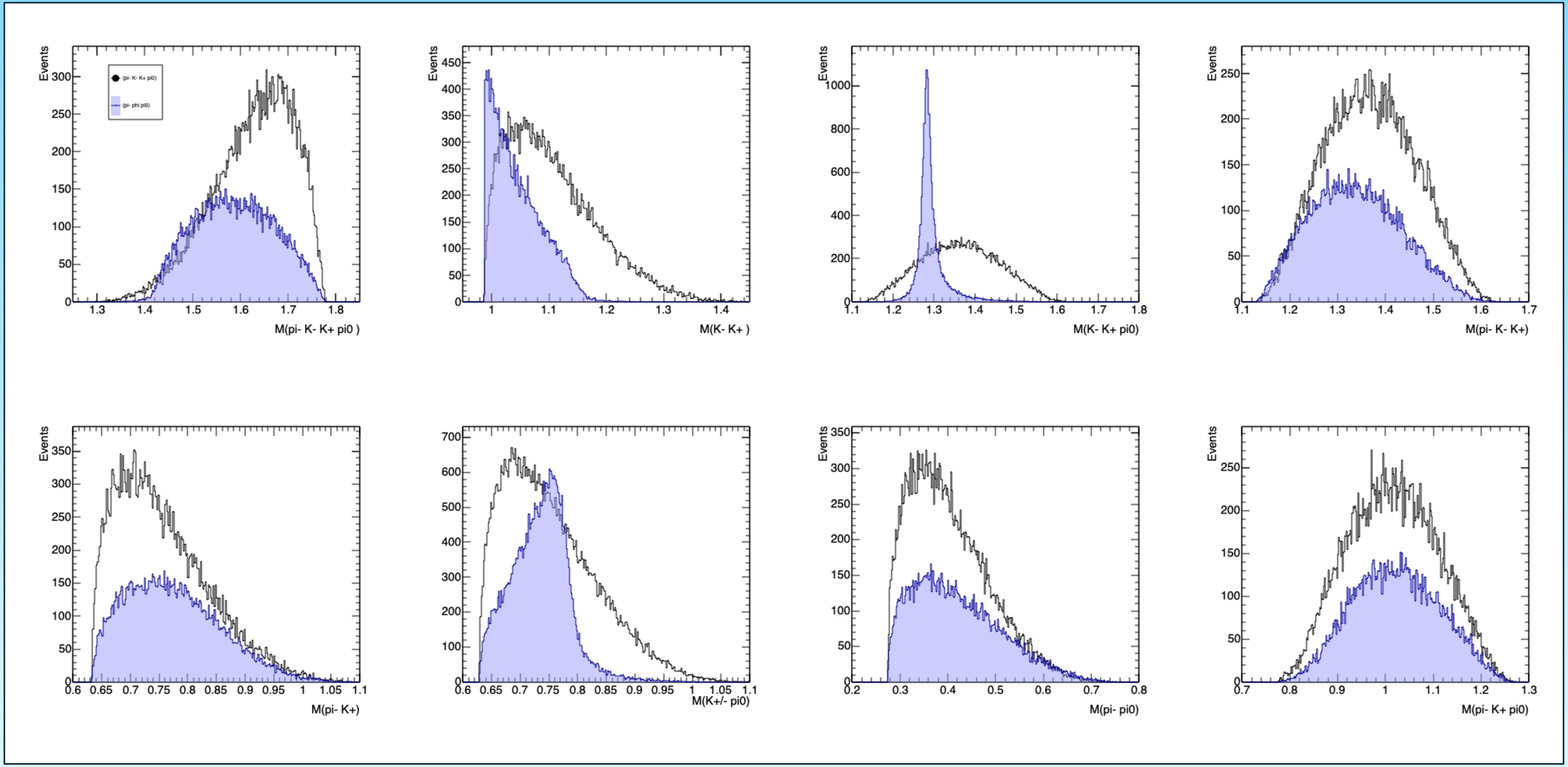
Tau+ to (pi+ f1285) with f1285 to (kkz) Jan 26 2026

Weighted (kkz)



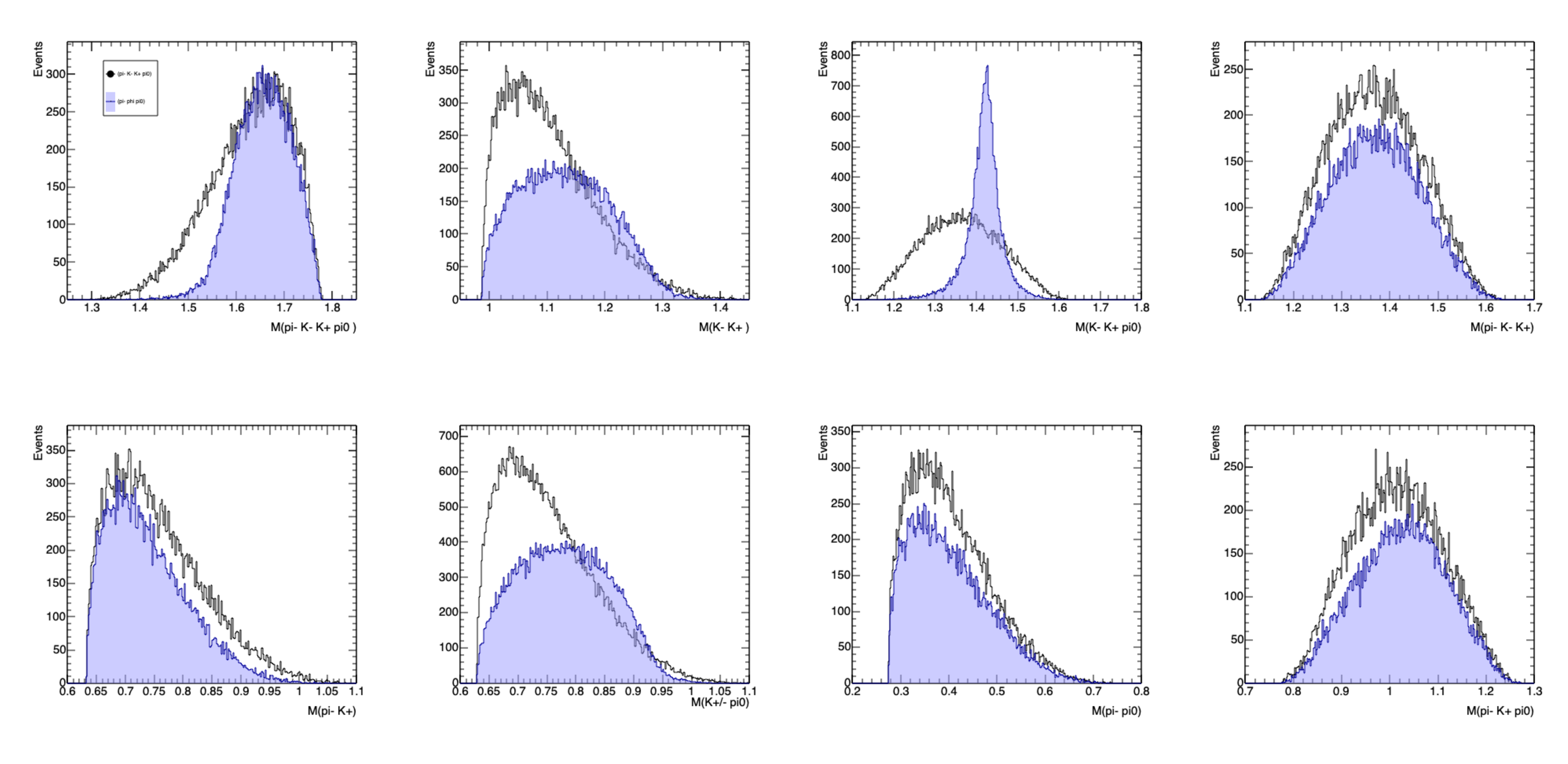
Tau+ to (pi+ f1285) with f1285 to a0 pi0 with a0 to K+K-) Jan 26 2026

Weighted by (kkz) and (kk)



Tau+ to (pi+ f1420) with f1420 to kkz Jan 26 2026

Weighted by (kkz)

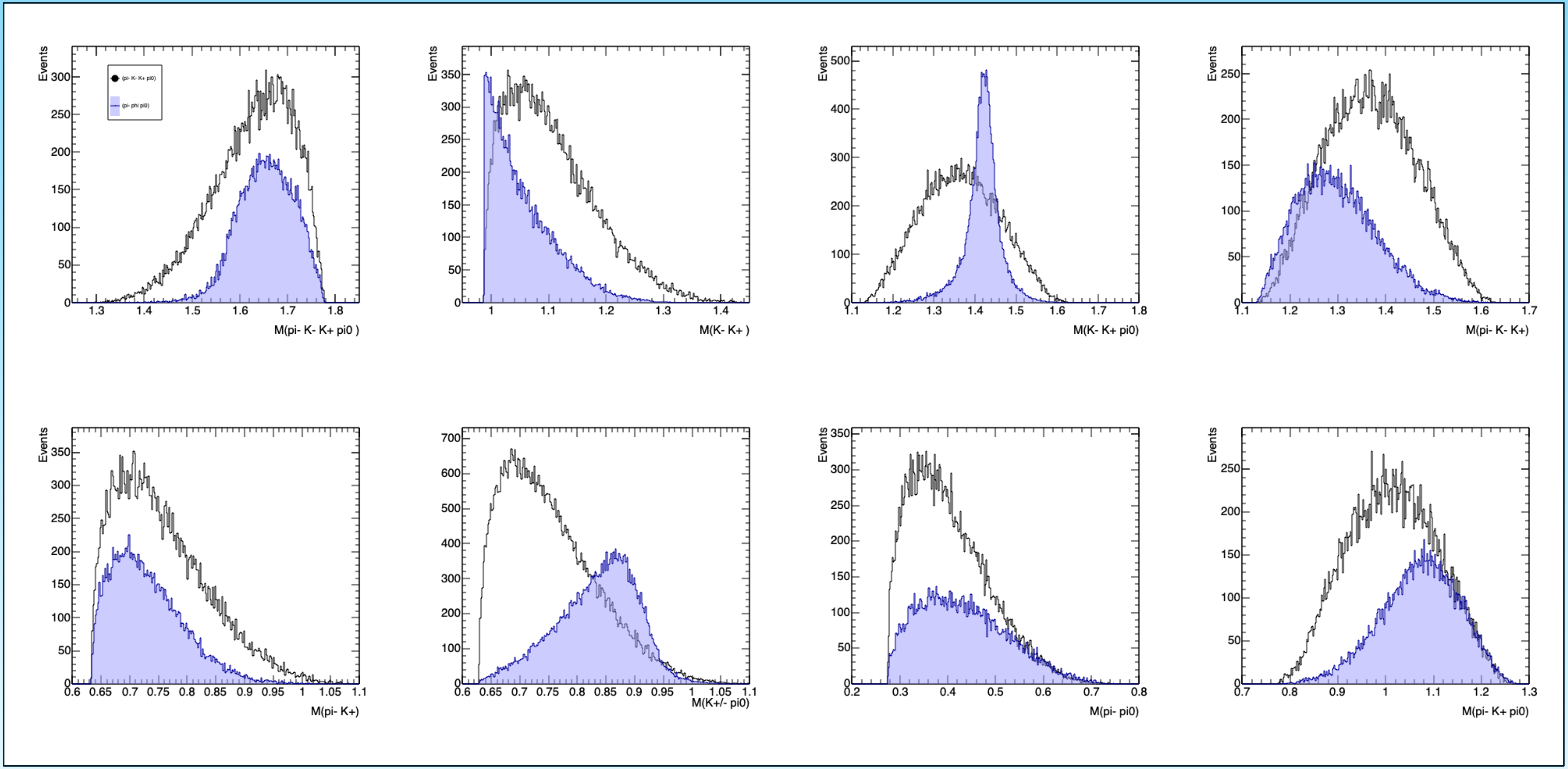


Tau+ to (pi+- f1420) with f1420 to a0 pi0 with a0 to K+K0)

Jan 26 2026

Weighted by (kkz) and (kk)

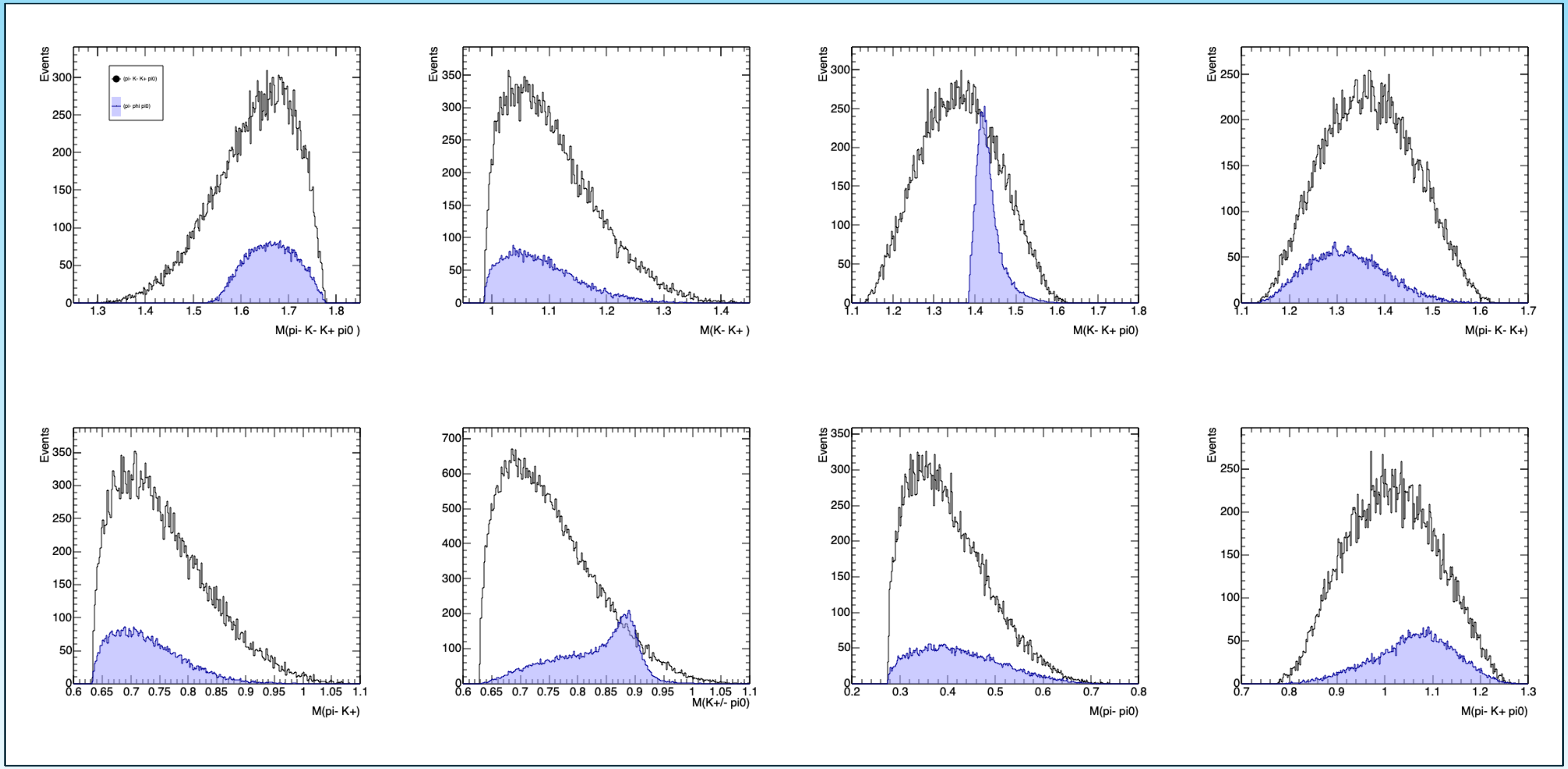
Also note the different KK-mass for this channel (with/without the a0)



Tau+ to (pi+ f1420) with f1420 to K*+ K- or K*- K+ Jan 26 2026

Weighted by (kkz) and (kz)

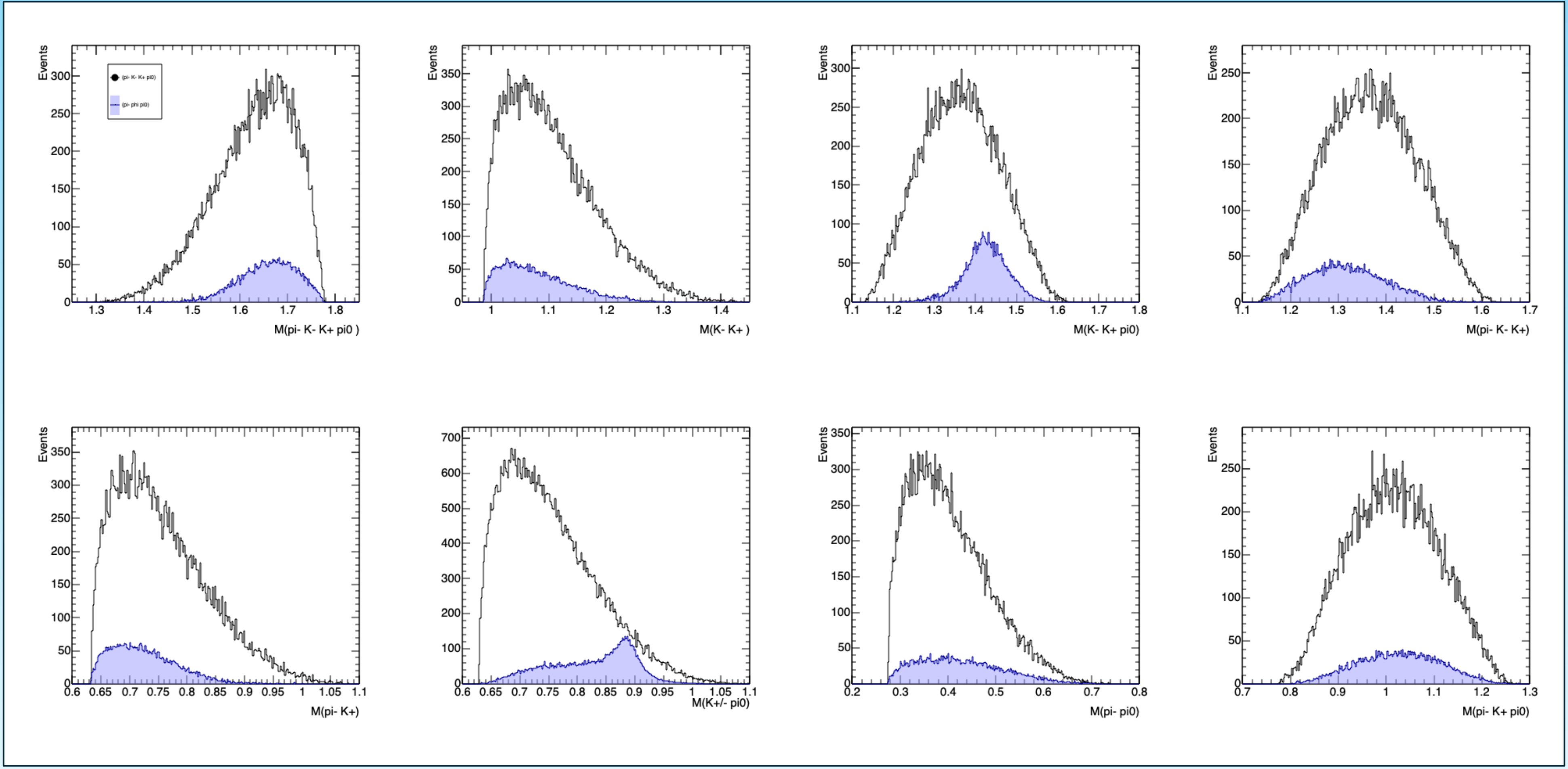
First use the weight for (kkz), then use the (Kp) weight but using the correct (K+pi0)/(K-pi0) mass
(massVector 5 (K+) and 6 (K-))



Tau+ to (pi+ if1420) with f1420 to Kstar+ K- or Kstar- K+ Jan 26 2026

Weighted by (kkz) and (kp)

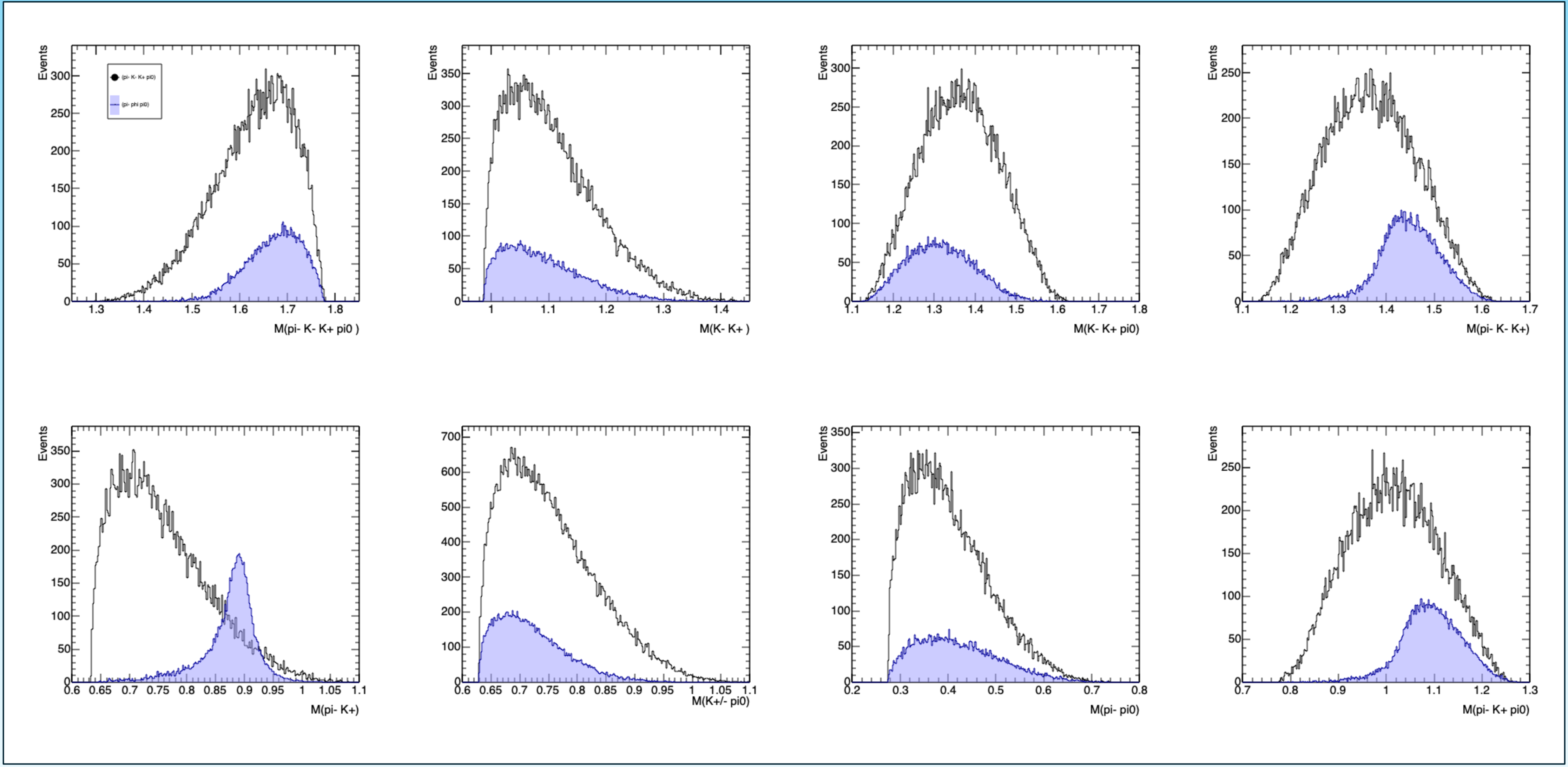
Notes: First use the weight for (kkz), then use the (K+p) weight but using the correct (K+pi0) mass (massVector 5 (K+)) - only generated the Kstar+ mode



Tau+ to (K*0 K+ pi0) K*0 to (pi+ K-) Jan 26 2026

weighted by (kkz) and (Kpi)

K*0 only to (K+ pi-) as other mode would give the wrong tau final state



Tau+ to (K*- K+ pi+)

Jan 26 2026

weighted by (kkz) and (kz)

K*- only to (K- pi0) as other mode would give the wrong tau final state

(K*+ K- pi+) assumed to be identical