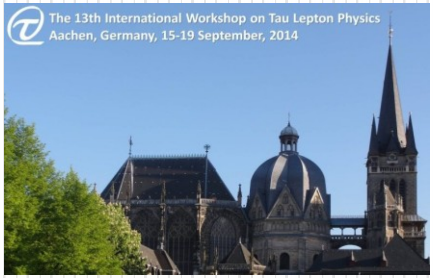
Measurement of the branching fraction and the spectral function of the $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ decay



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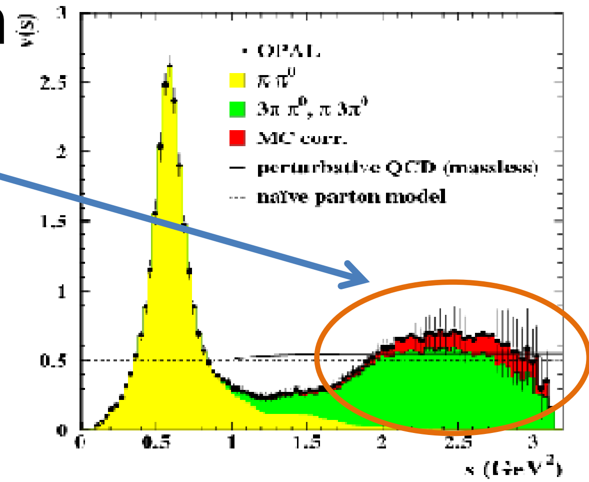
Motivation: Why $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$

- 4 π final state
- Important part of Vector Spectral Function
  - $\alpha_s(s)$
    - •"high" s region is important for a theoretical discussion on the α_s determination.
    - •4 π final state is dominating in this region.
    - •… B-Factory data are awaited



- CVC relation: $\tau^- \to (4\pi)^- \nu_\tau$ and $e^+e^- \to (4\pi)^0$

$$v(\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau) = \frac{s}{4\pi^2\alpha^2}\left[\frac{1}{2}\sigma(e^+e^- \to 2\pi^+2\pi^-) + \sigma(e^+e^- \to \pi^+\pi^-2\pi^0)\right]$$

- $\tau^- \to \omega\pi^-\nu_\tau$: 2nd class current can contribute.

For a direct comparison to theory, the detector effects must be removed (Unfolded).

Spectral Functions

$$v(s) = m_\tau^2 \left[6 S_{EW} \, | V_{ud} |^2 \left(1 - \frac{s}{m_\tau^2}\right)^2 \left(1 + 2\frac{s}{m_\tau^2}\right) \right]^{-1} \times$$

$$\frac{B\left(\tau^- \to V \nu_\tau\right)}{B(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} \left(\frac{1}{N_V} \frac{dN_V}{ds} \right)$$

- S_{EW}:EW radiative correction.
- $s=m_V^2$

- Need to measure both branching fraction and invariant mass spectra.

Branching Fraction Measurements

- Use e- μ events for normalization.

$$Br_{4\pi} = \frac{N_{4\pi-l}(1-b_{4\pi-l})}{\eta_{4\pi-l}} \times \frac{\eta_{e-\mu}}{N_{e-\mu}(1-b_{e-\mu})} \times \frac{B_e B_\mu}{(B_e + B_\mu)}$$

- Their branching fractions are well known.

B_e=(0.1783±0.0004) (0.2%)

B_μ =(0.1741±0.0004) (0.2%)

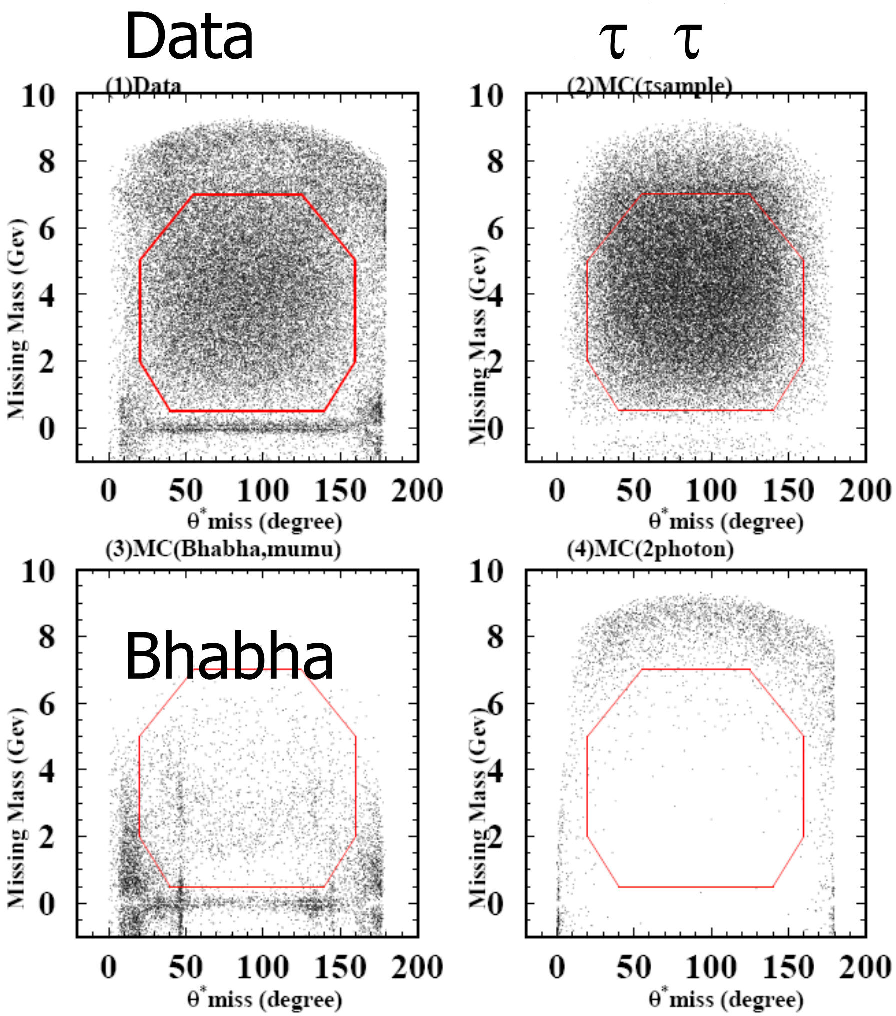
- Many systematics cancel in the ratio.
- Need e- μ events for the normalization.

Selection Criteria

- Require small number of tracks (2-4)
  - closest approach dr<0.5 cm |dz|<3.0cm
    pt>0.1GeV, $17^\circ < \theta_{lab} < 150^\circ$
- Good photons
  - E>0.05 GeV for Barrel, E>0.07 GeV for Endcaps
  - Cluster shape; E9/E25cut >0.75 and Shower wdith<6.0cm.
    (Barrel region : 32°-129° in lab.)
- Thrust in CMS
  Thrust >0.9, $35^\circ < \theta^*_{thrust} < 145^\circ$
- Missing mass and Missing directions

(To discriminate Bhabha, $\mu\mu$, two-photon processes)

Missing mass and Missing direction



Bhabha, μ μ ,
Two-photon rejection

two-photon

Event Selection (4 π events)

- 4 tracks with net Q=0
- Signal side 3 tracks, tag-side 1 track.
- not $\gamma \to e^+e^-$ candidates m_{ee}>0.15GeV
- one π^0 candidate

  -6< $S_{\gamma\gamma}$ <5

$$S_{\gamma\gamma} = \frac{(m_{\gamma\gamma} - m_{\pi^0})}{\sigma_{\gamma\gamma}}$$

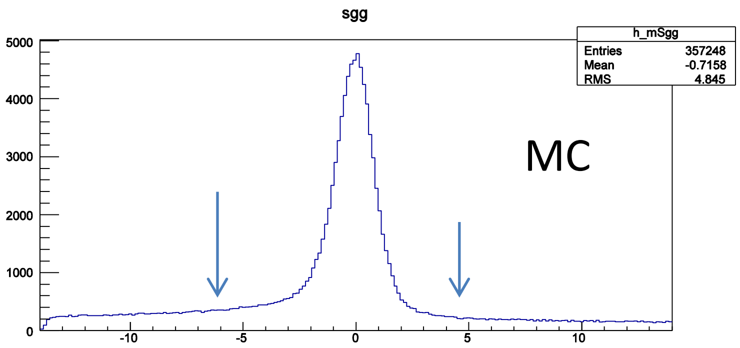
- Three charged tracks are identified as pions.

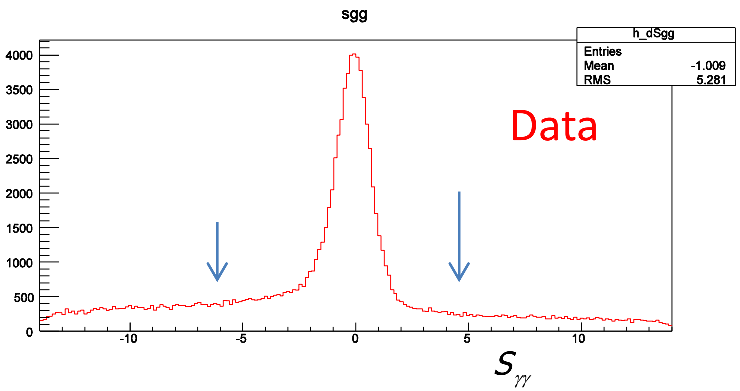
  Likelihood ratio $L_{\pi/K}$ > 0.6
- Tag-side: track is identified either e or μ .

  Likelihood ratio L_e >0.9 and L_μ > 0.9
- Energy of the extra photon candidates should be <0.2GeV

4 π candidates (π ^{0})

$$S_{\gamma\gamma} = \frac{(m_{\gamma\gamma} - m_{\pi^0})}{\sigma_{\gamma\gamma}}$$

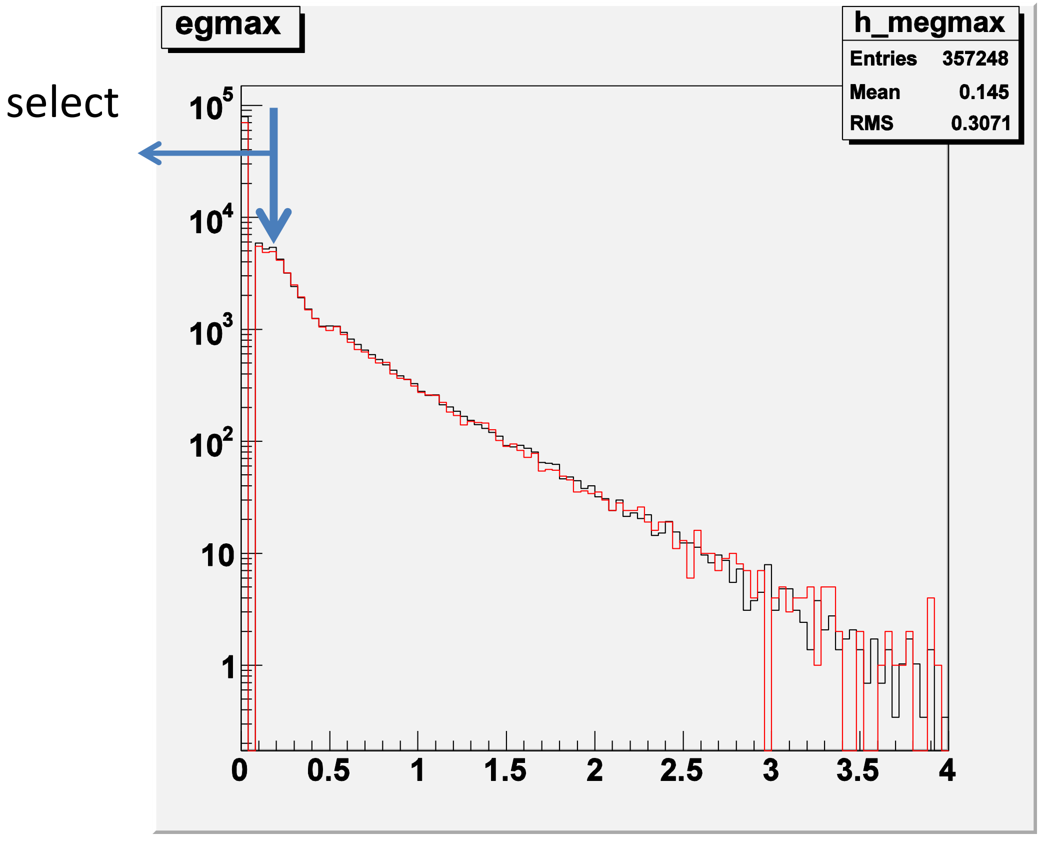




- Resolution: 4 MeV – 10 MeV
- Arrows show the signal region.

$$-6 < S_{\gamma\gamma} < 5$$

Extra photon Energy



$E_{\gamma}^{Extra,Max}$ (GeV)

Data:

MC: TAUOLA

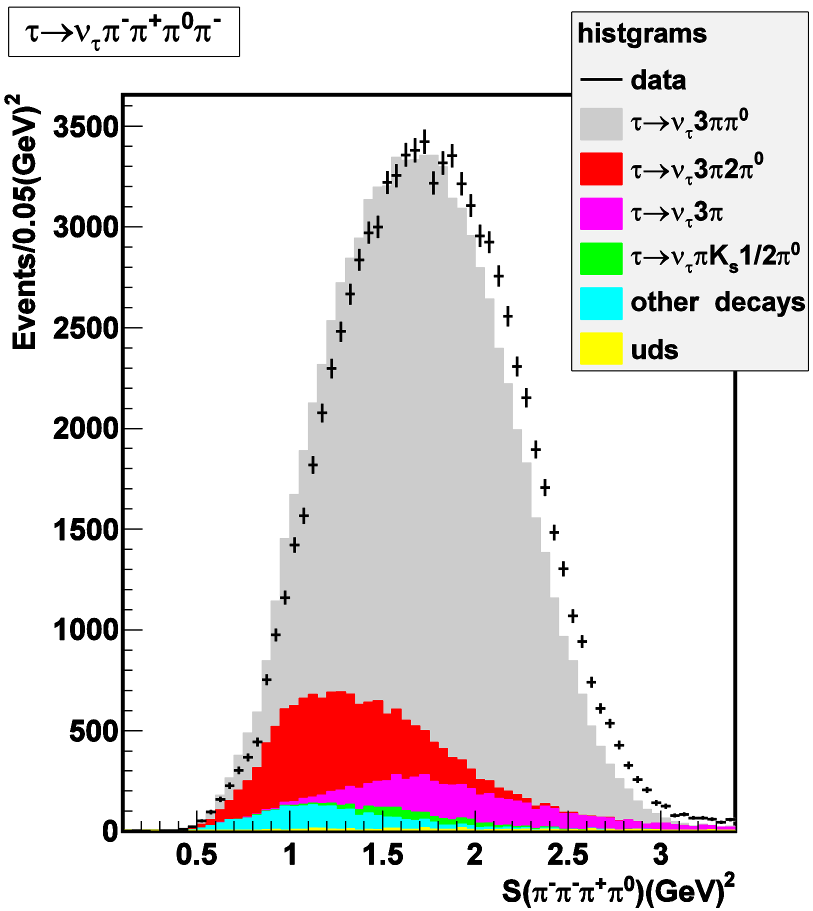
including Background

Normalized to the luminosity

Insensitive to the cut position.

4 π mass^2 distribution

- Plotted with $s = (m_{4\pi})^2$



Gray: 4 π signal MC (TAUOLA)

- TAUOLA 4 π spectrum is based on the $e^+e^- \rightarrow 4\pi$ data taken by CMD-2 and SND experiments at Novosibirsk)
- There is a systematic shift btw data and MC
- Background:

Mode	fractions (%)
3 π 2 π ^{0}	4.88
3 π	4.20
3 π ≥3 π ^{0}	0.20
K2 π π ^{0}	0.22
π Ks ≥1 π ^{0}	0.88
other τ decays	0.70
qq continuum	0.47
Total	11.6

Particle identification

- Method for calibrating Particle Identification

  Control sample for efficiency correction.

- e/ μ two-photon events

  $\eta_e^{cor} \approx 0.981 \pm 0.008$

  $\eta_\mu^{cor} \approx 0.974 \pm 0.005$

  $e^+e^- \rightarrow e^+e^-\ e^+e^-$, $e^+e^-\ \mu^+\mu^-$, Bhabha, $\mu^+\mu^-$

  prepare correction table as a function of p, θ

- π /K $D^{*+} \rightarrow \pi^+ D^0\ (D^0 \rightarrow \pi^+ K^-)$

  $\eta_\pi^{cor} = 0.971 \pm 0.007$

  prepare correction table as a function of p, θ

- π^0

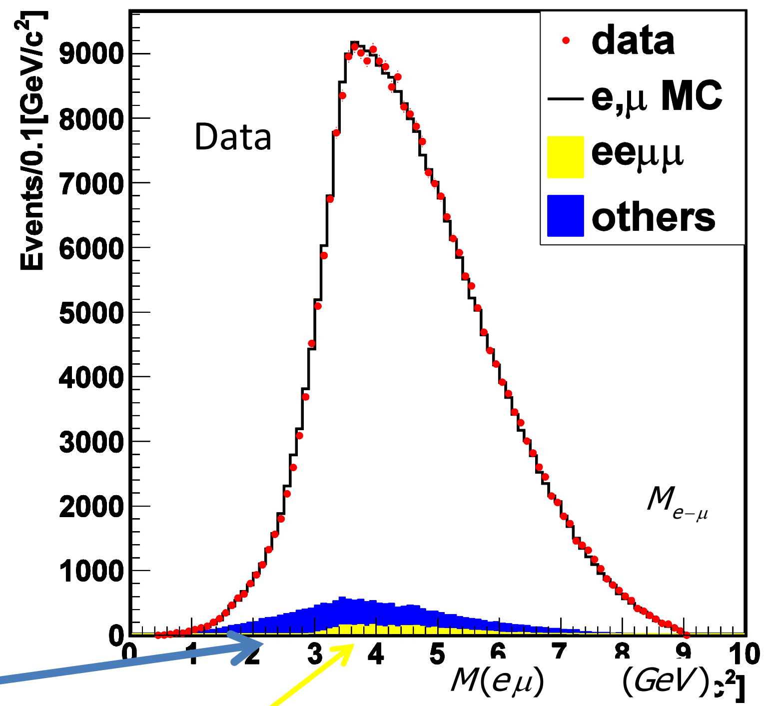
$$R = \frac{N(\tau^- \rightarrow h^- \pi^0 \nu_\tau, \tau^+ \rightarrow h^+ \pi^0 \nu_\tau)}{N(\tau^- \rightarrow h^- \pi^0 \nu_\tau, \tau^+ \rightarrow l^+ \nu_l \nu_\tau)}$$

$\eta_{\pi^0}^{cor.} \approx 0.951 \pm 0.013$

e- μ events: properties

- Selection
  - 2 good tracks with net Q=0
  - Acoplanarity $\theta_{acop} > 1^{\circ}$ (reject Bhabha)
  - Electron and muon ID
    $P_{e/\pi} > 0.9$, $P_{\mu/\pi} > 0.9$
- Background

Mode	fraction
π - e	1.57 %
ρ - e	0.40 %
π - μ	0.13 %
K - e	0.15 %
Other tau decays	0.13 %
e e μ μ	1.54 %
Total	3.94



- Red points : data
- Black histogram :MC
- Normalized by luminosity
- Including e/ μ ID correction(2-3 %)
- Yield is consistent with the expectation within 1.0 %.

Systematic uncertainty

- Br measurements
  - Main systematic is from the uncertainty of the calibration constant.

Error Source	B/B (%)	Sources
Tracking efficiency	0.7	Track finding
Particle identification	1.5	Uncertainty of correction factor.
π^0 reconstruction	1.5	Correction fac.
Background (other τ decays)	0.3	Background Br
Background (qq continuum)	0.3	Control. Stat.
Photon veto	1.2	E_γ spectrum dif.
Trigger efficiency	0.8	
Hadron decay model	0.7	MC-data difference
Total uncertainty	2.8	

Preliminary

Branching Fraction Results

$$B_{4\pi} = \frac{N_{4\pi-l}(1-b_{4\pi-l})}{\eta_{4\pi-l}} \times \frac{\eta_{e-\mu}}{N_{e-\mu}(1-b_{e-\mu})} \times \frac{B_e B_\mu}{(B_e + B_\mu)}$$

$$B(\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau)_{ex\ K^0} = (4.38 \pm 0.02(stat.) \pm 0.12(sys.)) \quad \%$$

(This is the branching fraction excluding K^0)

Preliminary !!

- Based on subset of data set (25 fb^{-1})
- Dominated systematic errors
- Consistent with PDG av. within 1 σ .
- On going efforts for reducing systematic errors.

Br(4 π)	
(4.60±0.06±0.06) %	ALEPH
(4.19±0.10±0.21) %	CLEO
(4.48±0.06) %	PDG 2012

Invariant mass measurement

- Unfolding
- Finite efficiency and resolution and ISR effect should be removed from the measurement spectrum.

$$\mathbf{b} = A\,\mathbf{x}$$

$$\mathbf{b}: \textit{observed spectrum}$$

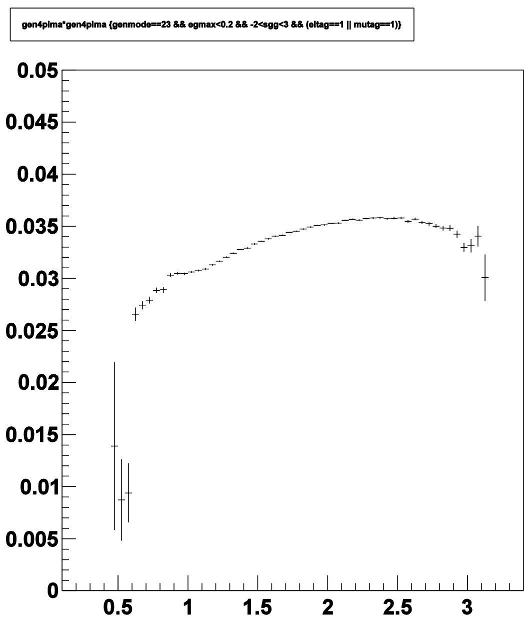
$$\text{A: efficiency matrix}$$

$$\mathbf{x}: \text{"true" spectrum}$$

- We need some unfolding technique since A^{-1} has singularity (unstable) for the statistical fluctuation of the MC events.
- We use Singular-Value-Decomposition (SVD) method for the unfolding.
- This is now available in the name TSVDunfold in the ROOT package.

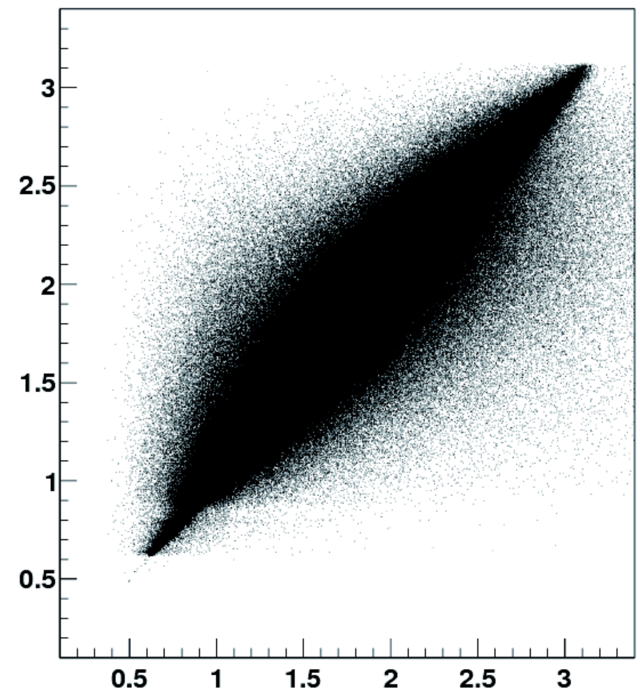
Efficiency and smearing effects

Efficiency



s (GeV)^2

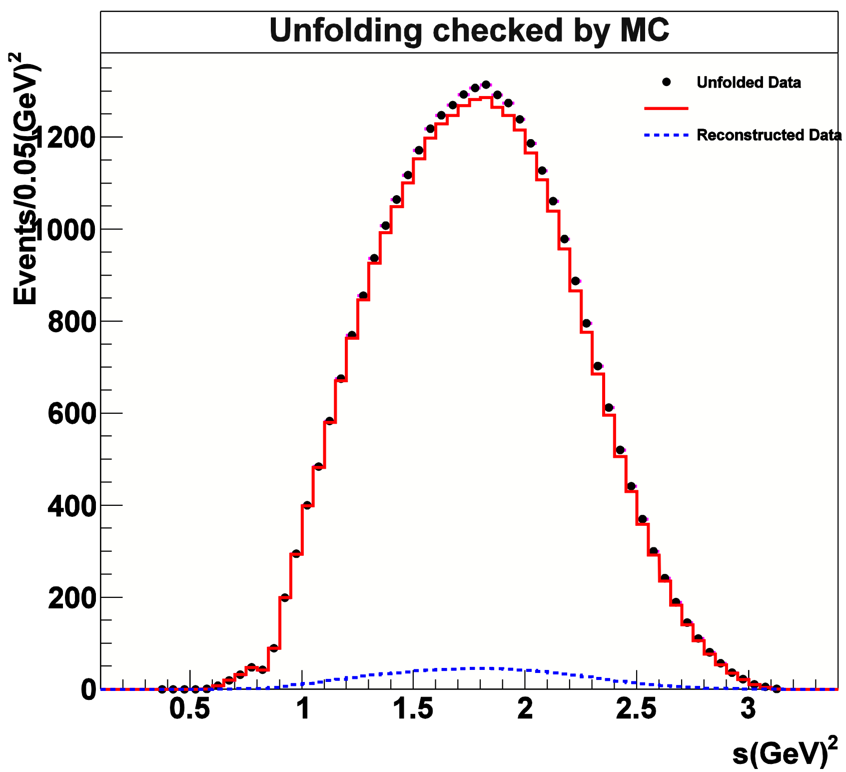
Observed s



Generated s

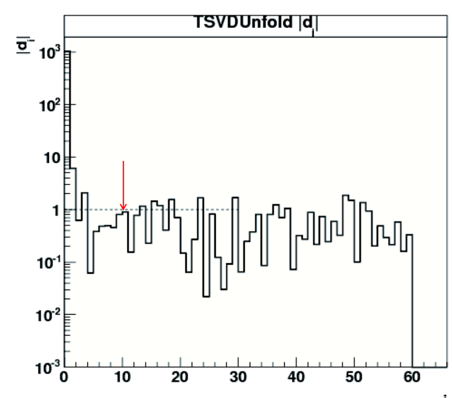
Test of the SVD unfolding (MC)

- In order to test the unfolding procedure, we used two statistically independent MC samples.
  - One for efficiency determination, the other for "data"



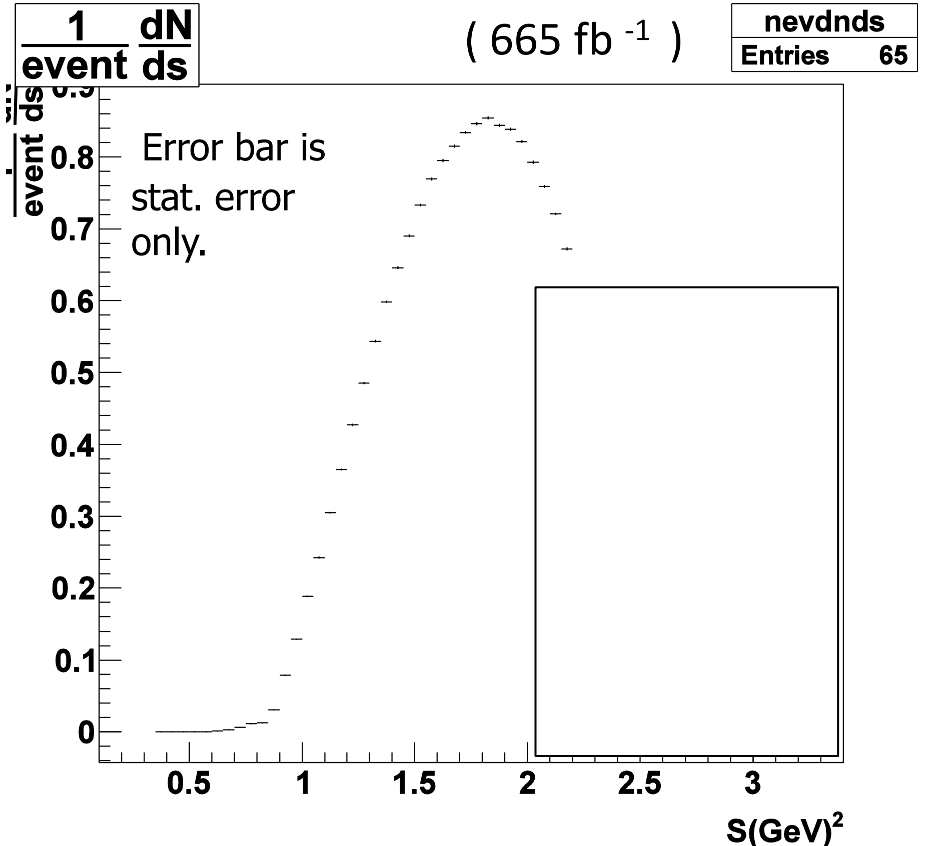
Closed circles: Unfolded results
Red histogram : True distribution

A plot used to determine the regularization parameter .

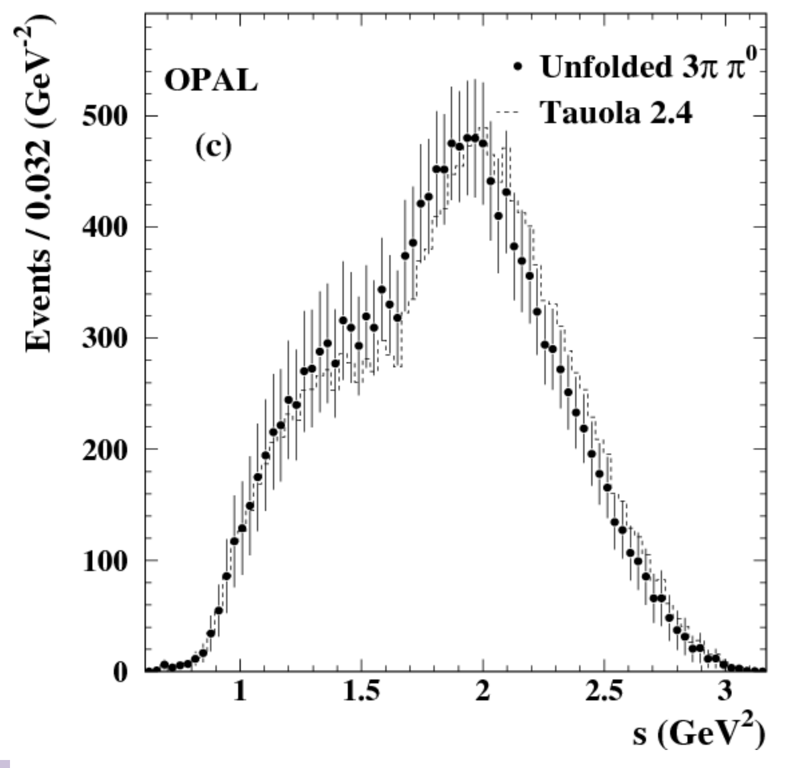


Unfolded spectrum for data

Belle unfolded $3\pi\ \pi^0$ spectrum



OPAL unfolded $3\pi\pi^0$ spectrum



* Smoothly distributed. No shoulder like structure at s= 1.5 GeV^2 is seen.

Summary

- We report the branching fraction and the invariant mass-square spectrum of the decay

  $\tau^- \longrightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$

- The branching fraction is measured to be

$$B(\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau)_{ex\ K^0} = (4.38 \pm 0.02(stat.) \pm 0.12(sys.))\%$$

(preliminary)

  - Based on the subset of dataset(25fb^{-1}).
  - On going efforts for reducing systematic errors.

- The unfolded spectrum is under investigation. Understanding of the 5 π background is important .

Backup

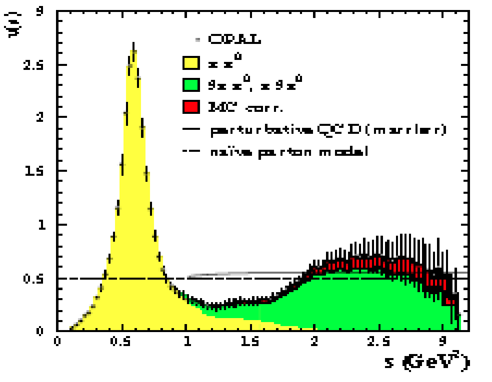
Tau2012 Talk by M. Golterman

"master" equation:

$$\int_0^{s_0} ds\, w(s)\, \rho_{\rm exp}(s) = -\frac{1}{2\pi i}\oint_{|z|=s_0} dz\, w(z)\, \Pi_{\rm OPE}(z) - \frac{1}{\pi}\int_{s_0}^{\infty} ds\, w(s)\, {\rm Im}\,\Pi_{\rm DV}(s)$$

$w(s)$ polynomial weight (picks out condensates)

$\rho_{\rm exp}(s)$ inclusive spectral function from experiment:



$\Pi_{\rm OPE}(z)$ perturbation theory ($\alpha_s(m_\tau^2)$)
plus OPE condensates

$\Pi_{\rm DV}(z) = \Pi_{\rm QCD}(z) - \Pi_{\rm OPE}(z)$ Duality Violations not small near Minkowski axis! (OPE ≠ spectral function)

Assume: $\frac{1}{\pi}{\rm Im}\,\Pi_{\rm DV}(s) = e^{-\gamma s-\delta}\sin\left(\alpha+\beta s\right)$, and take s_0 large enough
however $s_0 \leq m_\tau^2$!

Based on asymptotic behavior of Regge-inspired model (Blok, Shifman & Zhang '98, Bigi et al. '99, Catà, MG & Peris '05 & '08, Gonzalez-Alonso, Pich & Prades '10)