

Bundesministerium für Bildung und Forschung

GEFÖRDERT VOM







Modeling Tau Decays for the Energy and Luminosity Frontiers.

<u>Outline</u>

Introduction - τ Phyiscs

CAP Congress 2014 16.06.2014

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III. Physikalisches Institut B RWTH Aachen University The BaBar Experiment Hadronic τ Decays Modelling τ Decays The CMS Experiment Motivation: Tau on the energy Frontier Simulation of τ on CMS Summary & Outlook

Introduction



Physics at the LHC:

- Study electro-weak physics
- → SM Measurements: W \rightarrow τν, Z \rightarrow ττ
- \rightarrow Higgs $\rightarrow \tau \tau$
- Search for new physics:
- → Susy
- → Lepto-quarks
- → Charged Higgs Doublet
- Modeling τ Decays for the Energy and Luminosity Frontiers Ian M. Nugent | III. Physikalisches Institut B | 16.06.2014

 τ are the heaviest of the leptons and provide unique oppertunities Physic at B-Factories:

- Searches for new Physics
 - → Lepton Flavour Violations
 - → CP Violation
- Study electro-weak physics
 - → Electro-weak couplings: $|V_{us}|/g_e/g_{\mu}/g_{\tau}$
 - → Michel Parameters
 - → τ EDM
- Low energy QCD
 - $\rightarrow \alpha(s)$ strong
 - \rightarrow g-2 measurements
 - → Second Class Currents
 - → Resonances structure
 - \rightarrow K₁(1280) and K₁(1400) mixing
 - τ properties
 - → mass, life-time, ...

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SLAC and **BaBar**

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LCLS Far Ha

3

The BaBar Detector is located on the PEP II, an e⁺e⁻ collider, at SLAC. Collected data from 1999-2008. $e^+e^- \rightarrow \gamma^* \rightarrow \Upsilon(nS)$ CUSB threshold Γ_{15.25.35}~ 20-50 keV (qu) 20 15 10 Beam energy spread ~ 5 MeV B Γ_{4s}~ 20 MeV σ(e⁺-1-10-1- 1- A-A Ϋ́(4S) r(1S) Y(2S) Ϋ́(3S) 9,44 9,46 10,00 10,02 10.34 10.37 10.54 10.58 10.62 Mass (GeV/c^2)

BABAR collected about 531 fb⁻¹ of data

- ~470 x 10⁶ events Y(4S)
- ~120 x 10⁶ events Y(3S) (10x Belle)

Modeling τ **Decays for the Energy and Luminosity Frontiers** ~100 x 10⁶ events $\Upsilon(2S)$ (10x CLEO) **Ian M. Nugent** | III. Physikalisches Institut B | 16.06.2014 ~ 18 x 10⁶ events $\Upsilon(1S)$ from $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$

BaBar Detector

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Extracting $|V_{us}|$ in τ Decays

Branching Ratio

Theory Uncertainty: 0.5% $\frac{B(\tau^{-} \to K^{-} v_{\tau})}{B(\tau^{-} \to \pi^{-} v_{\tau})} = \frac{f_{K}^{2} |V_{us}|^{2}}{f_{\pi}^{2} |V_{ud}|^{2}} \frac{(1 - m_{K}^{2} / m_{\tau}^{2})^{2}}{(1 - m_{\pi}^{2} / m_{\tau}^{2})^{2}}$

Branching Fraction

Theory Uncertainty: 0.7%

$$B(\tau \to K\upsilon) = \frac{G^2 \tau_{\tau} m_{\tau}^3 f_K^2 S_{EW} |V_{us}|^2}{16\pi\hbar} \left(1 - m_K^2 / m_{\tau}^2\right)^2$$

Finite Energy Sum Rules

Theory Uncertainty: 0.2-0.5%

$$|V_{us}|^{2} = \frac{R_{\tau,strange}^{w}}{R_{\tau,non-strange}^{w} / |V_{ud}|^{2} - \delta R_{\tau}^{w}}$$

Requires SDF for Finite Energy Sum Rules:

Branching fraction for all τ decay modes Invariant mass for all measured τ decay modes Upper limit on all unobserved τ decay modes



τ at the B-Factories

τ -Pair Signature:

Leptonic vs Hadronic Decay



Backgrounds	Discriminants
Bhabha, μ-pair	Lepton Momentum Multiplicity Conversion veto $\cos(\theta)$
Two-Photon	Missing Transverse Momentum Missing Mass cos(θ ^{Miss}) Thrust Total Reconstructed Energy
e⁺e⁻→ qq q=u,d,s,c,b	Thrust Invariant mass Multiplicity

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Once the τ -pairs are identified, selection criteria are applied to the signal hemisphere: -K/ π separation -Neutral Identification: π^0, η, γ

Unfolding Procedure

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Distributions are unfolded to remove detector scale and resolution effect and are efficiency corrected to obtain the true distribution...



Hadronic Structure of $\tau \rightarrow hhhv$



1.6

1.6

P5

1.6

 $M(K^{T}\pi^{T}K^{+})$ (GeV/c²)

1.4

BABAR preliminary

1.7

BABAR preliminary

1.7

 $M(K^{T}K^{T}K^{+}) (GeV/c^{2})$

M(K⁻K⁻K⁺) (GeV/c²)

BaBar-Preliminary [arXiv:1301.7105] **Cross-Feed** Other τ-Bkg **Other Bkg** Events/(10MeV/c²) 00000 00000 Events/(10MeV/c² Events/(10MeV/c² Events/(10MeV/c² BABAR preliminary BABAR preliminary BABAR 1000 preliminary 2000 20 500 20000 1000 10 10000 0 1.2 1.6 0.5 1.5 1.4 1.6 1.2 1.4 Ť.5 1 $M(\pi \pi \pi^{+}) (GeV/c^{2})$ M(K π π⁺) (GeV/c²) M(K⁻π⁻K⁺) (GeV/c²) **CLEO Tauola Tune'98 BaBar Tauola MC Stat.Error (Data)** Stat.⊕Svs. Error (Data) ([dN/dM(π⁻π⁻π⁺)]/N)/(10MeV/c²) 0.03 [[dN/dM(K⁻π⁻K ⁺)]/N)/(10MeV/c²) 0.06 [dN/dM(K⁻π⁻π⁺)]/N)/(10MeV/c² [dN/dM(K⁻K⁺)]/N)/(10MeV/c² BABAR preliminary BABAR preliminary BABAR preliminary 0.04 0.1 0.02 0.04 0.03 0.02 0.05 0.01 0.02

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1.2

1.4

1.6

 $M(K^{-}\pi^{-}\pi^{+})$ (GeV/c²)

1.2

0.0

1.5

 $M(\pi^{-}\pi^{-}\pi^{+})$ (GeV/c²)

0.5

Hadronic Structure of $\tau \rightarrow hhhv$



BaBar-Preliminary [arXiv:1301.7105]



Hadronic Structure of $\tau \rightarrow \pi \pi \pi \nu$



The CLEO, OPAL, DELPHI, ARGUS, + ... Experiments have used model dependent Fits: Törnqvist Unitarized Quark Model, Kühn Santamaria Model, Isgur, Morningstar and Reader (IMR) Model, Flux Tube Models, + ...

[Nucl.Phys.Proc.Suppl. 123 (2003) 40-46], [Z.Phys. C75 (1997) 593-605] [Phys. Lett. B bf 426, 411 (1998)], [Phys.Rev. D61 (2000) 012002] and many more ...

"The models used are not unique, as significant variations in their form and content can lead to similar features in the distributions of observable quantities. In addition, no model has so far given a fully satisfactory description of the data."

[Phys.Rev. D61 (2000) 052004]

Hadronic Structure of $\tau \rightarrow \pi \pi \pi \nu$

Moments for the structure functions have been measured based on the method proposed by:

[Z. Phys. C 56, 661 (1992) and Erratum Z. Phys. C67, 364 (1995).]

Both the OPAL and CLEO experiments have the structure functions where α has been integrated over. [Z.Phys. C75 (1997) 593-605][Phys.Rev. D61 (2000) 052004]



 $W_{4} = (x_{1}^{2} + x_{3}^{2})|F_{1}|^{2} + (x_{2}^{2} + x_{3}^{2})|F_{2}|^{2} + 2(x_{1}x_{2} - x_{3}^{2})\operatorname{Re}(F_{1}F_{2}^{*}),$ $W_B = x_4^2 |F_3|^2$, $W_{\rm C} = (x_1^2 - x_3^2)|F_1|^2 + (x_2^2 - x_3^2)|F_2|^2 + 2(x_1x_2 + x_3^2)\operatorname{Re}(F_1F_2^*),$ $W_{D} = 2[x_{1}x_{3}|F_{1}|^{2} - x_{2}x_{3}|F_{2}|^{2} + x_{3}(x_{2} - x_{1})\operatorname{Re}(F_{1}F_{2}^{*})],$ $W_E = -2x_3(x_1 + x_2) \operatorname{Im}(F_1 F_2^*),$ $W_F = 2x_4 [x_1 \operatorname{Im}(F_1 F_3^*) + x_2 \operatorname{Im}(F_2 F_3^*)],$ $W_G = -2x_4 [x_1 \operatorname{Re}(F_1 F_3^*) + x_2 \operatorname{Re}(F_2 F_3^*)],$ $W_{H} = 2x_{3}x_{4}[\operatorname{Im}(F_{1}F_{3}^{*}) - \operatorname{Im}(F_{2}F_{3}^{*})],$ $W_I = -2x_3x_4[\operatorname{Re}(F_1F_3^*) - \operatorname{Re}(F_2F_3^*)],$ $W_{SA} = Q^2 |F_4|^2$ $W_{SB} = 2\sqrt{Q^2} [x_1 \operatorname{Re}(F_1 F_4^*) + x_2 \operatorname{Re}(F_2 F_4^*)],$ $W_{SC} = -2\sqrt{Q^2} [x_1 \operatorname{Im}(F_1 F_4^*) + x_2 \operatorname{Im}(F_2 F_4^*)],$ $W_{SD} = 2\sqrt{Q^2} x_3 [\operatorname{Re}(F_1 F_4^*) - \operatorname{Re}(F_2 F_4^*)],$ $W_{SE} = -2\sqrt{Q^2} x_3 [\operatorname{Im}(F_1 F_4^*) - \operatorname{Im}(F_2 F_4^*)],$ $W_{SF} = -2\sqrt{Q^2} x_4 \operatorname{Im}(F_3 F_4^*),$ $W_{SG} = -2\sqrt{Q^2} x_4 \operatorname{Re}(F_3 F_4^*).$

 $\tau \rightarrow K\pi\pi\nu$ - mixing of K₁(1280) and K₁(1400) related to theory error on $|\alpha - \alpha_{eff}|$ $\tau \rightarrow K\pi\pi\nu / K\pi K\nu$ - Wess-Zunimo Anomaly

[Phys. Lett. B37B (1971) 95][Phys.Rev. D47 (1993) 4012-4021]

Fitting the Hadronic Spectra



To improve the modeling of τ decays Tauola authors tuned Tauola using BaBar data Model based on a RCHL model [Phys.Rev. D88 (2013) 093012].

Main discrepancies point to the resonances measured by CLEO and other former experiments...

[Phys.Rev. D61 (2000) 012002] [Nucl.Phys.Proc.Suppl. 123 (2003) 40-46].

 σ model is constructed based on a Breit-Wigner and a exponential function. The large width and numerical instability suggest problems with the σ description.



Hadronic Spectra Tunes

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Legend

- --- BaBar Experiment Tauola MC.
- --- CLEO Experiment Model [Pythia: arXiv:1211.6730] Phys.Rev. D61 (2000) 012002
- --- [Pythia: arXiv:1211.6730] R. Decker, et al., Z.Phys. C58 (1993) 445–452.
- --- Tauola CLEO'98 Tune Comput.Phys.Commun. 174 (2006) 818-835.
- --- RCHL Models Tauola Phys.Rev. D88 (2013) 093012.



Hadronic Spectra Tunes



Legend

- --- BaBar Experiment Tauola MC.
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 [Pythia: arXiv:1211.6730] Phys.Rev. D61 (2000)
 012002.
- --- [Pythia: arXiv:1211.6730] R. Decker, et al., Z.Phys.
 C58 (1993) 445–452.
- Tauola CLEO'98 Tune Comput.Phys.Commun.
 174 (2006) 818-835.
- --- RCHL Models Tauola -Phys.Rev. D88 (2013) 093012.



The CMS Detector







MUON CHAMBERS



Motivation: τ 's at the LHC



Many interesting channels at the LHC contain a τ lepton: SM Bosons, Higgs, SUSY, Lepto-Quarks



 $H \rightarrow \tau \tau$ results from LHC: Atlas (4.2 σ) and CMS (3.2 σ). Expect Z value of greater then 5σ in Run II



Matrix Element

Generator





Monte-Carlo Simulation at CMS

In CMS software framework the MC Generators are built as RPMs which are accessed through interfaces in CMSSW.

Legend



For reproducibility of the MC, the default generators are not allowed to change in a given release series.

To allow for upgrades and patches for the external decays the software was upgraded to use plugins: EvtGen, Photos++, TauSpinner(Tauola++).

Conclusions & Outlook

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τ decays provide a unique opportunity to probe the SM:



Low energy QCD, Electro-weak couplings

Many interesting channels at the LHC contain τ : Higgs/Susy/Lepto-Quarks/... Simulation of τ decays is essential for any

- analysis that uses τ at the LHC.
 - → Upgrade of external generators include:
 - » EvtGen 1.3.0
 - » Tauola++
 - » Photos++





The 13th International Workshop on Tau Lepton Physics Aachen, Germany, 15-19 September, 2014



Electro-Weak physics Hadronic decays and QCD Neutrino physics

Committees

International Advisory Committee Local Organizing Committee



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Thank you! Merci!

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Raw Invariant Mass Distributions







Main background: $\tau^- \rightarrow \pi^- \pi^- \pi^+ \pi^0 \nu$ (~3.6%)

Unfolded Invariant Mass Distributions





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Unfolded Invariant Mass Distributions





Unfolded Invariant Mass Distributions

Invariant mass distributions for: $\tau^- \rightarrow K^- \pi^- K^+ \nu$ ([dN/dM(K⁻π⁻K⁺)]/N)/(10MeV/c²) 0.06 [[dN/dM(K⁺K⁺)]/N)/(10MeV/c² BABAR BABAR preliminary CLEO Tauola Tune (98) preliminary 0.04 0.04 **BaBar Tauola MC** 0.02 0.02 1.6 1.2 1.4 1.2 1.4 Stat. Error (Data) $M(K^{-}\pi^{-}K^{+})$ (GeV/c²) M(K⁻K⁺) (GeV/c²) 0.15([dN/dM(**π**⁻K ⁺)]/N)/(10MeV/c²) [[dN/dM(K⁻π⁻)]/N)/(10MeV/c² BABAR preliminary BABAR 0.04 preliminary Stat. \oplus Sys. Error (Data) 0.1 0.03 0.02 0.05 0.0 0.8 0.8 1.2 $M(\pi^{-}K^{+})$ (GeV/c²) $M(K^{\pi})$ (GeV/c²)

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Raw Invariant Mass Distributions





Cross-Feed

Other τ-Bkg

Other Bkg



Main background: Cross-feed (~28%)

Unfolded Invariant Mass Distributions



Upper edge of M(K-K-K+) Plot: 1.76GeV/c² PDG: $M(v_{\tau})$ <18.2MeV/c² @ 95% CL