MEASURING THE TAU YUKAWA PHASE AT THE LHC AND ILC

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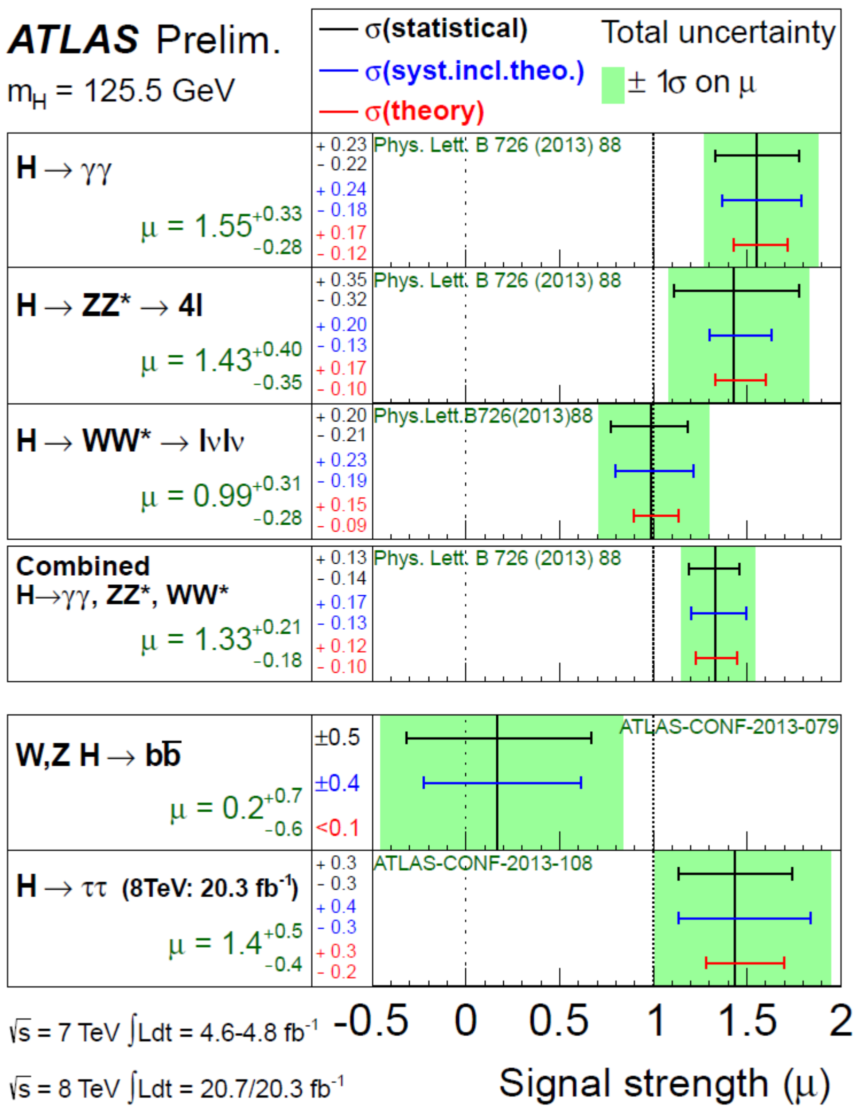
CP and the Higgs

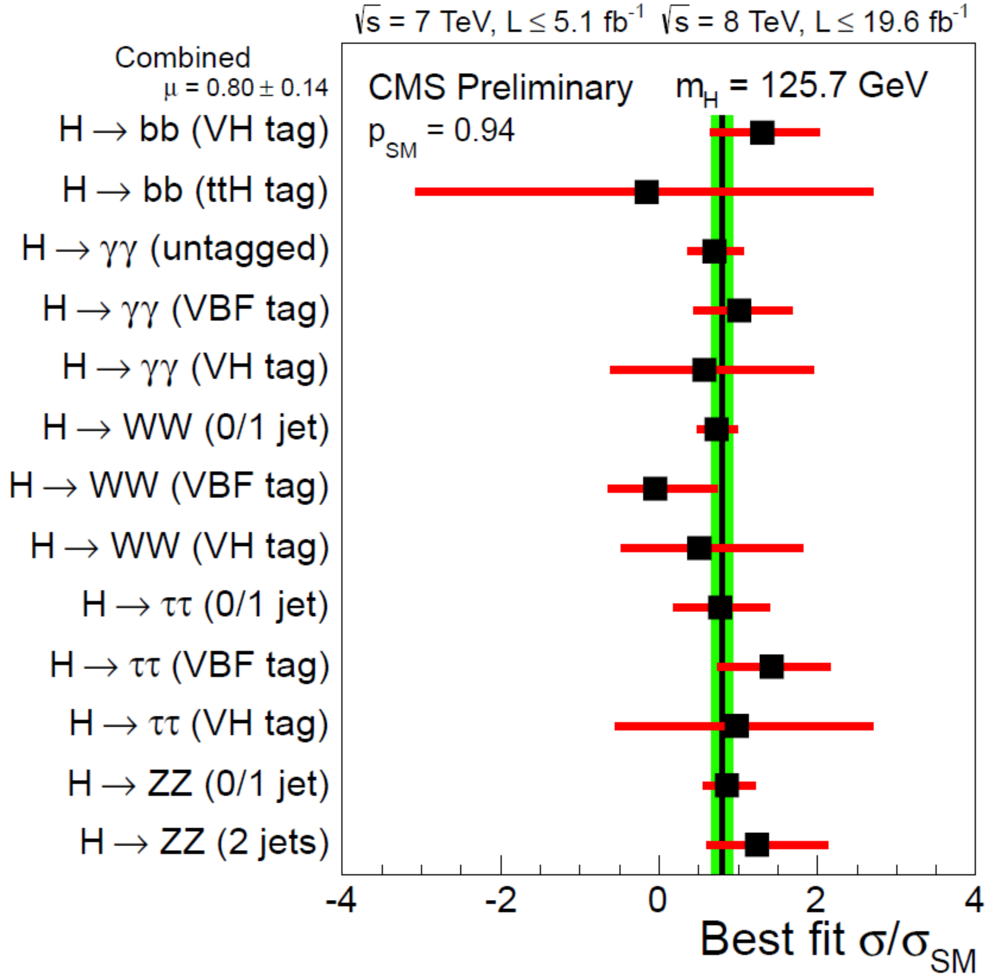
- Sakharov's conditions for baryogenesis motivate searches for new sources of CP violation
- A natural place to test for CP violating phases is with Higgs physics
  - scalar-pseudoscalar admixture
  - couplings to gauge bosons
  - couplings to fermions
    - [full UV models to connect any given CP phase to a baryogenesis mechanism is BTSOTW]

Outline

- Review current status of CP tests in Higgs physics, Higgs decay to taus
- Constructing the Θ variable
- Sensitivity studies at colliders
  - Discuss both e^+e^- machines and LHC (first proposal for an LHC measurement)
  - Comparison with previous proposals
- Summary

Signal strength constraints



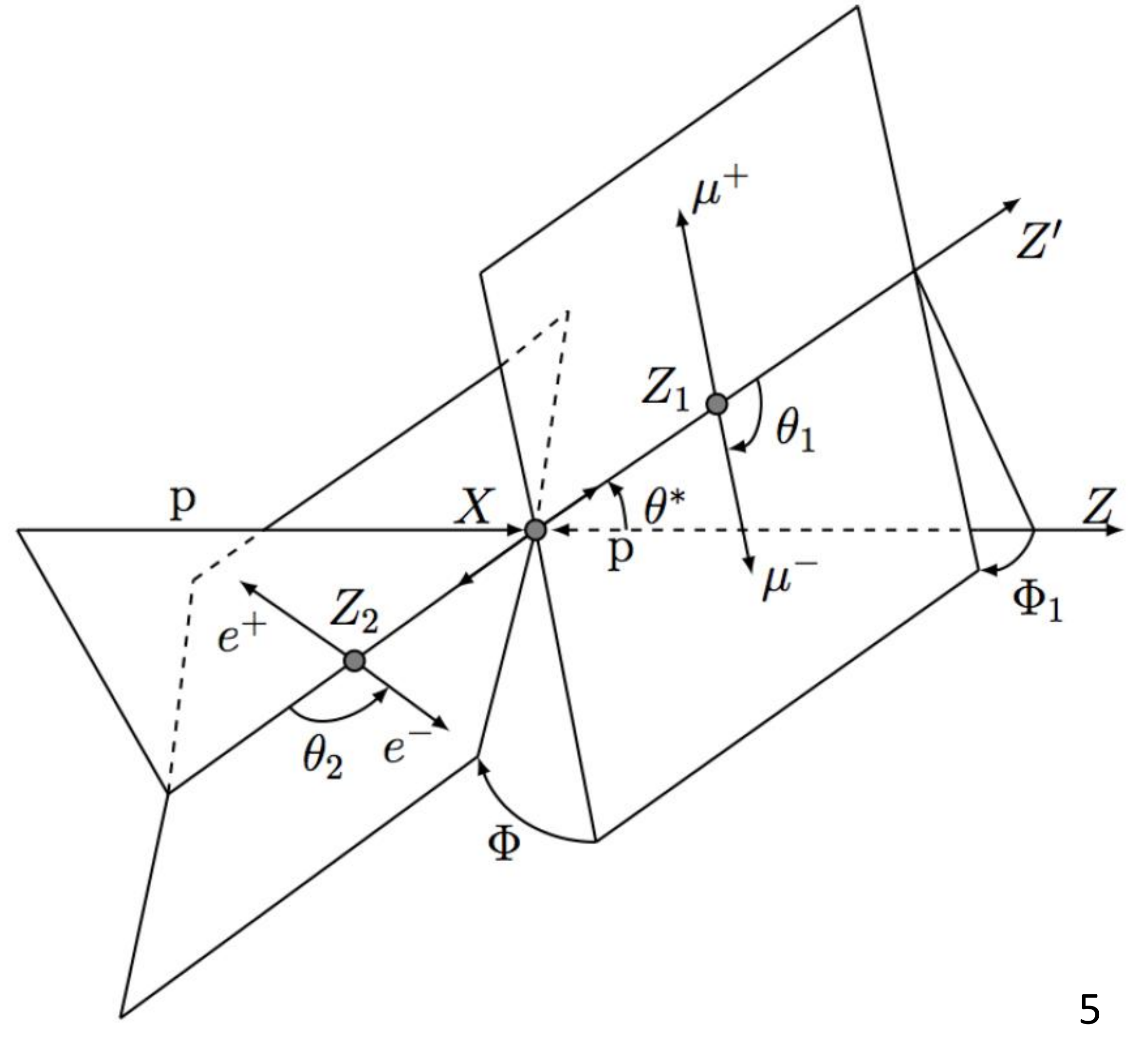


[Separate channel measurements cannot be combined without assumptions!]

ATLAS-CONF-2013-108, CMS PAS-HIG-13-005

Testing CPV in hZZ

- Measure acoplanarity angle (angle between Z_1 and Z_2 decay planes)



Testing CPV in hZZ

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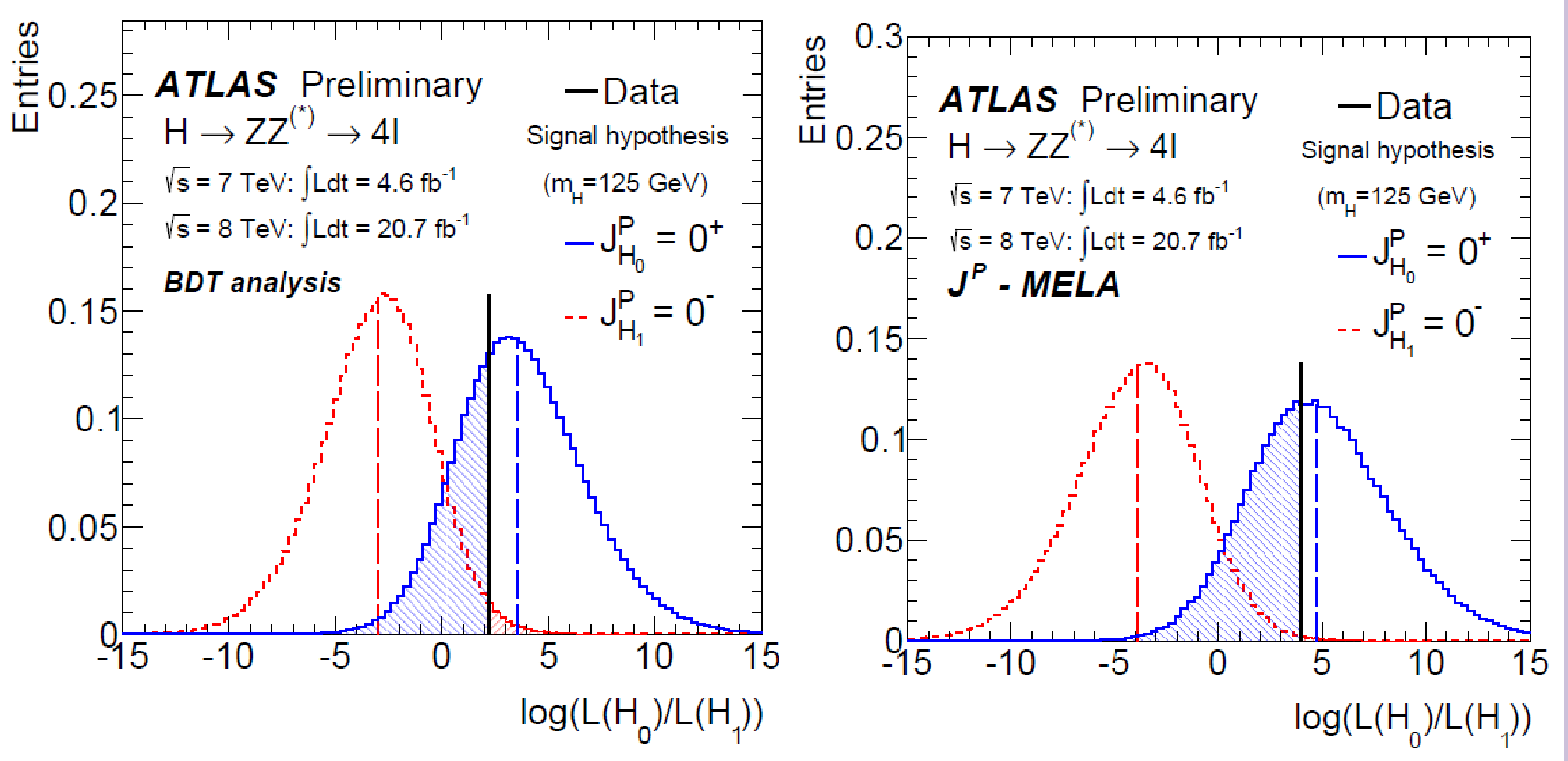


0^- excluded in favor of 0^+ hypothesis at 97.8% C.L.

Testing CPV in hZZ

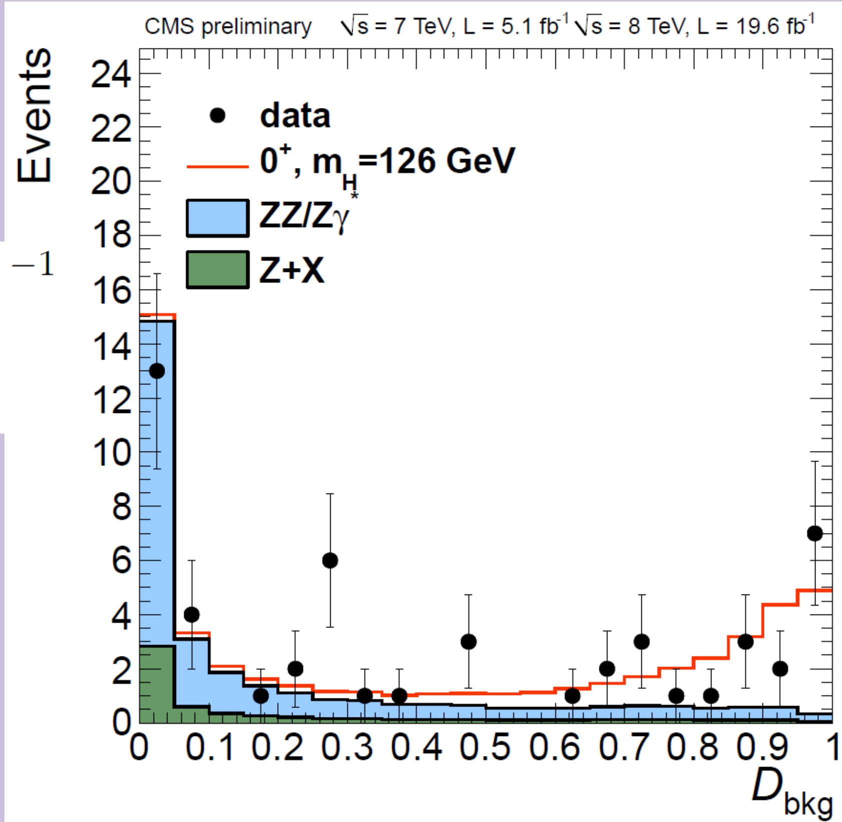
- Can test combination of $hZ_\mu Z^\mu$ and $hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$ couplings

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

$$f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$$

- Use kinematic discriminant

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$



CMS PAS-HIG-13-002

Testing CPV in hZZ

- Can test combination of $hZ_\mu Z^\mu$ and $hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$ couplings

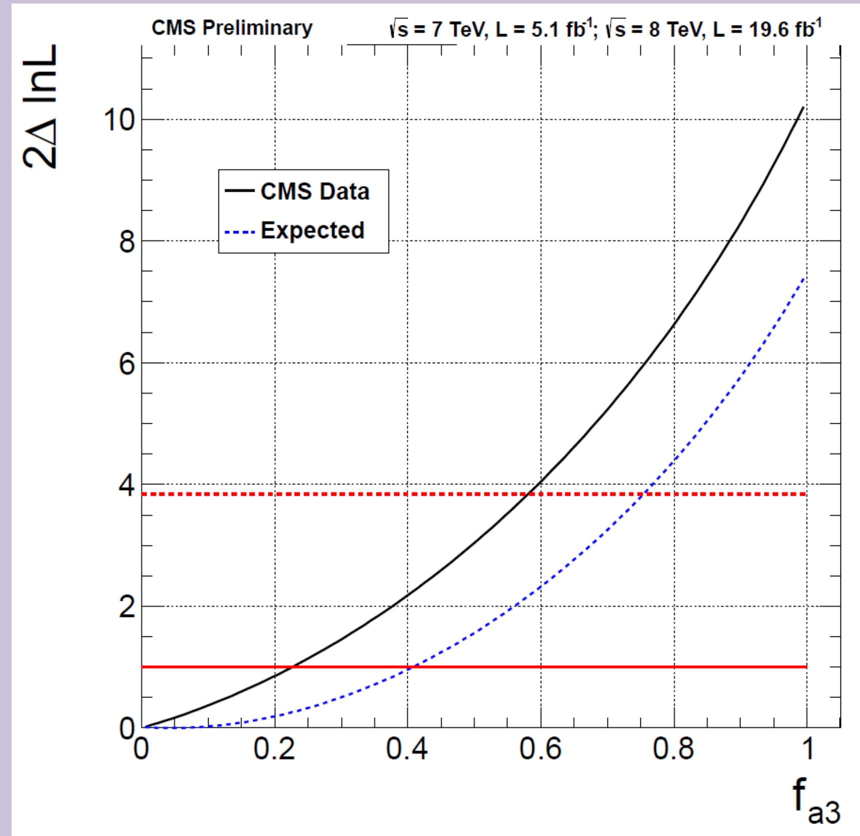
$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

$$f_{a3} = |A_3|^2/(|A_1|^2 + |A_3|^2)$$

- Results in constraint

$$f_{a3} = 0.00^{+0.23}_{-0.00}$$

$$f_{a3} < 0.58 \text{ at } 95\% \text{ CL.}$$



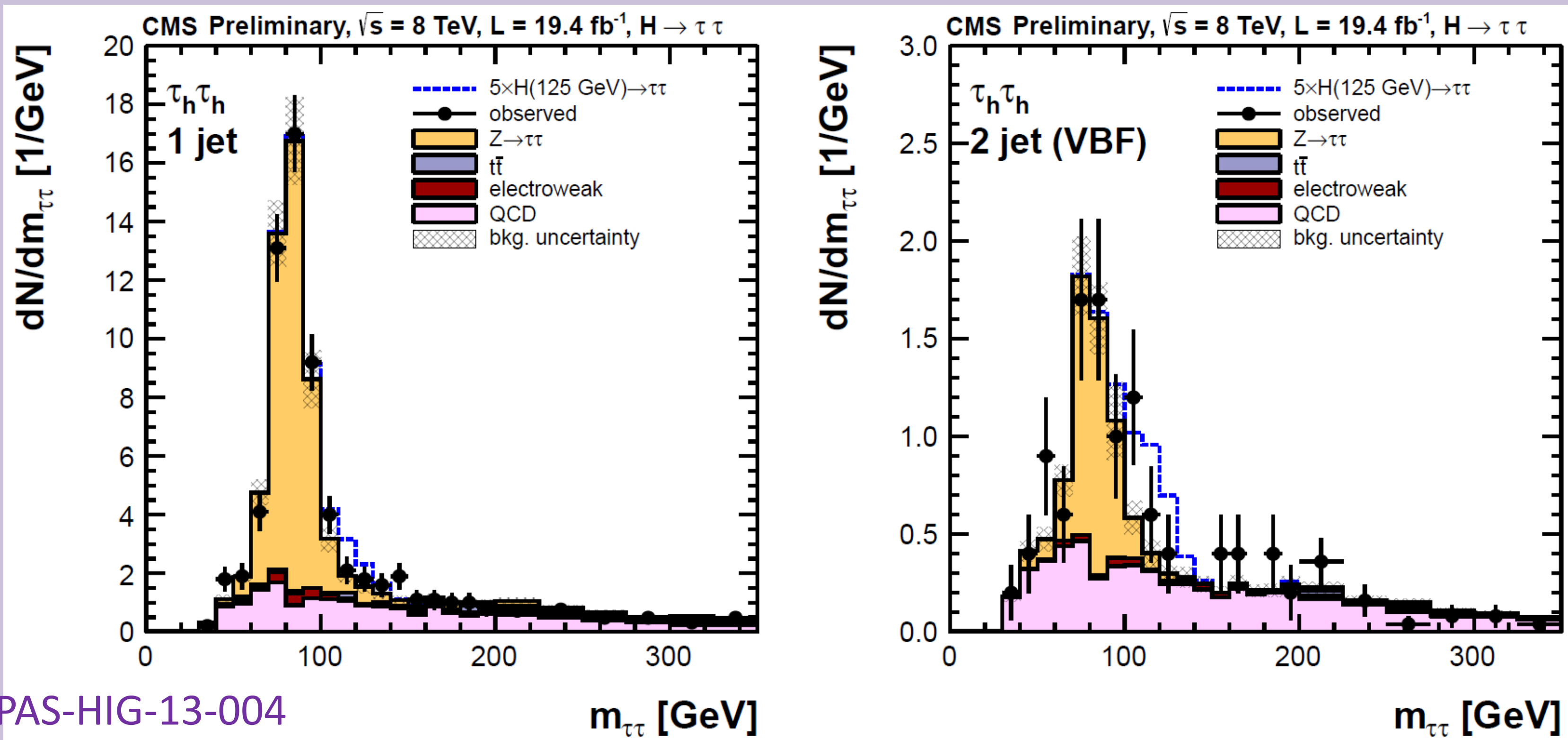
CMS PAS-HIG-13-002

Testing CPV in Yukawa couplings

- Source of a BSM CPV phase in SM Yukawa couplings is distinct from possible phases in the scalar potential or pseudoscalar couplings to gauge bosons
  - Motivates testing for CPV in fermionic couplings even if bosonic CPV coupling tests give null results
- The Higgs decay to taus is the most promising system for direct measurement of fermionic CPV couplings
  - Top coupling only probed via loops or ttH (tH) production
  - Bottom quark polarizations washed out by QCD

Measuring Higgs to ττ

- Use SVFit to reconstruct $m_{\tau\tau}$ (creates likelihood function based on observed kinematics)
  - Anticipating the CP phase measurement, focus on the fully hadronic analysis



CMS PAS-HIG-13-004

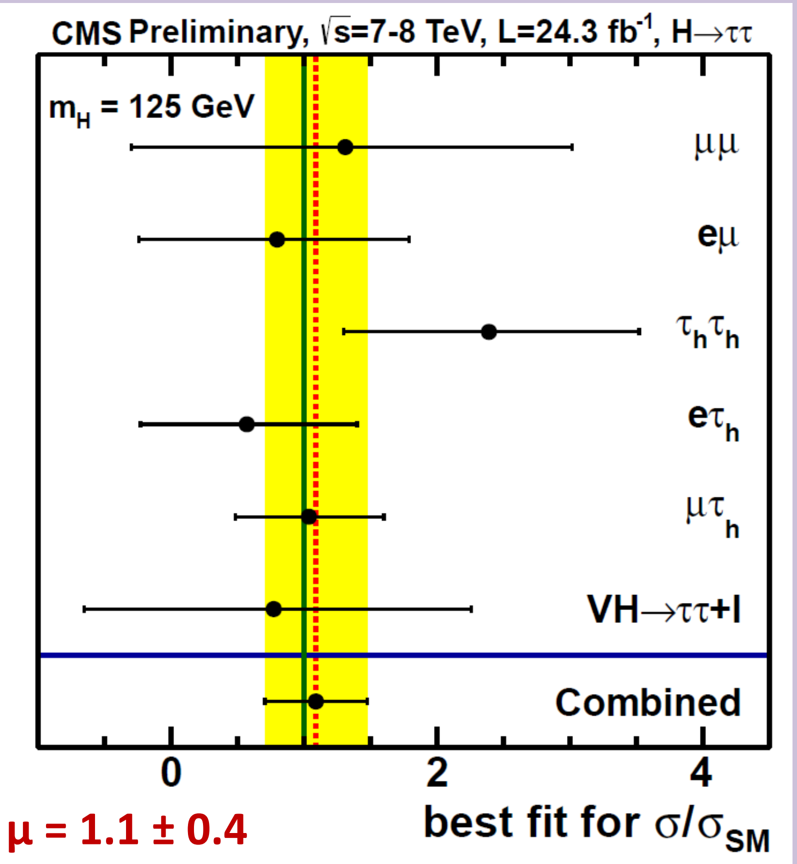
Measuring Higgs to ττ

- Use SVFit to reconstruct $m_{\tau\tau}$ (creates likelihood function based on observed kinematics)
  - Anticipating the CP phase measurement, focus on the fully hadronic analysis

Process	*1-Jet*	*VBF*
$Z \to \tau\tau$	428 ± 90	47 ± 28
QCD	210 ± 31	61 ± 10
EWK	41 ± 9	4 ± 1
$t\bar{t}$	29 ± 6	2 ± 2
Total Background	709 ± 95	114 ± 30
$H \to \tau\tau$	9 ± 4	4 ± 2
Observed	718	120

Signal Eff.

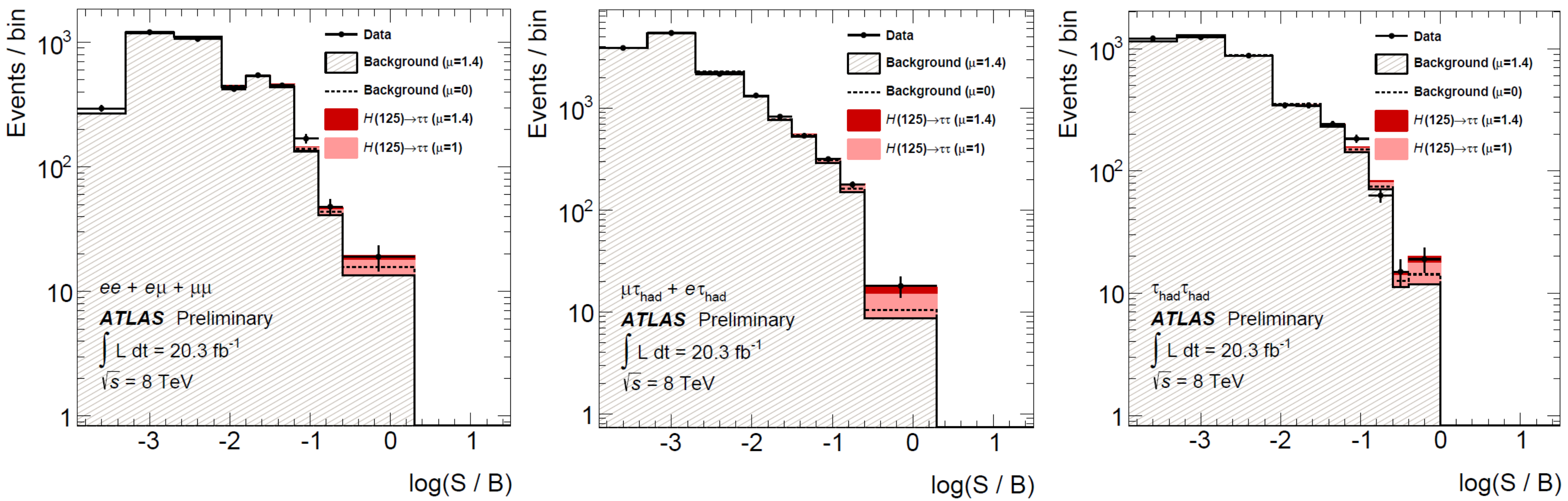
$gg \to H$	$2.52 \cdot 10^{-4}$	$4.99 \cdot 10^{-5}$
$qq \to H$	$5.93 \cdot 10^{-4}$	$1.20 \cdot 10^{-3}$
$qq \to Ht\bar{t}$ or VH	$9.13 \cdot 10^{-4}$	$3.59 \cdot 10^{-5}$



Combined: μ = 1.1 ± 0.4

ATLAS Update

- Use BDT output to categorize events



(a) (b) (c)

ATLAS Update

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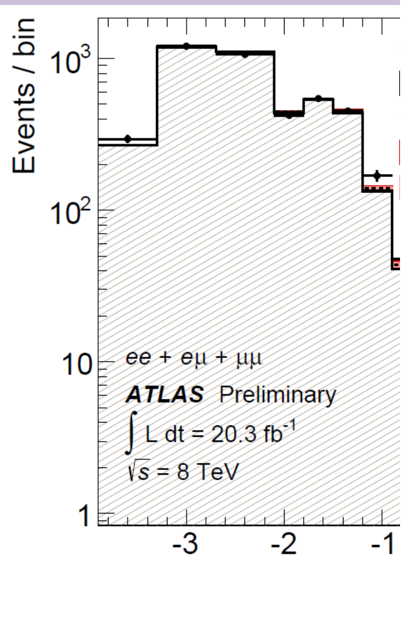
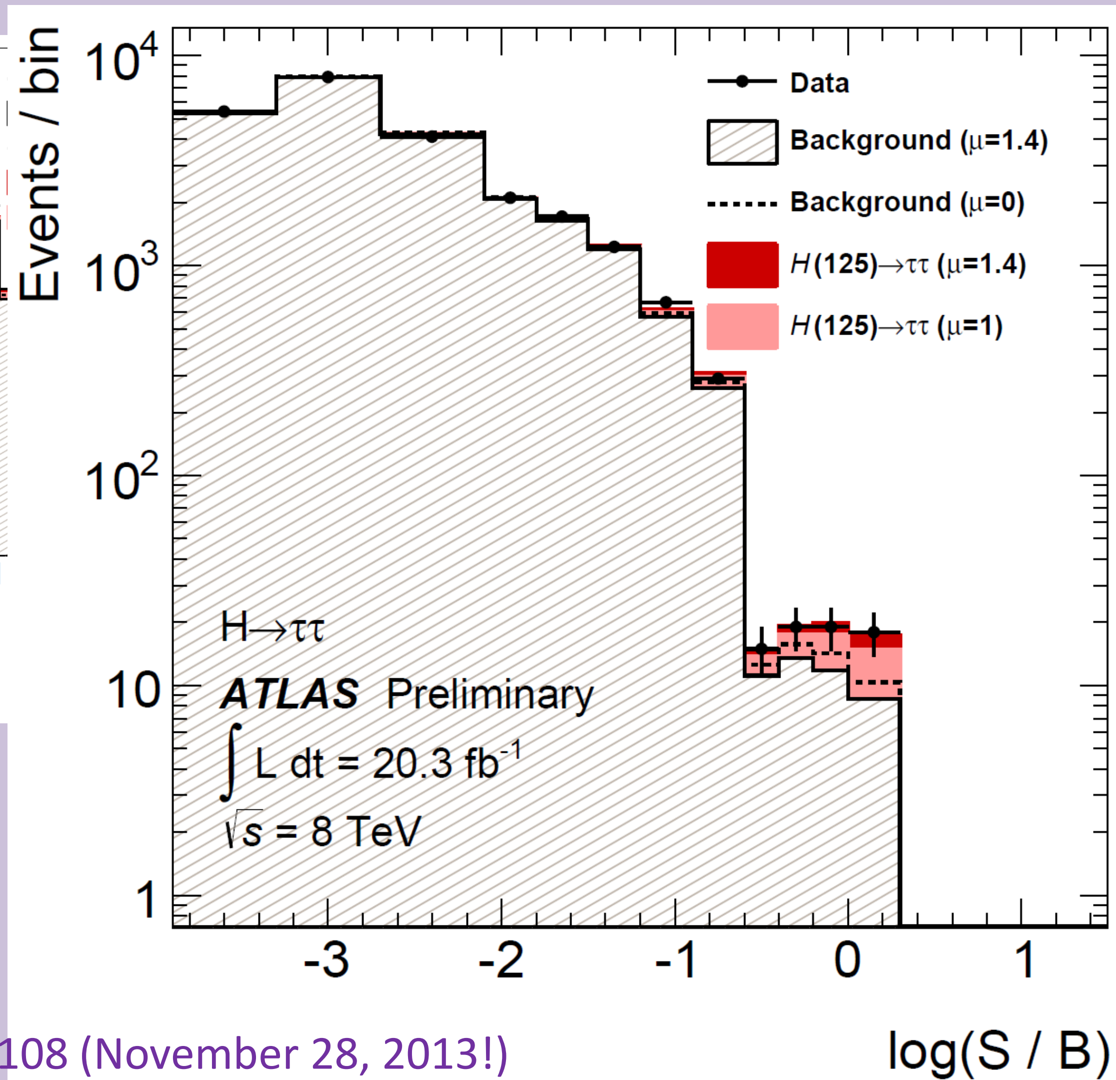
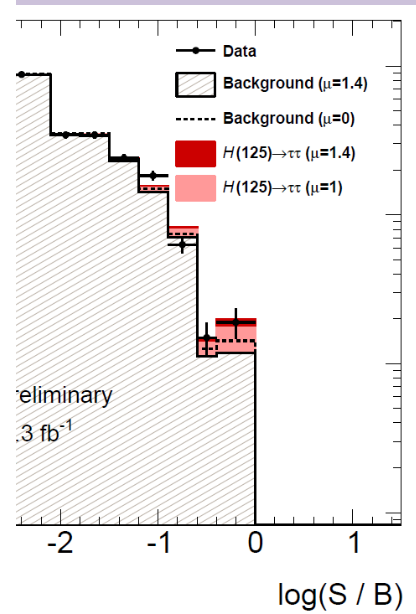


(a)





(c)

ATLAS-CONF-2013-108 (November 28, 2013!)

ATLAS Update

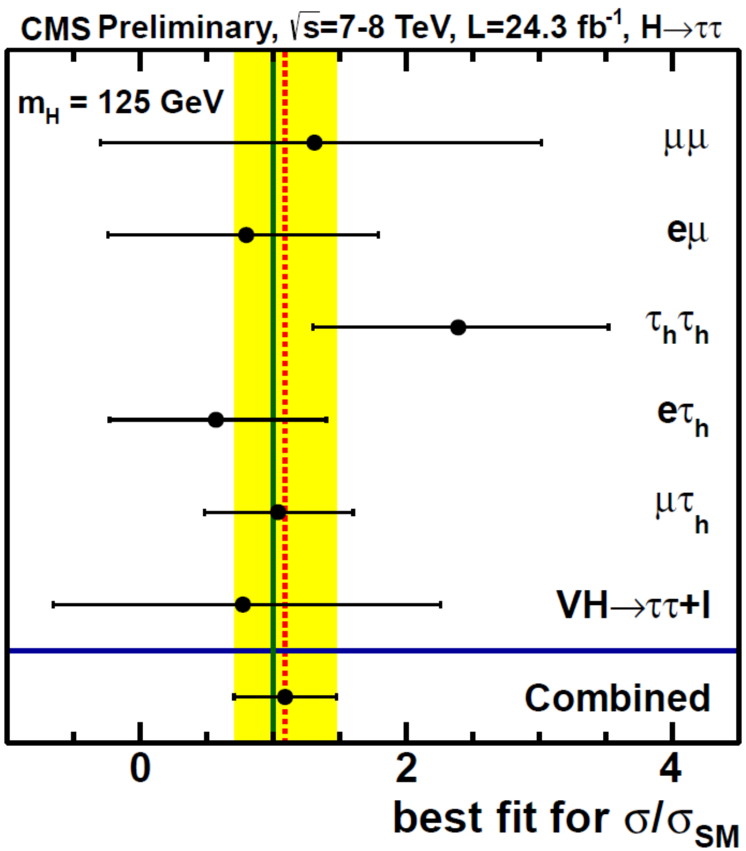
- Focus on fully hadronic channel
  - Main backgrounds are still irreducible Z →ττ and QCD multijets

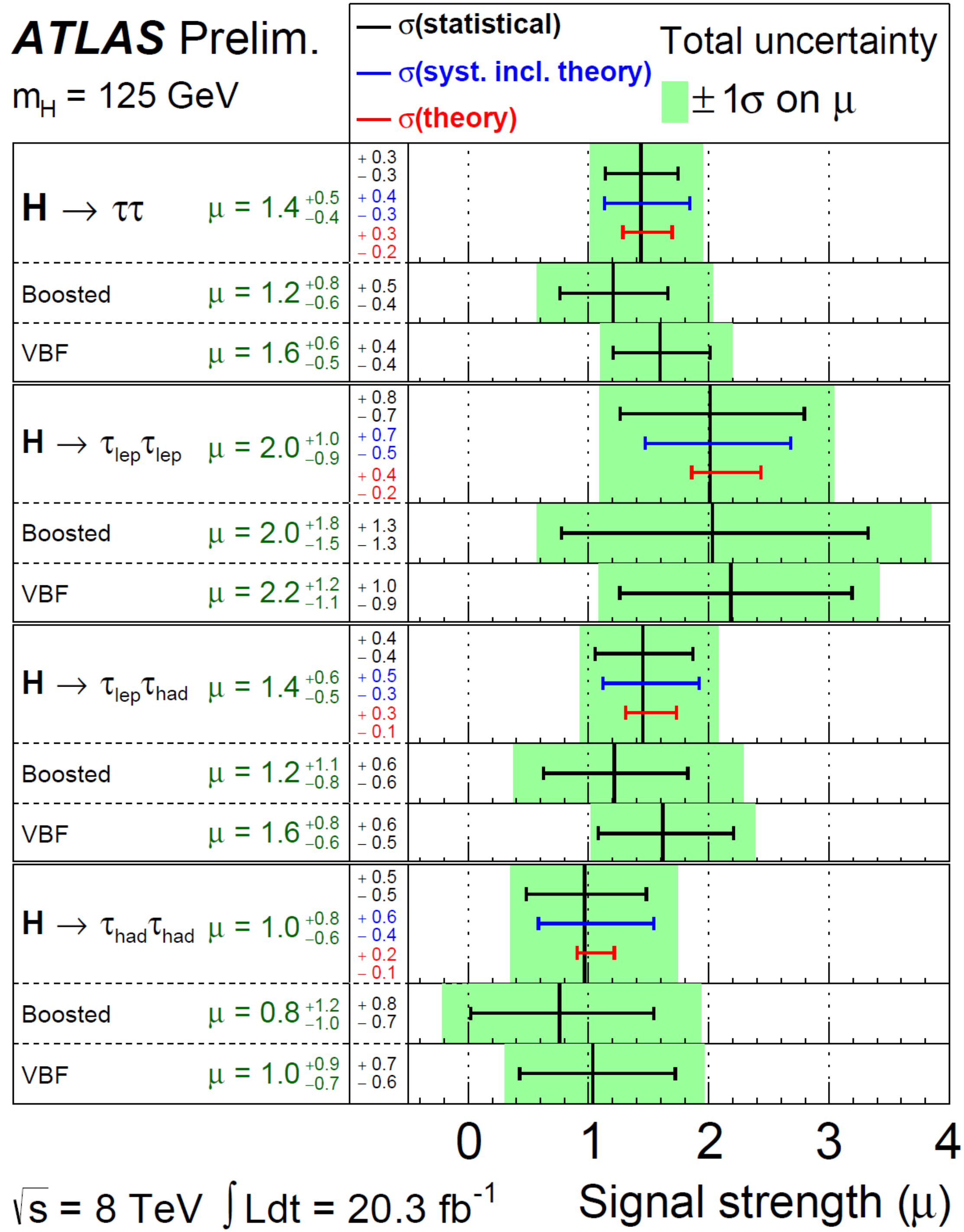
Process/Category	VBF			Boosted		
BDT score bin edges	0.85-0.9	0.9-0.95	0.95-1.0	0.85-0.9	0.9-0.95	0.95-1.0
ggF	0.39 ± 0.17	0.35 ± 0.16	2.0 ± 0.9	2.2 ± 0.8	2.5 ± 1.0	2.3 ± 0.9
VBF	0.57 ± 0.18	0.72 ± 0.22	5.9 ± 1.8	0.55 ± 0.17	0.61 ± 0.19	0.57 ± 0.17
WH	< 0.05	< 0.05	< 0.05	0.34 ± 0.11	0.40 ± 0.12	0.44 ± 0.14
ZH	< 0.05	< 0.05	< 0.05	0.22 ± 0.07	0.22 ± 0.07	0.22 ± 0.07
$Z \rightarrow \tau^+\tau^-$	3.2 ± 0.6	3.4 ± 0.7	5.3 ± 1.0	15.7 ± 1.7	12.3 ± 1.8	9.7 ± 1.6
Multijet	3.3 ± 0.6	2.9 ± 0.6	5.9 ± 0.9	5.2 ± 0.6	3.7 ± 0.5	1.40 ± 0.22
Others	0.38 ± 0.09	0.49 ± 0.12	0.64 ± 0.13	1.49 ± 0.27	2.8 ± 0.5	0.07 ± 0.02
Total Background	6.9 ± 1.3	6.8 ± 1.3	11.8 ± 2.6	22.4 ± 2.5	18.8 ± 2.8	11.2 ± 1.9
Total Signal	0.97 ± 0.29	1.09 ± 0.31	8.0 ± 2.2	3.3 ± 1.0	3.8 ± 1.2	3.6 ± 1.1
S/B	0.14	0.16	0.67	0.15	0.2	0.32
Data	6	6	19	20	16	15

ATLAS-CONF-2013-108 (November 28, 2013!)

LHC Summary

CMS combined: μ = 1.1 ± 0.4





CMS PAS-HIG-13-004

ATLAS-CONF-2013-108

A Tau Yukawa CPV phase

- From an EFT perspective, can readily generate a tau Yukawa phase via the addition of a dimension 6 operator

$$\mathcal{L}_{\rm eff} \supset -\left(\alpha + \beta \frac{H^\dagger H}{\Lambda^2}\right) H \ell^\dagger_{3\rm L} \tau_{\rm R} + {\rm c.c.}$$

  - α and β are generally complex
  - After inserting Higgs vevs, use the τ_R redefinition to get

$$\alpha + \beta \frac{v^2}{\Lambda^2} = y_\tau^{\rm SM} > 0 \,,$$

  - Then, the Higgs coupling to taus is $y_\tau^{\rm SM} + 2\beta \frac{v^2}{\Lambda^2}$

A Tau Yukawa CPV phase

- The new phase can thus be captured by considering the Lagrangian

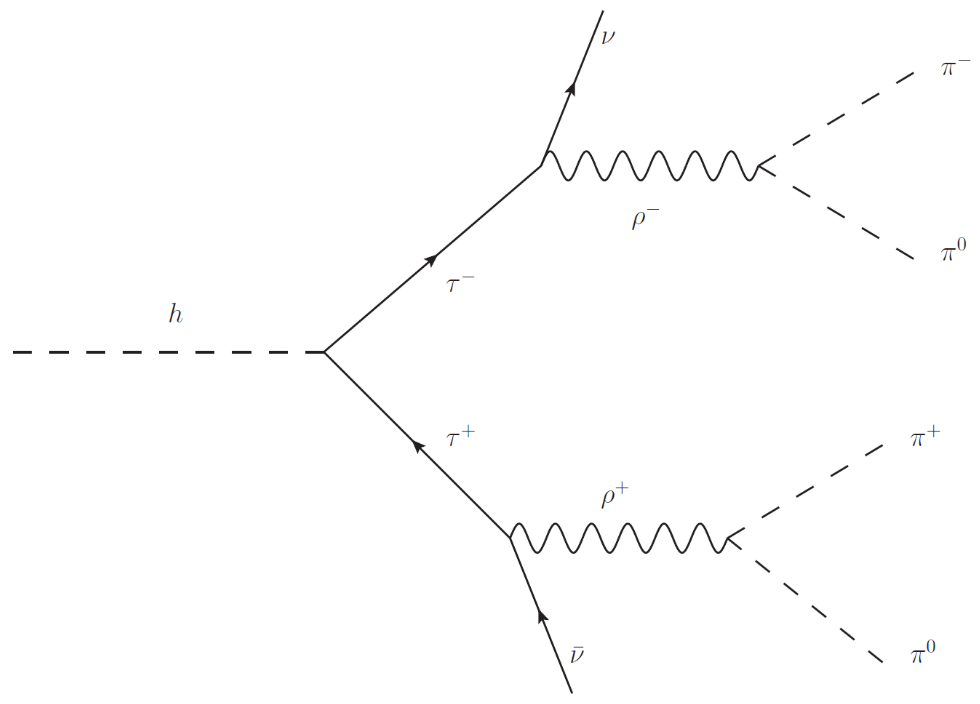
$$\mathcal{L}_{\text{pheno}} \supset -m_\tau \bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}} h\bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau$$
$$= -m_\tau \bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}} h\big(\tau_L^\dagger(\cos\Delta + i\sin\Delta)\tau_R + \text{c.c.}\big),$$

  - Δ = 0 is SM (CP-even)
  - Δ = π/2 is CP-odd (and CP conserving)
  - Δ = ±π/4 is maximally CP-violating
  - Δ is currently unconstrained

Extracting the phase in Higgs decays

- Need a tau decay that preserves polarization information
  - Some information always lost in escaping neutrinos
  - Use decay via the $\rho^{\pm}$ vector meson (Br = 26%)

$$
\begin{aligned}
h &\longrightarrow \tau^- \tau^+ \\
&\longrightarrow \rho^- \nu_\tau \, \rho^+ \bar{\nu}_\tau \\
&\longrightarrow \pi^- \pi^0 \, \nu_\tau \, \pi^+ \pi^0 \, \bar{\nu}_\tau \, .
\end{aligned}
$$



Matrix element calculation

- Will trace how Δ appears in the squared matrix element by treating the Higgs decay as a sequence of on-shell 2-body decays

$$\mathcal{M}_{h\to\tau\tau} \propto \sum_{s,s'} \chi_{s,s'}\, \bar{u}^{s}_{\tau^-}\, (\cos\Delta + \mathrm{i}\gamma_5 \sin\Delta)\, v^{s'}_{\tau^+}$$

$$\mathcal{M}_{\tau\to\rho\nu} \propto\; (\epsilon^*_{\rho^-})_\mu\; \bar{u}_{\nu_\tau} \gamma^\mu P_\mathrm{L}\, u_{\tau^-}$$

$$\mathcal{M}_{\rho\to\pi\pi} \propto\; \epsilon_{\rho^-}\cdot(p_{\pi^-} - p_{\pi^0})$$

- Together, gives

$$\begin{aligned}\mathcal{M}_\mathrm{full} \propto\; & \bar{u}_{\nu^-}(\not{p}_{\pi^-} - \not{p}_{\pi^0-})\, P_\mathrm{L}\, (\not{p}_{\tau^-} + m_\tau) \\ & \times (\cos\Delta + \mathrm{i}\gamma_5 \sin\Delta) \\ & \times (-\not{p}_{\tau^+} + m_\tau)\, (\not{p}_{\pi^+} - \not{p}_{\pi^0+})\, P_\mathrm{L} v_{\nu^+}\end{aligned}$$

Matrix element calculation assumptions

$$\mathcal{M}_{\text{full}} \propto \bar{u}_{\nu^-} (\not{p}_{\pi^-} - \not{p}_{\pi^0 -}) P_{\text{L}} (\not{p}_{\tau^-} + m_\tau) \times (\cos\Delta + \mathrm{i}\gamma_5 \sin\Delta) \times (-\not{p}_{\tau^+} + m_\tau)(\not{p}_{\pi^+} - \not{p}_{\pi^0 +}) P_{\text{L}} v_{\nu^+}$$

- Neglect π^0 exchange (spatially separated; the τ's are boosted and back-to-back in the Higgs rest frame)
- All intermediate particles assumed on-shell
- Neglect $\pi^\pm$–π^0 mass difference
- Obtain $\mathcal{M}_{\text{full}} \propto \bar{u}_{\nu^-} \not{q}_- (e^{i\Delta} \not{p}_{\tau^-} - e^{-i\Delta} \not{p}_{\tau^+}) \not{q}_+ P_{\text{L}} v_{\nu^+}$ with $q_\pm \equiv p_{\pi^\pm} - p_{\pi^0 \pm}$

Calculating the Theta Variable

- Introduce the variable $k_{\pm}^{\mu} \equiv y_{\pm}\, q_{\pm}^{\mu} + r\, p_{\nu\pm}^{\mu}$

  with coefficients
$$y_{\pm} \equiv \frac{2q_{\pm}\cdot p_{\tau\pm}}{m_{\tau}^2 + m_{\rho}^2} = \frac{q_{\pm}\cdot p_{\tau\pm}}{p_{\rho^{\pm}}\cdot p_{\tau\pm}}\,,$$
$$r \equiv \frac{m_{\rho}^2 - 4m_{\pi}^2}{m_{\tau}^2 + m_{\rho}^2} \approx 0.14\,.$$

- We then write the squared matrix element as
$$|\mathcal{M}|^2 \propto \;\; P_{\not\Delta,\mathrm{S}} + P_{\Delta,\not\mathrm{S}} + P_{\Delta,\mathrm{S}} + P_{\Delta,\mathrm{S}}^{*}$$

  where the most interesting piece is
$$P_{\Delta,\mathrm{S}} \equiv -\mathrm{e}^{2\mathrm{i}\Delta}\big[(k_{-}\cdot p_{\tau+})(k_{+}\cdot p_{\tau-}) - (p_{\tau-}\cdot p_{\tau+})(k_{-}\cdot k_{+}) - \mathrm{i}\epsilon_{\mu\nu\rho\sigma}\, k_{-}^{\mu}\, p_{\tau-}^{\nu}\, k_{+}^{\rho}\, p_{\tau+}^{\sigma}\big]. \qquad (26)$$

Calculating the Theta Variable

$$P_{\Delta,\,\mathrm{s}} \equiv -\mathrm{e}^{2\mathrm{i}\Delta}\big[(k_-\cdot p_{\tau+})(k_+\cdot p_{\tau-}) - (p_{\tau-}\cdot p_{\tau+})(k_-\cdot k_+) - \mathrm{i}\epsilon_{\mu\nu\rho\sigma}\, k_-^{\mu}\, p_{\tau-}^{\nu}\, k_+^{\rho}\, p_{\tau+}^{\sigma}\big]. \qquad (26)$$

- We can define an antisymmetric 2[nd]-rank tensor

$$F_{\pm}^{\mu\nu} \equiv k_{\pm}^{\mu}\, p_{\tau\pm}^{\nu} - k_{\pm}^{\nu}\, p_{\tau\pm}^{\mu} = -F_{\pm}^{\nu\mu}$$

$$P_{\Delta,\,\mathrm{s}} = \mathrm{e}^{2\mathrm{i}\Delta}\left(\frac{1}{2}F_{-\mu\nu}F_{+}^{\mu\nu} + \frac{\mathrm{i}}{4}\epsilon_{\mu\nu\rho\sigma}\, F_{-}^{\mu\nu}\, F_{+}^{\rho\sigma}\right)$$

- Or, even better, identify “electric” and “magnetic” components $E_{\pm}^{i} \equiv F_{\pm}^{i0}\,, \quad B_{\pm}^{i} \equiv -\frac{1}{2}\epsilon^{ijk}F_{\pm jk}$

$$P_{\Delta,\,\mathrm{s}} = -\mathrm{e}^{2\mathrm{i}\Delta}\big[(\vec{E}_- + \mathrm{i}\vec{B}_-)\cdot(\vec{E}_+ + \mathrm{i}\vec{B}_+)\big]$$

Calculating the Theta Variable

$$F_{\pm}^{\mu\nu} \equiv k_{\pm}^{\mu}\, p_{\tau\pm}^{\nu} - k_{\pm}^{\nu}\, p_{\tau\pm}^{\mu} = -F_{\pm}^{\nu\mu}$$

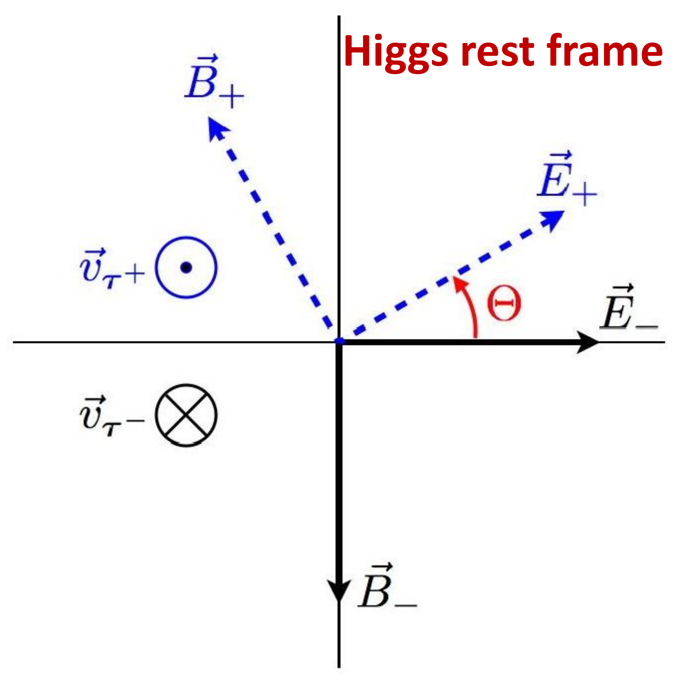
- We can calculate

$$\vec{B}_{\pm} = \vec{p}_{\tau\pm} \times \vec{k}_{\pm} = \vec{v}_{\tau\pm} \times \vec{E}_{\pm}$$

- Specialize to Higgs rest frame (back-to-back taus)
  - E_+B_+ and E_-B_- planes are parallel
  - Motivate a new acoplanarity between E_+v_+ and E_-v_- planes

$$\Theta = \mathrm{sgn}\left[\vec{v}_{\tau+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \mathrm{Arccos}\left[\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+|\,|\vec{E}_-|}\right]$$

$$P_{\Delta,\,\mathrm{S}} = -2\mathrm{e}^{\mathrm{i}(2\Delta - \Theta)}\,|\vec{E}_+|\,|\vec{E}_-|$$



Calculating the Theta Variable

$$\Theta = \mathrm{sgn}\left[\vec{v}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \mathrm{Arccos}\left[\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+|\,|\vec{E}_-|}\right]$$

$$P_{\Delta,\mathrm{S}} = -2\mathrm{e}^{\mathrm{i}(2\Delta-\Theta)}\,|\vec{E}_+|\,|\vec{E}_-|$$

- In the Higgs rest frame, the "electric" components are $\vec{E}_\pm = \frac{m_h}{2}\left[(y_\pm - r)\,\vec{p}_{\pi^\pm}\big|_0 - (y_\pm + r)\,\vec{p}_{\pi^0\pm}\big|_0\right]^\perp$

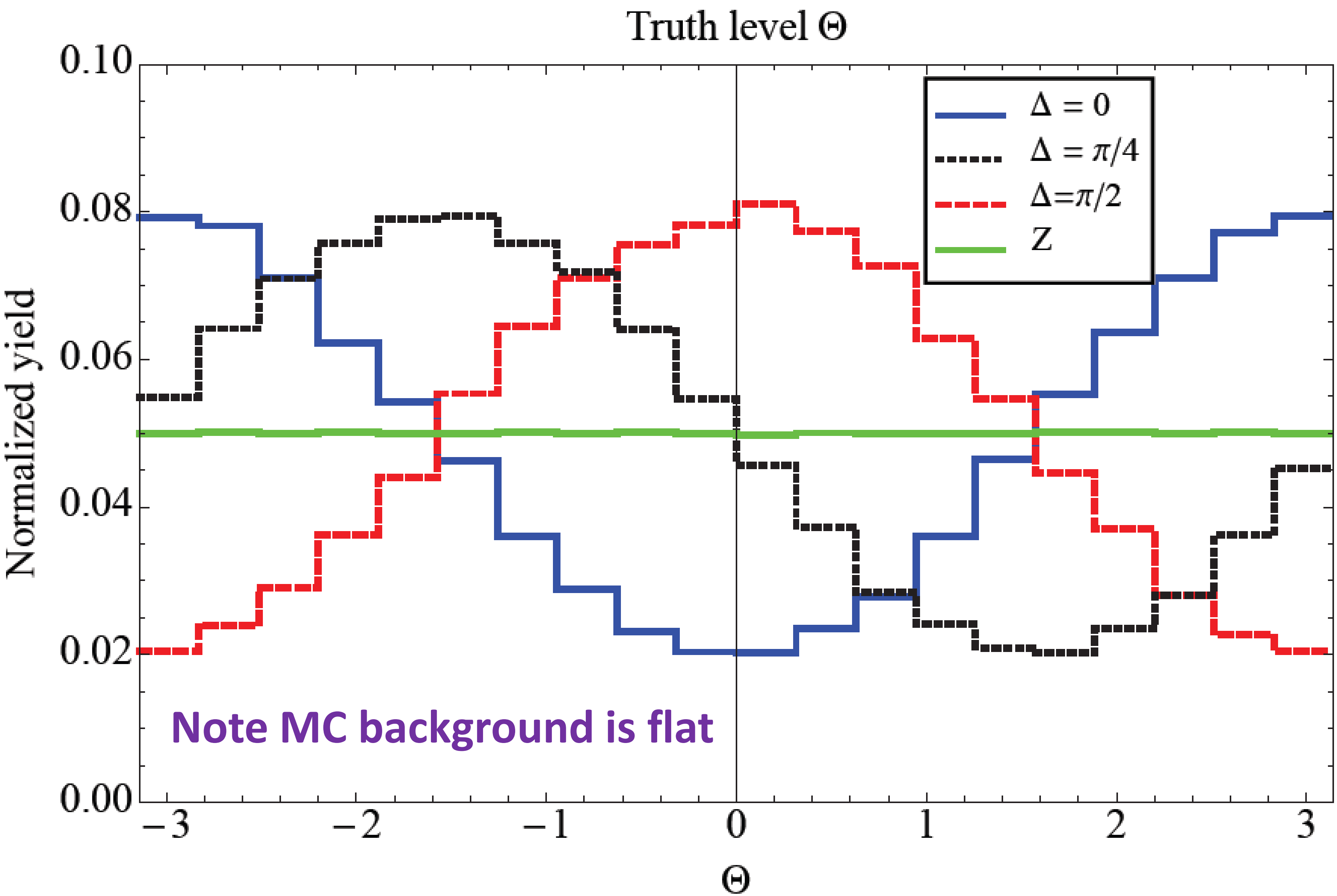
$|_0$ = tau rest frame

- If neutrinos were measured, we would have complete information to reconstruct tau momentum, tau and Higgs rest frames

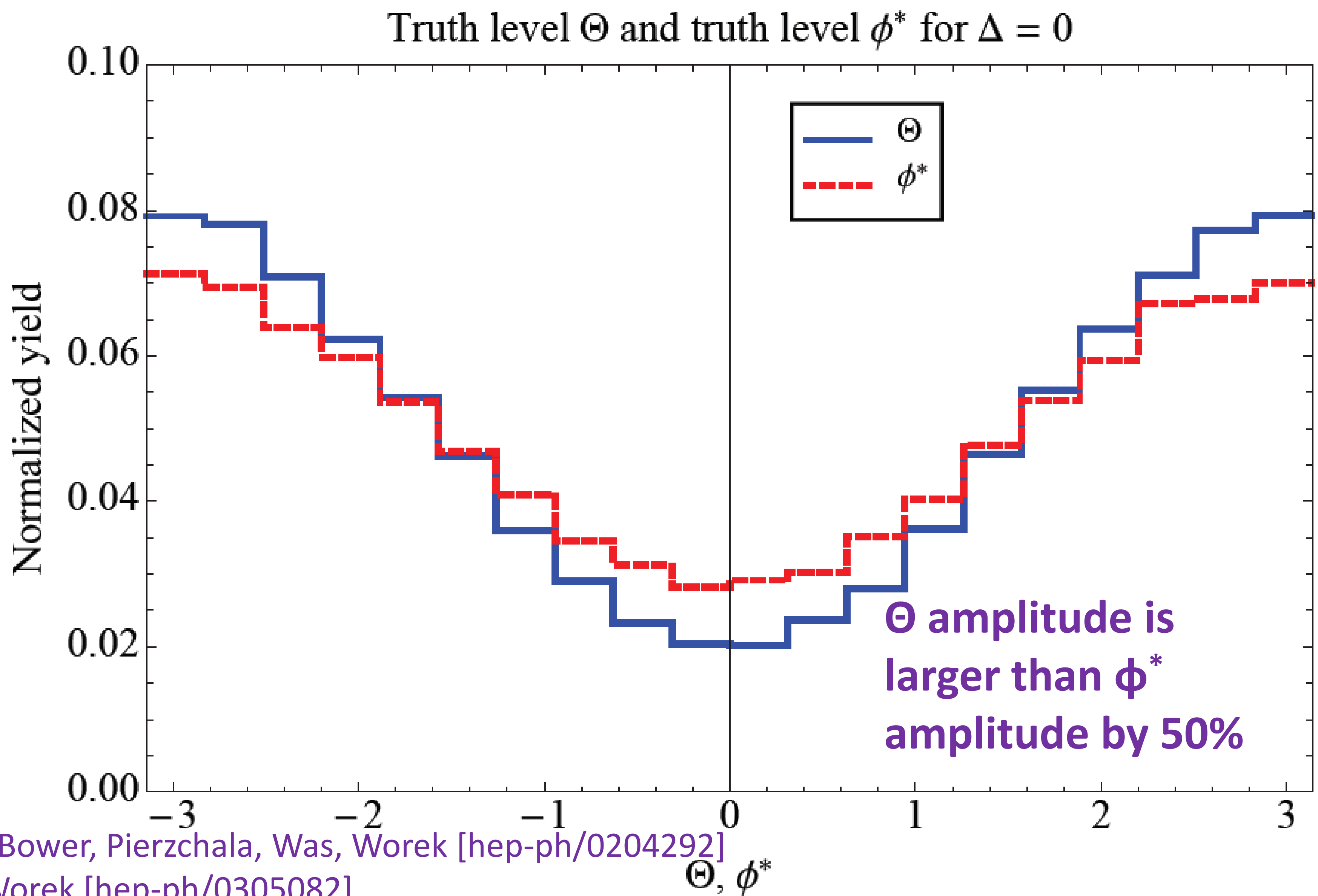
$$y_\pm \equiv \frac{2q_\pm \cdot p_{\tau^\pm}}{m_\tau^2 + m_\rho^2} = \frac{q_\pm \cdot p_{\tau^\pm}}{p_{\rho^\pm} \cdot p_{\tau^\pm}}\,,$$

$$r \equiv \frac{m_\rho^2 - 4m_\pi^2}{m_\tau^2 + m_\rho^2} \approx 0.14\,.$$

Ideal situation



Ideal – compare $\rho^+\rho^-$ acoplanarity*

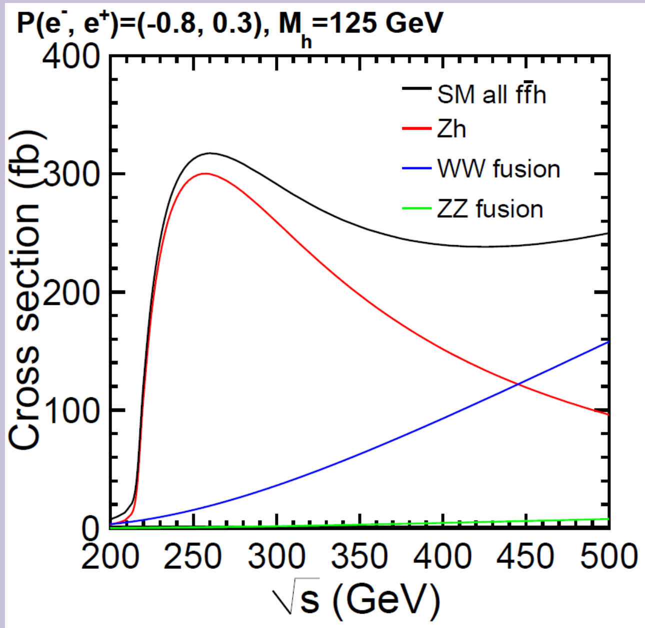


Θ amplitude is larger than ϕ^* amplitude by 50%

*Bower, Pierzchala, Was, Worek [hep-ph/0204292]
Worek [hep-ph/0305082]

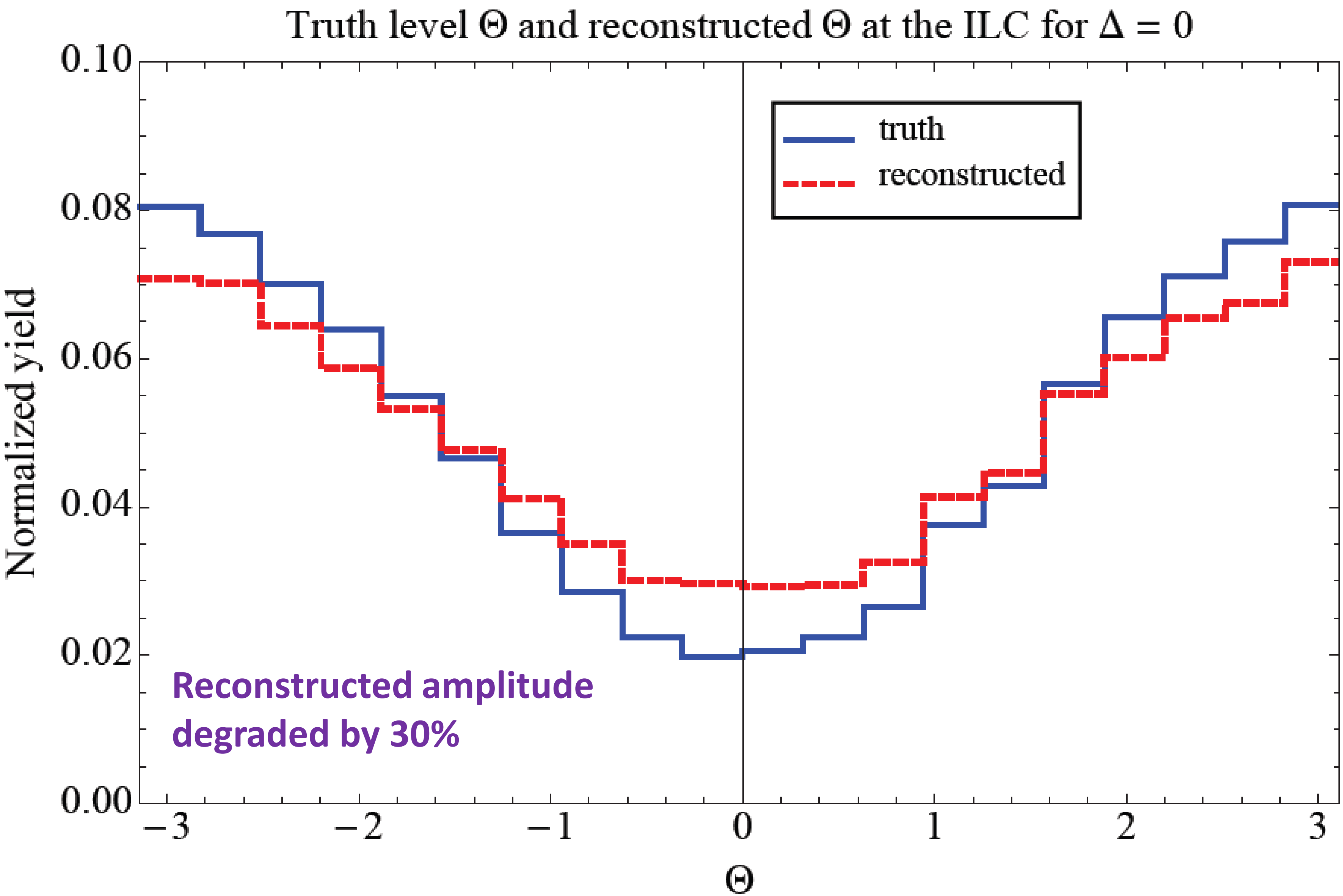
Lepton collider possibilities

- We obviously cannot directly measure neutrino momenta
- At a lepton collider, have enough constraints to solve algebraically for neutrino momenta
  - Have two neutrino momenta solution sets
    - Necessarily require visible Z decay
    - Both solutions give correct Higgs mass
    - Weight each solution by half an event



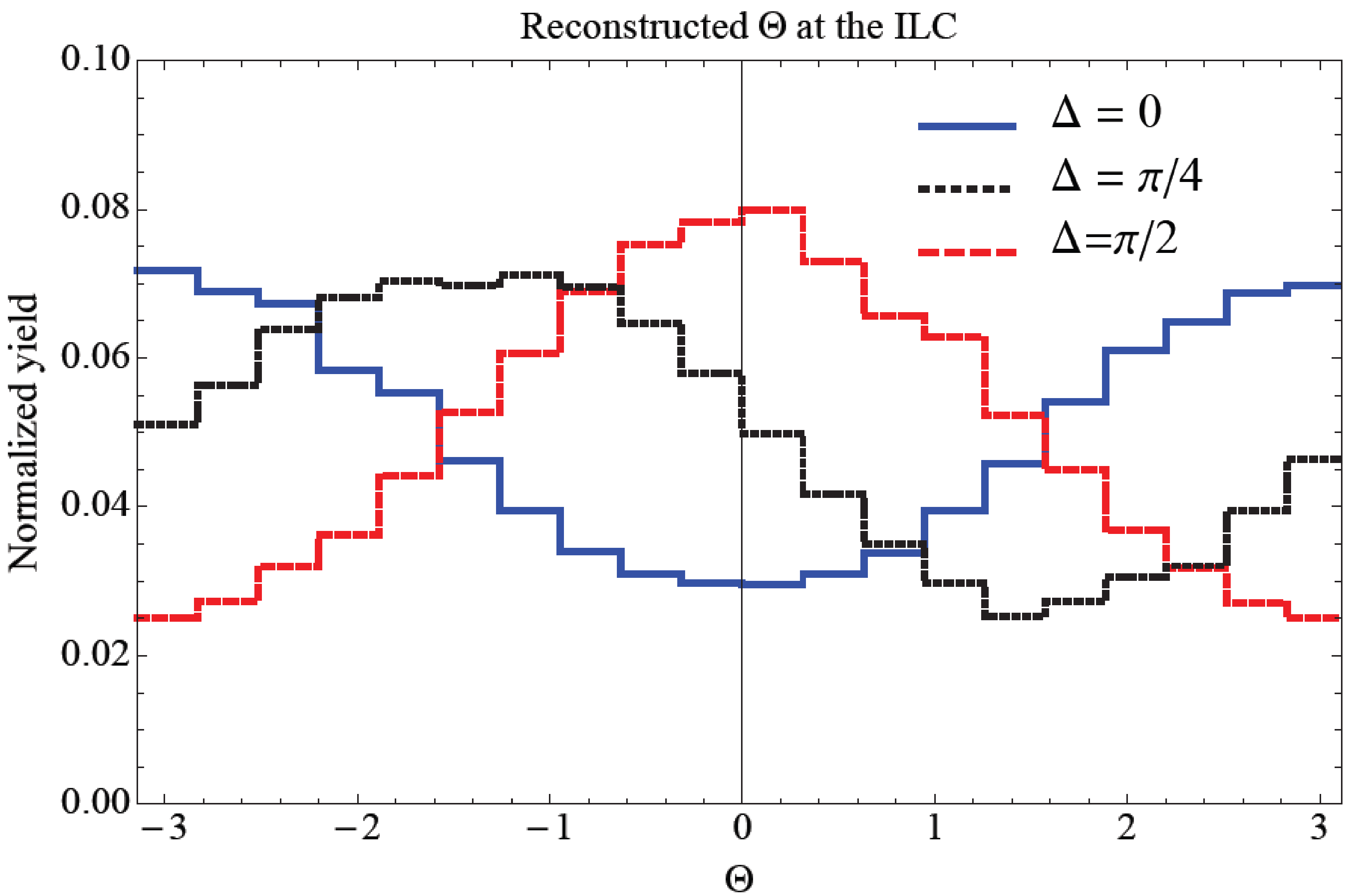
ILC TDR Volume 2

Lepton collider – reconstructed



Reconstructed amplitude degraded by 30%

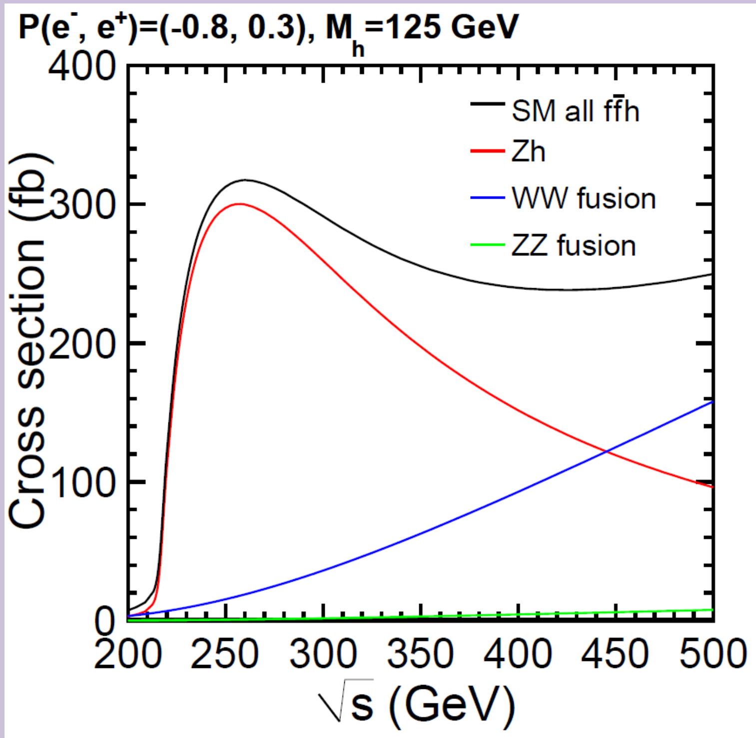
Lepton collider – reconstructed



Lepton collider possibilities

- For √s = 250 GeV ILC, polarized beams, Zh production is about 0.30 pb
- Signal yield (using SM Higgs to taus decay width and restricting to visible Z decays) is 990 events with 1 ab^{-1} luminosity

$\sigma_{e^+e^-\to hZ}$	0.30 pb
$\mathrm{Br}(h\to\tau^+\tau^-)$	6.1%
$\mathrm{Br}(\tau^-\to\pi^-\pi^0\nu)$	26%
$\mathrm{Br}(Z\to\text{visibles})$	80%
$\mathrm{N_{events}}$	990



ILC TDR Volume 2

Lepton collider possibilities

- For √s = 250 GeV ILC, polarized beams, Zh production is about 0.30 pb
  - Signal yield (using SM Higgs to taus decay width and restricting to visible Z decays) is 990 events with 1 ab^{-1}
  - Construct binned likelihood using a sinuisoidal fit to signal, determine sensitivity by variation of test Δ

With 1 ab^{-1} of ILC √s=250 GeV, expect 1σ discrimination of 4.4° (compared* to 6° using ϕ^* [albeit included backgrounds and detector effects])

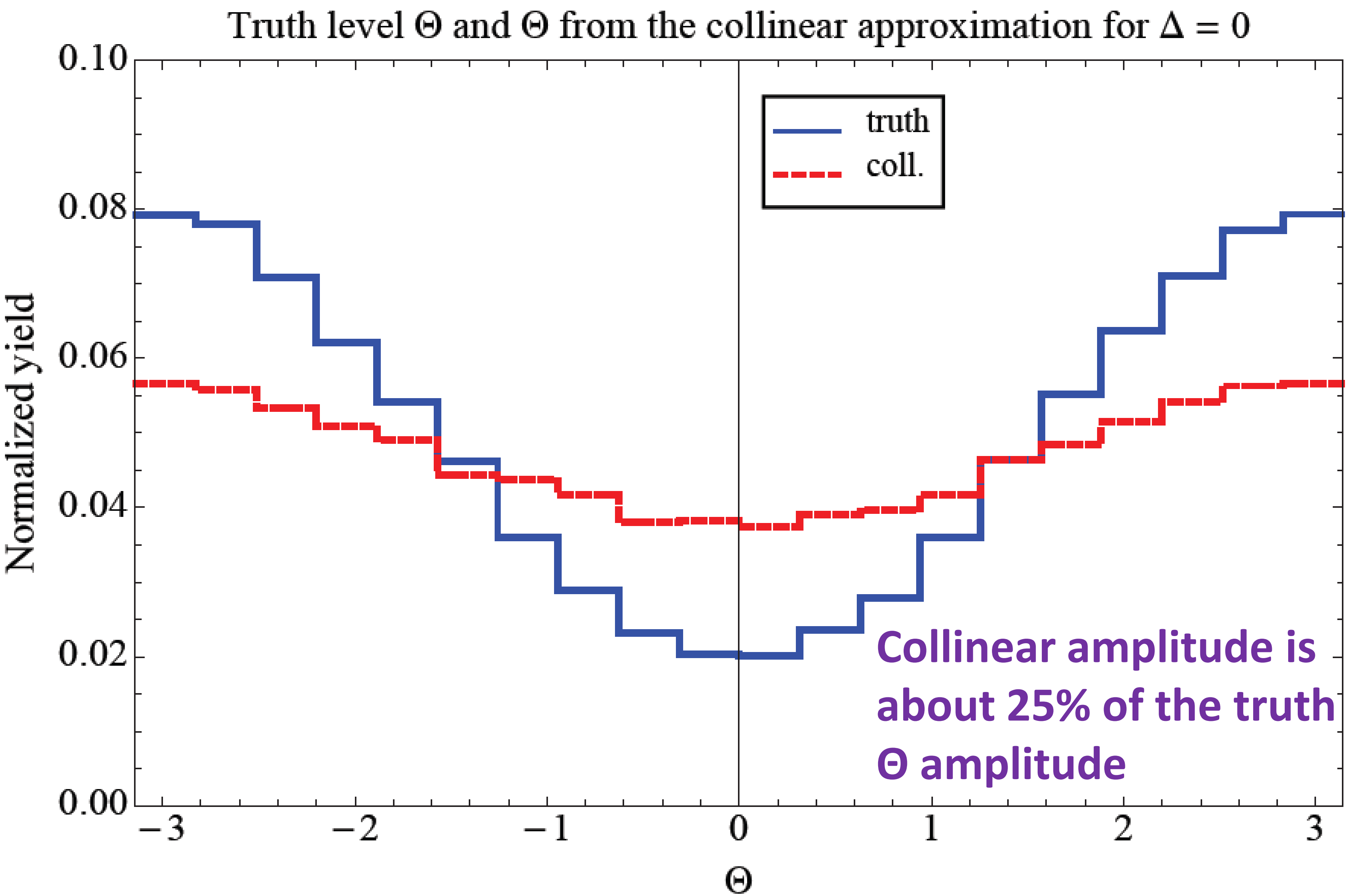
$$L = \frac{\prod_{i=1}^{N} \mathrm{Pois}\left(B_i + S_i^{\Delta=0} | B_i + S_i^{\Delta=\delta}\right)}{\prod_{i=1}^{N} \mathrm{Pois}\left(B_i + S_i^{\Delta=0} | B_i + S_i^{\Delta=0}\right)}$$

*Desch, Imhof, Was, Worek [hep-ph/0307331]

LHC prospects

- Can also study this phase at the LHC
  - Consider h+j events (can also consider VBF production)
  - Will use collinear approximation for neutrino momenta
    - In this approximation, Θ is identical to ϕ^*
  - First proposal to measure Δ at the LHC with prompt tau decays and kinematics

LHC prospects



Collinear amplitude is about 25% of the truth Θ amplitude

Signal and background generation

- Use MadGraph5 for h+j and Z+j events at LHC14
  - Mimic cuts for 1-jet, hadronic taus Higgs search category
  - Impose preselection of $p_T(j) > 140$ GeV, $|\eta(j)| < 2.5$
  - Normalize to MCFM NLO $\sigma(h+j)=2.0$ pb, $\sigma(Z+j)=420$ pb
  - No pileup or detector simulation, aside from tau-tagging efficiencies
    - Pileup degrades primary vertex determination for charged pion tracks and adds ECAL deposits that reduce neutral pion resolution
    - Tracking and detector resolution will clearly smear the Θ distribution

Yields for 3 ab^{-1} LHC

- Signal region: MET > 40 GeV, $p_T(\rho)$ > 45 GeV, $|\eta(\rho)|$ < 2.1, m_{coll} > 120 GeV
  - Inject an additional 10% contribution to (flat) Zj background to account for QCD multijets

	$h\,j$	$Z\,j$
Inclusive σ	2.0 pb	420 pb
$\mathrm{Br}(\tau^+\tau^-$ decay)	6.1%	3.4%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%	26%
Cut efficiency	18%	0.24%
N_{events}	1100	1800

Yields for 3 ab^{-1} LHC

- Consider τ tagging efficiency benchmarks of 50% and 70%, use similar likelihood analysis as before

τ_h efficiency	50%	70%
3σ	$L = 550$ fb^{-1}	$L = 300$ fb^{-1}
5σ	$L = 1500$ fb^{-1}	$L = 700$ fb^{-1}
Accuracy($L = 3$ ab^{-1})	11.5°	8.0°

  - Discriminating pure scalar vs. pure pseudoscalar at **3σ** requires 550 (300) fb^{-1} with 50% (70%) τ tagging efficiency
  - For **5σ**, require 1500 (700) fb^{-1} with 50% (70%) τ tagging efficiency
- Again, detector effects and pileup are neglected

Improving the measurement of the tau Yukawa CP phase

- Consider including MET information for LHC analyses
  - *e.g.* MELA-type likelihood incorporating signal hypotheses with different Δ
- Consider other tau decay modes
- Improve tau tagging efficiency
- Add decay vertex information
- Consider VBF production

Summary

- New CP phases are motivated from general baryogenesis arguments
- Have a new suite of measurements to perform in Higgs physics
  - Fermionic CP phases play a special role
  - Look forward to discussion with experimentalists to implement this analysis in future Higgs studies

ILC, 250 GeV, 1 ab^{-1}

$\sigma_{e^+e^-\to hZ}$	0.30 pb
$\mathrm{Br}(h \to \tau^+\tau^-)$	6.1%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%
$\mathrm{Br}(Z \to \text{visibles})$	80%
$\mathrm{N_{events}}$	990
Accuracy	4.4°

LHC, 14 TeV

τ_h efficiency	50%	70%
3σ	$L = 550\ \mathrm{fb}^{-1}$	$L = 300\ \mathrm{fb}^{-1}$
5σ	$L = 1500\ \mathrm{fb}^{-1}$	$L = 700\ \mathrm{fb}^{-1}$
Accuracy($L = 3\ \mathrm{ab}^{-1}$)	11.5°	8.0°

UV completion

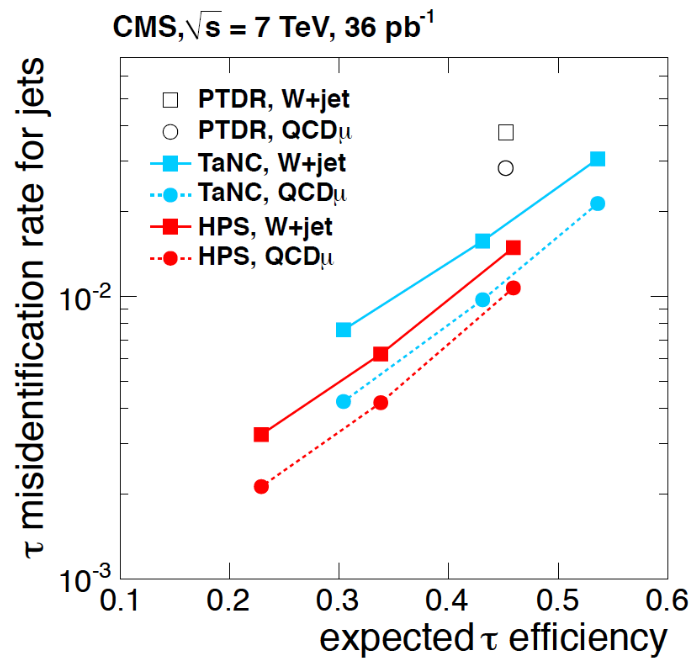
$$\begin{aligned}\mathcal{L}_{\rm tree} = \mathcal{L}_{{\rm SM}-y_\tau} \\ + |{\rm D}\Phi|^2 - m_\Phi^2|\Phi|^2 - \lambda_\Phi|\Phi|^4 \\ - (yH\ell_{\rm 3L}^\dagger\tau_{\rm R} + y'\Phi\ell_{\rm 3L}^\dagger\tau_{\rm R} + \lambda'(\Phi^\dagger H)|H|^2 + {\rm c.c.})\,,\end{aligned} \tag{A1}$$

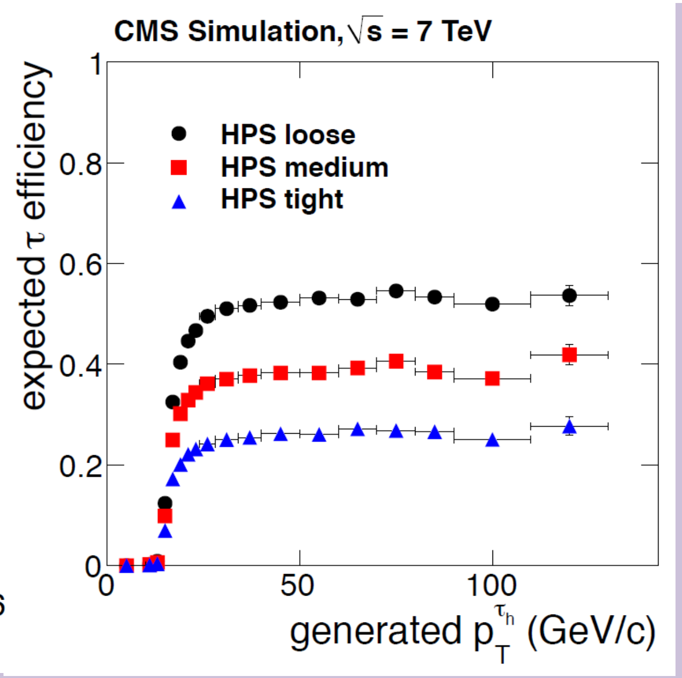
$$\mathcal{L}_{\text{dim-6}} = \frac{|\lambda'|^2}{m_\Phi^2}|H|^6 + \Big(\frac{\lambda' y'}{m_\Phi^2}|H|^2 H\ell_{\rm 3L}^\dagger\tau_{\rm R} + {\rm c.c.}\Big).$$

Tau measurement details

Table 1. Branching fractions of the dominant hadronic decays of the τ lepton and the symbol and mass of any intermediate resonance [9]. The h stands for both π and K, but in this analysis the π mass is assigned to all charged particles. The table is symmetric under charge conjugation.

Decay mode	Resonance	Mass (MeV/c^2)	Branching fraction (%)
$\tau^- \rightarrow h^- \nu_\tau$			11.6%
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	ρ^-	770	26.0%
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	a_1^-	1200	9.5%
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	a_1^-	1200	9.8%
$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$			4.8%





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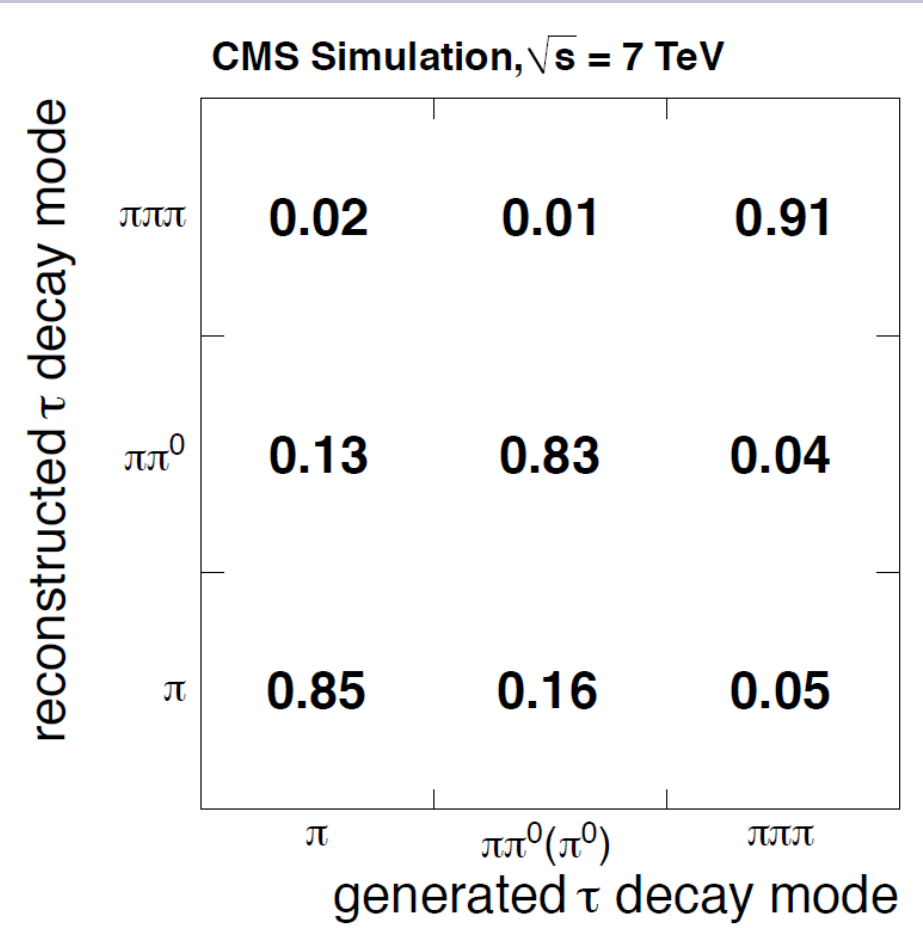
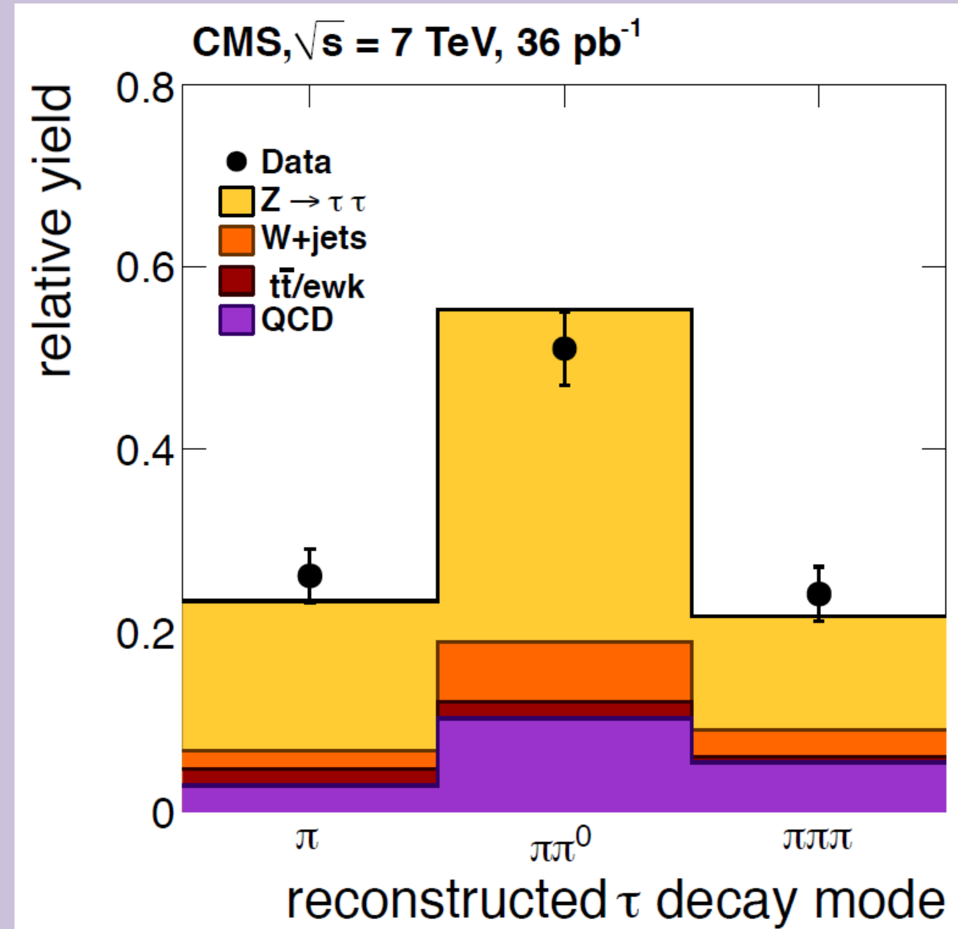
Tau measurement details





Tau measurement details

Table 4. The MC predicted τ_h misidentification rates and the measured data-to-MC ratios, integrated over the p_T and η phase space typical for the $Z \to \tau\tau$ analysis.

Algorithm	QCD		QCDμ		W + jets	
	MC (%)	Data/MC	MC (%)	Data/MC	MC (%)	Data/MC
HPS "loose"	1.0	1.00 ± 0.04	1.0	1.07 ± 0.01	1.5	0.99 ± 0.04
HPS "medium"	0.4	1.02 ± 0.06	0.4	1.05 ± 0.02	0.6	1.04 ± 0.06
HPS "tight"	0.2	0.94 ± 0.09	0.2	1.06 ± 0.02	0.3	1.08 ± 0.09
TaNC "loose"	2.1	1.05 ± 0.04	1.9	1.12 ± 0.01	3.0	1.02 ± 0.05
TaNC "medium"	1.3	1.05 ± 0.05	0.9	1.08 ± 0.02	1.6	0.98 ± 0.07
TaNC "tight"	0.5	0.98 ± 0.07	0.4	1.06 ± 0.02	0.8	0.95 ± 0.09

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