CP VIOLATION TESTS IN HIGGS MEASUREMENTS AT FUTURE COLLIDERS

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Motivating CPV tests

- Sakharov's three conditions for baryogenesis motivate searches for new sources of CP violation
  - Need B violation
  - Need C and CP violation
  - Need interactions to happen out of thermal equilibrium
- Our picture of baryogenesis is currently incomplete
  - SM EW baryogenesis is insufficient
  - Should probe for new sources of CPV

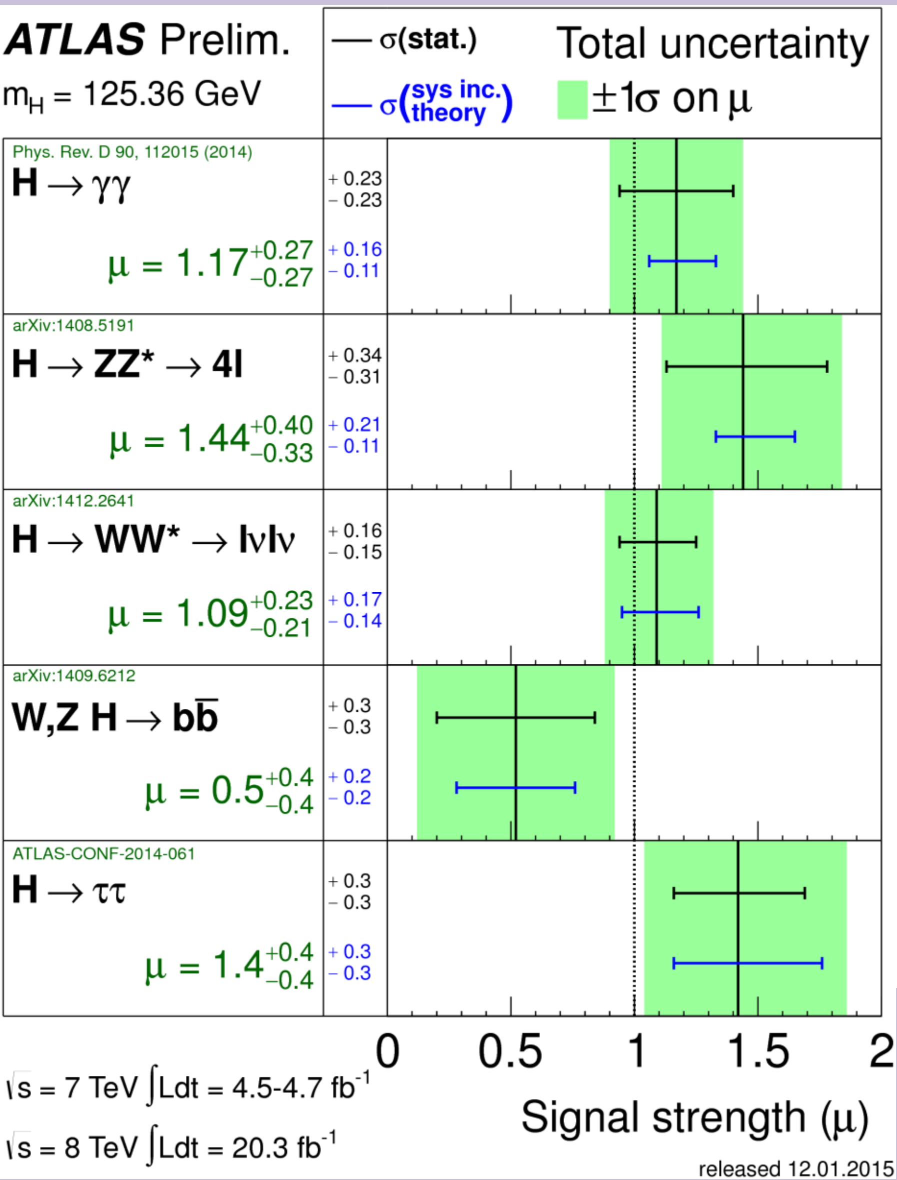
CP and the Higgs

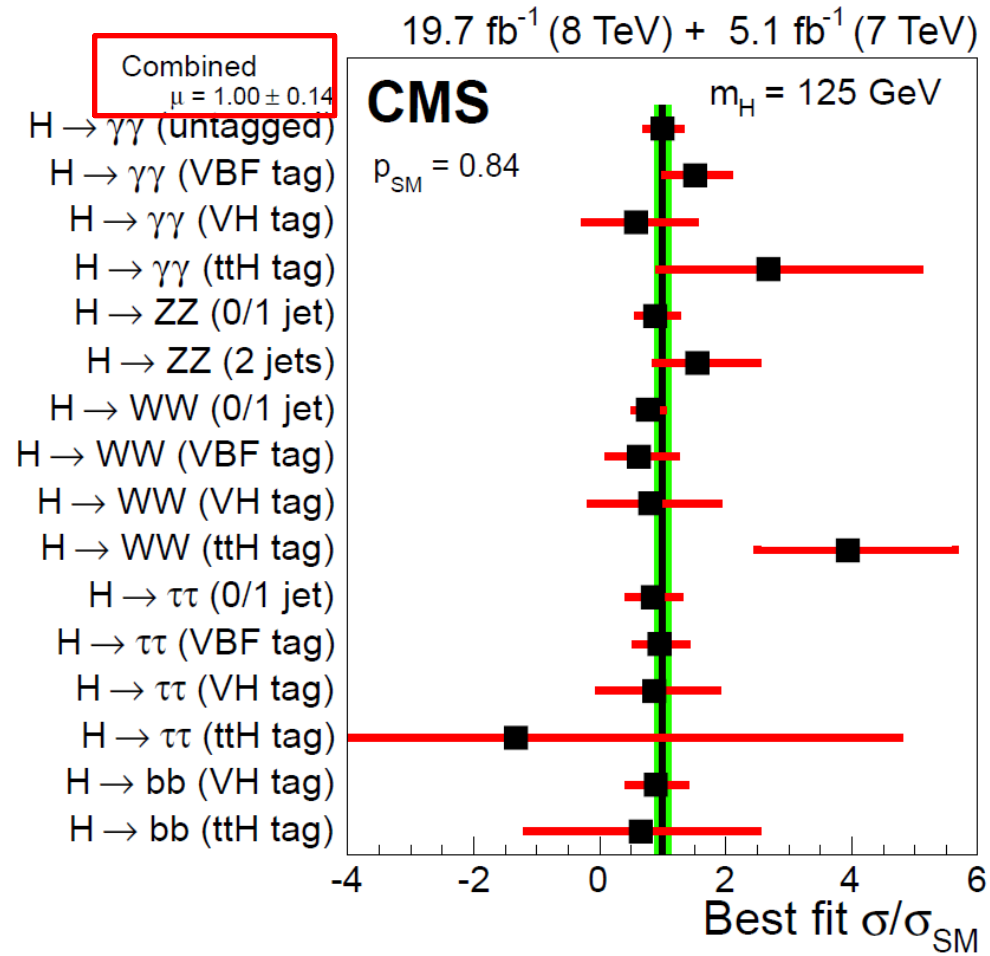
- A natural place to test for CP violating phases is with Higgs physics
  - scalar-pseudoscalar admixture (*e.g.* scalar potential)
    - naïvely tested via rate suppression
  - couplings to gauge bosons (*e.g.* bosonic CPV)
    - for example, tested via acoplanarity measurement in $h \to ZZ^* \to 4l$
  - couplings to fermions (*e.g.* fermionic CPV)
    - our work: test via $h \to \tau^+ \tau^- \to (\rho^+\nu)\,(\rho^-\nu) \to (\pi^+\pi^0)\nu\,(\pi^-\pi^0)\nu$
- [Full UV models to connect any given CP phase to a baryogenesis mechanism is BTSOTW]

Outline

- Brief review of current status of Higgs CP properties
- Motivate new measurement in $\tau^+\tau^-$ decay channel
- Sensitivity studies at colliders
  - Lepton collider prospects
  - First proposal for an LHC measurement
- Summary

Admixture constraints from signal strengths





[Separate channels cannot be combined without assumptions!]

atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/; CMS [1412.8662]

Testing CPV in Higgs decays to (electroweak) gauge bosons

- Using Higgs EFT, assuming spin-0, write dimension-6 operators for scalar coupling to dibosons
- Perform simultaneous fit to coefficients of non-SM coupling structures based on differential distribution

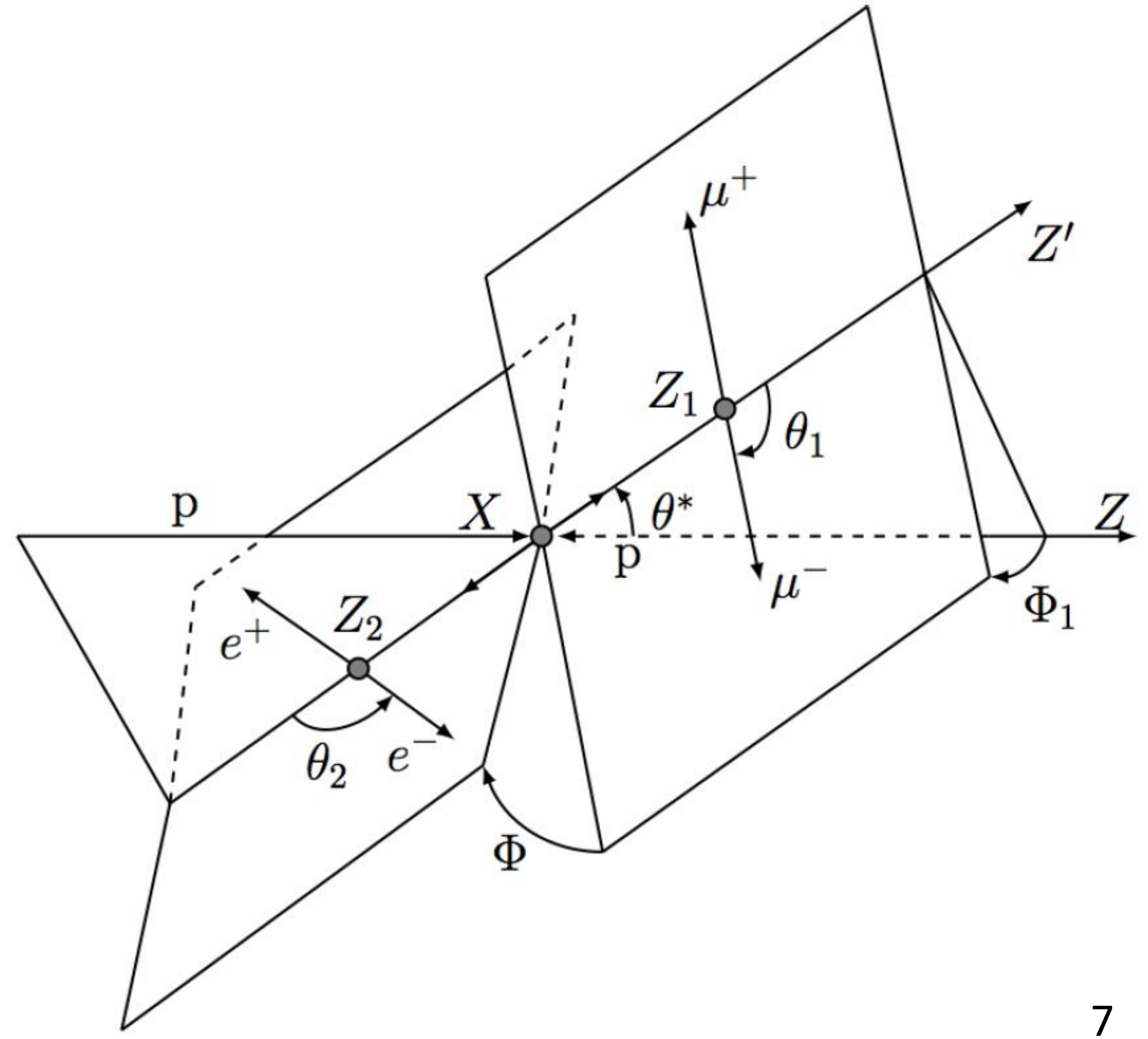
$$
\begin{aligned}
L(\mathrm{HVV}) \sim\; & a_1 \frac{m_Z^2}{2}\mathrm{H}Z^\mu Z_\mu + \frac{1}{(\Lambda_1)^2} m_Z^2 \mathrm{H} Z_\mu \Box Z^\mu - \frac{1}{2} a_2 \mathrm{H} Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} Z^{\mu\nu} \tilde{Z}_{\mu\nu} \\
& + a_1^{\mathrm{WW}} \frac{m_W^2}{2} \mathrm{H} W^\mu W_\mu + \frac{1}{(\Lambda_1^{\mathrm{WW}})^2} m_W^2 \mathrm{H} W_\mu \Box W^\mu - \frac{1}{2} a_2^{\mathrm{WW}} \mathrm{H} W^{\mu\nu} W_{\mu\nu} - \frac{1}{2} a_3^{\mathrm{WW}} \mathrm{H} W^{\mu\nu} \tilde{W}_{\mu\nu} \\
& + \frac{1}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 \mathrm{H} Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} \mathrm{H} F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} \mathrm{H} F^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \mathrm{H} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \mathrm{H} F^{\mu\nu} \tilde{F}_{\mu\nu},
\end{aligned}
$$

- Can also test spin-2

CMS [1411.3441]

Testing CPV in Higgs decays to (electroweak) gauge bosons

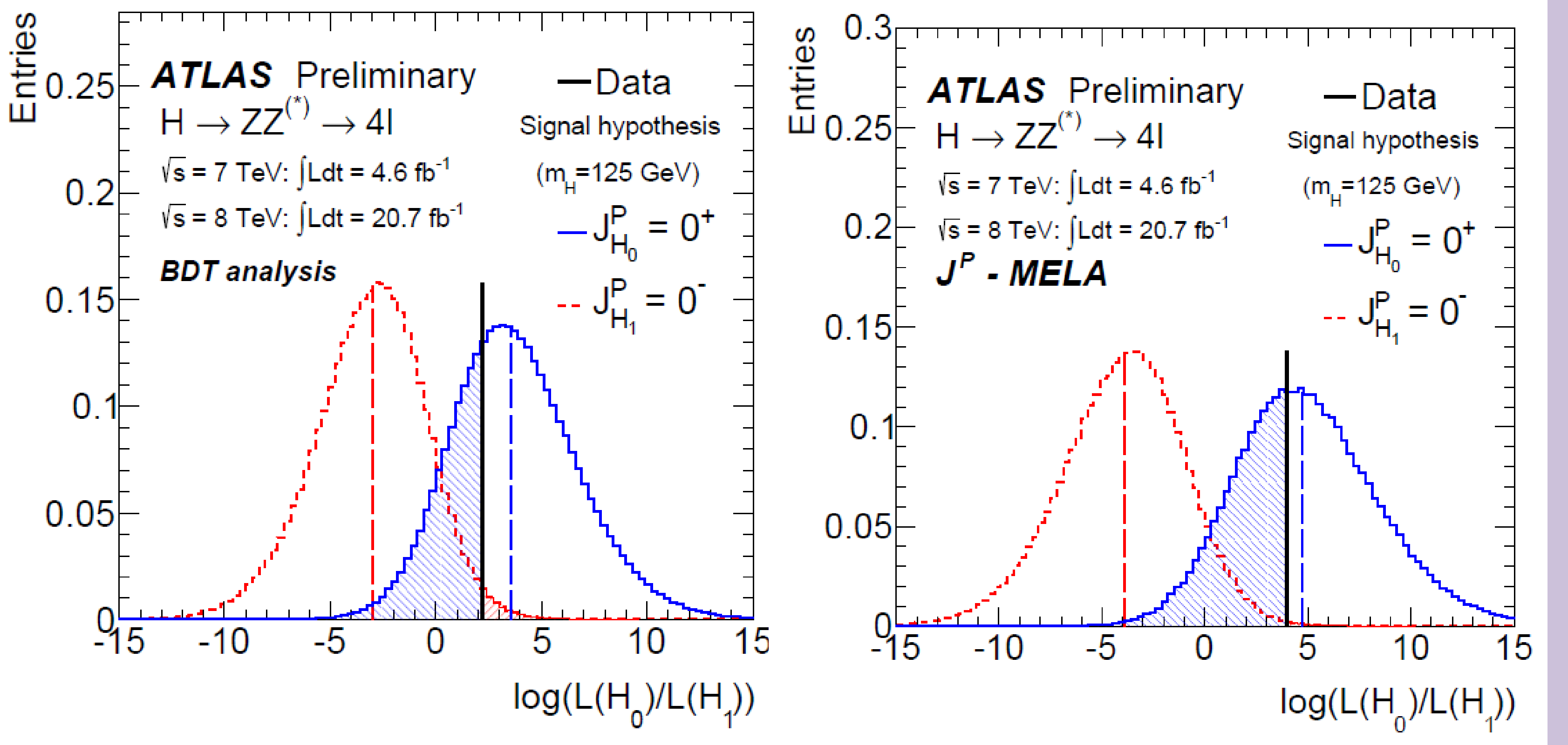
- For ZZ^*, measure acoplanarity angle Φ (angle between Z_1 and Z_2 decay planes)
- Golden channel
  - everything measureable, can reconstruct the Higgs rest frame and appropriate decay planes



ATLAS-CONF-2013-013

Testing CPV in $h \to ZZ^*$ – ATLAS

- ATLAS performs likelihood test between pure scalar and pure pseudoscalar hypotheses



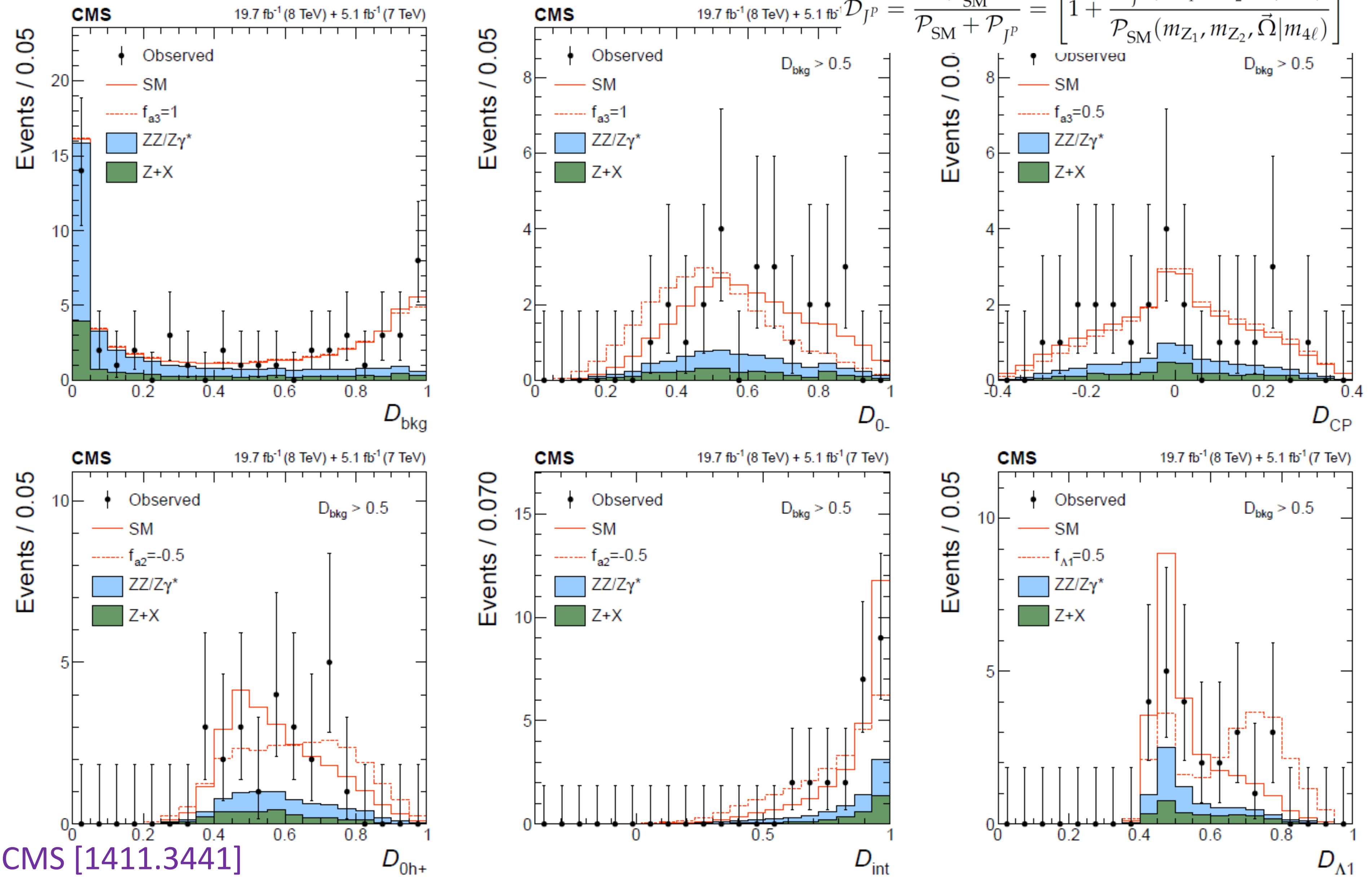
0^- excluded in favor of 0^+ hypothesis at 97.8% C.L.

ATLAS-CONF-2013-013

Testing CPV in h→ZZ* – CMS

$$f\left(J^P\right) = \frac{\sigma_{J^P}}{\sigma_{0^+} + \sigma_{J^P}}$$

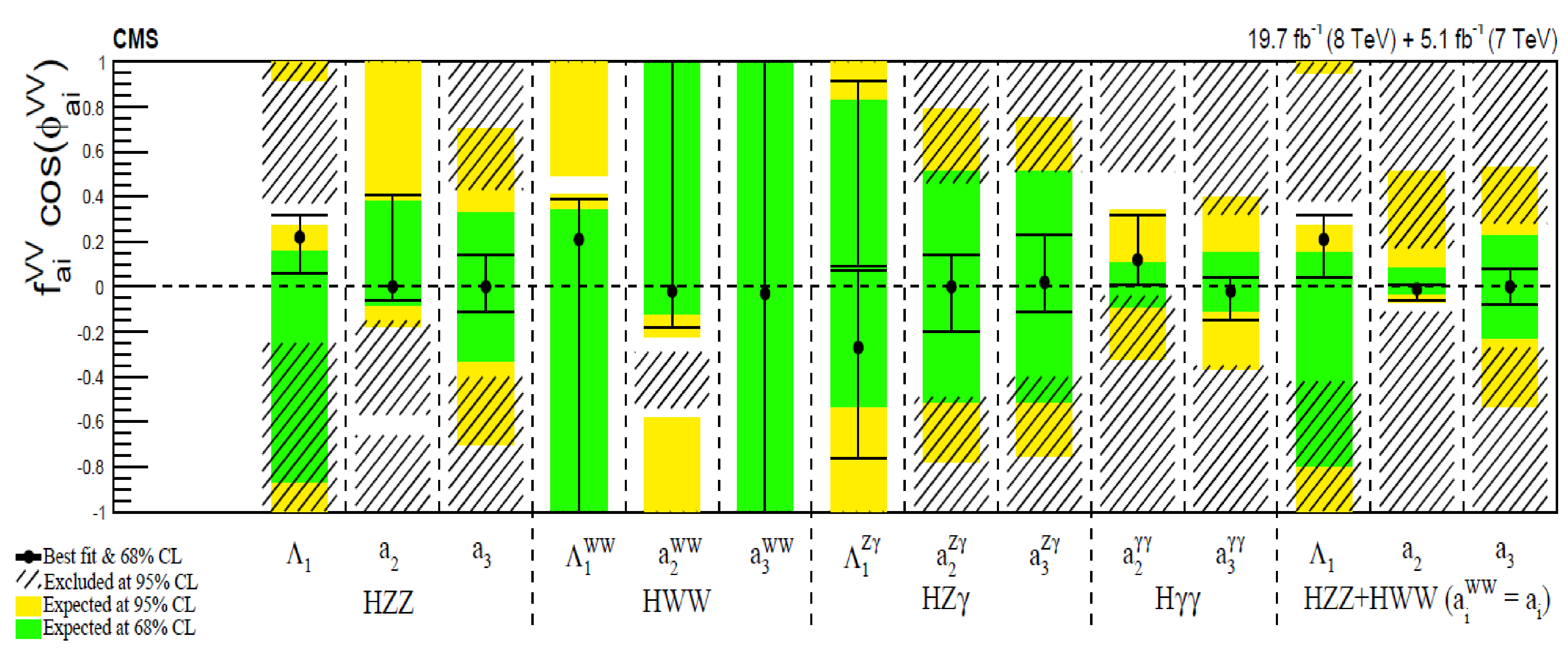
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$



CMS [1411.3441]

Electroweak diboson results

- Thus far, measurements consistent with SM



- $f_{a3} = 1$ excluded at 99.98% CL

$f_{a3} < 0.43$ (0.40) at a 95% CL for the positive (negative) phase

Testing “fermionic” CPV

- The BSM source of a CPV phase in SM Yukawa couplings is distinct from possible phases in the scalar potential or pseudoscalar couplings to gauge bosons
  - Motivates CPV tests in fermionic couplings even if bosonic CPV coupling tests give null results
  - For example, new fermions which mix with SM fermions could introduce explicit phases in the Yukawa sector

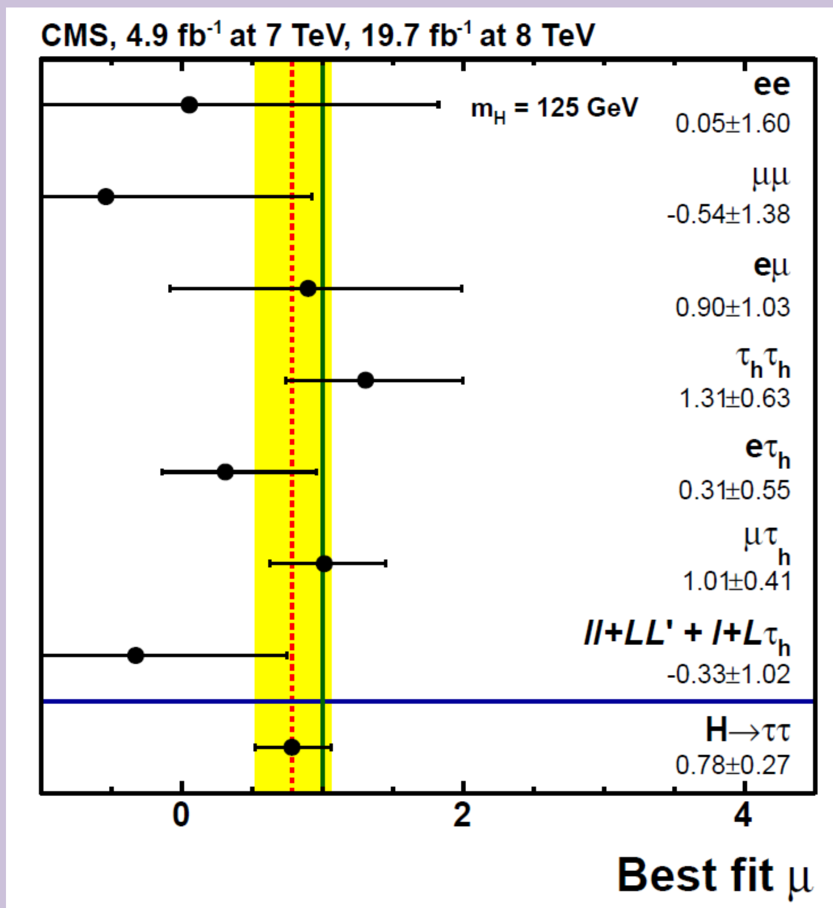
Testing “fermionic” CPV with Higgs

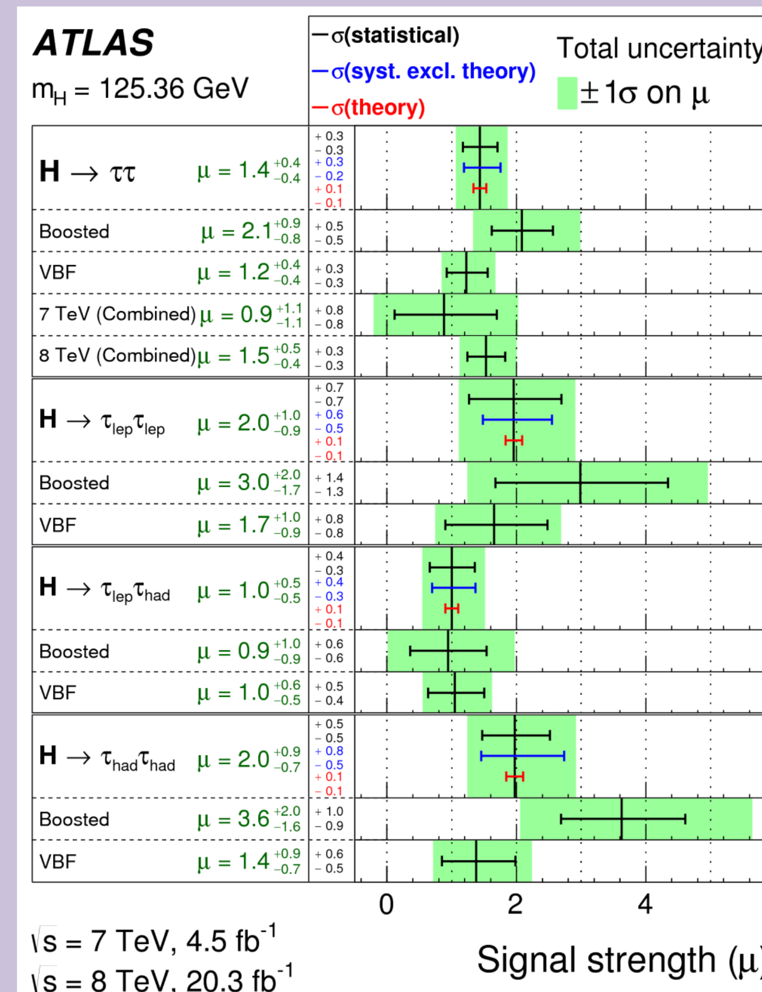
- The tau decay channel for the Higgs is the most promising system for direct measurement of fermionic CPV couplings
  - Top coupling only probed via loops or ttH (tH) production
  - Bottom quark polarizations generally washed out by QCD
  - Tau channel suffer from lost information via neutrinos (at hadron colliders), but still have an appreciable rate

M_H = 126 GeV	SM Br
bb	56.1%
WW^*	23.1%
gg	8.48%
ττ	6.16%
ZZ^*	2.89%
cc	2.83%
γγ	0.228%
Zγ	0.162%
μμ	0.0214%

The h → $\tau^+ \tau^-$ experimental status

- Both experiments have evidence and are actively searching in all τ decay modes





CMS [1401.5041], ATLAS-CONF-2014-061

A Tau Yukawa CPV phase

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

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

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

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

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

Also see, *e.g.* Kearney, Pierce, Weiner [1207.7062]

A Tau Yukawa CPV phase

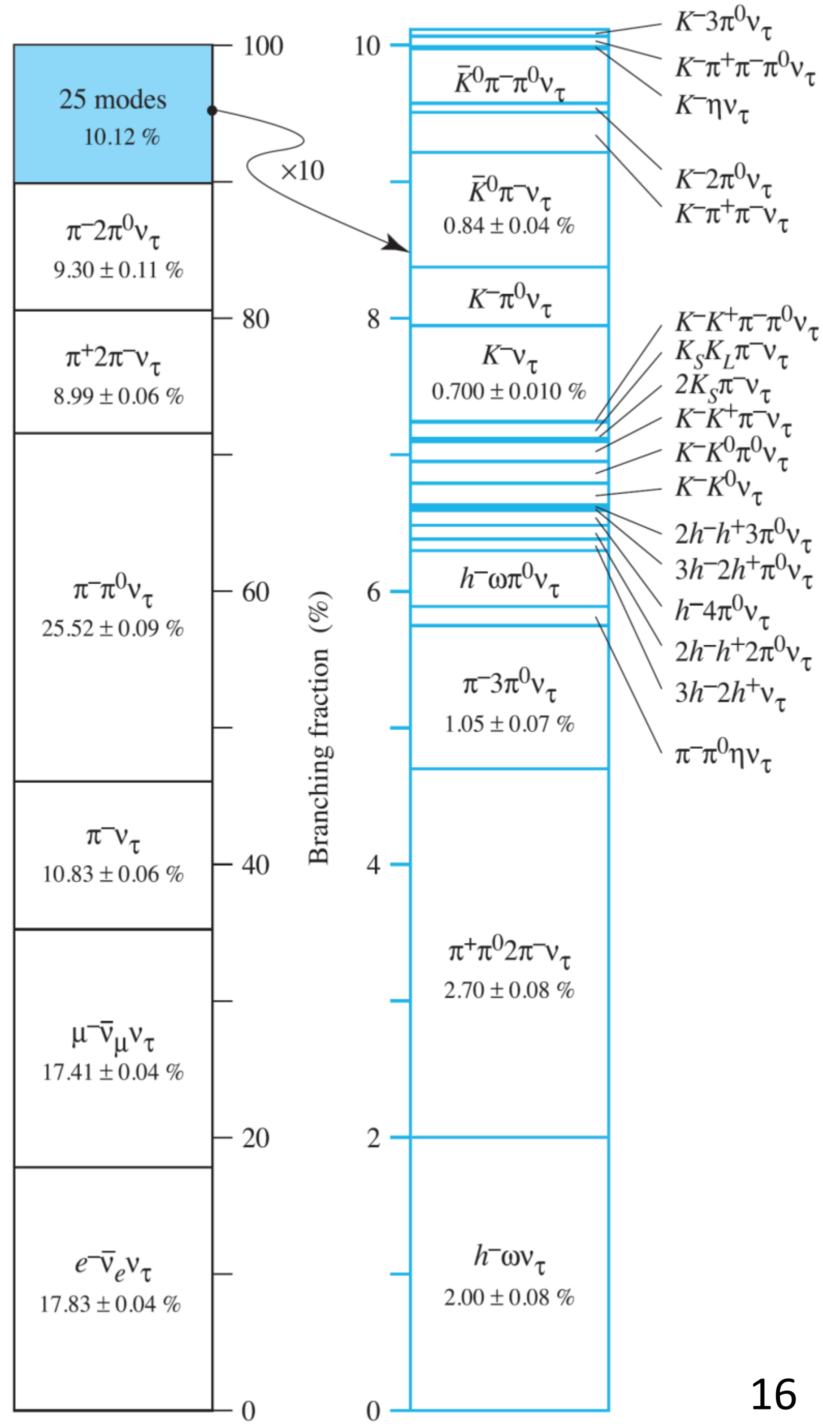
- The new phase can thus be captured by considering the Lagrangian

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

  - Δ = 0 is SM (CP-even)
  - Δ = π/2 is pure CP-odd (and CP conserving)
  - Δ = ±π/4 is maximally CP-violating
  - Δ is currently unconstrained
- We will assume the y_τ magnitude is SM strength

A CPV Observable

- We already lose information from missing neutrinos
  - Leptonic decays, though clean, lose even more information
- Need an intermediate vector (not scalar) in the tau decay: focus on the ρ vector meson
  - Br($\tau^+ \to \rho^+ \nu$) ≈ 26%
  - Br($\rho^+ \to \pi^+ \pi^0$) ≈ 100%



PDG

Extracting the phase in Higgs decays

- Tau Yukawa CPV is imprinted on the tau polarizations relative to each other
  - Tau polarizations then get imprinted on the ν and ρ, ρ polarization is imparted to the πs
- Simplest observable (appropriate for LHC) is $\rho^+\rho^-$ acoplanarity angle
- New, better observable (appropriate for e^+e^- collider) is Θ

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

Matrix element calculation

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

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

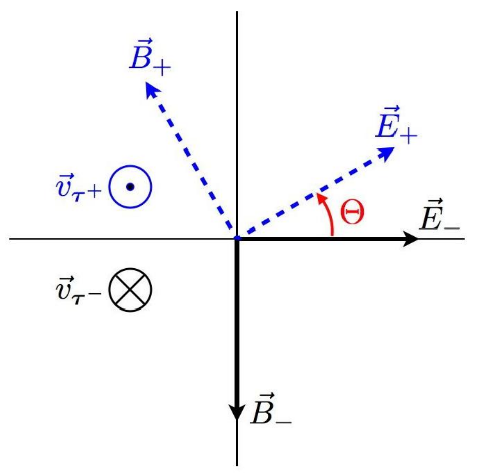
$$\mathcal{M}_{\tau\to\rho\nu} \propto\ (\epsilon^*_{\rho^-})_\mu\ \bar{u}_{\nu_\tau}\gamma^\mu P_{\mathrm{L}}\, u_{\tau^-}$$

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

- Together, gives

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

The Theta Variable*



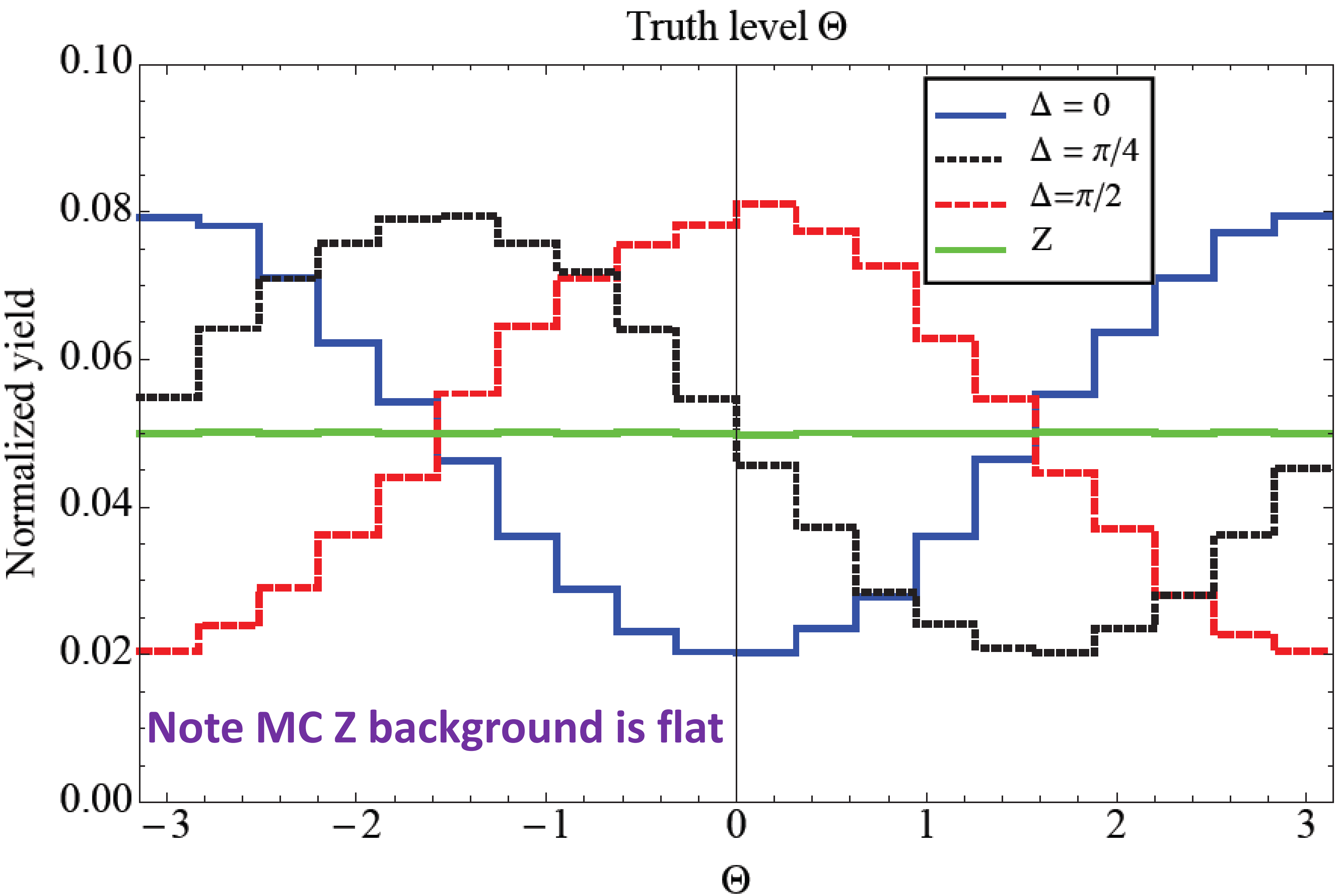
$$\Theta = \mathrm{sgn}\left[\vec{v}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \mathrm{Arccos}\left[\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+|\,|\vec{E}_-|}\right]$$

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

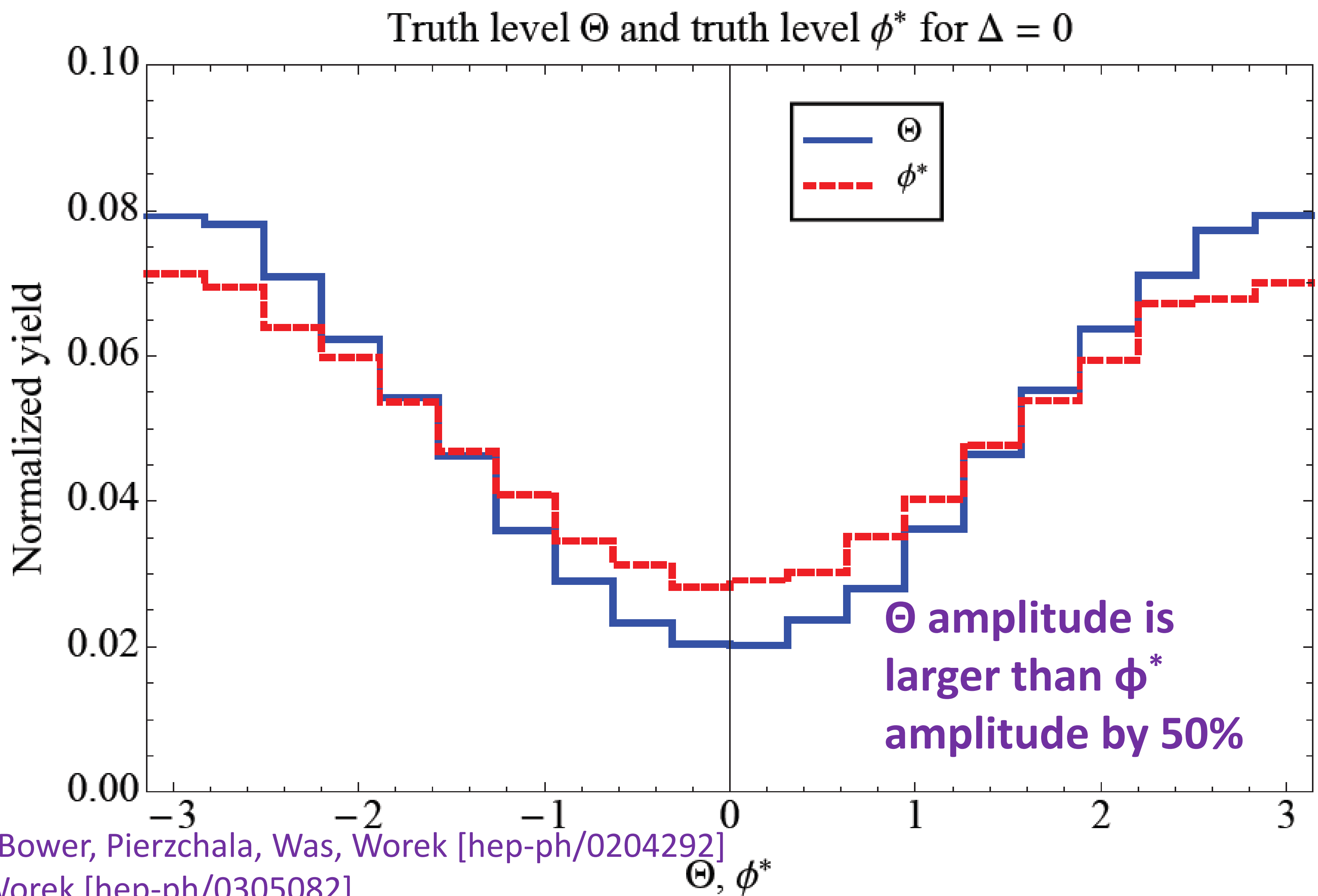
- In the Higgs rest frame, the "electric" components are $\vec{E}_\pm = \frac{m_h}{2}\left[(y_\pm - r)\,\vec{p}_{\pi^\pm}\big|_0 - (y_\pm + r)\,\vec{p}_{\pi^0\pm}\big|_0\right]^\perp$ $|_0$ = tau rest frame
- If neutrinos were measured, we would have complete information to reconstruct tau momentum, tau and Higgs rest frames

*See backup or [1308.1094] for details

Ideal situation



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

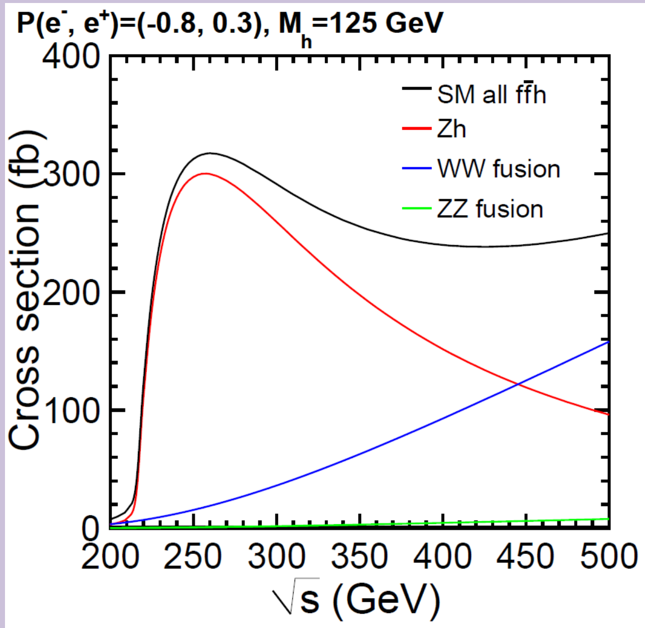


Θ amplitude is larger than ϕ^* amplitude by 50%

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

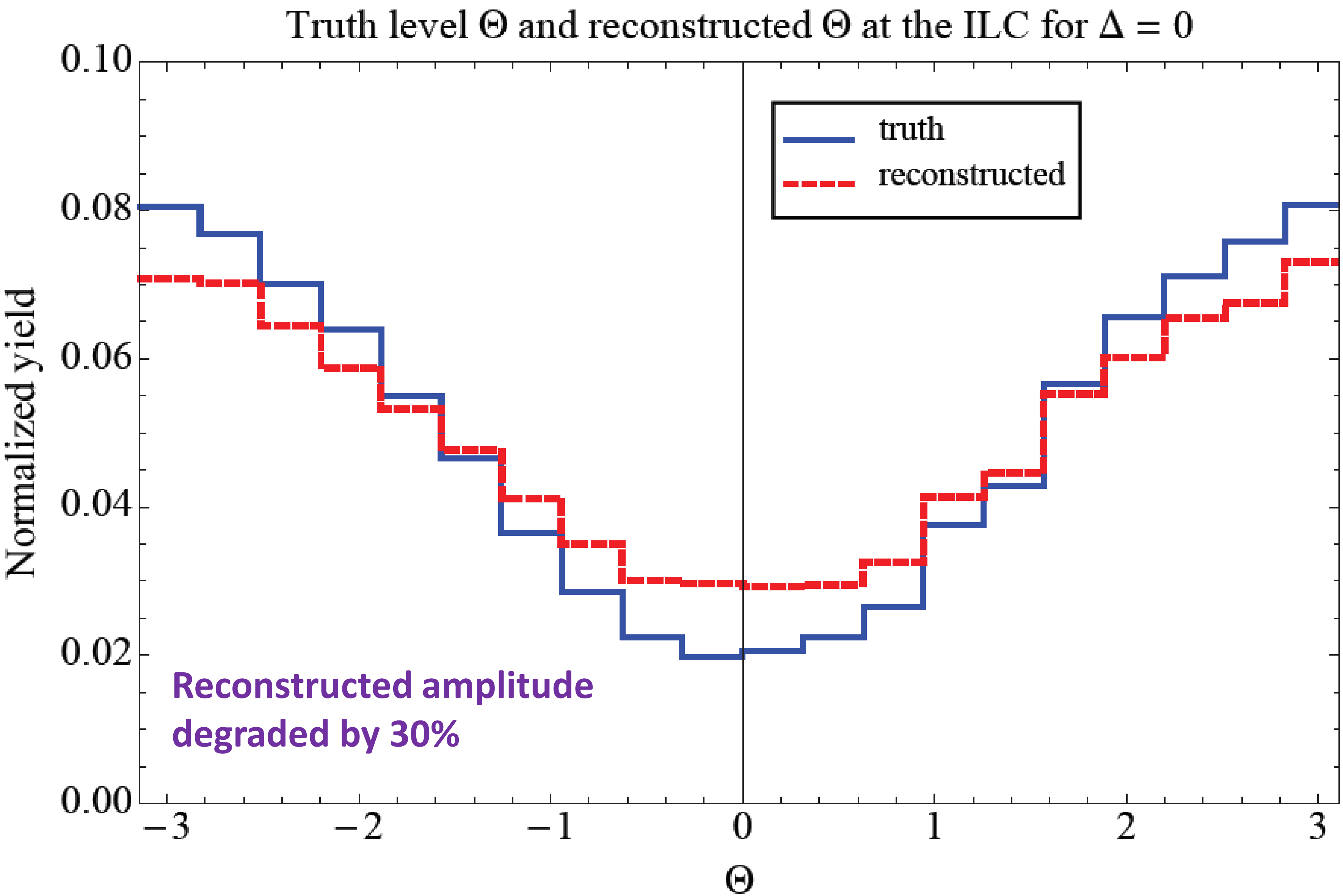
Lepton collider possibilities

- 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
    - Both solutions give correct Higgs mass
    - Weight each solution by half an event
    - Necessarily require visible Z decay

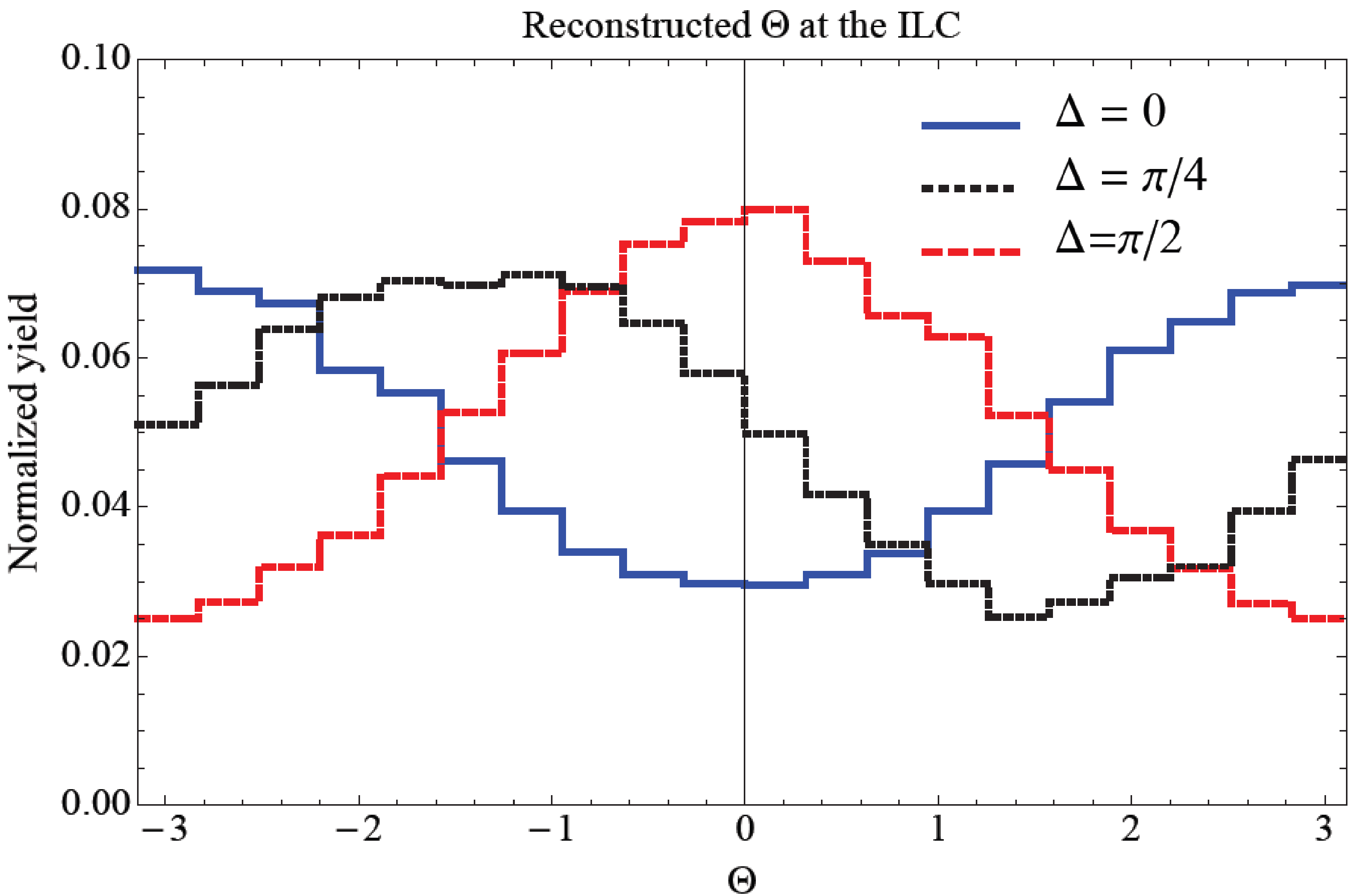


ILC TDR Volume 2

Lepton collider – reconstructed



Lepton collider – reconstructed



Lepton collider possibilities

- For √s = 250 GeV ILC, polarized beams, Zh production is about 0.30 pb
- With unpolarized beams (FCC-ee or CEPC), cross section is about 30% less
- ILC signal yield (using SM Br(h →ττ) 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%
$\mathrm{N}_{\text{events}}$	990

Lepton collider possibilities

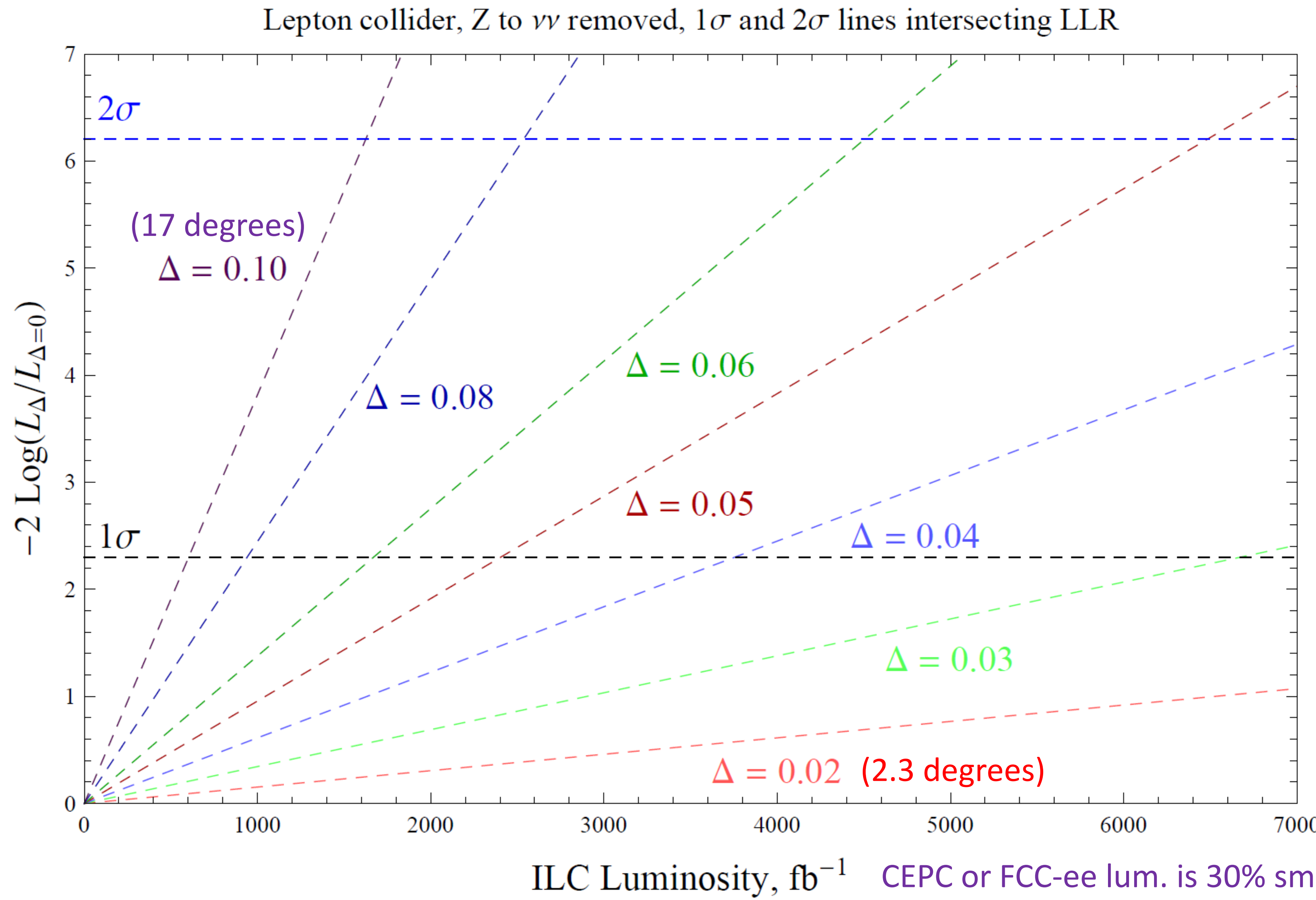
- For √s = 250 GeV ILC, polarized beams, Zh production is about 0.30 pb
  - ILC signal yield (using SM Br(h →ττ) and restricting to visible Z decays) is 990 events with 1 ab^{-1}
  - Construct binned likelihood using a sinuisoidal fit to signal, determine sensitivity by variation of test Δ

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]

Luminosity scaling (without systematics)



CEPC or FCC-ee lum. is 30% smaller

Lepton Collider Prospects

- Systematics will affect high luminosity estimates
- Expect some minor sensitivity losses from detector resolution

ILC (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%
$\mathrm{N}_{\text{events}}$	990
Accuracy	4.4°

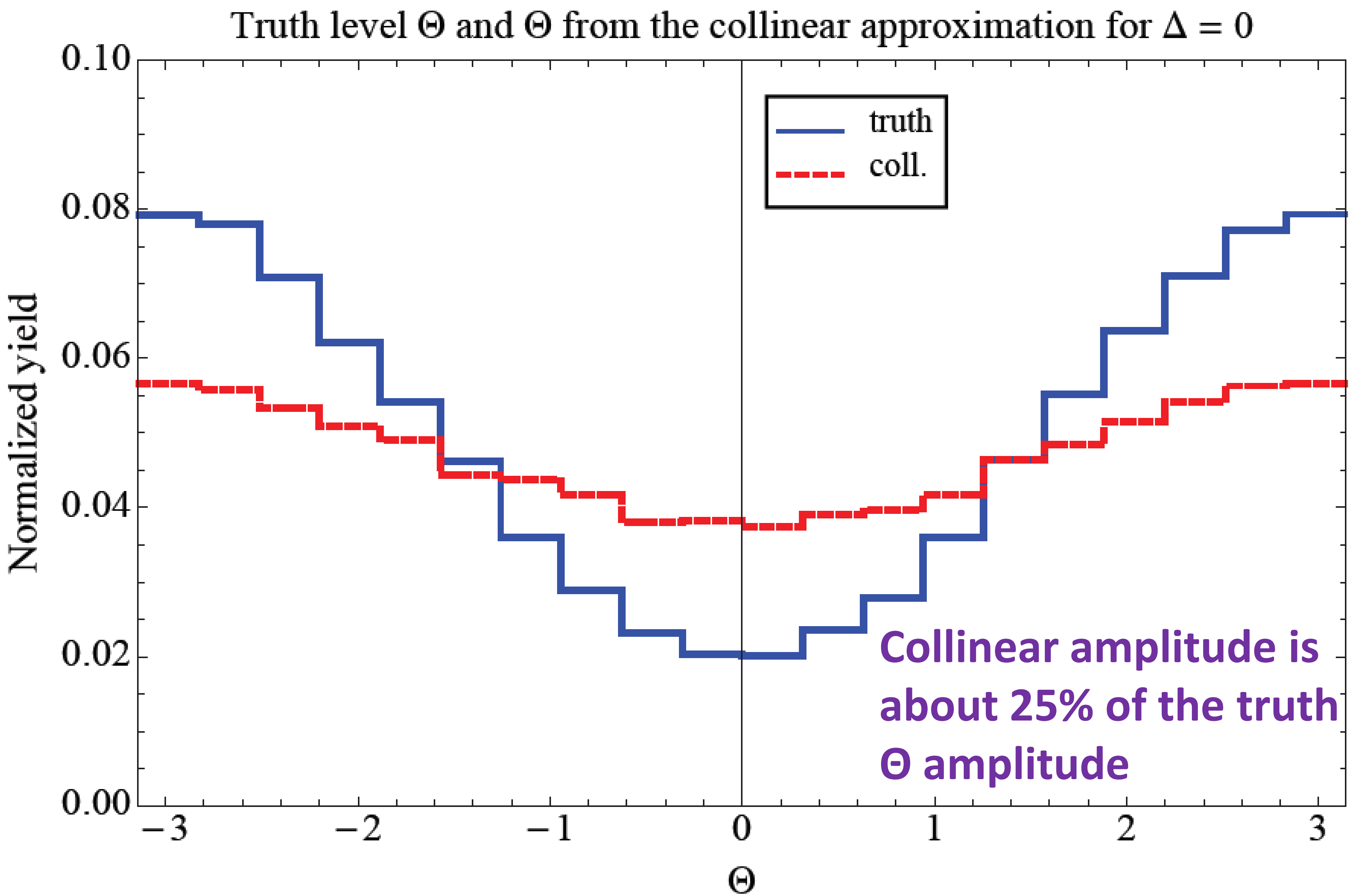
CEPC (ab^{-1})

CEPC1	CEPC5	CEPC10
5.5°	2.5°	1.7°

LHC prospects

- Consider h+j events ("boosted" $\tau_{had}\tau_{had}$ sample)
- At the LHC, need to approximate neutrino momenta
  - Have (8-2-2-2=) 2 unknown four-momentum components
  - Will use collinear approximation for neutrino momenta
    - In this approximation, Θ is identical to ρρ acoplanarity angle
    - Other approximations considered tended to wash out or distort the sinuisoidal shape of the Θ distribution
  - First proposal to measure Δ at the LHC with prompt tau decays and kinematics

Ideal vs. Collinear approximation



LHC14 simulation details

- 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:

  $$\text{MET} > 40\text{ GeV},\ p_T(\rho) > 45\text{ GeV},\ |\eta(\rho)| < 2.1,$$
  $$m_{coll} > 120\text{ GeV}$$

  - 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
$\mathrm{Br}(\tau^+\tau^-\ \text{decay})$	6.1%	3.4%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%	26%
Cut efficiency	18%	0.24%
$\mathrm{N}_{\text{events}}$	1100	1800

N_{events} for 3 ab^{-1} with τ-tagging 50% efficiency

Yields for 3 ab^{-1} LHC

- Consider τ tagging efficiency benchmarks of 50% and 70%, use likelihood analysis testing different Δ

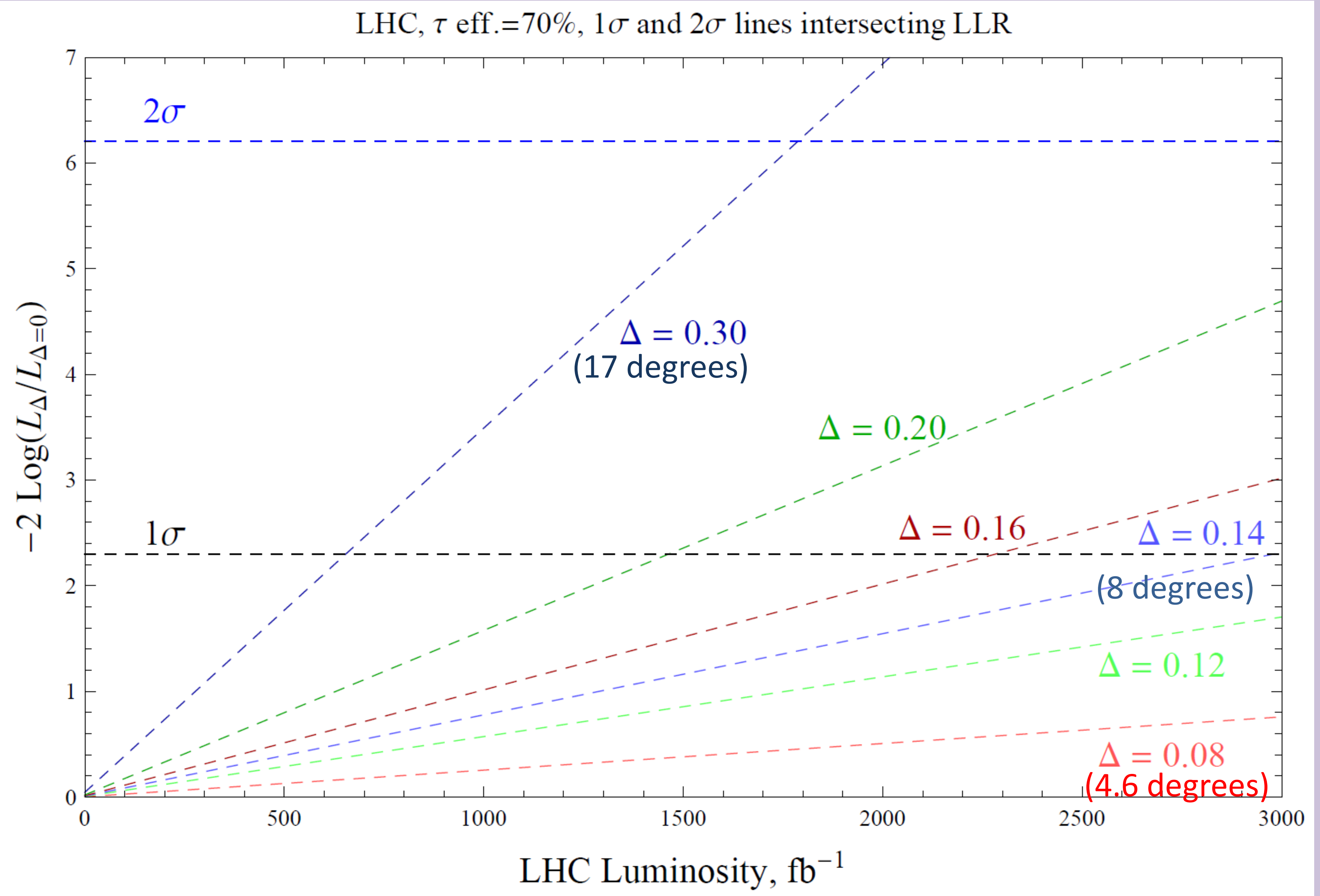
τ_h efficiency	50%	70%
3σ	$L = 550\ \text{fb}^{-1}$	$L = 300\ \text{fb}^{-1}$
5σ	$L = 1500\ \text{fb}^{-1}$	$L = 700\ \text{fb}^{-1}$
Accuracy$(L = 3\ \text{ab}^{-1})$	11.5°	8.0°

  – 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

Luminosity scaling (without systematics)

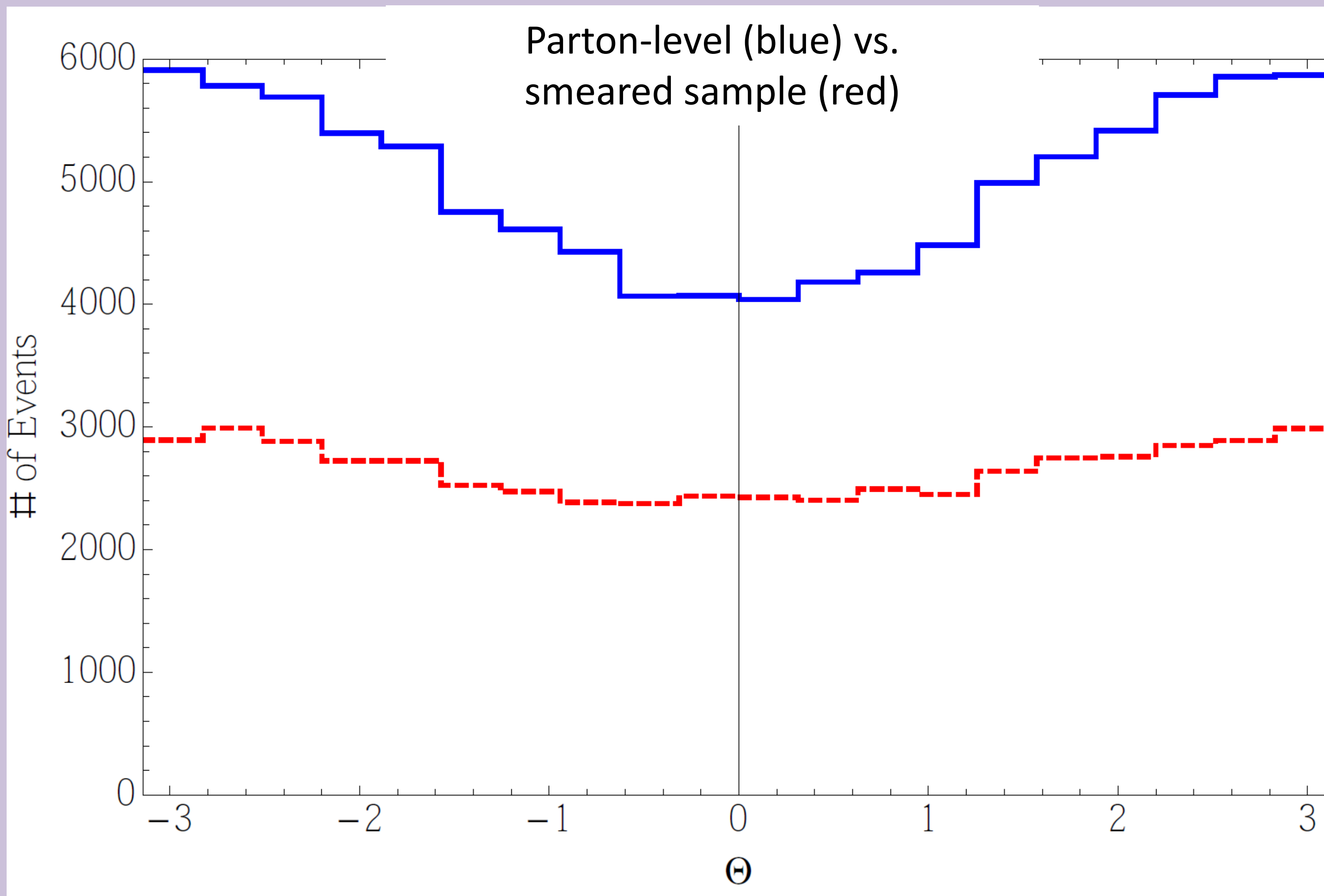


Improving the measurement of the tau Yukawa CP phase

- Consider including MET information for LHC analyses
  - *e.g.* MELA-type likelihood incorporating signal hypotheses with different Δ
- Consider other tau decay modes or add decay vertex information
- Improve tau tagging efficiency
- Dedicated di-tau hadronic trigger
- Consider VBF production, Zh production
  - For VBF, 3 ab^{-1}, expect 52k $\pi^+\pi^0\nu\ \pi^-\pi^0\nu$ total events (no cuts)
    - S/B is about 0.4 from ATLAS 8 TeV BDT analysis

Incorporate detector effects

- Amplitude of Theta distribution diluted by about half



PRELIMINARY

Summary

- New CP phases are motivated from general baryogenesis arguments
- Many physics studies are needed to motivate the physics case of future machines
- Have a new suite of measurements to perform in Higgs physics
  - Fermionic CP phases play a special role
  - Look forward to implementing this analysis in future Higgs studies
  - Can also consider prospects at FCC-hh and SPPC

Colliders	LHC	HL-LHC	ILC ($1\ \mathrm{ab}^{-1}$)	CEPC1	CEPC5	CEPC10
Accuracy(1σ)	25°	8.0°	4.4°	5.5°	2.5°	1.7°

UV completion

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

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

Matrix element calculation assumptions

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

- 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 $\mathcal{M}_{\text{full}} \propto \bar{u}_{\nu^-} \not{q}_-\left(\mathrm{e}^{\mathrm{i}\Delta}\not{p}_{\tau^-} - \mathrm{e}^{-\mathrm{i}\Delta}\not{p}_{\tau^+}\right)\not{q}_+ P_{\text{L}} v_{\nu^+}$
  with $q_{\pm} \equiv p_{\pi^{\pm}} - p_{\pi^0\pm}$
  - Recall $\rho_{\pm}$ polarization is generally aligned with $q_{\pm}$

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
$$|\mathcal{M}|^2 \propto \; P_{\cancel{\Delta},\,\mathrm{S}} + P_{\Delta,\,\cancel{\mathrm{S}}} + P_{\Delta,\,\mathrm{S}} + P^{*}_{\Delta,\,\mathrm{S}}$$

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

Calculating the Theta Variable

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

- We can define an antisymmetric 2nd-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 $E_{\pm}^{i} \equiv F_{\pm}^{i0}\,, \quad B_{\pm}^{i} \equiv -\frac{1}{2}\epsilon^{ijk}F_{\pm jk}$

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

Calculating the Theta Variable

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

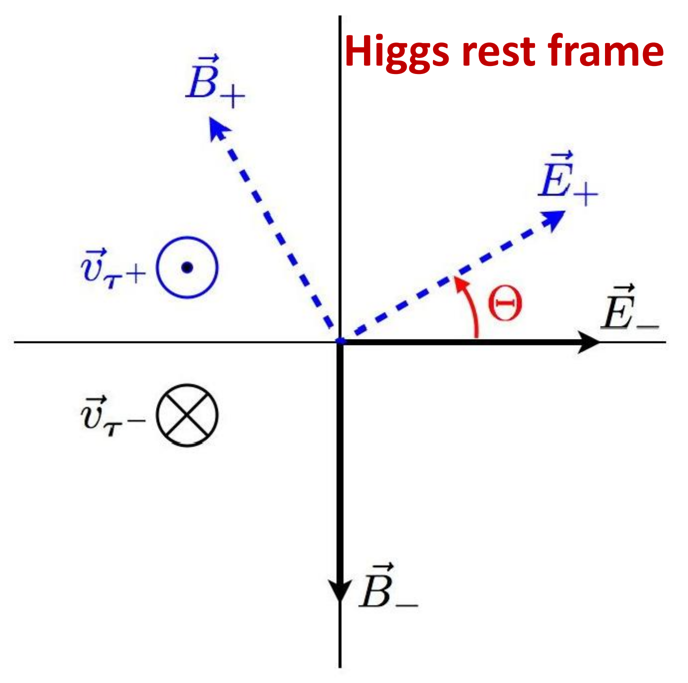
- We can calculate

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

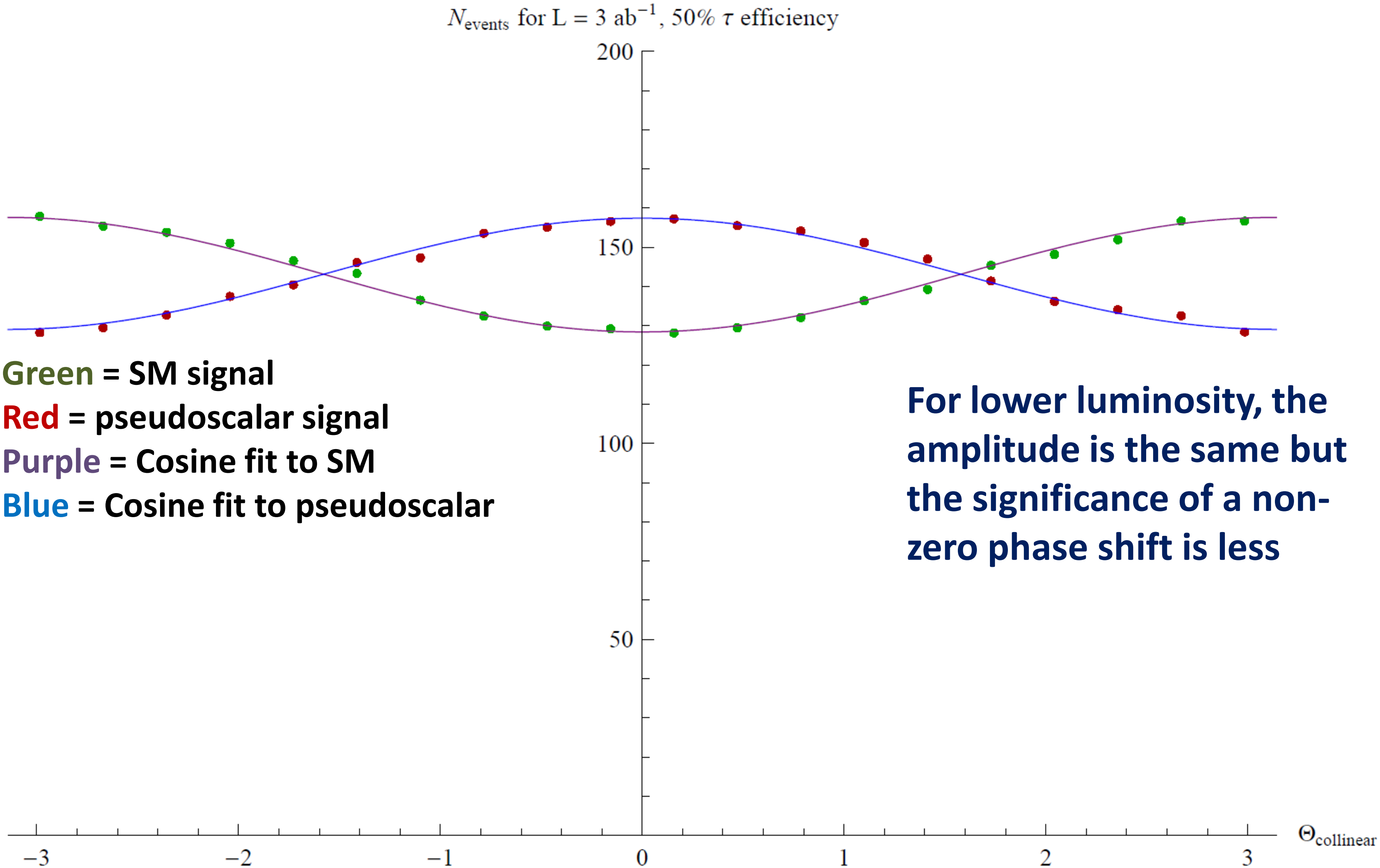
- Specialize to Higgs rest frame (back-to-back taus)
  - E_+B_+ and E_-B_- planes are parallel
  - Motivate a new acoplanarity between E_+v_+ and E_-v_- planes

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

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



Yields for 3 ab^{-1} LHC

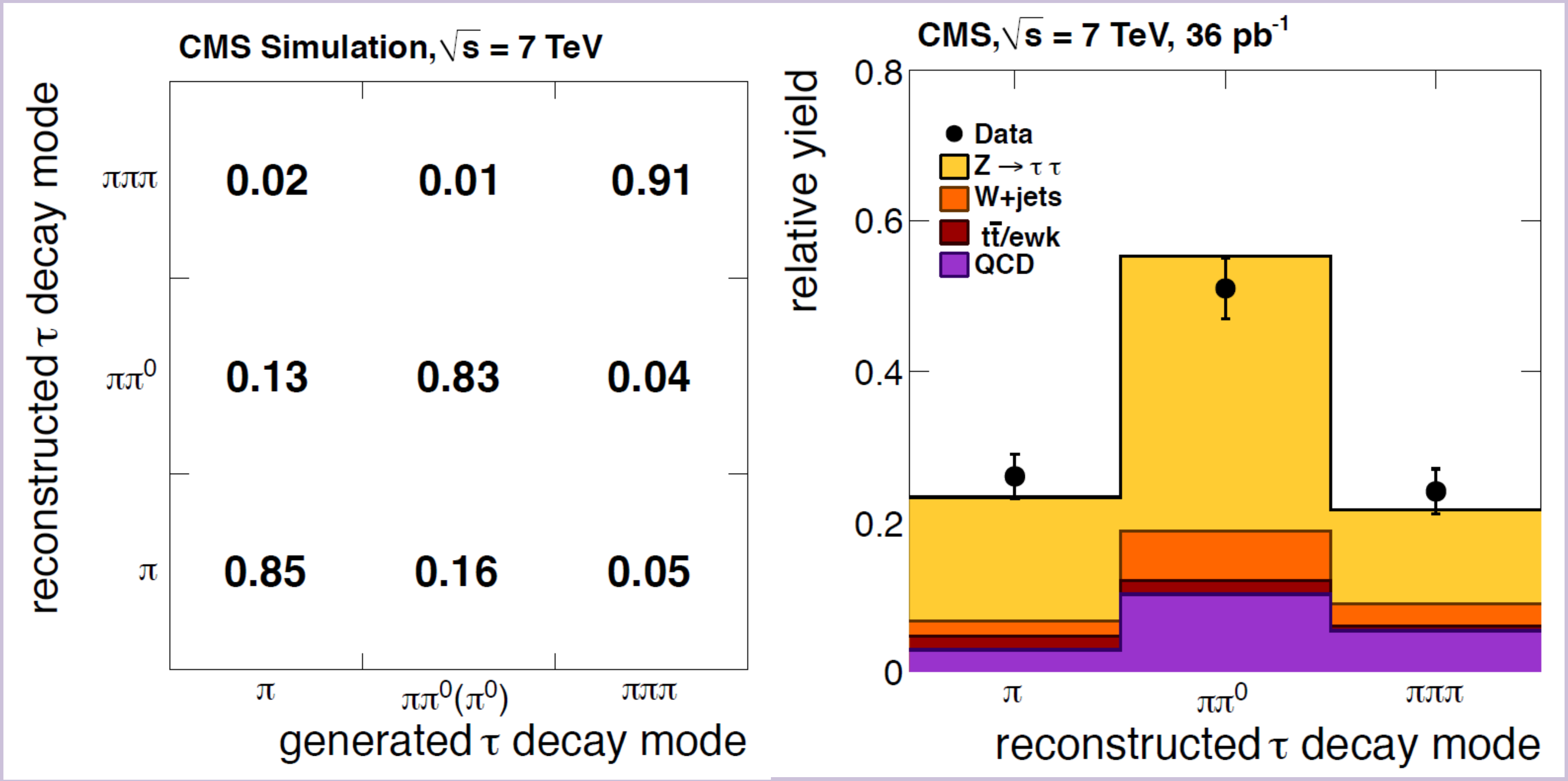


Green = SM signal
Red = pseudoscalar signal
Purple = Cosine fit to SM
Blue = Cosine fit to pseudoscalar

For lower luminosity, the amplitude is the same but the significance of a non-zero phase shift is less

Tau measurement details

- Method relies on reconstructing neutral and charged pions with good resolution and efficiency



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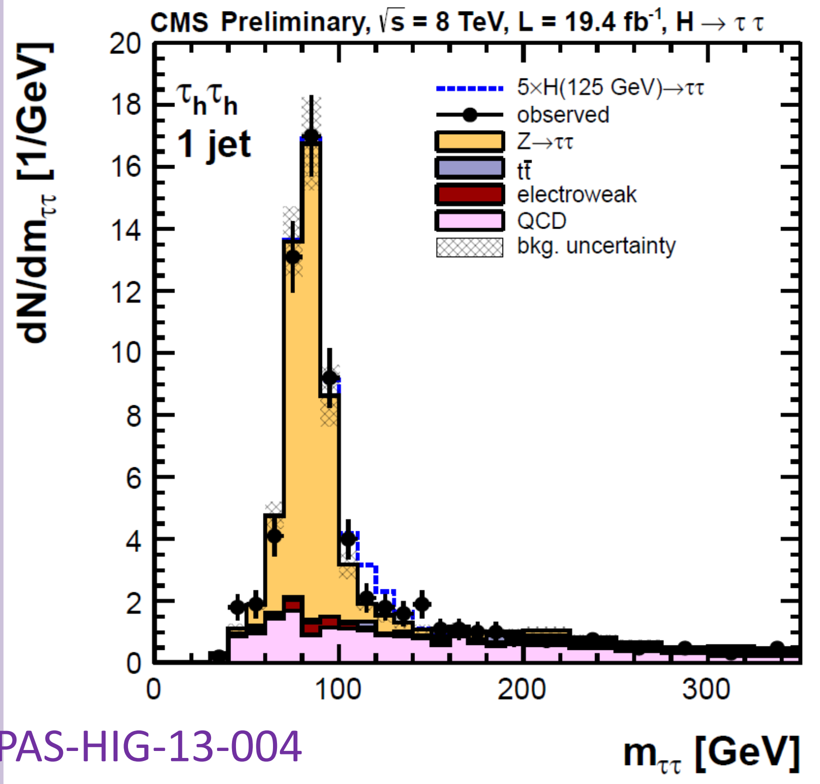
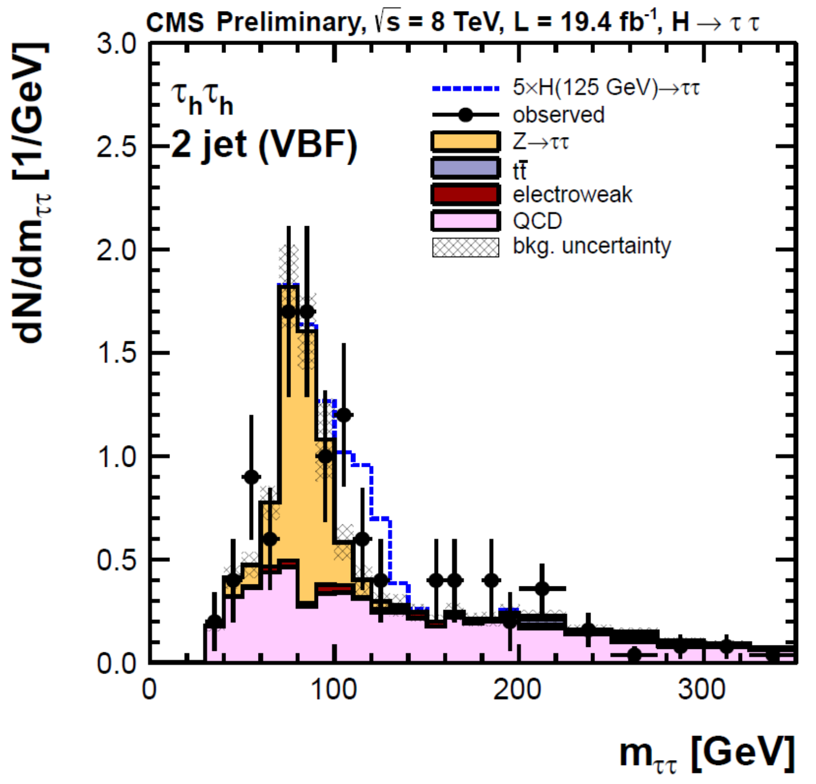
Measuring Higgs to $\tau\tau$

- 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

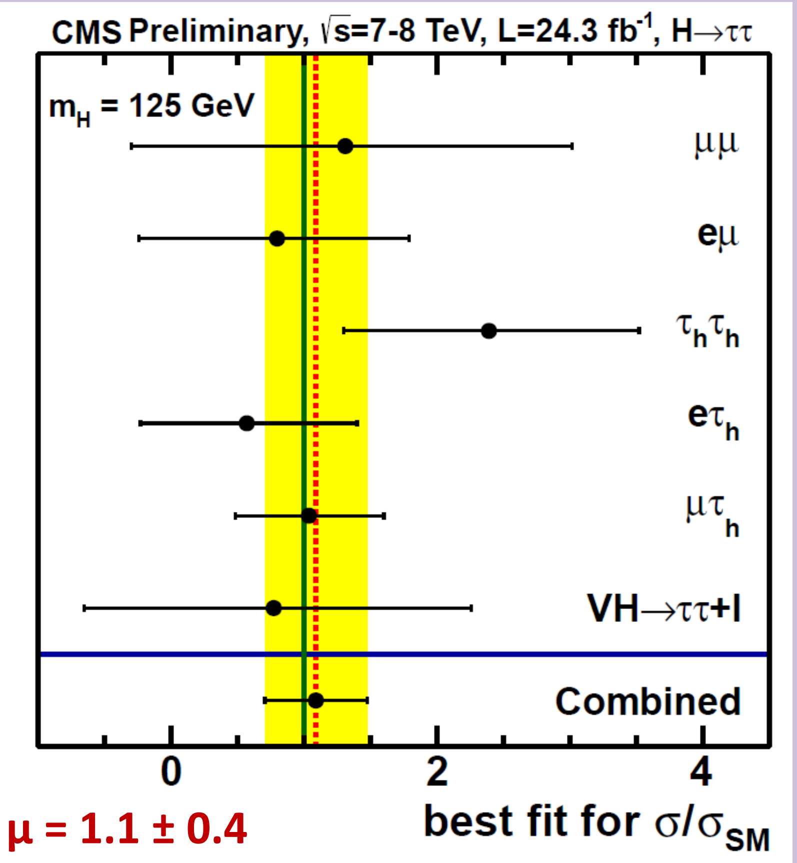
Measuring Higgs to ττ

- 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*
$Z \rightarrow \tau\tau$	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
$H \rightarrow \tau\tau$	9 ± 4	4 ± 2
Observed	718	120

Signal Eff.

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



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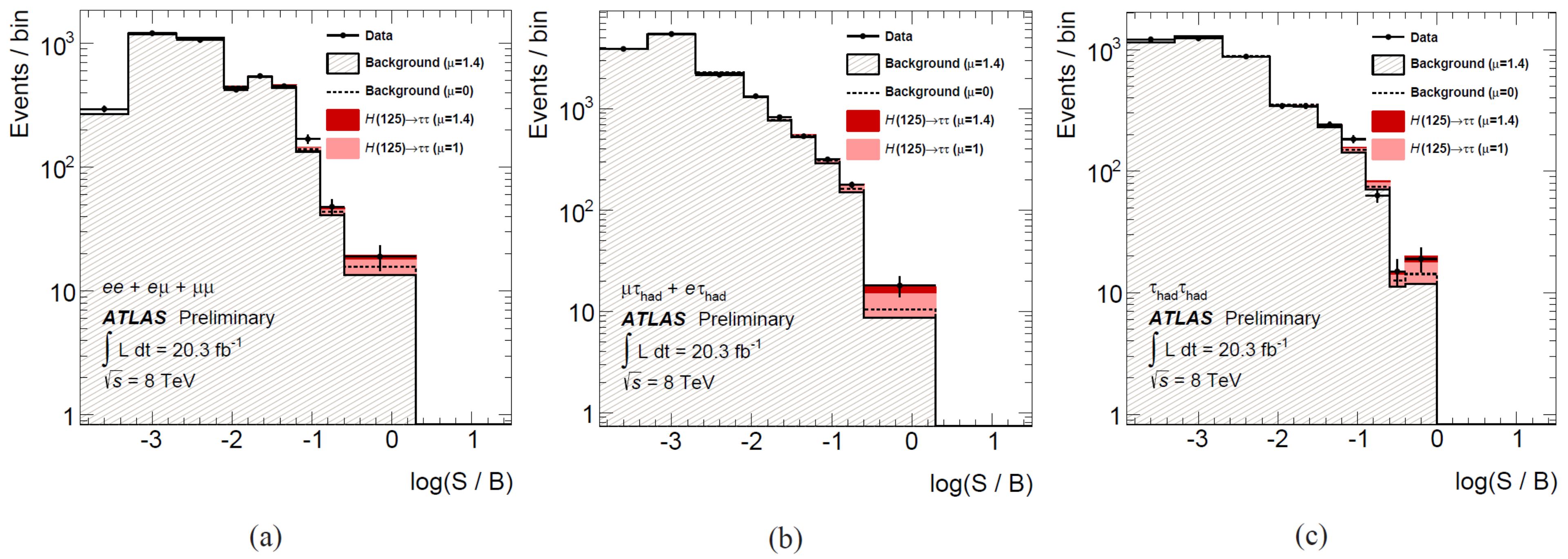
Combined: μ = 1.1 ± 0.4

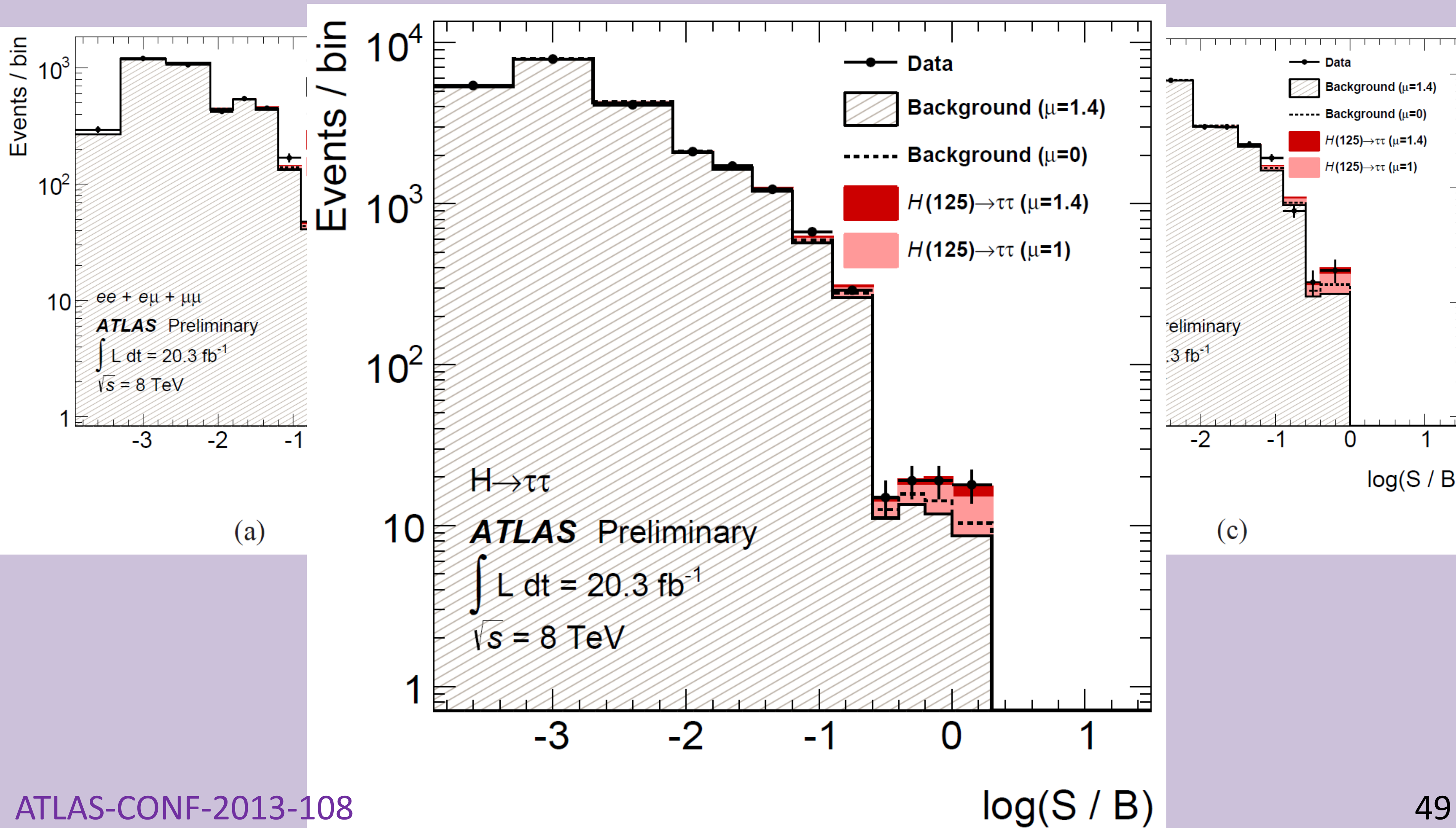
ATLAS Update

- Use BDT output to categorize events



ATLAS Update

- Use BDT output to categorize events



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
$Z \to \tau^+\tau^-$	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

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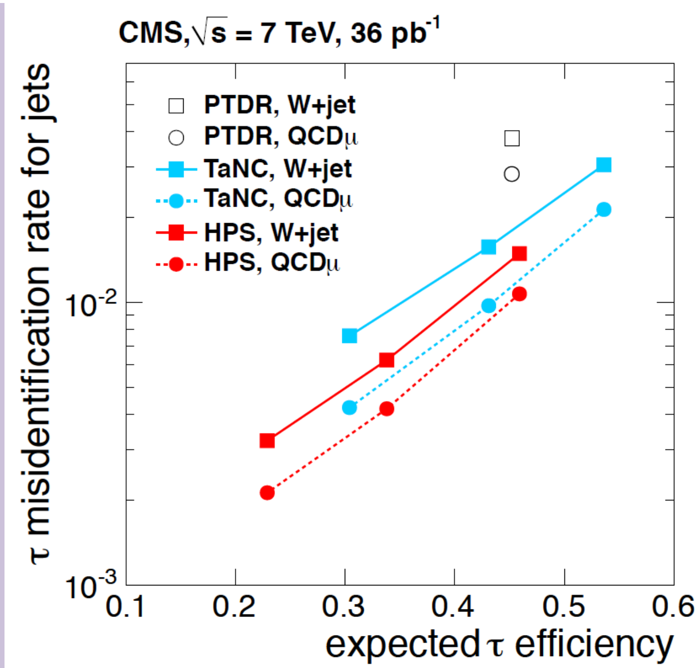
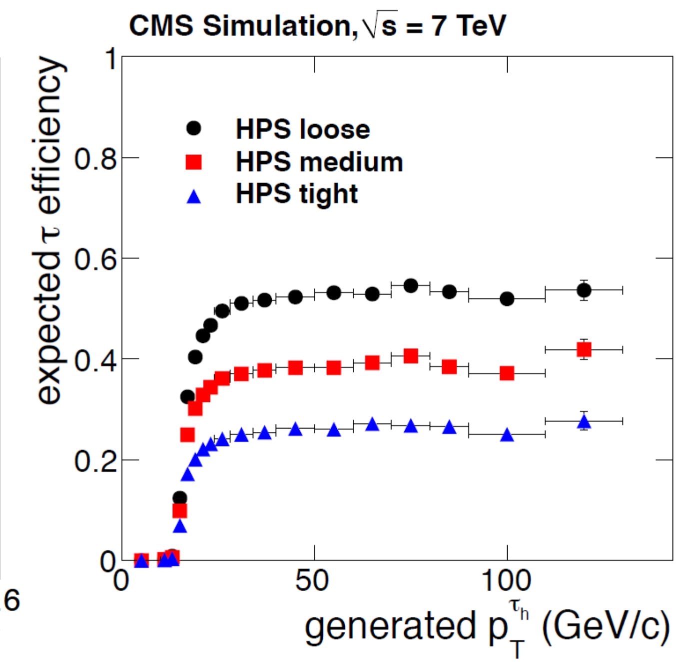
Tau measurement details

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%





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 $Z \rightarrow \tau\tau$ 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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