

MEASURING CP VIOLATION IN $H \rightarrow \tau^+ \tau^-$ AT COLLIDERS

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Outline

- Motivation for CPV in Higgs physics
- Introduce CPV in tau Yukawa coupling
- Constructing and measuring the Θ variable
- Sensitivity studies at colliders
 - First proposal for an LHC measurement
 - ILC prospects, comparison with previous proposals
- Summary

Motivating searches for CPV

- 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)
 - tested via acoplanarity measurement in $h \rightarrow ZZ^* \rightarrow 4l$
 - couplings to fermions (*e.g.* fermionic CPV)
 - this work: test via $h \rightarrow \tau^+ \tau^- \rightarrow (\rho^+ \nu) (\rho^- \nu) \rightarrow (\pi^+ \pi^0) \nu (\pi^- \pi^0) \nu$
- Full UV models to connect any given CP phase to a baryogenesis mechanism is for future study

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 washed out by QCD
- Tau channel suffer from lost information via neutrinos (at hadron colliders), but still have an appreciable rate

$M_H = 126 \text{ GeV}$	SM Br
bb	56.1%
WW	23.1%
gg	8.48%
$\tau\tau$	6.15%
ZZ	2.89%
cc	2.83%
$\gamma\gamma$	0.228%
Z γ	0.162%
$\mu\mu$	0.0214%

CMS combined: $\mu = 1.1 \pm 0.4$ (CMS PAS-HIG-13-004)

ATLAS combined: $\mu = 1.4^{+0.5}_{-0.4}$ (ATLAS-CONF-2013-108)

A Tau Yukawa CPV phase

- From EFT, use dimension 6 operator

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

- 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 $y_\tau^{\text{SM}} + 2\beta \frac{v^2}{\Lambda^2}$

A Tau Yukawa CPV phase

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

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

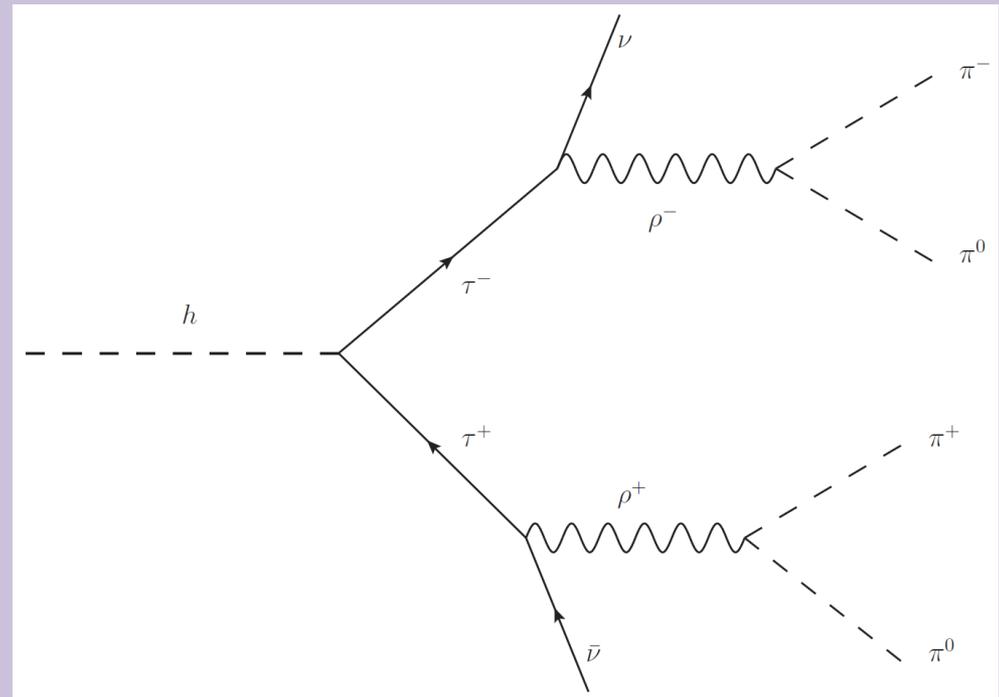
- $\Delta = 0$ is SM (CP-even)
- $\Delta = \pi/2$ is CP-odd (and CP conserving)
- $\Delta = \pm\pi/4$ is maximally CP-violating
- Δ is currently unconstrained

- We will assume the y_τ magnitude is SM strength

Extracting the phase in Higgs decays

- CPV in the tau coupling to Higgs is imprinted on the tau polarizations relative to each other
 - Tau polarizations then get imprinted on the ν and ρ
 - The ρ^\pm polarization is finally imparted to the $\pi^\pm\pi^0$ decay

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



Matrix element calculation

- Treat the Higgs decay as a sequence of on-shell 2-body decays

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

$$\mathcal{M}_{\tau \rightarrow \rho\nu} \propto (\epsilon_{\rho-}^*)_{\mu} \bar{u}_{\nu\tau} \gamma^{\mu} P_L u_{\tau-}$$

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

- Together, gives

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

Calculating the Theta Variable

- We then write the squared matrix element as

$$|\mathcal{M}|^2 \propto P_{\Delta,S} + P_{\Delta,\not{S}} + P_{\Delta,S} + P_{\Delta,S}^*$$

where the most interesting piece is

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

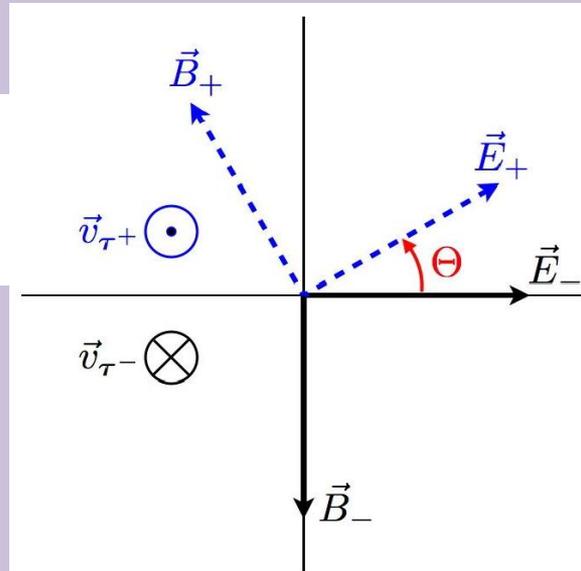
- In the Higgs rest frame, the “electric” components are

$$\vec{E}_\pm = \frac{m_h}{2} \left[(y_\pm - r) \vec{p}_{\pi^\pm}|_0 - (y_\pm + r) \vec{p}_{\pi^0\pm}|_0 \right]^\perp$$

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

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

$|_0$ = tau rest frame, y_\pm and r are kinematic constants

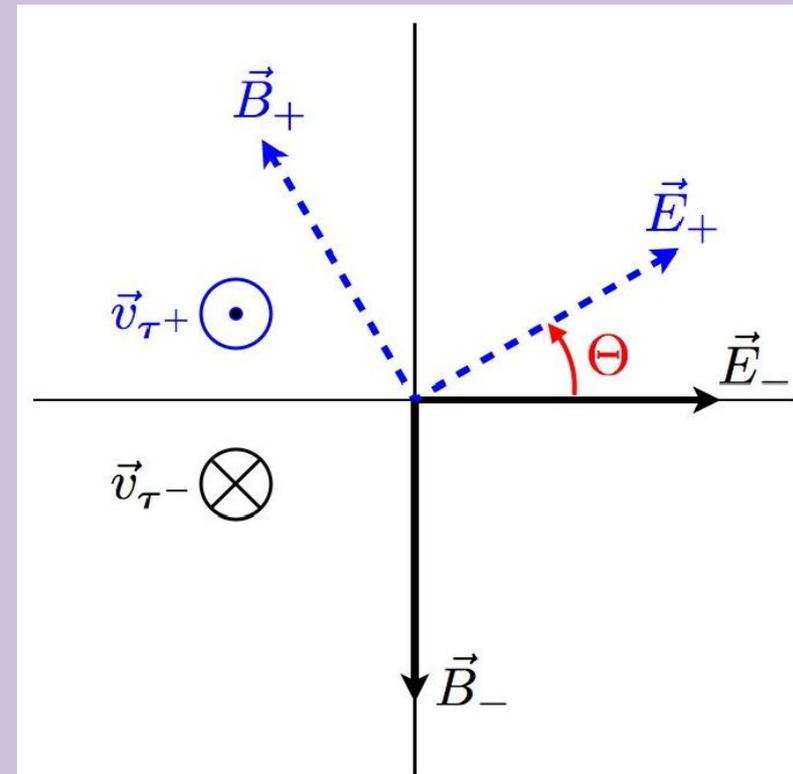


Calculating the Theta Variable

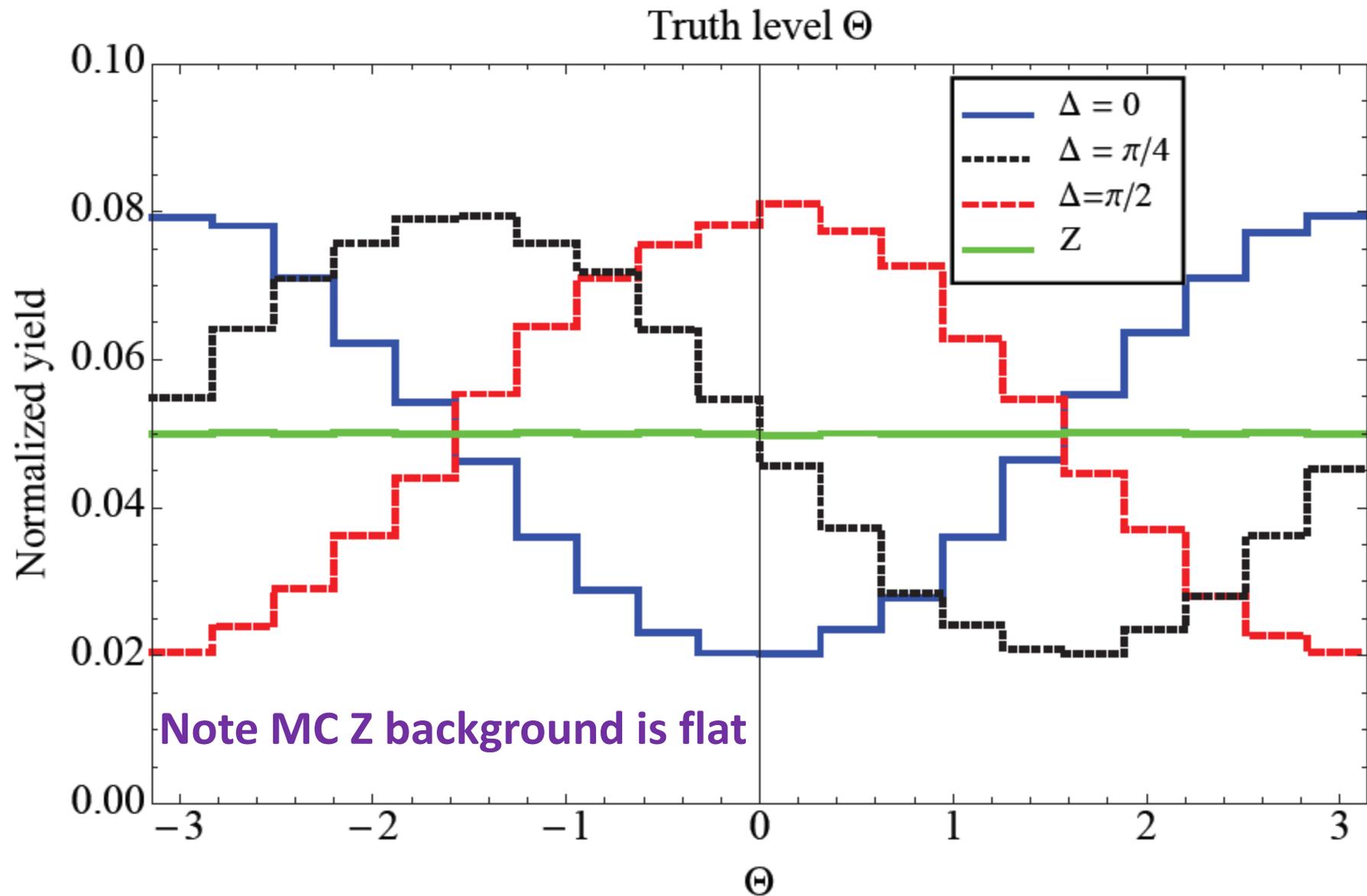
$$\Theta = \text{sgn} \left[\vec{v}_{\tau+} \cdot (\vec{E}_- \times \vec{E}_+) \right] \text{Arccos} \left[\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+| |\vec{E}_-|} \right]$$

- If neutrino 4-momenta were determined, could then reconstruct tau momentum as well as tau and Higgs rest frames

- Not possible at LHC
 - Have 2 undetermined momenta
- Possible at ILC!

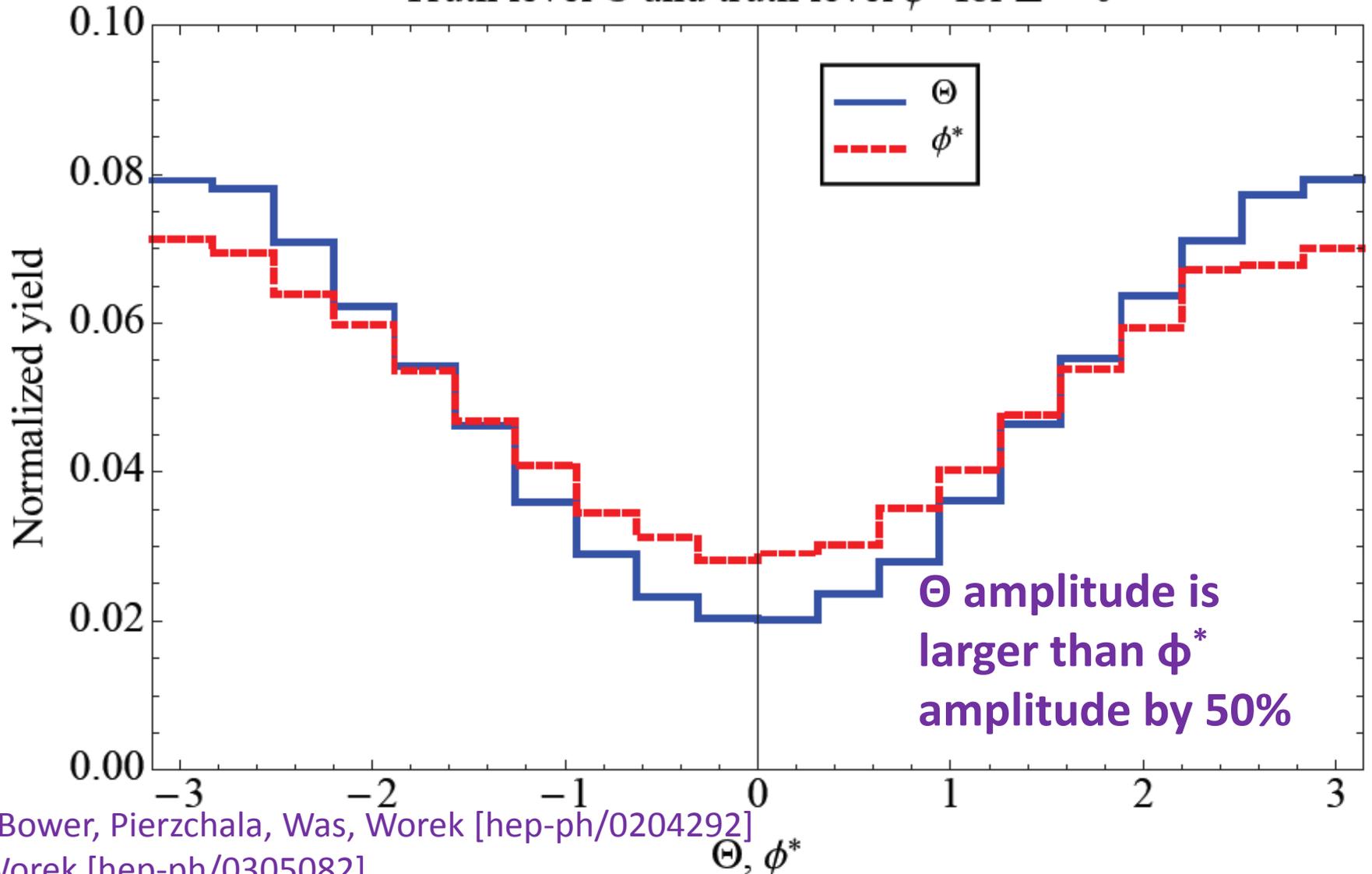


Ideal situation



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

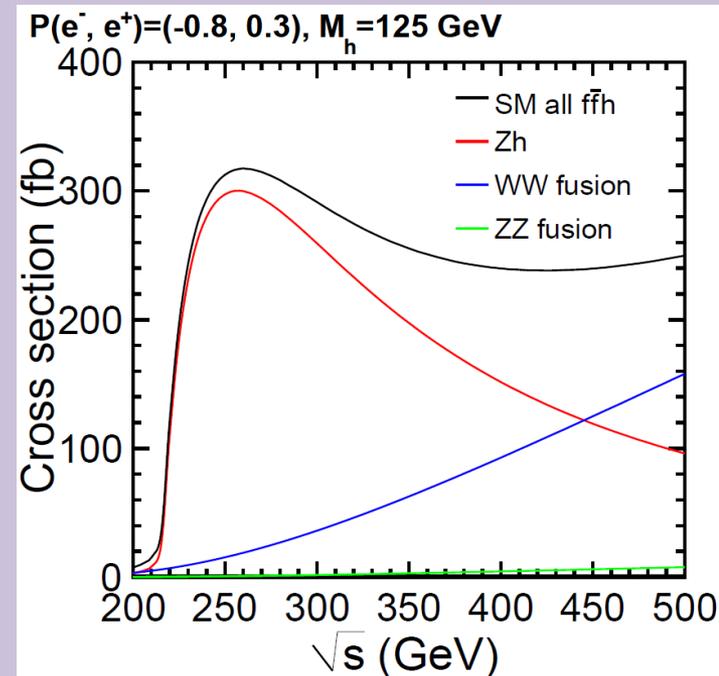
Truth level Θ and truth level ϕ^* for $\Delta = 0$



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

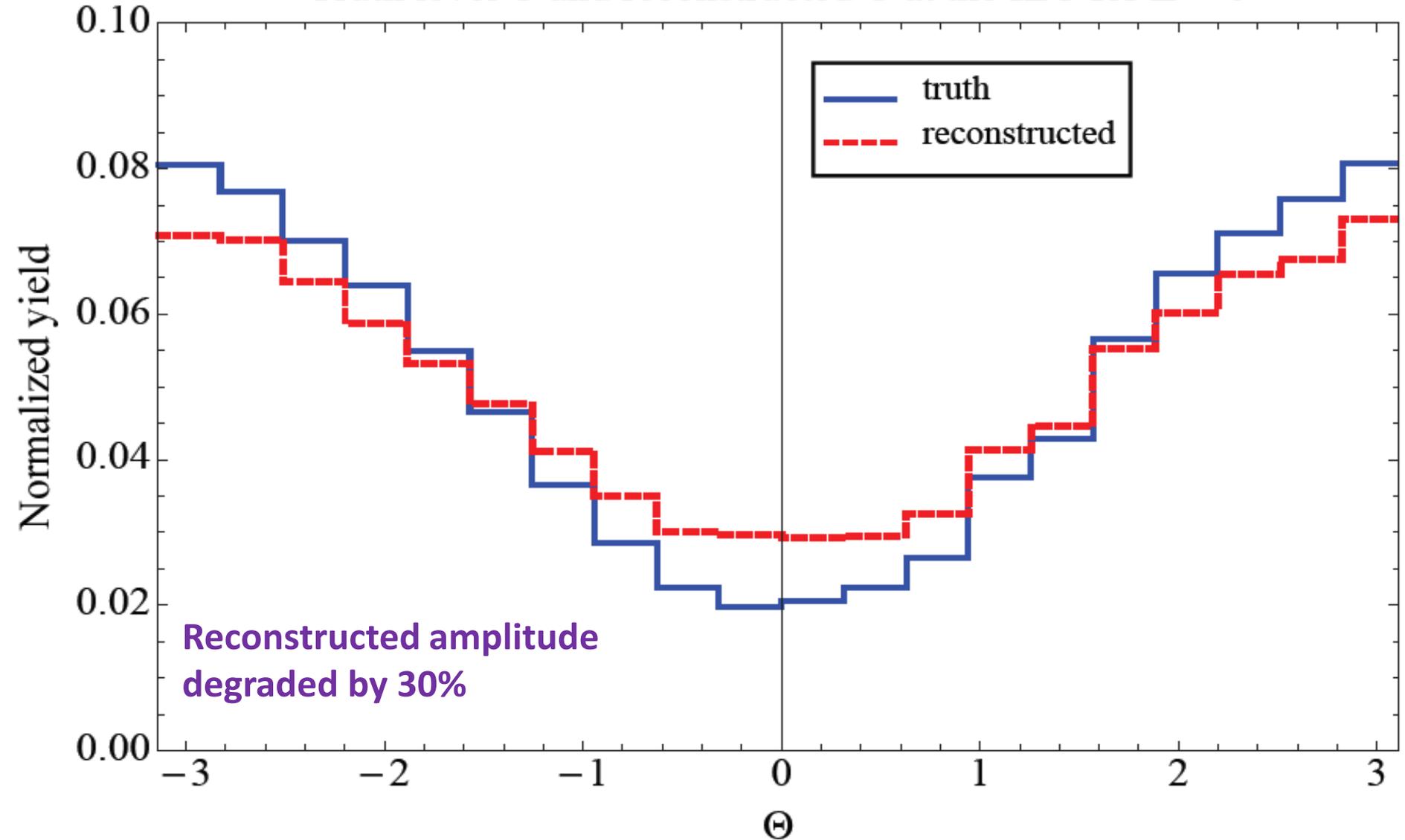
Lepton collider possibilities

- Have enough constraints to solve algebraically for neutrino momenta at lepton collider
 - Have two neutrino momenta solution sets
 - Both solutions give correct Higgs mass
 - Weight each solution by half an event
 - Necessarily require visible Z decay



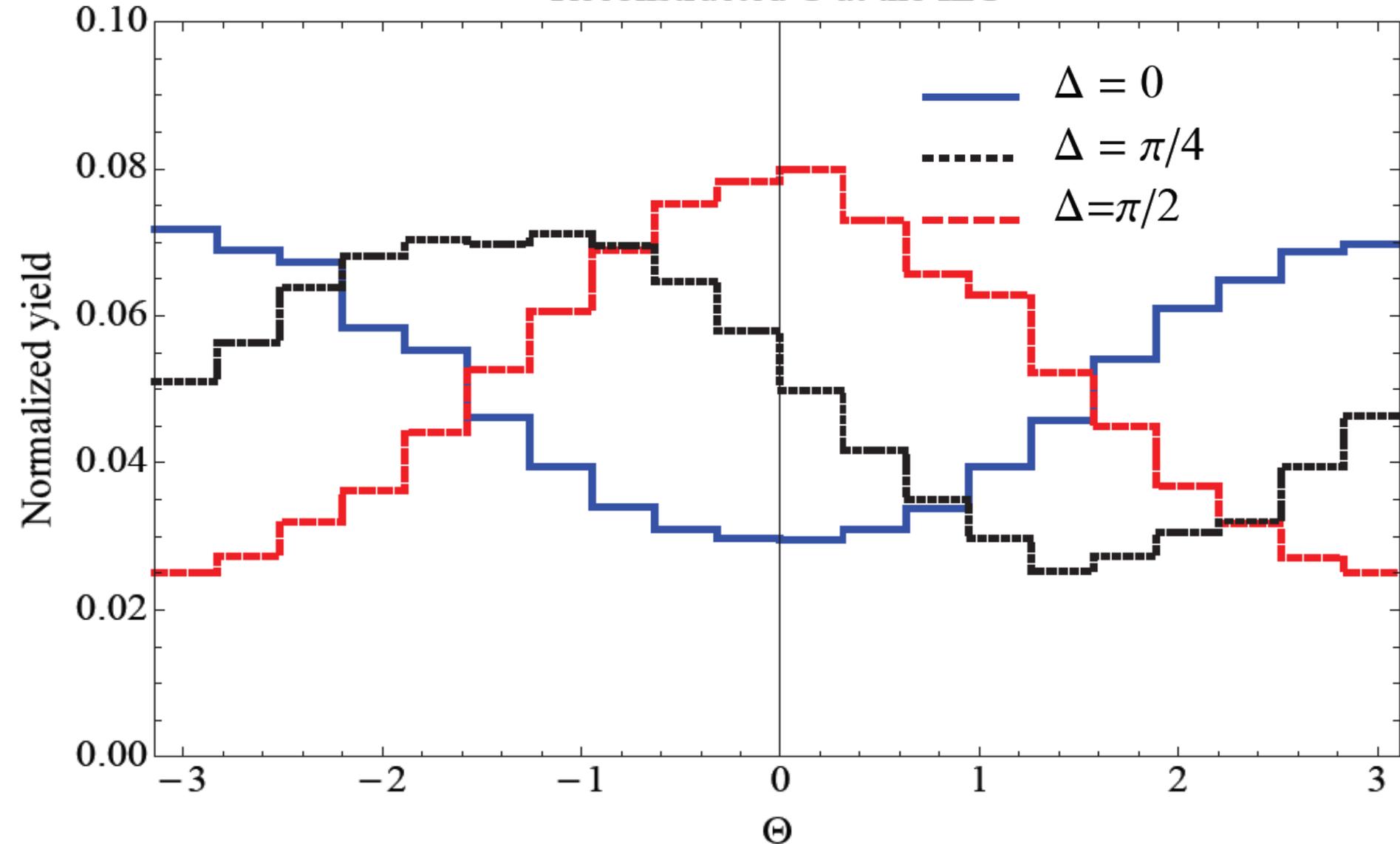
Lepton collider – reconstructed

Truth level Θ and reconstructed Θ at the ILC for $\Delta = 0$



Lepton collider – reconstructed

Reconstructed Θ at the ILC



Lepton collider possibilities

- For $\sqrt{s} = 250$ 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}

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

Lepton collider possibilities

- For $\sqrt{s} = 250$ 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 sinusoidal fit to signal, determine sensitivity by variation of test Δ

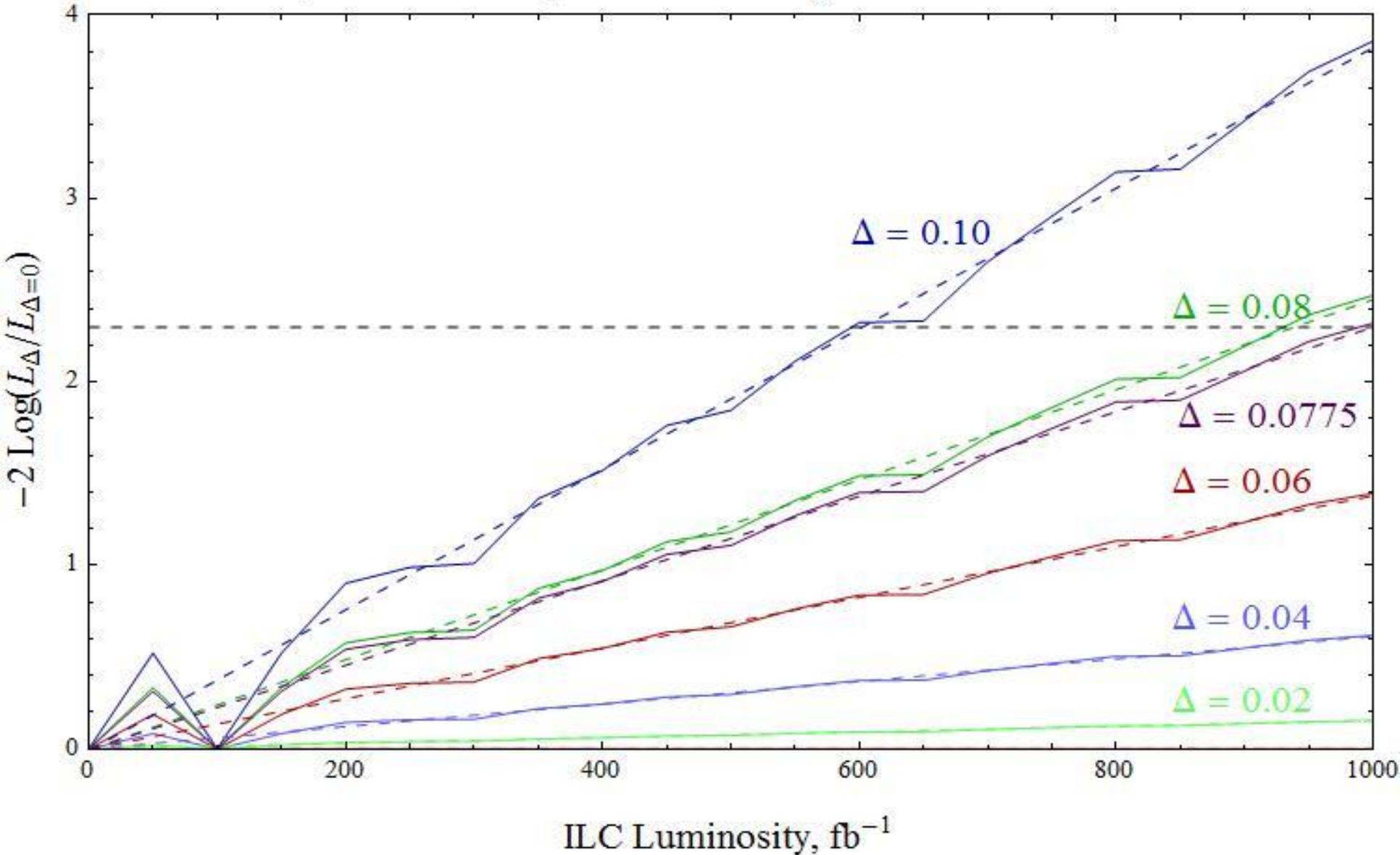
With 1 ab^{-1} of ILC $\sqrt{s}=250$ GeV, expect 1σ discrimination of 4.4° (compared* to 6° using ϕ^* [albeit included backgrounds and detector effects])

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

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

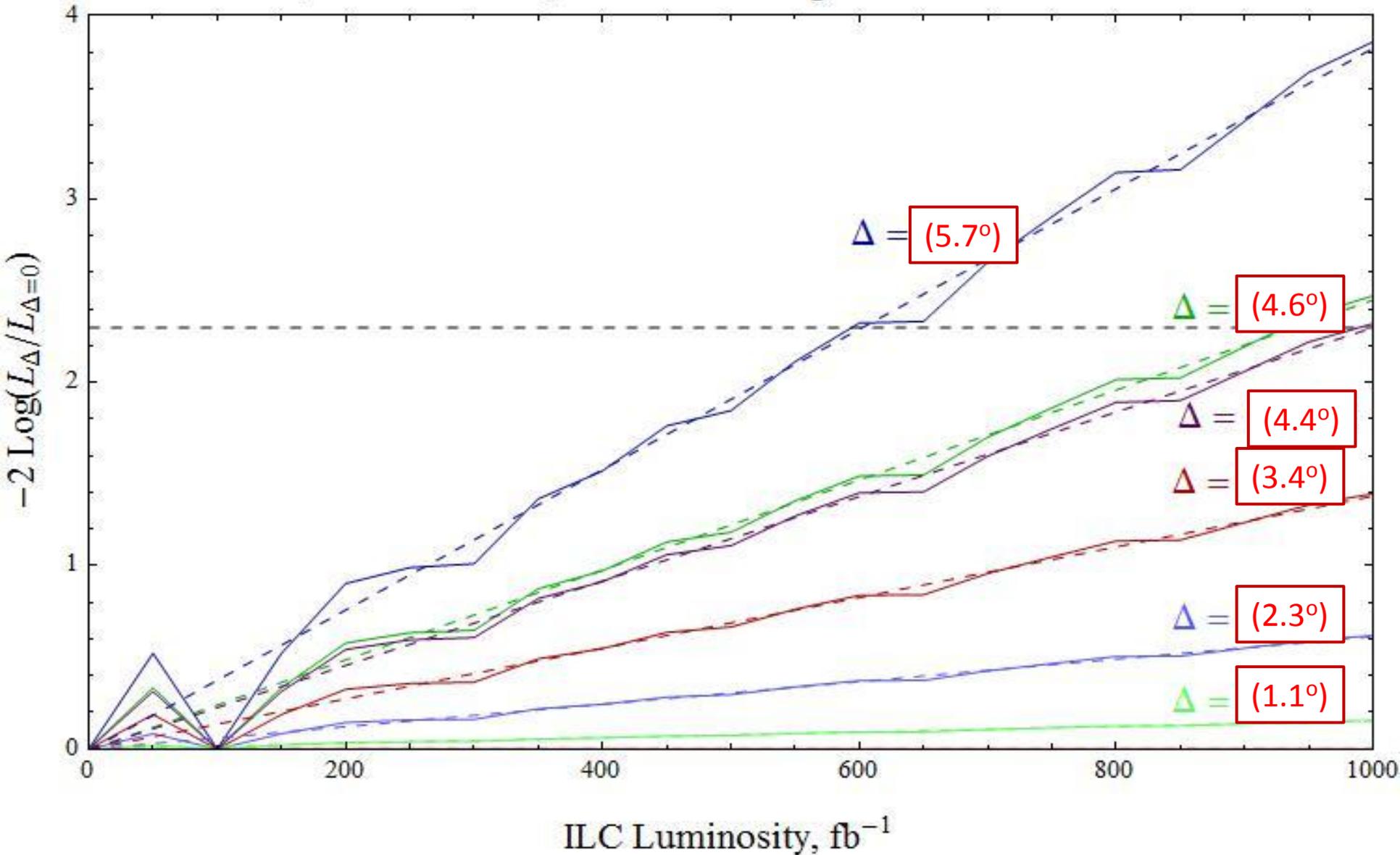
Luminosity scaling (without systematics)

ILC, Z to $\nu\nu$ removed, 1σ line intersecting LLR for $\Delta=0.02$ to $\Delta=0.10$



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ILC, Z to $\nu\nu$ removed, 1σ line intersecting LLR for $\Delta=0.02$ to $\Delta=0.10$

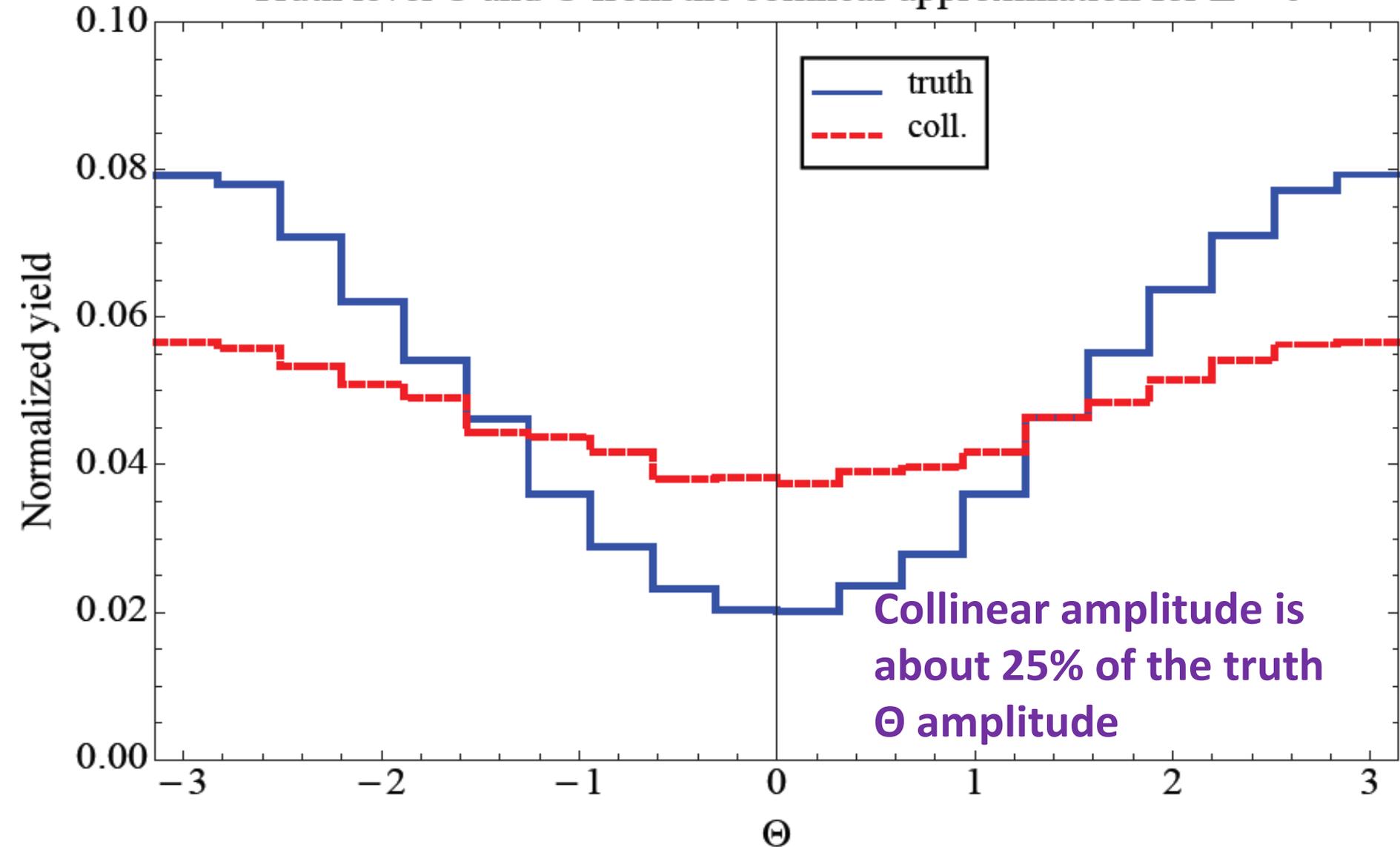


LHC prospects

- Consider h+j events (“boosted” $\tau_{\text{had}}\tau_{\text{had}}$ 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 ϕ^*
 - Other approximations considered tended to wash out or distort the sinusoidal shape of the Θ distribution
 - First proposal to measure Δ at the LHC with prompt tau decays and kinematics

Ideal vs. Collinear approximation

Truth level Θ and Θ from the collinear approximation for $\Delta = 0$



Yields for 3 ab⁻¹ LHC

- Signal region:

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

- Inject an additional 10% contribution to (flat) Zj background to account for QCD multijets

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

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

Yields for 3 ab⁻¹ LHC

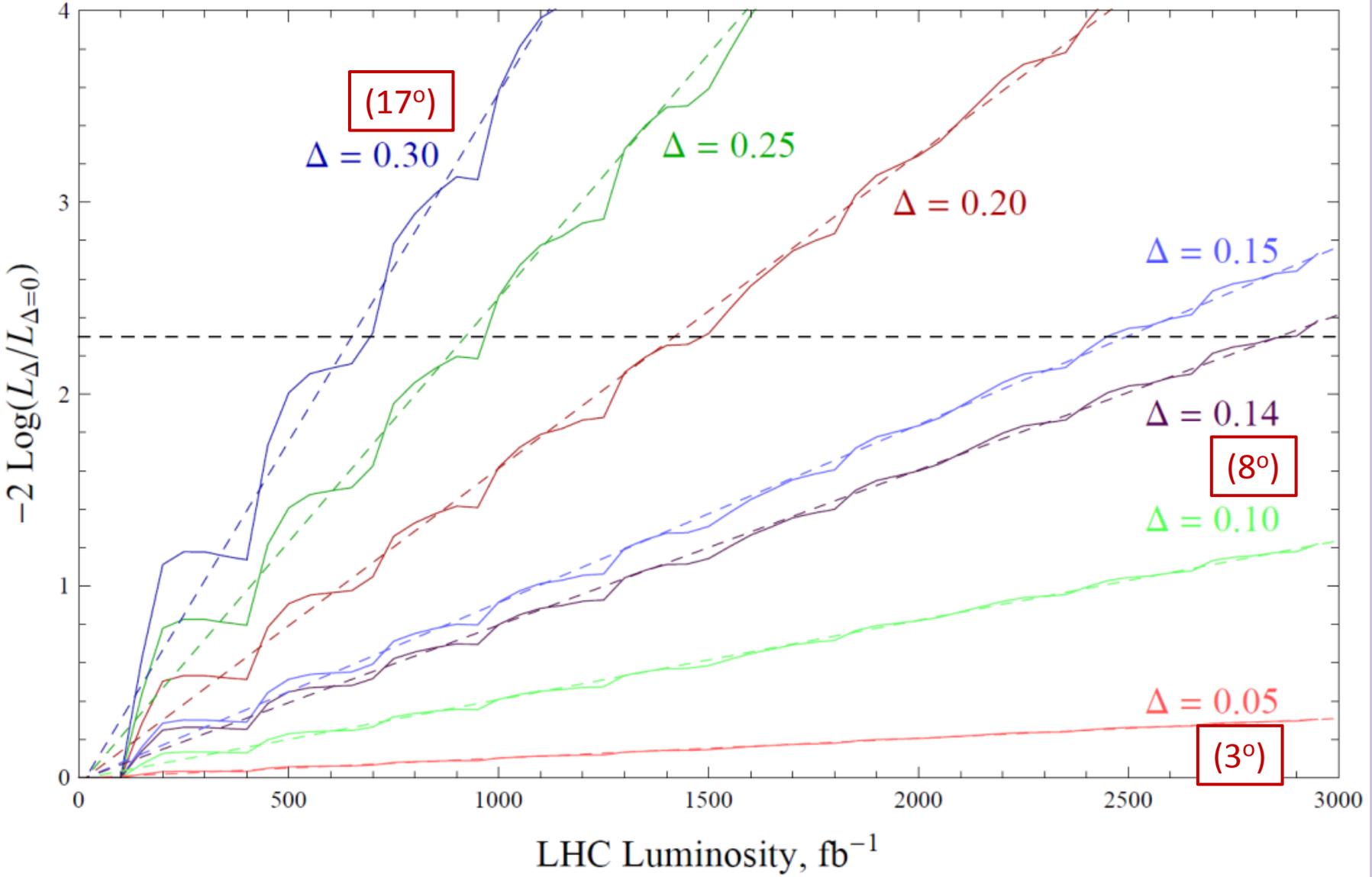
- Consider τ tagging efficiency benchmarks of 50% and 70%, use likelihood analysis testing different Δ

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 **3 σ** requires 550 (300) fb⁻¹ with 50% (70%) τ tagging efficiency
- For **5 σ** , require 1500 (700) fb⁻¹ with 50% (70%) τ tagging efficiency
- Again, detector effects and pileup are neglected

Luminosity scaling (without systematics)

LHC, τ eff.=70%, 1σ line intersecting LLR for $\Delta=0.05$ to $\Delta=0.30$



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 implementing this analysis in future Higgs studies

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

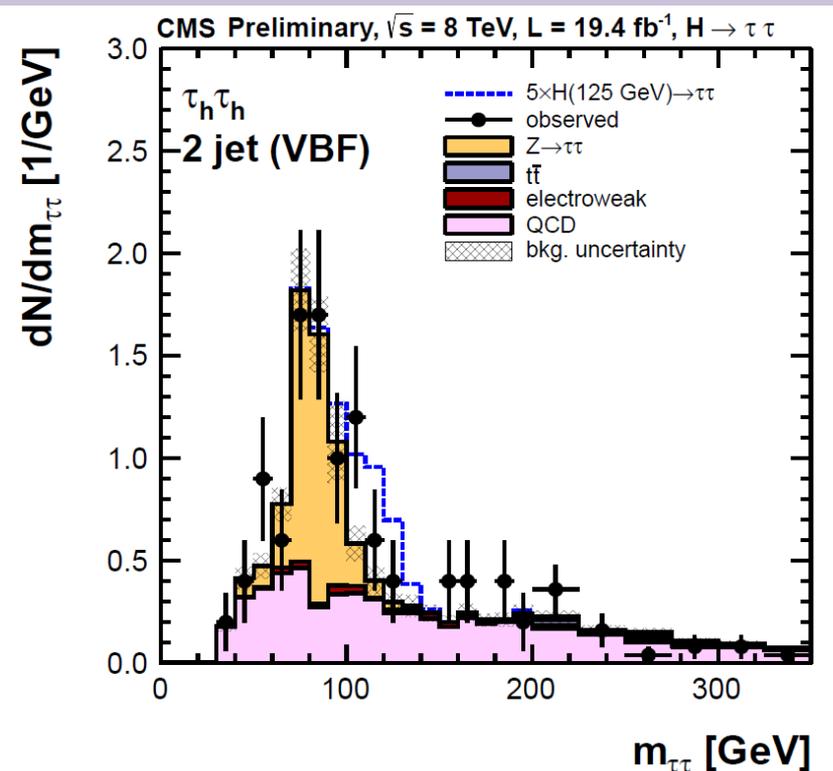
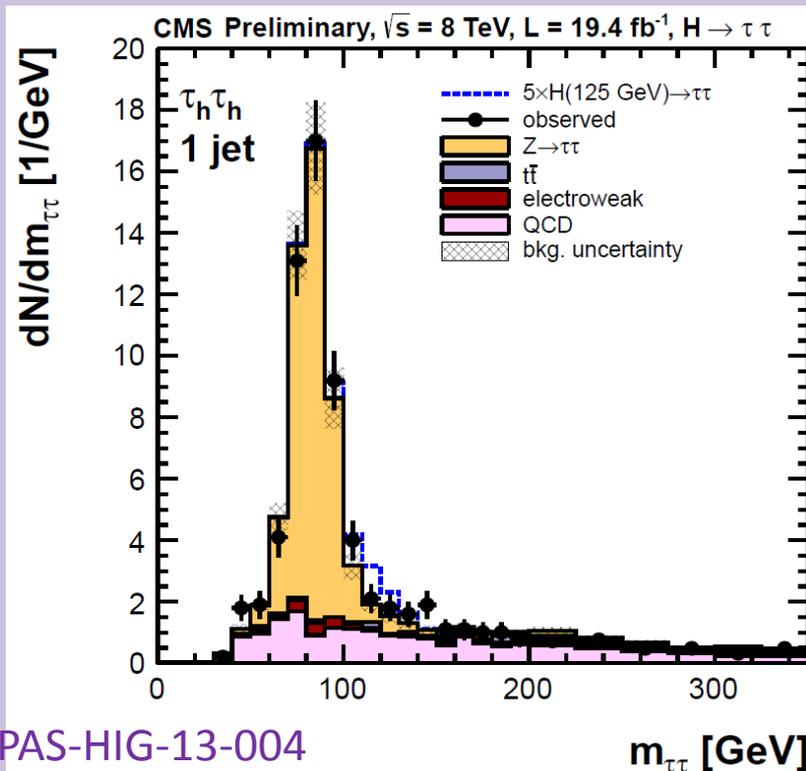
[ILC, 250 GeV, 1 ab⁻¹]

LHC, 14 TeV

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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



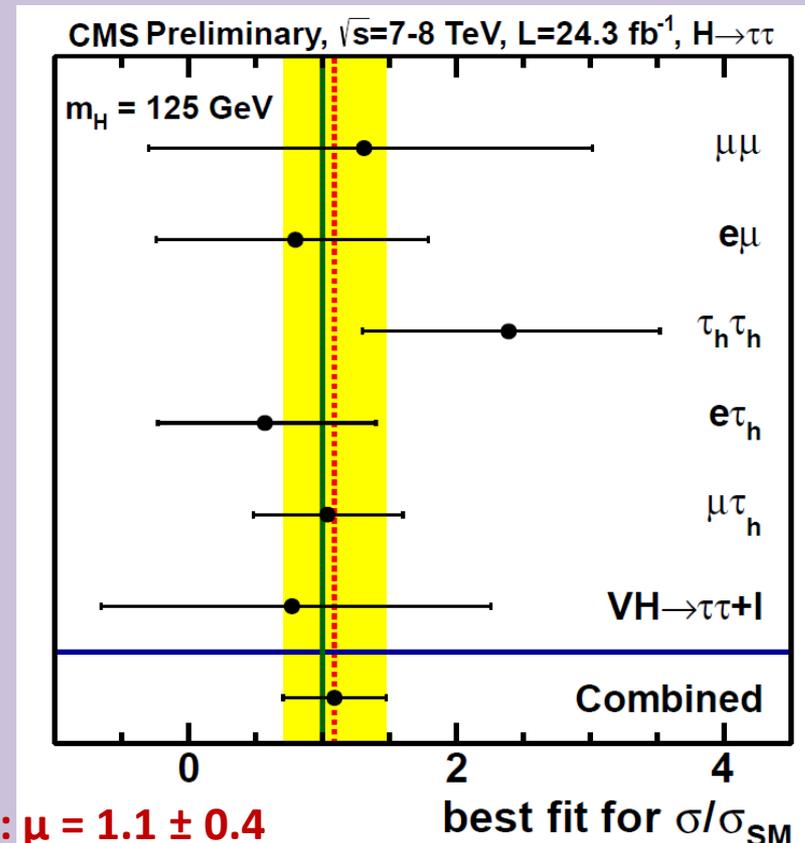
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Process	1-Jet	VBF
$Z \rightarrow \tau\tau$	428 ± 90	47 ± 28
QCD	210 ± 31	61 ± 10
EWK	41 ± 9	4 ± 1
$t\bar{t}$	29 ± 6	2 ± 2
Total Background	709 ± 95	114 ± 30
$H \rightarrow \tau\tau$	9 ± 4	4 ± 2
Observed	718	120

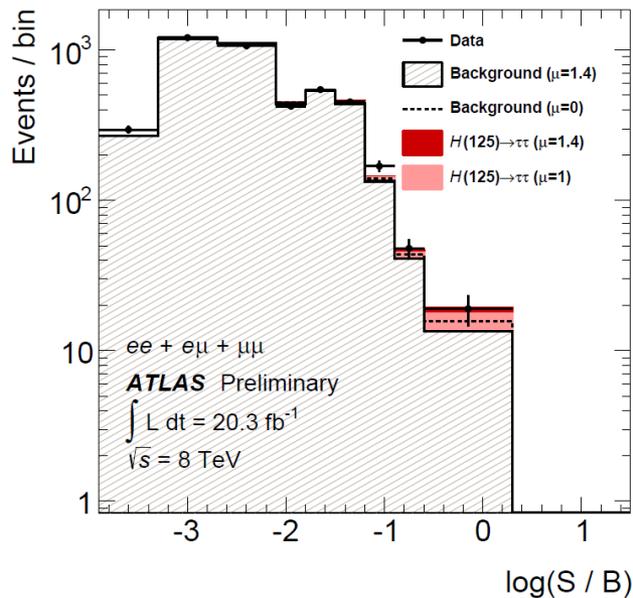
Signal Eff.

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

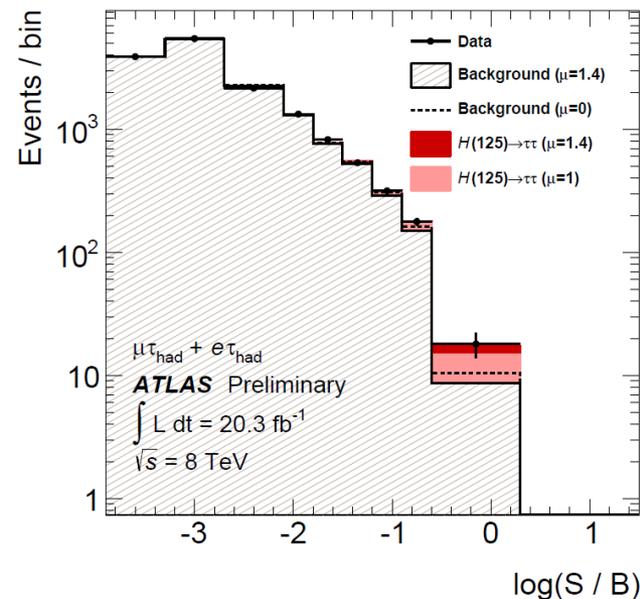


ATLAS Update

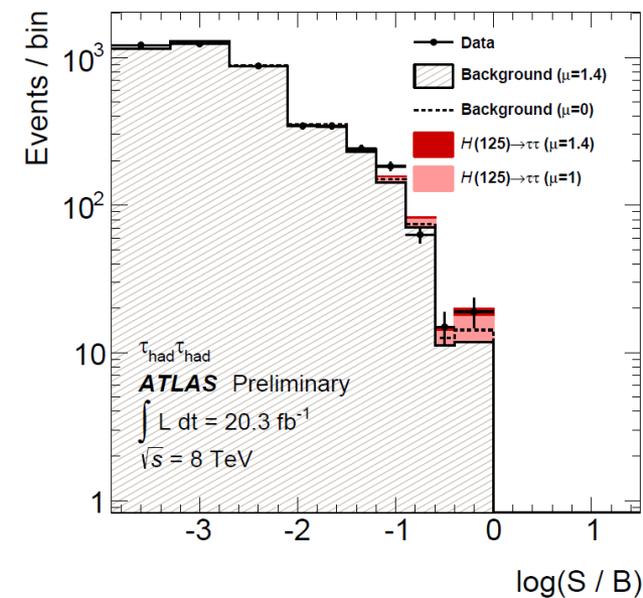
- Use BDT output to categorize events



(a)



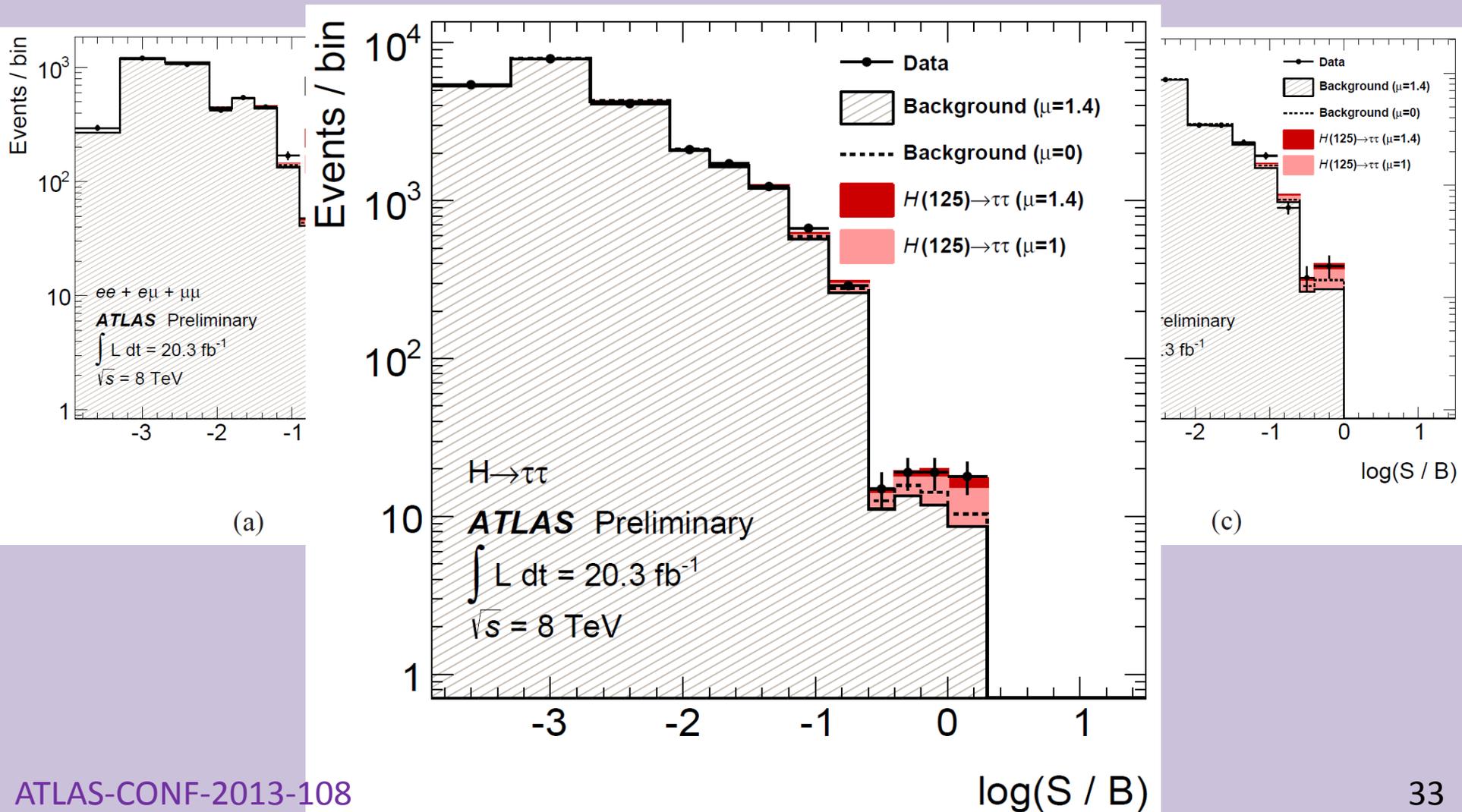
(b)



(c)

ATLAS Update

- Use BDT output to categorize events



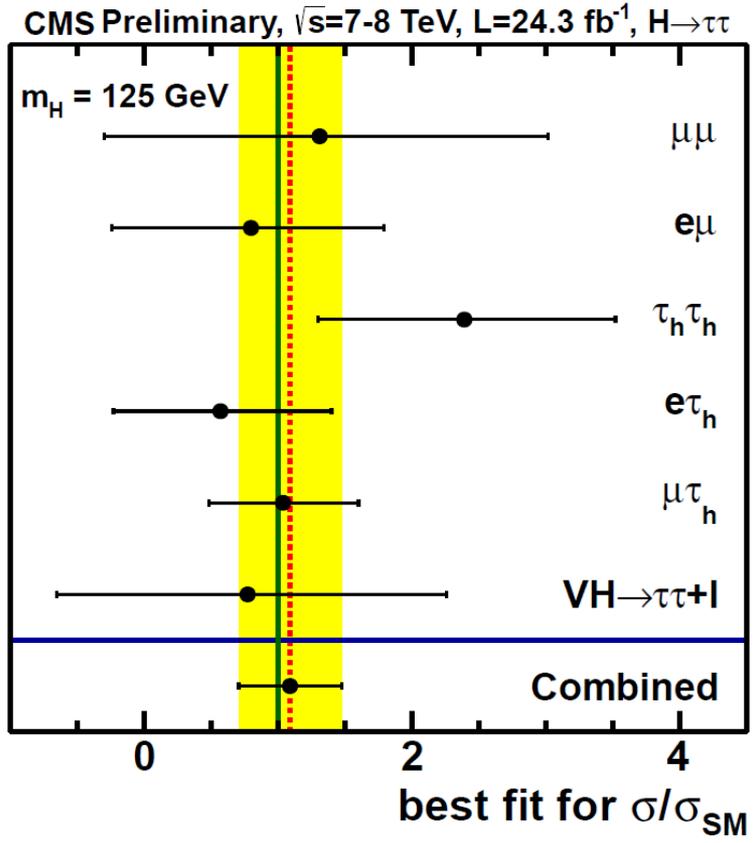
ATLAS Update

- Focus on fully hadronic channel
 - Main backgrounds are still irreducible $Z \rightarrow \tau\tau$ 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
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

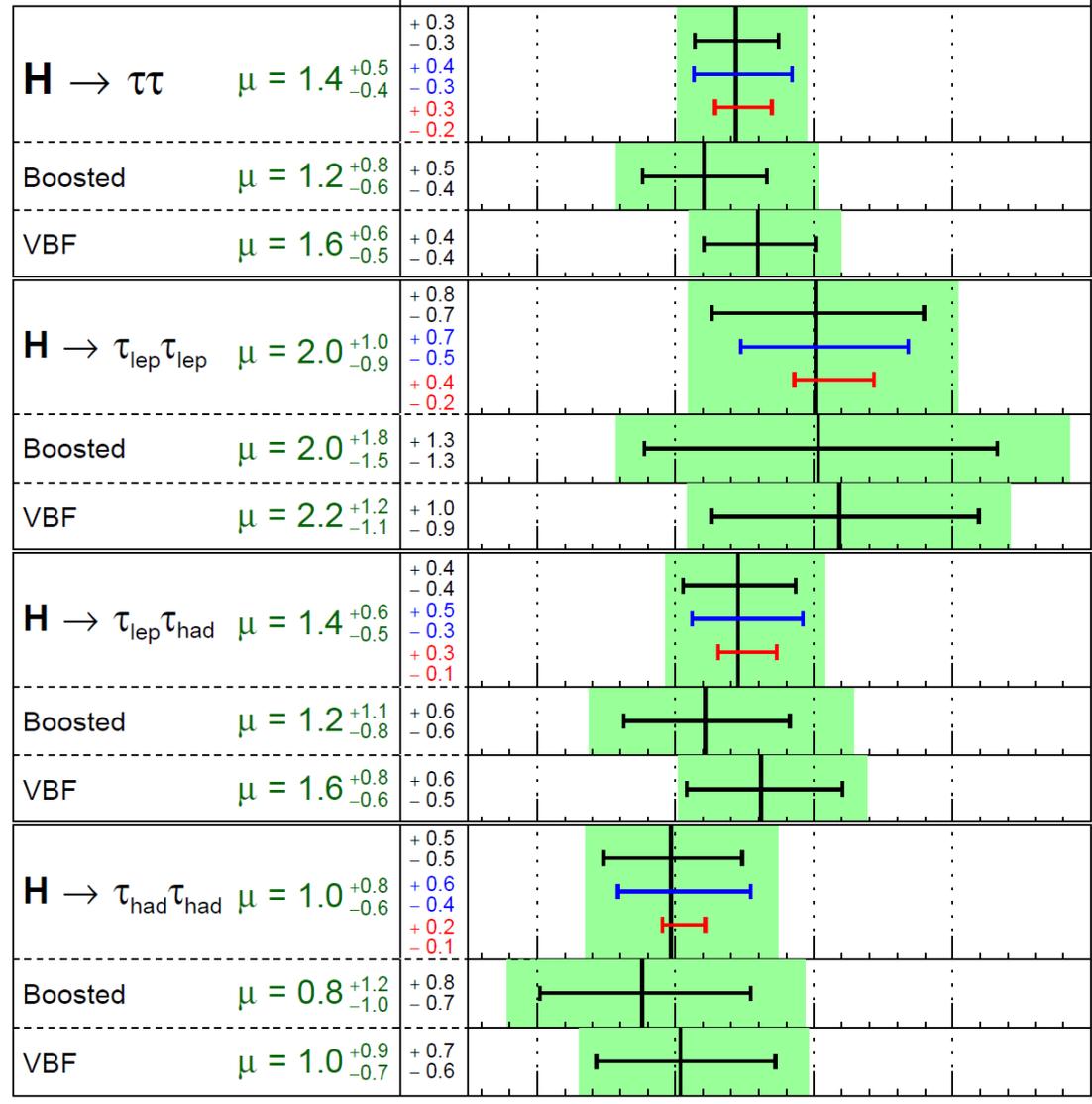
LHC Summary

CMS combined: $\mu = 1.1 \pm 0.4$



ATLAS Prelim.
 $m_H = 125$ GeV

— $\sigma(\text{statistical})$ Total uncertainty
 — $\sigma(\text{syst. incl. theory})$
 — $\sigma(\text{theory})$ $\pm 1\sigma$ on μ

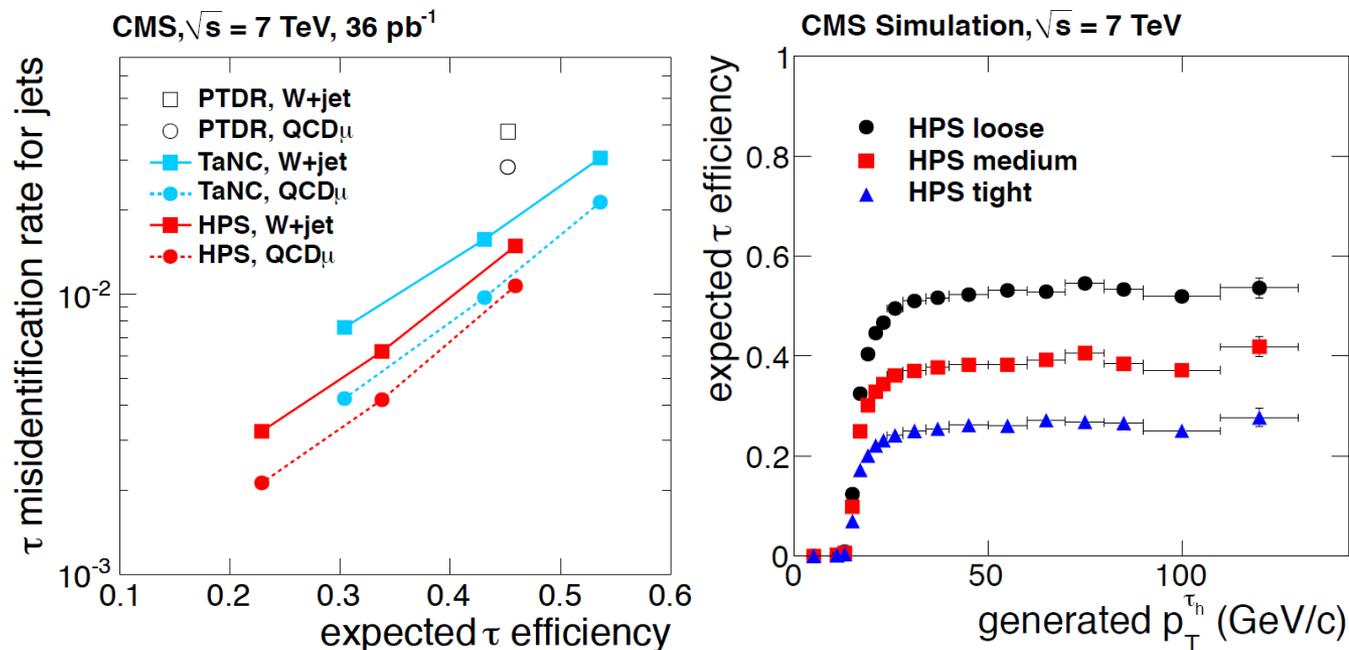


$\sqrt{s} = 8$ TeV $\int Ldt = 20.3$ fb $^{-1}$ Signal strength (μ)

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%

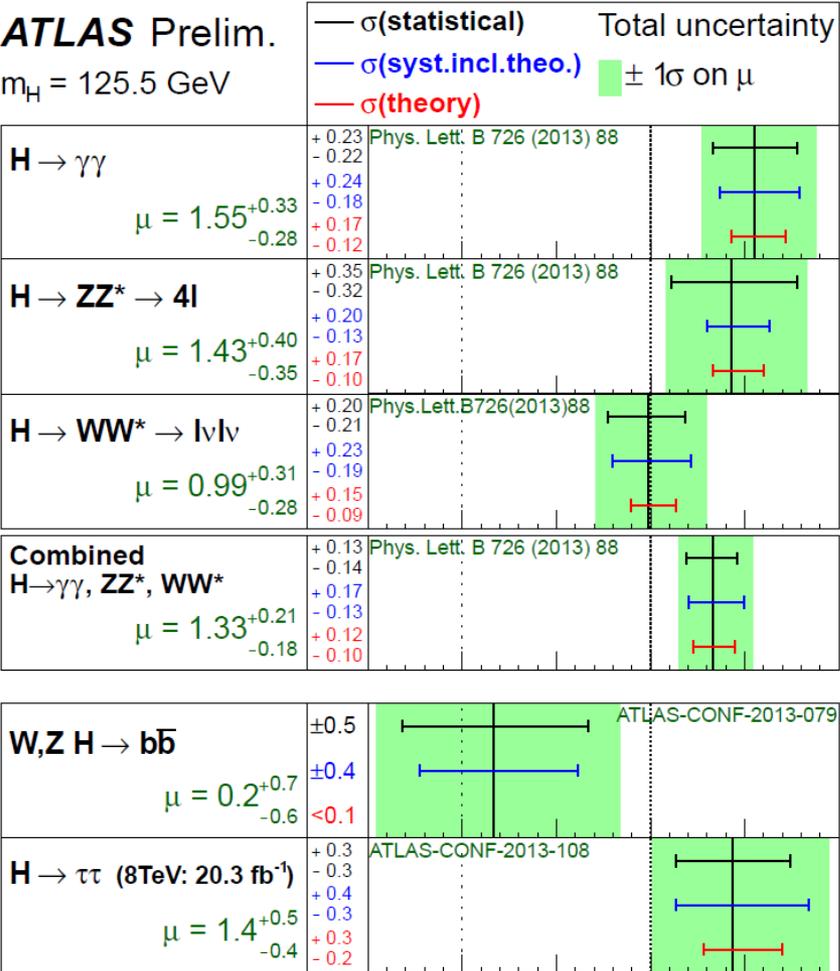


Tau measurement details

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.

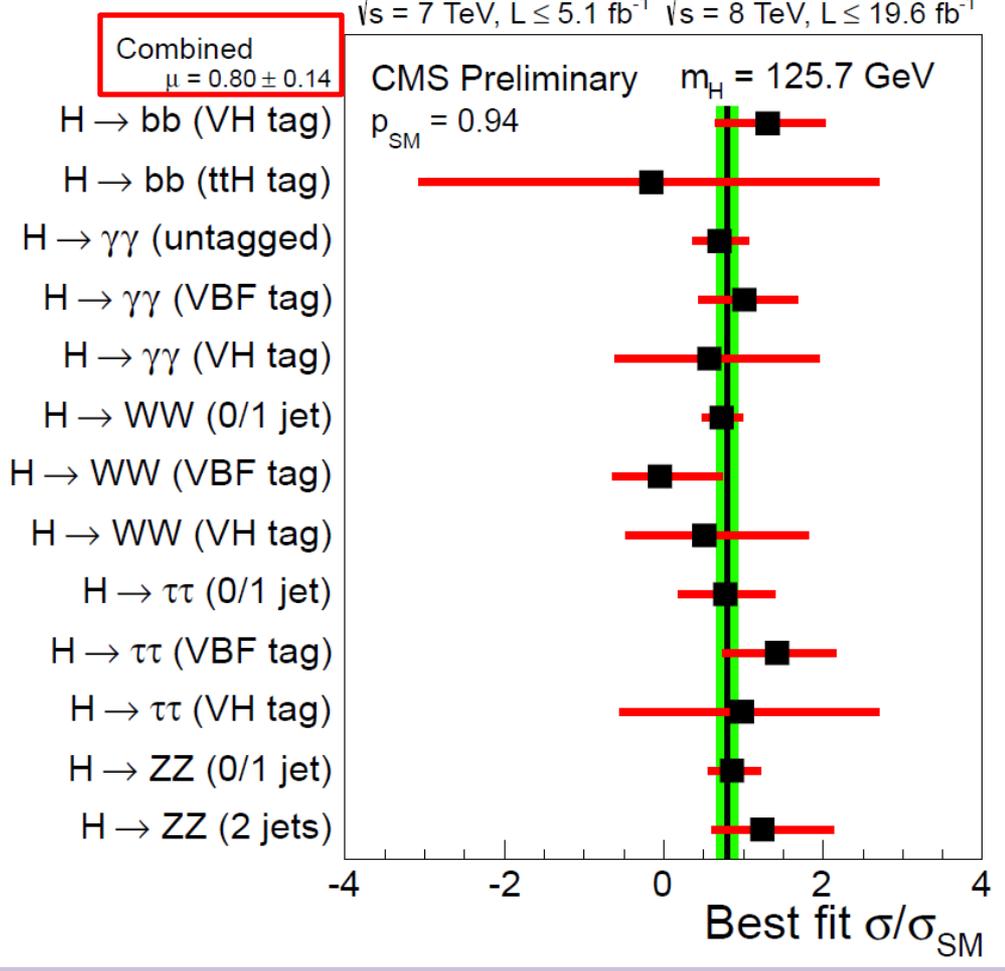
Algorithm	QCD		QCD μ		W + jets	
	MC (%)	Data/MC	MC (%)	Data/MC	MC (%)	Data/MC
HPS “loose”	1.0	1.00 ± 0.04	1.0	1.07 ± 0.01	1.5	0.99 ± 0.04
HPS “medium”	0.4	1.02 ± 0.06	0.4	1.05 ± 0.02	0.6	1.04 ± 0.06
HPS “tight”	0.2	0.94 ± 0.09	0.2	1.06 ± 0.02	0.3	1.08 ± 0.09
TaNC “loose”	2.1	1.05 ± 0.04	1.9	1.12 ± 0.01	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

Admixture constraints from signal strengths



$\sqrt{s} = 7 \text{ TeV} \int L dt = 4.6-4.8 \text{ fb}^{-1}$
 $\sqrt{s} = 8 \text{ TeV} \int L dt = 20.7/20.3 \text{ fb}^{-1}$
 Signal strength (μ)

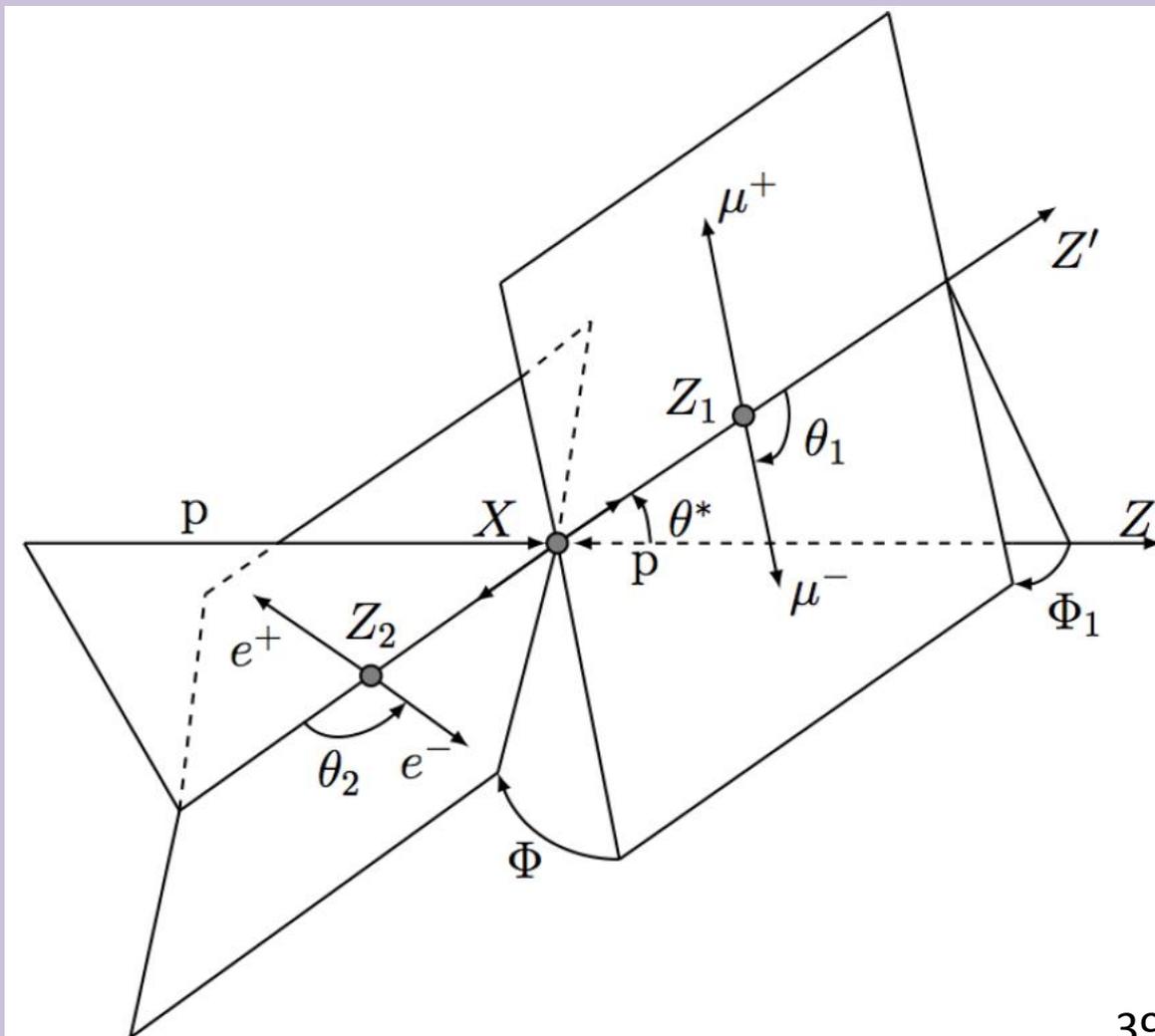
$\mu = 1.43^{+0.31}_{-0.29}(\text{stat.})^{+0.41}_{-0.30}(\text{syst.})$ for $m_H = 125 \text{ GeV}$



[Separate channel measurements cannot be combined without assumptions!]

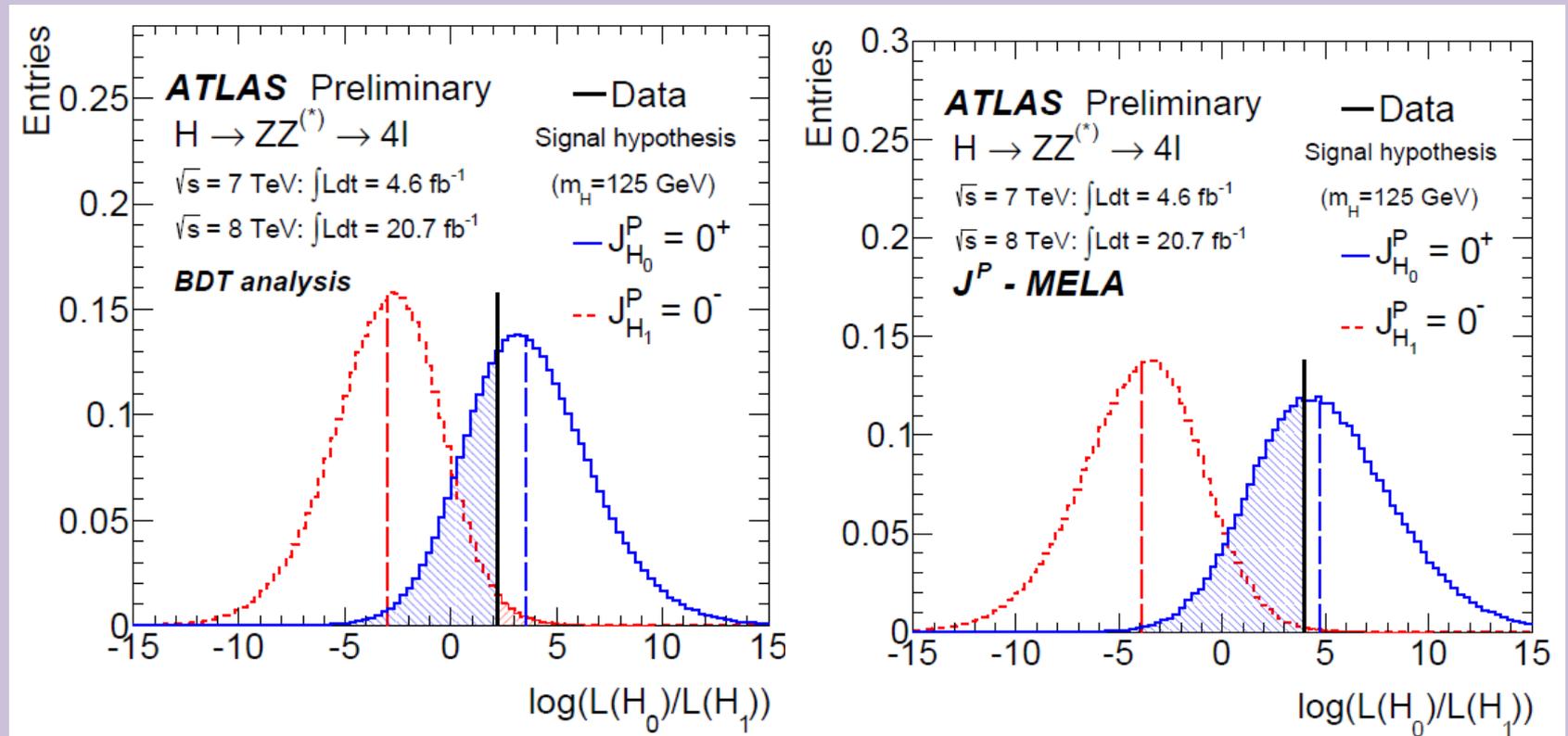
Testing CPV in $h \rightarrow ZZ^*$

- Measure acoplanarity angle Φ (angle between Z_1 and Z_2 decay planes)
- Golden channel
 - everything measurable, can reconstruct the Higgs rest frame and appropriate decay planes



Testing CPV in $h \rightarrow ZZ^*$ – ATLAS

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



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

Testing CPV in $h \rightarrow ZZ^*$ – CMS

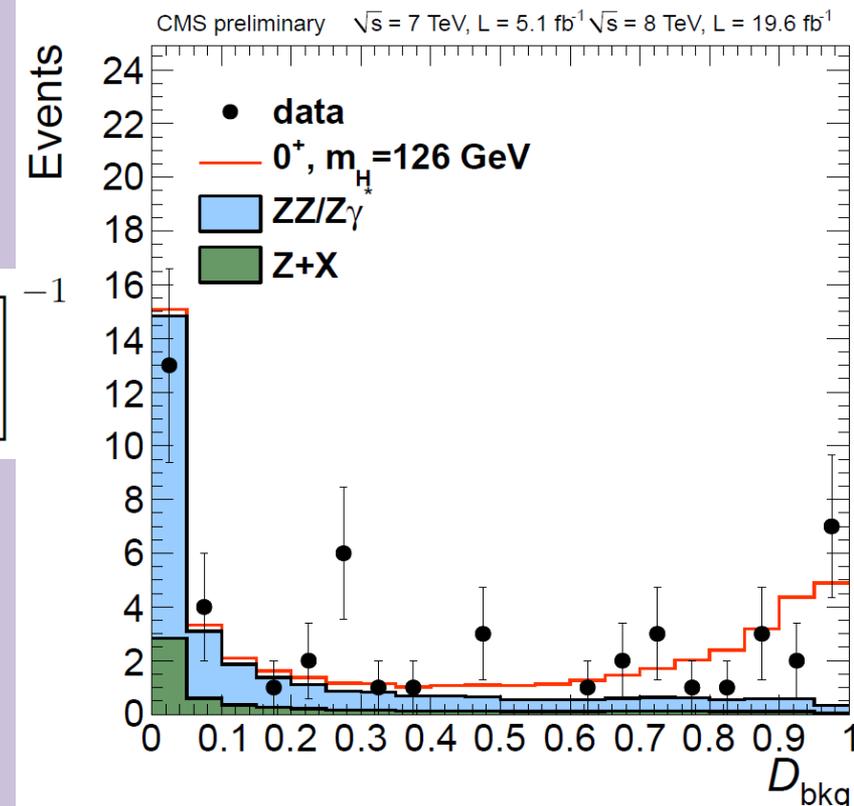
- CMS tests for a combination of $hZ_\mu Z^\mu$ and $hZ_{\mu\nu} \tilde{Z}^{\mu\nu}$

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

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

- Use kinematic discriminant

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



Testing CPV in $h \rightarrow ZZ^*$ – CMS

- CMS tests for a combination of $hZ_\mu Z^\mu$ and $hZ_{\mu\nu} Z^{\mu\nu}$

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

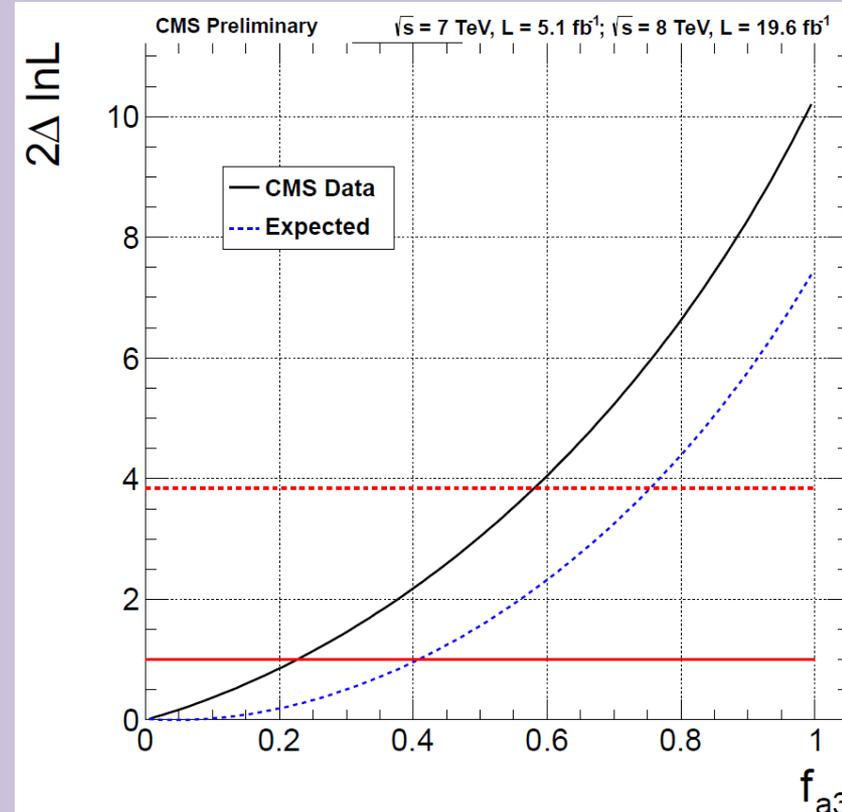
$$f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$$

- Results in constraint on f_{a3}

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

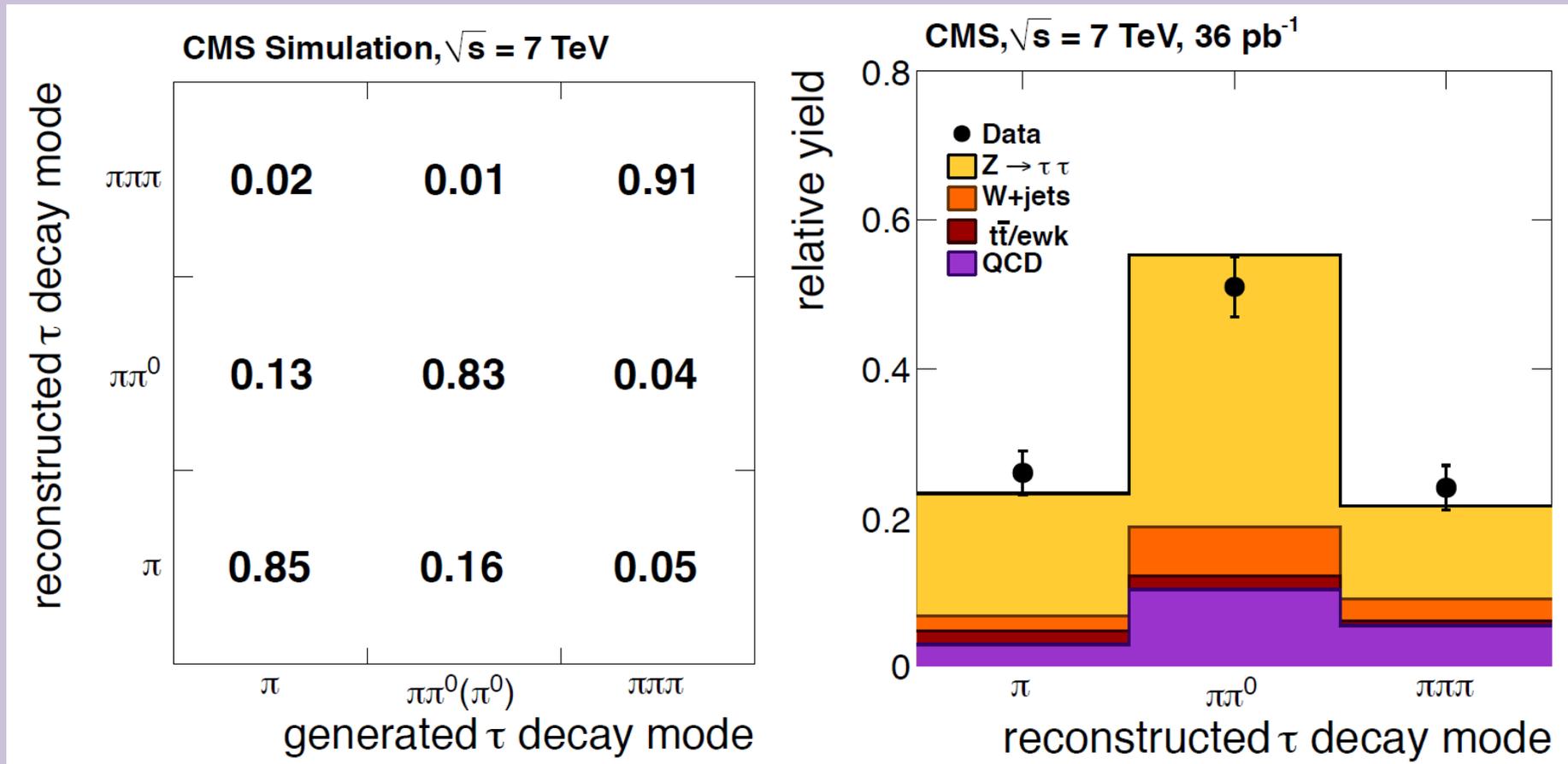
$$f_{a3} < 0.58 \text{ at } 95\% \text{ CL.}$$

- Will certainly improve with more data



Tau measurement details

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



Matrix element calculation assumptions

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

- 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 $\pi^\pm - \pi^0$ mass difference

- Obtain $\mathcal{M}_{\text{full}} \propto \bar{u}_{\nu-} \not{q}_- (e^{i\Delta} \not{p}_{\tau-} - e^{-i\Delta} \not{p}_{\tau+}) \not{q}_+ P_L v_{\nu+}$
with $q_\pm \equiv p_{\pi^\pm} - p_{\pi^0\pm}$

– Recall ρ_\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

$$|\mathcal{M}|^2 \propto P_{\Delta, S} + P_{\Delta, \not{S}} + P_{\Delta, S} + P_{\Delta, S}^*$$

where the most interesting piece is

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

Calculating the Theta Variable

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

- We can define an antisymmetric 2nd-rank tensor

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

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

- Or, even better, identify “electric” and “magnetic” components

$$E_{\pm}^i \equiv F_{\pm}^{i0}, \quad B_{\pm}^i \equiv -\frac{1}{2} \epsilon^{ijk} F_{\pm}^{jk}$$

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

Calculating the Theta Variable

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

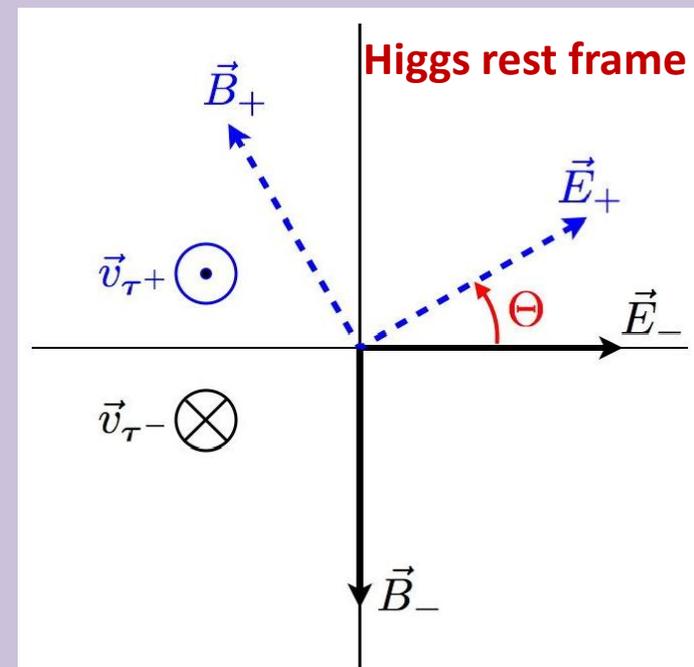
- We can calculate

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

- 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

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

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

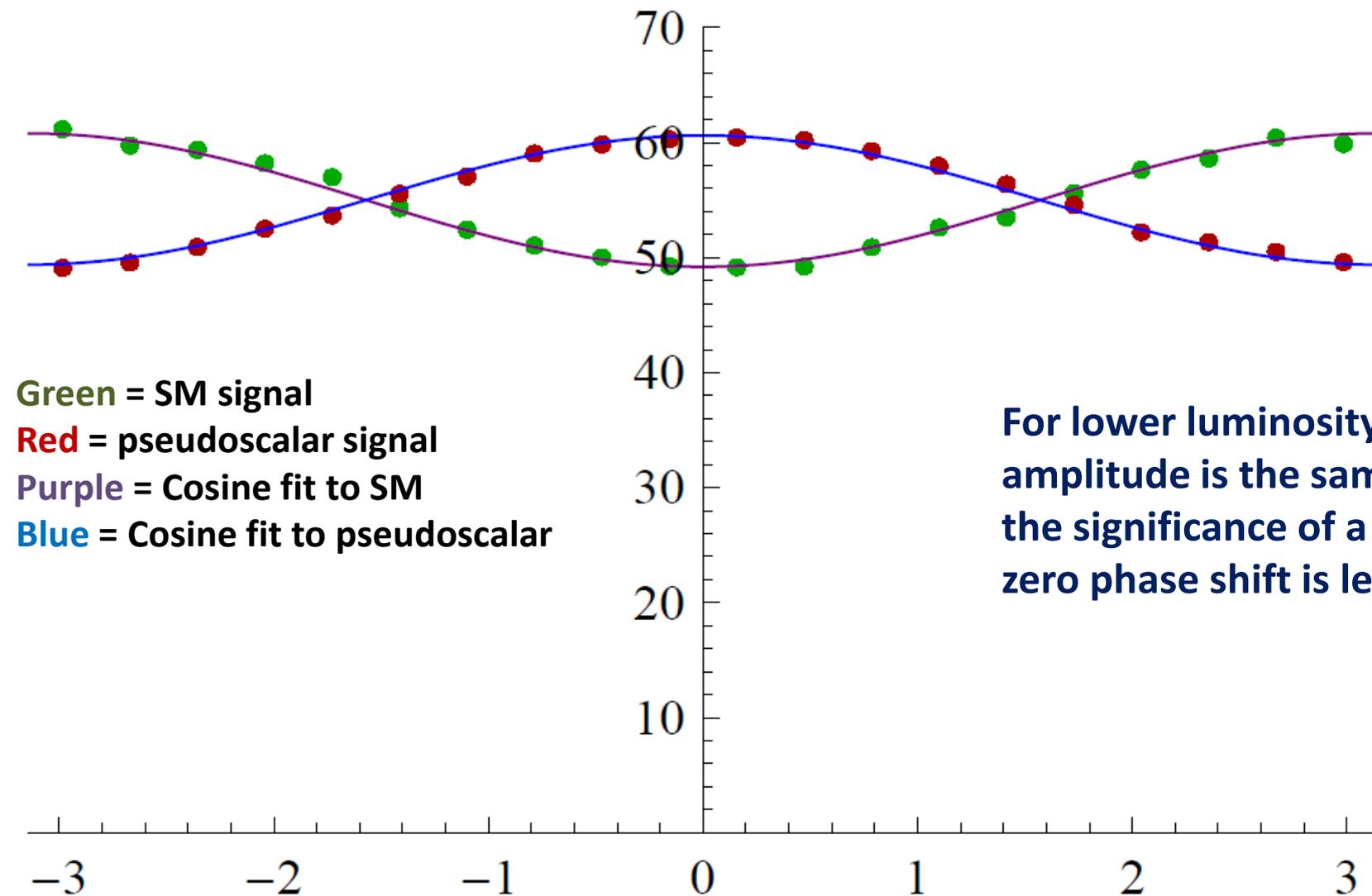


Signal and background generation

- Use MadGraph5 for h+j and Z+j events at LHC14
 - Mimic cuts for 1-jet, hadronic taus Higgs search category
 - Impose preselection of $p_T(j) > 140 \text{ GeV}$, $|\eta(j)| < 2.5$
 - Normalize to MCFM NLO $\sigma(h+j)=2.0 \text{ pb}$, $\sigma(Z+j)=420 \text{ pb}$
 - 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

N_{events} for $L = 3 \text{ ab}^{-1}$, 50% τ efficiency



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

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

UV completion

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

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