ATLAS+CMS ultimate precisions on H(125)

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on behalf of the **ATLAS+CMS collaborations**

Higgs Hunting 2015

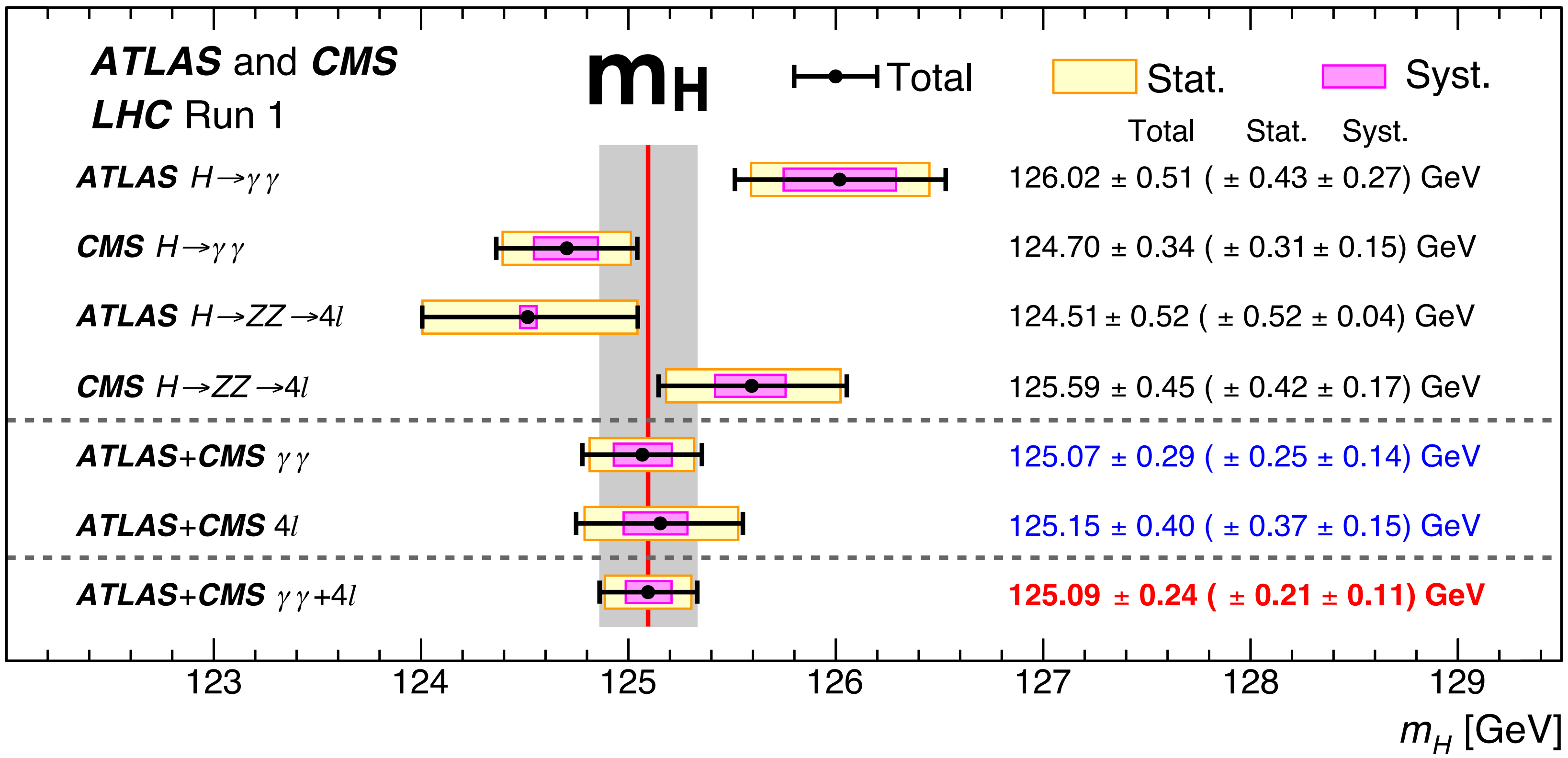
01/08/15

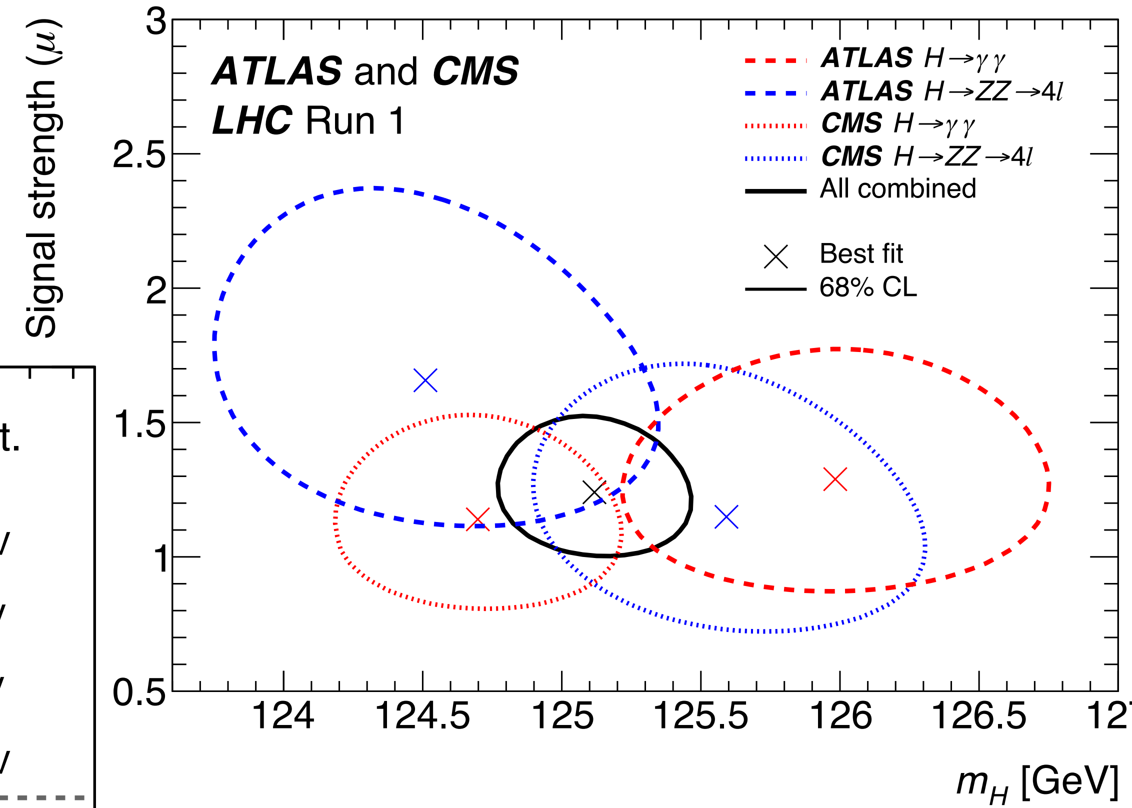
Outline of talk

1. Current Higgs boson measurement precisions
2. Future physics program highlights
3. Measurement precisions at 300, 3000 fb^{-1}
   i. Coupling strength (κ, λ) measurements
   ii. Signal strength (μ) measurements
   iii. CP-mixing in $H \rightarrow ZZ^* \rightarrow 4l$
   iv. Rare, interesting Higgs processes
4. Conclusions

The story so far ...

ATLAS+CMS Higgs boson mass (m_H) per channel:



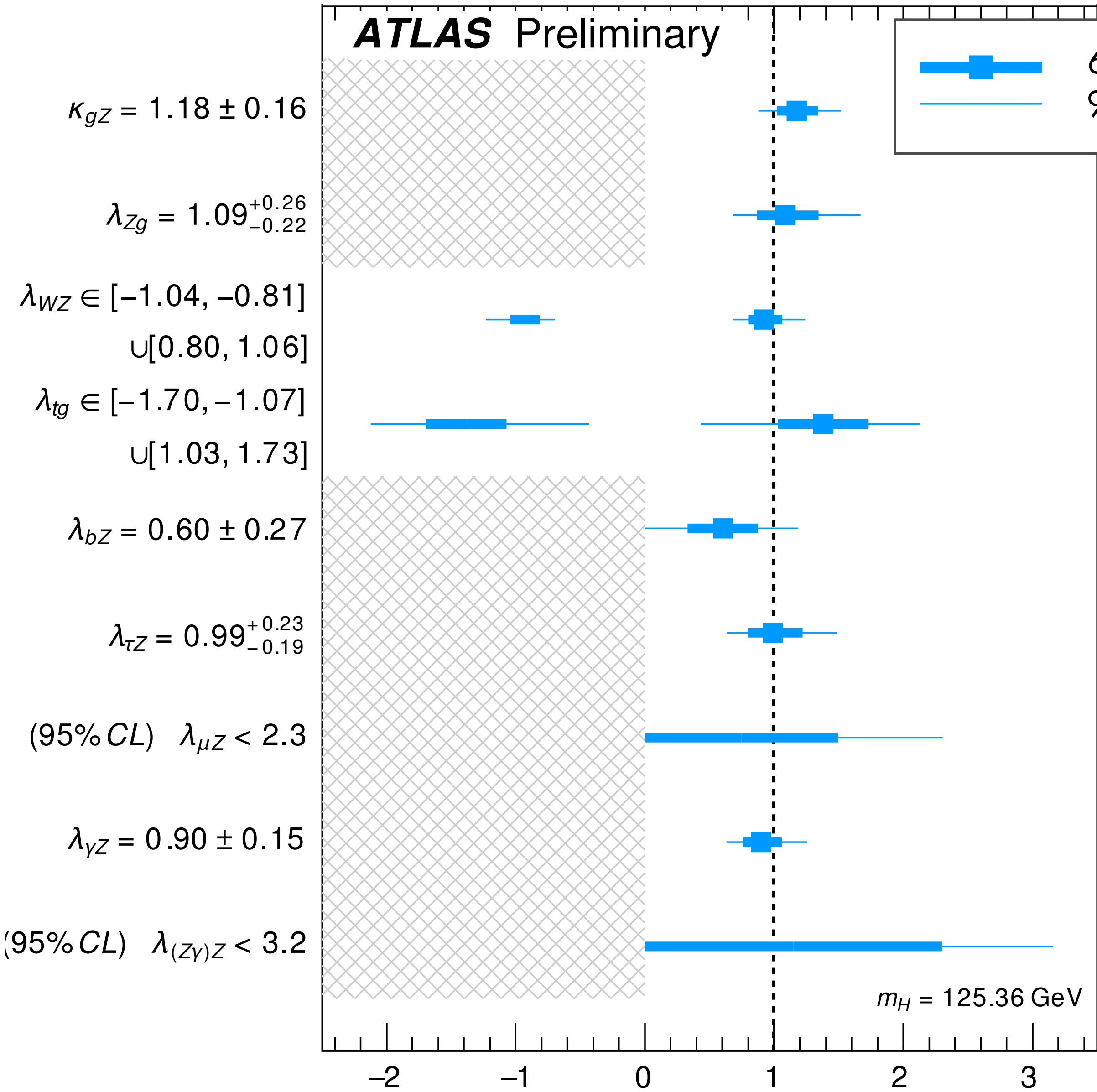


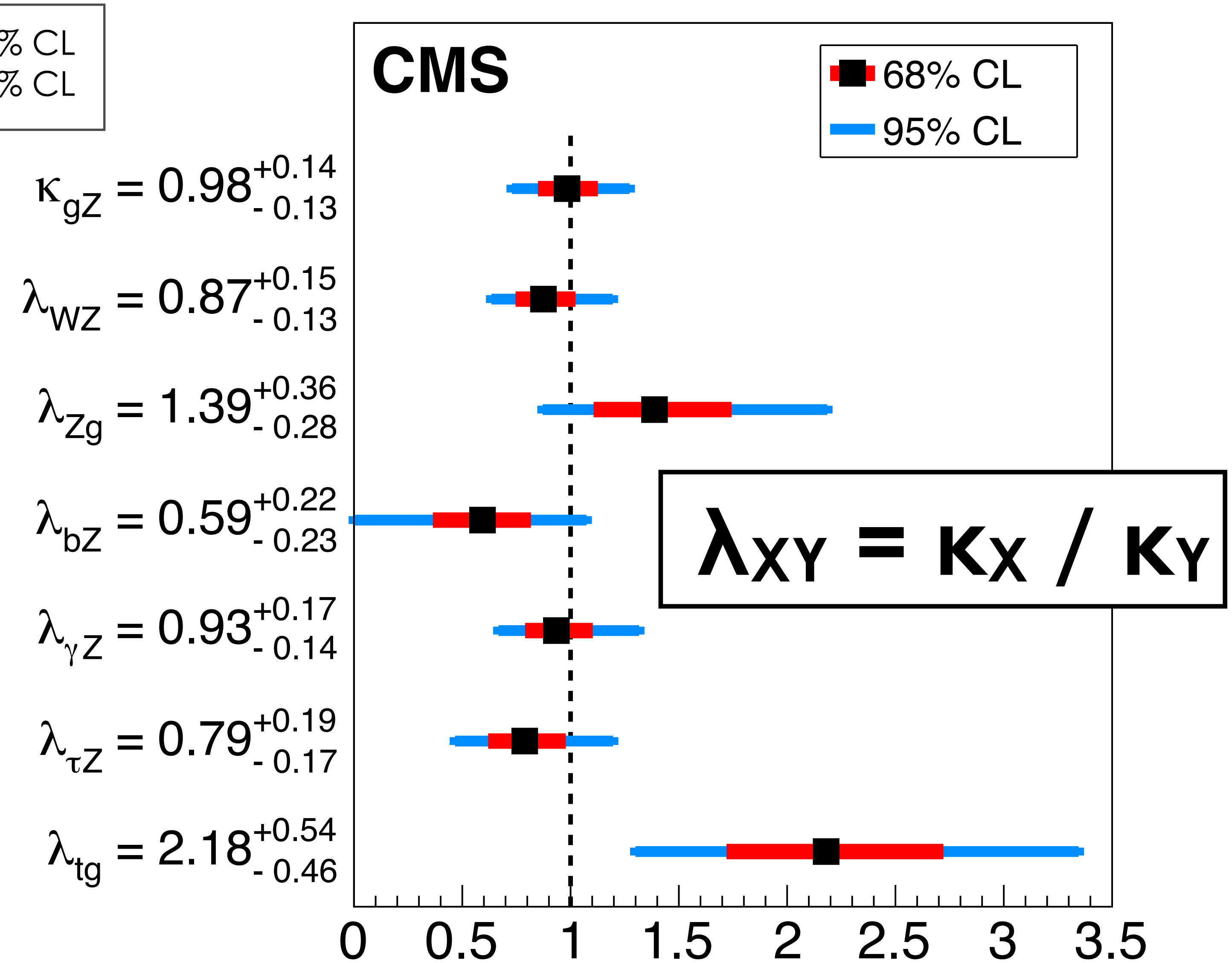
Signal strength (μ) vs. m_H

- Latest ATLAS+CMS **combined results** as of March 2015 using 7+8 TeV datasets
  - Combines measurements from $H \to ZZ \to 4l$ and $H \to \gamma\gamma$ decay channels
- Combined **CMS+ATLAS m_H measurement** found to be ($\sigma(m_H)$ derived from LL width),

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.}) \text{ GeV}$$

The story so far …





- Channel-specific **ratios of coupling scale factors** calculated both for CMS, ATLAS using the 7+8 TeV dataset
  - Make no assumptions on Higgs boson width, loop particle coupling strengths
- Signal strength, coupling precisions generally **$\Delta\mu/\mu$, $\Delta\lambda/\lambda$ < 20-50%**

Physics program highlights for 300, 3000 fb^{-1}

100 fb^{-1}		300 fb^{-1}				3000 fb^{-1}
2015 - 2018	…	2020 - 2023	…	2025 - 2028	…	2030 - beyond

μ ~ 40

Run II, III

μ ~ 80

HL-LHC

μ ~ 140-200

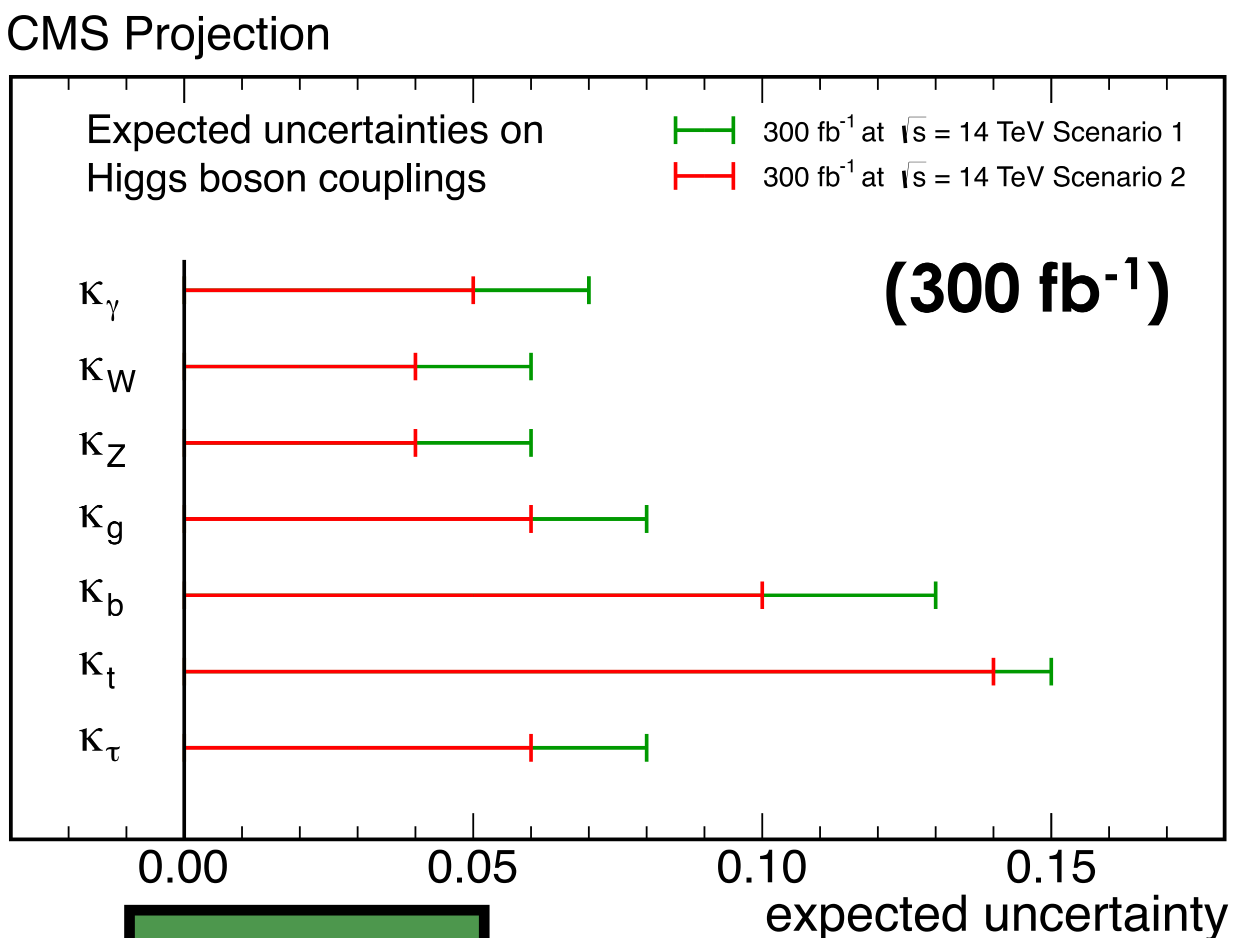
- Updated **σ(ZZ), σ (γγ)** measurements
- Higgs boson **couplings, μ** at O(10%) level
- **Spin, CP** at O(10%) level

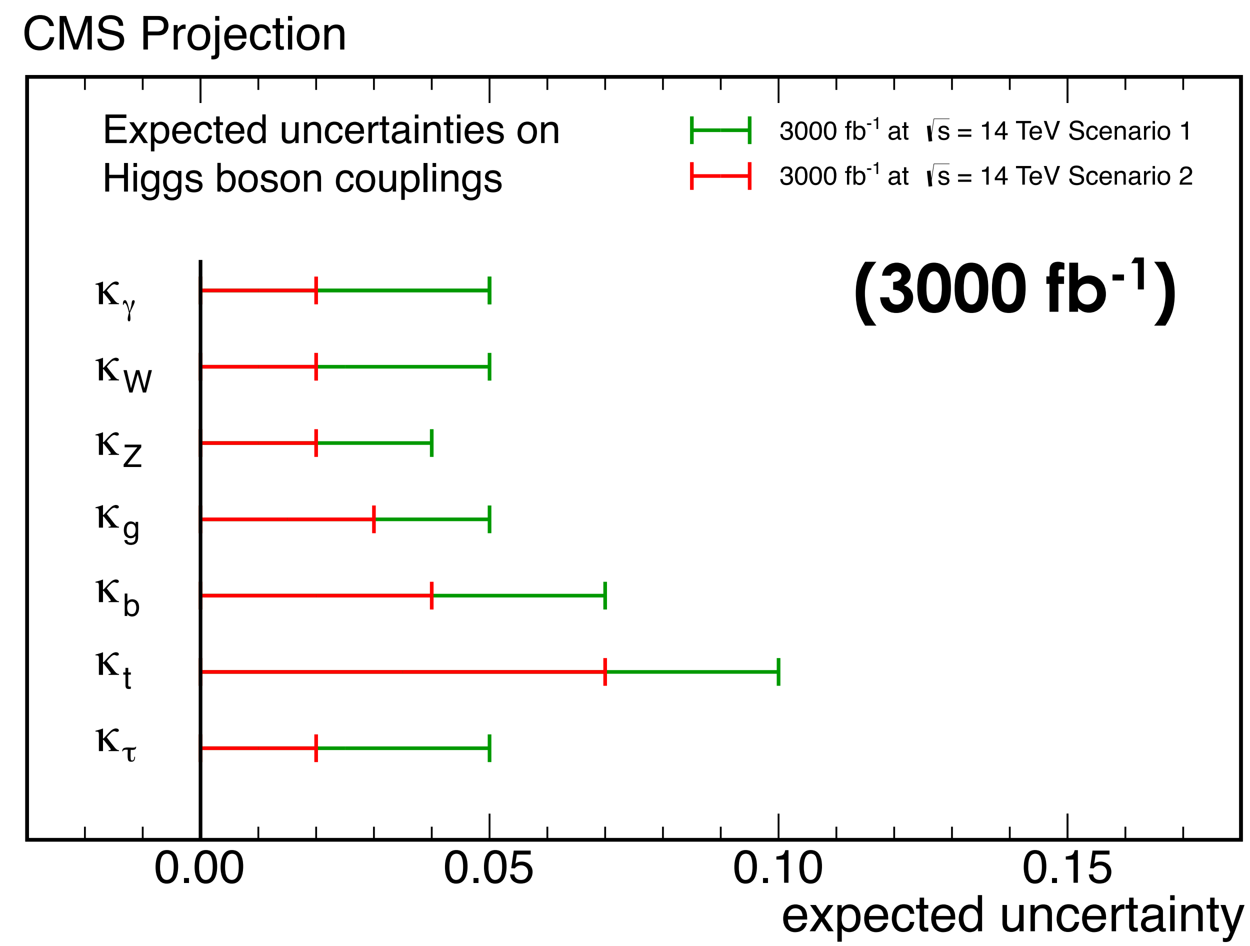
- Rare decays, couplings (μμ, Zγ), **HH production**
- 1-2% precision on **γγ, ZZ couplings**, 2-10% precision for other channels

- CMS, ATLAS will undergo **L1 trigger, muon, calorimeter upgrades** to offset pileup
- Differences in 300, 3000 fb^{-1} result estimation approaches:
  - **CMS:** Extrapolate **2012-equivalent performance** to higher ℑ, √s
  - **ATLAS:** Truth samples, **smearing functions** for detector response

Refs: CMS NOTE-13-002, ATL-PHYS-PUB-2014-016

Expected Higgs coupling (κ_X) precisions





Scenario 1:

All systematic uncertainties are left unchanged

Scenario 2:

- Theoretical uncertainties scaled by 1/2
- Other systematic uncertainties scaled by √(int. lumi.)

- Using **zero-width approximation**, we can decompose signal rates as,

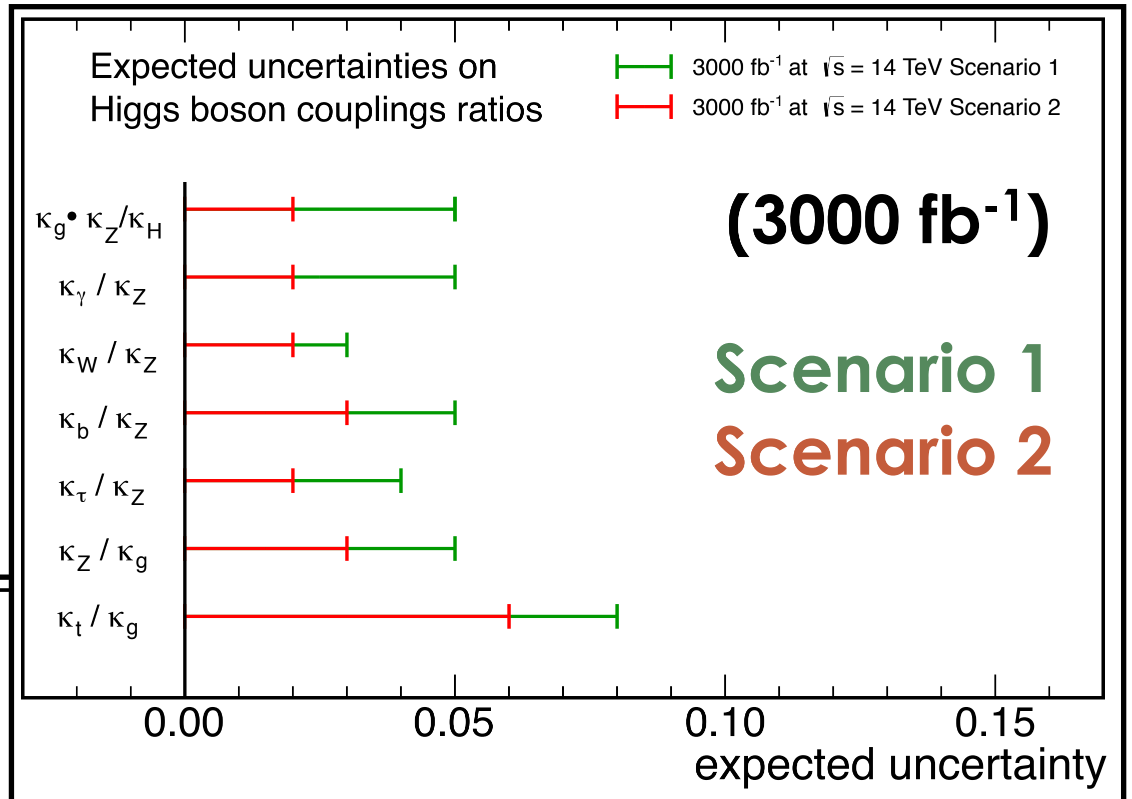
$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

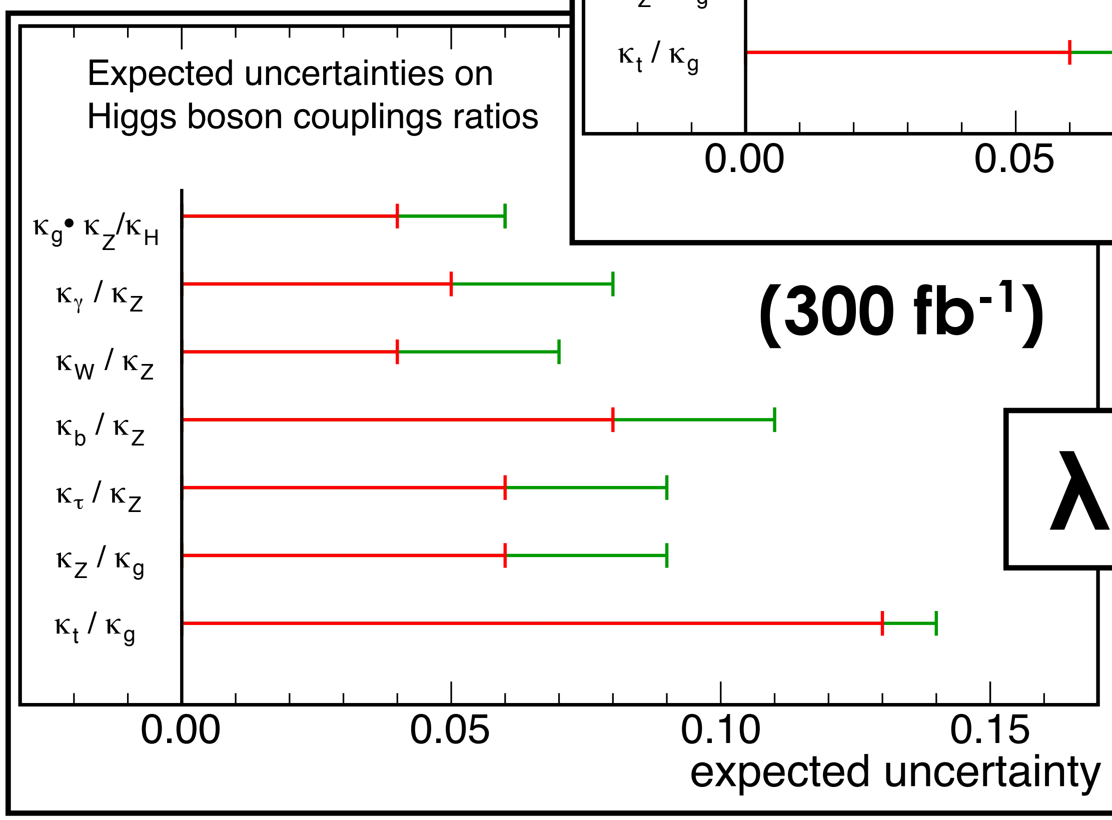
- Can therefore rewrite σ • B, μ using scale factors κ^2
- Good agreement in CMS, ATLAS predictions → expect **5-15% ultimate precision**, varies by coupling

Expected Higgs coupling ratio (λ_{XY}) precisions

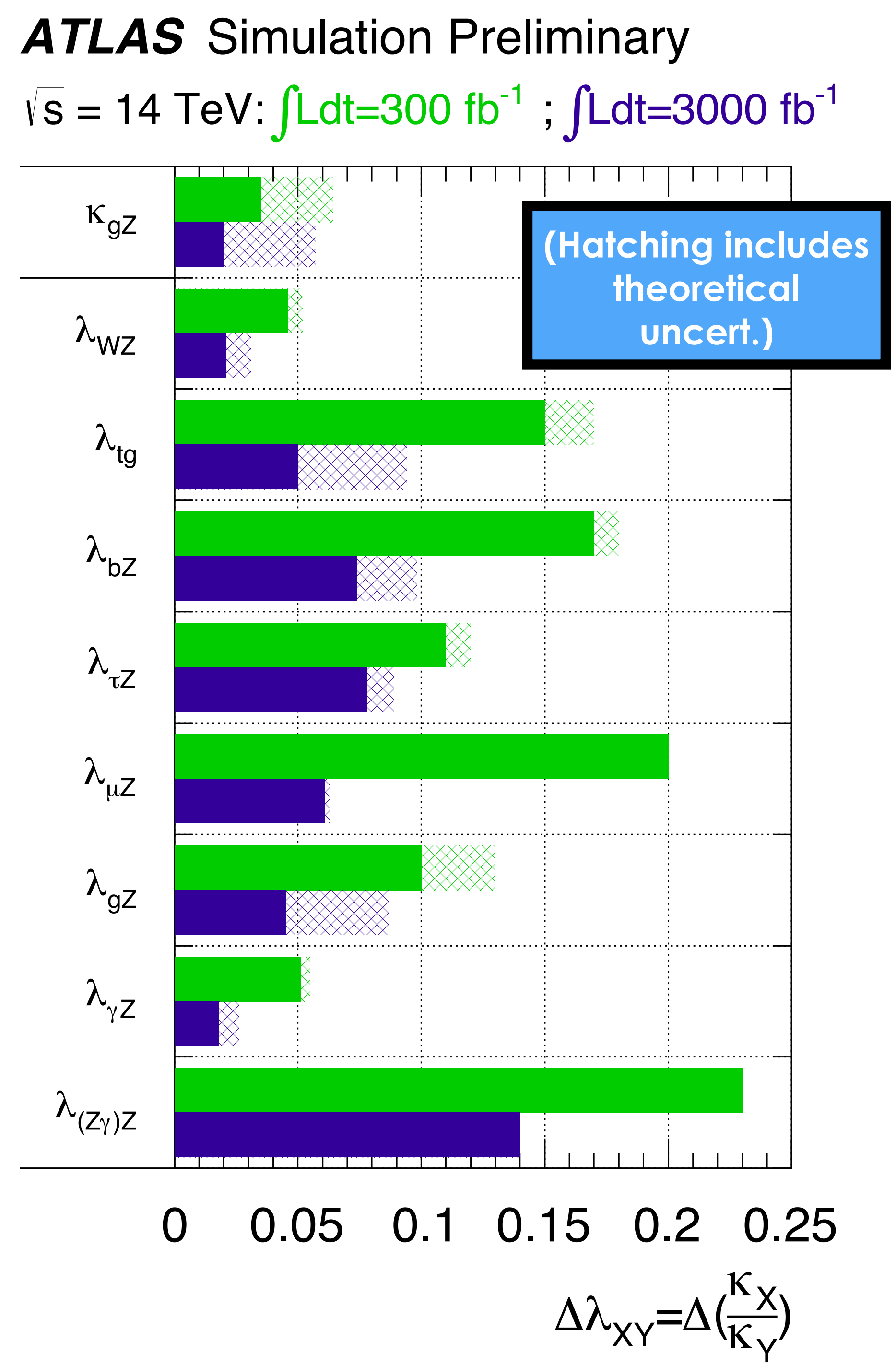
λ_{WZ}, $\lambda_{\gamma Z}$ most precise

CMS Projection





$$\lambda_{XY} = \kappa_X / \kappa_Y$$



- Ratios of **coupling scale factors** make no assumptions on Higgs boson width, cancel uncertainties
- Most uncertainties on couplings $\Delta\lambda/\lambda \leq 10\%$ for 3000 fb^{-1}

Expected Higgs coupling ratio (λ_{XY}) precisions

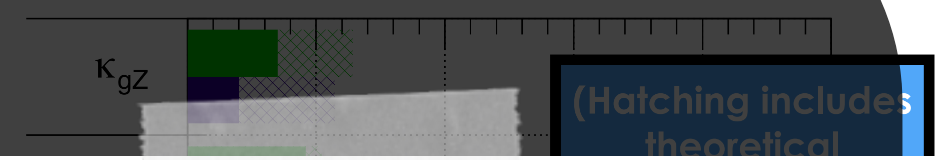
Expected uncertainties on Higgs boson couplings ratios

3000 fb^{-1} at $\sqrt{s}$ = 14 TeV Scenario 1

3000 fb^{-1} at $\sqrt{s}$ = 14 TeV Scenario 2

ATLAS Simulation Preliminary

$\sqrt{s}$ = 14 TeV: $\int Ldt$=300 fb^{-1} ; $\int Ldt$=3000 fb^{-1}

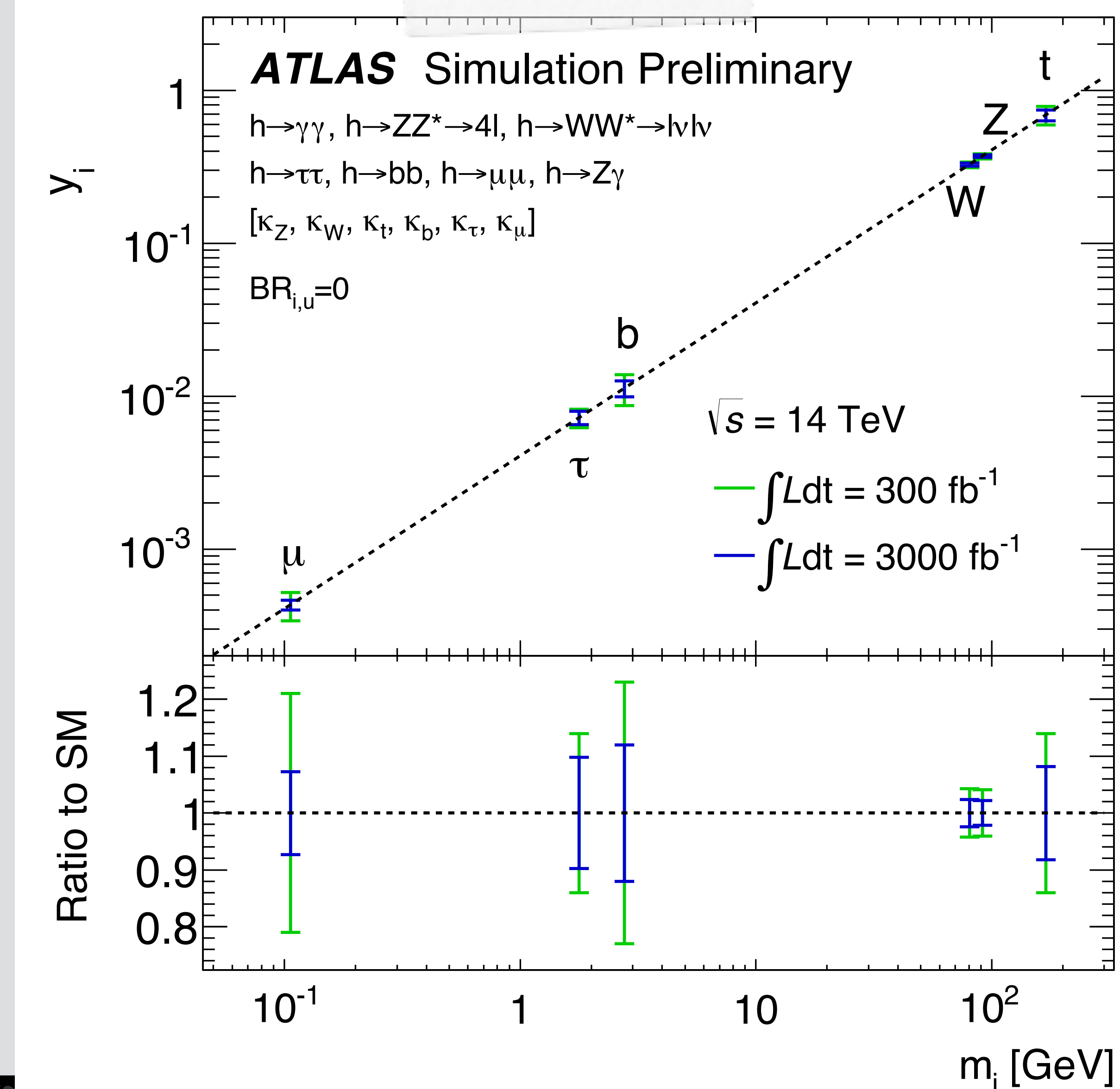


Can define reduced, **mass-dependent couplings**,

$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

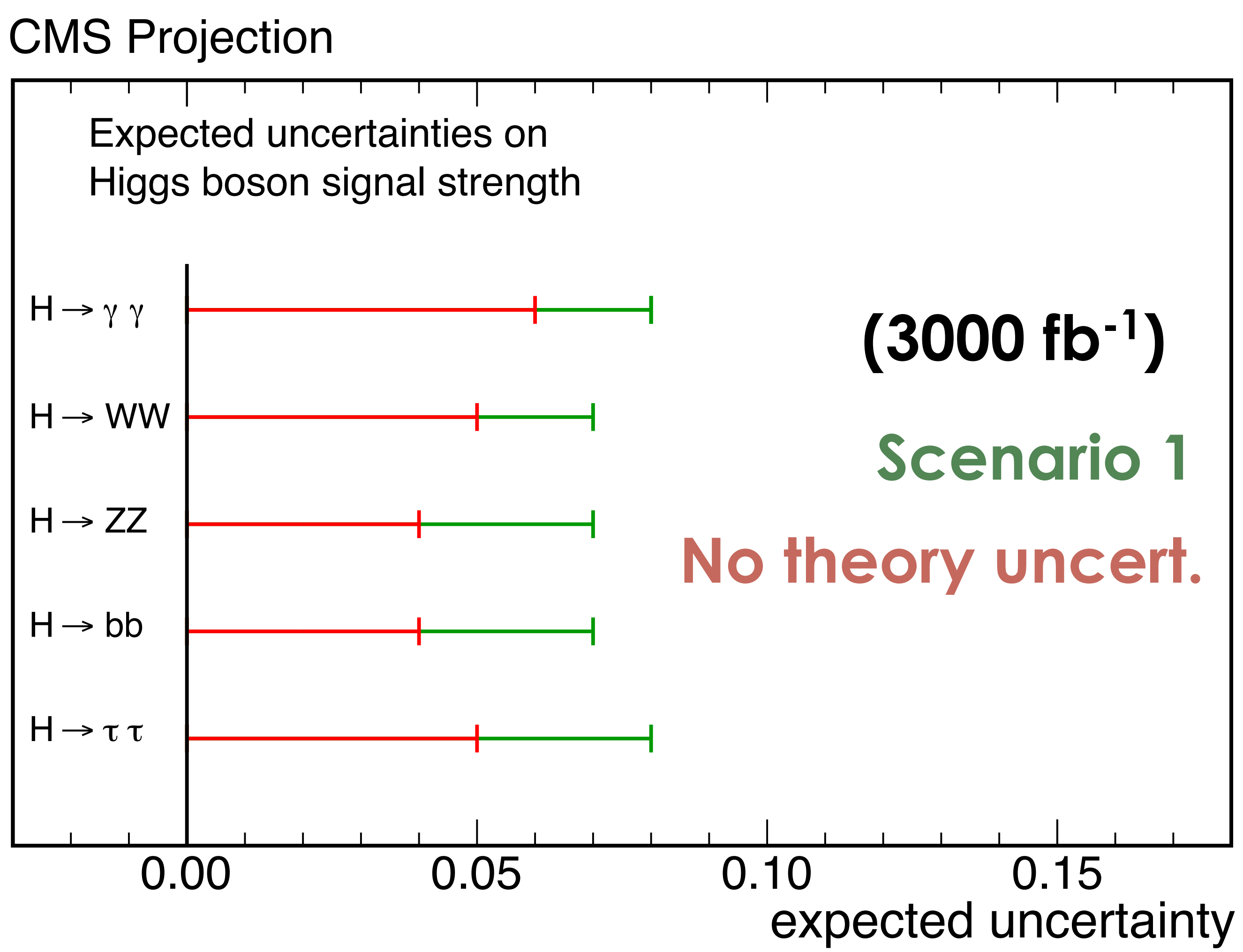
$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$

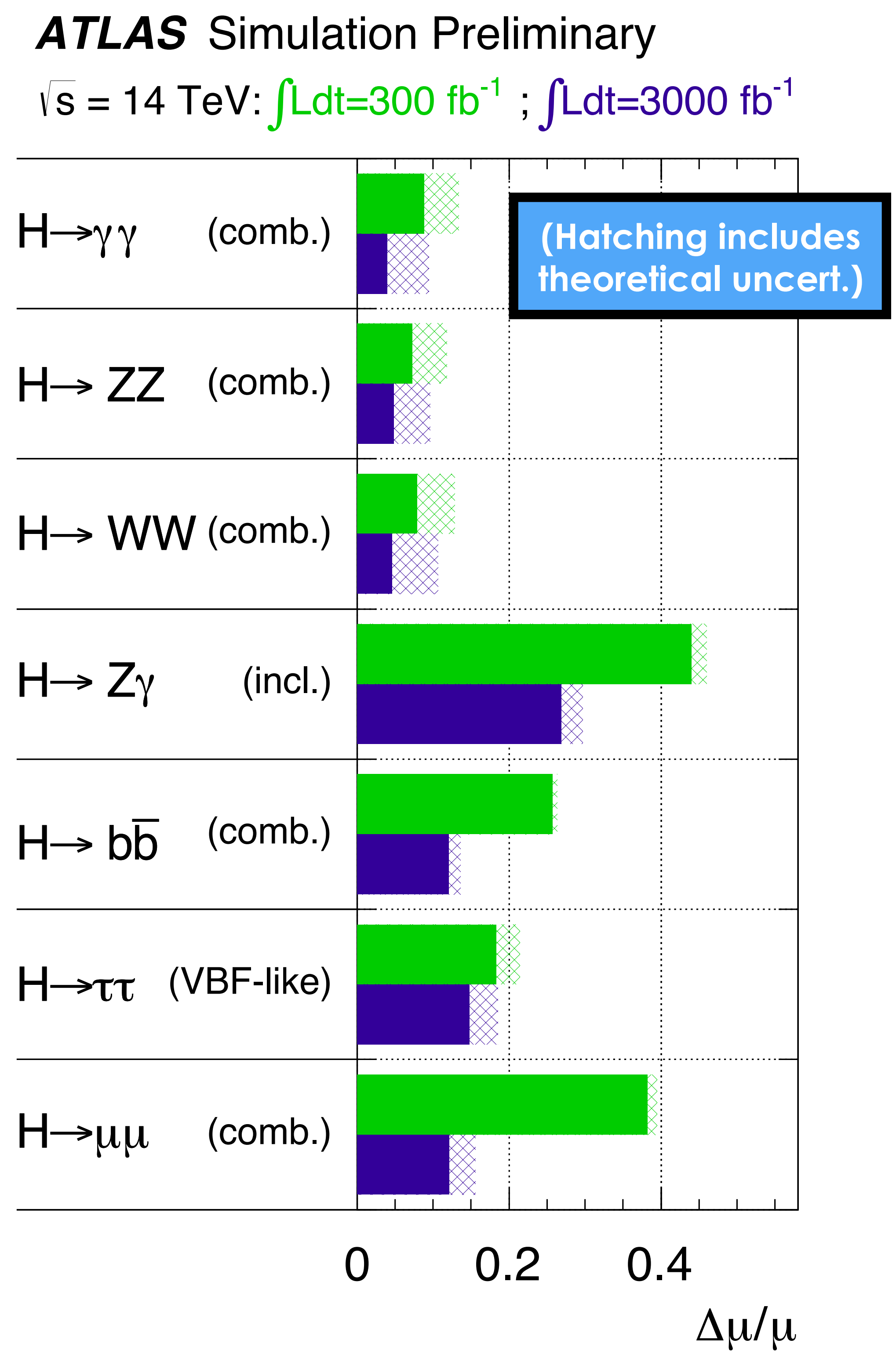
- Fit results **assume no new Higgs decay modes**
- Can plot reduced coupling scale factors y_i as **against mass** of particle *i* (see right)
- $\Delta y_X/y_X$ smallest for W, Z (**≤ 5%**), largest for b, t quarks



- Ratios of **coupling scale factors** make no ass... on Higgs boson width, cancel uncertainties
- Most uncertainties on couplings **Δλ/λ ≤ 10%** for 3000 fb^{-1}

Expected Higgs signal strength (μ) precisions



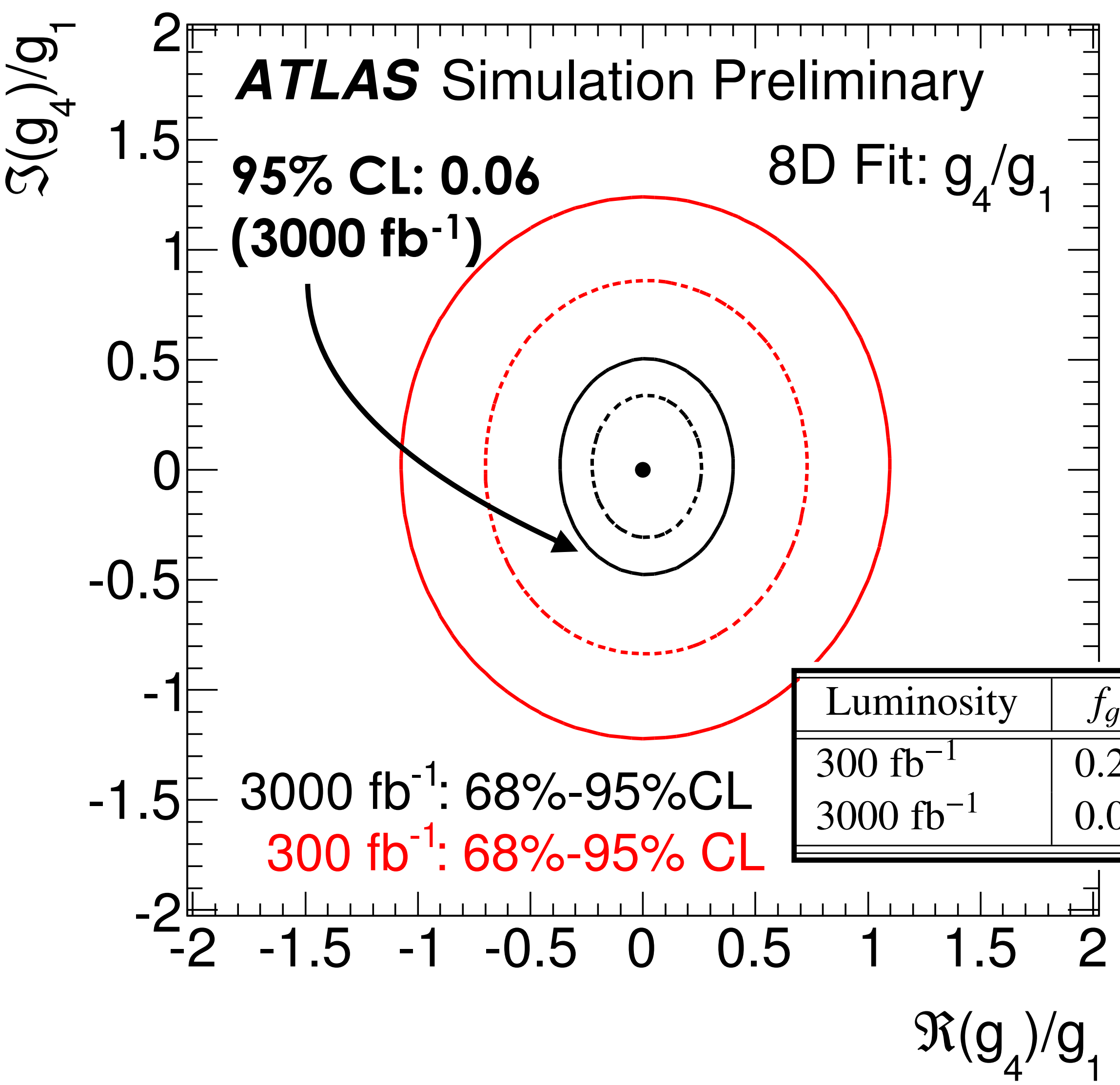


- Measurements of σ × BR expressed in terms of the ratio **μ = σ / σ$_{SM}$**
- Uncertainties of **Δμ/μ ~ 4%** reachable with 3000 fb^{-1} for **diboson states**
- Signal strength measurement of **gg → H production** has **Δμ/μ ~ 4%**

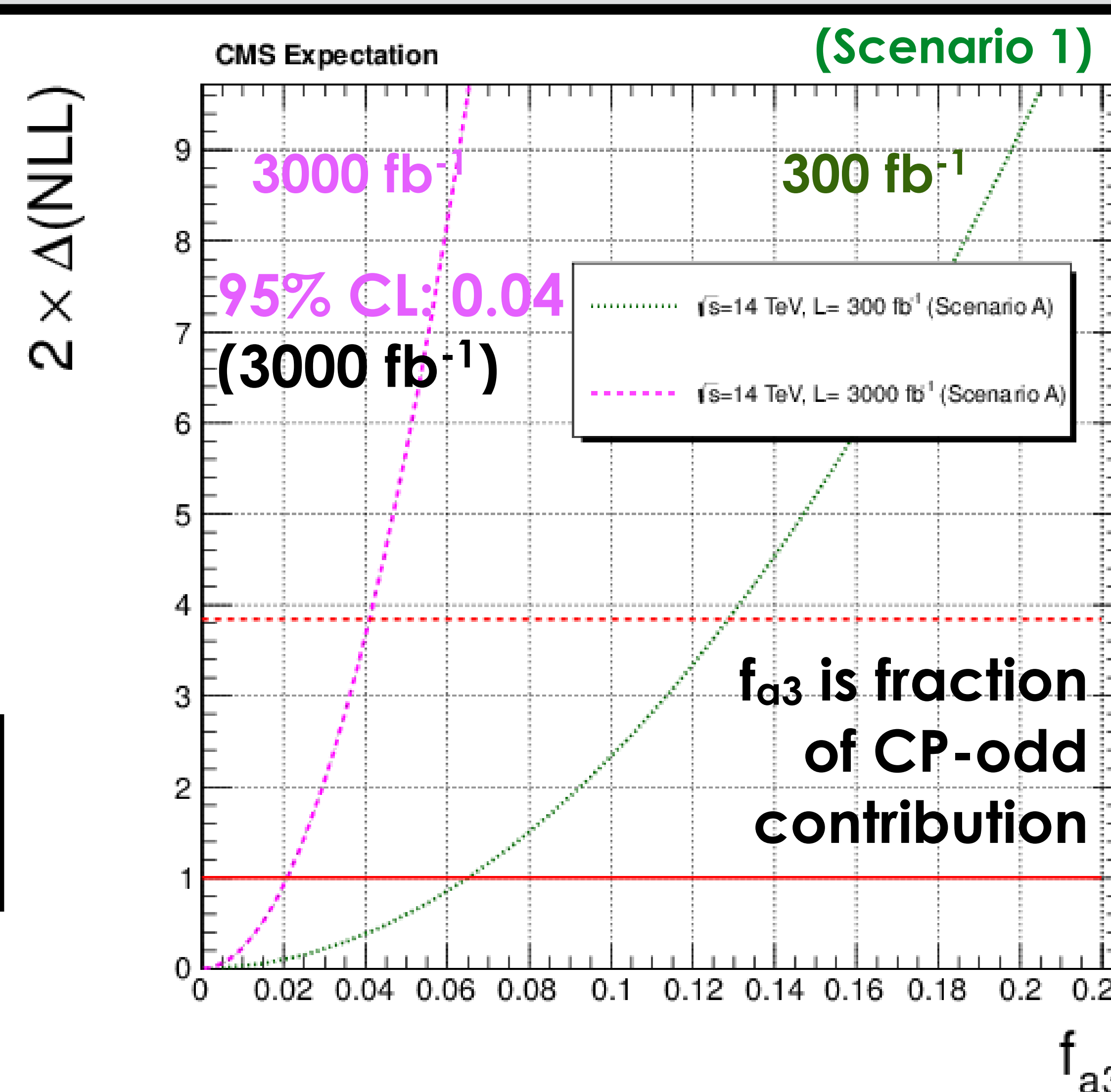
CP-mixing in $H \rightarrow ZZ^{(*)} \rightarrow 4l$

Decay amplitude for **spin-0 boson** decaying to **spin-1 gauge bosons**:

$$A(H \rightarrow ZZ) = v^{-1}\left(\underbrace{a_1 m_Z^2 \epsilon_1^* \epsilon_2^*}_{\text{SM tree process}} + \underbrace{a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{Loop CP-even terms}} + \underbrace{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{CP odd terms (BSM)}}\right)$$



Luminosity	f_{g_4}	f_{g_2}
300 fb^{-1}	0.20	0.29
3000 fb^{-1}	0.06	0.12

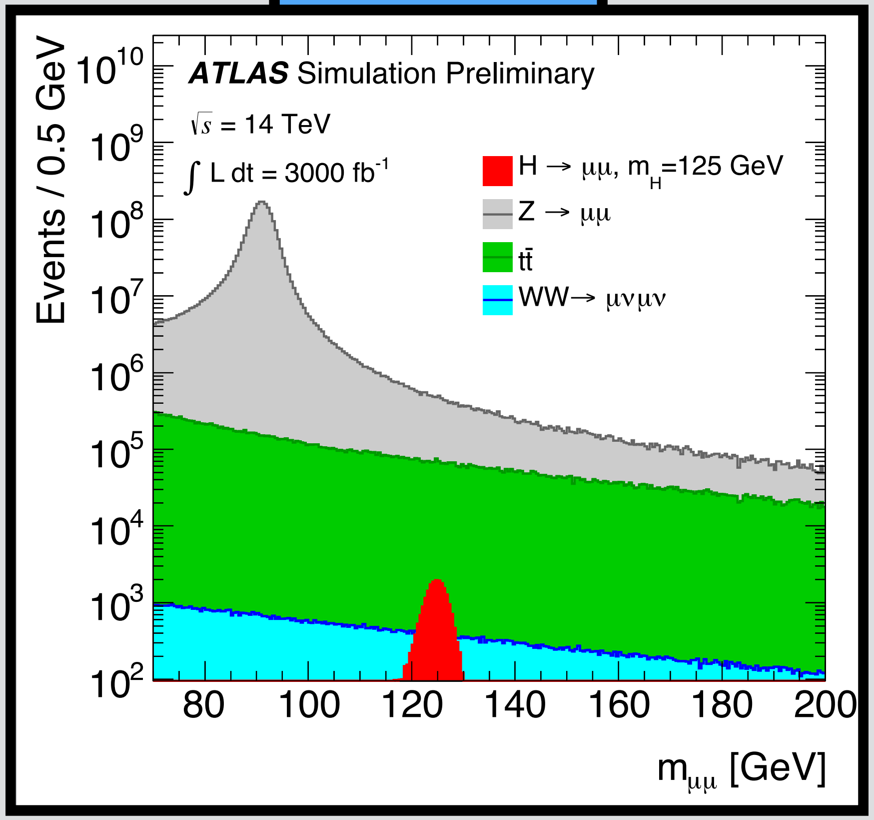


Note: $f_{a_3} \equiv f(g_4) = \dfrac{|g_4|^2\sigma_4}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}$

(CMS neglects small $|g_2|$ term)

Rare, interesting Higgs processes at 3000 fb^{-1}

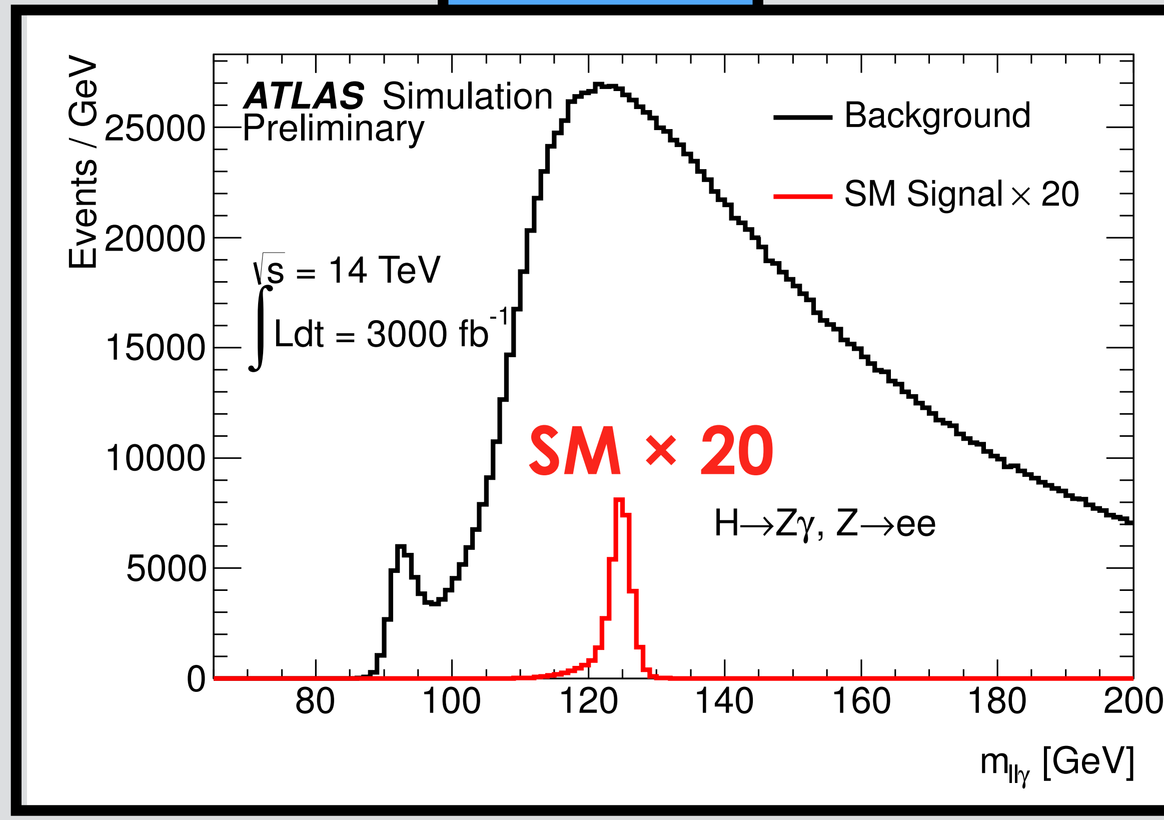
$H \to \mu\mu$



- Direct probe of H coupling to 2nd generation fermions
- CMS quotes **5%** precision on *μ* coupling for fully upgraded detector

Quantity	ATLAS	CMS
Z_0	7.0σ	$\geq 5\sigma$
$\Delta\mu/\mu$	0.21	0.20 – 0.24

$H \to Z\gamma$

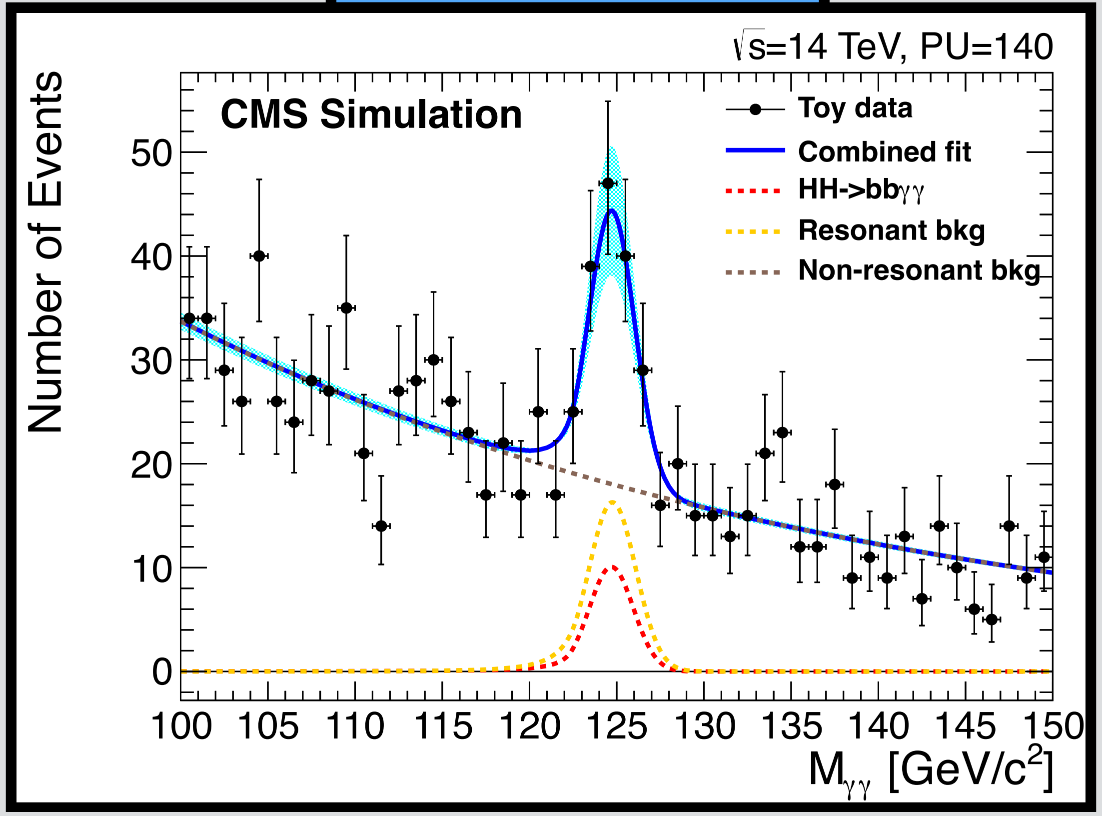


- Proceeds entirely through loops of heavy charged particles
  - Sensitive to new heavy states

Quantity	ATLAS	CMS
Z_0	3.9σ	–
$\Delta\mu/\mu$	${}^{+0.25}_{-0.26}$ (stat) ${}^{+0.17}_{-0.15}$ (syst)	0.20 – 0.24

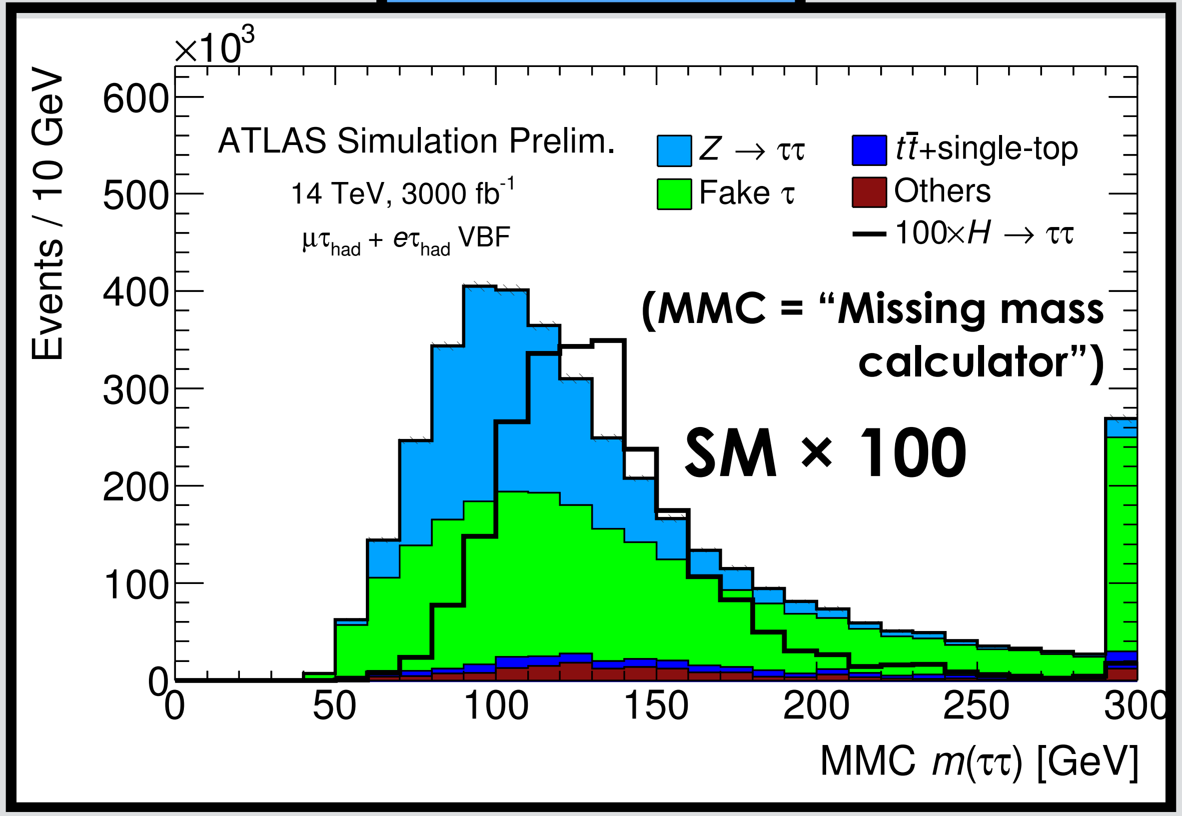
Rare, interesting Higgs processes at 3000 fb^{-1}

HH → bbγγ



- Allows measurement of Higgs self-coupling λ_{HHH}
- **CMS Z_0 (3000 fb^{-1}):** **1.9σ** for **bbγγ + bbττ**
  - **54%** exp. uncertainty in signal yield
- **ATLAS Z_0** (λ_{HHH} / λ_{SM} = 1): **1.3σ**

H → τlτhad

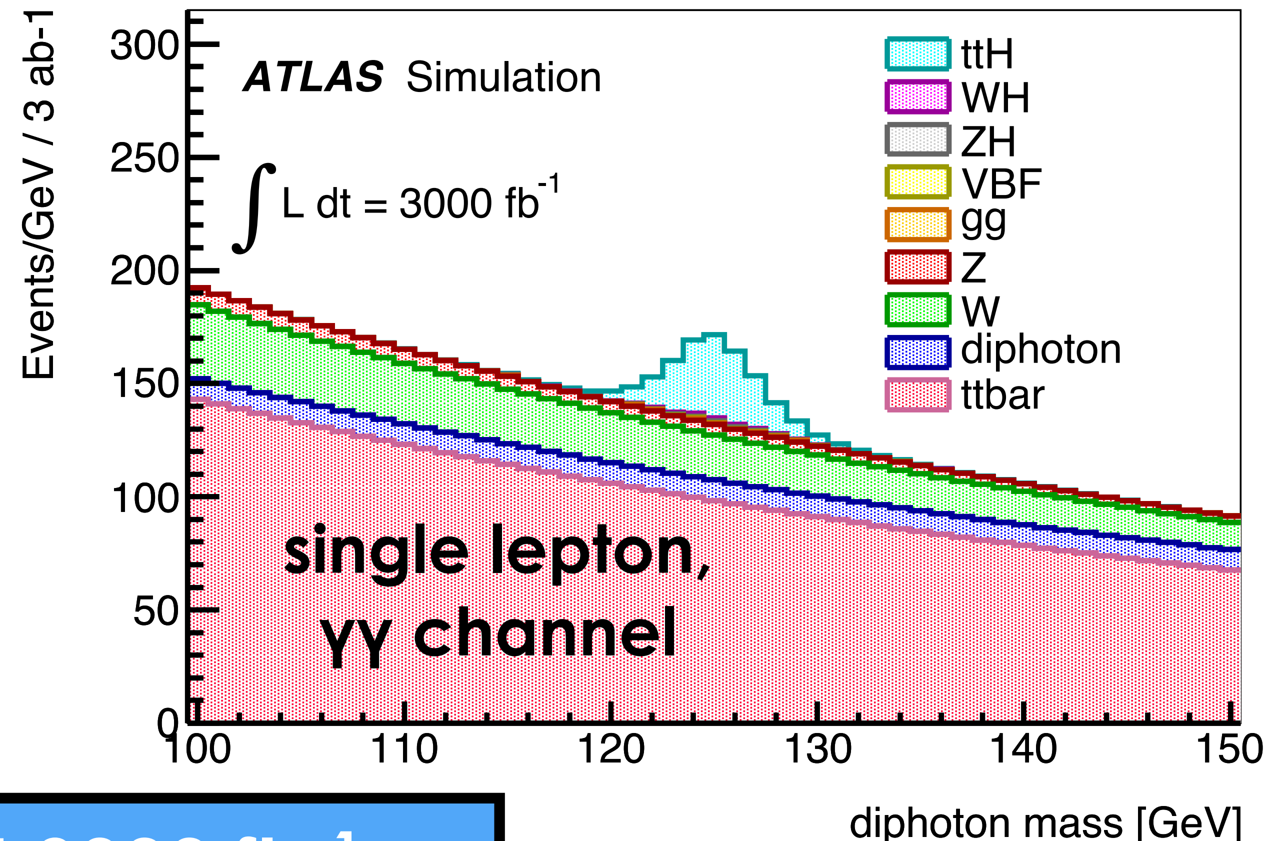


- Tests ratio of third-to-second generation lepton couplings
- **Exp. Δμ/μ (3000 fb^{-1}): 24%**
  - Ignores theory uncertainties
  - Assumes **5-10%** experimental uncertainties

Refs: ATL-PHYS-PUB-2013-007, ATL-PHYS-PUB-2014-012

ttH, WH/ZH production (H → γγ, H → μμ channels)

- Measurement of the t-H Yukawa coupling crucial for understanding EWSB
- ttH production rare, but **> 100 signal events** expected at 3000 fb^{-1}
  - 1, 2 lepton selections, dilepton mass, jet requirements separate WH/ZH, ttH
  - Events categorized according to **# of final state jets**



Expectations at 3000 fb^{-1}:

- S/B for **ttH** channels in H → γγ: **0.54 (1L)**, **0.39 (2L)**
  - Also have S/B for **WH (0.23)** and **ZH (1.15)**
- Signal significances with 3000 fb^{-1}, μ = 140:
  - ttH: **8.2σ**, WH: **4.2σ**, ZH: **3.7σ**
- At 3000 fb^{-1}, expect **signal strength uncertainty** on ttH production of **Δμ / μ ~ 23%** for H → μμ, **~ 17%** for H → γγ

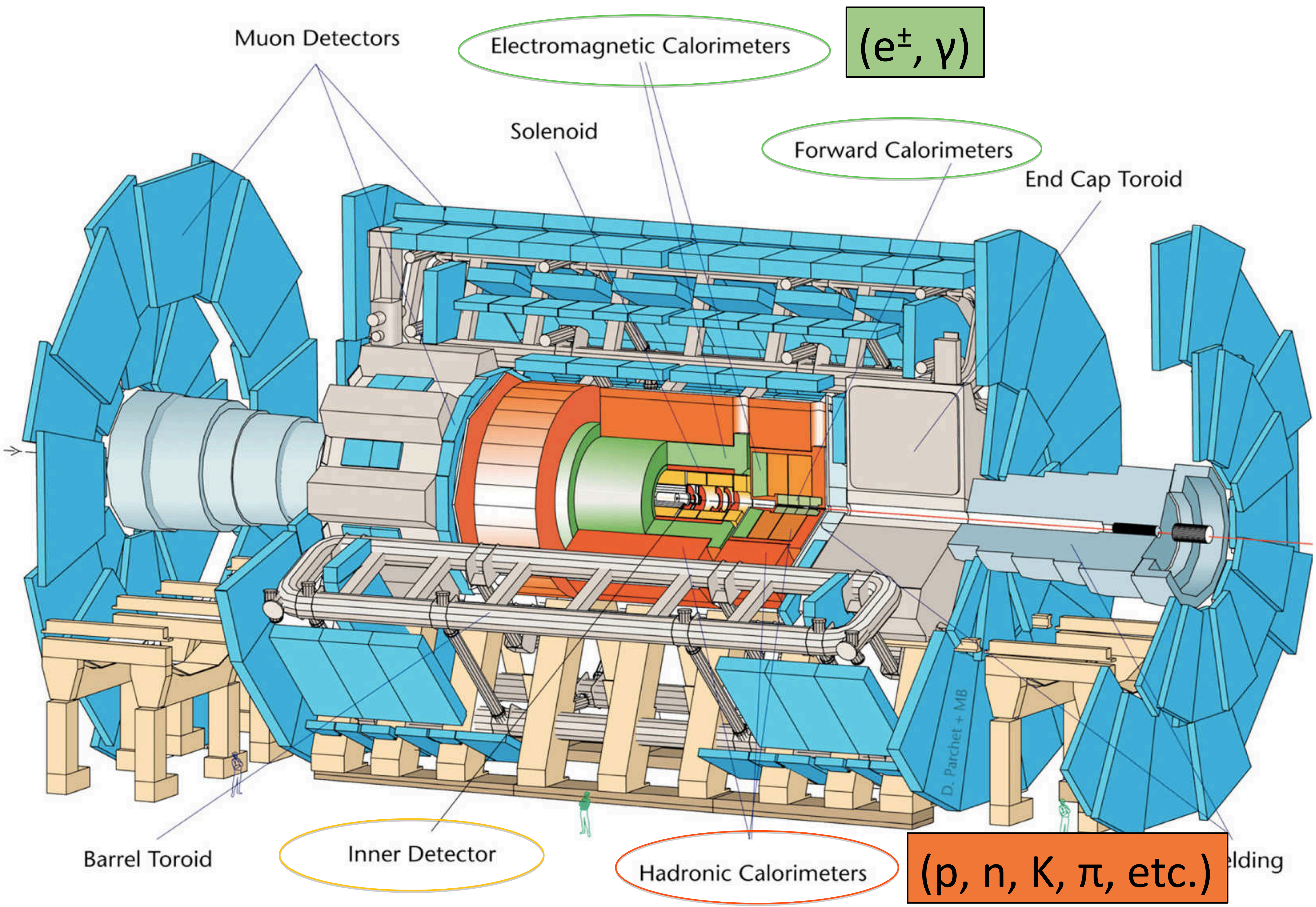
Category	#γ	# Jets	#ℓ	$\lvert m_{\ell^+\ell^-} - m_Z \rvert$
WH	2	< 2	1	-
ZH		-	2	< 15 GeV
ttH-2ℓ		≥ 2		> 15 GeV
ttH-1ℓ			1	-

Conclusions

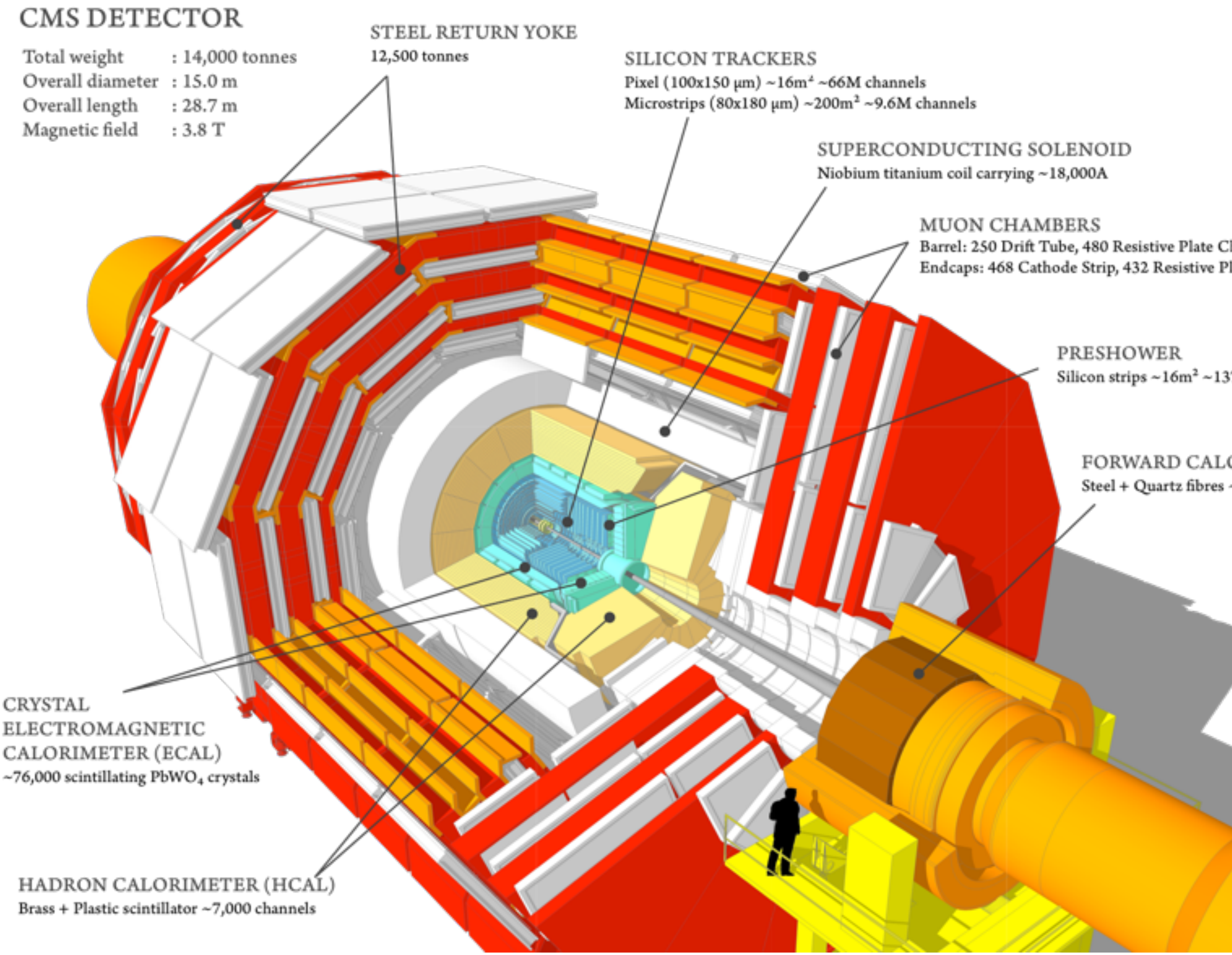
- ATLAS, CMS expect to measure Higgs boson signal strengths, couplings to **$\Delta\mu / \mu$, $\Delta\lambda / \lambda \leq$ 10%** after 3000 fb^{-1} of 14 TeV data
- **Discovery (> 5σ) of rare $H \rightarrow \mu\mu$ decay, ttH, $H \rightarrow \gamma\gamma$ process**, observation of Zγ final state (**~4σ**) expected
- **2σ significance** expected for HH-related final states (**bbγγ, bbττ**)
- 95% CL on CP-odd mixing fraction in $H \rightarrow 4l$ decay expected to be **CL(95%) = 0.04 – 0.06**

Extra slides

The ATLAS detector



The CMS detector



CMS, ATLAS detector upgrades

Upgrade phase	Years	ATLAS upgrades	CMS upgrades
Phase 0	2013-2014	(✔) Insertable b-layer (IBL) (✔) Level-1 topological trigger (✔) Complete muon coverage (✔) Additional repairs (TRT, LAr, tile)	(✔) 4th muon endcap station (✔) Complete muon endcap coverage (✔) New detector consolidation (✔) Colder tracker
Phase 1	2018-2019	• Fast Track Trigger (FTK) • High granularity Level-1 calorimeter trigger • New muon small wheel (MSW) for Level-1 trigger	• New Level-1 trigger system • New Si pixel detector • New photo-detector • New electronics for HCAL
Phase 2	2023-2025	• New silicon tracker • New forward calorimeter & electronic • Improved Level-1 track trigger	• New tracker with Level-1 capability • DAQ/HLT upgrade • Replace end-cap & forward calo • EM pre-shower system

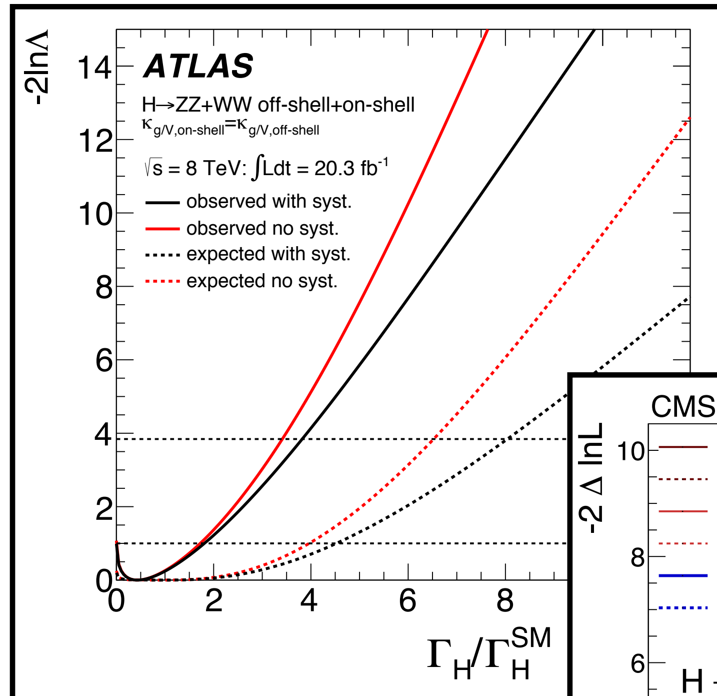
(R. Konoplich, Blois 2014, 21/05/14)

Higgs boson width measurements

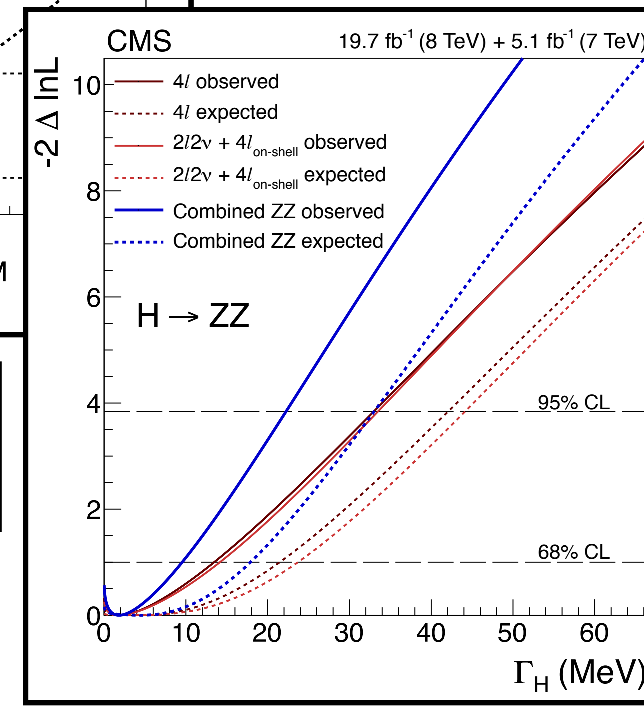
- ATLAS, CMS studied off-shell production of Higgs boson in $H \to 4l$ channel for 8 TeV data (CMS 7+8 TeV)
  - **Indirect** Γ_H limit from σ_{ggF} when $\mathbf{m_{ZZ} > 2m_Z}$,

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

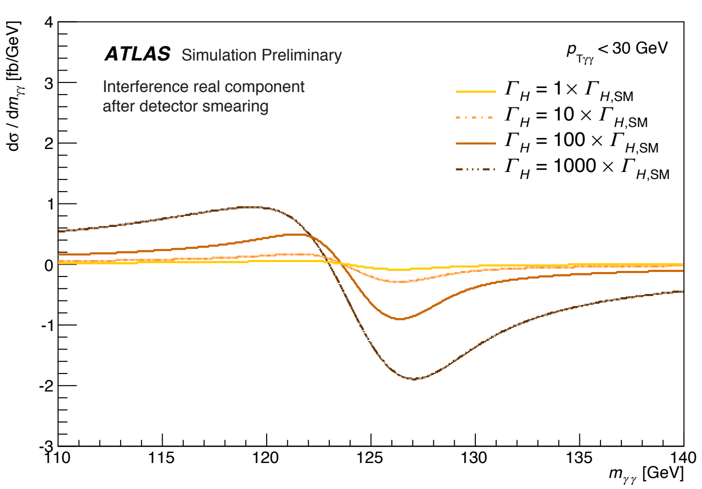
  - Uses **2l2ν final state** to enhance statistics, increase Γ_H sensitivity (8 TeV only)
- Can **directly** estimate Γ_H from **interference** of $H \to \gamma\gamma$ signal with **continuum gg → γγ** background (box diagrams) at 3000 fb^{-1}
  - Real component is **odd around Higgs mass**, induces **negative shift** in m_H
  - Expected **95% CL** at 300 (3000) fb^{-1}: **880 (160) MeV**



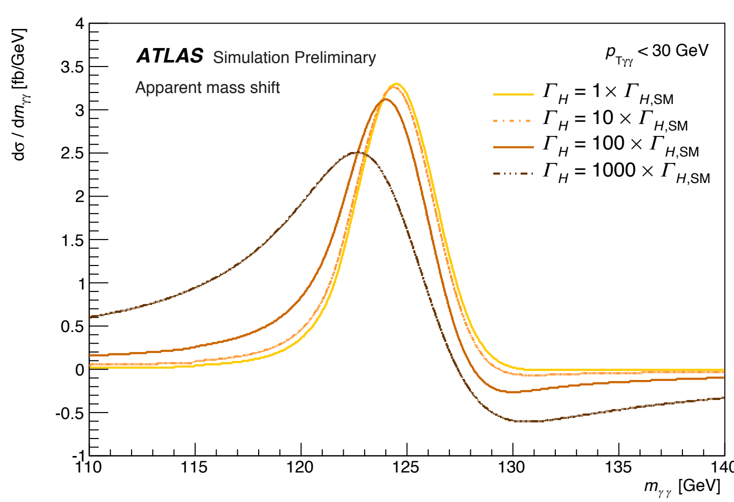
ATLAS 95% CL: Γ_H < 22.7 MeV



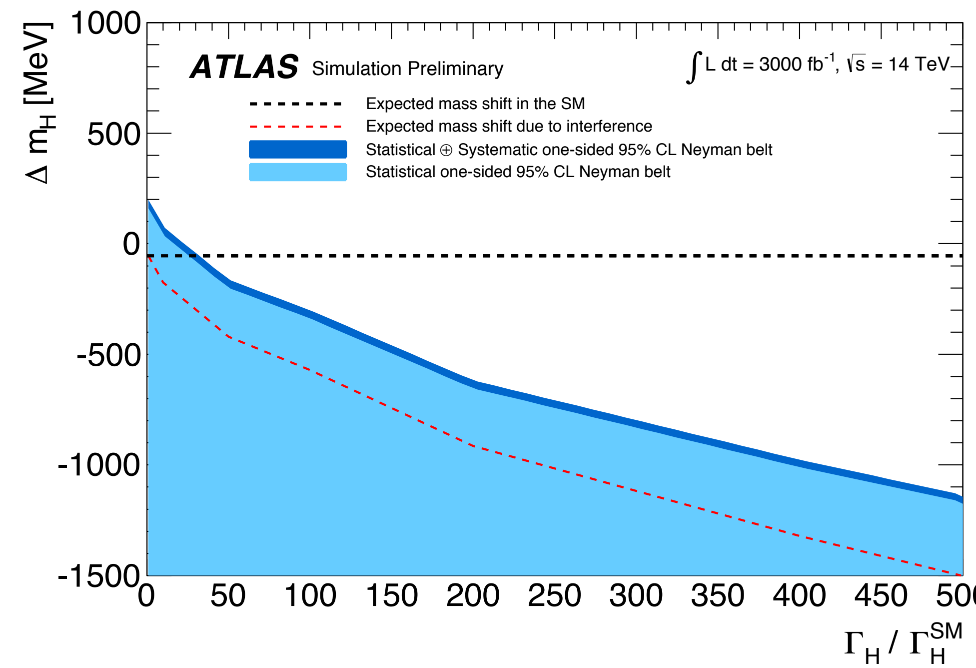
CMS 95% CL: Γ_H < 22 MeV



Real interference term



Apparent mass shift

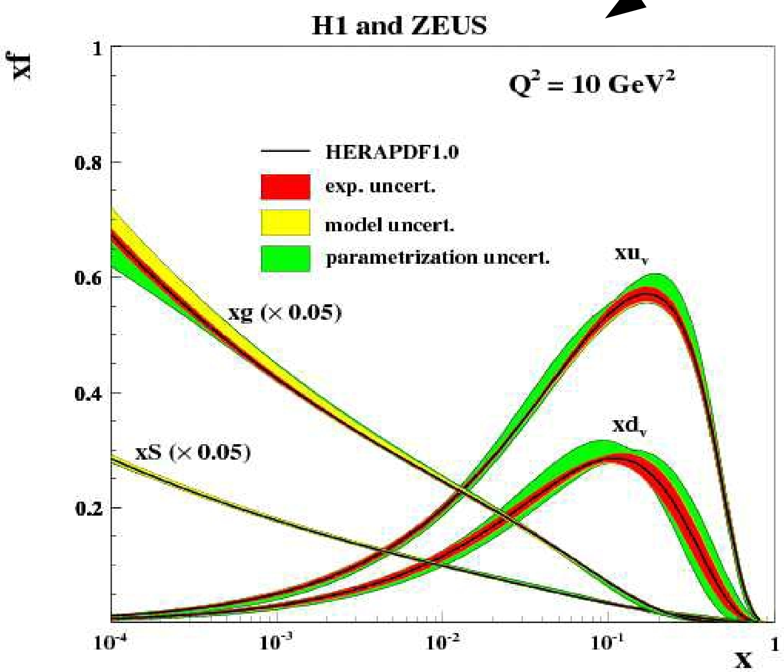


The Matrix Element Likelihood Analysis (MELA) method

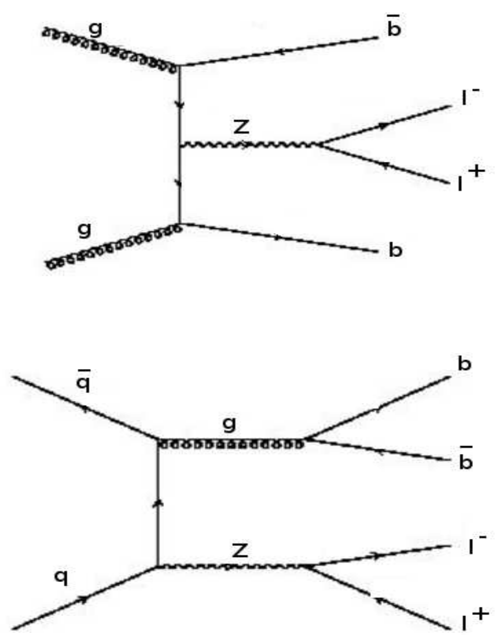
- Event-by-event discriminator built upon matrix elements
- Contains the maximal amount of theoretical information available for the hard process
- Combined with reconstruction level information

Probability that the event with reconstructed kinematics x matches the hypothesis α:

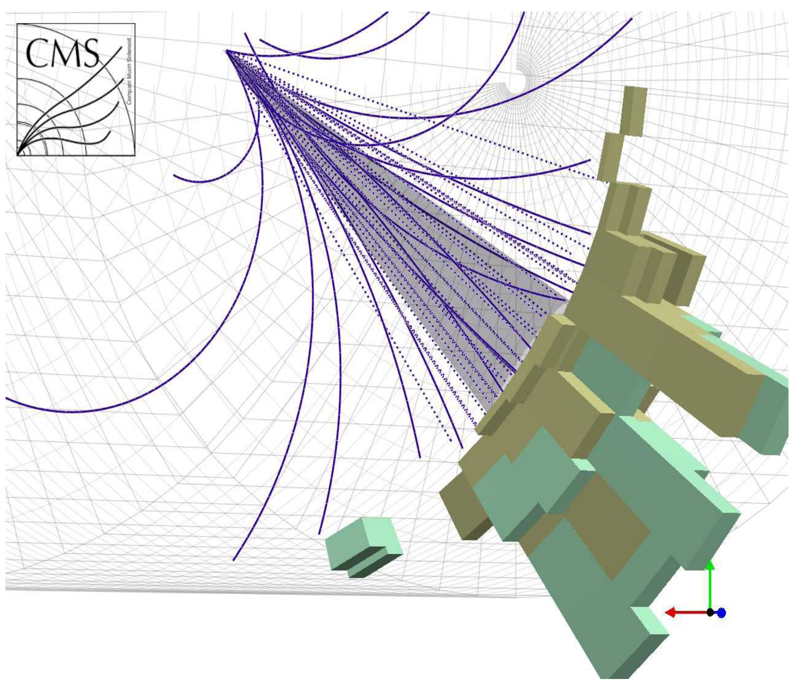
$$P(x^{vis}|\alpha) = \frac{1}{\sigma_\alpha} \int dx_1 dx_2 f(x_1) f(x_2) \int d\phi |M(p)_\alpha|^2 W(p^{vis}, p)$$



Proton density functions



Matrix Element at LO of the hypothesis

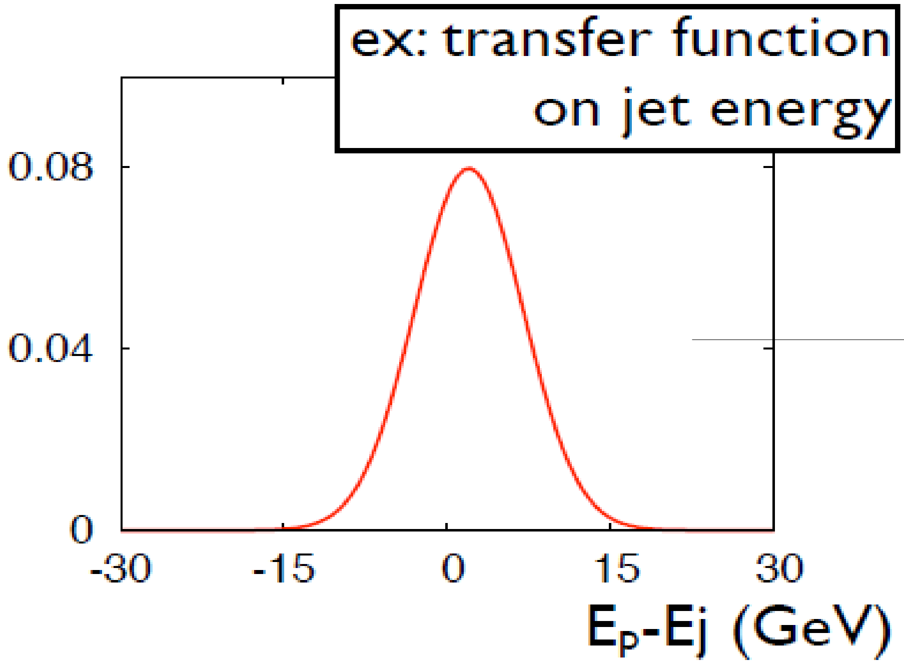


Transfer functions extracted from simulation

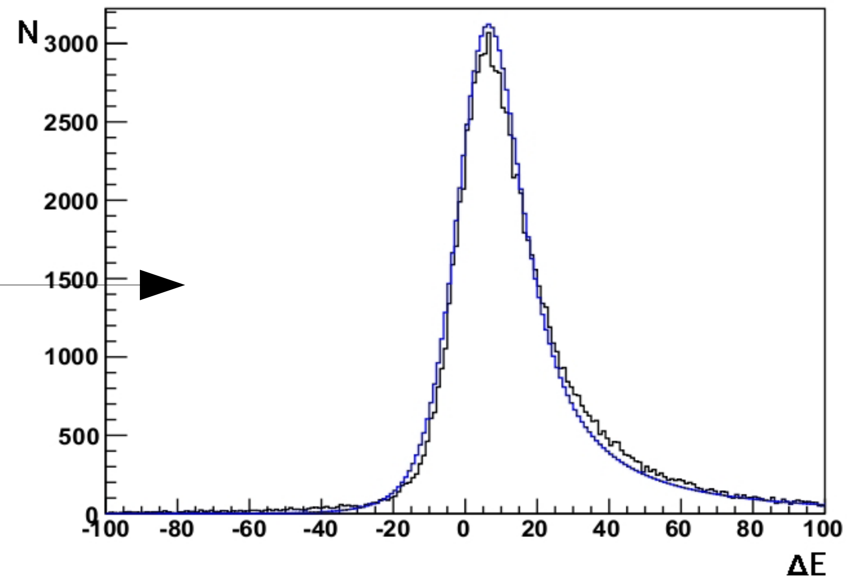
(C. Beluffi, "ACAT 2014 – The MEM in CMS", 01/08/14)

MELA: Transfer functions + discriminant

- **Transfer functions** take into account showering/hadronization effects + experimental resolution/reconstruction → P(x, a) convoluted with transfer function, $W(p^{Vis}, p)$
  - i.e. It is a likelihood fit on $\Delta(E_{Parton} - E_{Jet})$
- Assumes particles are not correlated, usable for other variables (e.g. muons with $1/p_T$ dependence)



Reality



- In H → ZZ → 4l analysis, build kinematic discriminant D_{bkg} to separate signal, background using angular vector **Ω** = {θ*, ϕ_1, θ_1, θ_2, φ) as,

$$D_{\rm bkg} = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_{4l}; m_1, m_2, \Omega)}{\mathcal{P}_{\rm sig}(m_{4l}; m_1, m_2, \Omega)}\right]^{-1}$$

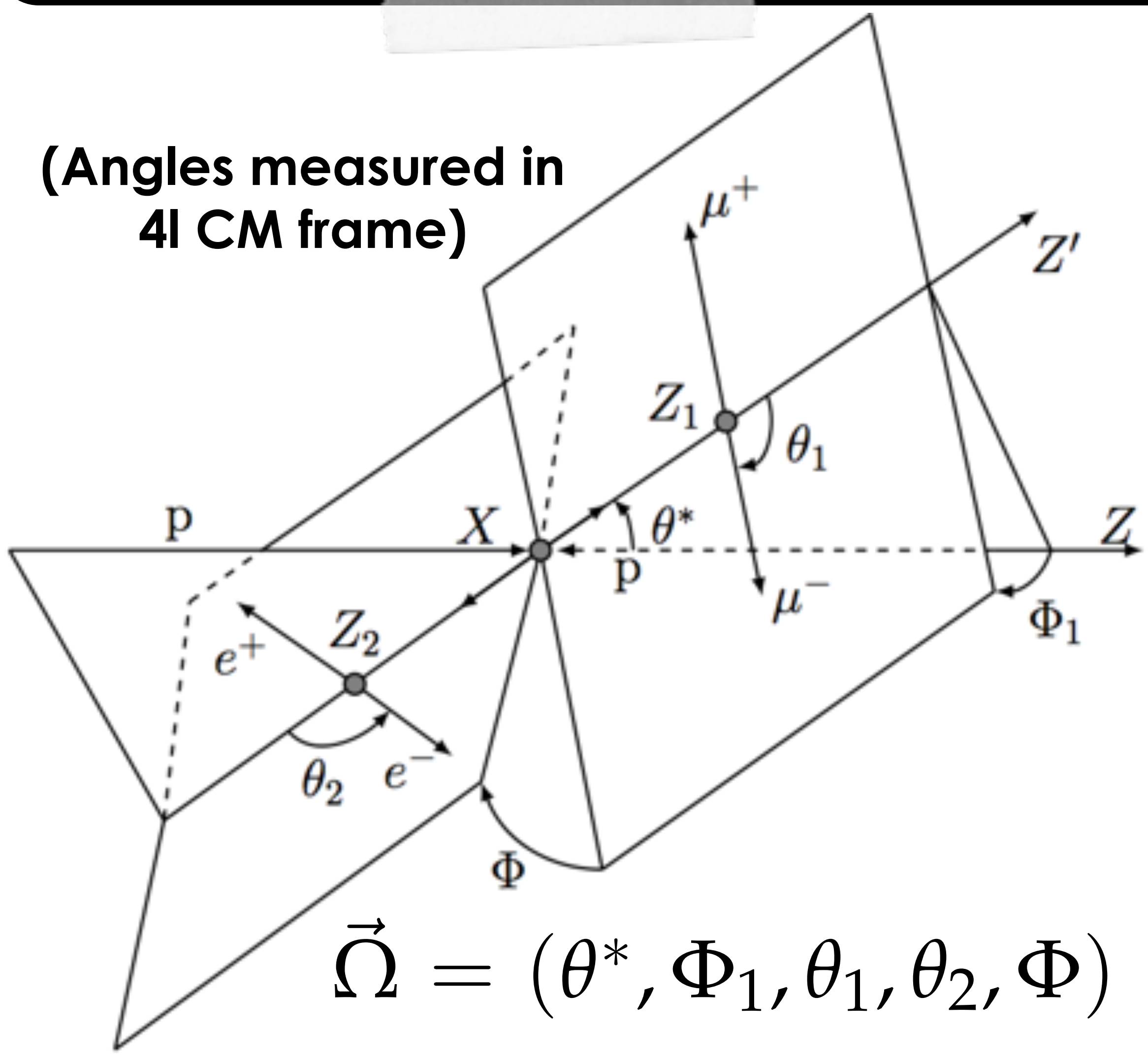
- Can also use similar approach to discriminate spin hypotheses
  - i.e. Build **likelihood L = -2 ln (L_{0-} / L_{0+})** with signal rate as free parameter

Spin-parity measurement details

Decay amplitude for **spin-0 boson** decaying to **spin-1 gauge bosons**:

$$A(H \to ZZ) = v^{-1}\left(\underbrace{a_1 m_Z^2 \epsilon_1^* \epsilon_2^*}_{\text{SM tree process}} + a_2 \underbrace{f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{Loop CP-even terms}} + a_3 \underbrace{f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{CP odd terms (BSM)}}\right)$$

(Angles measured in 4l CM frame)



$$\vec{\Omega} = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$$

$$K_D = \frac{\mathcal{P}_{\text{Sig}}}{\mathcal{P}_{\text{Sig}} + \mathcal{P}_{\text{Bkg}}}$$

Presence of multiple Higgs bosons / CP violation in 4l final state could lead to 125 GeV Higgs boson as **admixture** of **CP-scalar and pseudo scalar** states.

- CMS uses **MELA discriminant K_D based on Ω, m_{Z1}, m_{Z2}**, minimize test statistic $q = -2 \ln (\mathscr{L}_{JP}/\mathscr{L}_{SM})$
  - Based on **ratio of ME probabilities** for different J^P scenarios
  - Likelihood scanned w.r.t. CP-odd fraction of decay rate, f_{a3}
- ATLAS uses **8D likelihood fit to Ω, m_{Z1}, m_{Z2}** to determine $\Re(g_i) / g_j$
  - Convert back to f_{gi} using numerical formulae

8D likelihood fit

- The likelihood is constructed by using the **full analytical expression of the ME** of the H → ZZ → 4l process **at LO**
  - Depends on coupling constants & angular observables Ω
- Detector acceptance, resolution effects are described by **parameterizations** based on simulated events
- 8D likelihood function defined as,

$$L(\mu, N_{\mathrm{sig_i}}, N_{ZZ_i}, N_{Red_i}, \mathrm{syst}) \propto$$
$$\sum_i \prod_{events} \left[\mu N_{\mathrm{sig_i}} \mathrm{pdf}_{\mathrm{sig_i}} \left(\vec{x}, \frac{g_2}{g_1}, \frac{g_4}{g_1} \right) + N_{\mathrm{ZZ_i}} \mathrm{pdf}_{\mathrm{ZZ_i}}(\vec{x}) + N_{\mathrm{Red_i}} \mathrm{pdf}_{\mathrm{Red_i}}(\vec{x}) \right]$$

- Sum runs over 4μ / 2e2μ / 2μ2e / 4e final states
  - Here, we have $\vec{x} = (m_{4\ell}, m_1, m_2, \cos\theta^*, \phi_1 \cos\theta_1, \cos\theta_2, \phi)$
- For **each point in $\Re(g_i)$ / g_1, $\Im(g_i)$ / g_1** plane, a **simultaneous fit** is done to all four decay channels
  - NLL values are plotted in a 2D histogram → **global minimum found**
- To convert back to (f_{g2}, f_{g4}, ϕ_{g2}, ϕ_{g4}) parameterization, use the following,

$$f_{g_i} = \frac{r_{i1}^2}{1 + r_{i1}^2}, \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right), \quad \text{where} \quad r_{31}^2 \approx 0.16\frac{|g_4|^2}{|g_1|^2} \quad \text{and} \quad r_{21}^2 \approx 0.382\frac{|g_2|^2}{|g_1|^2}.$$

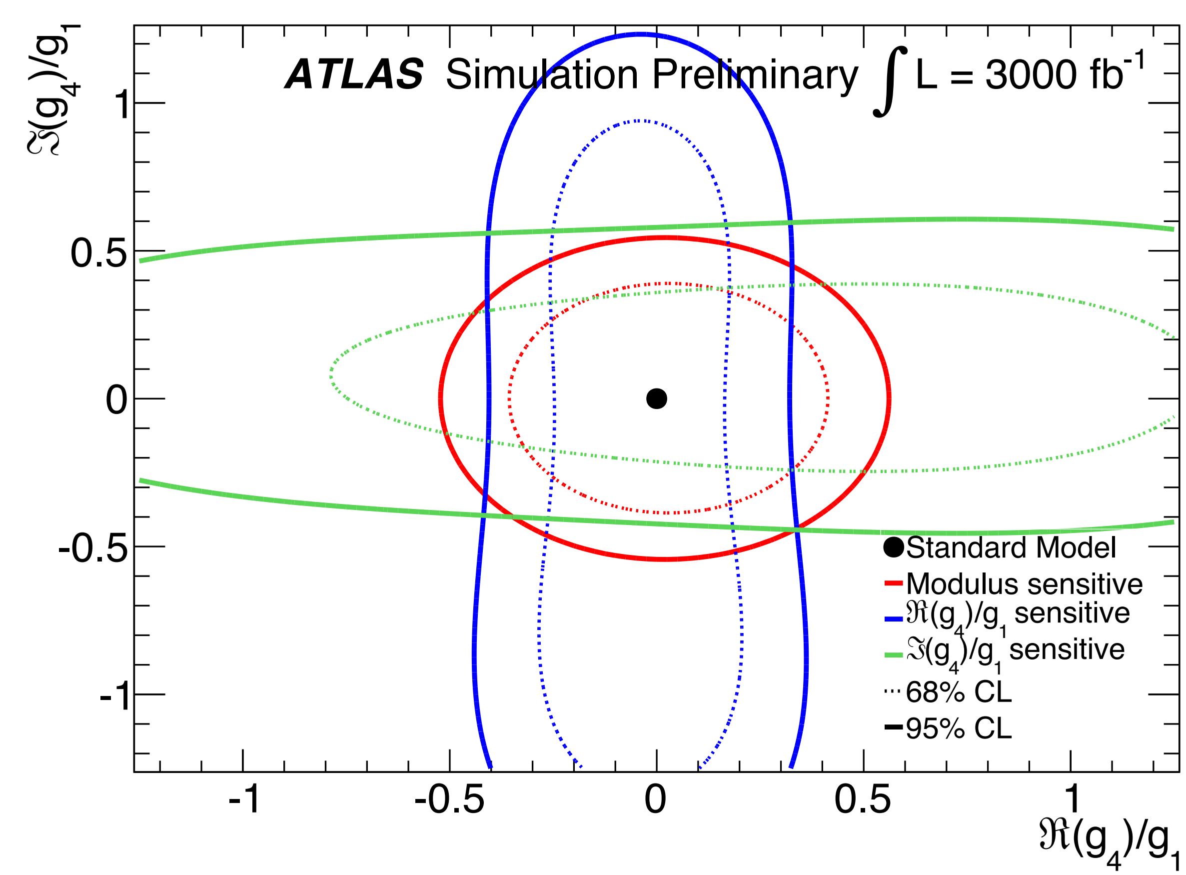
ATLAS ME likelihood fit

- Based on MC modelling of expected signal in **bins of ($\Re(g_i)$ / g_1, $\Im(g_i)$ / g_1)**
  - Dedicated MC sample created for each bin, $g_i = g_2$ or g_4
  - Done by **re-weighting samples** using analytical calculation of **corresponding ME** at LO
- Expected values of **P-sensitive observables** calculated for signal, background in each bin (see right)
  - Combined with information from **BDT which separates ZZ signal from background**
- Comparison of test data to alternative MC distributions in each bin done by **likelihood fit** using,

$$L(\mu, N_{\rm sig}, N_{bckg}, {\rm syst}) = \sum_{\rm FS} \prod_{\rm Bins} (\mu N_{\rm sig} {\rm pdf}_{\rm sig} + N_{\rm bckg} {\rm pdf}_{\rm bckg}),$$

- Product runs over all final states, bins
  - Fitted value taken as **centre of lowest bin**

Observable	Sensitivity
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=0)\rvert^2}{\lvert ME(g_1=0,g_2=0,g_4=1)\rvert^2}$	$\lvert g_4\rvert/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=-2+2i)\rvert^2}{\lvert ME(g_1=1,g_2=0,g_4=2+2i)\rvert^2}$	$\Re(g_4)/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=2-2i)\rvert^2}{\lvert ME(g_1=1,g_2=0,g_4=2+2i)\rvert^2}$	$\Im(g_4)/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=0)\rvert^2}{\lvert ME(g_1=1,g_2=1,g_4=0)\rvert^2}$	$\lvert g_2\rvert/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=-1+i,g_4=0)\rvert^2}{\lvert ME(g_1=1,g_2=1+i,g_4=0)\rvert^2}$	$\Re(g_2)/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=1-i,g_4=0)\rvert^2}{\lvert ME(g_1=1,g_2=1+i,g_4=0i)\rvert^2}$	$\Im(g_2)/g_1$

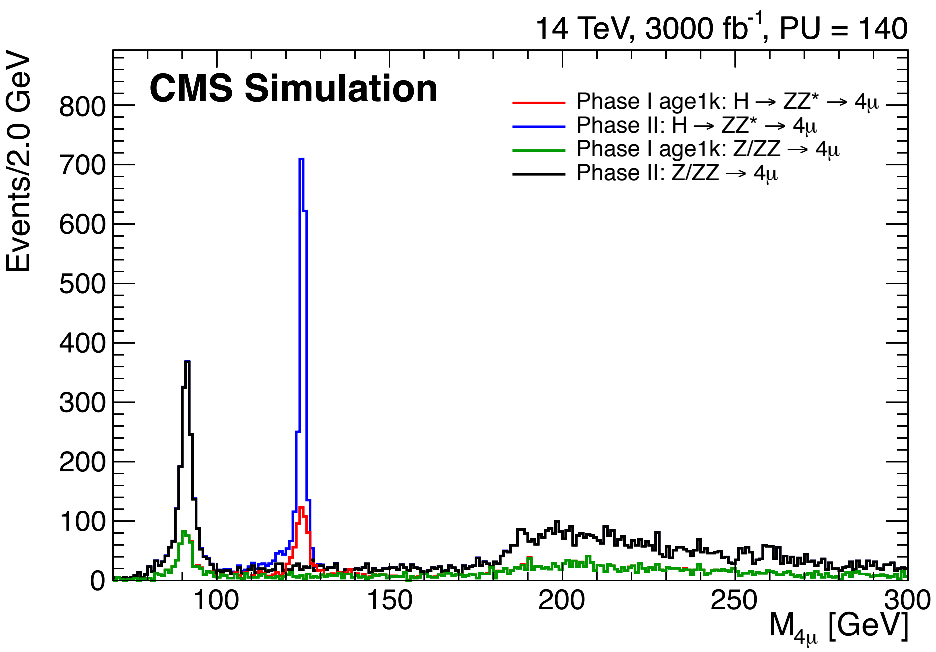


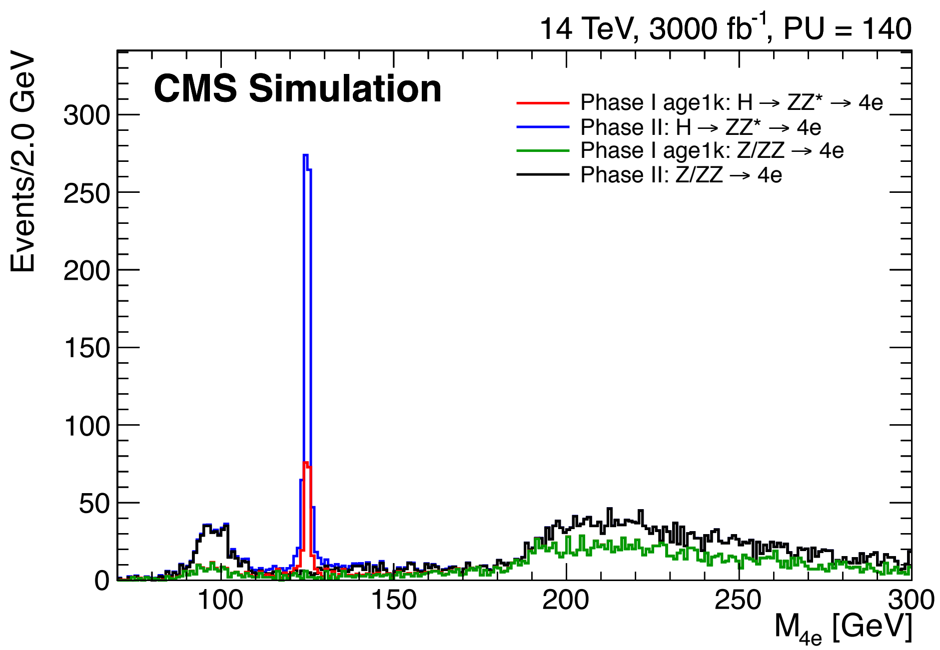
95% CLs:

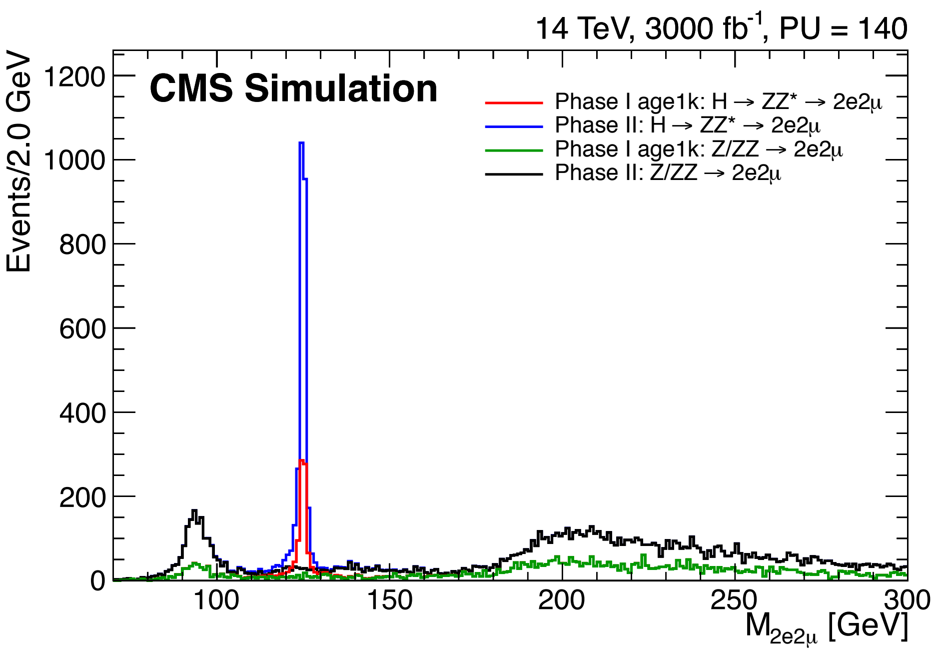
Luminosity	f_{g4}	f_{g2}
300 fb^{-1}	0.15	0.43
3000 fb^{-1}	0.037	0.20

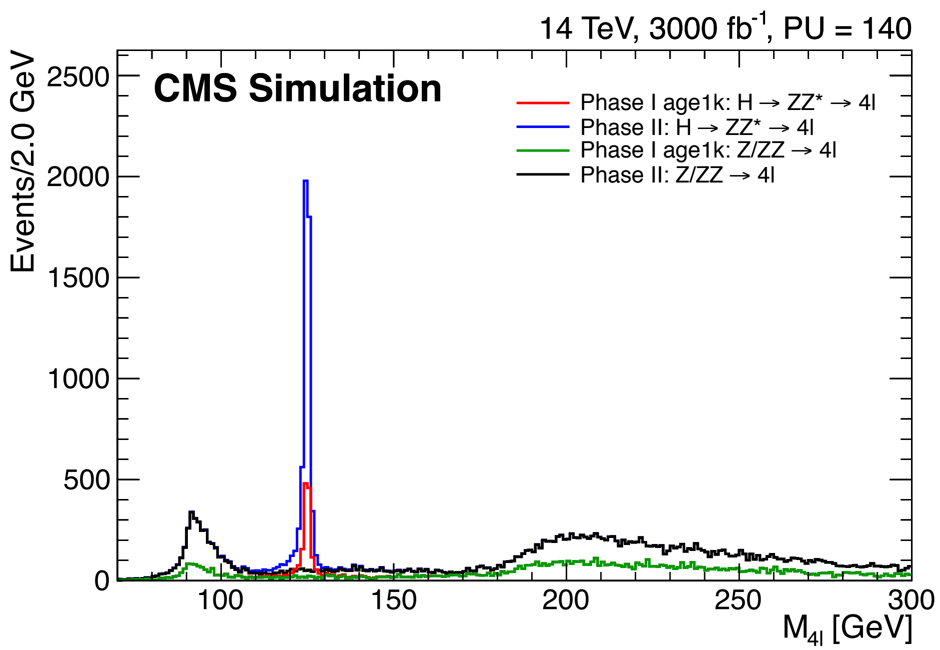
Potential CMS Phase II detector resolution

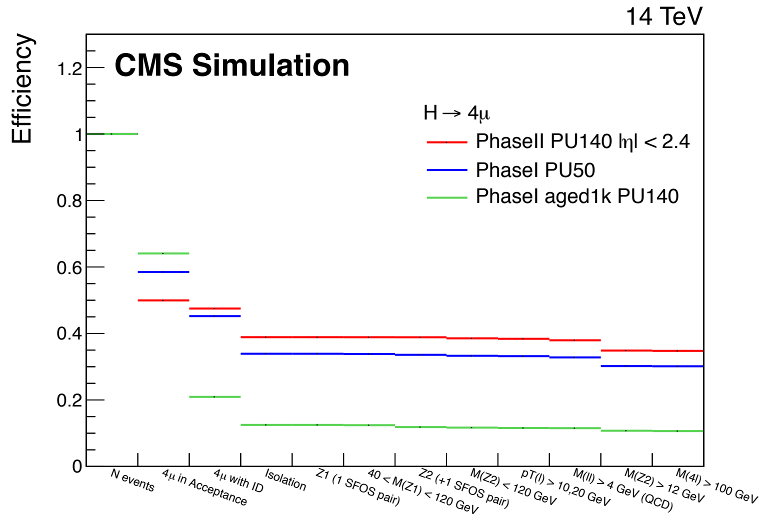
4l mass distributions, cut flows at 3000 fb^{-1} for the signal samples and irreducible ZZ → 4l background for Phase I (aged), Phase II detector setups:

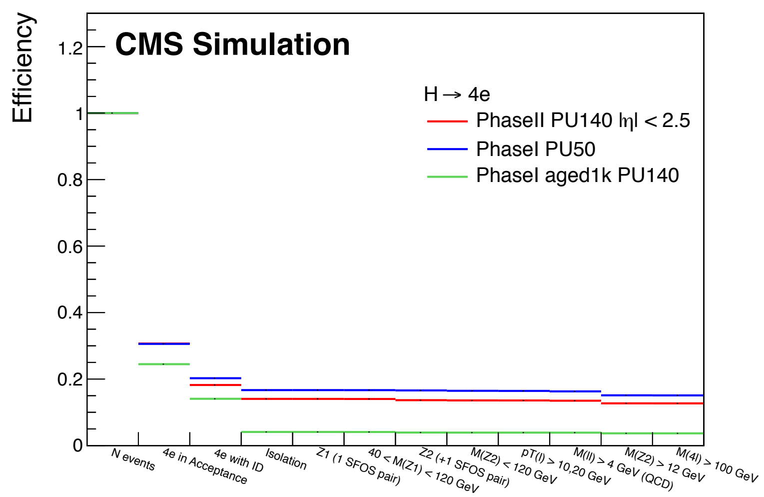


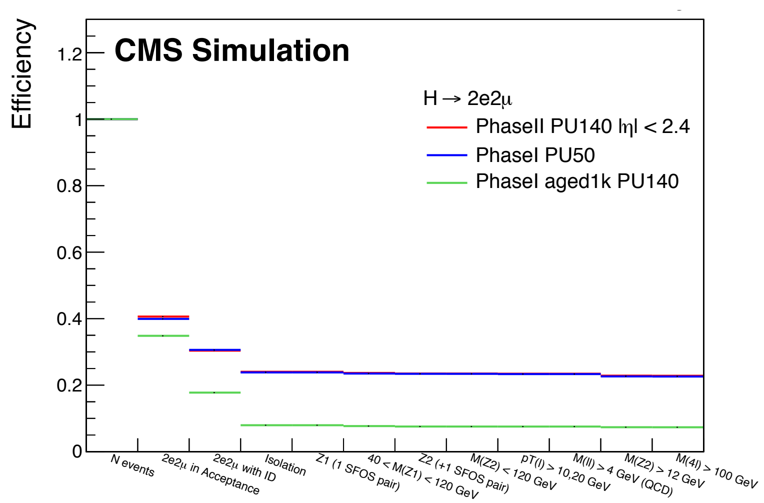






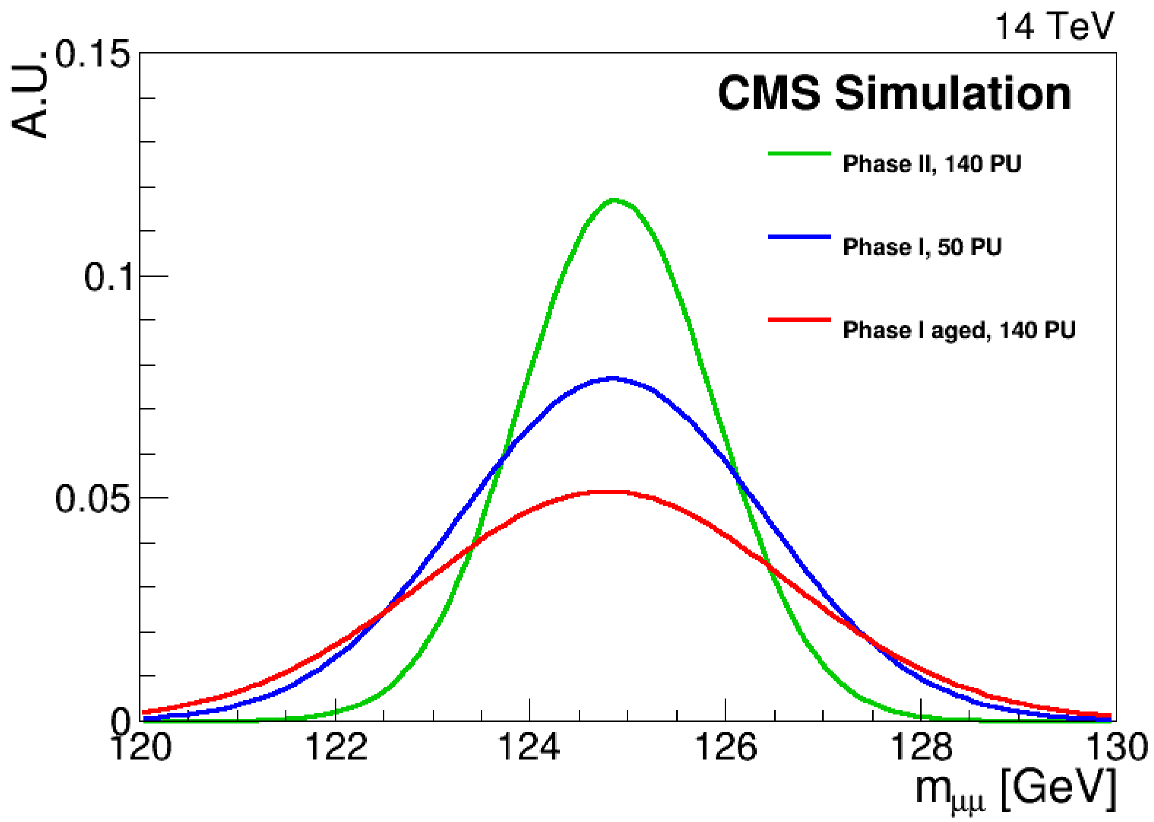




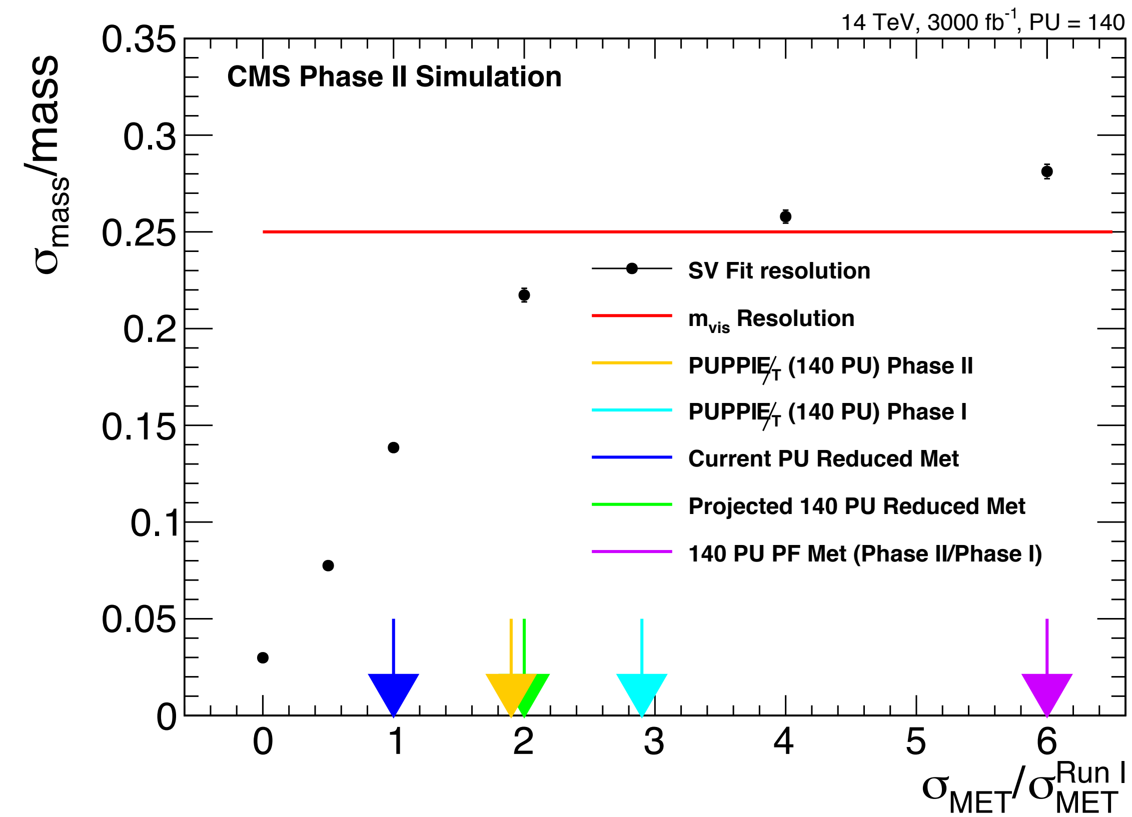


Potential CMS Phase II detector resolution

Di-muon mass spectrum for Phase I, Phase II detector setups:

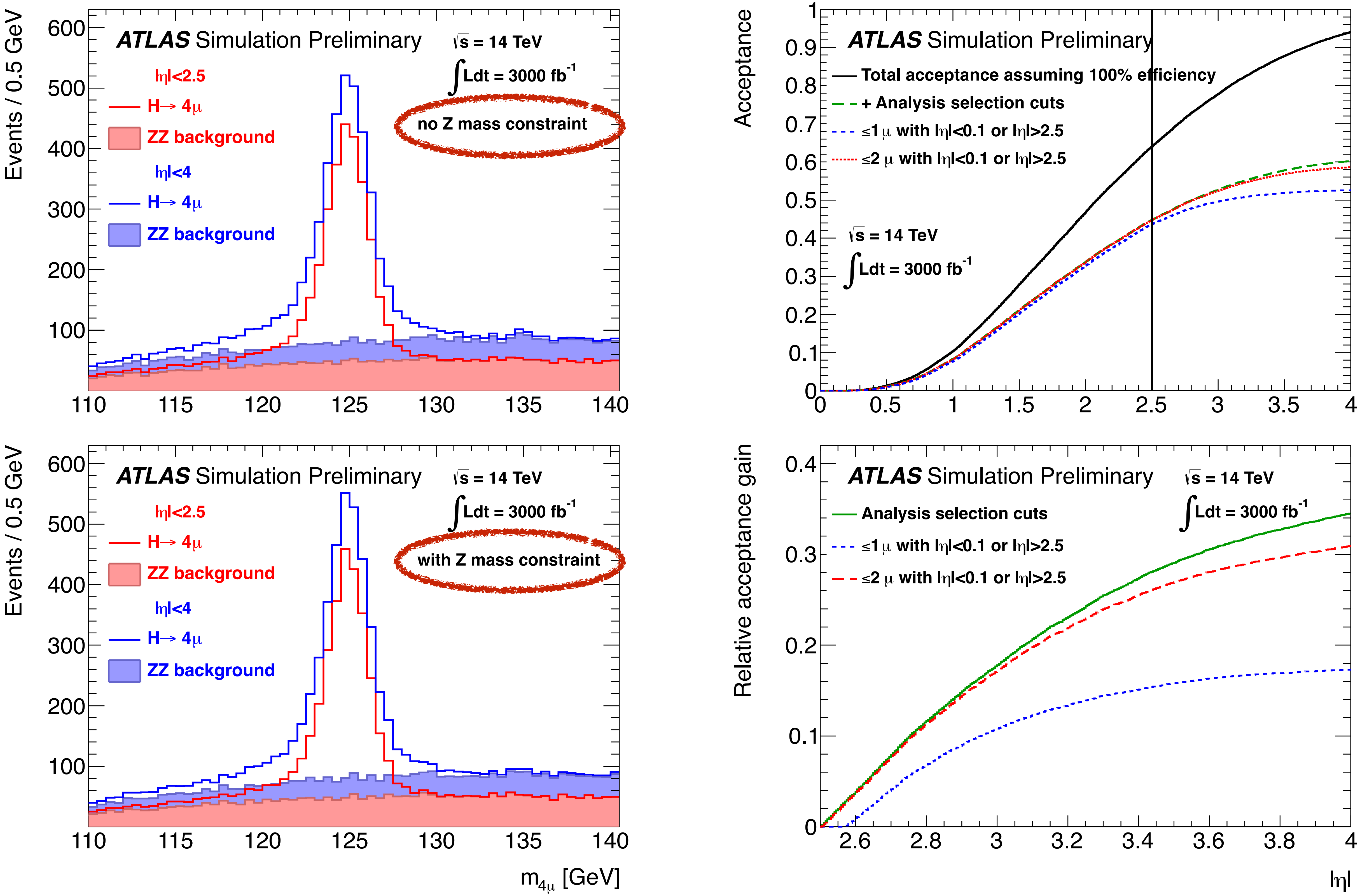


Di-tau mass resolution vs. MET resolution, normalized to Run I performance:



- Due to material reduction and better spatial measurements in Phase-II tracking detector, mass resolution is 40% better
  - Efficiency to reconstruct the muon pair is 20 % larger
- Combination of single, double tau track triggering increases the absolute trigger acceptance by 1.7×
  - Compared to applying Run-I analysis p_T threshold on same $|\eta|$ region

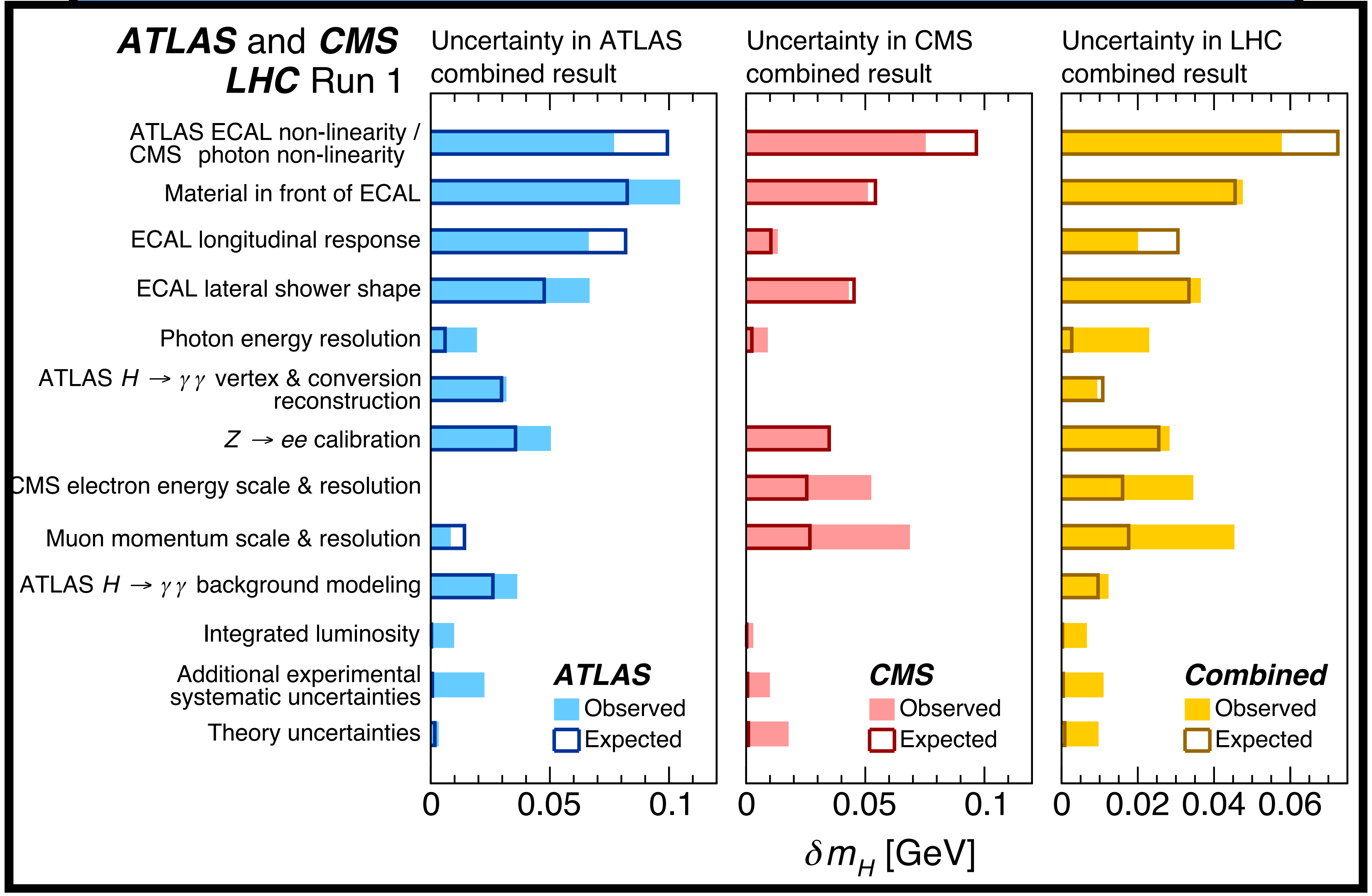
ATLAS m_H resolution with extended tracking



Predicted H → 4μ acceptance, mass distributions at l = 3000 fb^{-1} for **nominal (|η| < 2.5)** and **extended (|η| < 4)** tracking.

Mass combination systematics

Current combined systematic uncertainties:



- Dominant contributions to total mass uncertainty **ECAL-related**
  - **i.e.** Non-linearity, shower shape, material before ECAL
- Also have non-trivial contribution from **Z → ee calibration**
- Theory contributions (PDF, QCD, etc.) yield ~small contribution to inclusive mass uncertainty (δm_H)

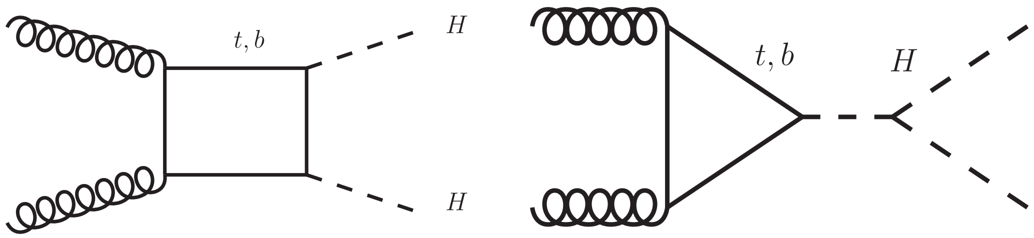
"Back of the envelope" calculation:

Significance of Higgs boson resonance scales approximately as **s/√b**

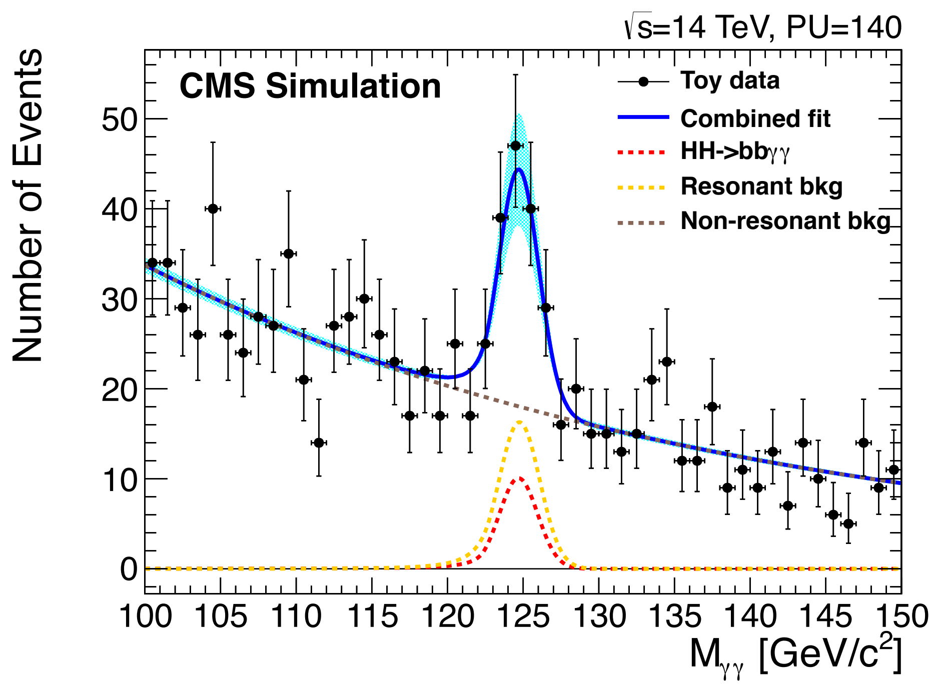
→ Sensitivity scales with **√(int. luminosity)** — expect ~√(3000 fb-1 / 25 fb-1) ≃ 11× improvement in sensitivity, e.g. **δm_H = 0.24 GeV → 0.022 GeV**

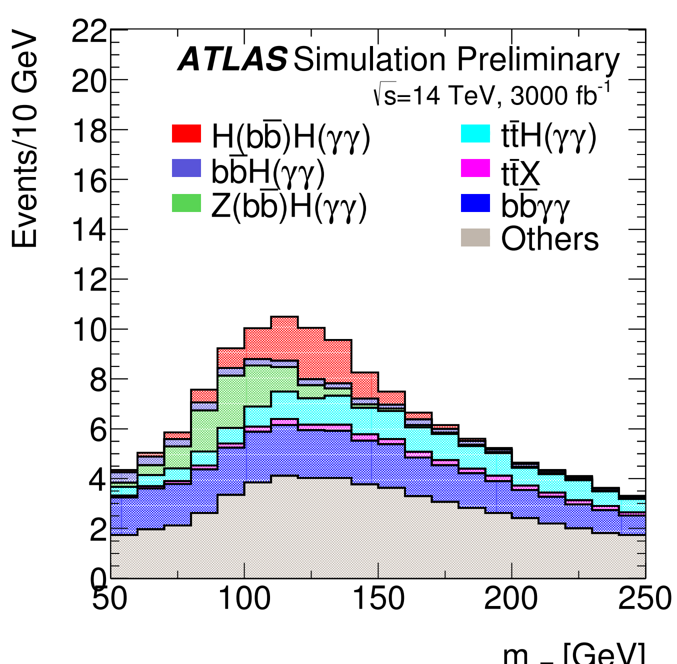
→ Assumes stat. uncertainty dominates, acceptance stays ~the same

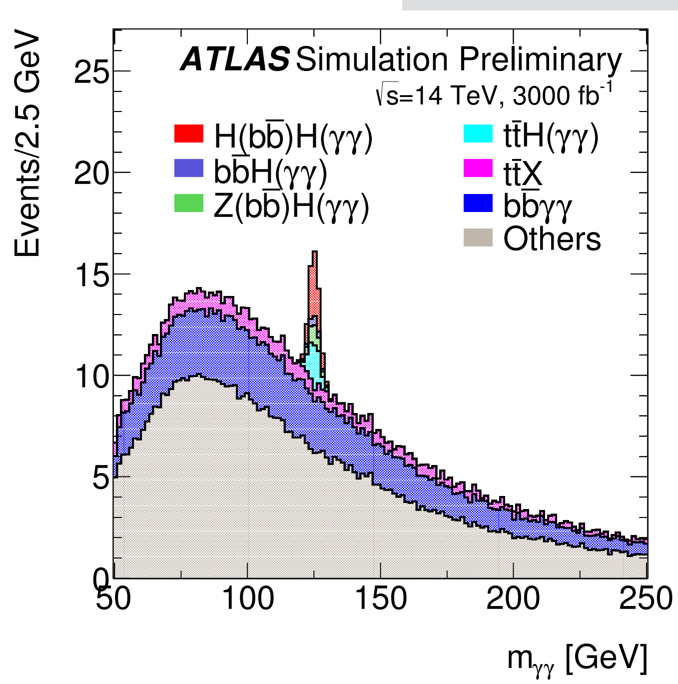
Higgs boson self-coupling measurements

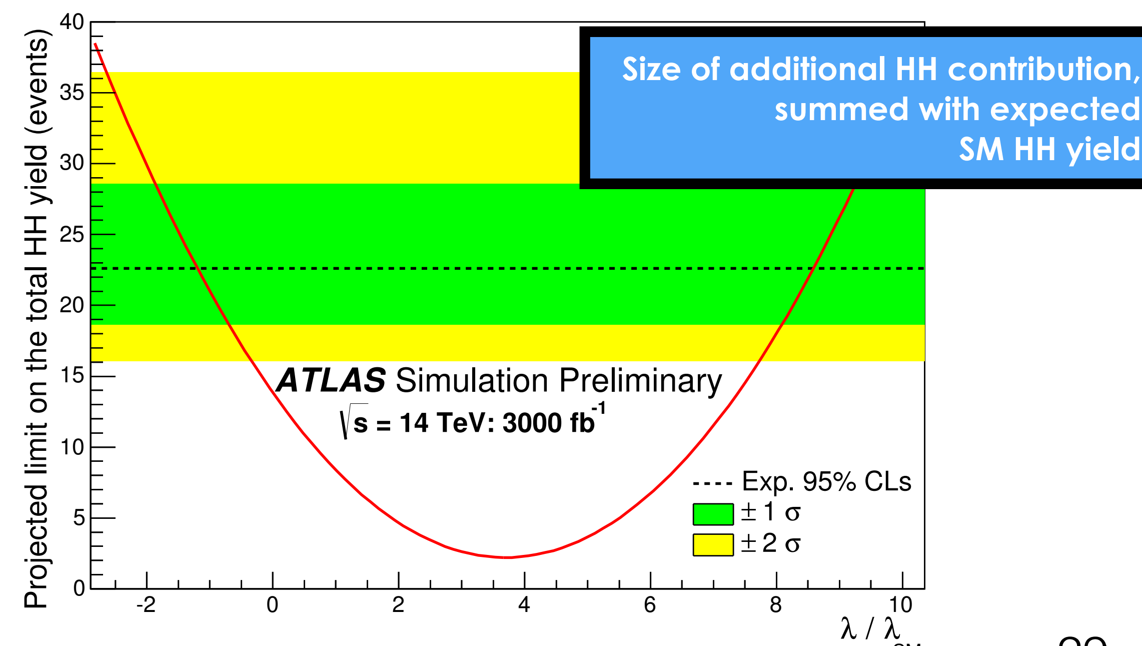


- **Main motivation:** Higgs self-coupling λ_{HHH} determines shape of Higgs potential
  - Also sensitive to BSM effects → modifies HH production rate
- Important decay modes are **bbγγ and bbττ**
  - **Destructive interference** of box, loop diagrams; σ minimized for $\lambda_{HHH} / \lambda_{SM} = 1$
- Only **~320 bbγγ events** will be generated in 3000 fb^{-1}
  - ATLAS, CMS expect signal yield of **~9 bbγγ events**
- CMS predicts **Z_0 ~ 0.9σ, Δμ/μ ~ 105%** from measuring $\tau_\mu\tau_h$ and $\tau_h\tau_h$ final states
  - Final significance will be **1.3-1.9σ**, based on final states measured (bbγγ and/or bbττ)



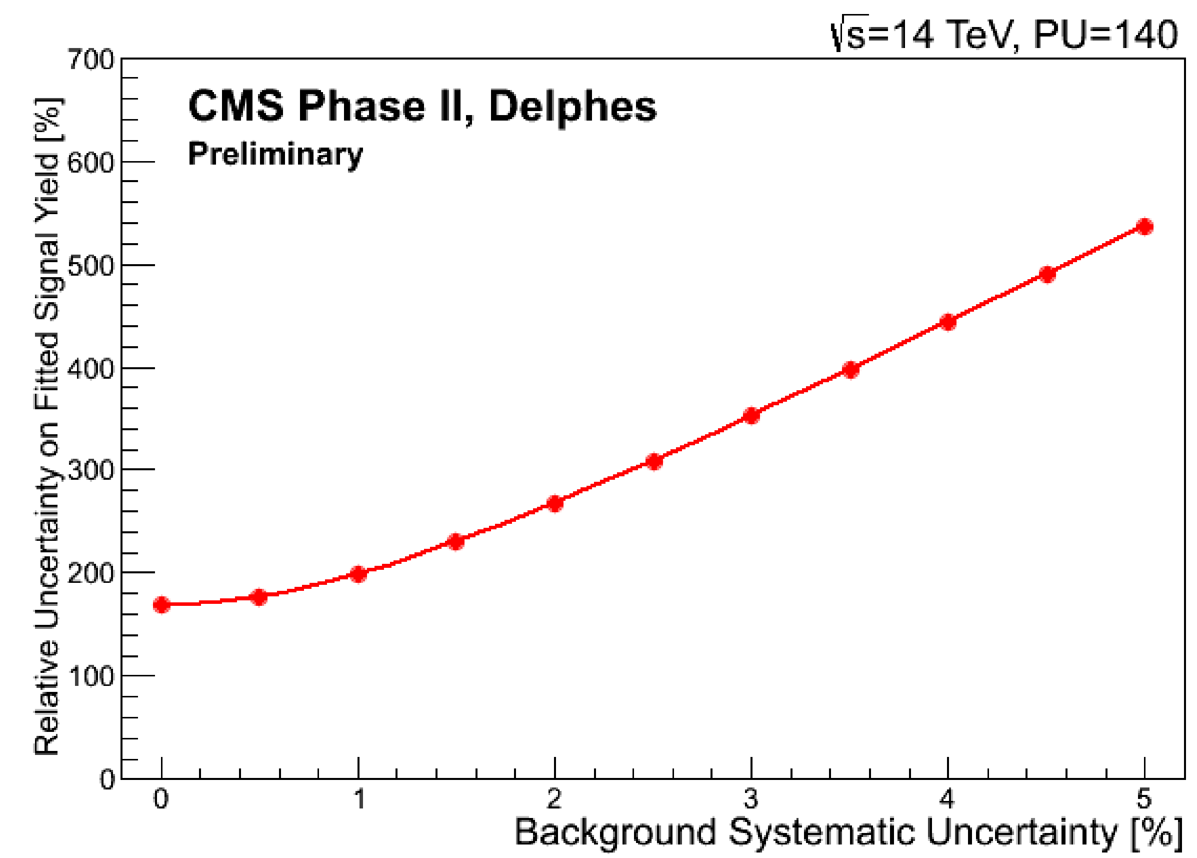






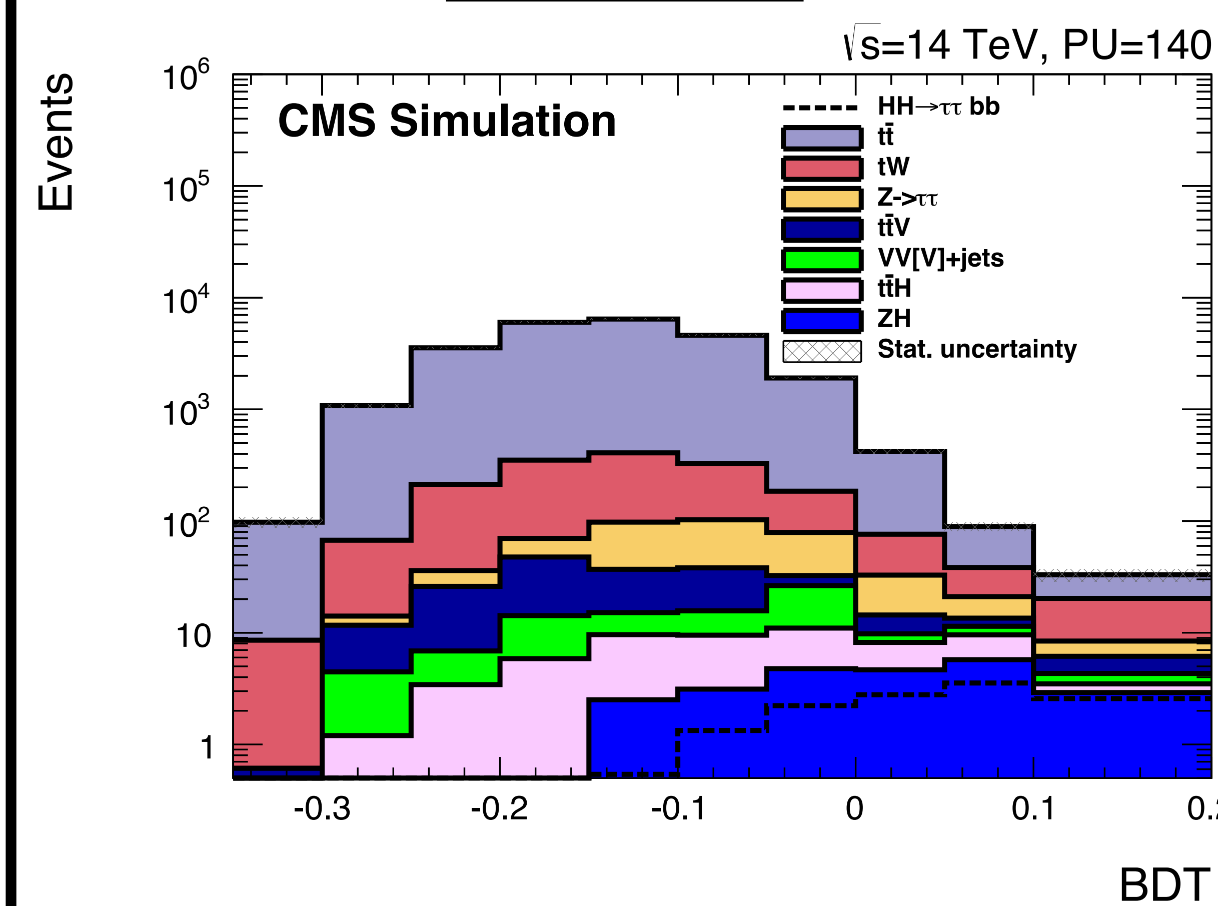
HH → bbWW, bbττ final states

H → bbWW:



- ~1500 fully leptonic signal events expected in 3000 fb^{-1}, where the leptons are either muons or electrons
  - Dominant background process is the tt production, fully leptonic decay
- Events require required two b-tagged jets with p_T > 30 GeV, two opposite-sign leptons with muon p_T > 20 GeV, electron p_T > 25 GeV
  - Neural network also trained to separate signal, background

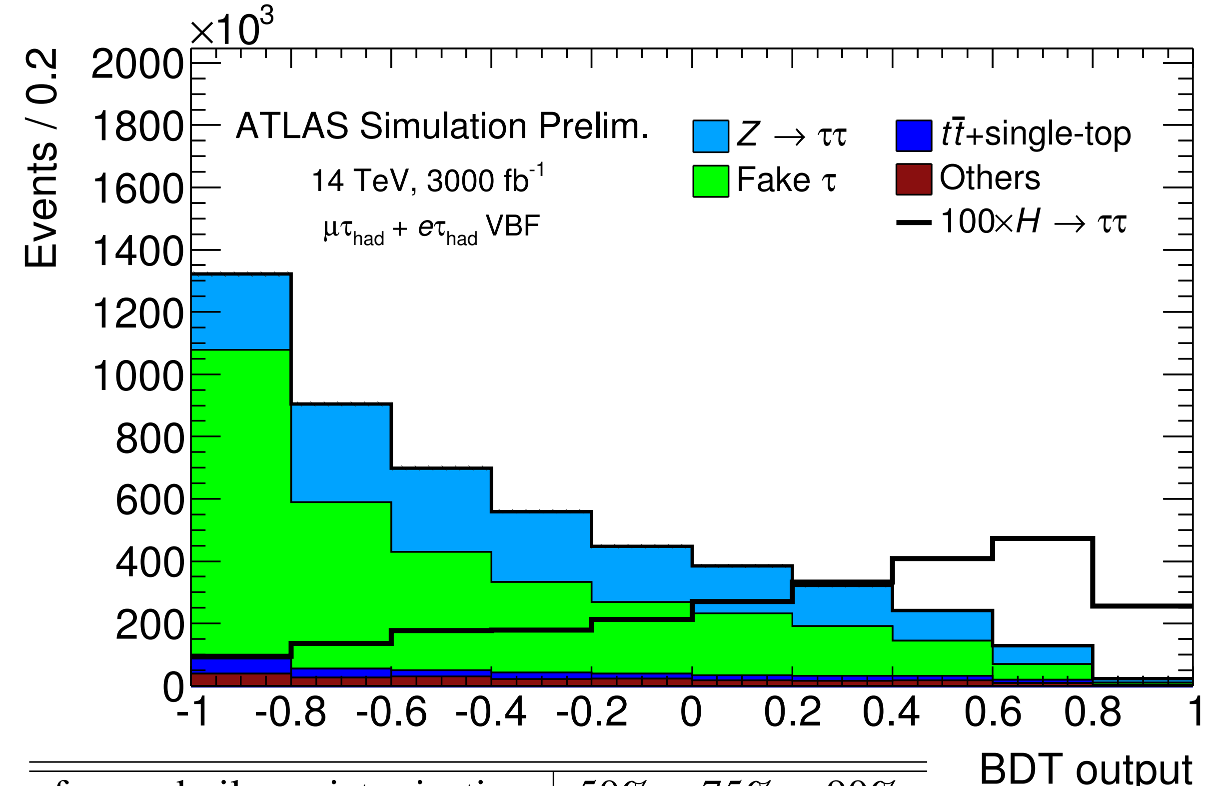
H → bbττ:



- ~9000 bbττ di-Higgs events expected in 3000 fb-1
  - $\tau_\mu\tau_h$, $\tau_h\tau_h$ final states studied by CMS
- Likelihood-based mass reconstruction technique (SVFIT) is used to reconstruct $m_{\tau\tau}$
- BDT discriminant trained to exploit boosted kinematics of HH
- **Z_0 = 0.5σ** for μh, **0.7σ** for hh, **0.9σ** for combination, overall **Δμ / μ ~ 105%**

$H \rightarrow \tau_l\tau_{had}$ analysis details

- BDT trained to separate **$H \rightarrow \tau_l\tau_{had}$ signal** from backgrounds (see variables below)
  - Only **VBF production** targeted
- Lepton, τ reconstruction, identification efficiencies assumed **equivalent to 2012** data
- Require isolated leptons with p_T > 26 GeV, τ candidate p_T > 20 GeV, jet p_T > 30 GeV
  - Require **$m_T(l, E_T^{Miss})$ < 100 GeV** due to degradation of E_T^{Miss} at high <μ>
- **"Missing mass calculator"** used to estimate **$m_{\tau\tau}$**



forward pile-up jet rejection	50%	75%	90%
forward tracker coverage	Δμ		
Run-I tracking volume	0.24		
$\|\eta\| < 3.0$	0.18	0.15	0.14
$\|\eta\| < 3.5$	0.18	0.13	0.11
$\|\eta\| < 4.0$	0.16	0.12	0.08

43% smaller

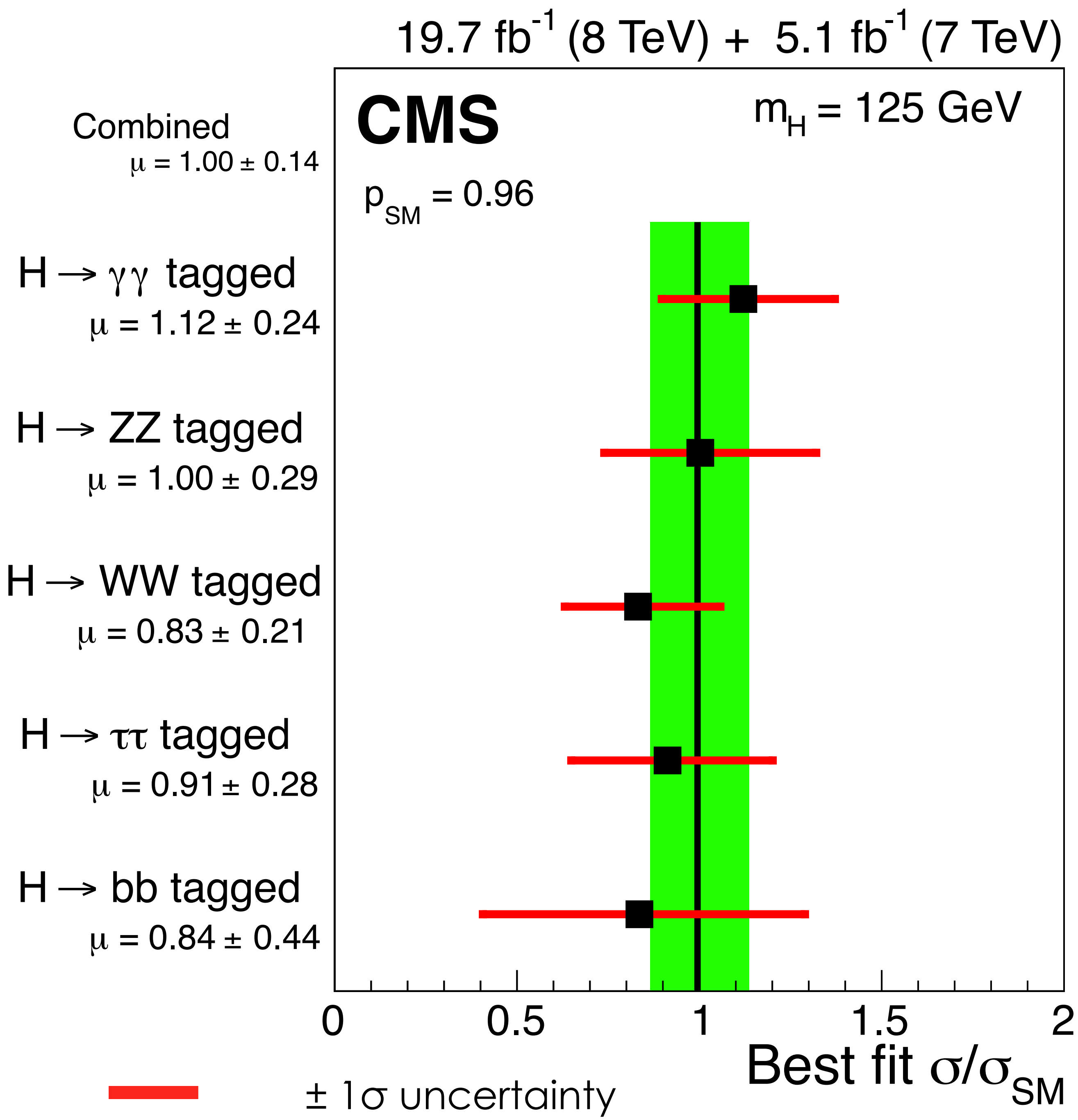
Impact of forward tracking:

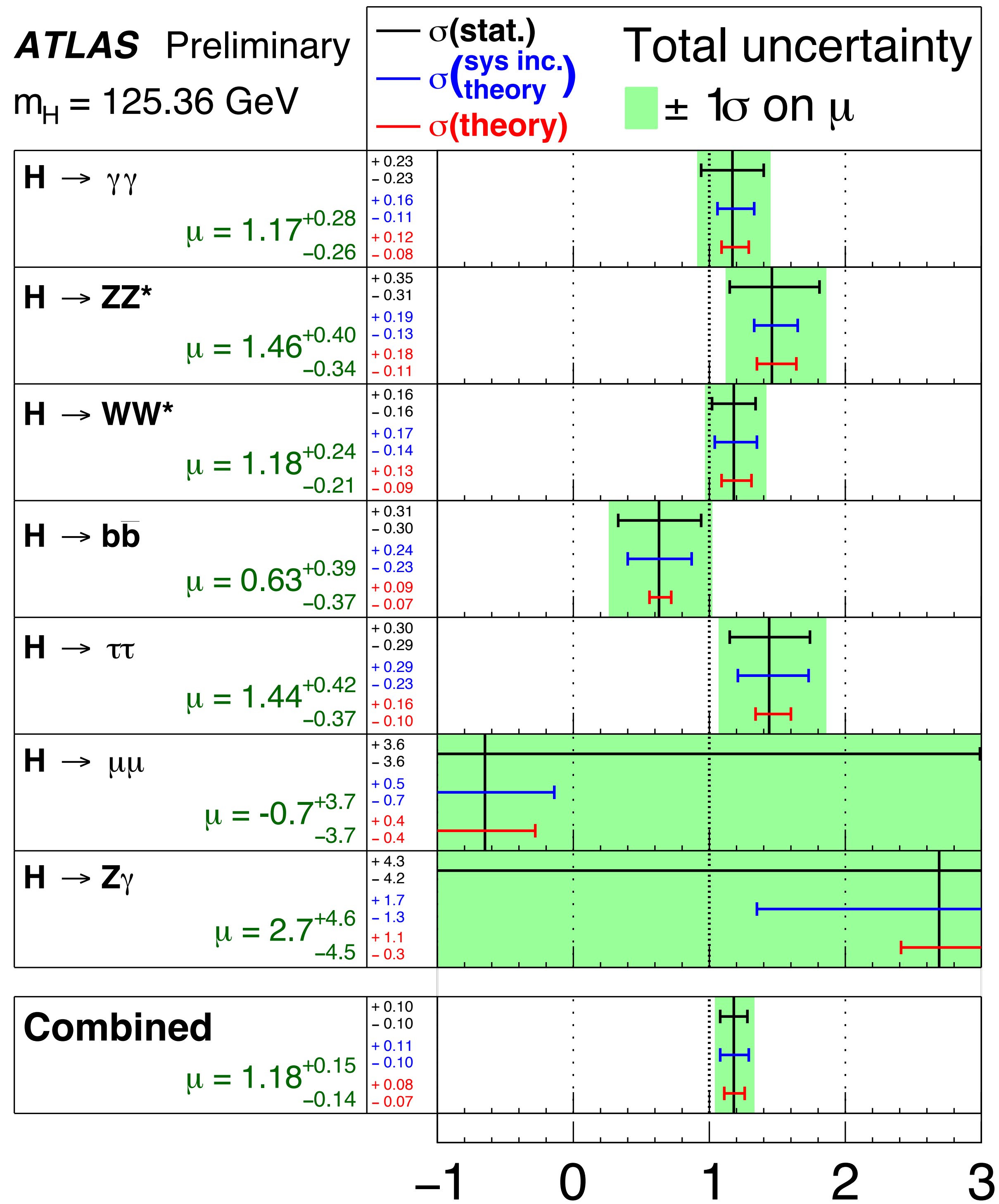
- Tested effects of pileup rejection (50%, 75%, 90% efficiency) for three tracking scenarios: |η| < [3, 3.5, 4]
  - Simulated pile-up jet multiplicity at μ = 140, jet p_T ≥ 30 GeV — rate is ~2.4 extra jets/event
  - Analysis is re-run with **forward pile-up jet** insertion, rejection imposed by hand
- Observe **~43% decrease** in expected Δμ/μ by extending tracking volume (hence PU rejection)

BDT training variables:

Variable	Definition
$\Delta R(\tau, \ell)$	Separation of the lepton and τ_{had}
m_T	Transverse mass of the lepton and E_T^{miss}
E_T^{miss} ϕ-centrality	Centrality of the E_T^{miss} between the lepton and τ_{had}
MMC mass	$\tau\tau$ mass estimator
$m_{j1,j2}$	Invariant mass of the 2 leading jets
$\eta_{j1} \times \eta_{j2}$	Product of the ηs of the two leading jets
$\|\eta_{j1} - \eta_{j2}\|$	Absolute difference ηs of the two leading jets
ℓ η-centrality	Centrality of the lepton between the two leading jets
p_T^{Total}	$\|\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\tau_h} + \vec{p}_T^{\,j1} + \vec{p}_T^{\,j2} + \vec{E}_T^{miss}\|$

Most recent signal strength measurements





ATLAS couplings for narrow-width approximation

ATLAS couplings:

	$\Delta\kappa/\kappa$ (%)	
Coupling	300 fb^{-1}	3000 fb^{-1}
κ_Z	8.1	4.4
κ_W	9.0	5.1
κ_t	22	11
κ_b	23	12
κ_τ	14	9.7
κ_μ	21	7.5
κ_g	14	9.1
κ_γ	9.3	4.9

(includes full theory uncertainties)