Search for Non-Standard Model Behavior, including CP Violation, in Higgs production and decay to *ZZ**

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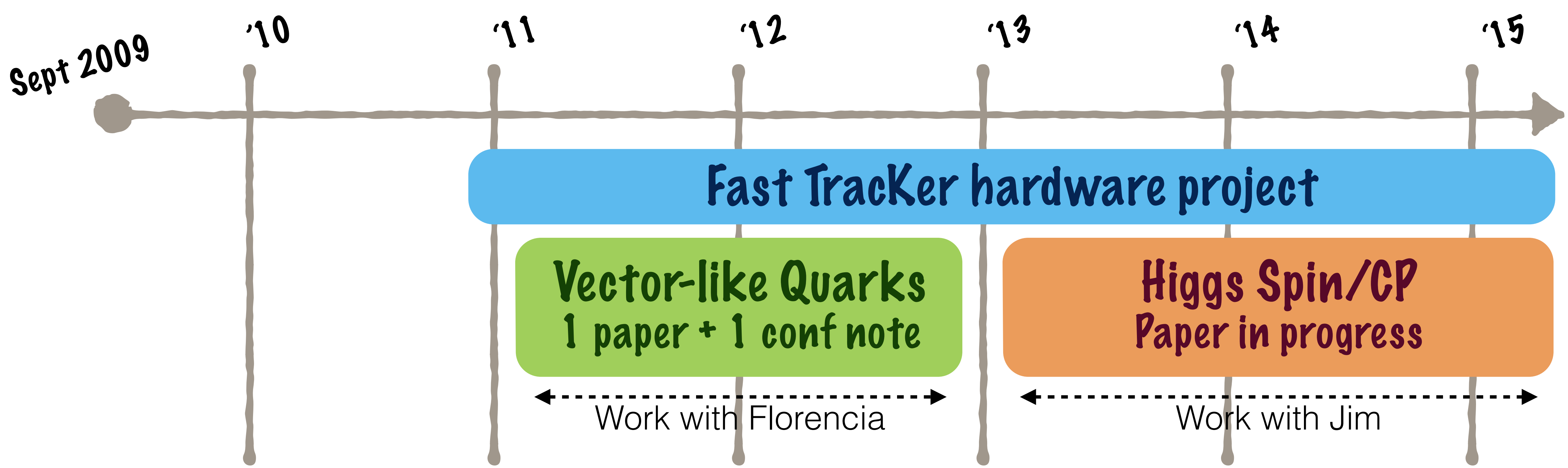
2015.05.27

Outline

* LHC and ATLAS
* The Standard Model
* Higgs spin & CP
* $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis
* Results

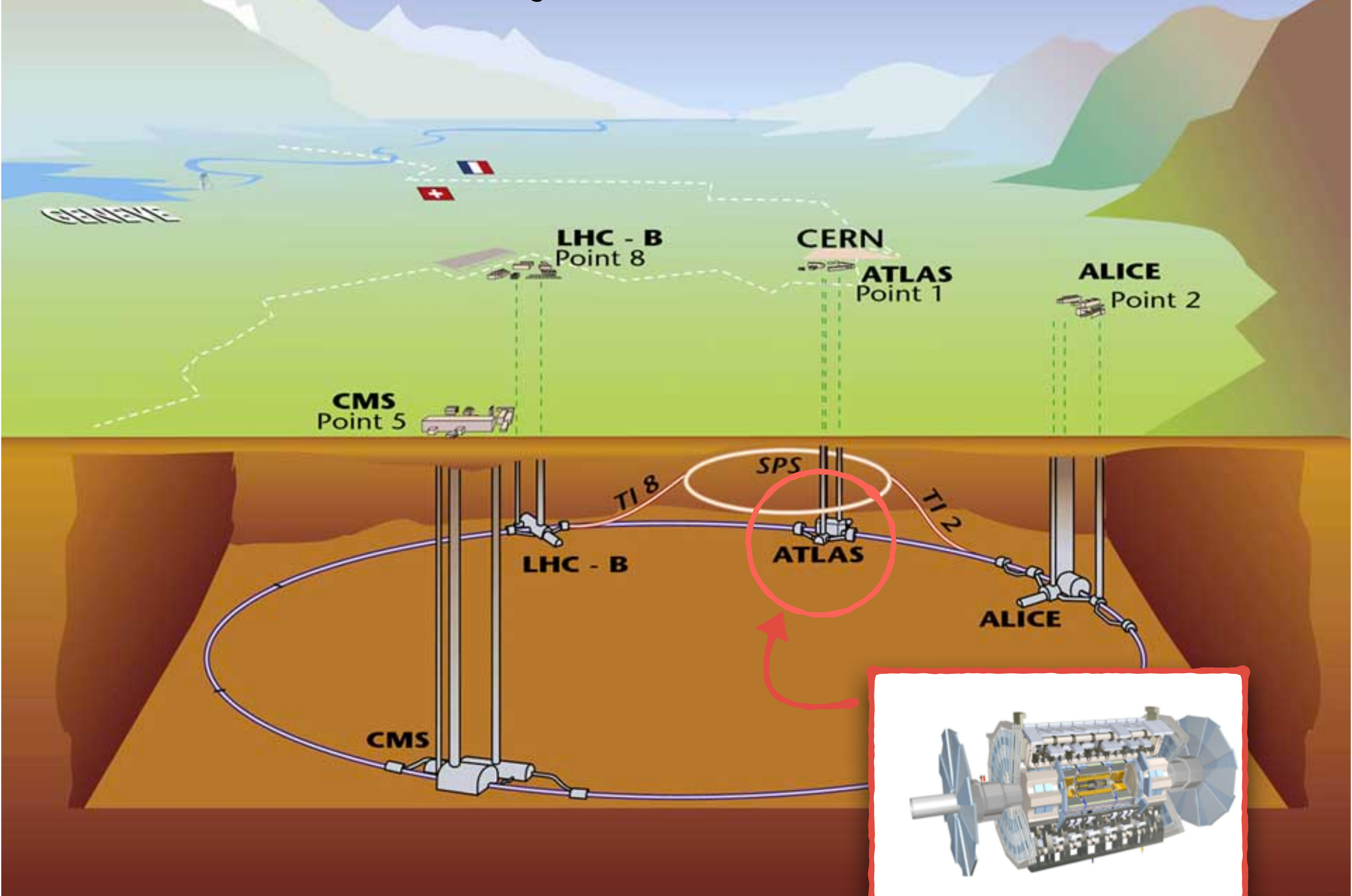
Special thanks to…

- Jim, Jeff Dandoy, and Eric Feng, who have all worked closely with me on my thesis analysis
- Mel for advising me on hardware projects
- Woowon and Marcela for being active committee members

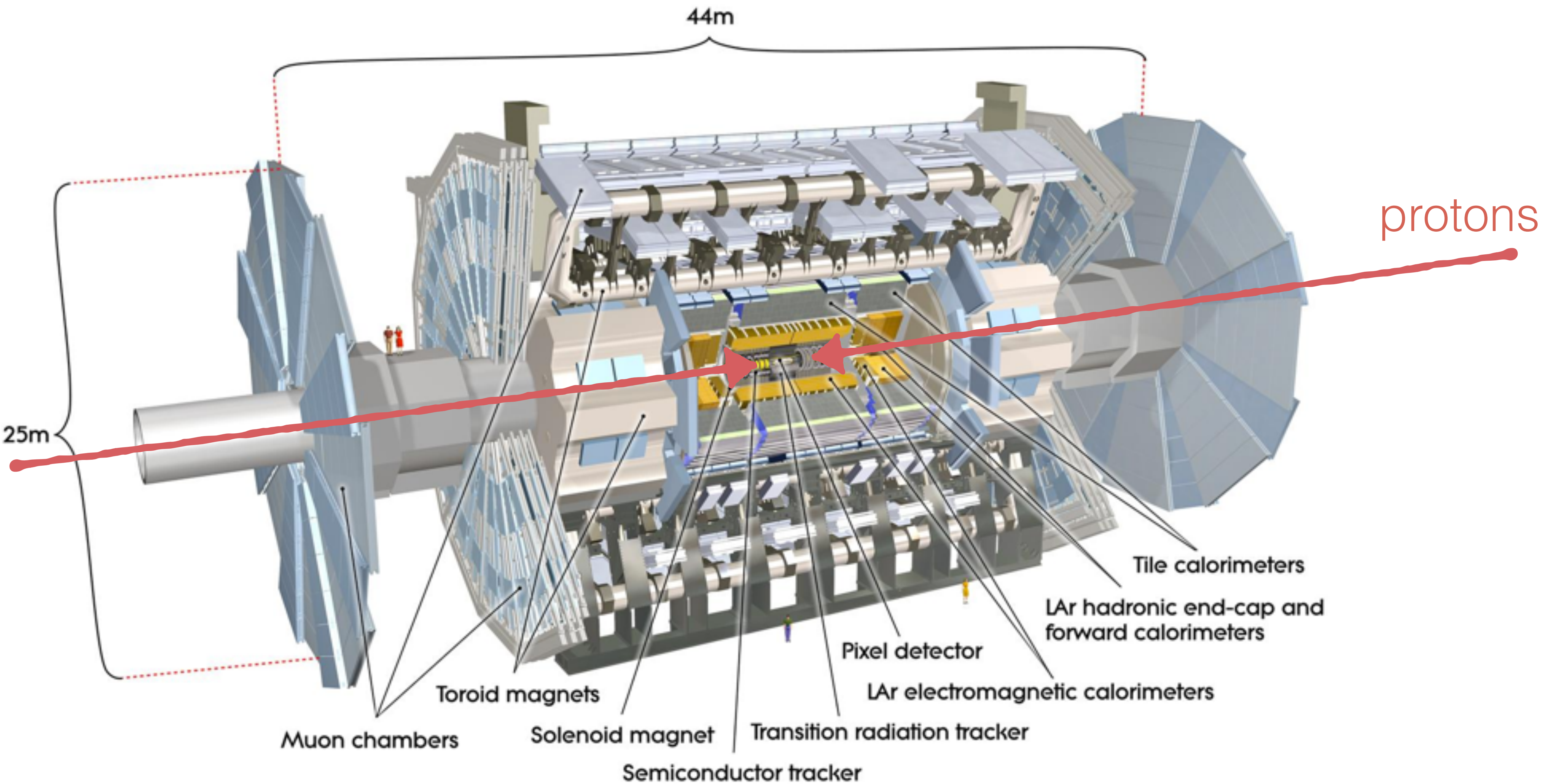


Time working on Ph.D. ~6 years

Large Hadron Collider



ATLAS: A Toriodal LHC ApparatuS



* Multi-layer detector with trackers, calorimeters & muon chambers
* For reconstructing electrons, muons, photons, and jets from quark hadronization

The Standard Model (SM) and the Higgs

* Simple & accurate description of elementary particles and their interactions
* Consistent theory of strong, weak & electromagnetic forces
* Gauge theory: SU(3)⊗SU(2)⊗U(1)
    * Implies massless matter particles and gauge bosons

Matter particles:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Gauge bosons:

$$g \qquad W \qquad Z \qquad \gamma$$

* "Spontaneous symmetry breaking" allows for massive fermions & weak bosons, and predicts additional Higgs boson

The Higgs Discovery

July, 2012: Higgs-like boson observed in γγ, ZZ*, and WW* events by both ATLAS and CMS collaborations

2013 Nobel to Higgs & Englert

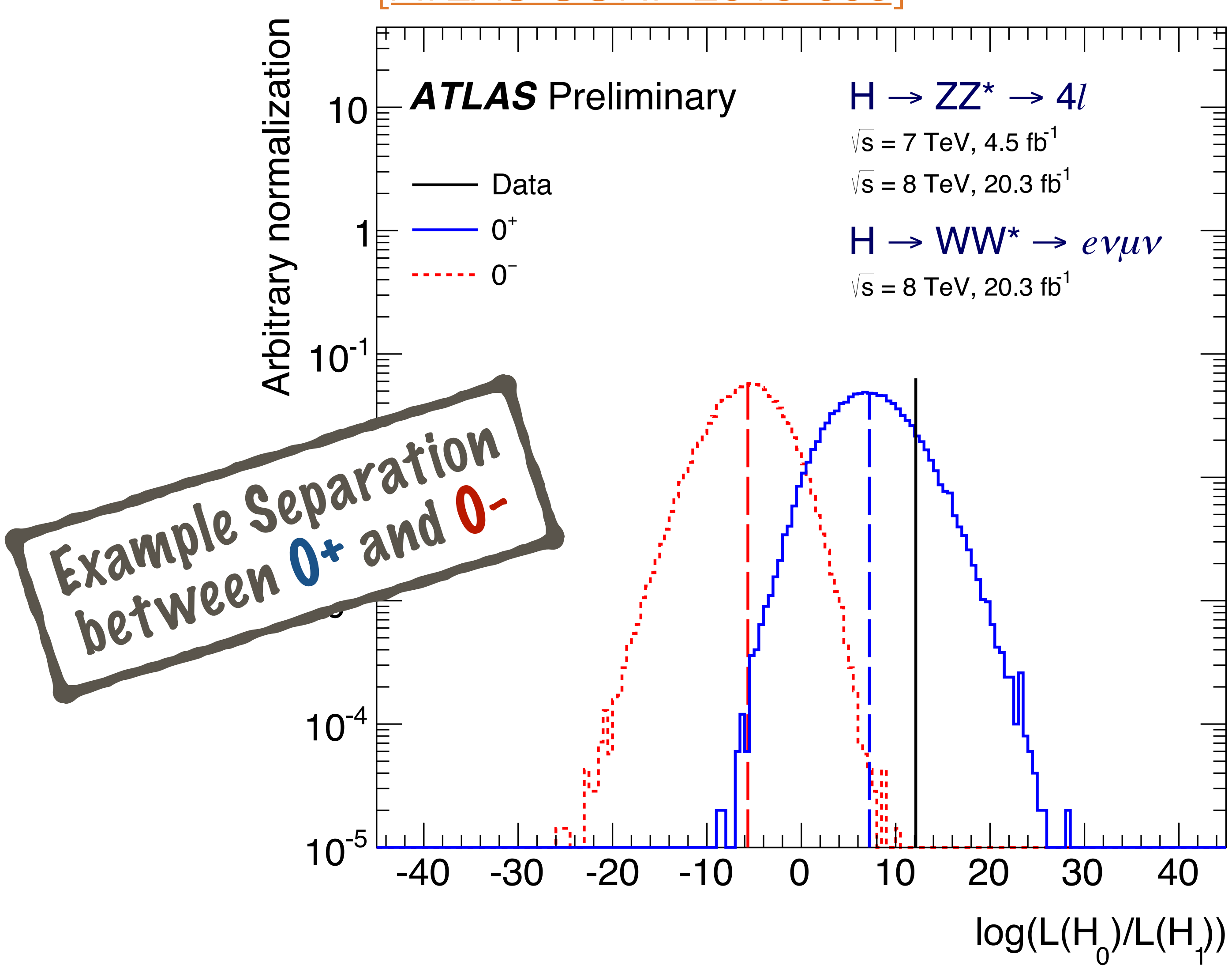
excited reactions at CERN

* All particles in the SM have now been observed, but questions remain:
    * Dark matter, Matter-antimatter asymmetry, Neutrino mass / oscillations, hierarchy problem
* Motivation to make precise measurements of the Higgs to expose any signs of possible new physics beyond the SM

Higgs boson spin/CP

- SM Higgs is CP-even scalar, 0^+
- Final state observables can be used to test this hypothesis against other discrete eigenstates, e.g. CP-odd (0^-), CP-even with BSM couplings to higher dimensional operators (0^+_h), graviton-like 2^+
- ATLAS combination of $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*\rightarrow 4\ell$, $H\rightarrow WW^*\rightarrow e\nu\mu\nu$

[ATLAS-CONF-2015-008]



0- Excluded at >99.97% CL

Higgs boson spin/CP

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- ATLAS combination of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

Tested Hypothesis	Exclusion confidence level, tested against 0^+
0^-	> 99.97%
0^+_h	99.95%
2^+, $\kappa_q/\kappa_g=0$	> 99.99%
2^+, $\kappa_q/\kappa_g=1$	99.99%
2^+, $\kappa_q/\kappa_g=2$	> 99.99%

- For the 2^+ model there are no constraints on the quark and gluon couplings so exclusions are calculated for $\kappa_q/\kappa_g = 0, 1, 2$

CP Mixing

- Also possible to have a mixture of CP eigenstates
  - CP violation in the Higgs sector, exists in Two-Higgs Doublet Models

- Characterized by couplings in a tree level scattering amplitude for a generic scalar *X*:

$$A(X \to VV) = v^{-1}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* - g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

[arXiv:1208.4018]

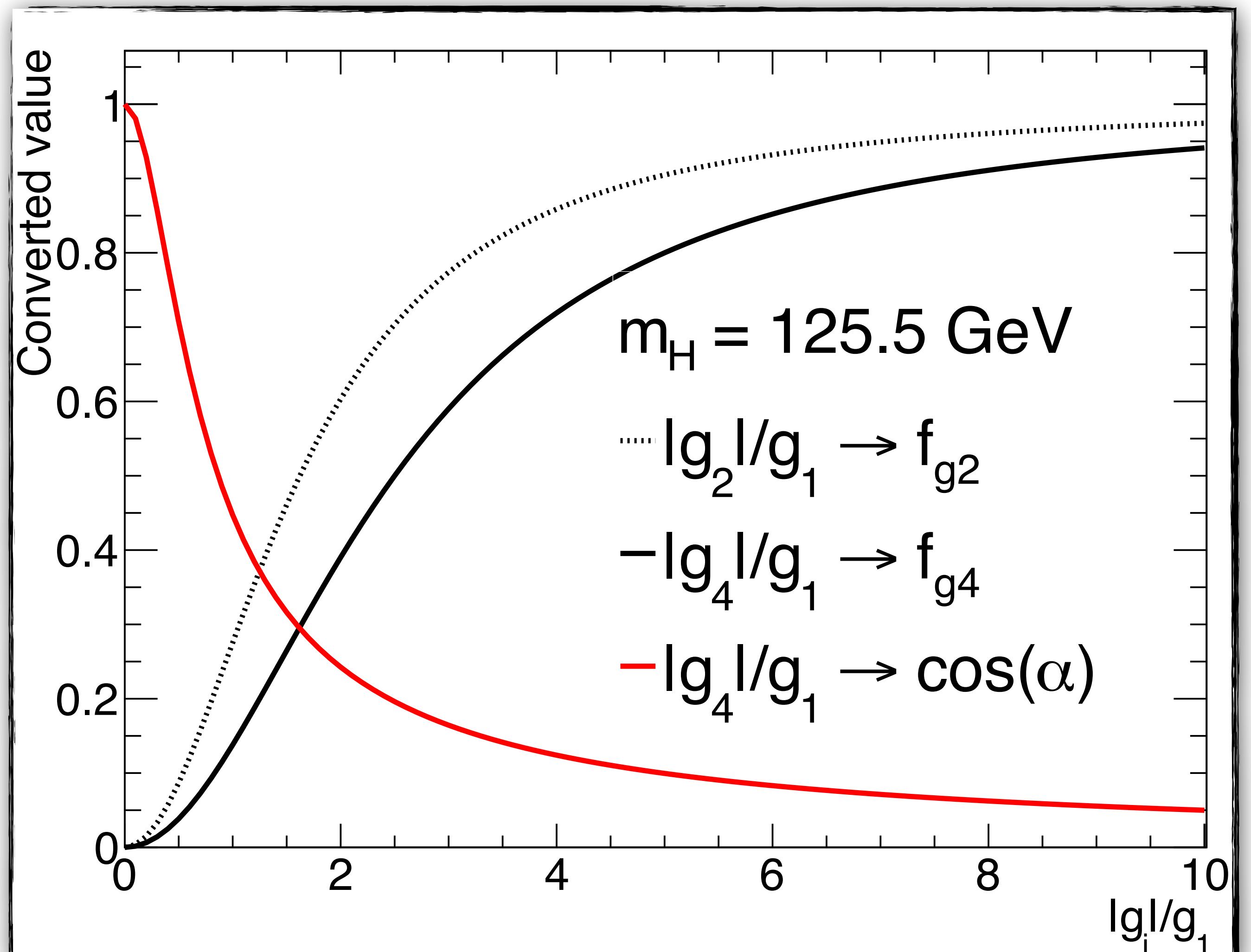
SM Higgs — BSM CP-even contribution — BSM CP-odd contribution

- $g_{1,2,4}$ are complex numbers that specify the CP mixture
  - $0^+ \to g_1=1,\ g_{2,4}\approx 0$
  - $0^- \to g_4=1,\ g_{1,2}\approx 0$

- Can measure directly using final state observables in Higgs decays

CP Mixing

* $g_{1,2,4}$ are easily mapped to couplings + mixing angle α in an effective Lagrangian, or admixtures f_{g2} and f_{g4}



σ_i := x-sec when g_i=1, g_{others}=0

$$f_{gi} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}$$

* Effective Lagrangian conversion (notation from my abstract/thesis):

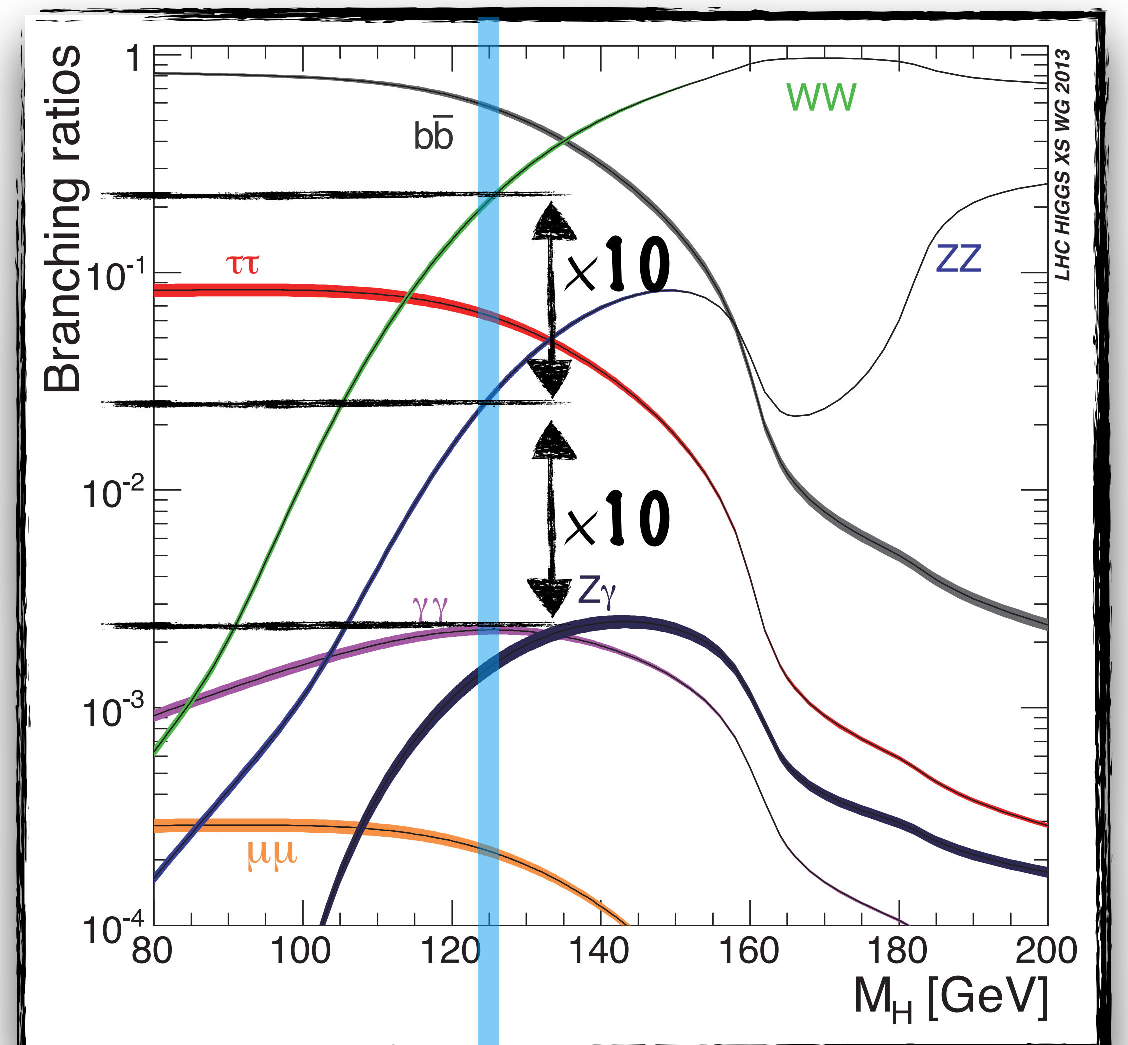
$$g_4/g_1 = (\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha, \quad g_2/g_1 = \tilde{\kappa}_{HVV}/\kappa_{SM}$$

BSM CP-odd coupling

BSM CP-even coupling

H→ZZ*→4ℓ final state

- Considered "golden channel" for the Higgs because of extremely low background and because leptons can be precisely measured
- Con: Low total yield



Diboson production:

- BR(H→ZZ*) ≈ **2.8%**
  - ~10x lower than H→WW*
  - ~10x higher than H→γγ

$H \to ZZ^* \to 4\ell$ final state

- Considered "golden channel" for the Higgs because of extremely low background and because leptons can be precisely measured
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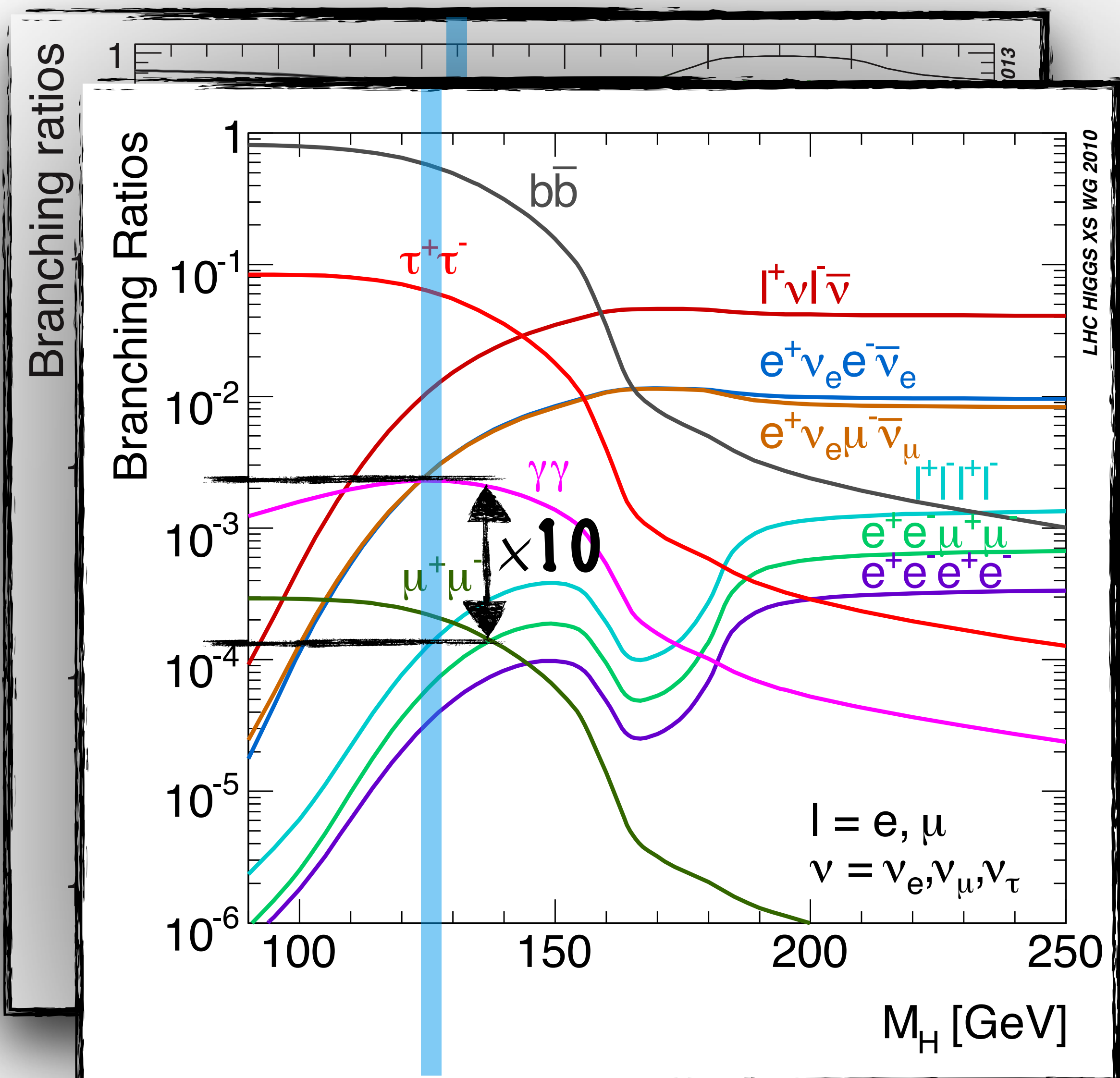


Diboson production:

- $BR(H \to ZZ^*) \approx$ **2.8%**
  - ~10x lower than $H \to WW^*$
  - ~10x higher than $H \to \gamma\gamma$

Diboson decay:

- $BR(H \to ZZ^* \to 4\ell) \approx$ **1.3×10^{-4}**
  - ~10x lower than $H \to \gamma\gamma$ and $H \to WW^* \to e\nu\mu\nu$
- Low reconstruction efficiency

  ~ (lepton reconstruction eff)^4

$H \to ZZ^* \to 4\ell$ observables

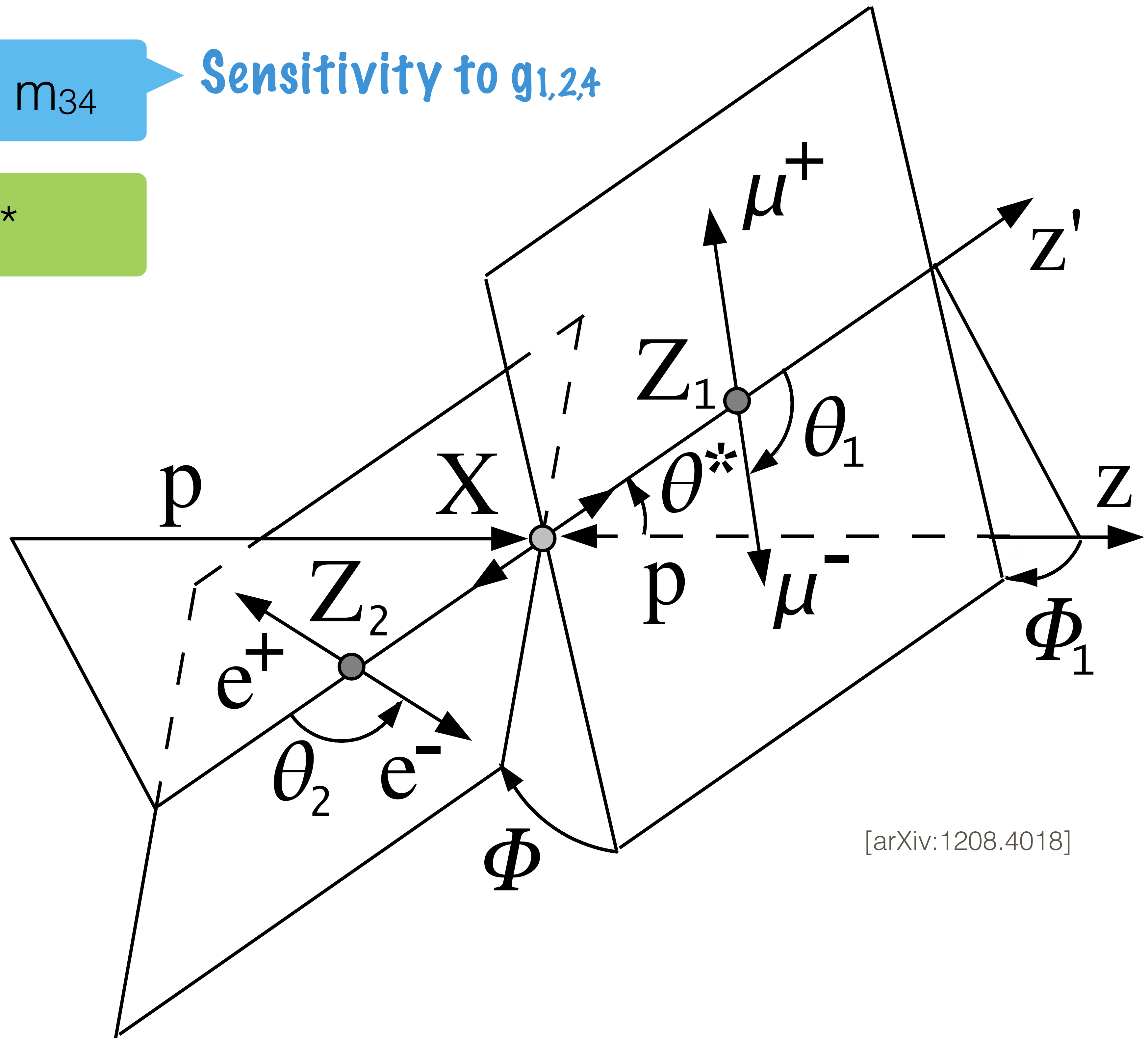
Lots of useful observables with 4 leptons in final state…

$\cos\theta_1$, $\cos\theta_2$, Φ, m_{12}, m_{34}

Sensitivity to $g_{1,2,4}$

m_{4l}, $p_{T,4l}$, η_{4l}, $\cos\theta^*$

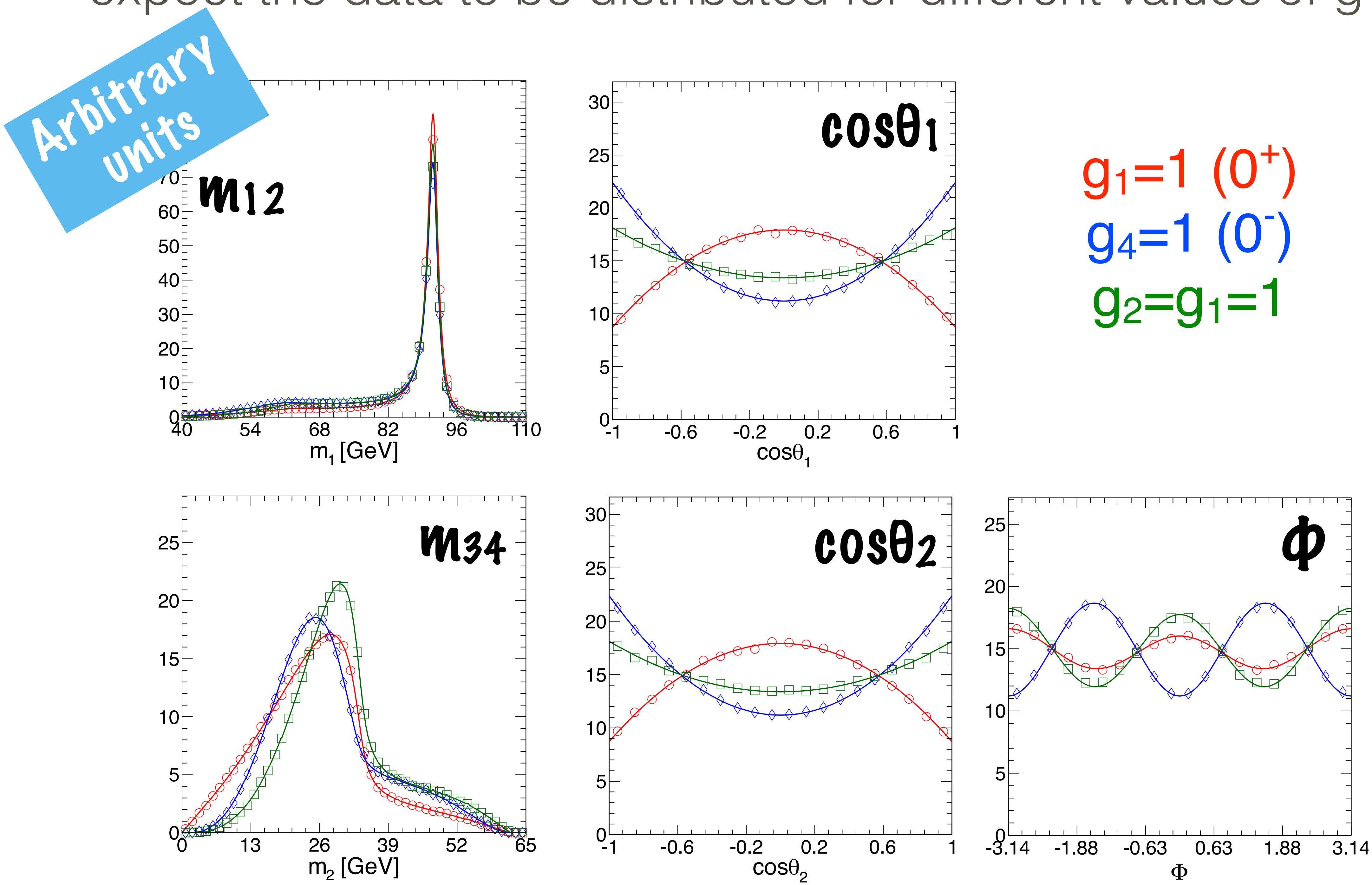
Background separation



[arXiv:1208.4018]

Signal distributions at parton-level

The scattering amplitude can be used to calculate an analytical matrix-element $\mathscr{M}(\cos\theta_1, \cos\theta_2, \Phi, m_{12}, m_{34} \mid g_{1,2,4})$ that tells us how to expect the data to be distributed for different values of $g_{1,2,4}$



[arXiv:1208.4018]

J. Webster

Simulated data for the measurement

ZZ Background: MC

Reducible backgrounds: Z+jets, ttbar, WZ
Mix of MC and data-driven methods

Signal:

- Production in PowHeg @ NLO; decay with JHU generator at LO
- We need simulated signal for many different CP-mixtures
- Save computer time by using the matrix-element to reweight a single MC sample to any target CP-mixture
- Each event is weighted separately based on the truth-level observables $\vec{x}=(\cos\theta_1, \cos\theta_2, \Phi, m_1, m_2)$

$$w_i = \frac{|\mathcal{M}(\vec{x}_i|\text{target } g_{1,2,4})|^2}{|\mathcal{M}(\vec{x}_i|\text{source } g_{1,2,4})|^2}$$

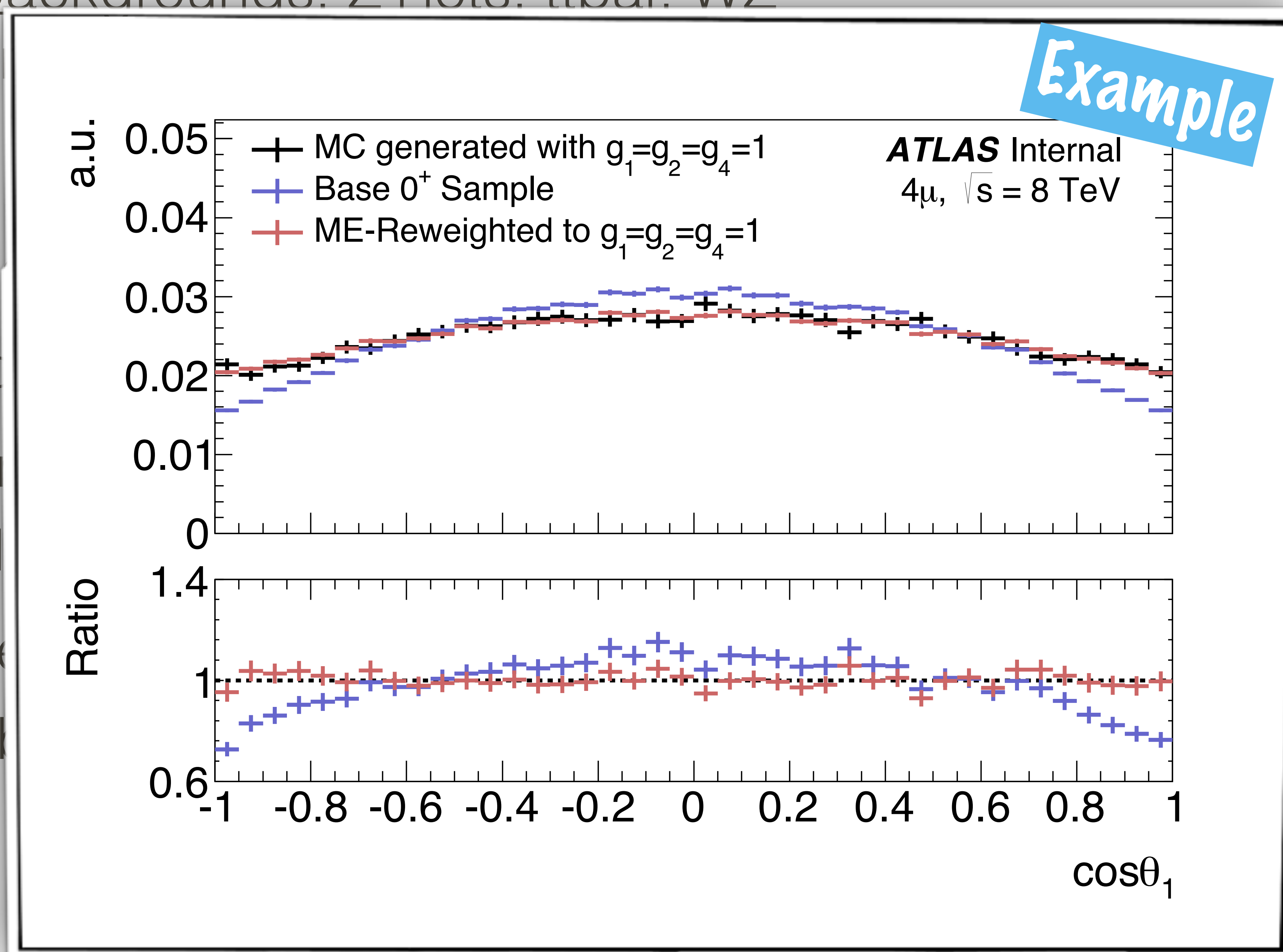
Simulated data for the measurement

ZZ Background: MC

Reducible backgrounds: Z+jets, ttbar, WZ
Mix of MC a

Signal:

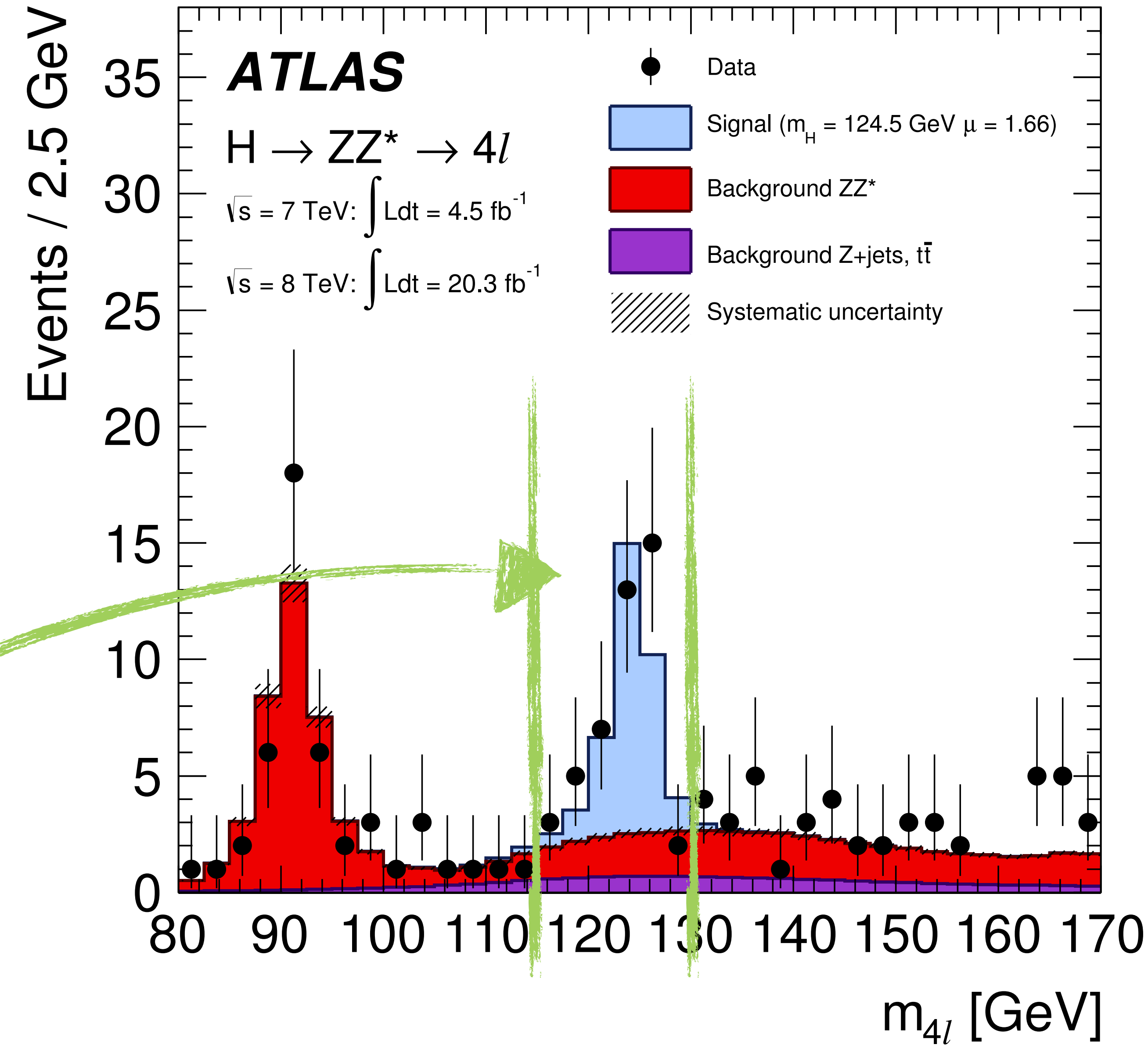
- Producti … at LO
- We need
- Save co … ht a single M
- Each eve … l observa



$$|\mathcal{M}(x_i|\text{source } g_{1,2,4})|^2$$

(Approximate) Event selection

- Single + di-lepton triggers
- Electrons:
  - $E_T > 7$ GeV
  - $|\eta| < 2.47$
- Muons:
  - $p_T > 6$ GeV
  - $|\eta| < 2.7$
- Require 4 separated leptons with $\Delta R=\sqrt{[\Delta\phi^2+\Delta\eta^2]}>0.1$, 2 OSSF pair
- $50 < m_{12} < 106$ GeV
- $12 < m_{34} < 65$ GeV
- $115 < m_{4\ell} < 130$ GeV (retains 95% of signal)



- Events divided into 4 final states: 4μ, 2e2μ, 2μ2e, 4e

Event Yields

Dataset: 20.3 fb^{-1} @ 8 TeV, 4.7 fb^{-1} @ 7 TeV

Final State	Signal	ZZ^*	Reducible Bkg	Total Expected	Observed
$\sqrt{s} = 8$ TeV					
4μ	5.81	3.36	0.97	10.14	13
$2e2\mu$	3.72	2.33	0.84	6.89	9
$2\mu2e$	3.00	1.59	0.52	5.11	8
$4e$	2.91	1.44	0.52	4.87	7
Combined	15.44	8.72	2.85	27.01	37
$\sqrt{s} = 7$ TeV					
4μ	1.02	0.65	0.14	1.81	3
$2e2\mu$	0.64	0.45	0.13	1.22	2
$2\mu2e$	0.47	0.29	0.53	1.29	1
$4e$	0.45	0.26	0.59	1.30	2
Combined	2.58	1.65	1.39	5.62	8

Events passing selection in data = 45

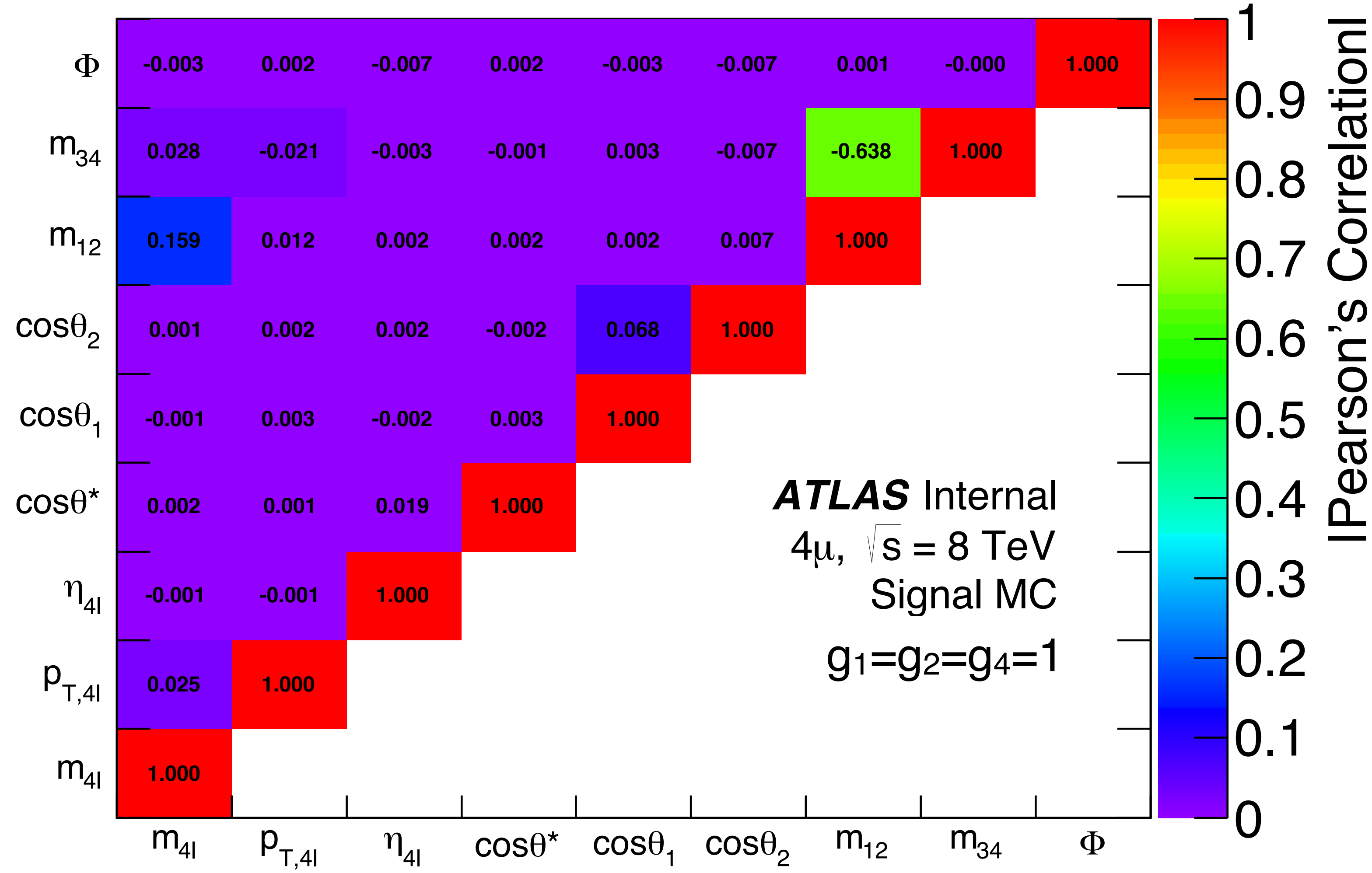
Observed S/B = 2.1 (Expected = 1.2)

Measurement strategies

- Two approaches done in parallel to cross-check one another, both using of the analytical matrix-element:
  - 9D Matrix-Element Method (9DMEM): Fit using 9-dimensional shape of all the useful observables
  - Matrix-Element Observable Method (ME-Obs): Collapse the many observables into 3 multivariate discriminants and fit using 3D shape of discriminants
    - Boosted Decision Tree (BDT) for background separation
    - Matrix-element ratios for sensitivity to $g_{1,2,4}$

9DMEM signal model

- Binned 9D histogram would require unrealistically large number of simulated events!
- <u>Solution</u>: slice 9D shape into 4 pieces, neglecting small correlations
- m_{4l}, ($p_{T,4l}$, η_{4l}), $\cos\theta^*$ & ($\cos\theta_1$, $\cos\theta_2$, Φ, m_{12}, m_{34})



- For the 5D piece, we start with the parton-level shape from the matrix-element and apply corrections for detector efficiency, acceptance & resolution
  - Corrections are 2D and 3D MC histograms divided by matrix-element

9DMEM background model

- Similar approach for backgrounds, but we have fewer MC events and no validated ME-based parton-level prediction, so there are more neglected correlations:
  - m_{4l}, ($p_{T,4l}$, η_{4l}), $\cos\theta^*$, ($\cos\theta_1$, $\cos\theta_2$), Φ, (m_{12}, m_{34})
  - m_{4l} piece is smoothed using Kernel Density Estimation

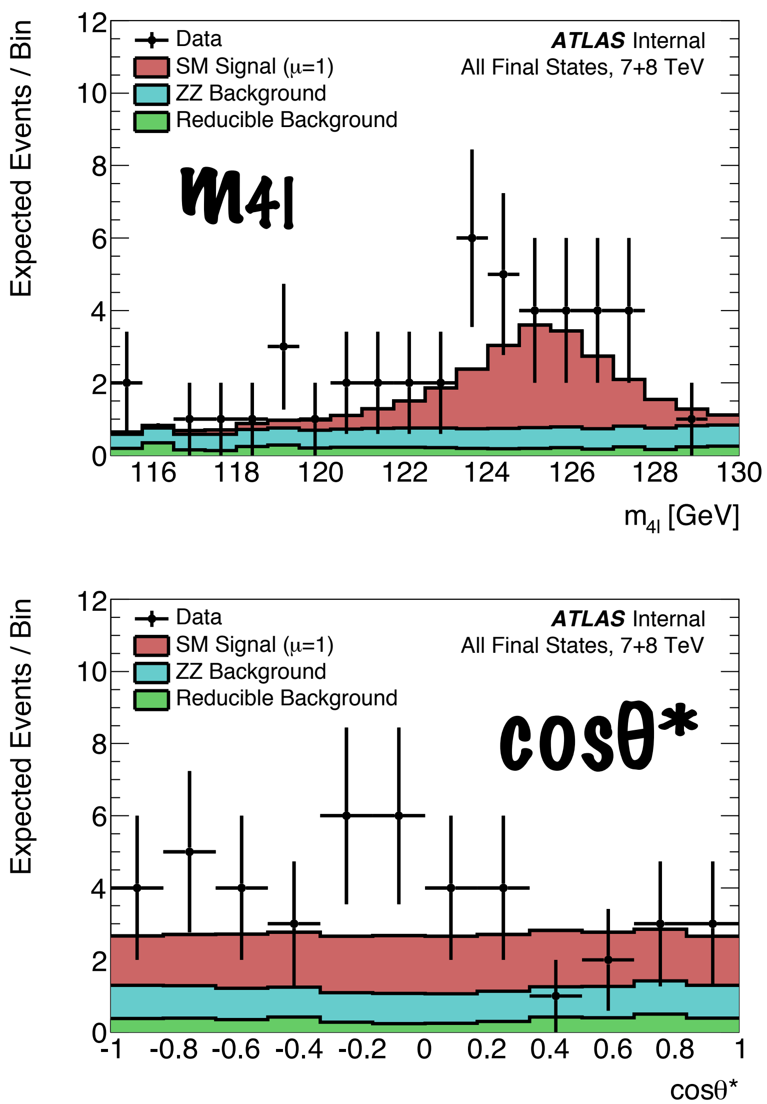
- Note: Neglecting more correlations in background than signal could lead to biased measurement. This gets incorporated as a systematic uncertainty, which ends up being negligible.

Reconstructed shapes & data

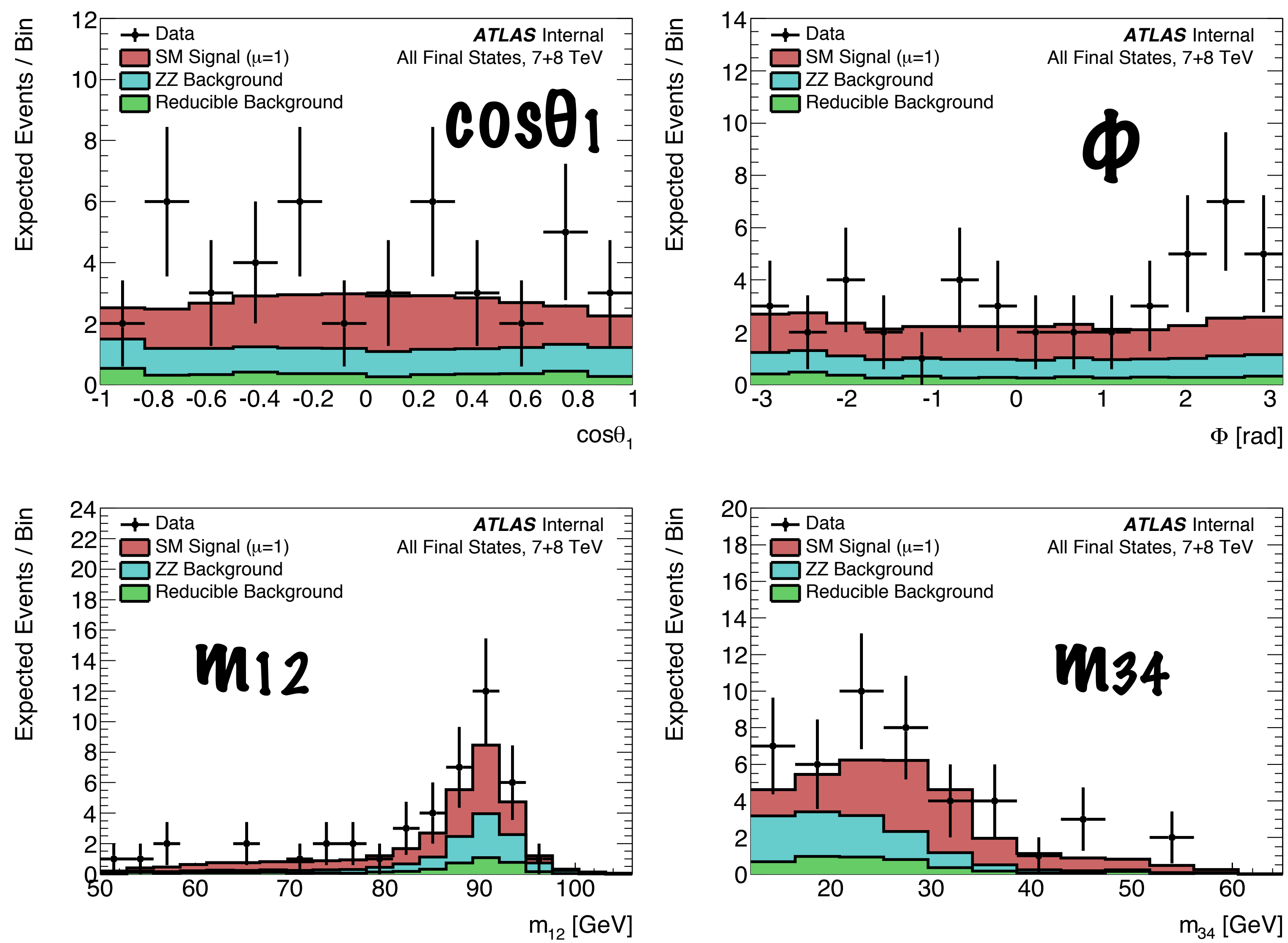
Projected onto 6 of the 9 observables

0^+ Higgs with SM cross-section
ZZ background
Reducible background

Background separation



g1,2,4 sensitivity

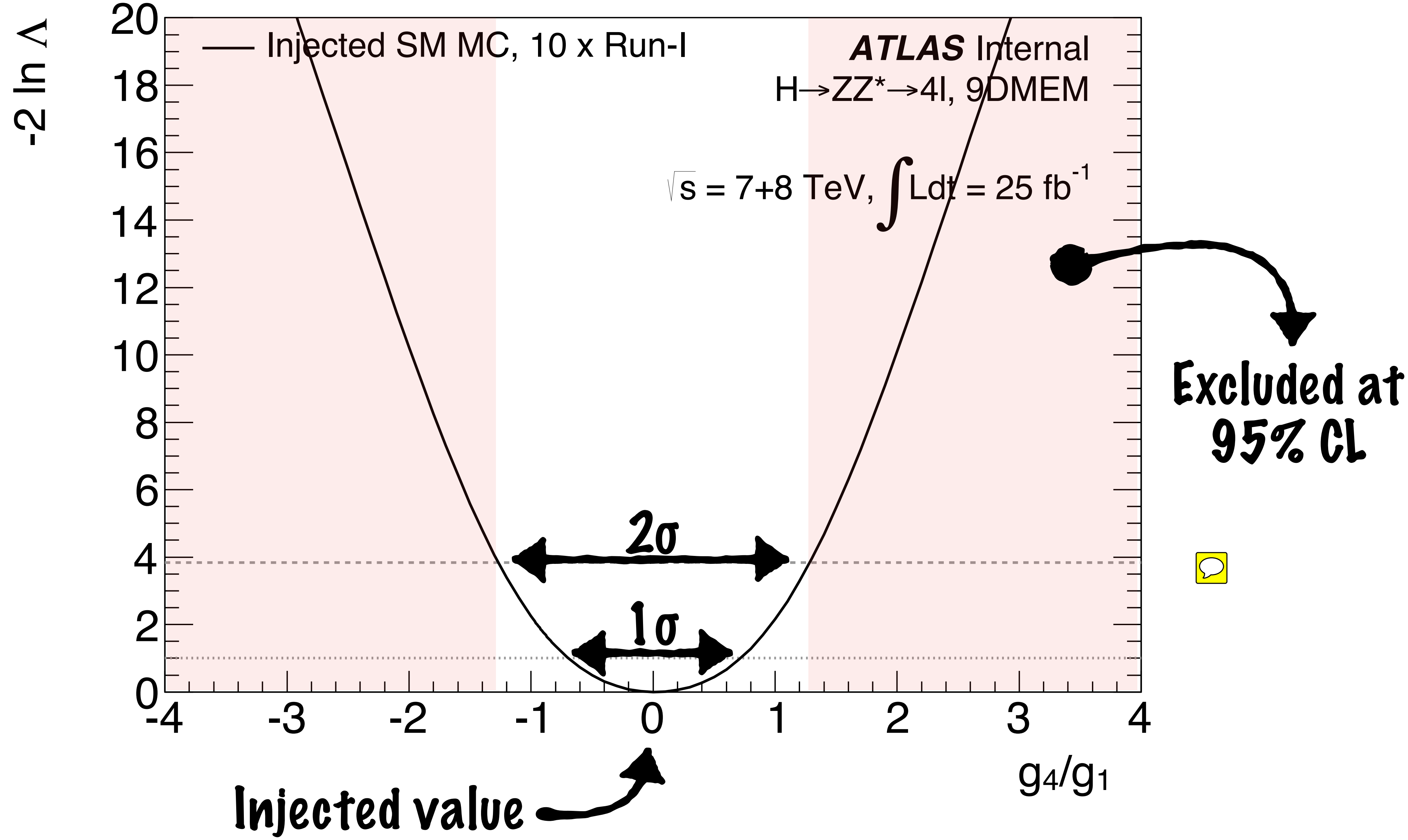


Fit strategy

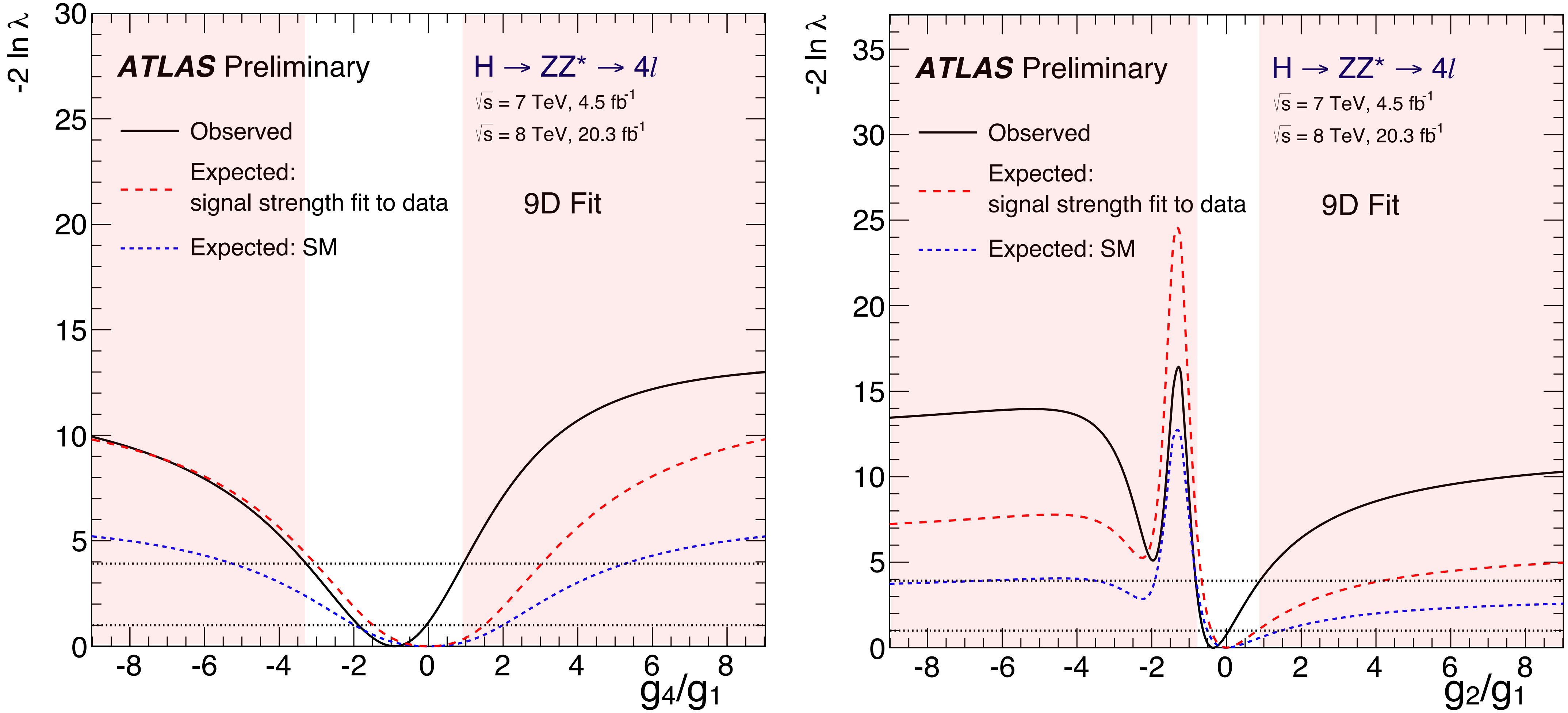
- Measure of g_2/g_1 & g_4/g_1 separately assuming real values & focusing on interval [-10, 10] where we currently have sensitivity
- Profile-likelihood fit
- Signal strength $\mu=\sigma/\sigma_{SM}$ and Higgs mass m_H are free parameters determined by fit
  - Measured values consistent with SM
- Dominant systematics:
  - Theoretical ZZ* background rates from parton distribution function and QCD Scale
  - Reducible background uncertainties from transfer factor method
  - Luminosity uncertainty
- Dominant uncertainties combined have < O(0.5%) impact on expected g_4/g_1 95% CL limits

Example fit

- Validate model by fitting to MC and checking that the measured results are consistent with the injected values
- Example: Fitting to O(100K) SM events, reweighted to 10 x the current luminosity:



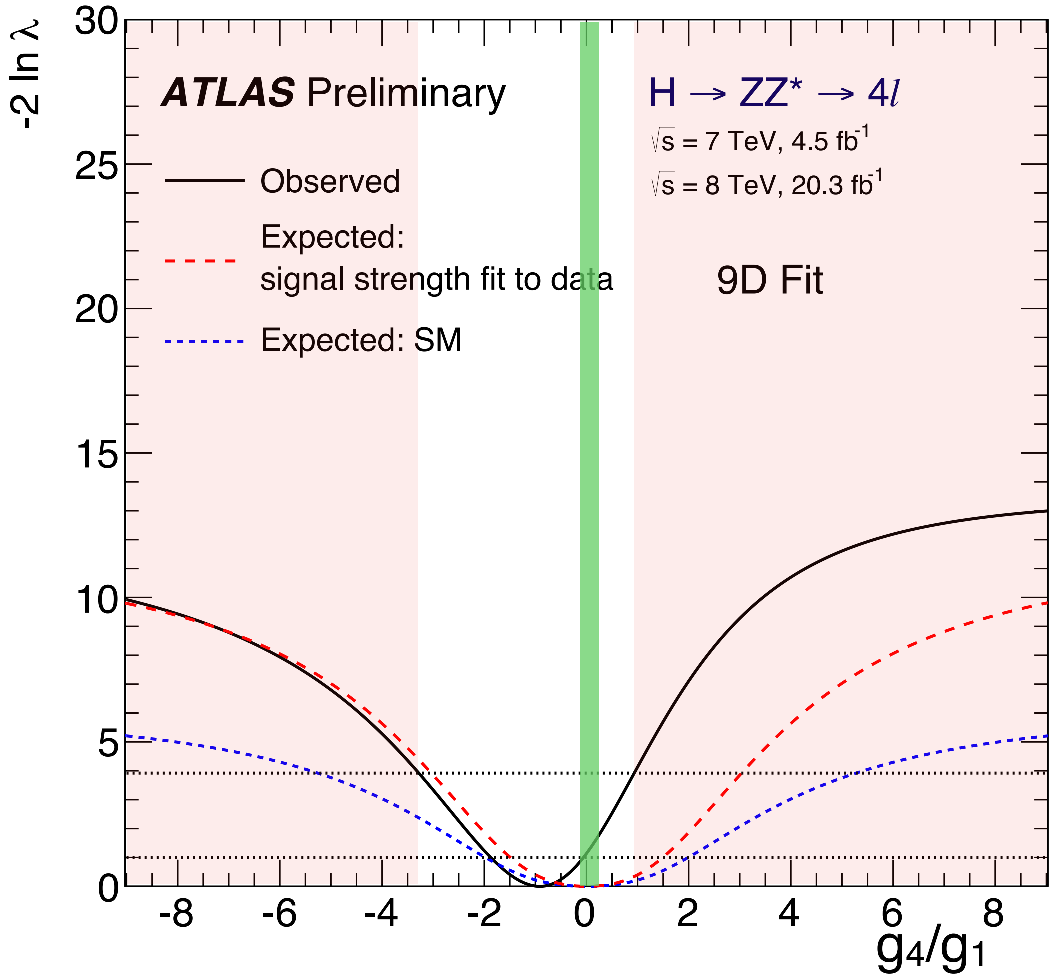
Results

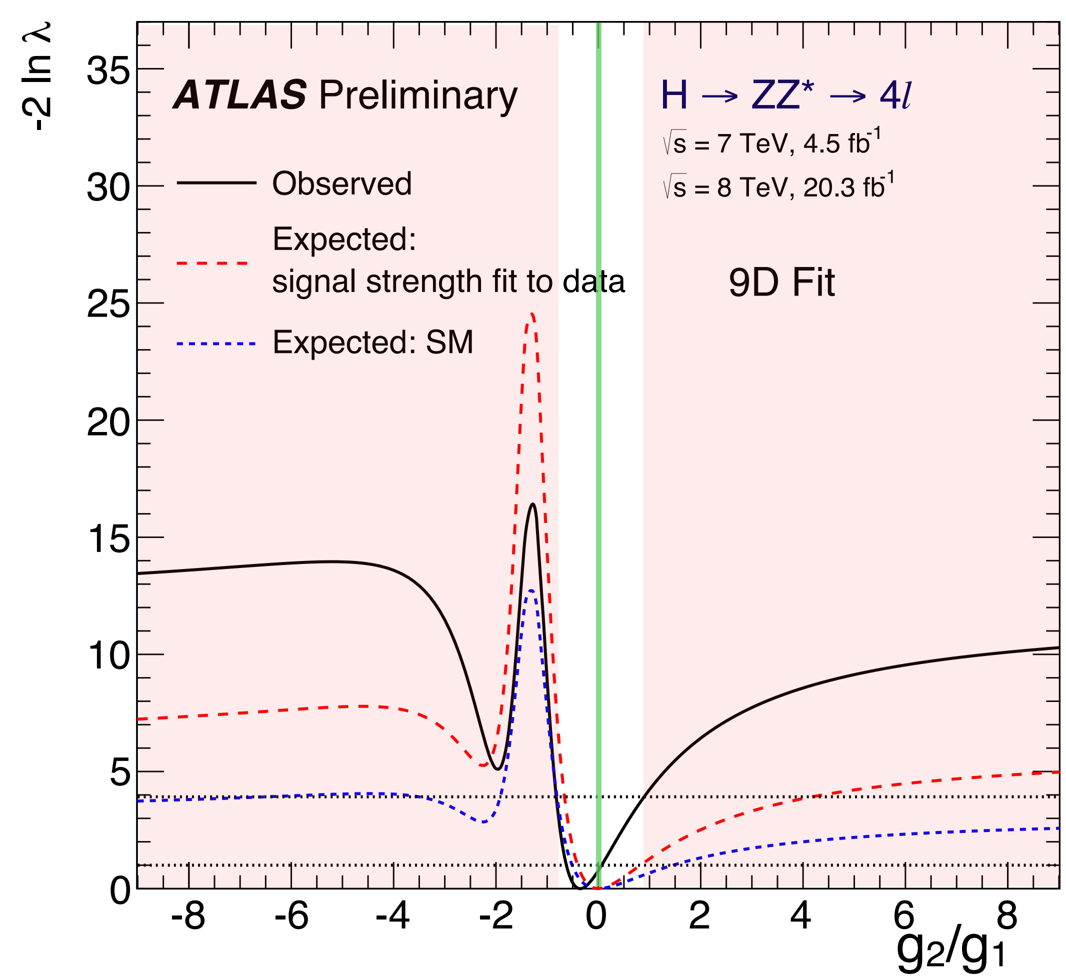


Parameter	Best-fit		Excluded at 95% CL	
	Expected [red]	Observed	Expected [red]	Observed
g_4/g_1	$0.00^{+1.49}_{-1.49}$	$-0.91^{+0.85}_{-0.96}$	<-2.99 and >2.99	<-3.24 and >0.91
g_2/g_1	$0.00^{+0.82}_{-0.40}$	$-0.36^{+0.42}_{-0.26}$	<-0.65 and >3.99	<-0.82 and >0.87

- Best-fit signal strength $\hat{\mu}=\hat{\sigma}/\sigma_{SM}\approx1.7$ assuming 0+
- Results are consistent with SM @ 0

Results





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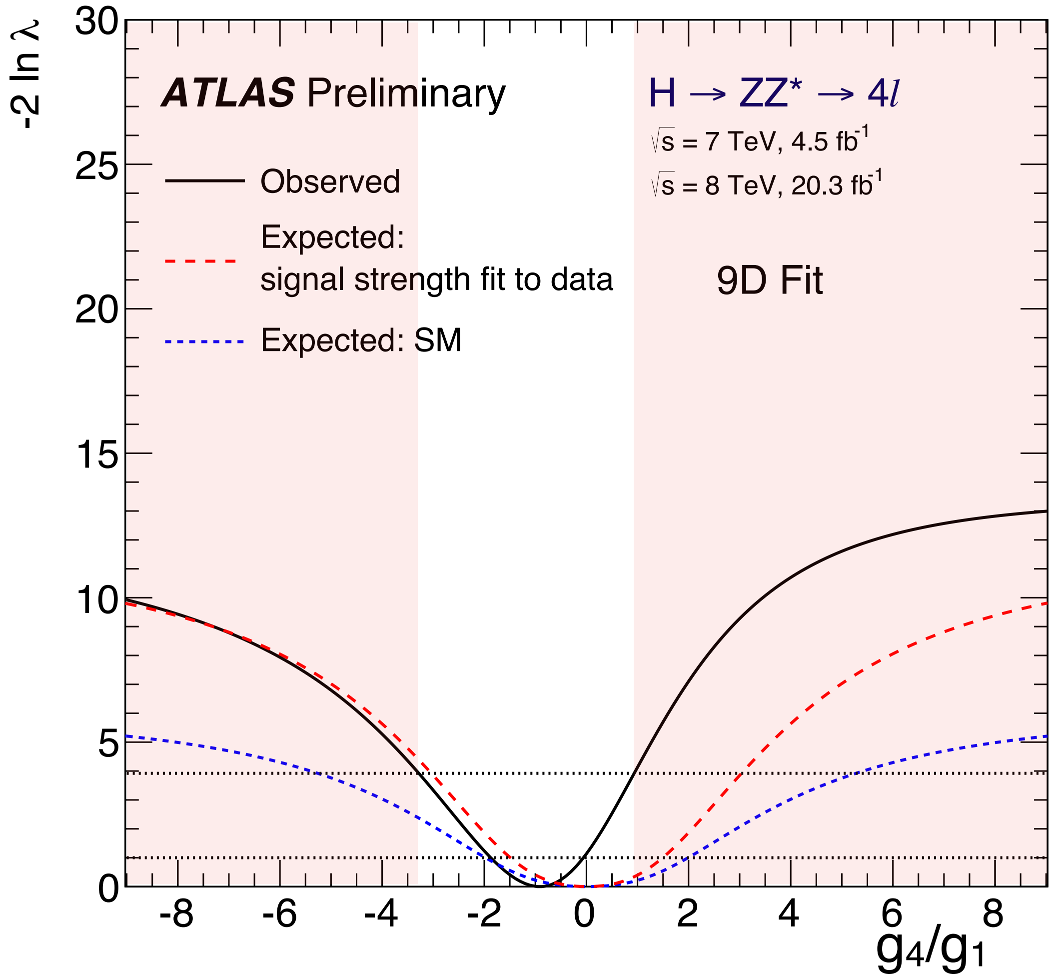
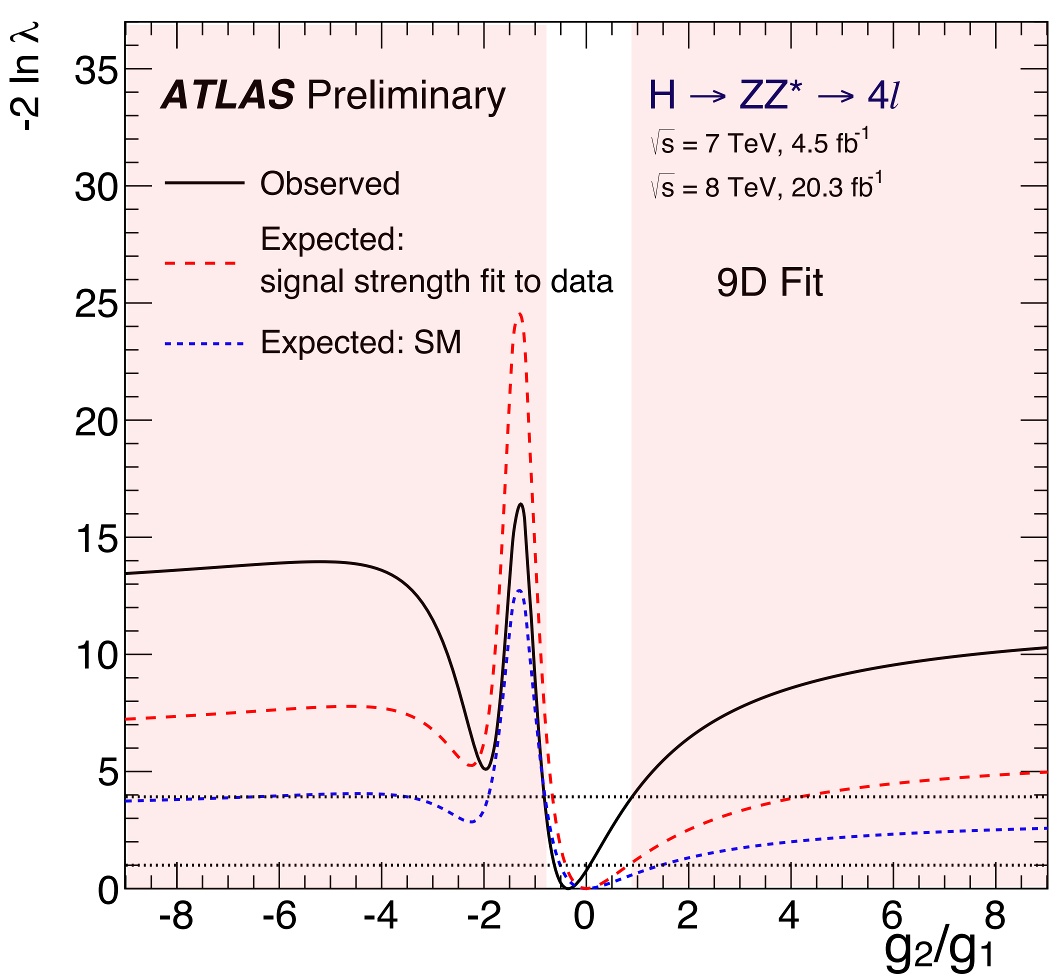
g_2/g_1	$0.00^{+0.82}_{-0.40}$	$-0.36^{+0.42}_{-0.26}$	<-0.65 and >3.99	<-0.82 and >0.87

* 2HDM/Technicolor Models predict $g_4/g_1 \approx O(0.1)$ [arXiv:1307.1347]
* SM electroweak corrections predict $g_2/g_1 \approx O(0.01)$

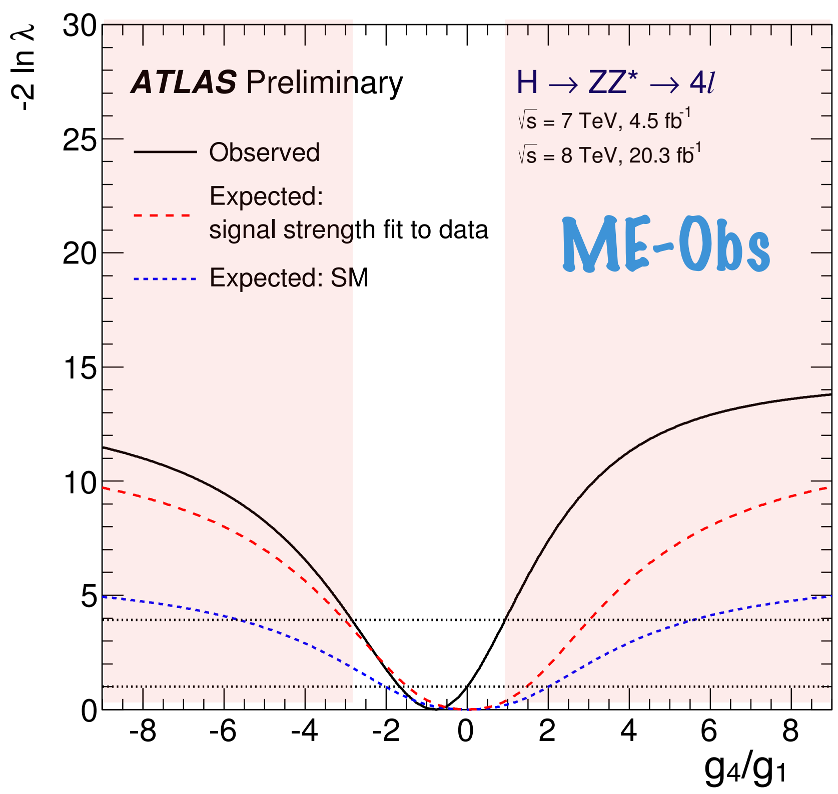
Comparison with ME-Obs Method

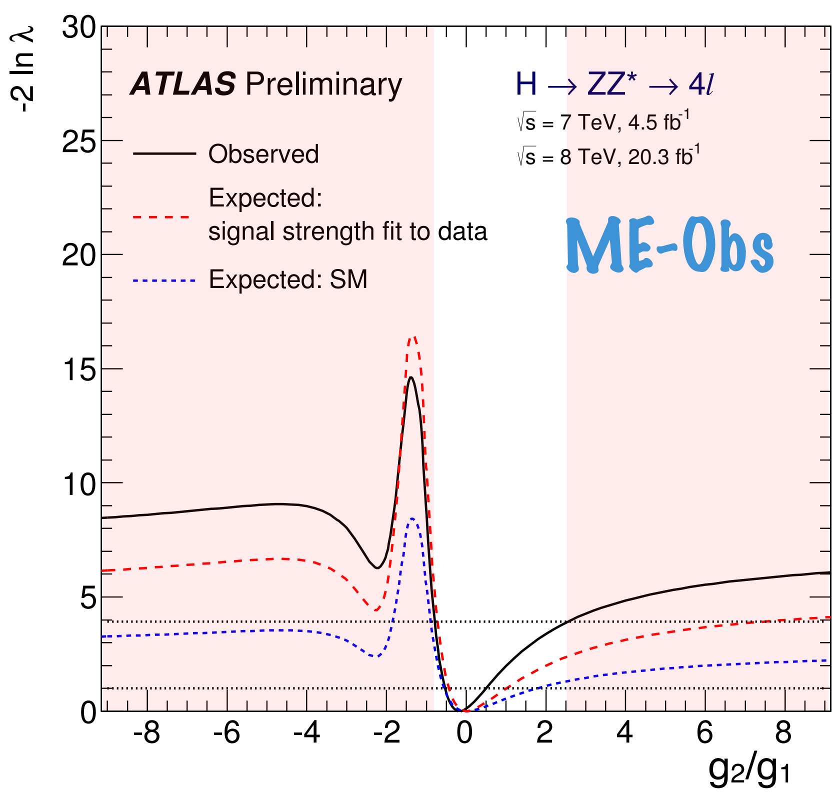




Comparison to ME-Obs

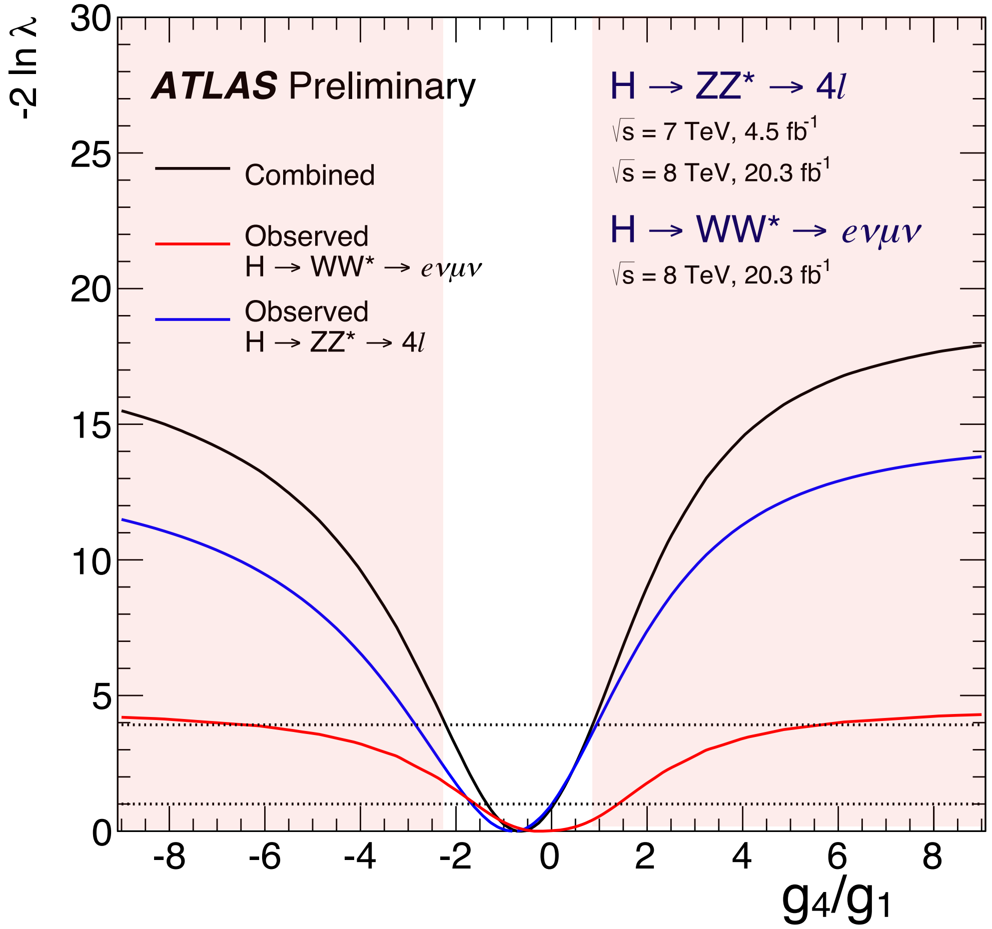
Results are compatible

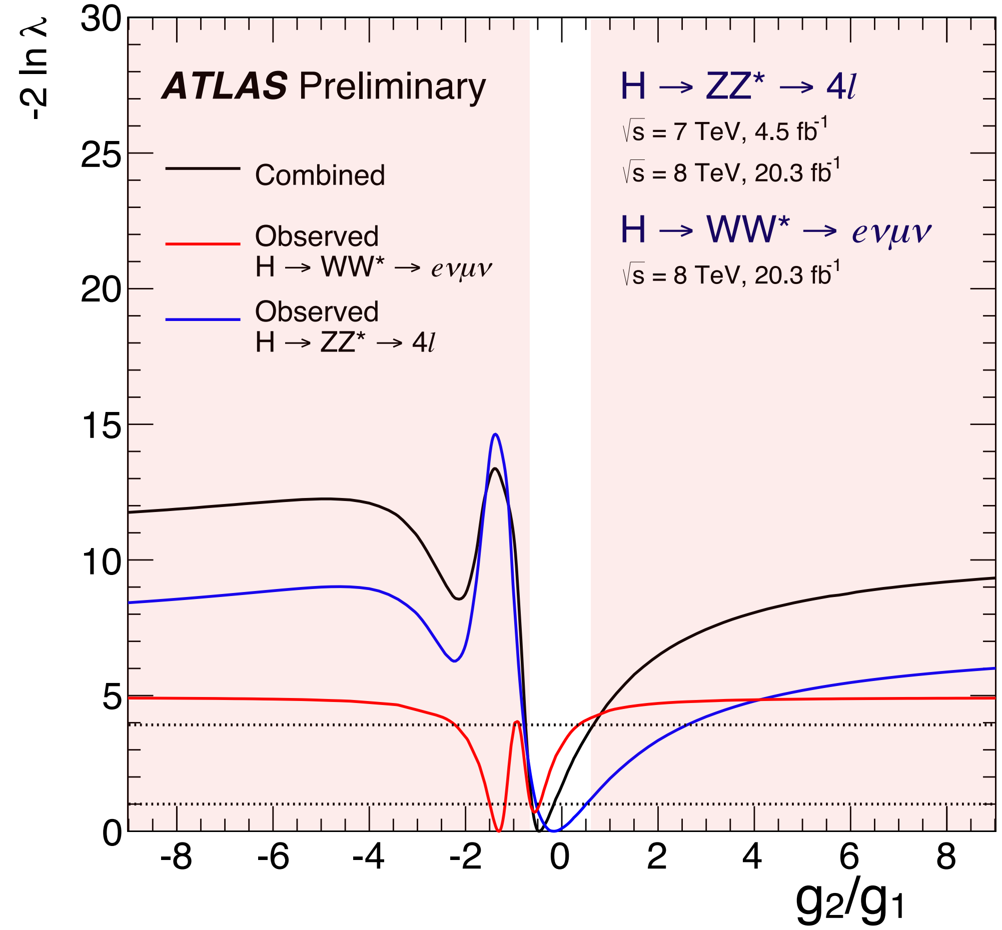




Combination with WW*

- Also measured in H→WW*→eνμν channel with slightly less sensitivity
  - Fit with two multi-variate discriminants:
    One for background rejection and one for separating CP-hypotheses
- Combination with ZZ* results from ME-Obs method because it is computationally faster



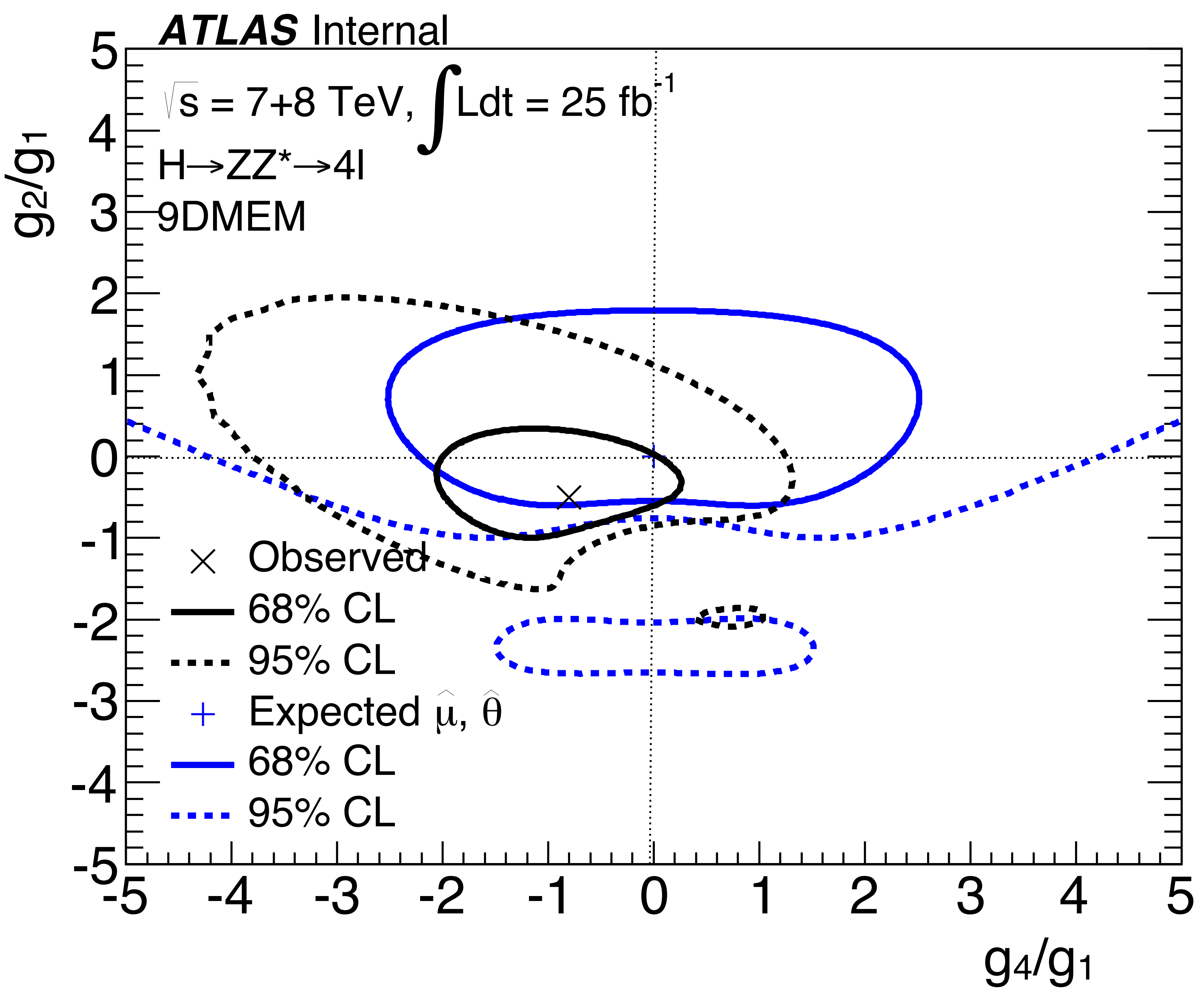


Parameter	Best-fit		Excluded at 95% CL	
	Expected [red]	Observed	Expected [red]	Observed
g_4/g_1	0.00	-0.68	<-2.33 and >2.30	<-2.18 and >0.83
g_2/g_1	0.00	-0.48	<-0.55 and >4.80	<-0.73 and >0.63

Nice consistency with SM

Two-dimensional 9DMEM Fit

- Also possible to do simultaneous measurement of both parameters
- 9DMEM results within ~1σ of SM prediction (solid black contour):



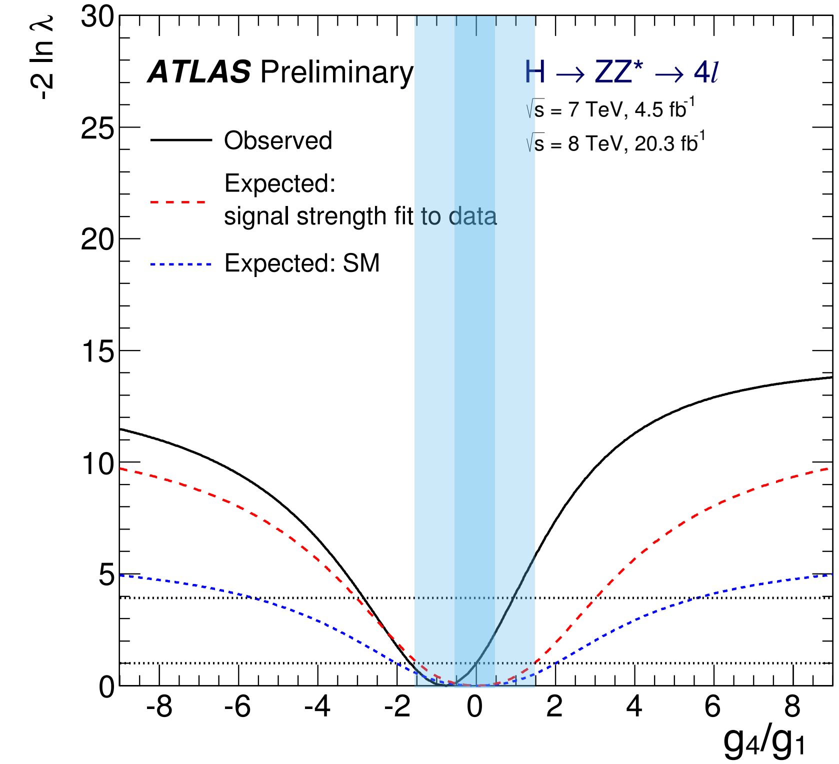
Looking Ahead

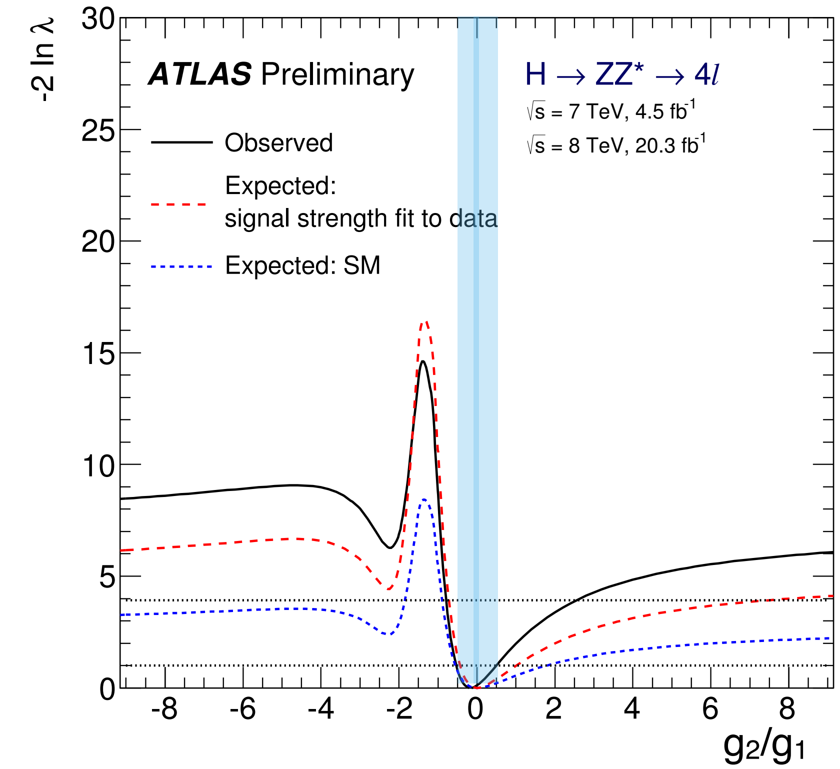
- We have nice fundamental limits characterizing the WW* and ZZ* final states

- Part of the motivation is to lay the groundwork for future measurements during Run II at the LHC

- Extrapolated expected 95% CL limits from $H \to ZZ^* \to 4\ell$ alone:
  - **300 fb^{-1}**: $|g_2/g_1| < O(0.5)$, $|g_4/g_1| < O(1.6)$
  - **3000 fb^{-1}**: $|g_2/g_1| < O(0.1)$, $|g_4/g_1| < O(0.4)$

- Barely probe current models with ~3000 fb^{-1}





Conclusion

First CP-mixing measurement from ATLAS:

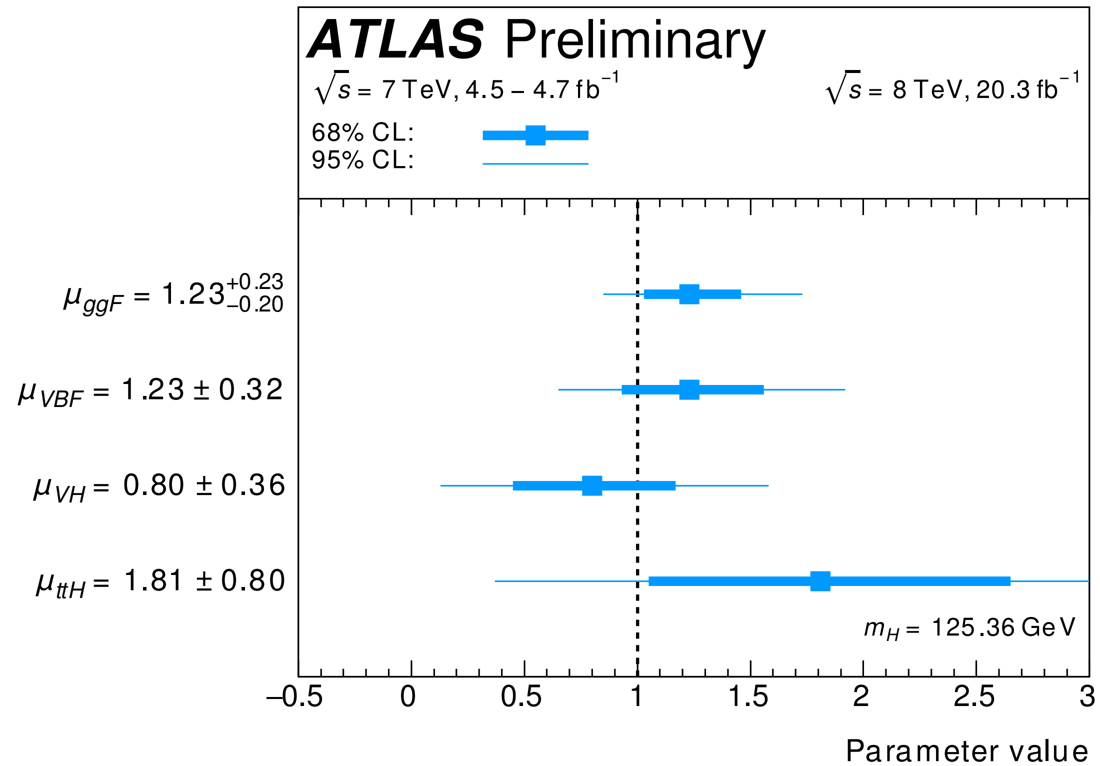
Channels	95% CL intervals	
	BSM CP-odd contribution	BSM CP-even contribution
ZZ*-only (9DMEM)	$-3.24 < g_4/g_1 < 0.91$	$-0.82 < g_2/g_1 < 0.87$
ZZ* + WW*	$-2.18 < g_4/g_1 < 0.83$	$-0.73 < g_2/g_1 < 0.63$

- Fundamentally characterization of the HVV vertex
- Groundwork for future measurement with many discriminant observables
  - Multi-dimensional fits will become more critical with more data to justify the simultaneous measurement of more parameters
- Small improvement estimated in Run II, but there will be more room for creativity

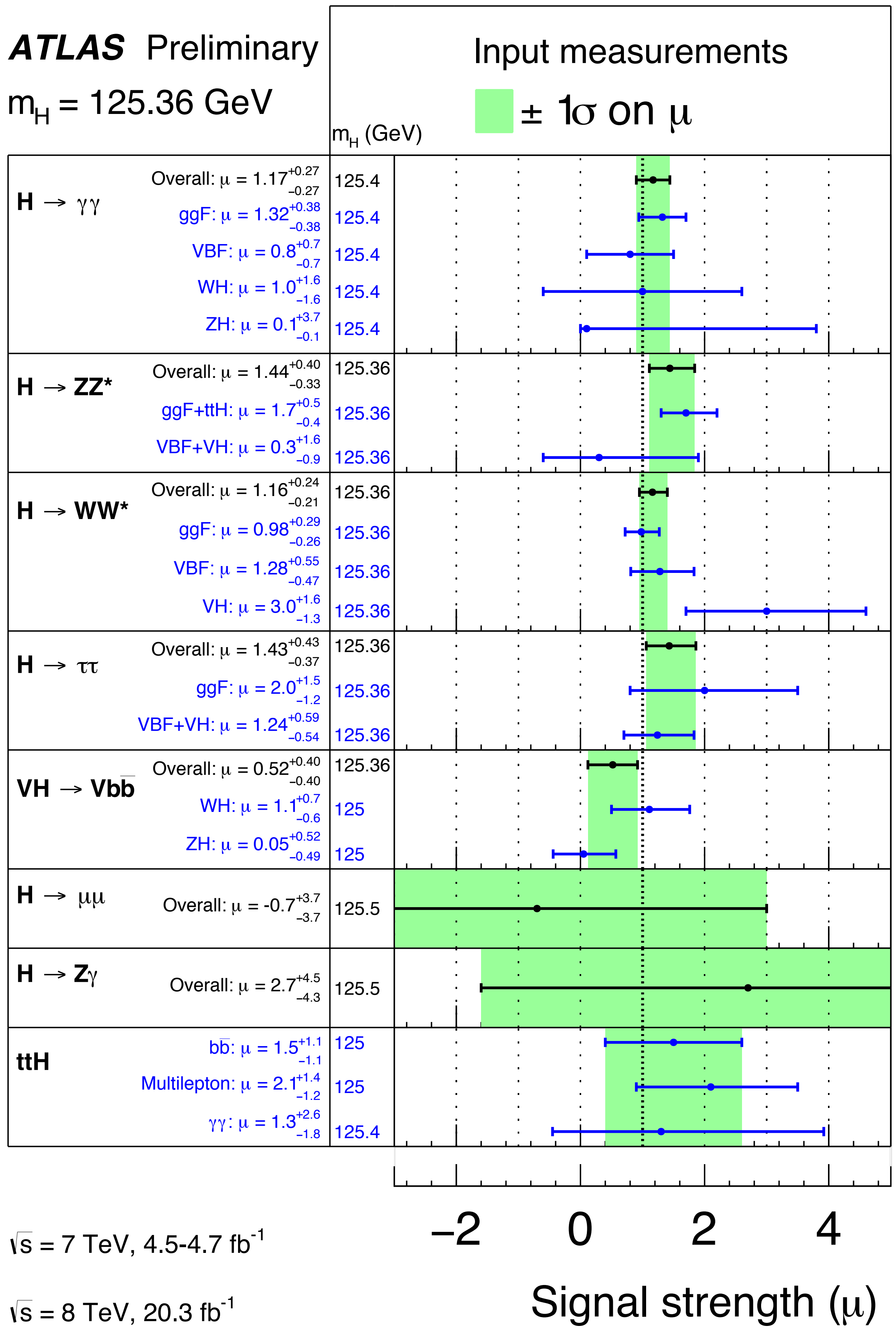
Backup

Higgs Properties

Just some of the highlights:

<table>
<tr><th>Property</th><th>Channels</th><th>Result</th></tr>
<tr><td>Mass [1503.07589]</td><td>ATLAS+CMS: γγ, ZZ</td><td>125.09 ± 0.21(stat) ± 0.11(syst) GeV</td></tr>
<tr><td>xsec (8 TeV) [1504.05833]</td><td>ATLAS: γγ, ZZ</td><td>$\sigma_{pp\to H}$ = 33.0 ± 5.3(stat) ± 1.6(syst) pb
(expected ~24 pb)</td></tr>
<tr><td>Couplings</td><td>ATLAS:
γγ, ZZ, WW, ττ, Vbb,
μμ, Zγ, ttH</td><td>
</td></tr>
<tr><td rowspan="2">Decay width
via off-shell couplings</td><td>ATLAS: ZZ, WW</td><td>$\Gamma_H/\Gamma_{H,SM} < 5.5\times$ @ 95% CL [1503.01060]</td></tr>
<tr><td>CMS: ZZ</td><td>$\Gamma_H/\Gamma_{H,SM} < 5.4\times$ @ 95% CL [1405.3455]</td></tr>
<tr><td>Spin/CP</td><td colspan="2">details in this talk…</td></tr>
</table>

ATLAS Higgs rates in different final states



Effective Lagrangian Approach

- Mixture characterized by non-SM couplings in Eff. Lagrangian:

$$\begin{aligned}\mathcal{L}_0^V = \; & \Big\{ c_\alpha \kappa_{\mathrm{SM}} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] \\ & - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right] \\ & - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu}\right]\Big\} X_0.\end{aligned}$$

$$s_\alpha := \sin\alpha \qquad c_\alpha := \cos\alpha$$

BSM CP-even contributions

BSM CP-odd contributions (CP-violation!)

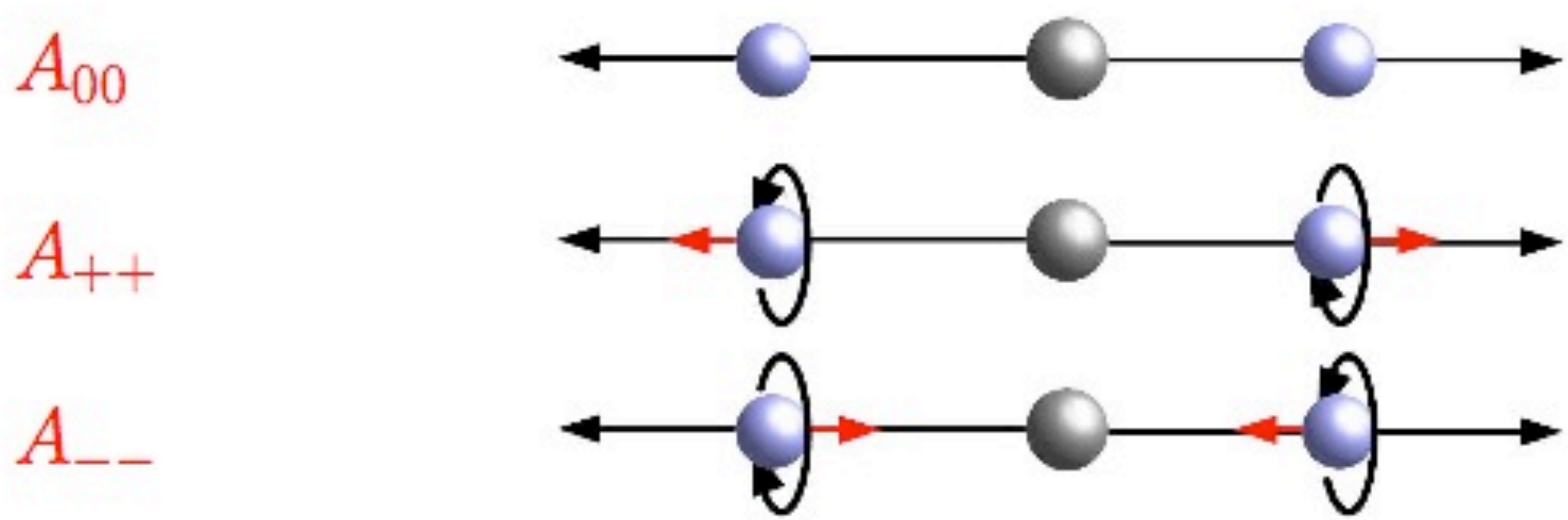
- Coupling ratios **$(\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha$** and **$\tilde{\kappa}_{HVV}/\kappa_{SM}$** measured directly, where $\tilde{\kappa}_X$ is the non-SM coupling scaled by the vacuum expectation value over 4×energy scale for new physics (Λ) to be consistent with g_4/g_1 and g_2/g_1
  - E.g.

$$0^+ \rightarrow (\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha = 0,\; \tilde{\kappa}_{HVV}/\kappa_{SM} = 0$$

$$0^- \rightarrow (\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha = 1,\; \tilde{\kappa}_{HVV}/\kappa_{SM} = 0$$

Matrix-element calculation

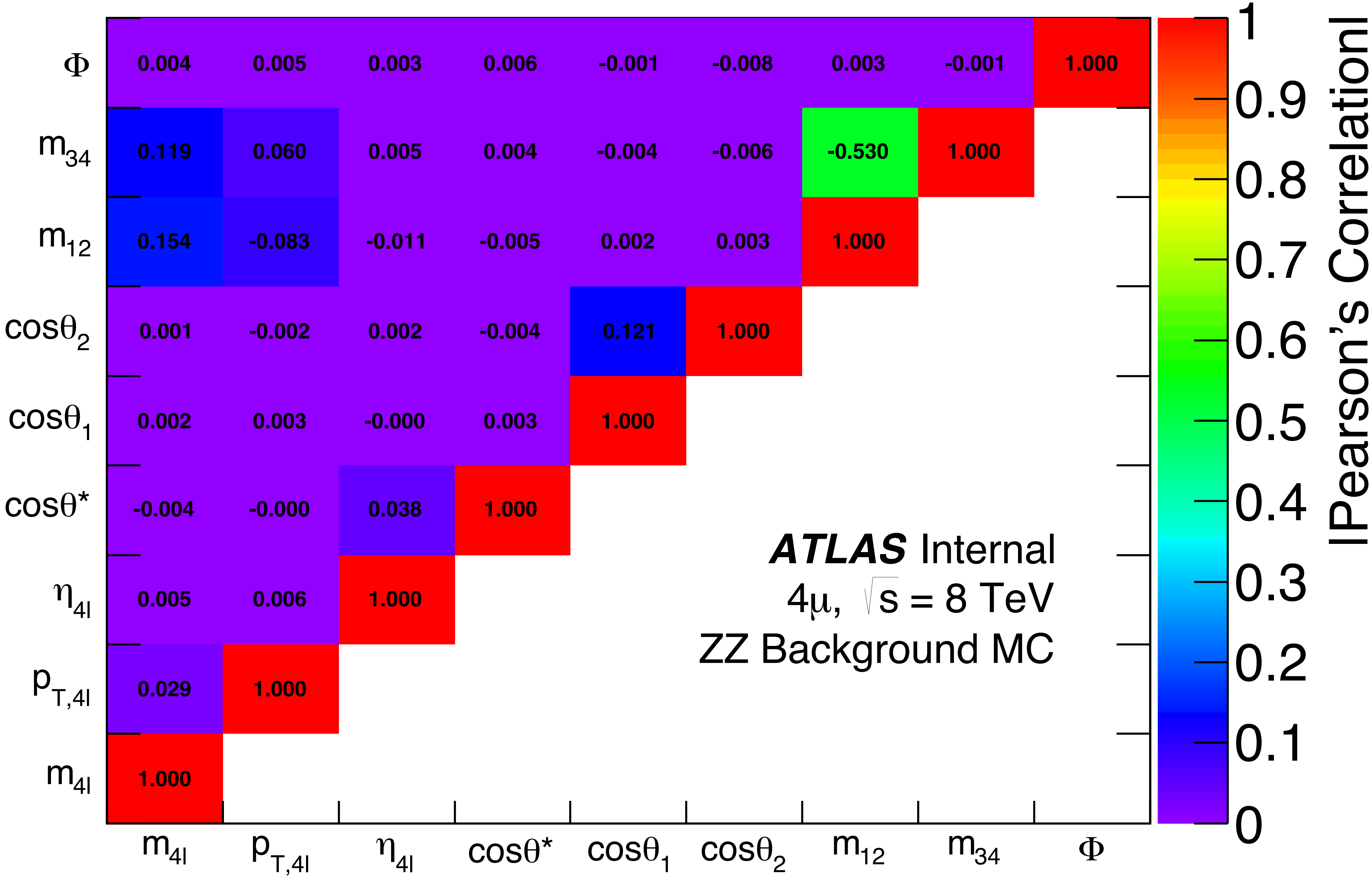
Scattering amplitude can be separated into 3 helicity states with amplitudes dependent on $g_{1,2,4}$



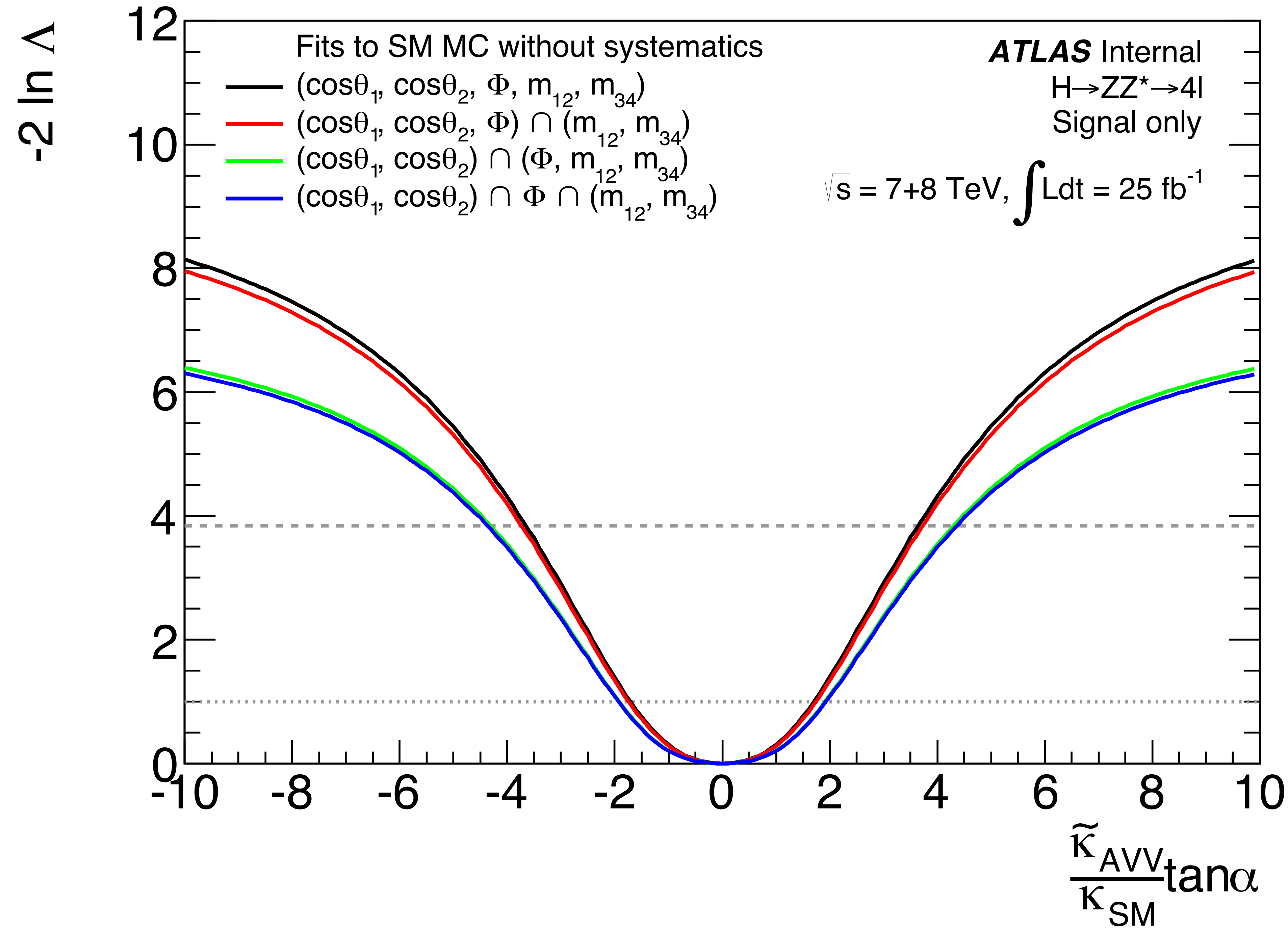
$$\frac{\mathcal{N}_J \, d\Gamma_J(m_1, m_2, \cos\theta^*, \Psi, \cos\theta_1, \cos\theta_2, \Phi)}{d\cos\theta^* d\Psi d\cos\theta_1 d\cos\theta_2 d\Phi} =$$

$$F^J_{0,0}(\theta^*) \times \Big[4\,|A_{00}|^2 \, \sin^2\theta_1 \sin^2\theta_2$$
$$+ |A_{++}|^2 \left(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right)$$
$$+ |A_{--}|^2 \left(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right)$$
$$+ 4|A_{00}||A_{++}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++})$$
$$+ 4|A_{00}||A_{--}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--})$$
$$+ 2|A_{++}||A_{--}|\sin^2\theta_1\sin^2\theta_2\cos(2\Phi - \phi_{--} + \phi_{++}]\Big]$$

ZZ Background correlations

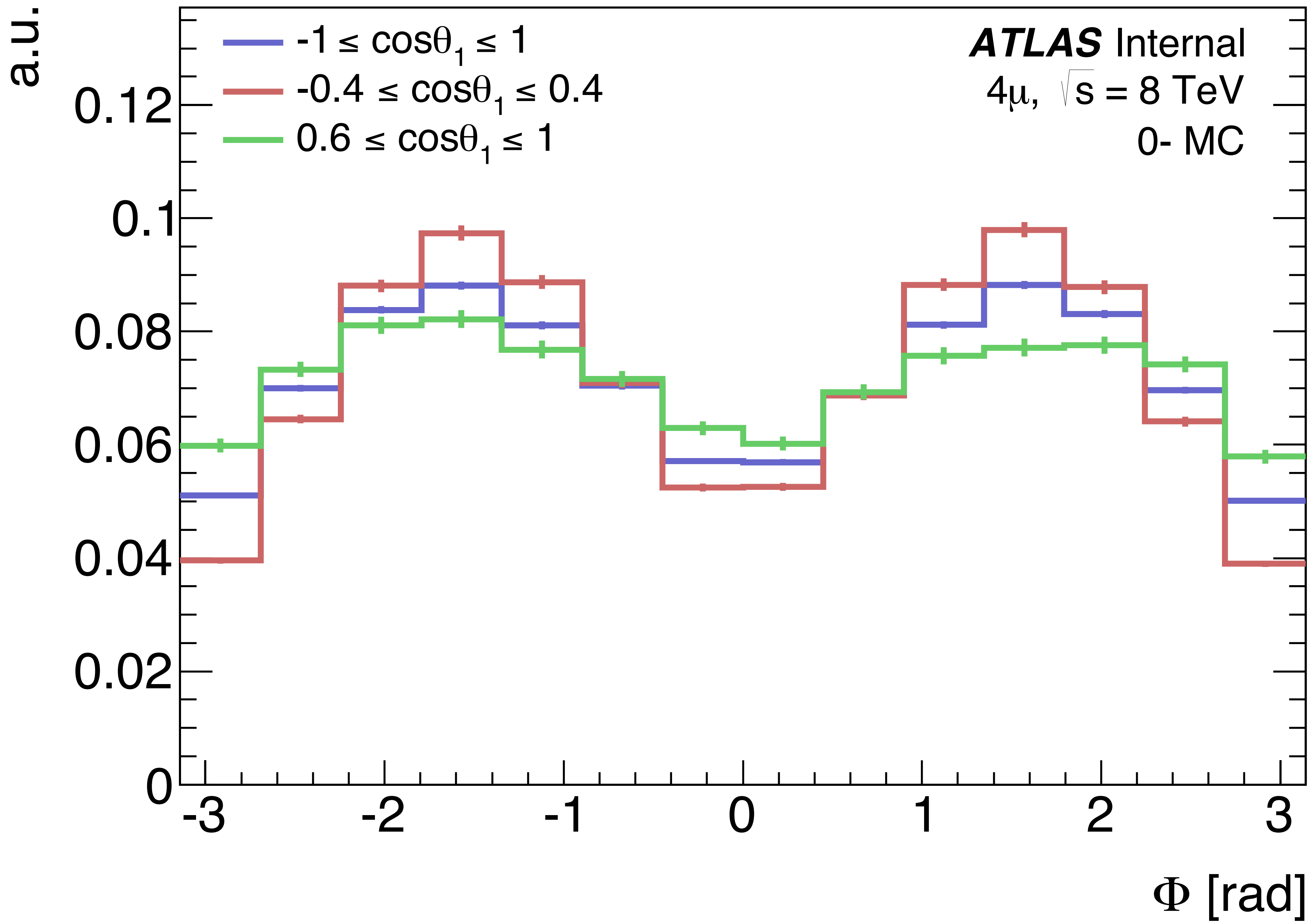


Signal Correlations



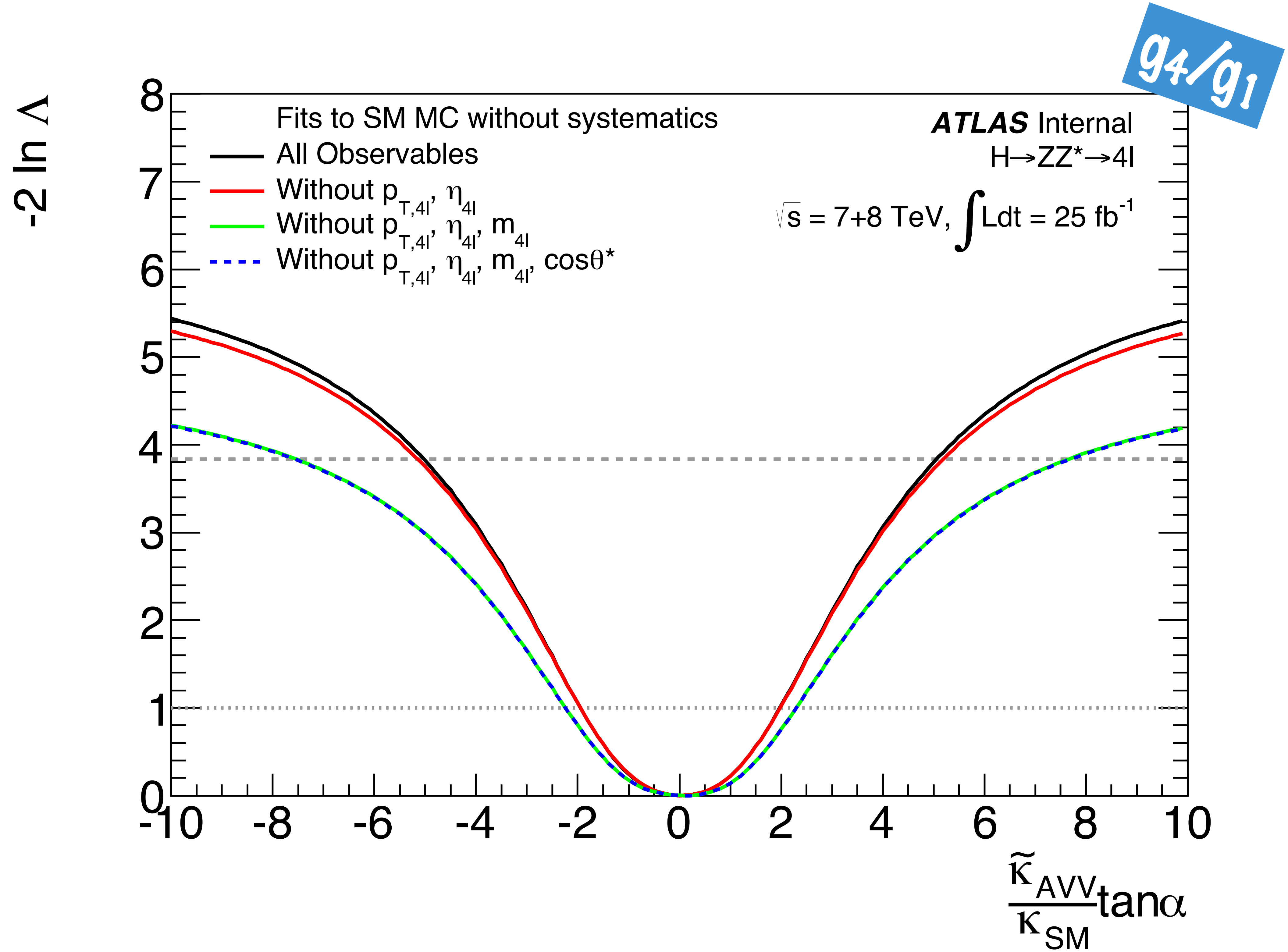
Impact on the expected likelihood curve (fitting with signal-only model) from removing more correlations in the 5D shape sensitive to $g_{1,2,4}$

Signal Correlations



Example of a small functional dependence between Φ and $\cos\theta_1$ that appears for CP-states "nearby" 0- (also occurs for $\cos\theta_2$ vs. Φ)

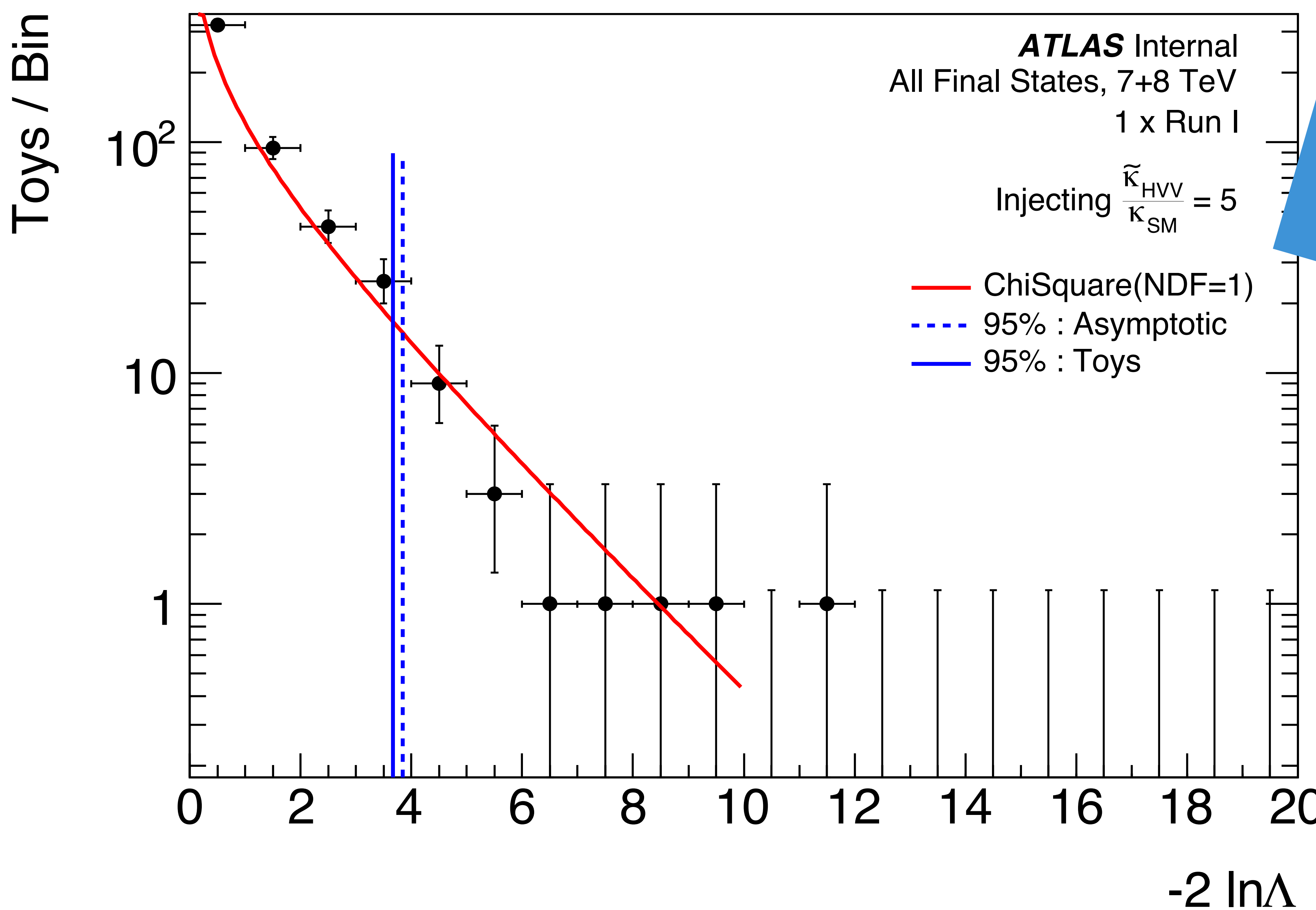
Impact from background-rejection observables



m_{4l} has largest impact by far out of background discriminants

Test of asymptotic approximation

- Asymptotic approximation allows us to infer uncertainty intervals from a single -2lnΛ scan, which saves lots of CPU time
- This is only valid if -2lnΛ values at the injection point are distributed like a ChiSquare function (typically the case when Nevents is large)



Example profile-likelihood distribution from 300 toys with $g_4/g_1=5$

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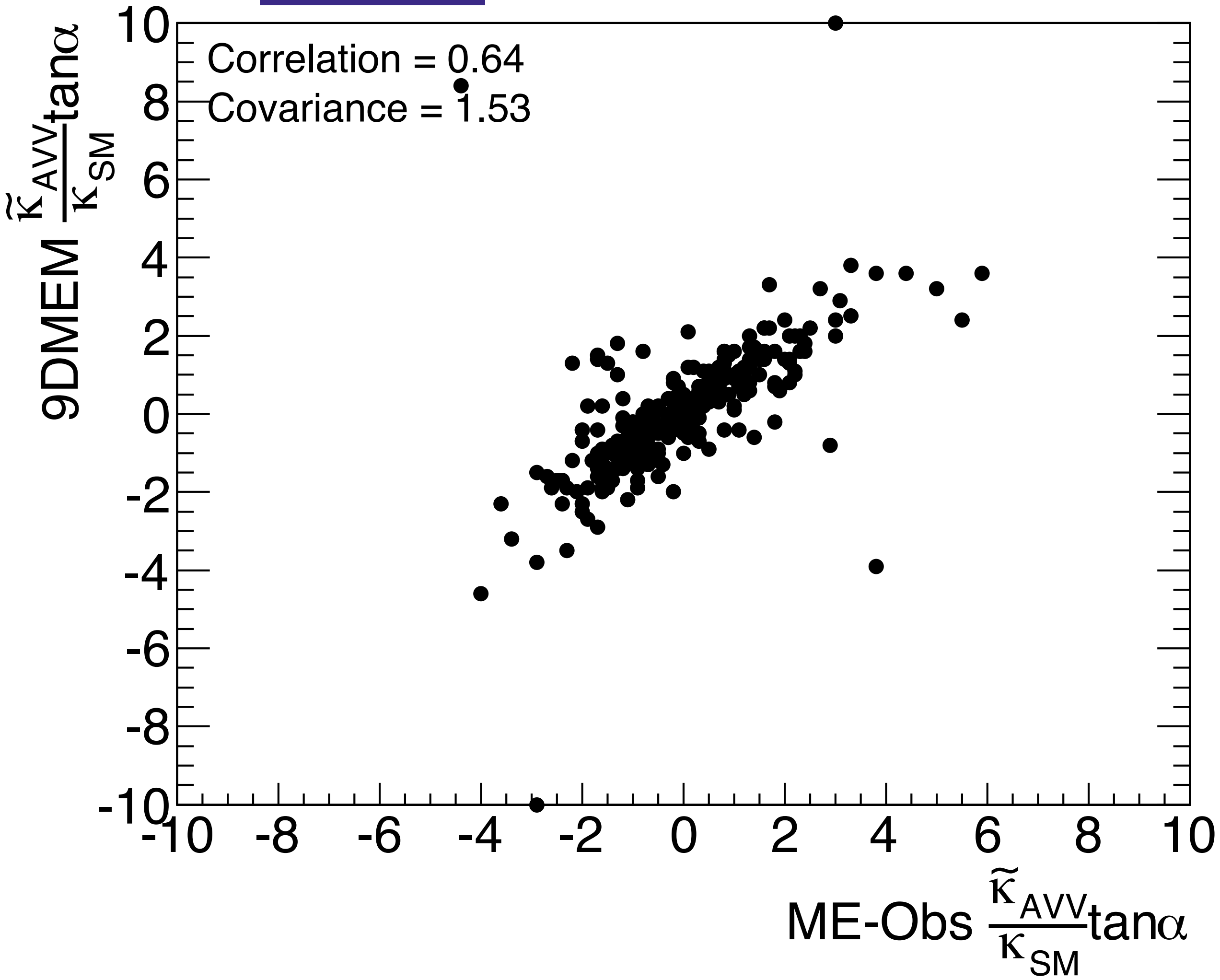
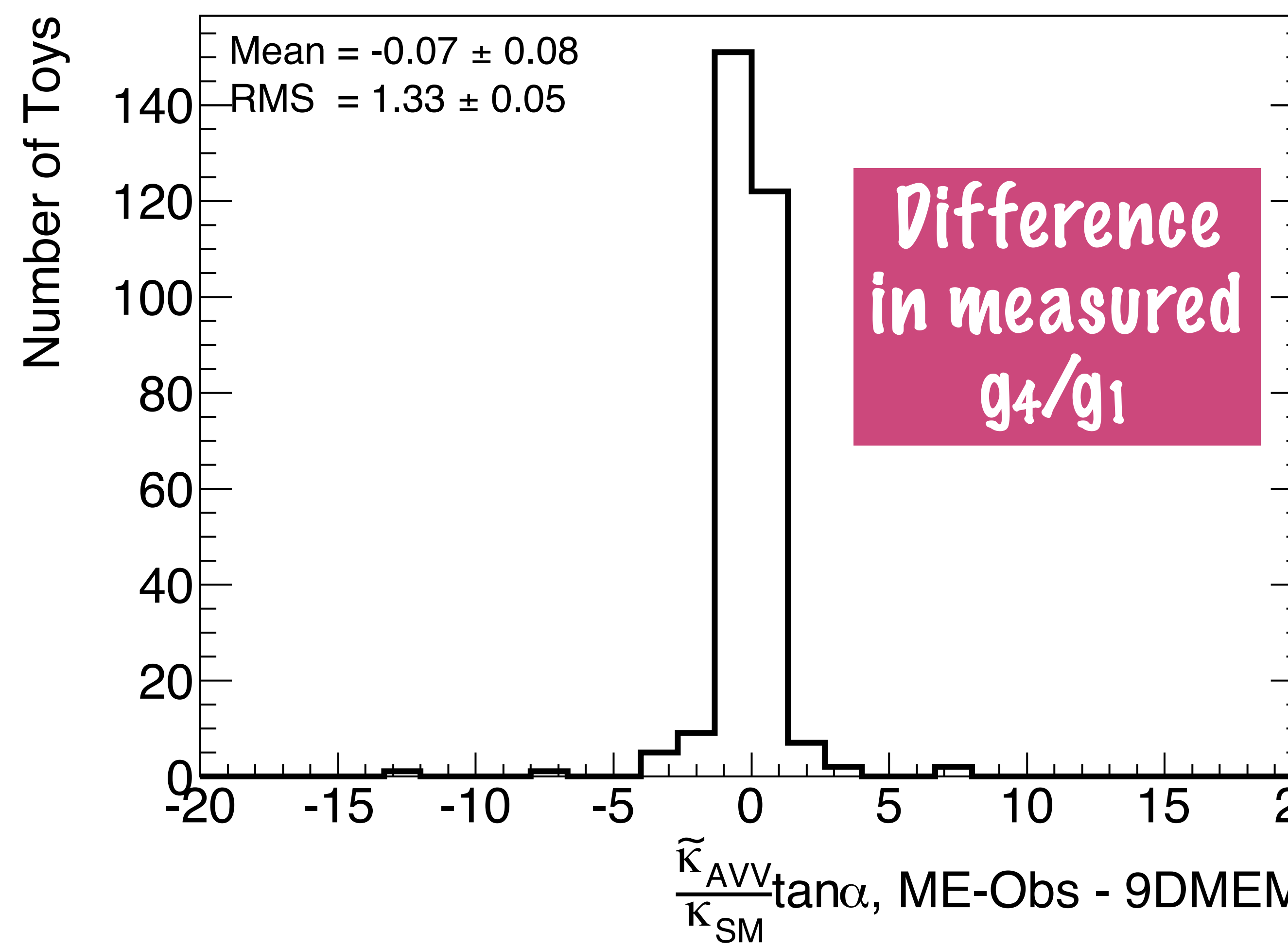
Compatibility of the two methods

- Same set of checks done for alternative ME-Obs fitting method as well
- How do the expected results compare for the 2 methods?
  - Results compared for 300 SM toys generated from MC:

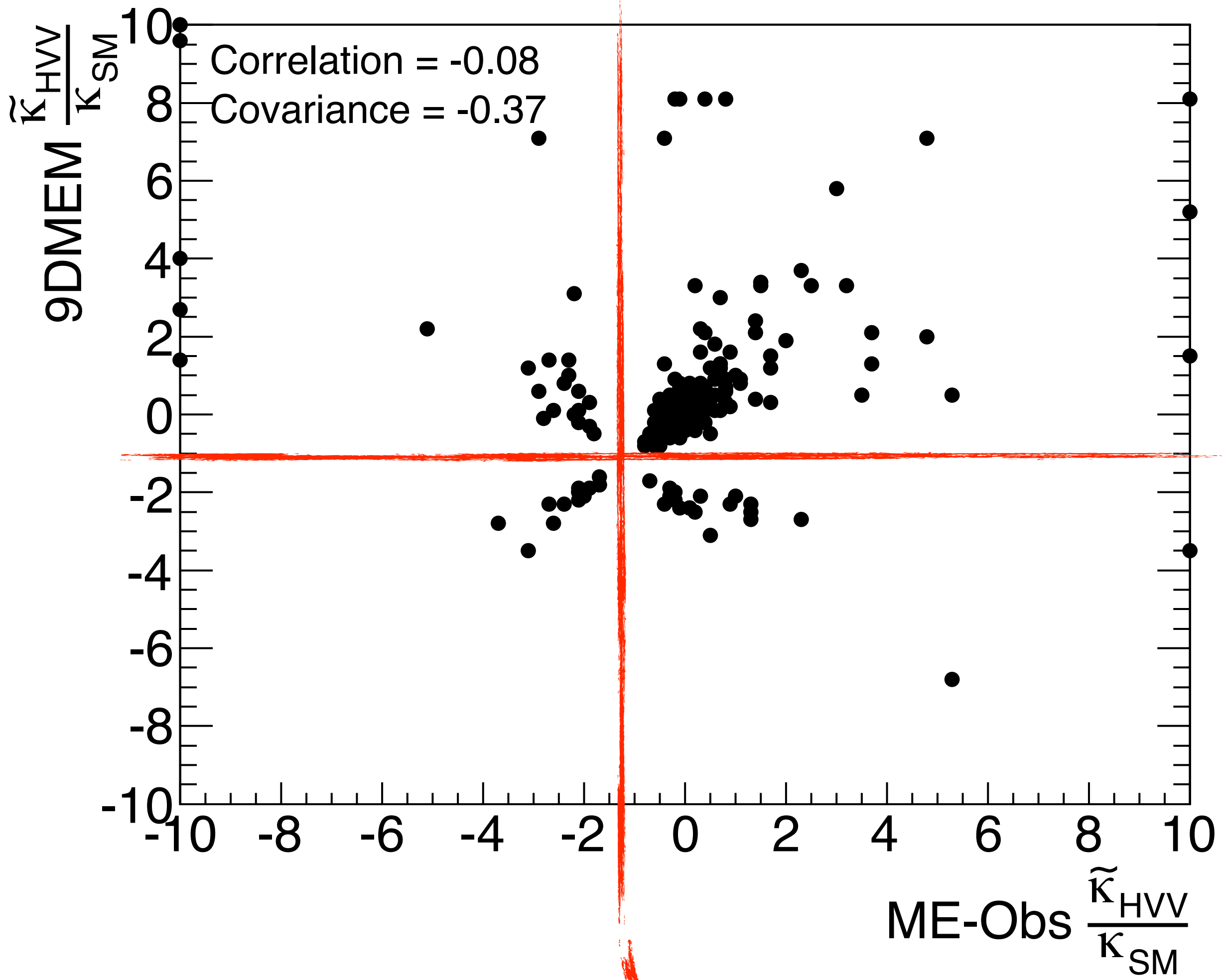
g_4/g_1

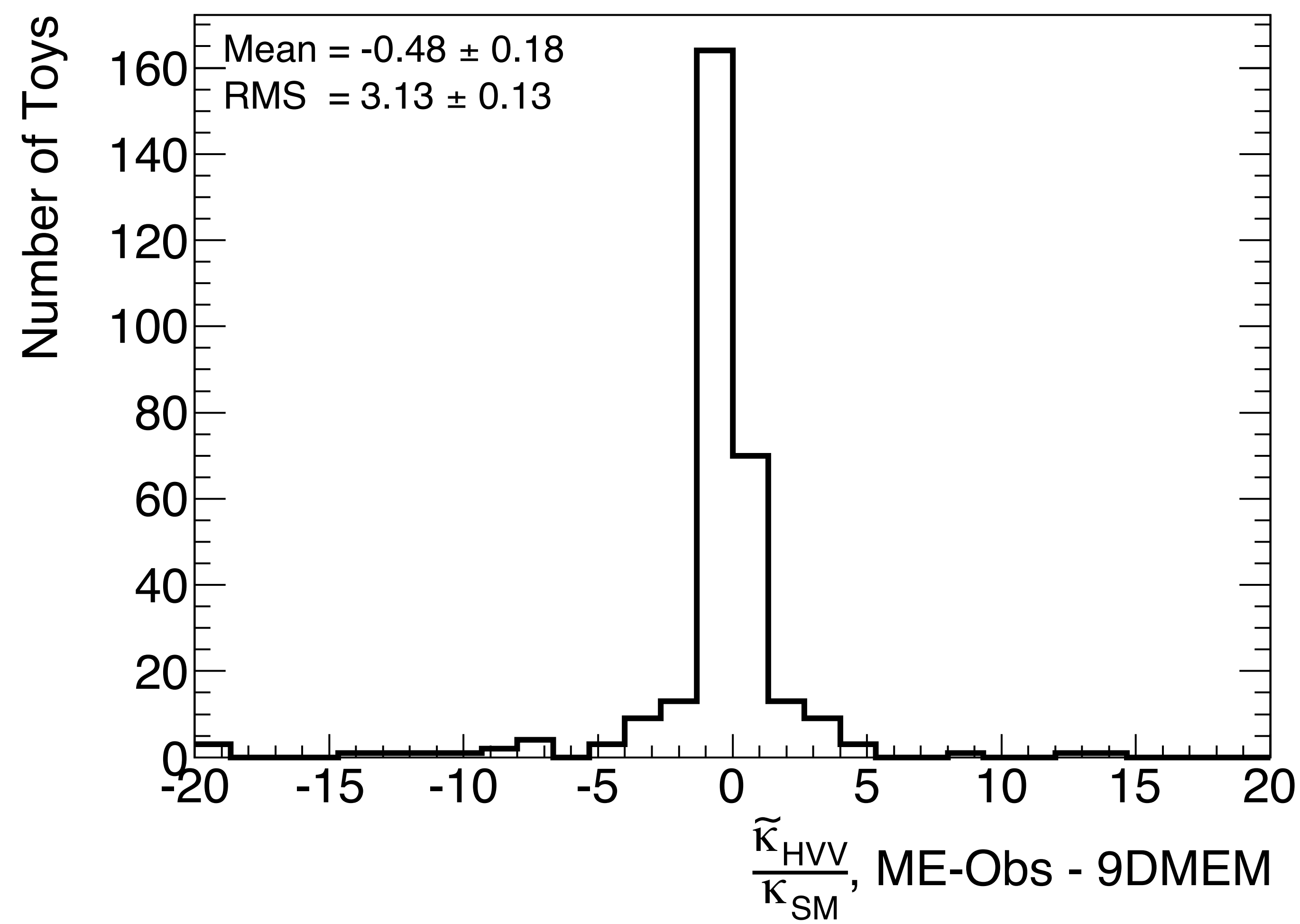




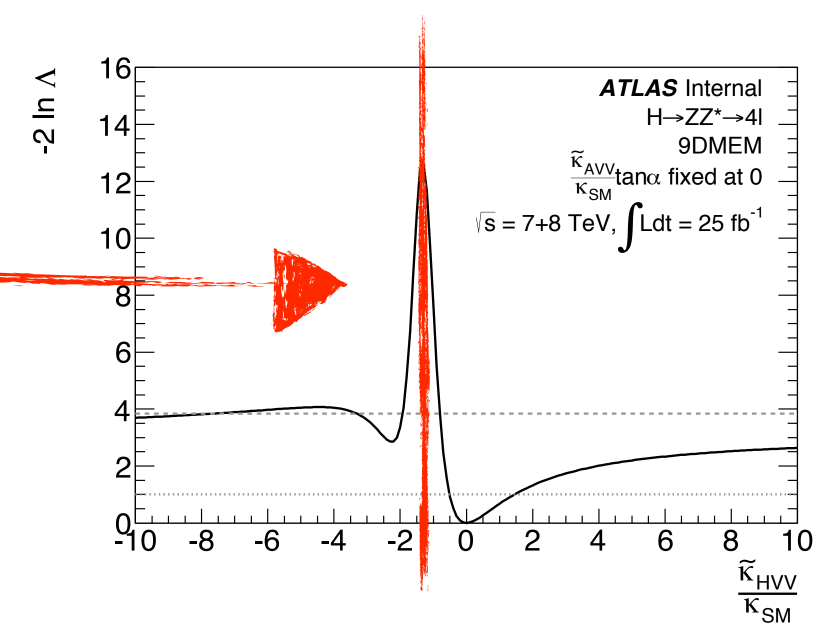
Compatibility of the two methods

g2/g1





Gaps at peak expected exclusion near -1.5



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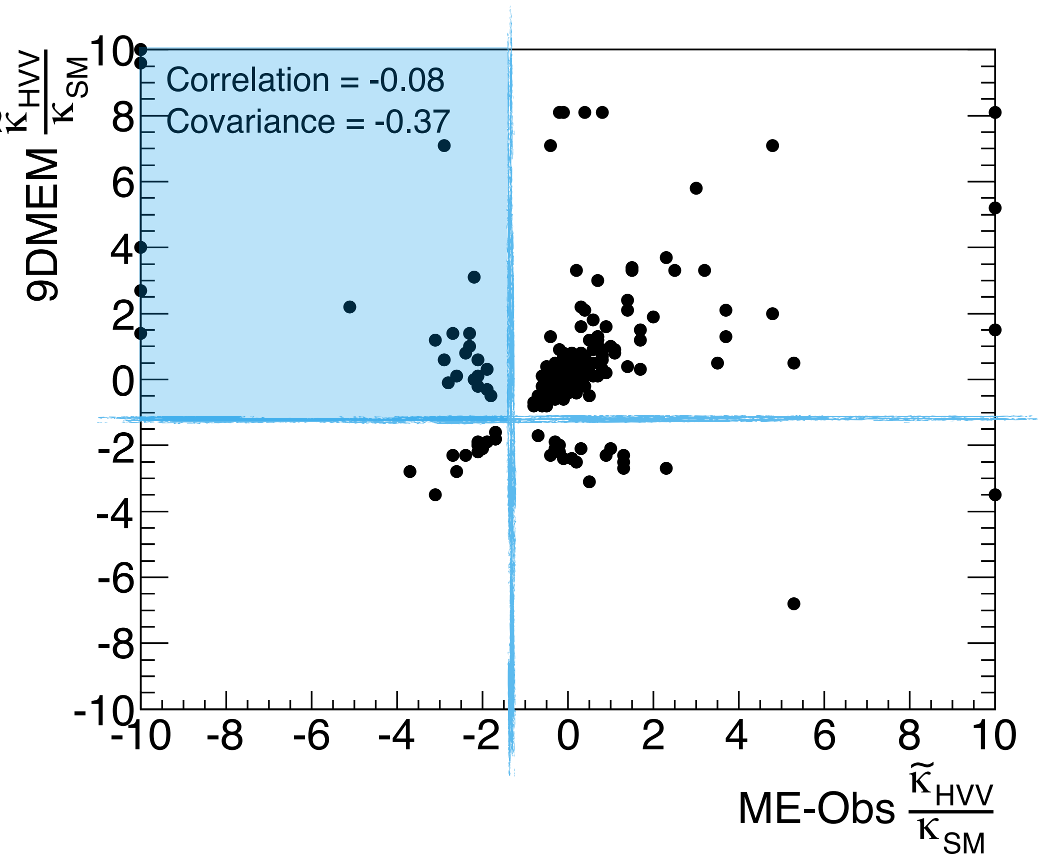
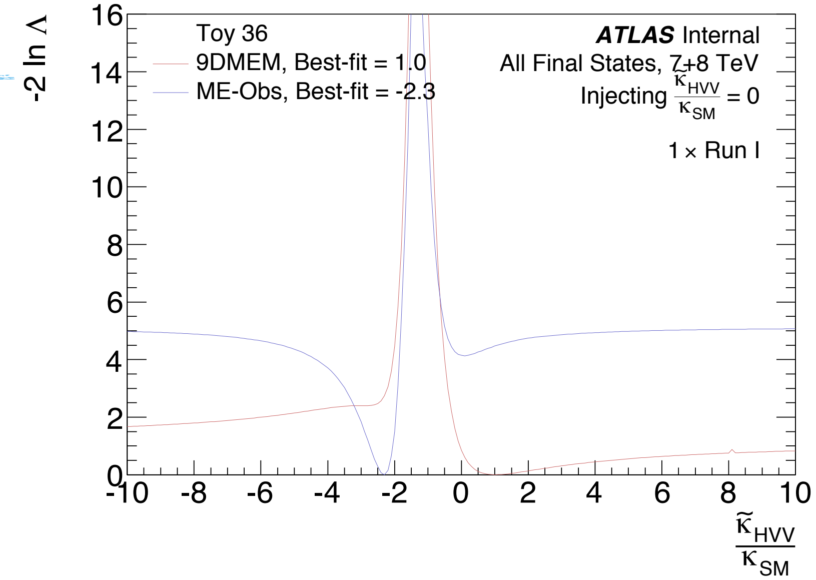
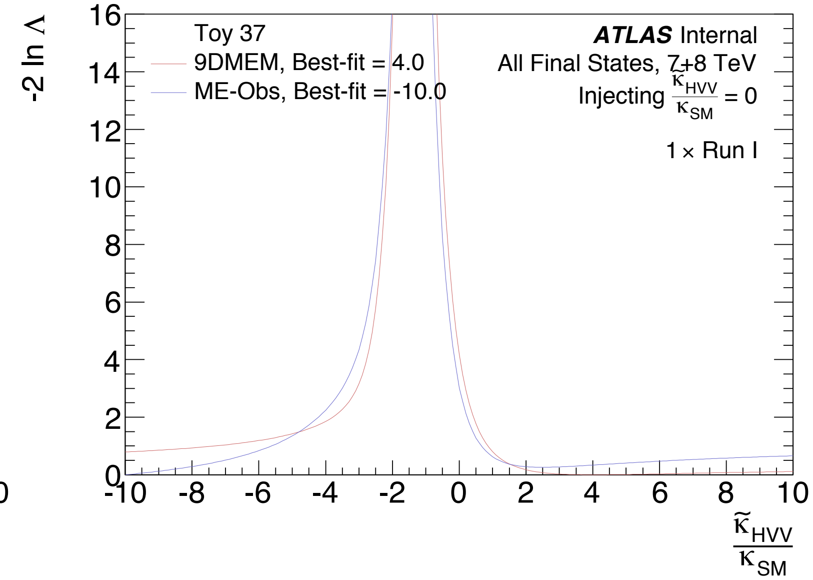
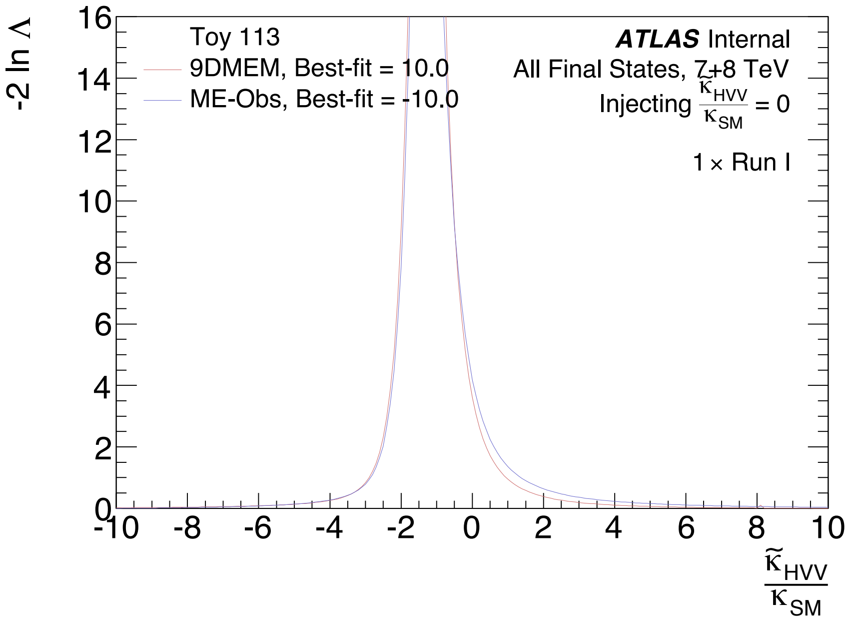
Distributions from Toys: g_2/g_1

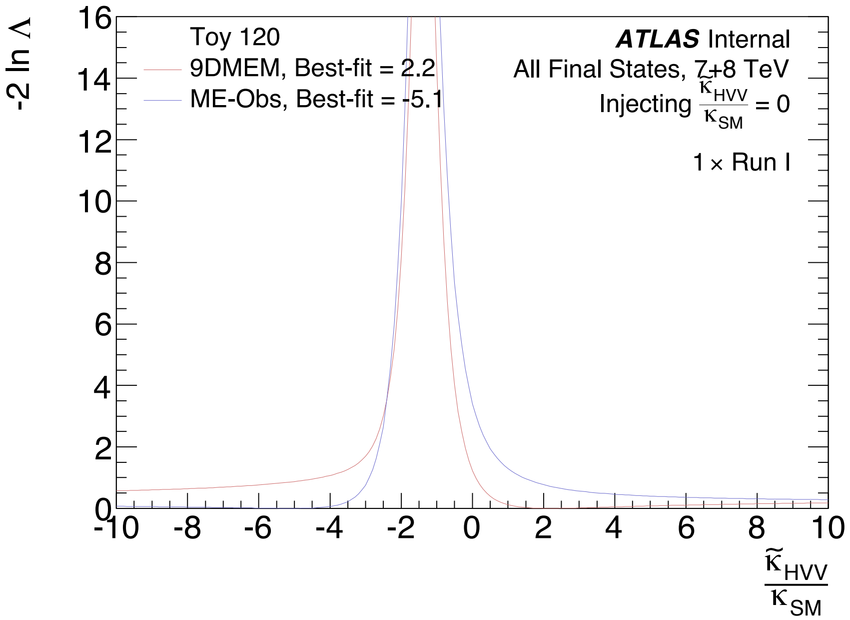


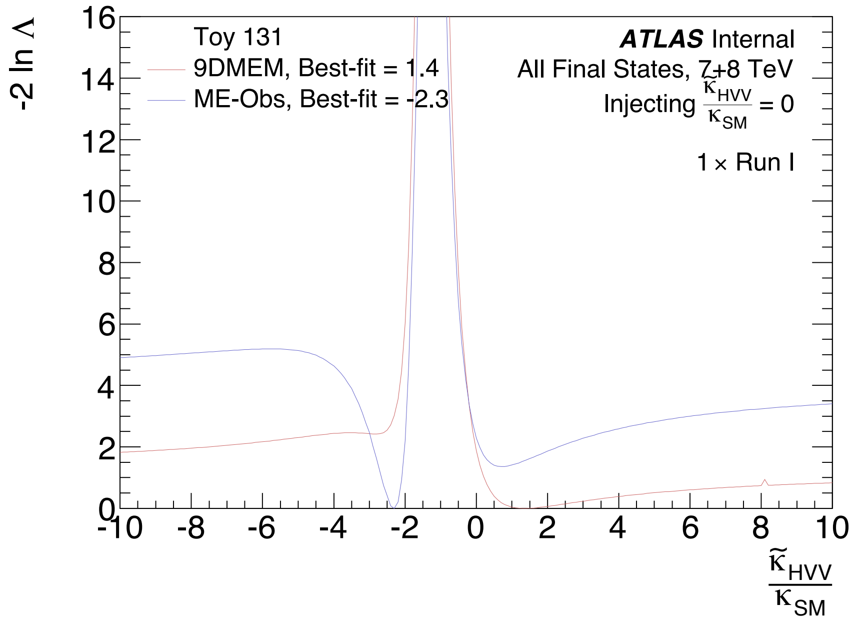
* Example toys for 9DMEM>-1.5 and ME-Obs<-1.5…





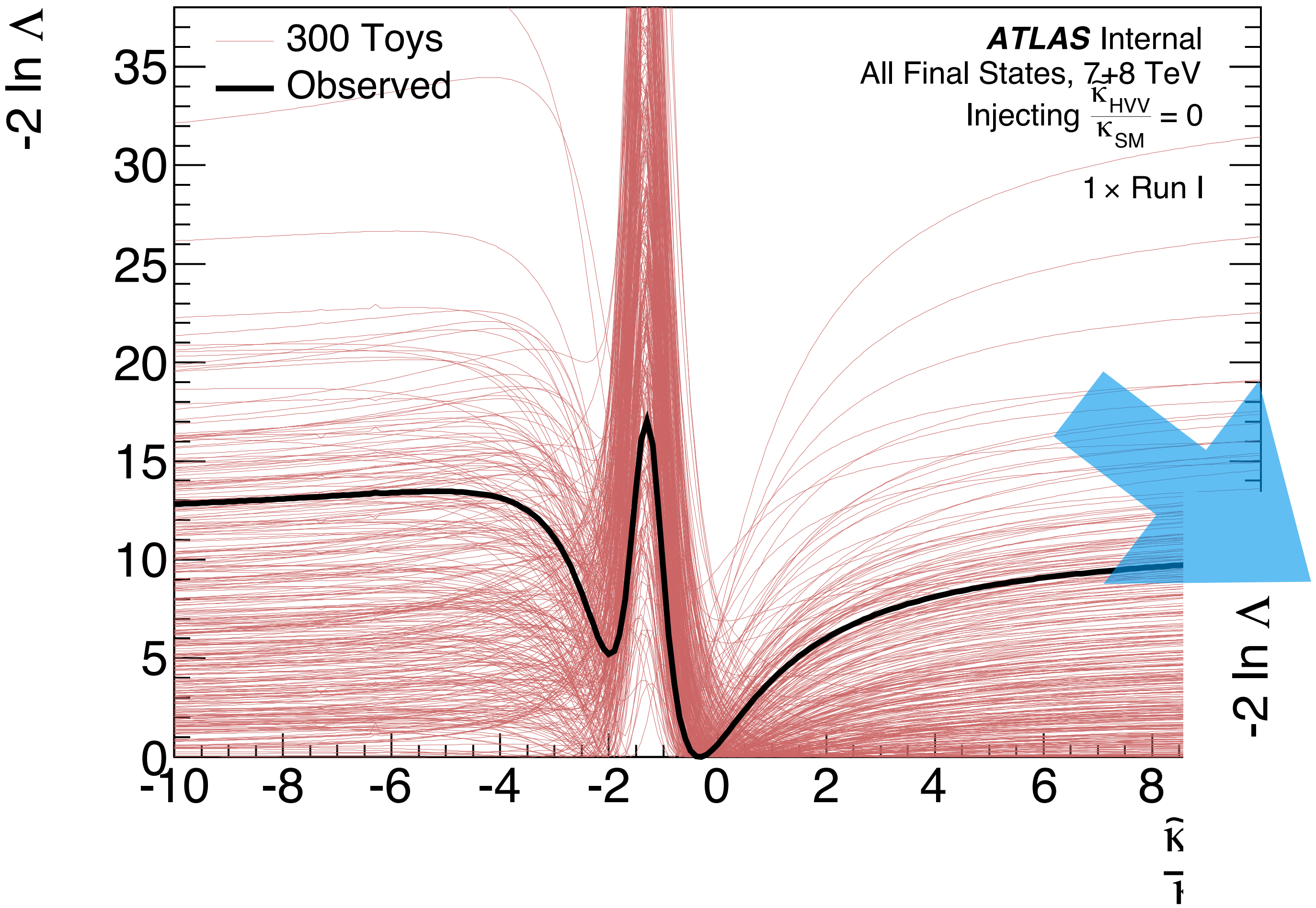




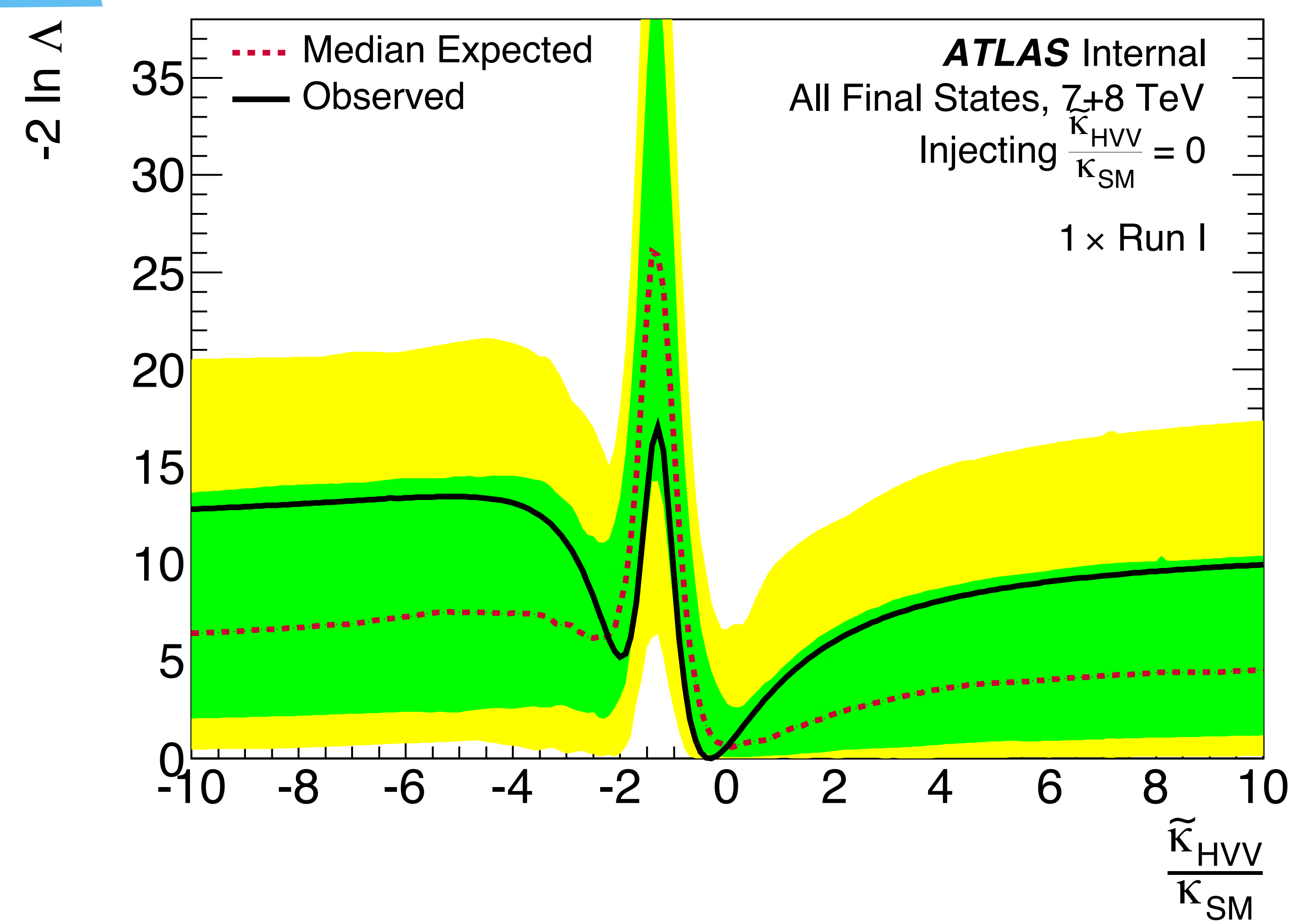


Post-analysis

9DMEM



* Distribution of toys used to produce expected uncertainty band for comparison with data



Dashed red: Median

Green band: 68% interval

Yellow band: 95% interval

Comparison to CMS

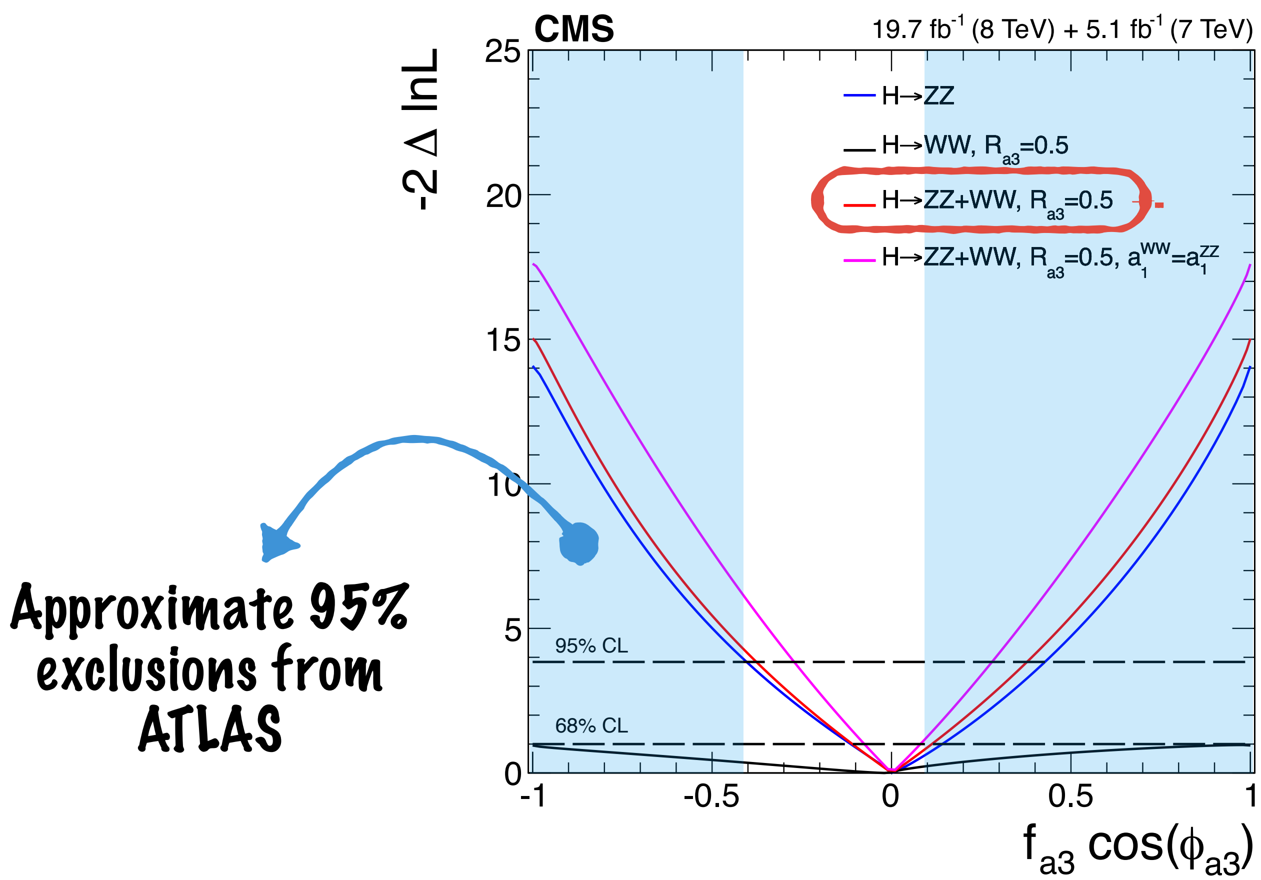
- CMS spin/CP combination published in November, 2014 [arXiv:1411.3441]

- Some differences w.r.t. ATLAS
  - Results reported in terms of admixtures $f_{a2}(=f_{g2})$ and $f_{a3}(=f_{g4})$
  - More data: 7 TeV included for $H \rightarrow WW^* \rightarrow e\nu\mu\nu$
  - Multiple parameters allowed to float at the same time (analogous to a simultaneous fit for g_4/g_1 and g_2/g_1)
  - More inclusive selection: 50 events passing in ZZ* final state, 56 expected

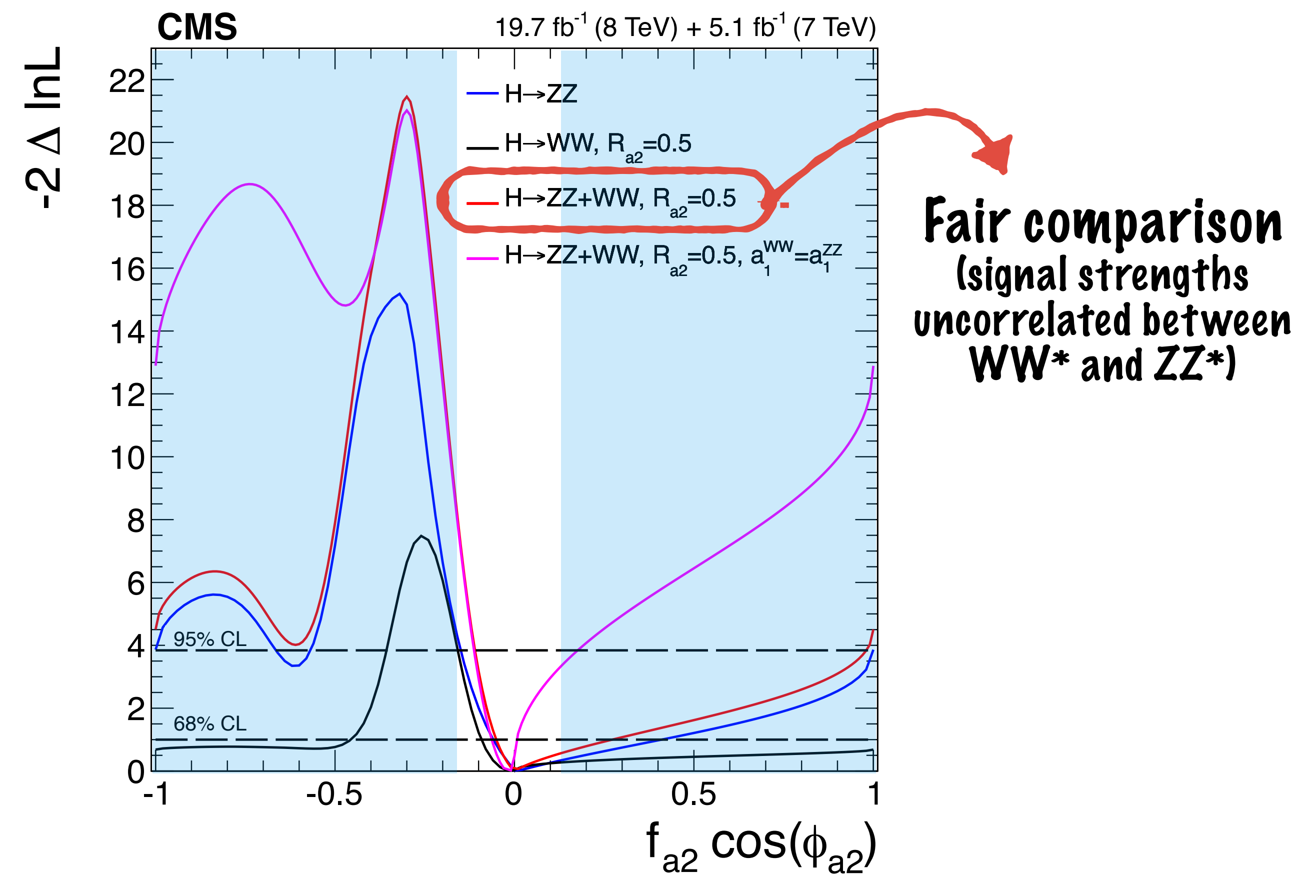
Comparison to CMS

* CMS spin/CP combination published in November, 2014 [arXiv:1411.3441]

BSM CP-odd fraction (calculated from g_4/g_1)



BSM CP-even fraction (calculated from g_2/g_1)

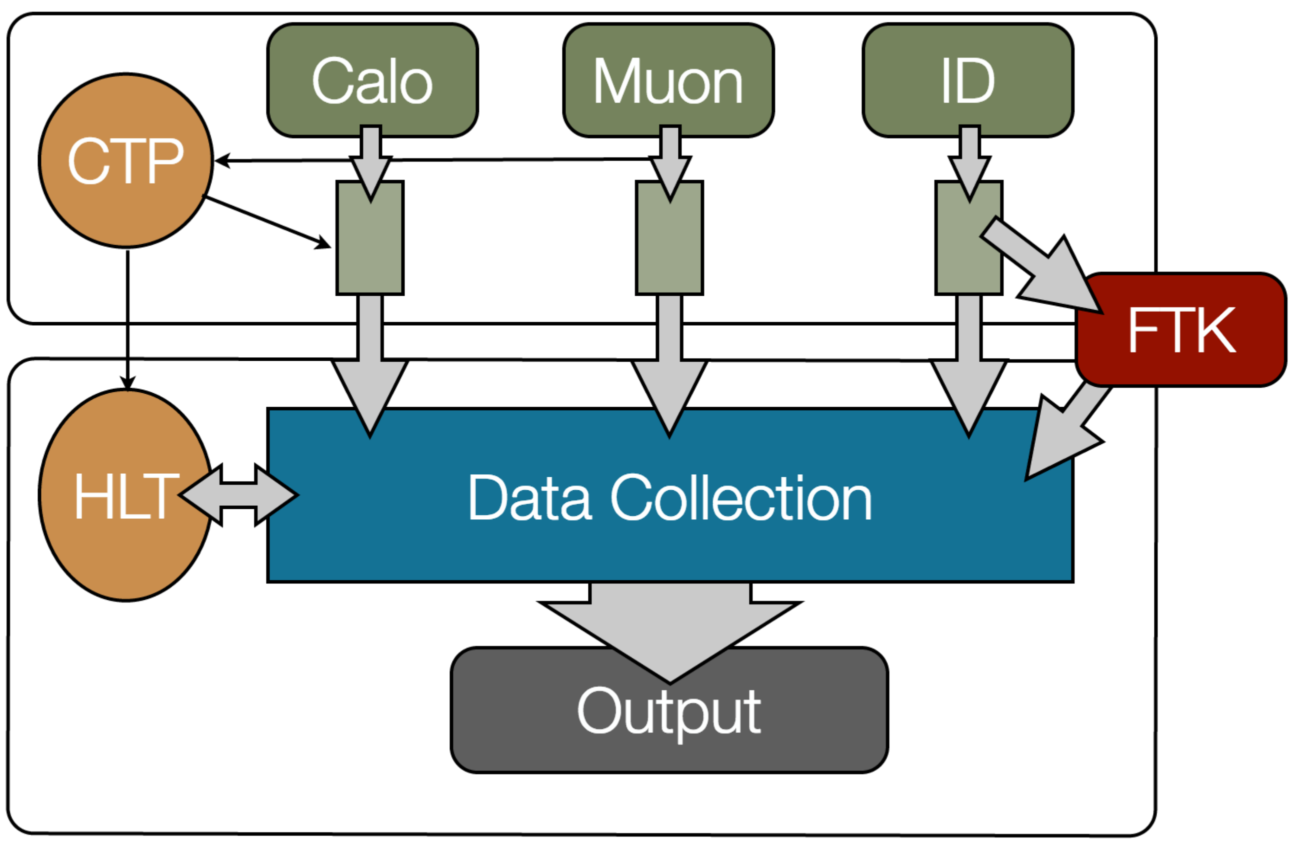


Experiment & Channels	95% CL intervals	
	BSM CP-odd contribution	BSM CP-even contribution
ATLAS: WW, ZZ	$-2.18 < g_4/g_1 < 0.83$ $-0.41 < f_{a3}*\cos(\phi_{a3}) < 0.09$	$-0.73 < g_2/g_1 < 0.63$ $-0.16 < f_{a2}*\cos(\phi_{a2}) < 0.12$
CMS: WW, ZZ	$-0.27 < f_{a3}*\cos(\phi_{a3}) < 0.28$	$-0.11 < f_{a2}*\cos(\phi_{a2}) < 0.17$

Fast **T**rac**K**er Trigger Upgrade

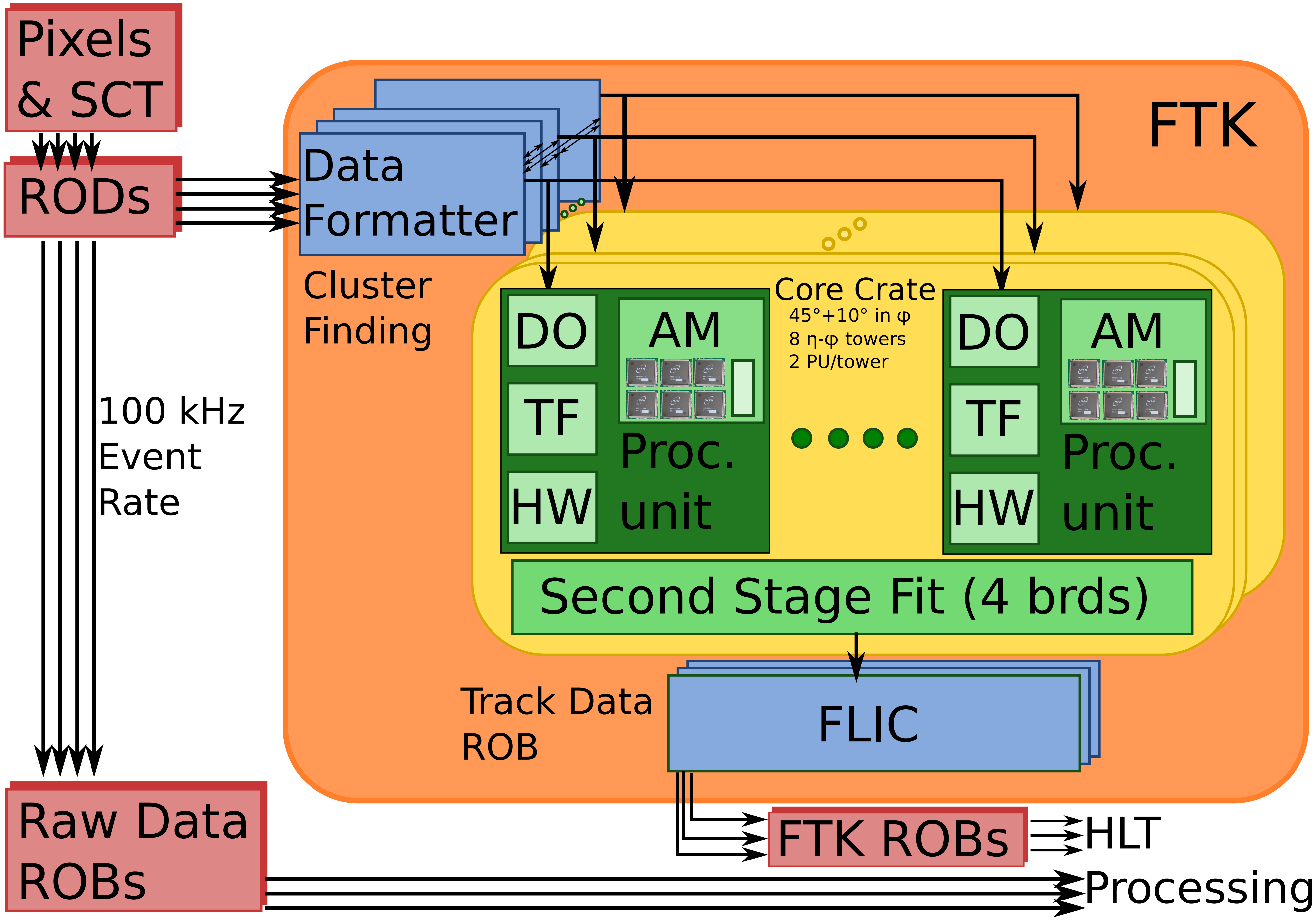
FTK Overview

* Track reconstruction in the trigger is challenging and slow
* FTK is a hardware solution designed to do full track reconstruction at the O(100 KHz) level 1 output rate
  * helix parameters and χ^2 values get passed to level 2, freeing up resources for more complicated trigger decisions
  * b-jets, τ leptons, track-MET, etc.
* Parallel pattern matching for hits with Associative Memory (AM)



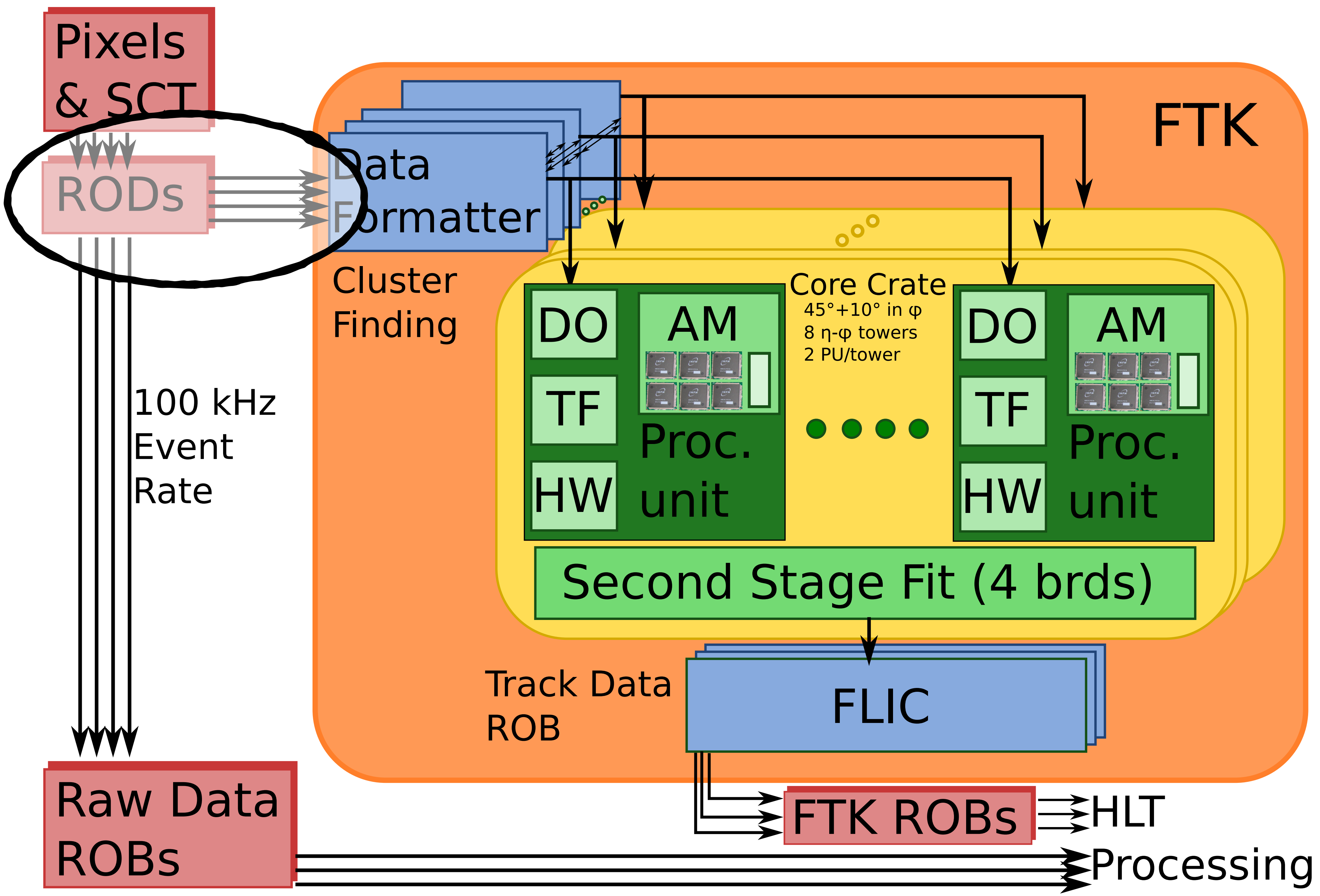
FTK Design

A potpourri of boards and technologies



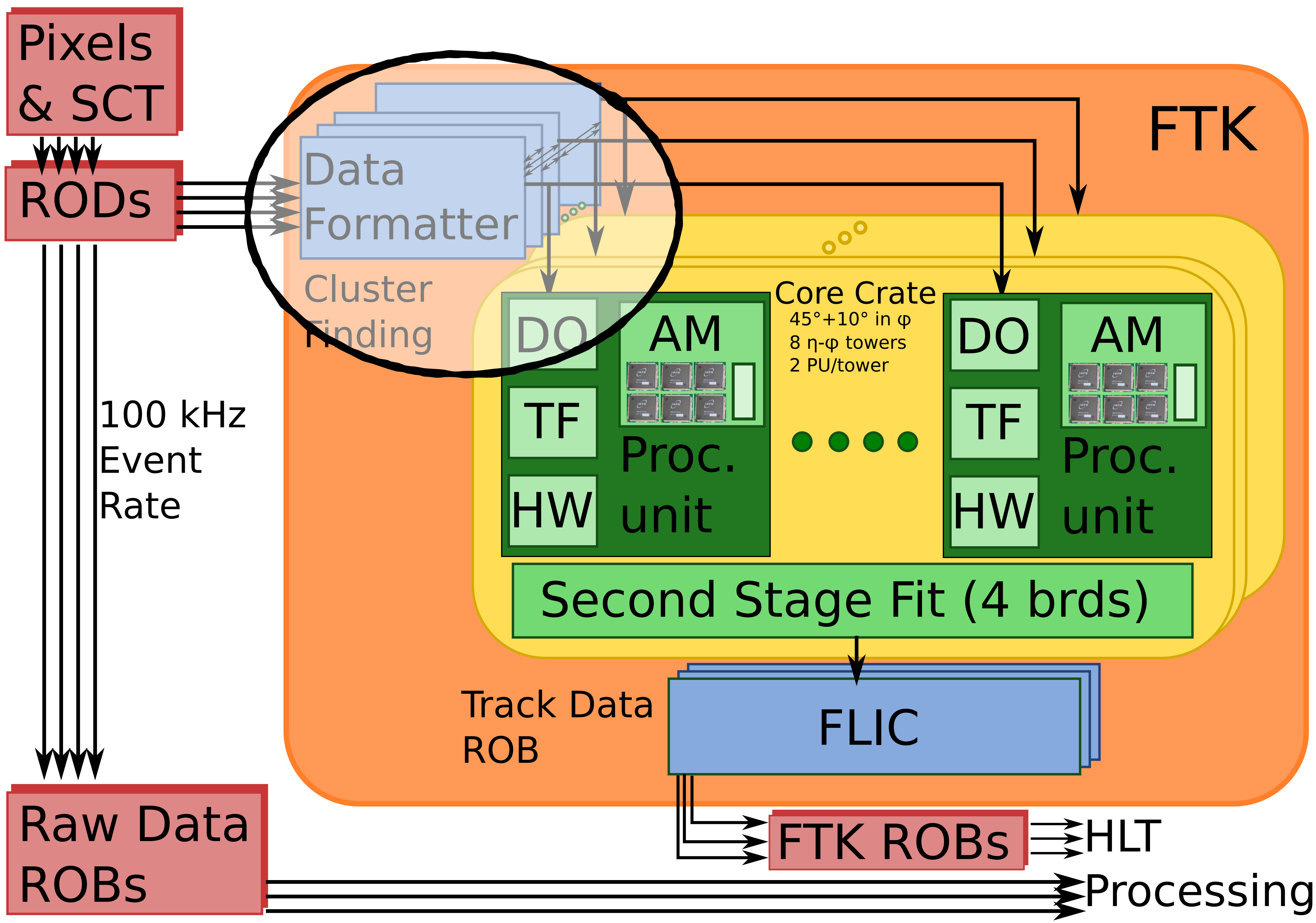
FTK Design

Dual HOLA splits ROD data streams for DAQ and FTK



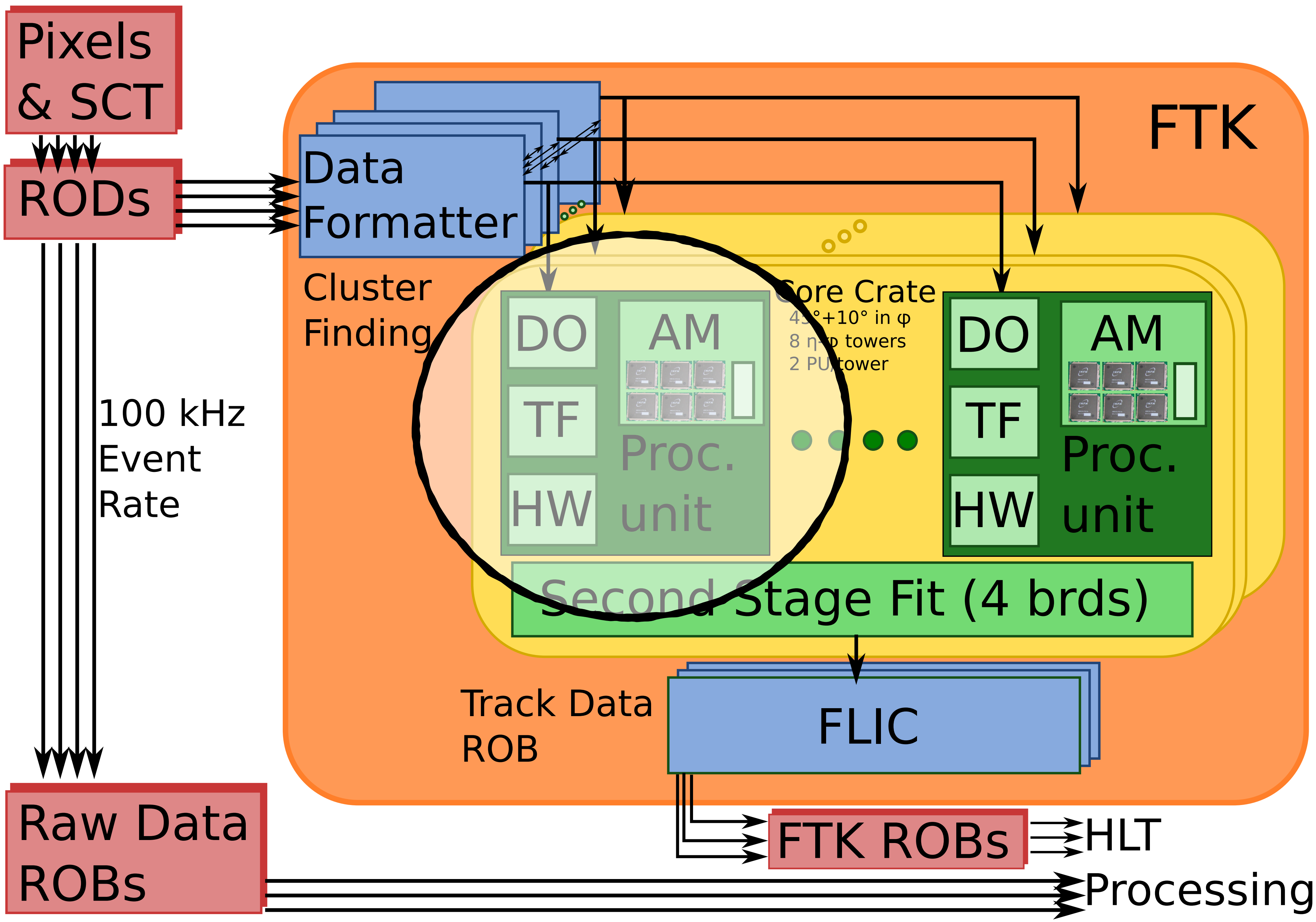
FTK Design

An input mezzanine clusters incoming hits, and the Data Formatter sorts hits into η-ϕ towers (64 FTK towers)



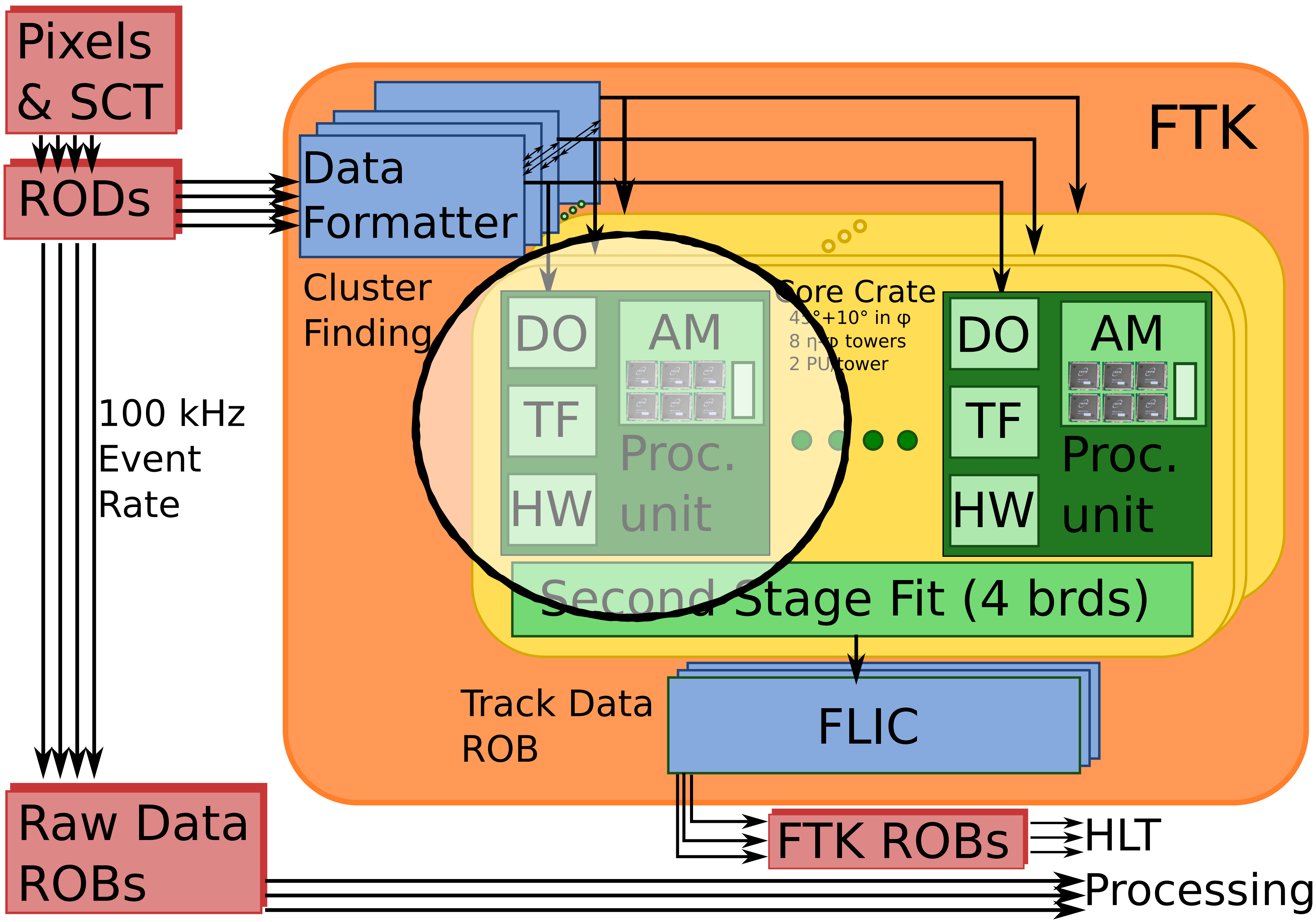
FTK Design

AUX calculates course resolution hits ("superstrips") and sends them to AM for pattern matching



FTK Design

AM sends matched patterns ("roads") to AUX and χ^2 values are calculated with full resolution hits from 8 layers



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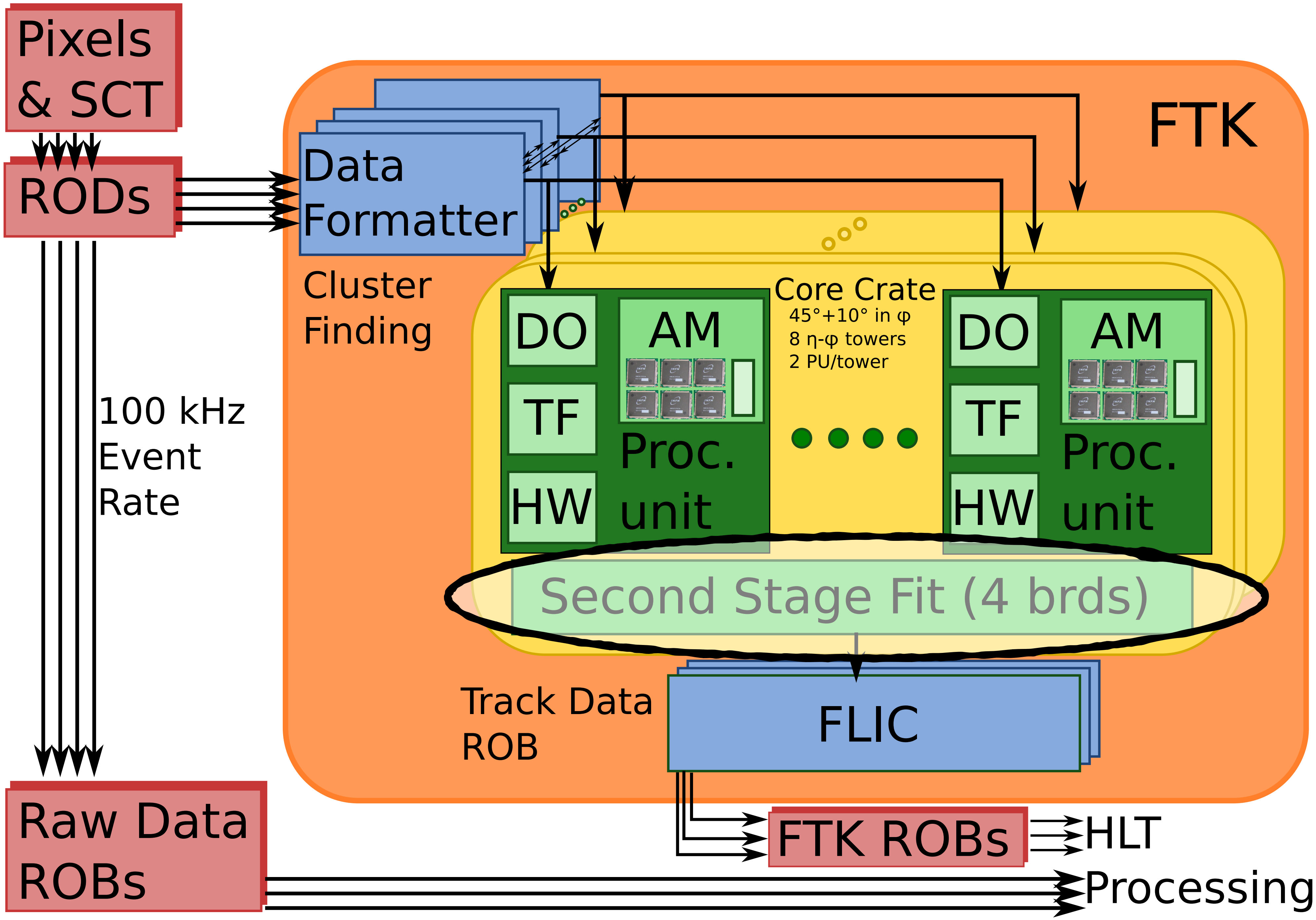
FTK Design

SSB performs extrapolation to 12 layers using candidate tracks passing first stage, calculates helix parameters



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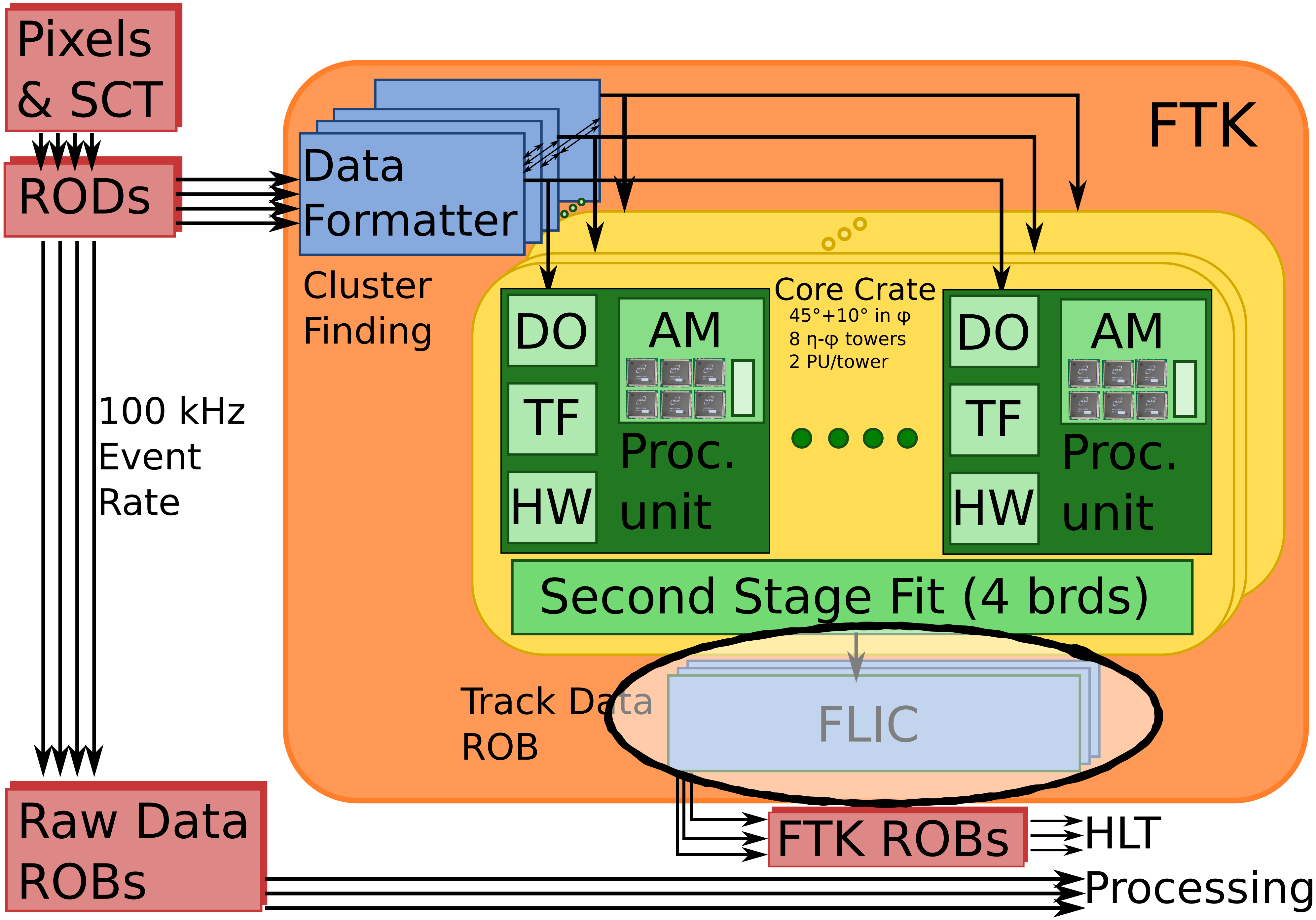
FTK Design

FLIC formats output for HLT



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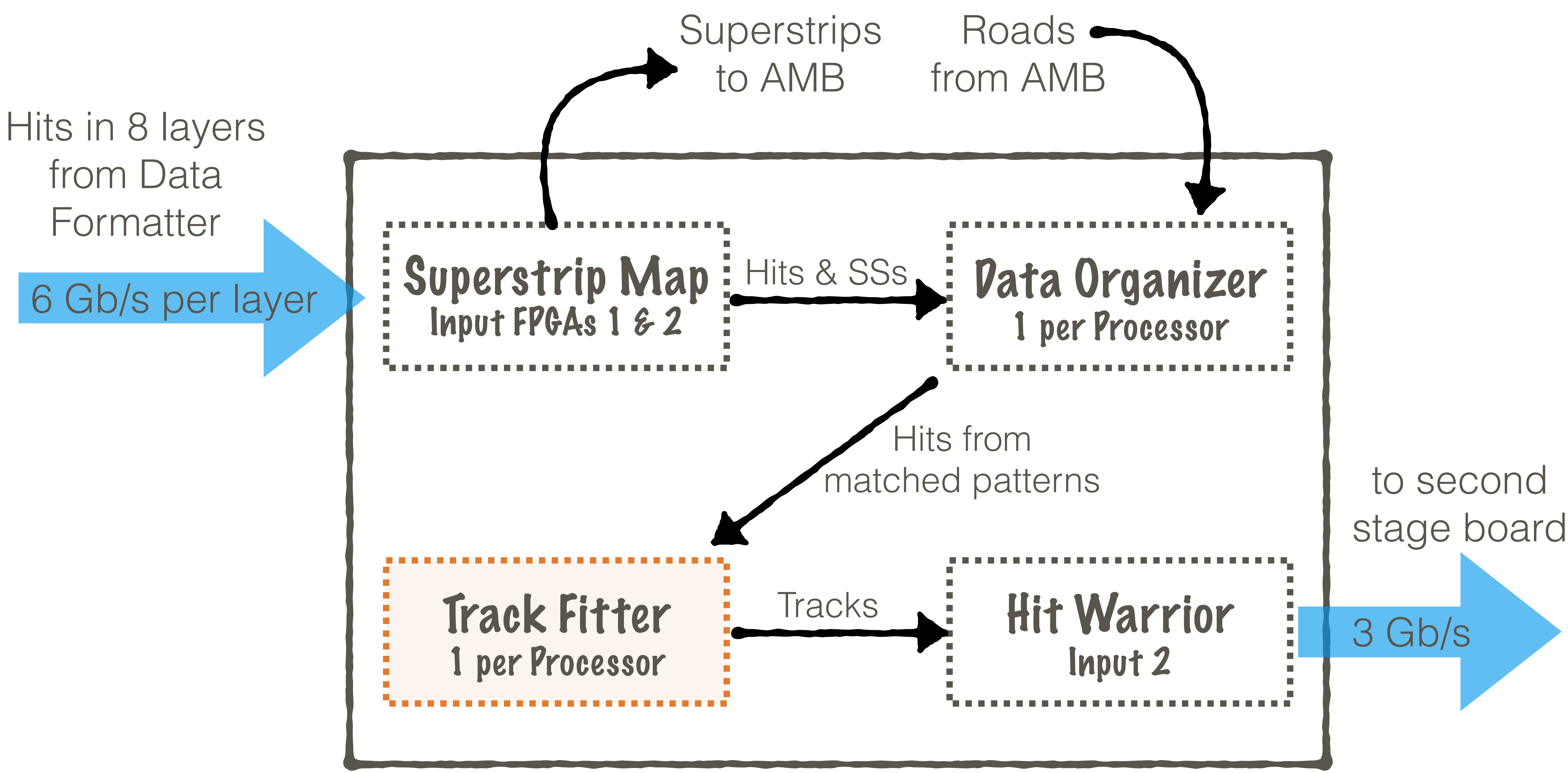
More detail on the AUX

- Full FTK system contains 128 AUX boards
- 2 “Input” FPGAs + 4 “Processor” FPGAs per board



Track Fitter

* χ^2 values calculated using linear approximation, multiplying hits by pre-stored constants
    * 5 Mb of constants stored on each FPGA
    * Mixture of fixed and floating point formats
* Calculation is done for all combinations of hits in each road (there are often multiple hits per layer)
* Hits are sometimes missing in layers due to detector inefficiency
    * Solution: If one layer is missing, calculate a "guessed" hit value that minimizes the χ^2
* Design spec: average of 1 fit/ns per FPGA, 200 MHz clock speed
* Functional firmware in place: ~25,000 lines VHDL, ~10 W
    * Ongoing work to increase speed (will be taken over by Karol Krizka)

FTK Installation Schedule

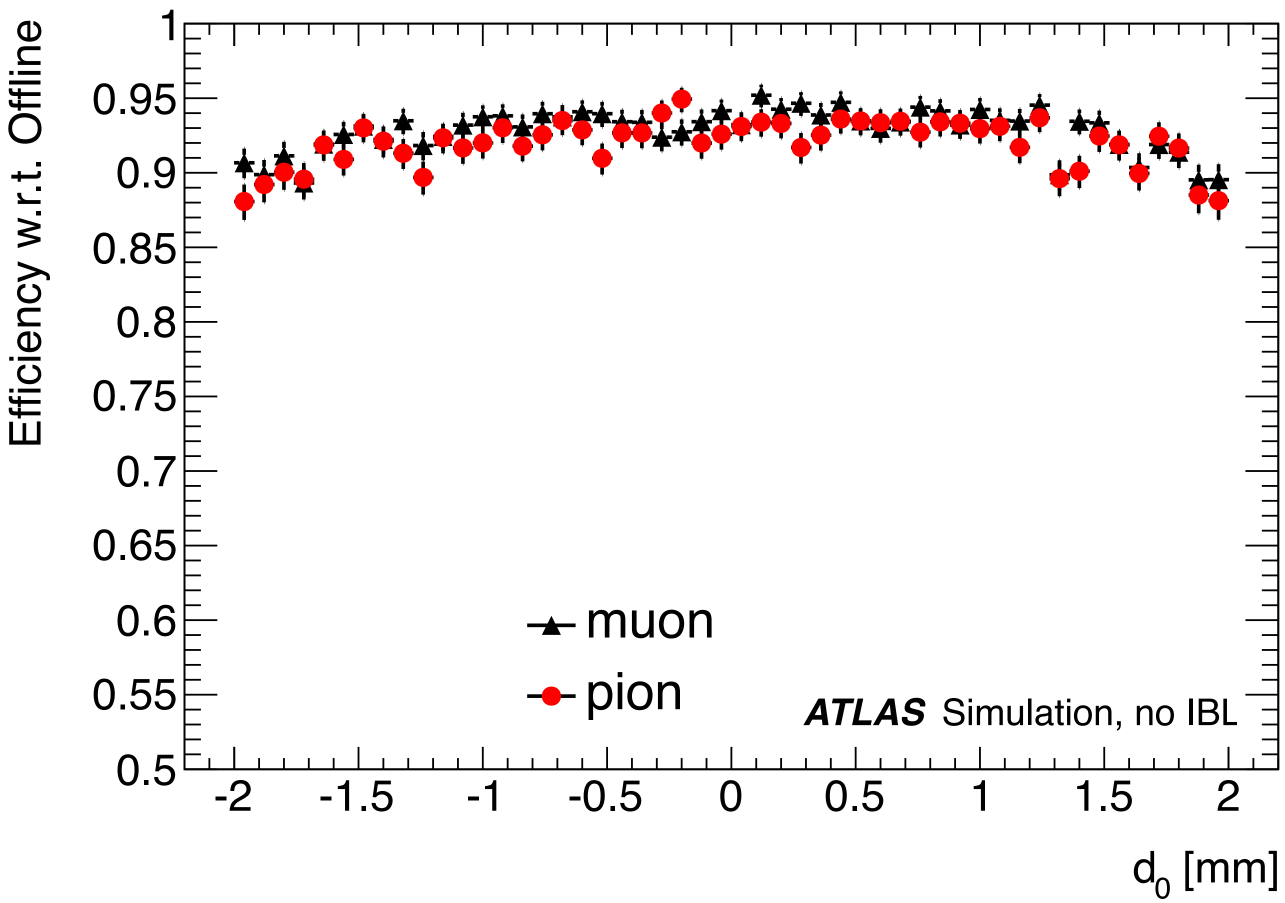
	IM	DF	AUX	AMB	AM	SSB	FLIC	Milestones	Expected
1st	a few	a few	1	1	05	1	1	Included TDAQ	09/2015
2nd	128	32	16	1	06	8	2	Included TDAQ	11/2015
3rd	128	32	16	16	06	8	2	Full barrel (mu=40)	02/2016
4th	128	32	32	32	06	16	2	Full detector (mu=40)	08/2016
Final	128	32	128	128	06	32	2	TDR Specs	2018 / Lumi driven

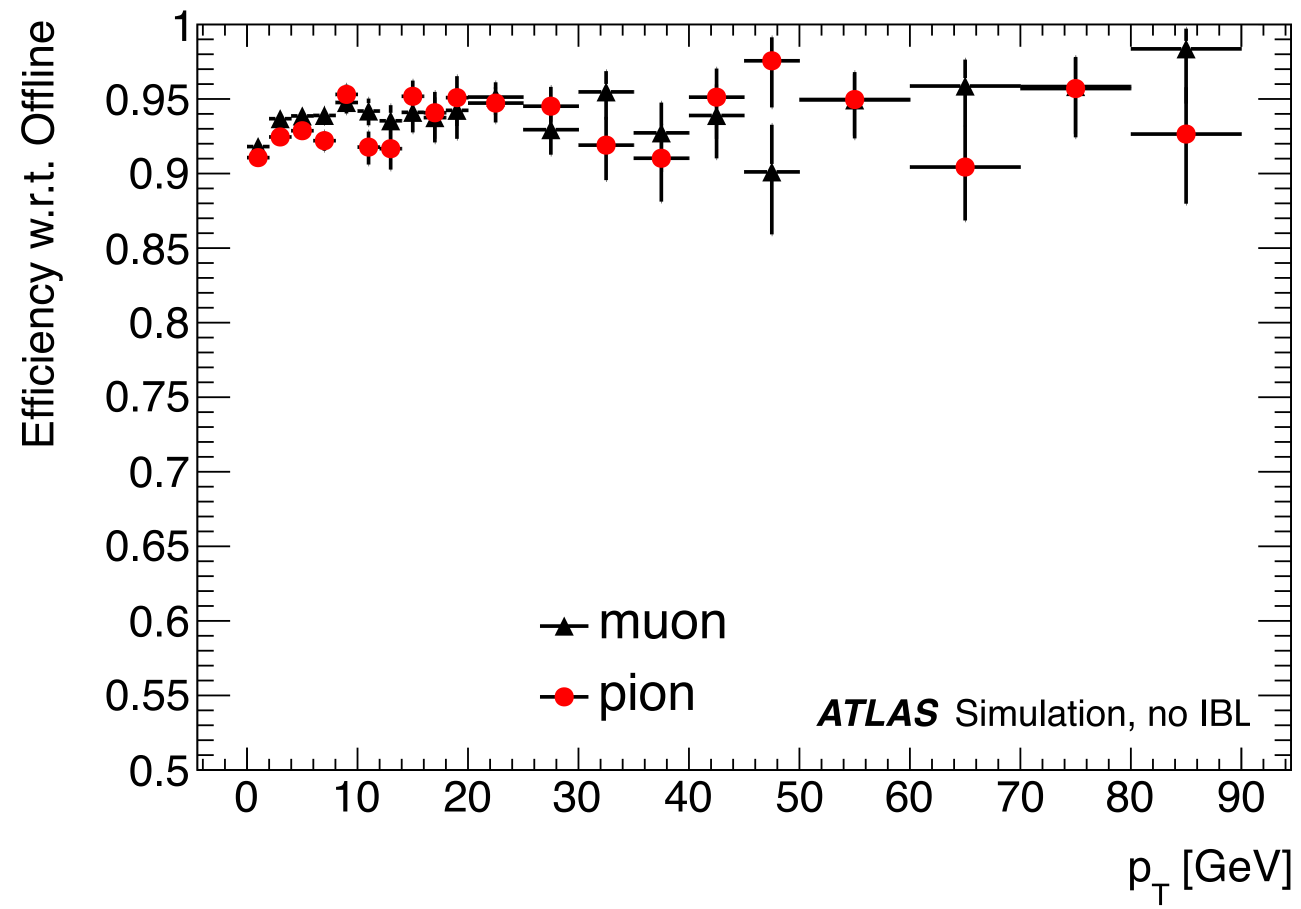
- Dual-output HOLA cards installed in 2012-2013
- "Vertical slice" tests done with live data in 2013: just testing HOLAs and pattern matching in slice of detector
- Recent data tests during M7

- AUX status: TDR done, PRR early 2015, testing prototypes at Chicago and CERN

Performance in Simulation

- Efficiency evaluated w.r.t. offline for single muons & pions
  $= N_{Off}(dR_{Off\text{-}FTK} < 0.05) / N_{Off}$

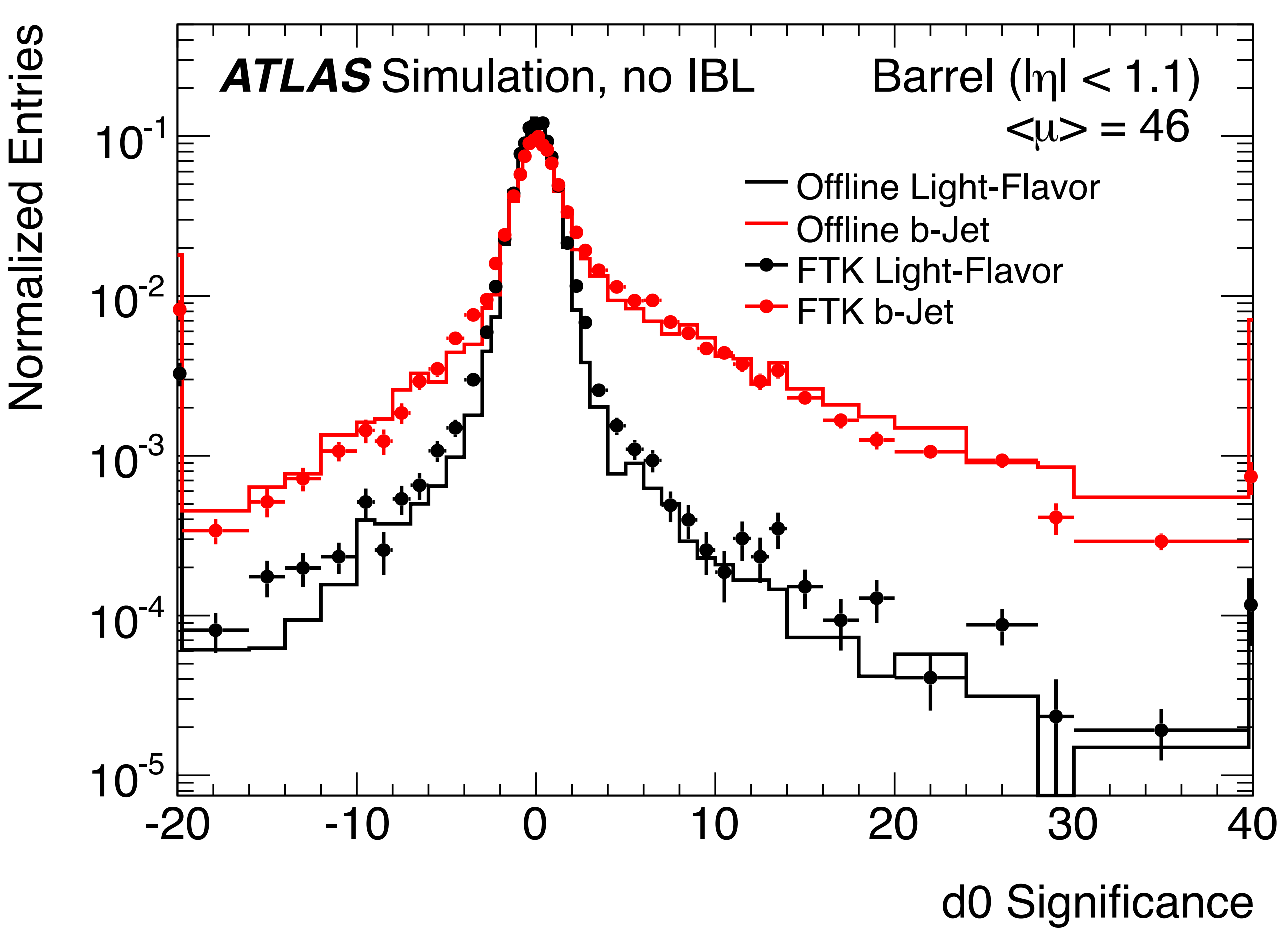


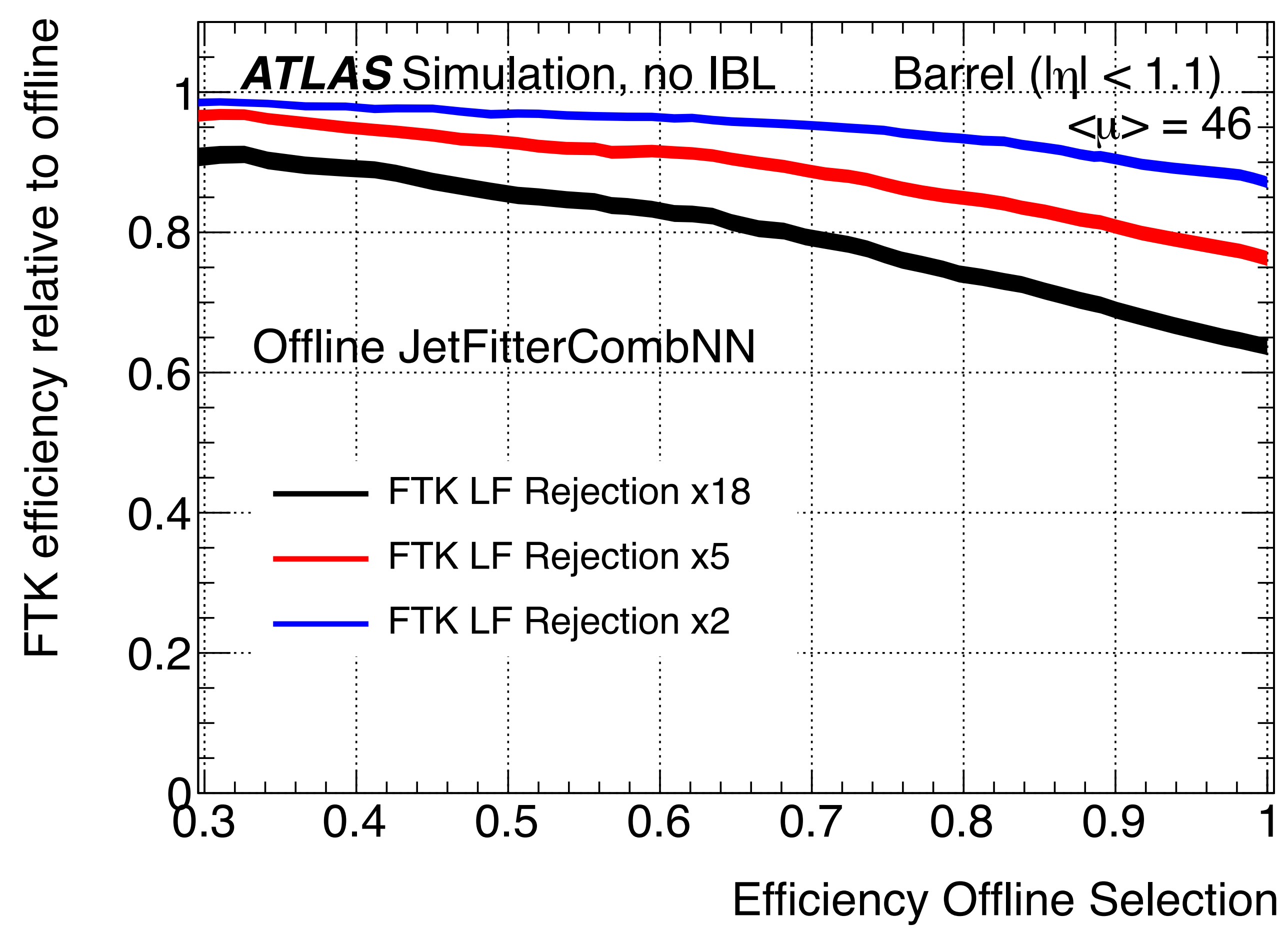


- Efficiency w.r.t. truth ~ 90% for muons, lower for pions due to more hadronic interactions

Performance in Simulation

- Simple b-tagger built using FTK d_0 significance
- b-tag trigger efficiency calculated for three different rejections w.r.t. offline b-tag efficiency





Conclusion

* FTK will be a critical tool for doing physics at high pile-up
* Full detector implementation by 2017
* Start thinking about final states with lots of b's and τ's!