HIGGS COMBINATION EXPERIENCE

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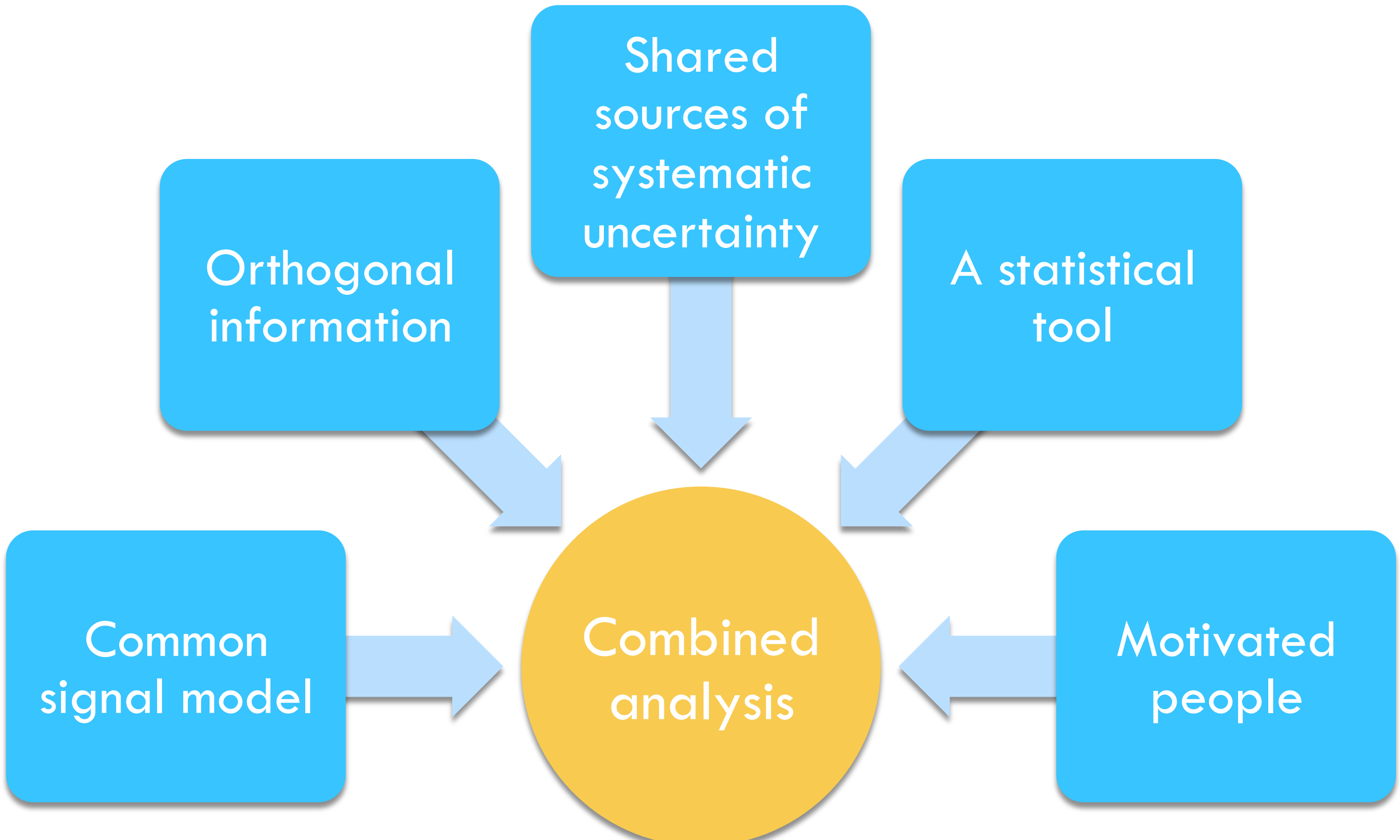
The pillars of combinability



Common signal model

- Usually OK for SM measurements.
  - But predictions should be "standardized":
    - Which generator.
    - Which sources of uncertainty.
    - Which p_T spectrum.
    - Which normalization (cross-sections).
    - Etc.
  - For Higgs, this was obviated by the LHC Higgs Cross Section Working Group.
- *Much more of an issue for BSM.*

Orthogonal information

- In general, orthogonalise event samples:
  - Event categories.
  - Channels require b-tag, others veto b-tag.
  - Exclusive jet bins.
  - Etc.
- Same events have complementary information:
  - Eminently the case for m_W: M_T, p_T, and MET.
  - Simultaneous description needed (3D analysis):
    - For instance, m_H in CMS $H \rightarrow ZZ \rightarrow 4\ell$ from $m_{4\ell}$, $\sigma_{m4\ell}$, K_D.

Sources of systematic uncertainty

Experimental

- Jet energy scale variations are due to: flavor corrections, **material**, etc.
- Lepton energy scale variations are due to: **material**, B-field, alignment.
- Luminosity.

Theory

- Underlying event: Pythia tune X vs. tune Y vs. Herwig.
- "Scale variations".
- PDF uncertainties.
- Parametric uncertainties.

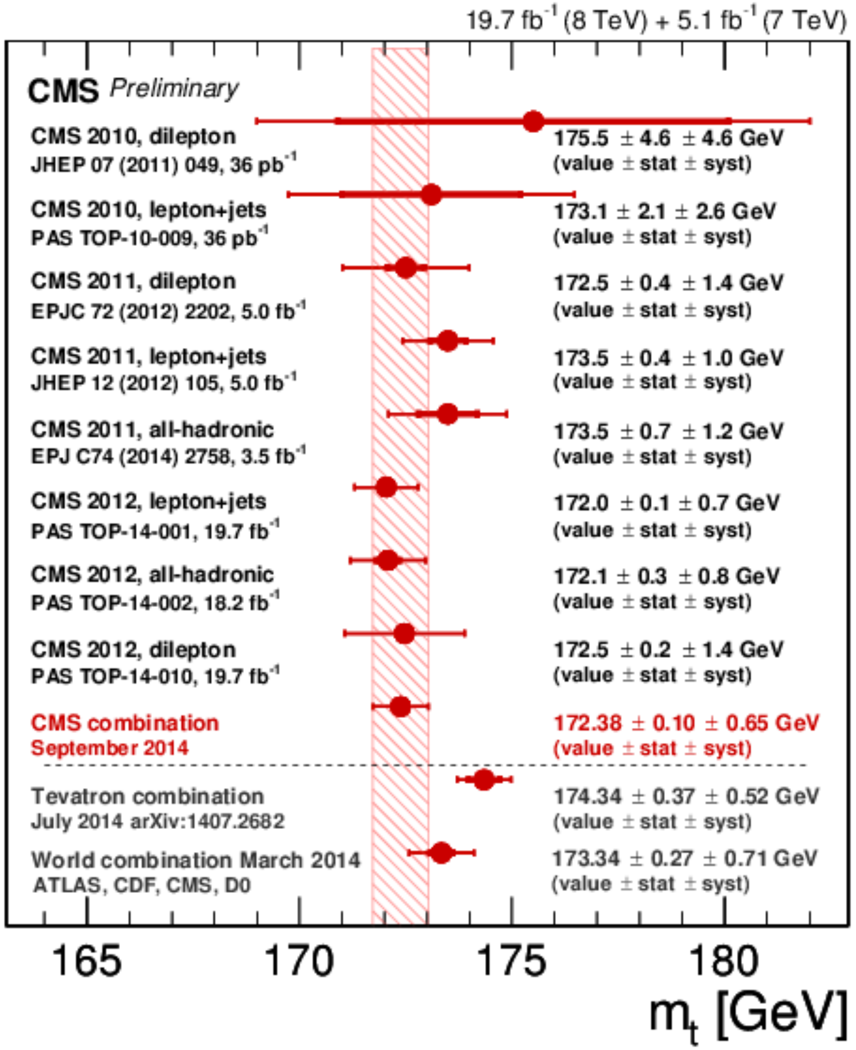
- And in every case: what do the ranges of variation mean?
  - "Any value is as likely as any other" or "some values more likely than others"?

A tool or algorithm

- Several combinations across LHC experiments performed up to now.
- Seem to have either used:
  - Best Linear Unbiased Estimator (BLUE), or
  - (Profile) Likelihood.

Some combinations

- LHC+Tevatron
  - Top mass: BLUE
- ATLAS+CMS
  - Top cross-sections: BLUE
  - Higgs limits (2011): Profile Likelihood
- CMS+LHCb
  - $B_s \to \mu\mu$: Profile Likelihood



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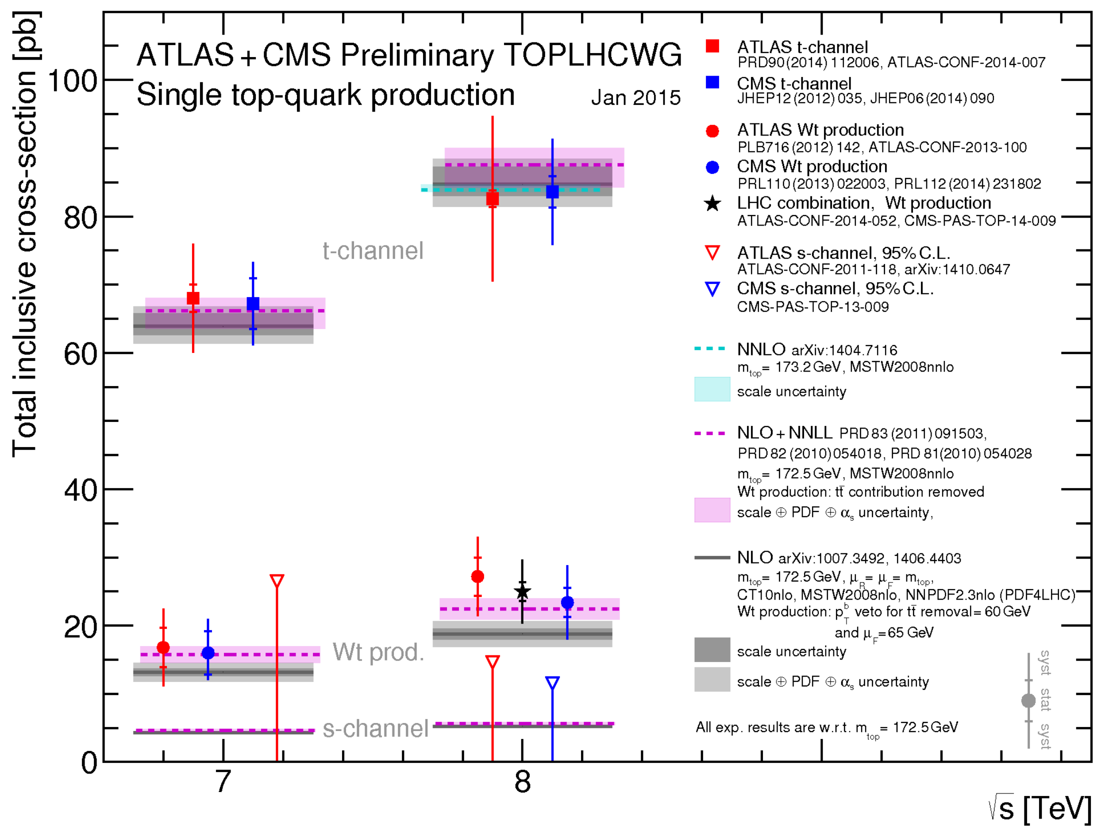

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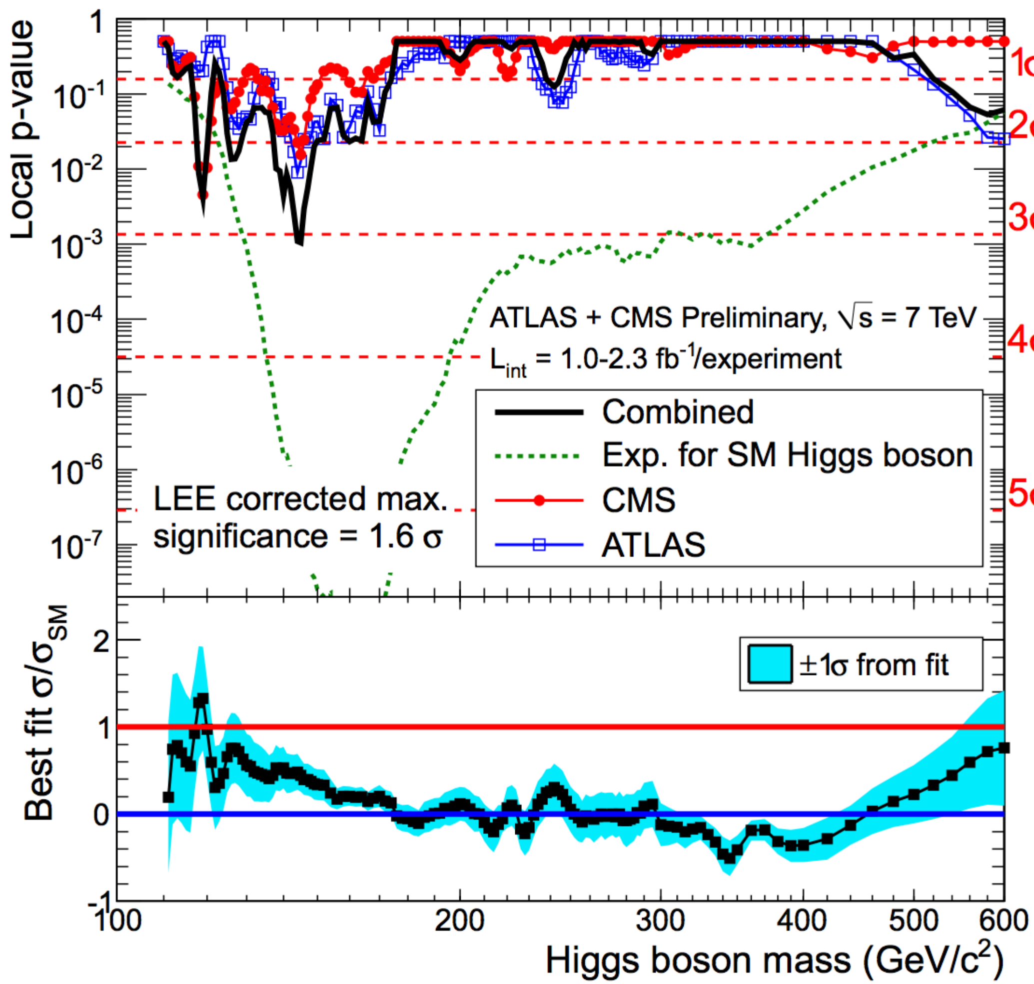

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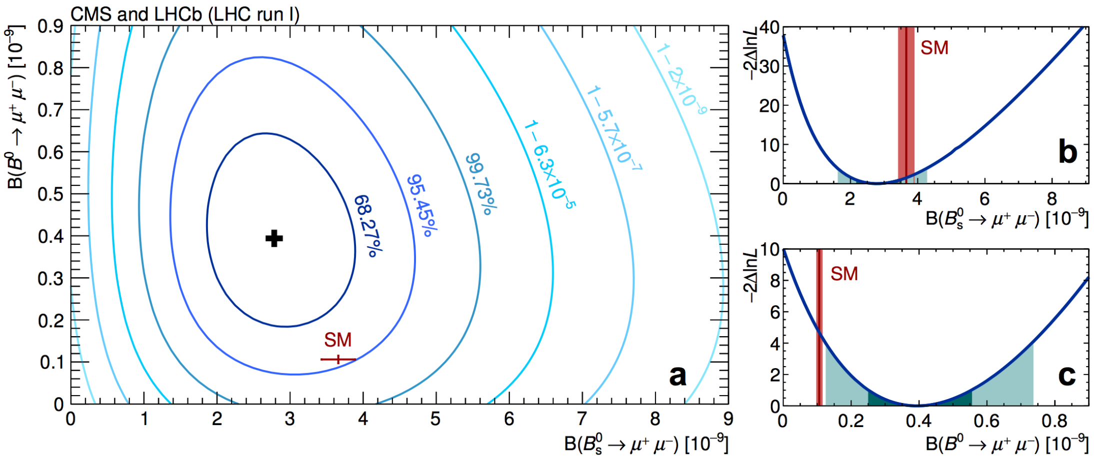


BLUE – Best Linear Unbiased Estimator

- Minimises the total uncertainty of the combined result.
- Assumes that all uncertainties (stat. and syst.) are Gaussian.
- Linear correlations are taken into account.
  - Effect of the correlation assumptions on the final result can be evaluated.

BLUE in action

- Assume a correlation structure between the sources of uncertainty:

	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{ATL-TEV}$	$\rho_{CMS-TEV}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
b-tag	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
LepPt	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
BGMC†	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
BGData	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0

BLUE in action

- Tabulate all the sources of uncertainty for each result being combined:

	Input measurements and uncertainties in GeV											
	CDF				D0		ATLAS		CMS			World
Uncertainty	l+jets	di-l	all jets	E_T^{miss}	l+jets	di-l	l+jets	di-l	l+jets	di-l	all jets	Combination
m_{top}	172.85	170.28	172.47	173.93	174.94	174.00	172.31	173.09	173.49	172.50	173.49	173.34
Stat	0.52	1.95	1.43	1.26	0.83	2.36	0.23	0.64	0.27	0.43	0.69	0.27
iJES	0.49	n.a.	0.95	1.05	0.47	0.55	0.72	n.a.	0.33	n.a.	n.a.	0.24
stdJES	0.53	2.99	0.45	0.44	0.63	0.56	0.70	0.89	0.24	0.78	0.78	0.20
flavourJES	0.09	0.14	0.03	0.10	0.26	0.40	0.36	0.02	0.11	0.58	0.58	0.12
bJES	0.16	0.33	0.15	0.17	0.07	0.20	0.08	0.71	0.61	0.76	0.49	0.25
MC	0.56	0.36	0.49	0.48	0.63	0.50	0.35	0.64	0.15	0.06	0.28	0.38
Rad	0.06	0.22	0.10	0.28	0.26	0.30	0.45	0.37	0.30	0.58	0.33	0.21
CR	0.21	0.51	0.32	0.28	0.28	0.55	0.32	0.29	0.54	0.13	0.15	0.31
PDF	0.08	0.31	0.19	0.16	0.21	0.30	0.17	0.12	0.07	0.09	0.06	0.09
DetMod	<0.01	<0.01	<0.01	<0.01	0.36	0.50	0.23	0.22	0.24	0.18	0.28	0.10
b-tag	0.03	n.e.	0.10	n.e.	0.10	<0.01	0.81	0.46	0.12	0.09	0.06	0.11
LepPt	0.03	0.27	n.a.	n.a.	0.18	0.35	0.04	0.12	0.02	0.14	n.a.	0.02
BGMC	0.12	0.24	n.a.	n.a.	0.18	n.a.	n.a.	0.14	0.13	0.05	n.a.	0.10
BGData	0.16	0.14	0.56	0.15	0.21	0.20	0.10	n.a.	n.a.	n.a.	0.13	0.07
Meth	0.05	0.12	0.38	0.21	0.16	0.51	0.13	0.07	0.06	0.40	0.13	0.05
MHI	0.07	0.23	0.08	0.18	0.05	<0.01	0.03	0.01	0.07	0.11	0.06	0.04
Total Syst	0.99	3.13	1.41	1.36	1.25	1.49	1.53	1.50	1.03	1.46	1.23	0.71
Total	1.12	3.69	2.01	1.85	1.50	2.79	1.55	1.63	1.06	1.52	1.41	0.76

Profile Likelihood interlude

[ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005]

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\tilde{\theta})}{\mathcal{L}(data\|0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|0,\hat{\theta}_0)}$	yes	Bayesian-frequentist hybrid
LHC	$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|\hat{\mu},\hat{\theta})}$	yes $(0 \leq \hat{\mu} \leq \mu)$	frequentist

- **LEP**: nuisances parameters (θ) kept at nominal values (~).
- **Tevatron**: maximise likelihood against nuisances (^).
  - Denominator considers **background-only hypothesis** (μ=0).
- **LHC**: frequentist profiled likelihood.
  - Denominator considers **global best-fit likelihood** with **floating signal strength**.
  - **Nice asymptotic properties, savings in computational power.** [arXiv:1007.1727]

BLUE vs. PL – my personal view

BLUE	Profile Likelihood

BLUE

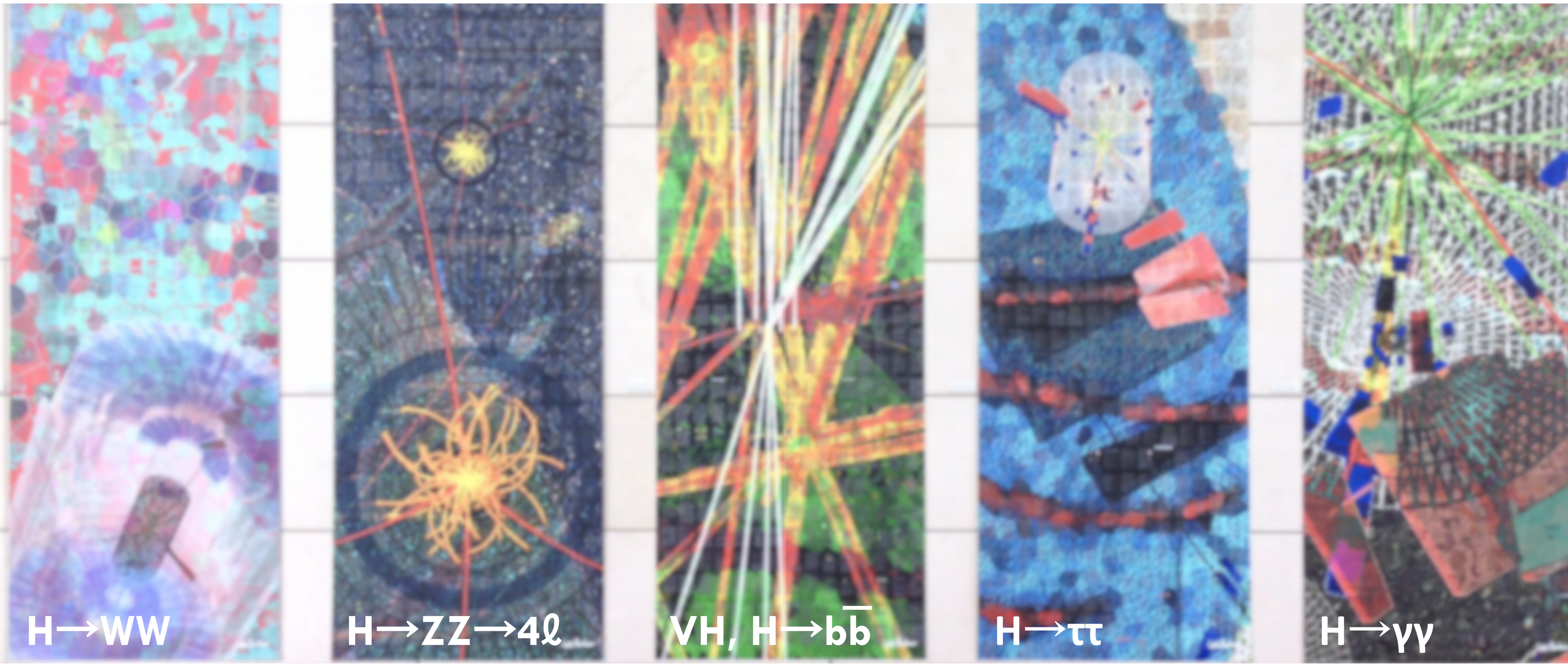
- Everything's Gaussian.
  - Hence all the (Top) measurement combinations.
- Linear correlations taken into account in effective way.
- ***"Combination of individual results"***

Profile Likelihood

- Deals well with low-stat cases.
  - Well-suited for (Higgs) discoveries.
- Nuisances either correlated or uncorrelated, period.
- ***"Result of combined analysis"***

Bringing it all together in CMS

[arXiv:1412.8662]



JHEP 01(2014) 096 | **PRD 89 (2014) 092007** | **PRD 89 (2014) 012003** | **JHEP 05 (2014) 104** | **EPJC 74 (2014) 3076**

Also combines:

- JHEP 05(2013)145 – ttH, $H\to b\bar{b}$ (7 TeV).
- JHEP 09(2014)087 – ttH, $H\to b\bar{b}$, $H\to\tau\tau$, and H decaying to multiple leptons (8 TeV).
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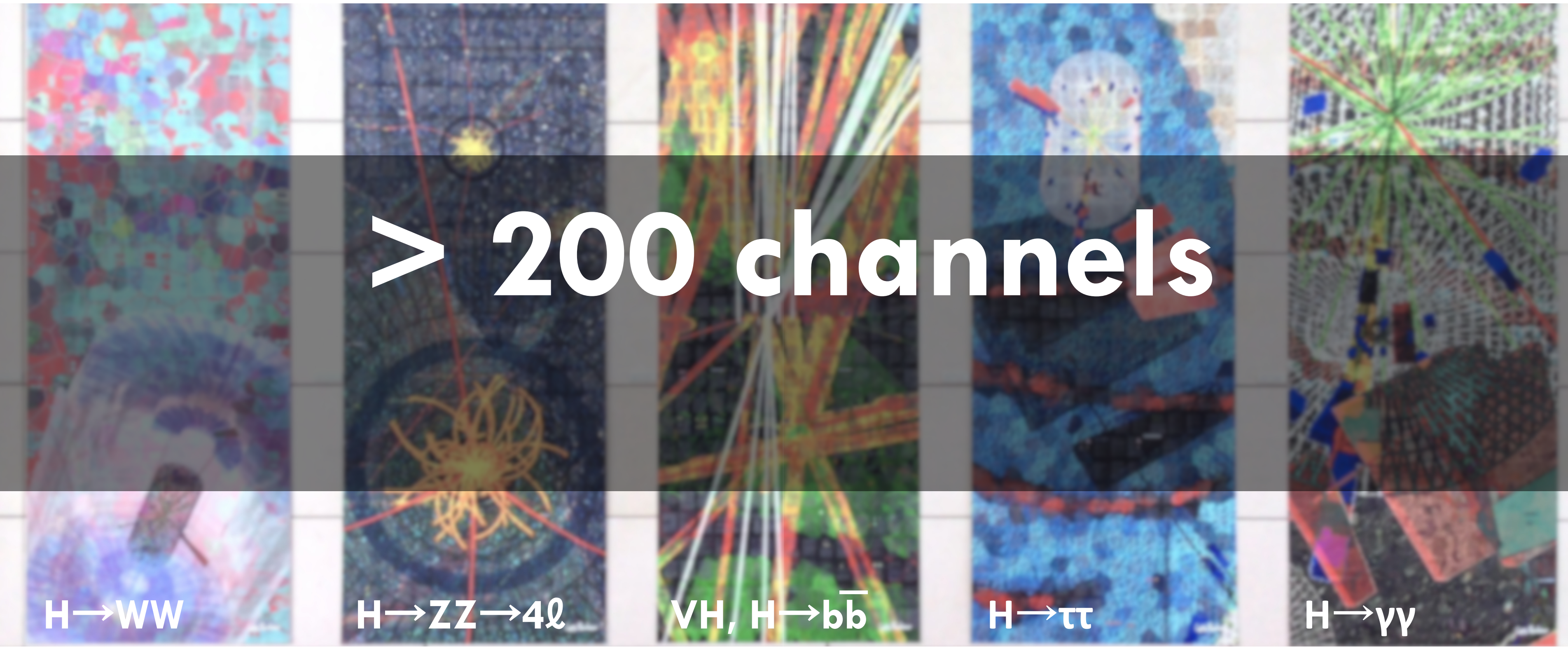

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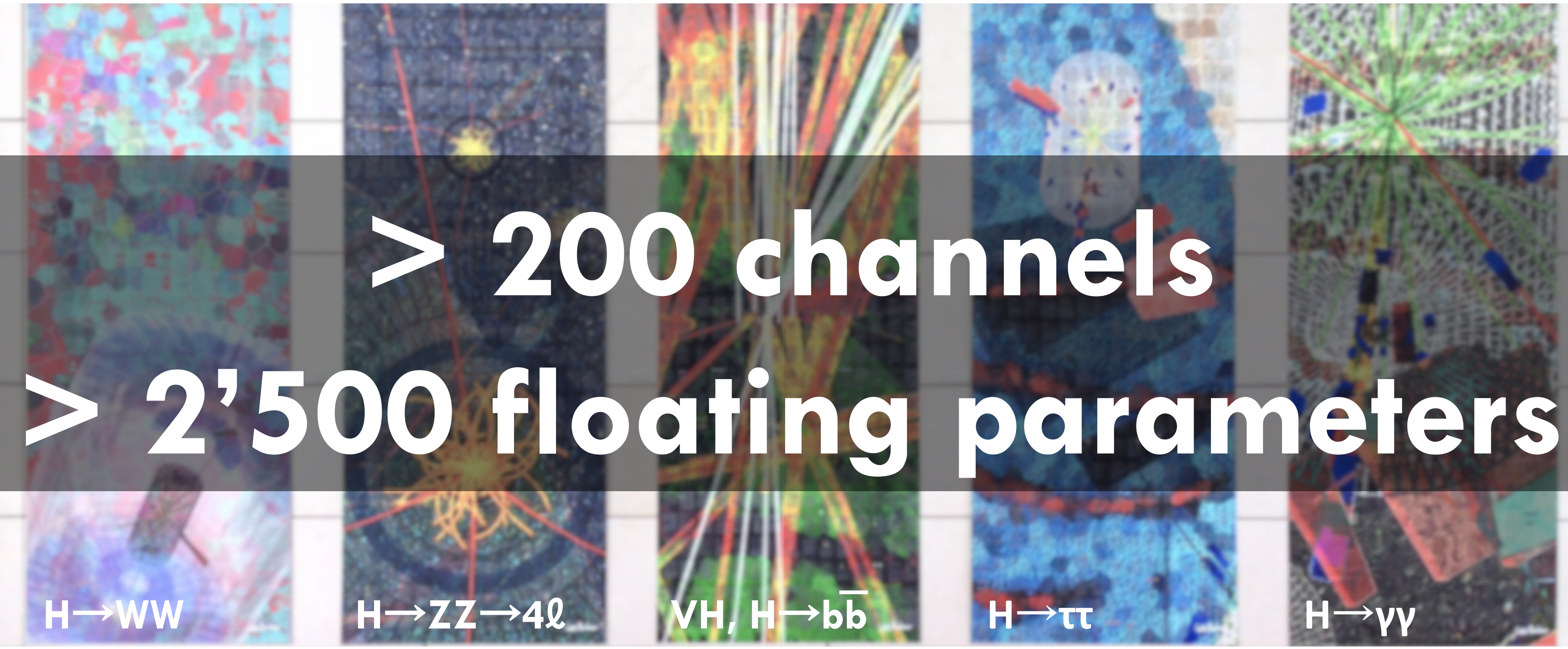

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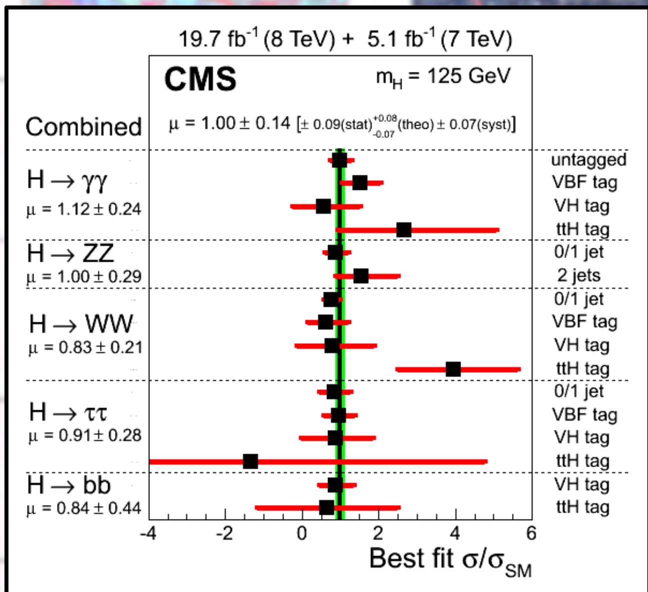

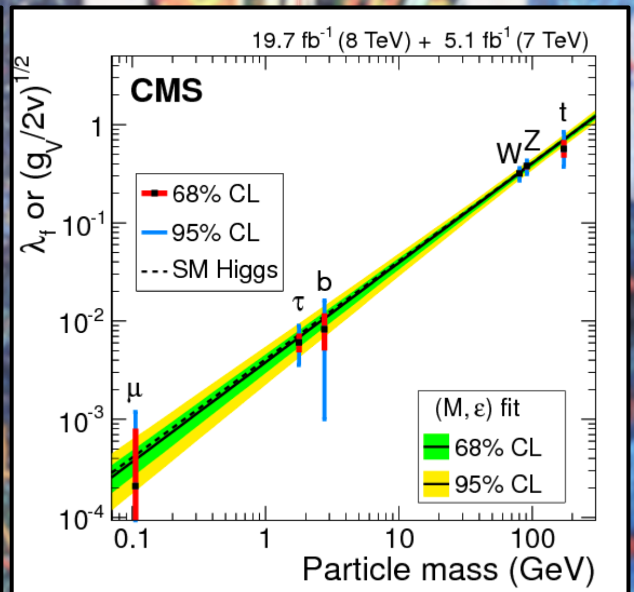

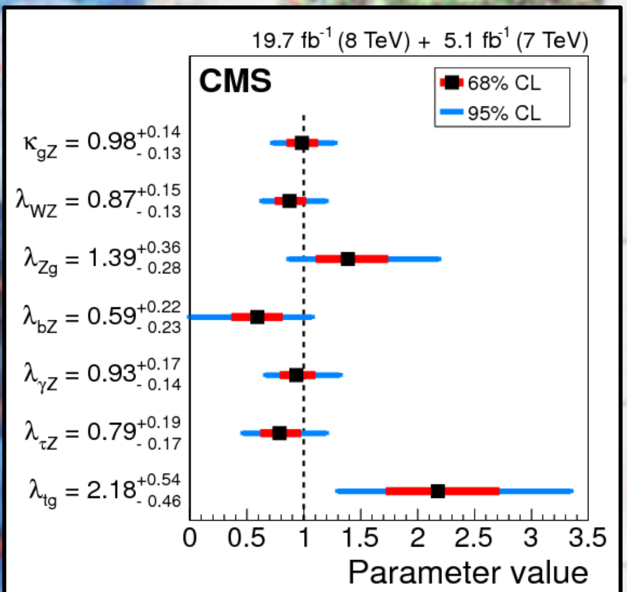

$H \to WW$	$H \to ZZ \to 4\ell$	VH, $H \to b\bar{b}$	$H \to \tau\tau$	$H \to \gamma\gamma$
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Upcoming LHC m_H combination

- Done by the LHC Higgs Combination Group.
  - Some O(10) people from ATLAS and CMS.
- Using Profile Likelihood.
  - Based on 2011 agreement.
- In the works since February 2014.
  - Speed is also limited by experiment publication strategies.

LHC m_H combination – lessons learned

- ***"What did you/I do in your/my measurement?"***
  - I.e., what should be correlated, what should not be correlated, etc.
- ***"Which physics model to use when performing the measurement?"***
  - I.e., the assumptions under which the mass is measured, possibly changes w.r.t. original analyses.

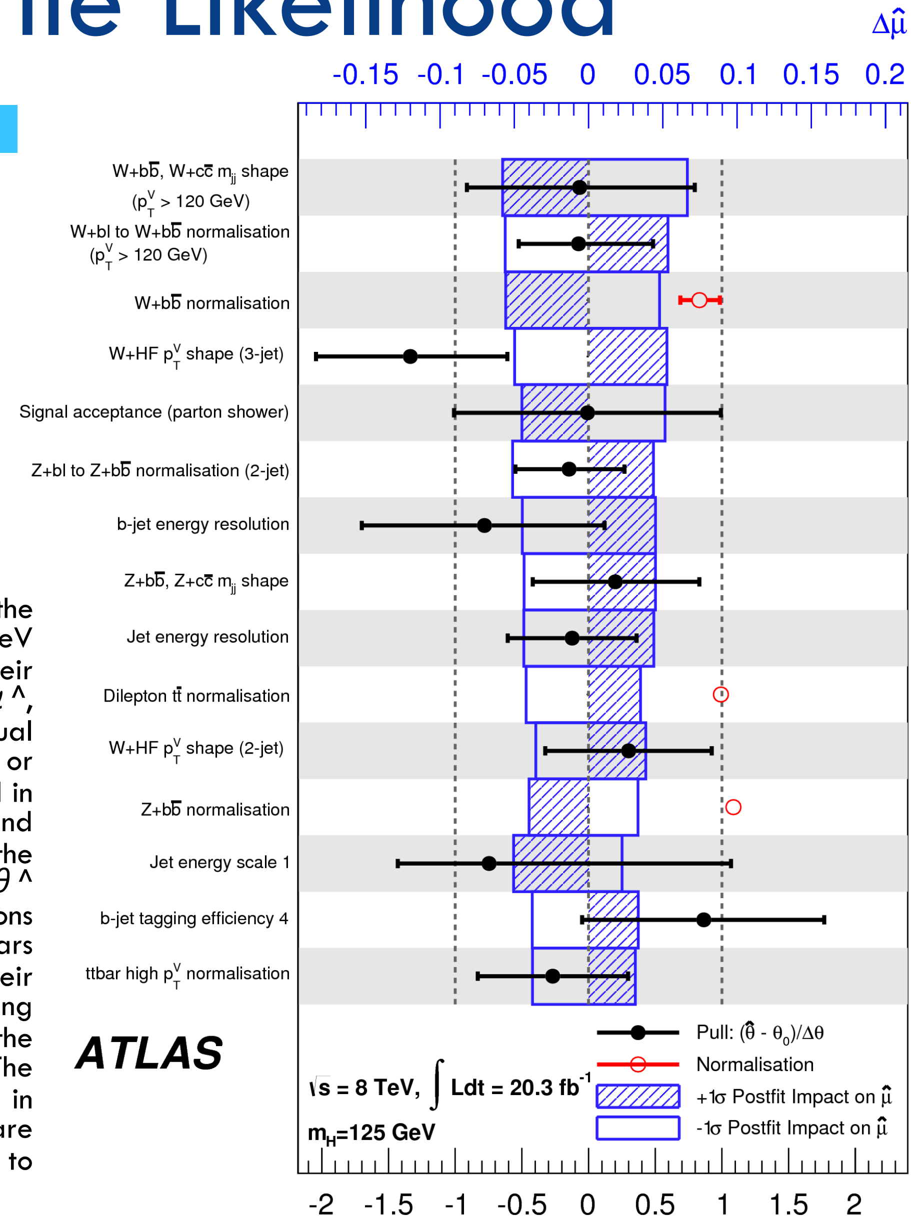
LHC m_H combination – lessons learned

- ***Scan the likelihood down to the O(10^{-6}) level.***
  - For O(10) MeV uncertainty precision evaluations.

- ***"Why do the results look the way they do?"***
  - I.e., which are the important nuisances, what are the pre-fit expectations, what are the post-fit expectations, compatibility tests, post-fit nuisance values and uncertainties, **and other ways to deconstruct the observation.**

Diagnostics of Profile Likelihood

- Example from arXiv:1409.6212: Impact of systematic uncertainties on the fitted signal-strength parameter $\hat{\mu}$ for the MVA applied to the 8 TeV data. The systematic uncertainties are listed in decreasing order of their impact on $\hat{\mu}$ on the y-axis. The boxes show the variations of $\hat{\mu}$, referring to the top x-axis, when fixing the corresponding individual nuisance parameter θ to its post-fit value $\hat{\theta}$ modified upwards or downwards by its post-fit uncertainty, and repeating the fit as explained in the text. The hatched and open areas correspond to the upwards and downwards variations, respectively. The filled circles, referring to the bottom x-axis, show the deviations of the fitted nuisance parameters $\hat{\theta}$ from their nominal values θ_0, expressed in terms of standard deviations with respect to their nominal uncertainties $\Delta\theta$. The associated error bars show the post-fit uncertainties of the nuisance parameters, relative to their nominal uncertainties. The open circles with their error bars, also referring to the bottom x-axis, show the fitted values and uncertainties of the normalisation parameters that are freely floating in the fit. The normalisation parameters have a pre-fit value of one. As explained in section 8.1, the jet energy scale and b-tagging uncertainties are decomposed into uncorrelated components; the labels 1 and 4 refer to such components.

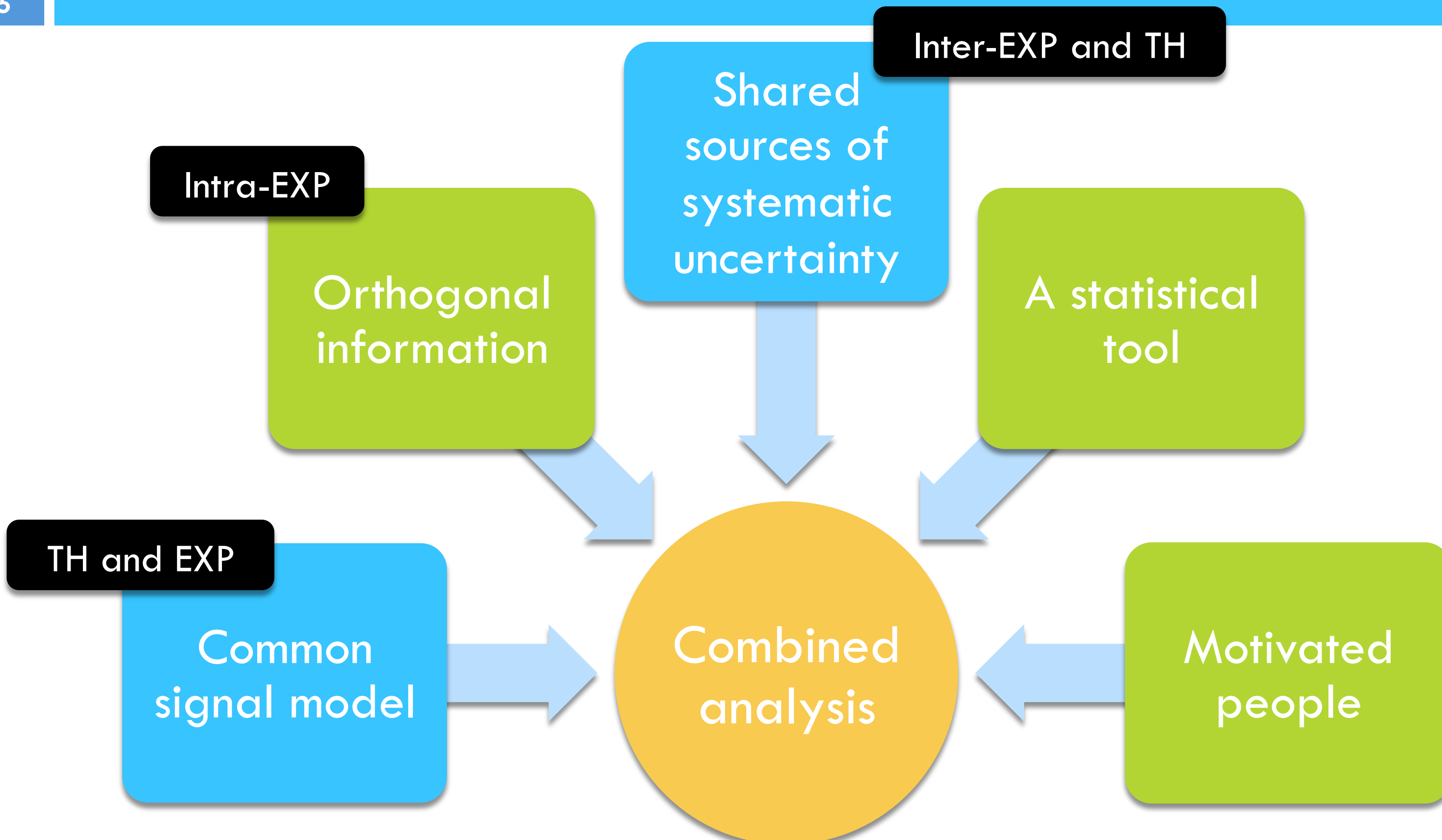


Observables

- When Higgs was at the **threshold of discovery.**
  - **"Squeeze" as much information as possible into one number**, like the overall signal strength.
  - More granular measurements can only come later.

- In contrast, **m_W need not be the only number.**
  - Many useful measurements can be done concomitantly: unfolded **M_T and p_T distributions.**
  - But we must keep tabs on what information is used where. (PDF fits to M_T might not be appropriate to use for m_W)

Summary


Inter-EXP and TH
Shared sources of systematic uncertainty
Intra-EXP
Orthogonal information
A statistical tool
TH and EXP
Common signal model
Combined analysis
Motivated people

Conc

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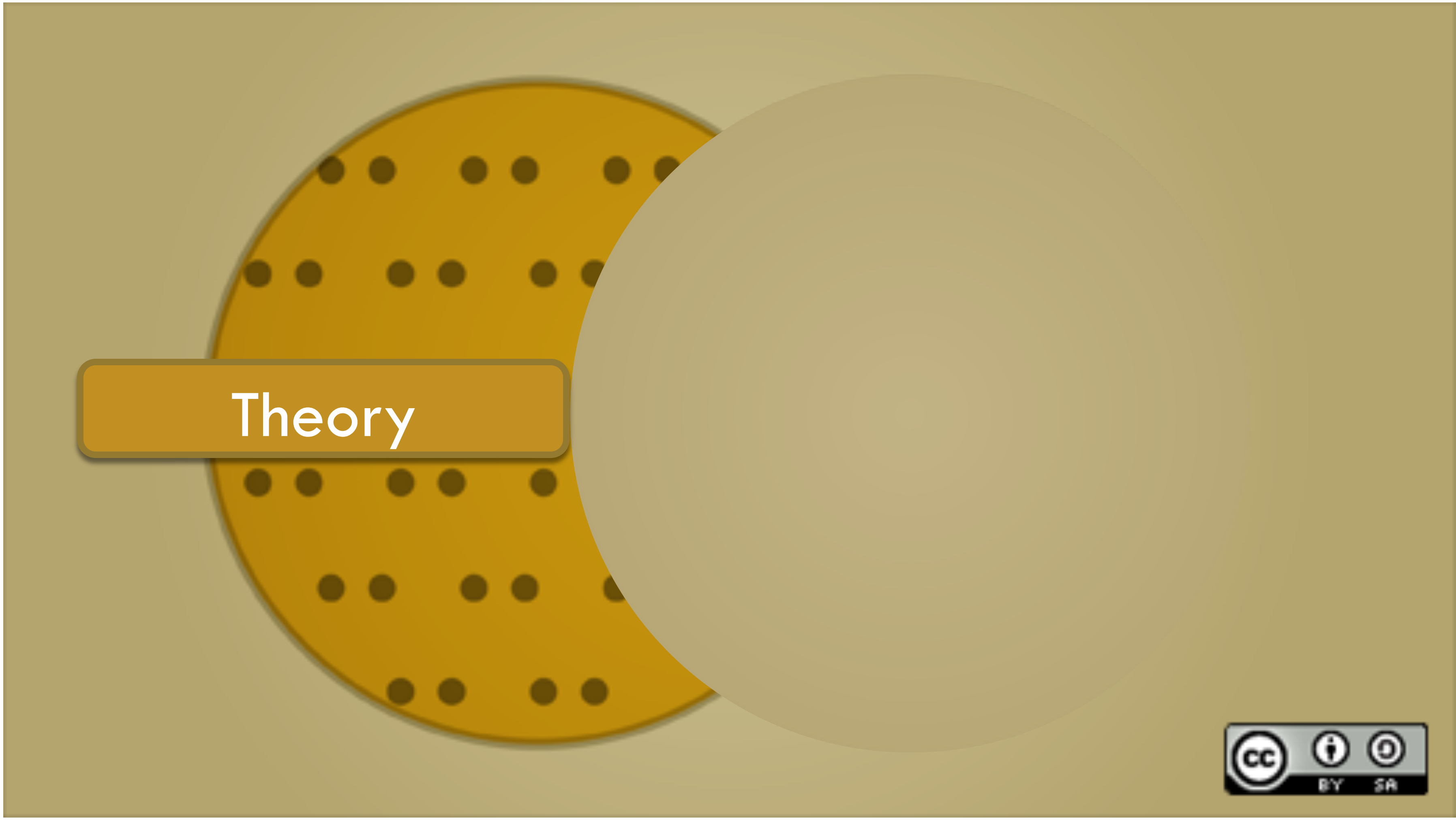

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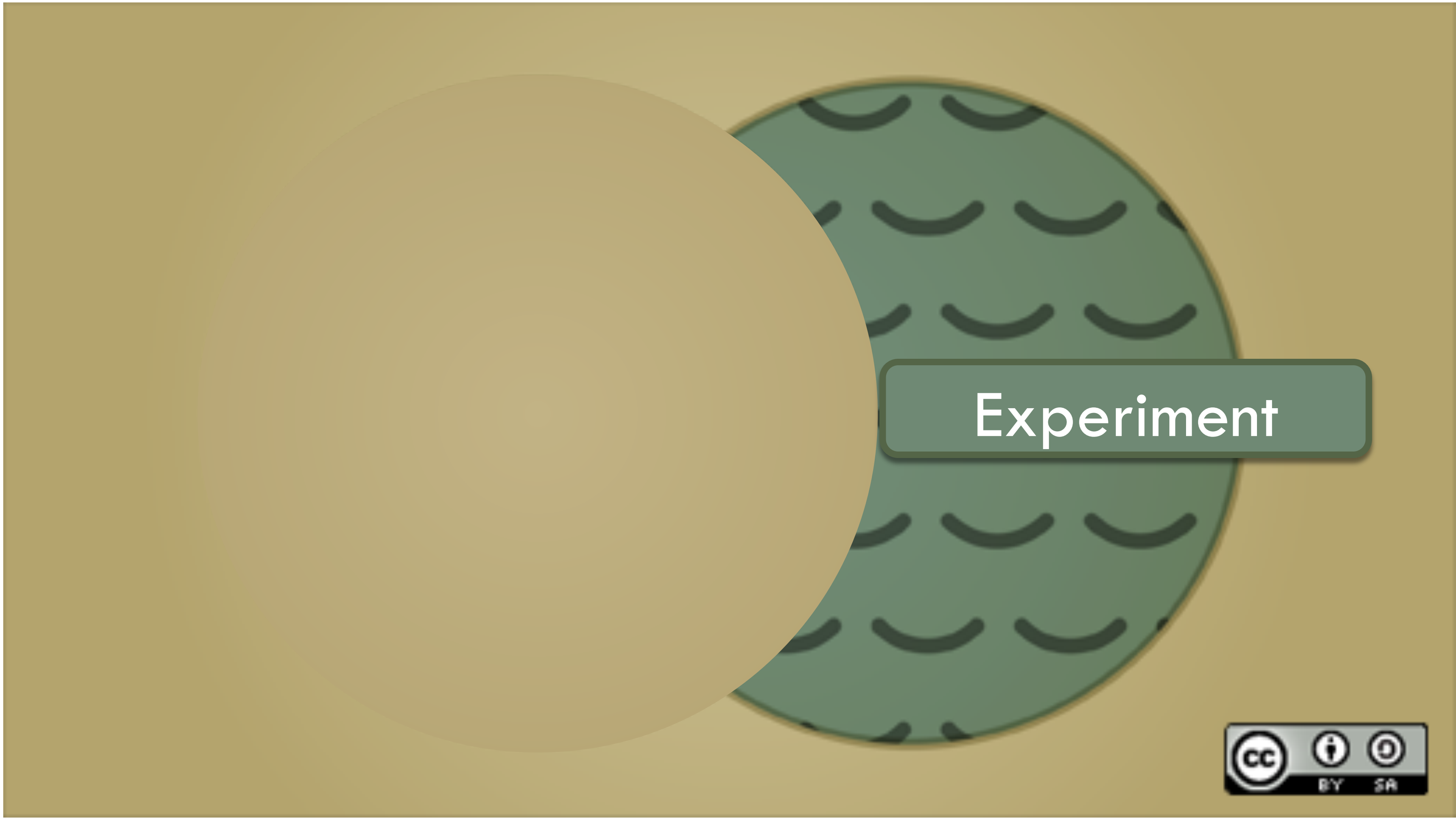
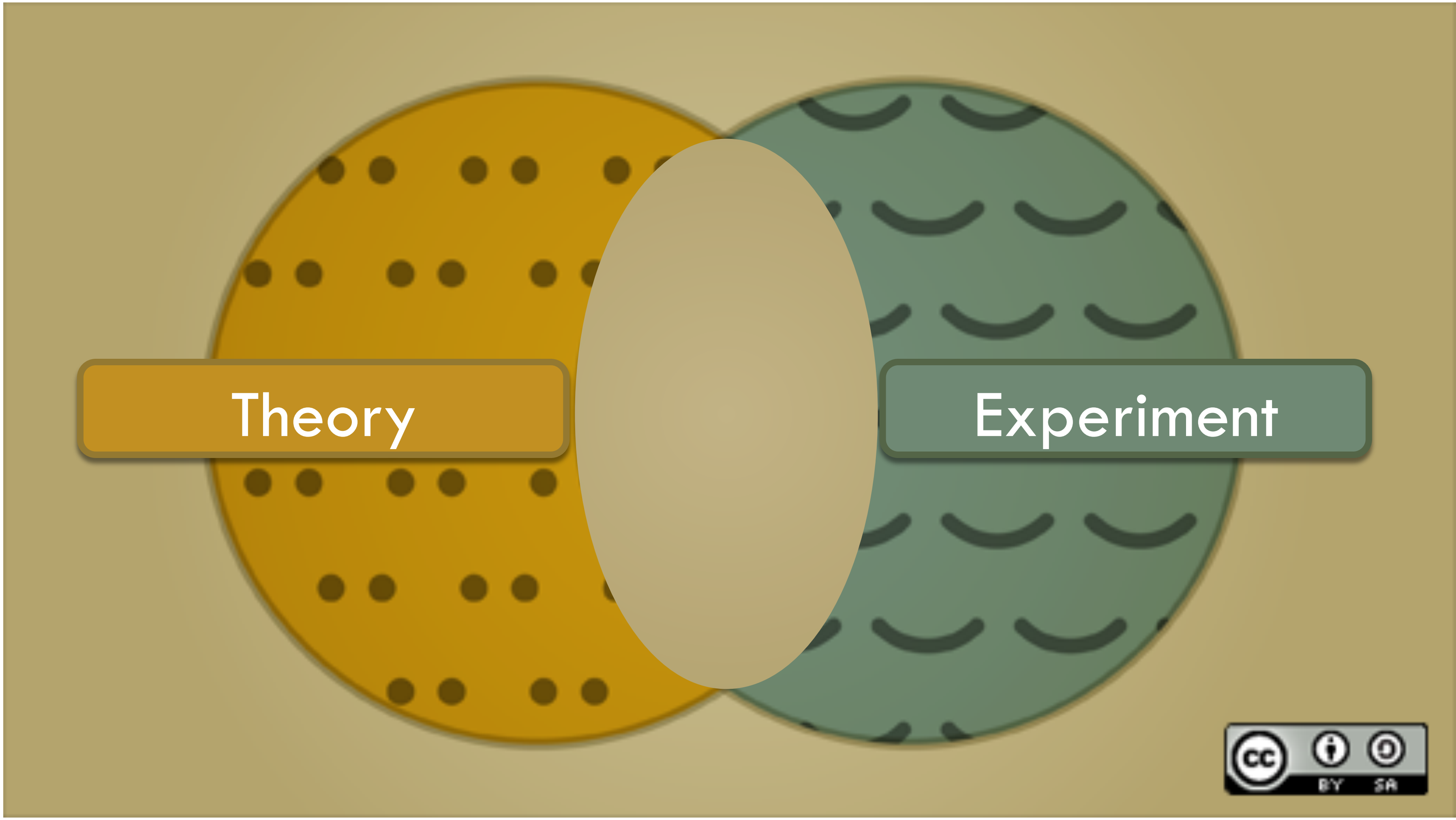


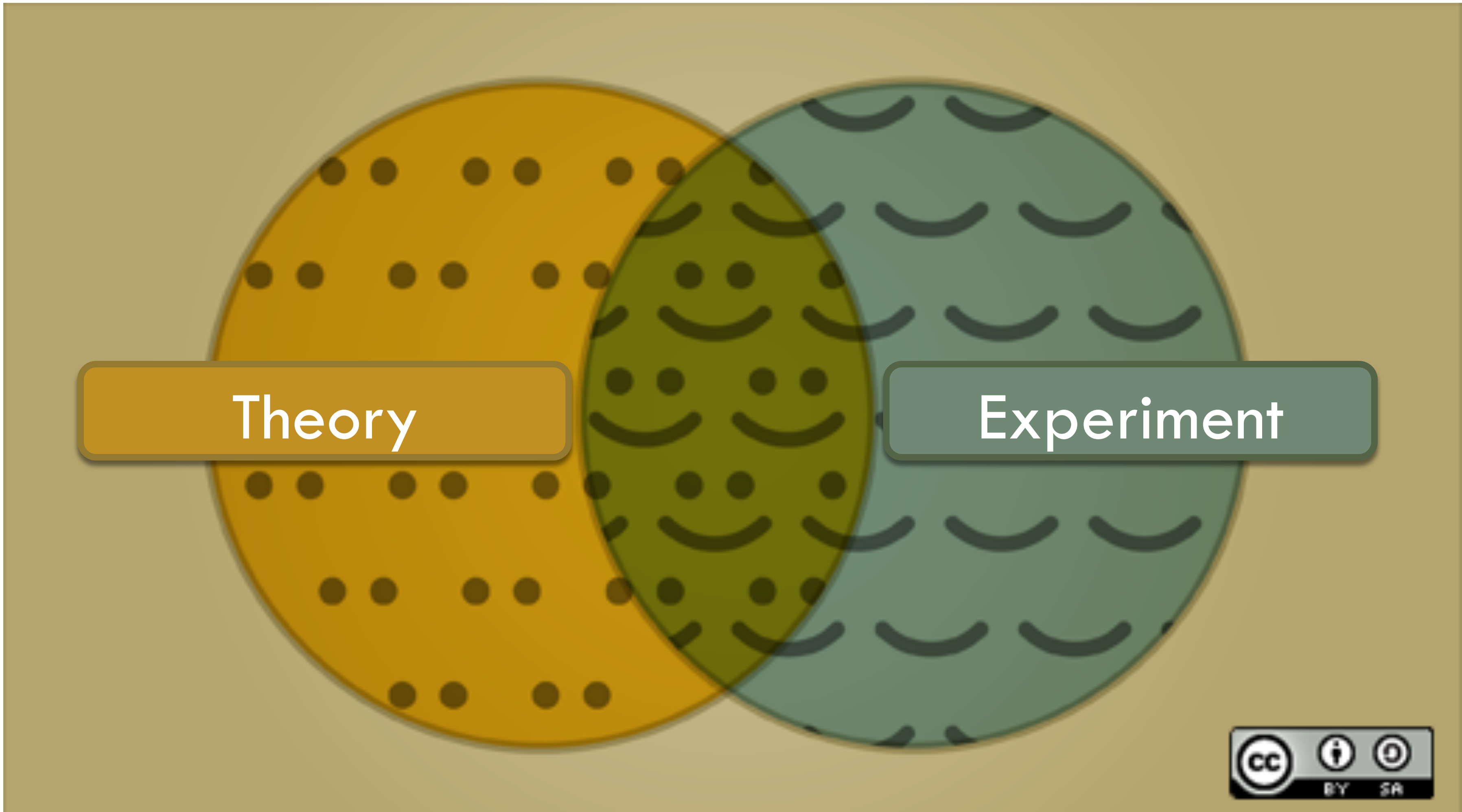
Conclusion

[opensource.com]



Conclusion

[opensource.com]



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