Measurement of the properties of the new particle observed within the search for the Standard Model Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ decay channel at ATLAS

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PhD Thesis defended at Sapienza Università di Roma
thesis advisors: Carlo Dionisi, Stefano Giagu, Marco Rescigno


we discovered a new fundamental particle!
Higgs Boson
(not to scale)


we discovered a new fundamental particle!
we have reasons to be happy!
Higgs Boson
(not to scale)


we discovered a new fundamental particle!
we have reasons to be happy!
was it obvious? -> making of a discovery
Higgs Boson
(not to scale)

we discovered a new fundamental particle!

we have reasons to be happy!

was it obvious? -> making of a discovery

+ where are we actually going next

Higgs Boson ↘
(not to scale)

The (Unnecessary) Outline Slide

- discovery
  - H->ZZ*->4l
  - happiness
- discovery, more in detail
  - crucial ingredients
  - characterising our signal
- what's next (or, why should we keep on running)

PhD thesis defended on February 18th, 2014

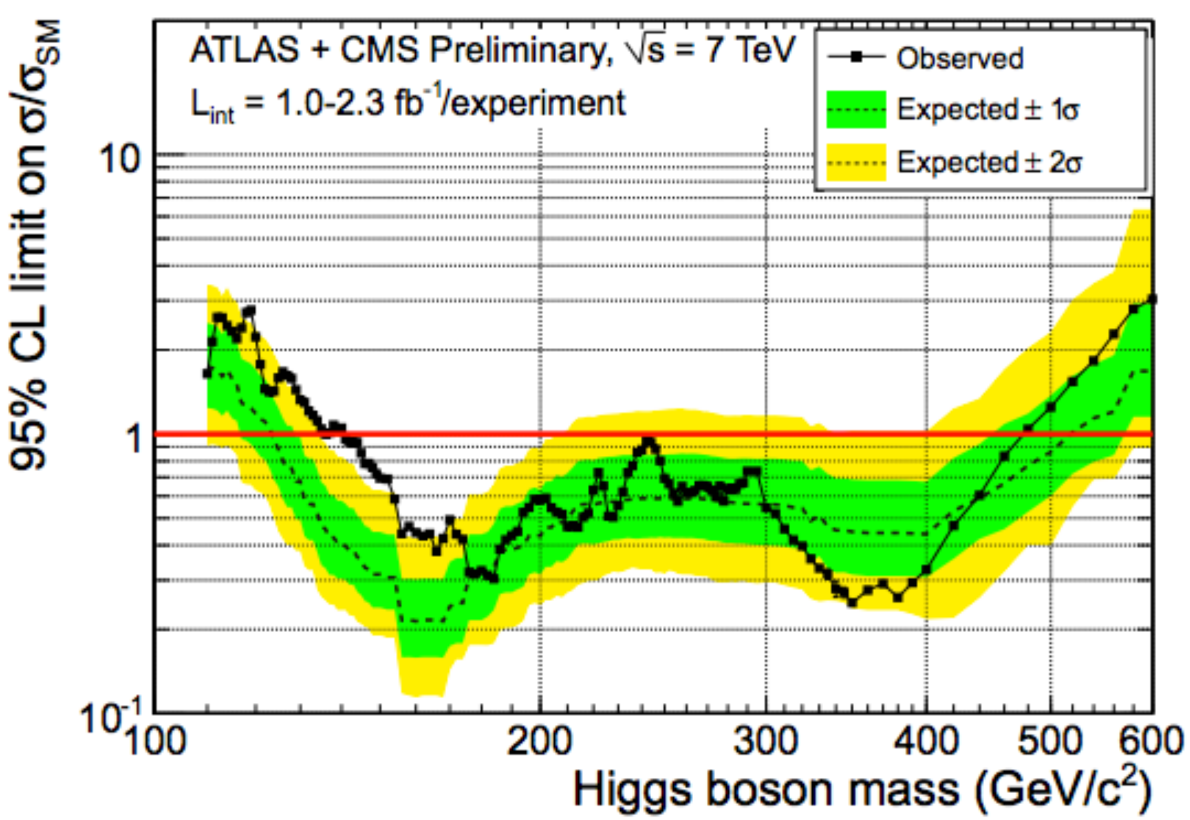
Why Do We Even Care?

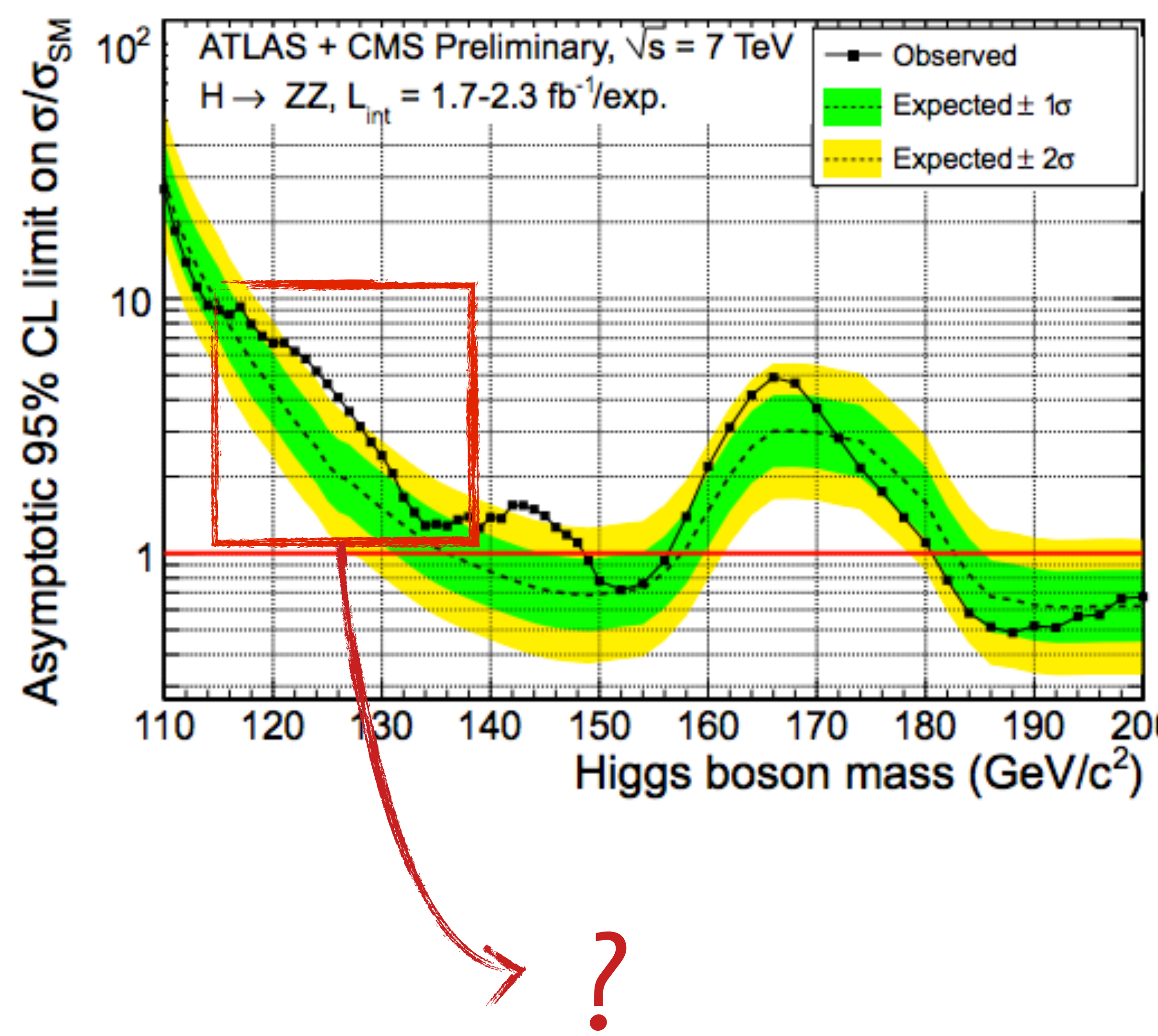
or: a short slide about motivations

- tremendous agreement between SM and experimental results
  - + missing particle (Higgs boson)
  - + unsolved mysteries (e.g. Dark Matter, baryon/antibaryon asymmetry)
- knowledge advances usually require attentive scrutiny of newfoundthings
  - like no-more-missing particles (Higgs boson)
  - like the SM itself (probe possible extensions)
- TeV scale is our sky, LHC our telescope!

O Higgs Boson, where Art Thou?

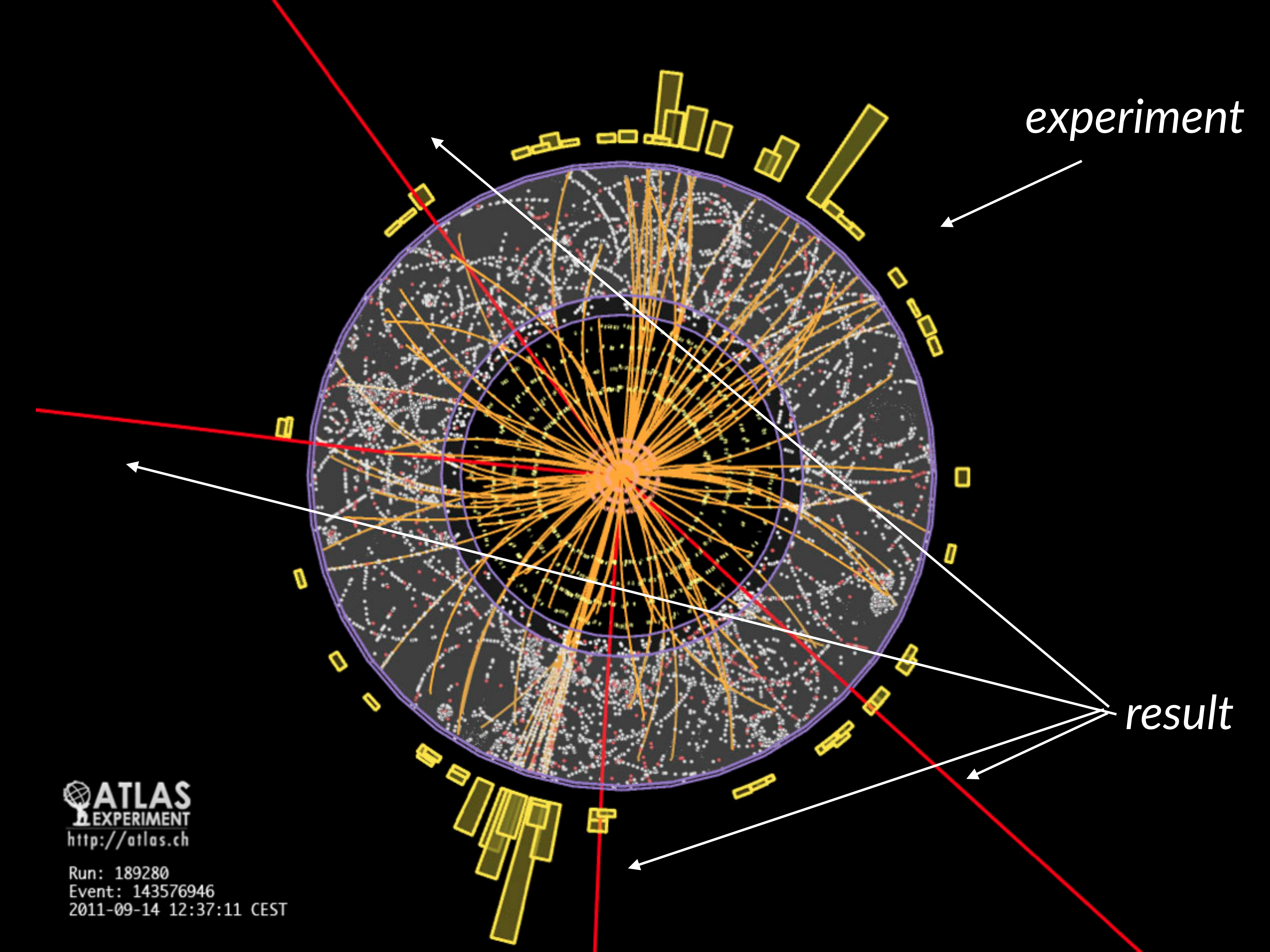
Status in ~October 2011 (my PhD thesis day-0)

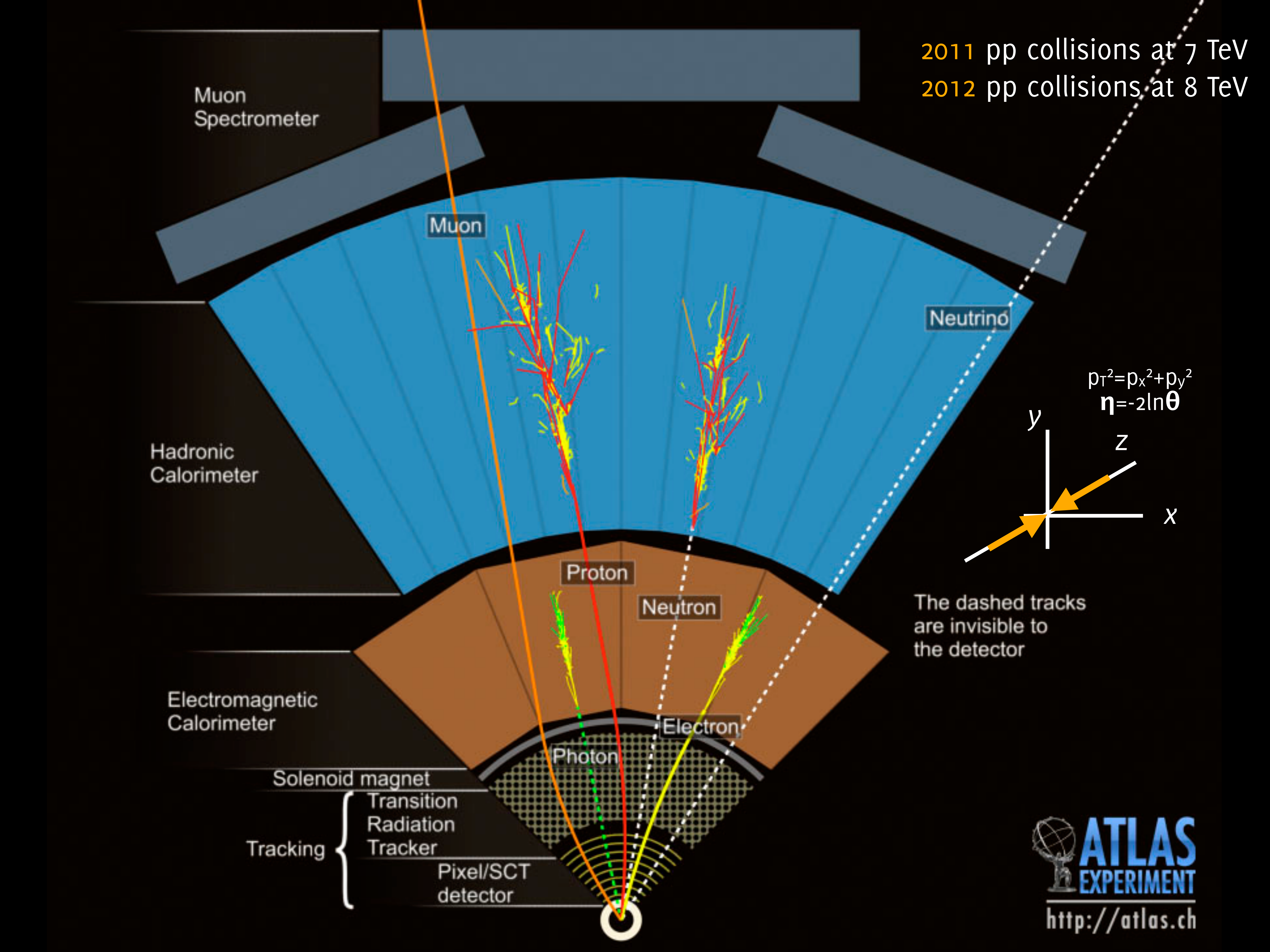




Discovery

Phys. Lett. B 726 (Jul, 2013) 88-119
Phys. Lett. B 716 (Aug, 2012) 1–29

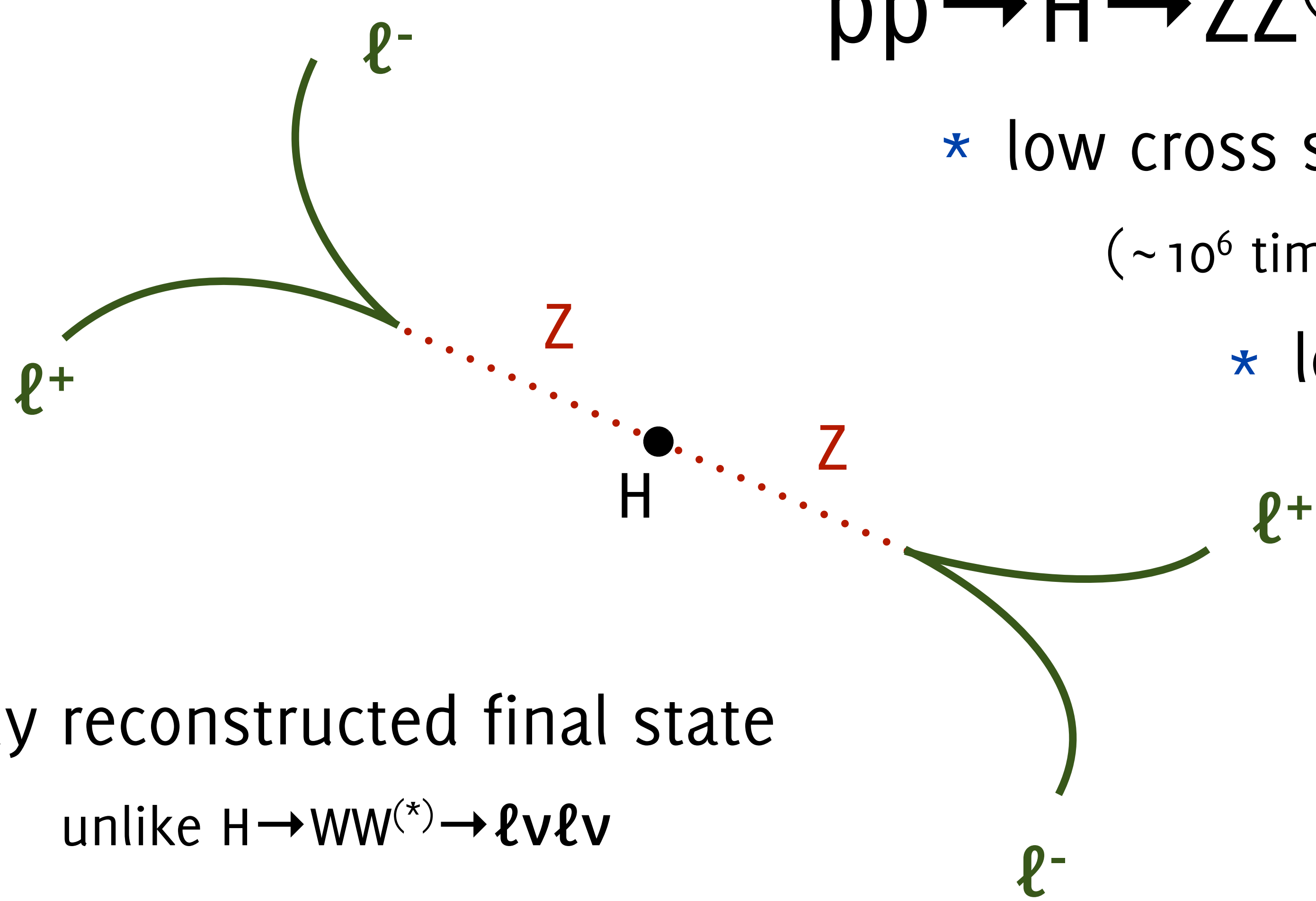

experiment
result
ATLAS
EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST


2011 pp collisions at 7 TeV
2012 pp collisions at 8 TeV
Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
$p_T^2=p_x^2+p_y^2$
$\eta=-2\ln\theta$
y
z
x
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

The Golden Channel

charged leptons give the cleanest signatures:

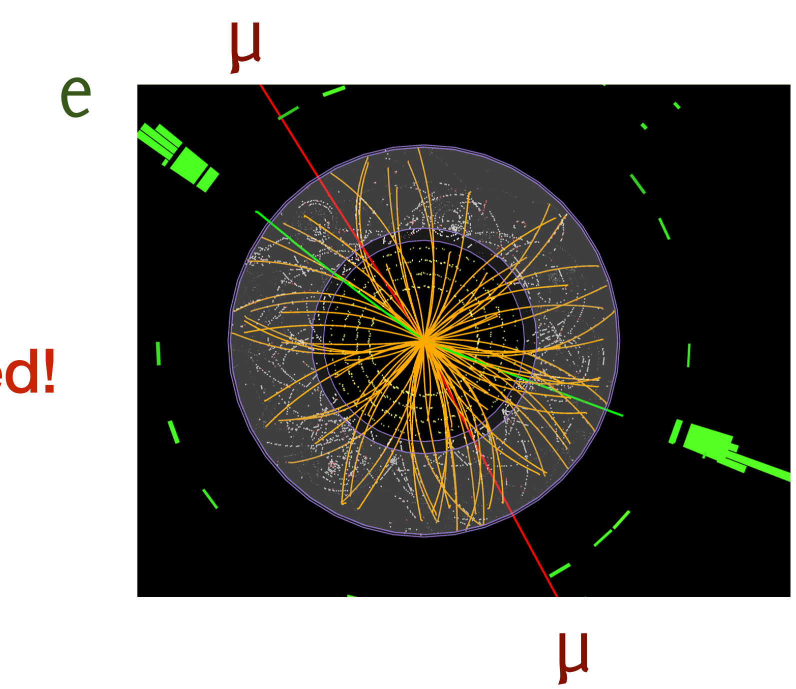
$pp \rightarrow H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ [m_H=100÷600 GeV]



* low cross section: 2-5 fb
  (~10^6 times less probable than $pp \rightarrow Z \rightarrow \ell^+\ell^-$)
* low background contamination
  from other processes faking signal
* fully reconstructed final state
  unlike $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$

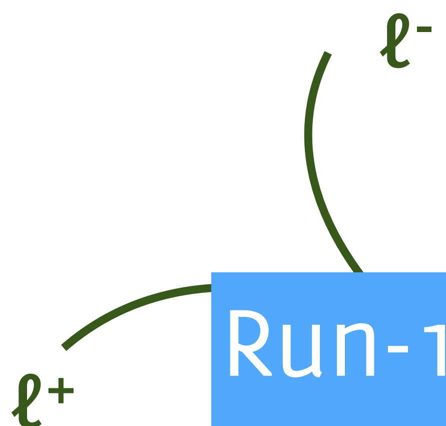
➲ **handy when you want to know what you discovered!**

* if $m_H < 2m_Z$, only one Z boson is on-shell
  let's call it Z_1
  we label final states like e.g. 2μ2e ($Z_1 \rightarrow \mu\mu$, $Z_2 \rightarrow ee$)



The Golden Channel

charged leptons give the cleanest signatures:



$pp \to H \to ZZ^{(*)} \to 4\ell$ [m_H=100÷600 GeV]

* low cross section: 2-5 fb

(~10^6 times less probable than $pp \to Z \to \ell^+\ell^-$)

...ontamination

...ses faking signal

Run-1 signal region means O(30) events!

1. understand your detector
2. maximise your acceptance
3. optimise signal sensitivity

* fully recon...

unlike $H \to WW^{(*)} \to \ell\nu\ell\nu$

ℓ-

➲ **handy when you want to know what you discovered!**

* if $m_H < 2m_Z$, only one Z boson is on-shell

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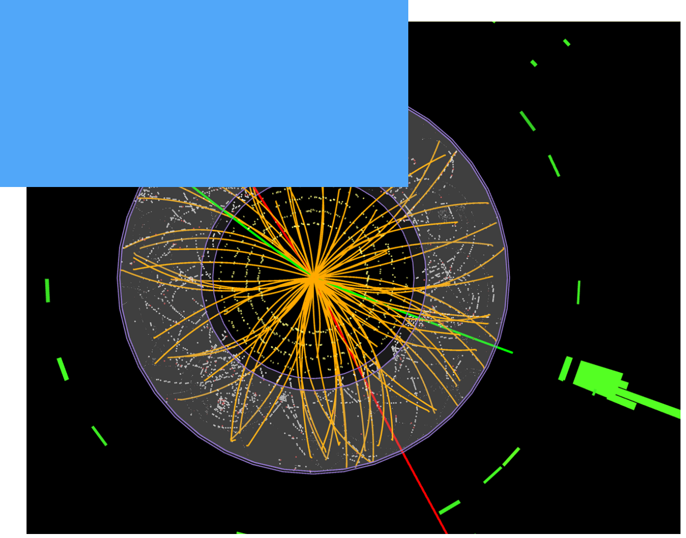
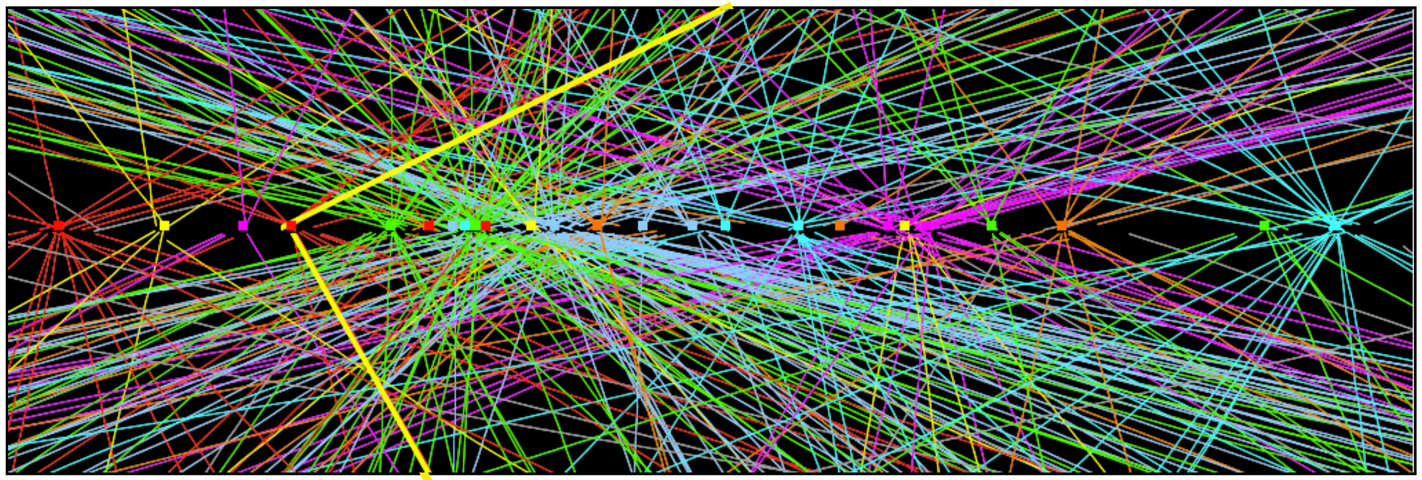


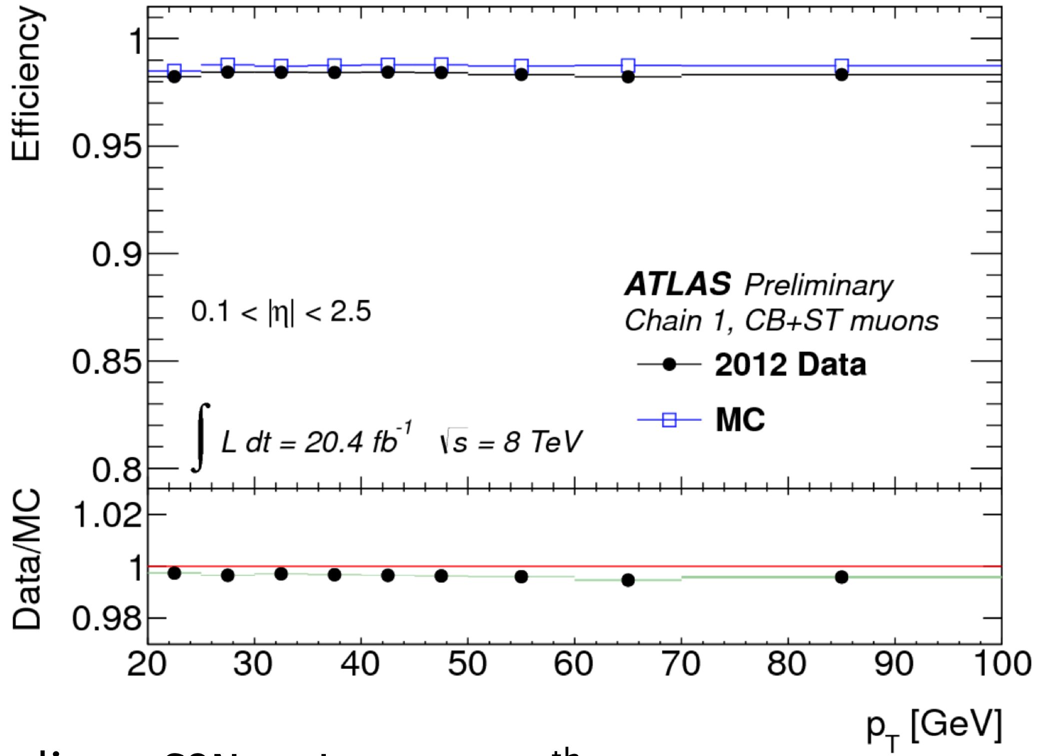
Reconstruction: a Challenge

pile-up is the price you have to pay if you want a discovery in <3 years…

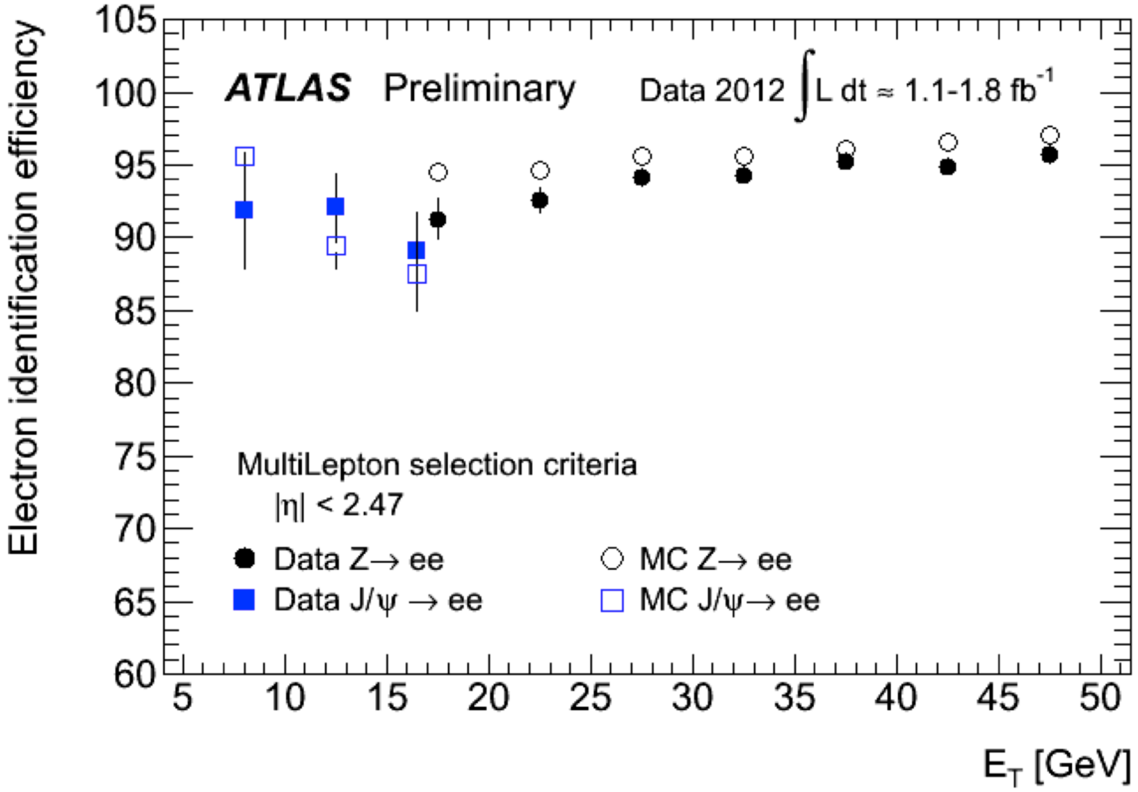


L up to 7.7×10^{33} cm^{-2} s^{-1}

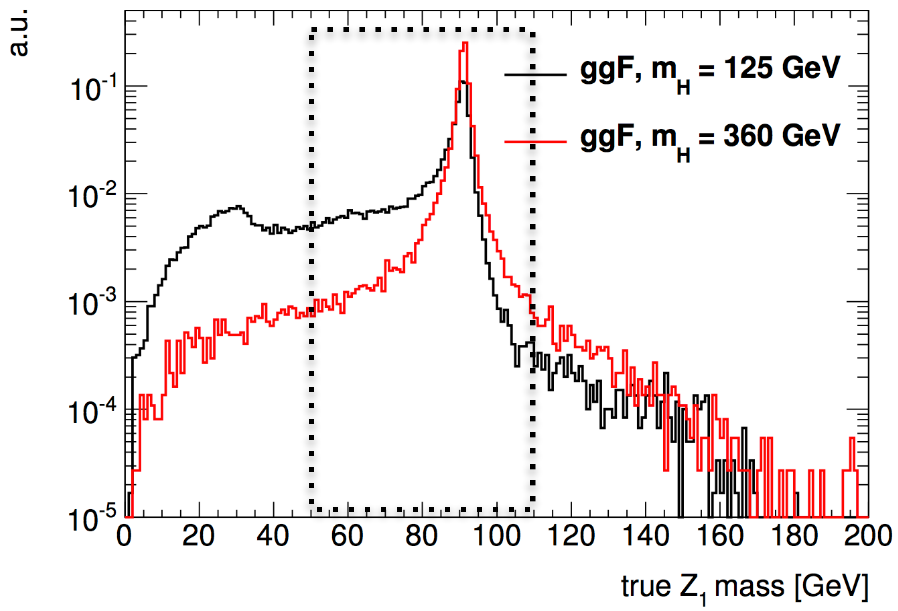
Muons

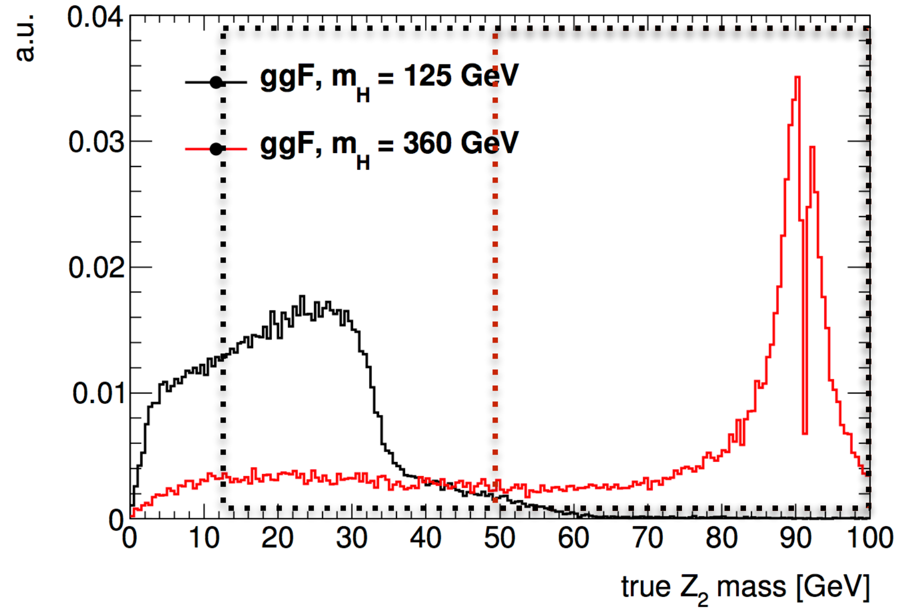


Electrons



Event Selection





four leptons with p_T > (20, 15, 10, 6/7) GeV

- isolated (ptcone20/p_T < 15%, etcone20/p_T < 20/30%)
- from primary interaction ($|d_0|$/err < 3.5/6.5)

m_{4l}-dependent mass cut on Z_1, Z_2

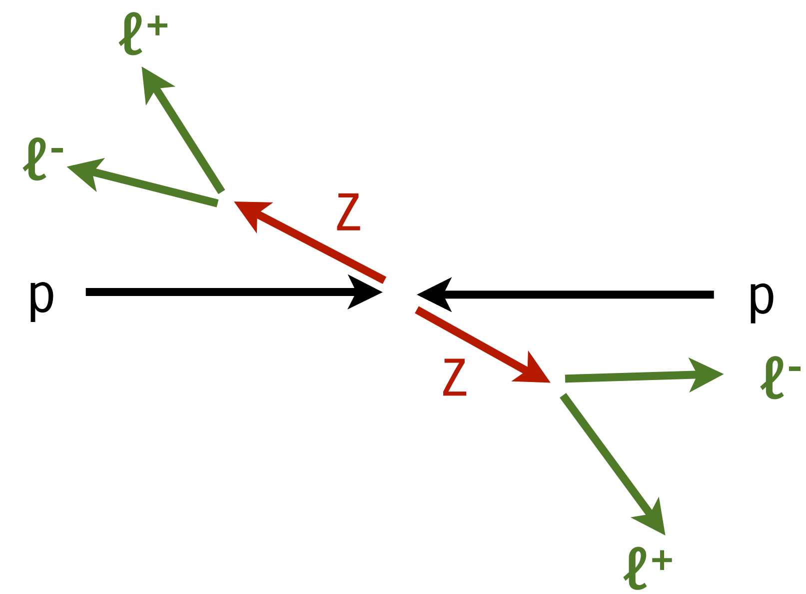
- $50 < m_1 < 106$ GeV
- $m_2 > 12$ GeV if $m_{4l} < 140$ GeV
  growing linearly up to
  $m_2 > 50$ GeV if $m_{4l} > 190$ GeV

overall signal efficiency is
(4μ, 2μ2e+2e2μ, 4e) = (39%, 26%, 19%)

Background processes

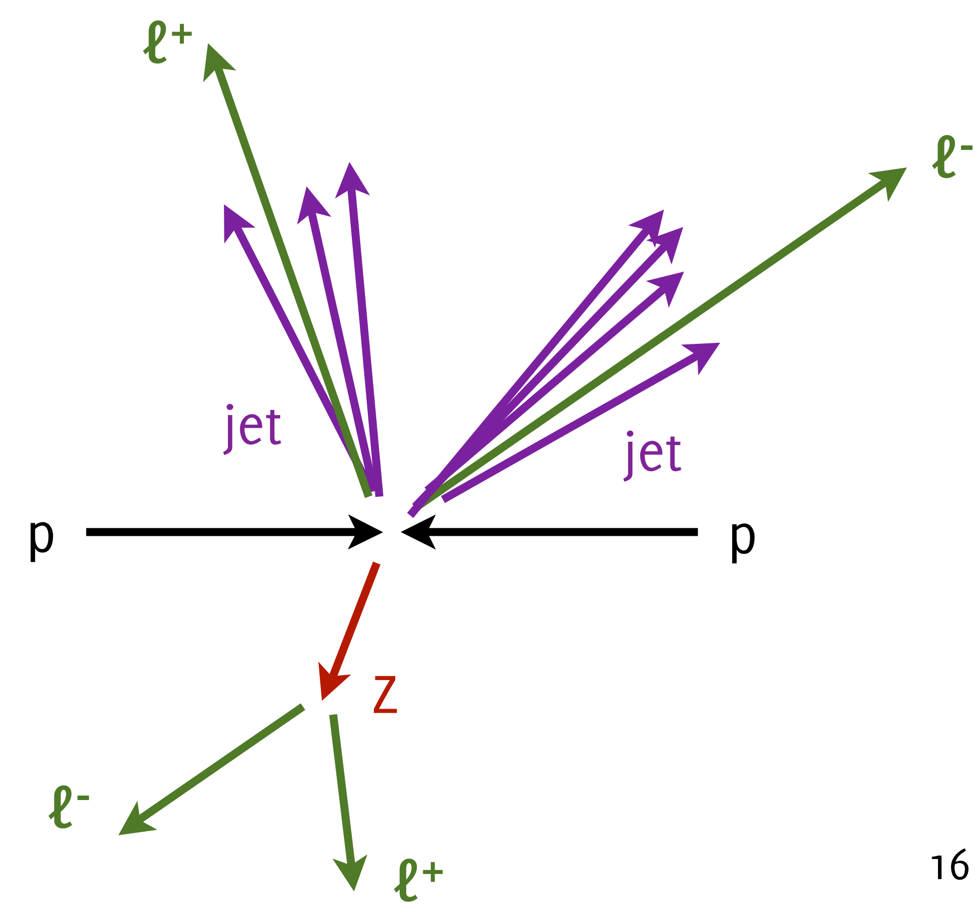
irreducible background

* $pp \rightarrow ZZ^{(*)} \rightarrow 4\ell$ [MC]
* same final state as signal
* dominant at high m_H

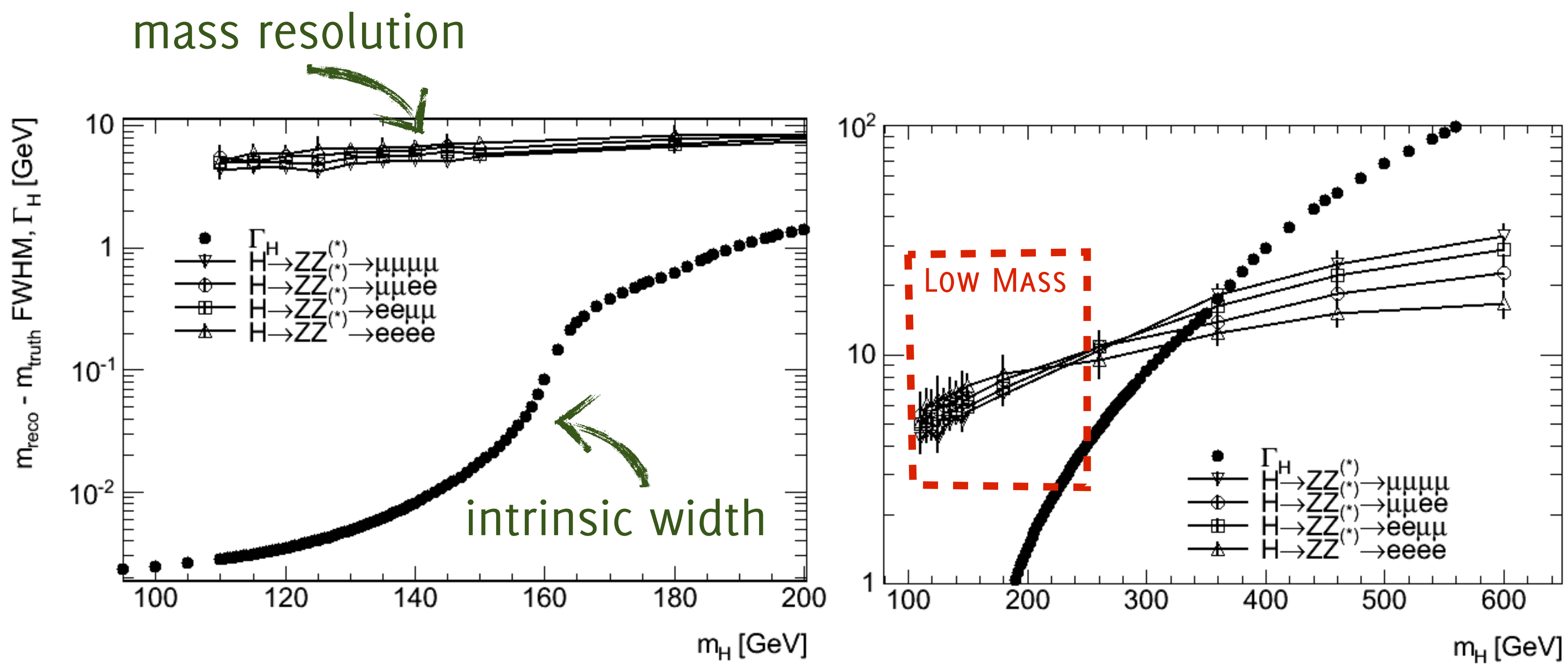


reducible backgrounds

* Z+bb, Z+jets, tt [data, MC]
* relevant contribution at low m_H
* rejection: ask leptons to be isolated and compatible with the primary interaction
* estimated from data [MC modeling is hard]



The Z Mass Constraint Fit



good mass resolution is crucial in the low m_H region

- * one way to improve it at analysis level is to refit leptons from on-shell Z with a constraint on their mass m_{2l}
- * we can't do that using m_Z=91 GeV, but must use m_Z^{true} which is an event-by-event observable

HOW?

From m_{2l} to m_Z^{true}

we need a meaningful constraint $m_{2l}=m_Z^{true}$

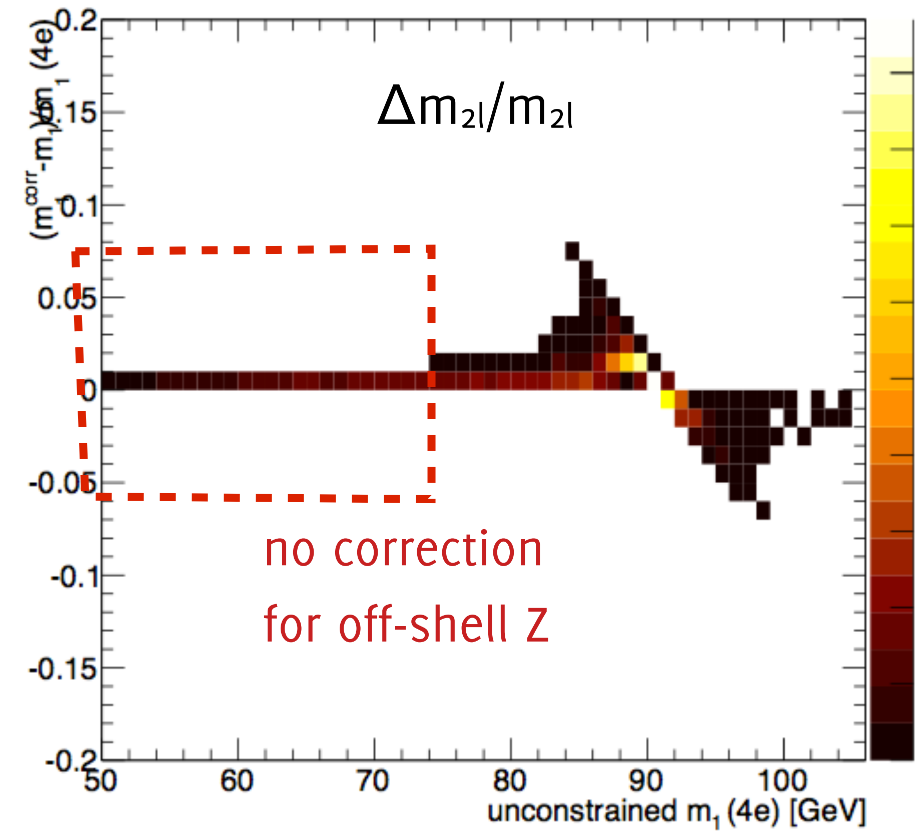
* the more uncertain the momentum measurement, the more m_{2l} is let to go back to m_Z
* the way this happens is a consequence of event-by-event resolution

<u>maximize</u>

prior on m_Z^{true} (Breit-Wigner)

$$p(m_Z^{\mathrm{true}}|m_{2\ell}) \propto p(m_{2\ell}|\sigma_{m_{2\ell}}, m_Z^{\mathrm{true}}) \cdot p(m_Z^{\mathrm{true}}|m_Z, \Gamma_Z)$$

resolution term (gaussian with σ_{m2l} from lepton momentum covariance matrices)



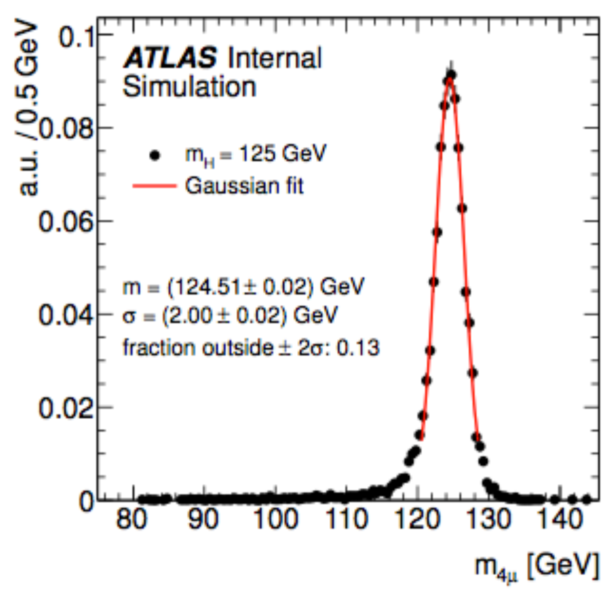
correction is applied using constrained fit of lepton momenta (Lagrange multipliers)

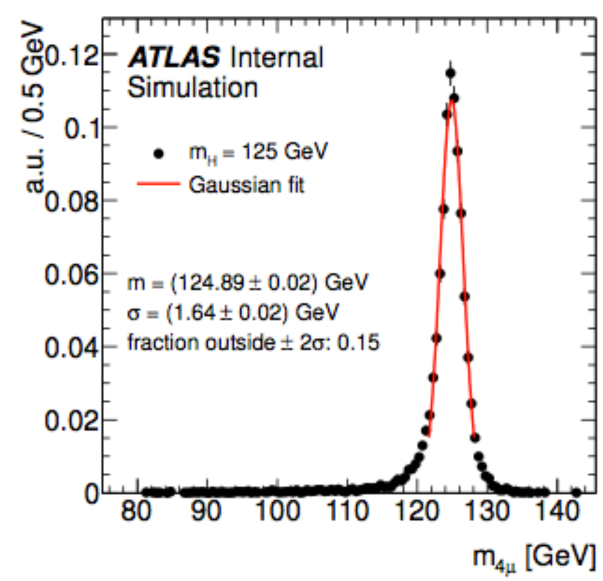
Z Mass Constraint Fit

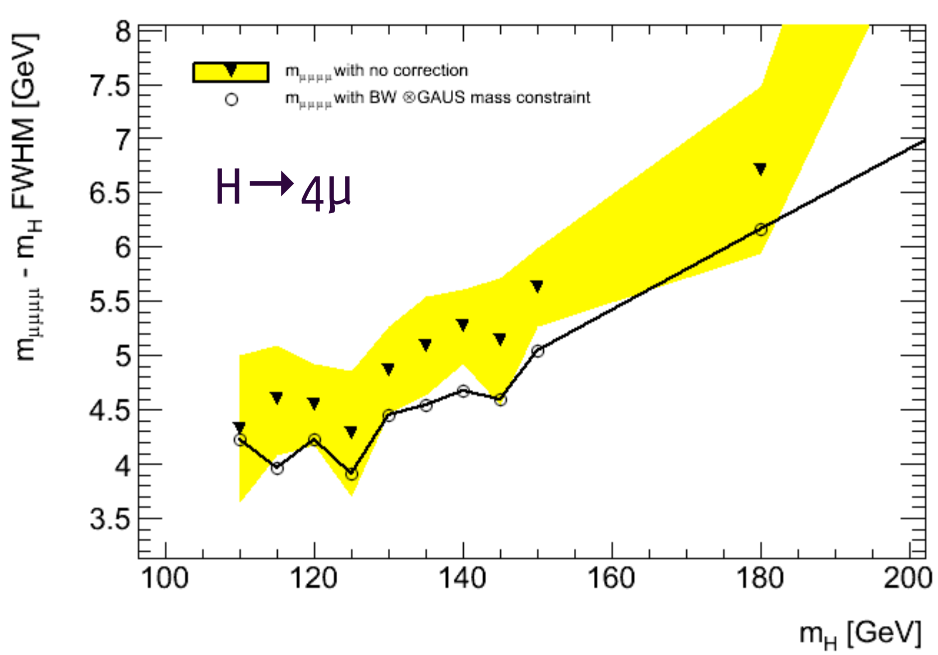
O(10%) improvement in resolution

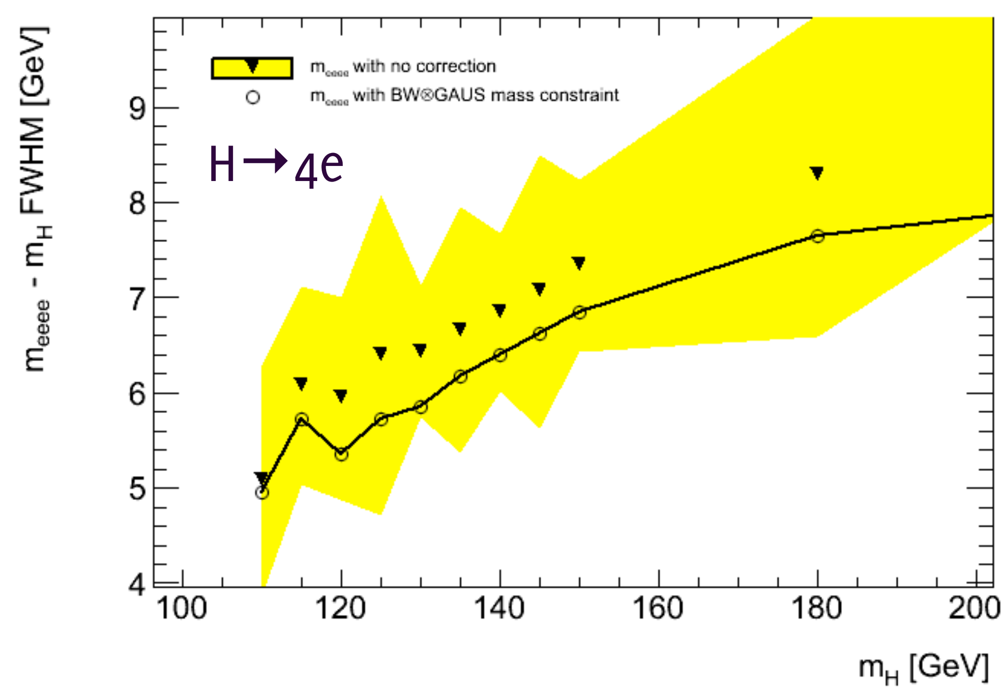
need 5% less luminosity to obtain the same significance

channel (125 GeV)	σ [GeV]	σ^{constr} [GeV]
4μ	2.00	1.64
2μ2e	2.38	2.15
2e2μ	2.10	1.85
4e	2.70	2.54

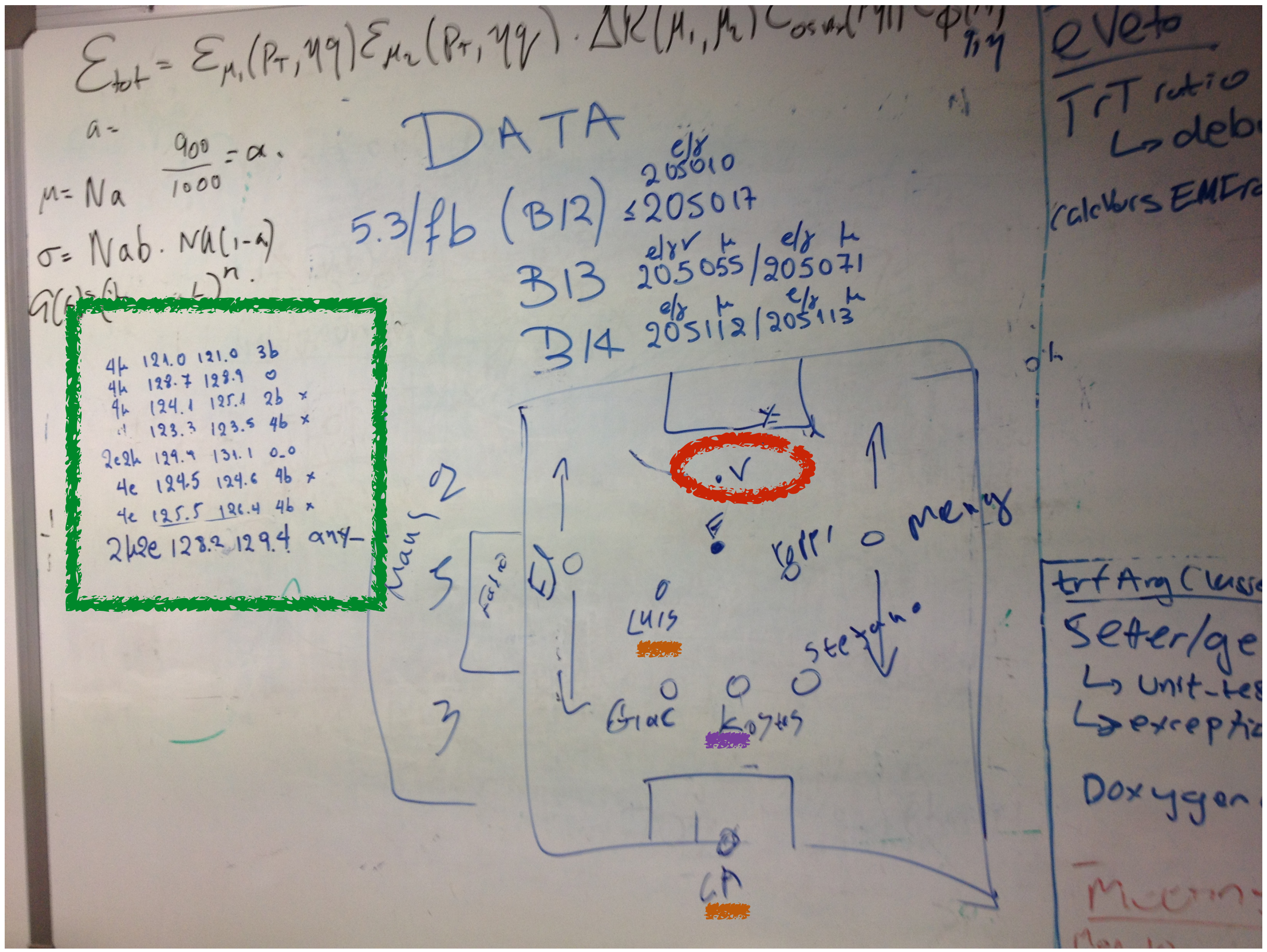








Intermezzo: Building a Discovery



CERN 40/4-C08 - Sunday June 24th, 2012 - ~2 AM

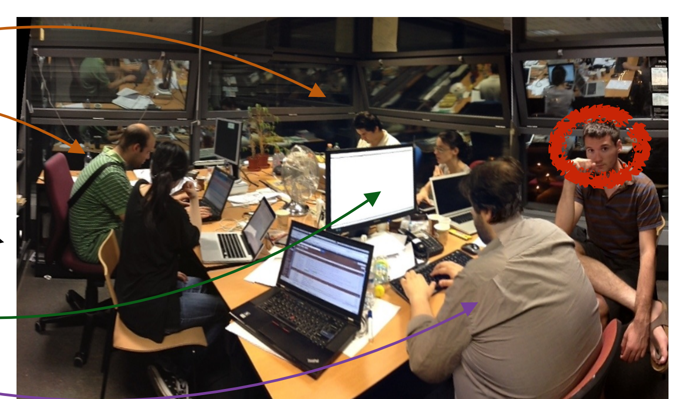
paper editor

paper editor

discovery whiteboard

Higgs boson

convener



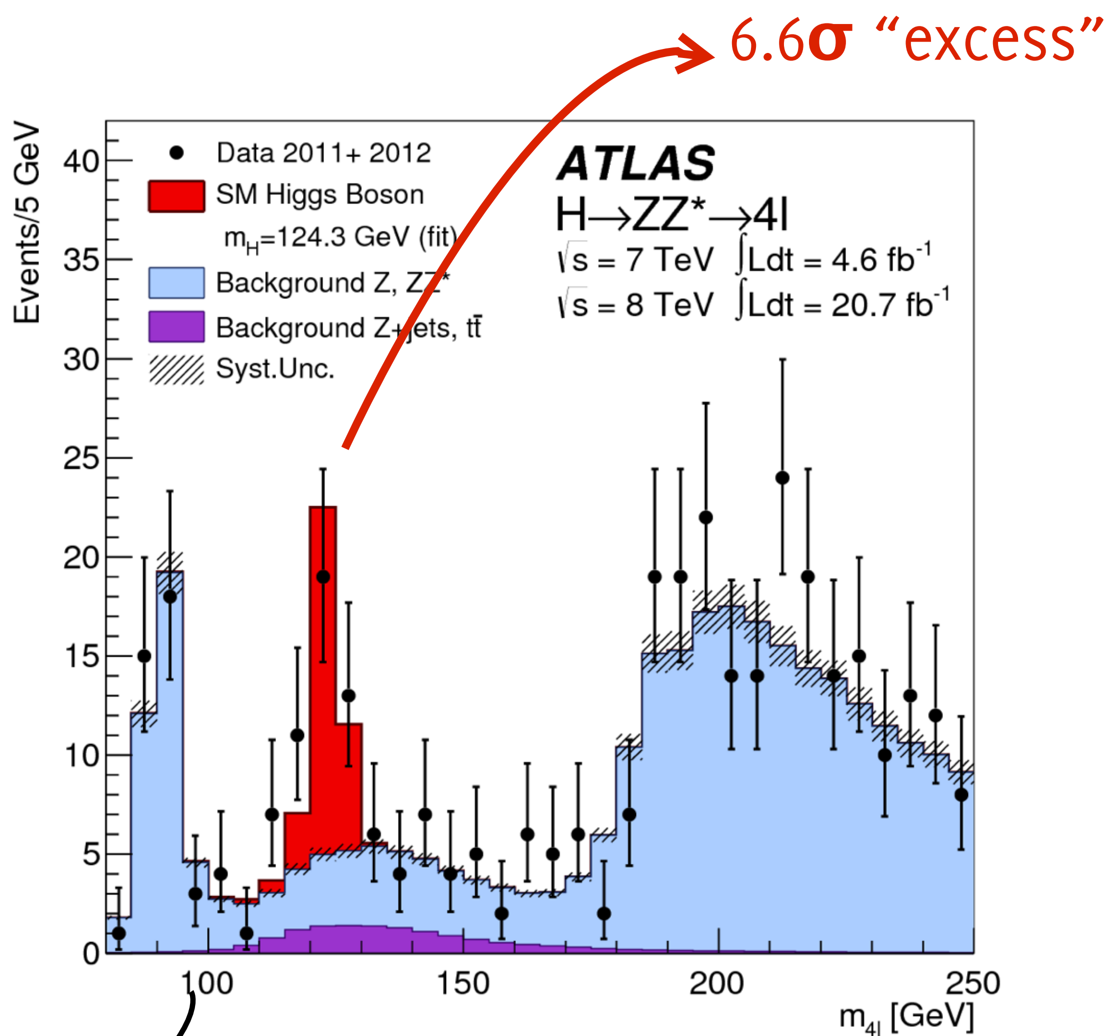
an exciting team work!

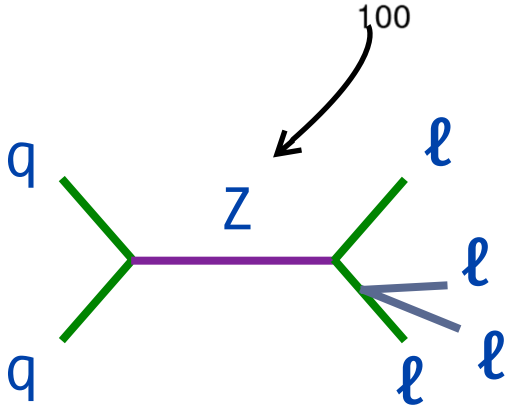
* first hints at a 5**σ** discovery on June 19th, 2012 (at 1h02 AM…)

* different layers well represented by the "discovery whiteboard" team

* from day-to-day candidate search with increasing integrated luminosity to paper editors, group conveners, ATLAS management…

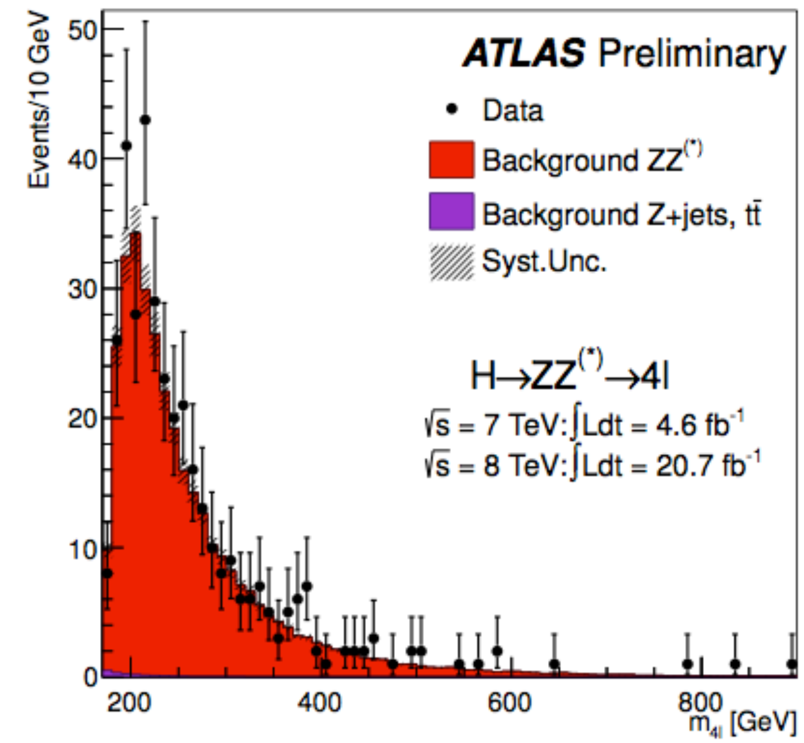
Born on the Fourth of July (2012)

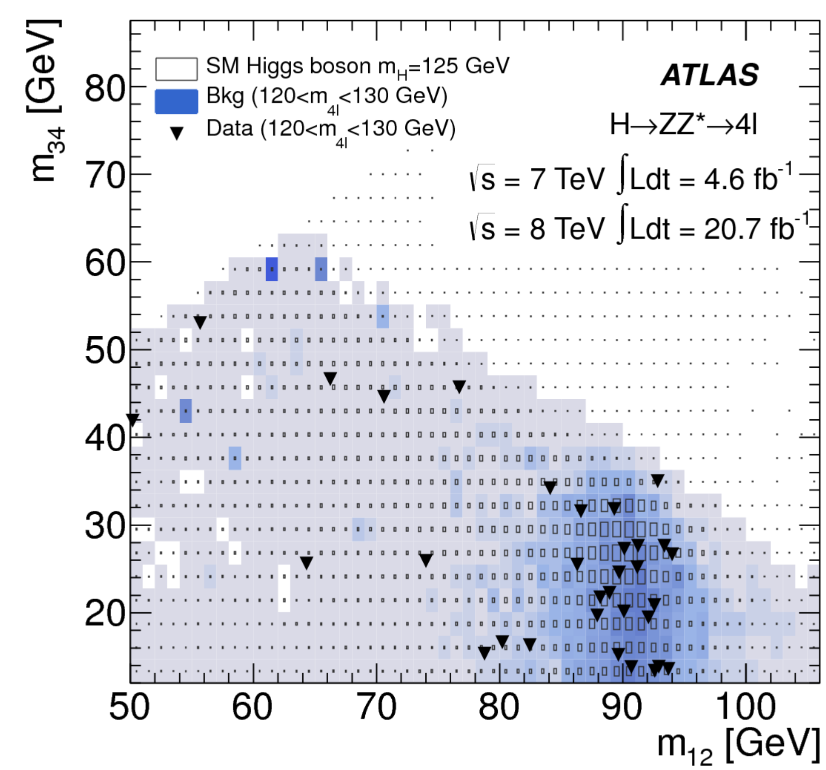




main systematics:

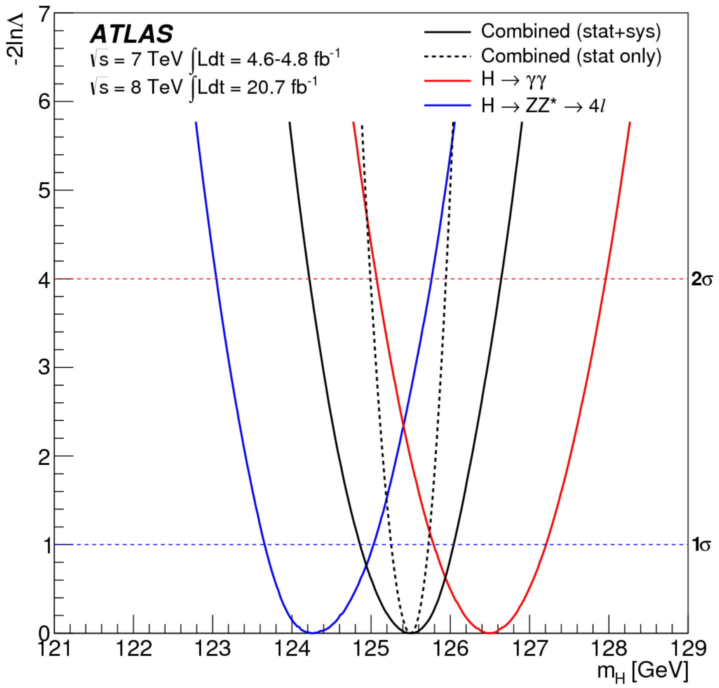
* ZZ production (~5-8%)
* electron ID/reco (~9%)
* luminosity (~4%)
* signal production (~8%)
* momentum scale (<1%)

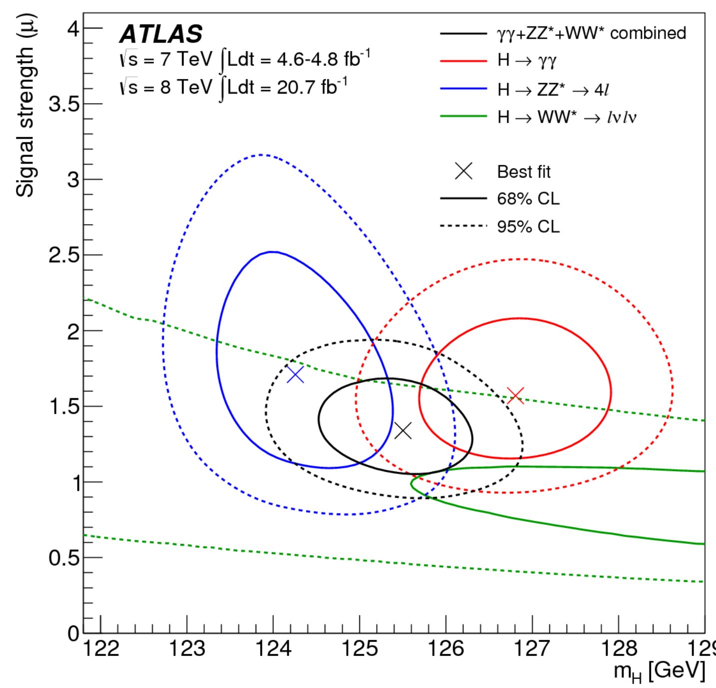


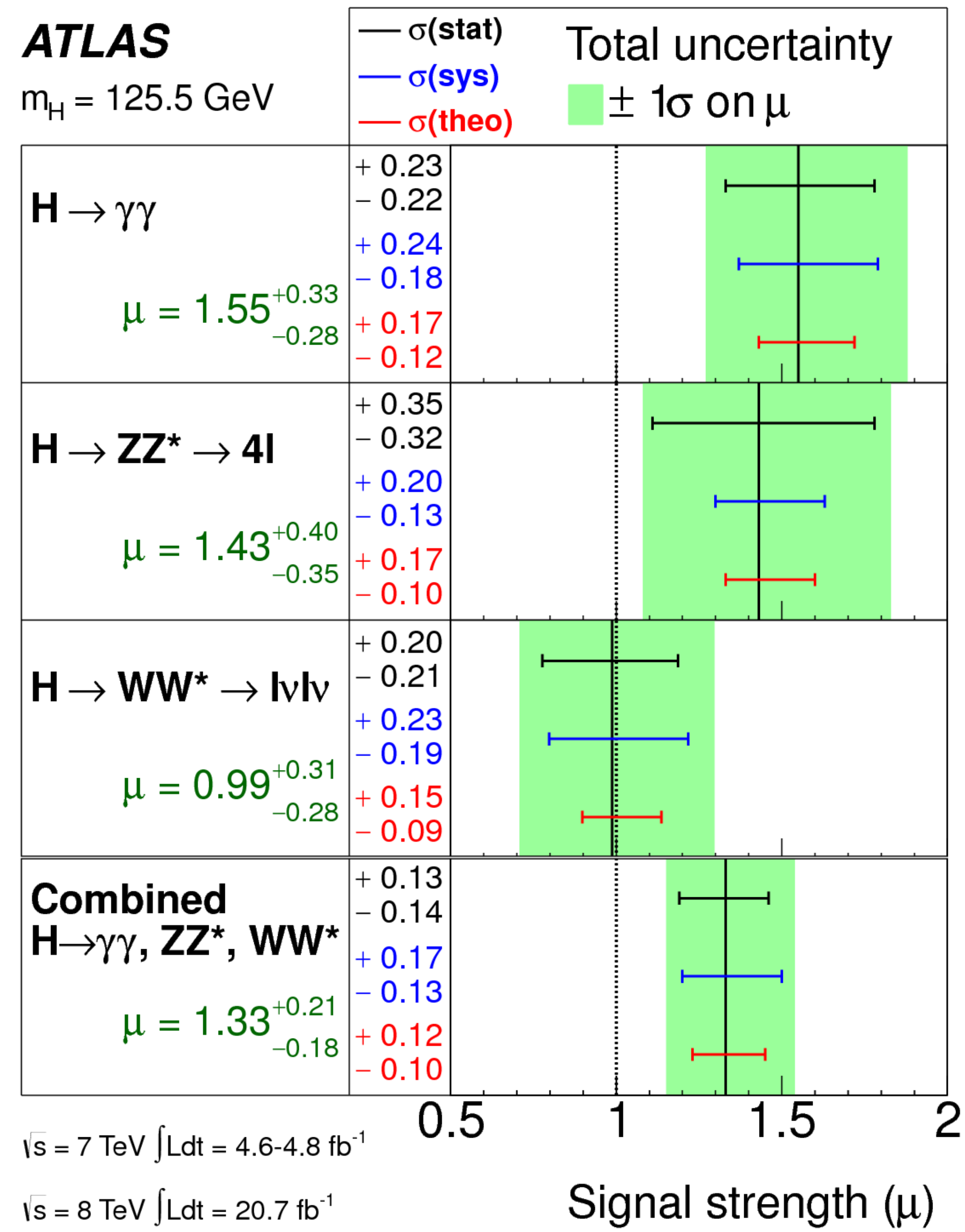


Combined results

$\mu = \frac{\text{events observed}}{\text{events expected}}$







combination with other channels

$$m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\ \text{GeV}$$

$$\mu = 1.33 \pm 0.14\,(\text{stat}) \pm 0.15\,(\text{sys})$$

we discovered a new particle…

=> is it the Higgs boson?

From B-physics to A-physics

(or, the importance of spin-parity studies)

Phys. Lett. B 726 (Jul, 2013) 120–144
ATLAS-CONF-2013-013
arXiv:1506.05669

Why Spin-Parity?

the SM requires H to be a parity-even scalar (0^+)

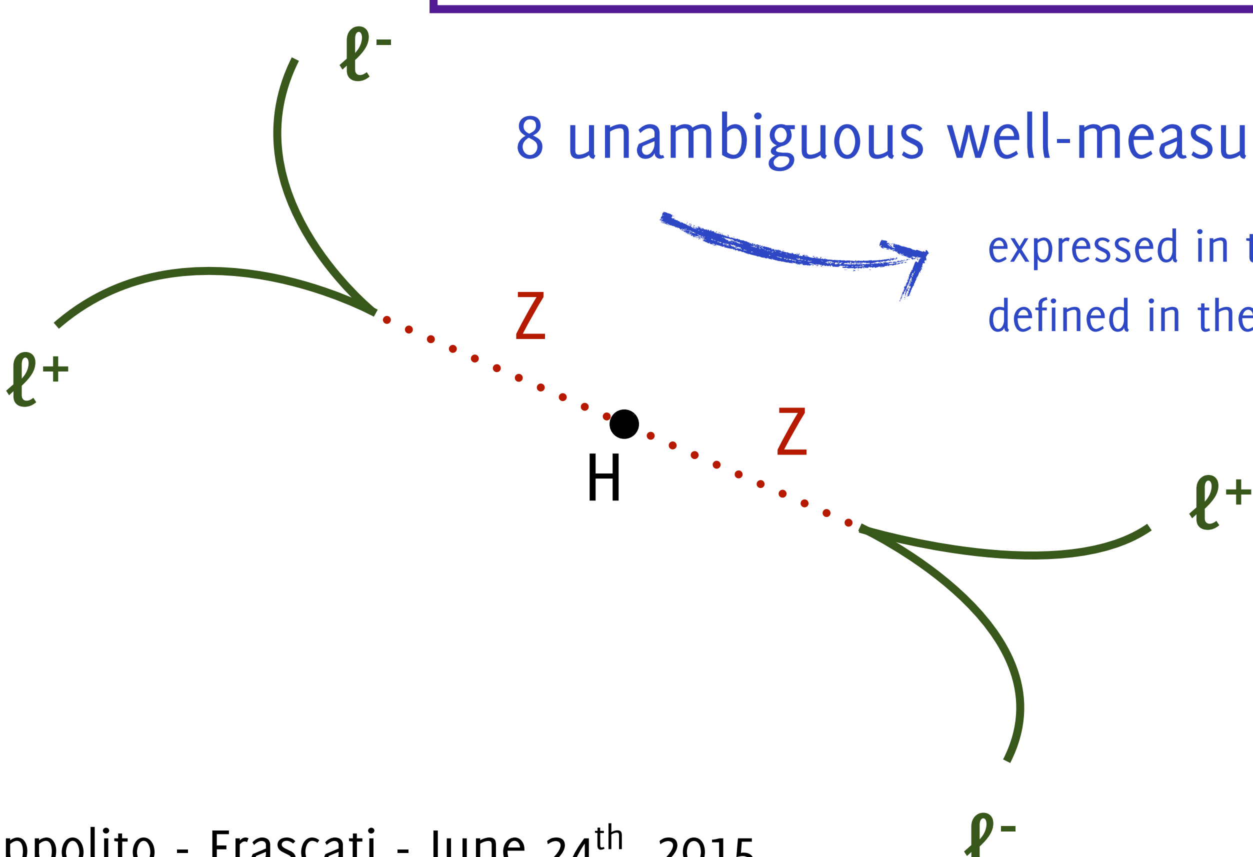
- it could be a J=1 state (and $H \rightarrow \gamma\gamma$ would be a different particle)
- it could be a graviton-like J=2 state, or a pseudo scalar…
- it could be a CP-even/odd admixture

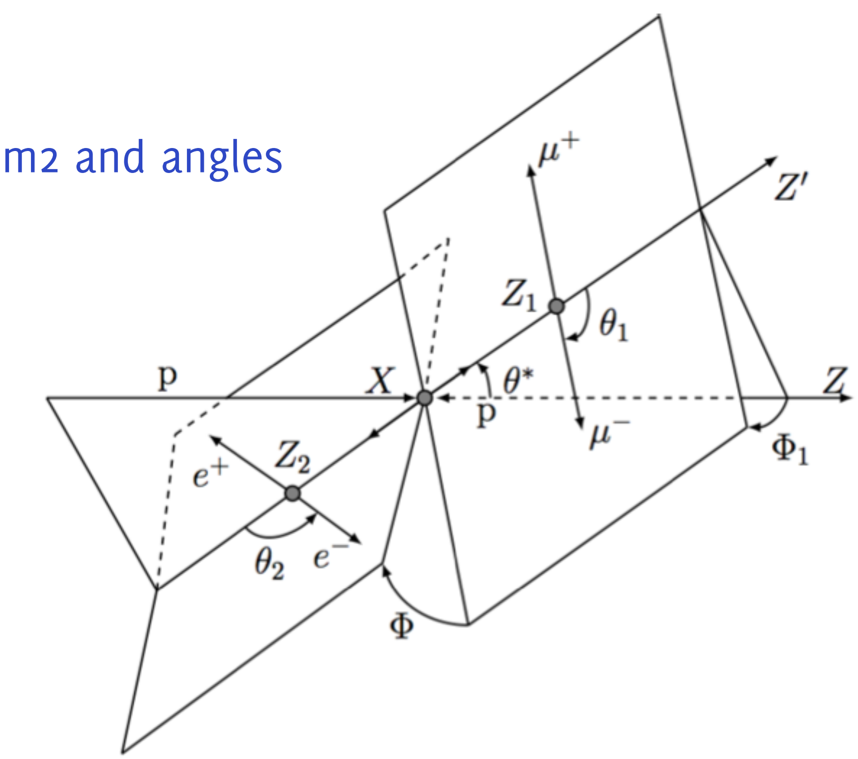
we can relate what we measure and what we want to know

$(p_1,p_2,p_3,p_4) = f\,[A(H \rightarrow ZZ)]$

8 unambiguous well-measured DOF

expressed in terms of m_{4l}, m_1, m_2 and angles defined in the final state





Know Your ~~Onions~~ Bosons!

we write the most general Lorentz-invariant decay amplitude A(H→ZZ)

e.g.: for J=0

$$A(X \to Z_1 Z_2) = v^{-1}\left(g_1 m_Z^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

SM Higgs

pseudoscalar

we relate it to the differential mass and angular distribution

phase space + propagator

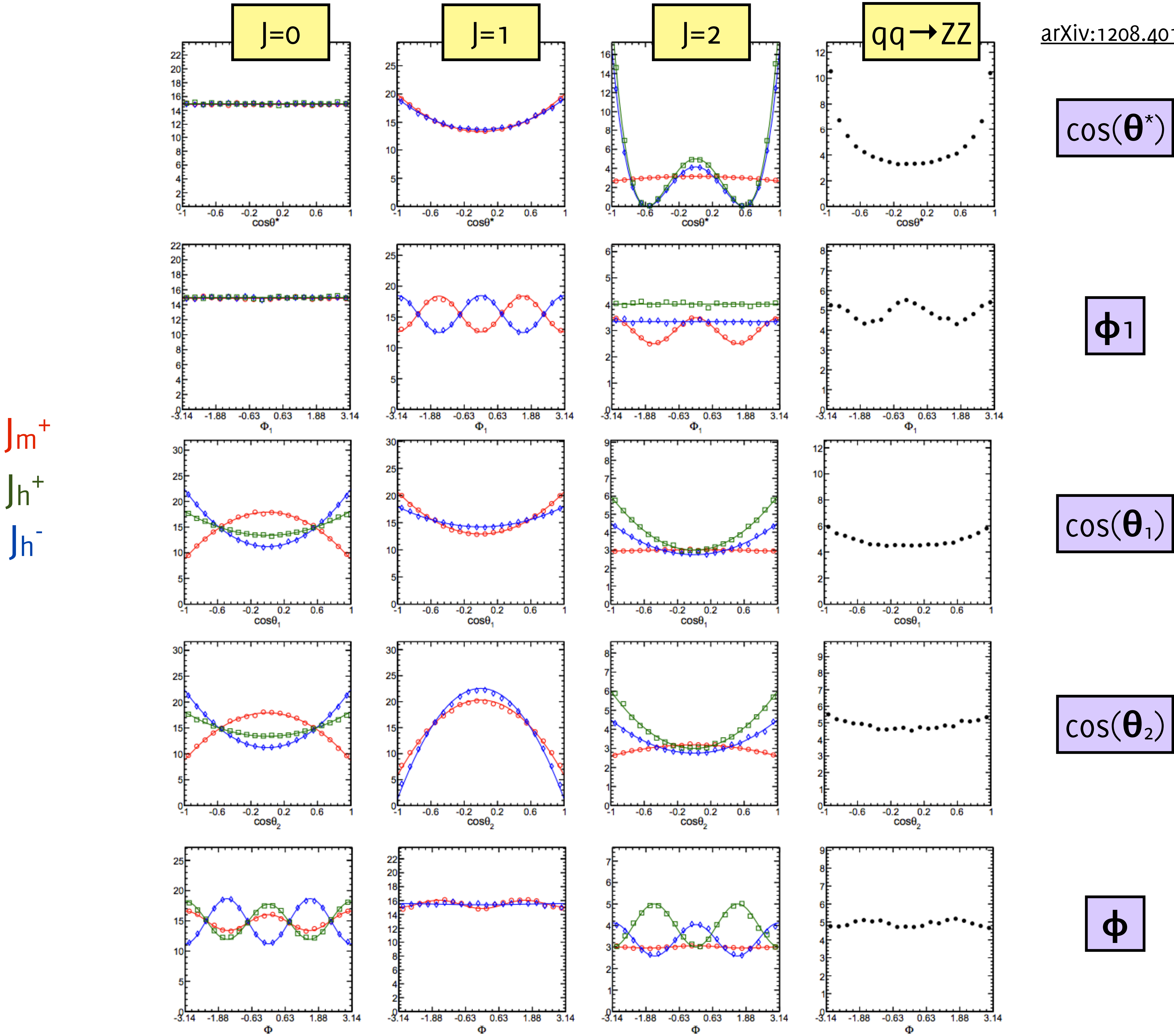
$$\frac{d\Gamma_J(m_1, m_2, \Omega)}{dm_1 dm_2 d\Omega} \propto P(m_1, m_2) \cdot \sum_i K_i(m_1, m_2) f_i(\Omega)$$

J=0: three helicity combinations (A_{++}, A_{--}, A_{00})

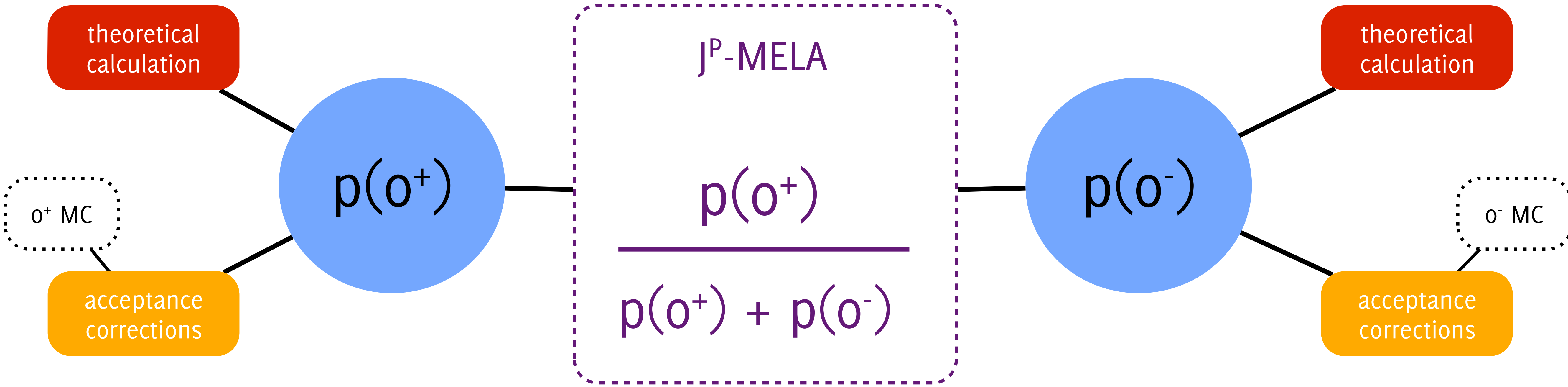
⇒ K_i = $|A_{++}|^2$, $Re(A_{++}A_{00}^*)$, $Im(A_{++}A_{00}^*)$ ... (9 terms)

$$\mathbf{\Omega} = \{\cos\theta^*, \phi_1, \cos\theta_1, \cos\theta_2, \phi\}$$

arXiv:1208.4018



Hypothesis Testing



collapse the 7D information on the final state on a single observable

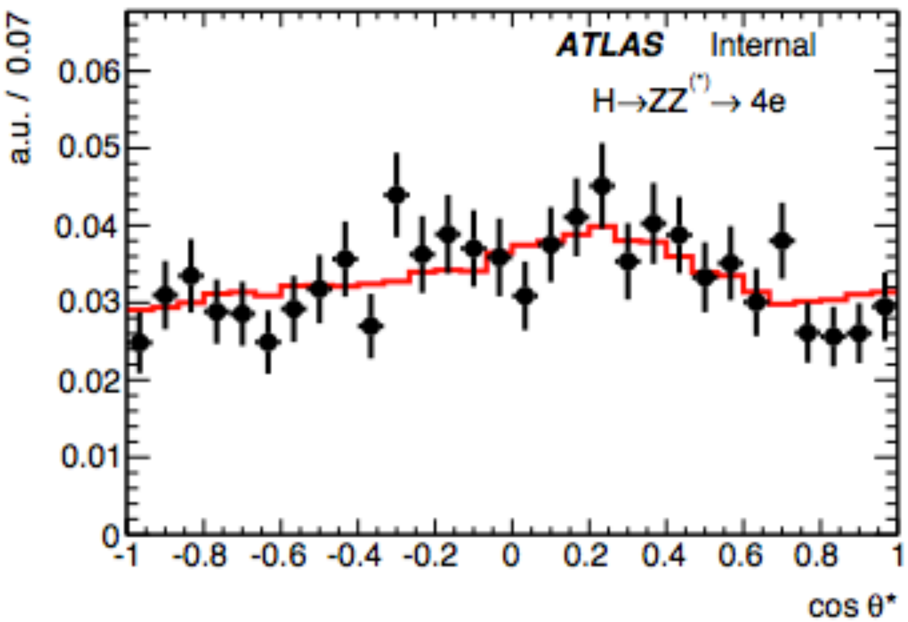
→ it is the Bayes discriminant between data likelihood in H0 and H1 hypotheses

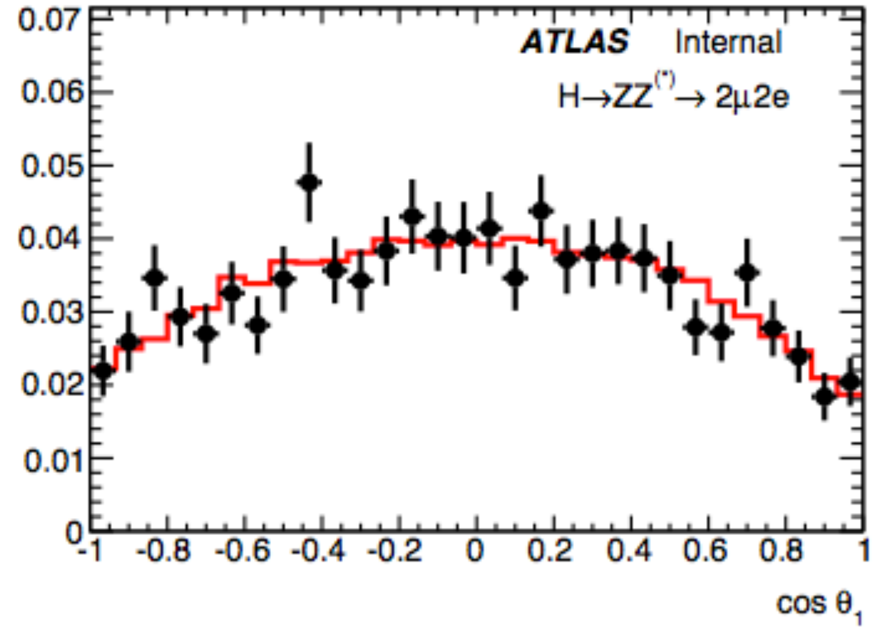
→ mathematically it's the optimal discriminant in the ideal case

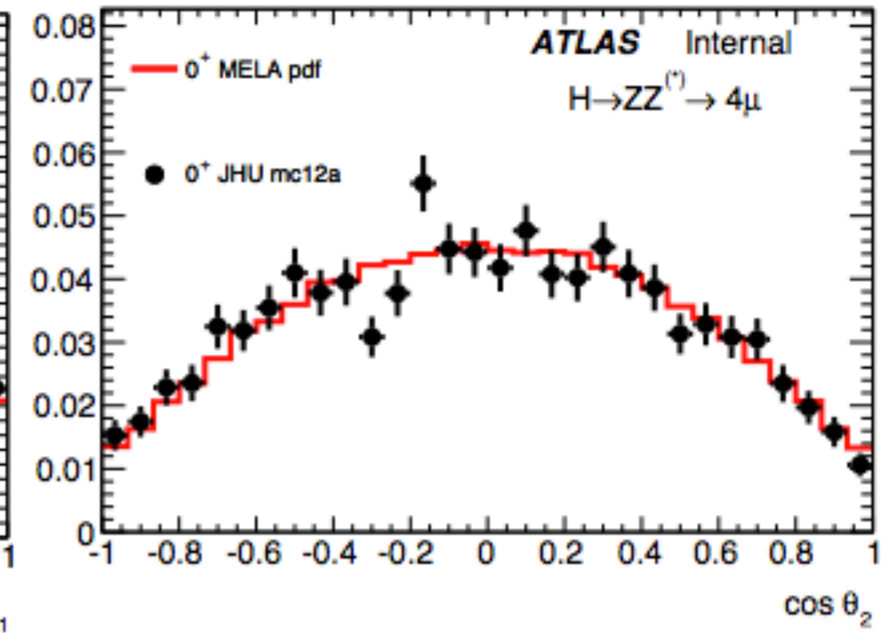
the difference between "real" and "ideal" is the effect of reconstruction and selection criteria

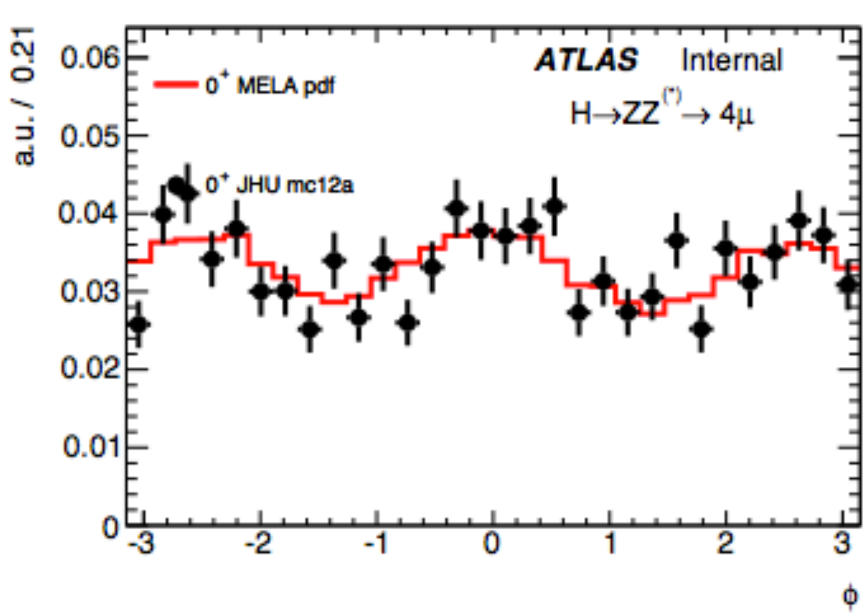
☛ $p(m_1, m_2, \Omega)$ is corrected using acceptance functions

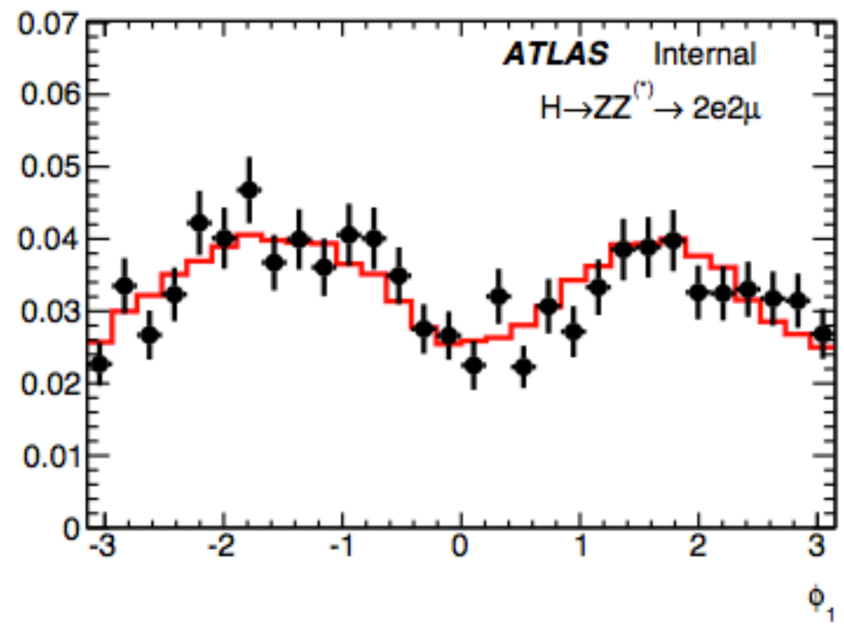
How Good ?

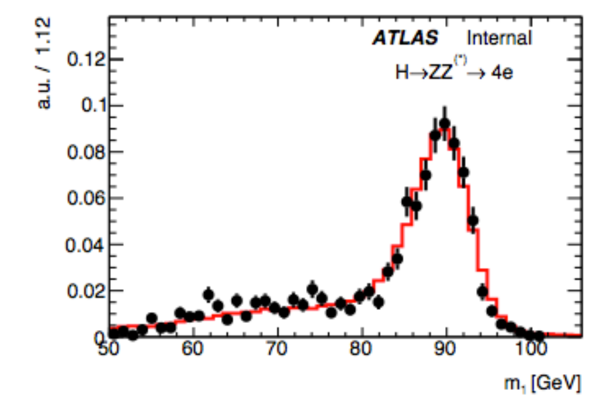


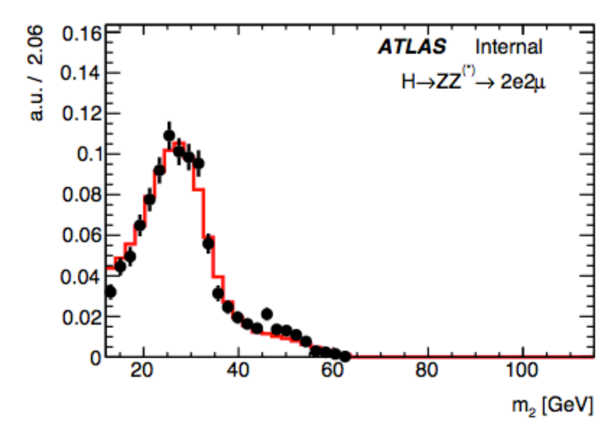












good description of full-sim MC for all tested models

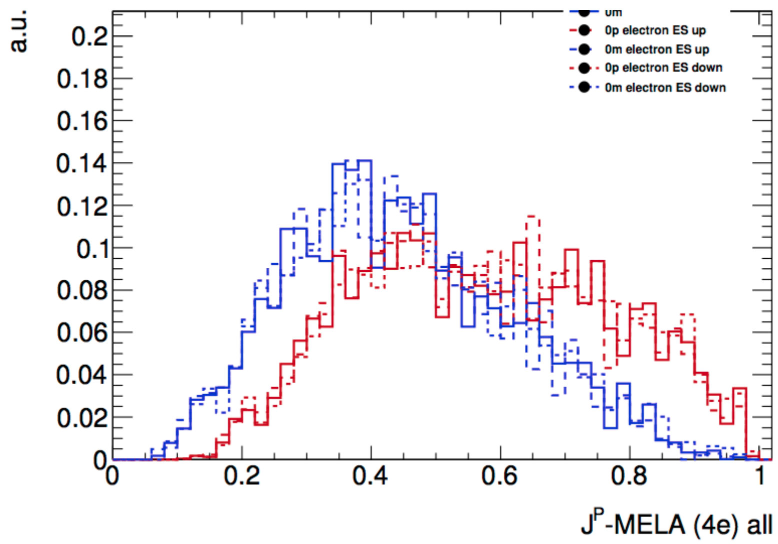
this avoids loss in separation between hypotheses

The J^P-MELA Discriminant

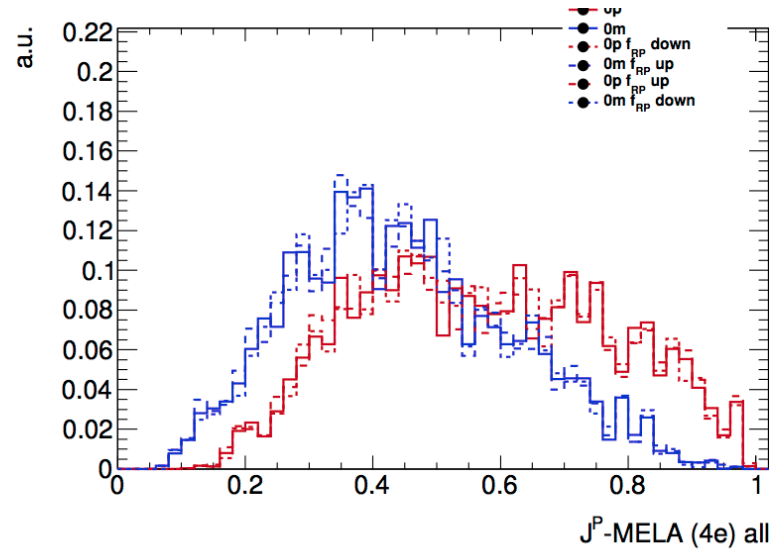
distributions of the discriminant D are calculated on full-sim MC

obtain discriminant shapes for the two signal hypotheses and for backgrounds

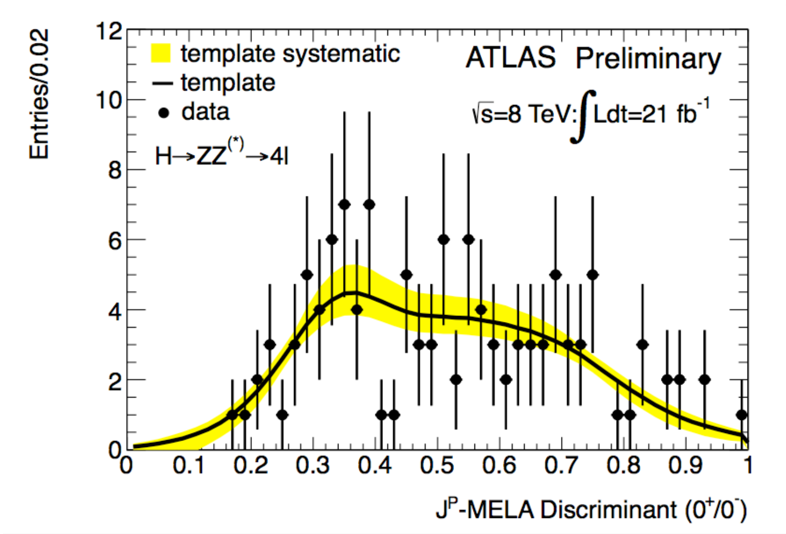
effect of ESS



wrong pairing effects



reducible background



build a likelihood model in the observable D

J^P-MELA discriminant

$$L(\epsilon|\mu) = \text{Pois}(N|\mu N_s + N_b) \cdot \left\{ f_s \left[\epsilon \cdot p(\text{data}|H_0) + (1-\epsilon) \cdot p(\text{data}|H_1)\right] + \sum_{i=ZZ,\text{red}} f_{b_i} p(\text{data}|B_i) \right\}$$

ϵ=0,1

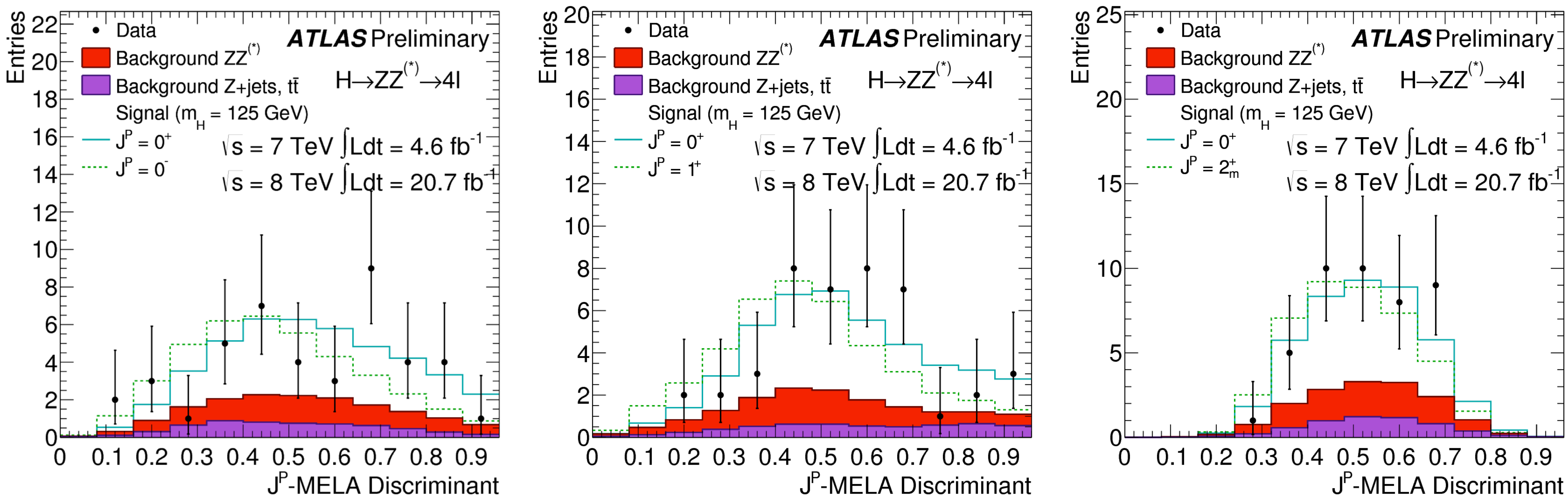
sum across two m4l bins: 4×2×2 channels

([121,127] and [115,130]\[121,127] GeV)

The J^P-MELA Discriminant

shapes of the discriminant with 7+8 TeV data

J^P-MELA = **0** for alternative hypothesis, **1** for SM Higgs



8 TeV

Final State and bin	Signal	ZZ	Reducible
4μ High	4.62	1.42	0.29
4μ Low	0.93	1.92	0.39
4e High	1.95	0.58	0.32
4e Low	0.77	0.83	0.43
2e2μ High	3.01	1.02	0.31
2e2μ Low	0.79	1.41	0.42
2μ2e High	2.22	0.68	0.44
2μ2e Low	0.65	0.94	0.61

7 TeV

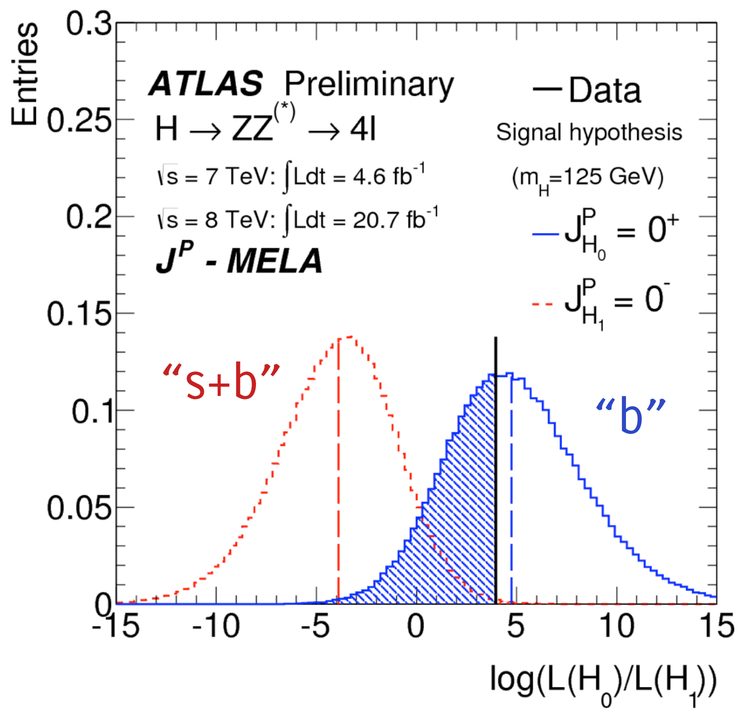
Final State and bin	Signal	ZZ	Reducible
4μ High	0.83	0.27	0.06
4μ Low	0.17	0.40	0.09
4e High	0.24	0.09	0.07
4e Low	0.11	0.12	0.10
2e2μ High	0.51	0.20	0.07
2e2μ Low	0.13	0.28	0.09
2μ2e High	0.33	0.11	0.10
2μ2e Low	0.09	0.17	0.14

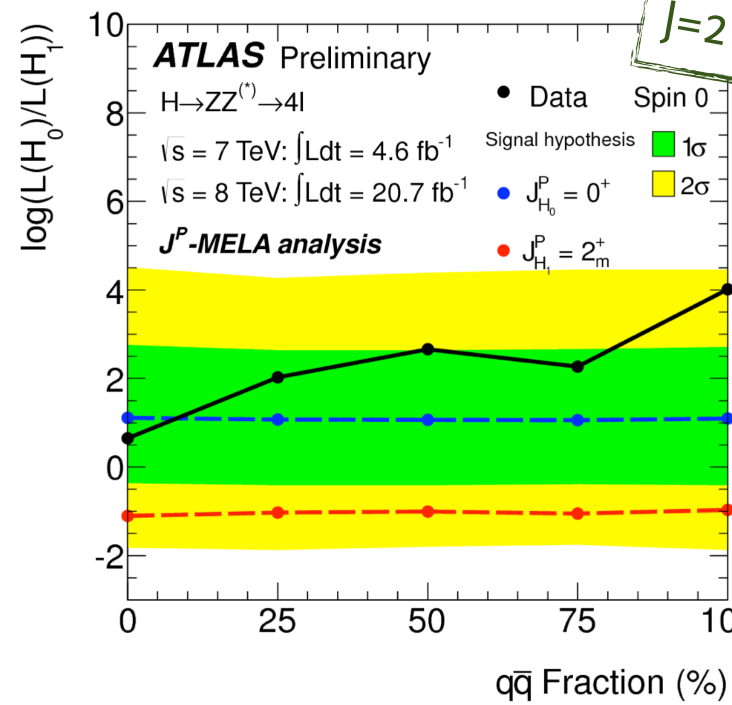
statistical analysis is split in 4 final states, 2 c.o.m. energies, 2 m4l bins ⇒ enhanced H_0/H_1 separation

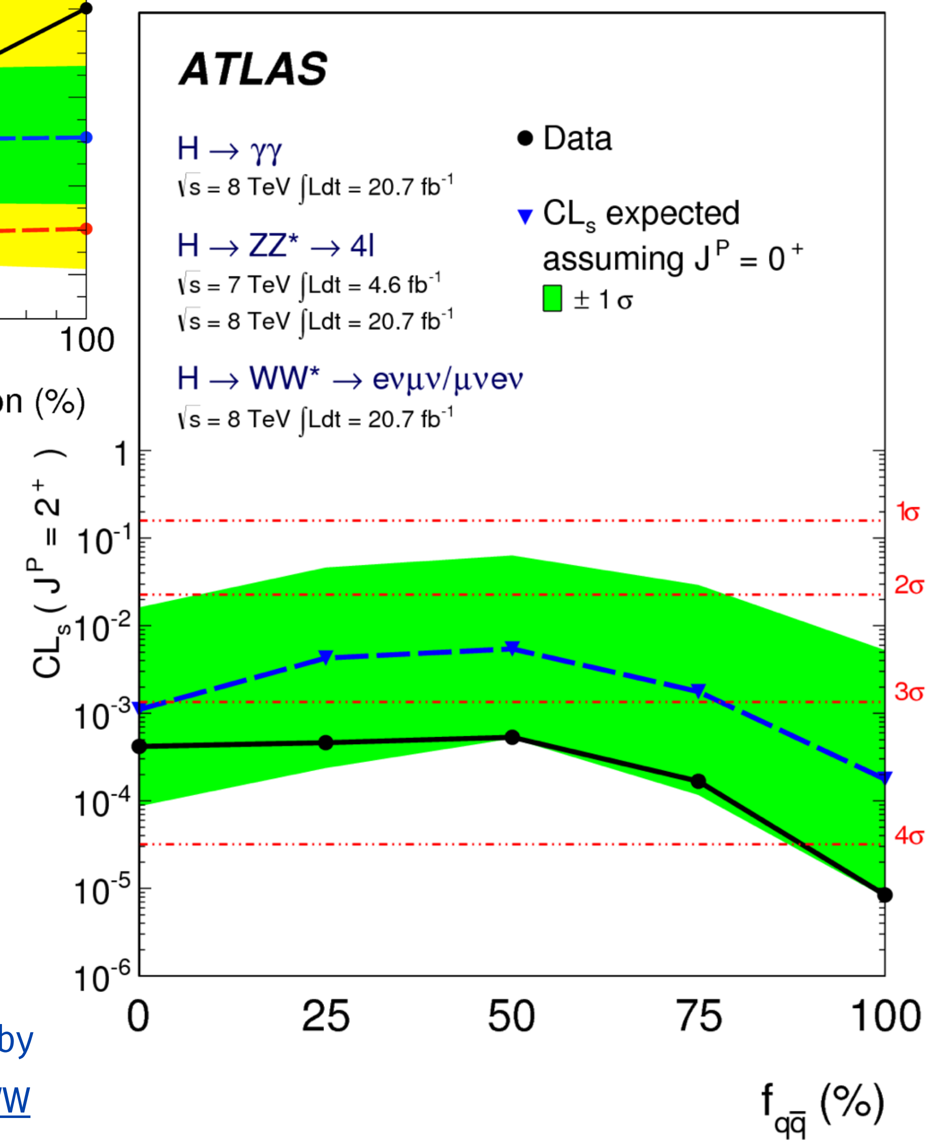
Hypothesis Testing Results

use distribution of log[L(H₀)/L(H₁)] sampled on pseudo-events to build a test statistics

J=2 production mechanism unknown ⇒ f_{qq}







exclusion given w.r.t. 0^+ with $CL_S = CL_{S+b}/CL_b$ method

		J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.064	0.11	0.38	0.182
2^-	p_0	0.0032	0.11	0.08	0.116

>95%

excluded by 4ℓ+γγ+WW

only sensitive to 0^+ vs $1^{+/-}$ (WW), 2^+

Probing the HZZ vertex

ATL-PHYS-PUB-2013-013
arXiv:1506.05669

Can We Say More?

— yes, if we assume J=0

let's take again the most general H→ZZ decay amplitude

$$A(X \to Z_1 Z_2) = v^{-1} \left(g_1 m_Z^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

in the SM:

2i

O(10⁻²) (one loop diagrams)

(suppressed by scale² of NP)

≈0 (three loops diagrams)

non-zero g_2, g_4 affect final state distributions

* CP even/odd admixture present if g_4 and g_1 are both non-zero
  can hint to CP violation (e.g. mixing between multiple Higgs particles à la 2HDM) which might explain matter/antimatter asymmetry
  (excluded) pure pseudoscalar state corresponds to the limit $|g_4/g_1| \to \infty$
* new physics could contribute in loops giving $g_2 \neq 0$

The Idea

Q: How good will we be able to probe the HZZ vertex in the next future?

→ sensitivity to CP-even/odd admixtures

$$f_{g_i} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right)$$

$$f_{CP} = \frac{|A_\perp|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} \sim f_{g4}$$

start from the parton-level description of the 7D final state

* add acceptance corrections (2D for m_1 vs m_2, 1D for angular observables)
* add m_{4l} to obtain discrimination power against backgrounds

parametrise backgrounds

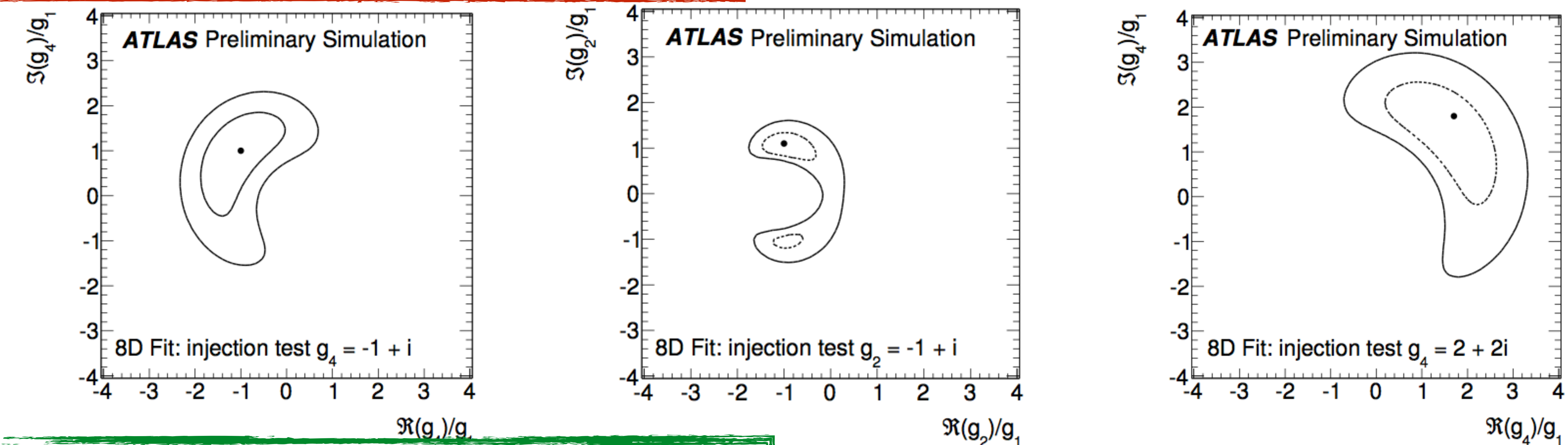
* use full-simulation Monte Carlo
* empirical parametrisation (2D for m_1 vs m_2, 1D for angular observables)

perform 8D fit for imaginary and complex parts of either g_4 or g_2

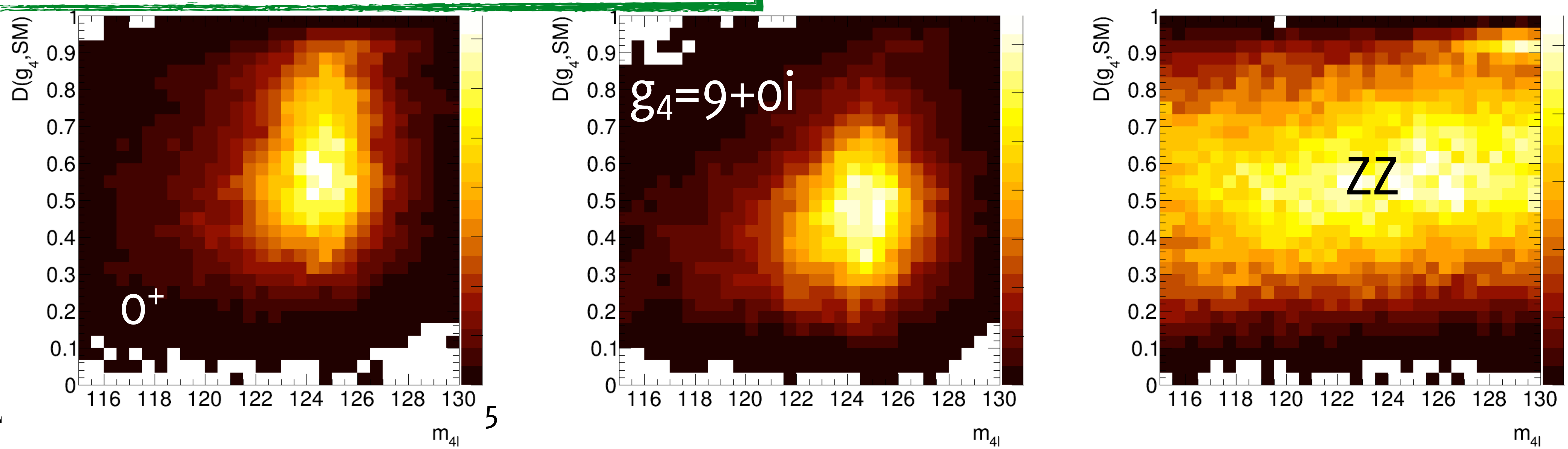
→ cross-check validity of empirical parametrisations with 2D MELA-like discriminant method

How it looks like

closure test of 8D fitting technique (injection)



discriminant shapes for 2D cross-check method



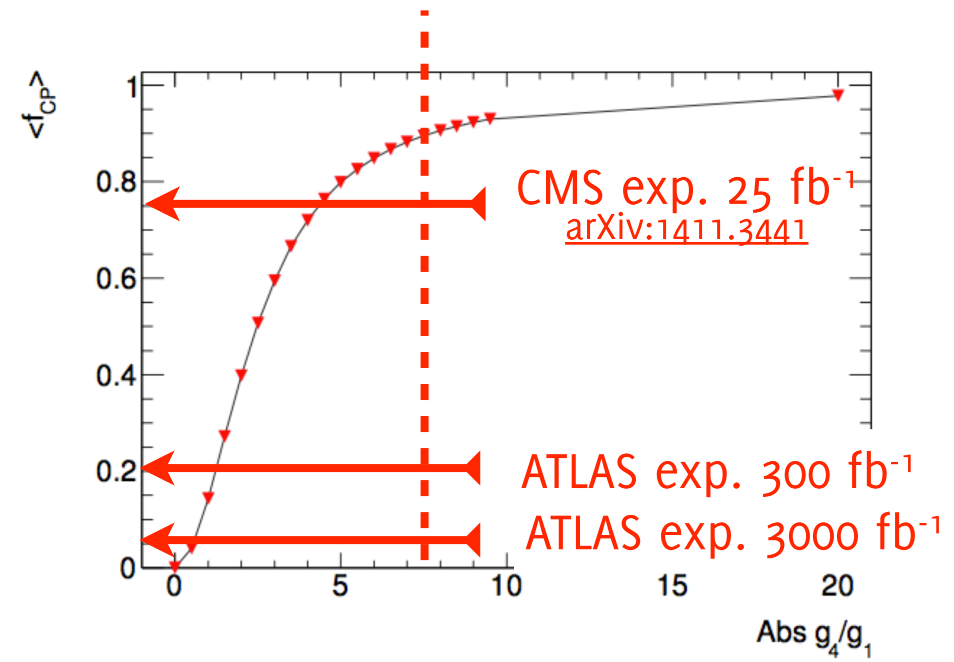
Prospects @HL-LHC

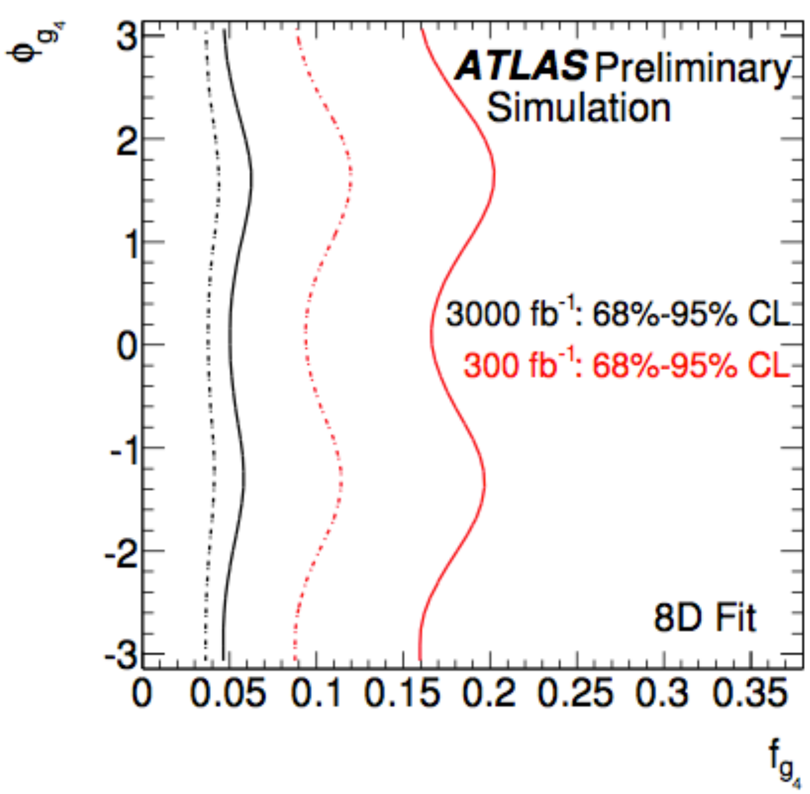
High Luminosity upgrade of the LHC foreseen in the next future (> 2020)

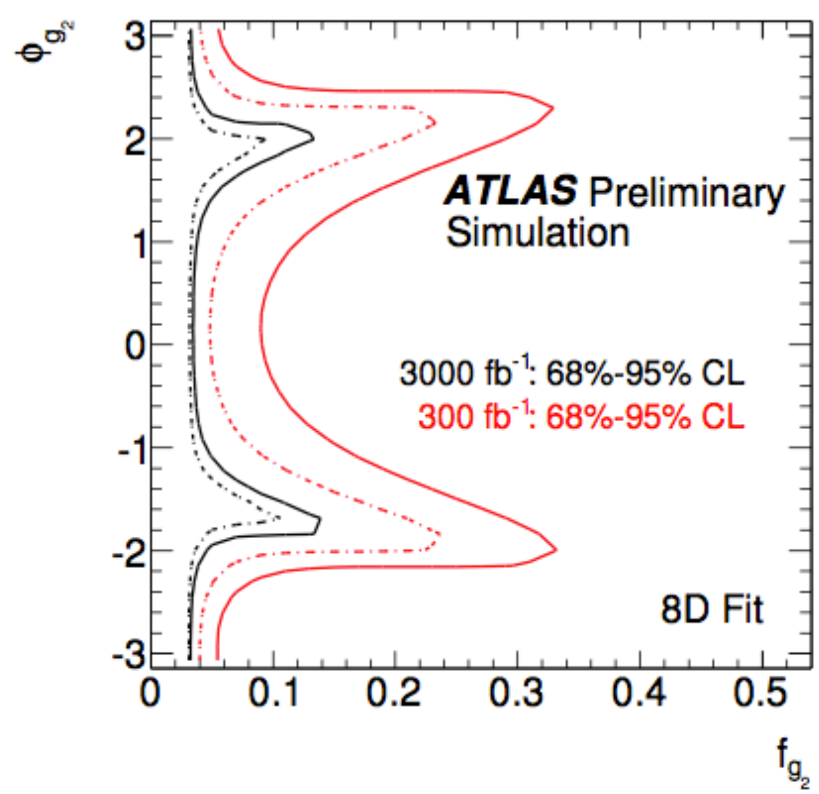
* studied sensitivity on HZZ vertex structure with 300 and 3000 fb^{-1} at 14 TeV

Final State	Signal	ZZ^*	Reducible Backgrounds
4μ	1186	427	214
$2\mu 2e$	867	287	144
$2e2\mu$	1035	383	191
$4e$	871	317	158

* systematics: 3% (lumi) + 5% (lepton reco) + 7-10% (bkg, acc)





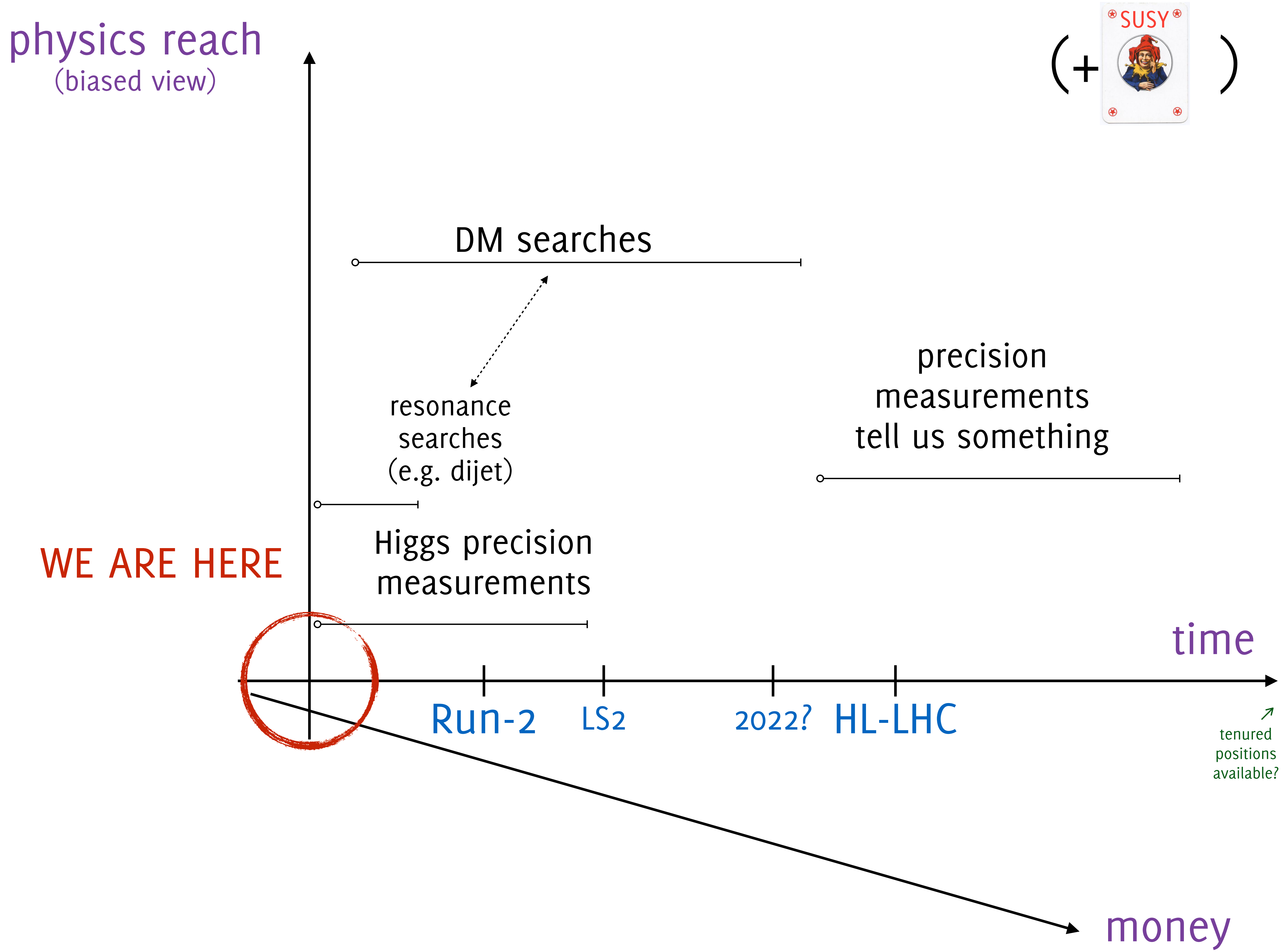


Luminosity (fb^{-1})	f_{g_4}	f_{g_2}
300	0.20	0.29
3000	0.06	0.12

+ arXiv:1506.05669 for recent update

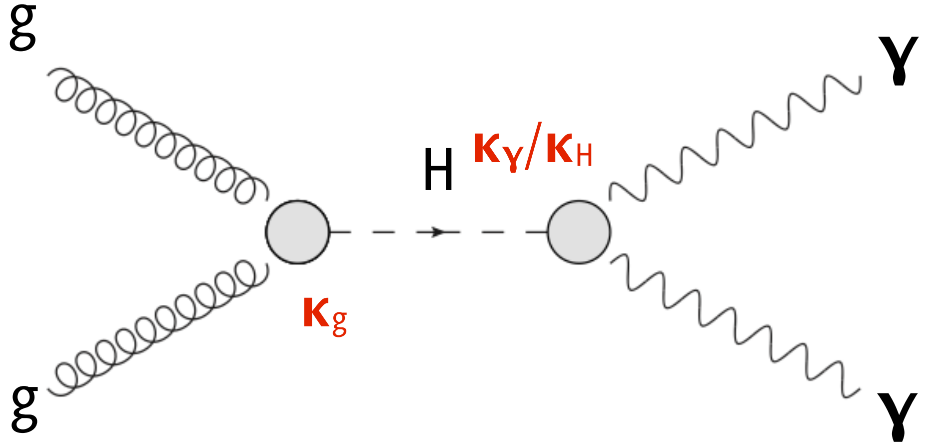
Beyond

— Qu'est-ce qu'on fait en attendant Godot ?
— Une excellente pièce...



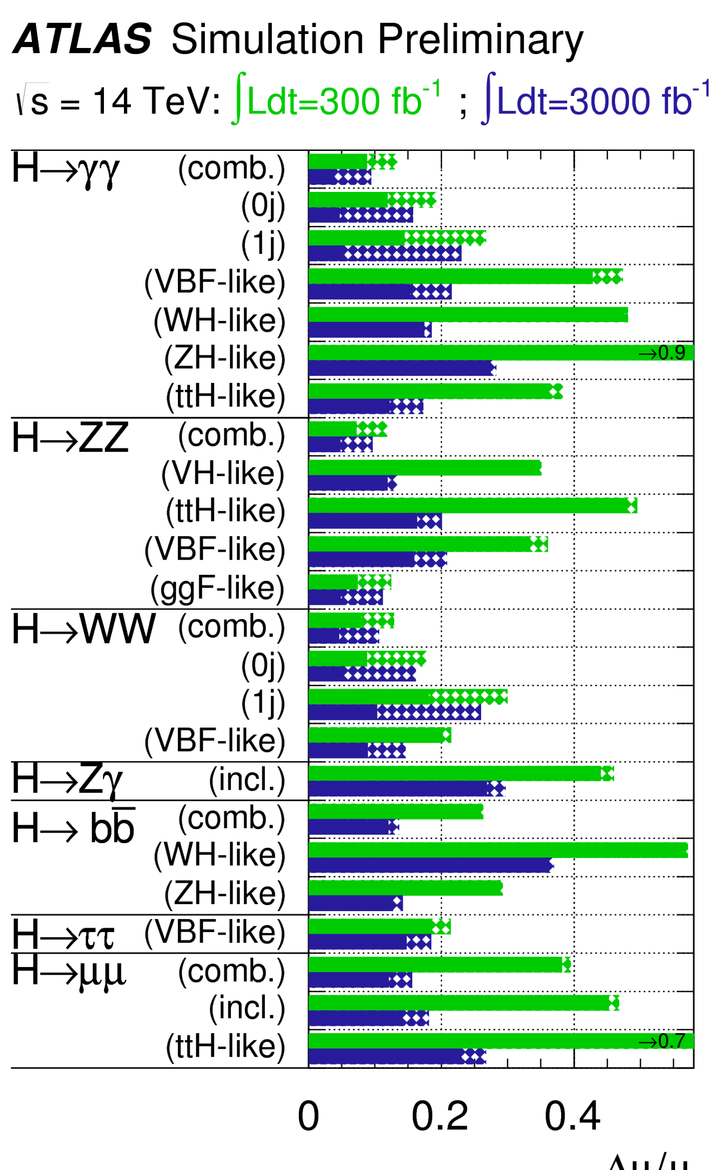
physics reach
(biased view)
(+ SUSY)
DM searches
resonance searches (e.g. dijet)
precision measurements tell us something
WE ARE HERE
Higgs precision measurements
time
Run-2
LS2
2022?
HL-LHC
tenured positions available?
money

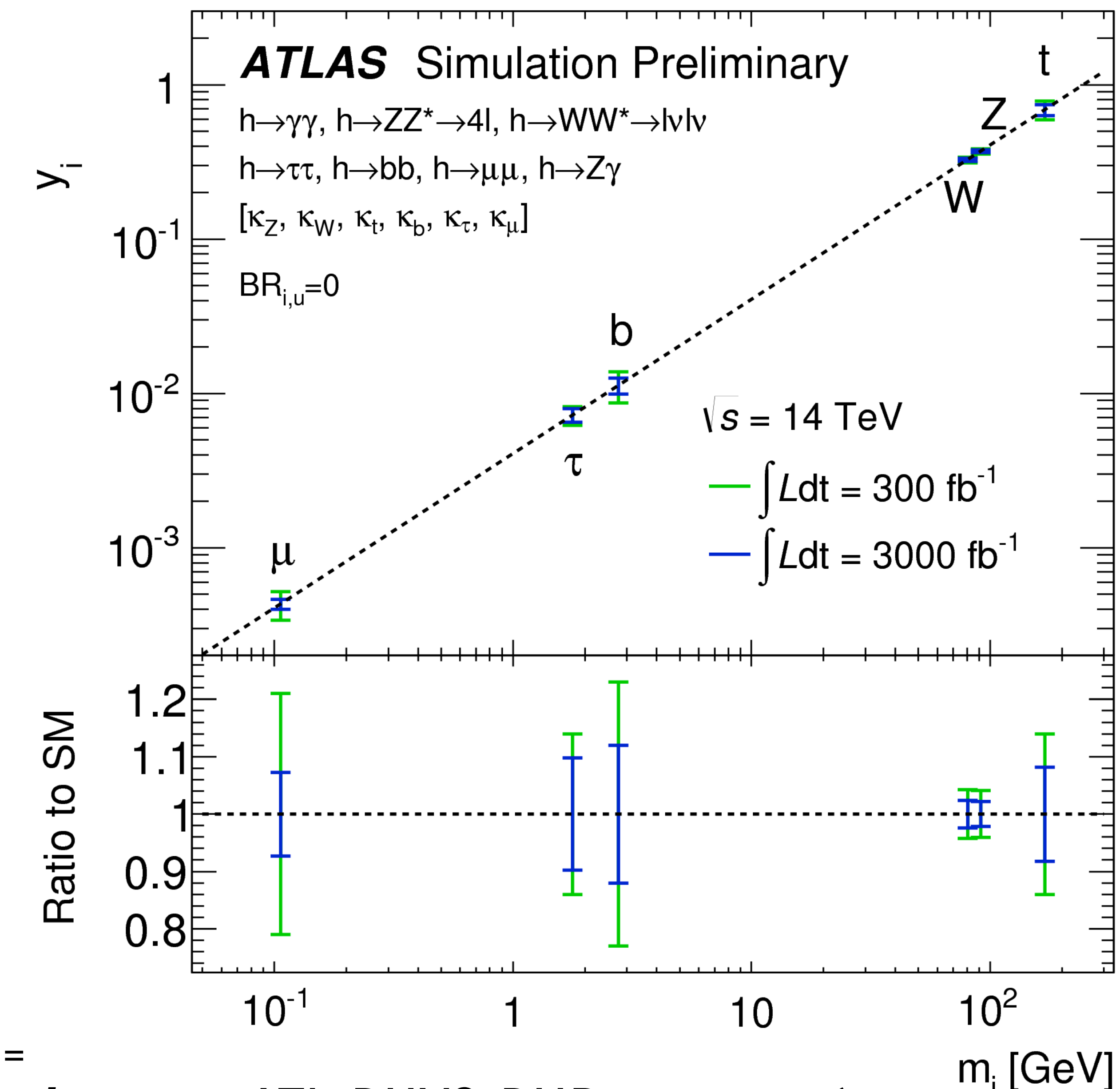
LHC as a Higgs Factory



precision measurement of coupling scale factors

* test for NP in loops, wider H sector, custodial symmetry…
* typically need O(1-5%) precision to test sensible SM extensions





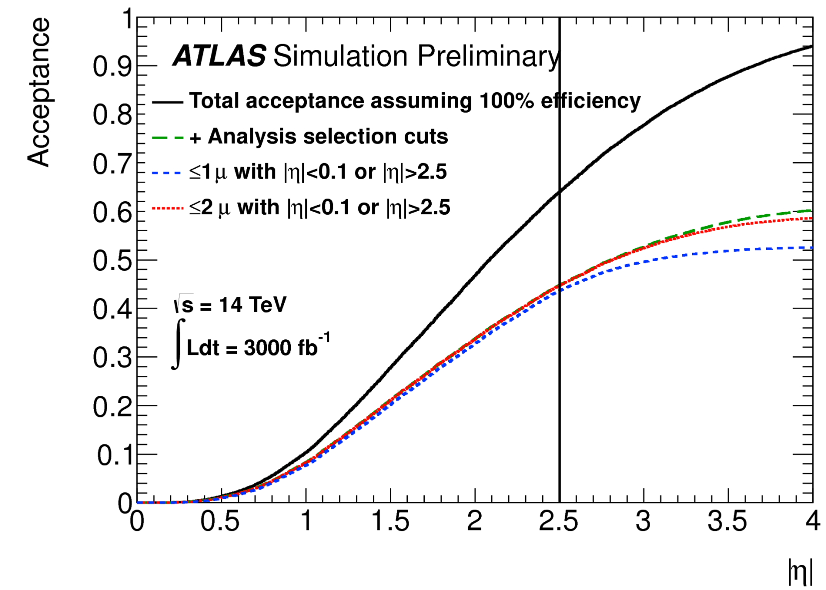
[hashed bands = theoreticians' fault]

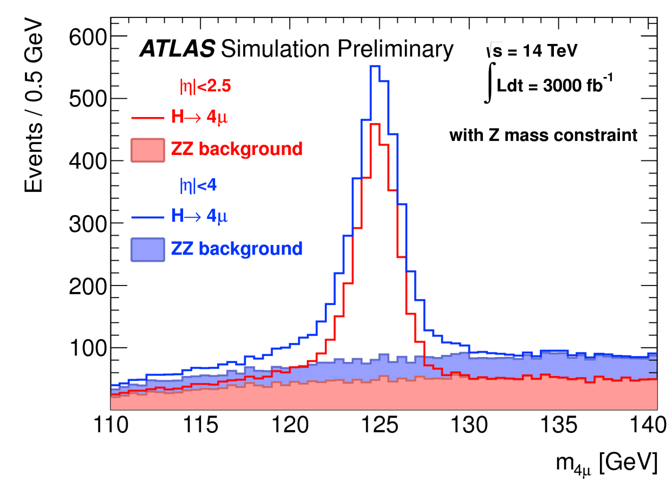
ATL-PHYS-PUB-2014-016

Going Forward (in **η**)

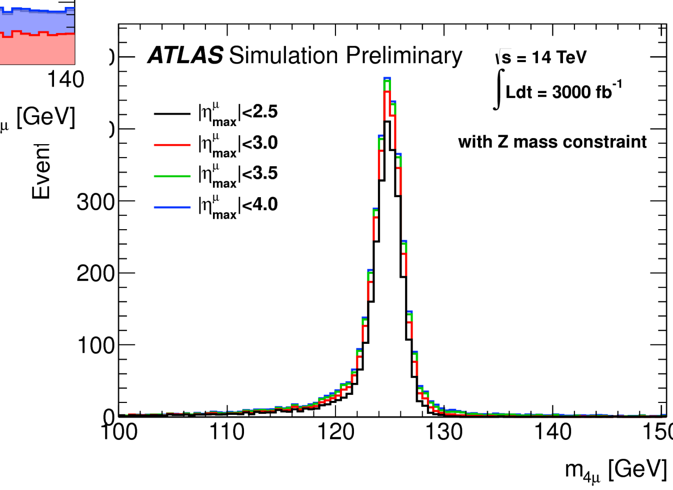
- extending tracking capabilities in forward region for HL-LHC
  - improved pileup rejection, VBF sensitivity, MET resolution...
- silicon tracker (ITK) extension up to 4.0 (depends on funding)
- foresee 20/30% gain in HZZ acceptance
  - aim at significant s/sqrt(s+b) improvement in bbH
  - 10-20% better precision on couplings
- http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/PLOT-UPGRADE-2014-002/

acceptance gain in H->ZZ*->4l

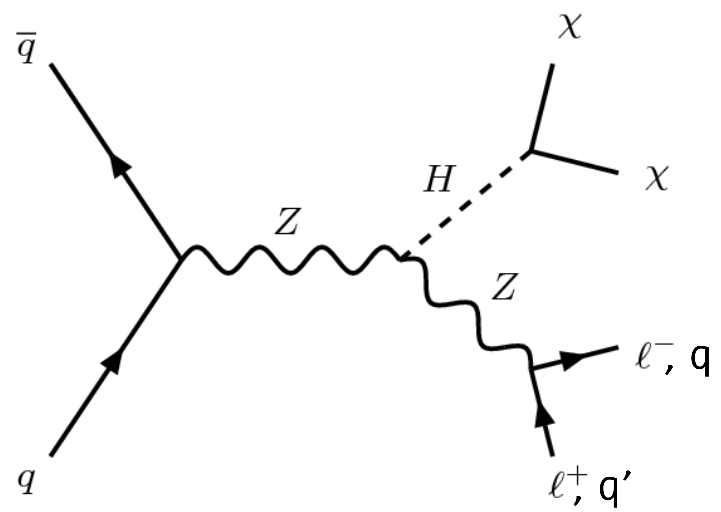


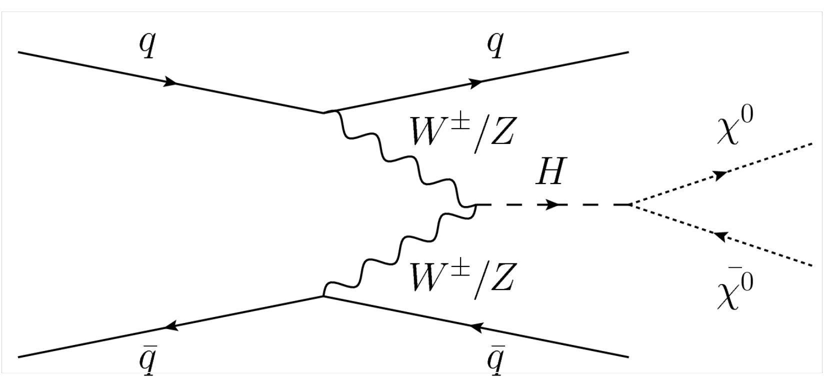


H4l mass (after Z mass constraint)



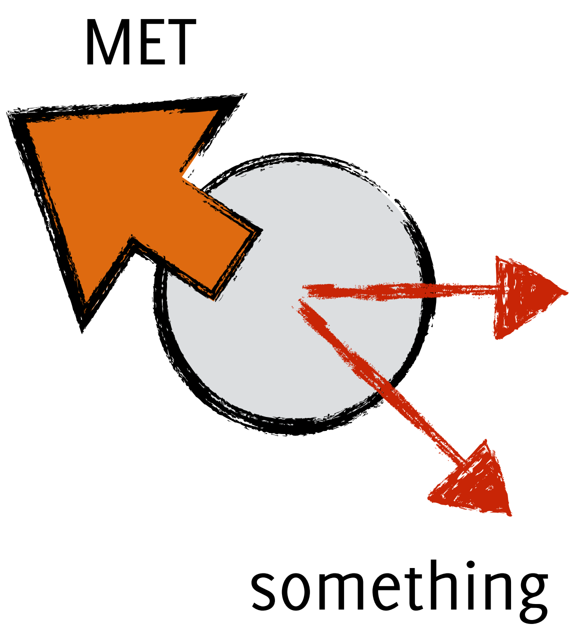
Seeing Through The Invisible





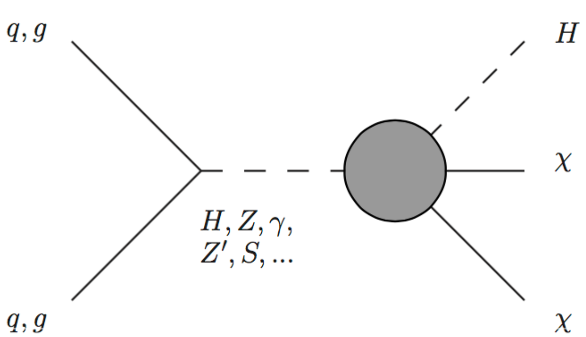
ATLAS-CONF-2015-004
ATLAS-CONF-2015-007
arXiv:1402.3244

- invisible Higgs decays are precious for looking for new physics
  - many models predict H as "interface" between SM and a dark sector
- BR_H can be probed with direct or indirect searches
  - VBF H->inv: BR < 0.29 @ 95% CL
  - Z(ll)H->inv: BR < 0.75 @ 95% CL
  - W/Z(qq)H->inv: BR < 0.78 @ 95% CL
  - couplings: BR < 0.27 @ 95% CL
- most sensitive to Dark Matter!
  - coupling either directly to H or via scalar mediators/ mixing/MSSM-like scenarios…



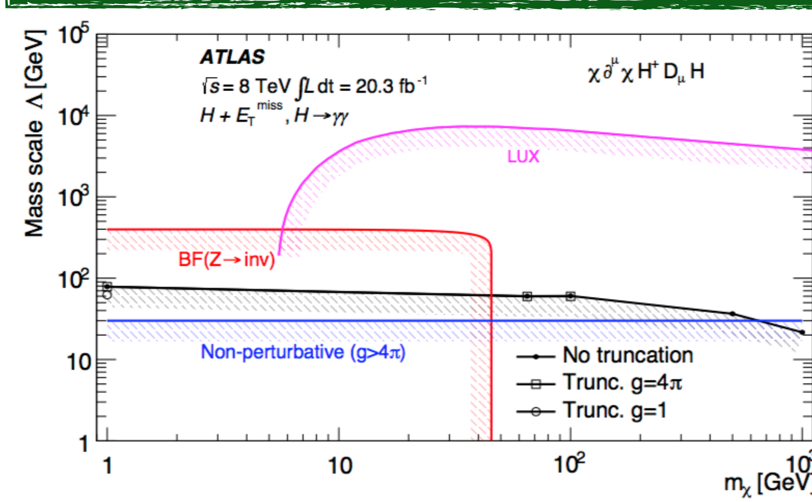
A Dark Matter Factory?

- "Higgs portal" models: unique sensitivity at LHC to low-mass DM
  - for each value of $m_{DM} < m_H/2$, BR_H is connected to DM/nucleon scattering cross-section measured by direct detection experiments
- EFT approach allows to look for massive DM probing coupling to Higgs boson
  - complementary to (more general) mono-X searches, e.g. via e.g. H(->$\gamma\gamma$)+MET

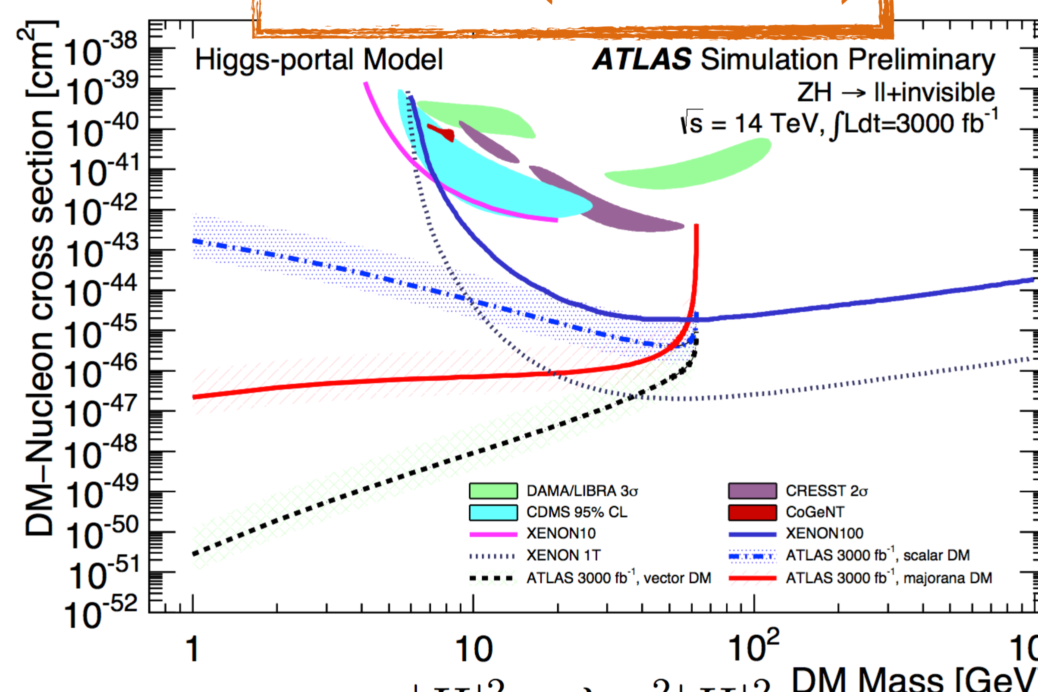


1506.01081v1

from H$\chi\chi$ contact interaction



from BR_H (via ZH->inv)



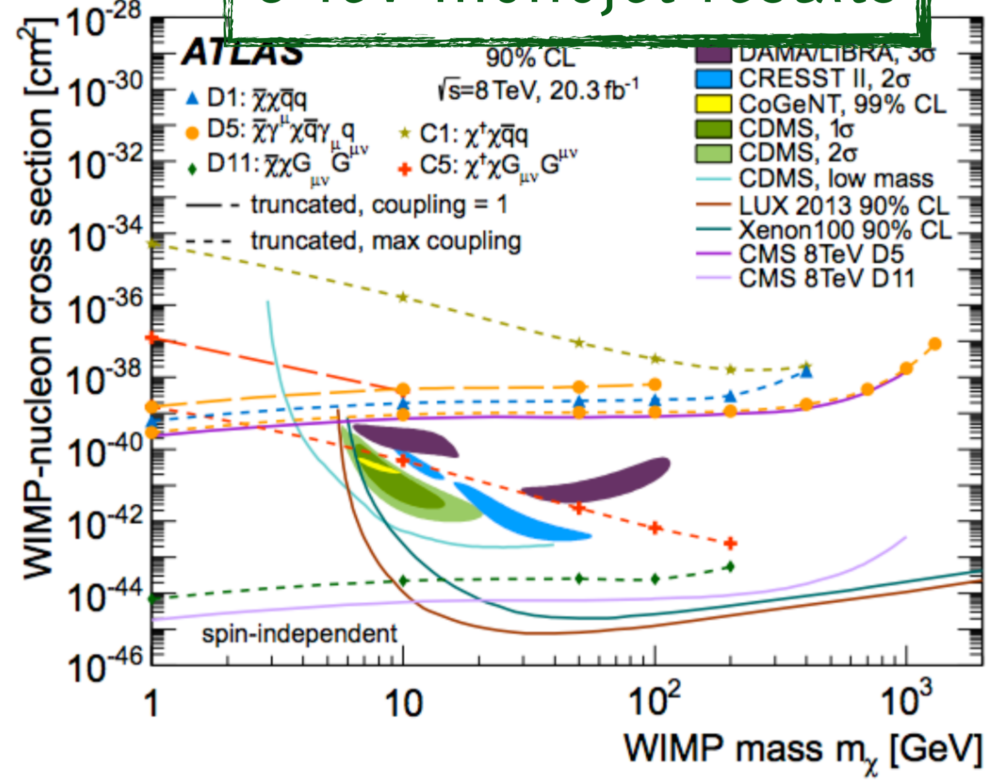
$$-y_\chi \bar{\chi}\chi s - \mu_p s|H|^2 - \lambda_p s^2|H|^2$$

Can We Get Into That Plane?

- how (and how far) can LHC go in the comparison to direct DM detection experiments?
  - the answer is **quite far** provided we use both EFT and simplified-model eyeglasses (arXiv:1506.03116)
- our ultimate job is to produce and study particles, and DM *is* a particle…
- experimental challenge for Run-2 and beyond
  - most signatures based on MET/jet/e-γ reconstruction, need to fight against pile-up!

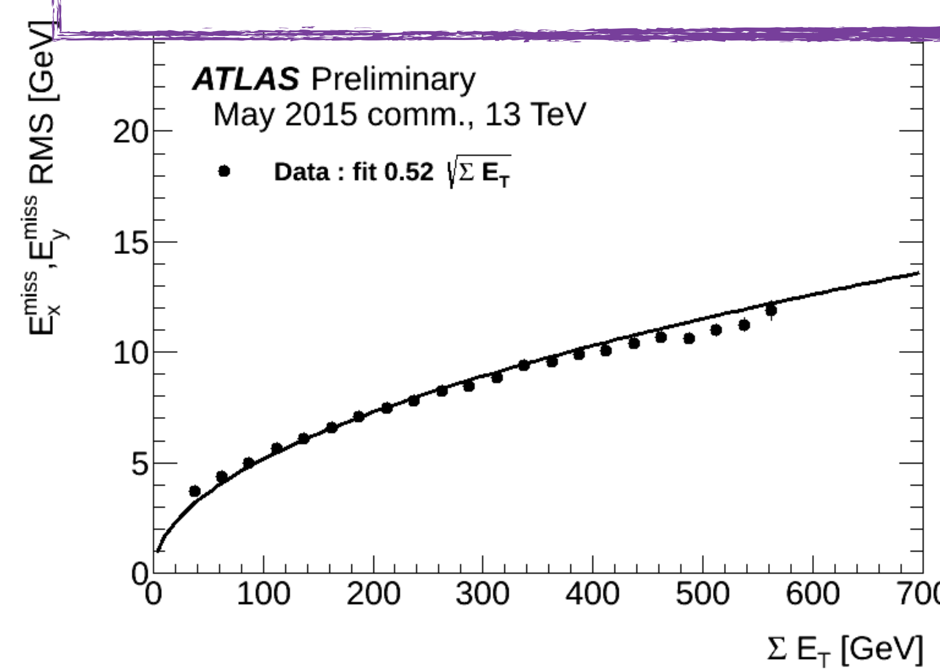
data will tell us how the DM puzzle talks to our brand new SM-ish Higgs, and if there are surprises…

8 TeV monojet results



arXiv:1502.01518

MET resolution with Run-2 data



Surprises

‹intentionally left blank›

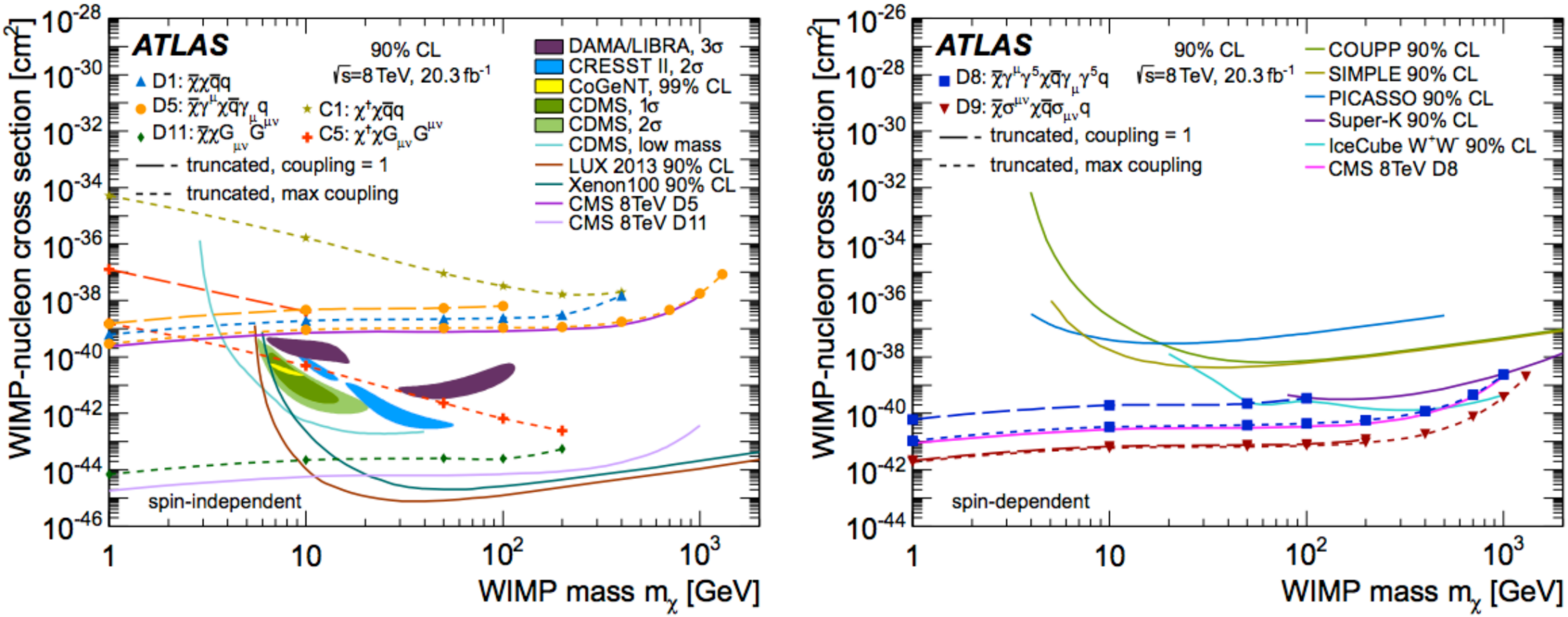
Conclusions

- July 4^{th} 2012 marked an historic milestone for particle physics
  - a new era of precision measurements and searches for new physics is now open
- the aim of this thesis was to contribute to the reaching of this milestone…
  - optimisation of selection criteria and Higgs mass resolution to achieve a timely discovery
- … and to go beyond
  - J^{PC} of the new particle, perspective studies for probing HZZ tensor structure
- they were (and are!) exciting times, which shed light on paths for new physics
  - can it be a doorway to the unknown? (e.g. Dark Matter)
    - LHC is an unique opportunity to be a Higgs-factory first, and a Dark Matter factory possibly…

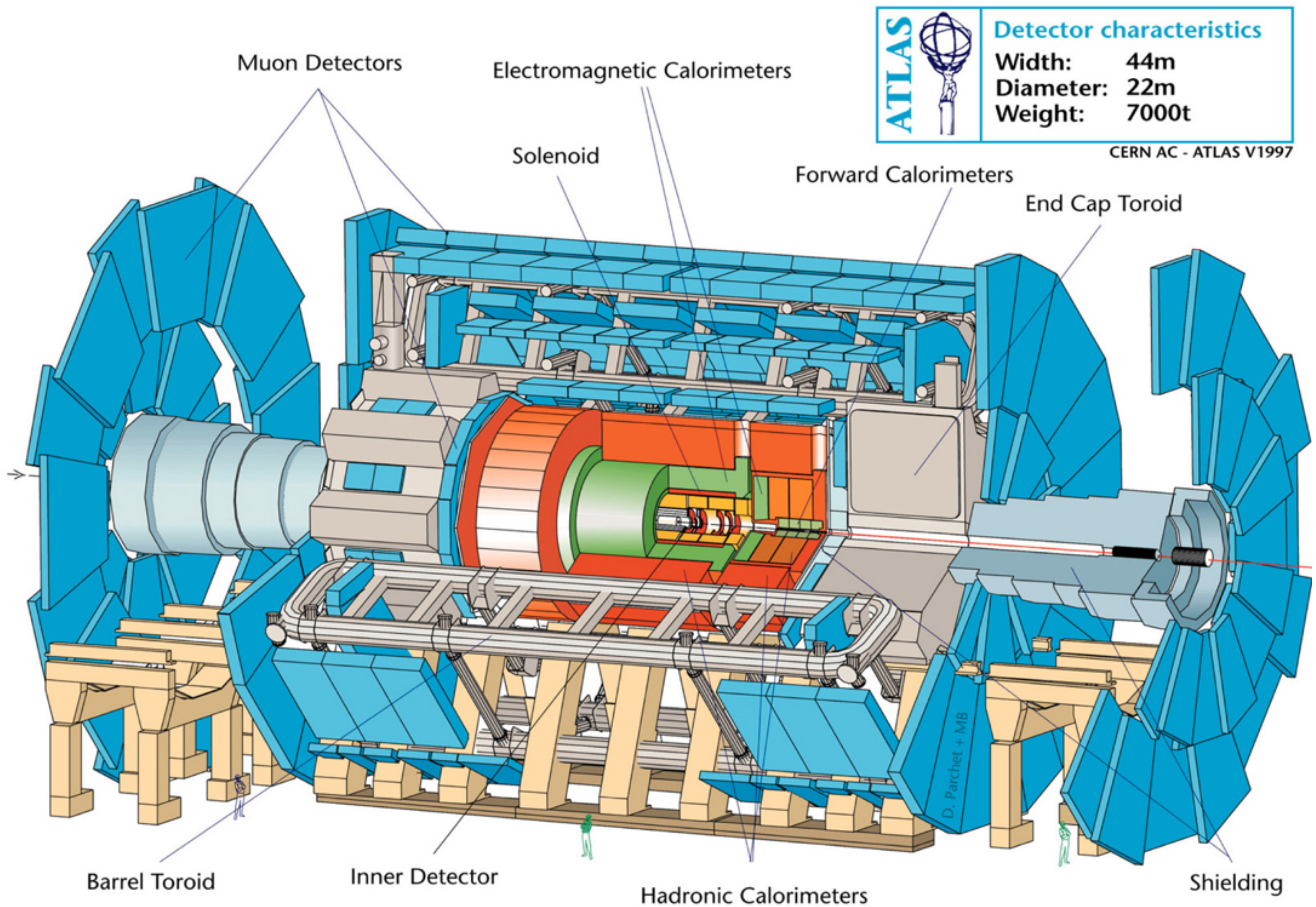
new data will tell us… let's remain open to the unknown!


That's all Folks!

Backup


ATLAS
90% CL
√s=8 TeV, 20.3 fb-1
D1: χ̄χq̄q
D5: χ̄γ^μχq̄γ_μq
D11: χ̄χG_μν G^μν
C1: χ†χq̄q
C5: χ†χG_μν G^μν
truncated, coupling = 1
truncated, max coupling
DAMA/LIBRA, 3σ
CRESST II, 2σ
CoGeNT, 99% CL
CDMS, 1σ
CDMS, 2σ
CDMS, low mass
LUX 2013 90% CL
Xenon100 90% CL
CMS 8TeV D5
CMS 8TeV D11
spin-independent
WIMP-nucleon cross section [cm2]
WIMP mass mχ [GeV]
ATLAS
90% CL
√s=8 TeV, 20.3 fb-1
D8: χ̄γ^μγ^5χq̄γ_μγ^5q
D9: χ̄σ^μνχq̄σ_μνq
truncated, coupling = 1
truncated, max coupling
COUPP 90% CL
SIMPLE 90% CL
PICASSO 90% CL
Super-K 90% CL
IceCube W+W- 90% CL
CMS 8TeV D8
spin-dependent
WIMP-nucleon cross section [cm2]
WIMP mass mχ [GeV]

ATLAS - the Instrument



[ID]
B = 2 T, up to $|\eta| < 2.5$
$\sigma/p_T \sim 3.4 \times 10^{-4}\ p_T \oplus 0.015$

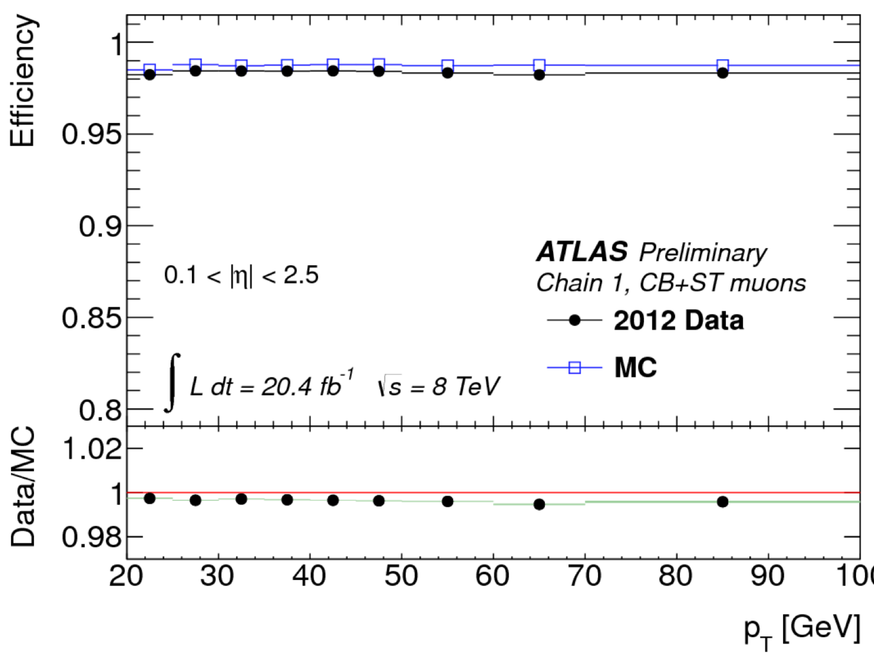
[ECAL]
up to $|\eta| < 3.2$
$\sigma/E \sim 10\%/\sqrt{E} \oplus 1 \div 3\%$

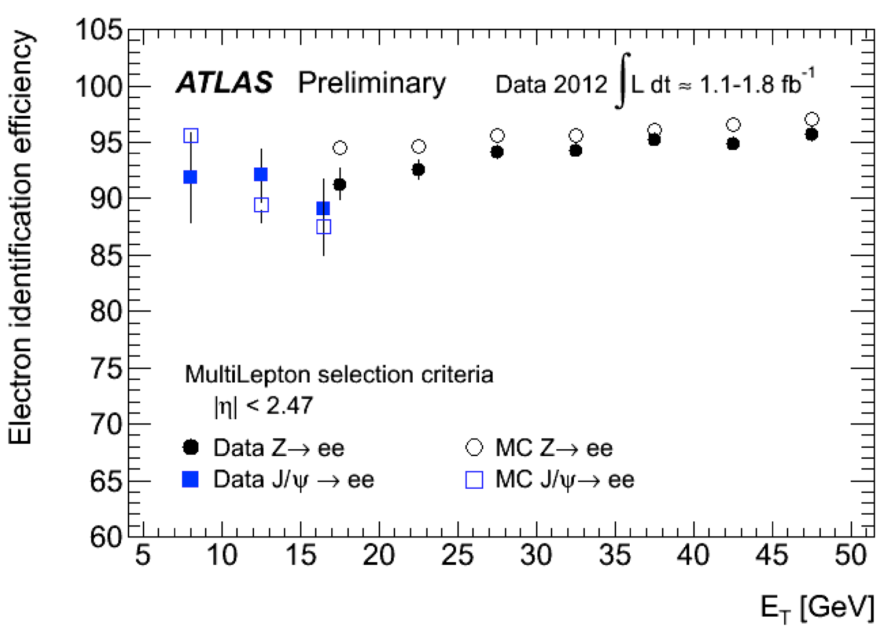
[HCAL]
up to $|\eta| < 3.2$ (FCAL: 4.9)
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

[MS]
up to $|\eta| < 2.7$
$\sigma/p_T < 10\%$ up to 1 TeV

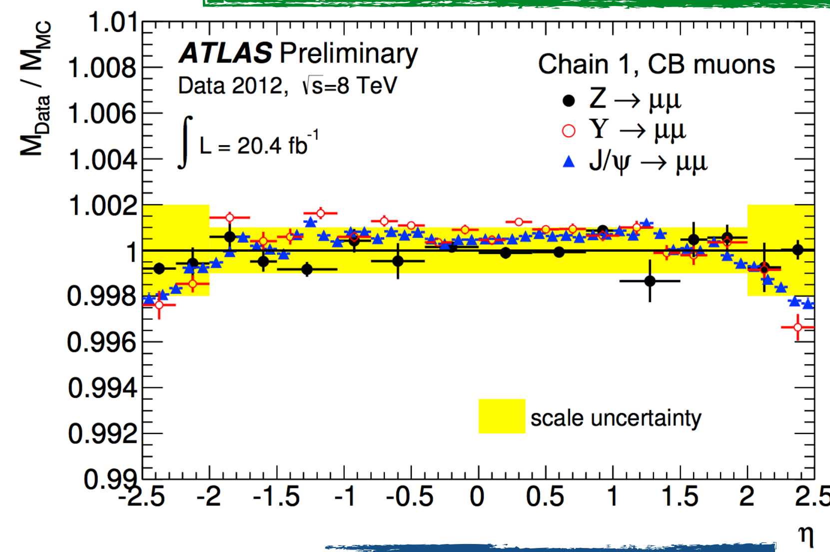
Reconstruction: a Challenge

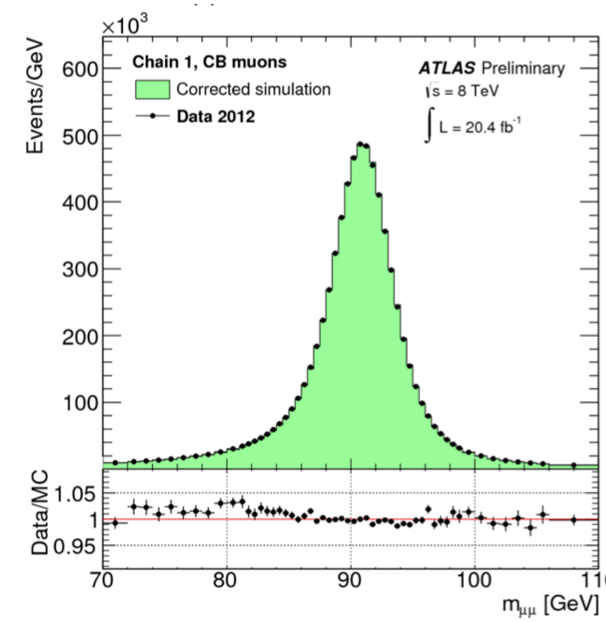
Reconstruction efficiency





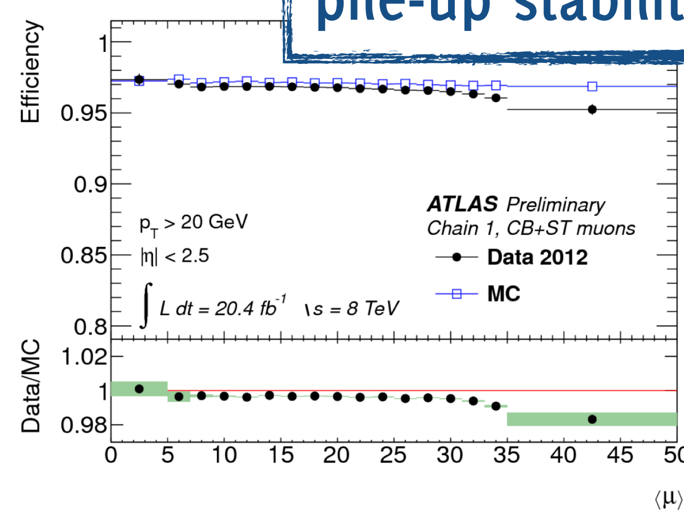
Energy/momentum scale

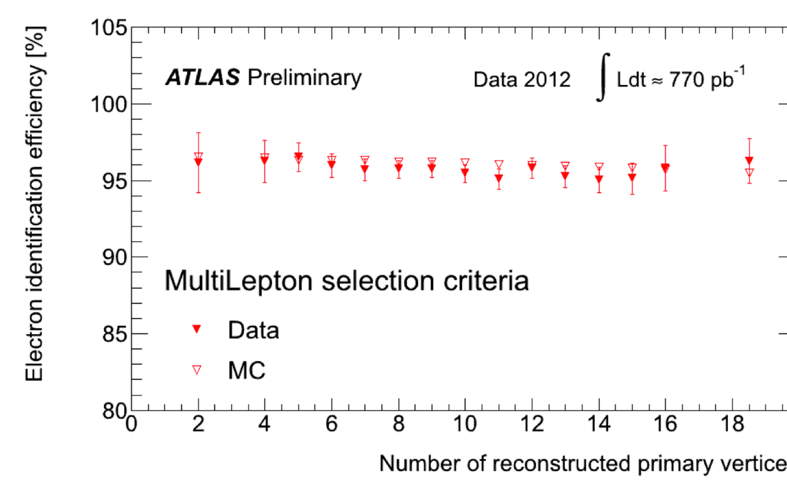


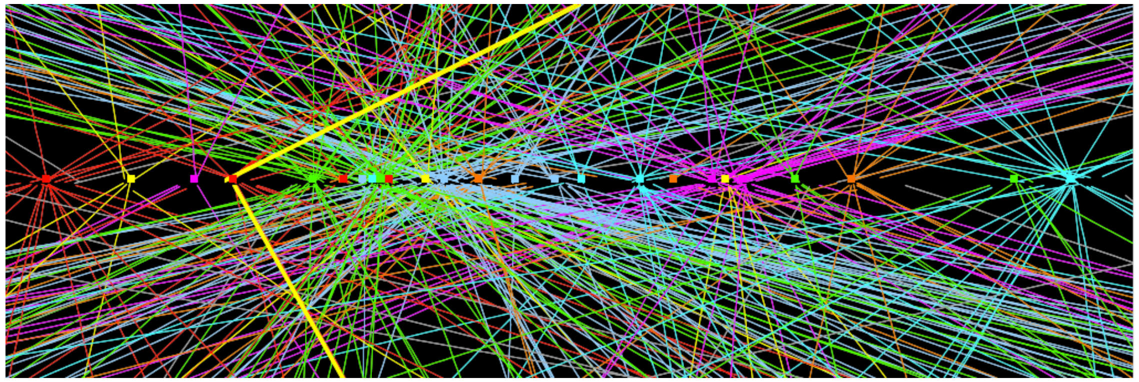


pile-up stability

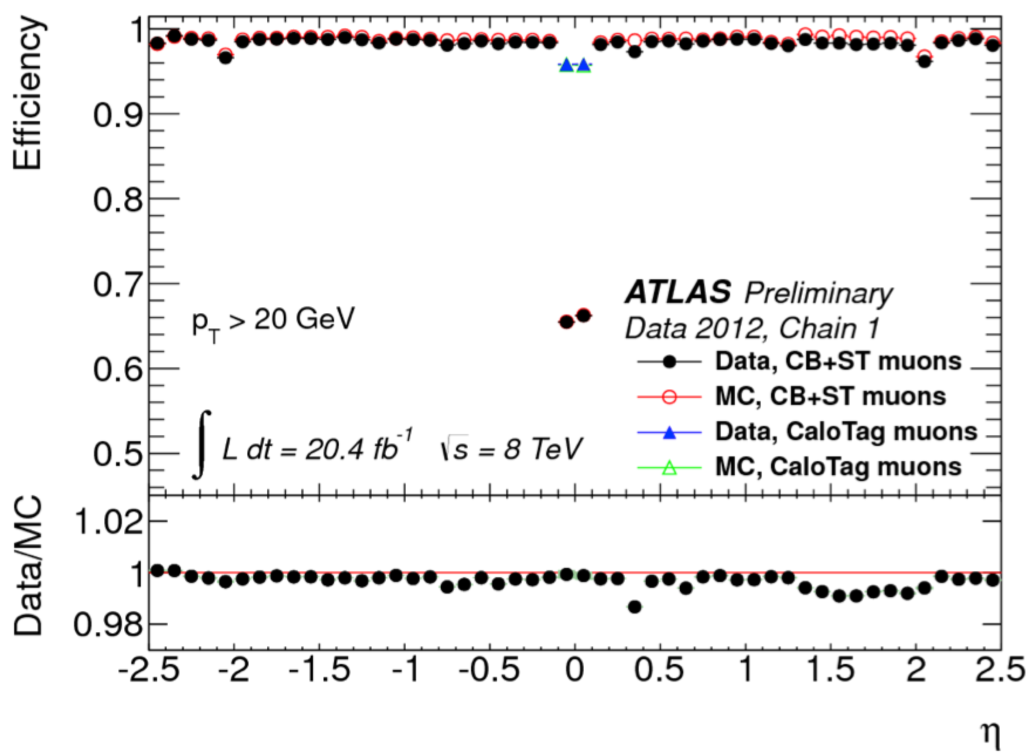
L up to 7.7×10^{33} cm^{-2} s^{-1}

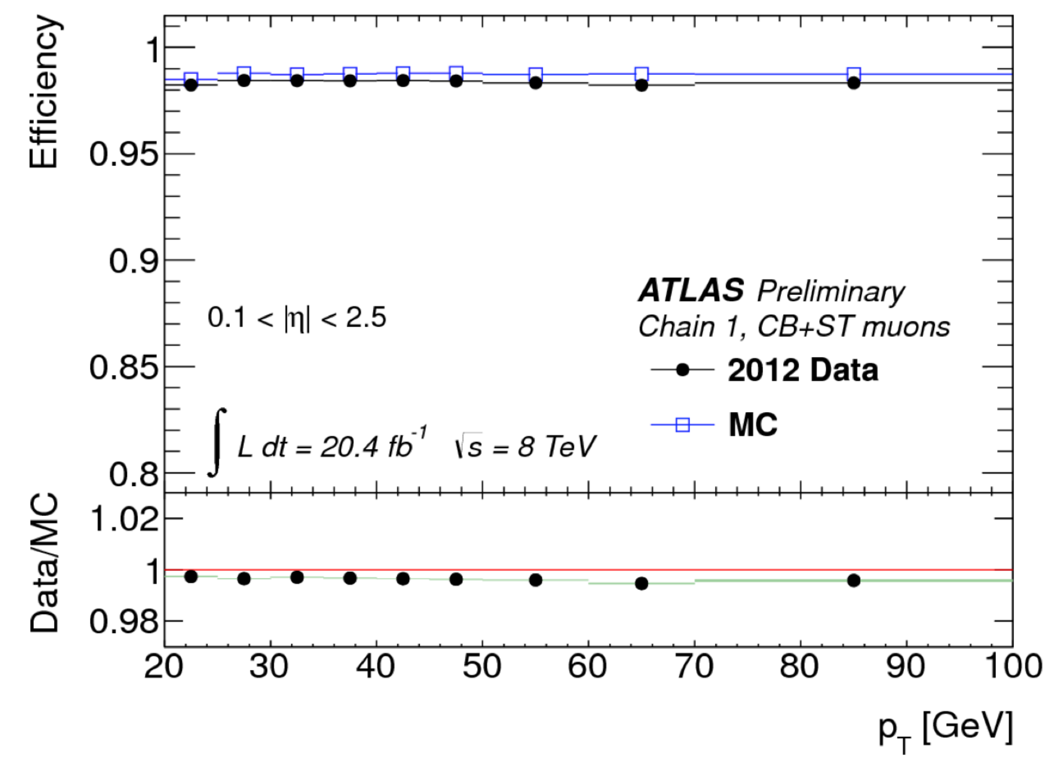


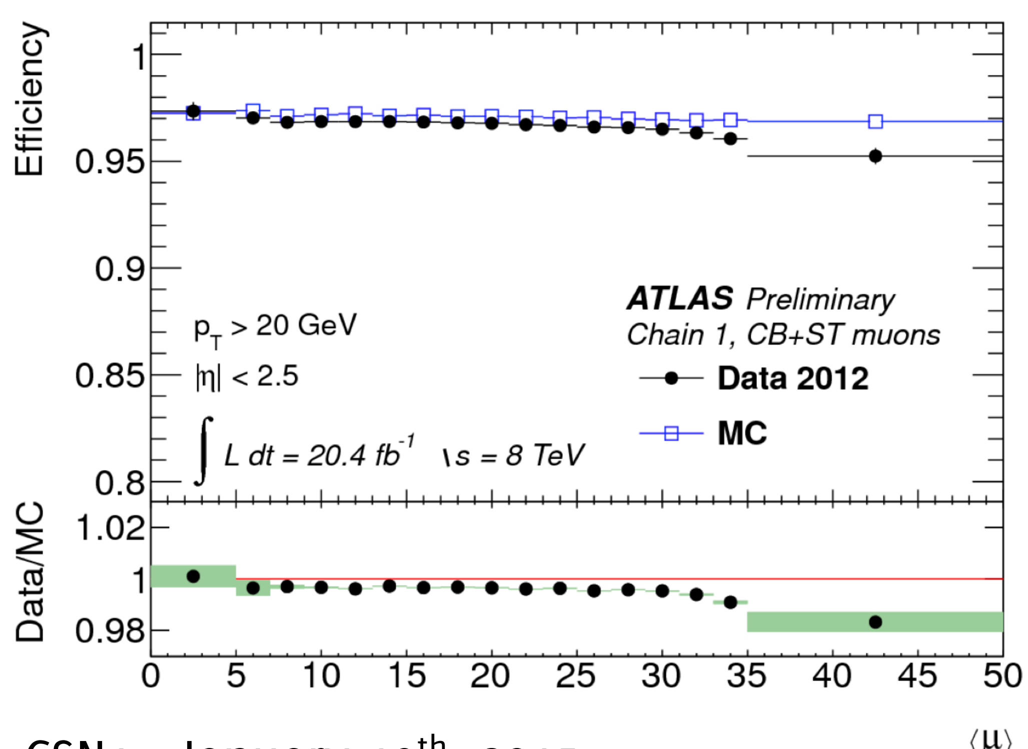


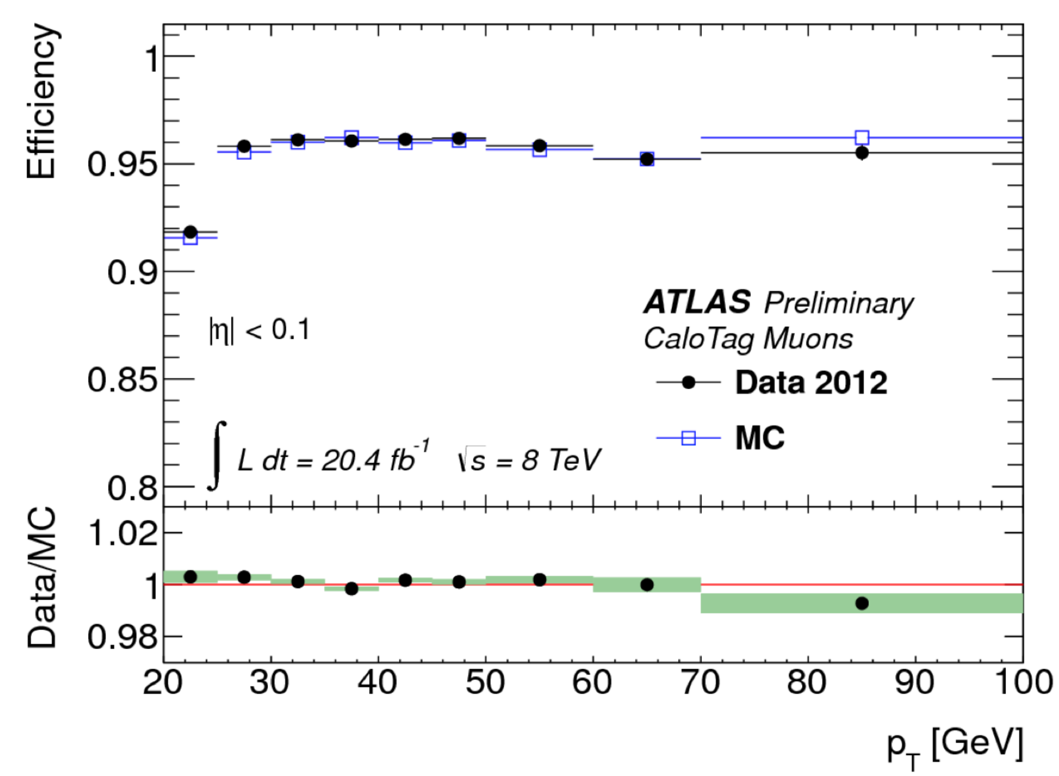


Muon Reconstruction

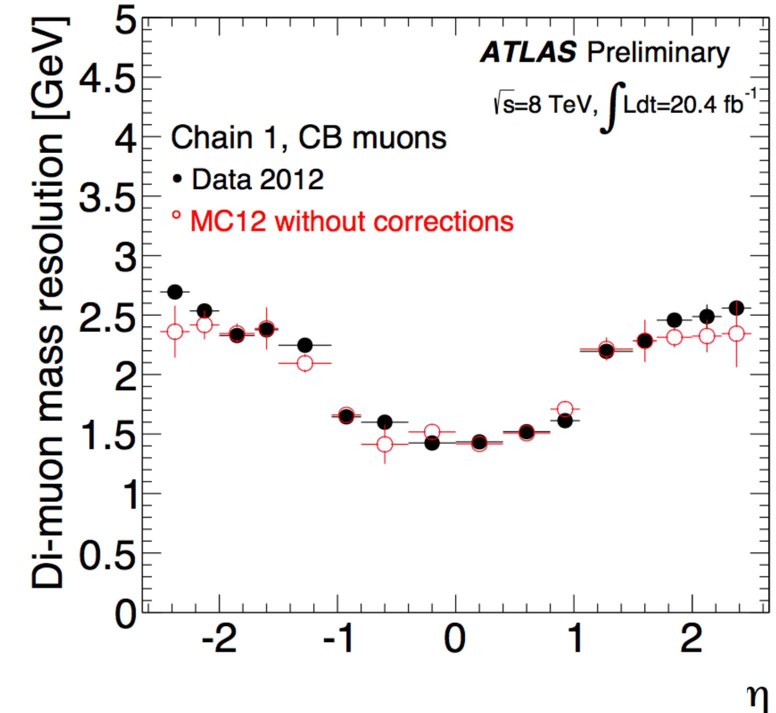


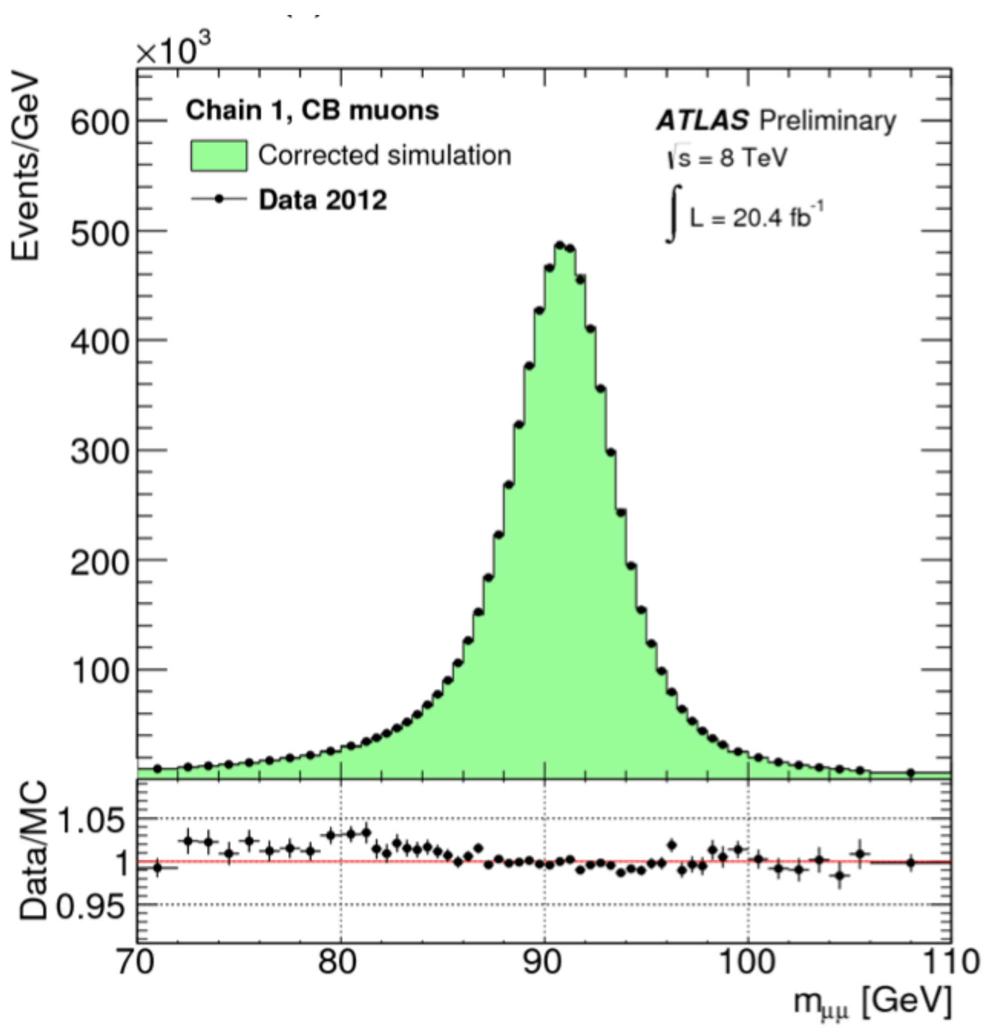


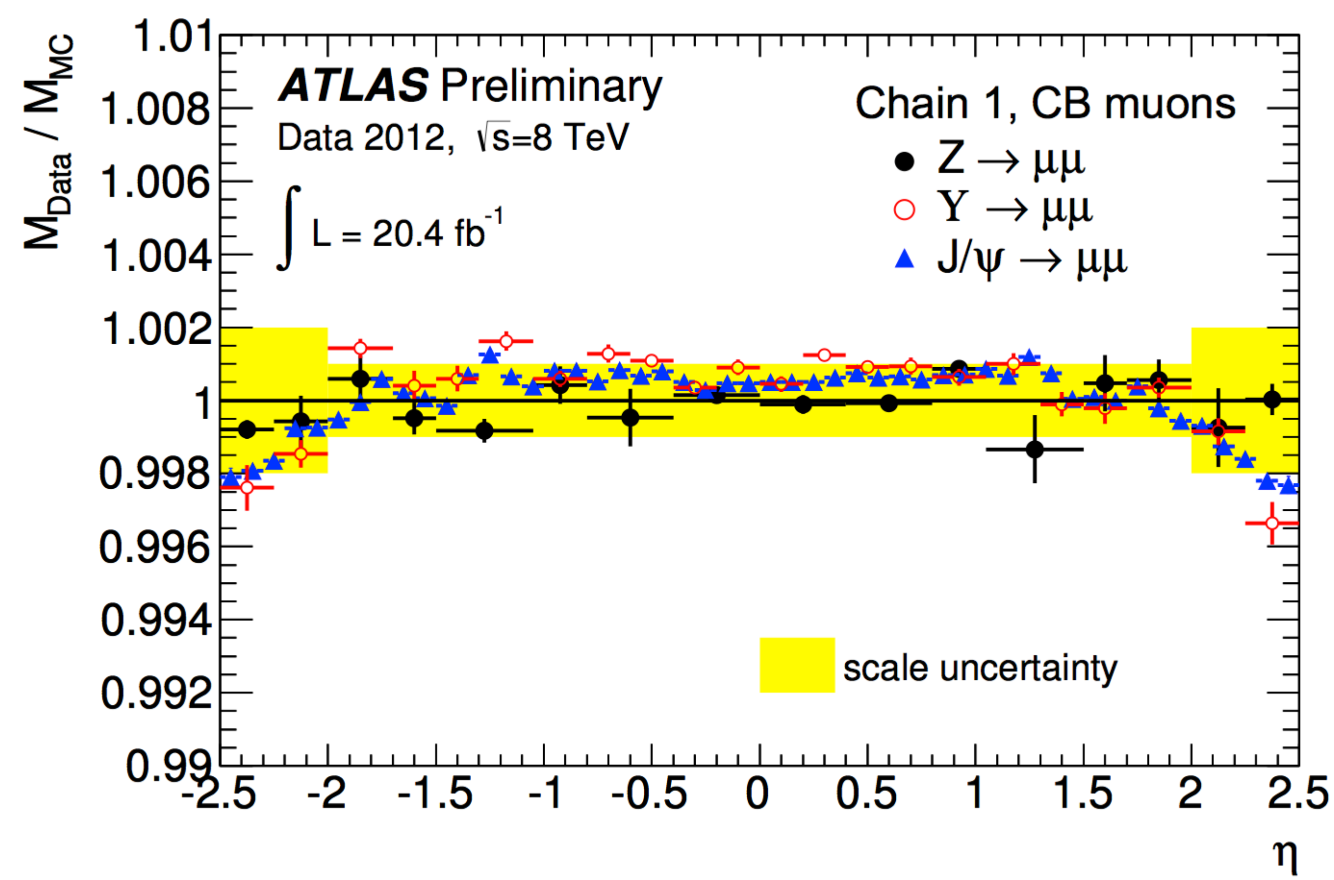




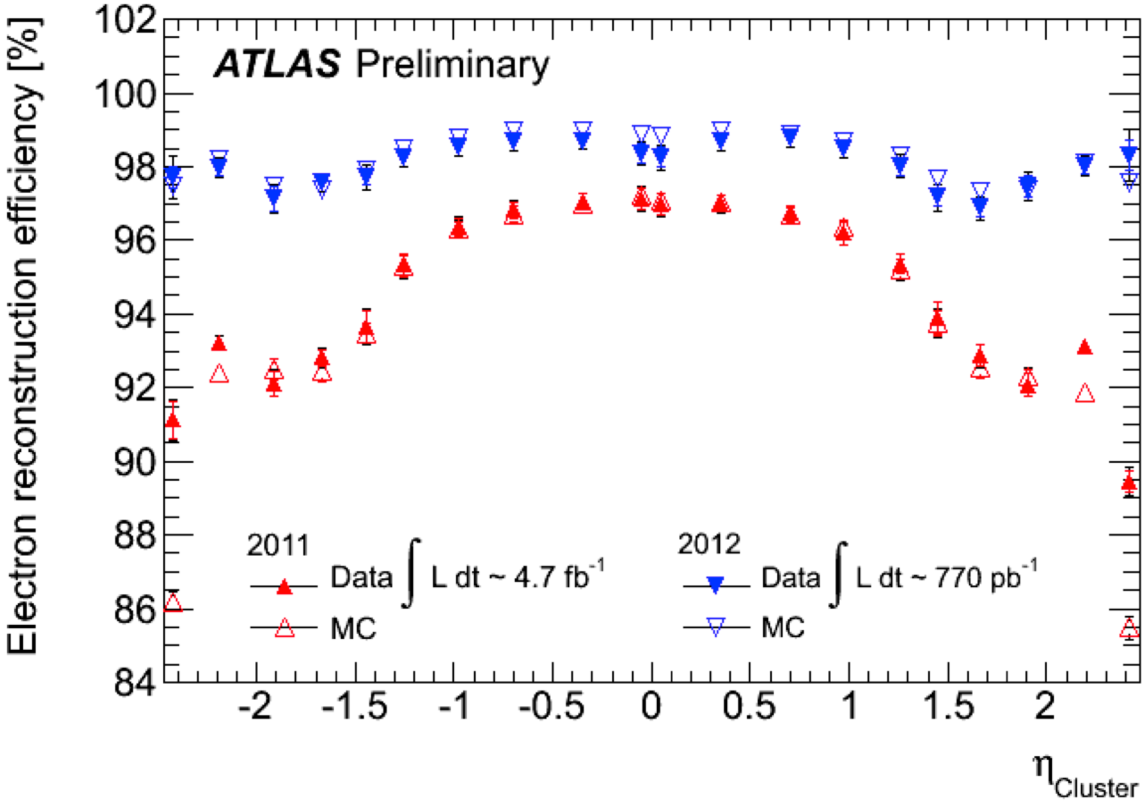
Muon reconstruction

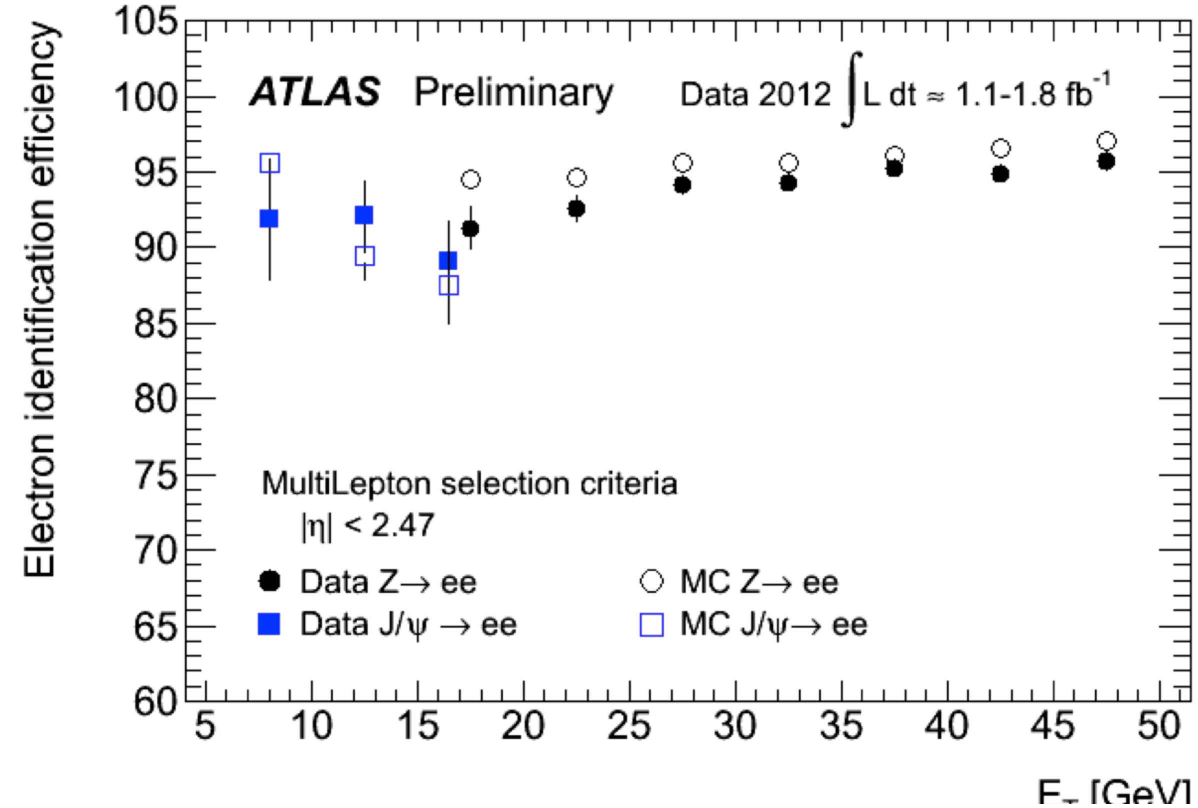


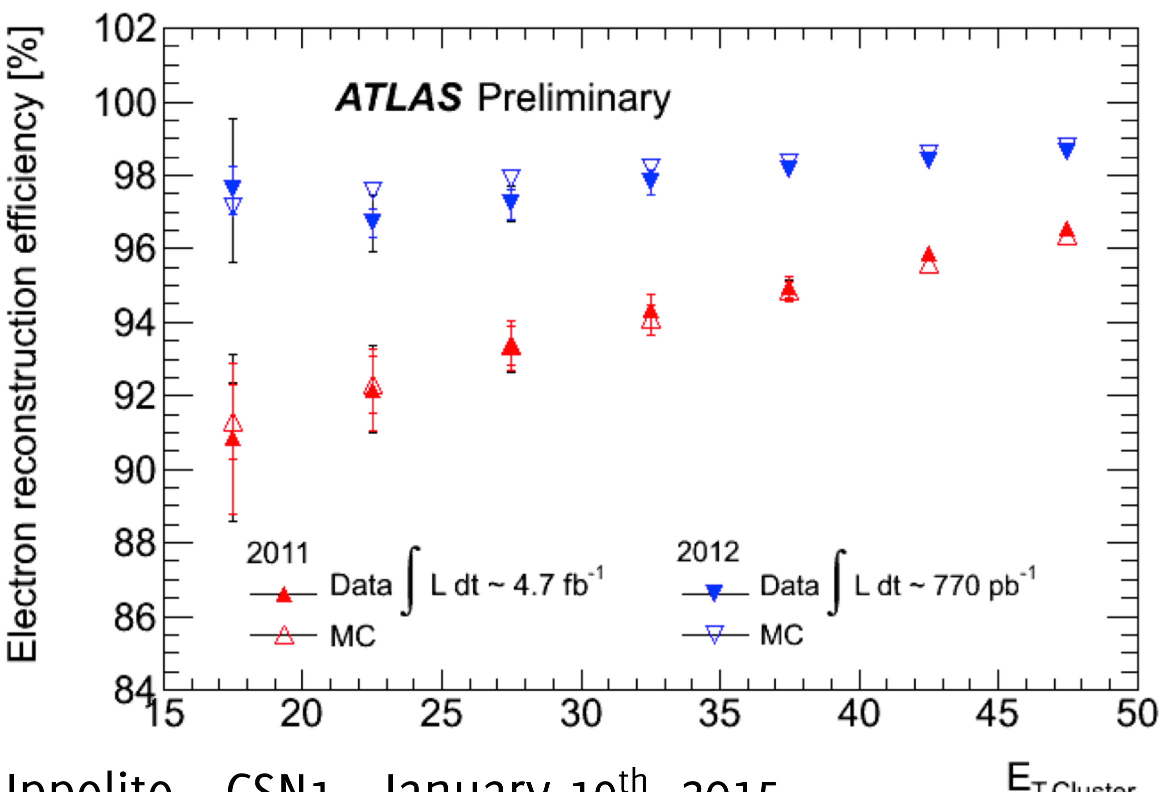


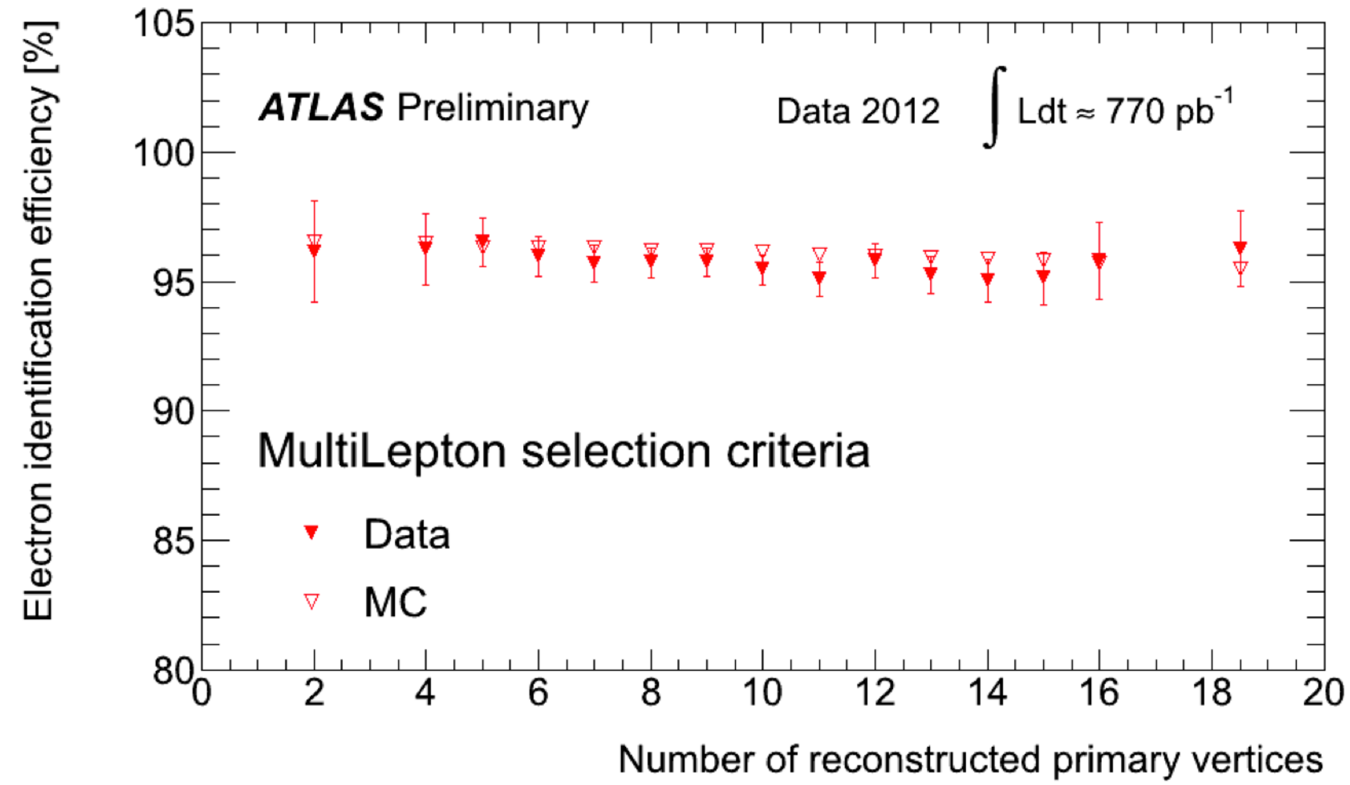


Electron Reconstruction





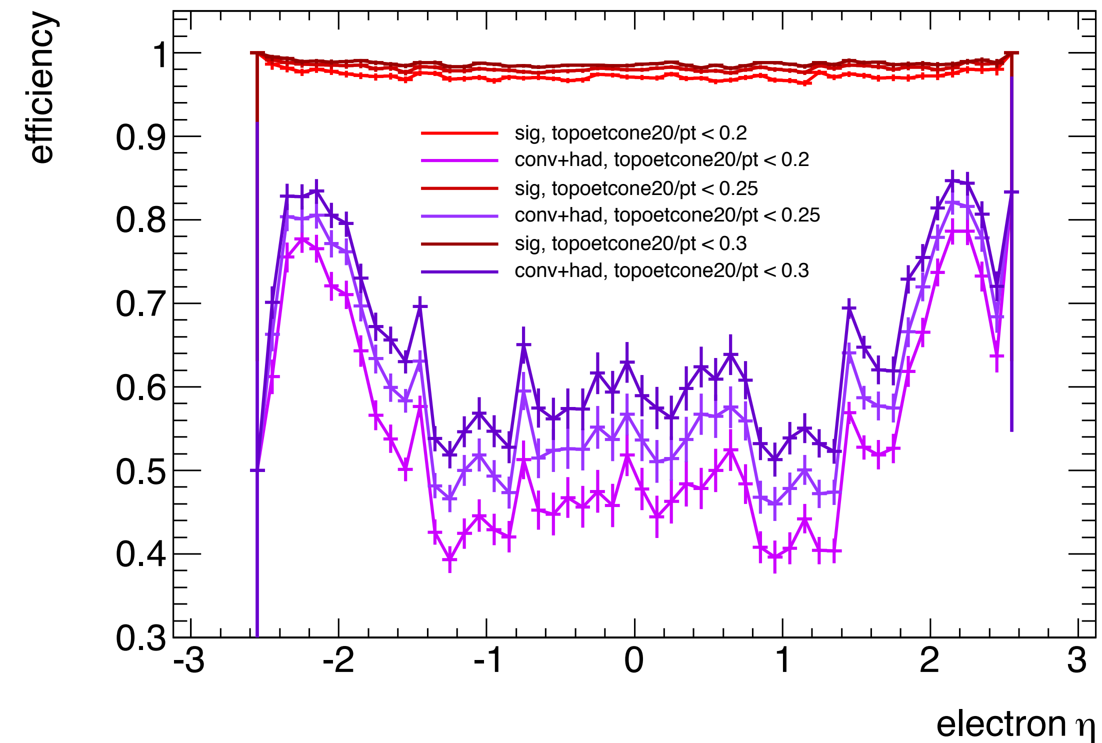


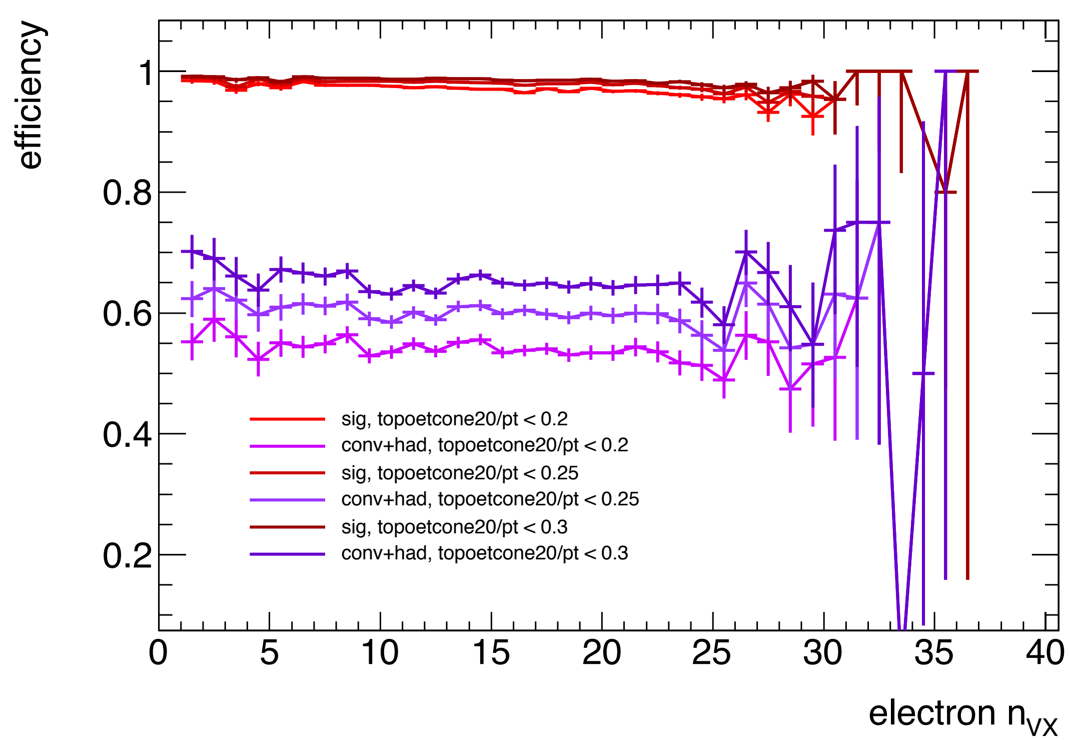


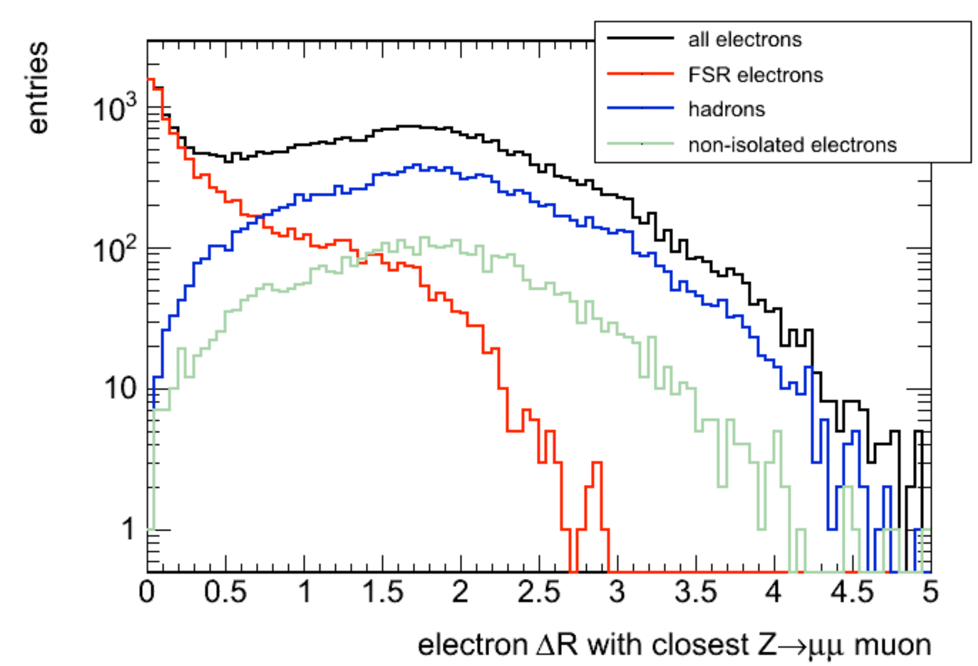
Isolation on $\ell\ell$+ee

optimization of electron isolation criteria

* introduced topocluster iso
* working point against electron fakes
* $\Delta R(e,\mu)$ to reject FSR fakes





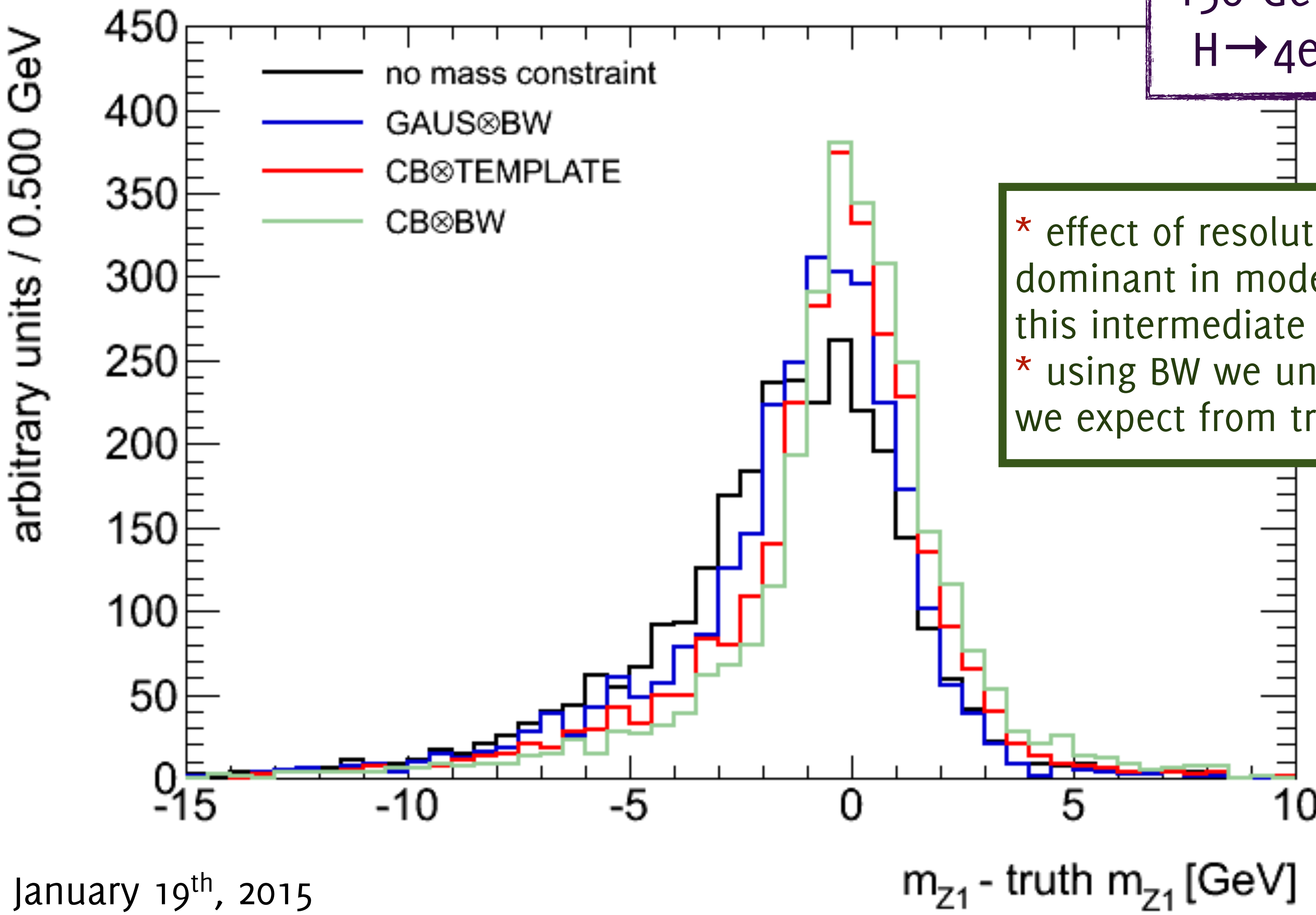


Choosing the model

Z mass resolution for different constraint methods

* include tails in m_{Z1} for low m_H
* use crystal ball model (fitted on MC) instead of gaussian resolution

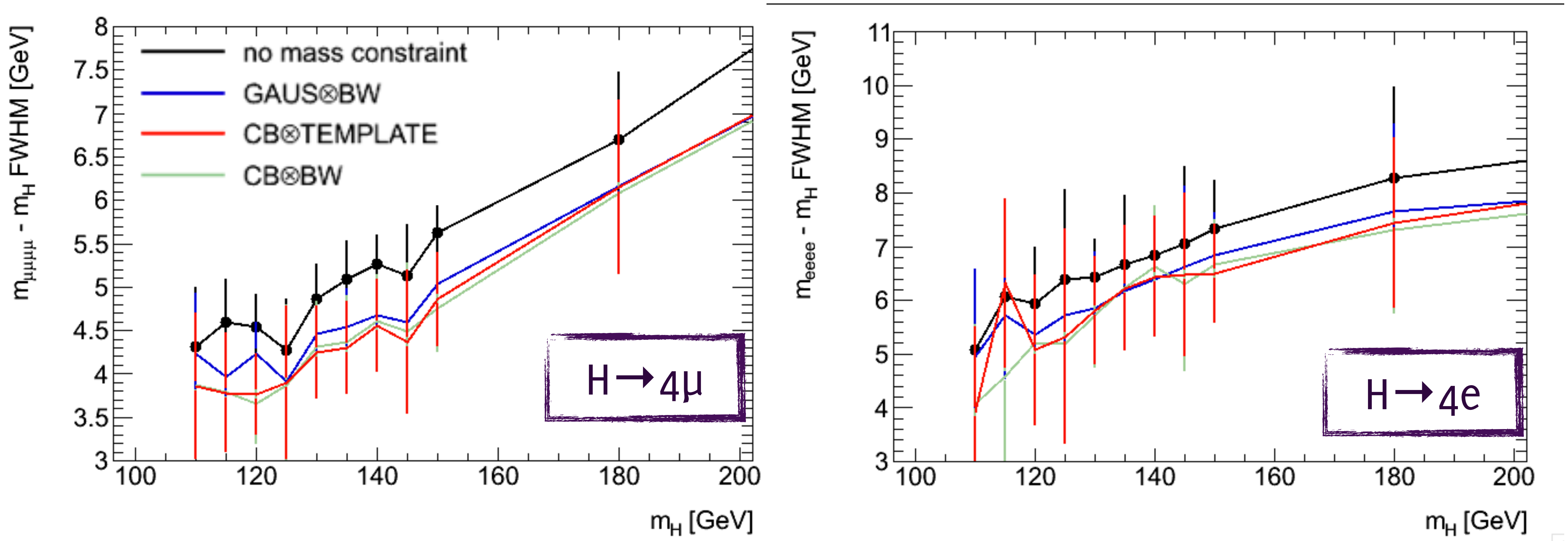
130 GeV
H→4e



* effect of resolution CB qualitatively dominant in model improvement at this intermediate mass
* using BW we underweigh left tail (as we expect from truth m_{Z1} shapes)

Comparing different models

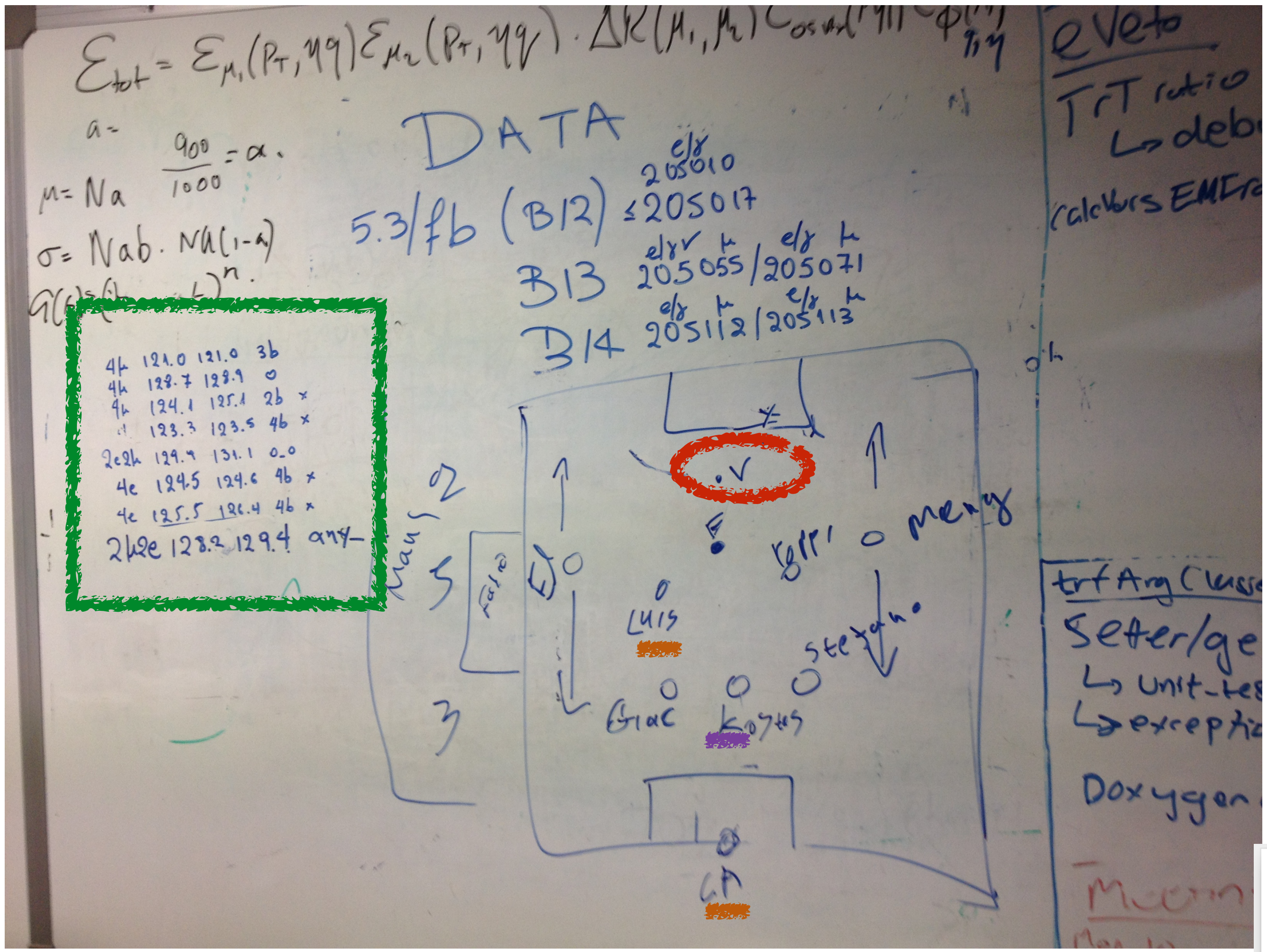
Higgs mass resolution vs m_H for different constraint methods



improvement in mass resolution from more complex models is negligible (covered by systematics needed for a m_H-dependent model)

introduced in H→4ℓ search the Z mass constraint fit with gaussian resolution and Breit-Wigner m_Z^{true} prior

Building a Discovery



CERN 40/4-C08 - Sunday June 24th, 2012 - ~2 AM

an exciting team work!

* first hints at a 5σ combined discovery on June 19th, 2012 at 01h02 AM

* from day-to-day candidate search with increasing integrated luminosity to paper editors, group conveners, ATLAS

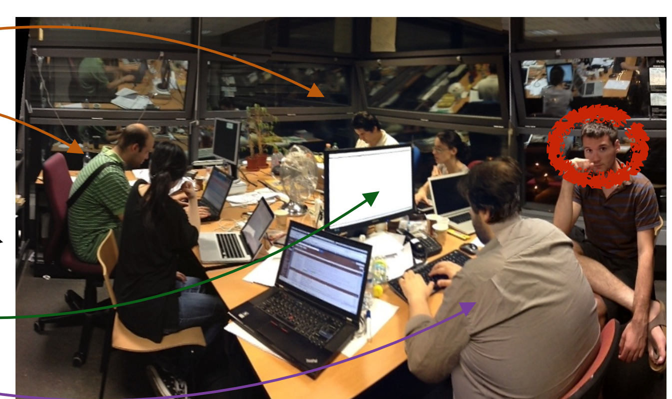
paper editor

paper editor

discovery whiteboard

Higgs boson

convener



Valerio Ippolito 19 Jun 2012 01:02

To: Konstantinos Nikolopoulos Cc: Luis Roberto Flores Castillo, and 2 more...

Re: resolutions

Hi Kostas,

you can find under

/afs/cern.ch/work/v/vippolit/kostas/candidate_lists

what you asked for. There you have three candidate lists:
- data11
- data12 (the 79 candidates)
- my list for data12 (full dataset available up to yesterday evening

Let me know, particularly for the third one! My biased and tired eye finds interesting the following:

4mu	204769	71902630	398	124.09	86.34	31.57	125.09		bb
4mu	204769	82599793	447	123.25	84.01	34.21	123.47		bbbb
4e	203602	82614360	429	124.49	70.63	44.66	124.61		bbbb
4e	204910	22993546	376	125.52	88.93	22.28	126.36		bbbb

(keep in mind that everything beyond run 204668 I accept blindly without GRL, so those three candidates might disappear - but maybe Fabien has hints on these runs/lumiblocks?)

Cheers,
Valerio

Building a Discovery

CERN 40/4-C08 - Sunday June 24th, 2012 - 2:13 AM

an exciting team work!

* first hints at a 5σ discovery on June 18th, 2012

* different layers well represented by the "discovery white board" team

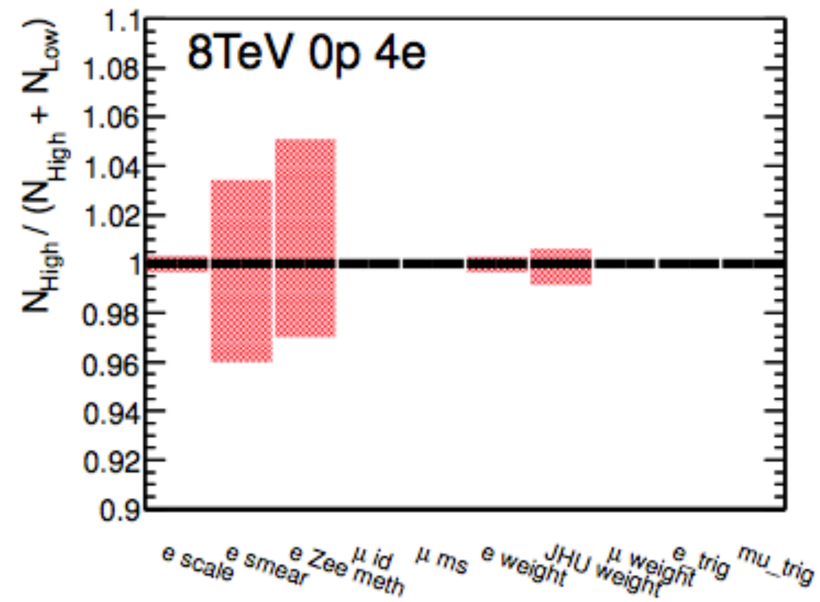
* from day-to-day candidate search with increasing integrated luminosity to paper editors, group conveners, ATLAS management...

Detector effects

Impact of different reconstruction regions on m_{4l} resolution

channel	name	description	frequency	m [GeV]	σ [GeV]	events outside $\pm 2\sigma$
$\mu\mu\mu\mu$	all	all events	1.00	124.89 ± 0.02	1.64 ± 0.02	0.15
$\mu\mu\mu\mu$	bbbb	all muons in the barrel	0.19	124.81 ± 0.04	1.42 ± 0.04	0.16
$\mu\mu\mu\mu$	bbb	three muons in the barrel	0.28	124.86 ± 0.04	1.69 ± 0.04	0.14
$\mu\mu\mu\mu$	bb	two muons in the barrel	0.26	124.91 ± 0.04	1.56 ± 0.04	0.17
$\mu\mu\mu\mu$	other	any other event	0.26	125.05 ± 0.04	1.74 ± 0.05	0.17
$\mu\mu ee$	all	all events	1.00	124.24 ± 0.04	2.15 ± 0.04	0.19
$\mu\mu ee$	any_onecrk	at least one electron in the crack region	0.10	124.15 ± 0.18	2.97 ± 0.04	0.19
$\mu\mu ee$	bb_bb	all leptons in the barrel	0.29	124.40 ± 0.06	1.73 ± 0.06	0.22
$\mu\mu ee$	other_bb	electrons in the barrel, at least a muon in the endcap	0.35	124.32 ± 0.07	2.08 ± 0.06	0.17
$\mu\mu ee$	other_other	any other event	0.26	124.05 ± 0.08	2.28 ± 0.08	0.21
$ee\mu\mu$	all	all events	1.00	124.22 ± 0.03	1.85 ± 0.03	0.25
$ee\mu\mu$	onecrk_any	at least one electron in the crack region	0.10	124.05 ± 0.14	2.62 ± 0.14	0.23
$ee\mu\mu$	bb_bb	all leptons in the barrel	0.31	124.34 ± 0.05	1.58 ± 0.04	0.25
$ee\mu\mu$	bb_other	electrons in the barrel, at least a muon in the endcap	0.25	124.32 ± 0.06	1.64 ± 0.05	0.24
$ee\mu\mu$	other_other	any other event	0.34	124.03 ± 0.07	2.10 ± 0.06	0.25
$eeee$	all	all events	1.00	123.37 ± 0.05	2.54 ± 0.05	0.20
$eeee$	bbbb	all electrons in the barrel	0.46	123.66 ± 0.07	2.08 ± 0.06	0.22
$eeee$	onecrk	at least one electron in the crack region	0.18	123.59 ± 0.16	3.05 ± 0.13	0.20
$eeee$	bbb	three electrons in the barrel (none in the crack)	0.22	123.15 ± 0.12	2.80 ± 0.12	0.20
$eeee$	other	any other event	0.15	122.91 ± 0.14	2.60 ± 0.13	0.23

Systematics



normalization systematics

- signal cross-section + MC statistics: 20%
- ZZ cross-section + MC statistics: 7%
- data-driven reducible background: 32%
- all: (anticorrelated) high/low $m_{4\ell}$ bin migration due to ESS and assumed m_H: 14%

shape systematics

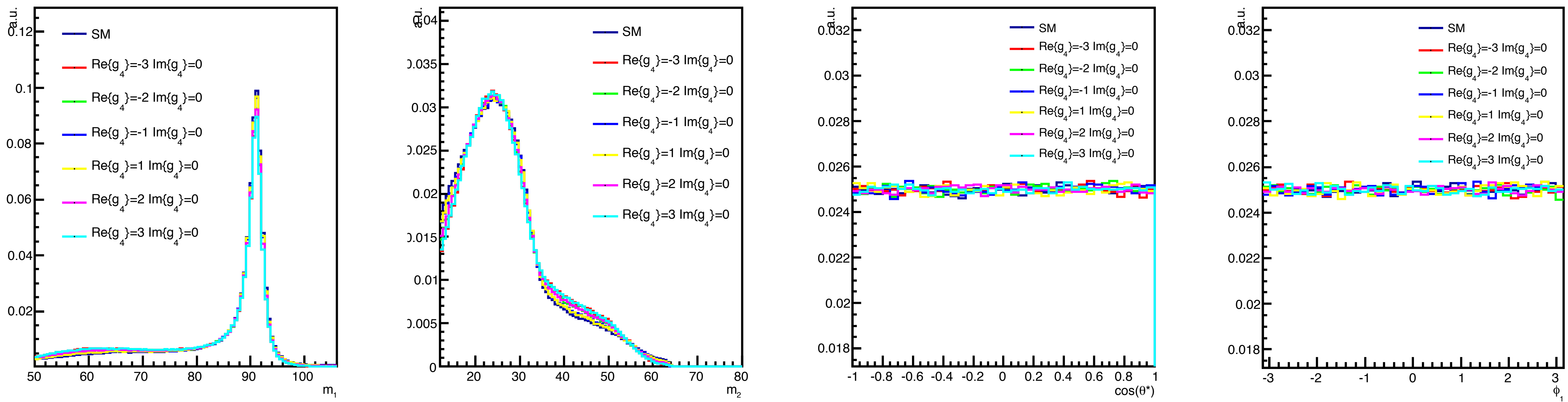
- wrong-pairing: very small with new selection
- ESS: negligible effect on J^P-MELA shapes
- reducible background shape parametrization: from variations in the multi-gaussian adaptive KDE models + variations related to the available data-driven statistics

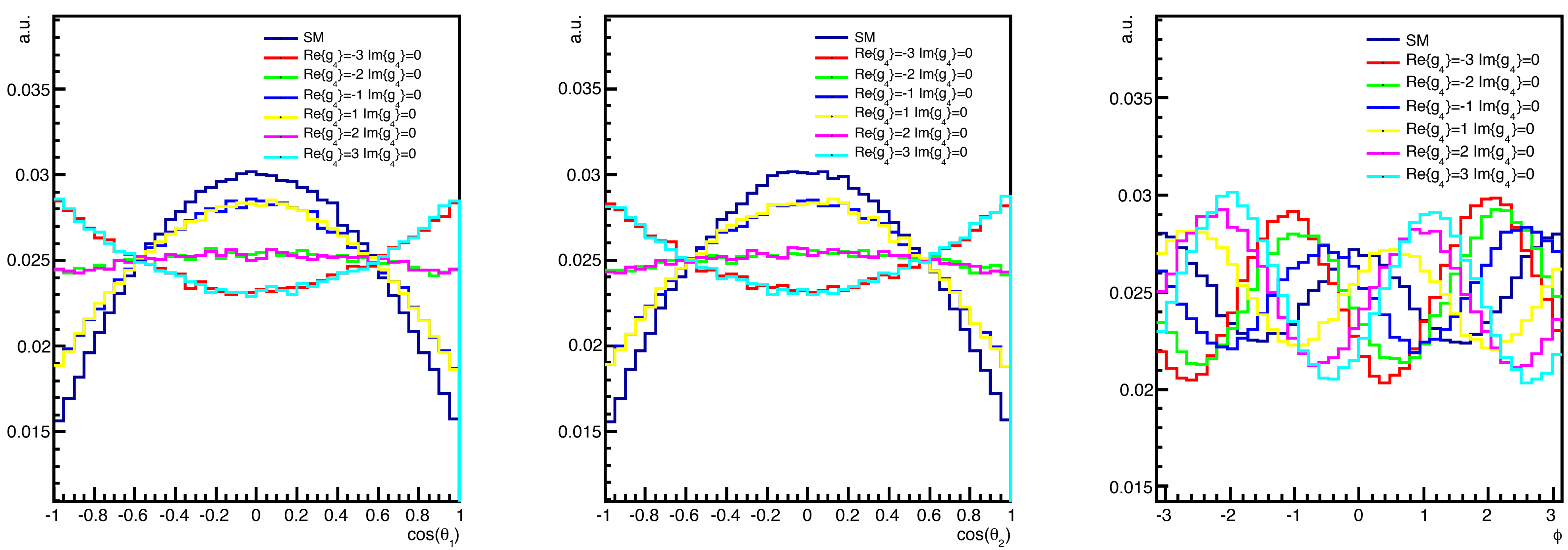
all systematics taken as not correlated between 2011 and 2012

- with the exception of reducible background (same sample for both years)

[parton-level]

Where does sensitivity come from?

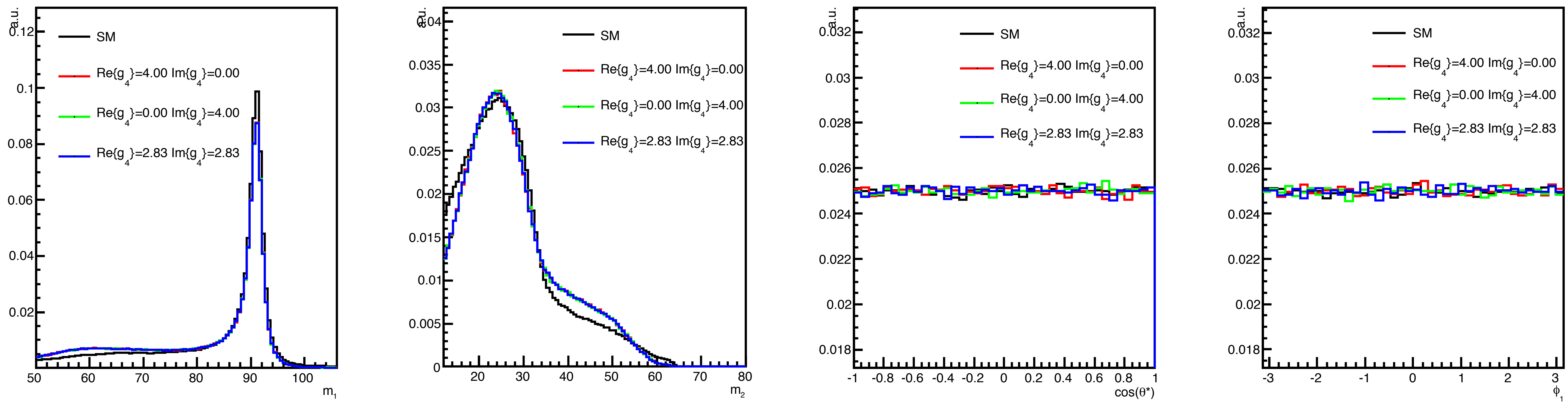


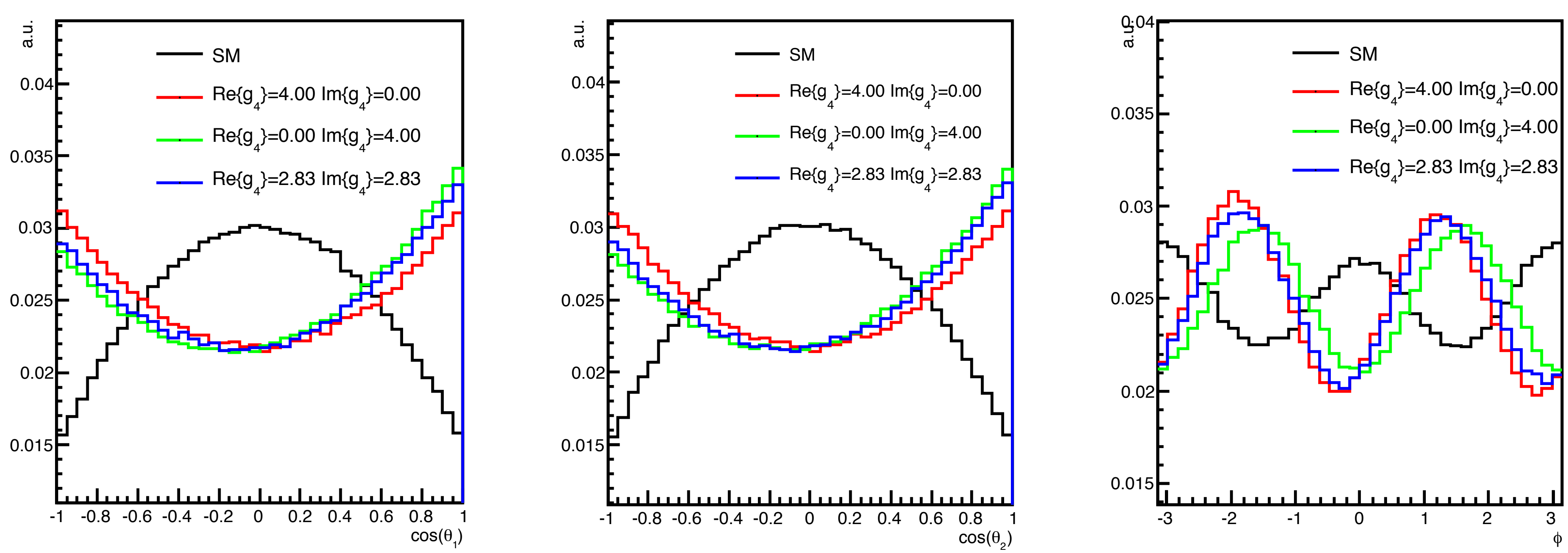


sensitivity on real g_4 comes from:

* $|g_4|$: mainly $\cos(\boldsymbol{\theta}_1)$ and $\cos(\boldsymbol{\theta}_2)$, a bit from $\boldsymbol{\phi}$
* sign(g_4): only from $\boldsymbol{\phi}$
* no contribution from other angles or masses as it's a spin zero decay (but they help against background)

Where does sensitivity come from?





sensitivity on complex g_4 is basically on $|g_4|$

* here you see $|g_4| = 4$
(g_4=4+0i, 0+4i, 4/sqrt(2)·(1+i))

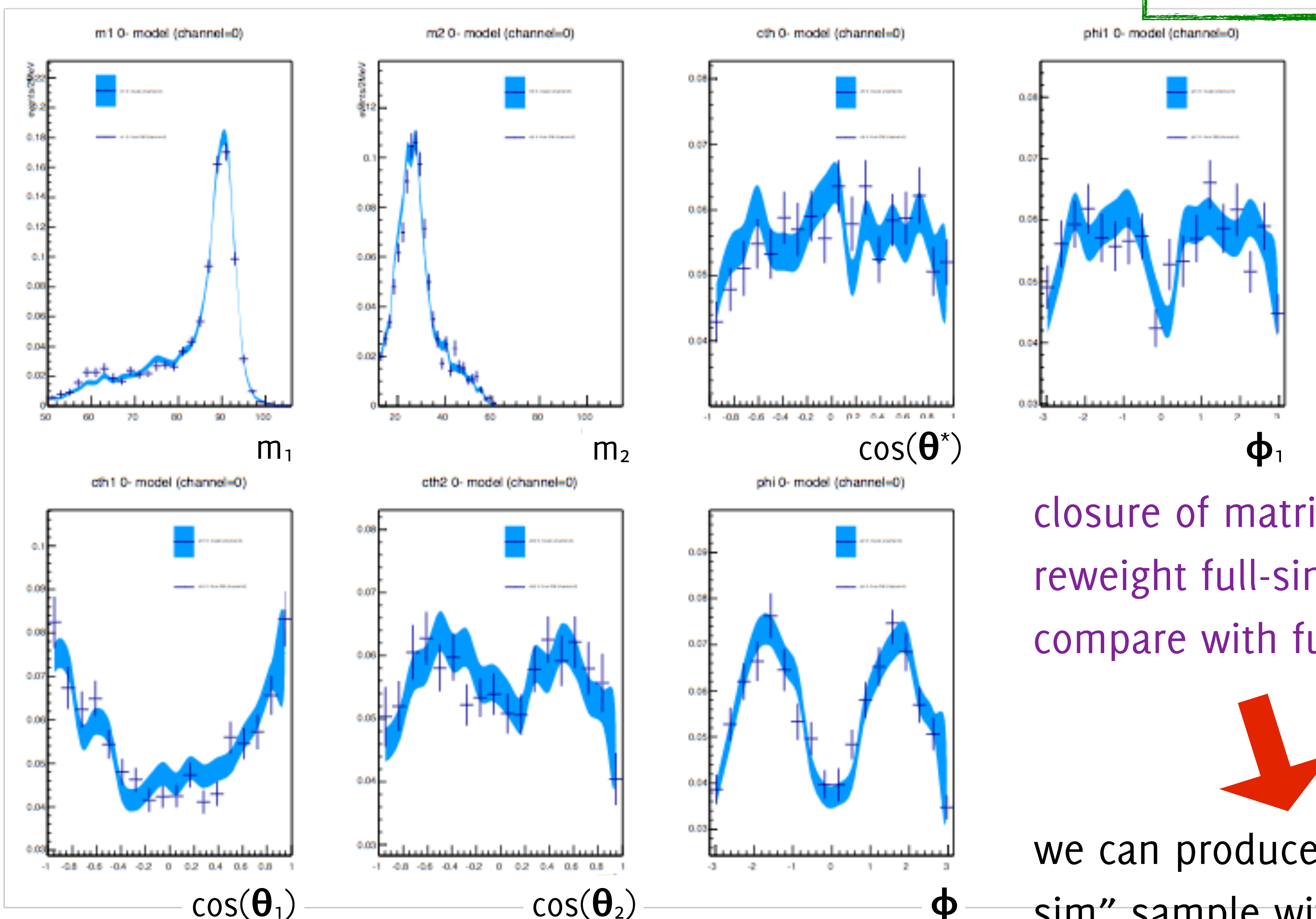
* some separation recovered from cos(**θ**$_1$), cos(**θ**$_2$) (asymmetry), **ϕ** and m_2

Reweighting samples

$0^{+} \times p(0^{-})/p(0^{+})$

full-sim 0^{-}

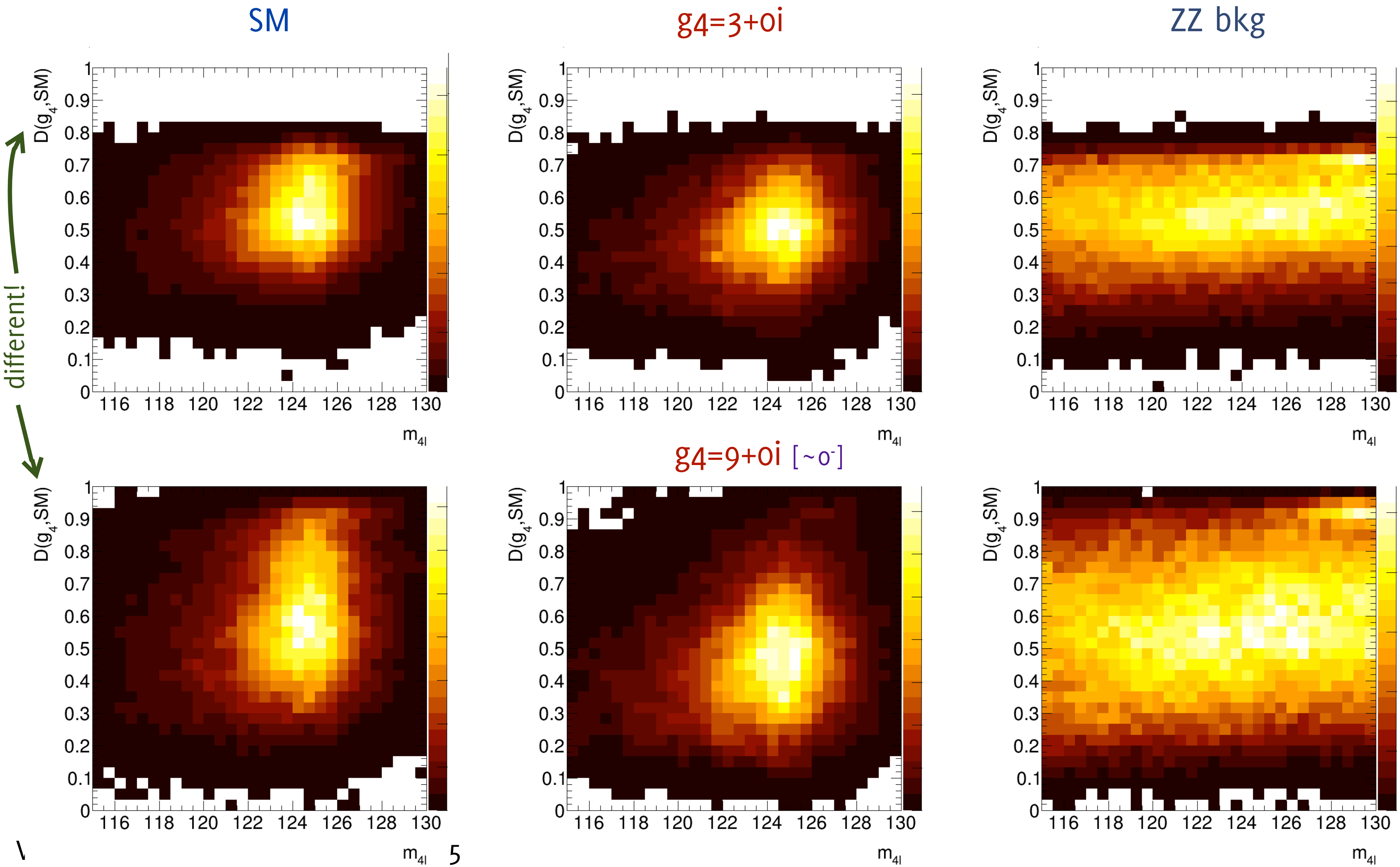
$H \rightarrow ZZ^{*} \rightarrow 4\mu$



closure of matrix element: reweight full-sim 0^{+} to 0^{-} and compare with full-sim 0^{-}

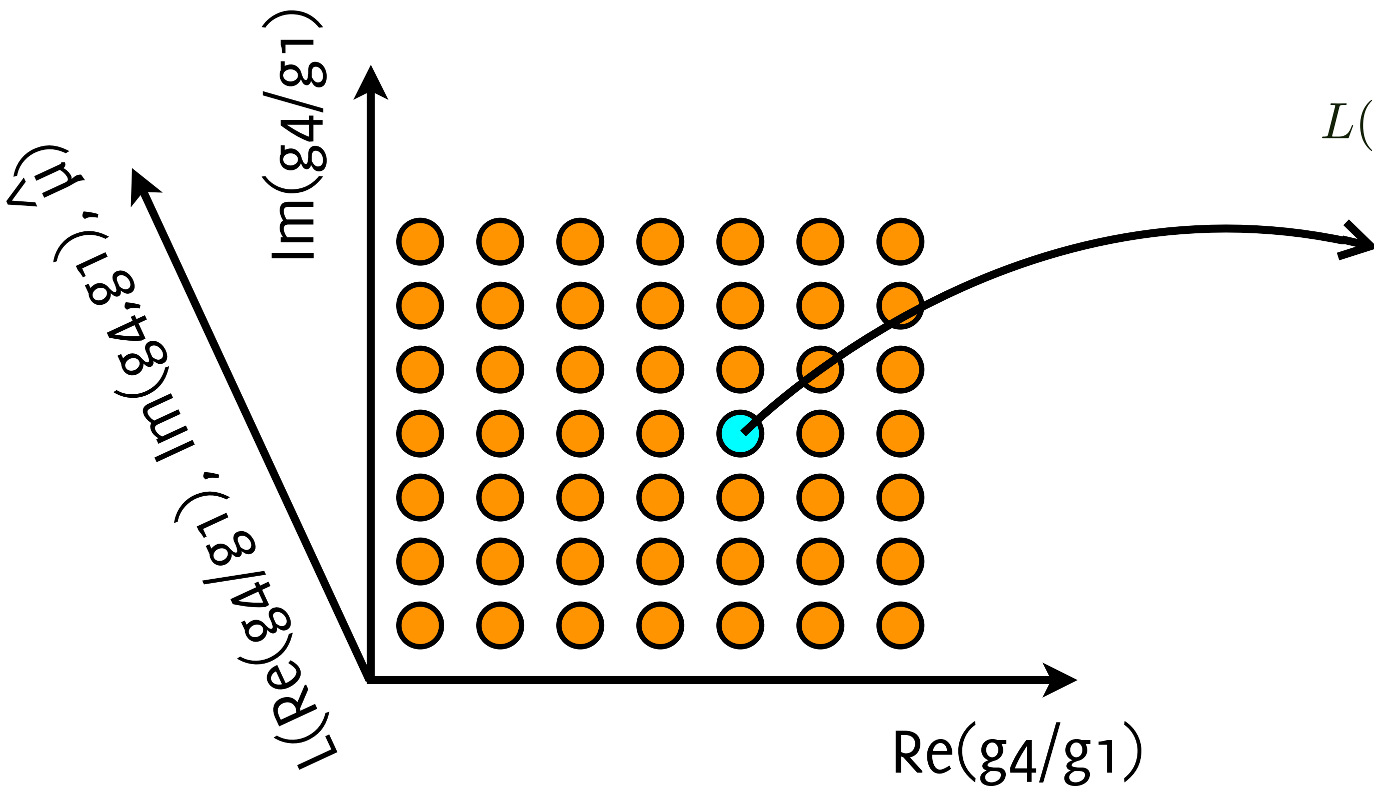
we can produce any "full-sim" sample with g_4 != 0 starting from the SM sample

2D discriminant



2D: statistical approach

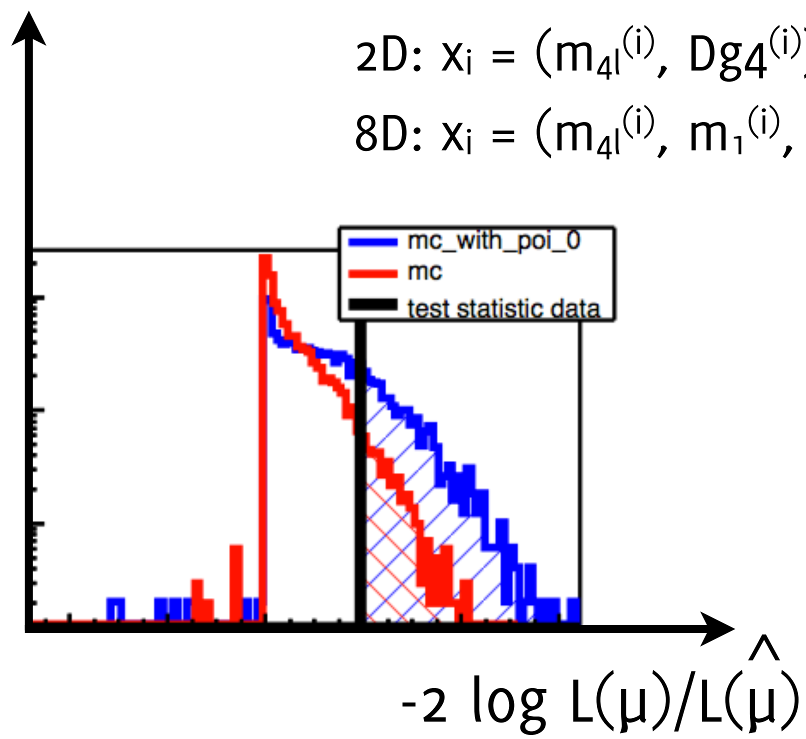
we assume SM and explore sensitivity in the complex plane g4/g1 (g2/g1)



$$L(\mu) = \mathrm{Pois}(N, \mu N_s + N_b) \sum_{i=1}^{N} (f_s p(x_i | g_1, g_2, g_4) + f_b p_B(x_i))$$

2D: $x_i = (m_{4l}^{(i)}, Dg4^{(i)})$

8D: $x_i = (m_{4l}^{(i)}, m_1^{(i)}, m_2^{(i)}, ^{e(i)})$



full information on g4 (g2) is obtained
with a scan of the complex plane g4/g1 (g2/g1)

approach similar to Higgs search vs m_H

Compatibility 2D vs 8D

2D

Luminosity (fb^{-1})	f_{g4}	f_{g2}
300	0.12	0.34
3000	0.04	0.15

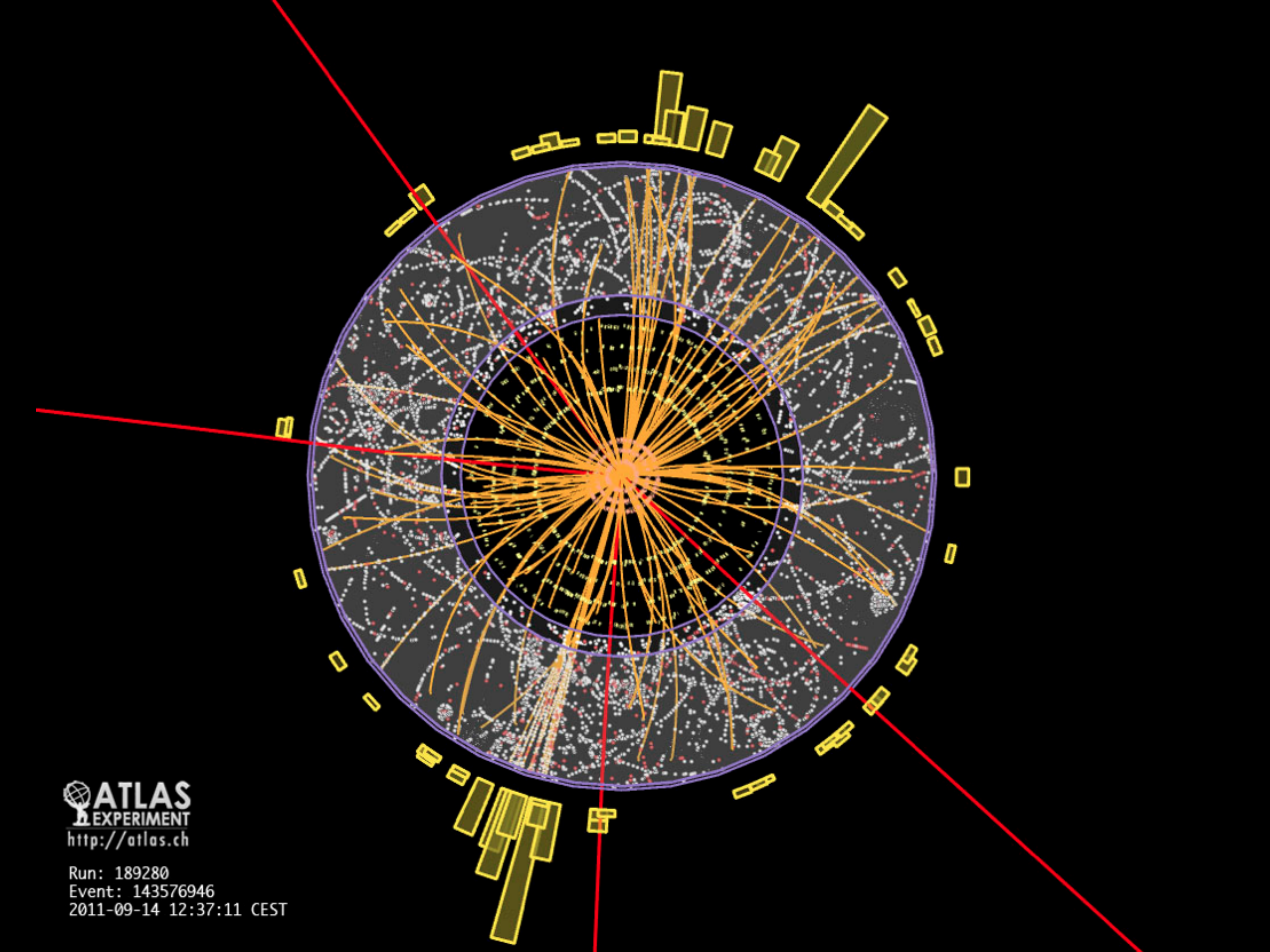
8D

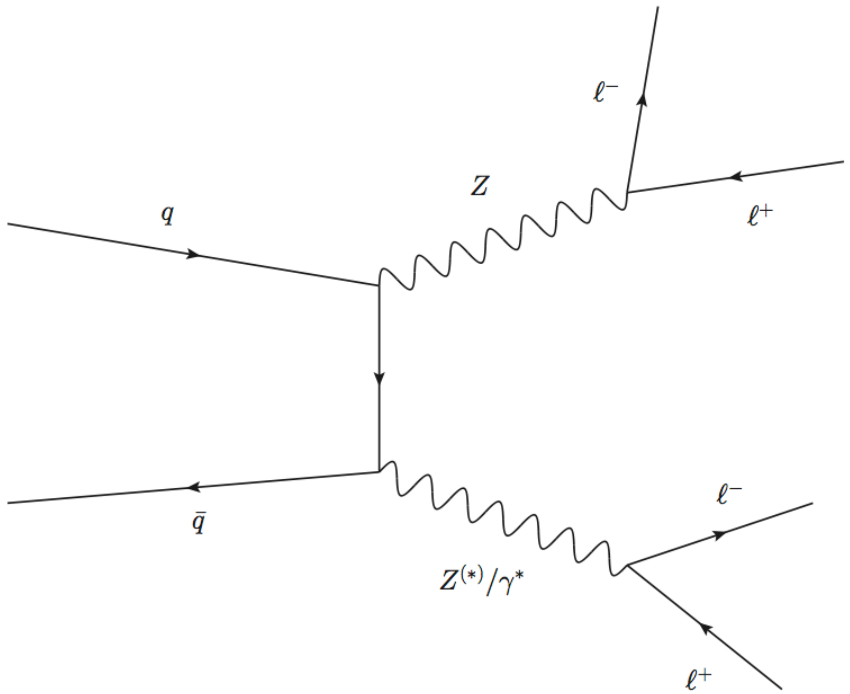
Luminosity (fb^{-1})	f_{g4}	f_{g2}
300	0.20	0.29
3000	0.06	0.12

compatible within granularity of the scan in the f_{gi} vs $Arg(g_i)$ plane (~0.02x0.02)

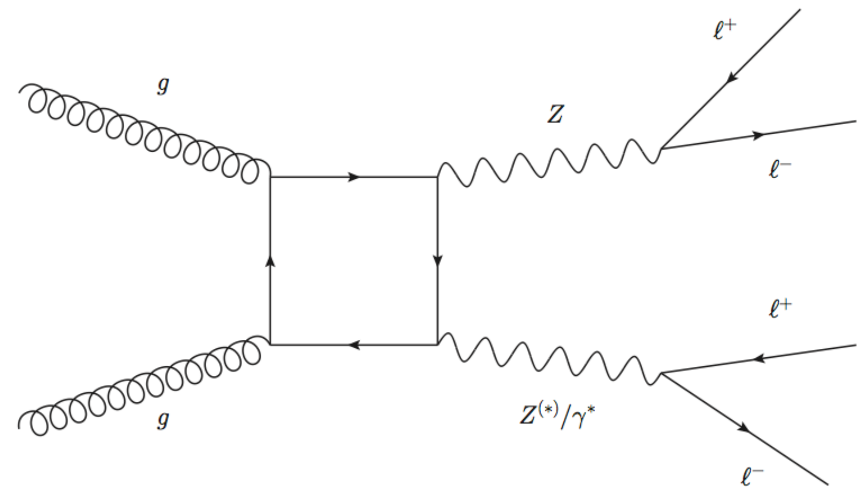
Conclusions

- discovery
  - looking for a low mass Higgs boson
  - how we improved sensitivity
  - a new particle has been found
- is it the Standard Model Higgs boson?
  - J^P-MELA discriminant: exploit final state kinematics
  - spin-parity studies: excluded 0-, 1+, 1-, 2+ against SM 0+
  - ... enough for 2013 EPS Prize and for the Nobel Prize in Physics!
- is it <u>really</u> the Standard Model Higgs boson?
  - probing the HZZ vertex: 8D and 2D matrix-element techniques
  - projections for high luminosity (300/3000 fb^{-1}): sensitive to 6-20% CPV fraction

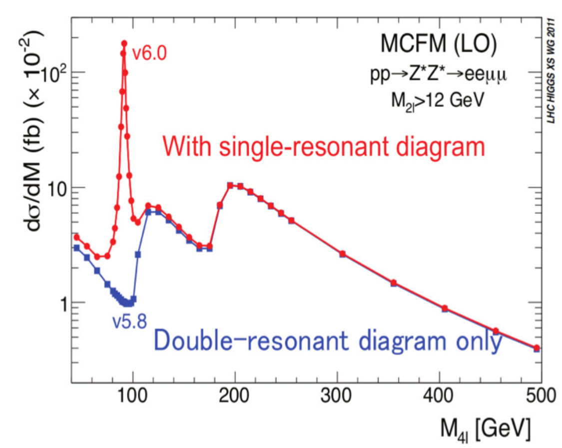

ATLAS
EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST

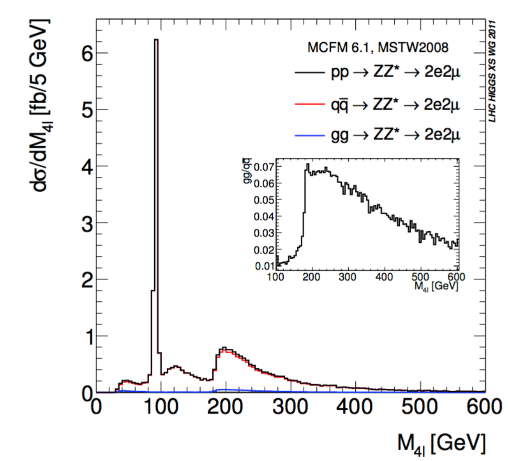


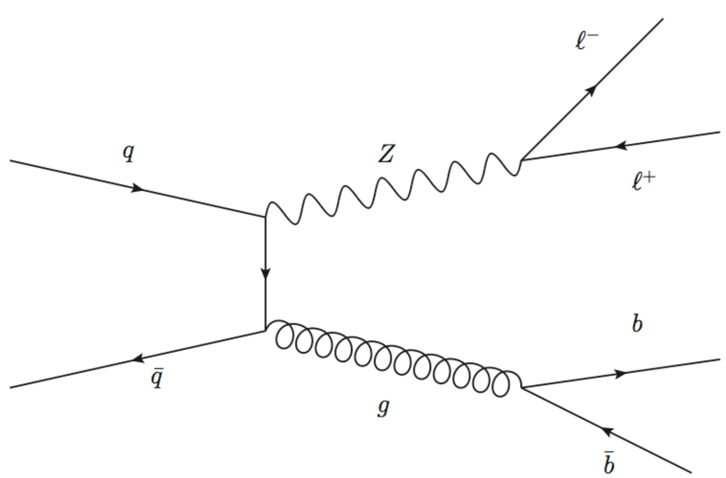
(a) $qq \to ZZ$

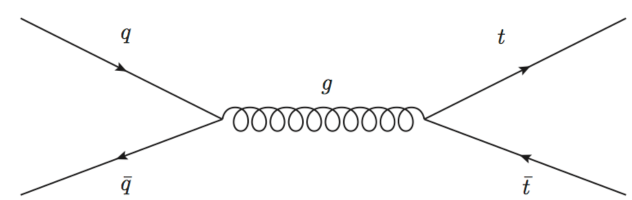


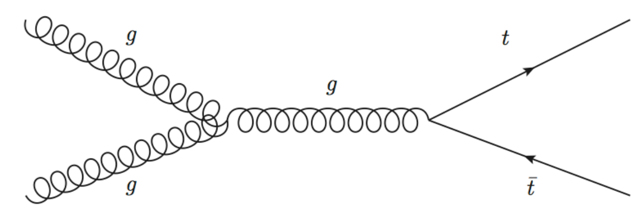
(b) $gg \to ZZ$

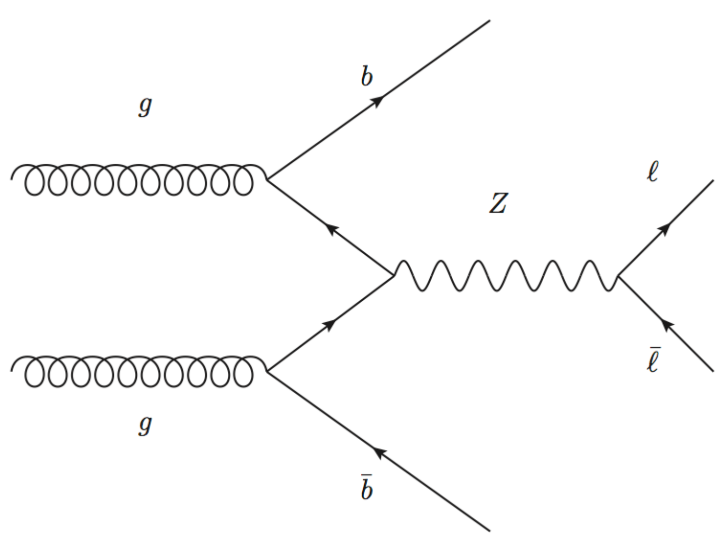


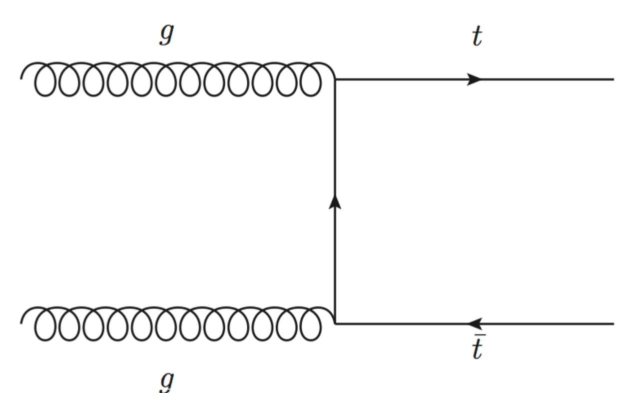




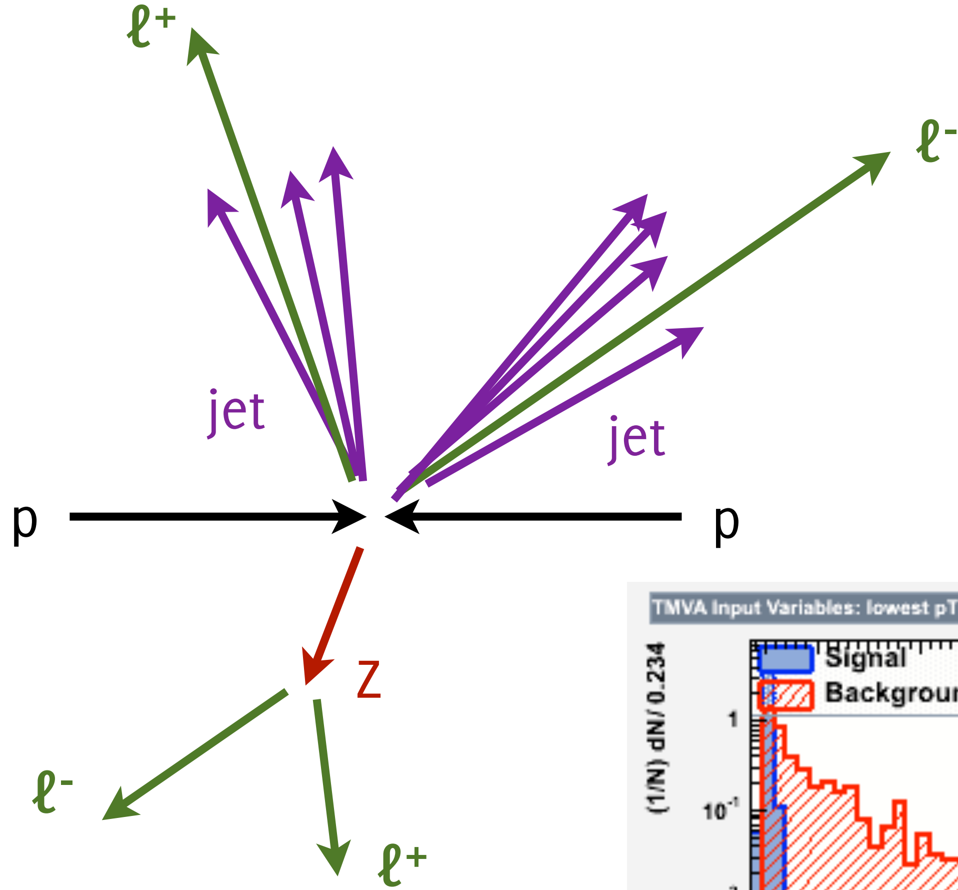


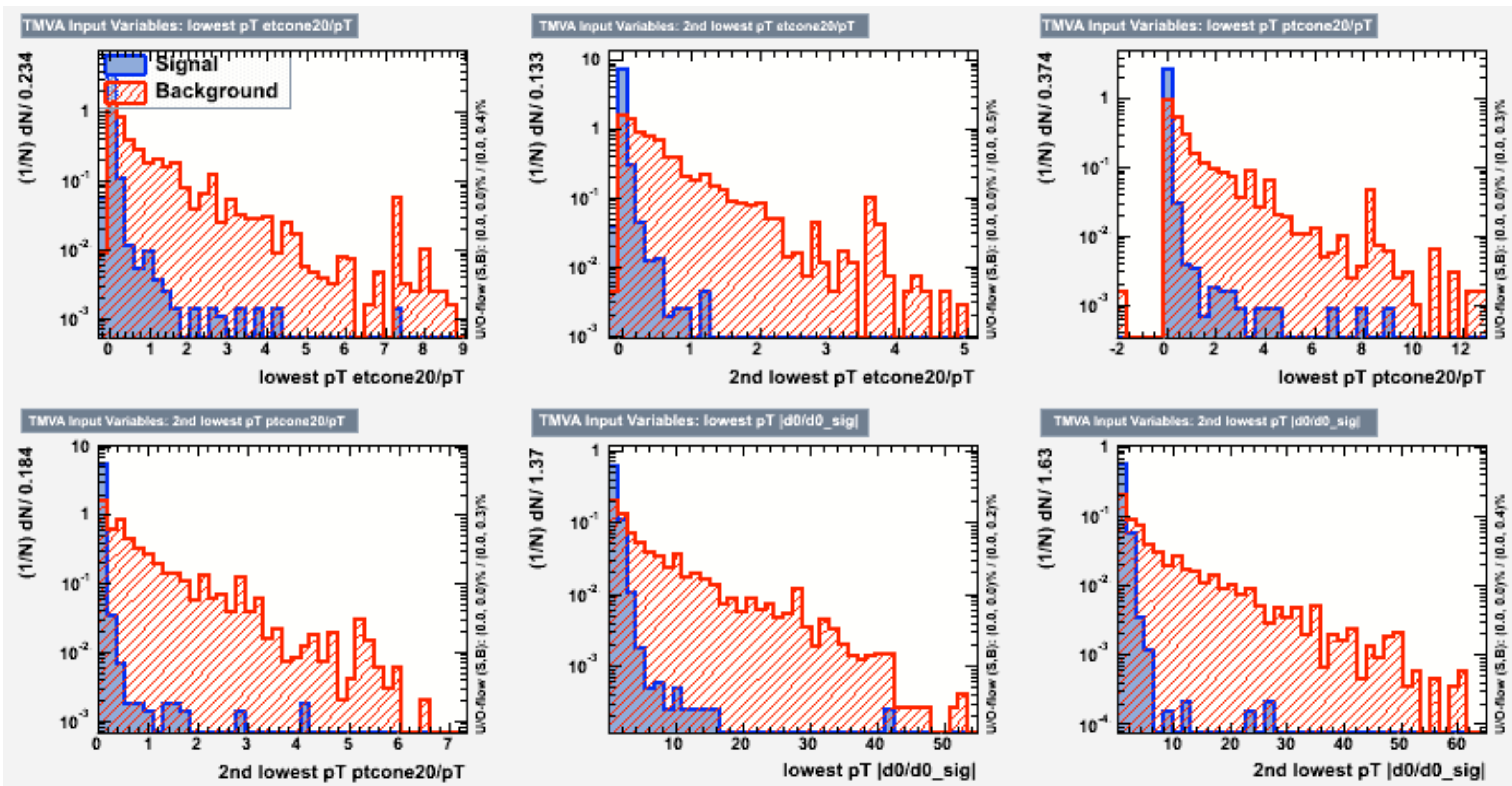




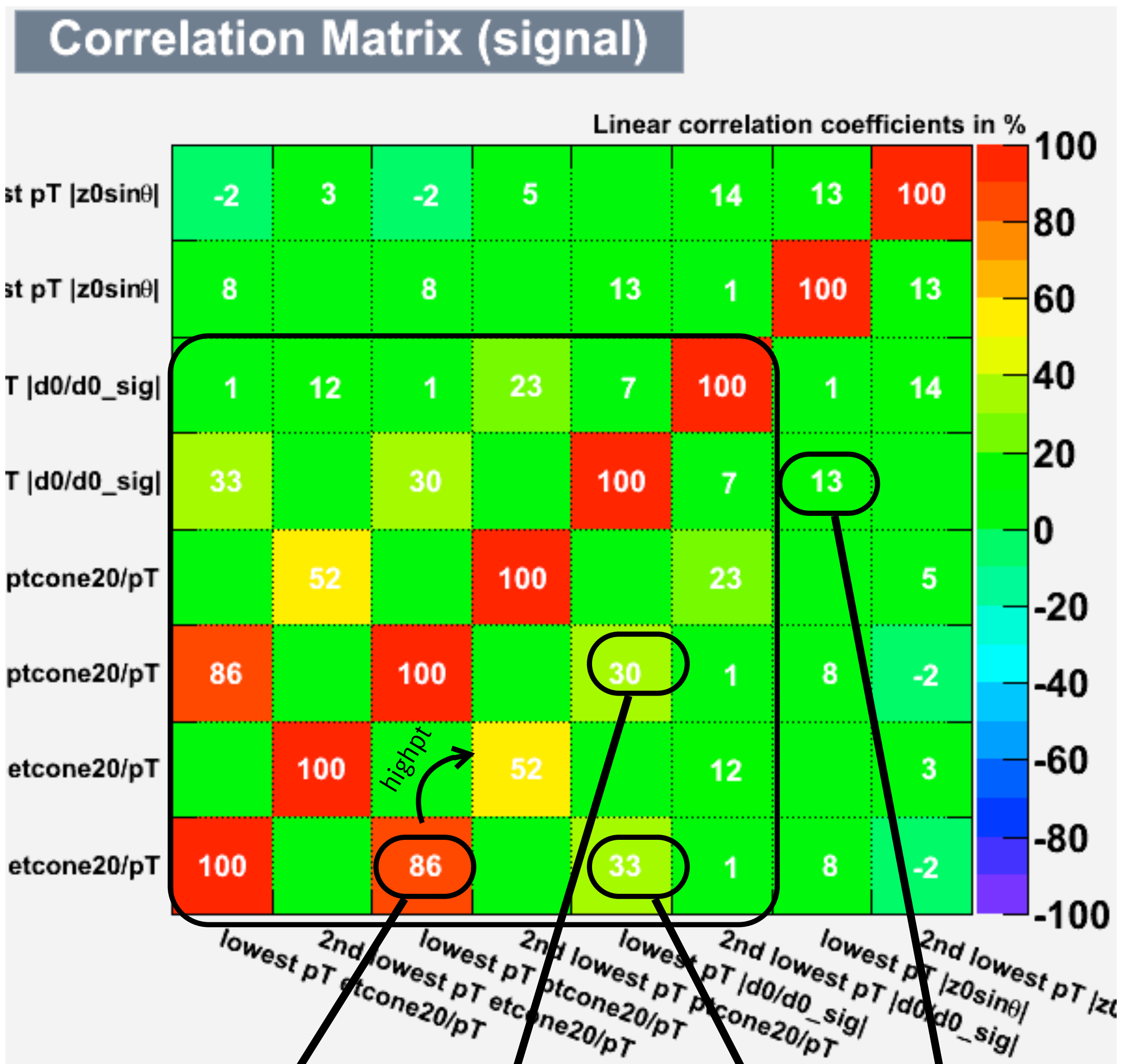


Reducing the Reducible





Reducing the Reducible

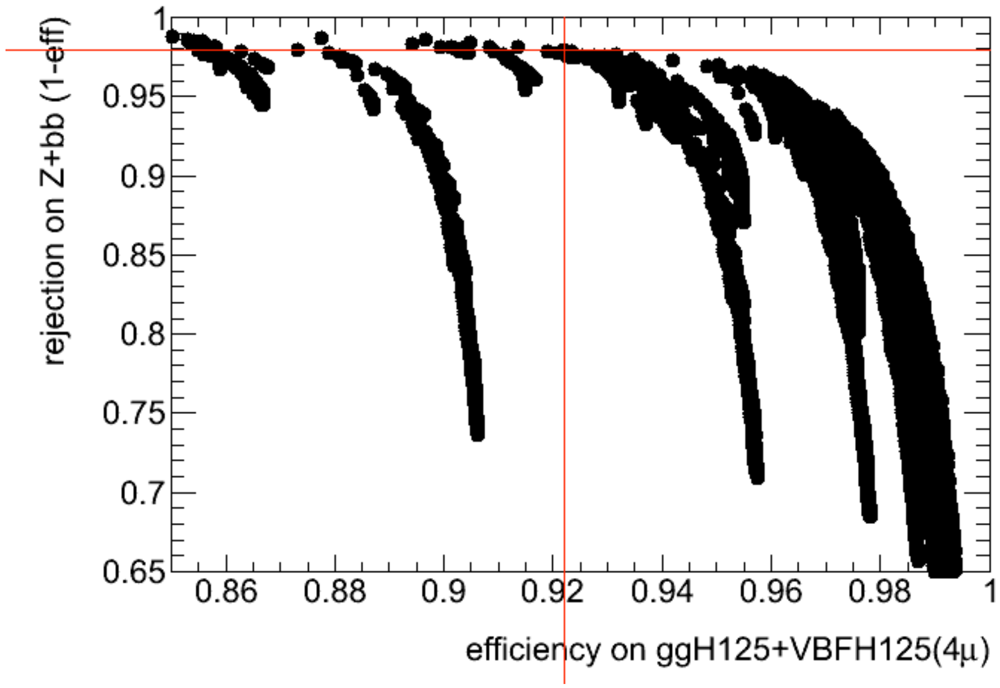


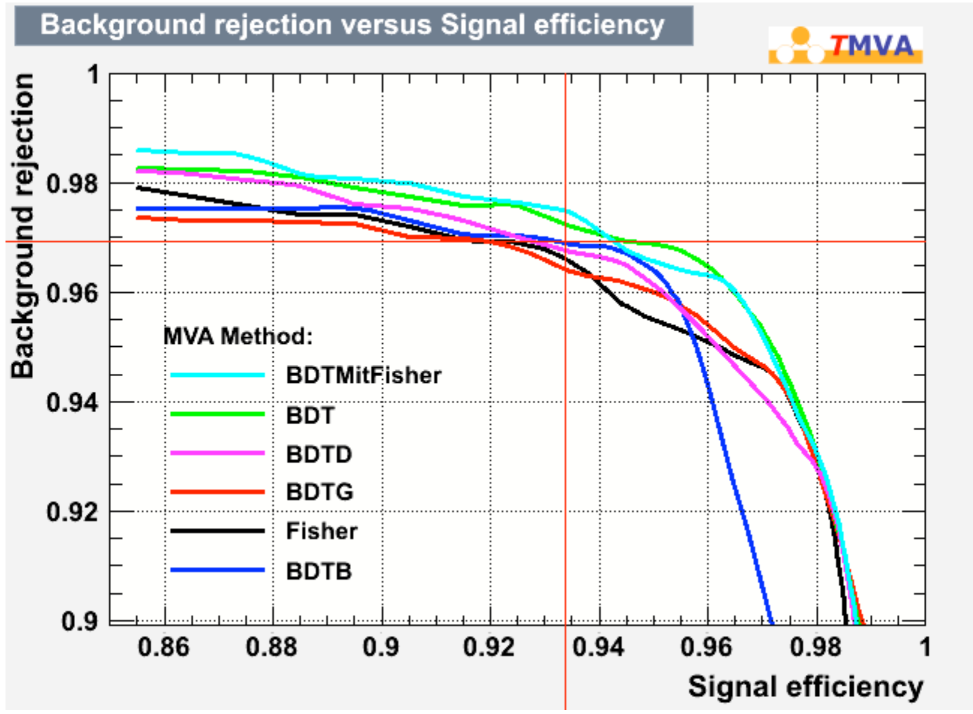
lowpt: etcone20, ptcone20

lowpt: ptcone20, d_0

lowpt: etcone20, d_0

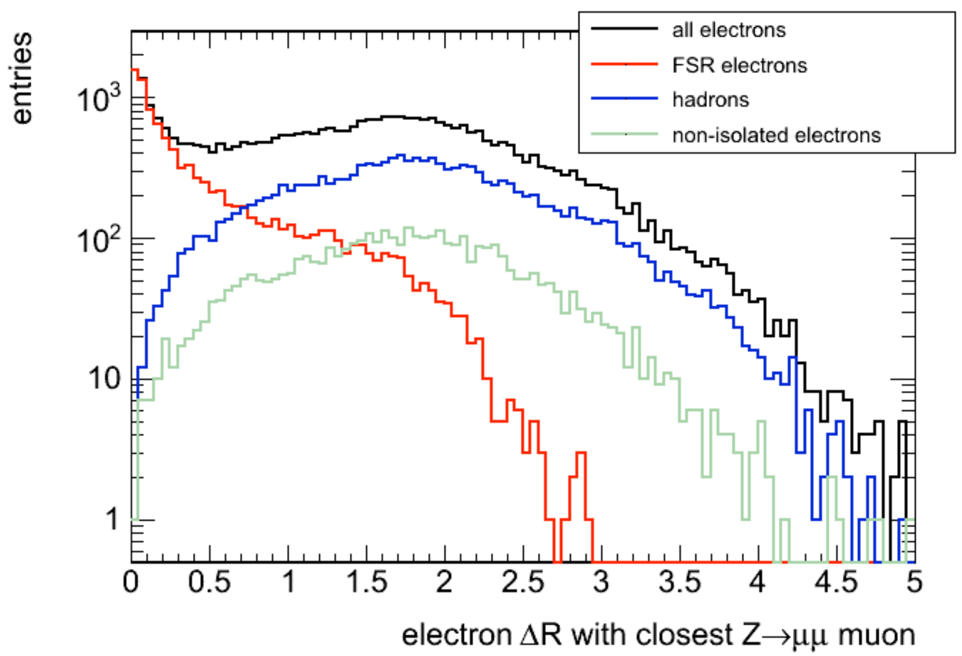
lowpt: z_0, d_0



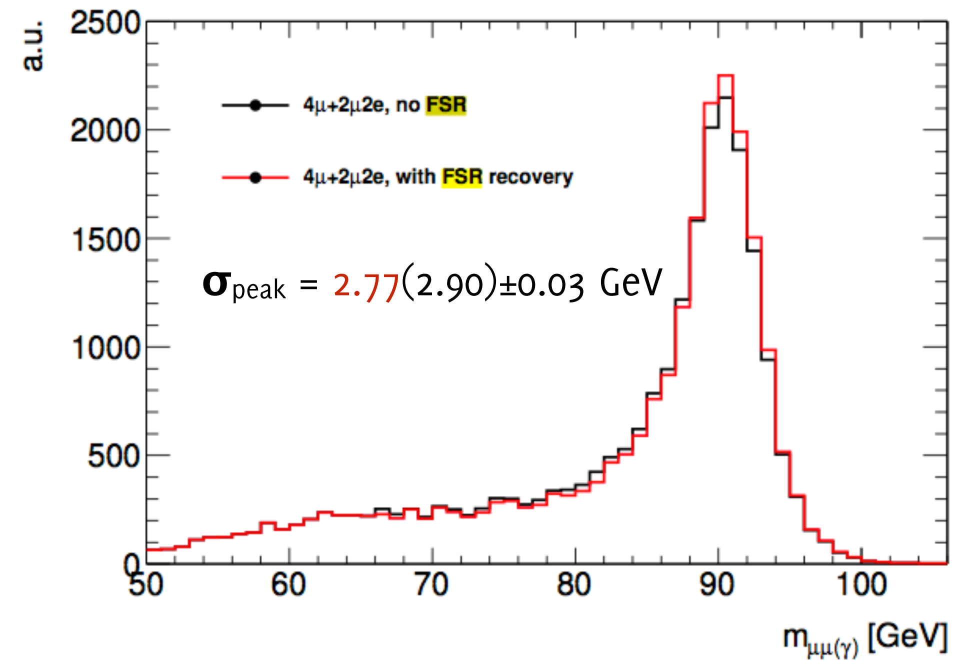


FSR

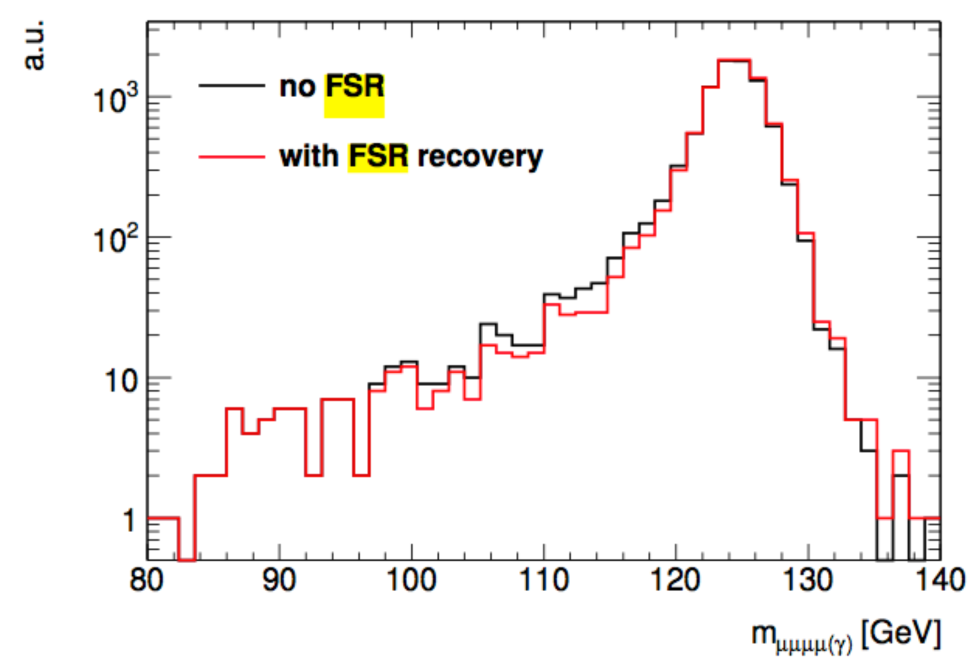
reject electron fakes



effect on Z peak



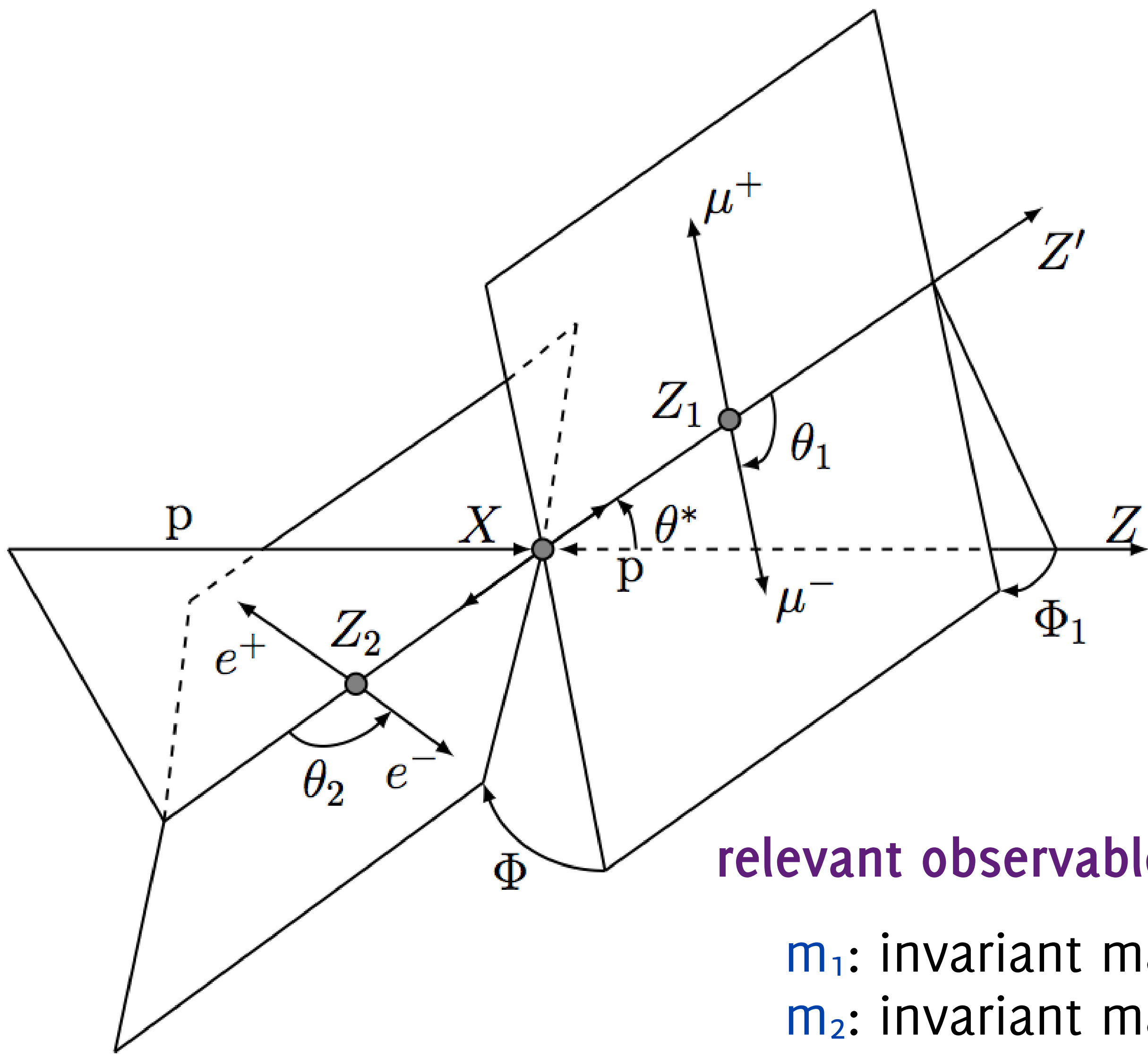
effect on H peak



sum back to on-shell $Z_1 \to \mu\mu$ final states up to a single photon with $E_T > 1$ GeV

4% effect on number of selected events

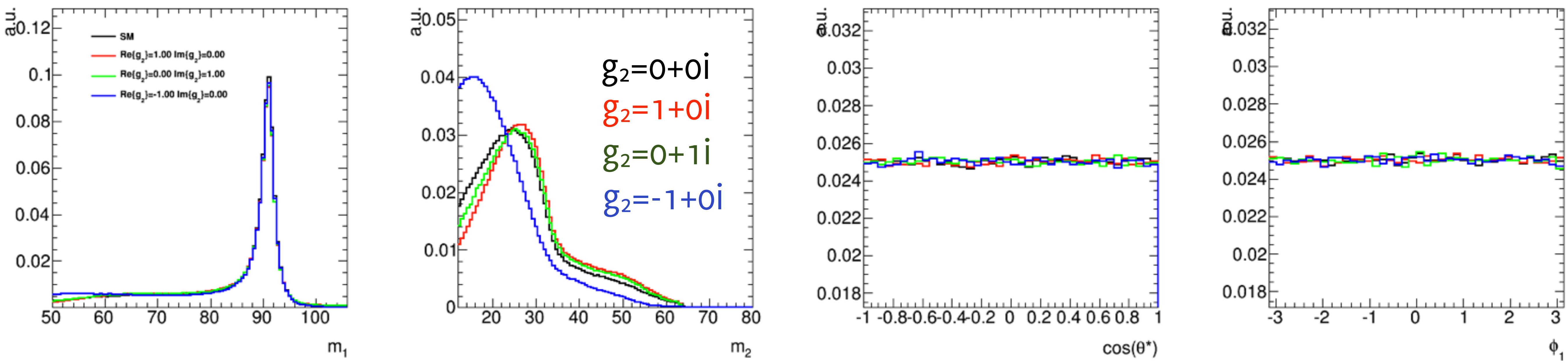
Angular Observables

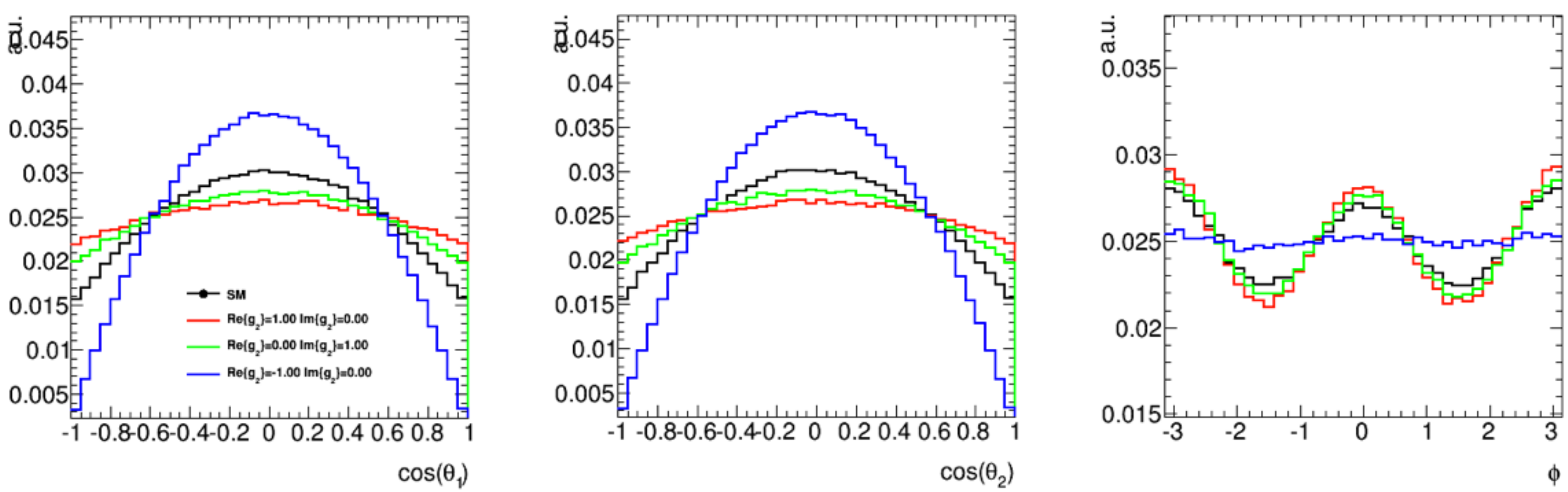


relevant observables in $H \to ZZ \to 4\ell$ J^{PC} analysis (similar for $H \to WW, \gamma\gamma$)

- m_1: invariant mass of the on-shell Z (Z_1)
- m_2: invariant mass of the off-shell Z (Z_2)
- θ^*: angle, in X reference frame, between Z_1 and beam axis
- φ, φ_1: azimuthal angles, in X reference frame, between X, Z_1 and Z_2 decay planes
- θ_i: angle, in Z_i reference frame, between lepton and Z_i flight line

Where does sensitivity come from?

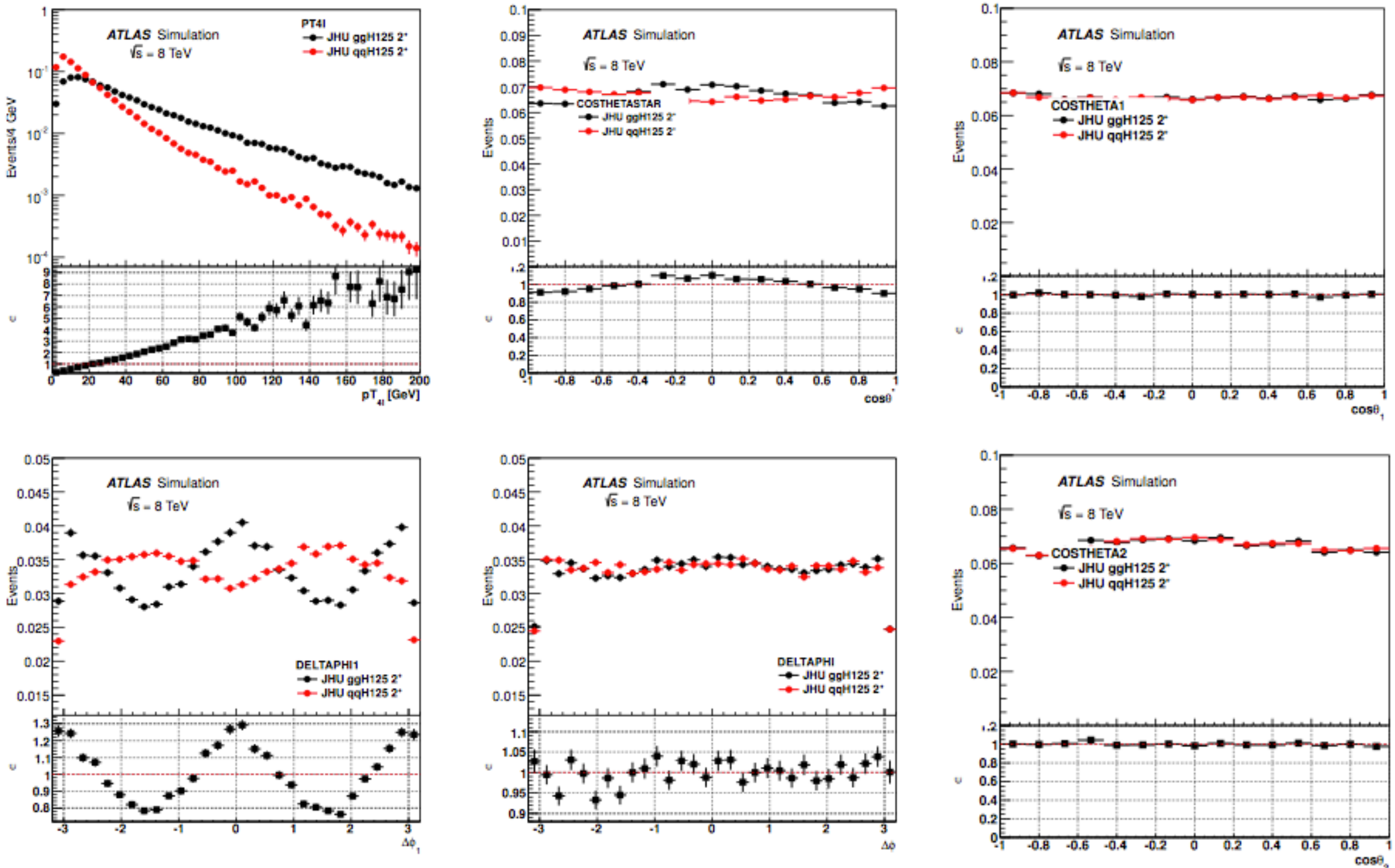




sensitivity on g_2 is asymmetrical

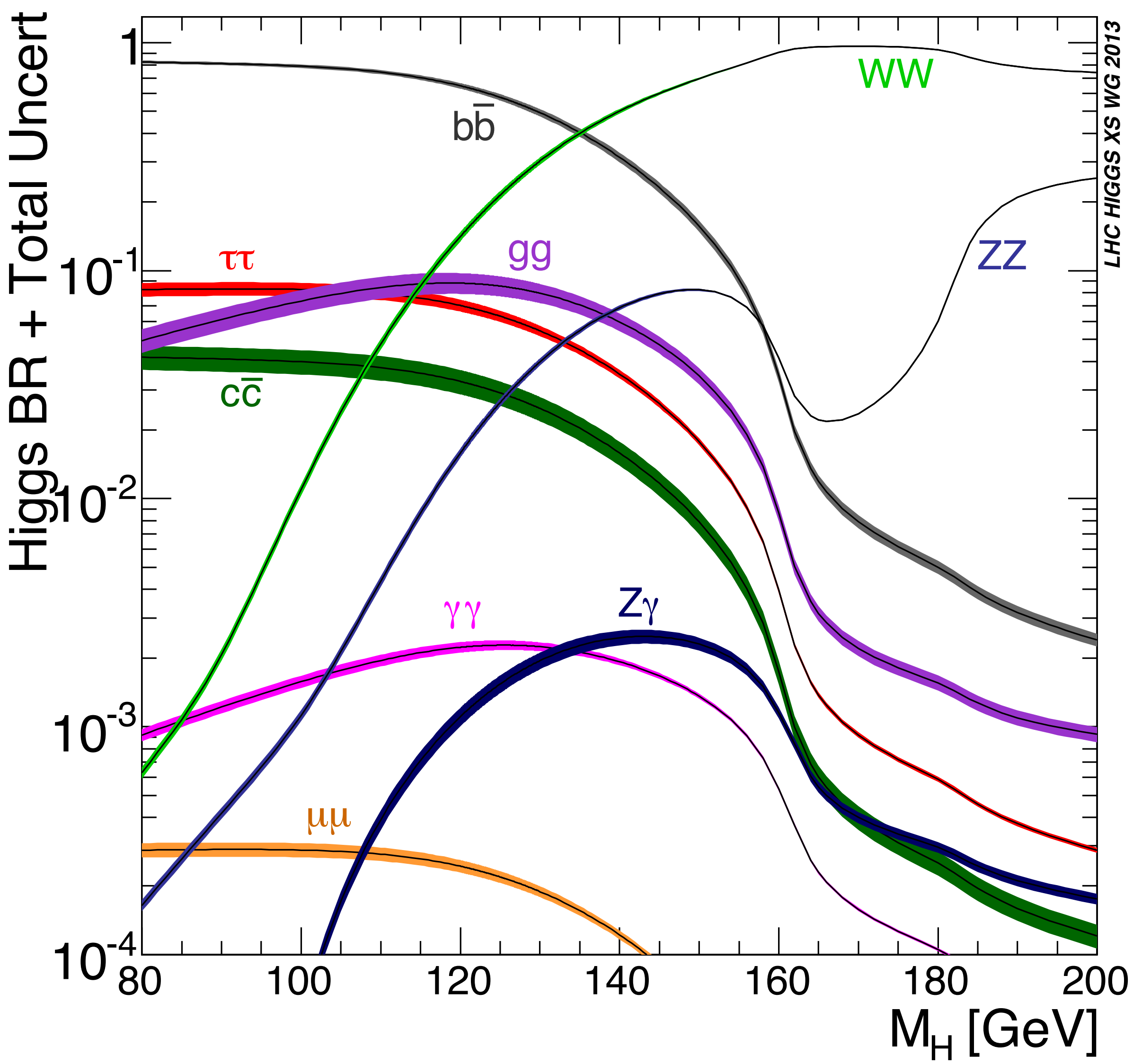
* $Re(g_2)<0$ has m_2, $\cos(\boldsymbol{\theta}_1)$, $\cos(\boldsymbol{\theta}_2)$, $\boldsymbol{\phi}$ distributions very different from SM 0^+
* less separation for the other half-plane

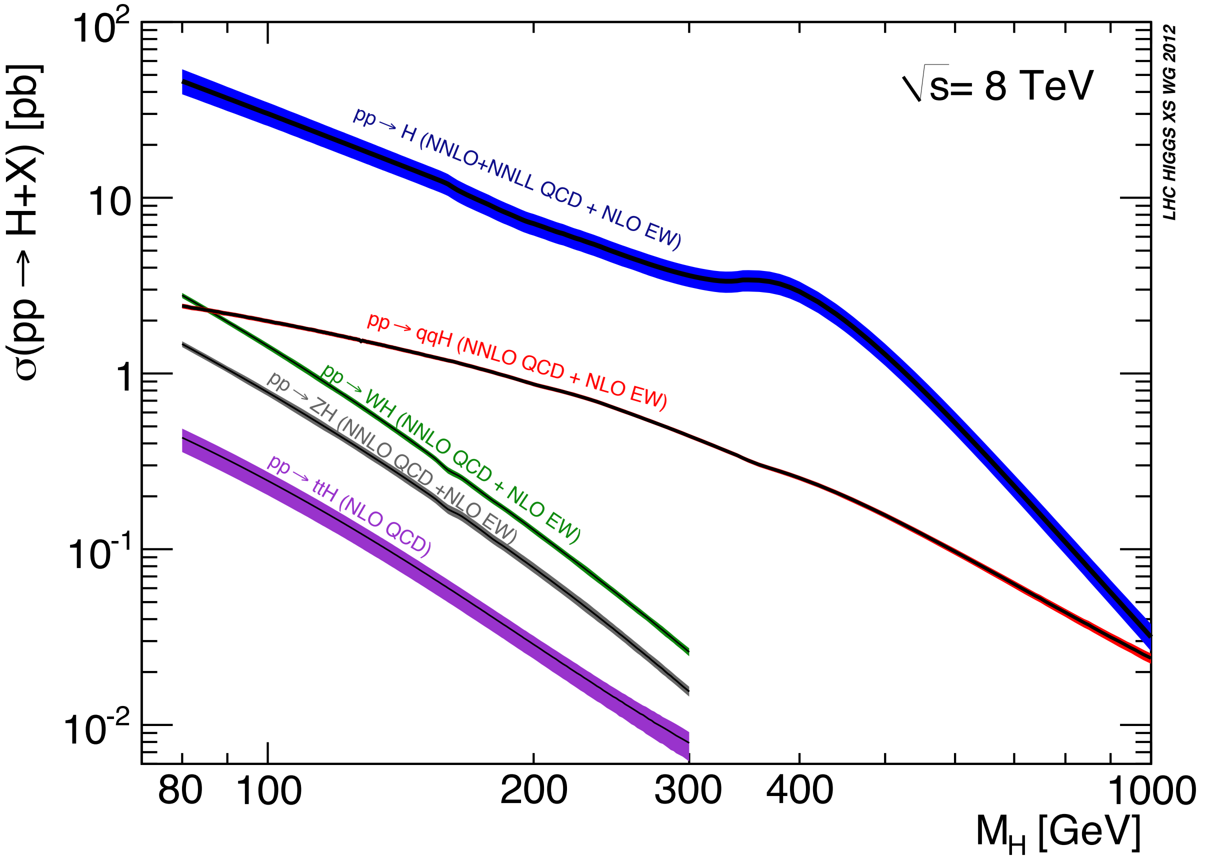
Spin 2^+: **gg** vs qq



2^+: qq production yields a softer p_T spectrum

Low mass searches

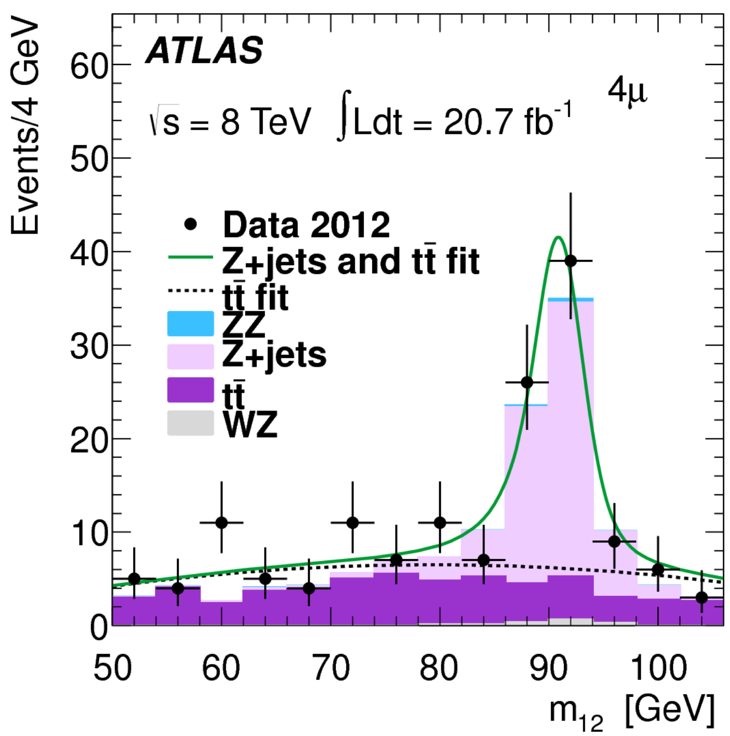


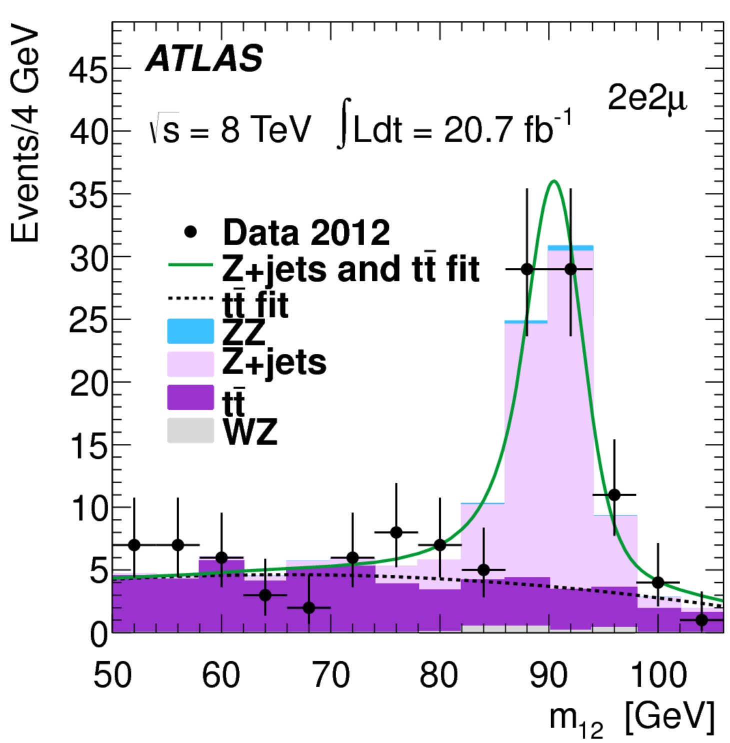


Signal cross-section

m_H [GeV]	$\sigma\,(gg \to H)$ [pb]	$\sigma\,(qq' \to Hqq')$ [pb]	$\sigma\,(q\bar{q} \to WH)$ [pb]	$\sigma\,(q\bar{q} \to ZH)$ [pb]	$\mathrm{BR}\left(H \to ZZ^{(*)} \to 4\ell\right)$ $[10^{-3}]$
			$\sqrt{s} = \S 7\mathrm{TeV}$		
123	$15.8^{+2.3}_{-2.4}$	1.25 ± 0.03	$0.60^{+0.02}_{-0.03}$	0.33 ± 0.02	0.103
125	15.3 ± 2.3	1.22 ± 0.03	0.57 ± 0.02	0.32 ± 0.02	0.125
127	14.9 ± 2.2	1.20 ± 0.03	0.54 ± 0.02	0.30 ± 0.02	0.148
400	$2.05^{+0.30}_{-0.29}$	0.18 ± 0.01	–	–	1.21
600	$0.34^{+0.06}_{-0.05}$	$0.062^{+0.005}_{-0.002}$	–	–	1.23
			$\sqrt{s} = 8\,\mathrm{TeV}$		
123	20.2 ± 3.0	1.61 ± 0.05	0.73 ± 0.03	0.42 ± 0.02	0.103
125	19.5 ± 2.9	$1.58^{+0.04}_{-0.05}$	0.70 ± 0.03	0.39 ± 0.02	0.125
127	18.9 ± 2.8	1.55 ± 0.05	$0.66^{+0.02}_{-0.03}$	0.37 ± 0.02	0.148
400	$2.92^{+0.41}_{-0.40}$	0.25 ± 0.01	–	–	1.21
600	$0.52^{+0.08}_{-0.07}$	0.097 ± 0.004	–	–	1.23

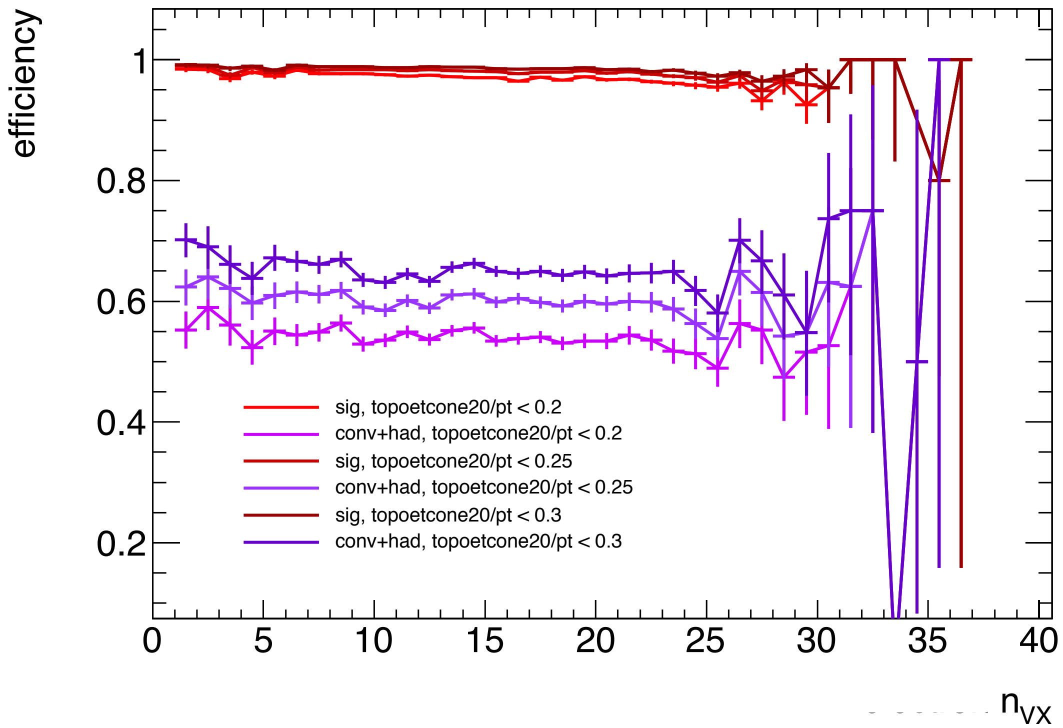
Reducible background





Method	Estimate for $\sqrt{s} = 8$ TeV	Estimate for $\sqrt{s} = 7$ TeV
	4μ	4μ
m_{12} fit: $Z + jj$ contribution	$2.4 \pm 0.5 \pm 0.6^\dagger$	$0.22 \pm 0.07 \pm 0.02^\dagger$
m_{12} fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03^\dagger$	$0.03 \pm 0.01 \pm 0.01^\dagger$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.10 \pm 0.05 \pm 0.004$	-
	$2e2\mu$	$2e2\mu$
m_{12} fit: $Z + jj$ contribution	$2.5 \pm 0.5 \pm 0.6^\dagger$	$0.19 \pm 0.06 \pm 0.02^\dagger$
m_{12} fit: $t\bar{t}$ contribution	$0.10 \pm 0.02 \pm 0.02^\dagger$	$0.03 \pm 0.01 \pm 0.01^\dagger$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.12 \pm 0.07 \pm 0.005$	-
	$2\mu 2e$	$2\mu 2e$
$\ell\ell + e^\pm e^\mp$ relaxed cuts	$5.2 \pm 0.4 \pm 0.5^\dagger$	$1.8 \pm 0.3 \pm 0.4$
$\ell\ell + e^\pm e^\mp$ inverted cuts	$3.9 \pm 0.4 \pm 0.6$	-
$3\ell + \ell$ (same–charge)	$4.3 \pm 0.6 \pm 0.5$	$2.8 \pm 0.4 \pm 0.5^\dagger$
same–charge, full analysis	4	0
	$4e$	$4e$
$\ell\ell + e^\pm e^\mp$ relaxed cuts	$3.2 \pm 0.5 \pm 0.4^\dagger$	$1.4 \pm 0.3 \pm 0.4$
$\ell\ell + e^\pm e^\mp$ inverted cuts	$3.6 \pm 0.6 \pm 0.6$	-
$3\ell + \ell$ (same–charge)	$4.2 \pm 0.5 \pm 0.5$	$2.5 \pm 0.3 \pm 0.5^\dagger$
same–charge, full analysis	3	2

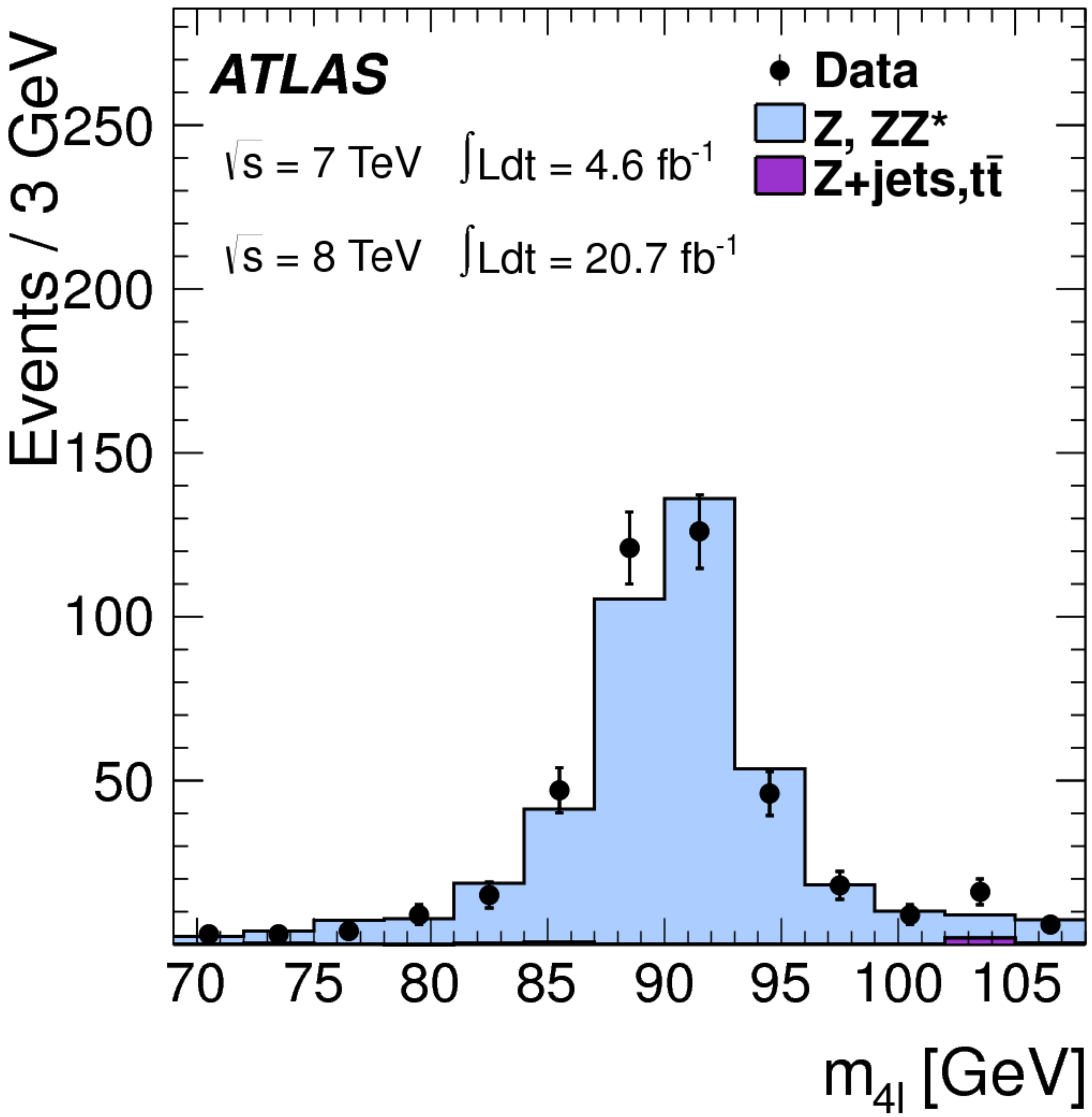
Isolation efficiency



Systematic uncertainties

- muon ID/reco
  - 0.8% (4μ), 0.4% (2μ2e,2e2μ)
- electron ID/reco
  - m_H = 125 GeV: 9.5% (4e), 8.7-2.4% (2e2μ, 2μ2e)
  - m_H = 1 TeV: 2.4% (4e), 1.8-1.6% (2e2μ, 2μ2e)
- luminosity
  - 7 TeV: 1.8%
  - 8 TeV: 3.6%
- signal
  - QCD: 8% (ggF), 1% (VBF/VH)
  - alpha strong: 8% (ggF), 4% (VBF)
- ZZ background
  - QCD: 5%
  - alpha strong: 4% (VBF), 8% (ggF)
- energy and momentum scale
  - electrons: 0.4% (4e), 0.2% (2e2μ)
  - muons: 0.2% (4μ), 0.1% (2μ2e)

Single resonant



20 GeV < m_1 < 106 GeV

1 GeV < m_2 < 115 GeV

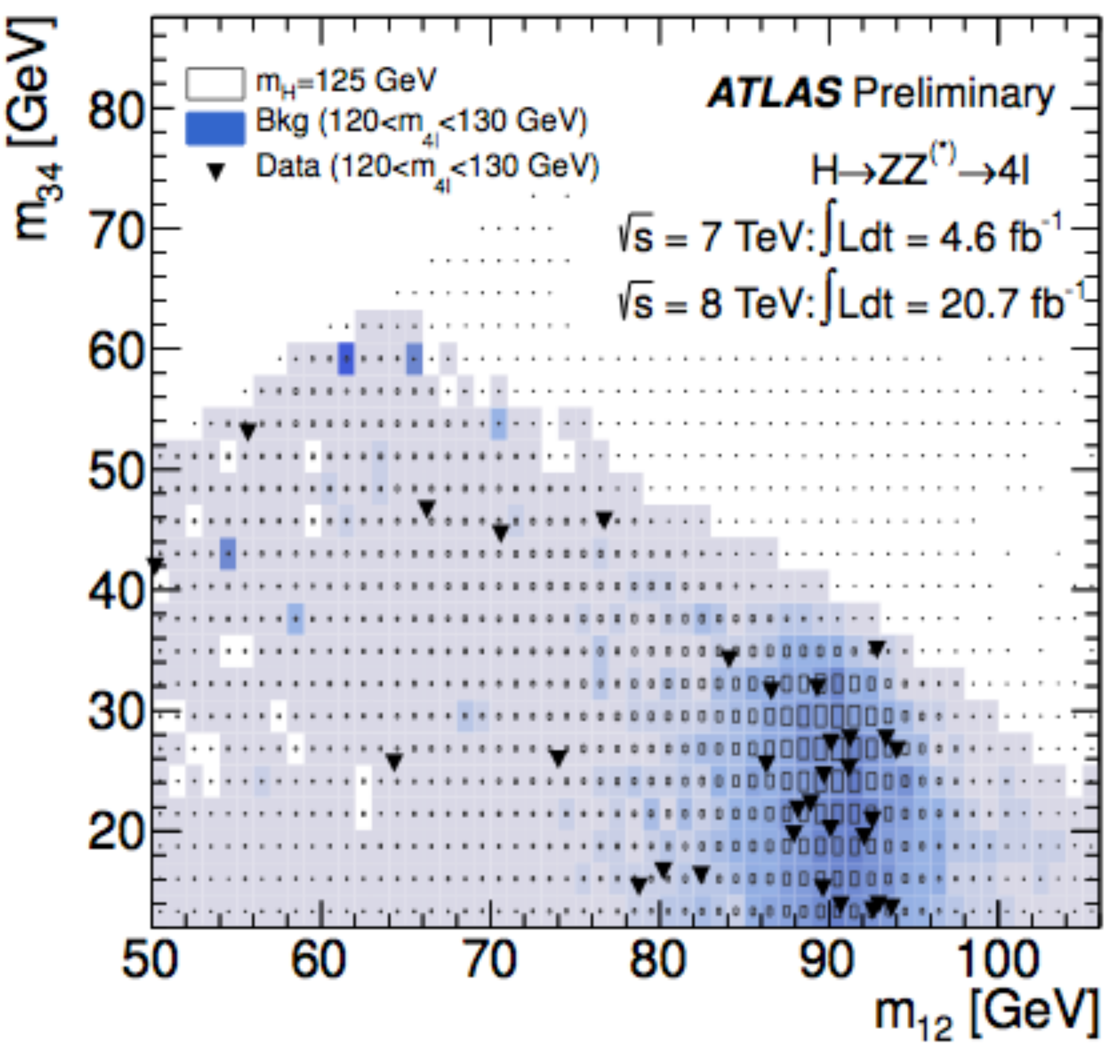
pT > (20, 15, 10/8, 4) GeV

The likelihood model

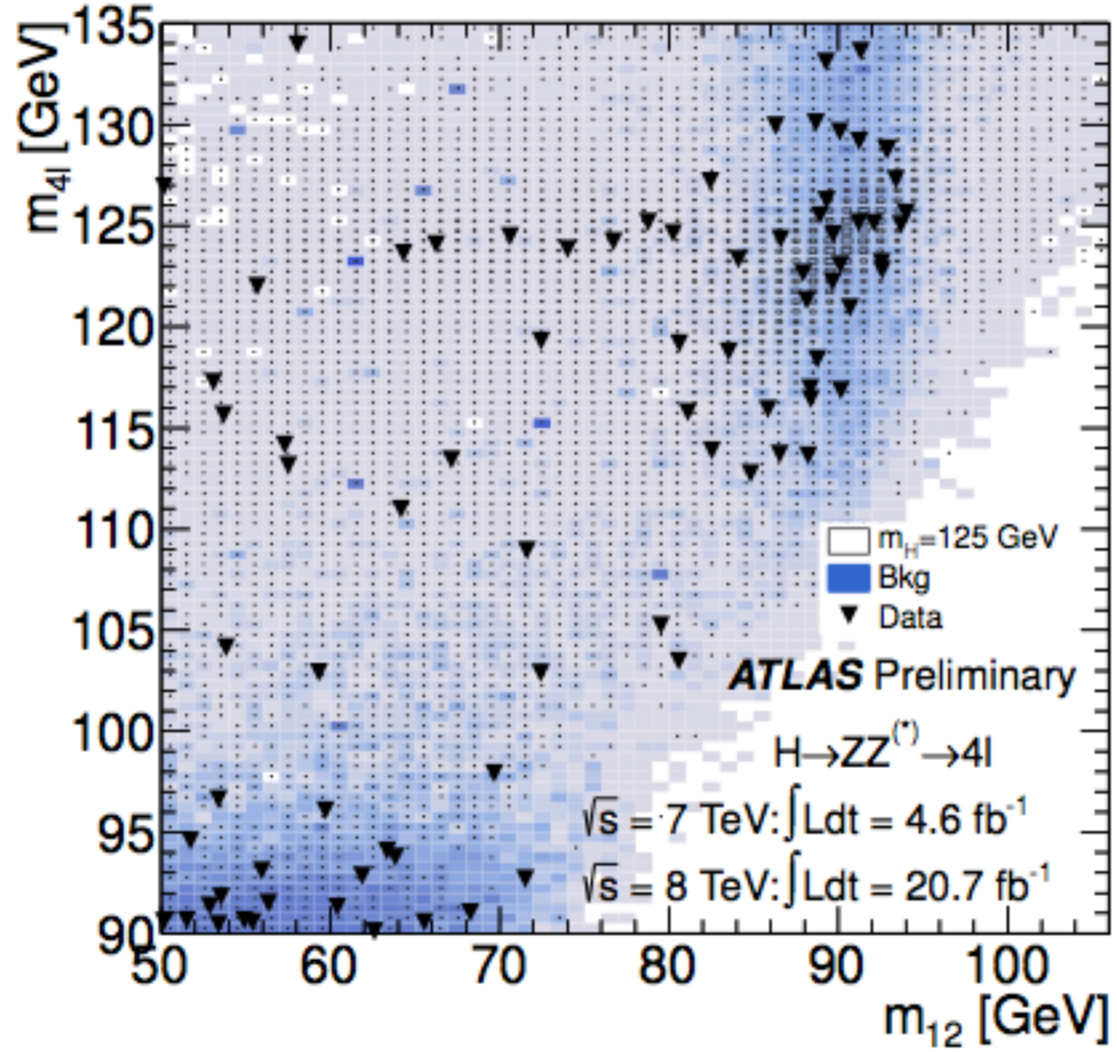
$$n^k_{\text{signal}} = \left(\sum_i \mu_i \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^k$$

$$\Lambda(\boldsymbol{\mu}) = \frac{L(\boldsymbol{\mu}, \hat{\hat{\boldsymbol{\theta}}}(\boldsymbol{\mu}))}{L(\hat{\boldsymbol{\mu}}, \hat{\boldsymbol{\theta}})}$$

$$\Lambda(m_H) = \frac{L(m_H\,,\, \hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\, \hat{\hat{\mu}}_{4\ell}(m_H)\,,\, \hat{\hat{\boldsymbol{\theta}}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\boldsymbol{\theta}})}$$



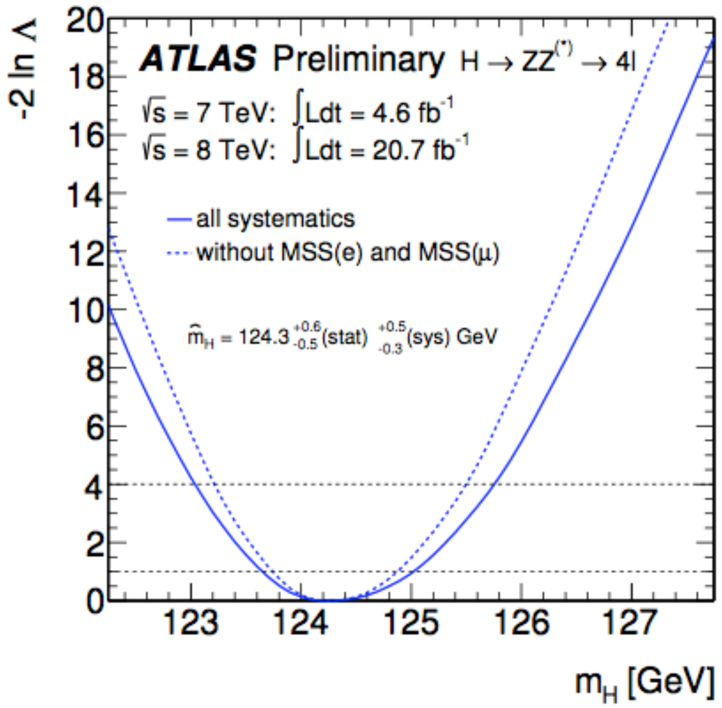
m_H=125 GeV
Bkg (120<m_4l<130 GeV)
Data (120<m_4l<130 GeV)
ATLAS Preliminary
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
m34 [GeV]
m12 [GeV]

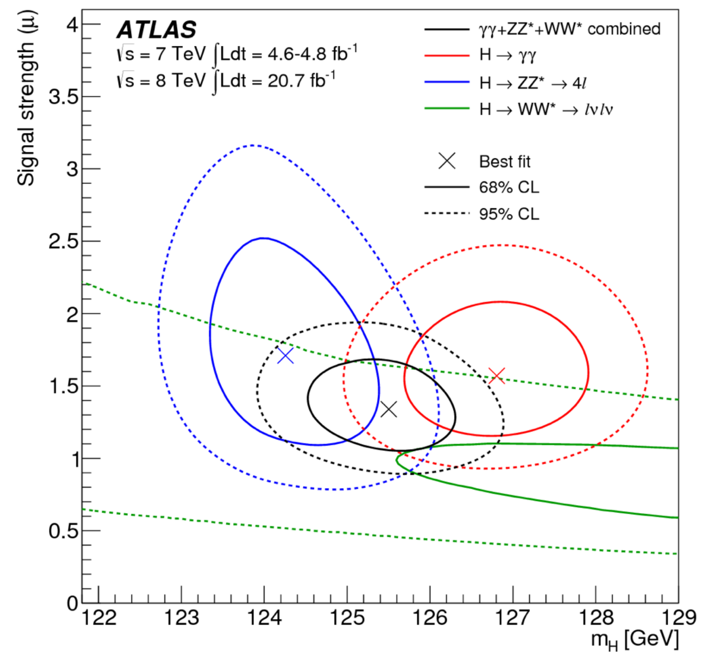


m_H=125 GeV
Bkg
Data
ATLAS Preliminary
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
m4l [GeV]
m12 [GeV]

Results

mass measurement



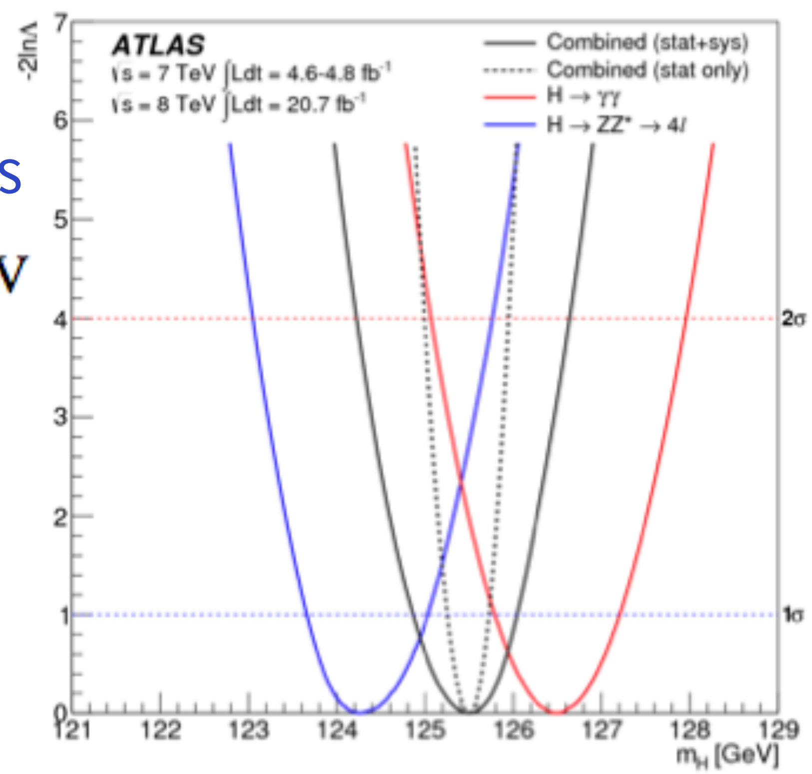


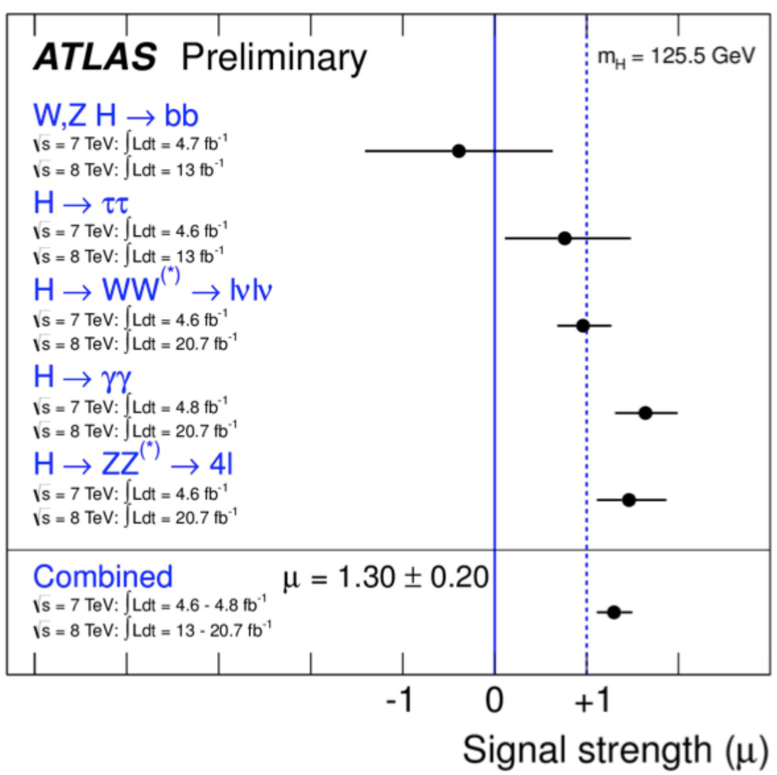
$$\mu = \frac{\text{events observed}}{\text{events expected}}$$

combination with other channels

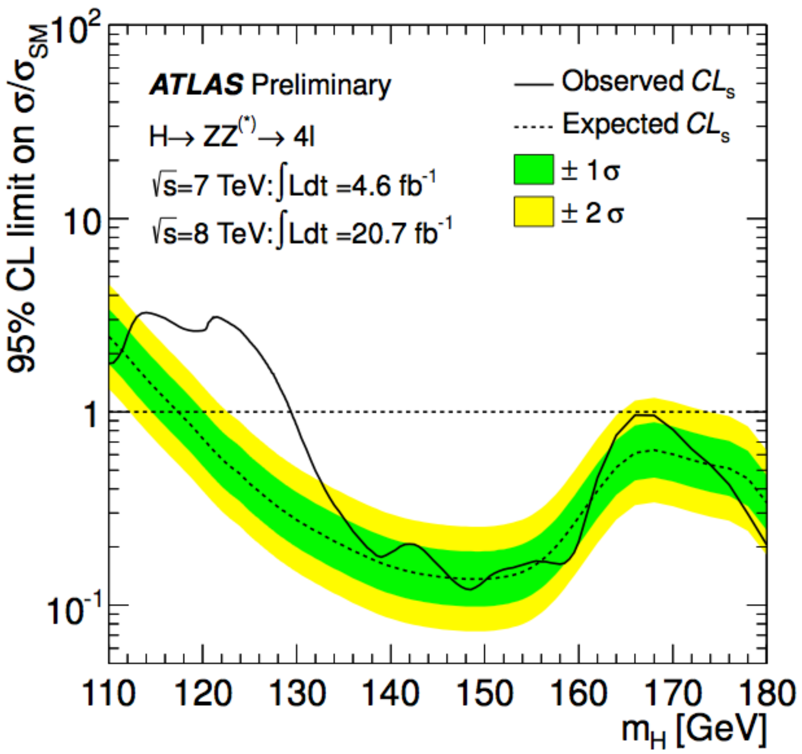
$$m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\ \text{GeV}$$

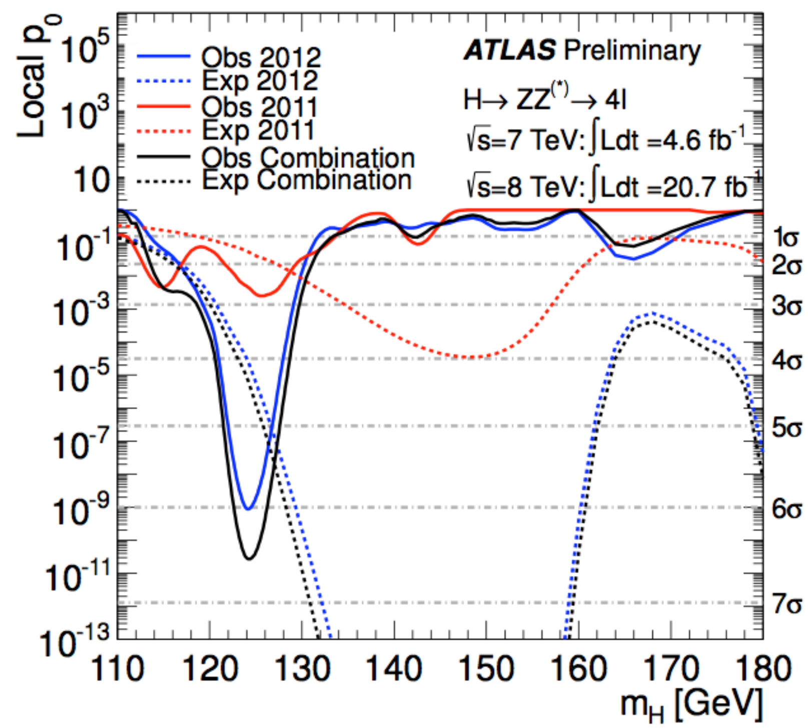
$$\mu = 1.33 \pm 0.14\,(\text{stat}) \pm 0.15\,(\text{sys})$$

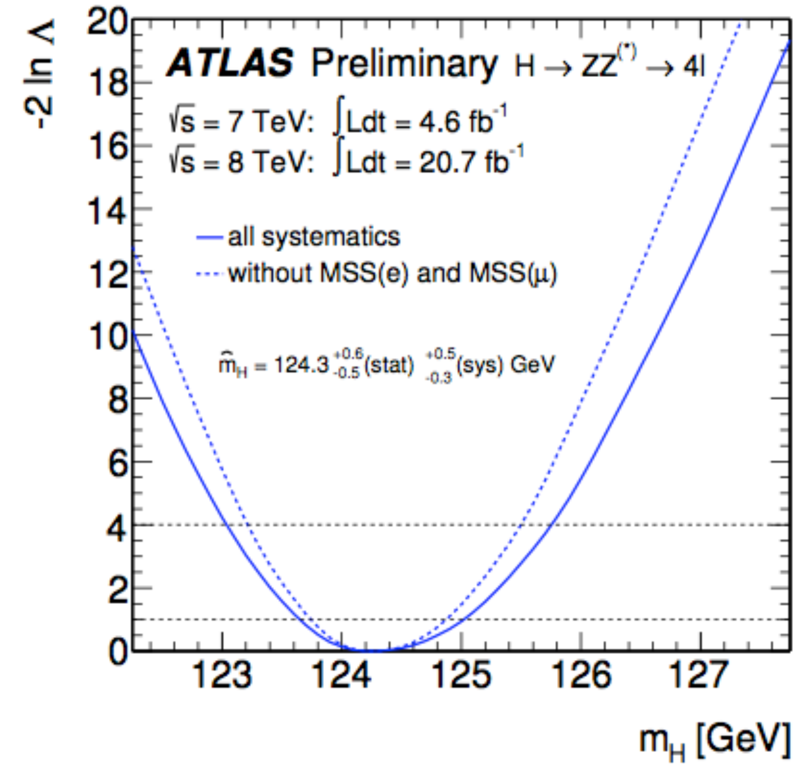


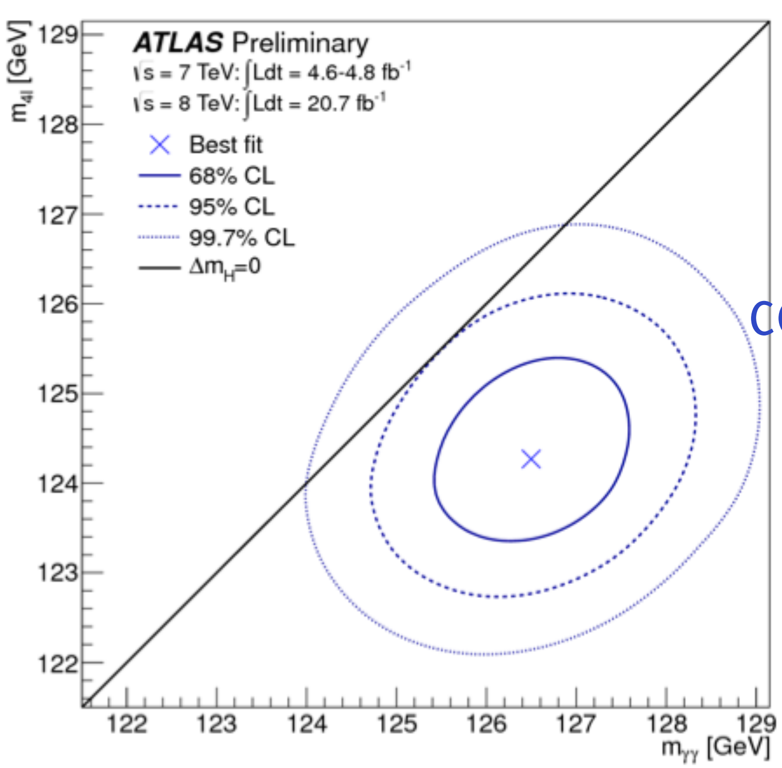


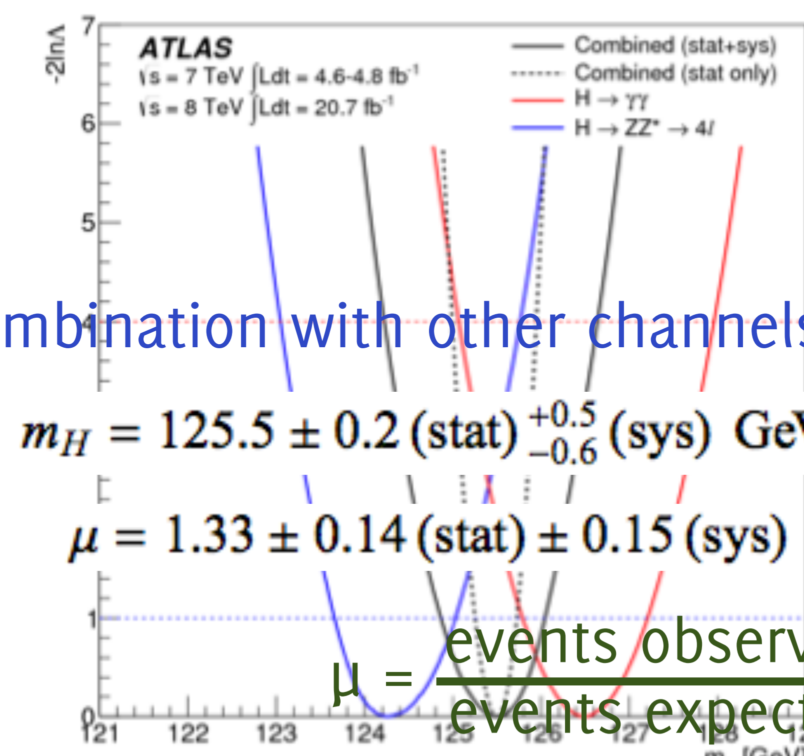
Results

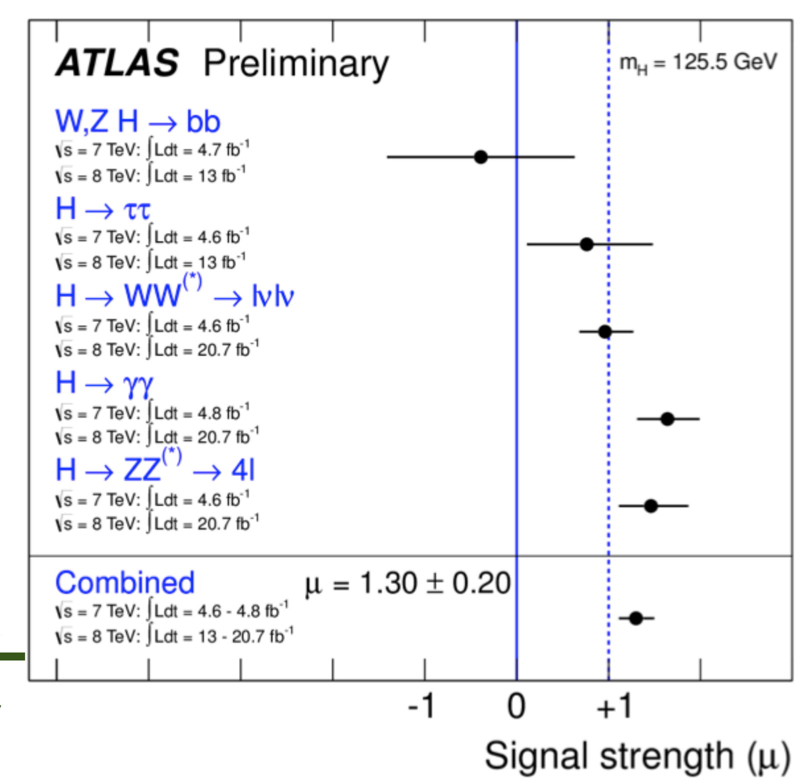












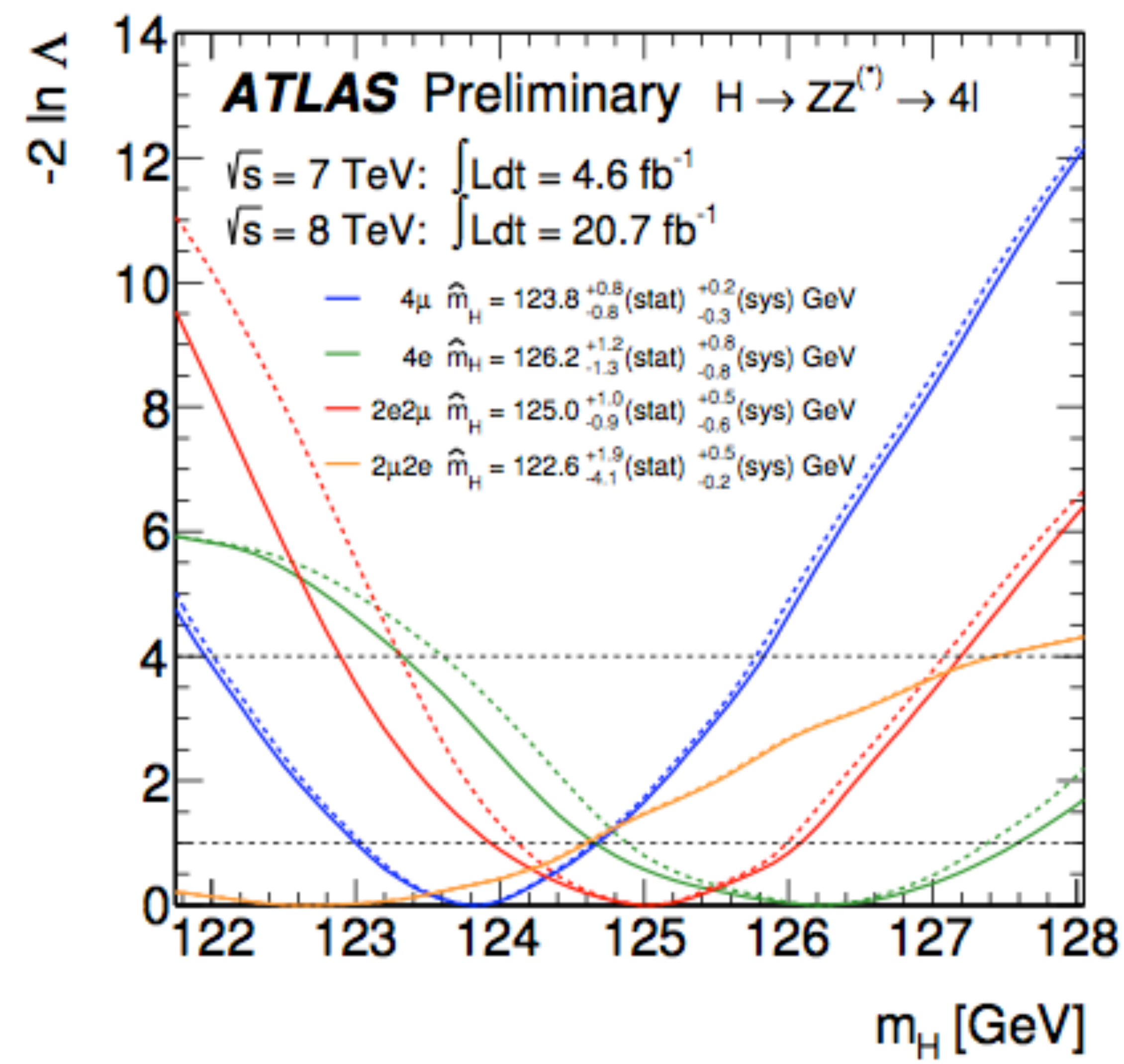
combination with other channels

$$m_H = 125.5 \pm 0.2\,(\text{stat})\ {}^{+0.5}_{-0.6}\,(\text{sys})\ \text{GeV}$$

$$\mu = 1.33 \pm 0.14\,(\text{stat}) \pm 0.15\,(\text{sys})$$

$$\mu = \frac{\text{events observed}}{\text{events expected}}$$

4-lepton breakdown

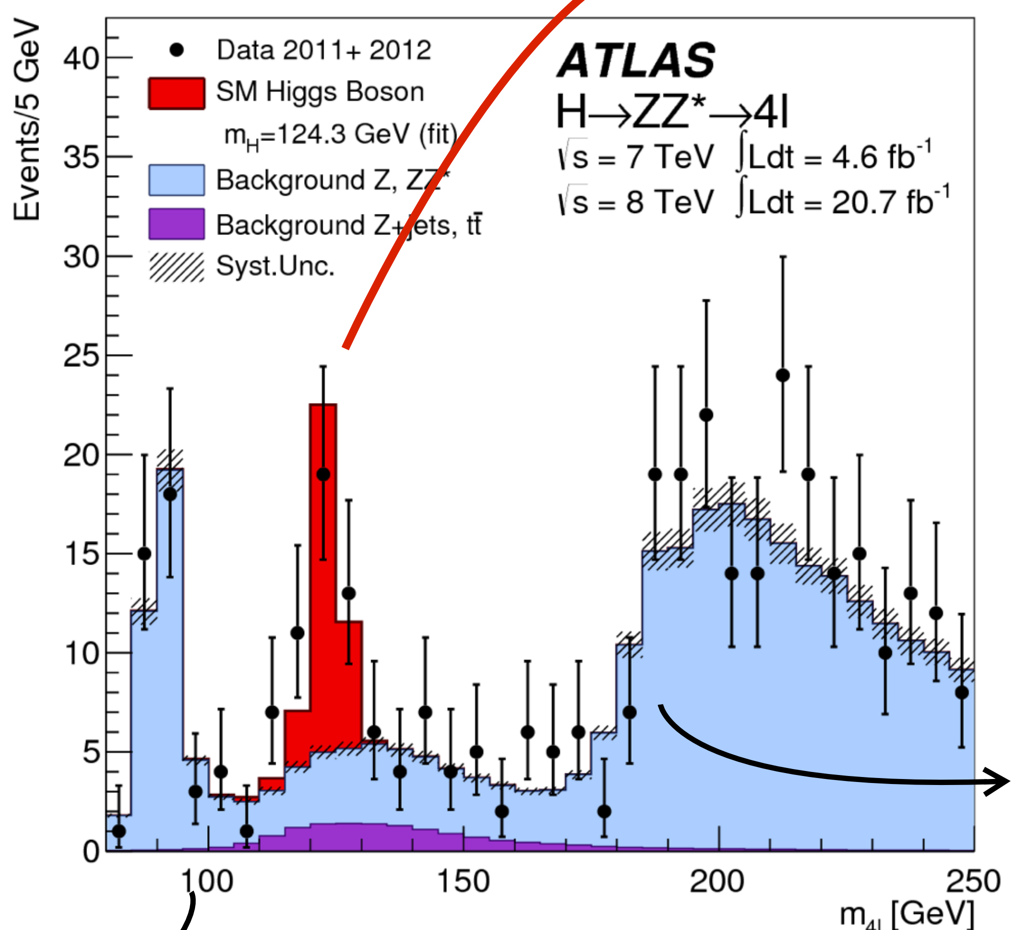


	observed			expected	
data set	min p_0	significance $[\sigma]$	$m_H(p_0)$	min $p_0(m_H)$	significance $[\sigma]$
$\sqrt{s} = 7\,\text{TeV}$	2.5×10^{-3}	2.8	125.6 GeV	3.5×10^{-2}	1.8
$\sqrt{s} = 8\,\text{TeV}$	8.8×10^{-10}	6.0	124.1 GeV	2.8×10^{-5}	4.0
combined	2.7×10^{-11}	6.6	124.3 GeV	5.7×10^{-6}	4.4

Results

is it the SM Higgs boson?

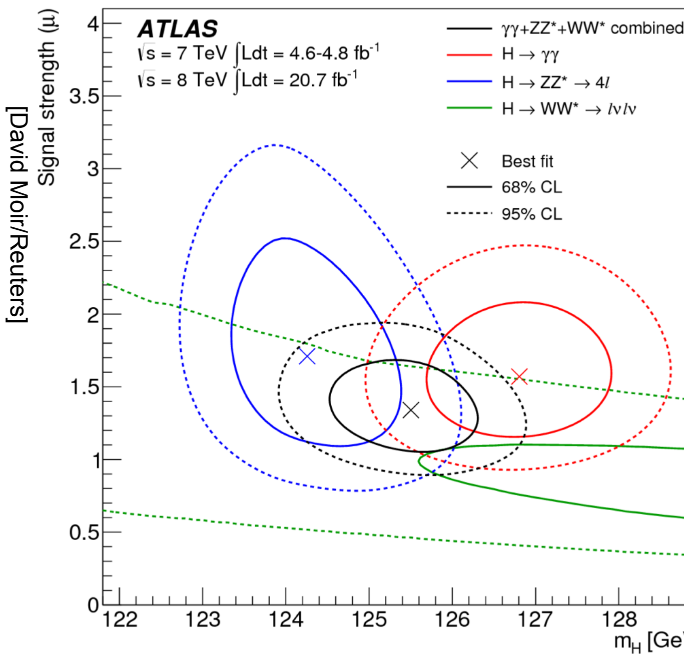
6.6σ "excess"

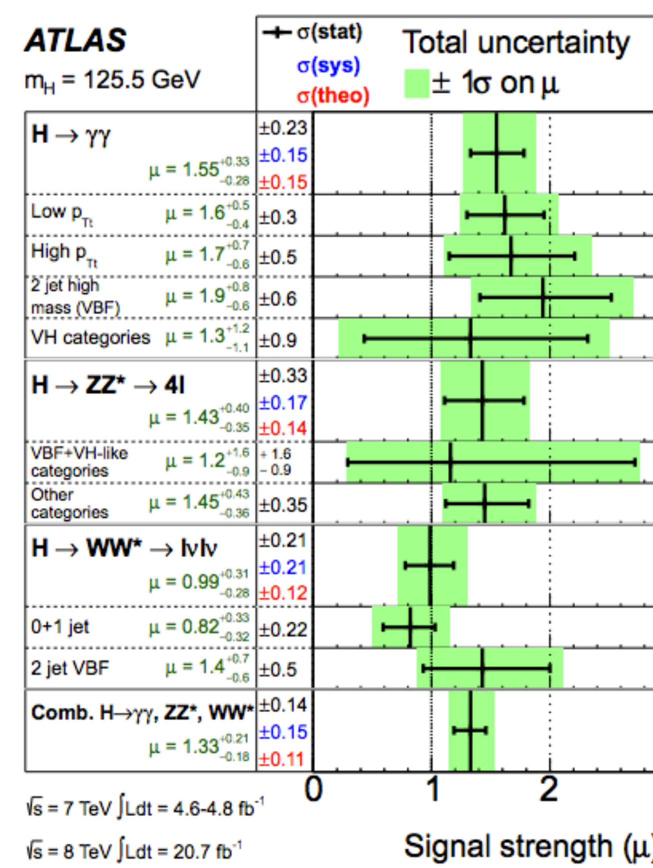


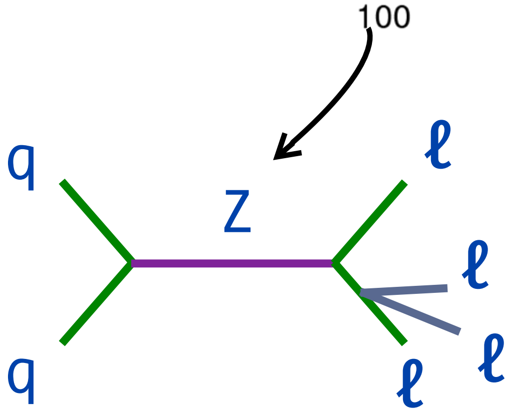
m$_{4l}$>2m$_Z$

[David Moir/Reuters]

mass measurement







combination with other channels

$$m_H = 125.5 \pm 0.2\,(\mathrm{stat})\ ^{+0.5}_{-0.6}\,(\mathrm{sys})\ \mathrm{GeV}$$

$$\mu = 1.33 \pm 0.14\,(\mathrm{stat}) \pm 0.15\,(\mathrm{sys})$$

$$\mu = \frac{\text{events observed}}{\text{events expected}}$$