Status of Higgs-boson measurements in ATLAS

presented by D. Froidevaux

on behalf of the ATLAS collaboration

Outline

- A short (personal) historical perspective
- Performance issues: muon momentum and electron/photon energy scales, electron and photon efficiencies (NEW)
- Final Higgs-boson mass measurement from run-1 (NEW!)
- Overview of some recent results and outlook

Status of Higgs-boson measurements in ATLAS

Disclaimer

- **Many more results covered in this conference, primarily in the parallel sessions**
- **See e.g. following talks:**
  - **Measurement of properties of the Higgs boson in bosonic decay channels using the ATLAS detector** **Higgs 1 Speaker: Bruno Lenzi (CERN)**
  - **Search for the Higgs boson in fermionic channels using the ATLAS detector**
    Higgs 1 Speaker: Dr. Carl Bryan Gwilliam (University of Liverpool, GB)
  - **Search for the Higgs boson in the ttH production mode using the ATLAS detector** **Higgs 2 Speaker: Rustem Ospanov (University of Pennsylvania)**
  - **Combined measurements of the properties of the Higgs boson using the ATLAS detector**
    Higgs 3 Speaker: Ludovica Aperio Bella (University of Birmingham, GB)
  - **These talks will cover recent results on H to Zγ, H to $\tau\tau$, VH with H to bb, couplings and more … not to mention BSM Higgs boson searches …**

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Physics Letters B

Volume 726, Issues 1–3, 7 October 2013, Pages 88–119

Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC ☆

ATLAS Collaboration

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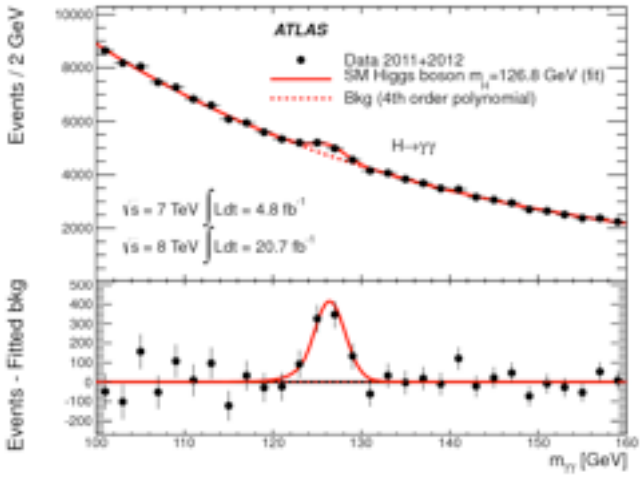

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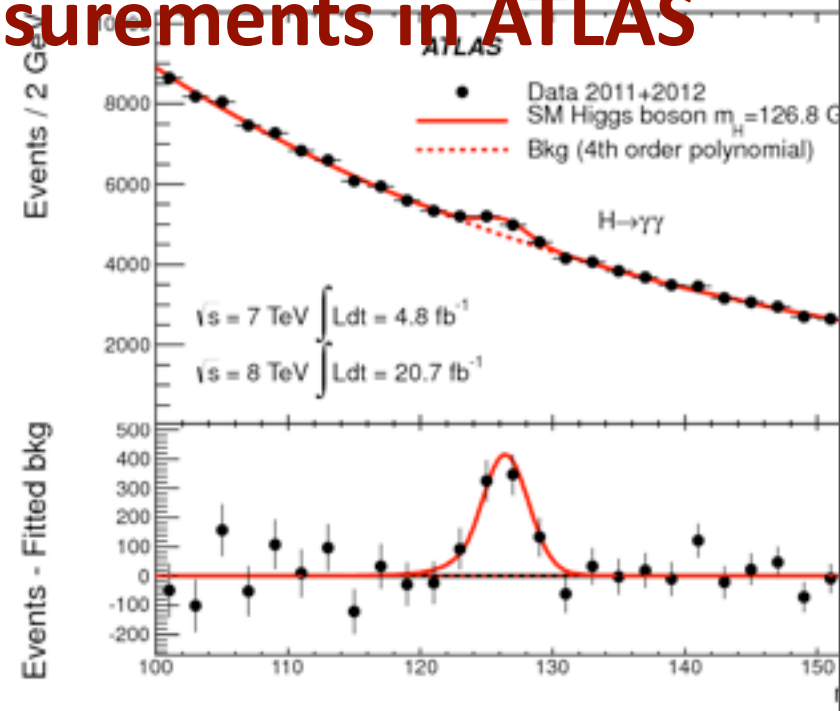

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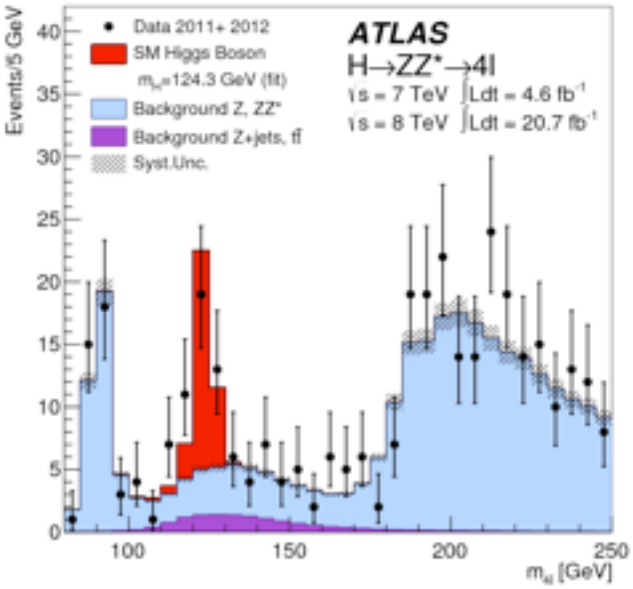

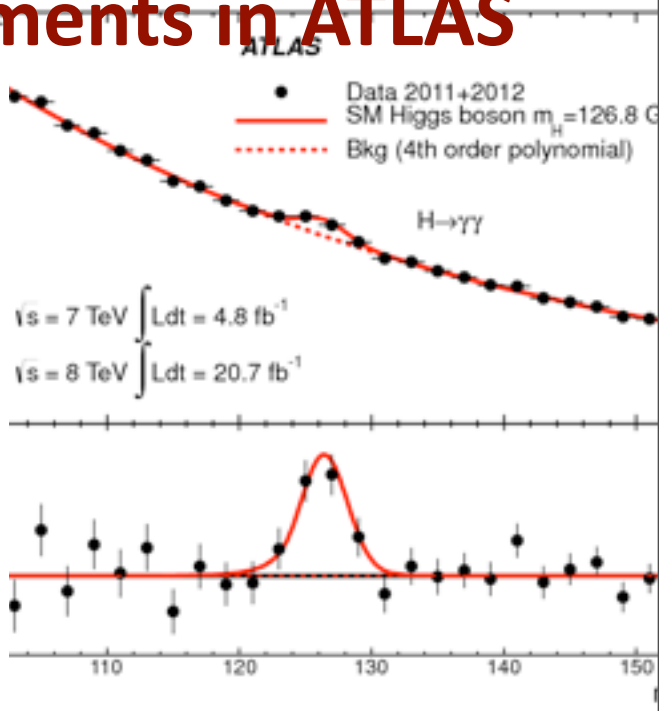

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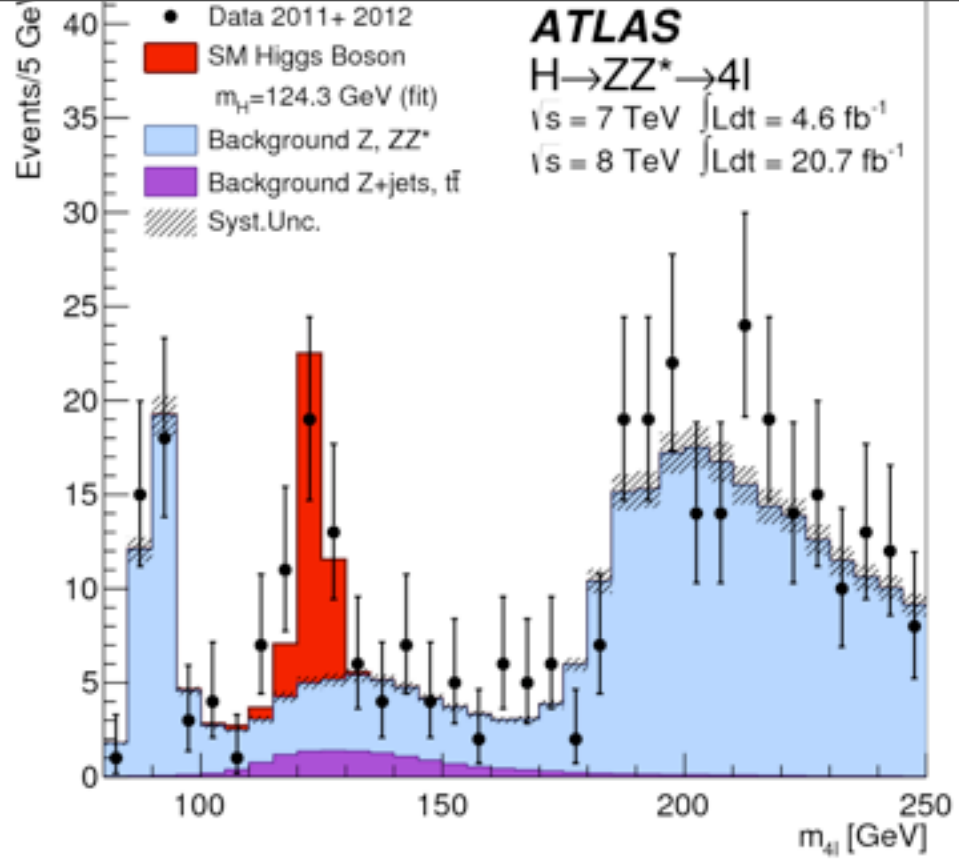

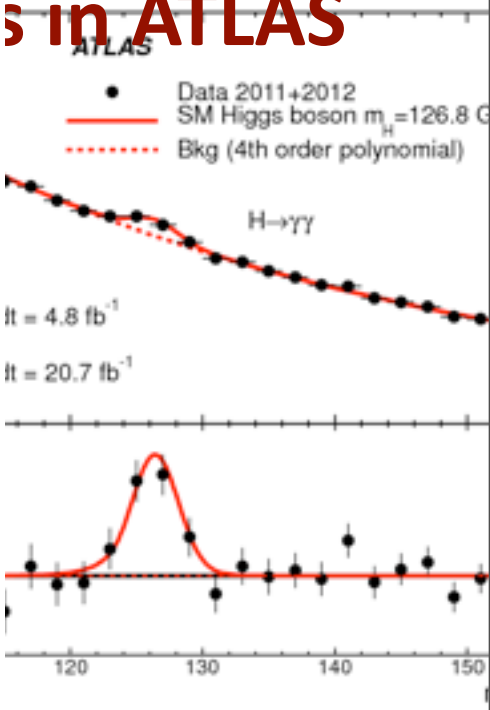

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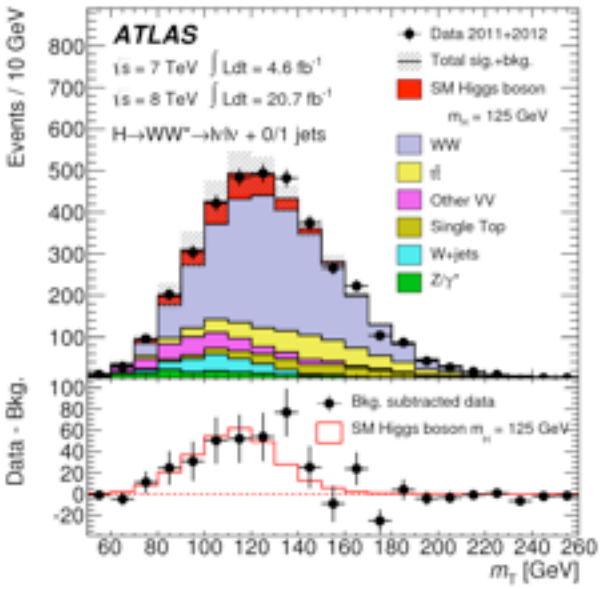

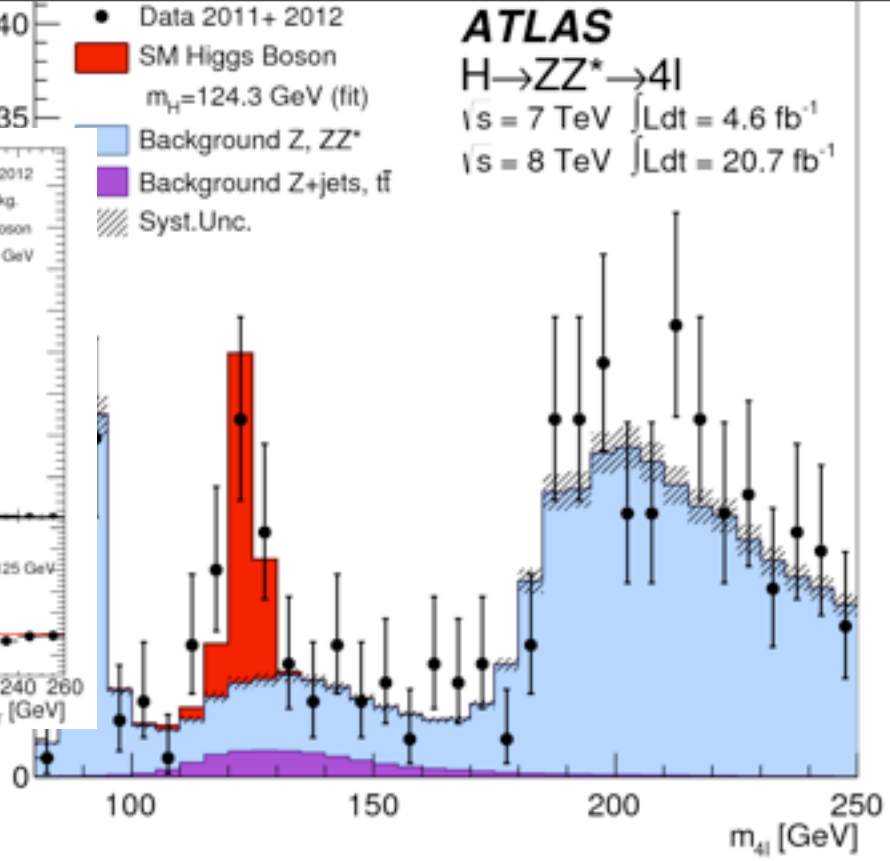

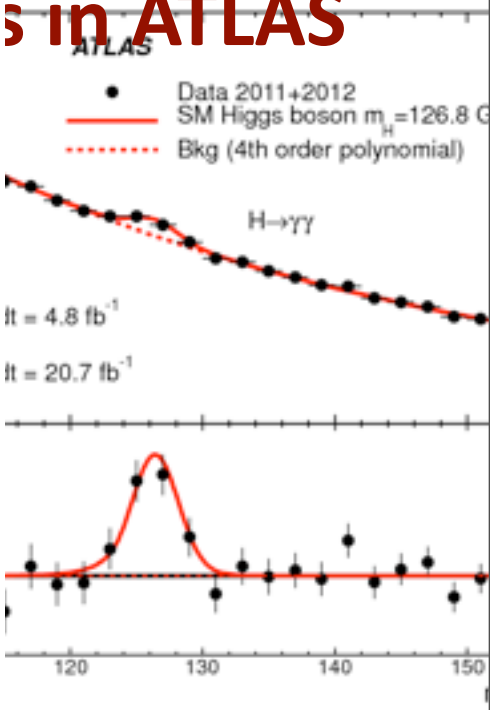

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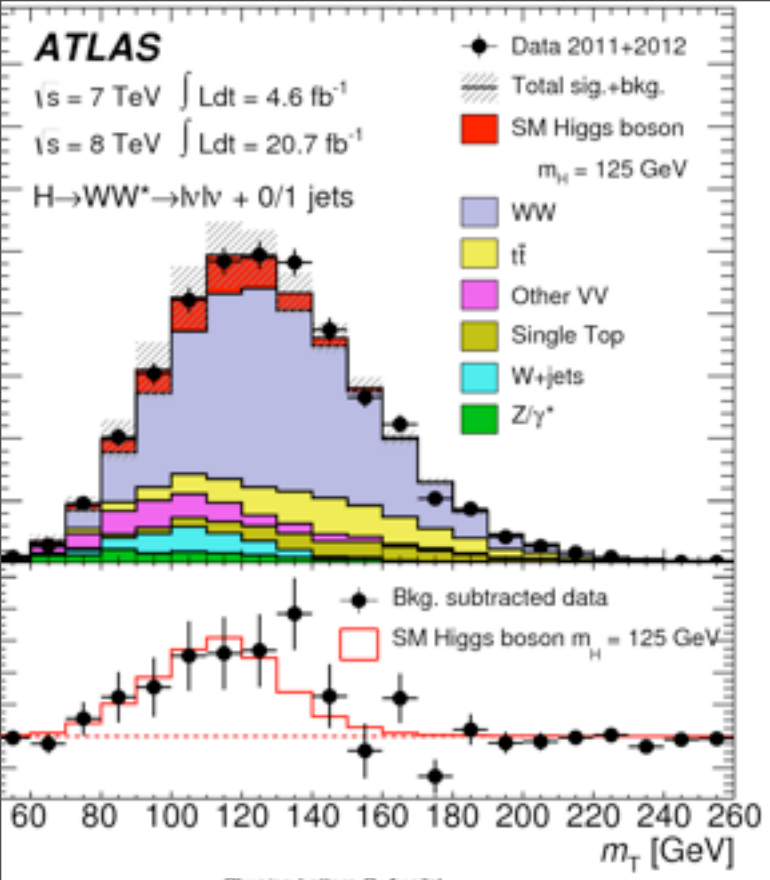

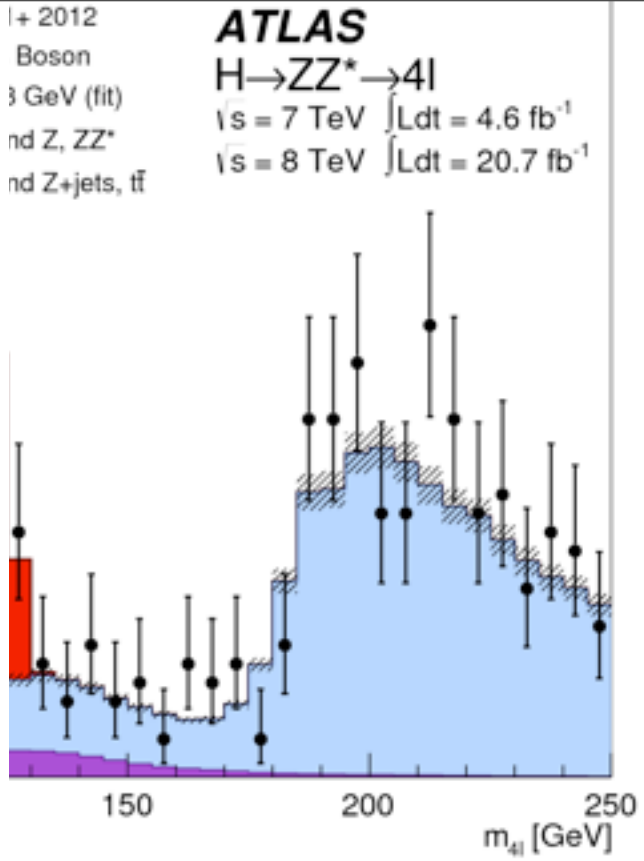

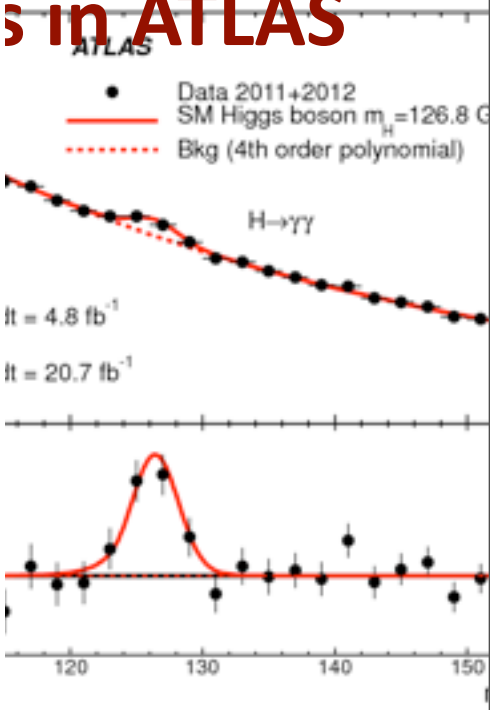

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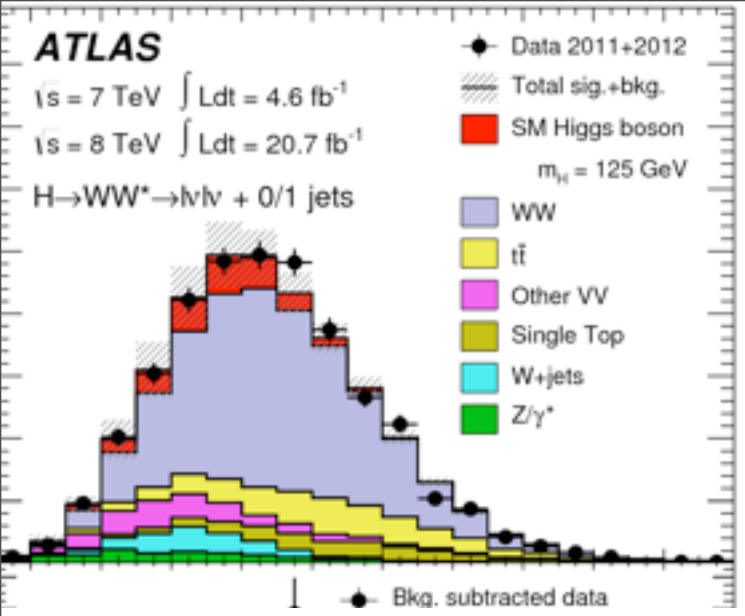

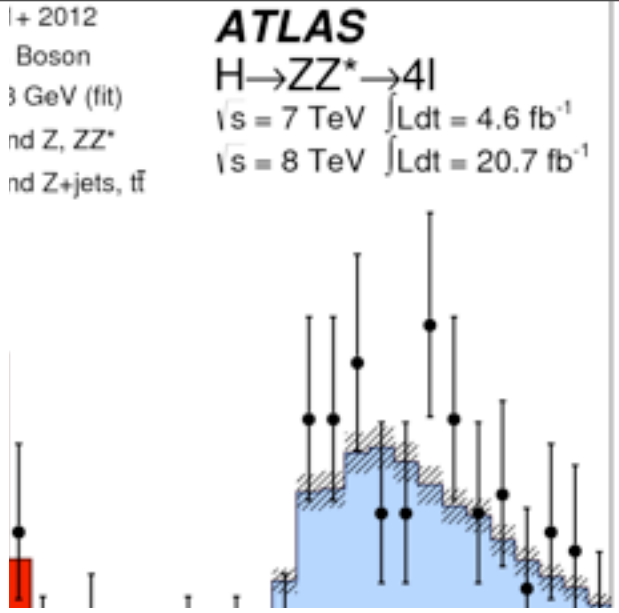

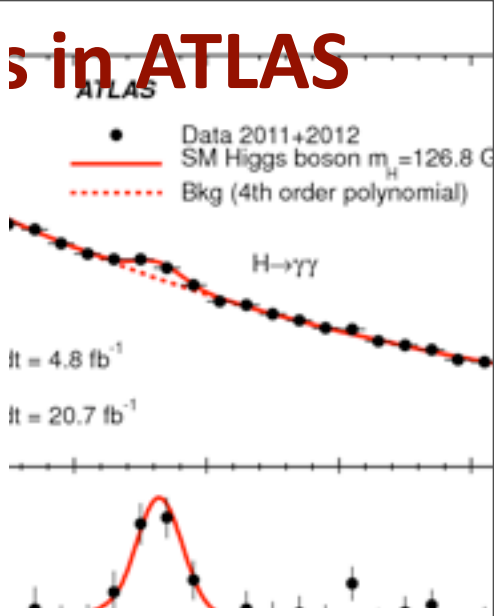

Published in August 2013

m_H = 125.49 ± 0.24 ± 0.54 GeV

Some tension between the H to γγ and H to 4l channels:

$$\Delta m_H = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$

This discrepancy was at the 2.5σ level

based on the complete pp collision data sample recorded by the ATLAS experiment at the CERN Large Hadron Collider at centre-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of about 25 fb^{-1}. Evidence for Higgs boson production through vector-boson fusion is reported. Results of combined fits probing Higgs boson couplings to fermions and bosons, as well as anomalous contributions to loop-induced production and decay modes, are presented. All measurements are consistent with expectations for the Standard Model Higgs boson.

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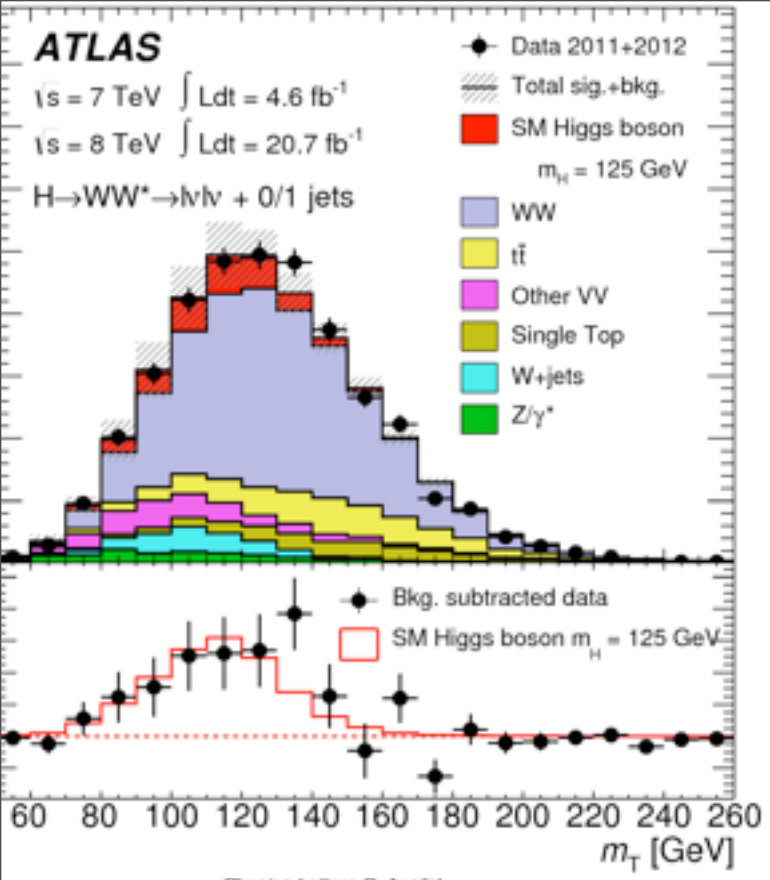

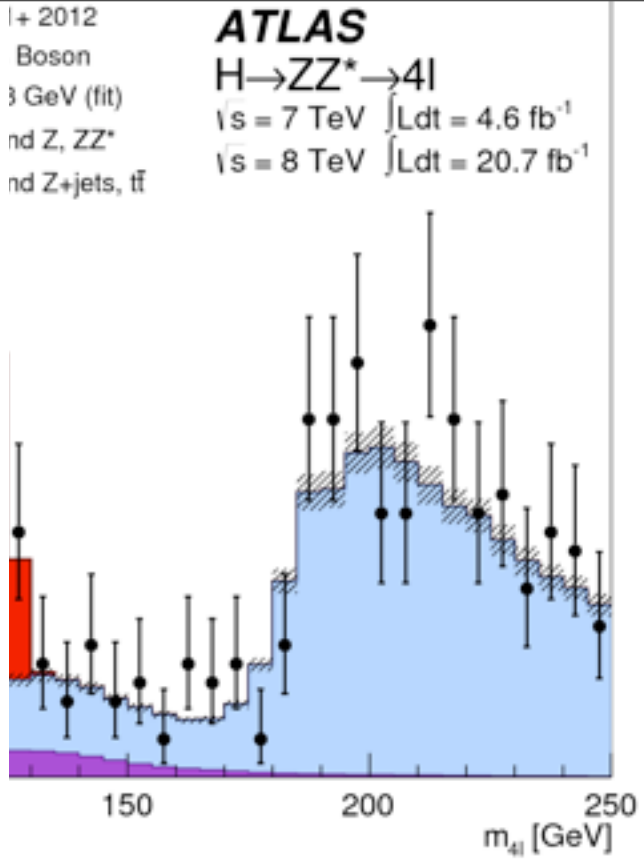

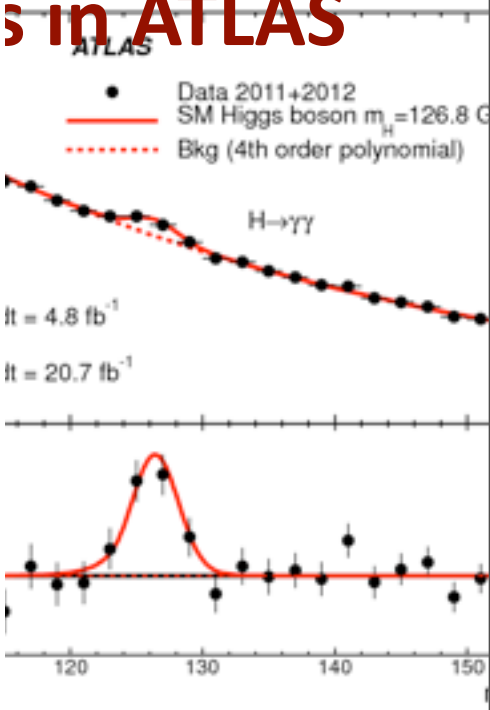

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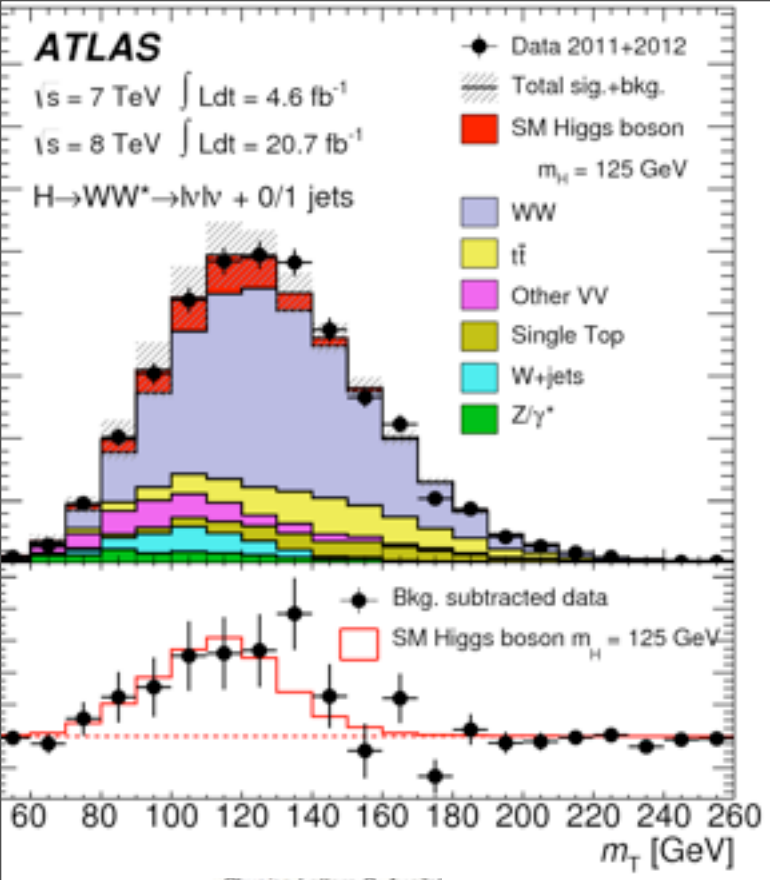

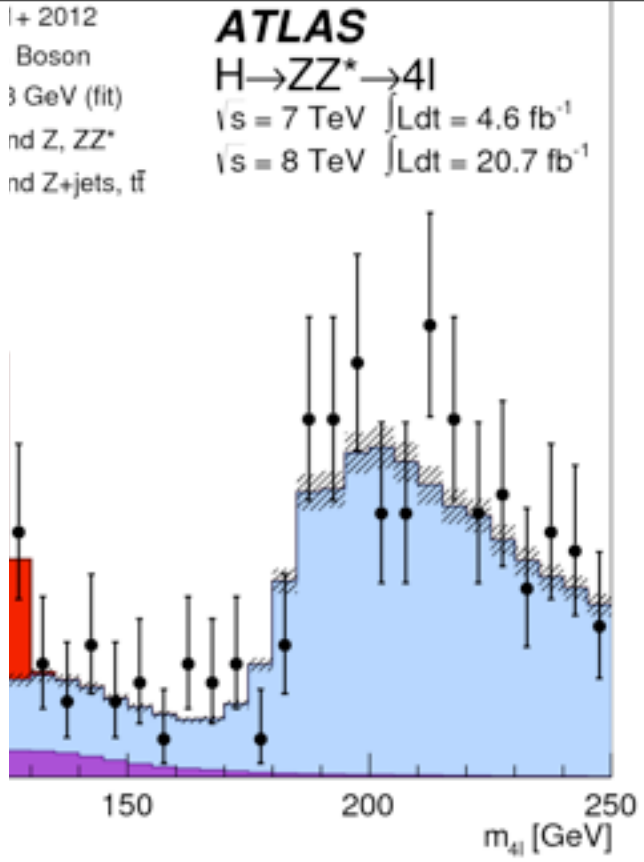

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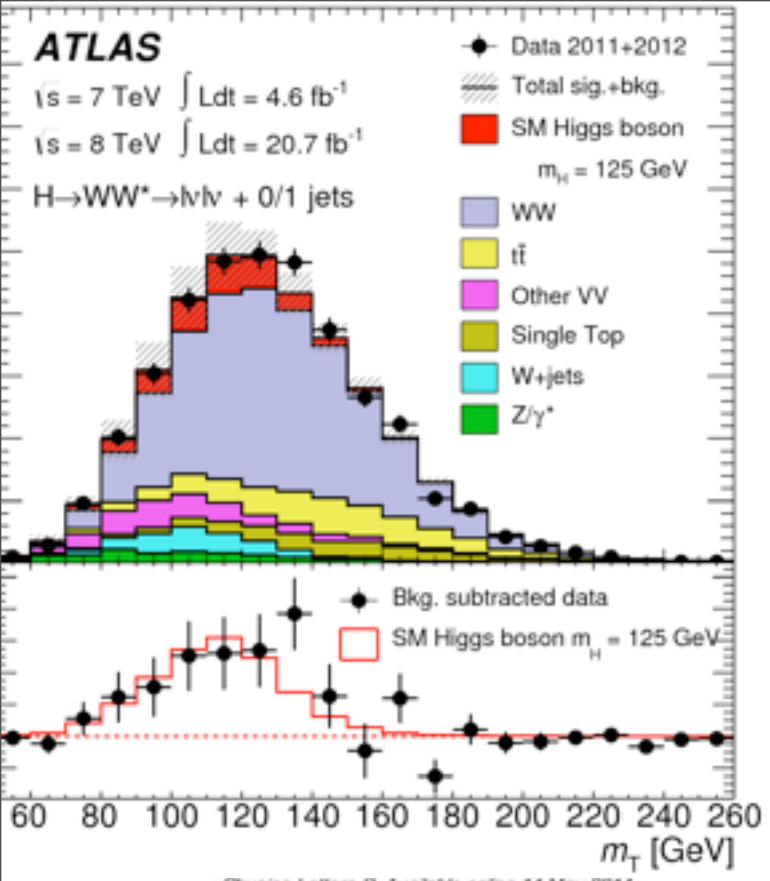

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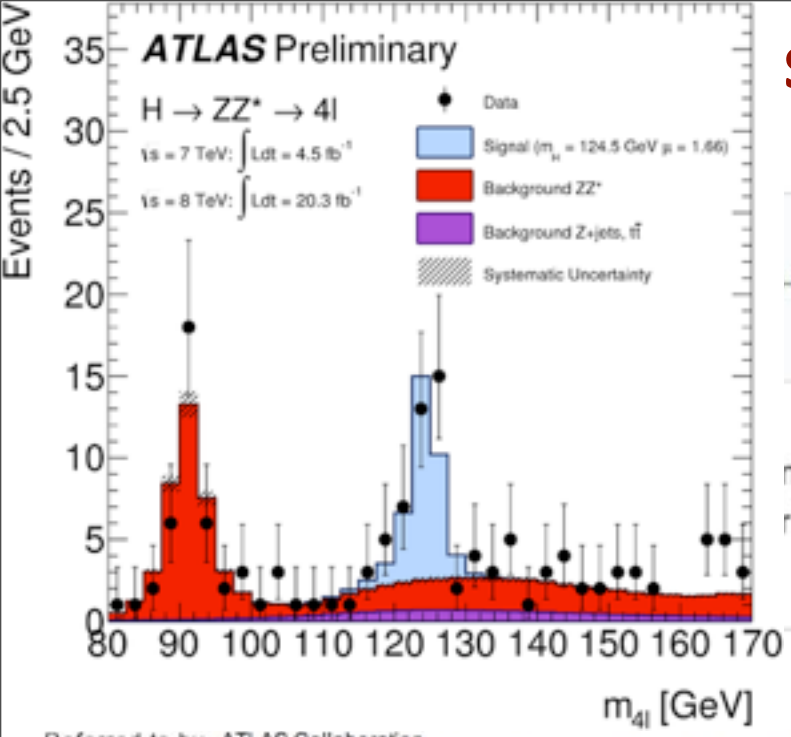

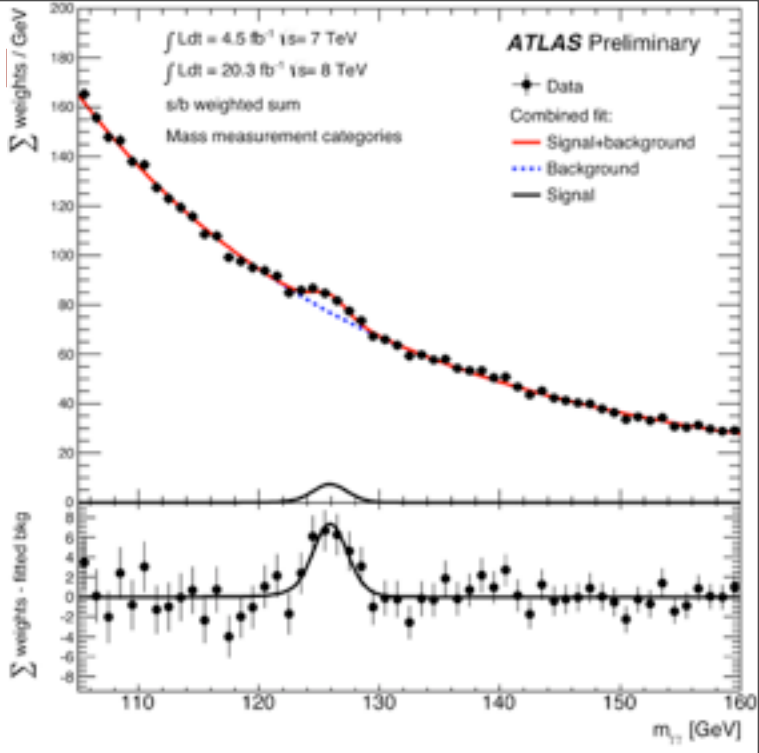

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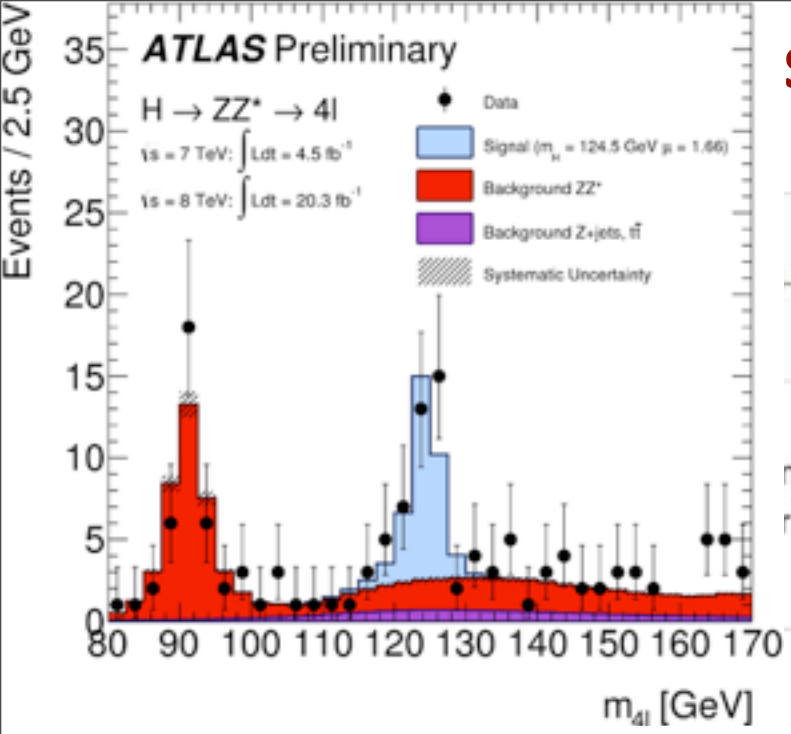

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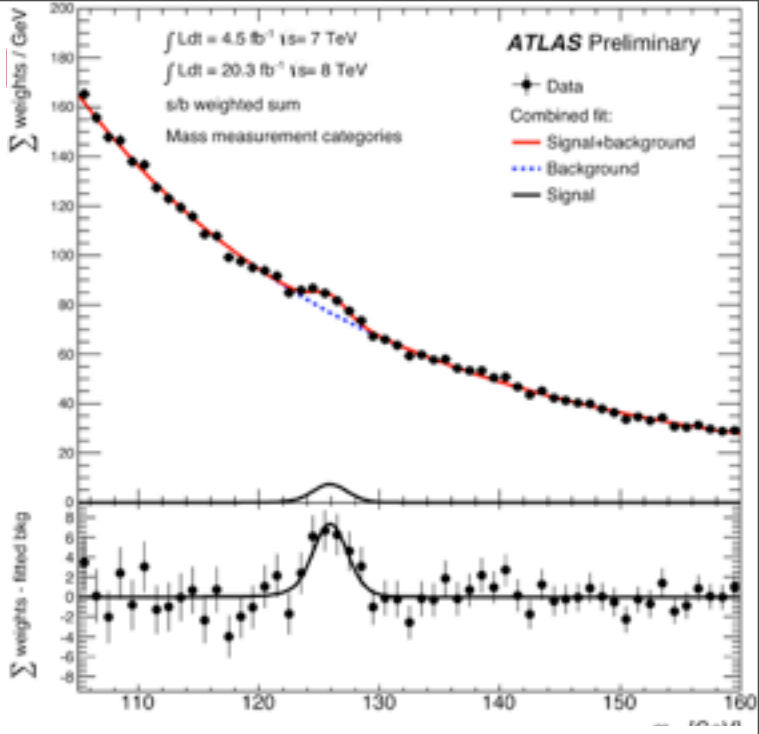


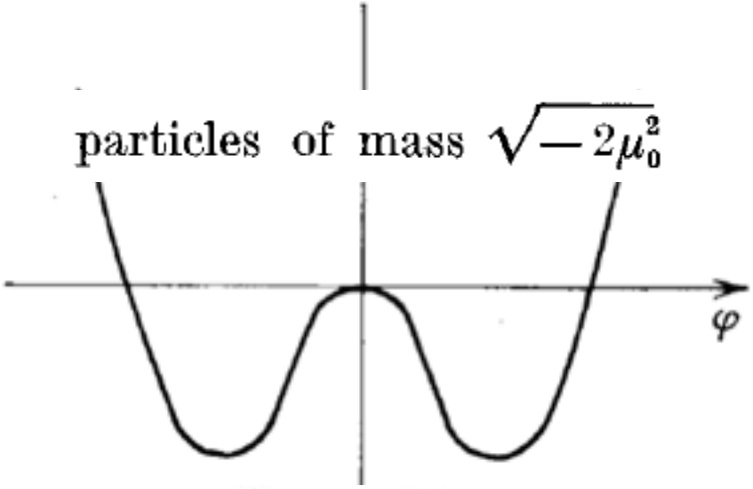
ATLAS LHCP result (to be submitted soon to PRD)

Channel	Mass measurement (GeV)
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{sys}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.04\,(\text{sys}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{sys}) = 125.36 \pm 0.41$

Systematic uncertainty reduced by a factor 3.

Nevertheless, overall tension decreased (2.0σ):

$$\Delta m_H = 1.47 \pm 0.67\,(\text{stat}) \pm 0.28\,(\text{sys})\ \text{GeV} = 1.47 \pm 0.72\ \text{GeV}$$



Courtesy of L. Fayard

$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4$$

1950 Ginzburg-Landau (Meissner-Ochsenfeld effect → London penetration length)

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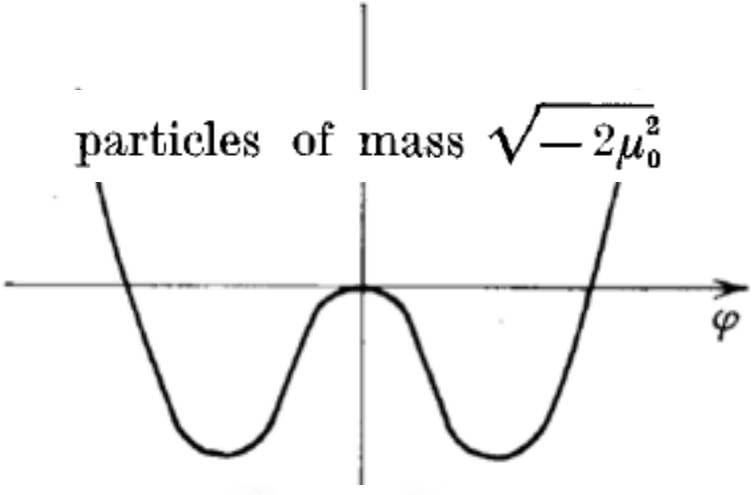

$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4$$

Courtesy of L. Fayard

1950 Ginzburg-Landau (Meissner-Ochsenfeld effect → London penetration length)
1959 Nambu
1960 Goldstone
1961 Schwinger
1962 Anderson

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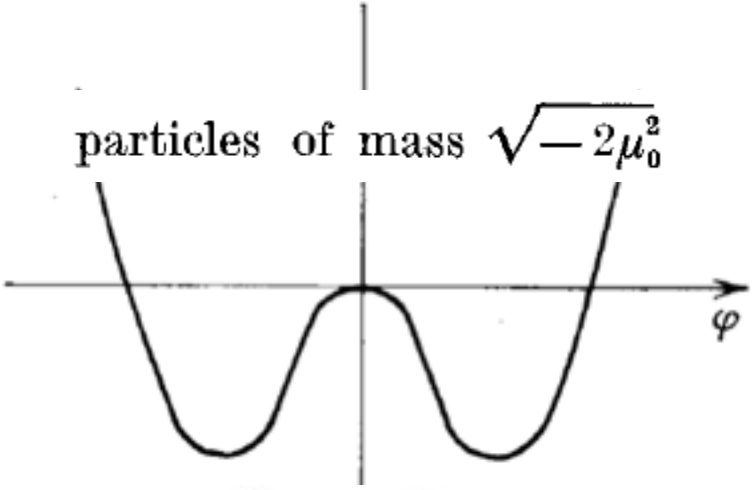

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Courtesy of L. Fayard

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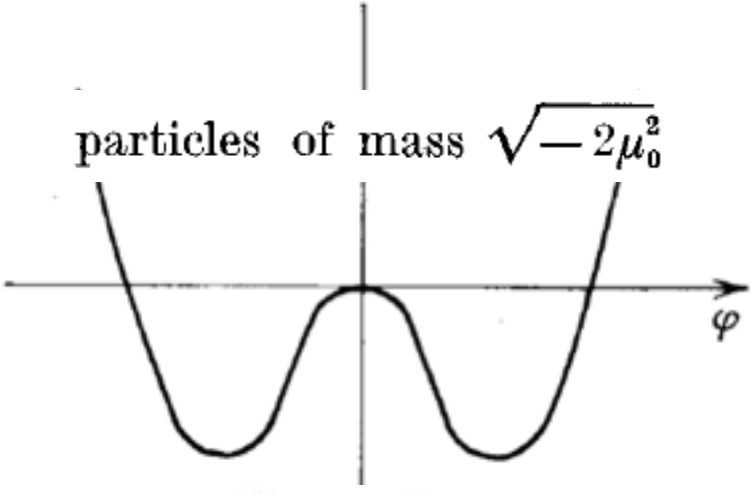

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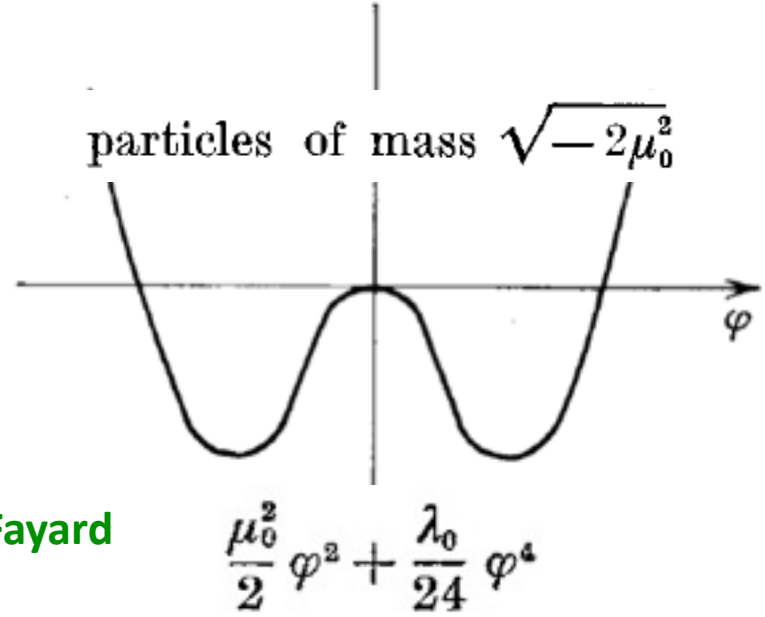

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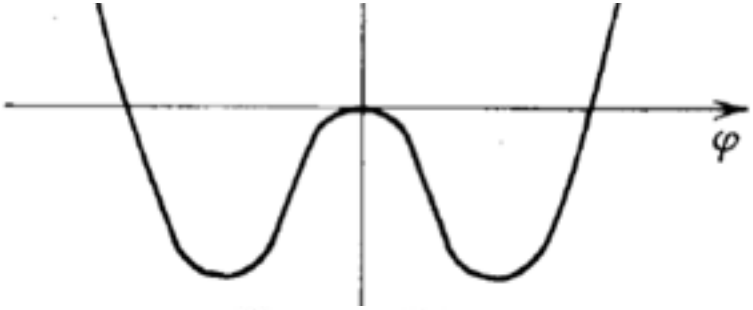

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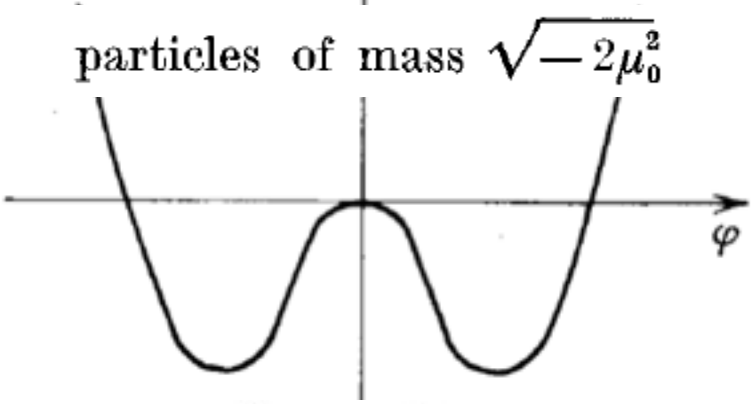

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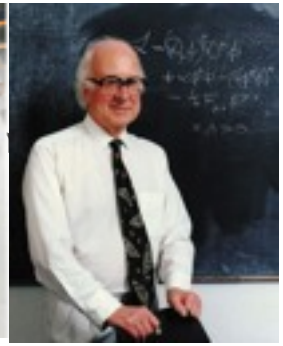

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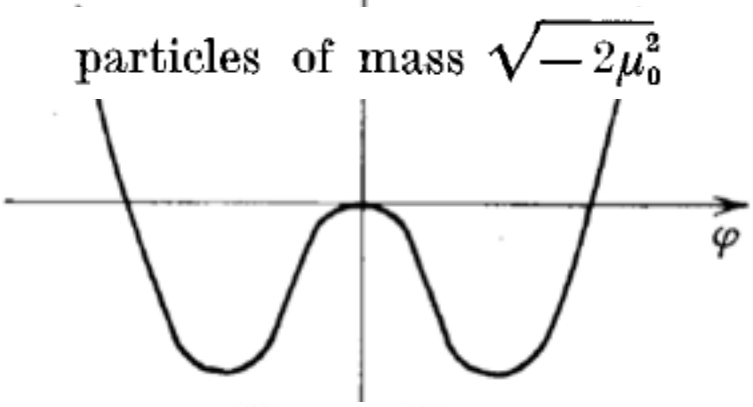

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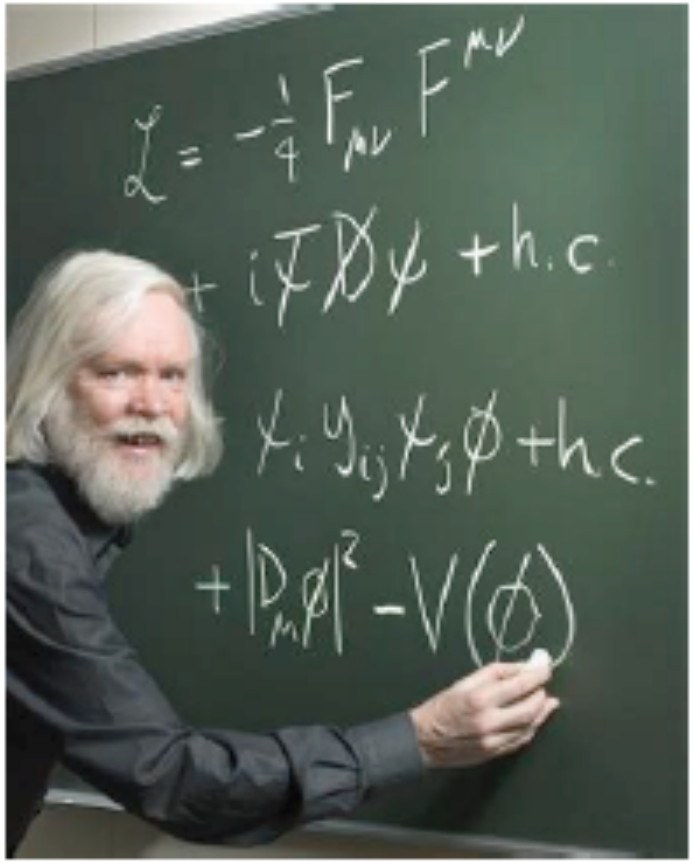

1976

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

We should perhaps finish with an apology and a caution. We apologise to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Searching for the intermediate-mass Higgs boson

John F. Gunion
Physics Department, University of California, Davis, California 95616

Pat Kalyniak
Physics Department, Carleton University, Ottawa, Ontario, Canada K1S 5B6

M. Soldate
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Peter Galison
Physics Department, Stanford University, Stanford, California 94305
(Received 30 September 1985)

We study the feasibility of detecting a neutral Higgs boson H^0, with mass between $2m_t \approx 80$ GeV (by assumption) and $2m_W$ at an e^+e^- machine or the Superconducting Super Collider (SSC). Backgrounds to the production at an e^+e^- machine of H^0 in association with a Z are calculated with particular emphasis on the case when $m_H \approx m_z$. We present a detailed survey of the signals for and backgrounds to the inclusive or associated production at the SSC of H^0 followed by the decay of H^0 into one of the available channels. There is no signature which is established to be identifiable at the SSC. Only a few signatures remain to be studied, and the further calculations of most immediate interest are pointed out.

SEARCH TECHNIQUES FOR CHARGED AND NEUTRAL INTERMEDIATE-MASS HIGGS BOSONS*

J.F. GUNION

Department of Physics, U.C. Davis, Davis, CA 95616, USA

G.L. KANE and Jose WUDKA

Randall Laboratory of Physics, University of Michigan, Ann Arbor, MI 48104, USA

Received 12 October 1987

J.Gunion **G.Kane**

A short historical digression

- Most of the techniques used for Higgs-boson discovery were developed in the 80s with studies for the SSC and for the ECFA La Thuile workshop (87-88): comparison of LHC (20 TeV) vs SSC (40 TeV) vs CLIC (2-3 TeV).
- Many of the theoretical tools used at the time were only LO but they were nevertheless vital for the design of ATLAS and CMS

A few examples in a nutshell are given below and in next slide

- Vector boson fusion first proposed by Cahn et al., at that time for heavy Higgs-boson searches

- Fat jets to measure substructure properties (in reality top-quark mass) first proposed by GEM collaboration in their TDR

- And also, lack of tools to model complex SM backgrounds in an accurate way. History repeats itself at different moments in time, with the requirements for the tools having progressed basically as rapidly as the tools.

- And the LEPC wanted to understand the LHC potential for MSSM Higgs discovery

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Physics Division

Submitted for publication

PRODUCTION OF VERY MASSIVE HIGGS BOSONS

R.N. Cahn and S. Dawson

December 1983

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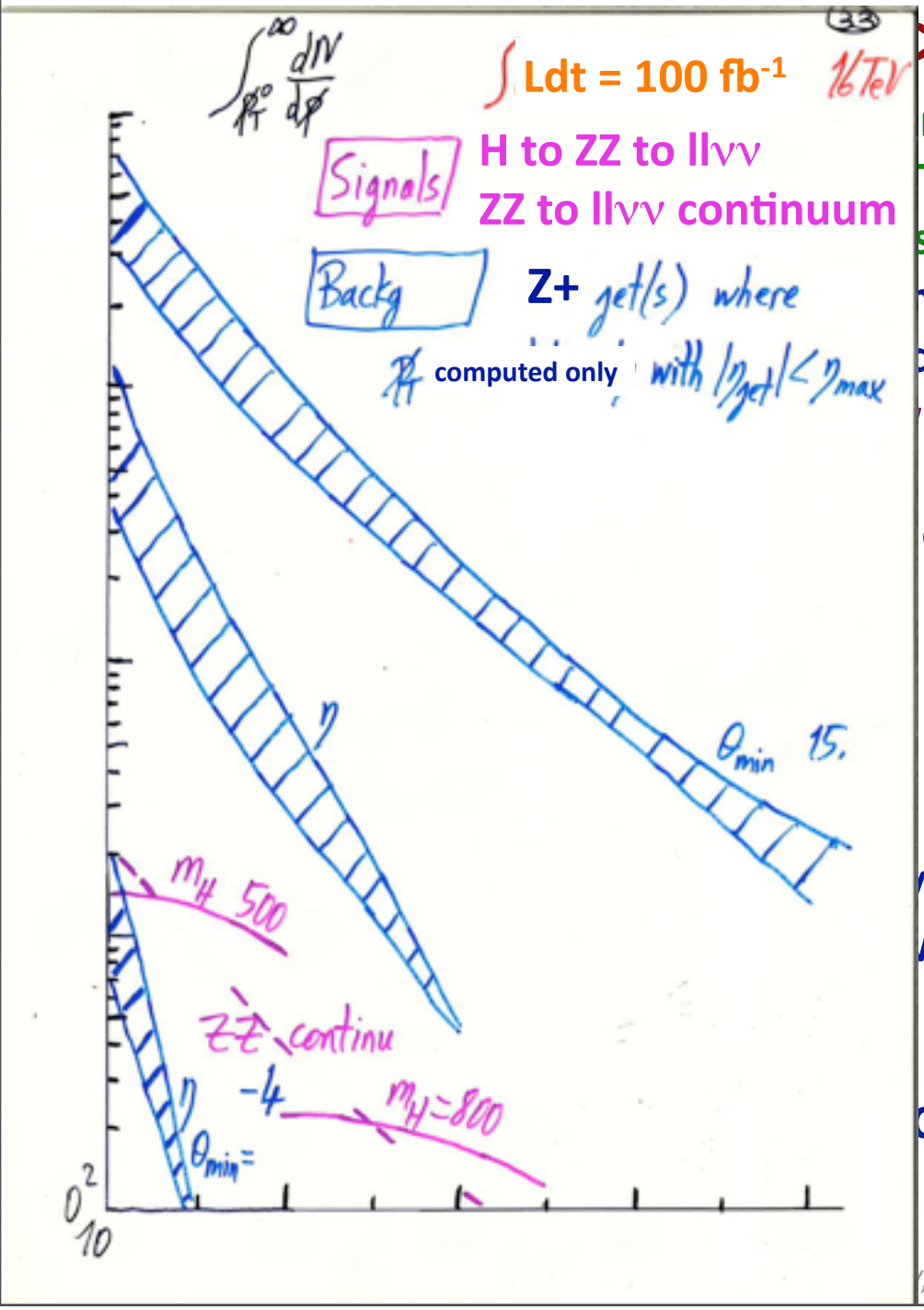

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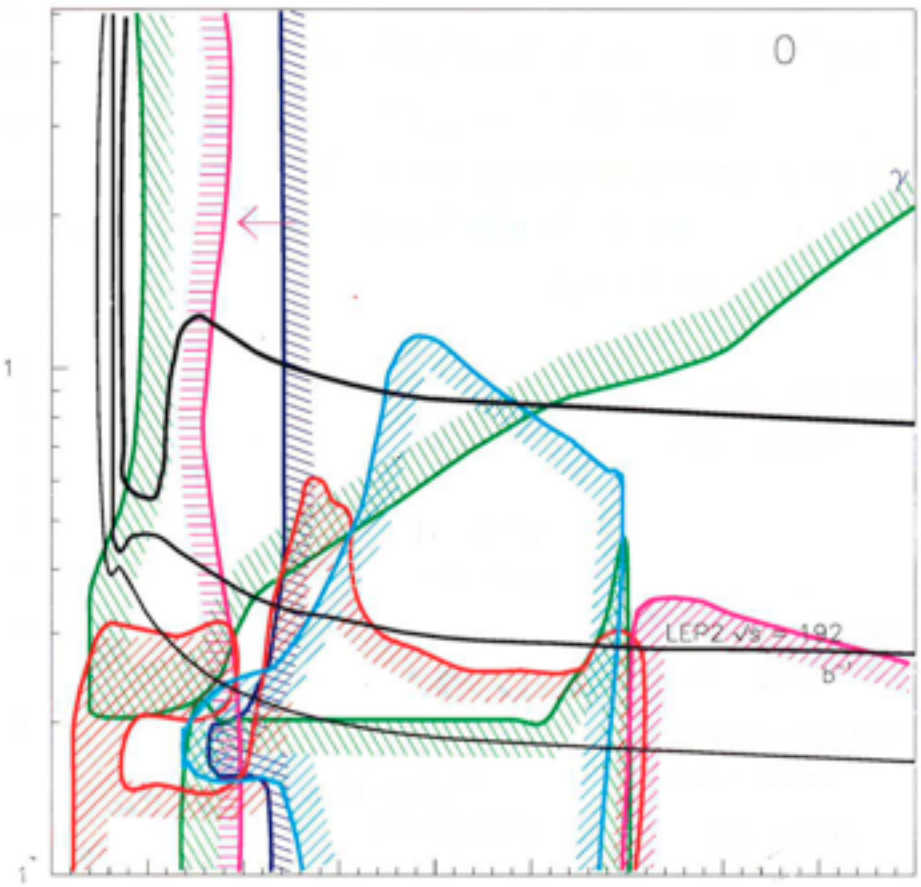
MSSM Higgs sector at LHC
(discovery curves)
for m_{top} = 175 GeV



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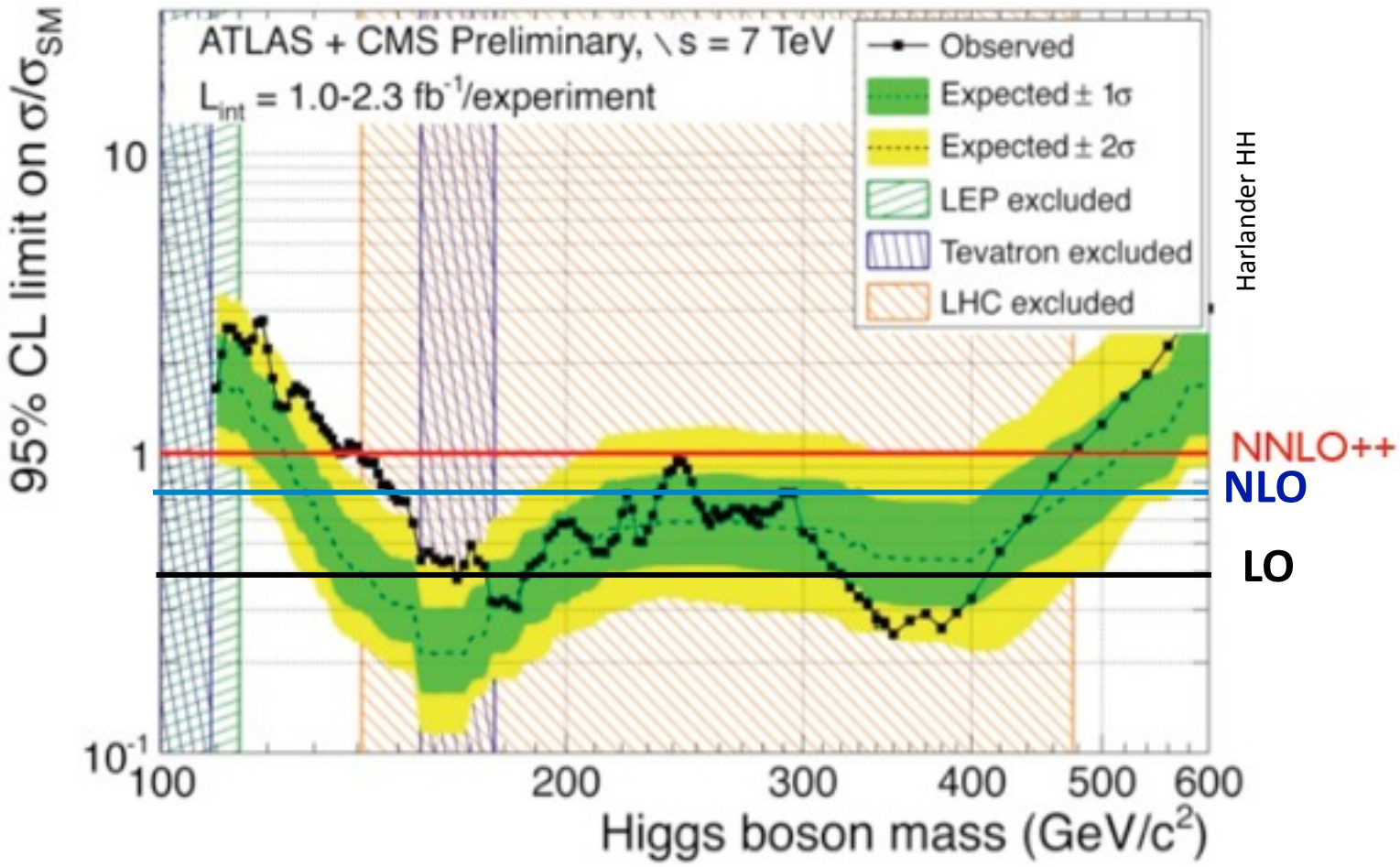
Importance of theory (QCD): not only NNLO cross-sections, but more importantly NNLO differential calculations

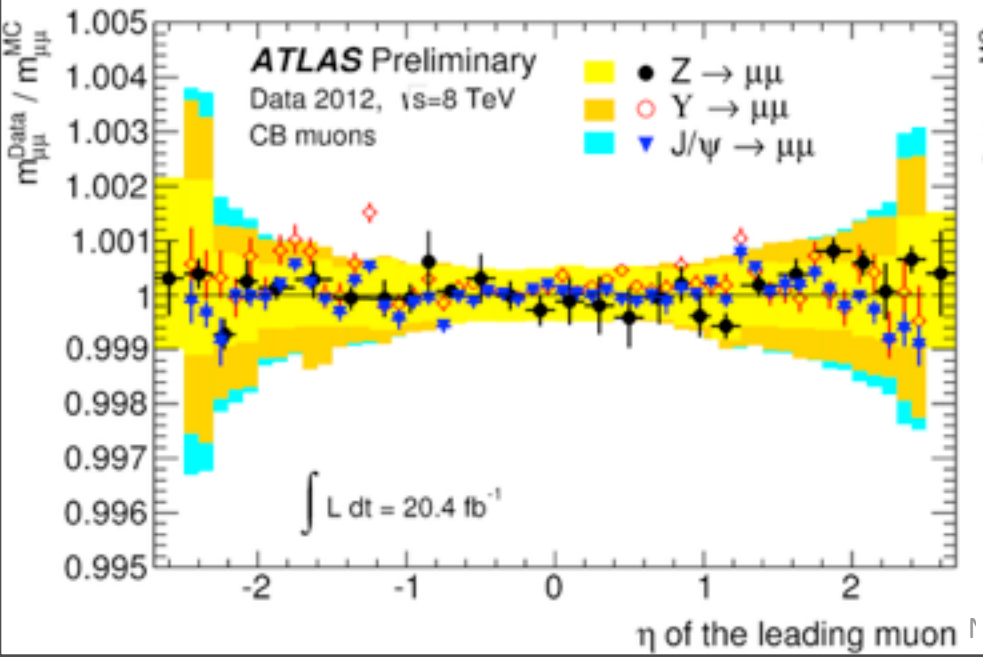


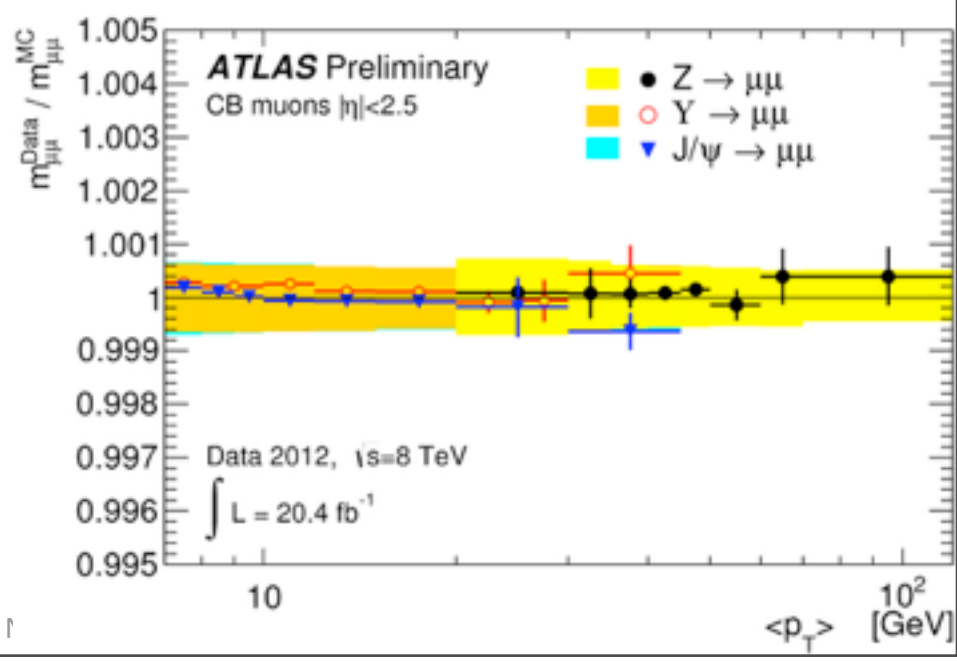
Daniel Froidevaux, CERN

Muon momentum scale: new calibration

2012 data: 9M Z to μμ, 6M J/ψ to μμ
used to set the muon momentum scale and resolution
(accounting for residual effects related to alignment, material and magnetic field).
Note that muon measurement is based on the combination of two independent measurements with inner detector/solenoid and muon spectrometer/toroids)

5M Υ to μμ plus 17M J/ψ to μμ and 9M Z to μμ
then used to verify results and systematic uncertainties assigned
Systematic uncertainty varies from 0.04% for η ~ 0 to 0.2% for |η| > 2.0
Impact on H to 4μ mass measurement is 40 MeV





Electrons and photons: efficiency measurements

2011 data: 7M W to eν, 2M Z to ee, 0.12M J/ψ to ee probes

- **Dedicated triggers for difficult probes such as W and J/ψ**
- **Overall efficiency stable versus pile-up but quite a bit lower at 7 GeV than at 40 GeV**
- **Uncertainties decrease from 5% at 7 GeV to 0.1% at 40 GeV**

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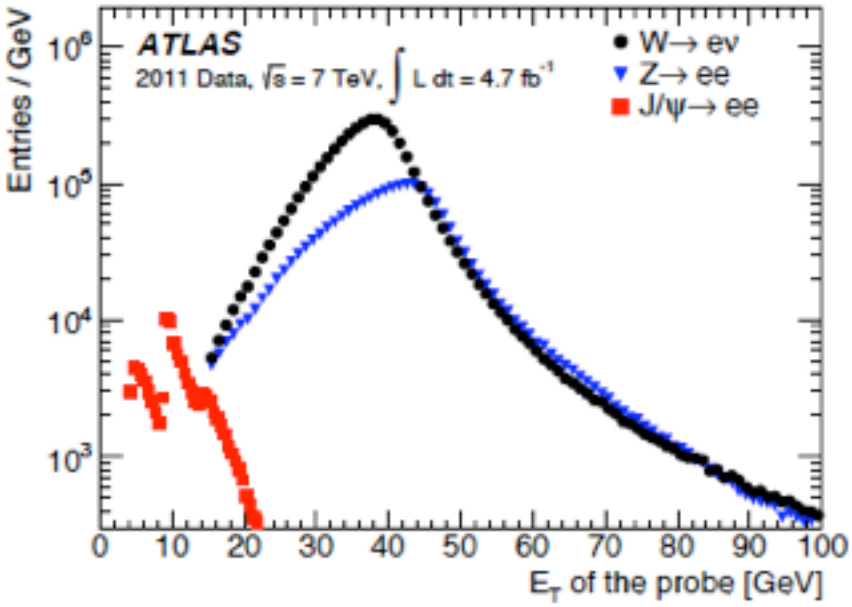

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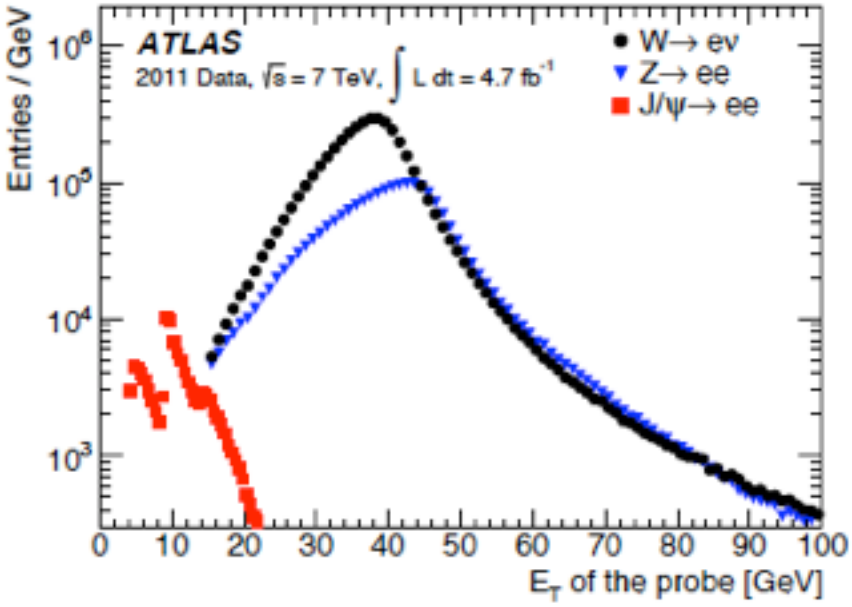
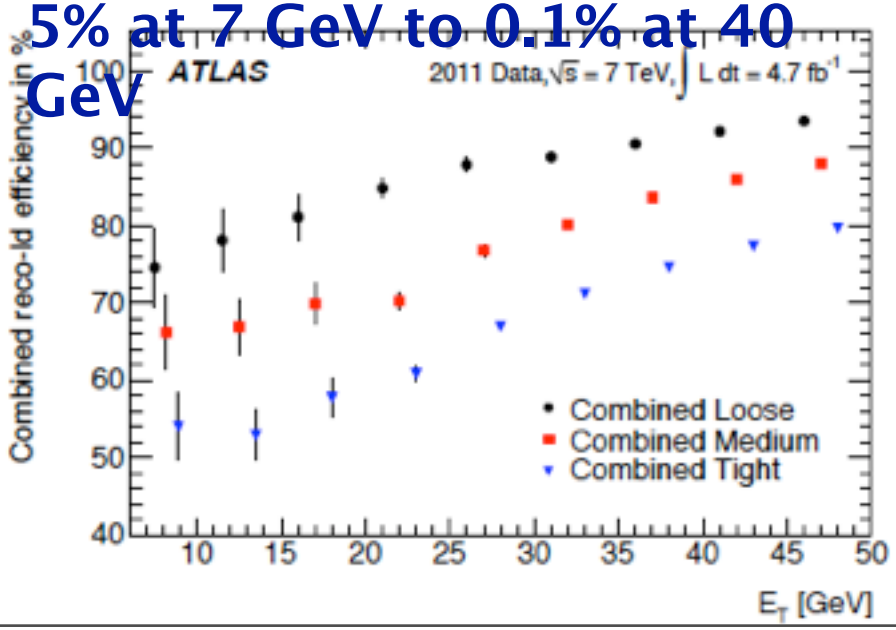
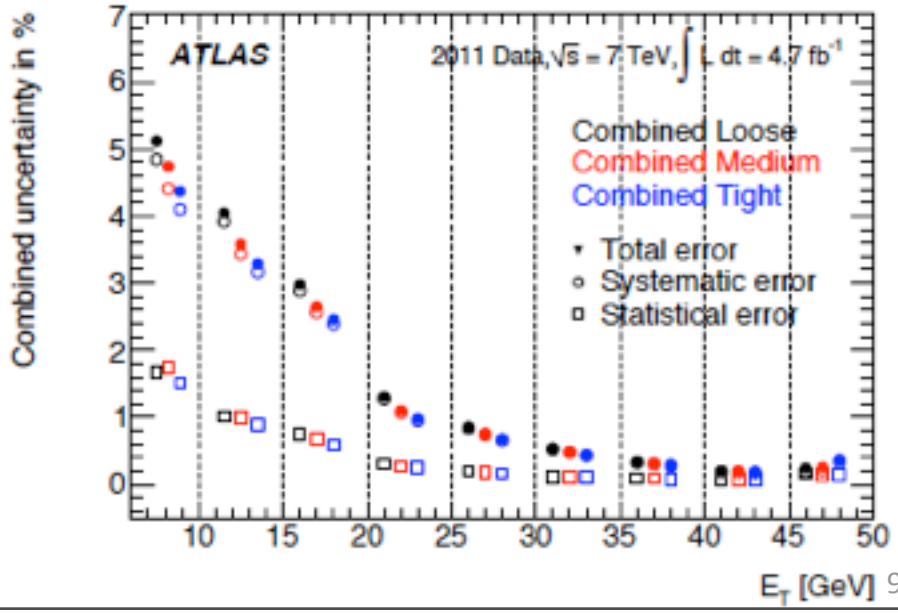
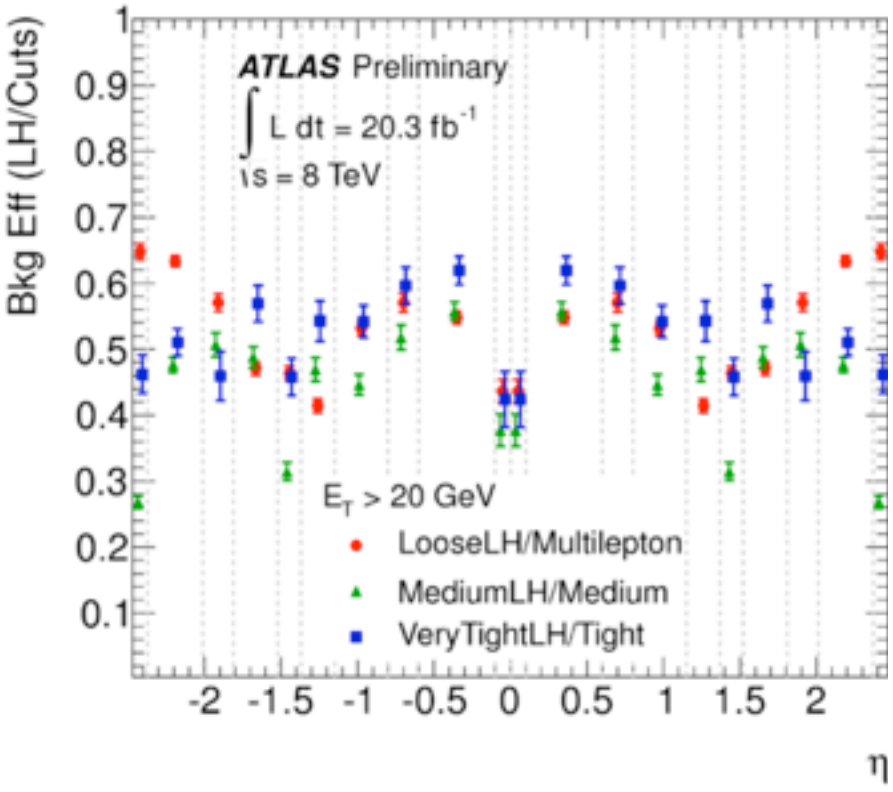


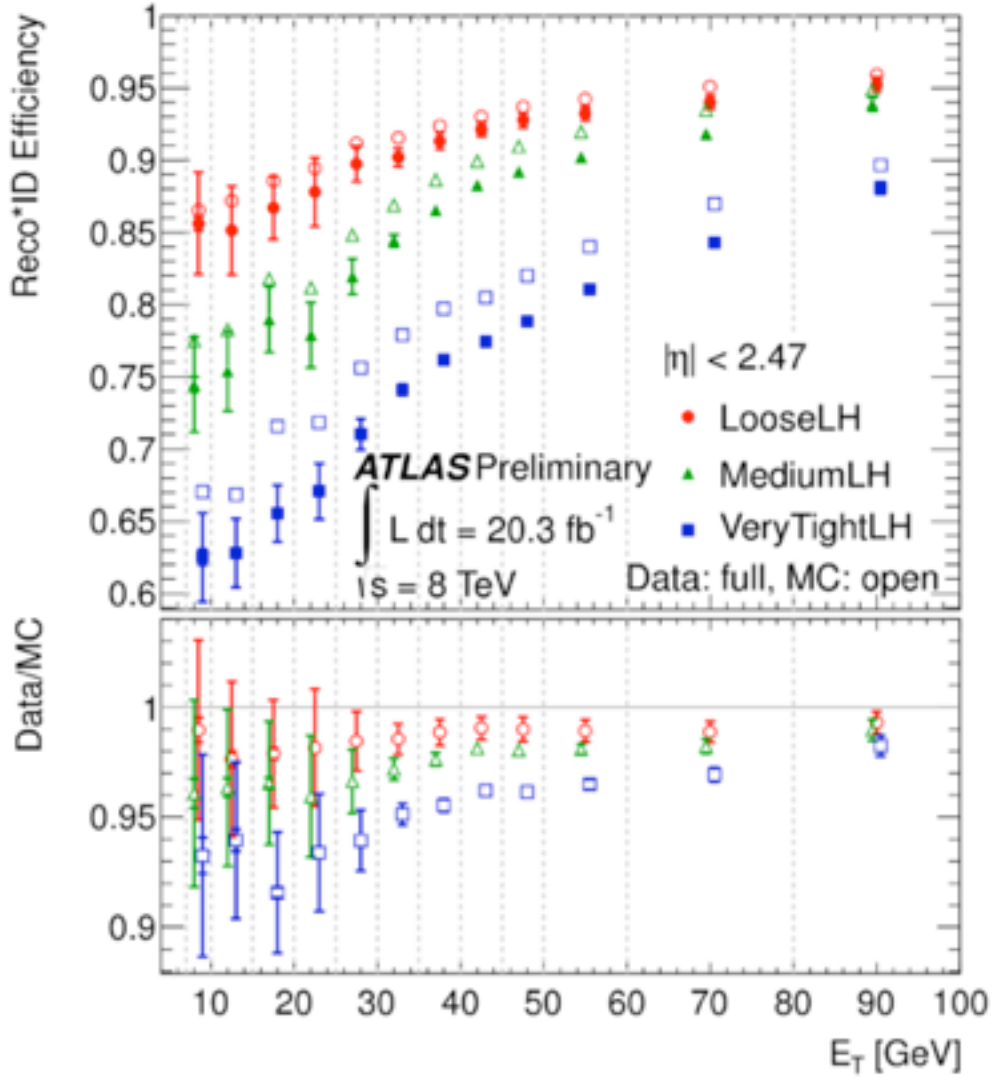




Electrons and photons: efficiency measurements

Improve electron id further using likelihood:
gain ~ factor 2 rejection for same ε_e over whole E_T range

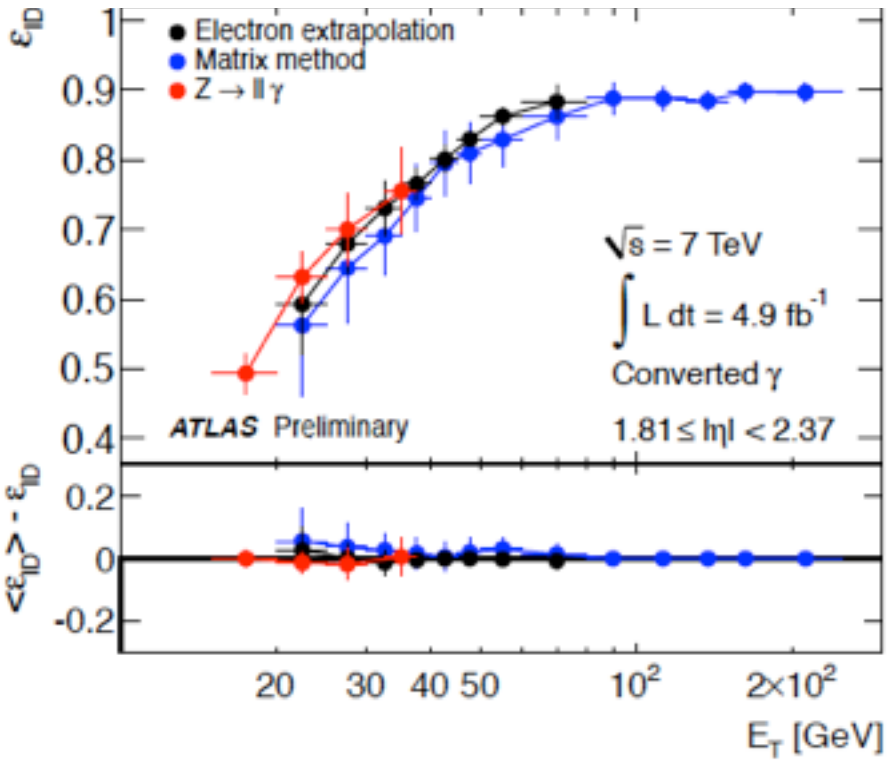


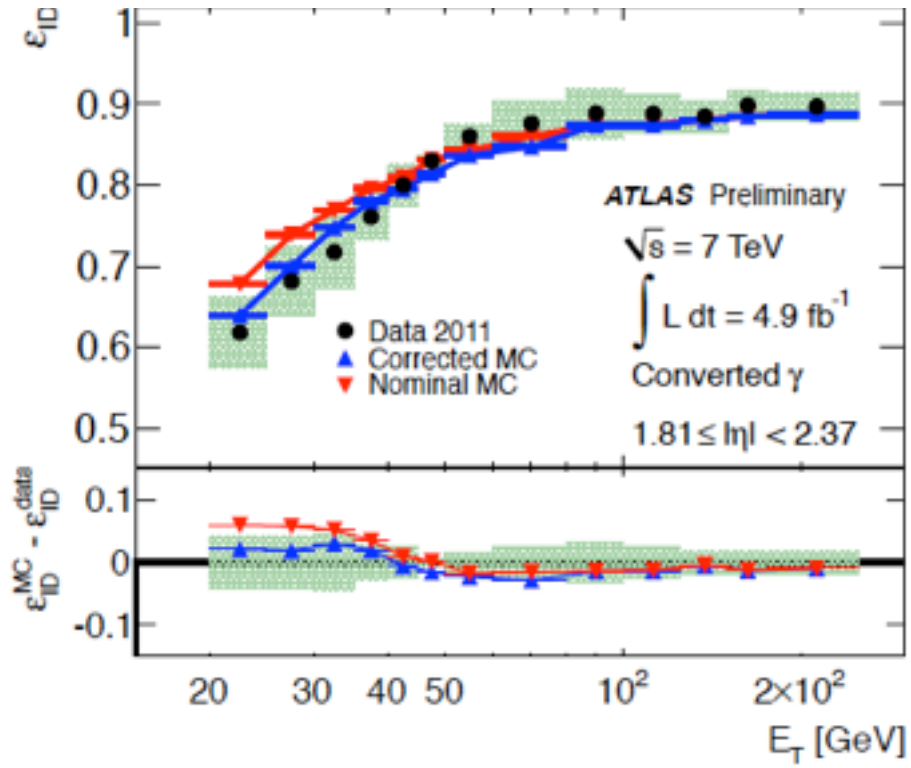


Electrons and photons: efficiency measurements

Use Z to ee, tag-and-probe with single photons, and Z to llγ decays to measure photon identification efficiencies in data and compare to MC:

2011 data shown below for converted photons in end-caps



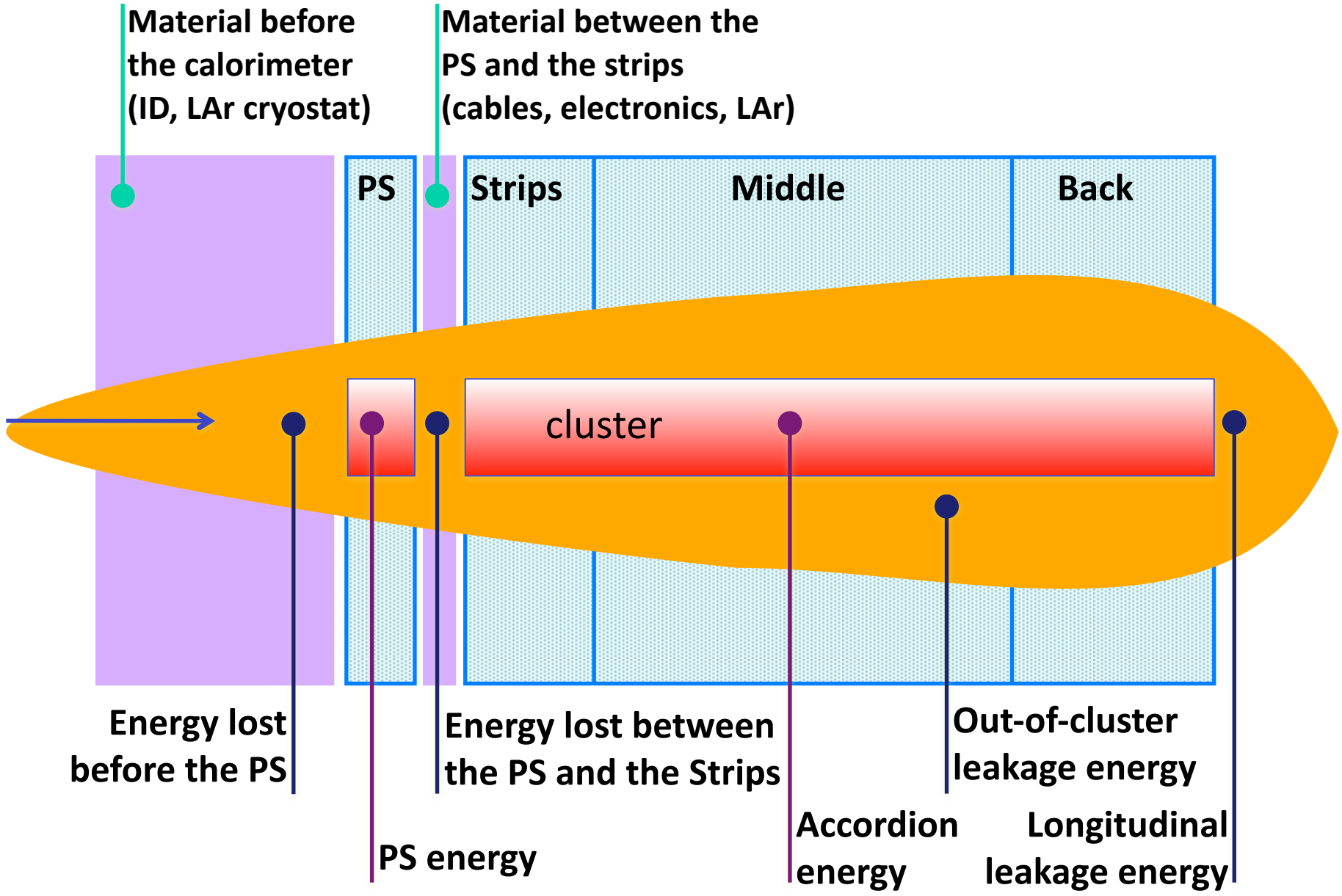


Including 2012 data,

the overall systematic on $\varepsilon_{\gamma\gamma}$ (including identification and isolation) for a pair of photons from H to $\gamma\gamma$ decay has decreased

from ~ 10.8% in summer 2012 to ~ 2.6% in summer 2013 and to ~ 1.5% now

New geometry description and new calibration



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- EM response is extremely stable as a function of time and of pileup (rms < 0.05%)
- ATLAS EMC response is on average insensitive to out-of-time pileup
- Local fluctuations are very well described by MC!

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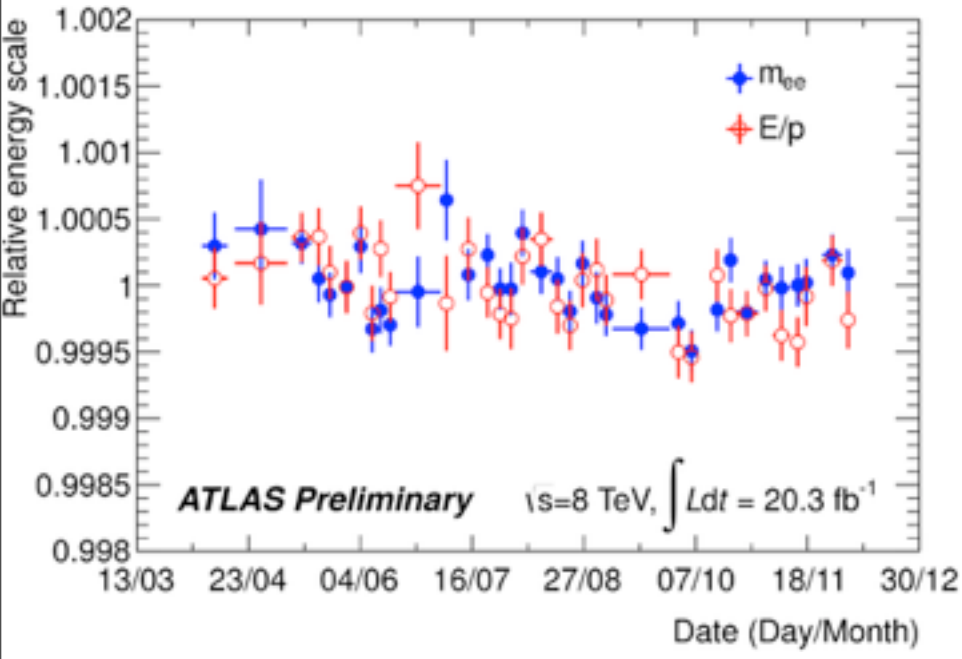

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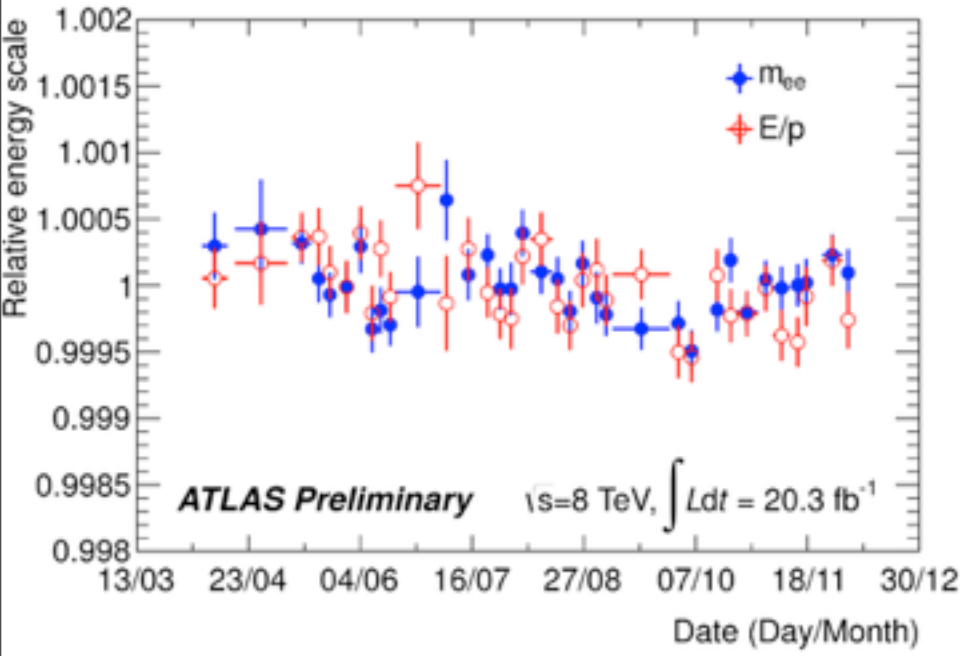

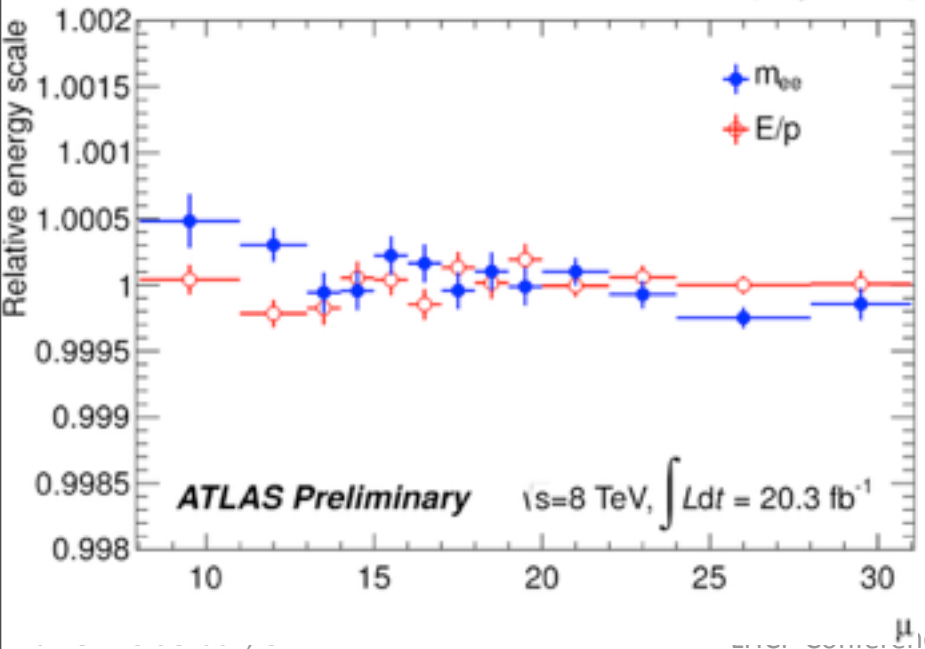

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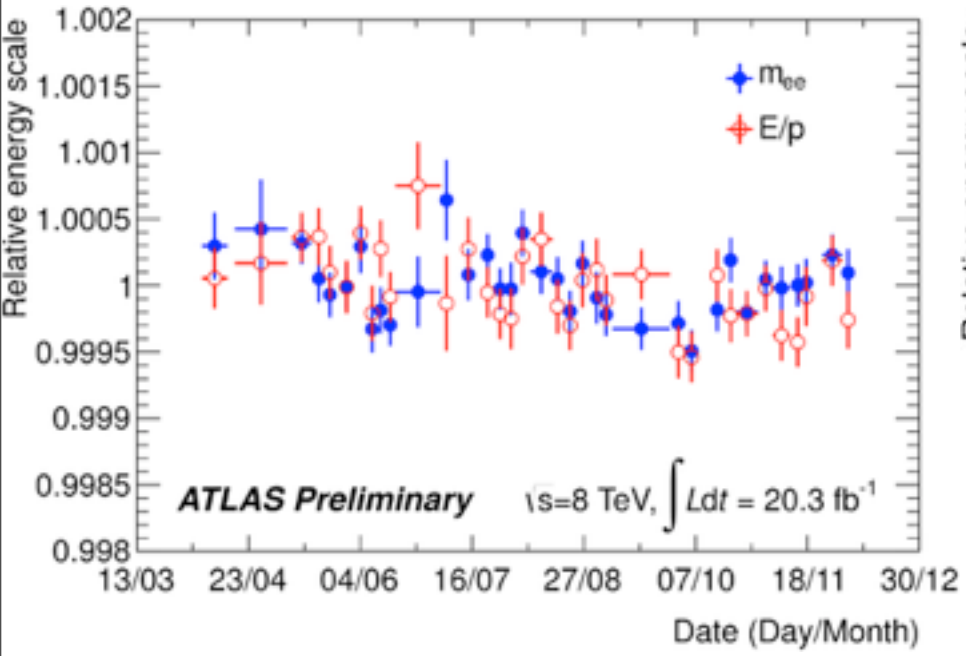

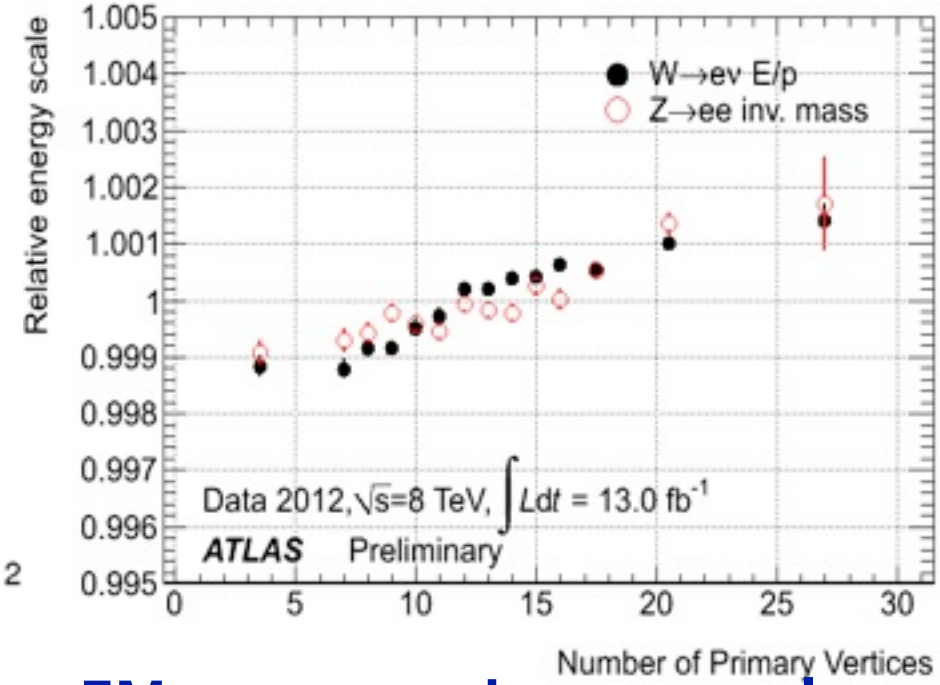

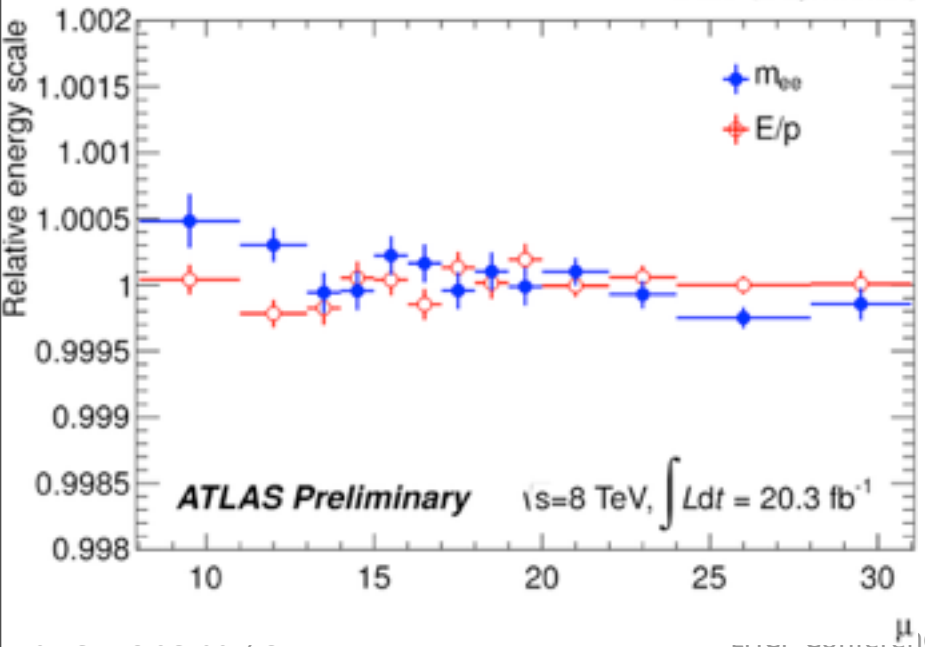

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6.6M Z to ee (plus 8M Z to $\mu\mu$)

- Calibrate calorimeter individual layers with muons, electrons, unconverted photons
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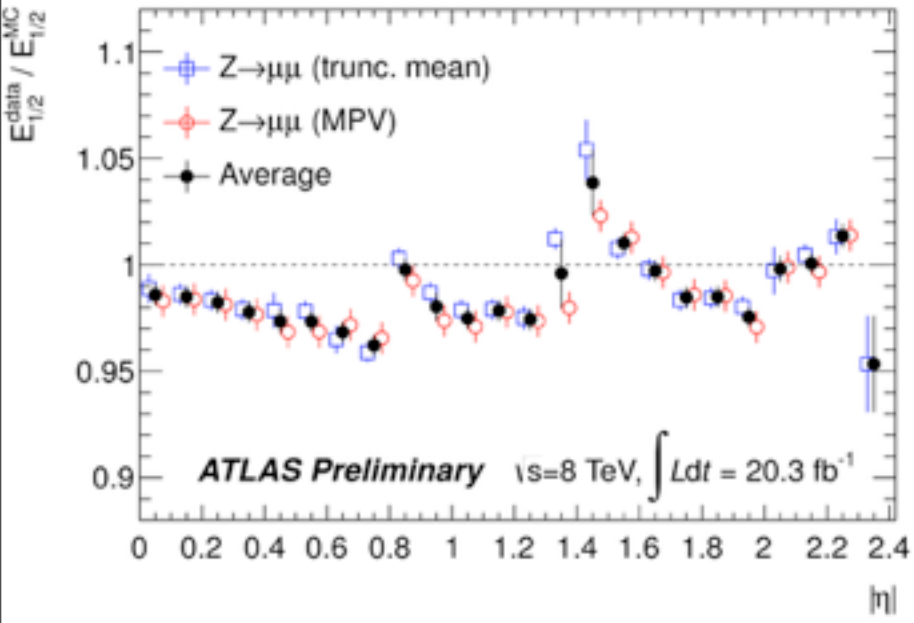

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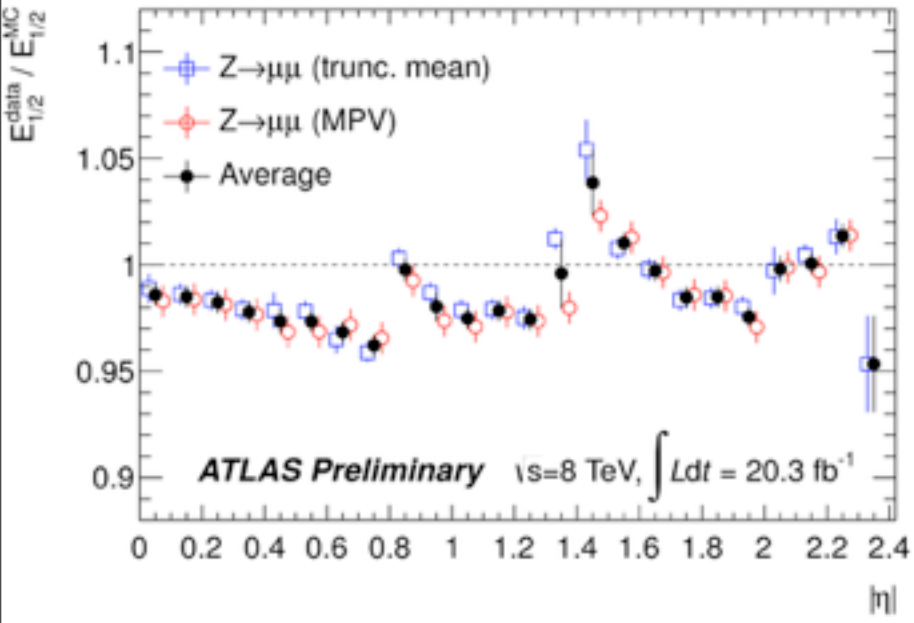

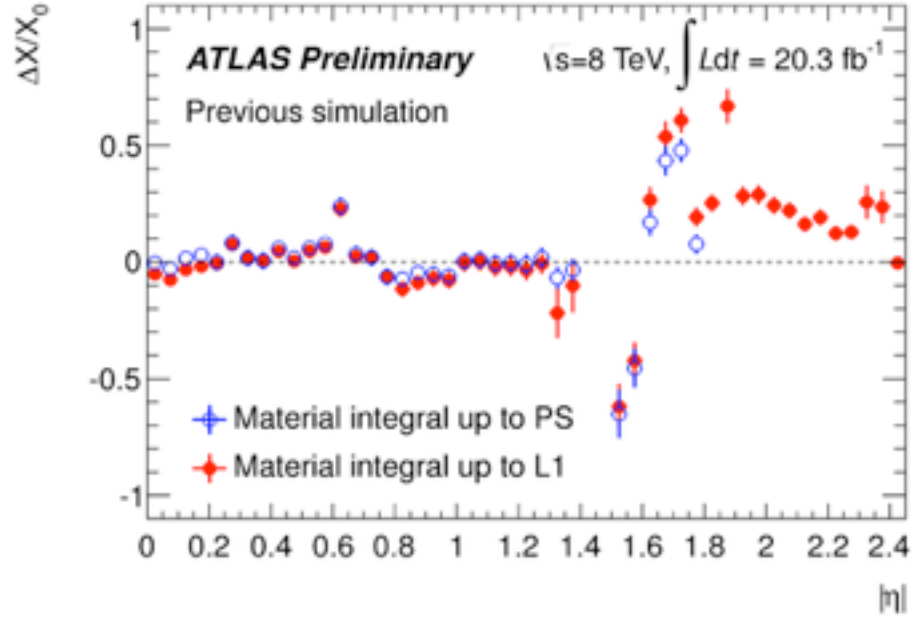

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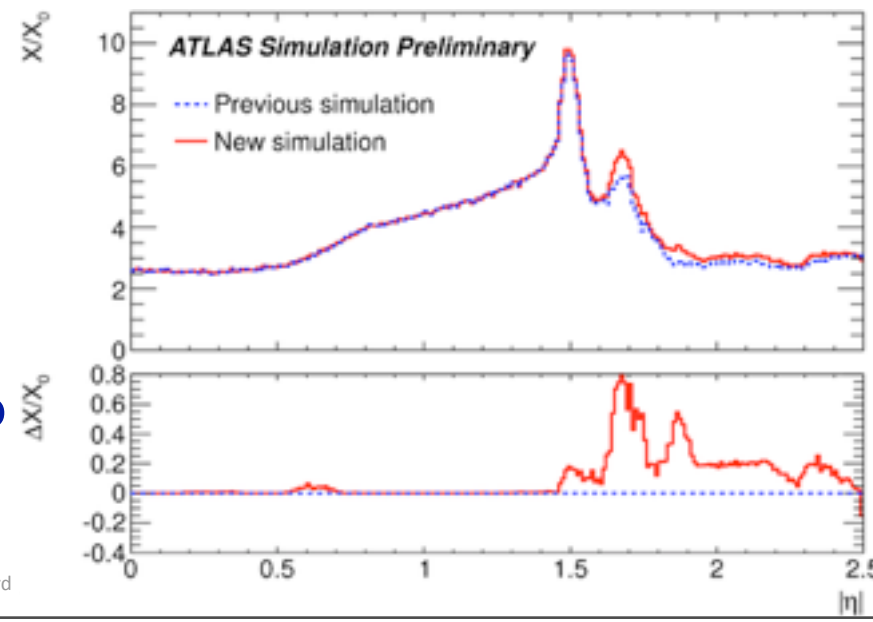

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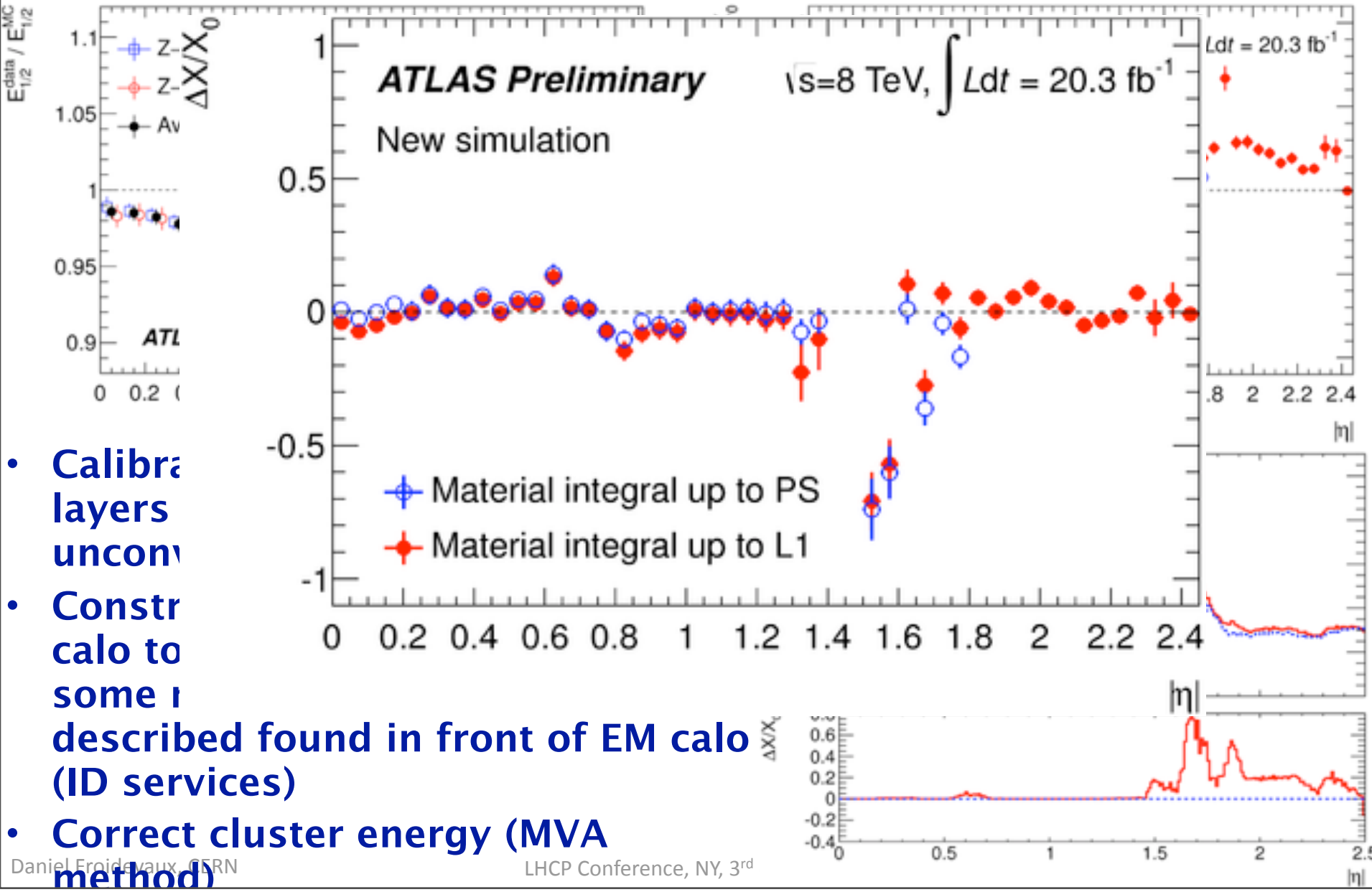

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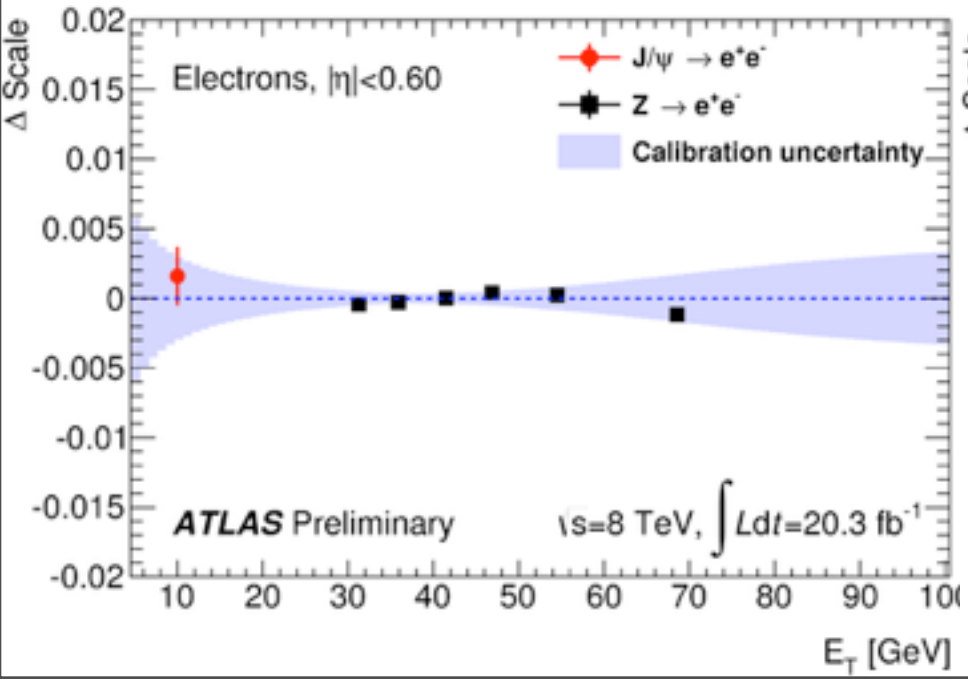

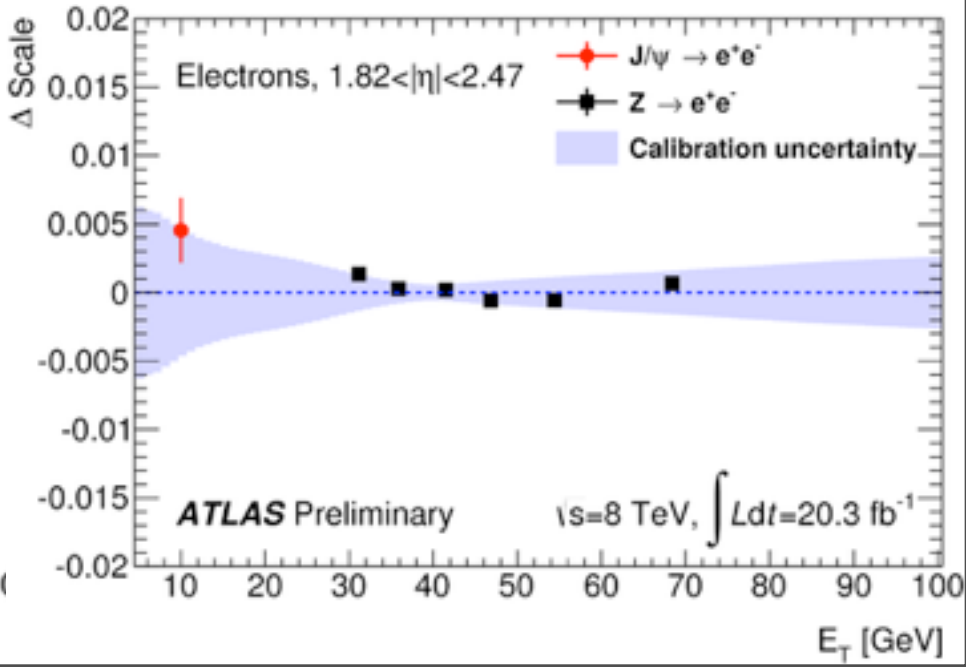

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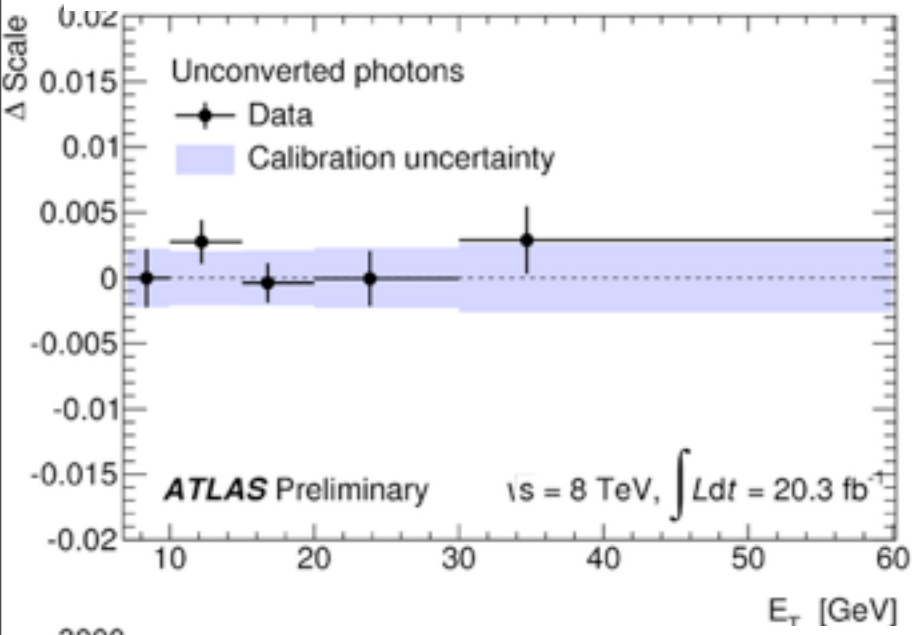

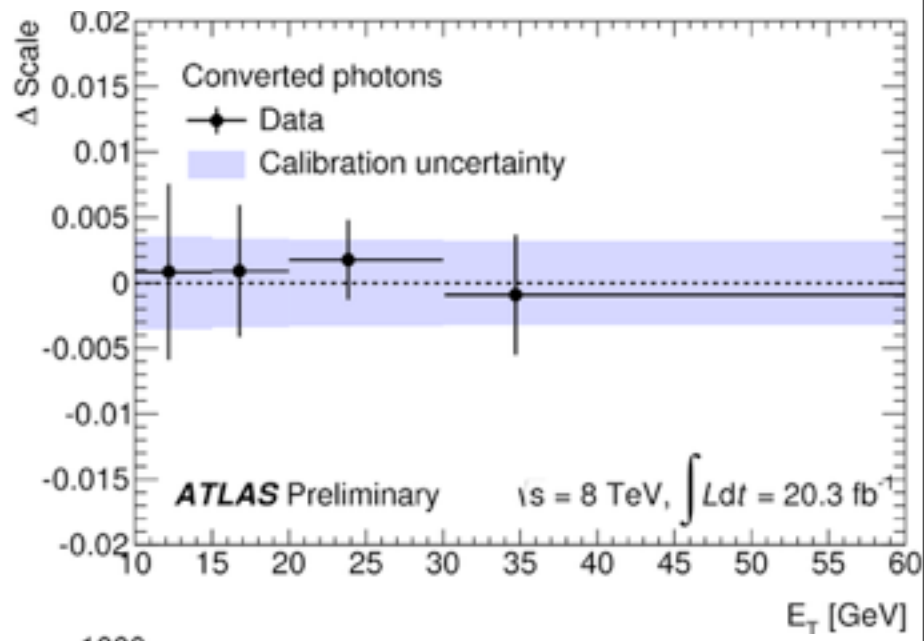

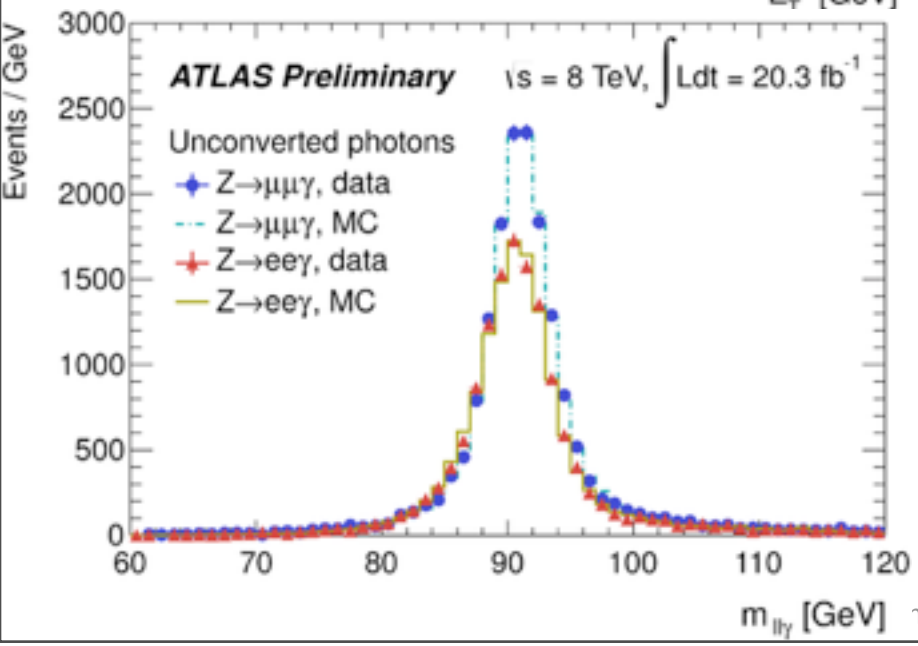

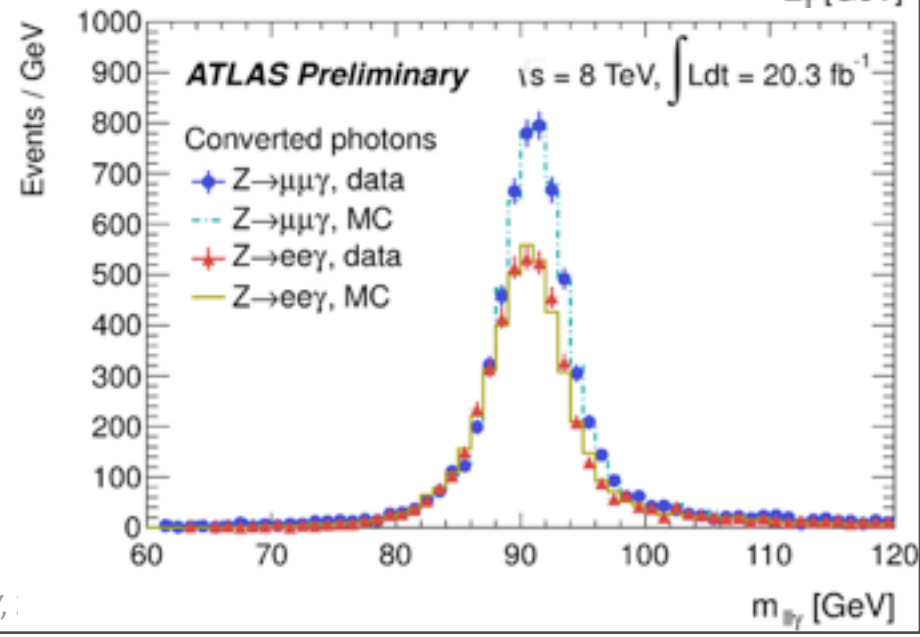

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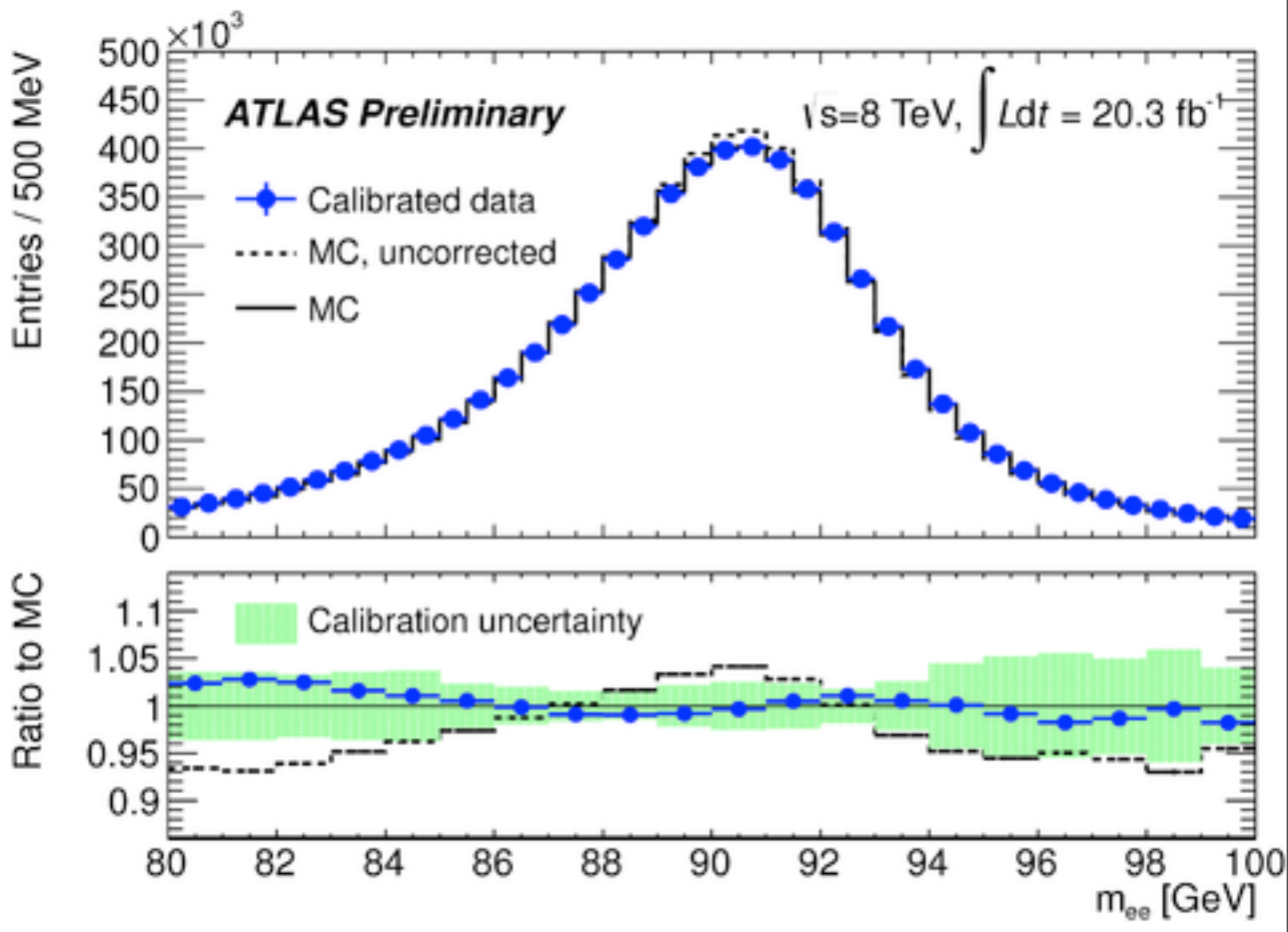

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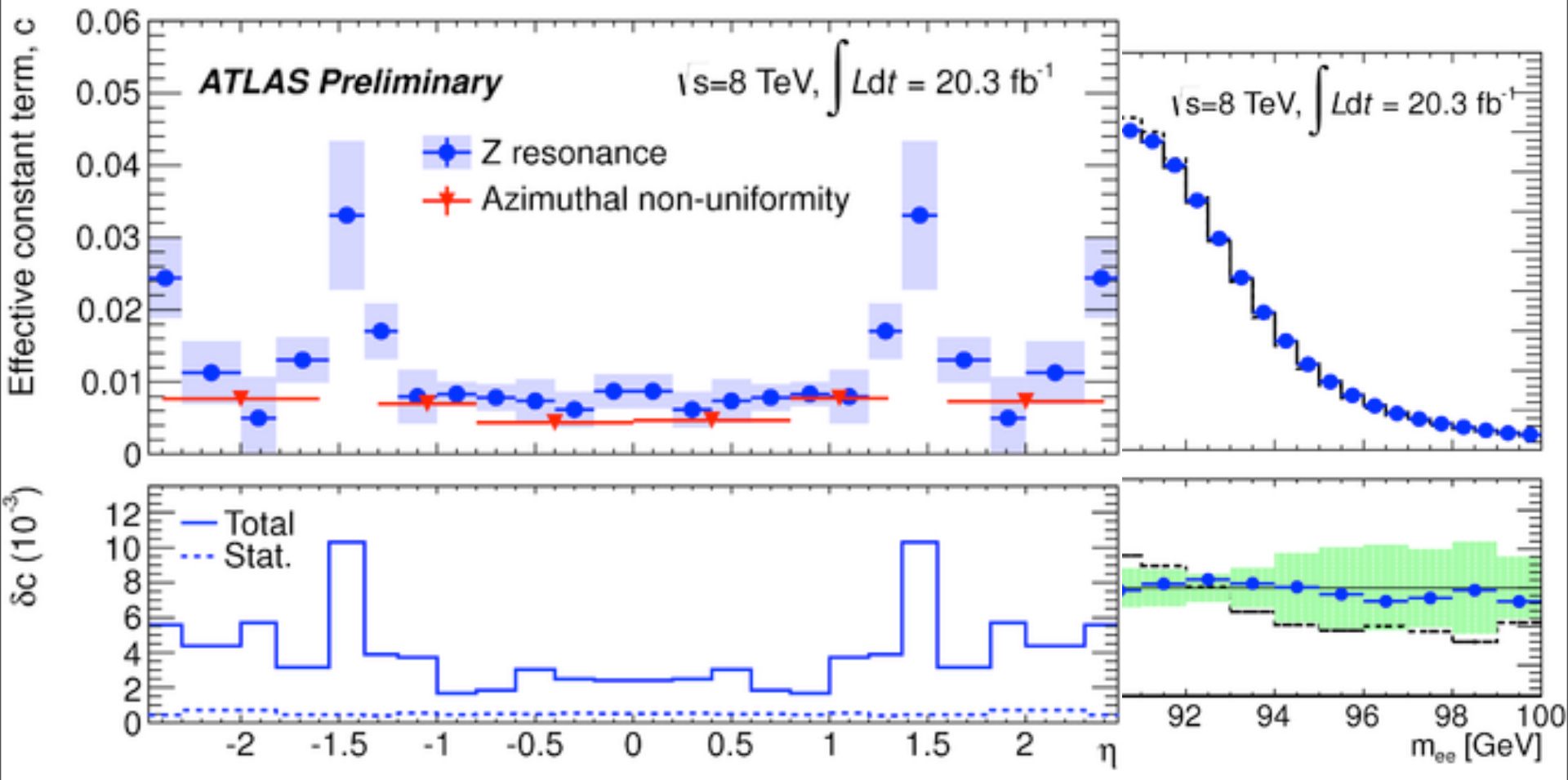


New geometry description and new calibration

Uncertainty on combined mass from H to $\gamma\gamma$ and H to 4l is ~ 180 MeV (compared to ~ 540 MeV in the PLB summer 2013 publication)

- **Note that uncertainties in table not known to better than ~ 10-20 MeV**
- **Expect for H to $\gamma\gamma$ a mass shift of approximately Δm_H = -0.45 GeV (modulo large 0.35 GeV stat uncertainty)**

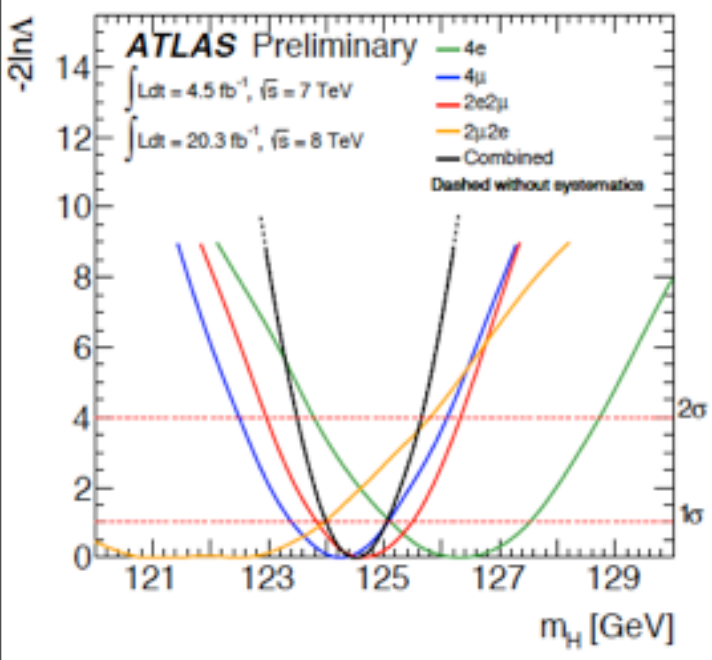
Systematic	Uncertainty on m_H (MeV)
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr electronics non-linearity (layer 2)	60
LAr electronics non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

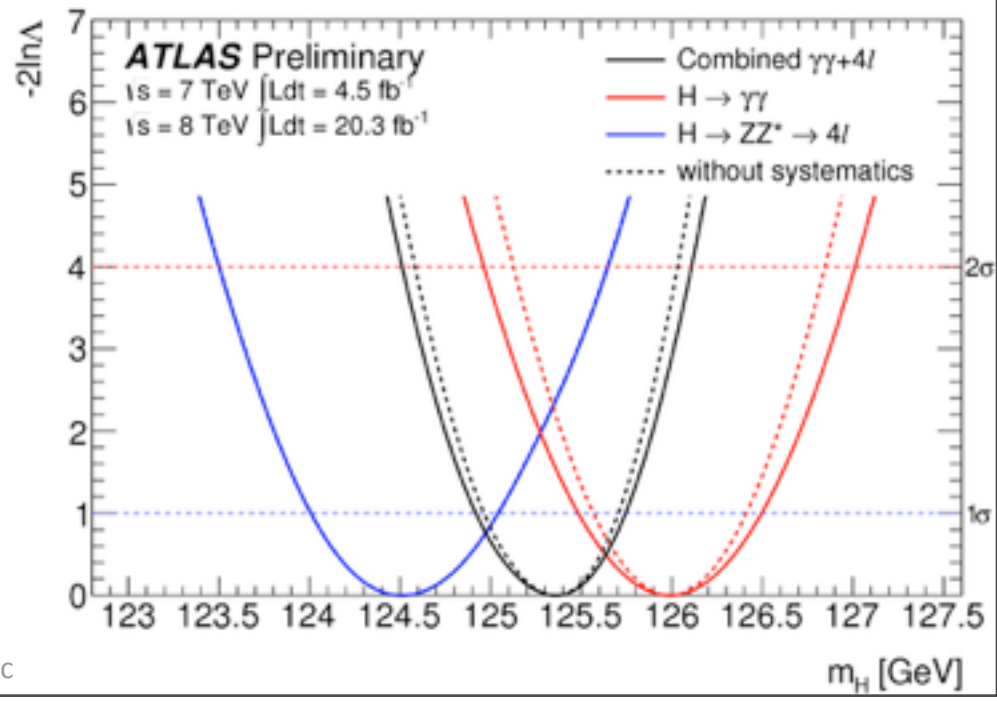
New mass measurement

Statistical uncertainty has gone up however compared to previous publication, m_H = 125.49 ± 0.24 ± 0.54 GeV, partly because of smaller observed μ in the H to $\gamma\gamma$ channel, μ = 1.29 ± 0.30 compared to μ = 1.55 ± 0.30 previously

The difference in mass between the two channels is measured to be Δm_H = 1.47 ± 0.67 (stat) ± 0.28 (sys) GeV, leading to a 2.0σ compatibility (compared to 2.5σ previously)

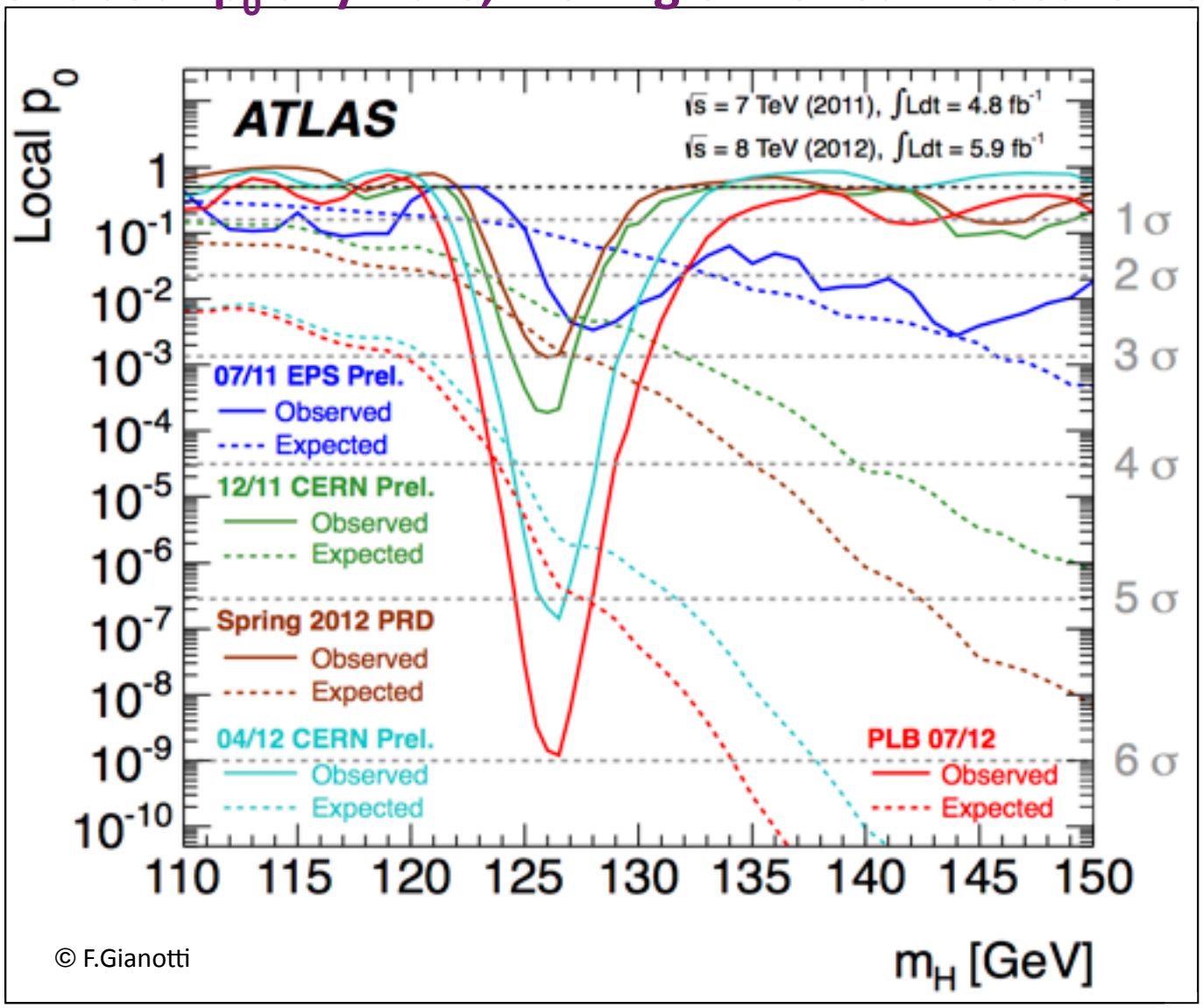
$H \to \gamma\gamma$	125.98 ± 0.42 (stat) ± 0.28 (sys) = 125.98 ± 0.50
$H \to ZZ^* \to 4\ell$	124.51 ± 0.52 (stat) ± 0.04 (sys) = 124.51 ± 0.52
Combined	125.36 ± 0.37 (stat) ± 0.18 (sys) = 125.36 ± 0.41





Recent results on Higgs-boson couplings

- Not about p_0 anymore, moving on to real measurements...



ATLAS-CONF-2013-034

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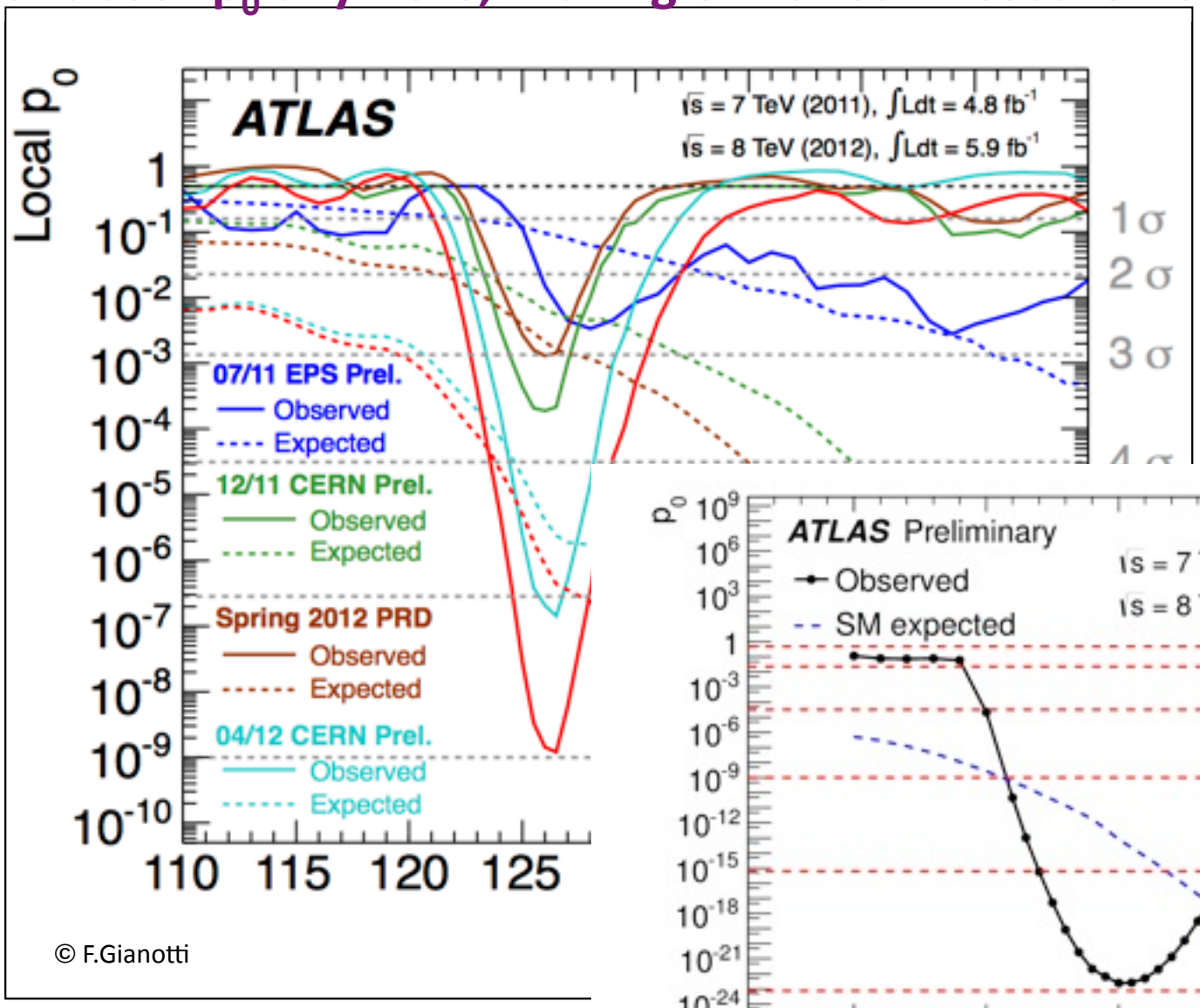
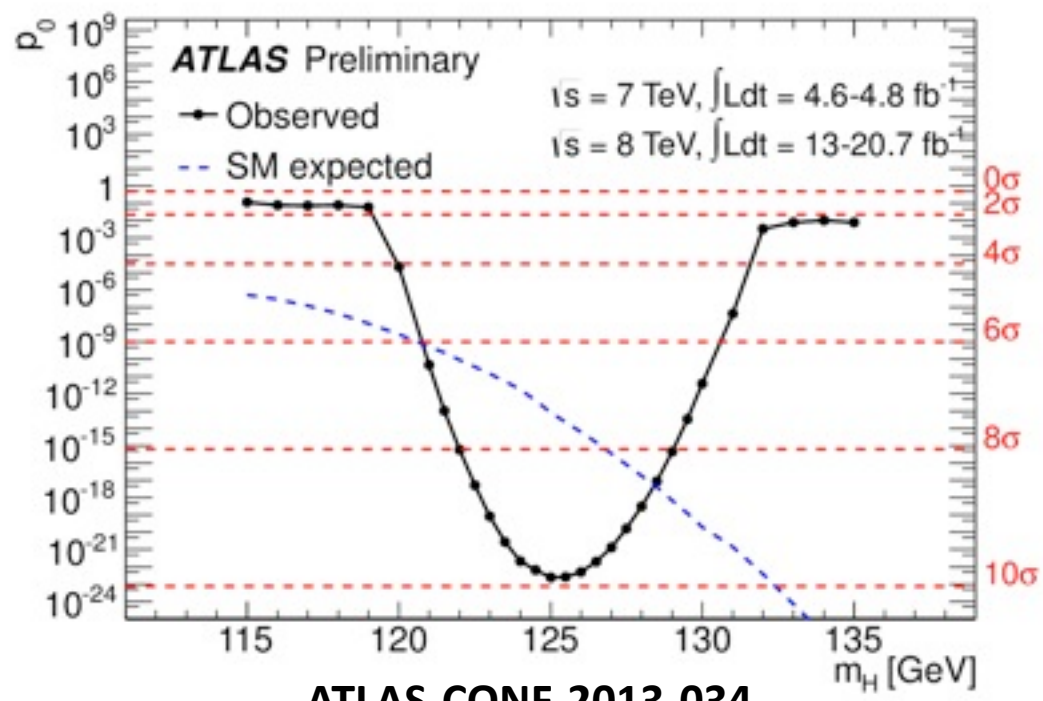
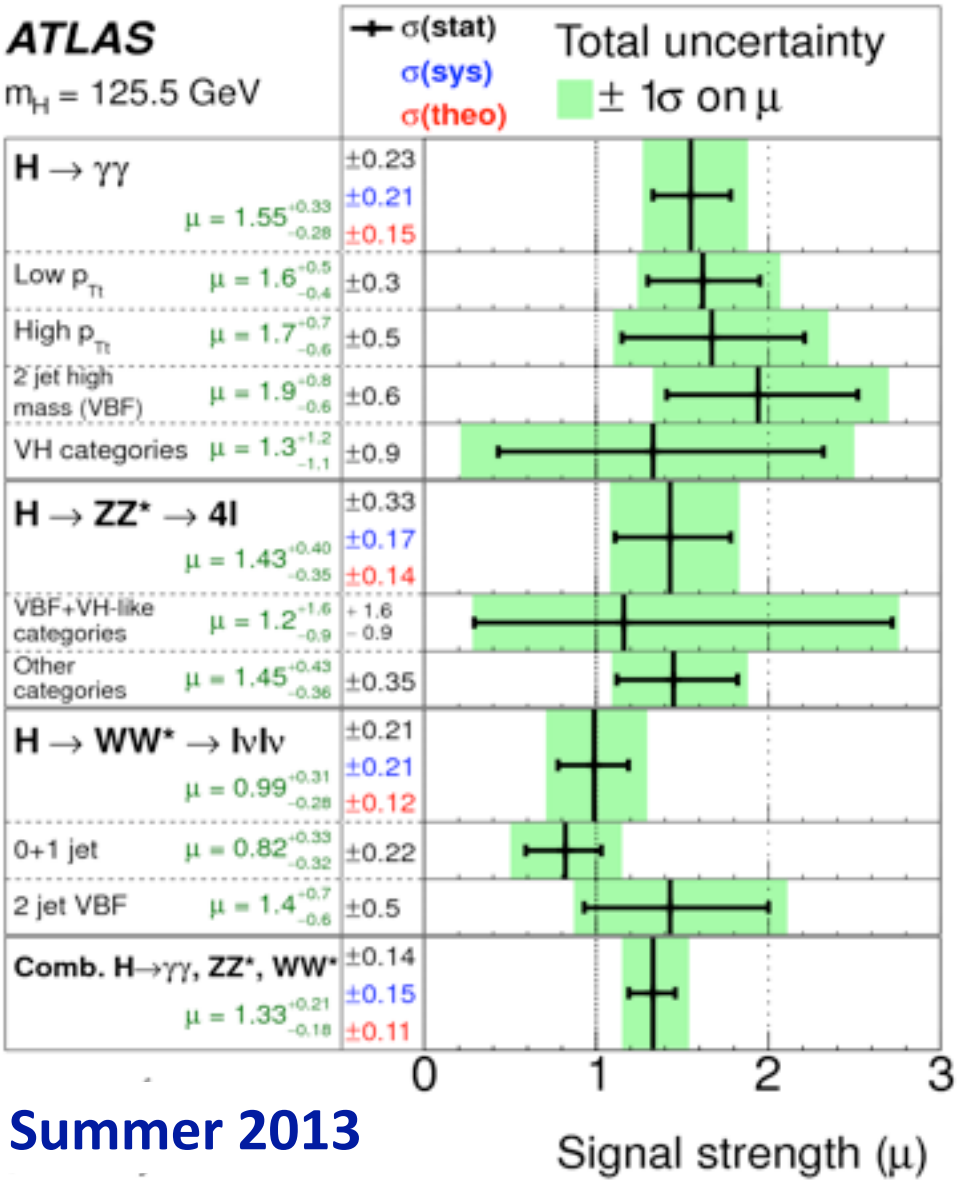




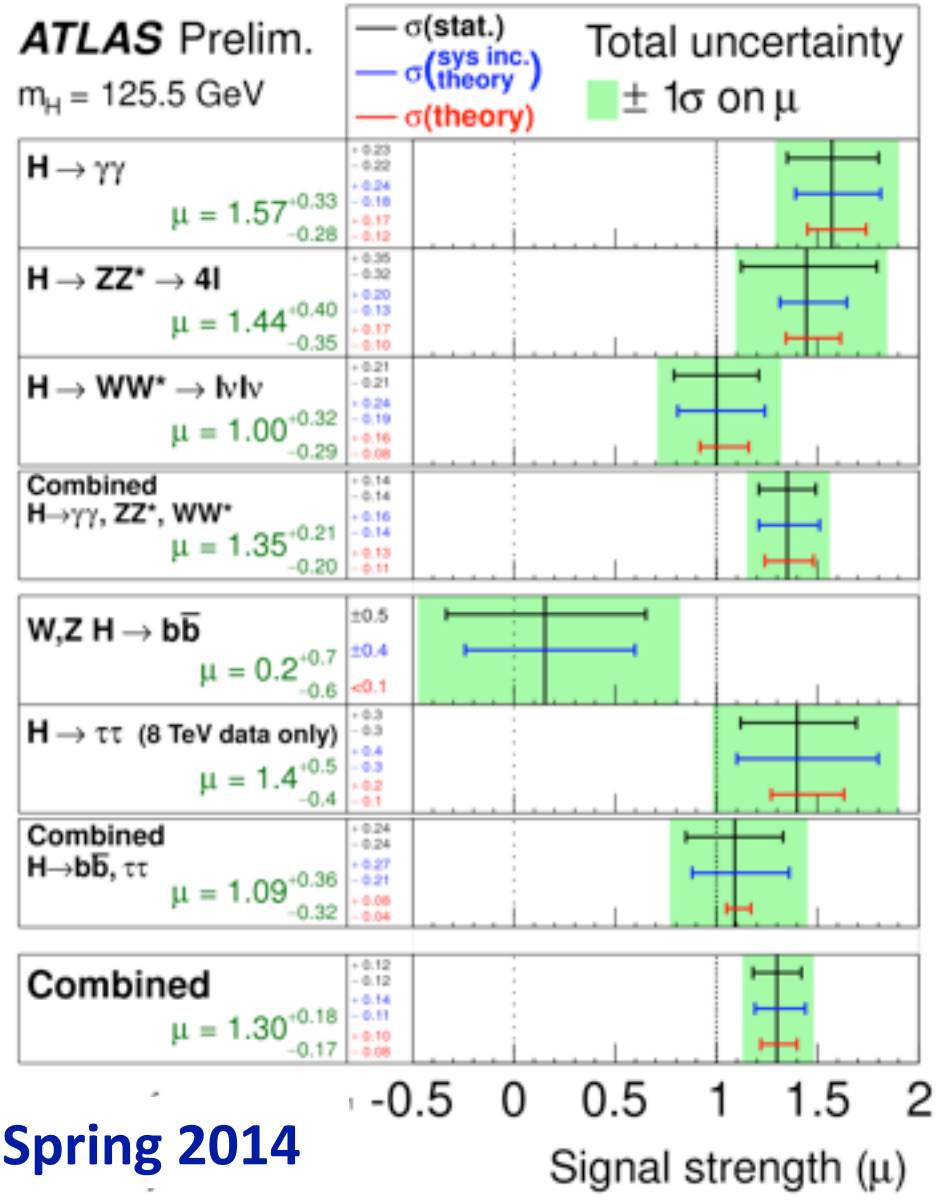
ATLAS-CONF-2013-034

Recent results on Higgs-boson couplings

- Inclusion of fermion results (H to ττ and VH, H to bb) does not improve overall error on μ very much, $\mu = 1.30 \pm 0.12\,(\text{stat})\,^{+0.14}_{-0.11}\,(\text{sys})$

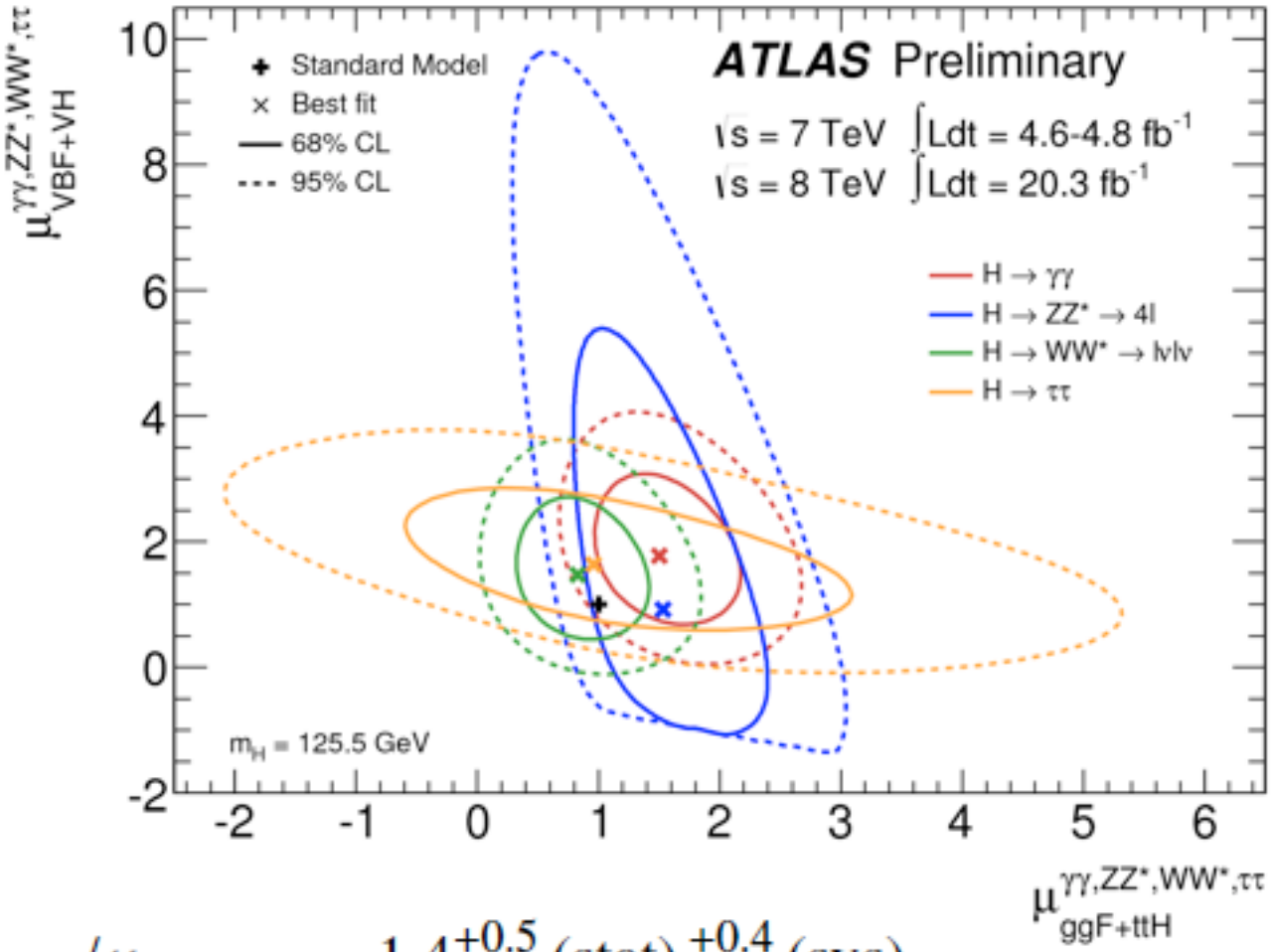


Summer 2013



Spring 2014

Recent results on Higgs-boson couplings

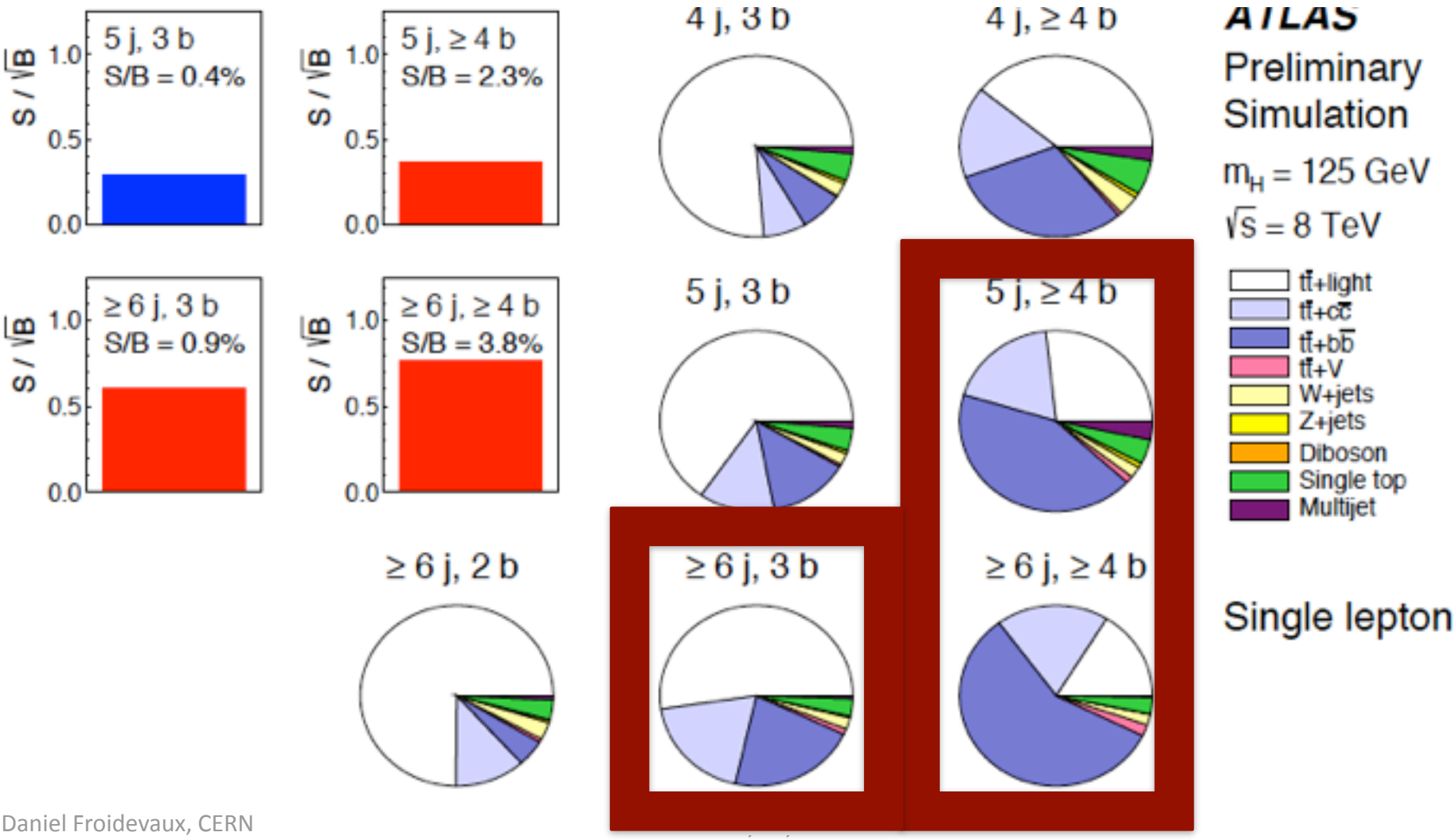


$$\mu_{\mathrm{VBF}}/\mu_{\mathrm{ggF}+ttH} = 1.4^{+0.5}_{-0.4}\,(\mathrm{stat})\,^{+0.4}_{-0.3}\,(\mathrm{sys})$$

- **This result provides evidence at the 4.1σ level that a fraction of Higgs-boson production occurs through vector boson fusion**

One of the difficult channels: ttH with H to bb

Search for the Standard Model Higgs boson produced in association with top quarks and decaying into $b\bar{b}$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC



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Post-fit event yields in the three most signal-like categories (single-lepton channel)

	5 jets, ≥ 4 b-tags	≥ 6 jets, 3 b-tags	≥ 6 jets, ≥ 4 b-tags
$t\bar{t}H$ (125)	$11 \pm 1 \pm 9$	$69 \pm 3 \pm 57$	$28 \pm 2 \pm 23$
$t\bar{t}$+ light	78 ± 9	2380 ± 130	78 ± 11
$t\bar{t} + c\bar{c}$	45 ± 12	750 ± 190	75 ± 19
$t\bar{t} + b\bar{b}$	149 ± 20	1160 ± 170	300 ± 40
$t\bar{t} + V$	3.3 ± 1.0	44 ± 13	8.9 ± 2.7
non-$t\bar{t}$	23.2 ± 2.5	218 ± 23	18.8 ± 2.2
Total	309 ± 11	4620 ± 80	507 ± 27
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Variable	($\geq$ 6j, $\geq$ 4b)
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$m_{bb}^{min\ \Delta R}$	2
Centrality	3
H1	4
p_T^{jet5}	5
$\text{Aplanarity}_{b-jet}$	6
$m_{uu}^{min\ \Delta R}$	7
$\Delta R_{bb}^{max\ p_T}$	8
$\Delta R_{lep-bb}^{min\ \Delta R}$	9
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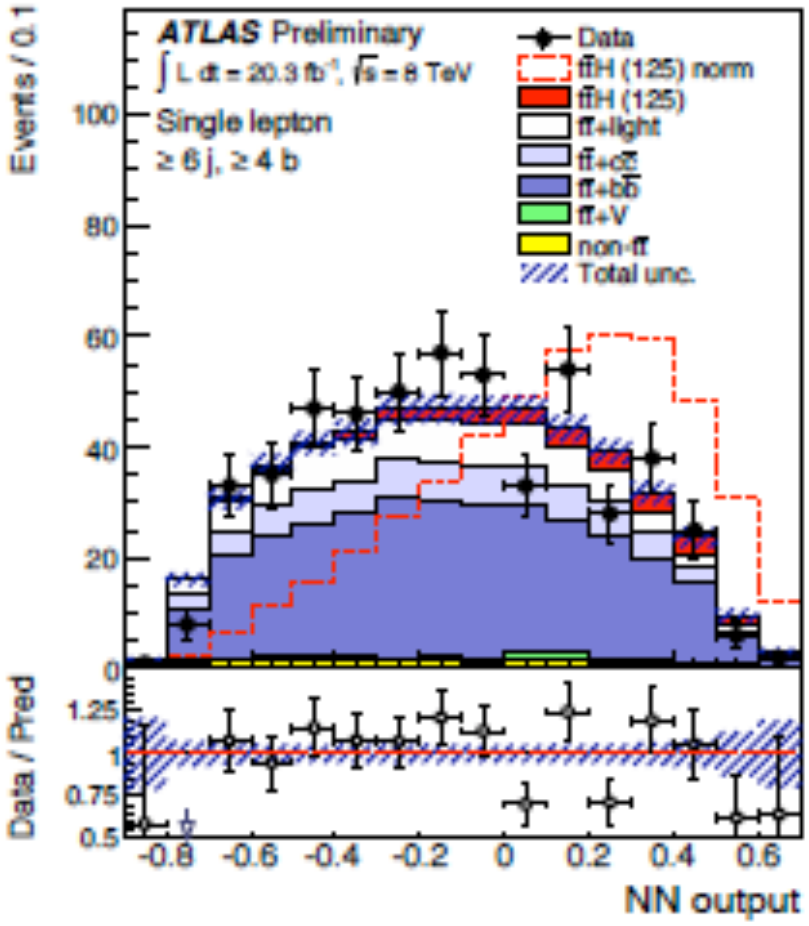

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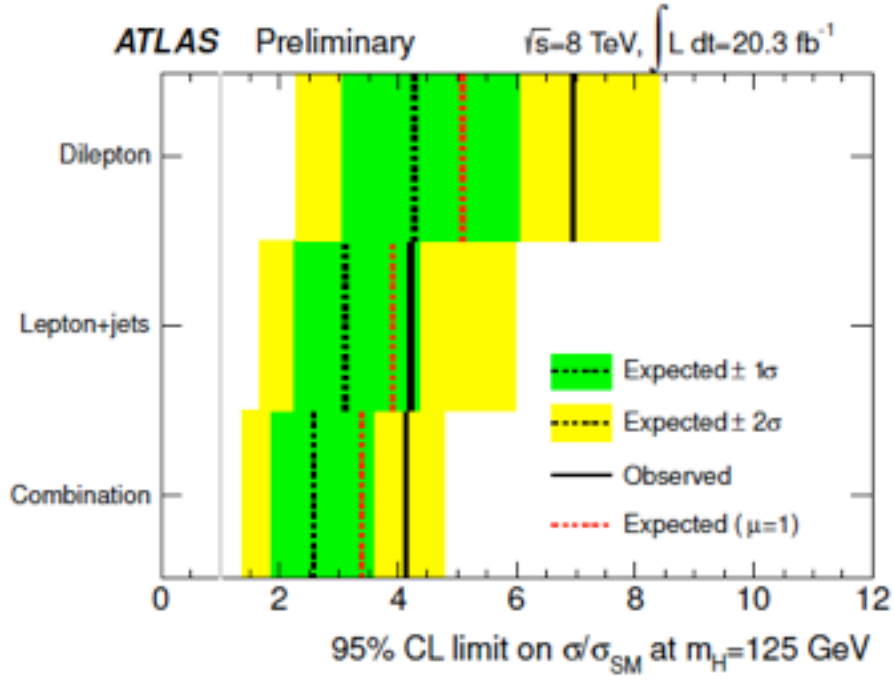

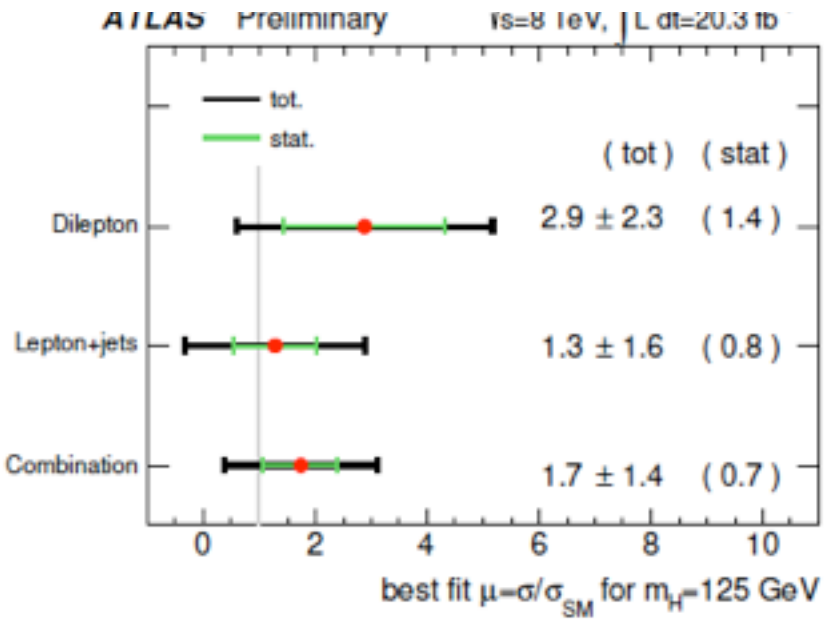

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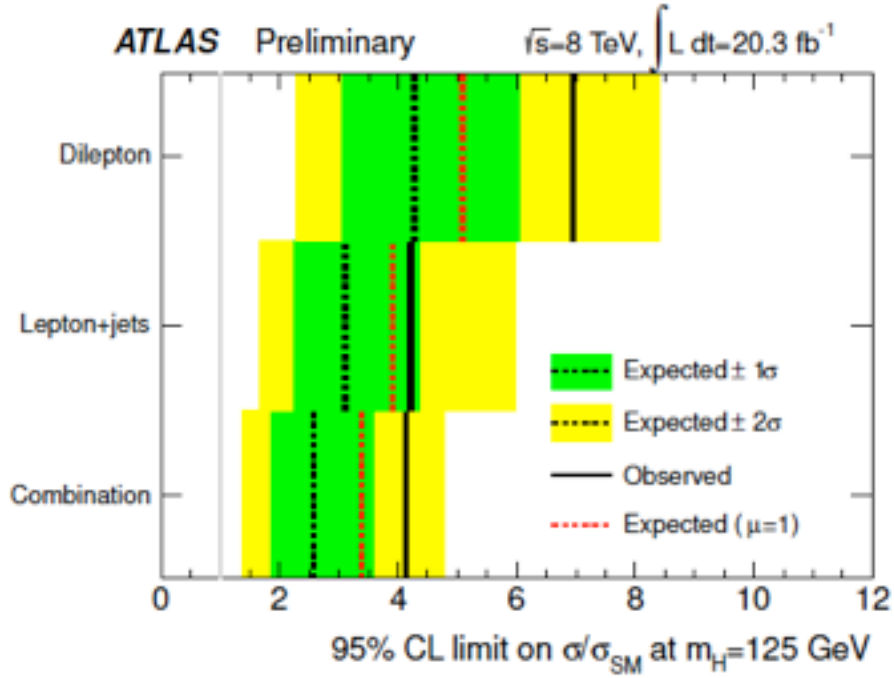

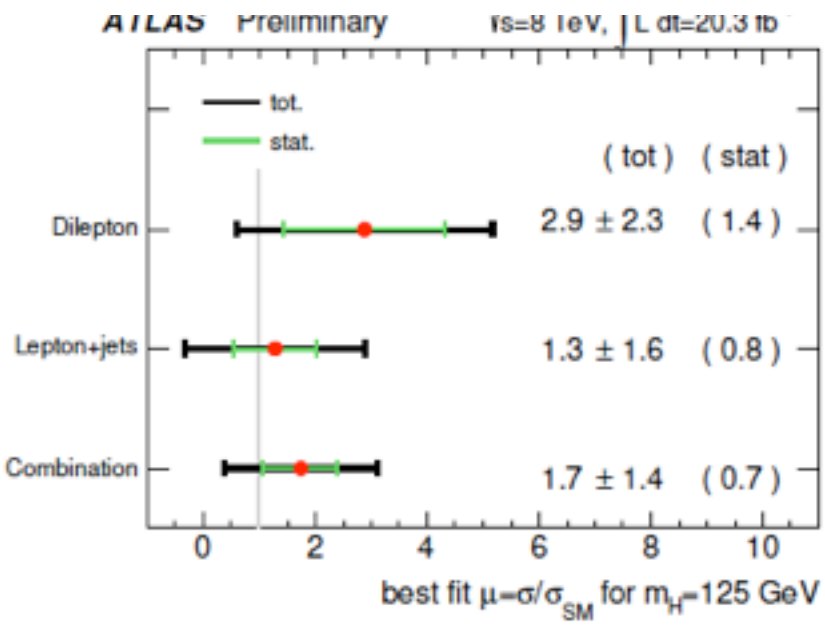

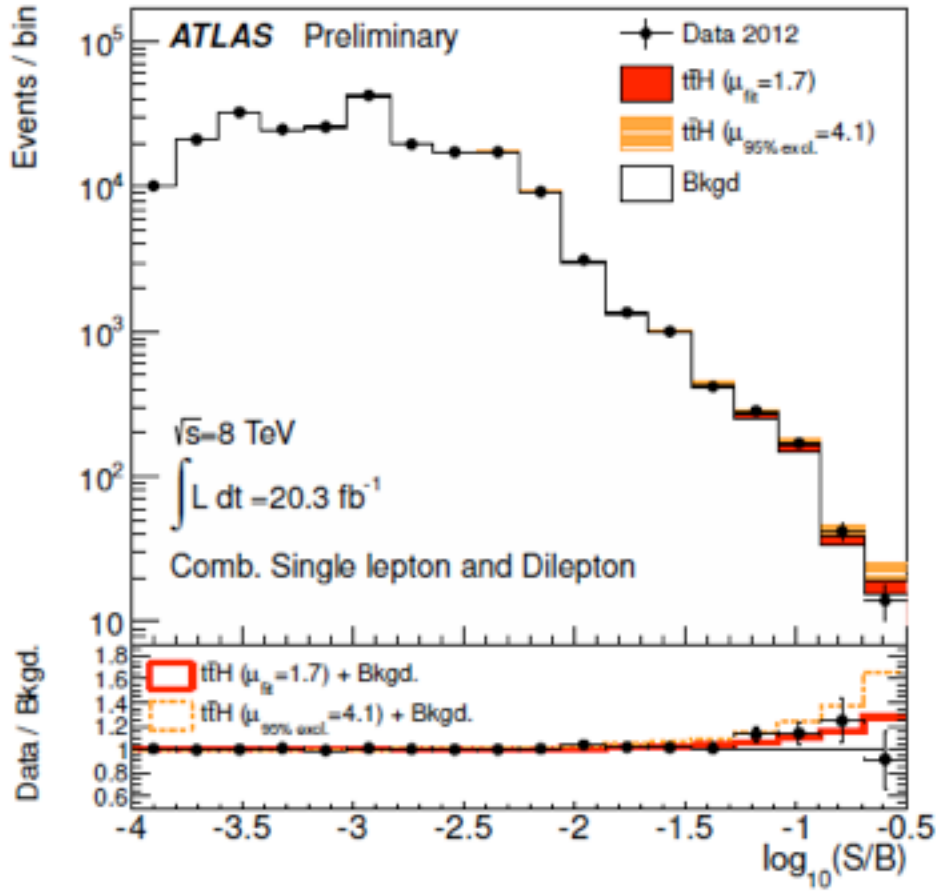

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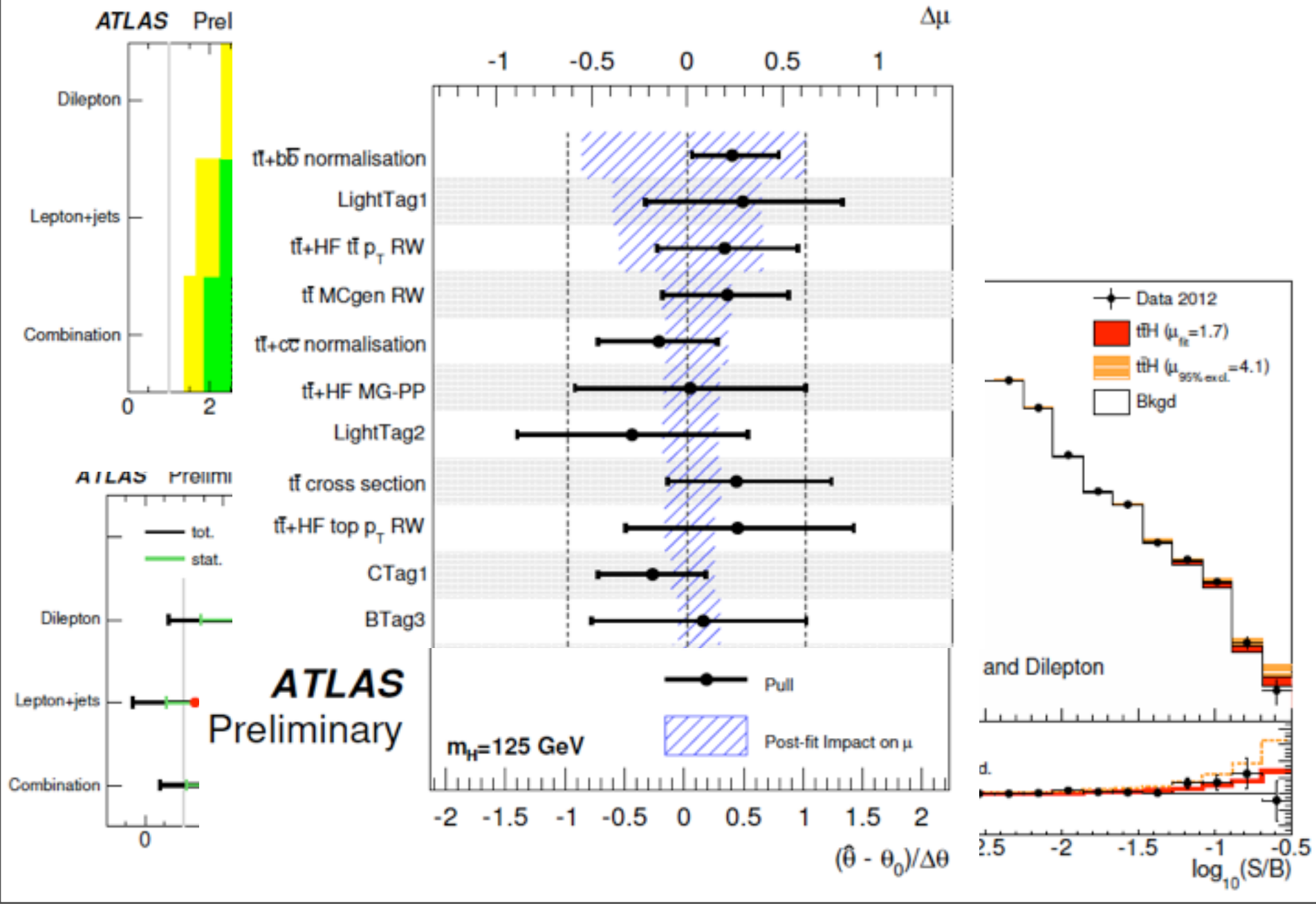

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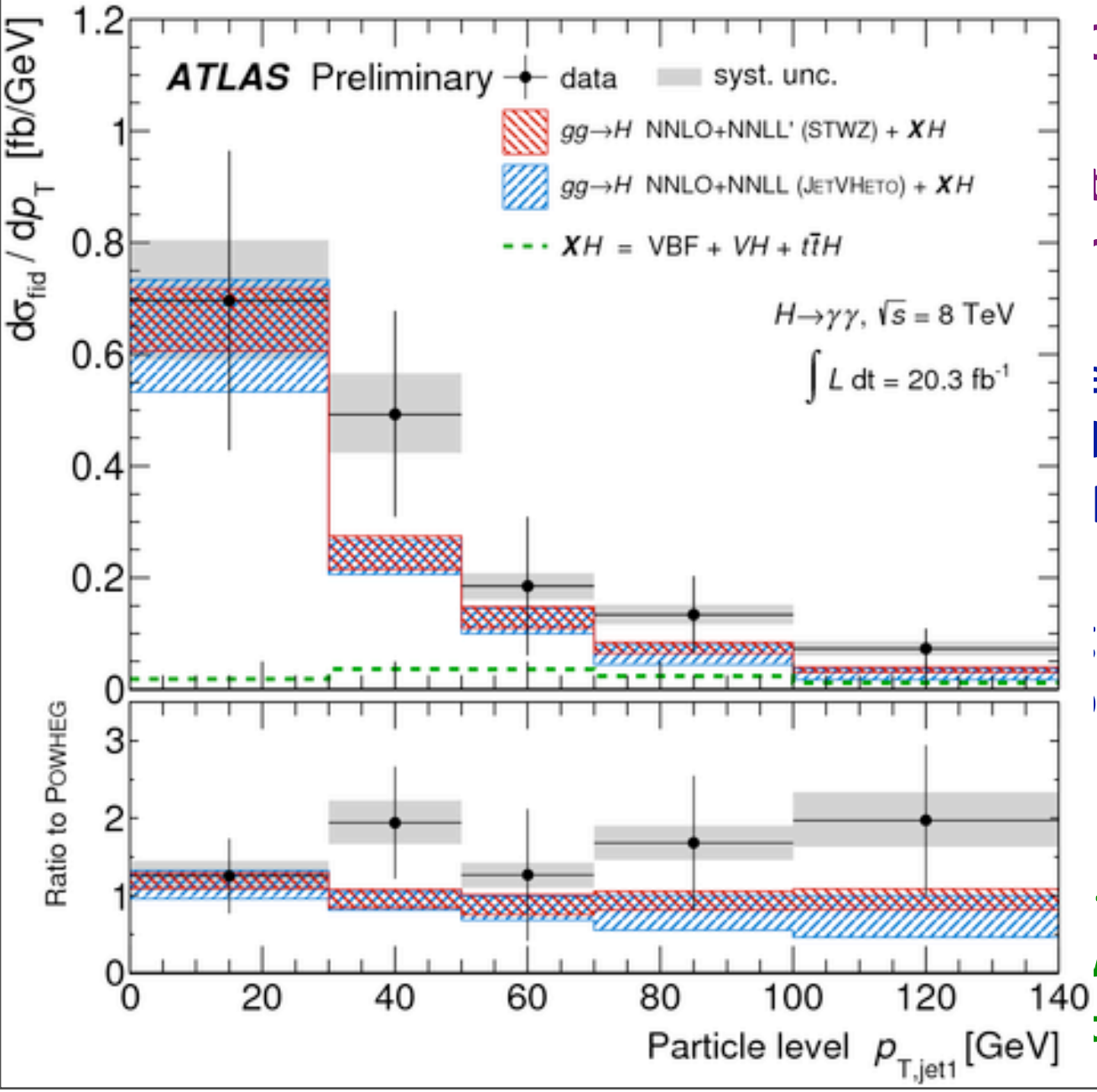

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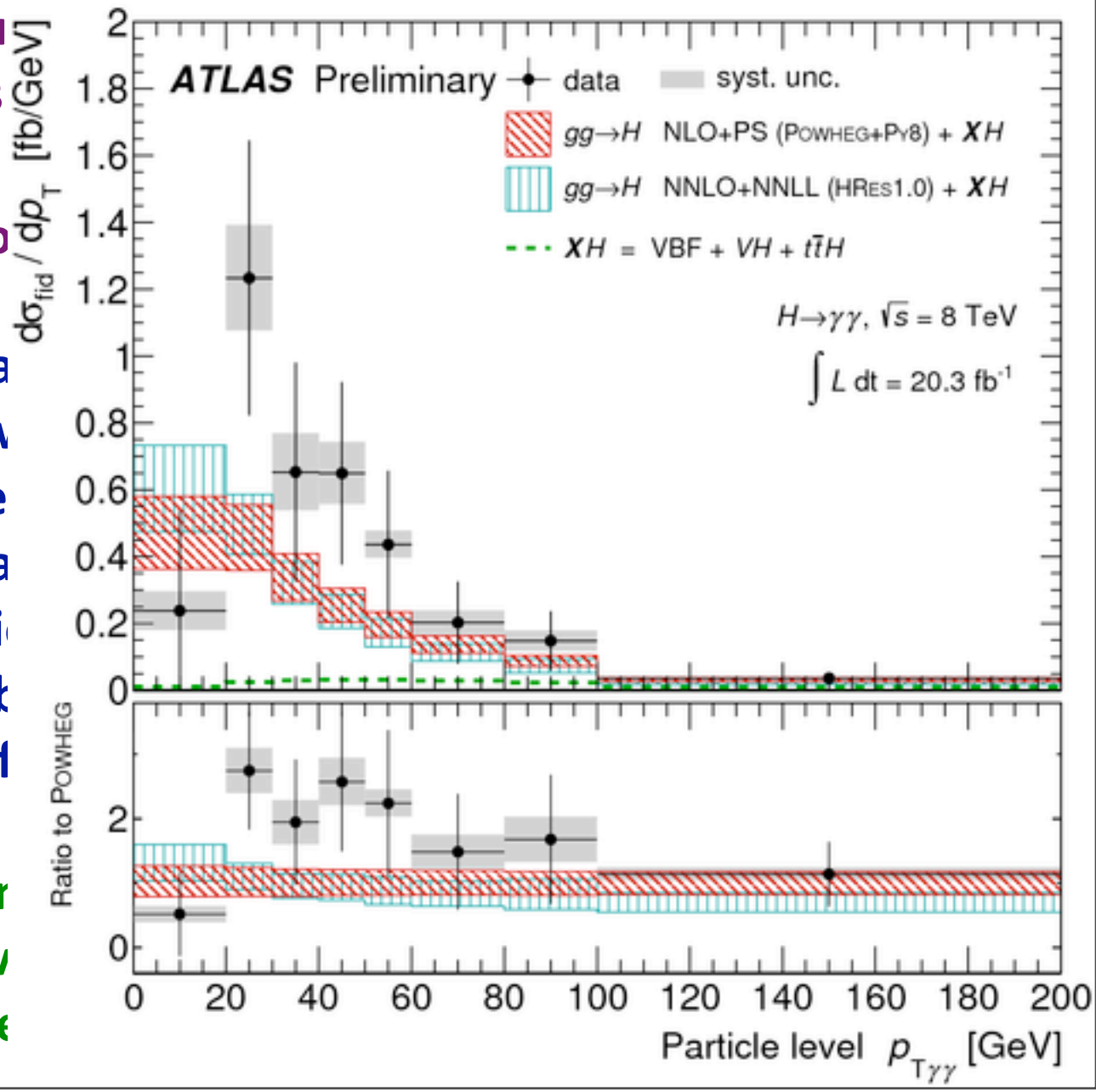

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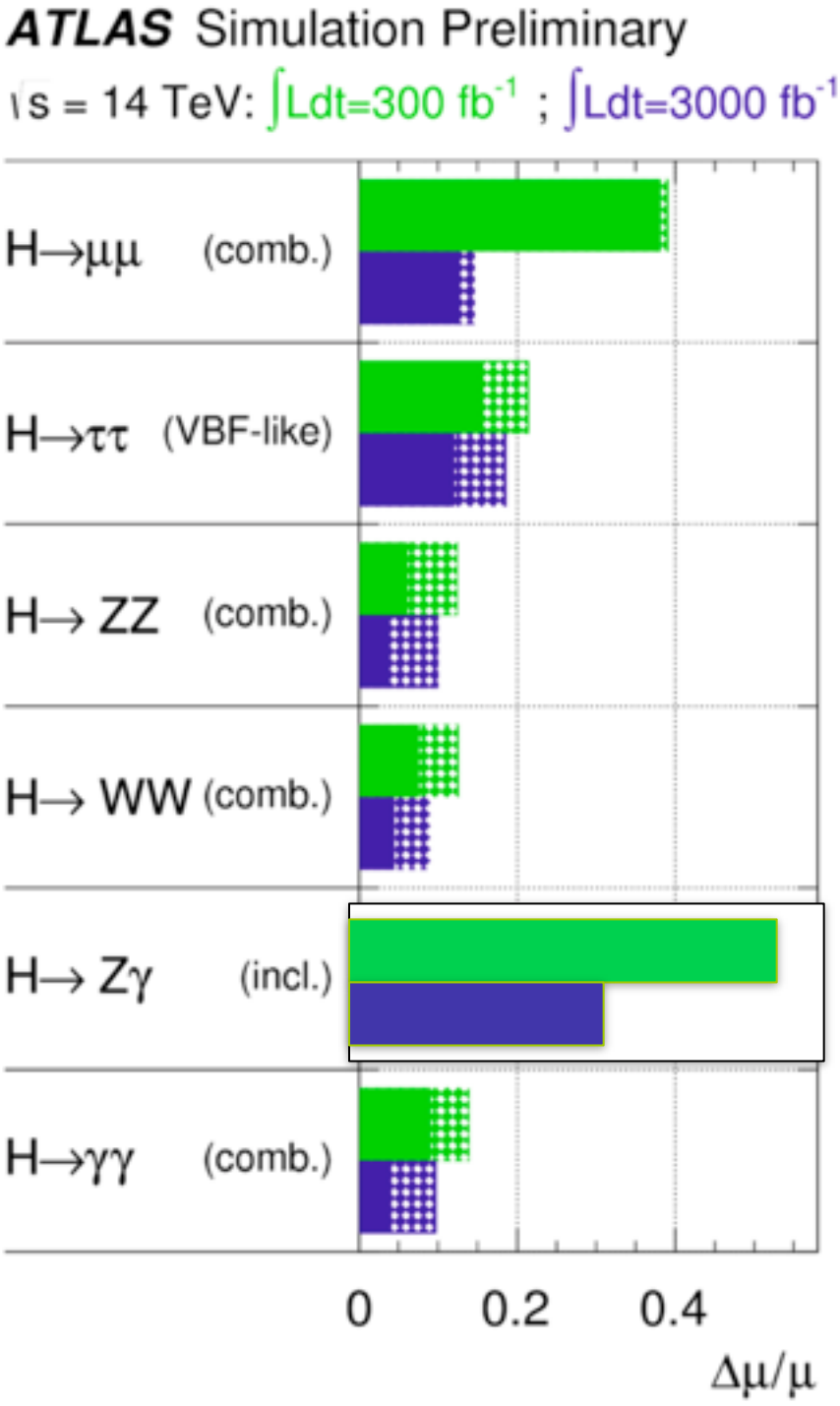
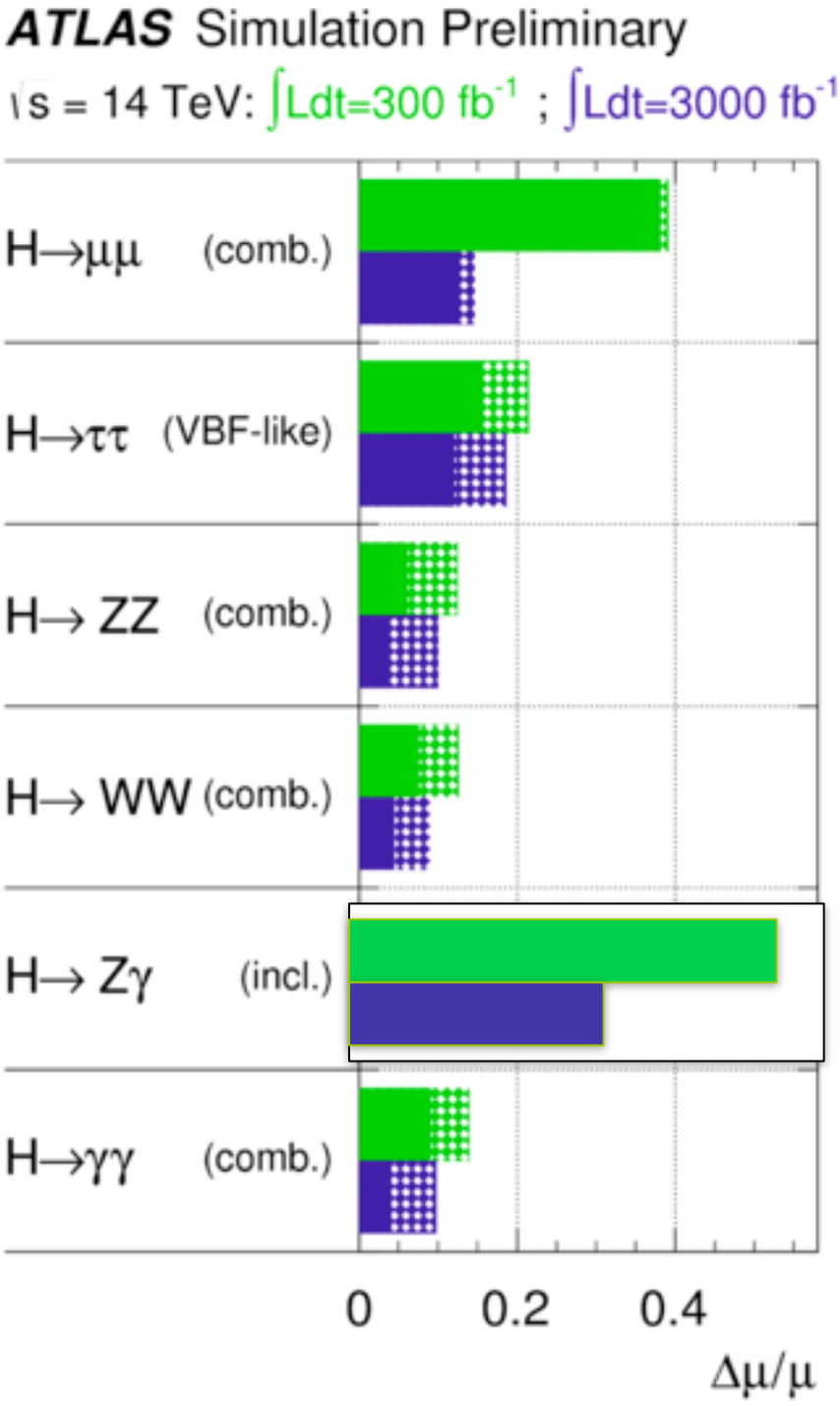
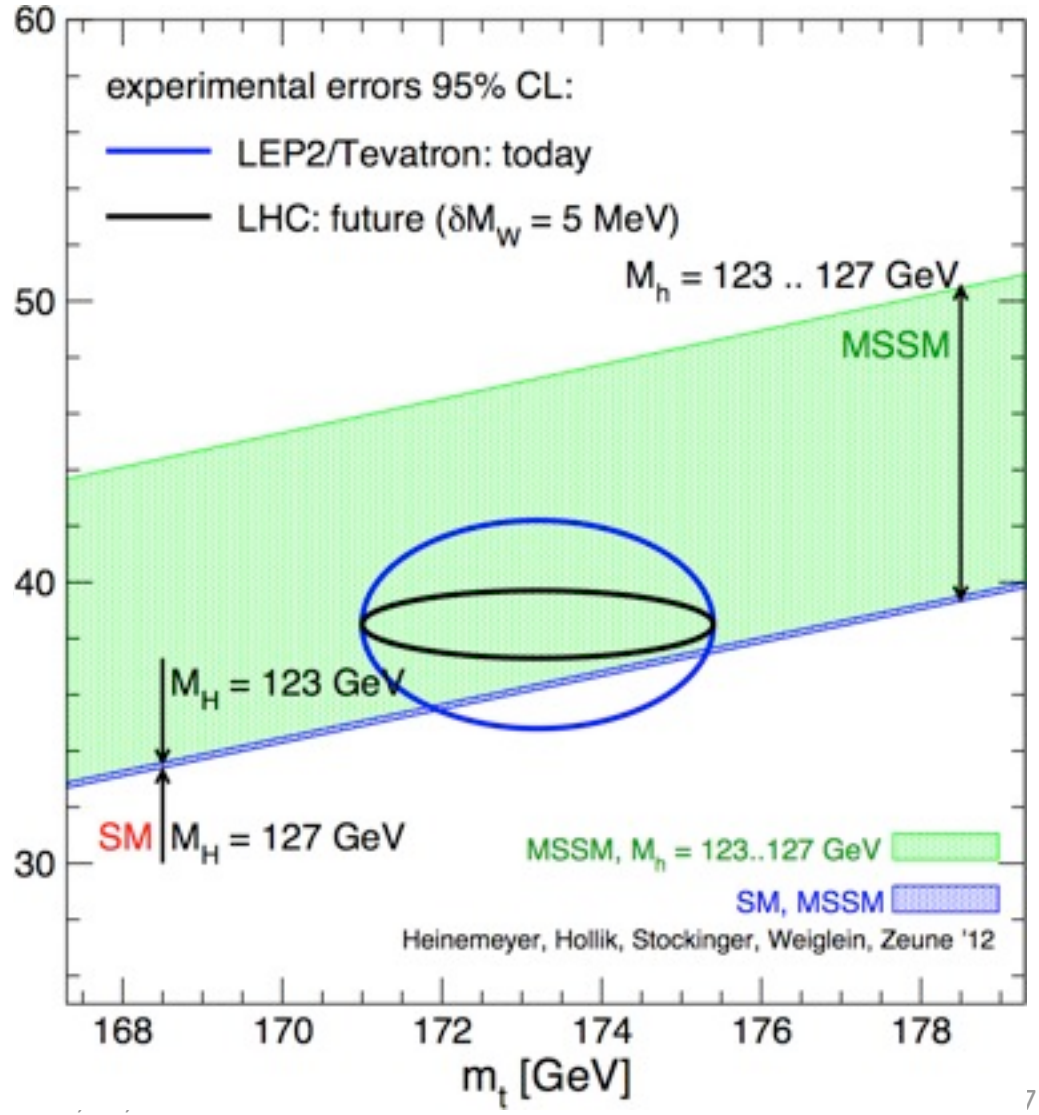

ATLAS Simulation Preliminary
√s = 14 TeV: ∫Ldt=300 fb⁻¹ ; ∫Ldt=3000 fb⁻¹
H→μμ (comb.)
H→ττ (VBF-like)
H→ ZZ (comb.)
H→ WW (comb.)
H→ Zγ (incl.)
H→γγ (comb.)
0
0.2
0.4
Δμ/μ

What next?



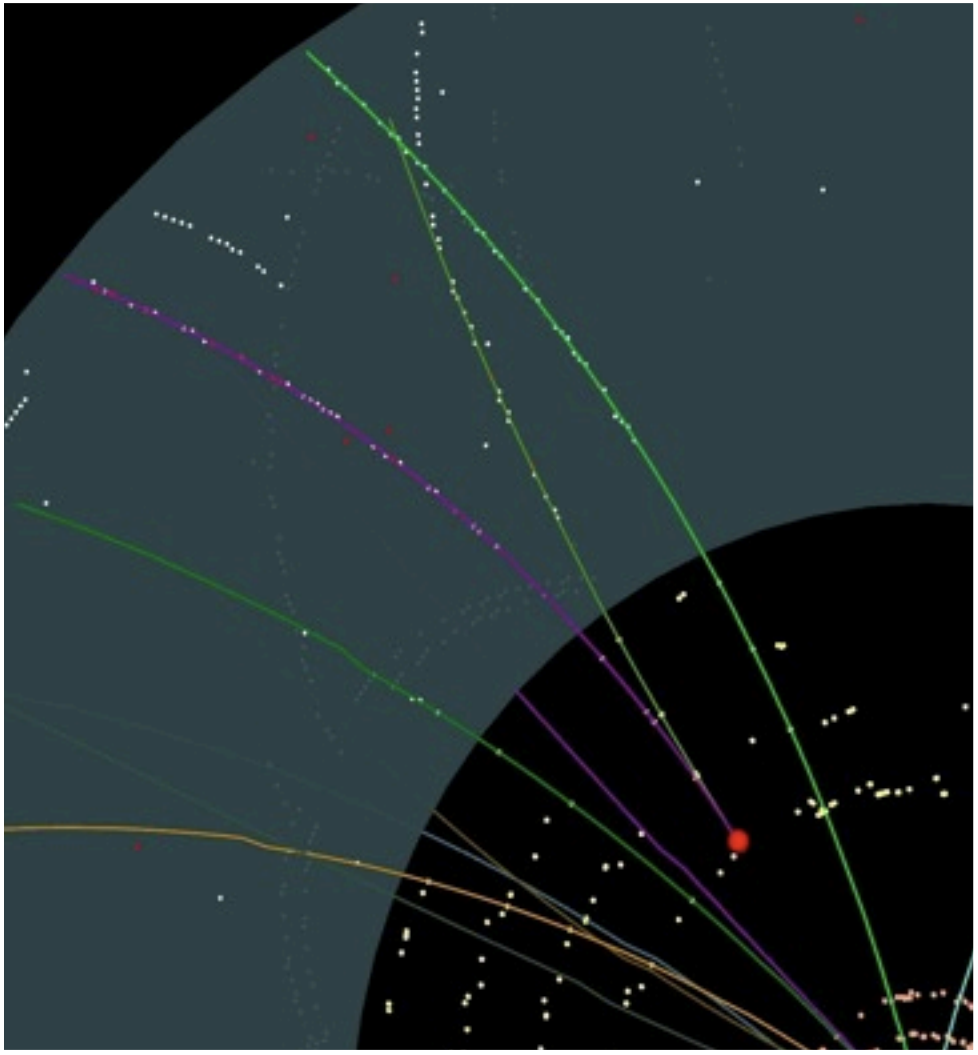
See eg http://arxiv.org/pdf/1112.3026.pdf



Back-up

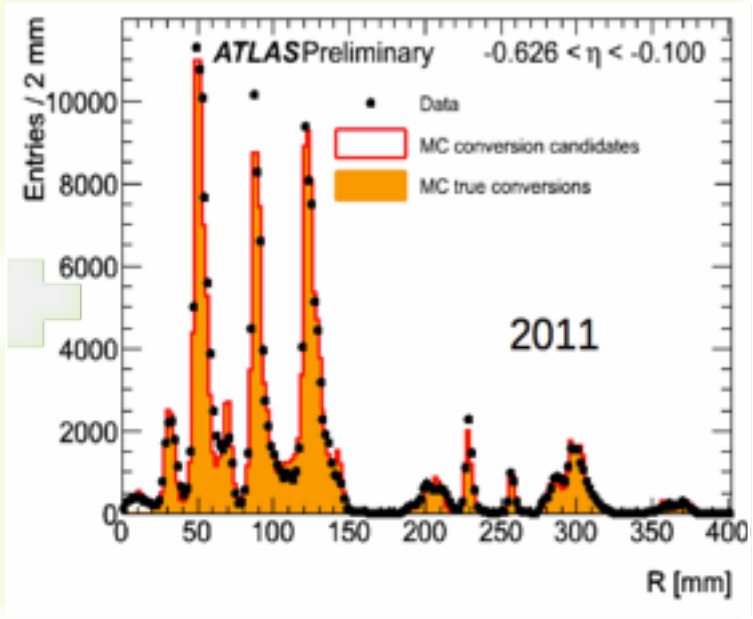
Photon conversion reconstruction

- **Candidate photon conversion vertices reconstructed from tracks pre-selected as loosely matching EMC clusters**
  - 1 or 2 tracks
  - 1-track conversions from tracks that missing the hit in innermost ID layer
- Photon reconstruction expected efficiency
  - ~ 98% for photons $E_T > 25$ GeV
  - > 99% for unconverted photons
  - ~ 95% for converted (R < 80 cm)
- **Expected fraction of converted photons**
  - ~ 20% at $|\eta| \sim 0$ - ~ 45% $|\eta| \sim 1.6$
- Relative fraction of reconstructed photon conversion depends on:
  - Material upstream EMC
  - In MC, on conversion model…



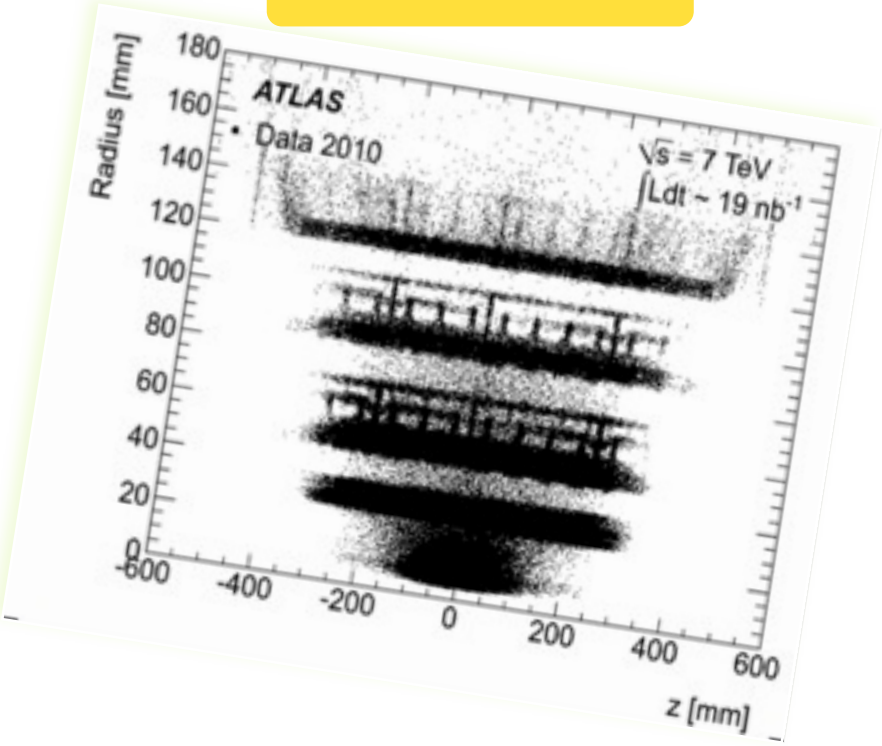
Probing the material before the EMC in ATLAS

Photon conversions



Measure radiation length
(i.e. amount of material at a given distance)

Hadronic interactions



Measure interaction length
Compared with diffractive MC (PYTHIA6 AMBT1)

- Both methods allowed to constrain **local variations of "early" material at ~5-10% X_0**
  - Important to specify and locate accurately certain ID elements for improved geometry description
  - Final material systematics from bottom-up scrutiny of engineering drawings (2-5% X_0)
  - **These methods cannot constrain "late" material** (after ID, before EMC)

Recent results on Higgs-boson couplings

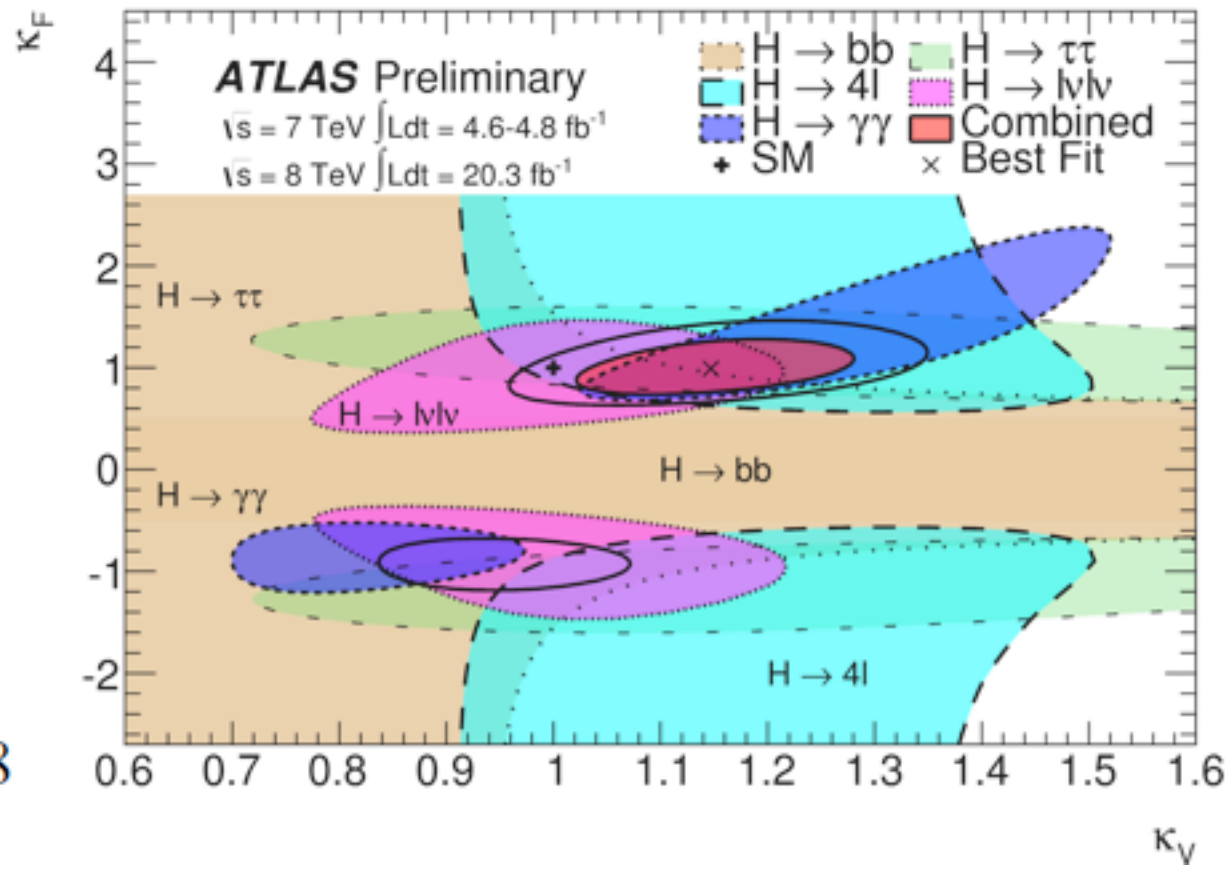
- Inclusion of fermion results (H to $\tau\tau$ and VH, H to bb) does not improve overall error on μ very much, $\mu = 1.30 \pm 0.12\,(\text{stat})\,^{+0.14}_{-0.11}\,(\text{sys})$
- Note that the total systematic uncertainty on μ contains a large contribution which purely belongs to theory (approximately 0.10), so the uncertainties which matter for us as experimentalists for the next steps, e.g. measurements of the Higgs-boson properties in individual channels through differential unfolded distributions, are the experimental one (see below) and the theoretical uncertainties related to acceptance and modelling of the signal and of the various backgrounds (e.g. jet bins, VBF topologies) → μ = 1.30 ± 0.12 (stat) ± 0.09 (syst)
- With the final run-1 performance systematics (photons, electrons, muons, jets and E_T^{miss}, b-tagging), the experimental uncertainties are expected to be sub-dominant for channels such as H to $\gamma\gamma$ or H to 4μ. Modelling systematics are often dominant in specific regions of phase space such as VBF production

Source (experimental)	Uncertainty (%)
Luminosity	±1.8 (2011), ±3.6 (2012)
Electron efficiency	±2–5
Jet energy scale	±1–5
Jet energy resolution	±2–40
Source (theory)	**Uncertainty (%)**
QCD scale	±8 (ggF), ±1(VBF, VH), $^{+4}_{-9}$ (ttH)
PDFs + α_s	±8 (ggF, ttH), ±4 (VBF, VH)

d of June 2014

Recent results on Higgs-boson couplings

$$\mu^{bb,\tau\tau} = 1.09 \pm 0.24\,(\text{stat})\,^{+0.27}_{-0.21}\,(\text{sys}) \quad \kappa_\gamma^2 \quad \sim \quad 1.59 \cdot \kappa_W^2 - 0.66 \cdot \kappa_W \kappa_t + 0.07 \cdot \kappa_t^2$$

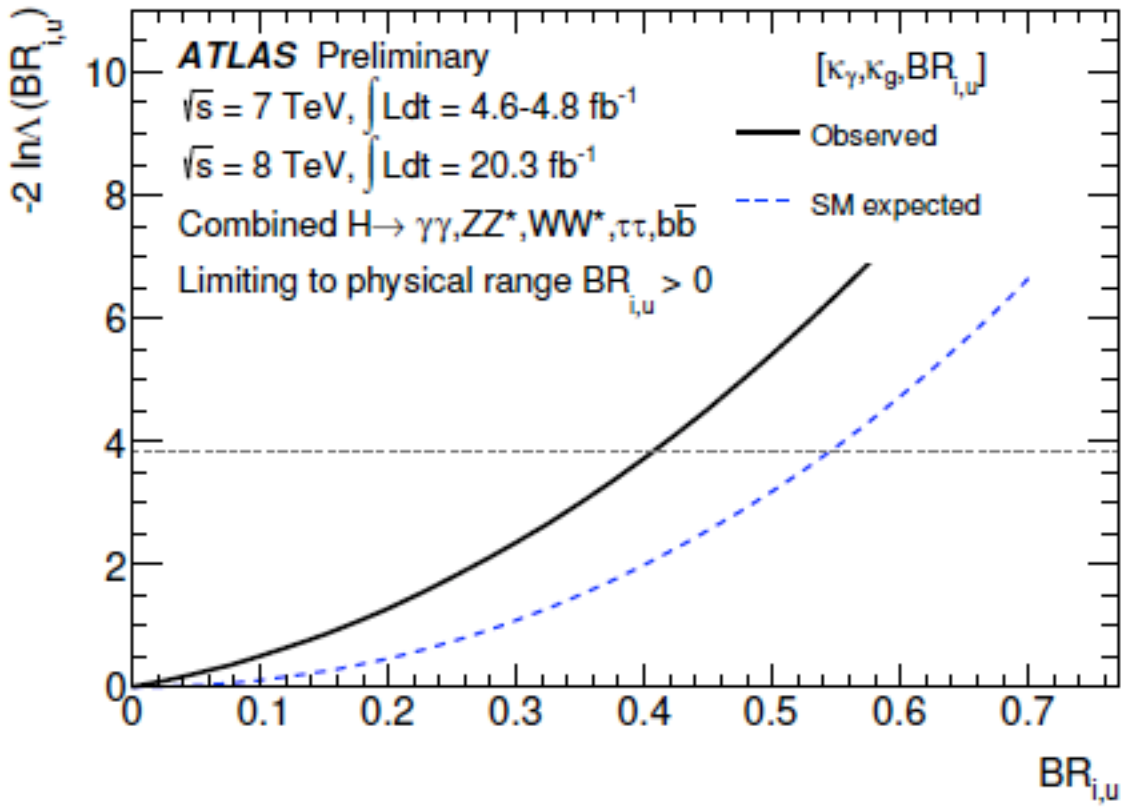


$$\kappa_V = 1.15 \pm 0.08$$

$$\kappa_F = 0.99^{+0.17}_{-0.15}.$$

- **Above results assume only SM particles contributing to Higgs-boson width and to loops, not a precision measurement yet by far.**

Status of Higgs-boson measurements in ATLAS



$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{i.,u.})}\Gamma_H^{SM}$$

Under the hypothesis that all tree level couplings of the new boson to SM particles are fixed to their SM values, no significant deviations are observed in the effective couplings to photons and gluons (κ_γ and κ_g, respectively) regardless of the assumption on the total width. Releasing the assumption on the total width constrains $BR_{i.,u.}$ to < 0.41 at 95% CL.