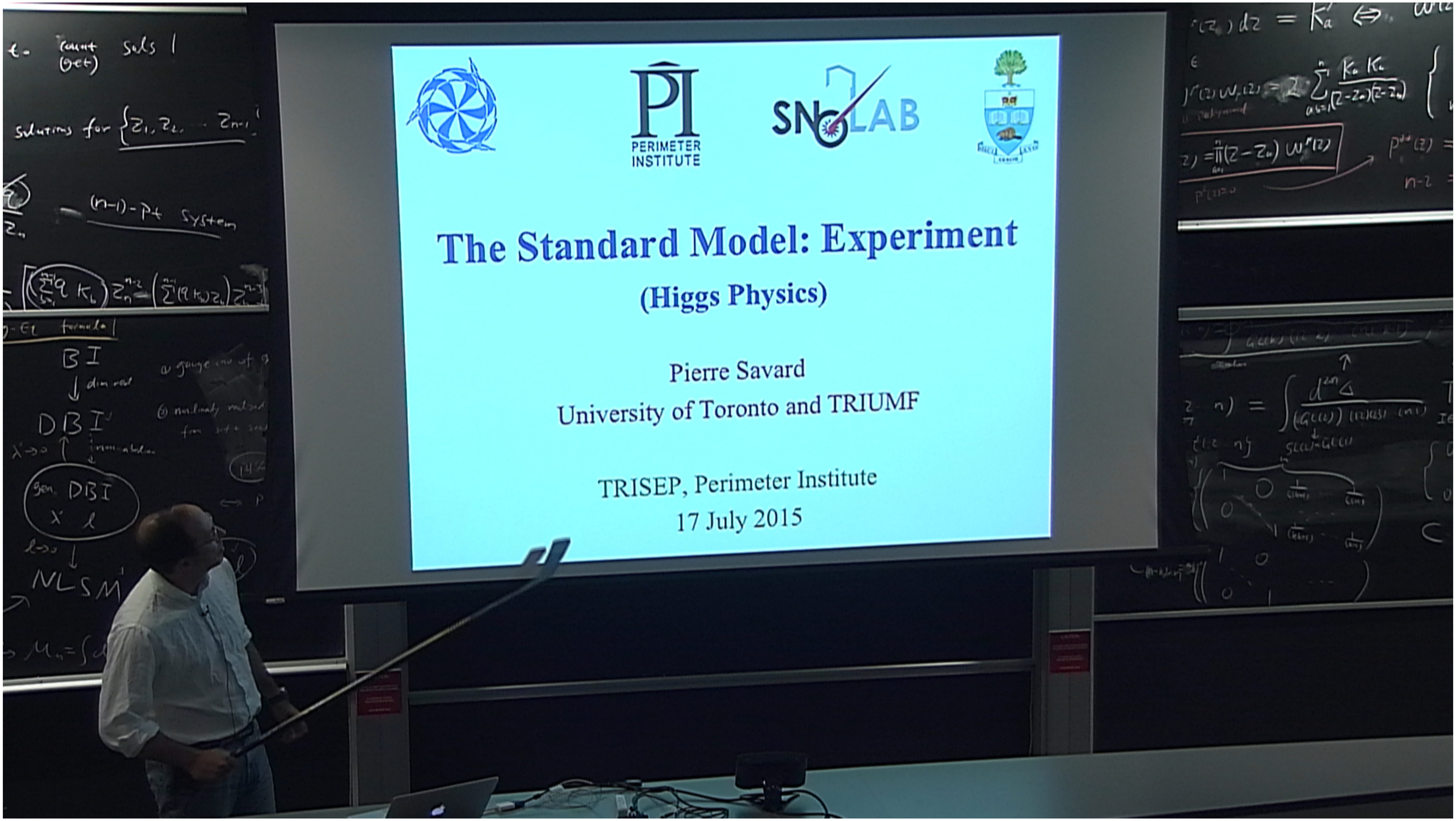
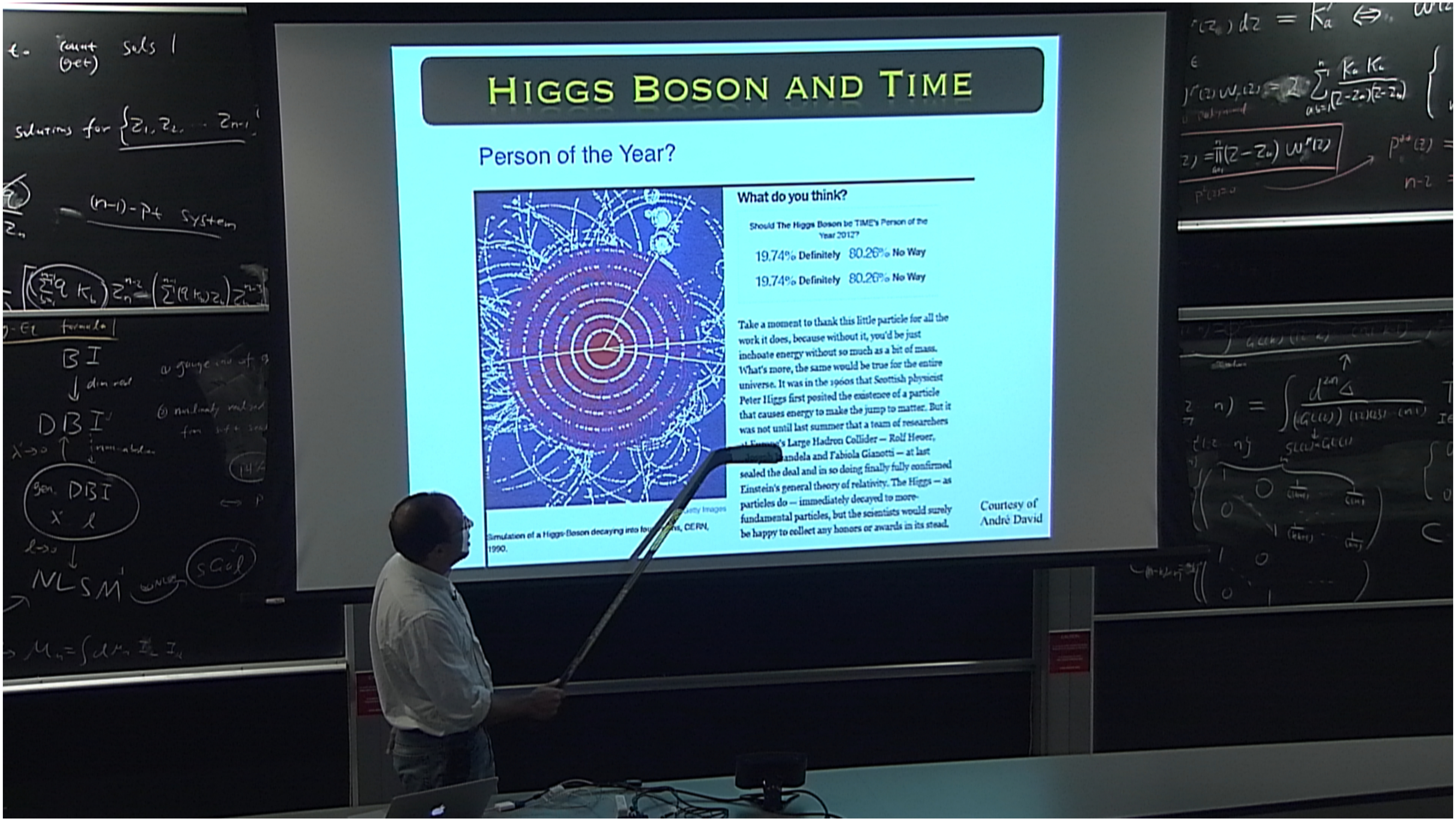
Title: The Standard Model Experiment: Higgs Discovery

Date: Jul 17, 2015 11:00 AM

URL: http://pirsa.org/15070057

Abstract:


PERIMETER INSTITUTE
SNOLAB
The Standard Model: Experiment
(Higgs Physics)
Pierre Savard
University of Toronto and TRIUMF
TRISEP, Perimeter Institute
17 July 2015


HIGGS BOSON AND TIME
Person of the Year?
What do you think?
Should The Higgs Boson be TIME's Person of the Year 2012?
19.74% Definitely 80.26% No Way
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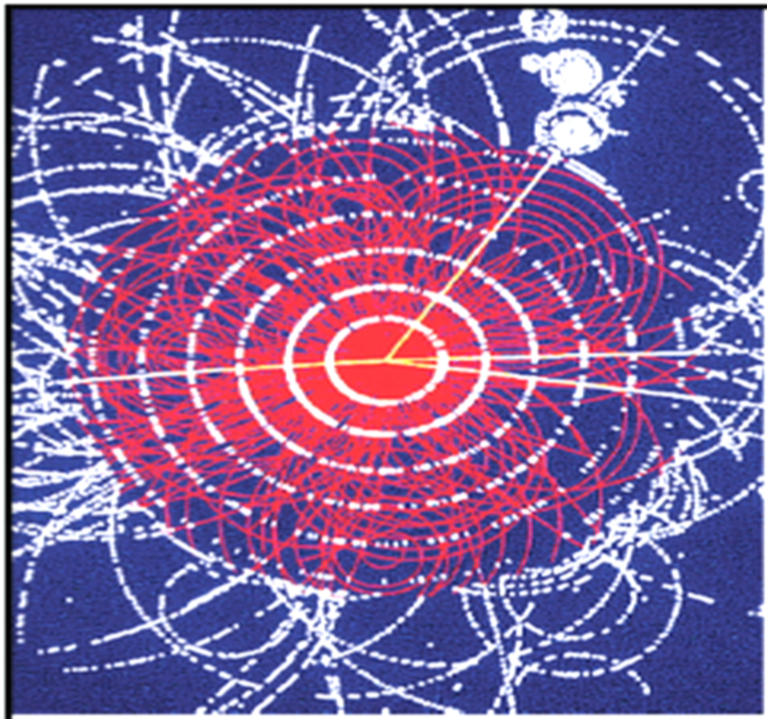
Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers
's Large Hadron Collider — Rolf Heuer,
andela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.
Simulation of a Higgs-Boson decaying into fo
ns, CERN, 1990.
Courtesy of André David

Higgs Boson and Time

Person of the Year?



SSPL/Getty Images

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

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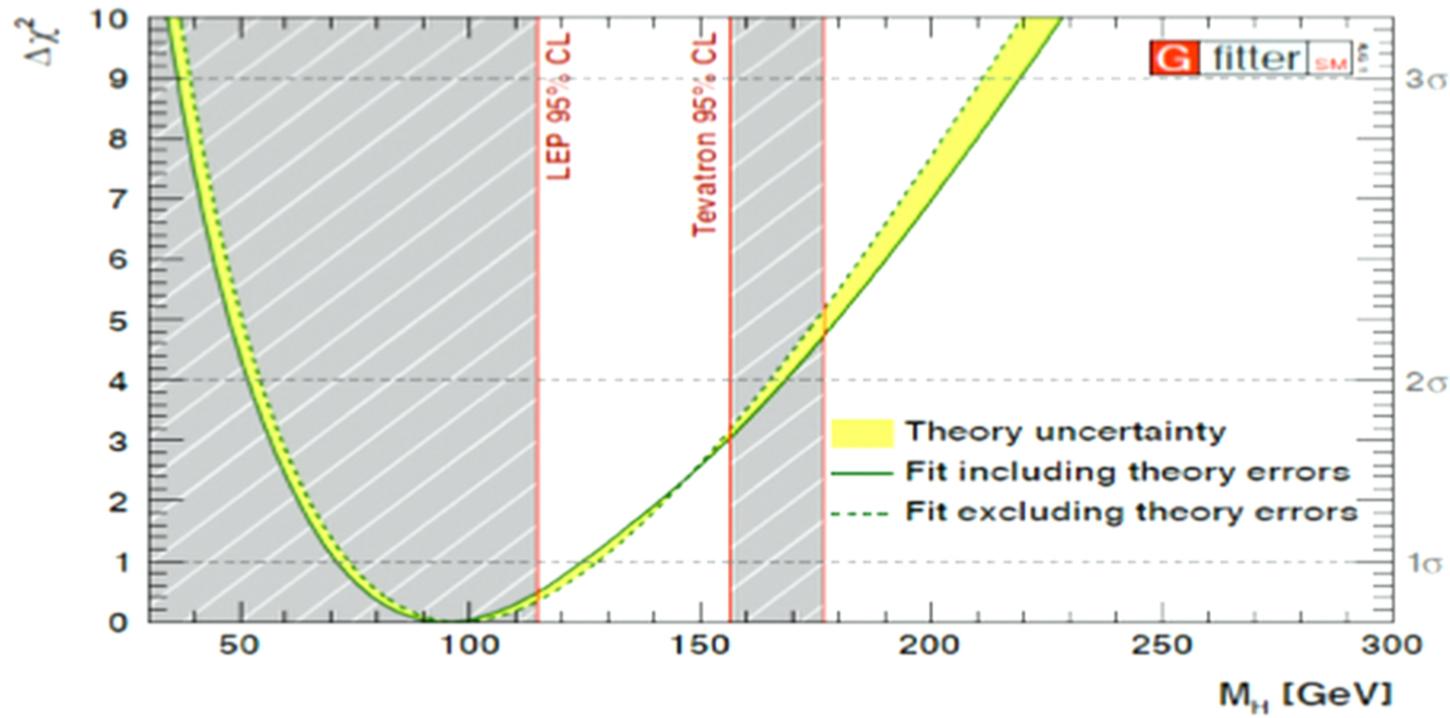
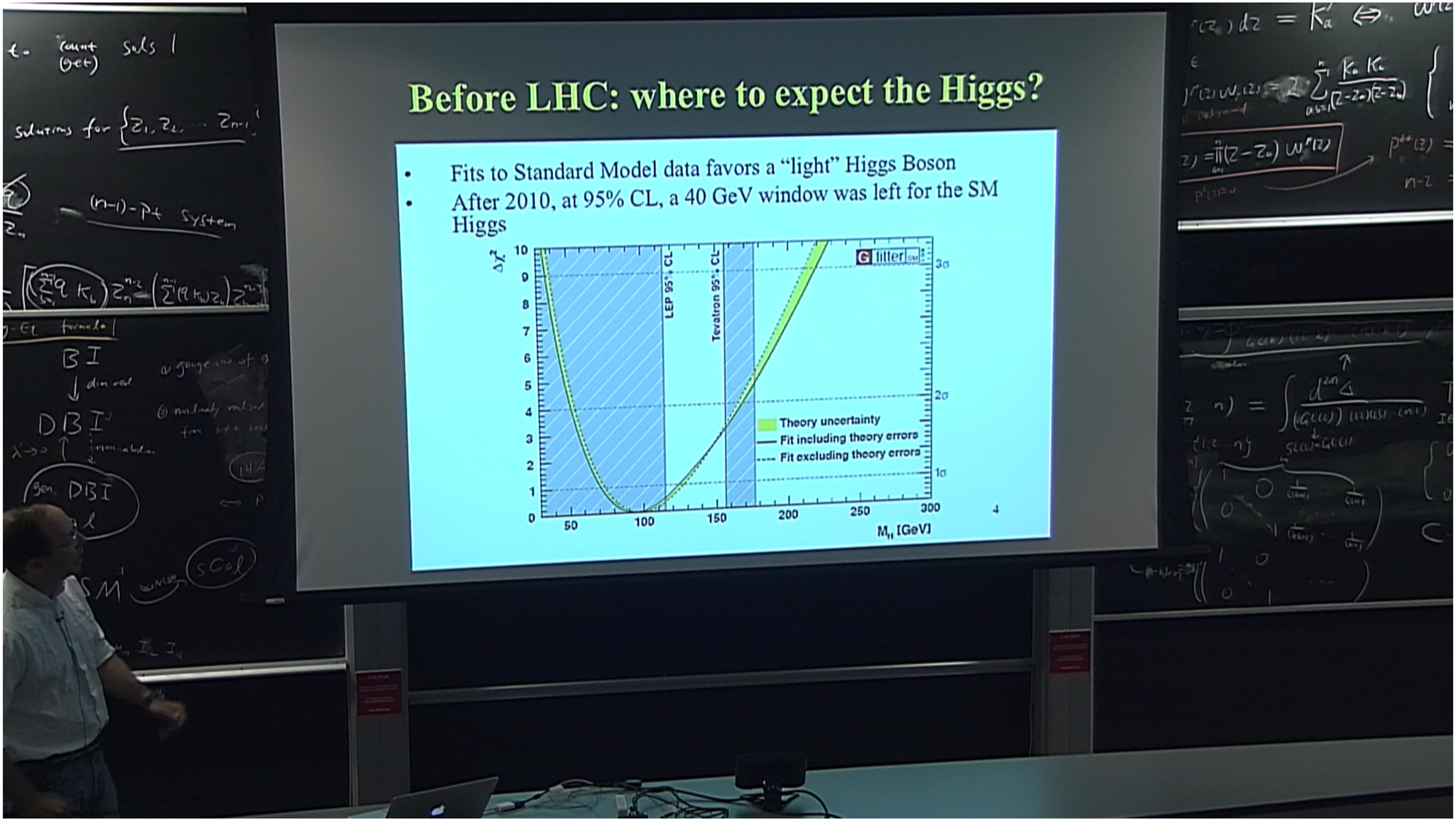
Courtesy of André David

Before LHC: where to expect the Higgs?

- Fits to Standard Model data favors a "light" Higgs Boson
- After 2010, at 95% CL, a 40 GeV window was left for the SM Higgs



4


Before LHC: where to expect the Higgs?
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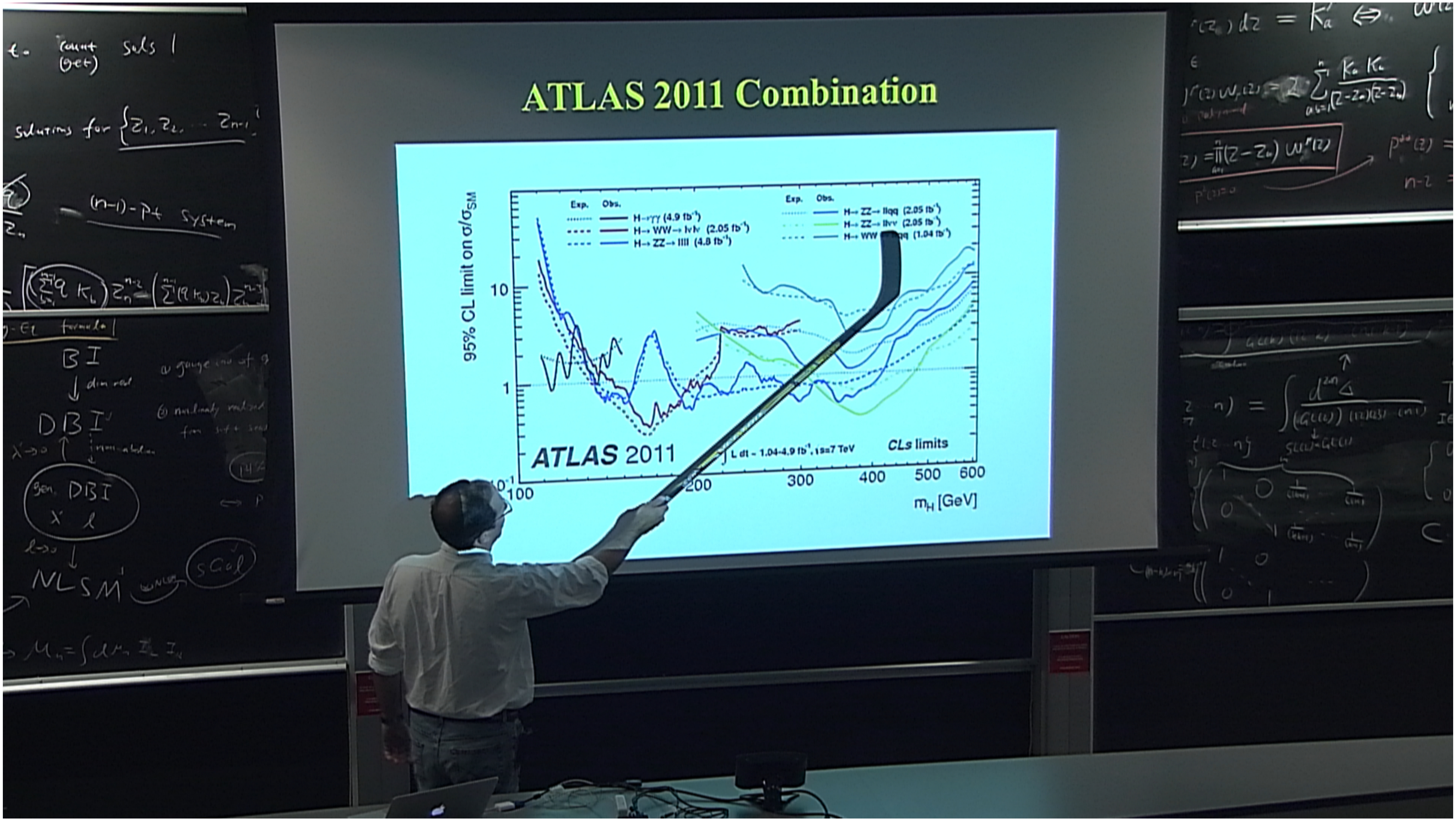
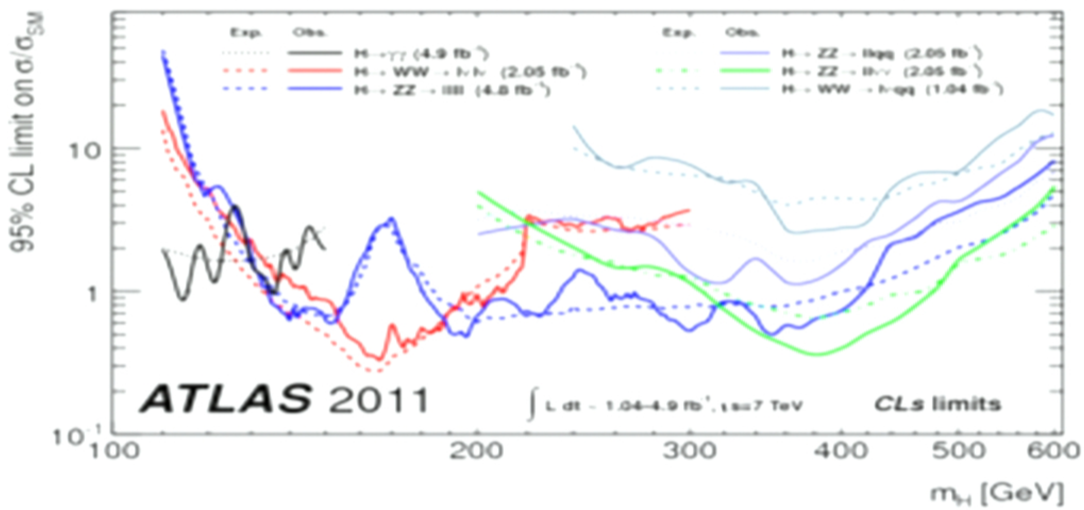
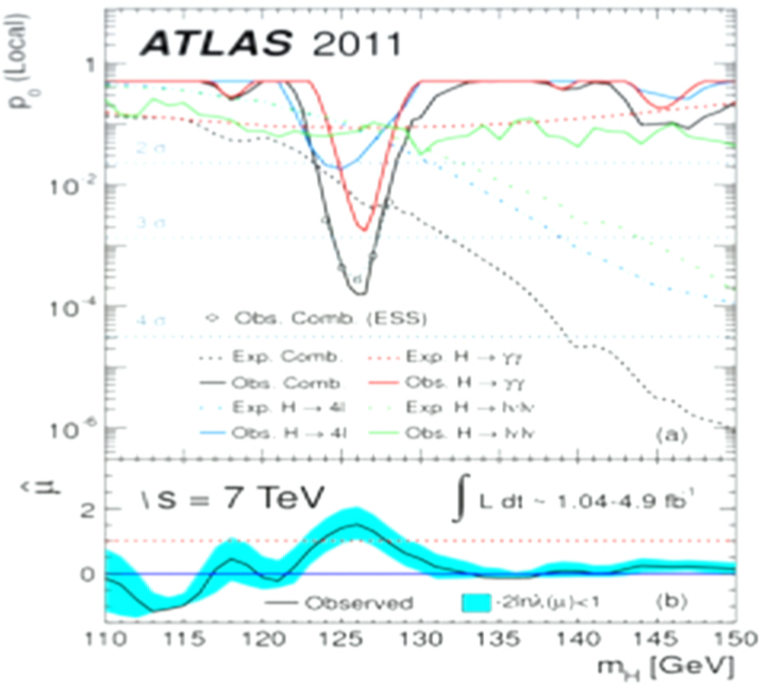
Δχ²
LEP 95% CL
Tevatron 95% CL
Gfitter SM
3σ
2σ
1σ
Theory uncertainty
Fit including theory errors
Fit excluding theory errors
M_H [GeV]
4


ATLAS 2011 Combination
95% CL limit on σ/σ_SM
Exp. Obs.
H→γγ (4.9 fb⁻¹)
H→ WW→ lνlν (2.05 fb⁻¹)
H→ ZZ→ llll (4.8 fb⁻¹)
H→ ZZ→ llqq (2.05 fb⁻¹)
H→ ZZ→ llνν (2.05 fb⁻¹)
ATLAS 2011
CLs limits
10
1
100
200
300
400
500
600
m_H [GeV]

ATLAS 2011 Combination

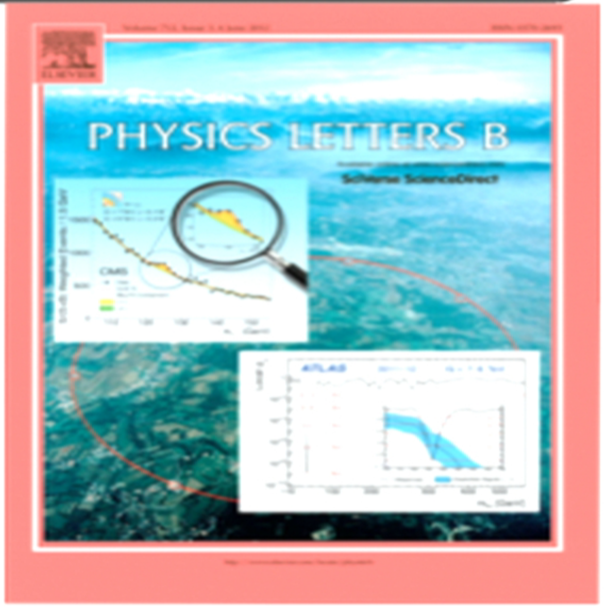
- At 126 GeV local signif.: 3.5σ (p_0: 2.7x 10^{-4})
- Accounting for Look Elsewhere Effect (LEE)::
  - Global p_0~0.6% (2.5 σ) for 114-146 GeV (HCP mass range)
  - Global p_0~1.4% (2.2 σ) for full mass range 110-600 GeV





7

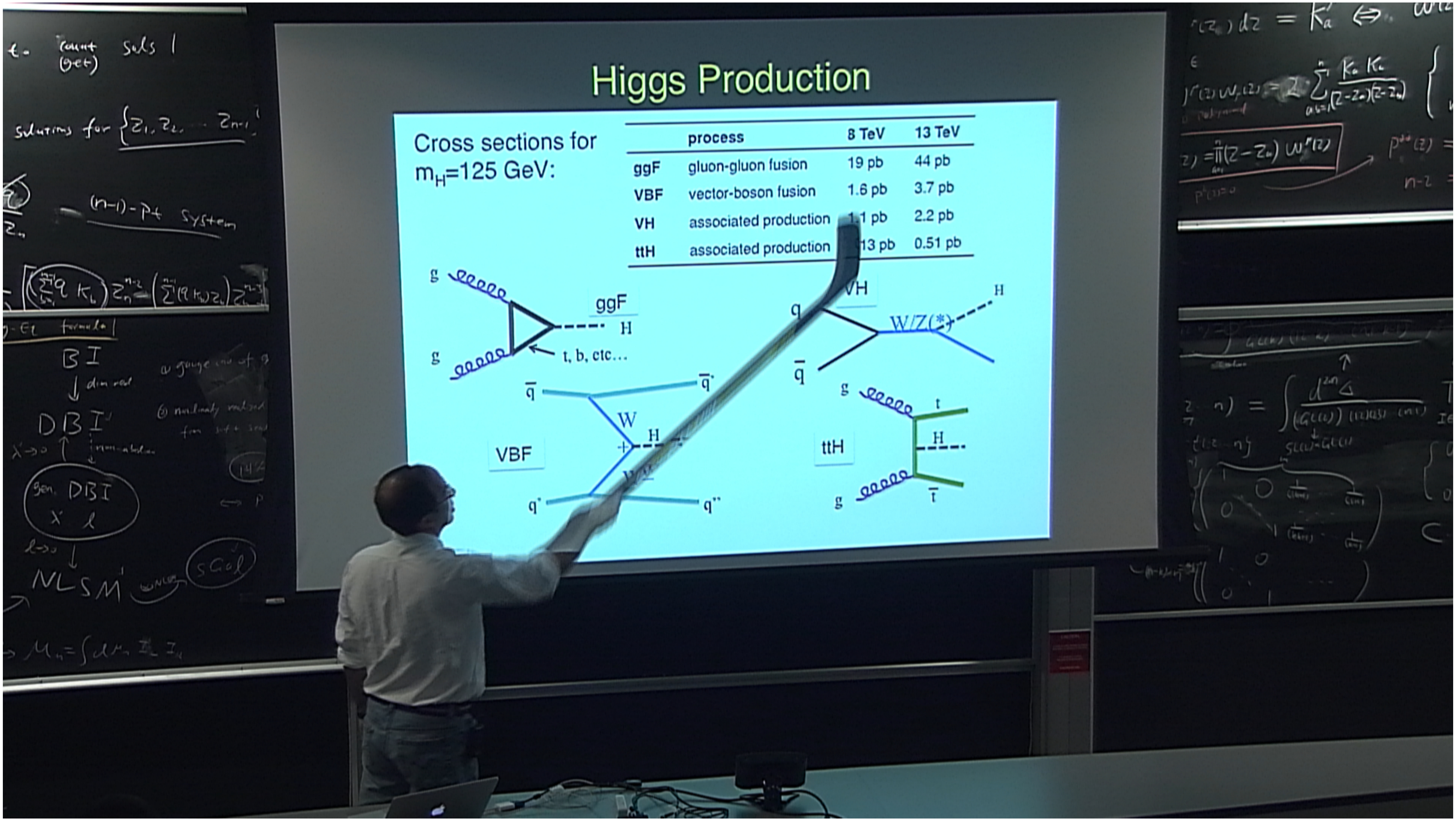
CHRONOLOGY



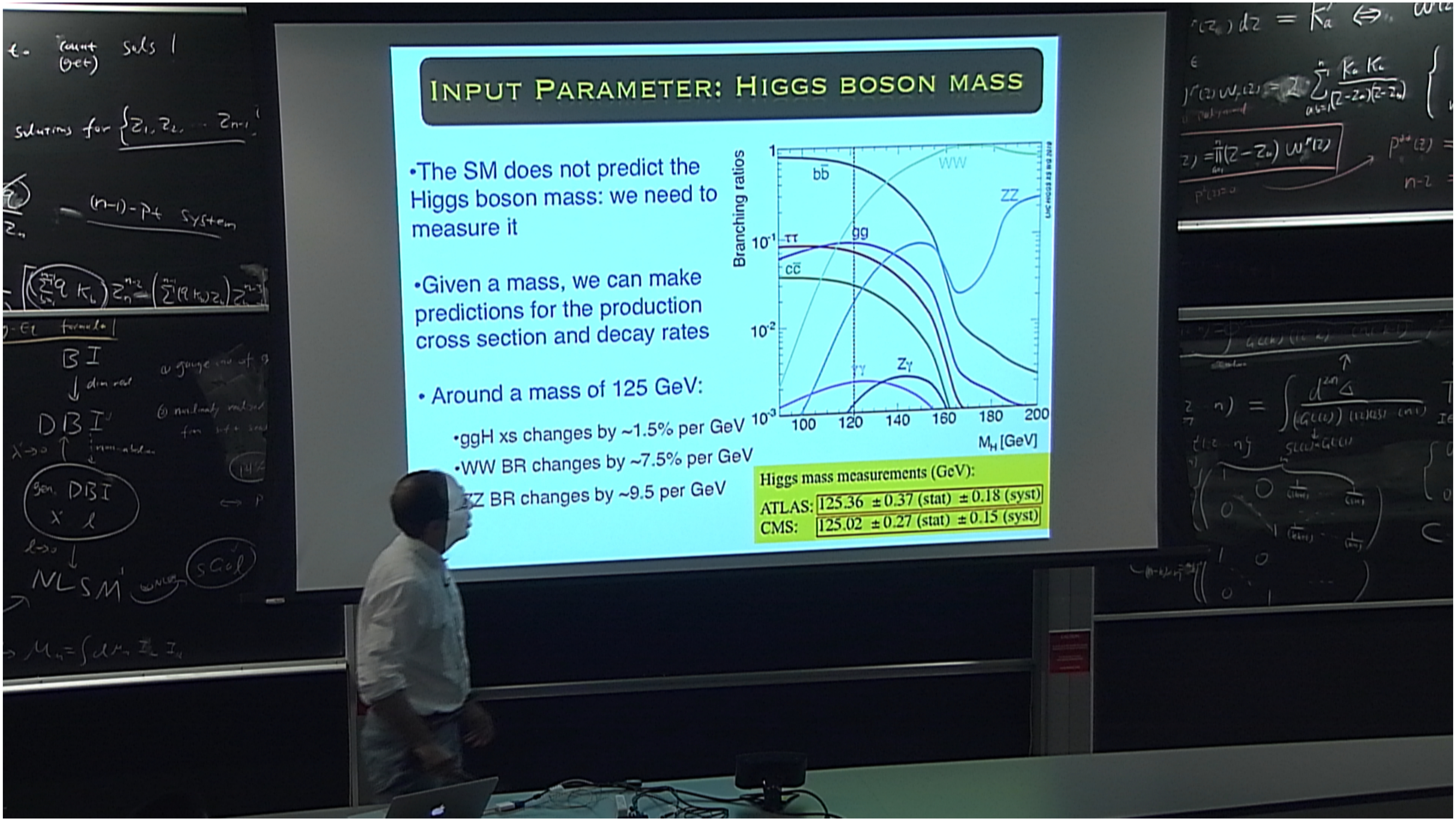
- 3 years ago, the LHC started to produce collisions at a centre of mass of 8 TeV. The 7 TeV run showed some hints of a signal consistent with the Standard Model (SM Higgs boson
- On July 4th of 2012, both ATLAS and CMS announced that they had discovered a new particle consistent with what was expected in the SM. Two papers were then submitted at the end of July

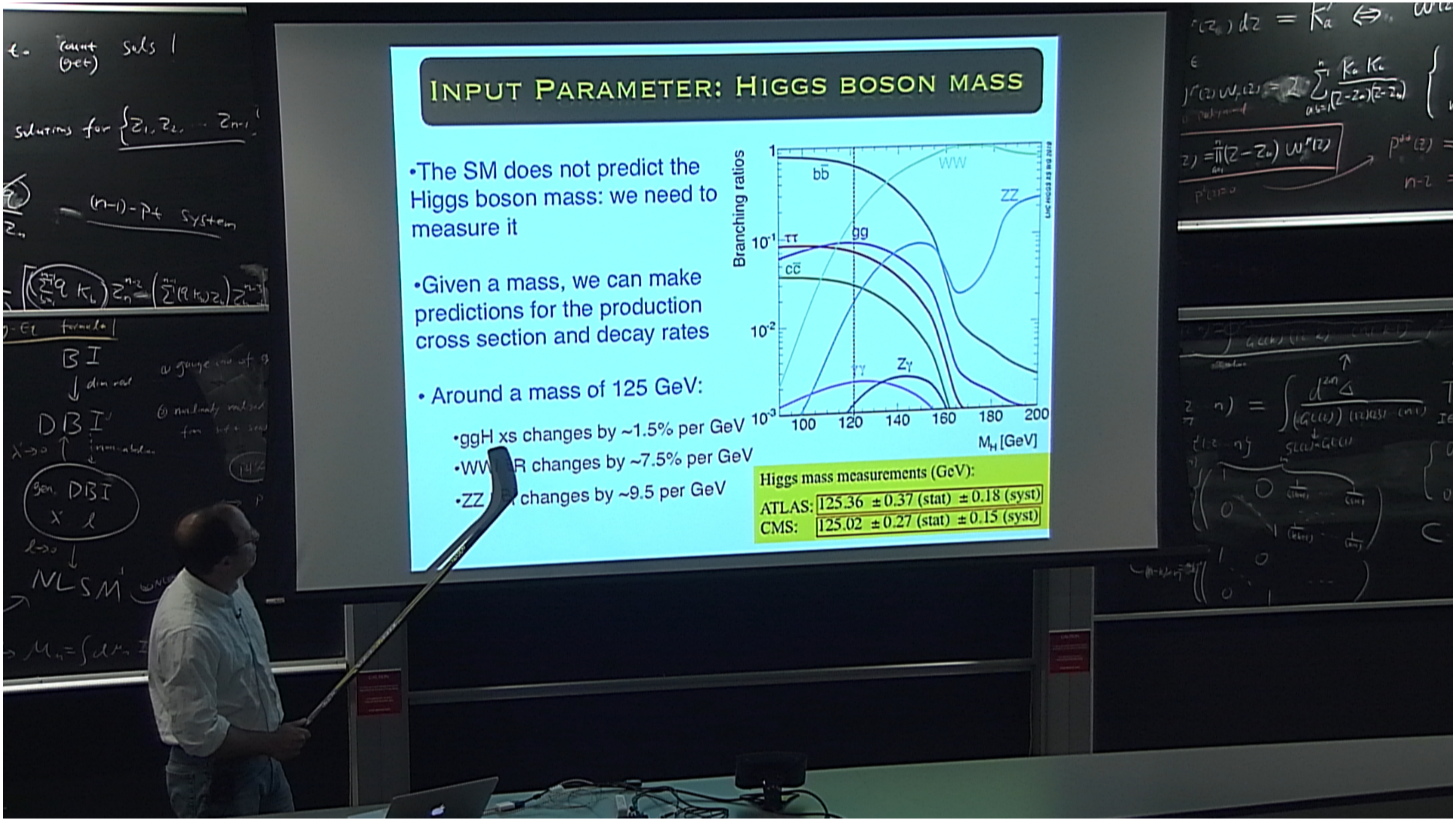
  - The ATLAS paper was titled: "Observation of a New Particle in the Search for the Standard Model Higgs Boson"

- The LHC delivered 4 times the data used for the discovery by the end of 2012. Results using the full dataset were presented in March 2013 prompted CERN to declare that the new particle was "a" Higgs boson (two key ATLAS papers)



Higgs Production
Cross sections for m_H=125 GeV:
process | 8 TeV | 13 TeV
ggF gluon-gluon fusion 19 pb 44 pb
VBF vector-boson fusion 1.6 pb 3.7 pb
VH associated production 2.2 pb
ttH associated production 0.51 pb
ggF
VBF
VH
ttH
W/Z(*)
t, b, etc…


INPUT PARAMETER: HIGGS BOSON MASS
•The SM does not predict the Higgs boson mass: we need to measure it
•Given a mass, we can make predictions for the production cross section and decay rates
• Around a mass of 125 GeV:
•ggH xs changes by ~1.5% per GeV
•WW BR changes by ~7.5% per GeV
•ZZ BR changes by ~9.5 per GeV
Branching ratios
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
M_H [GeV]
Higgs mass measurements (GeV):
ATLAS: 125.36 ± 0.37 (stat) ± 0.18 (syst)
CMS: 125.02 ± 0.27 (stat) ± 0.15 (syst)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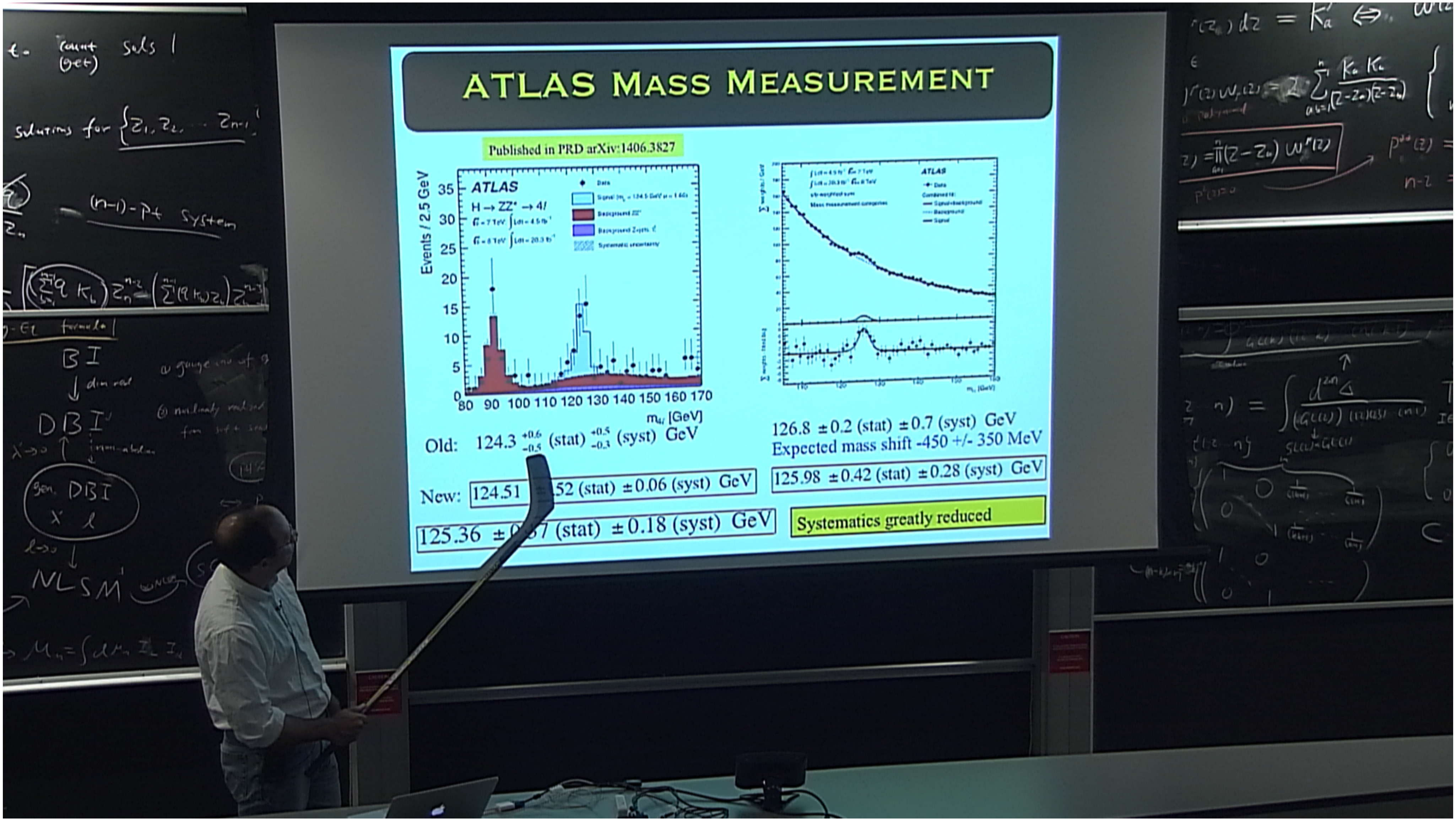
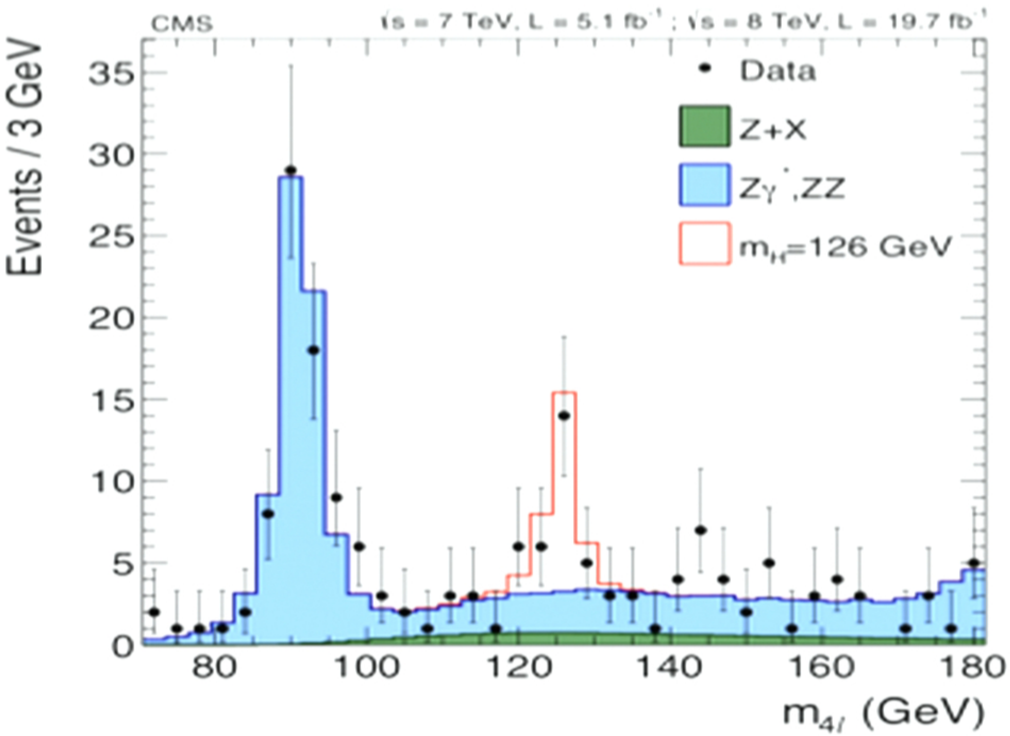
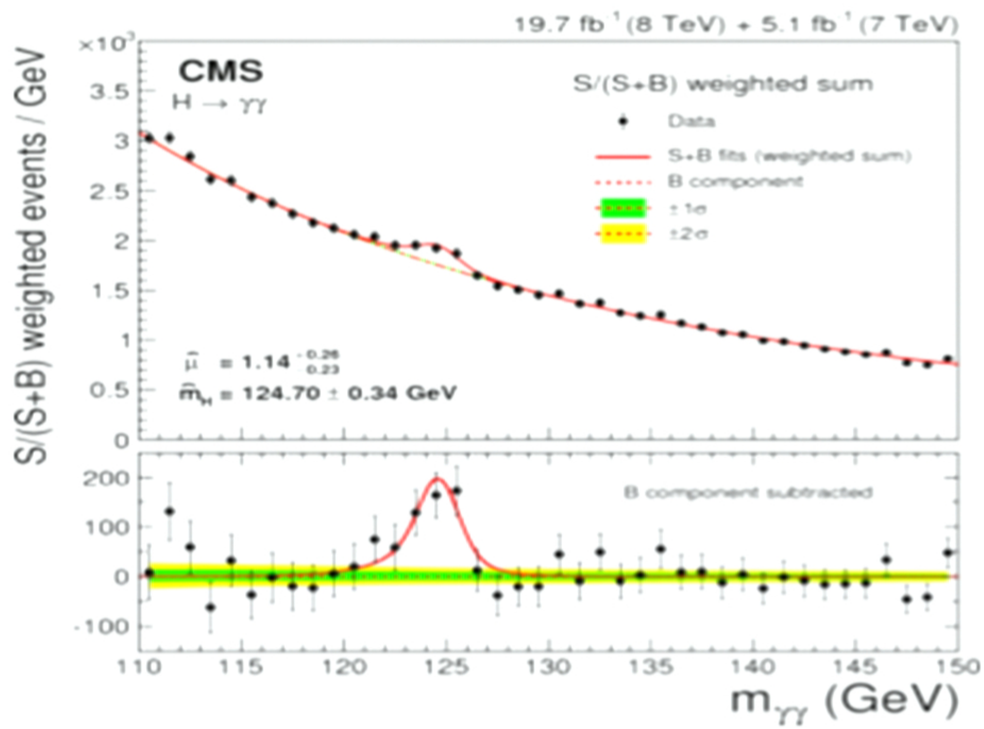

ATLAS Mass Measurement
Published in PRD arXiv:1406.3827
Old: 124.3 +0.6 -0.5 (stat) +0.5 -0.3 (syst) GeV
126.8 ±0.2 (stat) ±0.7 (syst) GeV
Expected mass shift -450 +/- 350 MeV
New: 124.51 ... 52 (stat) ±0.06 (syst) GeV
125.98 ±0.42 (stat) ±0.28 (syst) GeV
125.36 ... 7 (stat) ±0.18 (syst) GeV
Systematics greatly reduced

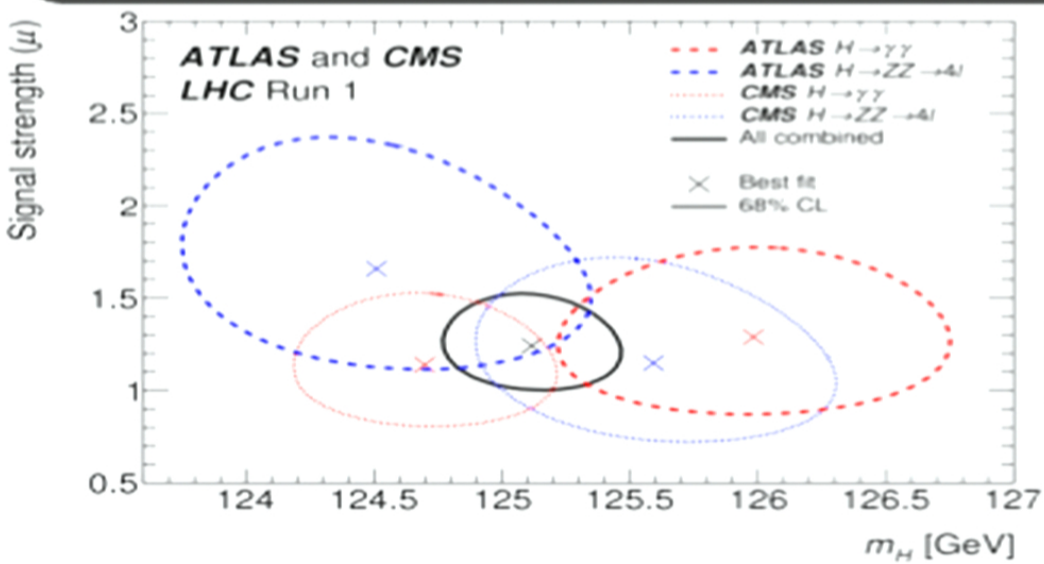
CMS Mass Measurement





CMS combined mass result: 125.02 ± 0.27 (stat) ± 0.15 (syst) GeV

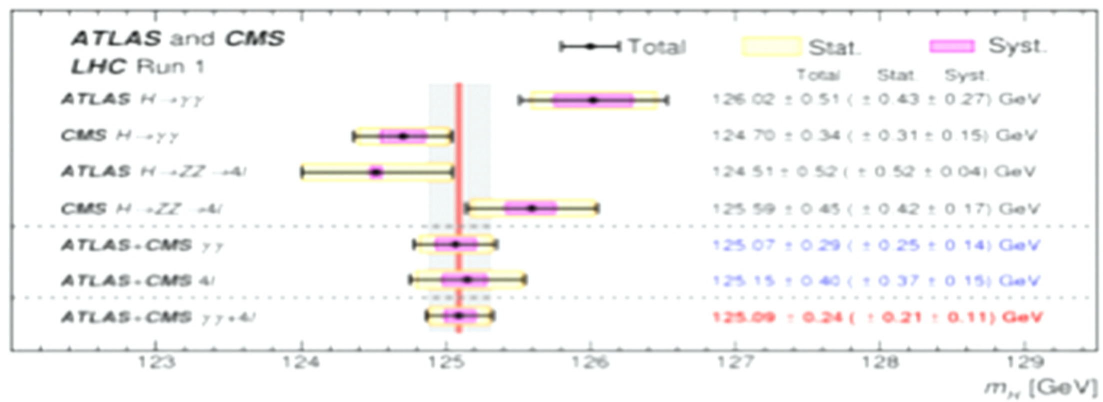
Higgs Mass Measurement

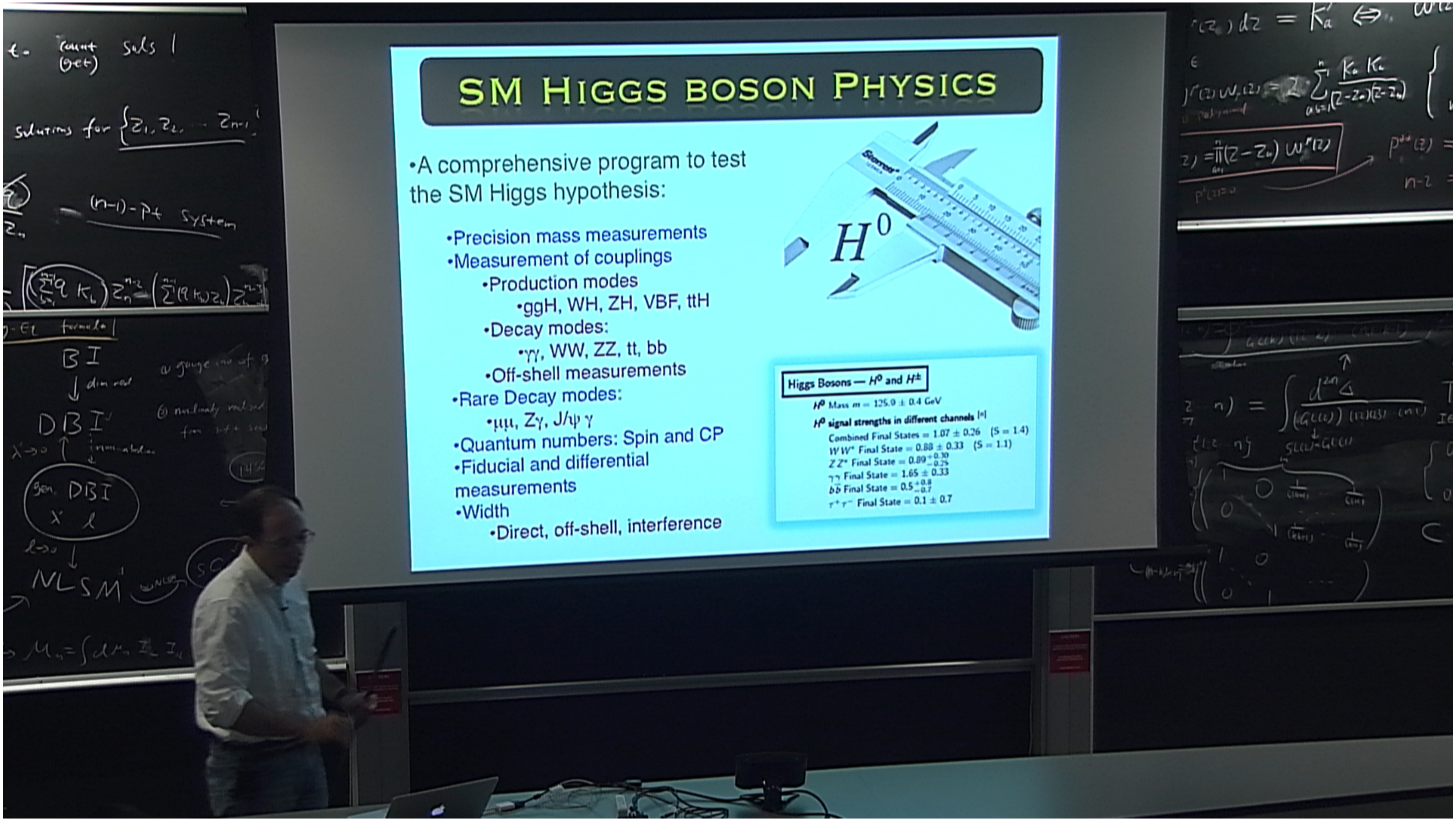


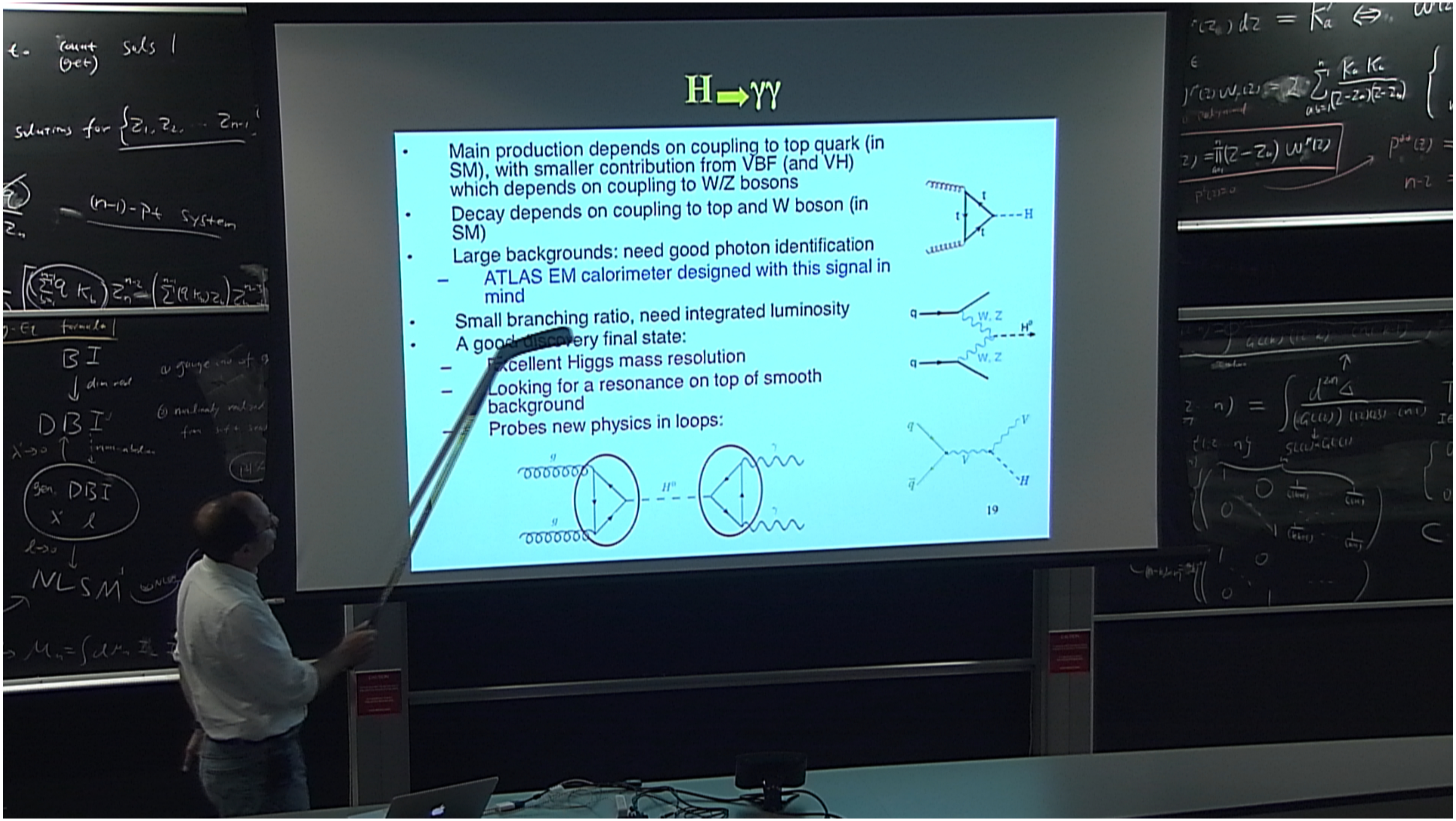
Combined ATLAS/CMS Mass:

$125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{syst})\ \text{GeV}$

0.2% precision measurement. Statistical uncertainty is the dominant uncertainty




SM Higgs boson Physics
•A comprehensive program to test the SM Higgs hypothesis:
•Precision mass measurements
•Measurement of couplings
•Production modes
•ggH, WH, ZH, VBF, ttH
•Decay modes:
•γγ, WW, ZZ, tt, bb
•Off-shell measurements
•Rare Decay modes:
•μμ, Zγ, J/ψ γ
•Quantum numbers: Spin and CP
•Fiducial and differential measurements
•Width
•Direct, off-shell, interference
H^0
Higgs Bosons — H^0 and $H^\pm$
H^0 Mass $m = 125.0 \pm 0.4$ GeV
H^0 signal strengths in different channels [a]
Combined Final States = 1.07 ± 0.26 (S = 1.4)
WW^* Final State = 0.88 ± 0.33 (S = 1.1)
ZZ^* Final State = $0.89^{+0.30}_{-0.25}$
$\gamma\gamma$ Final State = 1.65 ± 0.33
$b\bar{b}$ Final State = $0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State = 0.1 ± 0.7


H→γγ
Main production depends on coupling to top quark (in SM), with smaller contribution from VBF (and VH) which depends on coupling to W/Z bosons
Decay depends on coupling to top and W boson (in SM)
Large backgrounds: need good photon identification
ATLAS EM calorimeter designed with this signal in mind
Small branching ratio, need integrated luminosity
A good discovery final state:
Excellent Higgs mass resolution
Looking for a resonance on top of smooth background
Probes new physics in loops:
19

$H \rightarrow \gamma\gamma$

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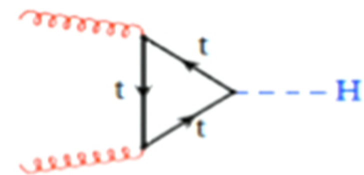

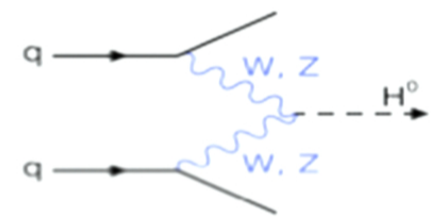

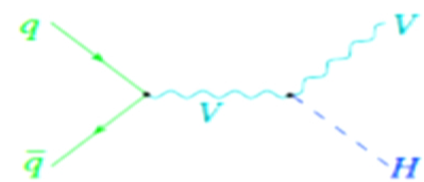

19

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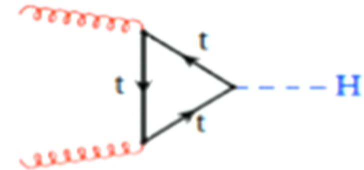
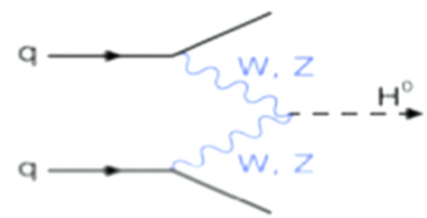
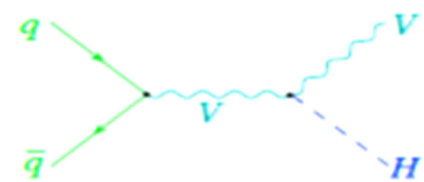
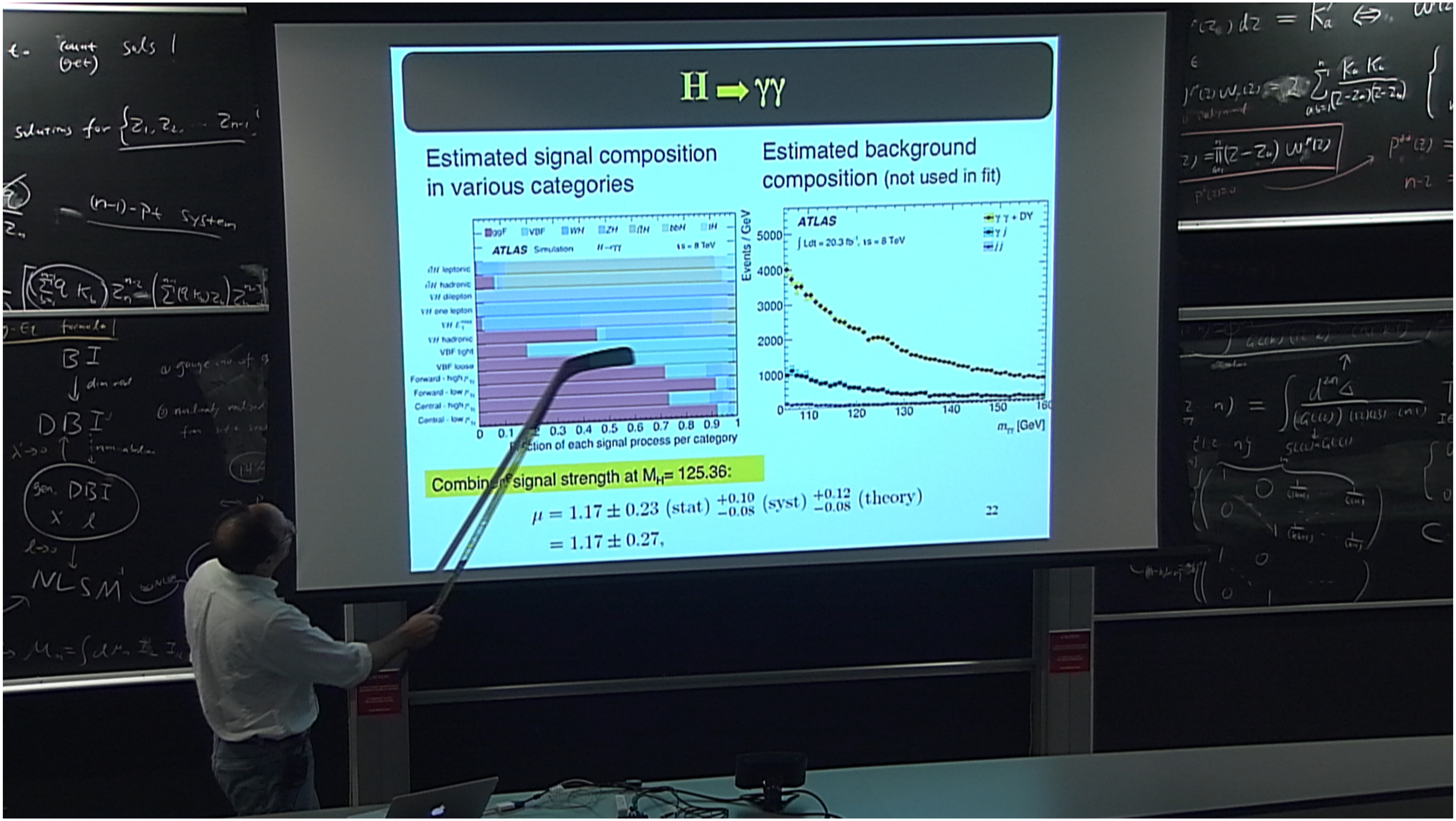
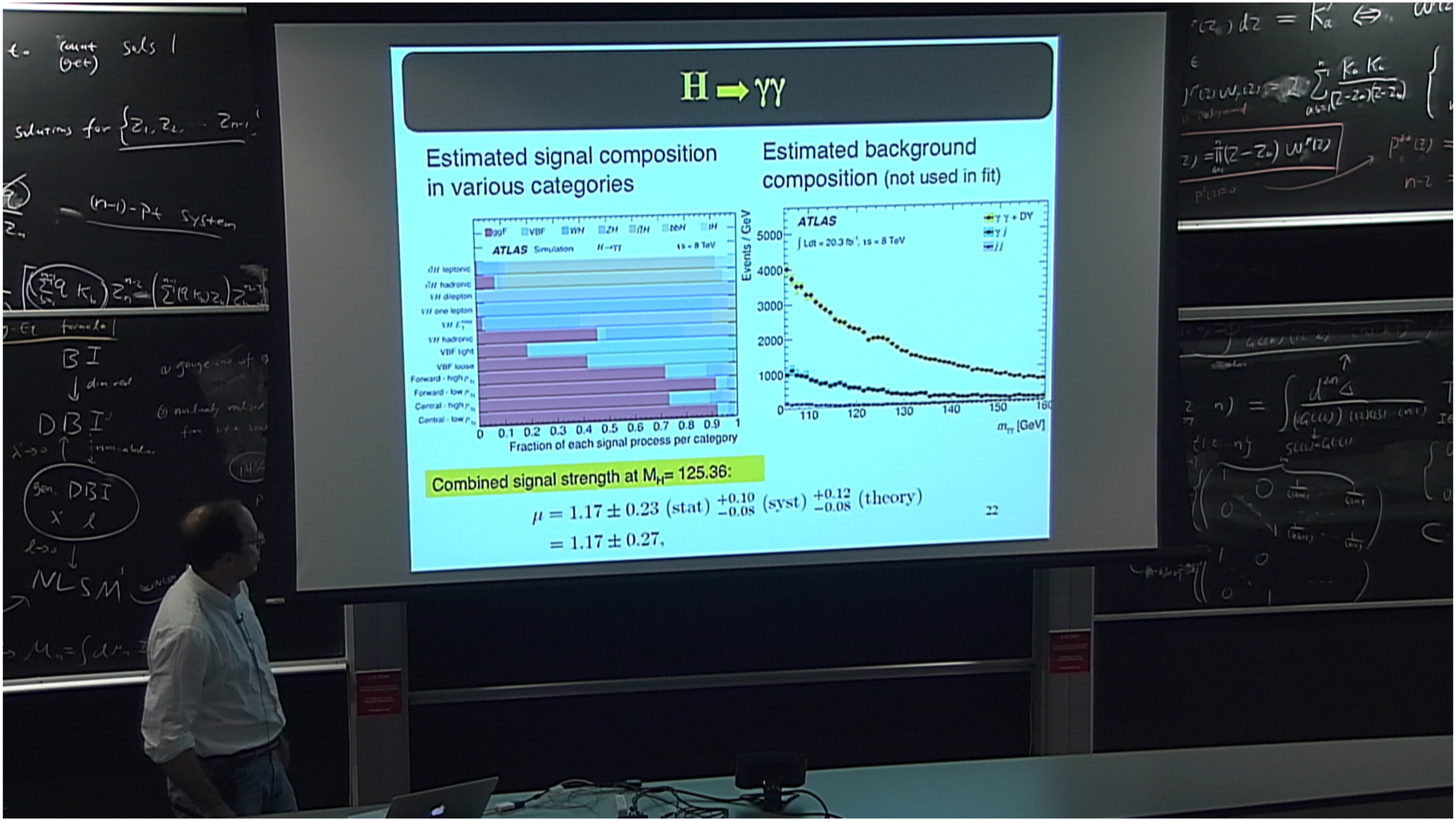






19


H ⇒ γγ
Estimated signal composition in various categories
Estimated background composition (not used in fit)
ATLAS Simulation
ATLAS
Fraction of each signal process per category
Events / GeV
$m_{\gamma\gamma}$ [GeV]
Combined signal strength at M_H= 125.36:
$\mu = 1.17 \pm 0.23\ (\text{stat})\ ^{+0.10}_{-0.08}\ (\text{syst})\ ^{+0.12}_{-0.08}\ (\text{theory})$
$= 1.17 \pm 0.27,$
22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ATLAS
Events / GeV
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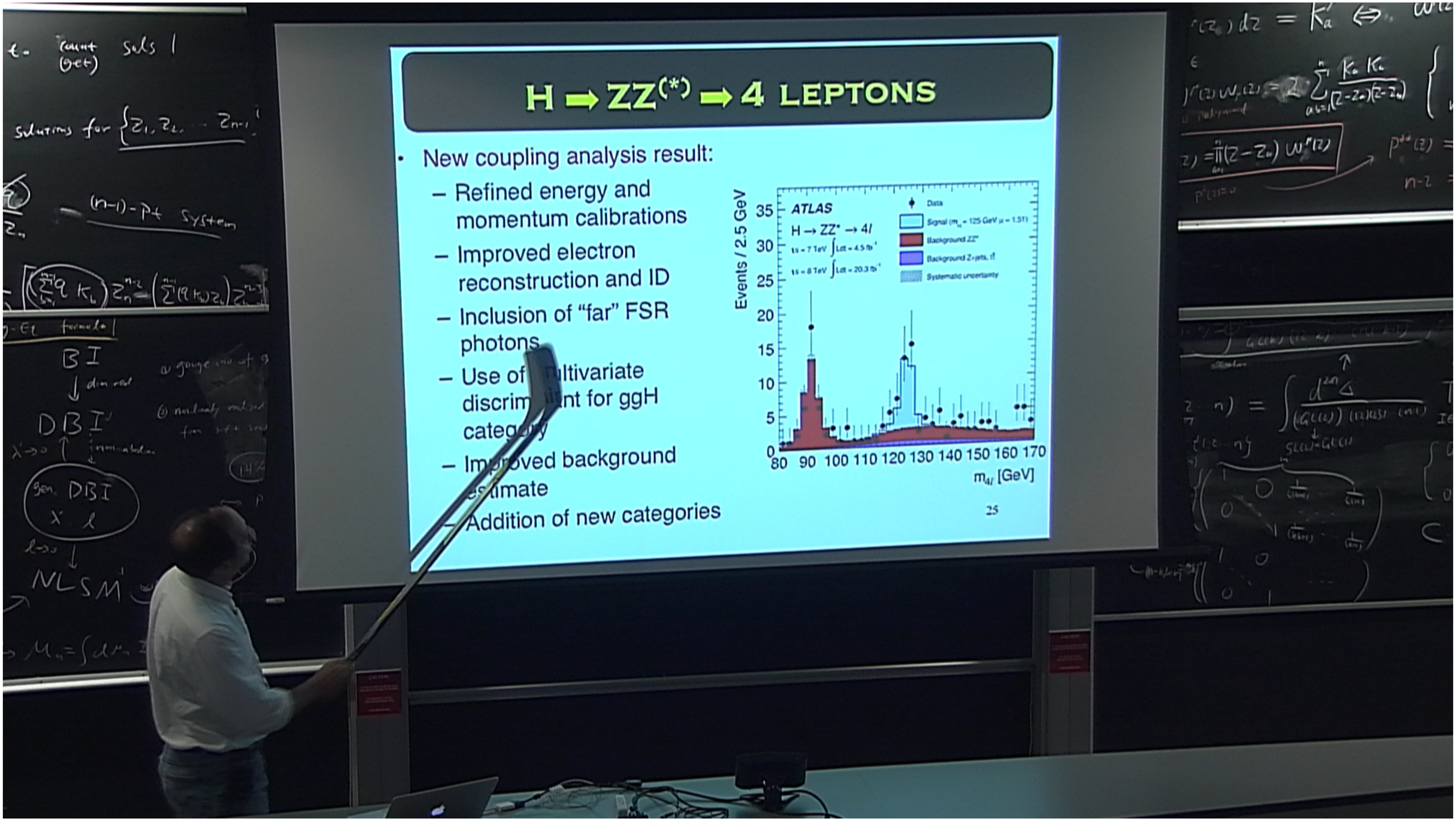
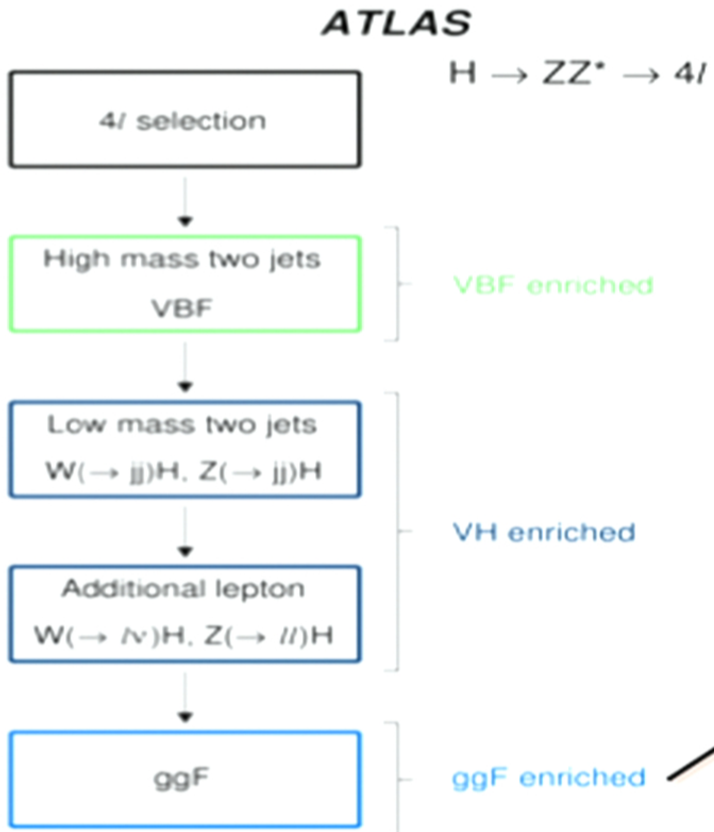
= 1.17 ± 0.27,
22


H ⇒ ZZ(*) ⇒ 4 LEPTONS
New coupling analysis result:
– Refined energy and momentum calibrations
– Improved electron reconstruction and ID
– Inclusion of "far" FSR photons
– Use of ultivariate
– Im oved background
– Addition of new categories
ATLAS
H → ZZ* → 4l
Data
Background ZZ*
Systematic uncertainty
Events / 2.5 GeV
m4l [GeV]
25

$H \rightarrow ZZ^{(*)} \rightarrow$ 4 LEPTONS

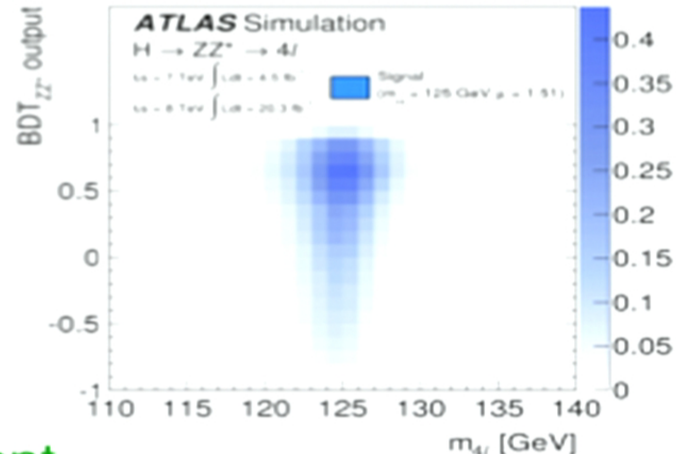
Event categorization:

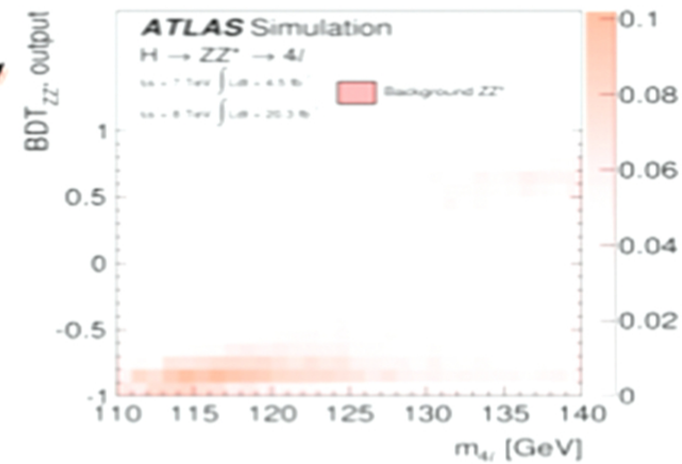


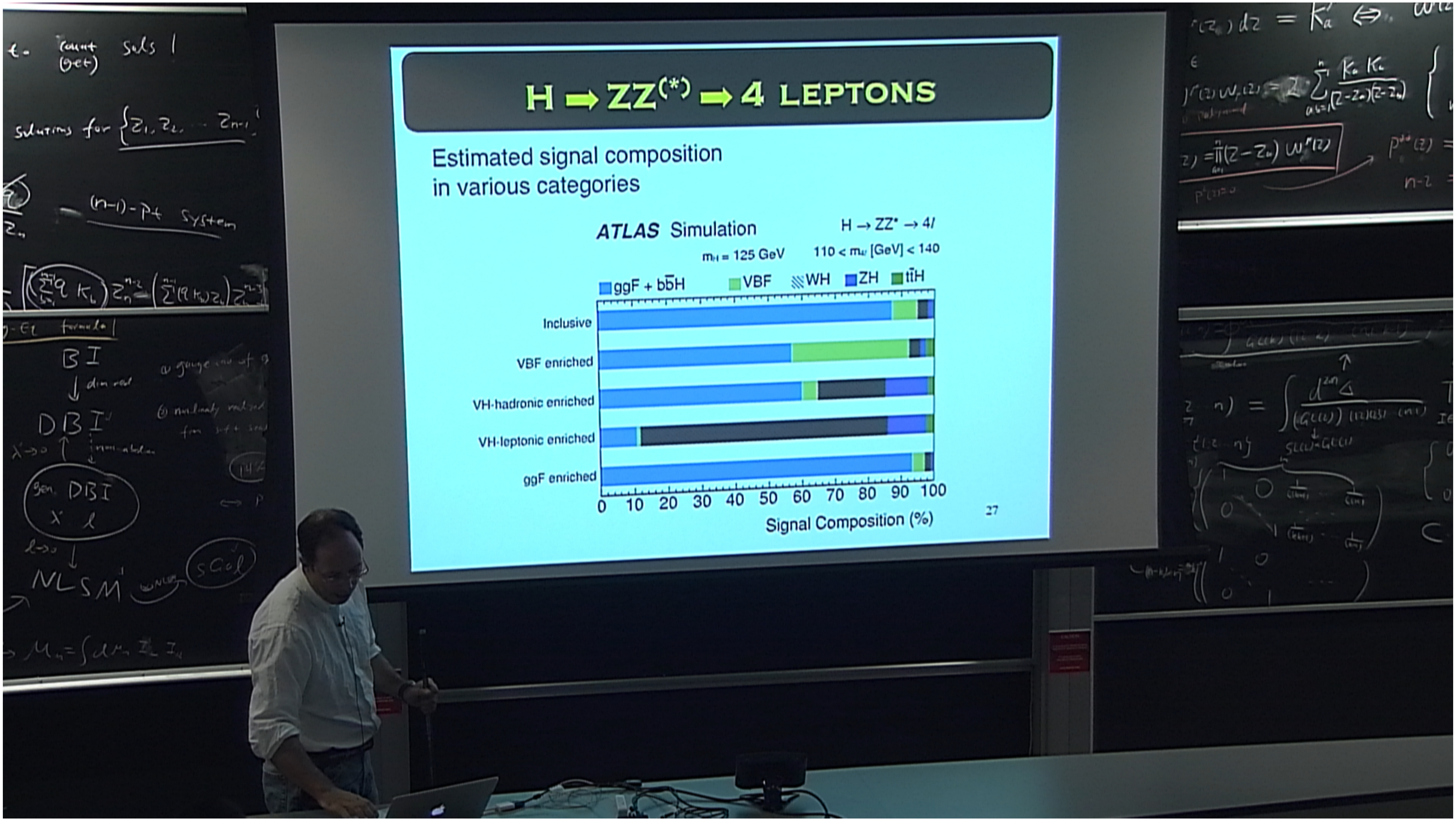
BDT vs mass

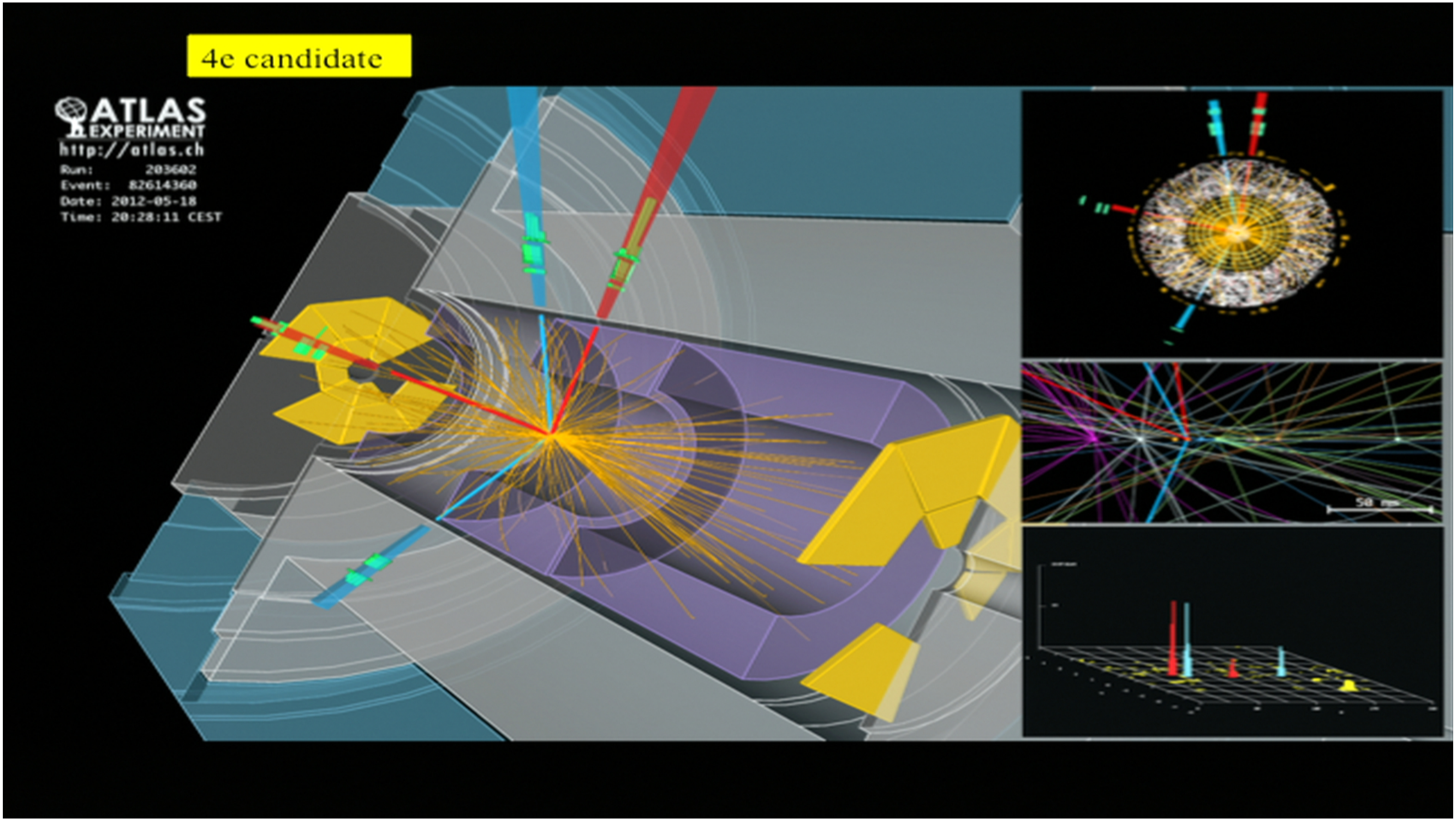
BDT variables:

- $P_T(4l)$
- $\eta(4l)$
- Matrix Element Discriminant





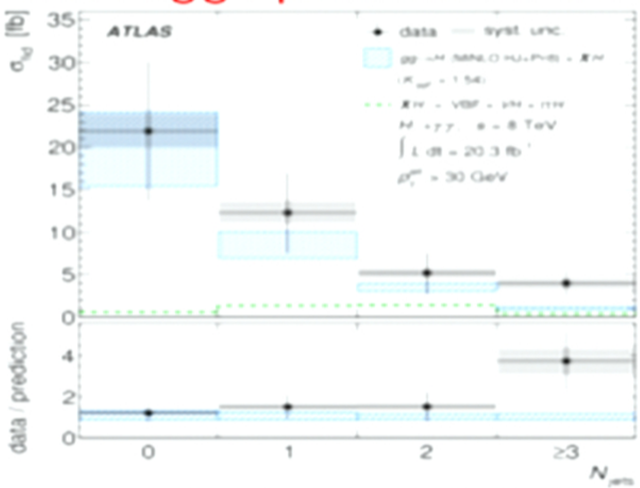

H → ZZ(*) → 4 LEPTONS
Estimated signal composition
in various categories
ATLAS Simulation
H → ZZ* → 4l
mH = 125 GeV
110 < m4l [GeV] < 140
ggF + bb̄H
VBF
WH
ZH
tt̄H
Inclusive
VBF enriched
VH-hadronic enriched
VH-leptonic enriched
ggF enriched
0 10 20 30 40 50 60 70 80 90 100
Signal Composition (%)
27



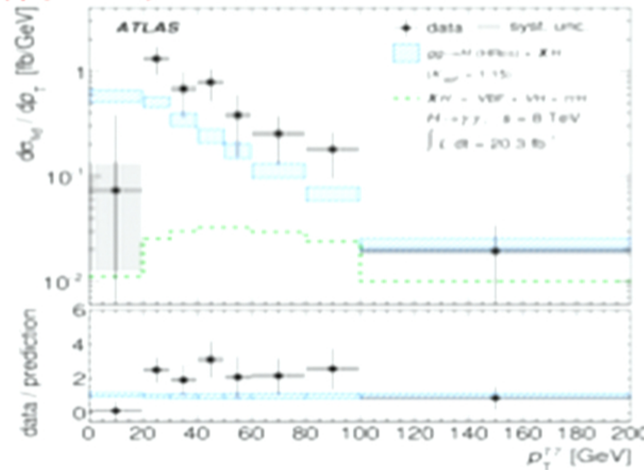
4e candidate
ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm

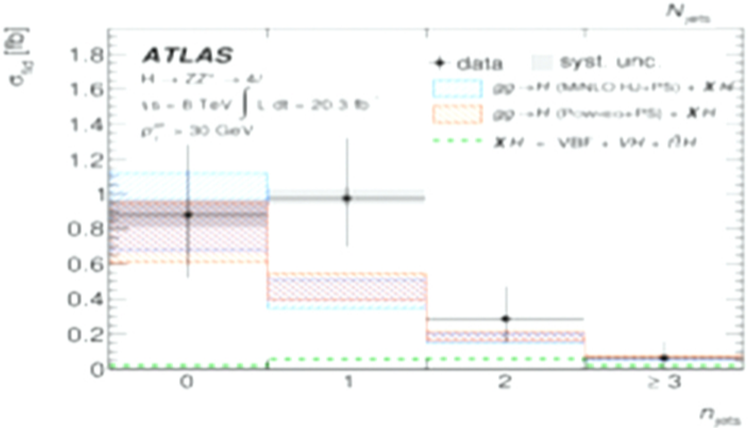
Differential Cross Sections

Test SM Higgs production theory predictions (γγ,ZZ)

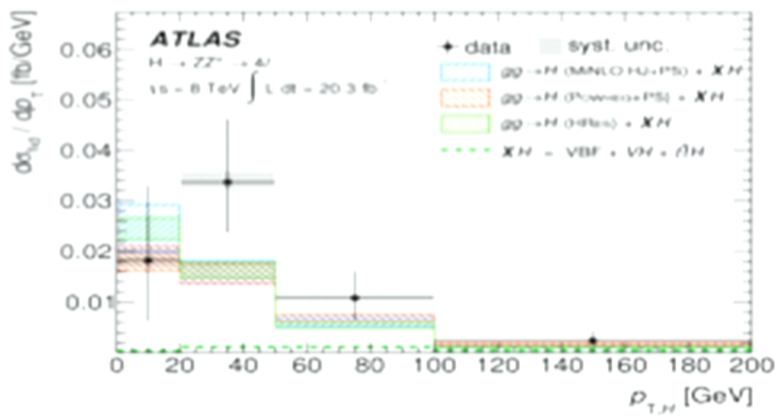


γγ



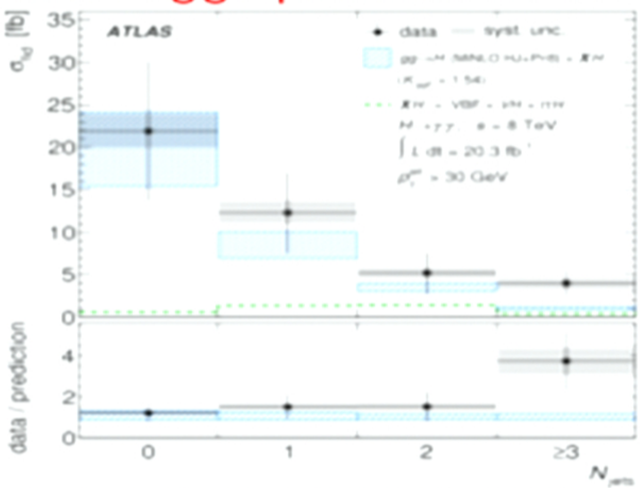


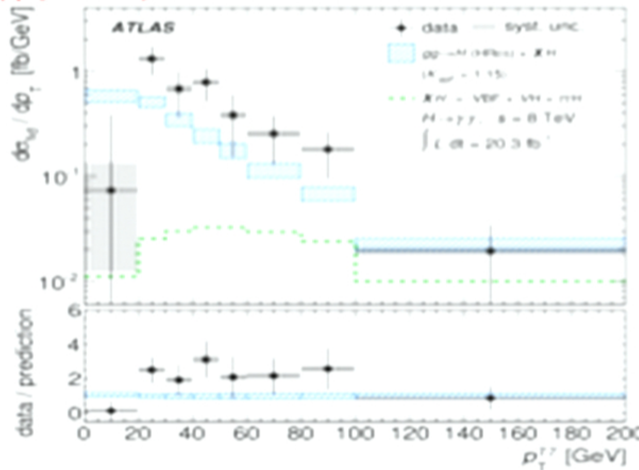
ZZ



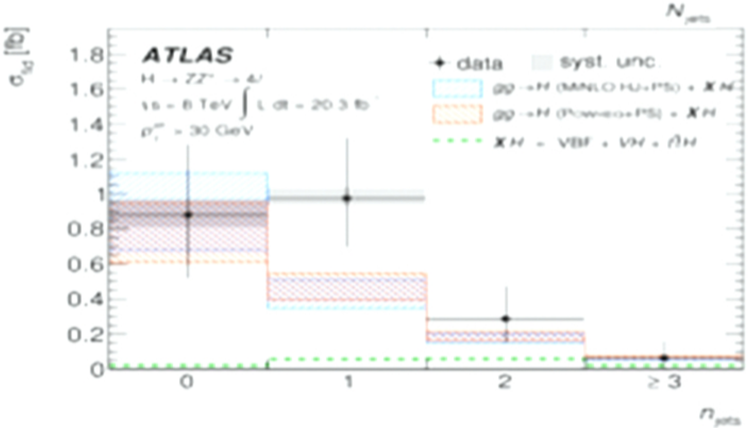
Differential Cross Sections

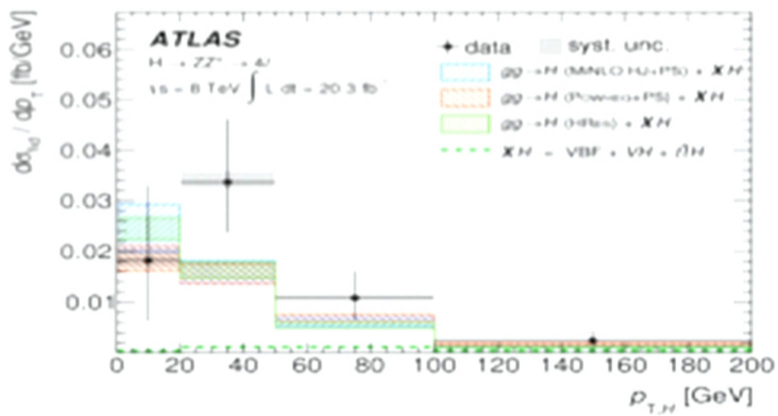
Test SM Higgs production theory predictions (γγ,ZZ)





γγ

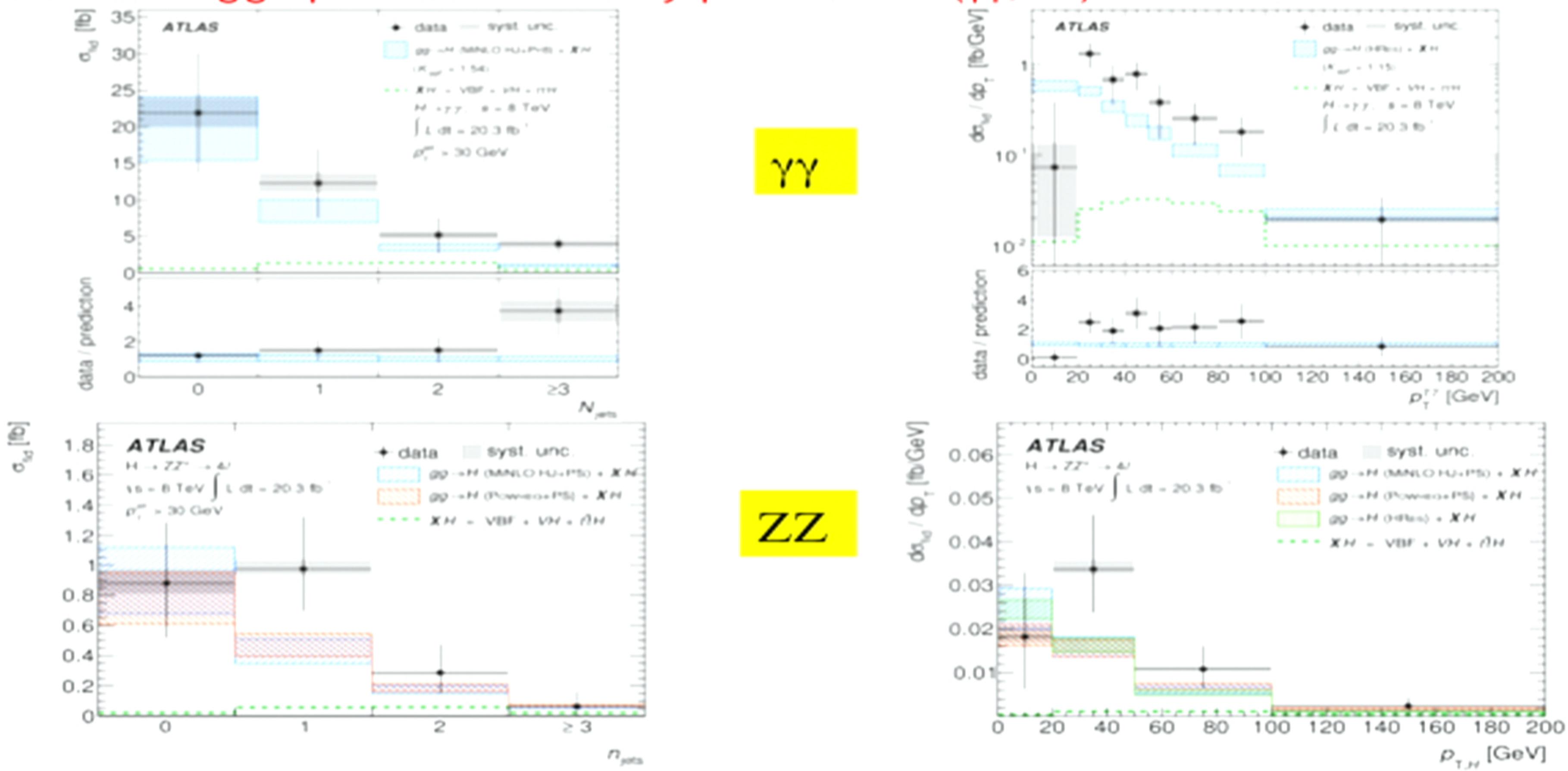


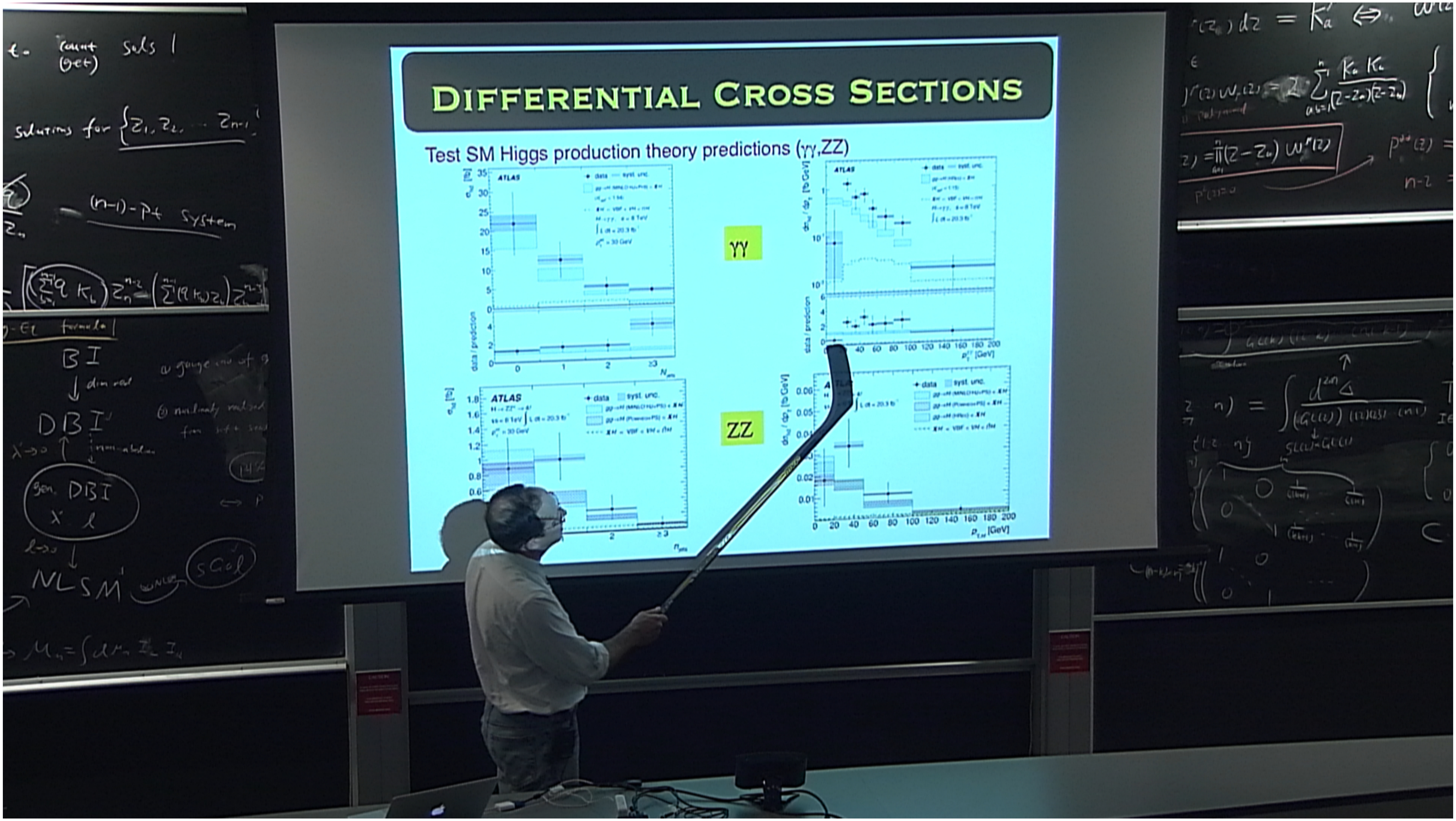


ZZ

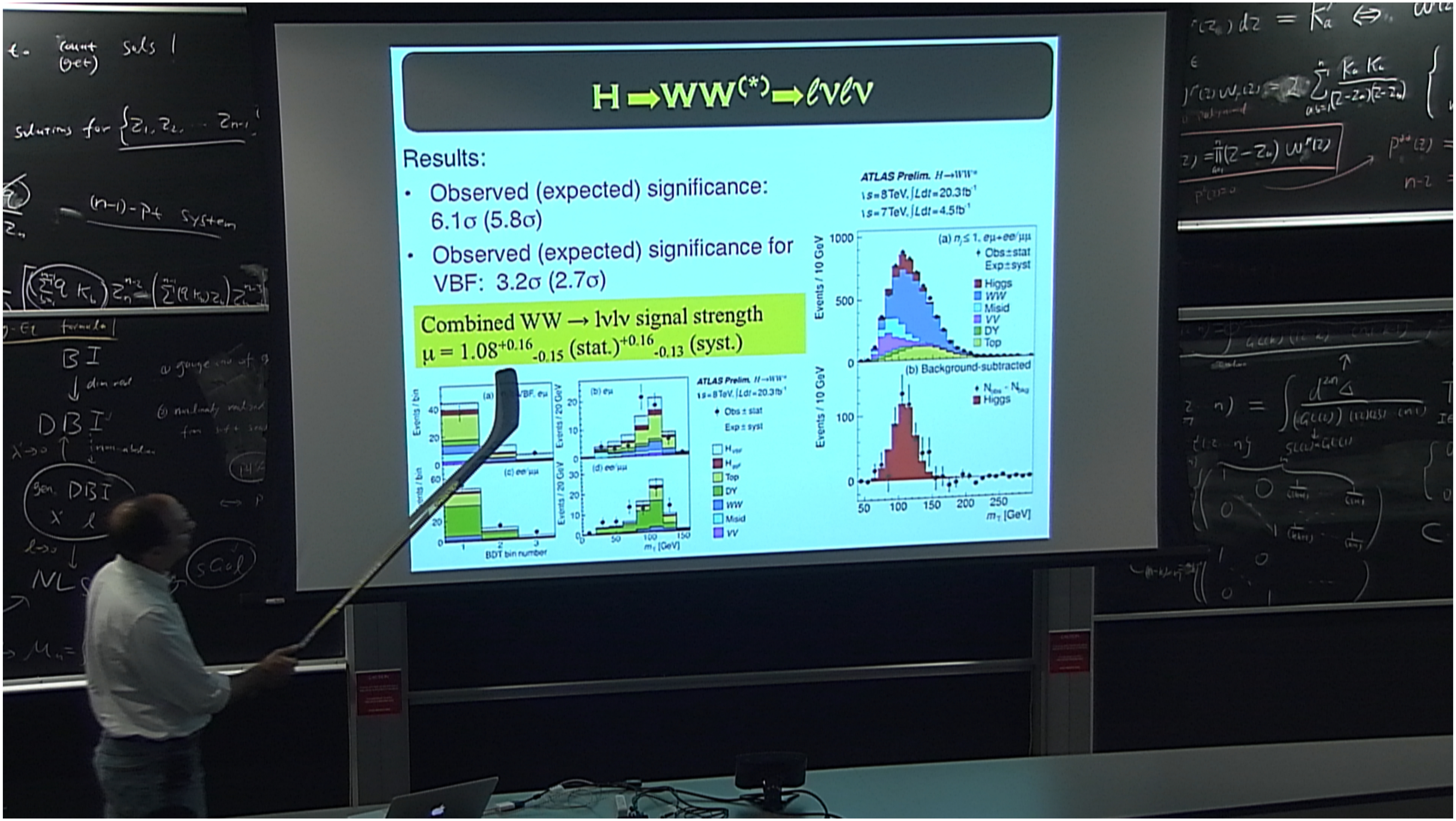
DIFFERENTIAL CROSS SECTIONS

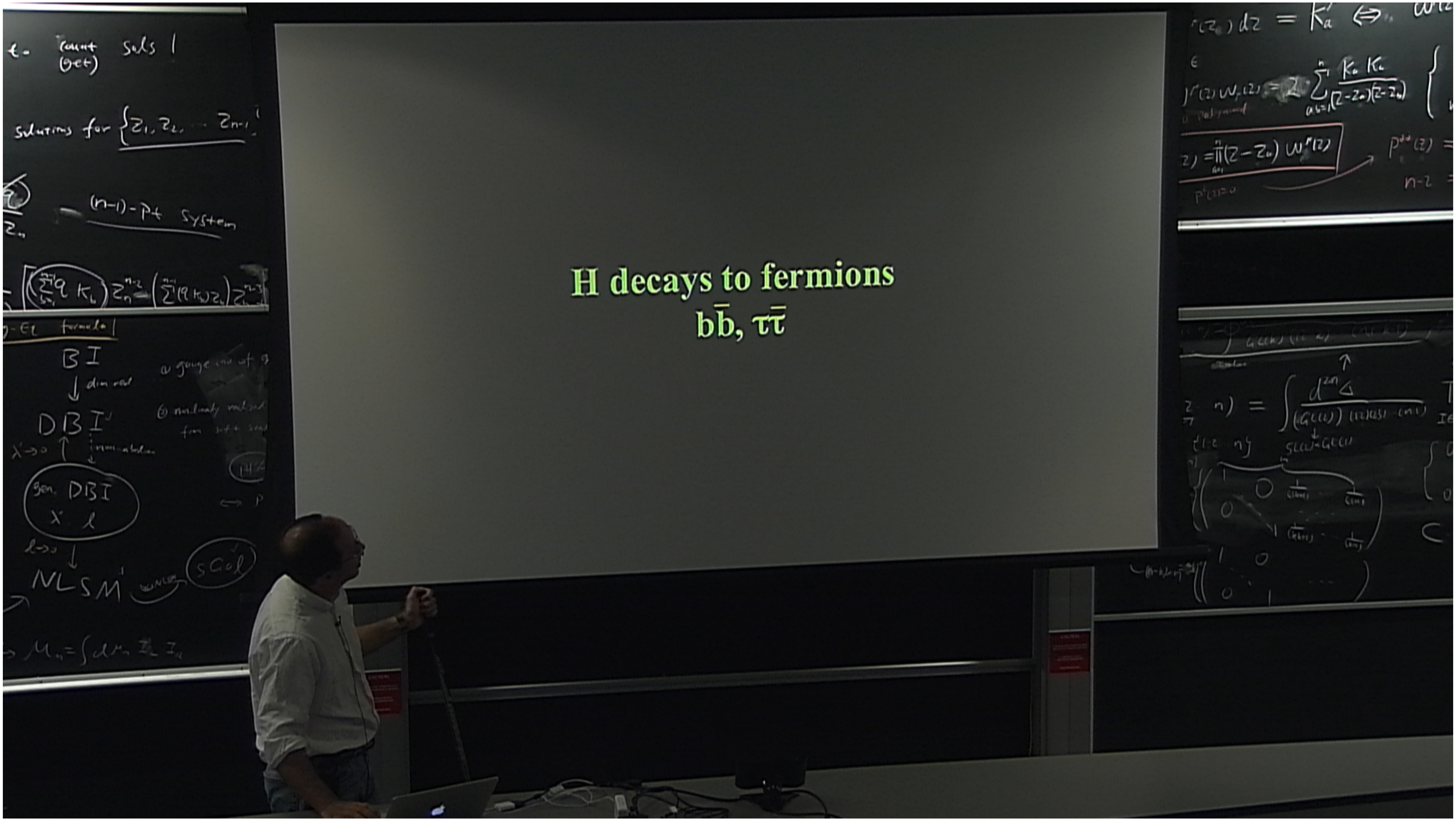
Test SM Higgs production theory predictions (γγ,ZZ)

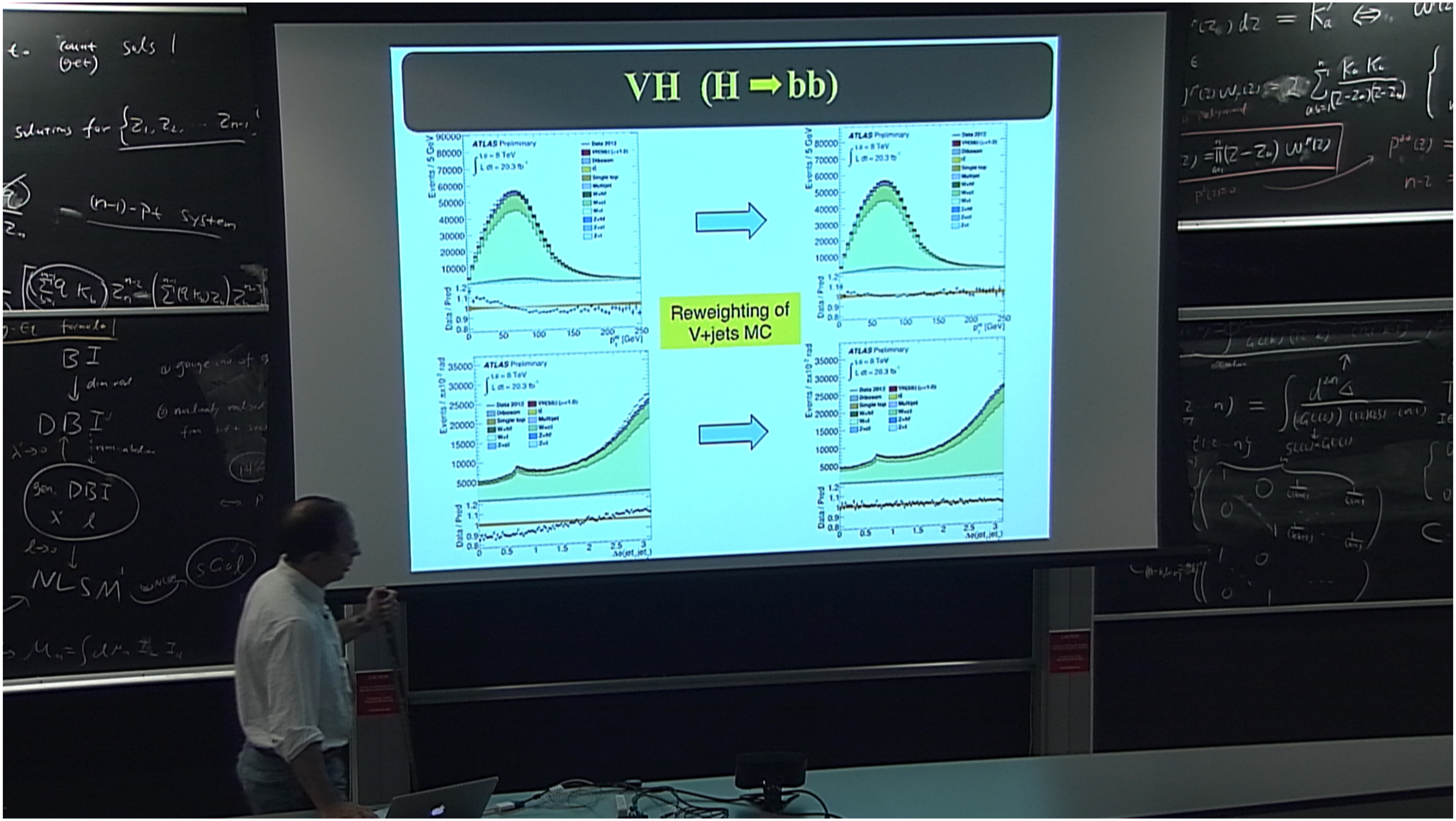


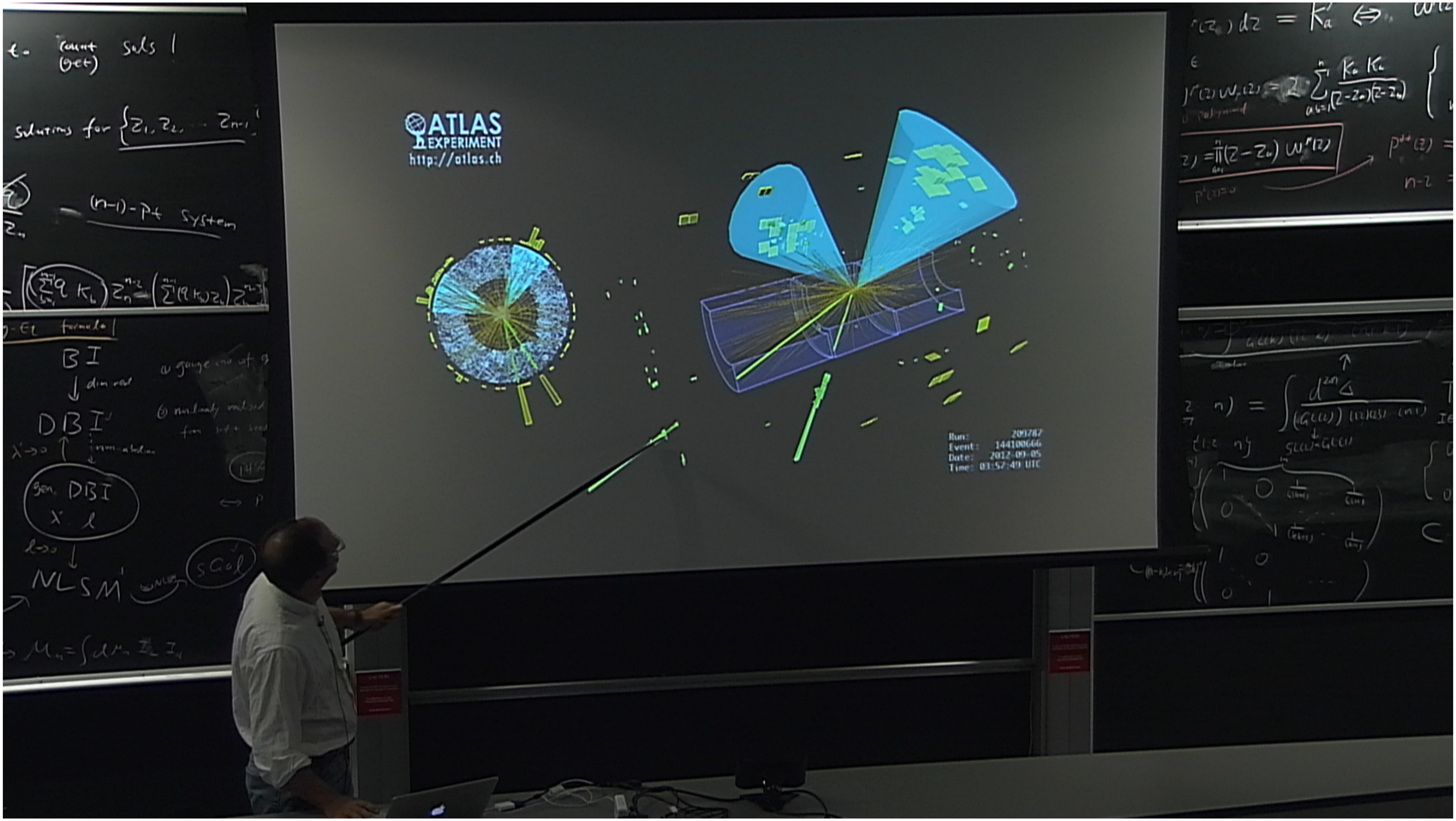


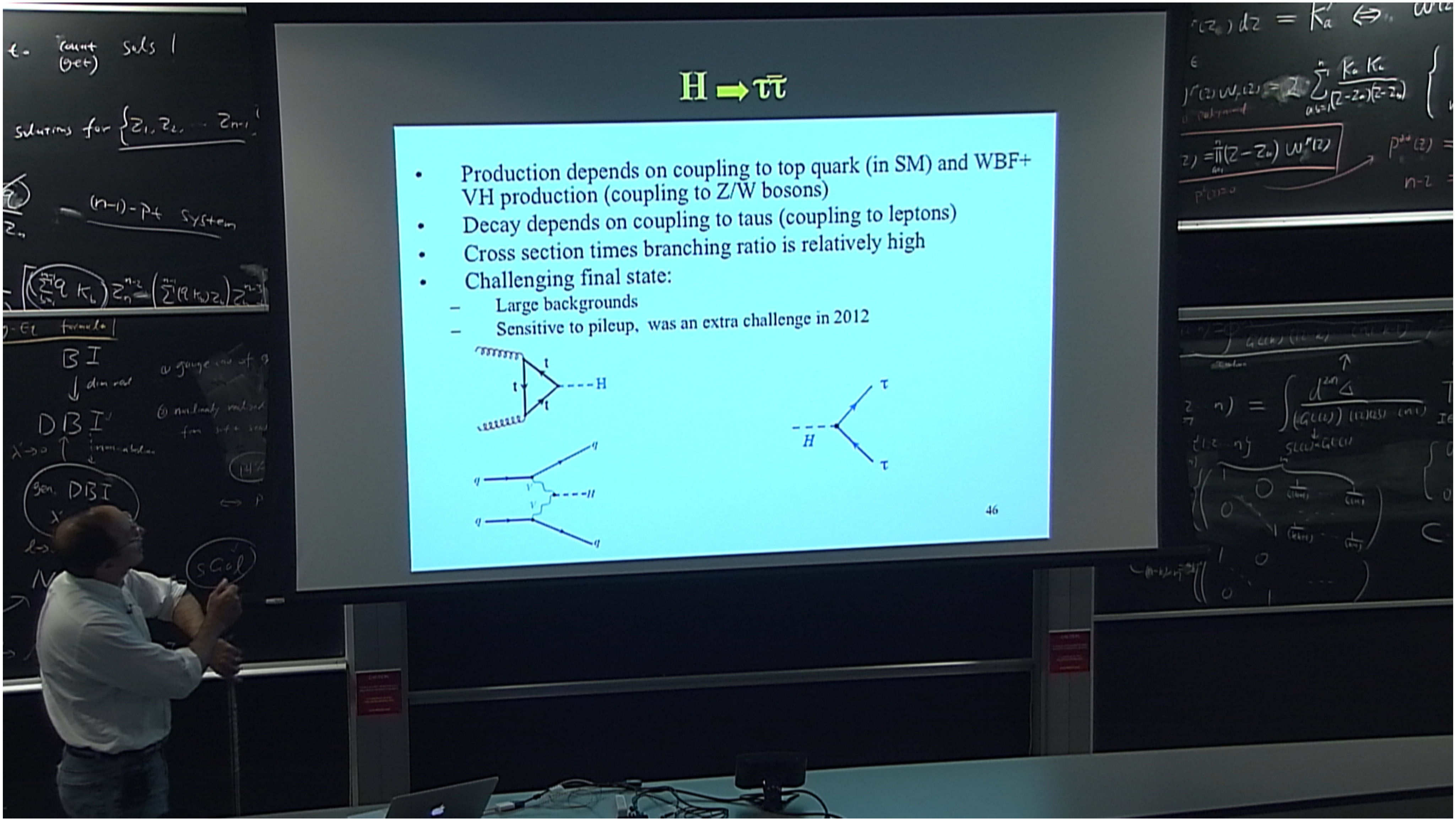
Differential Cross Sections
Test SM Higgs production theory predictions (γγ,ZZ)
γγ
ZZ
ATLAS

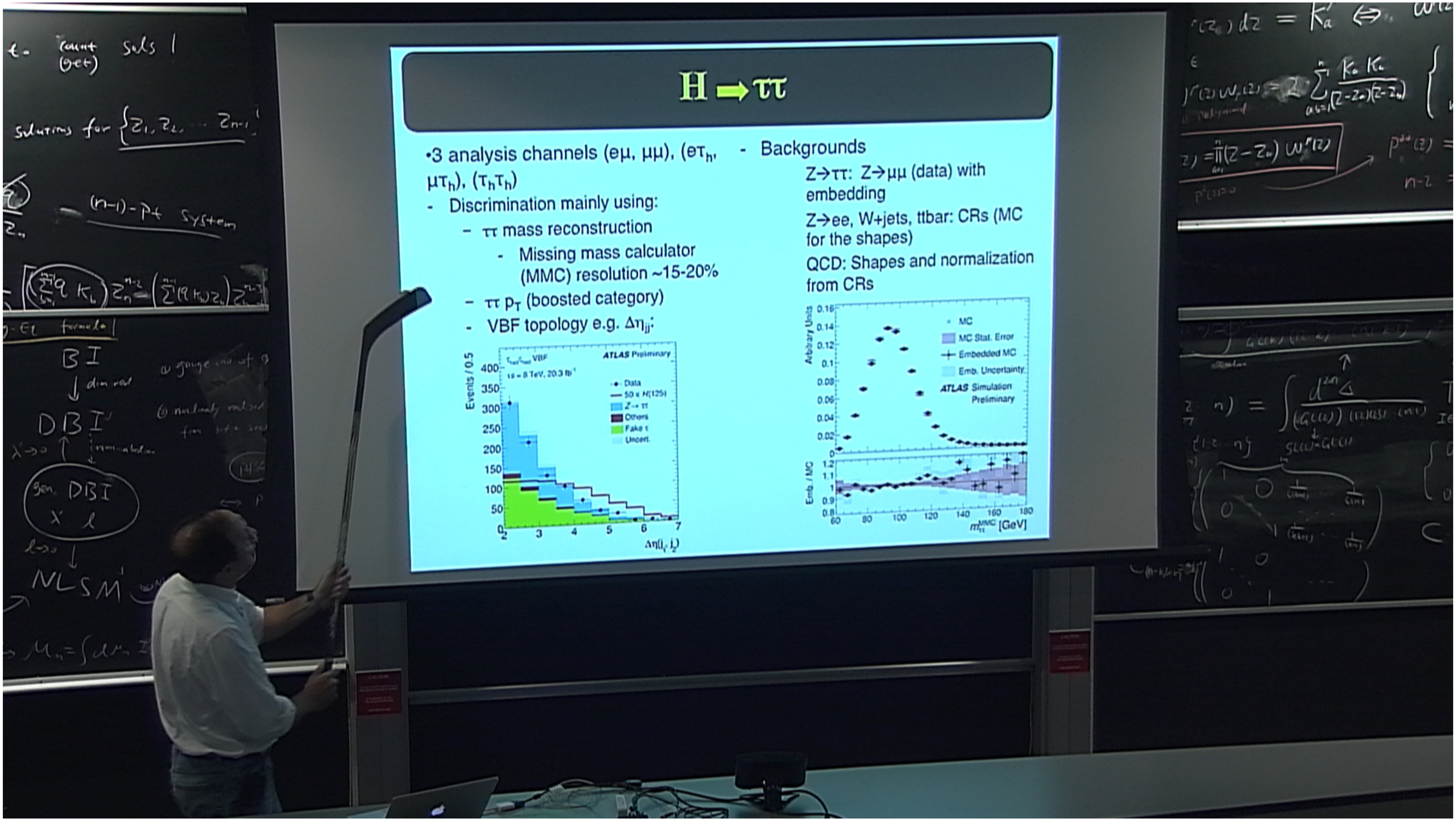

H ⇒ WW(*) ⇒ ℓνℓν
Results:
• Observed (expected) significance: 6.1σ (5.8σ)
• Observed (expected) significance for VBF: 3.2σ (2.7σ)
Combined WW → lνlν signal strength
μ = 1.08+0.16-0.15 (stat.)+0.16-0.13 (syst.)
ATLAS Prelim. H→WW*
√s=8TeV, ∫Ldt=20.3fb⁻¹
√s=7TeV, ∫Ldt=4.5fb⁻¹
(a) nj ≤ 1, eμ+ee/μμ
Obs±stat
Exp±syst
Higgs
WW
Misid
VV
DY
Top
(b) Background-subtracted
Events / 10 GeV
mT [GeV]
BDT bin number
Events / bin
Events / 20 GeV
(b) eμ
(d) ee/μμ
(c) ee/μμ

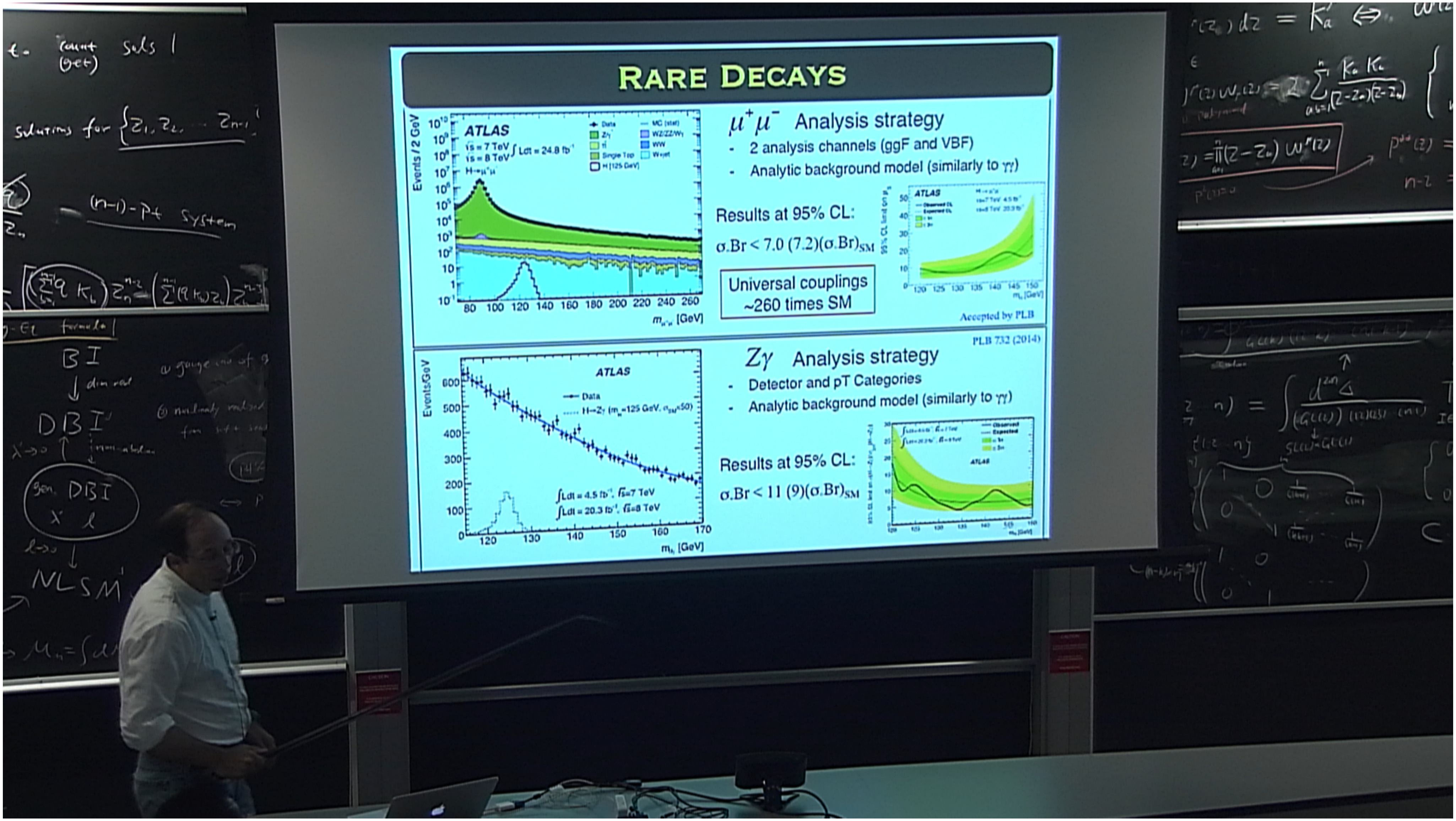

H decays to fermions
$b\bar{b}$, $\tau\bar{\tau}$

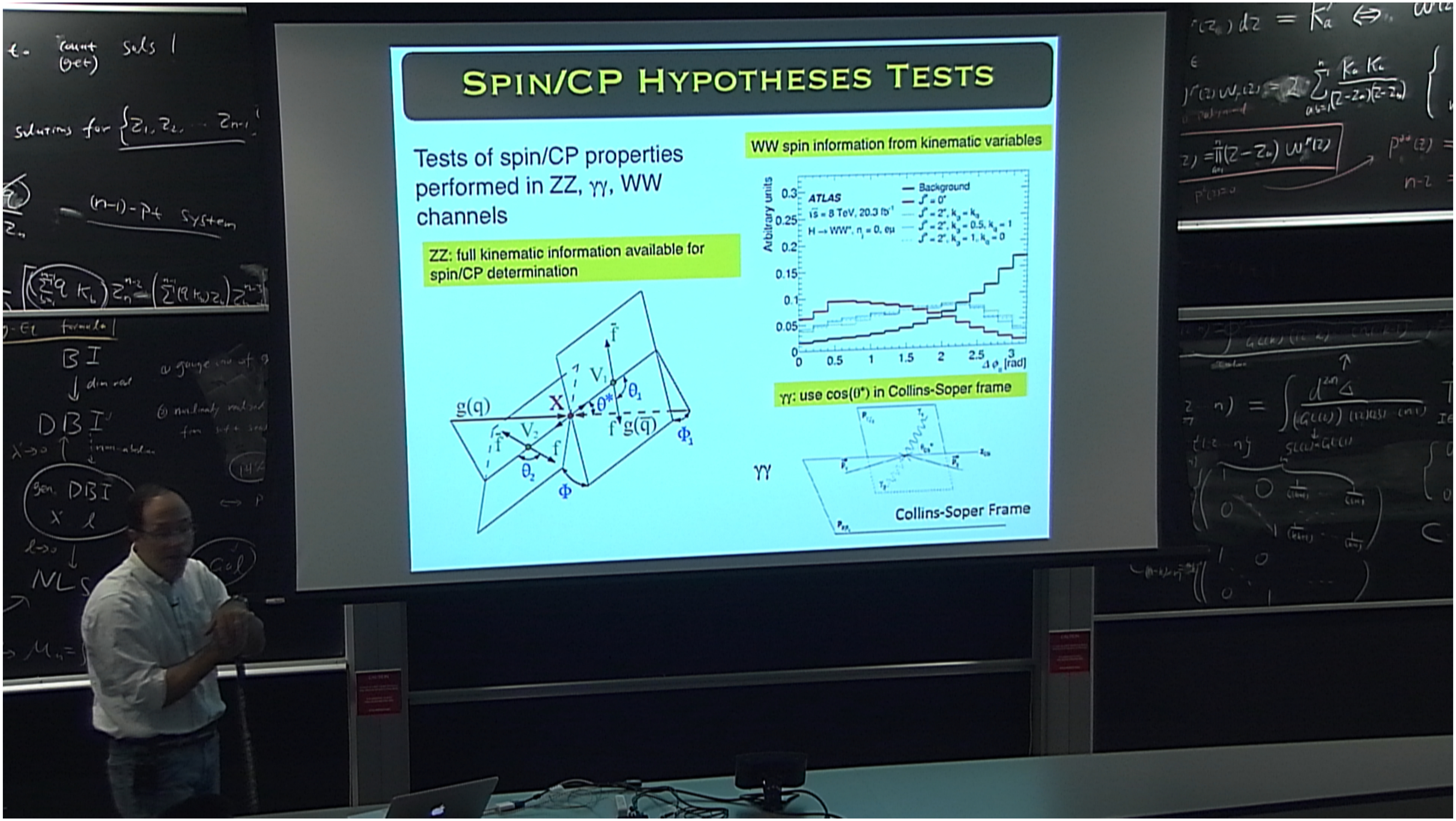

VH (H ⇒ bb)
ATLAS Preliminary
Reweighting of
V+jets MC

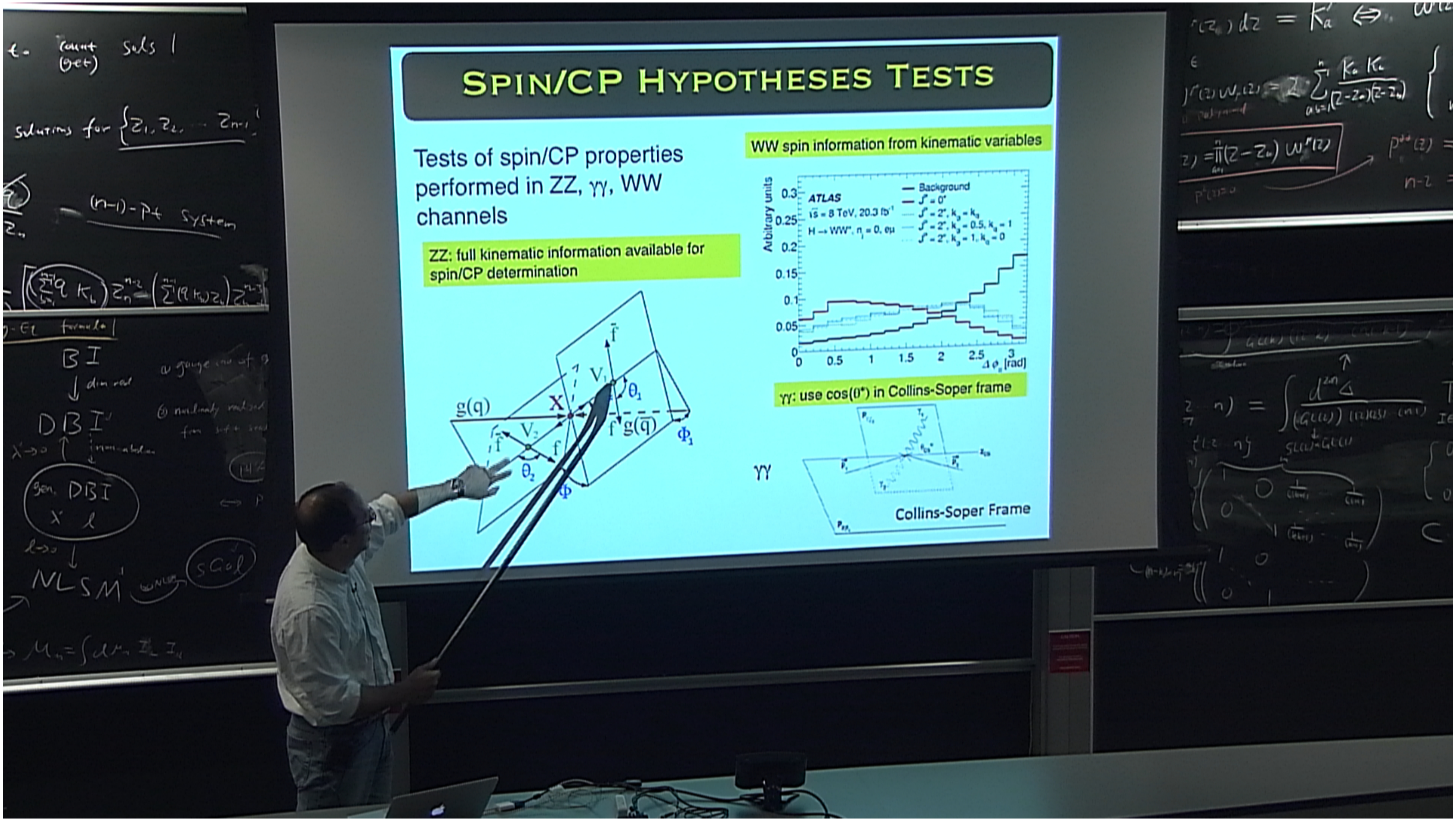

ATLAS
EXPERIMENT
http://atlas.ch
Run: 209787
Event: 144100666
Date: 2012-09-05
Time: 03:57:49 UTC


H ⟹ ττ̄
Production depends on coupling to top quark (in SM) and WBF+ VH production (coupling to Z/W bosons)
Decay depends on coupling to taus (coupling to leptons)
Cross section times branching ratio is relatively high
Challenging final state:
Large backgrounds
Sensitive to pileup, was an extra challenge in 2012
t
t
t
H
q
q
V
V
H
q
q
τ
H
τ
46


H ⇒ ττ
•3 analysis channels (eμ, μμ), (eτh, μτh), (τhτh)
- Discrimination mainly using:
– ττ mass reconstruction
- Missing mass calculator (MMC) resolution ~15-20%
– ττ pT (boosted category)
- VBF topology e.g. Δηjj:
- Backgrounds
Z→ττ: Z→μμ (data) with embedding
Z→ee, W+jets, ttbar: CRs (MC for the shapes)
QCD: Shapes and normalization from CRs
ATLAS Preliminary
ATLAS Simulation Preliminary


RARE DECAYS
μ+μ− Analysis strategy
- 2 analysis channels (ggF and VBF)
- Analytic background model (similarly to γγ)
Results at 95% CL:
σ.Br < 7.0 (7.2)(σ.Br)SM
Universal couplings ~260 times SM
Accepted by PLB
PLB 732 (2014)
Zγ Analysis strategy
- Detector and pT Categories
- Analytic background model (similarly to γγ)
Results at 95% CL:
σ.Br < 11 (9)(σ.Br)SM
ATLAS


Spin/CP Hypotheses Tests
Tests of spin/CP properties performed in ZZ, γγ, WW channels
ZZ: full kinematic information available for spin/CP determination
WW spin information from kinematic variables
γγ: use cos(θ*) in Collins-Soper frame
γγ
Collins-Soper Frame
ATLAS
Background
Arbitrary units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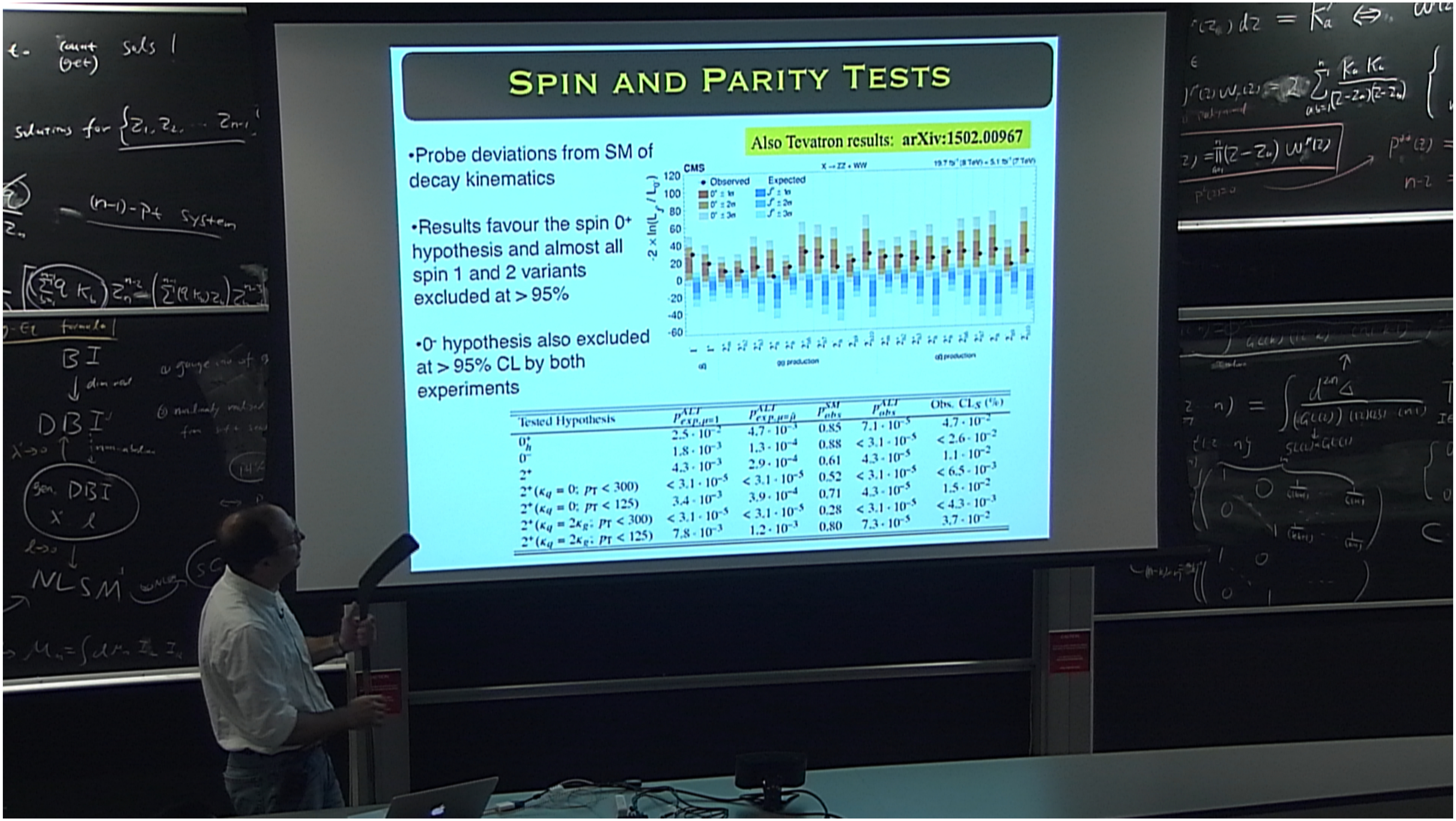
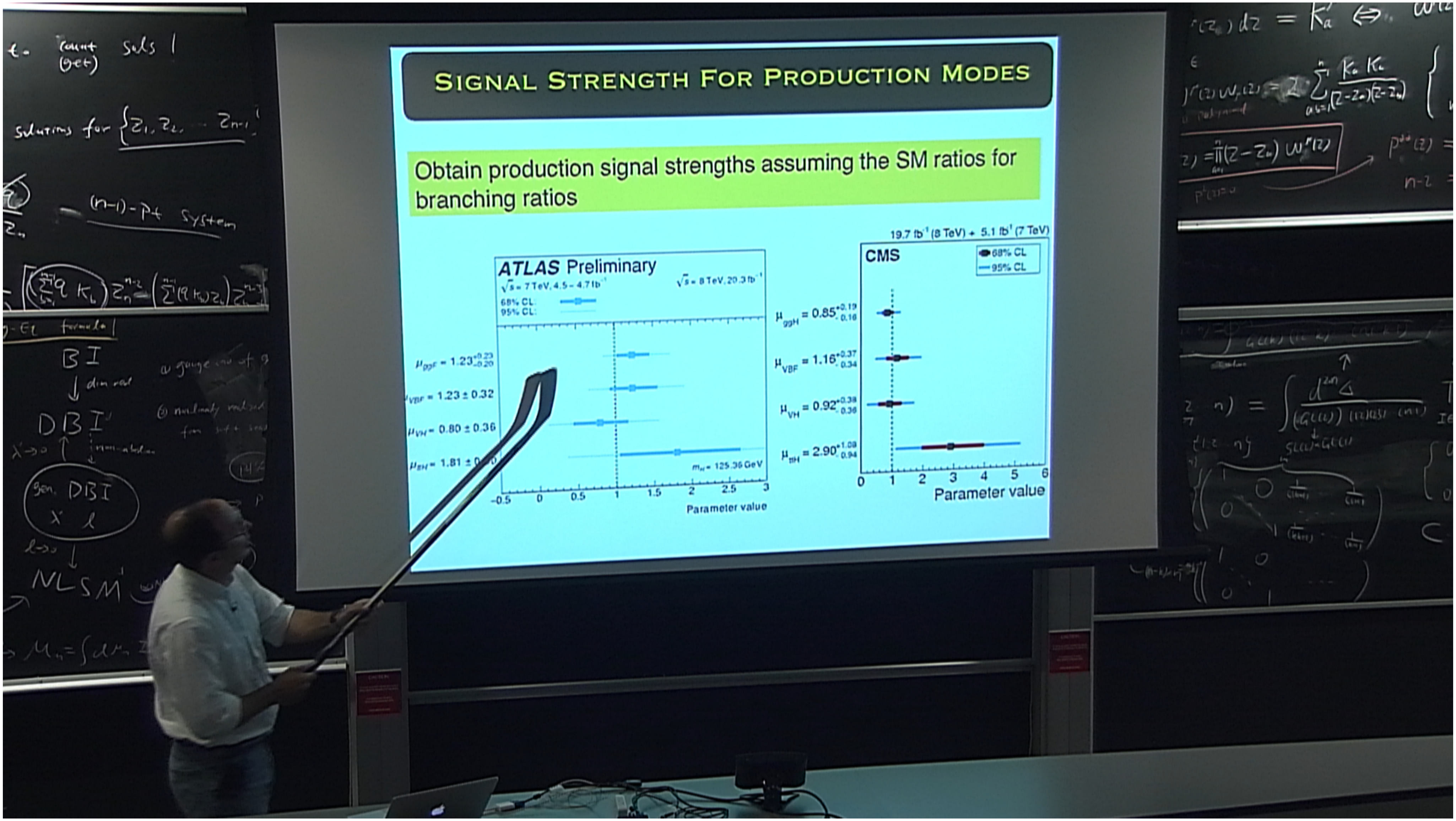
γγ
Collins-Soper Frame
ATLAS
Background
Arbitrary units


SPIN AND PARITY TESTS
Also Tevatron results: arXiv:1502.00967
•Probe deviations from SM of decay kinematics
•Results favour the spin 0+ hypothesis and almost all spin 1 and 2 variants excluded at > 95%
•0- hypothesis also excluded at > 95% CL by both experiments
CMS
Observed
Expected
Tested Hypothesis | p^ALT exp,μ=1 | p^ALT exp,μ=μ̂ | p^SM obs | p^ALT obs | Obs. CLs (%)
0+h | 2.5 · 10^-2 | 4.7 · 10^-3 | 0.85 | 7.1 · 10^-5 | 4.7 · 10^-2
0- | 1.8 · 10^-3 | 1.3 · 10^-4 | 0.88 | < 3.1 · 10^-5 | < 2.6 · 10^-2
2+ | 4.3 · 10^-3 | 2.9 · 10^-4 | 0.61 | 4.3 · 10^-5 | 1.1 · 10^-2
2+(κq = 0; pT < 300) | < 3.1 · 10^-5 | < 3.1 · 10^-5 | 0.52 | < 3.1 · 10^-5 | < 6.5 · 10^-3
2+(κq = 0; pT < 125) | 3.4 · 10^-3 | 3.9 · 10^-4 | 0.71 | 4.3 · 10^-5 | 1.5 · 10^-2
2+(κq = 2κg; pT < 300) | < 3.1 · 10^-5 | < 3.1 · 10^-5 | 0.28 | < 3.1 · 10^-5 | < 4.3 · 10^-3
2+(κq = 2κg; pT < 125) | 7.8 · 10^-3 | 1.2 · 10^-3 | 0.80 | 7.3 · 10^-5 | 3.7 · 10^-2


SIGNAL STRENGTH FOR PRODUCTION MODES
Obtain production signal strengths assuming the SM ratios for branching ratios
ATLAS Preliminary
√s = 7 TeV, 4.5 – 4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
68% CL:
95% CL:
μggF = 1.23 +0.23 −0.20
μVBF = 1.23 ± 0.32
μVH = 0.80 ± 0.36
m_H = 125.36 GeV
Parameter value
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
CMS
68% CL
95% CL
μggH = 0.85 +0.19 −0.16
μVBF = 1.16 +0.37 −0.34
μVH = 0.92 +0.38 −0.36
μttH = 2.90 +1.08 −0.94
Parameter value

Couplings Framework

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\overline{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\overline{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\overline{f}\right) H$$

•"κ framework": signal strength parameters (μ_p, μ^i_{BR}) are further interpreted in terms of modifiers to the SM couplings:

•Decay: $\Gamma_i = \kappa_i^2\ \Gamma_i^{SM}$
•Production: $\sigma_i = \kappa_i^2\ \sigma_i^{SM}$
•Width: $\Gamma_H = \Sigma_i\, \kappa_i^2\ \Gamma_i^{SM}$

Assumptions (see LHCXSWG YR3):
•Only one Higgs
•SM production and decay kinematics
  •Tensor structure is that of SM
  •0+ scalar
•Narrow resonance

Couplings Framework

- Loops and interference:

- Encoded in effective couplings κ_γ, κ_g

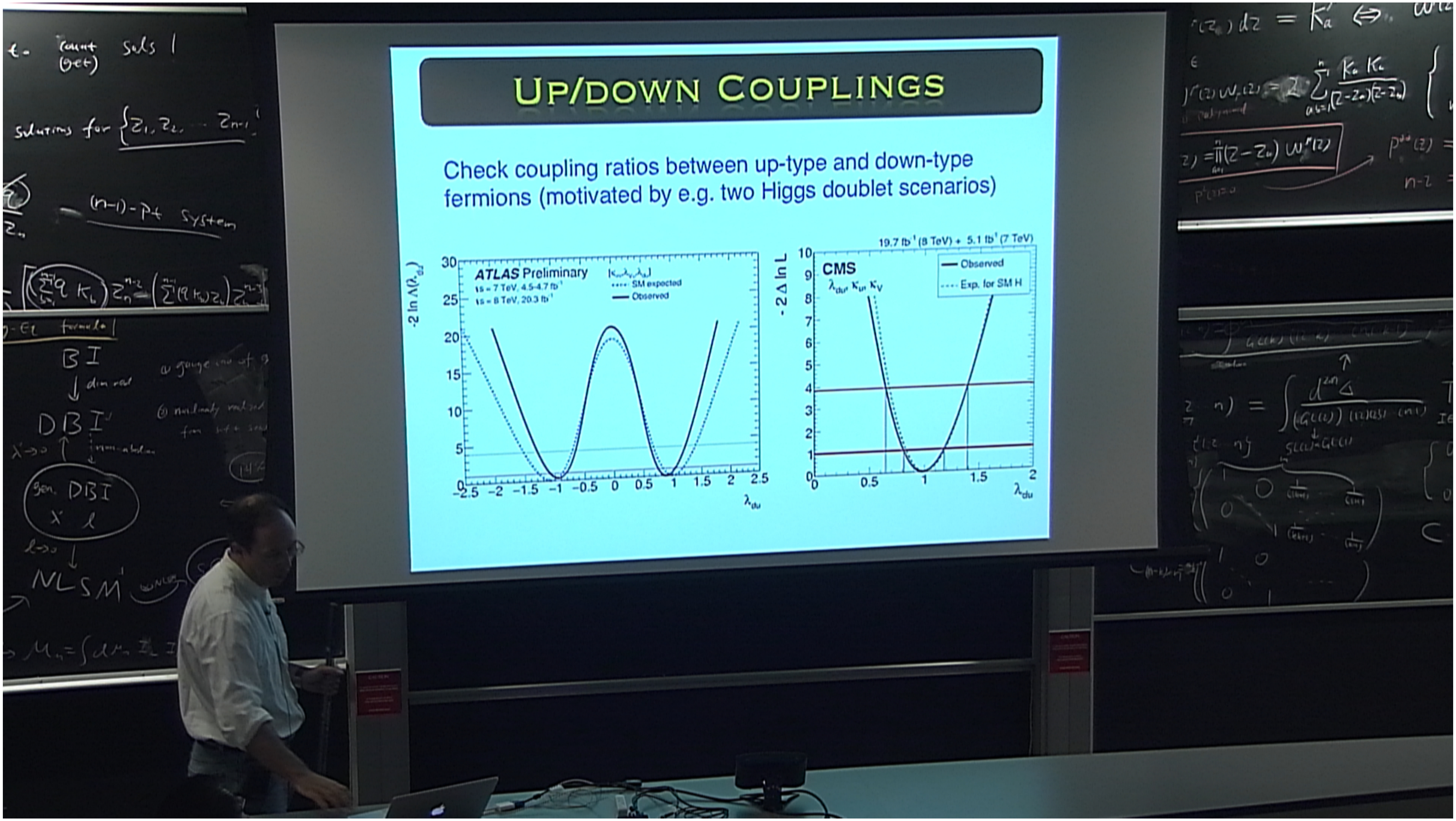
Example: gg -> H -> $\gamma\gamma$

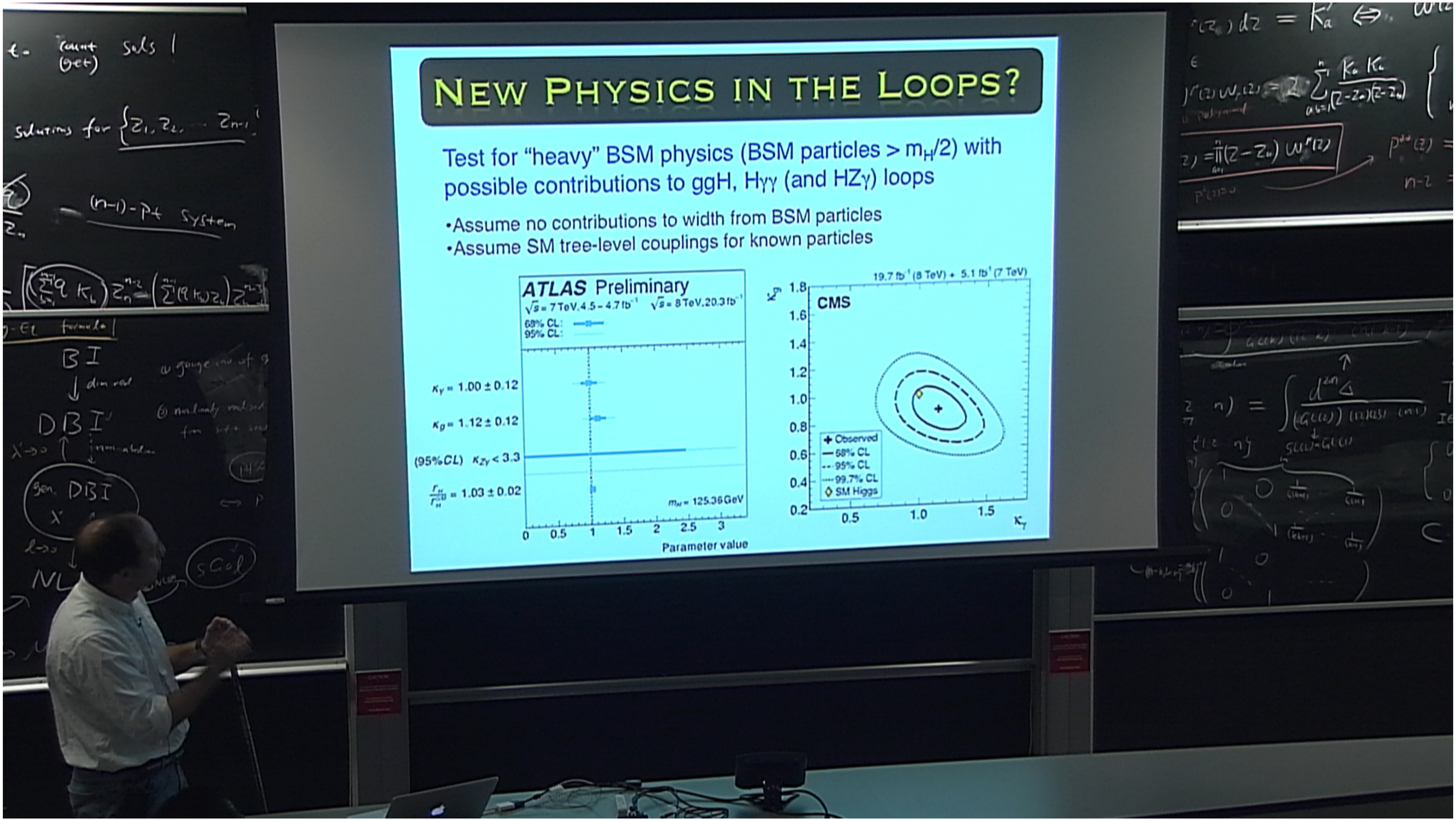
$$\frac{(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

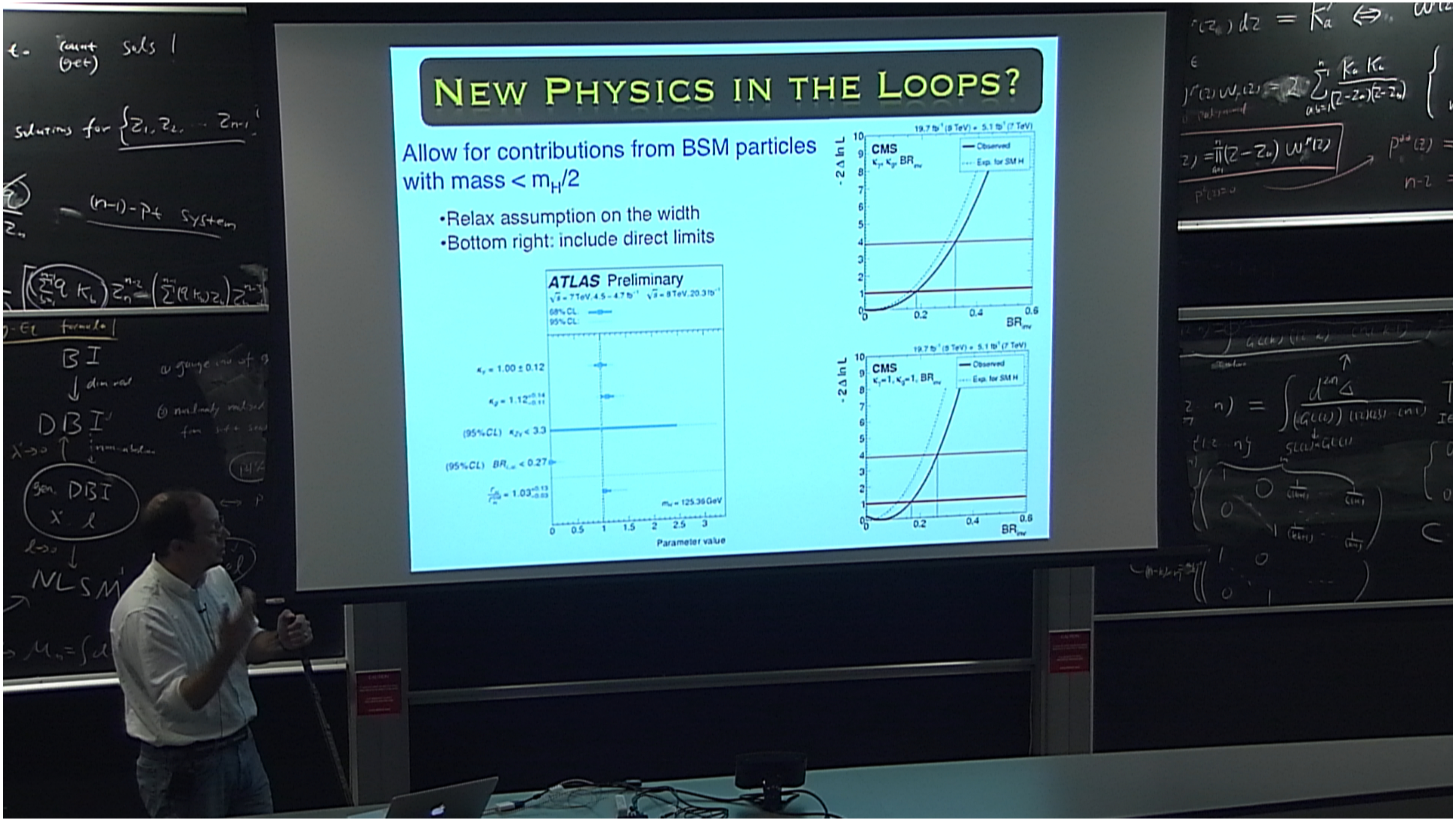
- In terms of SM coupling modifiers:

$$\kappa_g^2(\kappa_t, \kappa_b) = 1.06 \cdot \kappa_t^2 - 0.07 \cdot \kappa_t \kappa_b + 0.01 \cdot \kappa_b^2$$
$$\kappa_\gamma^2(\kappa_F, \kappa_V) = 1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$$

- BSM coloured or charged particles in loops could cause deviations


UP/DOWN COUPLINGS
Check coupling ratios between up-type and down-type fermions (motivated by e.g. two Higgs doublet scenarios)
ATLAS Preliminary
SM expected
Observed
-2 ln Λ(λdu)
λdu
CMS
λdu, κu, κV
Observed
Exp. for SM H
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
- 2 Δ ln L
λdu


New Physics in the Loops?
Test for "heavy" BSM physics (BSM particles > m_H/2) with possible contributions to ggH, Hγγ (and HZγ) loops
•Assume no contributions to width from BSM particles
•Assume SM tree-level couplings for known particles
ATLAS Preliminary
√s = 7 TeV, 4.5 – 4.7 fb⁻¹ √s = 8 TeV, 20.3 fb⁻¹
68% CL:
95% CL:
κγ = 1.00 ± 0.12
κg = 1.12 ± 0.12
(95%CL) κZγ < 3.3
= 1.03 ± 0.02
m_H = 125.36 GeV
Parameter value
CMS
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
Observed
68% CL
95% CL
99.7% CL
SM Higgs


NEW PHYSICS IN THE LOOPS?
Allow for contributions from BSM particles with mass < $m_H/2$
•Relax assumption on the width
•Bottom right: include direct limits
ATLAS Preliminary
Parameter value
m_H = 125.36 GeV
CMS
Observed
Exp. for SM H
$-2\Delta \ln L$
BR_{inv}

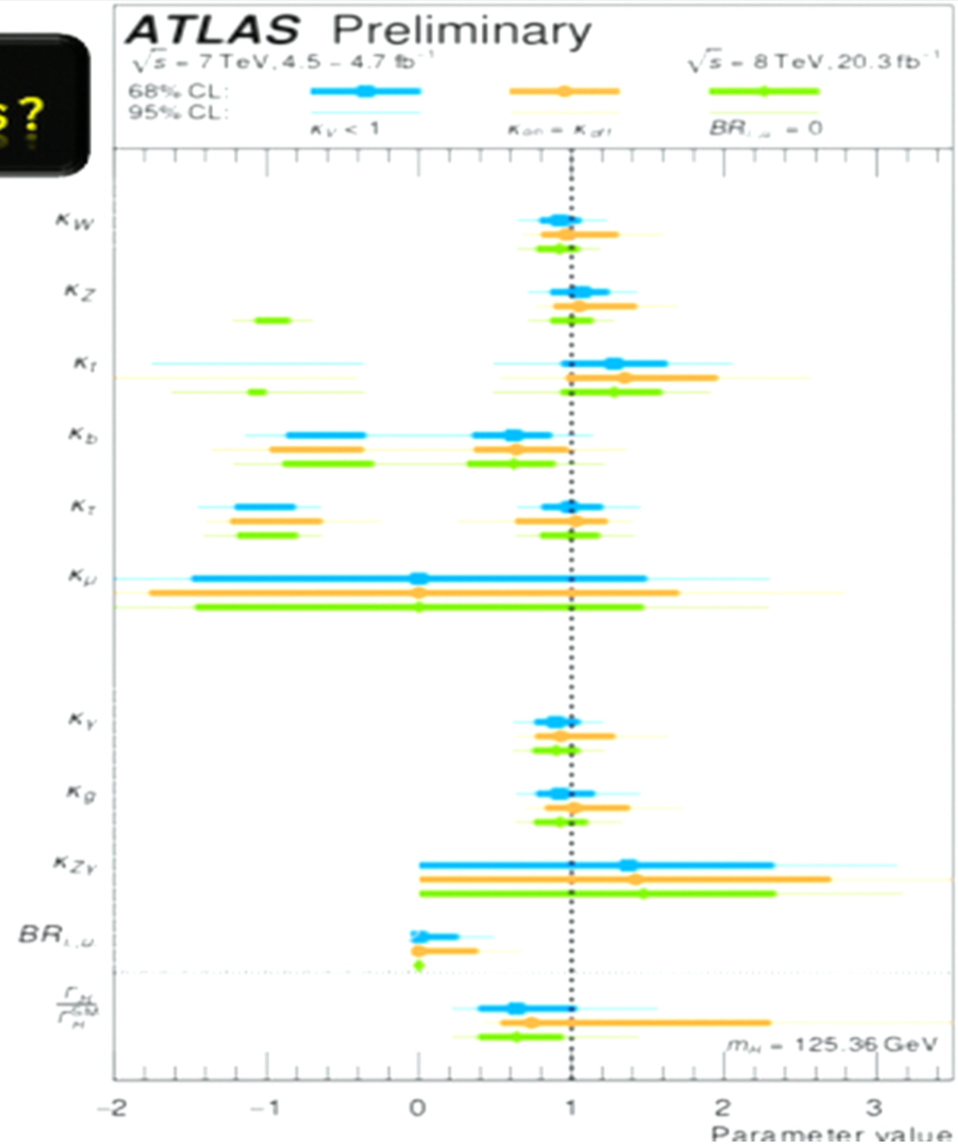
New Physics in the Loops?

Relax assumptions on SM couplings of known particles and consider various scenarios:

- Blue squares: models with Higgs singlets or doublets κ_V <=1. Impose this constraint on gauge couplings in the fit

- Orange circles: add off-shell measurements assuming on-shell couplings equal to off-shell couplings

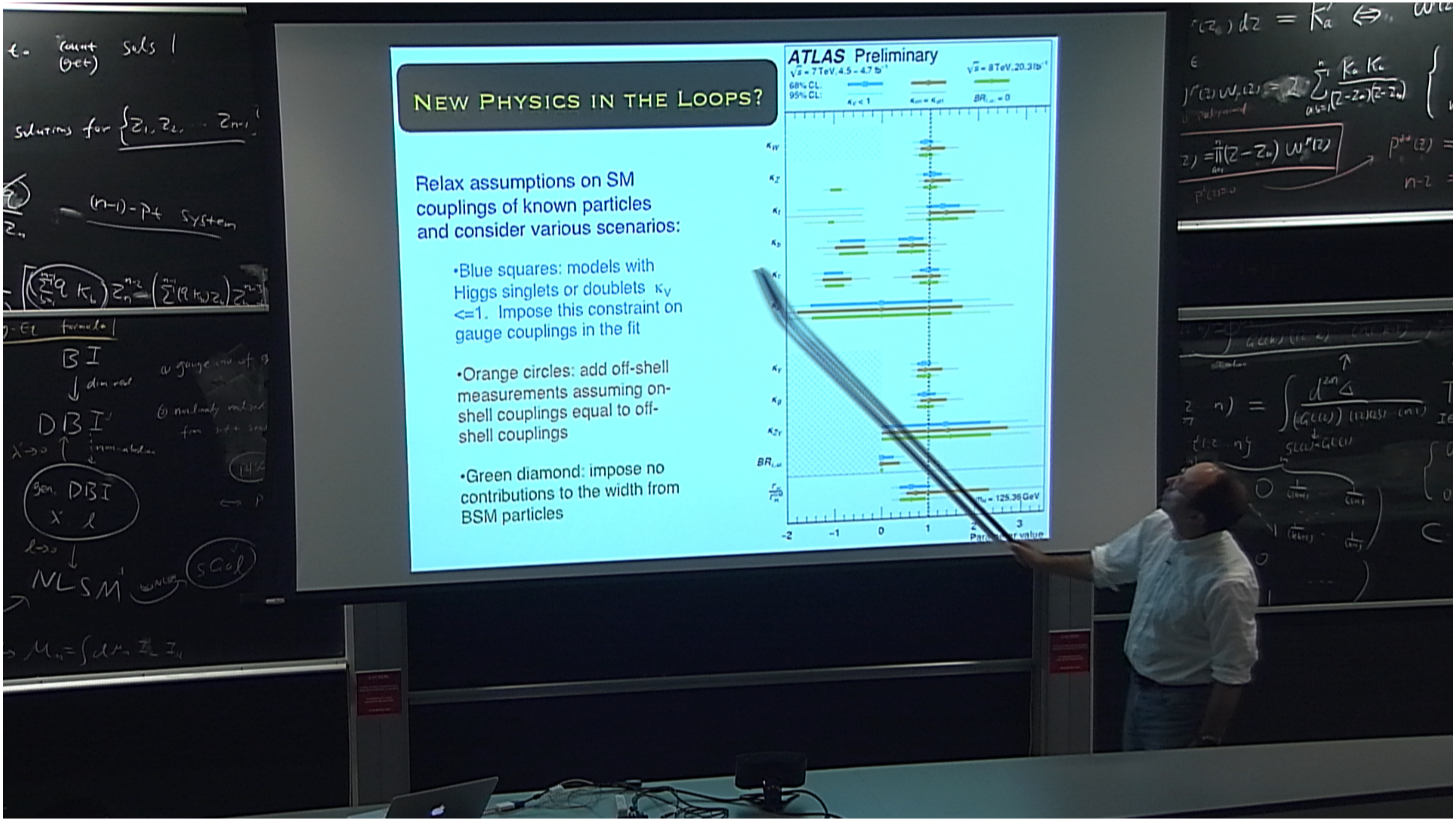
- Green diamond: impose no contributions to the width from BSM particles



Conclusions

- The Run I Higgs physics program that covered a wide array of measurements and searches is essentially complete
  - The measurements of the production and decay properties of the Higgs boson are consistent with SM predictions
    - The SM 0^+ hypothesis is preferred over all other tested spin/parity alternatives (almost all excluded at > 95% CL)
    - Tests of coupling strengths consistent with SM: ongoing combination between CMS and ATLAS
  - To test the consistency with the SM with higher precision will require substantial effort in improving experimental techniques, MC generators, and theory calculations (for both signal but also many backgrounds)
- We have a very exciting and challenging Higgs physics program for Run II

Thanks to Eilam Gross and Michael Duehrssen for contributing slide material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ATLAS Preliminary