Hunting the Higgs Boson at the LHC

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NExT PhD Workshop
University of Sussex – 21 August 2012

Hunting the Higgs Boson at the LHC

…and finding a New Particle with a mass of around 125 GeV/c^2 which could very well be… the Higgs boson!

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS

CERN

CERN-PH-EP-2012-218
Submitted to: Physics Letters B

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

Outline of the lecture

- Part I: Introduction & old history
- Part II: tools of the trade
  - The LHC
  - The ATLAS and CMS experiments
  - Statistics survival guide
- Part III: LHC Higgs searches
  - The search channels
- Part IV: what now?
  - The big questions
  - Roadmap for the LHC

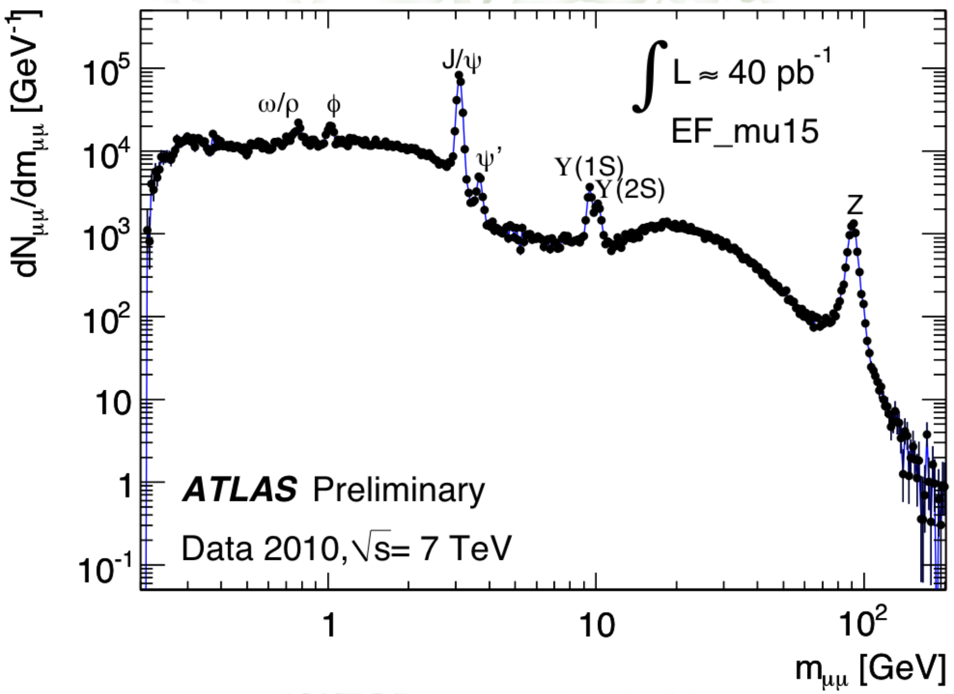
Part I: Higgs Physics and (old) history

Why look for the Higgs boson?

- Because the Standard Model **works very well!**
- For everything, except…

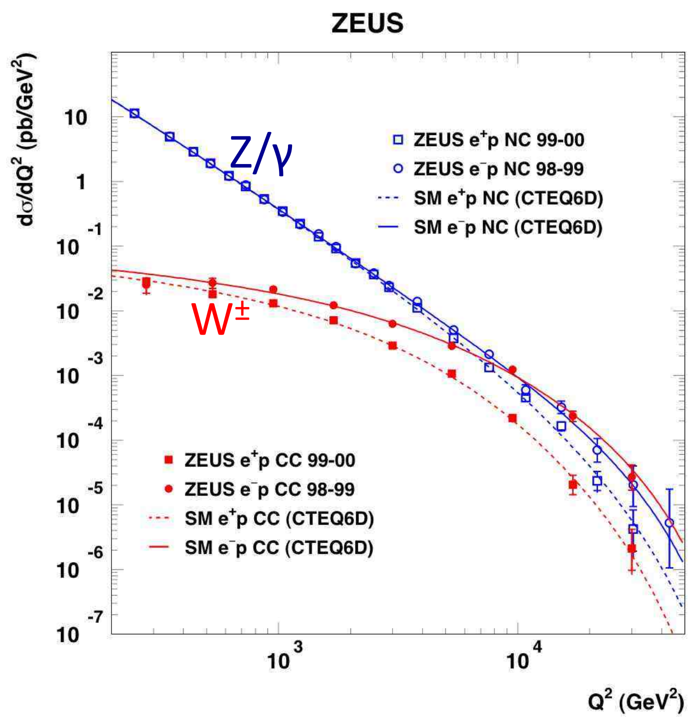
  Local gauge invariance of the Standard Model would be violated by particle mass terms

  Theory would become non-renormalizable…



Why look for the Higgs boson?

- Simplest solution:
  - Introduces doublet of complex fields – 4 degrees of freedom
  - Assume Mexican hat potential, to allow spontaneous symmetry breaking – potential follows symmetry but new vacuum doesn't
  - Three degrees of freedom turn into $W^{\pm}$ and Z longitudinal polarization ($W^{\pm}$ and Z now have mass!)
  - Remaining degree of freedom becomes new scalar particle – the Higgs boson
  - Fermions acquire mass through different mechanism – interaction with the Higgs field
  - Higgs boson mass is the only unknown in the theory
- In the process, explain electroweak symmetry breaking



http://www-zeus.desy.de/physics/sfew/PUBLIC/sfew_results/preliminary/dis04/

$$\phi = \begin{pmatrix} \sqrt{2} \\ \frac{\phi_3 + i\phi_4}{\sqrt{2}} \end{pmatrix}$$

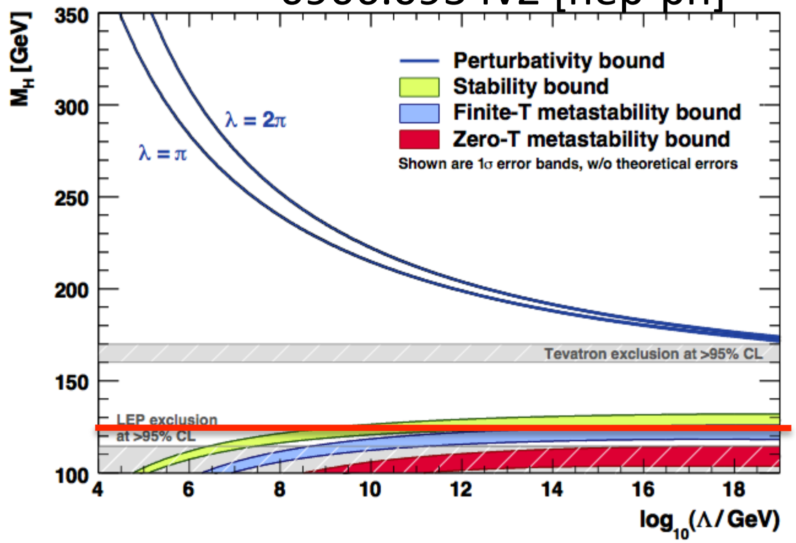
We need the SM Higgs mechanism to make sense of the data!

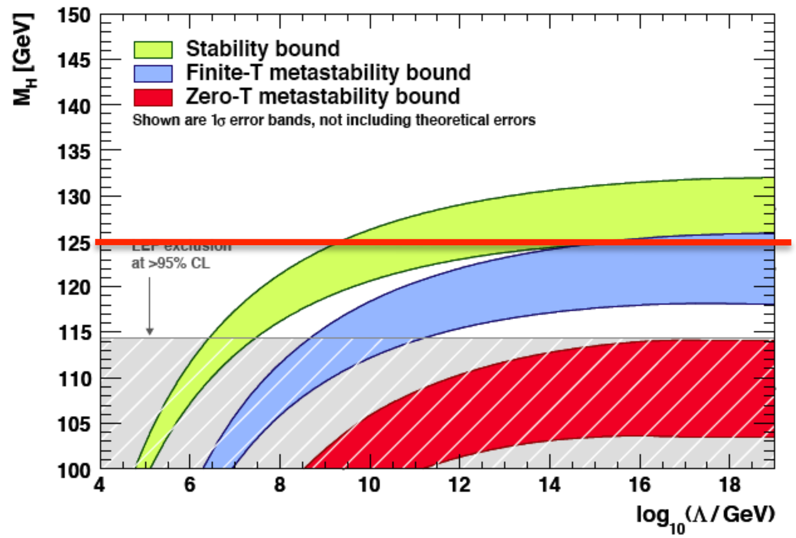
(in the most economical way…)

But there is more…

0906.0954v2 [hep-ph]

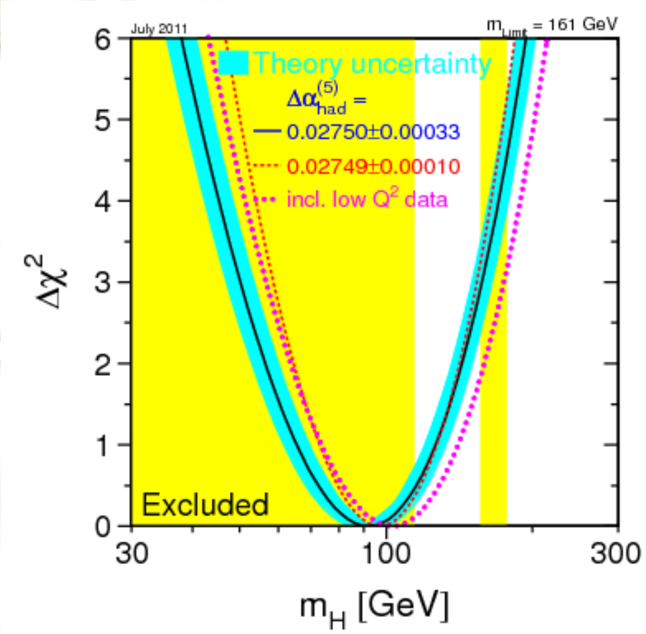
- We know the SM is incomplete
- For a low Higgs mass relative to the top quark mass, the quartic Higgs self-coupling runs at high energy towards lower values.
- At some point it would turn negative indicating that the vacuum is unstable.
- The universe could decay into a more stable lower energy vacuum state.
- Unless new physics appears at some energy scale
- The Higgs sector can give important clues to constrain new physics beyond the SM
- It is a great way to search for new physics!





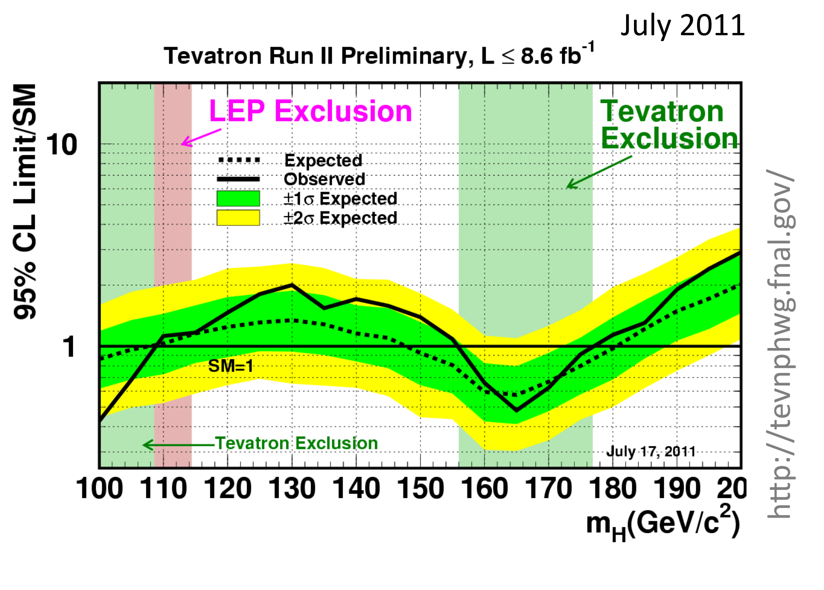
So how were we doing 1 year ago?

- 2011 limits on Higgs boson mass (only unknown parameter):
  - LEP **excluded** mass range below **114.4 GeV/c²**
  - EW fit: m_H = $\mathbf{92^{+34}_{-26}}$ **GeV/c²** (July 2011)
  - Including LEP: m_H < **185 GeV/c²** (July 2011)
  - Tevatron **excluded** ranges of **100 – 108 GeV/c²** and **156 – 177 GeV/c²**

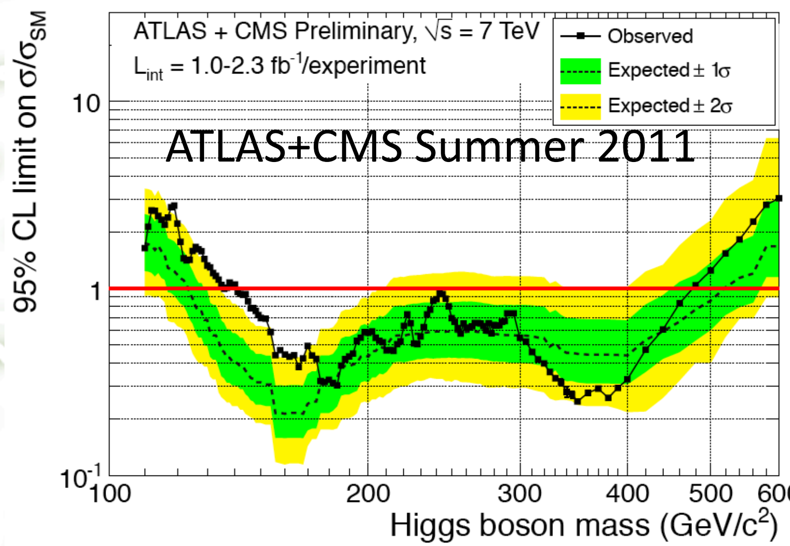


http://lepewwg.web.cern.ch/LEPEWWG/

The Brazil Plot

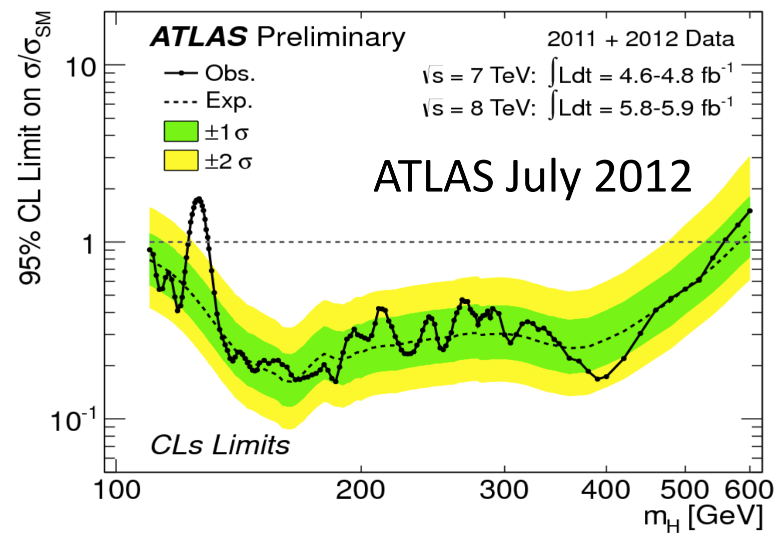


http://tevnphwg.fnal.gov/

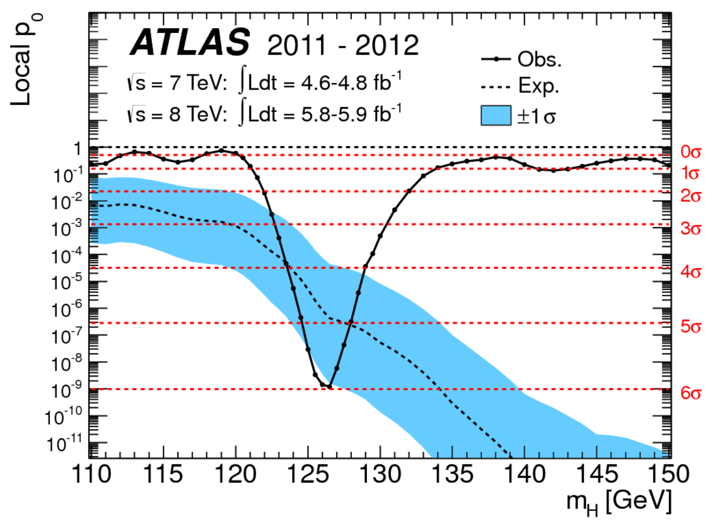


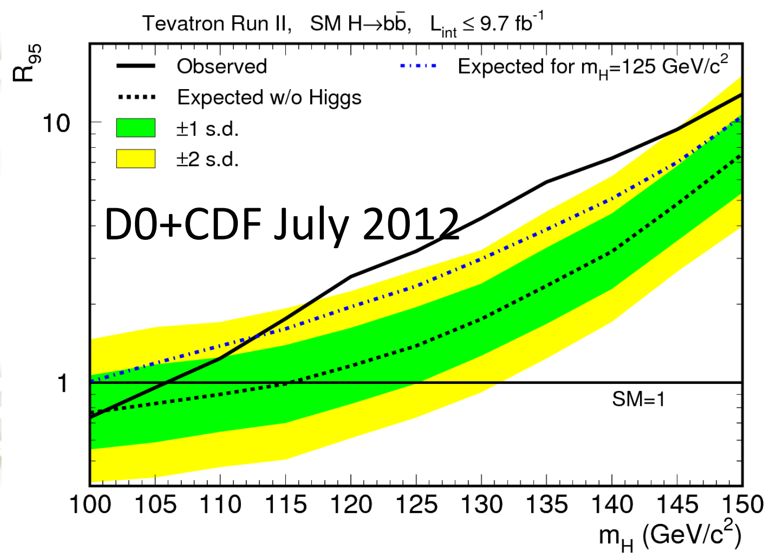
How were we doing 1 month ago?

- ≈5σ including announced on 4th of July by ATLAS and CMS independently!!
- ATLAS added H->WW later and published result with ≈6σ
- Did we find the Higgs boson?!



The p0 Plot






News on 04/07/2012
la Repubblica.it
Cern, scoperta la "particella di Dio"
« PRECEDENTE
Foto 1 di 19
SUCCESSIVO
Higgs boson-like particle discovery claimed at LHC
THANH NIÊN ONLINE
DIỄN ĐÀN CỦA HỘI LIÊN HIỆP THANH NIÊN VIỆT NAM
Chính trị - Xã hội
Quốc phòng
Thế giới trẻ
Kinh tế
Thế giới
Văn nghệ
Giáo dục
Công nghệ
Chủ nhật, 08/07/2012, 10:35:36 GMT+7
RSS
Newsletter
Quảng cáo
Đường dây nóng
Khoa học
Sân bóng của các hạt nhân
06/07/2012
Ngày 4.7 tại Geneva, Thụy Sĩ, Viện Nghiên cứu hạt nhân châu Âu (CERN) công bố đã phát hiện ra một loại hạt
mới được cho là tương ứng với hạt Higgs - còn gọi là "hạt của Chúa" mà các nhà khoa học dày công tìm kiếm
5 thập niên qua. Nếu thông tin này hoàn toàn chính xác, khám phá trên sẽ có tầm ảnh hưởng
tương đương với việc Christophe Columbus tìm ra châu Mỹ.
ZEIT ONLINE
WISSEN
Scoperto il Bosone di Higgs
la particella di Dio esiste davvero
The New York Times
U.S.
N.Y. / REGION
BUSINESS
Le boson de Higgs découvert avec 99,9999 % de certitude
Le Monde.fr | 04.07.2012 à 13h39 • Mis à jour le 04.07.2012 à 13h39
PHYSIK
Haarscharf am gottverdammten Teilchen vorbei
Die Belege scheinen überwältigend: Forscher könnten ein neues Teilchen gefunden haben. Unklar ist, ob es das Higgs-Boson ist, der letzte Baustein im Weltbild der Physik.
Physicists Find Elusive Particle Seen as Key to Universe
theguardian
News
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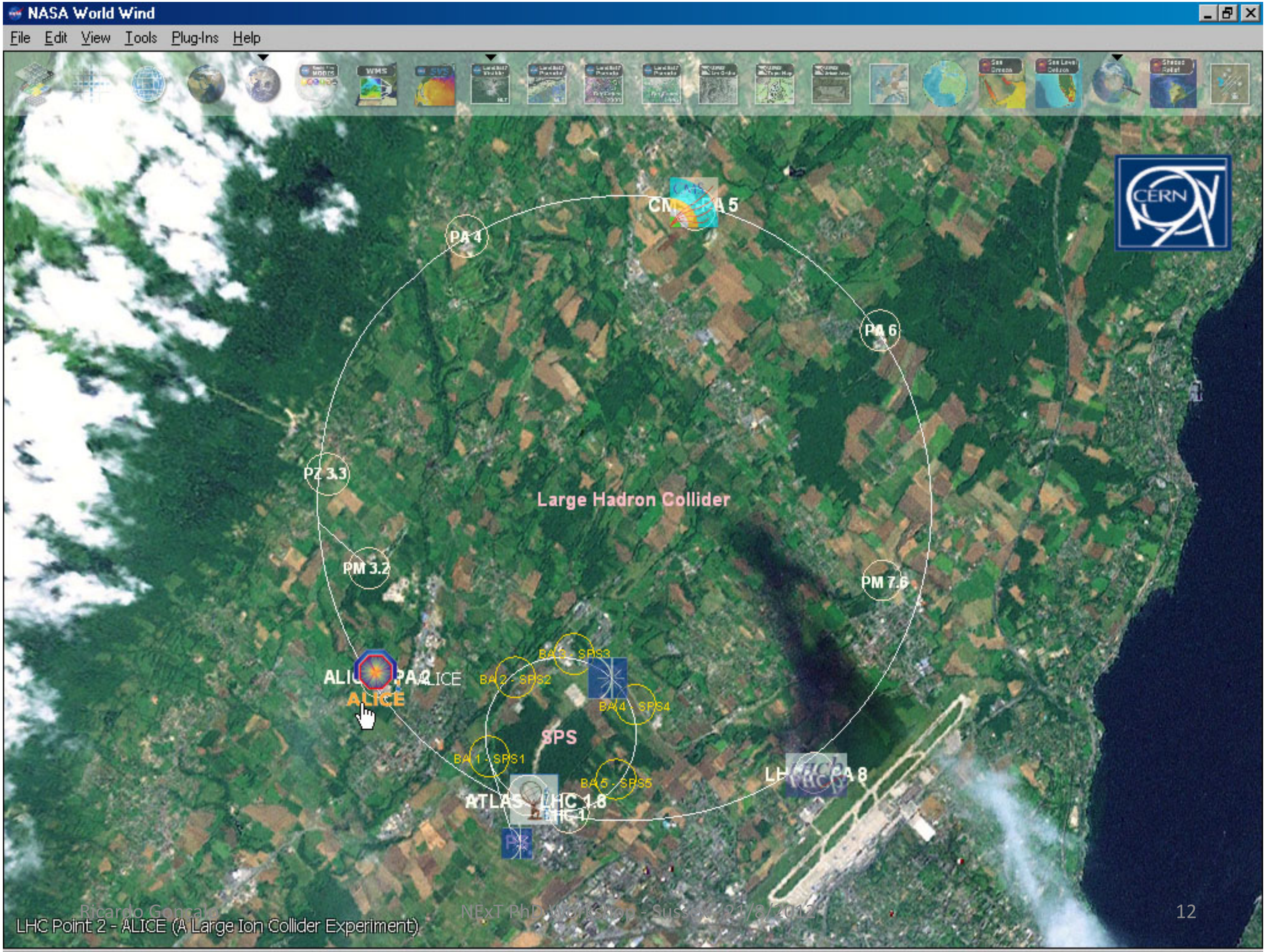
Money
London 2
Comment is free
The Higgs boson discovery is another giant leap for humankind
The Cern discovery of the Higgs particle is up there with putting man on the moon – something all humanity can be proud of
Scientists in Geneva on Wednesday applauded the discovery of a

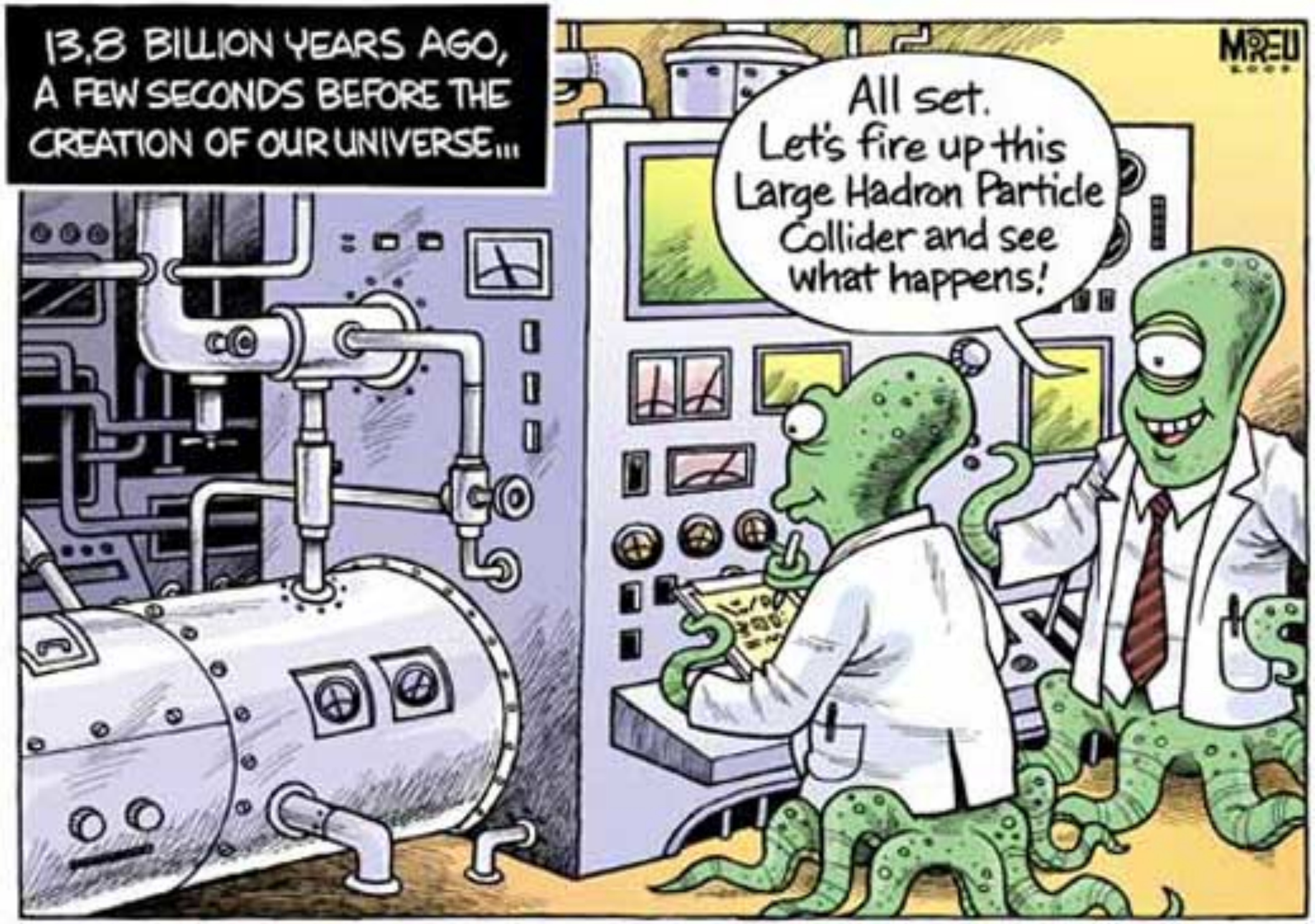
Part II: Tools of the Trade

The Hardware


NASA World Wind
File Edit View Tools Plug-Ins Help
CERN
PA 4
PA 5
PA 6
PZ 3.3
PM 3.2
PM 7.6
Large Hadron Collider
ALICE
SPS
BA 1 - SPS1
BA 2 - SPS2
BA 3 - SPS3
BA 4 - SPS4
BA 5 - SPS5
ATLAS
LHC 1.8
PA 8
LHC Point 2 - ALICE (A Large Ion Collider Experiment)

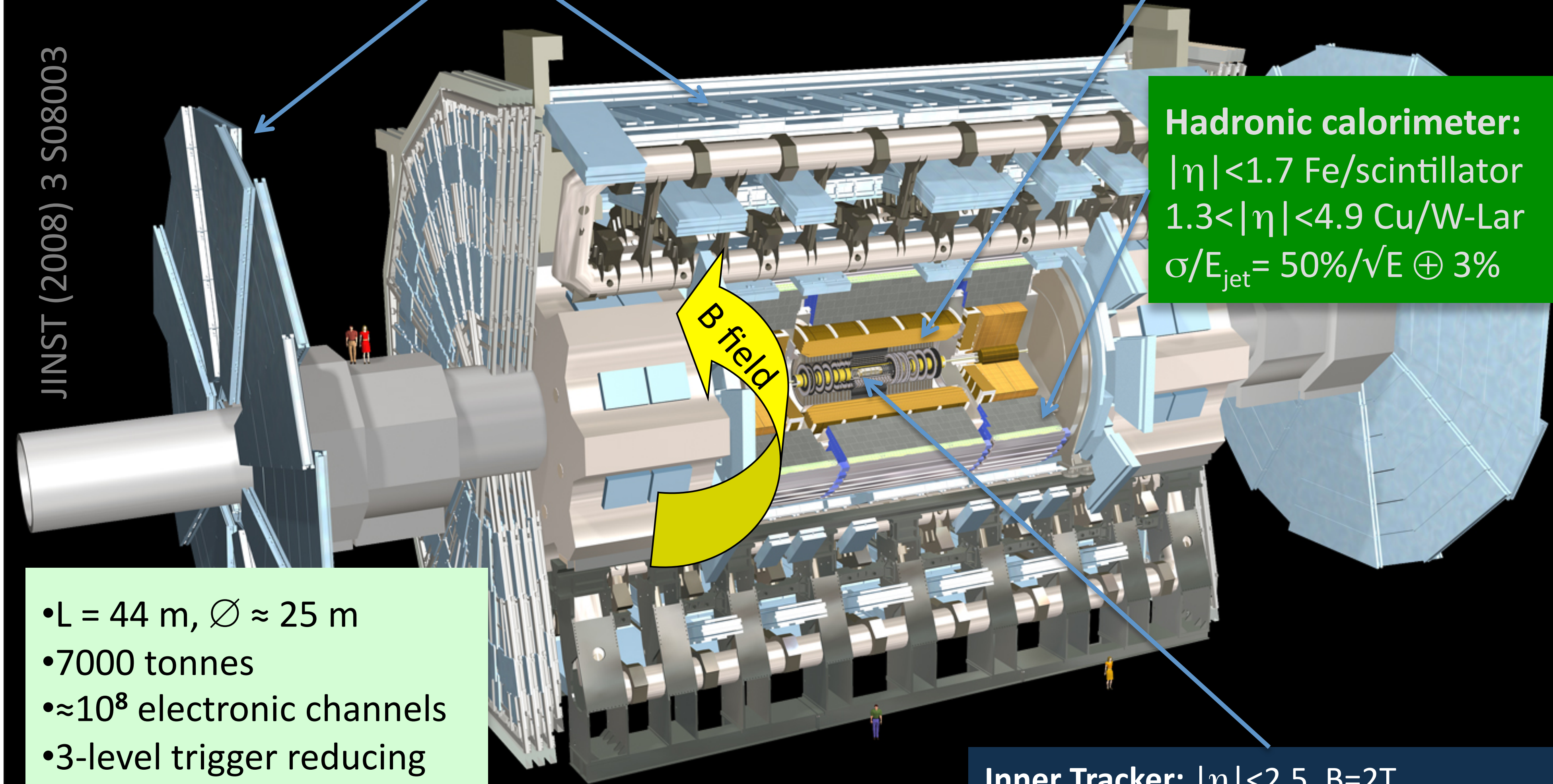
The Large Hadron Collider

- 26 659m circumference
- 9593 magnets: 1232 main dipoles (8T peak field)
- Cooled to 1.9K (colder than outer space) by 120 tonnes of liquid Helium
- Internal pressure 10-13 atm (10x less than on the Moon)
- $\sqrt{s}$ = 7TeV in 2010 and 2011
- $\sqrt{s}$ = 8TeV in 2012
- 50ns bunch crossing
- Design $\sqrt{s}$ = 14TeV and 25ns bunch crossing (7m at *c*)


13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!
MREU

Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$



JINST (2008) 3 S08003

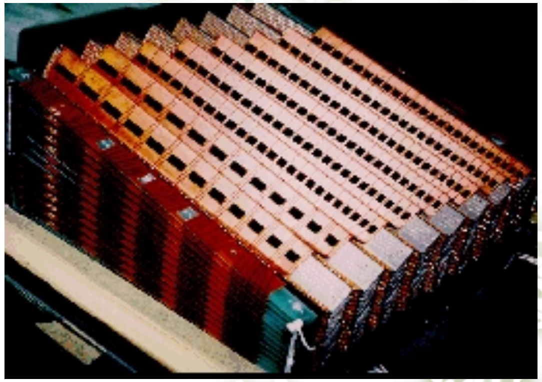
Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

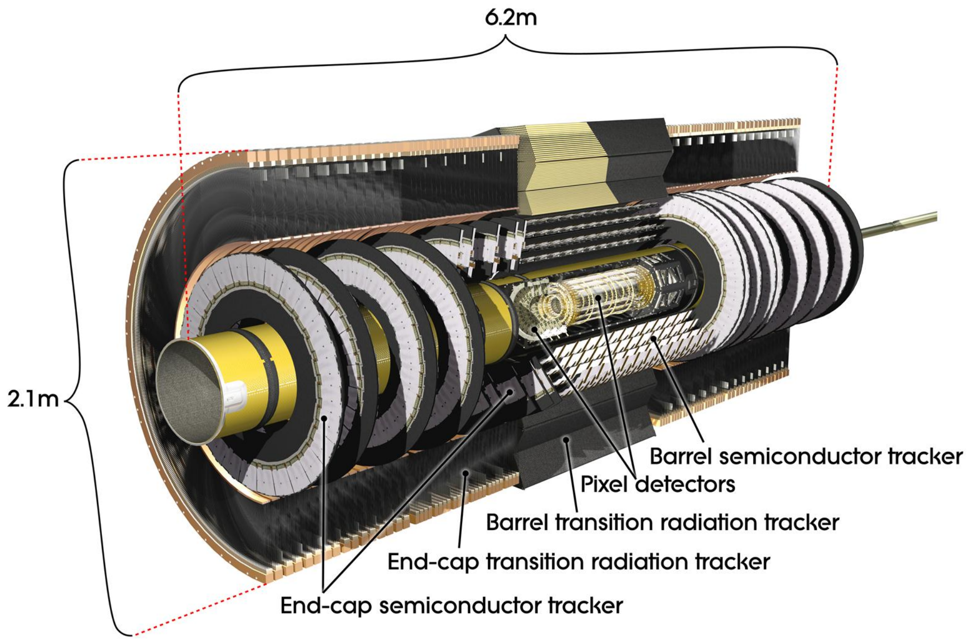
- $L = 44$ m, $\varnothing \approx 25$ m
- 7000 tonnes
- $\approx 10^8$ electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

Inner Tracker: $|\eta|<2.5$, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\text{GeV}) \oplus 1\%$

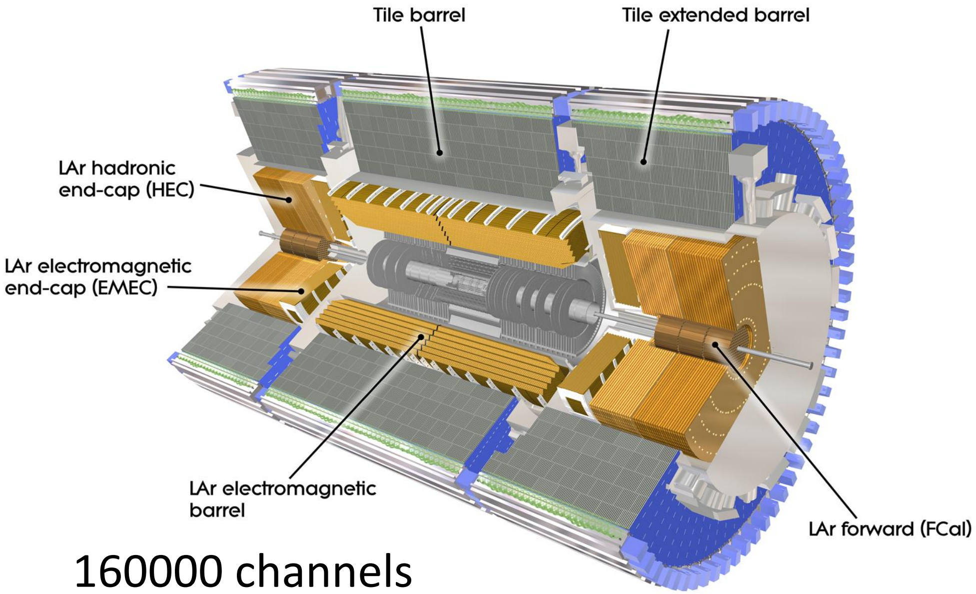
ATLAS

- Large angular coverage ($|\eta|<4.9$; tracking coverage up to η**~2.5**)
- Standalone muon spectrometer – separate fast muon chambers for trigger
- Toroidal magnetic field in muon spectrometer (supercondutor air-core toroids)
- Liquid Argon electromagnetic sampling calorimeter with accordion geometry





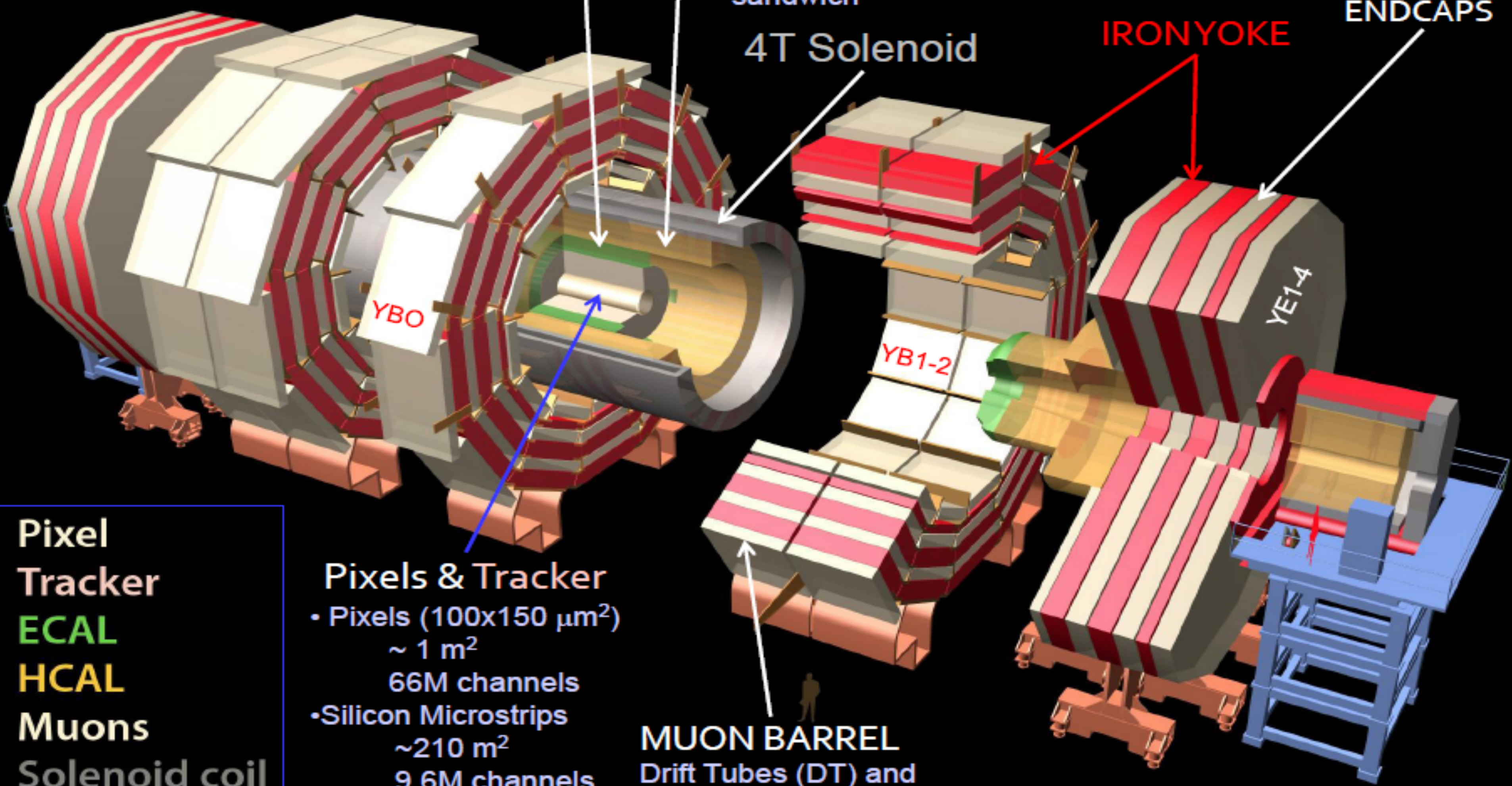
Pixel: 10x100µm; 80 M channels
Strips: 80µm; 6 M channels



160000 channels

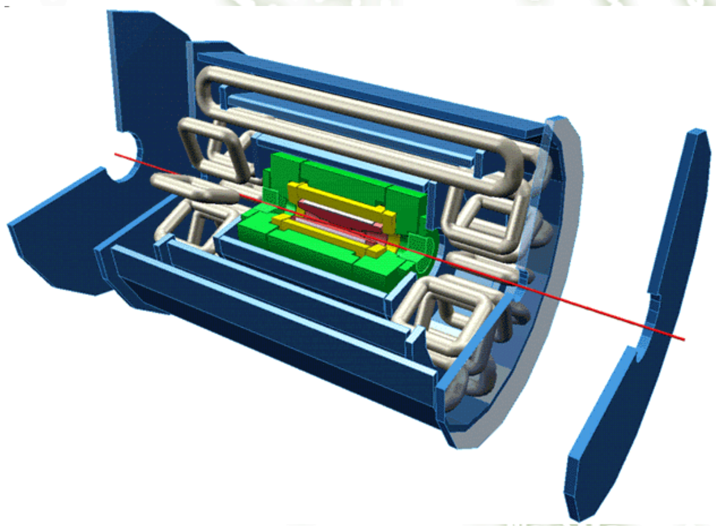
CMS

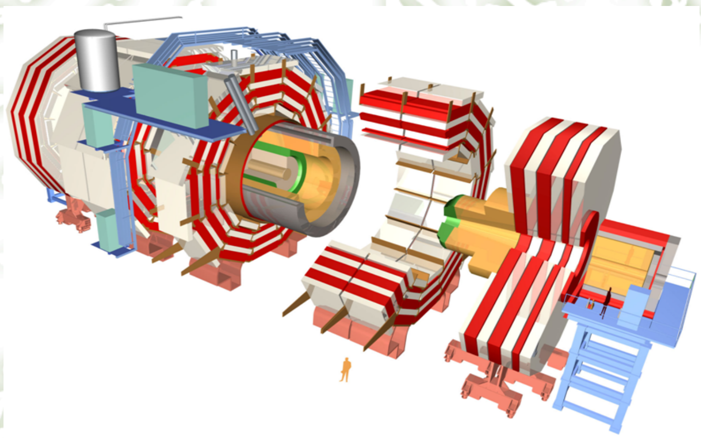
Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m



- Pixel
- Tracker
- ECAL
- HCAL
- Muons
- Solenoid coil

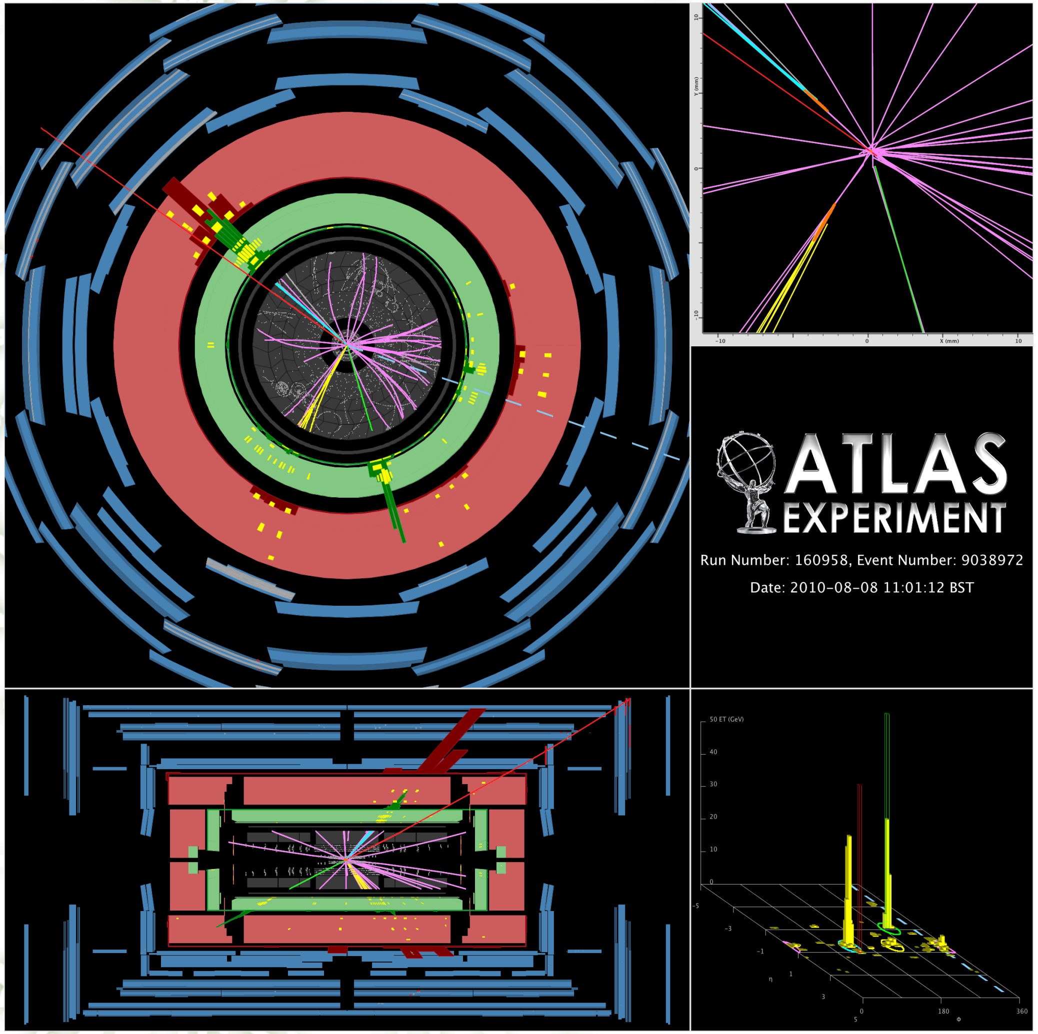
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5 \times 10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5 \times 10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)



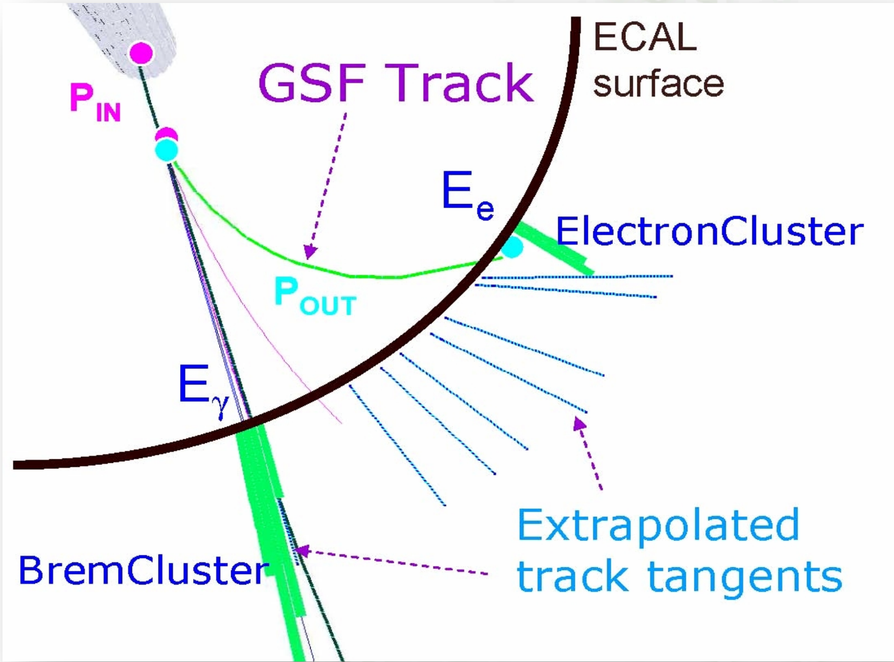


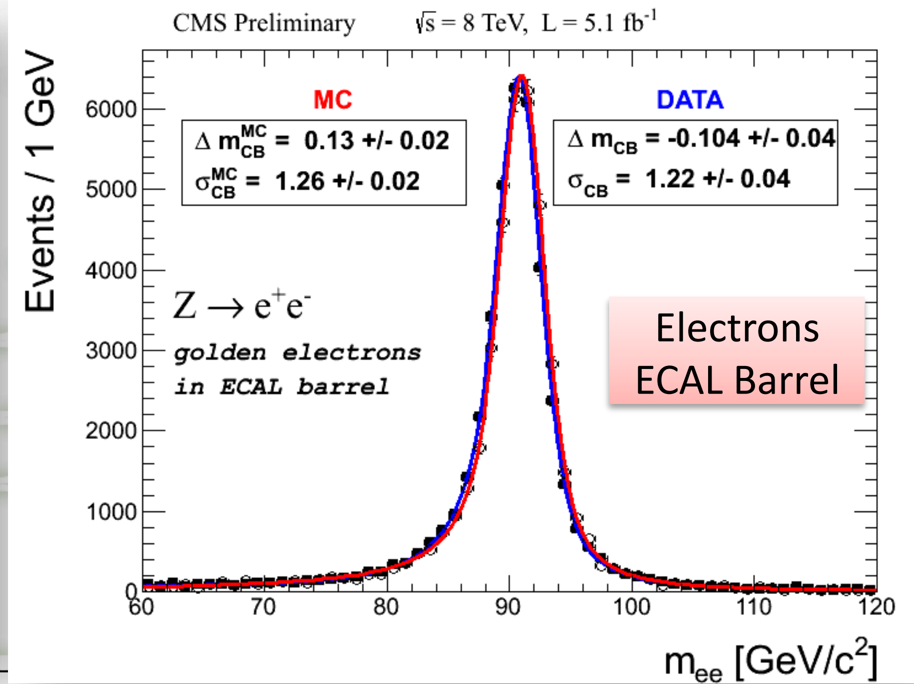
Event Reconstruction

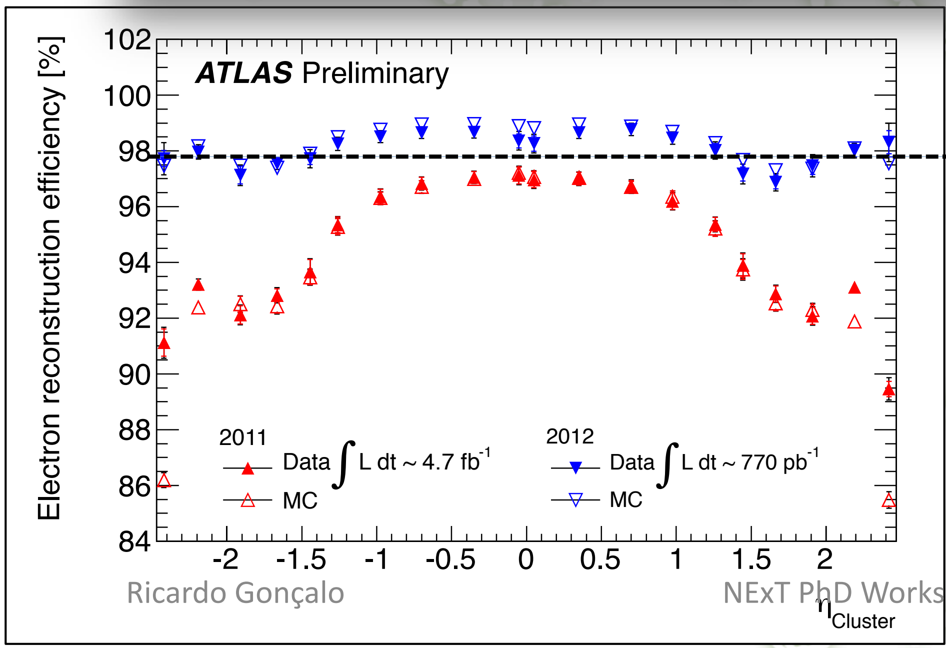
- Detector design is a balance between precision to reconstruct particles of interest, feasibility, cost, etc
  - E.g. CMS electromagnetic calorimeter: excellent energy resolution for photons – designed with H->γγ in mind
- Event reconstruction:
  - Go from information in every sub-detector to reconstructed physical objects:
  - Muons (inner detector + muon spectrometer)
  - Electrons, tau leptons, hadronic jets, b-quark initiated jets (inner detector+ calorimeter)
  - etc

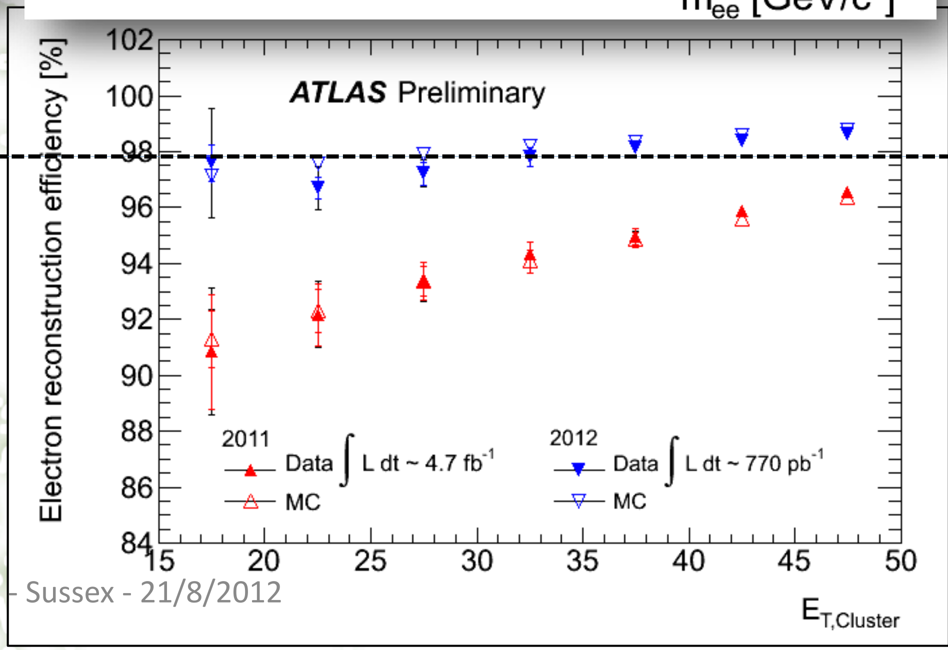


Electron & Photon Reconstruction



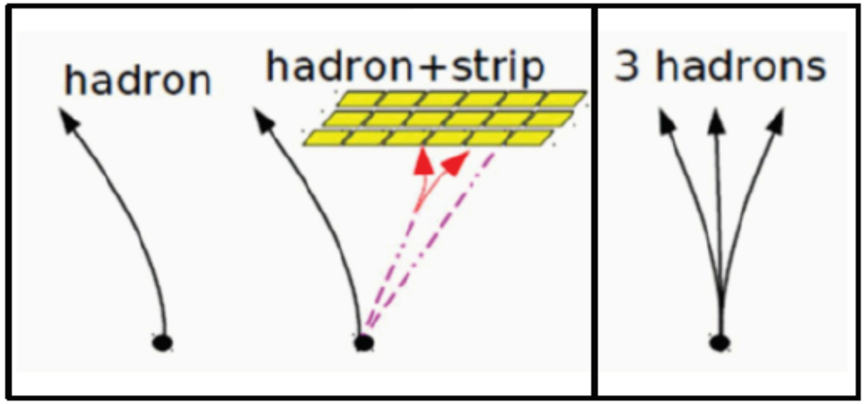


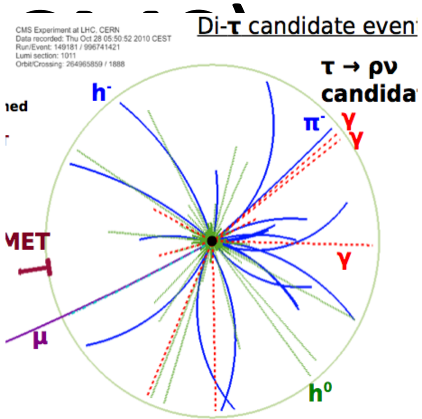




Hadronic Tau identification:

- Reconstruct individual decay modes
- Charged hadrons + electromagnetic obj arranged in strips or single photons



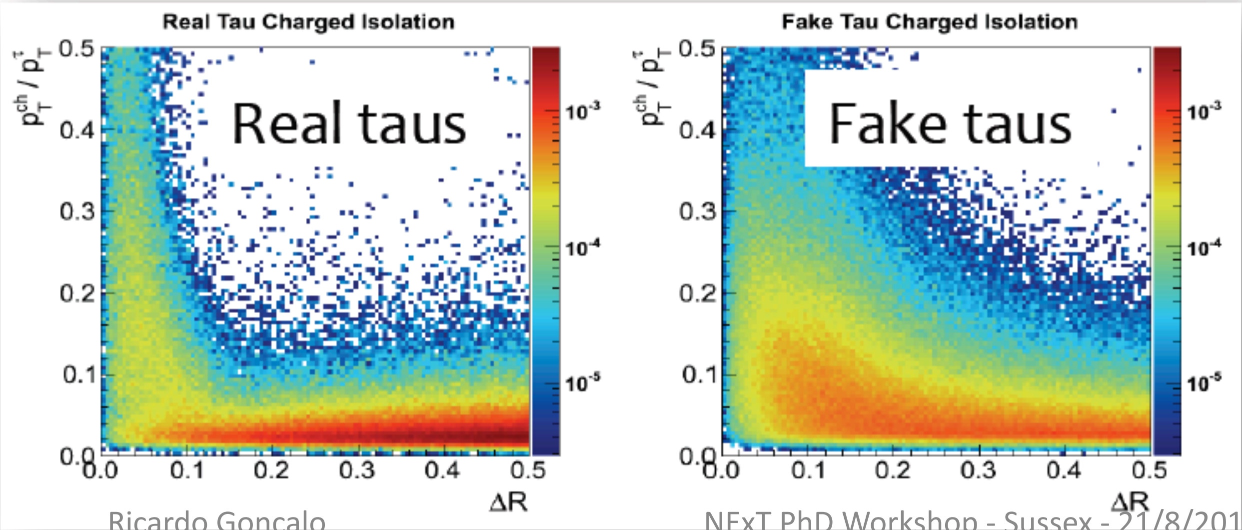


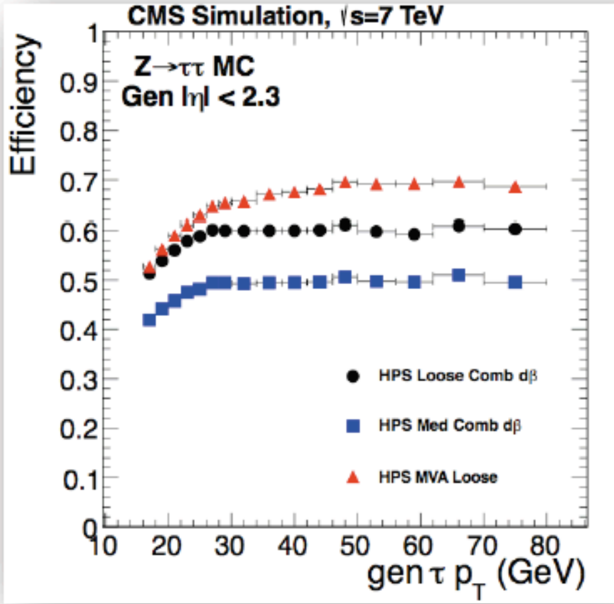
$\tau \to \pi\nu$	$\tau \to \rho\nu$	$\tau \to a_1\nu$
$\pi^\pm$	$\rho^\pm \to \pi^\pm \pi^0$	$a_1 \to \pi^\pm \pi^0 \pi^0$ $a_1 \to \pi^- \pi^+ \pi^-$ $a_1 \to \pi^+ \pi^- \pi^+$

Tau Isolation:

- Multivariate discriminator using sum of energy deposits in dR rings around the tau (from 0.1 to 0.5)

eff ~62% for a fake rate of ~6%

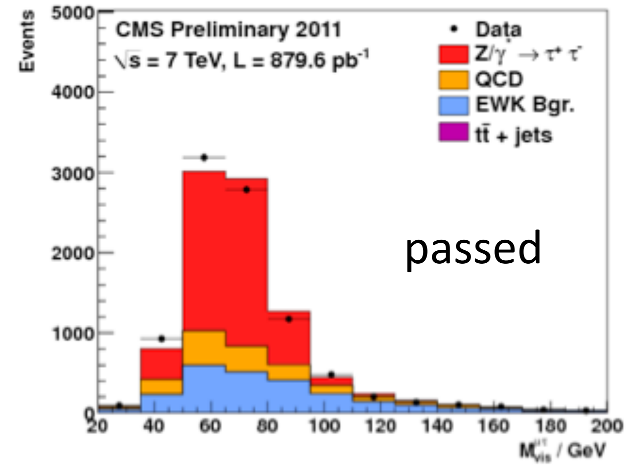


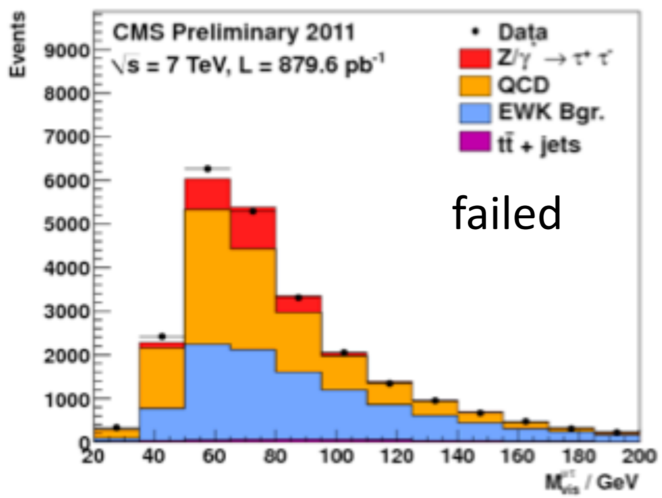


τ Identification and Energy Scale

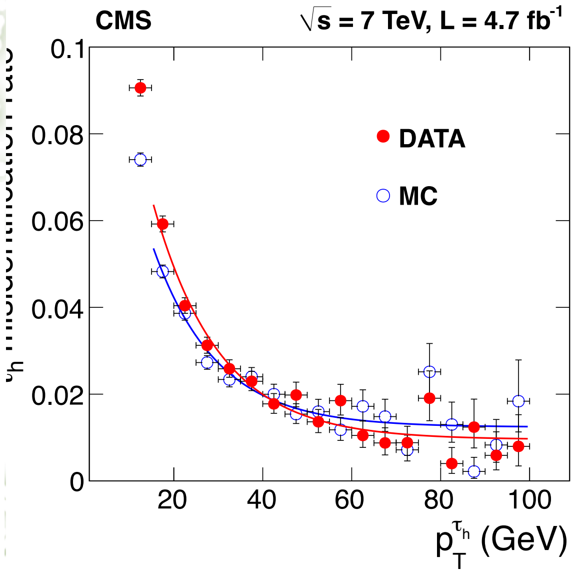
Using Tag & Probe on Z→ττ→τμ

events in data for eff. with 6%

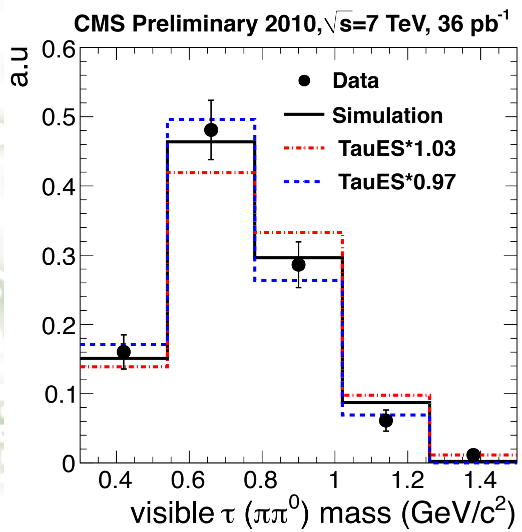




Misidentification rate measured in W+jets & Multi-jet events

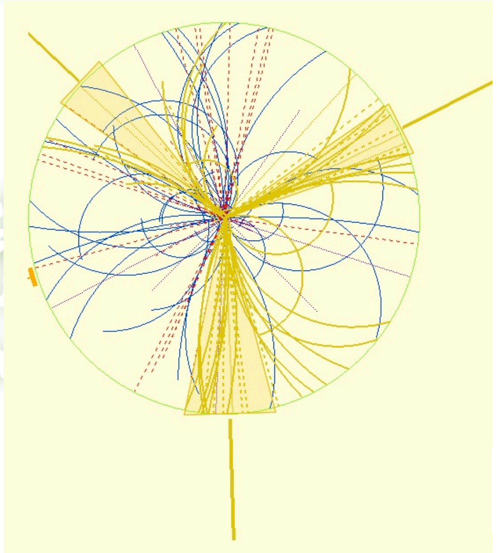


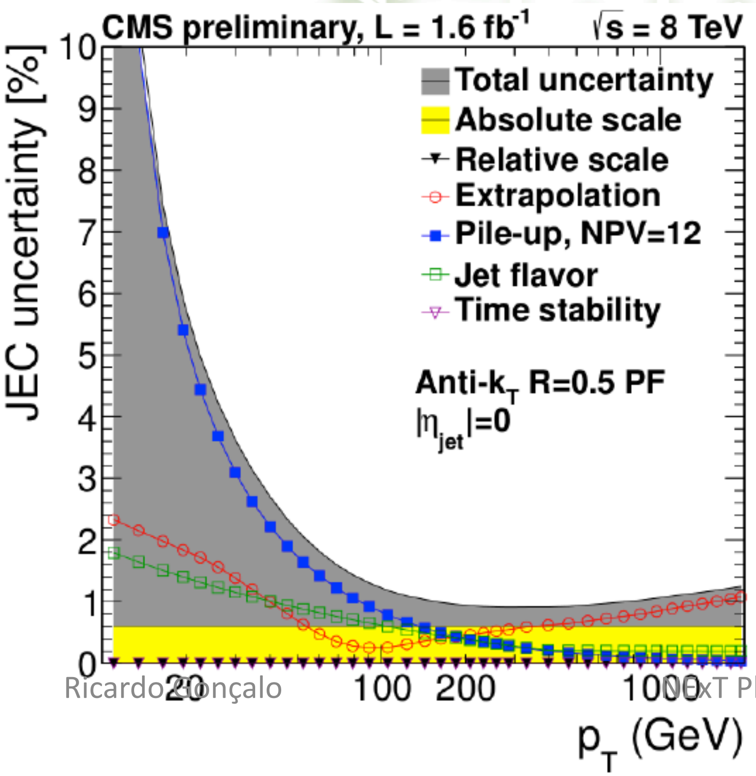
Tau energy scale is within 3%

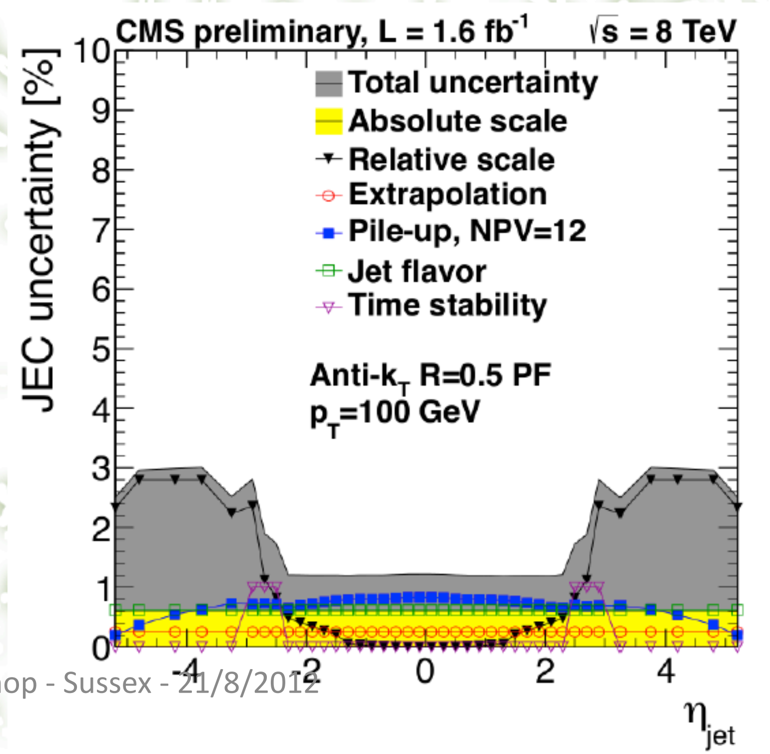


Jet Reconstruction

- Jets reconstructed in a cone of ΔR≈0.4 (ATLAS) and ΔR≈0.5 (CMS)
- Jet Energy Correction:
  - Electronic noise
  - Detector calibration & reconstruction efficiencies
  - Energy deposits from pileup
  - Dependence on η & P_T





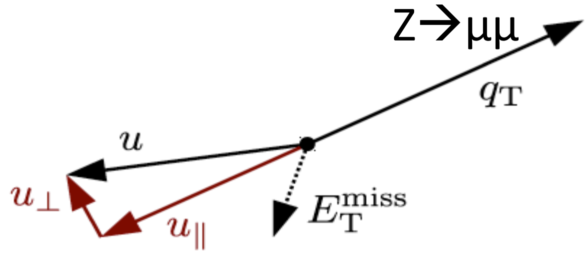


Transverse Missing Energy (M_{ET})

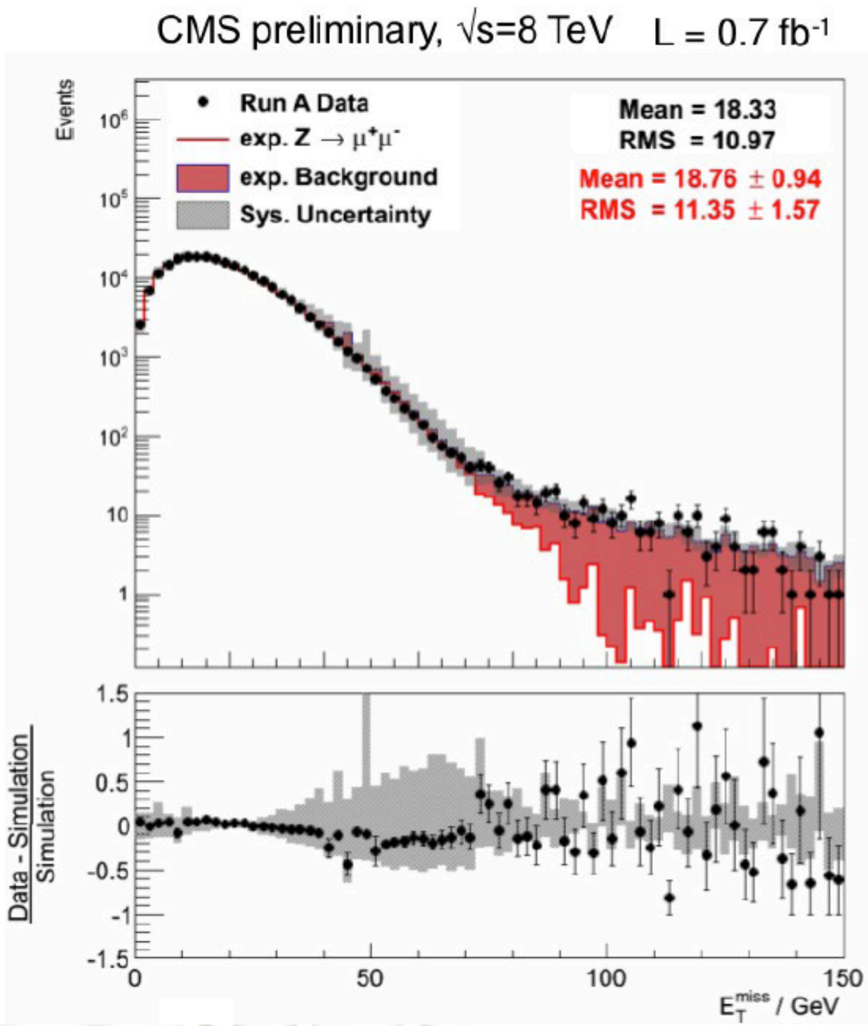
$$MET = -\sum_i \vec{E}_{T_i}$$

- Energy conservation in direction transverse to colliding p-p beams
- Need to account for
  - Non-linear calorimeter response
  - Instrumental noise, poorly instrumented area
  - mis-measured objects
- Use Z → μμ events with no intrinsic MET to measure MET resolution

$$\vec{u}^{\,\mathrm{recoil}} + \vec{q}_{\mathrm{T}}^{\,\mathrm{Z}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}} = 0$$

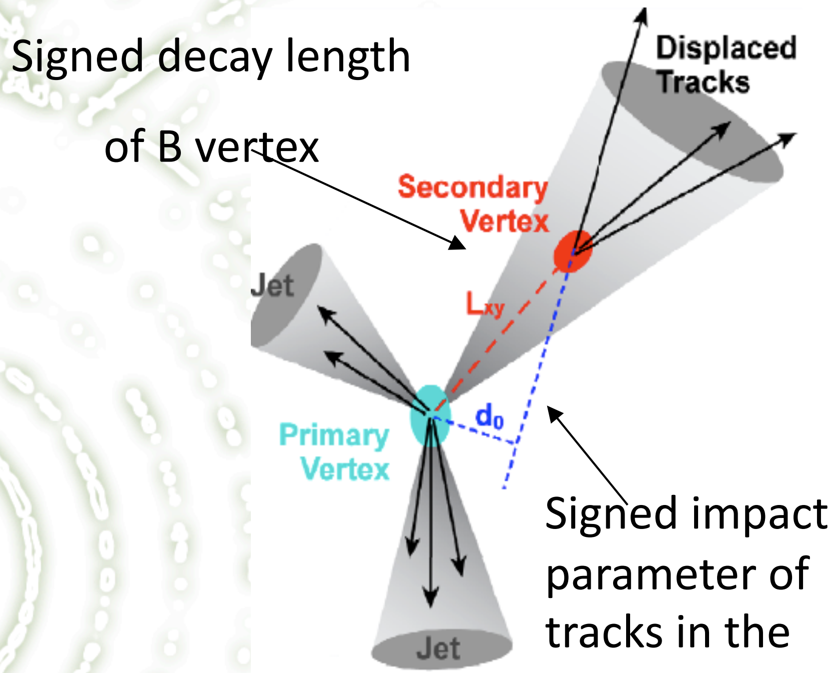


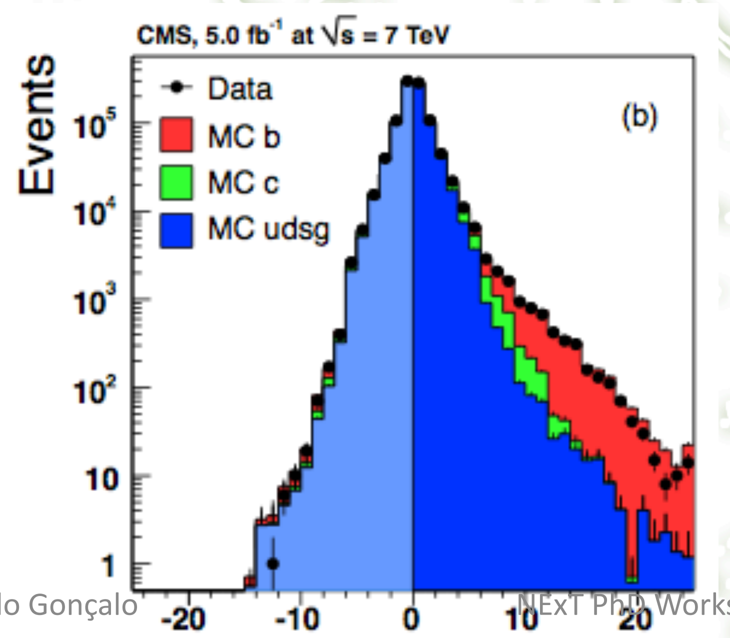
- measure for MET scale $\left\langle -\frac{u_\parallel}{q_T} \right\rangle$
- measure for MET resolution $\sigma(-u_\parallel - q_T), \sigma(u_\perp)$

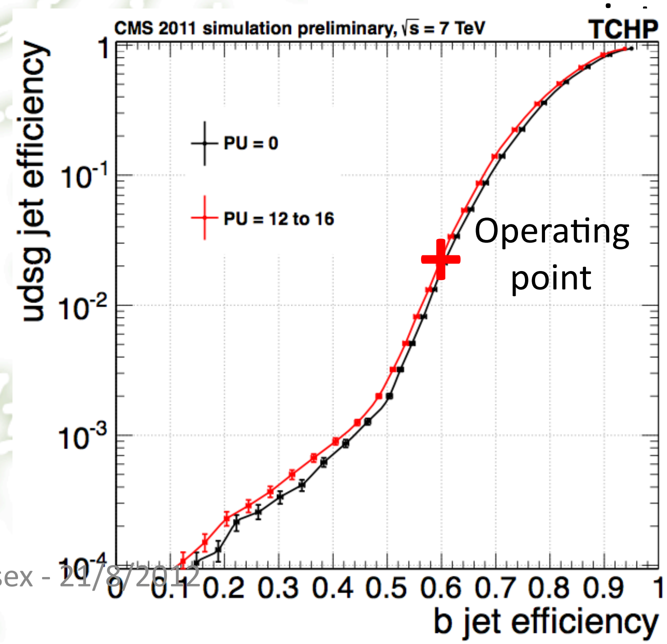


b-Jet Identification

- B-lifetime ≈ 1.5ps, <βγcτ> ≈ 1800μ
- Tracks from b-hadron decay have large P_T
- Average multiplicity ≈ 6
- B-taggers based on
  - Large signed impact parameter significance
  - Secondary vertex with large decay length
- Mistag rate measured from "negative tags"

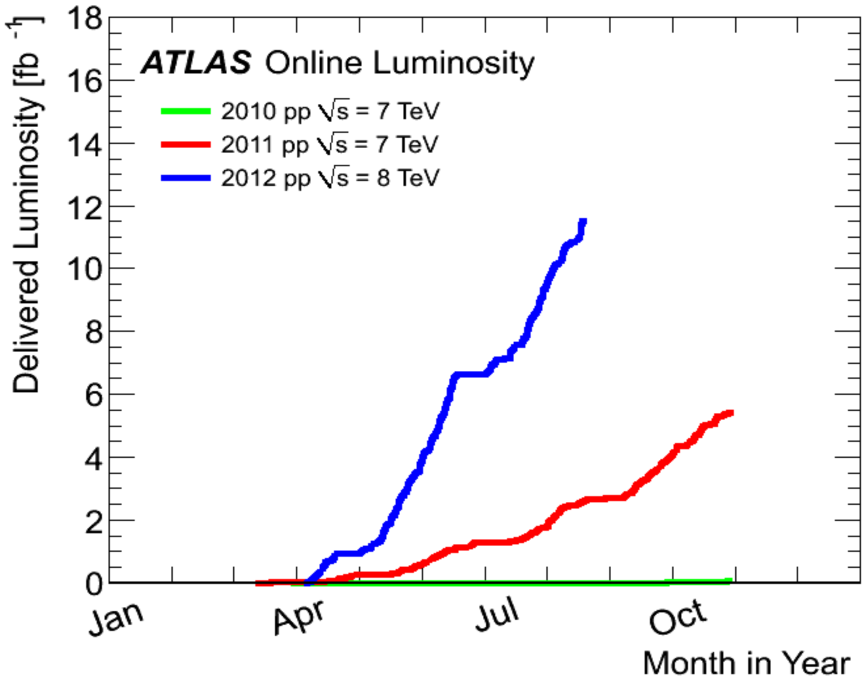


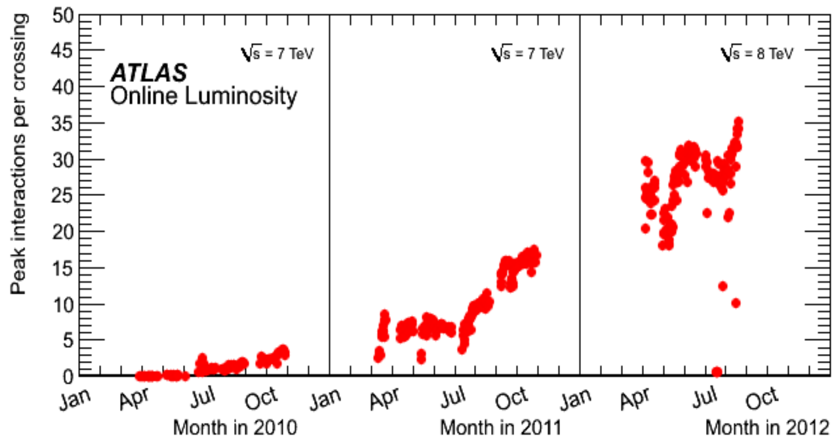




LHC Luminosity

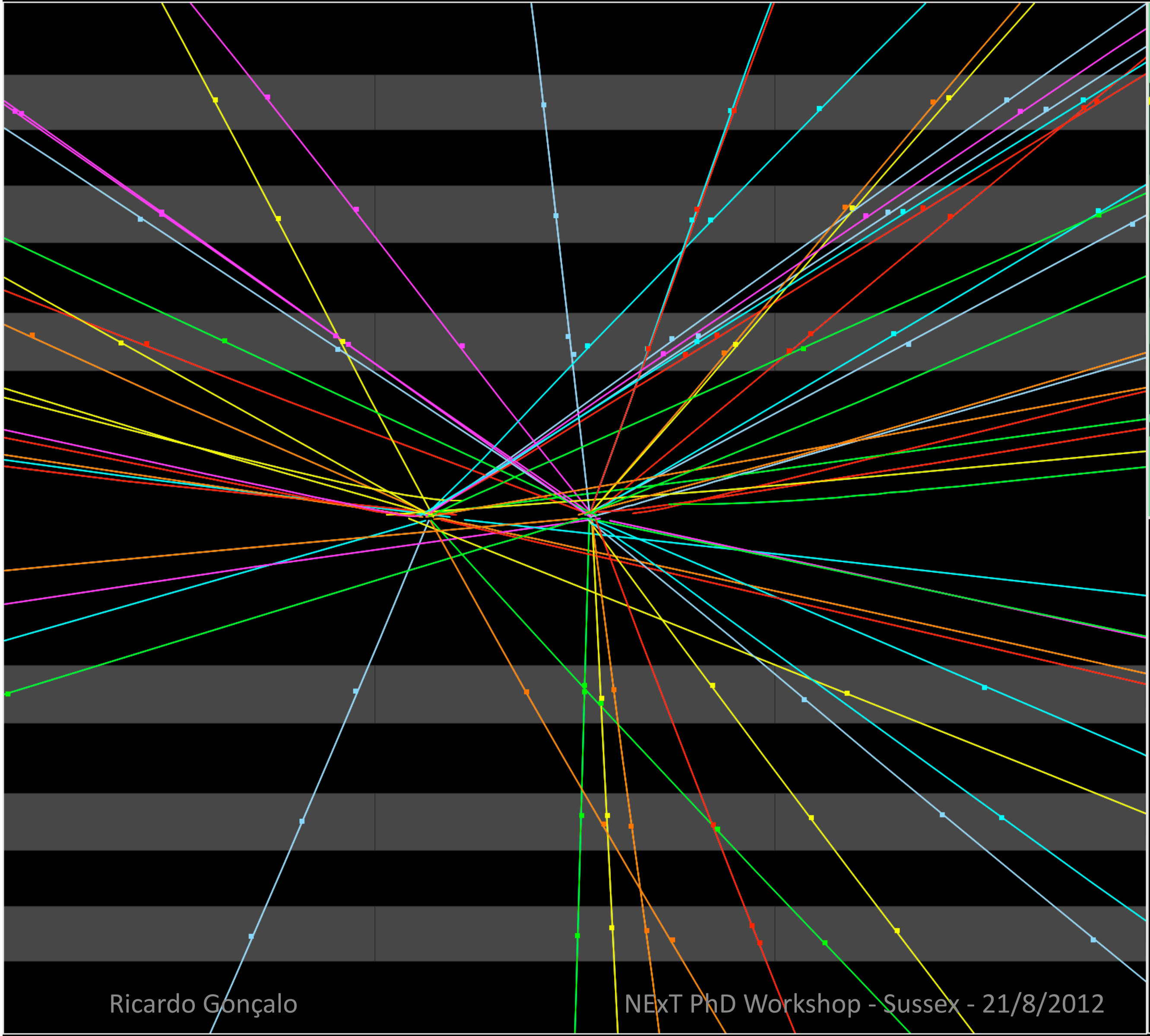
- 2010 – ≈45 pb^{-1} / experiment
  - No chance of searching for Higgs boson
  - But needed to understand our brand new detector!
- 2011 – ≈5 fb-1 per experiment
  - Things start to be (very) interesting
  - Tevatron breathing down the LHC's metaphorical neck
- 2012 – ≈11 fb^{-1} / experiment up to yesterday … and counting
  - New Particle discovery announced!
- And the rest is (will be) history

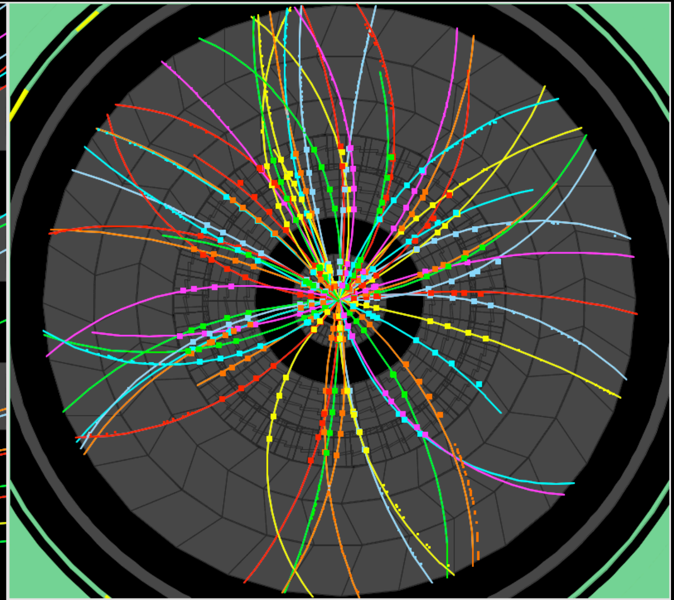




ATLAS: Pileup Evolution: 2010

Collision Event at 7 TeV with 2 Pile Up Vertices



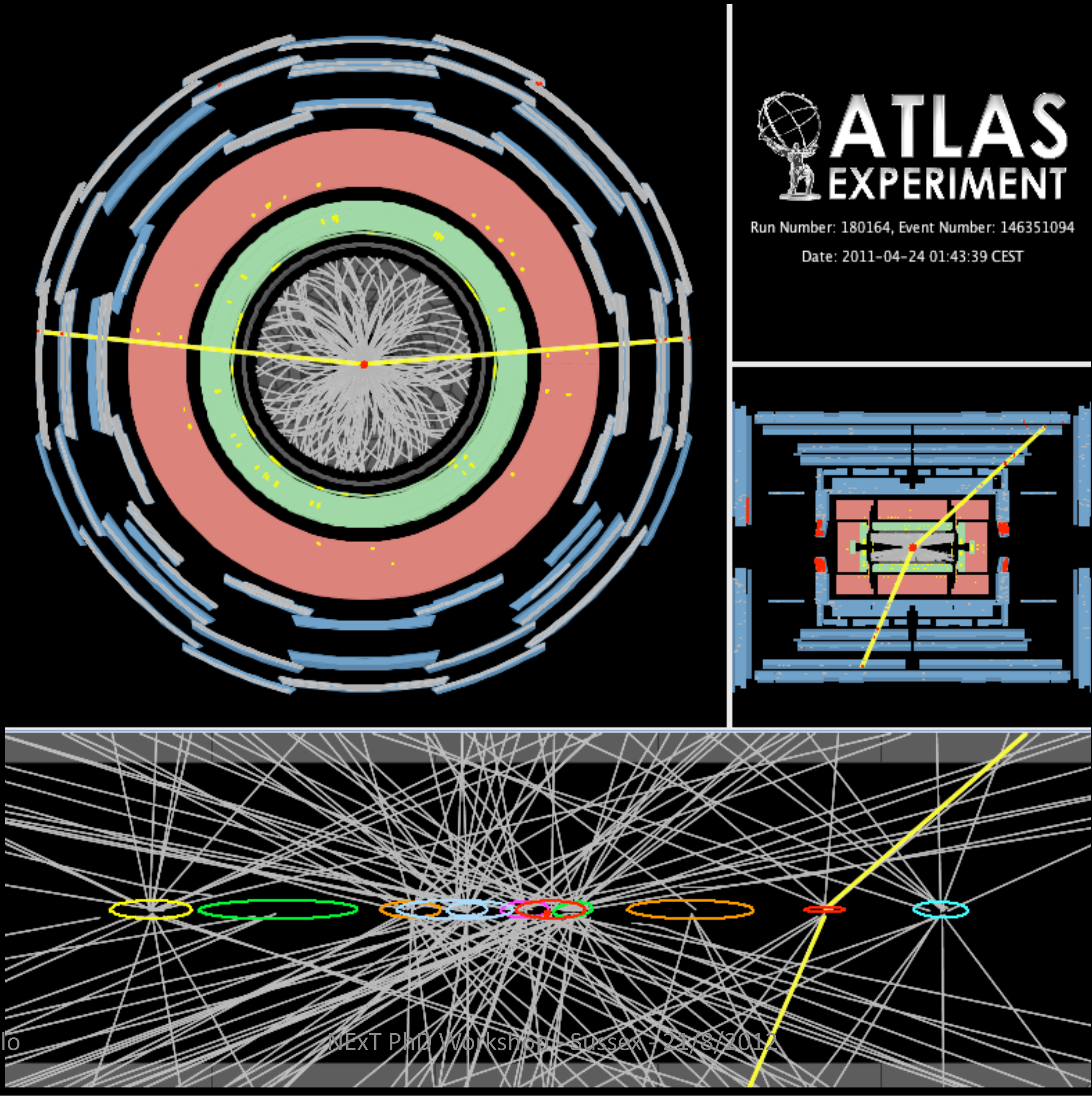


Run Number: 152166, Event Number: 467774

Date: 2010-03-30 13:31:46 CEST

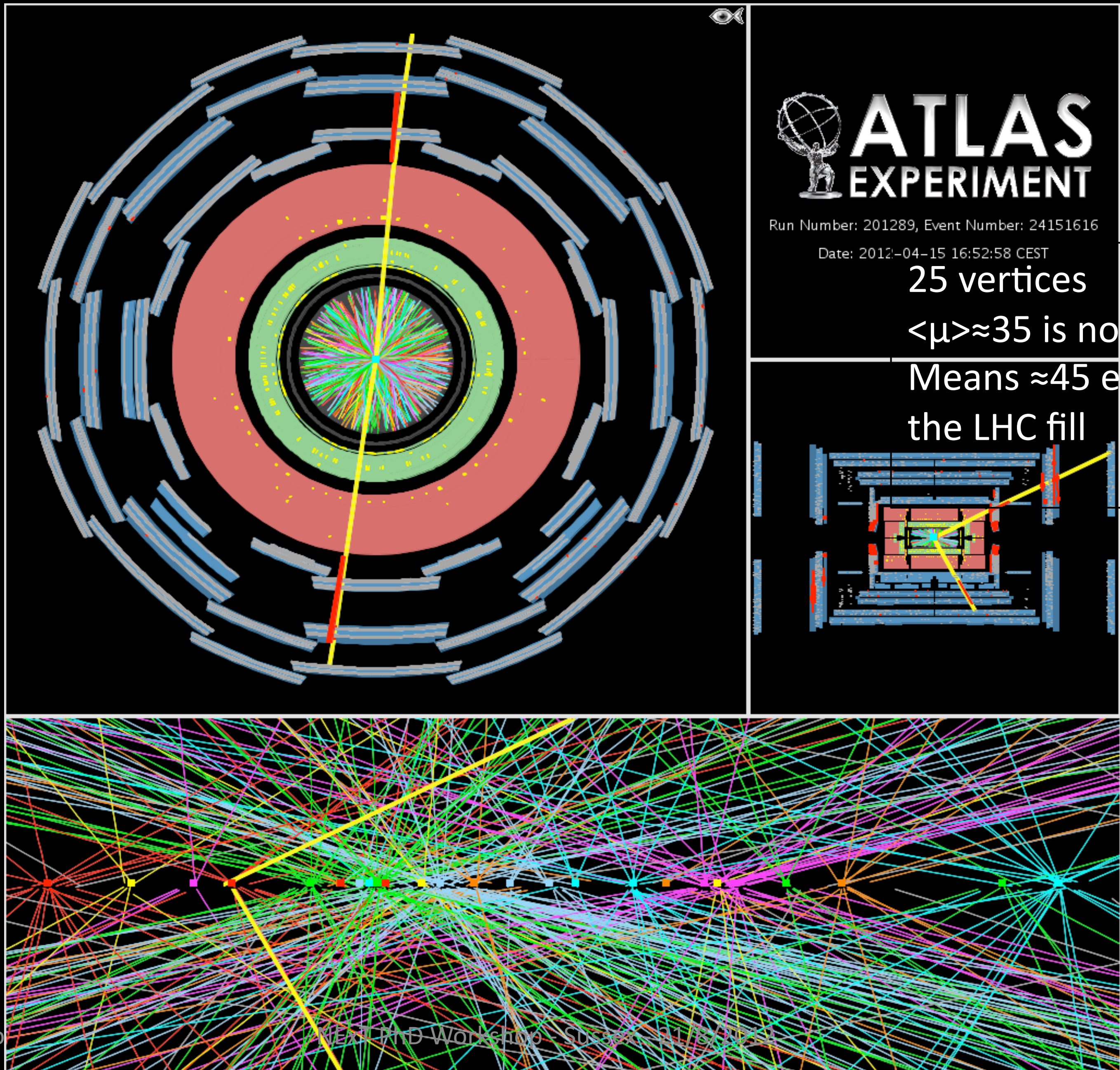
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

ATLAS: Pileup Evolution: 2011



11 vertices

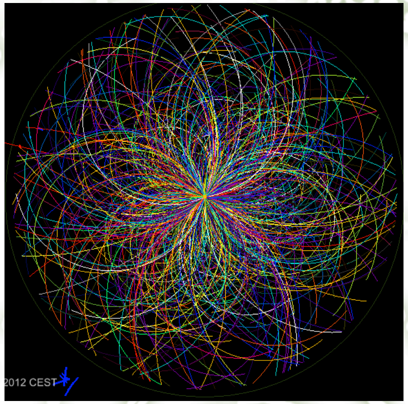
ATLAS: Pileup Evolution: 2012

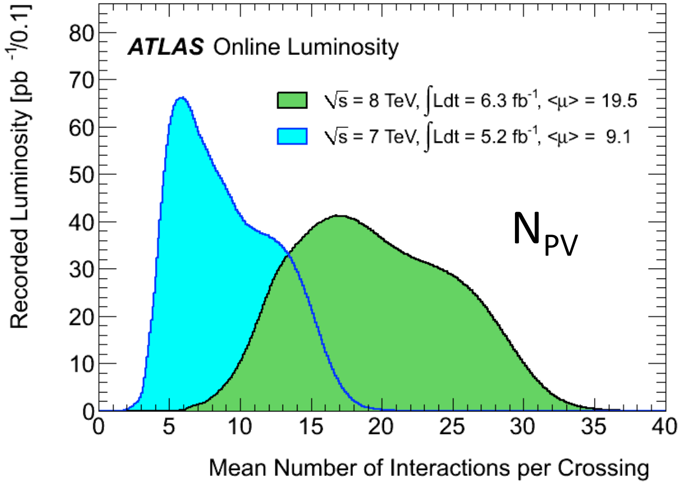


25 vertices
<μ>≈35 is now common
Means ≈45 early in the LHC fill

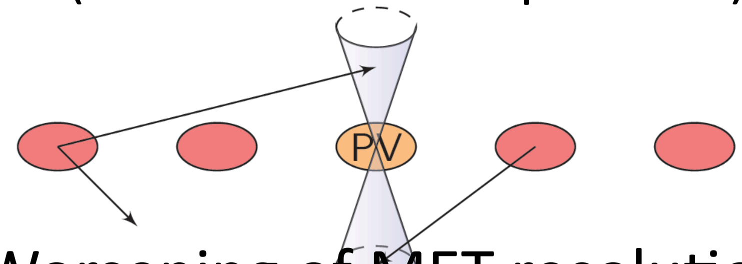
Pileup & Its Consequences

- Many more particles to reconstruct
  → more CPU & memory in event reconstruction

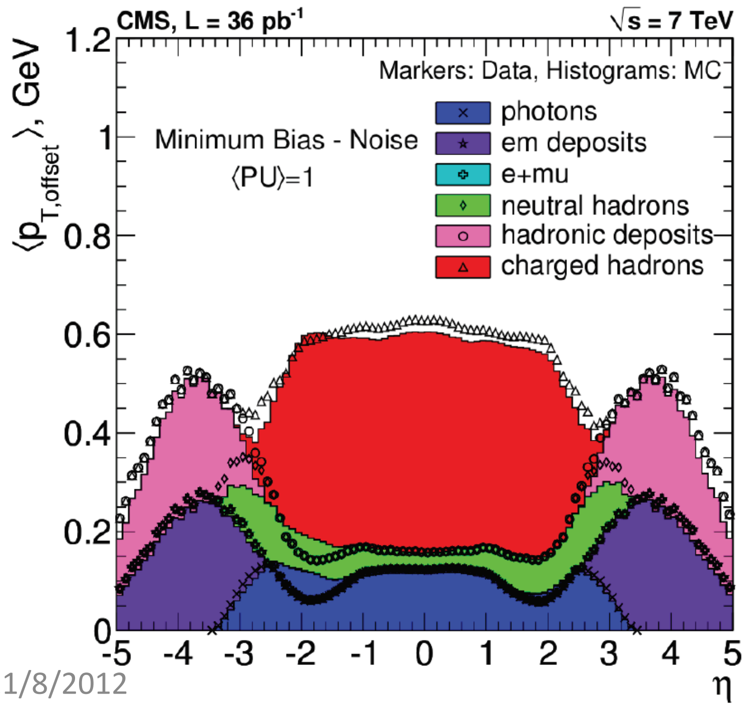




- Contaminated Jets
  - (due to additional particles)

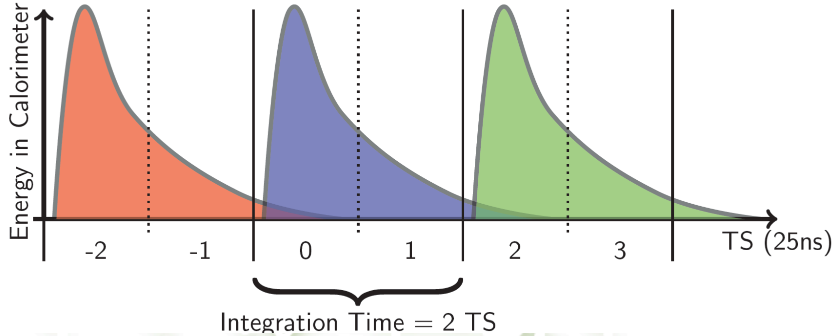


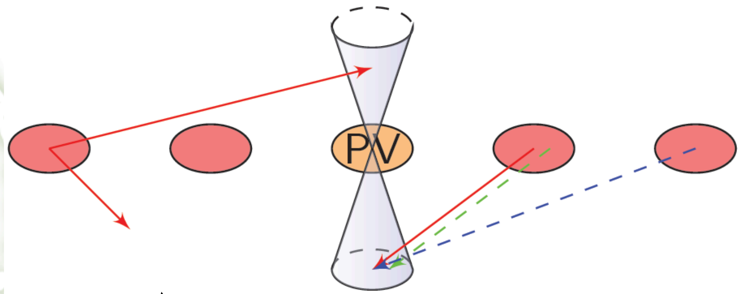
- Worsening of MET resolution
  - (more objects to sample)
- Worsening of Isolation observables
- Ambiguity in hard-scatter vertex identification, e.g. $H \rightarrow \gamma\gamma$

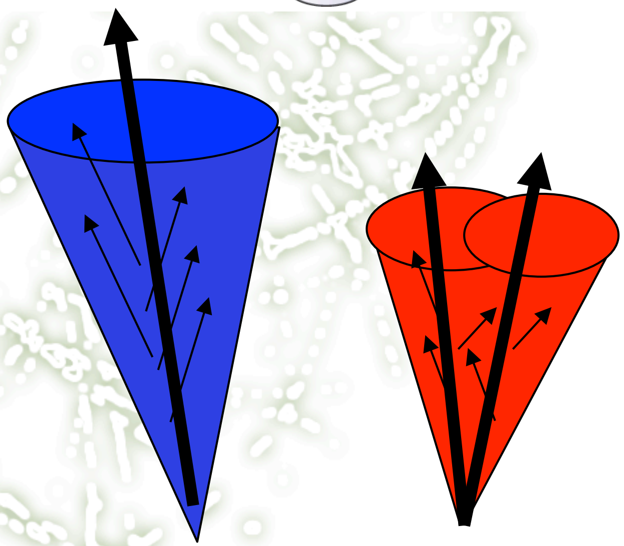


Mitigating Pileup

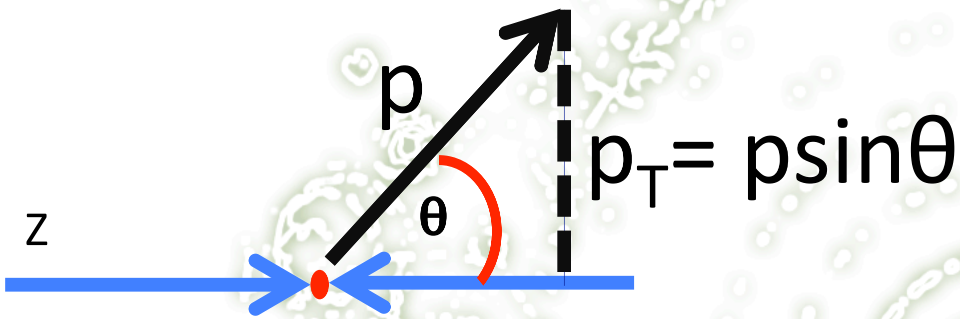
- Detector level mitigation: Readout over smaller time slice
  - Significantly reduces OOT pileup
- Remove from consideration charge hadrons that originate from pileup vertices
- Amount of additional pileup energy is determined by the jet area (A) and the energy per unit area (ρ)
  - and subtracted
- Take advantage of the topological shape differences between jets from pileup and more collimated jets from hard-scatter of partons

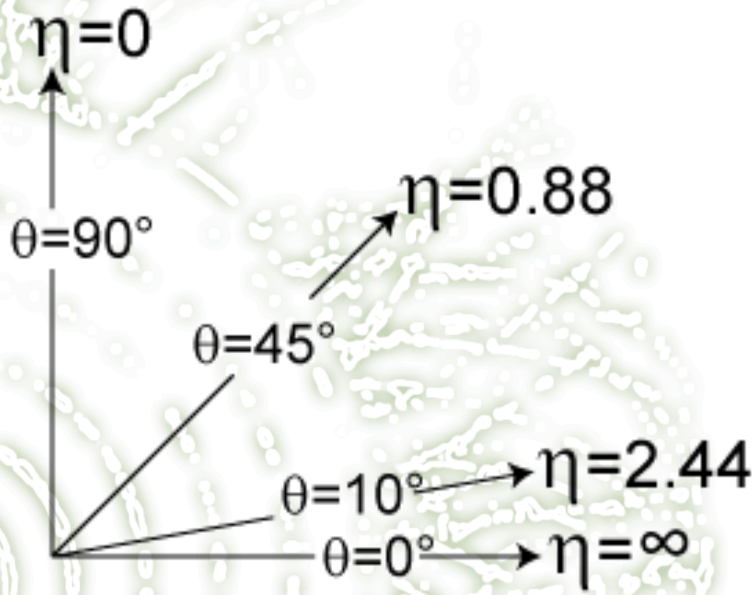




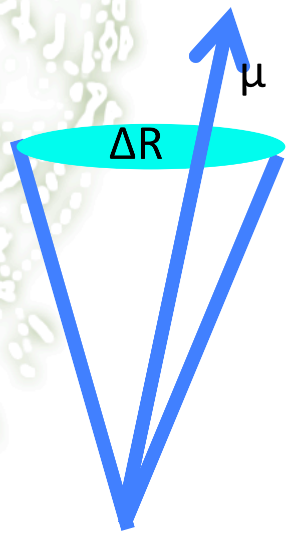


Hadron Collider Variables



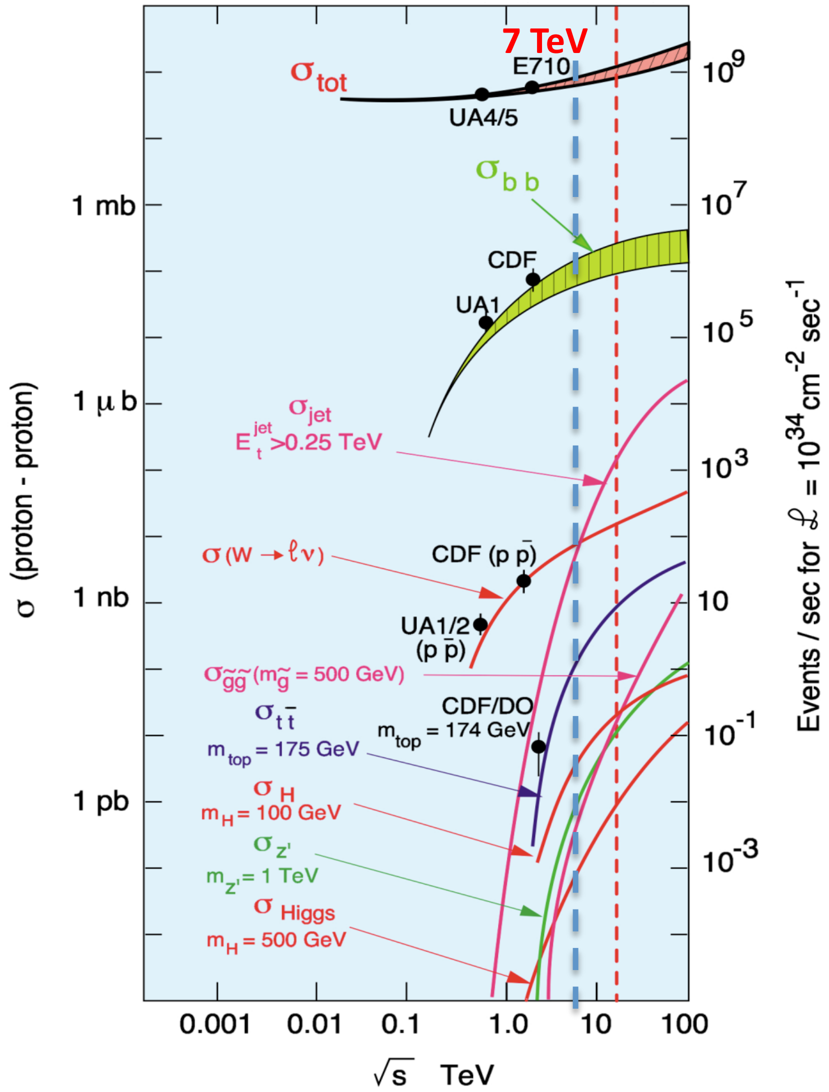


Pseudorapidity η = - ln(tanθ/2))



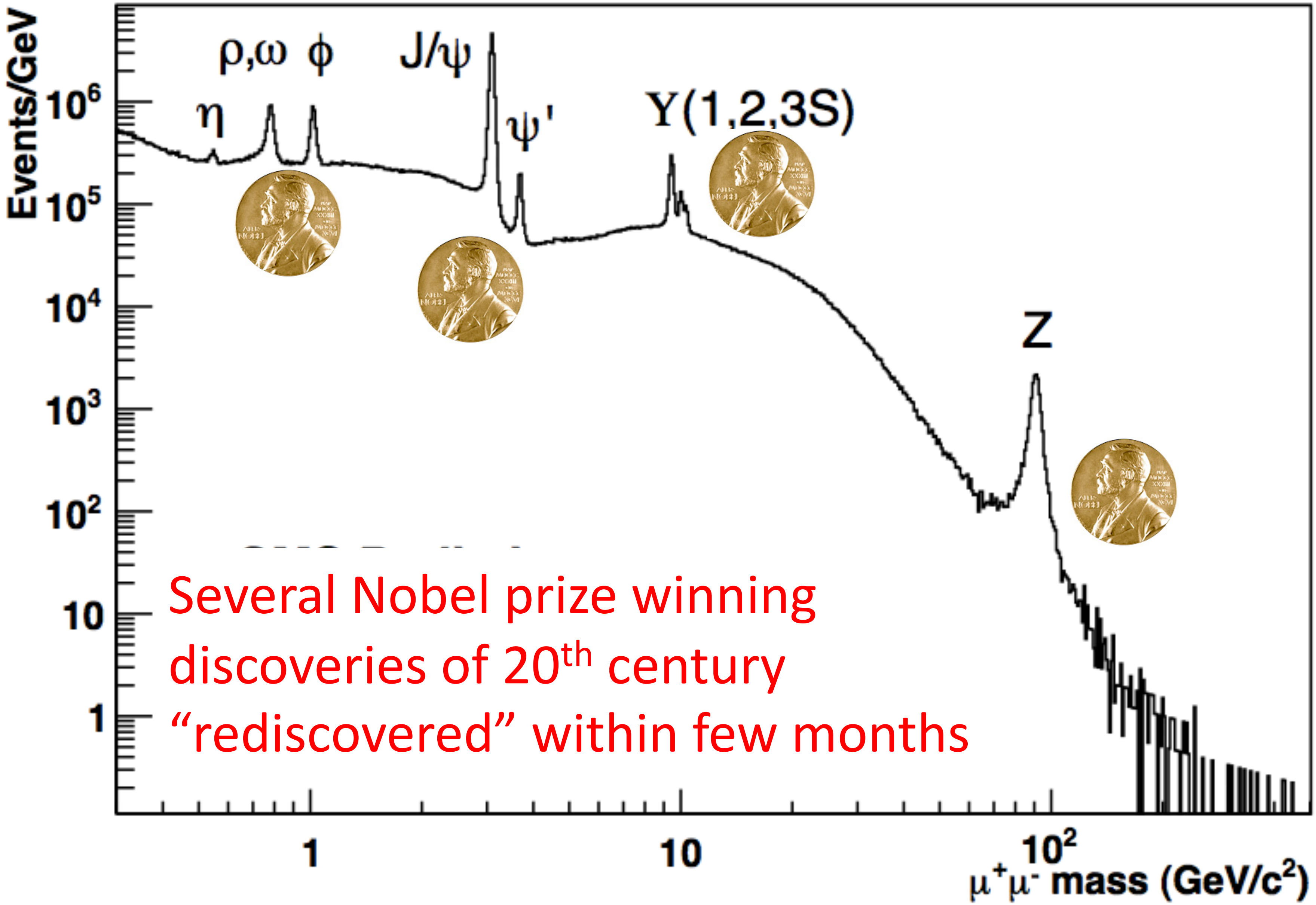
- Use relativistic cylindrical coordinates (r,η,φ)
  - dN/dη is invariant for boosts along z for particles in a jet
- For object definitions, identification criteria etc. use cones with apex at interaction point and a radius ΔR:
  - $\Delta R = \sqrt{[(\Phi-\Phi_0)^2+(\eta-\eta_0)^2]}$
  - where (Φ_0, η_0) gives the flight direction of object –e,μ,γ,τ.jets etc

Trigger



- First step in every physics analysis!
- Much of LHC physics means cross sections x10^6 times smaller than total cross section
- ATLAS offline processing: ≈400 Hz
  - ≈10 events per million crossings!
- In one second at design luminosity:
  - 40 000 000 bunch crossings
  - ≈2000 W events
  - ≈500 Z events
  - ≈10 top events
  - 400 events written out
- **Should take the right 400 events!...**
- Different designs in ATLAS and CMS
  - ATLAS has 3 processing levels; Region-of-Interest driven reconstruction; event built after Level 2
  - CMS has 3 levels but event built after Level 1
- Also different strategies:
  - ATLAS has most bandwidth assigned to exclusive triggers, e.g. muon trigger (+ anything)
  - CMS relies more on exclusive triggers e.g. muon + 2 jets

Old History – Rediscovering The SM



Several Nobel prize winning discoveries of 20th century "rediscovered" within few months

Part II: Tools of the Trade

Statistics Survival Guide

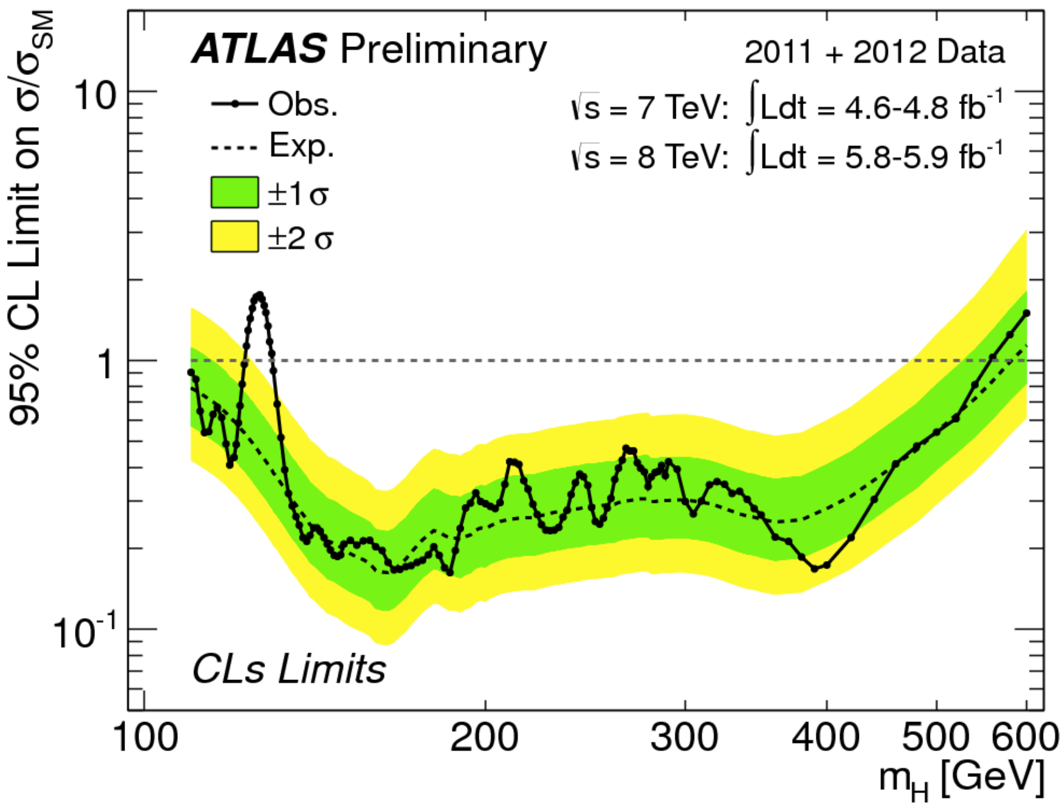
The Brazil Plot

Expected:

- Upper limit on σ(S+B)/σ(B) at 95% CL in Monte Carlo assuming B-only hypothesis

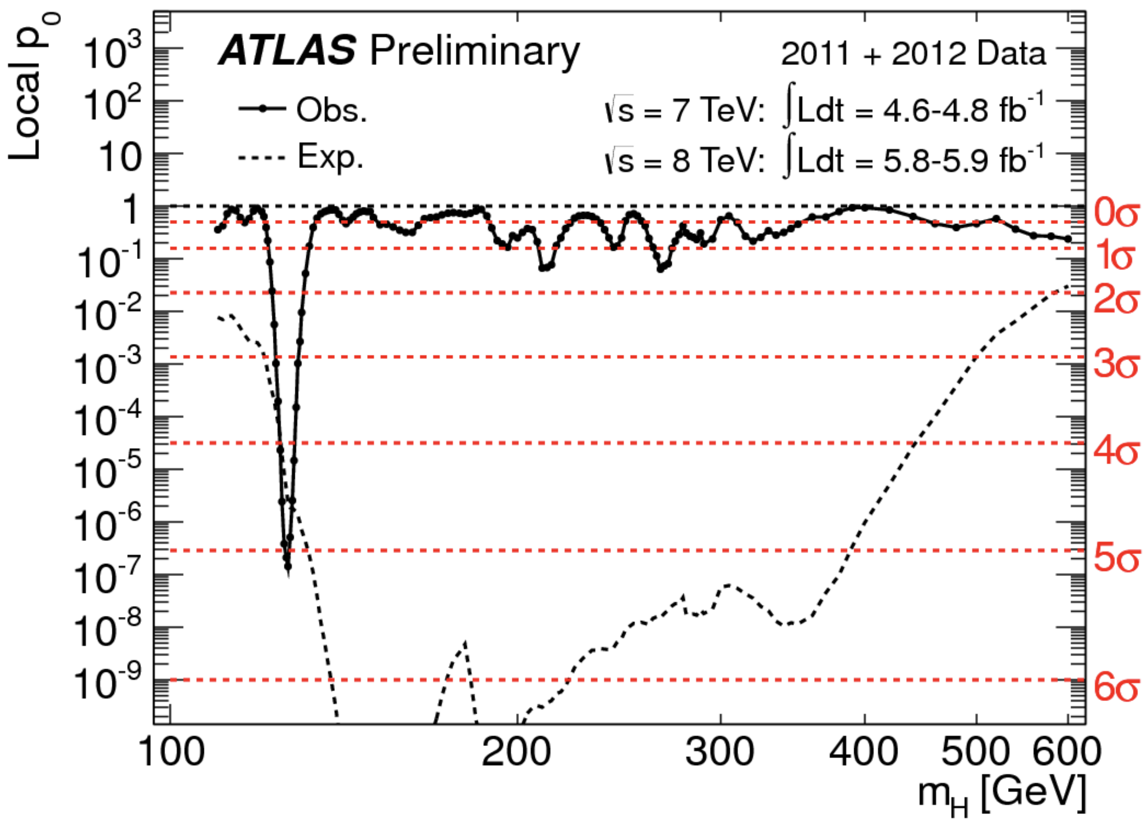
Observed:

- Upper limit on σ(S+B)/σ(B) at 95% CL seen in data assuming B-only hypothesis



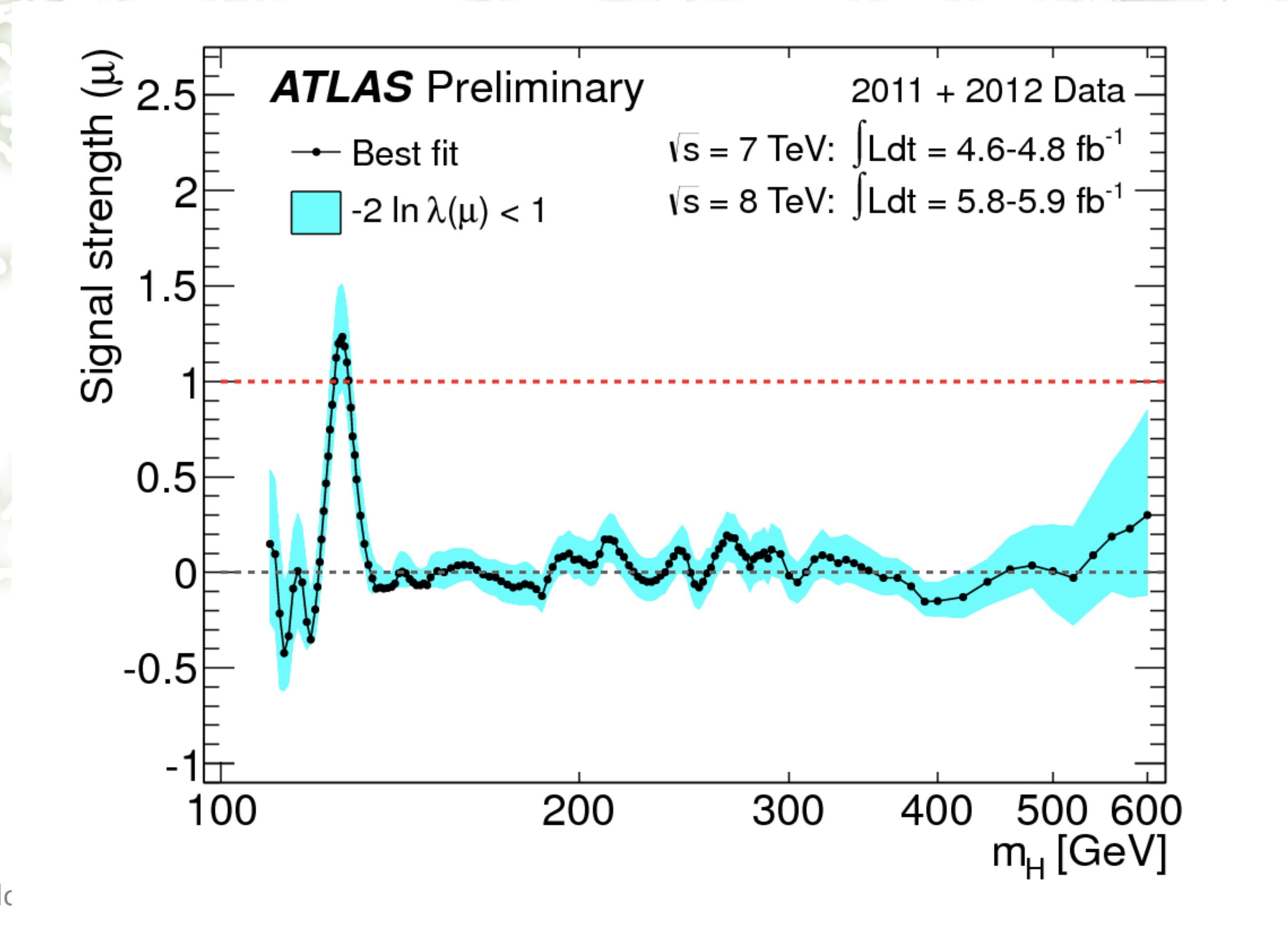
The *p0* Discovery Plot

- **p0** is the probability that the background fluctuates to look like signal
- Translated into the one-sided Gaussian probability



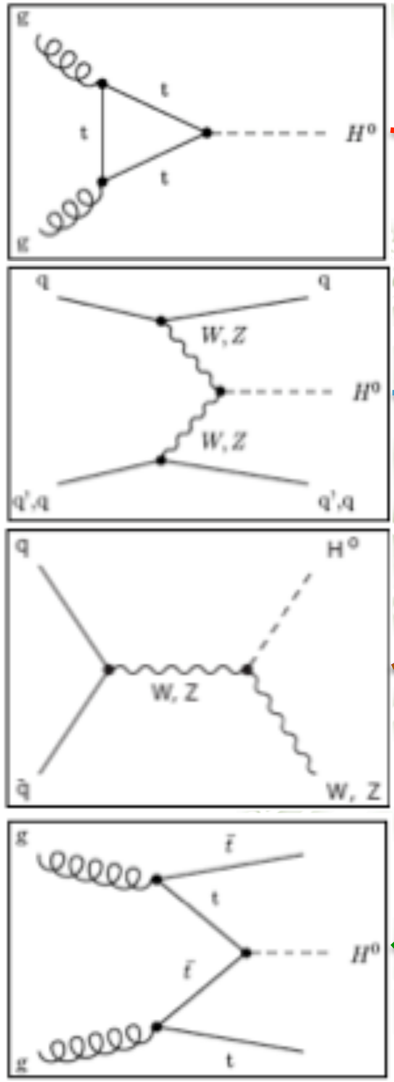
The Cyan Band Plot – signal strength

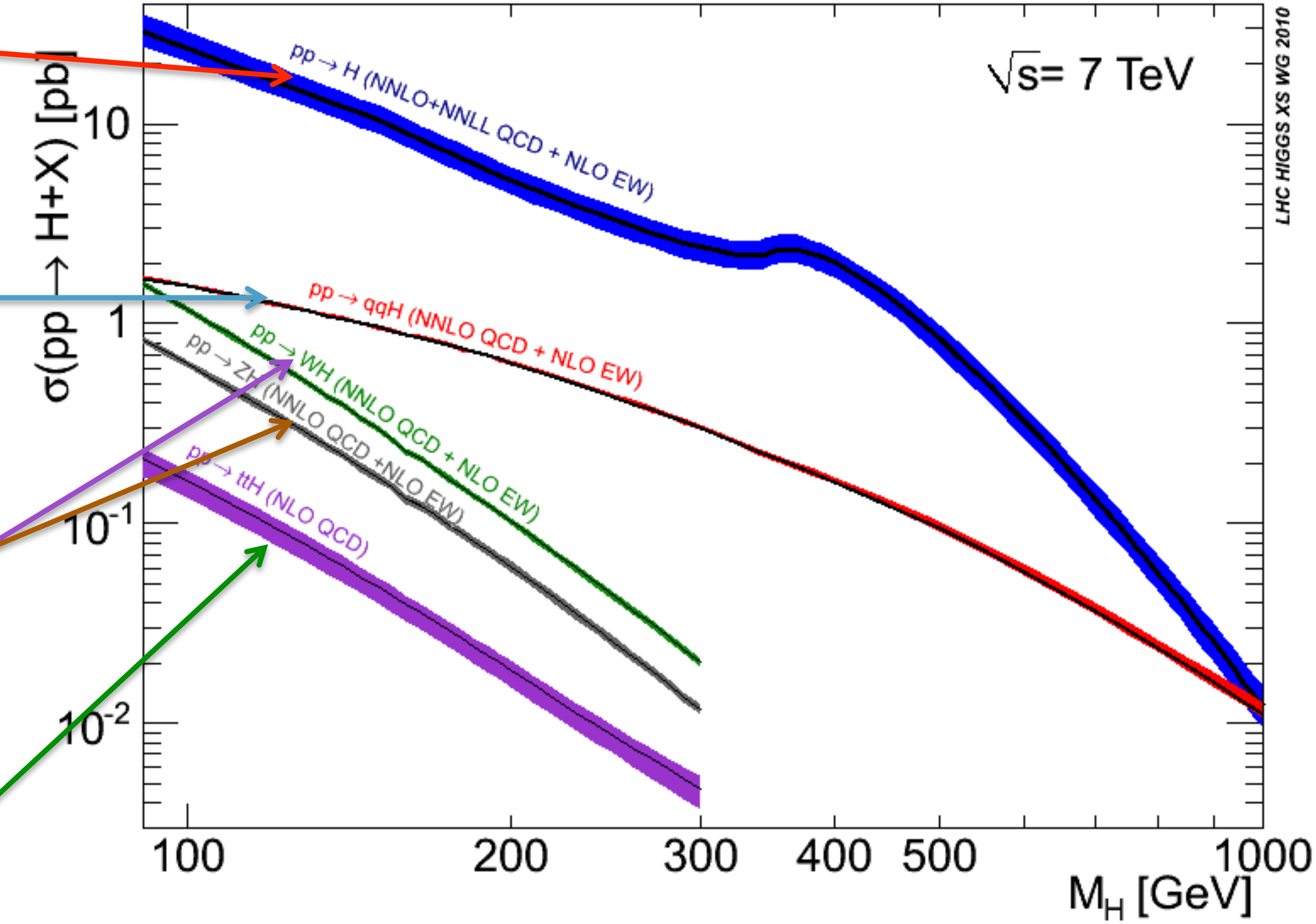
- Best fit of $\mu=\sigma(S+B)/\sigma(B)$ to data
- Error bands important…. As usual!



Part III: Higgs Hunting at the LHC

CERN-2011-002; arXiv:1101.0593

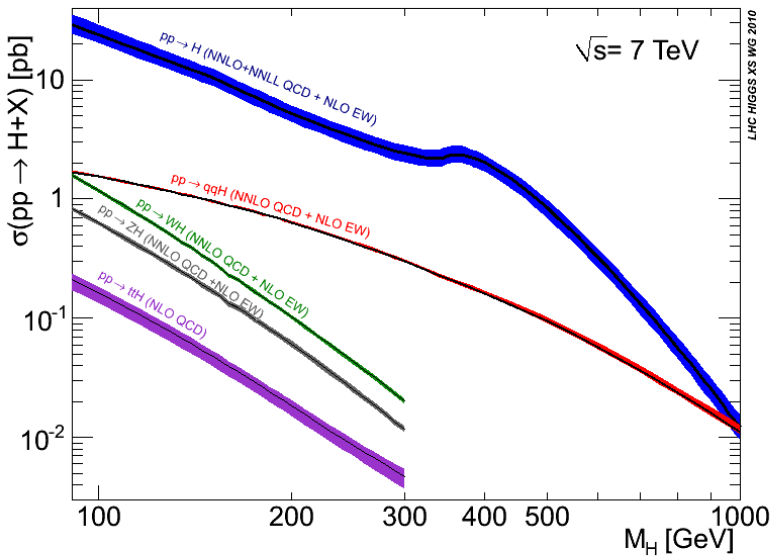


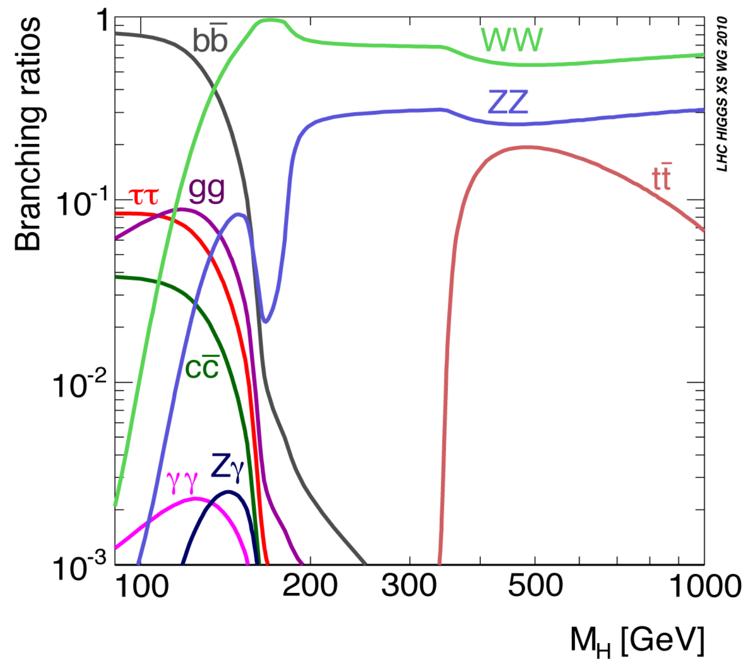


At √s = 8TeV cross sections 20-30% higher than at 7 TeV

Higgs Boson Decay Channels

- Gluon-fusion has highest cross section
  - BUT only useful in decay channels not overwhelmed by multi-jet background: H->γγ, H->ZZ, H->WW
- VBF still not easy to distinguish from multi jets
- H->ττ and H->bb very challenging due to very large backgrounds
- Not only the production cross section matters
- Decay branching ratio depends strongly on Higgs boson mass
- 5 decay modes studied:
  - High mass: **ZZ, WW**
  - Low mass: **bb, ττ, γγ, WW, ZZ**
- **Nature was kind!** At $m_H \approx 125$GeV many channels can be used for measurements. **Redundancy!**





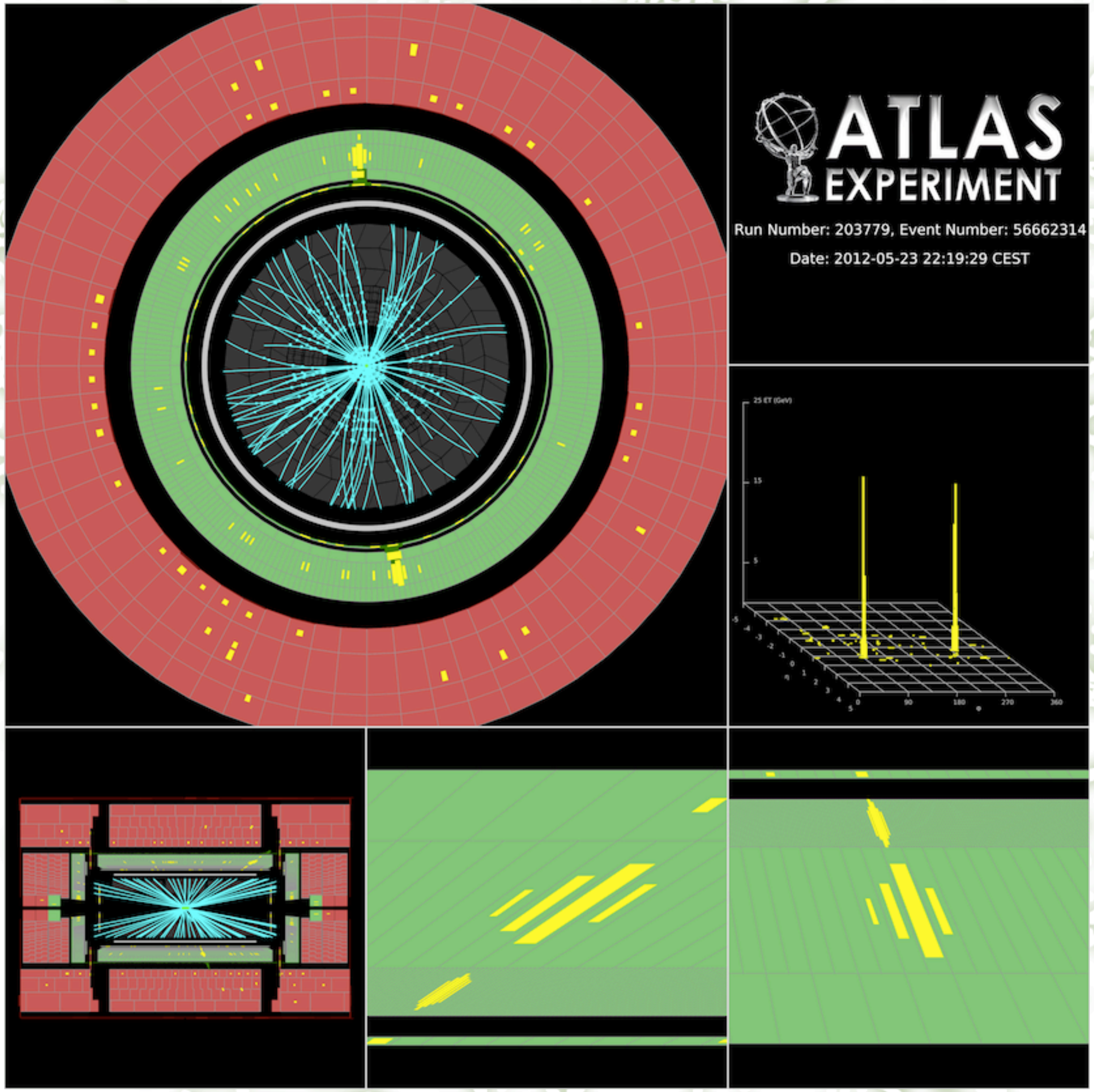
ICHEP results:

Higgs Decay	Final state	Mass range [GeV]	L [fb^{-1}]
H->γγ		110 – 150	4.8+5.9
H->ZZ	lll’l’	110 – 600	4.8+5.8
	llνν	200 – 600	4.7
	llqq	200 – 600	4.7
H->WW	lνlν	110 – 600	4.7+5.8
	lνqq	300 – 600	4.7
H->ττ	ll4ν	110 – 150	4.7
	$l\tau_{had}3\nu$	110 – 150	4.7
	$\tau_{had}\tau_{had}2\nu$	110 – 150	4.7
H->bb	llbb	110 – 130	4.7
	lνbb	110 – 130	4.7
	ννbb	110 – 130	4.7

Blind Analysis

- To avoid unintended experimenter's bias in search for the Higgs boson
- The analysis strategy, event selection & optimization criteria for each Higgs search channel were **fixed** by looking at data control samples before looking at the signal sensitive region
  - Logistically quite painful
  - But the right thing to do !

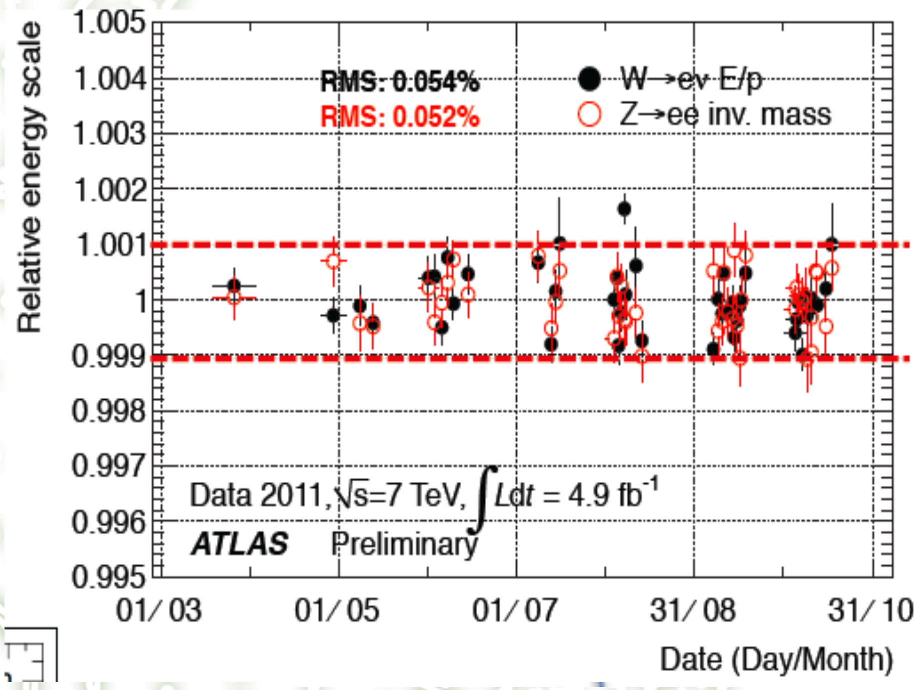
H->γγ

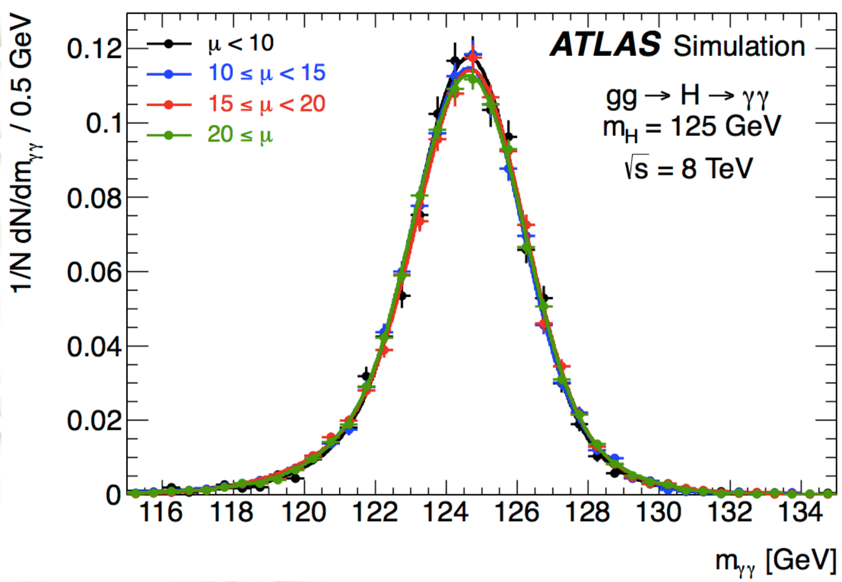


- $\sqrt{s}$ = 8 TeV
- ET1 = 62.2 GeV
- ET2 = 55.5 GeV
- E1 = 66.9 GeV
- E2 = 99.2 GeV
- Mγγ = 126.9 GeV

Diphoton mass reconstruction

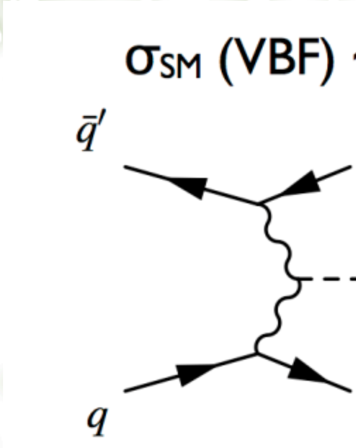
- $m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$
- Present understanding of calorimeter E response (from Z, J/ψ -> ee, W -> eν data and MC):
  - E-scale at m_Z known to ~ 0.3%
  - Linearity better than 1% (few-100 GeV)
  - "Uniformity" (constant term of resolution): ~ 1% (2.5% for 1.37<|η|<1.8)
- High pile-up: many vertices distributed over
- σZ (LHC beam spot) ~ 5-6 cm => difficult to know which one has produced the γγ pair
- Primary vertex from:
  - EM calorimeter longitudinal (and lateral) segmentation
  - Tracks from converted photons
- Calorimeter pointing alone reduces vertex uncertainty from beam spot spread of ~ 5-6 cm to ~ 1.5 cm and is robust against pile-up
  - Good enough to make contribution to mass
- Resolution from angular term negligible
- Addition of track information (less pile-up robust) needed to reject fake jets from pile-up in 2j/VBF category

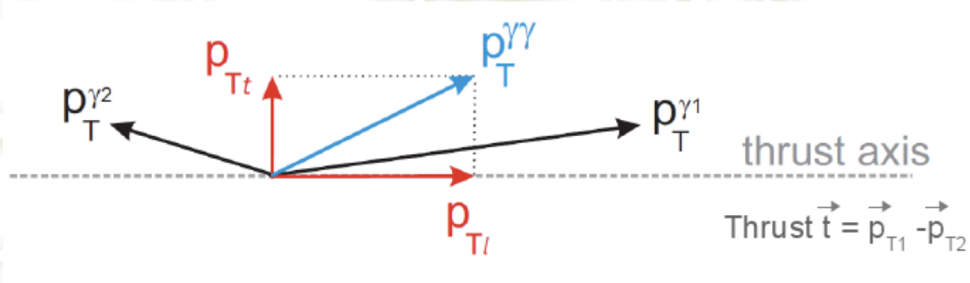




Optimization wrt 2011 analysis

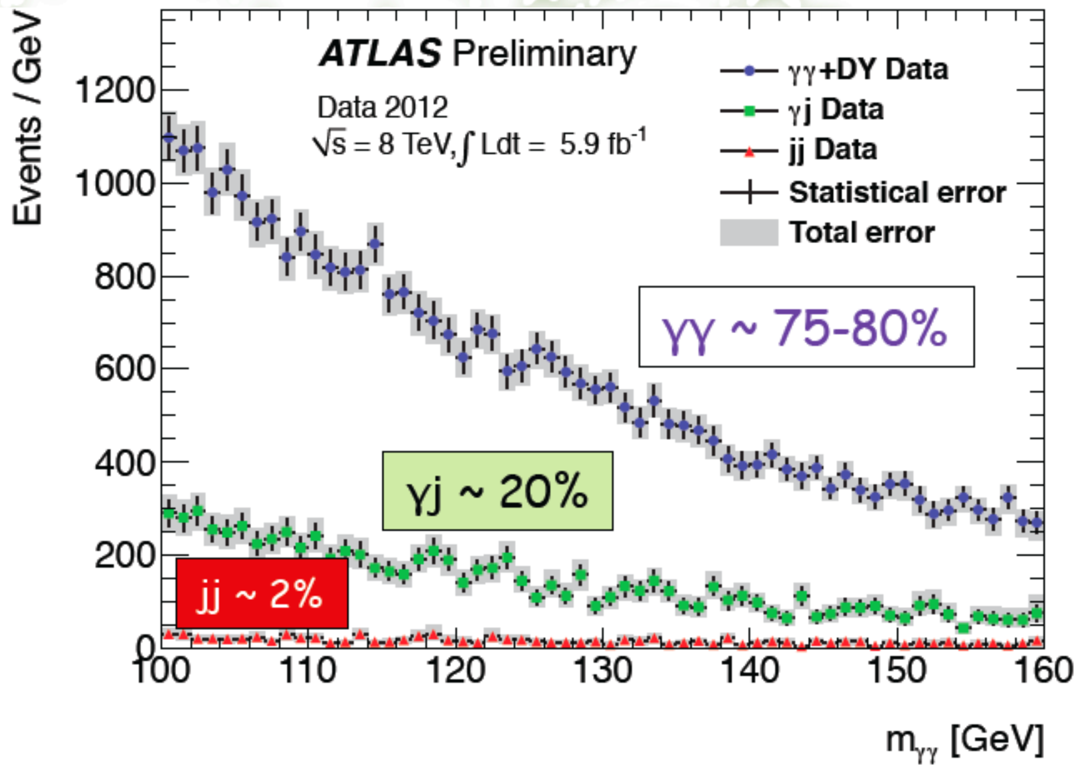
- Neural-net based photon ID for 2011 data
- Re-optimized cut-based photon ID for 2012, stable with high pileup
- New '2-jets' category to enhanced sensitivity to VBF
- Events divided in 10 categories based on:
  - γ rapidity,
  - converted/unconverted γ;
  - p_{Tt} ($p_T^{\gamma\gamma}$ perpendicular to γγ thrust axis);
  - 2jets (VBF-like)





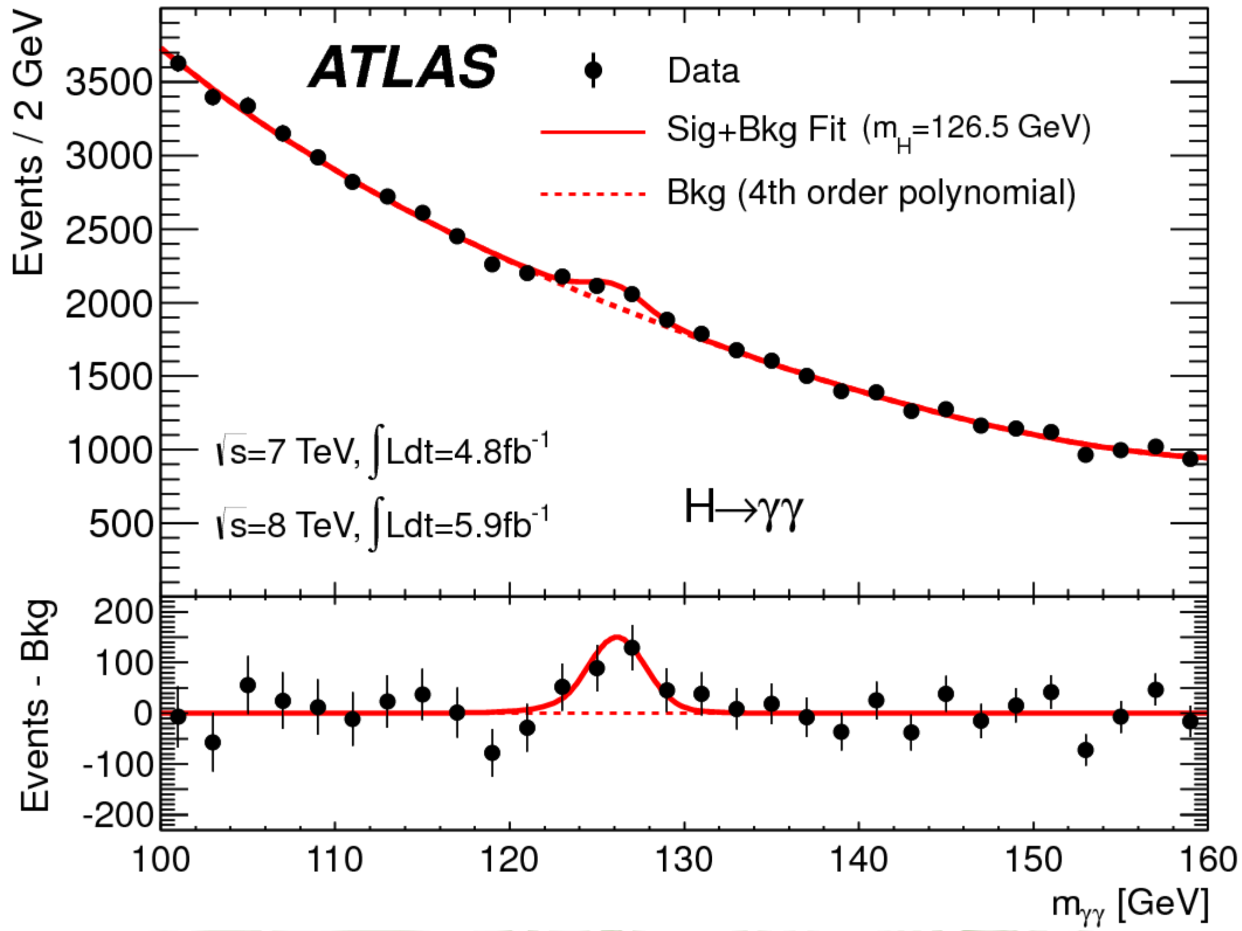
Backgrounds

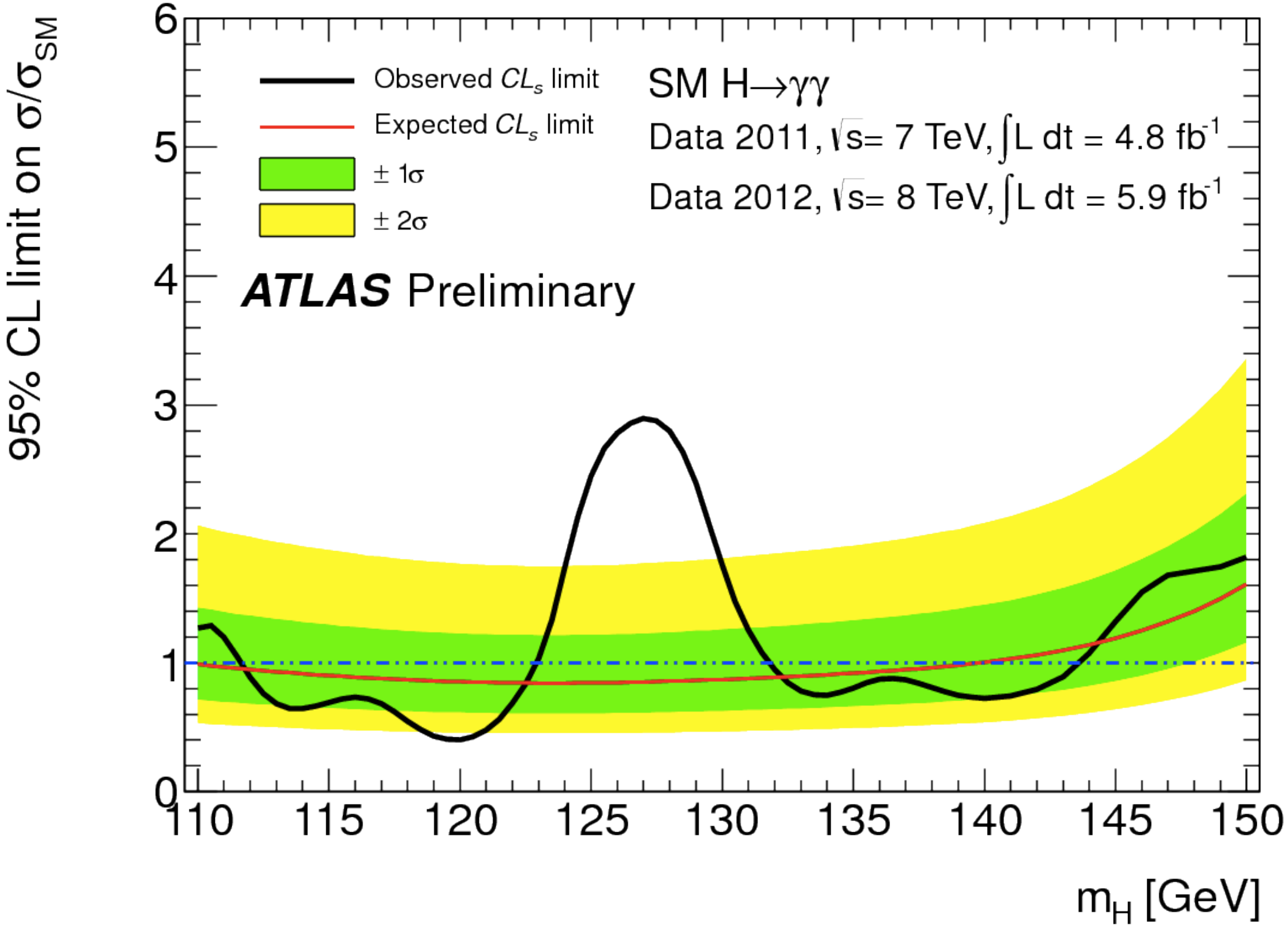
- Main backgrounds:
  - Continuum γγ production
  - Followed by γ mis-identification
- Smooth mγγ spectrum
  - Use sidebands to fit sum of backgrounds
- Confirm each background source by data-driven techniques
  - E.g. reverse quality cuts on photon identification



Results

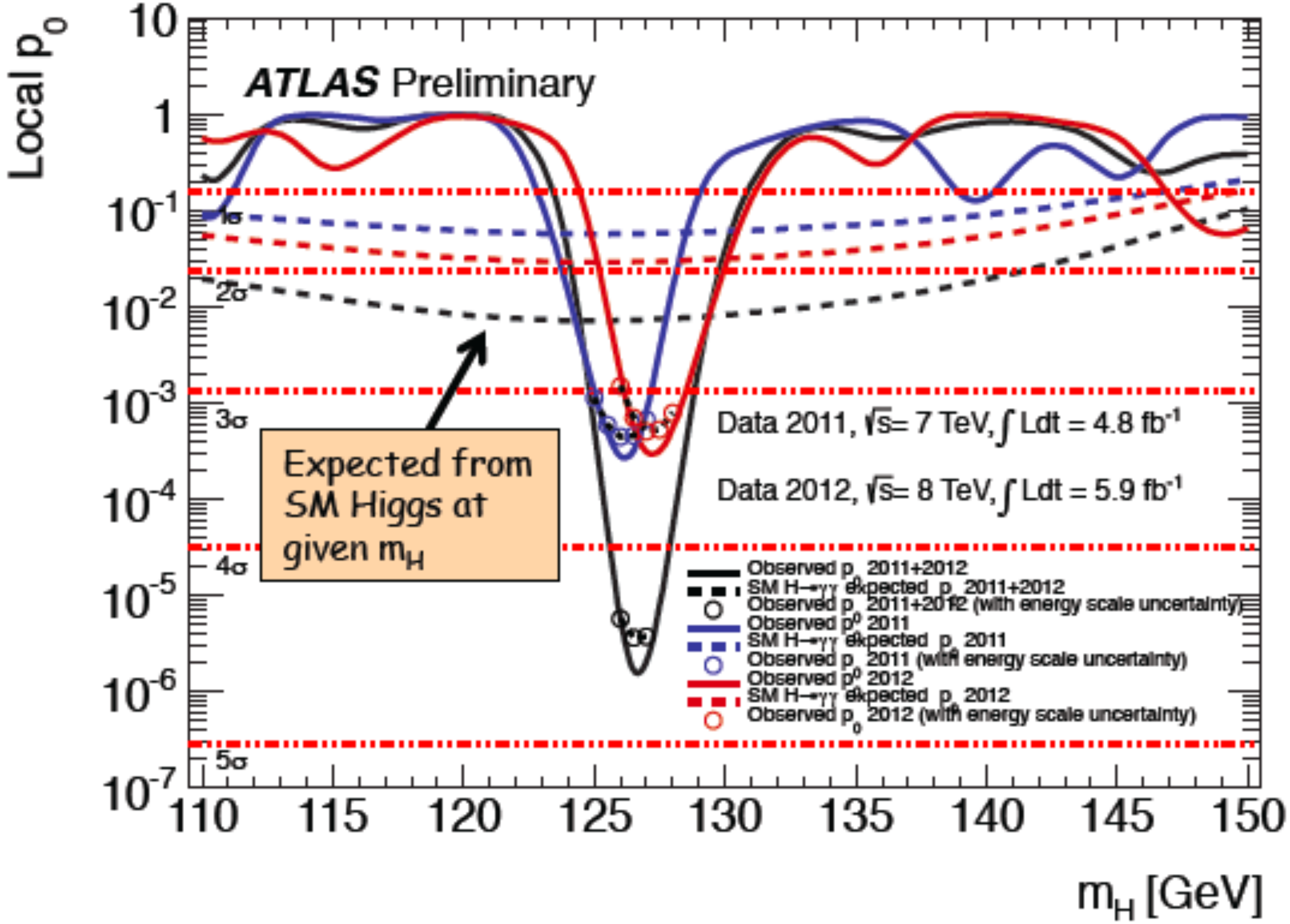
Combined $m_{\gamma\gamma}$ from all 10 categories and 7/8 TeV data





- Exclusion at 95% C.L. :
- Expected: 110 < mH < 139.5 GeV
- Observed: 112 < mH < 122.5 GeV 132 < mH < 143 GeV

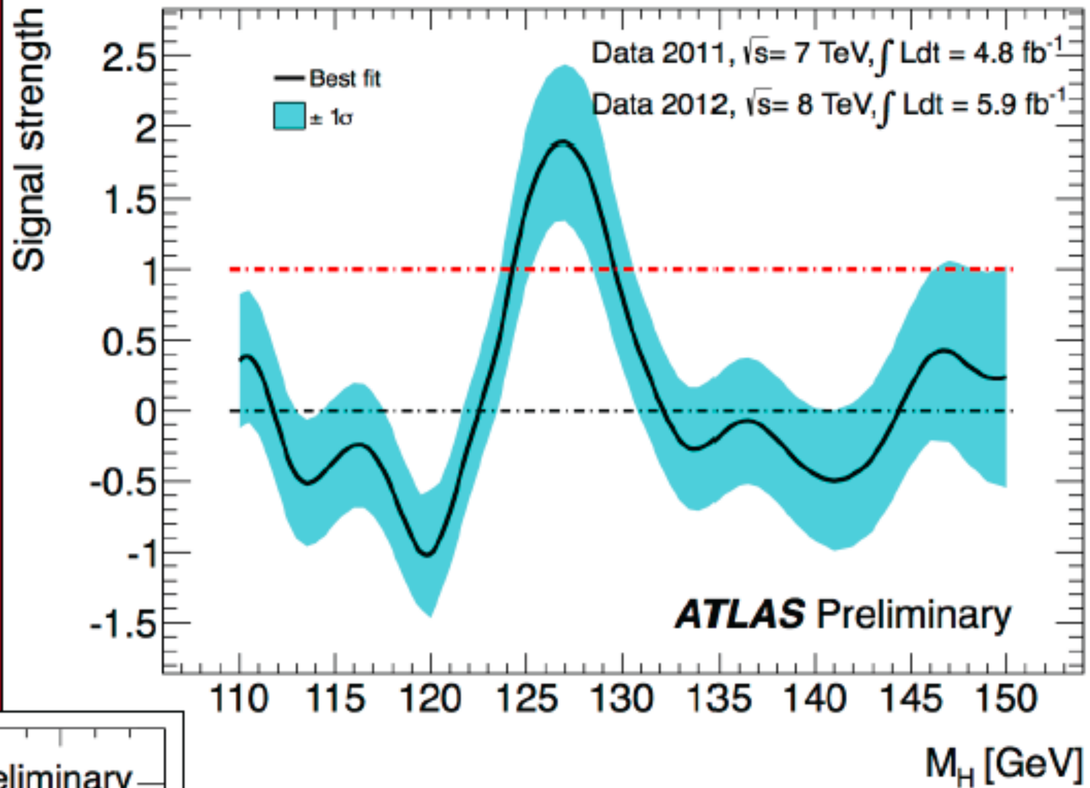
Results in more detail

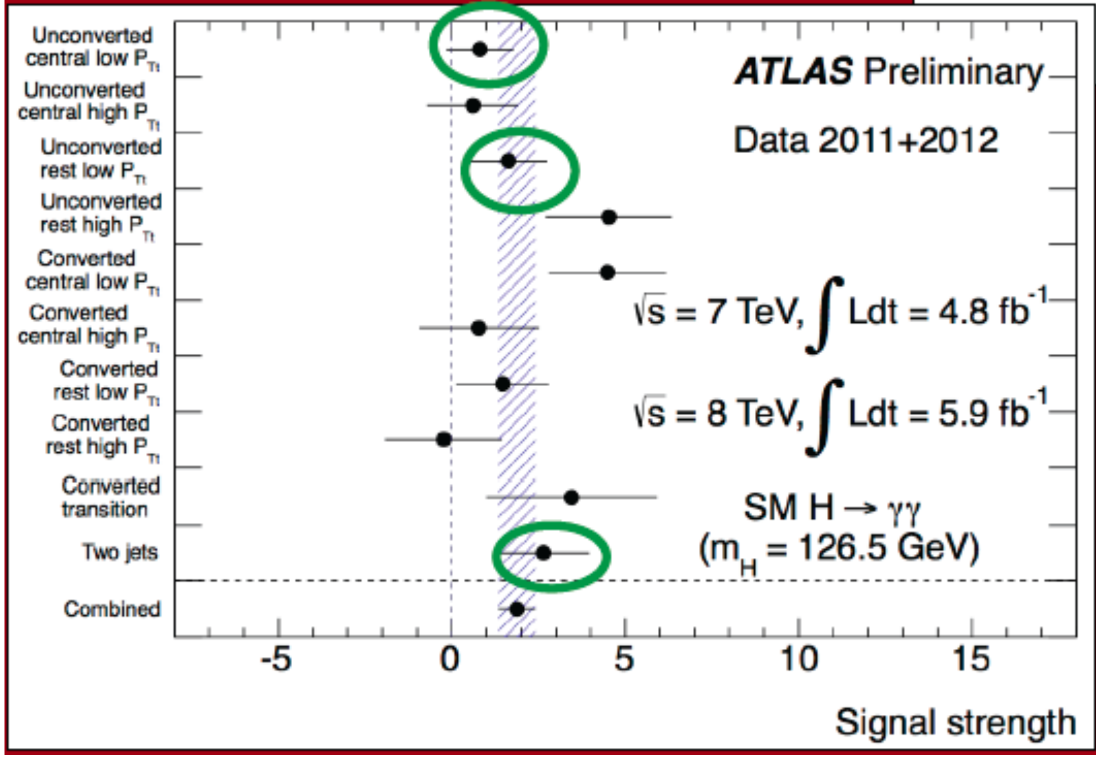


Fitted signal strength

Normalized to SM Higgs expectation at given m_H (μ)

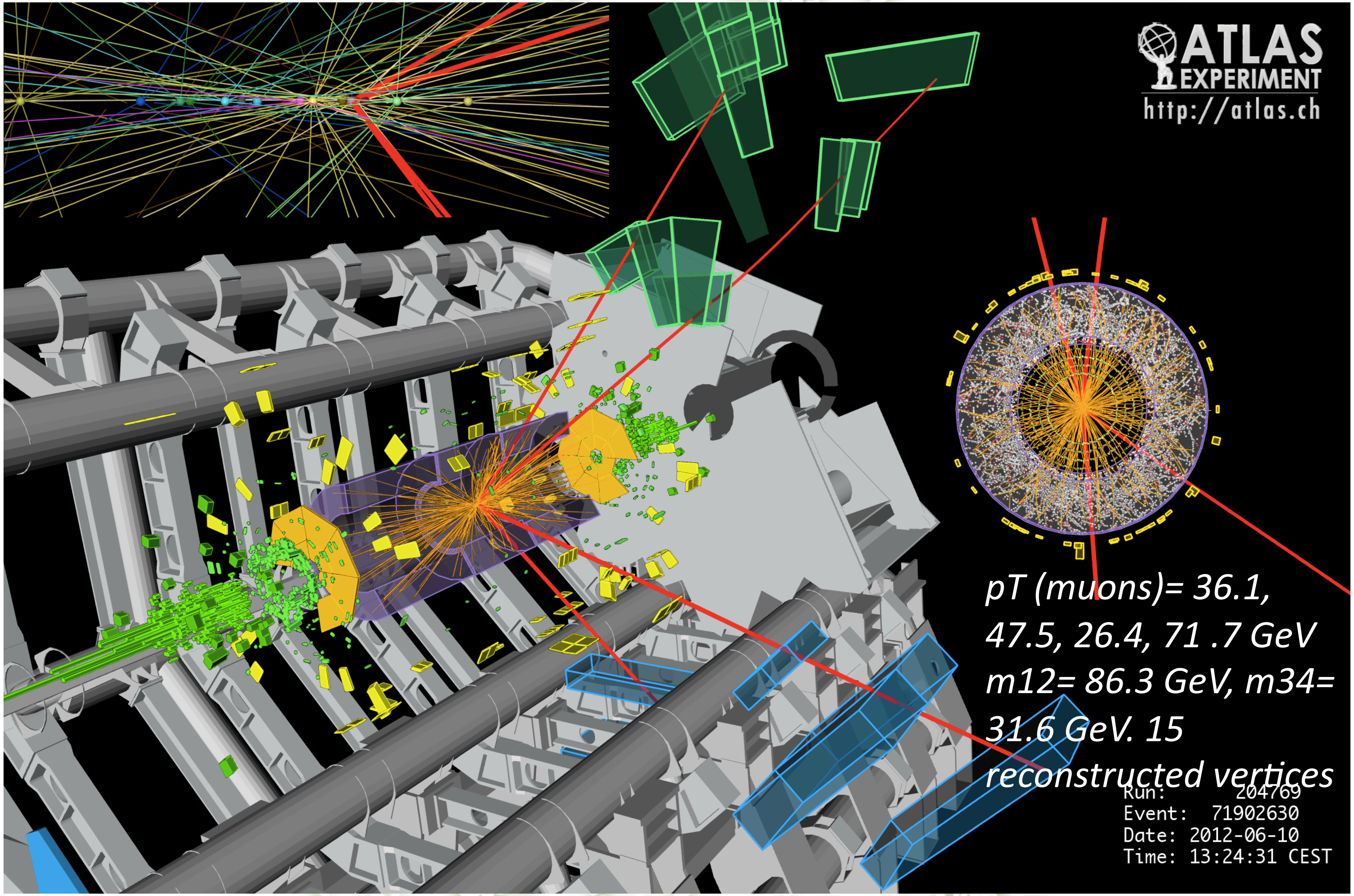
Best-fit value at 126.5 GeV: μ=1.9 ± 0.5



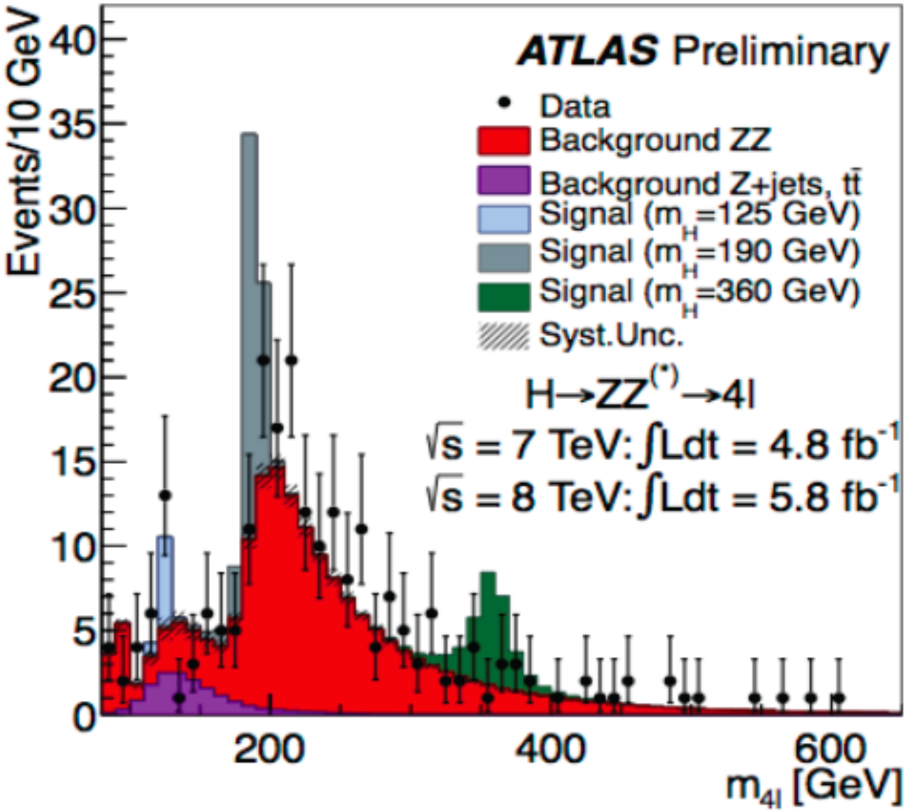


Consistent results from various categories within uncertainties (most sensitive ones indicated)

H->ZZ(*)->4l


ATLAS
EXPERIMENT
http://atlas.ch
pT (muons)= 36.1, 47.5, 26.4, 71 .7 GeV
m12= 86.3 GeV, m34= 31.6 GeV. 15 reconstructed vertices
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

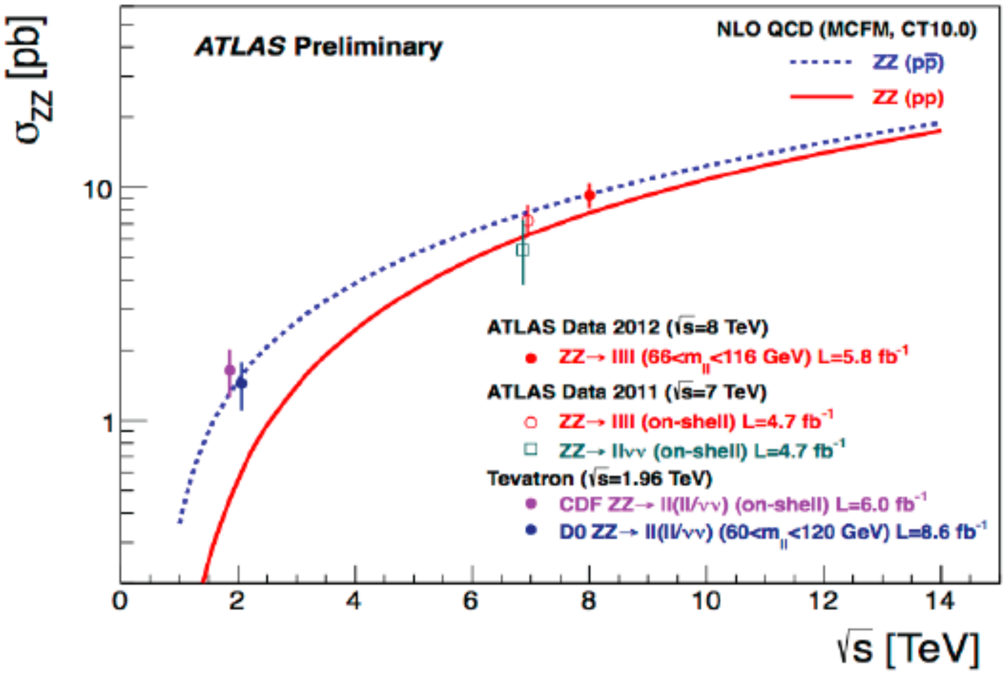
- The ”golden channel”:
  - Small rates, but high S/B
  - Can be fully reconstructed; mass resolution ~2% at 130 GeV
- Cross section times branching ratio (at mH=125 GeV):
- ~ 4 fb at √s=7 TeV
- ~ 5 fb at √s=8 TeV
- Backgrounds:
  - Irreducible: pp->ZZ(*)->4l
  - Reducible: Z+jets, Zbb, tt (sizeable at low Higgs masses)
- Suppress backgrounds with isolation and impact parameters cut on two softest
- Leptons
  - Mass range under consideration: 110 GeV to 600 GeV
  - Four final states: 4e, 4μ, 2e2μ, 2μ2e



m_{4l} > 160 GeV (dominated by ZZ background):
147 ± 11 events expected
191 observed

~ 1.3 times more ZZ events in data than SM prediction → in agreement with measured ZZ cross-section in 4l final states at $\sqrt{s}$ = 8 TeV

Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4 ± 0.4 pb

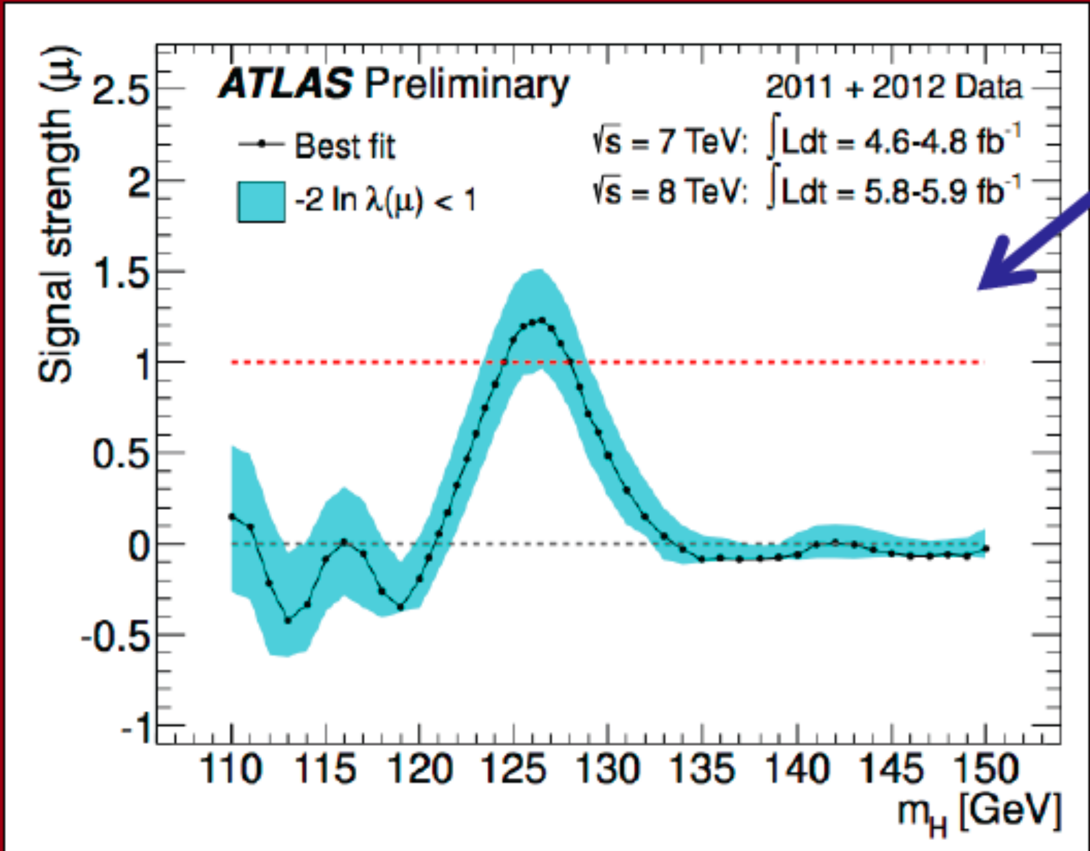


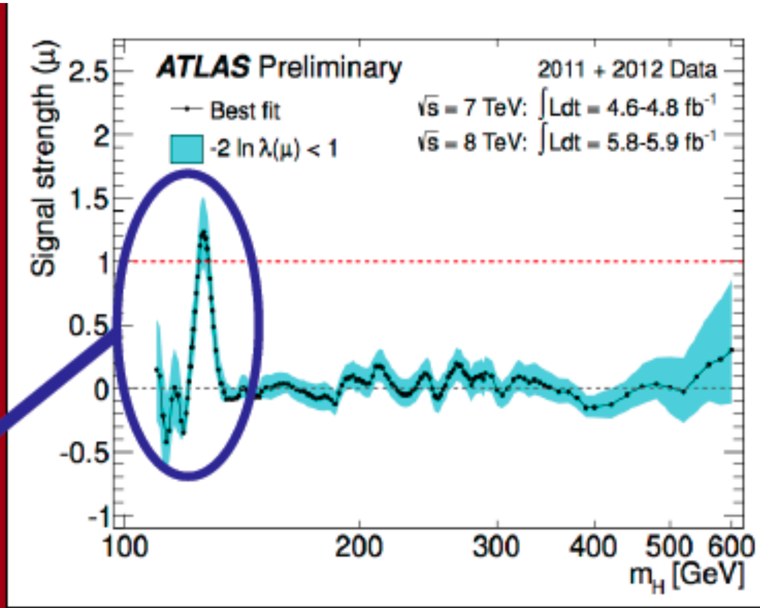
Discrepancy has negligible impact on the low-mass region < 160 GeV

(no change in results, if in the fit ZZ background is constrained within its uncertainty or left free)

Combined results: fitted signal strength

Normalized to SM Higgs expectation at given m_H (μ)

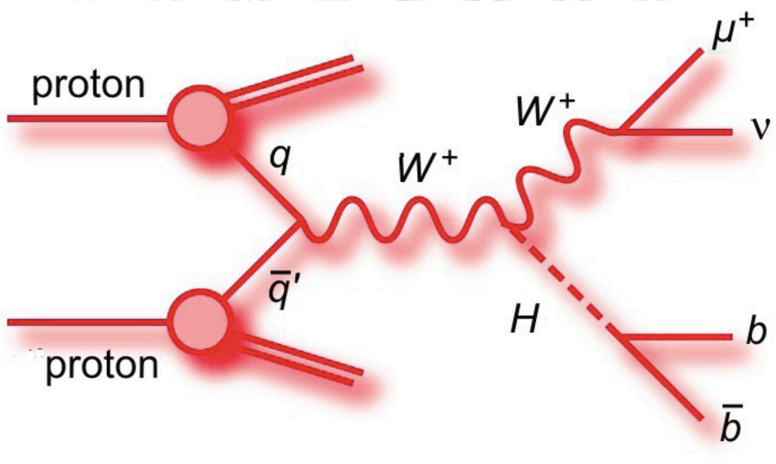




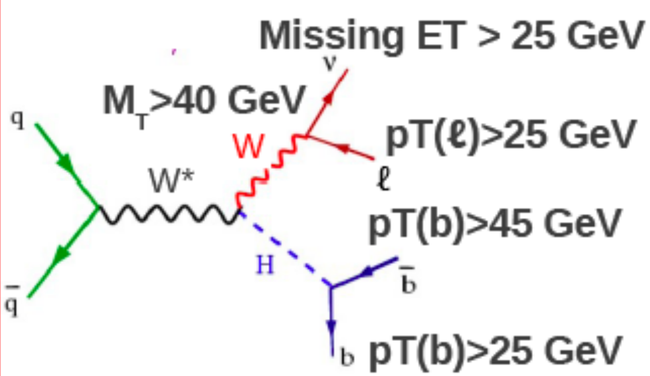
Best-fit value at 126.5 GeV:
$\mu = 1.2 \pm 0.3$

Good agreement with the expectation for a SM Higgs within the present statistical uncertainty

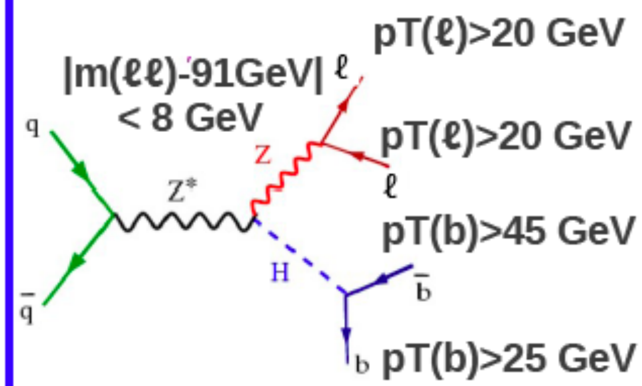
H→bb Searches in WH production



- Three channels considered: $WH \to \ell\nu b\bar{b}$ | $ZH \to \ell^+\ell^- b\bar{b}$ | $ZH \to \nu\bar{\nu} b\bar{b}$
- Analysis based on 4.6-4.7 fb^{-1} of 2011 data collected by ATLAS at $\sqrt{s}$ = 7 TeV
- Main selection cuts:

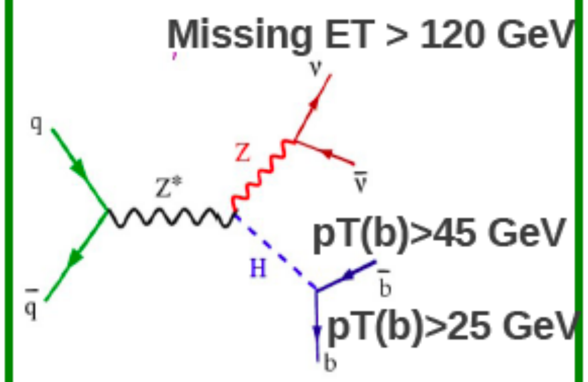


No additional jets with pT>20 GeV and |η|<4.



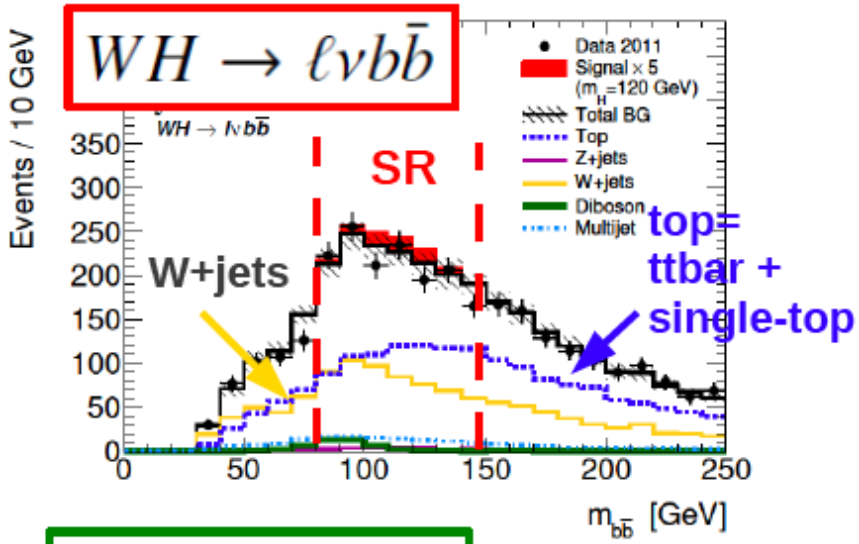
Missing E_T < 50 GeV
Any number of additional jets.

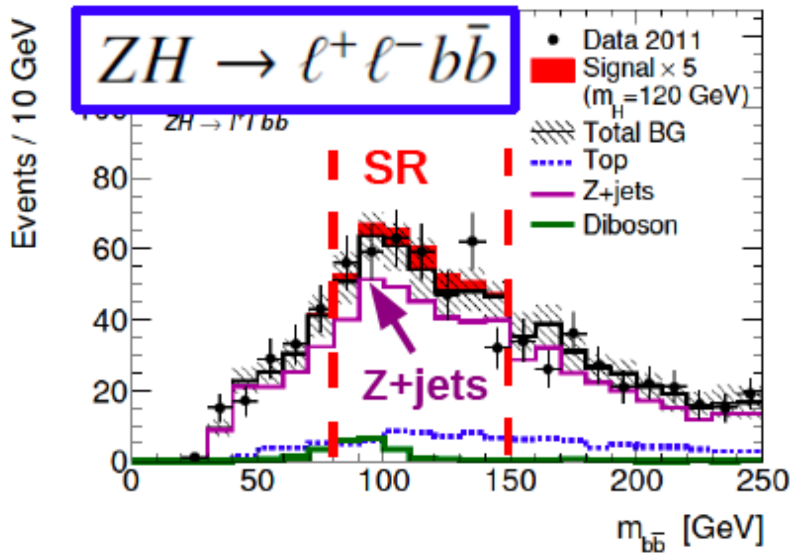
+ contributions from WH

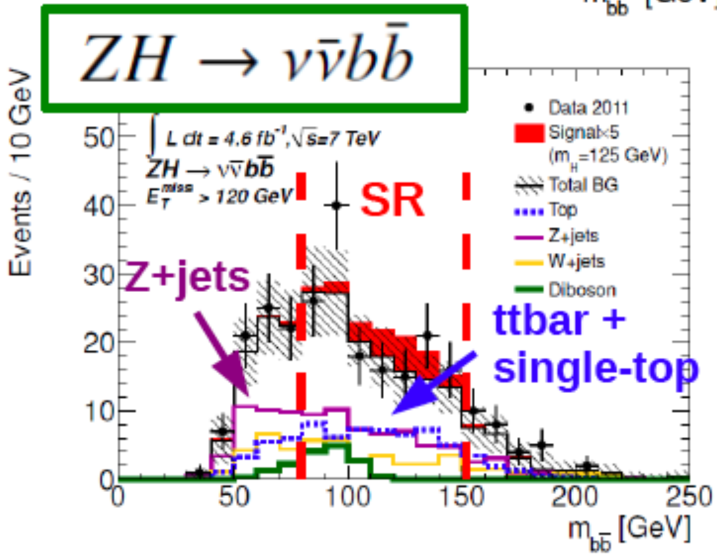


No additional jets with pT>25 GeV and |η|<2.5.

- Anti-Kt jets with R=0.4 are reconstructed from calorimeter energy deposits.
- Pile-up jets are suppressed by requiring more of 75% of the summed momenta of tracks matched to the jet to be associated to the primary event vertex.







+ **resonant background** from diboson

- M(bb) shape from MC, normalization of main backgrounds from data (excluding SR)
- $WH \to \ell\nu b\bar{b}$: Top and W+jet scale factors from m(bb) sidebands + WH top control region
- $ZH \to \ell^+\ell^- b\bar{b}$: Top and Z+jet scale factors from m(bb) sidebands + ZH top control region
- $ZH \to \nu\bar{\nu}b\bar{b}$: take scale factors from other channels, after cross-checking in dedicated control regions.

Leading background uncertainties

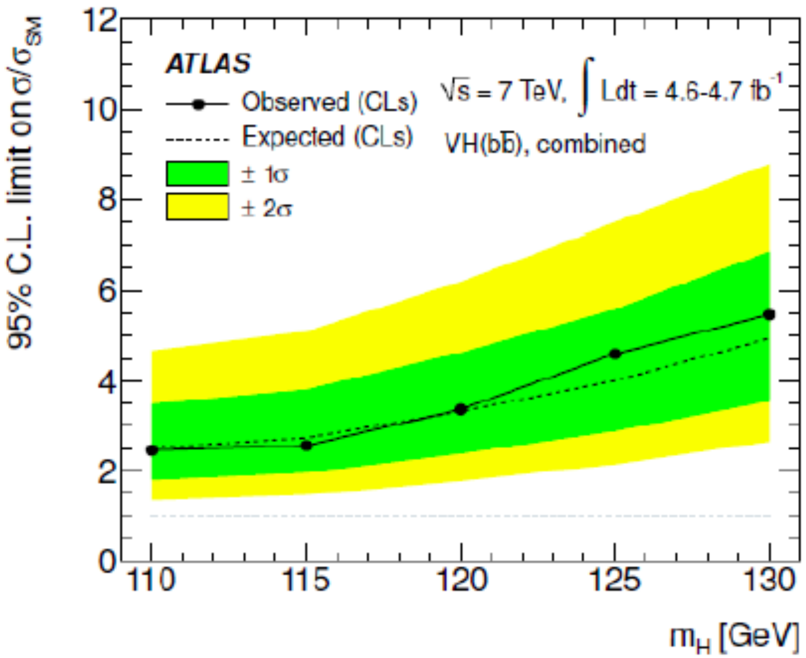
Bin	$ZH \to \ell^+\ell^- b\bar{b}$ p_T^Z [GeV] 0-50	50-100	100-200	>200	$WH \to \ell\nu b\bar{b}$ p_T^W [GeV] 0-50	50-100	100-200	>200	$ZH \to \nu\bar{\nu}b\bar{b}$ E_T^{miss} [GeV] 120-160	160-200	>200
Number of events for $80 < m_{b\bar{b}} < 150$ [GeV]											
Signal	1.3 ± 0.1	1.8 ± 0.2	1.6 ± 0.2	0.4 ± 0.1	5.0 ± 0.6	5.1 ± 0.6	3.7 ± 0.4	1.2 ± 0.2	2.0 ± 0.2	1.2 ± 0.1	1.5 ± 0.2
Total Bkg	148 ± 10	150 ± 6	67 ± 4	6.9 ± 1.2	596 ± 23	598 ± 16	302 ± 10	27 ± 5	85 ± 8	32 ± 3	20 ± 3
Data	141	163	61	13	614	588	271	15	105	22	25
Components of the Background Relative Systematic Uncertainties [%]											
B-tag Eff	1.4	1.0	0.3	4.8	0.9	1.3	0.9	7.2	4.1	4.2	5.5
Bkg Norm	3.6	3.4	3.6	3.8	2.7	1.8	1.8	4.5	2.7	2.2	3.2
Jets/E_T^{miss}	2.1	1.2	2.7	5.1	1.5	1.4	2.1	9.5	7.7	8.2	12.1
Leptons	0.2	0.3	1.1	3.4	0.1	0.2	0.2	1.7	0.0	0.0	0.0
Luminosity	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2	0.2	0.5	0.7
Pile Up	0.9	1.6	0.5	1.3	0.1	0.2	0.8	0.5	1.6	2.5	3.0
Theory	5.2	1.3	4.7	14.9	2.2	0.3	1.6	14.8	2.9	4.0	7.7
Total Bkg	6.9	4.3	6.6	17.3	3.9	2.7	3.4	19.6	9.7	10.6	16.0

- **Total background uncertainty : ~3-20 %**
  - The highest p_T bins suffer from the highest uncertainties, which limits the improvements from the better S/B.

Combined result

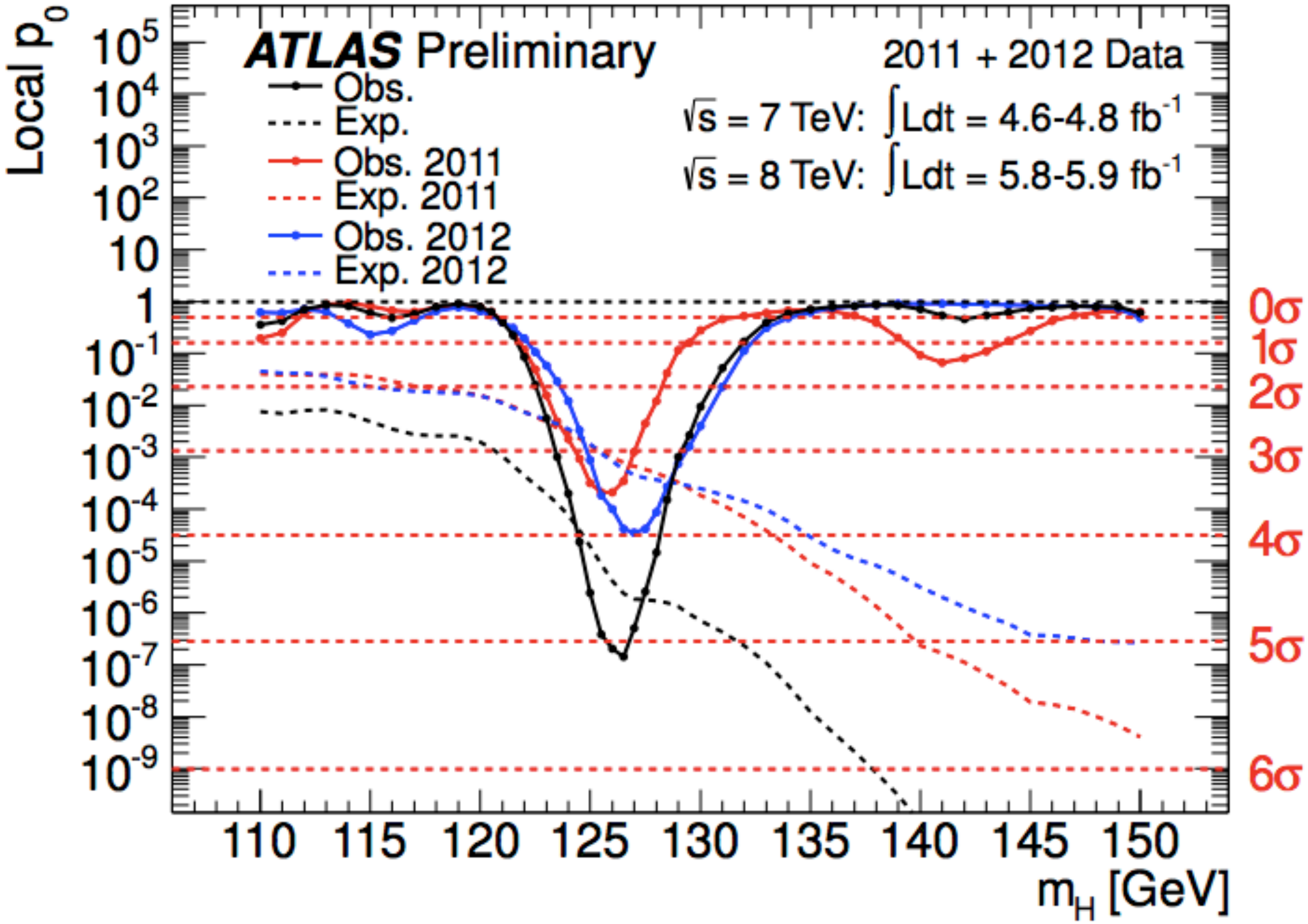
arXiv:1207.0210 (submitted to Phys. Rev. Lett. B)

- Hypothesis testing based on likelihood with m(bb-jet) distribution for signal and background in the signal region (80 GeV < m(bb) < 150 GeV).
- Systematic uncertainties through dependence of normalization and m(bb) shape on additional *nuisance* parameters, constrained within expected uncertainties.



- 95% confidence level upper limits on signal extracted using **CL_s** method.
- Expected limits **from ~2.5 to ~5 times the Standard Model** expectation, observed limits close to expectations (**exclude ~4.6xSM at m(H)=125 GeV**).
- Most of the sensitivity from WH → ℓνbb and ZH → ννbb.
- **Looking forward to release 2012 data results!**
- In the pipeline: better m(bb) resolution, MV analysis, lower theory systematics.

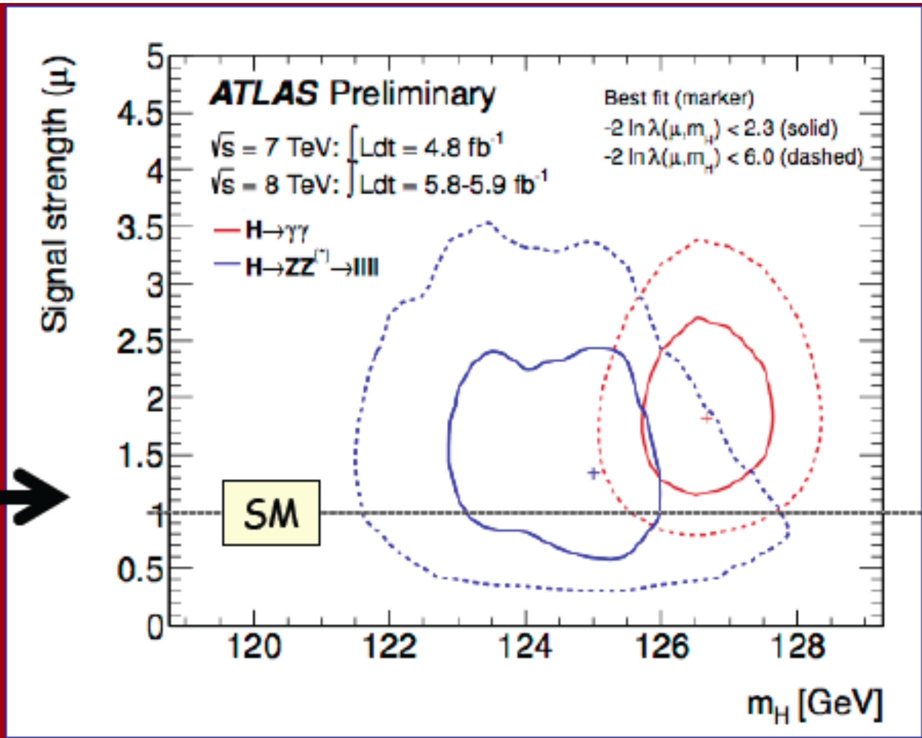
Where We Stand

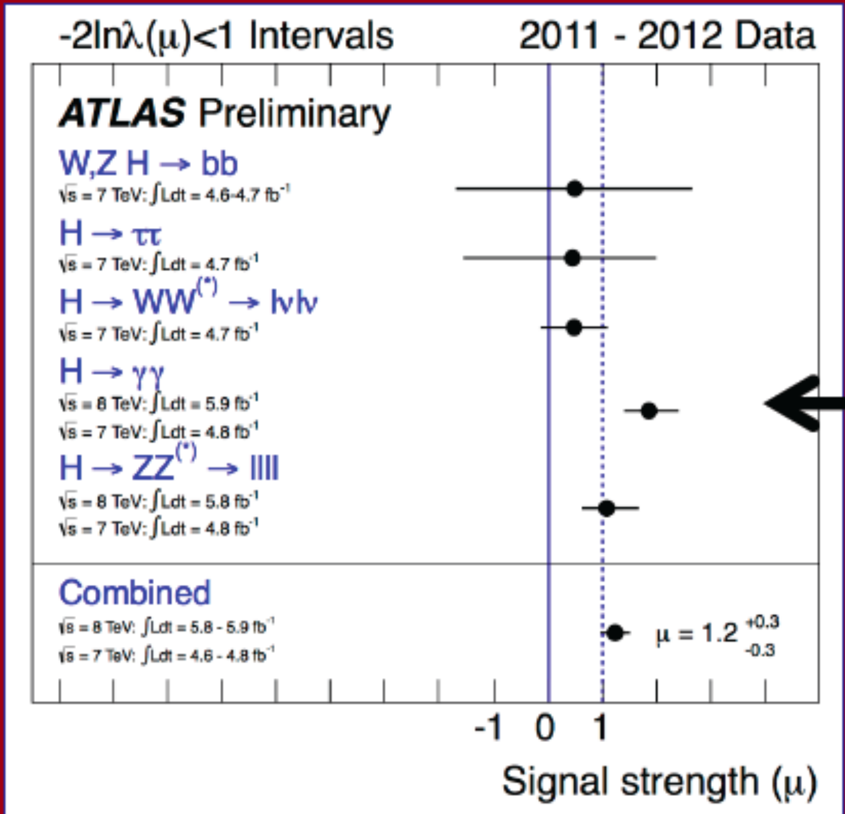

Local p_0
ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
Obs. 2011
Exp. 2011
Obs. 2012
Exp. 2012
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8-5.9 fb^{-1}
0σ
1σ
2σ
3σ
4σ
5σ
6σ
m_H [GeV]

Combined results: consistency of the global picture

Are the 4l and γγ observations consistent ?

From 2-dim likelihood fit to signal mass and strength →curves show approximate 68% (full) and 95% (dashed) CL contours





Best-fit signal strengths, normalized to the SM expectations, for all studied channels, at m_H = 126.5 GeV,

References

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- Search for the Higgs boson in the H--->WW--->lnujj decay channel at sqrt(s) = 7 TeV with the ATLAS detector ------ CERN--- PH---EP---2012---162 ------ arXiv:1206.6074v1 [hep---ex]
- Search for a Standard Model Higgs boson in the mass range 200------600 GeV in the H--->ZZ--->llqq decay channel with the ATLAS Detector ------ ATLAS---CONF---2012---017 ------ arXiv:1206.2443
- Search for a Standard Model Higgs boson in the mass range 200---600 GeV in the H--->ZZ--->llqq decay channel ------ CERN---PH---EP---2012---125 ------ arXiv:1206.2443v1 [hep---ex]
- Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 T---1 of ATLAS data at sqrt(s)=7 TeV ------ ATLAS---CONF---2011---161 ------ arXiv:1202.1414
- Search for the Standard Model Higgs boson in the decay channel H--->ZZ(*)--->4l with 4.8 T---1 of pp collisions at sqrt(s) = 7 TeV with the ATLAS detector ------ Phys.Lev. B710 (2012) 383---402 ------ arXiv: 1202.1415
- Search for the Standard Model Higgs boson in the H → WW(*) → lνlν decay mode with 4.7 T---1 of ATLAS data at √s = 7 TeV ------ ATLAS---CONF---2012---012, ATLAS---CONF---2012---060 ------ arXiv:1206.0756
- Search for the Standard Model Higgs boson in the H ---> tau tau decay mode in sqrt(s) = 7 Tev pp collisions with ATLAS ------ ATLAS---CONF---2012---014 ------ arXiv:1206.5971
- Search for the Standard Model Higgs boson produced in associaAon with a vector boson and decaying to a b---quark pair with the ATLAS detector ------ CERN---PH---EP---2012---138 ------ arXiv:1207.0210v1 [hep---ex
- An update to the combined search for the Standard Model Higgs boson with the ATLAS detector at the LHC using up to 4.9 T−1 of pp collision data at √s = 7 TeV ------ ATLAS---CONF---2012---019 ------ arXiv: 1207.0319
- Calculated cross sections:
- LHC Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables ------ arXiv:1101.0593, arXiv:1201.3084

Statistics

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- E. Gross and O. Vitells, Trial factors for the look elsewhere effect in high energy physics, Eur. Phys. J. C70 (2010) 525
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- T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instr. Meth. A 434 (1999) 435

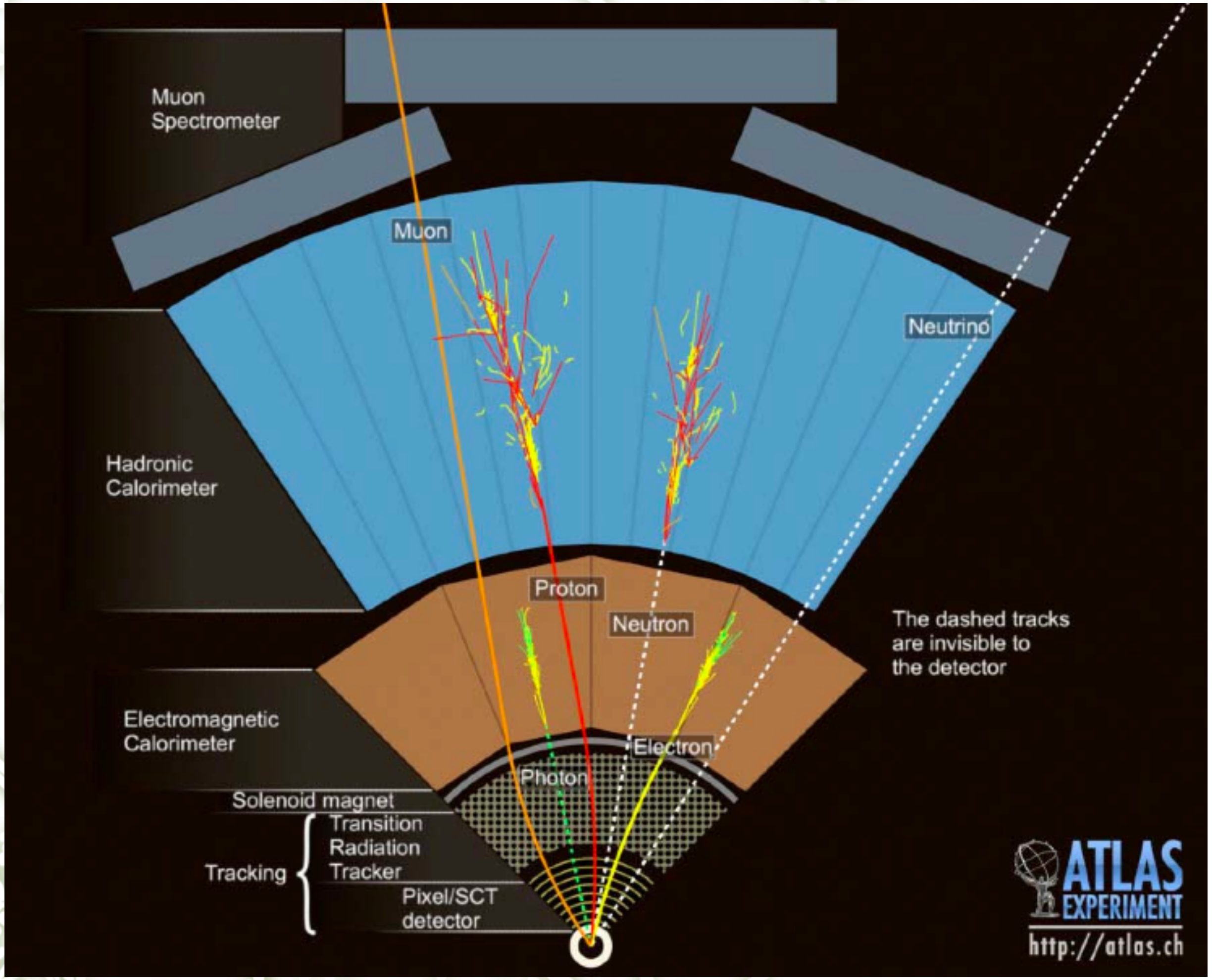
BACKUP SLIDES


I was looking for you for over 20 years
Now you have found me

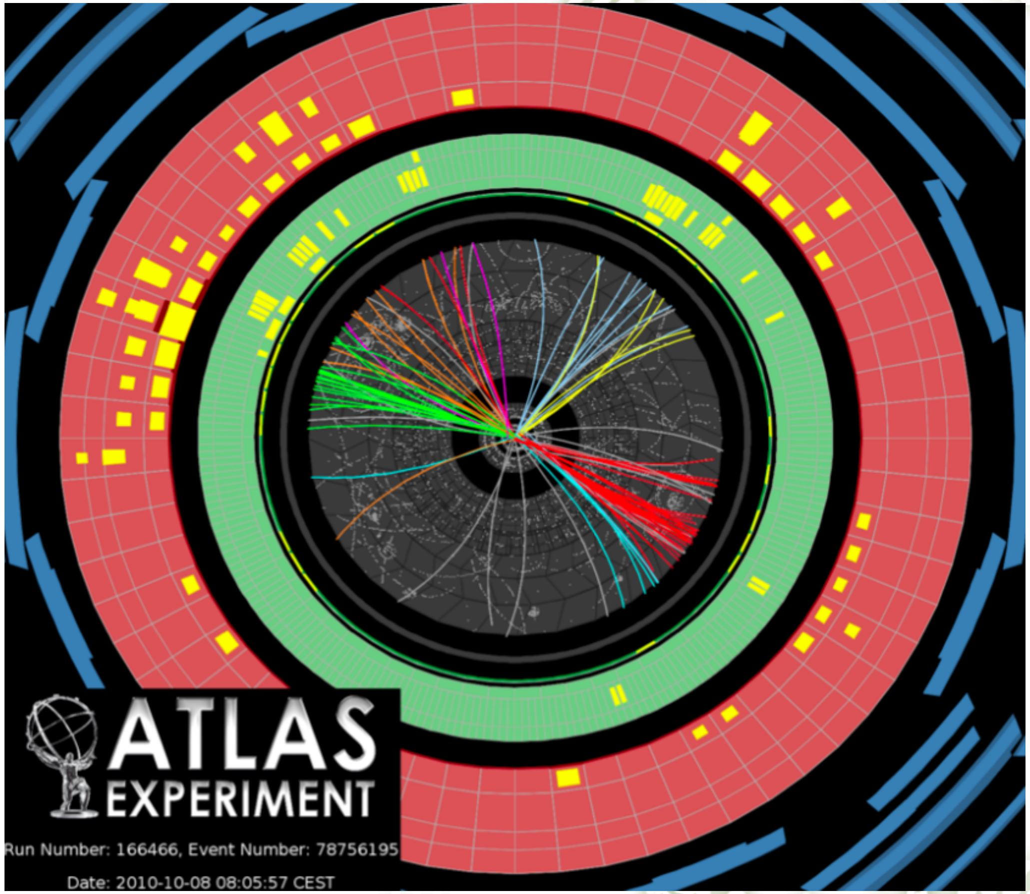
Particle Detectors

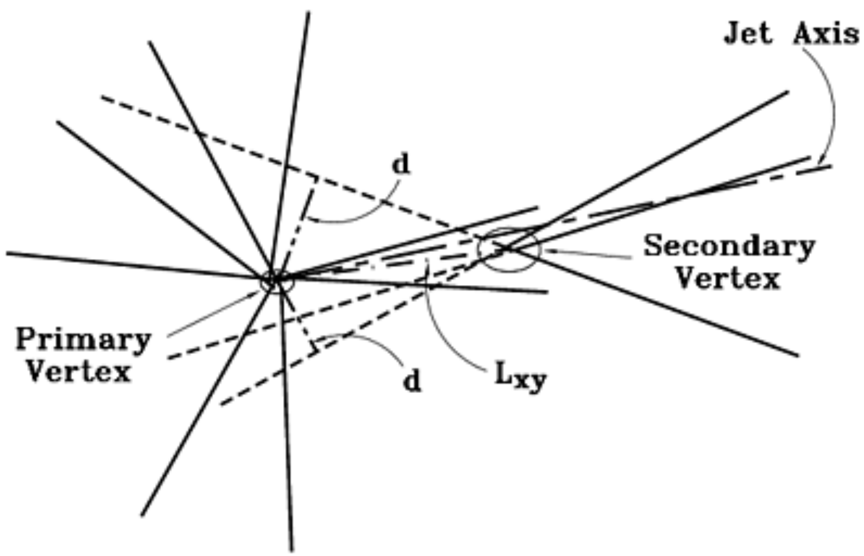
- Detectors and accelerators which push the boundaries of technology

- But that would need a much longer talk…



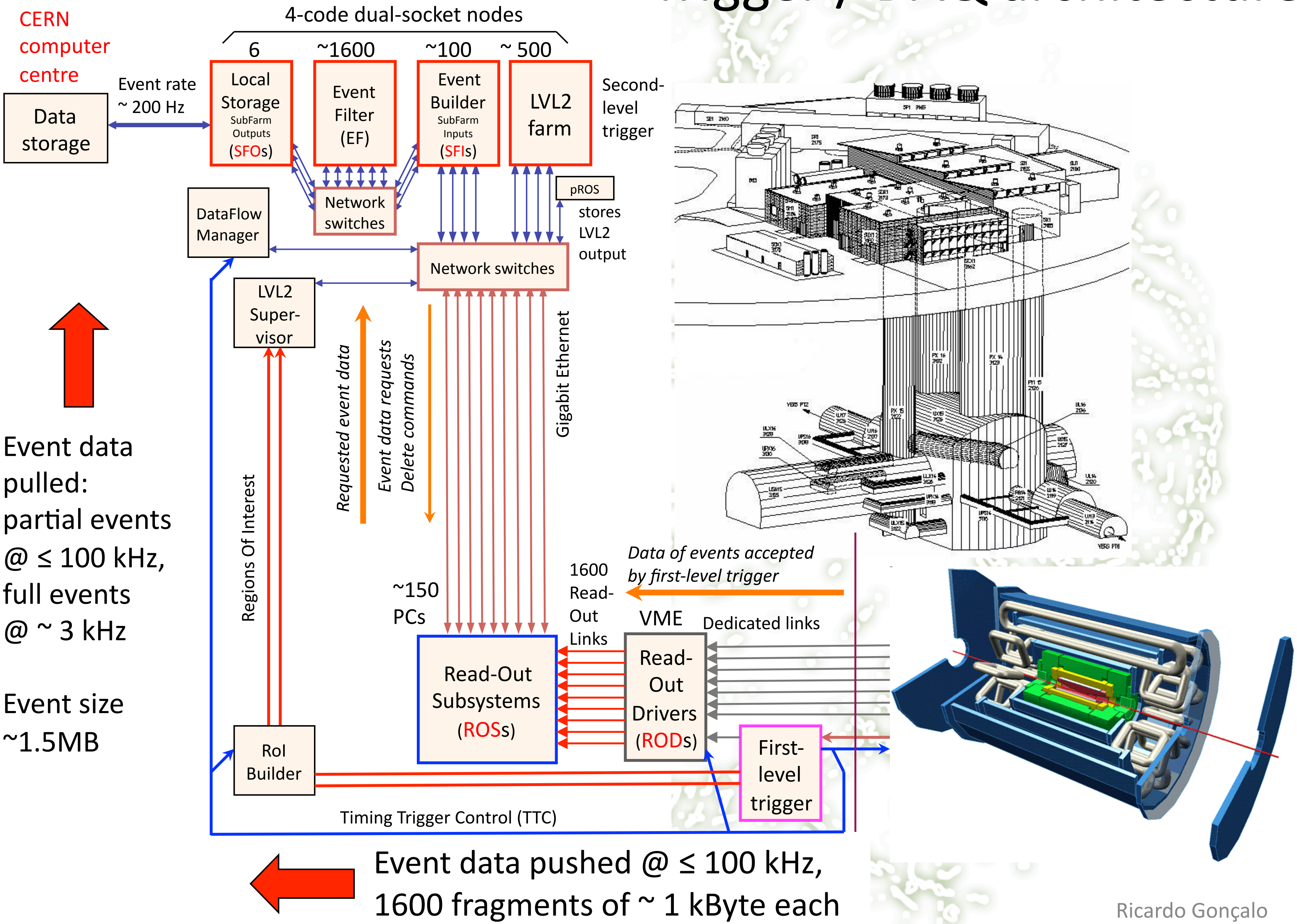
Jets and Heavy Flavour Tagging






GASP!
I'VE FOUND THE HIGGS BOSON!
Dilbert.com DilbertCartoonist@gmail.com
BUILD AN ARK!
2-21-12 ©2012 Scott Adams, Inc./Dist. by Universal Uclick
NOTHING BUT TROUBLE.
CLICK

Trigger / DAQ architecture



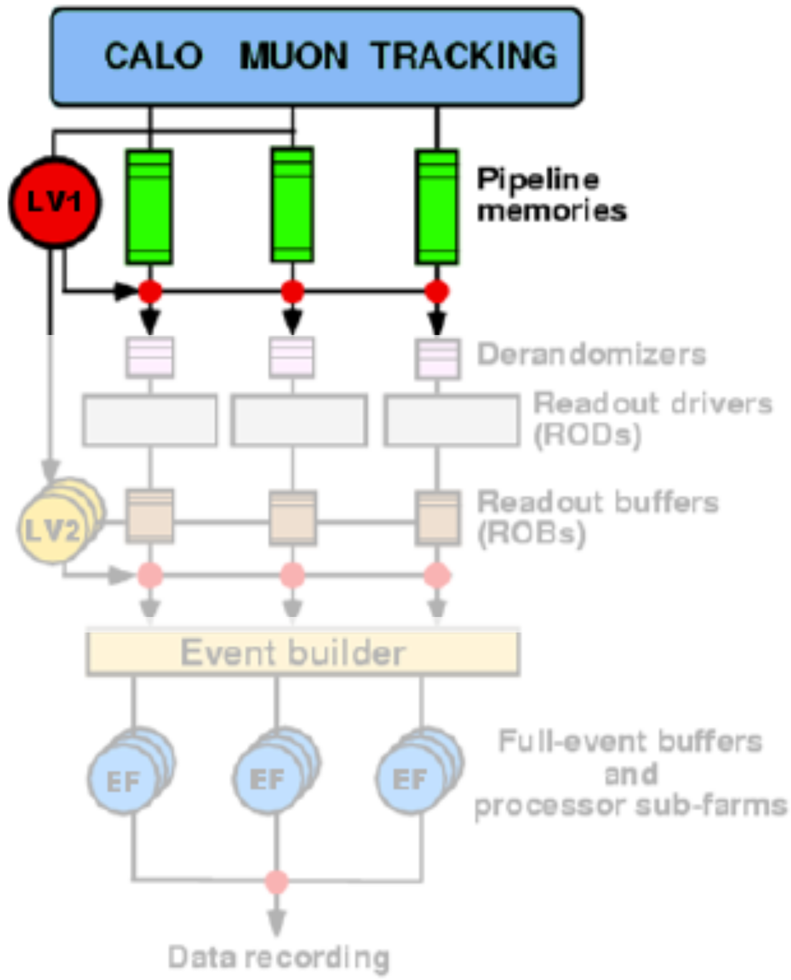
Ricardo Gonçalo

The ATLAS trigger

Three trigger levels:

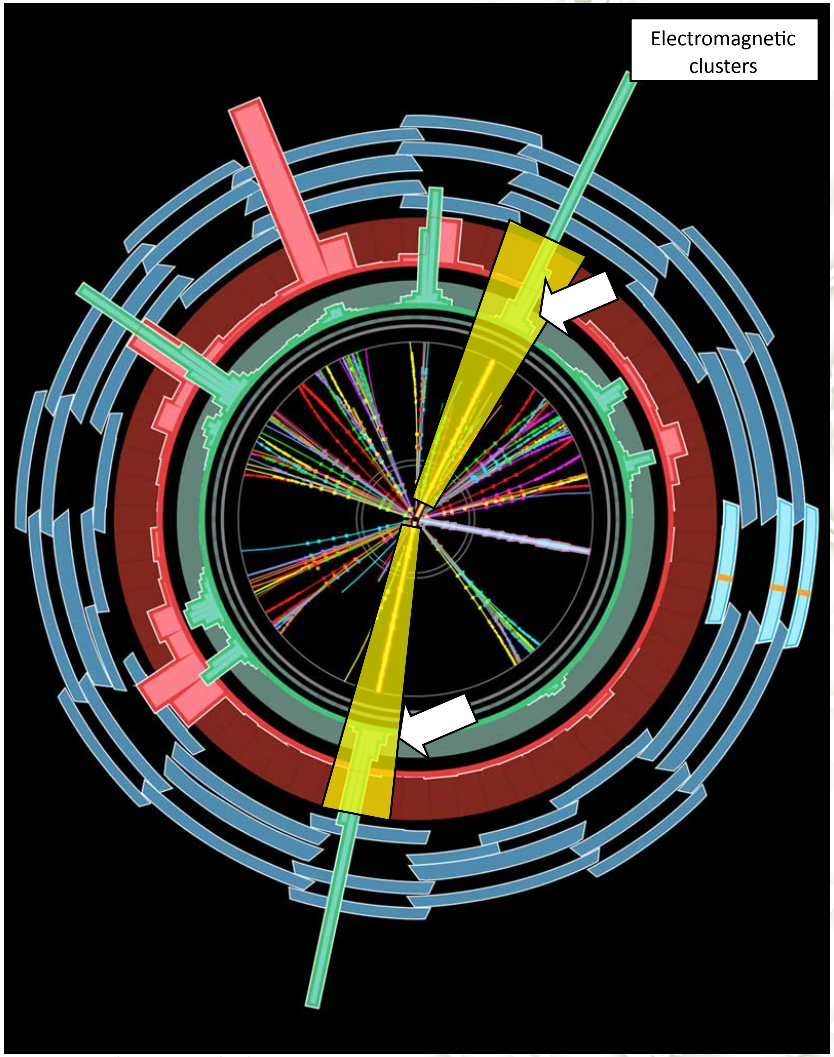
- Level 1:
  - Hardware based (FPGA/ASIC)
  - Coarse granularity detector data
  - Calorimeter and muons only
  - Latency 2.2 μs (on-detector buffer)
  - Output rate ~75 kHz
- Level 2:
  - Software based
  - Only detector sub-regions (**Regions of Interest**) processed; **seeded** by level 1
  - Full detector granularity in RoIs
  - Fast tracking and calorimetry
  - Average execution time ~10 ms
  - Output rate ~1 kHz
- Event Filter (EF):
  - Seeded by level 2
  - Full detector granularity
  - Potential full event access
  - Offline algorithms
  - Average execution time ~1 s
  - Output rate ~200 Hz

High-Level Trigger



Selection method

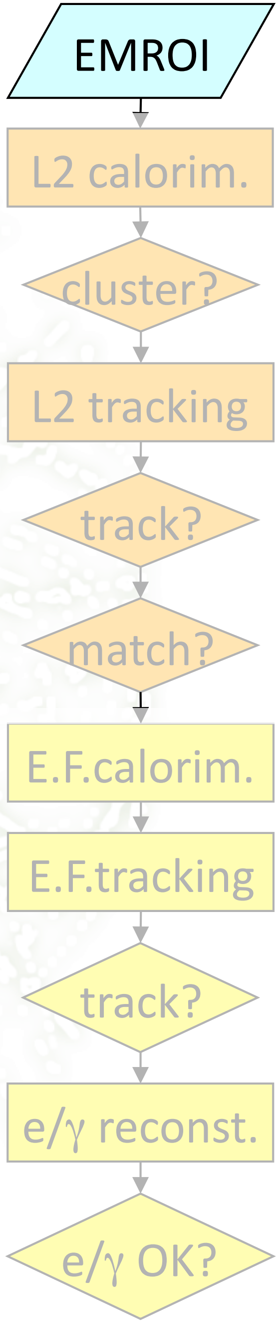
Event rejection possible at each step



Level1 Region of Interest is found and position in EM calorimeter is passed to Level 2

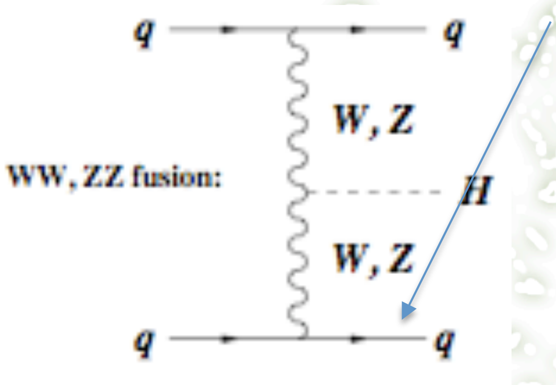
Level 2 seeded by Level 1
Fast reconstruction algorithms
Reconstruction within RoI

Ev.Filter seeded by Level 2
Offline reconstruction algorithms
Refined alignment and calibration



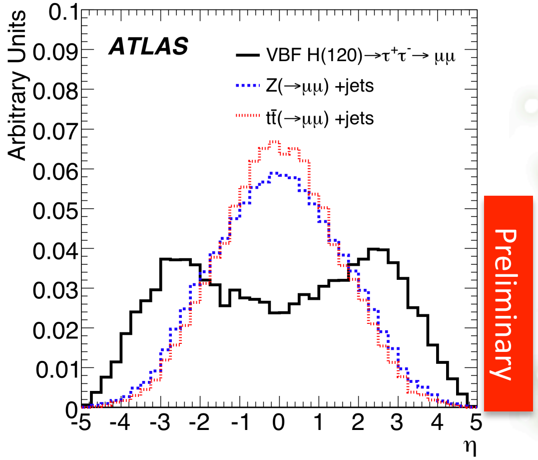
Interlude: Vector Boson Fusion

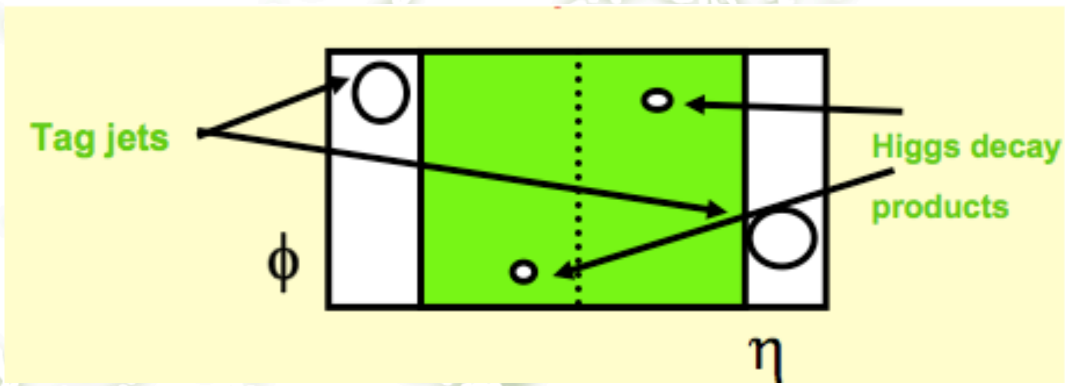
Established by Zeppenfeld et al. for low-mass region
Earlier studies by Dokshitzer, Khoze, Sjöstrand, Troyan, Kleiss, Stirling



- Important for low-mass region
  - Improve significance
  - Measure Higgs parameters
- Two high-p_T tag jets with large rapidity gap in between
- No color flow between tag jets – suppressed hadronic activity in central region
- Studied in Higgs decays to WW, ττ

Pseudorapidity of leading jet in VBF H→ττ and tt

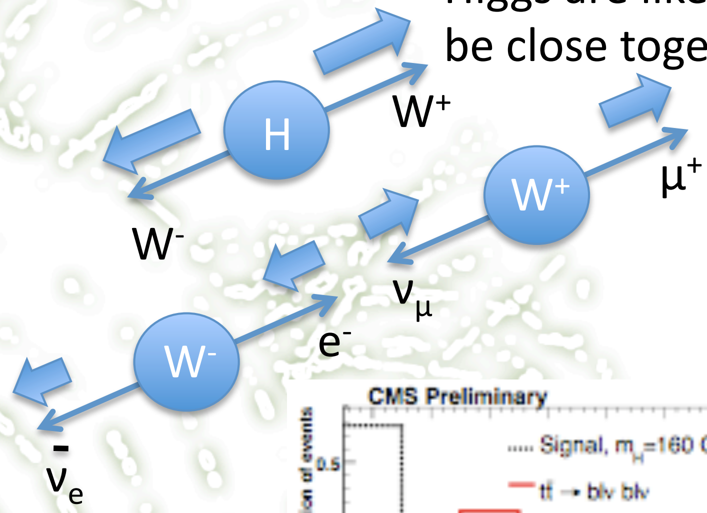


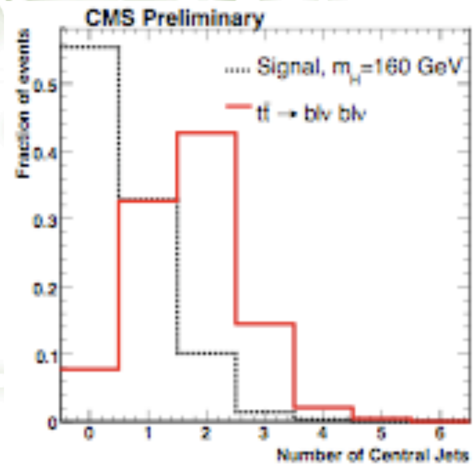


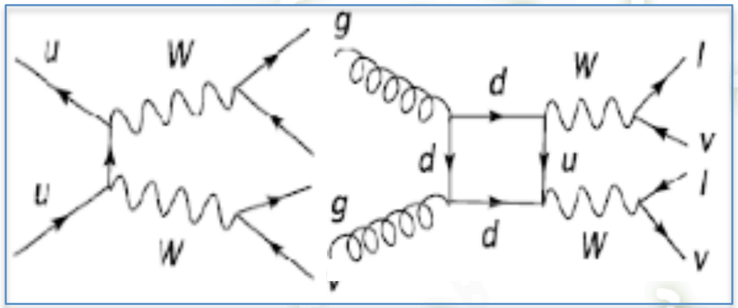
$H \rightarrow WW \rightarrow \ell\nu\ell\nu$

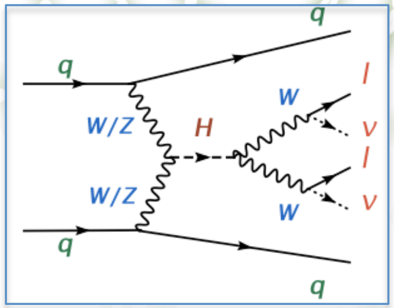
- Main search channel for mass in range: $2m_W < m_H < 2m_Z$
- Highest branching ratio above ~140 GeV/c^2 : 95% @ m_H = 160 GeV/c^2
- Analyses:
  - H + 0 jets -> lvlv (dominated by gluon fusion)
  - H + 2 jets -> lvlv; H + 2 jets -> lvqq (dominated by VBF)
- Main backgrounds: WW, Wt, tt

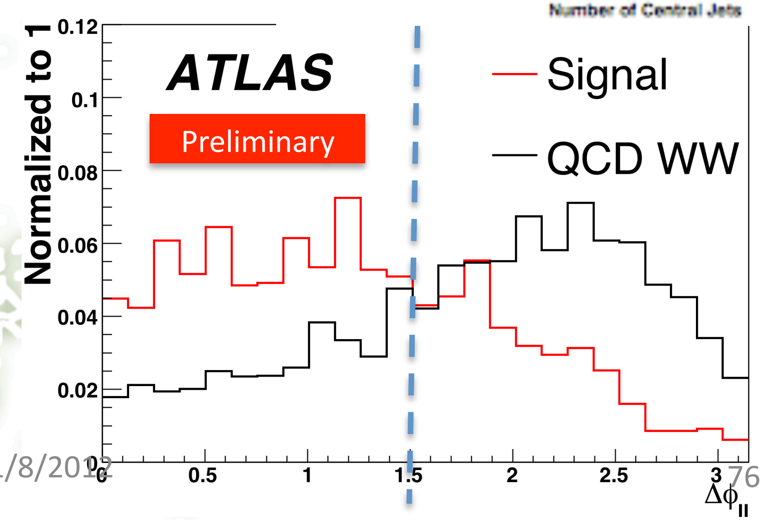
Leptons from the Higgs are likely to be close together











Two main discriminants:

- Angular correlation between leptons
- Veto on additional jets