Challenges of the LHC
(the hunt for the Higgs Boson)

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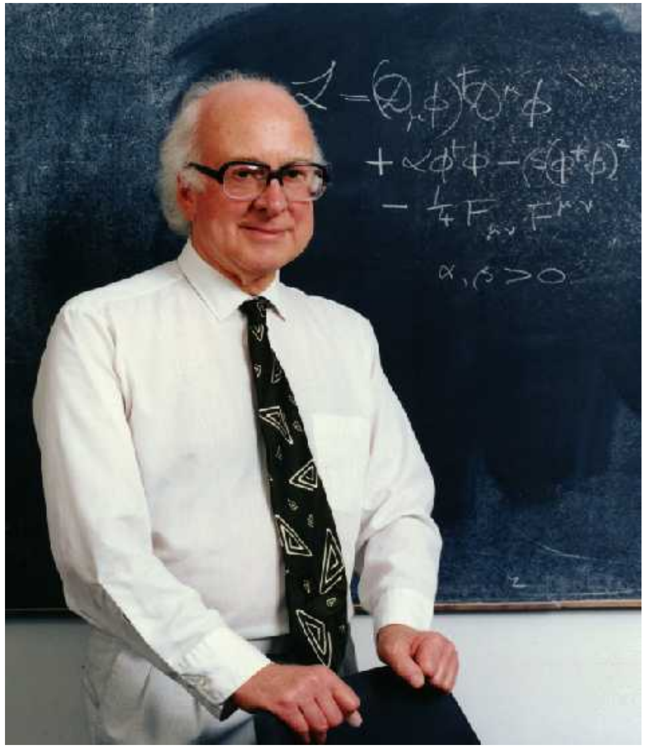
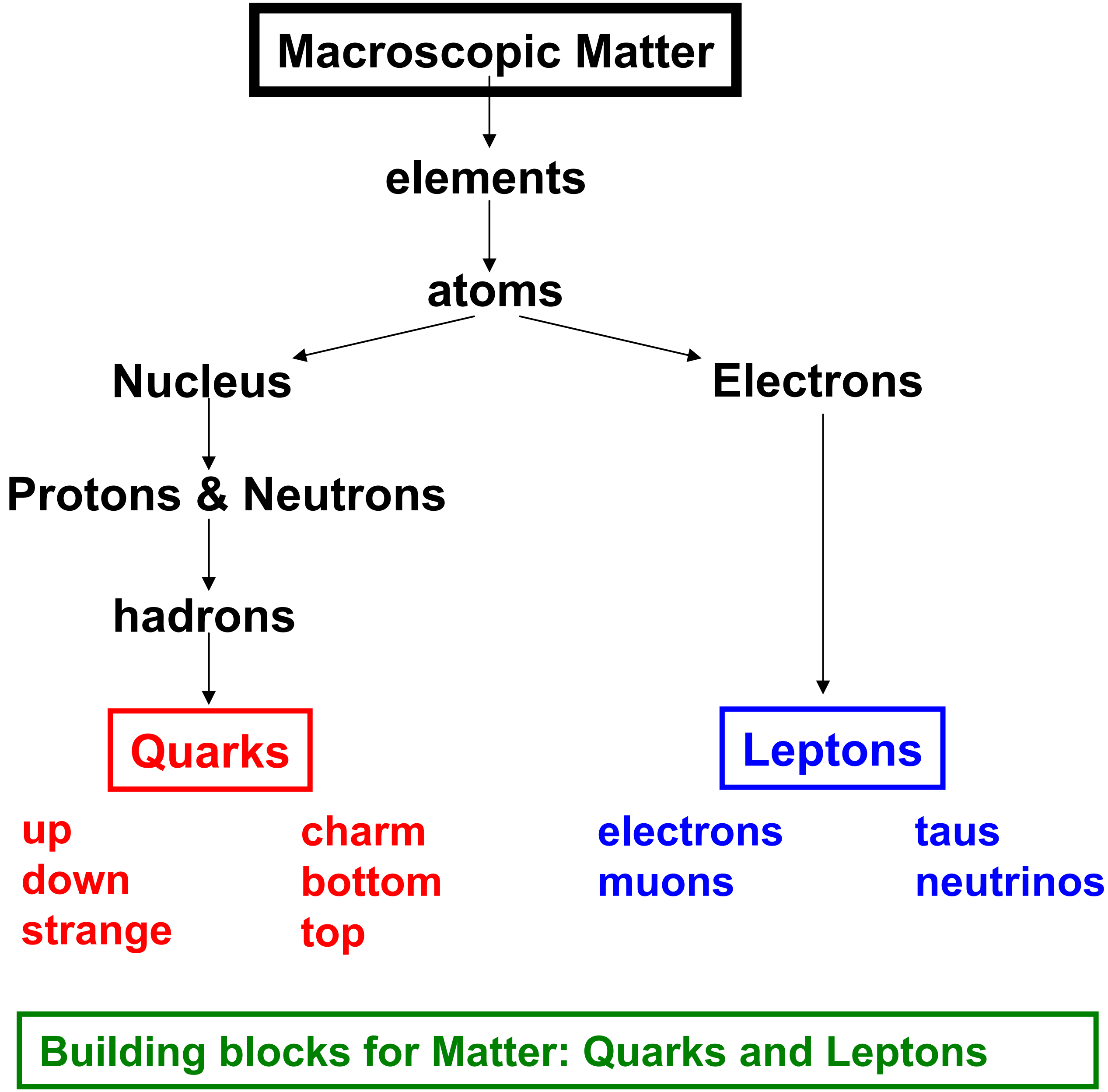
Outline

- Introduction
  - Quest for the Higgs Boson
- The challenges
  - Accelerator
  - The ATLAS and CMS Detectors
  - Triggering issues
  - Computing issues
  - Physics analysis
    - Detector requirements
- Summary




Macroscopic Matter
elements
atoms
Nucleus
Electrons
Protons & Neutrons
hadrons
Quarks
Leptons
up
down
strange
charm
bottom
top
electrons
muons
taus
neutrinos
Building blocks for Matter: Quarks and Leptons

QUARKS

up

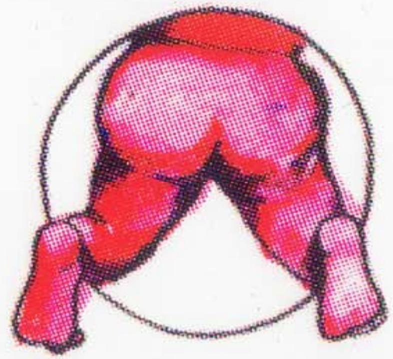
charm

top

down

strange

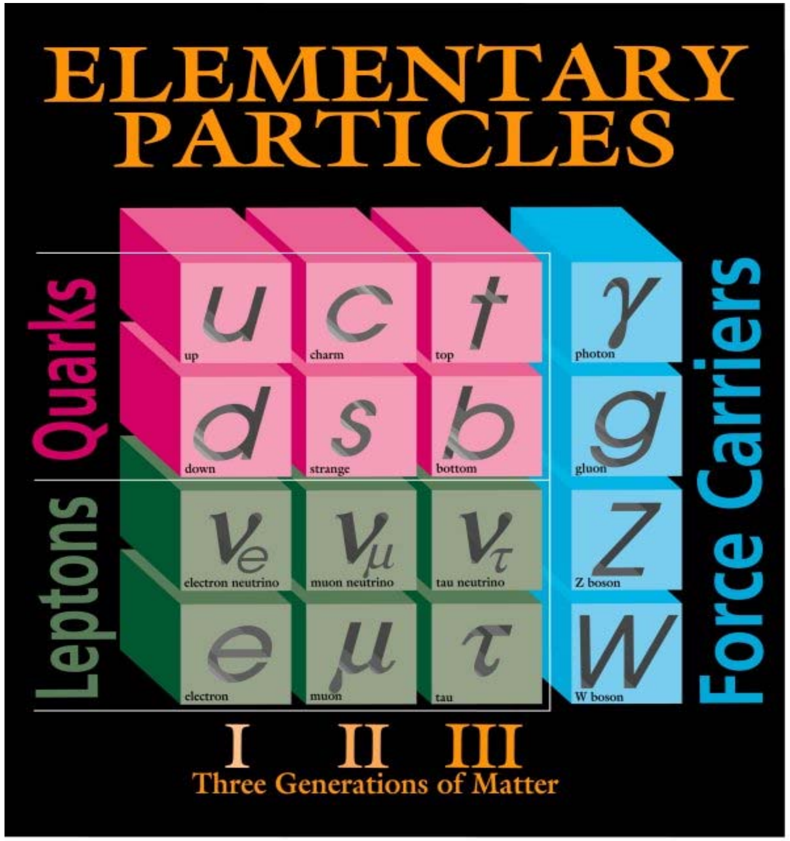
bottom



What is the origin of the particle masses?

Why some particles are heavier than others?

The discovery of the Higgs boson should answer these questions



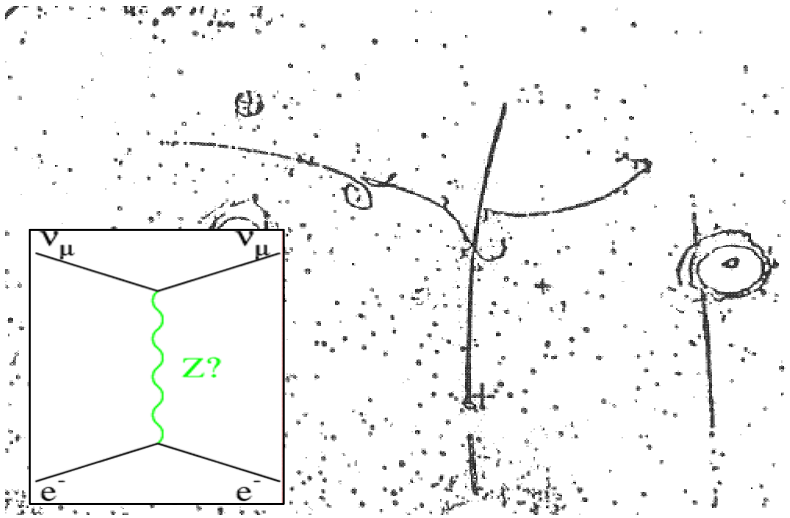
Fermilab 95-759

Brief Historical Perspective

1964: First formulation of Higgs mechanism (P.W.Higgs)

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam)

1973: Discovery of neutral currents in $\nu_\mu e$ scattering (Gargamelle, CERN)



1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$

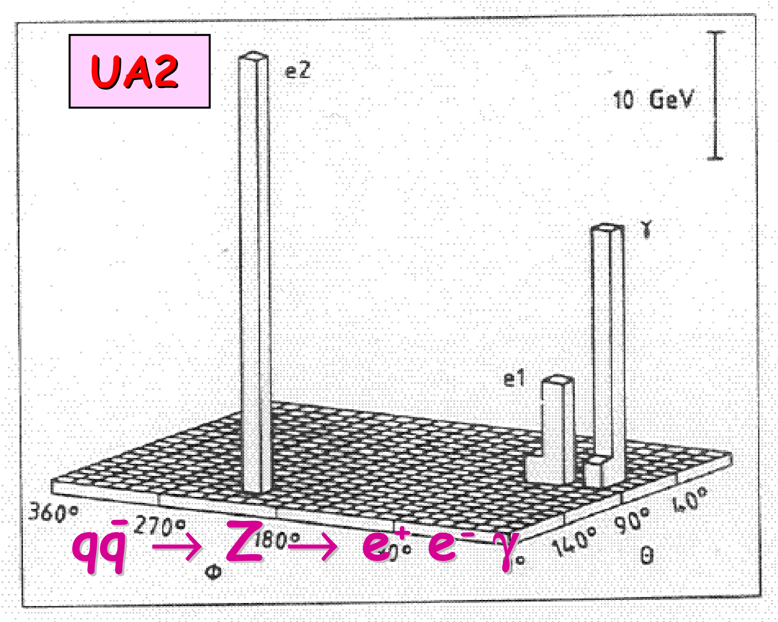
1981: The CERN SpS becomes a proton-antiproton collider

LEP and SLC are approved before W/Z boson discovery

1983: LEP and SLC construction starts

W and Z discovery (UA1, UA2)

One of the first Z-bosons detected in the world



1984: Glimmerings of LHC and SSC (pp collisions)

1987: First comparative studies of physics potential of hadron colliders (LHC/SSC) and e^+e^- linear colliders (CLIC)

1989: First collisions in LEP (e^+e^- collisions)

Precision tests of the SM and search for the Higgs boson begin in earnest

R&D for LHC detectors begins

1993: The SSC project is cancelled

1994: LHC machine is approved (start in 2005)

1995: Discovery of the top quark at Fermilab by CDF and D0

Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

2000: First possible hint of Higgs boson with Mass 115 GeV observed by the ALPEPH collaboration at LEP (e^+e^- collisions)

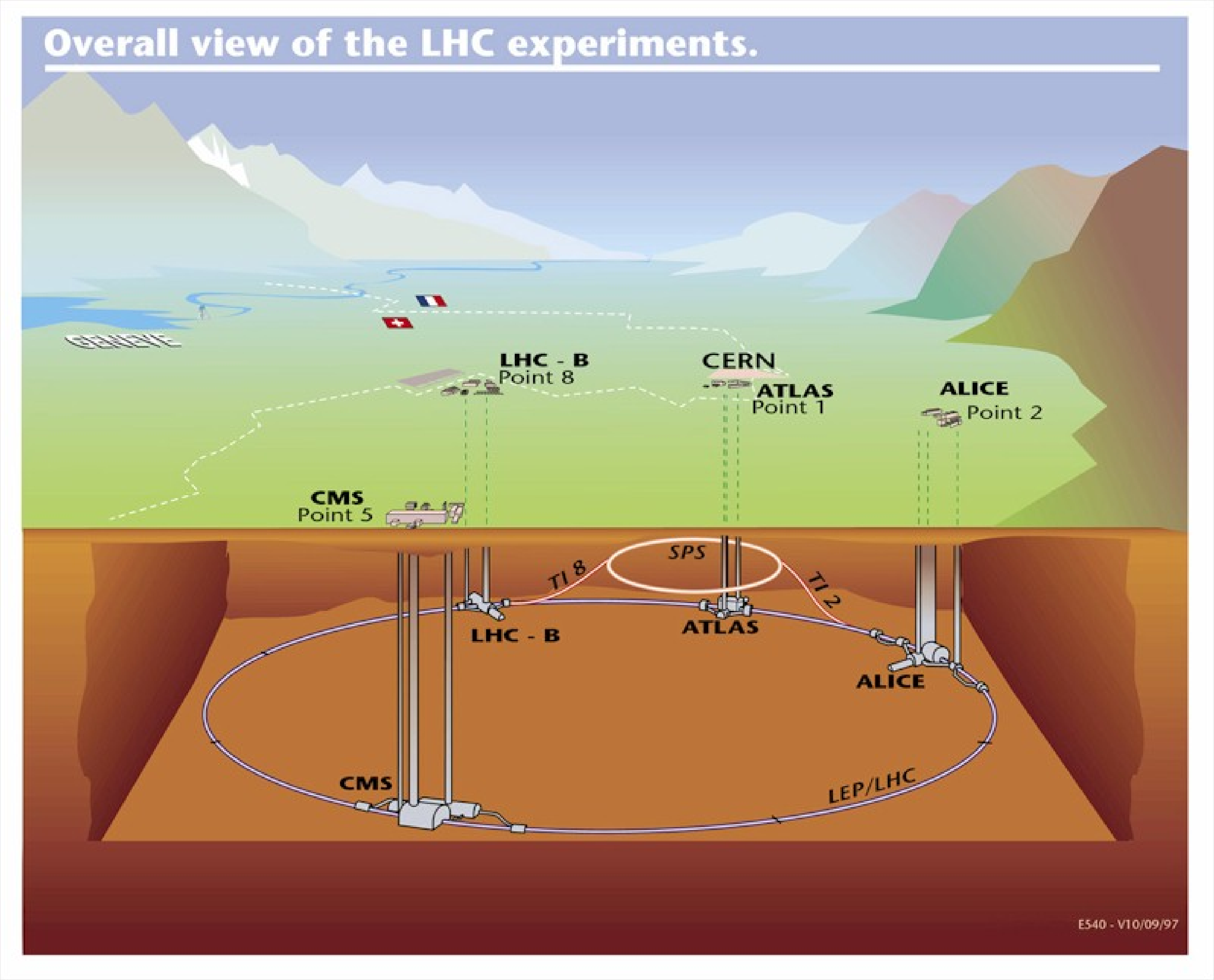
2000: Three other LEP experiments do not observe significant excess Higgs events. 95% Confidence Level limit is set to $M_H > 114$ GeV

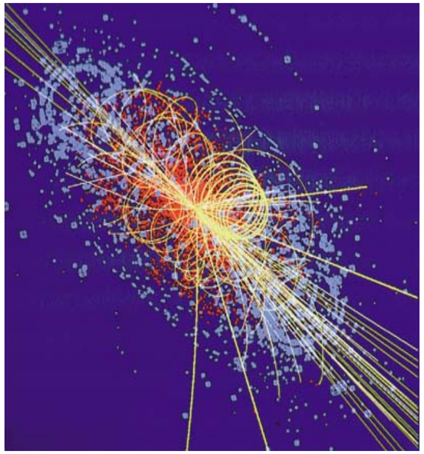
2000: End of LEP running

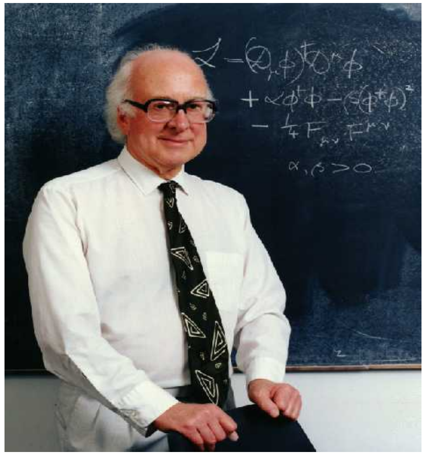
2001: LHC schedule delayed by two more years (2007)

2005: CERN DG, R.Aymar confirms LHC start-up for summer 2007

Higgs Discovery at LHC

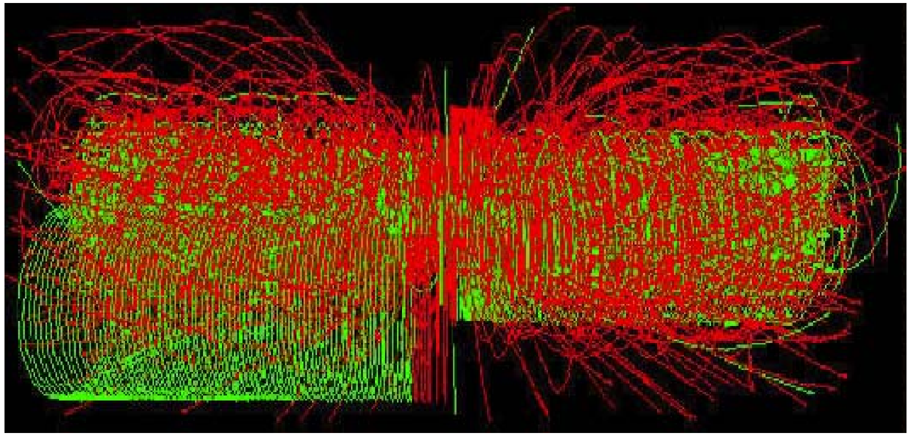




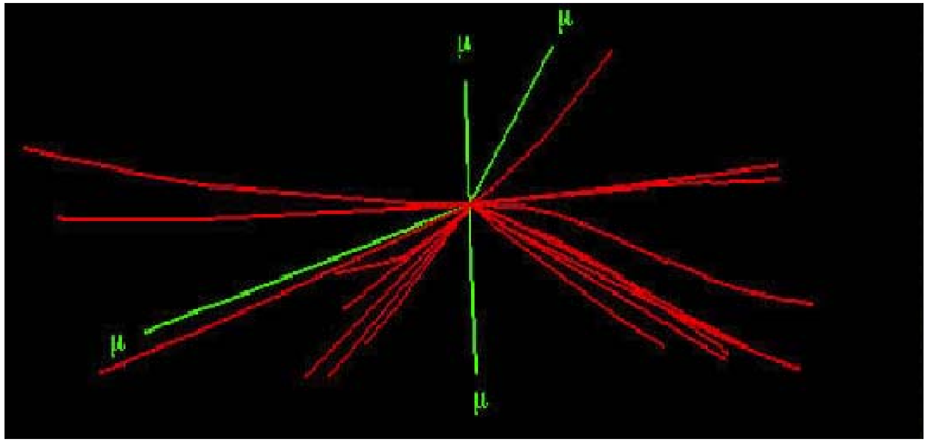


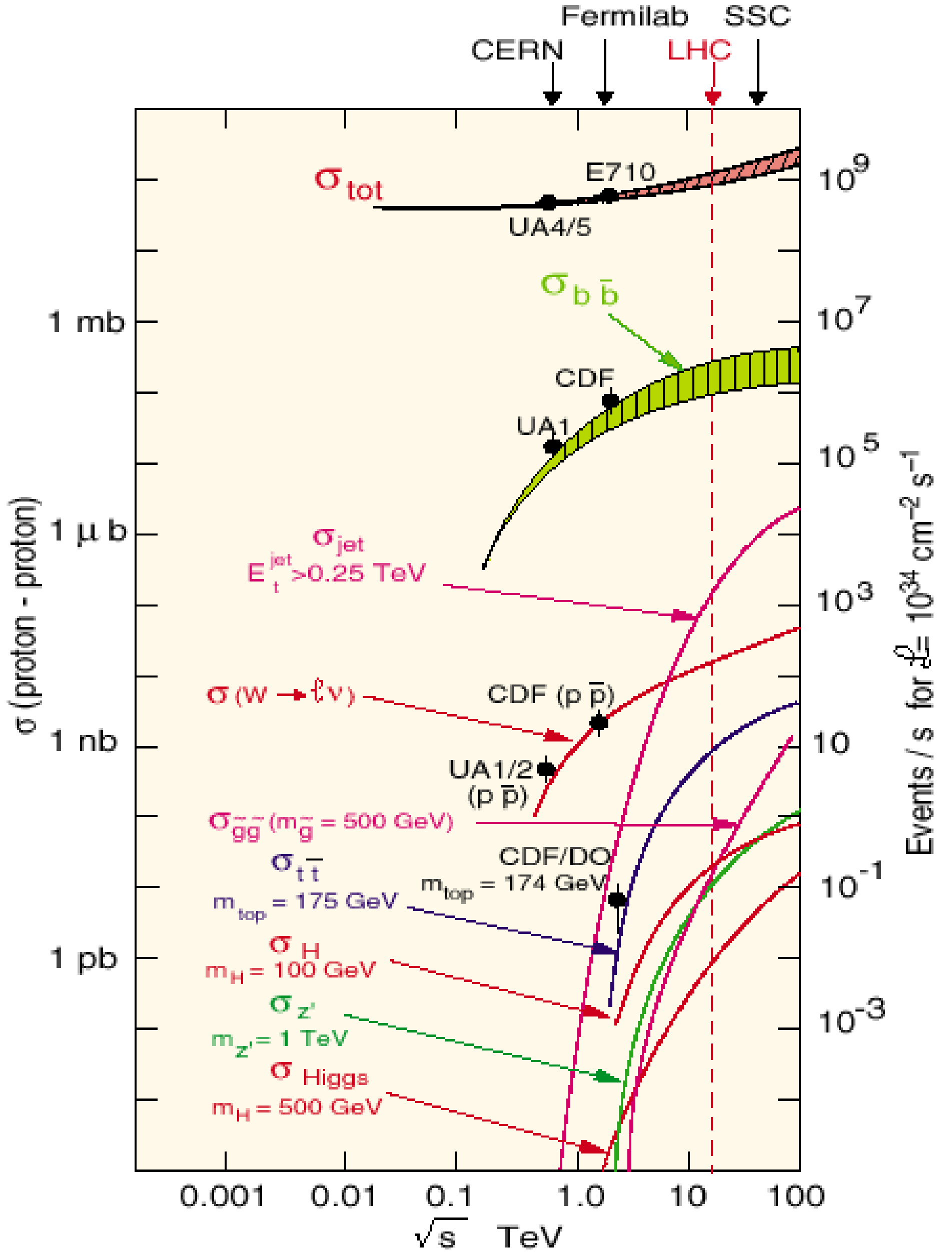
Higgs at the LHC: the challenge

Knowing that there are 10 thousand billions of:



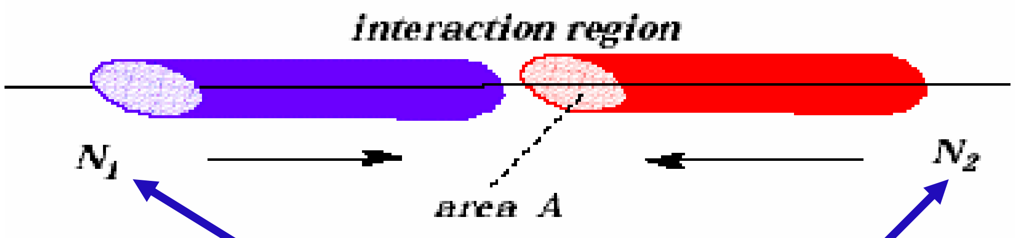
for ONE of:





Collider Luminosity

$$N_{ev}/sec = \sigma \cdot L \qquad [L] = cm^{-2} \cdot s^{-1}$$



Number of protons in bunches

$$L = \nu \frac{N_1 \cdot N_2}{A}$$

Frequency of bunch crossing

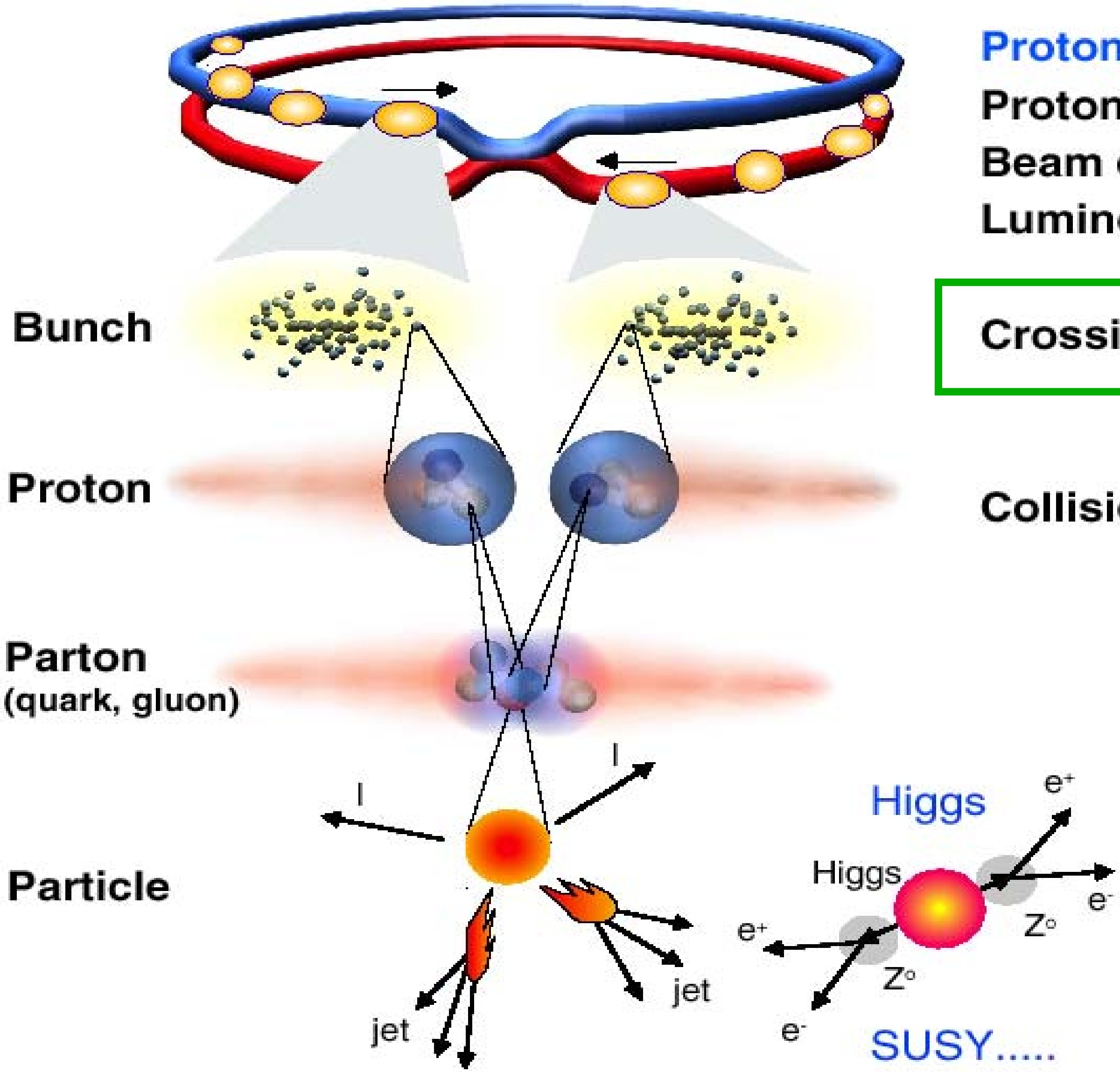
Colliding Area

- **Large luminosity is achieved by**
  - Increasing number of proton in bunches (beam current)
  - Increasing frequency of bunch crossing
  - Decreasing transverse size of interaction region

Challenges of accelerator physics

- *high bunch current*
  beam-beam; collective effects
- *many bunches*
  total current (RF); collective effects
- *small beam size*
  coupling; dispersion; hardware

Collisions at LHC

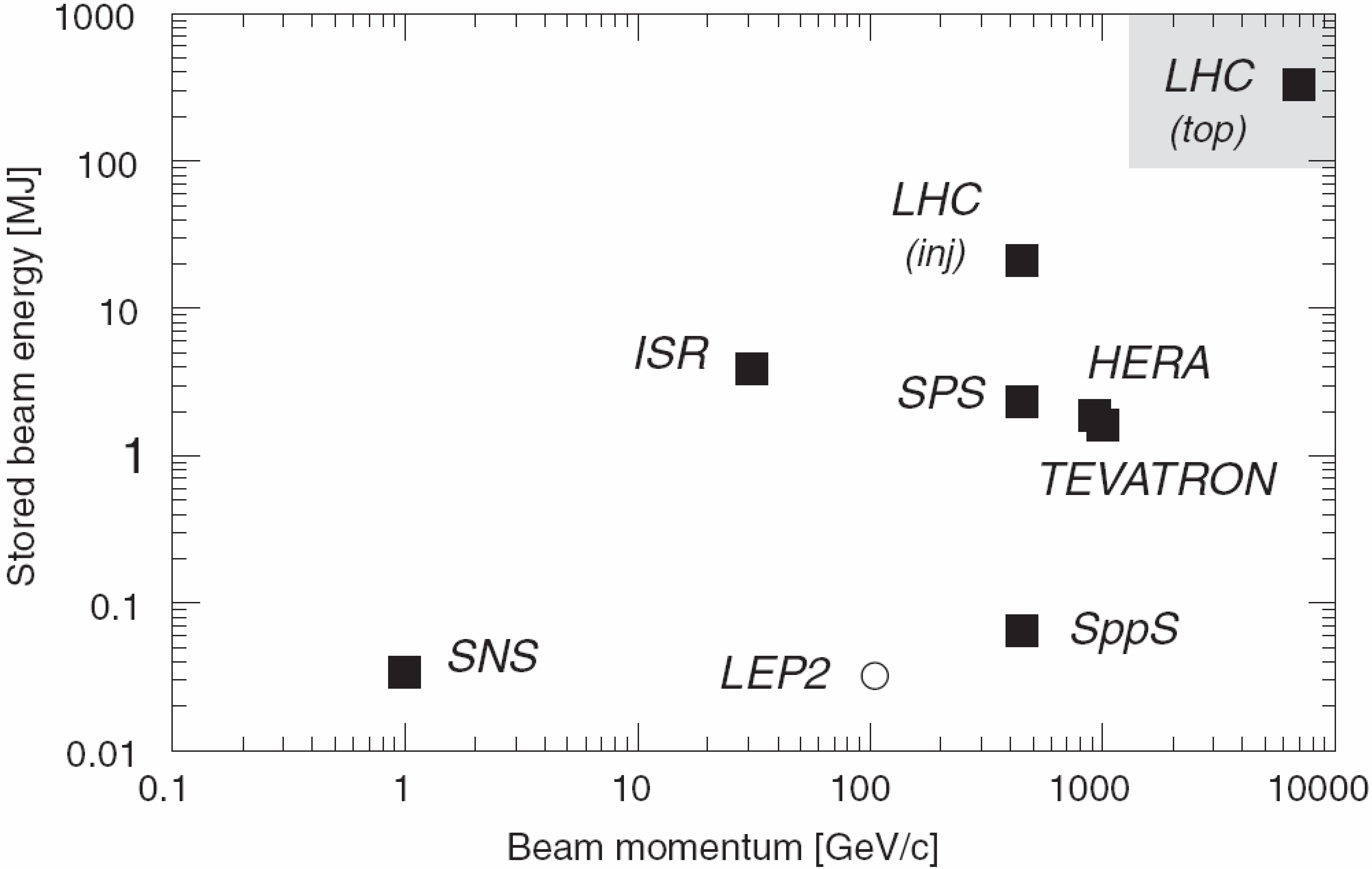


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

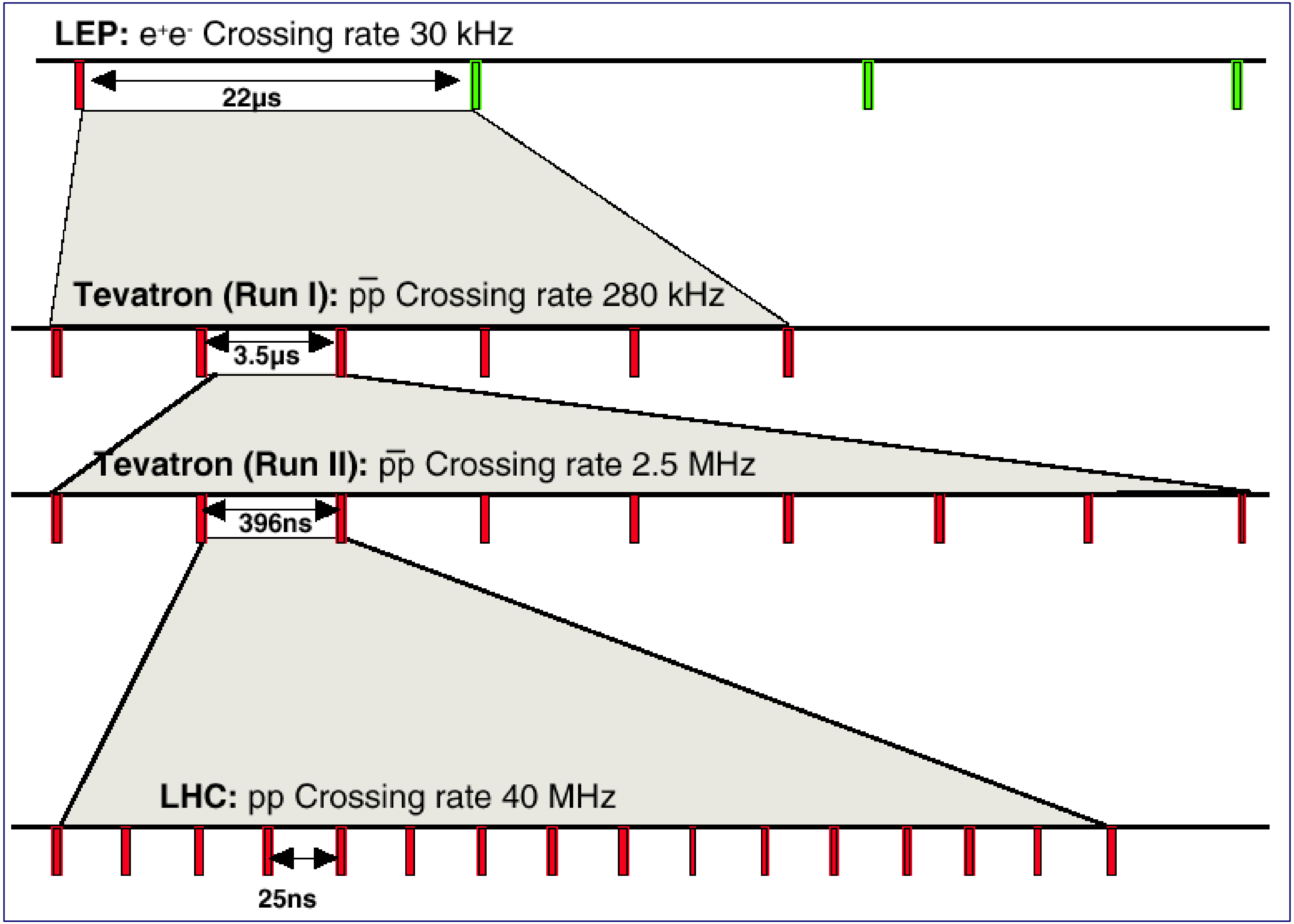
Crossing rate 40 MHz

Collisions ≈ 10^7 - 10^9 Hz

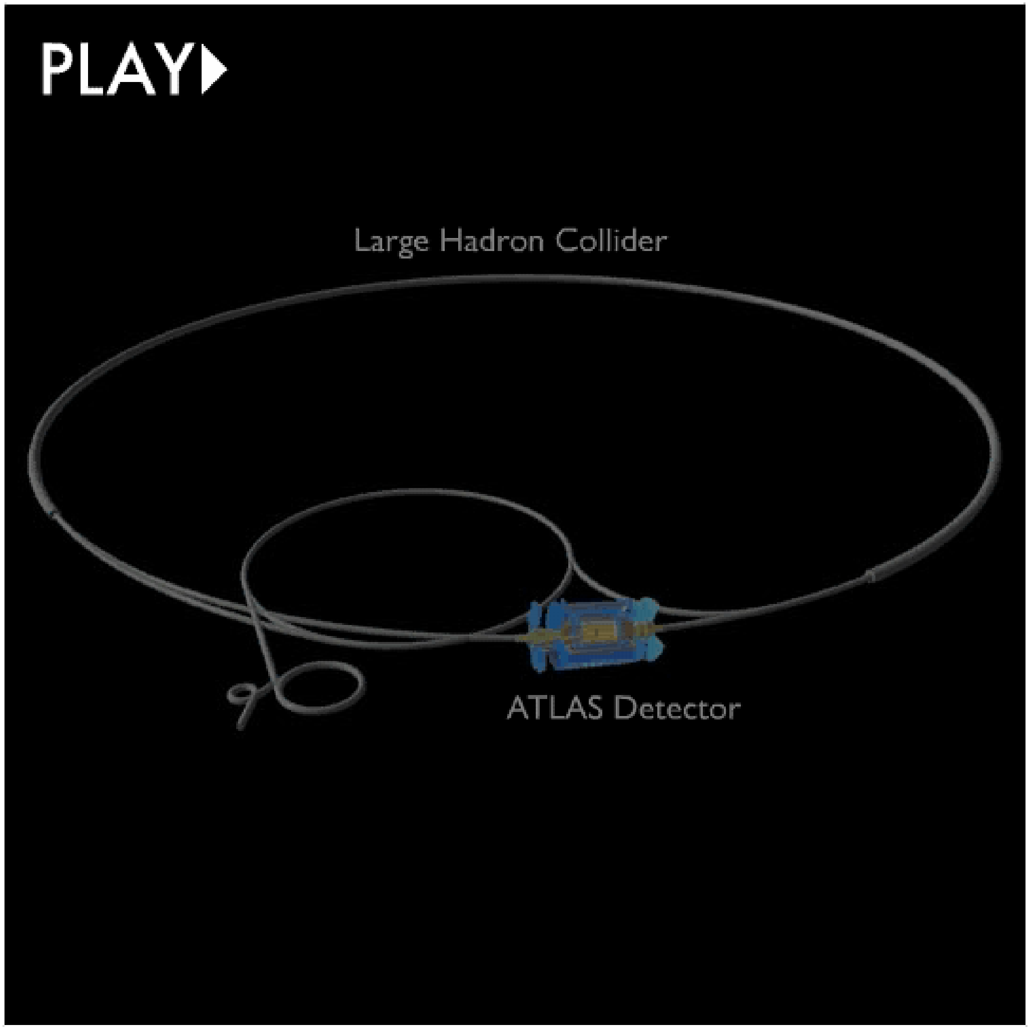
Selection of 1 in 10,000,000,000,000



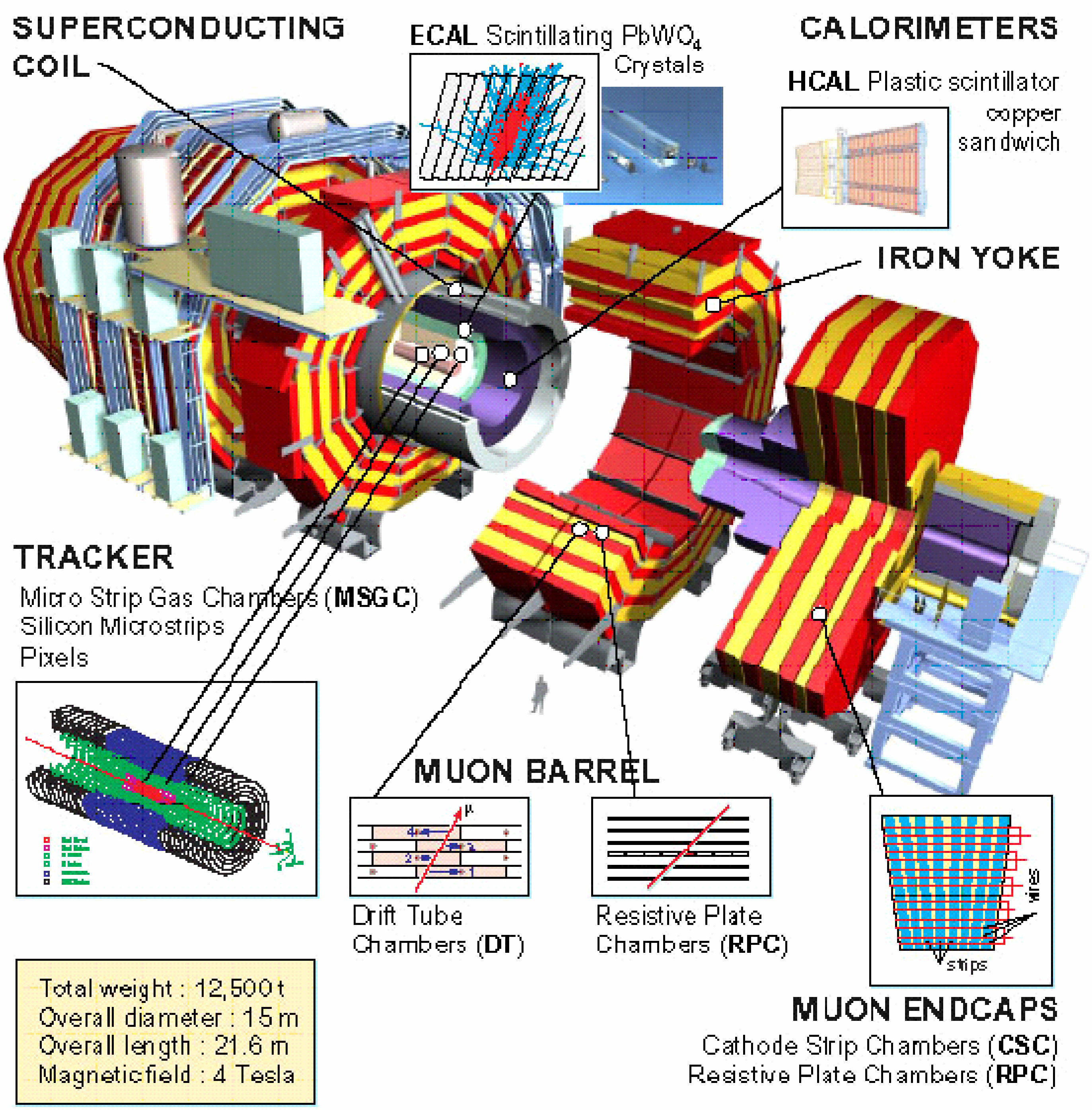
1000
100
10
1
0.1
0.01
Stored beam energy [MJ]
0.1
1
10
100
1000
10000
Beam momentum [GeV/c]
LHC
(top)
LHC
(inj)
ISR
SPS
HERA
TEVATRON
SppS
SNS
LEP2



LEP: e+e- Crossing rate 30 kHz
22μs
Tevatron (Run I): p̄p Crossing rate 280 kHz
3.5μs
Tevatron (Run II): p̄p Crossing rate 2.5 MHz
396ns
LHC: pp Crossing rate 40 MHz
25ns

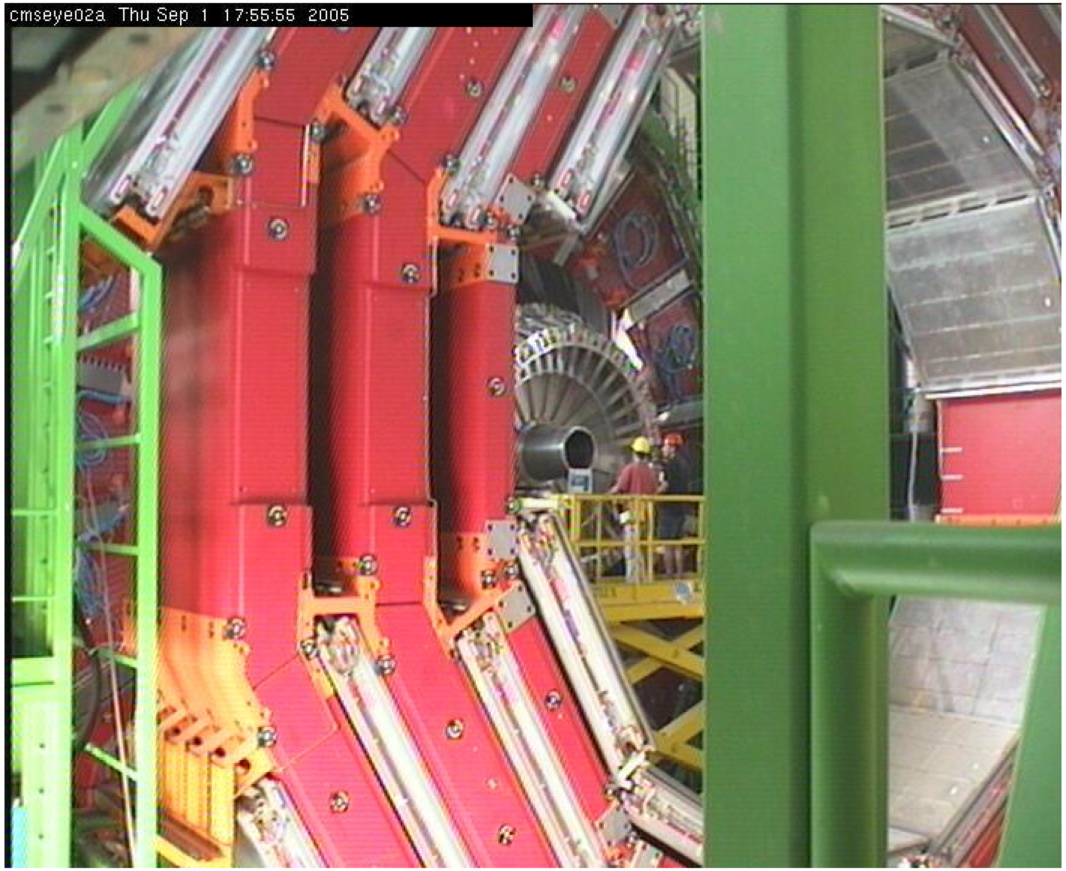

PLAY
Large Hadron Collider
ATLAS Detector

CMS



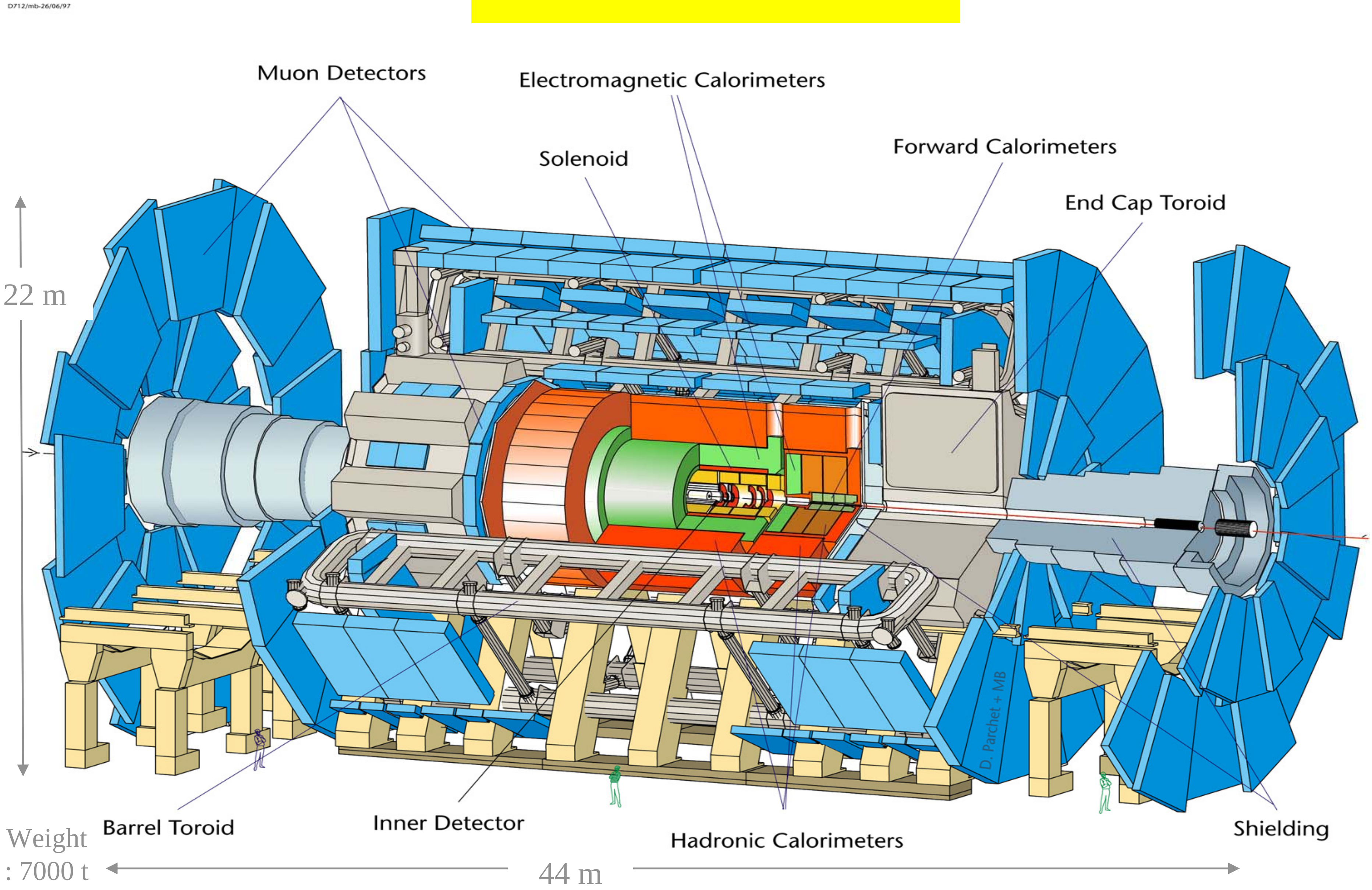
SUPERCONDUCTING COIL
ECAL Scintillating $PbWO_4$ Crystals
CALORIMETERS
HCAL Plastic scintillator copper sandwich
IRON YOKE
TRACKER
Micro Strip Gas Chambers (MSGC)
Silicon Microstrips
Pixels
MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
wires
strips
MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

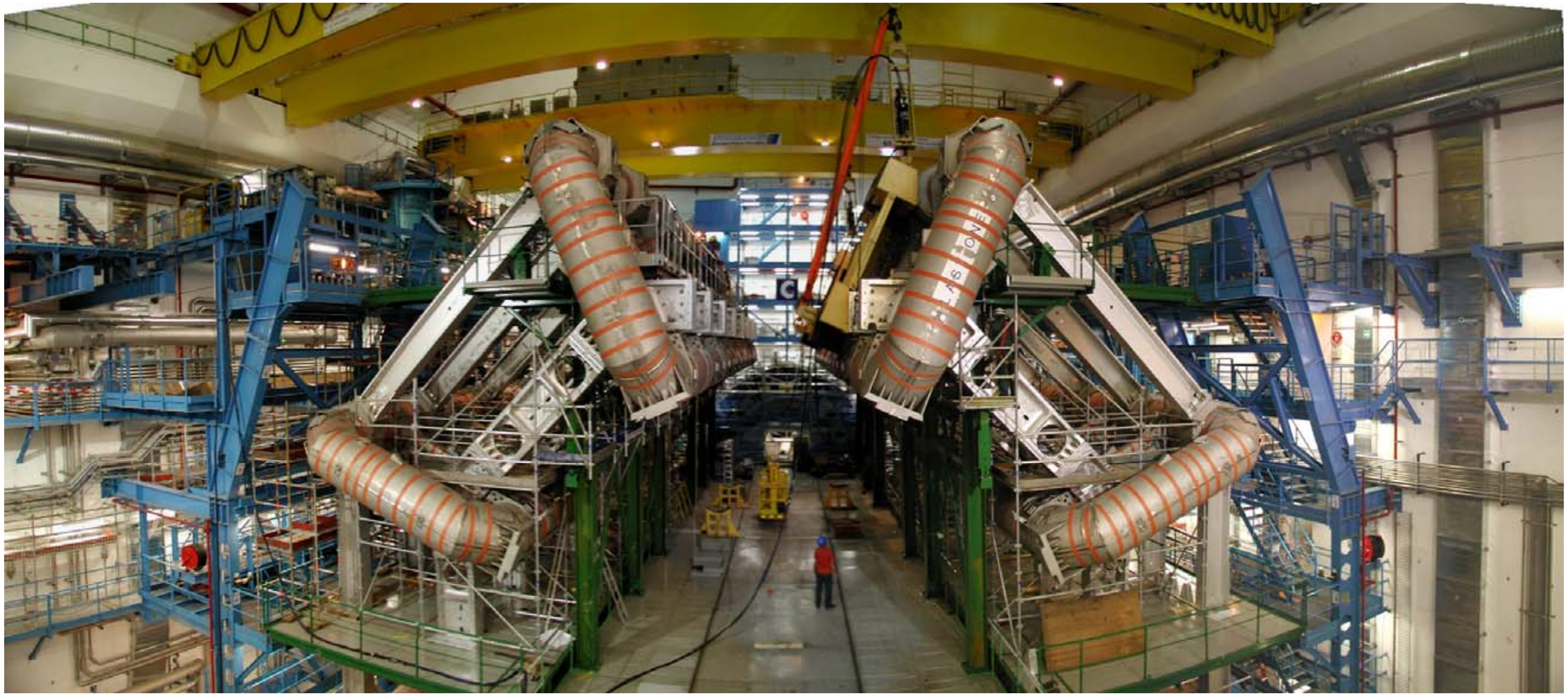
CMS is assembled on the surface

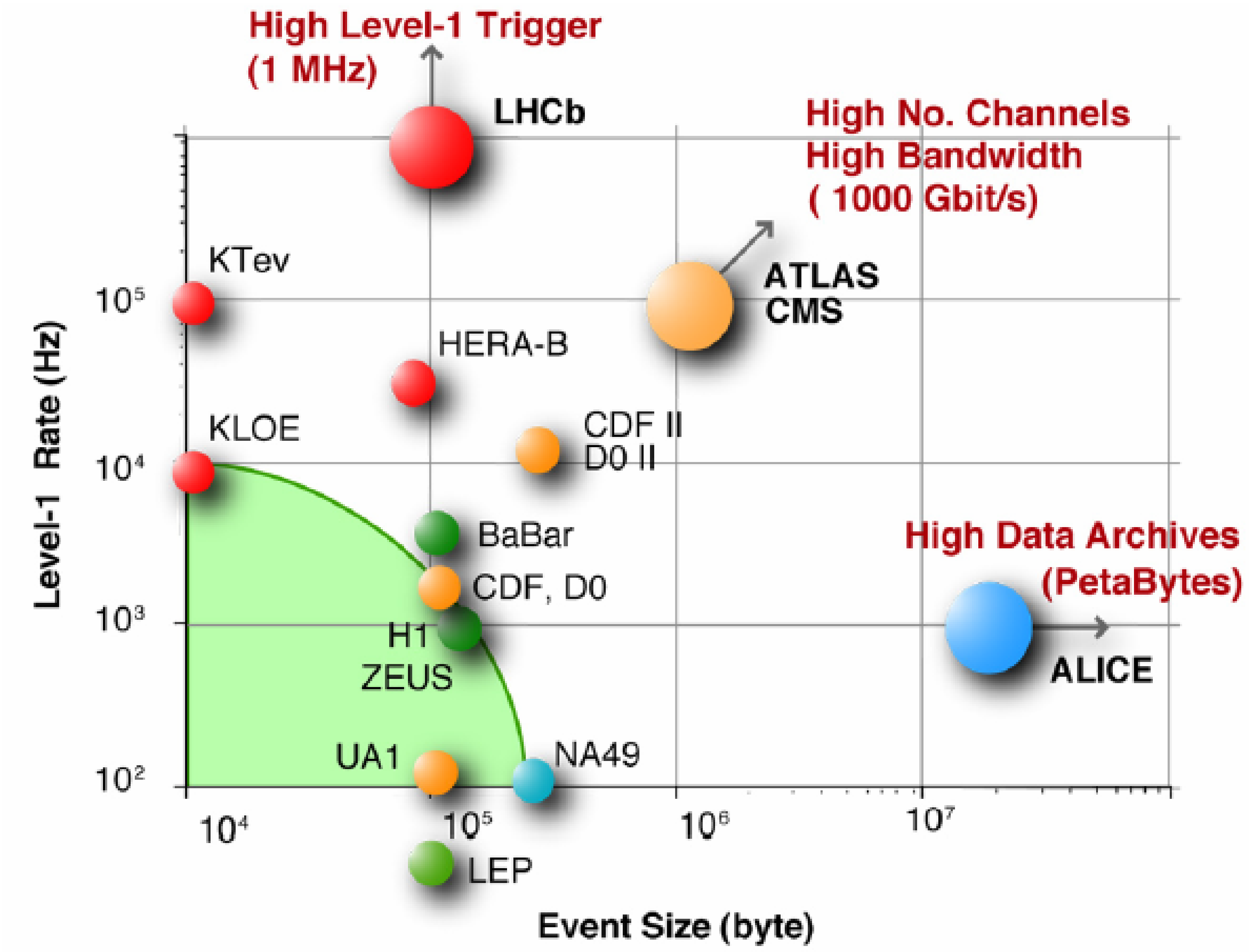


Services installation in CMS cavern

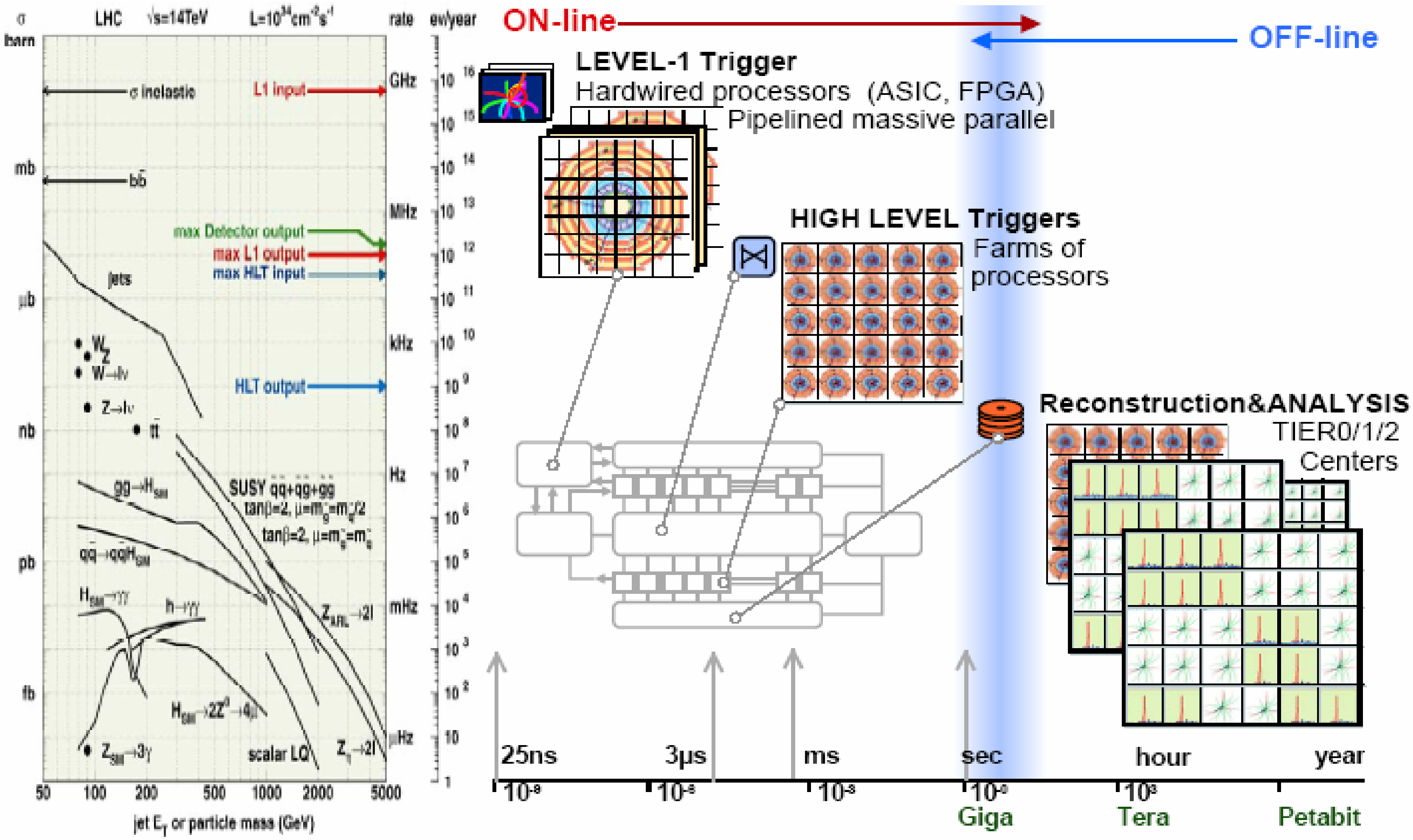
ATLAS


D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
22 m
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB
Weight
: 7000 t
44 m



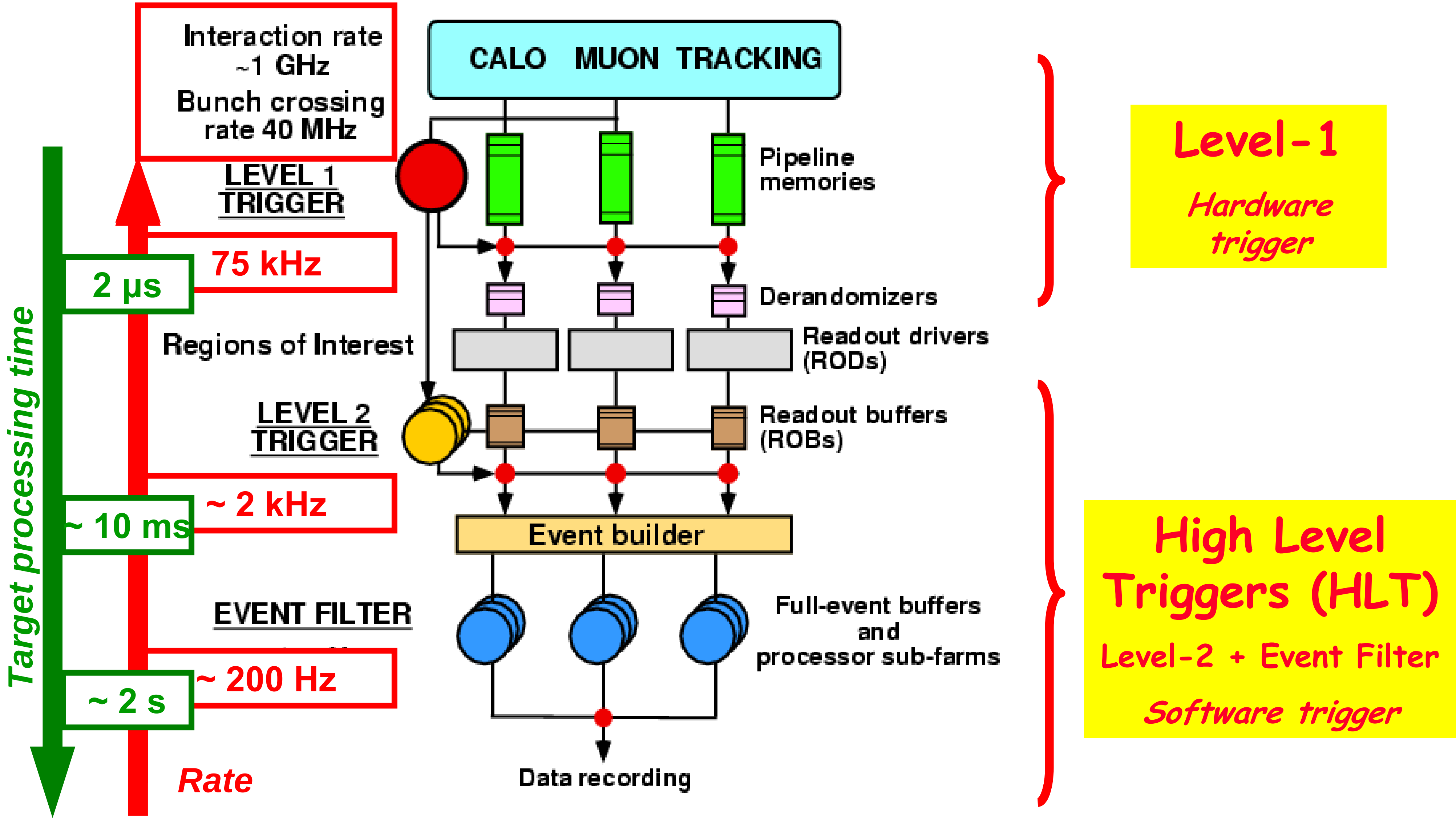


High Level-1 Trigger
(1 MHz)
LHCb
High No. Channels
High Bandwidth
(1000 Gbit/s)
KTev
ATLAS
CMS
HERA-B
KLOE
CDF II
D0 II
BaBar
High Data Archives
(PetaBytes)
CDF, D0
H1
ZEUS
ALICE
UA1
NA49
LEP
Level-1 Rate (Hz)
10^5
10^4
10^3
10^2
10^4
10^5
10^6
10^7
Event Size (byte)



ON-line
OFF-line
LEVEL-1 Trigger
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel
HIGH LEVEL Triggers
Farms of
processors
Reconstruction&ANALYSIS
TIER0/1/2
Centers
25ns
3μs
ms
sec
hour
year
Giga
Tera
Petabit
LHC √s=14TeV L=10^34 cm^-2 s^-1
σ inelastic
L1 input
max Detector output
max L1 output
max HLT input
HLT output
jets
jet E_T or particle mass (GeV)

The ATLAS Trigger System



The Eventflow

	Rate [Hz]	RAW [MB]	ESD rDST RECO [MB]	AOD [kB]	Monte Carlo [MB/evt]
ALICE HI	100	12.5	2.5	250	300
ALICE pp	100	1	0.04	4	0.4
ATLAS	200	1.6	0.5	100	2
CMS	150	1.5	0.25	50	2
LHCb	2000	0.025	0.025		0.5

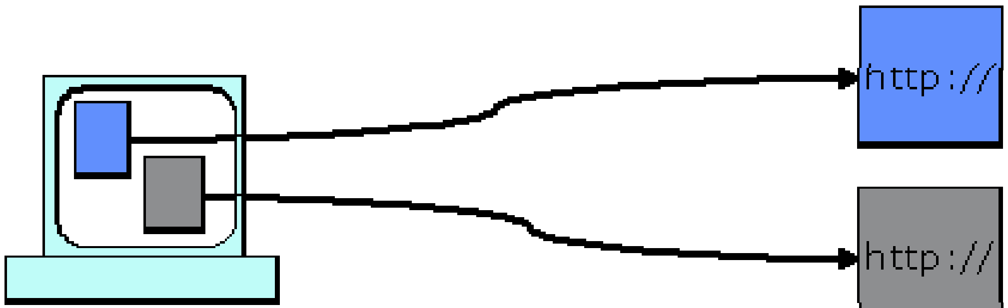
50 days running in 2007
10^7 seconds/year pp from 2008 on → ~10^9 events/experiment
10^6 seconds/year heavy ion


WHERE THE
WEB
WAS BORN
In the offices of this corridor, all the fundamental technologies of the World Wide Web were developed.
Started in 1990 from a proposal made by Tim Berners-Lee in 1989, the effort was first divided between an office in building 31 of the Computing and Networking Division (CN) and one in building 2 of the Electronics and Computing for Physics Division (ECP).
In 1991 the team came together in these offices, then belonging to ECP. It was composed of two CERN staff members, Tim Berners-Lee (GB) and Robert Cailliau (BE), aided by a number of Fellows, Technical Students, a Coopérant and Summer Students.
At the end of 1994 Tim Berners-Lee left CERN to direct the WWW Consortium (W3C), a world-wide organization devoted to leading the Web to its full potential. The W3C was founded with the help of CERN, the European Commission, the Massachusetts Institute of Technology (MIT), the Institut National pour la Recherche en Informatique et en Automatique (INRIA), and the Advanced Research Projects Agency (ARPA).
In 1995 Tim Berners-Lee and Robert Cailliau received the ACM Software System Award for the World Wide Web. In 2004, Tim Berners-Lee was awarded the first Millenium Technology Prize by the Finnish Technology Award Foundation.
The CERN Library
June 2004

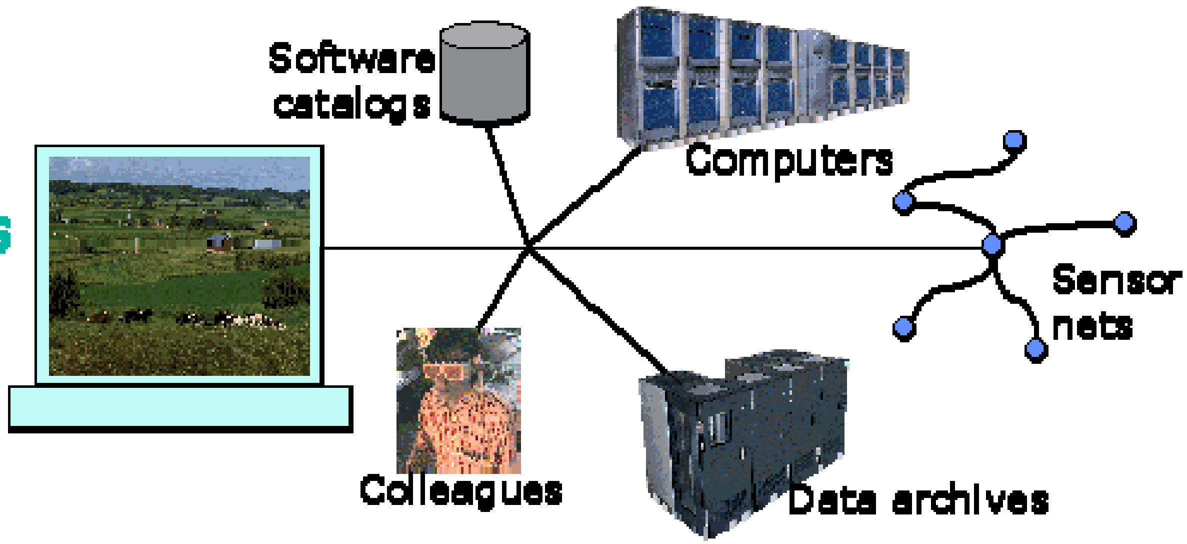
The Grid

The Grid: The Web on Steroids

Web: Uniform access to HTML documents



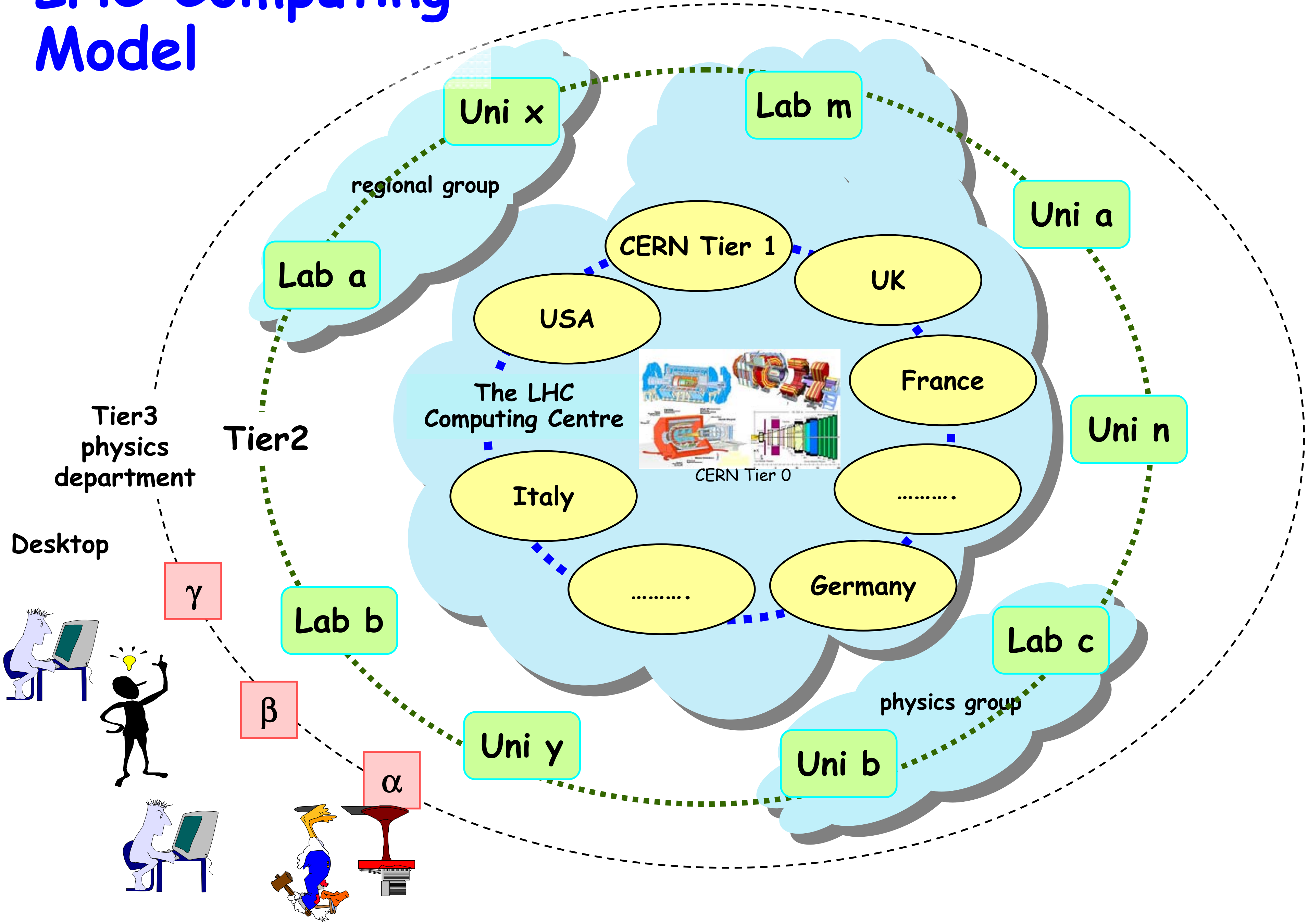
Grid: Flexible, high-perf access to all significant resources



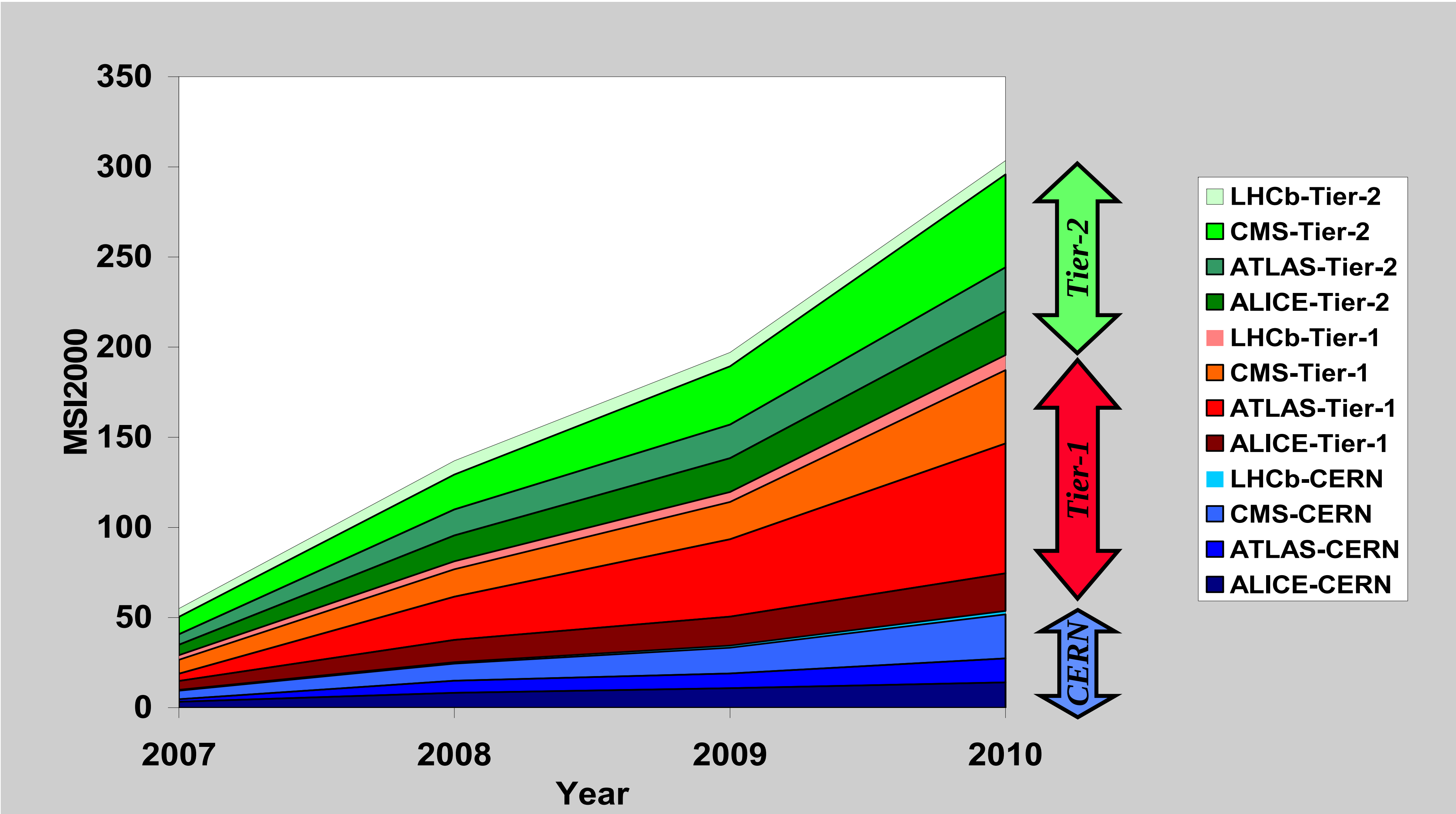
On-demand creation of powerful virtual computing systems

Grid Forum

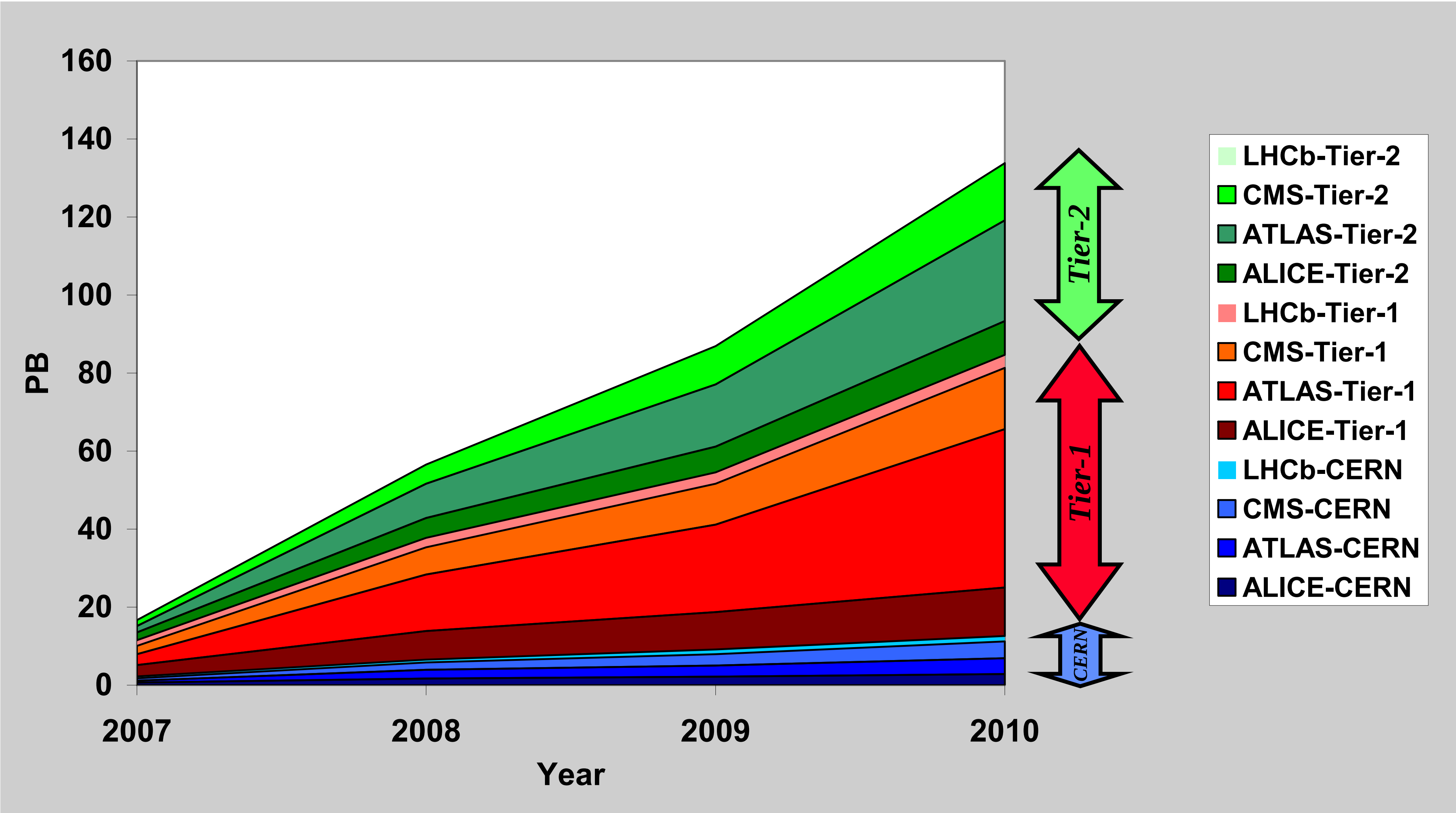
LHC Computing Model



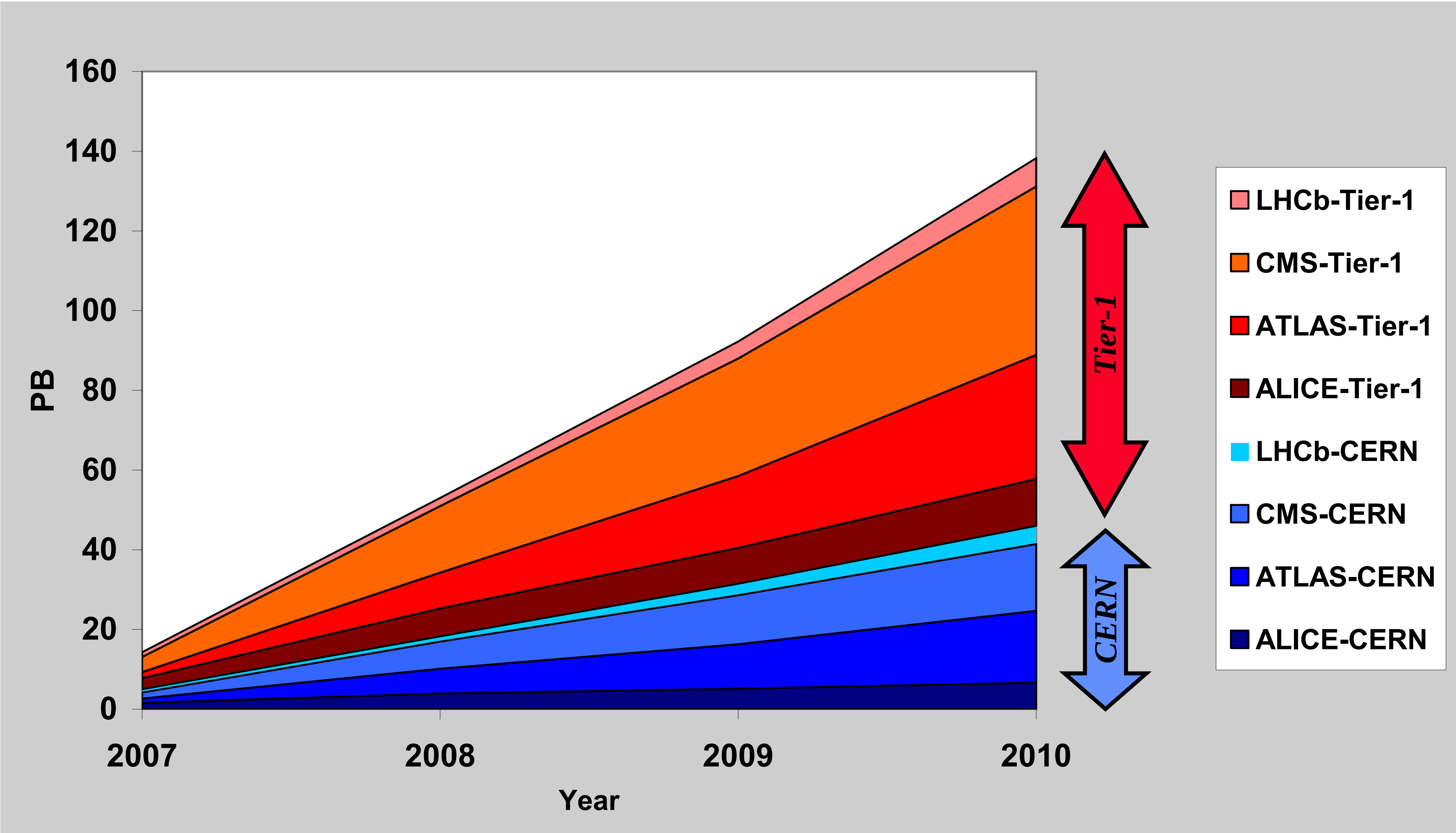
CPU Requirements



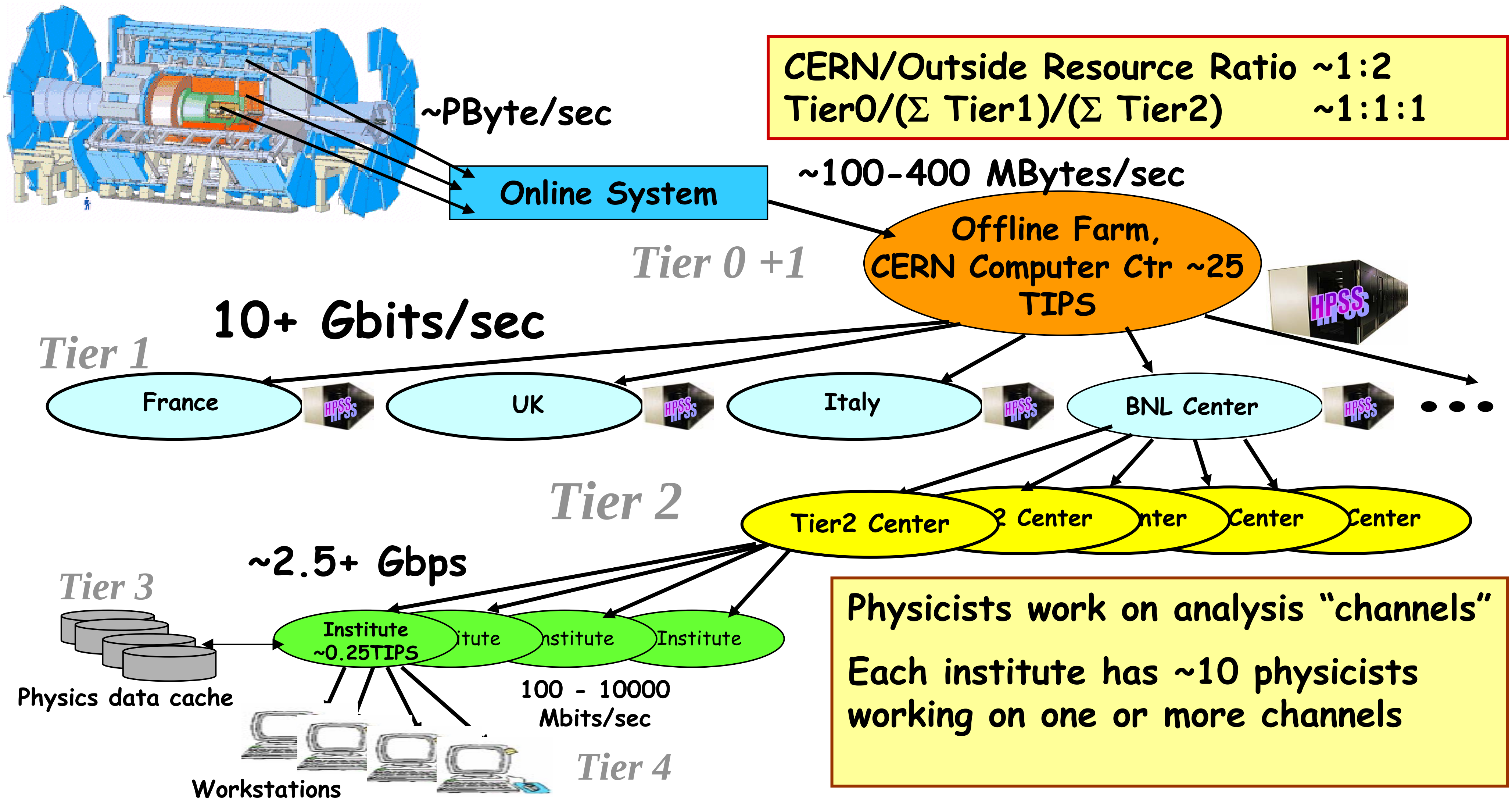
Disk Requirements

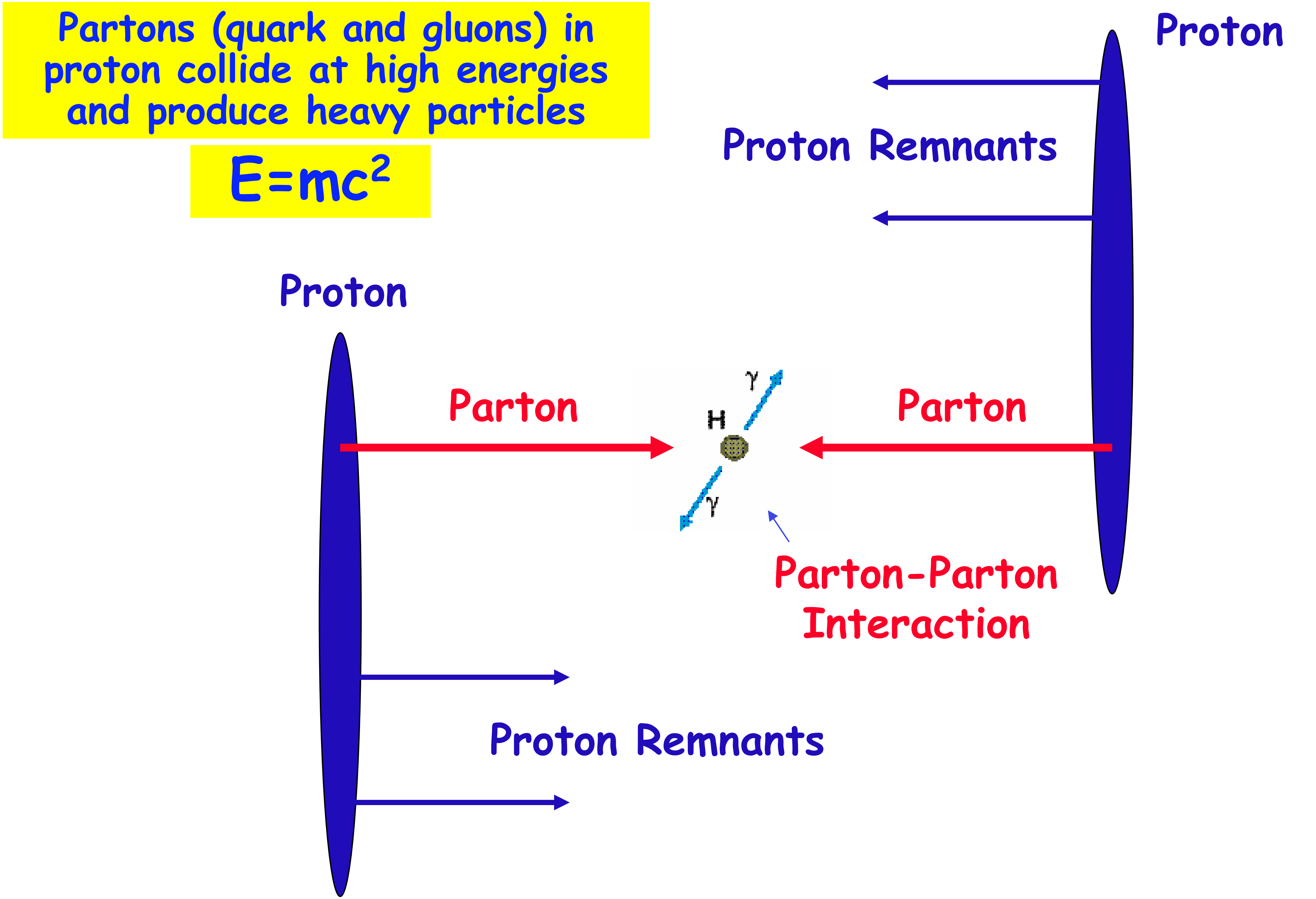


Tape Requirements



ATLAS Physics/Computing

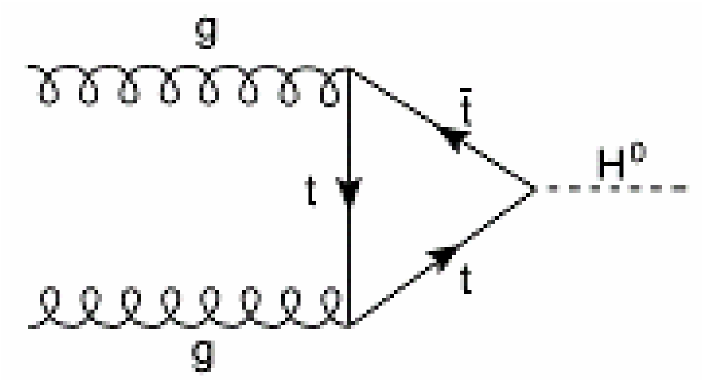




Partons (quark and gluons) in proton collide at high energies and produce heavy particles
$E=mc^2$
Proton
Proton Remnants
Proton
Parton
H
γ
γ
Parton
Parton-Parton Interaction
Proton Remnants

Main Production Mechanisms

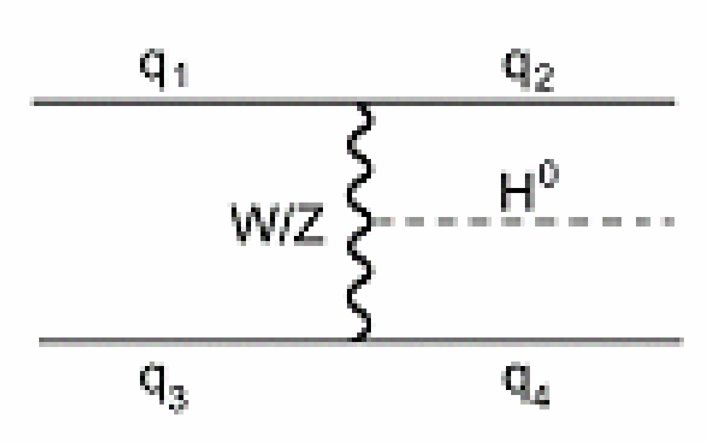
F.Wilczek PRL39 (1977)
H.M.Georgi, S.L.Glashow, M.E.Machacek and D.V.Nanopoulos
PRL40 (1978)



NLO corrections: M.Spira et. al. Nucl.Phys. B453 (1995) 17-82
NNLO corrections: W.Kilgore & R.Harlander,
C.Anastasiou & K.Melnikov
V.Ravindran, J.Smith & W.L. van Neerven

Residual 15-20% uncertainty in NNLO calculation

R.Cahn and S.Dawson
PL 136B 196 (1983)

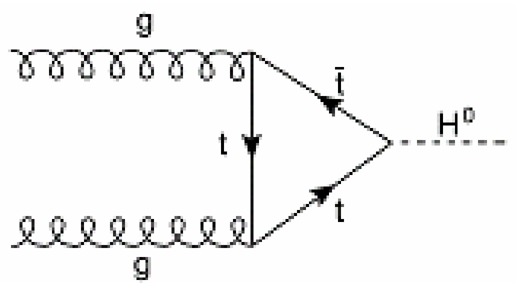


T.Han, G.Valencia, S.Willenbrock PRL69 (1991)
T.Figy, C.Oleari, D.Zeppenfeld PRD68 (2003)

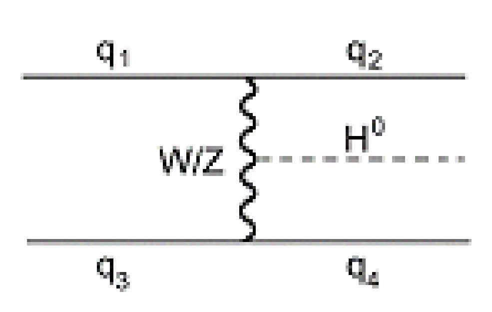
NLO K factor ~1.05÷1.1, small theoretical uncertainty <5%

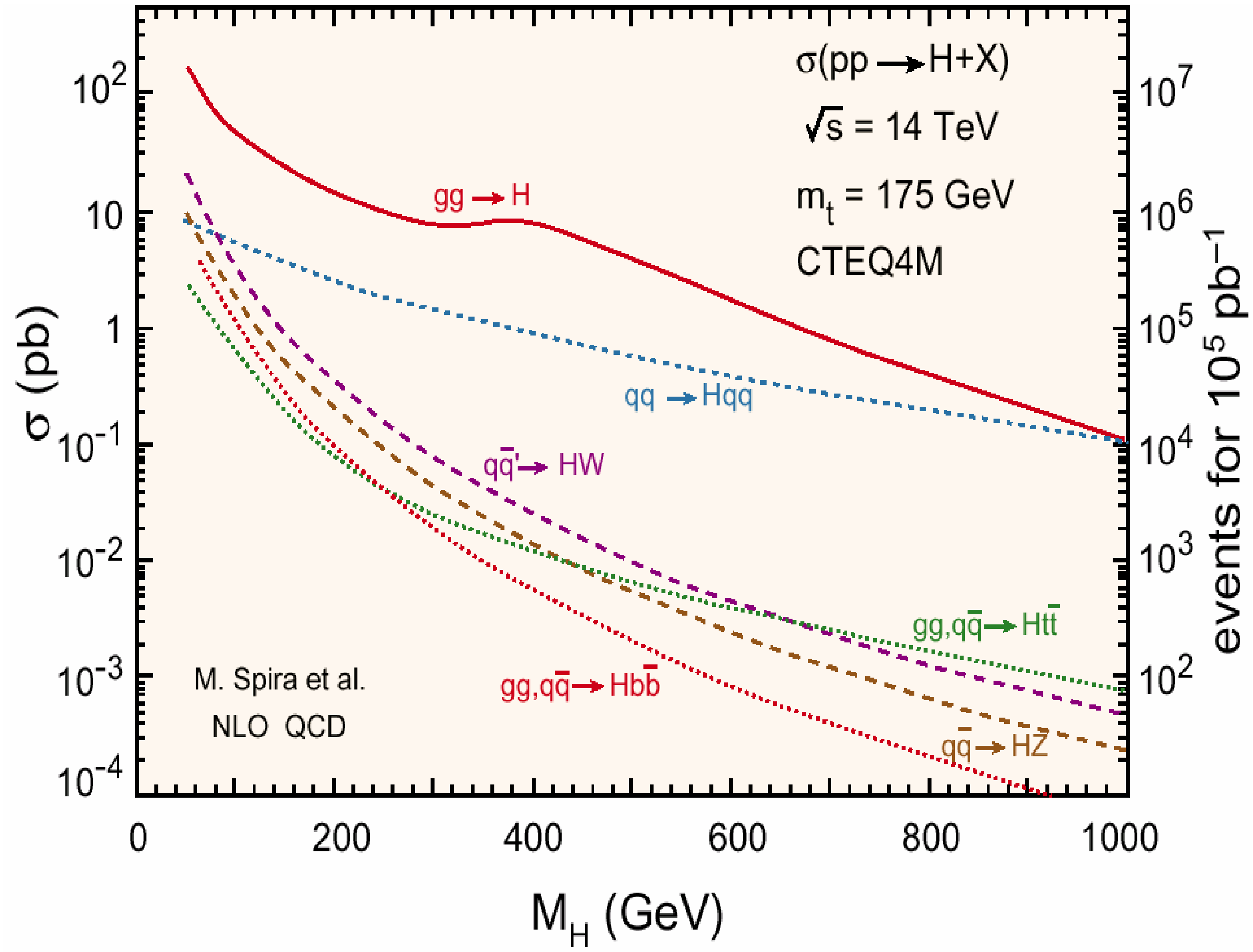
Higgs Production at LHC

Leading Process (gg fusion)



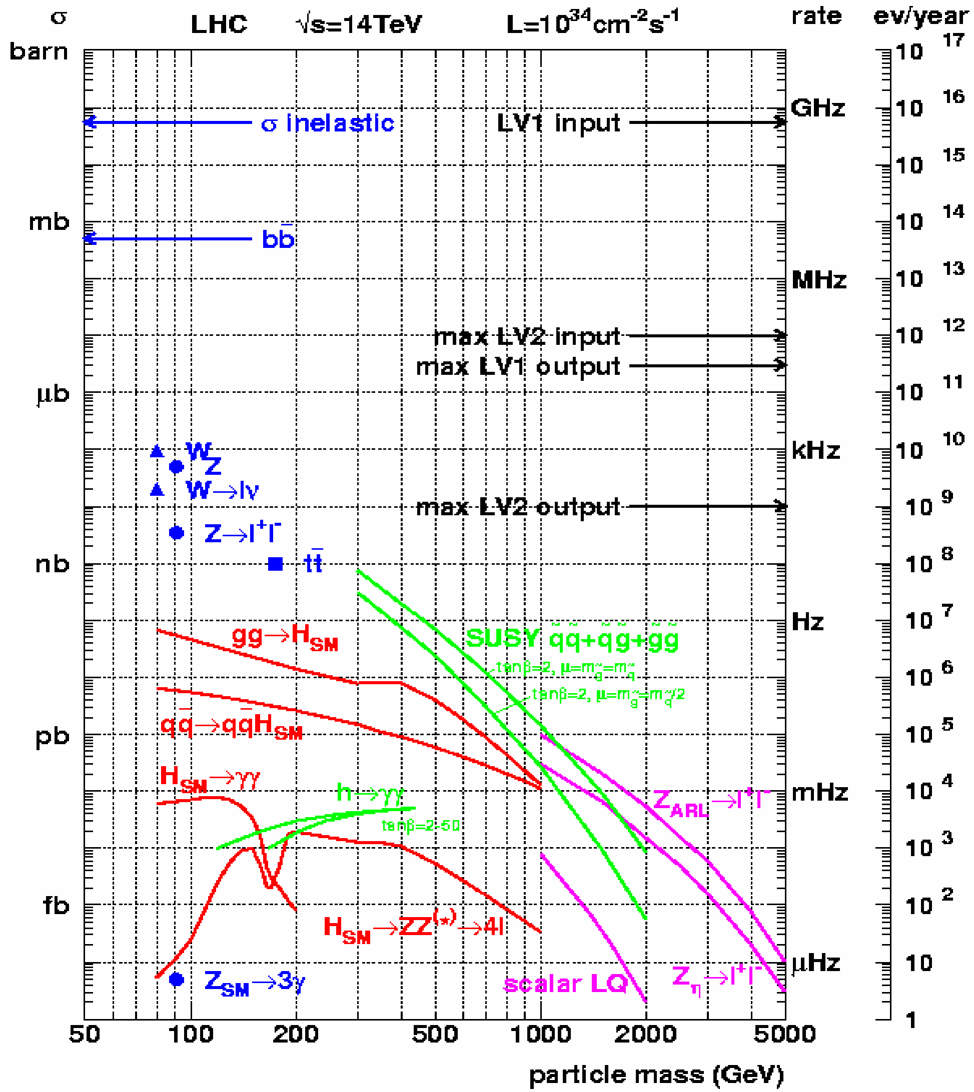
Sub-leading Process (VBF)



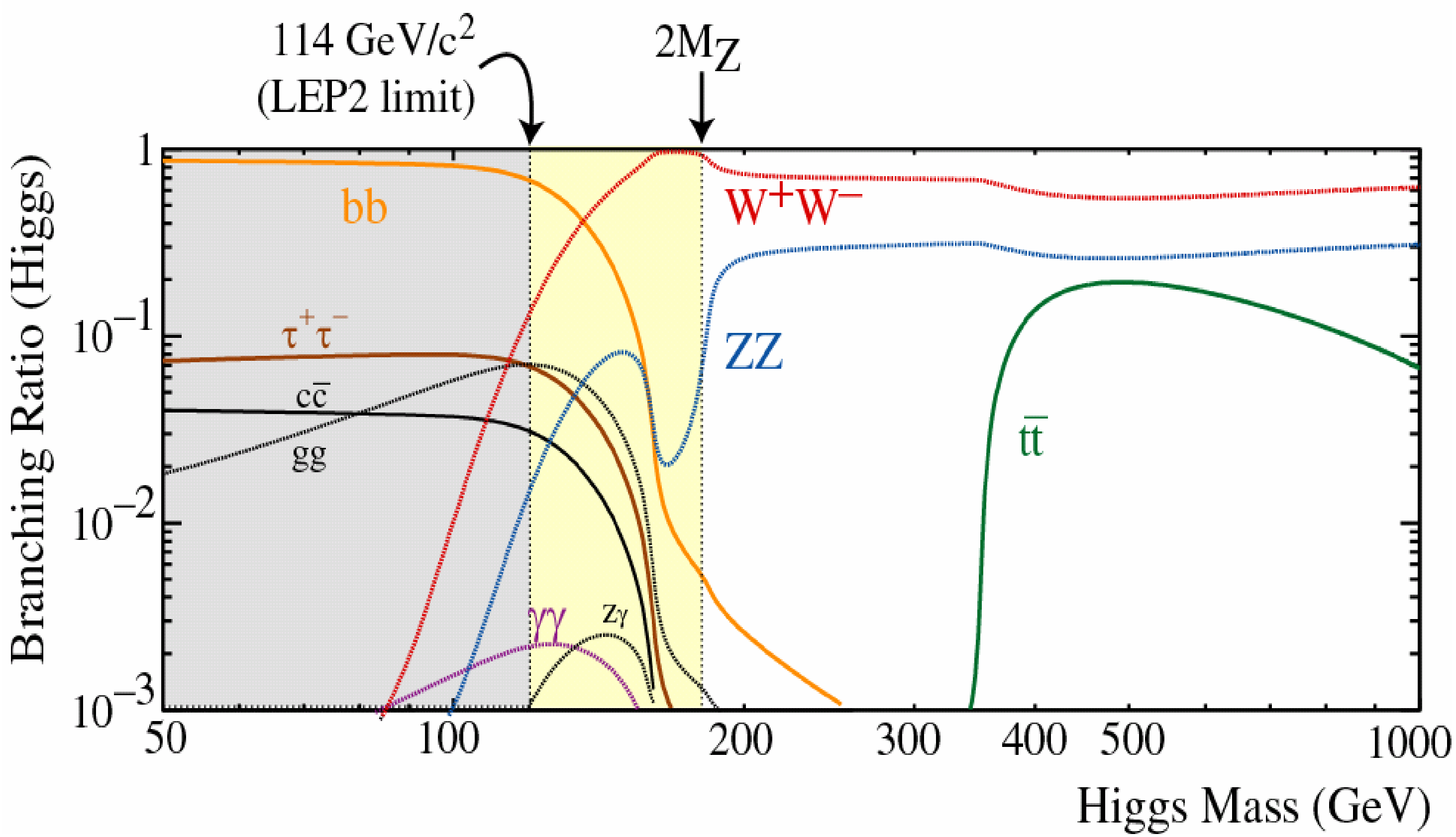


Cross-sections at LHC

- Search for Higgs and new physics hindered by huge background rates
  - Known SM particles produced much more copiously
- This makes low mass Higgs especially <u>challenging</u>
  - Narrow resonances
  - Complex signatures
    - Higgs in association with tops and jets.



Main Decay Modes

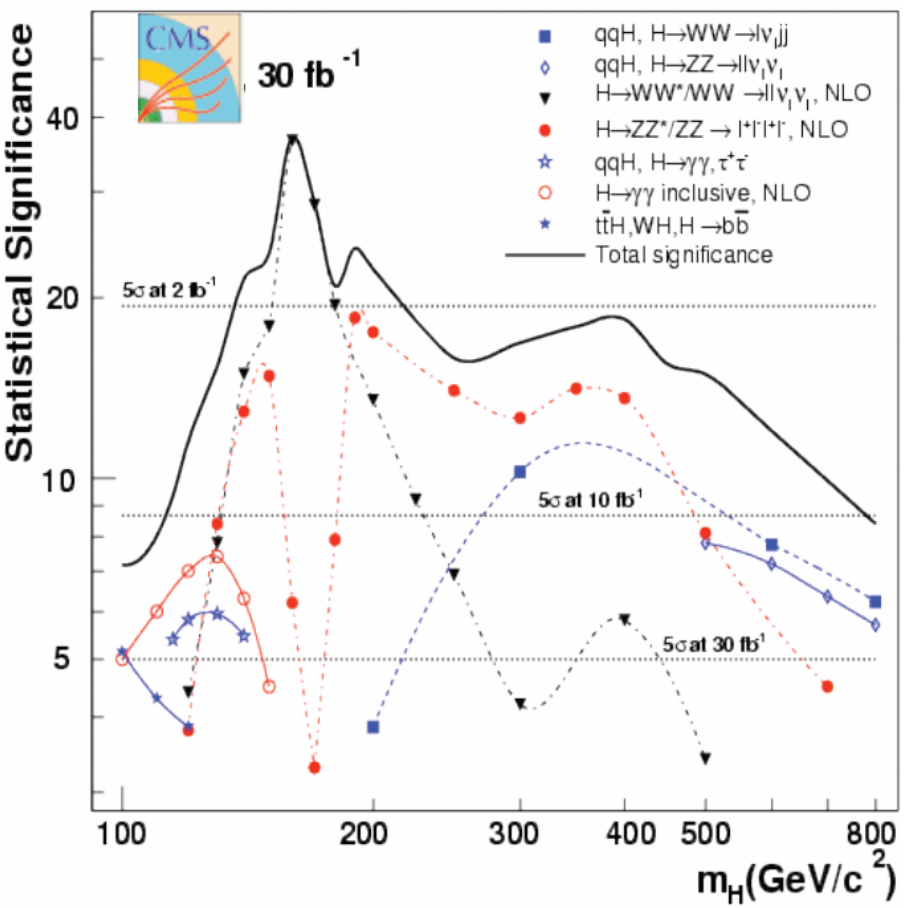


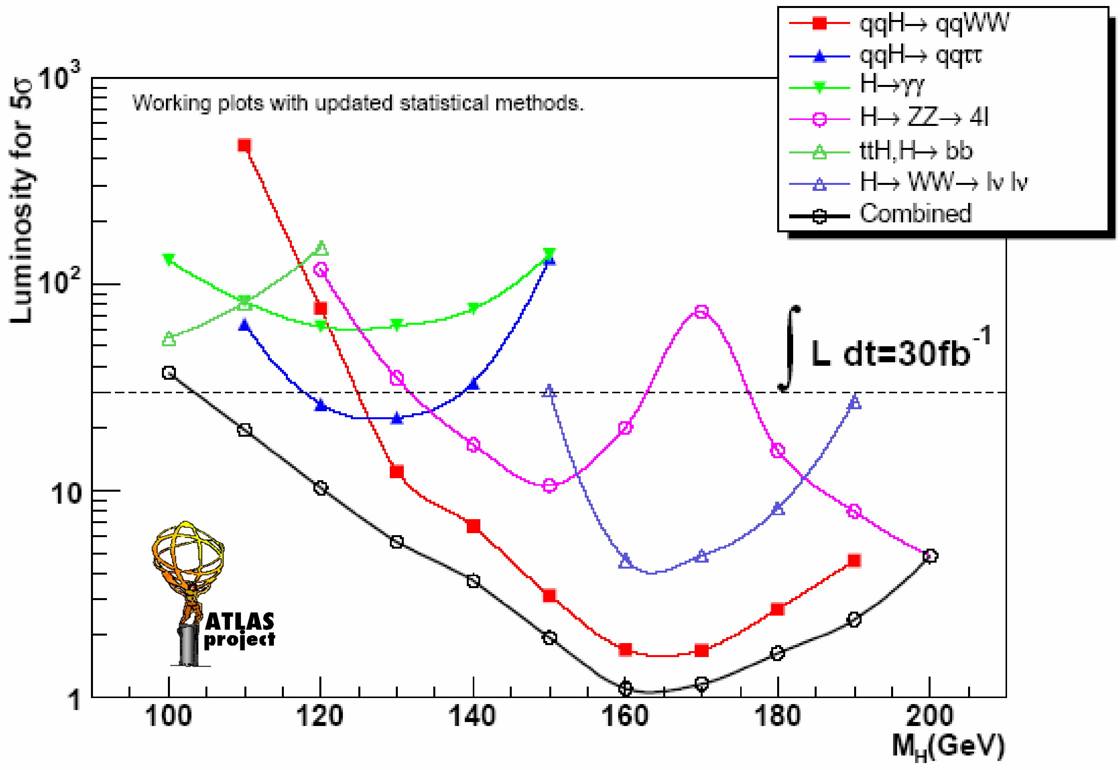
Close to LEP limit:
$H \rightarrow \gamma\gamma, \tau\tau, bb$

For M_H>140 GeV:
$H \rightarrow WW^{(*)}, ZZ^{(*)}$

5σ signal significance (criterion for particle discovery) may be achieved for SM MH>120 GeV and in most of the MSSM for 10 fb^{-1} (understood data)

- Improvements and new final states with $H\rightarrow\gamma\gamma,\tau\tau$, WW(*) not included
- Caveat: Higgs feasibility assumes nominal detector performance and present understanding of cross-sections

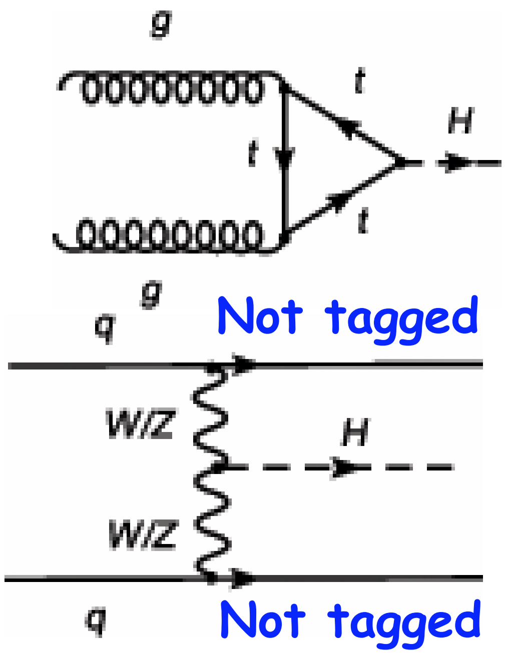




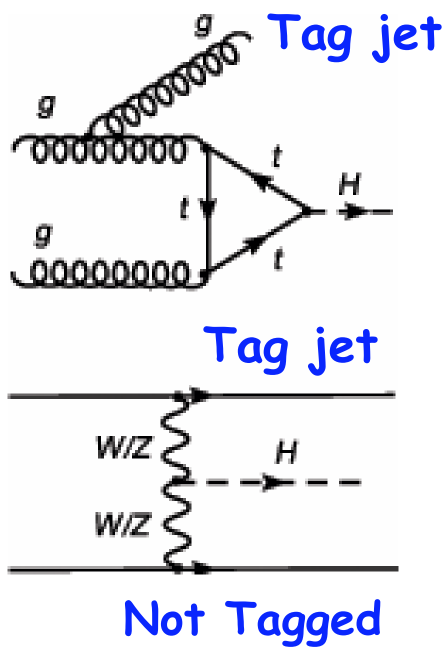
Low Mass Higgs Associated with Jets

- Slicing phase space in regions with different S/B seems more optimal when inclusive analysis has little S/B

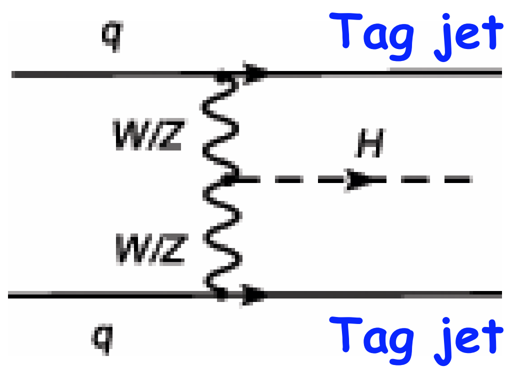
Inclusive

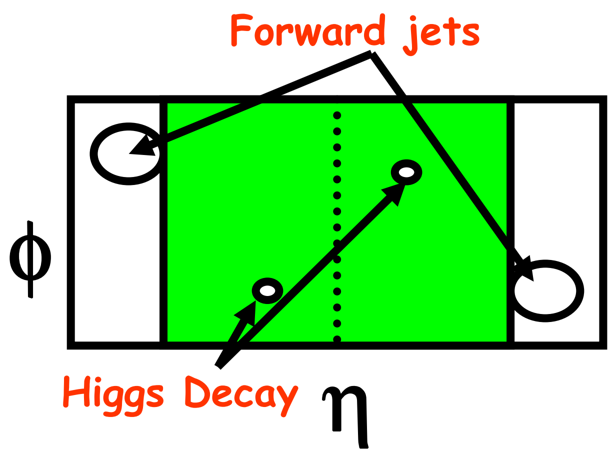


H+1jet



H+2jet



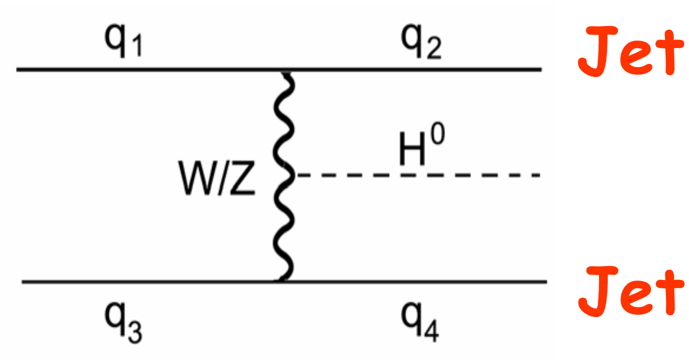


Applied to $H \rightarrow \gamma\gamma, \tau\tau, WW^{(*)}$

Analyses in TDR were mostly inclusive

SM Higgs + ≥2jets at the LHC

- D.Zeppenfeld, D.Rainwater, et al. proposed to search for a Low Mass Higgs in association with two jets with jet veto
  - Central jet veto initially suggested in V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)

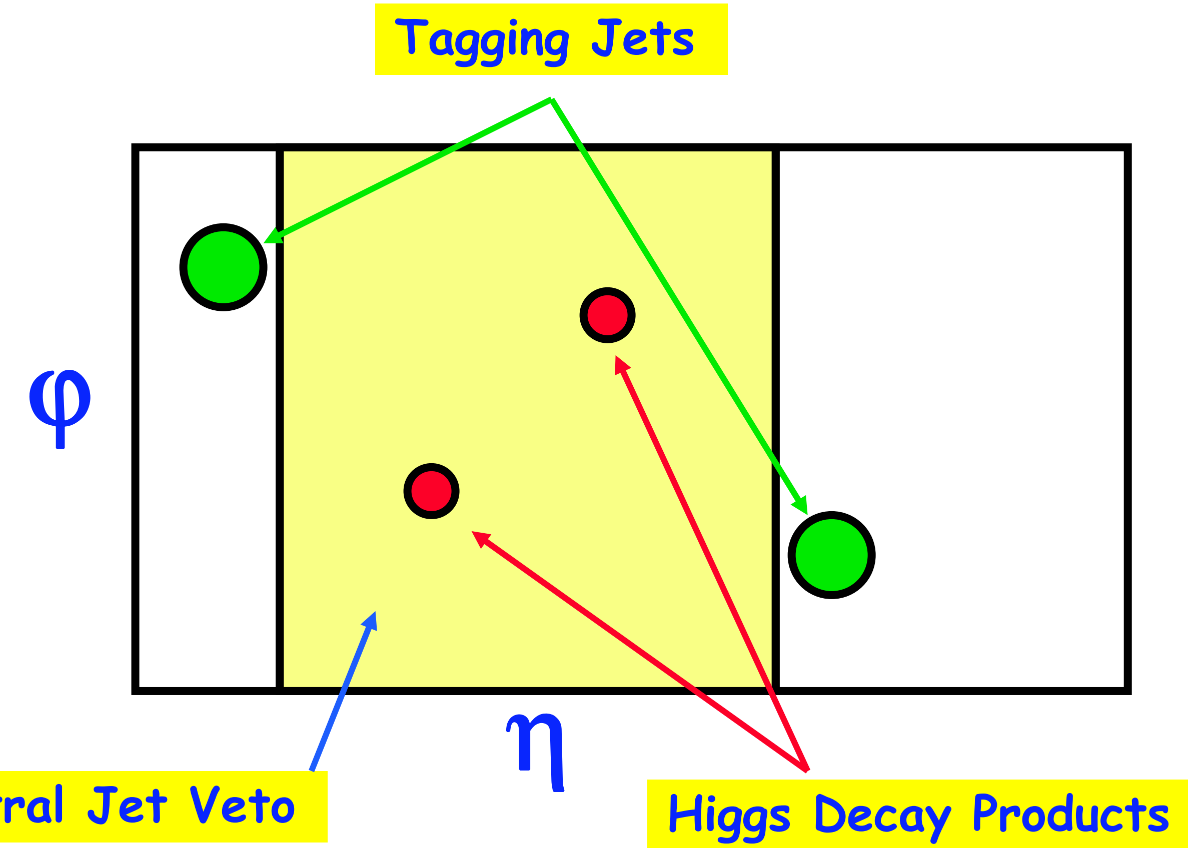


$\eta_{J1} \cdot \eta_{J2} < 0$

$\Delta\eta_{JJ} > 3.5 \div 4$

$M_{JJ} > 500 \div 700\,\mathrm{GeV}$

c.j.v.

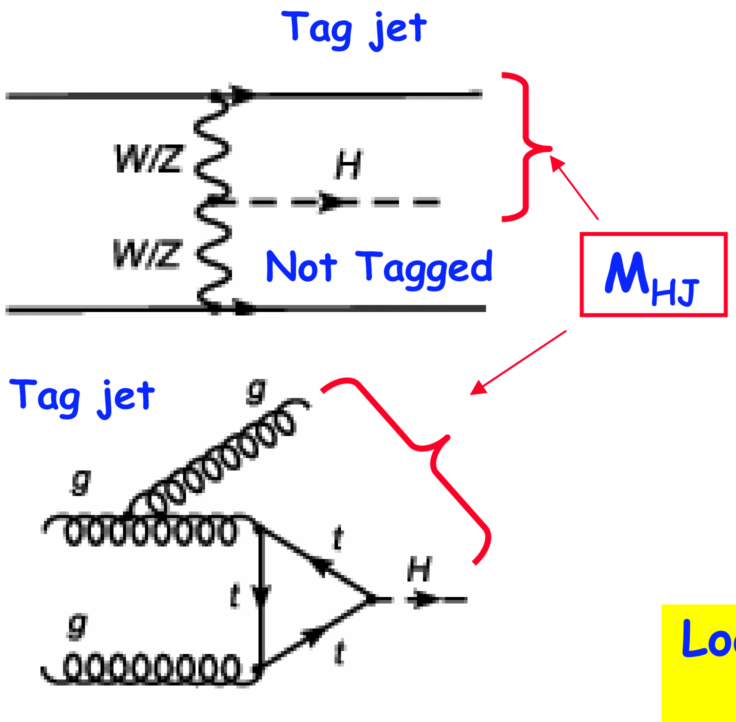


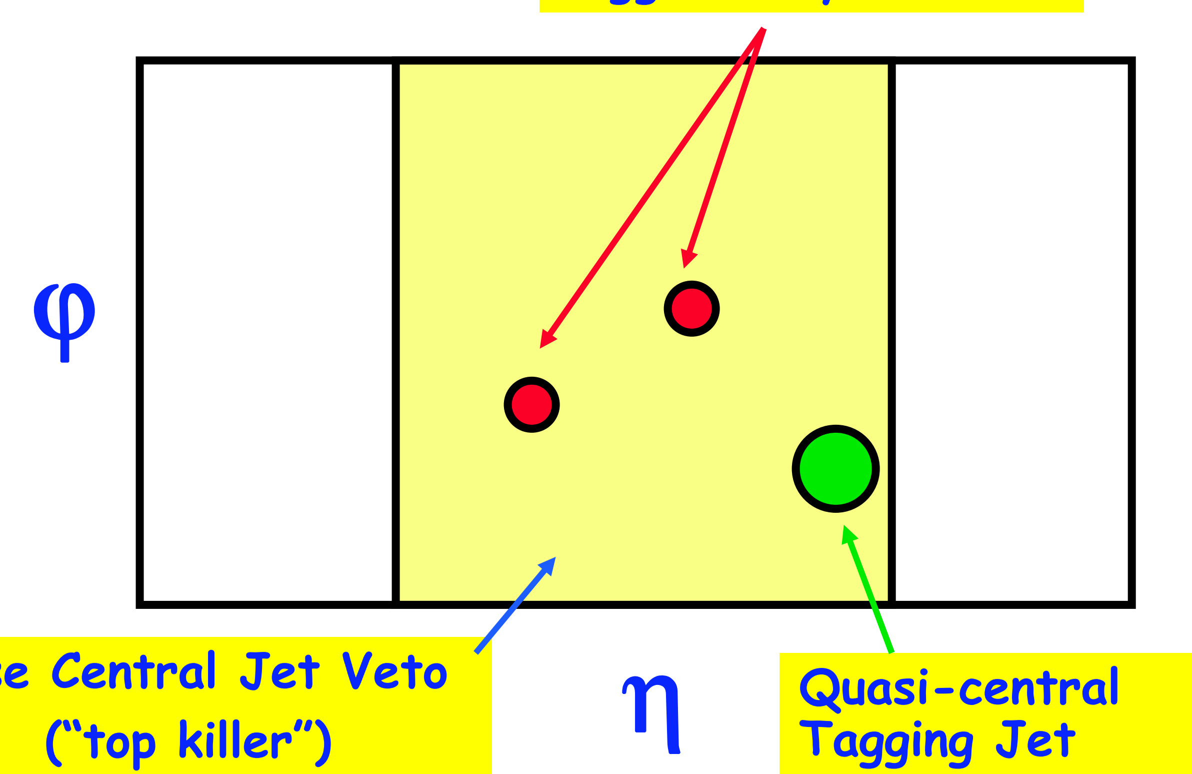
SM Higgs + ≥1jet at the LHC

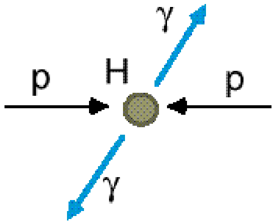
1. Large invariant mass of leading jet and Higgs candidate
2. Large P_T of Higgs candidate
3. Leading jet is more forward than in QCD background

S.Abdullin et al PL B431 (1998) for $H\to\gamma\gamma$

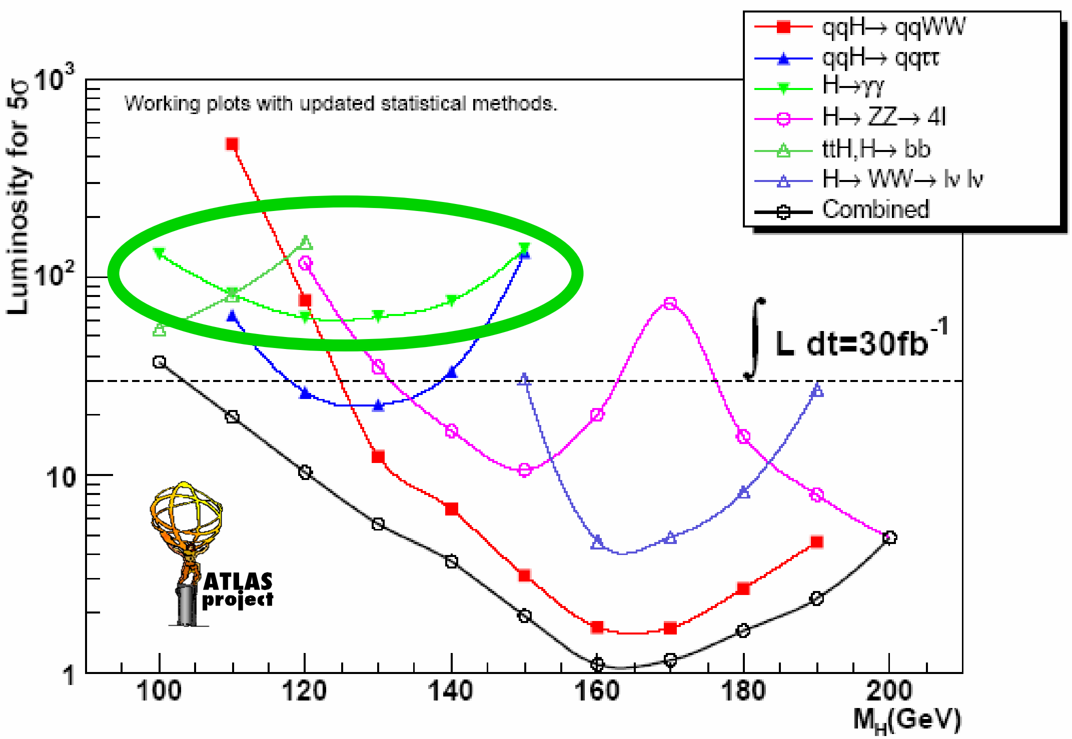
B.Mellado, W.Quayle and Sau Lan Wu Phys.Lett.B611:60-65,2005 for $H\to\tau\tau$ and $H\to WW(*)$

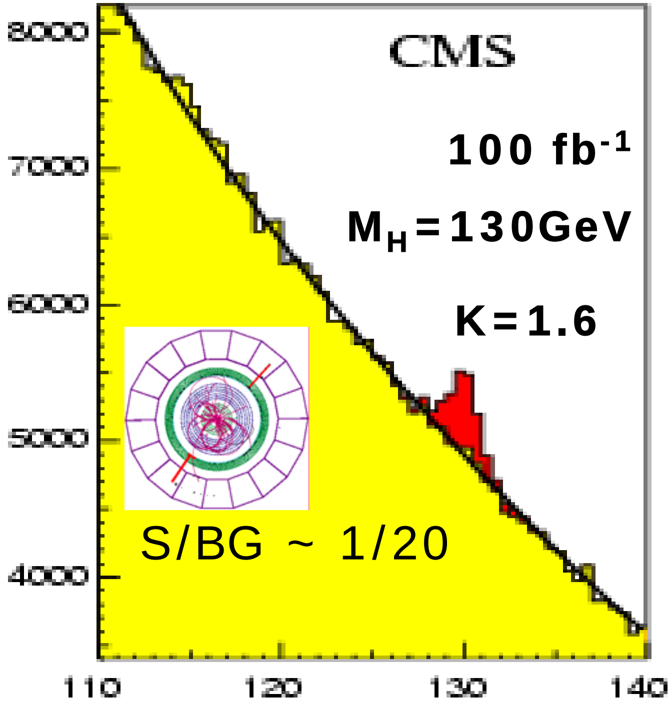


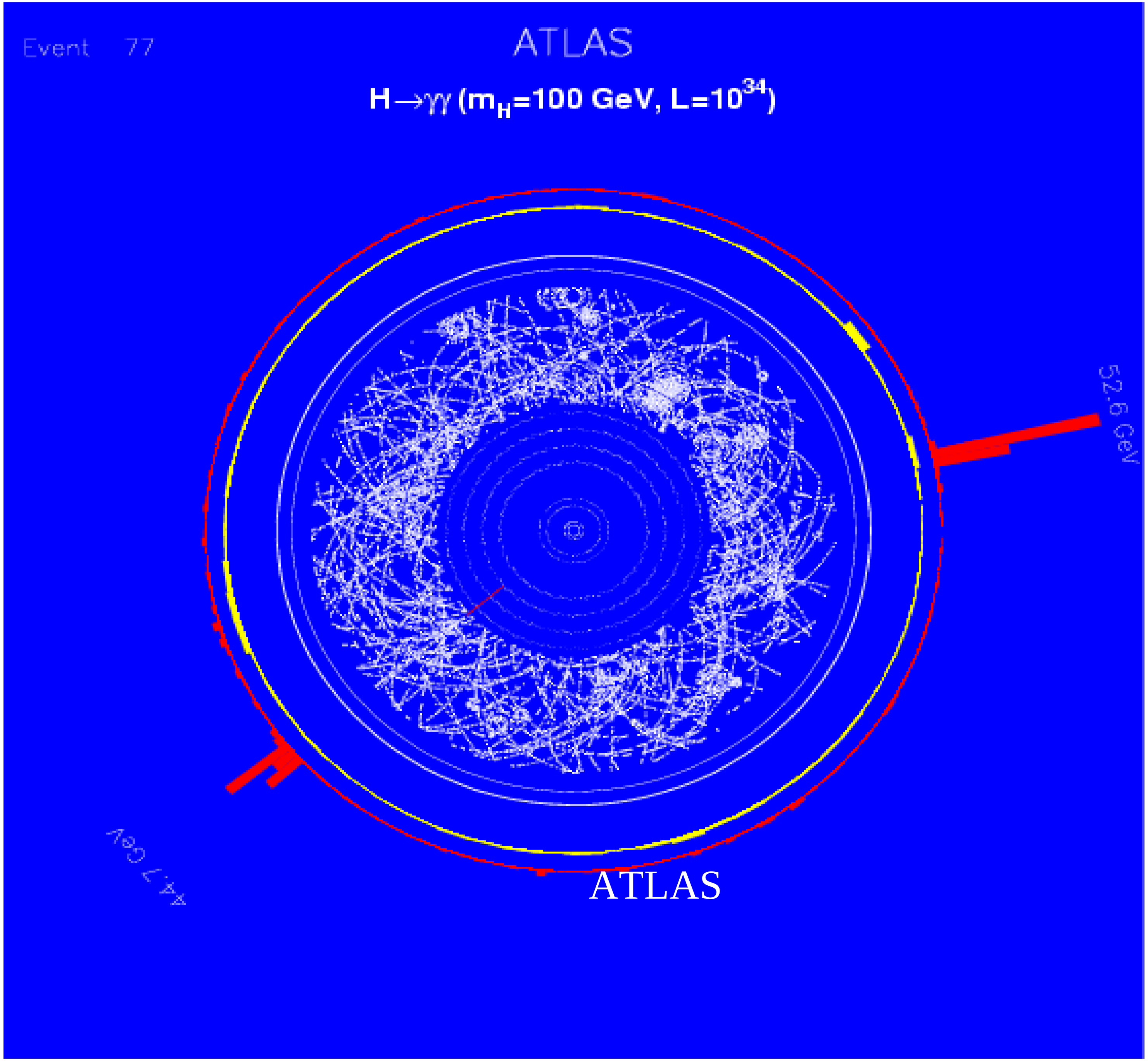




Low Mass SM Higgs: H→γγ



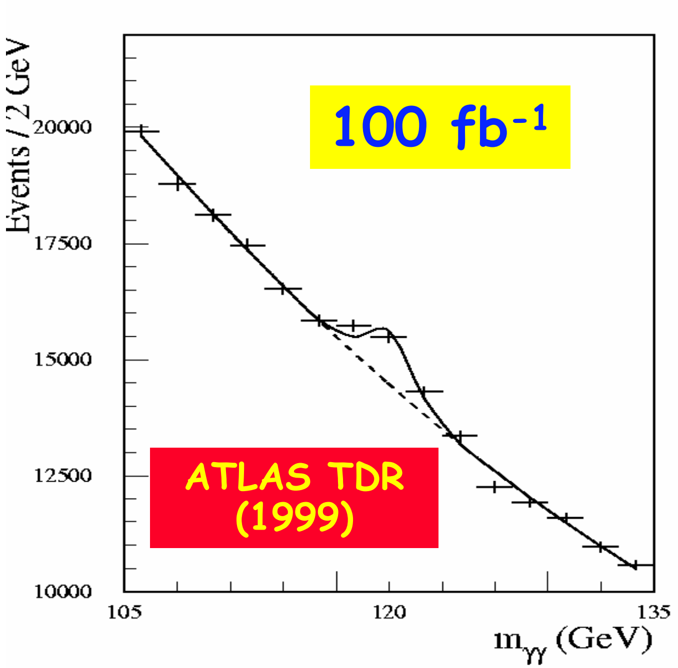



Event 77
ATLAS
H→γγ (m_H=100 GeV, L=10^34)
52.6 GeV
44.7 GeV
ATLAS

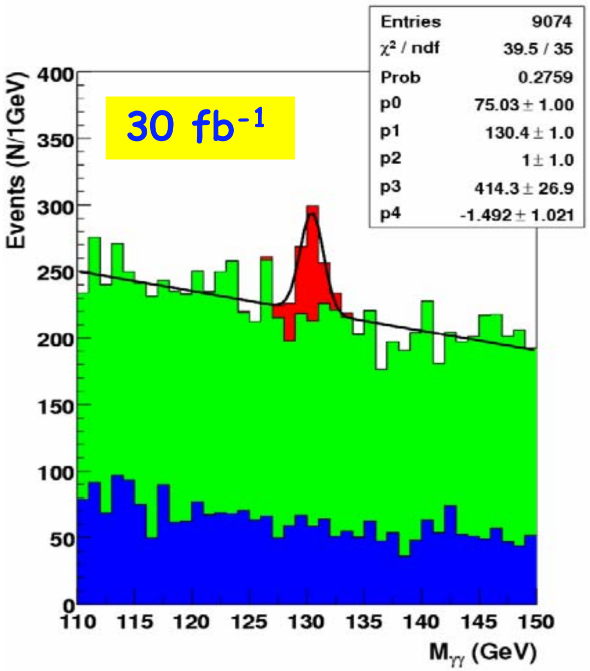
SM Higgs→γγ + 0,1,2 Jets

- Narrow peak on top of smooth background. Issues related H→γγ decay mode have been thoroughly addressed in CMS and ATLAS
  - Separation of events according to jet multiplicity maximizes sensitivity
  - But H→γγ +jets feasibility are subject to larger theoretical errors

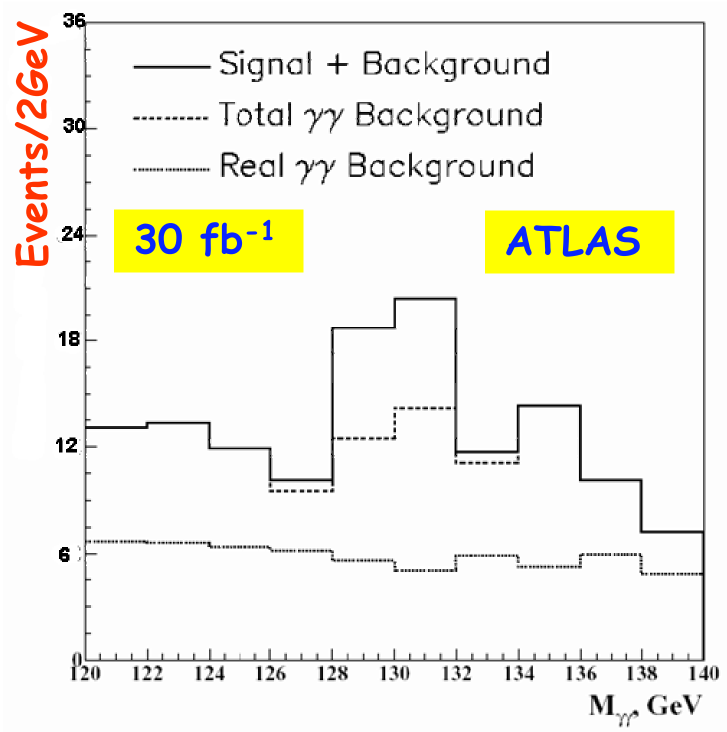
H(→γγ) Inclusive



H(→γγ) + 1 jet



H(→γγ) + 2 jets

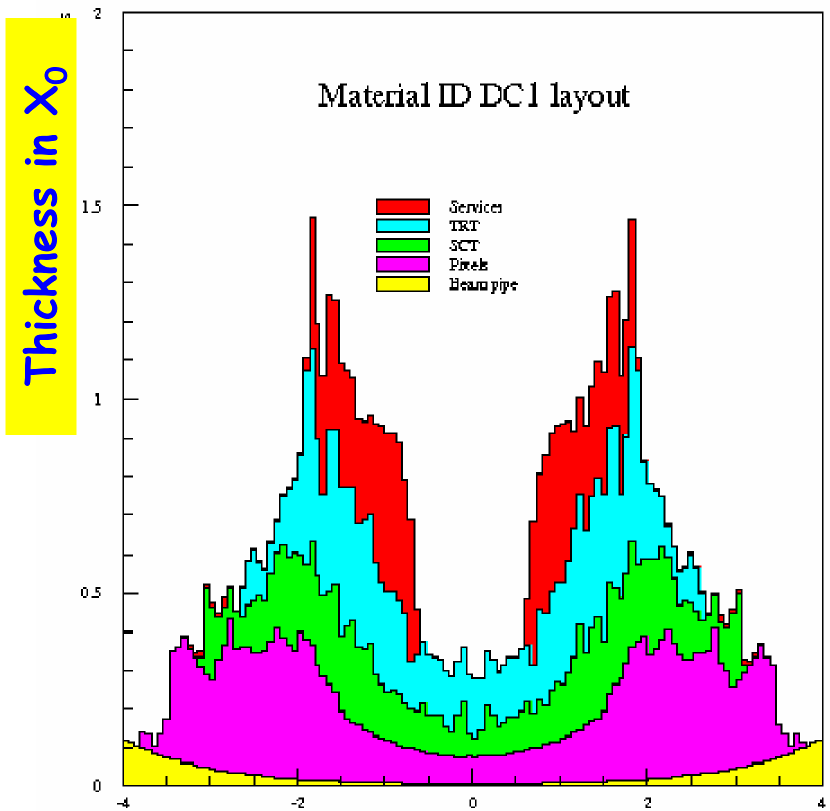


Calorimeter energy resolution

$$\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c_{tot}$$

- Signal to background for inclusive $H \rightarrow \gamma\gamma$ is 3-4% need excellent Higgs mass resolution of about 1%
- Constant term in EM resolution needs to be understood to $c_{tot} < 0.7\%$
  - Use cosmics, minimum-bias for first crude look at cell inter-calibration
  - Use $Z \rightarrow ee$ for absolute EM scale and refined cell inter-calibration
    - Need $O(10^5)$ events or $< 1\ fb^{-1}$
  - Use $Z \rightarrow ee\gamma, \mu\mu\gamma$ to study detector response to photons

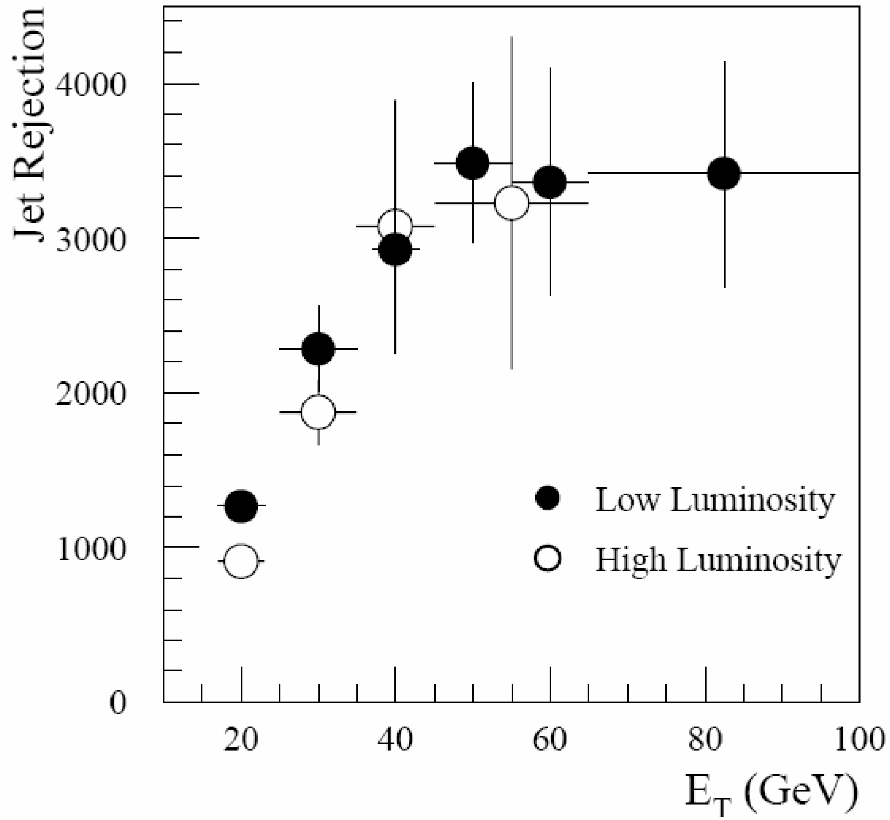
Passive material in front of the ATLAS calorimeters (in radiation lengths)



η (polar angle)

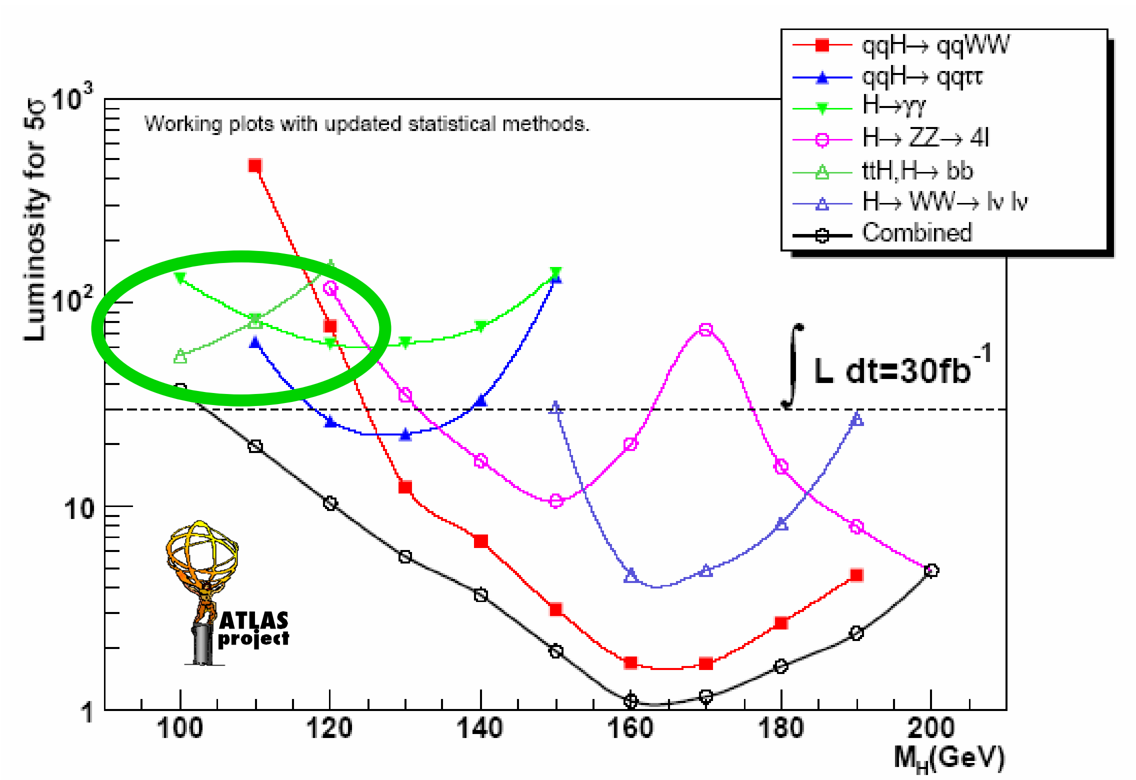
Photon Identification

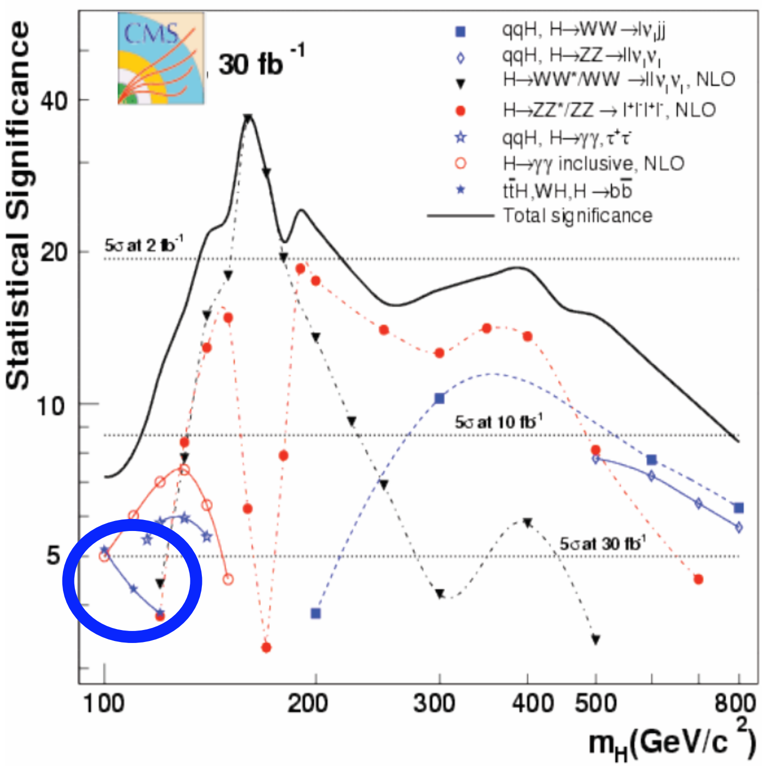
- To separate jets from photons is crucial for Higgs discovery
  - Need rejection of > 1000 against quark-initiated jets for ε_γ=80% to keep fake background about 20% of total background
  - Expect rejection against gluon-jets to be 4-5 times greater
- Jet rejection will be evaluated with data
  - Look into sub-leading jets in multi-jet final states with different P_T thresholds
    - Avoid trigger bias
    - Apply trigger pre-scaling if needed
    - Correct for contribution from prompt photons



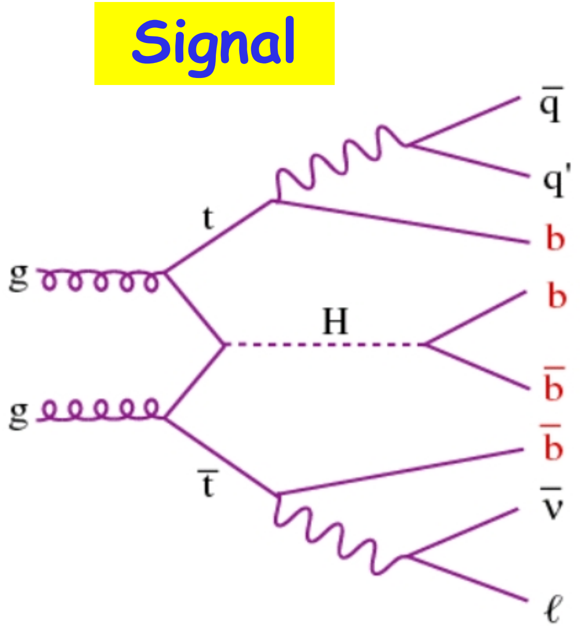
ATLAS TDR (1999)

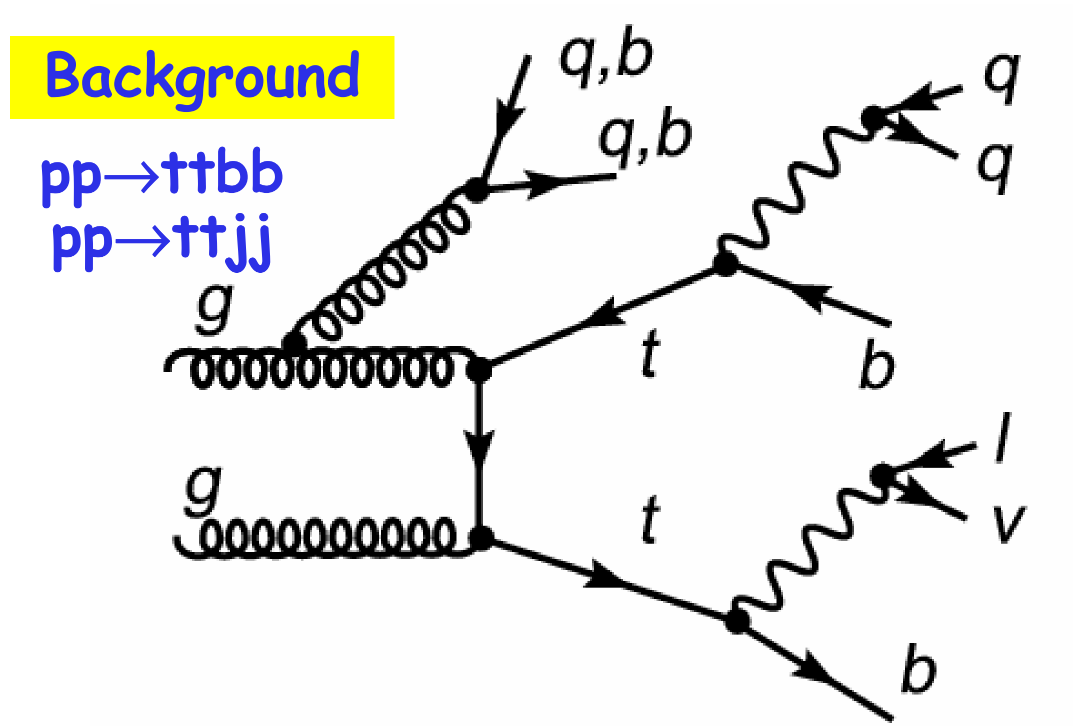
Low Mass SM Higgs: ttH→bb





Complex final state: ttH(→bb)→lepton+ν+bbbb+jj



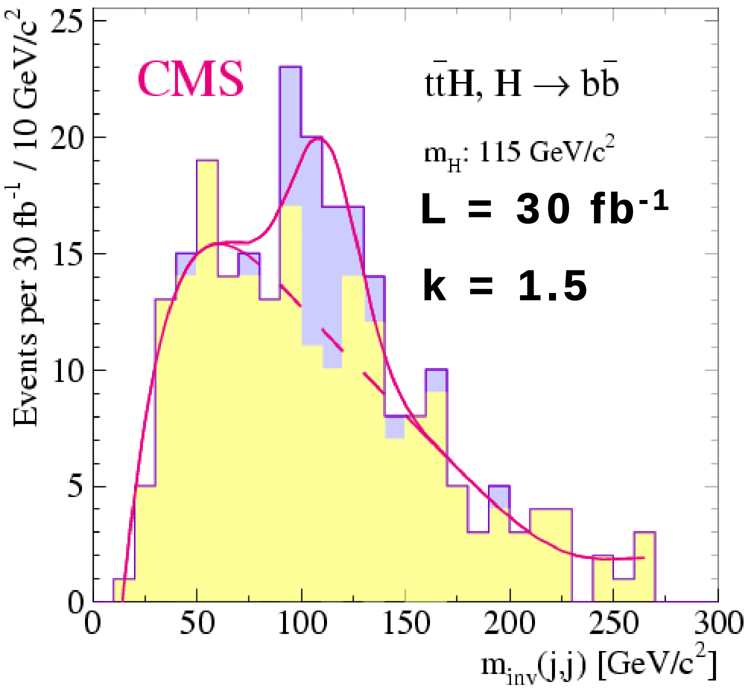


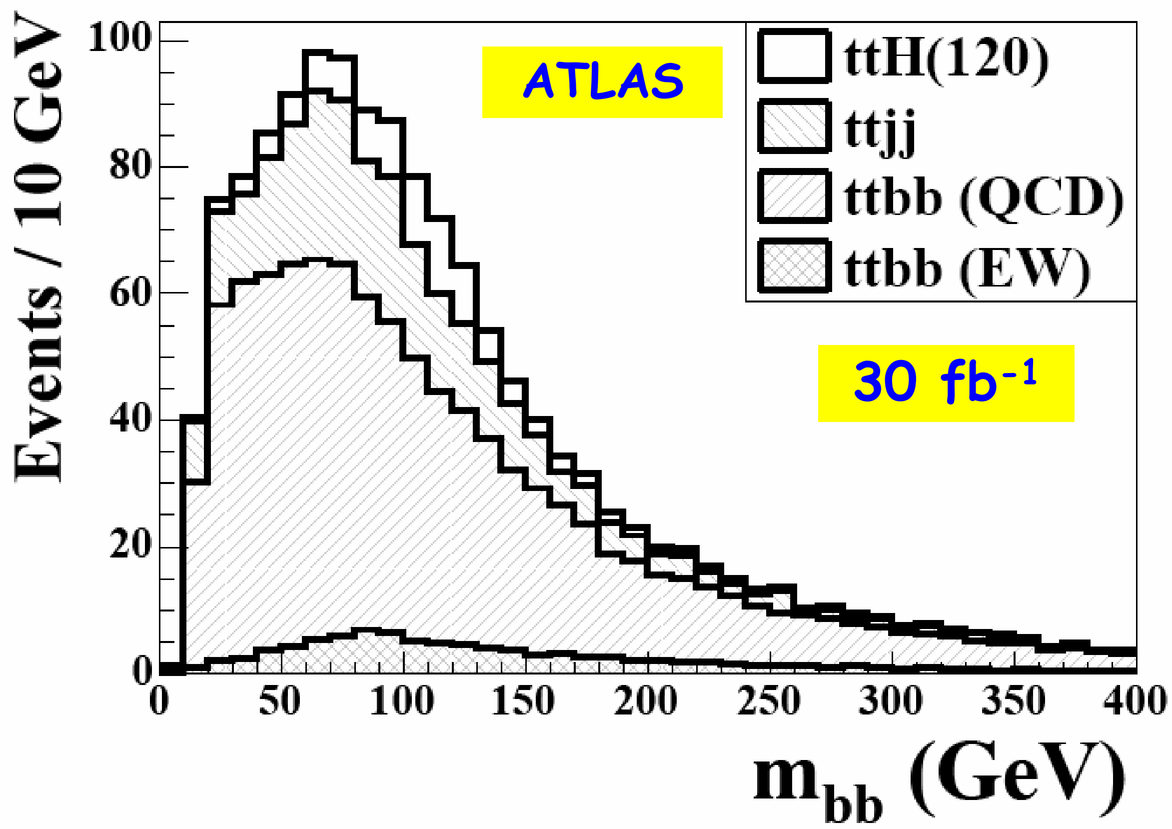
- Analysis very sensitive to b-tagging efficiency (ε_b^4)
  - Parton/Hadron level studies → $\varepsilon_b \geq 60\%$ needed
- Need ~100 times rejection against light jets and ~10 times against charm to suppress ttjj

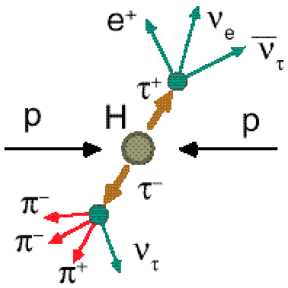
May achieve 3-5σ effect for M_H=120 GeV and 30 fb^{-1}

- Need to address issues related to background shapes and differences in hadronic scales for light and b-jets
- CMS and ATLAS have some differences in analysis
  - ATLAS LO for signal and ME for ttbb

σ_M ~ 15 GeV

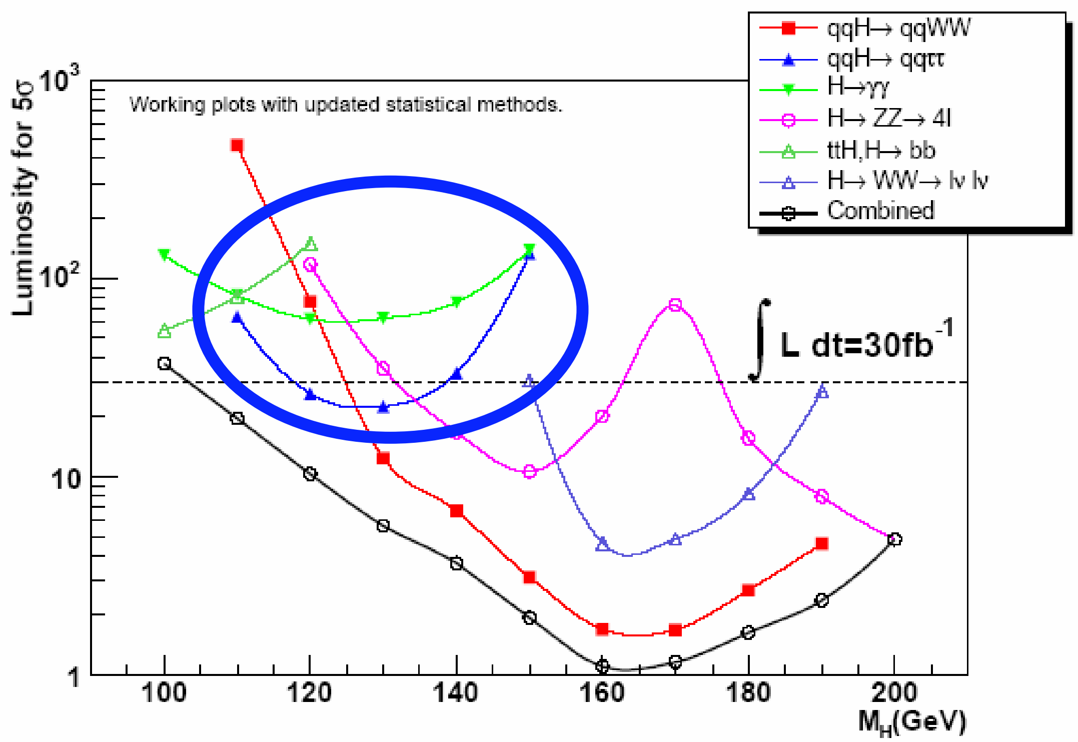




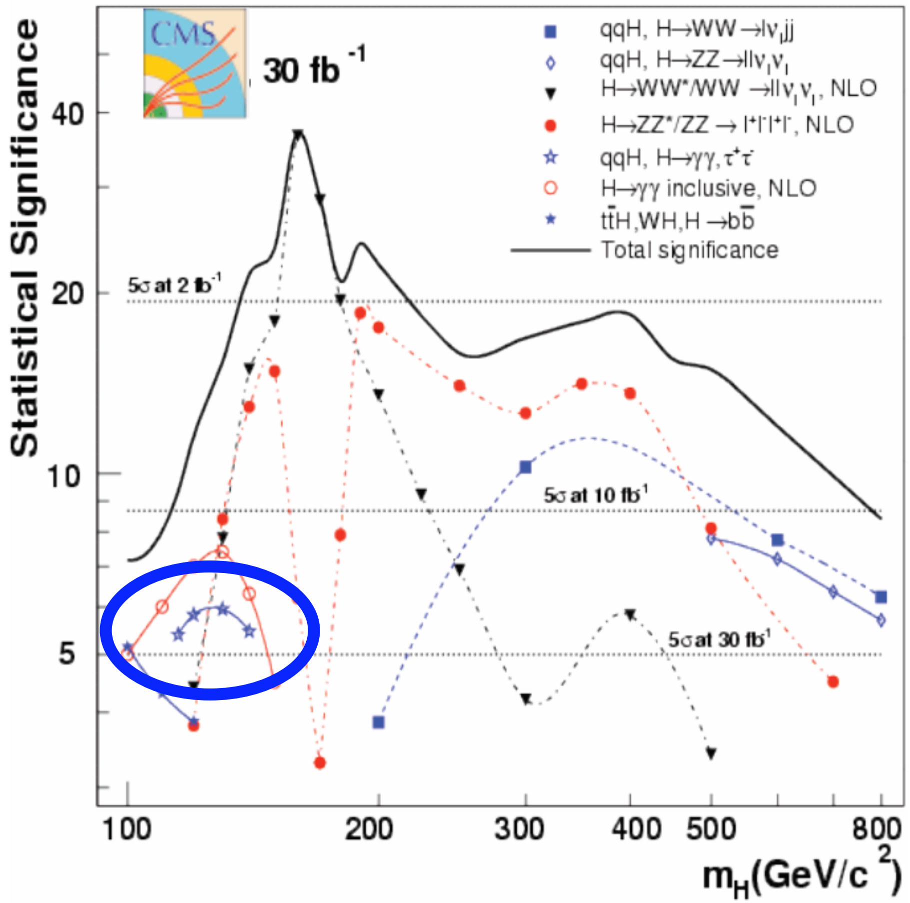


e+
νe
ντ
τ+
p
H
p
τ−
π−
π−
π+
ντ

SM H→ττ



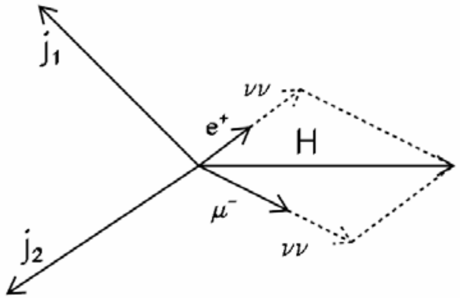
Luminosity for 5σ
Working plots with updated statistical methods.
qqH→ qqWW
qqH→ qqττ
H→γγ
H→ ZZ→ 4l
ttH,H→ bb
H→ WW→ lν lν
Combined
∫ L dt=30fb-1
M_H(GeV)



Statistical Significance
30 fb-1
qqH, H→WW→lνjj
qqH, H→ZZ→llνν
H→WW*/WW →lνlν, NLO
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ,τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
m_H(GeV/c²)

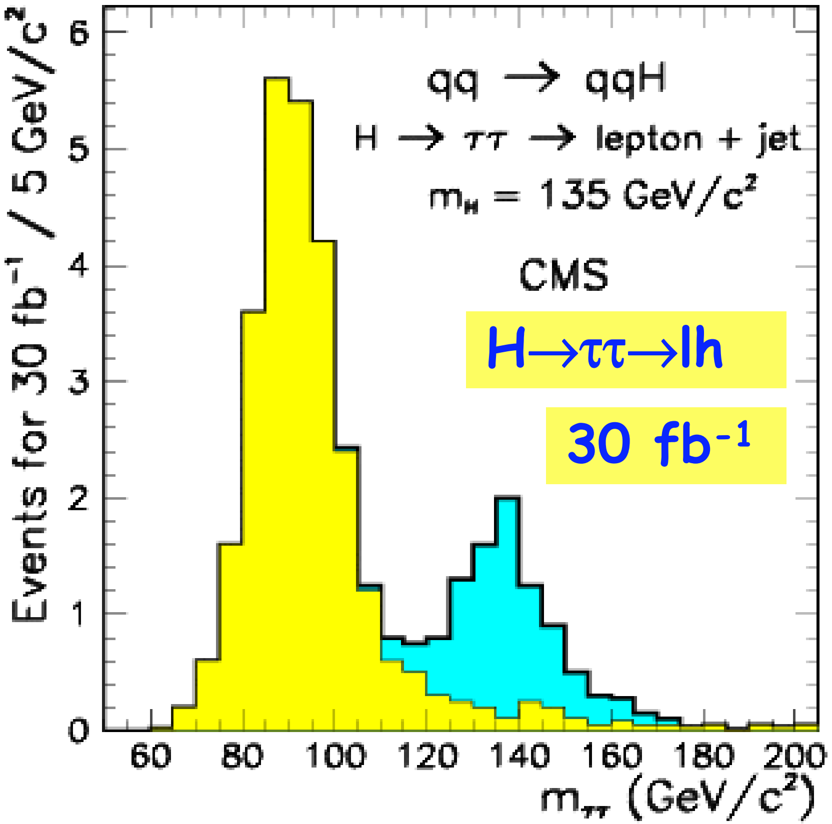
Low Mass SM H→ττ+jets

- Reconstruct Higgs mass with collinear approxim

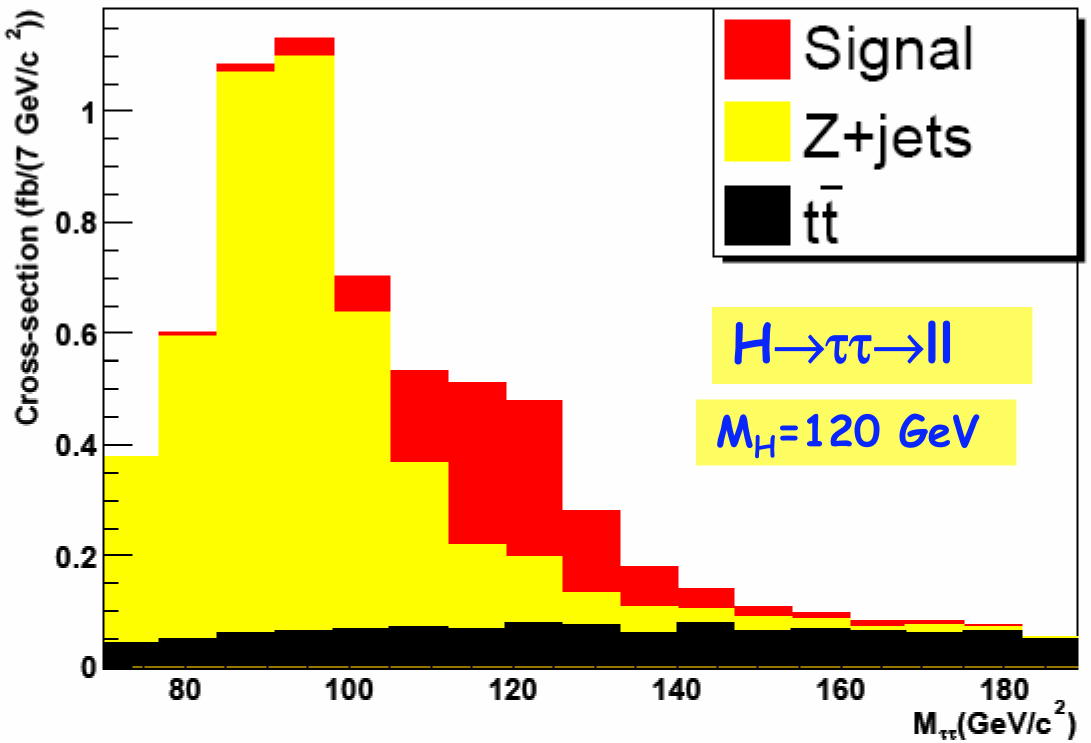


H(→ττ→lh) +≥2jets (VBF)

H(→ττ→2l) +≥1jet

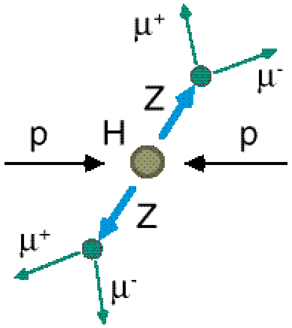


B.Mellado, W.Quayle and Sau Lan Wu
Phys.Lett.B611:60-65,2005

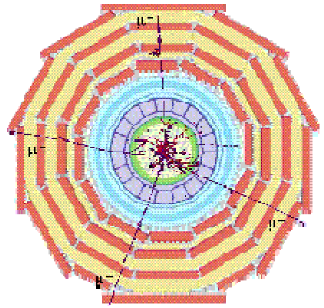


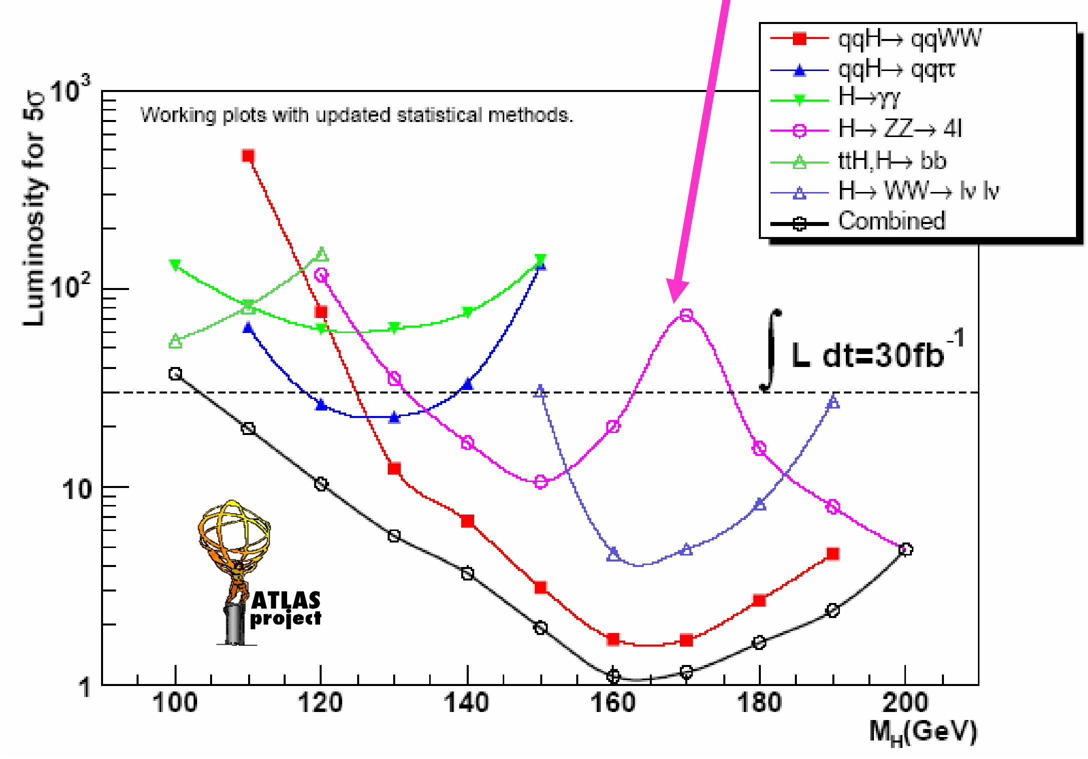
Main Detector Requirements (ATLAS)

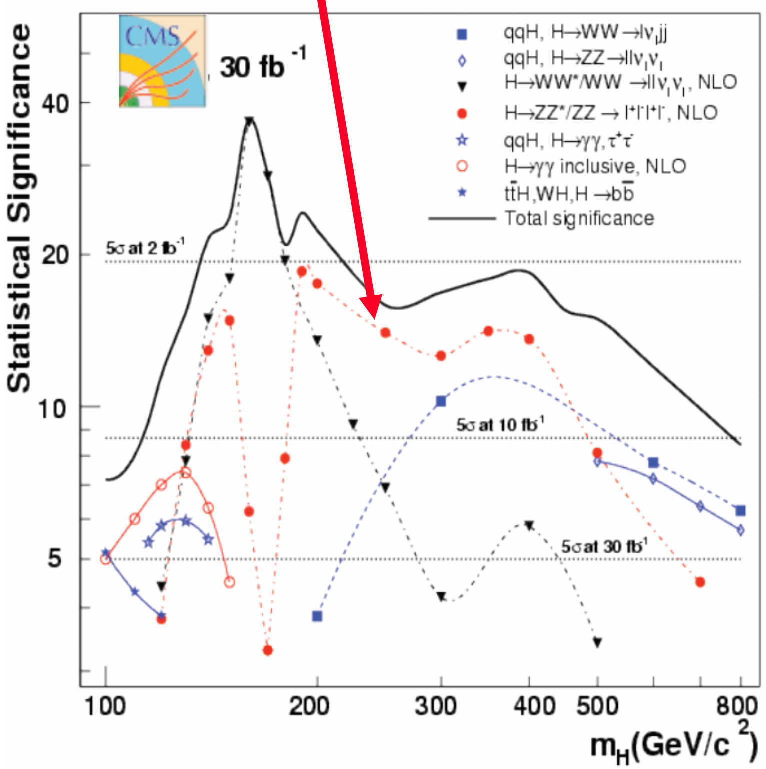
- Missing E_T reconstruction is a challenge (even with MC!)
- Missing E_T is crucial to reconstruct Higgs mass
  - Require mass resolution of <10%
  - Hadronic calibration with data: combination of
    - Minimum bias (low P_T depositions)
    - di-jets, $Z \rightarrow ll$+jets (γ-jet) events, $W \rightarrow \tau\nu$ for high P_T depositions.
    - Enough data with 1 fb^{-1} to cover necessary phase space to calibrate detector for Higgs discovery
- In order to suppress fake leptons (QCD background) to a level <10% of the irreducible background we need to achieve combined 10^7 rejection with lepton ID
  - May be achieved for $H \rightarrow \tau\tau \rightarrow ll$ ($l = e, \mu$)
    - May achieve >10^4 per lepton
  - Checking TDR QCD rejection estimates for $H \rightarrow \tau\tau \rightarrow lh$



SM Higgs: $H \to ZZ^{(*)} \to 4l$

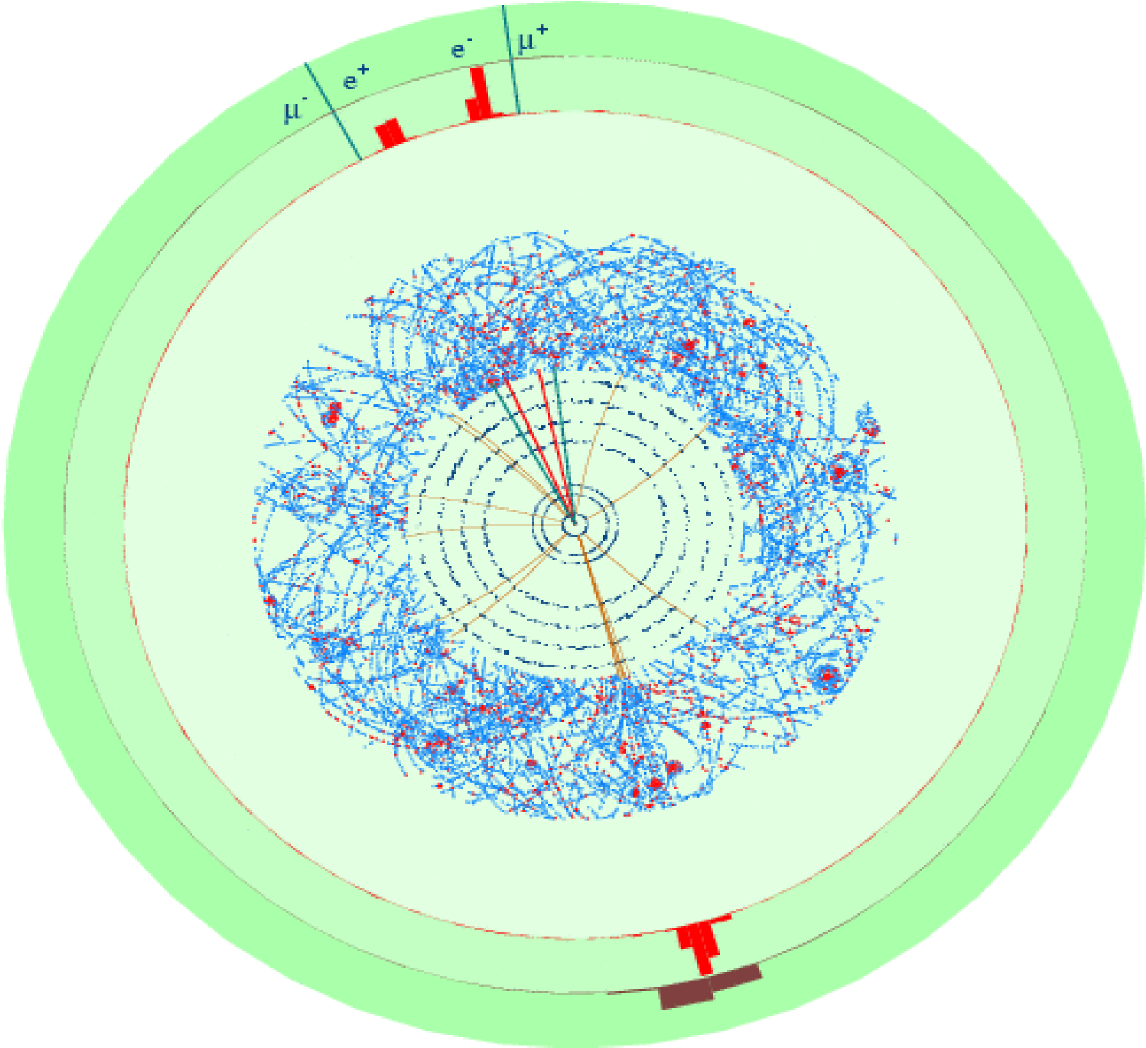






ATLAS barrel

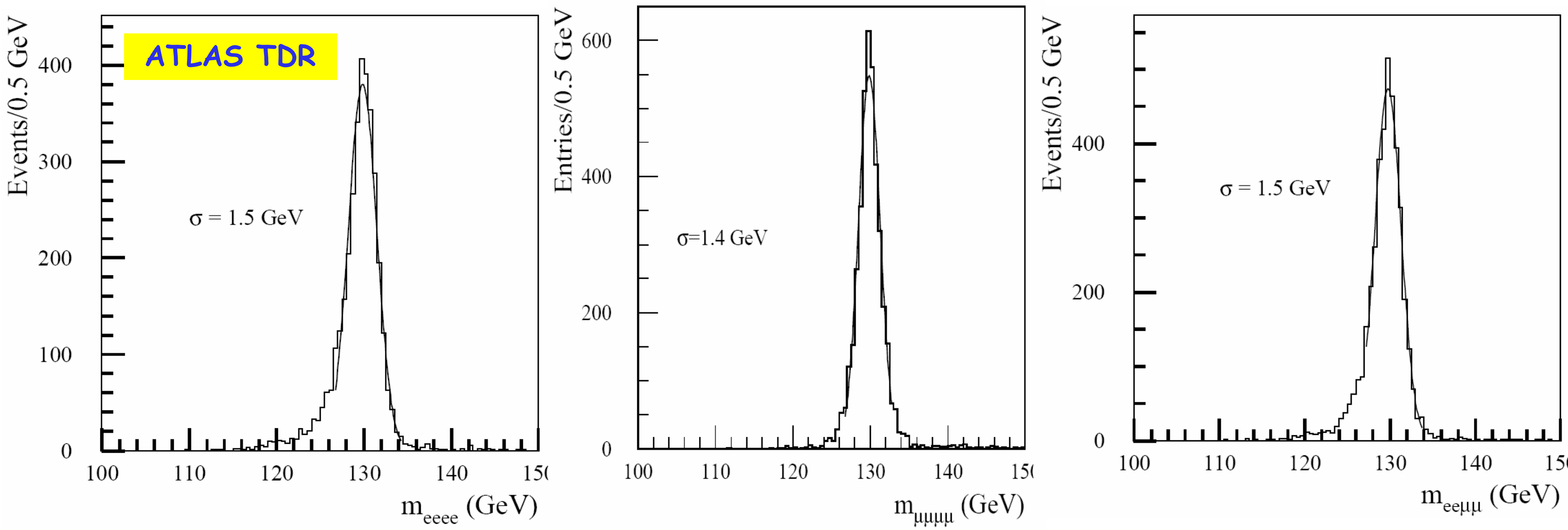
$H \rightarrow ZZ^{*} \rightarrow ee\mu\mu$ (m_H = 130 GeV)

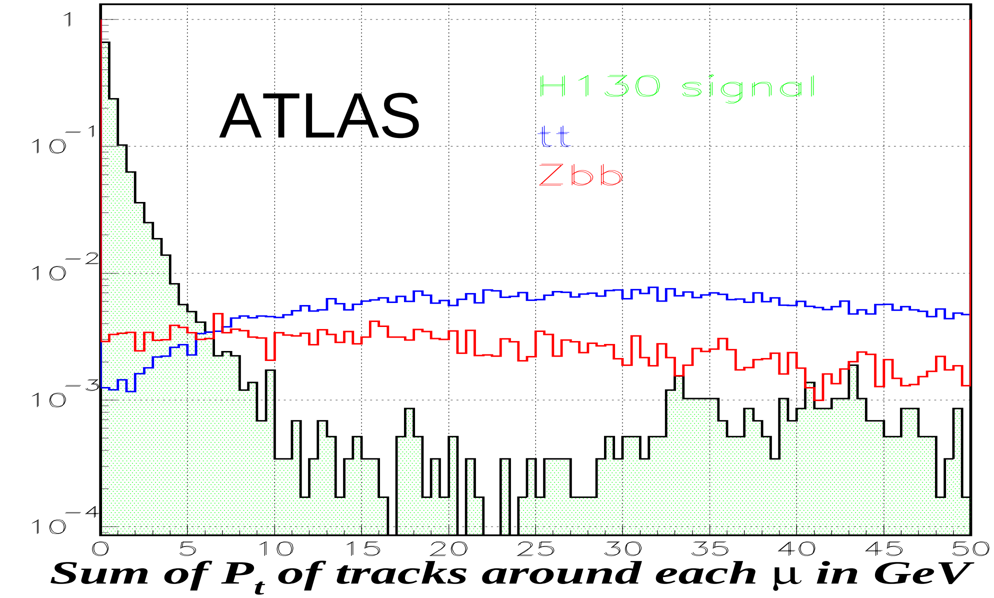


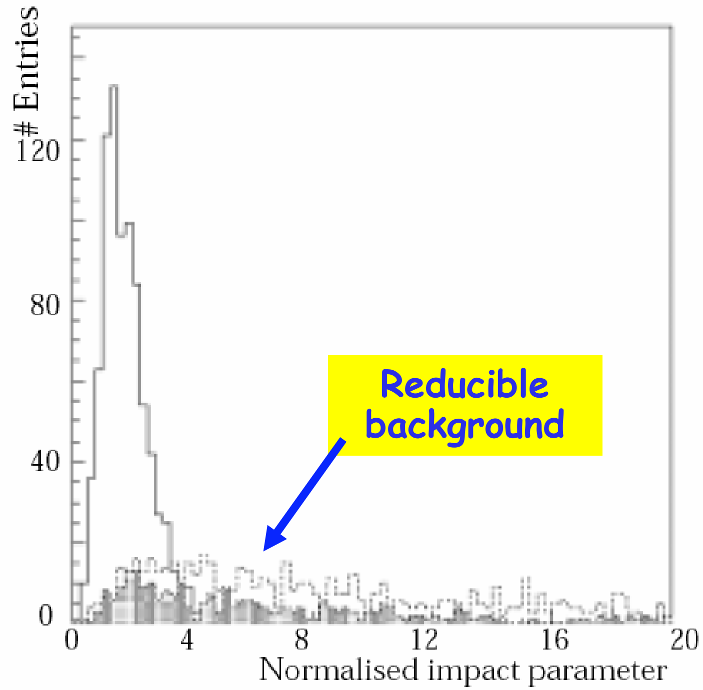
SM Higgs→ZZ$^{(*)}$→4l

- Able to reconstruct a narrow resonance, with mass resolution close to 1%. Can achieve excellent signal-to-background > 1
  - Major issue: Lepton ID and rejection of semi-leptonic decays of B decays. Suppress reducible background Zbb,tt→4l

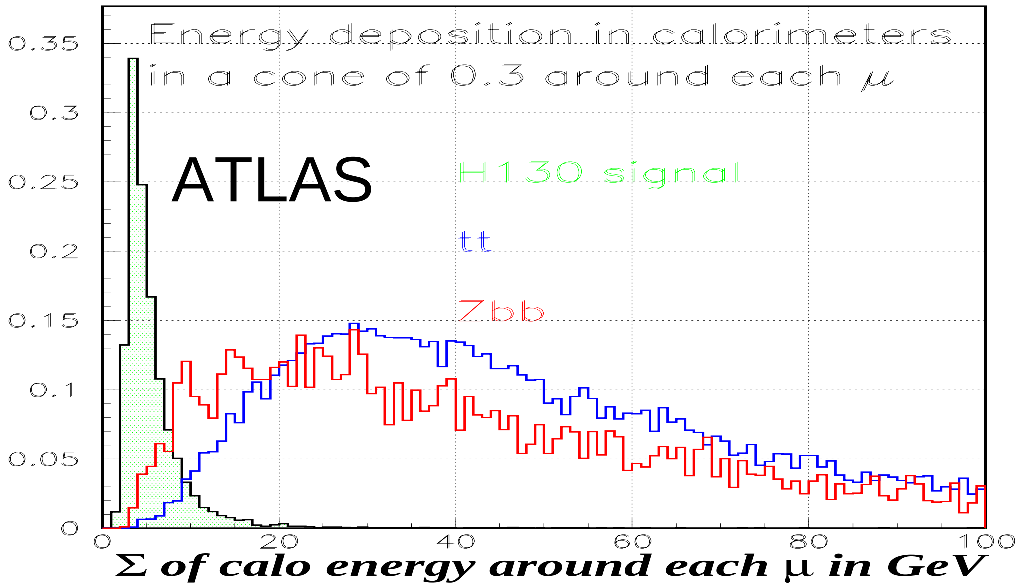
H[130 GeV]→4e H[130 GeV]→4μ H[130 GeV]→2e2μ

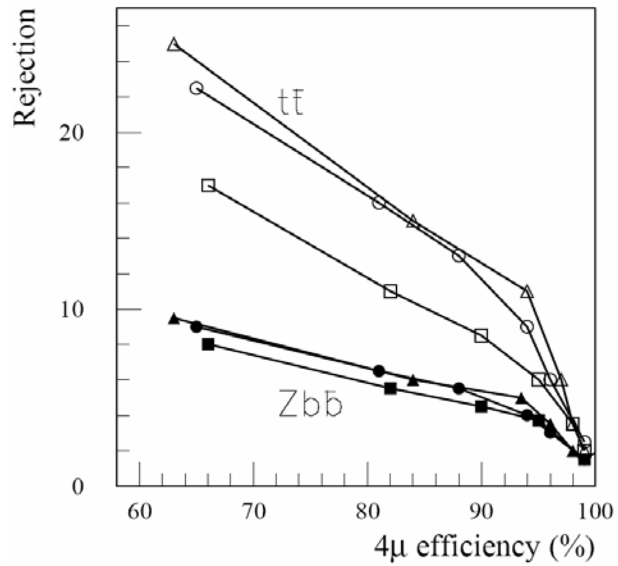




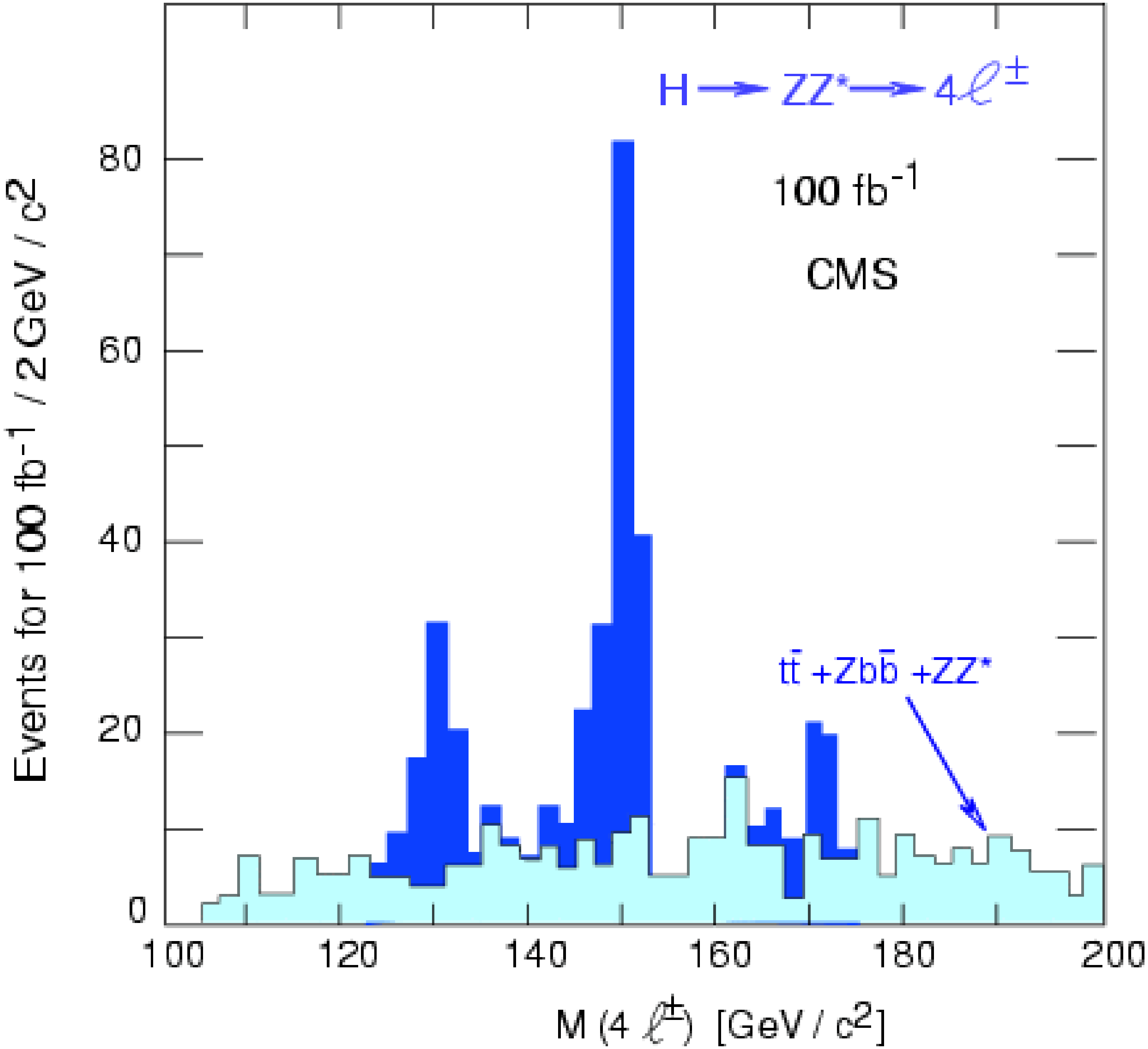


ATLAS TDR



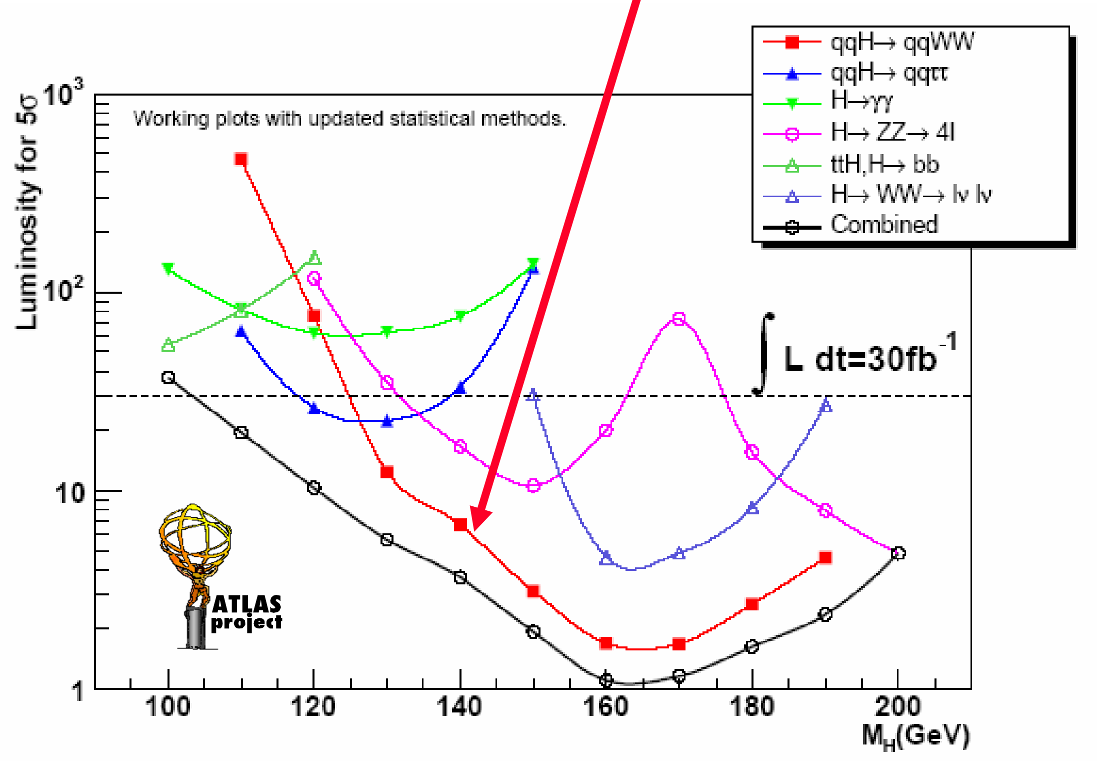


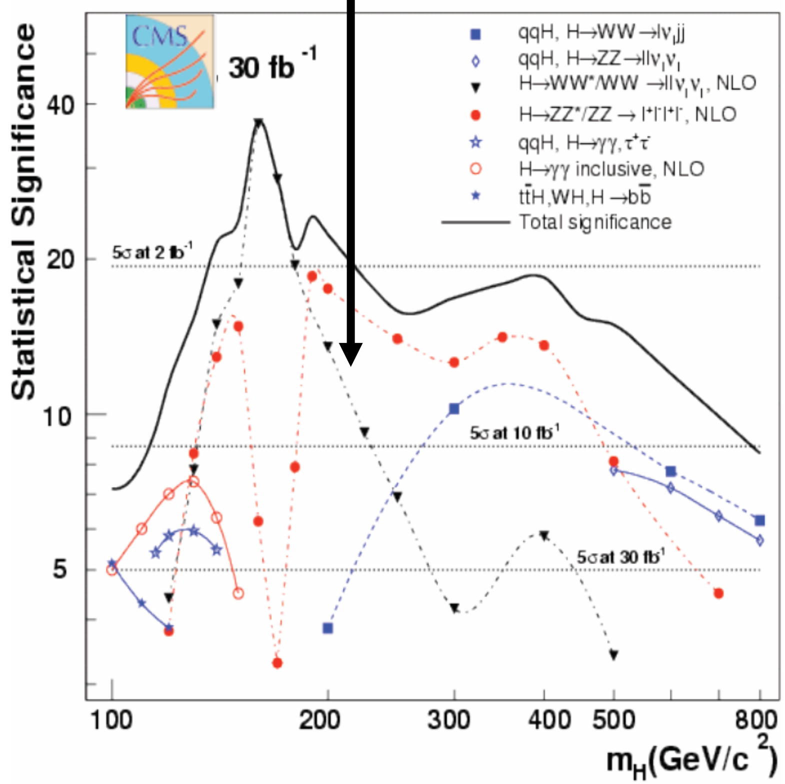
ATLAS TDR



H → ZZ* → 4ℓ±
100 fb-1
CMS
tt̄ +Zbb̄ +ZZ*
Events for 100 fb-1 / 2 GeV / c2
M (4 ℓ±) [GeV / c2]
0
20
40
60
80
100
120
140
160
180
200

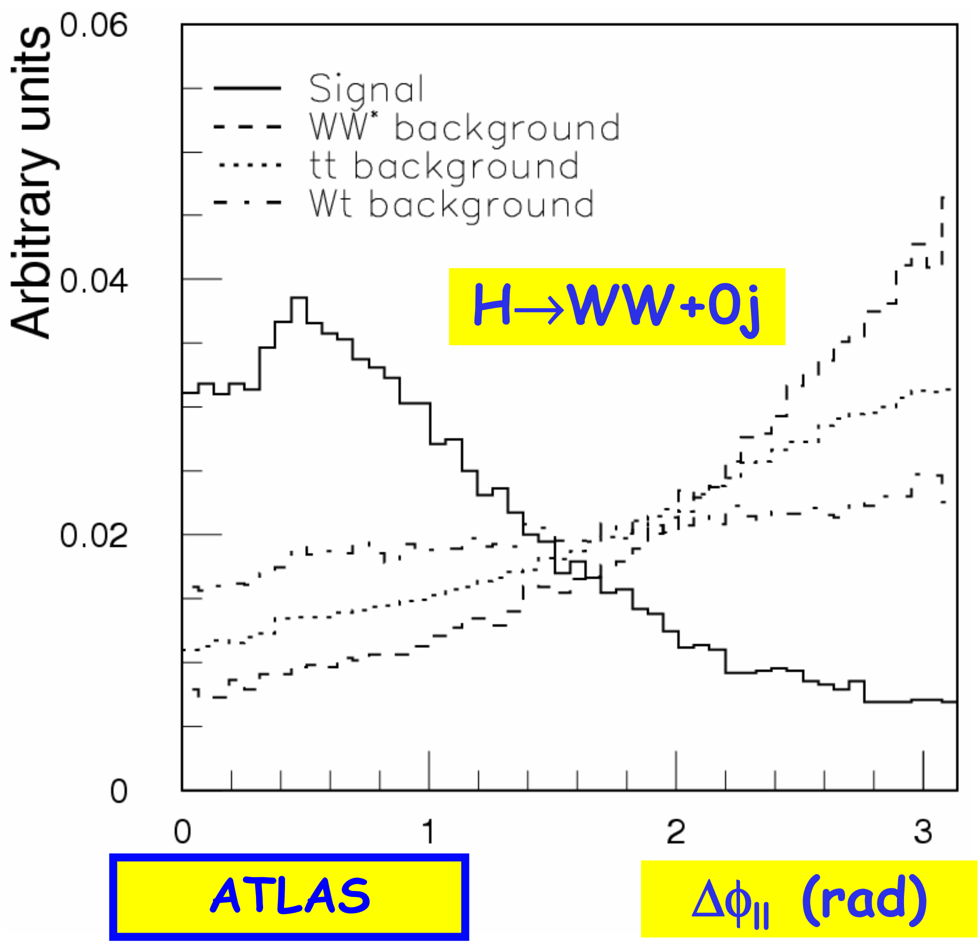
SM Higgs: $H \to WW^{(*)} \to 2l2\nu$

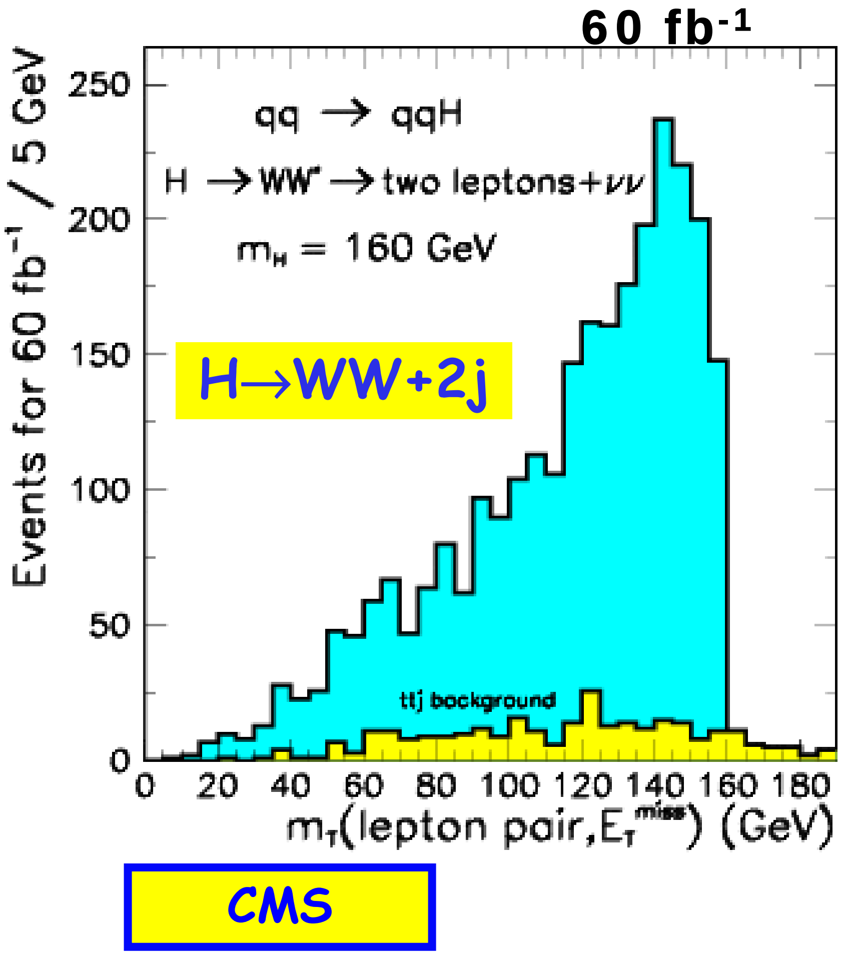




SM Higgs $H \rightarrow WW^{(*)} \rightarrow 2l2\nu$

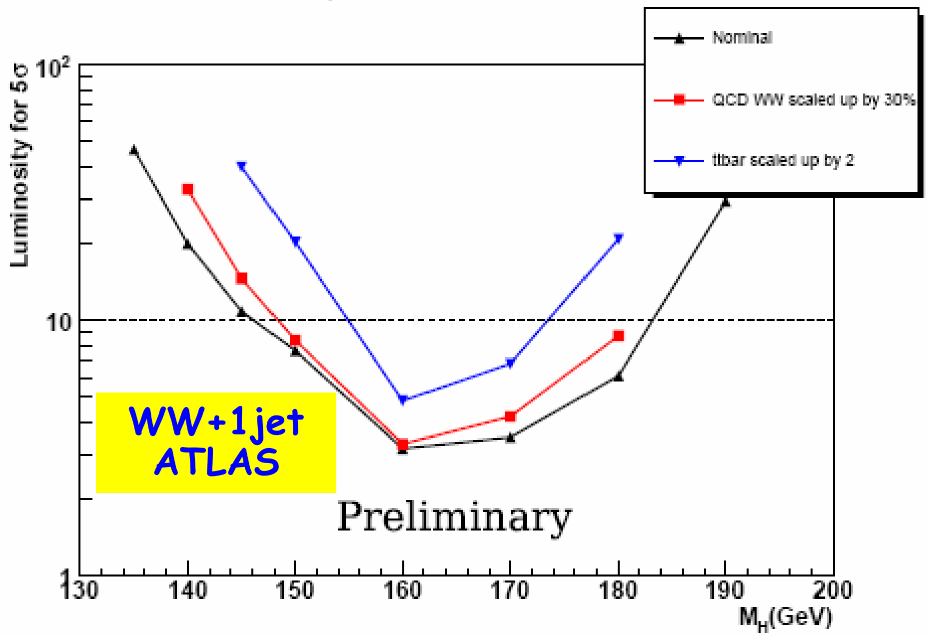
- Strong potential due to large signal yield, but no narrow resonance. Left basically with event counting experiment

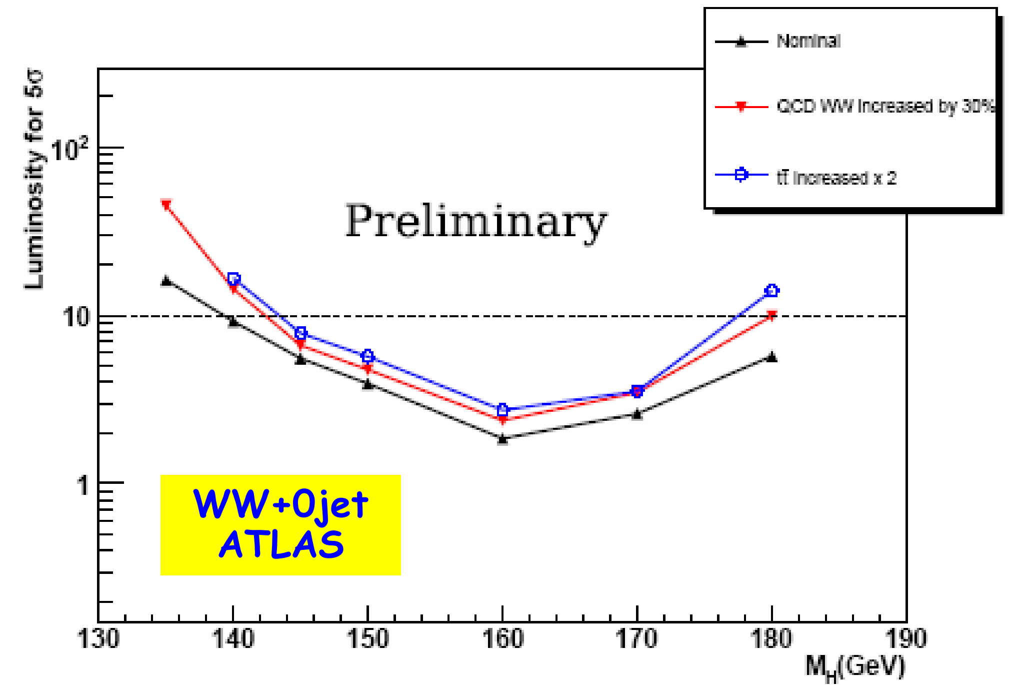


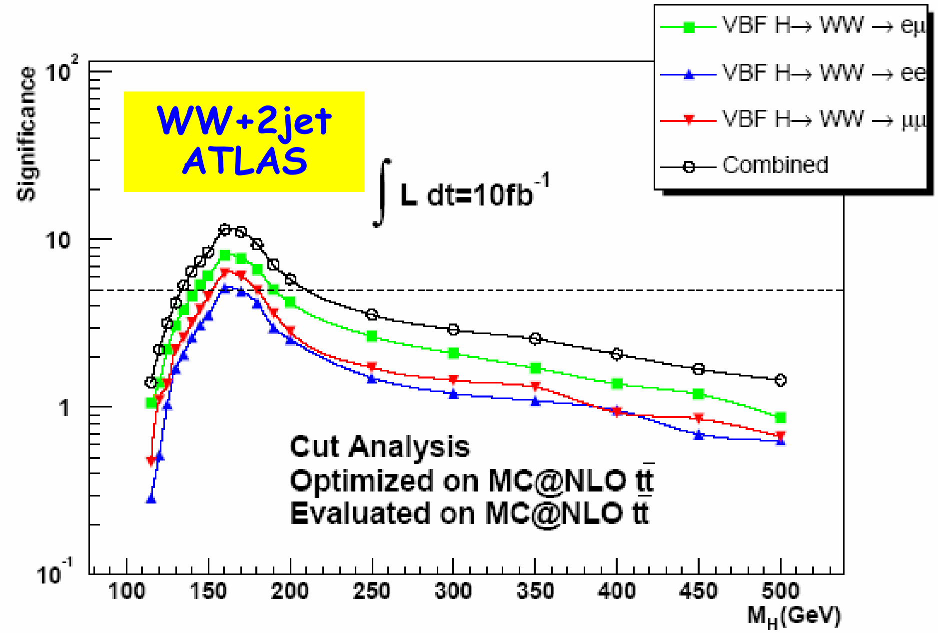


SM H→WW +0,1,2 jets

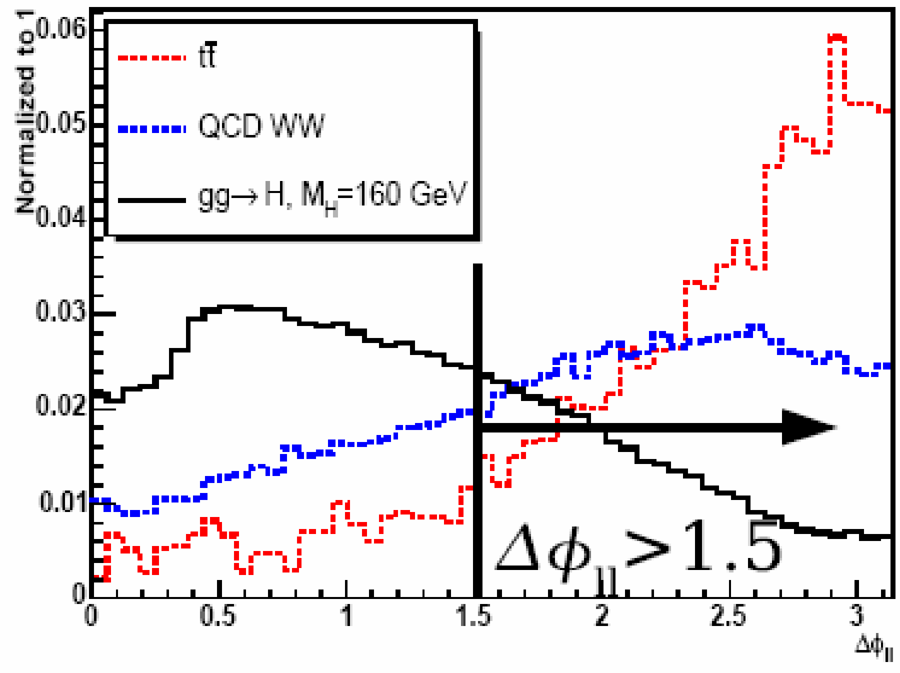
- Defined three independent analysis, depending on the number of tagged jets
  - Systematic errors added in significance calculation

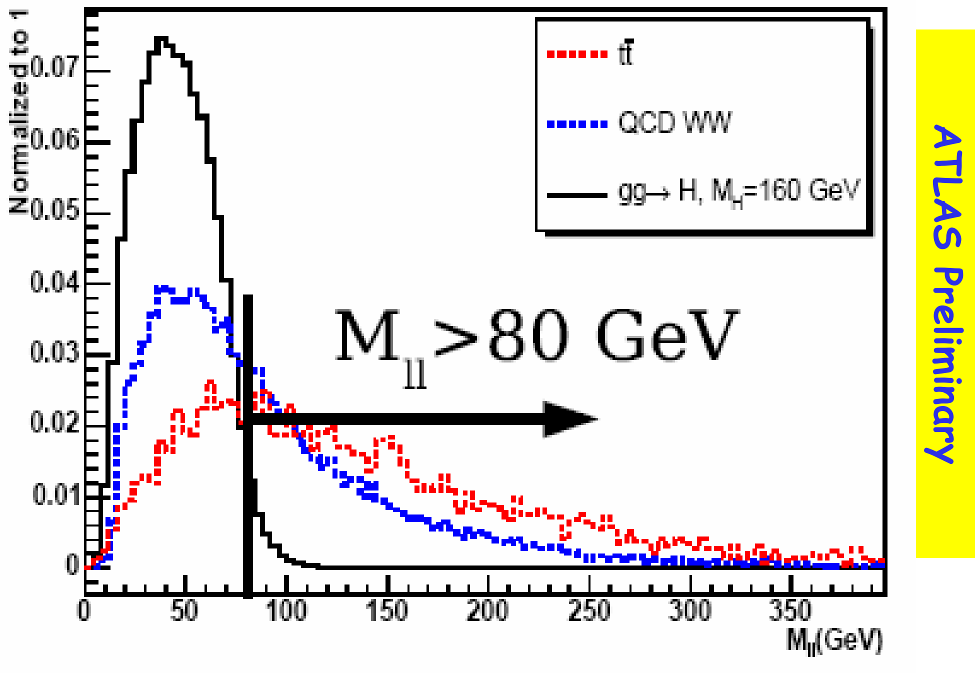






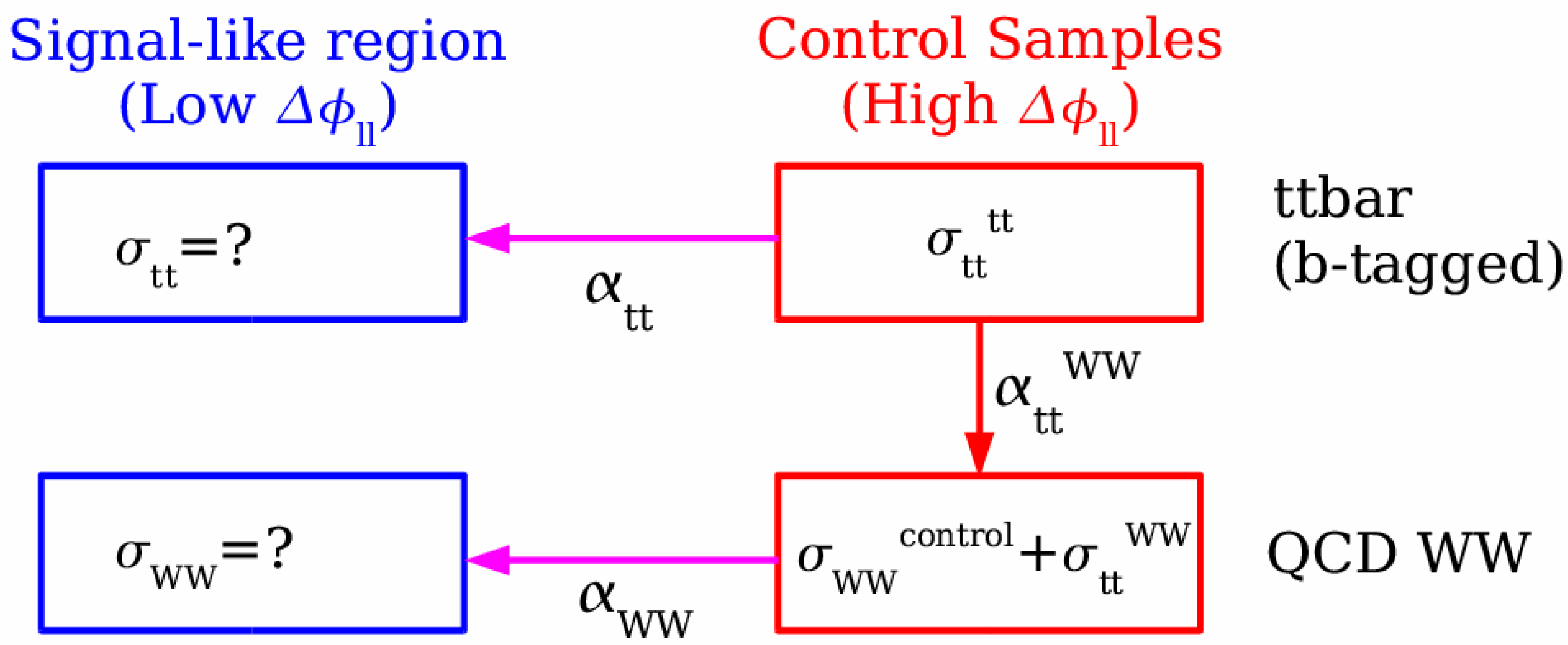
Control Samples for $H \rightarrow WW^{(*)}$





- Main control sample is defined with two cuts
  - $\Delta\phi_{ll}$>1.5 rad. and M_{ll}>80 GeV
- Because of tt contamination in main control sample, need b-tagged sample (M_{ll} cut is removed)

Control Samples for $H \to WW^{(*)}$



Define:

- α_{WW}=(QCD WW bg)/(QCD WW in control samp.)
- α_{tt}=(tt bg)/(tt in b-tagged control sample)
- α_{tt}^{WW}=(tt in WW sample)/(tt in b-tagged sample)

Systematic Errors (ATLAS preliminary)

- Error (in %) on extrapolation for $H \rightarrow WW^{(*)}+0jets$

	Jet E Scale uncertainty	Smearing of E_T miss resolution	PDF
$\Delta\alpha_{WW}$	1	2	5
$\Delta\alpha_{tt}$	7	1	-
$\Delta\alpha_{tt}^{WW}$	9	1	-

- Error (in %) on extrapolation for $H \rightarrow WW^{(*)}+1jets$

	Jet E Scale uncertainty	Smearing of E_T miss resolution	PDF
$\Delta\alpha_{WW}$	3	2	7
$\Delta\alpha_{tt}$	9	2	-
$\Delta\alpha_{tt}^{WW}$	9	1.5	-

Summary of Detector Performance Requirements (ATLAS)

- Combination of multiple channels will require a certain understanding of all signatures and sub-detectors
  - One fb^{-1} of usable data (or less) will be needed for calibration

$H \to \gamma\gamma$ (+0,1,2 jets)	$100 < M_H < 150$	γ calibration ($c_{tot} < 0.7\%$) γ/jet separation (>1000 rejection for quark jets for $\varepsilon_\gamma = 80\%$)
ttH, $H \to bb$	$80 < M_H < 130$	b-tagging ($\varepsilon_b = 60\%$, 100/10 rejection against light/c jets) extraction of background shape

Summary of Detector Performance Requirements (ATLAS)

$H \rightarrow \tau\tau$, $\tau \rightarrow l,h$ (+0,1,2 jets)	$110 < M_H < 150$	Missing E_T (<10% Higgs mass resolution), lepton ID (>10^7 fake suppression with ID), jet tagging (5%/10% energy scale uncertainty for central/forward jets), central jet veto (need to address low E_T jet resolution requirements)
$H \rightarrow ZZ^{(*)}$, $Z \rightarrow 4l$	$120 < M_H < 600$	Lepton isolation/efficiency (achieve ~100/1000 rejection against Zbb/tbb for ε_{lepton}~90%)
$H \rightarrow WW^{(*)}$, $W \rightarrow l\nu$ (+0,1,2 jets)	$120 < M_H < 200$	"top killer" (>10 rejection), jet tagging (5%/10% energy scale uncertainty for central/forward jets), jet veto