A brief introduction to Standard Model Measurements at the energy frontier

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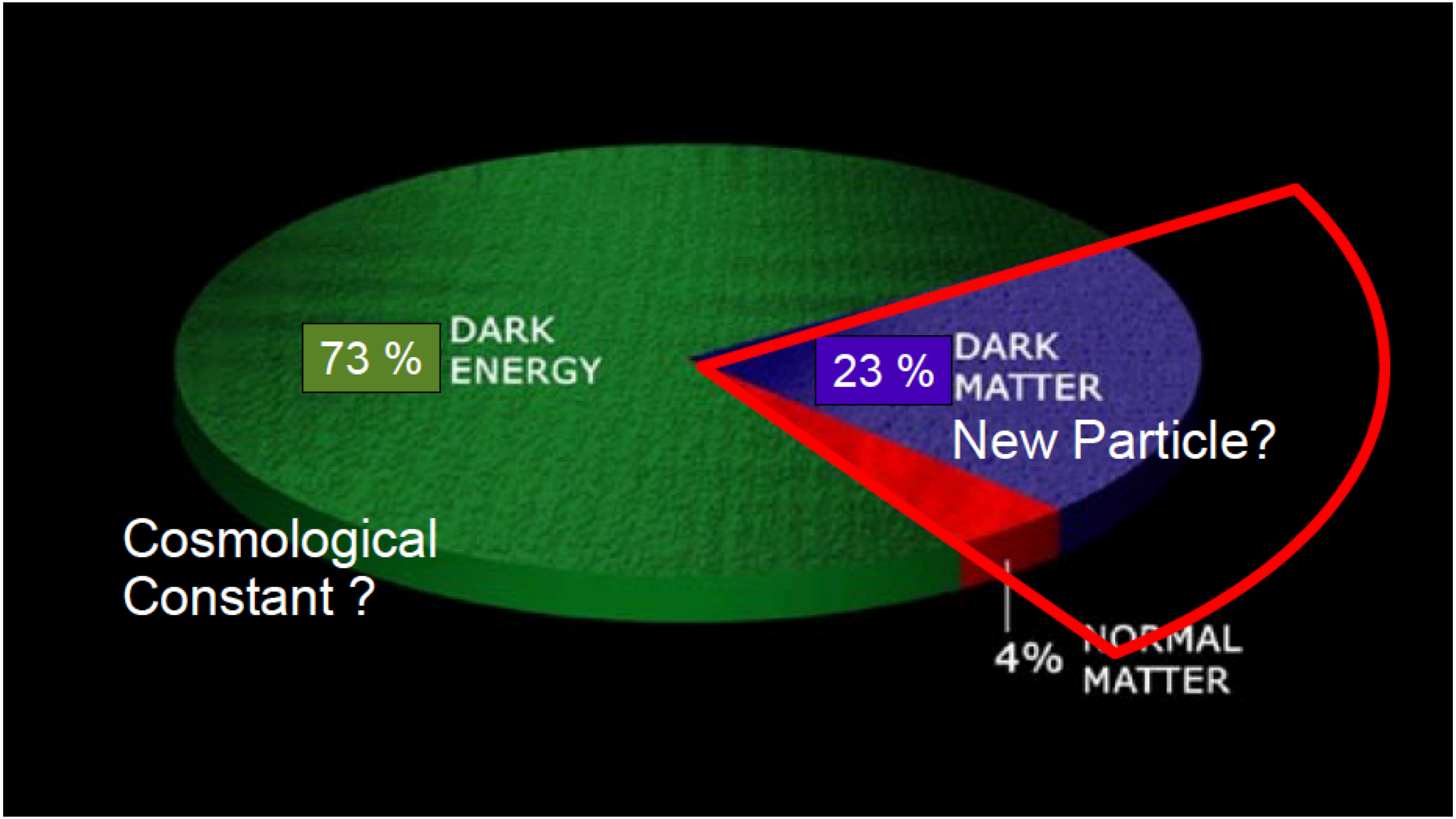
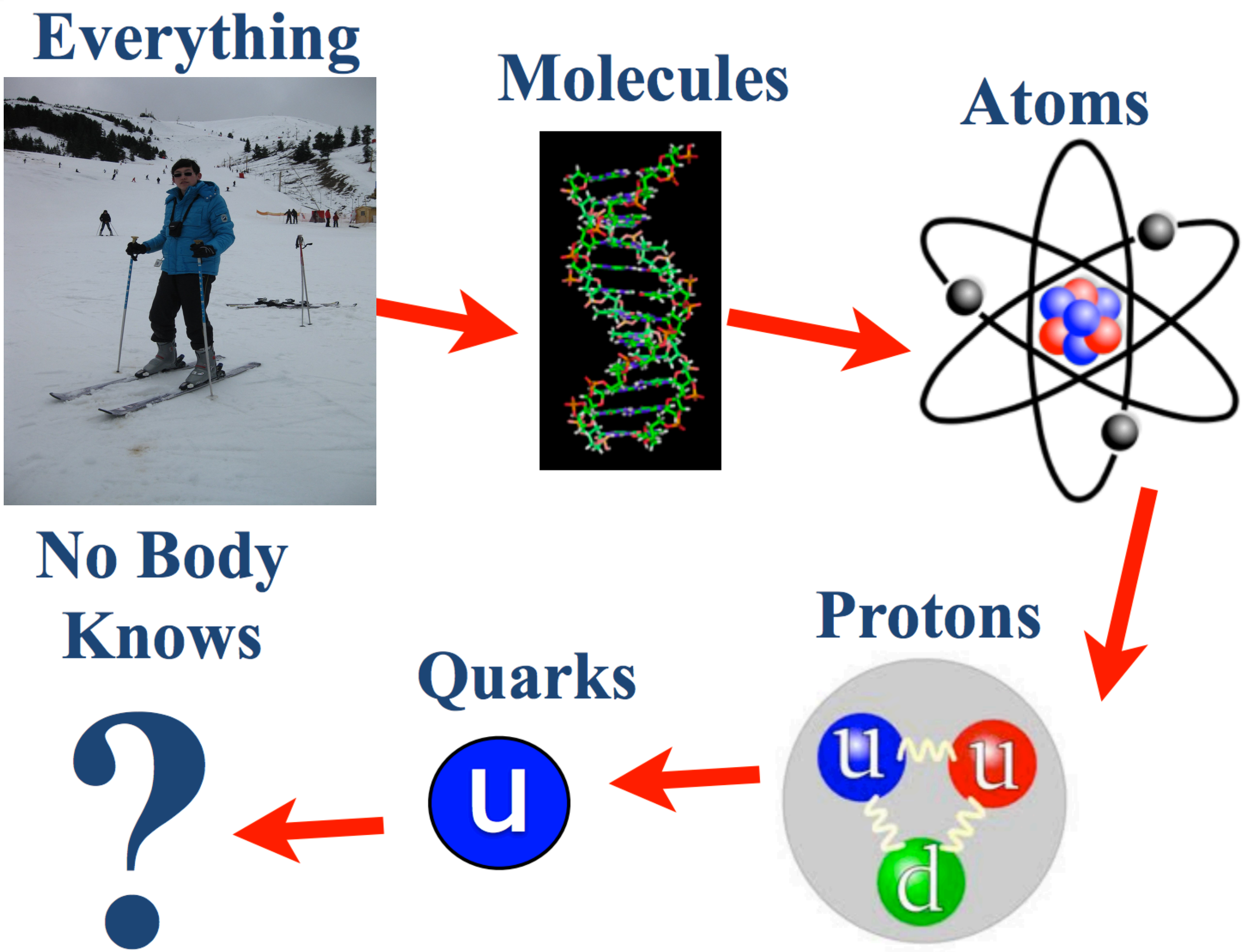
Particle physics: a deep probe of the foundation of the universe and "unknowns"



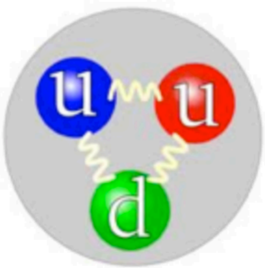
What our world looks like?



How we ever think of a machine that could explore the fundamental particles?

What's in the Proton ?

Protons are Too small to look inside.



SMASH THEM!!!

The Large Hadron Collider (LHC)

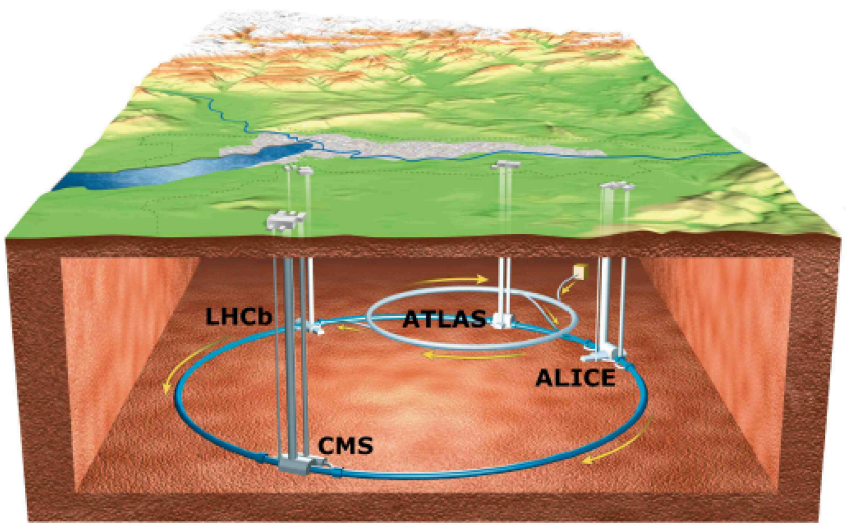
Worlds largest particle accelerator with the highest center of mass energy at CERN near Geneva, ~27 km tunnel spanning the border of France and Switzerland

General purpose: New physics and phenomenon searches, particularly Higgs boson (higher production rate at higher center-of-mass energy)

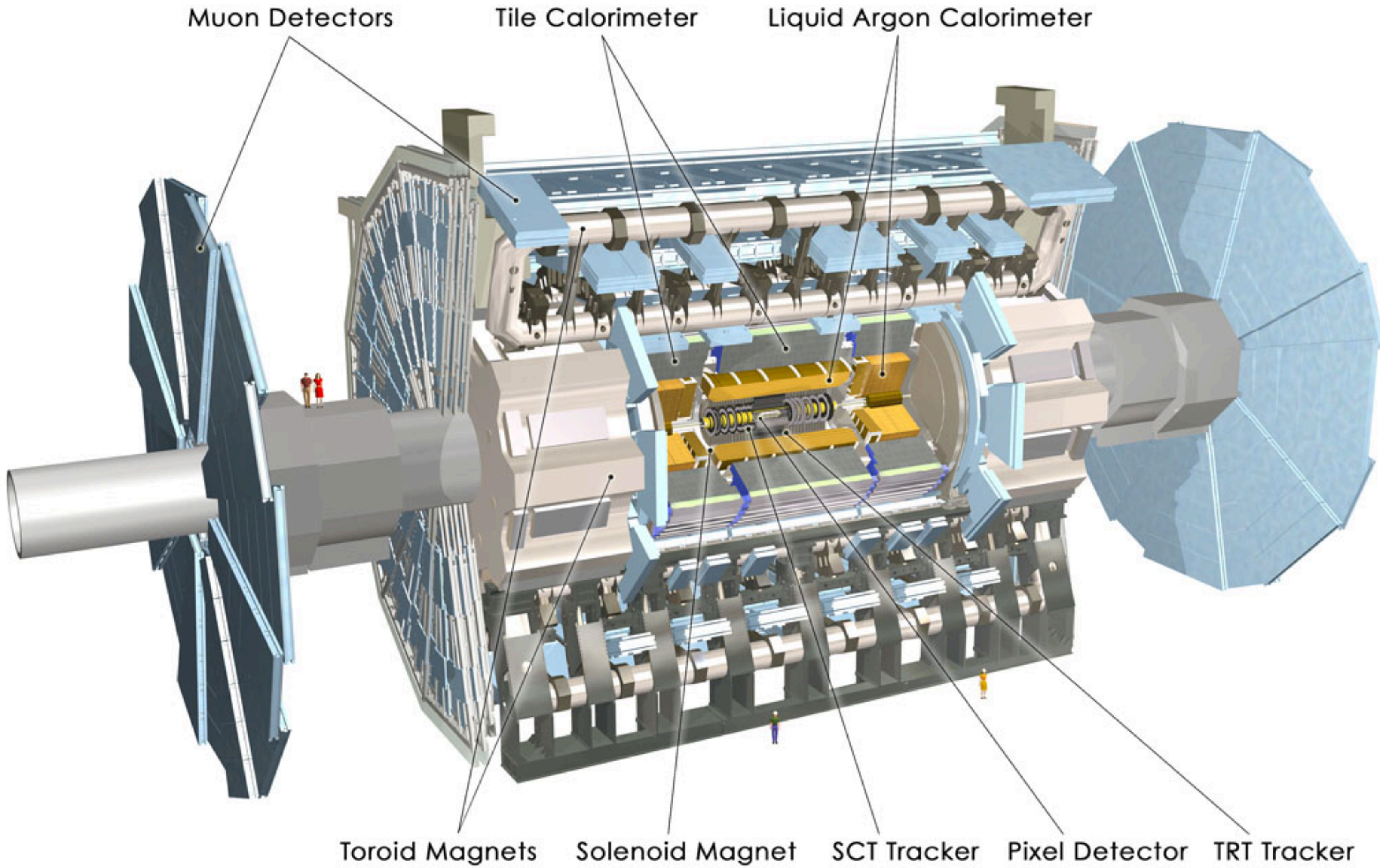
$\sqrt{s} = 7/8$ TeV (designed energy: 14 TeV) for proton-proton collision and 2.76 TeV for Pb-Pb nuclei collision

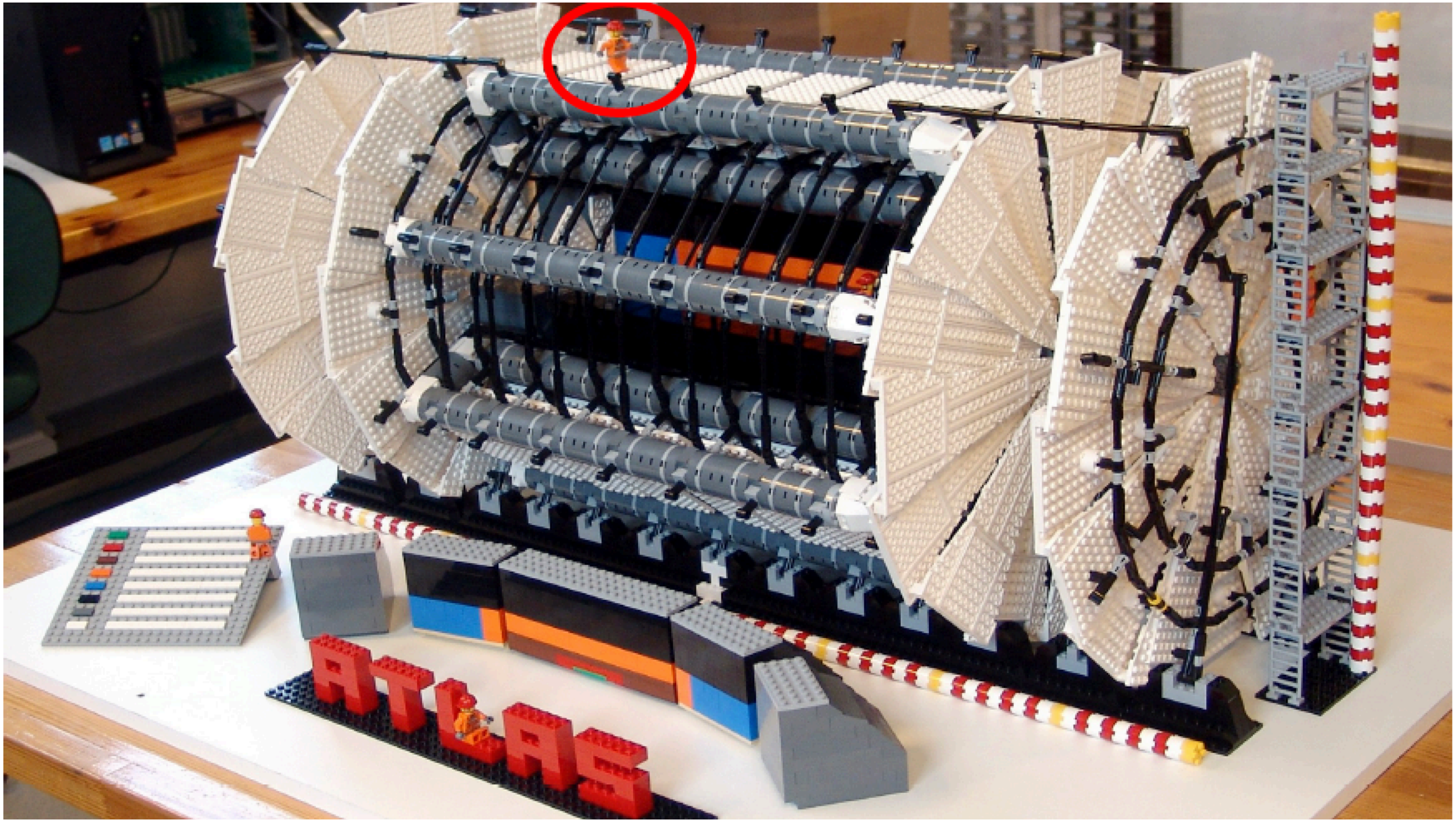
Six major detectors located at four collision points:
ALICE, **ATLAS**, CMS, LHCb, LHCf, TOTEM

Luminosity of
ATLAS/CMS: $10^{33} \sim 10^{34}$ cm^{-2}s^{-1}
(achieved $> 7 \times 10^{33}$ cm^{-2}s^{-1} in 2012)
ALICE: $10^{27} cm^{-2} s^{-1}$
LHCb: $10^{32} cm^{-2} s^{-1}$



About ATLAS: general purpose experiment covering SM




ATLAS

ATLAS: the calorimeters

Outside the ID and solenoid magnet

Measure particle energies using the energy deposit via the cascaded electromagnetic (EM) processes (e and γ) and hadronic processes (gluons and quarks reconstructed as "jets")

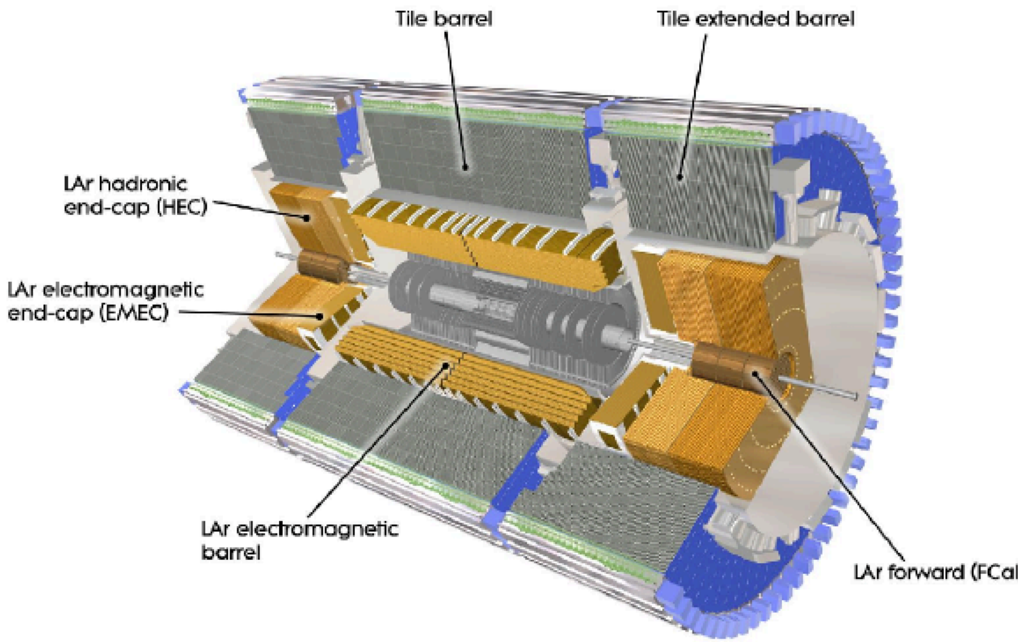
Two sampling calorimeters:
The lead-LAr calorimeter
Tile hadronic barrel calorimeter

Good pseudorapidity coverage: $|\eta| < 4.9$

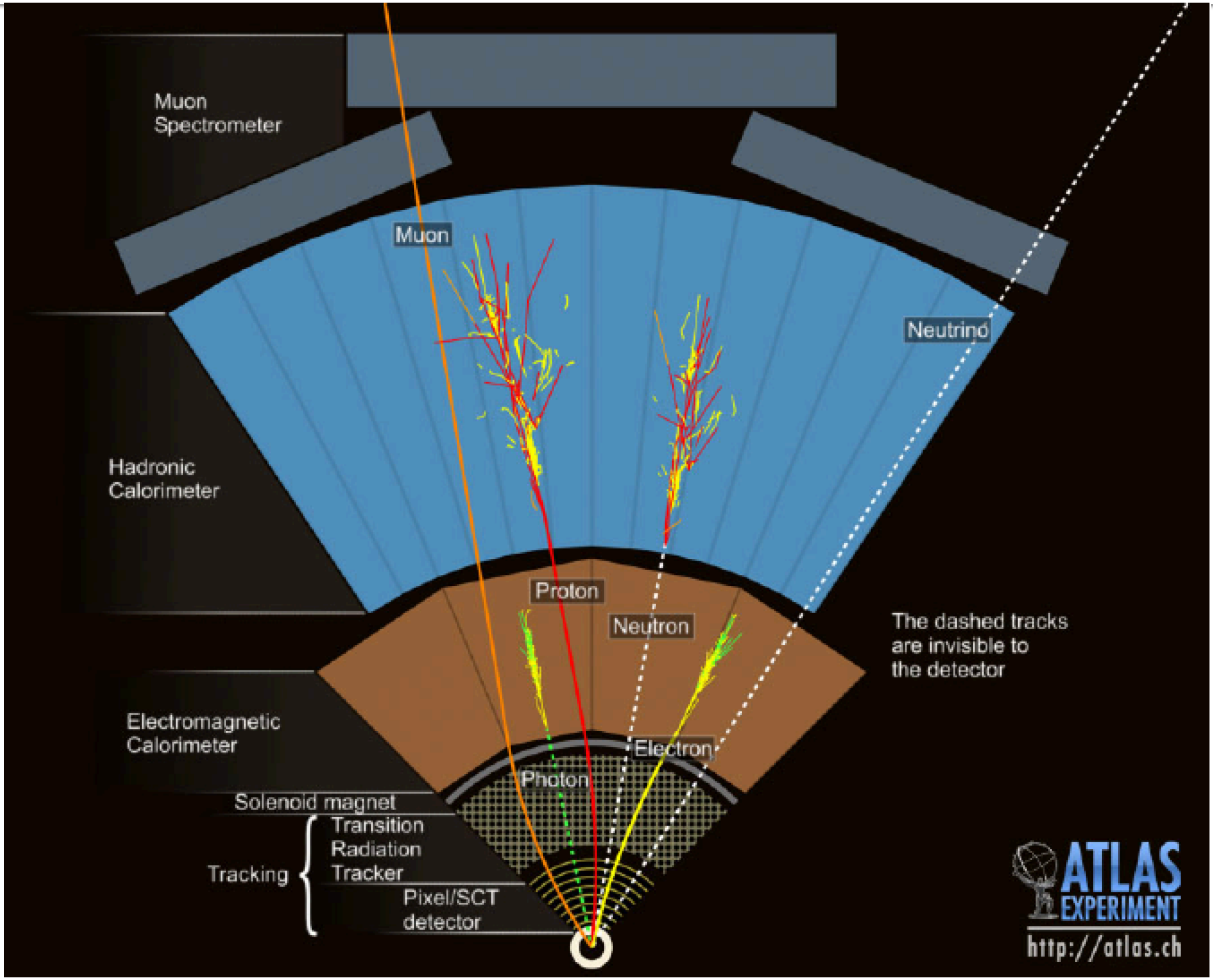
- Good reconstruction of missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) (important new physics signature)

EM depth: $\sim$22(24) X_0 (radiation length) in the barrel (endcaps). Overall 11 λ (interaction length) of active calorimeter, 1.3 λ for outer services (sufficient to suppress the punch-through into the MS)

Major subdetector where L1 and High Level Trigger originate for electrons, photons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$



ATLAS particle identifications

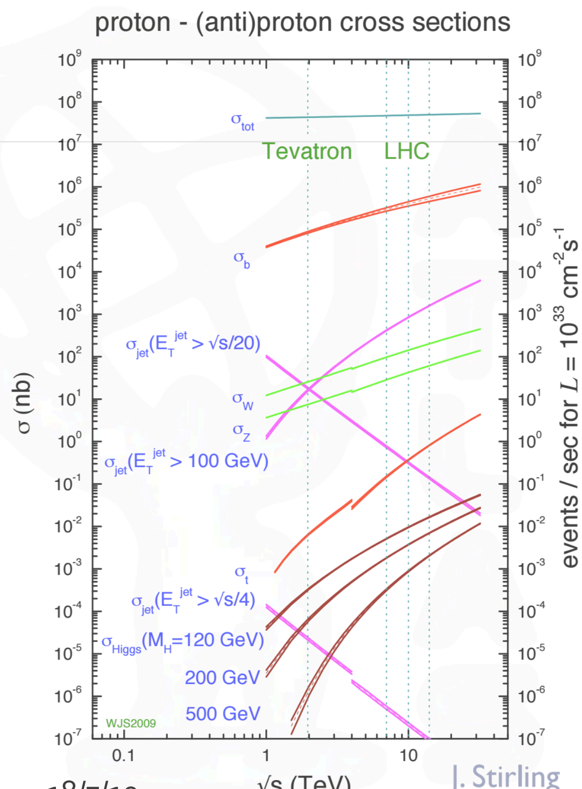


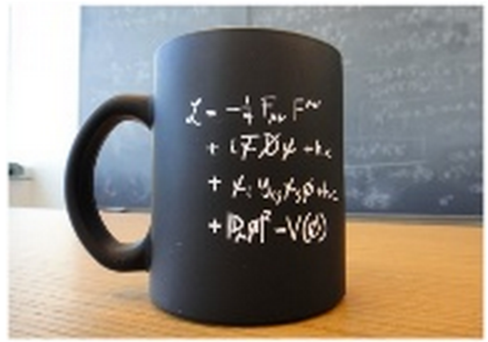
Really Big Camera!!!

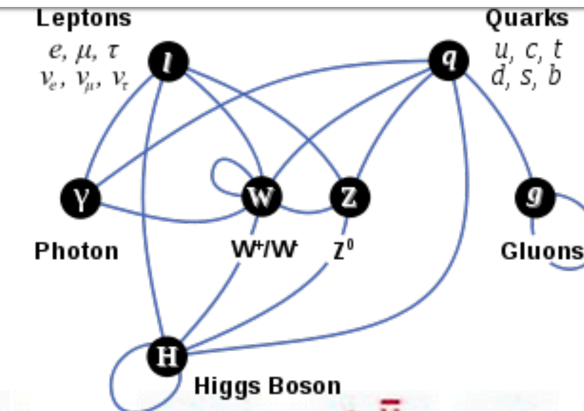
Standard Model Shortly

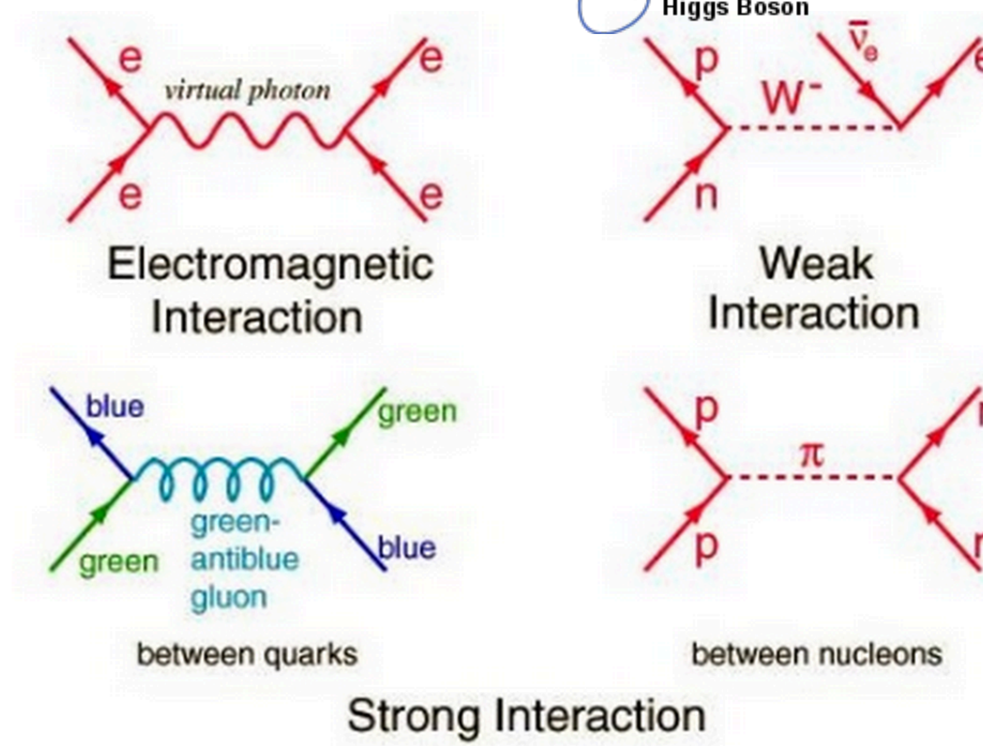
Applausive arguments:

SM widely succeeded in describing fundamental particles and Interactions with very few ingredient over reasonably broad range of energies









SM Input masses

3 charged lepton masses

m_e m_μ m_τ

6 quark masses

m_u m_d m_s m_c m_b m_t

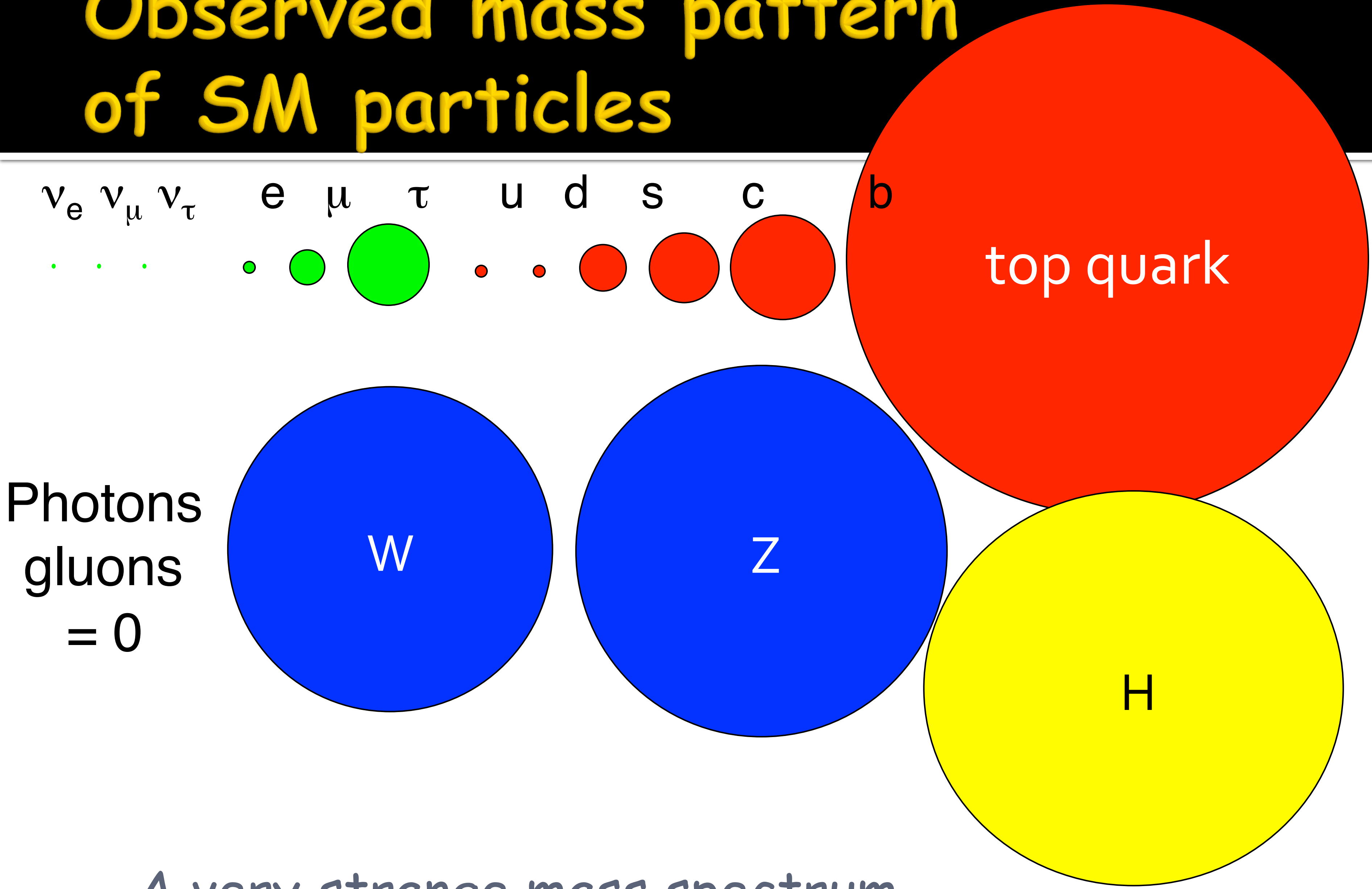
3 boson masses

m_W m_Z m_H

And now 3 neutrino masses

ν_1 ν_2 ν_3

Observed mass pattern of SM particles



A very strange mass spectrum ...

Measured Fermion Masses

Leptons	Mc^2	
Electron	0.511	MeV
Muon	0.106	GeV
Tau	1.78	GeV
ν	< 2	eV

- At least 2 neutrino masses non zero based upon observed neutrino mixing.
- The lepton masses can be measured directly as they propagate as free particles

Quarks	Mc^2	
up	~ 2	MeV
down	~ 5	MeV
strange	~ 104	MeV
charm	~ 1.27	GeV
beauty	~ 4.20	GeV
top	175	GeV

- The "current" quark masses that appear in the QCD Lagrangian are quoted. The quarks are bound in color singlet hadrons (except for the top quark) and the masses must be deduced indirectly.

Measured Boson Masses

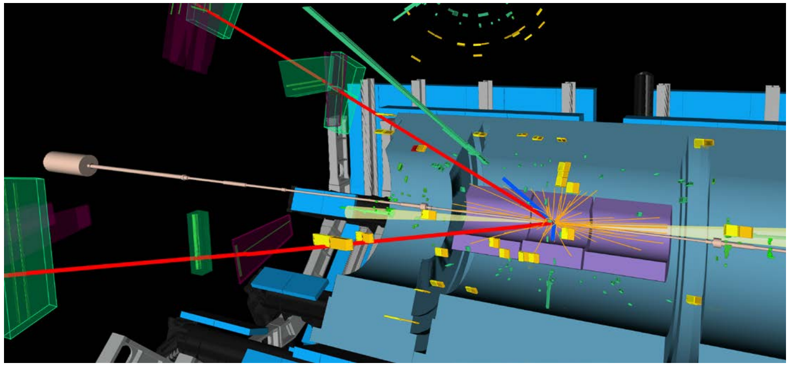
- The gauge boson masses are zero except for:

$$M_W c^2 = 80.40 \text{ GeV}$$
$$M_Z c^2 = 91.19 \text{ GeV}$$

- The Higgs boson has now been observed with a mass:

$$M_H c^2 = 125.1 \text{ GeV}$$

m_{4l}=129 GeV,
m_{12}=91 GeV,
m_{34}=29 GeV.



$H \rightarrow Z Z^*$
$\rightarrow e^+ e^- \mu^+ \mu^-$

- **Selection:** 4 lepton (e,μ), lowest/4th electron E_T>7 GeV, muon p_T> 5 GeV, m_{12}/m_{34} consistent with Z/Z
- **8% acceptance increasing by lowering muon p_T to** 5GeV from 6GeV compared to RUN-1
- **ttbar, Z+jets and WZ (15.7% of bkg): estimated with data driven methods, others from MC**

Input coupling strengths

- There are two independent coupling "constants" (not really constant) These must be measured at some energy scale that is convenient for making a precise measurement

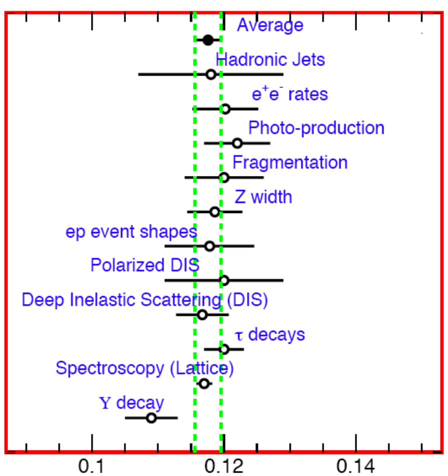
2 coupling constants

$\alpha_e(Q \sim 0)$ $\alpha_s(Q = m_Z)$

Measured Coupling Strengths

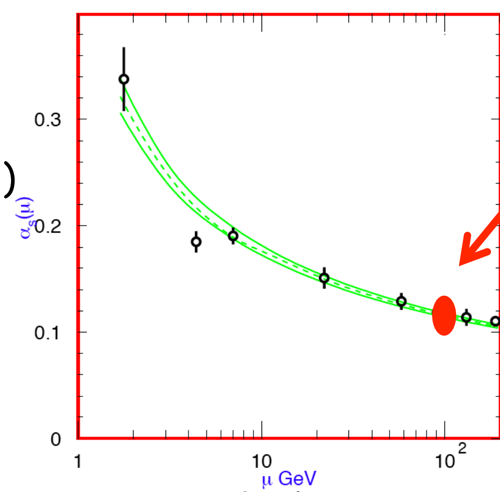
- The electromagnetic coupling strength is measured to high precision from atomic physics experiments.
  $\alpha_e(Q\sim0)$ = 1/137.036… (precision 1 part in 10^8)
  $\alpha_s(Q = M_Z)$ = 1/128 (slow evolution with Q^2)

- The strong coupling constant is measured to a precision of about 2%. It has a rapid evolution at low Q^2 slowing at high Q^2.



$\alpha_s(Q = M_Z)$

$\alpha_s(Q)$



$\alpha_s(Q = M_Z)$
$= 0.118 \pm 0.002$

energy Q of gluon probe

Finding the SM's input parameters

- A detailed summary of all measured parameters, and a discussion of the formalism of the Standard Model and other theories can be found in a HEP "bible" prepared by a Particle Data Group.
  - You can access this at : http://pdg.lbl.gov/

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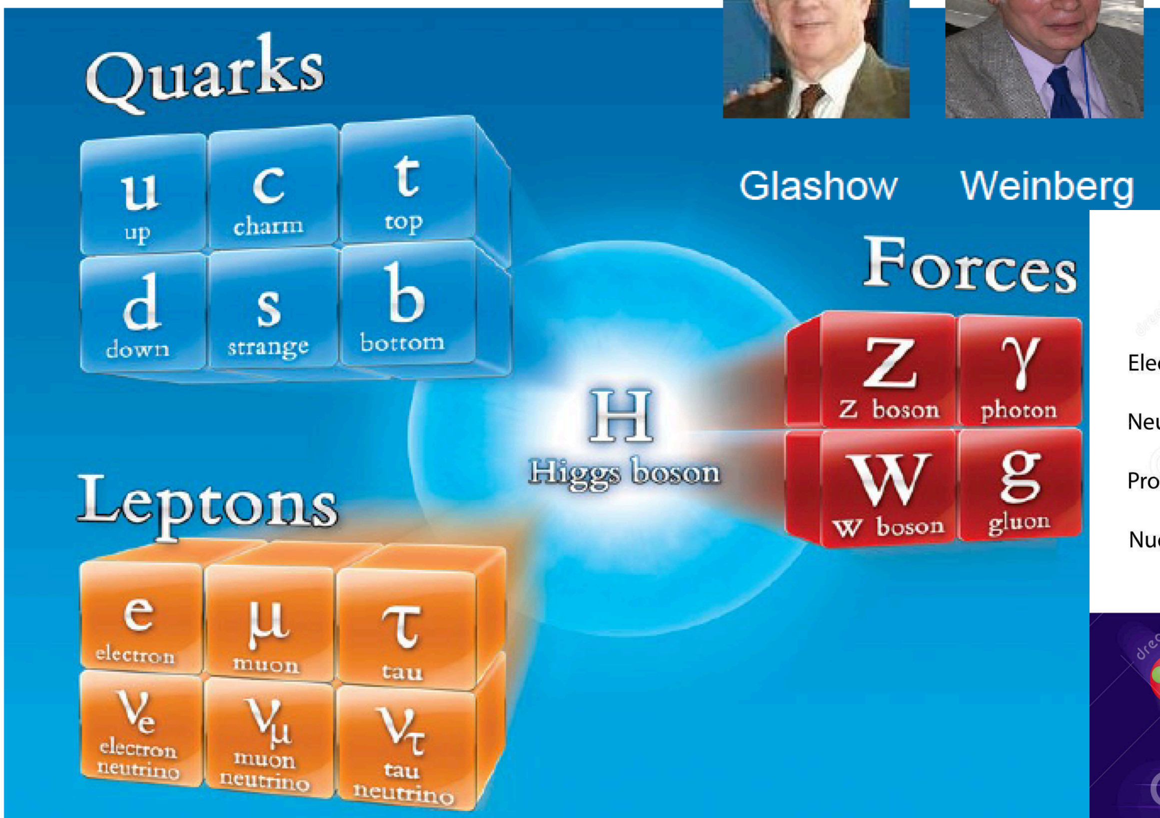
Higgs mechanism gives birth to SM particle mass

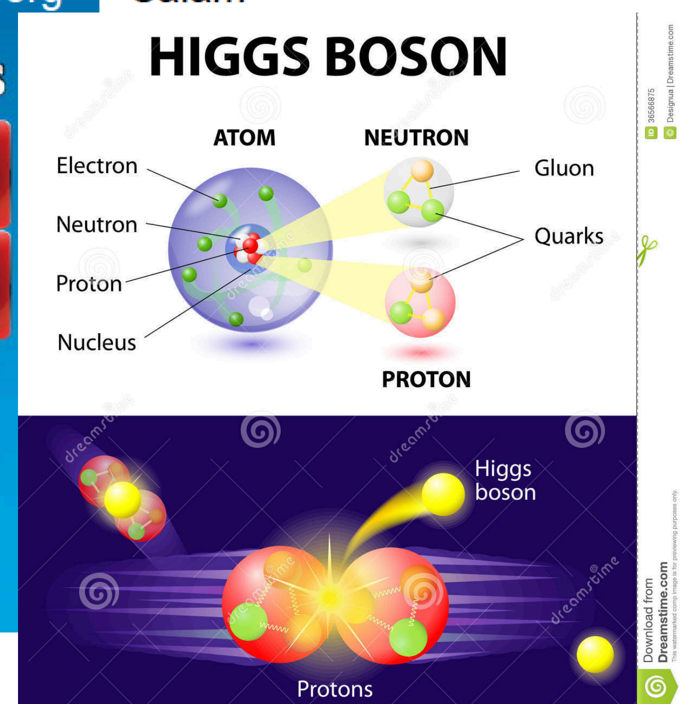
Applying Higgs mechanism to generate masses!

Glashow

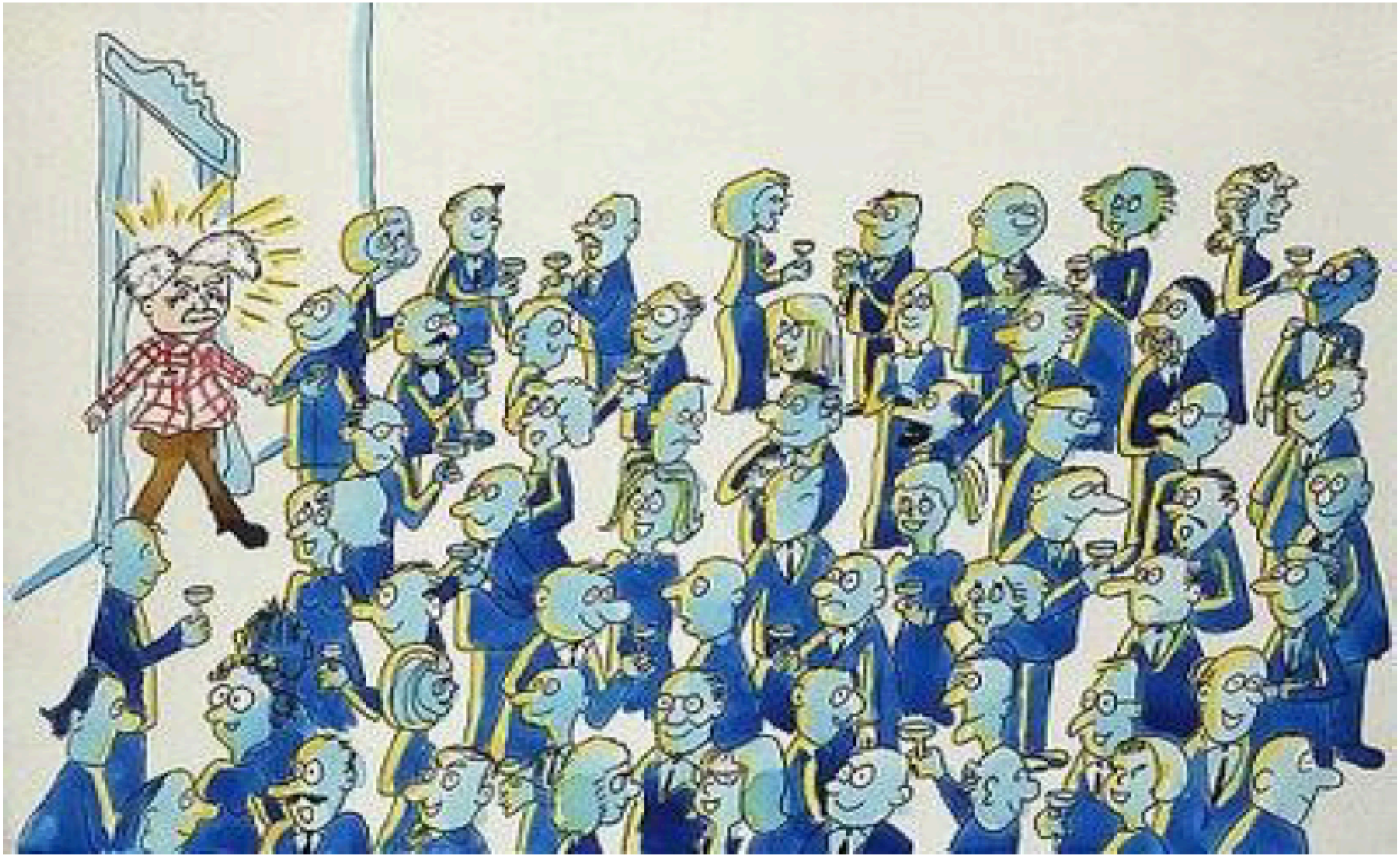
Weinberg

Salam

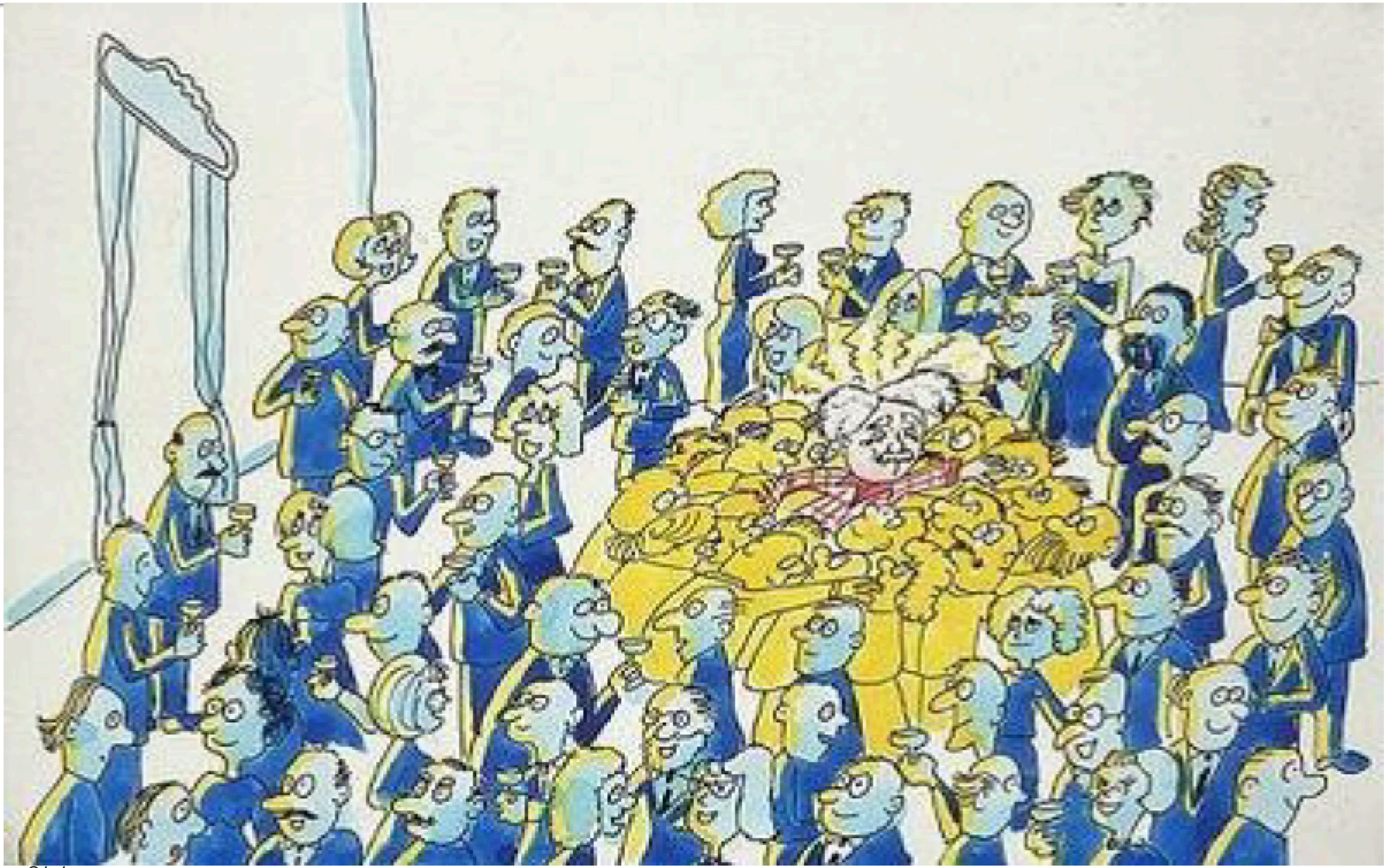




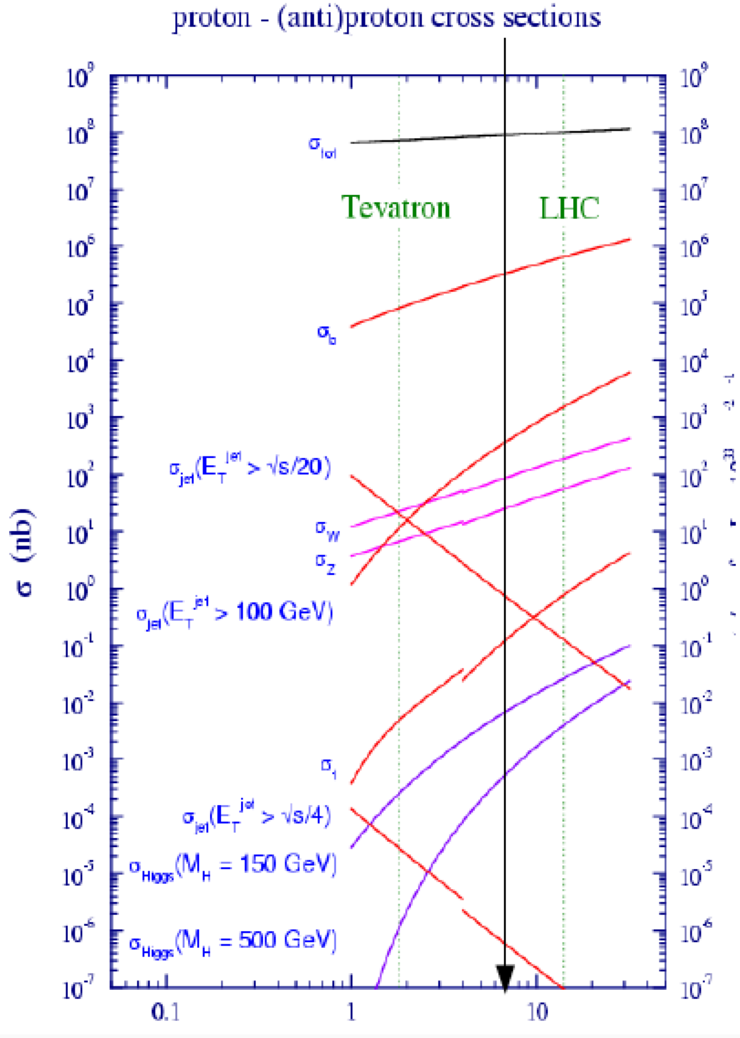
A vacuum is full of Higgs field

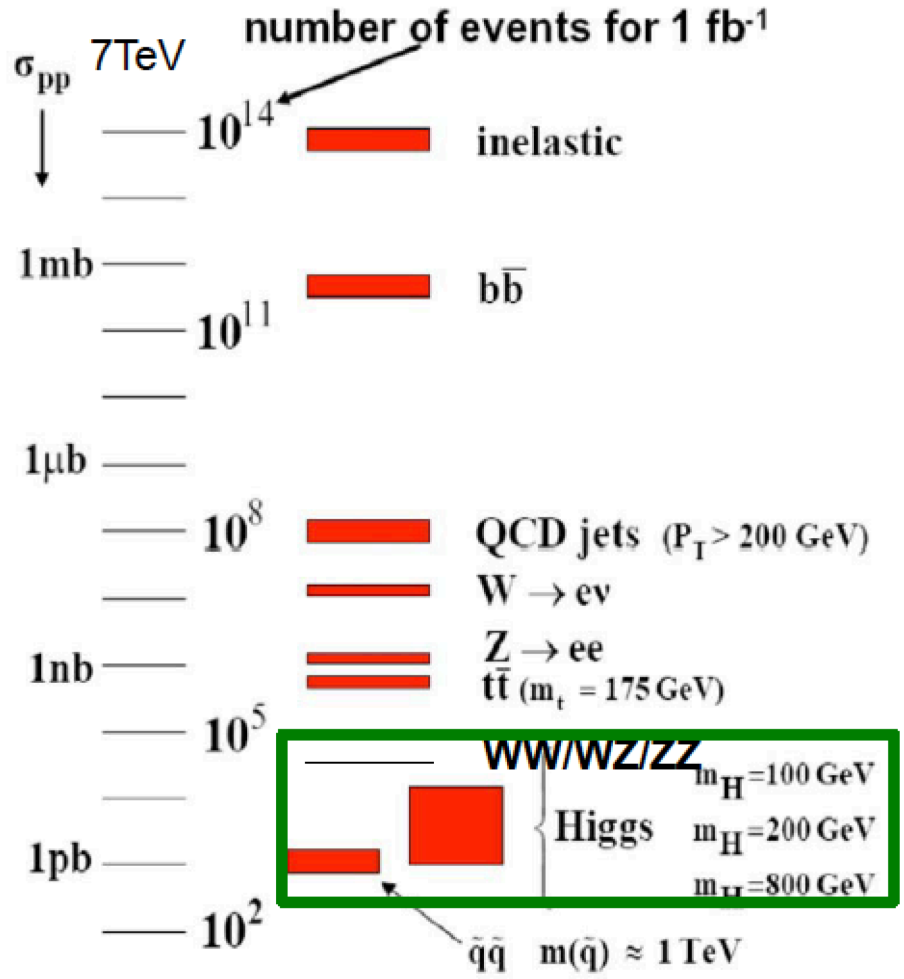


Particles interact Higgs and gain the mass

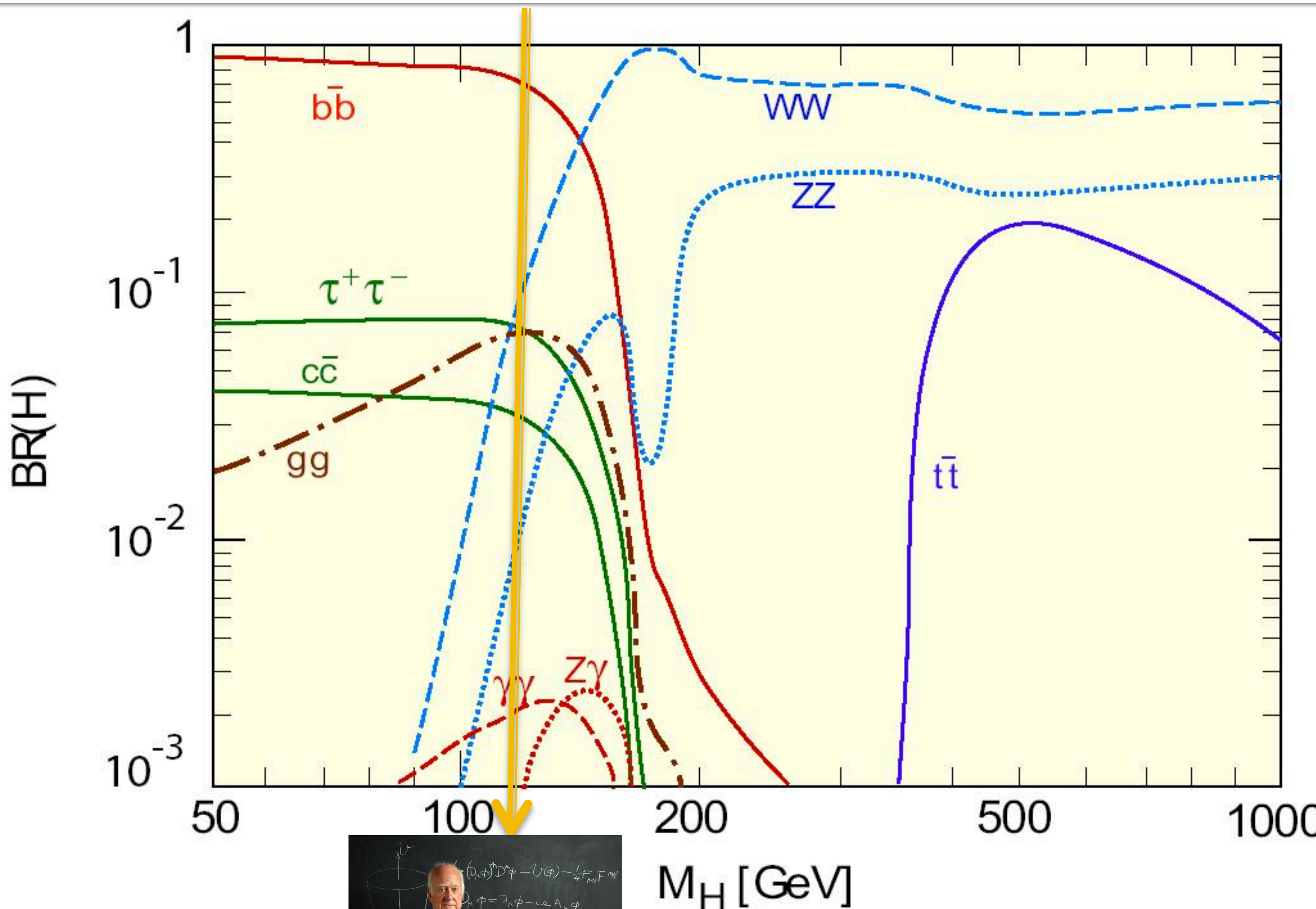


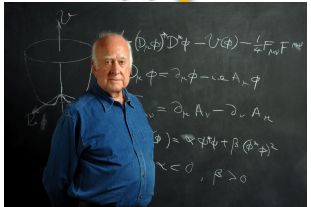
Diboson among the rare processes to be worked out in ATLAS





Why do multi-boson: signature matters essentially at ATLAS for new physics



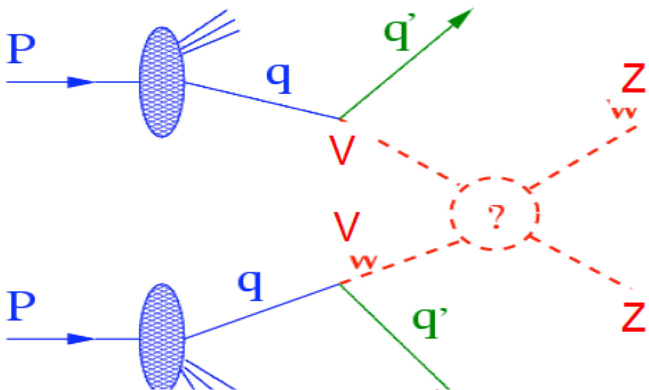


Why do multi-boson: SM, precision, unitarization and new physics

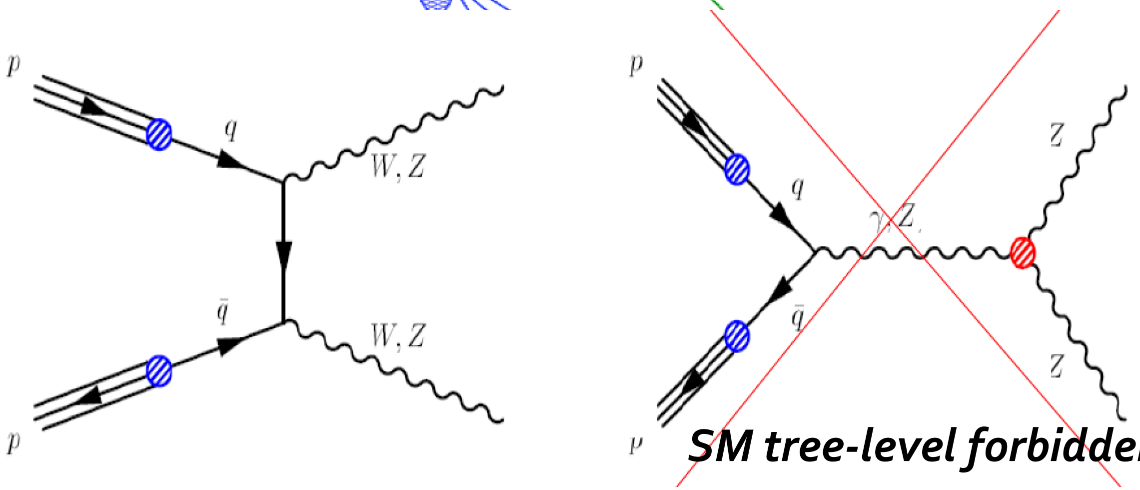
Unitarity violation of Vector Boson Scattering

$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{M_W^2}$$

"bulk" production mode incorporating SM processes and probing high precision QCD/EWK high order calculation via measuring the decay products of bosons



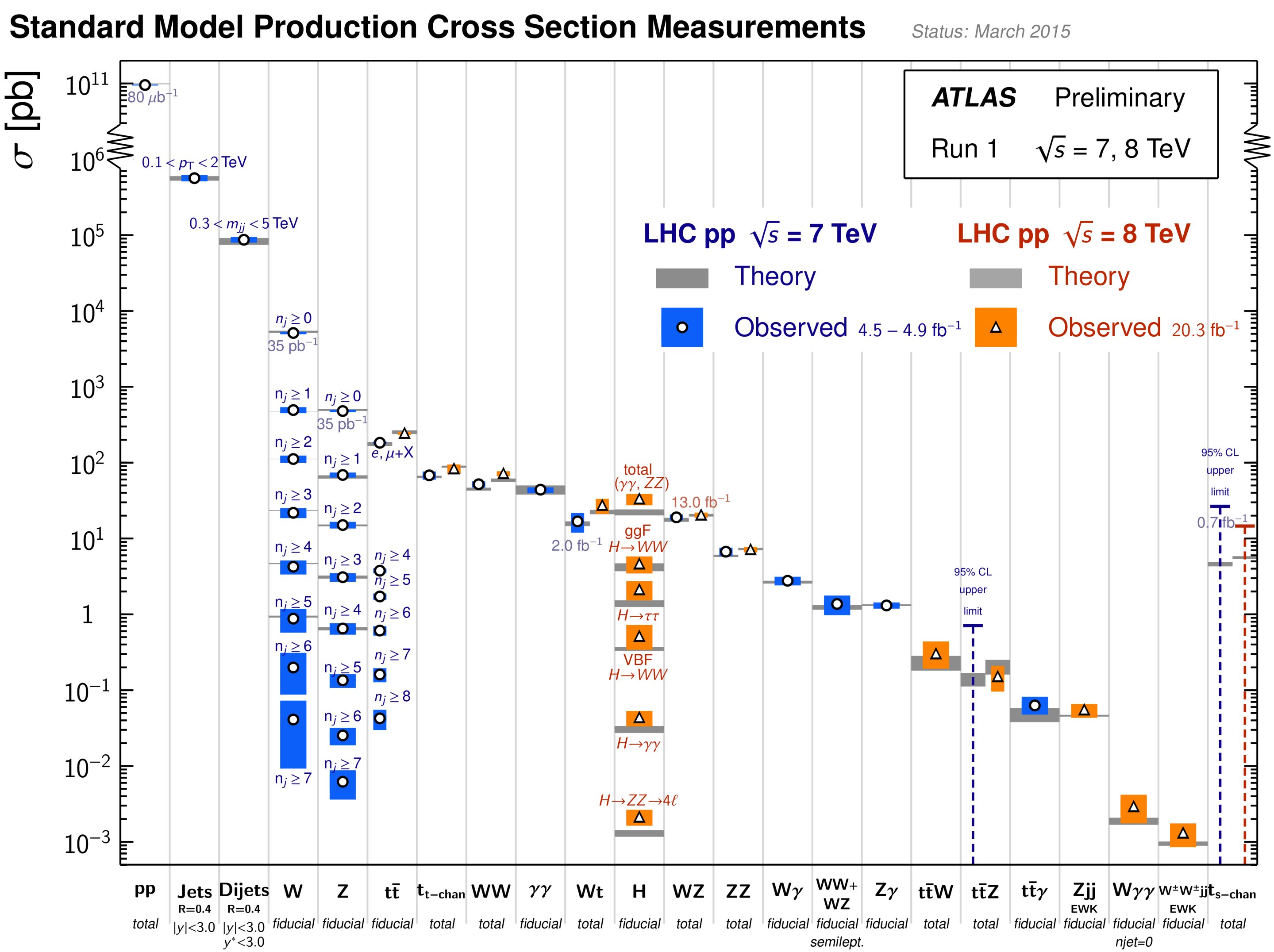
New physics show up via SM boson self-interactions, parameterized by effective lagrangians and effective field theories



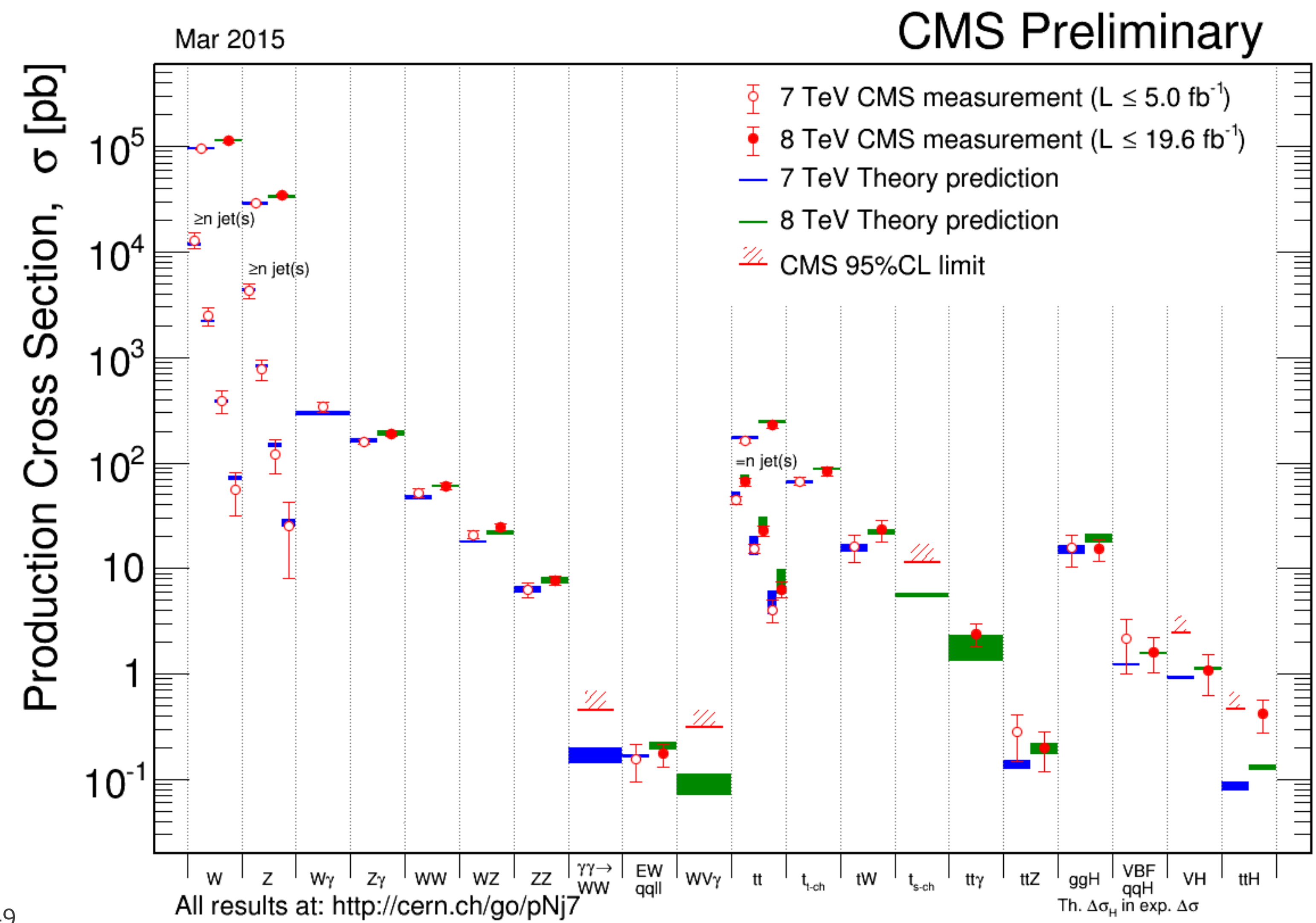
SM tree-level forbidden

SM measurements

Summary of SM measured total cross-section and comparisons with theory predictions from ATLAS

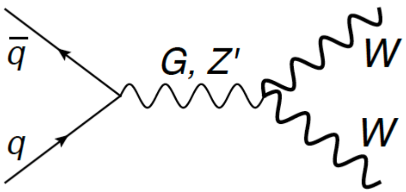


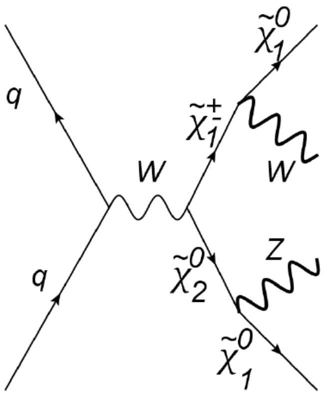
Summary of SM measured total cross-section and comparisons with theory predictions from CMS



BSM searches related to SM di-boson

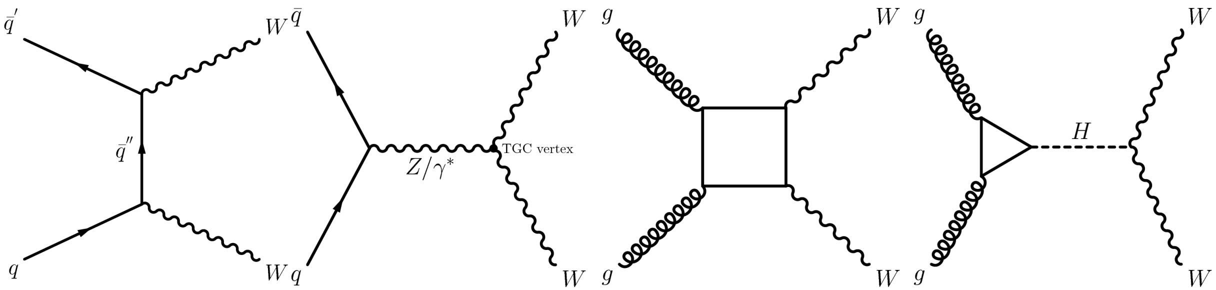
- $WW \to \ell\nu\ell\nu$ (signature: two leptons + missing energy)
  - $H \to WW$ (MSSM)
  - Graviton $G \to WW$ (mSUGRA)
  - $Z' \to WW$
- $WZ \to \ell\nu\ell\ell$ (signature: three leptons + missing energy)
  - $pp \to W^* \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (W^{\pm}\chi_1^0)(z^0\tilde{\chi}_1^0)$ (SUSY)
  - $\rho_T^{\pm} \to W^{\pm}Z$ (Technicolor)
- $ZZ \to \ell\ell\ell\ell$, $ZZ \to \ell\ell\nu\nu$
  - $H \to ZZ$ (MSSM)
  - $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\ell^+\ell^-)Z(\ell^+\ell^-)\tilde{G}\tilde{G}$ (GMSB)
- $W\gamma \to \ell\nu\gamma$
  - $\rho_T^{\pm}, a_T^{\pm} \to W^{\pm}\gamma$ (Technicolor)
  - General GMSB (Wino-like neutralino)
- $Z\gamma \to \ell\ell\gamma$:
  - $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\ell^+\ell^-)\gamma\tilde{G}\tilde{G}$ ($Z\gamma$+missing energy)
  - $\omega_T \to Z(\ell^+\ell^-)\gamma$ (Technicolor resonance)
  - ...

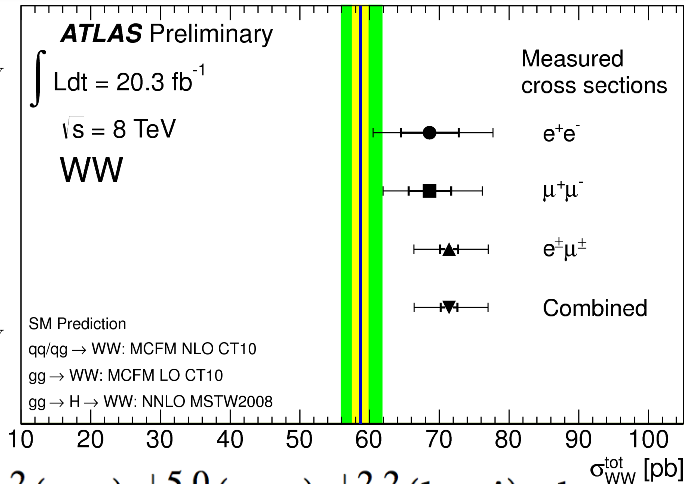




Measurement of the WW production cross section in full leptonic final state

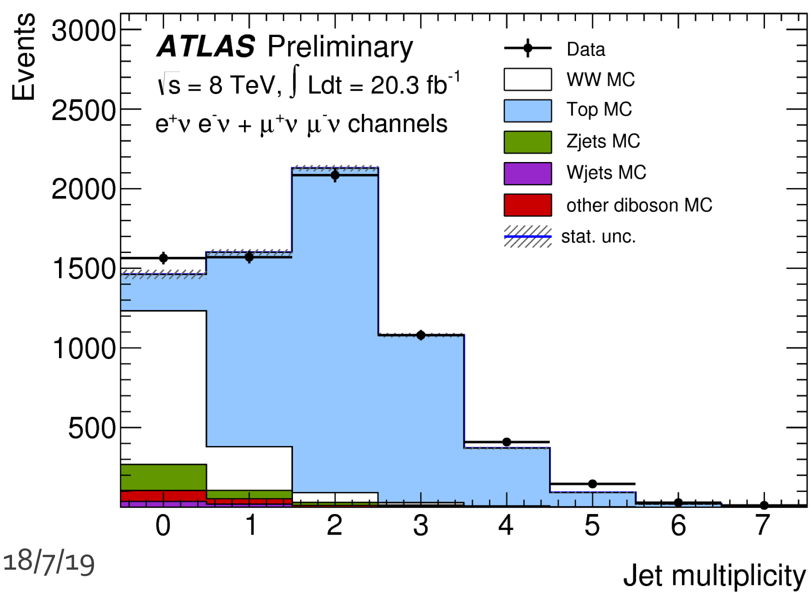
WW production via quark-antiquark annihilation(dominant) and gg-fusion

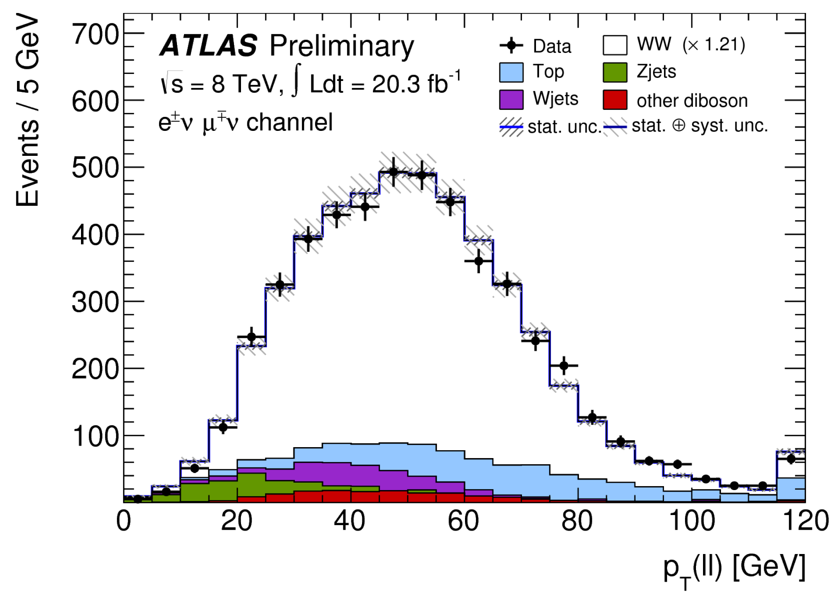




Bgd challenges: mainly Data-Driven (DD)
ttbar(DD: high #jet), DY(DD: low E_T^{miss}, low dilep pT)
W+X(DD: lepton fake), other diboson (MC)

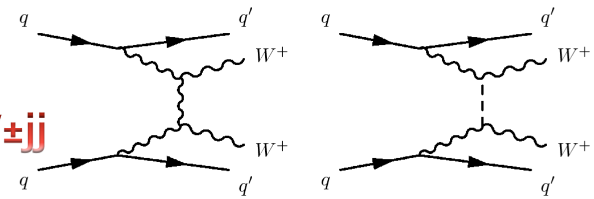
$$\sigma_{WW}^{tot} = 71.4\ ^{+1.2}_{-1.2}(\text{stat})\ ^{+5.0}_{-4.4}(\text{syst})\ ^{+2.2}_{-2.1}(\text{lumi})\ \text{pb}$$



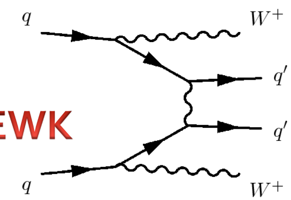


First evidence of Vector Boson Scattering in W±W±jj final state at 8TeV

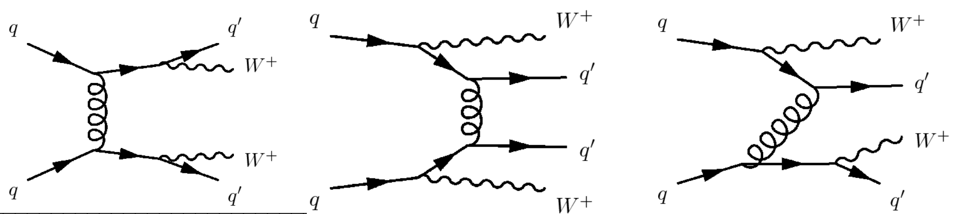
VBS W±W±jj

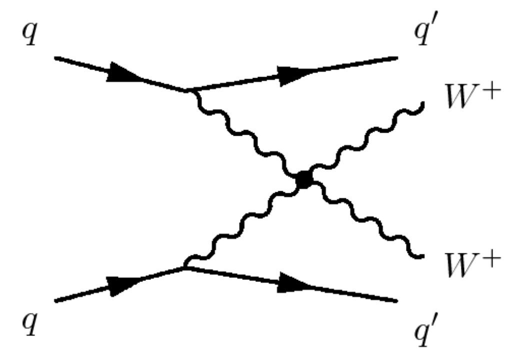


Non-VBS W±W±jj-EWK

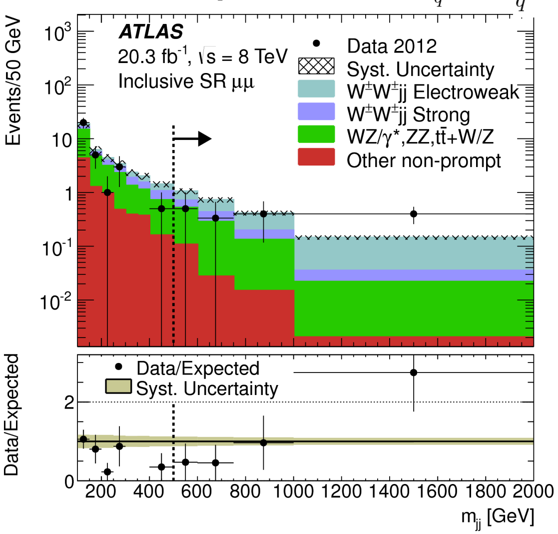


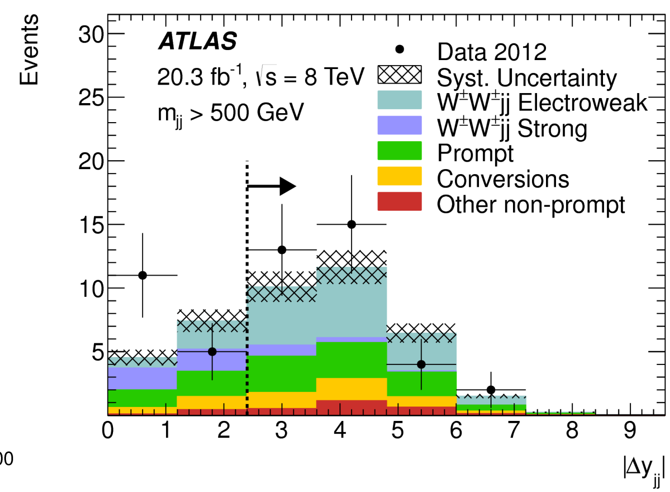
QCD W±W±jj

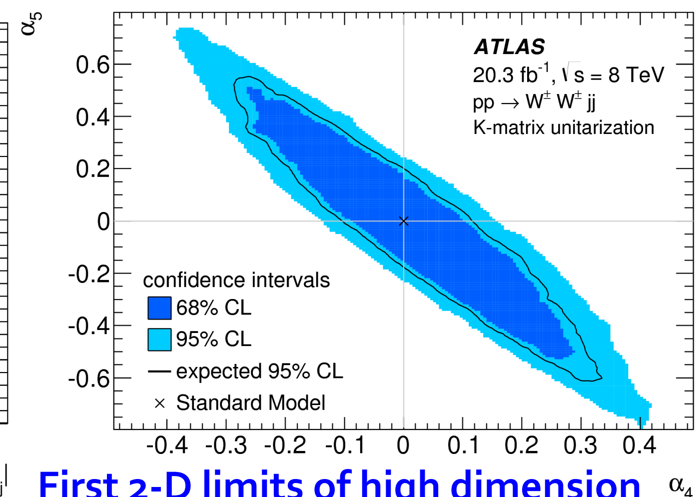




aQGCs of WWWW



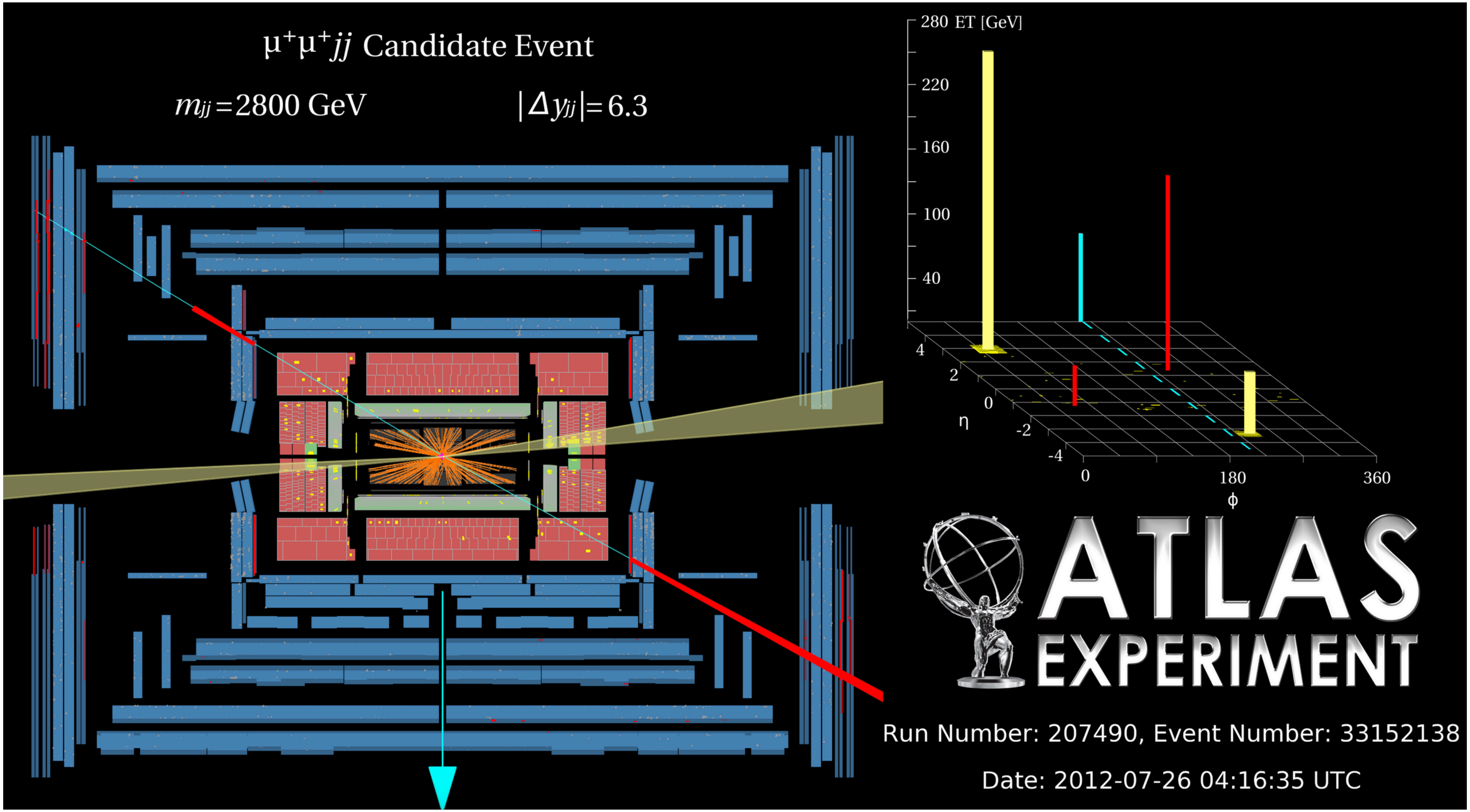




Signal extracted with VBS topology selection: dY(jj)>2.4, M(jj)>500GeV, fully leptonic

First 2-D limits of high dimension operators α_4/α_5 using measured cross-section in a VBS fiducial region k-matrix unitarized

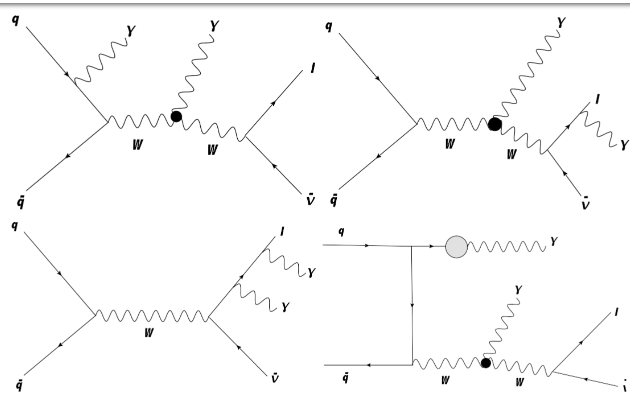
Event Display of a $W^{\pm}W^{\pm}jj$ VBS candidate



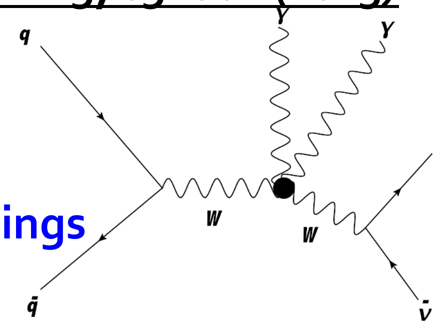
First evidence of tri-boson production in Wγγ final state at 8TeV

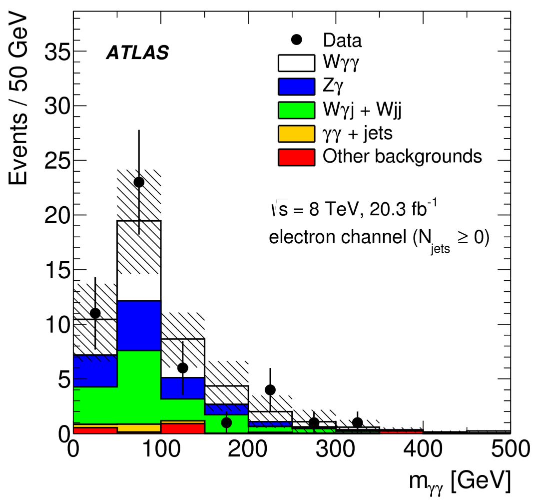
Phys. Rev. Lett. 115, 031802 (2015)

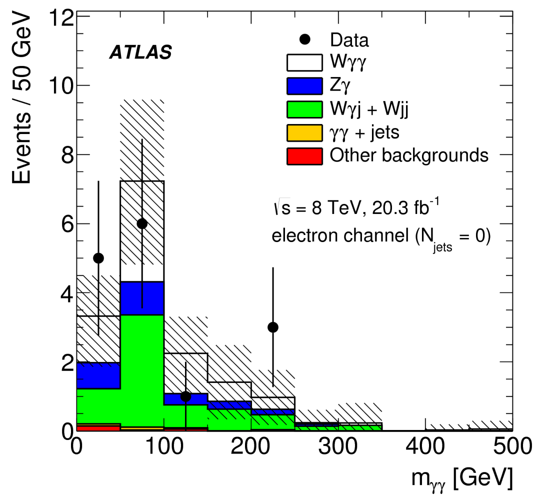
Wγγ topologies

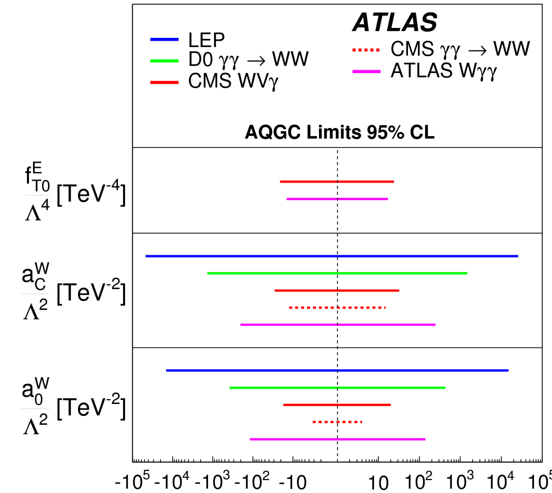


Anomalous Quartic Couplings





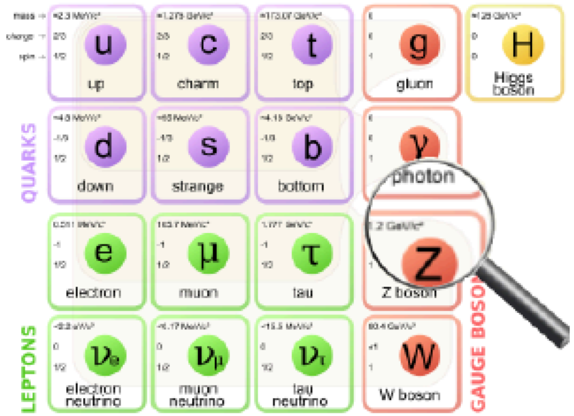




Cross section measured in fully leptonic (e/μ) channels
For inclusive(#jet>=0) and exclusive(#jet==0) regions

First triboson aQGC limits of high dimension operators f_{T0}, a_0^W and a_C^W, determined in jet-exclusive region with Mγγ>300GeV, dipole-FF unitarized

Zγ(γ) topologies in short

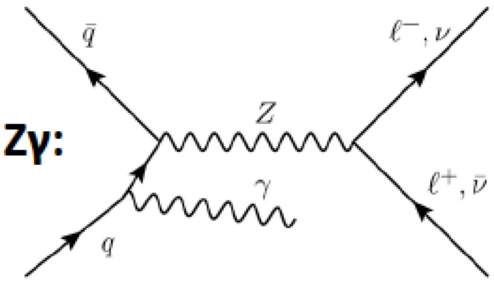


Measured processes

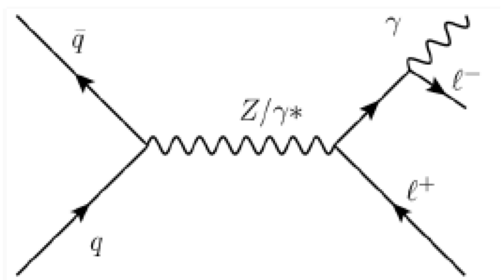
Study of Zγ and Zγγ production probes EW sector via interactions between two types of neutral bosons.

SM diagrams

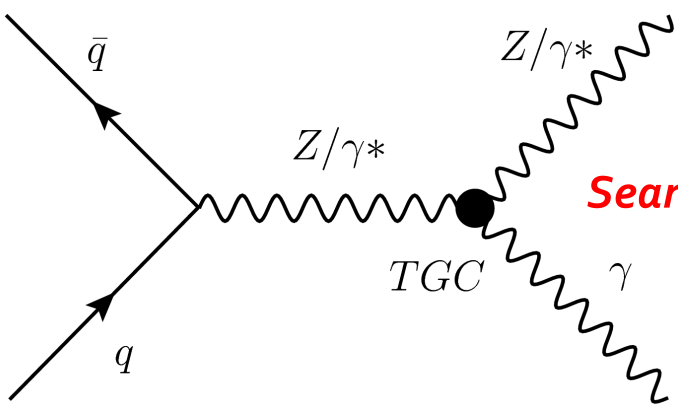
Zγ:



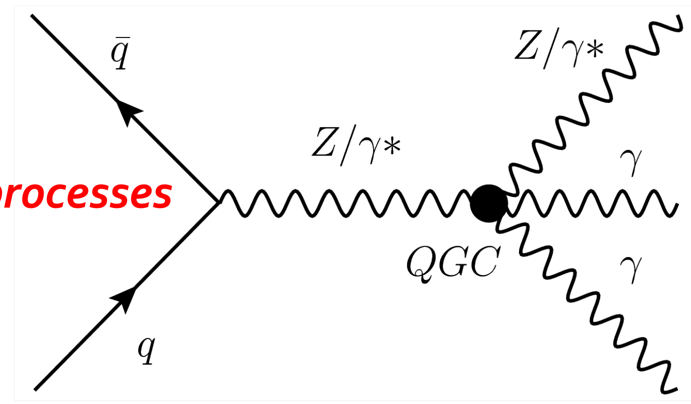
Initial state radiation (ISR)



Final state radiation (FSR)

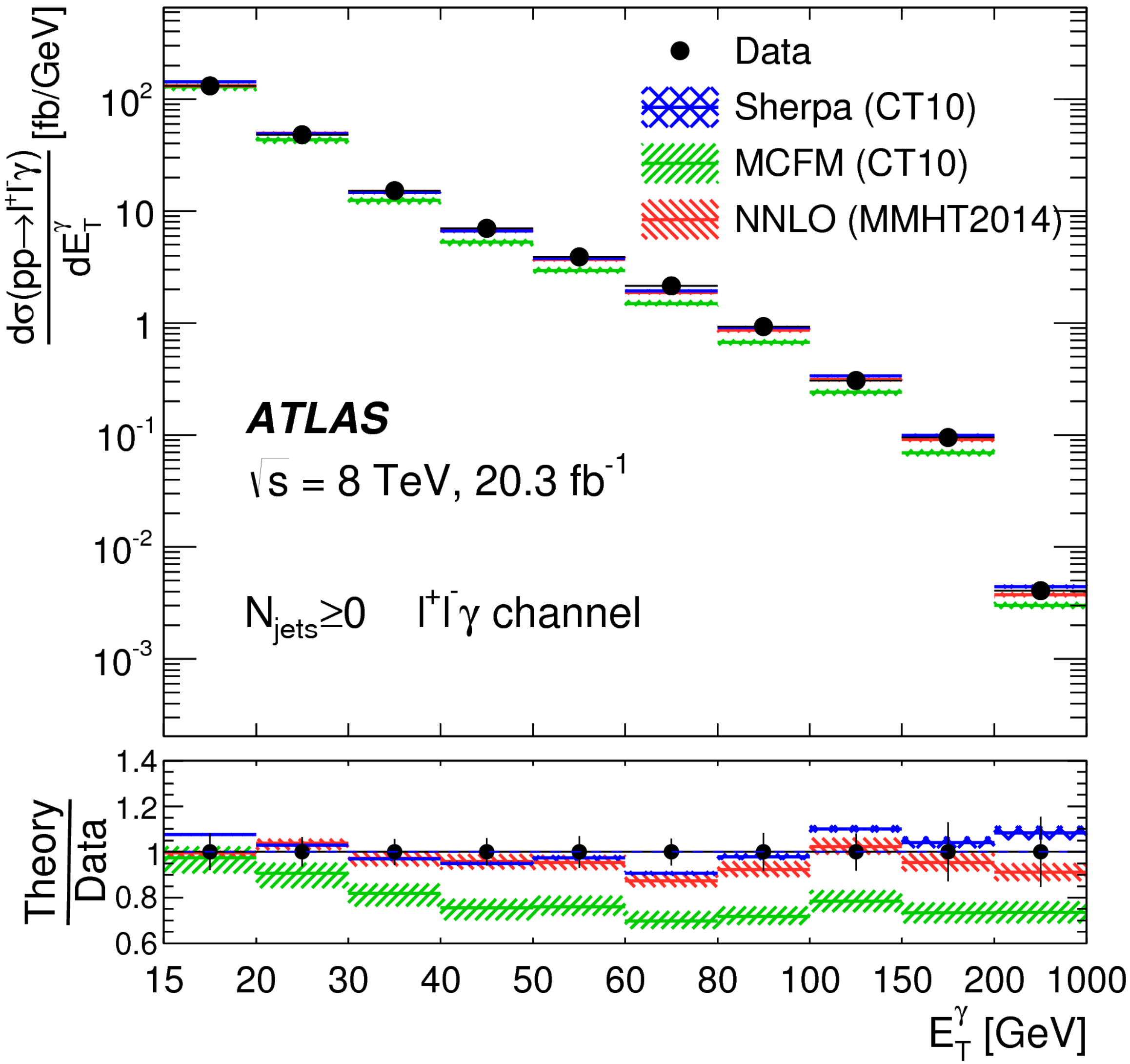


Searched processes



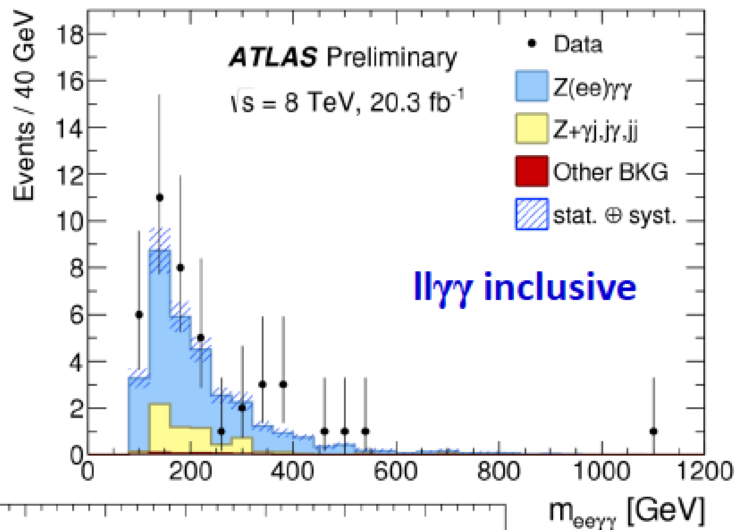
Zγ: SM Measurements vs SM Theory prediction (w/ high order corrections)

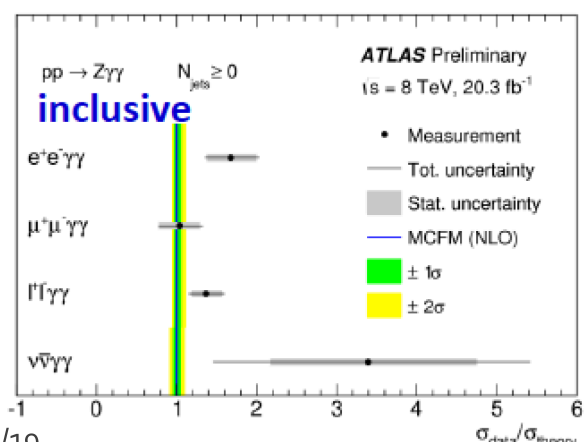
Measured Cross section Can only agree with theory prediction when NNLO correction is adopted



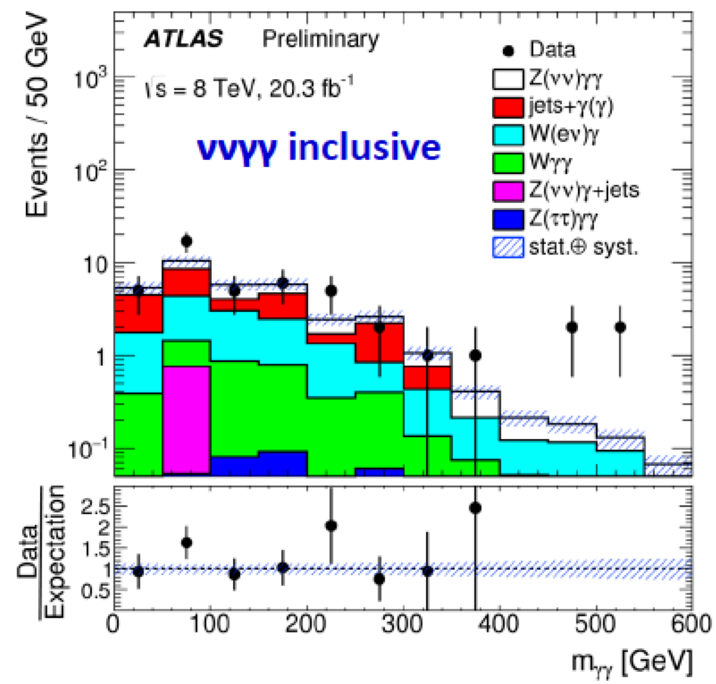
Zγγ: SM Measurements vs SM Theory prediction (First ever Discovery)

llγγ channels have 1 data-driven background Z+jets/γjets, which is dominant and estimated using matrix CRs method.





ννγγ channel has several data-driven backgrounds: γ+jets, W(lν/τν)+γγ and W(eν)γ, which are estimated either by CRs constructions or by 2D sidebands.



The shapes agree well for *llγγ* and fairly well for *ννγγ* between Zγγ data candidates and the expectations within uncertainties

Significance for *llγγ* combination is more than 5 sigma.

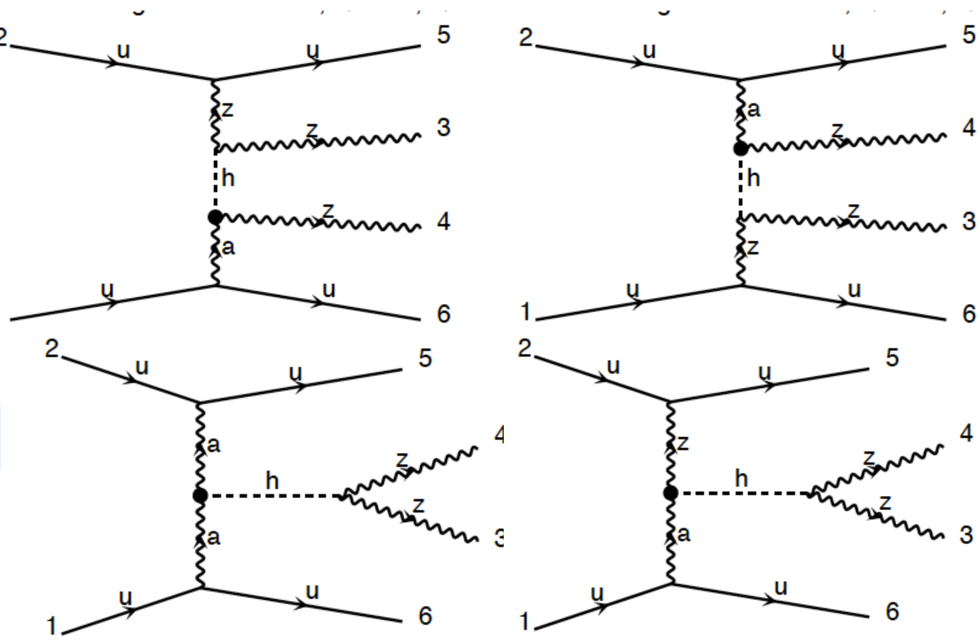
EFT with Dim6 operators II

- We choose to test dim6 operators unique to VBS
- Not constrained by inclusive diboson
- Fully gauge invariant

$$\mathcal{O}_{\phi d} = \partial_\mu \left(\phi^\dagger \phi\right) \partial^\mu \left(\phi^\dagger \phi\right)$$

$$\mathcal{O}_{\phi W} = \left(\phi^\dagger \phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}]$$

$$\mathcal{O}_{\phi B} = \left(\phi^\dagger \phi\right) B^{\mu\nu} B_{\mu\nu}$$

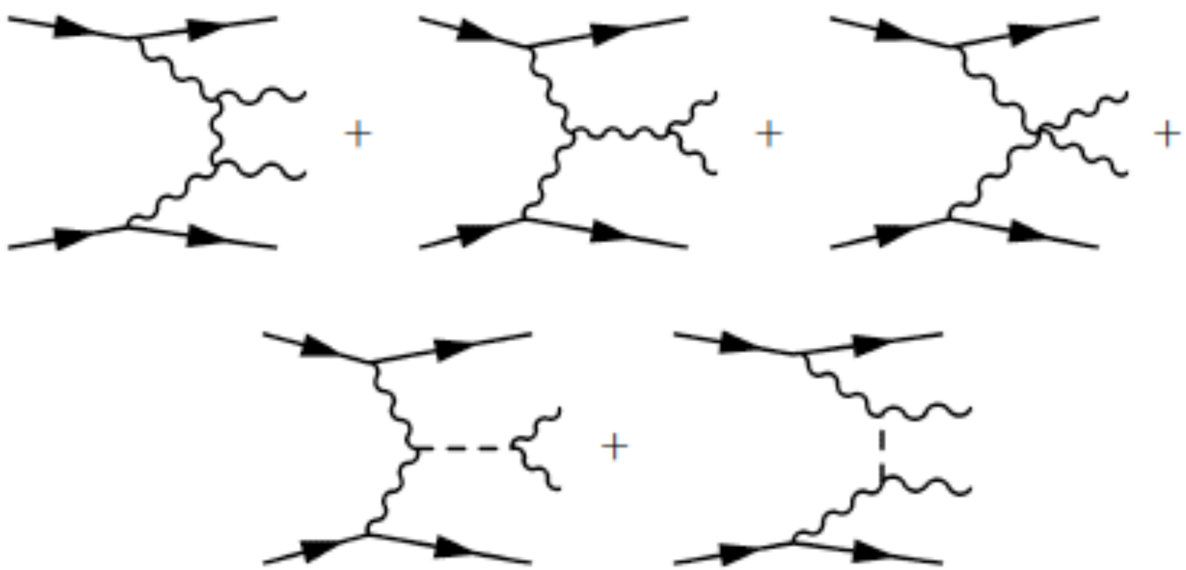


New physics (NP) on TGC vertices

EFT with dim8 operators I

- Assuming Higgs boson belongs to a $SU(2)_L$ doublet
- dimension 8: the lowest dimension operators exhibiting quartic couplings in VBS but NOT in two or three gauge boson vertices

EW signal with Vector Boson Scattering Topology:



EFT with dim8 operators II

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

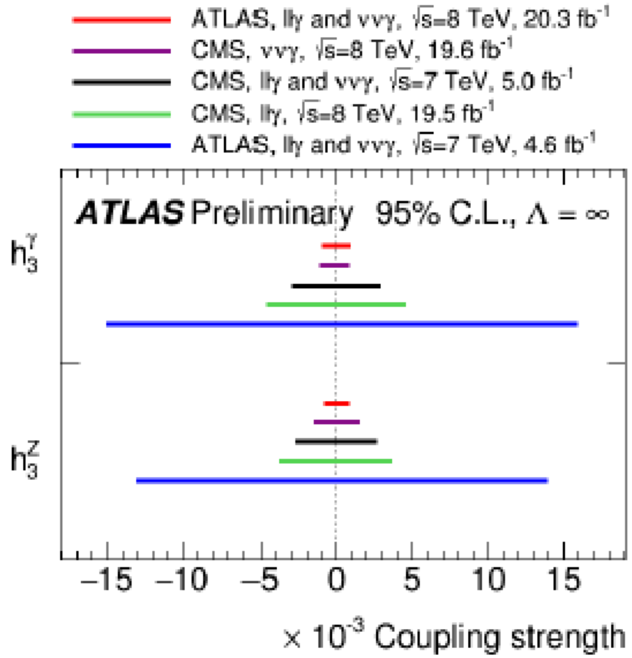
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

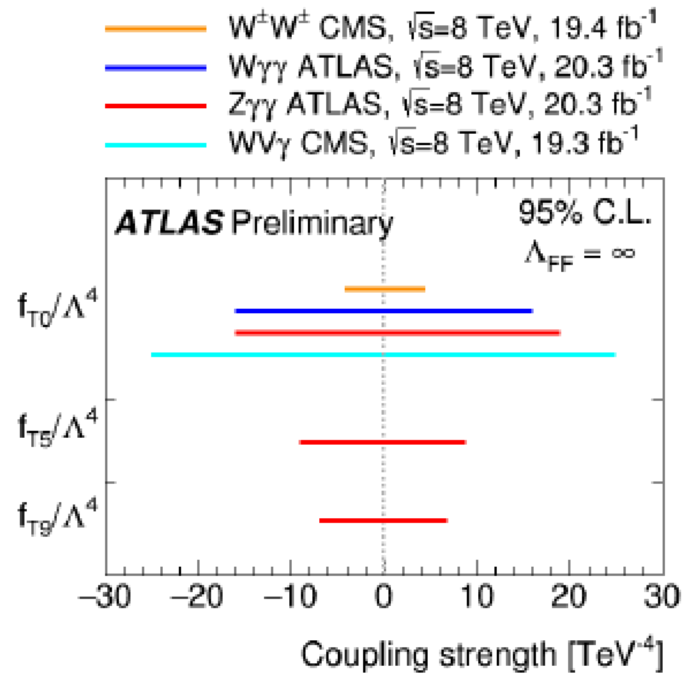
$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

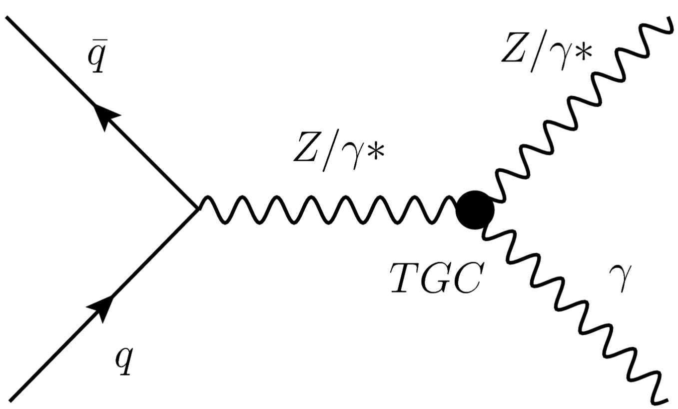
$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

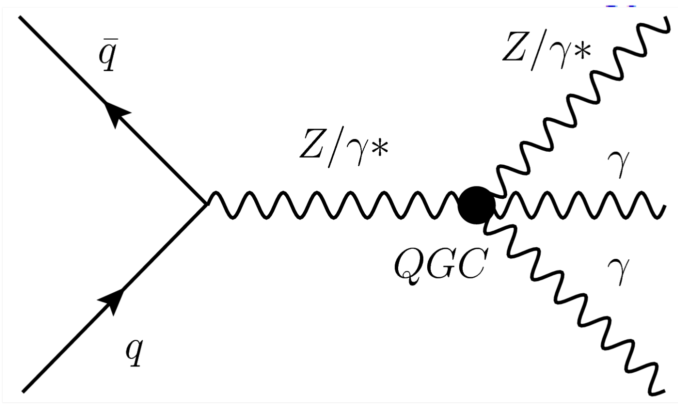
- Currently available dim8 operators in MadGraph
  - LS0,LS1: wwjj, wzjj, zzjj
  - LM0,LM1: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz,zzz
  - LM2,LM3: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz, zzz
  - LT012: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz, zzz
  - LT8,LT9: zzjj, zajj, zaa, zza, zzz

Anomalous coupling summary and comparisons

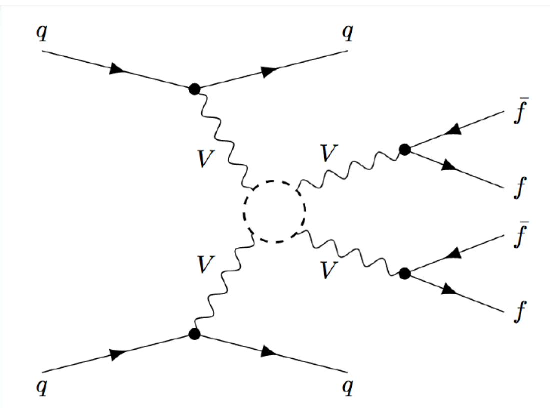


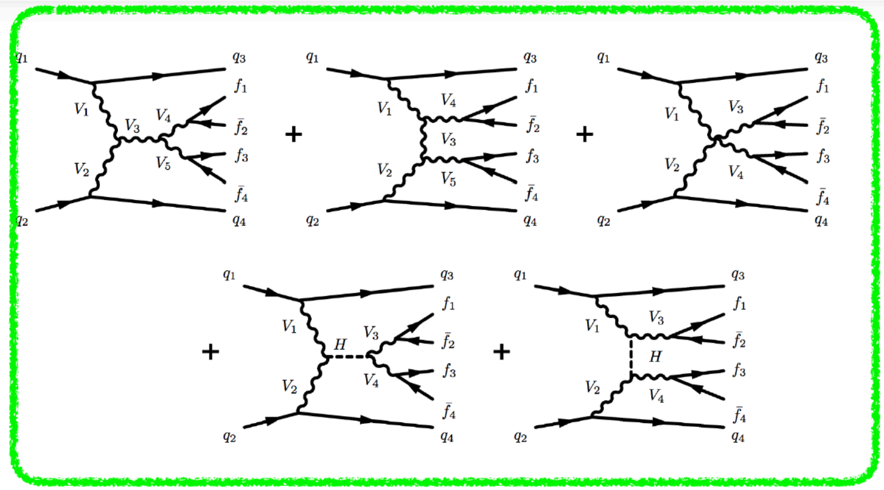






Vector Boson Scattering

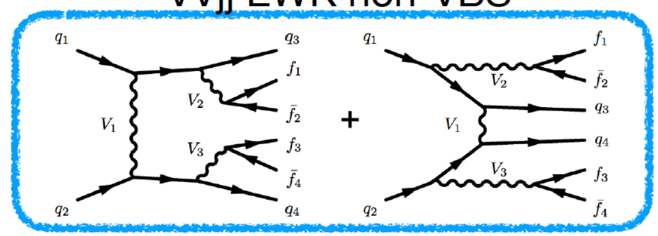




VV→VV scattering is a key process to probe the nature of electroweak symmetry breaking:

Higgs mechanism is required to unitarise longitudinal scattering $V_LV_L \rightarrow V_LV_L$ at high s

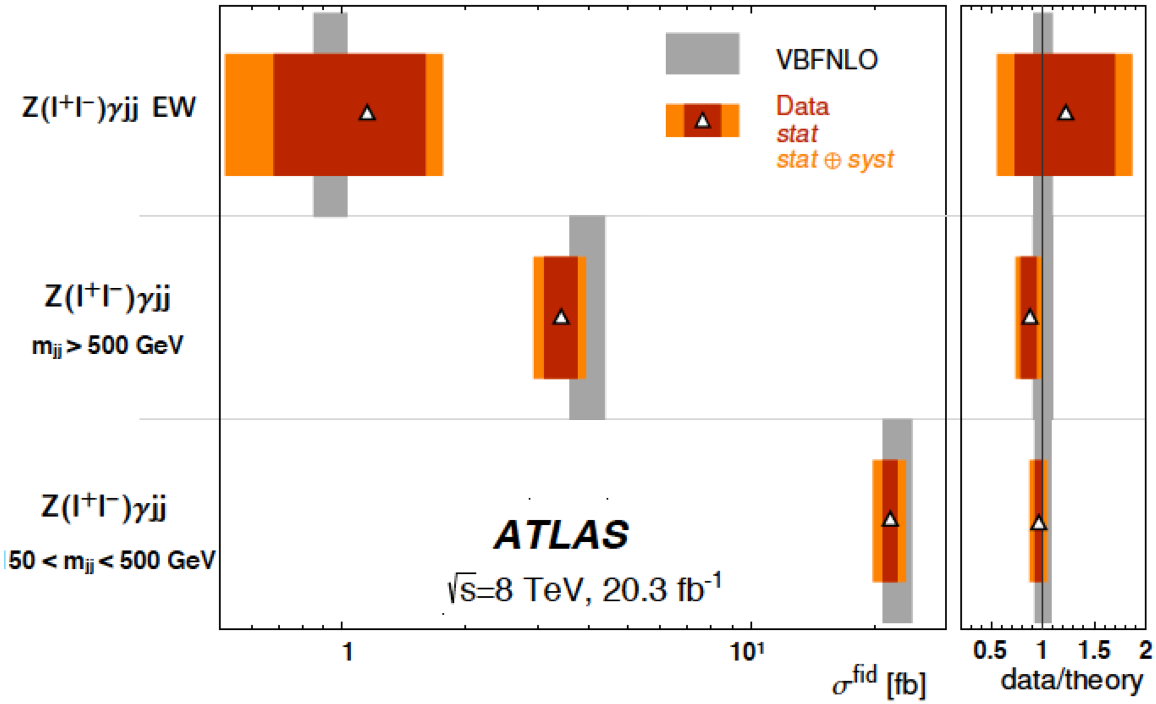
VVjj EWK non-VBS

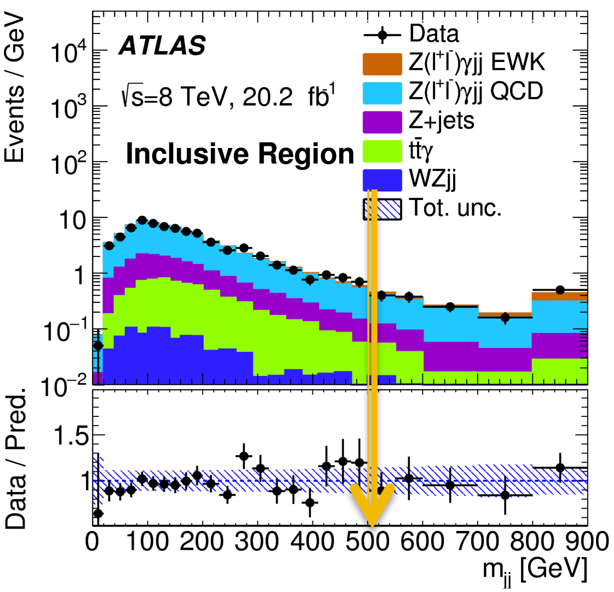


EWK VBS and EWK non-VBS processes cannot be separated in a gauge invariant way
=> both components are included in signal definition

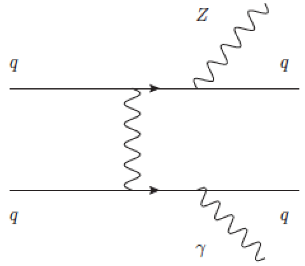
First ever Measurement of Zγ+jj Electroweak production in ATLAS

JHEP07(2017)107

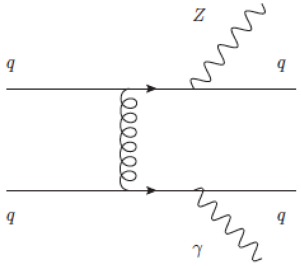




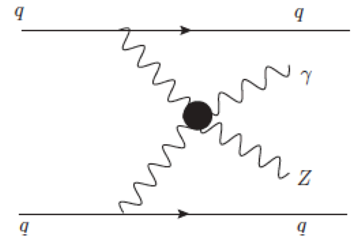
EW Zγjj Signal



QCD Zγjj Background



New Physics Vertex (BSM signal)

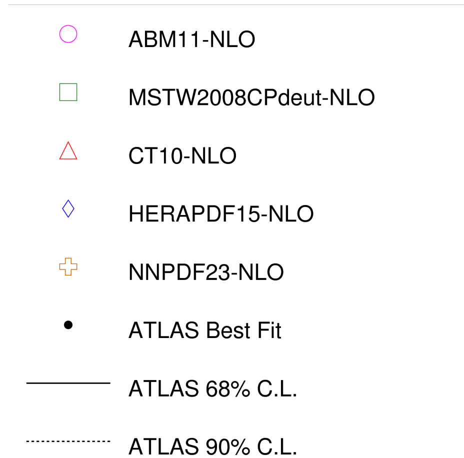


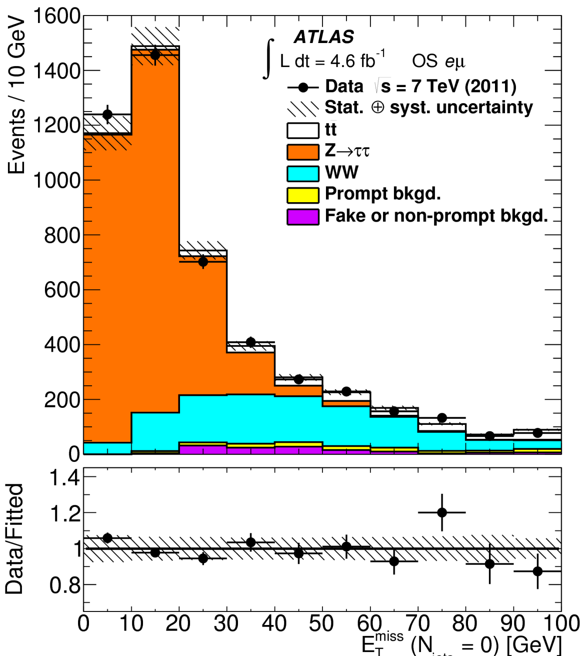
AIDA: Simultaneous measurements of the ttbar, WW, and Z→ττ production cross-sections at 7TeV

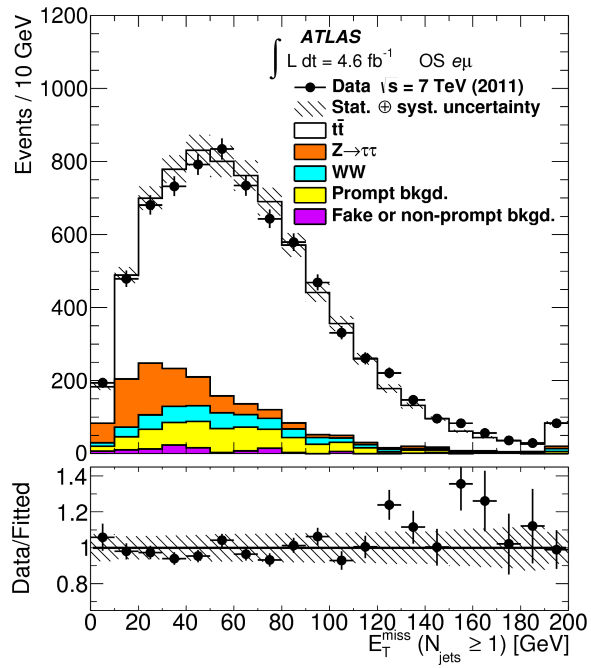
Global test of SM predictions of a common final state including Opposite Charge high pT eμ pairs, which specifically covers:

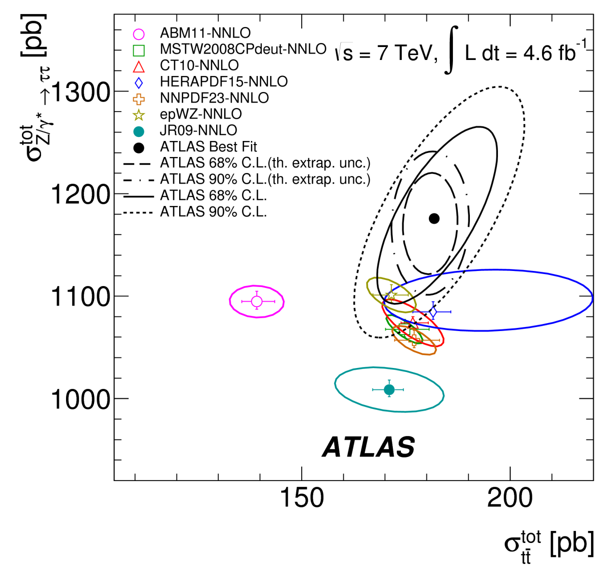
- ✧ ttbar (high E_t^{miss} and high #jet)
- ✧ WW (high E_t^{miss} and low #jet)
- ✧ DY $Z/\gamma^* \rightarrow \tau\tau$ (low E_t^{miss} and even lower #jet)

Motivation: broader test than dedicated measurements; probe effects of PDF accounting correlations; improve theo. calc. and SM bgd constraints



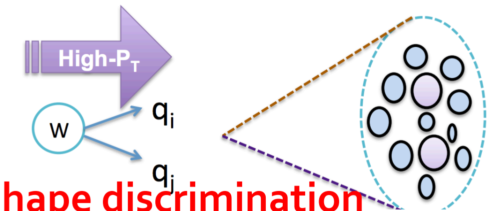






Measurement of the cross-section of high p_T single bosonic jets and studies of jet substructure at 7TeV

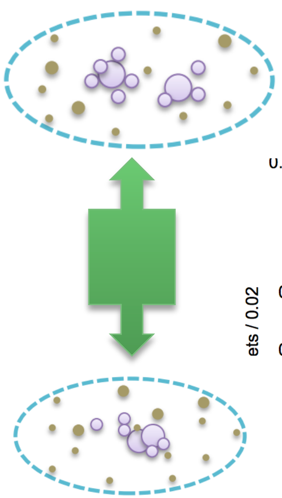
In boosted regime, close-by outgoing quarks from high momentum bosons can merge into one fat jet after hadronization and clustering

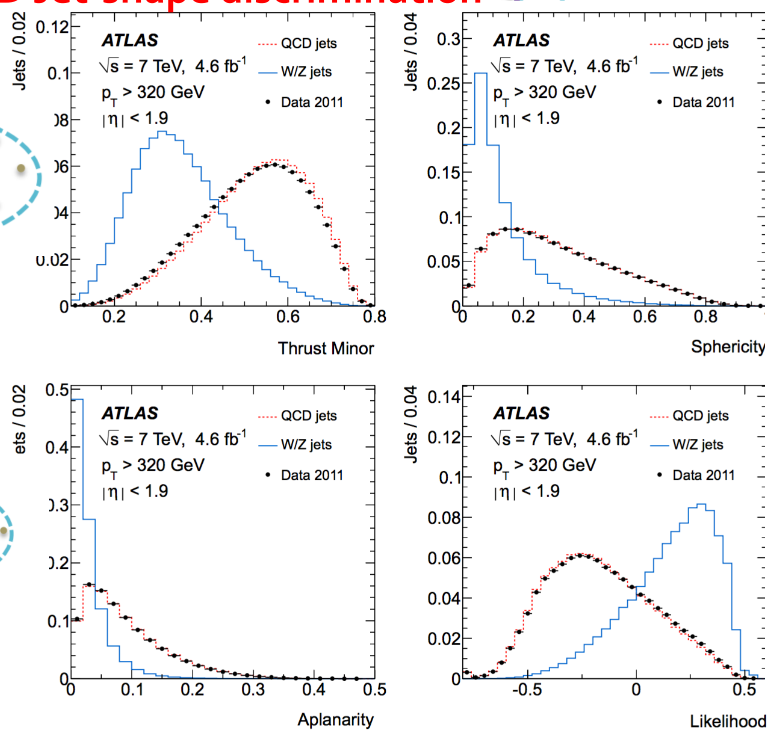


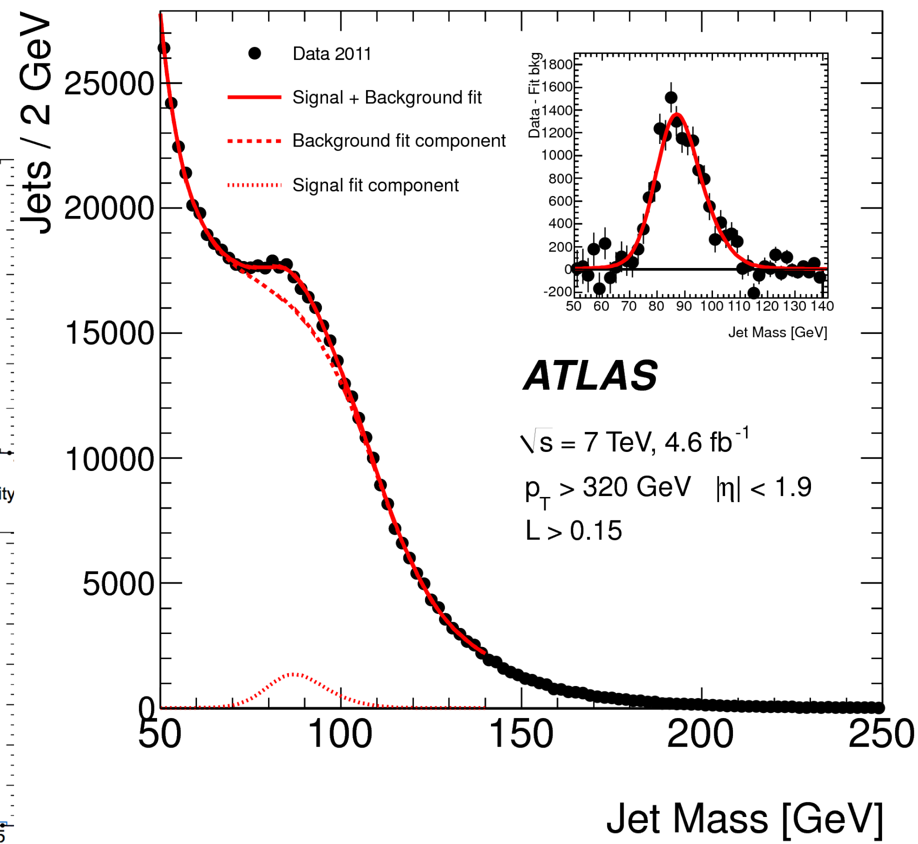
$$\sigma_{W+Z} = 8.5 \pm 0.8\ (\text{stat.}) \pm 1.5\ (\text{syst.})\ \text{pb}$$

Measured X-sec agrees with theory prediction within 2σ $\sigma_{W+Z} = 5.1 \pm 0.5\ \text{pb}$

Bosonic/QCD Jet-shape discrimination

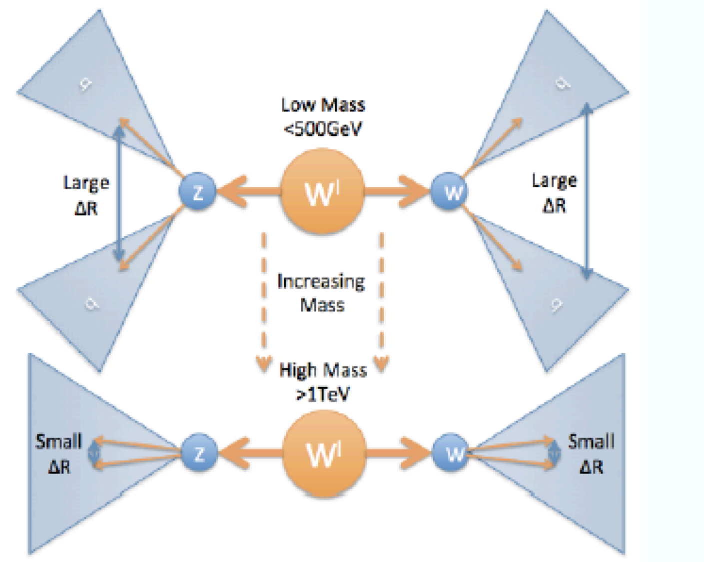


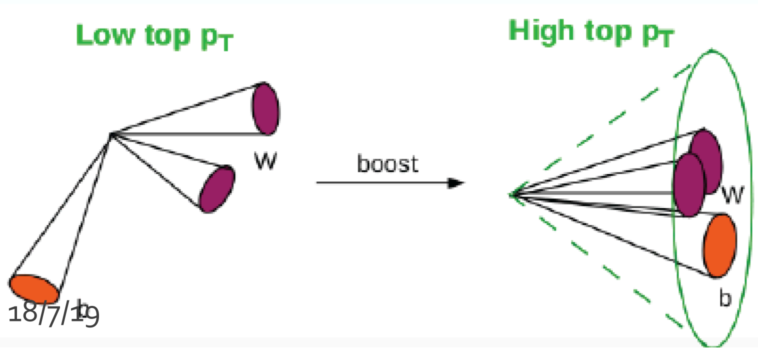




Boosted topology and experimental signature

- "Natural" angular separation $\Delta R \sim 2m/p_T$
- Resolved regime: the boson has relative low momentum in the lab frame so we are able to reconstruct one jet for each quark
- Boosted Regime: the boson has high momentum in the lab frame - the outgoing quarks are very close so the jets begin to merge

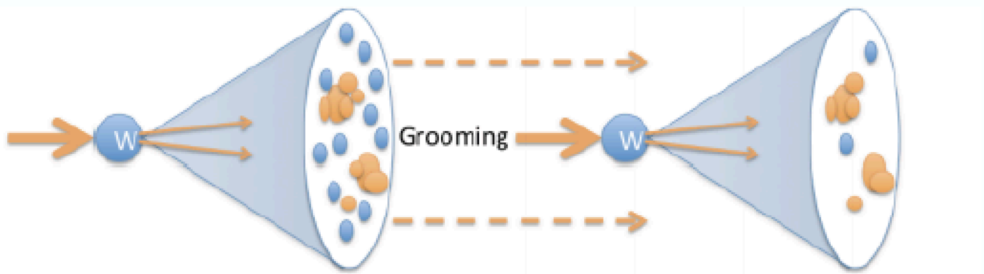




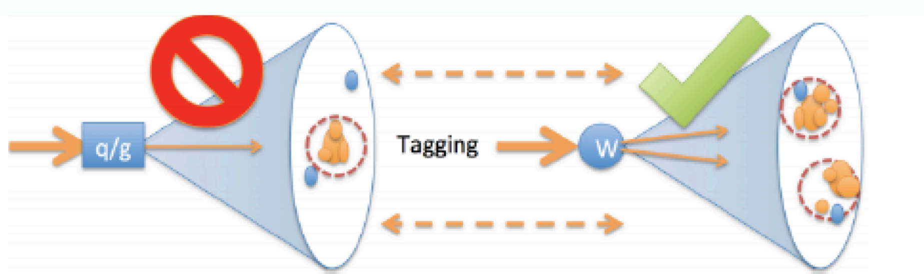
Traditional reconstruction techniques relying on one-to-one jet-to-parton assignment are inadequate

Boosted tagging techniques

1. Large-R jet: large distance parameter to pick up all the radiation from the original decay
2. Grooming (different techniques available):
   - Signal: take out jet constituents that don't belong to the signal decay
   - Background: preserve background characteristics in the jet



3. Tagging:
   - Use differences in signal and background jet characteristics to reject background jets



Summary

- SM measurements matters itself by definition
  - Solid validation of SM predictions and high precision/high order calculations of the SM coupling and interactions
  - Substantiate the findings of new physics signatures which decay into SM particles: irreducible backgrounds
  - Effective theory parameterization platform incorporating new physics inducing SM anomalous interactions

- Many Fruitful Run-I/II achievements in SM measurements and searches. Surely will be a continuous hotspot to explore further in a new Center-of-Mass energy era at ATLAS/LHC

谢谢