Multi-boson interactions at ATLAS: from measurements to searches

Shu Li

Division of Particle and Nuclear Physics,
Tsung-Dao Lee Institute
&
School of Physics and Astronomy,
Shanghai Jiao Tong University

Colloquium @ IHEP

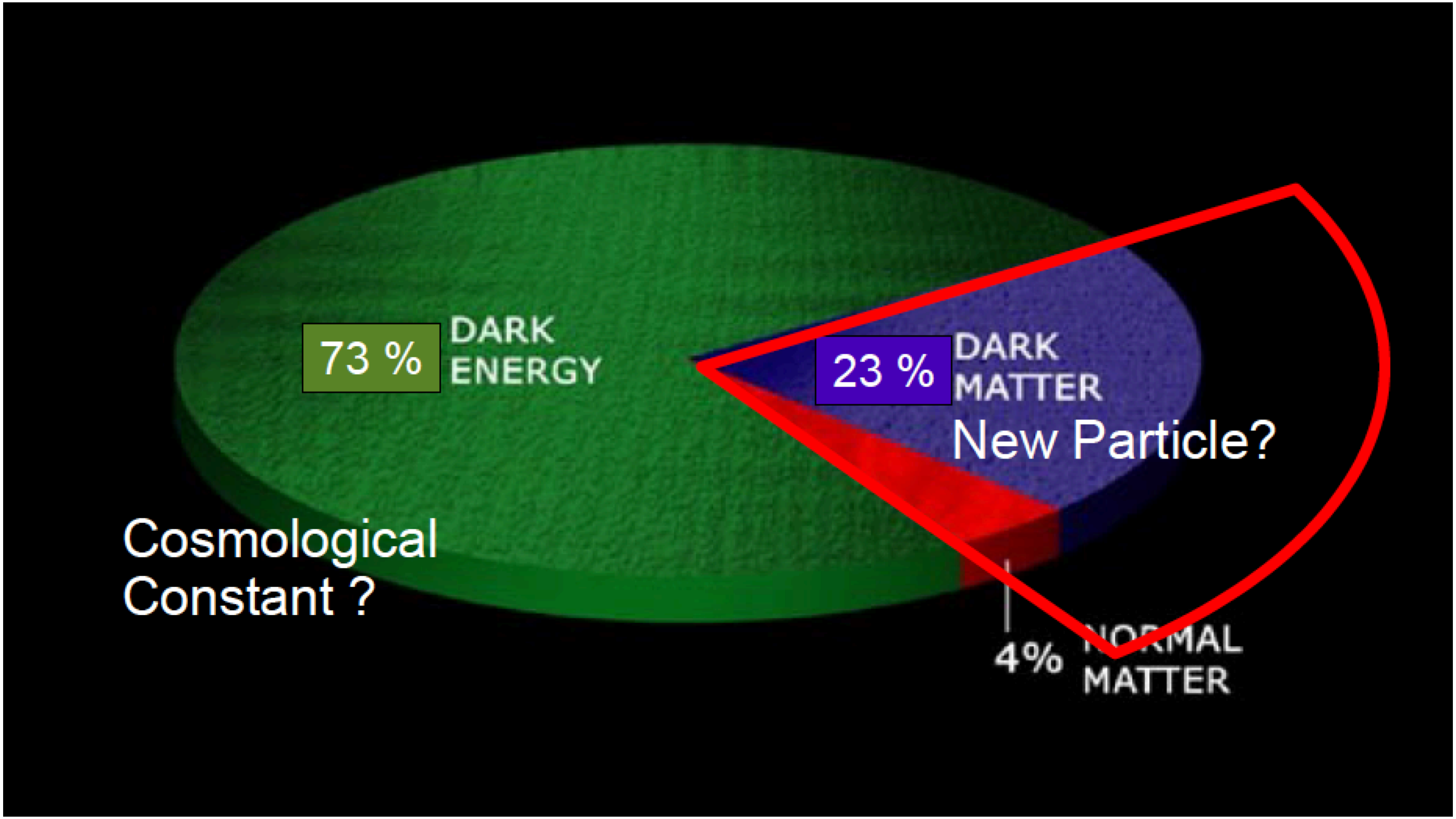
Bibliography

- 教育经历
  - 2004.9-2008.7，中国科学技术大学少年班学院，本科
  - 2009.9-2012.11，法国科学院马赛粒子物理中心/艾克斯-马赛大学，博士，导师：Emmanuel Monnier
  - 2008.9-2013.01，中国科学技术大学近代物理系,博士，导师：赵政国院士

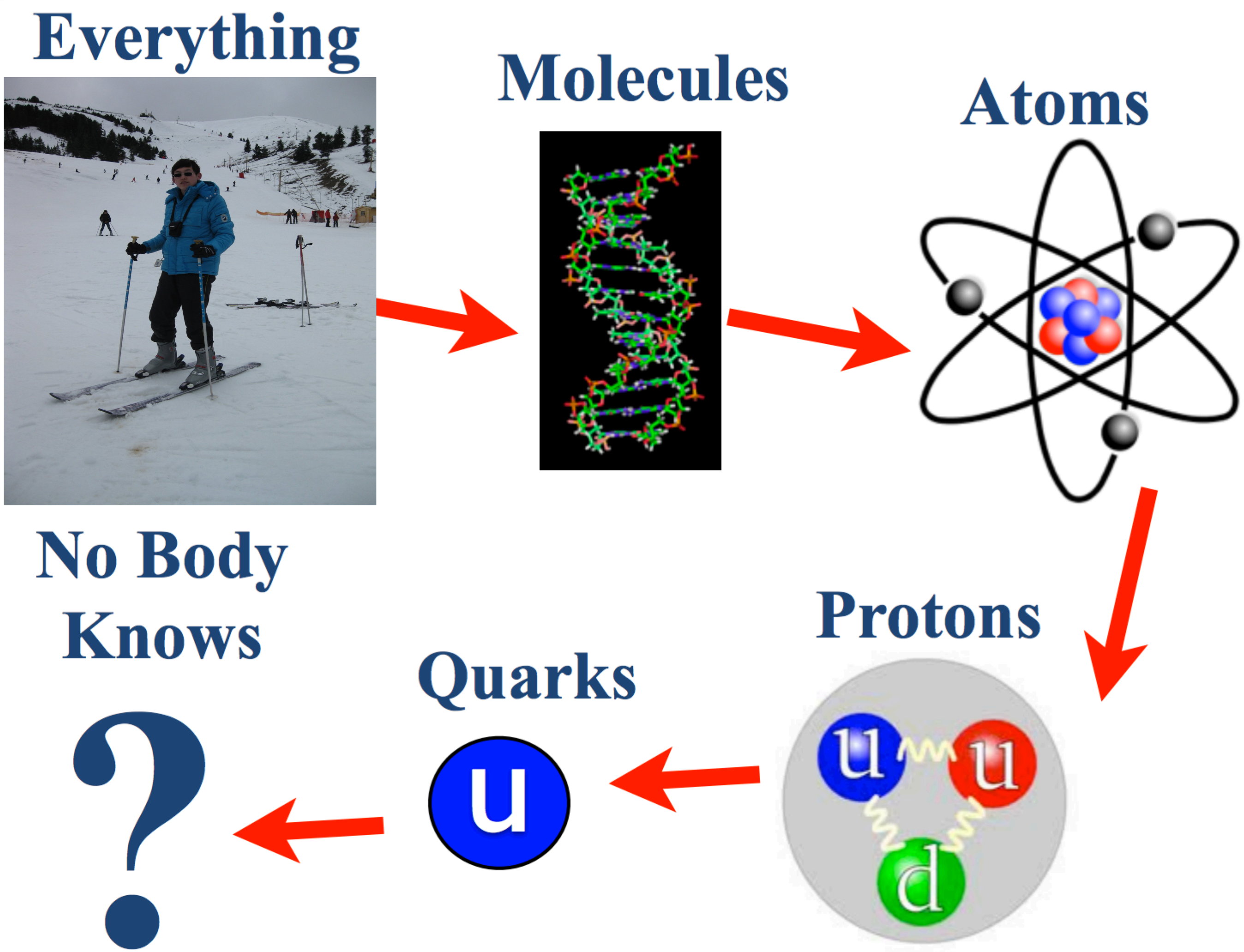
- 工作经历
  - 2013.2-2017.8，美国杜克大学物理系，博士后，导师：Ashutosh Kotwal（美国物理学会会士，Fritz London荣誉教授)
  - 2017.9至今，上海交通大学李政道研究所首位“李政道青年学者”，兼物理与天文学院双聘特别研究员，博士生导师

- 研究经历
  - 2009年至今，瑞士日内瓦欧洲核子中心，大型强子对撞机ATLAS大型国际合作项目成员，从事高能量前沿对撞机实验粒子物理研究，先后任标准模型电弱物理组、蒙特卡洛验证组、产生子研发组、LHC-电弱多玻色子工作组负责人(convener)

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



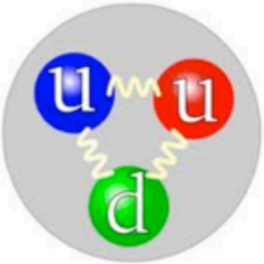
What our world looks like?



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)

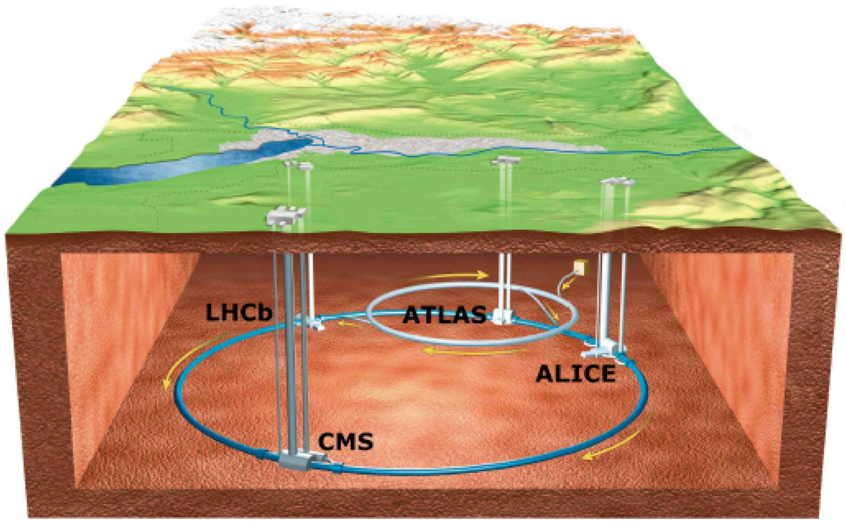
Worlds largest particle accelerator with the highest center of mass energy at CERN near Geneva, ~27 km tunnel spanning the border of France and Switzerland

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

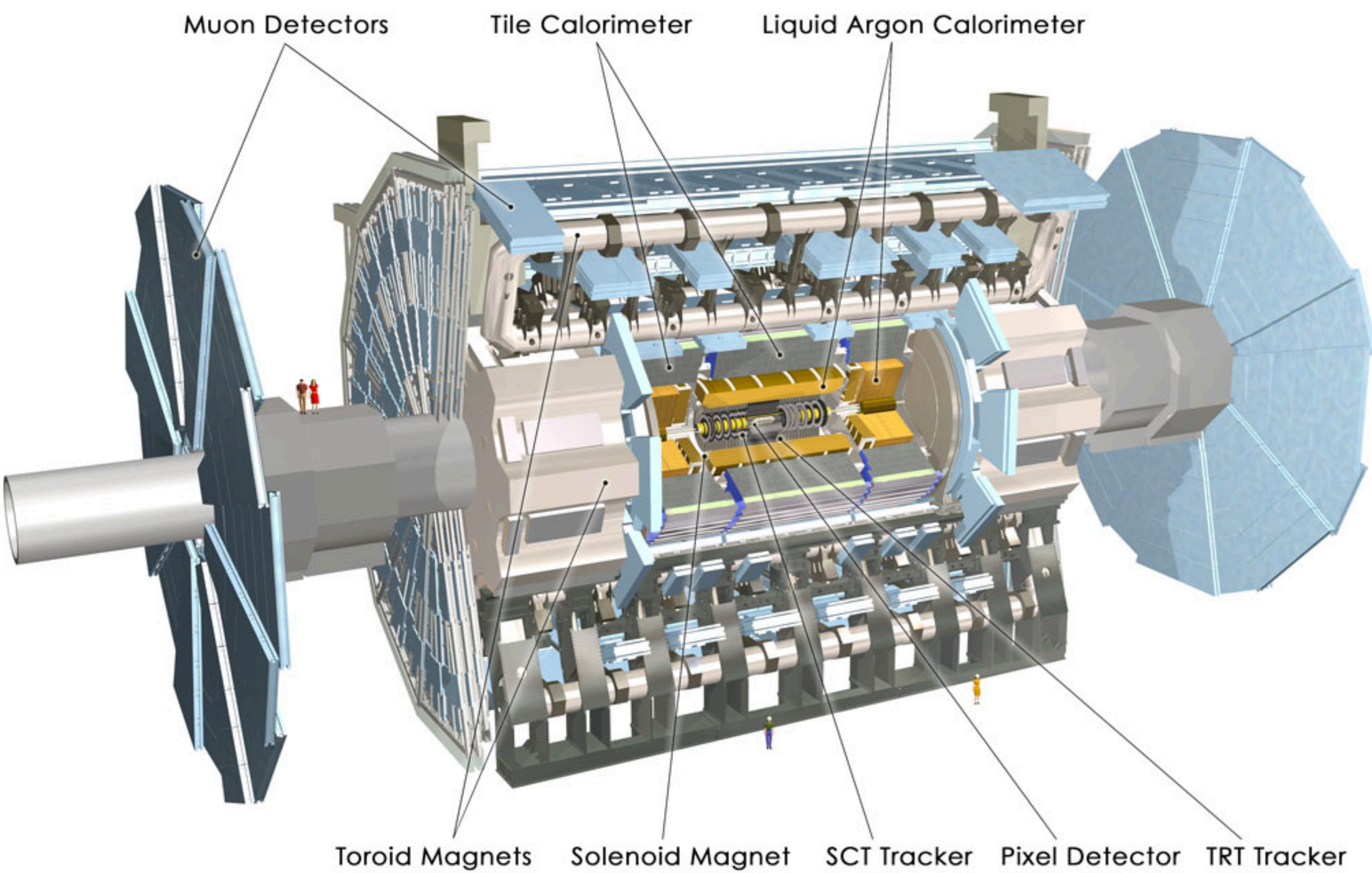
$\sqrt{s} = 7/8$ TeV (designed energy: 14 TeV) for proton-proton collision and 2.76 TeV for Pb-Pb nuclei collision

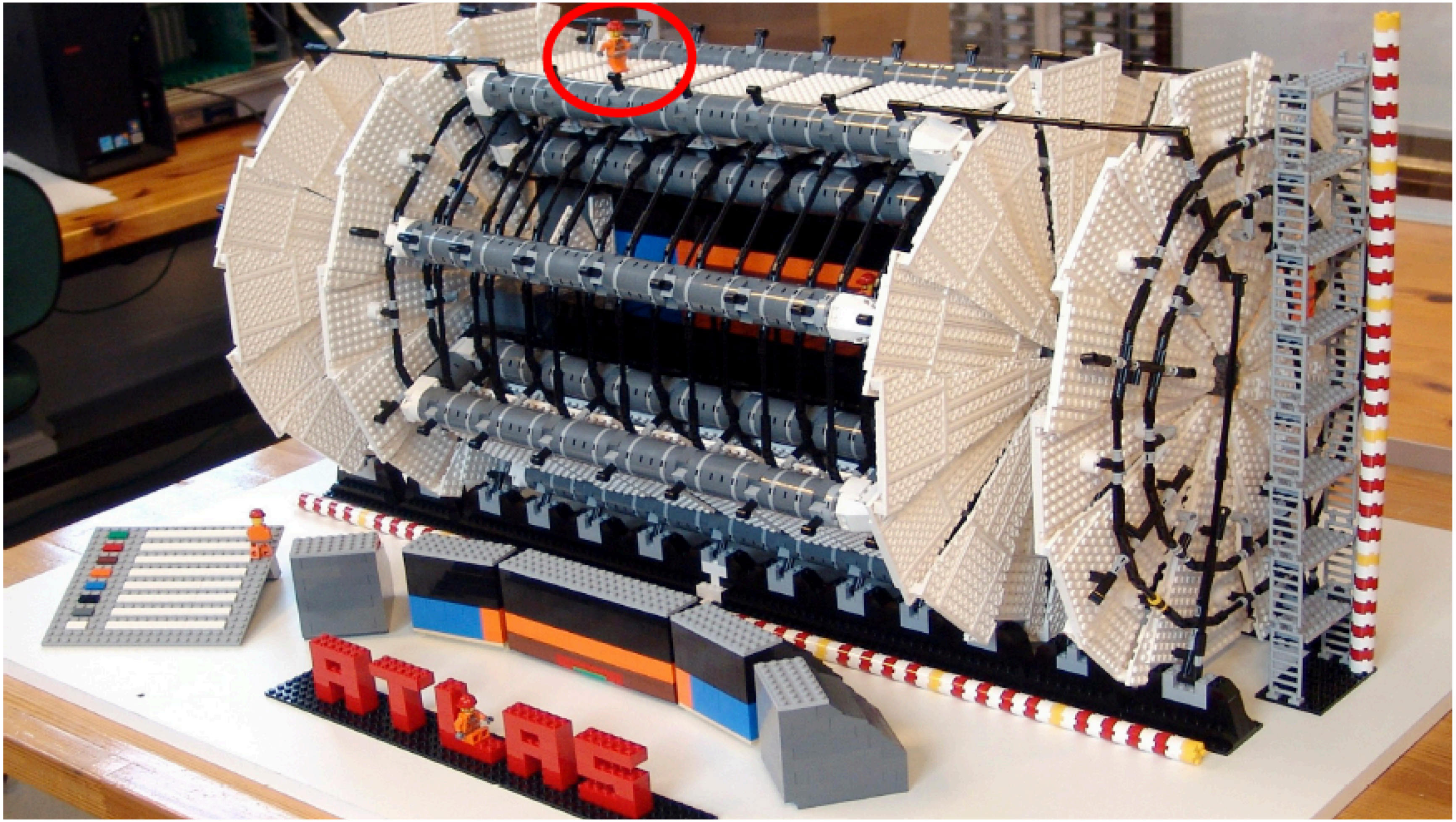
Six major detectors located at four collision points:
ALICE, **ATLAS**, CMS, LHCb, LHCf, TOTEM

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: $10^{32} cm^{-2} s^{-1}$



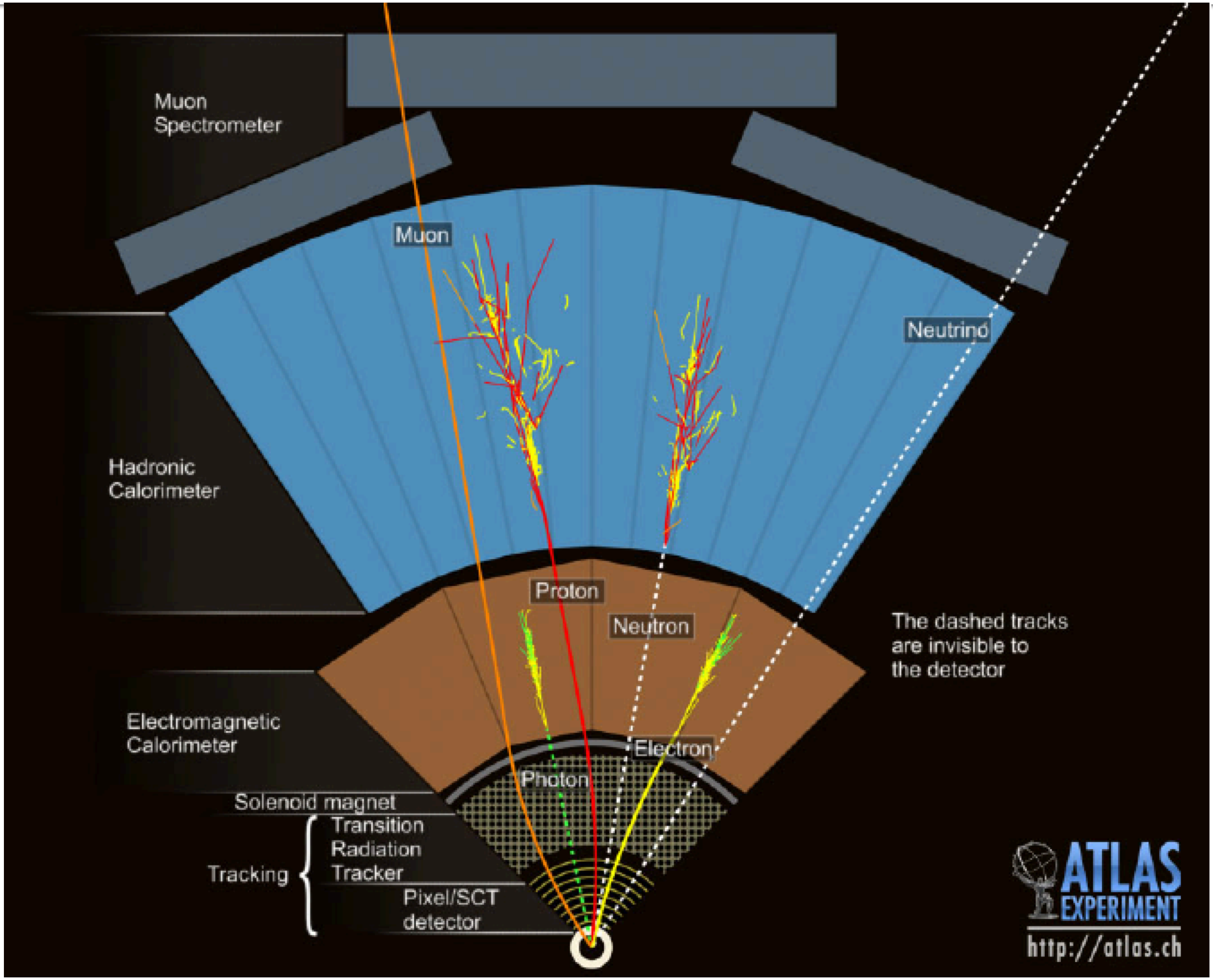
About ATLAS: general purpose experiment covering SM




ATLAS

Really Big Camera!!!

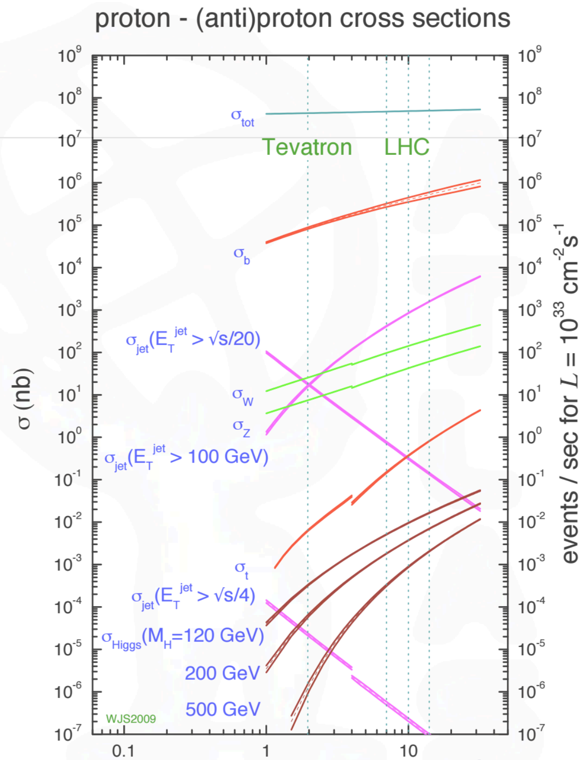
ATLAS particle identifications



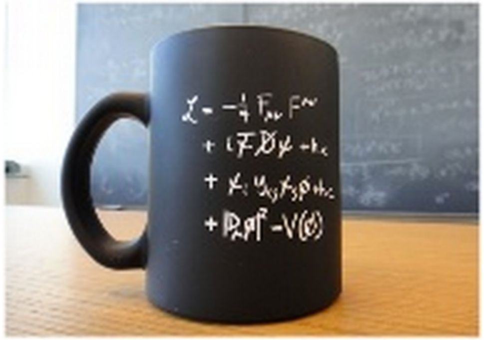
Standard Model Shortly

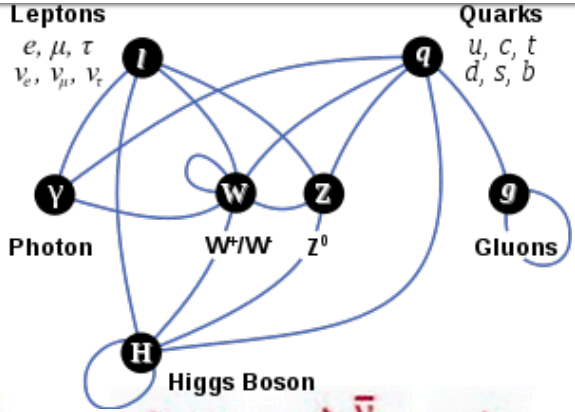
Applausive arguments:

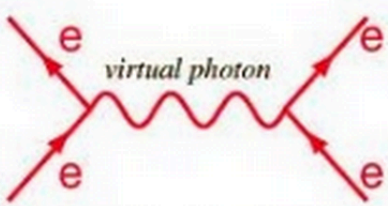
SM widely succeeded in describing fundamental particles and Interactions with very few ingredient over reasonably broad range of energies



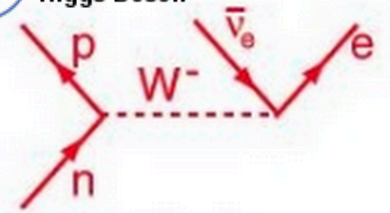
J. Stirling



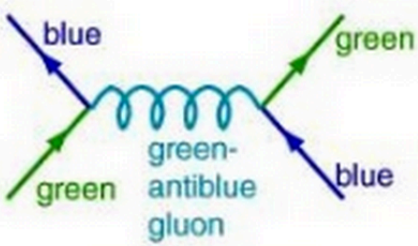




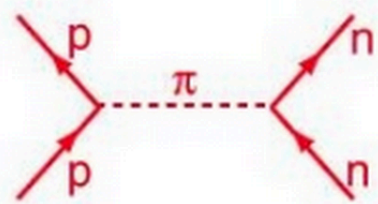
Electromagnetic Interaction



Weak Interaction



between quarks

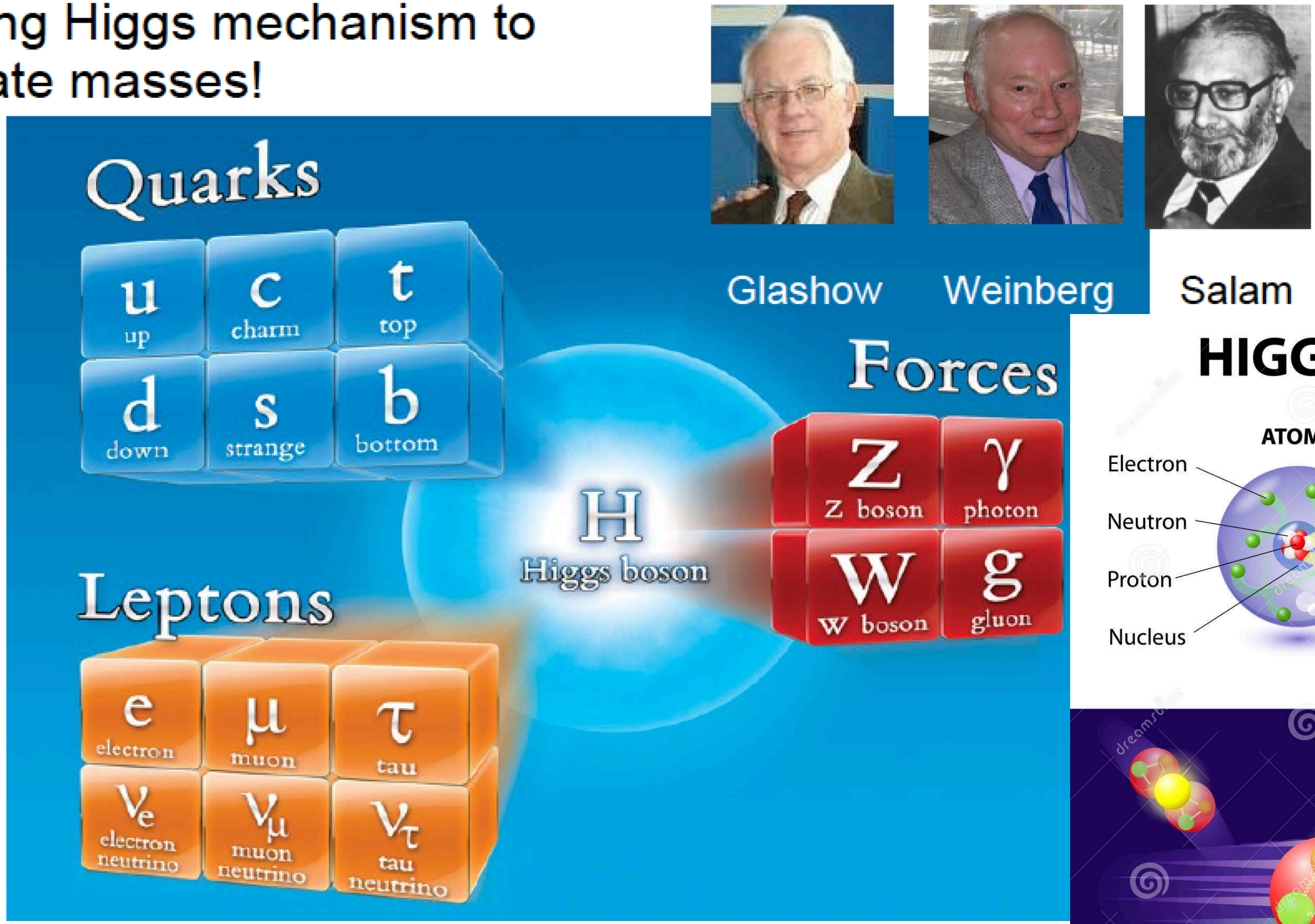


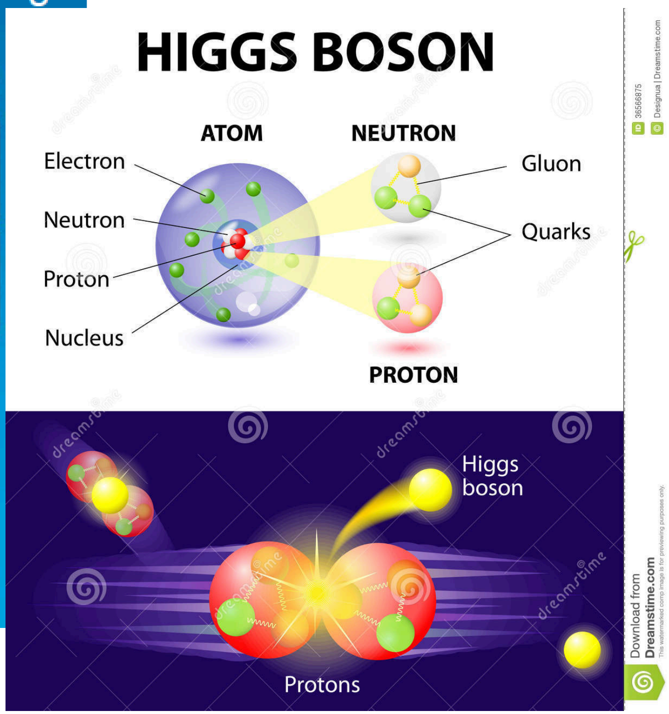
between nucleons

Strong Interaction

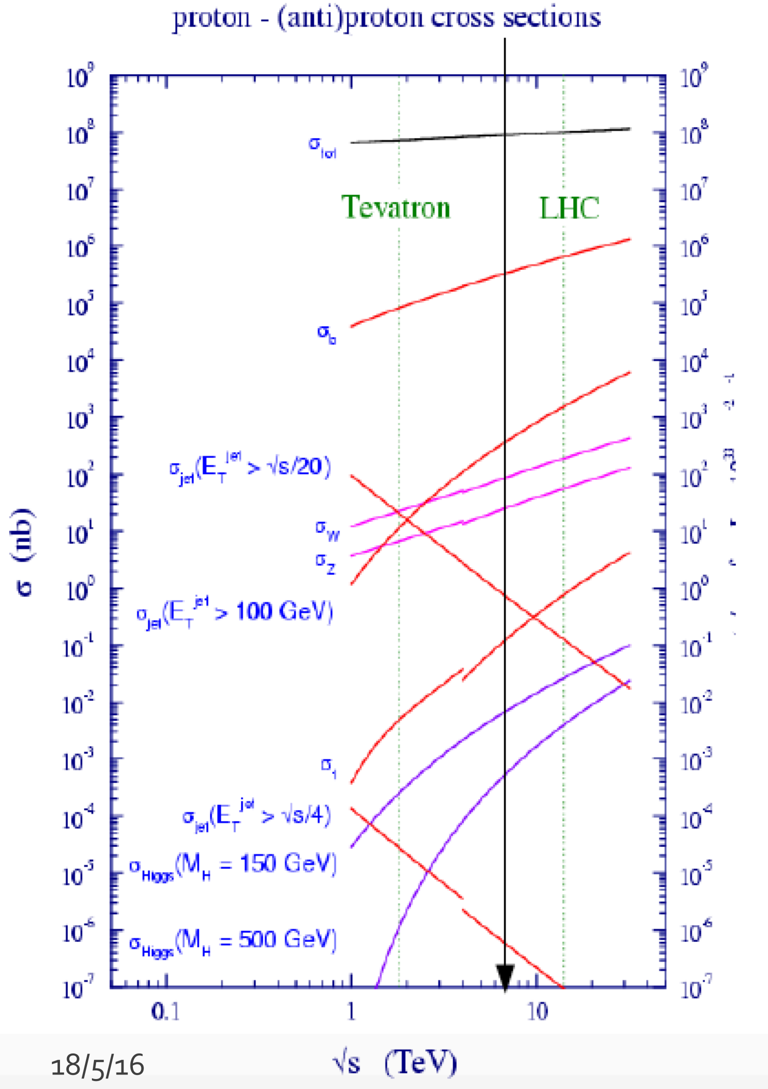
Higgs mechanism gives birth to SM particle mass

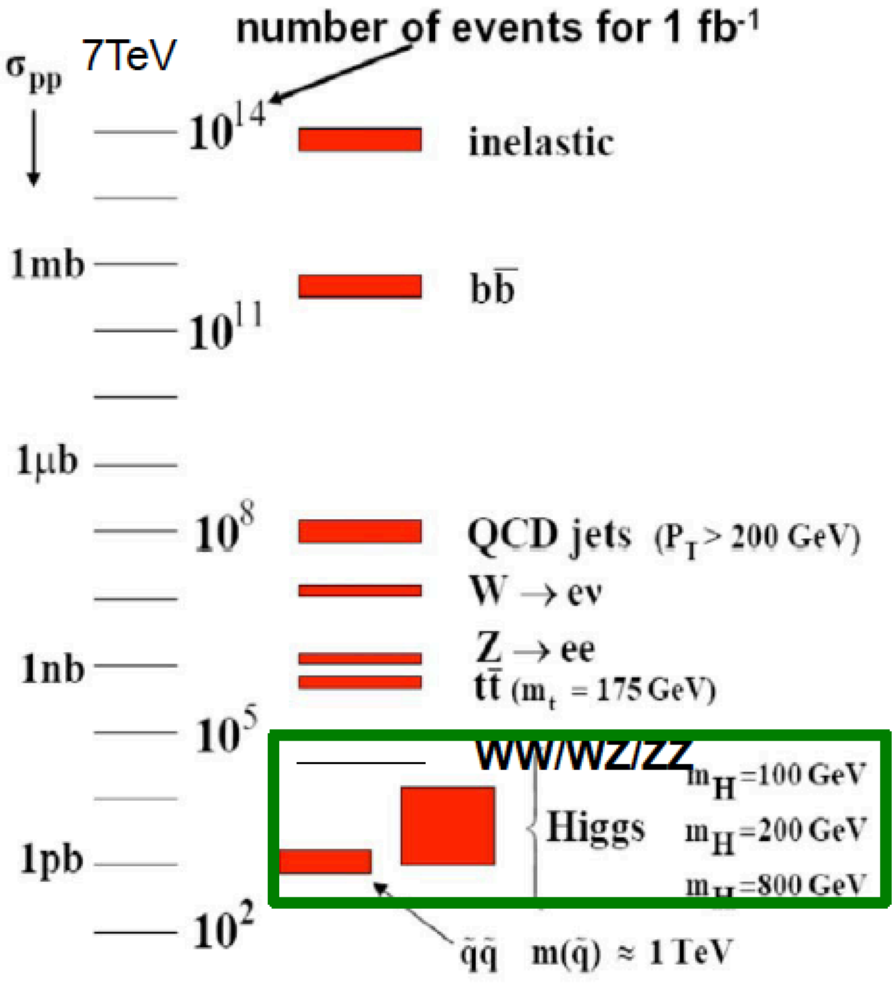
Applying Higgs mechanism to generate masses!



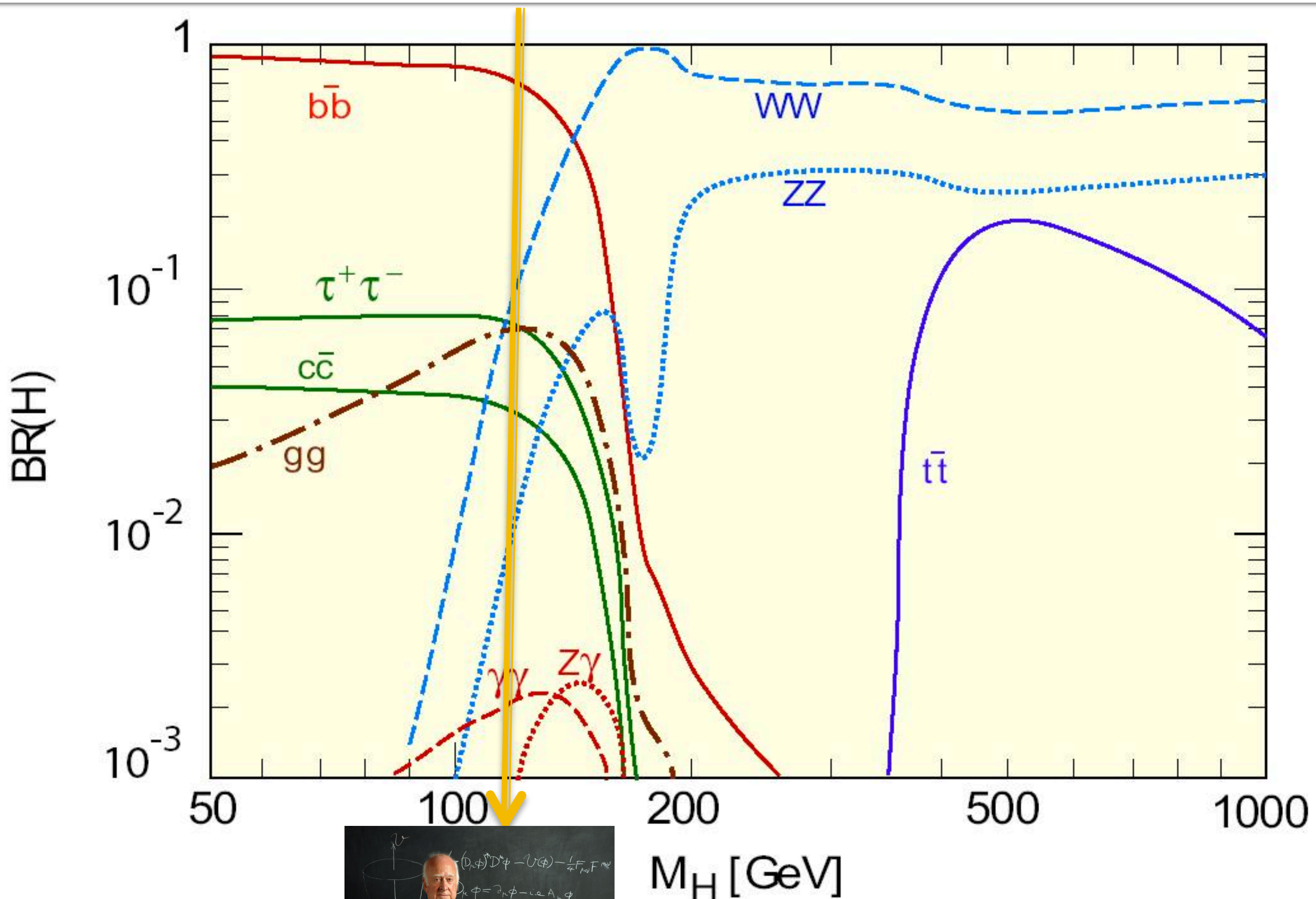


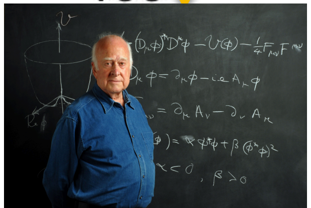
Diboson among the rare processes to be worked out in ATLAS





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





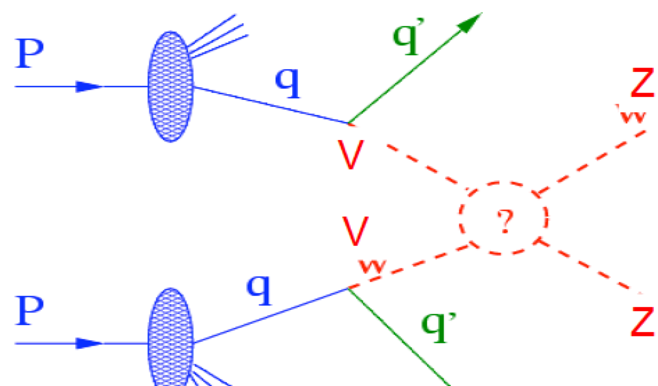
Why do multi-boson: SM, precision, unitarization and new physics

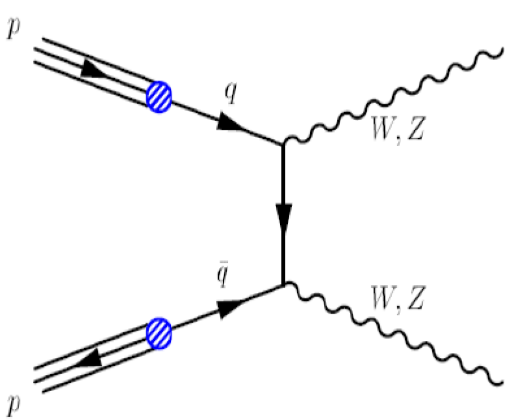
Unitarity violation of Vector Boson Scattering

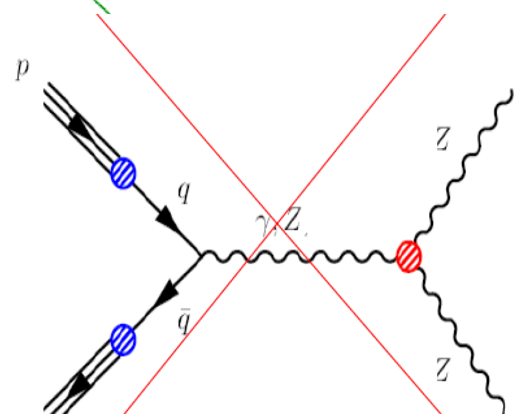
$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{M_W^2}$$

"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



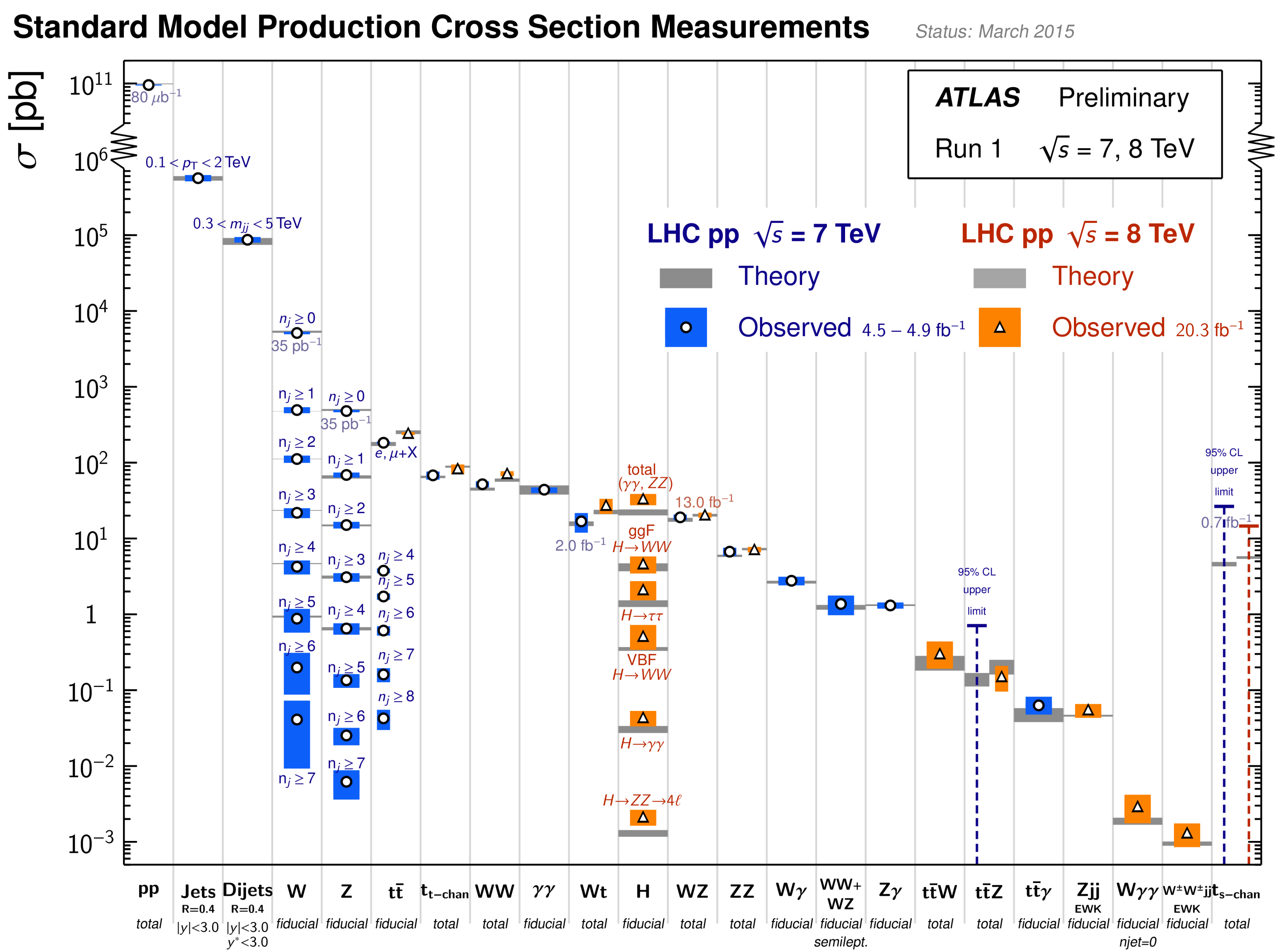




SM tree-level forbidden

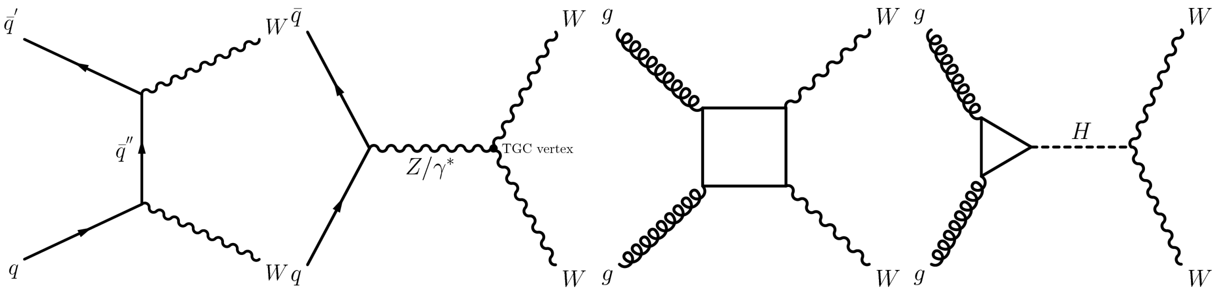
SM measurements

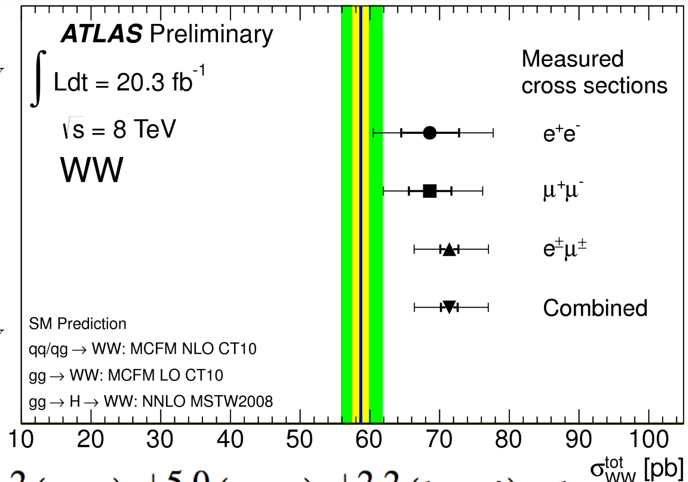
Summary of SM measured total cross-section and comparisons with theory predictions from ATLAS Run-I



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

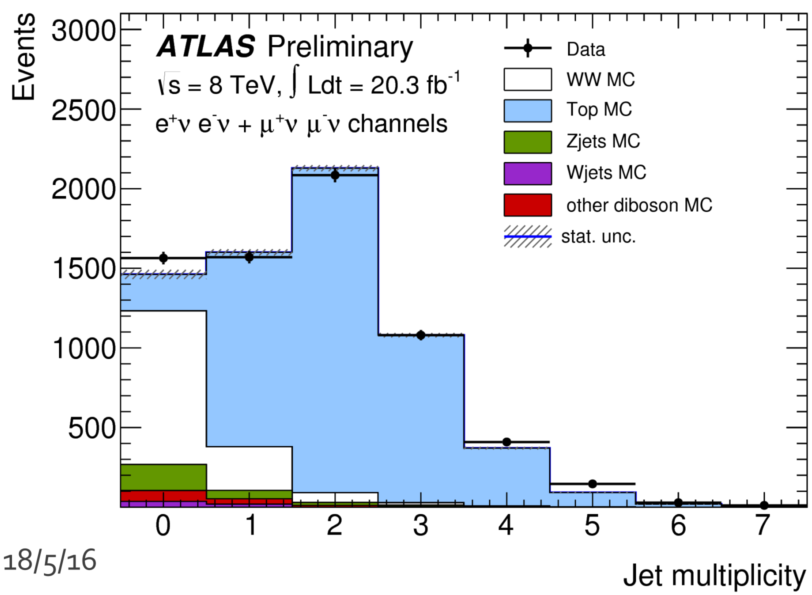
WW production via quark-antiquark annihilation(dominant) and gg-fusion

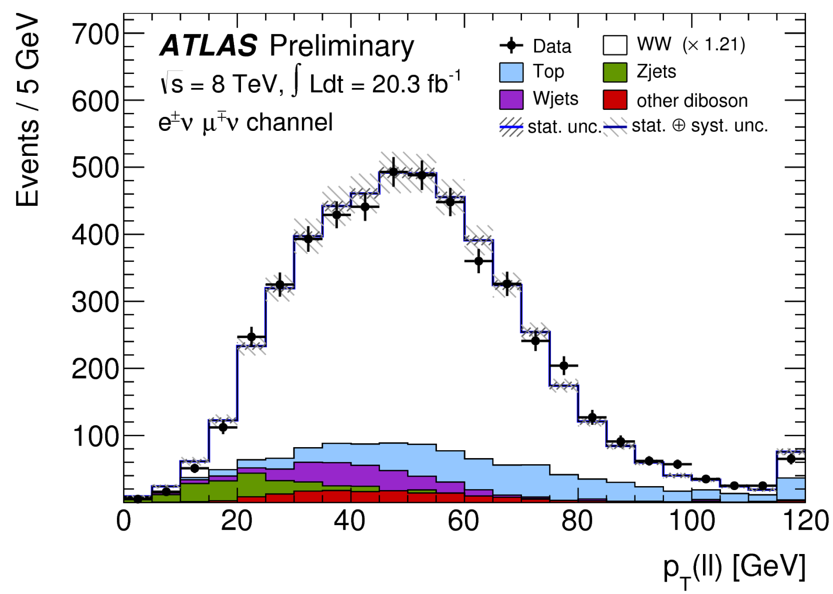




Bgd challenges: mainly Data-Driven (DD)
ttbar(DD: high #jet), DY(DD: low E_T^{miss}, low dilep pT)
W+X(DD: lepton fake), other diboson (MC)

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

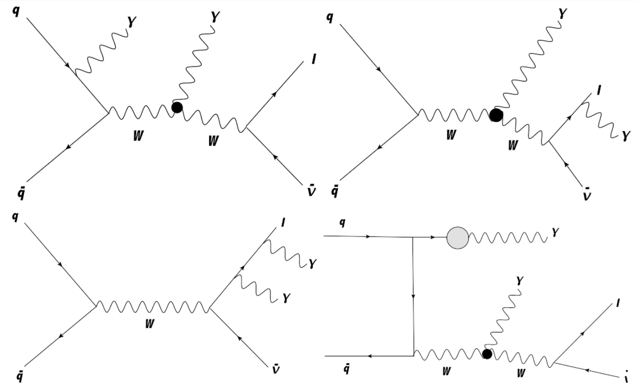




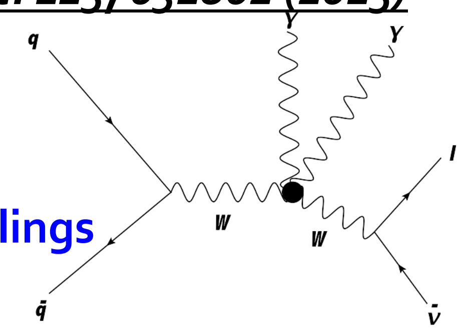
First evidence of tri-boson production in Wγγ final state at 8TeV

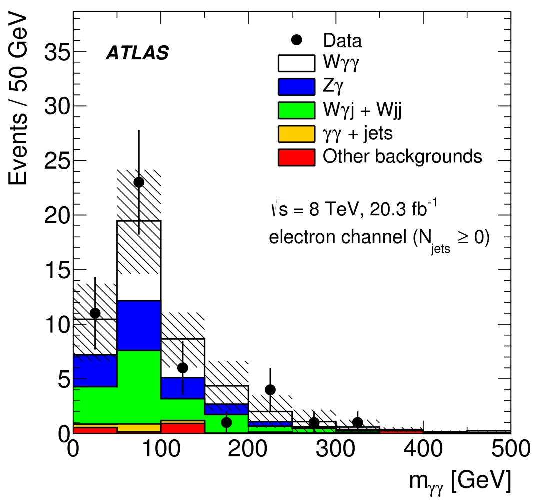
Phys. Rev. Lett. 115, 031802 (2015)

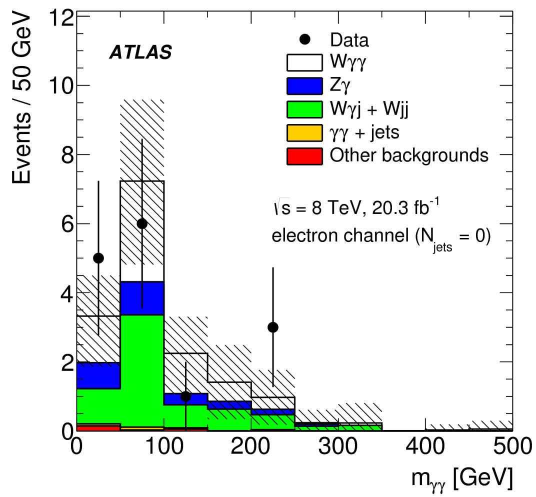
Wγγ topologies

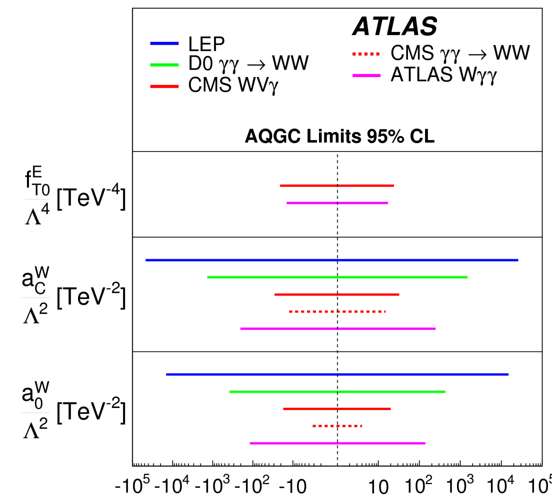


Anomalous Quartic Couplings





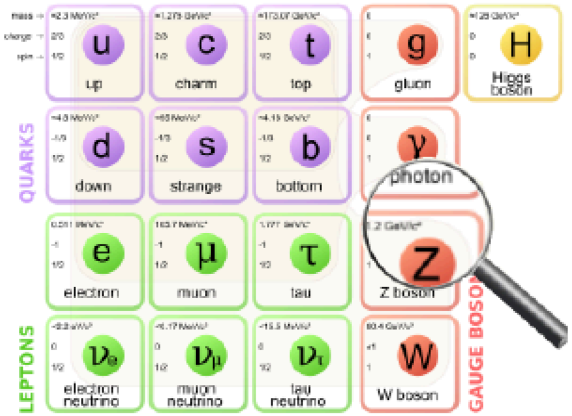




Cross section measured in fully leptonic (e/μ) channels For inclusive(#jet>=0) and exclusive(#jet==0) regions

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

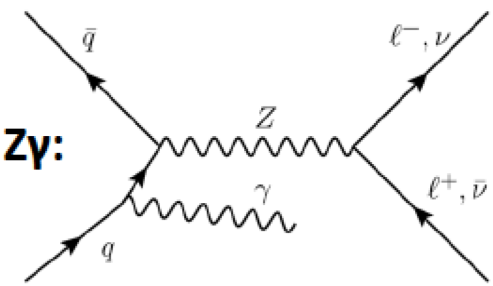


Measured processes

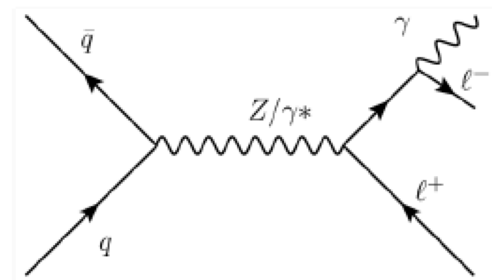
Study of Zγ and Zγγ production probes EW sector via interactions between two types of neutral bosons.

SM diagrams

Zγ:

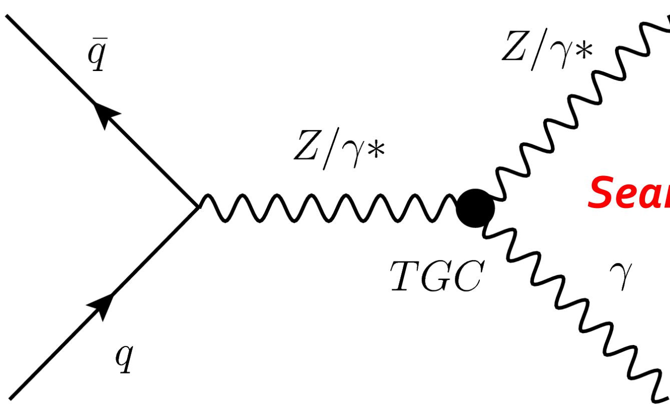


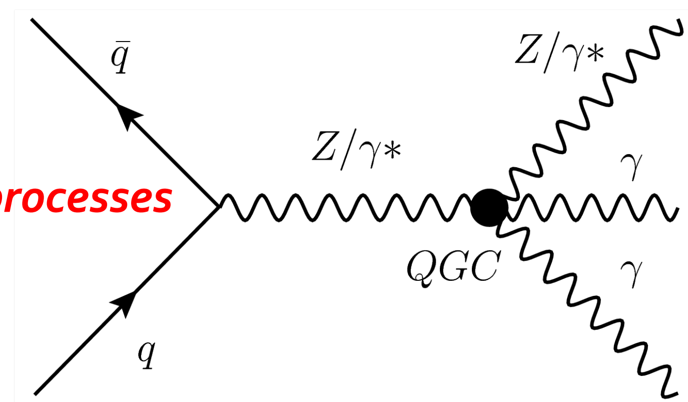
Initial state radiation (ISR)



Final state radiation (FSR)

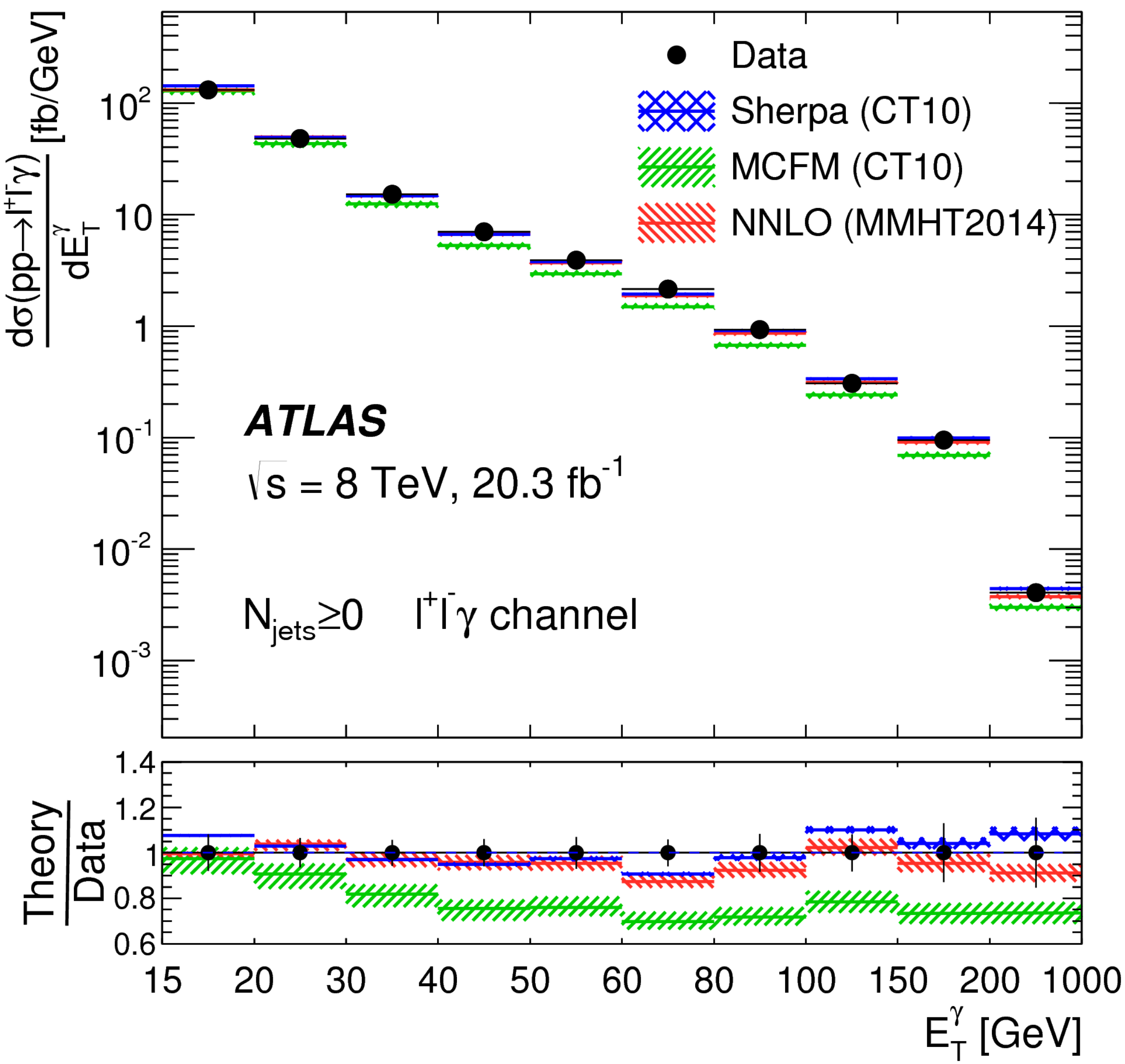
Searched processes



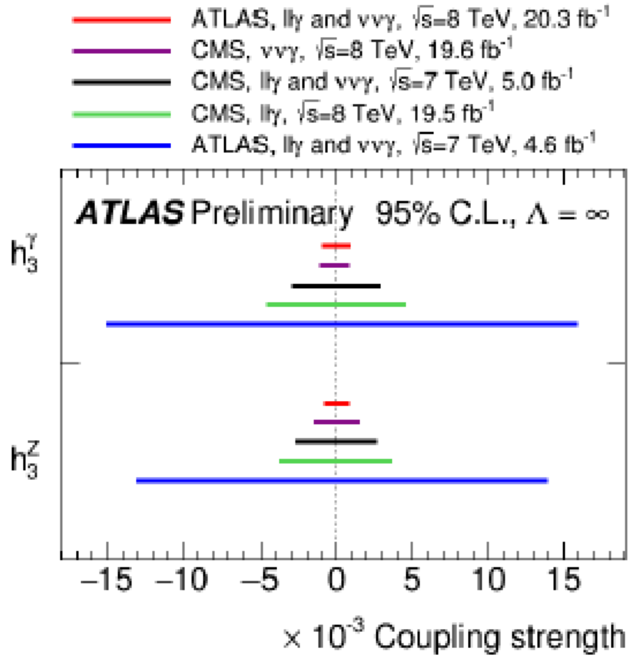


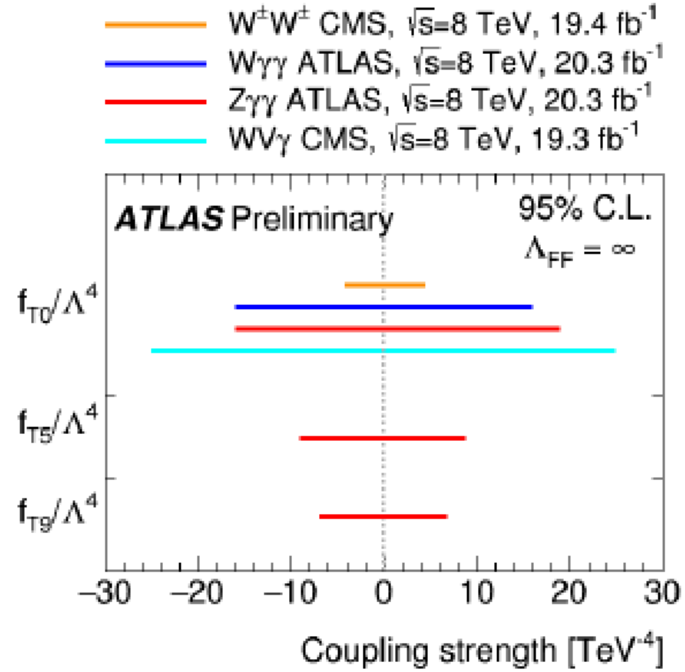
Zγ: SM Measurements vs SM Theory prediction (w/ high order corrections)

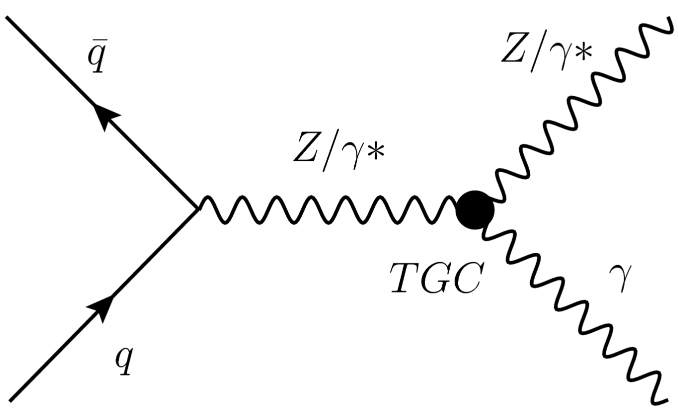
Measured Cross section Can only agree with theory prediction when NNLO correction is adopted

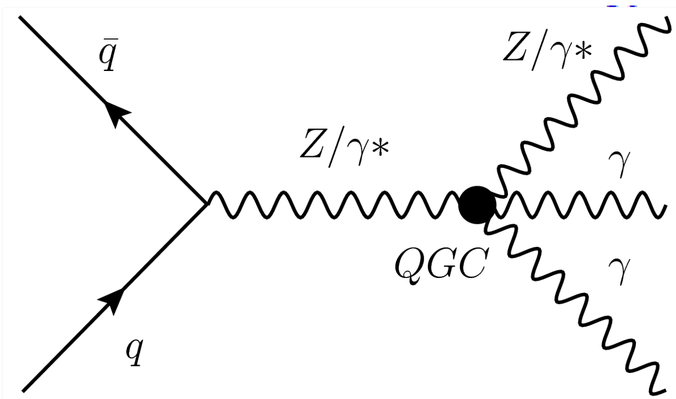


Anomalous coupling summary and comparisons



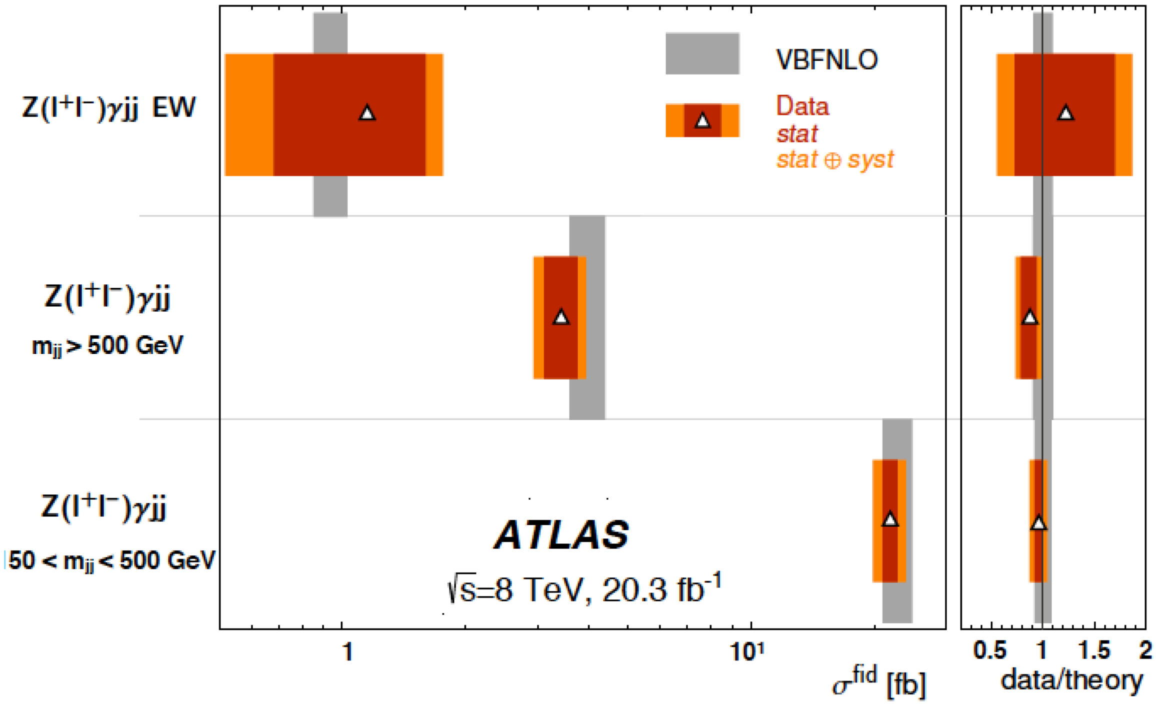


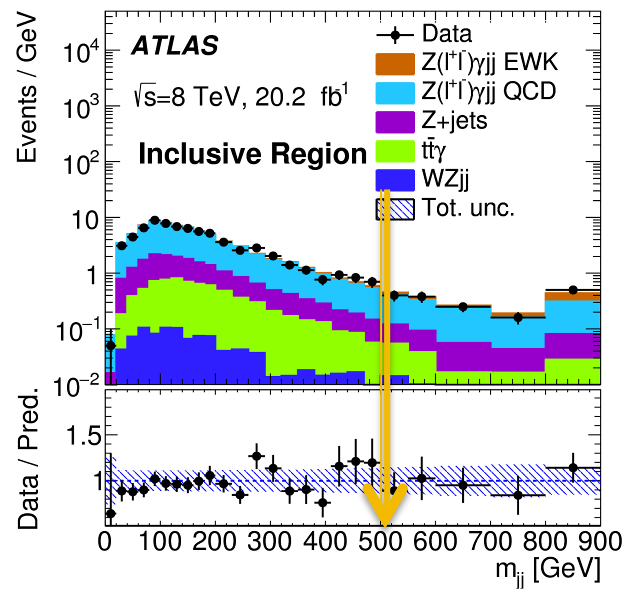




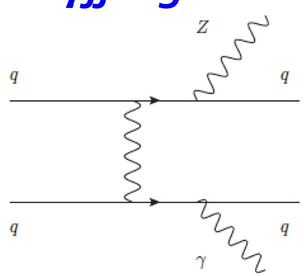
First ever Measurement of Zγ+jj Electroweak production in ATLAS

[JHEP07(2017)107]

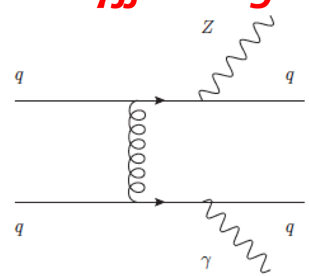




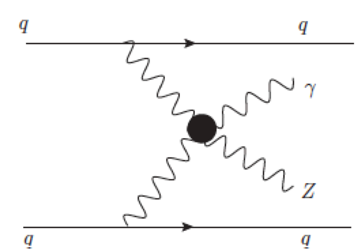
EW Zγjj Signal



QCD Zγjj Background



New Physics Vertex (BSM signal)

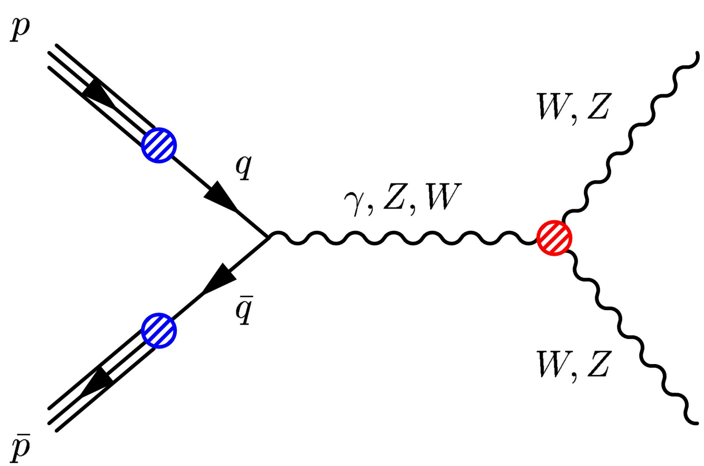


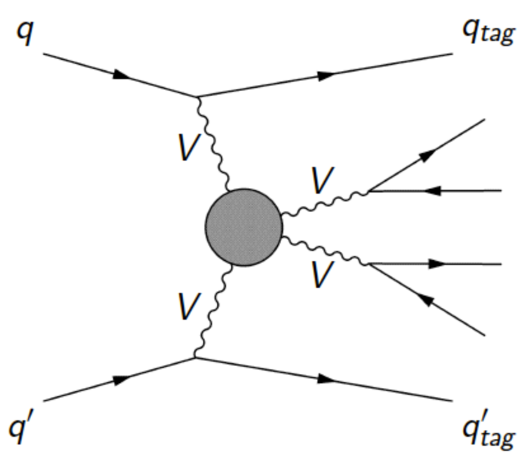
BSM searches

BSM physics methodology

Two general ways:

- ***Direct search of new particles***
- ***New interactions of known particles of SM***
  - Traditional anomalous coupling framework
  - Effective field theory approach





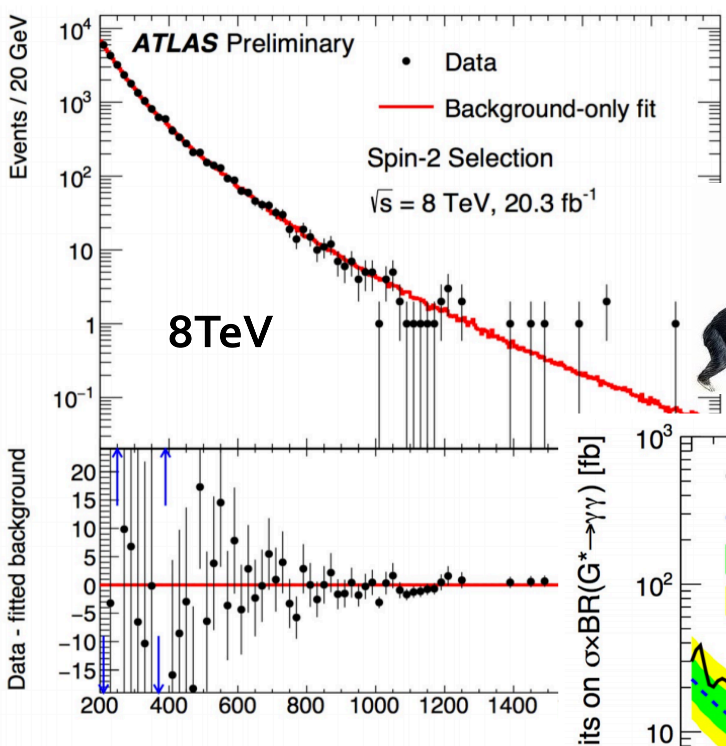
Di-boson resonance search

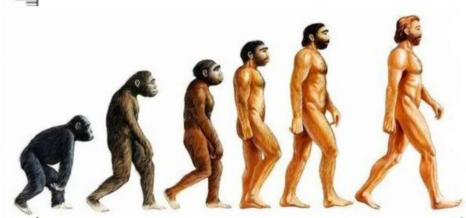
- Vast range of decay channels and various experimental signature categories to explore
  - WW: lvlv, lvqq, qqqq
  - WZ: lvll, lvqq, llqq, qqqq
  - ZZ: llll, llvv, llqq, qqqq, vvqq
  - Experimental signature of the "merged" outgoing jets from boson decays: large-R jets (boosted jets)
  - Spin property, polarization effect

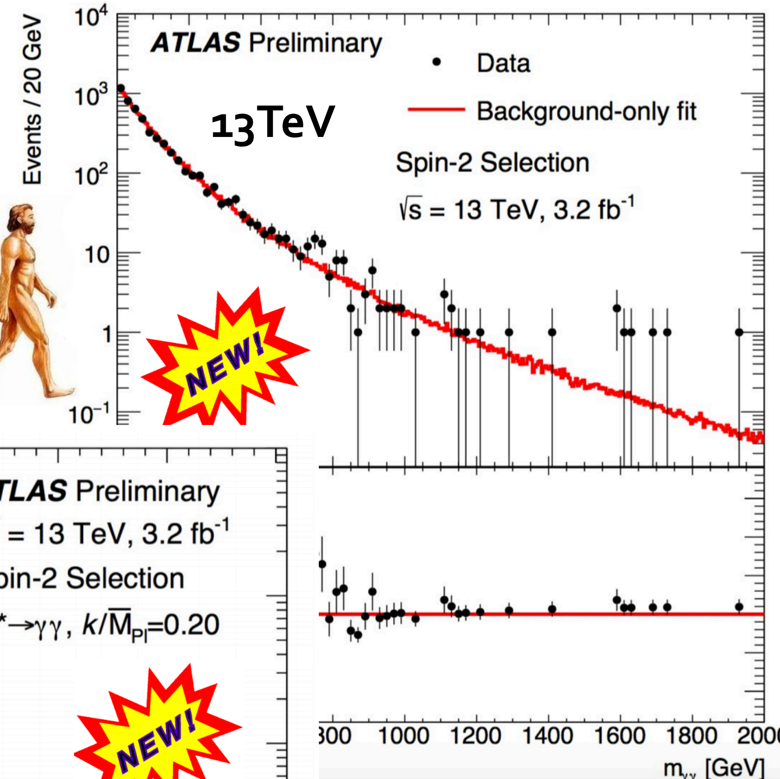
- Many inspiring models and effective theory interpretations: HVT, RS graviton, 2HDM, etc.

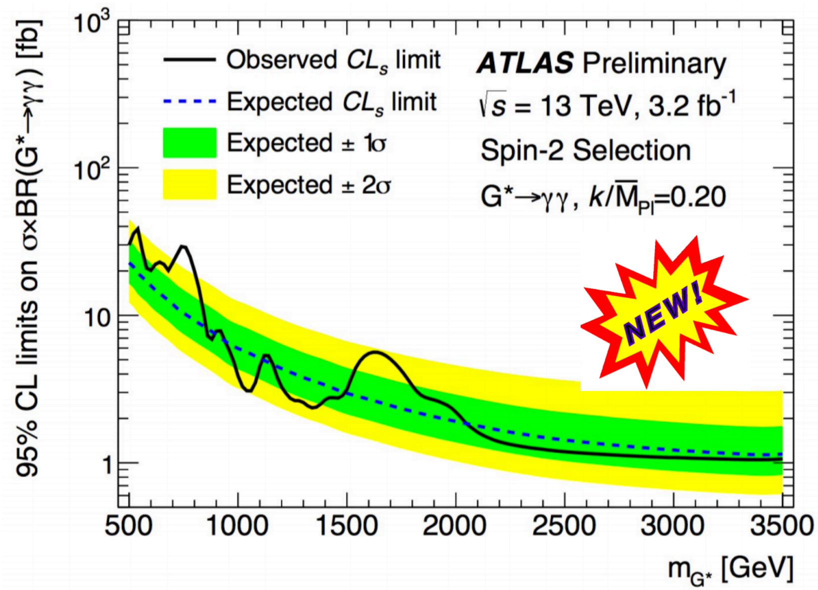
- Largely overlap the Higgs searches and SM measurements with similar final states

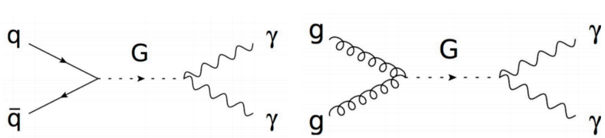
Extra Motivations: what do we learn from Zγ final state as inspired by diphoton excess?





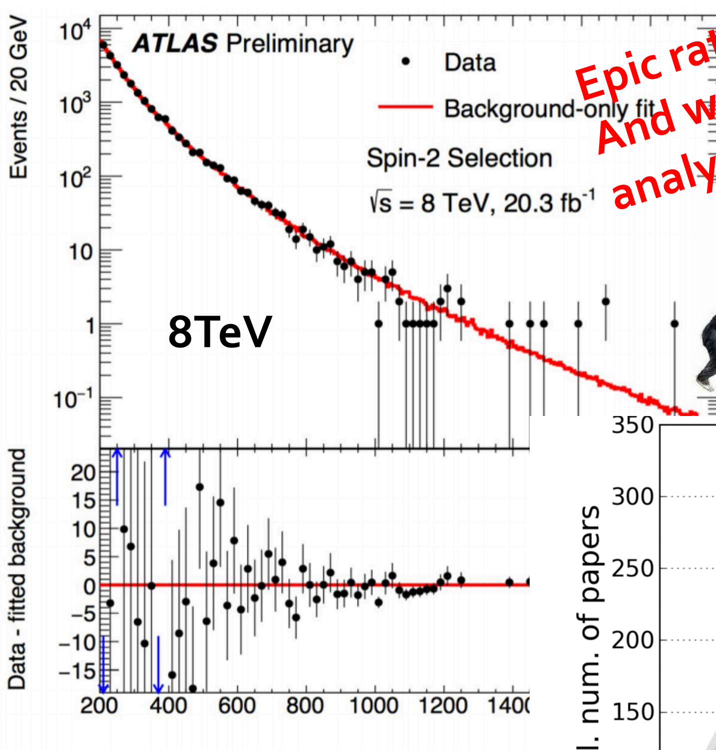


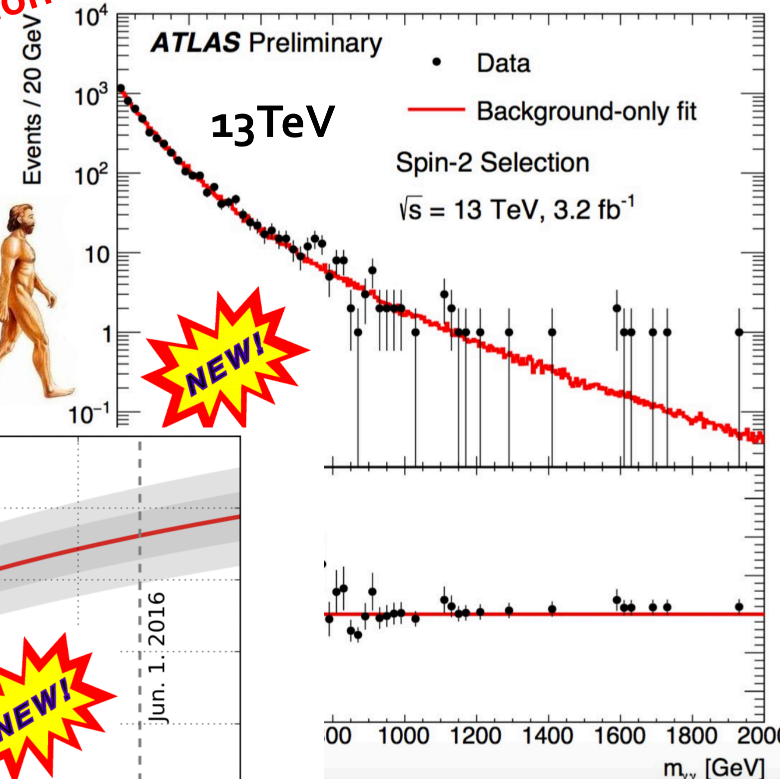


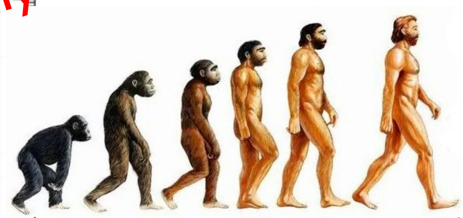


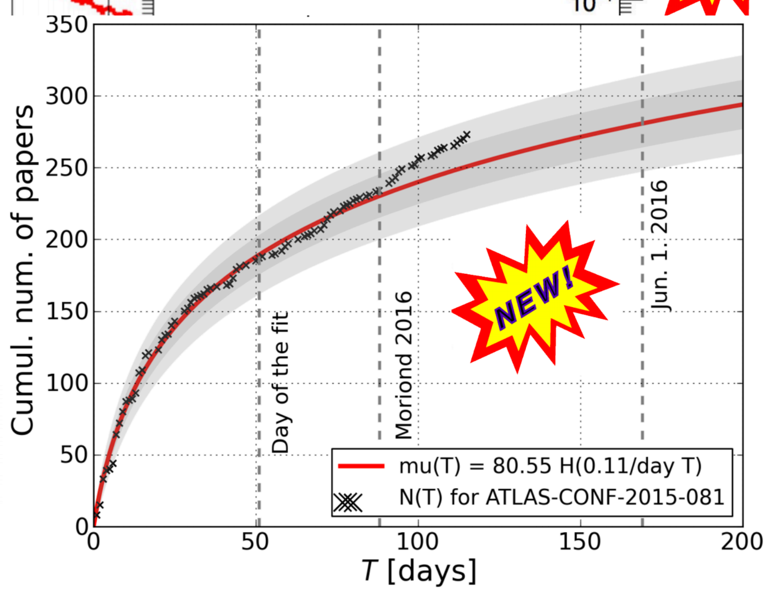
Extra Motivations: what do we learn from Zγ final state as inspired by diphoton excess?

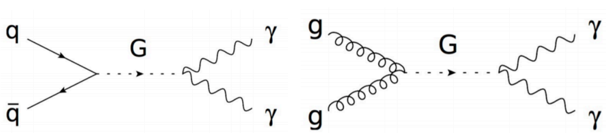
Epic rates of theory papers!
And what would other non-diphoton analyzers do?







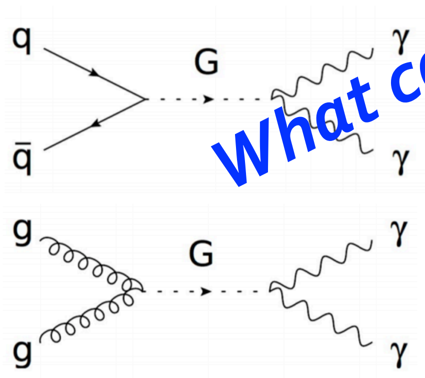


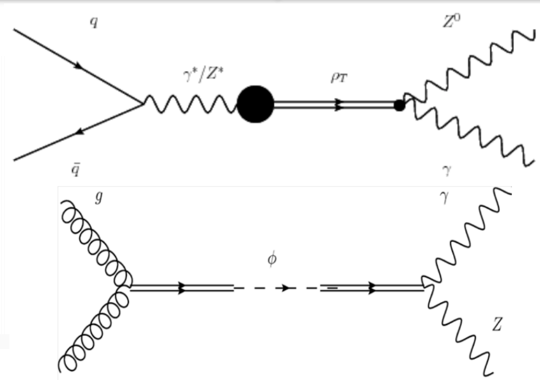


What can we learn from each other?

γγ	Zγ	Theorists	Experimentalist

What can we learn from each other?





Joint Exotic-DBL & HGam Moriond conf note follow by 2015 publications

ATLAS NOTE

EXOT-2015-XX

17th February 2016

Draft version 0.1

ATLAS NOTE

ATL-COM-PHYS-2016-086

27th February 2016

Draft version 0.6

[Phys. Lett. B 764 (2017) 11]

Search for $Z\gamma$ and $W\gamma$ resonances in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV collected with the ATLAS detector

Ayana Arce[a], Andrea Bocci[a], Sergey Burdin[b], Minyu Feng[a], Alfred Goshaw[a], Louis Helary[c], Enrique Kajomovitz[a], Evgeniy Khramov[e], Ashutosh Kotwal[a], Shu Li[a], Zhijun Liang[d], Dart-yin Soh[f], Ning Zhou[g], Nishu Nishu[g], Liang Li[h], Samuel Meehan[i], Shih-Chieh Hsu[i], Kyle Cranmer[j], Xiaohu Sun[d], Yaquan Fang[d], Kevin Hildebran[k], Gabriel Facini[k], Joseph Ennis[l]

[a]*Duke University*
[b]*Liverpool University*
[c]*Boston University*
[d]*IHEP ,Beijing*
[e]*JINR Dubna*
[f]*Academia Sinica, Taipei, Taiwan*
[g]*Tsinghua University*
[h]*Shanghai Jiao Tong University*
[i]*University of Washington*
[j]*New York University*
[k]*Univeristy of Chicago*
[l]*Univeristy of Warwick*

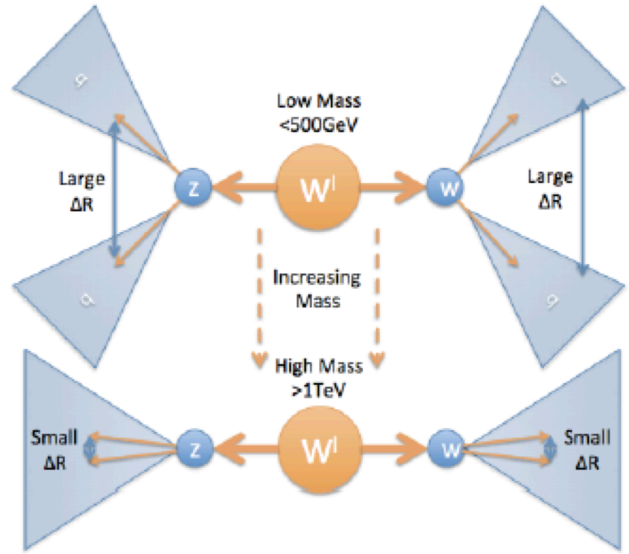
Support Note : Search for high-mass $Z\gamma$ resonances in di-lepton plus photon final states with 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV

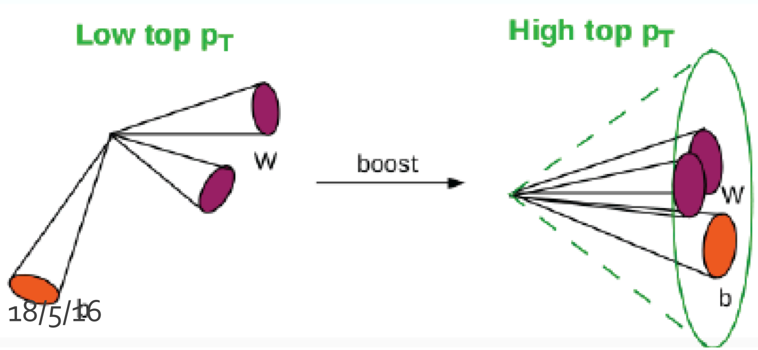
S. Burdin[1], T. Cuhadar Donszelmann[2], S. Han[3,5], H. Hayward[1], Y. Huang[3], S. Jin[5], B. Lenzi[4], S. Manzoni[6,7], G. Marchiori[7], C. Peng[3,5], E. Petit[8], N.P. Readioff[1], X.F. Ruan[9], K. Tackmann[3]

[1]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[2]*University of Sheffield, Sheffield, United Kingdom*
[3]*DESY, Hamburg and Zeuthen, Germany*
[4]*CERN, Switzerland*
[5]*IHEP, Beijing, China*
[6]*INFN Sezione di Milano and Dipartimento di Fisica, Universit'a di Milano, Milano, Italy*
[7]*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
[8]*Laboratoire de Physique Subatomique et Cosmologie, Grenoble, France*
[9]*University of the Witwatersrand, Johannesburg, South Africa*

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

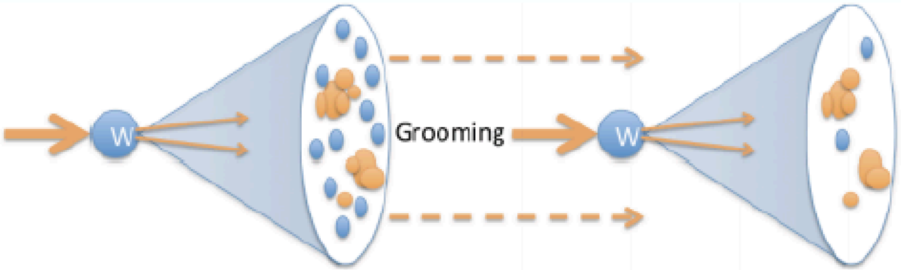




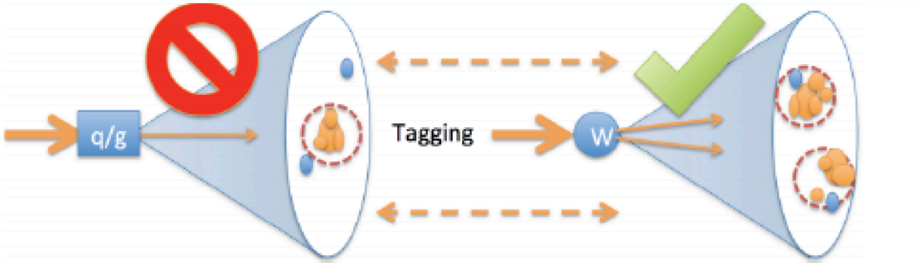
Traditional reconstruction techniques relying on one-to-one jet-to-parton assignment are inadequate

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



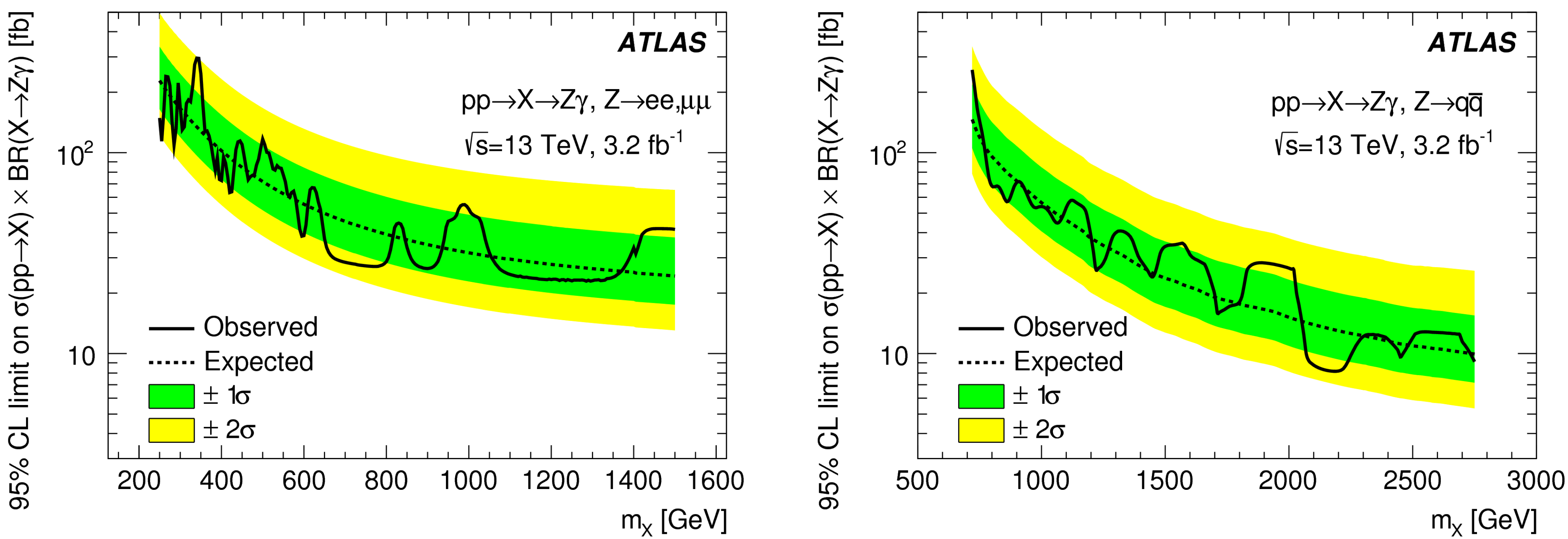
3. Tagging:
   - Use differences in signal and background jet characteristics to reject background jets



2015 limits on σ(X→Zγ)

leptonic analysis

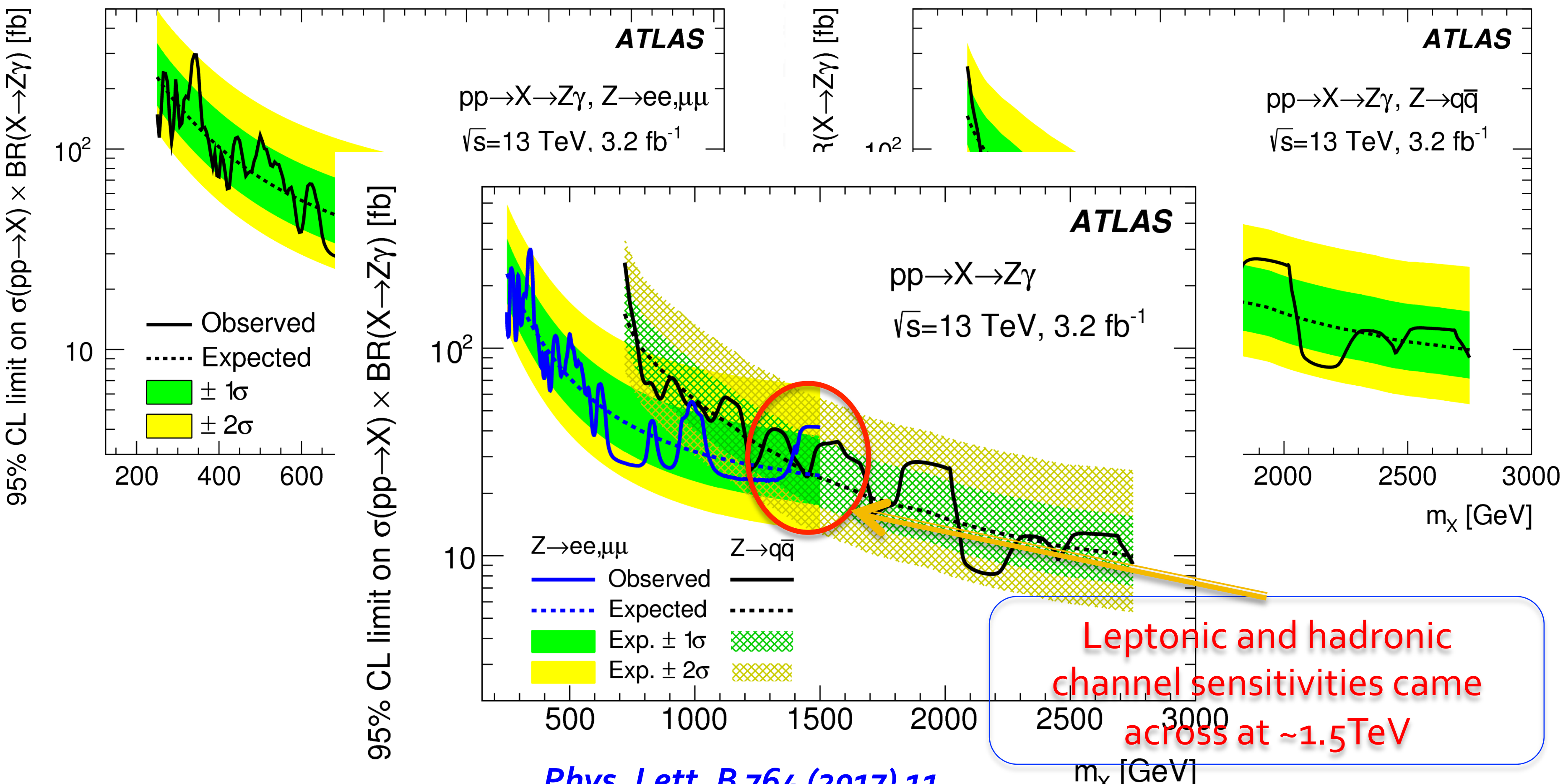
hadronic analysis



Expected limits [230, 10] fb from m_X =250 GeV to m_X =2.75 TeV
Observed limits [295, 8.2] fb from m_X = 340 GeV to m_X = 2.15 TeV
@750GeV: expecting cross section limit ~42 (130) fb and observing ~27 (200) fb for leptonic (hadronic)

2015 limits on σ(X→Zγ): cross point

leptonic analysis hadronic analysis

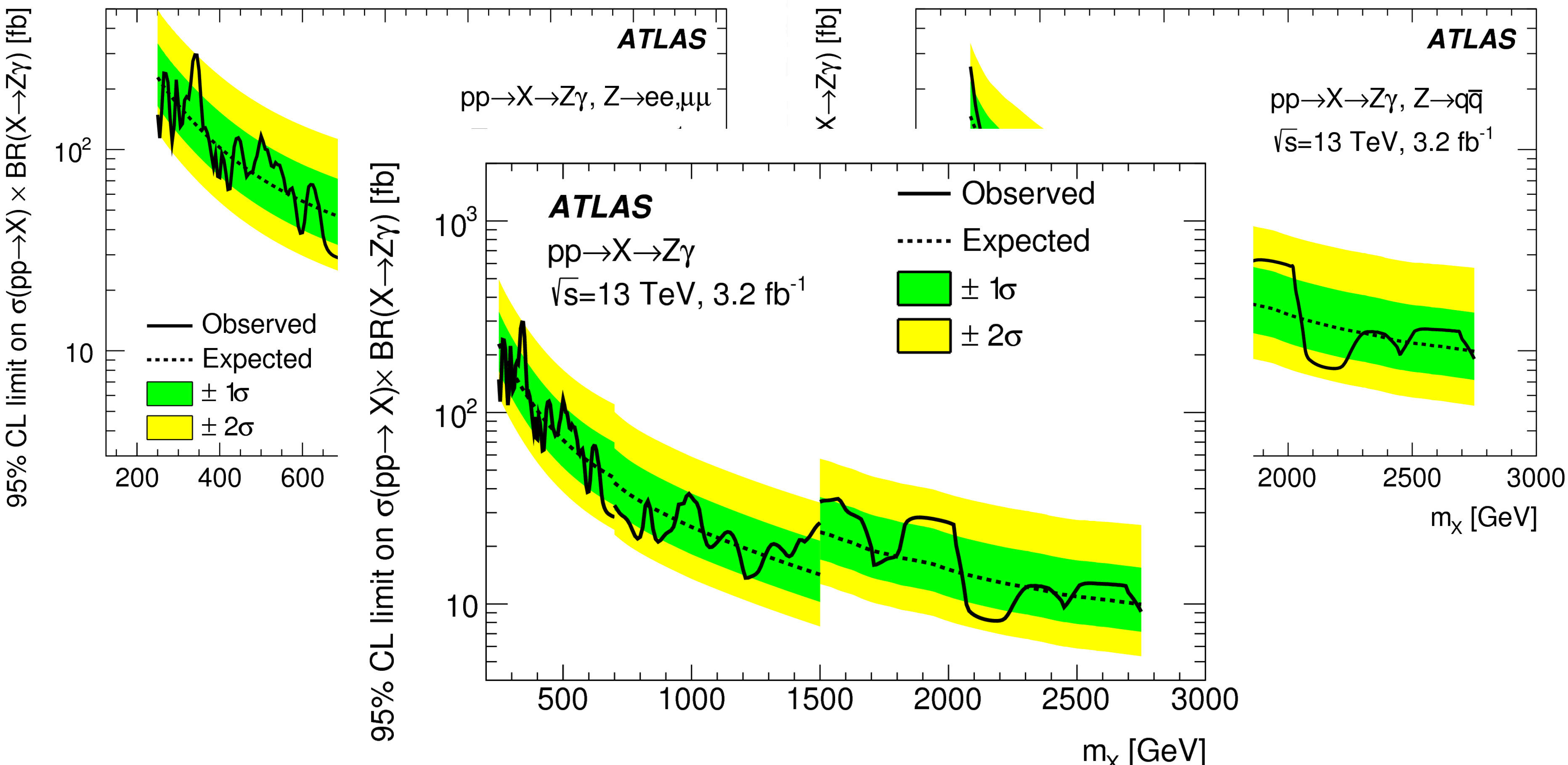


[Phys. Lett. B 764 (2017) 11](#)

2015 Combination of limits

leptonic analysis

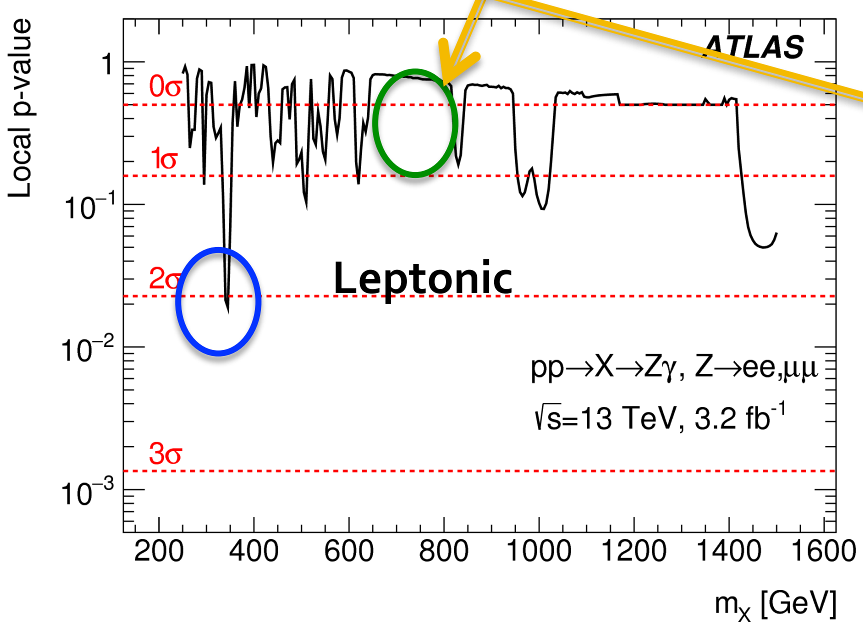
hadronic analysis

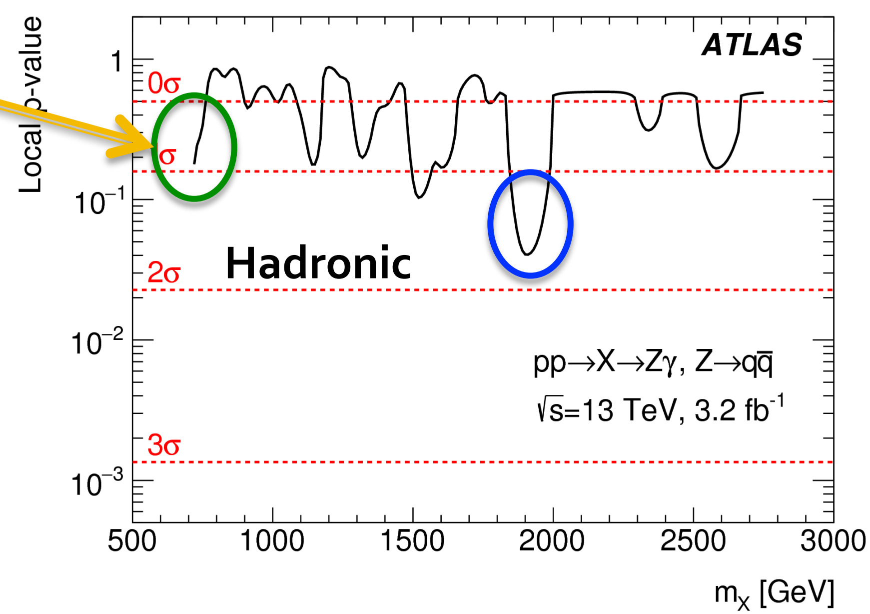


[*Phys. Lett. B 764 (2017) 11*]

2015 P-values

- Uncapped p-values for the full mass range [250, 2750] GeV
- Maximum local significance within 2σ
  - Largest significance ~2σ at 350GeV and 1.9TeV
  - *No 750 bonus ☺ by now*



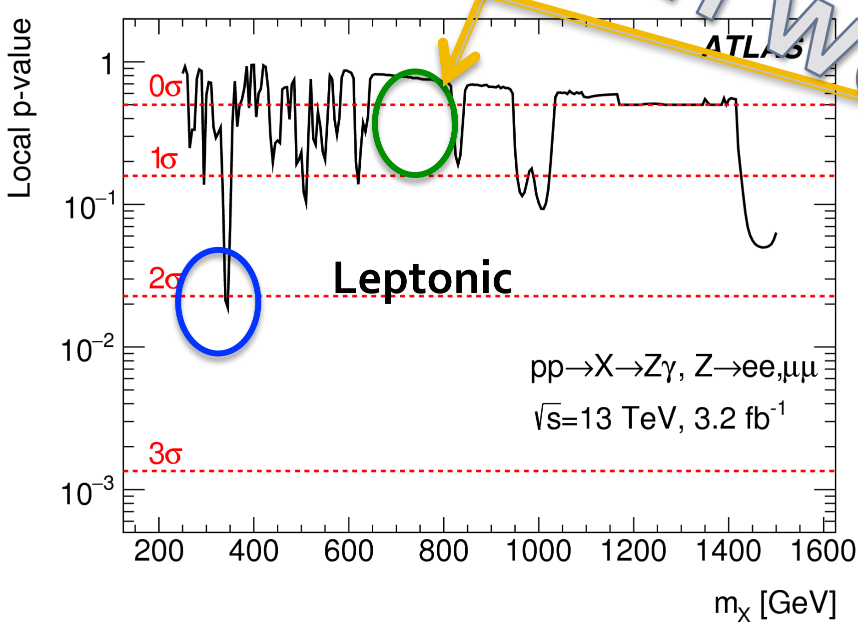


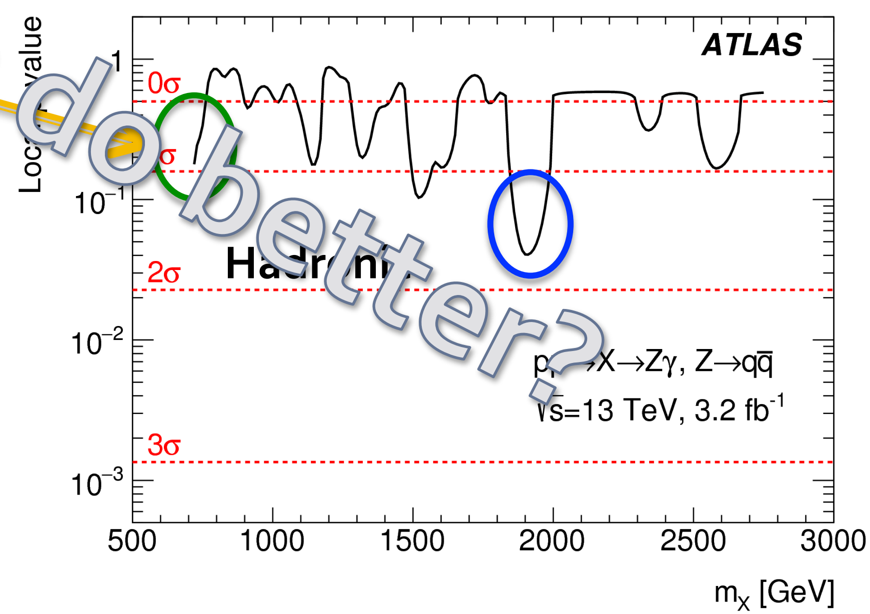
Phys. Lett. B 764 (2017) 11

2015 P-values

- Uncapped p-values for the full mass range [250, 2750] GeV
- Maximum local significance within 2σ
  - Largest significance ~2σ at 350GeV and 1.9TeV
  - ***No 750 bonus ☺ by now***

How can we do better?





[*Phys. Lett. B 764 (2017) 11*]

2015+2016 new BSM interpretations

Signal configuration and modeling

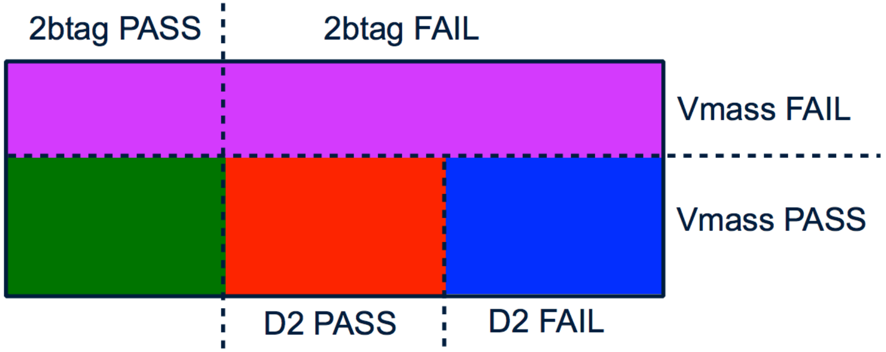
Channel	Generator	Spin	Production	V Polarization
$Z\gamma$	Powheg+Pythia8	0	$gg \to X$	Transvers
$Z\gamma$	MadGraph+Pythia8	2	$gg \to X$	Transvers
$Z\gamma$	MadGraph+Pythia8	2	$qq \to X$	Transvers
$W\gamma$	MadGraph+Pythia8	1	$qq \to X$	Longitudinal
$H\gamma$	MadGraph+Pythia8	1	$qq \to X$	-

Main backgrounds

Channel	Generator
γ+jets ***dominant***	Sherpa
SM W+γ	Sherpa
SM Z+γ	Sherpa
tt+γ(all hadronic and no all hadronic)	MadGraph + Pythia8

2015+2016 Event selection and categorization

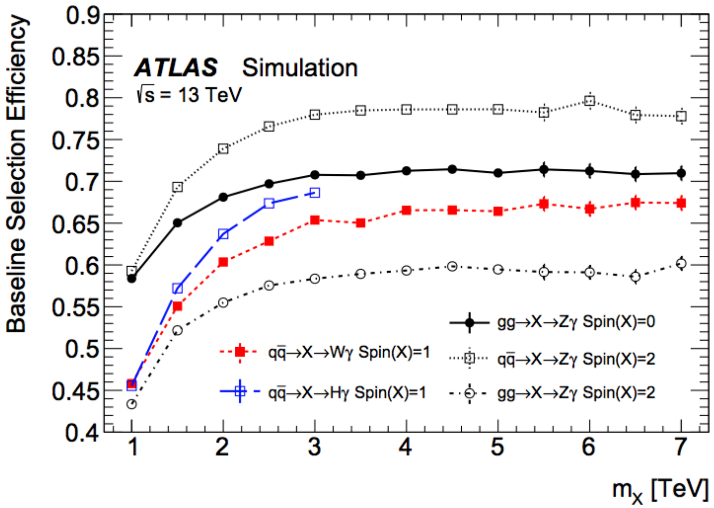
- Baseline selection
  - high p_T photon trigger: HLT_g140_loose
  - Preselection: GRL + LooseBadJet cut on Resolved jets
  - At least one photon in barrel calorimeter ($|\eta|<1.37$)
  - 1 Tight Photon in the barrel & 1 Fat Jet (anti-kt R=1.0)
  - Jet and photon OR: $\Delta R(\text{jet}, \gamma) > 1.0$



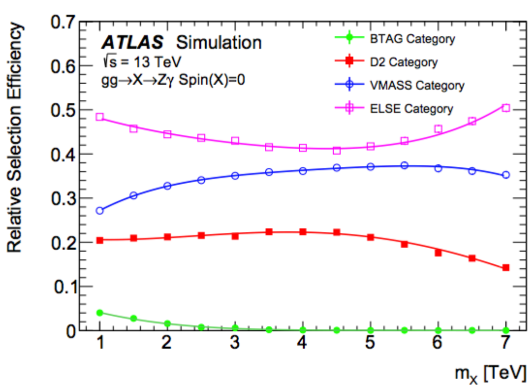
- Categorization:
  - Zγ: btagged, D2, Vmass, else
  - Wγ: D2, Vmass, else
  - Hγ: btagged
  - Note: "Else" recover high mass eff.
  - Note: only H→bb is considered

2015+2016 signal efficiency review

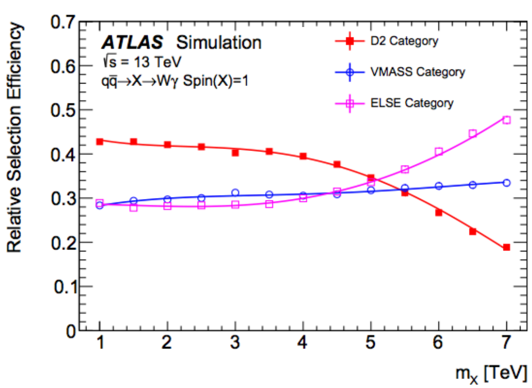
Baseline selection efficiency



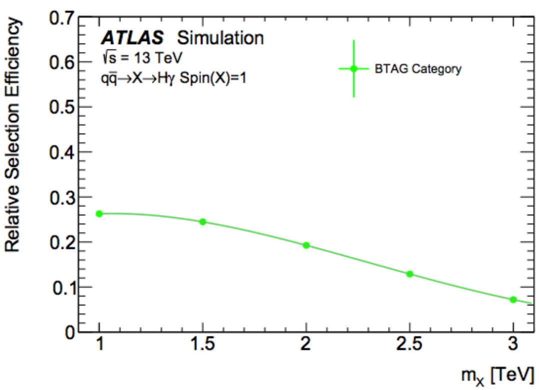
Zγ spin-2



Wγ spin-1



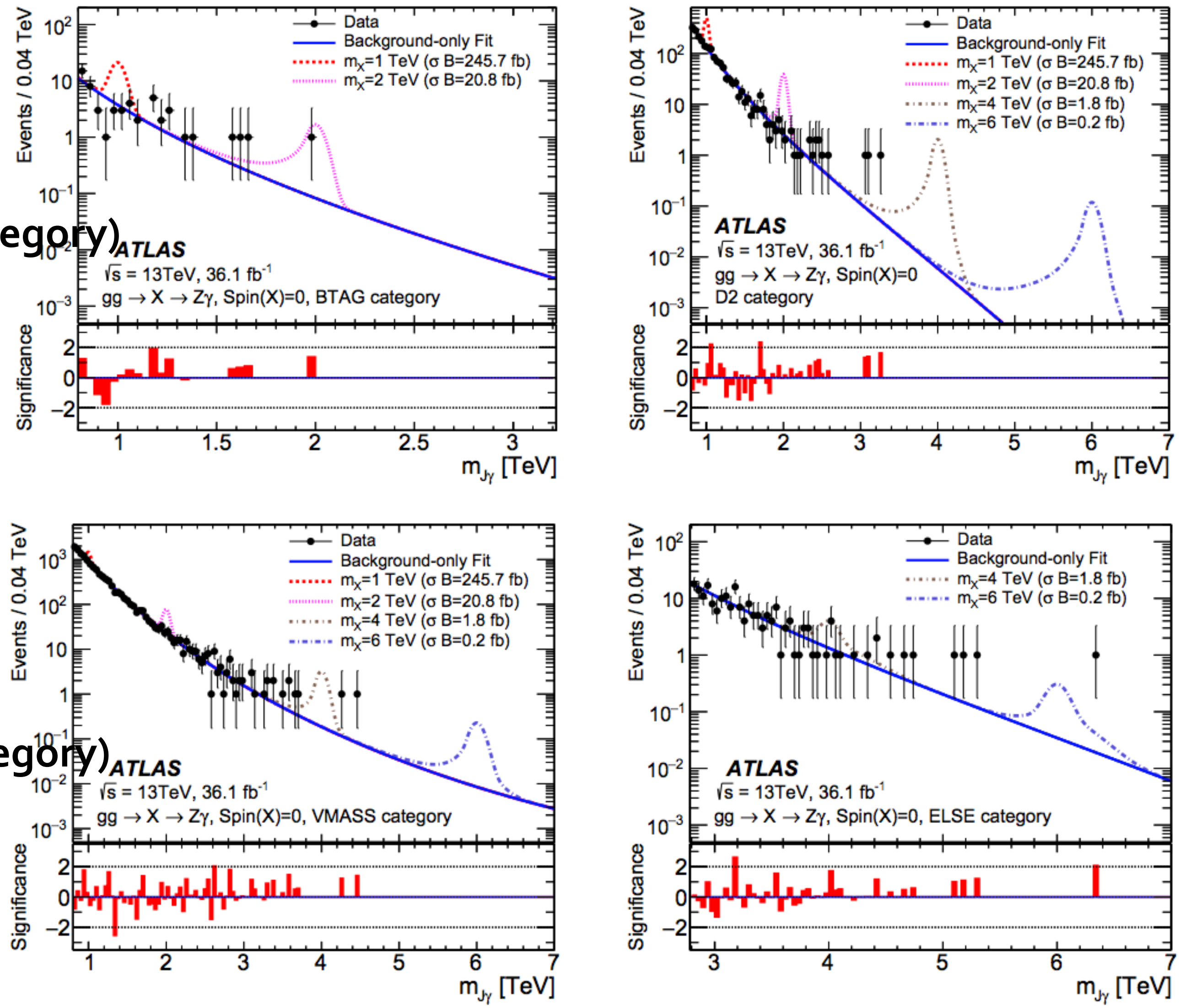
Hγ spin-1



2015+2016 Zγ mass spectra (spin-0)

Zγ
(btagged category)

Zγ
(D2 category)

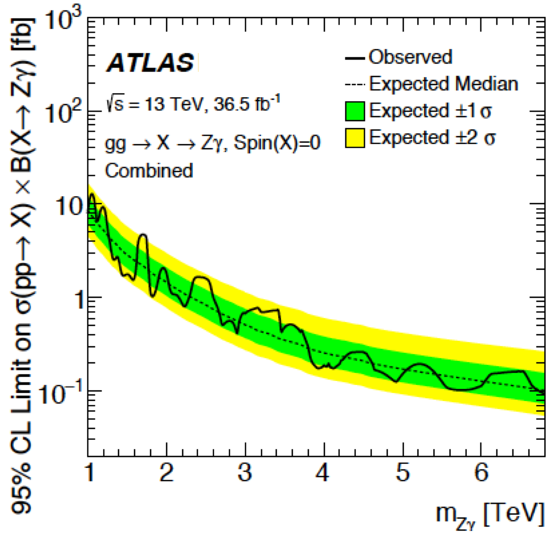


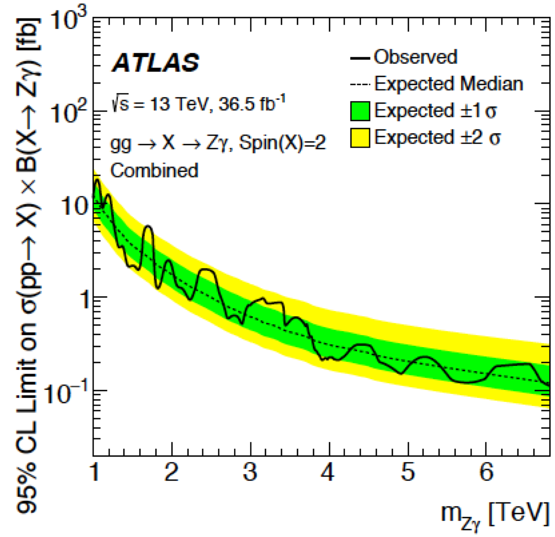
Zγ
(Vmass category)

Zγ
(else category)

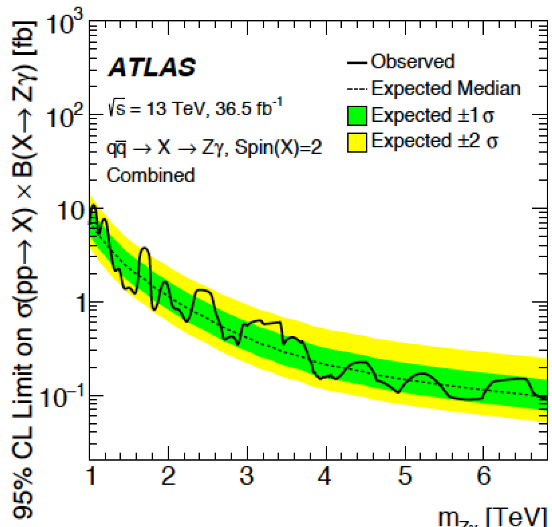
2015+2016 Zγ limits

gg→Zγ spin-0





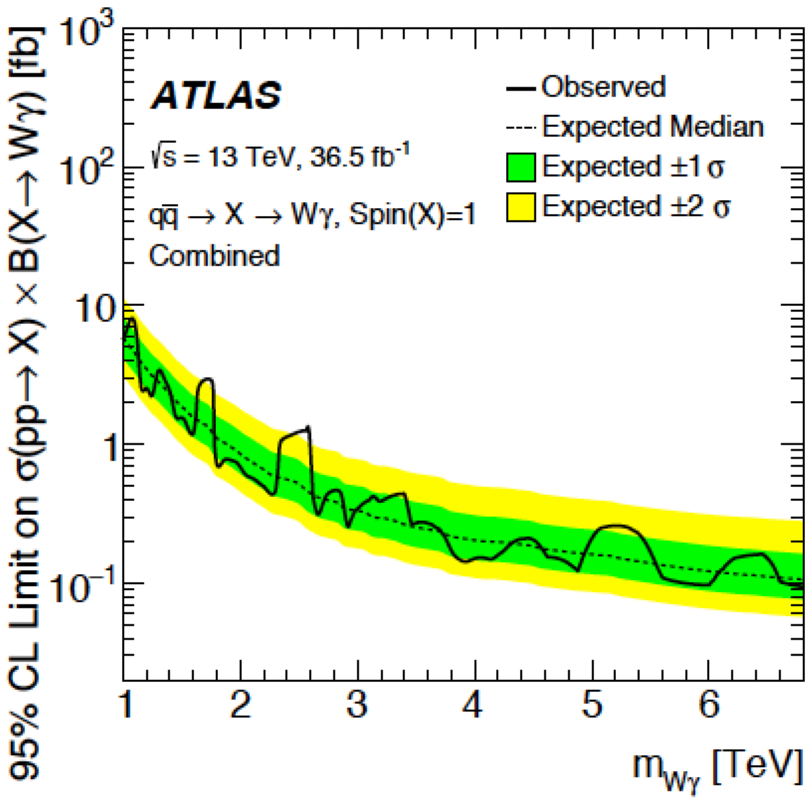
gg→Zγ spin-2



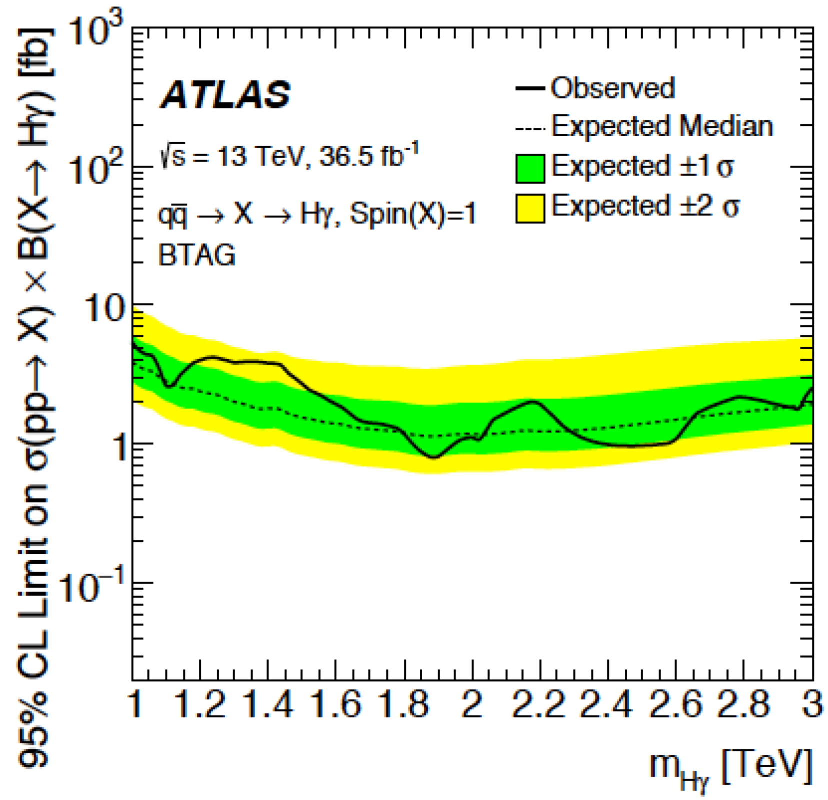
qq→Zγ spin-2

2015+2016 Wγ and Hγ limits

Wγ (combined limits)



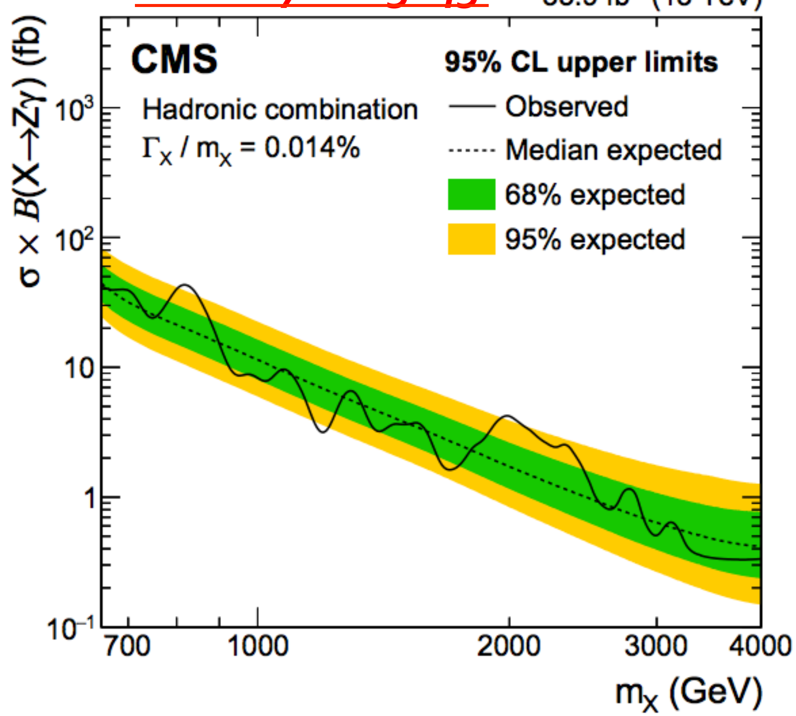
Hγ (combined limits)



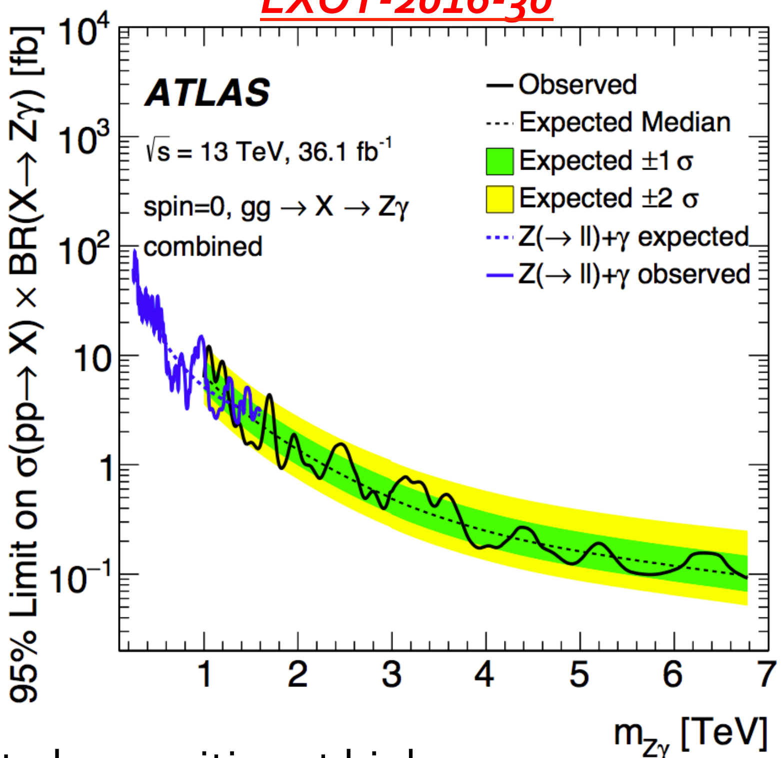
1st ever Hγ resonance search limits at LHC
CERN 2018 Physics Briefing highlight

Reminder: High mass resonance search in X->Zγ final states, leptonic vs hadronic

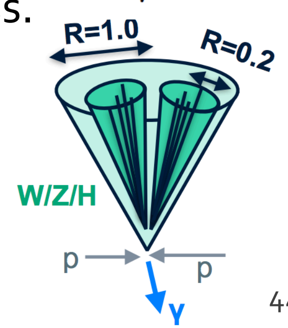
arXiv:1712.03143



EXOT-2016-30

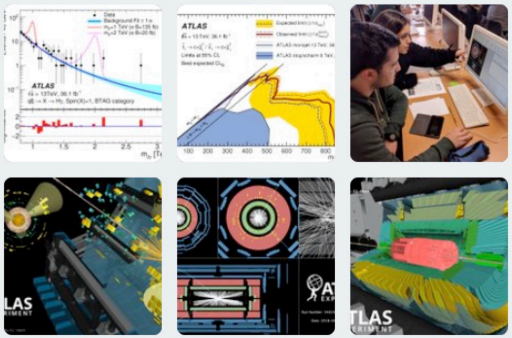


- The hadronic V/H+γ search analysis is designed to be sensitive at high mass.
  - Cross point of leptonic vs hadronic Zγ: m(X)~1.5TeV.
- The 2016 analysis of hadronic channel makes use of categorization in combination of btagged category to enhance the low mass sensitivity
  - W/H+γ channels are done for the 1st time!



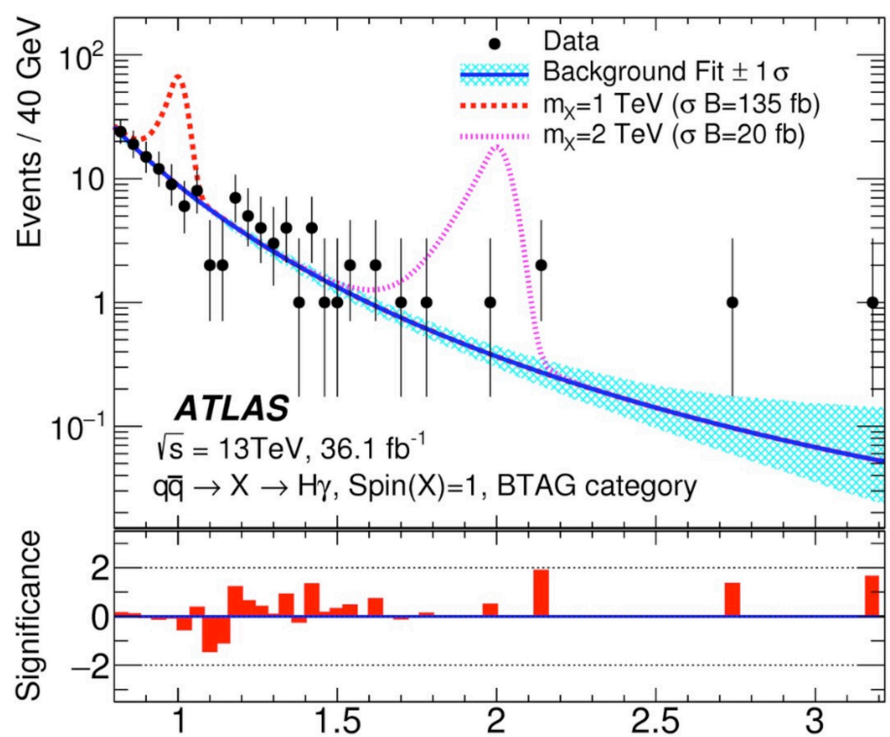
Physics Briefing highlight

882 Photos and videos



ATLAS Experiment @ATLASexperiment · 53m

[Physics Briefing] Searching for forces beyond the Standard Model: a new ATLAS measurement extends searches for new bosons up to masses about 70 times the mass of the Z boson. Find out more: cern.ch/go/p9Zj



Summary

- Multi-boson interactions are one of the most sharpened signatures to measure and explore because of so much topical items break into the particle physics foundations
  - Solid validation of SM predictions and high precision/high order calculations of the SM boson coupling and interactions
  - Substantiate the findings of new physics signatures which decay into SM bosons: irreducible backgrounds
  - Effective theory parameterization platform incorporating new physics inducing SM anomalous interactions

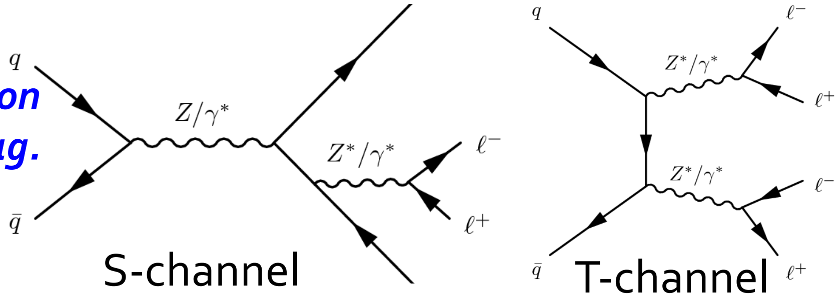
- Many Fruitful Run-I/II achievements in SM multi-boson production measurements and searches. Surely will be a continuous hotspot to explore further in a new Center-of-Mass energy era at ATLAS/LHC

谢谢

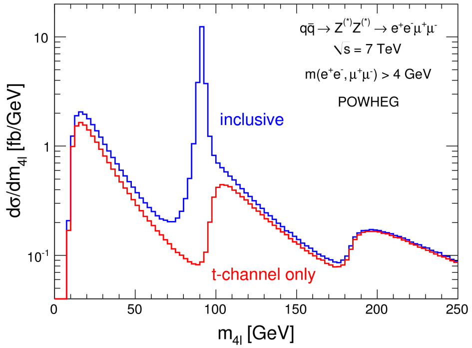
Backup

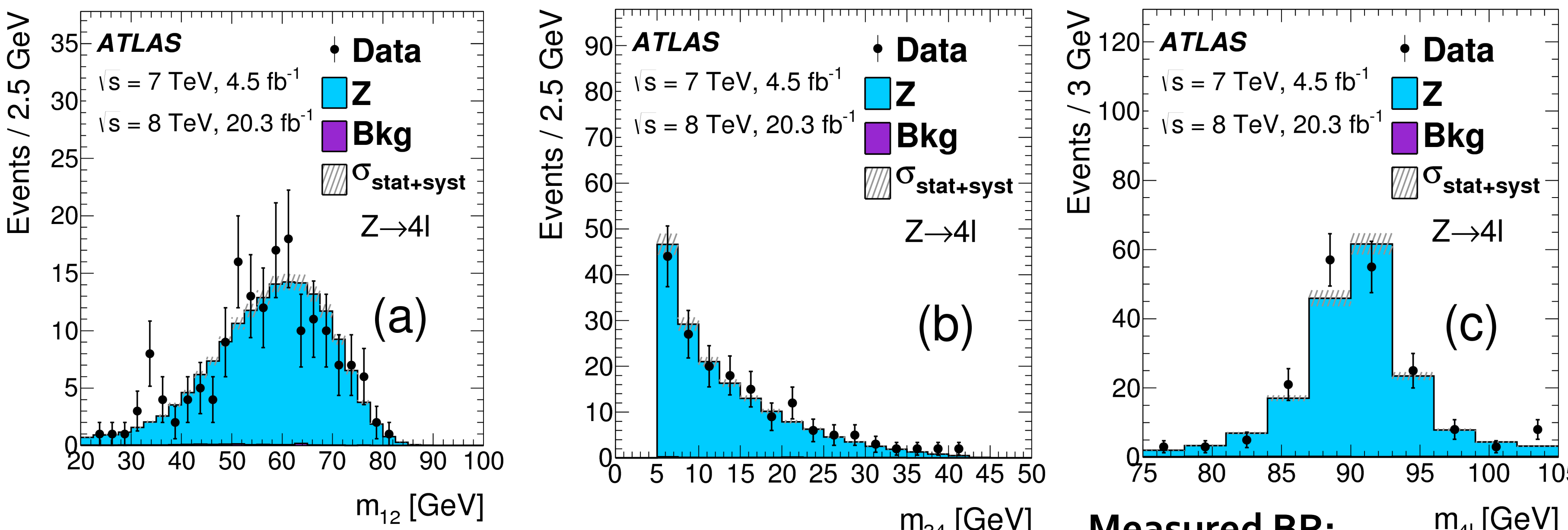
Measurement of Z→4l cross section and Branching Ratio at 7/8TeV

four-lepton Feyn. Diag.



Generator-level distribution of the four-lepton invariant mass by PowHeg.





7TeV X-sec: 76±18 (stat) ±4 (syst) ±1.4 (lumi)

8TeV X-sec: 107±9 (stat) ±4 (syst) ±3.0 (lumi)

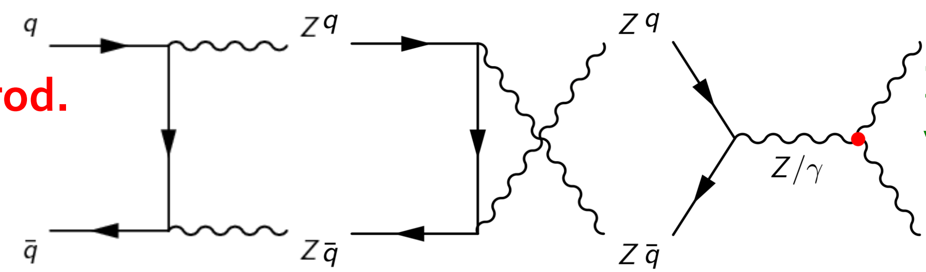
Measured BR:

$$\Gamma_{Z\to 4\ell}/\Gamma_Z = (3.20 \pm 0.25\ (\text{stat}) \pm 0.13\ (\text{syst})) \times 10^{-6}$$

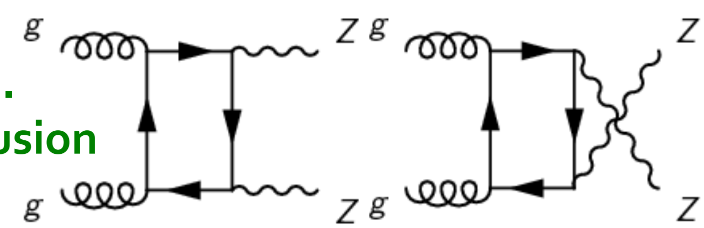
Prediction: $(3.33 \pm 0.01) \times 10^{-6}$

Preliminary measurement of the ZZ production cross section in ZZ→4l final state at 8TeV

ZZ prod.
LO



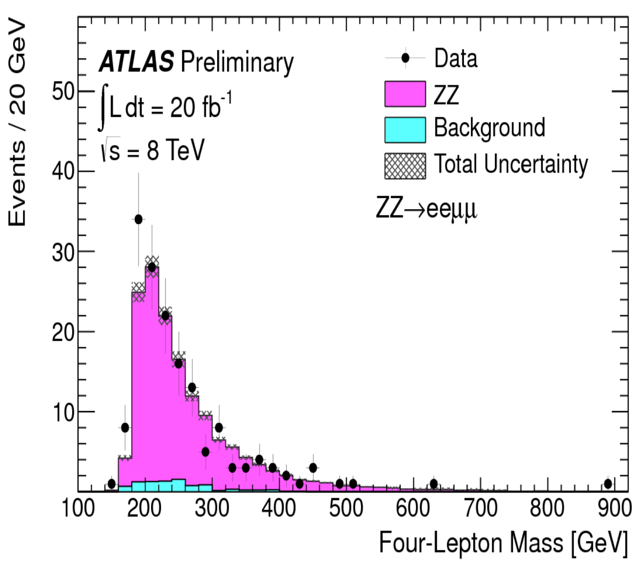
ZZ prod.
via gg fusion

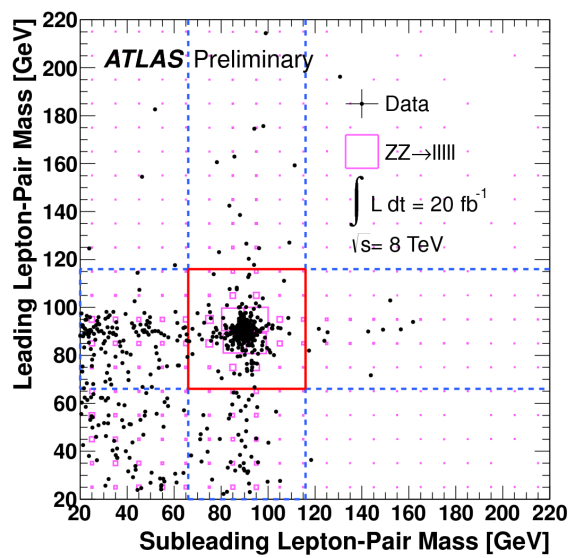


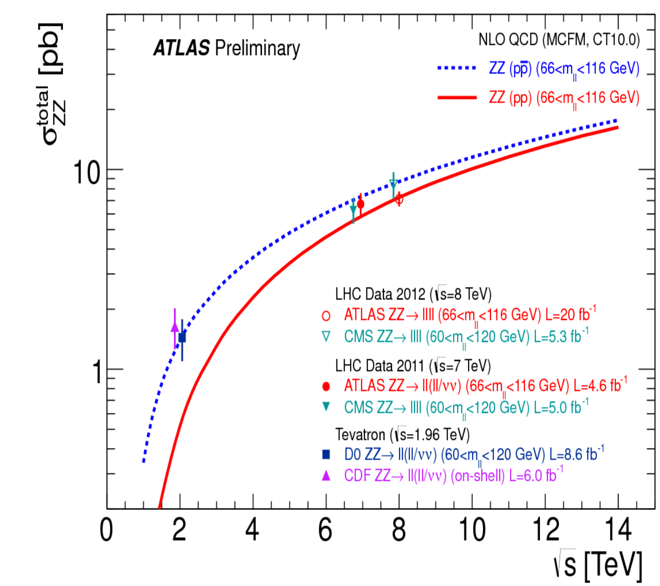
Measured X-sec $\sigma_{ZZ}^{tot} = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.2(\text{lumi.})$ pb

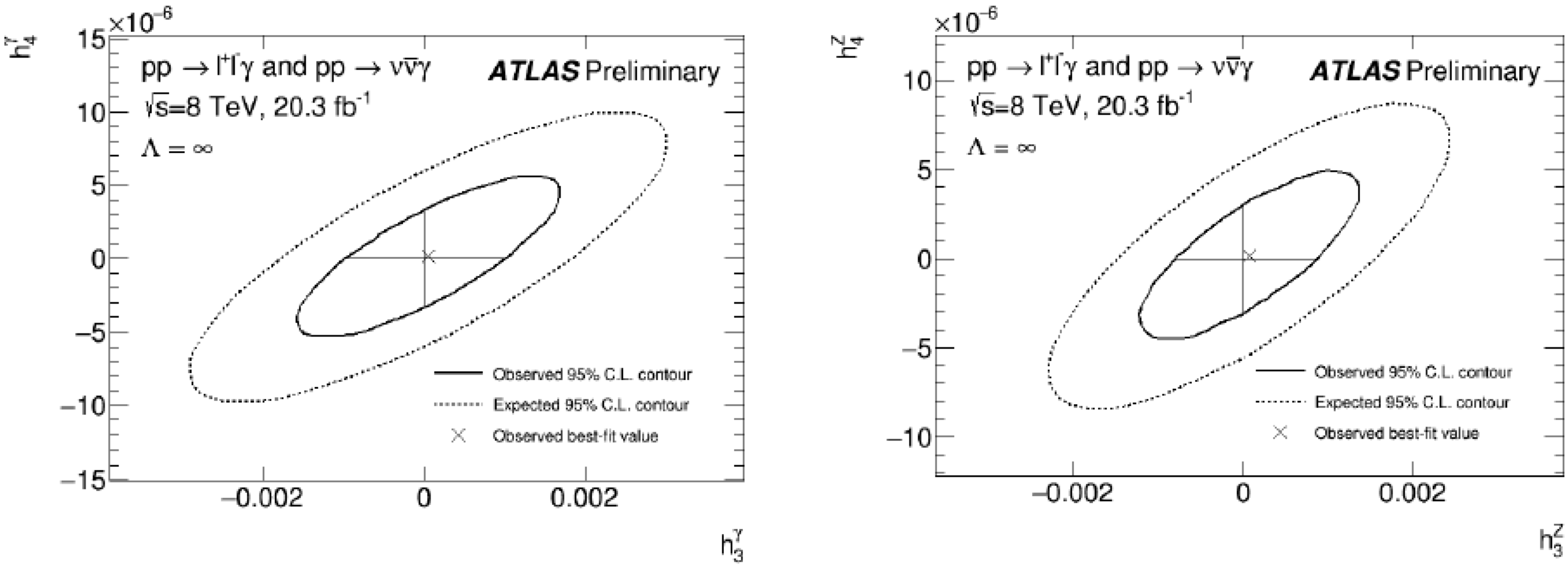
Theo. Prediction: $7.2^{+0.3}_{-0.2}$ pb (MCFM NLO with CT10 PDF)

Channel	Measured σ_{fid} [fb]	Theoretical σ_{fid} [fb]
$ZZ \to e^+e^-e^+e^-$	$4.6^{+0.8}_{-0.7}(\text{stat.})^{+0.4}_{-0.4}(\text{syst.})^{+0.1}_{-0.1}(\text{lumi.})$	$5.3^{+0.2}_{-0.2}$
$ZZ \to \mu^+\mu^-\mu^+\mu^-$	$5.0^{+0.6}_{-0.5}(\text{stat.})^{+0.2}_{-0.2}(\text{syst.})^{+0.2}_{-0.2}(\text{lumi.})$	$5.3^{+0.2}_{-0.2}$
$ZZ \to e^+e^-\mu^+\mu^-$	$11.1^{+1.0}_{-0.9}(\text{stat.})^{+0.5}_{-0.5}(\text{syst.})^{+0.3}_{-0.3}(\text{lumi.})$	$10.5^{+0.4}_{-0.4}$





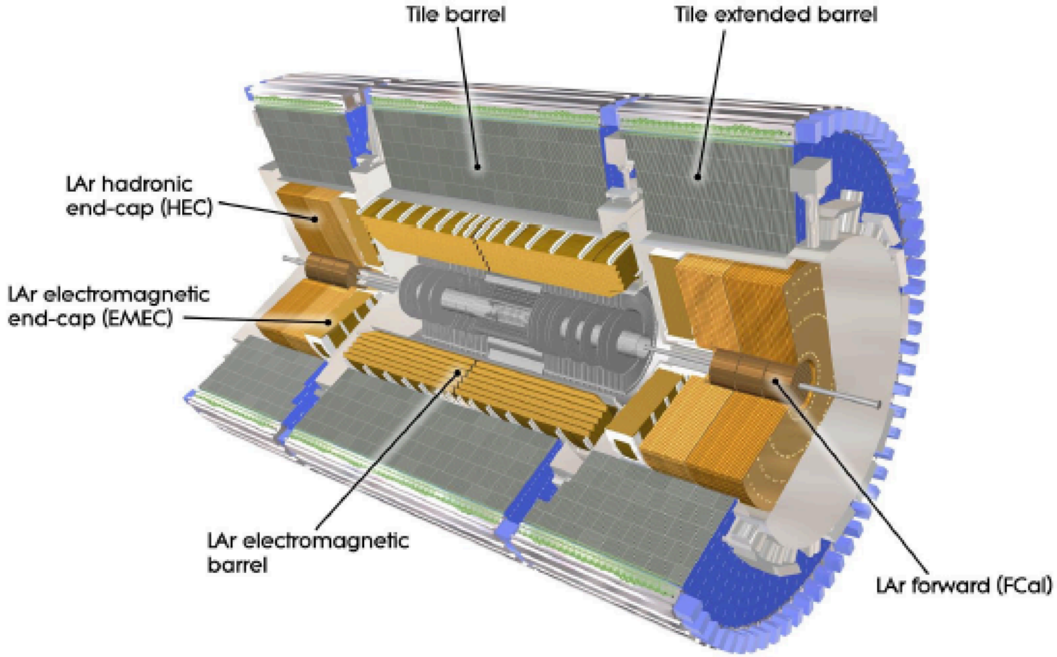




No sign of deviation from SM predictions

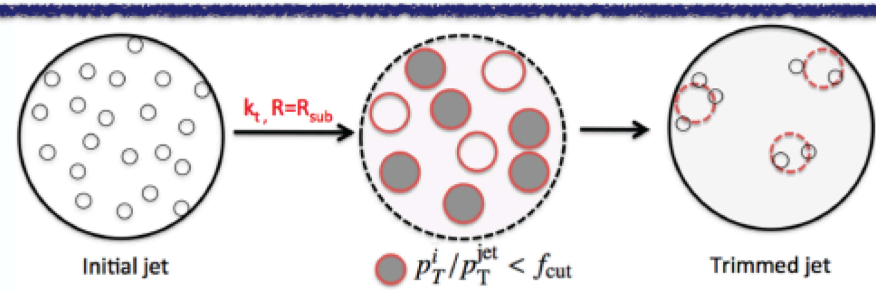
Calorimetry constraints

- Jets in ATLAS are formed from topoclusters
  - Combination of adjacent energy deposits in the calorimeter cells: arXiv:1603.02934
- The hadronic calorimeters in ATLAS have a fine granularity
  - Tile: ΔR ~ 0.1
  - LaR: ΔR ~0.025
- Great resolution to pick apart the large-R jets and look at its substructure



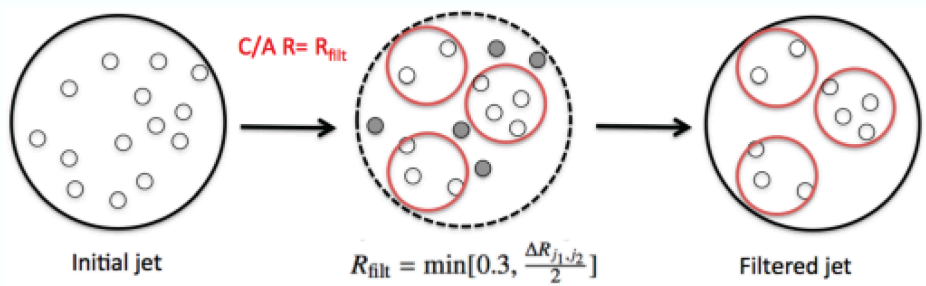
- Energy depositions in calorimeter are grouped into topological clusters, which are used to form large-R jet (R=1.0, anti-kt) JHEP09 (2013) 076

Trimming



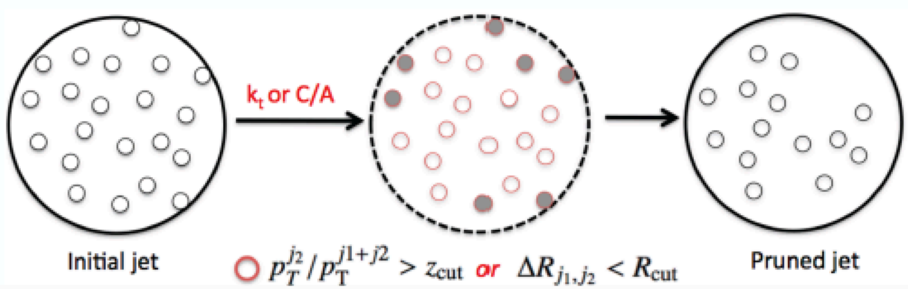
Compares pT(constituents) with pT(jet) – removes soft components which are primarily from UI & PU

Filtering



Remove constituents that are outside of subjets

Pruning



Similar to trimming but occurs during jet reconstruction ⇒

does not require subjet reconstruction

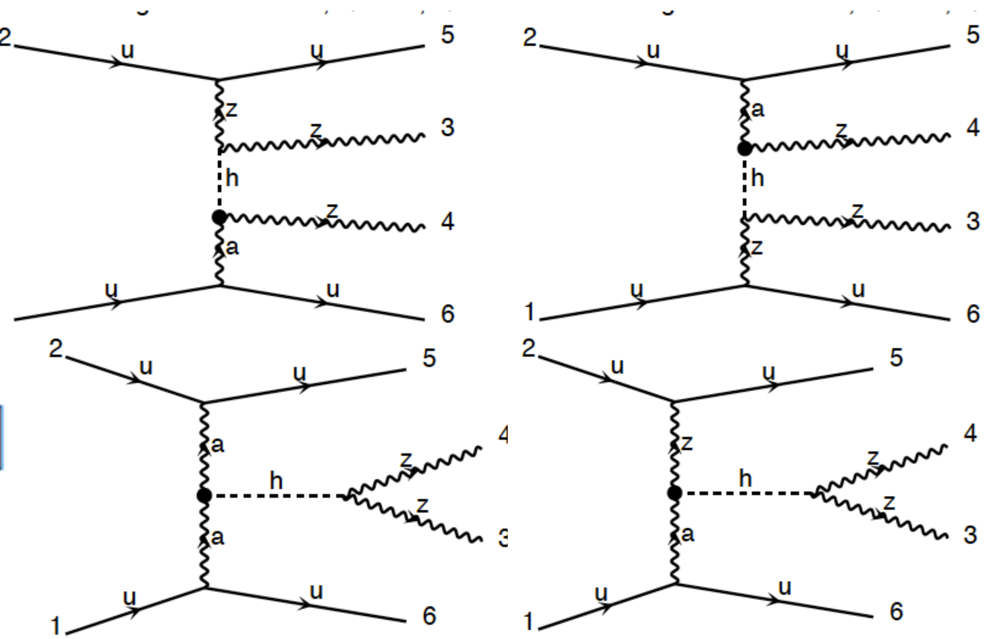
EFT with Dim6 operators II

- 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

Analysis framework (WZjj/ZZjj)

- Using the same showering/smearing/limit-setting framework as Chris Pollard's ATLAS upgrade physics study which was approved for European Strategy submission

- Generator choice:
  - MadGraph5 with EFT operators implemented and supported by our theorist colleagues (Celine Degrande, Oscar Eboli, Olivier Mattelaer, etc.)
  - Cross checked by VBF@NLO

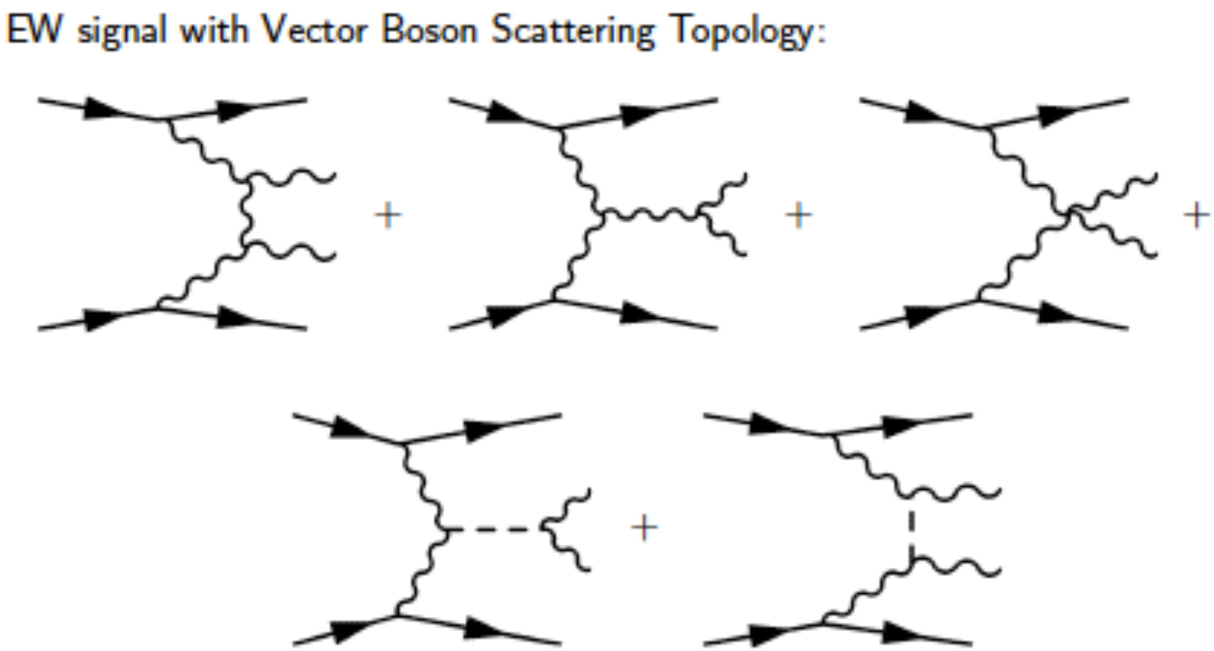
- Signal: VBS WZjj and VBS ZZjj
- Background: WZ+QCD jets and ZZ+QCD jets

- Analysis cuts: (same cuts for ssWWjj, WZjj and ZZjj)
  - Lepton: pT>25GeV,
  - Electron: |η|<2.47 (excluding crack region), Muon: |η|<2.4
  - Jets: pT>50GeV, |η|<5
  - M(jj) > 1TeV (optimized for ZZjj and WZjj)

- Sensitivities are studied for 300, 3000 fb^{-1} @ 14 TeV

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



EFT with dim8 operators II

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

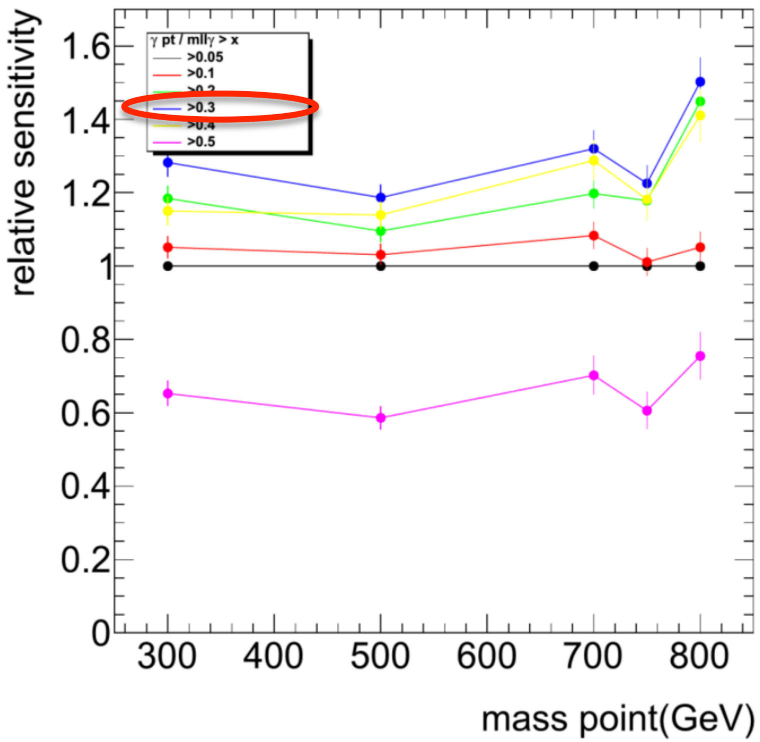
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

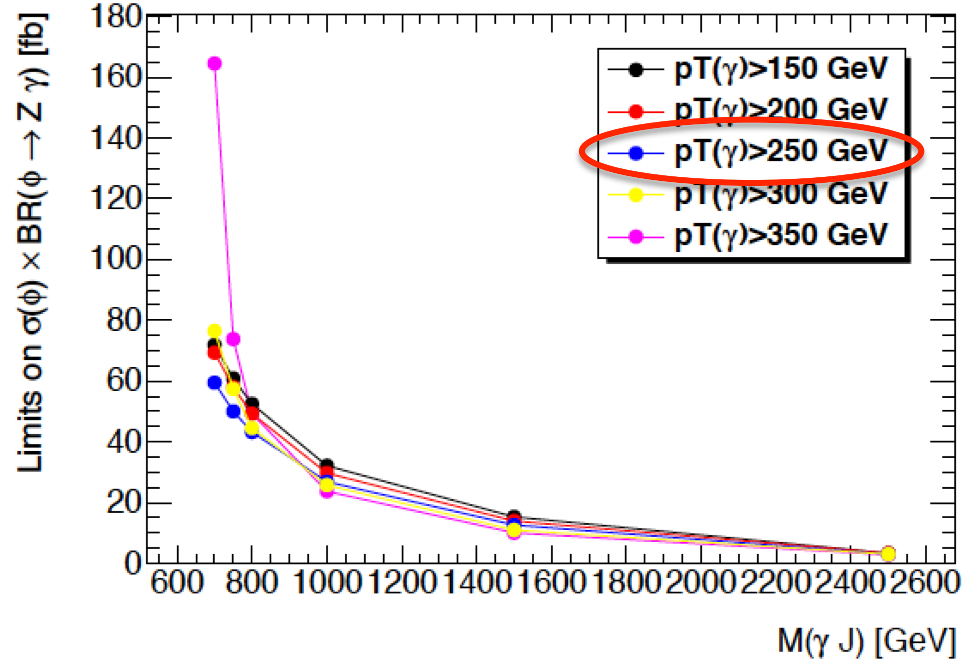
$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2}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

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

- 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

Event selections and optimizations





Maximized the expected cut-counting sensitivity independently in two channels

Leptonic Z(→ll) analysis

$E_T(\gamma)/M_X$>0.3, tight calo iso only

Single and dilepton trigger

Boosted Z(→J) analysis

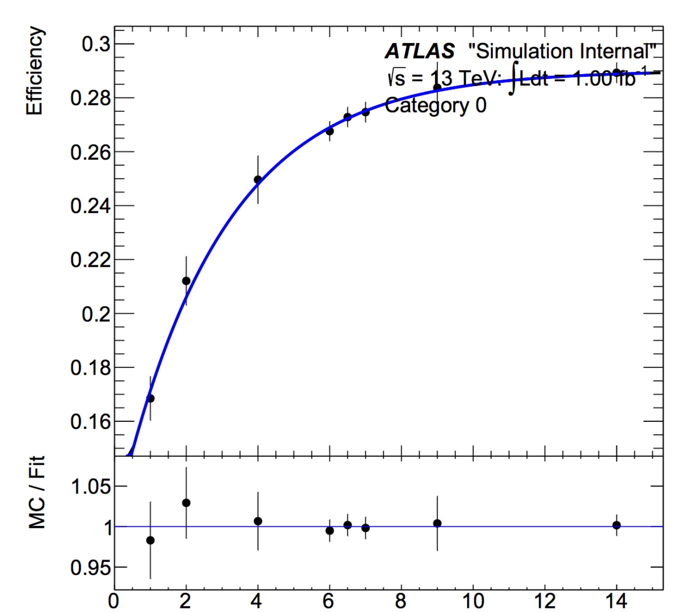
$E_T(\gamma)$>250GeV, tight calo iso only

Single photon trigger (HLT_g120_loose)

Medium Boson tagged Fat jets

Signal efficiency: review of leptonic channel

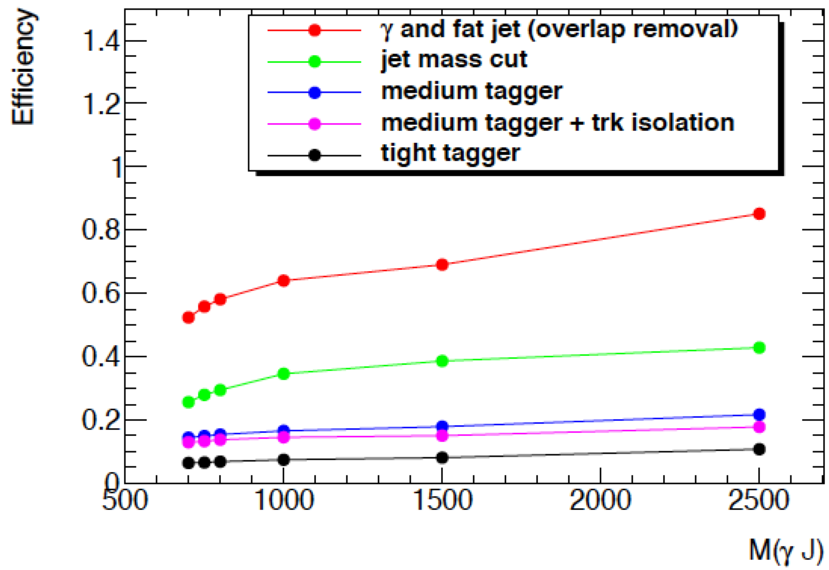
Signal overall efficiencies



Relative efficiency of e/μ channels in comparison

	$ee\gamma$		$\mu\mu\gamma$	
Selection	N	Relative efficiency (%)	N	Relative efficiency (%)
Trigger Matching	45692	100.0	62692	100.0
$\lvert m_{\ell\ell} - m_Z \rvert < 15\ GeV$	29754	65.1	40245	64.2
γ (tight) identification	746	2.5	951	2.4
γ isolation	473	63.4	635	66.8
$m_{\ell\ell\gamma} > 200$ GeV	262	55.4	329	51.8
$p_T^{\gamma}/m_{\ell\ell\gamma} > 0.3$	168	64.1	214	65.0

Signal efficiency: review of hadronic channel

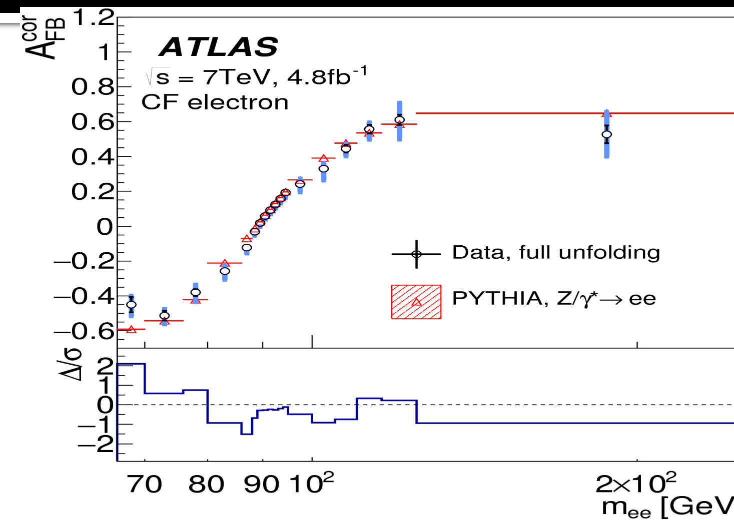


Absolute eff. only takes into account the DAOD total # of events.

$M(Z\gamma)$	750 GeV	1500 GeV	2500 GeV	γ+Jets (Sherpa MC)
a tight ID photon with $p_T > 250$GeV	57.2% (57.2%)	73.8% (73.8%)	89.7% (89.7%)	3.87% (3.87%)
photon isolation	55.8% (97.4%)	72.0% (97.6%)	88.2% (98.3%)	3.67% (94.8%)
g_120_loose Trigger	55.8% (100%)	72.0% (100%)	88.2% (100%)	3.67% (100%)
A fat jet $p_T > 200$GeV	51.2% (92.0%)	68.5% (95.1%)	85.0% (96.4%)	2.86% (78.1%)
$\|M_{jet} - M_Z\| < 15$GeV	25.7% (50.1%)	38.3% (55.8%)	42.7% (50.2%)	0.33% (11.6%)
medium boson tagging	13.5% (52.7%)	17.7% (46.2%)	21.7% (50.8%)	0.098% (29.5%)
medium boson tagging + track isolation	12.0% (88.9%)	14.9% (84.2%)	17.8% (82.0%)	0.063% (64.3%)

Measurement of the forward-backward asymmetry of lepton pair production and Weinberg angle extraction at 7 TeV

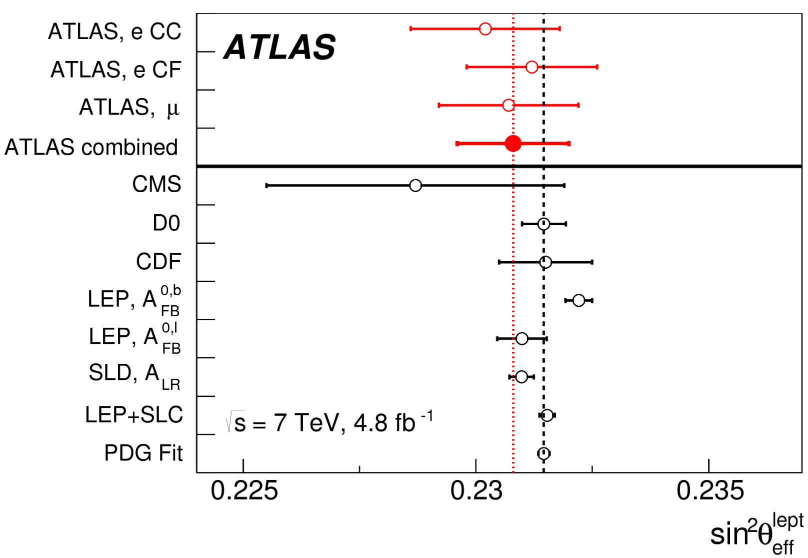
(axial-)vector couplings in the neutral current annihilation
$Z/\gamma^* \rightarrow ll$ polar angle distribution of the final state lepton w.r.t. the quark direction in the rest frame of the dilepton system.

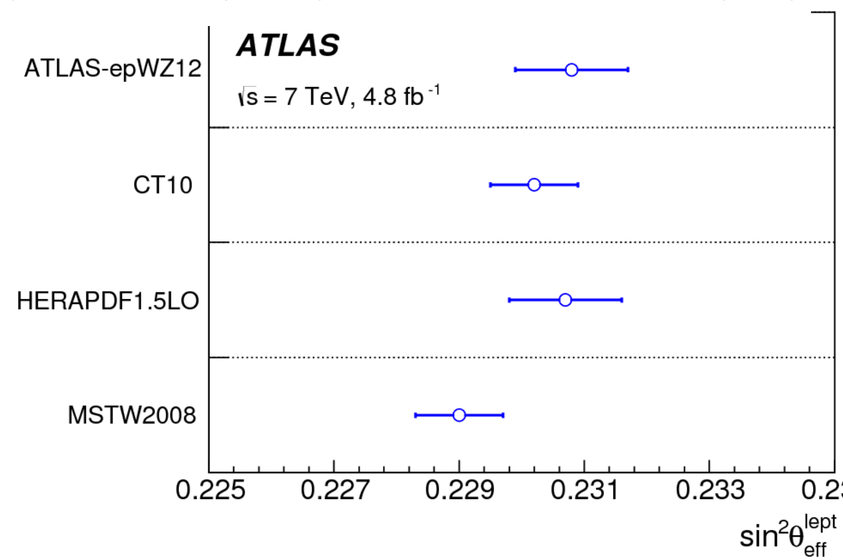


$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N_{\cos\theta^*_{CS} \geq 0} - N_{\cos\theta^*_{CS} < 0}}{N_{\cos\theta^*_{CS} \geq 0} + N_{\cos\theta^*_{CS} < 0}}$$

Measured effective weak mixing angle in good agreement with the current world average from PDG fit:

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2308 \pm 0.0012(\text{tot.}).$$



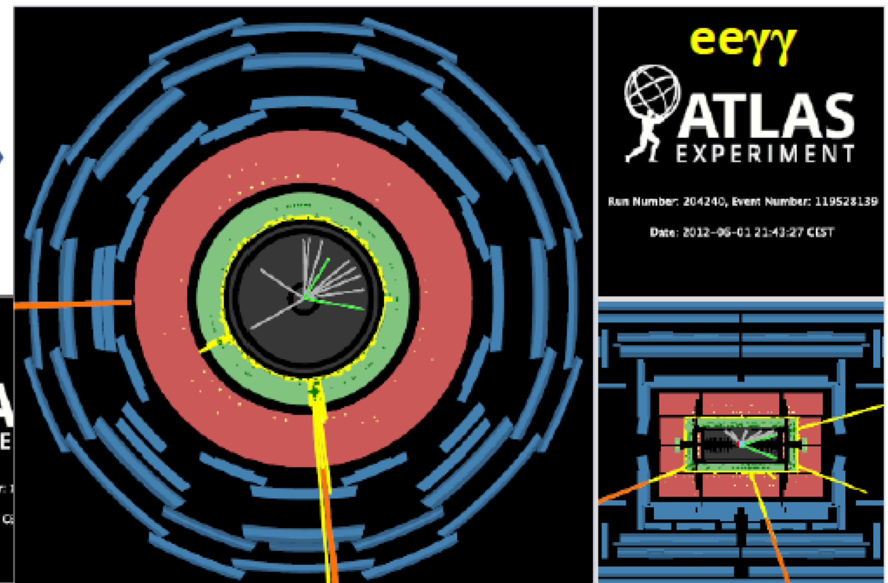


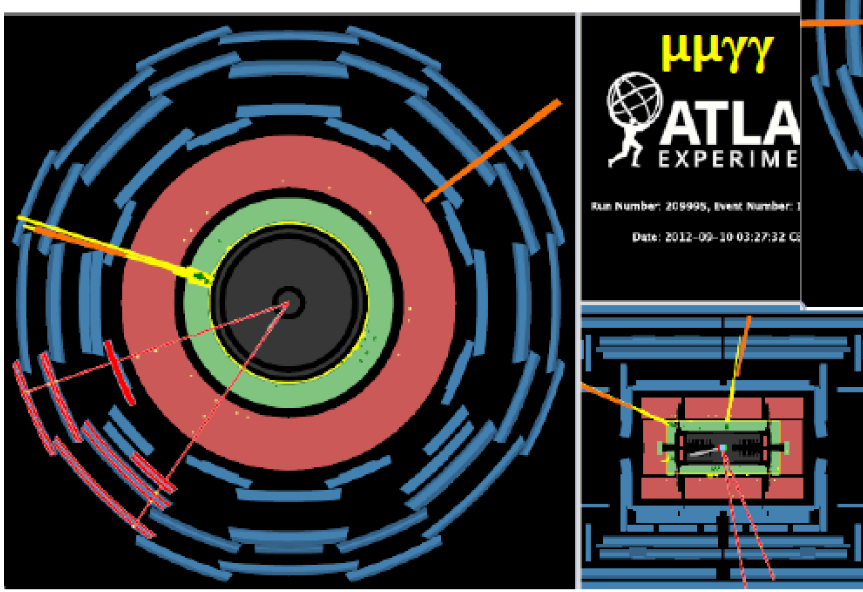
Zγ(γ) Event Characteristics

- Zγ events
  - *llγ* has signature of two good identified leptons (e or μ) and one isolated photon
  - *ννγ* has signature of high missing transverse momentum and one isolated photon

llγ: $p_T(l)>25$ GeV; $E_T(\gamma) > 15$ GeV
ννγ: $E_T(\text{miss}) > 100$ GeV; $E_T(\gamma) > 130$ GeV

- Zγγ events signatures differ from Zγ by presence of one more isolated photon





llγγ: $p_T(l)>25$ GeV; $E_T(\gamma) > 15$ GeV
ννγγ: $E_T(\text{miss}) > 110$ GeV; $E_T(\gamma) > 22$ GeV

Inclusive selection: without and constraints on hadronic activity; Exclusive selection: $N_{jets} = 0$

Signal modeling

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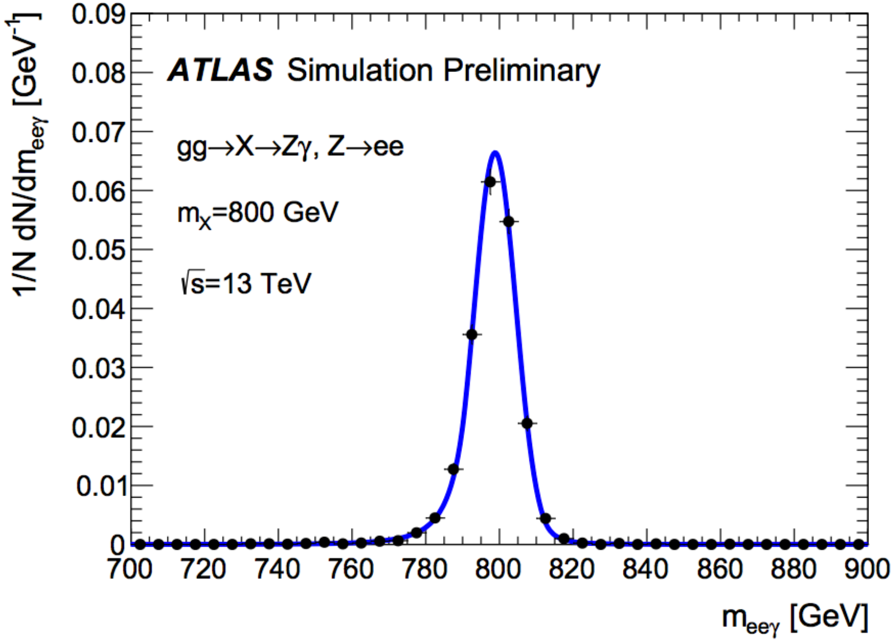
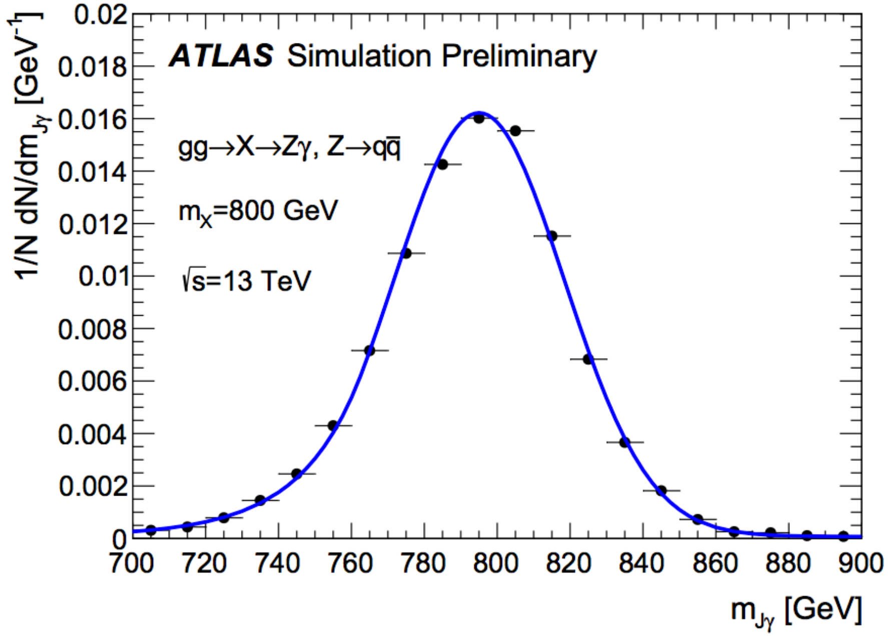
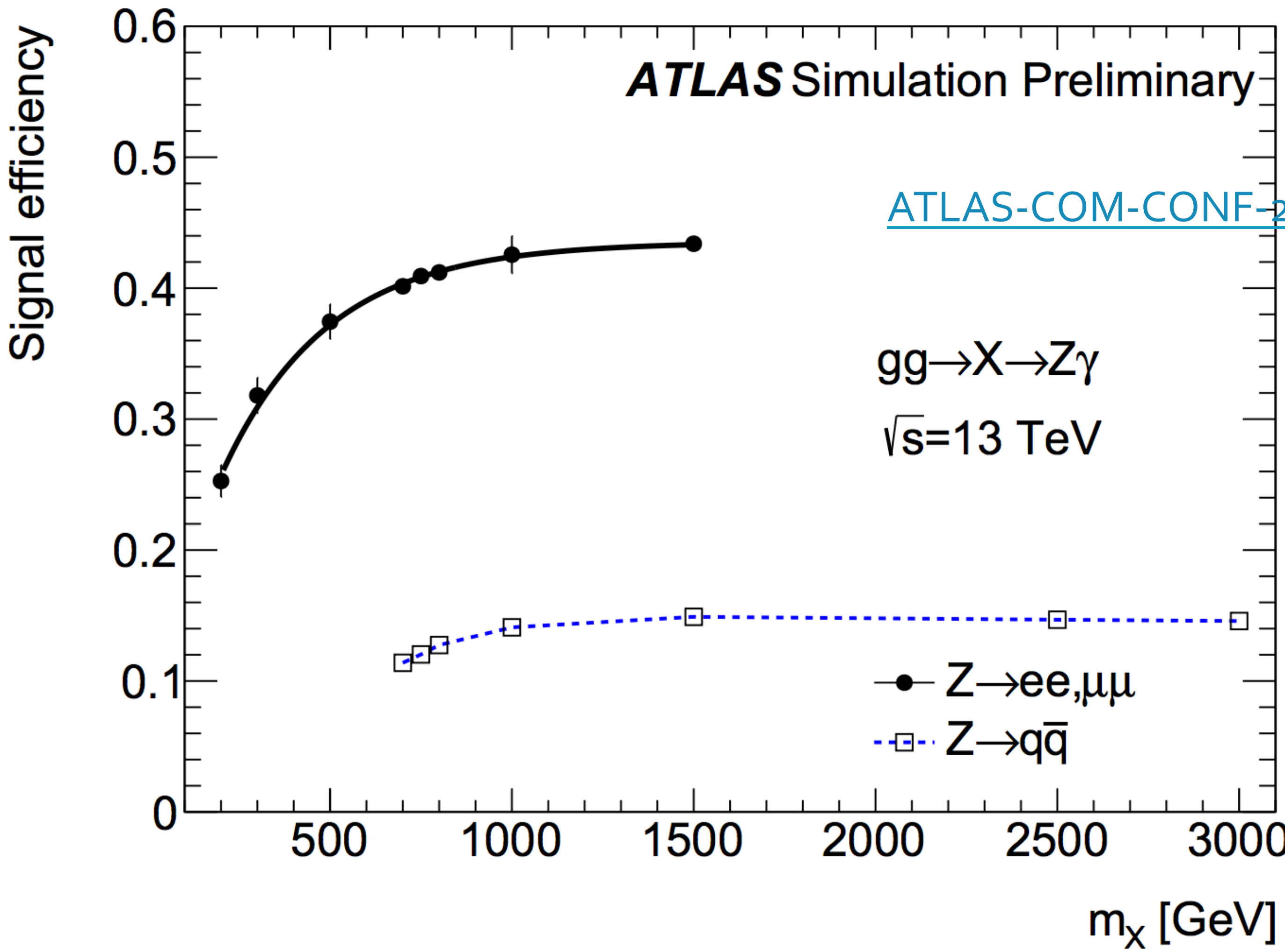




Signal invariant mass distribution of Z→ll and Z→J
Parametrised with analytical function: double-sided CB for leptonic channel and Crystal Ball (CB)+Gaussian for hadronic channel

$m_{ll\gamma}$ resolution ~1%; $m_{J\gamma}$ resolution between 3% GeV for m_X = 750GeV and 1.7% for m_X = 3 TeV

Signal efficiency comparison between two channels



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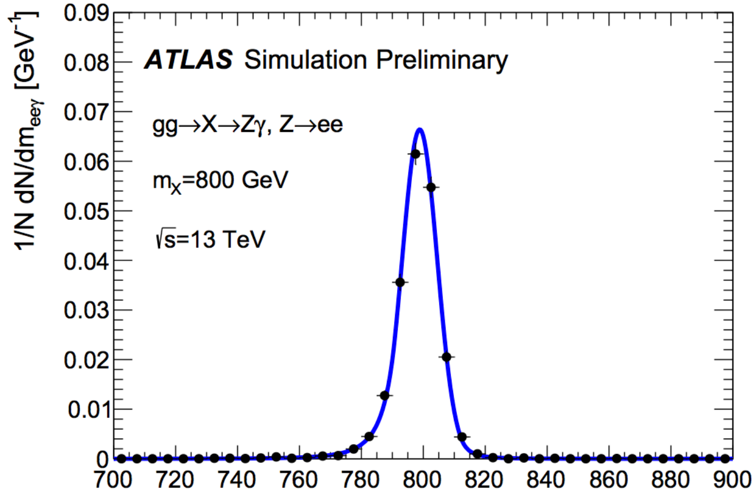
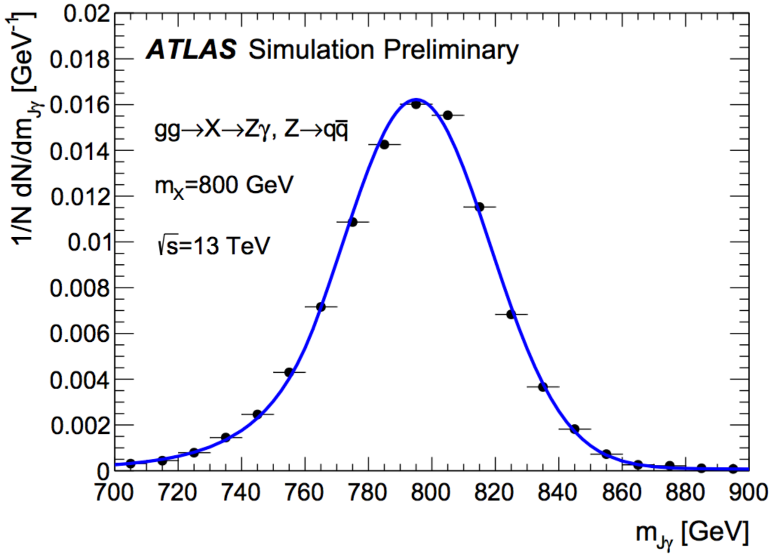
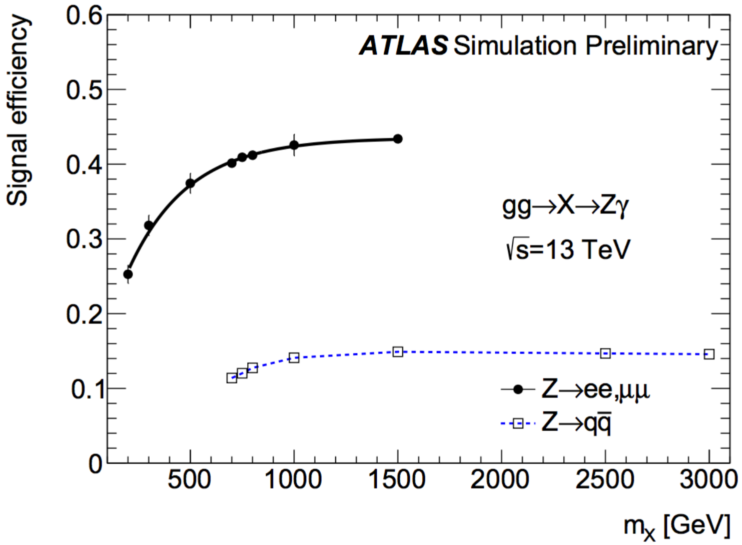
Signal modeling and acceptance difference



Boosted Hadronic channel relies on Jet Substructure cuts and can afford lower effciencies as motivated by higher signal production rate and worse background contaminations as well as worse detector resolutions





Background fit

Background is measured through a max-L fit of data with a suitable parametric form on M(Jg)

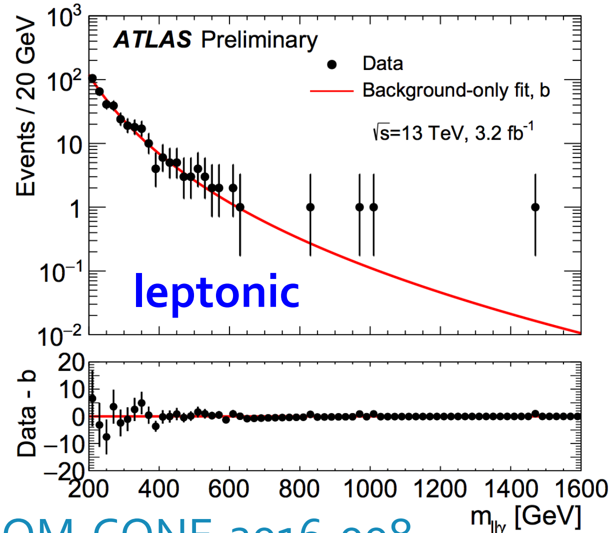
Hadronic $p_1(1-x)^{p_2+\xi p_3}x^{p_3}$

Leptonic $(1-x^{1/3})^b x^{a_0}$

Hadronic:
Tested with high stat. γ+jets MC events.
(other bgd verified by MC to be negligible: j->γ, ttγ+X, SM Vγ)

Leptonic:
High statistic SM Zγ and Zjets

Fit range:
Hadronic: [640, 3000]GeV, 20GeV-binned
Leptonic: [200, 1600]GeV, 20GeV-binned



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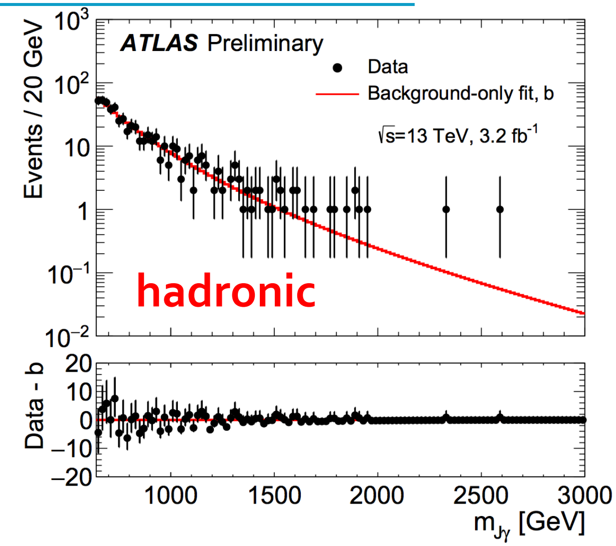
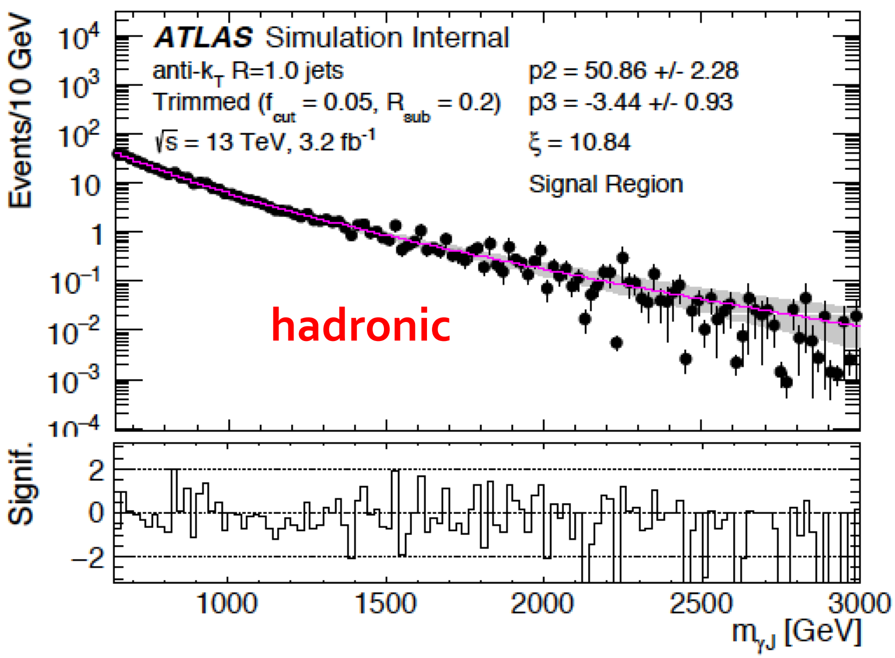
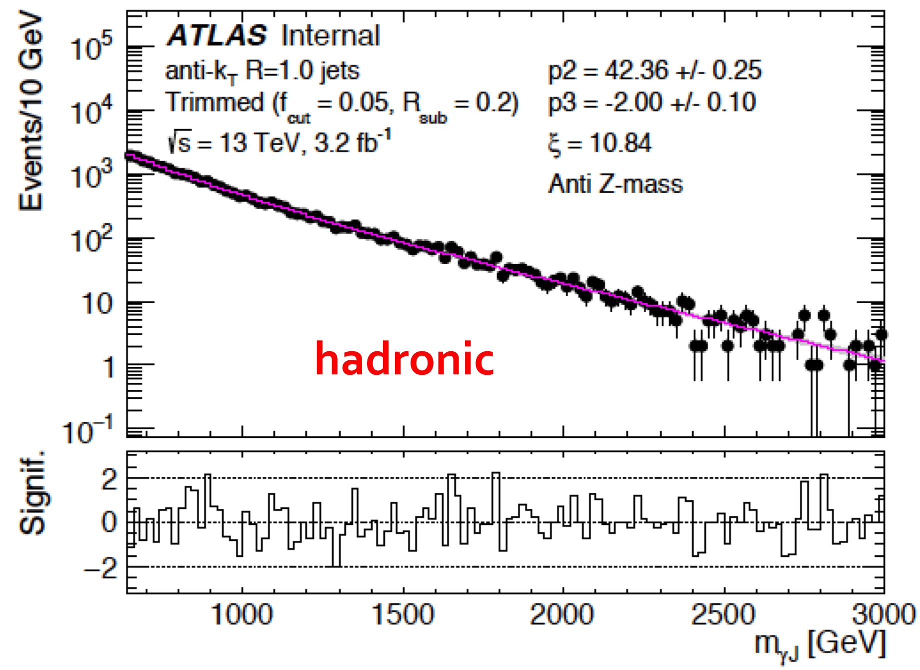


Background fit: validation in CR

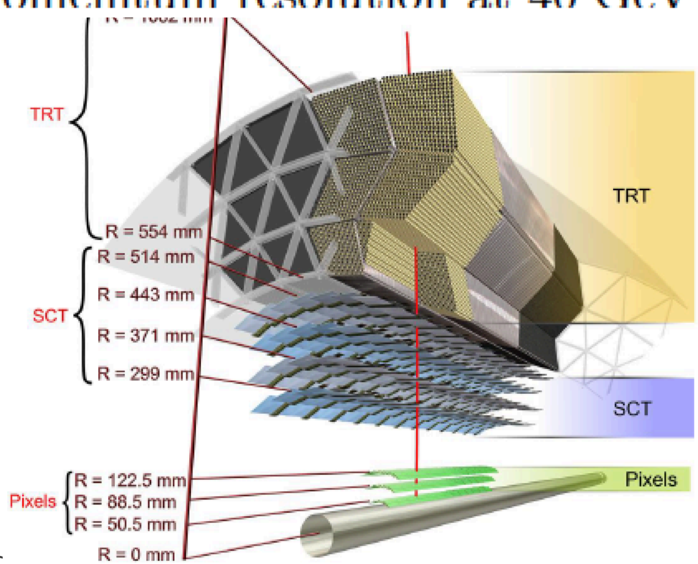
The background model is tested against a data $m_{\gamma J}$ distribution for events in a validation region
(i.e. Using the signal region requirements except the Z jet mass window cut being vetoed.)

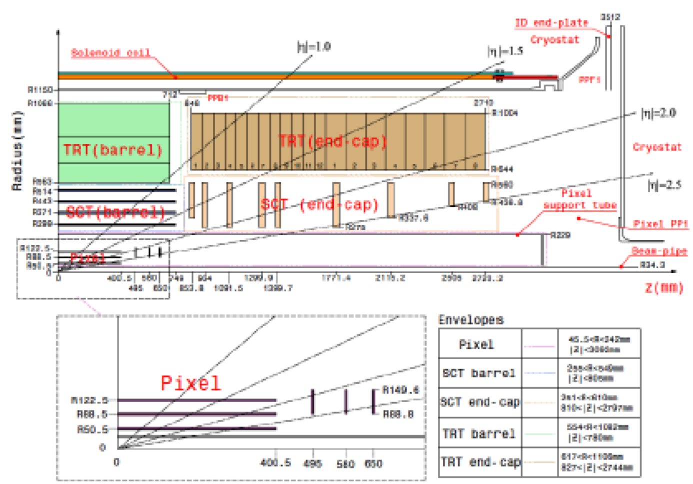




ATLAS: the inner detectors

- Extemely large inner track density (∼1000 particles per 25/50 ns)
- High granularity for the measurement of the track momenta, impact parameters and primary/secondary vertices of charged particles
- $|\eta| < 2.5$ geometry coverage within 2 T solenoid magnet field
- Three compartments:
  - Pixel Detector
  - Silicon Microstrip Tracker (SCT)
  - Transition Radiation Tracker (TRT)
- $\sim 4\%$ momemtum resolution at 40 GeV





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")

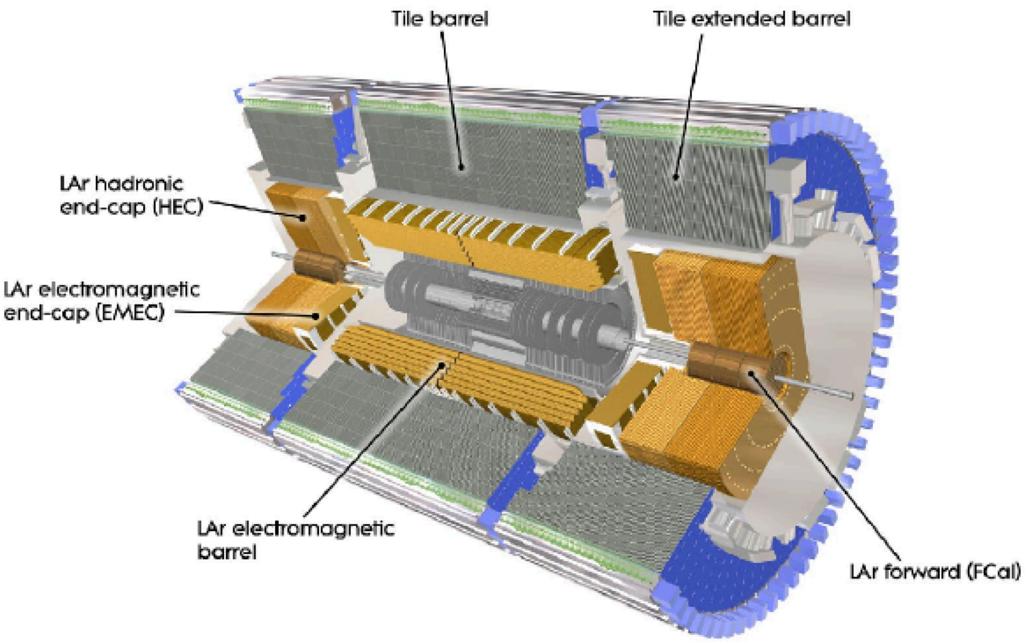
Two sampling calorimeters:
The lead-LAr calorimeter
Tile hadronic barrel calorimeter

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

- Good reconstruction of missing transverse energy (E_T^{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_T^{miss}



ATLAS: LAr Calorimeter

Accordion-shaped kapton electrodes + full-coverage lead absorber plates

One barrel ($|\eta| < 1.475$) + two end-cap ($1.375 < |\eta| < 3.2$)

1-layer presampler ($0 < |\eta| < 1.8$) to compensate energy loss before the EM calo

Absorber: lead and stainless steel, good containment of EM energy depositions

Precision measurement region: $0 < |\eta| < 2.5$

1^{st} and 2^{nd} layers: the finest segmentation along η, 3^{rd} layer: less segmented to take the residual of the EM showers deposition

Nominal resolution: $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E(GeV)}} \oplus 0.7\%$ over the full coverage, constant term achieved 1.2%~1.8% (indication of non-uniformity)

Electron/photon trigger