Observation and cross section measurements of electroweak $W(\rightarrow l\nu)\gamma jj$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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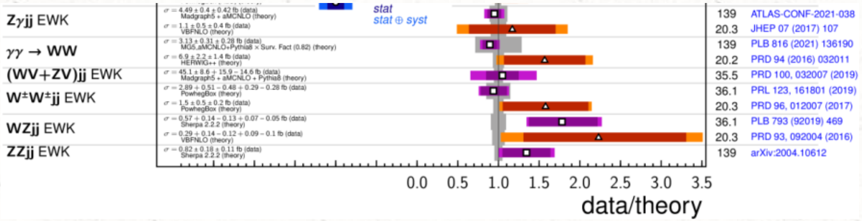
Introduction

- Vector Boson Scattering
  - Very rare process (~ fbs), precision test of SM
  - Crucial to understand the Electroweak Symmetry Breaking
  - To probe anomalous couplings between vector bosons, model independent search of BSM and set limits on EFT dimension-8 operators

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \frac{f_n}{\Lambda^{n-4}} \mathcal{O}_n$$

- VBS cross section measurement in ATLAS



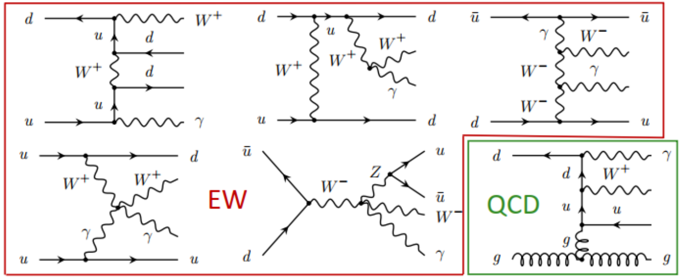
  - VBS $W\gamma$ hasn't been observed at ATLAS.

- CMS EW Wγjj
  - 1st observation, 35.9fb^{-1}, cut based, 5.3σ (combining 13TeV and 8TeV) PLB 811 (2020) 135988
  - Differential cross section measurement, 138fb^{-1}, 6.03σ CMS-PAS-SMP-21-011 Jing Peng's talk

Analysis overview

- Physics goal
  - Observe EW Wγjj
  - Measure a fiducial and differential cross section of EW production of Wγjj
  - Probe anomalous quartic gauge boson couplings in EFT
- Datasets
  - Full Run-2 datasets (139fb^{-1})

$$\xi(x) = \left|\frac{y(x) - 0.5(y(j0) + y(j1))}{\Delta y(jj)}\right|$$



- Analysis strategy
  - Neural network is used to discriminate signal and background and fit the output.
  - A control region is defined by reverse $\xi_{W\gamma}$ to constrain the QCD background.
  - Data driven methods are used to estimate all non-prompt, fake, pileup backgrounds.
  - $\triangle Y_{jj}$ cut-based fit is performed to check with NN results.
  - The extracted yields are unfolded to produce differential cross sections.

Selections

- Basic selection
  - Single lepton triggers, event cleaning, GRLs
- Object selection

At least 1 tight & isolated γ	1 tight & isolated lepton	At least 2 jets
$pT_{\gamma} > 22GeV$	$pT_{lep} > 30GeV$	$pT_{j1} > 50GeV$
$\lvert\eta_{\gamma}\rvert < 2.37$	$\lvert\eta_{lep}\rvert < 2.5$	$pT_{j2} > 50GeV$

- Event selection

$M_T^W > 30GeV$	$\Delta R(\gamma, lep) > 0.4$	$\Delta\phi(j1(2), MET) > 0.4$
$MET > 30GeV$	$\Delta R(j1, j2) > 0.4$	$m_{jj} > 500GeV$
$\lvert M_Z - M_{\gamma+lep}\rvert > 10$	$\Delta R(\gamma, j1(2)) > 0.4$	Standard object OR

- Additional selection
  - NN fit: $\triangle Y_{jj} > 2$
  - $\triangle Y_{jj}$ fit: $m_{jj} > 700GeV$
  - Differential extraction: $\triangle Y_{jj} > 2$, $m_{jj} > 1TeV$

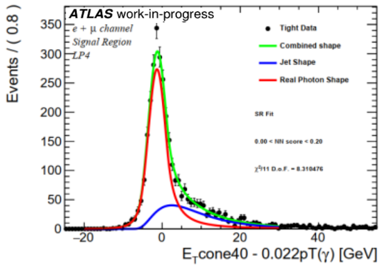
➢ Typical VBS topology

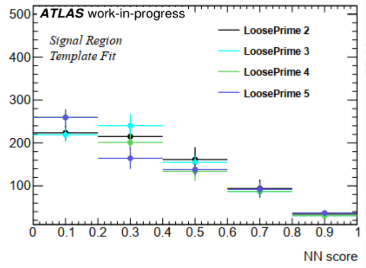
✓ Two tagging jets
✓ Large rapidity gap $\triangle Y_{jj}$
✓ Large Invariant mass m_{jj}
✓ Centrality - Little hadronic activity between the two jets

Data-driven background estimation

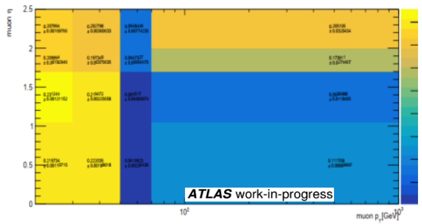
- Jet faking photons – template fit method
  - A prompt photon template shape f_T
    A real photon leakage shape f_{NT}
  - DSCB function is used as the pdf function.
  - The template parameters are floated but constrained by multivariate gaussians defined by the mean and sigma of the best fit values of the template fits.

$$-NLL = -log \prod f_T(x|\theta_T) f_{NT}(x|\theta_{NT}) G(\theta_T|\sigma_{\theta_T}) G(\theta_{NT}|\sigma_{\theta_{NT}})$$

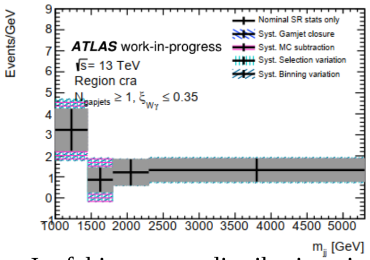




- Jet faking leptons(e/μ) – fake factor method
  - Dijet events are used to estimate the fake factor
  - Tight leptons: pass signal selection
    Anti-Tight leptons: fail isolation or { identification(e) / d_0 requirement(μ) }
  - $F = \frac{N_{\text{"Tight μ" + j}}}{N_{\text{"Anti-tight μ" + j}}}$ (Dijet events)
  - $N_{\text{"Fake and Tight μ" + γjj}} = F \times \left(N^{Data}_{\text{"Anti-tight μ"+γjj}} - N^{MC}_{\text{"Real and Anti-tight μ"+γjj}}\right)$



Muon fake factor in p_T and η

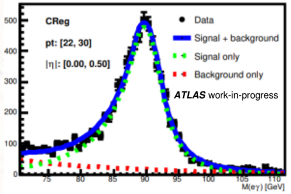


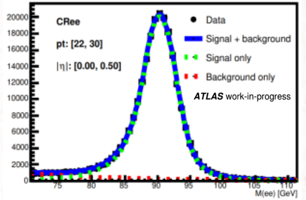
Jet faking muon distributions in m_{jj}

Data-driven background estimation

- Electron faking photons – fake factor method
  - Tag and probe method – Z (->ee) + jets events

Tag electron	Probe electron	Probe photon	Other selections
$p_T > 30GeV$	$p_T > 22GeV$	$p_T > 22GeV$	$m_T^{W(ev)} < 20GeV$
$\|\eta\| < 2.5$	$\|\eta\| < 2.37$	$\|\eta\| < 2.37$	$E_T^{miss} < 20GeV$
e_isoTightVarRad	e_isoTightVarRad	gam_isoTight	
e_idTight	e_idTight	gam_idTight	
$\|z_0 \times sin\theta\| < 5mm$	$\|z_0 \times sin\theta\| < 5mm$		
$\|d_0/\sigma_{d_0}\| < 3$	$\|d_0/\sigma_{d_0}\| < 3$		
pass single electron triggers	Opposite charge with tag electron		

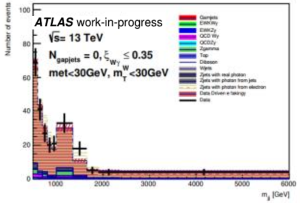


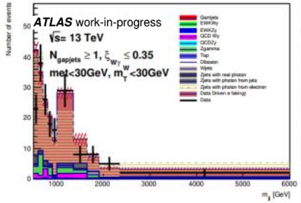


  - Z (ee) events: fitting with DSCB function + Exponential function
  - Fake factor

$$F_{e\rightarrow\gamma} = \frac{\epsilon_\gamma}{\epsilon_e} = \frac{N^{reco}_{e_{tag}\gamma_{probe}}}{2N^{reco}_{e_{tag}e_{tag}} + N^{reco}_{e_{tag}e_{probe}}}$$

  - Validated in the Z veto region with reversing MET and W_T^M cuts





- Pileup background – Estimated with only converted photons VBS Zγ analysis
  - For hard scatter photons, the $\Delta z(PV, \gamma)$ distribution should be sharply peaked at 0.
    For pileup photons, $\Delta z(PV, \gamma)$ is the difference of two uncorrelated gaussians with width of 35 mm (a gaussian of 35mm× 2 = 50mm)
  - Using the Gaussian properties of the pile-up Δz distribution, 32% of pile-up events are

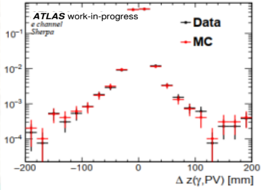
$$f_{PU} = \frac{N_{data}^{|\Delta z|>50mm} - N_{MC}^{|\Delta z|>50mm} * C}{N_{data} * 0.32}$$

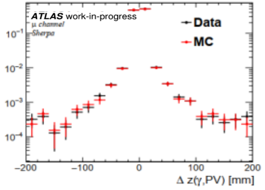
C is a normalization factor derived by comparing the QCD Wγ and EW Wγ to data.

  - This is only applied after data is unblinded!

$$f_{pu} = 1.24 \pm .81\%$$

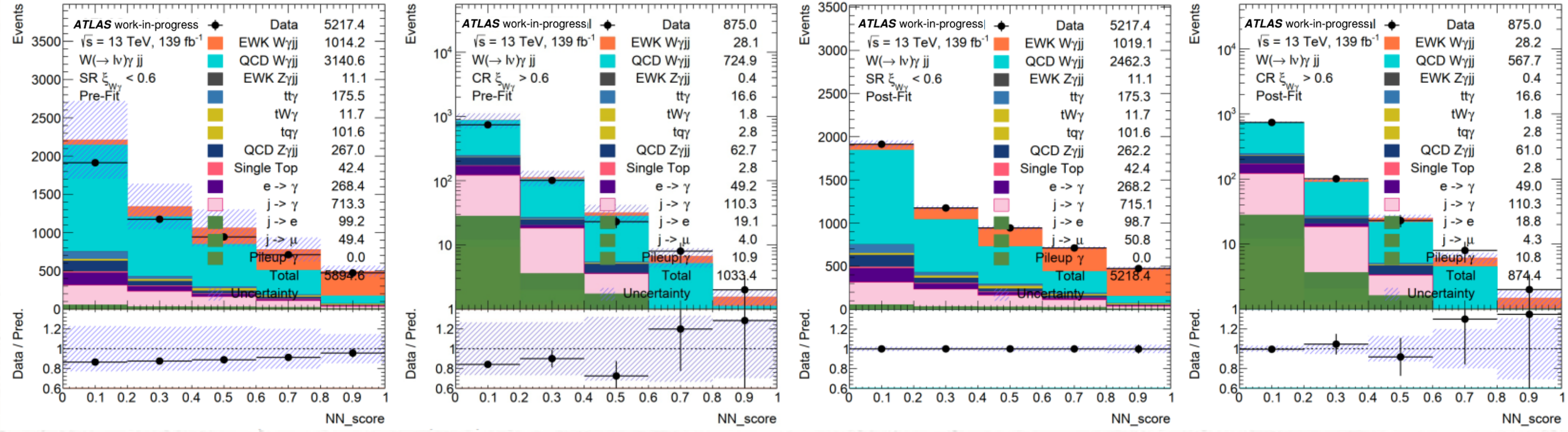
(work-in-progress)





Observation - Neural Network fit

- Simultaneously fit the NN output in signal region and control region. Expected significance is extracted on Asimov data.



- Signal strength and QCD normalization after fit to Asimov data
- Expected significance: **12.3 σ** (work-in-progress)

ATLAS work-in-progress

Parameter	Value
μ_{EW}	$1.01^{+0.16}_{-0.16}$
μ_{QCD}	$0.79^{0.28}_{-0.28}$

Observation - Neural Network fit

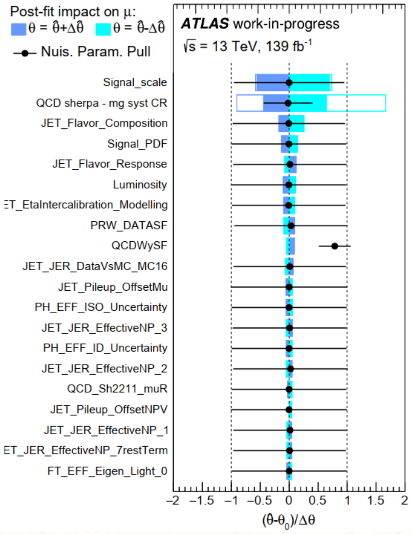
- The relative impact of each nuisance parameter is evaluated by performing the fit for each nuisance parameter with that nuisance parameter fixed and comparing the result to the nominal fit.
- Dominated by theory uncertainties
- The fiducial cross section is calculated as

$$\sigma^{fid} = \frac{N^{sig}}{C\mathcal{L}} \qquad C = \frac{N^{reco}}{N^{fid}}$$

N^{Sig} is the number of fitted events in data, $\mathcal{L}$ is the integrated luminosity of the dataset

C is a correction factor to account for the imperfect reconstruction efficiency of the detector.

Reco	Truth
TST MET	MET from non interacting truth particles
Object overlap removal	Reduced Object overlap removal
$Iso_\gamma < 2.45 + 0.022pT_\gamma$	$Iso_\gamma < 6.43 + 0.022pT_\gamma$

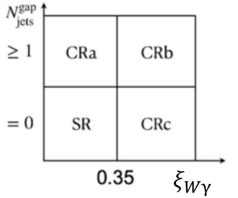


ATLAS work-in-progress

Uncertainty Source	$+\Delta\mu$	$-\Delta\mu$
Theory	0.150	−0.150
Jets	0.059	−0.059
Stat.	0.038	−0.038
Luminosity	0.012	−0.012
Pileup Reweighting	0.017	−0.017
NormFactors	0.014	−0.014
Photons	0.013	−0.013
Flavor Tagging	0.008	−0.008
Muon	0.007	−0.007
Jfakemu	0.004	−0.004
Missing E_T	0.004	−0.004
Jet fake photon	0.004	−0.004
Electron	0.004	−0.004
Egamma	0.003	−0.003
Jet fake elctron	0.035	−0.003
Electron fake photon	0.001	−0.001
Total	0.16	0.16

$$\sigma^{fid}_{exp} = 9.603 \pm 1.796(\pm 0.894(stat) \pm 0.714(sys.) \pm 1.343(th.) \pm 0.336(fakes))$$ fb (work-in-progress)

Differential cross section measurement of EW Wγjj



- Differential cross sections are measured as a function of m_{jj}, p_{Tjj}, and $\triangle\phi_{jj}^{signed}$.
- A binned maximum likelihood fit in SR + 1CR or 3CRs.
- The likelihood function is defined as (with indices r, i running over regions and bins respectively)

$$L = \prod_{r,i} \mathrm{Pois}(N_{ri}^{\mathrm{data}}|\gamma_{ri}\nu_{ri}(\alpha))\mathrm{Pois}\left(\left(\frac{\nu_{ri}(\mathbf{1})}{\delta_{ri}}\right)^2|\gamma_{ri}\left(\frac{\nu_{ri}(\mathbf{1})}{\delta_{ri}}\right)^2\right)$$

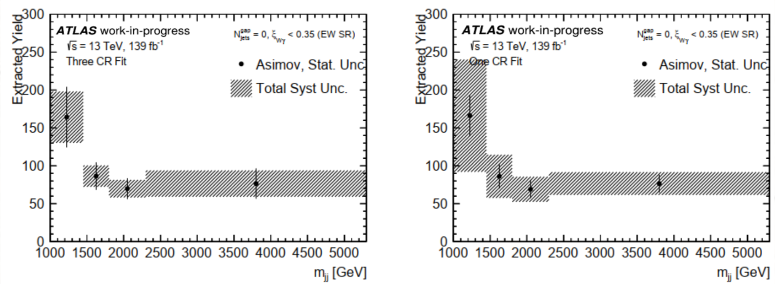
ν_{ri} is the total MC estimate given by

$$\nu_{ri} = \mu_i \nu_{ri}^{\mathrm{EW,MC}} + \nu_{ri}^{\mathrm{strong}} + \nu_{ri}^{\mathrm{non}\text{-}W\gamma,\mathrm{MC}}$$

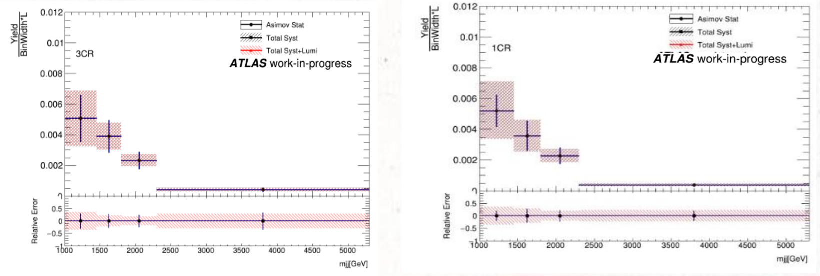
$$\alpha \equiv (\mu_1, \ldots, \mu_n, b_{L,1}, \ldots, b_{L,n}, b_{H,1}, \ldots, b_{H,n}, f(x_i))$$

N_{jets}^{gap}: Number of jets in rapidity gap Δy

- Extraction of differential event yields and Iterative Bayesian unfolding method



Unfolding



Summary

- The current progress of EW production of Wγjj with full run2 data are presented.
- The MC samples, phase space, event selection and background are studied in detail.
- The expected significance of EW production of Wγjj can be obtained by fitting NN output. A cross check with $\triangle Y_{jj}$ fit is also performed.
- The fiducial and differential cross sections are measured.
- AQGC study with EFT dimension-8 operators is performed in parallel.

Thanks!

any questions ?

Backup

Triggers

- Single lepton triggers

- **Electron**
  - HLT_e24_lhmedium_L1EM20VH
  - HLT_e60_lhmedium
  - HLT_e120_lhloose
  - HLT_e26_lhtight_nod0_ivarloose
  - HLT_e60_lhmedium_nod0
  - HLT_e140_lhloose_nod0
- **Muon**
  - HLT_mu20_iloose_L1MU15
  - HLT_mu26_ivarmedium
  - HLT_mu50

MC samples

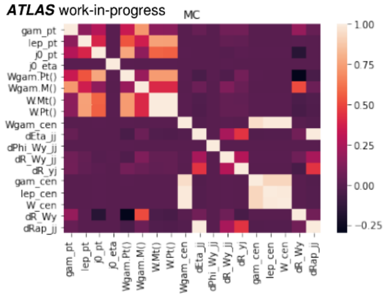
- release 21.2, STDM4

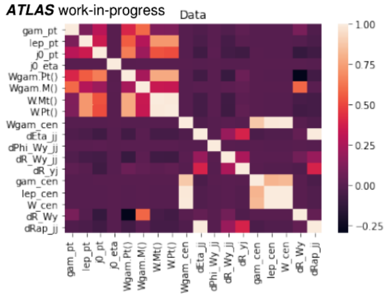
signal
nominal QCD sample
generator choice systematic
jets faking photon
jets faking lepton

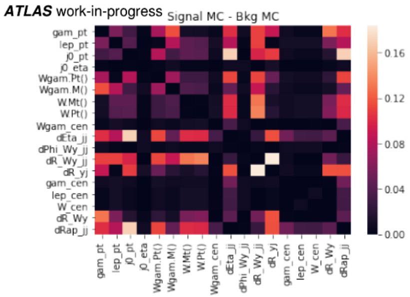
Process	Generator	ME Accuracy	PDF	Shower & Hadronization	Parameter Tune
EW $W\gamma jj$	Madgraph5	LO	NNPDF3.1 LO	Pythia8+EvtGen	A14
QCD $W\gamma jj$	Sherpa 2.2.11	NLO	NNPDF3.0 NLO	Sherpa	default
	Madgraph5	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
EW $Z\gamma jj$	Madgraph5	LO	NNPDF3.1 LO	Pythia8+EvtGen	A14
QCD $Z\gamma jj$	Sherpa 2.2.11	NLO	NNPDF3.0 NLO	Sherpa	default
$t\bar{t}\gamma$	Madgraph5	LO	NNPDF2.3 LO	Pythia8+EvtGen	A14
$tW\gamma$	Madgraph5	LO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
$tq\gamma$	Madgraph5	LO	NNPDF3.0 NLO	Herwig7+EvtGen	Default
Single Top	Powheg	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
W+jets	Sherpa 2.2.11	NLO	NNFDF3.0 NNLO	Sherpa	Default
Z+jets	Sherpa 2.2.11	NLO	NNPDF3.0 NNLO	Sherpa	Default
Diboson	Sherpa 2.2.2	NLO	NNPDF 3.0 NNLO	Sherpa	Default
Dijet	Pythia8	LO	NNPDF2.3 LO	Pythia8+EvtGen	A14
EW Wjj	Sherpa 2.2.1	NLO	NNPDF3.0 NNLO	Sherpa	default
EW Zjj	Sherpa 2.2.1	NLO	NNPDF3.0 NNLO	Sherpa	default
$t\bar{t}$	Powheg	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
tW	Powheg	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14

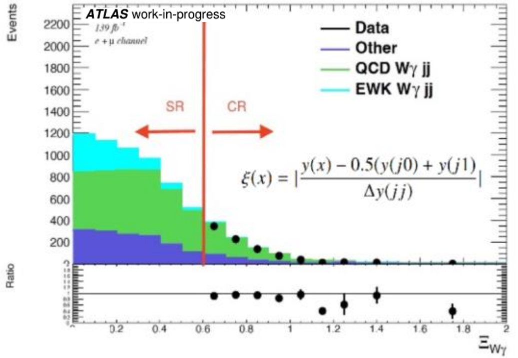
Neural network training

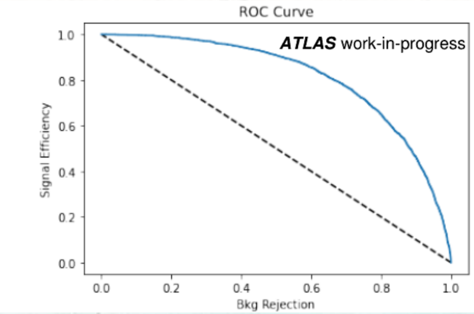
- Input variables used in NN training(ordered by importance)











ATLAS work-in-progress

Training Variable
$N_{gapjets}$
pt_{j1}
MT_W
ξ_γ
ξ_W
$\Delta R(W\gamma, jj)$
$\xi_{l\gamma}$
$\Delta Y(j, j)$
pT_l
pT_γ
$\Delta R(W, \gamma)$
$M_{W\gamma}$
$\Delta\eta(j1, j2)$
pT_W
$\xi_{W\gamma}$
$\Delta R(\gamma, j)$
$pT_{W\gamma}$
$\Delta\phi(W\gamma, jj)$
η_{j1}

Observation - ΔY_{jj} fit

- Fit ΔY_{jj} simultaneously in signal and control regions.
- Sideband CRs are used to constrain QCD background
  - Require $\xi_{l+\gamma} \leq 0.5$
- Fit performed in electron and muon channels separately.
- All theory and experimental systematics included as described above.

ATLAS work-in-progress

	μ-channel	e-channel
Expected (Asimov)	7.0σ	6.0σ