Search for quantum black holes with data of the ATLAS detector

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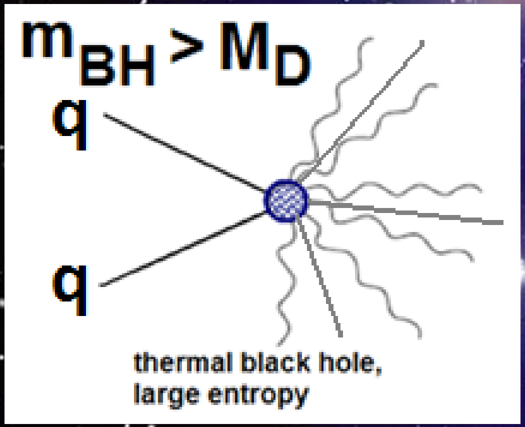
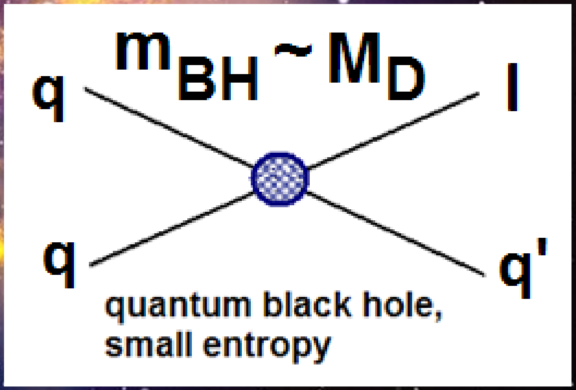
Hawking evaporation



Two-body decay



JINR ATLAS CERN

DLNP Seminar, 30 October, 2024

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Rev. D. 109 (2024) 032010
DOI: 10.1103/PhysRevD.109.032010

CERN-EP-2023-117
February 27, 2024

Search for quantum black hole production in lepton+jet final states using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration

Final publication links:

arXiv url:
✓ arXiv:2307.14967
GLANCE:
✓ EXOT-2018-14

A search for quantum black holes in electron+jet and muon+jet invariant mass spectra is performed with 140 fb^{-1} of data collected by the ATLAS detector in proton-proton collisions at $\sqrt{s} = 13$ TeV at the Large Hadron Collider. The observed invariant mass spectrum of lepton+jet pairs is consistent with Standard Model expectations. Upper limits are set at 95% confidence level on the production cross-sections times branching fractions for quantum black holes decaying into a lepton and a quark in a search region with invariant mass above 2.0 TeV. The resulting quantum black hole lower mass threshold limit is 9.2 TeV in the Arkani-Hamed-Dimopoulos-Dvali model, and 6.8 TeV in the Randall-Sundrum model.

Outlook

Part I

Search for QBH with Run2 data of the ATLAS detector

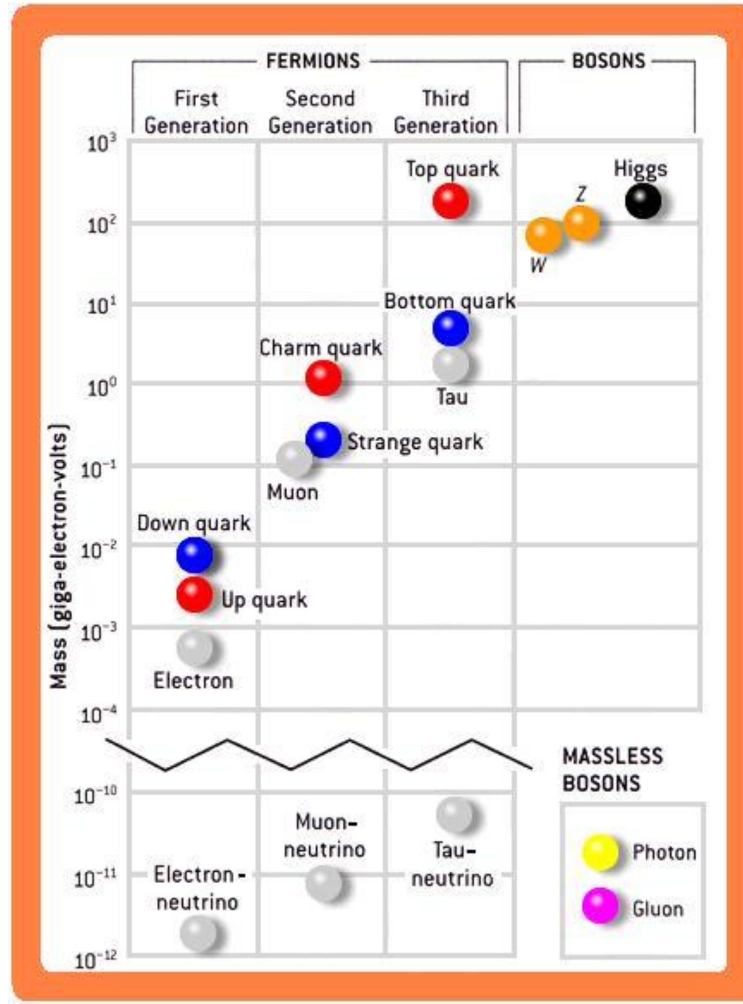
Part II

Neural networks using in search for QBH with Run3 data of the ATLAS detector

1.1. Introduction. Mass hierarchy problem.

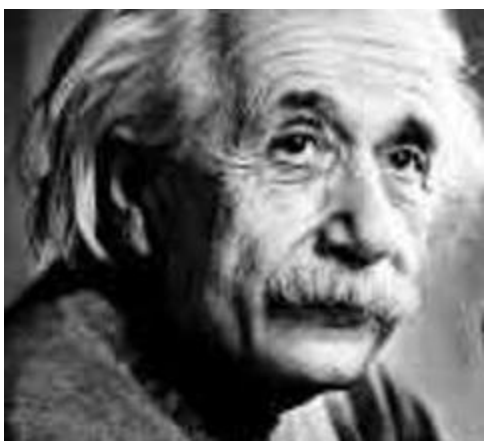
***The hierarchy problem:* masses of three generations fermions (leptons and quarks) differ between themselves in ten times and more. But other properties of the particles and their quantum numbers are identical.**

➢ Existence of the additional spontaneously-violation of global symmetry, which is linking **the generations of the fermions.**



❑ What we can do?

We can take into account some assumptions. The reasons of the mass hierarchy problem one can search in following:



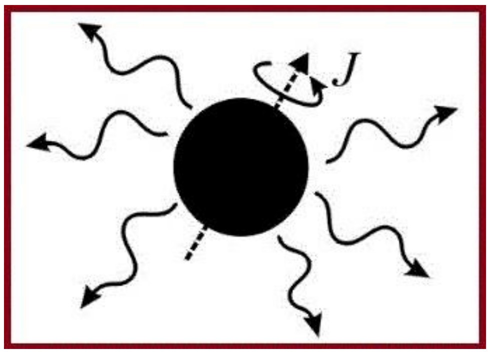
"We can not solve problems, using the same type of mentation…"

➢ **Existence of Multi-Dimensional model of the Universe.**

1.2. Introduction. Proposed models and BH properties.

- The quantum gravity models with extra spatial dimensions offer solutions to the mass hierarchy problem of the Standard Model (SM) by lowering the scale of quantum gravity (M_D) from the Planck scale (~10^{16} TeV) to the TeV region (1-10 TeV).
- In these new physics scenarios, gravity becomes strong, and quantum effects are relevant. Quantum black holes (QBHs) are predicted in these low-scale quantum gravity models.

General characteristics of black holes:



A. **Mass (M) – is main characteristic of Black Hole.**
B. **Electrical charge (Q) – is defined by charge of initial particles.**
C. **Angle moment (L) – is defined by spin and orbital momentum.**
D. **Color charge (C) – is defined by colored objects giving BH.**
E. **BH has no a metric radius, but only gravitational radius. This feature called – "BH has no hairs" (theorem).**
F. **Radius of Schwarzschild (event horizon) is size of QBH.**

- In the **ADD model** (Arkani-Hamed-Dimopoulos-Dvali), the **gravitational field** only is allowed to propagate in extra dimensions (**n = 6** in our analysis), while **all SM fields** are localized in the four-dimensional space-time. Total number of dimensions is **D = n+(3+1) = 10**. Every extra space dimension is sufficiently large with **compactification radius R ≤ 1 μm**.
- In the **RS1-model** (Randall and Sundrum) is a single warped extra dimension (**n = 1**), which separates two three-dimensional branes (**3-branes**) by some distance. **Gravitons** can propagate in this warped dimension. The effective Planck scale is determined by the curvature of the extra dimension (warp factor). Total number of dimensions is **D = 5.**

2.1. ADD & RS1 models. Common properties [*].

- ***The global symmetries*** of the SM do not need to conserve in the strong gravitation interactions. However, the local gauge symmetries of **color, total angular momentum (*l*+*s*) and electric charge** are conserved.
- ***The share of QBH decays into two-particles*** is 51% (74%) in ADD (RS1) models, if the QBH mass is near to M_D, while three-particle and four-particle decays are significantly less.
- ***Particles forming the QBHs*** are ***quarks, antiquarks and gluons*** in proton-proton collisions at the LHC. The QBH can be classified according to their $SU(3)_c$ and $U(1)_{em}$ representations.
- ***The 9 possible electric charge states*** of QBH can be formed: **±4/3, ±1, ±2/3, ±1/3, 0**.
- ***The QBH decaying*** into **electron or muon** and a **quark (antiquark)** is searched for in our analysis. This channel provides good branching (**46.8%**), and lepton in final state provides good ratio of signal and background.
- ***Six states only*** with fractional charge (**±4/3, ±2/3, ±1/3**) and with integer spin can decay to a lepton and a quark [*]. Baryonic and leptonic numbers violated in this channel.
- ***Branching of QBH decay*** into lepton+jet is the same in ADD-model and RS1-model.

11% branching fraction for $u + u,\ \bar{u} + \bar{u} \rightarrow QBH^{\pm 4/3} \rightarrow e\ (\mu) + jet$

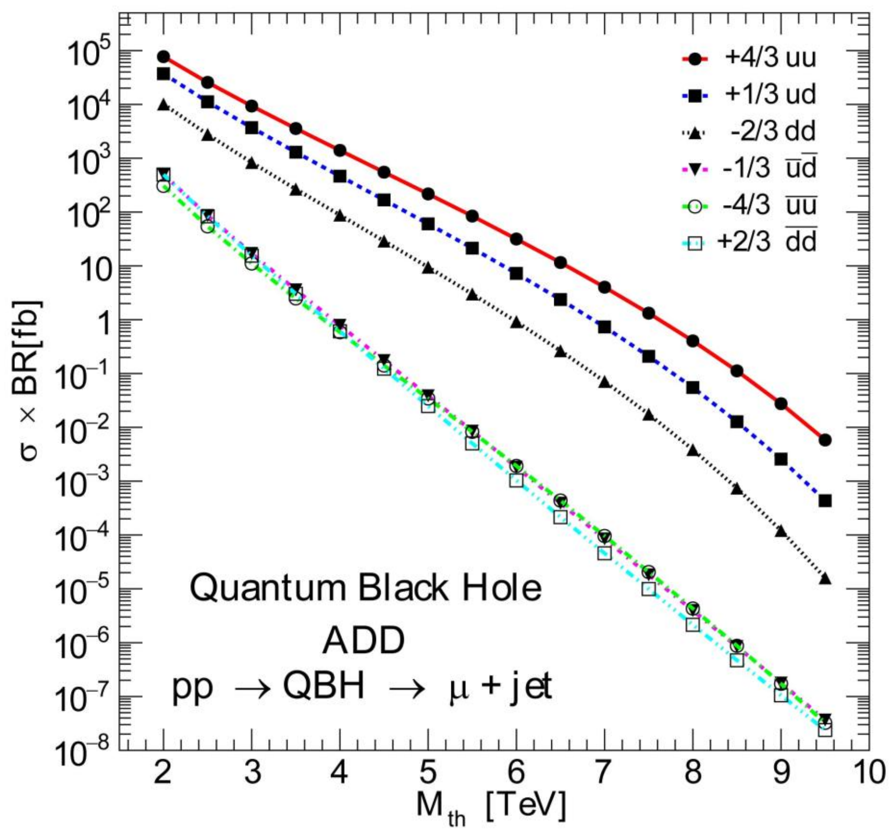
6.7% branching fraction for $d + d,\ \bar{d} + \bar{d} \rightarrow QBH^{\pm 2/3} \rightarrow e\ (\mu) + jet$

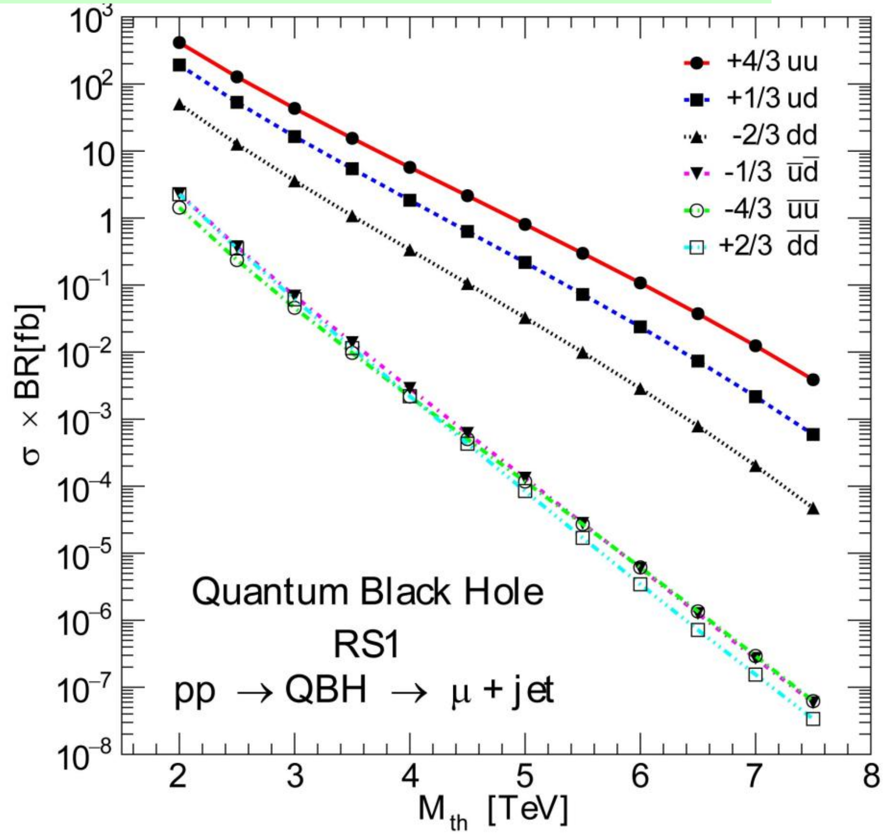
5.7% branching fraction for $u + d,\ \bar{u} + \bar{d} \rightarrow QBH^{\pm 1/3} \rightarrow e\ (\mu) + jet$

$$BF = (11 + 6.7 + 5.7) \times 2 = 46.8\%$$

[*] Douglas M. Gingrich, Quantum black holes with charge, color, and spin at the LHC, arXiv:0912.0826v4 [hep-ph] 13 Jul 2010

2.3. ADD & RS1 models.
Cross-section of the Quantum Black Holes production with decay into lepton + jet final state [*].



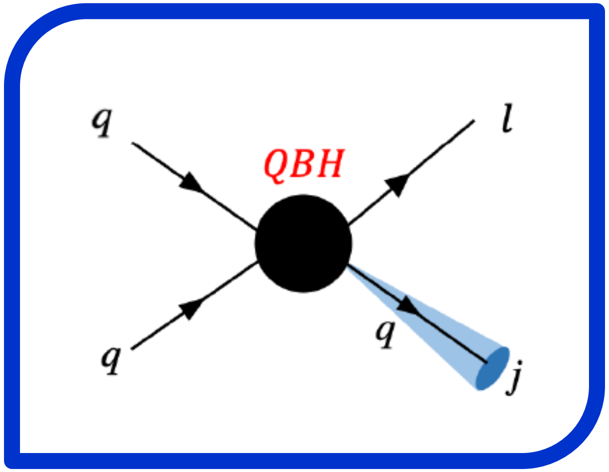


The QBH production cross-section of the quark-quark initial state is more than 100 times higher, than the cross-section of the antiquark-antiquark initial state. The cross-section in ADD-model is ~200 times more than in RS1-model.

[*] Douglas M. Gingrich, Quantum black holes with charge, color, and spin at the LHC, arXiv:0912.0826v4 [hep-ph] 13 Jul 2010

2.4. ADD & RS1 models.
Motivation to search for QBH at ATLAS. Signal generation [*].

- The ATLAS data obtained in Run2 at of √s = 13 TeV allow as to search for QBH at mass region ~1-10 TeV.
- The large cross-sections of QBH production in both models and the high integrated luminosity reached at the LHC in Run2 give us a hope to find a signal.



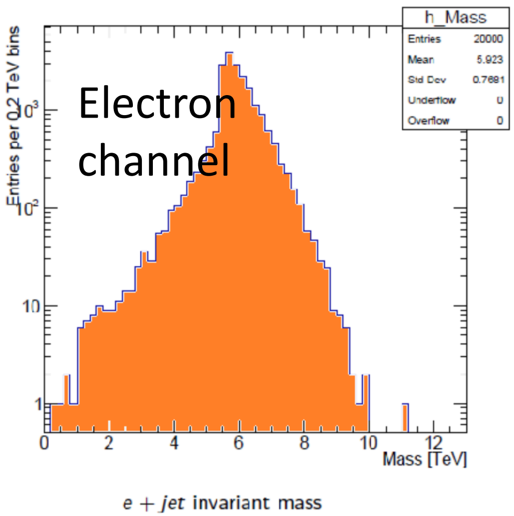
- The simulated QBH signal event samples are obtained from the QBH 3.0 generator [*], which uses the CTEQ6L1 leading-order PDF set.
- The parton showering and hadronization are performed in PYTHIA 8.205, using the CTEQ6L1 PDF set and the A14 tune. The QCD factorization scale for the PDFs is set to the inverse gravitational radius. The QBH simulation assumes massless parton interaction and conserves total angular momentum.

[*] D. M. Gingrich, Monte Carlo event generator for black hole production and decay in proton-proton collisions – QBH version 1.02, Comput. Phys. Commun. 181, 1917 (2010).

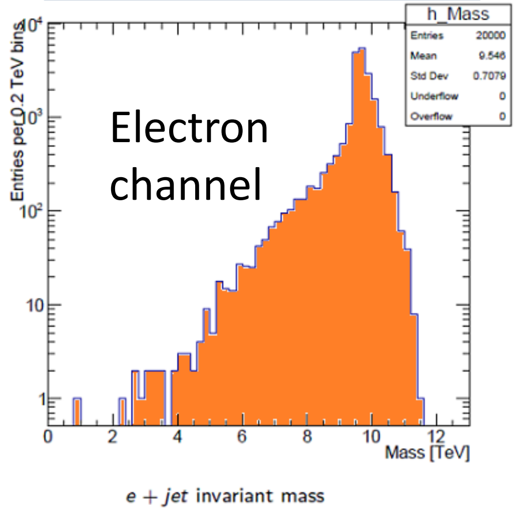
2.5. ADD & RS1 models.

Monte-Carlo QBH Signal at the ATLAS, M_{th} = (5.5, 9.5) TeV.

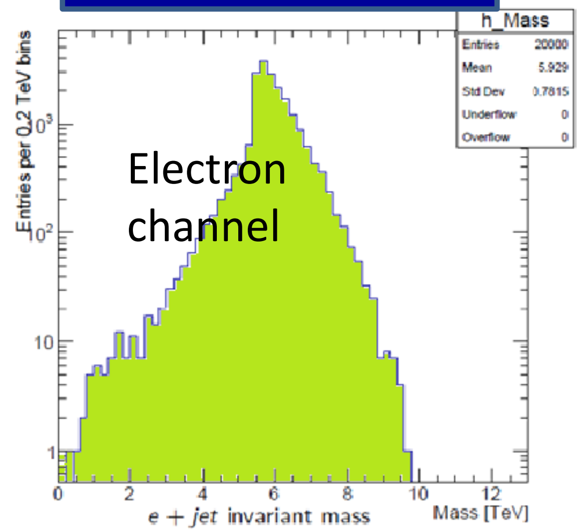
ADD M_{th} = 5.5 TeV



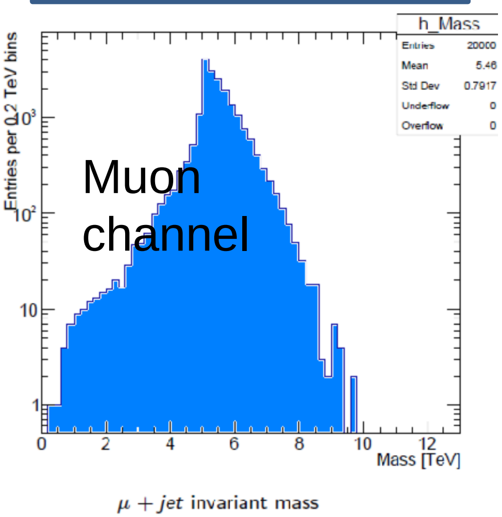
ADD M_{th} = 9.5 TeV



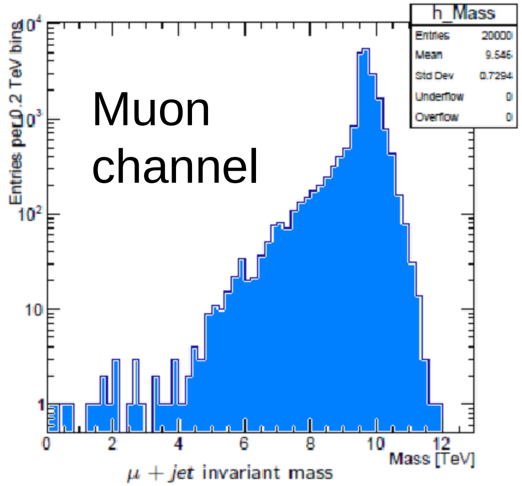
RS1 M_{th} = 5.5 TeV

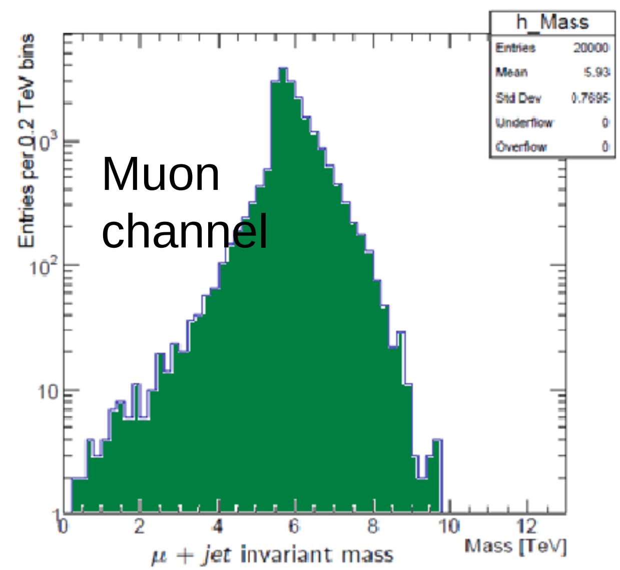


ADD M_{th} = 5.5 TeV



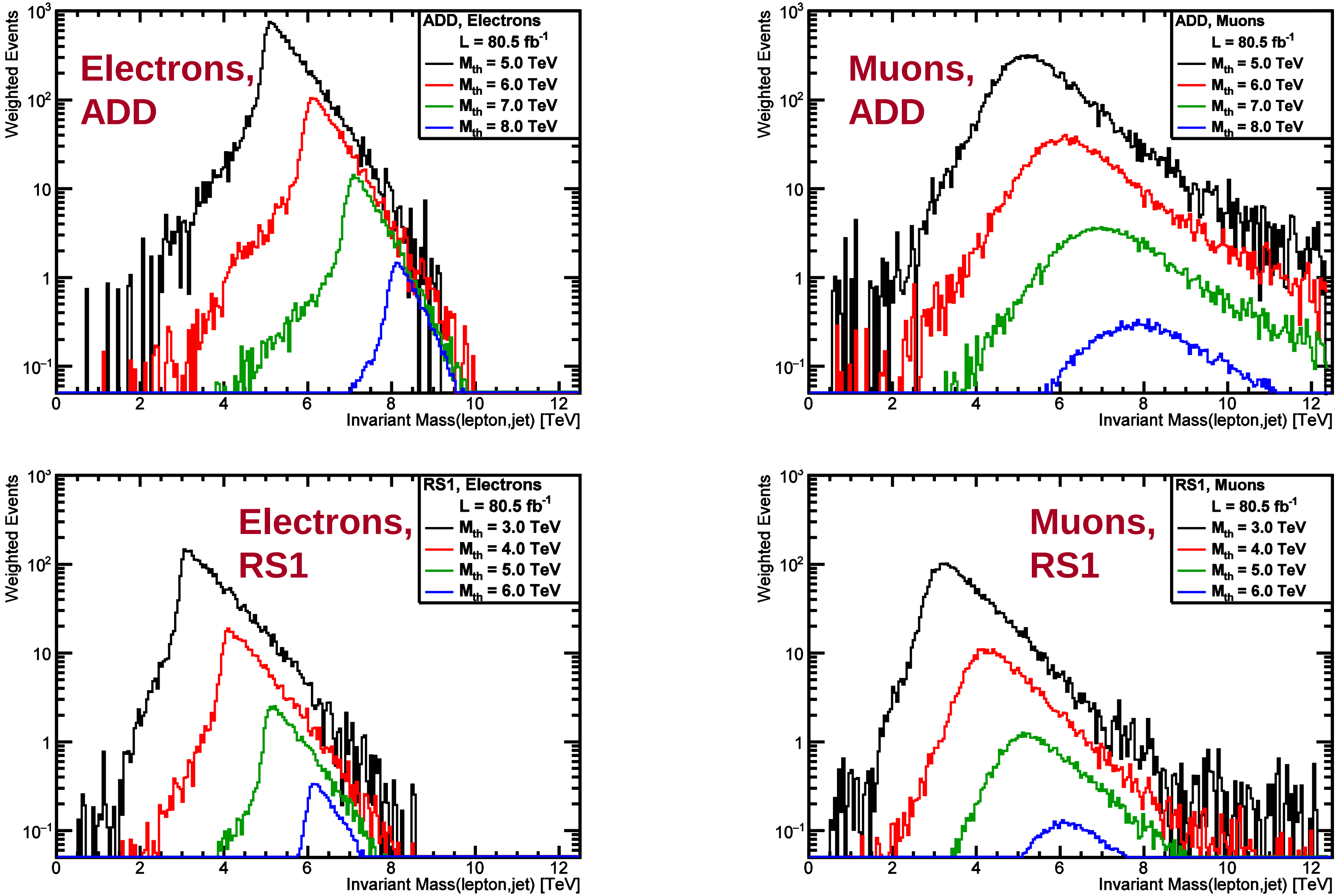
ADD M_{th} = 9.5 TeV





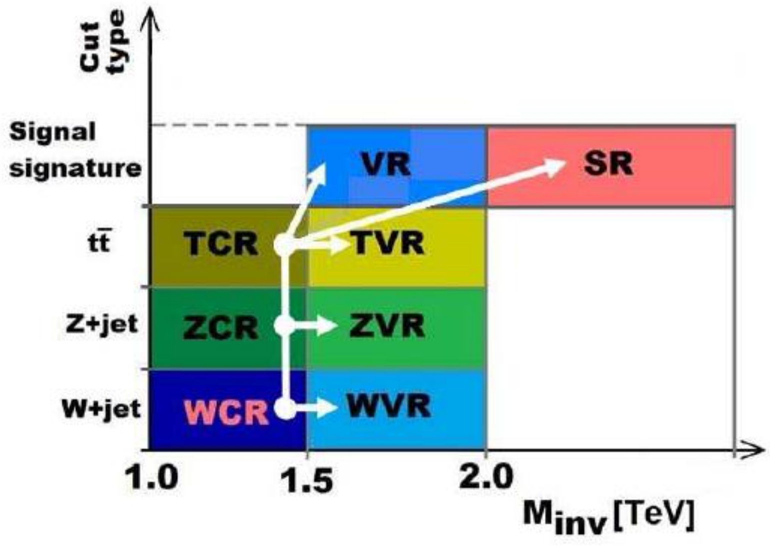
[*] https://indico.cern.ch/event/340438/contribution/0/material/1/0.pdf

2.6. ADD & RS1 models. Reconstructed Signal.



The distributions of events over invariant mass **after reconstruction and selection.** **M_{th}= 5.0, 6.0, 7.0, 8.0 TeV for the ADD-model. M_{th}= 3.0, 4.0, 5.0, 6.0 TeV for the RS1-model.** They are normalized to 80.5 fb^{-1}.

3.1. Analysis. Strategy and method.



1) The signal, control and validation regions (SR, CR and VR) are defined with using of invariant mass m_{inv} of lepton and leading jet.
2) Three CRs are used for normalization and likelihood shape fit of the MC background. The *"background-only fit"* is performed simultaneously for all control regions.
3) *The VRs are not fitted at all.* They are used only to check modeling and for control of the fit quality.
4) The *statistical analysis* is performed with using of the *HistFitter* package based on *HistFactory, RooFit* and *RooStats*.

5) The *fit in SR* is performed simultaneously with the fit of CRs. All background mu-values and nuisance parameters are propagated from CRs to SR. The signal strength (mu-value) is also included in the SR fit.
6) The *"discovery fit"* in SR is used to set model-independent limits on the expected BSM signal.
7) Purpose of the model-dependent signal fit (*"exclusion fit"*) is to set limits on a specific model of the QBH production (ADD-model and RS1-model in our case).

8) *Systematic uncertainties* are added as nuisance parameters in the fit and they are constrained with taking into account of mutual correlations.
9) All *nuisance parameters* (JES, JER etc.) including the *norm-factors* (mu-values) of backgrounds are *propagated into the VR and SR.*
10) The analysis is performed *separately for muon and electron* channels. *Combination of channels* will be implemented at the estimation of upper limits on the product of cross section and branching fraction.

3.2. Analysis. Control, signal and validation regions + selection of events with signal signature.

The control, signal and validation regions are defined with using of **invariant mass (M_{inv})** of **lepton** and **leading jet.**

Definitions of the Control, Validation and Signal regions. Note, that "…" means that this criterion is not applied. Two same flavor opposite-sign (SFOS) leptons satisfying the **`Signal`** selection criteria are required in the Z + jets control and validation regions, while **`Signal`** and **`Baseline`** stand for the corresponding sets of the lepton and jet selection criteria.

Event selection	WCR (WVR)	ZCR (ZVR)	TCR (TVR)	SR (SVR)
m_{inv} [TeV]	1.0–1.5 (1.5–2.0)	1.0–1.5 (1.5–2.0)	1.0–1.5 (1.5–2.0)	>2.0 (1.5–2.0)
Leading lepton, p_T [GeV]	`Signal`, >130	`Signal`, >130	`Signal`, >130	`Signal`, >130
Subleading leptons, p_T [GeV]	`Baseline`, <10	SFOS, >30	`Baseline`, <10	`Baseline`, <10
Leading jet, p_T [GeV]	`Signal`, >130	`Signal`, >130	`Signal`, >130	`Signal`, >130
Subleading jets, p_T [GeV]	`Signal`, <130	`Signal`, <130	`Signal`, <130, N ≥ 3	`Signal`, <130
Number of b-tagged jets	0	…	≥2	…
E_T^{miss} [GeV]	>60	…	…	…
$m_{\ell^+\ell^-}$ [GeV]	…	70–110	…	…

3.3. Analysis. Background for QBH.

- **Full analysis machinery includes statistical analysis of data as well as the background estimation (MC-based and data-driven).**

MC generator	Background	Comments
Sherpa 2.2.1	**W+jets ($W^{\pm} \rightarrow e\nu, \mu\nu, \tau\nu$)**	sliced on max(H_T, W_{pT})
Sherpa 2.2.1	**Z+jets ($Z \rightarrow ee, \mu\mu, \tau\tau$)**	sliced on max(H_T, Z_{pT})
Sherpa 2.2.1	**Di-bosons (WW, WZ, ZZ → lvqq, llqq, lvvv, llvv)**	small background
Powheg+Pythia8	**Ttbar, non all hadronic**	small background
Powheg+Pythia8	**W+t**	small background
Powheg+Pythia8	**Single top, t- and s-channel**	small background

- **The data-driven matrix method was used for estimation of the fake leptons background. It gives second-large contribution in electron channel and it is negligible for muons.**

Data:

Year	Periods	Runs Numbers	Total Luminosity, fb^{-1}
2015	D-J	276262-284484	3.220
2016	A-L	297730-311481	32.988
2017	B-K	325713-340453	44.307
2018	B-Q	348885-364292	59.937

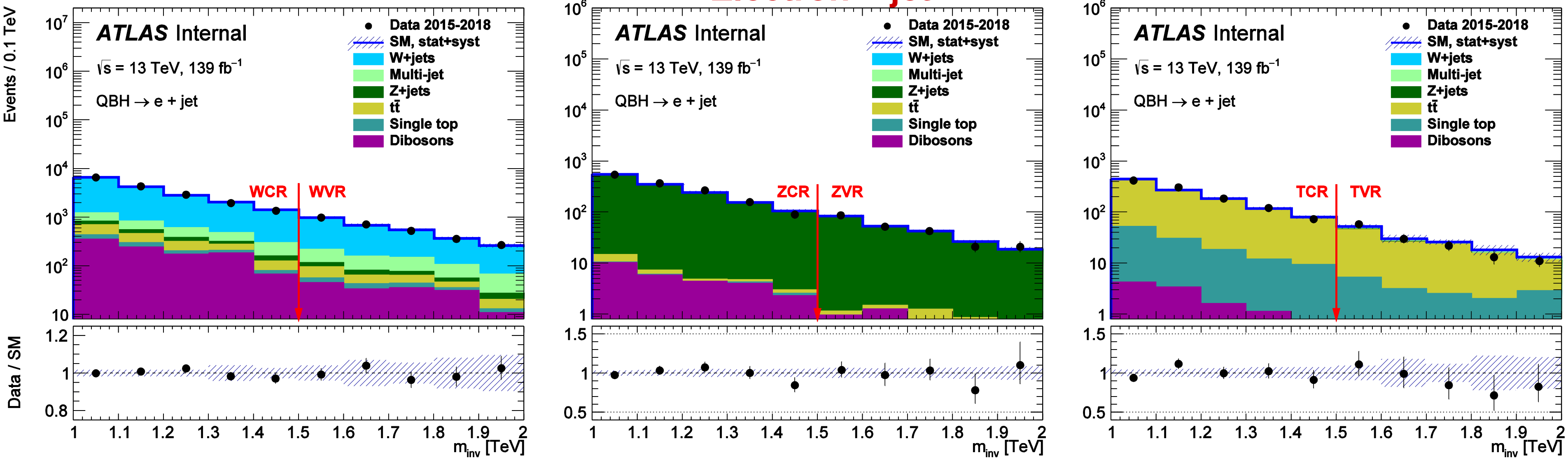
In total for 2015-2018 : $L = 140\ fb^{-1}$

3.4. Analysis. Background-only fit.

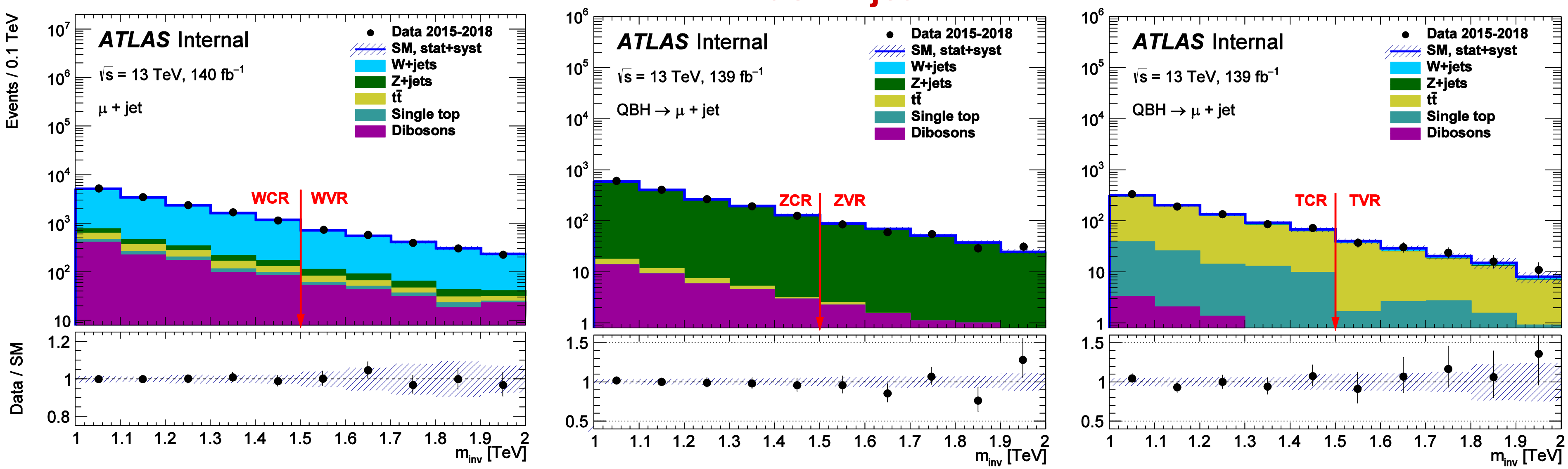
Results of background-only fit in CRs and VRs

Extrapolation of distributions from CRs into VRs shows a good agreement with the data after the background-only fit.

Electron + jet



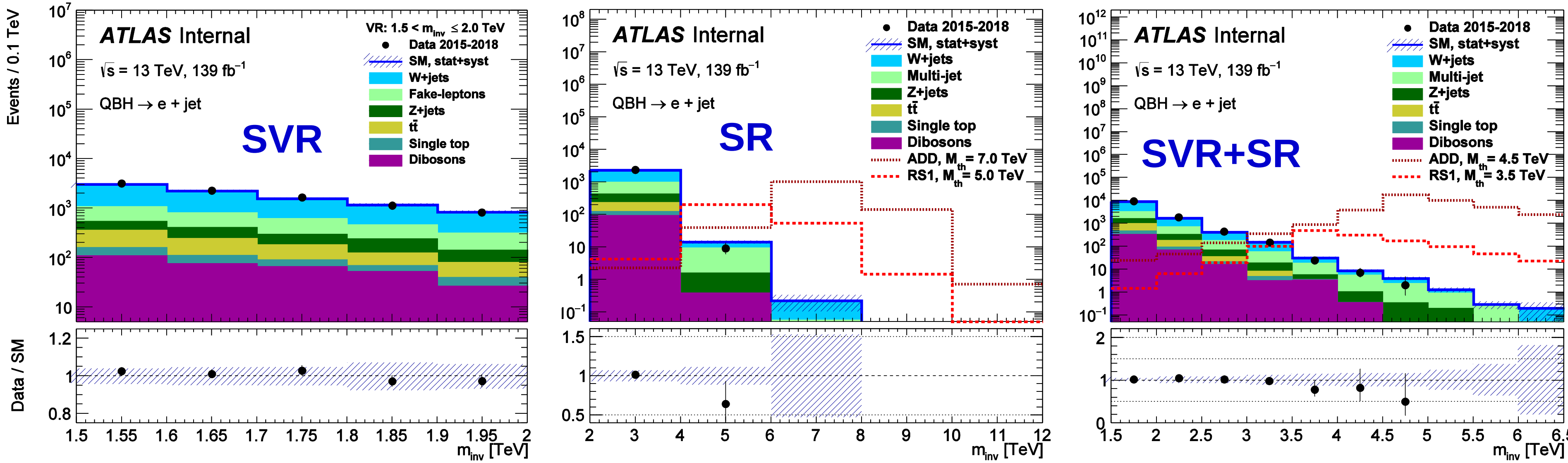
Muon + jet



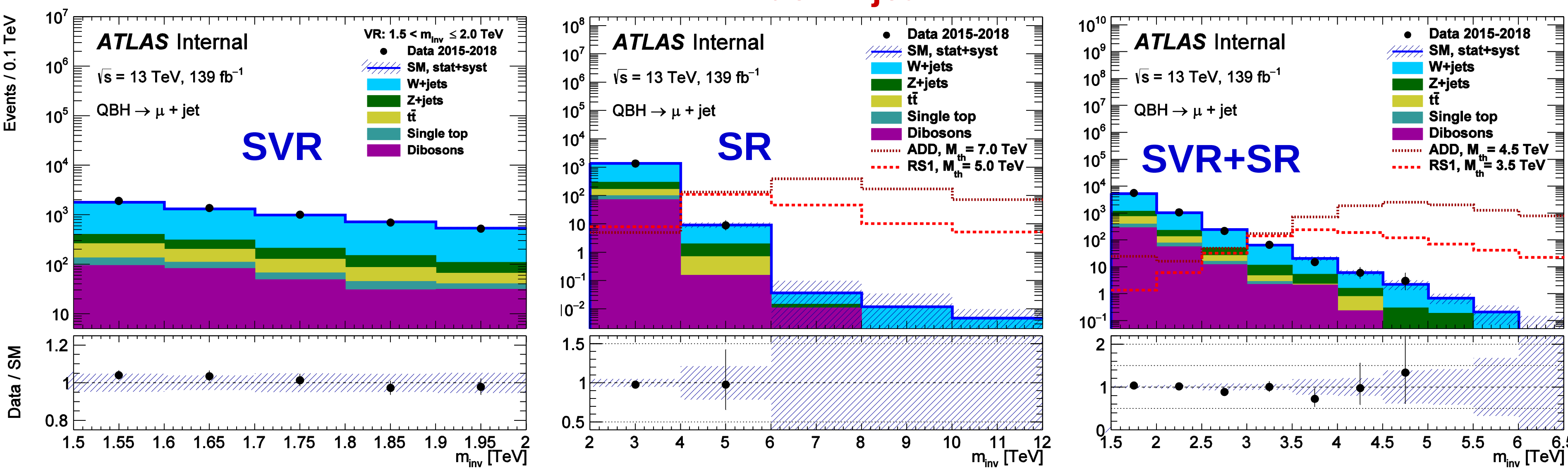
Results of background-only fit in SVR and SR

Extrapolation of distributions from CRs into SVR and SR shows a good agreement with the data after the background-only fit.

Electron + jet



Muon + jet



4. Systematics of background and signal in SR

4.1. Systematic uncertainties, uncertainty sources.

- **Systematic uncertainties of objects in events:**

✓ Electron/Muon reconstruction efficiency
✓ Electron/Muon isolation efficiency
✓ Electron/Muon trigger efficiency
✓ Electron/Muon identification efficiency
✓ Electron/Muon scale and resolution
✓ Muon track-to-vertex-association

✓ Jet Scale/Resolution
✓ Jet JVT efficiency

✓ b-tagging efficiency
✓ MET Resolution
✓ MET Scale
✓ Fake leptons systematic

- **Uncertainties on detector performance:**

✓ Luminosity uncertainty
✓ Pile-up reweighting

- **Modeling systematics:**

✓ Monte Carlo statistics

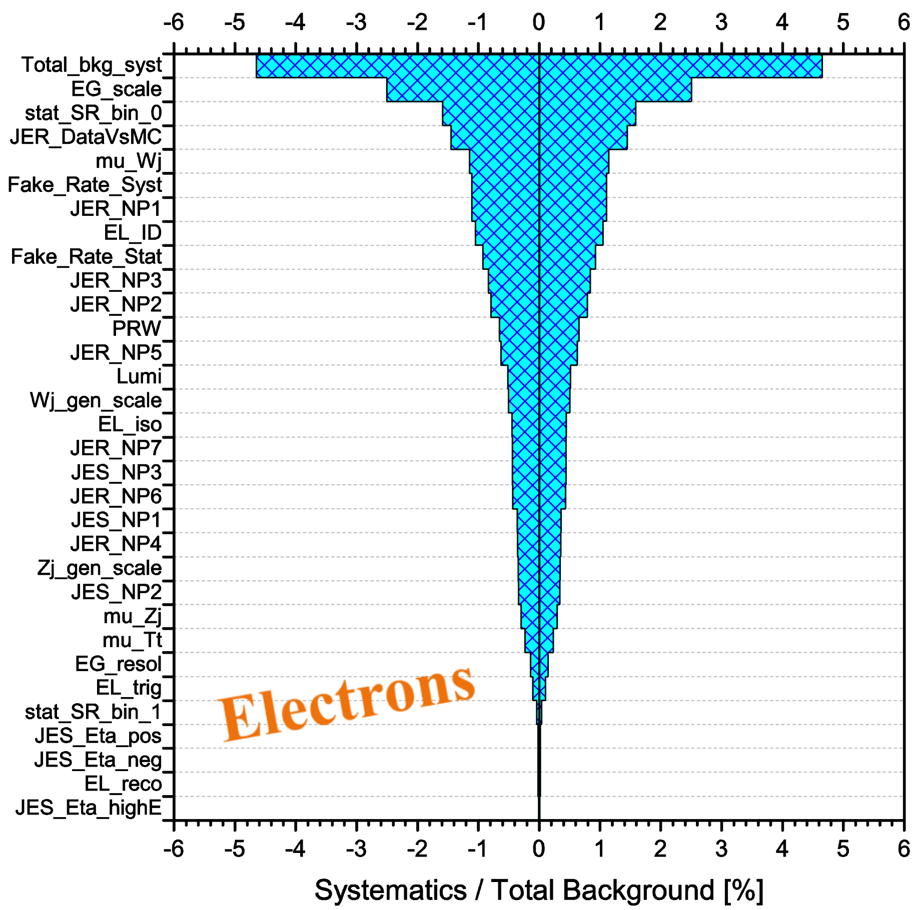
✓ Errors of the MC background normalization and shape fit
✓ PDF and scale uncertainties of MC generators, EW corrections

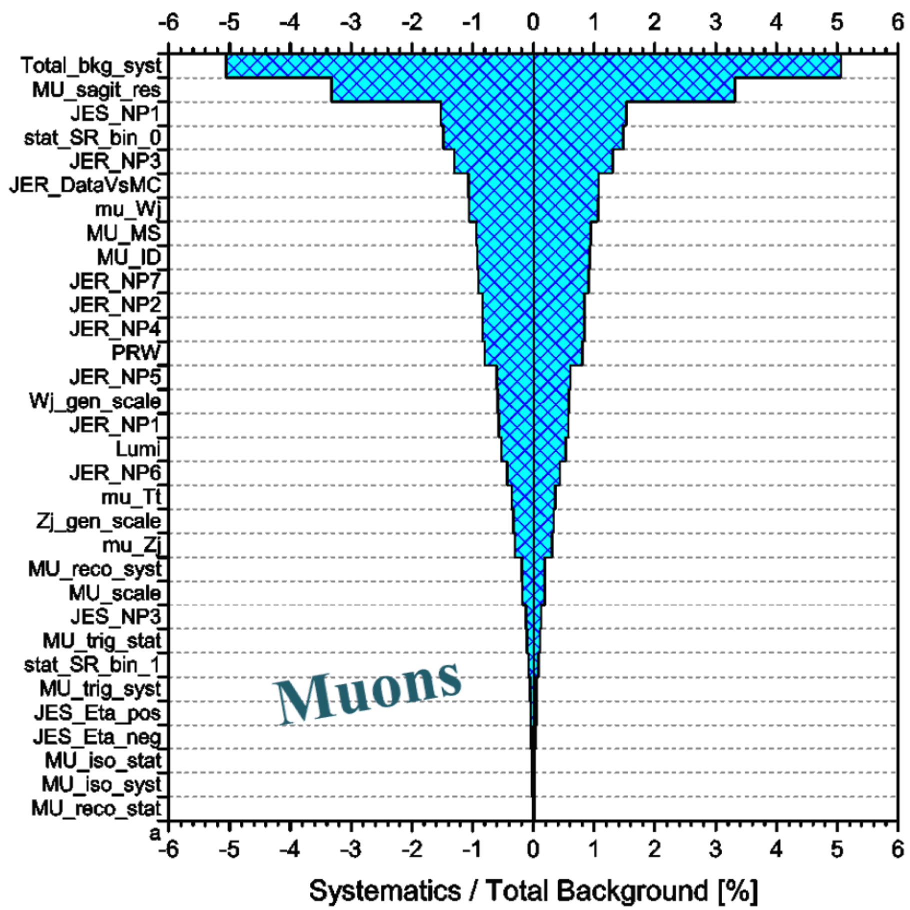
Applied to signal and background in all regions

Applied to background only

Not applied to signal, to fake leptons and to small backgrounds: di-bosons, single top

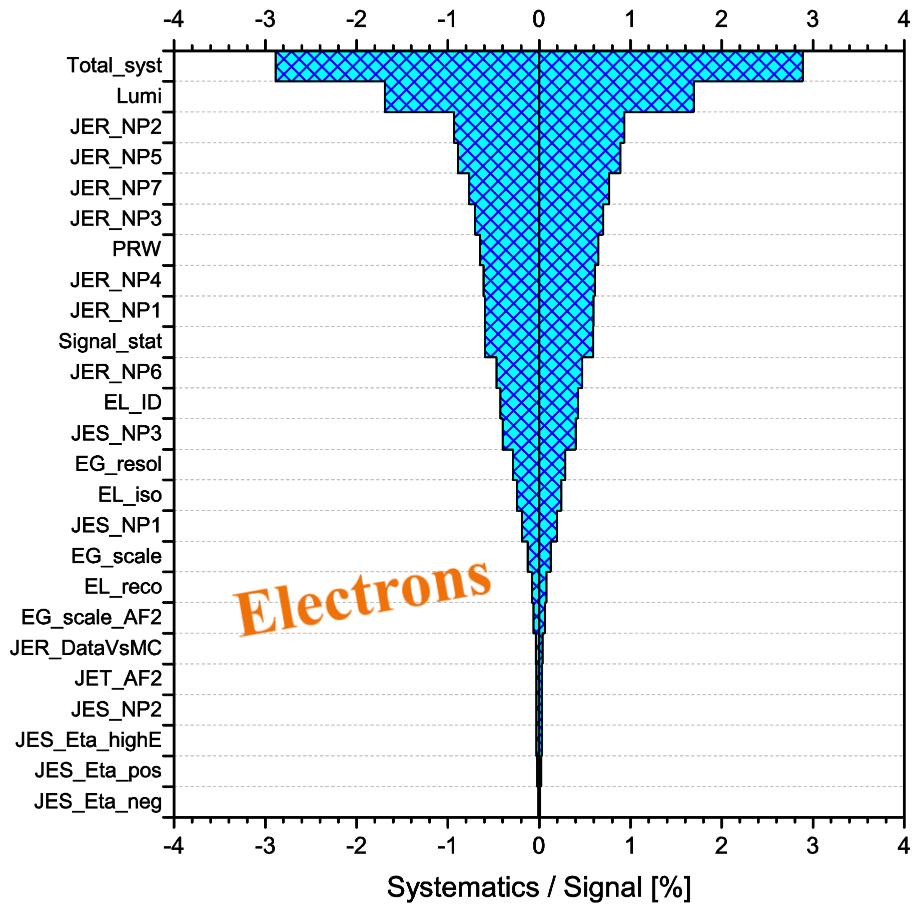
4.2. Systematic of background in SR.

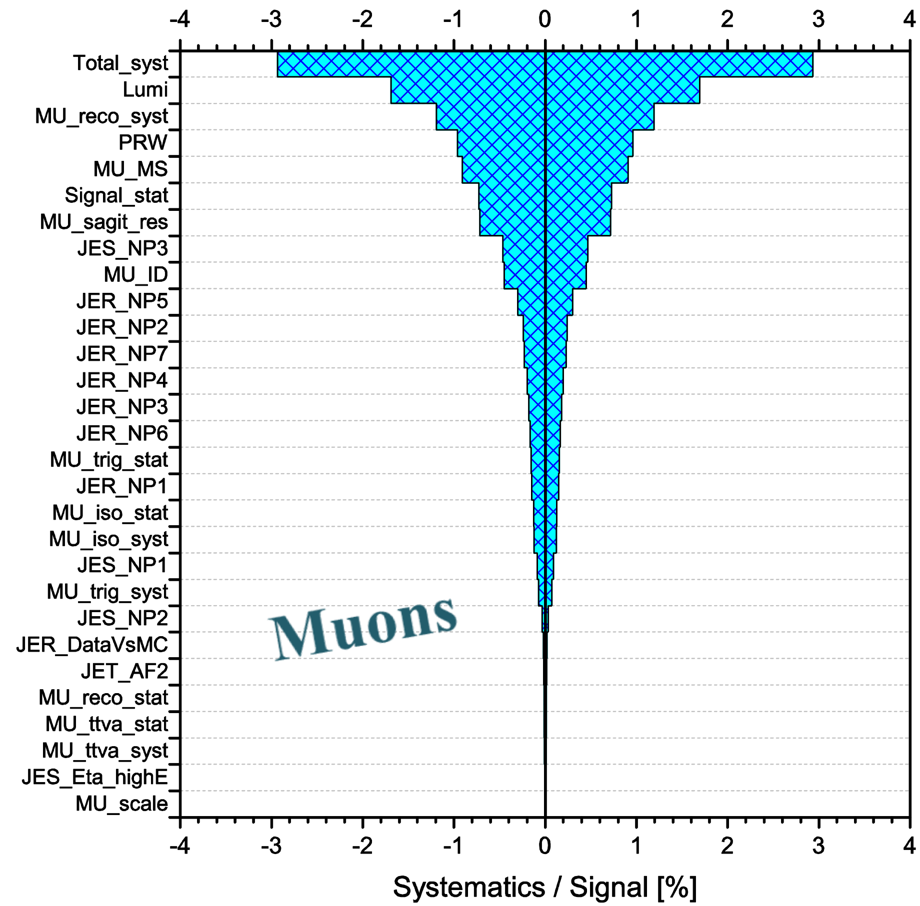




Systematics / Total background [%]

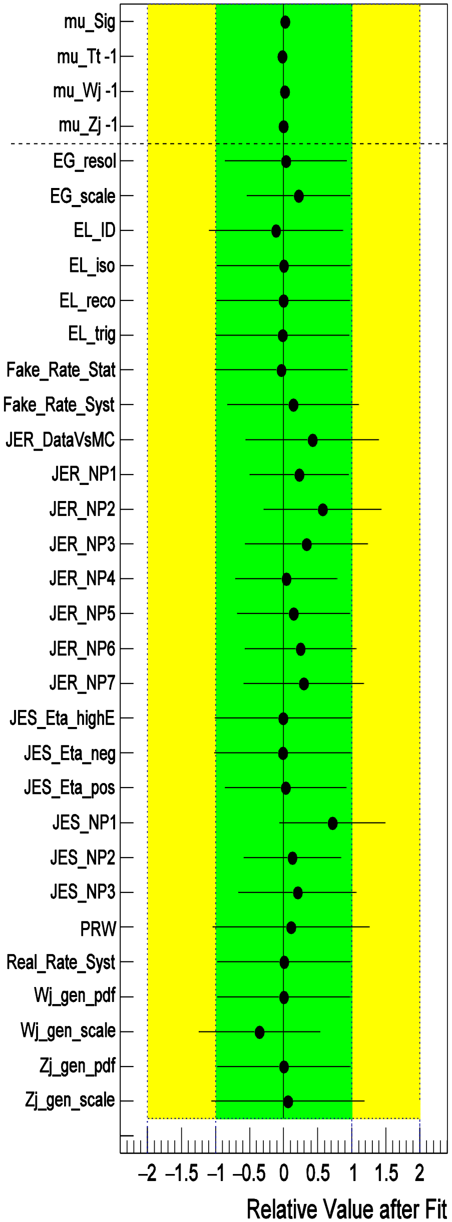
4.3. Systematic of signal in SR.
ADD-model at threshold QBH mass M_{th}= 6.0 TeV.



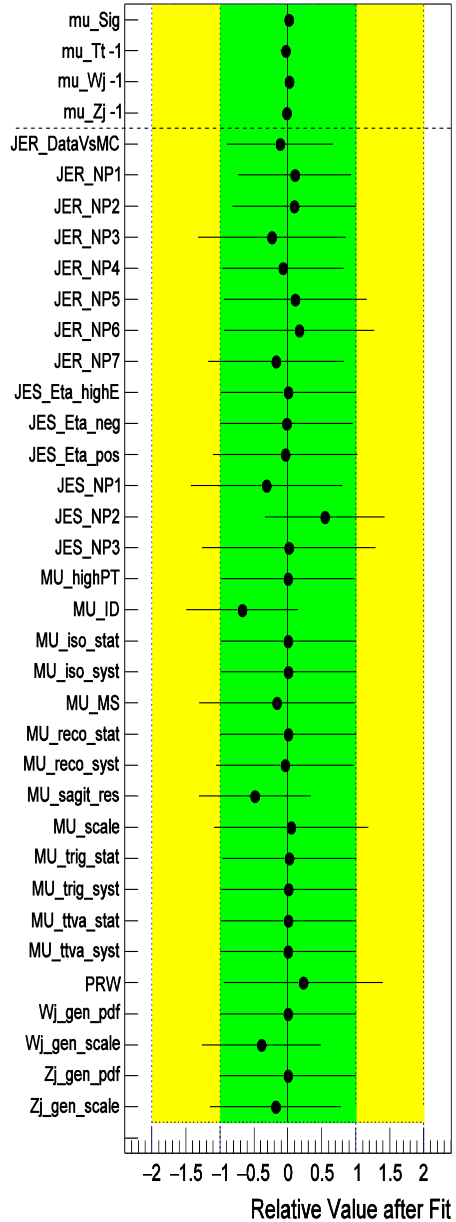


Systematics / Signal [%]

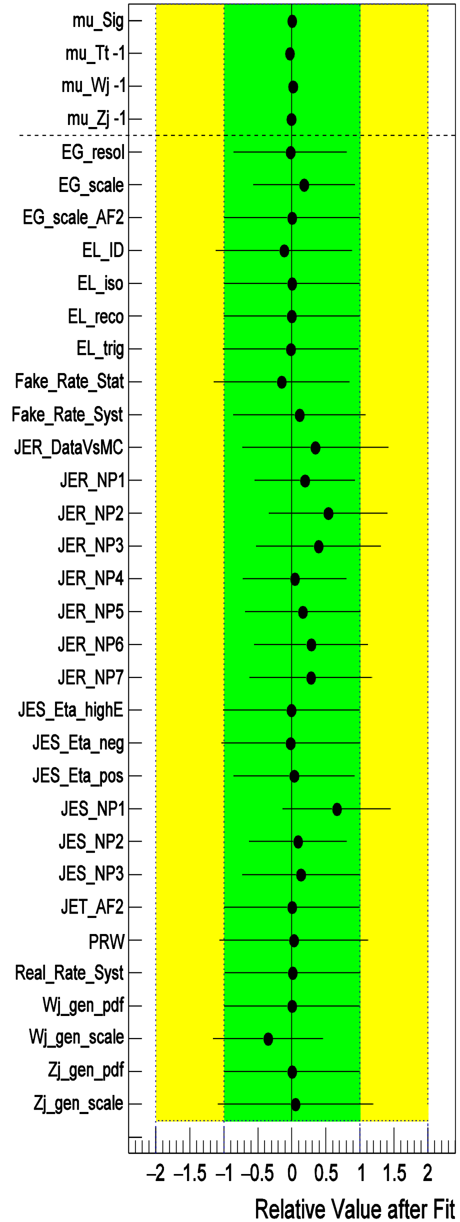
4.4. Systematics – pulling and constraining. Discovery & Exclusion.



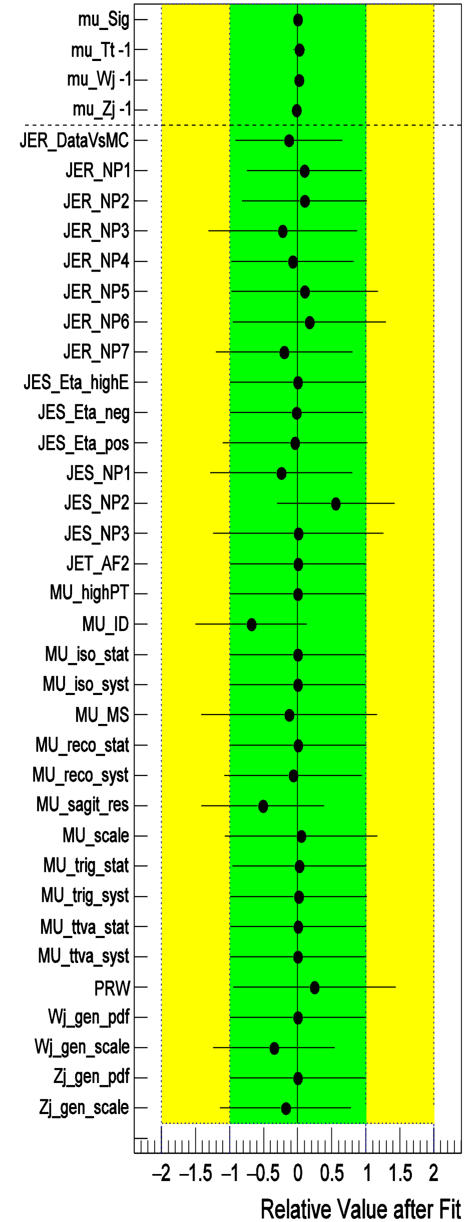
Discovery, Electrons



Discovery, Muons



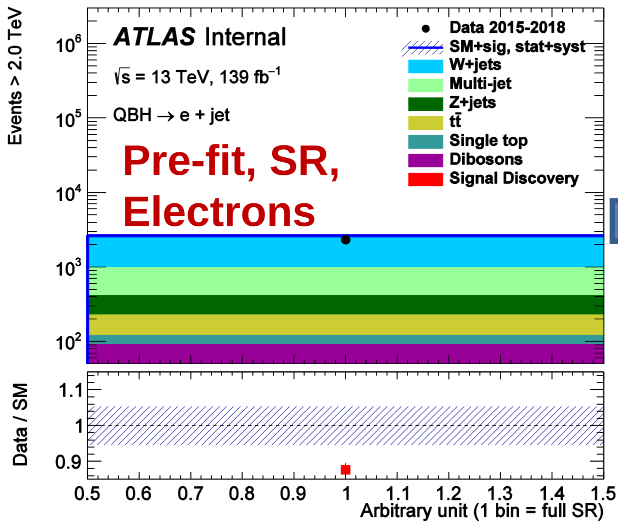
ADD-7.0, Electrons

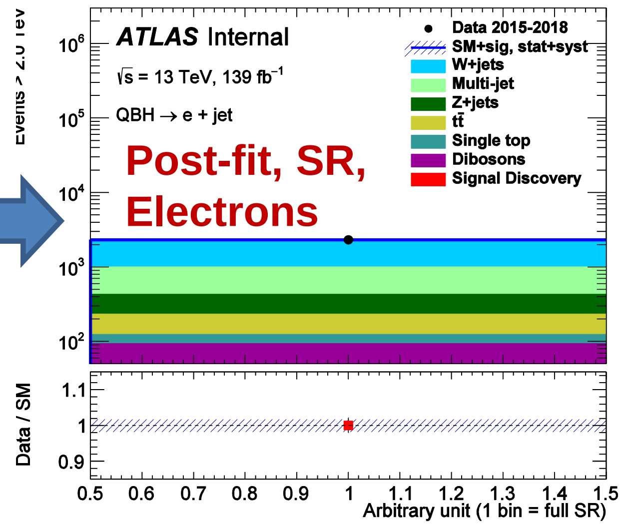


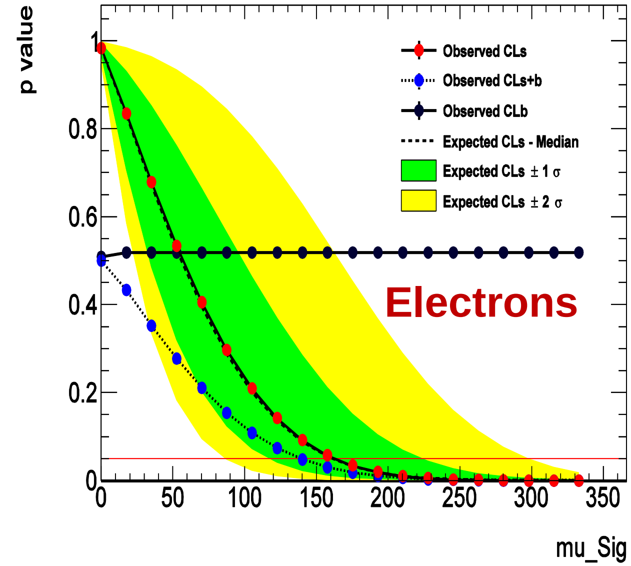
ADD-7.0, Muons

5. Upper limits in model-independent (discovery) fit

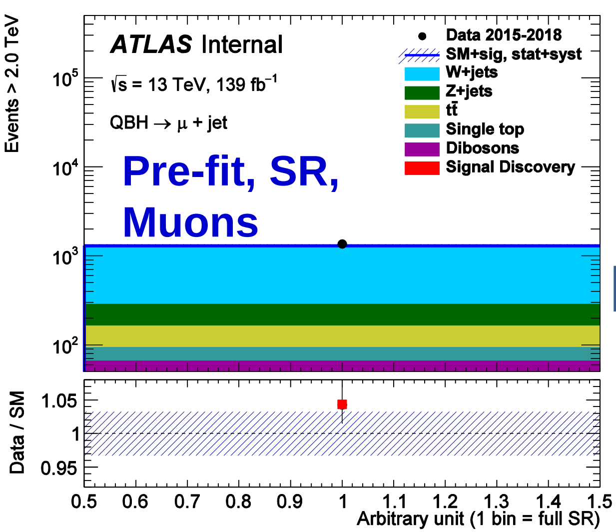
5.1. Upper limits. Discovery fit (model-independent).

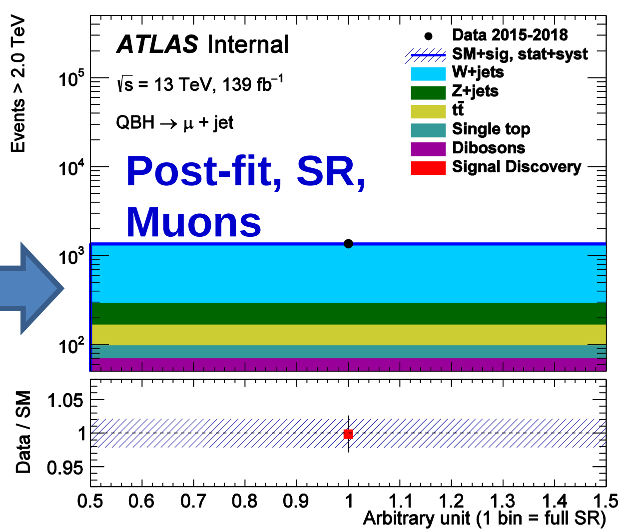


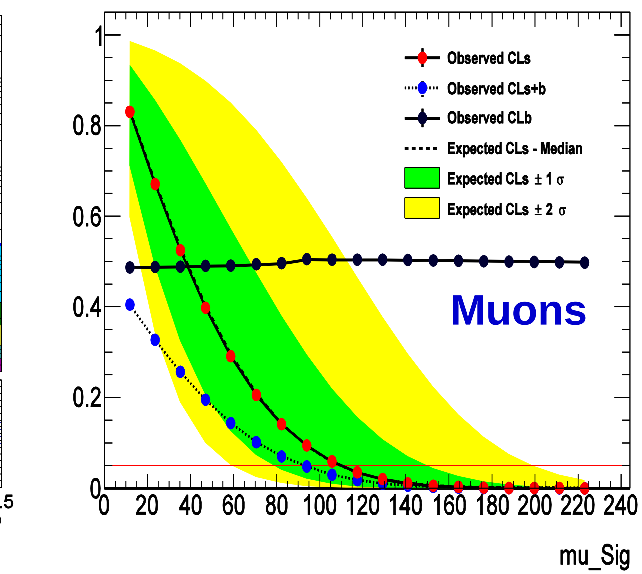




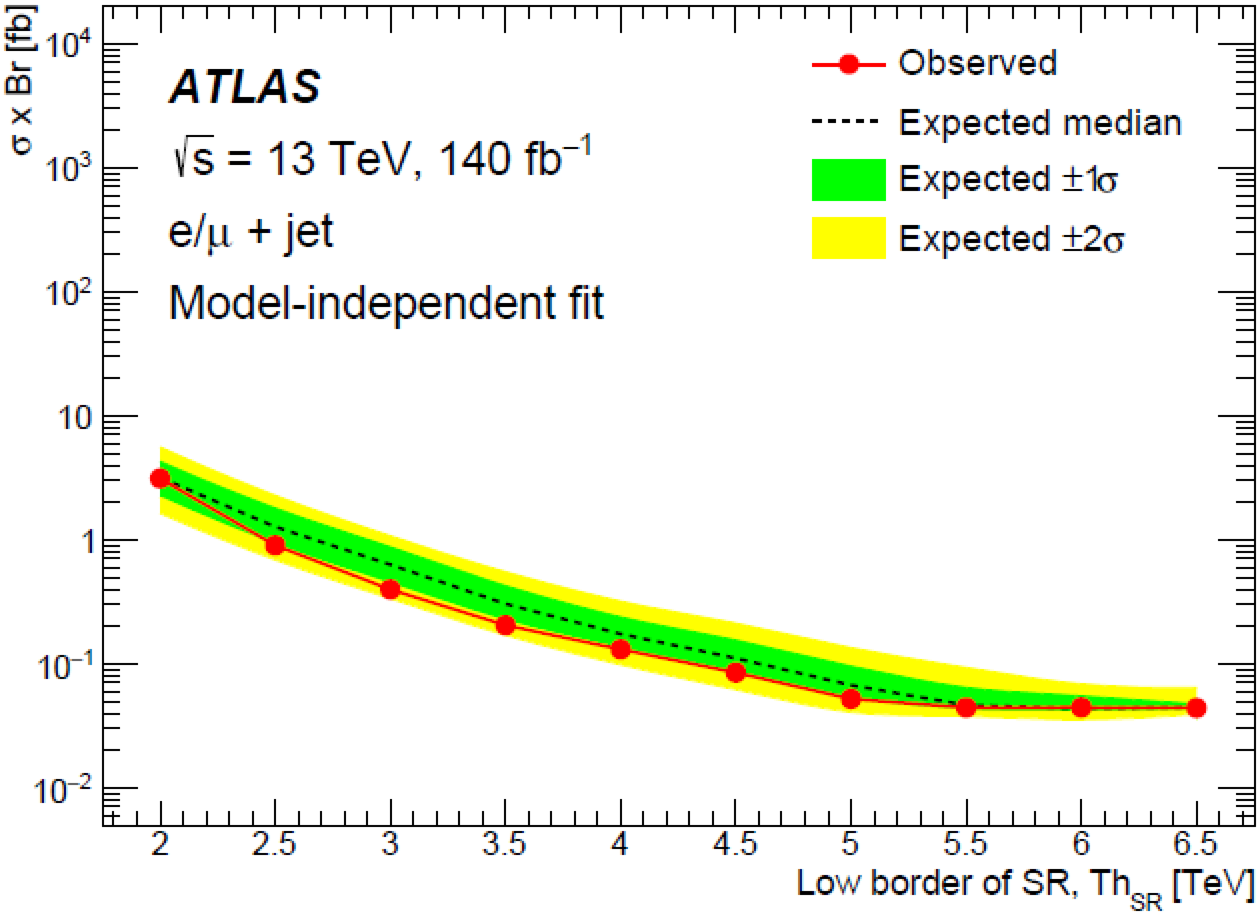
Upper limit scan over μ_Sig







5.2. Upper limits. Model-independent (discovery) fit.

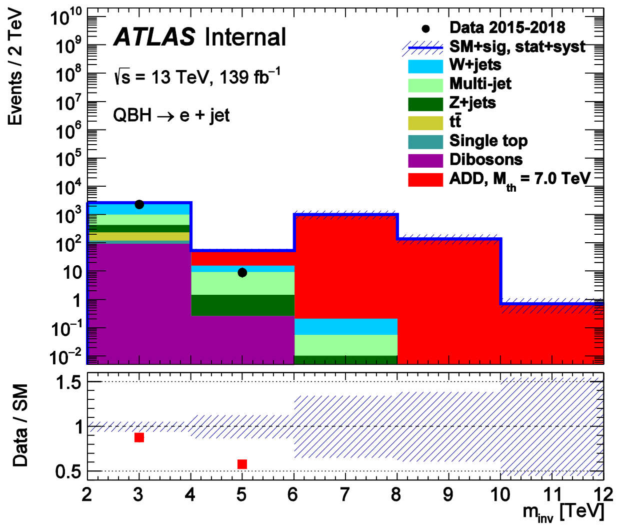


The 95% C.L. model-independent upper limits on $\sigma \times Br$ for the non-SM signal production with decay into lepton + jet (combined channel).

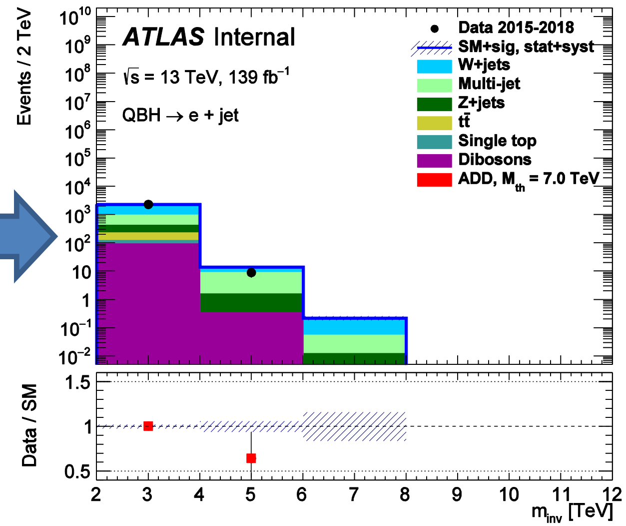
The limits take into account statistical and systematic uncertainties. Circles along the solid red line indicate the lower border of the SR (threshold of SR, Th_{SR}), above which the observed limits are shown in green and yellow, respectively. The limits are obtained with pseudoexperiments.

6. Upper limits with modeled signal (exclusion) fit

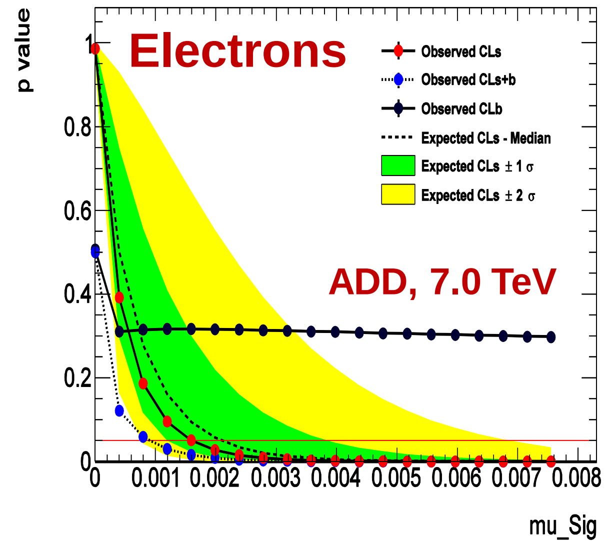
6.1. Upper limits. Exclusion fit (with modeled signal)



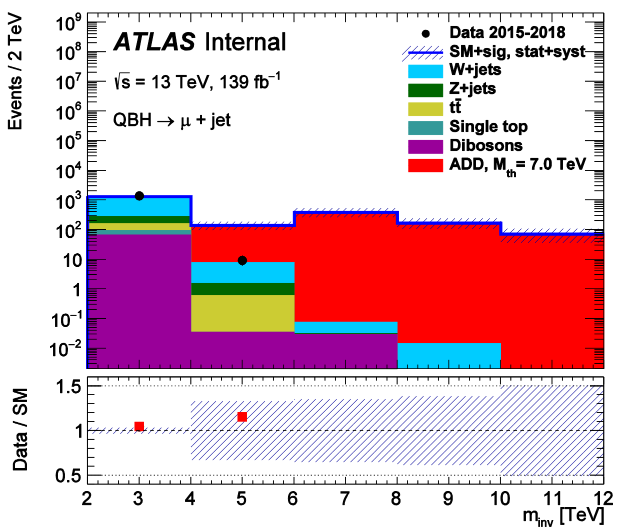
Pre-fit, Electrons, ADD 7.0 TeV



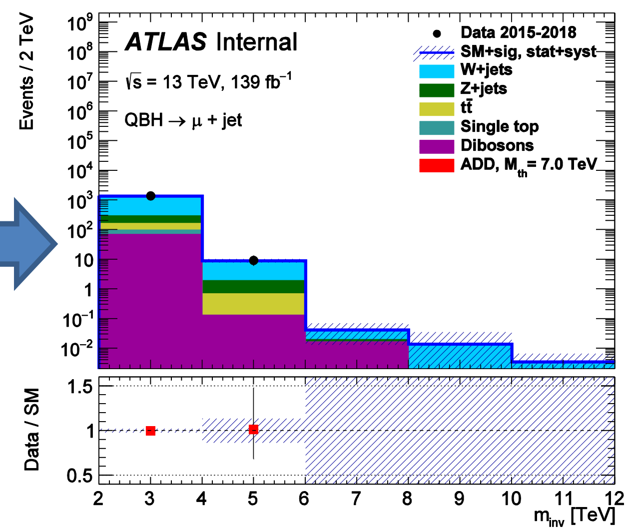
Post-fit, Electrons, ADD 7.0 TeV



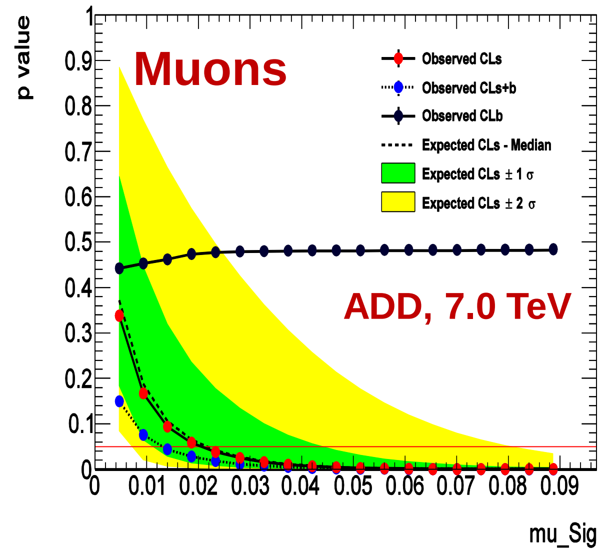
Upper limit scan over μ_Sig



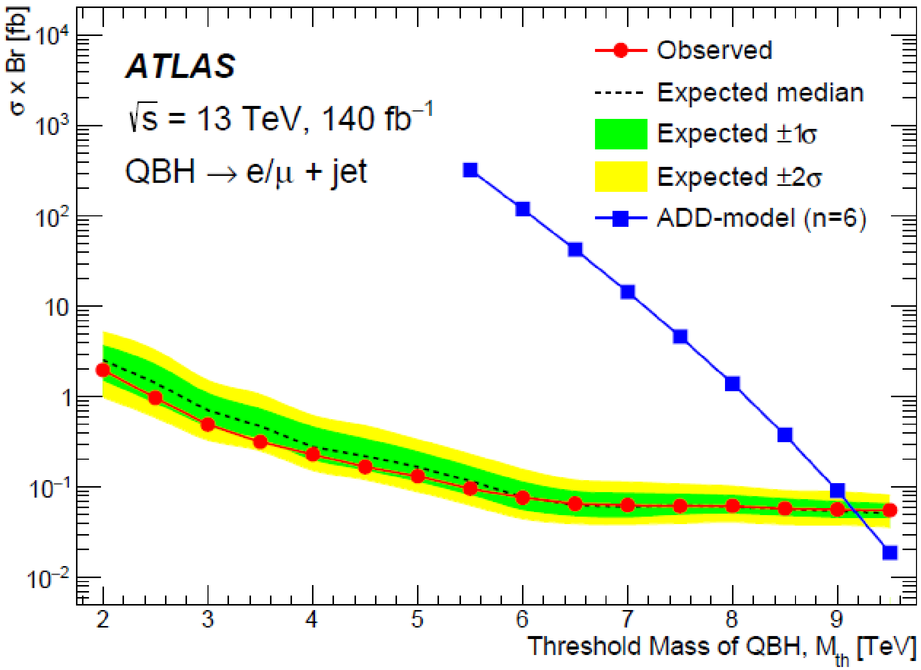
Pre-fit, Muons, ADD 7.0 TeV



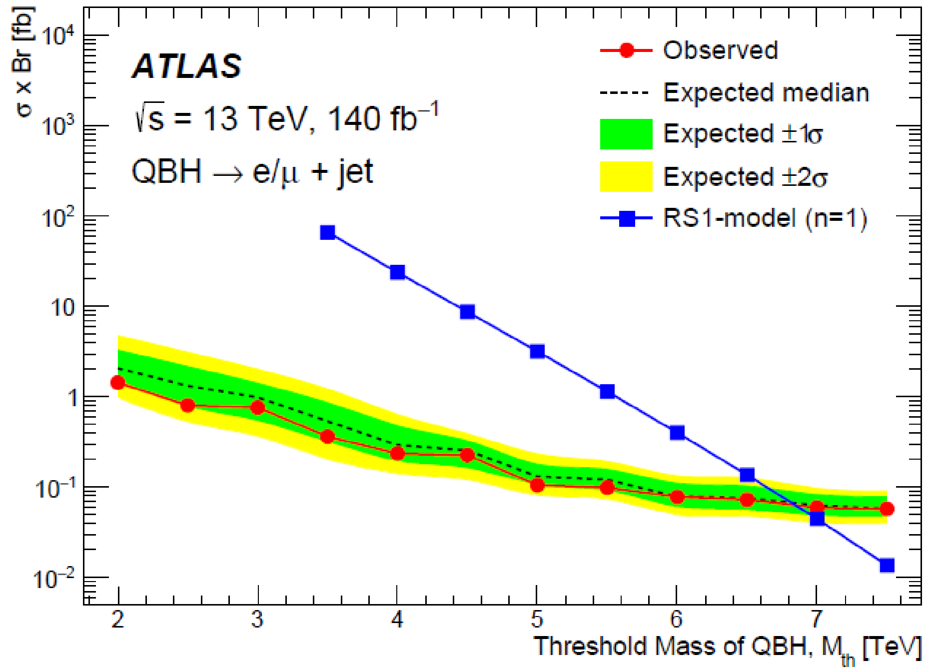
Post-fit, Muons, ADD 7.0 TeV



6.2. Upper limits with modeled signal (exclusion) fit.



(a)



(b)

The combined 95% C.L. upper limits on $\sigma \times Br$ as a function of M_{th} for QBH production at $M_{th} = M_D$ with decay into lepton + jet for (a) ADD (extra dimensions n=6) and (b) RS1 (extra dimensions n=1).

The limits take into account statistical and systematic uncertainties. Circles along the solid red line indicate the mass M_{th} of the signal where the observed limit is computed. The expected limits are shown by the dashed line. The $\pm 1\sigma$ and $\pm 2\sigma$ bands are shown in green and yellow, respectively. The theoretically predicted $\sigma \times Br$ for the QBH production and decay is shown as the solid blue curve with squares. The limits are obtained with pseudoexperiments.

6.3. Upper limits. Final values.

Table.
The lower limits on M_{th} and the upper limits on $\boldsymbol{\sigma} \times \boldsymbol{Br}$ at these mass points for QBHs decaying to a lepton and jet in the **ADD** and **RS1** models. The model-independent upper limits on $\boldsymbol{\sigma} \times \boldsymbol{Br}$ are shown at $\mathbf{m_{inv} > 5}$ **TeV**.

Channel	ADD $\sigma \times Br$ [fb]	ADD M_{th} [TeV]	RS1 $\sigma \times Br$ [fb]	RS1 M_{th} [TeV]	Model-independent $\sigma(m_{\text{inv}} > 5 \text{ TeV}) \times Br$ [fb]
Electron+jet	0.091	9.0	0.099	6.6	0.095
Muon+jet	0.083	9.0	0.087	6.7	0.084
Combined	0.056	9.2	0.061	6.8	0.052

- **No significant excess is found, but stringent limits are placed on parameters in variety of models that introduce extra dimensions and lead to the prediction of new particles.**

7. Conclusion of Run2 study.

- Analysis was done for Run2 and for three types of fit: background-only, model-independent (discovery) and with modeled signal (exclusion).
- The observed invariant mass spectrum of lepton-jet pairs is consistent with SM expectations.
- The obtained model-independent limit on σ x Br (0.052 fb) show a factor of 3.5 improvement with respect to the previous upper limit at 8 TeV collisions .*)
- The QBH threshold mass limit for the ADD model (9.2 TeV) is 3.9 TeV higher compared to the previous result at 8 TeV collisions in ATLAS.*) The limit on σ x Br for the ADD model is 0.056 fb.
- The limit on the QBH mass (6.8 TeV) and on σ x Br (0.061 fb) for the RS1 model is determined for the first time in the lepton+jet decay mode.

*) Previous limits on M_{th} at QBH → e/μ/ℓ + jet were 5.2, 5.1 and 5.3 TeV respectively. Upper limit on σ×Br for M_{th} > 3.5 TeV was estimated as 0.18 fb. (ATLAS, $\sqrt{s}$=8 TeV, Phys. Rev. Lett. 112, 2014, 091804)

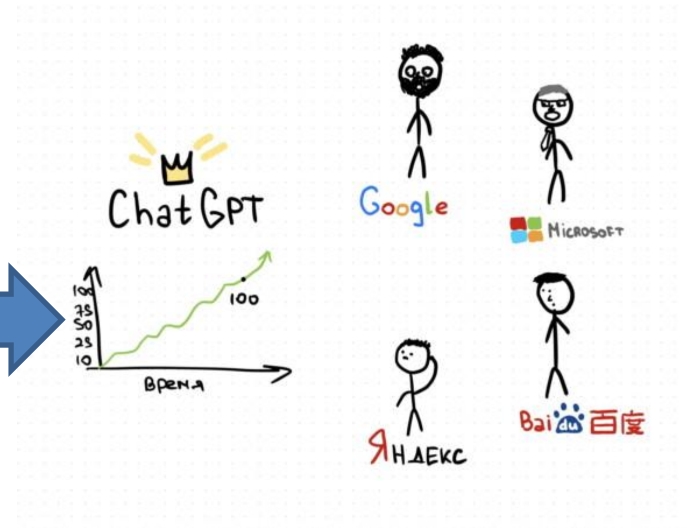
- **More details** (kinematic distributions, tables and figures of systematic, expected yields of background and many other things) are represented in **supporting note:** http://cds.cern.ch/record/2637190
- **Paper** Phys. Rev. D publication DOI: 10.1103/PhysRevD.109.032010

Part II
Neural networks using in search for QBH with Run3 data of the ATLAS detector

1. **Introduction.**
2. **Neural Network (NN) - from Simple to Deep. Architecture of a DNN.**
3. **Task formulation for the QBH analysis.**
4. **Quality check of the input data of NN.**
5. **Training and testing of NN.**
6. **Results of separation of modelled background and modelled signal.**
7. **Conclusion for Run3 analysis.**

1.1. Introduction. Very short history of neural networks

○ 1940-1960: First concept of neural networks. <u>Algorithm forward.</u>
○ 1970-2000: <u>*Method of backward propagation of an error*</u> and nonlinear functions of activation.
○ 2000-2020: Development <u>*Deep Learning*</u> and modern neural networks.
○ 2020: Creation of <u>*model GPT-3*</u> (Generative Pretrained Transformer 3) - the language model developed OpenAI (they also have created **ChatGPT**).



<u>Names:</u>

➢ (1949) ***Donald Hebb***, theory of simultaneous activation neurons.
➢ (1950-60, Perceptron): ***Frank Rosenblatt*** - *American scientist in the field of psychology, neurophysiology and artificial intelligence. Was born in New York in a family of natives of the Russian empire.*
➢ (1974): ***Pol Verbos*** has developed <u>*algorithm (method) of backward propagation of errors*</u> which is used till now for training of neural networks.
➢ (1985-2001): ***Marvin Lee Minsky*** – American computer scientist concerned largely with research of <u>artificial intelligence (AI)</u>
➢ and others, etc.

1.2. Introduction. Base Problems.

➢ The Neural Network is the mathematical model constructed just like real biological neural systems. The mathematical-algorithmic tool, allows us to solve following *problems*:

-- Forecasting

-- Recognition of images

-- The analysis of the data

-- Information storing

-- Classification

-- Compression of the data

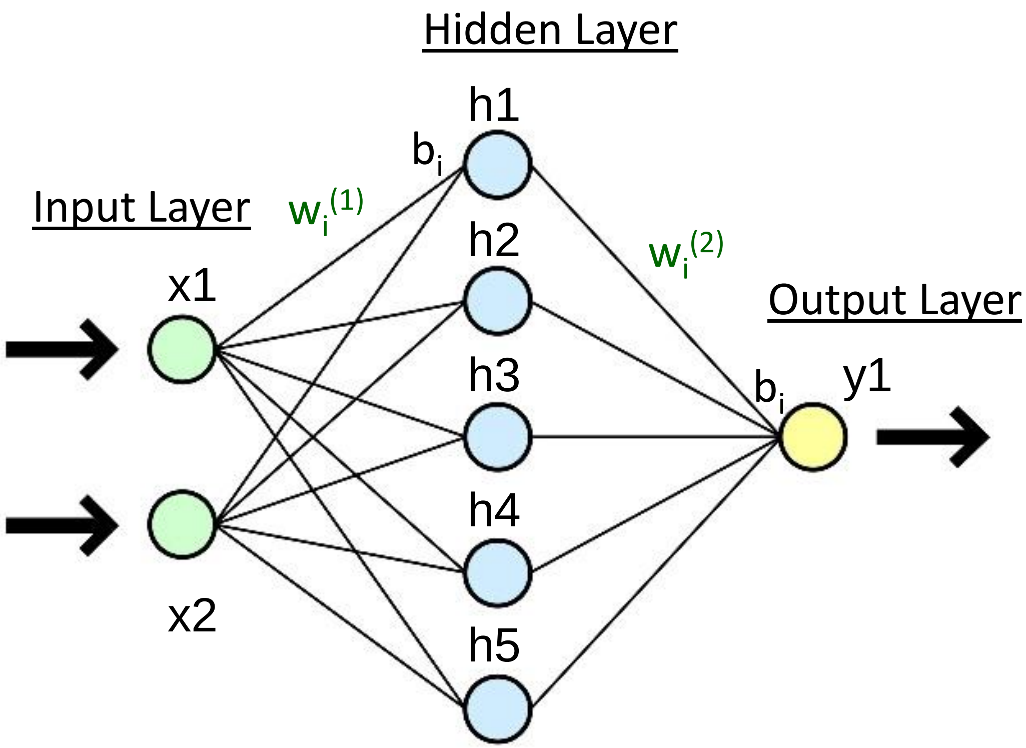
➢ NN may be to present in the form of a **black box,** which has **Inputs** and **Exits**. And in this box there is a set of neurons. Communications between them have the of **weights**.

➢ Neural Net is not a common Program. It has just different logic of work.

➢ **For good work Neural Net has to pass a Test.**

➢ **For good work Neural Net has to learn.**

1.3. Introduction. Terminology.



Simple Neural Network – SNN

Work NN: Forward propagation

$h_i = f(\Sigma(x_i \cdot w_i^{(1)}) + b_i)$

$h_{out} = y1$

$h_{out} = f(\Sigma\,(h_i \cdot w_i^{(2)}) + b_i)$

Terminology

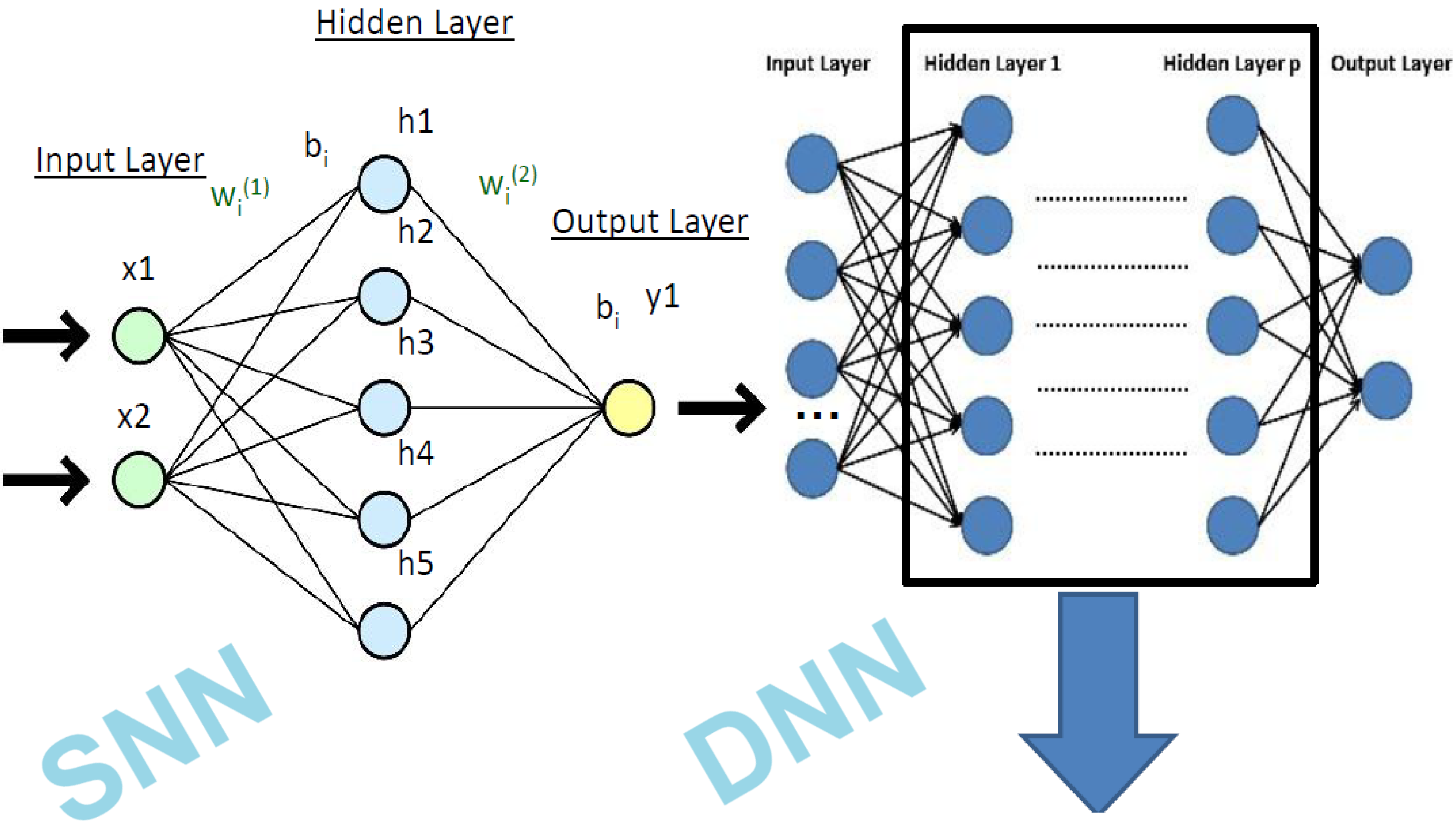
- Neural Network – NN
- Simple Neural Network – SNN
- Deep Learning Neural Network – DNN
- neuron (node)
- weights
- bias
- input layer – inputs
- hidden layer
- output layer – outputs (exits)
- activation function
- forward method
- backward method

Activation Function:

Sigmoid (x)

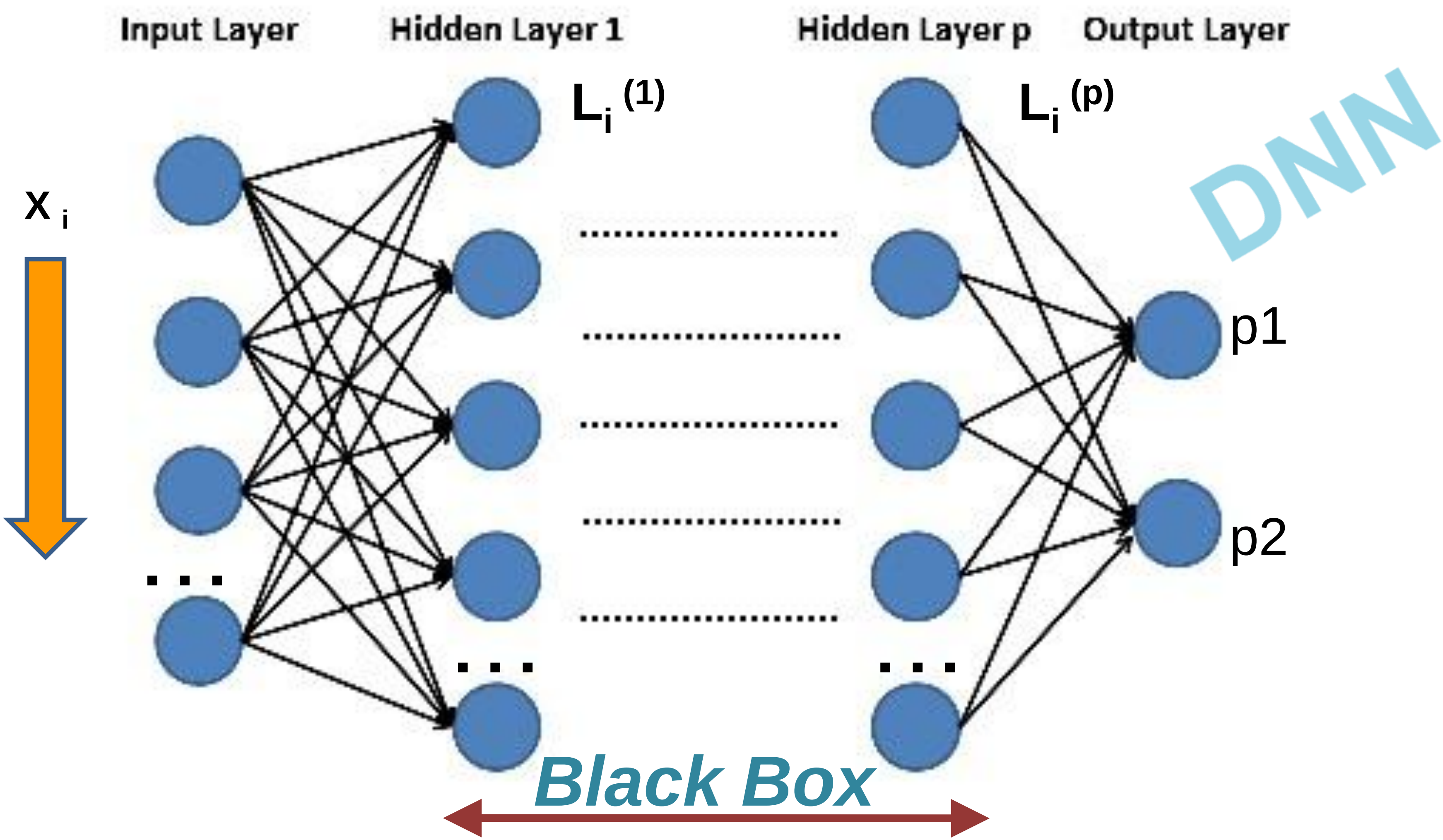
$f(x) = 1/(1 + \exp(-x))$

2.1. NN: from Simple to Deep. Architecture of DNN



Black box has many Hidden Layers.

2.2. NN: from Simple to Deep. Black Box.

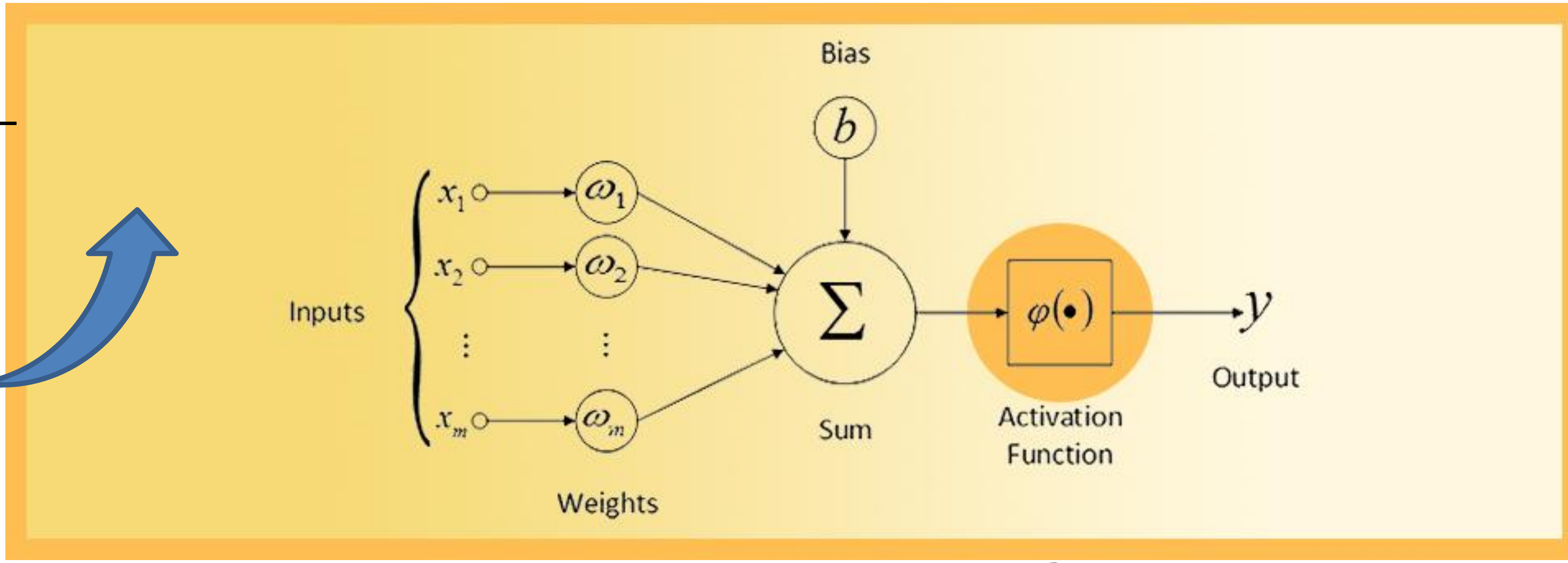


- What part we can supervise in work of DNN? – *Only {X_i}*
- What does *Black Box* do during work? – *We can't know.*

3.1.Task formulation for the QBH analysis.

1 stage – NN has to separate a background and a signal in MC datasets.
2 stage – NN has to search for a signal in real data of ATLAS detector.

❖ **I. Forward propagation**

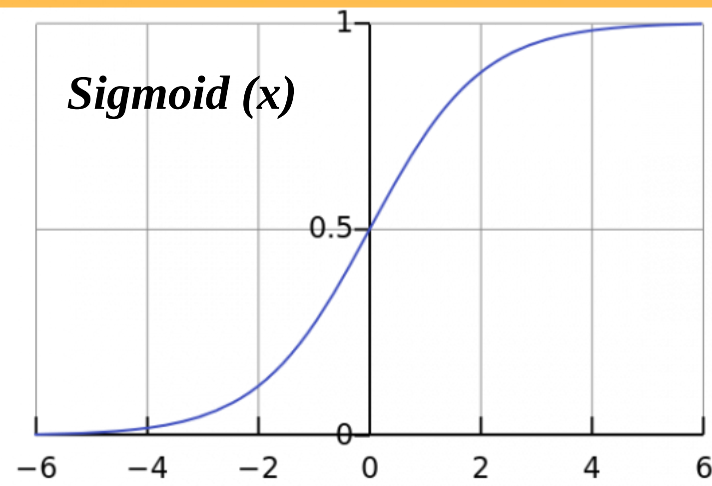


❖ **II. Learning NN:**

❖ **Back propagation**

Activation Function

$$A = \frac{1}{1+e^{-x}}$$

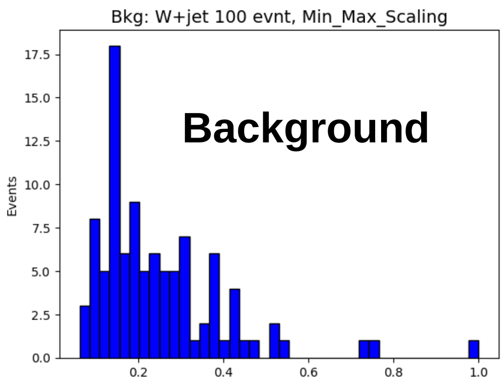


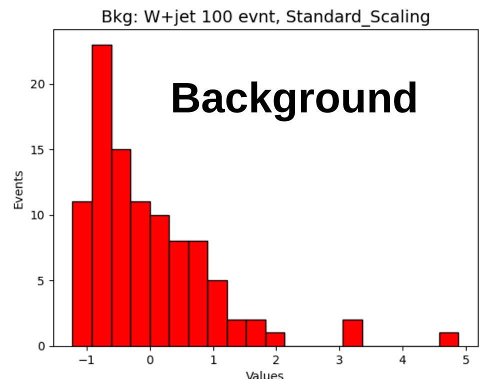
4. Quality check of the entrance data of NN.

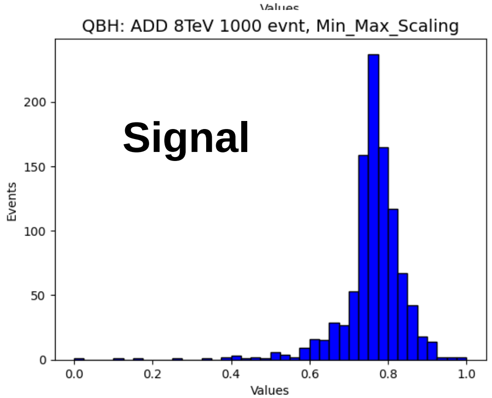
1) К «сырому» дата-фрейму (ДФ) применяется *масштабирование* (скейлинг), это пакеты **(Python)** :
--- a) «MinMax-Scaling»
--- b) «Standard-Scaling»

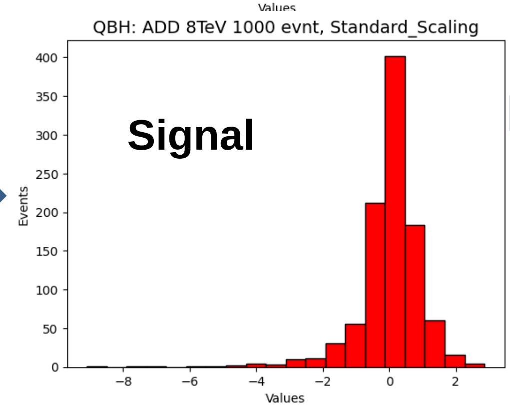
2) Делается проверка этого ДФ на *гауссовость*:
--- a) после MinMax-Scaling
--- b) после Standard-Scaling

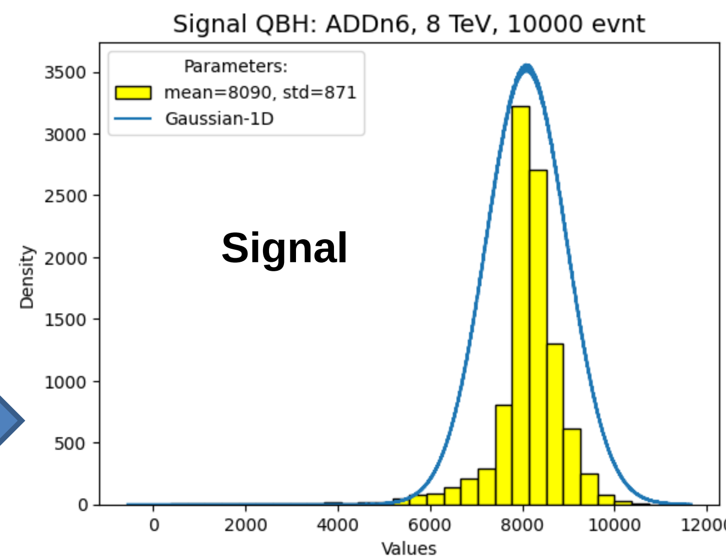
3) Если полученный ДФ не гауссиан, то происходит *чистка шумов*:
--- a) Отбрасывание «хвостов» - получаем гауссиан. Если не помогает:
--- b) Устраняем «выбросы» - *Spikes*. С помощью спец.пакетов **<data_clean.shape>** получаем гауссиан.











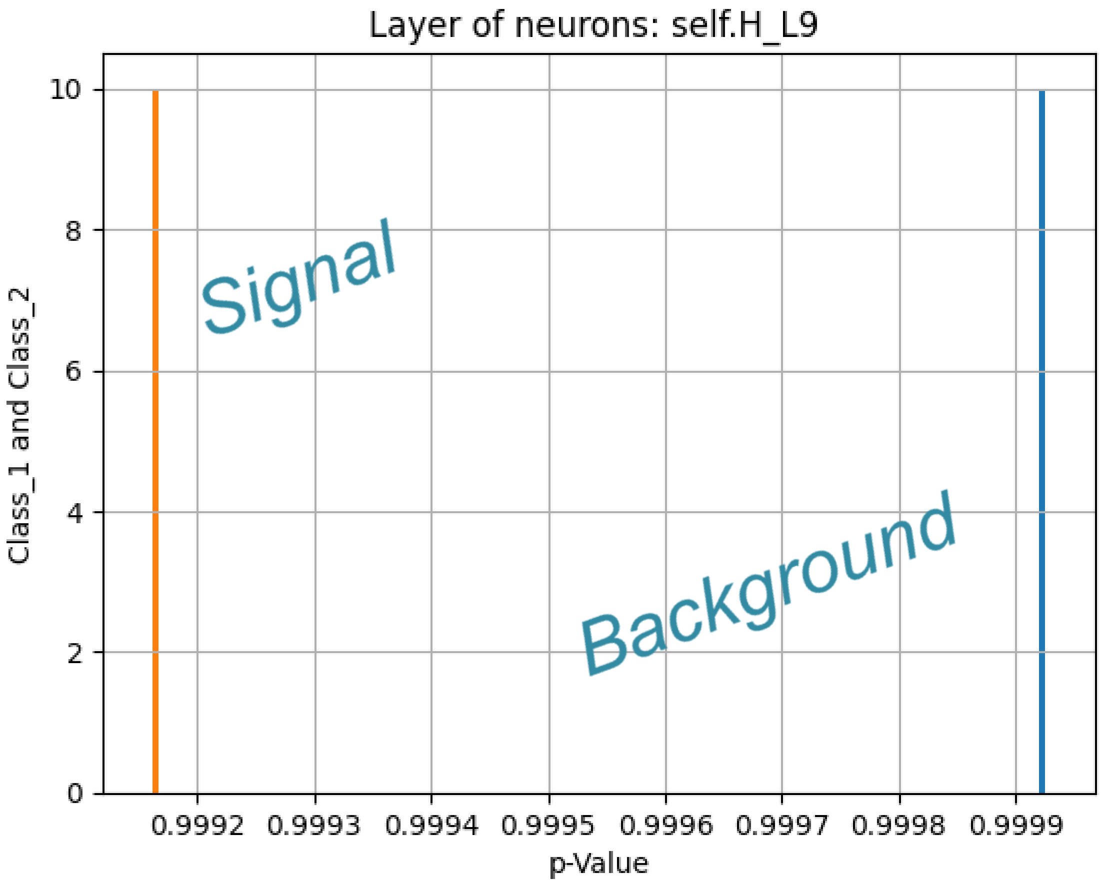
5. Training and testing of NN.

- Два датасета для **Signal** и **Background** объединены в один файл **<dataTotal_200_1.csv>**.
- Этот датасет разделен на выборки **- Train, Test and Validate**.
- Выборки: **Train, Test, Validate -** записаны в отдельные дата-фреймы типа ***Panda***.
- По полученным выборками созданы гистограммы <**dataTrain>, <dataTest>, <dataValidate>**. Качество данных после разделения общего датасета не ухудшилось.
- Для обучения NN есть 3 возможности: «Обучение с учителем», ***«Обучение без учителя»*** и «Обучение с подкреплением».
- Классификация. Разделение на фон **(W+jet)** и сигнал **(QBH: 8 TeV)** NN сделала.

--- При работе использовались *гиперпараметры*: скорость обучения, число слоев, число нейронов в NN и число эпох. Результат разделения получался при различном значении скорости обучения, числа слоев и числа нейронов. Чем меньше слоев, то тем при большем числе эпох получался результат. Первый предварительный результат получен при числе эпох **-** ***300 000***.

--- При обучении на датасете **<dataTrain>** считались ошибки: **MSE, RMSE** и точность модели **accuracy_net**.

6.1. Results of separation of modelled background and modelled signal



(Test region of NN).

Separation of Background and Signal with:

p-value = 0.9992 (Signal) and
p-value = 0.9999 (Background)

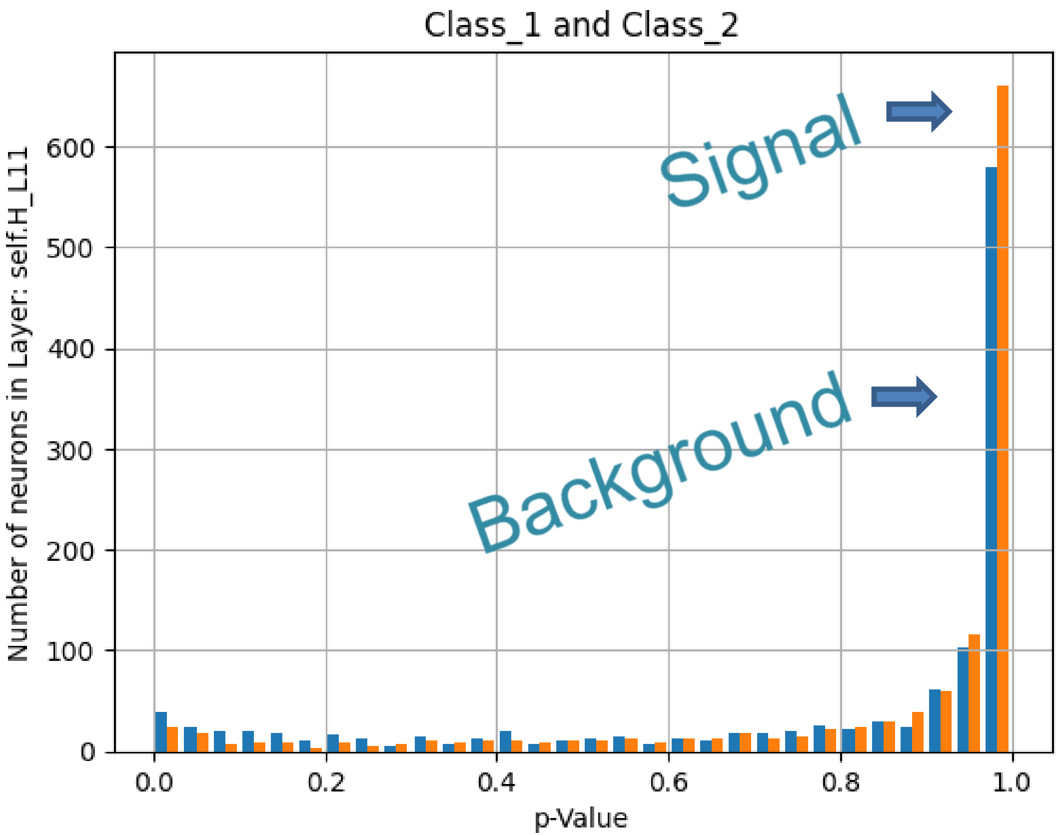
Data: Run3 (ATLAS, MC),
{X_i} → *Electron channel*.
Background : W+jet,
Signal: QBH_ADDn6_8TeV

Table1

Total layers	Number of hidden layers	Number of neurons	Learning rate	Number of epochs	Train loss (mse)	Accuracy of model, %	p-value signal / background
10	**8**	**82+{X_i}**	**0.001**	**300000**	**~0.0012**	**99.87**	**0.9992 / 0.9999**

***1- base parameter: “*mLepJet*”**

6.2. Results of separation of modelled background and modelled signal



(Test region of NN).
Separation of Background and Signal with:
p-value = 0.9999 (Signal) and
p-value = 0.9304 (Background)

Data: Run3 (ATLAS, MC),
$\{X_i\}$ → *Electron channel*.
Background : W+jet,
Signal: QBH_ADDn6_8TeV

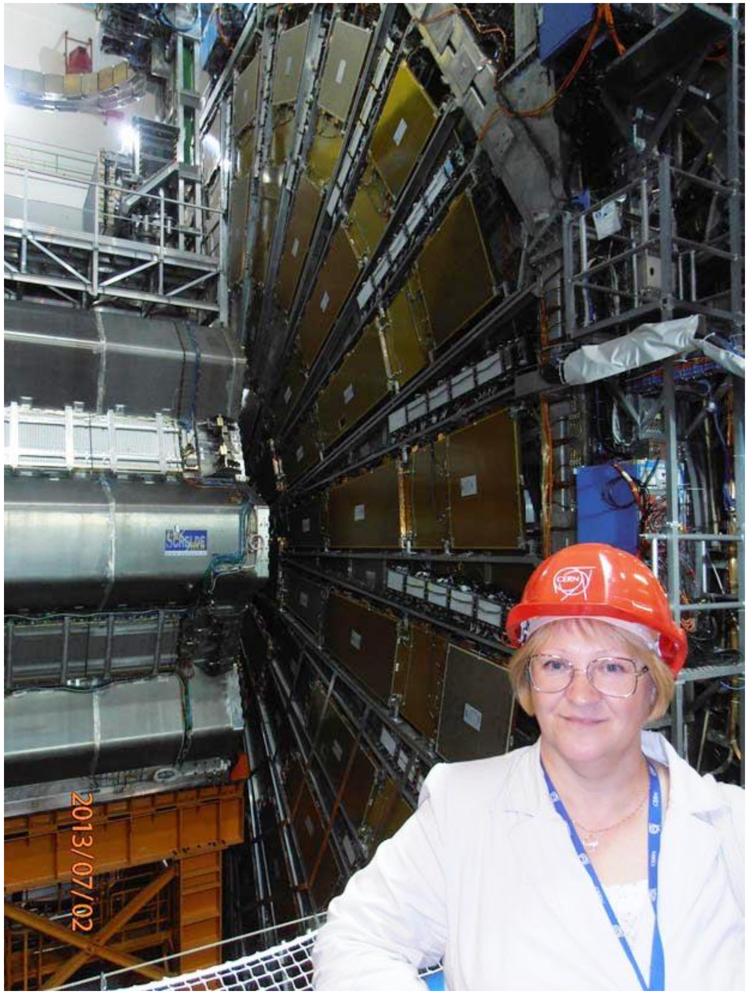
Table 2

Total layers	Number of hidden layers	Number of neurons	Learning rate	Number of epochs	Train loss (mse)	Accuracy of model, %	p-value signal / background
12	10	$12002+\{X_i\}$	1e-6	2000	6.88e-6	65.46	0.9999 / 0.9304

3- base parameters: *"mLepJet", "detaLepJet", "dphiLepJet"

7. Conclusion for Run3 analysis

- Deep Neural Network (DNN) was constructed for analysis.
- Training of two versions of our DNN model: **NN_BkgSig_007 & NN_BkgSig_008** with dataset of <dataTrain> in Training region is done.
- Testing of model of DNN with dataset of <dataTest> in Test region is done.
- In Validation region DNN with dataset of <dataValidat> works good.
- Classification task is executed - the DNN separates the dataset into two classes: background and signal. Later we shall add some classes of background.
- In model **NN_BkgSig_007** is used 1 observable value **-** it is: mass of lepton and leading jet - ***"mLepJet"***. Results of calculation for model **NN_BkgSig_007** are presented in Table 1.
- In model **NN_BkgSig_008** are used 3 observable value : mass of lepton and leading jet $m_{\ell j}$ - ***"mLepJet"*****,** $\Delta\eta_{\ell j}$ between lepton and leading jet ***"detaLepJet"*** and $\Delta\varphi_{\ell j}$ between lepton and leading jet ***"dphiLepJet".*** Results of calculation for model **NN_BkgSig_008** are presented in Table 2. Later we shall add some more observables ($p_{T\ell}$, p_{Tj}, η_{ℓ}, η_j, ...).
- The given versions of model of DNN are quite **satisfactory**.



For additional information mail to: zkarpova@cern.ch

Thank you!

Backup

Outlook

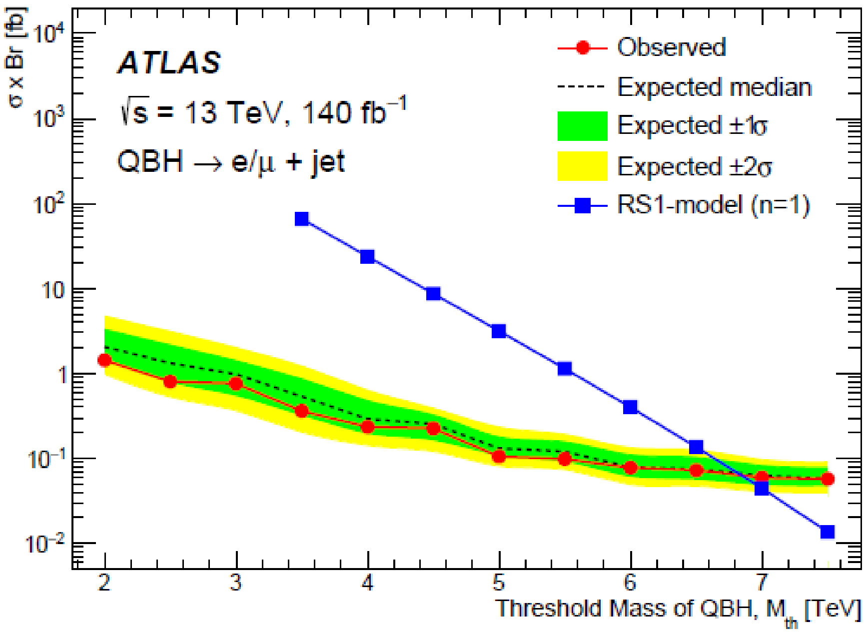
Part I:
Search for QBH with Run2 data of the ATLAS detector

1. Introduction and motivation to searching for Quantum Black Holes.
2. Models with extra space dimensions: ADD & RS1.
3. Analysis of the ATLAS data at collision energy of $\sqrt{s}$ = 13 TeV (Run2).
4. Systematic of background and signal in Signal region (SR).
5. Upper limits in model independent fit.
6. Upper limits for two models (ADD, RS1).
7. Conclusion for Run2 analysis.

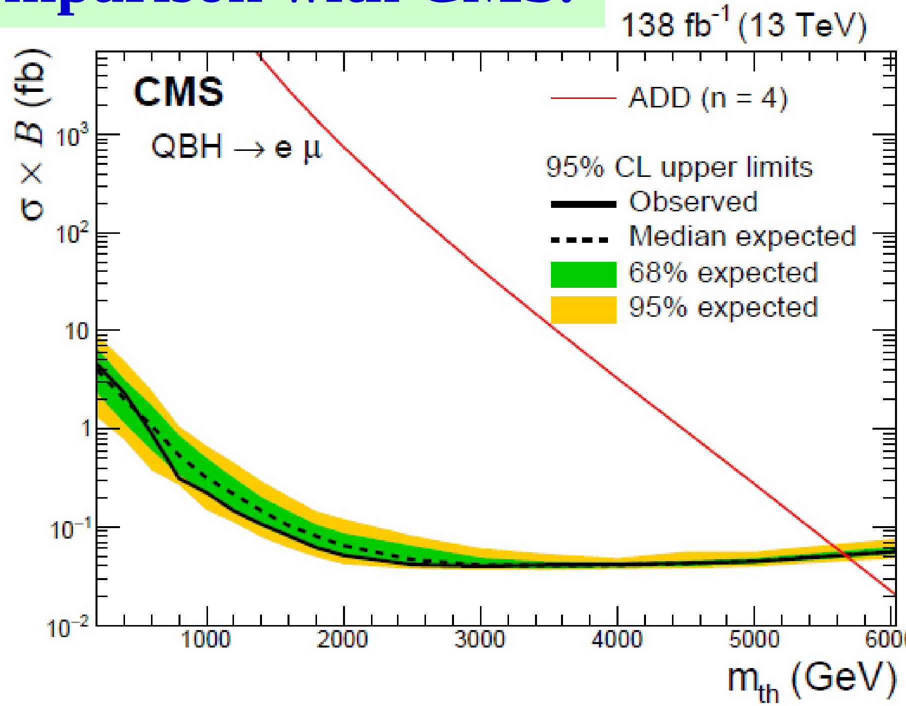
Part II:
Neural networks using in search for QBH with Run3 data of the ATLAS detector

1. Introduction & Terminology.
2. Neural Network (NN) - from Simple to Deep. Architecture of a DNN.
3. Task formulation for the QBH analysis.
4. Quality check of the input data of NN.
5. Training and testing of NN.
6. Results of separation of modelled background and modelled signal.
7. Conclusion for Run3 analysis.

6.4. Upper limits. Comparison with CMS.



(a)



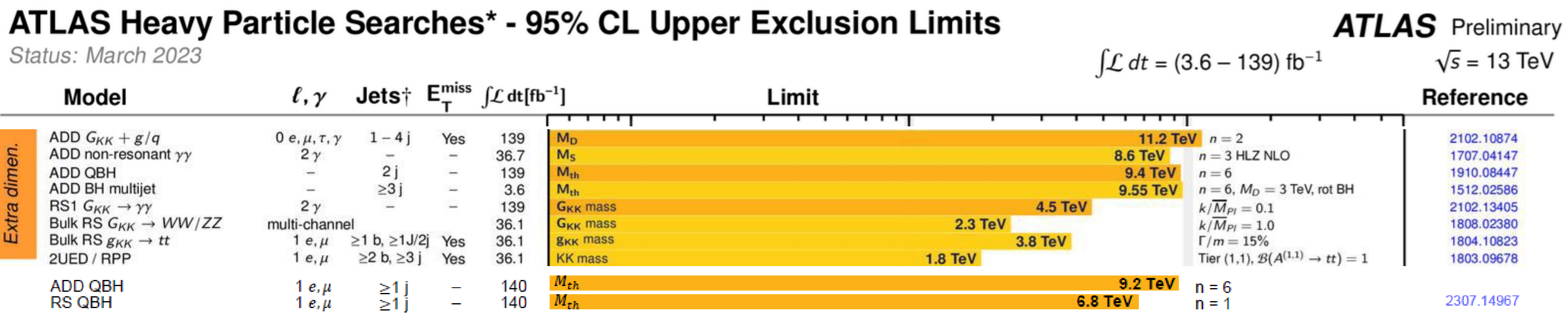
(b)

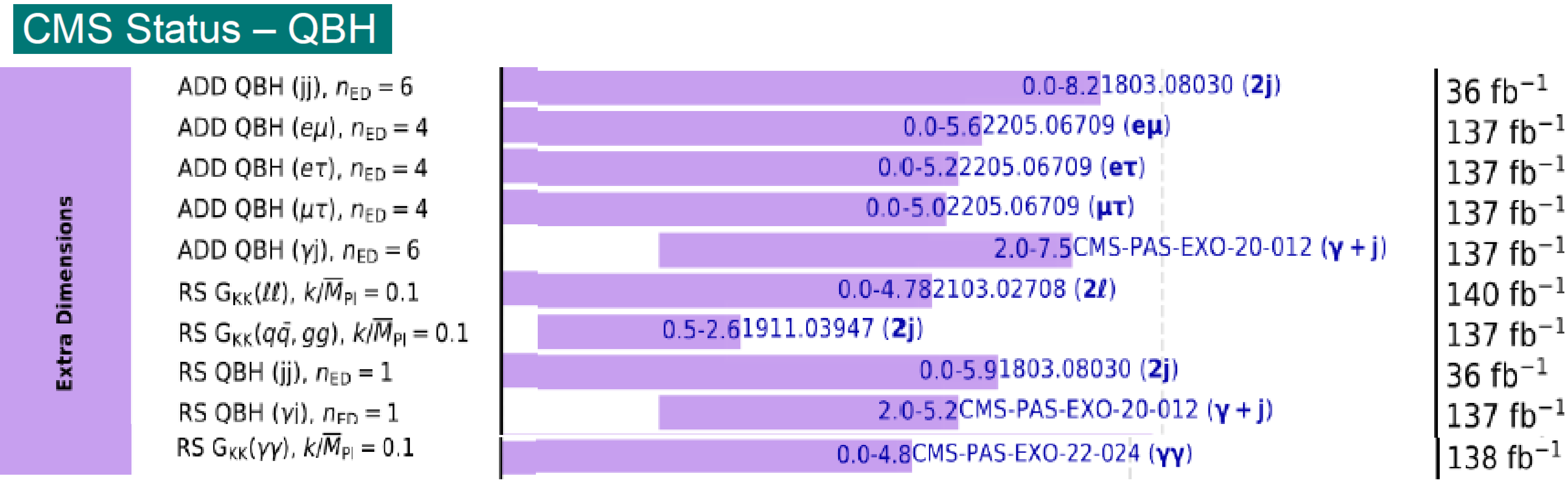
(a) The combined 95% CL upper limits from ATLAS on $\sigma \times Br$ as a function of the threshold mass for QBH production with decay into lepton+jet for the RS1 model (RS with one extra dimension). Circles along the solid red line indicate the threshold mass of the signal where the observed limit is computed.

(b) CMS 95% CL upper limits on the product of the cross section and the branching fraction for QBH production in an ADD model with 4 extra dimensions, in the electron+muon channel, as a function of the threshold mass [*].

[*] CMS Collaboration, Search for heavy resonances and quantum black holes in $e\mu$, $e\tau$, and $\mu\tau$ final states in proton-proton collisions at √s = 13 TeV, JHEP 05 (2023) 227. arXiv:2205.06709

6.5. QBH mass limits. Comparison with CMS.





ATLAS:
- **ADD QBH → j + j, 9.4 TeV, 139 fb^{-1}**
- **ADD QBH → ℓ + j, 9.2 TeV, 140 fb^{-1}**
- **RS1 G_{kk} → γ + γ, 4.5 TeV, 139 fb^{-1}**
- **RS1 QBH → ℓ + j, 6.8 TeV, 140 fb^{-1}**

CMS:
- **ADD QBH → j + j, 8.2 TeV, 36 fb^{-1}**
- **ADD QBH → γ + j, 7.5 TeV, 137 fb^{-1}**
- **RS1 G_{kk} → γ + γ, 4.8 TeV, 138 fb^{-1}**
- **RS1 QBH → γ + j, 5.2 TeV, 137 fb^{-1}**

2.1. ADD & RS1 models. Common properties [*].

- ***QBH is a multidimensional object*** like a quasi-particle in 4-dimentional space-time.
- ***QBH is a massive resonance*** can decay into some well **detected usual particles**.
- ***Global symmetries do not conserve***. Strong gravitation interactions do not need to conserve the global symmetries of the Standard Model. In the models the QBH production is supposed that baryon's and lepton's numbers can be violated. However, the local gauge symmetries of **color, total angular momentum (*l*+*s*) and electric charge** are conserved.
- ***Event horizon*** for QBH with mass of M_{QBH} ~TeV has gravitation radius $R \sim M_D^{-1}$.
- ***If the multi-dimensional scale*** is near the electroweak scale $M_D \approx M_{EWK}$, the hierarchy problem can be solved. The four-dimensional Planck scale M_{Pl} is related to the multi-dimensional scale M_D by

$$M_{Pl}^2 \sim M_D^{2+n} R^n \qquad (1)$$

- ***In both ADD and RS1 scenarios*** it is expected, that QBHs should form, when collisions energy will exceed a **certain threshold mass** M_{th} that is set equal to M_D. The QBH mass is required to be in range of **1–3** M_D.
- ***The final state multiplicity*** of the QBH decay depends on the definition of the M_D scale. 51% (74%) of the QBH decays two-particle in ADD (RS1) models, while three-particle and four-particle decays are significantly less.
- ***The QBH decaying*** into **electron or muon** and a **quark (antiquark)** is searched for in our analysis (**QBH → lepton + jet).** This channel provides good branching and lepton in final state provides good ratio of signal and background.

[*] Douglas M. Gingrich, Quantum black holes with charge, color, and spin at the LHC, arXiv:0912.0826v4 [hep-ph] 13 Jul 2010

2.2. ADD & RS1 models.
Production and decay of Quantum Black Holes [*].

- For proton-proton collisions at **LHC** the allowed particles forming the QBHs are ***quarks, antiquarks and gluons***. Quantum Black Holes (QBH) can be classified according to their $SU(3)_c$ and $U(1)_{em}$ representations.
- The 9 possible electric charge states of QBH can be formed: **±4/3, ±1, ±2/3, ±1/3, 0**.
  - -- The ±4/3 charge state can only be formed by ***quark pairs***.
  - -- The ±2/3 charge state can be formed either by ***an antiquark-antiquark or a quark-gluon pair.***
  - -- The ±1/3 charge state can be formed either by ***a quark-quark pair or an antiquark-gluon pair.***
  - -- The ±1 charge state can only be formed by ***a quark-antiquark pair.***
  - -- The 0 charge state can be formed by ***a quark-antiquark or a gluon-gluon pair.***

- Six states only (**±4/3, ±2/3, ±1/3**) with integer spin can decay to a lepton and a quark [*]:
  - *u + u* → $QBH^{+4/3}$ → $e^+ (\mu^+)$ + *dbar;*
  - *dbar+ dbar* → $QBH^{+2/3}$ → $e^+ (\mu^+)$ + *d;*
  - *u + d* → $QBH^{+1/3}$ → $e^+ (\mu^+)$ + *ubar;*
  - *ubar + dbar* → $QBH^{-1/3}$ → $e^- (\mu^-)$ + *u;*
  - *d + d* → $QBH^{-2/3}$ → $e^- (\mu^-)$ + *dbar;*
  - *ubar + ubar* → $QBH^{-4/3}$ → $e^- (\mu^-)$ + *d.*

- **11% branching fraction for** $QBH^{\pm 4/3}$ → **e (μ) + jet**
- **6.7% branching fraction for** $QBH^{\pm 2/3}$ → **e (μ) + jet**
- **5.7% branching fraction for** $QBH^{\pm 1/3}$ → **e (μ) + jet**
- **BF = (11+6.7+5.7)×2 = 46.8%**

- BR of QBH decay into lepton+jet in RS1-model is the same as in ADD-model. The cross-section in ADD-model is ~200 times more than in RS1-model.

[*] Douglas M. Gingrich, Quantum black holes with charge, color, and spin at the LHC, arXiv:0912.0826v4 [hep-ph] 13 Jul 2010

3. ADD & RS1. Key moment: Production of Quantum Black Holes [*] - 2

❖ For proton-proton collisions at **LHC** the allowed particles forming the QBHs are ***quarks, antiquarks and gluons***. Quantum Black Holes (QBH) can be classified according to their $SU(3)_c$ and $U(1)_{em}$ representations. The 9 possible electric charge states can be formed: **±4/3, ±1, ±2/3, ±1/3, 0**.

-- The ±4/3 charge state can only be formed by ***quark pairs***.

-- The ±2/3 charge state can be formed either by ***an antiquark-antiquark or a quark-gluon pair.***

-- The ±1/3 charge state can be formed either by ***a quark-quark pair or an antiquark-gluon pair.***

-- The ±1 charge state can only be formed by ***a quark-antiquark pair.***

-- The 0 charge state can be formed by ***a quark-antiquark or a gluon-gluon pair.***

❖ A priori the cross section for QBH production is not known. Based on classical arguments and only one available scale, the cross section is most often is taken as the geometrical cross section:

$$\sigma \sim \pi r_g^2, \qquad (2)$$

where r_g is the **gravitational radius** of the *two-particle system*.

$$\sigma(QBH^q_{p_1p_2}) = \sum_{a,b} \int_{M^2/s}^{1} dx_{min} \int_{x_{min}}^{1} \frac{dx}{x} f_a\left(\frac{x_{min}}{x}\right) f_b(x) \pi r_g^2, \qquad (3)$$

where a and b are the parton types in the two protons, and f_a, and f_b are the parton distribution functions (PDFs) for the proton. The sum is over all the possible quark and gluon pairings that can make a particular quantum black hole state.

[*] Douglas M. Gingrich, Quantum black holes with charge, color, and spin at the LHC, arXiv:0912.0826v4 [hep-ph] 13 Jul 2010

3.1. Model with extra space dimensions: ADD - 3

➢ **Key moment: Production of Quantum Black Holes,** [*]

❖ Then the gravitational radius $\mathbf{r_g}$ of a quantum black hole of mass M is:

$$r_g = k(D)\frac{1}{M_D}\left(\frac{M}{M_D}\right)^{\frac{1}{D-3}}, \quad (3)$$

where D is the total number of Spacetime Dimensions, and $k(D)$ is a numerical coefficient, depending on the number of dimensions and the definition of the fundamental Plank scale (for low gravity scale). At energies of the fundamental Plank scale M_D, the sizes in Spacetime of the incoming partons and the gravitational radius r_g of the QBH are both of order M_D^{-1}. If Γ is a width of the QBH resonance, for PDG the definition of the Planck scale we have:

$$k(D) = \left(2^{D-4}\sqrt{\pi}^{D-4}\frac{\Gamma\left(\frac{D-1}{2}\right)}{D-2}\right)^{\frac{1}{D-3}}. \quad (4)$$

❖ Some fraction of the total centre-of-mass energy $\sqrt{s}$ in a proton-proton collision is available in the hard scattering process. One can define $sx_a x_b = sx_{min} = \hat{s}$, where x_a and x_b are the fractional energies of the two partons relative to the proton energies. The full particle-level cross section is given by:

$$\sigma(QBH^q_{p_1p_2}) = \sum_{a,b}\int_{M^2/s}^{1} dx_{min}\int_{x_{min}}^{1}\frac{dx}{x} f_a\left(\frac{x_{min}}{x}\right) f_b(x)\pi r_g^2, \quad (5)$$

where a and b are the parton types in the two protons, and f_a, and f_b are the parton distribution functions (PDFs) for the proton. The sum is over all the possible quark and gluon pairings that can make a particular quantum black hole state.

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Literature

[1] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Lett. B 429, 263 (1998), arXiv:hep-ph/9803315.
[2] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Lett. B 436, 257 (1998), arXiv:hep-ph/9804398.
[3] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Rev. D 59, 086004 (1999), arXiv:hep-ph/9807344.

[4] Douglas M. Gingrich, Quantum black holes with charge, color, and spin at the LHC, arXiv:0912.0826v4 [hep-ph] 13 Jul 2010.

[5] Savas Dimopoulos and Greg Landsberg, Black Holes at the LHC, arXiv:hep-ph/0106295v1 27 Jun 2001.

[6] Igor Volovich, Sakharov's Extra Timelike Dimensions and Hawking's Chronology Protection Principle, 4th International Sakharov Conference on Physics, FIAN, Moscow, May 18-23, 2009.

[7] The ATLAS Collaboration, Search for Quantum Black Hole Production in High-Invariant-Mass Lepton+Jet Final States Using pp Collisions at $\sqrt{s}$=8 TeV and the ATLAS Detector, arXiv:1311.2006v2 [hep-ex] 6 Mar 2014.

[8] Karpova Zoya, Karpov Sergey, ATLAS Collaboration, Search for Quantum Black Holes in Lepton+Jet Final State Using pp-collisions at $\sqrt{s}$ = 8 TeV with the ATLAS, 09 Dec 2015, 5 p., ATL-PHYS-PROC-2015-182.

[9] Karpov Sergey, Karpova Zoya, Gingrich Douglas, ATLAS Collaboration, Supporting note of Search for Quantum Black Holes using pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS, 04 Dec 2016, mult. p., ATL-COM-PHYS-2016-1762.

5.2. Analysis: Event cleaning and object pre-selection

1. **Data quality and event cleaning:** GRL, problematic regions of the Lar and TileCal, incomplete events, check of primary vertex with ≥2 tracks.
2. **Trigger:** HLT_e26_lhtight_iloose, HLT_e26_lhtight_nod0_iloose, HLT_e60_lhmedium, HLT_e120_lhloose, HLT_mu26_imedium, HLT_mu26_ivarmedium, HLT_mu50
3. **Candidates of electrons ("Baseline"):** "LooseAndBLayerLLH" quality, $|\eta| \leq 2.47$ and p_T>10 GeV after calibration.
   "Baseline" muons: "Medium" quality, $|\eta| \leq 2.7$ and p_T>10 GeV.
   "Baseline" jets: "AntiKt4EMTopojets", JVT cut, $|\eta| \leq 2.8$ and p_T>20 GeV.
4. **Bad Jet Veto:** "LooseBad" condition in the JetCleaningTool package.
5. **Overlap Removal: a)** if ΔR(jet,lepton)<0.2 and jet is b-jet, then lepton is removed and jet is kept; if jet is no b-jet, then vice versa jet is removed;
   b) using only remaining jets if ΔR(jet,lepton)<0.4, we need to remove the lepton and keep the jet.
5. **Bad muon veto:** muon is "bad", if σ(q/p) / abs(q/p) >0.2.
6. **Cosmic muon veto:** muon is cosmic, if it has a track with $|z_0^{PV}| \geq 1$ mm and $|d_0^{PV}| \geq 0.2$ mm.
7. **Selection of "Final" objects:** isolated lepton with the "GradientLoose" condition, trigger matched and with p_T>30 GeV; good jets with p_T>20 GeV.
8. **Event pre-selection:** one or more "Final" lepton and one or more "Final" jet.

5.4.2. Some other features of analysis

- **Statistical analysis is done with using of the HistFitter package v0.63.**
- We use the **W+jet, Z+jet** and **TTbar** control regions **(WCR, ZCR and TCR)** for both electron and muon channels. These samples are normalized and fitted in CRs and extrapolated to VR, because they are main three background modeled by MC.
- **Each control region** is fitted in **5 bins over M_{inv}** (from **1.0 to 1.5 TeV** with step of **0.1 TeV**), what allows us to use shape information of distributions.
- **Systematic uncertainties** are added as nuisance parameters. They are constrained also by the fit with taking into account of mutual correlations.
- **The background-only fit** is applied now: the control regions are used to constrain the fit parameters and to extrapolate distributions into validation region.
- **Small backgrounds** (W+t, single top and di-bosons) are not fitted and used as it is. Nevertheless, small variations within their systematic uncertainties are allowed for better performance of the fit.
- **All MC events are weighted** with following factors:
  totWeight = genWeight * mcEvtWeight * pileupWeight * lepSF * btagSF * jvtSF * tauSF,
  where **genWeight = (σ * L) / (∑mcEvtWeight)** and **lepSF= trigSF * idSF * recSF * isoSF.**
- **Background of fake leptons** is estimated with **data-driven matrix method.** It is not fitted. Special weights are calculated for events selected from the data by the LPXMatrixMethod package. Fake leptons bring a **second-large contribution** in total SM background in some regions in **electron channel.** However, this background can be **neglected for muons.**

Normalization in Background-only fit

Fitted background normalization factors in the simultaneous background-only fit of 3 CRs for the electron+jet and muon+jet channels.

Background	electron+jet	muon+jet
$W + jets$	1.009 ± 0.021	1.015 ± 0.014
$Z + jets$	0.992 ± 0.036	0.973 ± 0.032
$t\bar{t}$	0.962 ± 0.061	0.959 ± 0.087