



Institute of High Energy Physics Chinese Academy of Sciences

Seminar at IHEP, Tuesday, Dec. 19, 2017

## **Direct and Indirect Searches of New Physics** at Hadron Colliders

李衡讷

Hengne Li **University of Virginia** 

# Big picture of particle physics today



## The Hierarchy Problem

- \* The Hierarchy Problem:
- \* The large difference between the weak force and gravity.
- \* There is no scientific consensus on why, for example:
- \* Why the weak force is 10<sup>24</sup> times as strong as gravity?
- \* Why the Higgs and weak gauge boson masses are so small?
- \* **Possible solutions**:
- \* Warped extra dimensions: gravity is actually strong, but outside our 3 spacial dimensional world
- **Composite Higgs: the Higgs is not elementary**
- \* SUSY: protecting the Higgs mass by a symmetry





## Warped extra-dimension

- \* Introducing the fourth spacial dimension
- \* Warped: Gravity force is strong near the "gravity brane" while weak near the SM "weak brane".
- \* Key idea explains why gravity is so weak in "our world" (the SM weak brane).
- \* Randall-Sundrum 1 (RS1):
- \* The SM particles confined on the "weak brane".
- \* Only gravitons are allowed to "exist" in the 4th spacial dimension
- \* "Bulk" model:
  - \* Not only gravitons, but also SM particles are allowed to "travel" in the "bulk" in the 4th spacial dimension.



\* When the extra-dimensional graviton travels through the SM "weak brane", it will leave a series (quantized) of "shadows" in our world, the so called "Kaluza-Klein partners" of graviton.

## 3D particle in a 2D world



Hengne Li, 19 Dec. 2017

## Warped extra-dimension

## 4D particle in a 3D world







# Composed Higgs model

- \* Suppose the Higgs not a fundamental particle
- \* But a bound state of a new strong interaction
  - \* Technicolor, at Fermi scale ~ 100 GeV
- \* A bound state just like a pion but bounding the new strong force.
- \* Solves the hierarchy problem
  - \* Brings along new heavy particles/states
- \* Heavy partners of SM particles decay to lighter ones (W, Z, H, top, ...):
  - \* "heavy vector triplet": W', Z', etc.





- \* Direct searches:
- \* Based on a theory hypothesis, looking for excesses in the mass spectrum.
- \* E.g. Heavy Diboson resonance searches
- \* Indirect searches, indirect constraints:
- \* Precisely measure SM properties, compare with SM predictions, looking for differences.
- \* The differences can come for contributions from new particles
- \* E.g. W boson mass measurements









FOR STUEL DURING TO B

# The Large Hadron Collider



SPS\_7 km

CERN Meyrin

CERN Prévessin





## Direct Searches of New Particles

## Direct Search: Heavy Diboson Resonance Search

### **Diboson final states as example.** \*

Channel	V=V	N/Z	Final	states			
γγ	γγ						
Vγ	llγ	Ινγ	qqγ				
VV	41	llvv	llqq	lvqq	vvqq	4q	
VH	llbb	lvbb	vvbb	qqbb	Ινττ	11ττ	qqττ
qV	qqq						





### Heavy Vector Triplet W'/Z'

Hengne Li, 19 Dec. 2017

- **Composed Higgs:** \*\*
  - \* EW composed vector resonances (heavy vector triplet) W' or Z' decay to pairs of W, Z, H
- \* Extra-dimension Gravitons:
  - \* **RS1: decay dominantly to leptons**
  - \* Bulk: decay to pairs of W, Z





### **Bulk Graviton**

## Previous Results

### \* Exhausting all possible final state combinations:

	Channel	V=W	/ <b>Z</b>	Final	states			
	γγ	γγ						
	Vγ	llγ	Ινγ	qqγ				
	Resonances/to heav	y quar <b>ks</b>	llvv	Etdited quark	«slvqq	vvqq	<b>4</b> q	
Z'(1.2%) a→ qW	ectort-fike quark pair production	Resonances	s to heavy guarks/2		actited quarks	Ινττ	ΙΙττ	qqττ
Z'(10%) T→tH T→tZ	tt	Z'(10%) → tt gK <b>C NA 53551 21101655</b>	t* → tg S=1/2	t* → tg S=1/2 b* → tW Kk⊑11 <b>E</b>	wcittedi quuariks	ev		
<sup>-</sup> →bW QqWrqW 3→bHW →TeH++tH	$\rightarrow \text{tb} \xrightarrow{7 \text{ fb}} Z'(\overline{4})$	2.20 AV Tt <sup>th</sup> t 20 AV AV to Besonance:	b* → tW KR <sub>I</sub> =11	pt*	8 T	●V		
3 → bZ → <b>10 M W</b> A 3 → 1W Towt bW	≪MMW/ W' -2	B2G Dibosons	b*.→ tW.K=K===1 action limit [10]		0.4 0.8 1.2 Observed limit 35	1.6 2 ∑C'_ (TeV)		
	/H (H→bb) (model B) (H (H→bb) (model B) (H (H→bb) (model B)		43.8		0.8 1.2 1.6 Wed Jimit 95%CL	2 (TeV)	MS	Results
੶ <i>ᢩ</i> <del>៹</del> ᡖ₩,%) ᠻᠯᢍᠯᡖᡰ₩ <b>ਫ਼</b> ᢩᠯ <b>ᡣ᠋᠑%</b>	Z'→WW(model D) Z'→WW(model A) L2 V w <sup>W</sup> d L2 V w <sup>W</sup> d		32.0 19.5	b* → tWKRan==110 <sup>0</sup> F b* → tWKa∈kKan=1	0.4 0.8 1.2 Observed limit 95 Resonarices vo diboson	1:8 2 &EL (T&V)		[Rof Link]
/3,	Vector-like quase smaller p Z'tt WW (model B) W'→WZ (model B)	ZK 19963-199001 ZZ(8076-1)- t210	14.7 33.8 15.6	radion → HH <sub>0</sub> W' → WH	0.4 0.8 1.2 Observed limit 95 <sup>o</sup>	1.6 2 %CL (TeV)		
	0.3 WZ (filled 19) F2V 1.5 	2'(10)% K→ ttt 0 0.5 1 GKK → tt Obse 2'(30%) → tt2 T	1.5 2 2.5 3.5 17 4 erved limit 95%C1 (下述) 23.0	Resonances @Boullon + WWM radion → HH	to dibosons ons	avy quarks	E)	xcited quarks
Ċ <u>Z</u> Ţ=29000 \$V\$01=155 \$400=155 \$400=155 \$400=155 \$255	tor-like quark single production $\rightarrow$ to 0.6 0.9 1.2 1.5 Observed denta by $7 - \sqrt{2}$	$V \rightarrow 10$ $Z' - gKK \rightarrow 12t$ $T \rightarrow tZt$ $W' \rightarrow tD$	radion → HH 8+13 Te <sup>1/1</sup>	2'(1.2%) → COBAUIk → W252 F W' → WH 4W' - radio 74' → 141H	tt Resonances to dibu 6 fb 13	TeV TeV	t <sup>*</sup> → tg S=3/2 t <sup>*</sup> → tg S=1/2	80 fb 500 fb
	IVT (W'+Z') (model A) 0.5 1 W' (model B)	2'→ Tt → tZt Obs 2'→ Tt → tZt Obser 2.5 3 3.5 4 0 0.5 S⊕a	ervéd limit 95% (140) yed limit 95% (140) 23 2 2 3 3 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	) Z → ZH W' Gbulk → WW GBBulk → WW 4 Z' Gbulk → ZZ	<b>13ºTe</b> 30 fb		$b^* \rightarrow tW  K_L=1$	70 fb
	Z' (model <b>B)</b> served limi	t 95%CL (TeV) Obse neavy		GBebulk → ZZ W'-CEBEWKshHAAT(AM) W'→ VW HVT(B) W'→ CABENNK V+T (237 <sup>0</sup>	<b>20 fb</b> 0.5 1 1.5 2	2.5 3	$* \rightarrow tW K_{L/K_R} = 1$	70 fb
(Wh)=155 (Wh)=1.55 (Wh)=11.55 (Wh)=11.55 (Zh)=11.55 (Zh)=11.55	Observed limit 95%CL (TeV) ()	1.6 1.6 lower mass limit [79]	<sup>2</sup> Ċ <b>G</b> bulk → <sup>3</sup> ZZ	W' → WH HVT(B) WZ'→WWH HVT(B) Z' → VH $HZ$ /(fl(B)) → W' →r2vHi4 de1\ATT(B)	Observed limit 95%Cl	L (TeV)	0	0.4 0.8 1.2 1.6 2 Observed limit 95%CL (TeV)
(V¢b)=1.0 V40=155 )≡1:0 V40)=1.5	0.25 0.5 0.75 1 1.25 1.5		$\rightarrow$ VW HVI(B)	radio $\underline{Z}' \rightarrow VH HVT(B)$ $Z' \rightarrow VH HVT(B)$ 0 $z_{1} = Z'(30\%) \rightarrow 0$	tt 0.5 1 1.5 2 Øðservéd limit <sup>5</sup> 95%@L tt Observed limit 05% Cl	2.5 3 _(TeV⊅) <sup>3</sup>		
V¢by)≡11.90	Observed limit 35%GL (16V)	0.000				-(100)	-	

### X->γγ at ~750 GeV

Sometimes...nature makes jokes. But we can take a joke, and continue to play!



	Model	∫£ dt[fb	<sup>1</sup> ] <b>Limit</b>				
dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\ell\ell$ ADD QBH $\rightarrow \ell q$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \ell\ell$	3.2 20.3 20.3 15.7 3.2 3.6 20.3	Mp         6.58 TeV           Ms         4.7 TeV           Mth         5.2 TeV           Mth         8.7 TeV           Mth         8.2 TeV           Mth         9.55 TeV           Gyr, mass         2.68 TeV	AT	Pre LAS	vic 5 R	ous esults
Extra c	RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$ Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$ Bulk RS $g_{KK} \rightarrow HH \rightarrow bbbb$	3.2 13.2 13.3	G <sub>KK</sub> mass         3.2 TeV           G <sub>KK</sub> mass         1.24 TeV           G <sub>KK</sub> mass         260-860 GeV				[Ref. Link]
	2UED / RPP	3.2	KK mass 1.46 TeV	√s = 8 TeV	√s = 13	3 TeV	95% CL Exclusion
su	$\begin{array}{l} \text{SSM } Z' \to \ell\ell \\ \text{SSM } Z' \to \tau\tau \end{array}$	13.3 19.5	Z' mass         4.05 TeV           Z' mass         2.02 TeV		∫∫ dt[fb <sup>_1</sup> ]		l imit
osoq	Leptophobic $Z' \rightarrow bb$ SSM $W' \rightarrow \ell v$	3.2 13.3	Z' mass 1.5 TeV W' mass 4.74 TeV	Excited quark $q^*$ Excited quark $q^*$	$\rightarrow q\gamma$ 3.2 $\rightarrow q\sigma$ 15.7	q* mass	4.4 TeV
nge	HVT $W' \rightarrow WZ \rightarrow qqvv \text{ model A}$ HVT $W' \rightarrow WZ \rightarrow qqqq \text{ model B}$	A 13.2 B 15.5	W mass 2.4 TeV W mass 3.0 TeV	Excited quark q	$\rightarrow bg$ 8.8	b* mass	2.3 TeV
Ga	HVI $V' \rightarrow WH/ZH$ model B LRSM $W'_R \rightarrow tb$	n 3.2 20.3	V' mass 2.31 TeV W' mass 1.92 TeV	Excited quark $b^*$	$\rightarrow VVt$ 20.3 20.3	b* mass l* mass	1.5 IEV 3.0 TeV
	LRSM $W'_R \to tb$	20.3	W mass         1.76 TeV           10 <sup>-1</sup> 1         Mass scale [TeV]         10	Excited lepton v*	20.3	$v^*$ mass $10^{-1}$	1.6 TeV







### **Observable:**

system





. 5.0 Data

### \* Background modeling

\* Z+Jets:



\* using the side-band outside the Z mass window to get the absolute yields

Hengne Li, 19 Dec. 2017

800 1000 1200 1400 600  $p_{T}(Z)$  (GeV)

Grav.->ZZ->2l2nu, CMS

### **Muon Channel for example**

Data

0.5

ZpT

MET

600

g

800





Hengne Li, 19 Dec. 2017





Hengne Li, 19 Dec. 2017



## Results summary from all channels at CMS



# Discussion of the discovery potential

effect at around 2 TeV. A discovery potential adding up 2017-2018 datasets (120/fb)!



Hengne Li, 19 Dec. 2017

\* ATLAS VV at 13 TeV hasn't come out yet. Compare ATLAS @ 8 TeV and CMS @ 13 TeV, both show a 2-sigma



17



# Discussion of the discovery potential

- \* Compare CMS VV all-hadronic and ZZ->2l2nu at 13 TeV, advantage of ZZ->2l2nu:
- \* Can look at the mass region below 1 TeV, because of low background suppressed by MET
- Current 2016 dataset (36/fb) still has low statistics at ~ 900 GeV (~ 2-sigma effect), potential discovery point adding up 2017-2018 datasets (120/fb)!
- Current 2016 dataset (36/fb) has no data events yet at 2 TeV, if all-hadronic signature is real, adding up 2017-2018 datasets (120/fb) + low background, ZZ->2l2nu will have higher sensitivity at 2 TeV!



Hengne Li, 19 Dec. 2017



## Indirect Searches, Constraints on New Particles



# Indirect Search: Precisely measure SM properties

- \* Precisely measure SM properties, compare with SM predictions, looking for differences.
- \* The differences can come for contributions from new particles.
- \* Giving a particular new theoretical model, the difference can be translated to the upper limits of the new theory.



Under current plan, LHC will not go above 14 TeV. If no new physics discovered directly, indirect constraints can probe new physics at much higher energy scale!

Hengne Li, 19 Dec. 2017

## **Pull plot of SM global fit**

### M<sub>H</sub> 0.0 Mw -1.2 $\Gamma_{W}$ 0.2 Mz 0.2 $\Gamma_{z}$ 0.1 $\sigma_{had}^{0}$ -1.7 $R_{lep}^{0}$ -1.1 $A_{FB}^{0,I}$ -0.8 A<sub>I</sub>(LEP) 0.2 A<sub>I</sub>(SLD) -1.9 sin<sup>2</sup>⊖<sup>lept</sup><sub>eff</sub>(Q<sub>FB</sub>) -0.7 0.0 Ac 0.6 A A<sup>0,c</sup><sub>FB</sub> 0.9 $\mathbf{A}_{\mathsf{FB}}^{0,\mathsf{b}}$ 2.5 $R_c^0$ 0.0 $\mathbf{R}_{b}^{0}$ -2.4 **m**<sub>c</sub> 0.0 0.0 m m, 0.4 $\Delta \alpha_{had}^{(5)}(M_z^2)$ -0.1 -2 -1 0 1 2 3

(**O**<sub>fit</sub> - **O**<sub>meas</sub>) / σ<sub>meas</sub> Eur. Phys. J. C (2012) 72:2205





## The W mass measurements

\* The Standard Model (SM) predicts a relationship \* Precisely test the electroweek theory at the between the W boson mass and other parameters of loop level. electroweak theory:

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Contributions to MW through radiative corrections  $\Delta r$ . \*



Hengne Li, 19 Dec. 2017

W mass related to SM Higgs mass:  $\Delta r \propto \ln M_H$ e.g.  $\sim \sim \sim$ W W

- \* In case of SM, the precise W mass and top mass measurements can predict the SM Higgs boson mass.  $\sim$
- By comparing the prediction and direct Higgs mass measurement, we can know how good is the SM prediction. If disagreement is big, we can infer contributions from theories beyond SM

**Beyond SM, contribution from SUSY particles can** induce a total radiative correction to M<sub>W</sub> of 100 to 200 MeV.

W



W

## The W mass measurements



A difference of ~1.3 sigma.

The difference can come from new particles interacting with the SM bosons (Higgs, W, Z). Giving a particular new theoretical model, the difference can be translated to the upper limits of the new theory.

Hengne Li, 19 Dec. 2017

### $M_W = 80356 \text{ MeV} \pm 8 \text{ MeV}$ $M_W = 80385 MeV \pm 15 MeV$ Predicted Measured $\Delta\chi^2$ and M<sub>u</sub> measurements SM fit with minimal input – M<sub>w</sub> world average [arXiv:1204.0042] 80.33 80.34 80.35 80.36 80.37 80.38 80.39 80.4 80.41 M<sub>w</sub> [GeV]

A ~1.3 sigma difference between the two M<sub>W</sub> central values.





## A combined Tevatron+LHC effort LHC

### **Tevatron** pp interaction, 1.96 TeV



d and ū mostly from valence quarks

### **D0**

### CDF

**Integrated Luminosity** used 5.3 /fb electron channel lepton letal<1.05

**Results:** 80375 +- 23 MeV PRL 108 (2012) 151804 **Integrated Luminosity** used 2.2 /fb electron and muon channels lepton letal<1.0

**Results:** 80387 +- 19 MeV PRL 108 (2012) 151803

Hengne Li, 19 Dec. 2017

### pp interaction, 7 TeV, 8 TeV, 13 TeV



d and ū mostly from sea quarks

ATLAS **Integrated Luminosity** used: 4.1 /fb at 7 TeV electron and muon channels lepton letal<2.4 **Results:** 80370 +- 19 MeV ArXiv: 1701.07240 (2017) submitted to EPJC

### CMS

**Integrated Luminosity** being used: 4.1 /fb at 7 TeV

electron and muon channels **Results:** work is on going







## Analysis strategy in a nutshell



### D0/CDF

- PDF: CTEQ6.6
- Event generators:
  - **RESBOS**:
    - generates only W/Z with
      - ISR correction
  - Photos: FSR
- Parametrized Fast Simulation:
  - 1.) Hadronic Recoil: generated by smearing the W/Z true pT (from RESBOS) directly to get the
  - 2.) all detector effects of leptons, such as energy scale and efficiency

Hengne Li, 19 Dec. 2017



• **QCD corrections: NNLL gluon resummation (for low pT) and perturbation (for high pT)** 

reconstructed recoil including detector effects, (no parton shower, no hadronization intermediate steps).

# Parametrized Detector Model (D0/CDF)

### The parametrized detector model has to simulate:



- Lepton energy response and smearing
- Hadronic recoil energy response and smearing
- Underlying energy:
  - additional ppbar interactions (pileup):
    - average number of primary vertices:
  - spectator parton interactions
- Lepton selection efficiency
- Background

### Hengne Li, 19 Dec. 2017

**CDF** ~ 2; **D0** ~ 4

# Energy gain due to pileup Challenge in Run IIb analy

### **Electron Model:**

 $E_{reco} = R_{EM}(E_{true}) \bigotimes_{\text{Resolution}} \sigma_{EM}(E_{true}) + \sum_{\text{Energy contamination}} E_{corr}$ 

### $\Delta E_{corr}$ Model:

- **1. Energy loss due to FSR**
- 2. Recoil, spectator partons interactions and pileup contamination inside the electron reconstruction cone
- **3. Effects due to electronics noise subtraction and** baseline subtraction (to subtract residue energy deposition from previous bunch crossings)

Hengne Li, 19 Dec. 2017



Hard Recoil. spectator parton interactions, and pile-up electron





## Final electron energy scale

$$R_{EM}(E_{true}) = \alpha \cdot (E_{true})$$

### Essentially, measuring the ratio M<sub>W</sub>/M<sub>Z</sub>, limited by the Z->ee statistics

Scale and offset are determined in 4 inst. lumi. bins



Hengne Li, 19 Dec. 2017

After the correction and modeling of the non-linear energy responses, the final electron energy response is calibrated using Z->ee events assuming a linear response:

 $E_{true} - \overline{E}_{true}) + \beta + \overline{E}_{true}$ 

Fit back to determine the Z mass:

## Hadronic recoil modeling

### fast Sim: Recoil Re D0/CDF recoil model:



"pure" Hard Recoil balancing W or Z boson



Hengne Li, 19 Dec. 2017

Soft Recoil: pileup and spectator parton interactions

Recoil energy that falls in the electron reconstruction window, as well as electron energy leakage to the recoil. FSR photons that fly outside the electron reconstruction window.



Source	$\sigma(m_W)  { m MeV}  m_T$	$\sigma(m_W)  { m MeV}  p_T^e$	$\sigma(m_W) \operatorname{MeV} \not\!\!E_T$
Experimental			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Energy Nonlinearity	4	6	7
W and $Z$ Electron energy	4	4	4
loss differences			
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
Experimental Total	18	20	24
W production and			
decay model			
PDF	11	11	14
QED	7	7	9
Boson $p_T$	2	5	2
W model Total	13	14	17
Total Systematic Uncertainty	22	24	29

Z->ee MJ										
 <sup>55</sup> p <sub>T</sub> <sup>e</sup> , GeV										
Results fr	om A'	ΓL	AS:							
$m_W = 8$ = 8	30369.5 ± 30369.5 ±	= 6.8 N = 18.5	MeV(sta MeV,	ıt.) ±	10.6 Me	V(exp.	syst.)	± 13.6	MeV(1	mod.
Combined categories $m_{\rm T}$ - $p_{\rm T}^{\ell}$ , $W^{\pm}$ , e- $\mu$	Value [MeV] 80369.5	Stat. Unc. 6.8	Muon Unc. 6.6	Elec. Unc. 6.4	Recoil Unc. 2.9	Bckg. Unc. 4.5	QCD Unc. 8.3	EWK Unc. 5.5	PDF Unc. 9.2	Total Unc. 18.5

### **Results from CDF:**

Method $(2.2 f b^{-1})$	$M_W$ (MeV)
$m_T(e, u)$	$80408 \pm 19$ (stat)
$p_T(e)$	$80393 \pm 21 (stat)$
${\not\!\! E}_T(e,\nu)$	$80431 \pm 25 (\text{stat})$
$80387 \pm 19 Me$	V(syst + stat)

Electrons	Mu
10	
4	
5	
7	
0	
3	
4	
3	
10	1
4	
18	1
	Electrons 10 4 5 7 0 3 4 3 4 3 10 4 3 10 4 18

















**Including the new ATLAS results, the new world** average should be around 80379 +- 12 MeV [Not official, based on self-running the **combination codes.**]



- \* Direct searches for "bumps":
  - \* Based on a theory hypothesis, looking for excesses. E.g. Heavy diboson resonance search.
- \* Indirect searches, constraints on new physics:
- \* Discussion, if LHC is not go above 14 TeV:

  - **Effective Field Theory framework.**

Summary/Outlook

\* This talk gives an overview of the ways we search for new physics at Hadron colliders (LHC, Tevatron)

\* Precisely measure SM properties, compare with SM predictions, looking for differences. E.g. W mass.

\* Indirect constraints from precision measurements will become more important at LHC experimentally.

\* In principle, the difference between measured and predicted values of SM parameters can be "translated" to the upper limits of a given new theory hypothesis. But it is much less straight forward than direct searches.

\* More theoretical developments are expected to interpret the SM measurements, such as a general SM



# Backup Slides

## MC Simulation (generate templates for fitting to the data to extract W mass)

## ATLAS

- PDF: CT10nnlo
- Event generators:
  - Powheg:
    - W/Z

- $d\sigma$  $dp_1 dp_2$ **Breit-Wigner**
- **QCD/ISR/FSR corrections:** hadronic recoil parton showers
- Pythia8:
  - parton shower hadronization tuned to 7 TeV Z data
- Note:
  - pT + perturbation for high boson pT) to do things in one single shot.
  - ATLAS found the NNLL gluon resummation shows a big disagreement with the data.

Hengne Li, 19 Dec. 2017



• Powheg does not use RESBOS' technique (the 'partial' function of NNLL gluon resummation for low boson • GEANT4 Full detector simulation of all detector effects including both the leptons and the hadronic recoil



# Lepton energy scale at ATLAS/CMS

CMS: calibrate muon curvature ( $k=1/p_T$ ) using J/ $\psi$  (dominates the precision) & Y ATLAS: calibration of ID muons using Z Eur.Phys.J.C 74 (2014) 3130




# Hadronic recoil modeling





"pure" Hard Recoil balancing W or Z boson

Z ₱<sub>T</sub> hadronic recoil

Soft Recoil: pileup and spectator parton interactions

Hengne Li, 19 Dec. 2017

 $\vec{u}_T = \vec{u}_T^{\text{Hard}} + \vec{u}_T^{\text{Soft}} + \vec{u}_T^{\text{Elec}} + \vec{u}_T^{\text{FSR}}$ 

**Recoil energy that** falls in the electron reconstruction window, as well as electron energy leakage to the recoil. FSR photons that fly outside the electron reconstruction window.

ATLAS: vector sum of the momenta of all clusters measured in the calorimeters

full Sim:

**CMS**: vector sum of the particle flow charged hadrons, loss in recoil response but more robust against pile-up





D0 4.3 fb<sup>-1</sup>, e-channel

Source	$\sigma(m_W) { m MeV} m_T$	$\sigma(m_W)  { m MeV}  p_T^e$	$\sigma(m_W) \mathrm{MeV} E_T$		M	Г	PT(	)	MF
Experimental							(-	-	
Electron Energy Scale	16	17	16	Systematic (MeV)	Electrons	Muons	Electrons	Muons	Electrons
Electron Energy Resolution	2	2	3						
Electron Energy Nonlinearity	4	6	7	Lepton Energy Scale	10	7	10	7	10
W and $Z$ Electron energy	4	4	4	Lepton Energy Resolution	4	1	4	1	7
loss differences				Recoil Energy Scale	5	5	6	6	2
Recoil Model	5	6	14	Recoil Energy Resolution	7	7	5	5	11
Electron Efficiencies	1	3	5	Ffficioney		0	2	1	2
Backgrounds	2	2	2		0	0	2		J C
Experimental Total	18	20	24	Lepton Removal	3	2	0	0	0
W production and				Backgrounds	4	3	3	5	4
decay model				$p_T(W)$ Model $(g_2, g_3, \alpha_s)$	3	3	9	9	4
PDF	11	11	14	Parton Distributions	10	10	9	9	11
QED	7	7	9	QED Radiation	4	4	4	4	4
Boson $p_T$	2	5	2	Total	18	16	19	18	22
W model Total	13	14	17						
<b>Total Systematic Uncertainty</b>	22	24	29						

#### Hengne Li, 19 Dec. 2017

# es at D0/CDF

### CDF 2.2 fb-1, e- and µ-channels



# Systematic uncertainties at ATLAS

									=
	W-boson charge			W	r+	W	-	Com	oined
	Kinematic distri	bution		$p_{\mathrm{T}}^\ell$	$m_{\mathrm{T}}$	$p_{\mathrm{T}}^\ell$	$m_{\mathrm{T}}$	$p_{\mathrm{T}}^\ell$	$m_{\mathrm{T}}$
	$\delta m_W  [{ m MeV}]$								
	Fixed-order P	DF uncertainty		13.1	14.9	12.0	14.2	8.0	8.7
	AZ tune			3.0	3.4	3.0	3.4	3.0	3.4
	Charm-quark	mass		1.2	1.5	1.2	1.5	1.2	1.5
	Parton shower	$\mu_{\rm F}$ with heavy-flavour decorre	elation	5.0	6.9	5.0	6.9	5.0	6.9
	Parton shower	PDF uncertainty		3.6	4.0	2.6	2.4	1.0	1.6
	Angular coeffi	cients		5.8	5.3	5.8	5.3	5.8	5.3
	Total			15.9	18.1	14.8	17.2	11.6	12.9
		Decay channel	W -	$\rightarrow ev$	W -	$\rightarrow \mu \nu$	-		
		Kinematic distribution	$p_{\mathrm{T}}^\ell$	$m_{\mathrm{T}}$	$p_{\mathrm{T}}^\ell$	m <sub>T</sub>			
		$\delta m_W$ [MeV]					_		
EW		FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1			
		Pure weak and IFI corrections	3.3	2.5	3.5	2.5			
		FSR (pair production)	3.6	0.8	4.4	0.8			
		Total	4.9	2.6	5.6	2.6	_		



Resul	lts	from	<b>CDF</b> :

Method $(2.2 f b^{-1})$	$M_W$ (MeV)	Method $(2.2 f b^{-1})$	$M_W$ (M
$m_T(\mu, u)$	$80379 \pm 16$ (stat)	$m_T(e, u)$	$80408 \pm 19$
$p_T(\mu)$	$80348 \pm 18$ (stat)	$p_T(e)$	$80393 \pm 21$
	$80406 \pm 22$ (stat)	$\not E_T(e,\nu)$	$80431 \pm 25$
Combination	$(2.2 f b^{-1})$	$80387 \pm 19Me$	V(syst + state)

# Results ATLAS



Combined	Value	Stat.	Muon	Elec.	Recoil	Bckg.	QCD	EWK	PDF	Tota
categories	[MeV]	Unc.	Unc.	Unc.	Unc.	Unc.	Unc.	Unc.	Unc.	Unc
$m_{\mathrm{T}}$ - $p_{\mathrm{T}}^{\ell}$ , $W^{\pm}$ , e- $\mu$	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.

# The observables



Hengne Li, 19 Dec. 2017

42

# a hot topic discussed at Moriond EW 2017, to be followed QCD corrections (ATLAS)

### rapidity and angular coefficients prediction have been validated

#### **Rapidity and angular coefficients**

The rapidity distribution and Ai coefficients are modelled with NNLO predictions and the CT10nnlo PDF set. PDF choice validated on the observed weaker suppression of the strange quark in the W,Z cross-section data as published in <u>arXiv:1612.03016</u>



## slides from Moriond EW 2017 W mass talk

#### Hengne Li, 19 Dec. 2017

### parton shower Pythia tuned to Z data

#### Z transverse momentum

Parton shower MC Pythia 8 tuned to the 7 TeV data AZ tune (better description in rapidity bins than the AZNLO tune of Powheg+Pythia) JHEP09(2014)145

	Pythia8
Tune Name	AZ
Primordial $k_{\rm T}$ [GeV]	$1.71\pm0.03$
ISR $\alpha_{\rm S}^{\rm ISR}(m_Z)$	$0.1237 \pm 0.00$
ISR cut-off $[GeV]$	$0.59 \pm 0.08$
$\chi^2_{\rm min}/{ m dof}$	45.4/32

The agreement between data and Pythia AZ is better than 1% for  $p_T < 40$  GeV



The accuracy of Z data is propagated and considered as an uncertainty

<i>W</i> -boson charge Kinematic distribution		$p_{\mathrm{T}}^\ell$	$W^+ p_{\mathrm{T}}^\ell m_{\mathrm{T}}$		$W^-$ $p_{\rm T}^\ell m_{\rm T}$		Combined $p_{\rm T}^{\ell} m_{\rm T}$	
	AZ tune	3.0	17 <sup>3.4</sup>	3.0	3.4	3.0	3.4	



# a hot topic discussed at Moriond EW 2017, to be followed QCD corrections (ATLAS)

### But ATLAS found NNLL gluon resumation doesn't predict the data well

#### W transverse momentum

The Pythia8 AZ tune is fixed by the  $p_T^Z$  data; extrapolate to W considering relative variations of the W and Z  $p_T$  distributions under uncertainty variations.

Resummed predictions (DYRES, ResBos, CuTe) and Powheg MiNLO+Pythia8 were tried but they predict a harder W  $p_T$  spectrum for a given  $p_T^Z$  spectrum

Phys.Rev.D 50 (1994) R4239, Phys.Rev.D 56 (1997) 5558-5583, JHEP12 (2015) 047, JHEP03 (2011) 032, JHEP10 (2012) 155, JHEP05 (2013) 082...

To validate the choice of Pythia8 AZ for the baseline, use  $u_{II}$  distribution which is very sensitive to the underlying  $p_T$ <sup>W</sup> distribution

NNLL resummed predictions and Powheg+MiNLO strongly disfavoured by the data however PS MC are in a good agreement; tested using Pythia8 , Herwig7 and Powheg+Pythia8



### slides from Moriond EW 2017 W mass talk

18

Hengne Li, 19 Dec. 2017

### **Understanding and uncertainties**

#### **p**<sub>T</sub><sup>w</sup> uncertainties

**Heavy flavour initiated production** (HFI) introduces differences between Z and W and determines a harder pT spectrum, expect certain degree of decorrelation.

However higher-order QCD expected to be largely correlated between W and Z produced by light quarks

Uncertainty: heavy quark mass variations (varying  $m_c$  by  $\pm 0.5$  GeV), factorisation scale variations in the QCD ISR (separately for light and heavy-quark induced production)

Largest deviation of  $p_T(W)/p_T(Z)$  for the parton shower PDF variation: CTEQ6L1 LO (nominal) to CT14lo, MMHT2014lo and NNPDF2.3lo



W-boson charge	W	<b>/</b> +	V	$V^{-}$	Cor	nbined
Kinematic distribution	$p_{\mathrm{T}}^\ell$	$m_{\mathrm{T}}$	$p_{\mathrm{T}}^{\ell}$	$m_{\mathrm{T}}$	$p_{\mathrm{T}}^{\ell}$	$m_{\mathrm{T}}$
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower $\mu_{\rm F}$ with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
10						

19

W/Z pt ratio measurements can reduce this uncertainty



# The Large Hadron Collider

SUISSE

FRANCI

CMS

CERN Prévessin

ATLAS

SPS 7 km

LHC 27 km



# **CMS** Detector



#### Hengne Li, 13 Dec. 2017

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

> PRESHOWER Silicon strips  $\sim 16m^2 \sim 137,000$  channels

FORWARD CALORIMETER Steel + Quartz fibres ~2,000 Channels

![](_page_45_Picture_7.jpeg)

![](_page_45_Picture_8.jpeg)

![](_page_46_Figure_0.jpeg)

![](_page_46_Picture_2.jpeg)

![](_page_46_Picture_3.jpeg)

# W'/Z'->VH->di-jets

![](_page_47_Figure_2.jpeg)

#### Hengne Li, 19 Dec. 2017

Event display

# **Grav->ZZ->21 + MET**

	V-jet
$p_{\mathrm{T}}$	1962 GeV
η	-0.65
φ	-2.30
m <sub>i</sub>	72.8 GeV
$ au_{21}$	0.49

CMS Experiment at LHC, CERN Data recorded: Fri Aug 5 02:45:13 2016 CEST Run/Event: 278239 / 427634038

![](_page_47_Figure_8.jpeg)

# **CMS** Particle Flow Algorithm

- \* The Particle Flow Algorithm (PFA) combining the information from all the sub-detectors.
- \* Using the 4-momentum that measured from most precise subdetectors.
- \* Reconstruct and identify final states particles:
  - \* Result in a collection of PF objects of different types
  - \* Just like the MC true particle list out from the event generator =>

![](_page_48_Picture_6.jpeg)

Muon

![](_page_48_Figure_9.jpeg)

# **Sequential Elig** Jet and MET reconstruction

- \* Jet reconstruction:
- \* Based on the following distance measures
  - \* distance d<sub>ij</sub> between two particles i and j:
- \* distance between any particle i and the beam (B) d<sub>iB</sub>
- \* Compute all distances d<sub>ij</sub> and d<sub>iB</sub>, find the smallest:
- \* if smallest is a  $d_{ij}$ , combine (sum 4-momenta)  $d_{bB}t \overline{w}o h p r t i cles i and j,$ update distances, proceed finding next smallest
- \* if smallest is a d<sub>iB</sub>, remove particle i, call it a jet
- \* Repeat until all particles are clustered into jet
- **\* MET reconstruction:** 
  - \* Inverse vectorial sum of all Particle Flow objects 4-momenta

Hengne Li, 19 Dec. 2017

![](_page_49_Picture_13.jpeg)

 $d_{ij} = \min$ 

$$d_{iB} = k_{\mathrm{T}i}^{2p}$$

![](_page_49_Picture_17.jpeg)

![](_page_49_Picture_20.jpeg)

# Jet Reco/Grooming Algorithms

- \* Boosted large-R jets (R=0.8 or 1.0) can be easily contaminated by pileup interactions.
- "Grooming" is to remove those pileup contaminations, to achieve stronger discrimination power for boosted jets.
- \* CMS:
- PUPPI [1] algorithm: pileup mitigation algorithm identifying and assigning small weights to the pileup particles served as input to jet clustering.
- \* **Softdrop [2] algorithm:** dropping soft jet constitution particles.

The V-jets tagging variables and V/H-jet mass are calculated based on the groomed jets.

Hengne Li, 19 Dec. 2017

[1] JHEP10(2014)059.
[2] JHEP09(2013)029, JHEP05(2014)146,
[3] JHEP02(2010)084,
[4] ATLAS-CONF-2016-035

![](_page_50_Picture_9.jpeg)

#### \* ATLAS:

- Trimming [3] algorithm: re-cluster sub-jets with R=0.2 cone, and remove sub-jets with p<sub>T</sub><sup>subjet</sup> / p<sub>T</sub><sup>jet</sup> < 0.05</li>
- \* New algorithm to calculate jet mass by combining calo-jet mass and track-jet mass [4].

![](_page_50_Picture_14.jpeg)

# Tagging Boosted W/Z/H Jets

- \* Boosted W/Z-jets have intrinsic sub-jet structure difference w.r.t. QCD jets
  - \* The goal is to distinguish:
  - \* W/Z jets (2-prong) vs. QCD q/g jets (1-prong)
  - \* Sub-jet structure discriminators:
    - \* ATLAS: D<sub>2</sub>, energy correlation ratio [1]
    - \* CMS: τ<sub>21</sub>, N-subjettiness [2]
- \* Boosted H-jets tagging:
- \* ATLAS: b-tagging on ghost associated anti-kt track-jets with R = 0.2 [3]
- \* CMS: "double b-tagger" [4], dedicated discriminator to identify a pair of b quarks in a single jet.

Hengne Li, 19 Dec. 2017

![](_page_51_Picture_11.jpeg)

[1] ArXiv:1305.0007, 1409.6298; JHEP 05 (2016)117, etc.
[2] CMS-PAS-JME-16-003, JHEP03(2011)015
[3] ATL-PHYS-PUB-2015-035,
[4] CMS-PAS-BTV-15-002

#### **boosted W/Z jet keeps the 2-prong sub-structure even after the boost**

QCD q/g jet 1-prong signature

#### W/Z jet 2-prong signature

![](_page_51_Figure_16.jpeg)

![](_page_51_Figure_18.jpeg)

# New ATLAS/CMS 2016 full dataset results!

### **Only full hadronic** channel results come out so far.

The Grav.->ZZ->2l2nu results from CMS have been approved already, to be made public soon. Will present the method today, but the results still cannot be shown in public today.

Hengne Li, 21 March 2017

Hengne Li, 19 Dec. 2017

![](_page_52_Picture_6.jpeg)

![](_page_52_Picture_7.jpeg)

![](_page_52_Picture_8.jpeg)

52nd Rencontres de Moriond EW 2017

# Search for Heavy Resonance Decaying in Diboson with 13 TeV data

### Hengne Li

(University of Virginia) on behalf of the CMS and ATLAS collaborations

1

52nd Rencontres de Moriond EW 2017

![](_page_52_Picture_15.jpeg)

# VV/VH all hadronic analysis summary

all-hadronic	VH ATLAS	VH CMS	VV/qV CMS				
	ATLAS-CONF-2017-018	CMS-PAS-B2G-17-002	CMS-PAS-B2G-17-001				
Observable	Invari	ariant mass of di-jet system					
Large-R ("Fat") jet reco.	anti-kt jets with R=1.0	anti-kt jets	with R=0.8				
Jet grooming	"trimming" algorithm	"PUPPI" + "softd	lrop" algorithms				
V-tagging	sub-jets energy correlation ratio (D <sub>2</sub> )	N-subjettiness ( $\tau_{21}$ )					
H-tagging	1 or 2 track-jet b-tagging	"double b-tagger"					
		Lepton Veto					
	MET<150GeV or $\Delta \phi$ (MET,H) < 2/3 · $\pi$	MET<2	50 GeV				
<b>Event selection</b>	two large-R jets with  η <2.0, leading mass jet is H-jet: p <sub>T</sub> > 450 GeV, subleading is V-jet: p <sub>T</sub> > 250 GeV	two large-R jets with p <sub>T</sub> > 200 GeV and  η <2.4	two large-R jets with $p_T > 200$ GeV and $ \eta  < 2.5$				
	W/Z/H-jets fall in corresponding jet mass windows						
	75 < M(H-jet)< 145 GeV p <sub>T</sub> -dependent V-jet mass windows	mutually exclusive W/Z/H jet mass windows: 65 < M(W-jet) < 85 < M(Z-jet) < 105 < M(H-jet)< 135 GeV					
	$ \Delta y_{jj}  < 1.6$	Δη <sub>jj</sub>	< 1.3				

# **ATLAS-CONF-2017-018**

# New **Results!**

- \* Two categories: 1-btag and 2-btag
- \* Background modeling

Hengne Li, 13 Dec. 2017

- \* ~90% multijets, ~10% ttbar, <1% V-jets
- corrections: extracted from sidebands.

![](_page_54_Figure_8.jpeg)

VH, all hadronic, ATLAS

![](_page_54_Picture_10.jpeg)

#### **Verify background prediction in VR-SR regions** 2-btag category **1-btag category**

![](_page_54_Figure_13.jpeg)

m<sub>JJ</sub> [GeV]

# New **Results!**

# **ATLAS-CONF-2017-018**

# VH, all hadronic, ATLAS

- \* Exclusion of HVT Model B(A) mass window 1.10 2.5(2.4) TeV for WH, and 1.10 2.6(2.3) TeV for ZH.
- Largest excess at ~ 3.0 TeV with a local significance of 3.3  $\sigma$  and a global significance of 2.2  $\sigma$ .

![](_page_55_Figure_5.jpeg)

![](_page_55_Picture_8.jpeg)

# New Results!

# VH, all hadronic, CMS

- \* Event categorization (8 categories in total)
  - \* **V-jet mass:** W (65<m<sub>j</sub><85 GeV) or Z (85 < m<sub>j</sub> < 105 GeV)
- \* V-jet  $\tau$ 21: high purity ( $\tau_{21}$ <0.35), low purity (0.35< $\tau_{21}$ <0.75) \* Fit to the data using an empirical function
- \* H-jet b-tag: tight (H<sub>bb</sub>>0.9), loose (0.3<H<sub>bb</sub><0.9)

![](_page_56_Figure_6.jpeg)

Hengne Li, 13 Dec. 2017

# **CMS-PAS-B2G-17-002**

![](_page_56_Figure_9.jpeg)

- \* Background modeling
- \* Multijets (dominant), tt, V-jets
- \* Fisher-test CL 10% to decide the number of parameters

![](_page_56_Figure_13.jpeg)

Predicted background for category [Z mass, low purity, loose b-tag]

![](_page_56_Picture_16.jpeg)

# New **Results!**

# VH, all hadronic, CMS

![](_page_57_Figure_5.jpeg)

# New **Results!**

- \* Event categorization
- \* V-jet mass: W (65<m<sub>j</sub><85 GeV) or Z (85 < m<sub>j</sub> < 105 GeV  $_{i}$  r technologie
- \* V-jet  $\tau$ 21: high purity ( $\tau_{21}$ <0.35), low purity (0.35< $\tau_{21}$ <0.75) \* Fit to the data using an empirical
- \* 6 categories for VV: \* (WW/WZ/ZZ) x (low/high purity) \* 4 categories for qV: \*  $(W/Z) \times (low/high purity)$

![](_page_58_Figure_7.jpeg)

![](_page_58_Figure_9.jpeg)

Hengne Li, 13 Dec. 2017

![](_page_58_Figure_11.jpeg)

### Background modeling

- \* Multijets (dominant), tt, V-jets
- - \* Fisher-test CL 10% to decide the

![](_page_58_Figure_16.jpeg)

#### W or Z mass categories 35.9 fb<sup>-1</sup> (13 TeV) Events / 100 GeV 1 ( GeV CMS 🔶 CMS data - W (G<sub>Bulk</sub>→ WW (Madgraph)) Preliminary / 100 2 par. background fit − Z (G<sub>Bulk</sub>→ ZZ (Madgraph)) ····· G(2 TeV)→WW (σ = 0.020 pb) — W (Z' $\rightarrow$ WW (Madgraph)) Events -----Z (W $\rightarrow$ WZ (Madgraph)) 10<sup>3</sup> WW, high-purity ----- 1.0 TeV -4.0 TeV lηl ≤ 2.5, p<sub>⊤</sub> > 200 GeV Z mass M<sub>ii</sub> > 1050 GeV, l∆η<sub>ii</sub>l ≤ 1.3 10<sup>2</sup> 10 10 2 :=I :=I <u>Data-F</u> σ<sub>data</sub> 120 100 PUPPI softdrop mass (GeV) 1500 2000 2500 Dijet invariant mass (GeV) 35.9 fb<sup>-1</sup> (13 TeV) 59 > <sup>10°</sup> > <sup>10°</sup>

![](_page_58_Picture_18.jpeg)

CNAC

## **CMS-PAS-B2G-17-001** New VV, qV, all hadronic, CMS **Results!**

\* Excluded HVT Model B for mass regions 1.0-3.6 TeV for WH, and 1.0-2.7 TeV for ZH.

![](_page_59_Figure_2.jpeg)

Hengne Li, 13 Dec. 2017

![](_page_60_Picture_0.jpeg)

#### \* Compatible with SM, and no exclusion above 1 TeV yet for Bulk Graviton model with $\tilde{k} = 0.5$

![](_page_60_Figure_2.jpeg)

Hengne Li, 13 Dec. 2017

# CMS-PAS-B2G-17-001

VV, qV, all hadronic, CMS

# New **Results!**

# **CMS-PAS-B2G-17-001**

# VV, qV, all hadronic, CMS

\* Excluded excited quark model q\*->qV for mass regions 1.0-5.0 TeV for qW, and 1.0-4.8 TeV for qZ.

![](_page_61_Figure_4.jpeg)

# **ATLAS-CONF-2017-018**

# New Results!

# VH, all hadronic, ATLAS

#### Z'->ZH, Data vs. Background Prediction, for two categories 2-btag and 2-btag

![](_page_62_Figure_4.jpeg)

![](_page_62_Figure_5.jpeg)

![](_page_63_Figure_0.jpeg)

![](_page_63_Figure_2.jpeg)

# New

![](_page_64_Figure_3.jpeg)

Henş

![](_page_64_Figure_6.jpeg)

# New **Results!**

# VH, all hadronic, ATLAS

**Empirical function to describe the mutijets background** 

 $f_{\text{Multijet}}(x) = p_a(1)$ 

$$f_{t\bar{t}}^{1-\text{tag}}(x) = p_d(1-x)^{p_e} x^{p_f}, \text{and}$$
$$f_{t\bar{t}}^{2-\text{tag}}(x) = p_g e^{-p_h x}$$

Hengne Li, 13 Dec. 2017

## **ATLAS-CONF-2017-018**

$$-x)^{p_b}(1+x)^{p_cx},$$

#### **Empirical function to describe the ttbar background**

# New Results! VH, all hadronic, CMS \* The combined V' (W'/Z')->VH limits excluded mass ranges from 1.00–2.66(2.51) and 2.72(2.80)–3.39(3.26) TeV in model B(A)

![](_page_66_Figure_2.jpeg)

# New Results!

tau21

# VH, all hadronic, CMS

![](_page_67_Figure_3.jpeg)

Hengne Li, 13 Dec. 2017

#### double b-tagger discriminator

# New Results!

### **Invariant masses of the 8 categories**

![](_page_68_Figure_4.jpeg)

Hengne Li, 13 Dec. 2017

# VH, all hadronic, CMS

![](_page_68_Figure_7.jpeg)

# New Results!

# CMS-PAS-B2G-17-002

# VH, all hadronic, CMS

#### **Signal acceptance x efficiency vs. resonance mass**

![](_page_69_Figure_4.jpeg)

![](_page_69_Figure_6.jpeg)

# New **Results!**

# VH, all hadronic, CMS

![](_page_70_Picture_2.jpeg)

#### Hengne Li, 13 Dec. 2017

## **CMS-PAS-B2G-17-002**

### **Event display**

![](_page_70_Figure_8.jpeg)

# New Results! VH/VV/qV, all hadronic, CMS

Empirical functions with different number of parameters to describe the background shape, then use Fish-test CL 10% method to decide which one to be used.

2 parameters: p

3 parameters: p

4 parameters: p

5 parameters: p

$$p_{0} \cdot \frac{1}{(x)^{p_{1}}}$$

$$p_{0} \cdot \frac{(1-x)^{p_{1}}}{(x)^{p_{2}}}$$

$$p_{0} \cdot \frac{(1-x)^{p_{1}}}{(x)^{p_{2}+p_{3}\cdot\log(x)}}$$

$$p_{0} \cdot \frac{(1-x)^{p_{1}}}{(x)^{p_{2}+p_{3}\cdot\log(x)+p_{4}\cdot\log^{2}(x)}}$$
## CMS-PAS-B2G-17-001

New **Results!** 

# VV/qV, all hadronic, CMS

Jet mass



Hengne Li, 13 Dec. 2017

#### tau21

## CMS-PAS

## New Results!

# VV/qV, all ha

#### invariant mass of the





### **CMS-PA**

# New **Results!**

### invariant mass of t



