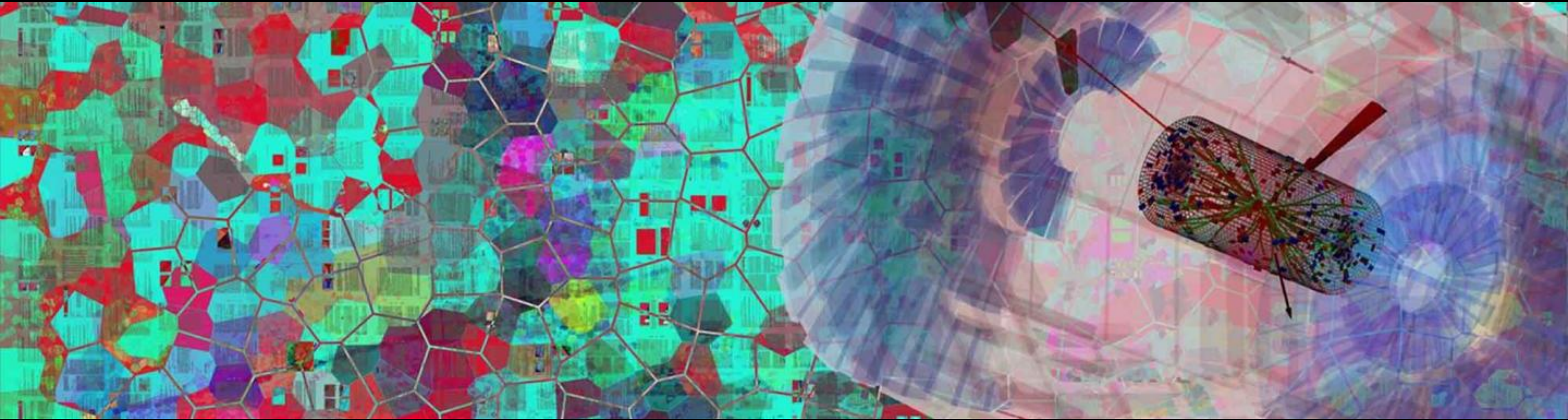
Search for heavy right-handed W bosons & neutrinos

Tópicos de Física de Partículas



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Introduction

→ I will review the two most recent papers from **CMS** and **ATLAS** concerned with the search of heavy right-handed W gauge bosons and neutrinos in final states $\boldsymbol{lljj, l = e, \mu, j = jet}$:

- **CMS** (2018) : $\sqrt{s} = 13$ TeV , $L = 35.9$ fb^{-1} (2016)
- **ATLAS** (2019) : $\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1} (2015+2016)

→ The right-handed W gauge bosons ($\boldsymbol{W_R}$) and neutrinos ($\boldsymbol{N_R}$) appear in **left-right symmetric models (LRSM)** containing a **see-saw mechanism**

→ LRSMs try to answer the question:

Why is the weak interaction left-handed ?

Left-right symmetric model (LRSM)

Standard model (electroweak sector)
~246 GeV

$SU(2)_L \times U(1)_Y$

Spontaneous Symmetry Breaking →

$U(1)_Q$

Electromagnetism

LRSM
1-1000 TeV?

$\boldsymbol{SU(2)_R} \times SU(2)_L \times U(1)_{(B-L)/2}$

Parity symmetry : $g_R = g_L$

$SU(2)_L \times U(1)_Y$

Standard model (electroweak sector)

$SU(2)_R$	$\boldsymbol{W_R}, Z_R$ g_R		W_L, Z_L g_L	$SU(2)_L$

→ The left-handedness of the weak interaction arises as the result of **spontaneous symmetry breaking (SSB)**

→ The standard model (SM) is the low-energy approximation of a more fundamental theory that possesses extra heavier gauge bosons ($\boldsymbol{W_R}, Z_R$)

See-saw mechanism

→ Attempt to explain the origin of the neutrino masses

Type-I see-saw

→ Adds right-handed neutrinos N_{iR}

Physical states (mass eigenvalues): $O(m) \gg O(d)$

- Light neutrinos $m_\nu \sim \frac{O(d^2)}{O(m)}$
- Heavy **Majorana** neutrinos w/ mass$\sim O(m)$

Majorana: particles which are their own antiparticles

Majorana mass term violates lepton number by 2 units

Lepton-number violating processes **can** occur

Inverted see-saw

→ Adds right-handed neutrinos N_{iR} and $SU(2)_L$ singlets neutral (sterile) fermions S_{iL}

Physical states (mass eigenvalues):

- Light neutrinos $m_\nu \sim O(\mu)\frac{O(d)}{O(n)}$
- Light sterile states w/ mass$\sim O(\mu)$
- **Pseudo-Dirac** heavy neutrinos w/ mass$\sim O(n) + O(d)$

$O(d), O(n) \gg O(m), O(\mu)$

Pseudo-Dirac: formed by a pair of degenerate Majorana particles

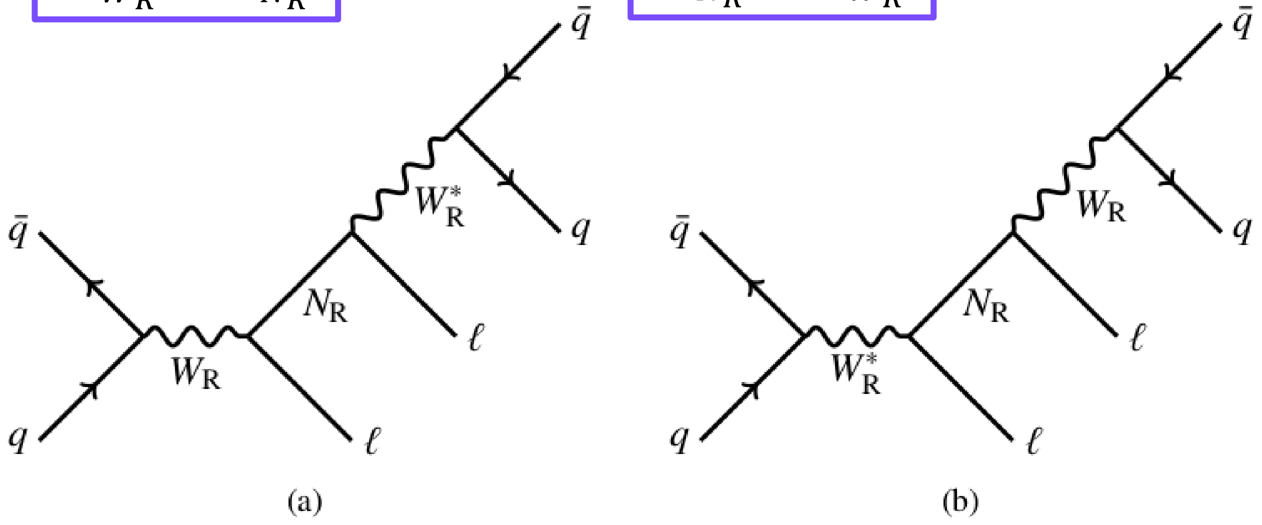
Lepton-number violating processes **cannot** occur

$The\ KS\ process: q\bar{q} \rightarrow llq\bar{q}$

Experimental signature (final state) : $lljj$ (2 charged leptons $l = e, \mu$ + 2 jets j)

$M_{W_R} > M_{N_R}$

$M_{N_R} > M_{W_R}$



Majorana vs Dirac

Charges of the dileptons in the final state:

- N_R **are Dirac**: dileptons in the final state have **opposite-sign (OS)** charges
- N_R **are Majorana**: mixture between dileptons with opposite-sign and **same-sign (SS)** charges

$M_{W_R} > M_{N_R}$: W_R mass is reconstructed from m_{lljj}

$M_{N_R} > M_{W_R}$: W_R mass is reconstructed from m_{jj}

Explored by ATLAS for the 1st time!

State of the art

→ The KS process has been studied by both CMS and ATLAS collaborations at $\sqrt{s} = 7,8,13$ TeV with $l = e, \mu$

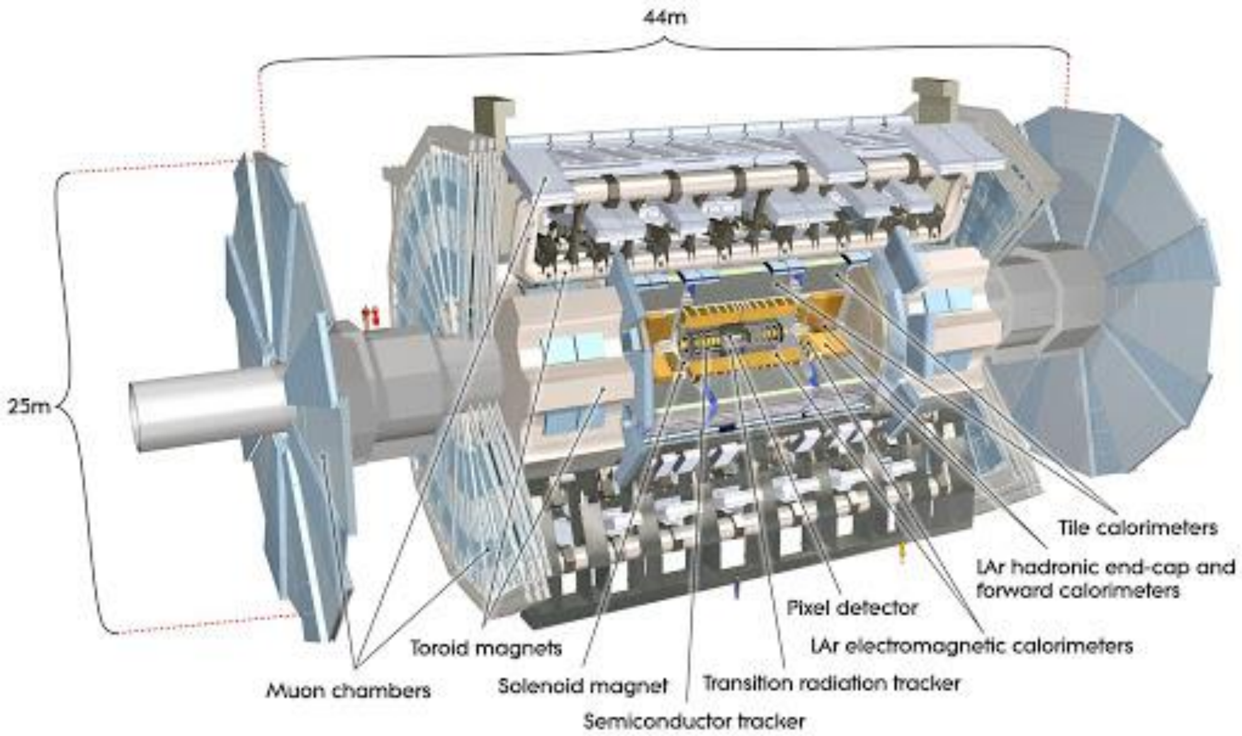
→ CMS also studied the final state $\tau\tau jj$ at $\sqrt{s} = 13$ TeV

→ **No significant deviations** from the SM predictions were observed

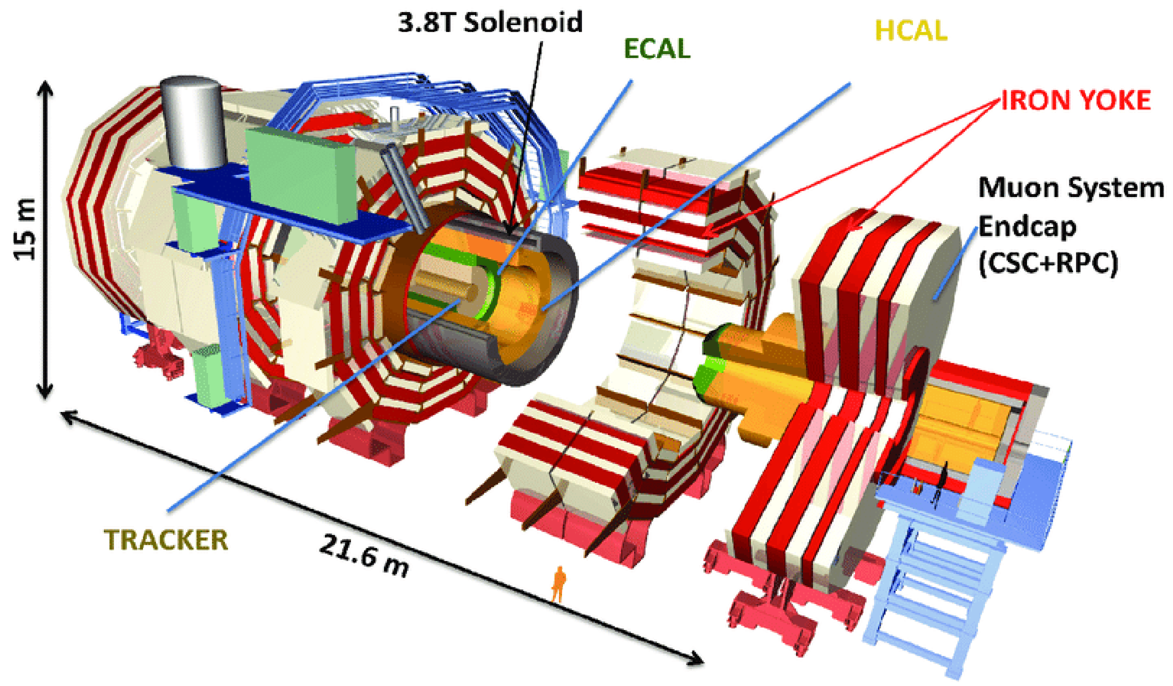
→ Prior to the reviewed articles, CMS detected a **2.8σ excess** over the SM background in the electron channel at $m_{eejj} \sim 2.1$ TeV

Detectors

ATLAS detector



CMS detector



ATLAS

Inner tracker	Solenoid (2T)	EM calorimeter	Hadron calorimeter	Muon spectrometer

Muon spectrometer →
- 3 toroids (0.5-1T)
- Tracking chambers
- Detectors for trigger

CMS

Inner tracker	EM calorimeter	Hadron calorimeter	Solenoid (3.8T)	Muon system

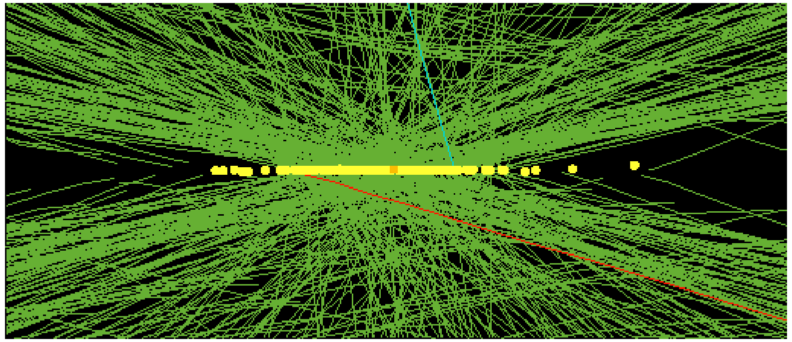
Muon system →
- 3 gaseous detectors
- Iron return yoke

Datasets & simulations

Signal model

Datasets : 2016 pp data (35.9 fb^{-1}) (CMS) ; 2015+2016 pp data (36.1fb^{-1}) (ATLAS) at $\sqrt{s} = 13$ TeV

Simulations are performed in order to optimise the event selection and to estimate background contamination



In the case of **ATLAS**:

→ Events are generated containing only Majorana N_R neutrinos

→ For Dirac neutrinos, only OS events are used in the analysis

→ Signal samples are generated for different W_R and N_R mass hypotheses ($\boldsymbol{m_{N_R} < 2\, m_{W_R}}$)

In the case of **CMS**, signal events are generated assuming $\boldsymbol{m_{N_R} < \frac{1}{2}\, m_{W_R}}$

Single event = hard scattering pp collision + pp interaction vertices (**pileup**)

Detector response is simulated with Geant4

Background model

Background : SM processes that produce events with the same final-state as the signal model

Signal would appear as excess over the SM background expectation in the kinematic distributions

Sources of background are similar in the two analyses:

ATLAS

OS channel

- $t\bar{t}$ production (≈49%)
- Z+jet(s) (≈35%)

SS channel

- Misidentified letpons
- Electron charge misidentification
- Diboson processes (ZZ, WW or WZ)

Other: $t\bar{t}V$ $(V = W, Z, H)$ & single top production

CMS

Main:
- Drell-Yan+jets
- $t\bar{t}$ production

- Diboson production (≈1.5%)
- W+jets (≈0.5%)
- Single top production (≈5%)
- QCD multijet events (≈0.1%)

Prompt lepton: lepton originating from a W,Z or H boson decay or from a τ –lepton if the τ originates from a prompt decay

Selections

Object reconstruction

→ **Electrons**

- Association of a charged particle track with energy deposits in the EM calorimeter (ECAL)
- Electrons in the transition region between the barrel and endcap of ECAL are rejected
- Must be isolated

→ **Muons**

- Association of a charged particle track with a track in the muon system
- Must be isolated

→ **Jets**

- Reconstructed with anti−k_T algorithm
- Jets originating from pileup interactions are removed

→ **Additional selections**

- To avoid overlap between diferente particle types
- Electrons are removed if they share track with a muon

ATLAS selections

Primary vertex (PV) : the vertex with the largest value of summed p_T^2 in the event

An **event** needs to have at least 1 reconstructed PV with at least 2 associated tracks w/ $p_T > 400$ MeV

- Events containing b-quarks are rejected (reduce contamination from top-quark production)
- Events need to have at least two leptons with the same flavour (ee or $\mu\mu$) and two jets w/ $p_T > 100$ GeV and $|\eta| < 2.0$

After these selections the **main SM background contributions** are:

- Z+jet(s) in OS and electron SS channel
- Diboson production in muon SS channel

$m_{jj} > 110$ GeV, $m_{ll} > 400$ GeV
p_T sum of two leptons and two most energetic jets (H_T) >400 GeV

Analysis regions

Signal regions (SR) : designed to contain majority of signal events & extract signal yields
Control regions (CR) : constrain background predictions
Validation regions (VR) : validate background predictions

CMS selections

Primary vertex (PV) : the vertex with the largest value of summed p_T^2 in the event

An **event** is formed with the two jets and two leptons with the largest p_T

- Leading (subleading) leptons must have $p_T > 60\ (53)$ GeV and $|\eta| < 2.4$
- Events need to have at least two leptons with the same flavour (ee or $\mu\mu$) and two jets w/ $p_T > 100$ GeV and $|\eta| < 2.0$

After these selections the **main SM background contribution** comes from Z production

- $m_{ll} > 200$ GeV to avoid contamination from Z production

- $m_{lljj} > 600$ GeV to ensure all kinematic requirements are fully efficient

Analysis regions

Signal regions (SR) : region of phase-space where signal is expected to appear
Control regions (CR) : estimate contribution of different SM backgrounds:
- *Low dilepton mass control regions* : study DY+jets
- *Flavour control region:* study $t\bar{t}$ production

$Efficiency \times acceptance$

- Fraction of events that pass the selection criteria
- Evaluated using simulated signal events

ATLAS:
- varies from **54**% in (W_R, N_R) high-mass region to $\approx \mathbf{30}$% in low-mass region

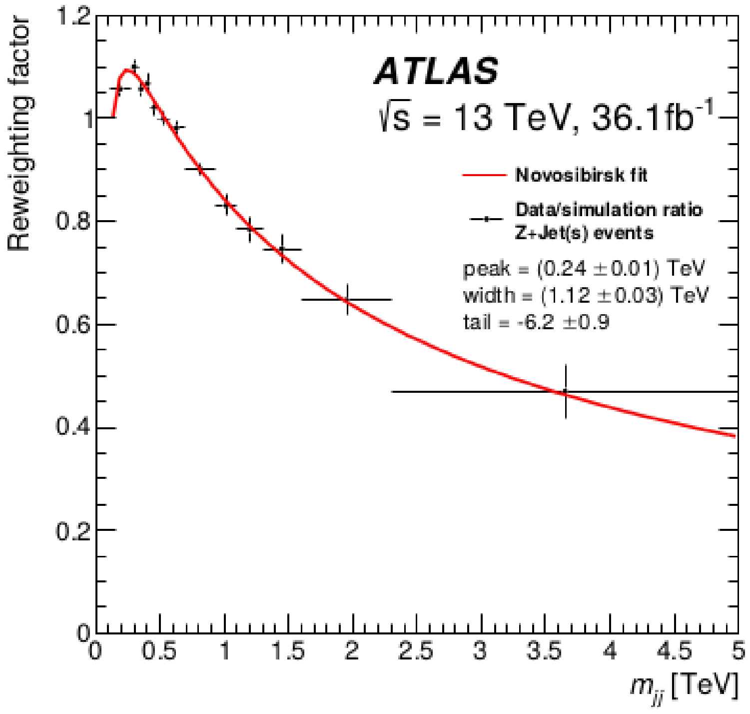
CMS :
- varies from **57**% at $m_{W_R} > 3000$ GeV to **30**% at $m_{W_R} > 1000$ GeV (electron channel)
- varies from **75**% at $m_{W_R} > 3000$ GeV to **40**% at $m_{W_R} > 1000$ GeV (muon channel)

Background estimation

ATLAS estimation

Reweighting factor

m_{jj} spectrum of simulated Z+jet(s) events not correctly modelly by simulation samples in CRs (OS channel)



"Fake-factor" method

Method used to estimate background contribution from misidentified leptons ("fakes") (SS channel)

Fake-factor

$$F = \frac{N_T}{N_L}$$

$N_T = \#\ tight\ leptons$
$N_L = \#\ loose\ leptons$

Number of events with at least 1 misidentified lepton in the analysis region:

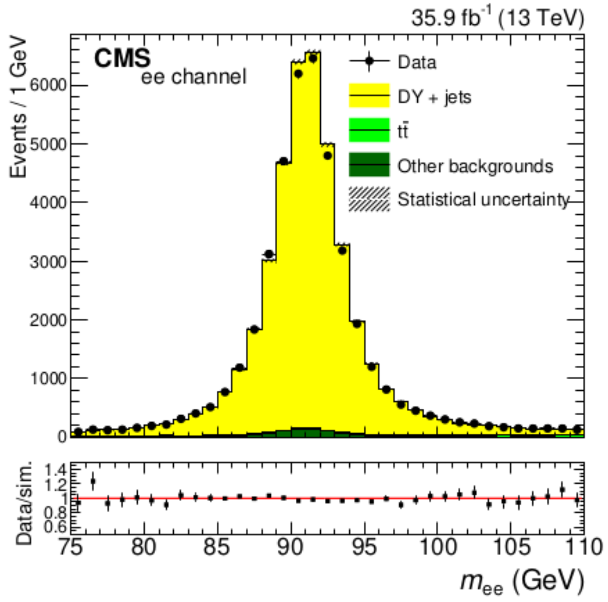
$$N^{fake} = [F(N_{TL}^{data} + N_{LT}^{data} - F^2 N_{LL}^{data})] - [F(N_{TL}^{MC} + N_{LT}^{MC} - F^2 N_{LL}^{MC})]^{\text{prompt only}}$$

CMS estimation

Scale factor (SF)

Used to adjust the normalization of DY+jets background in simulation to match the event coutns in data

Scale factor = ratio of data and simulation events under the Z resonance peak $80 < m_{ll} < 100$ GeV



$SF = 1.07 \pm 0.01$ (stat)

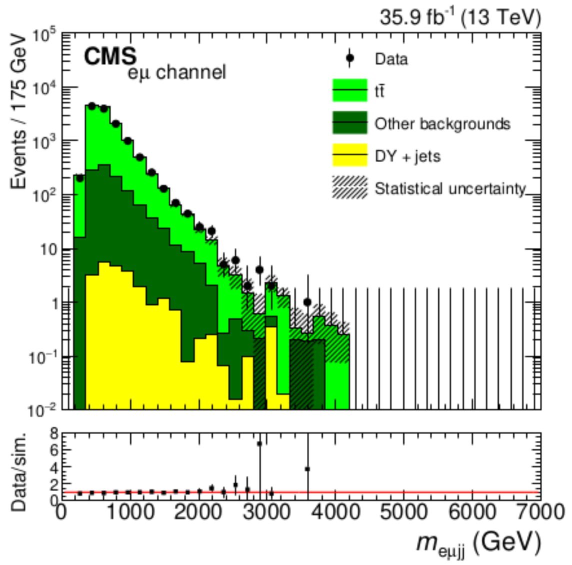
Low dilepton control region

Transfer factors ($R_{ll/e\mu}$)

Used to estimate the number of events from $t\bar{t}$ production in the SR

$$R_{ll/e\mu} = \frac{\#simulated\ t\bar{t}\ events\ in\ m_{lljj}\ distribution\ in\ SR}{\#\ events\ in\ m_{e\mu jj}\ distribution\ in\ flavour\ control\ region}$$

Number of events in SR: $\boxed{N_{t\bar{t}}(SR) = N_{t\bar{t}}(FCV) \times R_{ll/e\mu}}$



	stat	syst
$R_{ee/e\mu} = 0.42$	$\pm\ 0.01$	$\pm\ 0.07$
$R_{\mu\mu/e\mu} = 0.72$	$\pm\ 0.02$	$\pm\ 0.14$

Flavour control region

Systematic uncertainties

Have experimental and theoretical sources and affect both signal and background distributions

Experimental sources

→ Candidate reconstruction (CMS & ATLAS)

→ m_{jj} reweighting (ATLAS)

→ Electron charge misidentification probability (ATLAS)

→ Fake-factor estimation (ATLAS)

→ Transfer factor (CMS)

Theoretical sources

→ Choices / models used in the simulations:

  → QCD factorisation/renormalisation scales

  → PDF set choice & uncertainty

  → α_S uncertainty

  → Hard-scatter generation

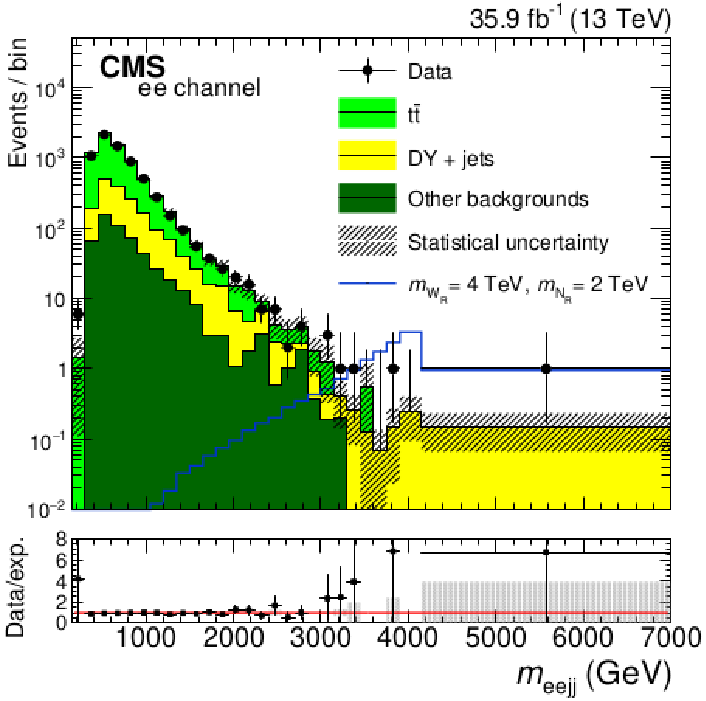
  → Amount of initial- and final-state radiation

→ Efficiency × acceptance

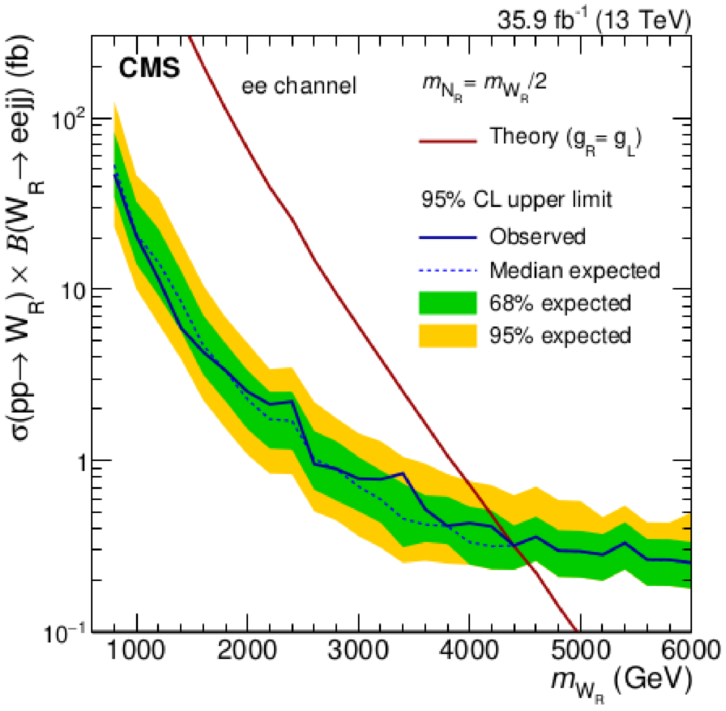
Results & conclusions

CMS results

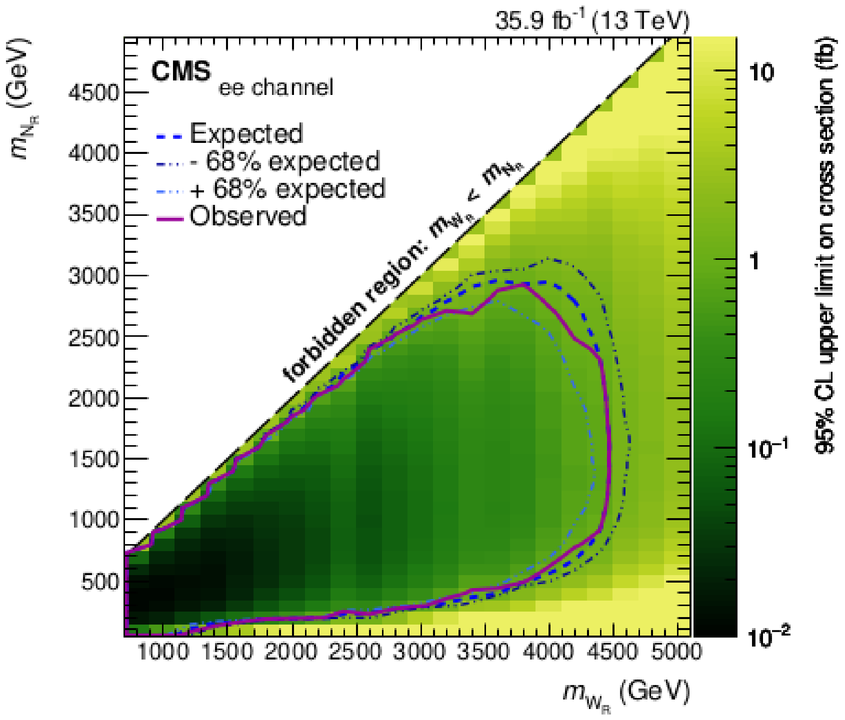
m_{eejj} distribution in SR



Expected & observed 95% CL on $\sigma(pp \to W_R) \times B(W_R \to eejj)$



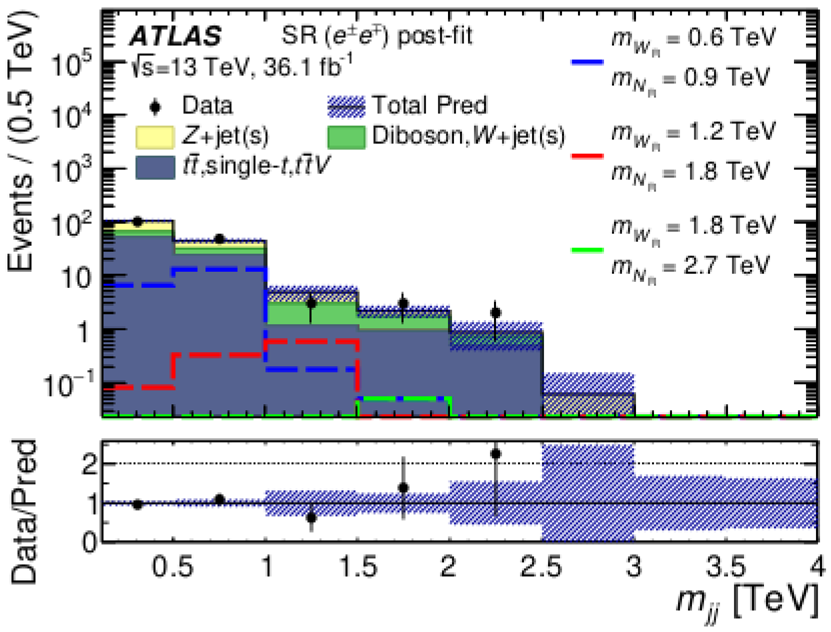
95% exclusion limit on W_R cross section for different m_{W_R} and m_{N_R}



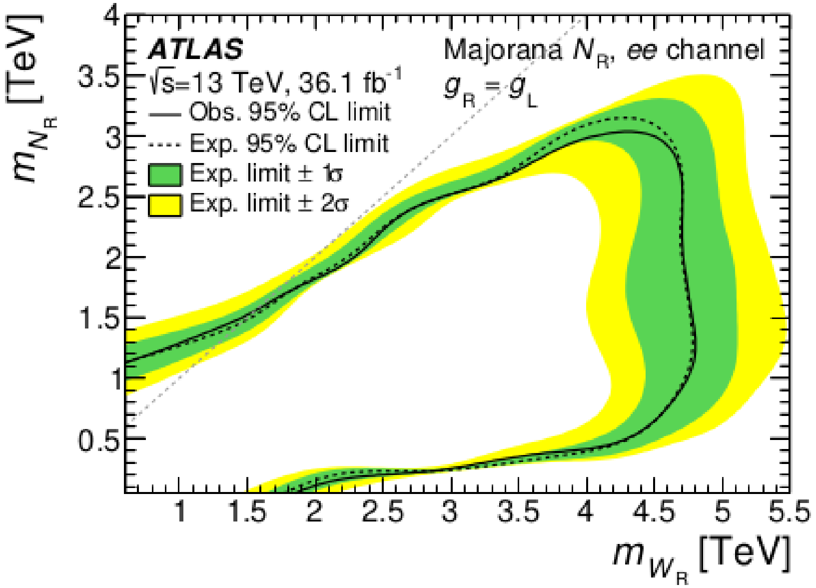
- No significant deviations from the SM expectations are seen
- **Lower limit** at 95% CL: 4.4 TeV (electron), 4.5 TeV (muon)
- Most significant excess of $\approx 1.5\sigma$ at $m_{eejj} \approx 3.4$ TeV

ATLAS results

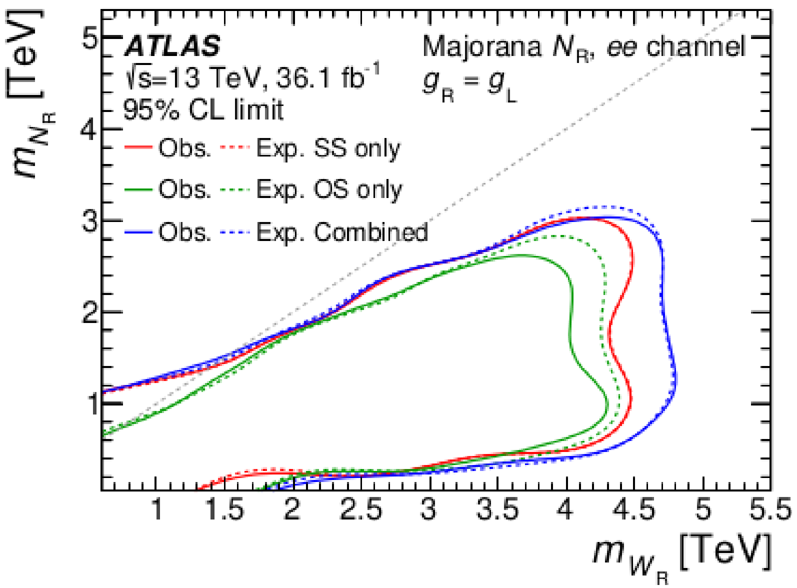
m_{jj} distribution for data & background after the CR+SR fit



Expected & observed 95% CL on $m_{W_R} - m_{N_R}$ plane



Expected & observed 95% CL on $m_{W_R} - m_{N_R}$ plane w/ separation between OS & SS channels



- No significant deviation from SM predictions is observed in any of the SRs
- Most significant local excess of $\approx 2\sigma$ at $m_{eejj} = 3.5 - 4$ TeV
- **Lower limit** at 95% CL: 4.7 TeV for $0.5 < m_{N_R} < 3.0$ TeV

Conclusions

- → I presented a review of the two most recente papers from CMS and ATLAS concerned with the search of heavy righ-handed W gauge bosons and neutrinos in final states: $lljj$ with $l = e, \mu$
- → These particles are predicted by LRSMs including a see-saw mechanism
- → They can be manifest as excesses over the SM background in distributions of several kinematic variables
- → CMS uses 2016 pp data ($\sqrt{s} = 13$ TeV, $L = 35.9$ fb^{-1}) & ATLAS uses 2015-2016 pp data ($\sqrt{s} = 13$ TeV, $L = 36.1$ fb^{-1}) and explores the $m_{N_R} > m_{W_R}$ scenario for the 1st time
- → No significant deviations from SM expectations are found
- → In CMS, a W_R boson with mass up to 4.4 TeV is excluded at 95% CL
- → In ATLAS, the excluded region extends to $m_{W_R} = 4.7$ TeV for both Majorana and Dirac neutrinos

Thank you! Questions?

Backup

Comparison

	ATLAS	CMS
Inner detector	Silicon strip + pixel detectors + transition radiation detector	Silicon strip + pixel detectors
Magnetic field strength and positioning	• 2T solenoid between ID & ECAL • 3 toroids (0.5-1T) outside MS	4T solenoid between HCAL and muon chambers
Calorimeter material	Liquid argon (Lar)	Tungstate crystals
Muon system	Independent muon spectrometer	Gaseous detectors + iron return yoke

- CMS has better resolution for charged particles, photons and electrons
- ATLAS has better background rejection

↓

Different systematic uncertainties in the results which make the LHC physics exploration more robust

Electrons

Association of a charged particle track with energy deposits in the EM calorimeter (ECAL)

Electrons falling in the transition region between the barrel and endcap sections of the ECAL are rejected ($1.444 < |\eta| < 1.566$ for CMS and $1.37 < |\eta| < 1.52$ for ATLAS)

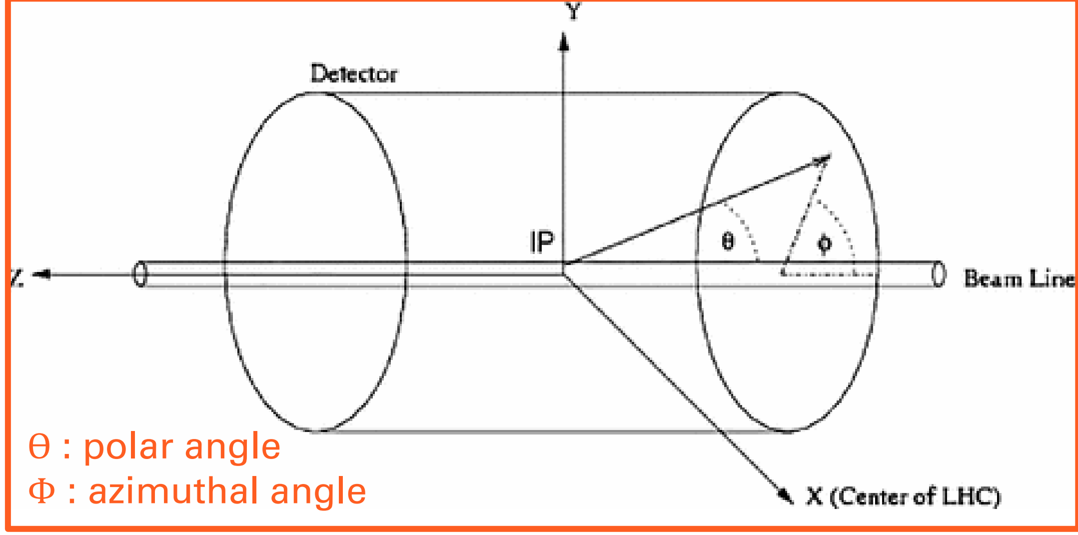
CMS:

- Electrons must be isolated : p_T sum of all tracks inside cone centered in electron, with $R < 0.3$ must be below 5 GeV

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

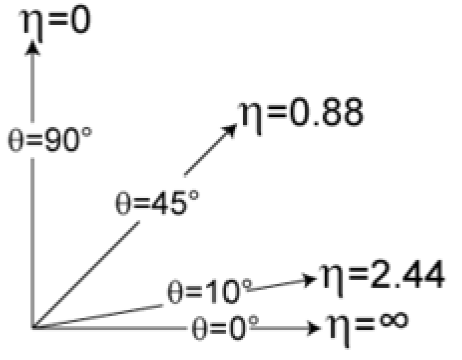
ATLAS:

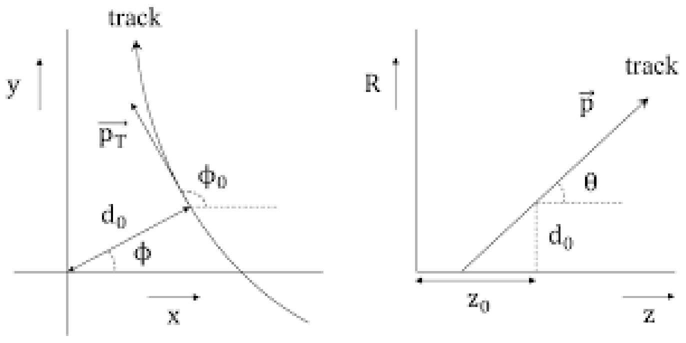
- $E_T > 25\ (30)$ GeV in OS (SS) channel
- $|\eta| < 2.47$
- Satisfy *LHMedium* identification criterion
- $|d_0|/\sigma(d_0)$ < 5 nm
- $|z_0 \sin\theta\,|$ < 5 $p_T > 400$ MeV)
- Satisfy track-based isolation criteria



Pseudorapidity

$$\eta = \frac{1}{2}\log\left(\frac{1+\cos\theta}{1-\cos\theta}\right)$$





z_0 , d_0

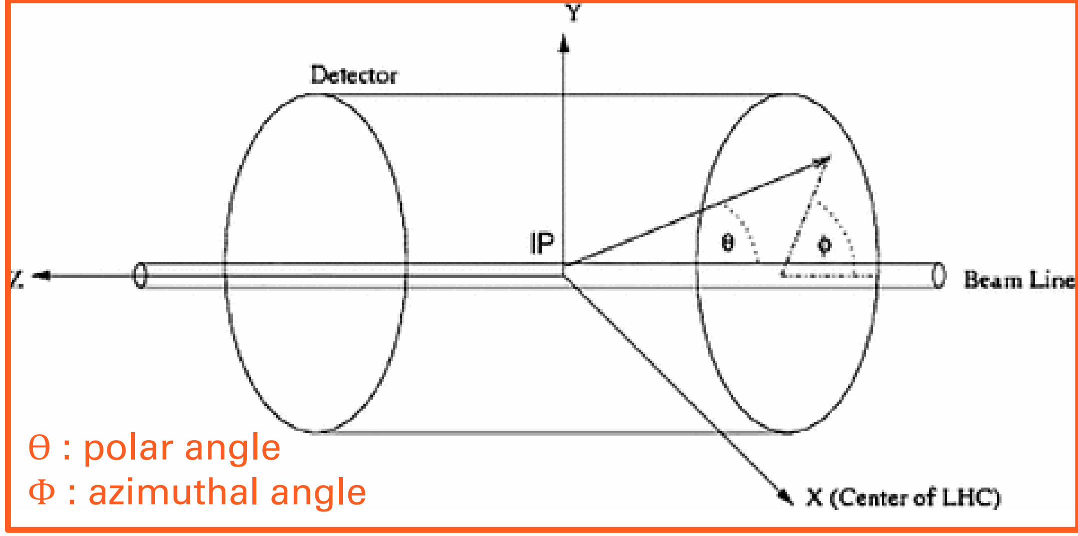
Muons

Association of a charged particle track with a track in the muon system

CMS:
- At least 1 hit in pixel detector, 6 tracker layer hits and segments in 2 or more muon detector stations
- $|\eta| < 2.4$
- Muons for which p_T sum of tracks originating in a cone around the muon $R < 0.3$ are removed

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

ATLAS:
- $p_T > 25\ (30)$ GeV in the OS (SS) channel
- $|\eta| < 2.5$
- $|d_0|/\sigma(d_0) < 3$
- $|z_0 \sin\Theta| < 5$ nm
- Satisfy *Medium* quality criterion



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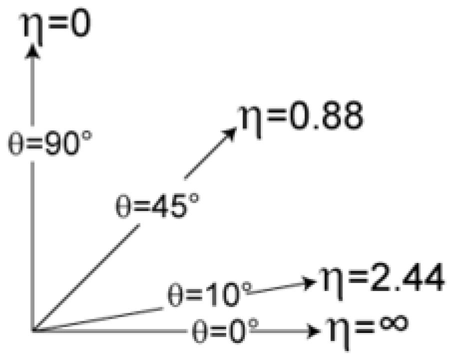
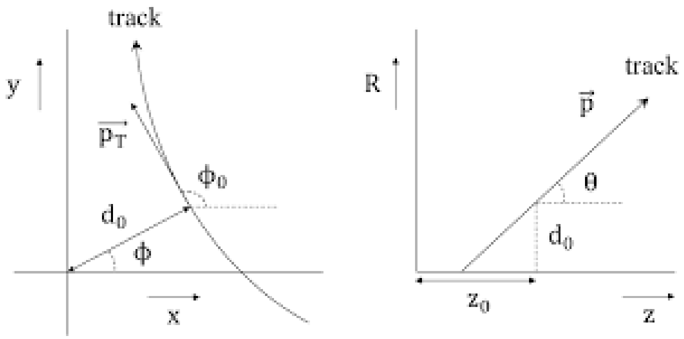




z_0 , d_0

Jets

Reconstructed with anti$-k_T$ algorithm with radius parameter $R = 0.4$ from energy deposits in clusters of the calorimeter

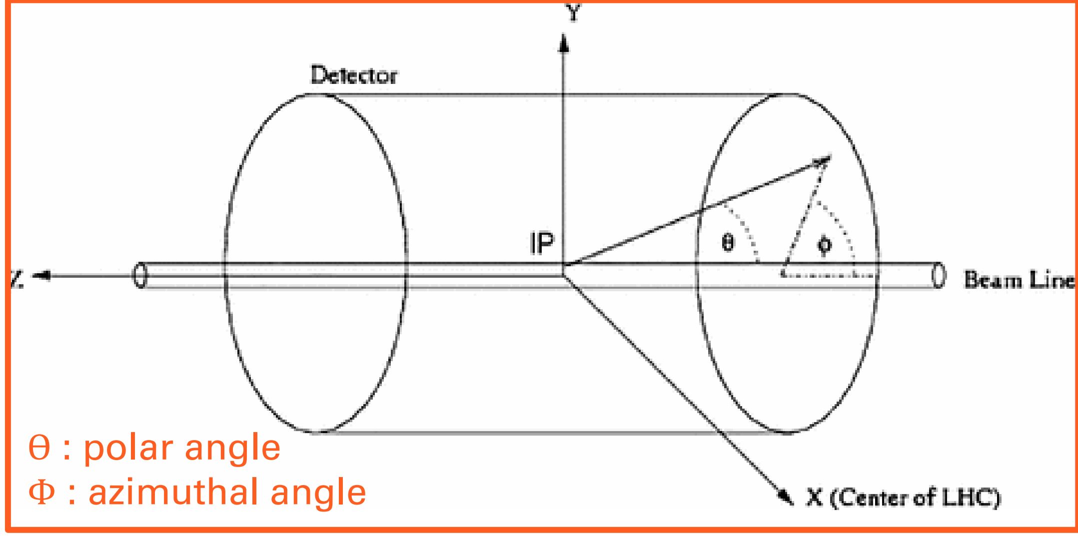
$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

CMS:

- Two jets must have $p_T > 40$ GeV, $|\eta| < 2.4$
- Charged hadrons orginating from pileup interactions removed w/ charged hadron subtraction algorithm
- Neutral hadrons form pileup interactions removed w/ average-area based correction

ATLAS:

- Two jets must have $p_T > 20$ GeV, $|\eta| < 2.5$
- Jets with b-hadrons are identified with multivariate tagging algorithm
- Pileup jets removed w/ jet-vertex tagger ($p_T < 60$ GeV, $|\eta| < 2.4$)



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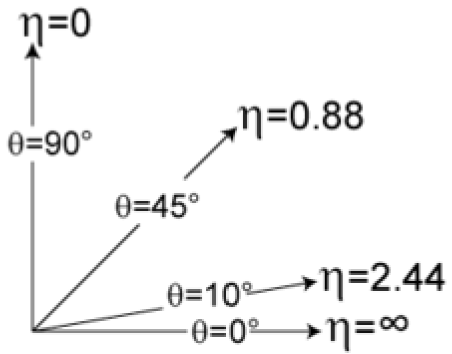
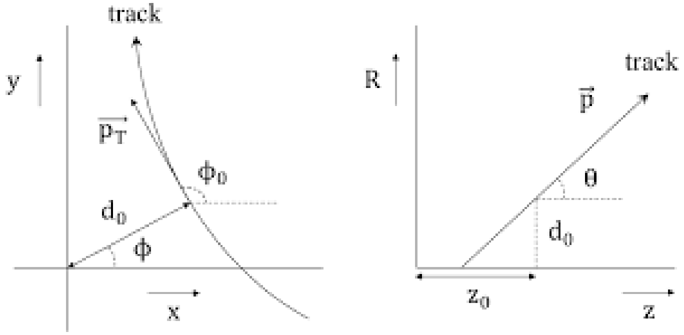




z_0 , d_0

Additional selections

To avoid overlap between different particle types

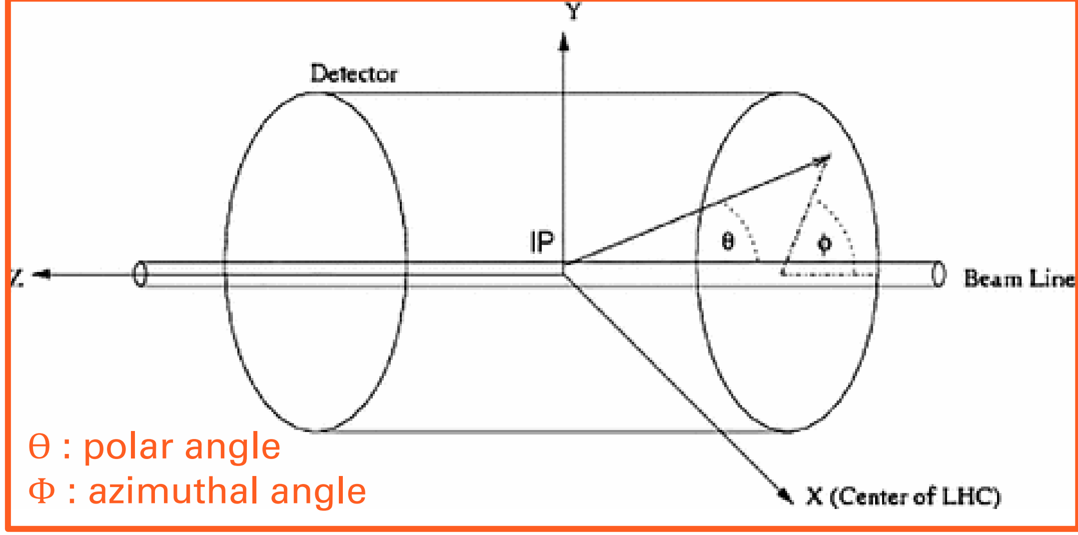
$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

CMS:

- $\Delta R > 0.4$ between all leptons and jets

ATLAS:

- Electrons are removed if they share track with a muon
- Ambiguities between **electrons** and **jets**:
  - If $\Delta R < 0.2$, jet is removed
  - If $0.2 < \Delta R < 0.4$, electron is removed
- Ambiguities between **muons** and **jets:**
  - If $\Delta R < 0.4$ + less than 3 associated tracks, jet is removed
  - Otherwise, muon is removed



Pseudorapidity

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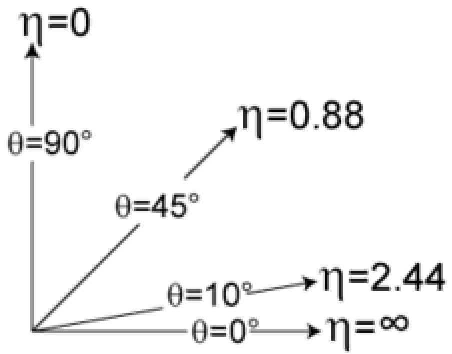

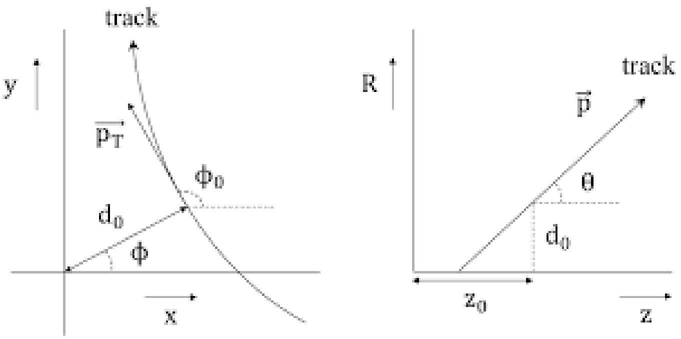

z_0 , d_0

Experimental sources - ATLAS

OS channel

5-20% **m_{jj} reweighting**

Estimated by comparing shape difference between simulated & reweighted distribution and that found on data

0.4-10% **Candidate reconstruction**

1. Jet & lepton energy and momentum callibration
2. Lepton detection & isolation efficiencies
3. Trigger efficiency

SS channel

10-20% **Charge misidentification probability of electrons**

Statistical uncertainty of data & and simulation samples used to calculate the probability

Fake-factor estimation

Unkown composition of fakes

Estimated by varying criteria used to select sample for fake-factor measurement

Yield of prompt leptons

Estimated by varying SM prediction of simulated samples by $\pm$10% (muon), $\pm$30% (electron)

Experimental sources - CMS

0.2-29%

Candidate reconstruction

1. Jet & lepton energy and momentum callibration
2. Lepton detection & isolation efficiencies
3. Trigger efficiency

Transfer factor

Estimated by fitting it to a linear function and taking the difference between the values of this function at the high and low m_{jj}

Systematic uncertainties associated with the momentum dependence of the **scale factors** are negligible

Theoretical sources - CMS

DY+jets estimation

Implemented as a function of m_{lljj} using the PDF4LHC prescription

Theoretical sources - ATLAS

Z+jet(s)

- Choice of QCD renormalisation & factorisation scales — 20-40%
  Estimated by varying them to half and twice their nominal values
- PDF choice and uncertainty
  Estimated by using different PDF sets in the simulations
- α_S uncertainty
  Evaluated by varying its nominal value of 0.118 by $\pm$0.001

$t\bar{t}$ processes

- Hard-scatter generation & uncertainty due to fragmentation/hadronisation model
  Evaluated by comparing different MC generators
- Amount of initial- and final-state radiation — 2-5%
  Estimated by varying parton shower settings

Efficiency × acceptance — 10%

Estimated by varying renormalisation/ **factorisation** scales & by using alternative PDF sets

Bayesian estimator

Bayes theorem: $$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

A : theoretical parameter
B : observed data

$$\underbrace{P(param|data)}_{\text{Posterior probability density}} \propto \underbrace{P(data|param)}_{\text{Likelihood function}} \times \underbrace{P(param)}_{\text{Prior density}}$$

Posterior probability density **Likelihood function** **Prior density**

Flat prior : independent of the parameter

Bayesian estimator

$$\underbrace{P(param|data)}_{\text{Posterior probability density}} \propto \underbrace{P(data|param)}_{\text{Likelihood function}} \times \underbrace{P(param)}_{\text{Prior density}}$$

Posterior probability density   Likelihood function   Prior density

To deal w/ systematic uncertainties, **nuisance parameters** are introduced in the likelihood function:

$$L(s,b|n_0,m_0) = \frac{e^{-(s+b)}(s+b)^{n_0}}{n_0!} \times \frac{e^{-b}b^{m_0}}{m_0!}$$

Event rate n follows Poisson distribution with mean $b+s$
s : signal rate
b : **nuisance parameter** (expected background)
m_0 : b estimation
n_0 : result of the measurement of $b+s$

Probability density of parameter of interest (signal rate): $$p(s) = \int p(s,b)db$$

Parameter range can be extracted (68%, 95%)

The result of the Bayesian estimation is a **probability density** for the parameter

CMS analysis

Bayesian estimator

- Probability of the observed # events being produced by a combination of signal & background w/ cross section σ, using a **flat prior** on the signal
- **Nuisance parameters** w/ log-normal priors
- Cross section **exclusion limit**: upper bound of 95% range of determined posterior density for signal σ

Expected # signal & background events : counting events falling in a particular m_{lljj} window (limits are function of m_{W_R})

Pseudo-experiments are performed, varying all systematic uncertainty sources, each according to a Gaussian distribution (mean = nominal value, width = uncertainty):

- Limit values = mean of pseudo-experiment distribution
- Propagated systematic uncertainty = standard deviation of pseudo-experiment distribution
- Statistical uncertainty = Gamma distribution

$$\rho(n) = \frac{1}{\alpha} \frac{(n/\alpha)^N}{N!} e^{-n/\alpha}$$

n : event rate; $n = \alpha N$
N: # pseudo-experiments

Maximum likelihood estimator

- Used to extract parameters of interest by means of a fit performed on data distribution in SRs and CRs
- ATLAS uses **binned** MLE implemented with HistFitter

$$L\left(\vec{n},\overrightarrow{\Theta_0}\middle|\mu_{sig},\vec{b},\vec{\Theta}\right) = P_{SR} \times P_{CR} \times C_{syst}$$
$$= P(n_S|\lambda_S(\mu_{sig},\vec{b},\vec{\Theta})) \times \prod_{i\epsilon CR} P(n_i|\lambda_i(\mu_{sig},\vec{b},\vec{\Theta})) \times C_{syst}(\overrightarrow{\Theta_0},\vec{\Theta})$$

C_{syst} is the probability density function inclusing the systematic uncertainties:

$$C_{syst}\left(\overrightarrow{\Theta_0},\vec{\Theta}\right) = \prod_{j\epsilon S} Gauss(\Theta_0^j - \Theta^j)$$

Number of events in SR (n_S) and CRs (n_i) are obtained from the maximisation of the likelihood function

The result of the MLE estimation is a **value** for the parameters

ATLAS analysis

N_R neutrinos

Majorana: OS and SS channels are fitted simultaneously

Dirac: only the OS channel is used

Discriminant variables

OS channel

m_{lljj} if $m_{W_R} > m_{N_R}$

m_{jj} if $m_{W_R} < m_{N_R}$

SS channel

m_{jj} in CR

H_T in SR

$\boldsymbol{C_{syst}}$: Gaussian functions whose widths give the magnitudes of the respective uncertainties

ATLAS analysis

To evaluate the **exclusion limits**, the profile-likelihood ratio is used to test a hypothesized value of μ_{sig}:

$$\lambda(\mu_{sig}) = \frac{L(\mu_{sig}, \hat{\hat{\theta}})}{L(\widehat{\mu_{sig}}, \hat{\theta})}$$

Defining $q_{\mu_{sig}} = -2\ln\left(\lambda(\mu_{sig})\right)$ for $\widehat{\mu_{sig}} \leq \mu_{sig}$, the **p-value**:

$$p_{\mu_{sig}} = \int_{q_{\mu_{sig,obs}}}^{\infty} f(q_{\mu_{sig}}|\mu_{sig})\, dq_{\mu_{sig}}$$

$p = 0.05 \rightarrow$ 95% confidence level (CL)