Left-Right Symmetry at the LHC

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on behalf of the ATLAS and CMS Collaborations

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University of Maryland, College Park, US

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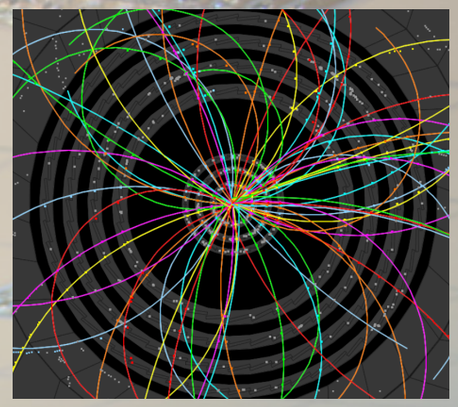
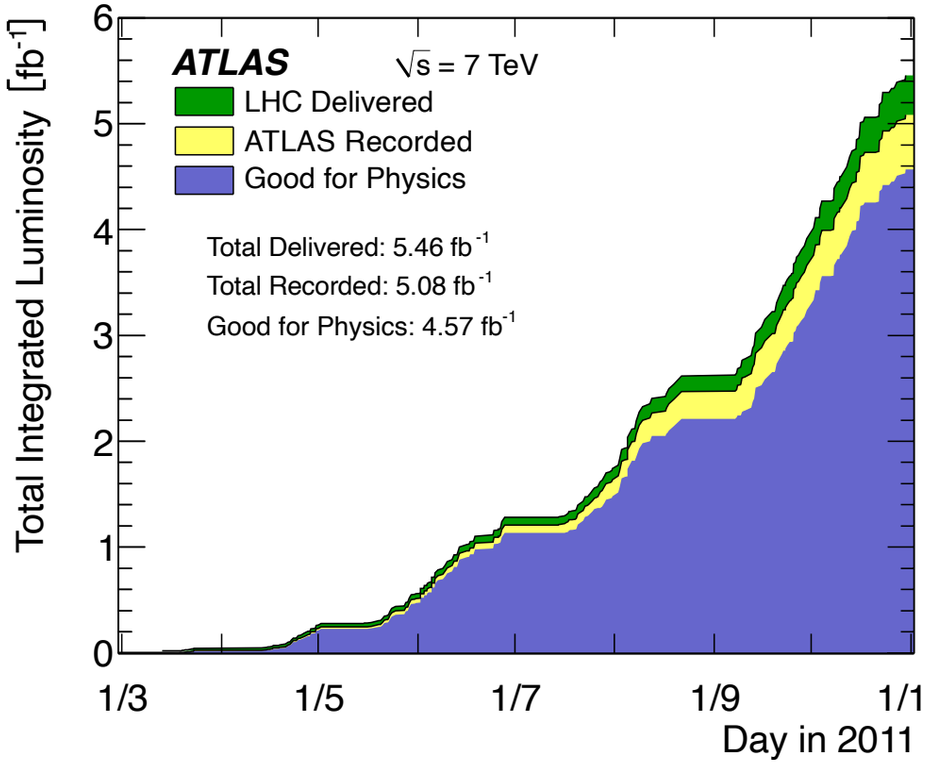
LHC startup

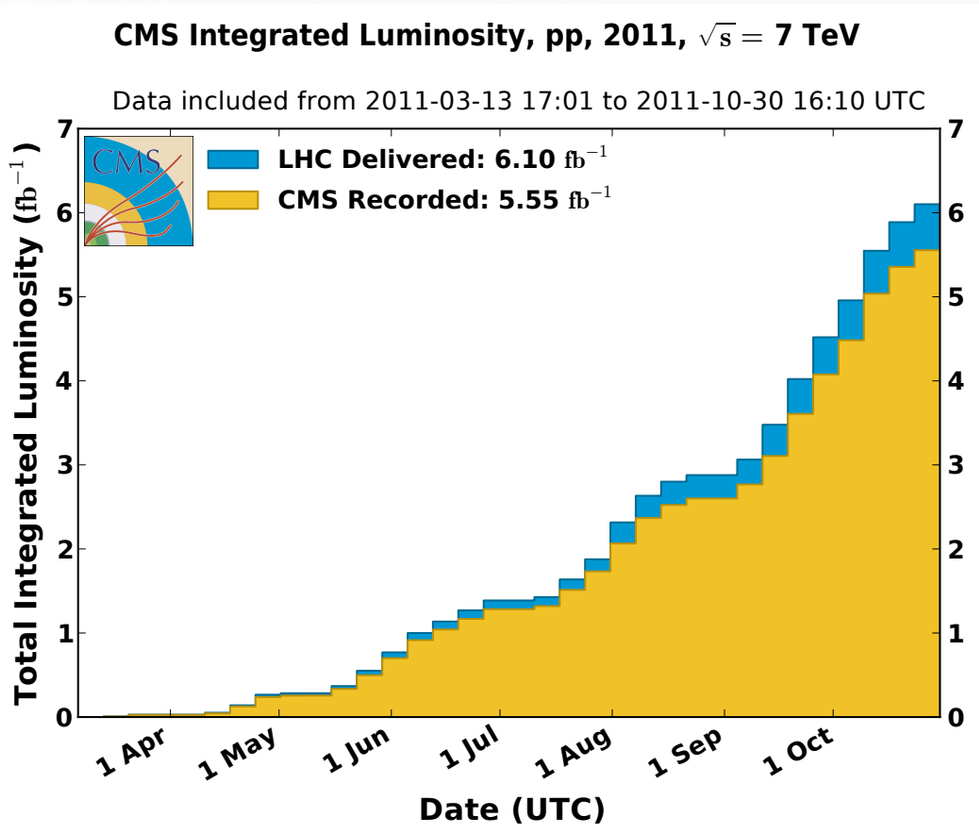


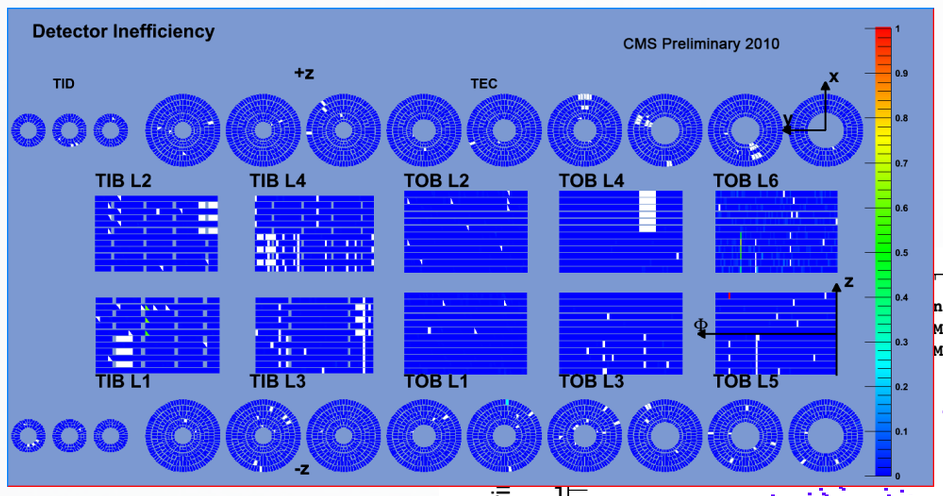
- First physics collisions at the LHC in 2010
- A large number of studies carried out for the first time in the history of particle-physics experiments
- Challenging experimental signatures
- Understanding of the performance of the LHC machine and its detectors is most crucial

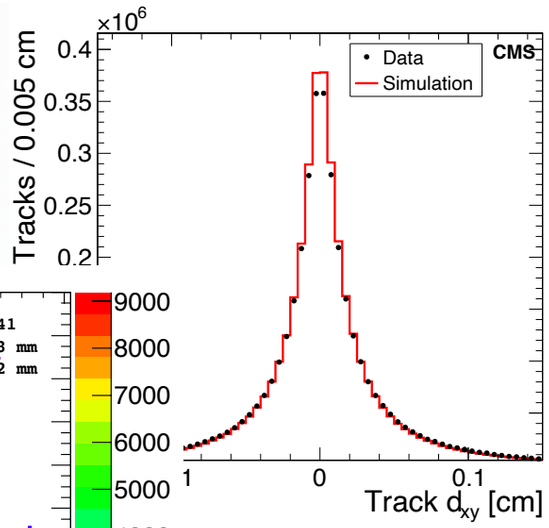
Collision data

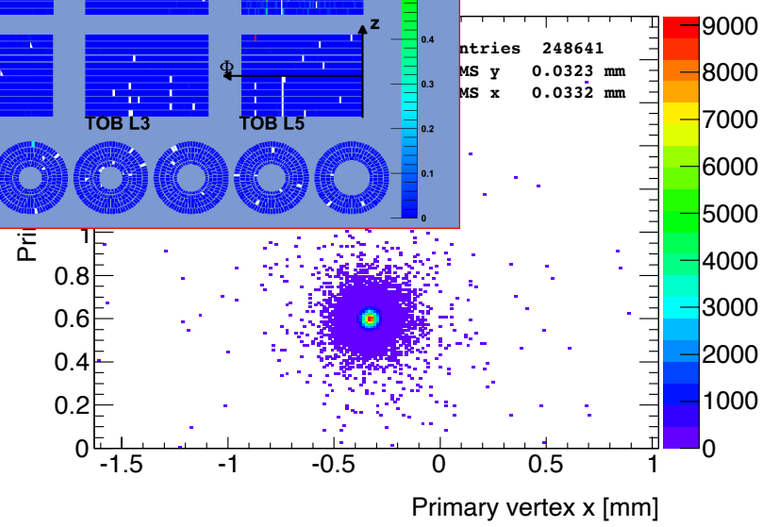
- LHC **delivered** the precious data
- **Remarkable performance** of ATLAS and CMS detectors throughout the whole data taking process

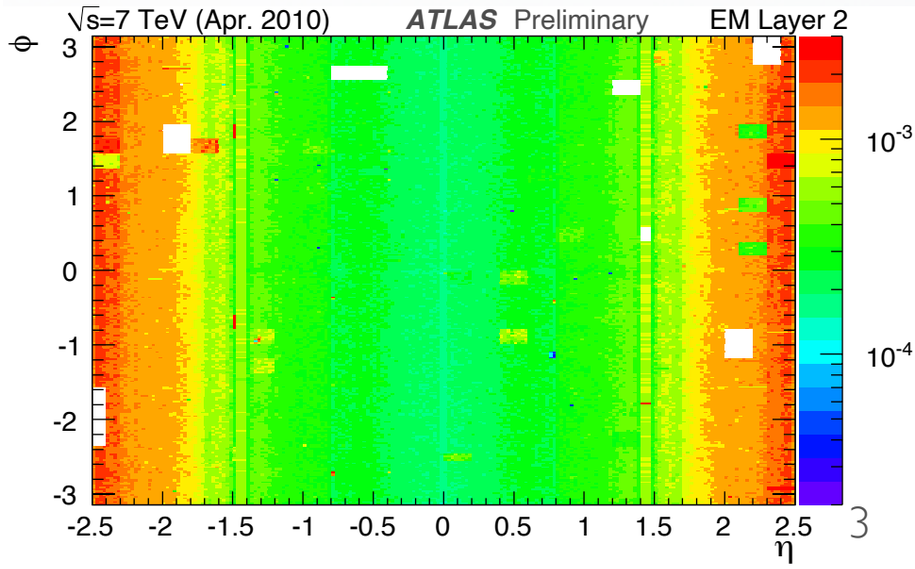




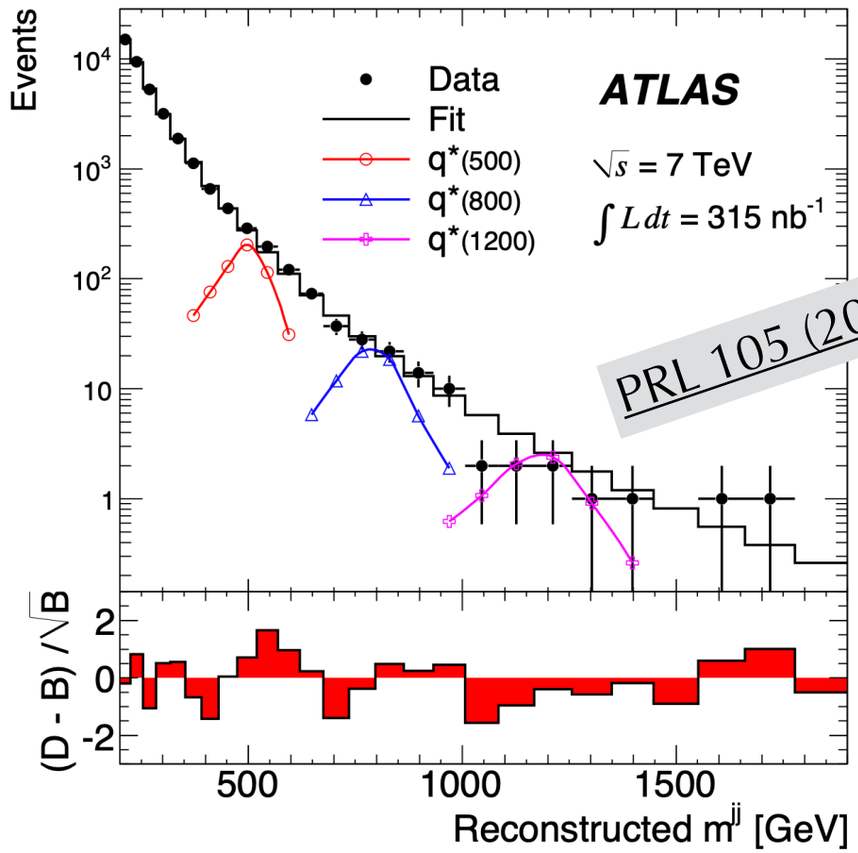




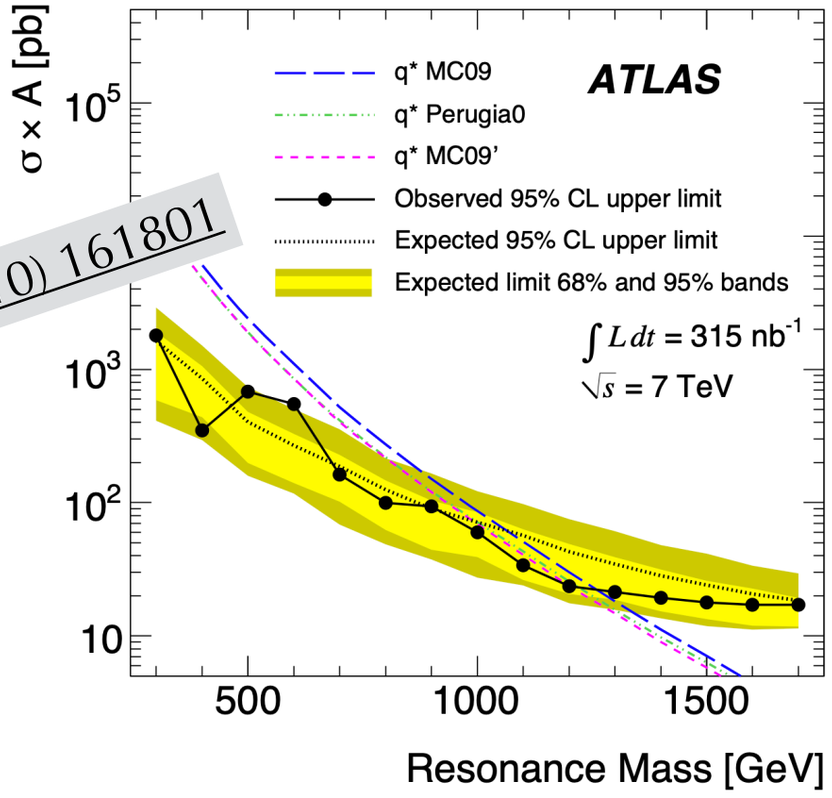




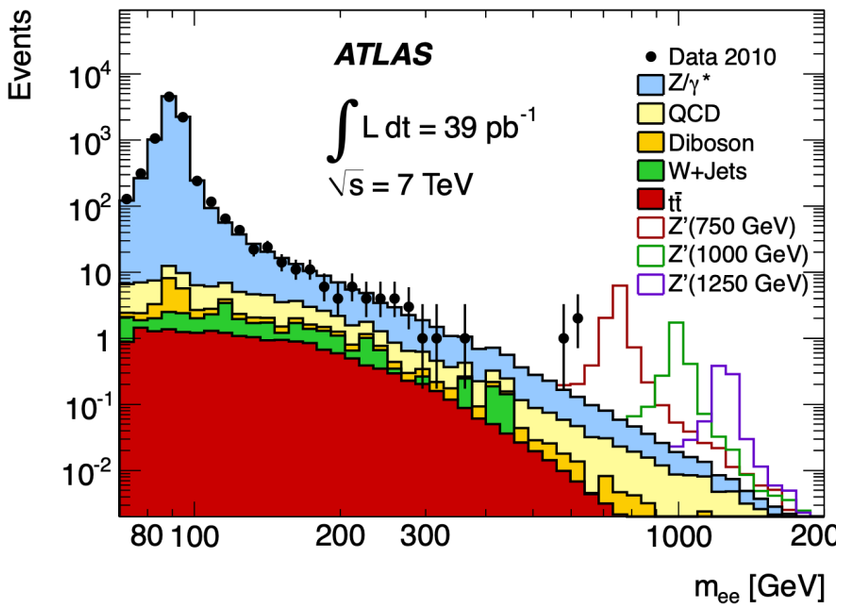
Uncharted territory

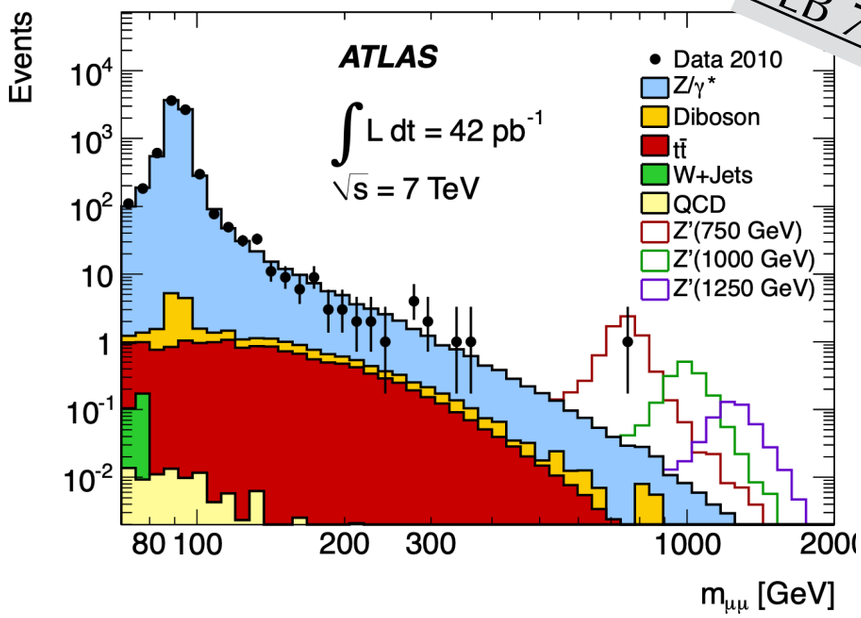


PRL 105 (2010) 161801

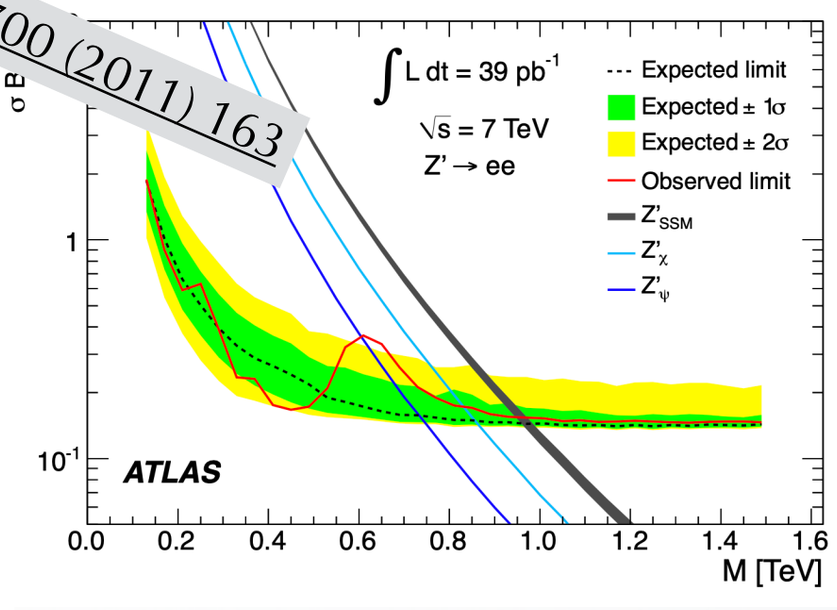


- Reaching out to **high-mass resonance** production probed in invariant mass spectra
- **Calibration** of the performance of physics-object reconstruction and identification is **essential**
- **First important constraints** on the new physics phenomena

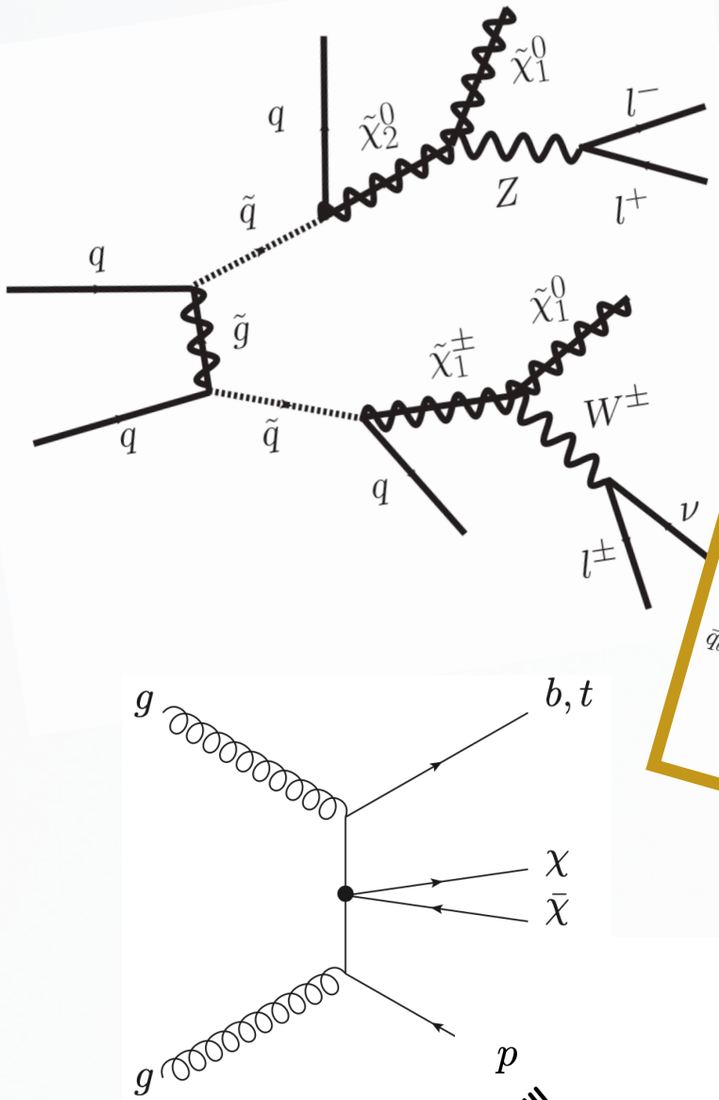


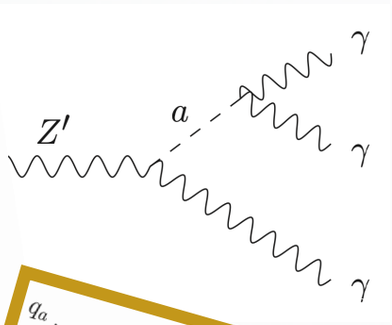


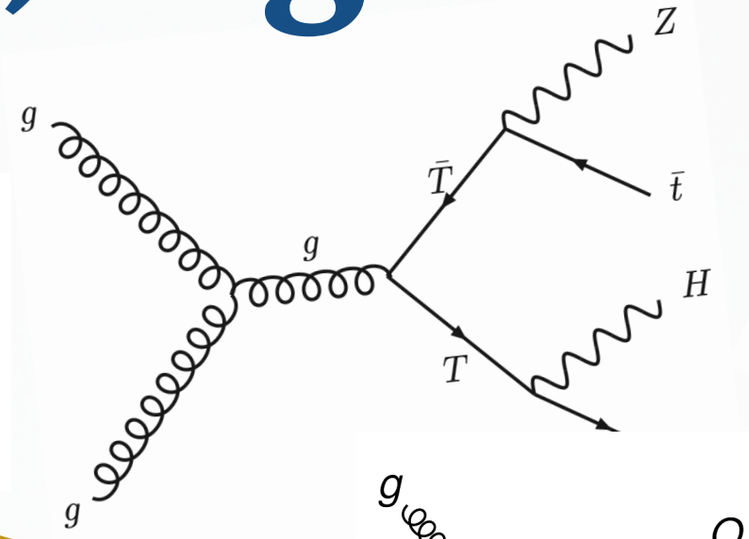
PLB 700 (2011) 163

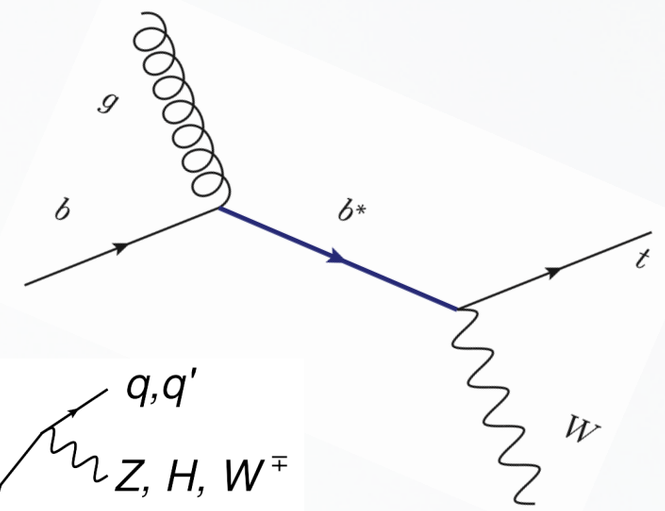


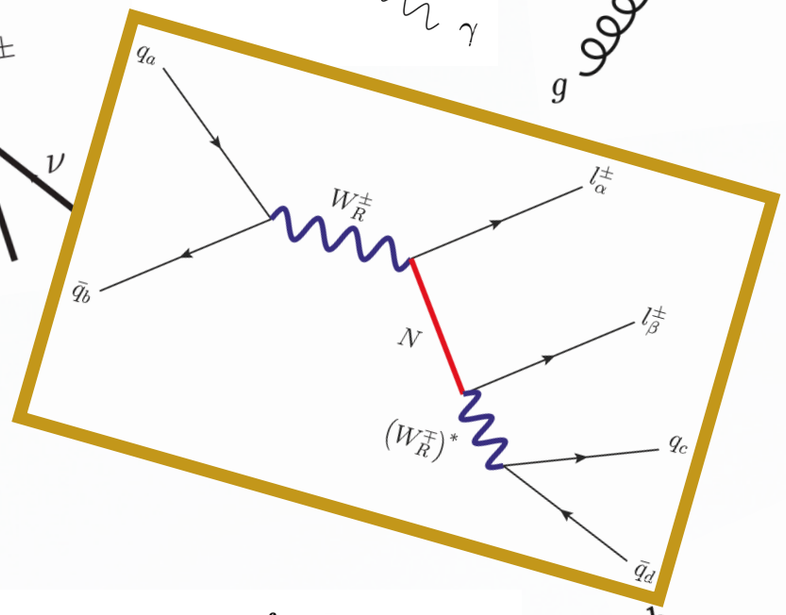
Exotic (?) signatures

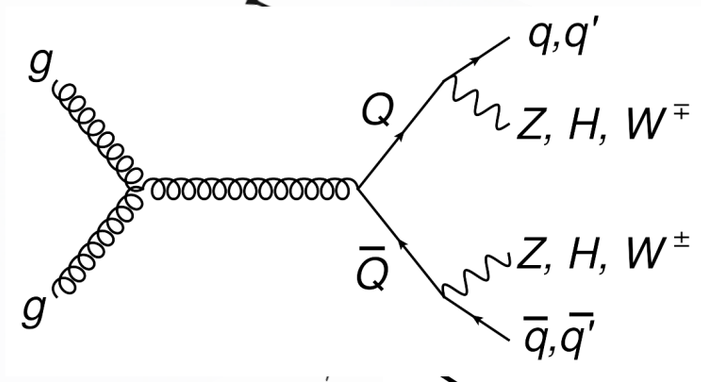


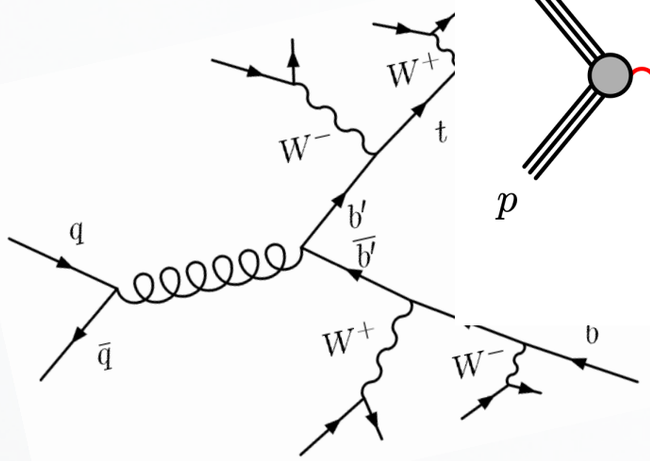


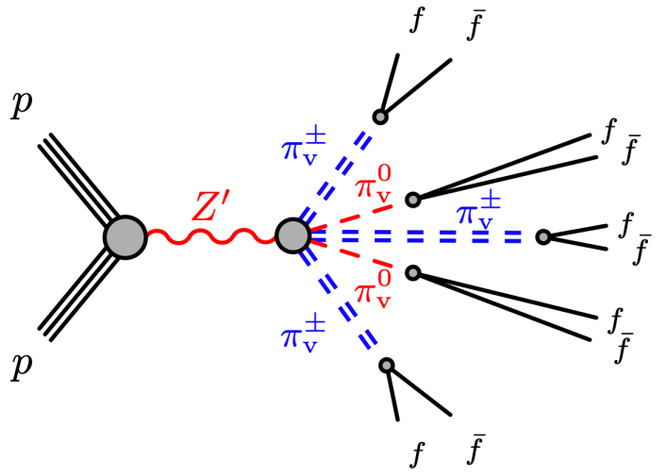


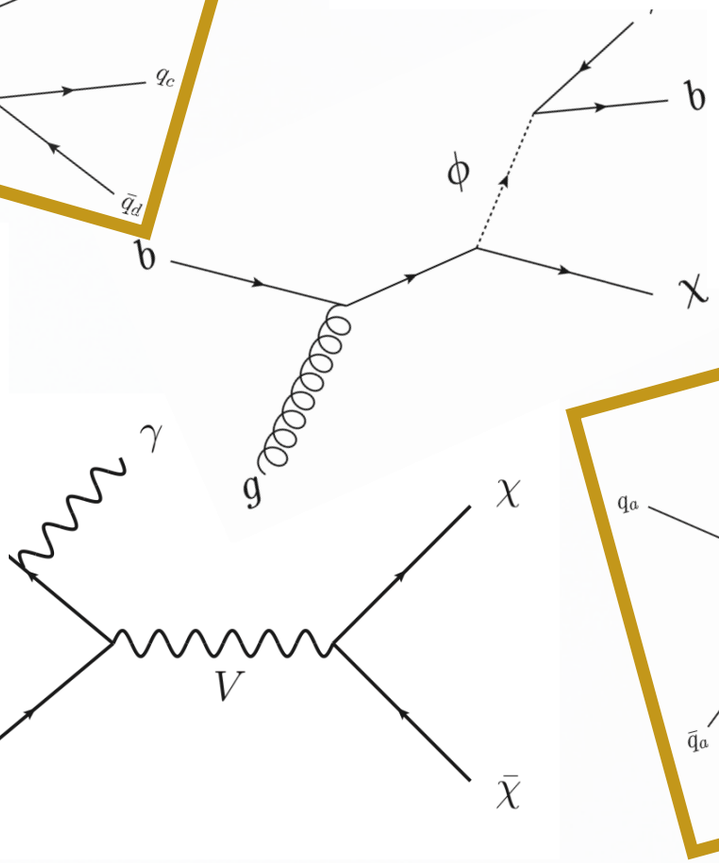


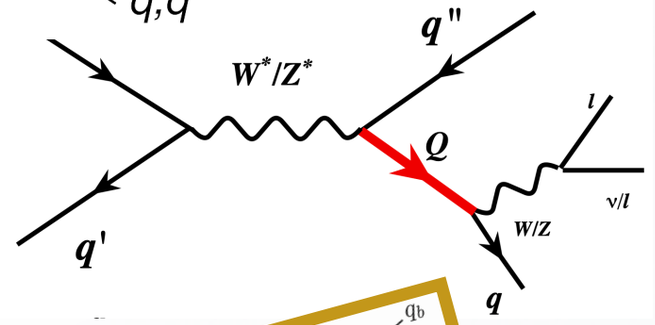


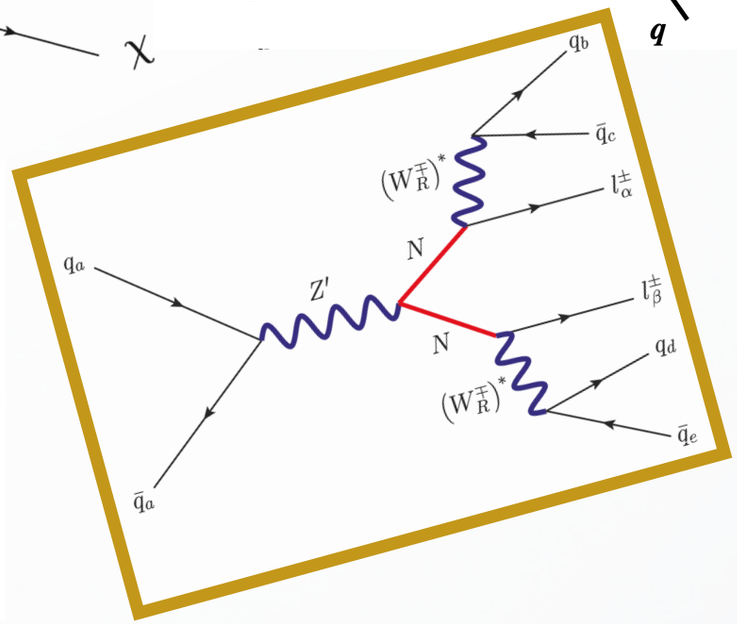












LRSM

PRD 10 (1974) 275 | PRD 11 (1975) 2258 | PRD 12 (1975) 1502 | PRL 44 (1980) 1316

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$Q_{L,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{L,R}, \qquad \ell_{L,R} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{L,R}$$

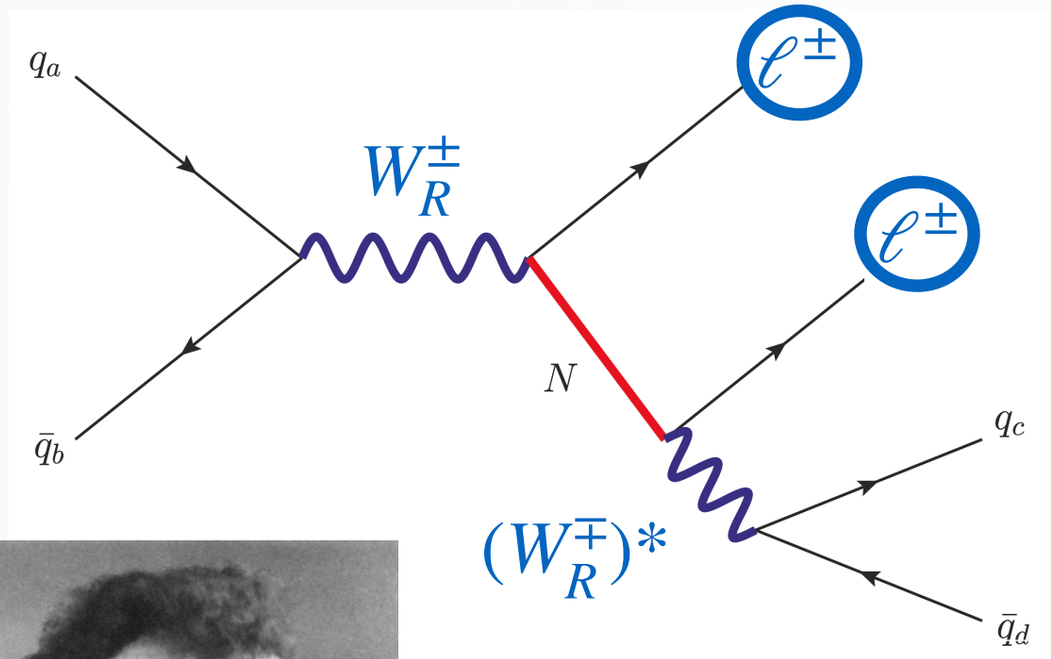
$$\frac{\lambda_{ij}}{\Lambda} L_i H L_j H$$

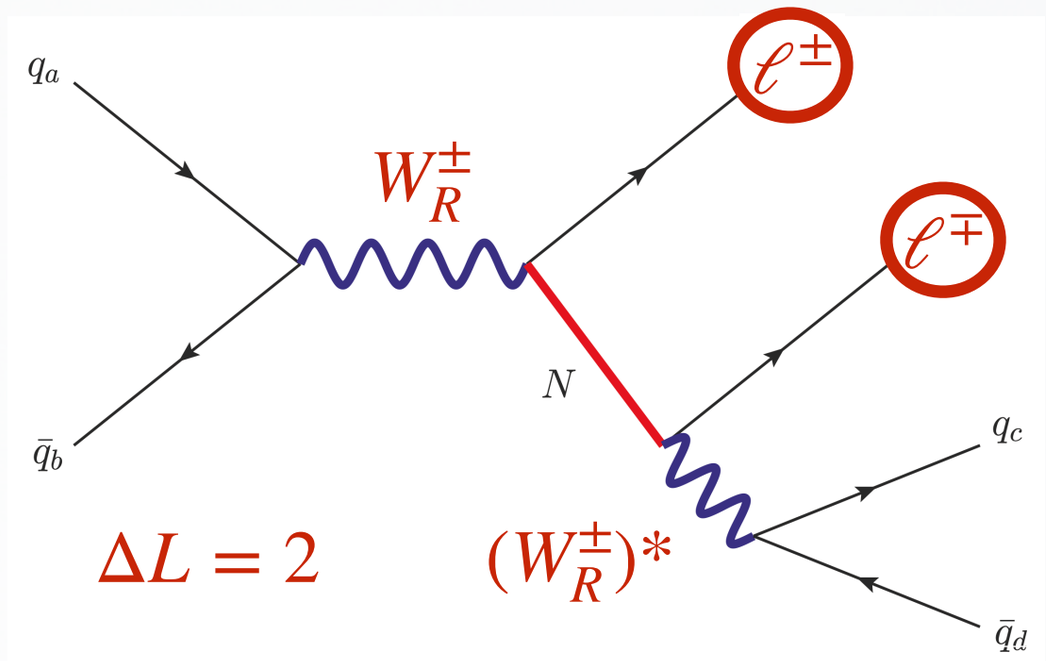
$$M_N = M_R \gg \text{vev}$$

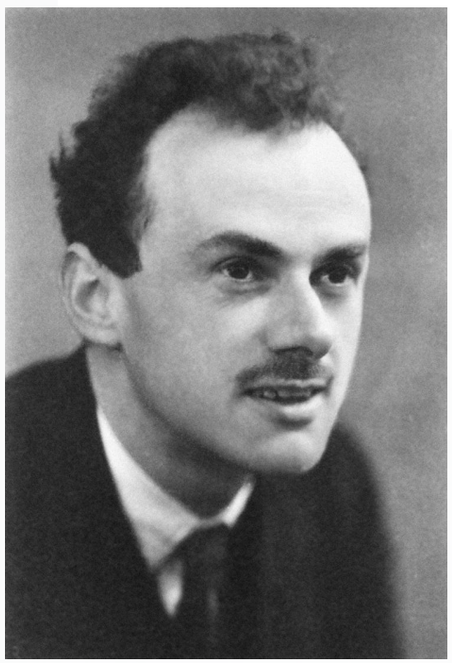
$$M_\nu = -m_D^T \frac{1}{M_N} m_D$$

- The origin of explicit **parity violation** in weak (V-A) interactions is not known
- Introduce the **left-right symmetry** to build a parity-conserving theory at higher energies
- Double the **weak gauge** sector
- Same **fermionic** content as in the SM
- Generation of the **Majorana** neutrino mass via **see-saw type-I mechanism**
- The **Higgs** sector becomes a multiplet: 2 charged and 2 doubly-charged scalars

Dirac or Majorana?







$\overline{\nu_i} \neq \nu_i$

Keung-Senjanović process

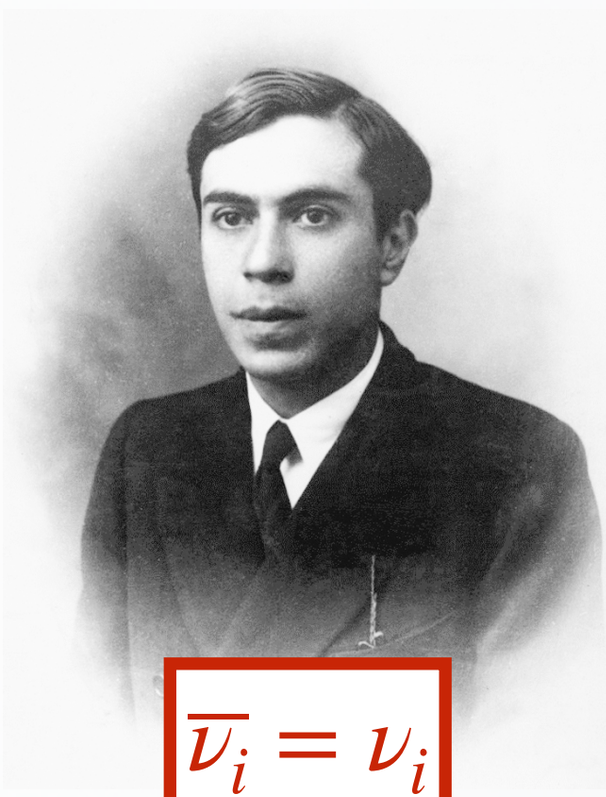
PRL 50 (1983) 1427

OS

- **Only OS leptons** in the final state
- **Larger SM background** at low energies

SS+OS

- Gives both **SS** and **OS** dileptons
- **Small SM background**



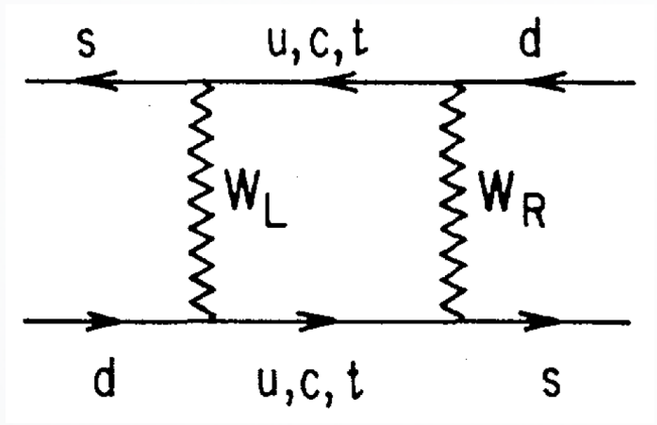
$\overline{\nu_i} = \nu_i$

Same-flavor dileptons, if **no mixing** between Ns

Pre-LHC constraints

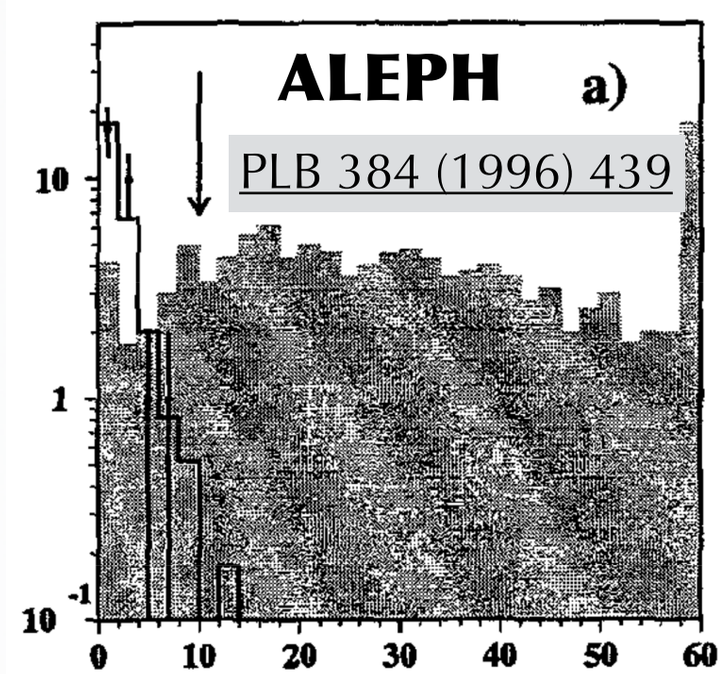
- Searches for **long-lived heavy neutral leptons** at **LEP** (130 GeV, 136 GeV)
- Pair production of charged leptons $L \to NW^*$ and N ($N \to \ell W^*$); **m(N) > 100 GeV**
- Searches for $W_R \to tb$ at **Tevatron** (1.96 TeV); **$m(W_R)$ > 0.8 TeV**
- Indirect constraints on W_R boson mass from **K_L-K_S** mass difference, **$m(W_R)$ > 1.6 TeV**
- **SN1987A**: **0.5 < $m(W_R)$ < 22 TeV**

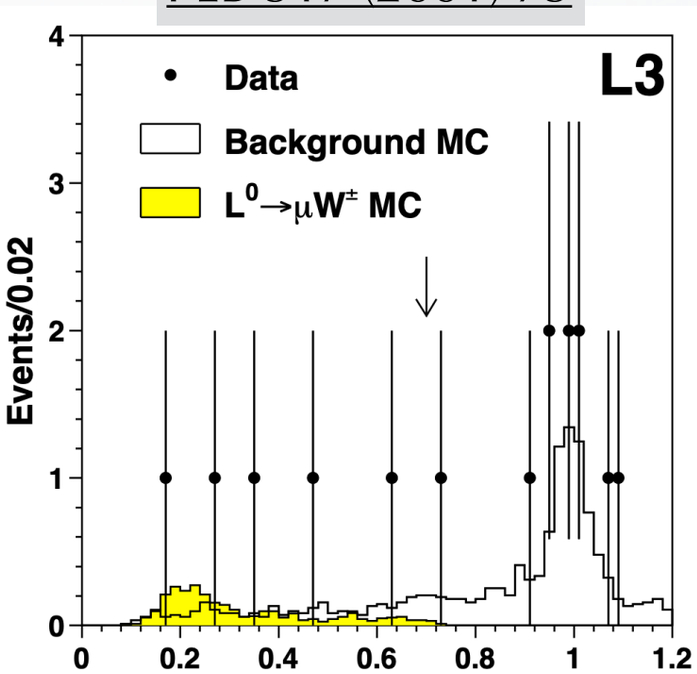
PRD 39 (1989) 1229

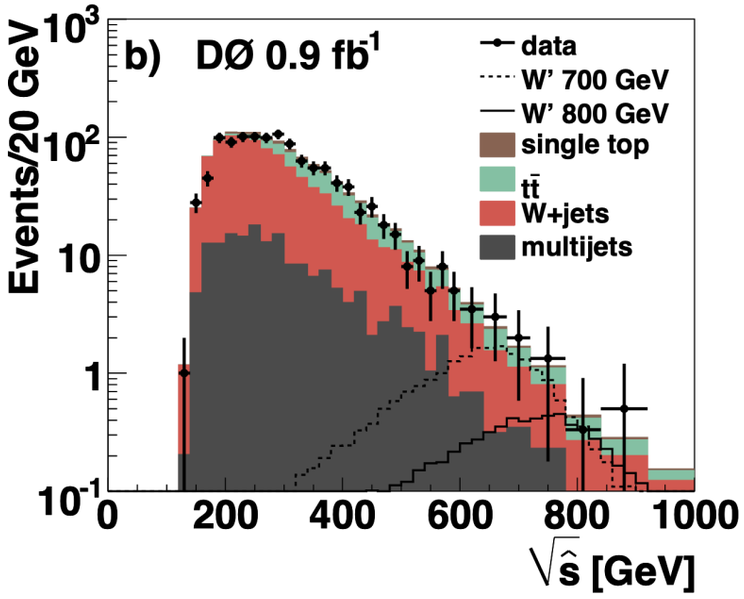


PRL 48 (1982) 848

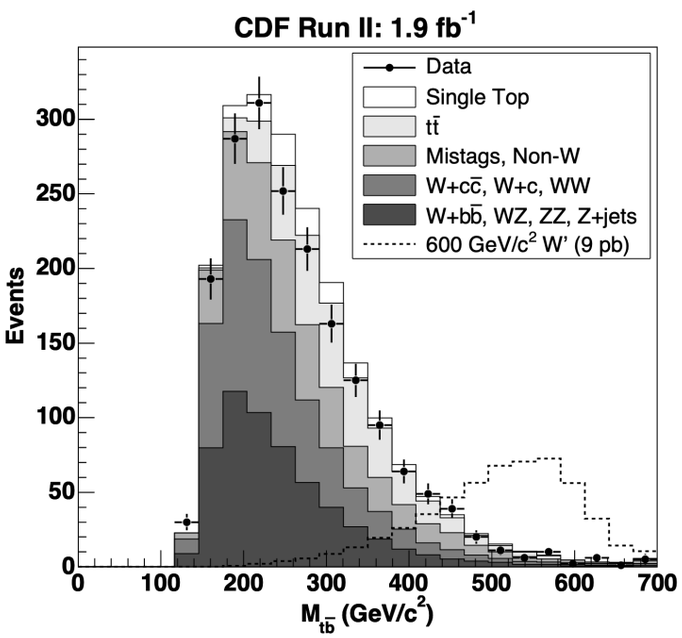
PLB 517 (2001) 75







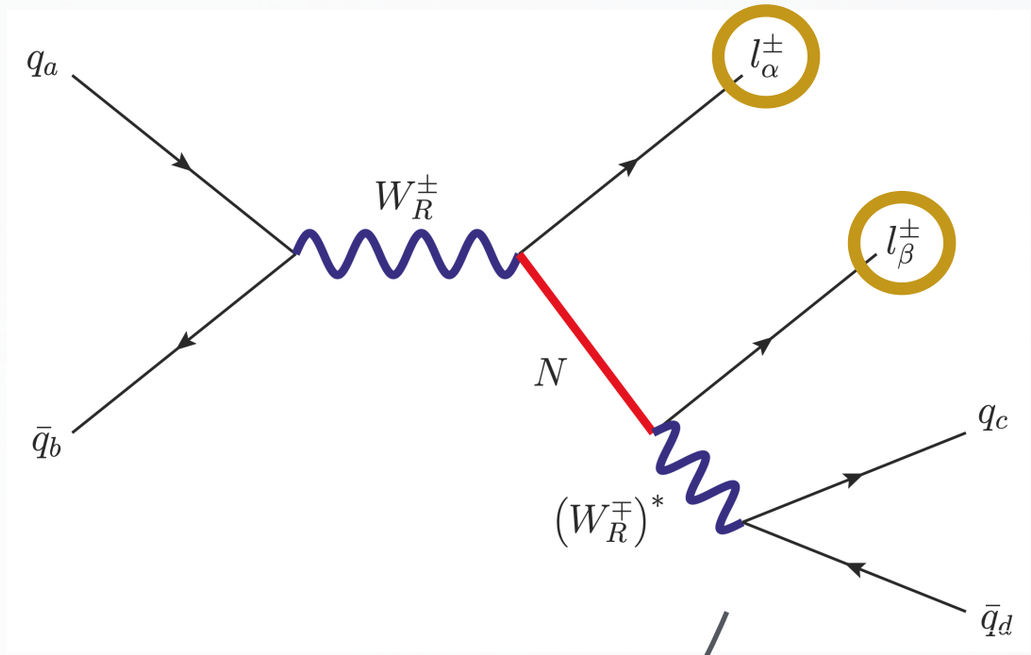
PRL 100 (2008) 211803

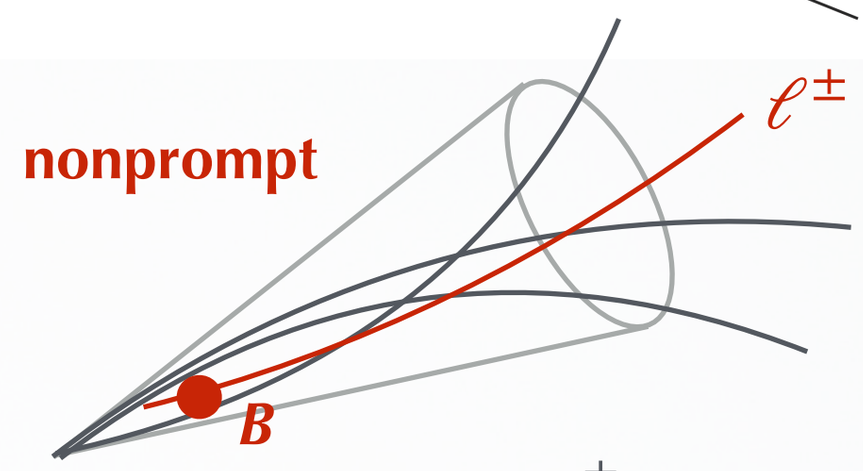


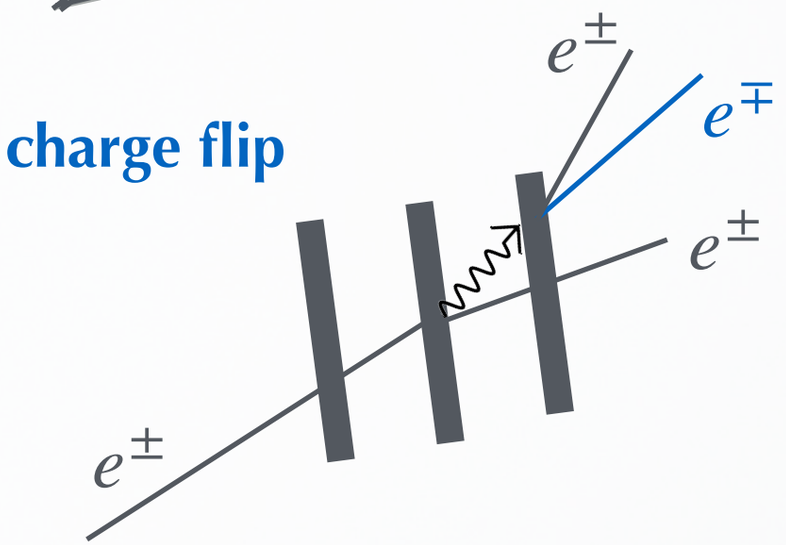
PRL 103 (2009) 041801

Golden final state

- Final states with two **same-sign** leptons
- **Small background** from SM processes (e.g. diboson) 👍
- Populated with **nonprompt** (aka **fake**) leptons 👎
- **Charge flip** probability for electrons is also important
- Simulation is not reliable (depends on detector material description, etc.) → estimate these background **from data**
- Measure lepton **fake rates** and **charge flip probabilities** and apply it in signal region
- Most commonly used **Tight-to-loose** and **Fake Matrix** methods
- **Cut-and-count** robust analyses to search for new physics; **almost background-free** at high energies

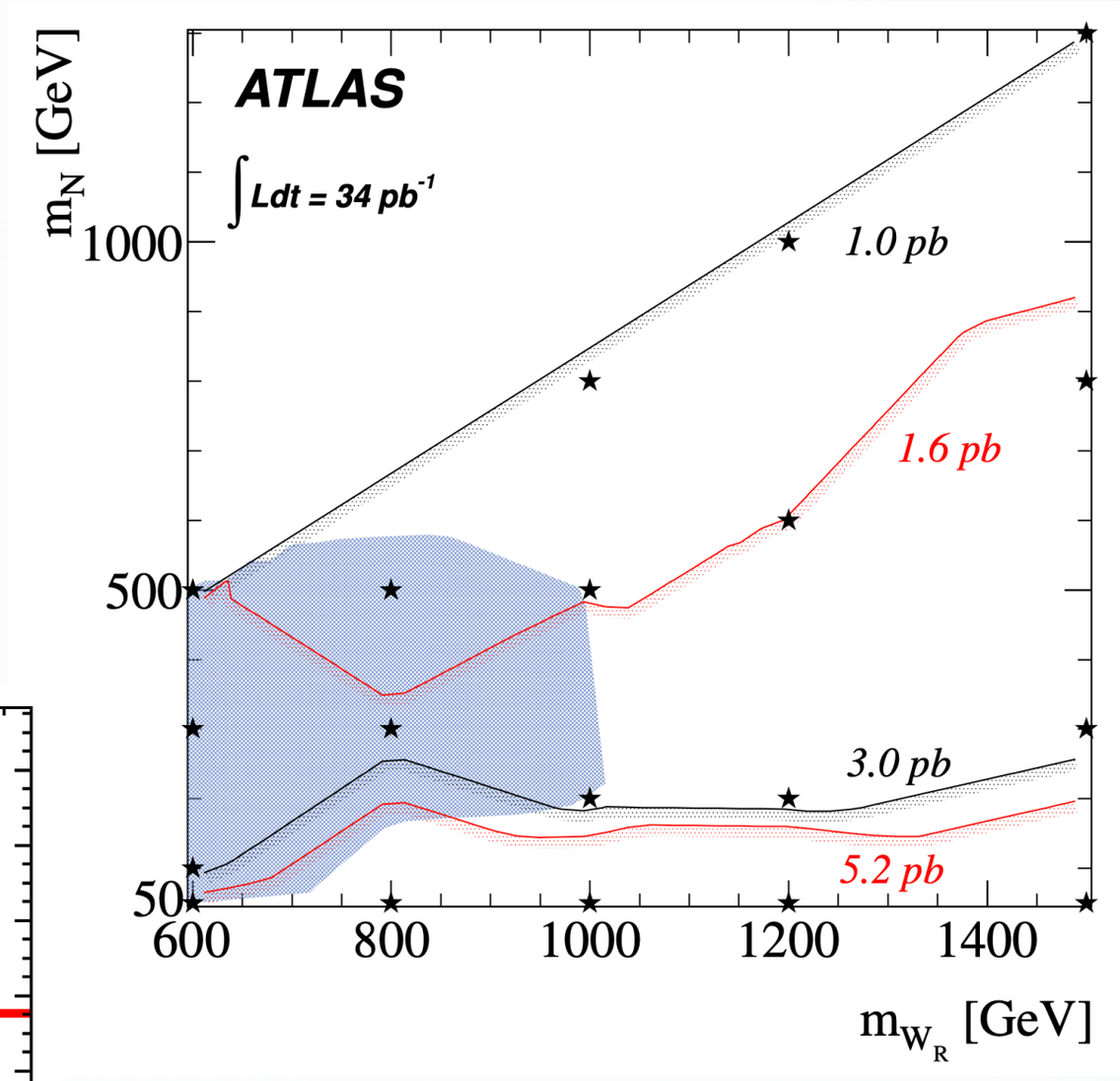


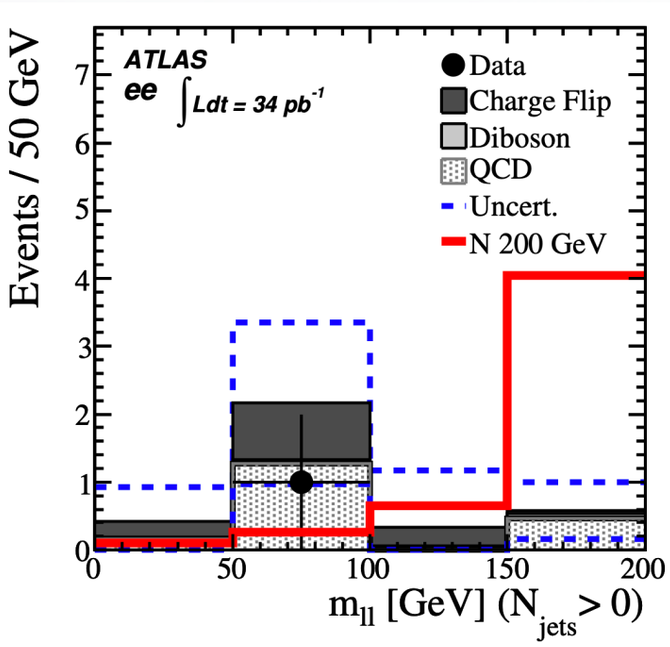


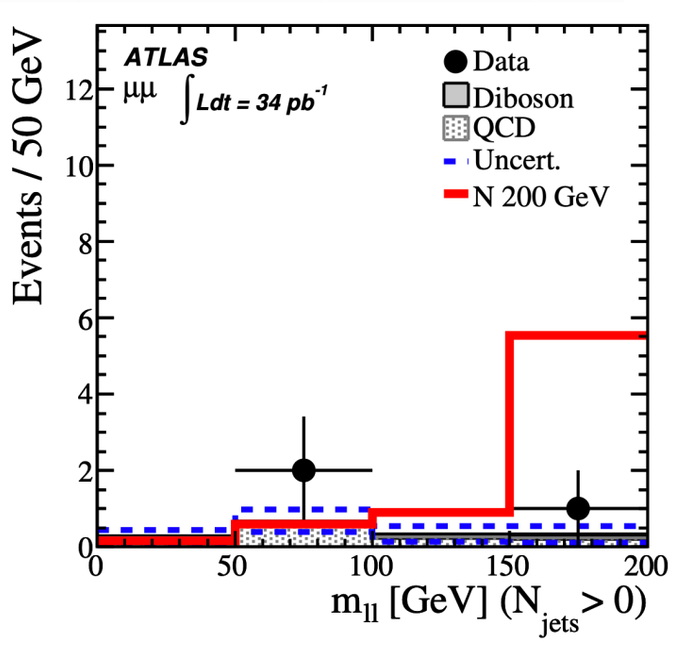


Inclusive search

- Use **same-sign dileptons** to probe a vast scope of new physics models
- Select two leptons with **at least one additional jet;** N decay products are boosted, if m(W_R) >> m(N)
- Probe new physics in **dilepton invariant mass** spectrum with $N_{jets} > 0$



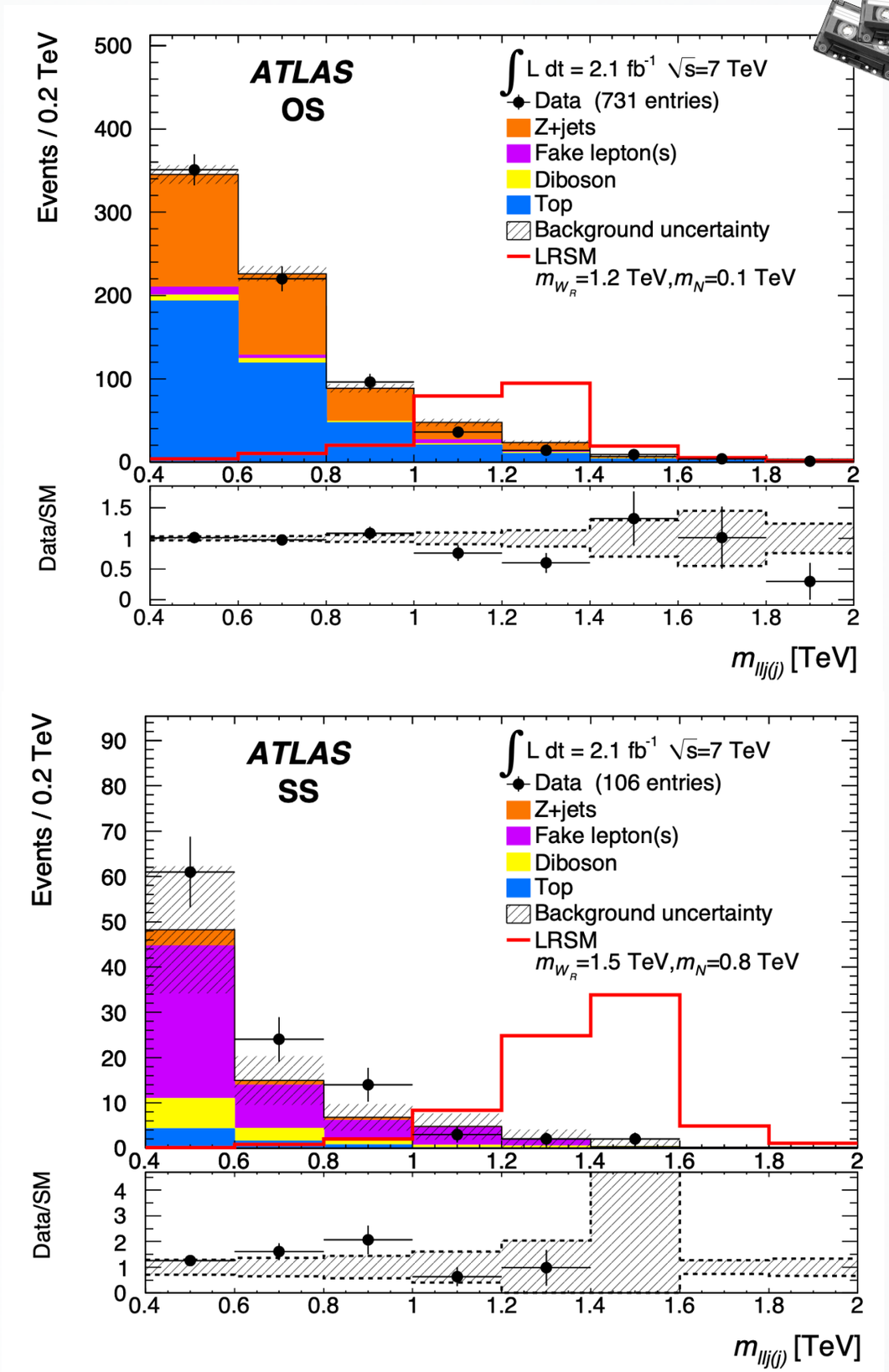


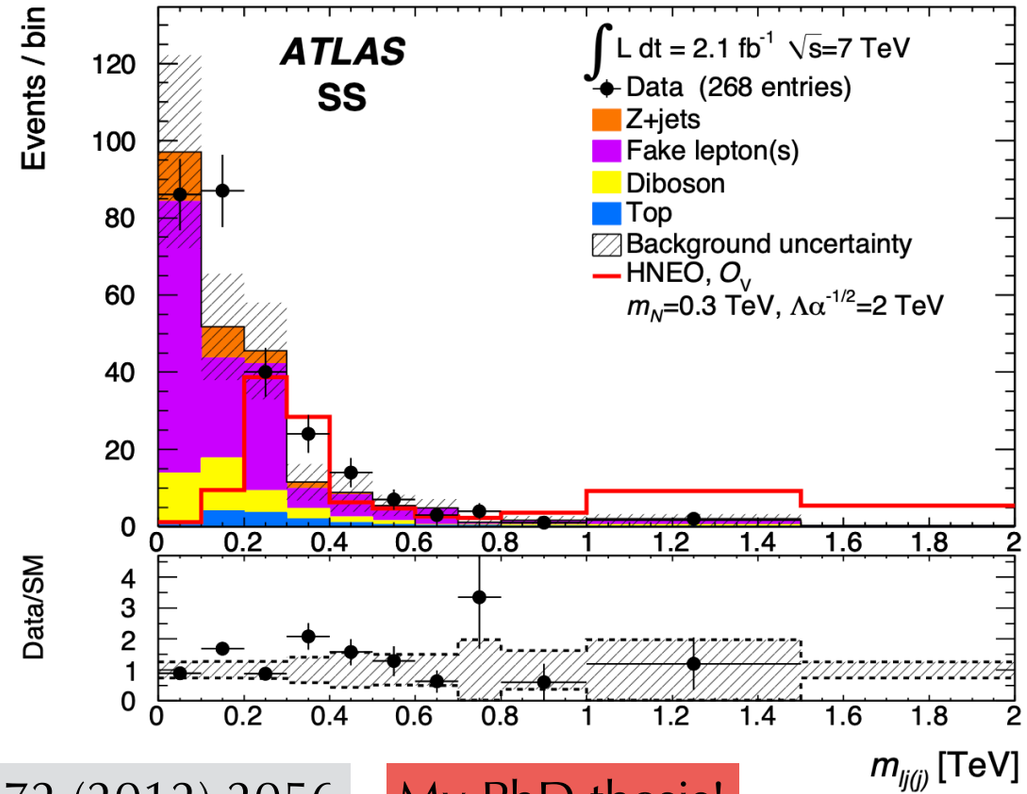


JHEP 1110 (2011) 107

First optimized searches

- Use the **Keung-Senjanović process** to search for **Dirac** and **Majorana N** production in the decay of $\mathbf{W_R}$ boson
- Also probe the **N** production and decay via four dim-6 **effective** operators
- **Cut-and-count** analysis: $m(\ell\ell) > 110$ GeV, $S_T > 400$ GeV, $m(\ell\ell j(j)) > 400$ GeV
- Use **optimized** strategy with $m(\ell\ell j(j))$ and $m(\ell j(j))$ to search for new physics



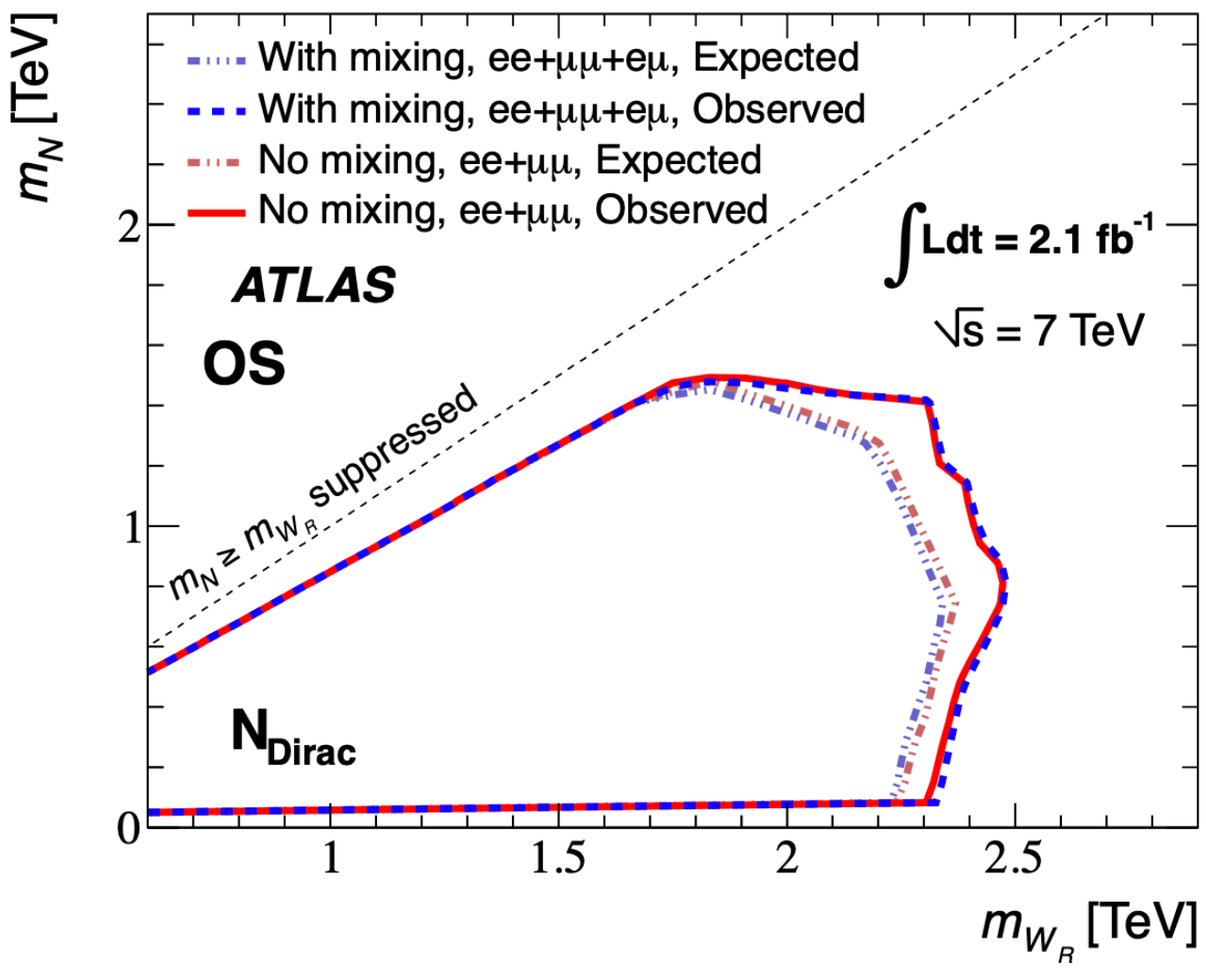


EPJC 72 (2012) 2056

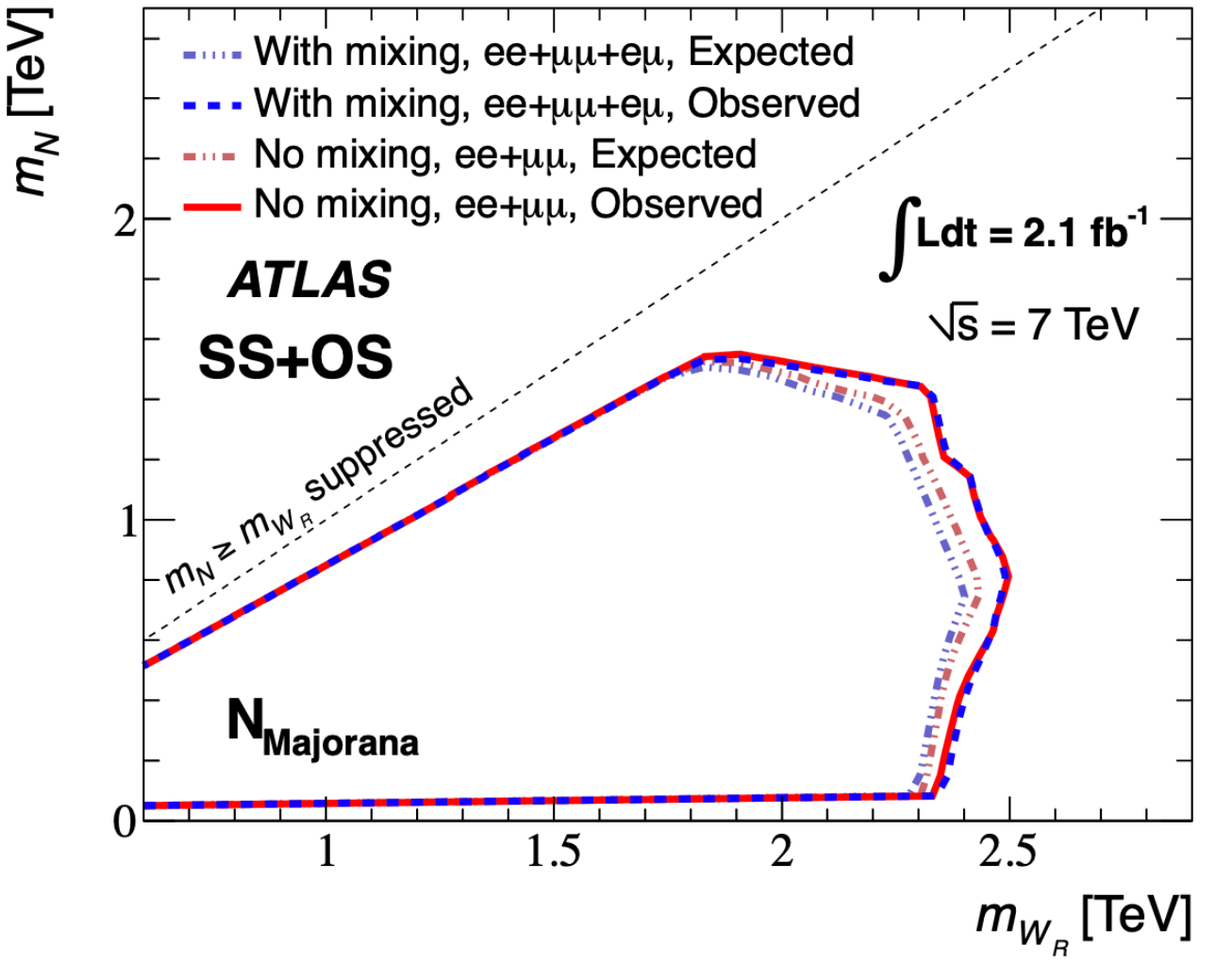
My PhD thesis!

First constraints

Dirac



Majorana



- Sensitivity is mainly **statistically** limited
- Consider $\mathbf{N_e\text{-}N_\mu}$ **mixing** scenario in the interpretation

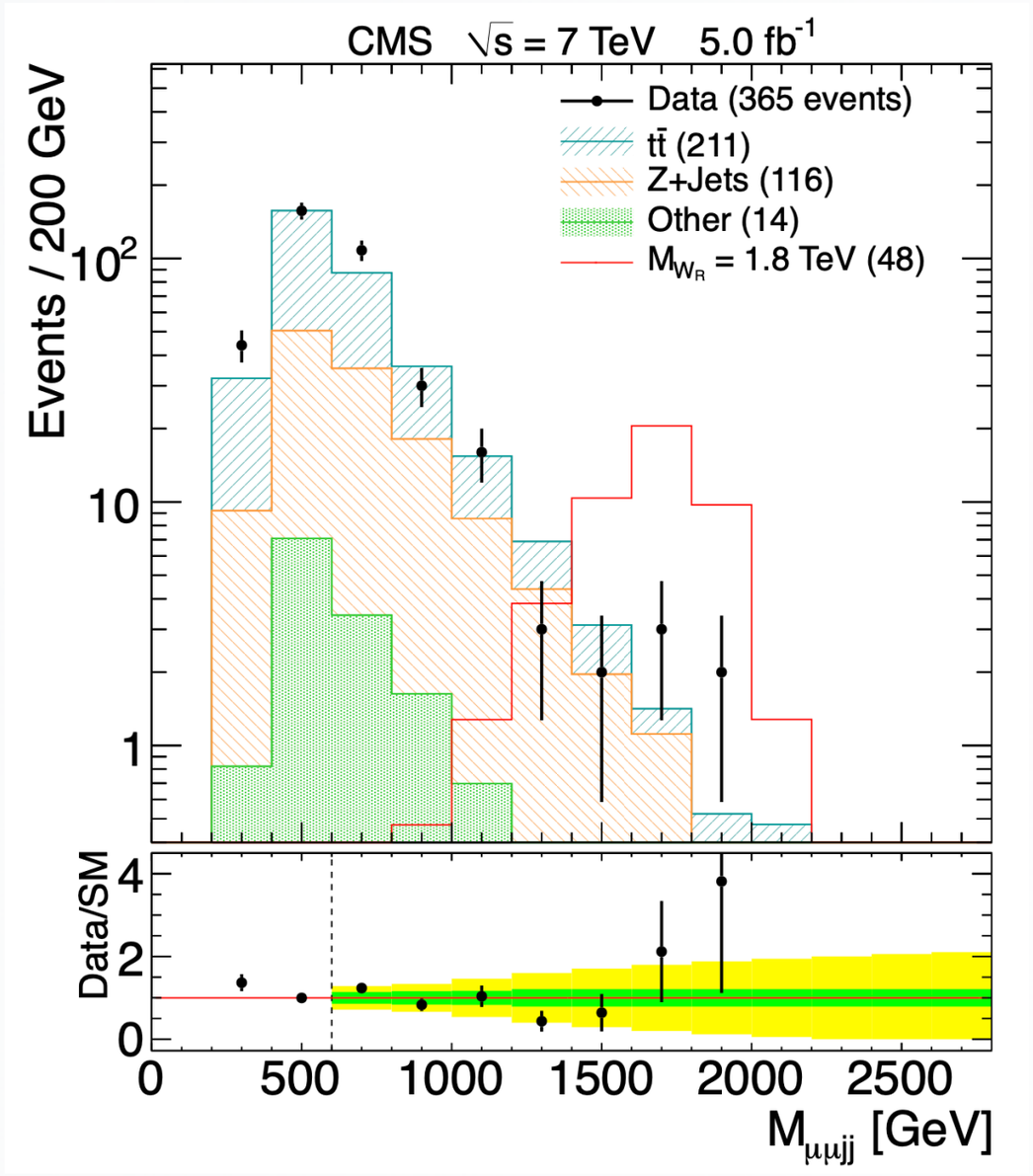
$m(W_R) > 1.8$ TeV, $m(N) > 0.3$ TeV

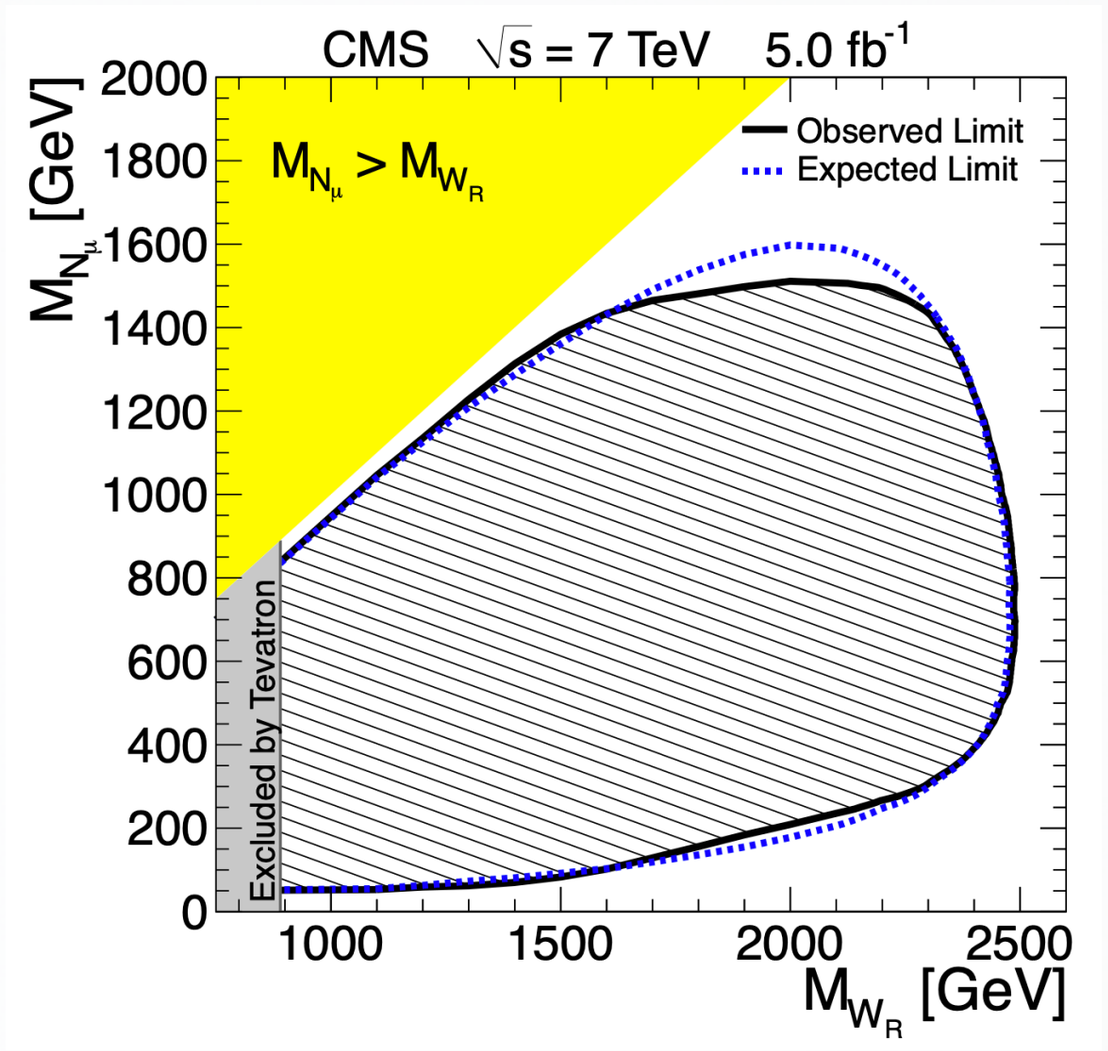
$m(W_R) > 2.3$ TeV, $m(N) > 0.9$ TeV

EPJC 72 (2012) 2056 My PhD thesis!

First optimized searches

- Focus on **μμjj** channel
- **Cut-and-count** analysis:
  $m(\mu\mu) > 200$ GeV, $m(\ell\ell jj) > 600$ GeV



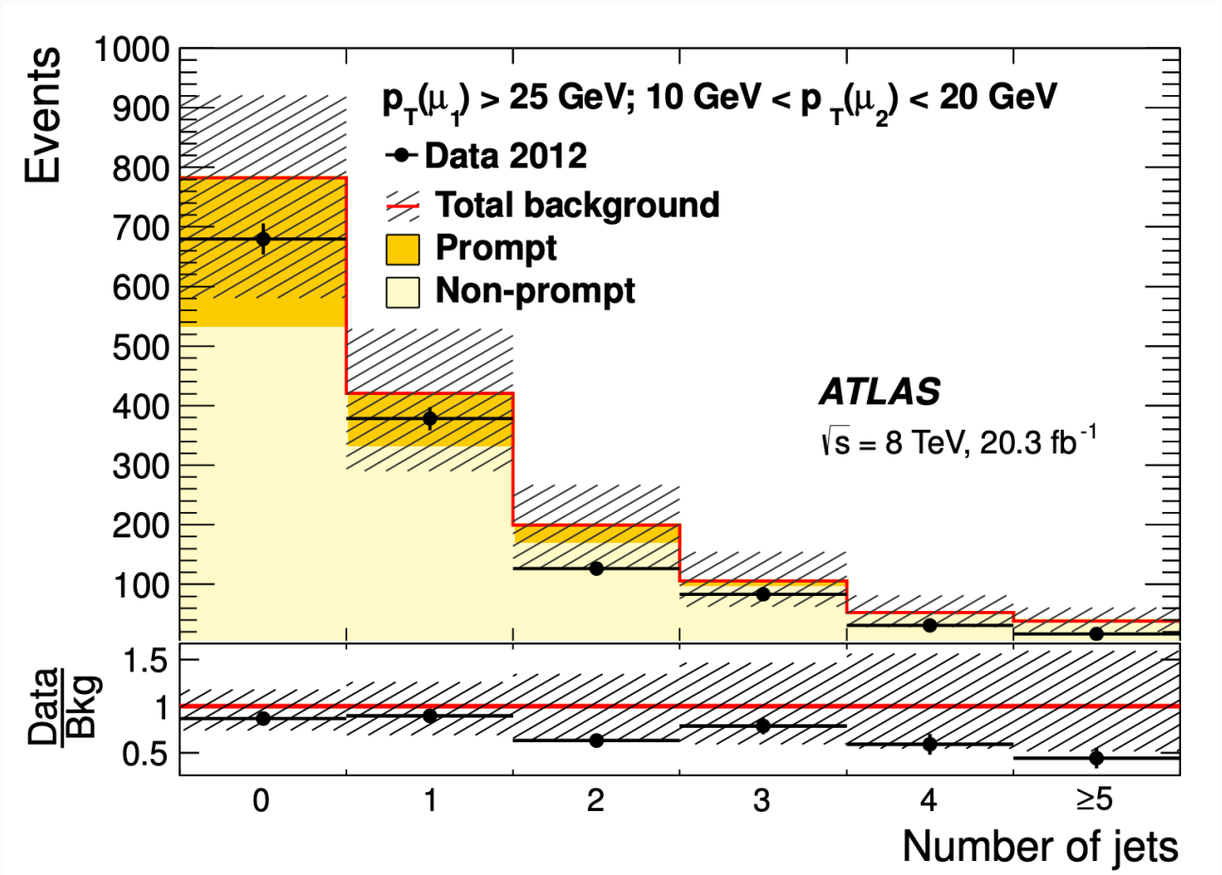


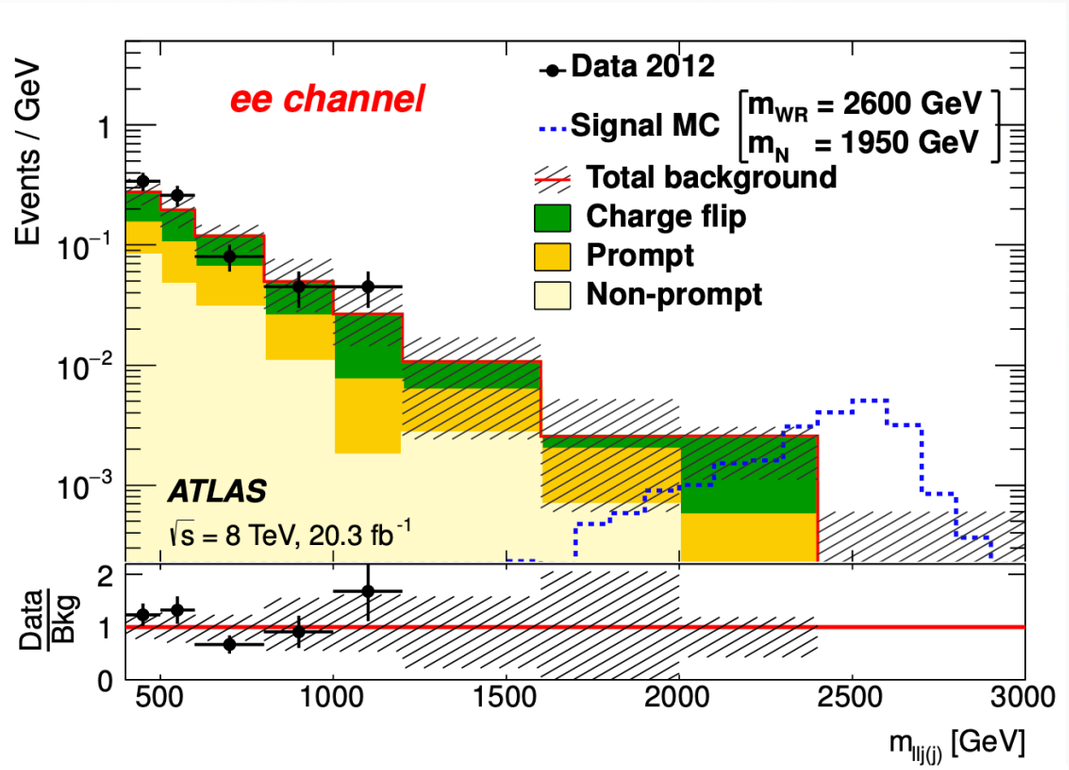
PRL 109 (2012) 261802

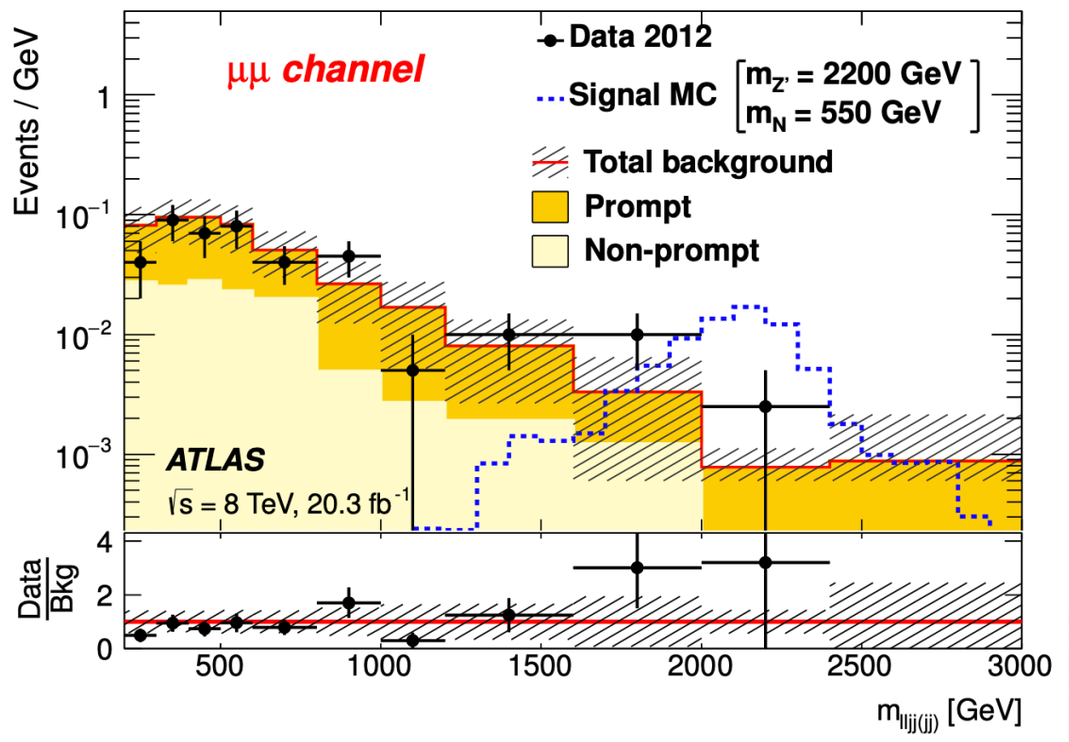
$m(W_R) > 2.5$ TeV

Moving to 8 TeV

- Focus on **Majorana** neutrinos
- Include the **first search for Z′** → NN, with an additional selection of m($\ell\ell$jj(jj)) > 200 GeV
- Include **N_e-N_μ mixing** scenario







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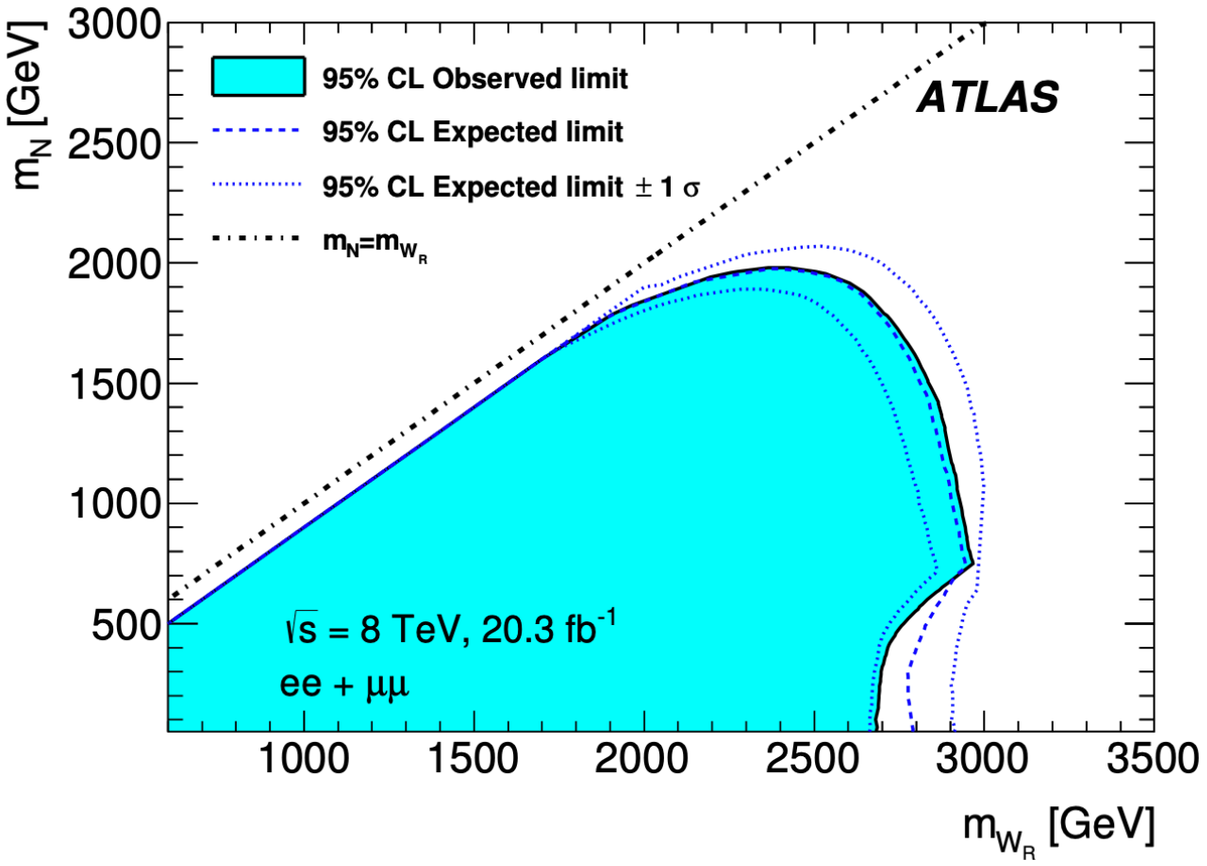
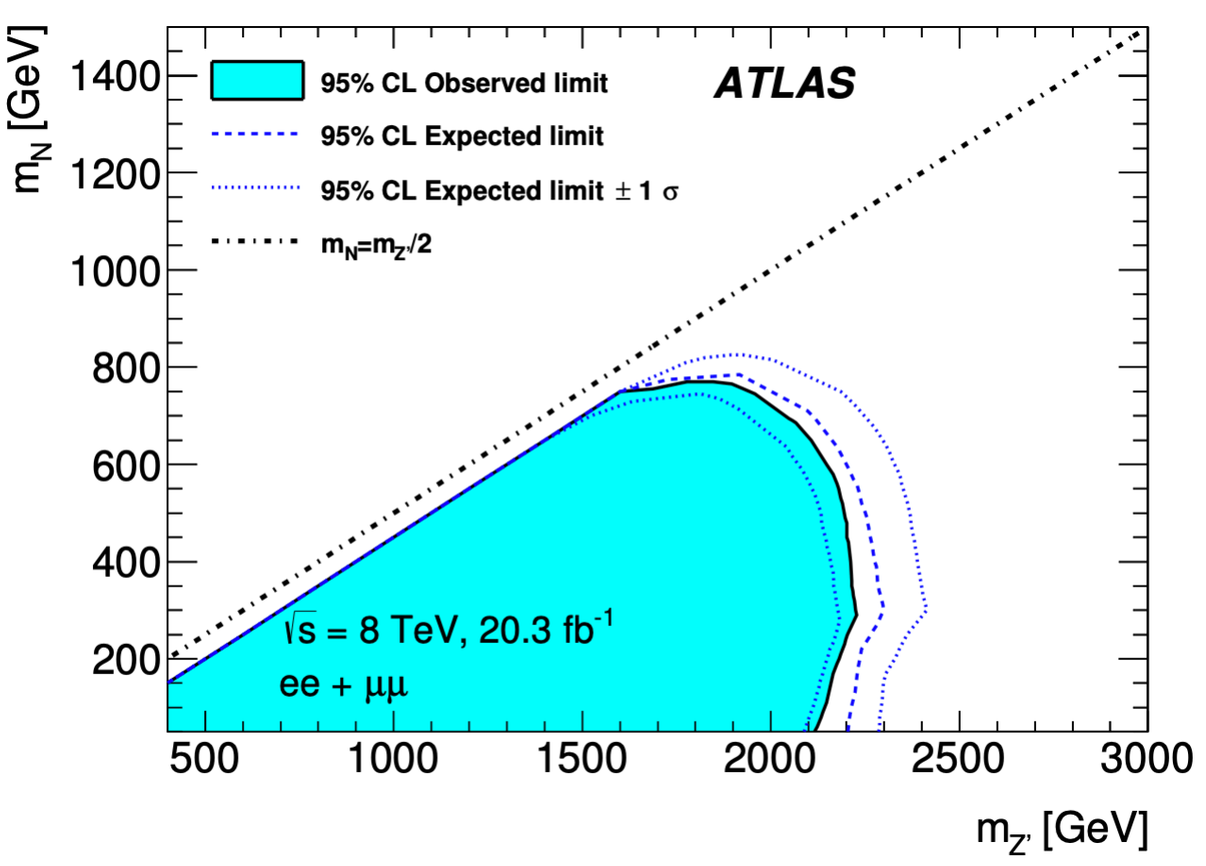
Moving to 8 TeV

W_R



Z'



$m(N) > 2$ TeV $m(W_R) > 2.8$ TeV $m(Z') > 2.2$ TeV

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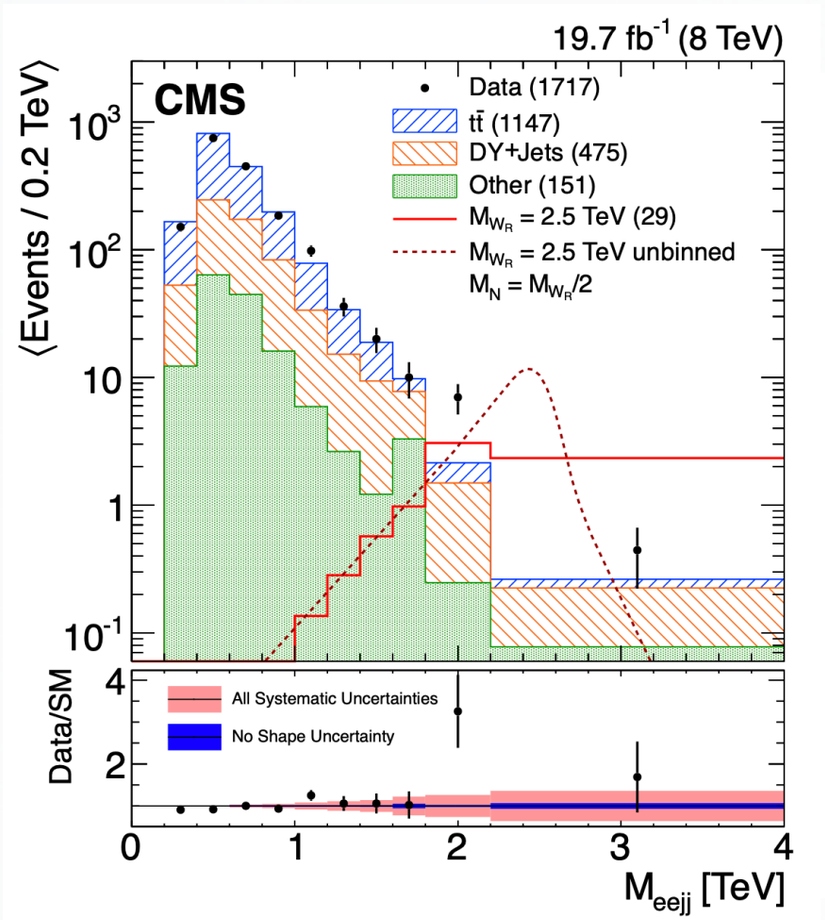
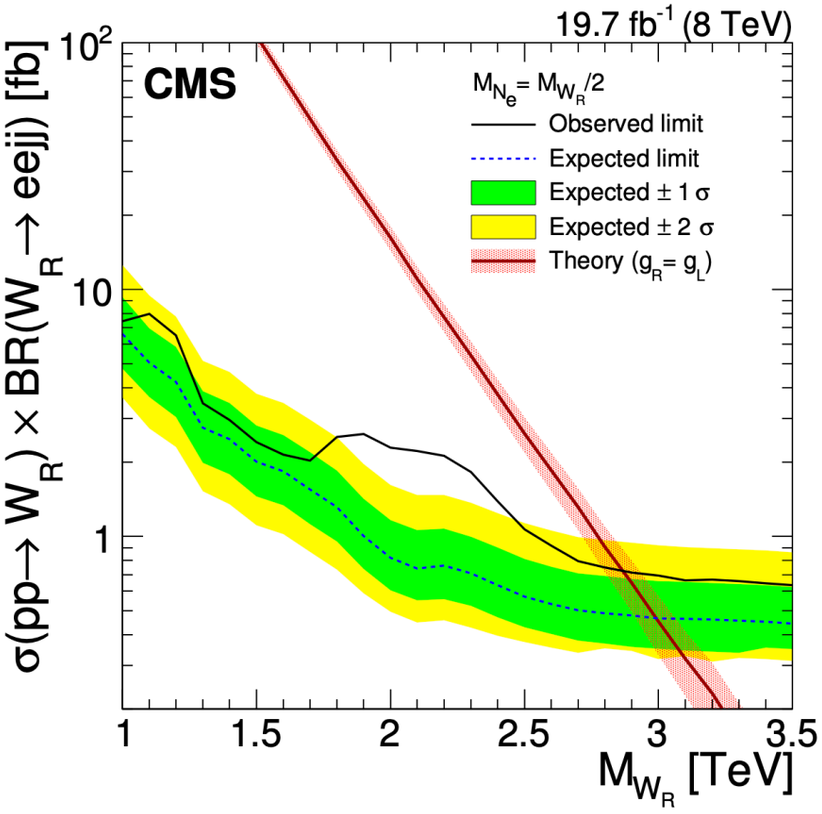
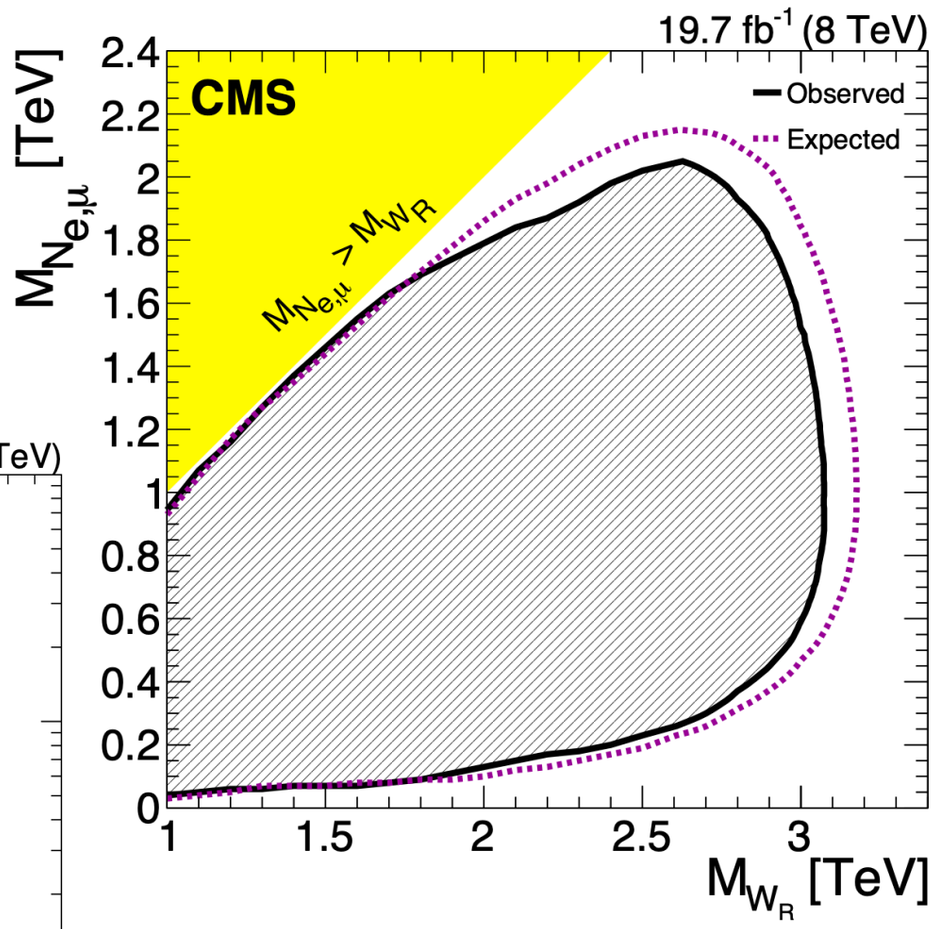
Moving to 8 TeV

- **Similar** analysis strategy as in the 7 TeV study
- Continue to **improve limits** on LRSM
- **Excess** (2.8σ, local) observed in the electron channel







$m(W_R) > 3$ TeV

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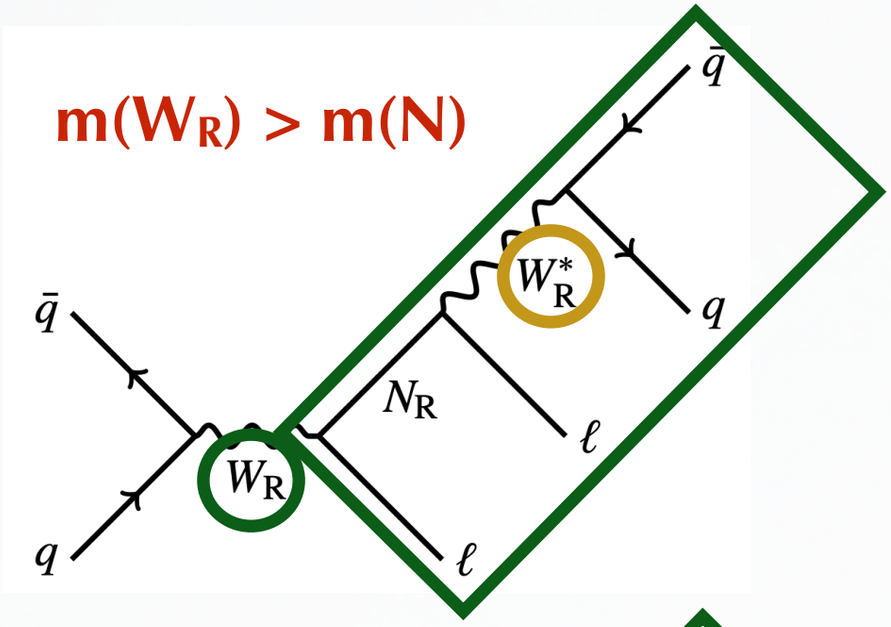
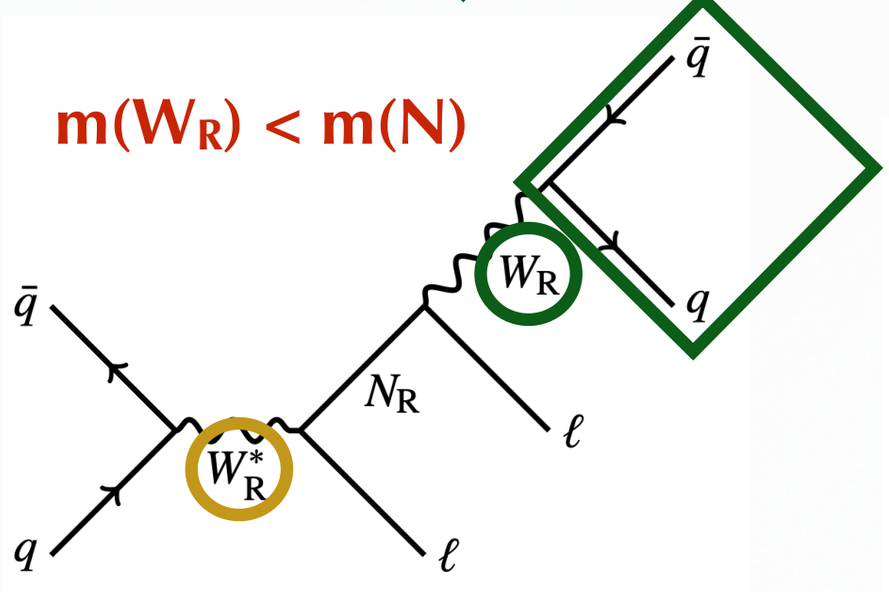
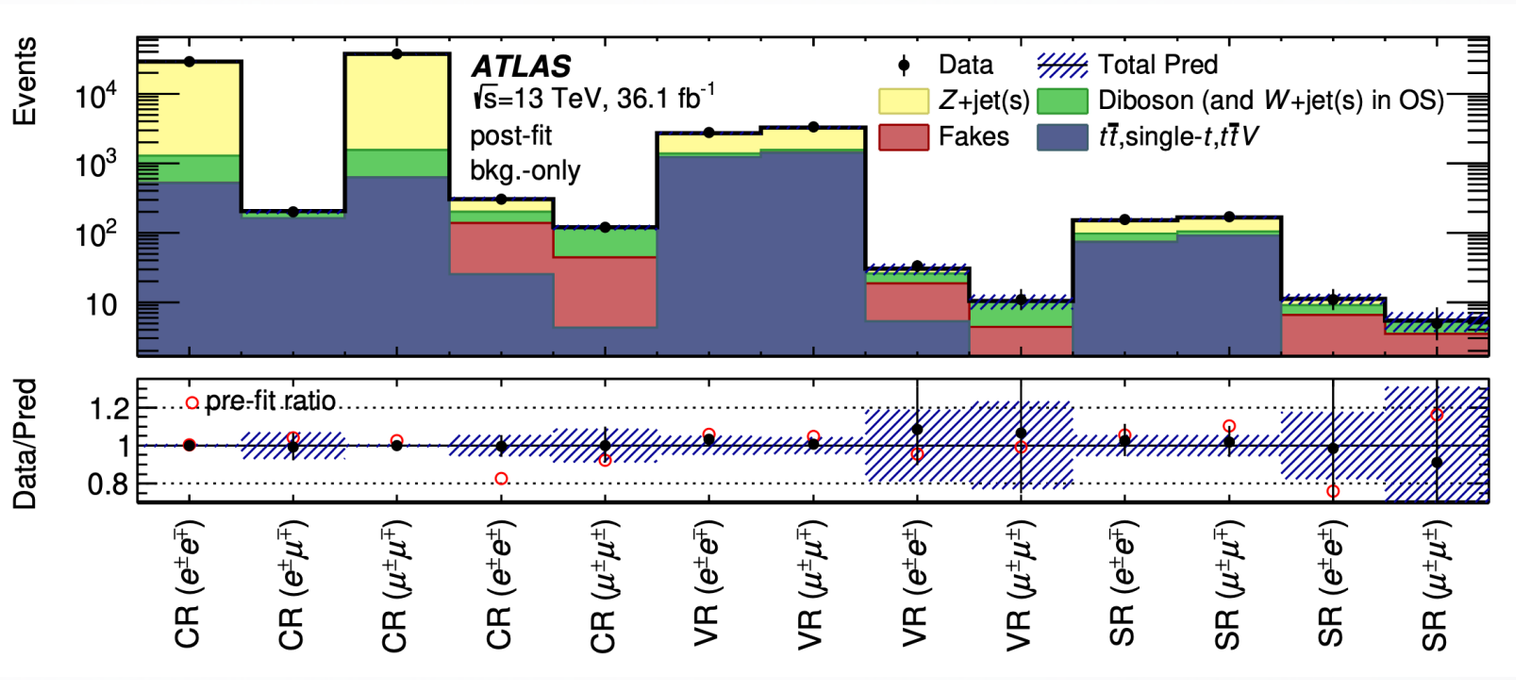
At the edge





- **Higher energy** and **more data** at **13 TeV**
- Extend the analysis for **Majorana** and **Dirac N** to the **$m(W_R) < m(N)$** case → on-shell W_R from **dijet** reconstruction
- Two jets with **$p_T > 100$ GeV**; $m(\ell\ell) > 400$ GeV, $m(jj) > 110$ GeV, $S_T > 400$ GeV
- Include several control (CRs) and signal (SRs) regions in a **common fit**
- **Validate** background predictions in validations regions (VRs)
- Use $m(\ell\ell jj)$ for **$m(W_R) > m(N)$** and $m(jj)$ for **$m(W_R) < m(N)$**



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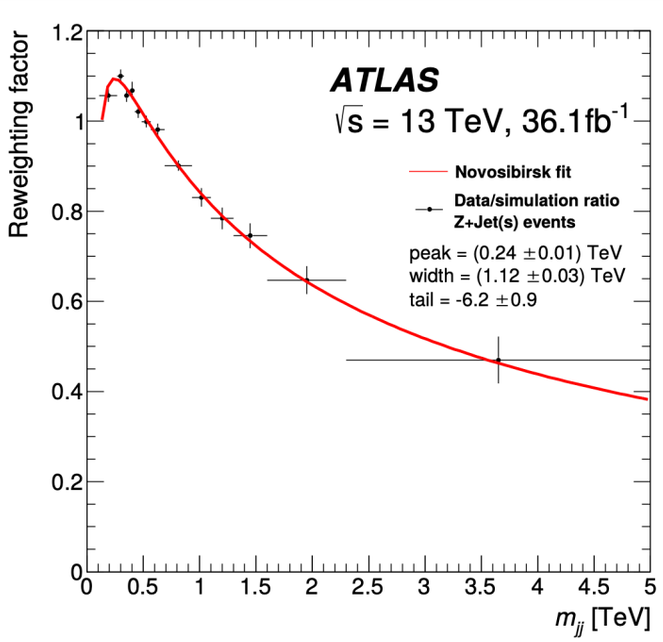
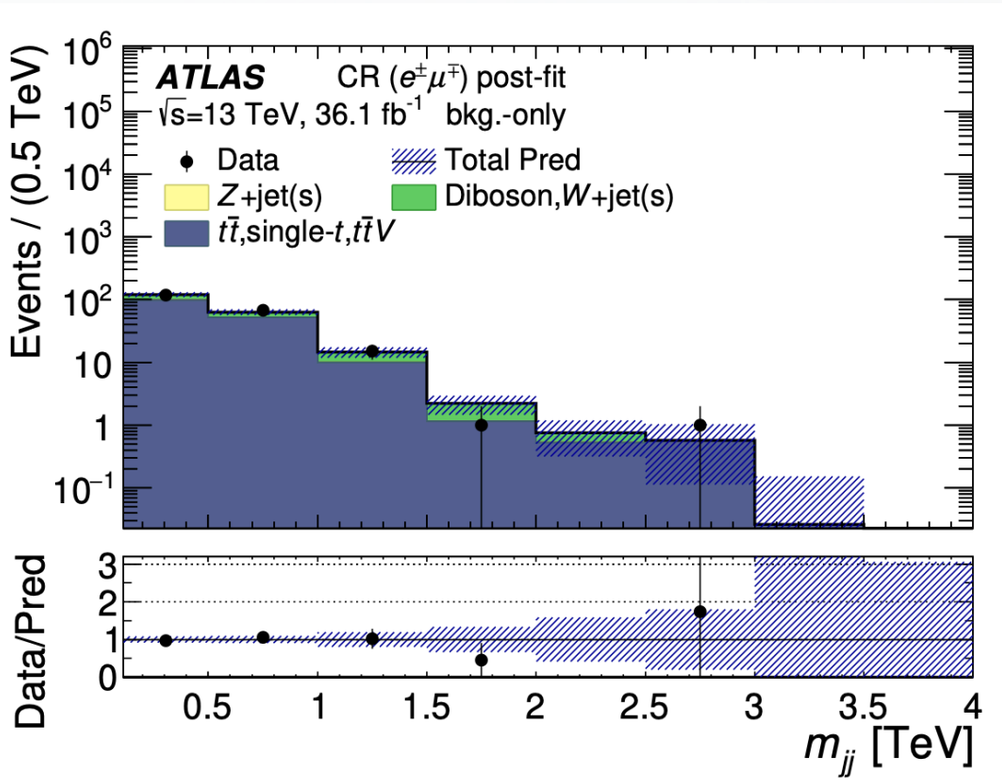
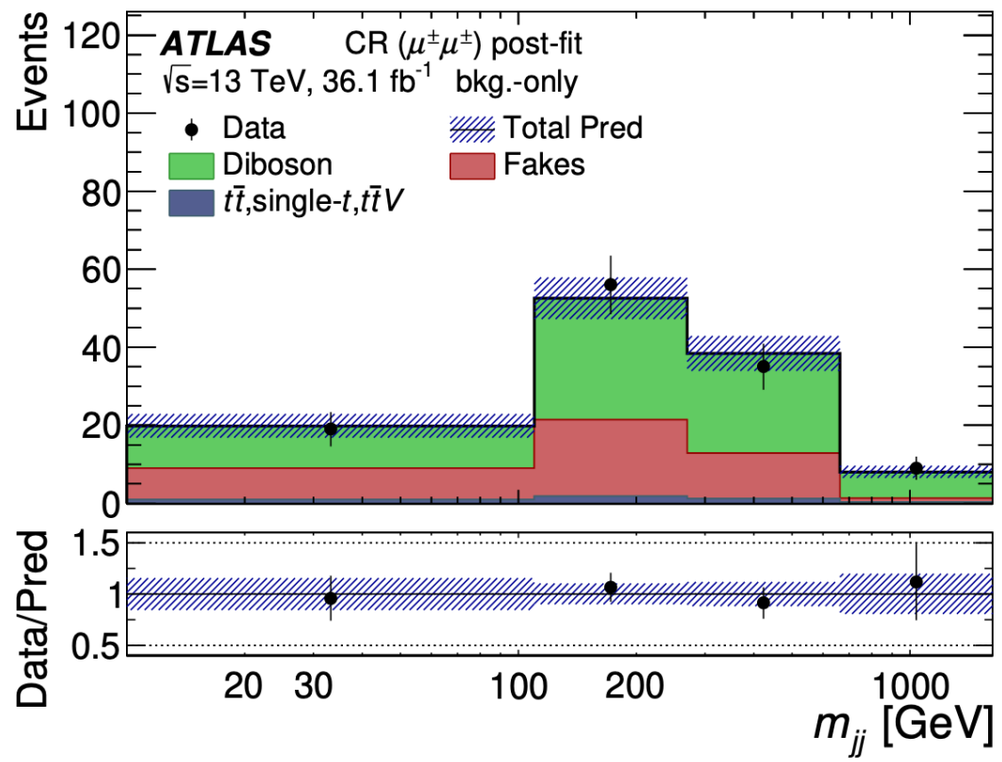
At the edge

- Correct the predicted **m(jj)** spectrum in data using **Z+jets** events
- Control **ttbar**, **diboson** and **Z+jets** backgrounds in CRs
- **Nonprompt** lepton background from data





Region	Control region			Validation region		Signal region	
Channel	CR($\ell^{\pm}\ell^{\mp}$)	CR($\ell^{\pm}\ell'^{\mp}$)	CR($\ell^{\pm}\ell^{\pm}$)	VR($\ell^{\pm}\ell^{\mp}$)	VR($\ell^{\pm}\ell^{\pm}$)	SR($\ell^{\pm}\ell^{\mp}$)	SR($\ell^{\pm}\ell^{\pm}$)
m_{ee} [GeV]	[60, 110]	—	[110, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{\mu\mu}$ [GeV]	[60, 110]	—	[60, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{e\mu}$ [GeV]	—	> 400	—	—	—	—	—
H_{T} [GeV]	> 400	> 400	—	> 400	—	> 400	> 400
m_{jj} [GeV]	> 110	> 110	—	> 110	—	> 110	> 110
Jet p_{T} [GeV]	> 100	> 100	> 50	> 100	> 50	> 100	> 100



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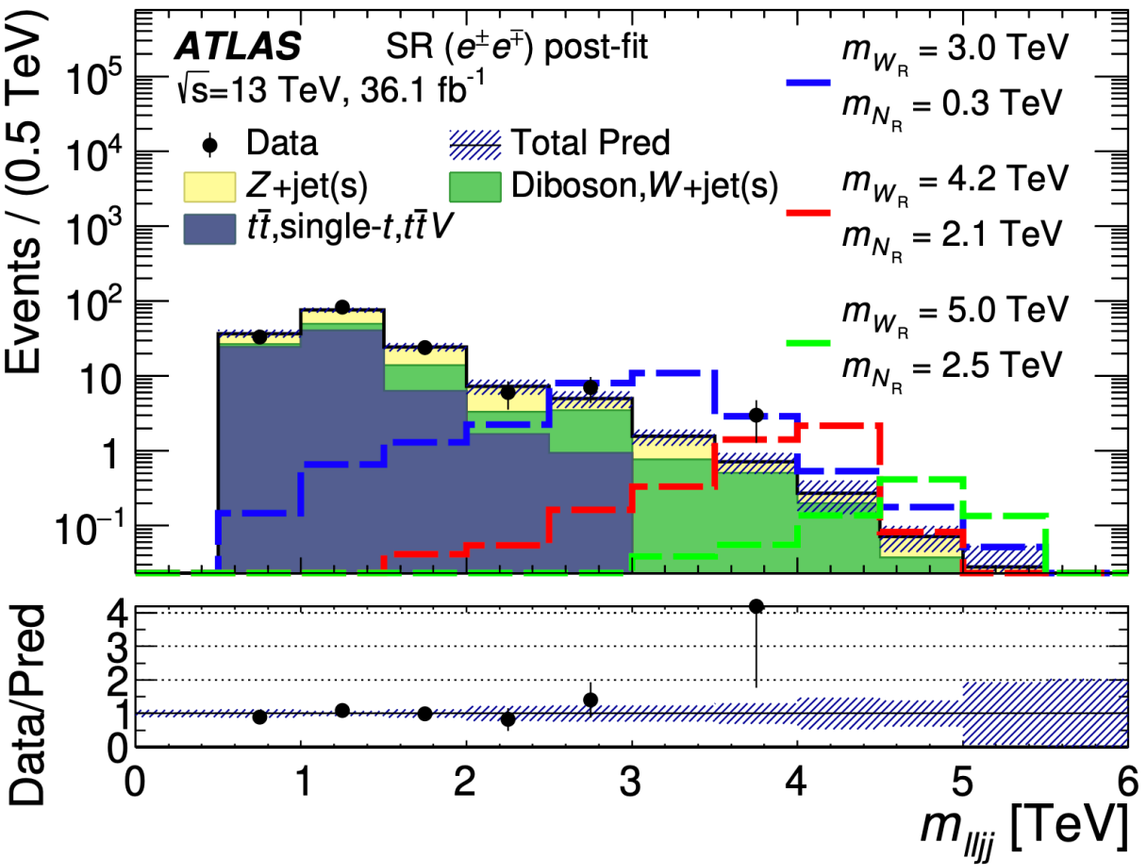
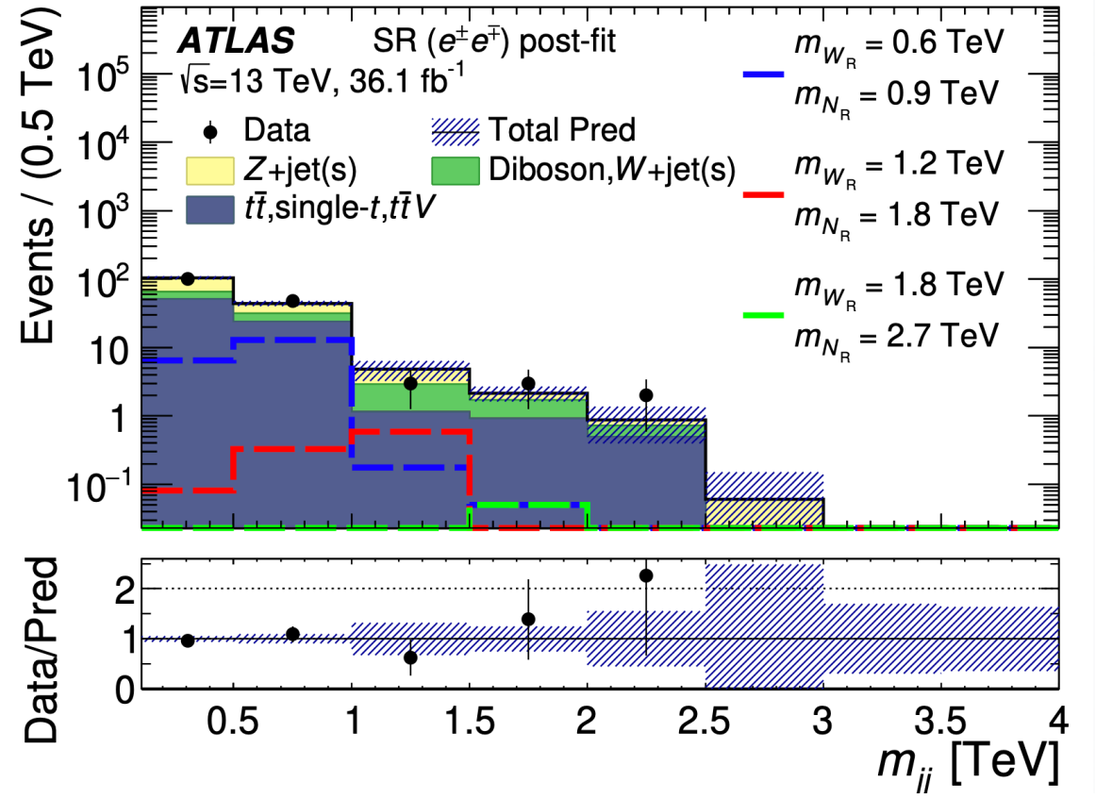
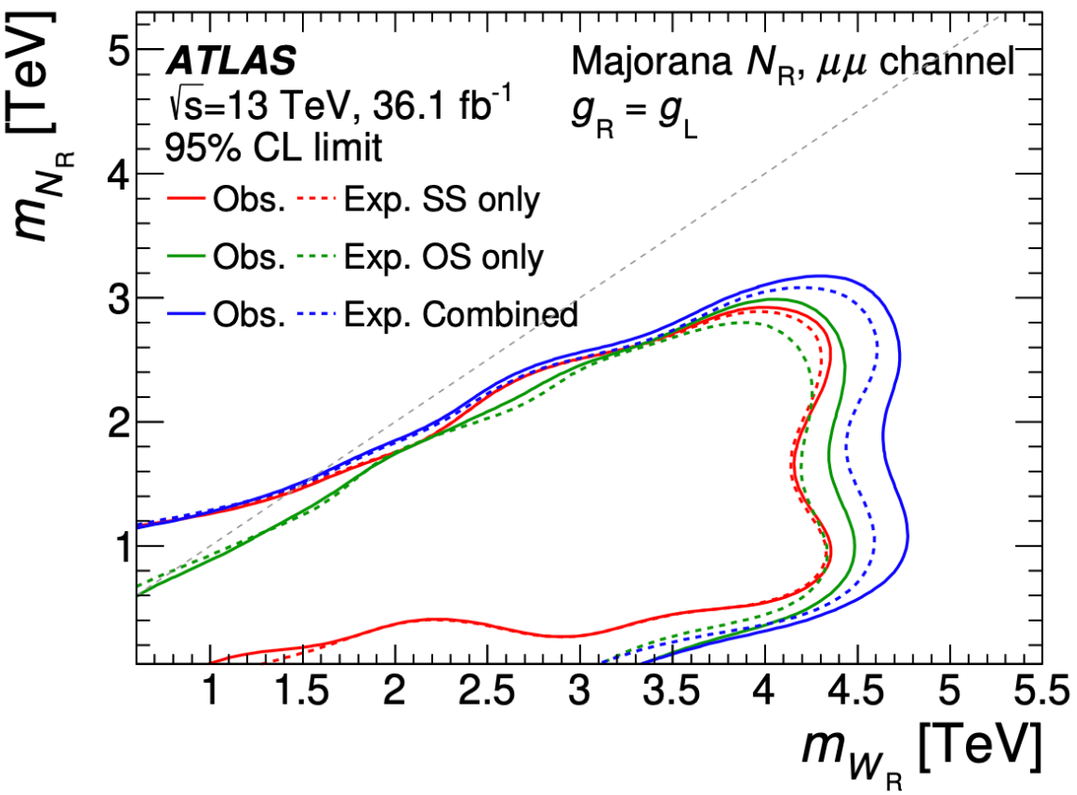
At the edge







- **Extending** the analysis reach to **m(N) > m(W_R)**
- **Excess** (2σ, local) observed in the **OS ee** channel

$m(W_R) > 4.7$ TeV

$m(N) > 1.2$ TeV

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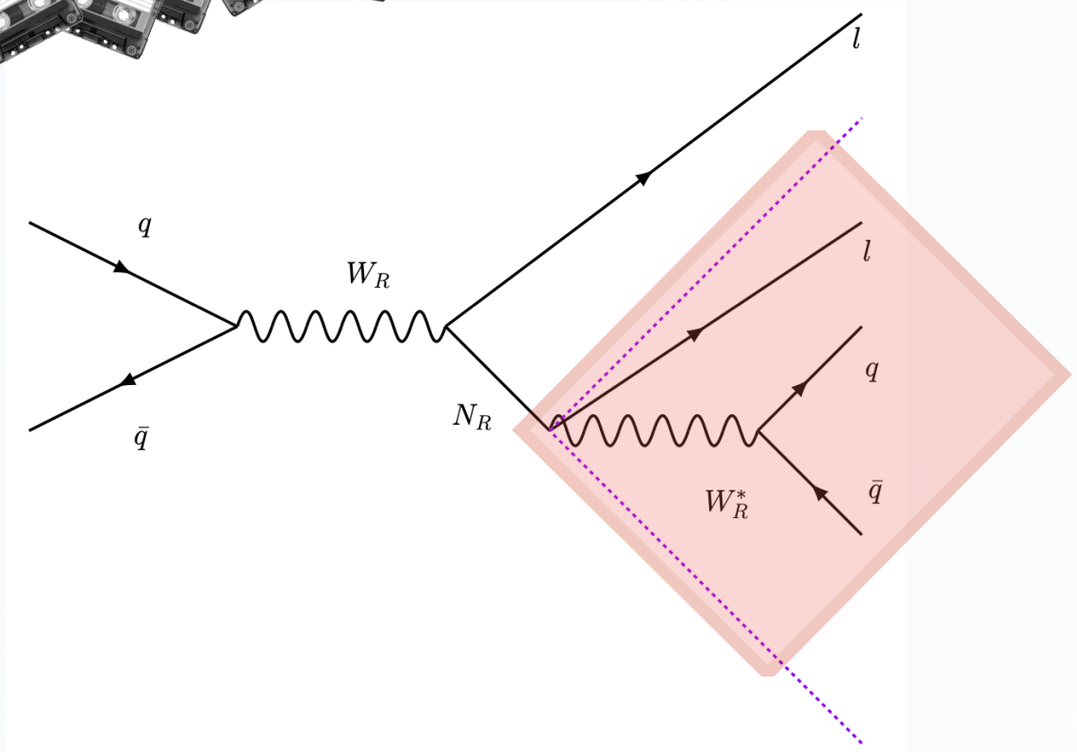
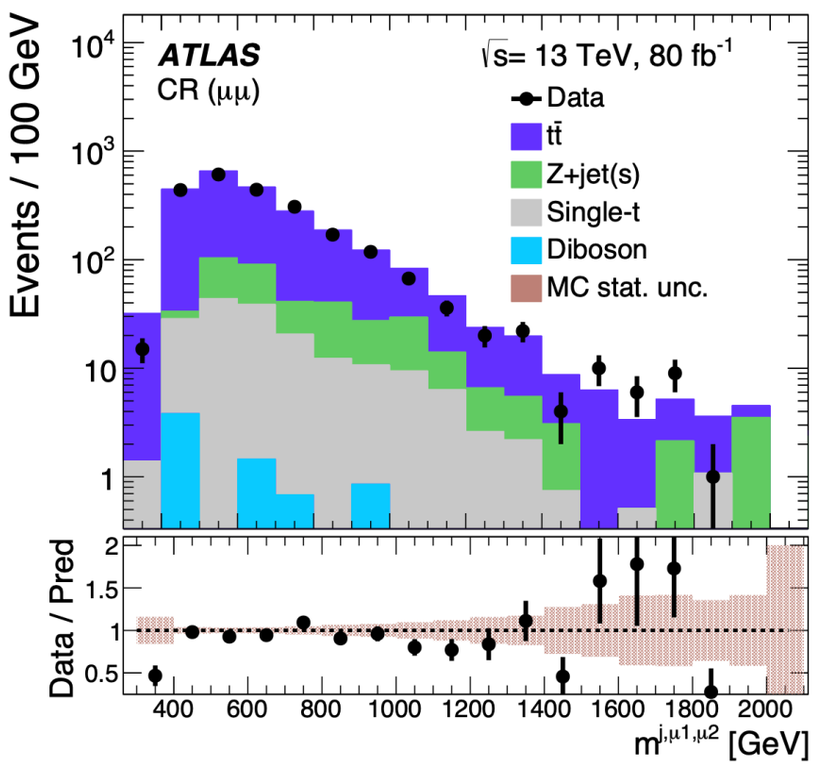
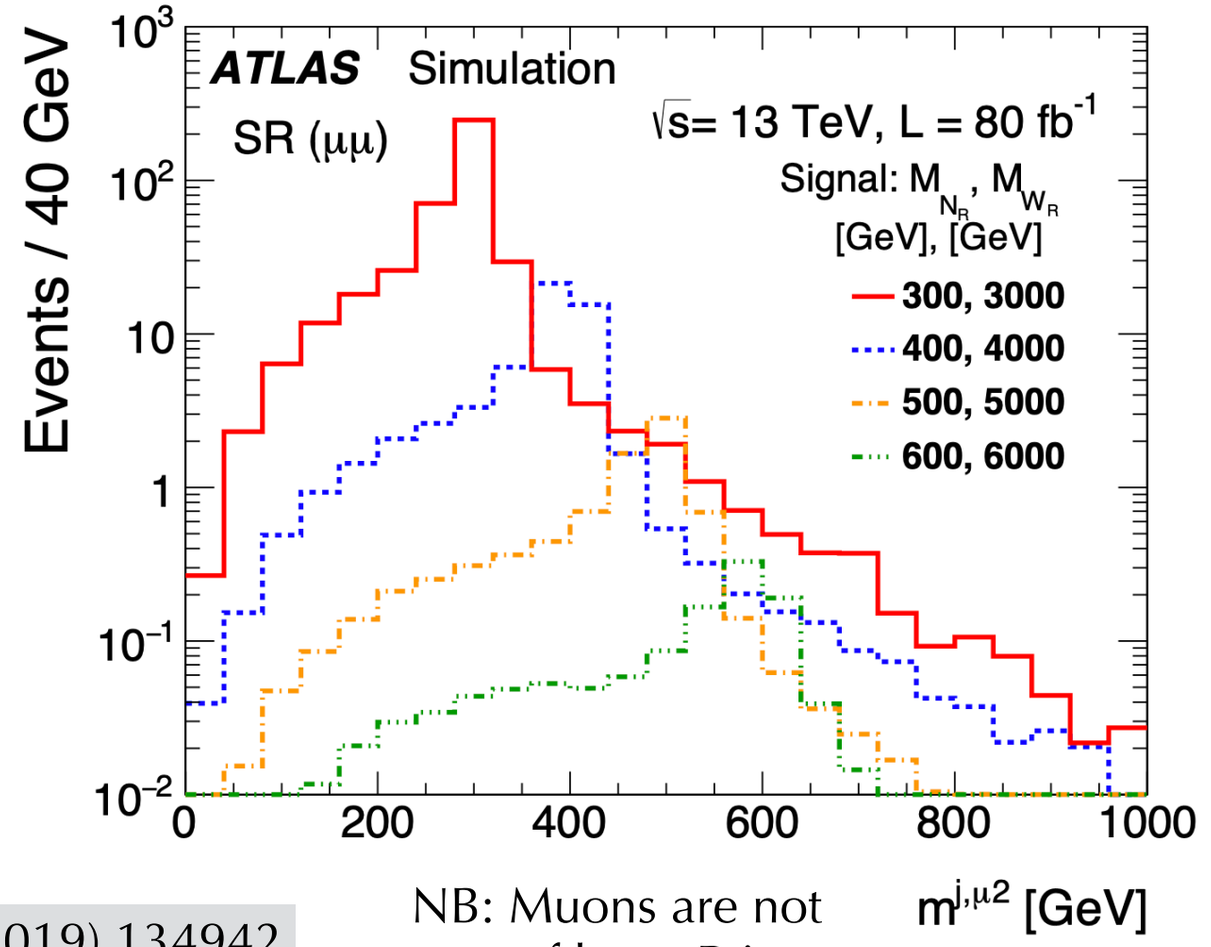
Boosted N



- Optimize for the **highly-boosted N** scenario
- Tag the **N decay** via a **large-R** (R=1.0) jet
- Select at least one large-R jet with p_T > 200 GeV, which is **back-to-back** with the highest-p_T lepton





NB: Muons are not part of large-R jets

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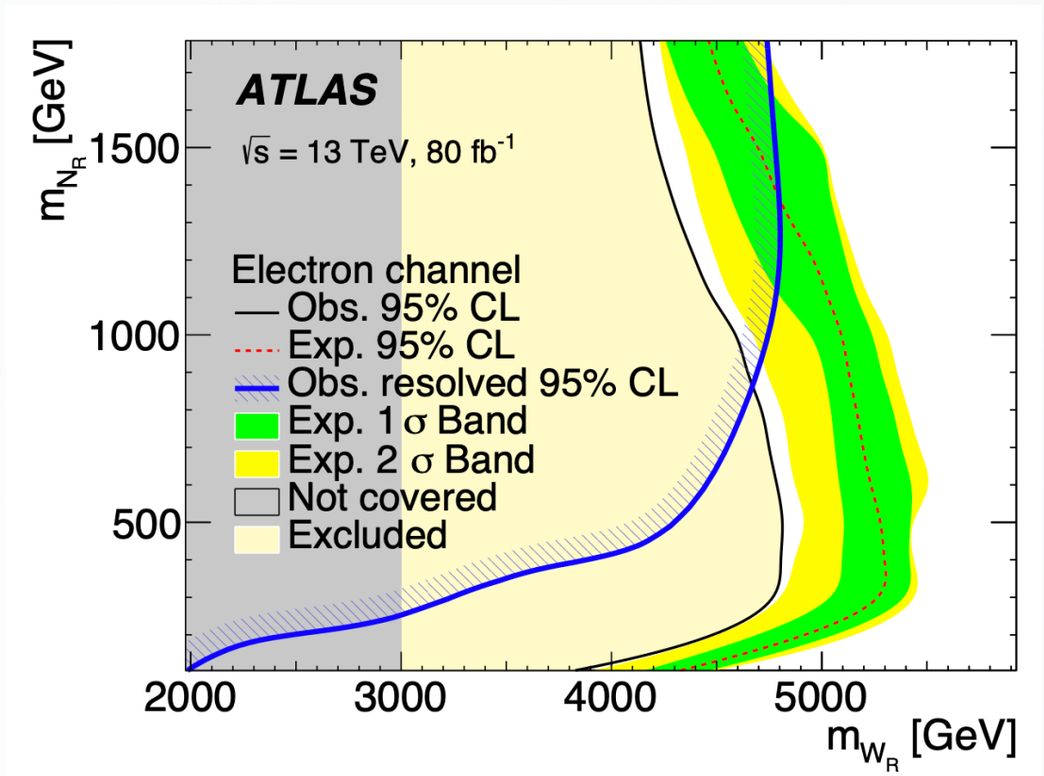
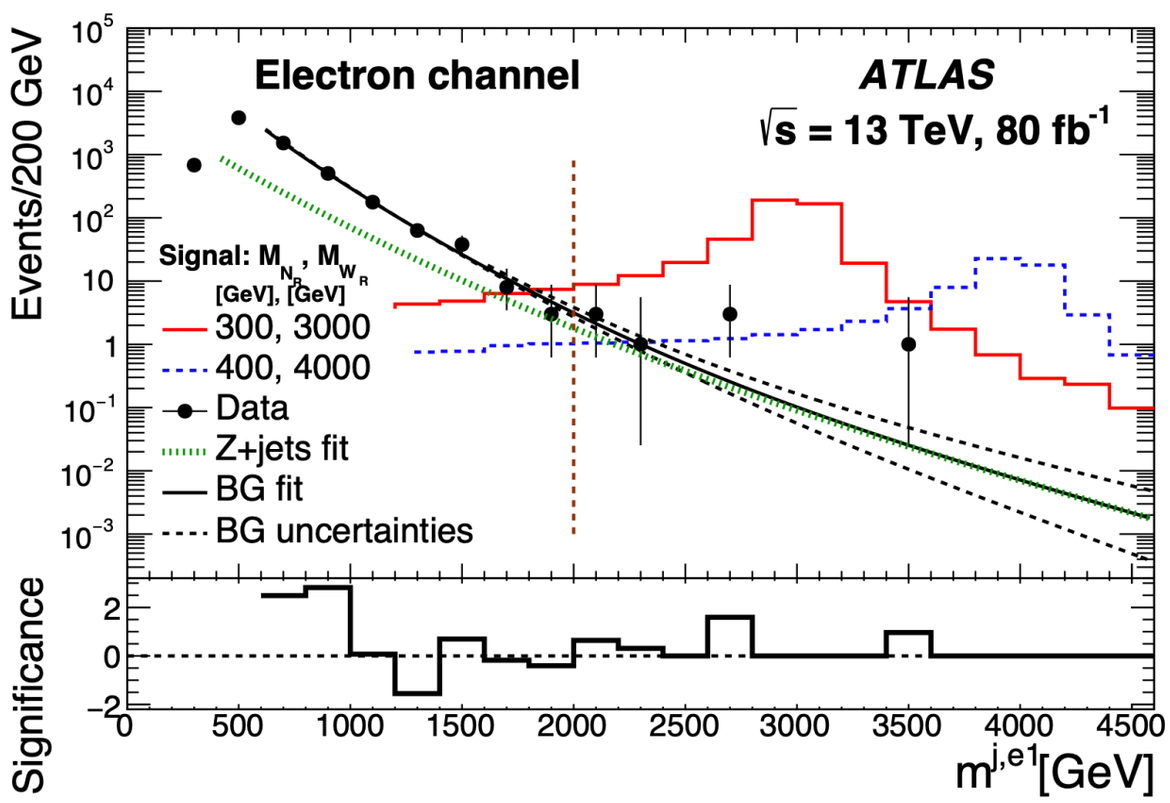
Boosted N

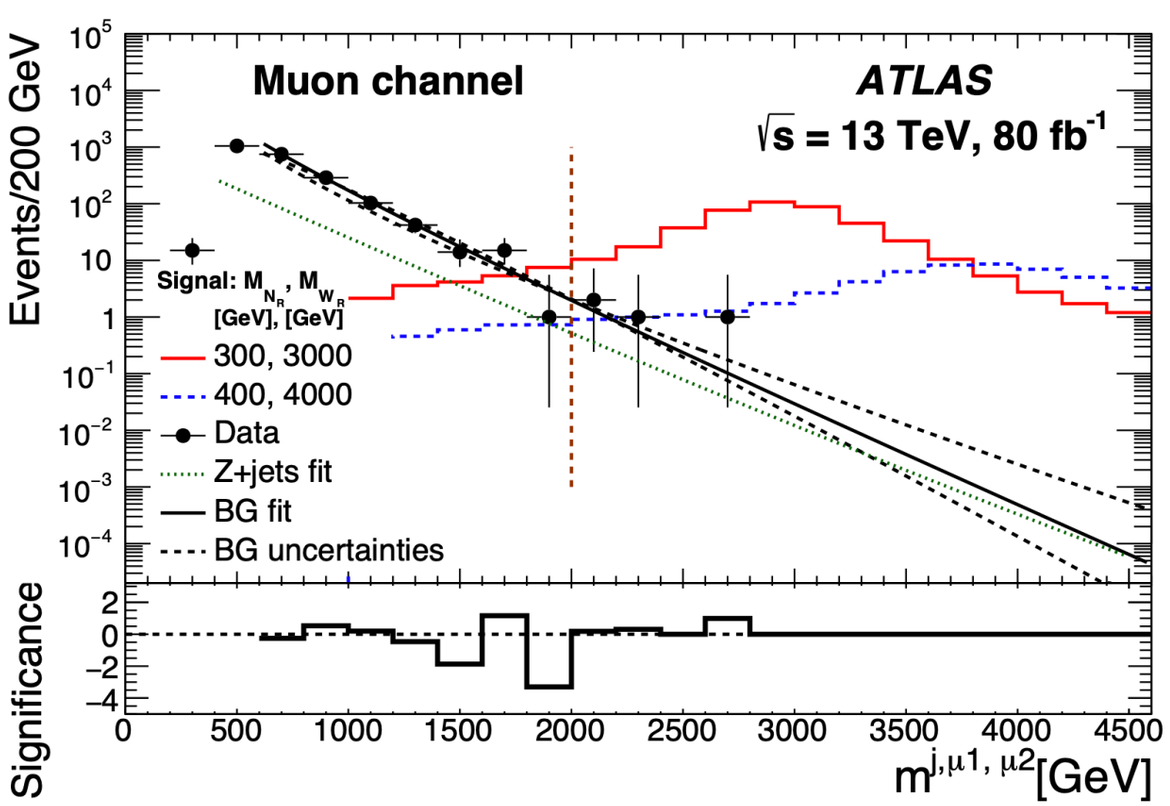
PLB 798 (2019) 134942

- Estimate background directly from the fit to data using **m(je$_1$)** and **m(jμ$_1$μ$_2$)** spectra
- **Extrapolate** to m(W_R) > 2 TeV
- **Complementary** to the resolved analysis

$$m(W_R) > 5.0 \text{ TeV}$$

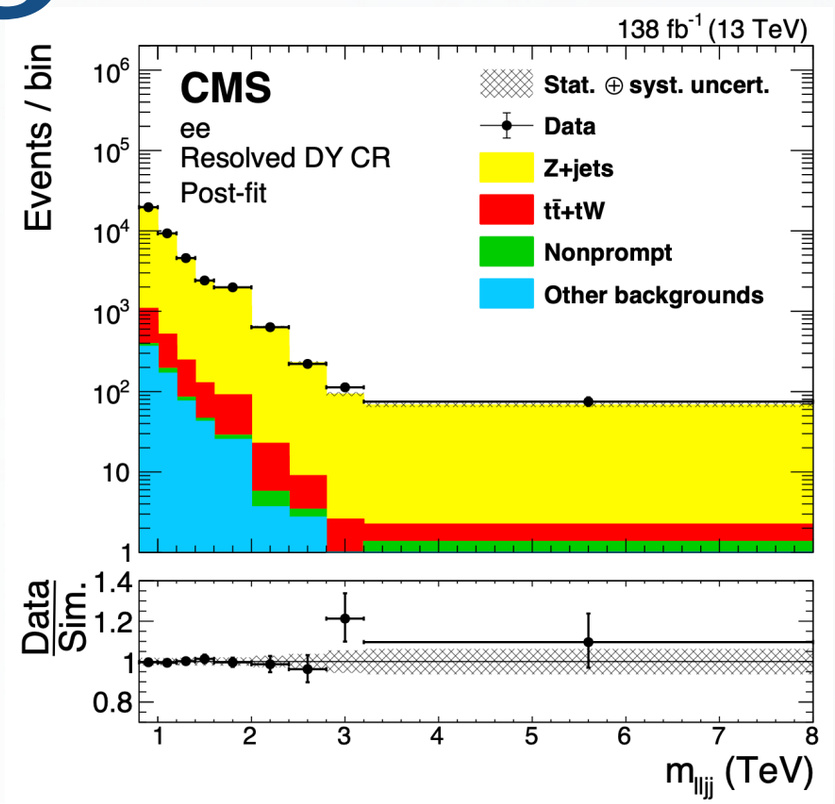


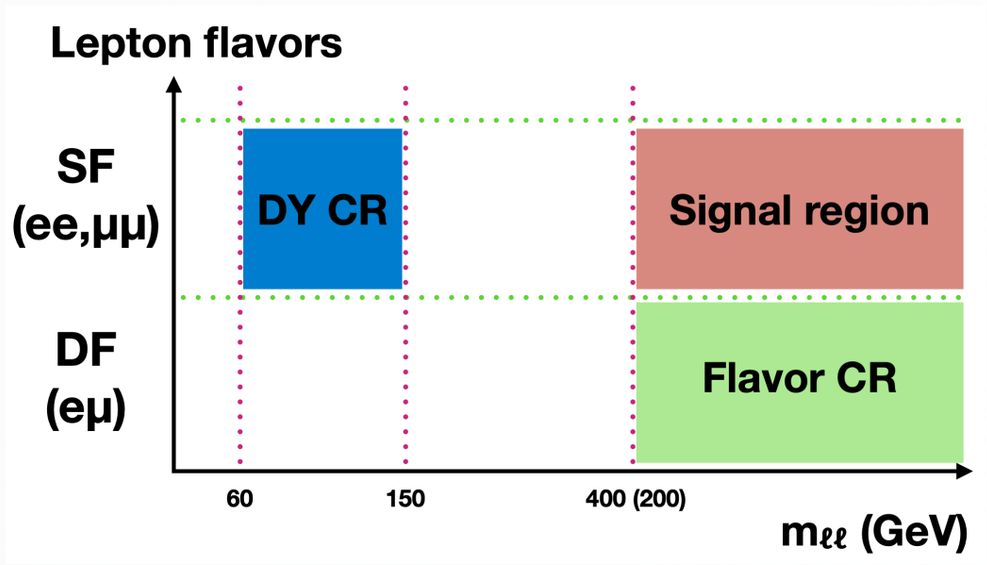


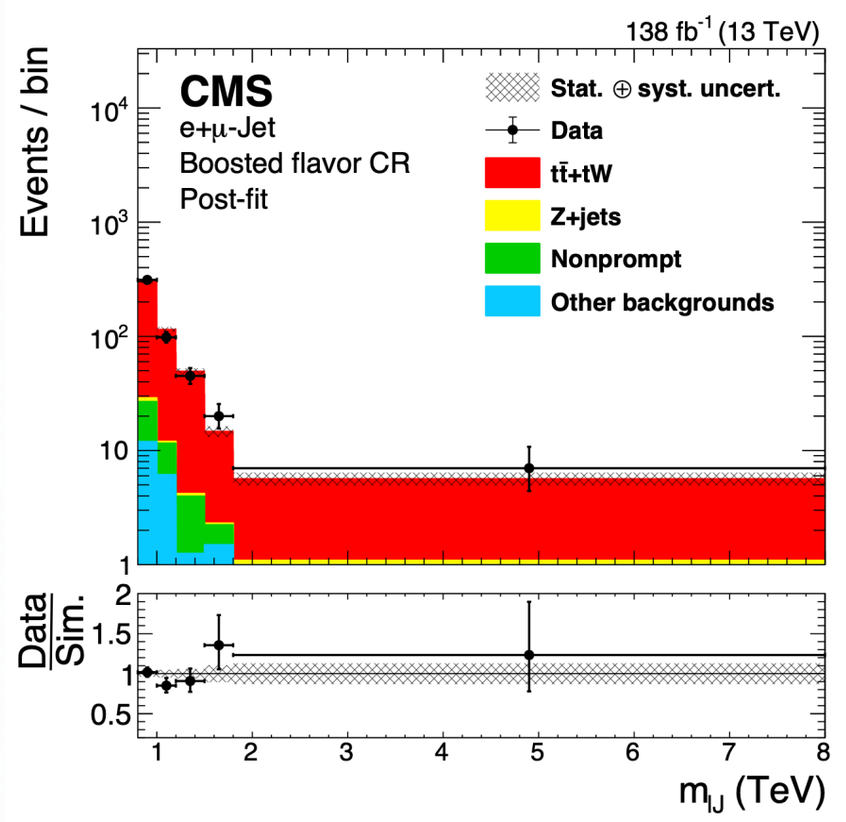


At the edge

- Apply both the **resolved** and the **boosted** analyses
- Use **jet substructure** techniques, AK8 jet (**J**) with p_T > 200 GeV, to check consistency with **three-jet structure**
- **Boosted DY CR**: lepton is not required to be part of the AK8 jet
- **ttbar CR**: apply 400 (200) GeV selection on $m(\ell\ell)$ for the resolved (boosted) analysis
- Include DY and ttbar CRs in a **common fit**







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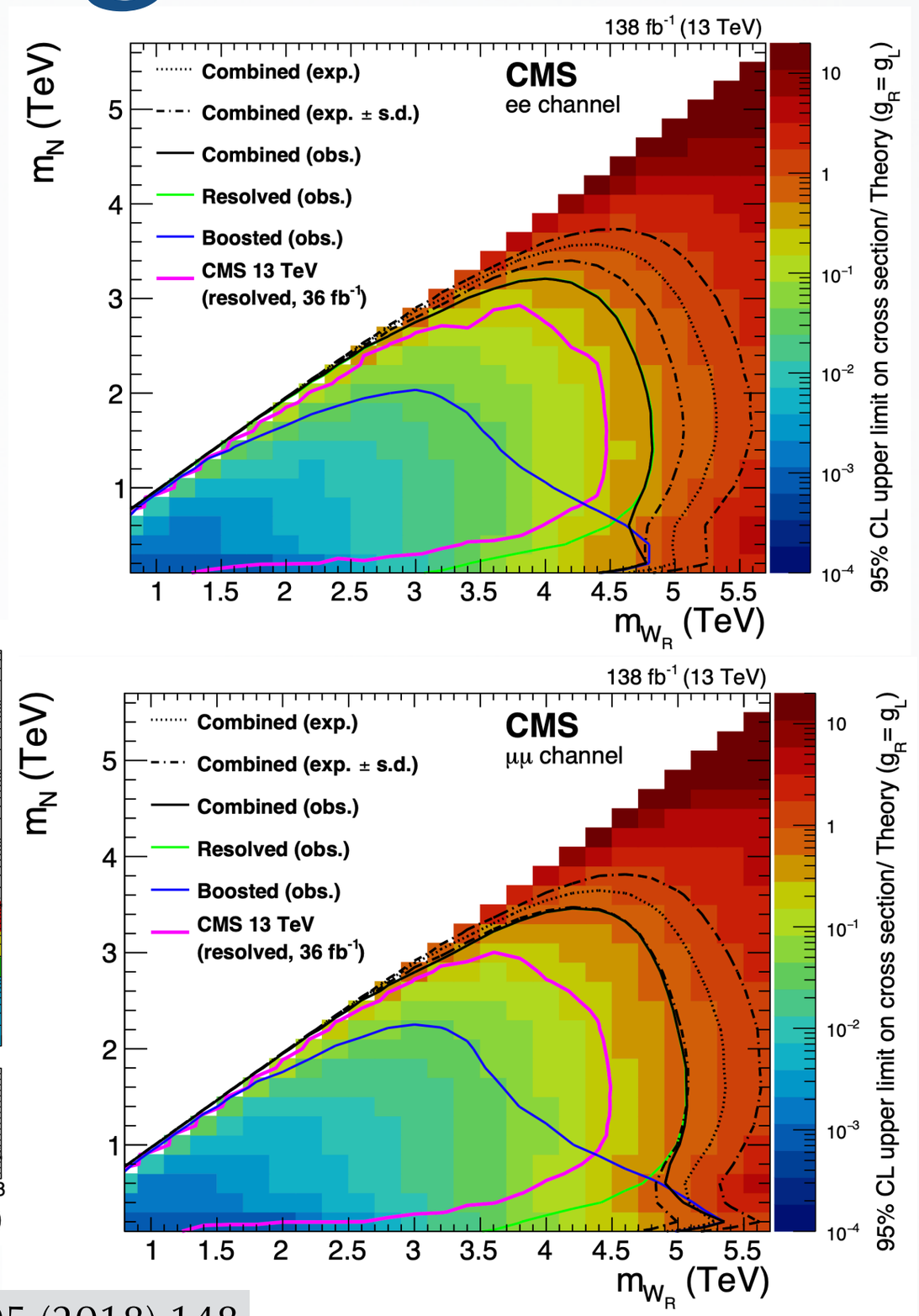
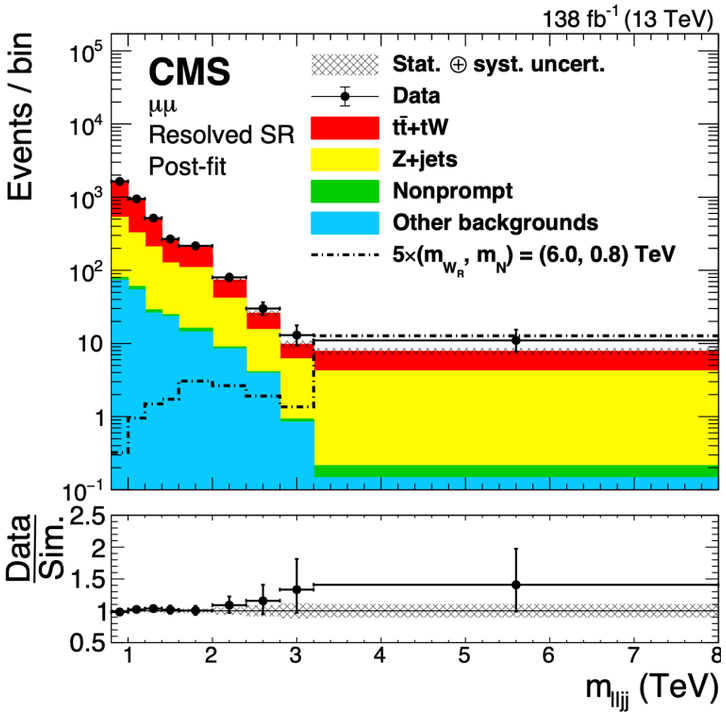
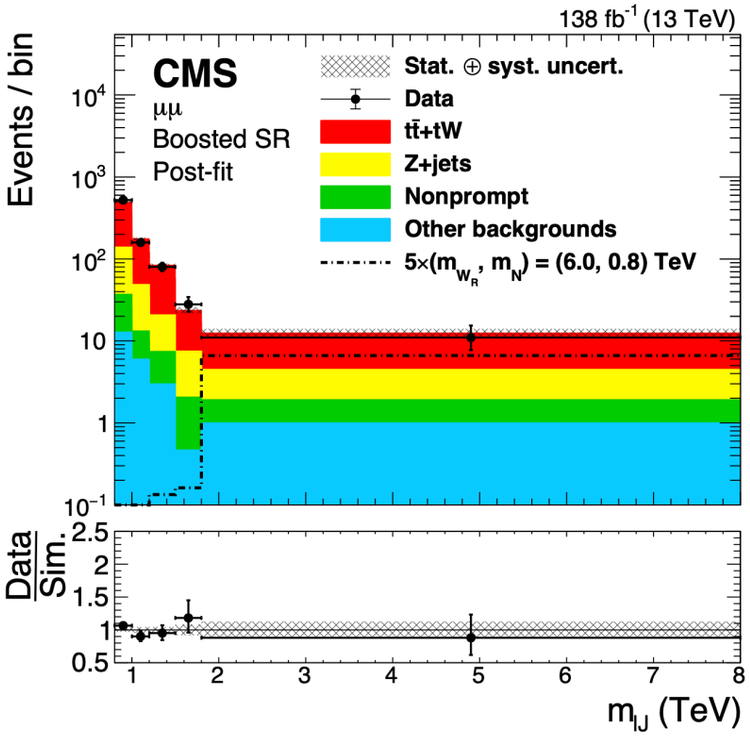
At the edge

- Probe new physics in **resolved**, m($\ell\ell$jj), and **boosted**, m(ℓJ), event topologies
- Largely improved sensitivity in the **boosted** regime
- **No significant excesses** this time :(

$$m(W_R) > 5.4 \text{ TeV}$$







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Future

- The **13.6 TeV data** started to flow in with 3 fb^{-1} already recorded!
- Looking forward to further **improvements** in the ATLAS and CMS sensitivities
- From the golden **prompt** signatures (lljj) to the presence of **displaced** vertices in the **N boosted** regime
- **Backgrounds** are challenging!

PRD 97 (2018) 115018

Prospects for LRSM using 300 fb^{-1} of data