Search for heavy Majorana neutrino production with the ATLAS detector at 7 and 8 TeV

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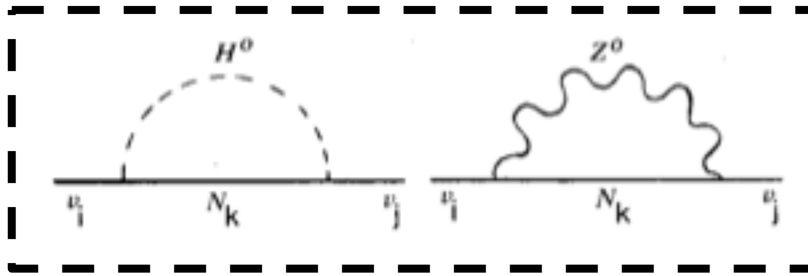
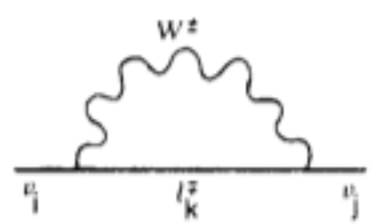
Introduction
Heavy Majorana neutrinos

- Neutrino oscillations mean that neutrinos have small, non-zero masses.
  - Typically generated by see-saw mechanisms
  - $M_N \sim$ GUT scale
  - Often embedded into a more fundamental theory such as GUT or LRSM (can require new bosons)
- However small neutrino masses can also be generated at one-loop level (right) [1]
  - $M_N \sim$ EW scale
  - Heavy neutrinos in this framework transform under the SM gauge symmetry

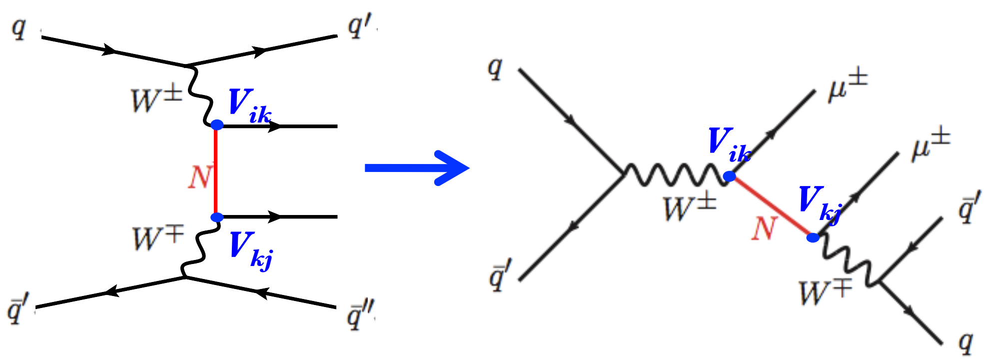




[1] A. Pilaftsis, arXiv:hep-ph/9901206 (1992)

Introduction
Limits on heavy neutrino production

- Heavy neutrino production at LHC in this framework is equivalent to neutrinoless double beta decay:



- This search has a striking BSM signature:
  - **Two same-sign muons**
  - **2 jets**
  - **No missing energy**

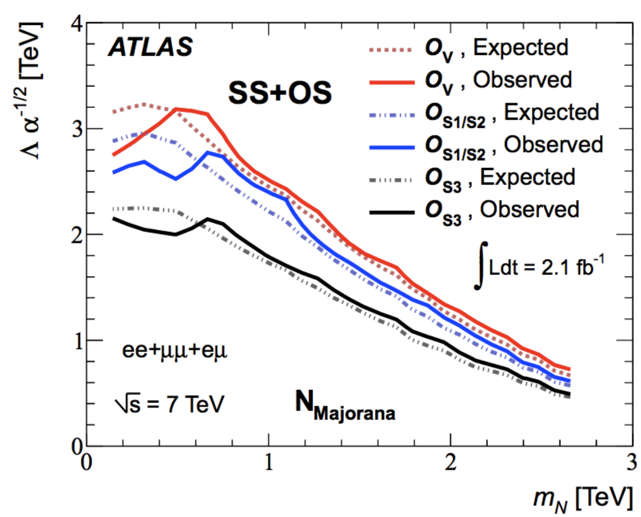
- Free parameters:
  - **Heavy neutrino mass**
  - **Lepton-heavy neutrino couplings** V_{ij}

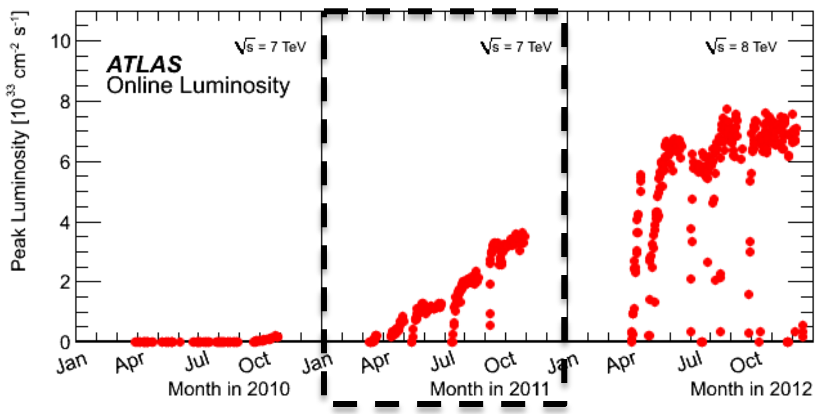
Limits:

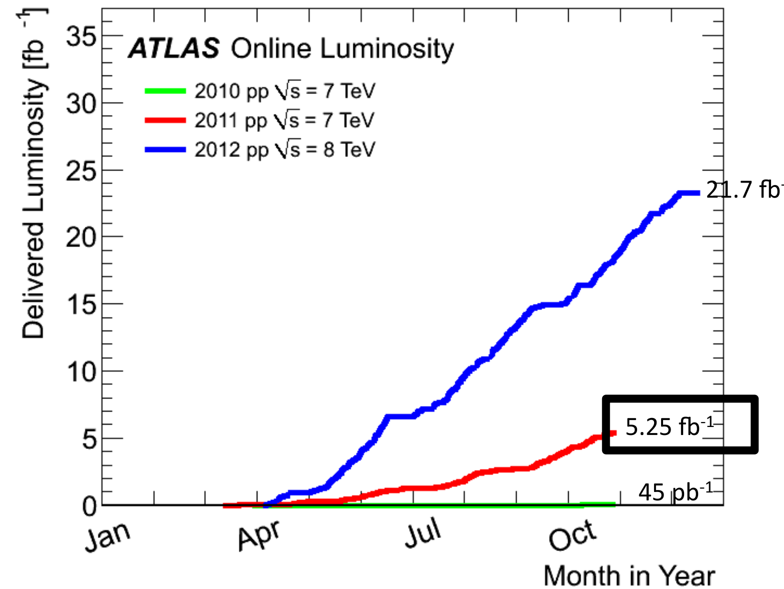
- **Electron flavour** heavy neutrinos from **neutrinoless double beta decay**.

- **Direct constraints** from L3 & DELPHI at LEP (**M_N < 90 GeV**).

- ATLAS have set limits **within LRSM framework** with 2.1 fb^{-1} data (http://arxiv.org/pdf/1203.5420v2.pdf)







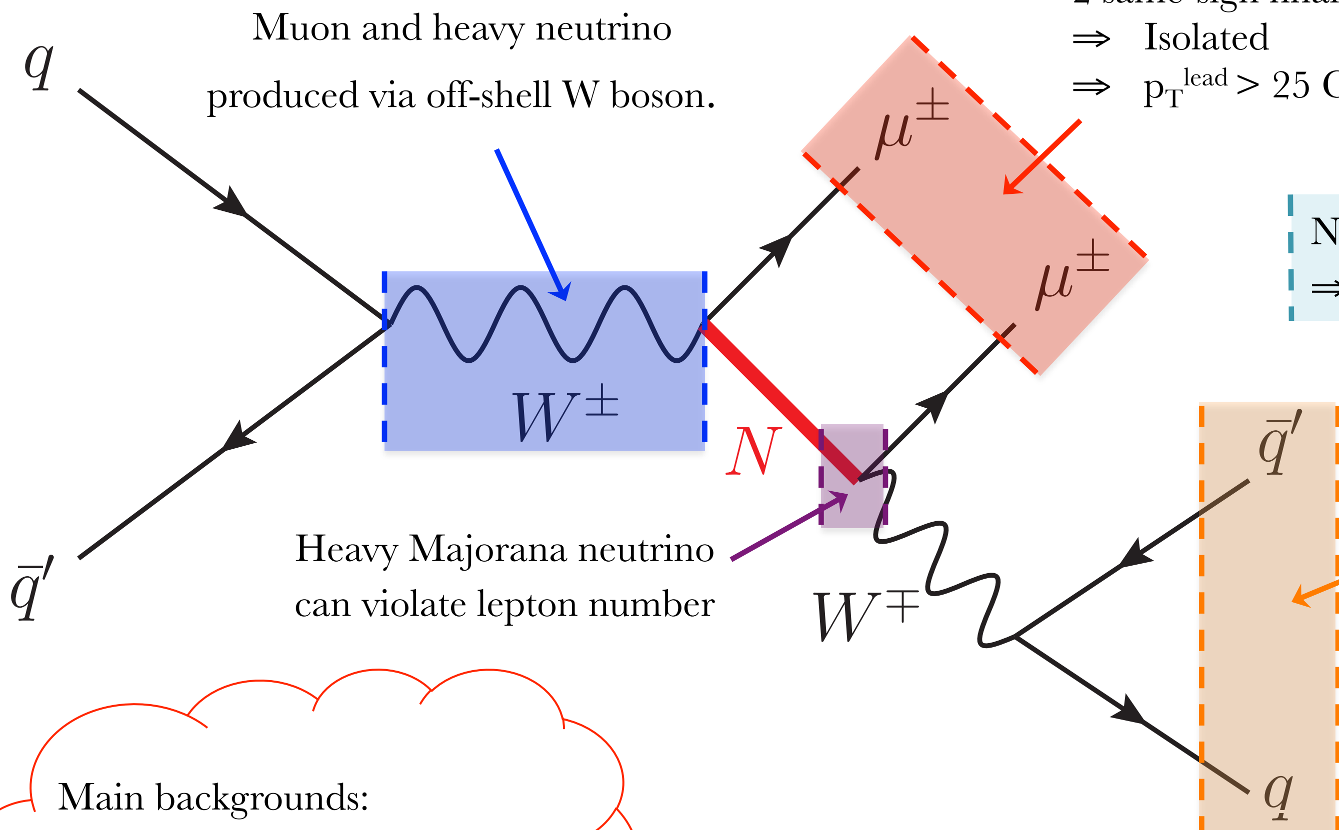
2012 Analysis (7 TeV)

ATLAS-CONF-2012-139

http://cds.cern.ch/record/1480645

2012 analysis (7 TeV)

Search channel & object selection



2 same-sign final state muons:
- ⇒ Isolated
- ⇒ $p_T^{lead} > 25$ GeV, $p_T^{sublead} > 20$ GeV

No missing energy
- ⇒ Require $E_T^{miss} < 35$ GeV

≥ 2 jets
- ⇒ $p_T > 20$ GeV
- ⇒ 55 < m(jj) [GeV] < 120

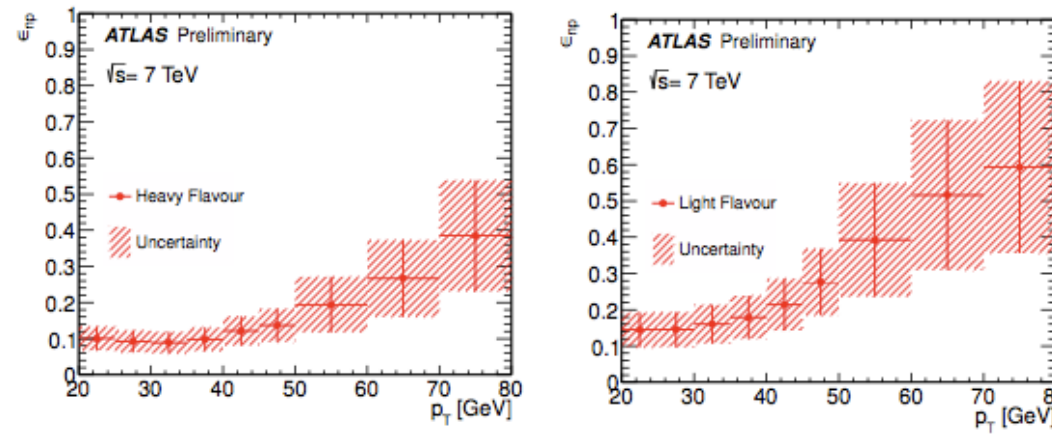
Main backgrounds:
- ⇒ Non-prompt leptons ('fakes')
- ⇒ Diboson

2012 analysis (7 TeV)

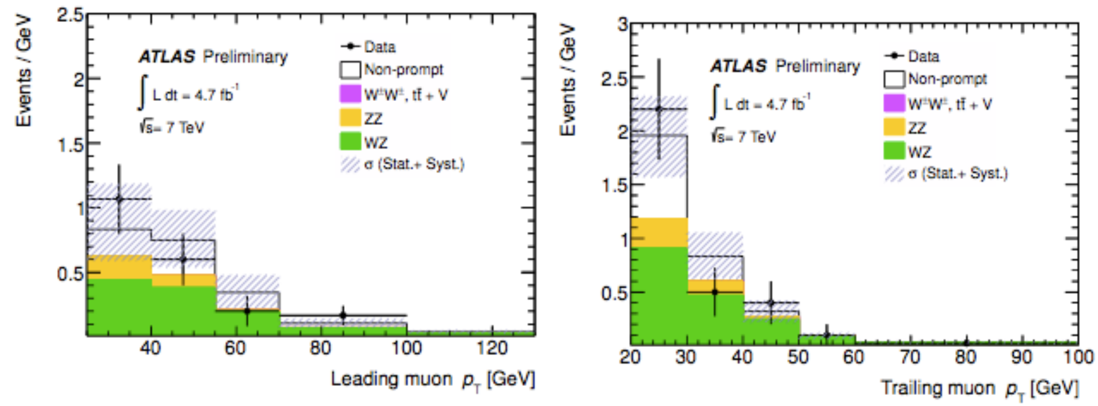
Background estimates and rejection

Backgrounds:

- Non-prompt muons (hadronic decays):
  - Estimated using data-driven probability distribution
  - Rejected using impact parameter and isolation cuts
- Prompt muons (EW):
  - Mainly **$WZ \rightarrow l\nu\, ll$** & **$ZZ \rightarrow ll\, ll$**
  - Rejected with veto on additional leptons
- Require cut m(μμ) > 15 GeV
- Background from muon charge misidentification shown to be negligible



Probability for non-prompt muons to pass the isolation requirements as a function of muon pT for (left) heavy flavour decays and (right) other processes.

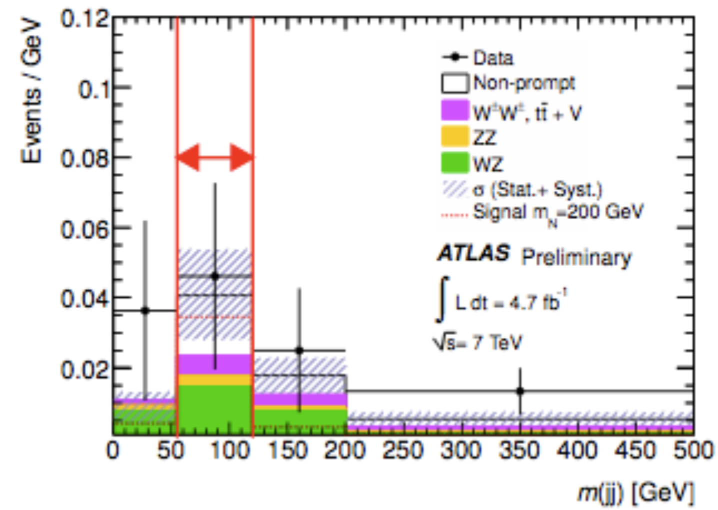


Events with two same-sign muons and zero jets

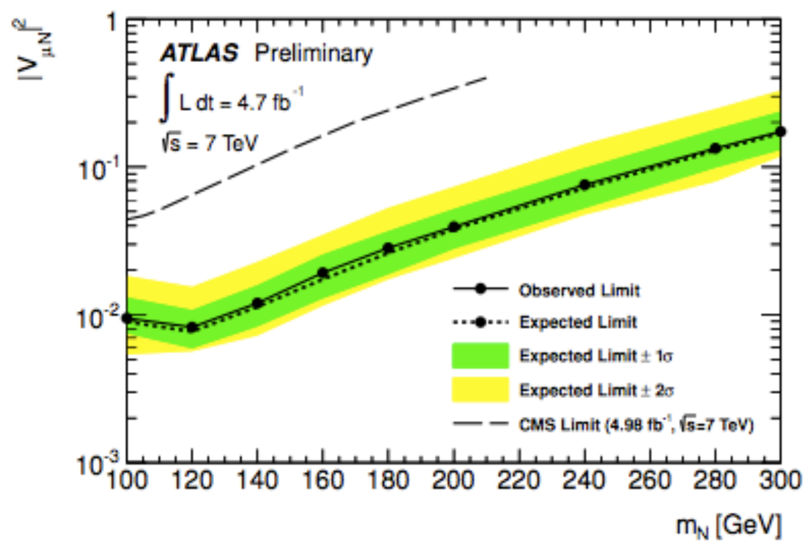
2012 analysis (7 TeV)

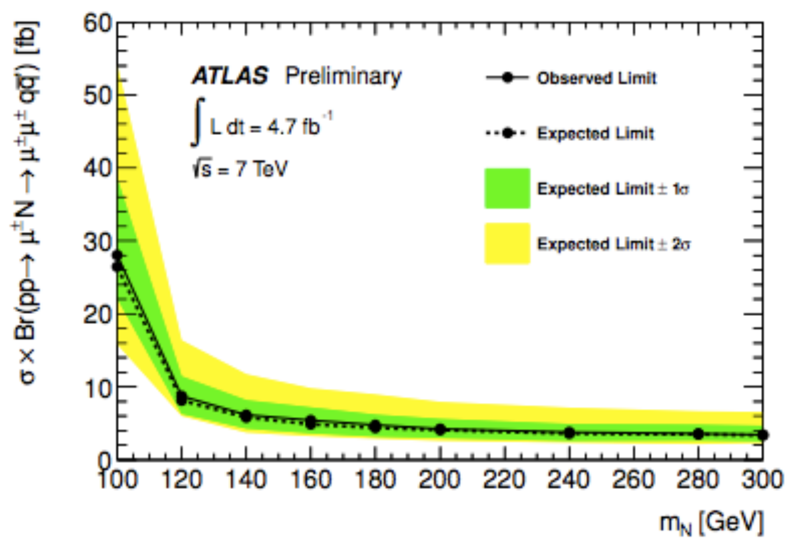
Limits

- No significant excess observed
- Cross-section and coupling limits set wrt heavy neutrino mass
- Most stringent direct limits to date (when compared to CMS result with equal dataset) on heavy Majorana neutrino production for $m_N > 100$ GeV



2 SS muons
≥ 2 jets
$E_T^{miss} < 35$ GeV





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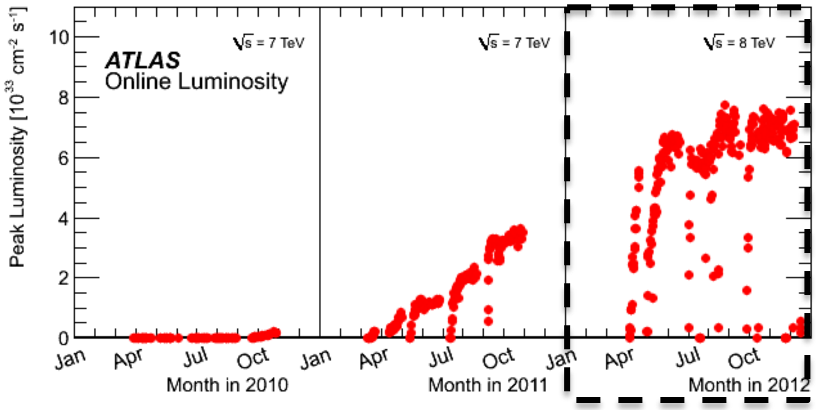
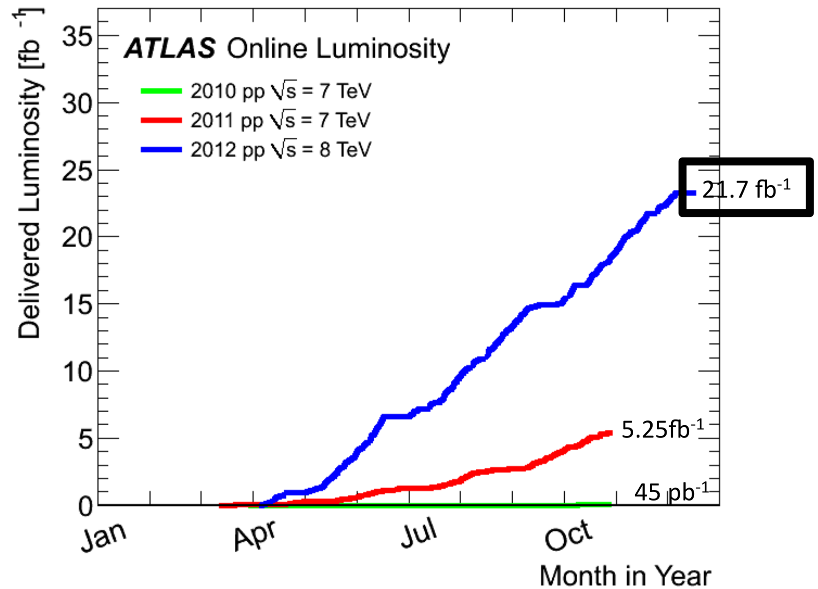


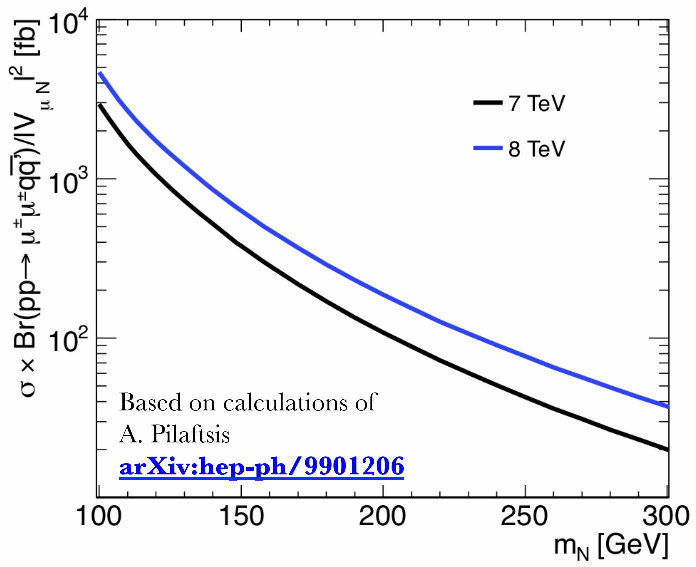


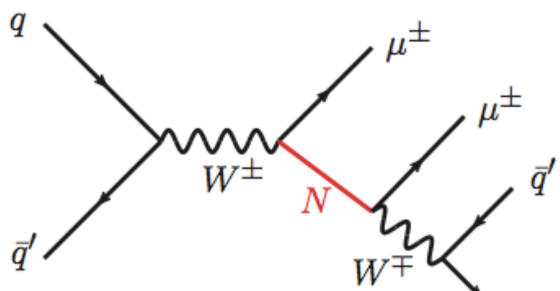
2013 Analysis (8 TeV)
Status

2013 analysis (8 TeV)

Moving from 7 TeV to 8 TeV

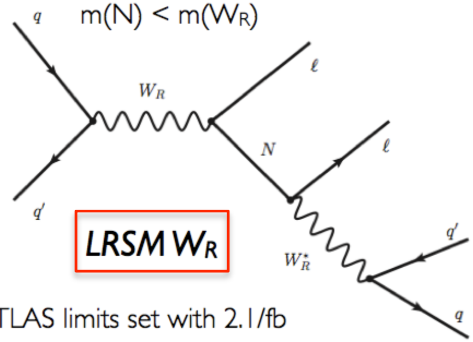
- Extending the analysis with 8 TeV dataset (~20fb^{-1})
- Profit from increased cross-section at higher energy
- Extended MC signal range (110 GeV, 400 GeV, 500 GeV)
- Looking at ee, μμ and eμ channels
- Collaborating with Left-Right Symmetric Model analysis (see back-up)





Minimal radiative (Type 1 Seesaw)

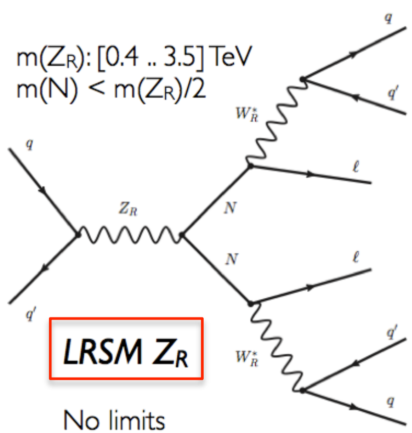
m(W_R): [0.6 .. 4.5] TeV
m(N) < m(W_R)



LRSM W_R

ATLAS limits set with 2.1/fb

m(Z_R): [0.4 .. 3.5] TeV
m(N) < m(Z_R)/2

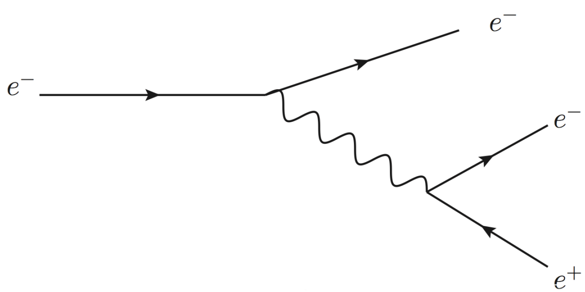


LRSM Z_R

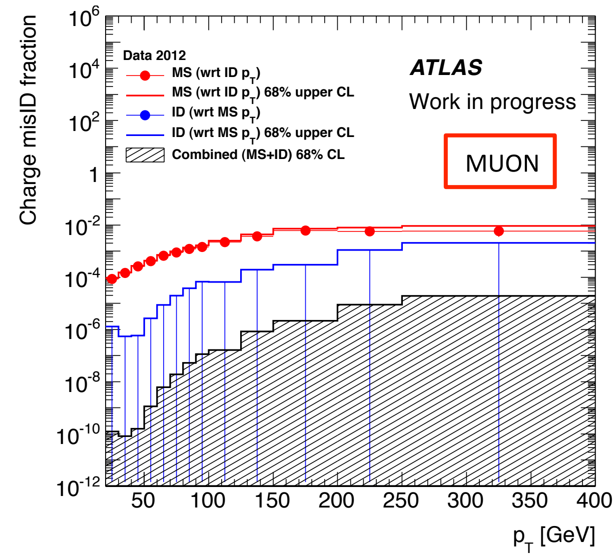
No limits

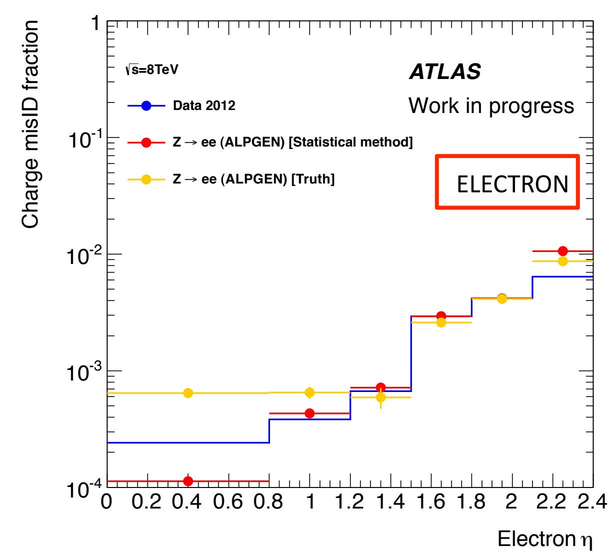
2013 analysis (8 TeV)
Charge misID

- Muon charge flip rate is negligible due to simultaneous MS and ID charge requirement
- Electron charge flip rate is **not negligible**
  - Electrons emit hard bremsstrahlung photon that subsequently converts



- Parameterise in η (associated with length of material interaction)
- Use MC to model pT dependance, then scale to rate (binned in η) observed in data

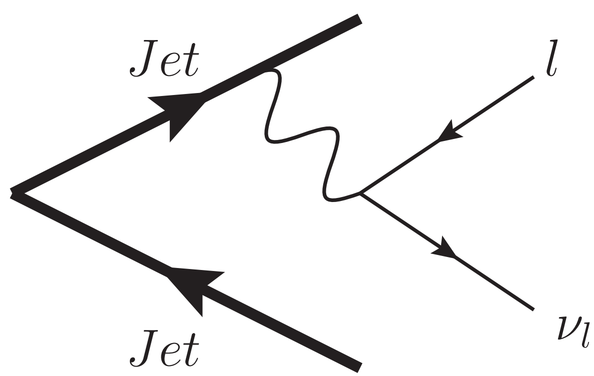


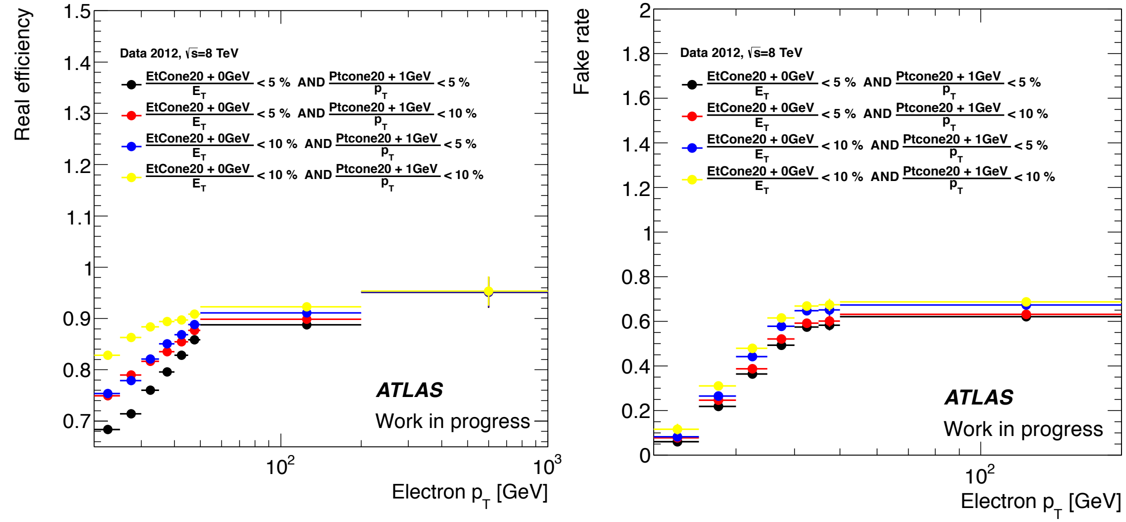


2013 analysis (8 TeV)

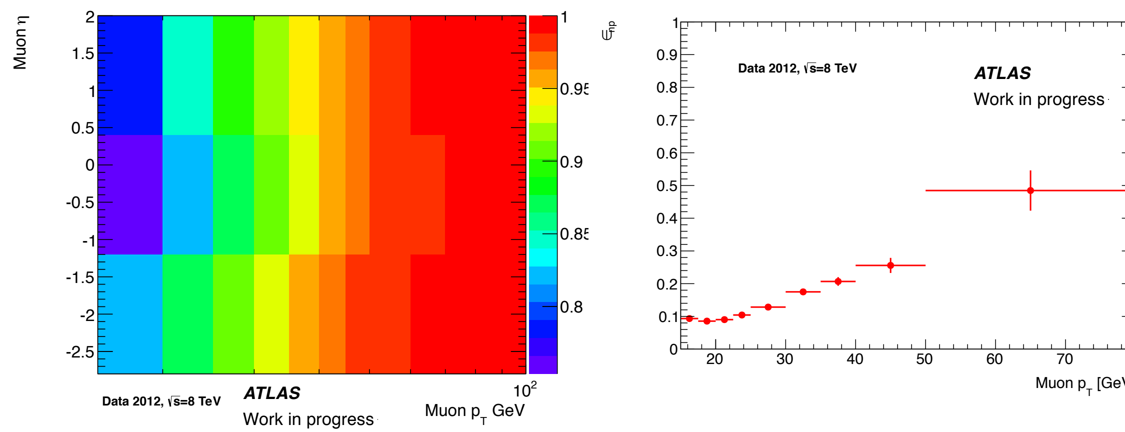
Background (prompt and non-prompt) estimates and rejection

- Prompt and non-prompt efficiencies (right) re-evaluated.
  - Important for electrons in order to minimise contamination in charge misID study





Probability for prompt electrons (left) and non prompt electrons (right) to pass isolation criteria



Probability for prompt muons (left) and non prompt muons (right) to pass isolation criteria

Summary

- 7 TeV analysis complete:
  - Analysis with 4.7 fb^{-1} data produced most stringent limits for heavy neutrino masses greater than 100 GeV
  - Coupling and cross-section limits set wrt heavy neutrino mass
  - Public conference note is available at:

    ATLAS-CONF-2012-139

    http://cds.cern.ch/record/1480645

- 8 TeV analysis ongoing:
  - Move from μμ to ee, eμ and μμ channels
  - ~20 fb^{-1} and increased cross-section at 8 TeV

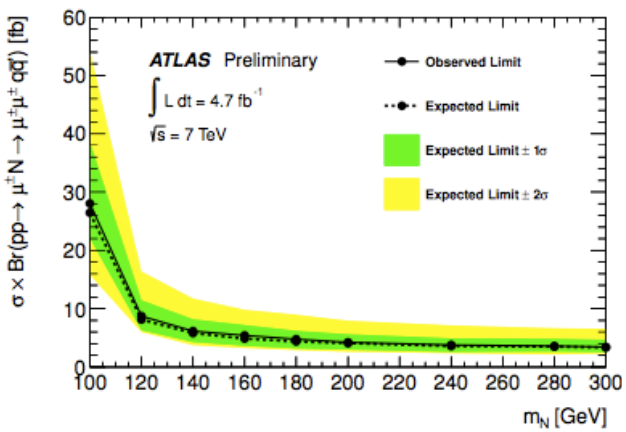
BACK UP

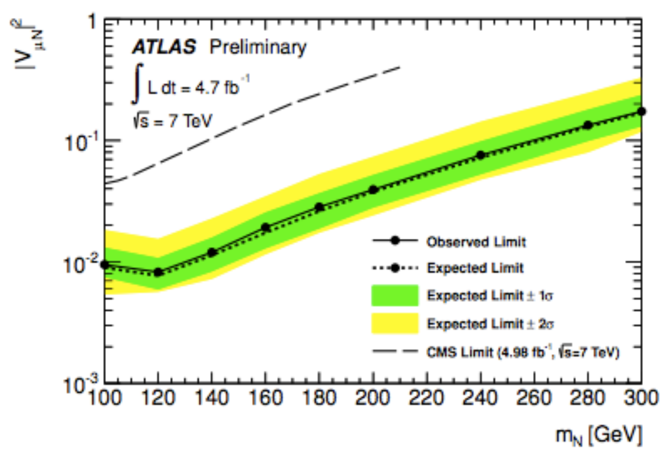
Suggested questions

- Why stop at 500 GeV?
- Why do you include a mass point at 110 GeV?
- Why the eμ channel?

ATLAS vs CMS analysis (7 TeV)

	ATLAS	CMS (Physics Letters B 717 (2012) 109–128)
Object selection	$E_t^{miss} < 35$ GeV $p_T^{Jet} > 20$ GeV $p_T^{\mu 1} > 25$ GeV $p_T^{\mu 2} > 20$ GeV	E_t^{miss}<50GeV p_T^{Jet}>30GeV $p_T^{\mu 1} > 20$ GeV $p_T^{\mu 2} > 10$ GeV
Signal efficiency	m_N = 100GeV, efficiency = 3.9% m_N = 200GeV, efficiency = 26%	m_N = 50 GeV, efficiency = 0.43% m_N = 210GeV, efficiency = 29.0%





Source	$\mu^\pm\mu^\pm$
WZ	$1.0 \pm 0.2 \pm 0.3$
ZZ	$0.22 \pm 0.05 ^{+0.07}_{-0.06}$
$W^\pm W^\pm$	$0.15 \pm 0.04 \pm 0.08$
$t\bar{t} + V$	$0.23 \pm 0.04 \pm 0.12$
Charge mis-measurement	< 0.03
Non−prompt	$1.1 \pm 0.5 ^{+0.6}_{-0.5}$
Total background	$2.7 \pm 0.5 ^{+0.7}_{-0.6}$
Data	3

7 (8) TeV analysis
Object selection

Leptons:

- $N_{leptons} = 2$
- $Q_1 = Q_2$
- Lead $p_T > 25$ GeV
- Subleading $p_T > 20$ GeV
- $|\eta| < 2.5$
- $M_{ll} > 15$ GeV

Jets:

- Anti-kT, R = 0.4
- Lead $p_T > 20$ GeV
- $|\eta| < 2.8$
- 55 GeV < $M_{j1,j2}$ < 120 GeV
- JVF > 0.5

$E_T^{Miss} < 35$ GeV

Isolation:

- Muons –
  - $\Delta R(\mu,jet) > 0.4$
    - PtCone30 < 0.05 p_T^μ for $p_T^\mu < 80$ GeV
    - EtCone20 + 1 GeV < 0.05 E_T^μ (EtCone20 < 0.05 E_T^μ)
  - $\Delta R(\mu,jet) < 0.4$
    - $p_T > 80$ GeV
    - EtCone20 + 1 GeV < 0.05 E_T^μ (EtCone20 < 0.05 E_T^μ) or $|m(\mu j) - m(j)| > 10$ GeV
- Electrons –
  - EtCone20 < 0.05 E_T^μ
  - PtCone20 < 0.05 p_T^μ

Impact parameters:

- $|d0| < 0.2$ mm
- $|z0| < 5.0$ mm
- $|d0|/\sigma(d0) < 3.0$

2012 analysis (7 TeV)
Prompt background

- 'Prompt' backgrounds come from EW processes:
  - WZ→$l\nu ll$
  - ZZ→$llll$
- These manifest as background to SS muon selection when:
  - Lepton falls outside of detector geometrical acceptance
  - Lepton pT is below threshold
  - Tau decays
- Modelled by MC [backup]

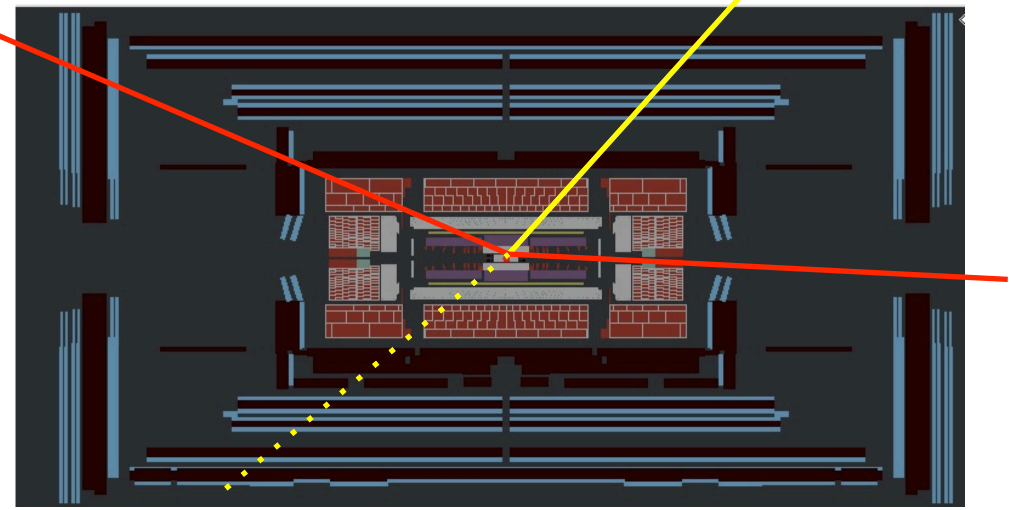
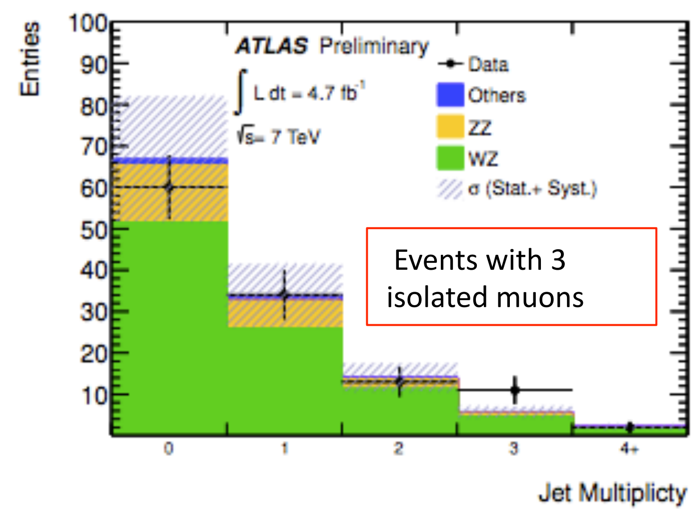


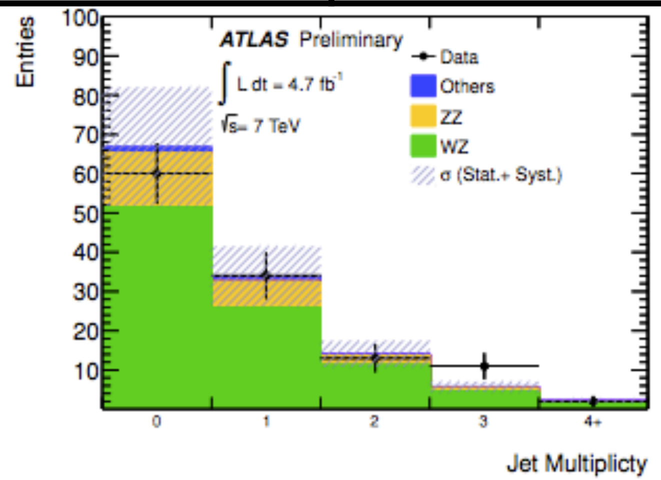
Illustration of a WZ→*lνll* event where one lepton is outside of detector geometry

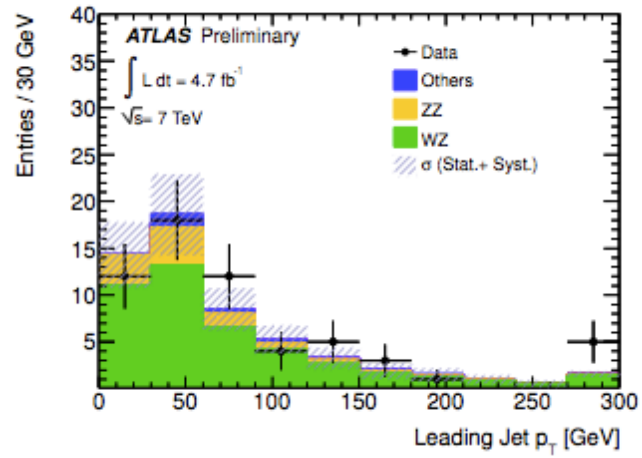


Events with 3 isolated muons

MC
Signal and prompt background

Process	Monte Carlo	Comments
W*→μN→μμW (Signal)	HvyN+HERWIG	HvyN: • modified Alpgen package using Alpgen phase space sampling. [attached]
WZ→lνll & ZZ→llll	SHERPA	• LO, up to 3 additional partons • Includes γ* contribution
ttV & WW+2jets	MADGRAPH+PYTHIA	• Small contribution
Additional interactions	PYTHIA min bias	





Jet multiplicity and jet p_T for events with 3 isolated muons

Signal m_N [GeV]	100	120	140	160	180	200	240	280	300
Selection Efficiency [%]	3.9	13.0	18.1	21.3	23.9	25.7	28.7	30.8	31.7

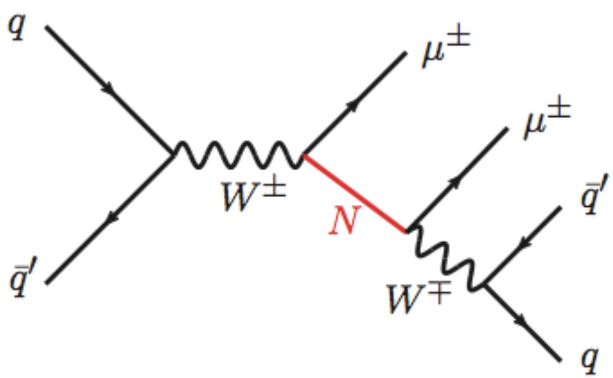
Efficiency for signal efficiency to pass event selection criteria

Type-1 Seesaw vs LRSM

Type-1 seesaw

(W*)

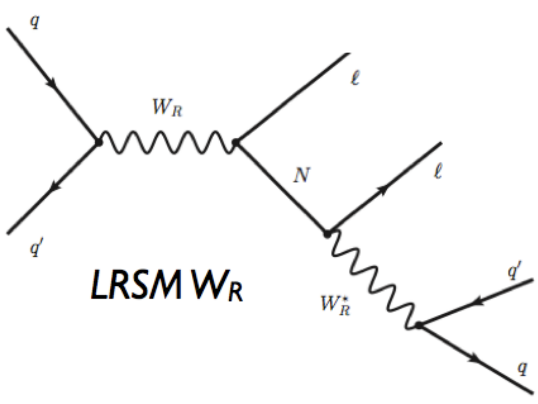
⇒ Neutrino mass scale ~ EW scale
⇒ Signal MC produced for $100 < M(N)$ [GeV] < 500
⇒ Muon pT range dependent on M(N)
⇒ 2 OS/SS muons in final state

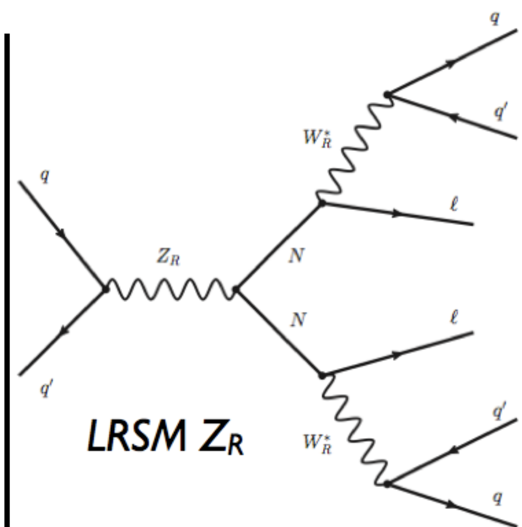


Left-right symmetric model (LRSM)

(WR & ZR)

⇒ W_R mass scale < few TeV
⇒ Z_R mass scale < few TeV
⇒ Neutrino mass scale < $M(W_R)$ && < $M(Z_R)/2$
⇒ 2 **high pT** OS/SS muons in final state





Non-prompt estimation

- Leptons from a loose selection that pass isolation criteria described as 'Tight' (T), otherwise described as 'Loose' (L).
- Categorise di-lepton events as TT, TL, LT, LL
- Relate prompt (R) leptons and non-prompt (F) leptons to Tight and Loose leptons using real efficiency r and fake rate f (measured in data), by the matrix:

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N^{ll}_{RR} \\ N^{ll}_{RF} \\ N^{ll}_{FR} \\ N^{ll}_{FF} \end{bmatrix}$$

- Invert the matrix:

$$\frac{1}{(r_1-f_1)(r_2-f_2)} \begin{bmatrix} (1-f_1)(1-f_2) & (f_1-1)f_2 & f_1(f_2-1) & f_1f_2 \\ (f_1-1)(1-r_2) & (1-f_1)r_2 & f_1(1-r_2 & -f_1r_2 \\ (r_1-1)(1-f_2) & (1-r_1)f_2 & r_1(1-f_2) & -r_1f_2 \\ (1-r_1)(1-r_2) & (r_1-1)r_2 & r_1(r_2-1) & r_1r_2 \end{bmatrix}$$

Electron charge misID

Truth

Start with Zee MC (Alpgen):

Require stable electron at truth level.

Require that the electron matches to a true Z-electron (min dR matching, dR = 0.1)

Measure the direct charge misID rate between the electron and truth electron

Likelihood

Consider a Poisson distribution of electrons pairs to 'contain a flip' in eta bin (k , l):

$$P\left(\varepsilon \mid N_{SS}, N\right) = \prod_{k,l} \frac{(N^{kl}(\varepsilon^k + \varepsilon^l))^{N_{SS}^{kl}} e^{-N^{kl}(\varepsilon^k+\varepsilon^l)}}{N_{SS}^{kl}}$$

We minimize:

$$\sum_{k,l} -N_{SS}^{kl} \ln(N^{kl}(\varepsilon^k + \varepsilon^l)) + N^{kl}(\varepsilon^k + \varepsilon^l) + \ln(N_{SS}^{kl})$$