# Search for anomalous production of same-sign lepton pairs and pair-produced doubly charged Higgs

arXiv:1210.4538v1
arXiv:1210.5070v1

Francesco Nuti on behalf of the ATLAS Collaboration

cH±arged Workshop
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THE UNIVERSITY OF MELBOURNE

ATLAS

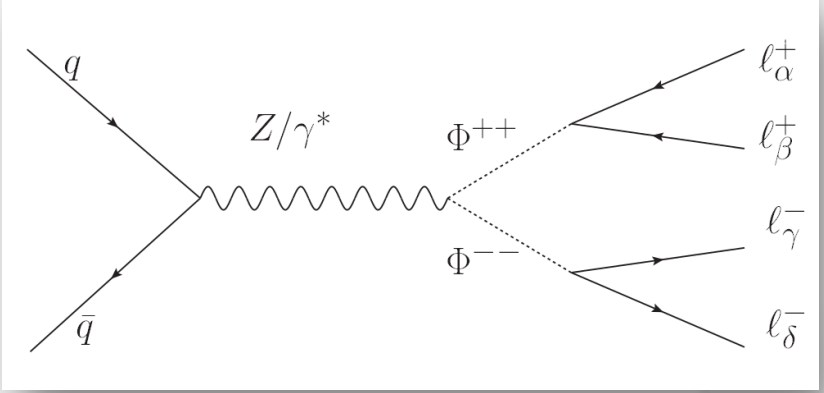
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

# Motivation

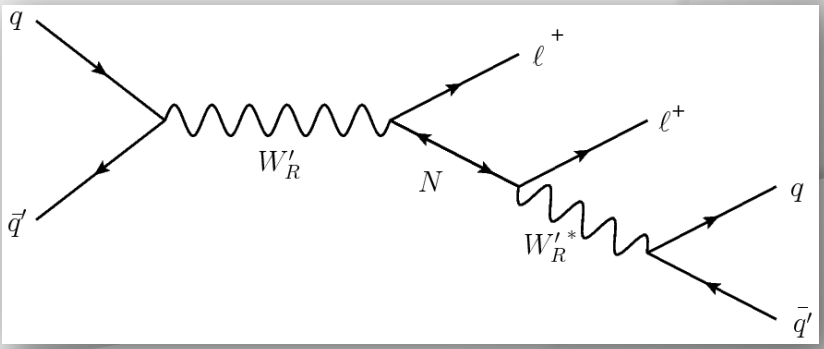
Same-sign (SS) lepton pairs:

- Predicted by Beyond standard Model (BSM) theories:
  - Supersymmetry
  - Zee-Babu model
  - universal extra dimensions
  - left-right symmetric models
  - Higgs Triplet models
  - Little Higgs model
  - vector-like quarks
- Relatively rare in Standard Model

Doubly charged Higgs pairs




$W_R \rightarrow N_R l$



# Motivation

Doubly charged fields necessary for some neutrino mass generation models:

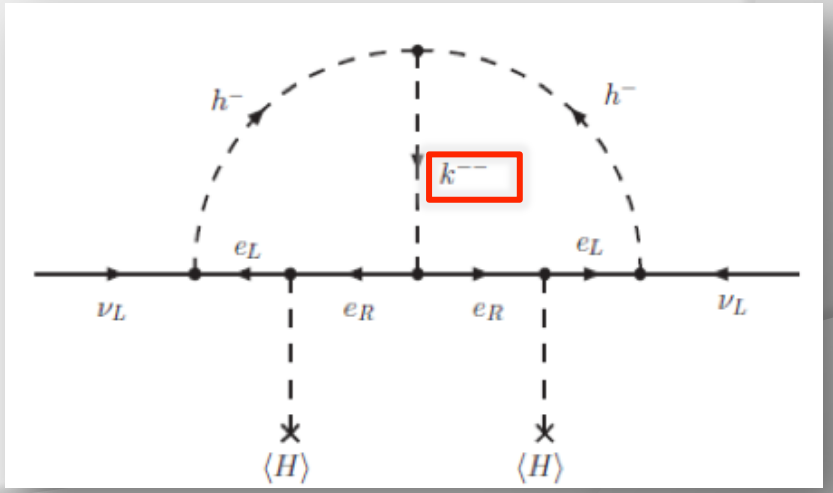
- See-saw Type II:

$$h/2\,\bar{l}_L l_L \Phi + H.c.$$

$$\Phi = \begin{pmatrix} \Phi^{++} \\ \Phi^{+} \\ \Phi^{0} \end{pmatrix}$$

- Radiative mechanisms: neutrino masses produced at loop-level

Two loop small mass generation in the Zee-Babu model



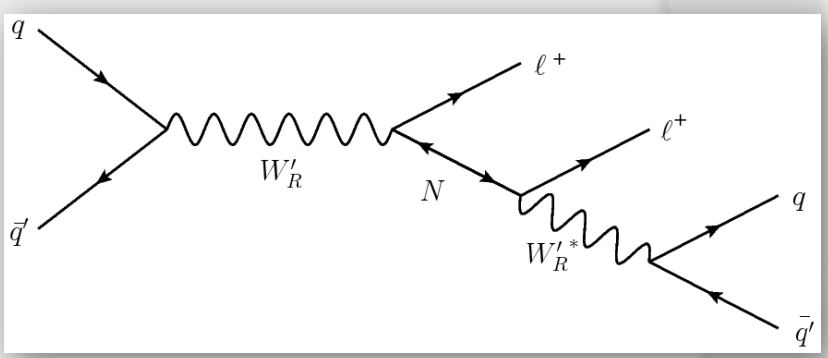

arXiv:0711.0483 [hep-ph]

# Aim

Observe excesses

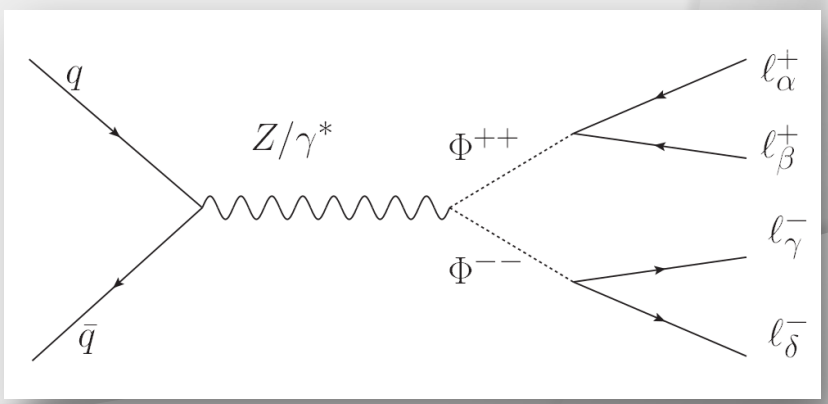
or

Set limits on the fiducial cross sections for processes BSM




and

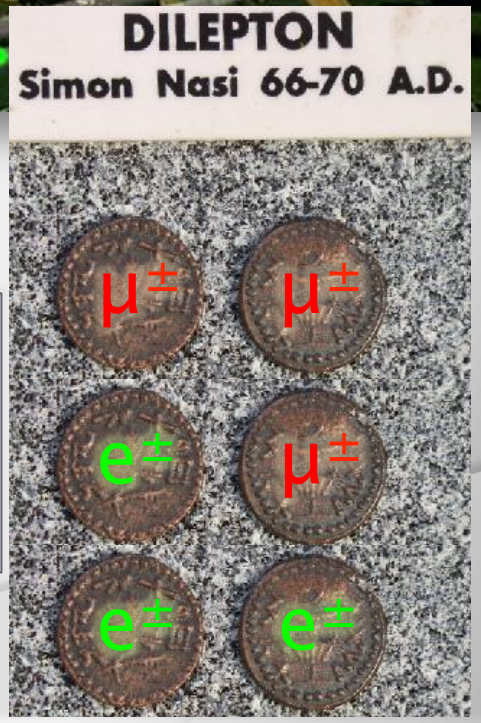
Set limits on the doubly charged Higgs (DCH) pair production



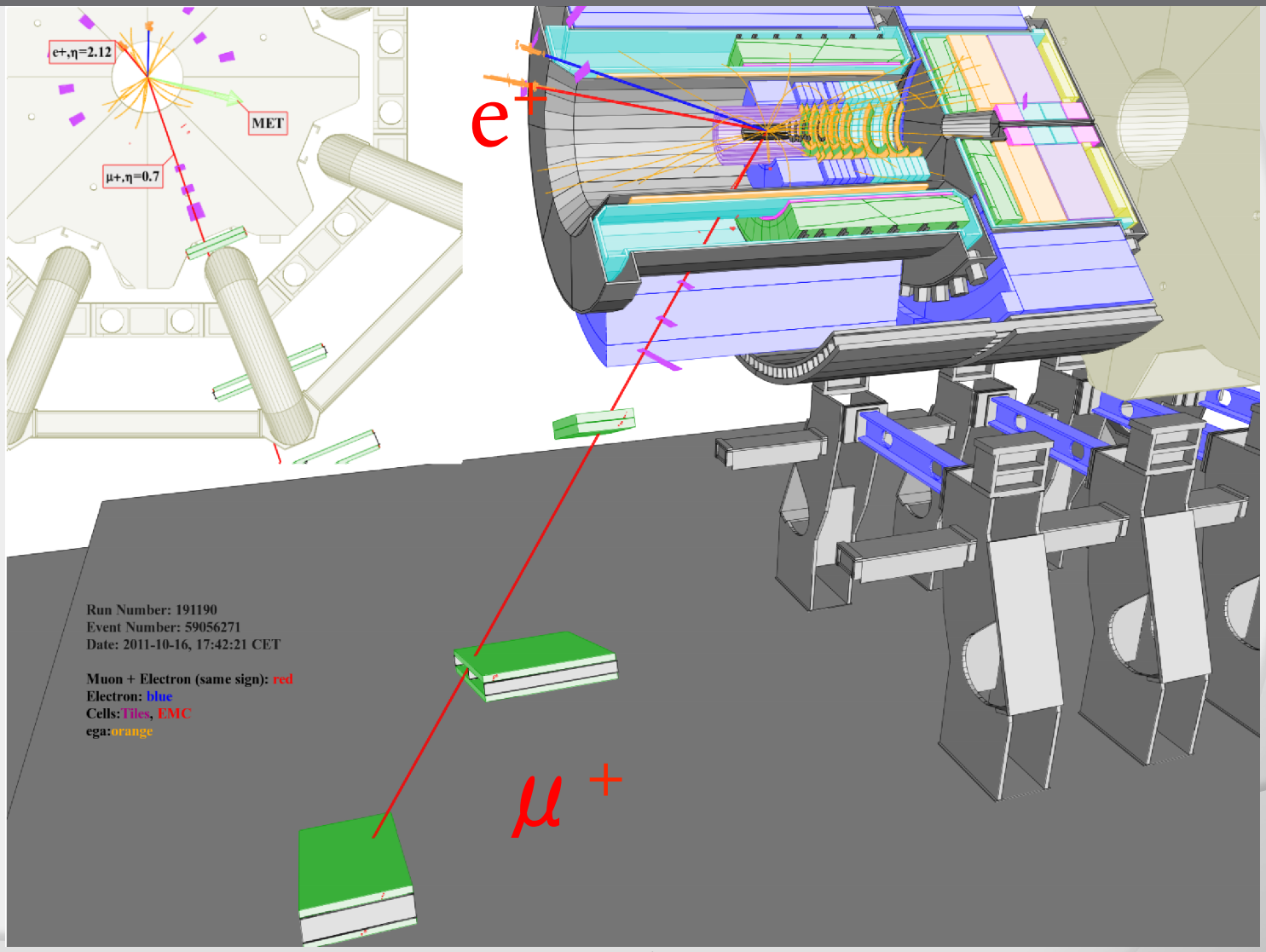
# THE IDEAL FACILITY

- Proton-proton collisions at $\sqrt{s}$=7-8 TeV
- ATLAS detector data $\int \mathcal{L}\, dt = 4.7 - 20.3\ fb^{-1}$
- High performance muon and electron detectors
- This analysis $\sqrt{s}$=7 TeV

Final States



# An $e^+ \mu^+$ pair
# invariant mass=464 GeV/$c^2$



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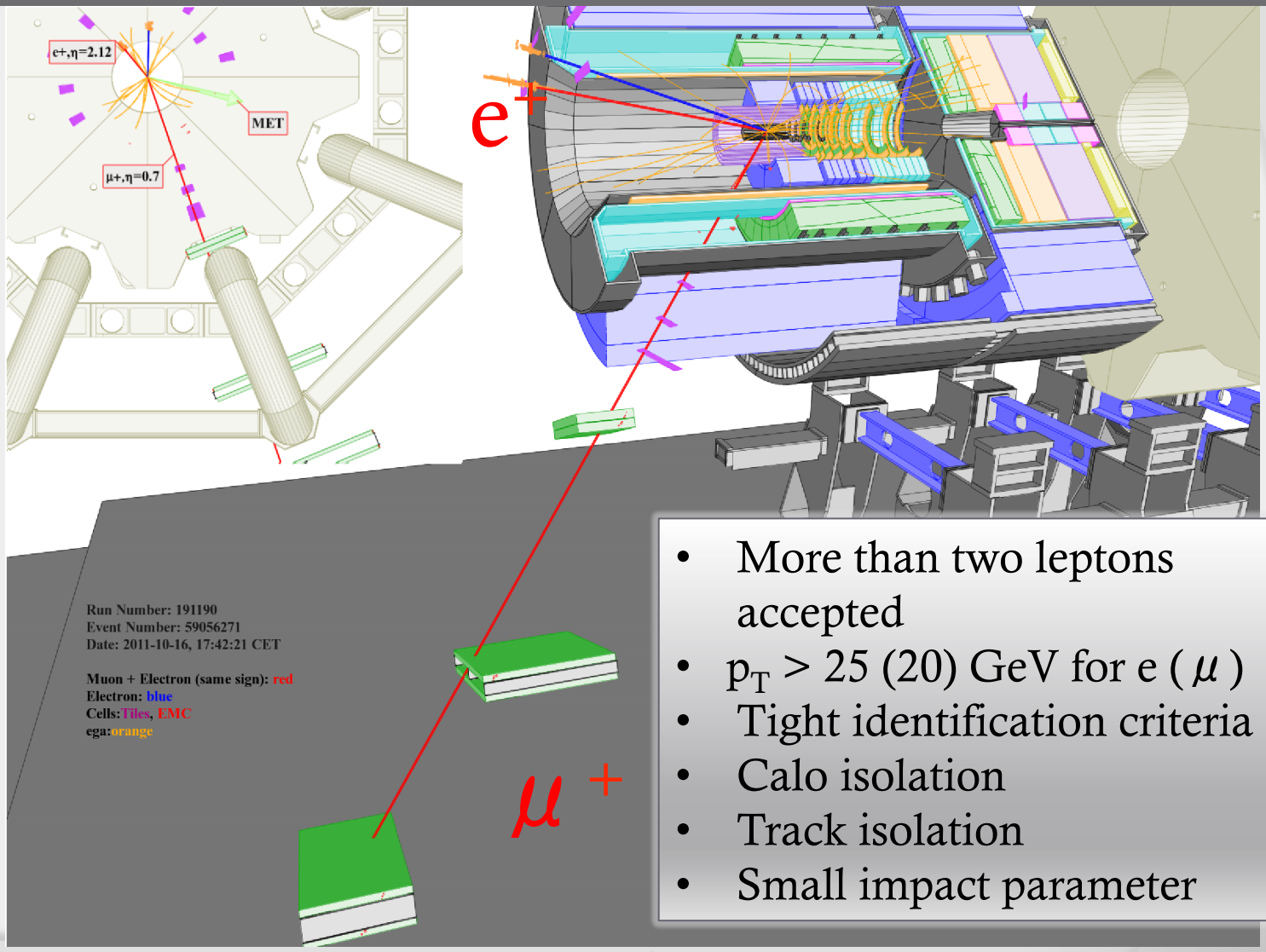
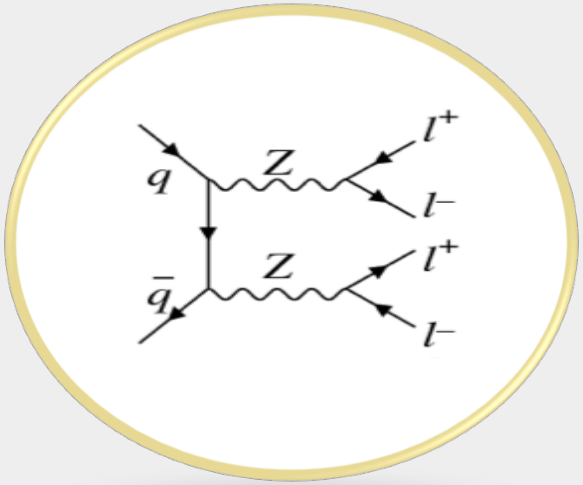


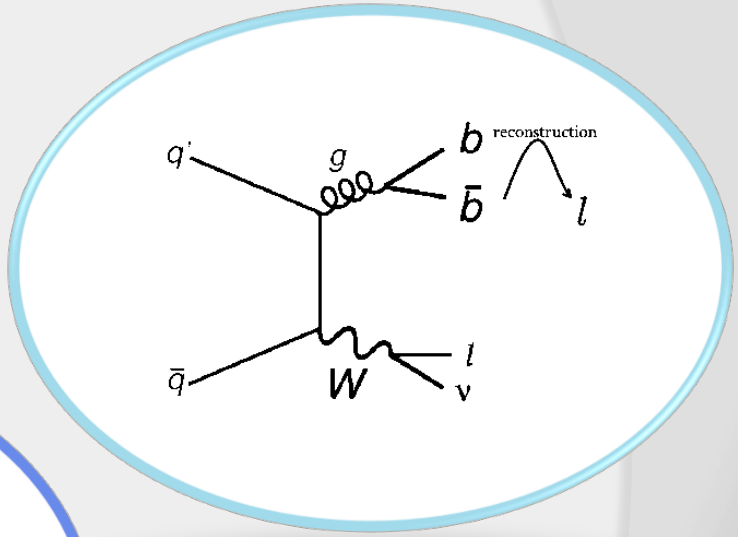

- More than two leptons accepted
- $p_T$ > 25 (20) GeV for e ( $\mu$ )
- Tight identification criteria
- Calo isolation
- Track isolation
- Small impact parameter

# SM Backgrounds

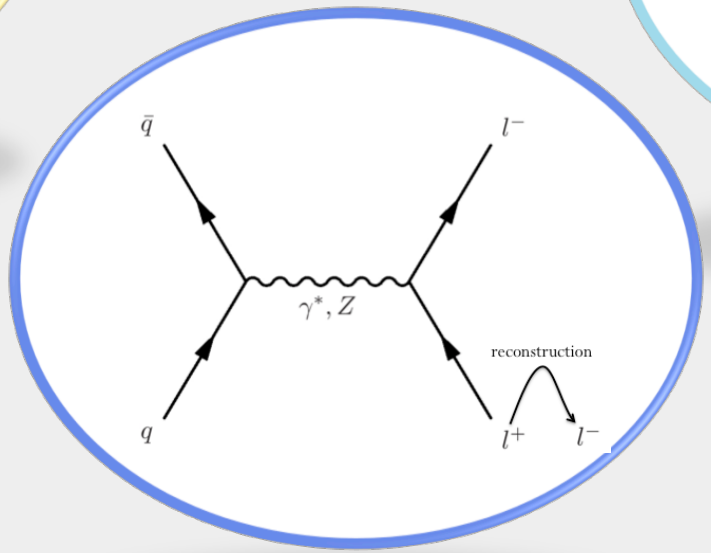
Prompt same-sign leptons




Non-Prompt




Charge mis-ID/W$\gamma$



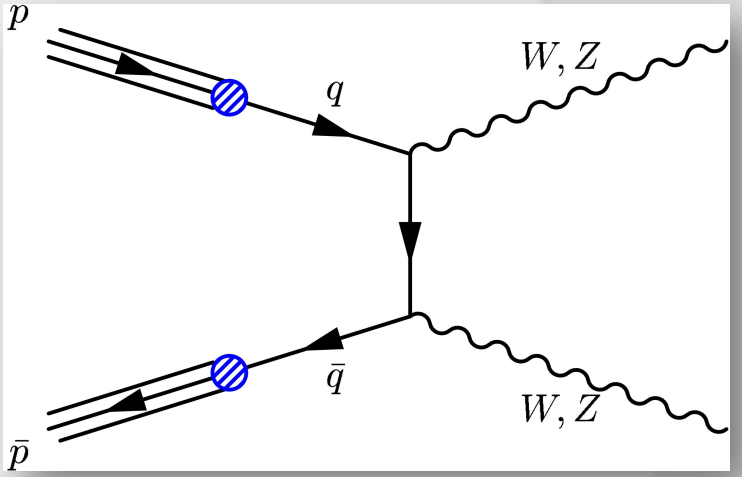
# Prompt Same-sign Bkg

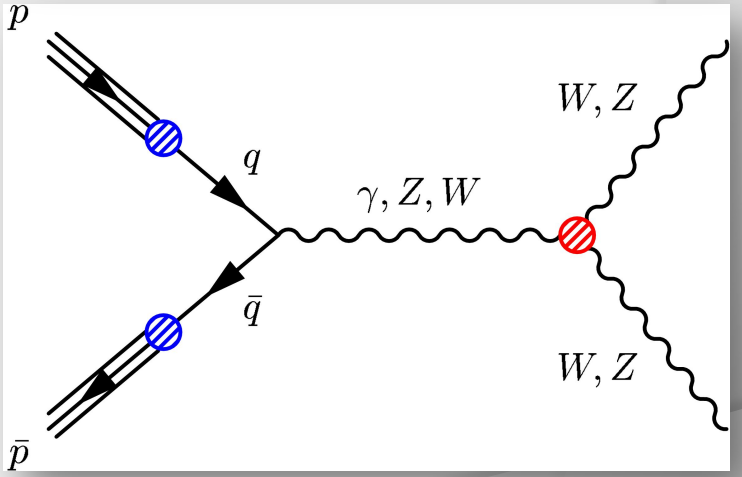
Origin:

- $W^{\pm}Z$, $ZZ$, $W^{\pm}W^{\pm}jj$, $t\bar{t}W^{\pm}$, $t\bar{t}Z$, multiple parton interactions

Estimate:

- MC simulation+data derived corrections



# Charge mis-ID/W$\gamma$ BKG

Origin:

- Drell-Yan, $t\bar{t}$, $W^+W^-$ when:
  - Trident event
  - Charge mis-reconstruction

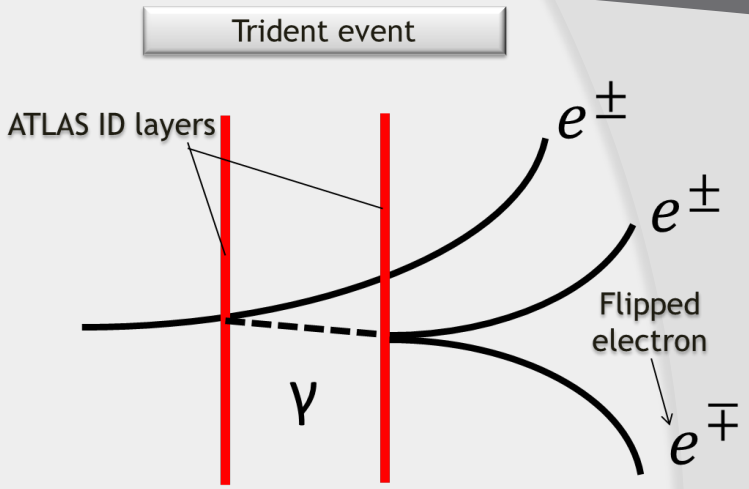
  relevant for e, negligible for $\mu$
- W$\gamma$ when pair production

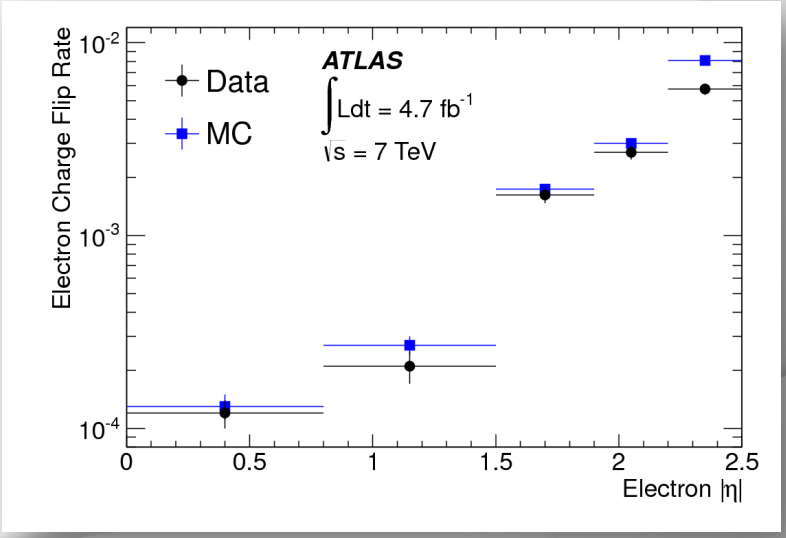
Estimate:

- MC simulation+data derived corrections

Suppression method:

- Tight *e* identification criteria
- Charge inner detector= charge muon spectrometer for $\mu$



# CHARGE MIS-ID/W$\gamma$ BKG

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- Drell-Yan, $t\bar{t}$, $W^+W^-$ when:
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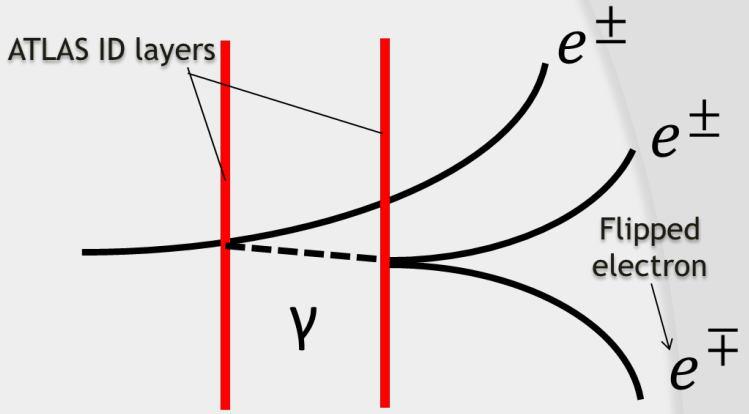
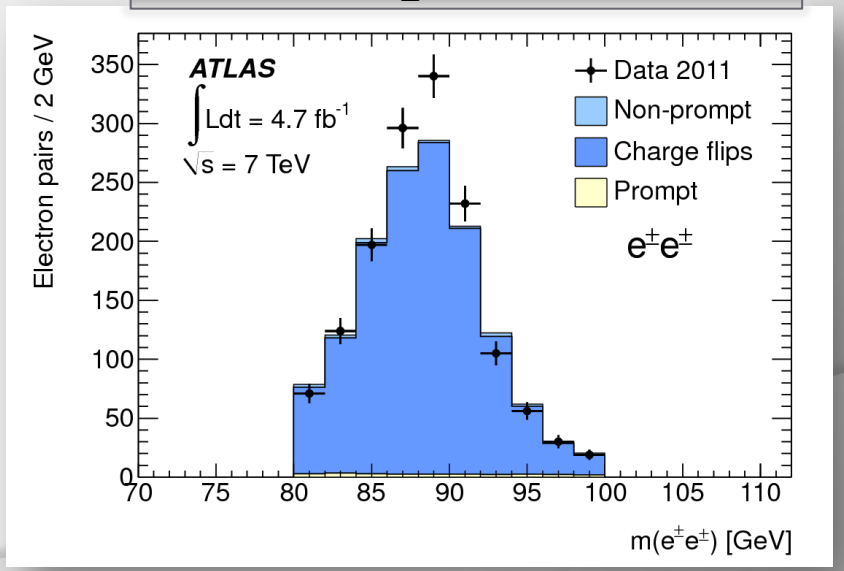
Trident event




$|M(e^{\pm}e^{\pm})-M_Z|<10$ GeV region



# Non-Prompt Bkg

Origin:

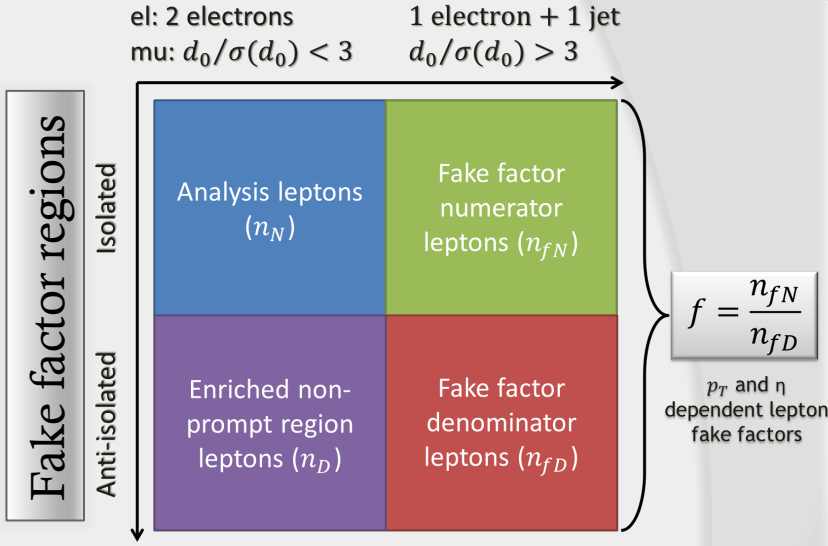
- QCD multijets, W+jets, Drell-Yan+jets, $t\bar{t}$ when:
  - heavy flavor decays
  - light mesons inflight decays
  - mis-identified hadrons

Estimate:

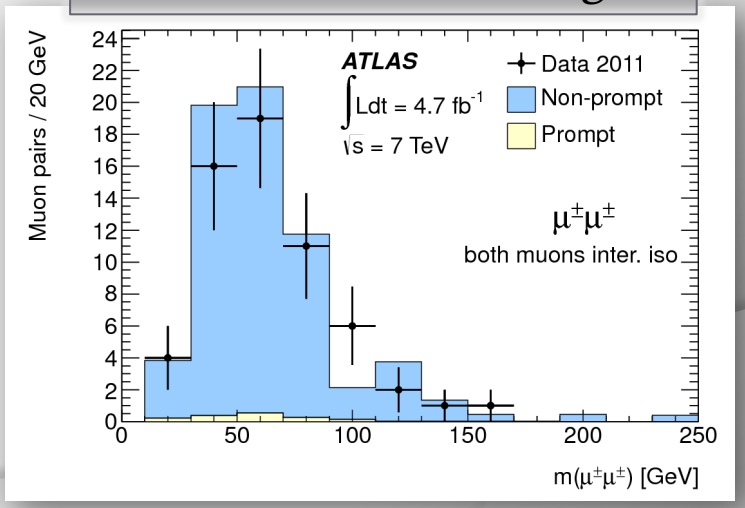
- Data driven via fake factor method

Suppression method:

- Tight lepton identification and isolation criteria
- Small impact parameter to the primary vertex

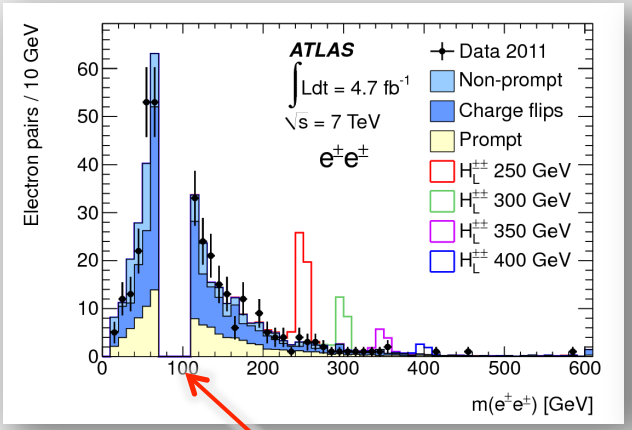


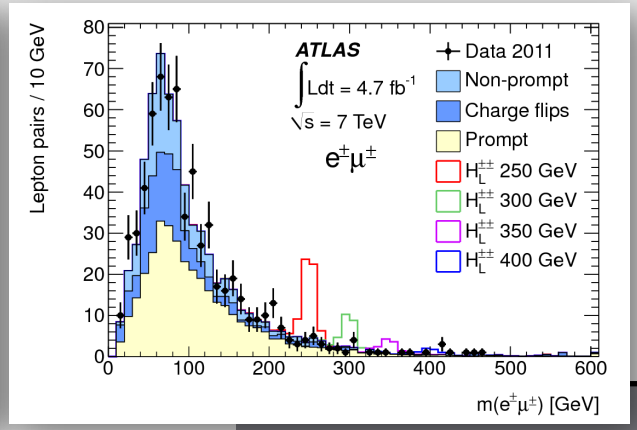

Weak isolation $\mu^{\pm}\mu^{\pm}$ region



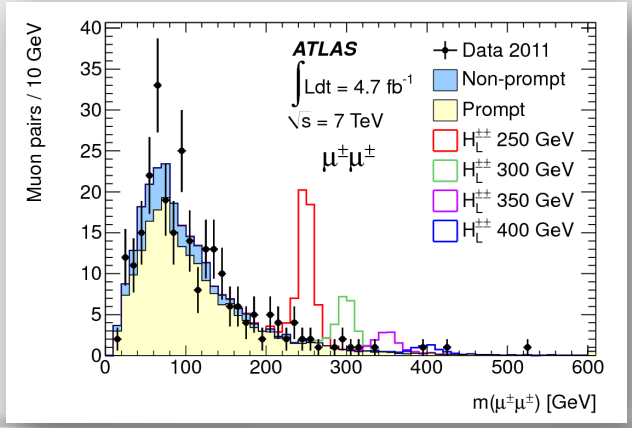
# SIGNAL EVENTS

## Invariant mass of selected same-sign lepton pairs




region $|M(e^{\pm}e^{\pm})-M_Z|<20$ GeV used for charge mis-ID corrections




Expected and observed numbers of selected same-sign lepton pairs

| Sample | Number of pairs | | |
|---|---|---|---|
| | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ |
| Prompt | 101±13 | 346 ± 43 | 205±26 |
| Non-prompt | 75±21 | 151 ± 47 | 42±14 |
| Charge mis-Id/ conversions | 170±33 | 142 ± 28 | 0.0+4.9 -0.0 |
| Total Bkg | 346±44 | 639 ± 71 | 247+30 |
| Data | 329 | 658 | 264 |

# FIDUCIAL CROSS-SECTION LIMITS

1. Set 95 % CL upper limit on the number of non-SM like-sign pairs ($N_{95}$)
2. Estimated fiducial efficiency ( $\varepsilon_{fid}$) in:
   - DCH pair production
   - $W_R$ to l+$N_R$
   - Fourth-gen down-type chiral quarks b'
   - Like-sign top-quark pairs

$$\epsilon_{fid} = \frac{selected\ reco\ pairs}{fiducial\ selected\ truth\ pairs}$$

See backup slides for details

min( $\varepsilon_{fid}$) = 43%, 55%, 59% for e±e±, e± $\mu$ ± and $\mu$ ± $\mu$ ± used for limits

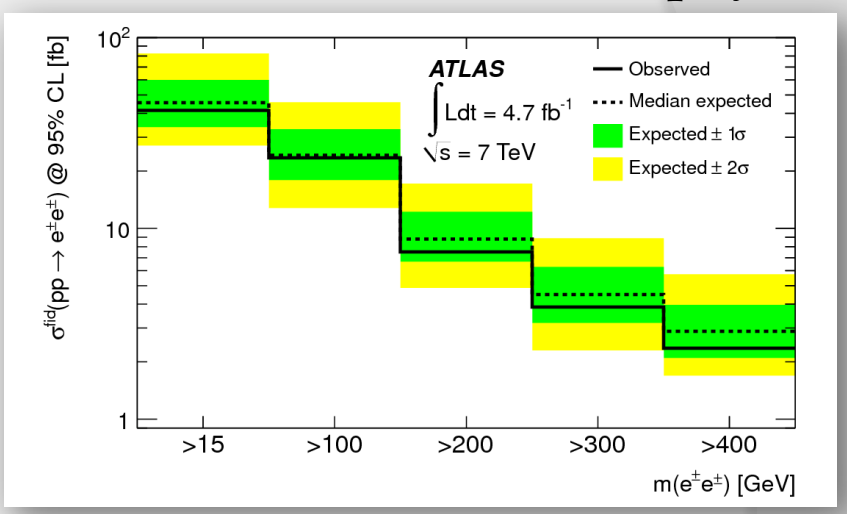
$$\sigma_{95}^{fid}(\ell\ell) = \frac{N_{95}}{\min(\varepsilon_{fid}) \int \mathcal{L} dt}$$

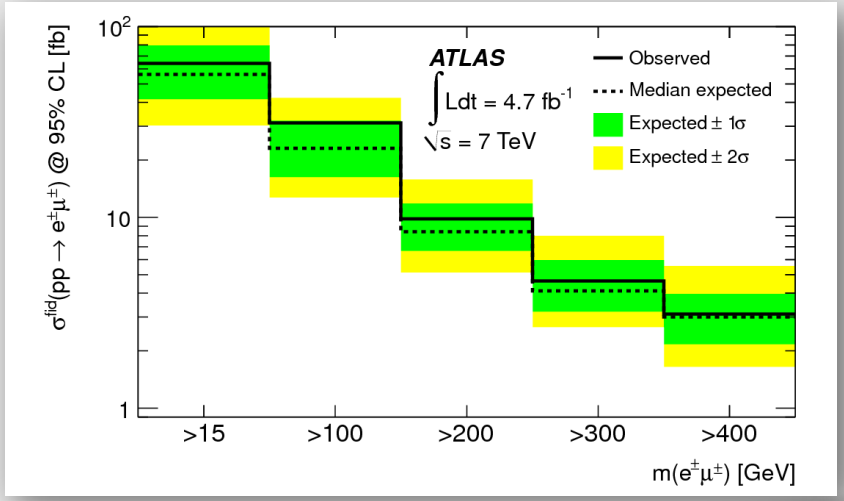
- conservative results
+ valid for many models

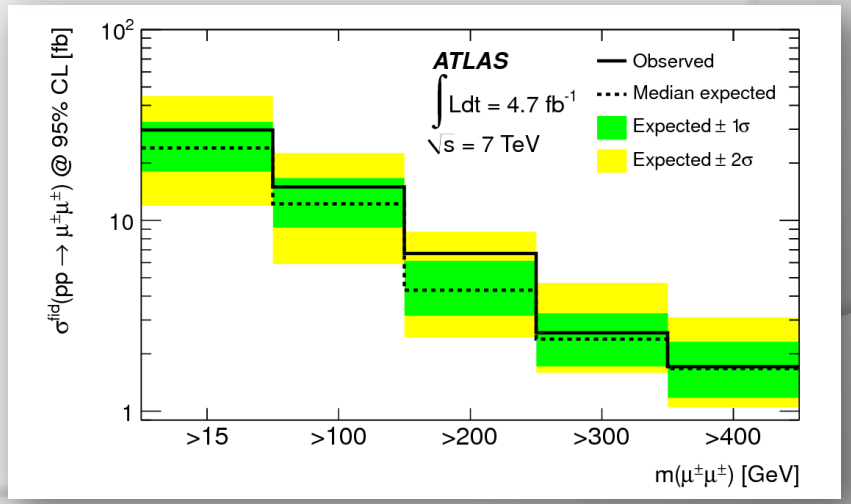
# FIDUCIAL CROSS-SECTION LIMITS

95% Confidence level limits on the fiducial cross-section of non-SM physics

| Fiducial Xsec (fb) | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ |
|---|---|---|---|
| M(ll)>15 GeV | 42 | 64 | 29.8 |
| M(ll)>400 GeV | 2.4 | 3.1 | 1.7 |

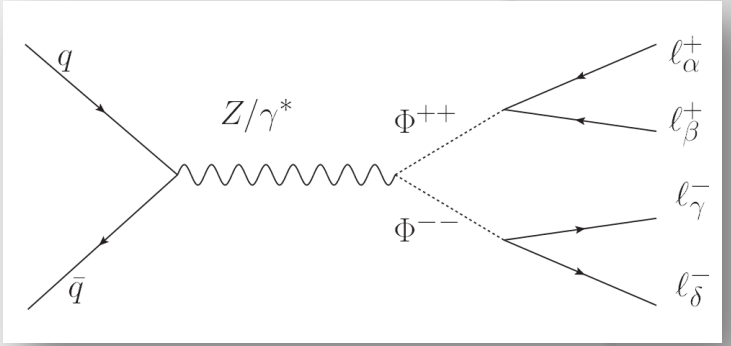


# DCH LIMITS

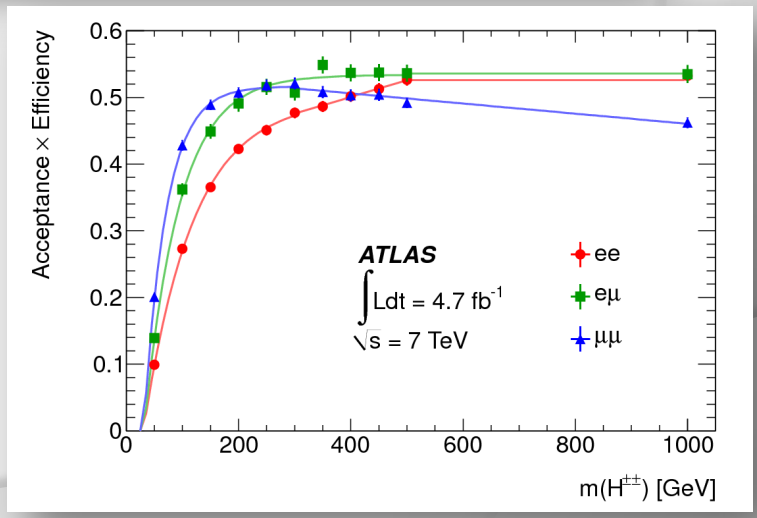
- Set a 95% CL limit on DCH pair production X BR
- Set mass limits on left-right symmetric model Higgs ($H_L^{\pm\pm}$, $H_R^{\pm\pm}$) and Zee-babu Higgs ($H_{ZB}^{\pm\pm}$)




$$\sigma(pp \to H^{\pm\pm}H^{\mp\mp}) \times BR(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = \frac{N^{rec}(\ell^{\pm}\ell'^{\pm})}{2 \times A \times \varepsilon \times \mathcal{L}}$$

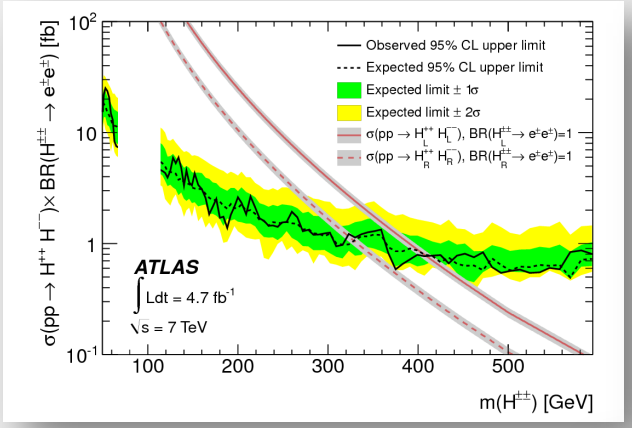
- $N^{rec}$ limit on the number of Higgs candidates
- A x $\varepsilon$ : Acceptance times efficiency to reconstruct a doubly charged Higgs

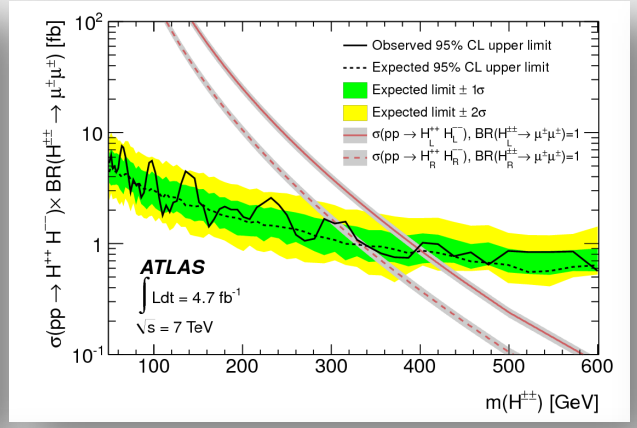
(~50% for high masses)

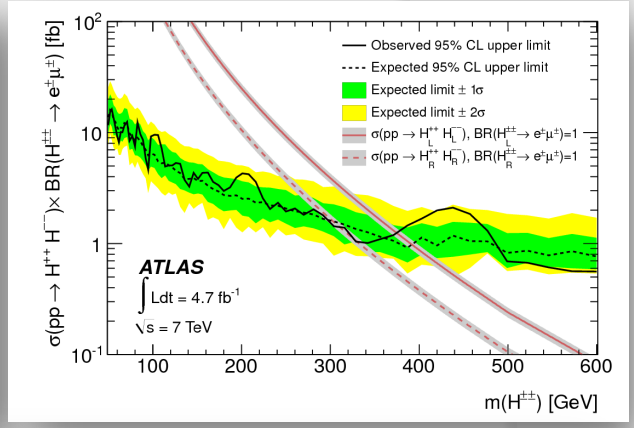


# DCH Limits

- DCH pair production cross-section limits




- $H_L^{\pm\pm}$, $H_R^{\pm\pm}$, $H_{ZB}^{\pm\pm *}$ mass limits

| $BR(H_L^{\pm\pm} \to \ell^\pm\ell'^\pm)$ | 95 % CL lower limit on $m(H_L^{\pm\pm})$ [GeV] | | | | | |
|---|---|---|---|---|---|---|
| | $e^\pm e^\pm$ | | $\mu^\pm\mu^\pm$ | | $e^\pm\mu^\pm$ | |
| | exp. | obs. | exp. | obs. | exp. | obs. |
| 100 % | 407 | 409 | 401 | 398 | 392 | 375 |
| 33 % | 318 | 317 | 317 | 290 | 279 | 276 |
| 22 % | 274 | 258 | 282 | 282 | 250 | 253 |
| 11 % | 228 | 212 | 234 | 216 | 206 | 190 |
| $BR(H_R^{\pm\pm} \to \ell^\pm\ell'^\pm)$ | 95 % CL lower limit on $m(H_R^{\pm\pm})$ [GeV] | | | | | |
| | $e^\pm e^\pm$ | | $\mu^\pm\mu^\pm$ | | $e^\pm\mu^\pm$ | |
| | exp. | obs. | exp. | obs. | exp. | obs. |
| 100 % | 329 | 322 | 335 | 306 | 303 | 310 |
| 33 % | 241 | 214 | 247 | 222 | 220 | 195 |
| 22 % | 203 | 199 | 223 | 212 | 194 | 187 |
| 11 % | 160 | 151 | 184 | 176 | 153 | 151 |

*$H_{ZB}^{\pm\pm}$ limit = $H_L^{\pm\pm}$ limit

# Conclusion

- Inclusive search for new physics in same-sign lepton pairs performed

- No significant excess found ☹
- 95% CL fiducial cross section upper limits set
- 95% CL left-right symmetric model $H_L^{\pm\pm}$, $H_R^{\pm\pm}$ and Zee-babu $H_{ZB}^{\pm\pm}$ mass lower limits set

| | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ |
|---|---|---|---|
| Fiducial Xsec (fb) M(ll)>15 (400) GeV | 42-2.4 | 64-3.1 | 29.8-1.7 |
| $H_{ZB}^{\pm\pm}=H_L^{\pm\pm}$ ($H_R^{\pm\pm}$) | 409 (322) | 375 (310) | 398 (306) |

- Looking forward to the 2015 data run at 13 TeV for more (massive) same-sign pairs

Thank you!

# Back up

# SYSTEMATICS

$e^{\pm}\mu^{\pm}$ channel

| Source of uncertainty | Processes affected | Effect on prediction |
|---|---|---|
| Lepton trigger | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$, $W\gamma$<br>Charge flips | ±0.4% |
| Electron reconstruction | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$, $W\gamma$<br>Charge flips | ±0.6 – 0.8% |
| Electron identification (*Tight++*) | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$, $W\gamma$<br>Charge flips | ±1.0 – 1.6% |
| Electron identification (isolation, impact params) | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$, $W\gamma$<br>Charge flips | ±1% |
| Muon identification | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$, $W\gamma$<br>Charge flips | ±0.3% |
| Muon isolation efficiency | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$ | ±2.0%<br>±1.3% |
| Electron energy scale and smearing | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$, $W\gamma$<br>Charge flips | ±1.0% |
| Muon pt smearing | Signal<br>$WZ$, $ZZ$, $W^{\pm}W^{\pm}$, $t\bar{t}W$, $t\bar{t}Z$, $W\gamma$<br>Charge flips | ±0.1% |
| Electron charge flip SF | Charge flip | ±14 – 17% |
| Electron / Muon fake factors | Fakes | ±20 – 35% |
| Electron fake/charge flip overlap | Fakes | ±18% |
| Electron light/heavy flavor | Fakes | ±5 – 30% |
| Photon reconstructed as electron | $W\gamma$ | ±12 – 18% |

# FIDUCIAL EFFICIENCY

$$\epsilon_{fid} = \frac{selected\ reco\ pairs}{fiducial\ selected\ truth\ pairs}$$

- Reconstructed pairs pass the analysis selection
- Truth pairs pass an ad-hoc selection (fiducial selection) which applies at particle level requirements equivalent to the reco selection. The dependence of $\varepsilon_{fid}$ by the model is minimized

| | Electron requirement | Muon requirement |
|---|---|---|
| Leading lepton $p_T$ | $p_T > 25$ GeV | $p_T > 20$ GeV |
| Sub-leading lepton $p_T$ | $p_T > 20$ GeV | $p_T > 20$ GeV |
| Lepton $\eta$ | $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$ | $\lvert\eta\rvert < 2.5$ |
| Isolation | $p_T^{\text{cone0.3}}/p_T < 0.1$ | $p_T^{\text{cone0.4}}/p_T < 0.06$ and $p_T^{\text{cone0.4}} < 4$ GeV $+ 0.02 \times p_T$ |

| Selection | Event selection |
|---|---|
| lepton pair | same-sign pair with $m_{\ell\ell} > 15$ GeV |
| electron pair | veto pairs with $70 < m_{\ell\ell} < 110$ GeV |

# DCH MASS LIMITS (7 TEV)

| $BR(H_L^{\pm\pm} \to \ell^{\pm}\ell'^{\pm})$ | 95 % CL lower limit on $m(H_L^{\pm\pm})$ [GeV] | | | | | |
|---|---|---|---|---|---|---|
| | $e^{\pm}e^{\pm}$ | | $\mu^{\pm}\mu^{\pm}$ | | $e^{\pm}\mu^{\pm}$ | |
| | exp. | obs. | exp. | obs. | exp. | obs. |
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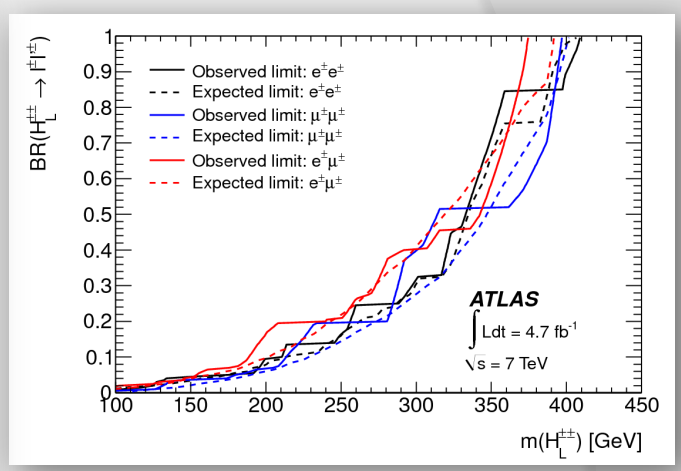
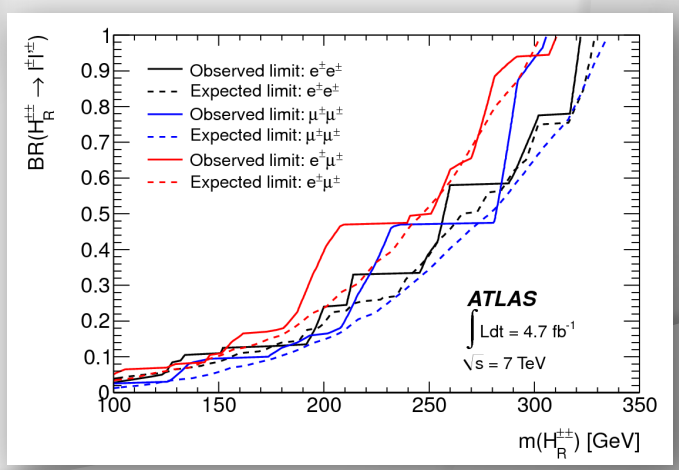
| $H_L^{\pm\pm}$ Mass limit (GeV) | ee | μμ | eμ |
|---|---|---|---|
| ATLAS 7 TeV, 4.7 fb$^{-1}$ | 409 | 398 | 375 |
| CMS 7 TeV (arxiv:1207:2666 [hep-ex]) | 382 | 395 | 391 |



# Event Selection

- Run has passed the Good Run List
- At least three tracks from the primary vertex
- Data cleaned for errors in the detectors
- Pass and match triggers:
  - $e^{\pm}e^{\pm}$: single electron pT>22 GeV
  - $\mu^{\pm}\mu^{\pm}$: single muon pT> 18 GeV
  - $e^{\pm}\mu^{\pm}$: single muon pT> 18 GeV or single electron pT>22 GeV
- Number of leptons $\geq 2$
- Any combination of same-sign $l^{\pm}l'^{\pm}$ pairs allowed
- $M(l^{\pm}l'^{\pm})>15$ GeV to avoid hadronic resonances
- $|M(e^{\pm}e^{\pm}) - 90\ \text{GeV}|>20$ GeV to avoid $Z/\gamma*$ events with a charge mis-ID lepton

# Lepton Selection

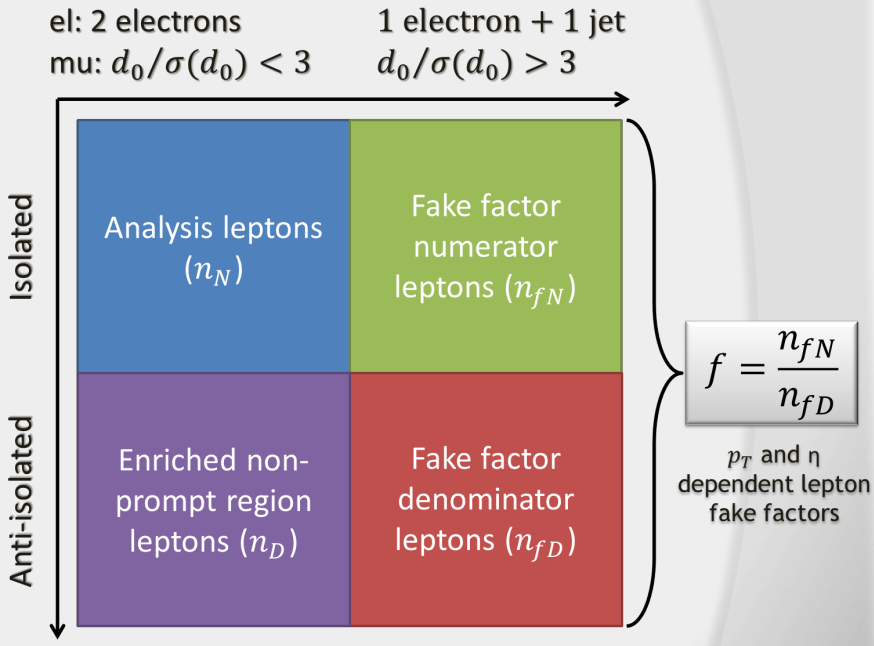
| Any Lepton: | Electron: | Muon: |
|---|---|---|
| Kinematic: $p_T$ > 25 (20) GeV for e ($\mu$) | $\lvert\eta\rvert$<1.37 or 1.52<$\lvert\eta\rvert$<2.47 | $\lvert\eta\rvert$<2.5 |
| Identification: | "tight" | combined muon |
| Calo Isolation: | $E_T$cone20<3GeV+($p_T$-20GeV)*0.037 | |
| Track iso: | $p_T$cone30/$p_T$<0.1 | $p_T$cone40/$p_T$<0.06 |
| $\Delta$R(lep, Jet)>0.4 when $p_T$(Jet)>25 GeV+0.05*$p_T$ | | $p_T$cone40<4GeV +0.02*$p_T$ |
| Impact parameter: $\lvert Z_0*\sin(\theta)\rvert$<1mm $\lvert d_0\rvert/\sigma(\theta)$<3 | | $\lvert$d0$\rvert$<0.2mm |
| Trigger matching | | |
| Truth prompt lepton matching | | |

# Fake Fator Method

Used to determine the expected background processes where at least one of the leptons is non-prompt in the signal region.

Fake factor derivation:

i. Define signal-like region enriched in non-prompt leptons
ii. Define the numerator selection (signal selection) and denominator selection (invert one or more signal cuts)
iii. Remove residual prompt leptons with MC subtraction
iv. Measure fake factors as a function of $p_T$ and $\eta$




$$f_i(p_T, \eta) = (n_{fL}(p_T)/n_{fD}(p_T)) \times (n_{fL}(\eta)/n_{fD}(\eta))$$

$n_{fL}$ = number of numerator leptons

$n_{fD}$ = number of denominator leptons

# Fake Fator Method

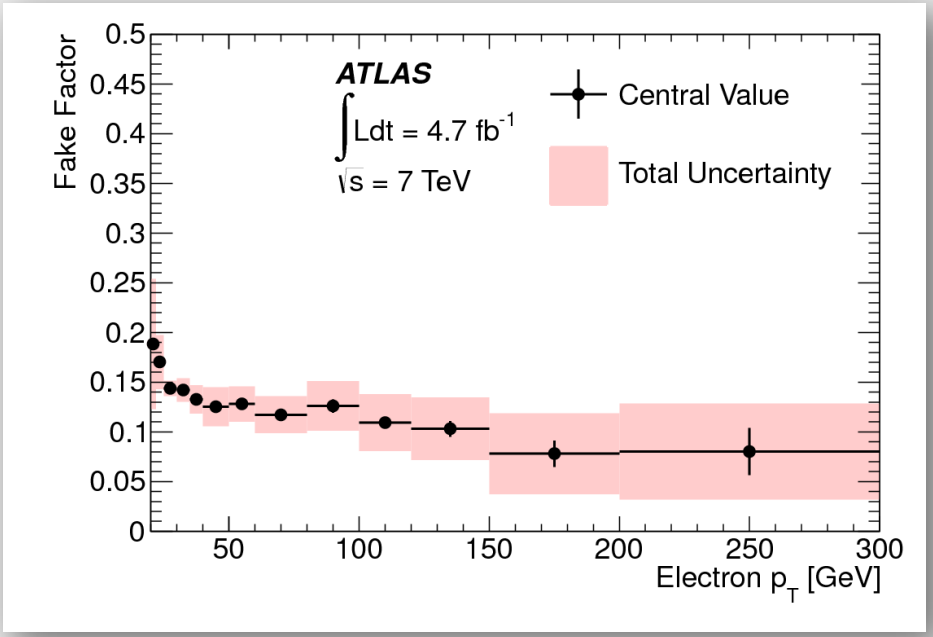
Application:

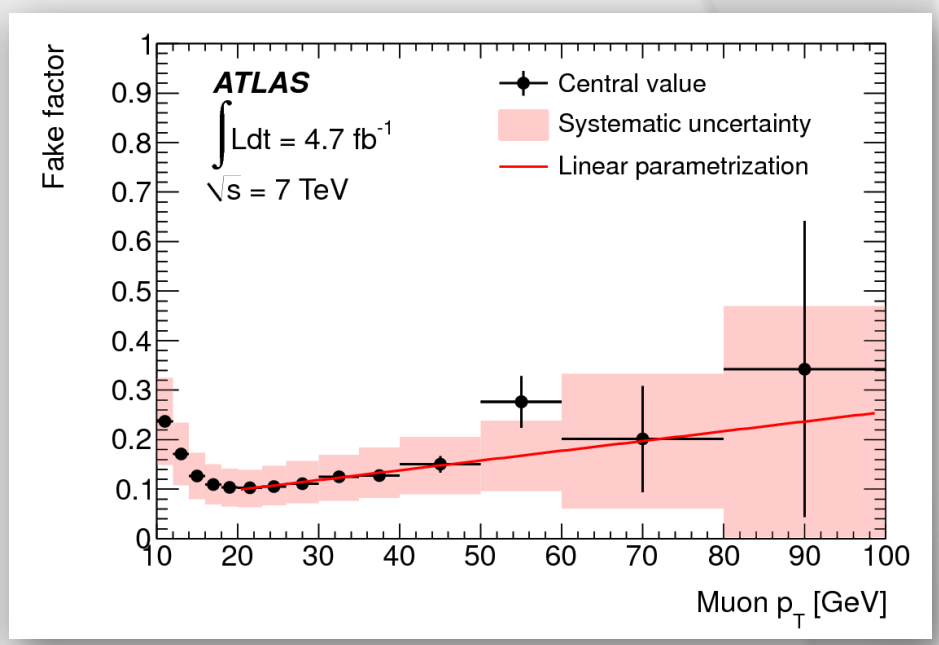
- Fake factor are used to scale the events in which a lepton passes the denominator selection
- The estimate of the number of fakes in the signal region is

$$n_{fakes} = \sum_{i=1}^{n_{(D+N)}} f_1 + \sum_{i=1}^{n_{(N+D)}} f_2 - \sum_{i=1}^{n_{(D+D)}} f_1 f_2$$

  - $n_{(D+N)}$: events with leading denominator and sub-leading numerator leptons
  - $n_{(N+D)}$: events with leading numerator and sub-leading denominator leptons
  - $n_{(D+D)}$: events with 2 denominator leptons
  - f1, f2 are the fake factors for leading and sub-leading denominator leptons. We assume f1=f2=f($p_T$,η) of the denominator lepton

# Fake factors




Electron fake factors vs $p_T$

Muon fake factors vs $p_T$

# Acceptance X efficiency

- Fitted using the function:

$$A \cdot \varepsilon(m) = \begin{cases} p_0(1 - e^{-(m-p_1)/p_2}), & \text{if } m < m_0 \\ p_3 - p_4 m, & \text{if } m \geq m_0 \end{cases}$$

$m_0$ = 450 GeV for ee, 300 GeV for e $\mu$ , $\mu$ $\mu$

ee

| Parameter | Value |
|---|---|
| $p_0$ | $4.76 \times 10^{-1}$ |
| $p_1$ | $2.94 \times 10^{+1}$ |
| $p_2$ | $1.05 \times 10^{+2}$ |
| $p_3$ | $4.51 \times 10^{-1}$ |
| $p_4$ | set by requiring continuity |

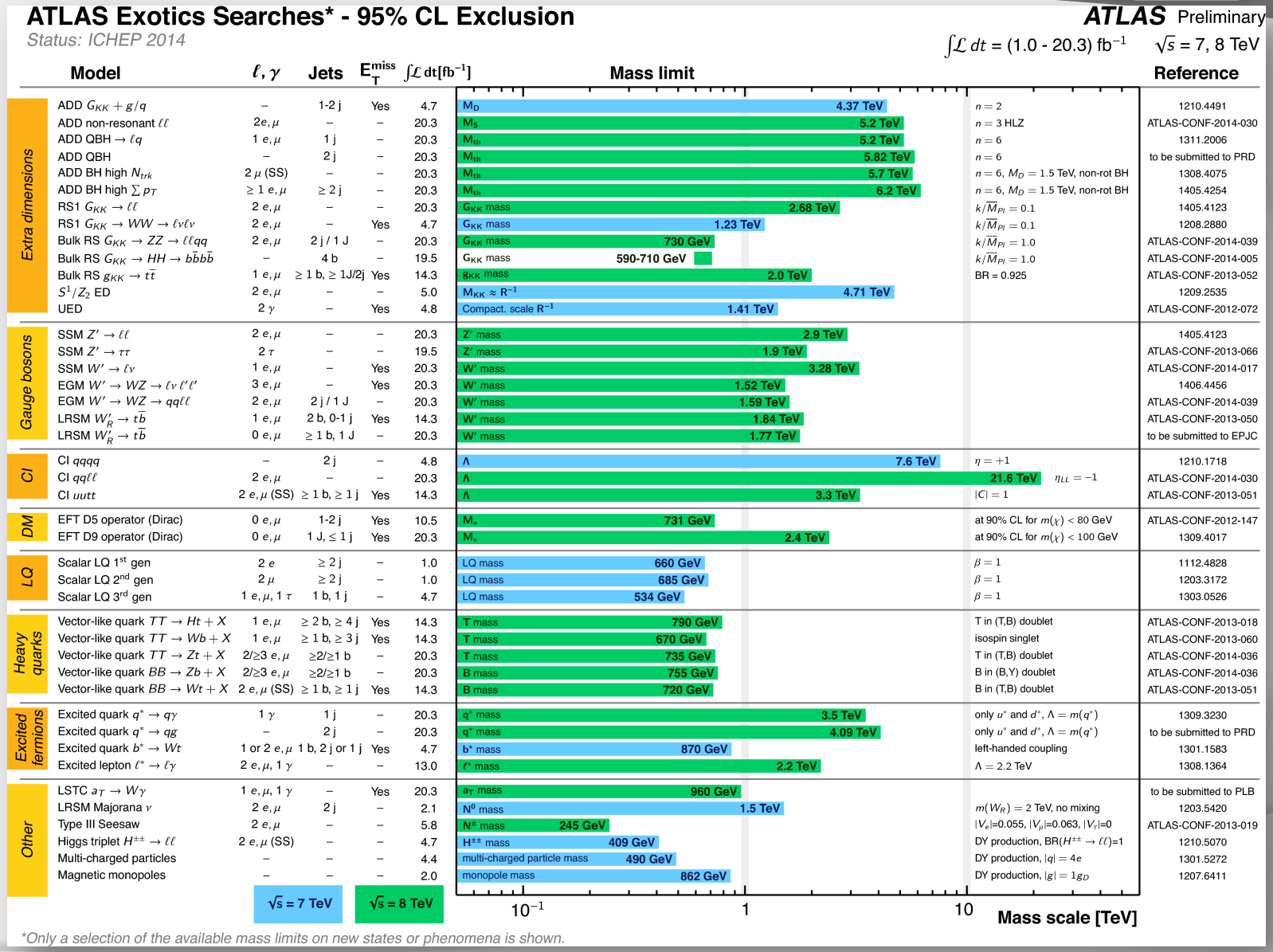
e $\mu$

| Parameter | Value |
|---|---|
| $p_0$ | $4.99 \times 10^{-1}$ |
| $p_1$ | $3.06 \times 10^{+1}$ |
| $p_2$ | $7.64 \times 10^{+1}$ |
| $p_3$ | $4.79 \times 10^{-1}$ |
| $p_4$ | set by requiring continuity |

$\mu$ $\mu$

| Parameter | Value |
|---|---|
| $p_0$ | $4.98 \times 10^{-1}$ |
| $p_1$ | $2.95 \times 10^{+1}$ |
| $p_2$ | $5.14 \times 10^{+1}$ |
| $p_3$ | $5.05 \times 10^{-1}$ |
| $p_4$ | set by requiring continuity |

# Status Exotic searches (ATLAS)




*Only a selection of the available mass limits on new states or phenomena is shown.