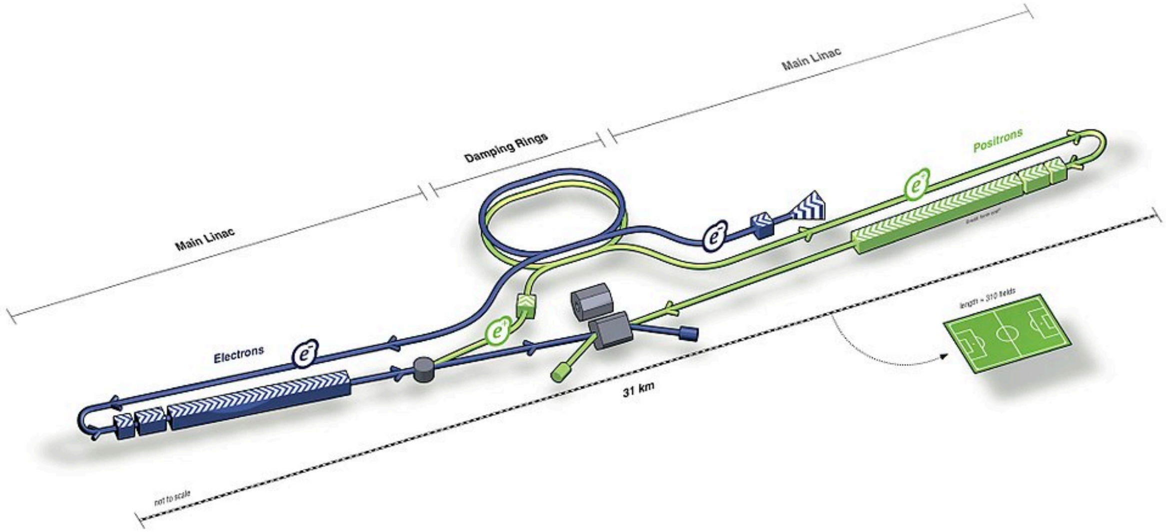
Future Dark Photon searches at the ILC

FIPS decays in the dimuon spectrum



Source: ILC technical design report, Behnke et al., 2013

- Project aims
- FIP motivation
- Simulation overview
- Familiarizing myself
- Cuts on backgrounds
- Leptonic and Hadronic backgrounds
- B Tagging – J/Psi
- Exclusion/Detection
- Weights/ beam polarization
- Statistics

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Project Aim

- Study 'Dark Photon' flavor of FIPS at ILC
- Dark photon (Z') decays into SM particles – specifically muons
- Study limits on detecting a peak in the DiMuon spectrum at ILC
- Look for narrow peak; primarily against dominant background from Z resonance
- Estimate background rates from full detector simulation data (DST files) using ILCSoft/LCIO in ROOT framework
- Discovery and exclusion potential of ILC for this scenario using SGV fast detector simulation signals (Whizard)

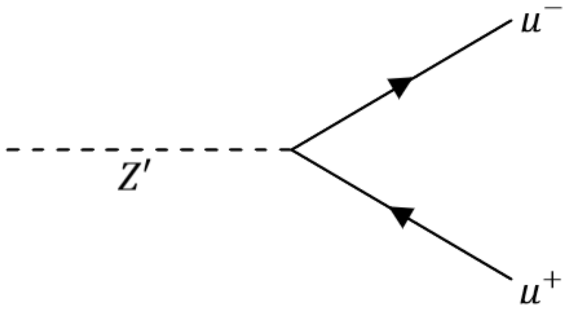

Fig 1 - Dark photon decaying to produce dimuon peak

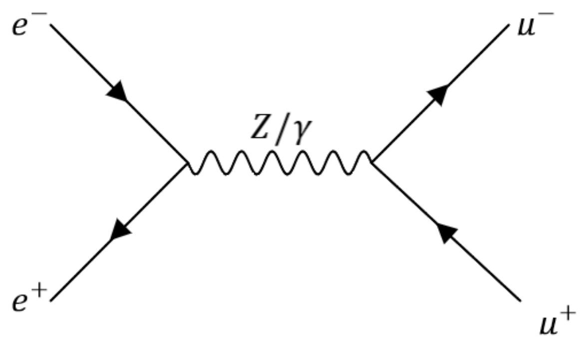

Fig 2 - Dominant background: muon pair production from Z resonance

Dark Matter – Motivation for 'FIP' search

- CMB
- Galaxy dynamics
- Relic abundance: **'Freeze out'** point depends on the particles mass, and cross section.
- Number one candidate: WIMPs. Coupling weakly
- Massive Astrophysical Compact Halo Objects (MACHOs)
- Also, **Feebly Interacting ParticleS (FIPS),** coupling somewhat weakly (not as weak as Weak interaction)

- Direct detection – DM scatters/interacts directly
- Indirect detection (ILC) reconstructed peaks in mass spectrum

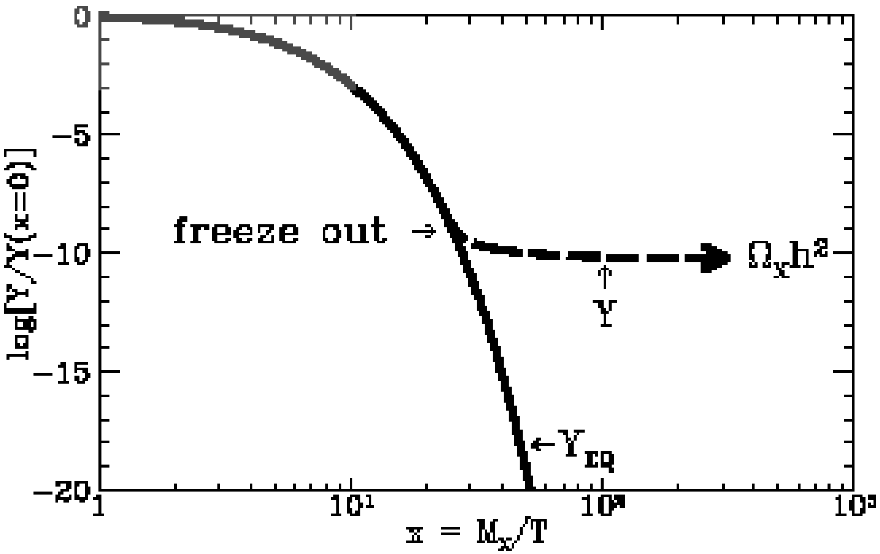

Fig 3 - Log Ratio number density (Y) at (T) to original density, as temperature T decreases with expansion.
[Source: https://ned.ipac.caltech.edu/level5/Kolb/Kolb5_1.html]

Dark Matter – Flavour of FIPS

- Requirements:
  - Not charged under strong force
  - Has not been excluded/discovered
  - Lighter than 10GeV (Relic abundance)

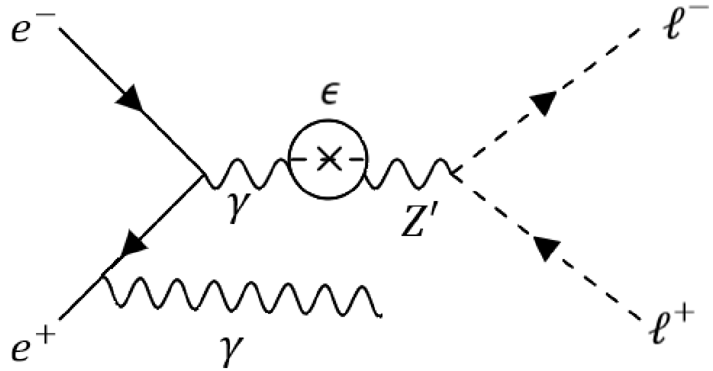

Fig 4 – Feynman diagram illustrating the production of Z’

- New proposed dark gauge boson (Z’) probing into dark sector (not dark matter itself)

- Does not interact through SM gauge interaction – new U(1) gauge symmetry

- Experimental search for an ISR photon and a Z’

- e^+e^- -> γ_{ISR} Z’, where Z’ -> $\ell^+ \ell^-$

- Focus on muon pair decay: Z’ -> $\mu^+ \mu^-$

Signal generation - Whizard

- Steering file (.sin) to produce signal distributions
- Utilizes Unified Feynrules Output (UFO) files: model for automated matrix element generators*
- Both **eLpR** and **eRpL** polarizations
- Center of mass energy 250 GeV
- Z' mass from 10GeV – 250GeV

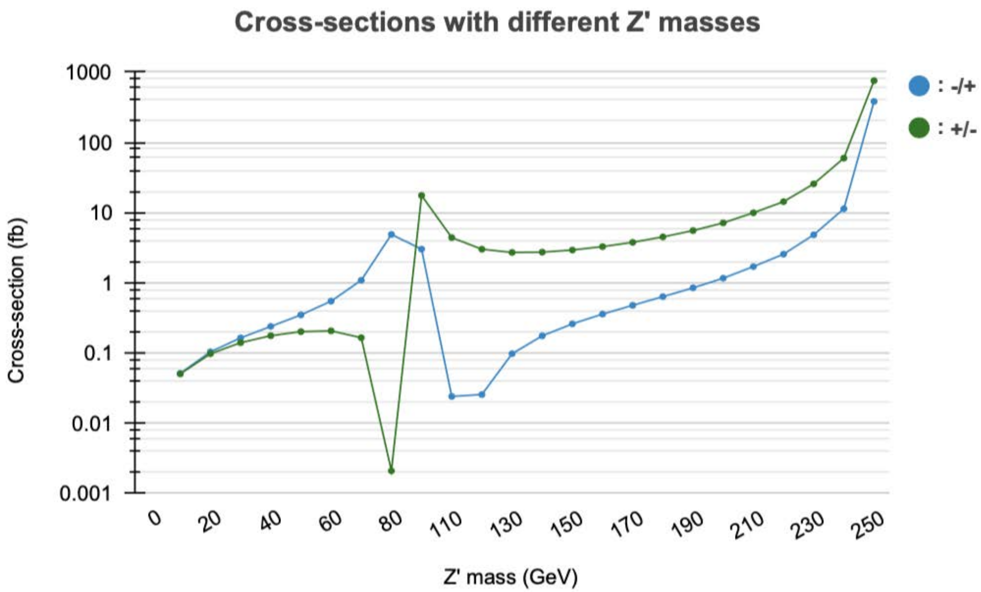

Fig 7 – Cross section varying with Z' masses for polarization left (blue), right (red)

- Z boson mass interference around 90GeV
- Resonance at 250GeV causes highest σ
- Cross section also scales with some power of η (coupling strength)

* SOURCE: Curtin, D., Essig, R., Gori, S. and Shelton, J., 2015. Illuminating dark photons with high-energy colliders.*Journal of High Energy Physics*, 2015(2).

Signal generation – SGV fast detector simulation

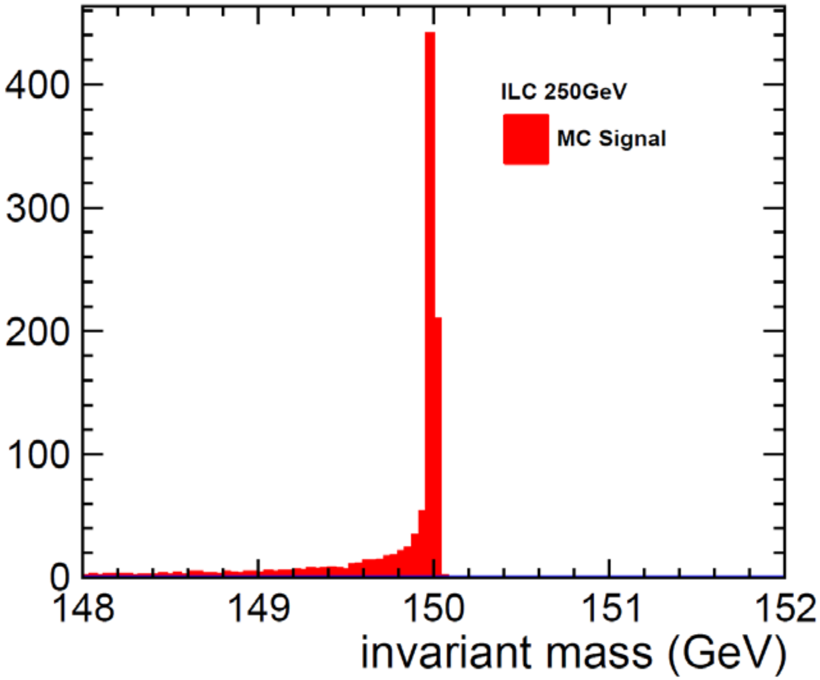

Fig 8 – invariant mass of muon pairs at generator Truth level

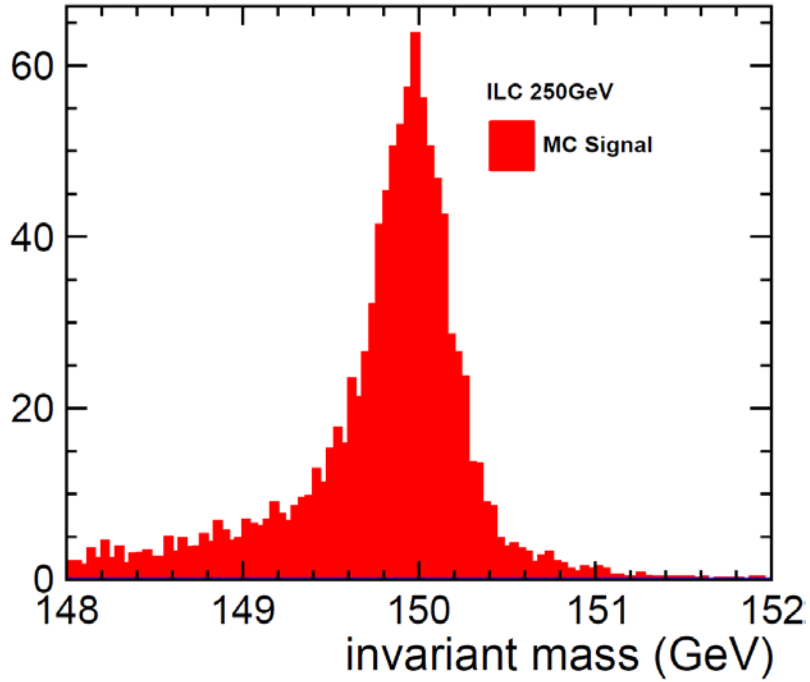

Fig 9 – invariant mass of muon pairs produced with SGV

- Signal is small narrow peak in dimuon spectrum
- Z’ to di-lepton resonance is expected to be narrower than detector resolution

Background – full detector simulation

- Full Monte Carlo simulation -> DST files
- DST contain collections of reconstructed event data
  - Particle objects
  - Vertex data
- DST to miniDST by ‘Marlin’ processor -> provides additional collections
  - Isolated leptons
  - Jet collections

Dimuon backgrounds: 2f_leptonic vs 4f_semileptonic

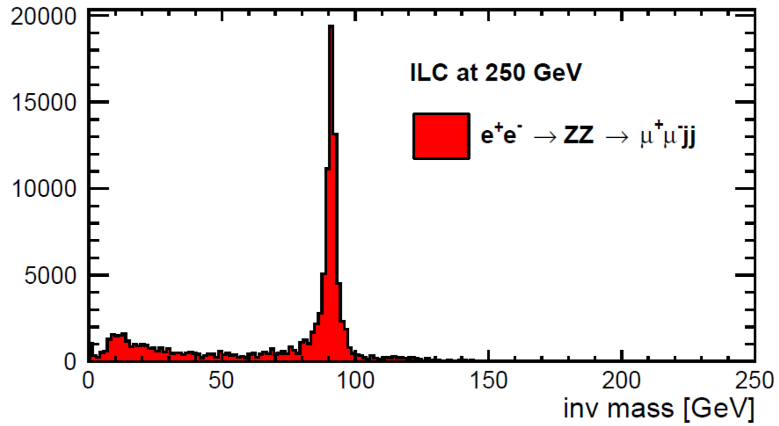

Fig 3 - Double Z resonance pair production of muons with 2 quarks producing hadronic jets

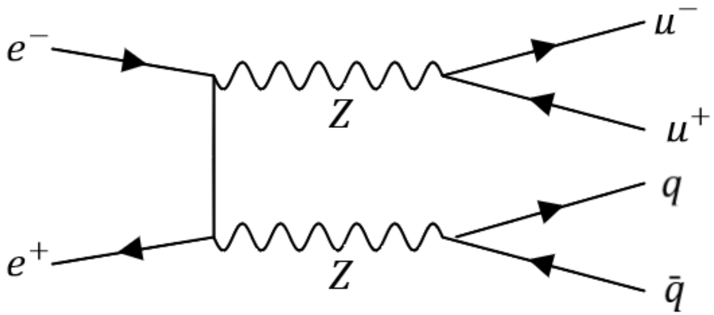

Fig 4 - Corresponding semi-leptonic Feynman diagram

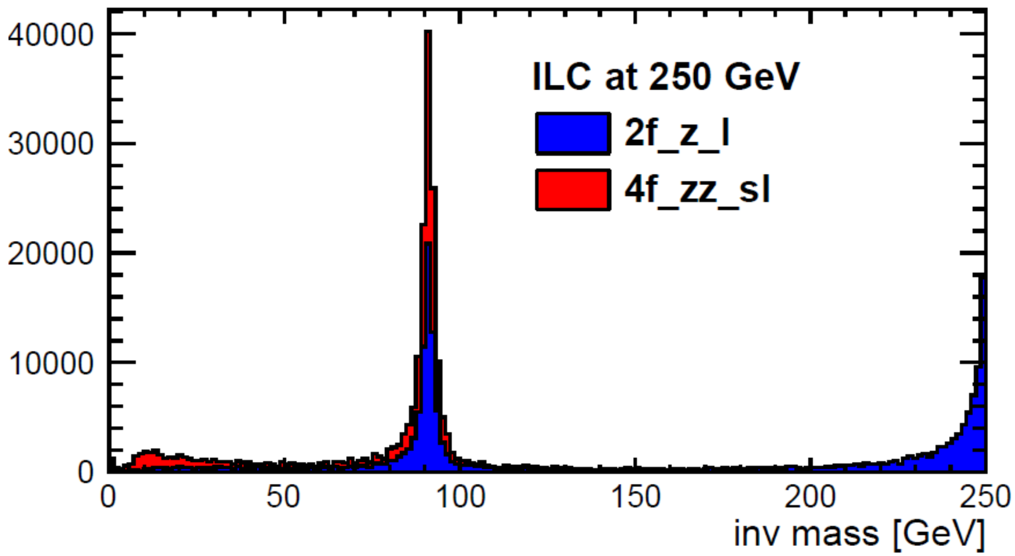

Fig 5 - 2 fermion leptonic spectrum stacked with 4 fermion lepton + QCD spectrum (semi-leptonic)

Another QCD background – 2 fermion hadronic – 2f_z_h

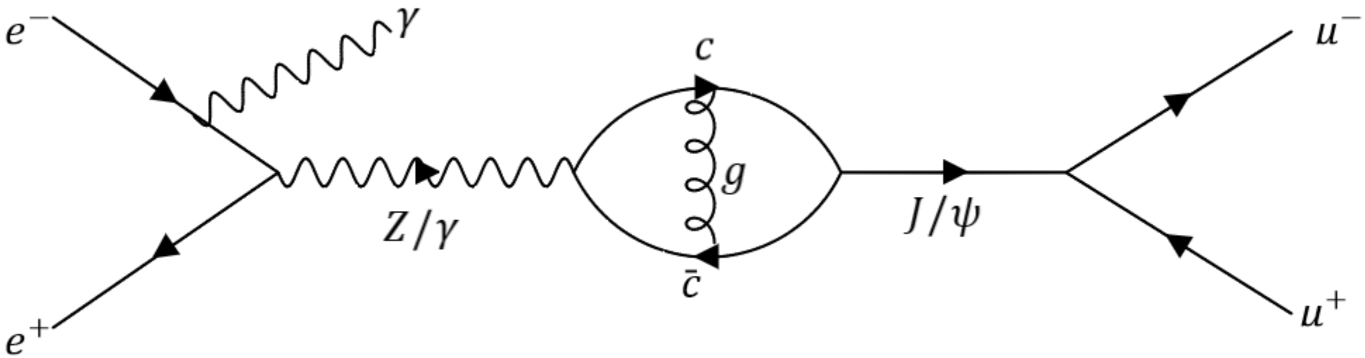

Fig 8 - Extended Feynman diagram showing ISR emission -> J/Psi decay into dimuon

- Mini DST files: 2f_z_h
- JPsi decays into dimuon with BR: ~6% [Source: PDG]
- b-quarks decay into charm OR up quarks

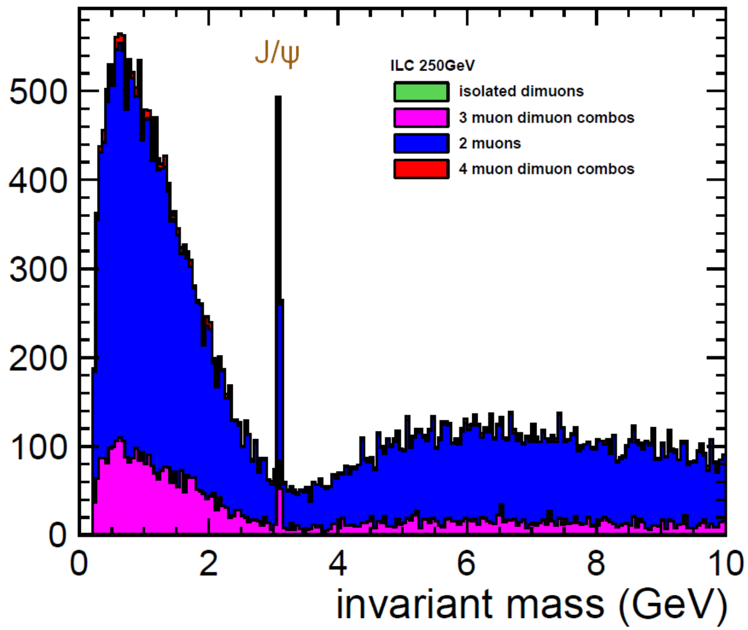

Fig 10 - Implemented B-Tagging cut to all DiMu PFO combinations

Signal exclusion and detection - Weights

- Luminosity $L = \frac{1}{\sigma}\frac{\mathrm{dN}}{\mathrm{dt}}$

- => Number of events is given by $N = \sigma * L$, where this L is the *integrated luminosity.*

- Known number of events in a process; must scale what is simulated

- Each event is weighted: $W = \frac{\sigma * L}{N}$.

- Correctly scaled number of events in each bin

Signal exclusion and detection - Polarization

- Example beam: **eLpR** is **NOT** 100% left polarized electrons and right polarized positrons
- Electrons polarized to 0.8, positrons polarized to 0.3
- Convention Right polarization = 1, Left polarization = -1
- Electrons: $(0.9 \times 1) + (0.1 * (-1)) = 0.8 \rightarrow$ 90% electrons have desired polarization
- Positrons: $(0.65 \times 1) + (0.35 * (-1)) = 0.3 \rightarrow$ 65% positrons have desired polarization
- LL and RR are disallowed by spin conservation (spin 1 bosons, spin 0 initial state)
- Scale Luminosities:
  - $L_{LR} = \mathrm{L} \times 0.9 \times 0.65$
  - $L_{RL} = \mathrm{L} \times 0.1 \times 0.35$
  - Num events $= \sigma_{LR} \times L_{LR} + \sigma_{RL} \times L_{RL}$

Signal exclusion and detection – Statistics

- Monte Carlo Simulation -> Number of events is a **Poisson Distribution**

- **Poisson** distribution: Probability of a given number of **independent** events occurring with a known **average rate/expected value** (based on SM)

- **Poisson** tends to **Gaussian** when variable is large (Central limit theorem)

- **Minimum Discoverable**:
  How **large** must **signal** be for observation not to be explained by an **upward fluctuation** in expected **background <b>** ?

- **Minimum Excludable**:
  How **small** can the number of signal events **s** be such that observation represents too much of a **downward fluctuation** in expected number of events **<s+b>** ?

Signal exclusion and detection – Hypothesis testing

First test, **Discovery**

- H_0: No signal present (s=0)
- H_1: Signal found (s>0)
- If N > x, reject H_0, **discover signal**
- Otherwise: accept H_0, no discovery
- Requirement if H_0 true: P(N>x) = $\frac{1}{1744278}$
- Assume H_0 True: Let $R = \frac{N-b}{\sqrt{b}}$ => P(R>x') = $\frac{1}{1744278}$ => **x'=5**
- Reject H_0 if $N > b + 5\sqrt{b}$
- If H_1 is **true** => <N> = <s+b> => $\boldsymbol{s > 5\sqrt{b}}$ **=> Discovery**

Signal exclusion and detection – Hypothesis testing

Second test, **Exclusion**

- H_0: Signal present (s>0)
- H_1: Signal excluded (s=0)
- If N < x, reject H_0, **exclude signal**
- Otherwise: accept H_0, signal is present
- Requirement if H_0 true: $P(N<x) = \frac{0.05}{2}$
- Assume H_0 True: Let $R = \frac{N-(b+s)}{\sqrt{(b+s)}}$ => $P(R<x') = 0.025$ => **x'=-2**
- Reject H_0 if $N < (s+b) - 2\sqrt{(s+b)}$
- If H_1 is **true** => <N> = <b> => $\boldsymbol{s > 2\sqrt{(s+b)}}$ **=> Exclusion**

These tests allow us to determine **s** and **b** for each Z' mass

How much does the signal need to be scaled to be within limits?

Weighted signal on background – generator level Z'=150GeV

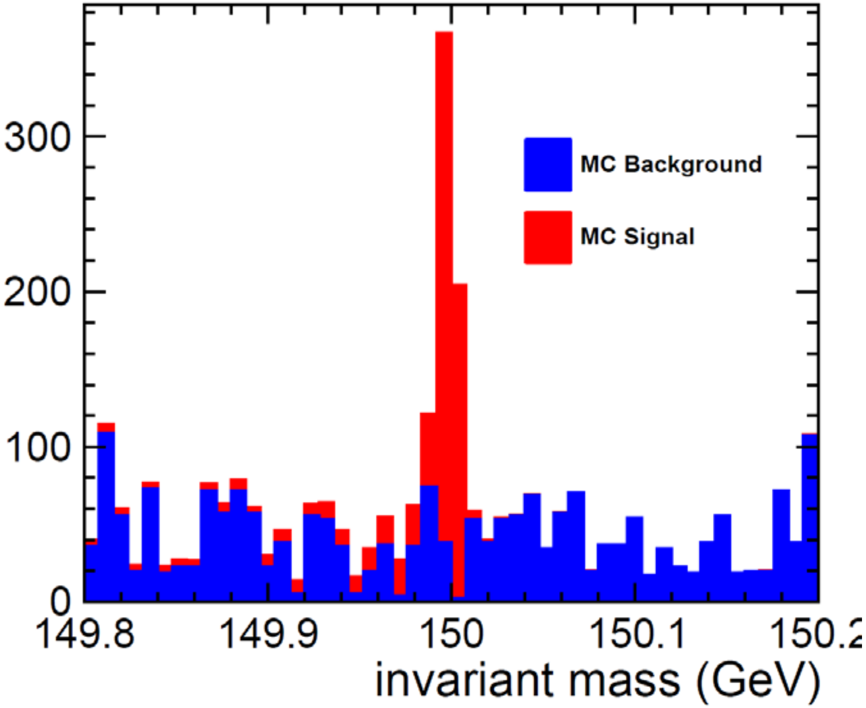

Fig 11 - Z'=150GeV with a window size of 200MeV either side. **787 signal events and 2084 background events**

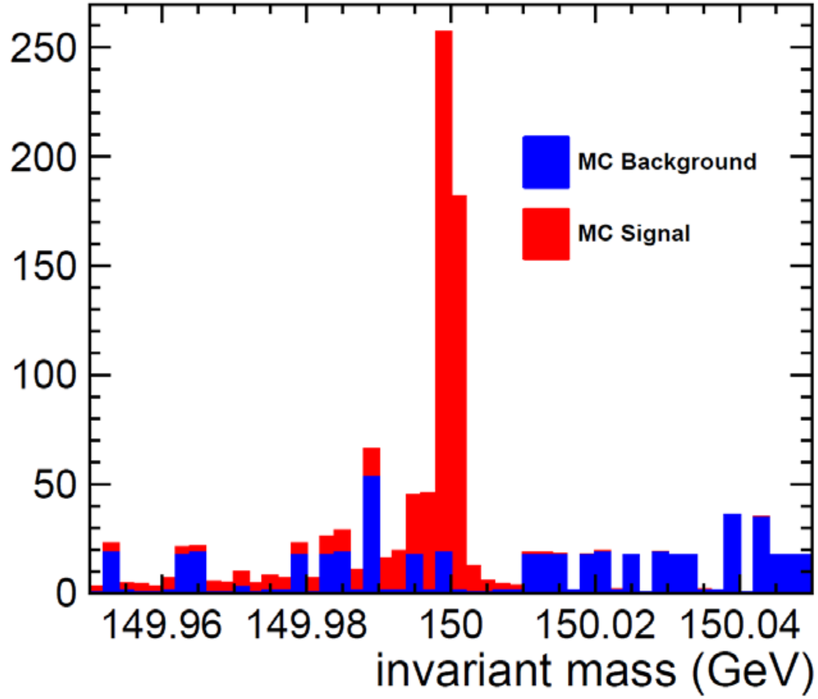

Fig 12 - Z'=150GeV with a window size of 50MeV either side. **669 signal events and 498 background events**

AT +/-50MeV: s> ~46.68 for DISCOVERY if there is signal, or s > 111.58 for EXCLUSION if there is no signal.

Weighted signal on background – fast detector example

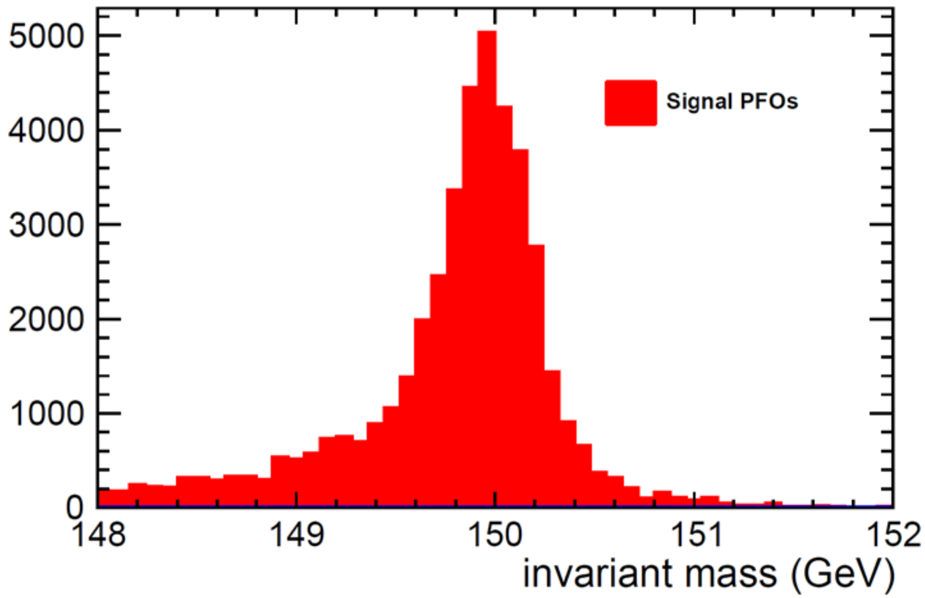

Fig 13 - 150GeV Signal only with 50 bins

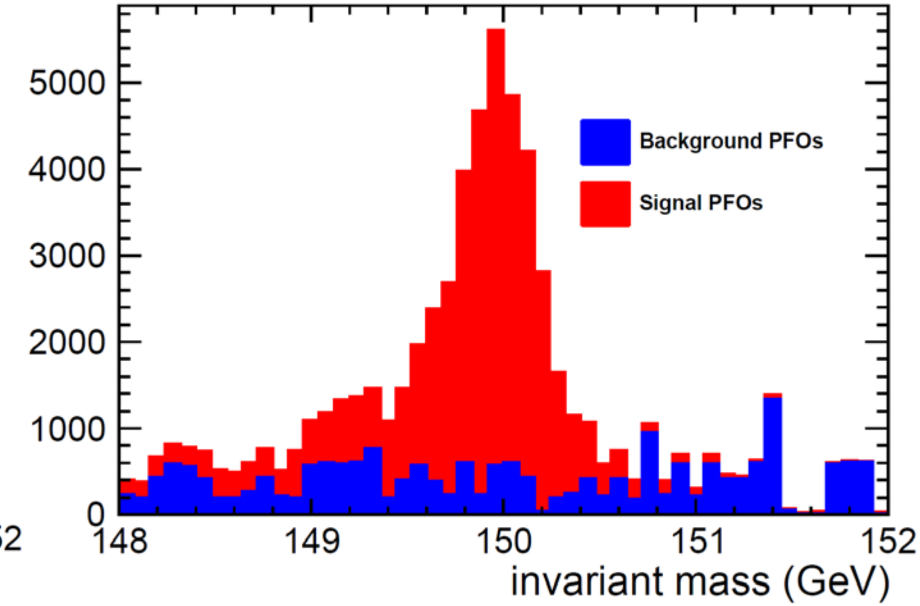

Fig 14 - 150GeV Signal plus background with 50 bins

Conclusion:

43024 signal muons 20269 background muons

Signal must be > 712.34 for a **DISCOVERY** if there is a signal

Signal must be > 286.94 for **EXCLUSION** if there is no signal

Preliminary analysis – optimal window size

150GeV Z' optimizing window size at the generator level

Width	Signal	BKG	s/sqrt(s+b)
0.2	725.976	1025.15	17.3485
0.18	717.913	922.639	17.7246
0.16	706.745	820.123	18.0868
0.14	695.729	717.608	18.5062
0.12	683.934	615.092	18.976
0.1	669.363	512.577	19.4699
0.08	650.899	410.062	19.9831
0.06	628.26	307.546	20.5374
0.04	597.546	205.031	21.0925

Width	Signal	BKG	s/sqrt(s+b)
0.02	546.058	102.515	21.4417
0.018	539.234	92.2639	21.4581
0.016	529.468	82.0123	21.4116
0.014	519.541	71.7608	21.3656
0.012	508.682	61.5092	21.3028
0.01	494.572	51.2577	21.169
0.008	475.664	41.0062	20.9264
0.006	453.317	30.7546	20.6038
0.004	418.861	20.5031	19.9829
0.002	337.444	10.2515	18.0968

Table 1 - Optimal width = 18MeV

Concluding remarks, next steps

- Investigate optimum window size post fast detector simulation
- Plot all other Z’ energies with complete 2f_leptonic DST files
- Calculate tolerances/limits for all Z’ energies when using **all** background files
- Add other less dominant backgrounds in to see how tolerances are affected
  - Hadronic
  - 4 fermion leptonic

Questions?