Search for Contact Interactions in the Dimuon Final State at ATLAS

E. Thompson[1], S. Willocq[1], K. Black[2]
[1] University of Massachusetts, Amherst
[2] Harvard University

DPF'09, Detroit, MI – Thursday, July 30, 2009

Introduction

- Standard Model has shown impressive predictive power and agreement with experiment
- However,
  - Cause of EWSB still unconfirmed
  - Also, unable to explain number of quark/lepton families, dark matter, gravity, matter/antimatter asymmetry

→ Motivates looking Beyond the Standard Model

Outline

- Motivation for high-mass dimuons as an early data BSM channel
- New BSM physics – Contact interactions
  - Quark Compositeness
  - Large Extra Dimensions in the ADD Model
- Setting new limits with early data at ATLAS

Early Analysis with High-mass Dimuons

UMASS ATLAS

- In the first year of running, expect 100 - 200 pb^{-1} at sqrt(s)=10 TeV
- Dimuons are a clean, simple event topology for first-year analysis
- Muon performance will be understood relatively quickly

Few pb^{-1}:

- Software robustness
- Monte Carlo validation
- ID-MS and internal MS alignment
- Trigger performance

Tens of pb^{-1}:

- Optimize muon selection from data
- Efficiency, resolution and momentum scale from resonances
- Fake rates

100 to 200 pb^{-1}:

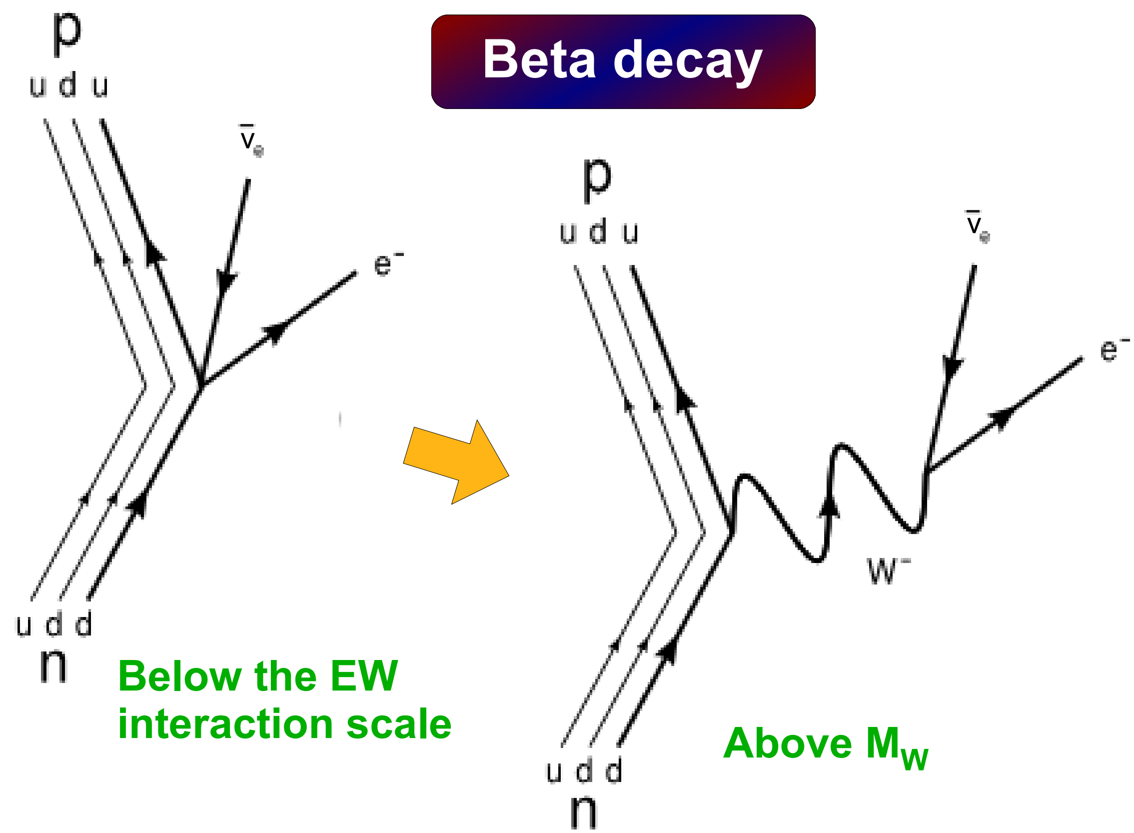
- Single and dimuon inclusive x-section measurements
- Efficiency, resolution etc measured in situ at the 1% level

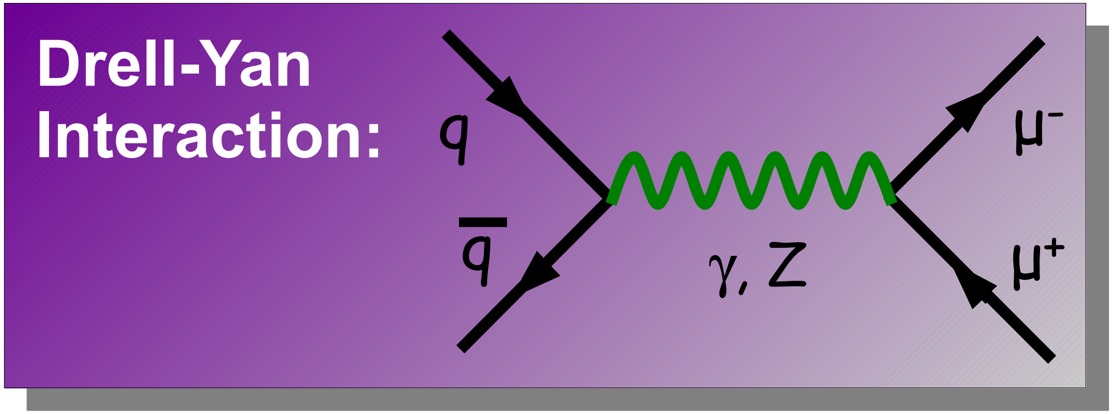
- Beyond the Standard Model signals with high-mass dimuons:
  - Resonant: Z prime, RS Graviton (spin 2), Technicolor
  - Non-resonant: Quark Compositeness, Large Extra Dimensions

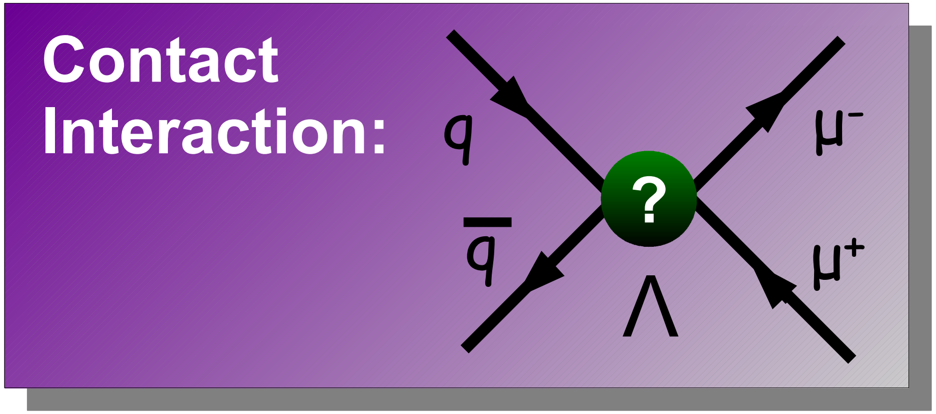
Contact interactions

- Looking for new physics eg: Fermi Interaction
- Described as an effective coupling between incoming partons and final state leptons (contact term in the Lagrangian)
- Similarly, new physics may exist at an energy scale (Λ) higher than we are able to probe at the LHC

Beta decay



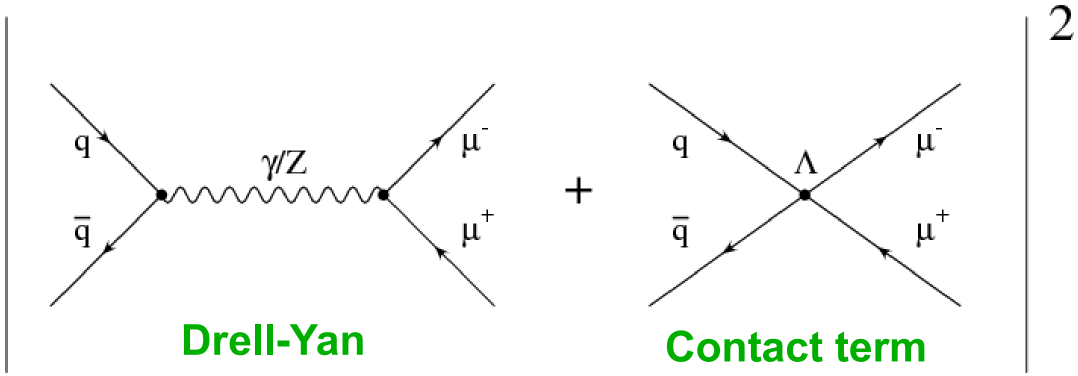




Contact interactions

- Observe a deviation from the Drell-Yan spectrum:

2→2 scattering cross-section:



$$\sigma = DY + \frac{I}{\Lambda^2} + \frac{C}{\Lambda^4}$$

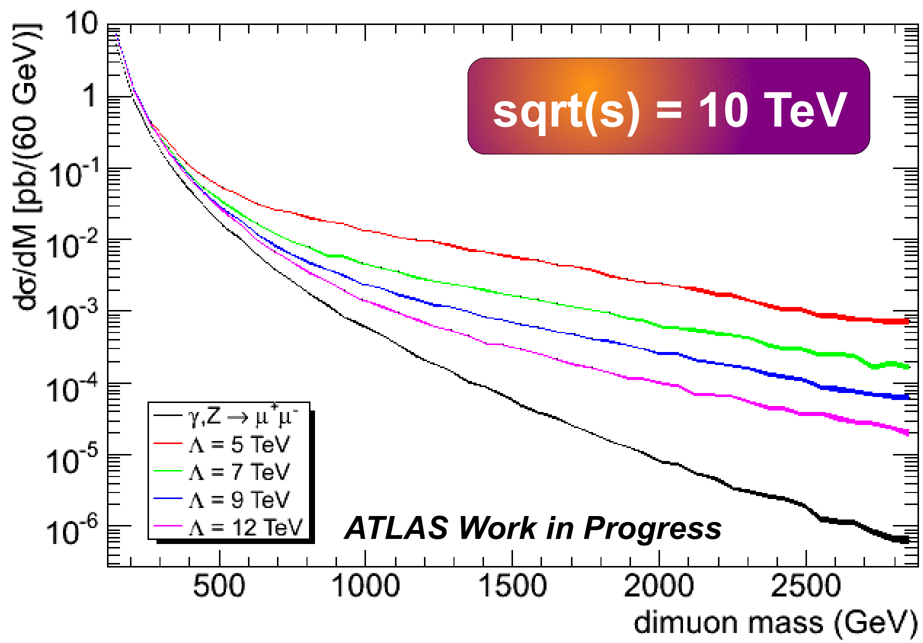
Full Lagrangian of *qqμμ* contact interaction:

$$\begin{aligned} L_{ql} = \frac{g_0^2}{\Lambda^2}\{ &\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_L\gamma_\mu\mu_L) + \eta_{LR}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_R\gamma_\mu\mu_R) \\ &+ \eta_{RL}(\bar{u}_R\gamma_\mu u_R)(\bar{\mu}_L\gamma^\mu\mu_L) + \eta_{RL}(\bar{d}_R\gamma_\mu d_R)(\bar{\mu}_L\gamma^\mu\mu_L) \\ &+ \eta_{RR}(\bar{u}_R\gamma^\mu u_R)(\bar{\mu}_R\gamma_\mu\mu_R) + \eta_{RR}(\bar{d}_R\gamma^\mu d_R)(\bar{\mu}_R\gamma_\mu\mu_R)\} \end{aligned}$$

- As $\Lambda \to \infty$, distribution → SM

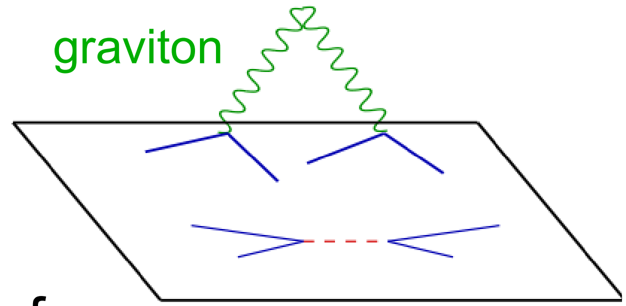
Fermion Compositeness

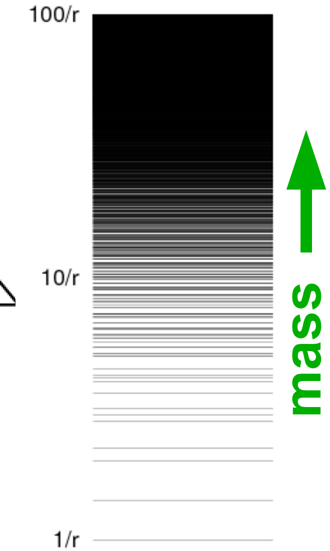
- Λ is the hypercolor scale below which quark/lepton constituents are bound together



Contact interactions

Large Extra Dimensions (ADD)

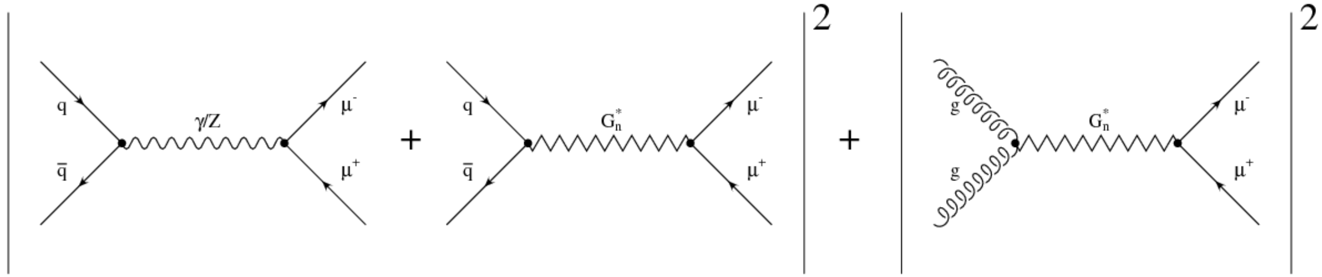




Mass spectrum of KK gravitons for n=2

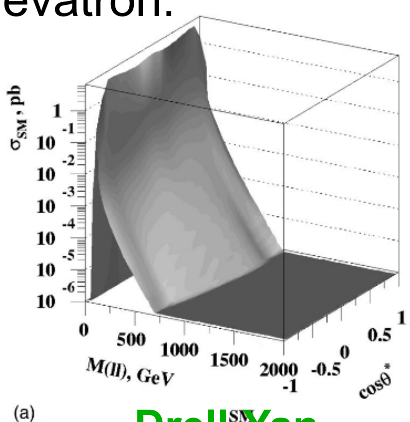
- Annihilation via virtual graviton → tower of mass states looks like a continuous spectrum
- Λ ~ fundamental Plank scale M_s where effective theory breaks down ($M_{Pl}^2 \propto M_s^{n+2} R^n$)

Modified cross-section:

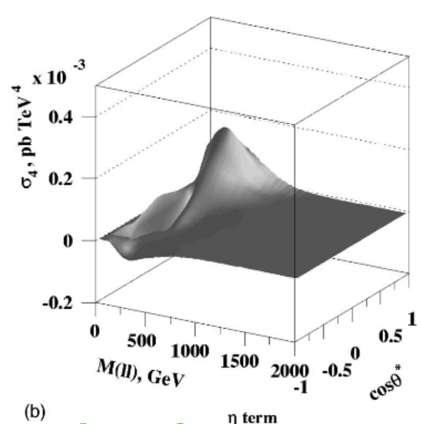


$$\sigma = f_{DY} + \frac{f_I}{M_s^4} + \frac{f_C}{M_s^8}$$

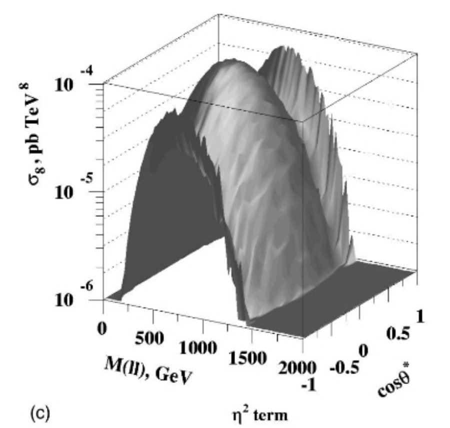
Tevatron:



Drell-Yan



Interference term



Graviton contribution

Gluon coupling adds another contribution

K. Cheung, G. Landsberg Phys. Rev. D 62: 076003 (2000)

Monte Carlo: Quark Compositeness

- Different compositeness models correspond to different values of η_{mn} in full Lagrangian

$$L_{ql} = \frac{g_0^2}{\Lambda^2}\{\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_L\gamma_\mu\mu_L) + \eta_{LR}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_R\gamma_\mu\mu_R) + \eta_{RL}(\bar{u}_R\gamma_\mu u_R)(\bar{\mu}_L\gamma^\mu\mu_L) + \eta_{RL}(\bar{d}_R\gamma_\mu d_R)(\bar{\mu}_L\gamma^\mu\mu_L) + \eta_{RR}(\bar{u}_R\gamma^\mu u_R)(\bar{\mu}_R\gamma_\mu\mu_R) + \eta_{RR}(\bar{d}_R\gamma^\mu d_R)(\bar{\mu}_R\gamma_\mu\mu_R)\}$$

- Left-Left Isoscalar Model, constructive interference: $\eta_{LL} = -1$, $\eta_{LR} = \eta_{RL} = \eta_{RR} = 0$

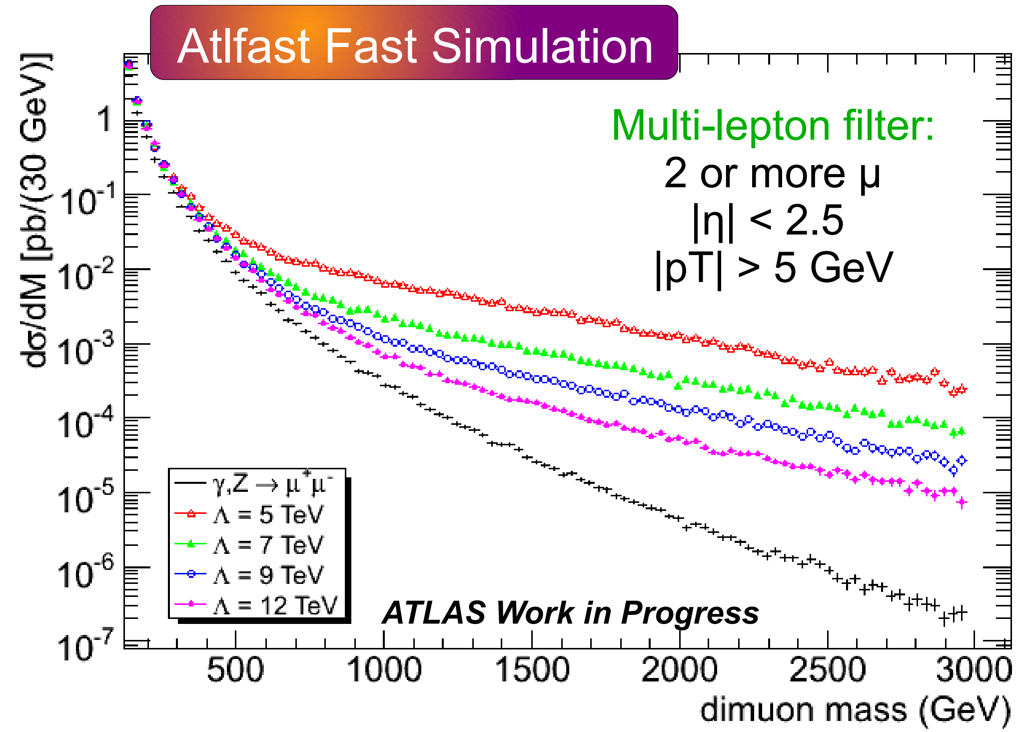
$$L = -\frac{g^2}{\Lambda_{LL^-}^2}\bar{q}_L\gamma_\mu q_L\bar{\mu}_L\gamma^\mu\mu_L$$

- Benchmark Λ scale values:

σ x BF(X → μμ) x k($M_{\mu\mu}$)
($M_{\mu\mu}$ > 120 GeV, √s = 10 TeV)

Λ = 5 TeV:	13.28 pb
Λ = 7 TeV:	12.85 pb
Λ = 9 TeV:	12.75 pb
Λ = 12 TeV:	12.54 pb

Compare with Drell-Yan: **12.52 pb**



Contact Interaction Analysis

UMASS ATLAS

- Ratio method: count # events above and below a mass cut

$$R = \frac{N_{M>M_0}}{N_{M<M_0}}$$

- Advantage: Many systematic uncertainties cancel in ratio (eg. Luminosity)

Turn ratio into a significance

$$S_{\lim} = \frac{R_{\Lambda} - R_{SM}}{\sqrt{dR_{\Lambda}^2 + dR_{SM}^2}}$$

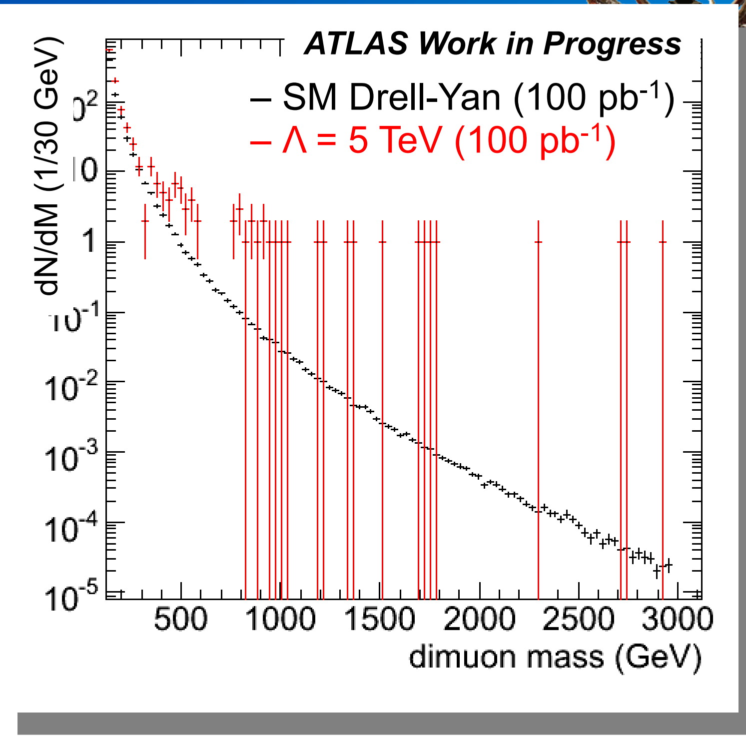
Discovery:
Compare ratio from data to ratio from background modeled from MC (look for excess > 5σ)

Limit setting:
Assume data is consistent with SM, compare with signal effective scale values (95% C.L. corresponds to S_{lim} = 1.96)

Expected limit:
Use Drell-Yan MC to model background, compare with signal MC

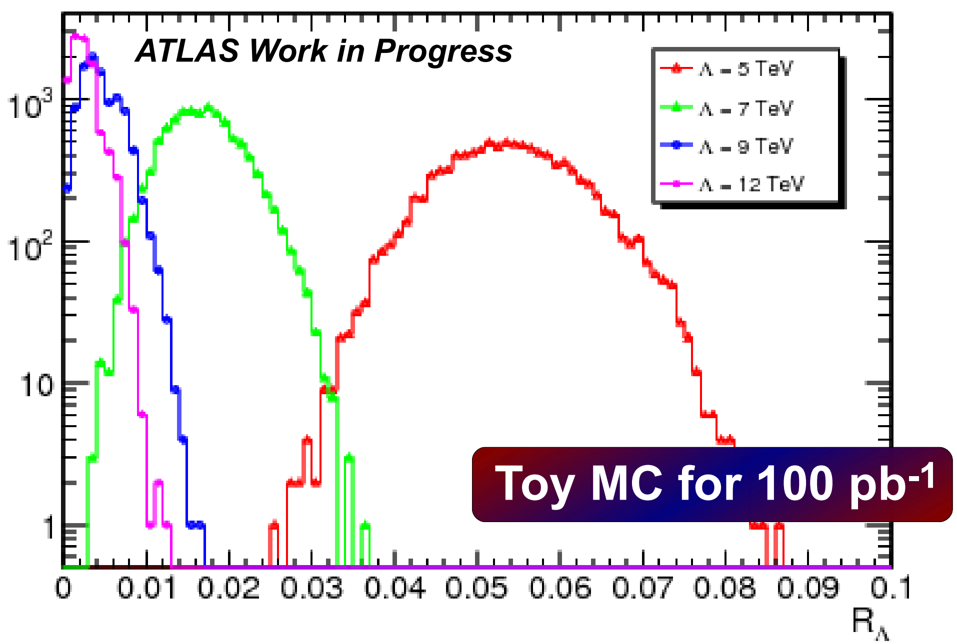
Statistical Uncertainty

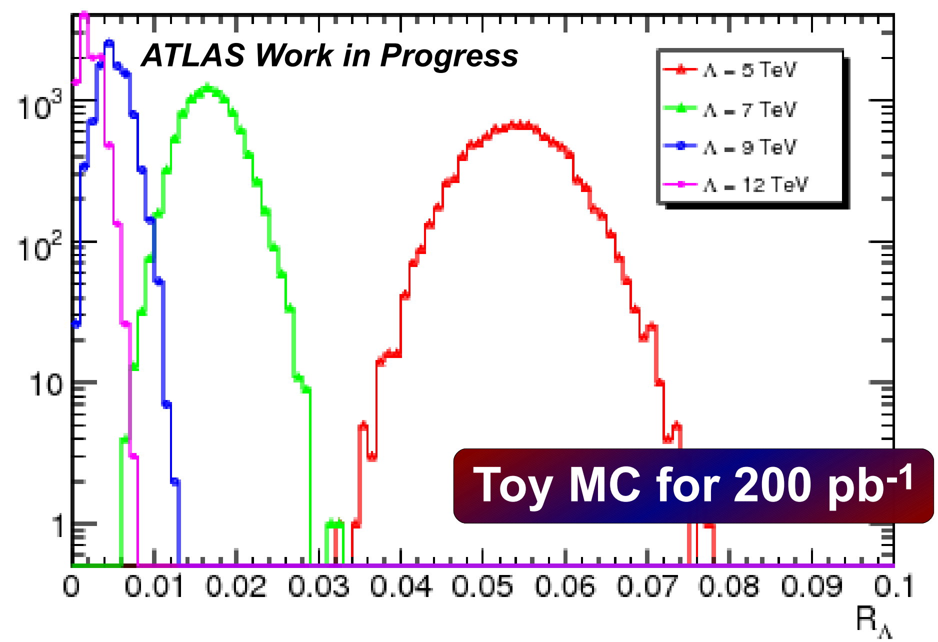
- In early data, statistical uncertainty dominates
- Benchmark signal values for limit setting:



Uncertainty on signal ratio:

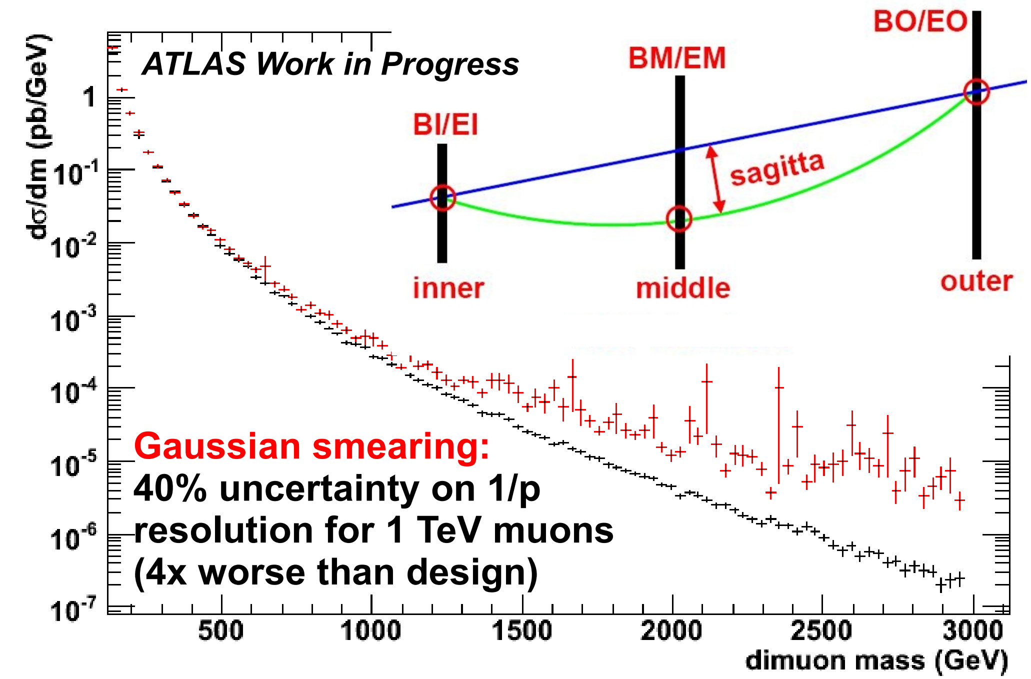
Lambda	100 pb^{-1}	200 pb^{-1}
5 TeV	15 %	11 %
7 TeV	27 %	19 %
9 TeV	47 %	33 %
12 TeV	60 %	42 %





Systematic Uncertainties

- Systematic uncertainties on background (DY) only
- Only mass-dependent uncertainties play a role in the ratio method
- Largest effect: resolution uncertainty from misalignment, showers, etc.



Mass cut @ 450 GeV	lowcount	highcount	DY ratio	% diff
NOMINAL SM	660.5	7.6	0.0115	
RESOLUTION	732.7	9.0	0.0123	6.7%
Pt SCALE (1% ↑)	699.3	7.9	0.0113	-1.5%
Pt SCALE (1% ↓)	632.5	7.3	0.0116	1.1%
EFFICIENCY (up to 15% ↑)	669.5	7.8	0.0117	2.0%
EFFICIENCY (up to 15% ↓)	651.4	7.3	0.0112	-2.1%
K FACTOR (max slope)	635.3	7.4	0.0117	1.9%
K FACTOR (min slope)	700.5	7.8	0.0111	-3.1%

Limit setting using the ratio method

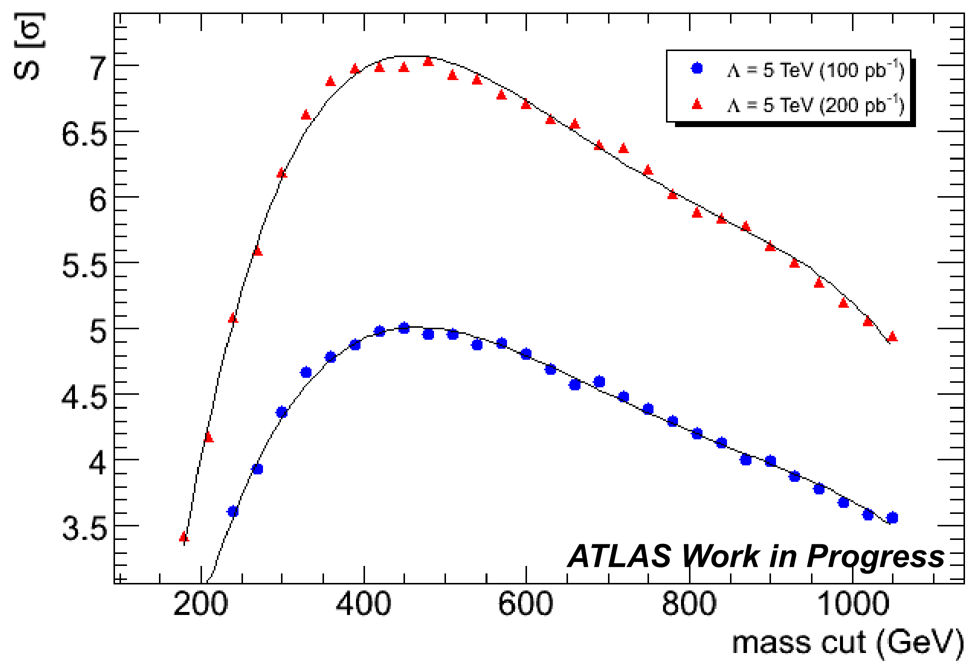
Find the expected limit

$$S_{\lim} = \frac{R(M_0)_\Lambda - R(M_0)_{SM}}{\sqrt{dR_\Lambda^2 + dR_{SM}^2}}$$

- dR_Λ (signal) is the statistical uncertainty on the signal ratio
- dR_{SM} (background) incorporates systematic uncertainties

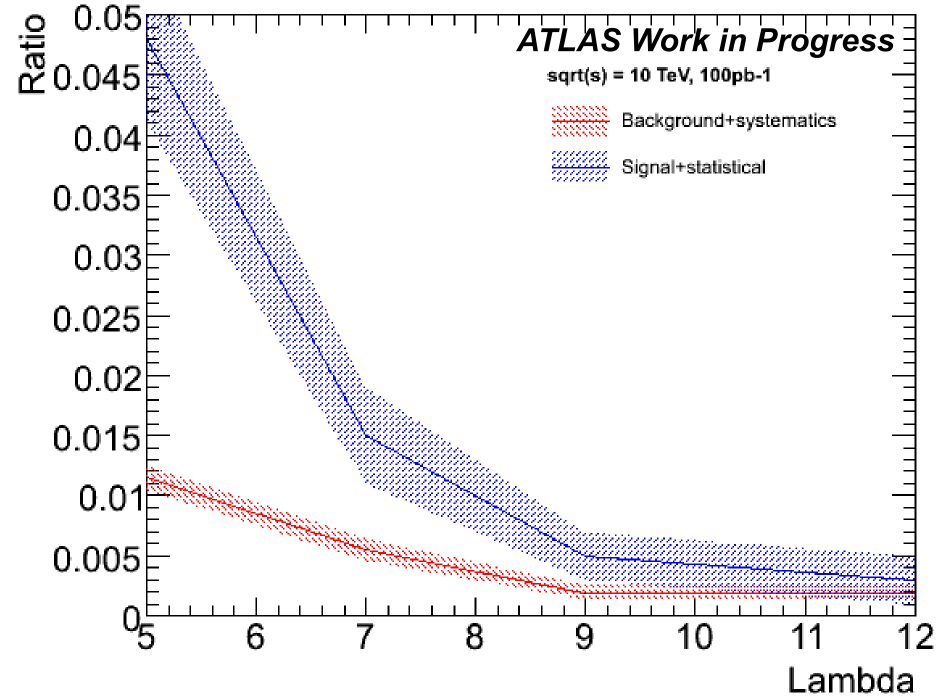
How to choose a mass cut?

- Maximize the significance for each signal effective scale value
- Peak value doesn't change up to 200 pb^{-1}

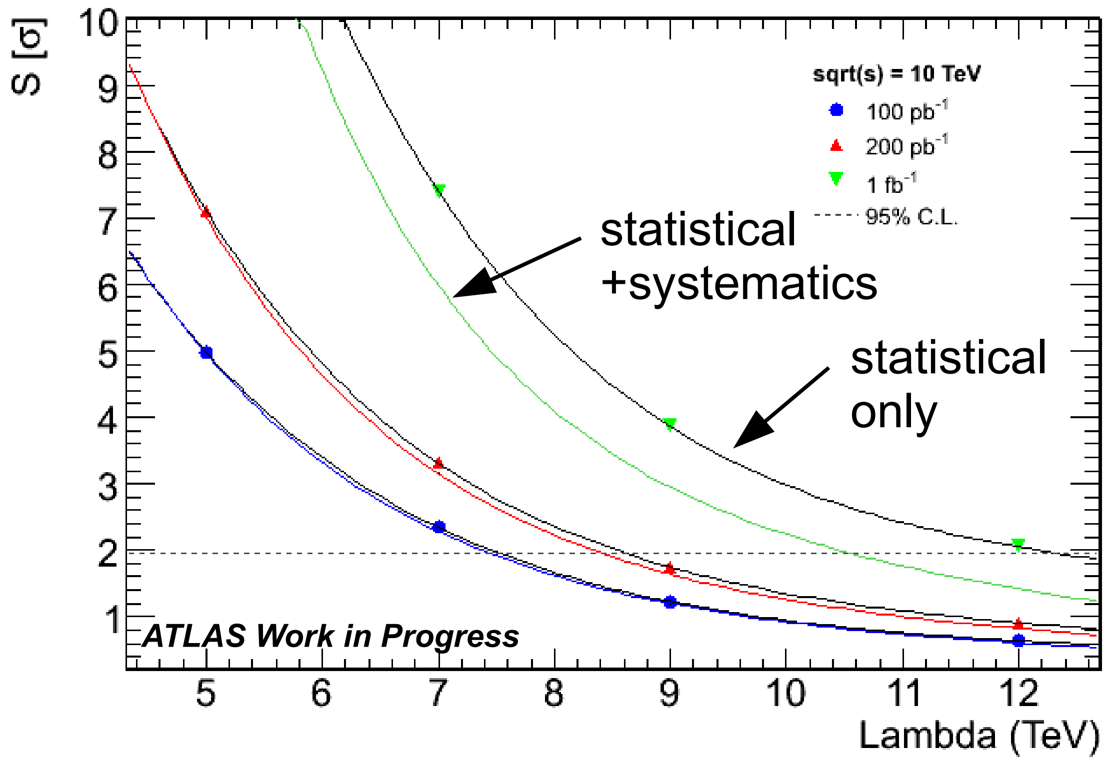


Limit setting using the ratio method

- Use the maximized mass cut for each Λ value
- In 100 pb^{-1}, systematics play no role
- Systematics highly overestimated for 1 fb^{-1} as performance will be well understood



$$S_{\lim} = \frac{R_{\Lambda} - R_{SM}}{\sqrt{dR_{\Lambda}^2 + dR_{SM}^2}}$$



95% C.L. lower limit corresponds to $S_{\lim} = 1.96\sigma$

Conclusions

- New BSM limits can be set with first year data at ATLAS!

- Expected limit for constructive LL-isocalar compositeness model:
  Λ = 7.5 TeV (100pb^{-1}), 8.4 TeV (200 pb^{-1})
  (Current limit: Λ = 6.9 TeV)

- Dimuons present a clean channel while still in the early stages of running

- The ratio method has shown to be advantageous in early data to reduce any large uncertainties

Backup

Early Analysis with High-mass Dimuons

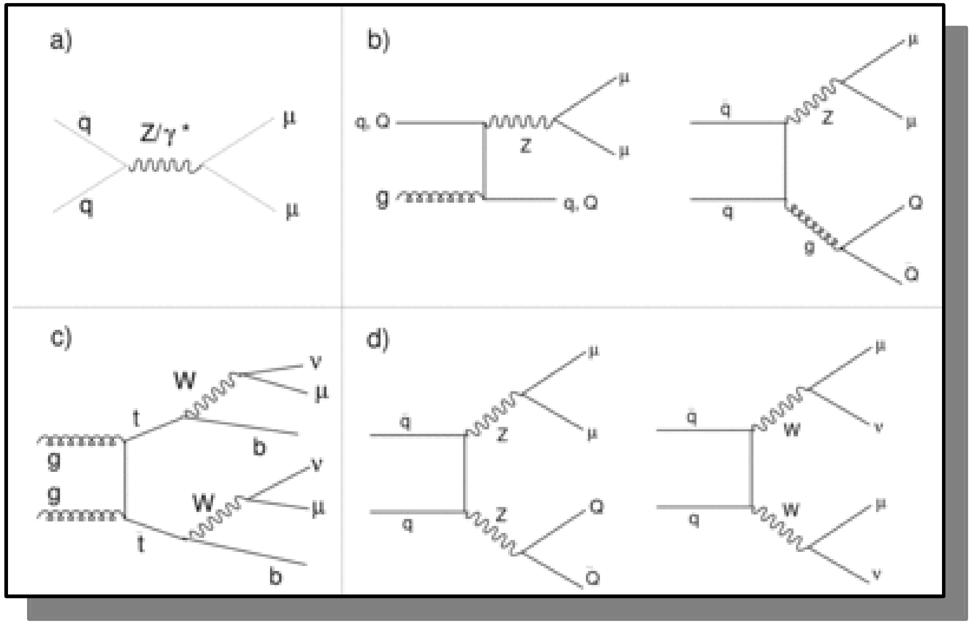
Backgrounds

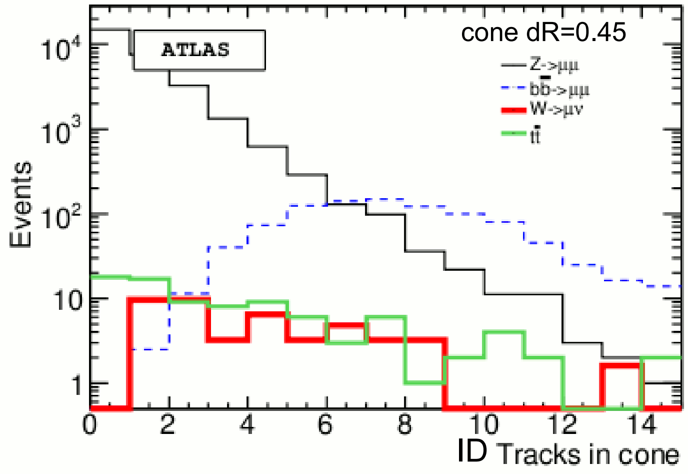
- (Drell-Yan)
- Z+jets, W+jets
- tt
- bb/dijets
- WW, ZZ
- Cosmics

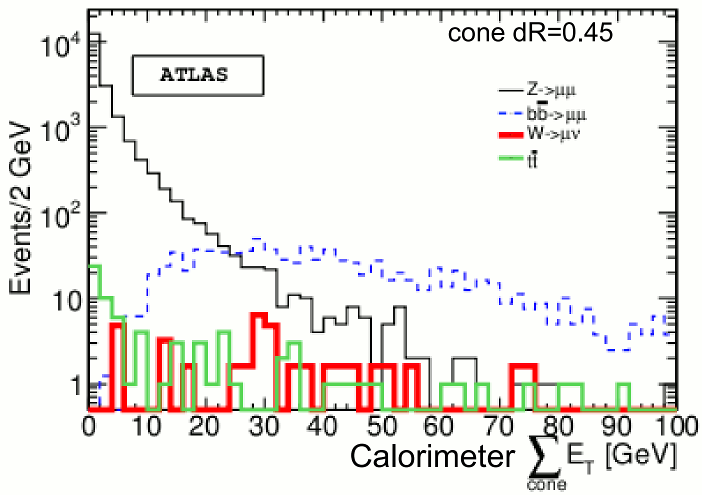
Selections

- $M_{\mu\mu}$ > 120 GeV
- $p_T(\mu)$ > 20 GeV
- Opposite sign
- Isolated muons
- Same vertex
- dφ < 3.14

Leading order background diagrams







Background expected to be very low at high-mass!

Limits

- Current limits:

Large Extra Dimensions: **(electron/photon channel)**

GRW formalism: ($\mathcal{F} = 1$) $M_s = 1.62$ TeV

HLZ formalism:

$\mathcal{F} = \ln(M_s^2/s)$ for $n_d = 2$

$\mathcal{F} = 2/(n_d - 2)$ for $n_d > 2$

$M_s = 2.06(1.29)$ for 2(7) extra dimensions

Quark/lepton compositeness: **(muon channel)**

Constructive interference ($\eta = -1$): $\Lambda = 6.9$ TeV (preliminary D0, 2005)

Destructive interference ($\eta = +1$): $\Lambda = 4.2$ TeV (preliminary D0, 2005)

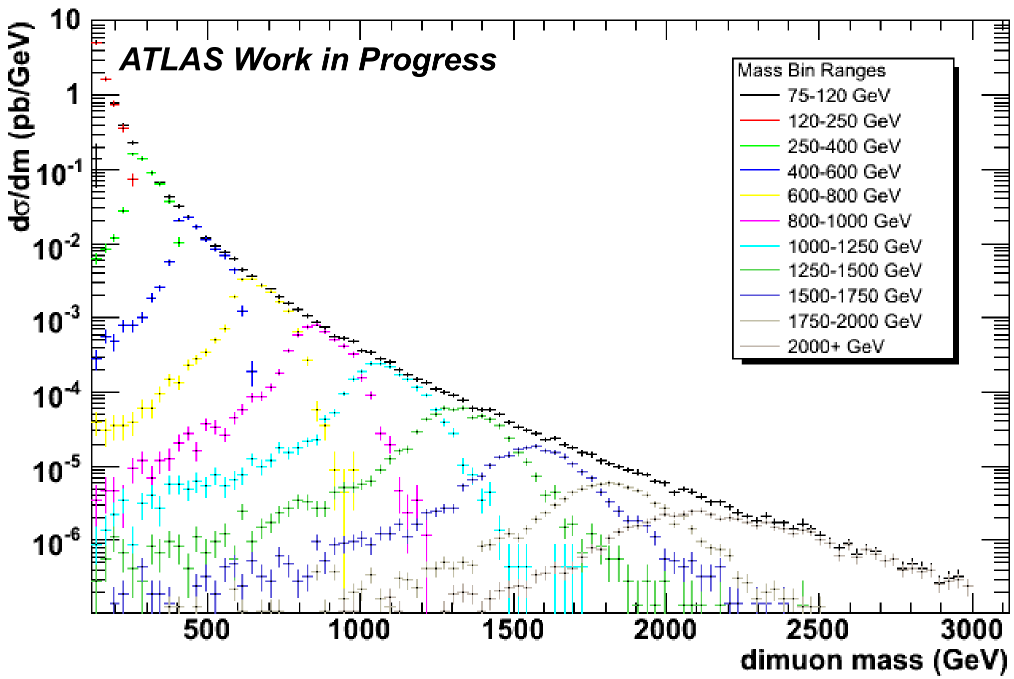
Original SM distribution

- Each of the 10 invariant mass bins are filled by:
  `mass_bin_histo[bin]->Fill(dimuonMass,weight)`
  where `weight = sigma[bin] * eff[bin] * kfactor[bin]`
  This scales according to cross-section on an event by event basis.

(Note: sigma = BF(X → uu) * lepton filter eff * cross-section)

- When the mass bin histogram is filled with all events in tree, then
  `mass_bin_histo[bin]->Scale(1/nEntries)`
  This ensures the area under the histo = weight/dM for that mass range

- Finally, the black curve is the addition of all 10 histograms



Resolution uncertainty

- Uncertainty from not understanding sagitta (proportional to 1/p)
- Sagitta = 50μm resolution for 1 TeV muons with 10% uncertainty

Back of the envelope calculation:

Sagitta + dSagitta = newSagitta → 1/(1TeV) + dSagita = 1/(1TeV) *1.1

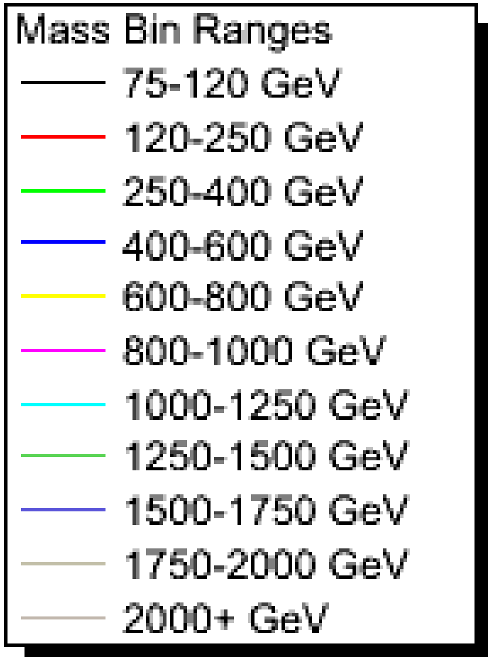
→ dSagitta = 0.0001 [1/GeV]

- However, probably more like ~200μm resolution for first year data, so mulitply by a factor of ~4

Smear two muons by random amount from Gauss with width = dSagitta:

```
mean = 0
sigma = 0.0005 // [1/GeV]
Trandom3 r
double res = r.Gaus(0,sigma);
p1new = 1/(1/p1+res);
res = r.Gaus(0,sigma);
p2new = 1/(1/p2+res);
```

Errors used



efferr[0] = 0.001;
efferr[1] = 0.01;
efferr[2] = 0.01;
efferr[3] = 0.02;
efferr[4] = 0.03;
efferr[5] = 0.04;
efferr[6] = 0.06;
efferr[7] = 0.08;
efferr[8] = 0.10;
efferr[9] = 0.12;
efferr[10] = 0.15;

kfactor[0] = 1.31;
kfactor[1] = 1.30;
kfactor[2] = 1.29;
kfactor[3] = 1.28;
kfactor[4] = 1.27;
kfactor[5] = 1.26;
kfactor[6] = 1.25;
kfactor[7] = 1.24;
kfactor[8] = 1.22;
kfactor[9] = 1.19;
kfactor[10] = 1.15;

Minimum slope:

kerr[0] = 0.1;
kerr[1] = 0.08;
kerr[2] = 0.06;
kerr[3] = 0.04;
kerr[4] = 0.03;
kerr[5] = 0.02;
kerr[6] = 0.01;
kerr[7] = 0;
kerr[8] = -0.02;
kerr[9] = -0.05;
kerr[10] = -0.1;