Universal Extra Dimensions at a Muon Collider

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Outline

- Why build a muon collider?
- Physics goals of a μC
- What is a muon collider?

- Universal Extra Dimensions
- Kaluza-Klein Excitations
- UED at a Muon Collider

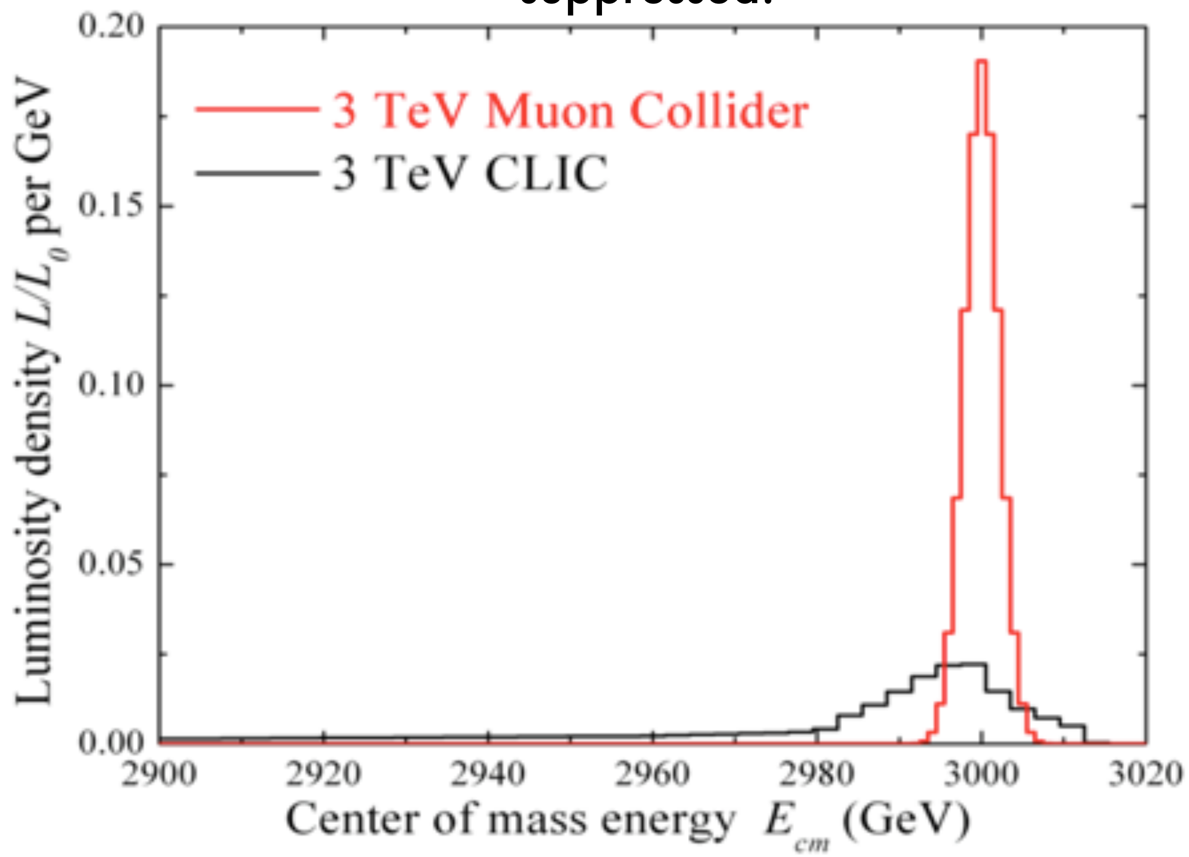
Why build a muon collider?

In comparison to current and planned ee, pp colliders:

Advantage over the electron:
$P_{\text{synchrotron}}$ goes as $1/m^4$.
$m_\mu = 207\ m_e \rightarrow P_\mu = 10^{-9}\ P_e$
meaning:
higher energies with smaller machines (d=2km)

Advantage over the proton:
Muon is a point-like particle
meaning:
well defined interaction energy (no PDFs)
higher precision

Beamstrahlung is also greatly suppressed:



(arXiv:1003.3051 Shiltsev, 2010)

Physics Potential

100 – 500 GeV CoM

Higgs Factory:
resonant mass scan (MeV res)
MSSM vs SM higgs
(A/H) Higgs doublet - CPV

Z Factory

threshold scans for pair production
with well-known beam energy:
W^+W^-, ttbar, Zh
light SUSY particles

3 – 4 TeV CoM

s-channel resonant-production of new particles:
Z′, Extra Dimensions
heavy SUSY particles

virtual effects on SM processes

pair production of new particles

t-channel resonant production

strong scattering of weak bosons

and...

front end muon physics:
$\mu \to e\gamma$, $\mu \to e$, g-2

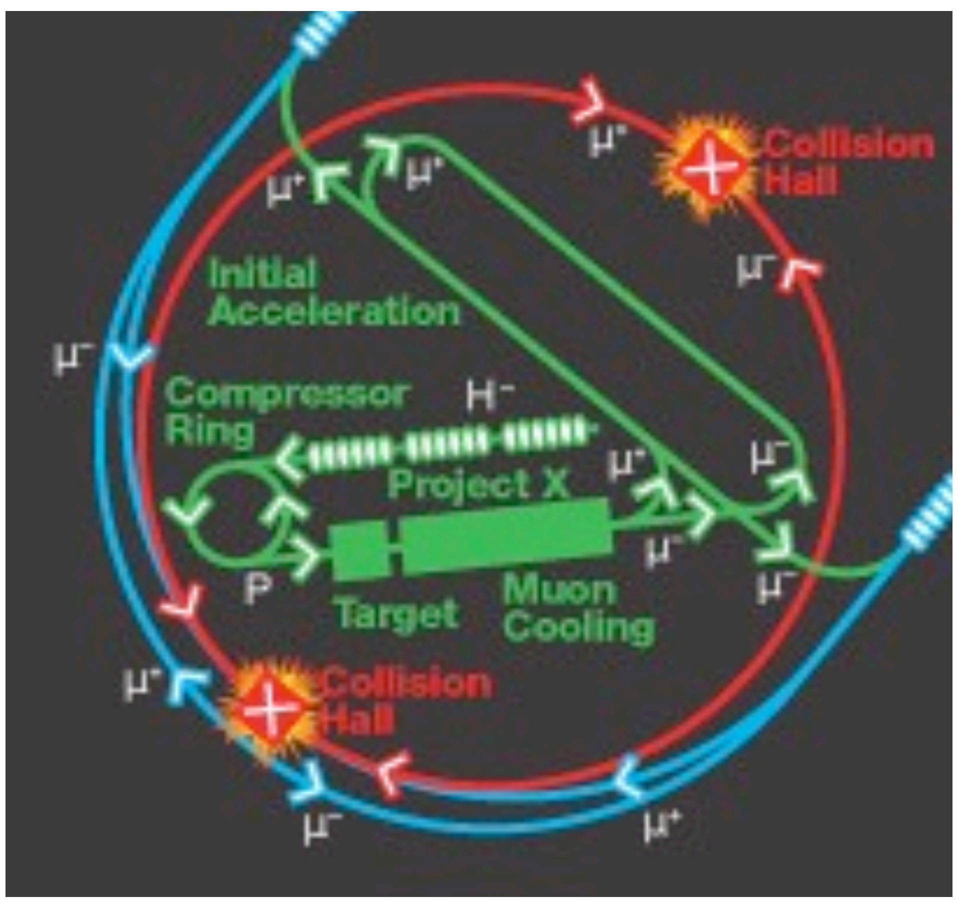
μp collider:
higher Q^2 reach than ep

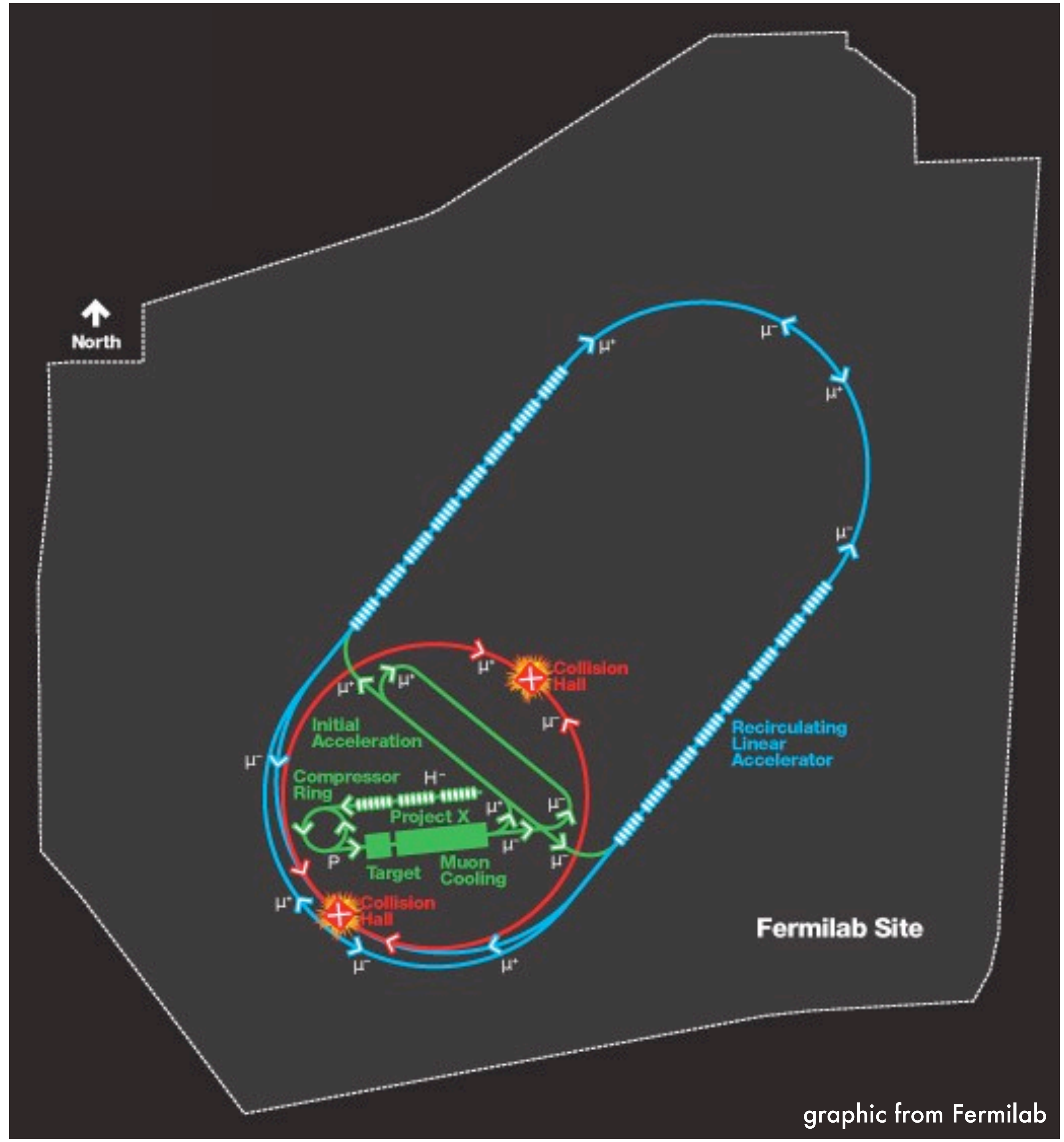
Collider Scheme

Multi-MW multi-GeV proton driver bombards target to produce pions that are captured by strong magnetic field and decay to muons.

Example parameter set for 3 TeV CoM energy:

muons/bunch	2×10^{12}
Luminosity	$7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$\varepsilon_{6D,N}$	$2 \times 10^{-10}\ (\pi\mathrm{m})^3$





graphic from Fermilab

Muon Collider Detector Design

High power proton driver: FermiLab Project X

Pion production target: MERIT experiment, CERN, 2007

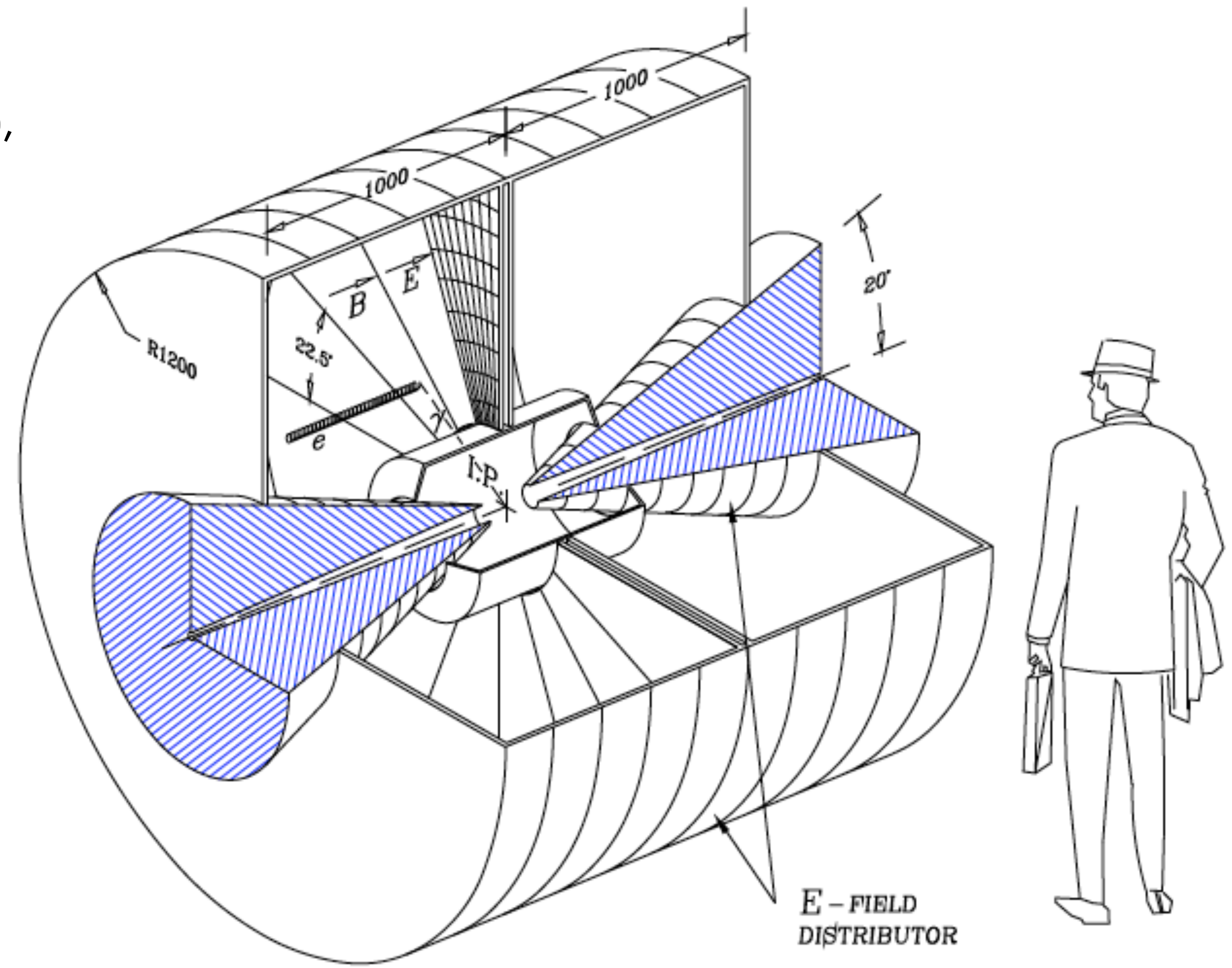
Muon cooling: ionization cooling (MICE, RAL), frictional cooling (FCD, MPP)

Detector design:
Backgrounds near interaction point from muon decay, beam halo, and other sources need to be shielded against

→ Tungsten cone extending out from IP along beam pipe

Cone angle is not yet fixed in stone

frictional cooling can provide high luminosity with fewer μ/bunch, reducing background
→ reducing cone angle



Universal Extra Dimensions

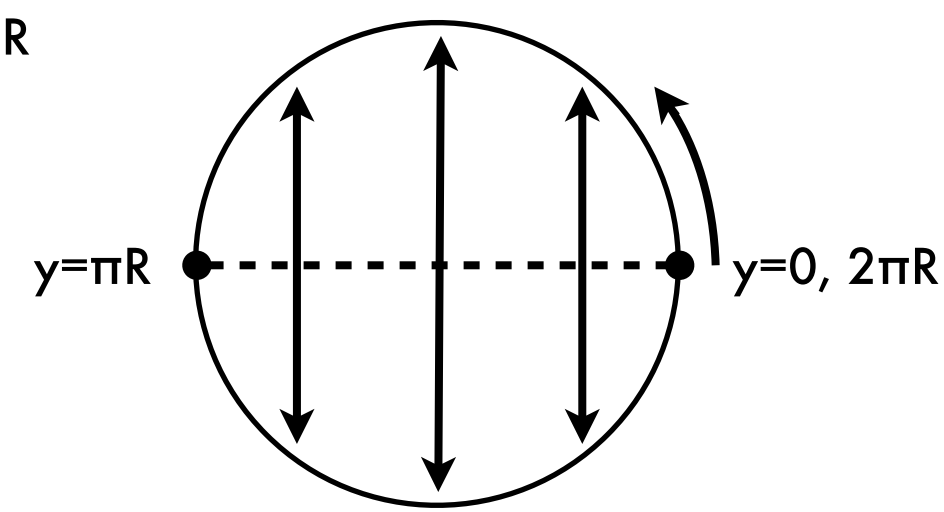
Extra dimensions (Kaluza Klein theories) can address hierarchy problem
(gauge coupling unification, lowering of Planck scale)

KK theories come in different flavors:
- which fields propagate in the extra dimensions
- what the extra dimensions look like

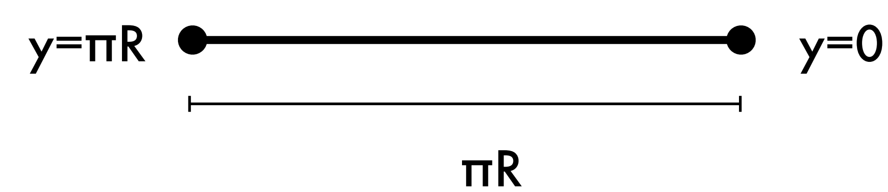
examples:
- Large Extra Dimensions: only gravity accesses the extra (flat) dimensions (ADD, hep-ph/9803315)
- Warped extra dimensions: nonflat metric (RS, hep-ph/9905221)
- Universal Extra Dimensions: flat dimensions accessible by all SM fields (Appelquist, et al., hep-ph/0012100)

One UED: add to the 4D **x** a *compact* dimension y (S_1/Z_2 orbifold):

(S_1) $y \sim y + 2\pi R$
(Z_2) $y \sim -y$



fields even or odd under Z_2



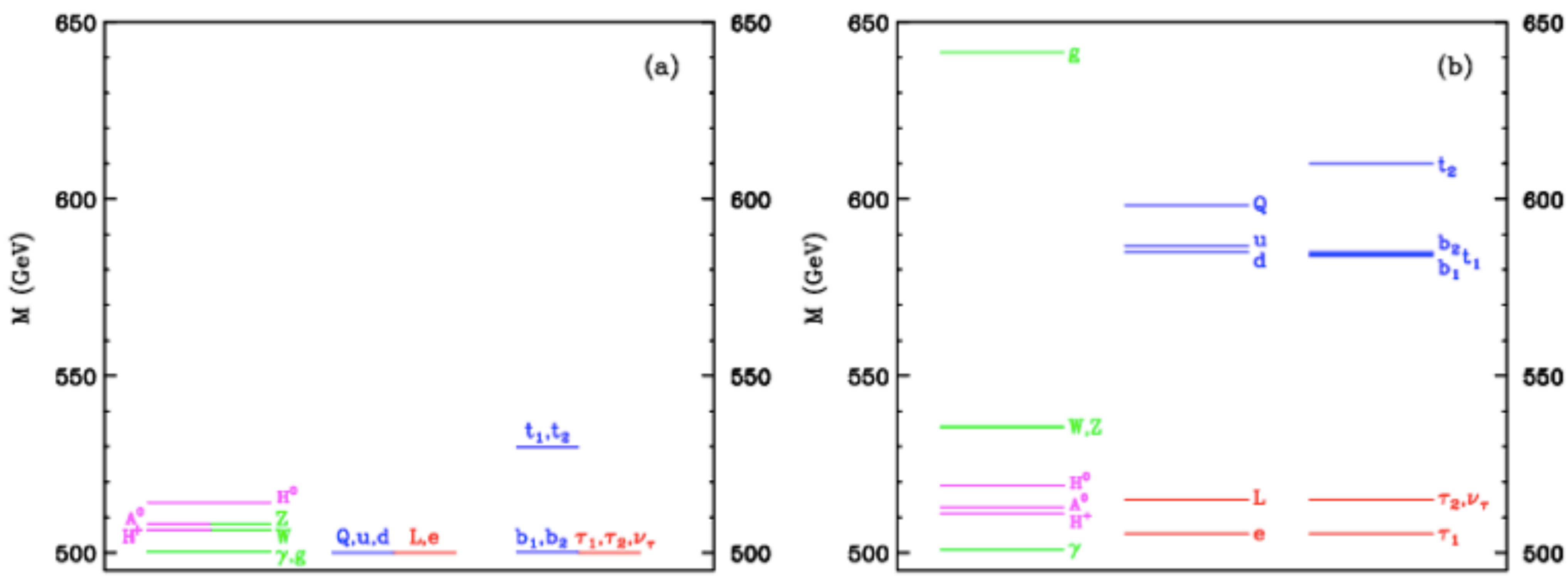
fields obey
Neumann or Dirichlet boundary conditions

Kaluza-Klein Excitations

Energy in 5D: $E^2 = \mathbf{p}^2 + m_0^2 + p_5^2$
fields excited in integral modes in y: $p_5^2 \rightarrow m_n^2 = n^2/R^2$
towers of Kaluza Klein states for each SM particle at $m_n = R^{-1}$

At tree level this is highly degenerate: $m \approx n/R$ for all KK_n particles, since $m_n >> m_0$
but with radiative corrections (Cheng et al., hep-ph/0204342) the degeneracy is broken:

2nd parameter added:
$\Lambda \equiv$ cutoff scale
for effective theory

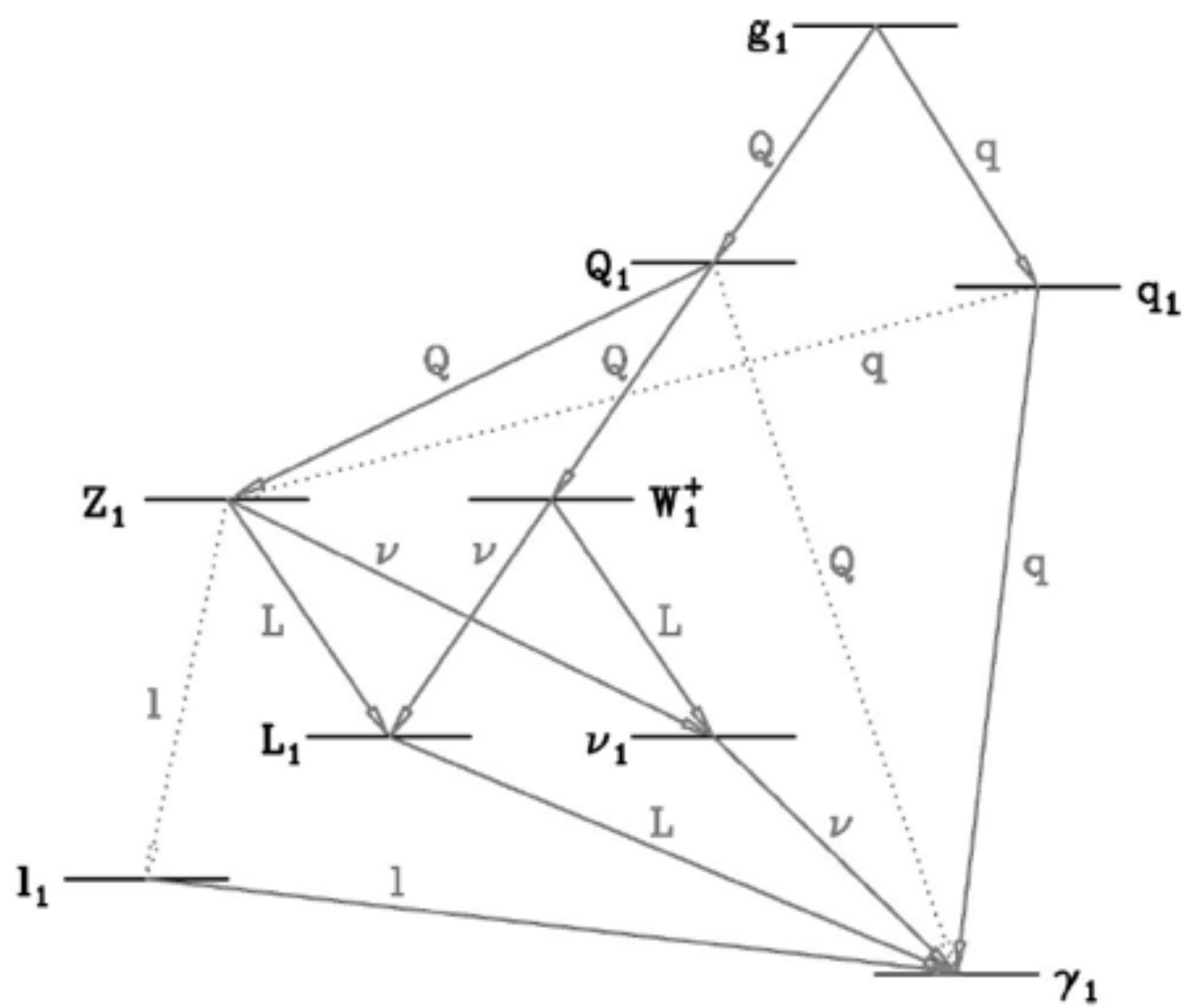


$R^{-1} = 500$ GeV, $\Lambda R = 20$

Compactification breaks KK-excitation number conservation to KK-Parity $= (-1)^n$
$\rightarrow$ Limits on R loose: $R^{-1} \geq 250$ GeV

KK Decay + stable LKP

KK₁ decay modes (Cheng et al., hep-ph/0205314)



ϒ₁ (B₁) is the Lightest KK₁ Particle (LKP) and therefore (by KK parity conservation) stable → DM candidate.

Lepton Collider Phenomenology of UED

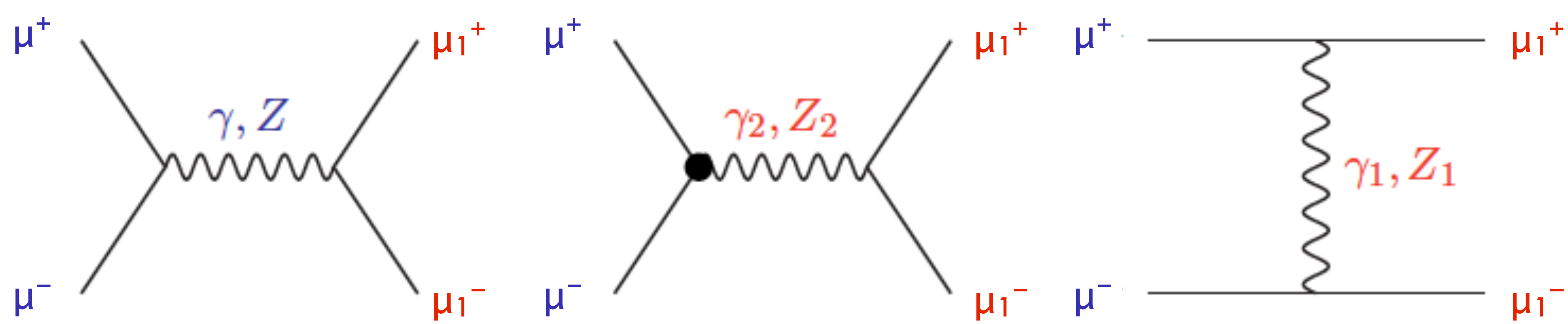
KK-Parity conservation means KK_1 particles created in pairs

KK_1 pairs decay down to SM particles and γ_1's
e.g.:

$$\mu^+ \mu^- \rightarrow \mu_1^+ \mu_1^- \rightarrow \mu^+ \mu^- \gamma_1 \gamma_1$$

The γ_1's escape the detector undetected, so that one sees a dimuonic final state with large missing energy

$$\mu^+ \mu^- \rightarrow \mu^+ \mu^- \not{E}$$



Investigate dependence of discovery potential and R-measurement resolution on angle of detector shielding.

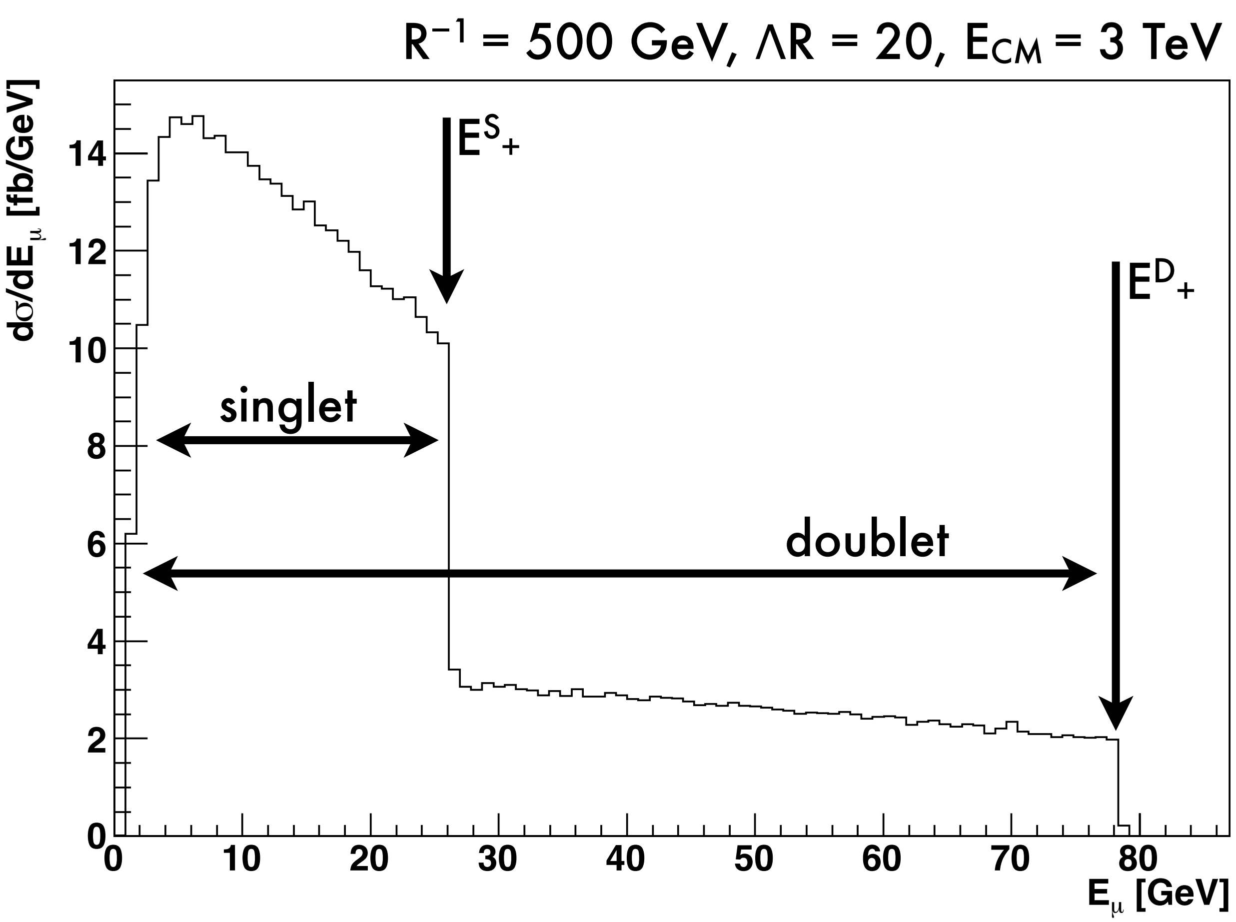
All event generation handled by CompHEP with UED implementation of Datta et al. (hep-ph/1002.4624)

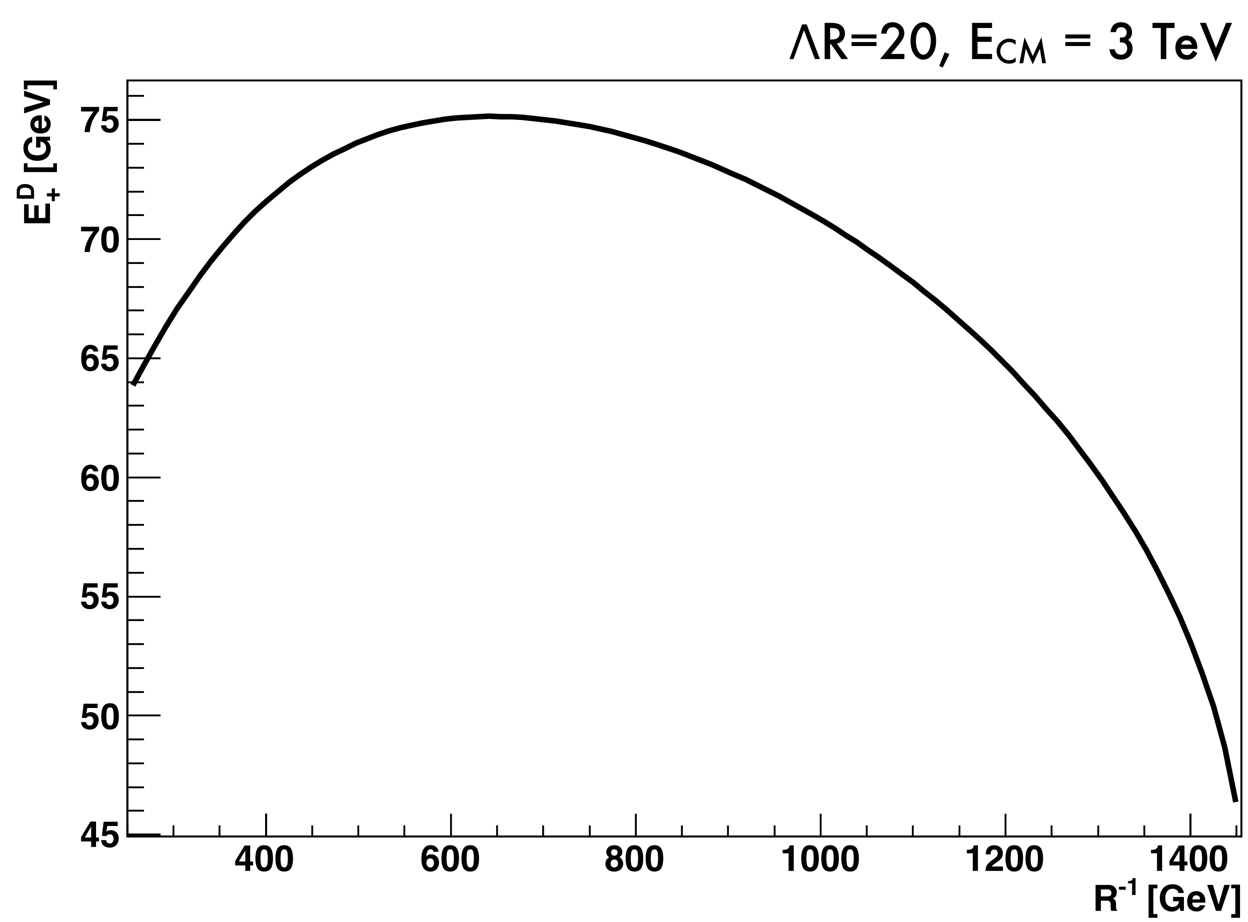
$\mu^+ \mu^- \rightarrow \mu_1^+ \mu_1^- \rightarrow \mu^+ \mu^-$ + Missing Energy

The muons have the usual flat distribution from a boosted two-body decay:

$E^X_\pm = \frac{1}{2} M^X_{\mu 1} (1 - (M_{B1}/M^X_{\mu 1})^2)\, \Upsilon\, (1 \pm \beta)$ $\Upsilon = (1-\beta^2)^{-1/2}$ $\beta = (1 - (M^X_{\mu 1}/E_{beam})^2)^{1/2}$

$M_{B1} = \Upsilon_1\, (B_1)$ mass $M^X_{\mu 1} = \mu_1^D$ or μ_1^S mass





UED signal is dimuonic final state with $E_\mu < 80$ GeV, $P_T < 80$ GeV

SM Background

Dimuonic final states with large missing energy: $\mu^+\mu^- \rightarrow \mu^+\mu^- + 2\nu$, $\mu^+\mu^- + 4\nu$, etc...
(thousands of Feynman diagrams)

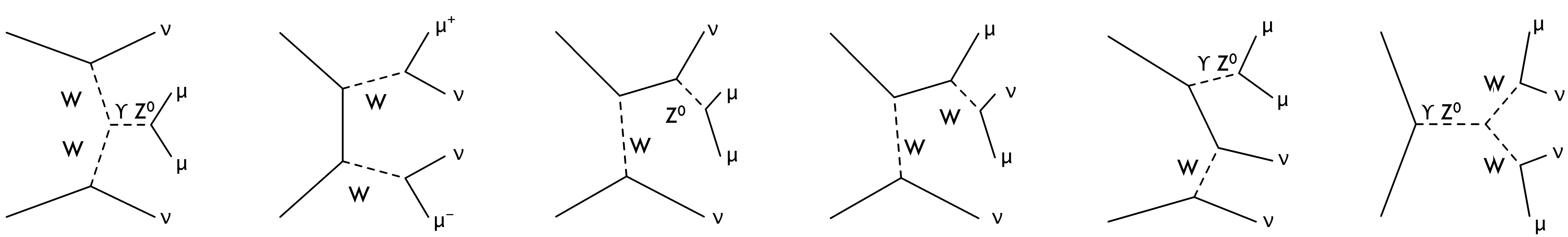
Restricting to $E_\mu < 80$ GeV, $E_T < 80$ GeV *nearly* brings the number of diagrams down to a calculable amount.

In an attempt to perform a nearly-cutless analysis, the following two cuts were made:

$\theta_\mu > 4°$
- cuts out 4ν diagrams involving W pair production
- no real impact since later assume $\theta_\mu > 9°$ due to detector construction

$M_{\mu\mu} > 5$ GeV
- cuts out Υ-mediated $\mu^+\mu^-$ production from ISR
- percent level reduction of UED cross section

The cuts reduce calculations to a smaller set of $\mu^+\mu^- \rightarrow \mu^+\mu^- + 2\nu$ only diagrams



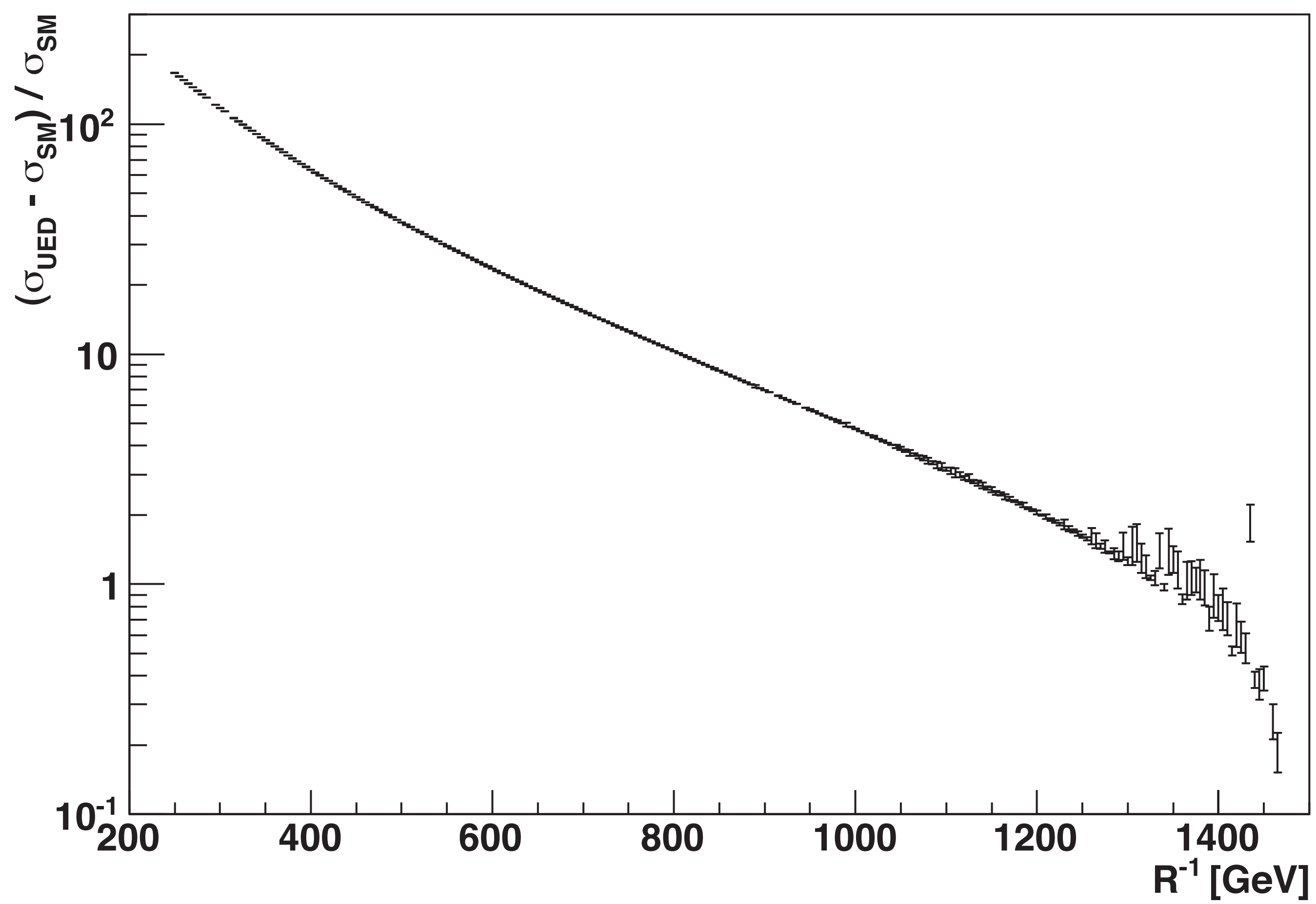
Cross Section Comparison

$\sigma_{SM} \approx 11$ fb (after E_μ, P_T, $M_{\mu\mu}$, θ cuts)

The cross section for the μμ + missing energy final state is orders of magnitude larger for UED with with large R.

The discoverability of UED is therefore high without the need to do a binned analysis at large R.

At small R, UED will cause only small deviation from SM, necessitating a binned analysis.



MC Analysis

Probability $R = R_J$
given data set D_K, generated at Luminosity L (and $R=R_K$)

$$P(R_J|D_K,L) = \frac{P(D_K|R_J,L)P_0(R_J)}{P(D_K|SM,L)P_0(SM) + \sum_I P(D_K|R_I,L)P_0(R_I)}$$

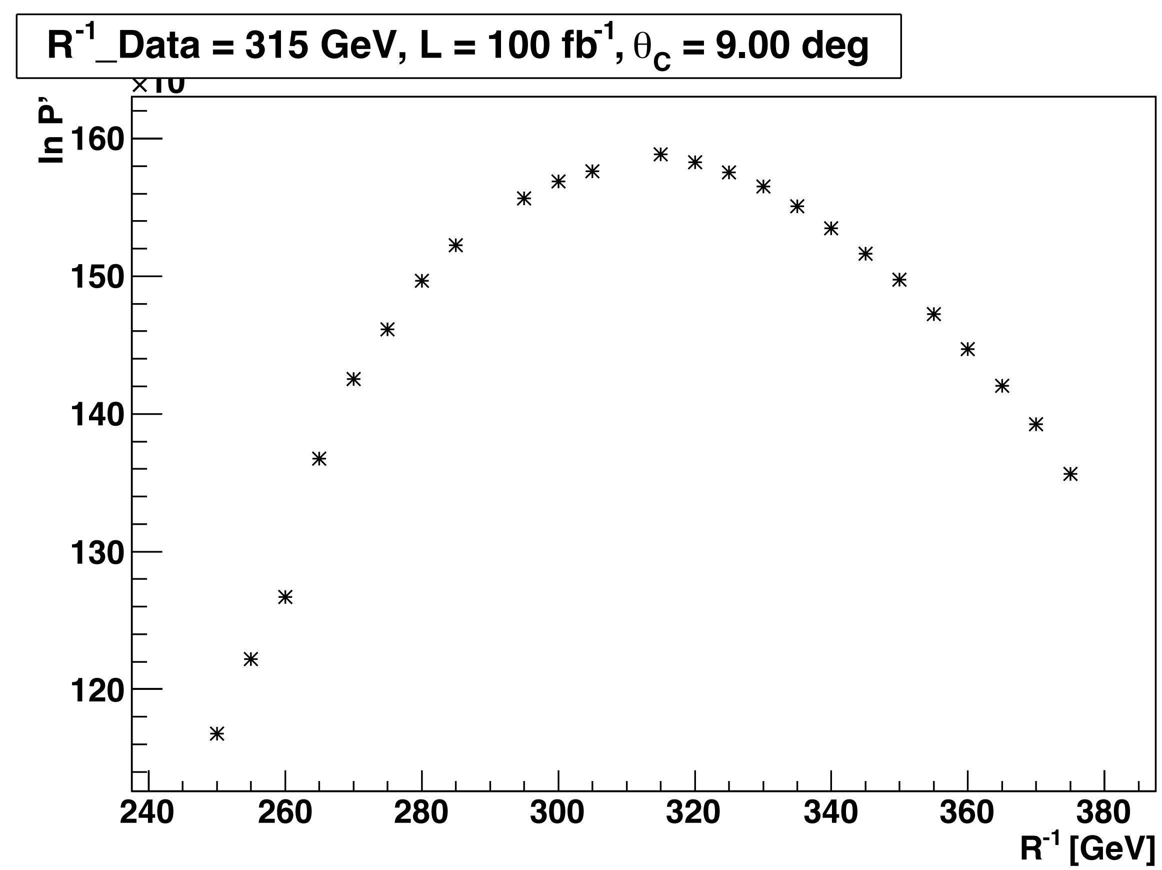
P(R|D) is calculated by binning D in 4D-Histogram ($E_\pm,\theta_\pm$)
and comparing to binned σ from MC for R, with Poisson stat.
(n_i, σ_i = number of events in D, xs for UED[R] in bin i)

$$\begin{aligned} P(D_X|R_Y,L) &= \prod_i \frac{\nu_i^{n_i} e^{-\nu_i}}{n_i!} \\ \nu_i &= \sigma_i^{(Y)} L \end{aligned}$$

for the computer to handle the very small numbers,
calculations are done handling ln(P)

$$\ln\left|P(D_X|R_Y,L)\right| = \sum_i \left(n_i \ln \nu_i - \ln n_i! - \nu_i\right)$$

For R-resolution calc: only likelihood (numerator) is needed
furthermore, D-dependent R-independent pedestal ($\ln n_i!$)
is discarded



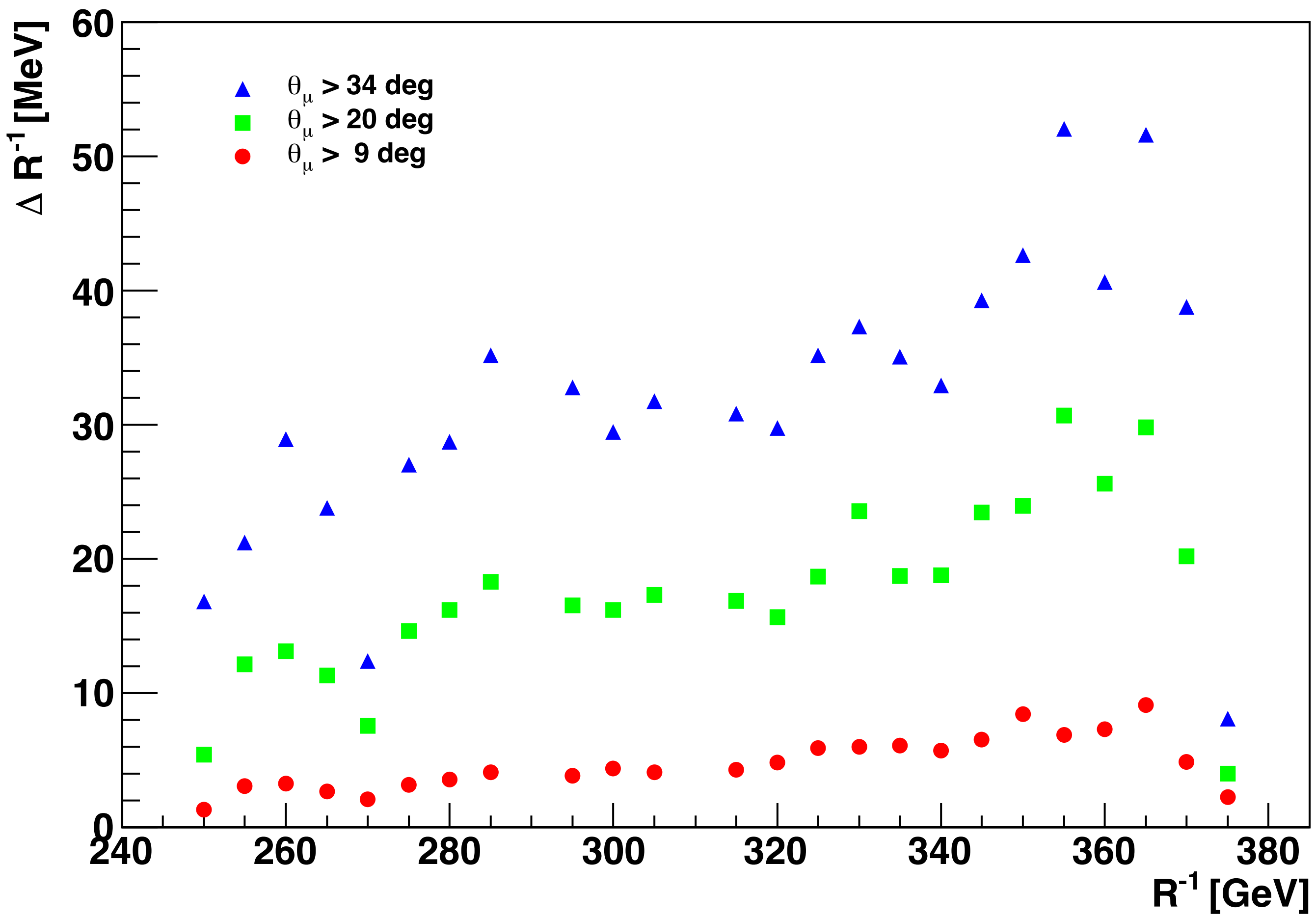
First Results (250 GeV ≤ R^{-1} ≤ 375 GeV)

Presently computers are calculating away to generate billions of events at values of R^{-1} between 250 GeV and 1475 GeV at 5 GeV intervals.

First results are available for $R^{-1} \leq 375$ GeV

At these R's, no interesting UED discoverability potential relationship on θ exist.

However the resolution on R depends strongly on θ
$\Delta R^{-1} = 1\sigma$ ($\Delta\ln(\text{likelihood})=0.5$)



UED vs SUSY

UED and SUSY mass spectra can be tuned to look alike

KK-Parity → R-Parity

LKP → LSP

E_μ distribution identical for SUSY (though σ smaller)

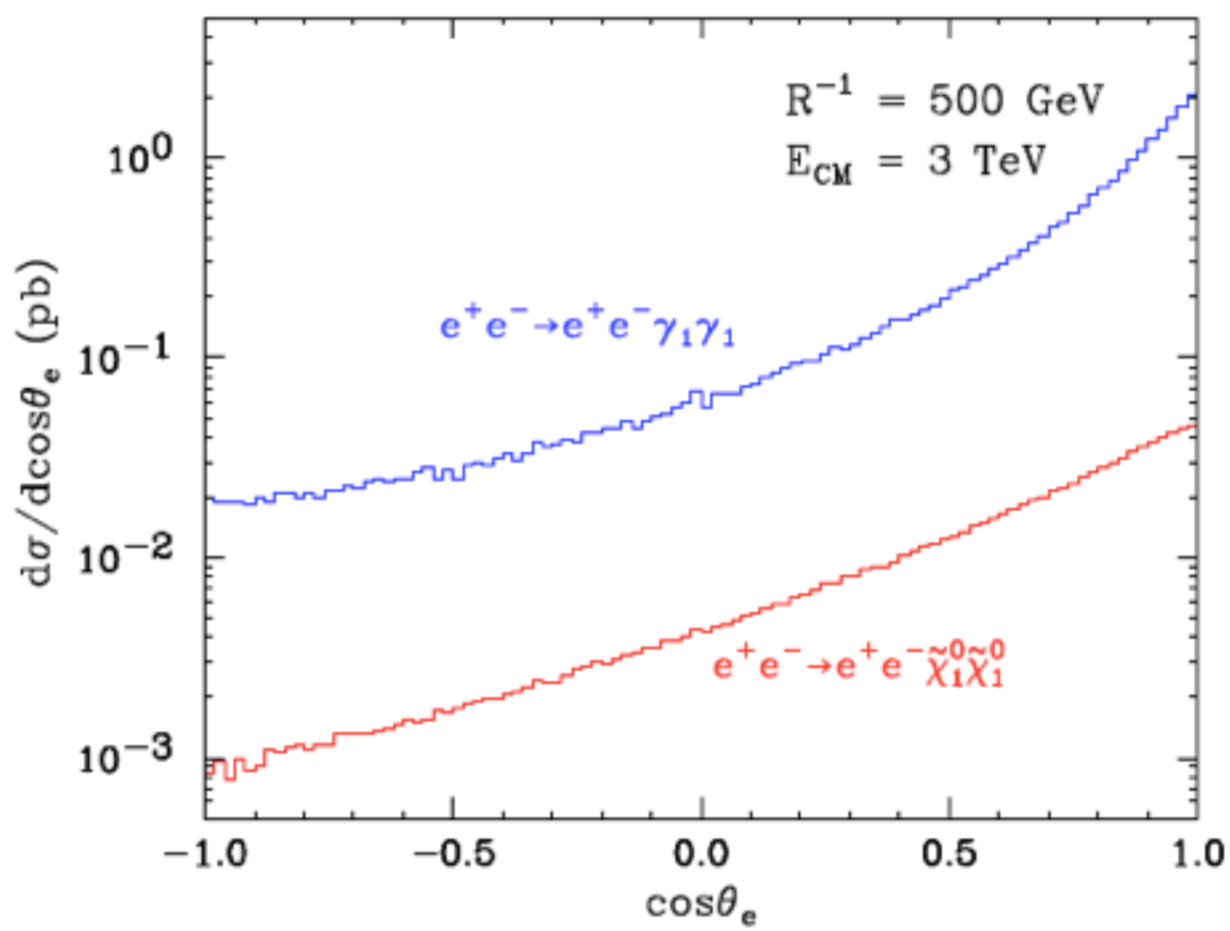
However:

KK excitations have same spin as SM particles

SUSY sparticles have spin differing by 1/2

This can be exploited to discern between UED and SUSY, if spin can be measured.

This sort of search is especially well suited to a lepton collider (CLIC: Battaglia et al., hep-ph/0507284, hep-ph/0502041, c.f. LHC: Smillie & Webber, hep-ph/0507170)



Outlook & Conclusions

Next steps:
Continuing calculations to smaller R
SUSY-UED discernment potential at Muon Collider

- The motivation for building a muon collider / neutrino factory is strong
- Challenges still exist but are being actively investigated
- The μC community is very motivated for the future
  - updating background calculations
  - updating detector designs
  - investigating new physics goals
    reducing angle of detector shielding cone beneficial