

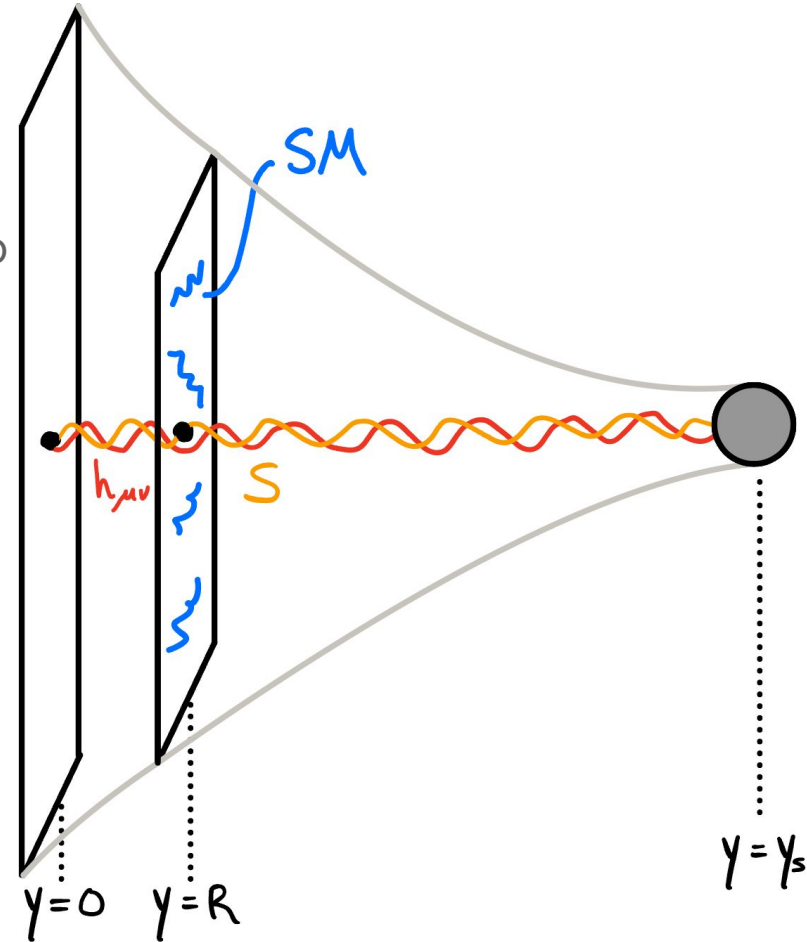
Collider Signatures of Near-Continuum Dark Matter

Steven Ferrante, Maxim Perelstein, (Cornell U.)
Seung J. Lee (Korea U.)

(Work In Progress)

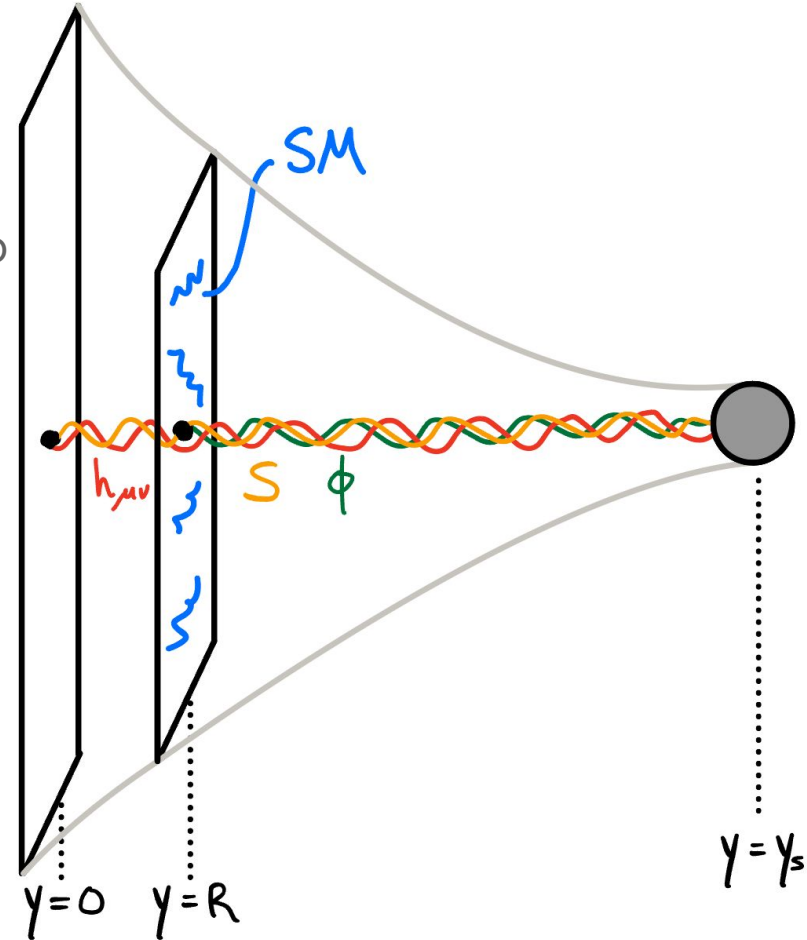
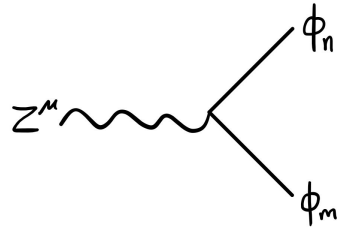
Continuum DM

- Planck brane @ $y = 0$
- SM brane @ $y = R$
- Coupled system of **graviton** and **scalar** leads to singularity @ $y = y_s$ (“ soft-wall ”)



Continuum DM

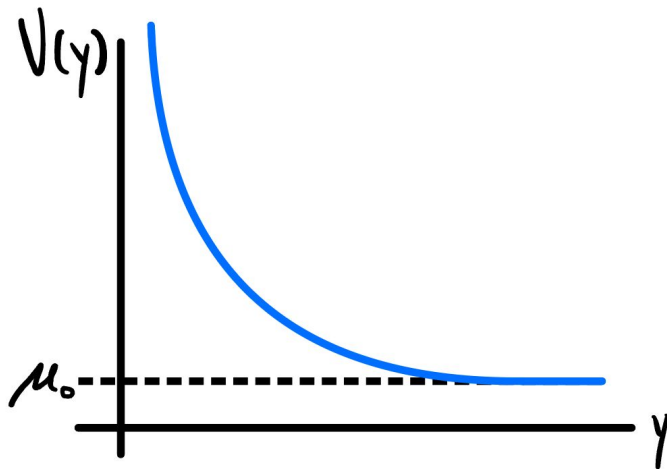
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- Talks to the SM via Z-Portal $\mathcal{L} \supset Z^\mu \Phi^\dagger \partial_\mu \Phi$



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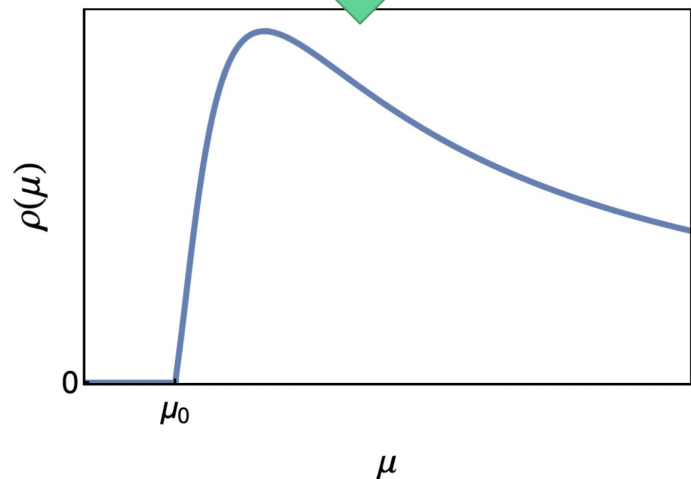
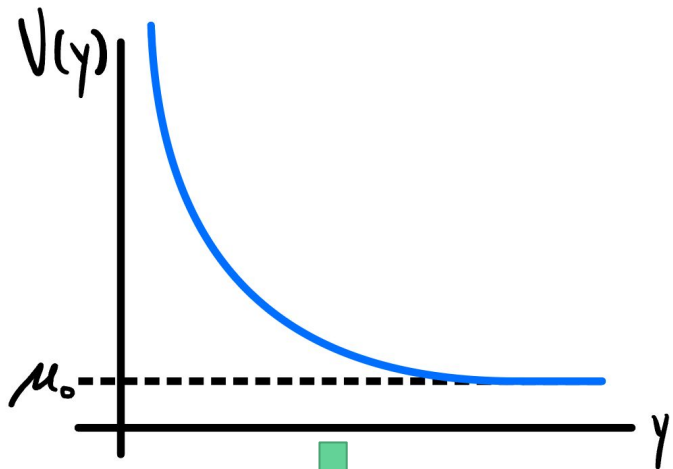
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$$-f_n'' + V(z)f_n = m_n^2 f_n$$



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- Spectrum of Φ is found by solving
- Result: Φ gets a gapped continuous KK spectrum !
- Goal: What is the pheno for continuous spectra ?

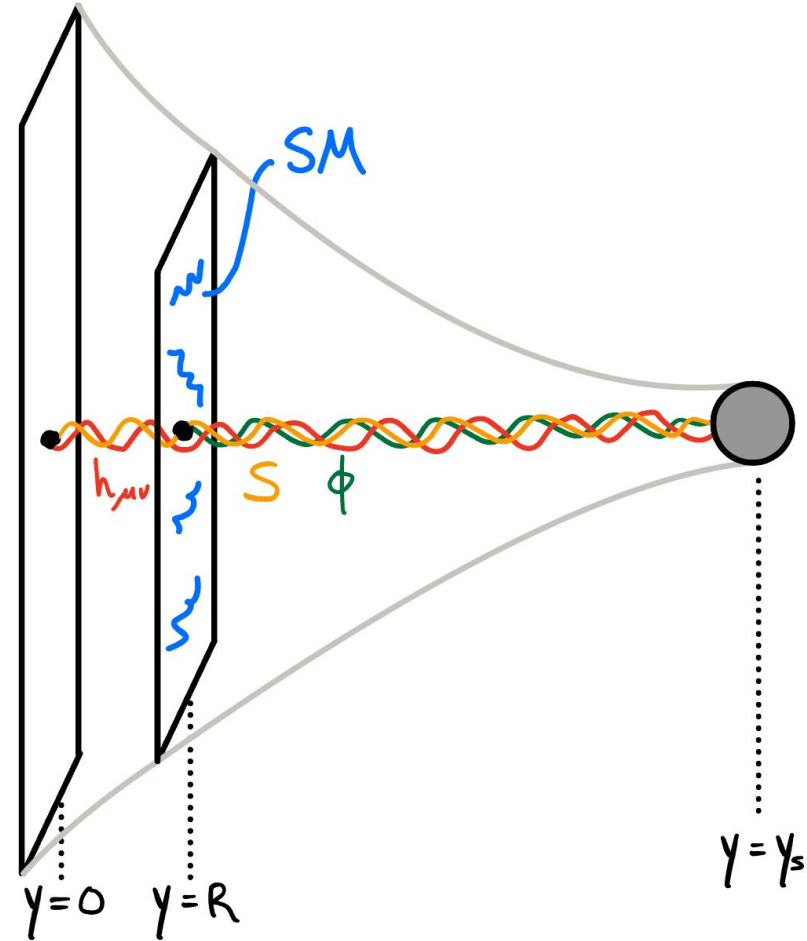


Quiros et al., 0907.5361

Csaki, Perelstein, et al., 2105.07035, 2105.14023

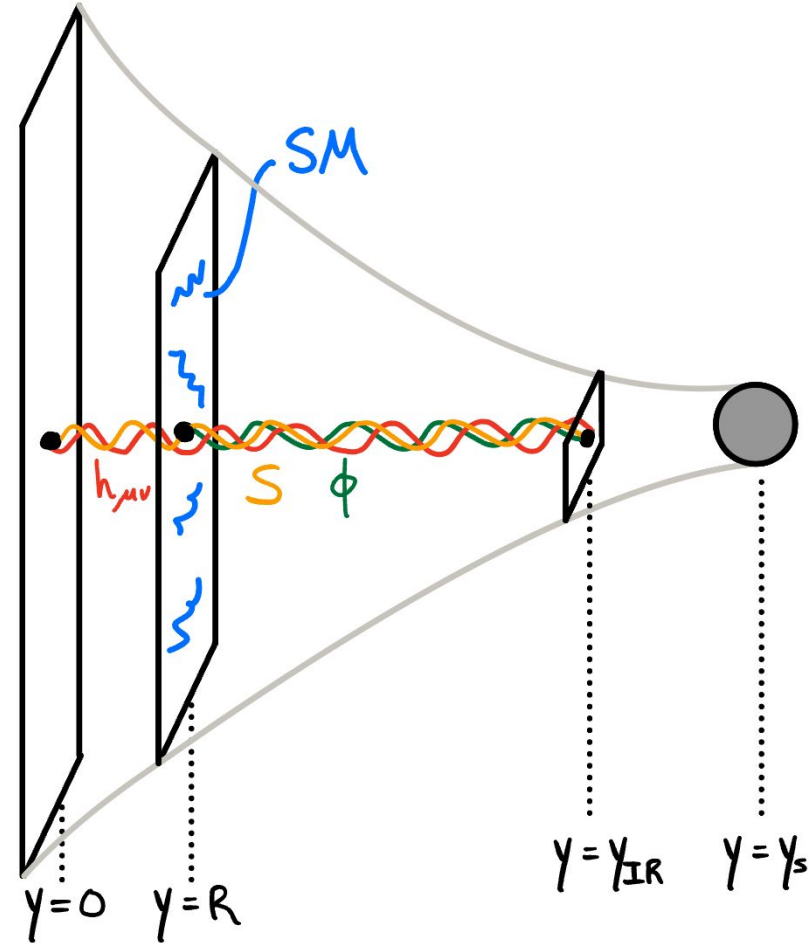
Near-Continuum DM

- Singularity must be resolved somehow



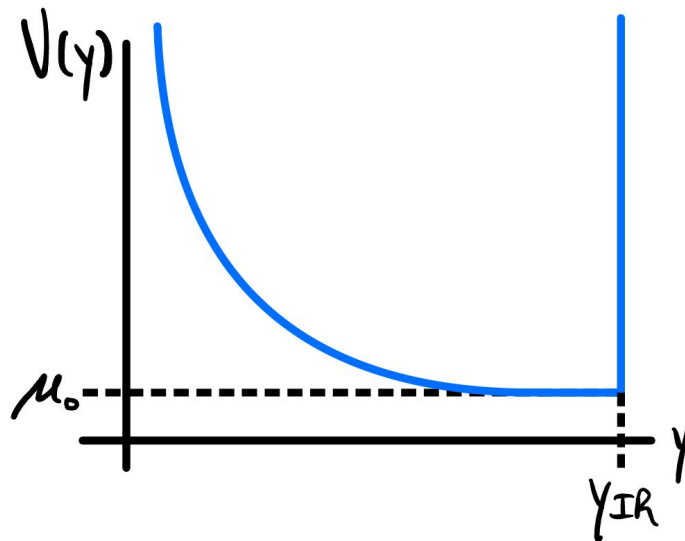
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- Can crudely model QG effects with “IR regulator brane”
- Broadens interest to a family of models, parameterized by a brane @ $y = y_{\text{IR}}$



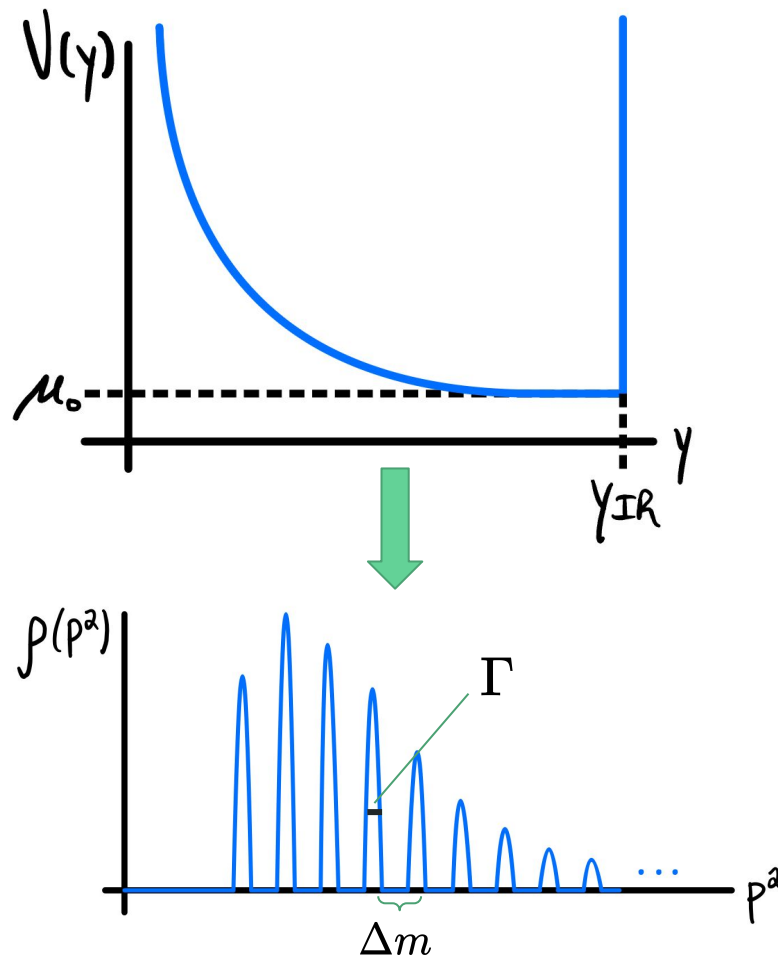
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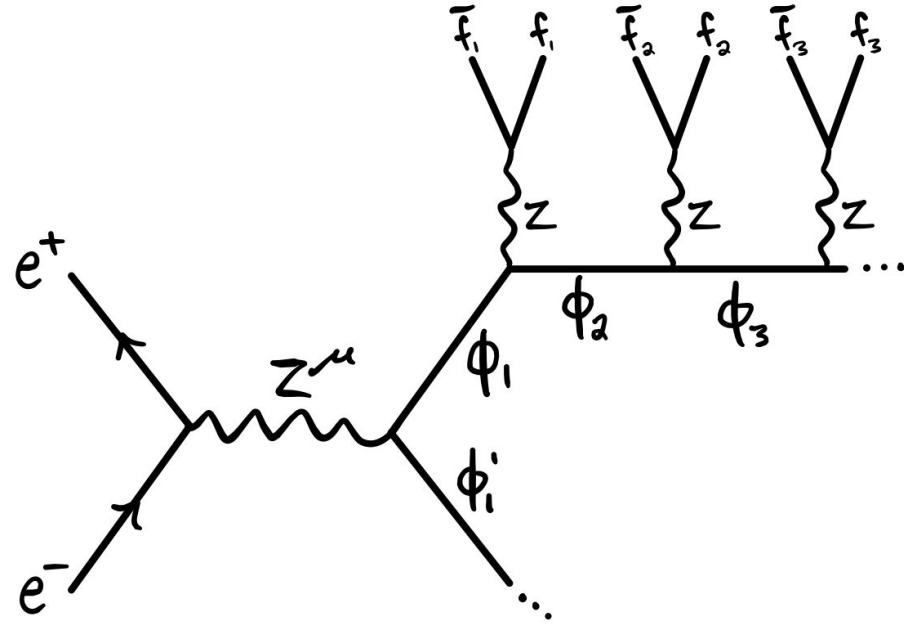
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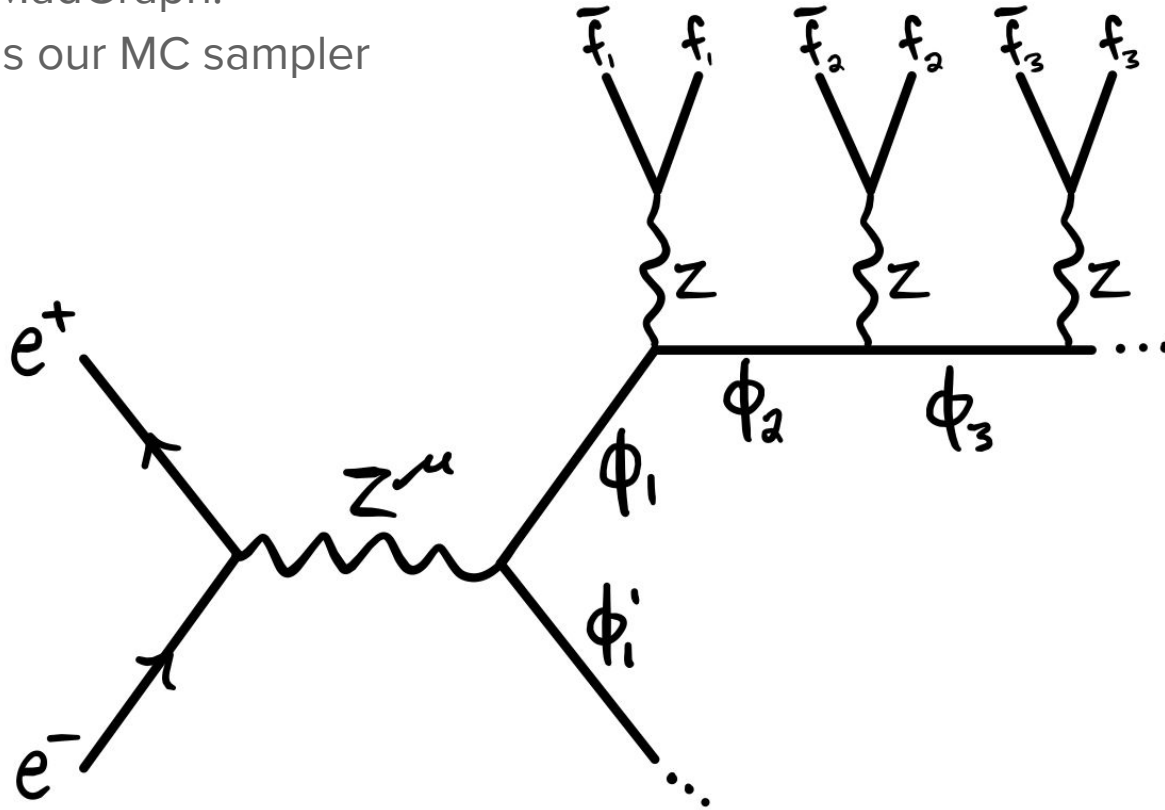
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- $V(y)$ now resembles infinite well from QM
- Makes the mass spectrum of Φ discrete!
- Z-portal & \mathbb{Z}_2 allows for “cascade decay”
- DM states become increasingly light & stable
- Requires $\Gamma_Z > \Gamma_g$ to be “visible”



Near-Continuum Phenomenology -- Visible Cascade

- Cannot use MadGraph!
- Use Vegas as our MC sampler



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Benchmark Point:

e⁺e⁻ Collider

$\sqrt{s} = 500 \text{ GeV}$

$\mu_0 = 100 \text{ GeV}$

$g_{\text{eff}} = 0.0074$

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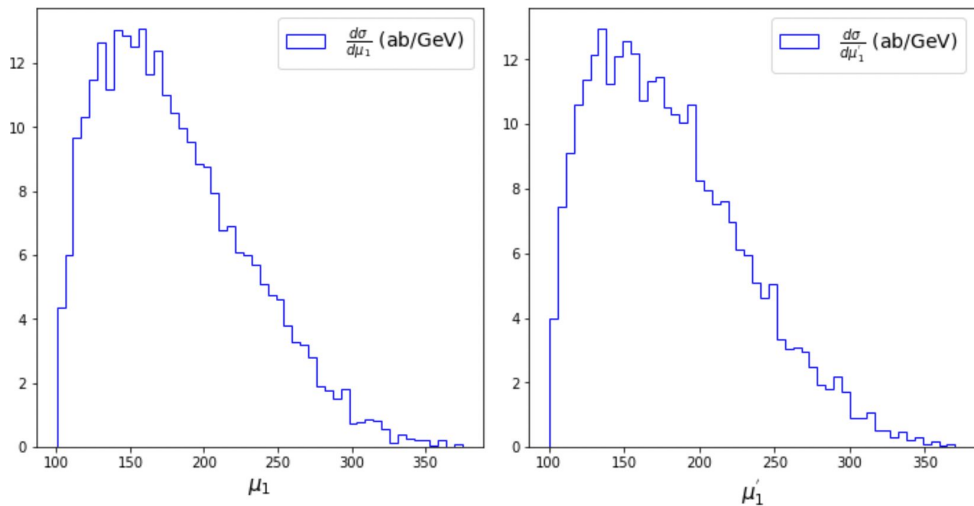
e+e- Collider

$\sqrt{s} = 500 \text{ GeV}$

$\mu_0 = 100 \text{ GeV}$

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~ 135 ab

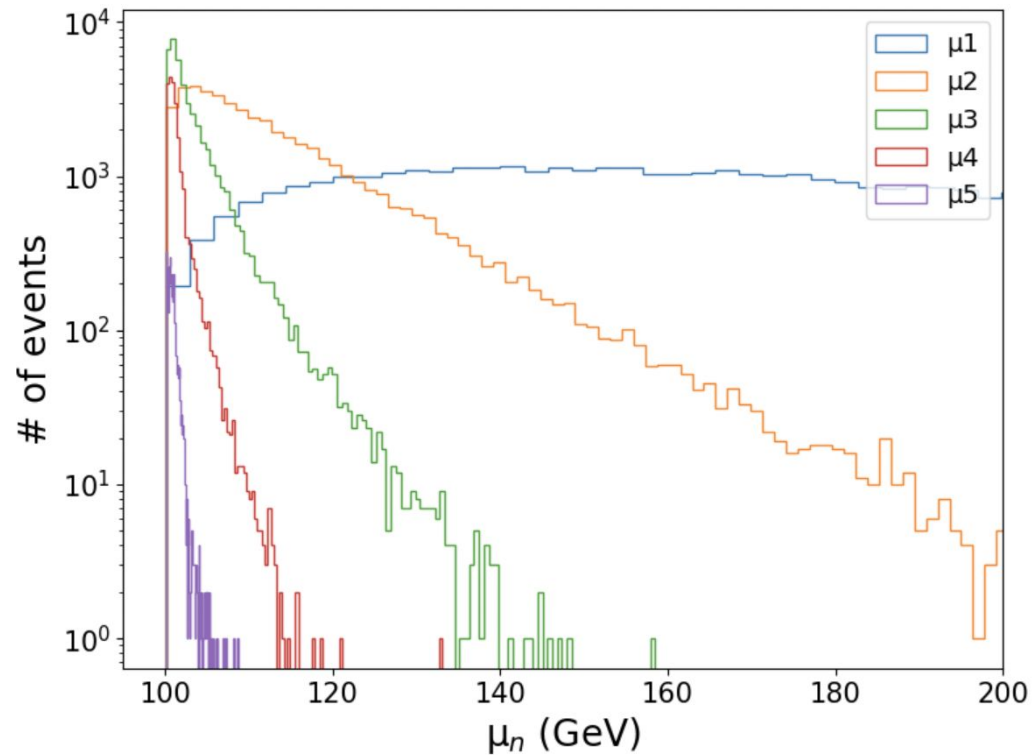


preliminary

Near-Continuum Phenomenology -- Visible Cascade

Non-Observables

- Φ_n masses at each step



preliminary

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- Φ_n masses at each step
- Φ_n velocities at each step
- Invariant mass of each fermion pair

(backup)

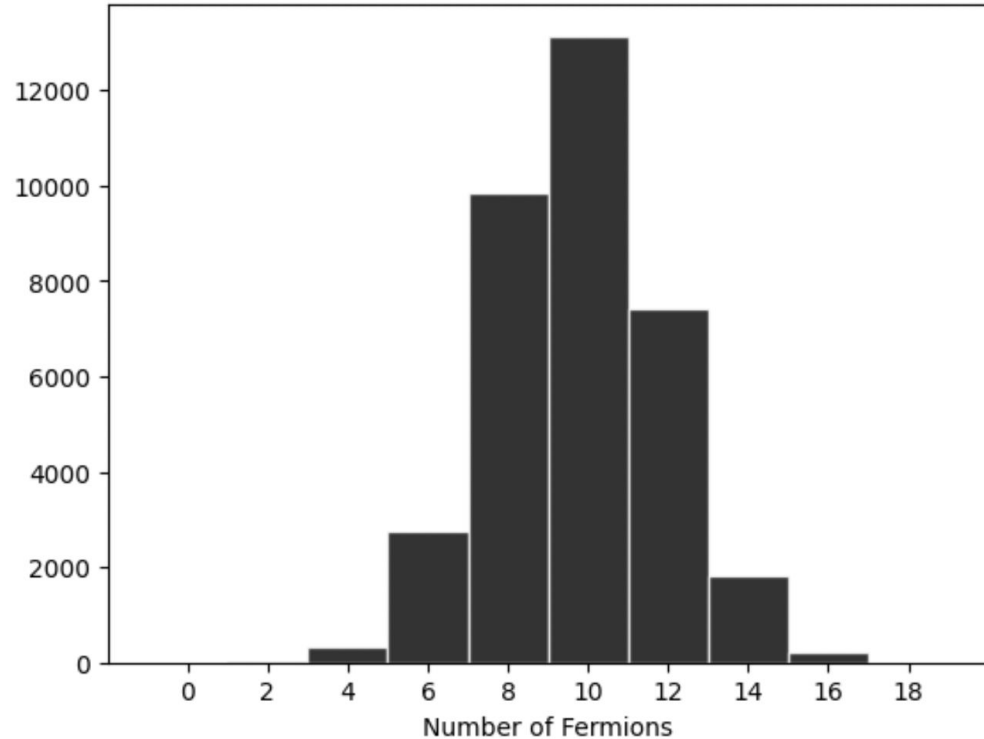
Near-Continuum Phenomenology -- Visible Cascade

Non-Observables

- Φ_n masses at each step
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Observables

- Multiplicities



preliminary

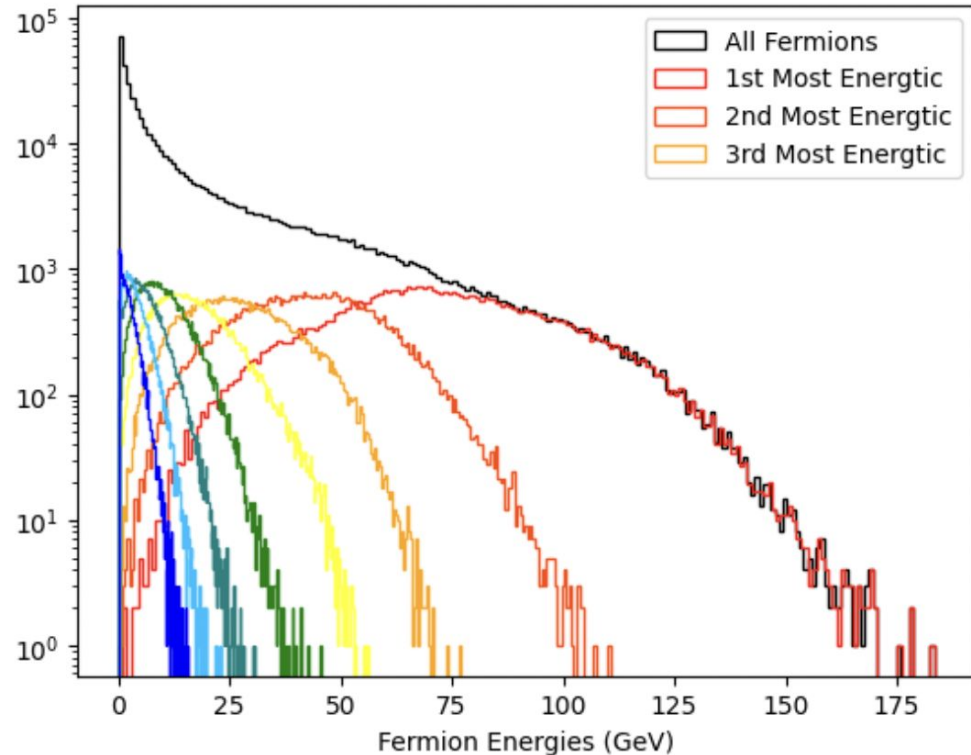
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Observables

- Multiplicities
- Fermion Energies



preliminary

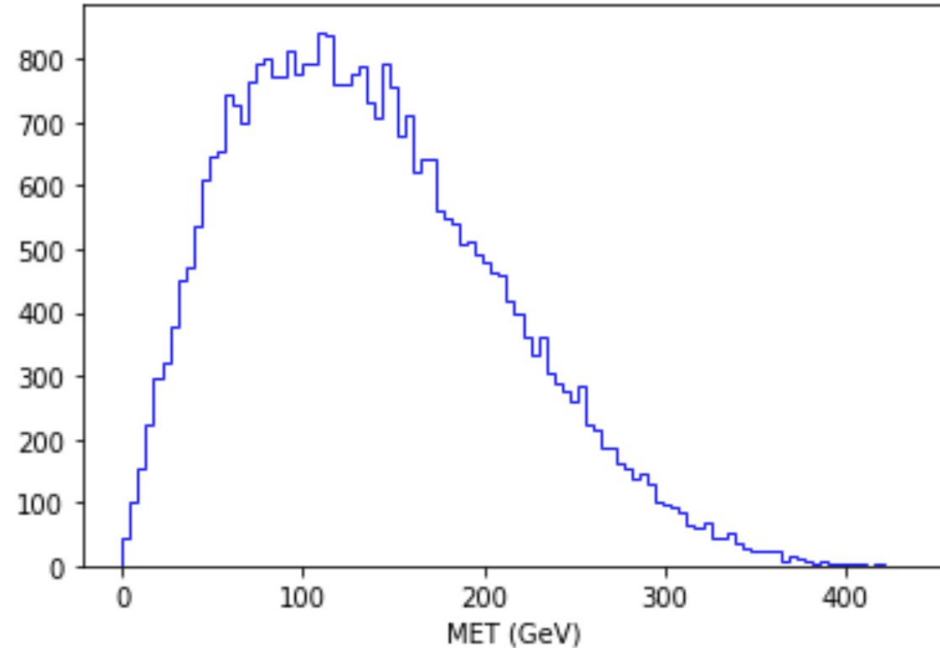
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Observables

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- Missing Energy



preliminary

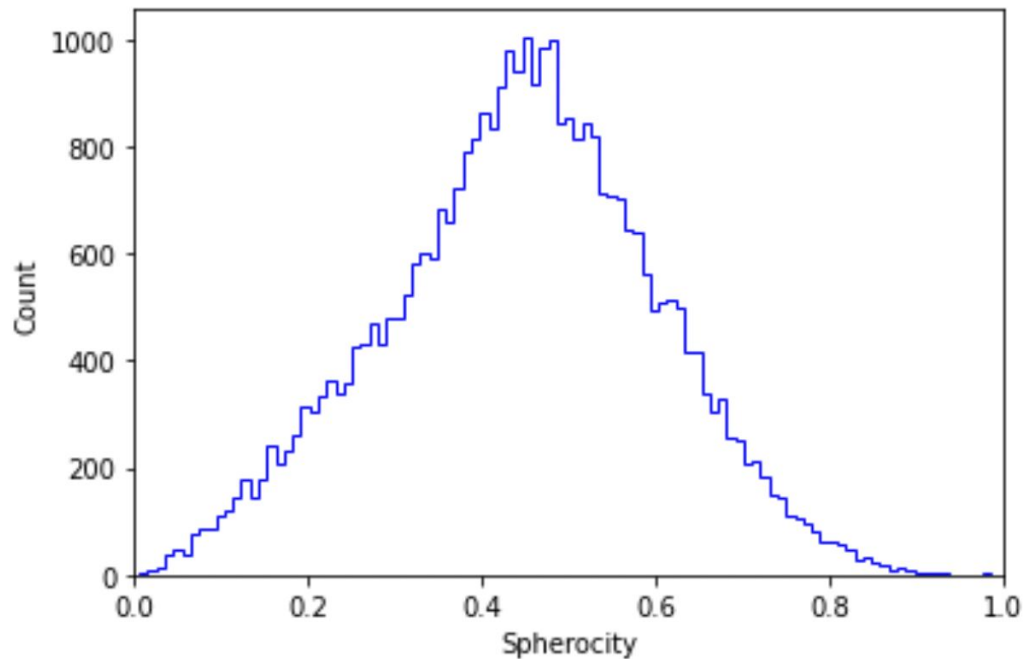
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- Fermion Energies
- Missing Energy
- Sphericity



preliminary

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Observables

- Multiplicities
- Fermion Energies
- Missing Energy
- Spherocity
- Displaced Vertices
- Fermion Angles
- etc ...

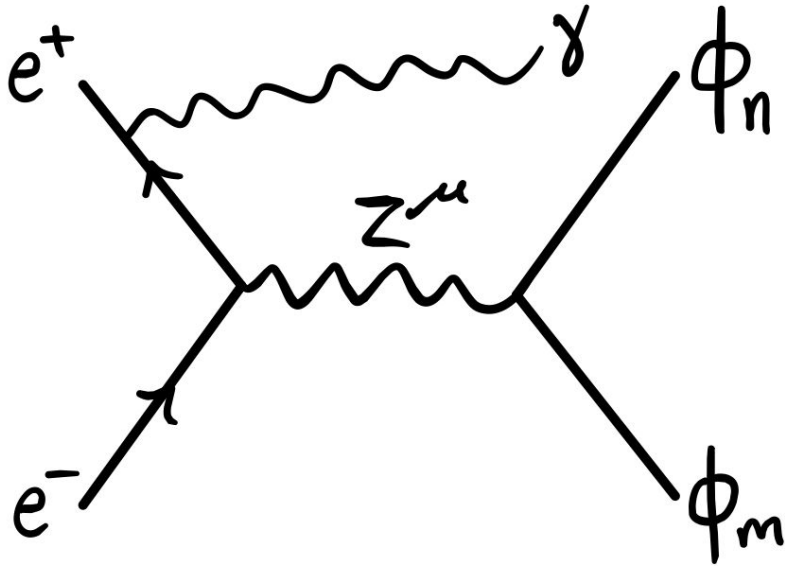
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Near-Continuum Phenomenology -- Invisible Cascade

- If $\Gamma_Z < \Gamma_g$, DM decays are dominated by gravitons in the bulk

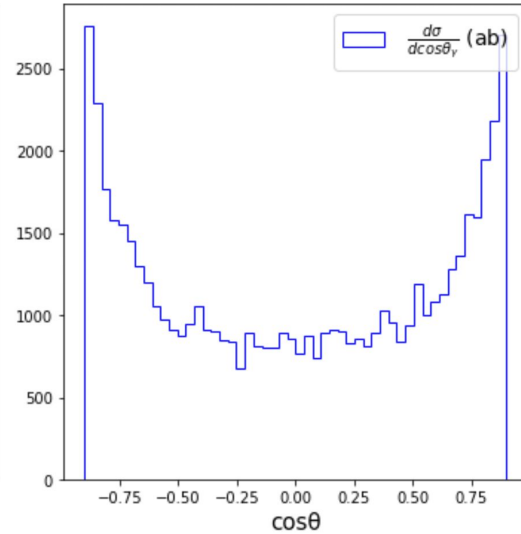
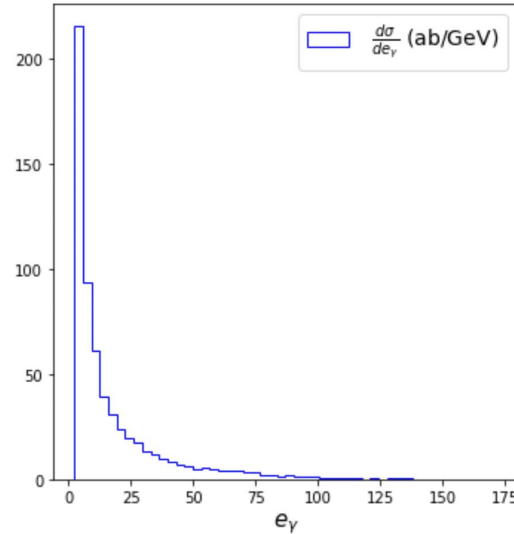
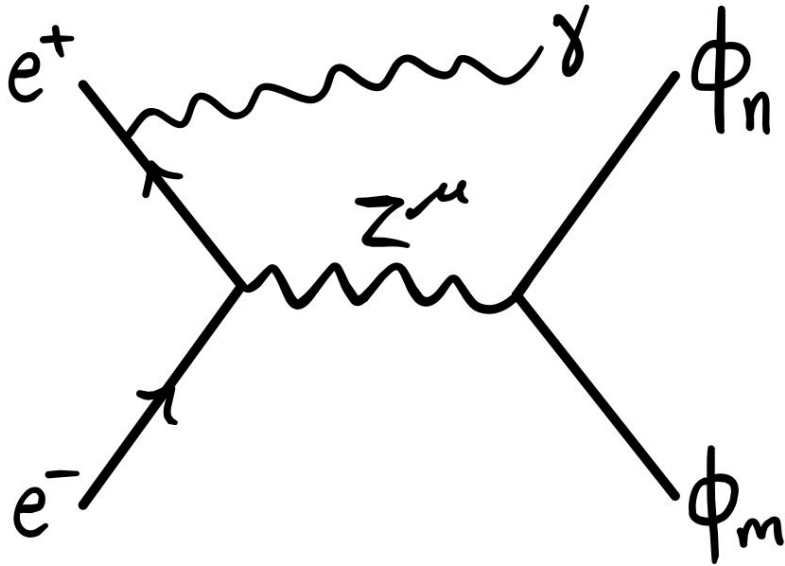
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- Signal is mostly invisible, so consider $\gamma + \text{MET}$ (initial state radiation)



Near-Continuum Phenomenology -- Invisible Cascade

- If $\Gamma_Z < \Gamma_g$, DM decays are dominated by gravitons in the bulk
- Signal is mostly invisible, so consider γ + MET (initial state radiation)
- Only observables are the photon energy & angle

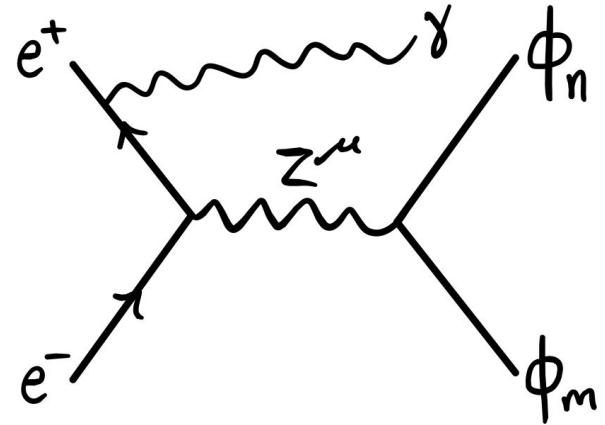


Back to Continuum DM: take the **Continuum Limit** $\Delta m \rightarrow 0$

- NWA breaks down!
- Assume the signal is invisible

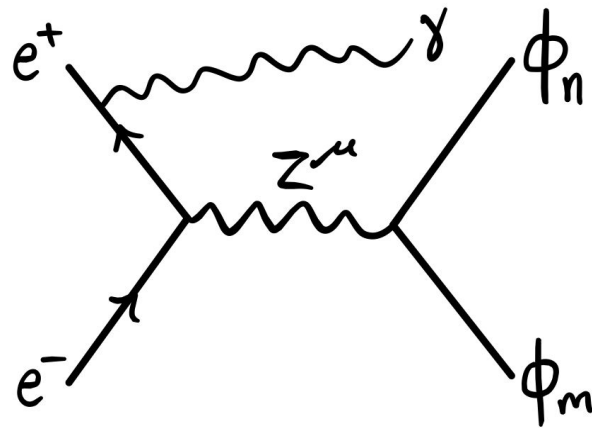
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- Need to use the Optical Theorem

$$\text{Im} \left(\text{Diagram 1} \right) \sim \left| \text{Diagram 2} \right|^2$$

The diagram on the left, enclosed in large parentheses, represents the imaginary part of a scattering amplitude. It shows an incoming electron-positron pair (e^- and e^+) interacting via a photon (γ) and a Z boson (Z) to produce a final state consisting of a scalar particle ϕ_n and an anti-scalar particle ϕ_m . The diagram on the right, enclosed in large vertical bars, represents the squared magnitude of the corresponding tree-level scattering amplitude for the same process, where the photon and Z boson exchange is shown as a single vertex.

Back to Continuum DM: take the **Continuum Limit** $\Delta m \rightarrow 0$

- NWA breaks down!
- Assume the signal is invisible \rightarrow ISR signal
- But the KK modes aren't asymptotic states!
- Need to use the Optical Theorem ... not clear if it works for continuum propagators
- **Should** still be equivalent to the Feynman diagram treatment
(as in the **Invisible** case)

$$\text{Im} \left(\text{Diagram 1} \right) \sim \text{Diagram 2}^2$$

Diagram 1: A Feynman diagram representing the imaginary part of a loop. It shows an incoming electron-positron pair (e^+e^-) and an outgoing electron-positron pair (e^+e^-). The internal lines consist of a photon (γ), a Z boson (Z), and a scalar field loop with mass ϕ_n and ϕ_m .

Diagram 2: A Feynman diagram representing the squared magnitude of a scattering amplitude. It shows an incoming electron-positron pair (e^+e^-) and an outgoing scalar field pair ($\phi_n\phi_m$). The internal lines consist of a photon (γ), a Z boson (Z^μ), and a scalar field loop with mass ϕ_n and ϕ_m .

preliminary

Conclusion

- Near-Continuum models can rise to different types of interesting phenomenology
- Cascade Decay in the **visible** case of Near-Continuum
- γ + MET signal in the **invisible** case of Near-Continuum or the full limit

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Outlook

- LHC Simulations
- Comparison to backgrounds
- Can consider other continuum models
- Strongly coupled dual description?

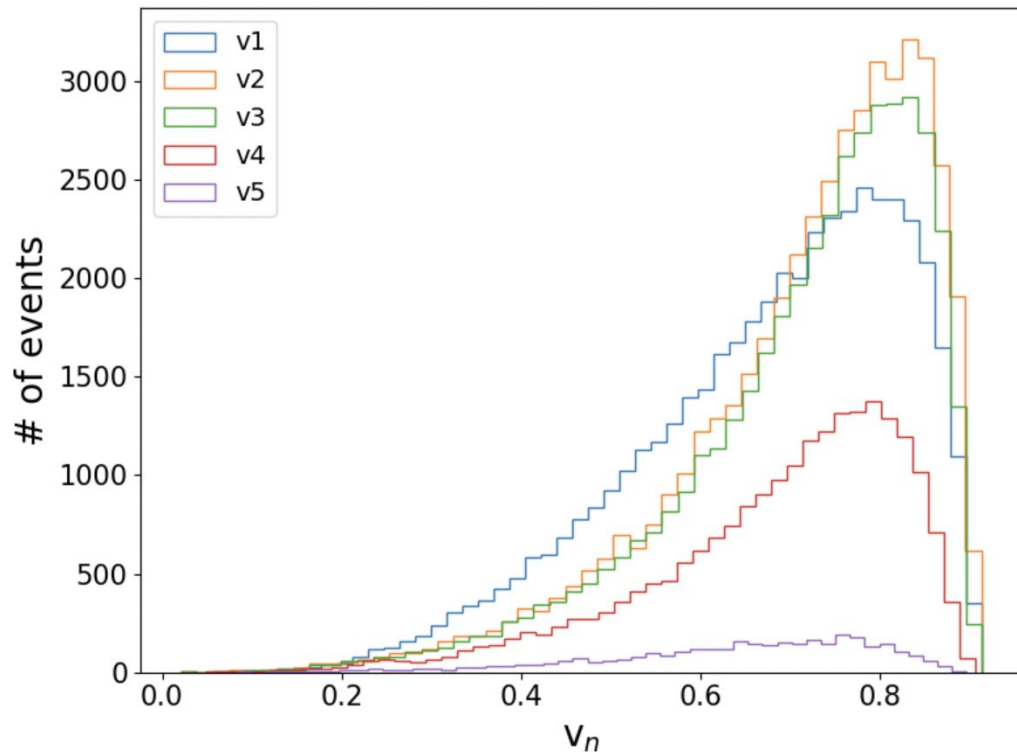
Thanks for (fine)tuning in

Backup

Near-Continuum KK Spectrum -- Narrow Width ✓ & Visible

Non-Observables

- Φ_n masses at each step
- Φ_n velocities at each step

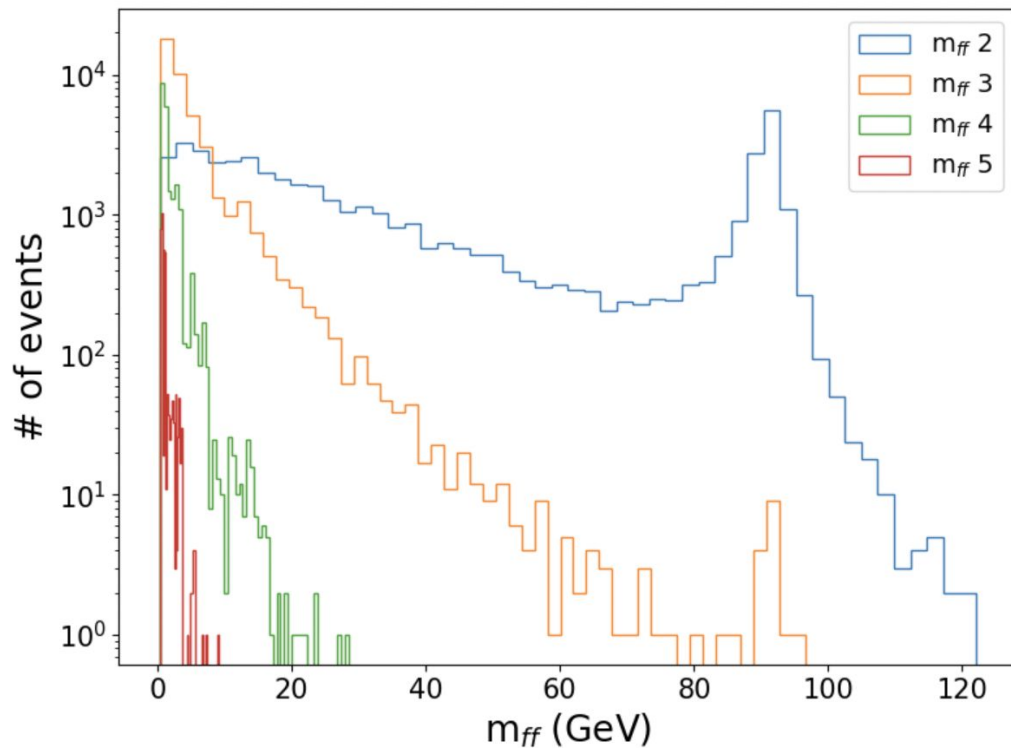


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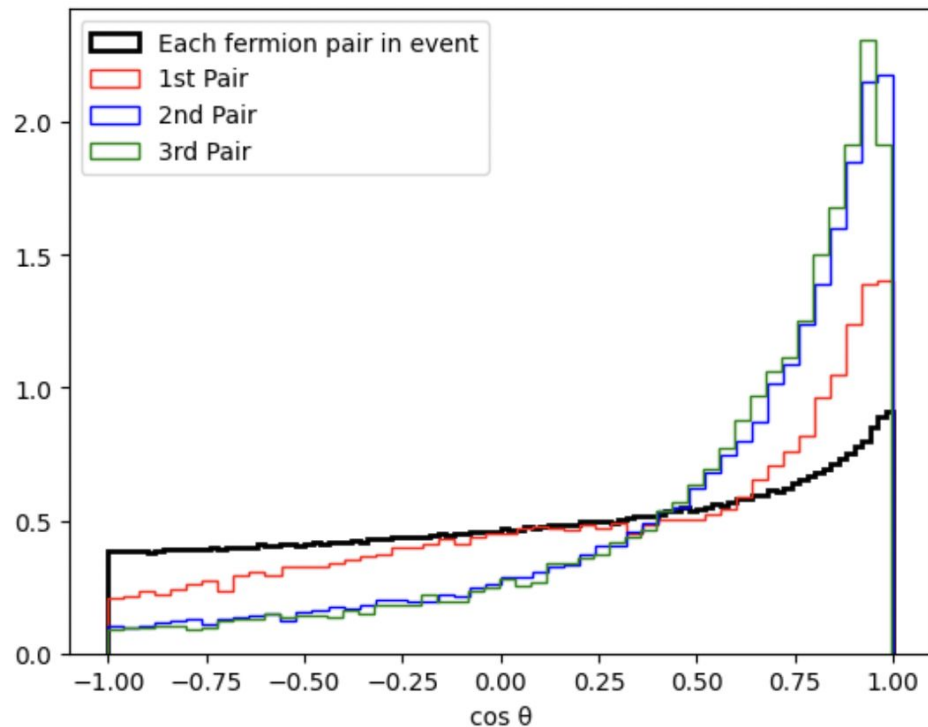
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Observables

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- Fermion Energies
- Fermion Angles



preliminary

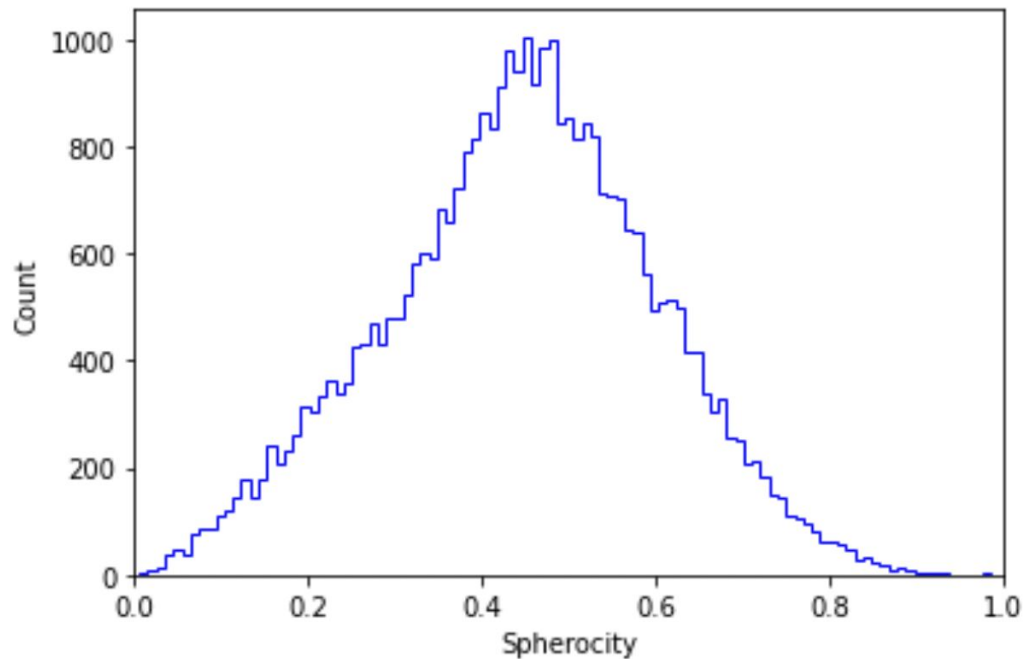
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- Missing Energy
- Sphericity



preliminary

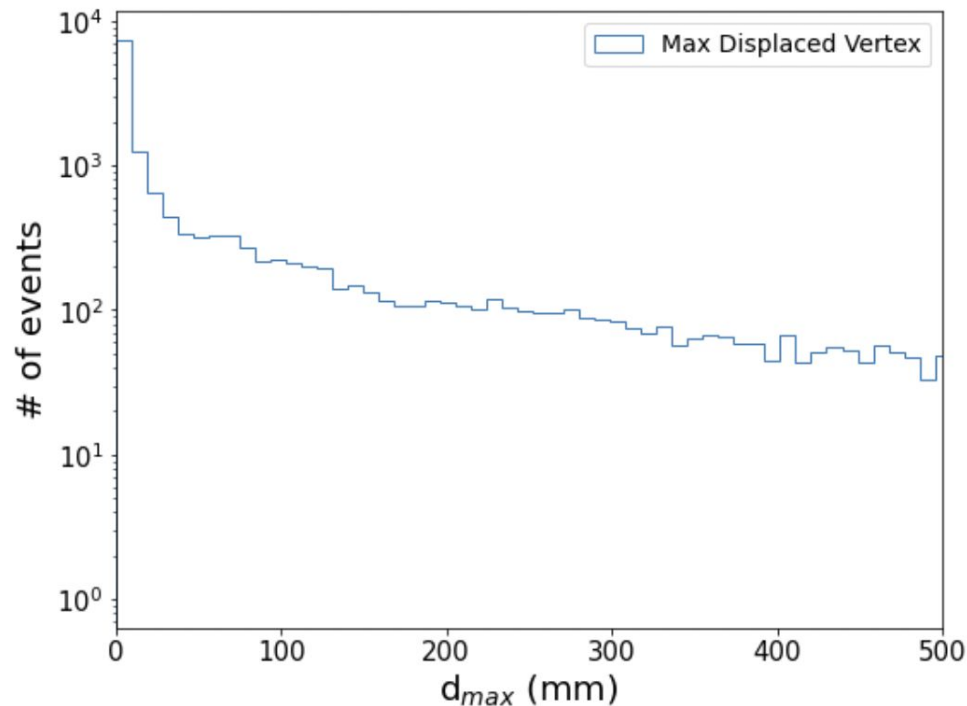
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- Displaced Vertices



preliminary

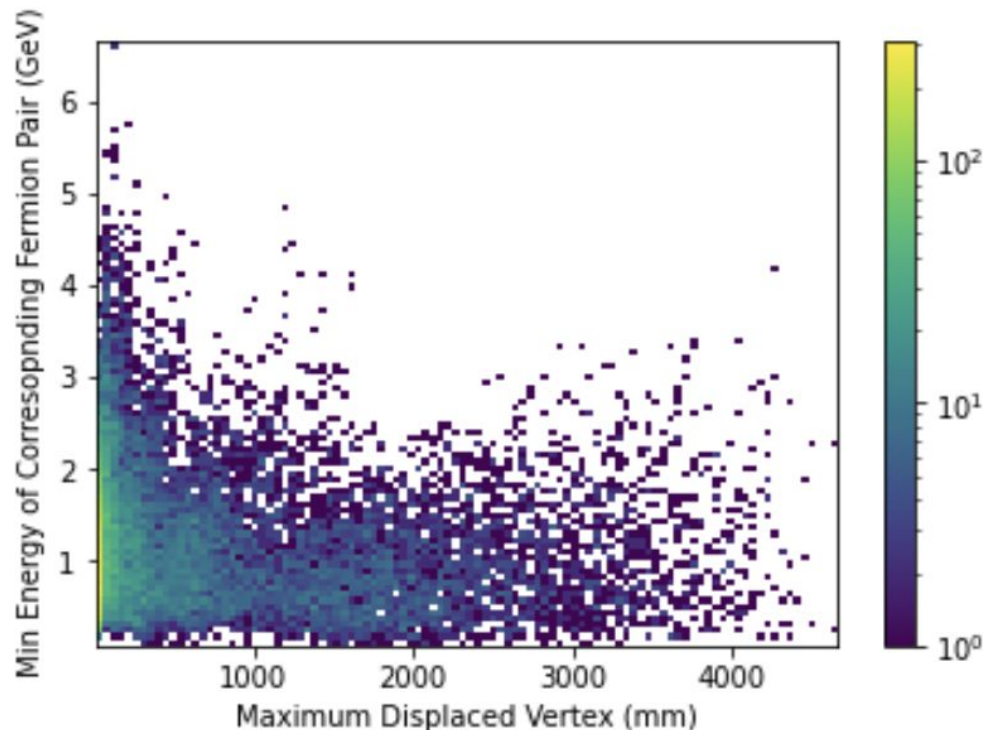
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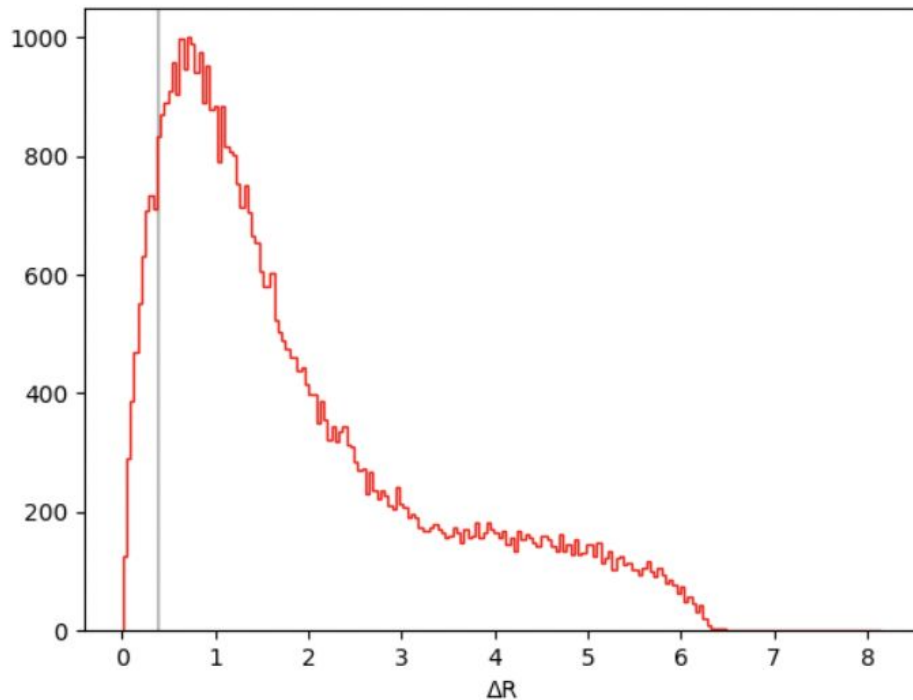
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preliminary

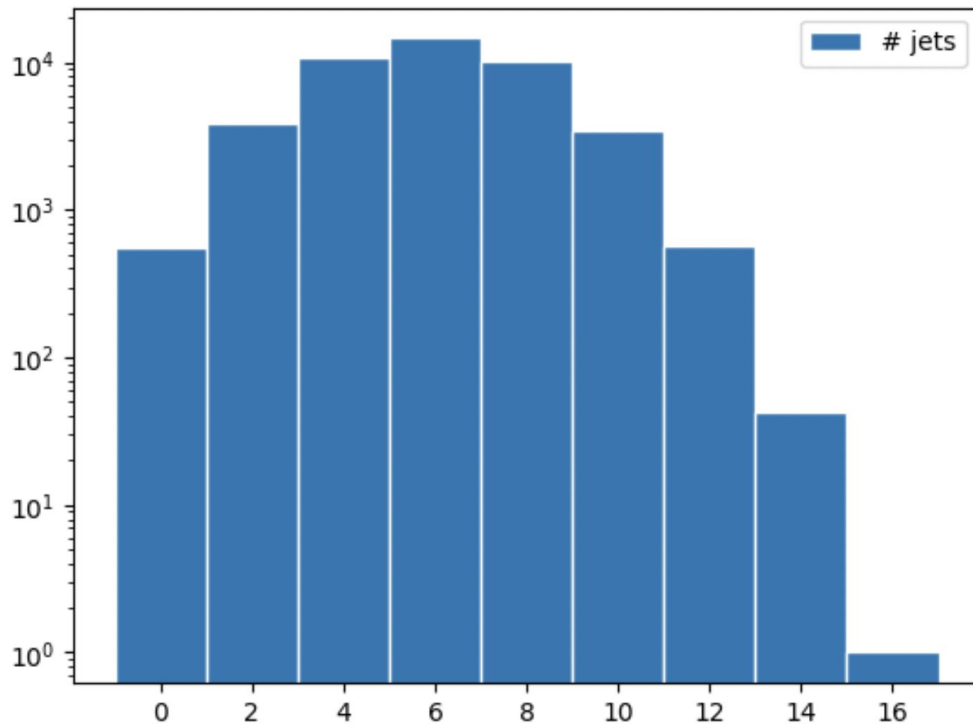
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- # jets



preliminary

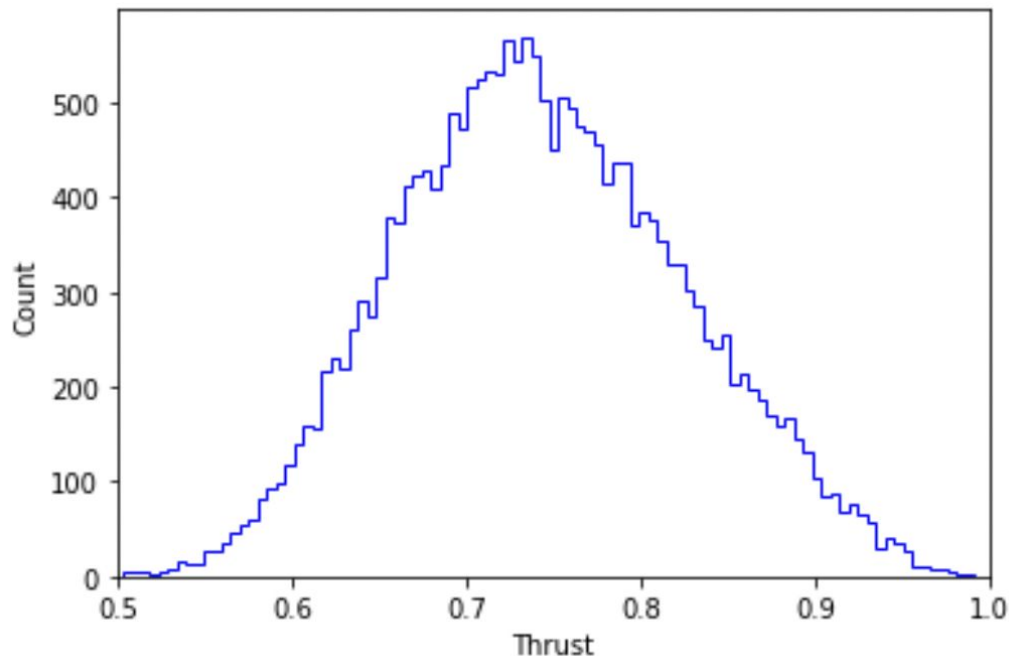
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- # jets
- Thrust



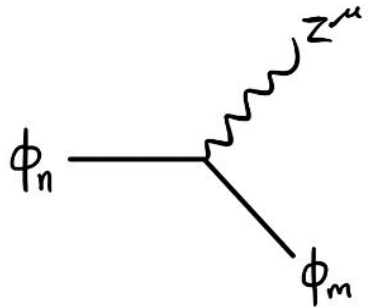
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Near-Continuum KK Spectrum -- Narrow Width ✗

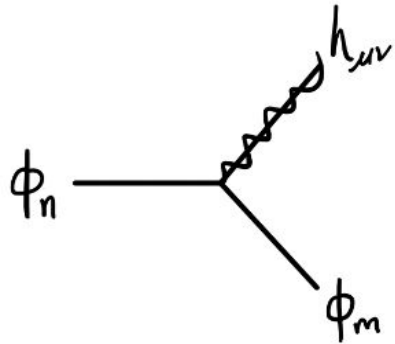
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Near-Continuum KK Spectrum -- Narrow Width ✗

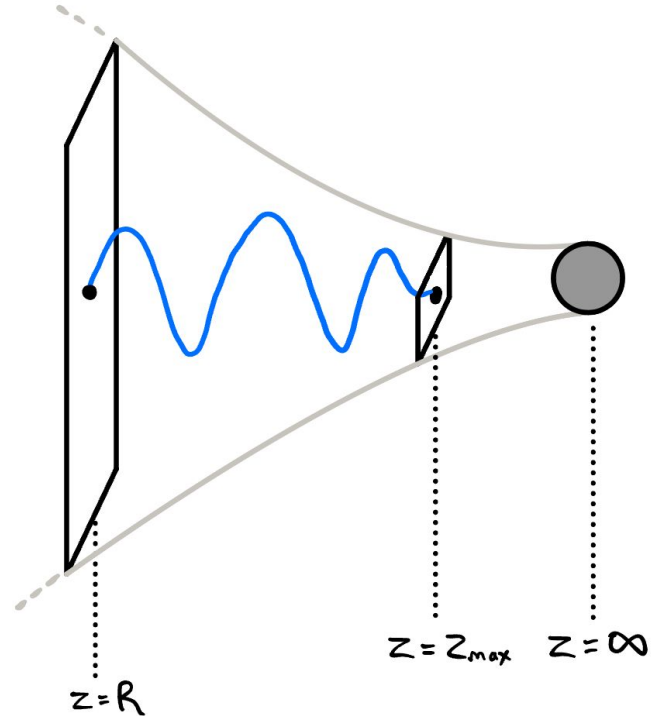
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$$\sim f(R)^2$$

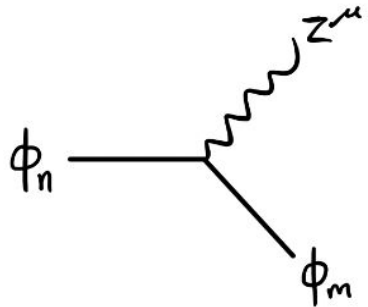


$$\sim \int_R^{z_{\max}} f(z)^2 h(z) dz$$

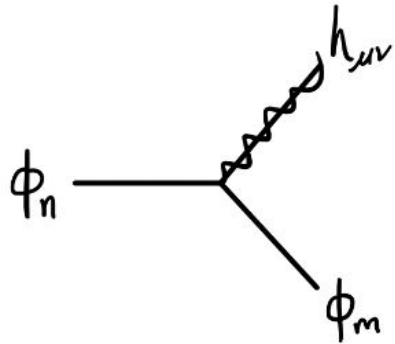


Near-Continuum KK Spectrum -- Narrow Width X

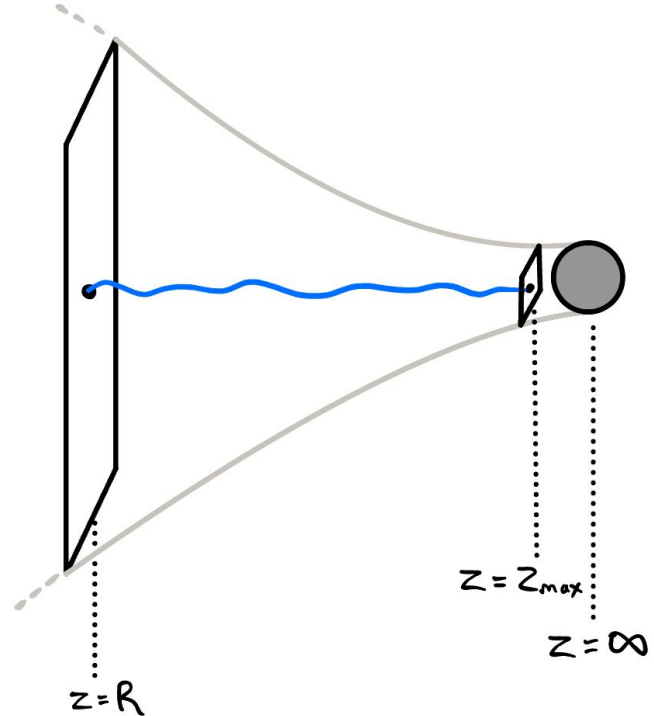
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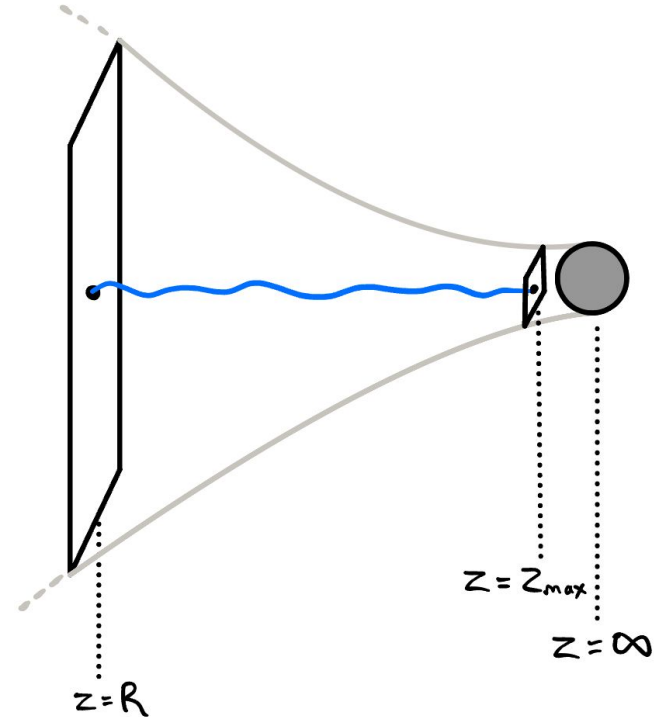
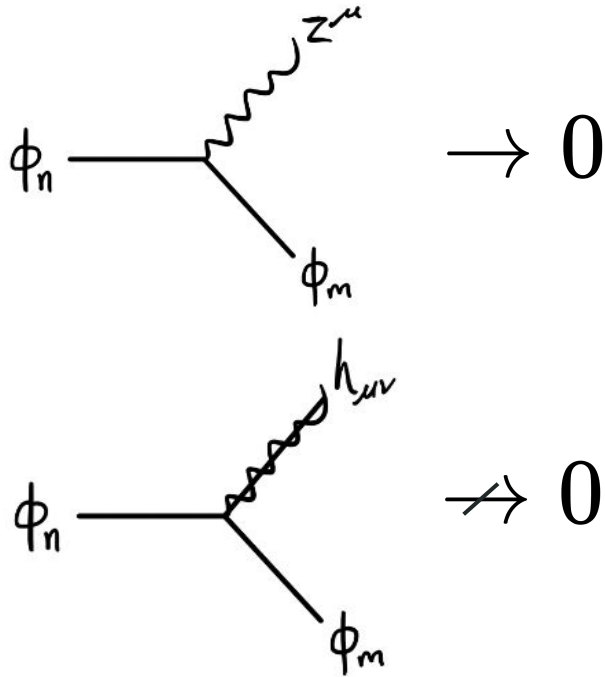


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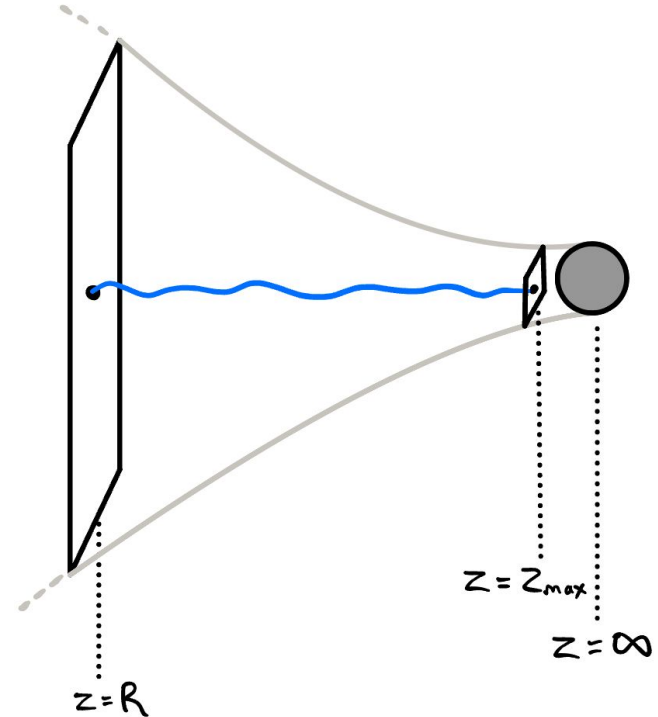
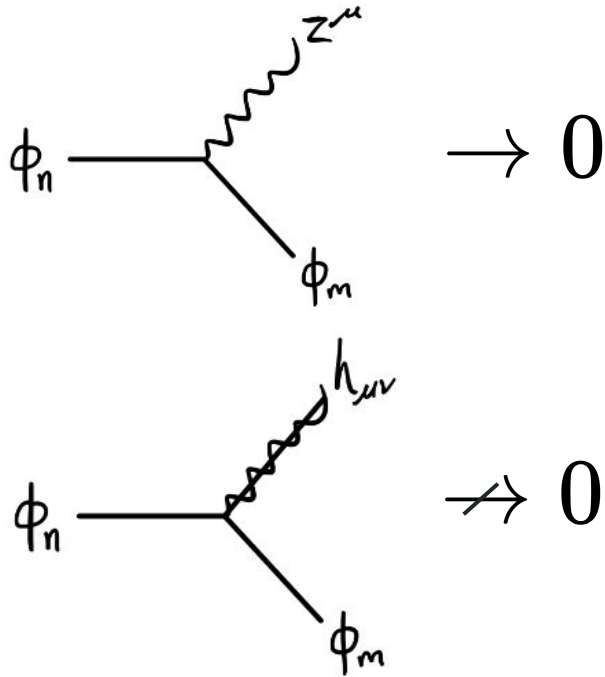
Near-Continuum KK Spectrum -- Narrow Width X

- Assume NWA holds, & consider the limit $z_{\max} \rightarrow \infty \dots$ then $\Delta m \rightarrow 0$



Near-Continuum KK Spectrum -- Narrow Width ✗

- Assume NWA holds, & consider the limit $z_{\max} \rightarrow \infty \dots$ then $\Delta m \rightarrow 0$
- By the time NWA breaks, $\Gamma_g > \Gamma_Z \rightarrow$ Invisible



Alternate explanation of $\Gamma_Z \rightarrow 0$

$$\begin{aligned} \langle \Phi(x, 0) \Phi(x, 0) \rangle &= \sum_{n,m} f_n(0) f_m(0) \langle \Phi_n(x) \Phi_m(x) \rangle \\ &= \sum_n |f_n(0)|^2 \frac{i}{p^2 - m_n^2} \\ &= \int dm^2 \underbrace{\left(\lim \frac{|f_n(0)|^2}{\Delta m^2} \right)}_{\rightarrow \rho(m^2)} \frac{i}{p^2 - m^2} \end{aligned}$$