Drell-Yan Bound on Continuum Spectra from Extra Dimensions

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Motivation

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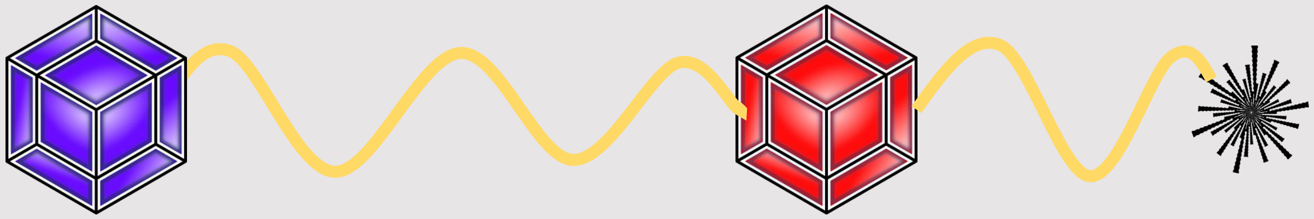
- Hierarchy problem
- Experimental bounds
- Single parameter theory
- One extra dimension



Setup

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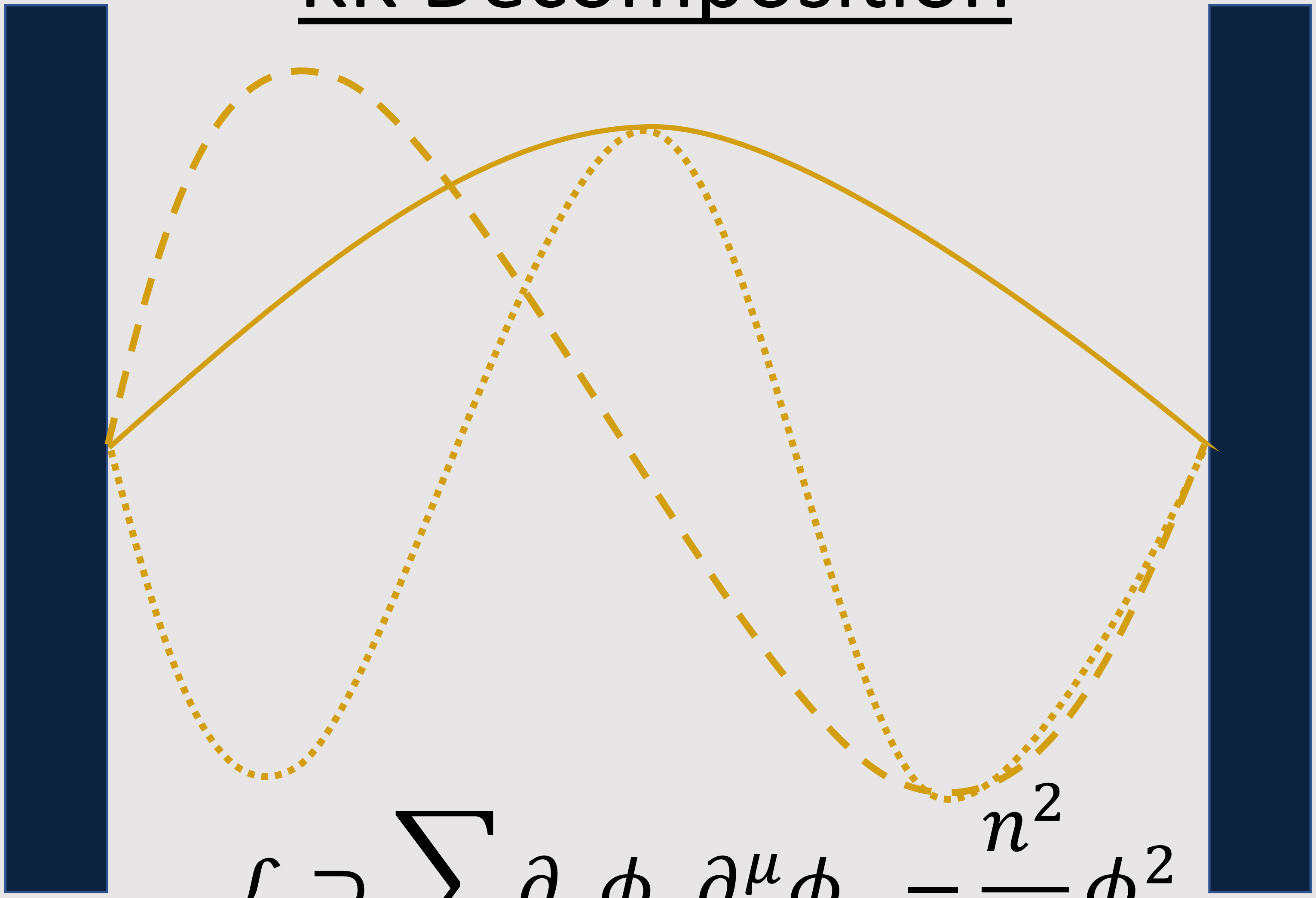
Tower of Particles
KK Decomposition



←Wave functions

$$\mathcal{L} \supset \sum_n \partial_\mu \phi_n \partial^\mu \phi_n - \frac{n^2}{L^2}\phi_n^2$$

Each ϕ_n has its own propagator, $\Pi_{\mu\nu}$!

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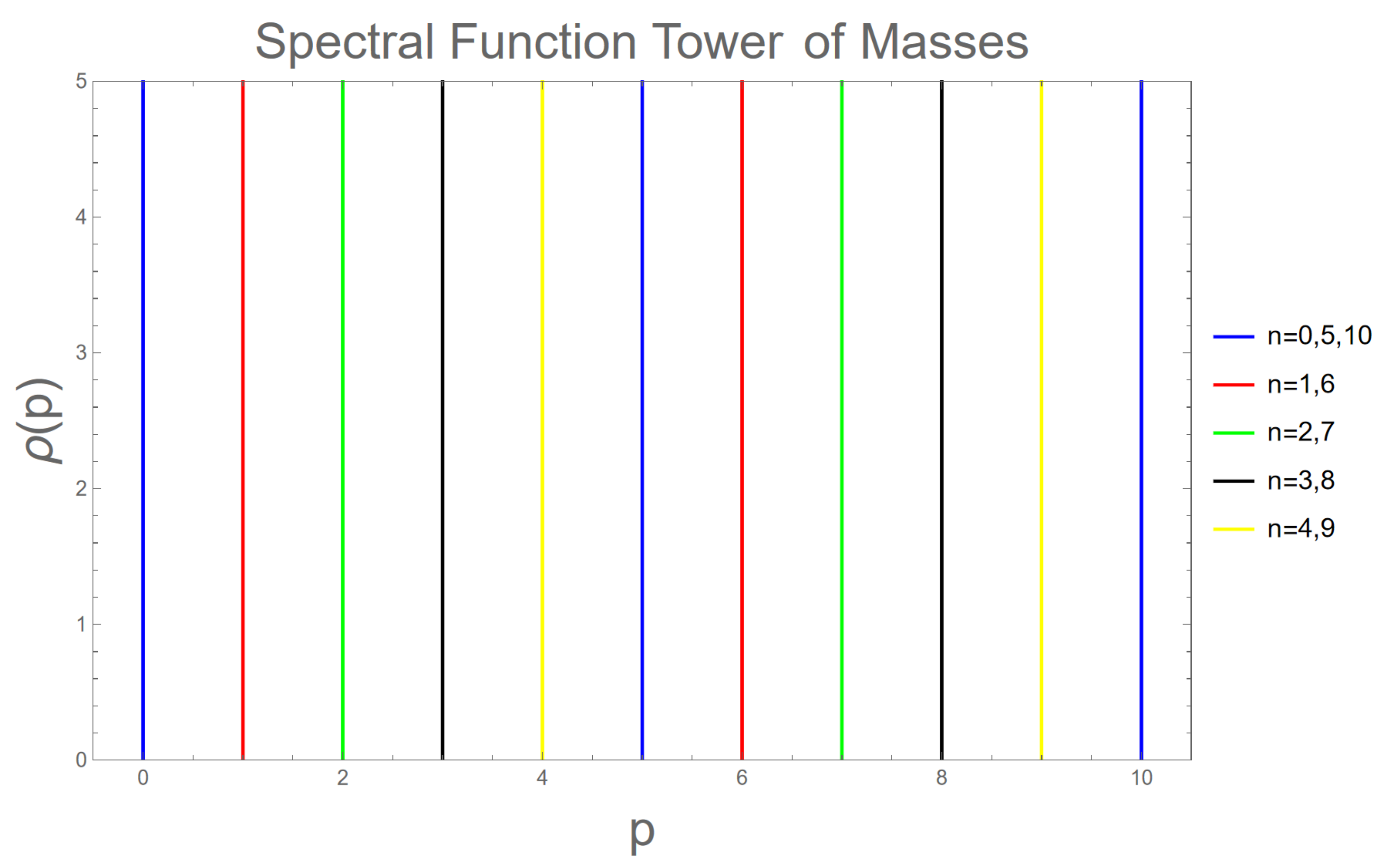
Tower Spectrum



$$\rho = -\frac{1}{\pi}\mathrm{Im}(\Pi)$$

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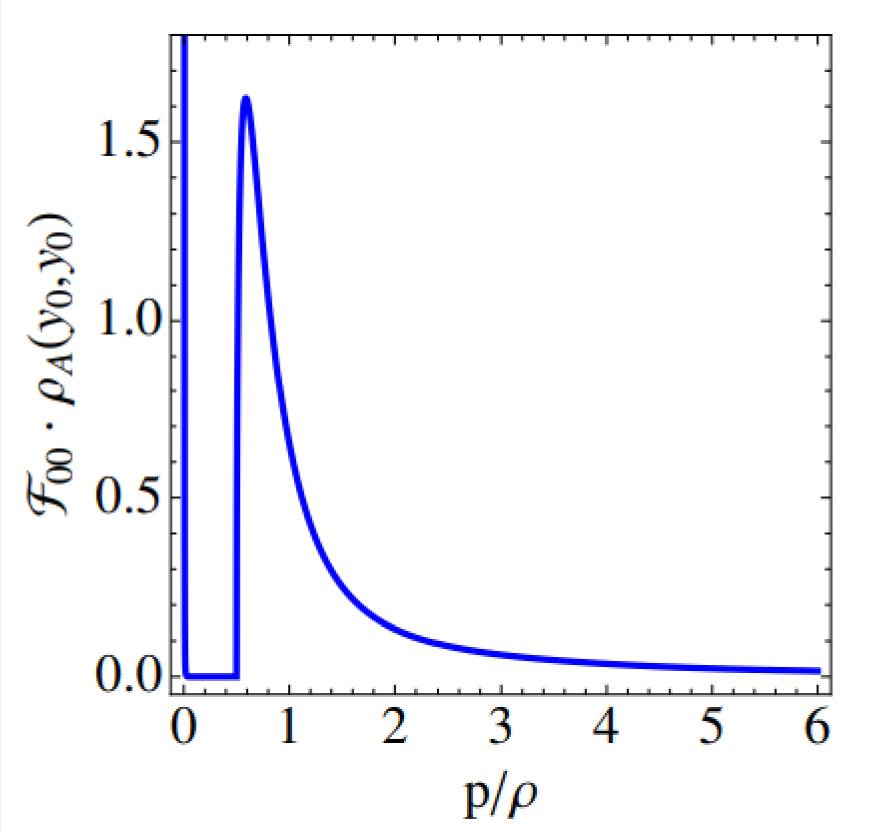
Gapped Continuum Spectrum



$$\mathcal{L} = \int_0^{y_s} dy\, [-\frac{1}{4}\,\mathrm{tr}\;\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu}$$

$$-\frac{1}{2}e^{-2\sigma}\,\mathrm{tr}\;A'_\mu A^{\mu\prime}]$$

$$\Pi^{\mu\nu}_{A5}(p) \sim \frac{J_+\left(\frac{p}{\rho}\right)}{\Phi(p)}$$

Megías, E., Quirós, M. Analytical Green's functions for continuum spectra. *J. High Energ. Phys.* **2021**, 157 (2021). https://doi.org/10.1007/JHEP09(2021)157

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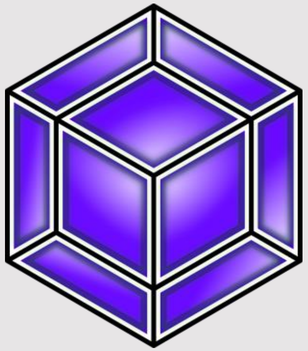
Branes



UV Brane at
$y = y_0$

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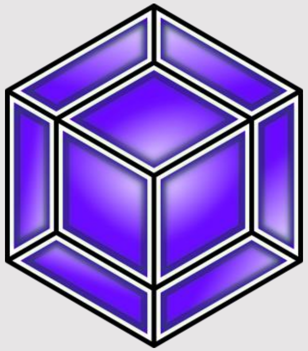
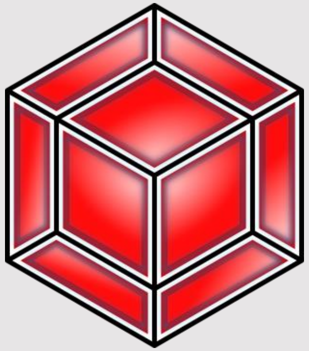


UV Brane at
$y = y_0$



IR Brane at
$y = y_1$

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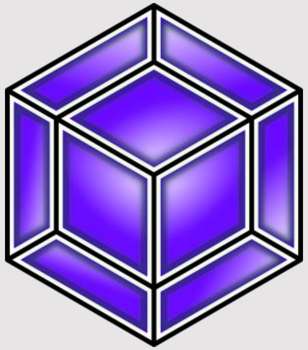
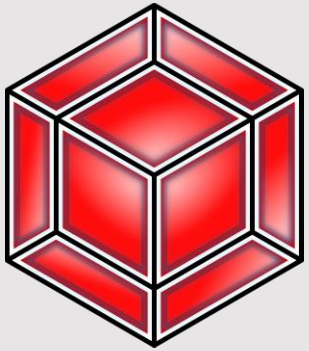


UV Brane at
$y = y_0$



IR Brane at
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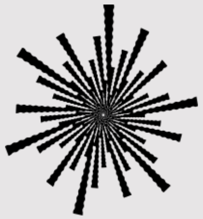

Singularity
at $y = y_s$

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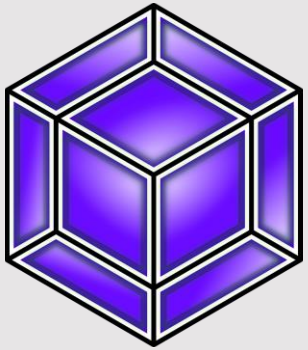
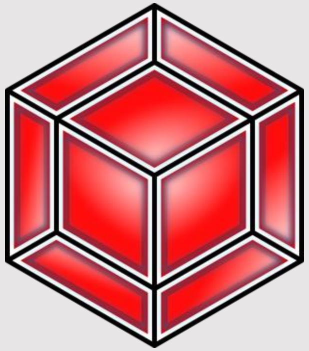
TeV Scale



UV Brane at
$y = y_0$



IR Brane at
$y = y_1$

Singularity
at $y = y_s$

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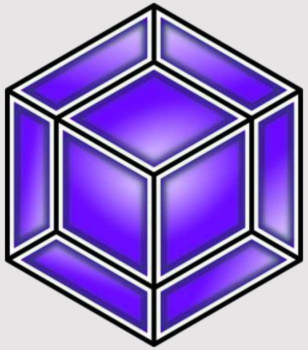
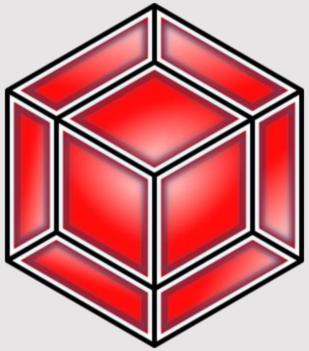
Planck Scale



UV Brane at
$y = y_0$



IR Brane at
$y = y_1$

Singularity
at $y = y_s$

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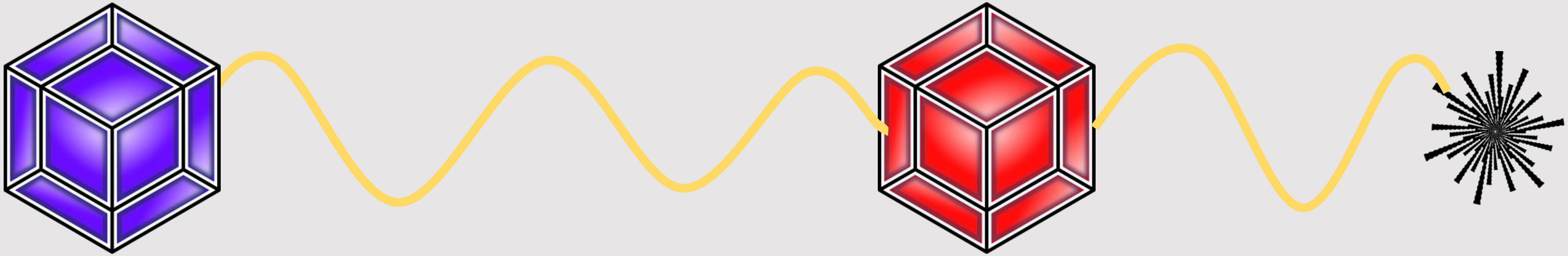

UV Brane at
$y = y_0$

IR Brane at
$y = y_1$

Singularity
at $y = y_s$

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The Model

- $ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

- $\mathcal{L} = \int_0^{y_s} dy\, [-\frac{1}{4}\,\mathrm{tr}\,\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} - \frac{1}{2}e^{-2\sigma}\,\mathrm{tr}\,A'_\mu A^{\mu\prime}]$ (massless)

- $\mathcal{L} = \int_0^{y_s} dy\, [-\frac{1}{4}\,\mathrm{tr}\,\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} - \frac{1}{2}e^{-2\sigma}\,\mathrm{tr}\,A'_\mu A^{\mu\prime}$
  $-(\frac{1}{2}M_Z^2 Z_\mu^2 + M_W^2|W_\mu|^2)\,\delta(y - y_1)]$ (massive)

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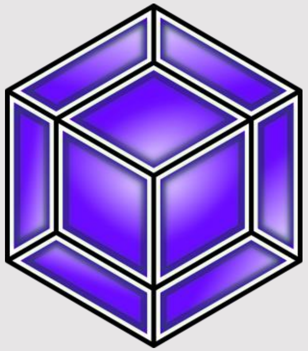
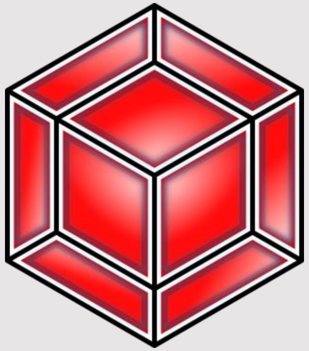
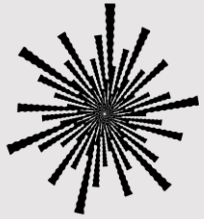
EWSB



UV Brane at
$y = y_0$



IR Brane at
$y = y_1$



Singularity
at $y = y_s$

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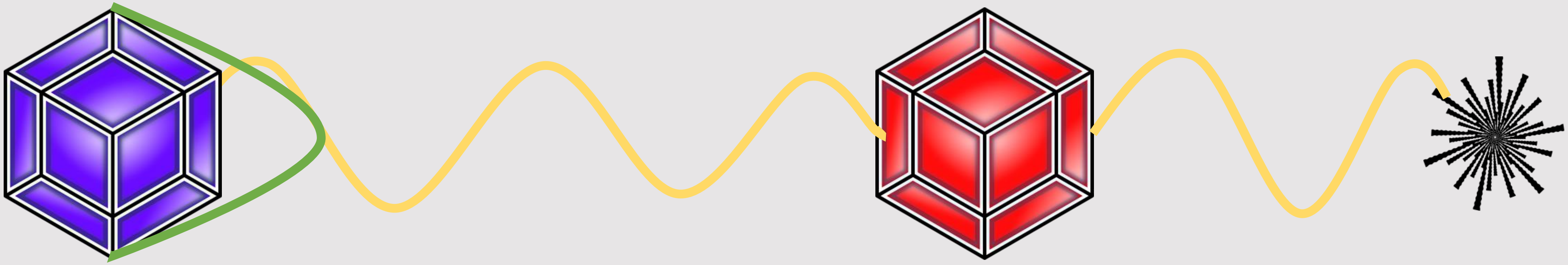
Propagator

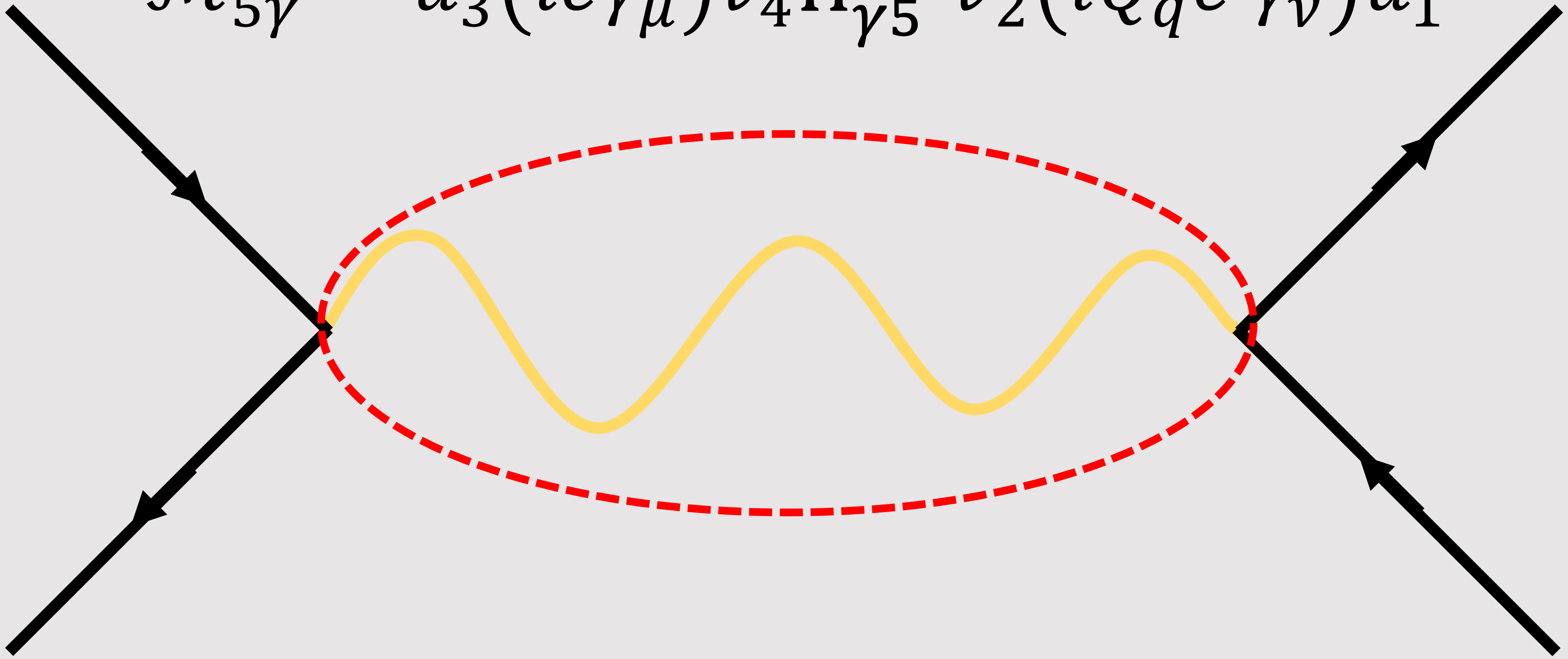
$$\Pi^{\mu\nu}_{A5} = -\frac{2ky_s}{\pi}\frac{J_+\left(\frac{p}{\rho}\right)}{\Phi(p)}\Pi^{\mu\nu}_{A}$$



$$\Pi^{\mu\nu}_{A,M5} = -\frac{2ky_s}{\pi}\frac{J_{M+}\left(\frac{p}{\rho}\right)}{\Phi_{\mathrm{M}}(p)}\frac{p^2 - m_A^2}{p^2}\Pi^{\mu\nu}_{A,M}$$

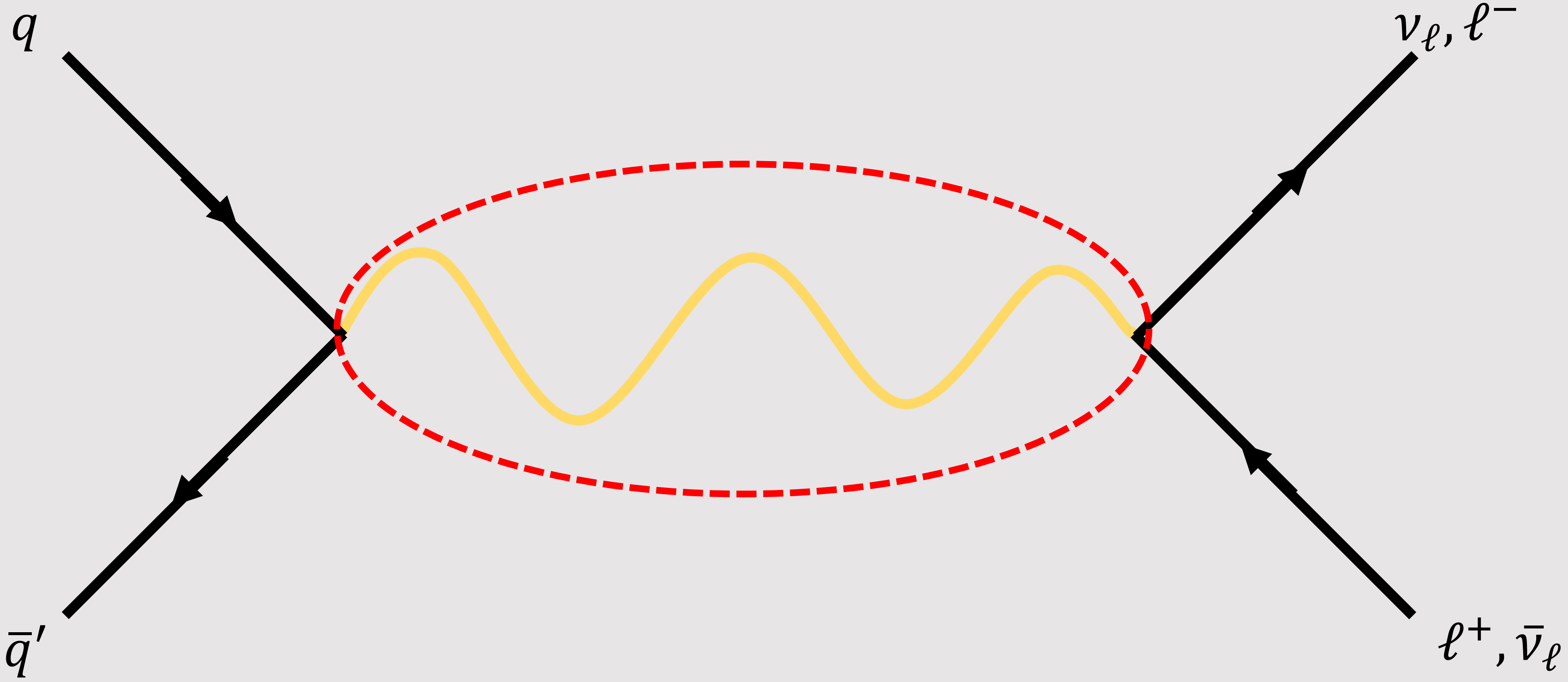
Drell-Yan

$$\mathcal{M}_{5\gamma} = \bar{u}_3\left(ie\gamma_\mu\right)v_4\Pi^{\mu\nu}_{\gamma 5}\ \bar{v}_2\left(iQ_q e\ \gamma_\nu\right)u_1$$



$$\mathcal{M}_{5Z} = \bar{u}_3\left(ig_\ell\gamma_\mu\right)v_4\Pi^{\mu\nu}_{Z,M5}\ \bar{v}_2\left(ig_q\ \gamma_\nu\right)u_1$$

Drell-Yan



$$\mathcal{M}_{5W} = \bar{u}_3\left(ig_\ell \gamma_\mu P_L\right) v_4 \Pi^{\mu\nu}_{W,M5}\, \bar{v}_2\left(ig_{qw} V_{qq'}\, \gamma_\nu P_L\right) u_1$$

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Collider Phenomenology

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Simulation

- Using MadGraph, simulated events at $\sqrt{s} = 13\text{ TeV}$
- The square amplitude was then calculated using analytical expressions by extracting the parton level momenta from the process
- For our 5D model, ρ was varied and the amplitude calculated at $\rho \in [1, 5]$ TeV in steps of 0.1 TeV.
- No UFO model for this theory, so reweighting had to be done external to MadGraph

$$w_{5D} = \frac{|\mathcal{M}_{5D}|^2}{|\mathcal{M}_{SM}|^2} w_{SM}$$

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Simulation

- These events were then run through Pythia8 and Delphes
- Events were filtered to exactly match final state
- Invariants calculated using Delphes level four-vectors
- Luminosity of MadGraph ≠ Luminosity of LHC, required scaling
- Used same binning scheme as found in HighPT, and scaled bin by bin to match predicted events, so our simulation can be compared with real data

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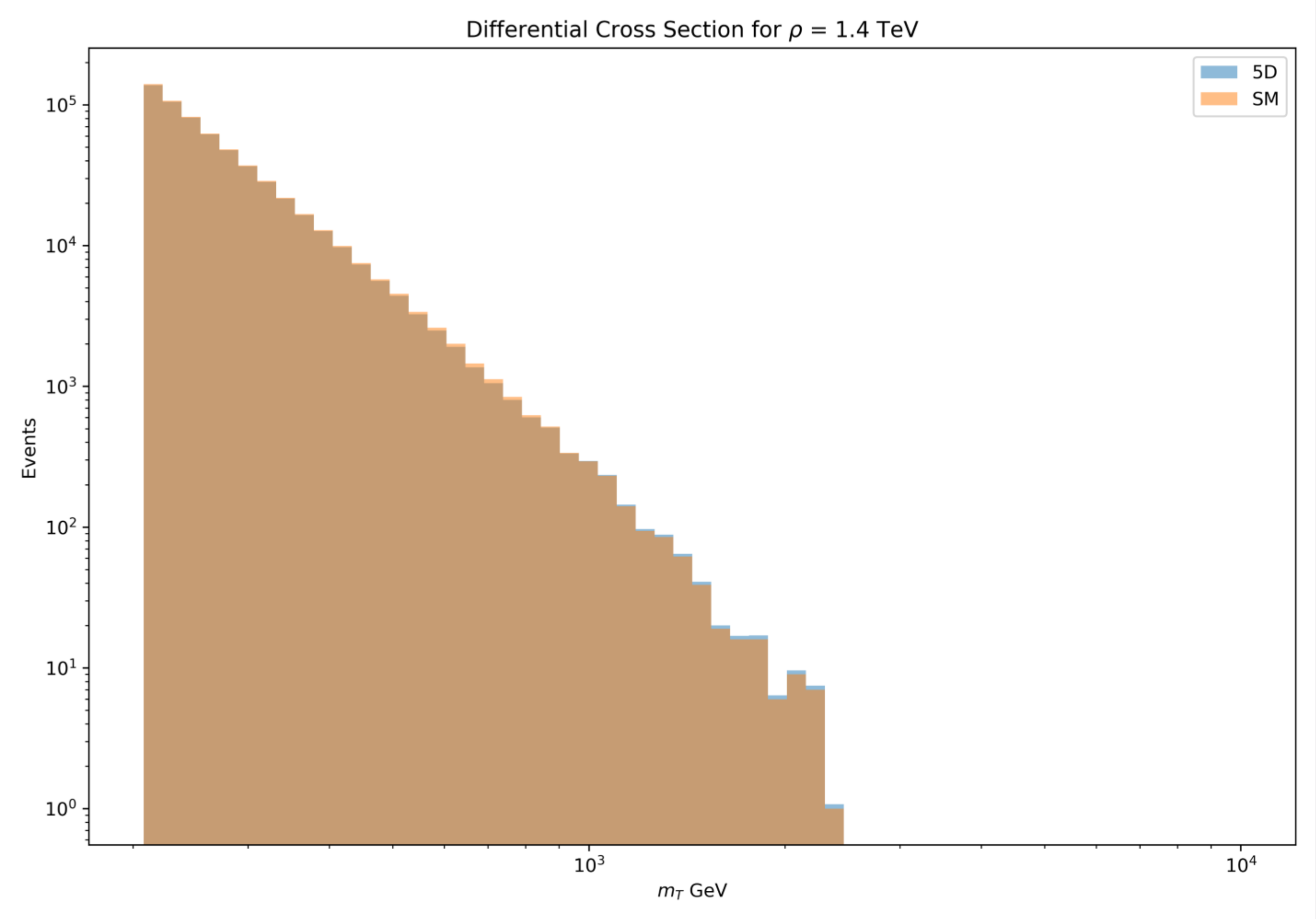
L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, and F. Wilsch, *HighPT: A Tool for high-�� Drell-Yan Tails Beyond the Standard Model*, [arXiv:2207.10756]

L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, and F. Wilsch, *Drell-Yan Tails Beyond the Standard Model*, [arXiv:2207.10714].

Preliminary Results

Preliminary



Weighted histogram for $e^+\nu_e$ final state transverse mass

$$w' = \frac{|\mathcal{M}'|^2}{|\mathcal{M}|^2} w$$

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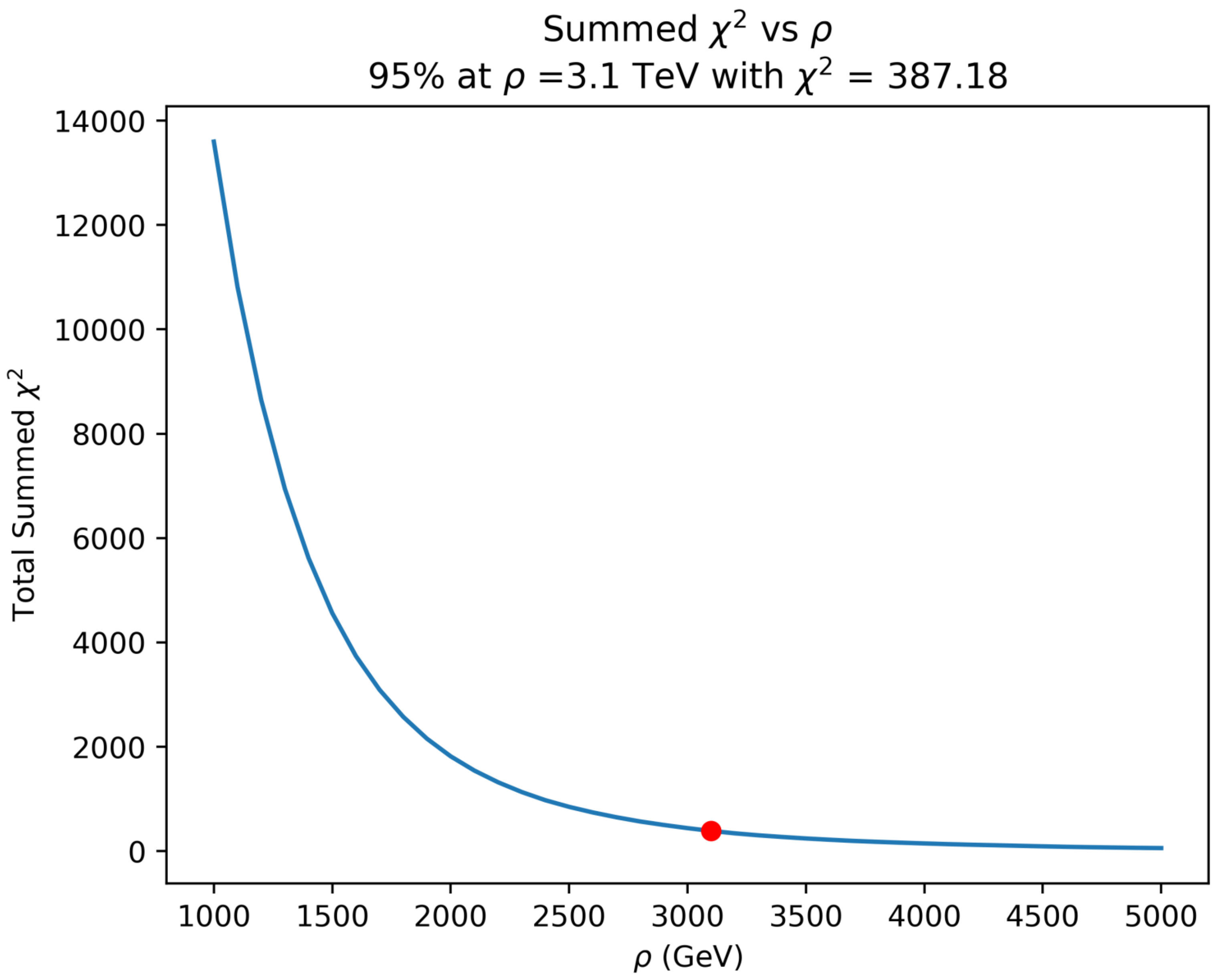


Channels:

$pp \to e^+e^-$

$pp \to e^+\nu_e$

$pp \to e^-\bar{\nu}_e$

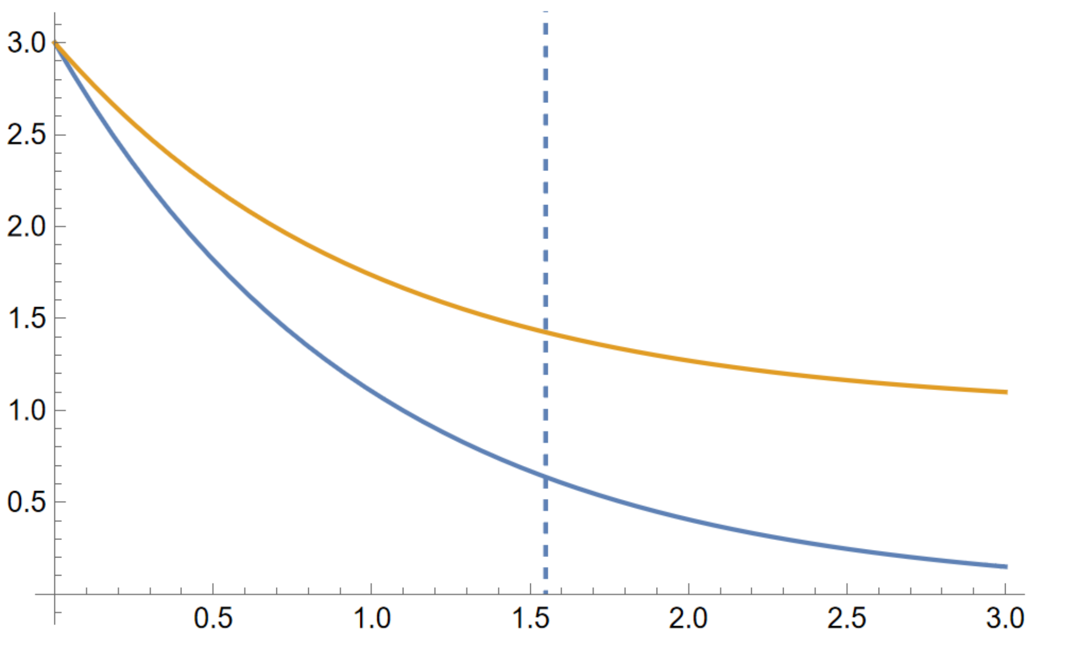
$pp \to \mu^+\mu^-$

$pp \to \mu^+\nu_\mu$

$pp \to \mu^-\bar{\nu}_\mu$

Conclusion

- Theory depends on single parameter ρ that we have bound from below



Rough sketch of smoothed distribution

- Rather than sharp peaks, the gapped continuum spectrum would result in a smoothed distribution

- $\rho \lesssim 3$ TeV is accessible by LHC Drell-Yan studies

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Thank you!

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Backup Slides

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Definitions

- $\Phi(p) = Y_0\left(\frac{p}{k}\right) \cdot J_+\left(\frac{p}{\rho}\right) - J_0\left(\frac{p}{k}\right) \cdot Y_+\left(\frac{p}{\rho}\right)$

- $\Phi_\mathrm{M}(p) = Y_0\left(\frac{p}{k}\right) \cdot J_{M+}\left(\frac{p}{\rho}\right) - J_0\left(\frac{p}{k}\right) \cdot Y_{M+}\left(\frac{p}{\rho}\right)$

- $J_\pm\left(\frac{p}{\rho}\right) = 2\frac{p}{\rho} J_0\left(\frac{p}{\rho}\right) + \Delta_A^\pm J_1\left(\frac{p}{\rho}\right)$

- $J_{M\pm}\left(\frac{p}{\rho}\right) = 2\frac{p}{\rho} J_0\left(\frac{p}{\rho}\right) + \Xi_A^\pm J_1\left(\frac{p}{\rho}\right)$

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Definitions

- $\mathrm{Y}_{\pm}\left(\frac{p}{\rho}\right) = 2\frac{p}{\rho}\ Y_0\left(\frac{p}{\rho}\right) + \Delta_A^{\pm} Y_1\left(\frac{p}{\rho}\right)$
- $\mathrm{Y}_{M\pm}\left(\frac{p}{\rho}\right) = 2\frac{p}{\rho}\ Y_0\left(\frac{p}{\rho}\right) + \Xi_A^{\pm} Y_1\left(\frac{p}{\rho}\right)$
- $\Delta_A^{\pm} = \pm\delta_A - 1$
- $\Xi_A^{\pm} = \Delta_A^{\pm} + 2ky_s \cdot \left(\frac{m_A}{\rho}\right)^2$
- $ky_s = ky_1 + 1$

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