* PIKIO 6 *

Relic Density of Scalar Dark Matter via an RS Graviton Portal

Dennis Foren
Michigan State University
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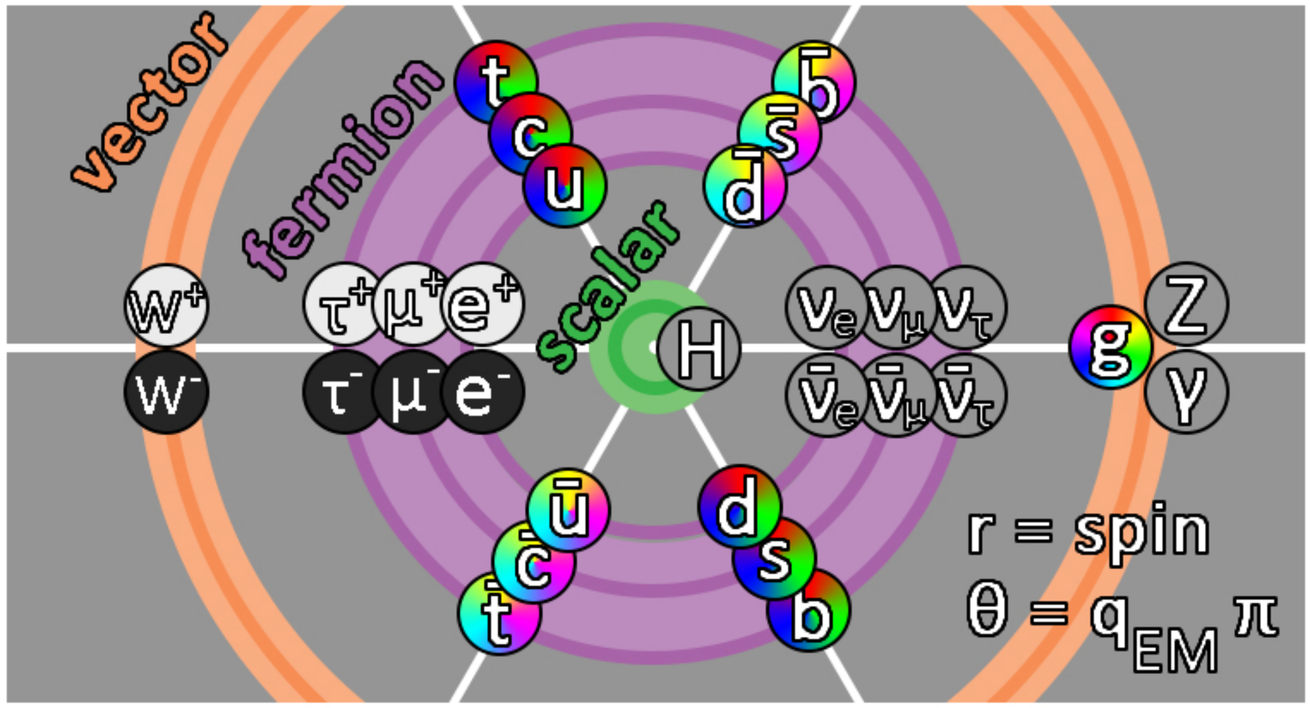
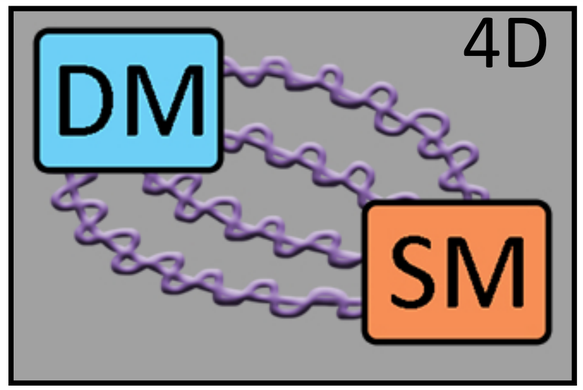
Presenting Work Performed With:

R. S. Chivukula **K. Mohan**
D. Sengupta **E. H. Simmons**

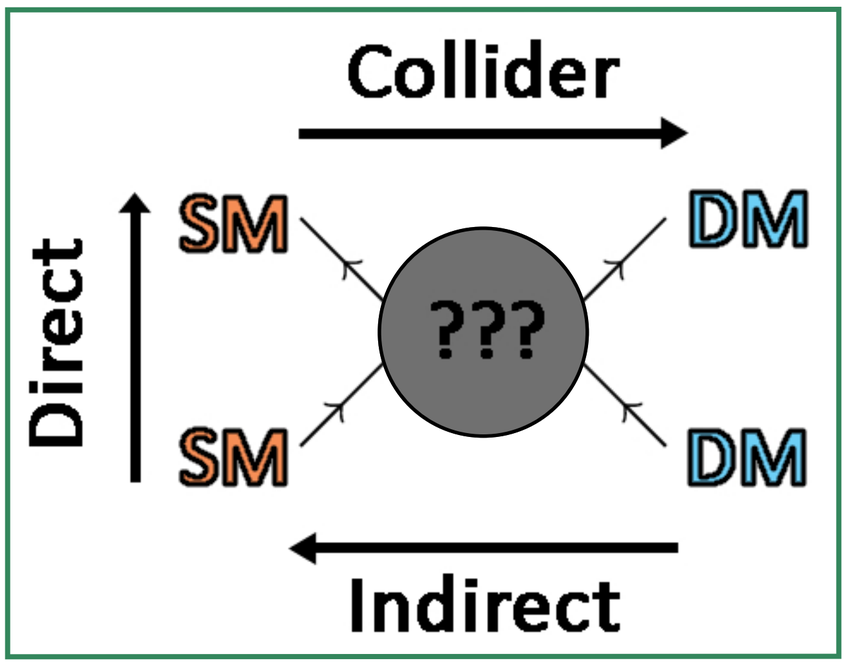
The Standard Model





SM doesn't explain...

- Gravity
- Dark Matter



Collider

- Missing Energy
- Resonances

Underground

- Recoils from DM in dense fluids (Direct)

Cosmological

- Photons from High DM Regions (Indirect)
- **Relic Density**

Usual 4D Massless Gravity

4D Graviton: massless spin-2 field $h_{4D}(x)$, from perturbing 4D GR

$$g^{\mu\nu}_{4D}(x) = \eta^{\mu\nu} + \kappa_{4D} h^{\mu\nu}_{4D}(x) \qquad \overline{\eta} = \mathrm{Diag}(+1, -1, -1, -1)$$

weak field expansion →

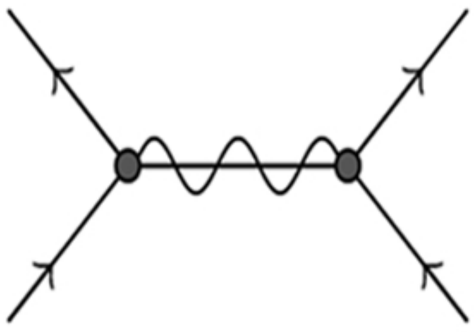
$$\mathcal{L}^{4D}_{grav} = \frac{2}{\kappa^2_{4D}} \sqrt{-\det \overline{g}_{4D}}\, (R_{4D} - 2\Lambda_{4D})$$

$$\mathcal{L}^{4D}_{matter} = \sqrt{-\det \overline{g}_{4D}}\, (\mathcal{L}_{SM} + \mathcal{L}_{DM})$$

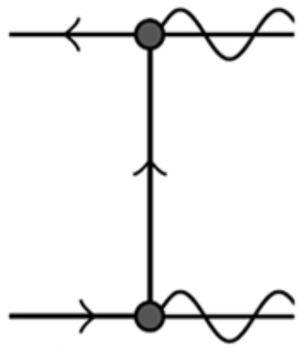
CC, negligible

Scalar Curvature

DM to SM

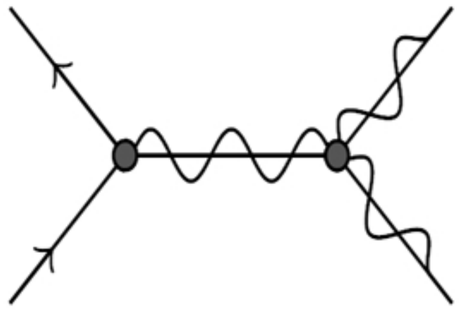


s-channel

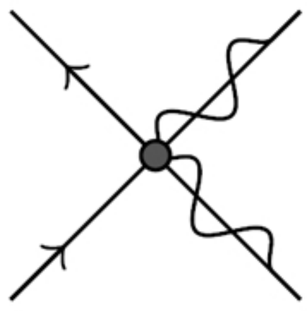


(t+u)-channel

DM to Gravitons



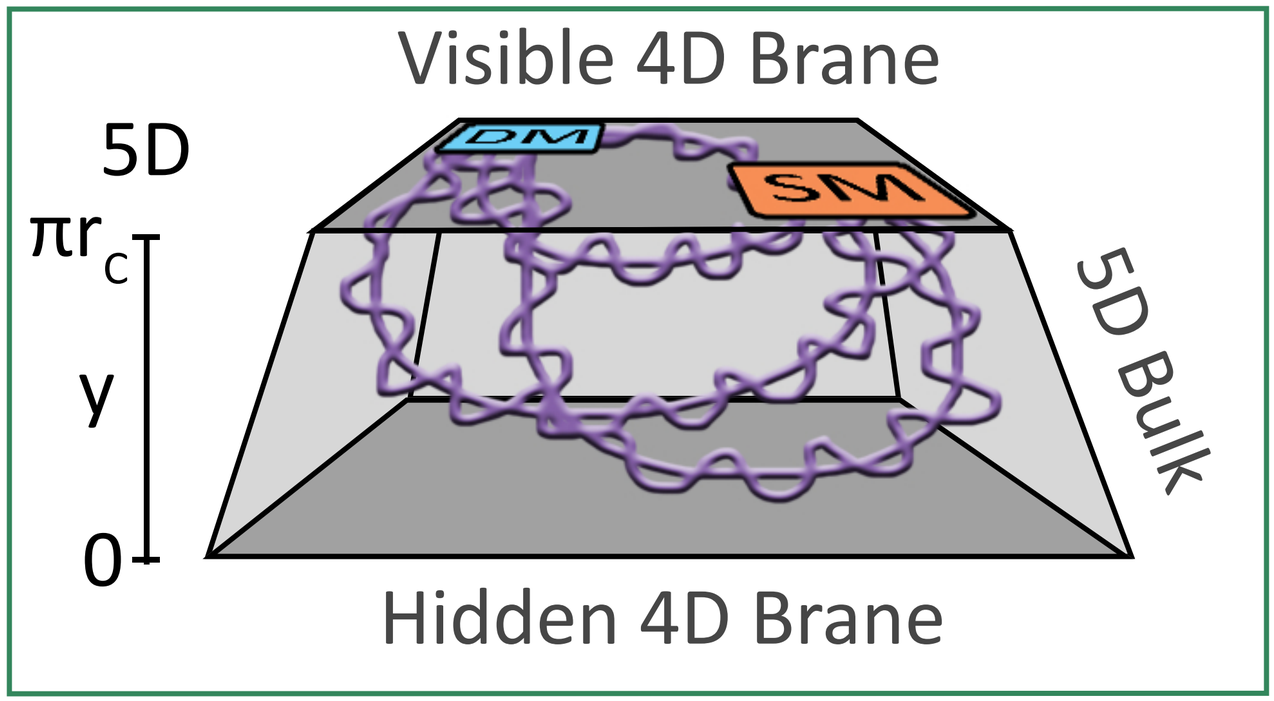
s-channel



seagull

CAUTION: Effective coupling = $[E]^{-1}$ → *Unitarity Compromised*

Randall-Sundrum (RS) Model



Two Parameters

- r_C = compact. radius
- k = RS curvature

We swap for...

- $\Lambda_\pi = \overline{M}_{Pl} \exp(-kr_C\pi)$
- $m_{KK1} = k\, x_1 \exp(-kr_C\pi)$

$$\overline{G}_{5D}(x,y) = e^{-2k|y|} \begin{pmatrix} \overline{\eta} + \kappa\, \overline{h}(x,y) & \vec{0} \\ \vec{0}^{\,T} & 1 \end{pmatrix}$$

$$\mathcal{L}^{5D}_{grav} = \frac{2}{\kappa^2} \sqrt{-\det \overline{G}}\; R_{5D}$$

$$\mathcal{L}^{5D}_{matter} = \sqrt{-\det \overline{g}_{4D}}\; e^{-4\pi k r_c} (\mathcal{L}_{SM} + \mathcal{L}_{DM})\; \delta(y - \pi r_c)$$

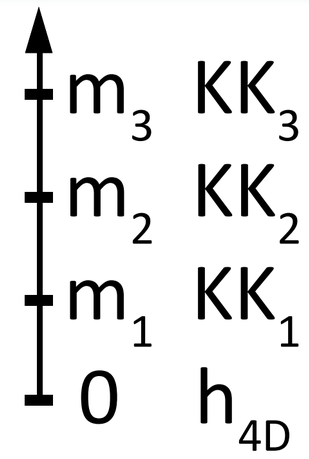
Graviton is now a field over 5D!

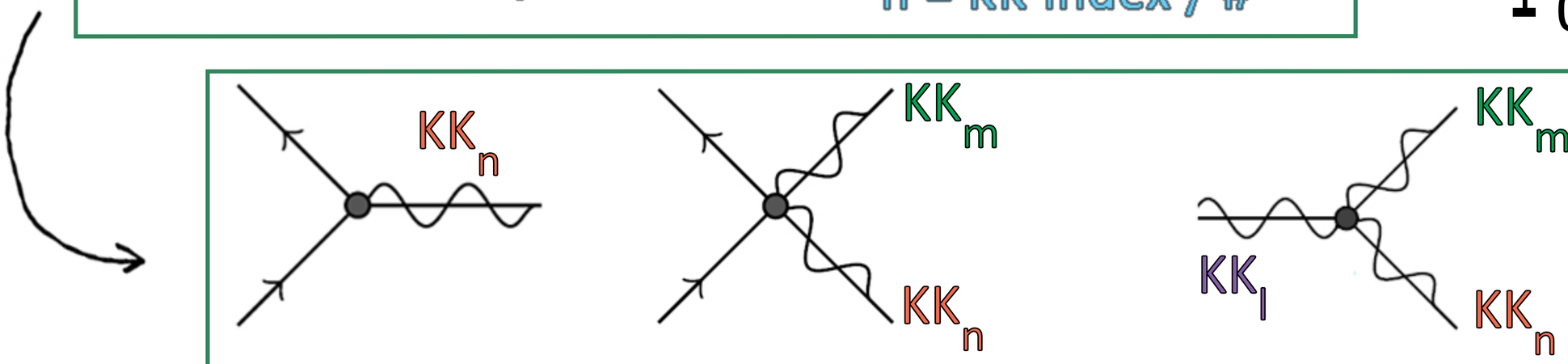
KK Decomposition Like a particle in a square well...

$$h_{\mu\nu}(x,y) = \sqrt{k}\, h^{(0)}_{\mu\nu}(x) + \frac{1}{\sqrt{r_c}} \sum_{n=1}^{+\infty} h^{(n)}_{\mu\nu}(x)\, \chi^{(n)}(\phi)$$

massless, usual graviton
"flat" in y

massive KK tower
n = KK index / #





^ like massless 4D gravity ^

^ much different ^

Triple Graviton Lagrangian:

$$\mathcal{L}^{5D}_{grav} \supset \frac{2}{\Lambda_\pi}(kr_c) \sum_{l,m,n=0}^{+\infty} \left[\overline{\alpha}^{(l,m,n)} \frac{\mathcal{L}^{(l,m,n)}_{4D,grav}}{\kappa} + m_m m_n \overline{\beta}^{(l,m,n)} \frac{Q^{(l,m,n)}}{\kappa} \right]$$

two p^μ zero p^μ

where $m_n = \frac{x_n}{x_1} m_1$ and $\Lambda_\pi = \overline{M}_{\mathrm{Pl}} e^{-kr_c\pi}$

Dark Matter

$$(\Omega h^2)_{exp} = \left[\frac{\rho_{\mathrm{DM}}}{\rho_{critical}}\right] h^2$$

$$= 0.11425 \pm 0.00311^{*}$$

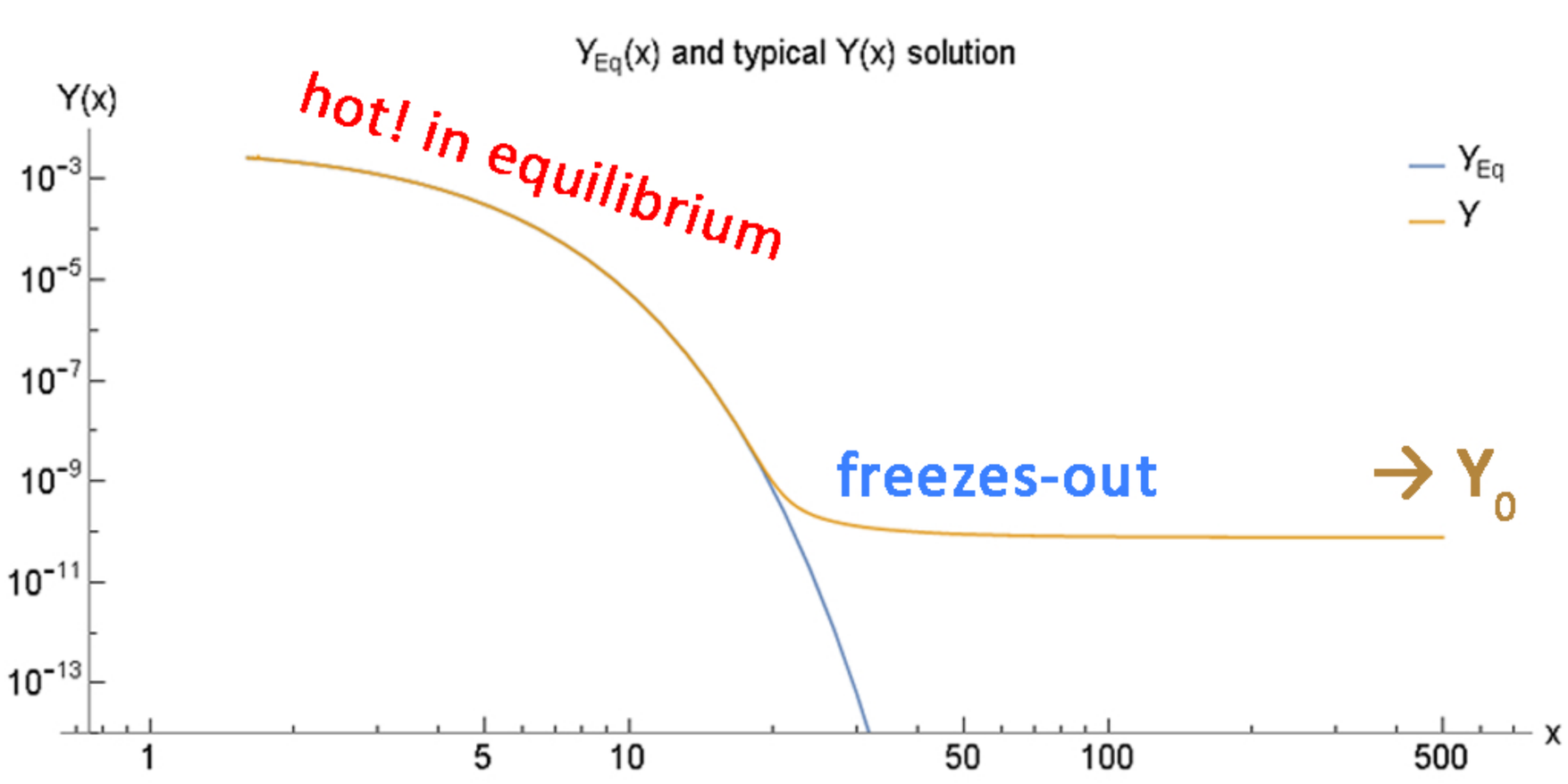
Assume Scalar & WIMP-like:

- O(TeV) mass
- Effectively weak-scale coupling to SM
- "Miracle" ≈ correct relic

Freeze-Out:

$$\Omega h^2 \propto Y_0$$

$$x = \frac{m_{DM}}{T}$$



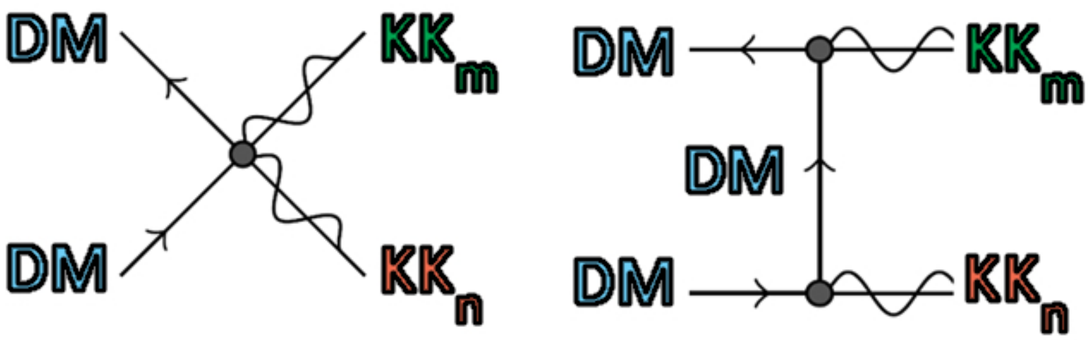
* P. A. R. Ade, et al., Planck 2015 results. XIII. Cosmological parameters, Astron. Astrophys. 594 (2016) A13.

Large XS → Small Relic Density

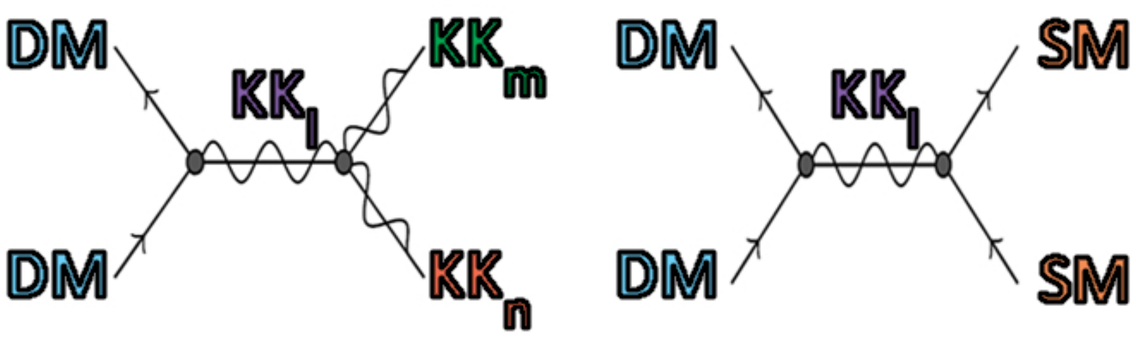
Thermally-Averaged XS

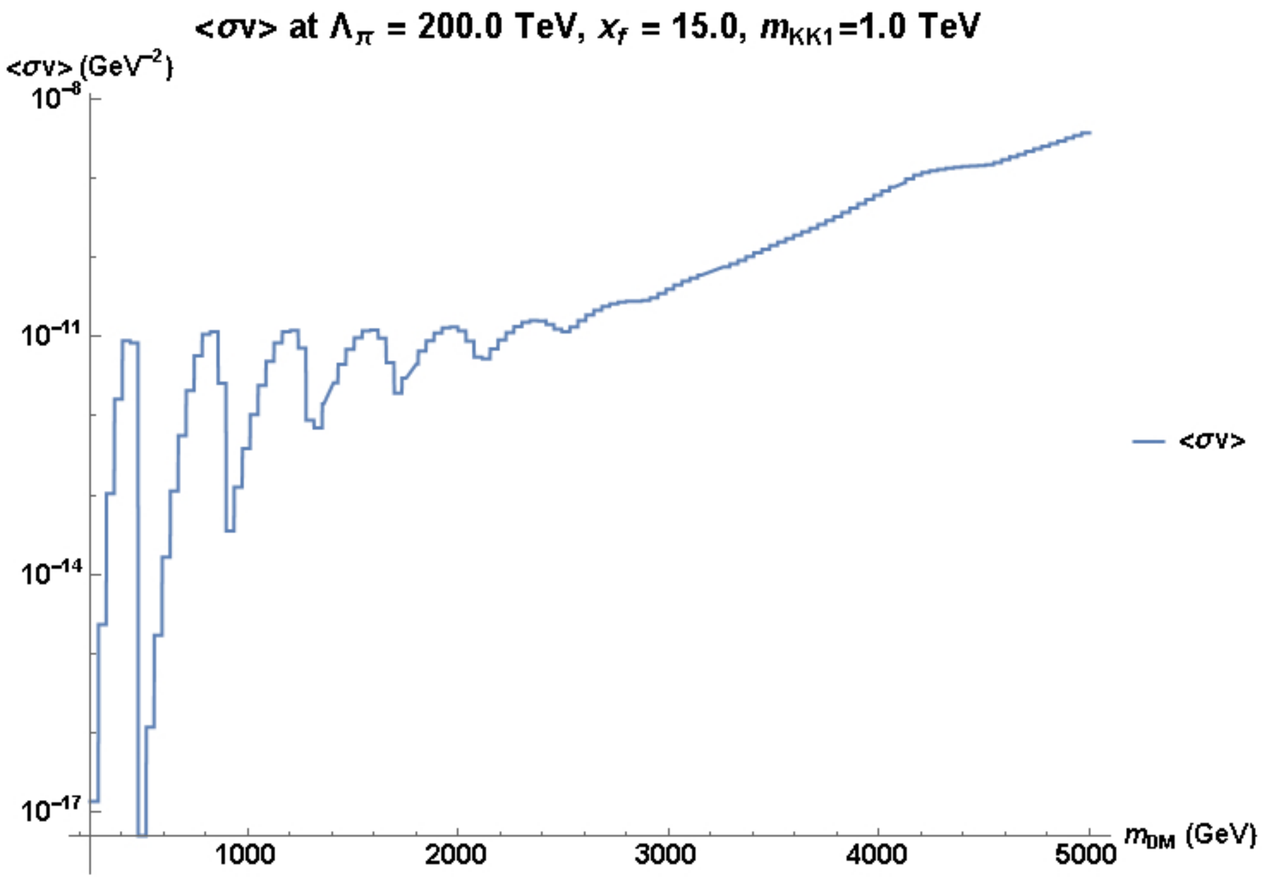
$$\frac{1}{\Omega h^2} = \left(\frac{(100\ \mathrm{GeV})/m_{DM}}{2.74\times 10^{10}}\right)\cdot\left[\frac{s_{tot}(T_f)}{n_{\chi,\mathrm{Eq}}(T_f)} + \frac{s_{tot}(m_{DM})}{H(m_{DM})}\cdot\left.\frac{\langle\sigma_{ann}v\rangle}{x}\right|_{x=x_f}\right]$$

No s-Channel Resonance

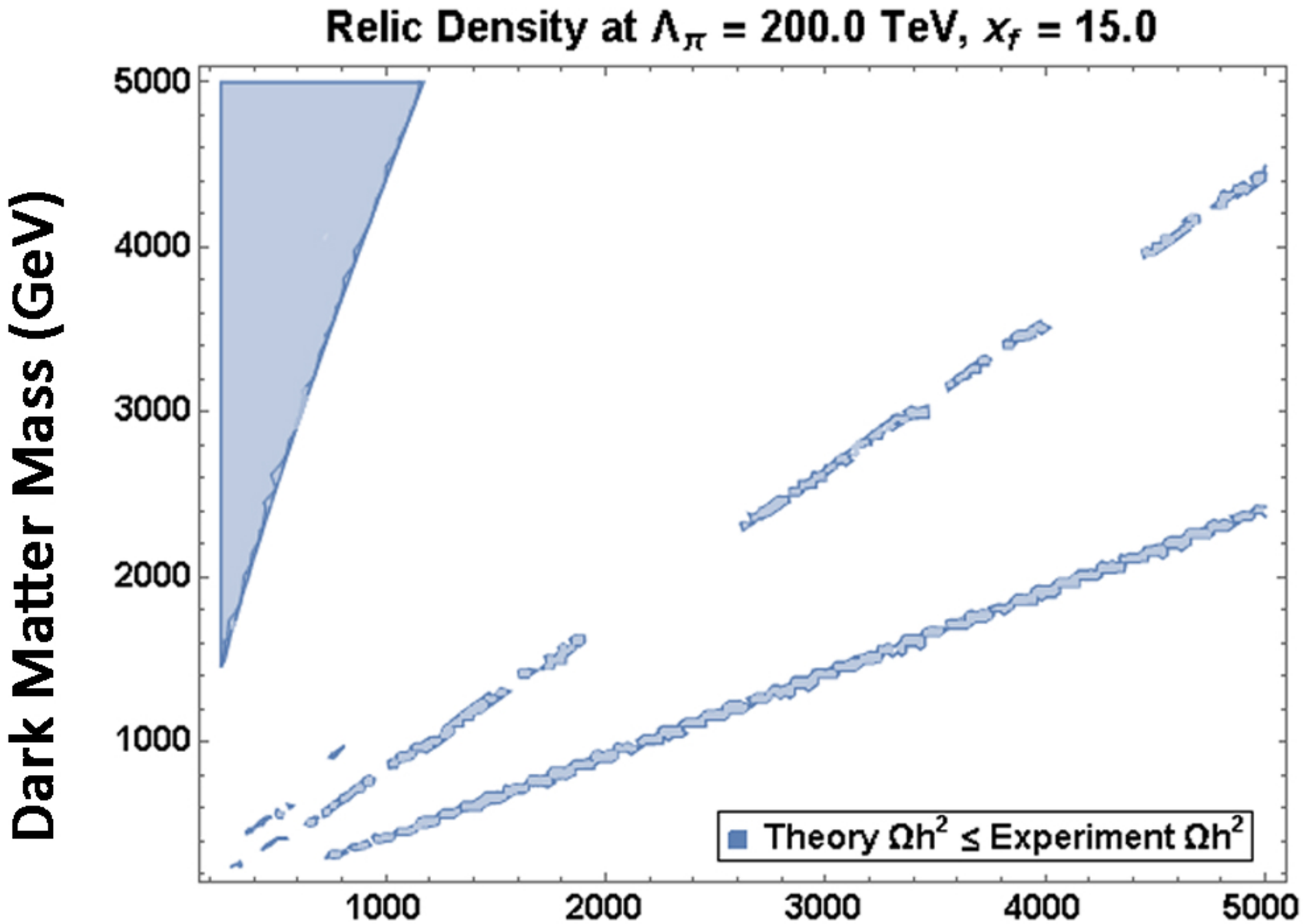


s-Channel Resonance





Relic Density Plot (Quick, Preliminary!)

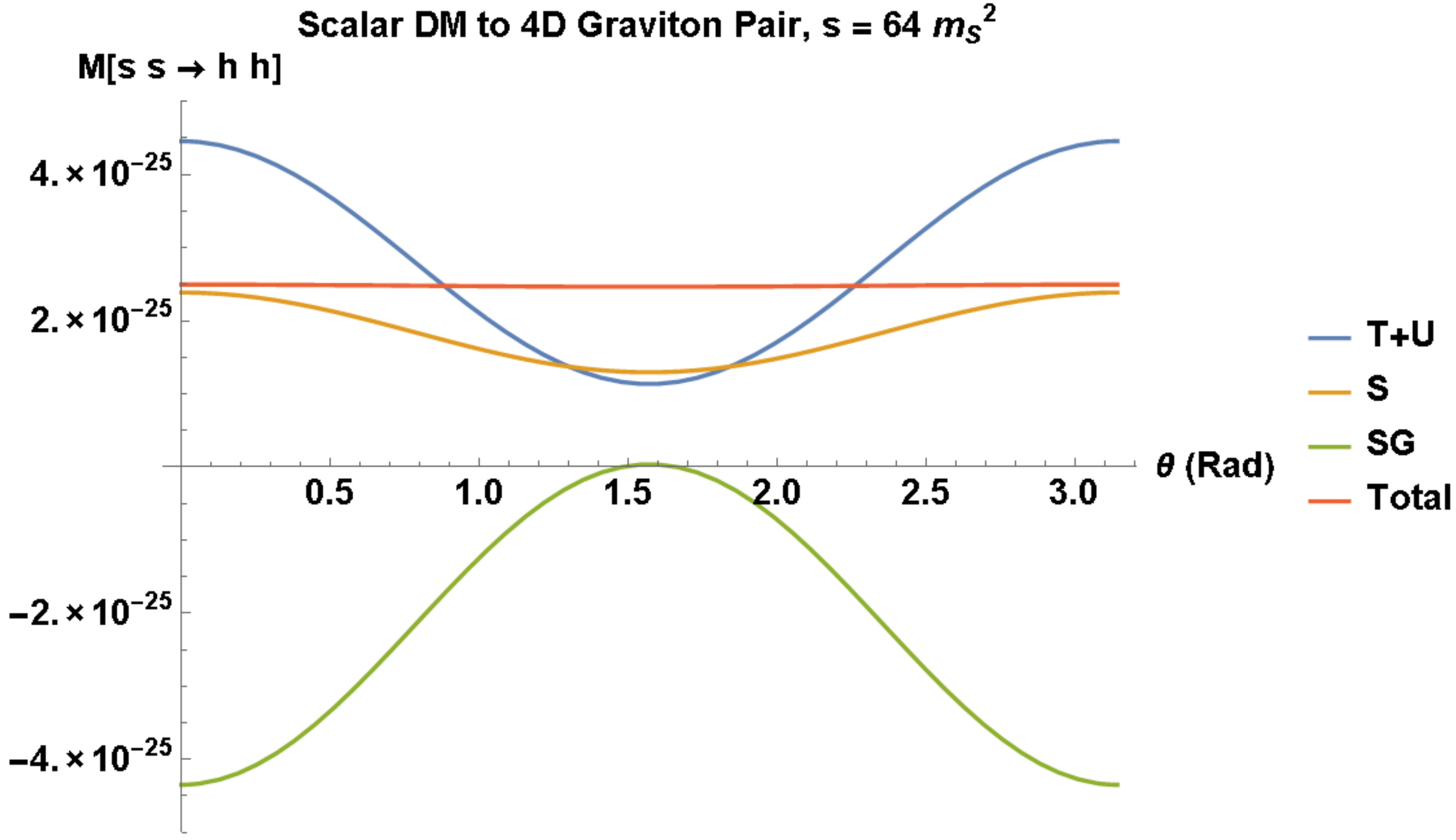


Running finer scans now & summarizing results!
(+ unitarity analysis, experimental constraints!)

Thank you!

Bonus Slides

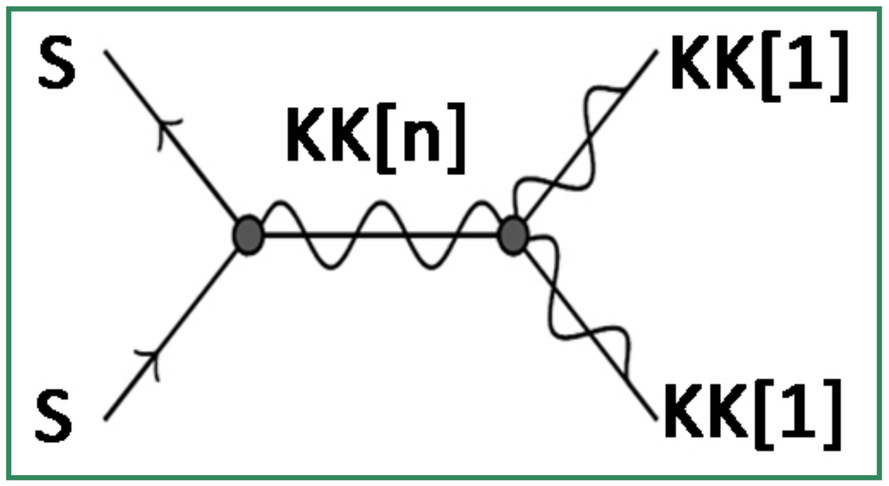
SS2: Matrix Element & Unitarity helicity combo: (0,0) to (0,0)



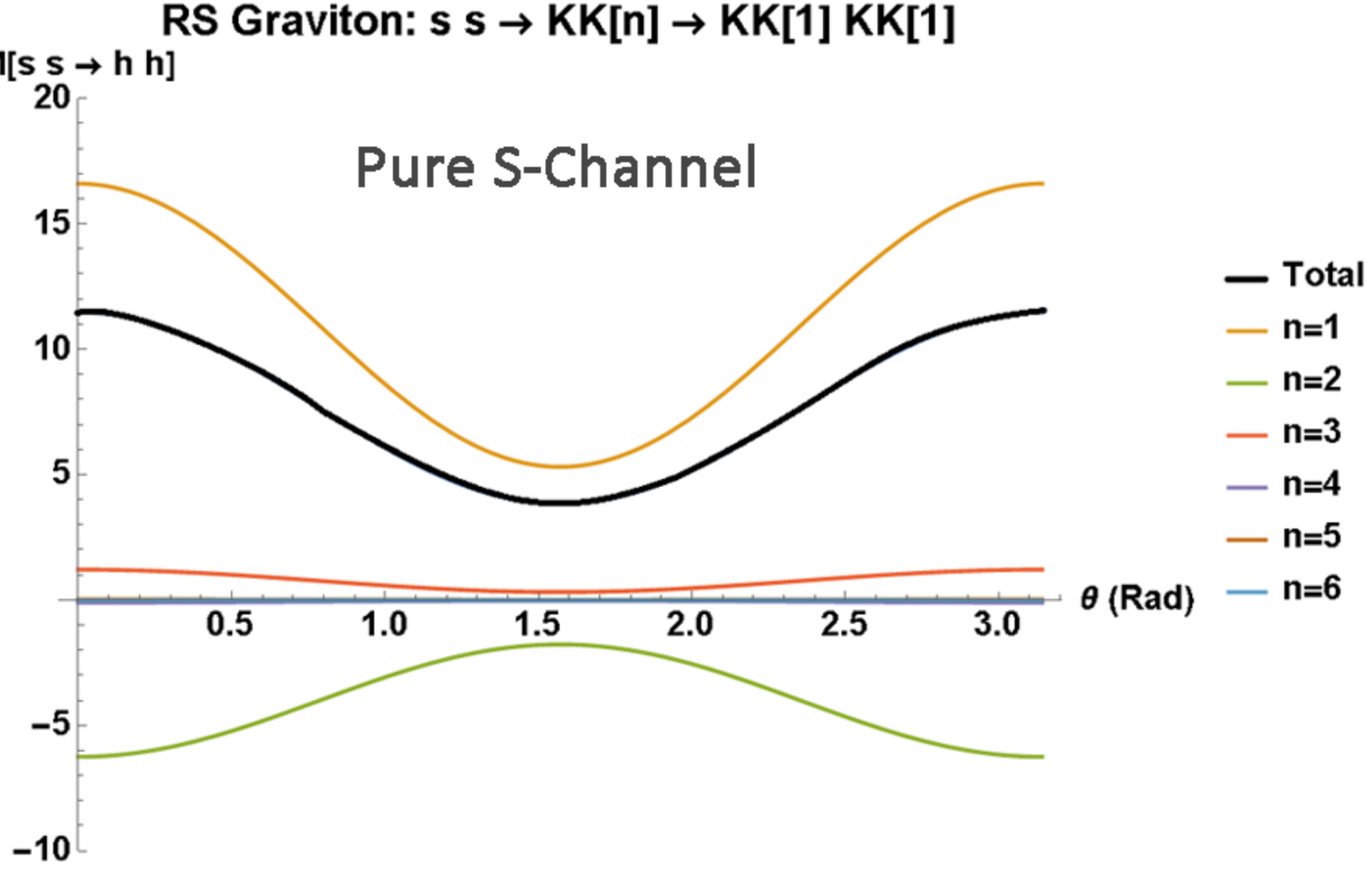
- seagull & (t+u) mostly cancel in simplifed model
- total matrix element is flat in θ

RS: Matrix Element & Unitarity

helicity combo: (0,0) to (0,0)

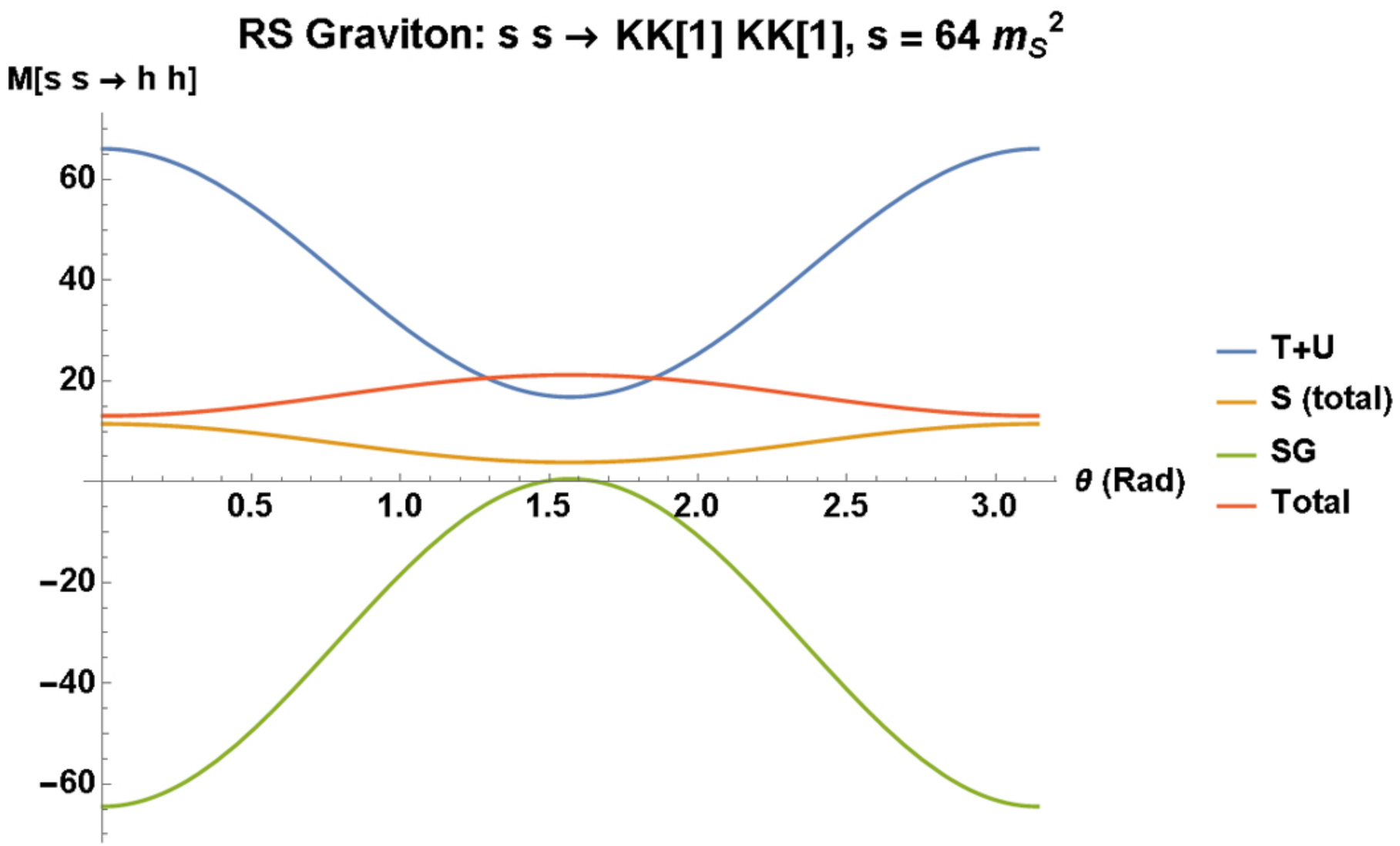


- **CON:** lots of new s-channel diagrams
- **PRO:** lots of cancellations!



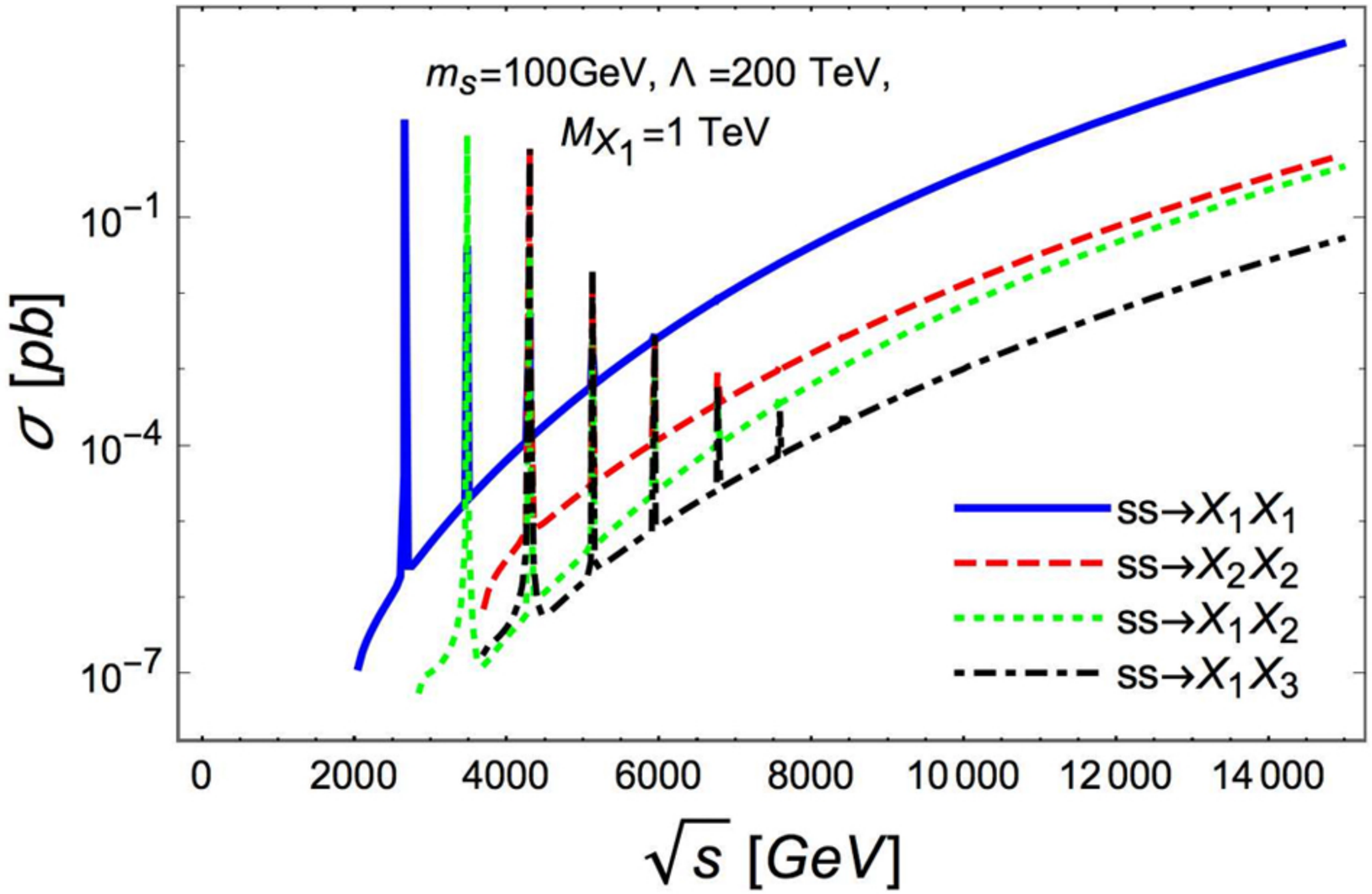
RS: Matrix Element & Unitarity

helicity combo: (0,0) to (0,0)



- unlike 4D graviton, total is not flat
- cancellation still largely occurs!

RS: Thermally-Averaged Cross-Section?



Many resonances = must be careful when integrating!

$$\langle \sigma v_{rel} \rangle (x) \equiv \frac{4x}{K_2(x)^2} \int_1^{+\infty} d\bar{s} \quad \sqrt{\bar{s}} \cdot (\bar{s} - 1) \cdot K_1(2x\sqrt{\bar{s}}) \cdot \sigma_{ann}$$