Jet Substructure from Dark Sector Showers

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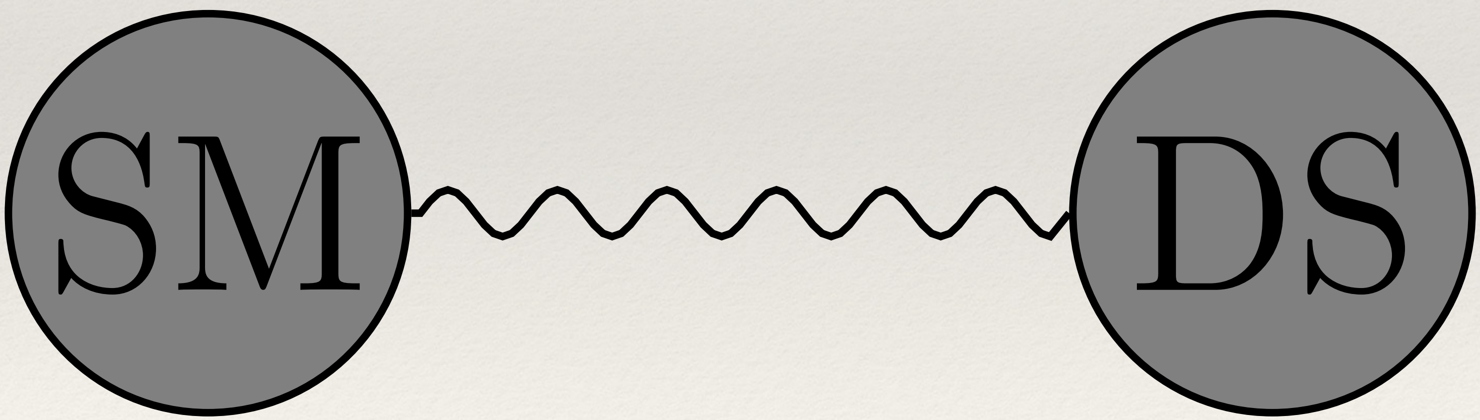
In Collaboration with Tim Cohen and Marat Freytsis

[arXiv: 2004.00631]

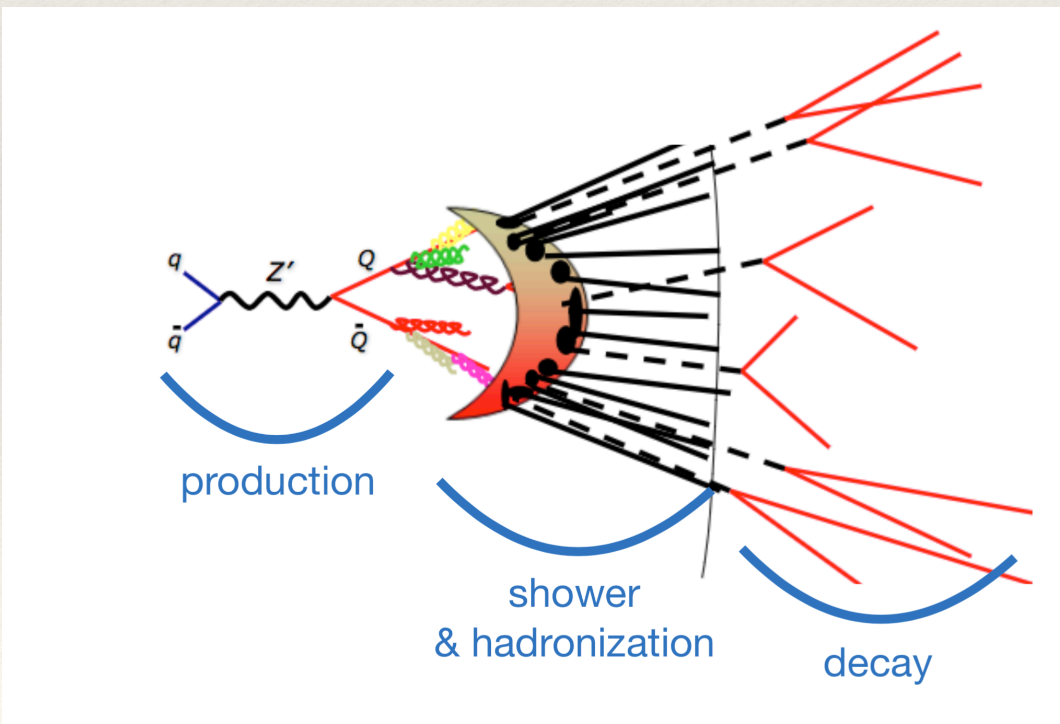
Motivation

- Searches for WIMP and SUSY signatures at colliders are very mature
- We wish to explore a larger signature space
- A dark sector could manifest rich dynamics



A Dark Sector Shower

- Assume the dark force carrier is non-Abelian
- High p_T quarks will shower
- Allow the final state to hadronize

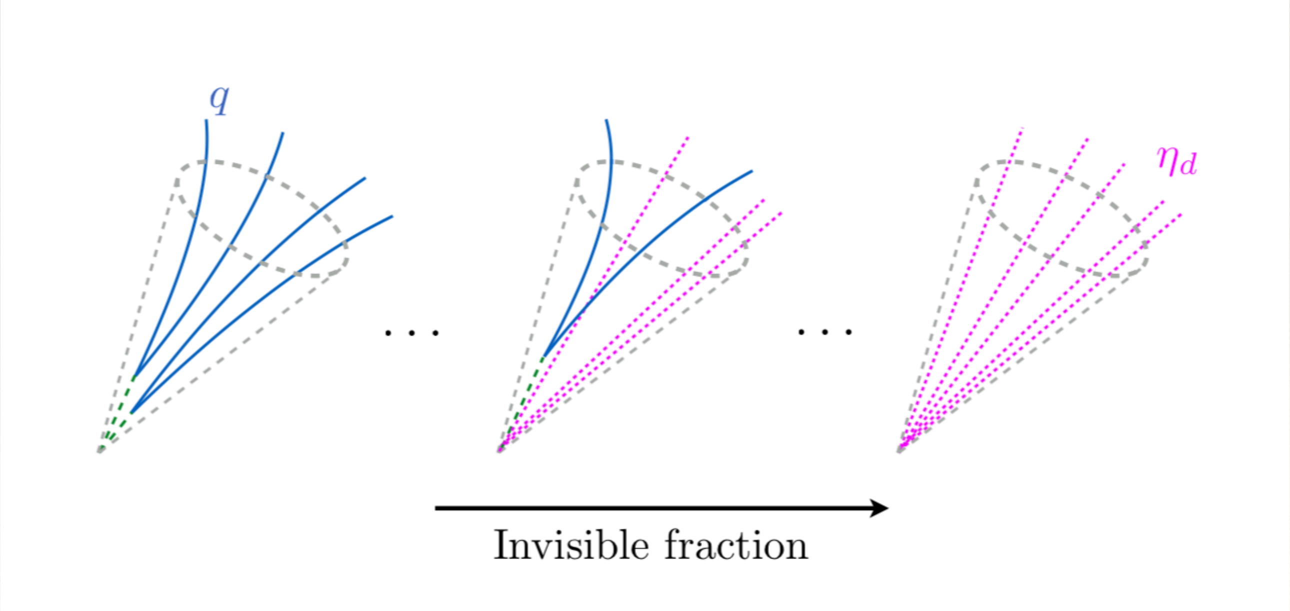


[arXiv: 1903.04497]

Dark Hadron Decays

- Some observable signatures have been identified: soft bombs, emerging jets, semi-visible jets, etc.
- Rely on extra handles, such as missing energy or displaced vertices
- Can we identify showering in a dark sector if dark hadrons fully decay to quarks?

[arXiv: 1707.05326]



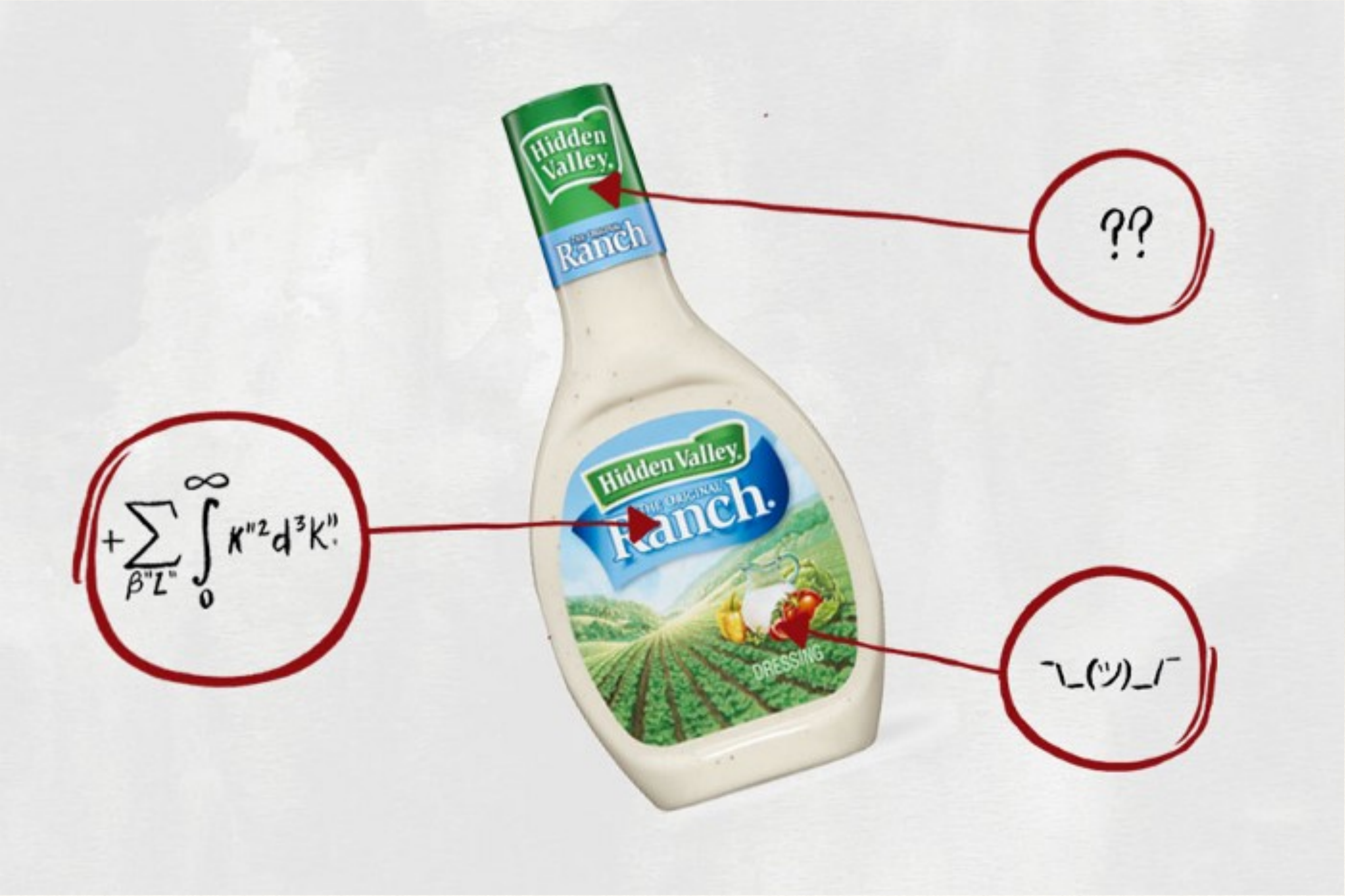
Benchmark Parameters

- Focus on the following choices of parameters for the dark sector:

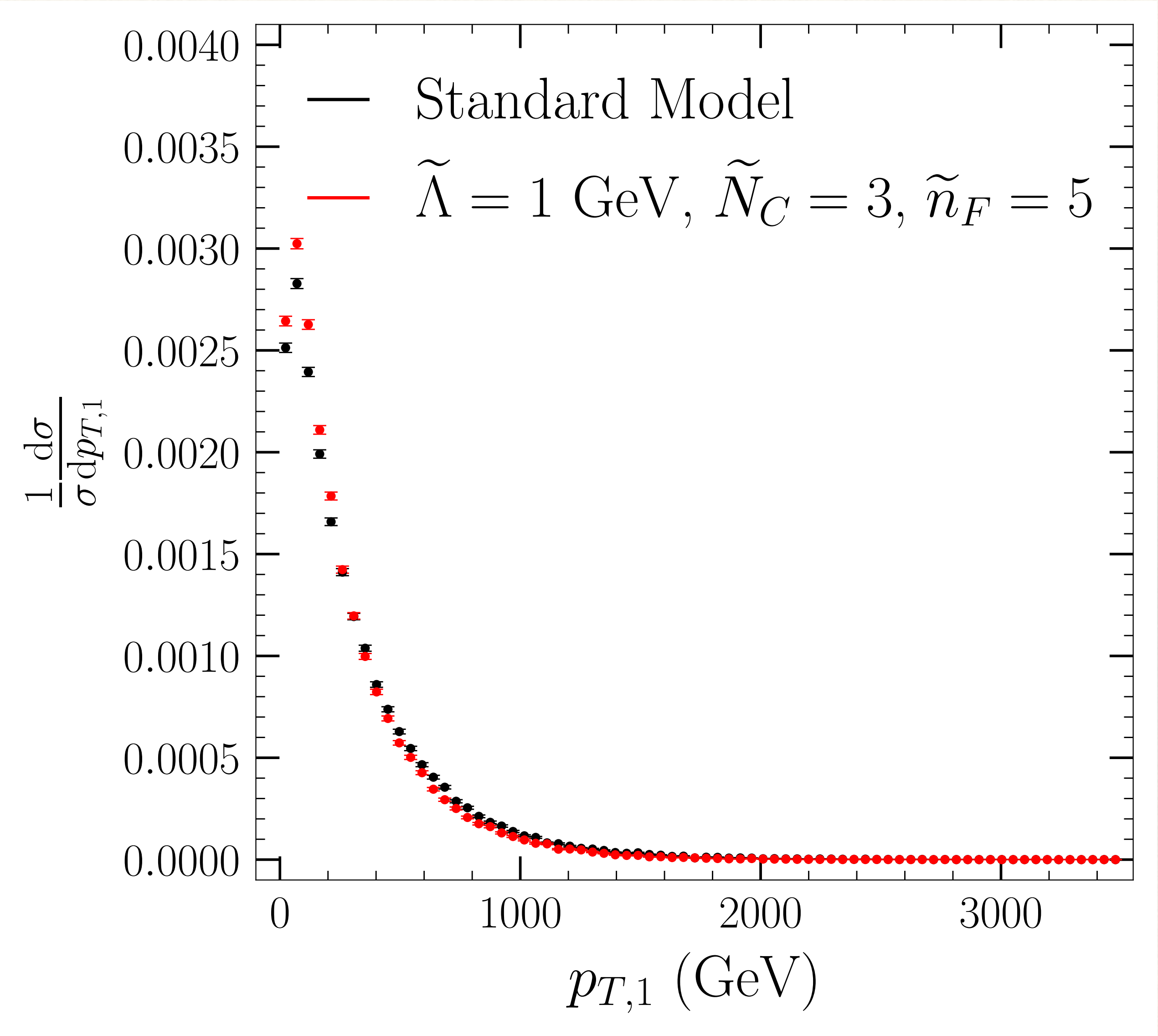
$$\widetilde{N}_C = 5$$

$$\tilde{n}_F = 3$$

$$\widetilde{\Lambda} = 1 \text{ GeV}$$



Why Appeal to Substructure?



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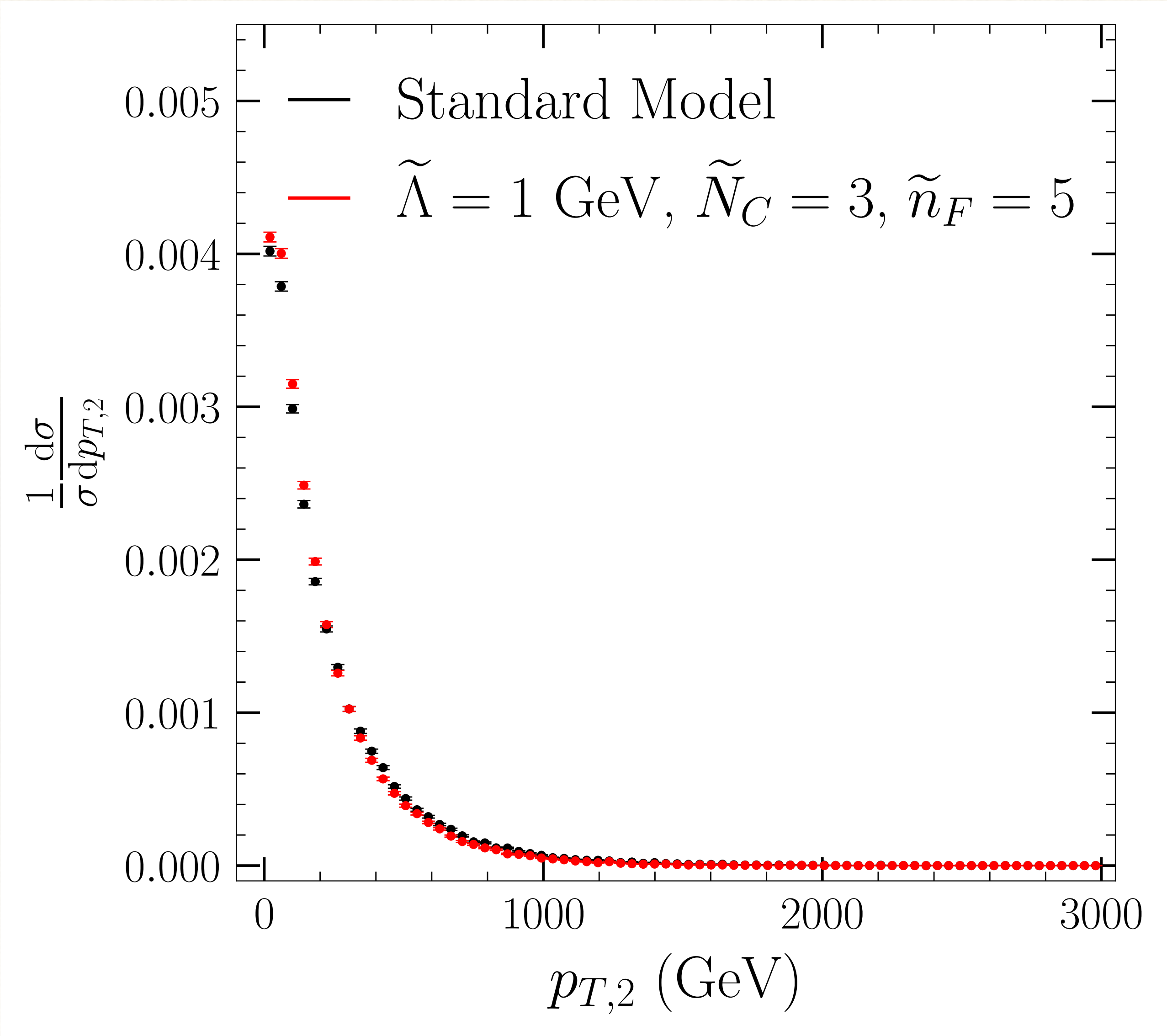

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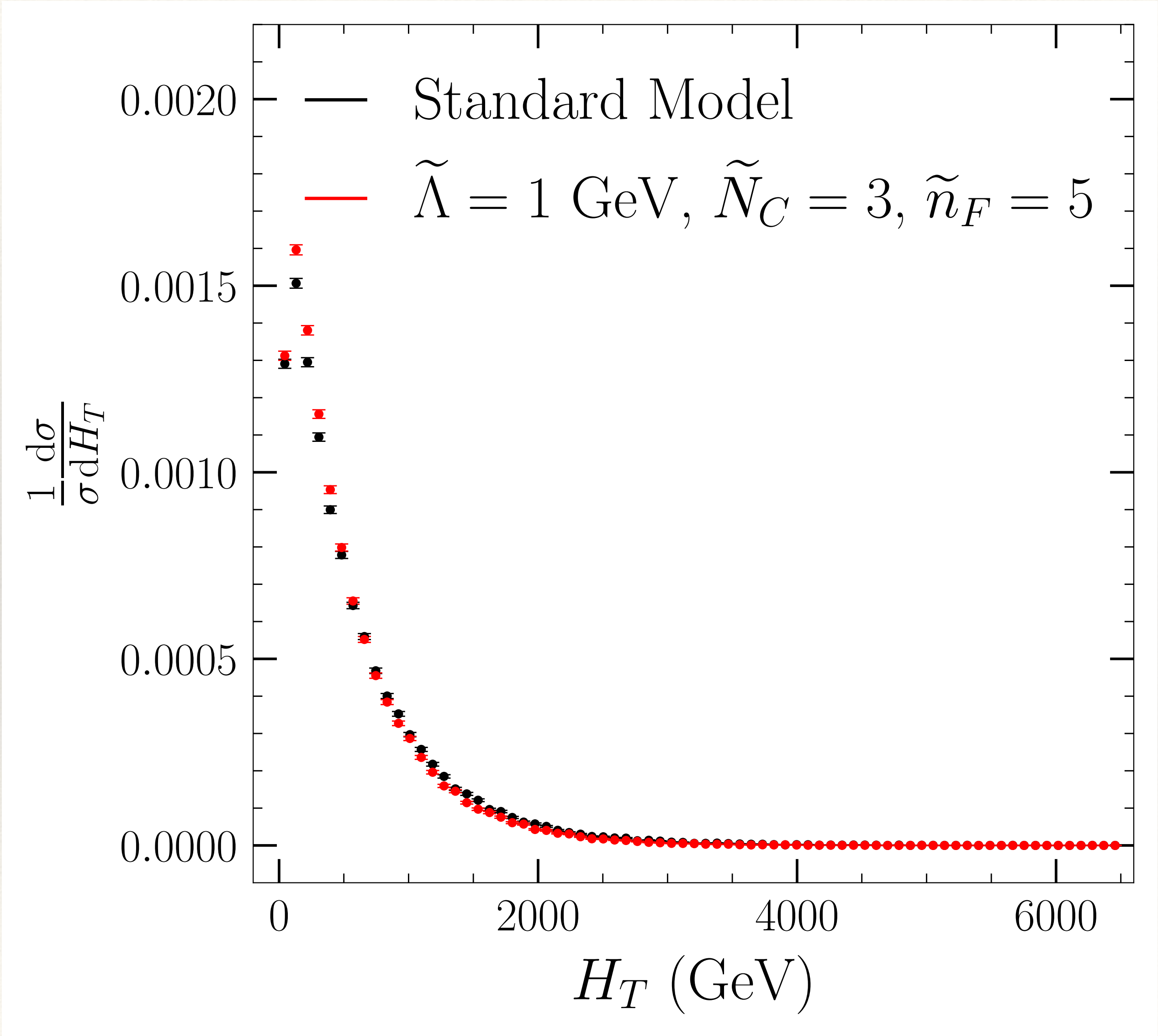
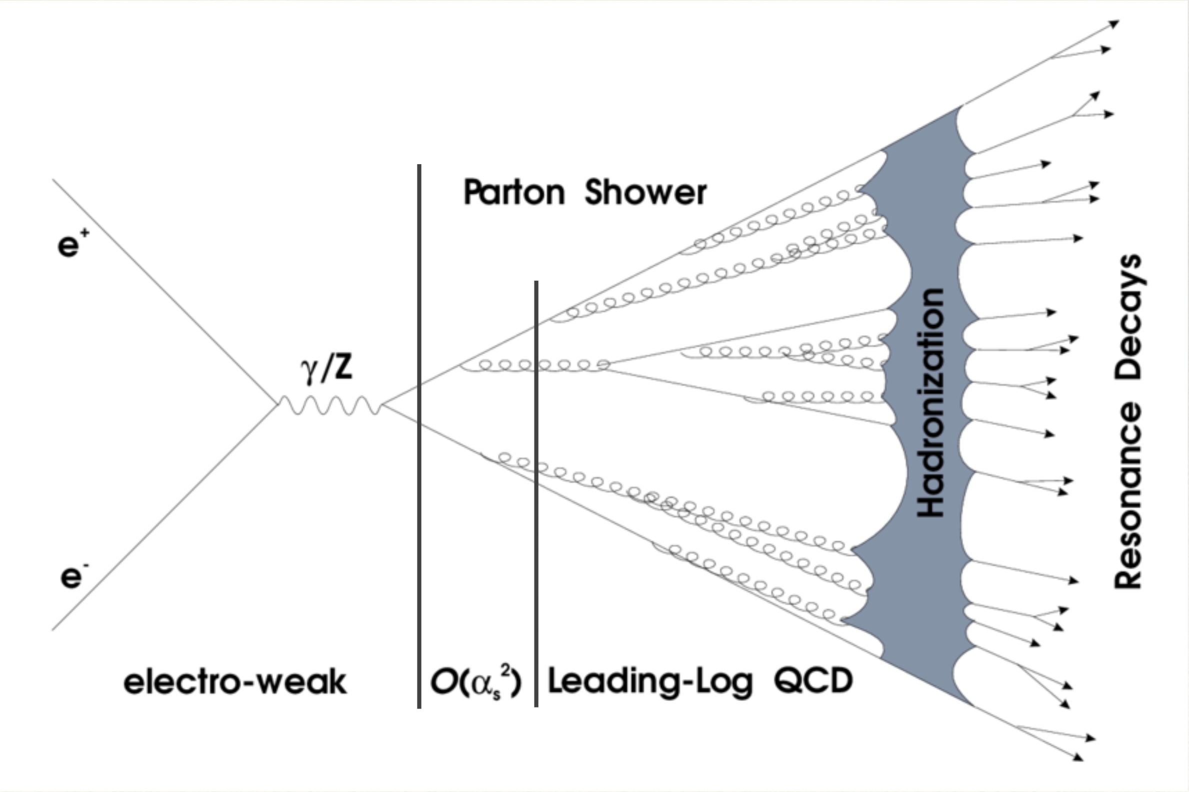


Strong Couplings Are Hard

- We lose predictive power in non-perturbative regimes
- Analytic techniques for handling logarithmic resummation
- Pythia is tuned to the Standard Model



Two-Point Energy Correlation Function

- e_2 is a generalization of jet mass incorporating arbitrary angularities

$$e_2^{(\beta)} = \sum_{i<j\in J} z_i\, z_j\, (\theta_{ij})^\beta$$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma_i^{\mathrm{LO}}}{\mathrm{d}e_2} = \frac{\alpha_s}{\pi}\int_0^{R_0}\frac{\mathrm{d}\theta}{\mathrm{d}\theta}\int_0^1 \mathrm{d}z\, p_i(z)\,\delta\!\left(z(1-z)\left(\frac{\theta}{R_0}\right)^\beta - e_2\right)$$

$$\frac{e_2}{\sigma}\frac{\mathrm{d}\sigma_i^{\mathrm{LO}}}{\mathrm{d}e_2} \simeq \frac{2\alpha_s}{\pi}\frac{C_i}{\beta}\left(\ln\frac{1}{e_2} + B_i + O\left(e_2\right)\right)$$

- Sigma is the cumulative distribution of the observable e_2

$$\Sigma_i^{\mathrm{LO}} \equiv \int_0^{e_2}\mathrm{d}x\frac{1}{\sigma}\frac{\mathrm{d}\sigma_i^{\mathrm{LO}}}{\mathrm{d}x} \simeq 1 - \frac{\alpha_s}{\pi}\frac{C_i}{\beta}\left(L^2 + 2B_iL + O\left(L^0\right)\right).$$

Event Shape Resummation

- For recursively IRC safe observables, Banfi et al. showed:

[arXiv: hep-ph/0407286]

$$\Sigma_i^{\mathrm{LL}} = e^{-R_i}$$

$$\Sigma_i^{\mathrm{NLL}} = N \frac{e^{-\gamma_E R_i'}}{\Gamma(1 + R_i')} e^{-R_i} \quad \text{where} \quad R_i' \equiv \frac{\mathrm{d}R_i}{\mathrm{d}L}$$

[arXiv: hep-ph/0407287]

$$R_i = \int_0^{R_0} \frac{\mathrm{d}\theta}{\theta} \int_0^1 \mathrm{d}z\, p_i(z) \frac{\alpha_s(\kappa)}{\pi} \Theta\left(z \left(\frac{\theta}{R_0} \right)^\beta - e_2 \right) \quad \text{where} \quad \kappa = z\theta p_{T_J}$$

Event Shape Resummation

- NLL order requires matching to the fixed-order distribution:

[arXiv: hep-ph/0407286]

$$\Sigma_i^{\text{NLL}} = N \frac{e^{-\gamma_E R_i'}}{\Gamma(1 + R_i')} \exp(-R_i) \exp\left(-\frac{\alpha_s}{\pi}\left(R_{1,i} - G_{2,i}L^2 - G_{1,i}L\right)\right)$$

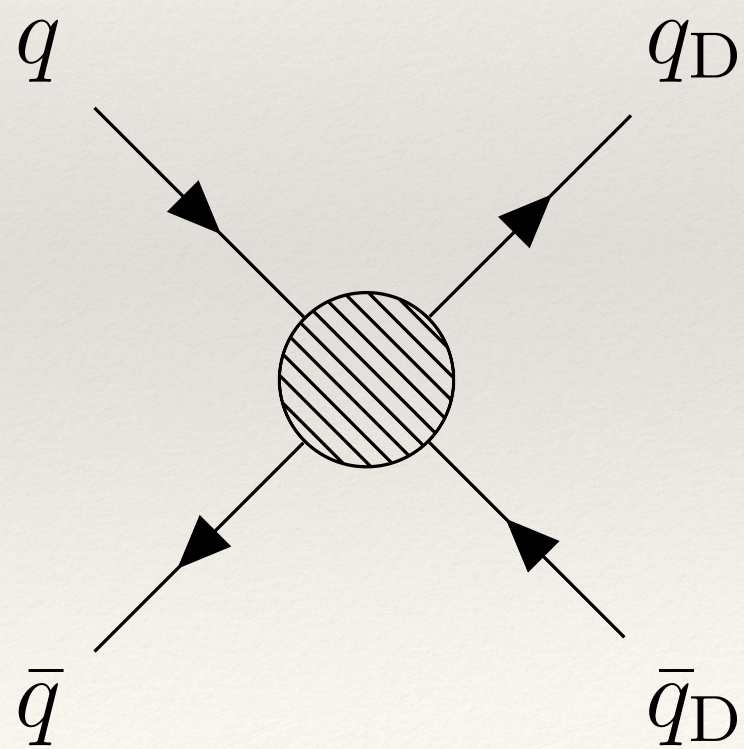
$$\ln \Sigma_i^{\text{LO}} = \frac{\alpha_s}{\pi} \int_0^{R_0} \frac{\mathrm{d}\theta}{\theta} \int_0^1 \mathrm{d}z\, p_i(z)\, \Theta\left(z\left(\frac{\theta}{R_0}\right)^\beta - e_2\right) = -\frac{\alpha_s}{\pi} R_{1,i}$$

[arXiv: hep-ph/0407287]

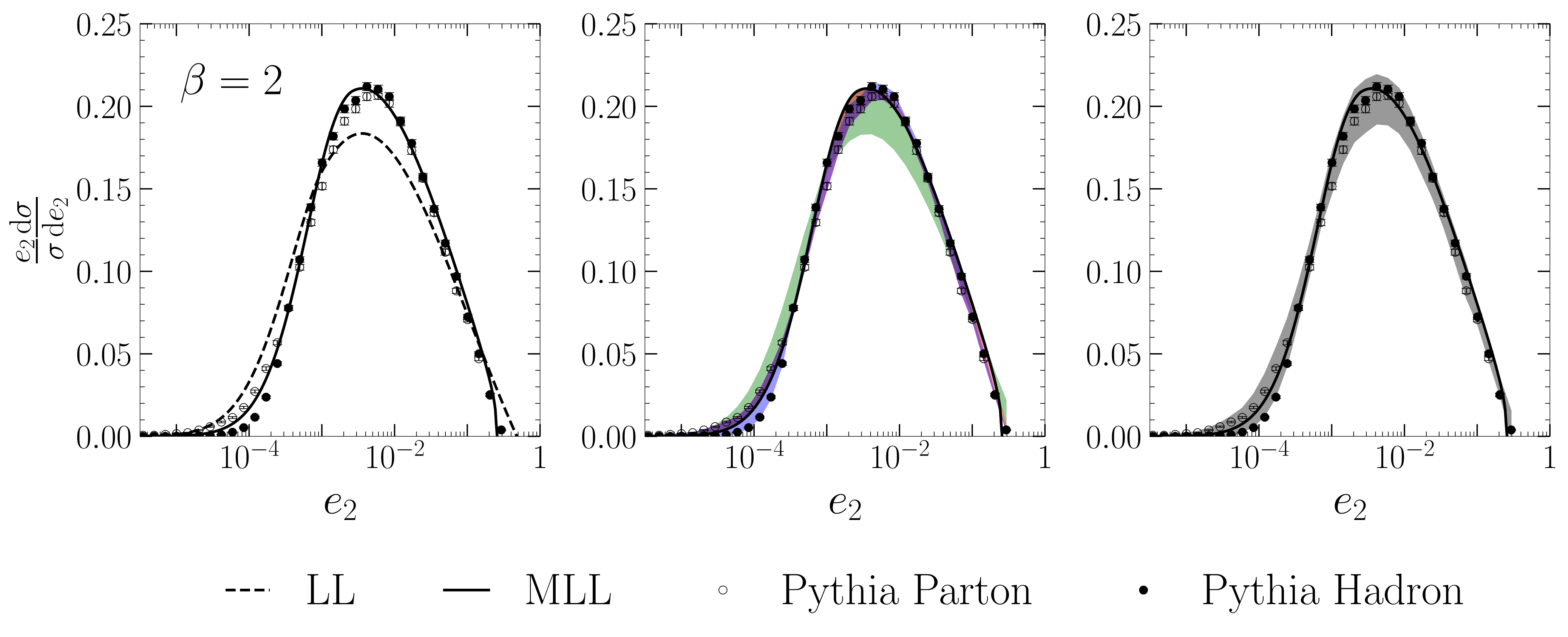
- Modified Leading Logarithmic (MLL) avoids the numerical computations required for a true NLL order calculation, such as two-loop running of the coupling

Numerical Approach

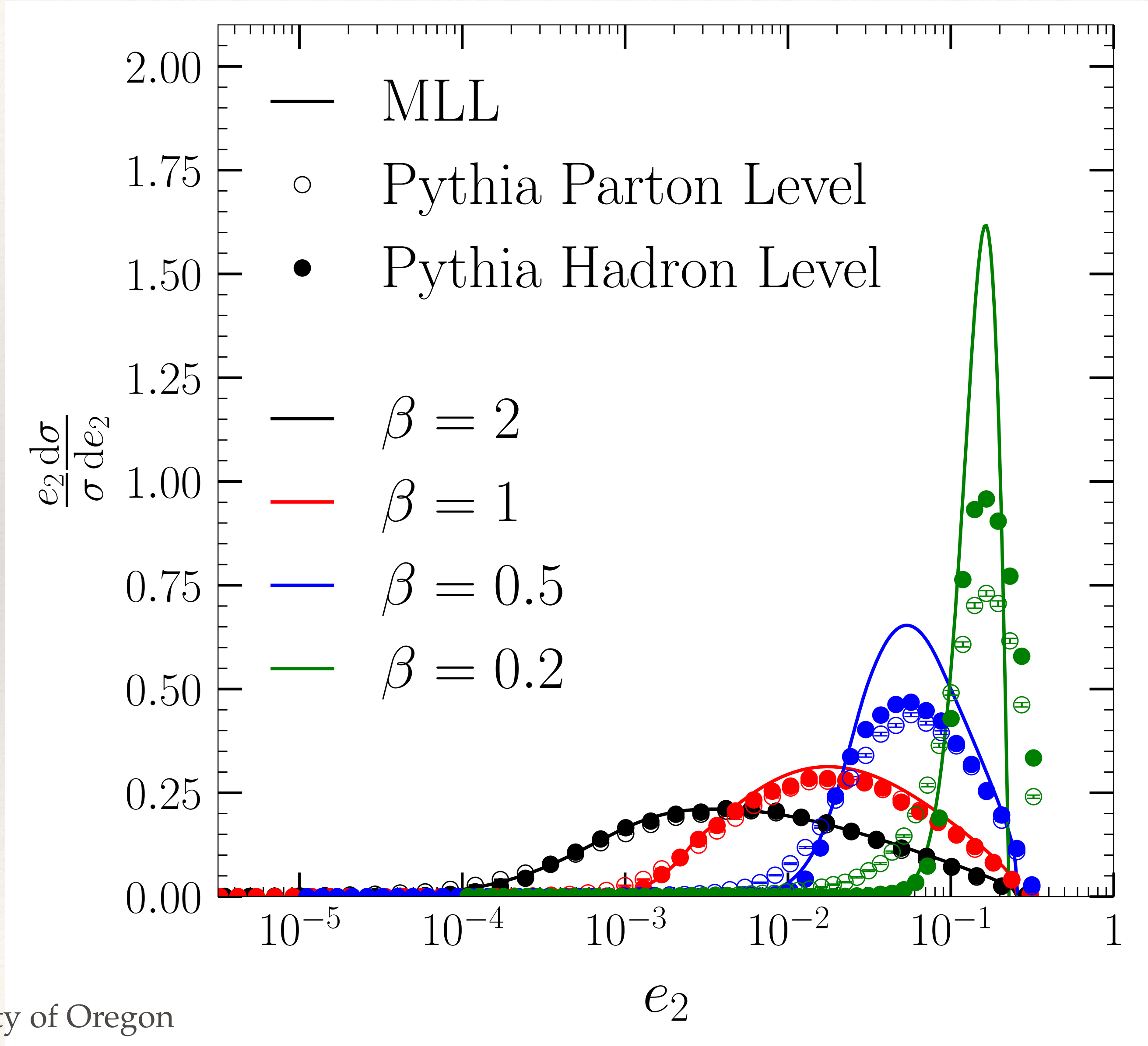
- Simulate with Pythia and cluster with FastJet
- Create dark quarks via contact operator
- Shower via Pythia's Hidden Valley module
- Select anti-k_T jets with $p_T \geq 1$ TeV
- Compare parton and hadron levels



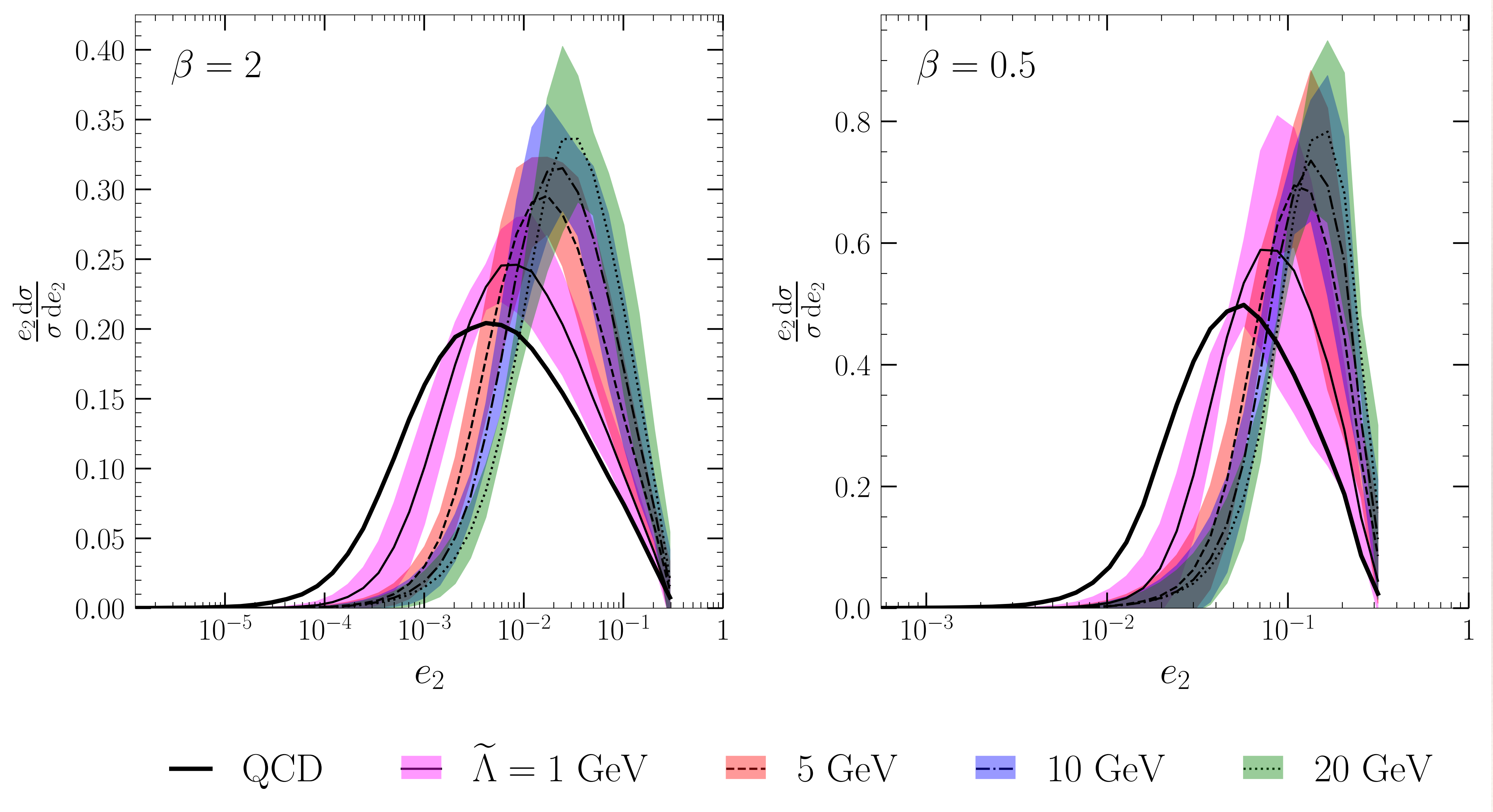
Error Envelopes



Angular Dependence



Λ Variations



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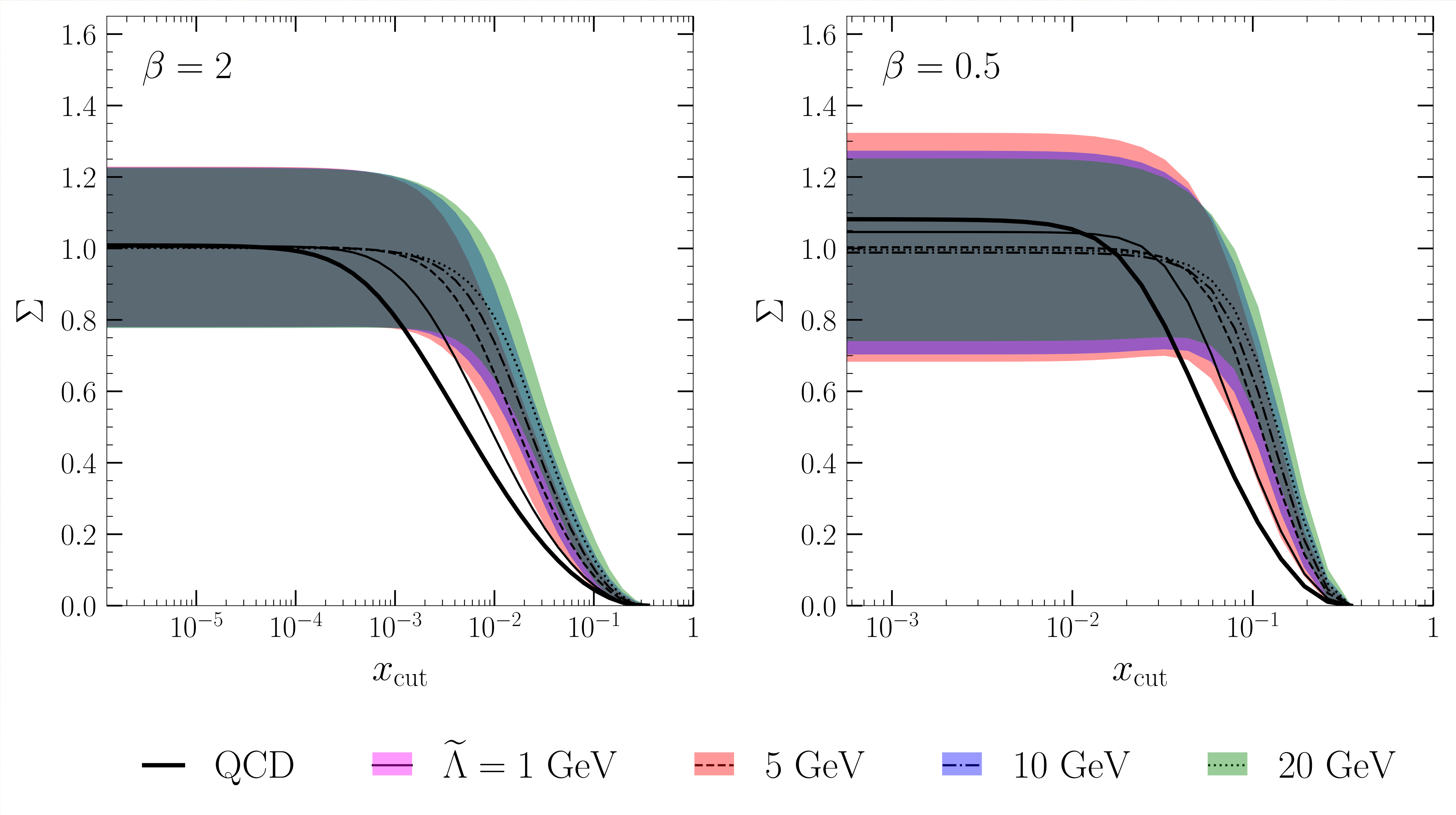
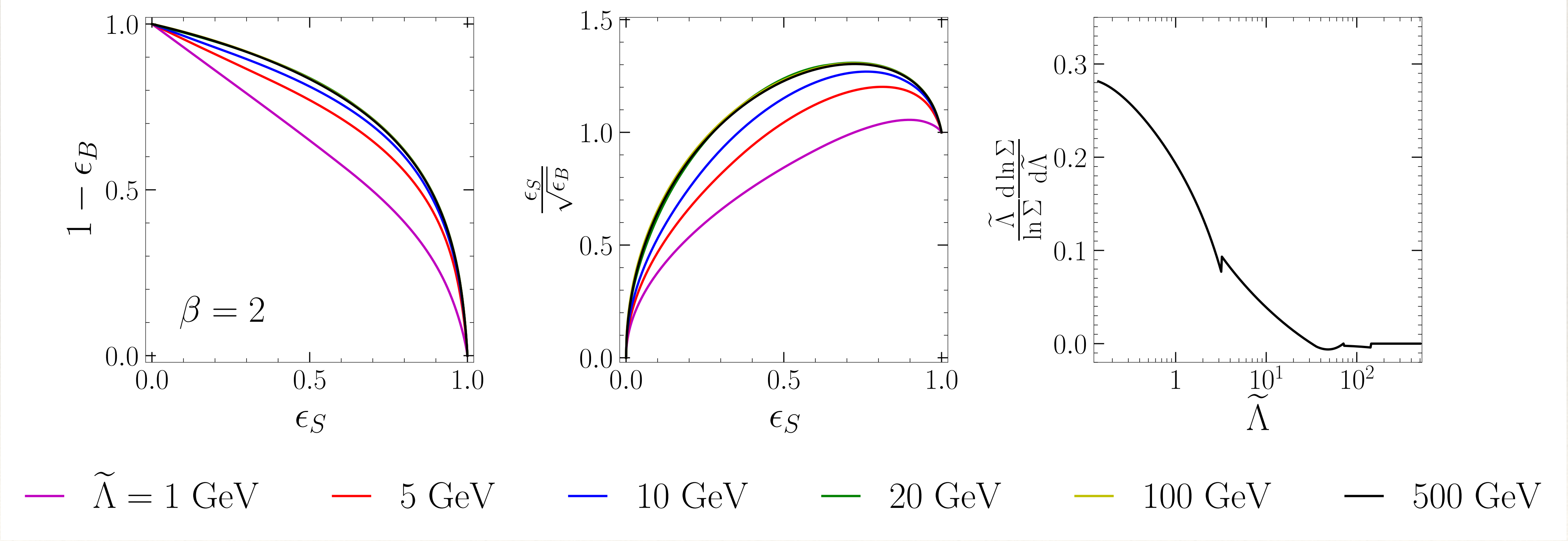


Λ Discrimination

- ϵ_S and ϵ_B are signal and background efficiencies

Discrimination | Efficiency Scaling | Dependence



Discovering Dark Substructure

- We assume the portal can be modeled by a contact interaction:

$$\mathscr{L}_{\text{int}} \supset \frac{1}{\Lambda^2_{\text{CI}}}(\bar{q}\,\gamma^\mu\, q)(\bar{\tilde{q}}\,\gamma_\mu\,\tilde{q})$$

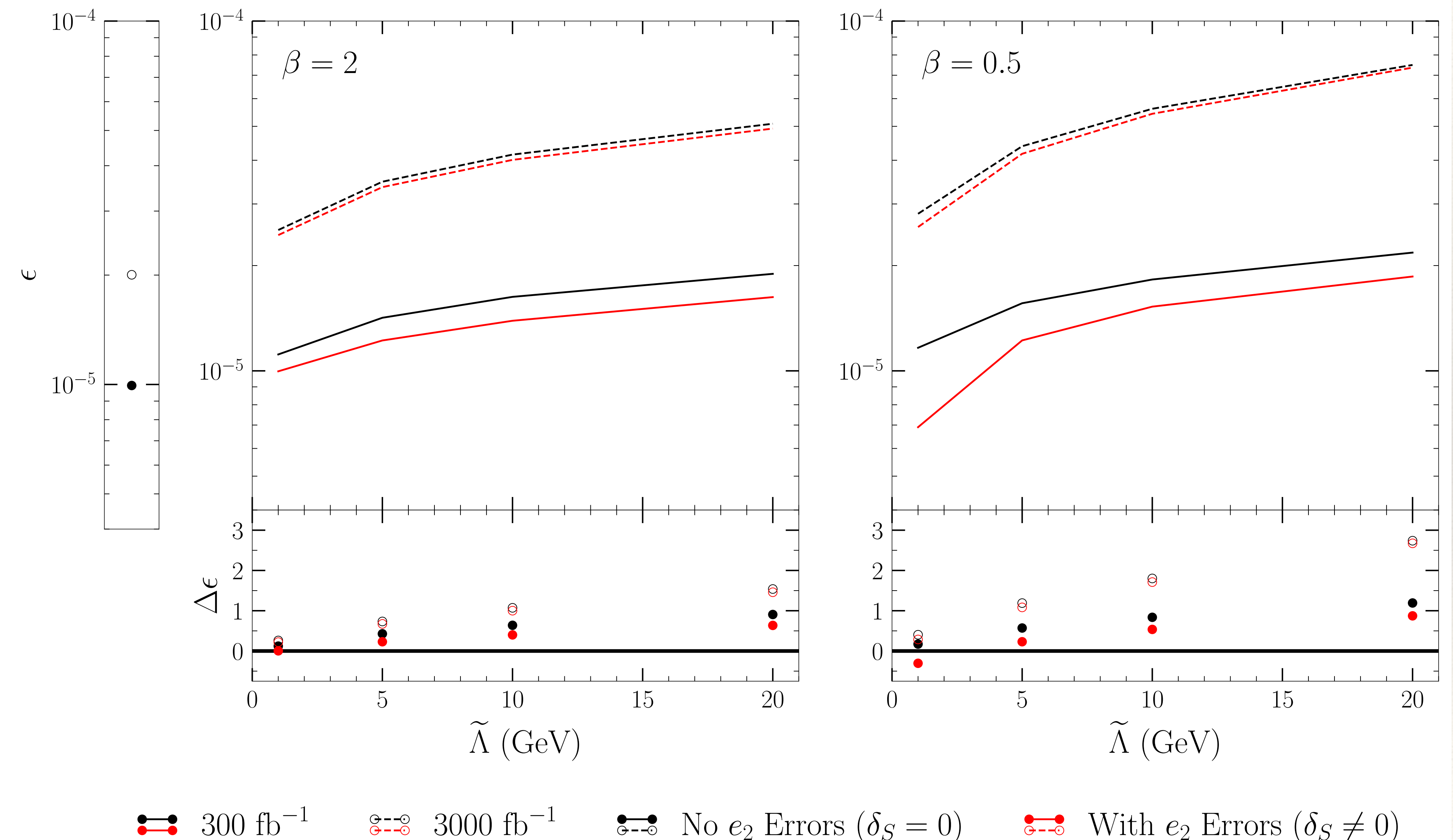
- Include statistical and systematic uncertainties in approximating discovery significance

$$\mathscr{Z} = \frac{S}{\sqrt{S + B + \delta_S^2 S^2 + \delta_B^2 B^2}}$$

- Compute background reduction ϵ via the substitution B → ϵB

$$\epsilon = \frac{\sqrt{1 - 4\delta_B^2\, S\left(1 + \left(\delta_S^2 - \frac{1}{\mathscr{Z}^2}\right)S\right)} - 1}{2\delta_B^2\, B}$$

Discovering Dark Substructure



Summary

- Dark sectors present a very exciting opportunity to develop new searches for BSM physics
- Signatures can be challenging
- Should take care with how much we trust theoretical predictions
- Utilizing dark substructure signal requires background reduction by a factor of $O(10^5)$