Jet Substructure, Hidden Sectors, and Theory Uncertainties

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Tim Cohen, Joel Doss, MF [arXiv:2004.00631]

The challenge of dark sectors

- LHC searches with clean final states at a mature stage
  - Many nearly-optimized channels
  - Model agnostic frameworks, *e.g.*, simplified models

- What is being missed in this framework?

- One example: strongly interacting dark sectors
  - Can have almost arbitrary complicated final states
  - *e.g.*, high jet multiplicities, displaced vertices, soft bombs
  - *e.g.*, lepton, photon, & emerging jets

- Many of these are low B, main concern is missing cases

- Worst case scenario: Only imprint of DS in parton shower
  - Have to distinguish QCD shower from novel dynamics

The challenge of dark sectors

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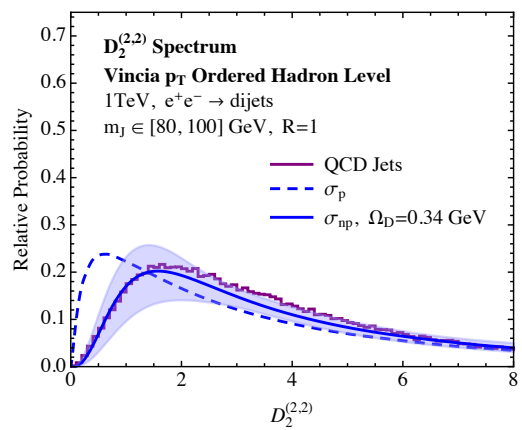
Jet substructure to the rescue?

- Explosion of tools for study of QCD jets in last 10+ years
  - hadronic t, W/Z, $h \to b\bar{b}$ tagging
  - (more recently) anomaly detection in jets
- Better theory calculations $\longrightarrow$ more subtle questions
  - quark/gluon discrimination
  - non-global logarithms
- Latter questions (more) sensitive to the underlying theory
  - Might tell us if our jets are non-QCD-like

e.g., Park, Zheng [arXiv:1712.09279]

- But how well do we understand these objects?



Larkoski, Moult, Neill [arXiv:1507.03018]

Plan

- Introduction
- (Mostly) Calculable Dark Substructure
  - C_1 as a test case
- Dark shower models & uncertainties
- Effect on sensitivities

Energy correlation functions

A well-studied example ($z_i = p_{T_i}/p_{T_J}$):

$$e_N^{(\beta)} = \sum_{i_1<i_2<\cdots<i_N \in J} \prod_{a=1}^{N} z_{i_a} \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} \frac{\theta_{i_b i_c}}{R_0} \right)^{\beta}$$

A probe of separation of energy into N "clumps" inside jet

Double ratios give a measure of how N-subjet-like a jet is,

$$C_N^{(\beta)} = \frac{e_{N+1}^{(\beta)}/e_N^{(\beta)}}{e_N^{(\beta)}/e_{N-1}^{(\beta)}}$$

Particularly simple $C_1^{(\beta)} = \sum_{i<j} z_i z_j (\theta_{ij}/R_0)^{\beta}$
A probe of width of radiation in jet — mass-like, useful for q vs. g

Jet observables and resummation

A LO calculation of the cumulative distribution ($L = \log 1/C_1^{(\beta)}$):

$$\Sigma^{\mathrm{LO}} \equiv \int_0^{C_1^{(\beta)}} \mathrm{d}x\, \frac{1}{\sigma}\frac{\mathrm{d}\sigma^{\mathrm{LO}}}{\mathrm{d}x} = 1 - \frac{\alpha_G}{\pi}\frac{C_{G,i}}{\beta}\Big(L^2 + 2B_i L + \mathcal{O}(1)\Big).$$

Sudakov $\log^2$ as $C_1^{(\beta)} \to 0$, resummation needed for efficiencies

Simple exponentiation at LL:

$$\Sigma^{\mathrm{LL}} = e^{-R}, \quad R = \int_0^{R_0} \frac{\mathrm{d}\theta}{\theta} \int_0^1 \mathrm{d}z\, p(z) \frac{\alpha_G(\kappa)}{\pi} \Theta\left(z\left(\frac{\theta}{R_0}\right)^{\beta} - C_1^{(\beta)}\right).$$

More involved at NLL: $\Sigma^{\mathrm{NLL}} = (e^{-\gamma_E R'}/\Gamma(1+R'))\, e^{-R}$
Higher order requires more heavy-duty machinery (*e.g*, SCET)

Can include fixed-order matching if desired

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Theoretical uncertainties

- Want to know theory uncertainty in $\Sigma^{(\mathrm{N})\mathrm{LL}}$
  - Compute scale choices of parts in Laplace transform $\tilde{\Sigma}^{(\mathrm{N})\mathrm{LL}}$
  - Typically larger than FO uncertainties
  - "Effective coupling" $\alpha_G/\beta \longrightarrow$ worse at low β

- Additional uncertainties from (dark) hadronization
  - For $C_1^{(\beta)}$ operator def. of hadronization corrections known
  - Can be parametrized by (unknown) universal shape function
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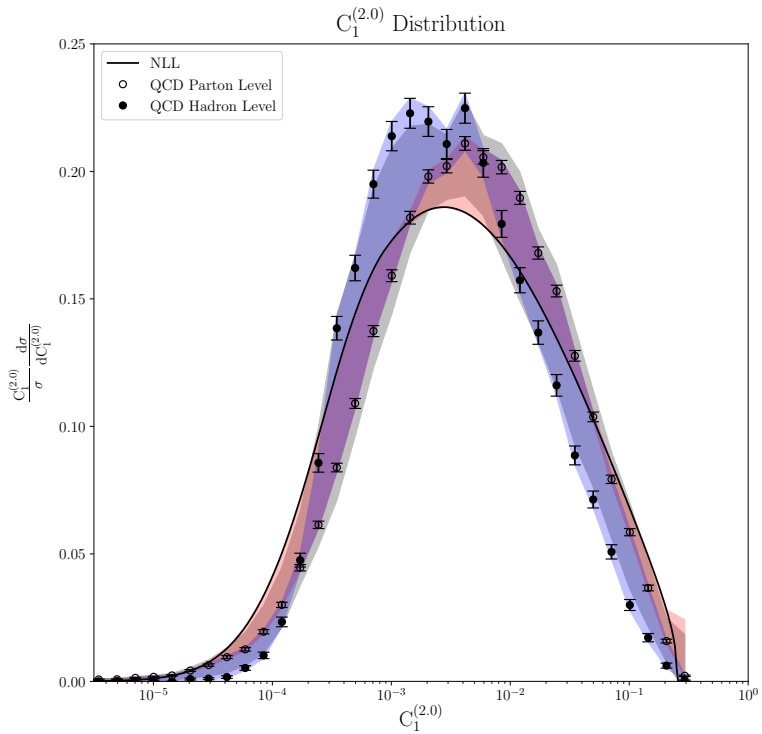
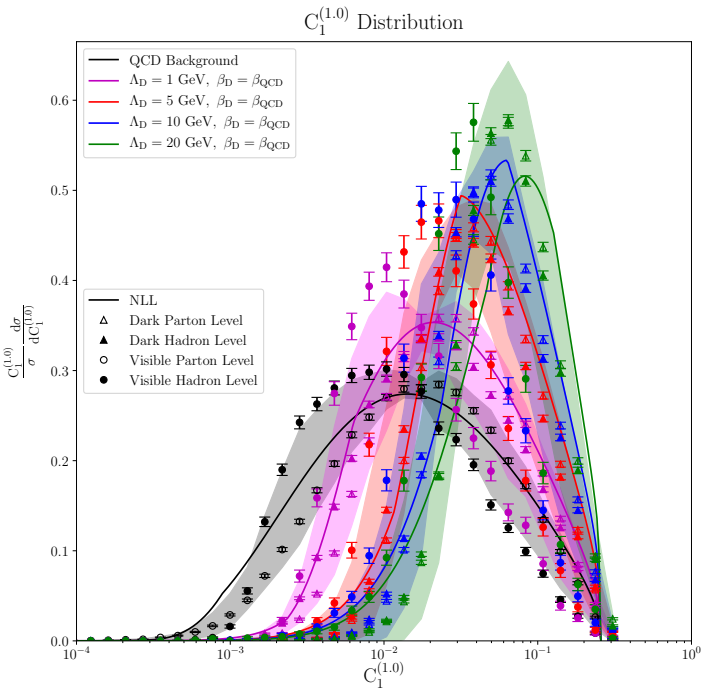
Everything together in QCD

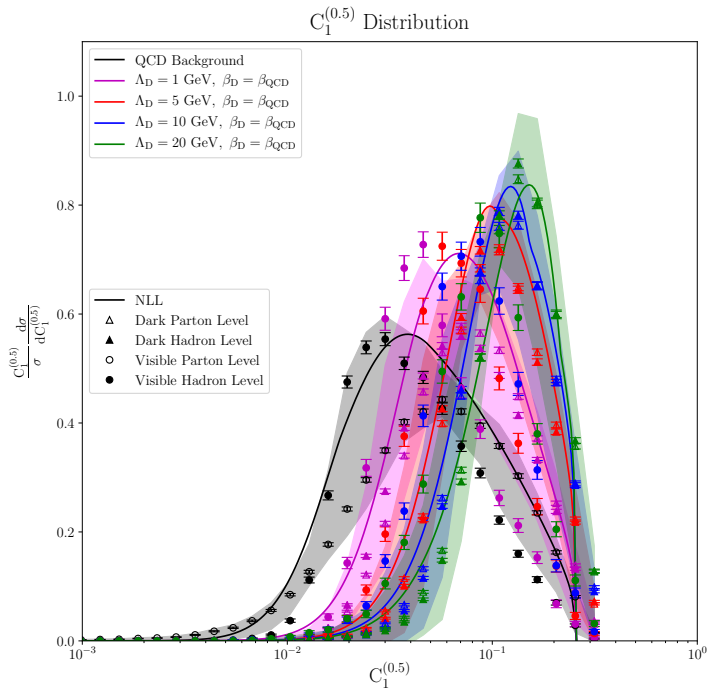
Scale and hadronization uncertainties in QCD:



A likely overestimate. Pythia parameters are calibrated to data, so distributions secretly include higher order corrections in tuning procedure.

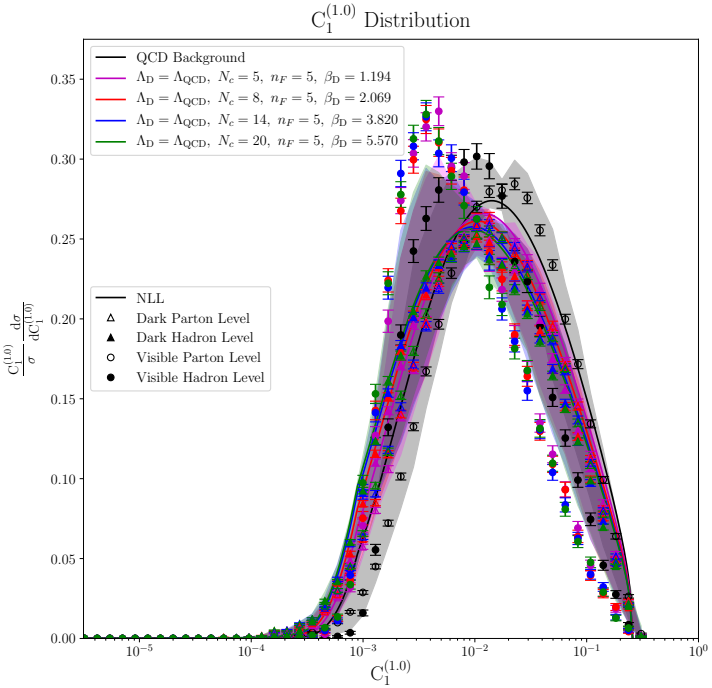
Effect of dark confinement scale

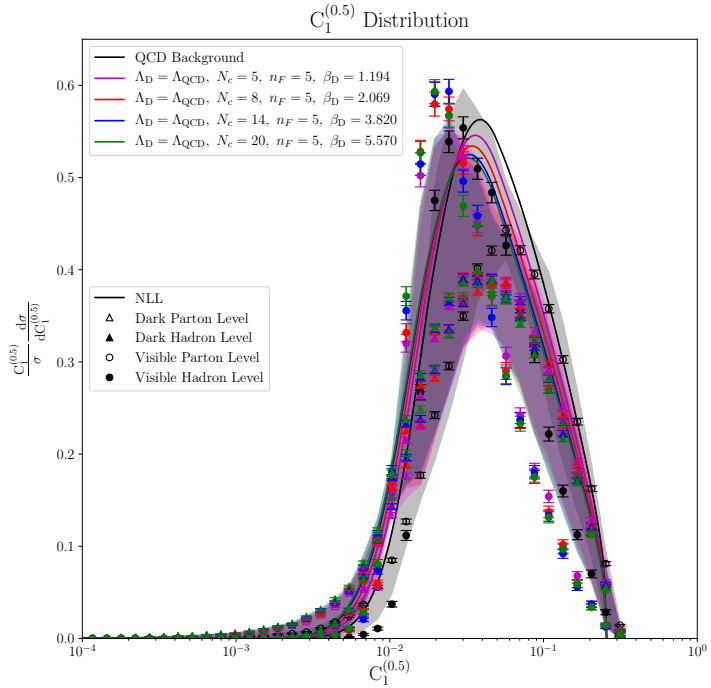




For $\Lambda_D > \Lambda_{\mathrm{QCD}}$, peak of $C_1^{(\beta)}$ shifted to higher values
Uncertainties get larger as $\beta \to 0$

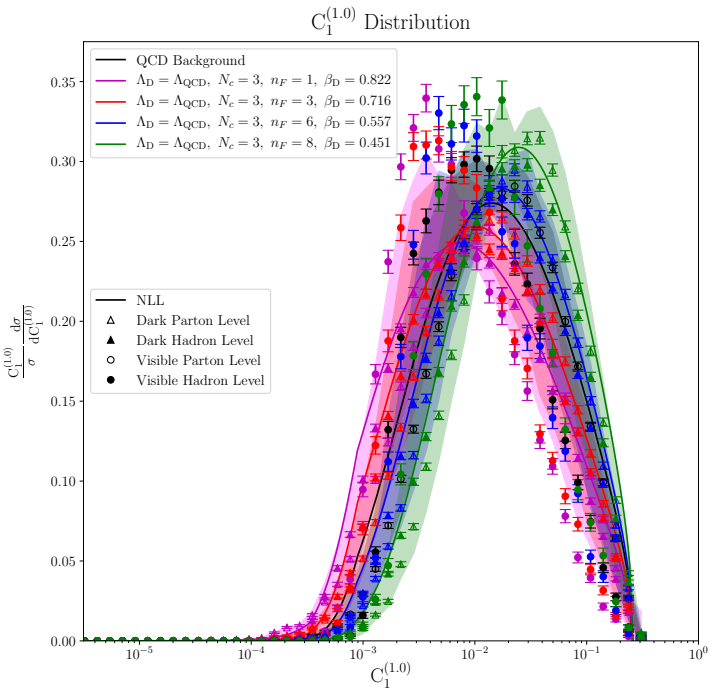
Changing the gauge group: N_c

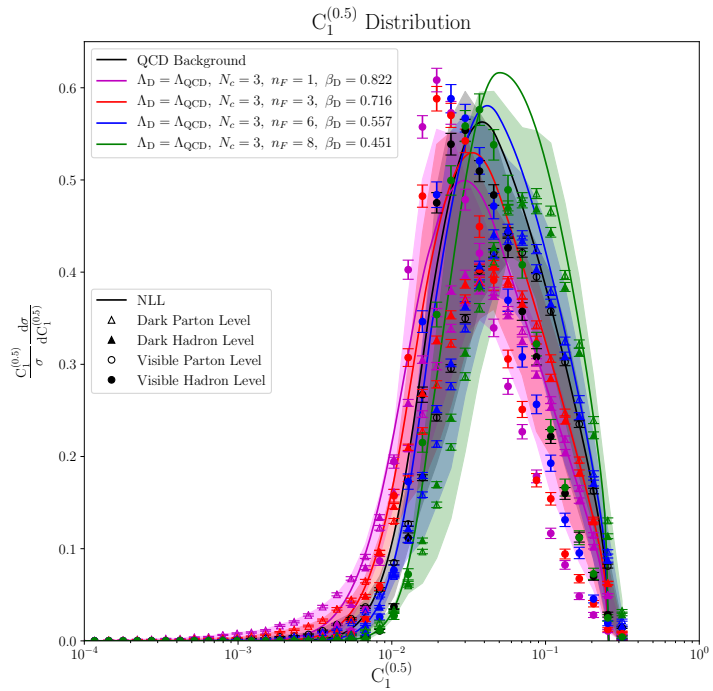




Larger gauge groups lead to increased uncertainties at lower $C_1^{(\beta)}$

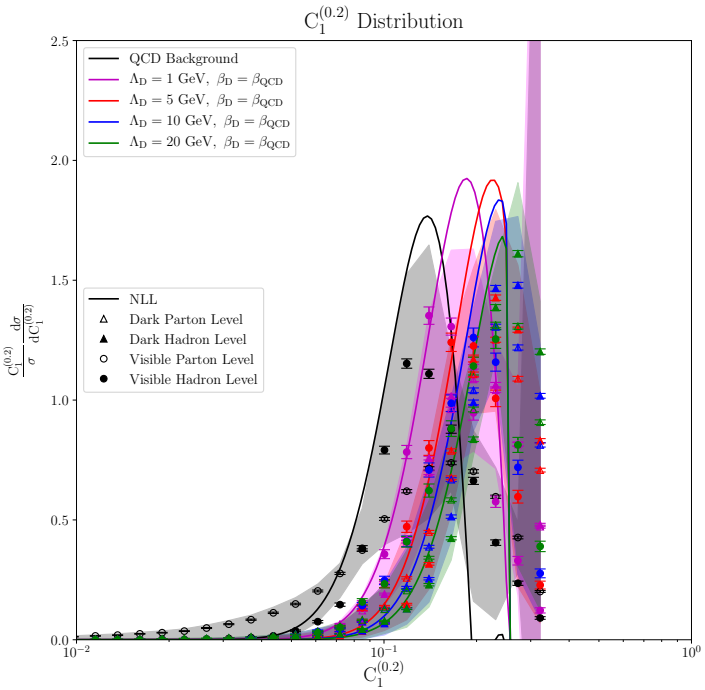
Changing the gauge group: n_f

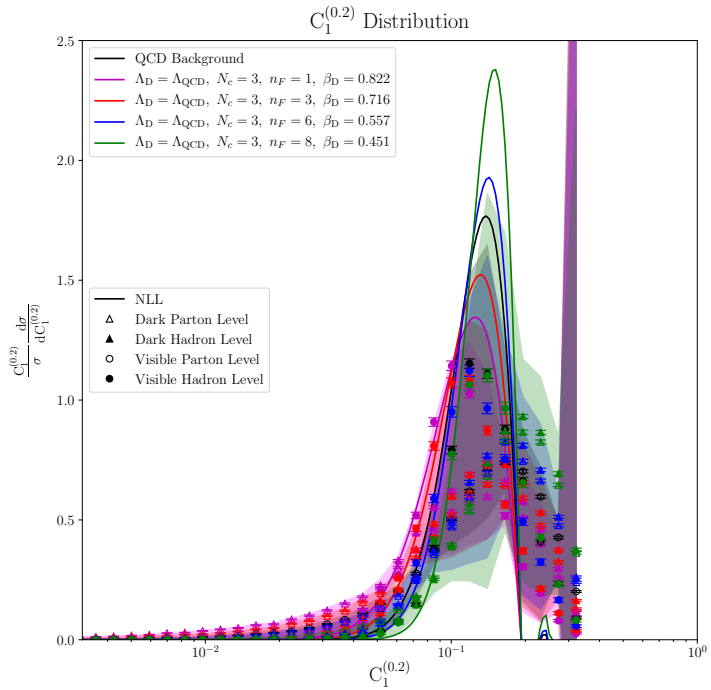




More flavors increases uncertainty throughout
Resummation uncertainties larger due to slower running

The dangers of low angular weight





- More sensitivity to parton shower radiation pattern as $\beta \to 0$
- Shows up as sensititiy to higher-order corrections in $C_1^{(\beta)}$ too
- By $\beta \approx 0$ perturbative control is mostly lost

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A toy muddle

How does this affect our actual searches?

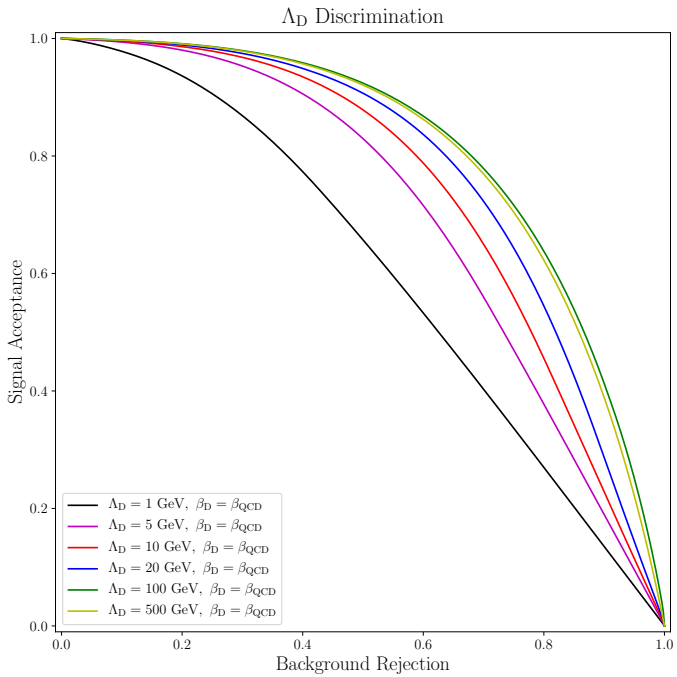
Consider a simple Z' hidden valley, with universal coupling g
For very massive Z', generates

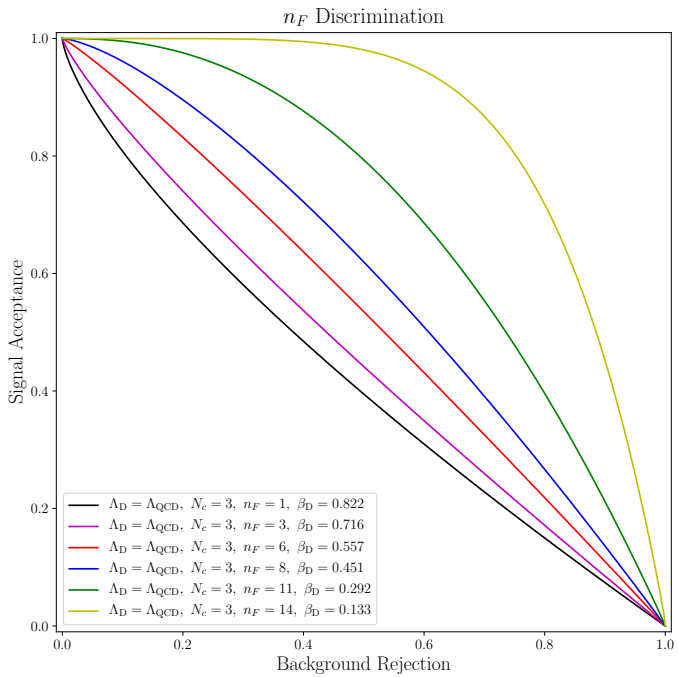
$$\frac{1}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu q) \simeq \frac{1}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{q}_D\gamma_\mu q_D) \tag{1}$$

Current $4q$ operator bounds: $\Lambda > 22\,\text{TeV}$

Can cutting of $C_1^{(\beta)}$ help reveal new physics?

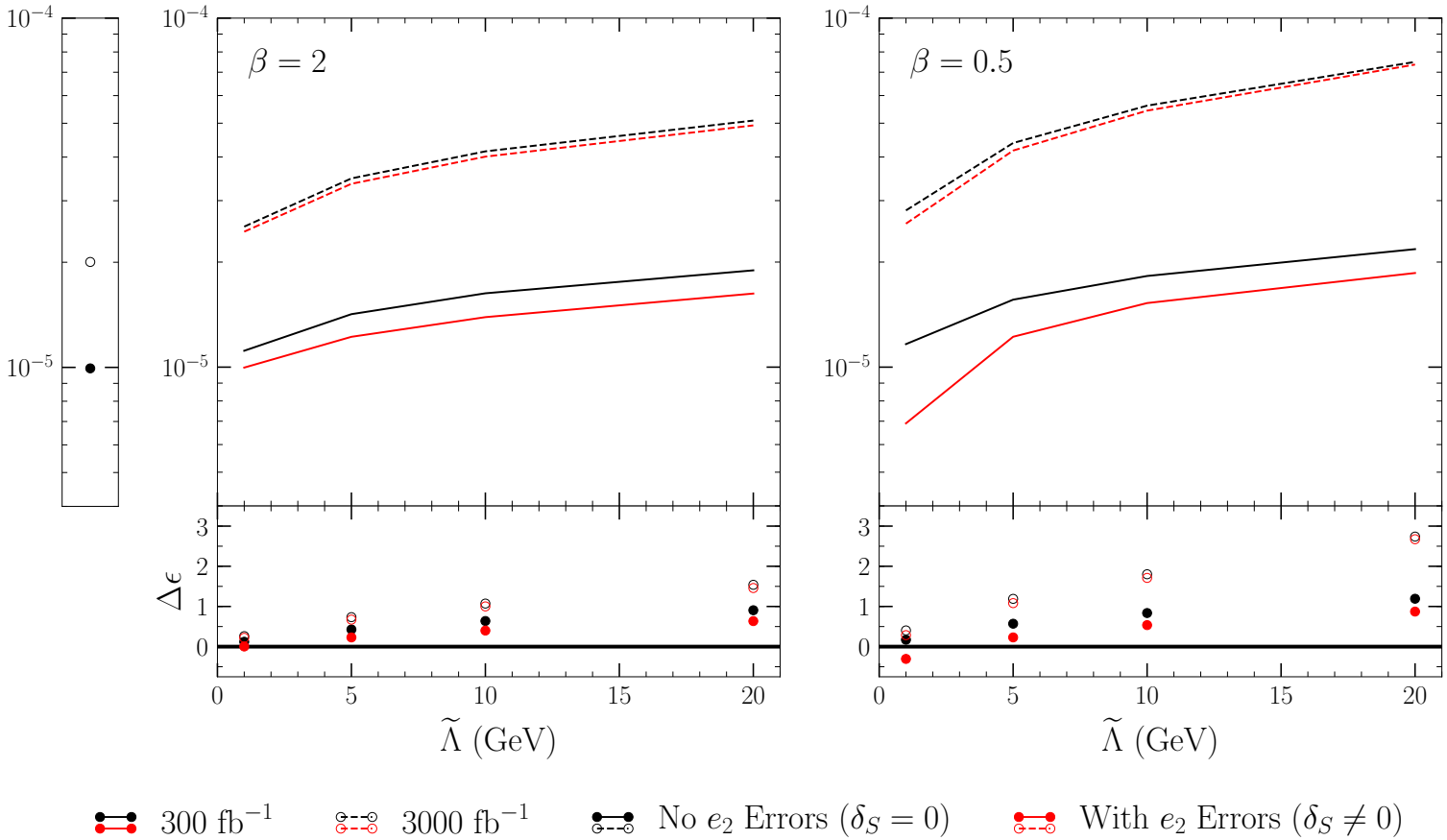
And a sensitivity plot





Using central values of distributions, cutting of $C_1^{(\beta)}$ helps
In addition, sensitivity to cut can act as probe of dark dynamics

One more thing to say



Central values would indicate easy discoverability at HL-LHC, but including systematics on QCD + signal has noticable effect on sensitivity at 300 fb^{-1}

Conclusions

- Hadronic jet-substructure is a common tool at today's LHC
  - Some form of substructure is used in virtually every search
- Now have first-principles understanding of some obs.
- Allows us to start looking for new physics in jet structure itself
- But
  - Uncertainties in jet observables tend to be sizable
  - Are often invisible in simple MC studies
  - Care must be taken to make sure our searches have the sensitivities claimed

Thank you!