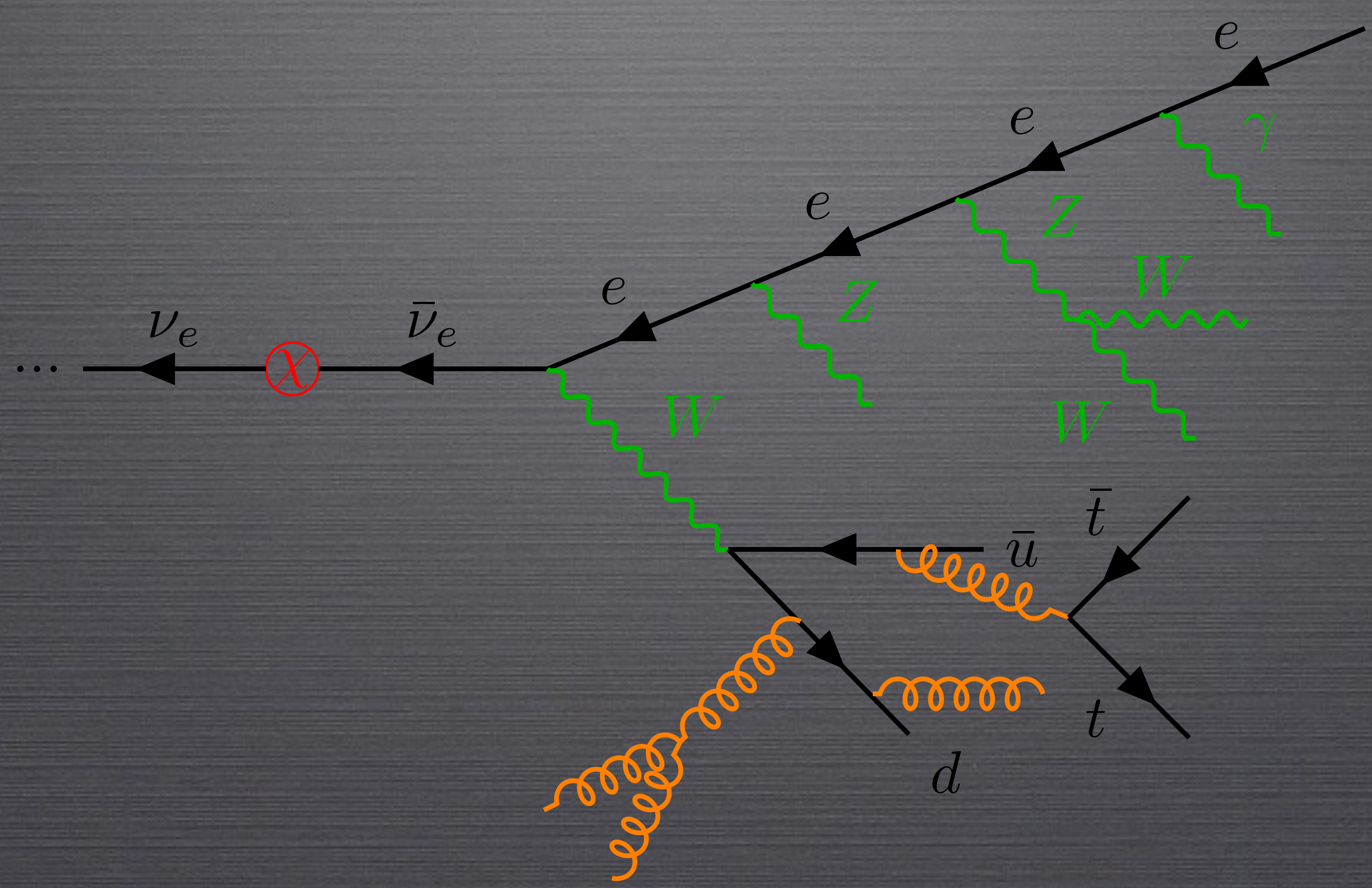
Spectra for Heavy Dark Matter



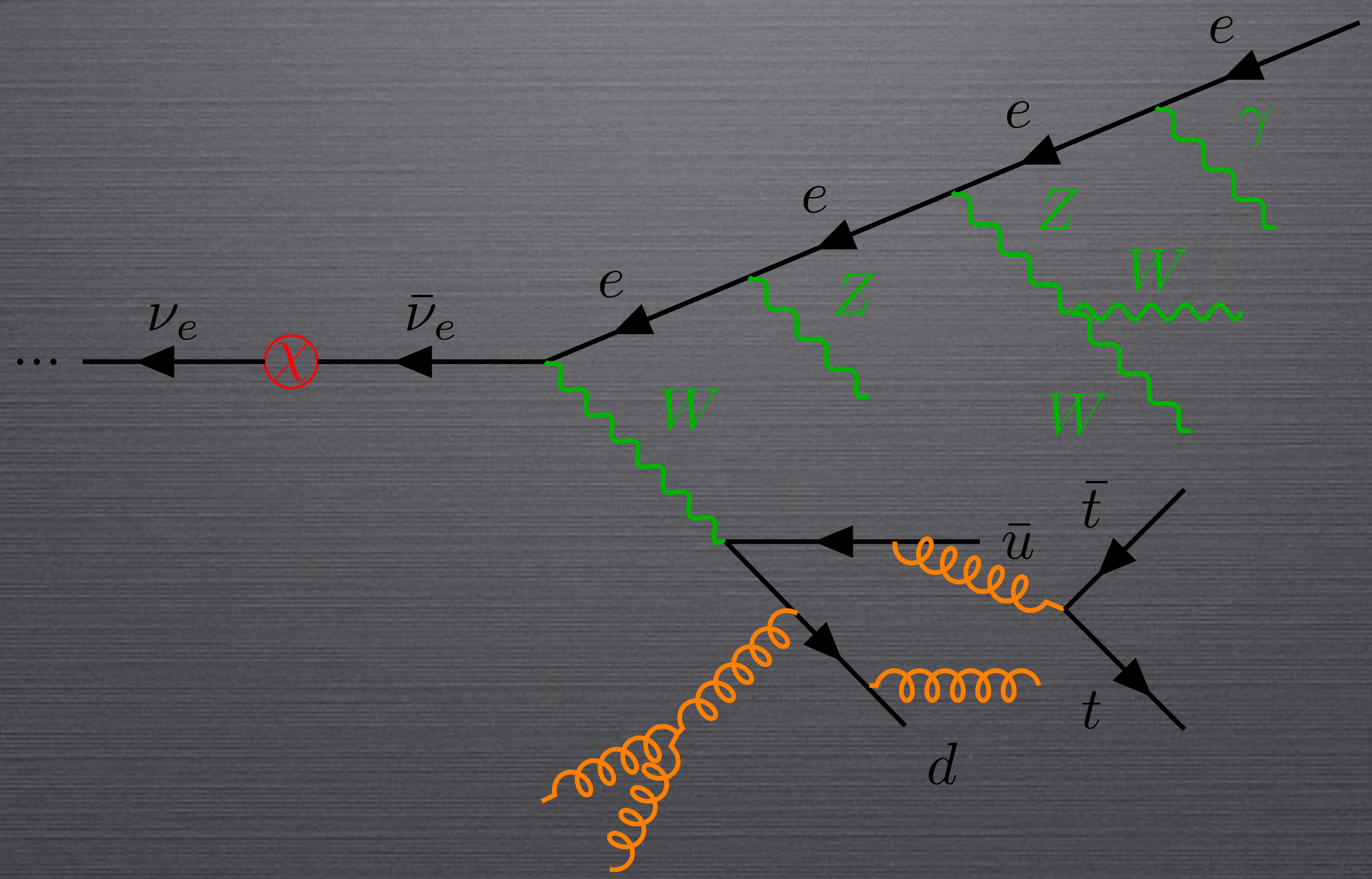
Nick Rodd

w/ Christian Bauer and Bryan Webber

TRIUMF, 12 March 2020

$^{*}\ m_\chi > 10$ TeV

Spectra for Heavy* Dark Matter



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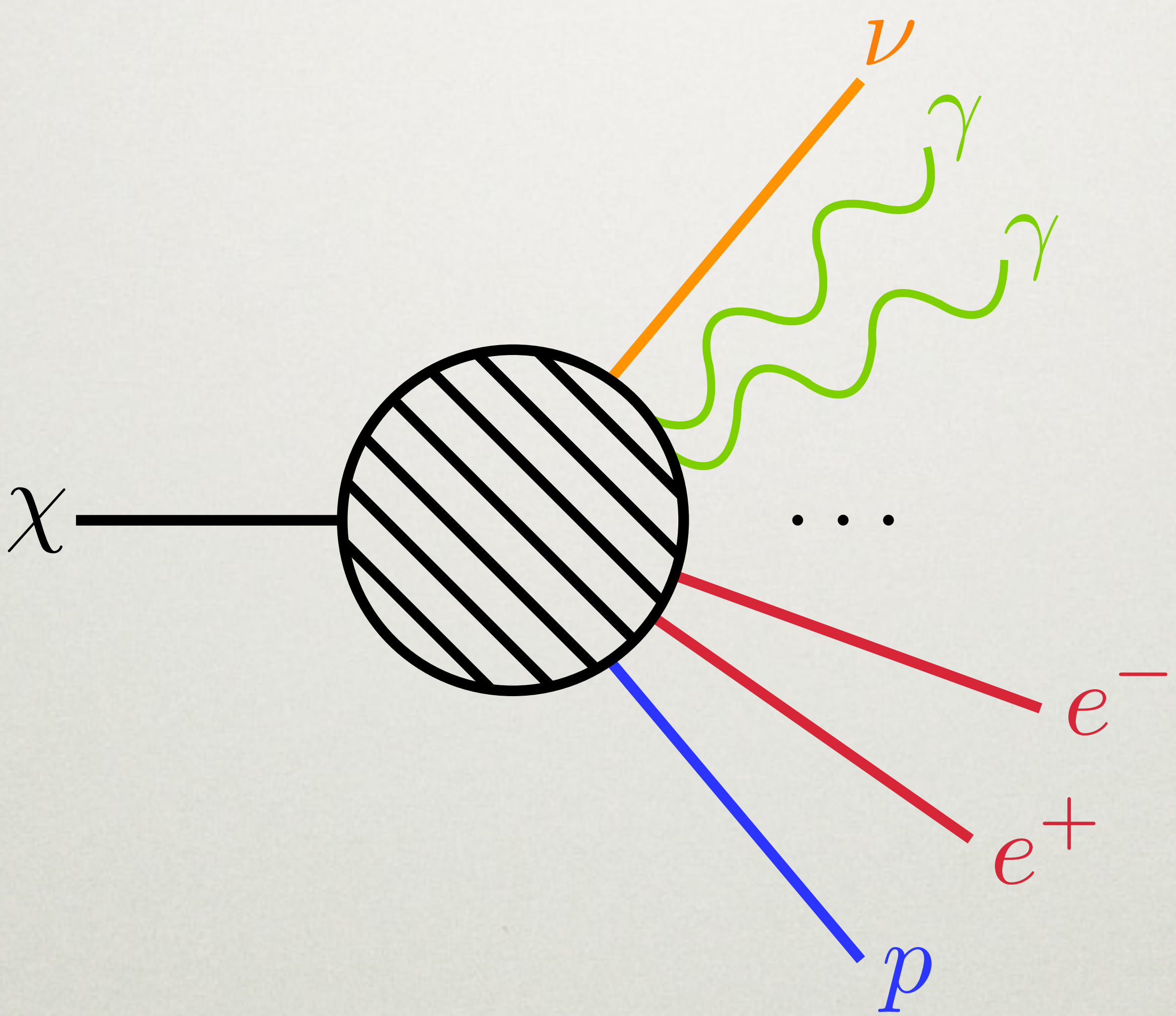
ID above 10 TeV: Overview

- Imagine EeV DM that can decay to neutrinos
- What is the **prompt*** spectrum of stable particles? $\{\gamma, \nu, e, p\}$



*__Note__ the spectrum at Earth can be quite different; [Cohen, Murase, **NLR**, Safdi, Soreq 1612.05638], [Murase, Beacom 1206.2595], [Esmaili, Serpico 1505.06486]

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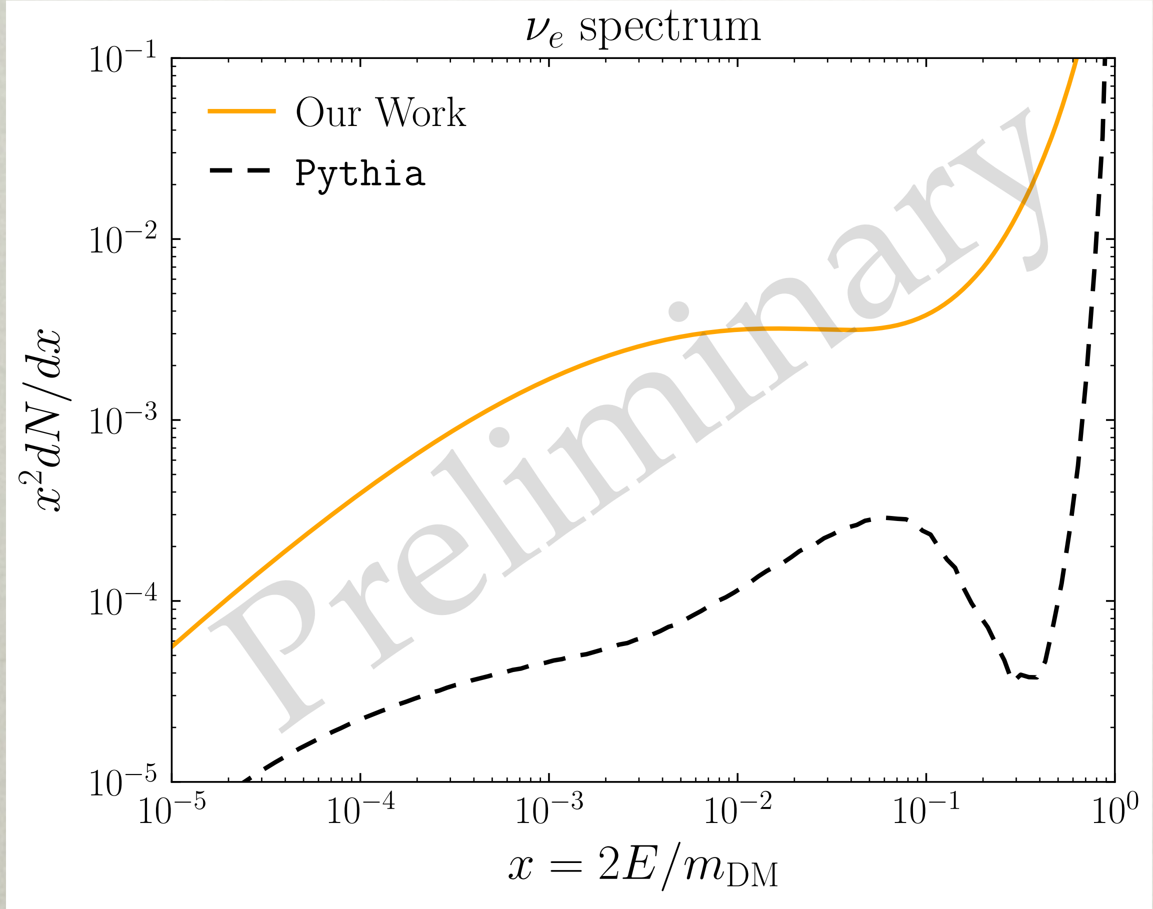

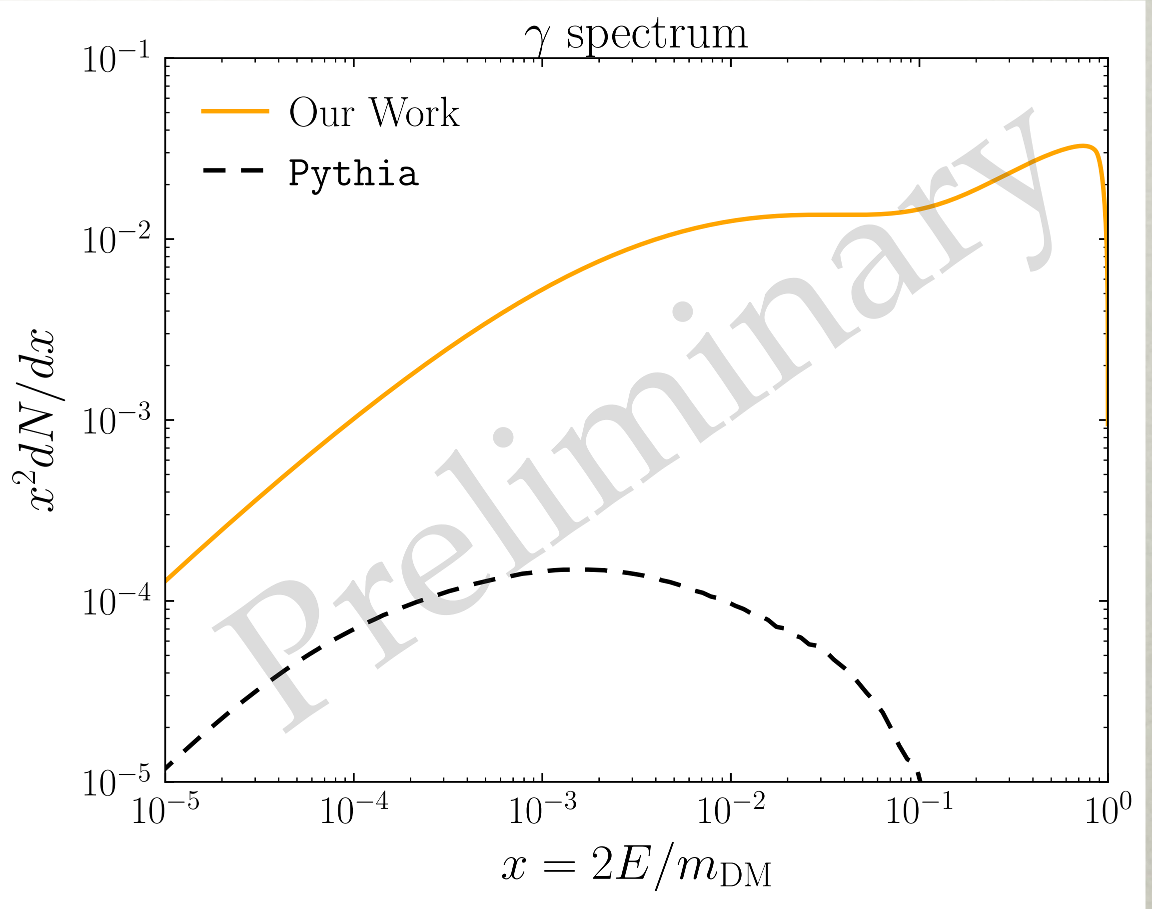

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our spectra

SCHEDULE I
TO ~~COLUMBIA METROPOLITAN CONVENTION CENTER~~
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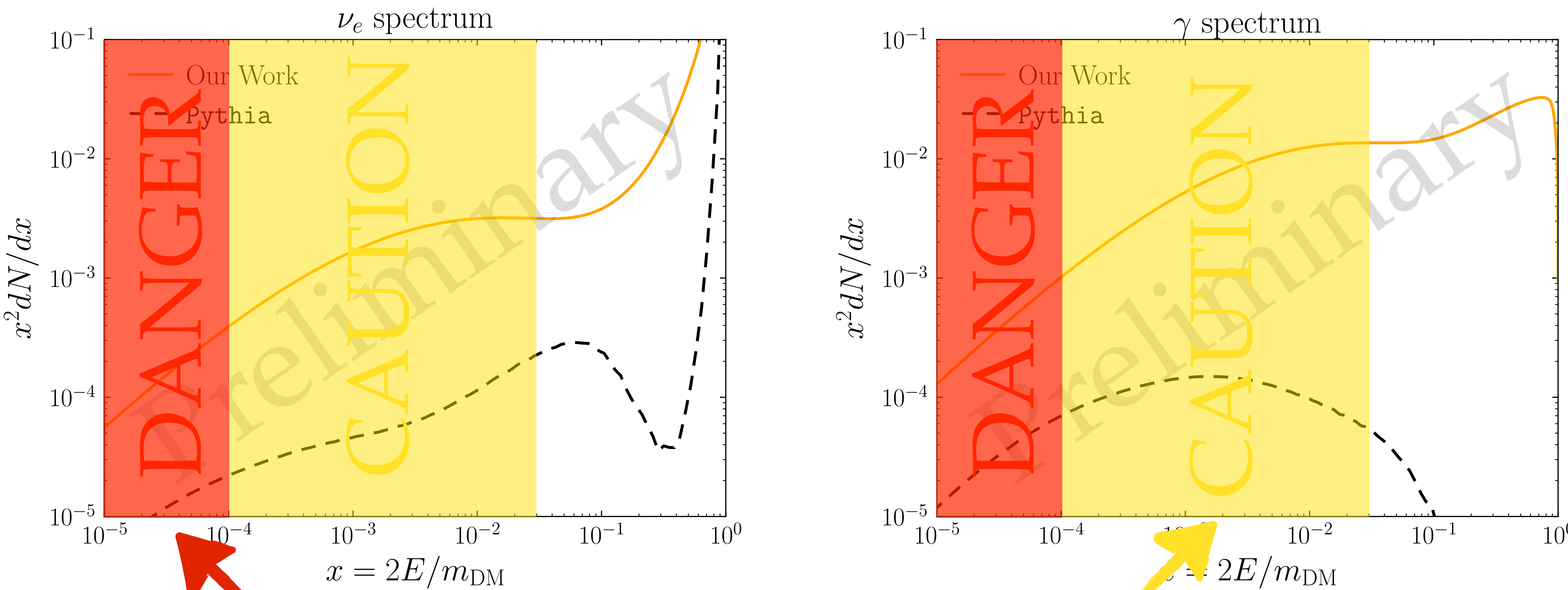
GENERAL TERMS AND CONDITIONS



Missing QCD single logs

Incomplete treatment of color coherence

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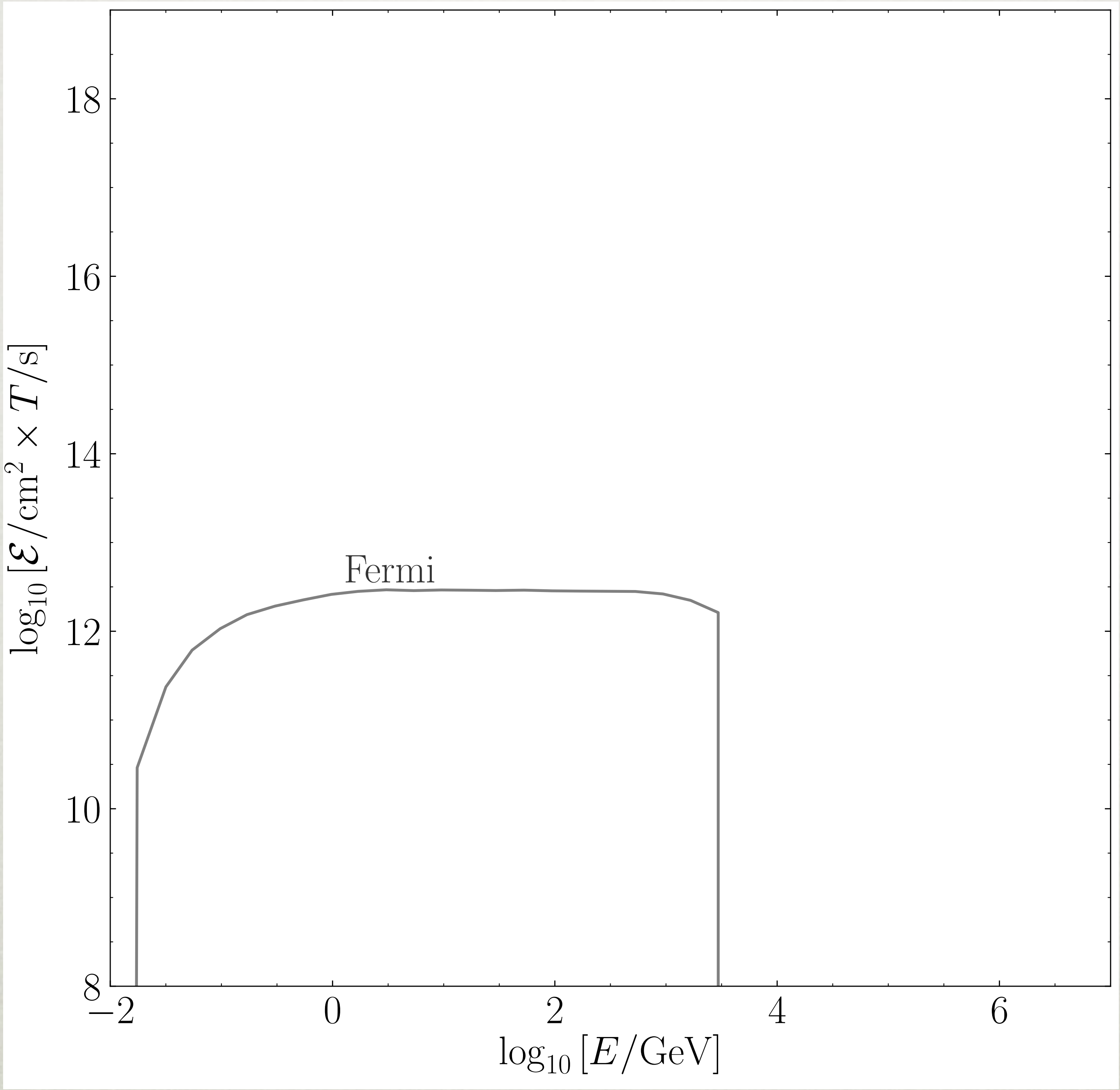
ID above 10 TeV: Experiments



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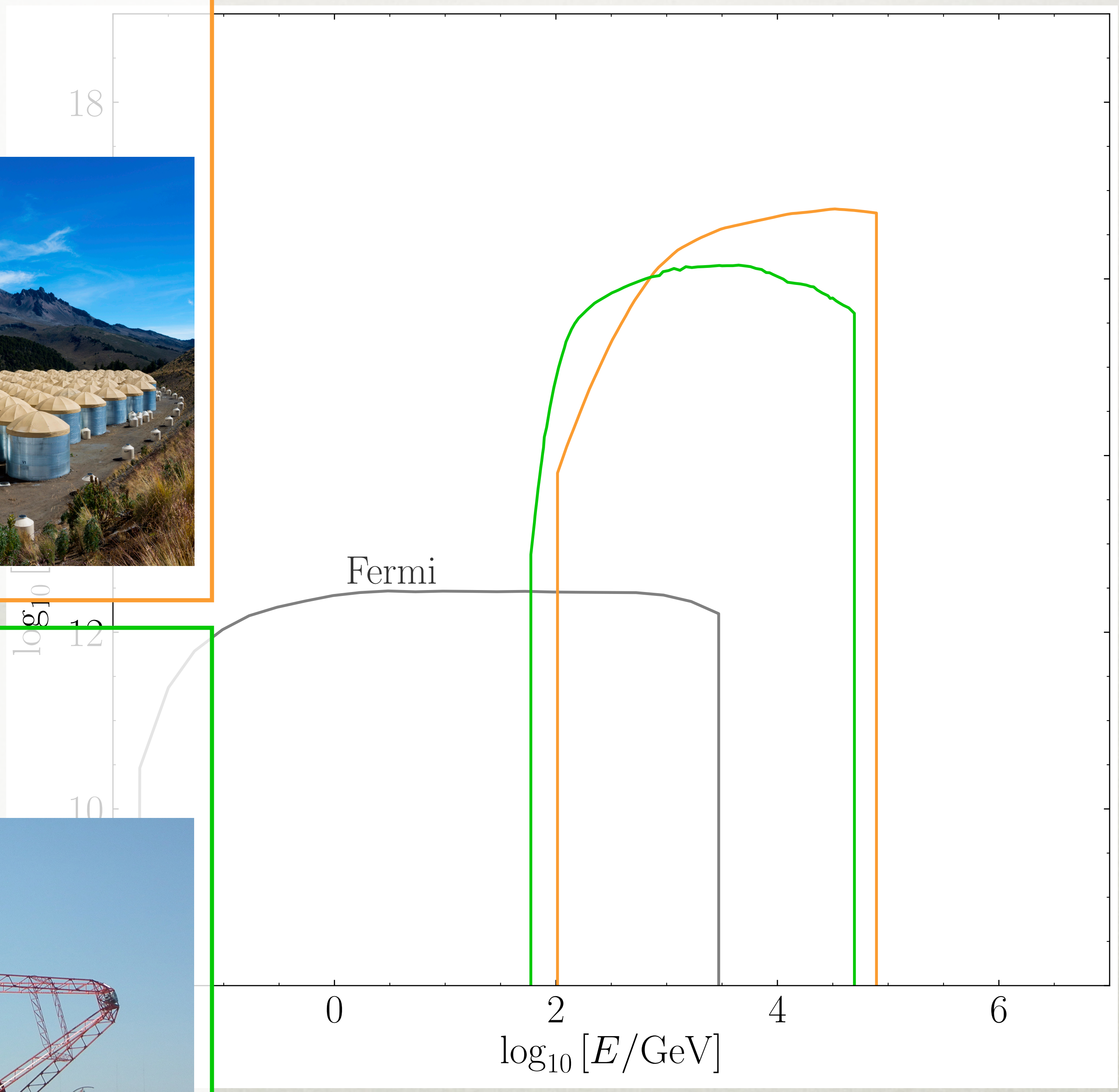


HAWC

2015-present

H.E.S.S.

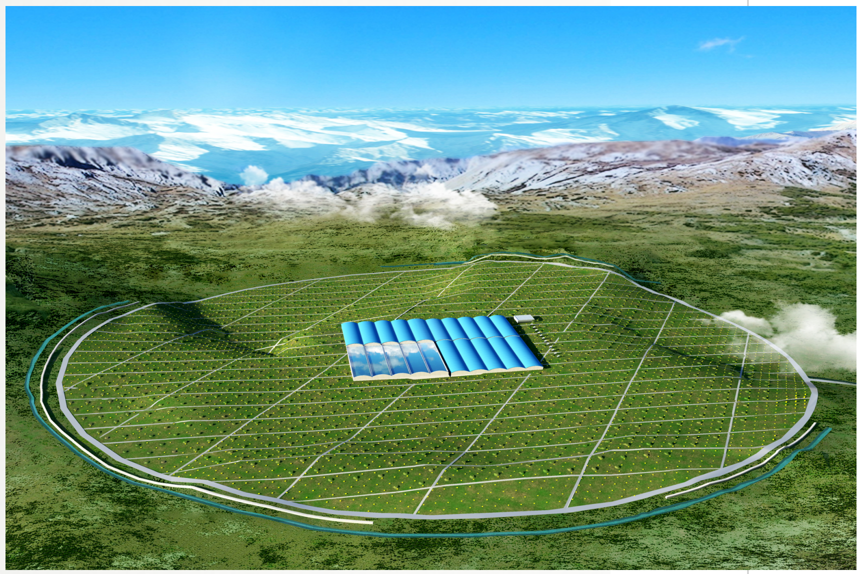
2002-present

(H.E.S.S. II 2012-)

ID above 10 TeV: Experiments

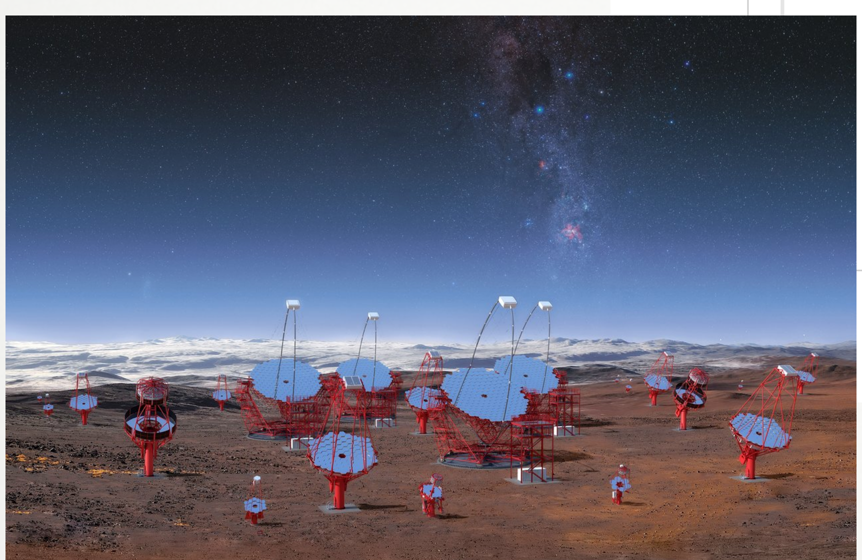
LHAASO

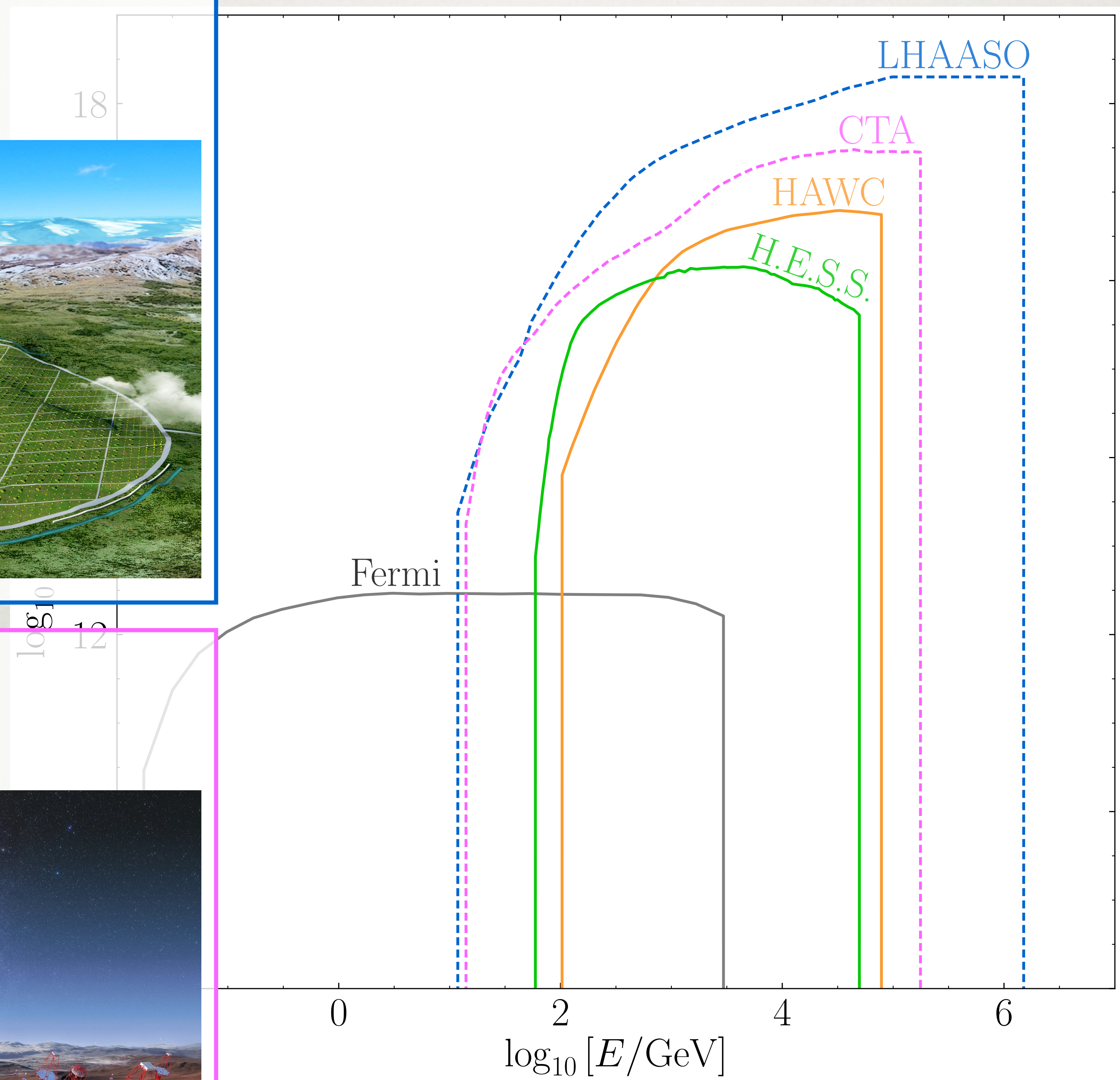
2020 [1905.02773]



CTA

~2025 [1709.07997]





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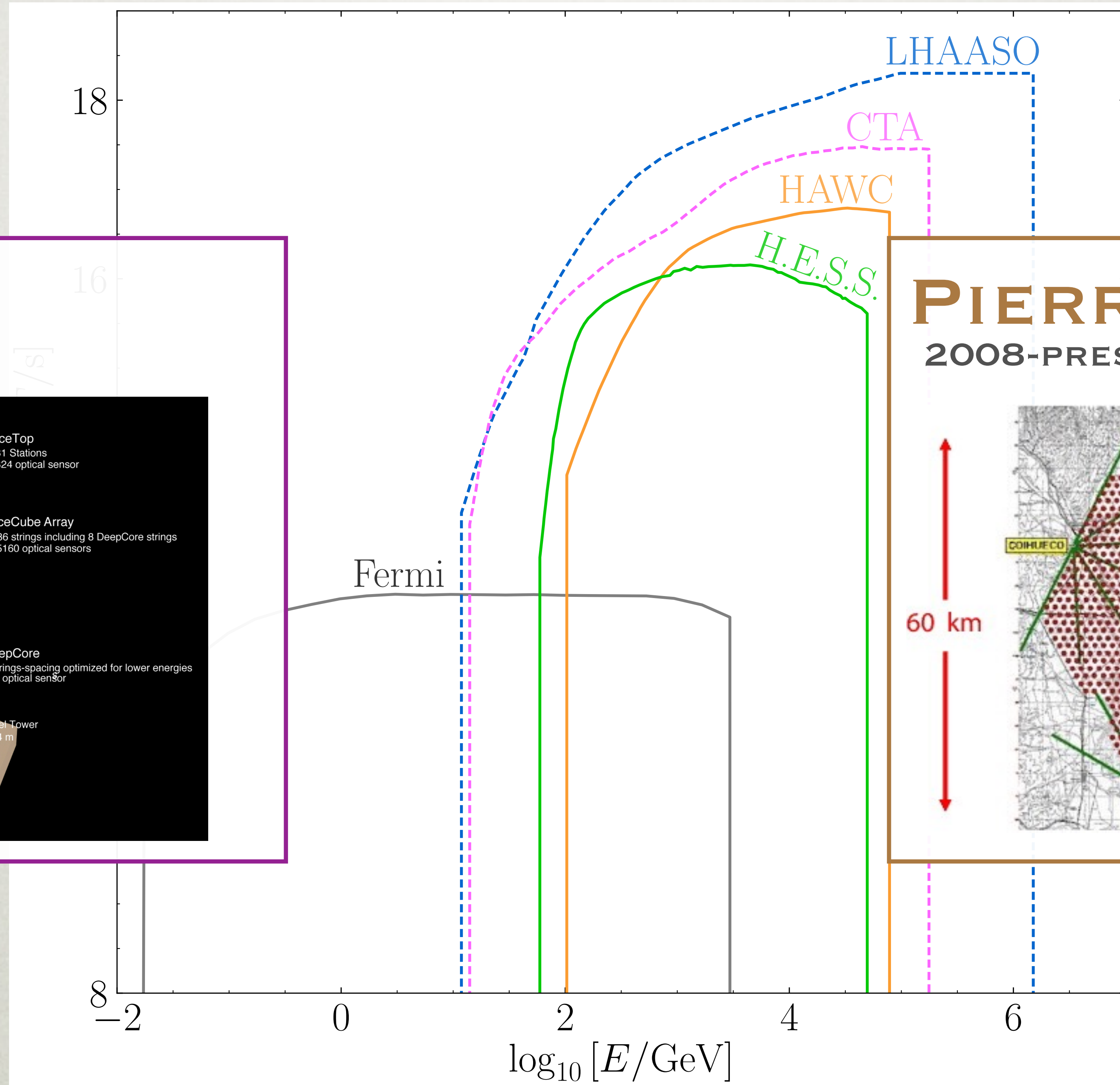
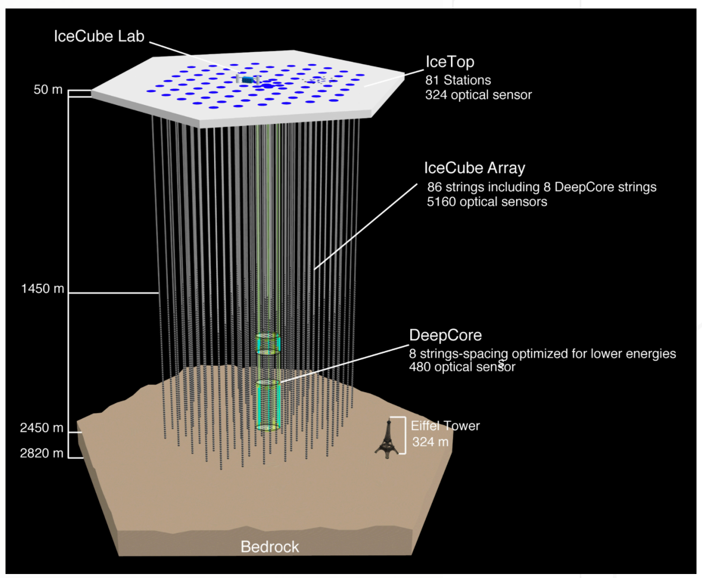


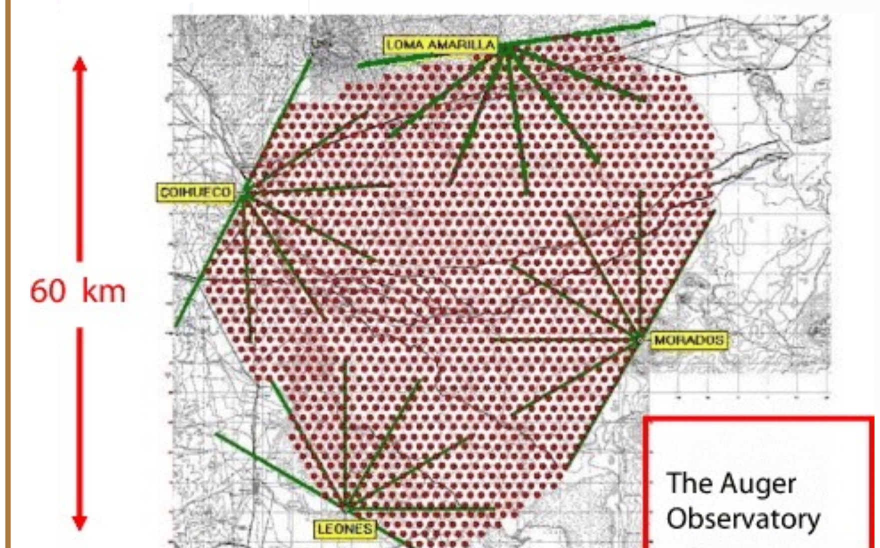
IceCube

2010-present



Pierre Auger

2008-present



ID above 10 TeV: Cutting Edge

- How are the collaborations getting their spectra?
  - IceCube: **Pythia** up to EeV [1804.03848]
  - HAWC: **Pythia** up to 10 PeV [NLR+ 1710.10288]
  - HESS: **Pythia** up to 20 TeV [1012.5602]
  - LHAASO: **PPPC4DMID** up to 100 TeV [1910.05017]
  - CTA: **PPPC4DMID** up to 10 TeV [1408.4131]
  - Pierre Auger:* **DGLAP** to GUT scale, e.g. [Kalashev, Kuznetsov 1606.07354]

PPPC 4 DM ID:
A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

Marco Cirelli[a,b], Gennaro Corcella[c,d,e], Andi Hektor[f], Gert Hütsi[g], Mario Kadastik[f], Paolo Panci[a,h,i,j], Martti Raidal[f], Filippo Sala[d,e], Alessandro Strumia[a,e,f,k]

[1012.4515]

Medical & Science

DGLAP

means

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi

by acronymsandslang.com

*__See also:__ [Barbot, Drees 2002, 2003] for a full treatment in the MSSM

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  - HESS: Pythia up to 20 TeV [1012.5602]

No Ideal Option

- Pythia: no electroweak TGC, difficult to run above ~PeV
- PPPC4DMID: Stops at 100 TeV, only LO electroweak
- DGLAP: can evolve arbitrarily high, but just done for b

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Our Approach

- Basic question: probability for an initial particle *j* to produce a particle *i* carrying momentum fraction x
- General description given by a **fragmentation function**

$$d_j^i(x;\,Q,\,0)$$

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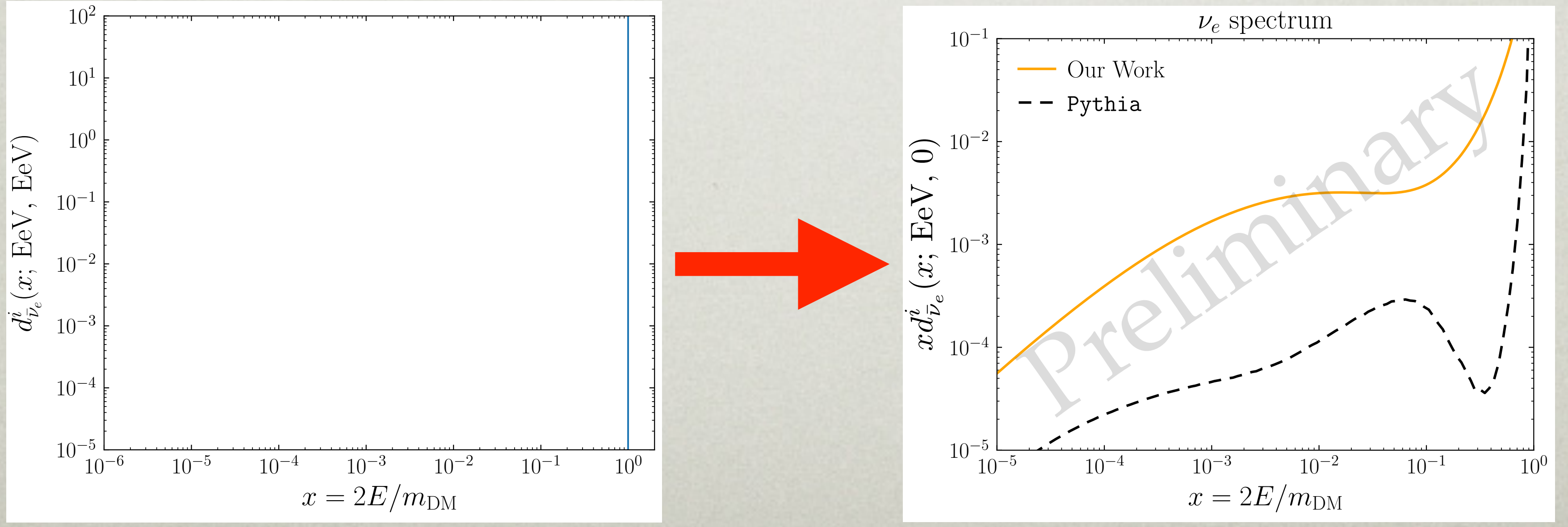
$$d_j^i(x;\, Q,\, 0)$$

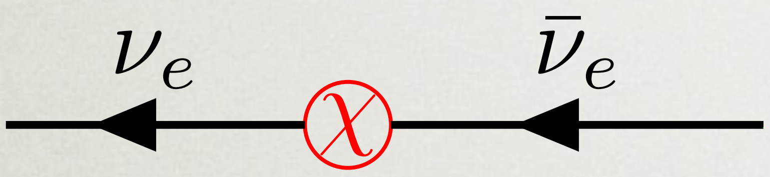
- Calculate in three steps:
  - 1. $Q \to q_W^+$: DGLAP evolution using the full unbroken SM
  - 2. $q_W^+ \to q_W^-$: integrate out weak states ($q_W^\pm = q_W(1 \pm \epsilon)$)
  - 3. $q_W^- \to 0$: low energy showering and hadronisation in Pythia

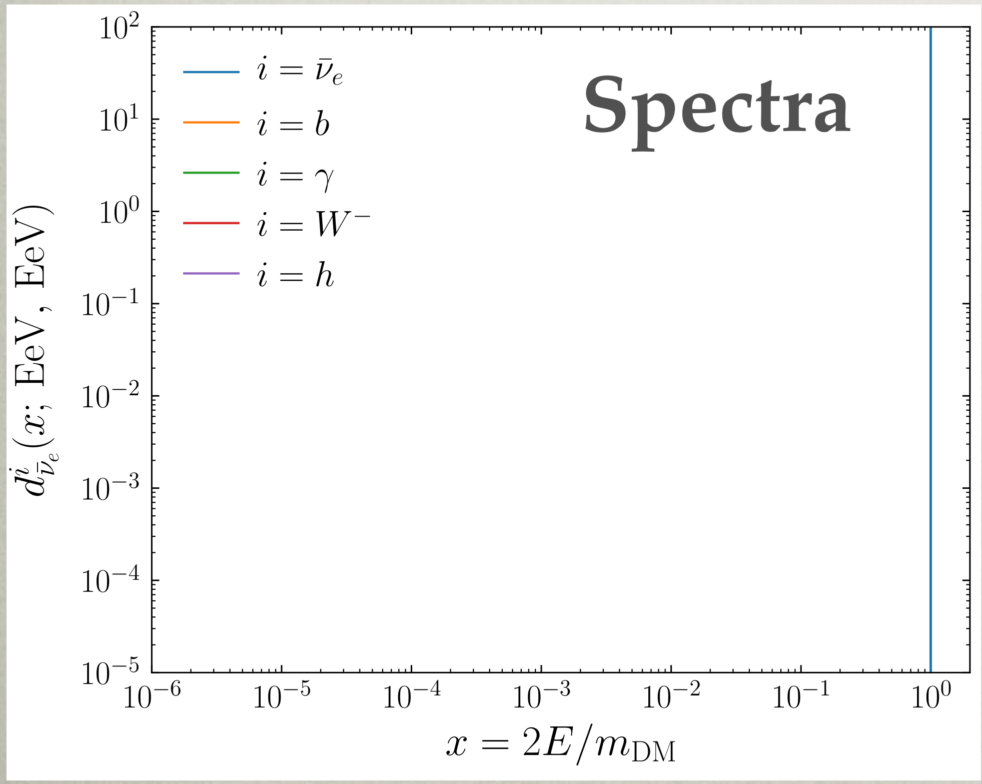


Step 1: DGLAP

Initial Condition

$$d(x;\, Q,\, Q) = \delta(1-x)$$

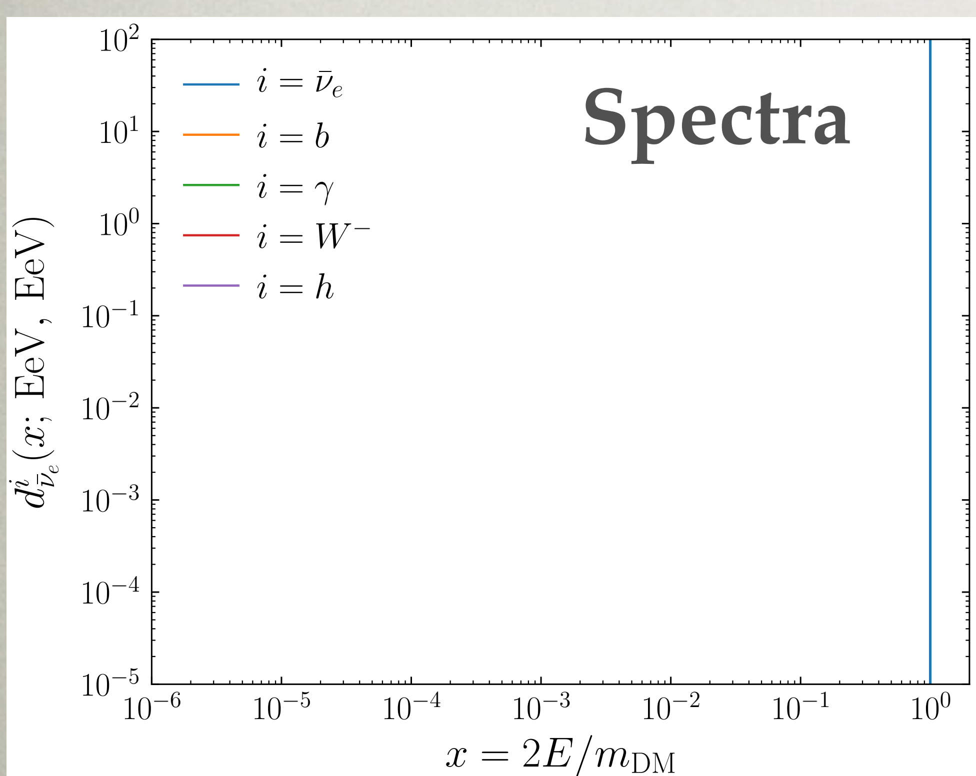




Step 1: DGLAP

Evolve with DGLAP,* using all interactions in the unbroken SM

$$\mu \frac{\partial}{\partial \mu} d(x;\, \mu) = \frac{\alpha}{\pi} \int_x^1 dz\, \hat{P}(z) d(x/z;\, \mu) - \frac{\alpha}{\pi} d(x;\, \mu) \int_0^1 dz\, \hat{P}(z)$$



*Suppressing particle indices.** In truth 1740 coupled FFs
In truth should have d_i^j, where j can take values:

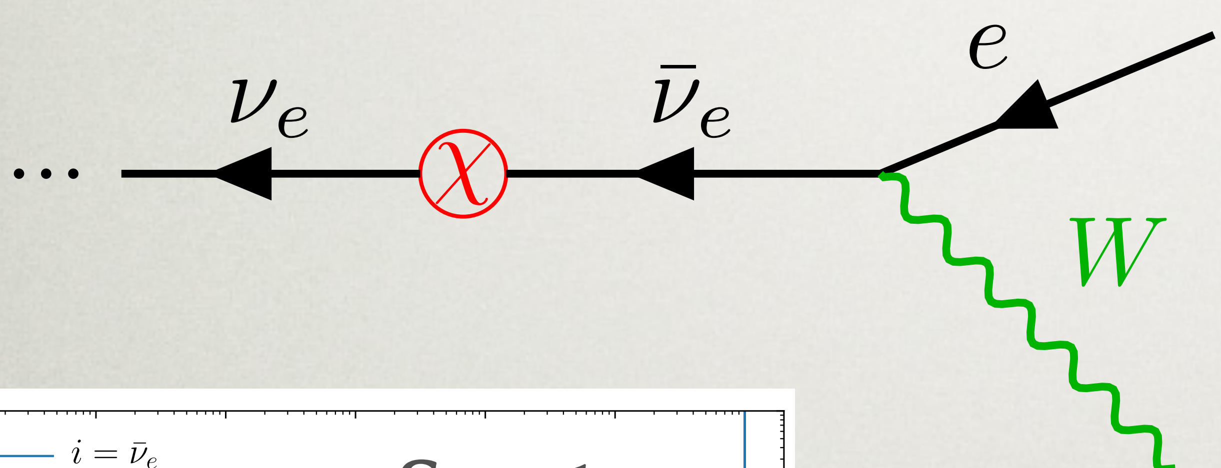
$$\{u_{L/R},\, d_{L/R},\, e_{L/R},\, \nu_L\} \times 3 \times 2 = 42$$

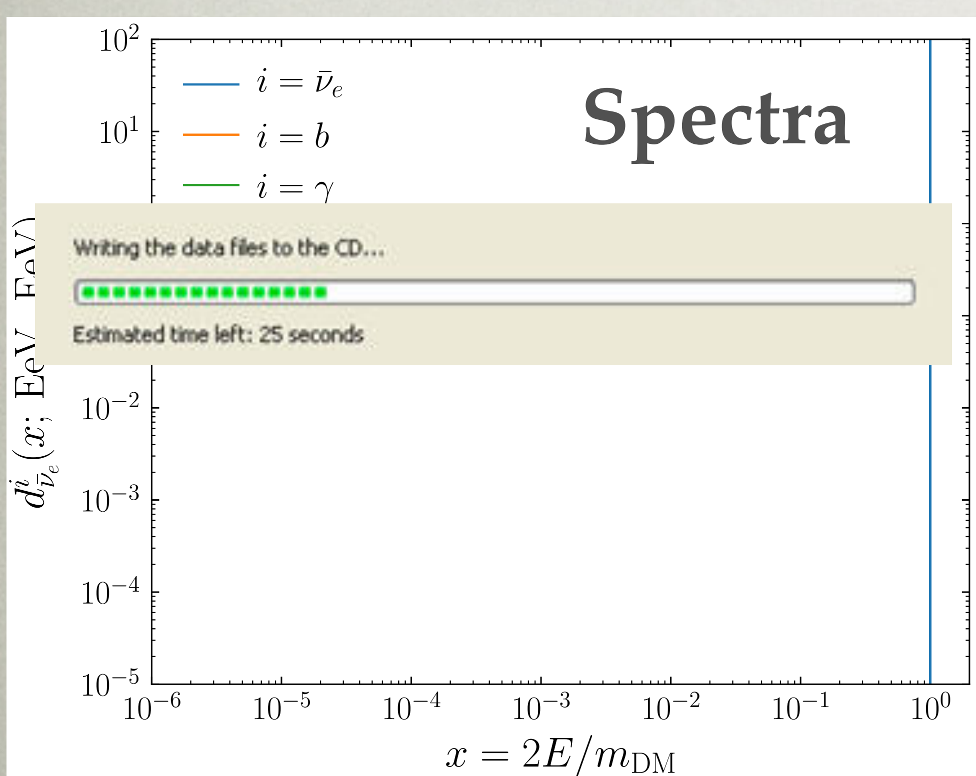
Lots of interesting physics, including electroweak double logs and polarisation generation

For detail see [Bauer, Provasoli, Webber 1806.10157], [Bauer, Webber 1808.08831]

Step 1: DGLAP

Semiclassical evolution





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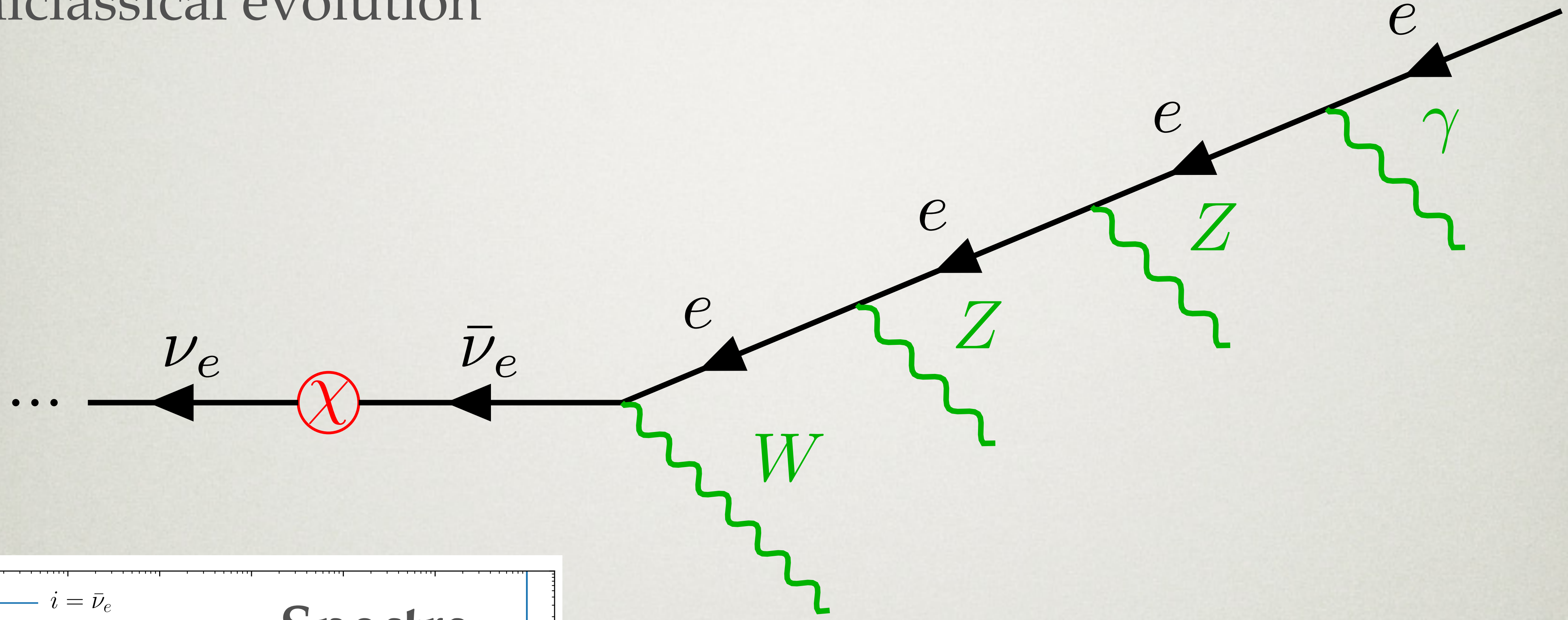

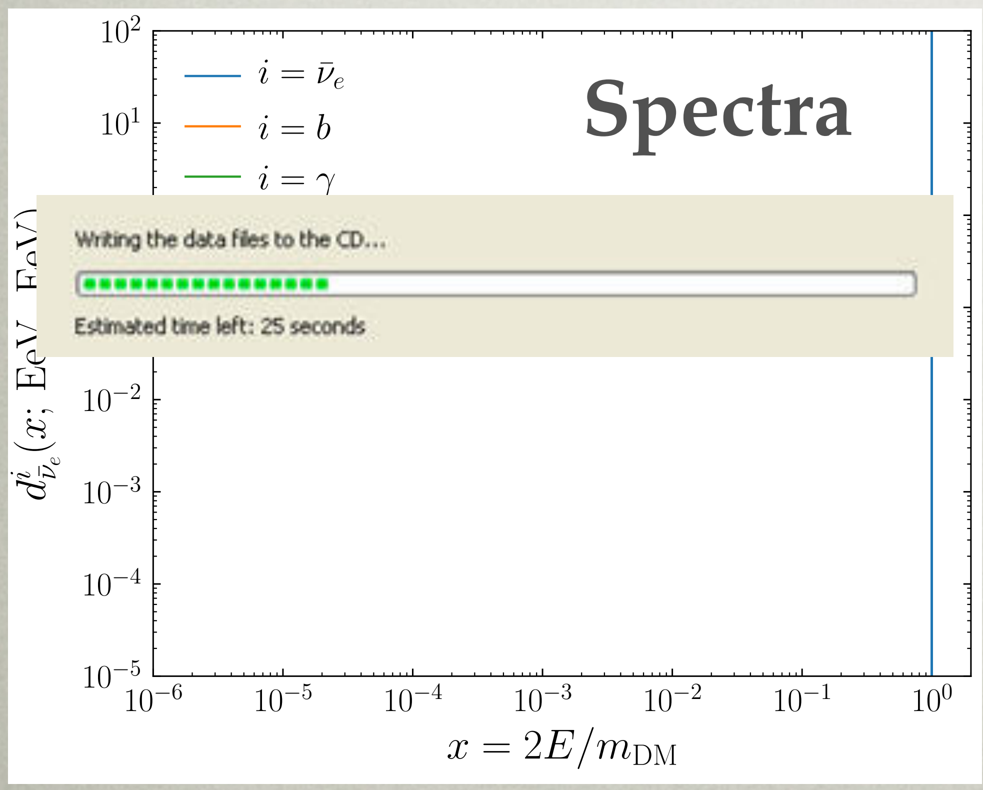

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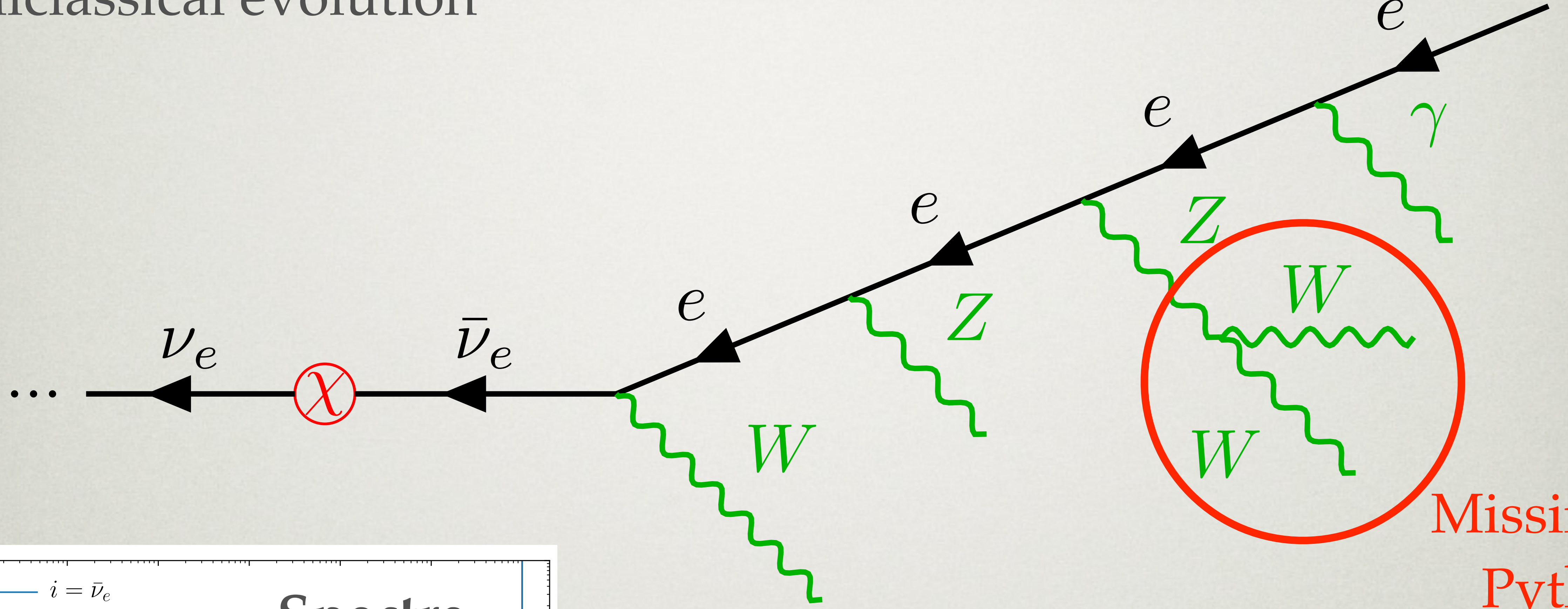
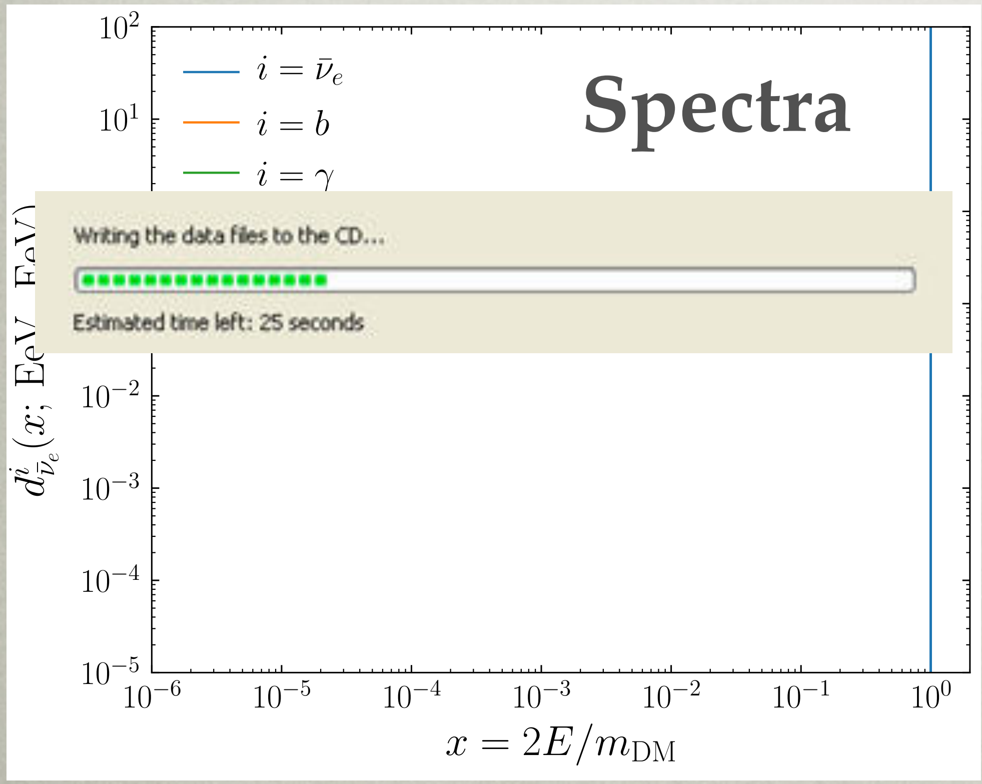


Missing in Pythia



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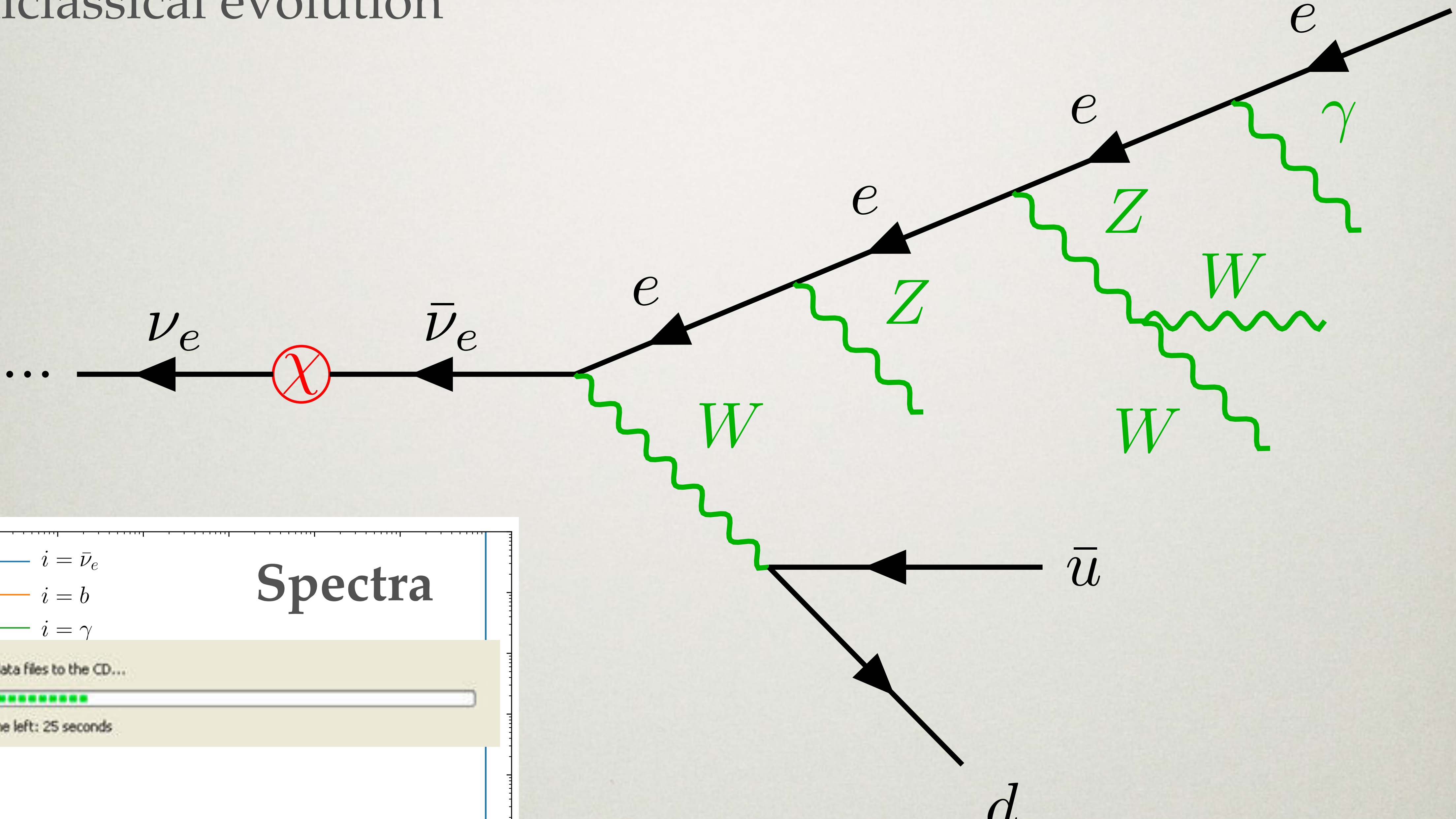

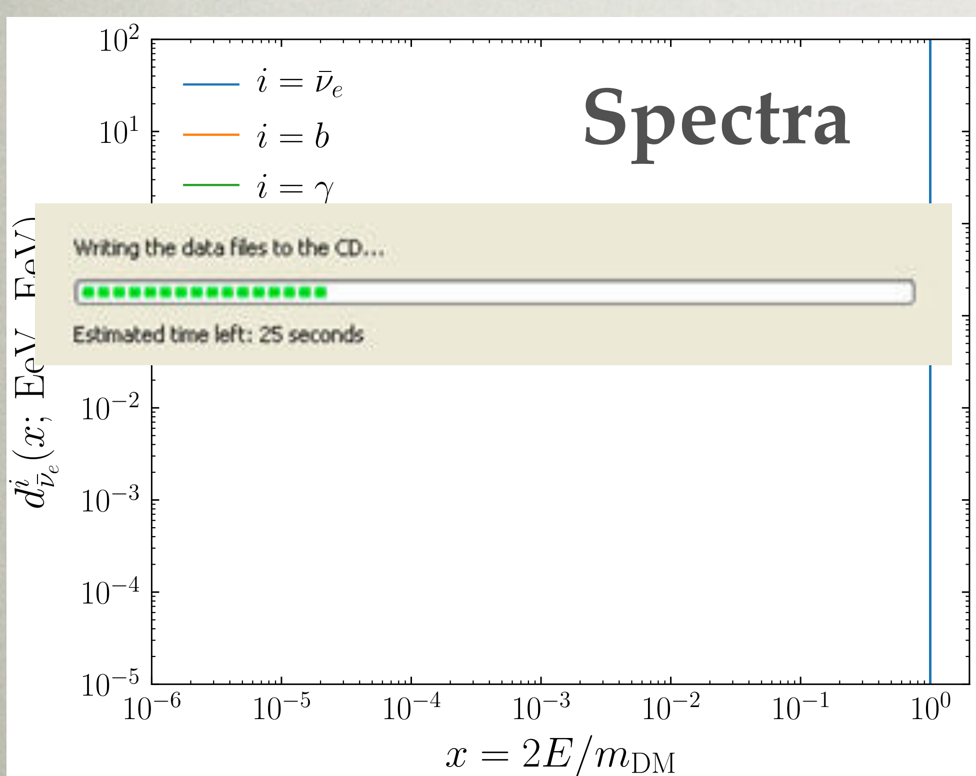

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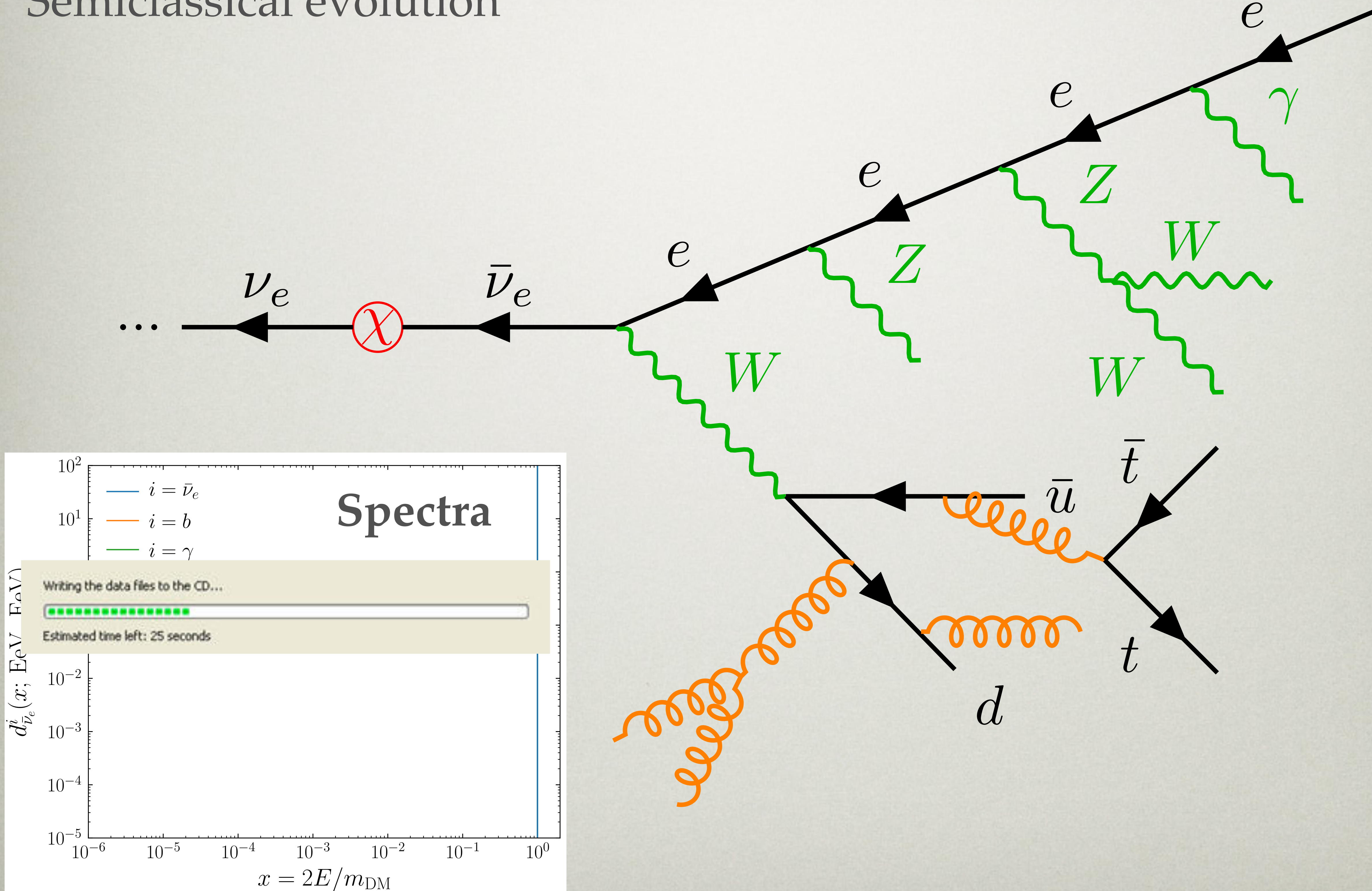
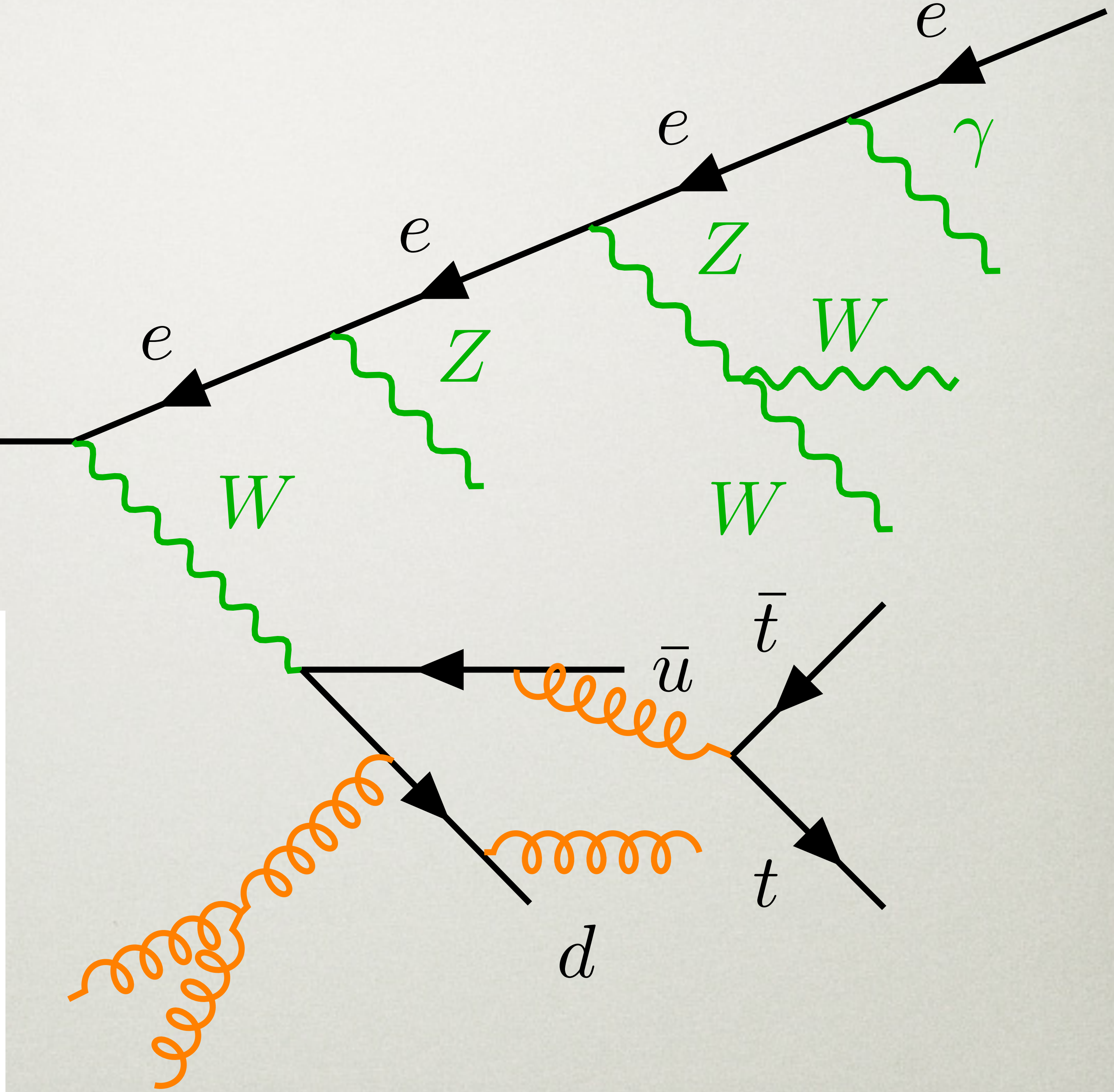
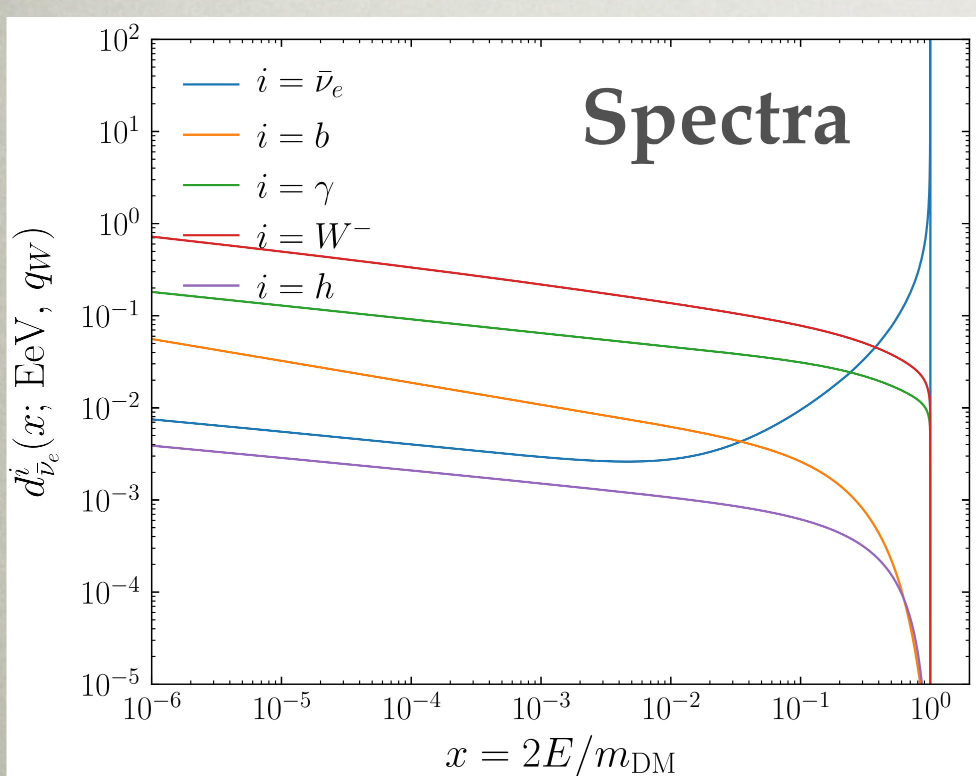


Step 1: DGLAP

Final result at EW scale

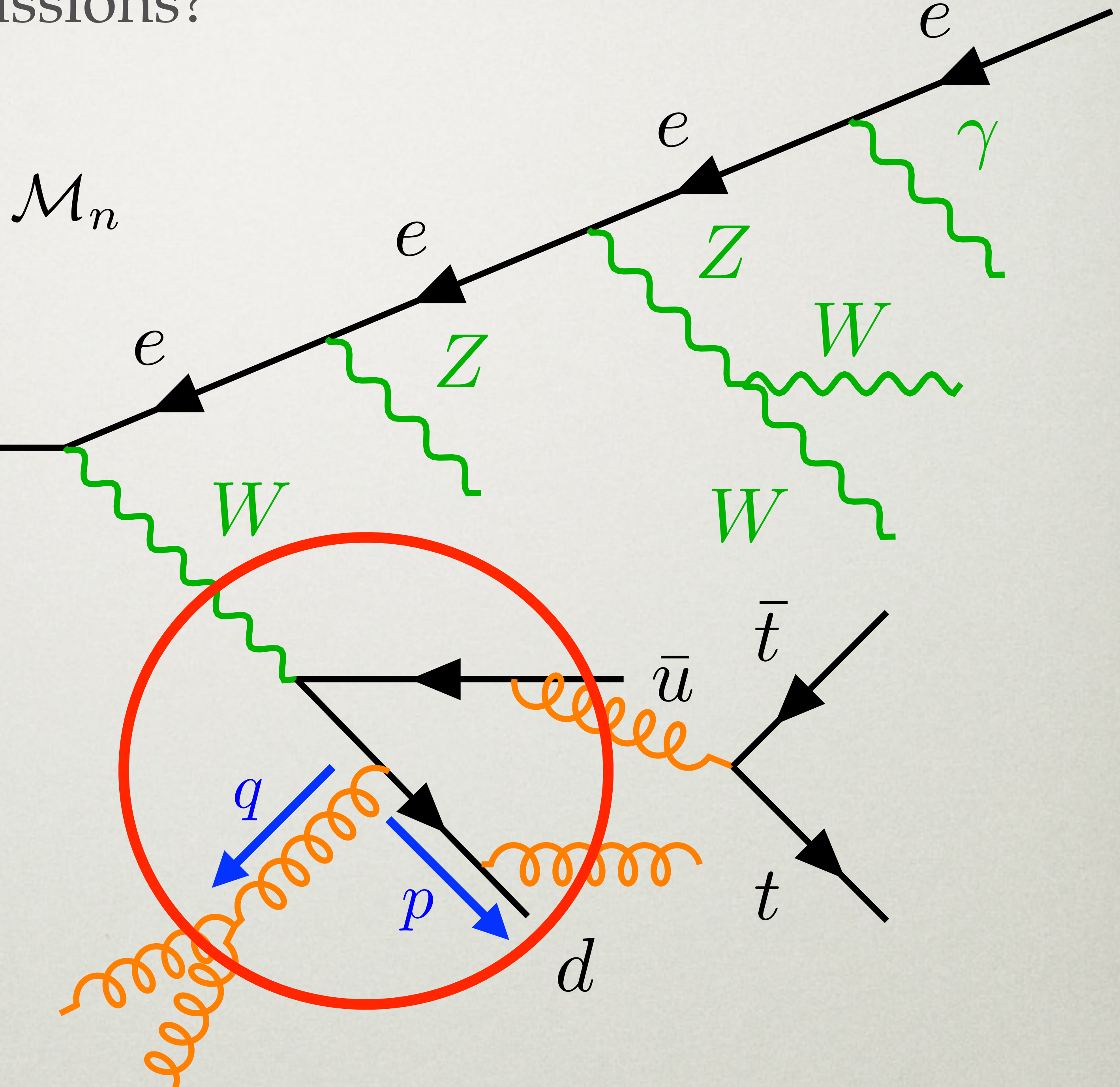


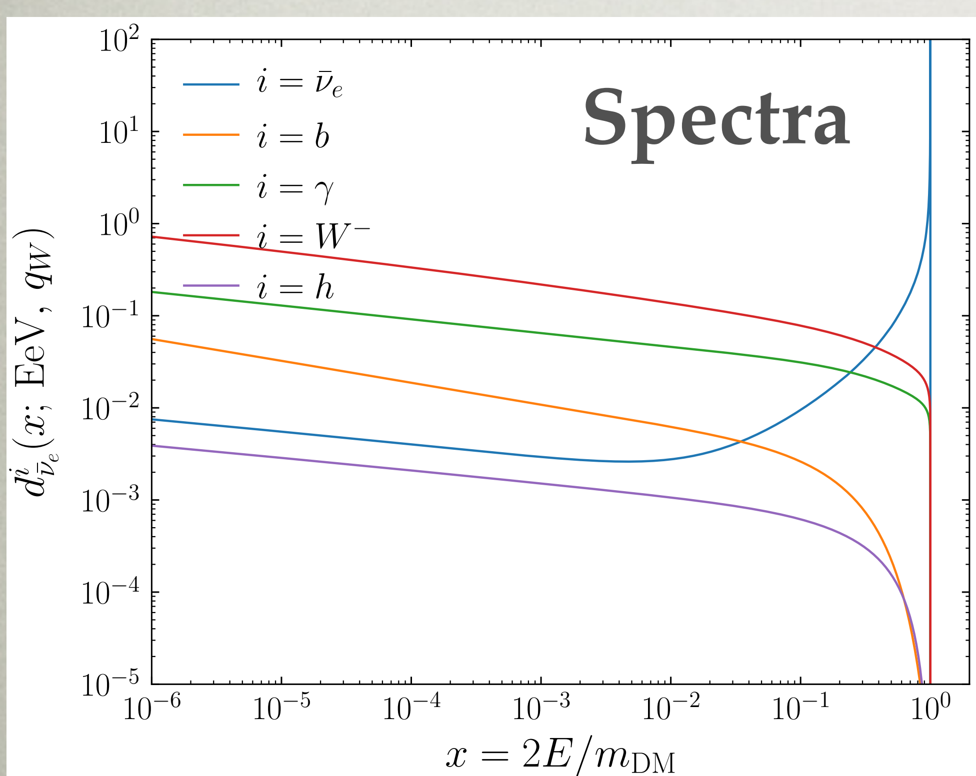


Step 1: DGLAP

What about purely soft emissions?

$$\lim_{q \to 0} \mathcal{M}_{n+1} \approx Q \left(\frac{p \cdot \epsilon}{p \cdot q} \right) \mathcal{M}_n$$





Soft gluon resolves combined color = 0, cannot emit!

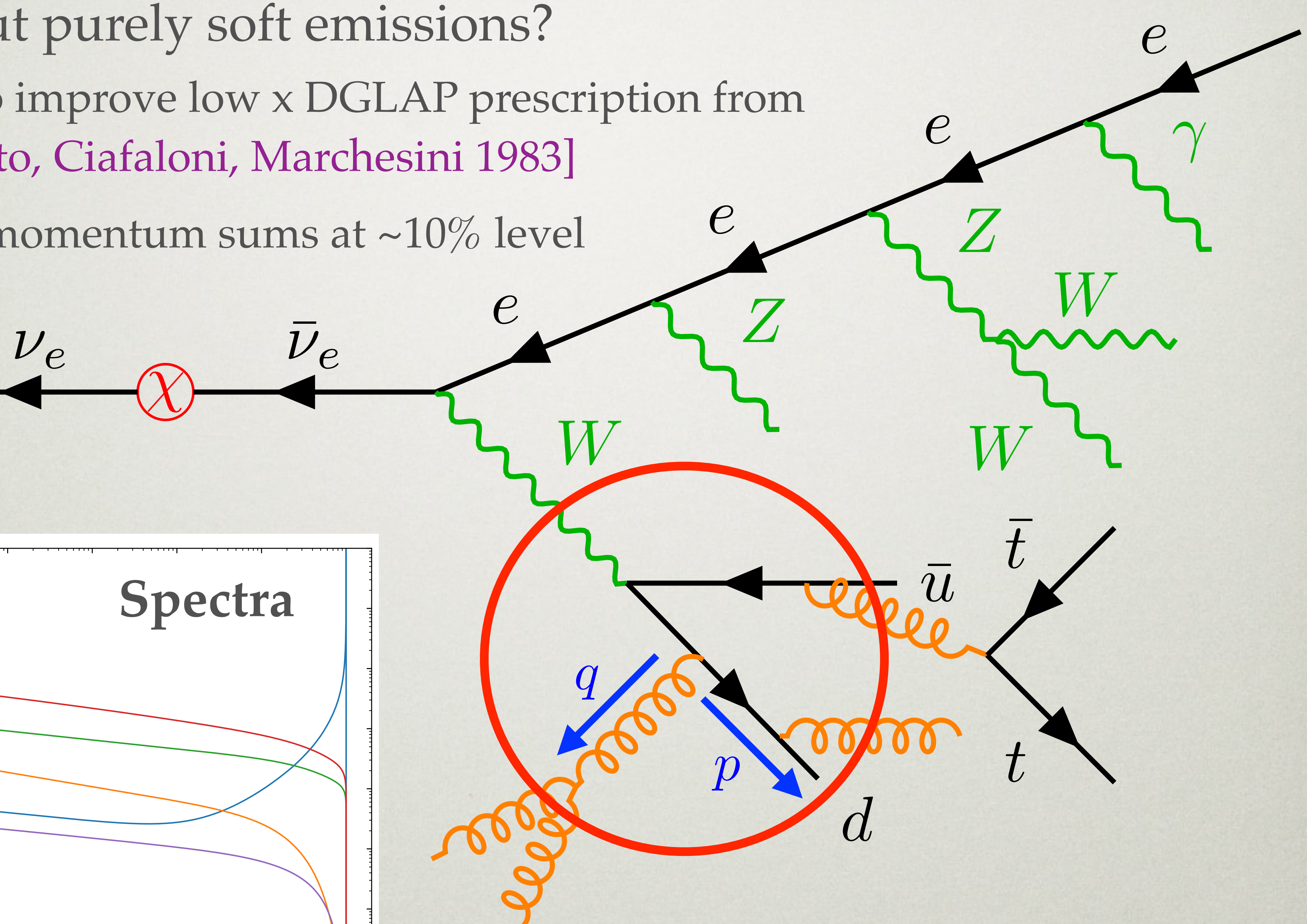
Generically destructive interference; "color coherence"

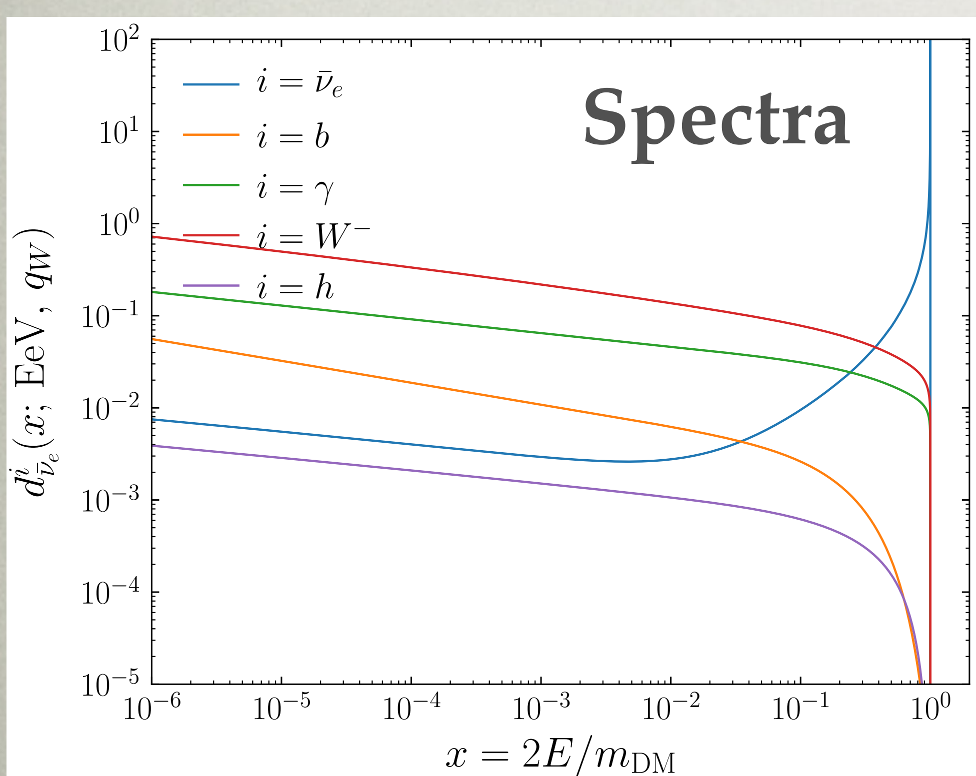
Step 1: DGLAP

THE UNIVERSITY OF CALIFORNIA BERKELEY 1868

What about purely soft emissions?

- Trick to improve low x DGLAP prescription from [Bassetto, Ciafaloni, Marchesini 1983]
- Ruins momentum sums at ~10% level





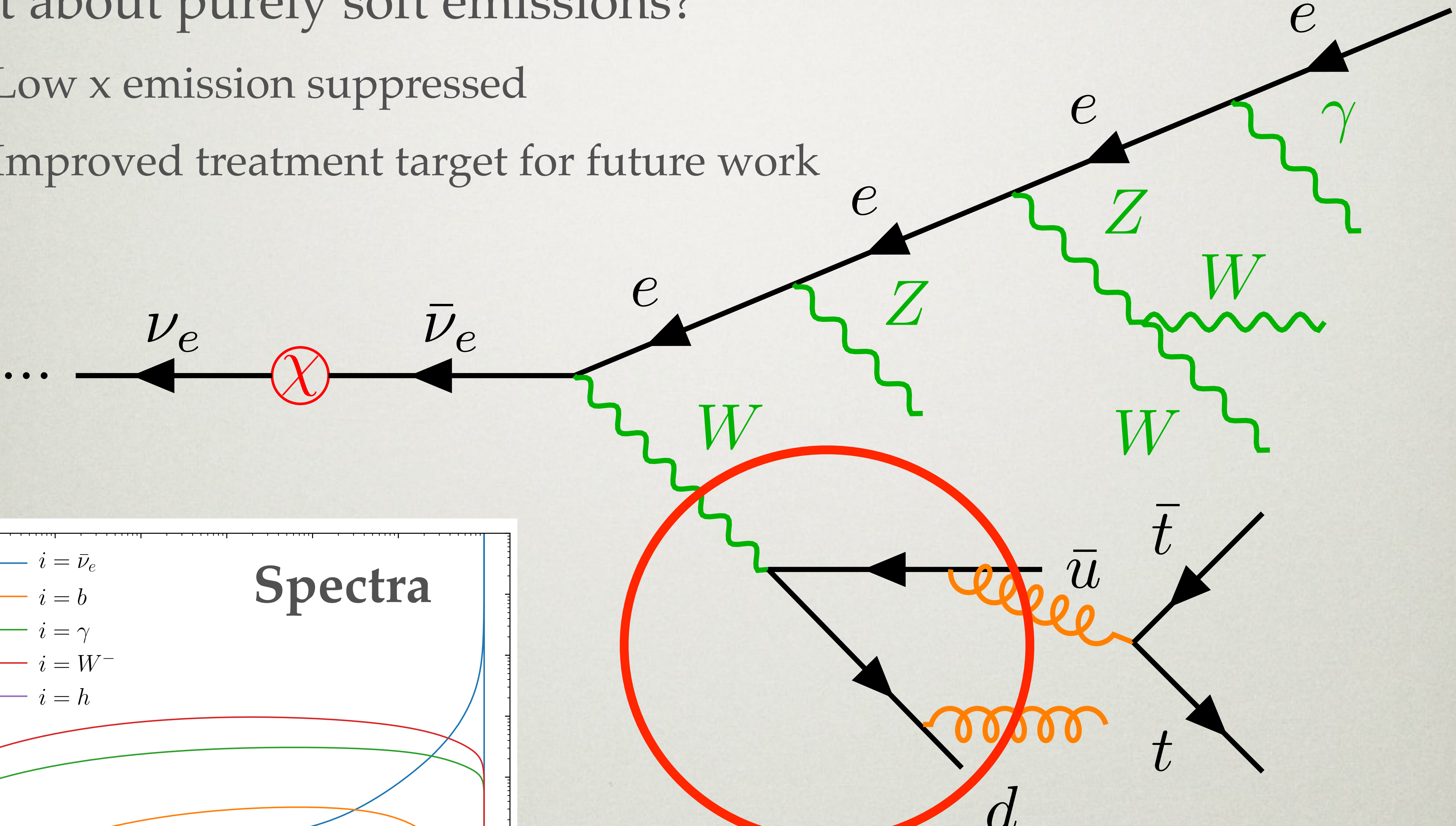
Soft gluon resolves combined color = 0, cannot emit!

Generically destructive interference; "color coherence"

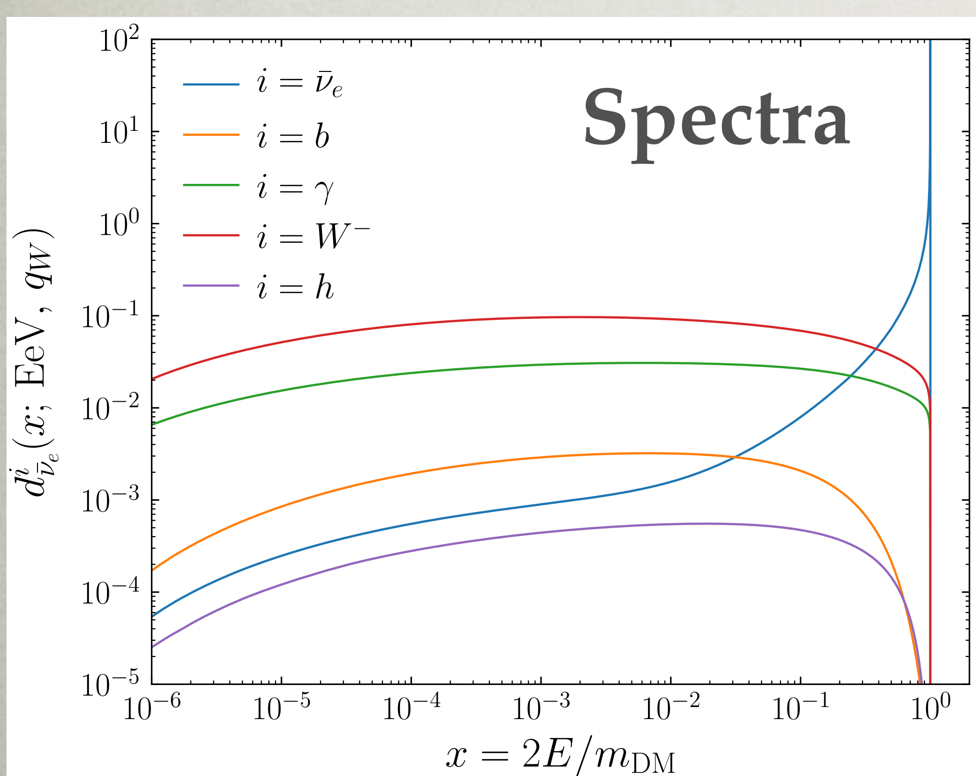
Step 1: DGLAP

What about purely soft emissions?

- Low x emission suppressed
- Improved treatment target for future work

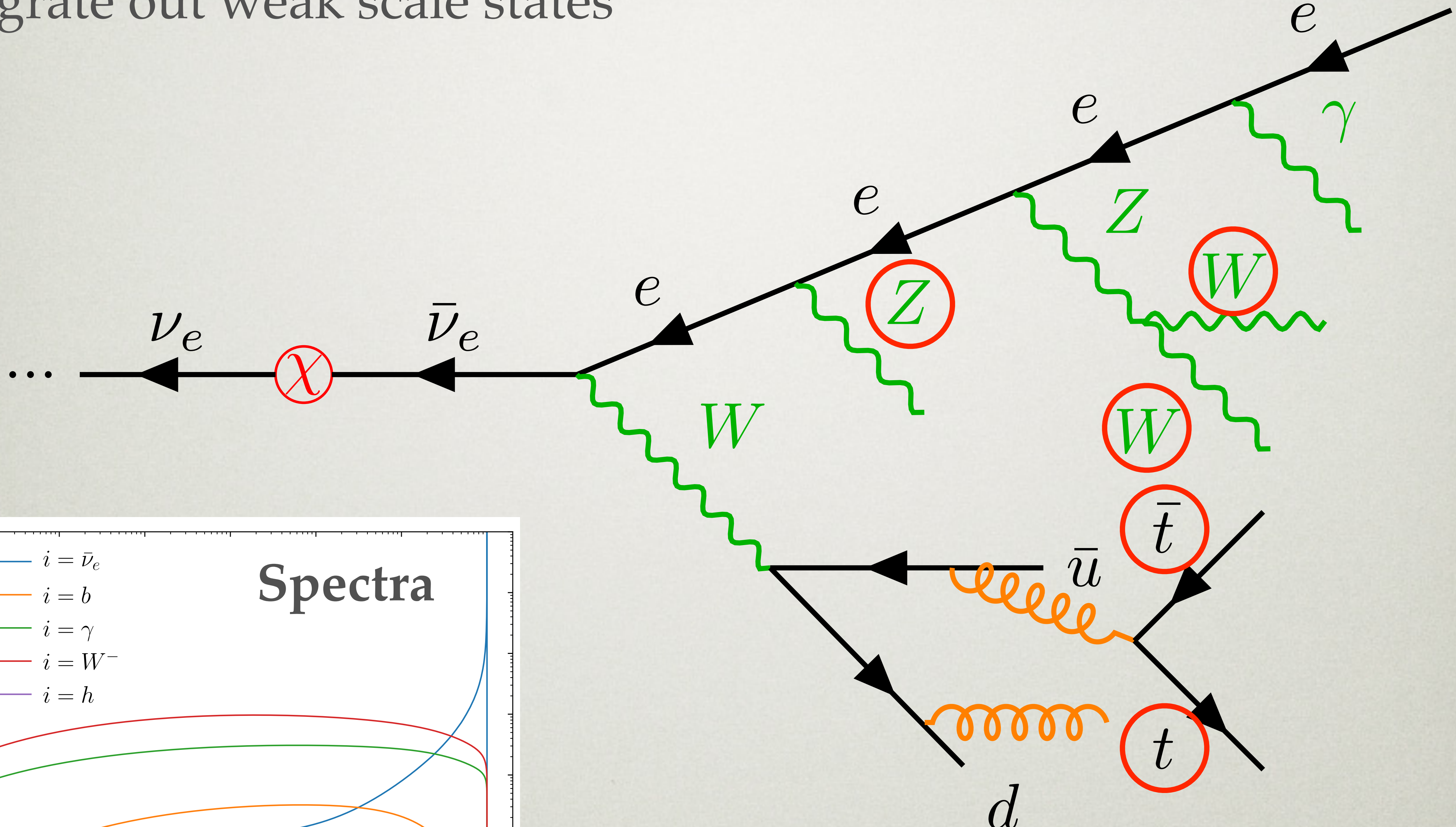


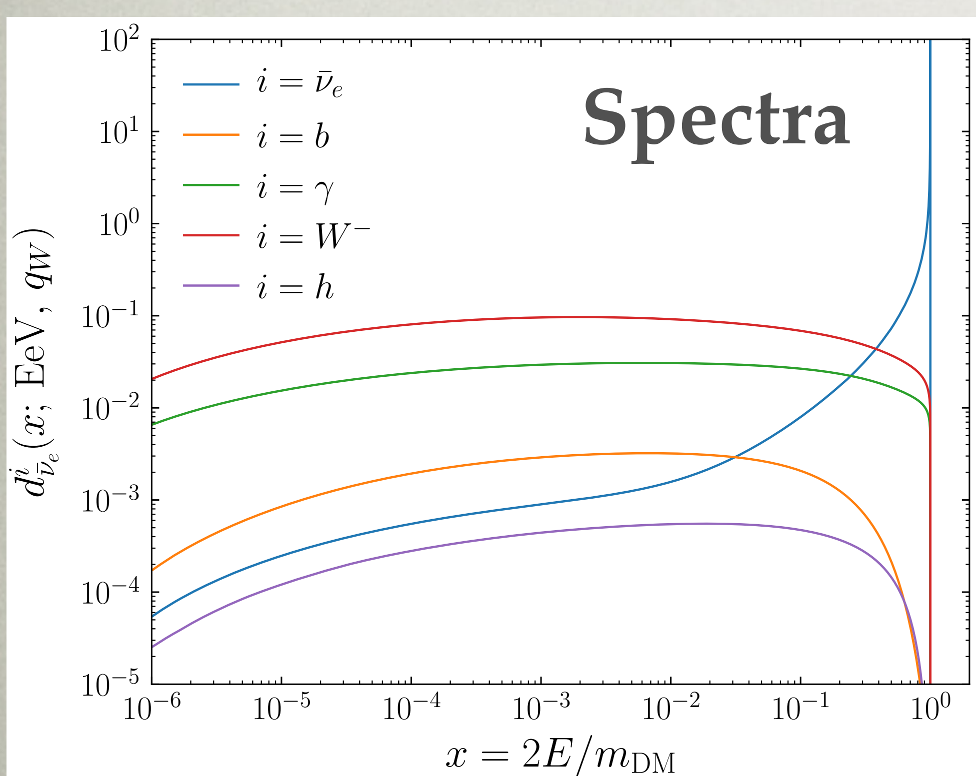
Soft gauge boson radiation suppressed



Step 2: Weak Matching

Integrate out weak scale states





Step 2: Weak Matching

- Exploit FF convolution property

$$d(x;\, Q,\, q_W^-) = \int_x^1 \frac{dz}{z} d(z;\, Q,\, q_W^+)\, d(x/z;\, q_W^+,\, q_W^-)$$

$$= d(x;\, Q,\, q_W^+) \otimes d(x;\, q_W^+,\, q_W^-)$$

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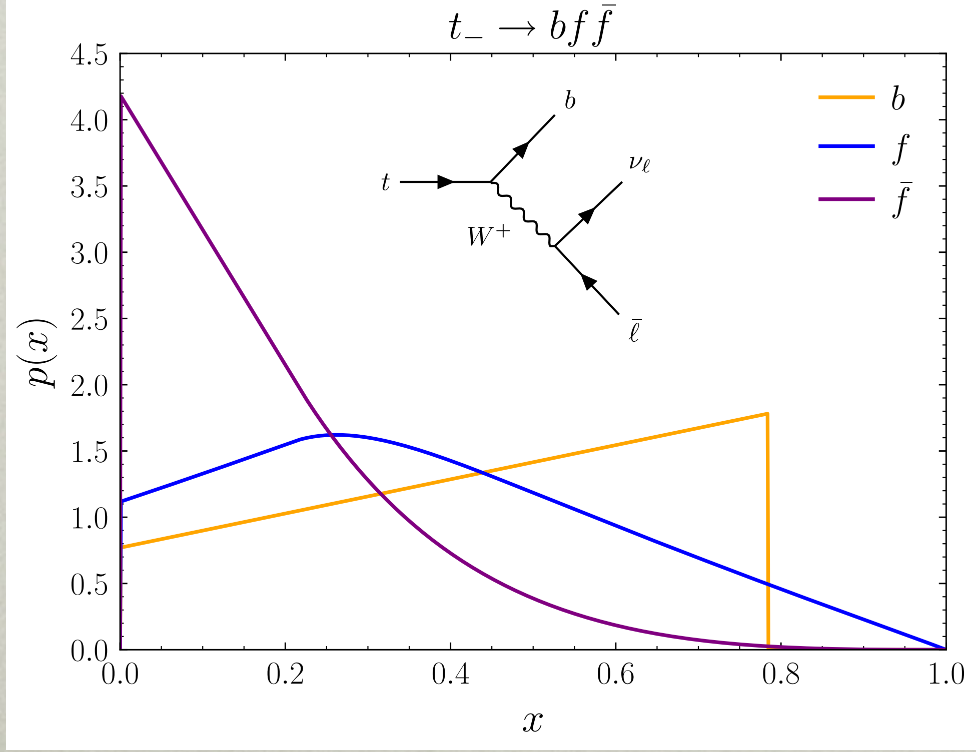
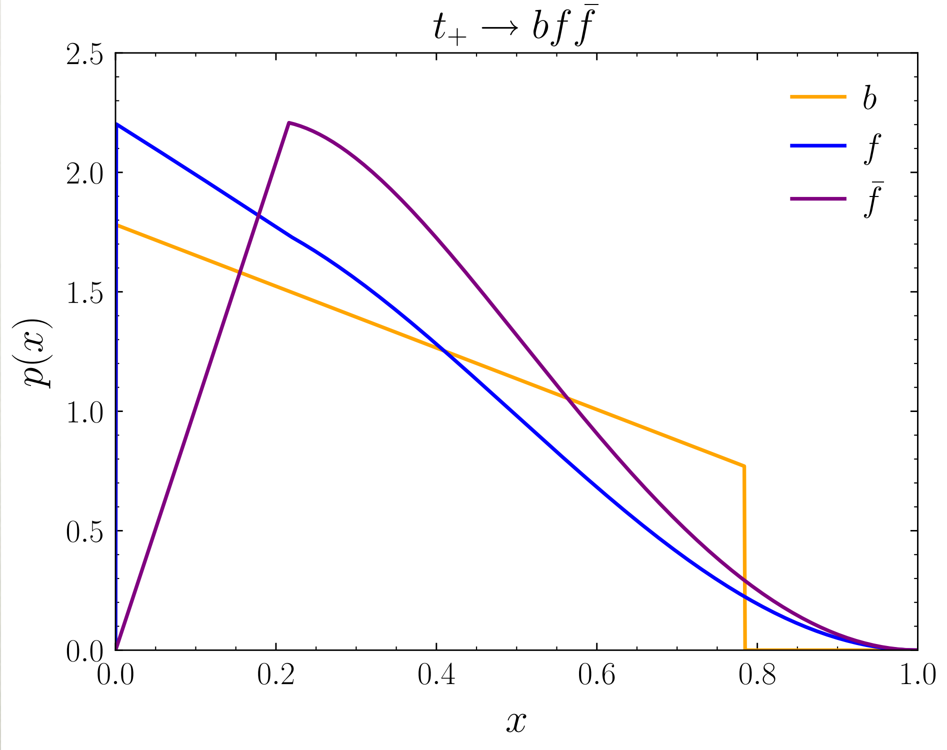
- Most states do not evolve, EW scale states (Z, W, h, t) decay
- Must account for polarised decays, all analytically



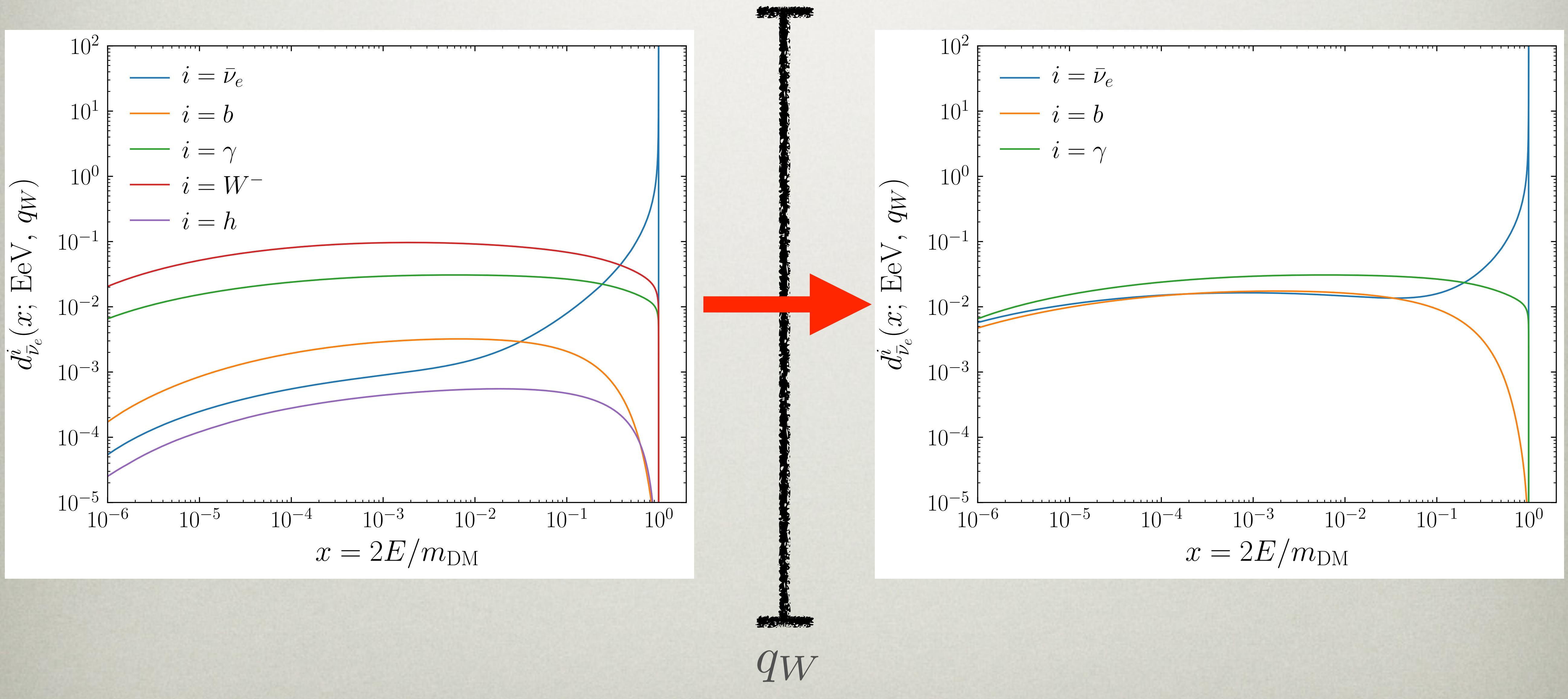


c.f. [hep-ph/9811482]

Step 2: Weak Matching

Impact on the spectra

$$d(x;\, Q,\, q_W^-) = d(x;\, Q,\, q_W^+) \otimes d(x;\, q_W^+,\, q_W^-)$$

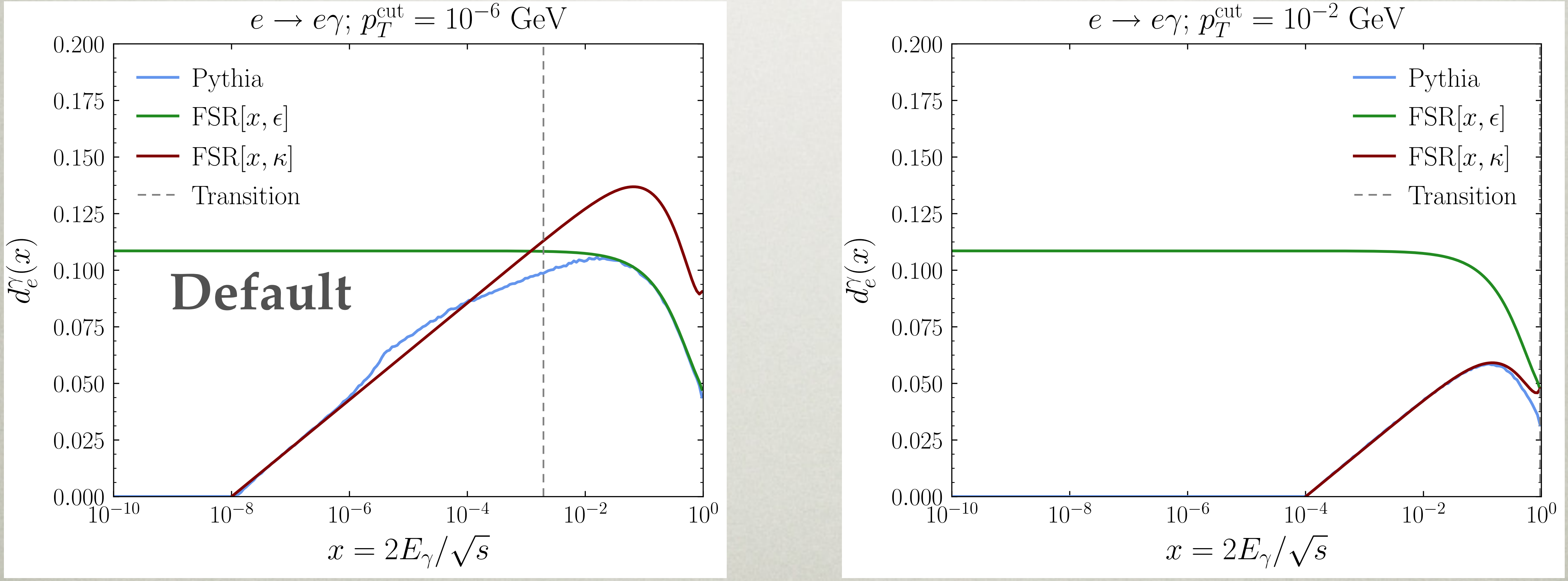


Step 3: Convolve with Pythia

- Use Pythia for showering and hadronization below EW scale

$$d(x;\,Q,\,0) = d(x;\,Q,\,q_{\overline{W}}) \otimes d(x;\,q_{\overline{W}},\,0)$$

- **Caveat:** Pythia's treatment of photon FSR
  - Implement emission (& momentum corrections) analytically

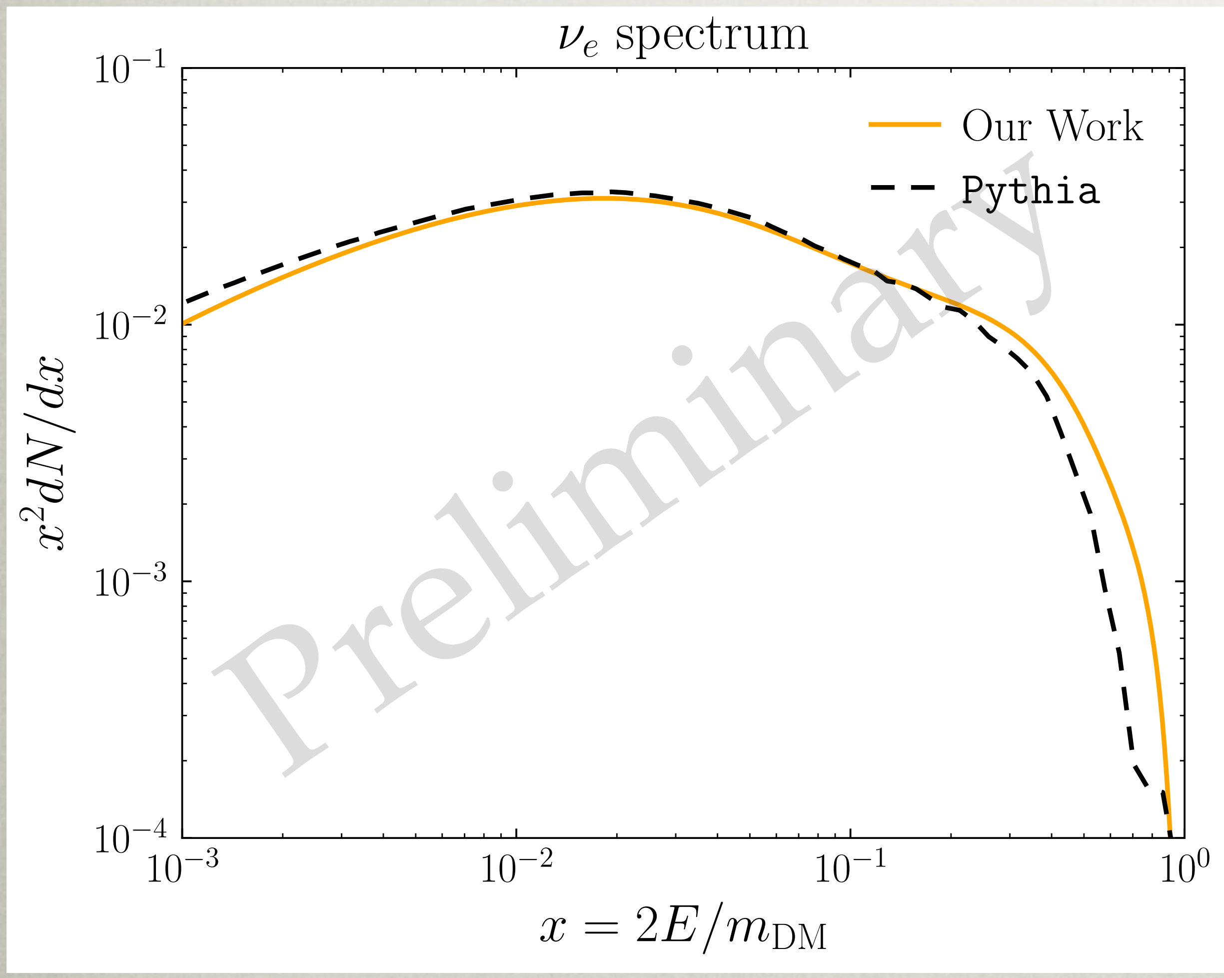


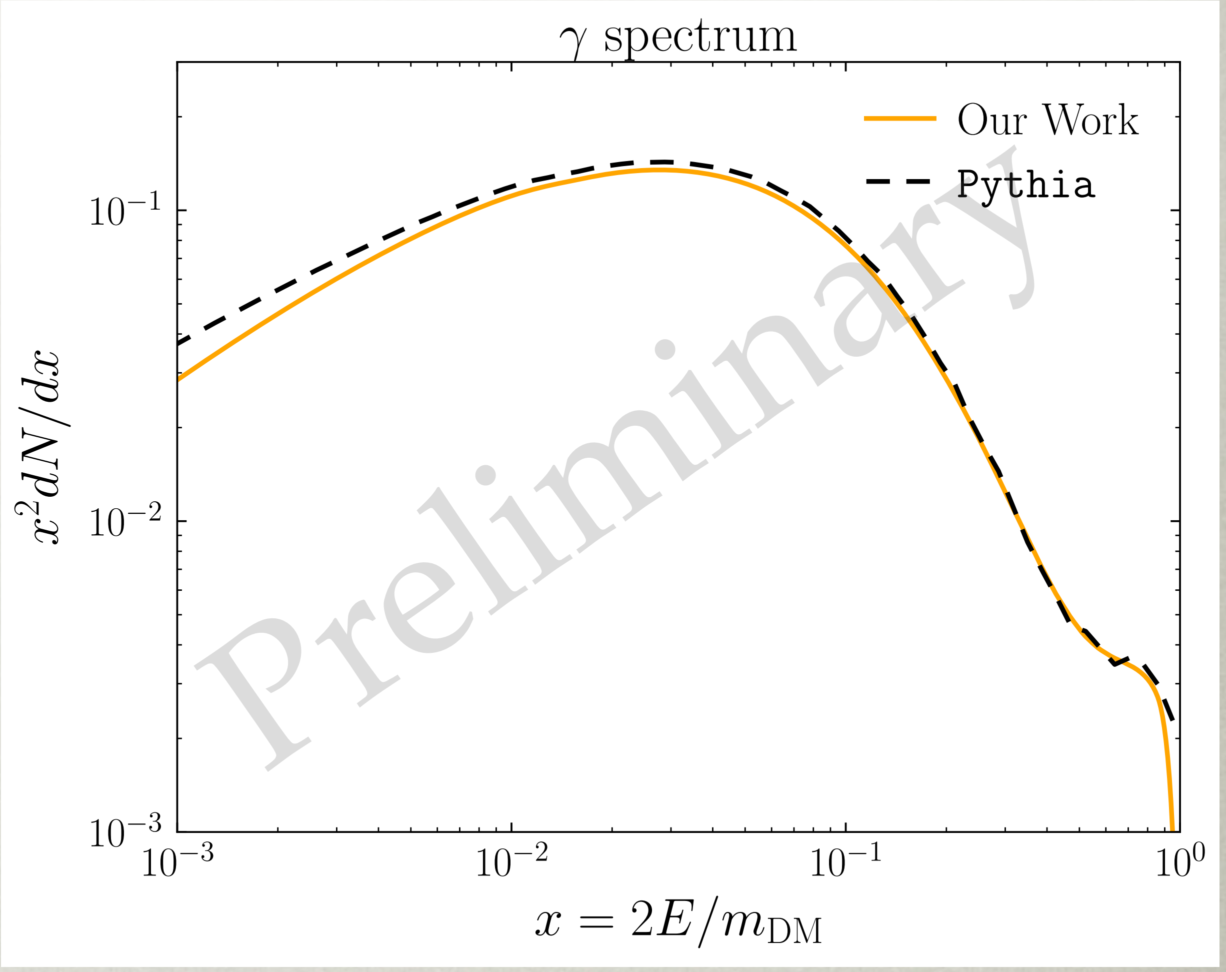
Results

- All together obtain spectra for all stable final state particles
- Impact for hadronic channels less pronounced

$\chi \to b\bar{b}$

$m_\chi = 2$ PeV

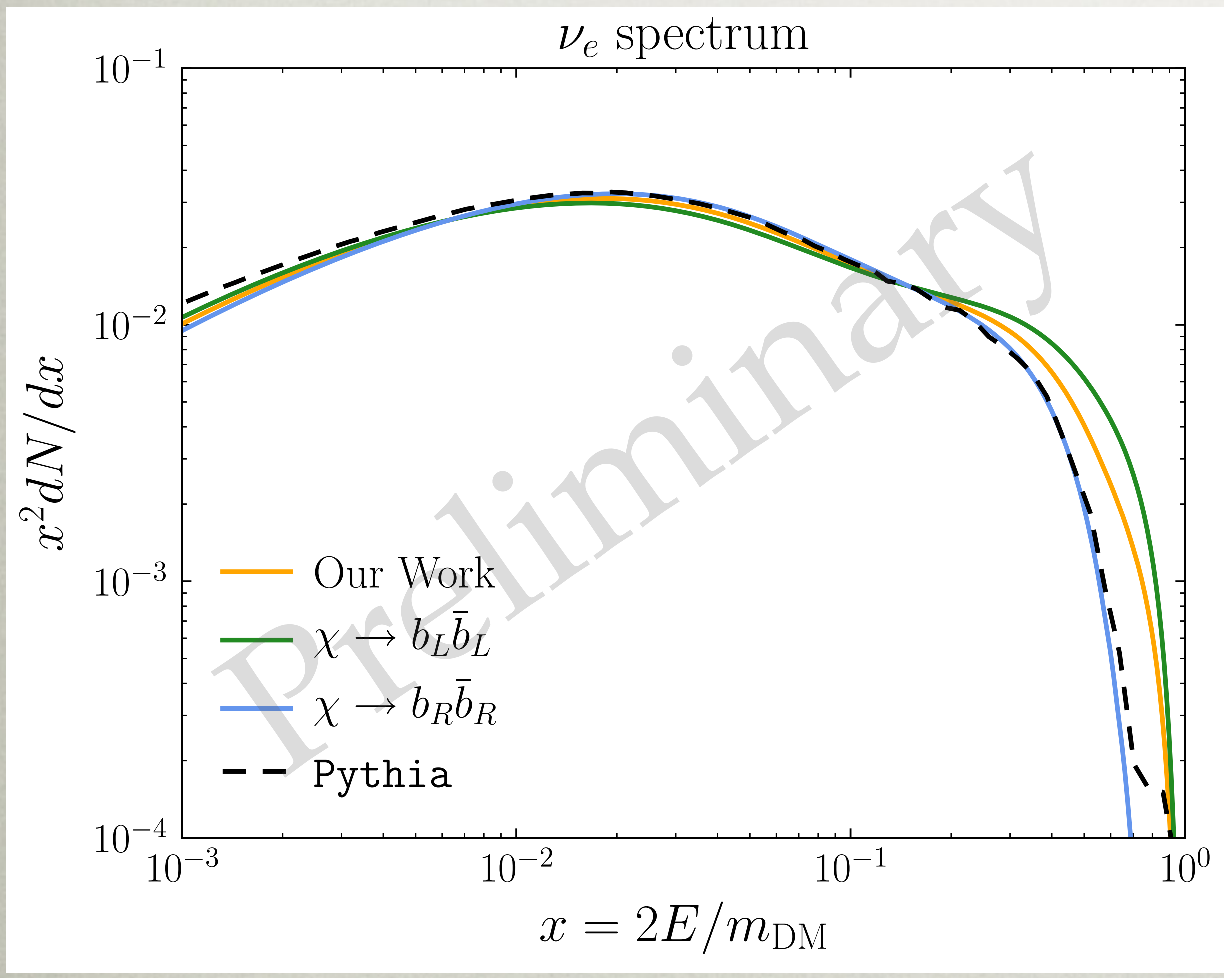




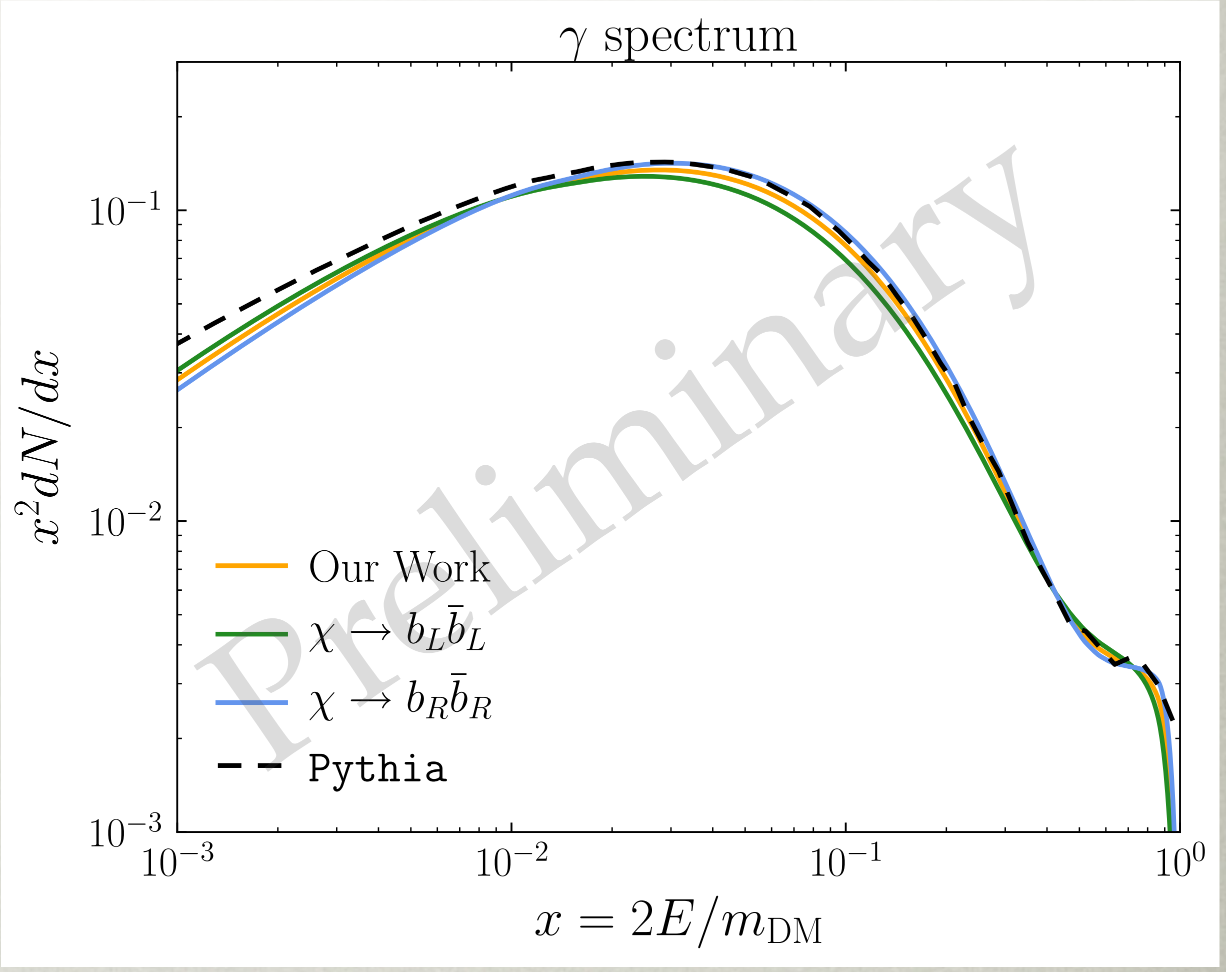
Results

- We have results for arbitrary unbroken initial states
- Can also go to higher energies than are practical in Pythia

$\chi \to b\bar{b}$



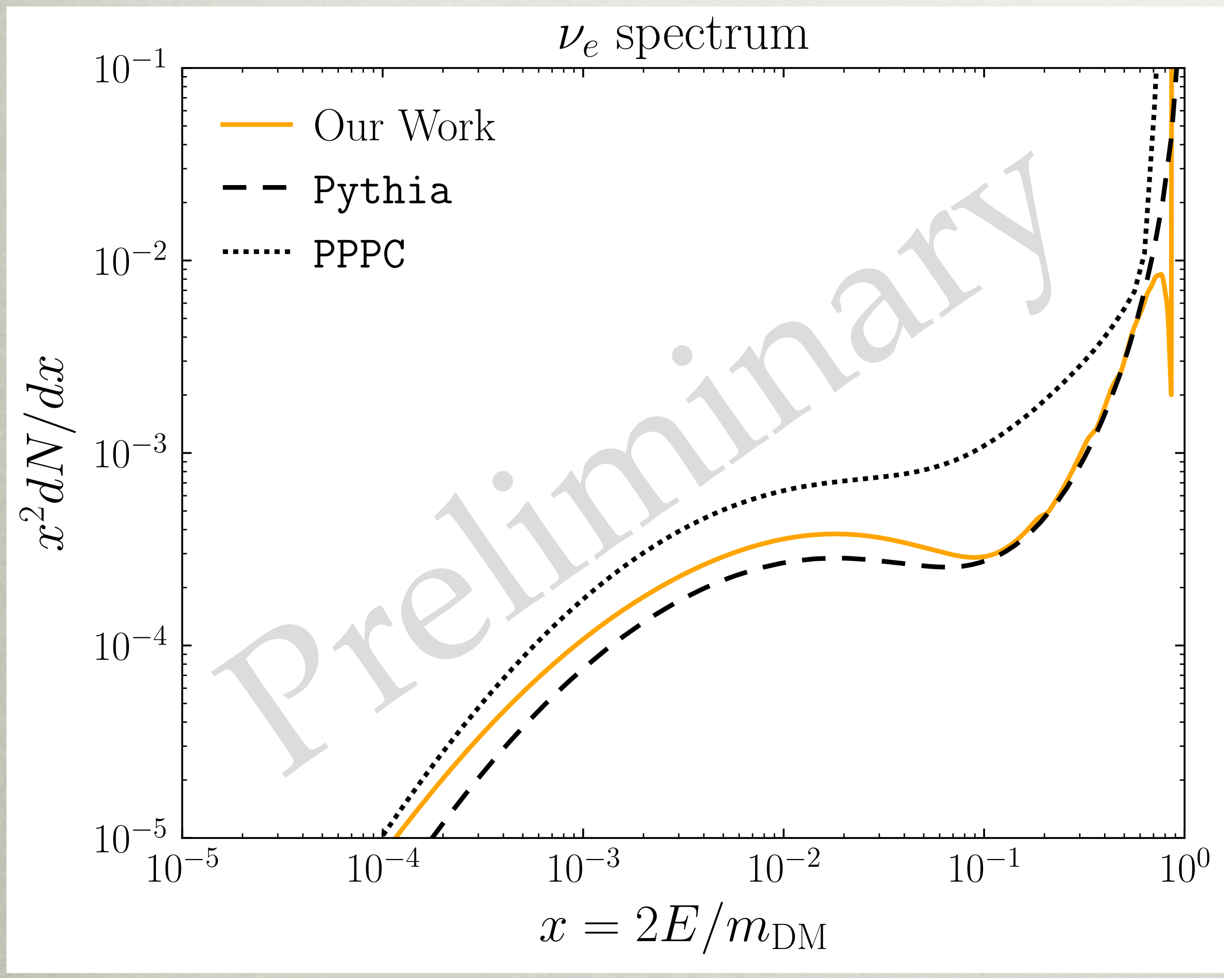
$m_\chi = 2$ PeV



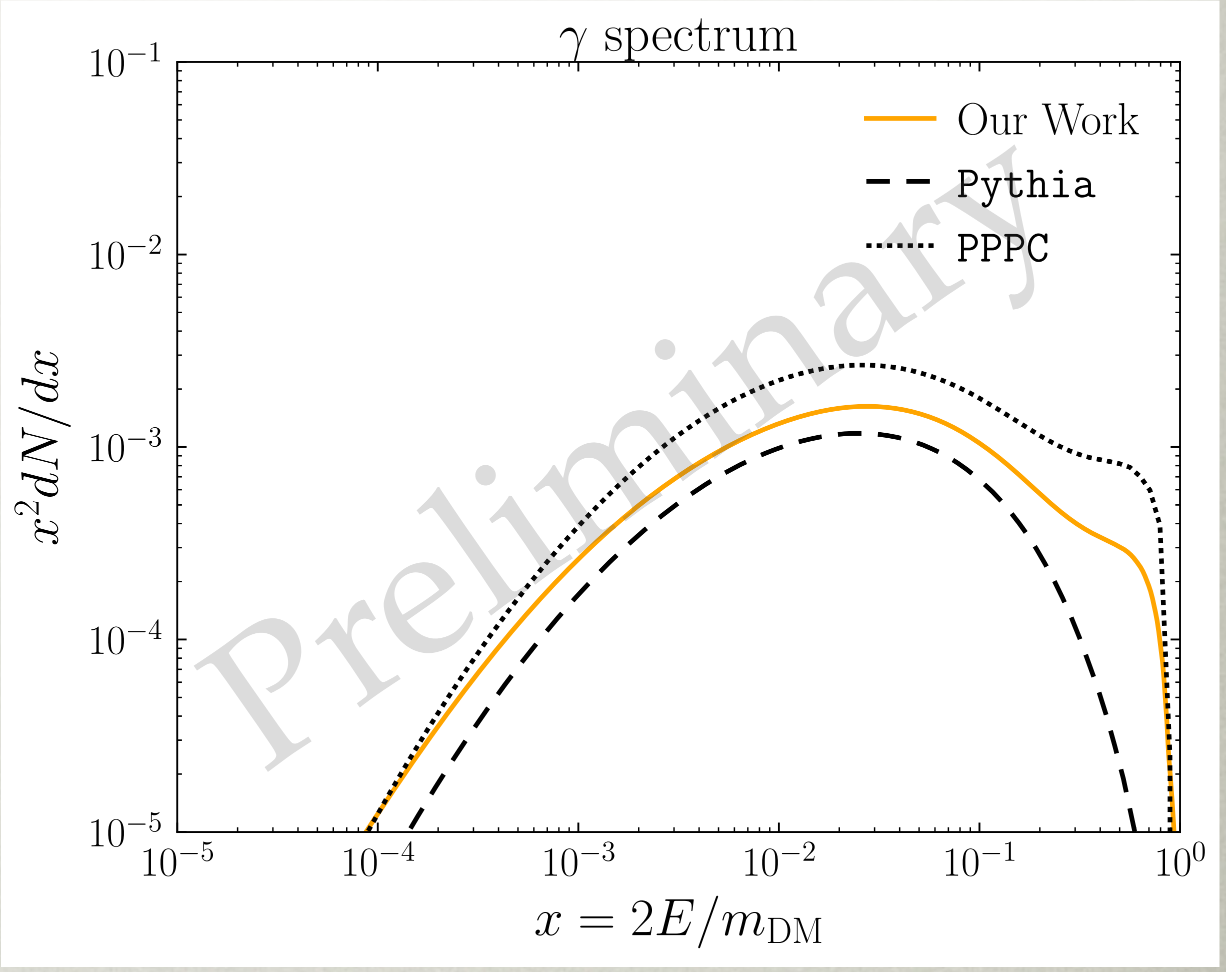
Results

- Larger impact for electroweak dominated final states
- Differ from existing results even at lower masses

$\chi \to \nu_e \bar{\nu}_e$



$m_\chi = 2$ TeV



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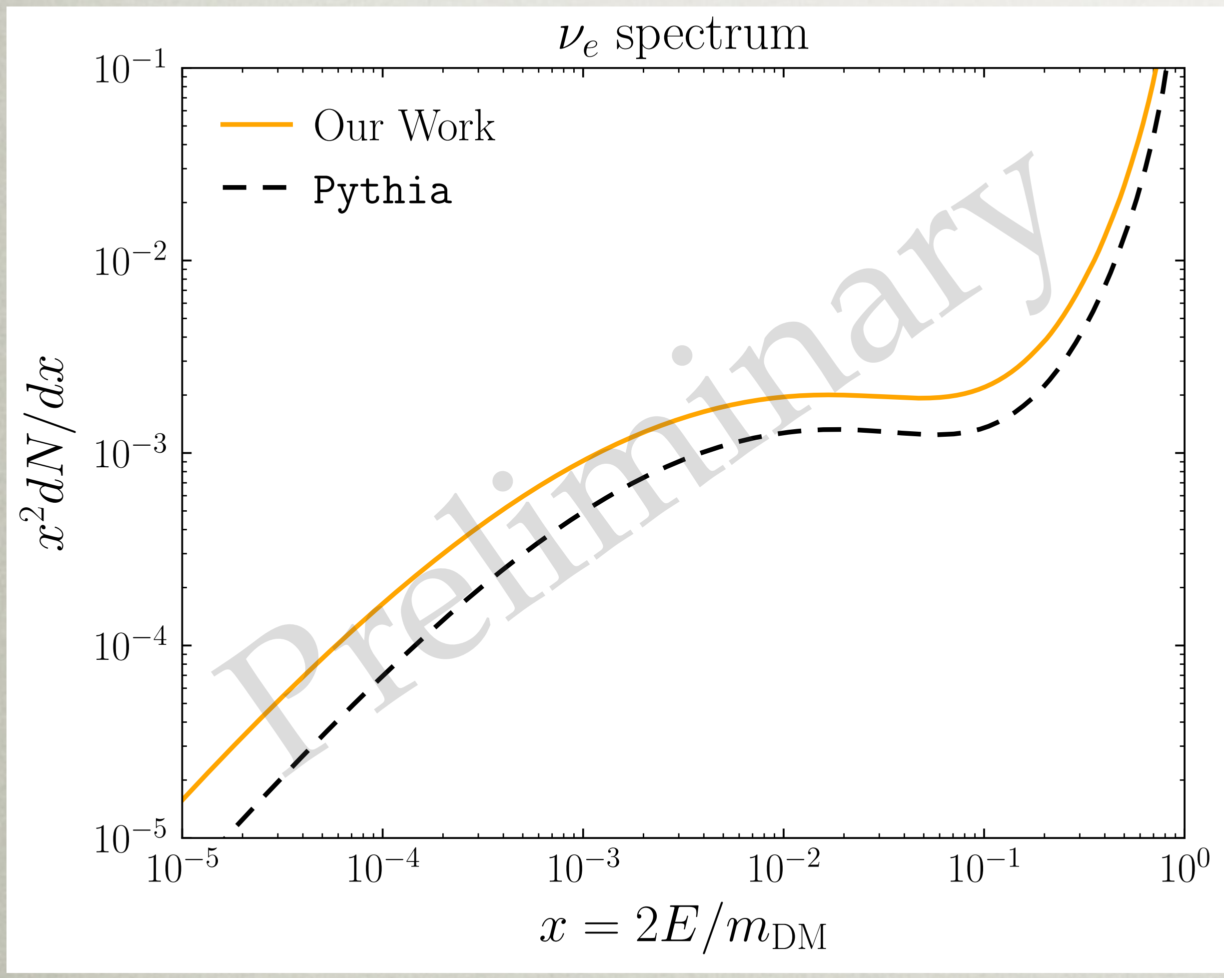
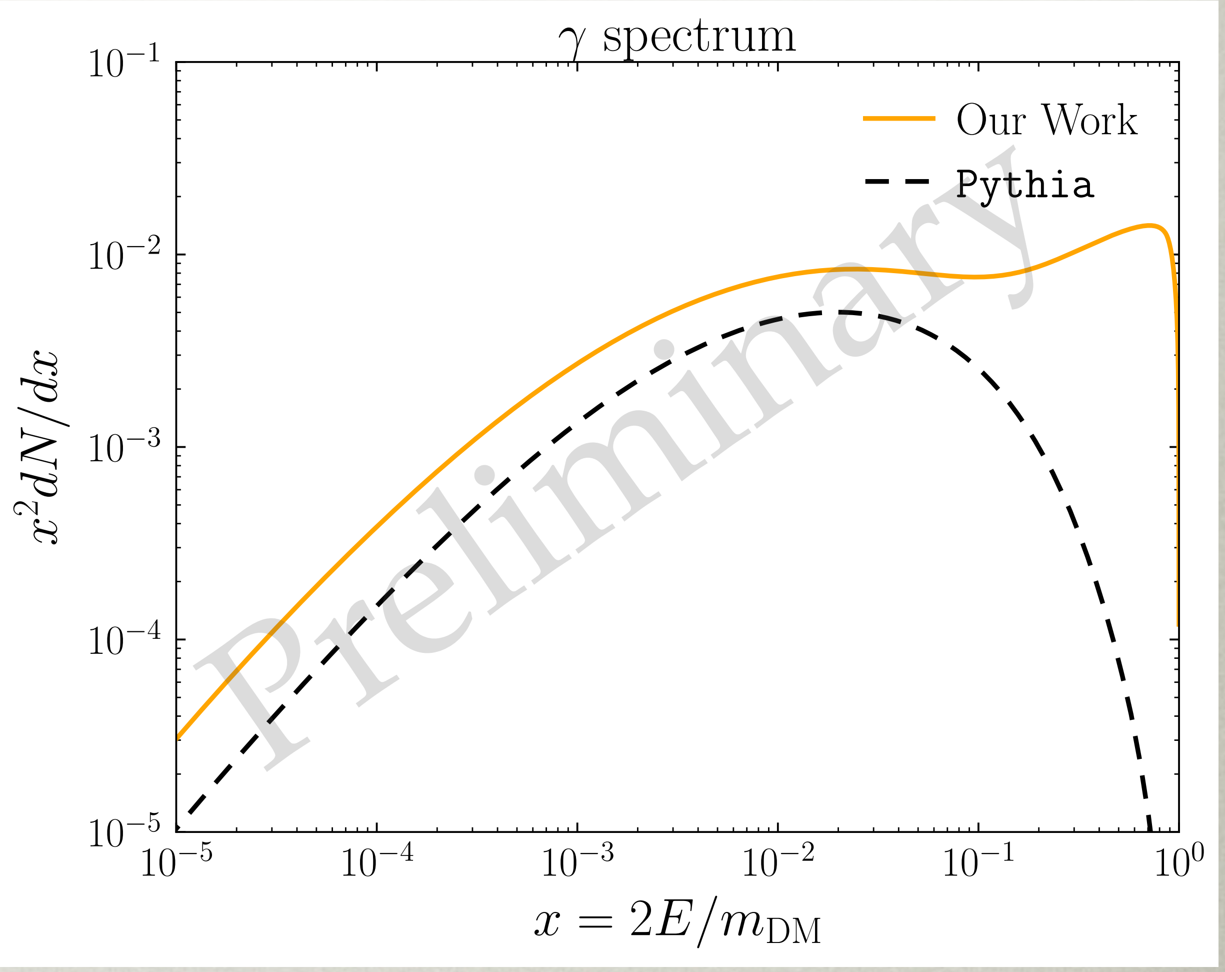


$m_\chi = 2$ PeV



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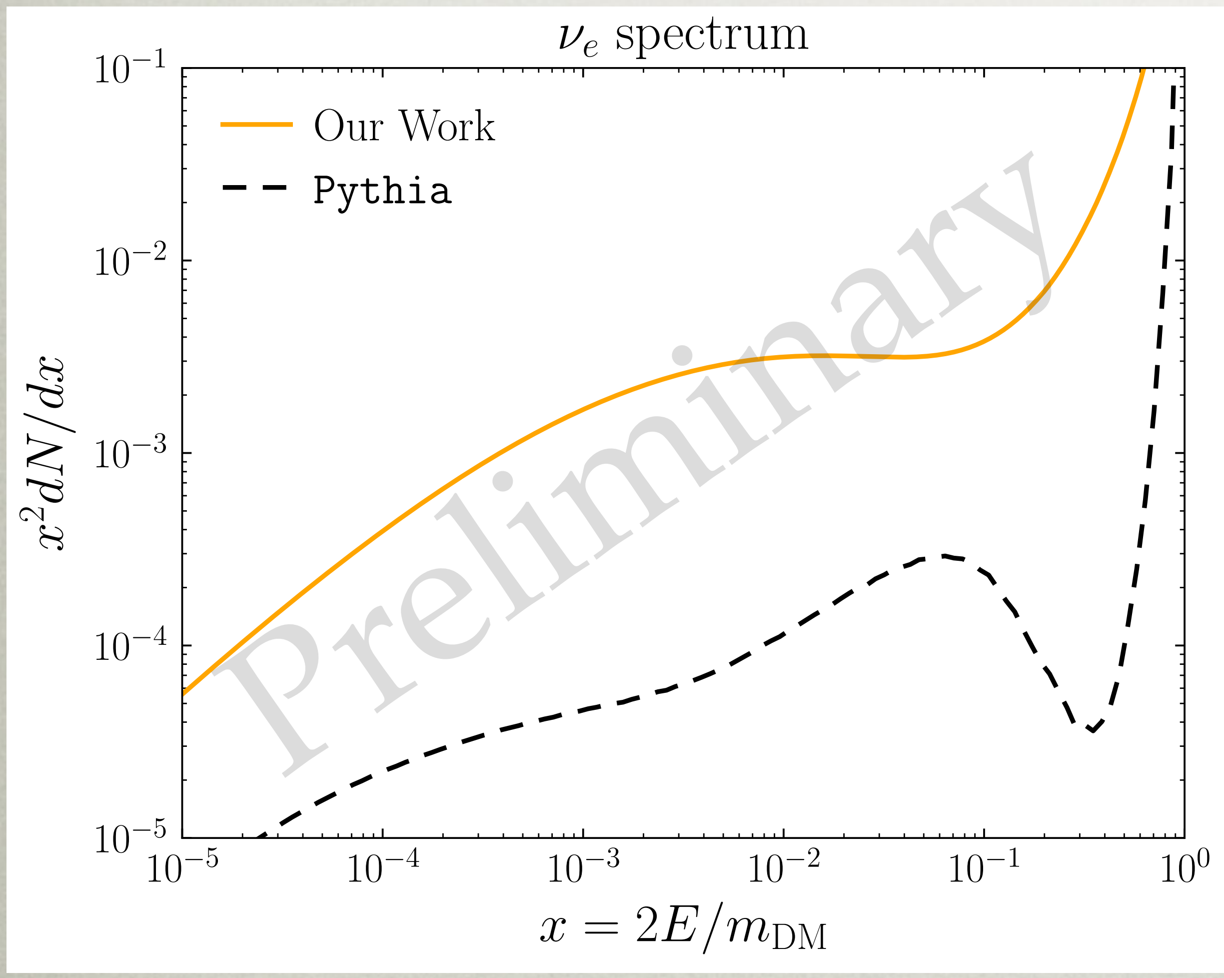
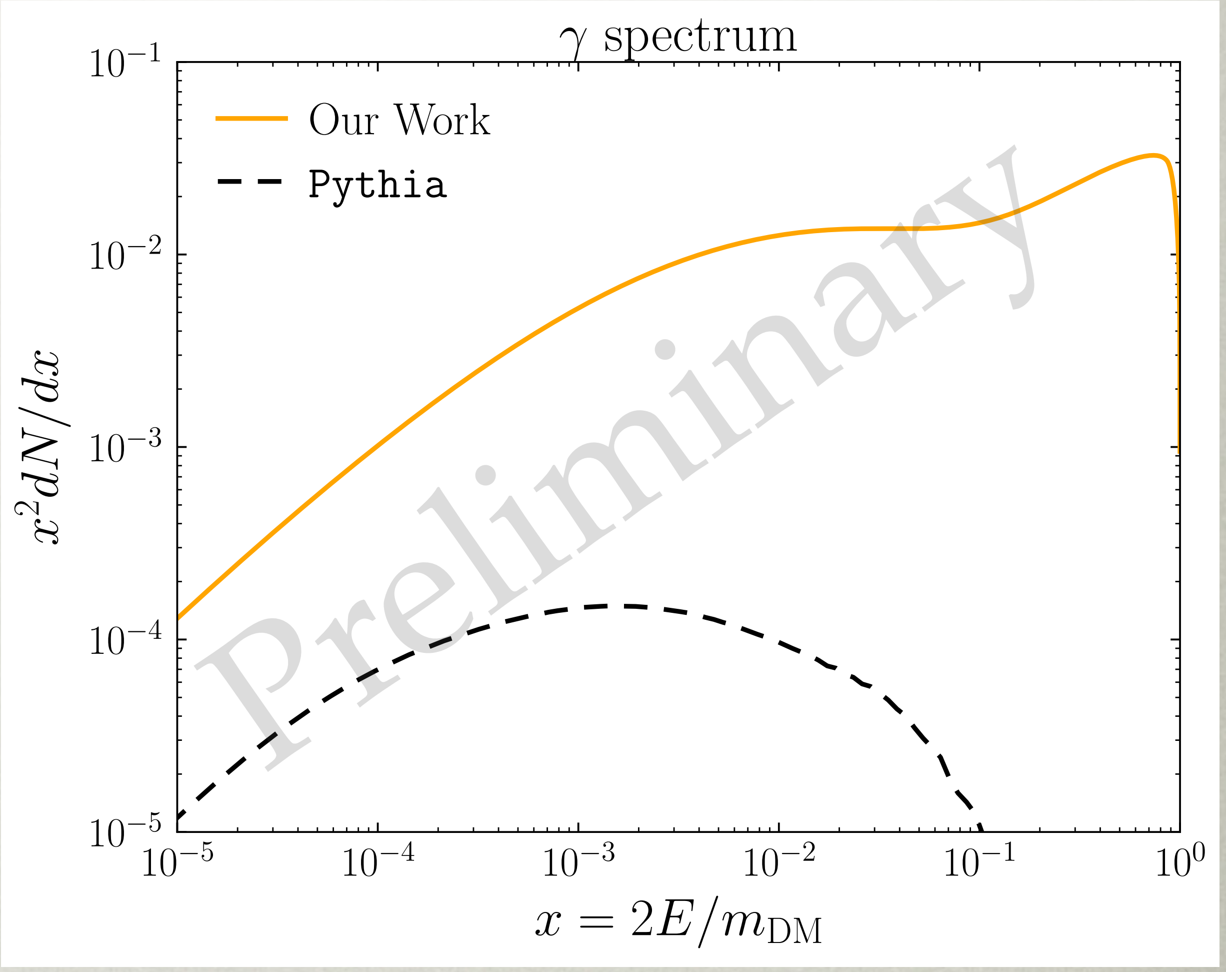
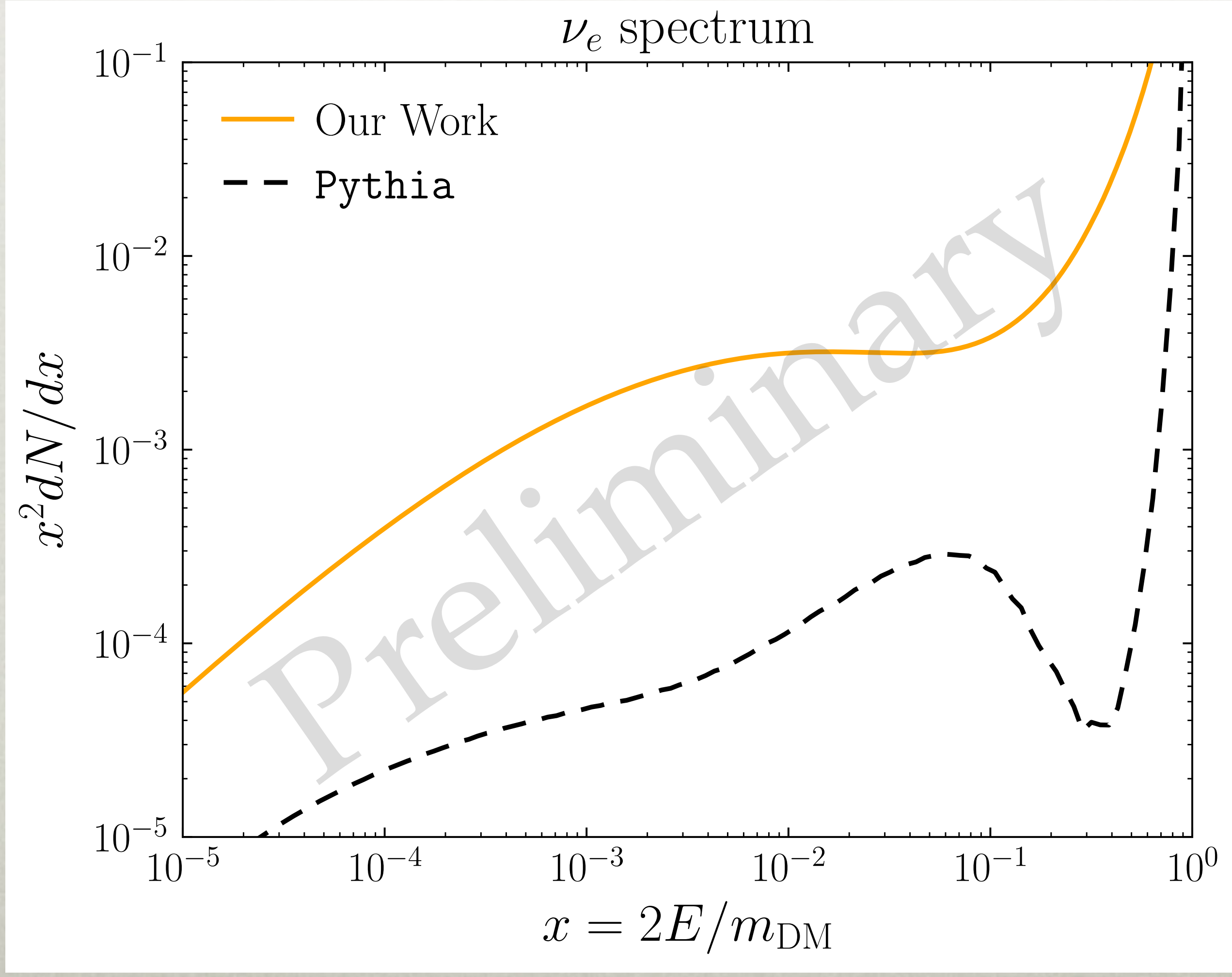


$m_\chi = 2$ EeV



Conclusion

- There is a robust experimental program sensitive to HDM decay
- Spectra currently used are known to be wrong
- **Our results represent a significant improvement**
  - Spectra will be made publicly available, à la PPPC4*H*DMID
- Future goal: obtain NLL accuracy with soft coherence

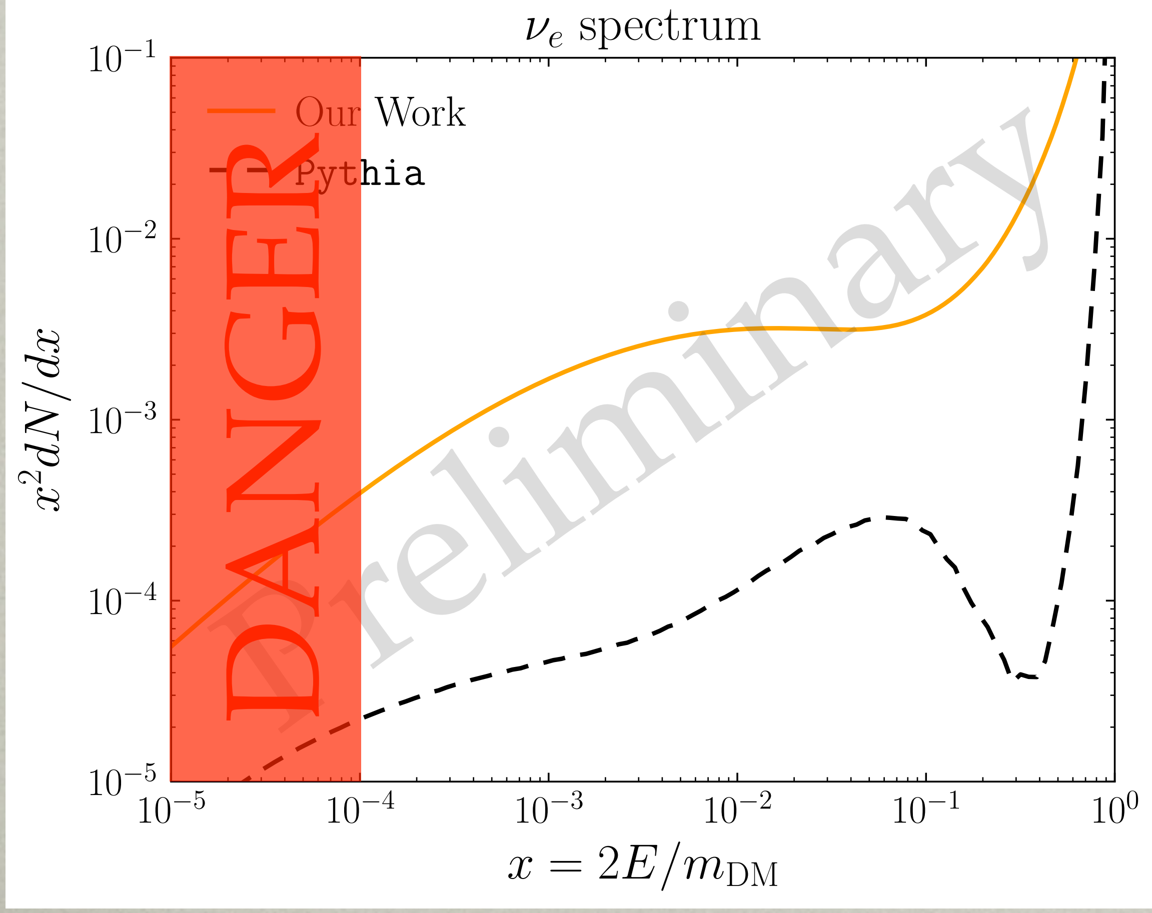


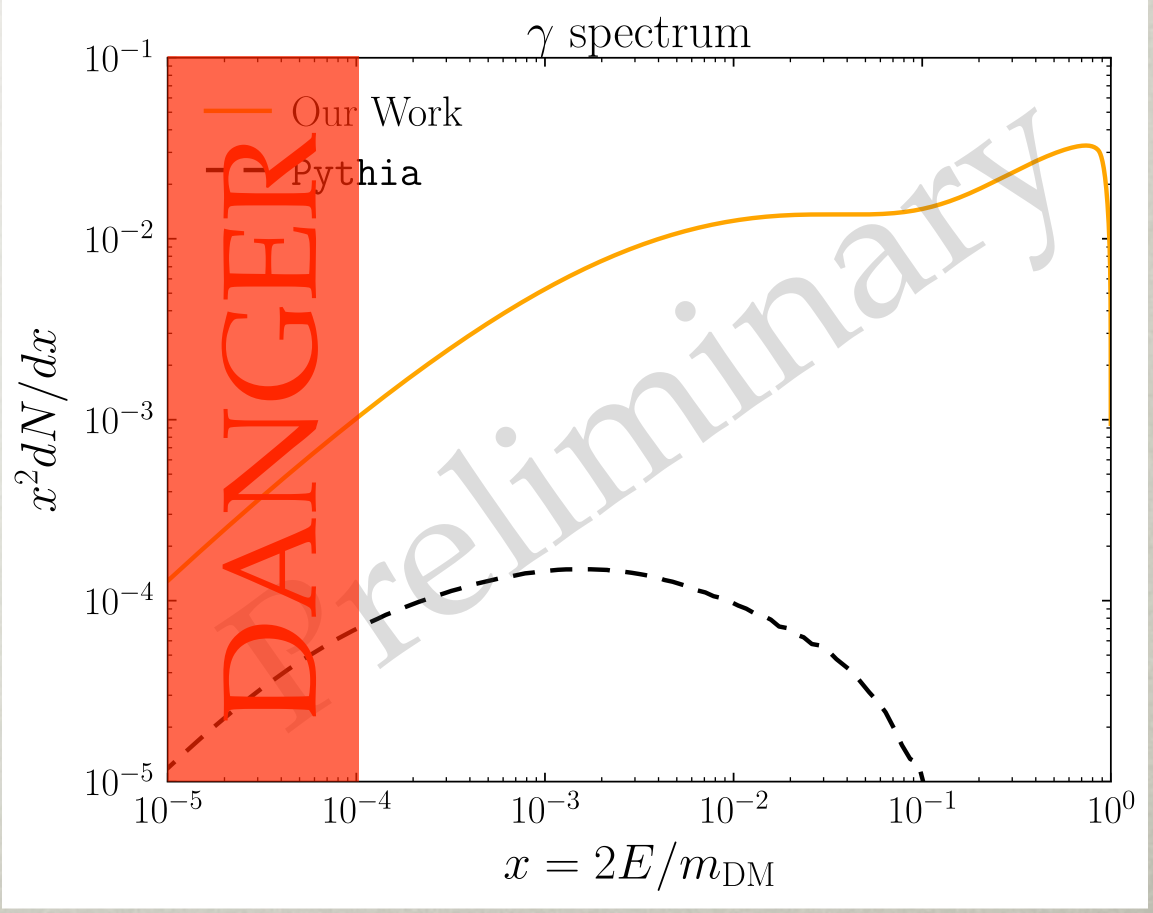
Backup Slides

Breakdown of our Results

- We are missing a complete treatment of (soft) QCD single logs
- Our result breaks down for $\alpha_s L \sim 1$
- i.e. $x \approx e^{-1/\alpha_s} \approx 10^{-4}$
- Simple argument, only an estimate of where results break

$\chi \to \nu_e \bar{\nu}_e$ $\quad$ $m_\chi = 2$ EeV



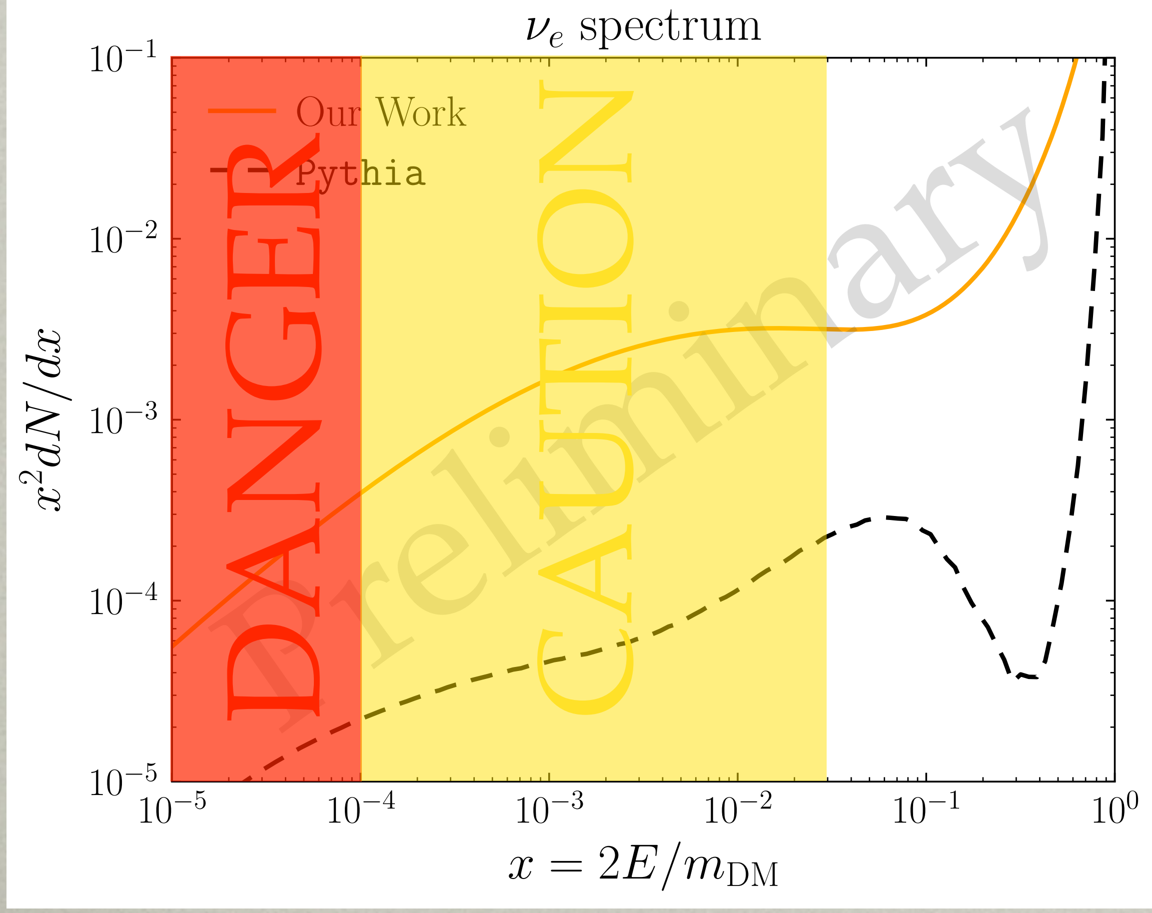


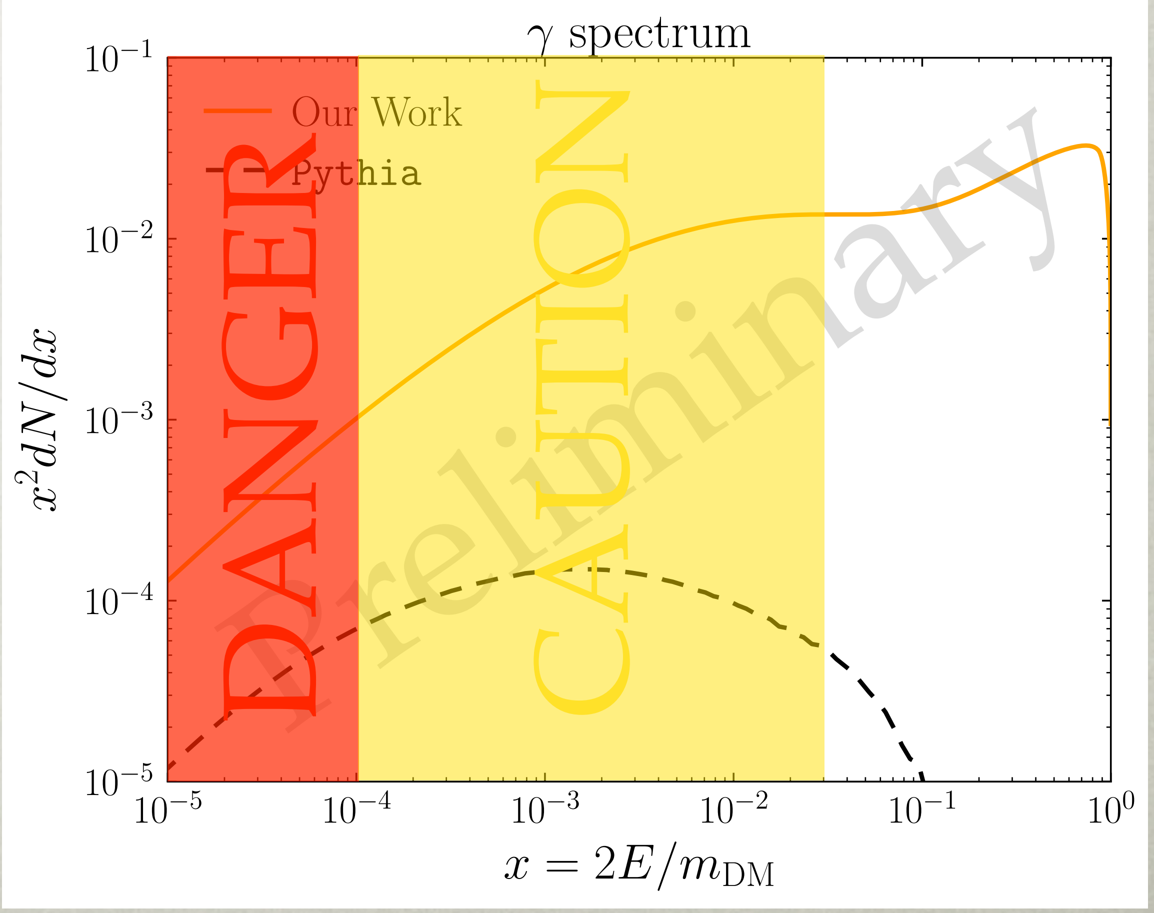
Breakdown of our Results

- Know the expected distribution due to color coherence [Fong, Webber 1989,1990]
- Important for $3\ln(1/x) \sim \ln^{3/4}(Q/\Lambda)$
- At EeV energies $x \approx 10^{-1.5}$

$\chi \to \nu_e \bar{\nu}_e$

$m_\chi = 2$ EeV





Pythia Spectra vs Energy