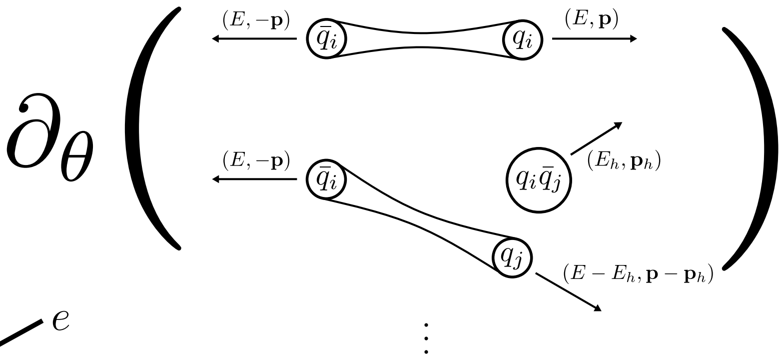
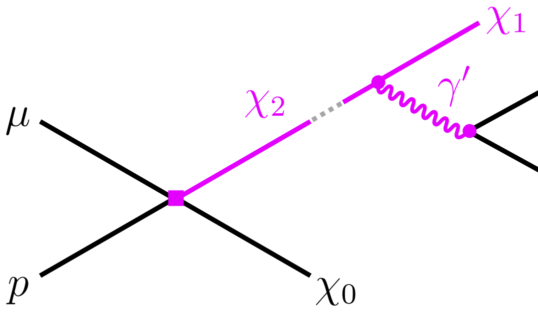
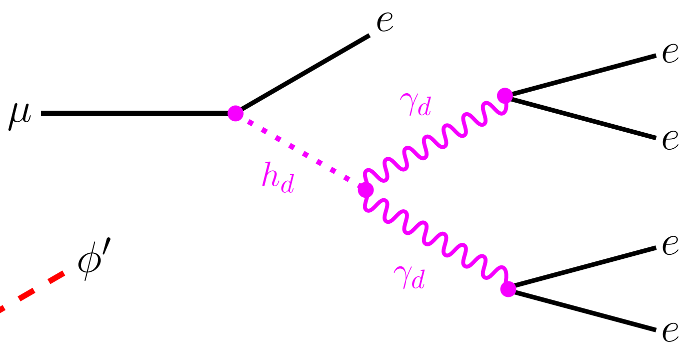
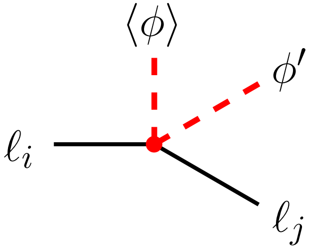
Differentiable hadronization models, heavy and light new physics in rare lepton decays, and more...









University of Alabama

July 31st, 2025

Tony Menzo

University of Cincinnati

Soon to be postdoc at *Alabama + Fermilab* :)

Based on work with MLHAD + MLhadML, Matheus, Maxim, Paddy, Evan, Wick, Ken, and Jure

Outline

1) Introduction to hadronization

2) The inverse problem of hadronization

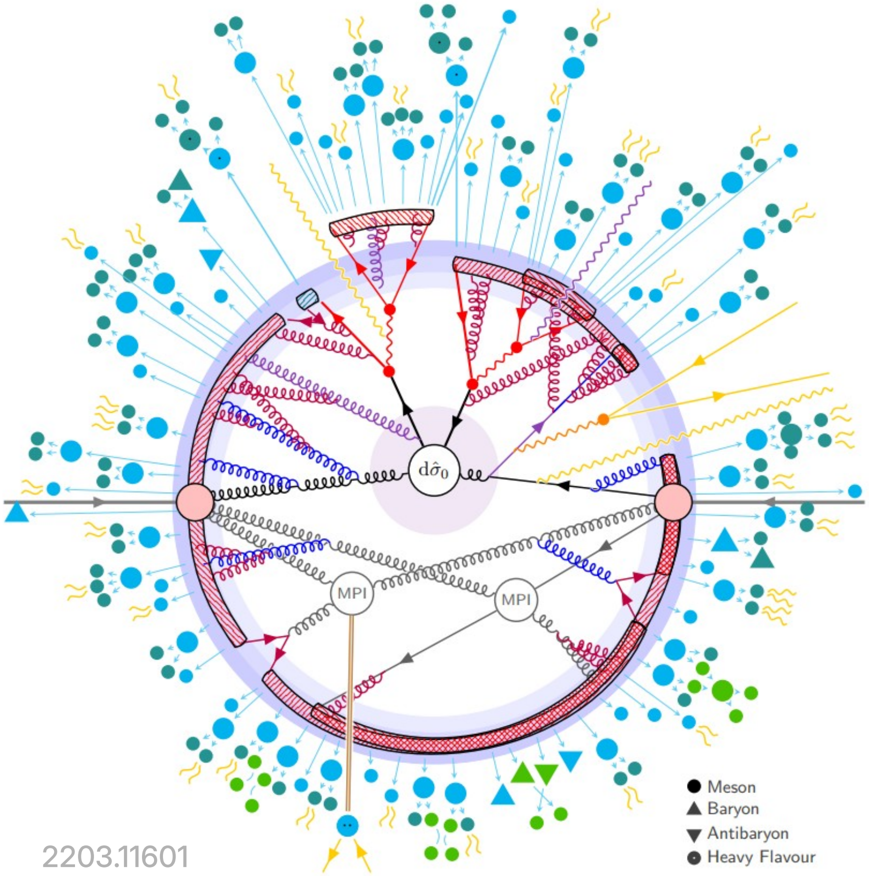
    - Pure ML solutions, hybrid solutions

3) Introduction to charged lepton flavor violation

4) Fun signatures at rare muon decay experiments

    - Multi-electron final states, exotic muon capture modes, time-dependent signals from ultralight dark matter

Monte Carlo Event generators



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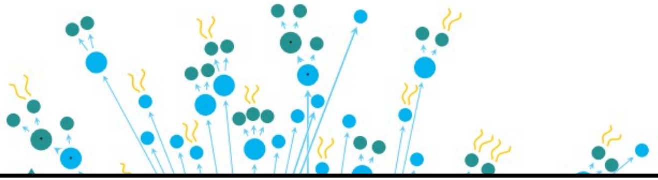
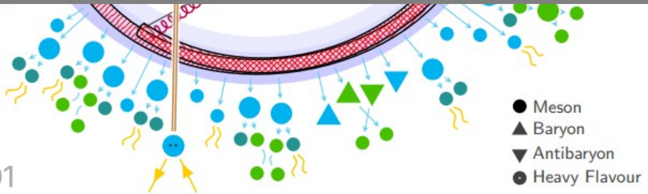
Monte Carlo Event generators



$$\mathcal{G} : \underbrace{\mathcal{S}(\mathcal{D}(\mathcal{H}(\mathcal{P}(\mathcal{M}))))}_{\text{Simulation}} = \mathcal{E} \simeq \underbrace{\begin{pmatrix} \{\texttt{id}, E, p_x, p_y, p_z, \cdots\}_1 \\ \{\texttt{id}, E, p_x, p_y, p_z, \cdots\}_2 \\ \vdots \\ \{\texttt{id}, E, p_x, p_y, p_z, \cdots\}_N \end{pmatrix}}_{\text{Event record}} .$$



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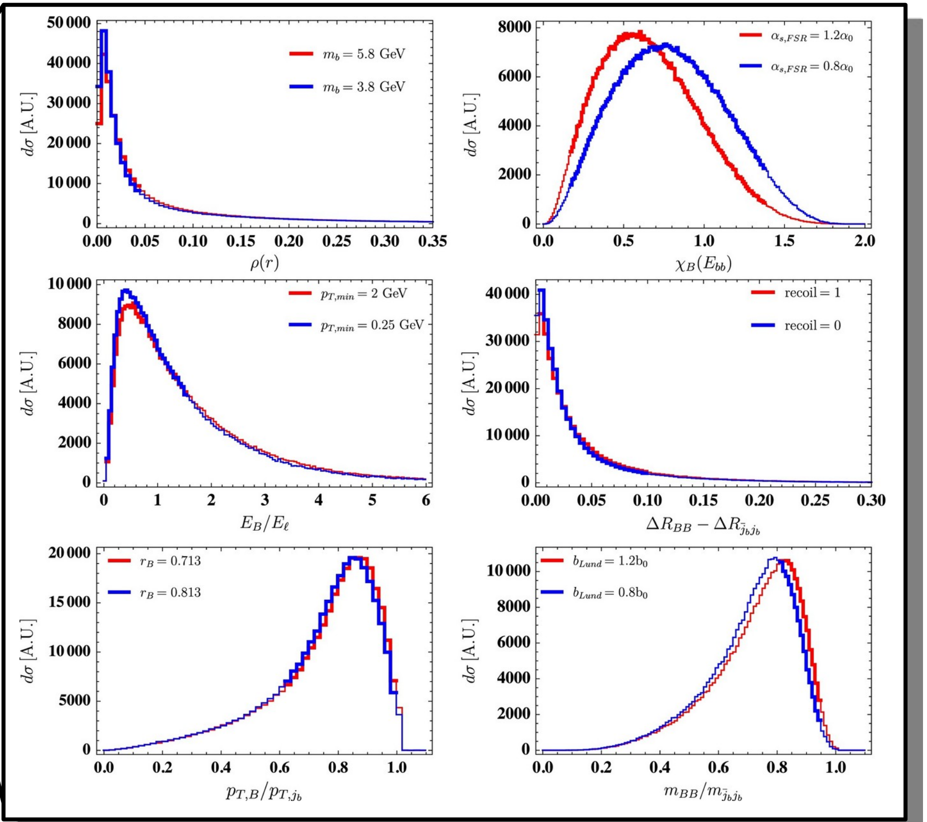
Motivation

Precision (exclusive) measurements dependent on hadronization!

- Uncertainty reduction
  - Top quark mass measurement (r_b)
  - e^+e^- determination of α_s
- Mis-modeling
  - High-multiplicity events
  - Tuning discrepancies



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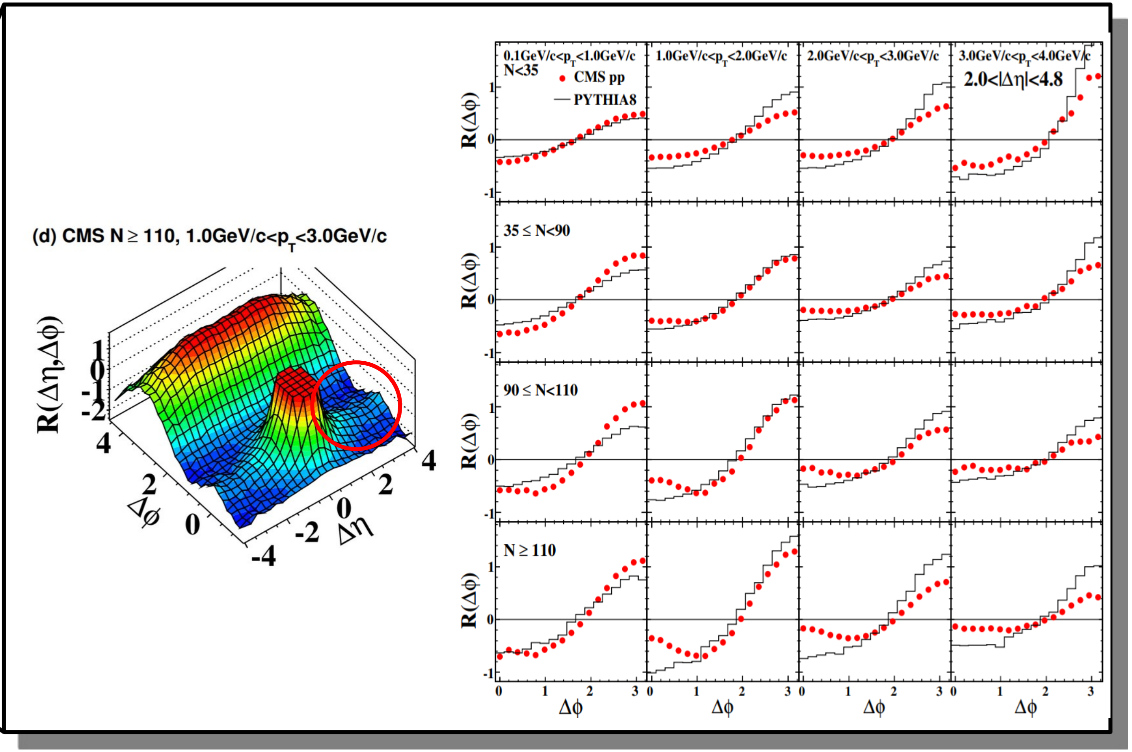

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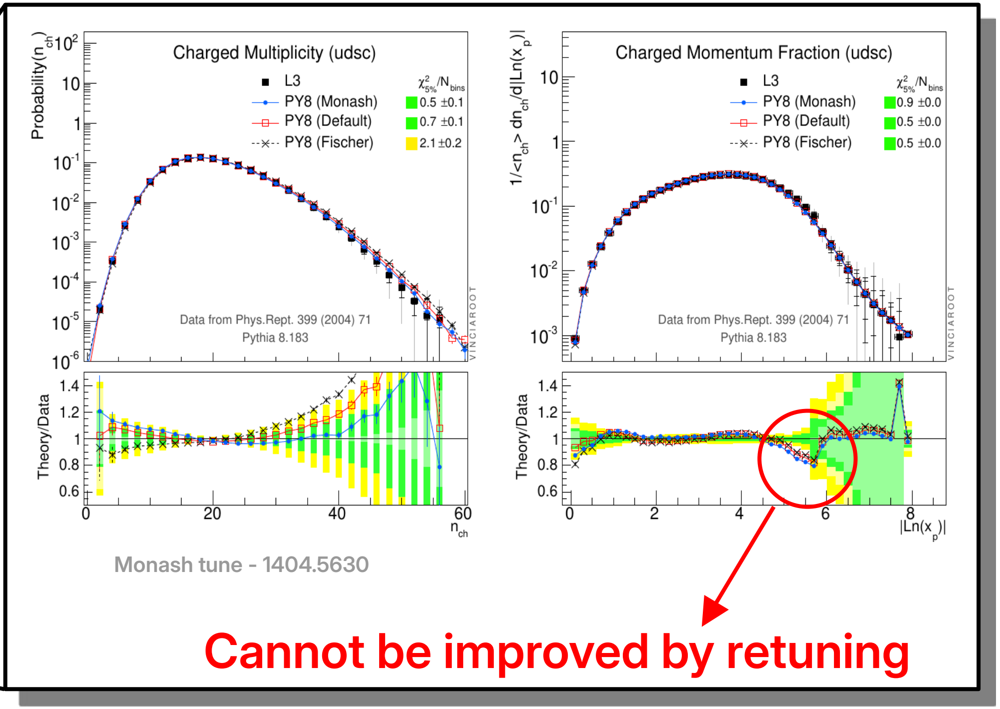
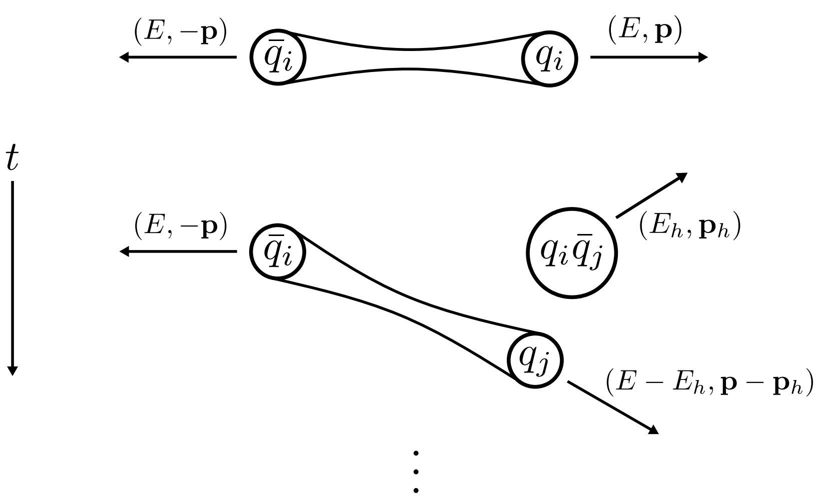


Phenomenological models

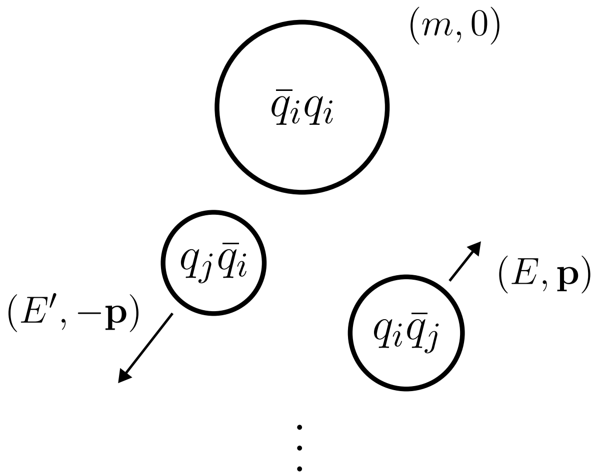
Lund string model

(used in Pythia)

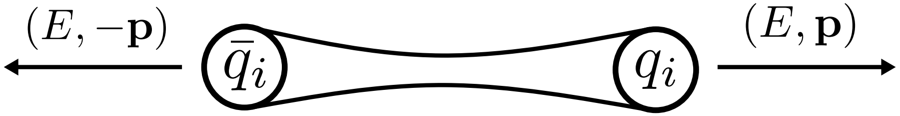


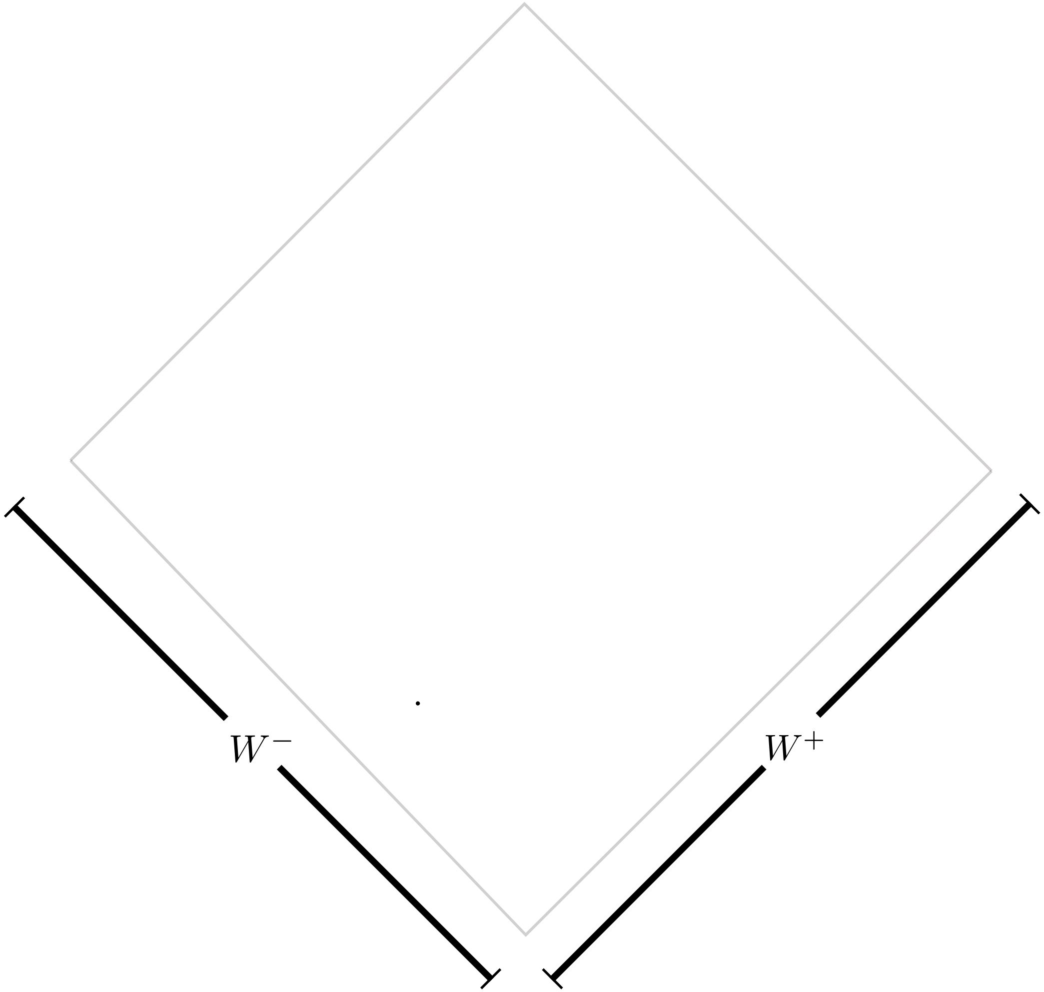
Cluster model

(used in Herwig, Sherpa)



The algorithm ($q\bar{q}$)





1) Randomly select one of the string ends
2) Sample new quark flavor
3) Sample transverse momentum of new quarks

$$\mathcal{P}(p_x, p_y; \sigma_{p_T}) = \frac{1}{\pi\sigma_{p_T}^2} \exp\left(-\frac{p_x^2+p_y^2}{\sigma_{p_T}^2}\right)$$

4) Sample longitudinal momentum fraction of new hadron

$$f(z) \propto \frac{(1-z)^a}{z} \exp\left(\frac{-bm_T^2}{z}\right), \quad z = \frac{p_z + E_h}{2E}$$

5) Repeat steps 1-4

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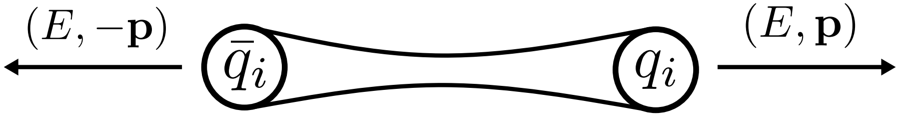

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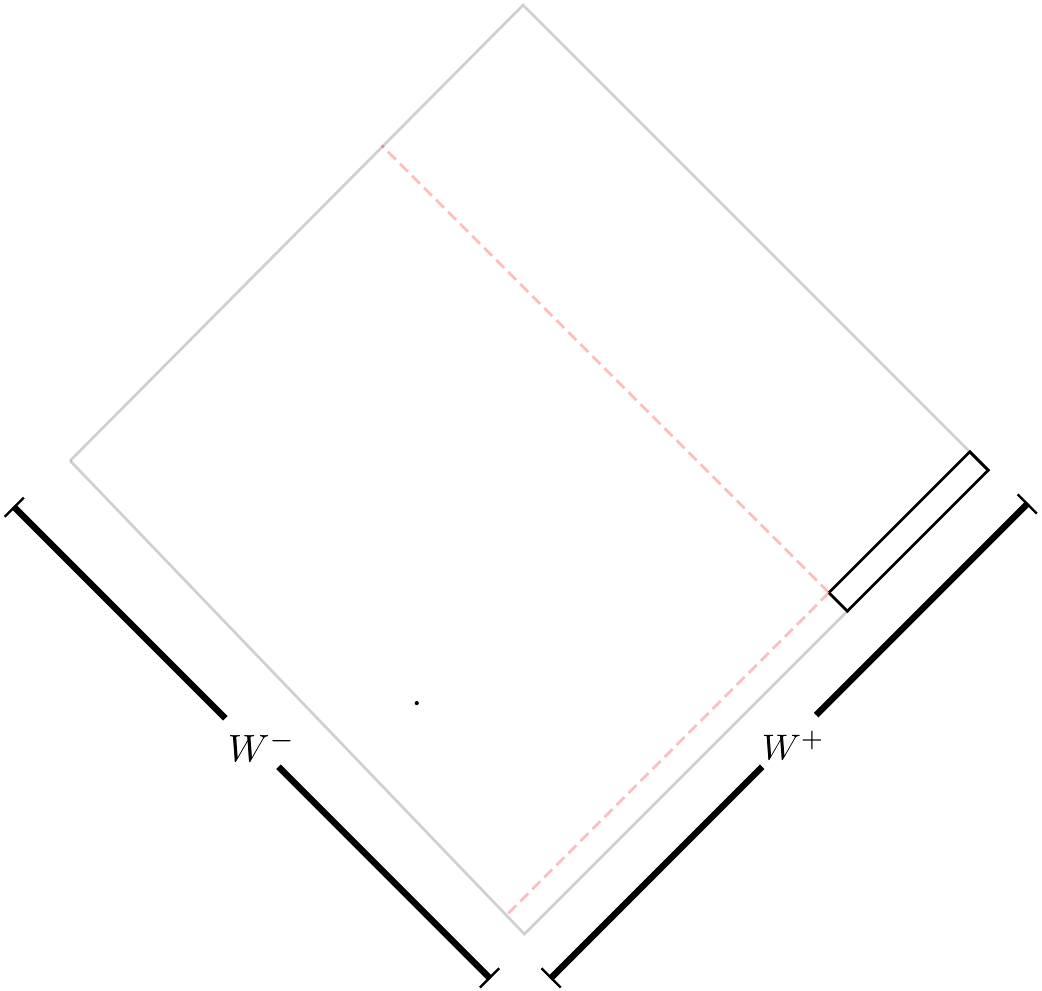

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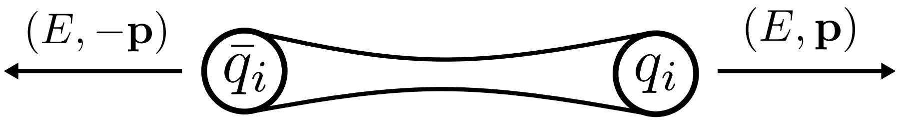

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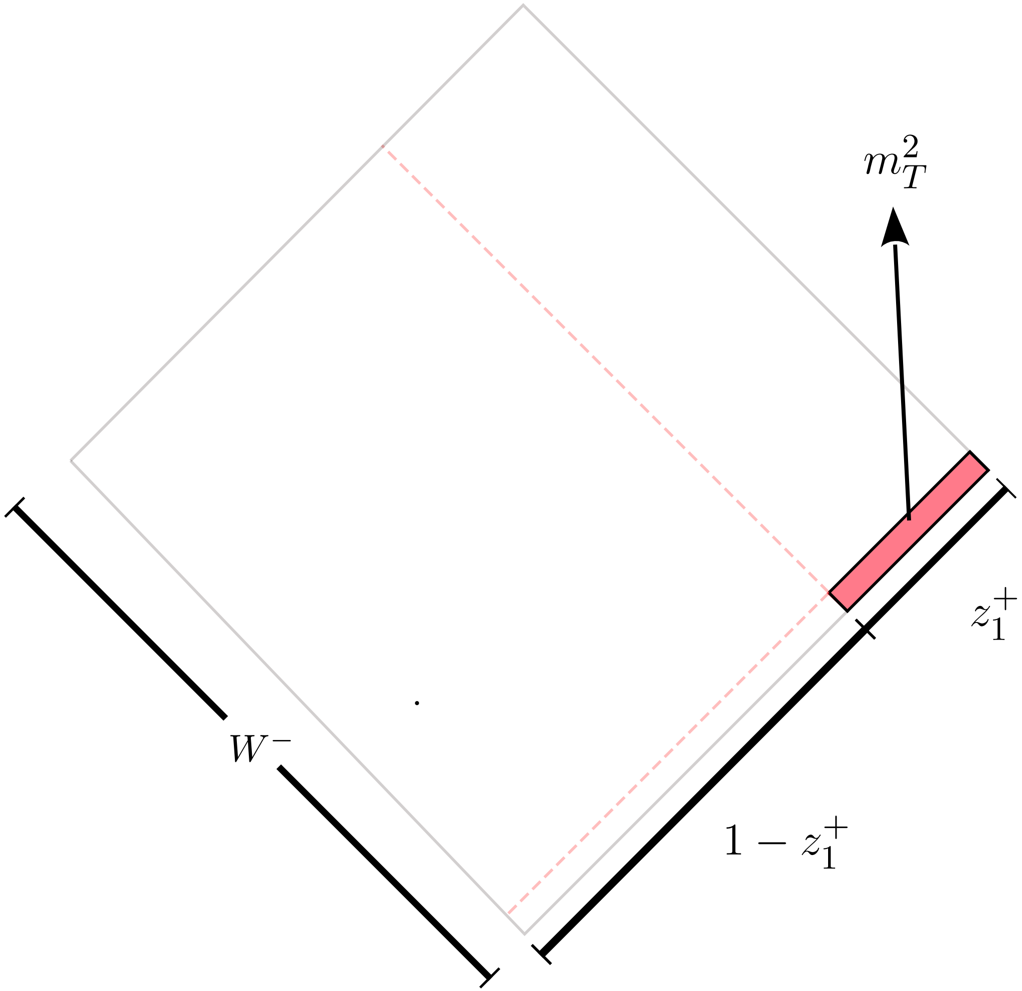

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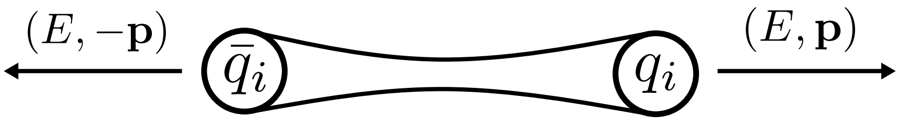

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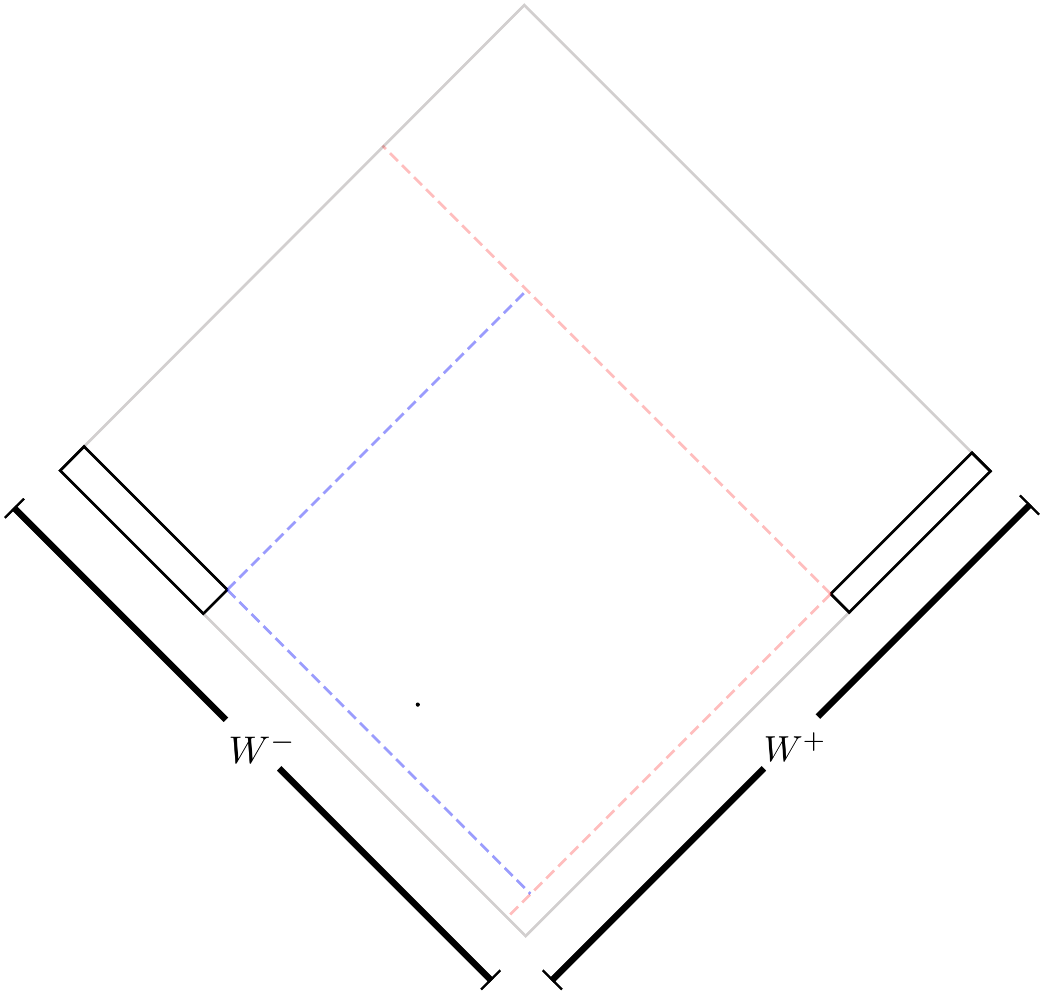

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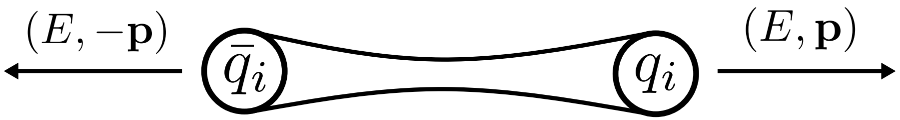

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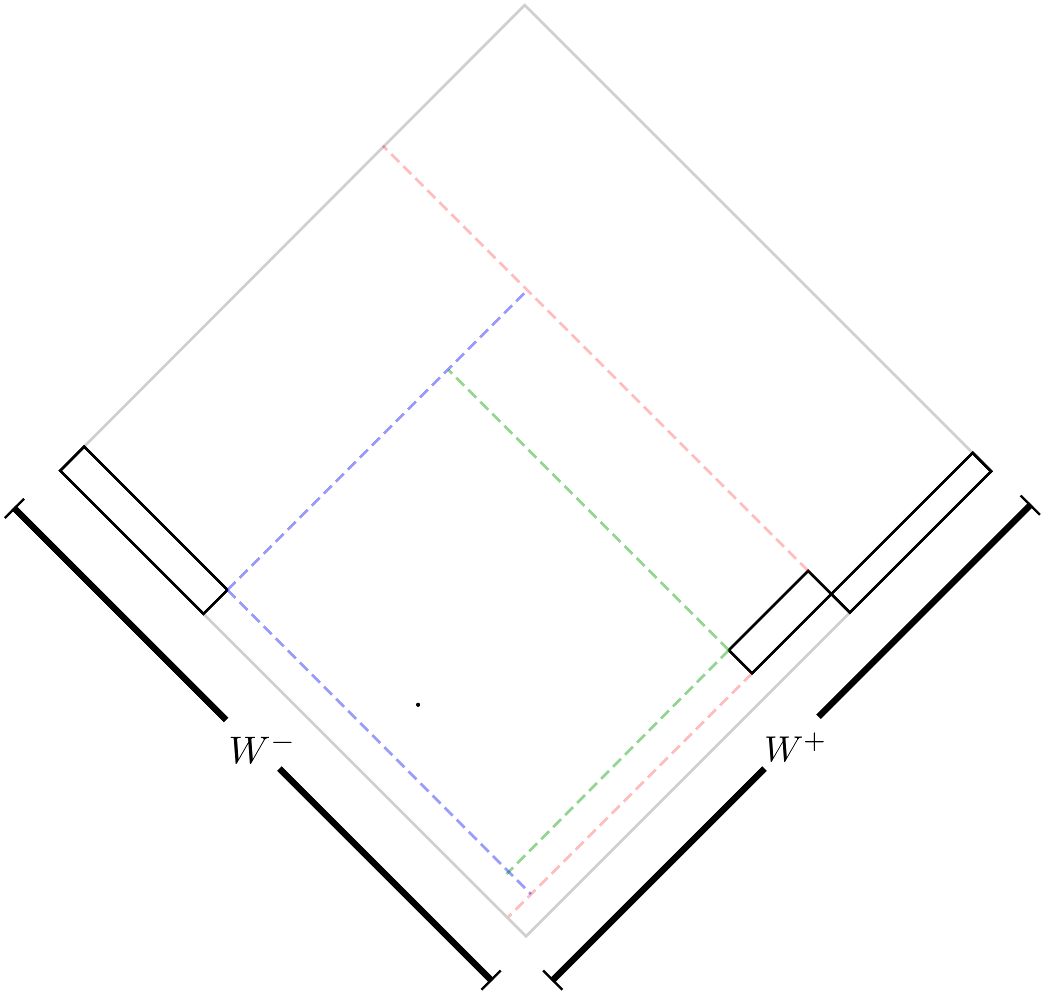

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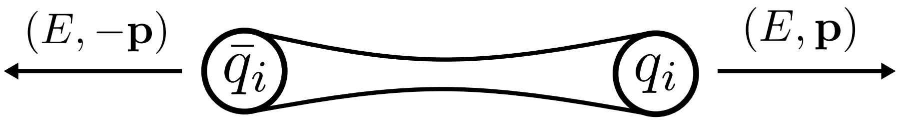

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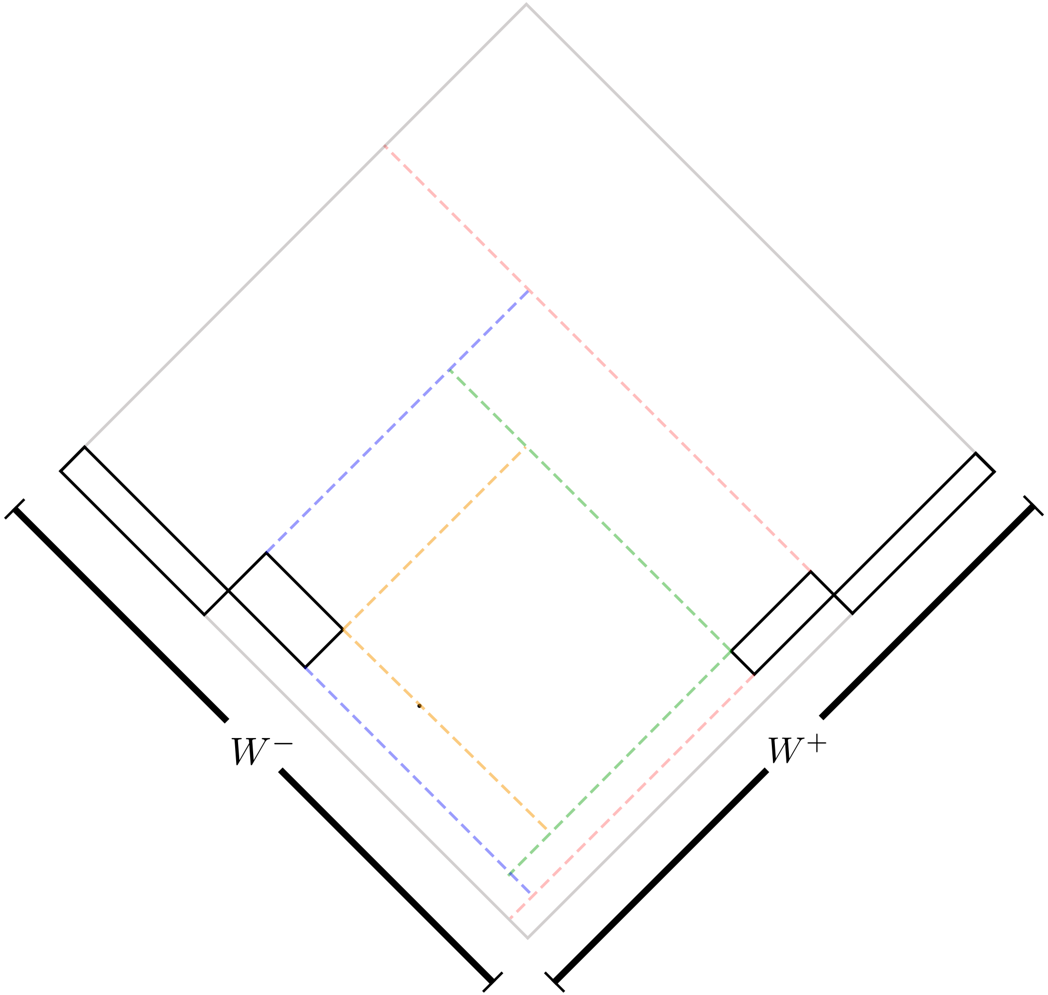

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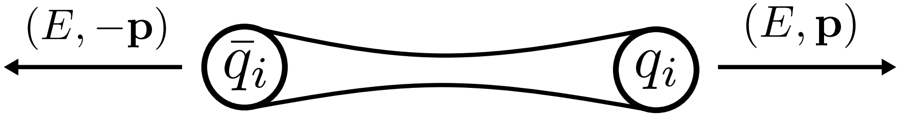

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$\mathcal{P}($

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new h

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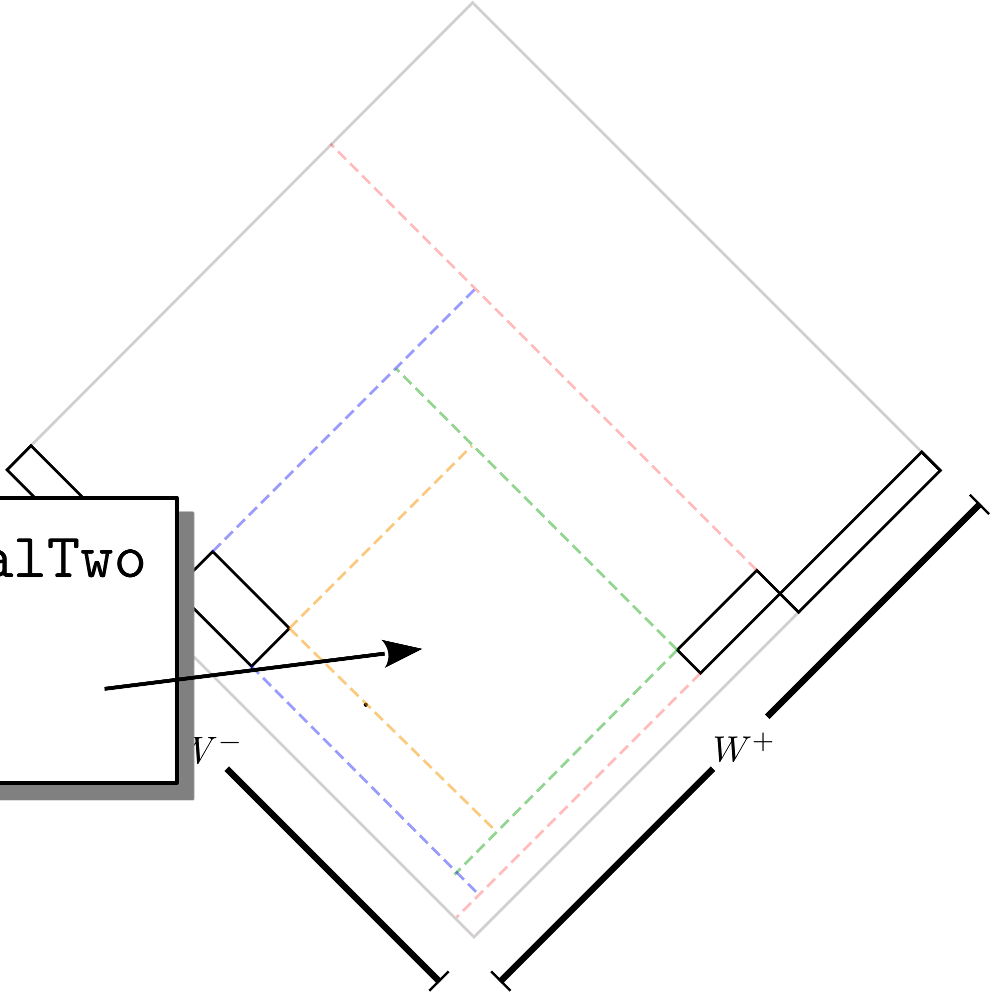
When E_{CM} goes below ~2 GeV, `finalTwo` is called. This can fail, when it does, the full string system is re-simulated from the beginning.



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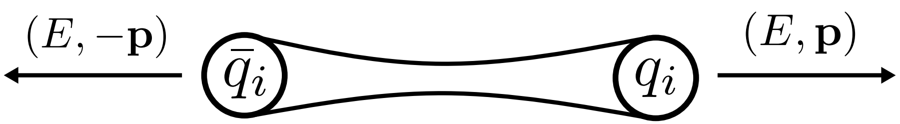

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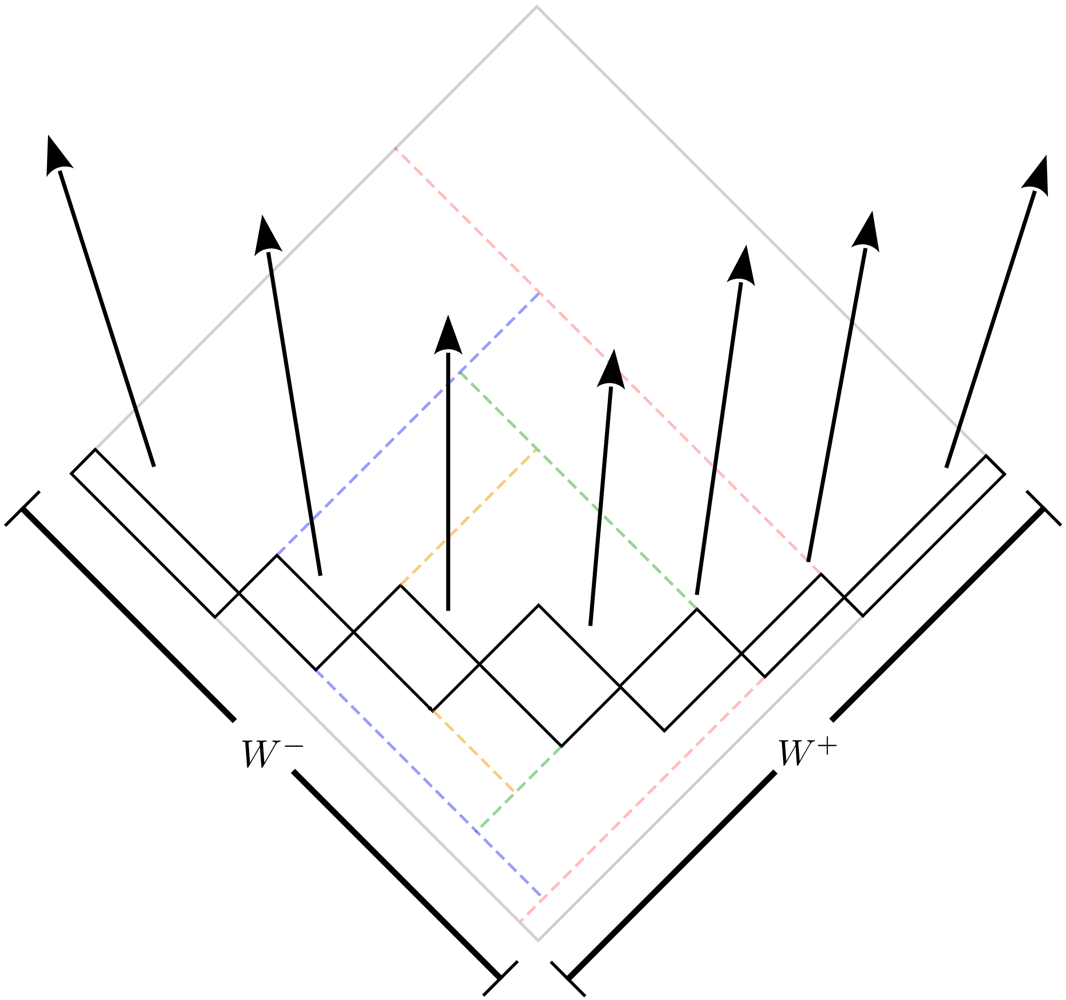
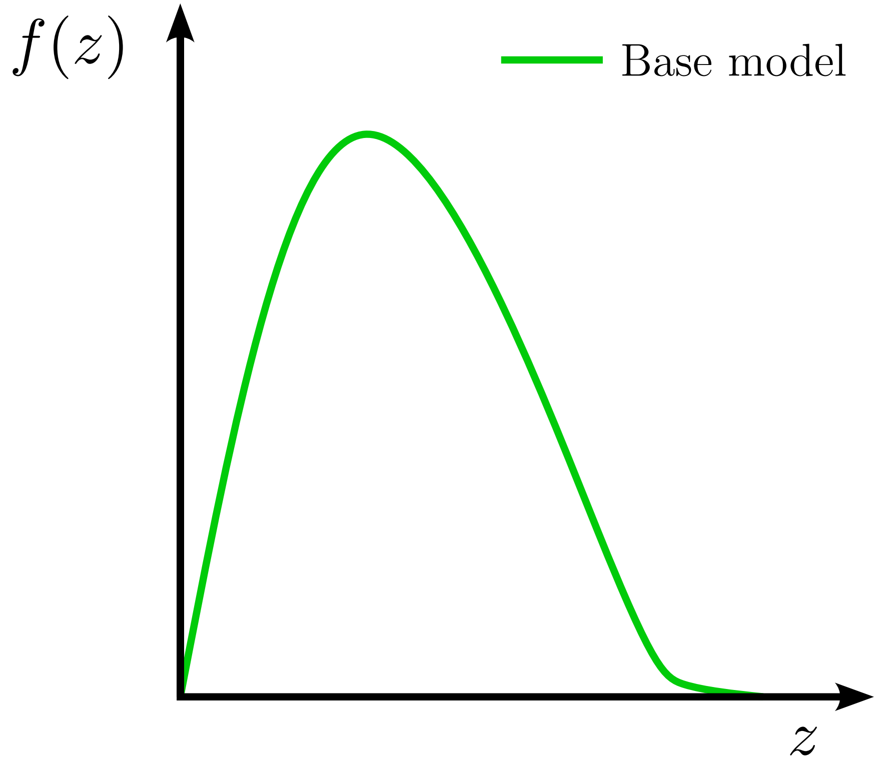


MLHAD efforts: big picture

Solving the "inverse problem of hadronization"



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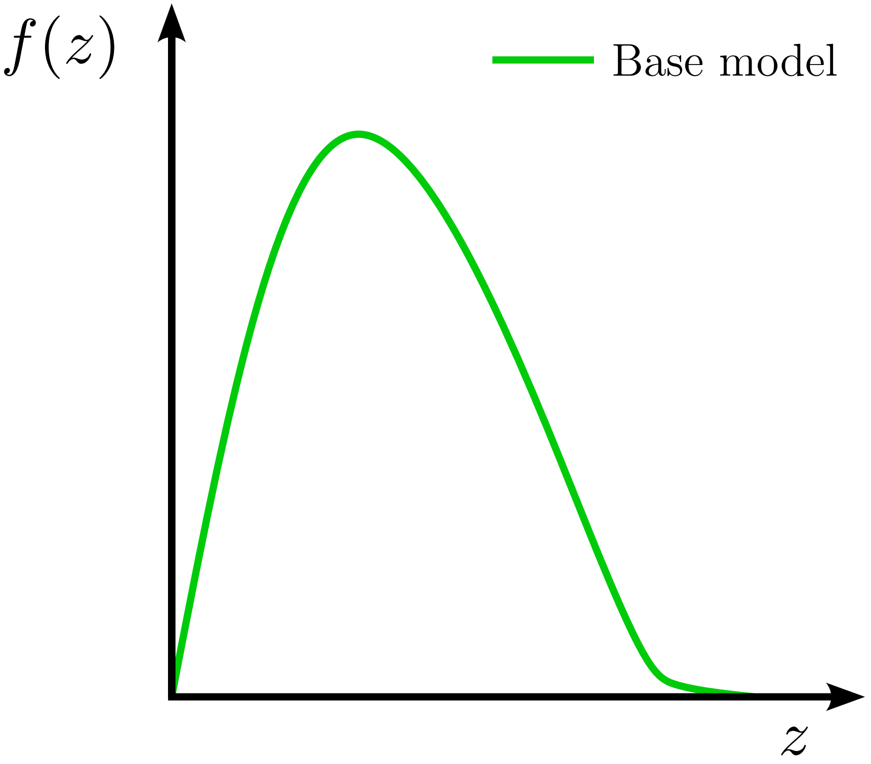

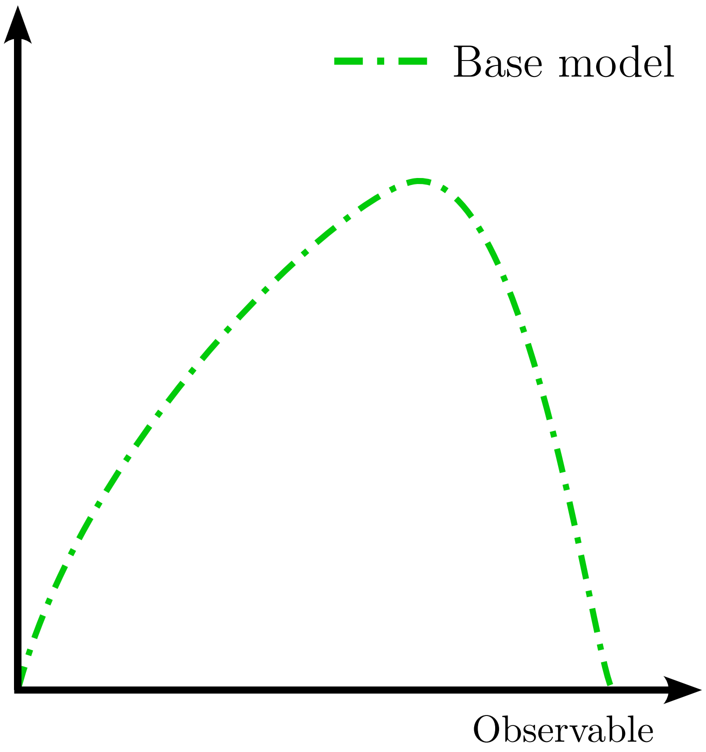

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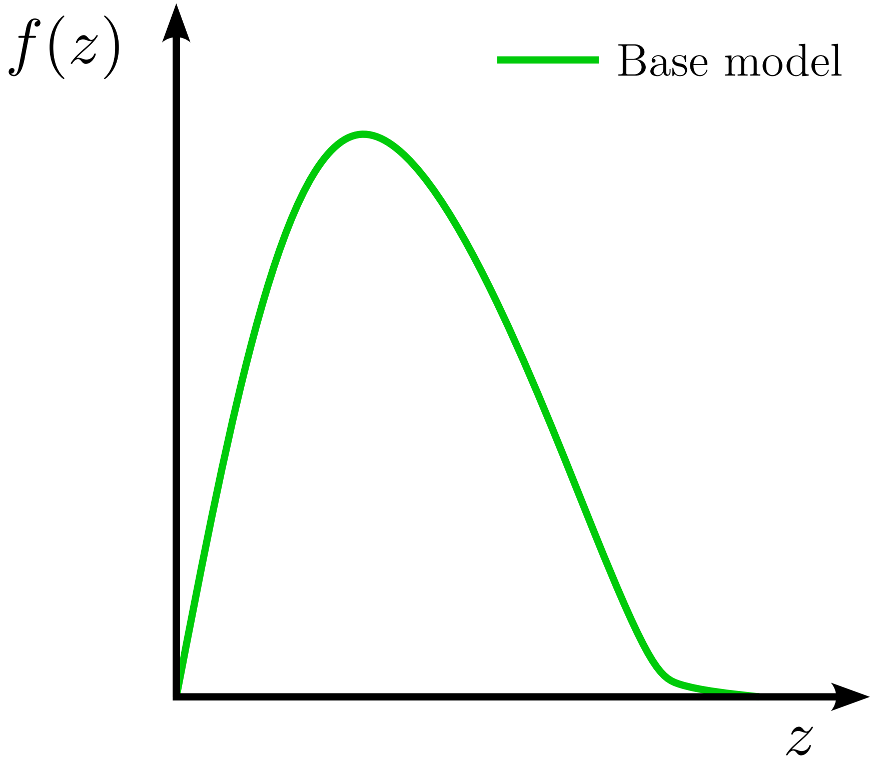

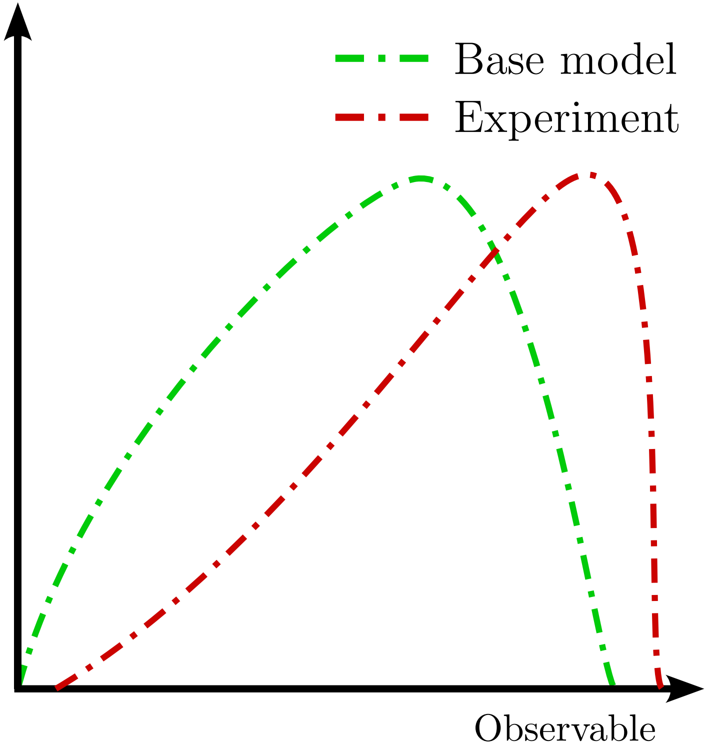

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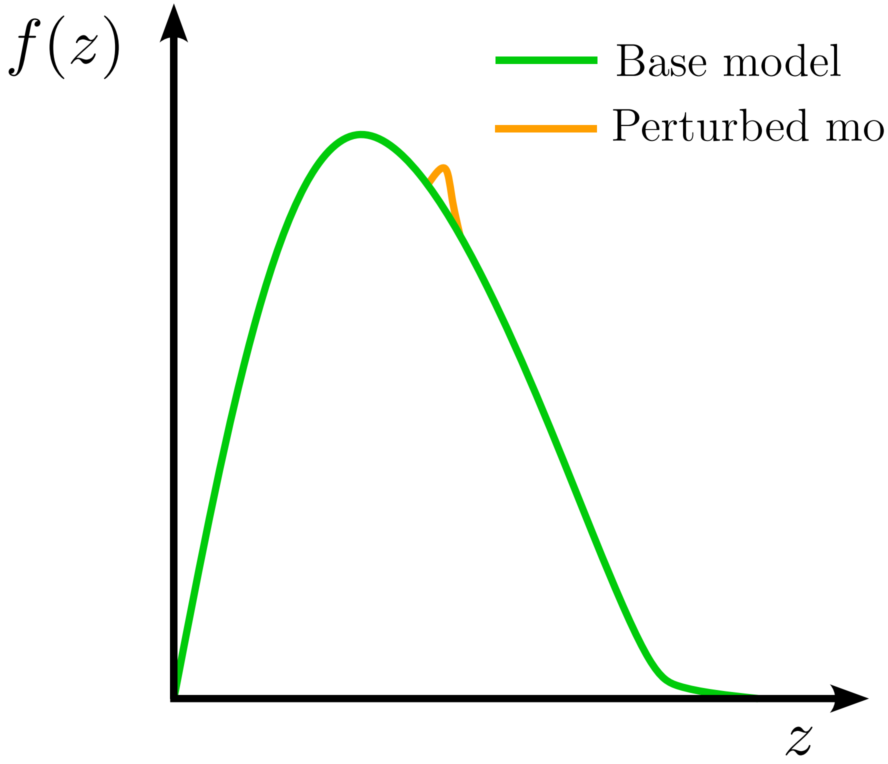

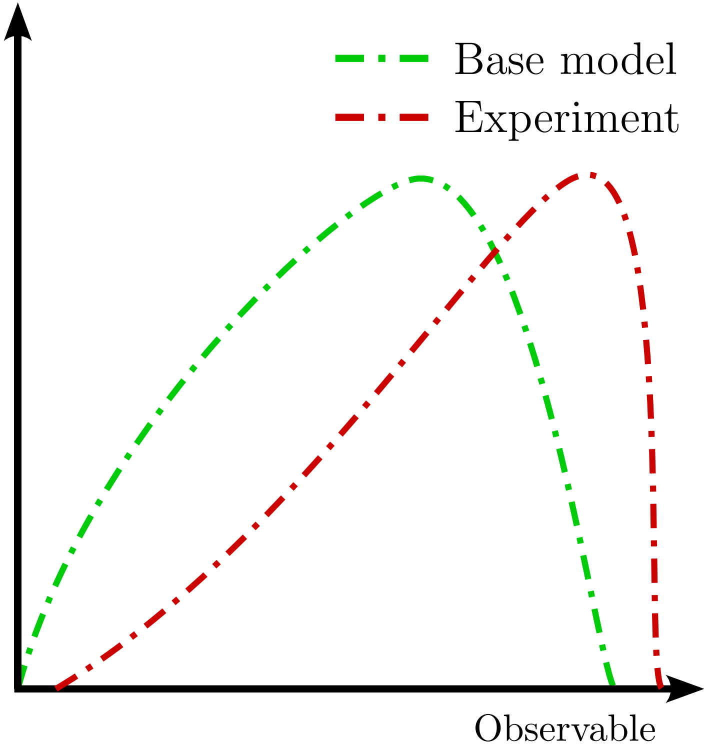

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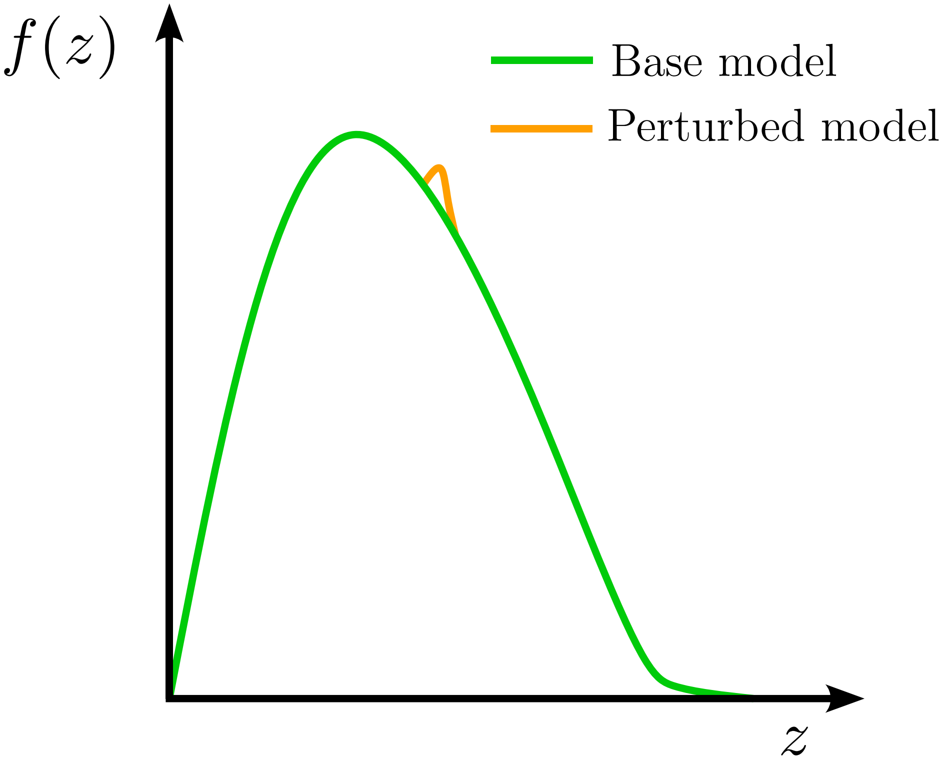

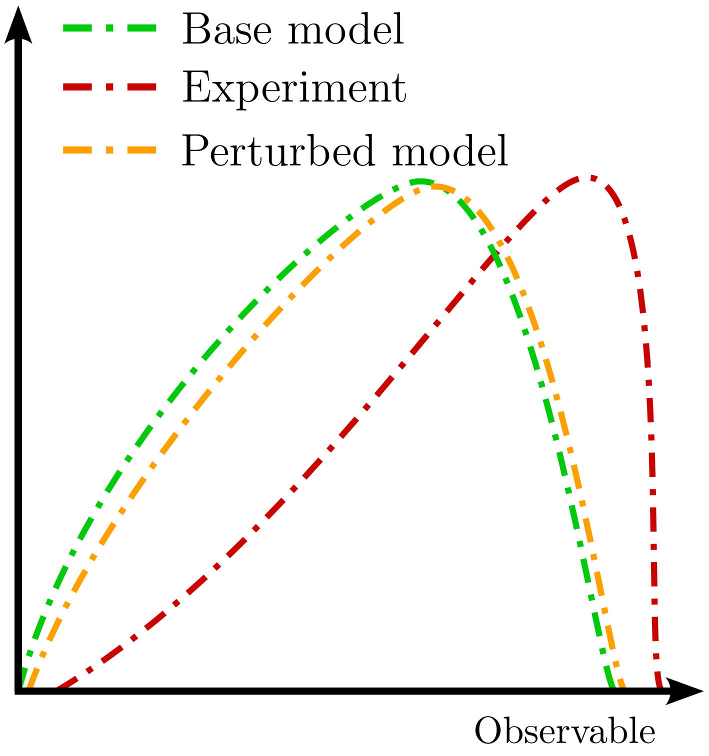

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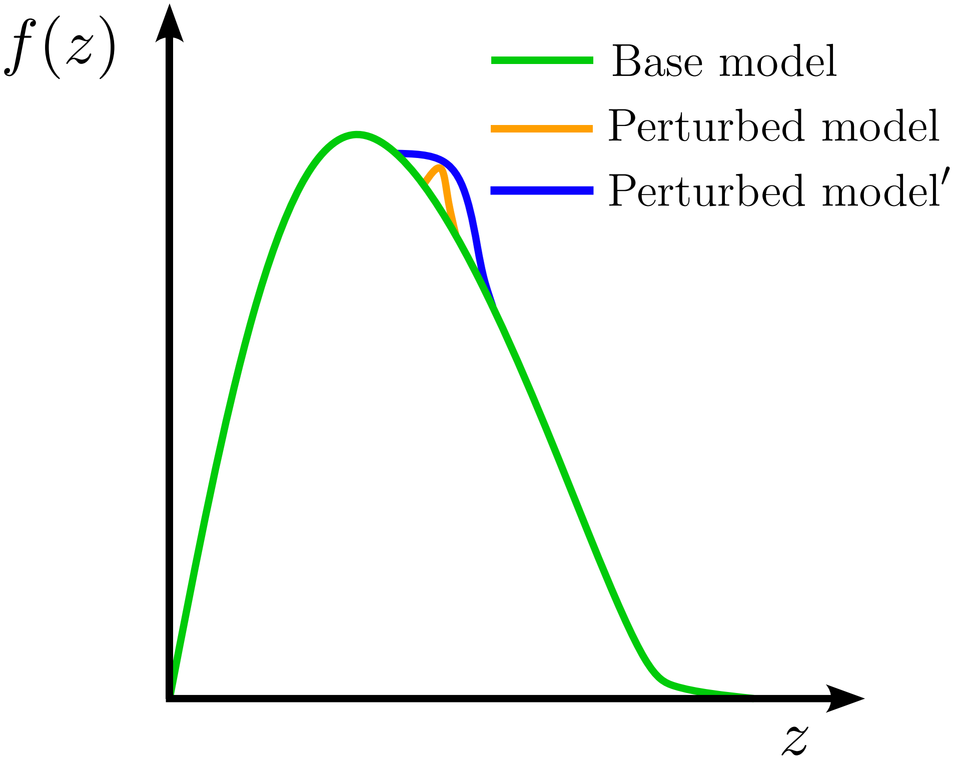

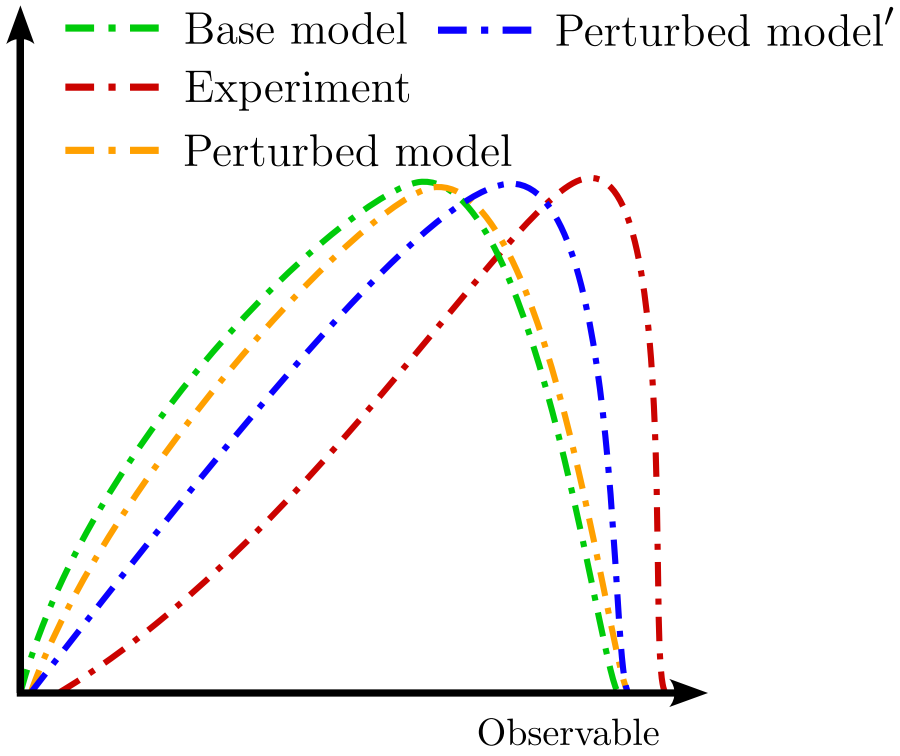

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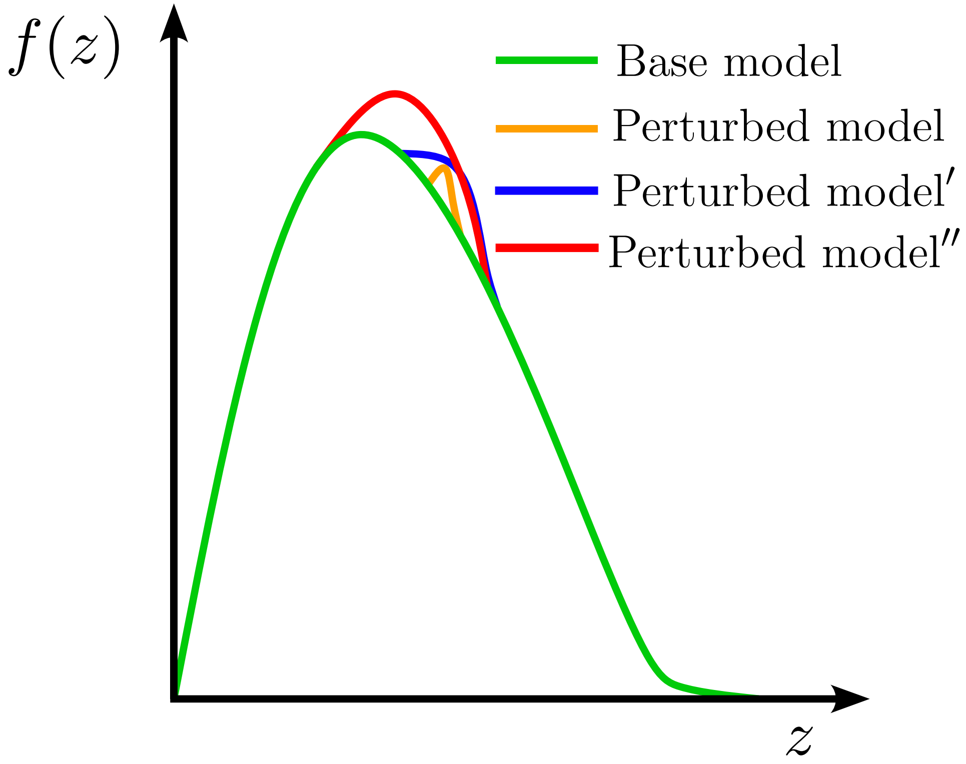

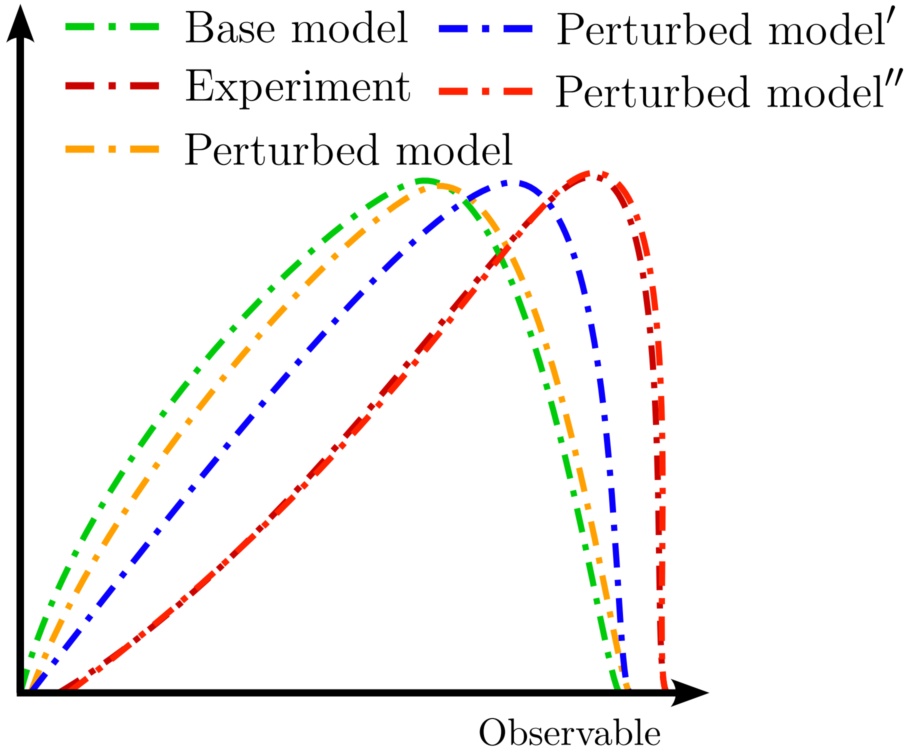

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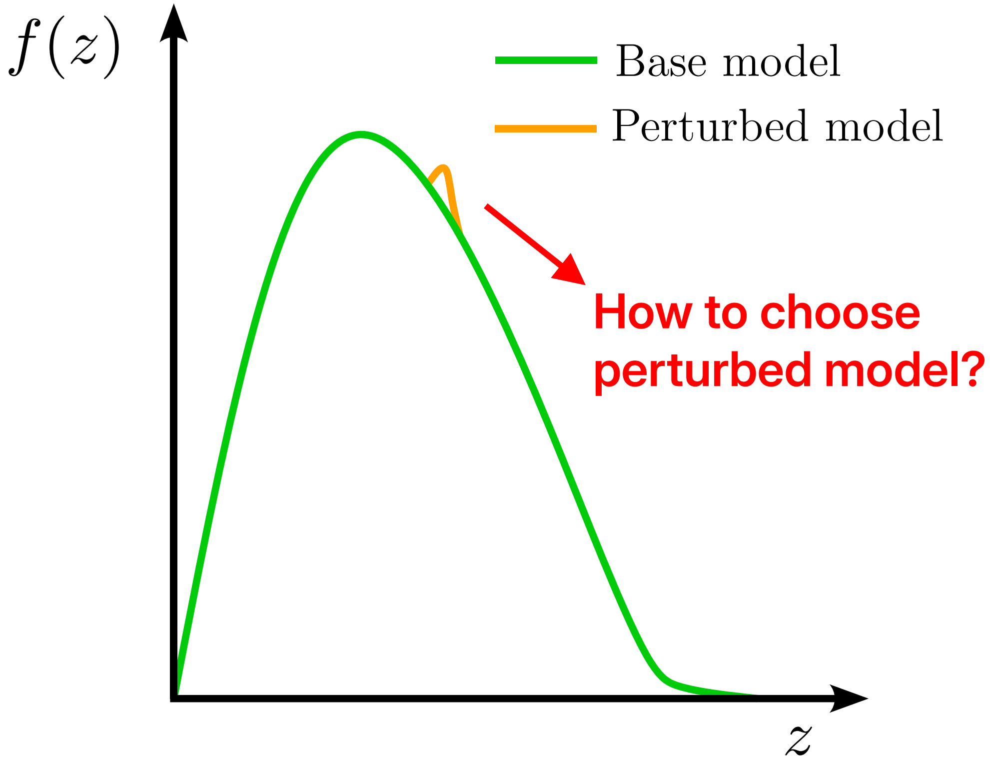

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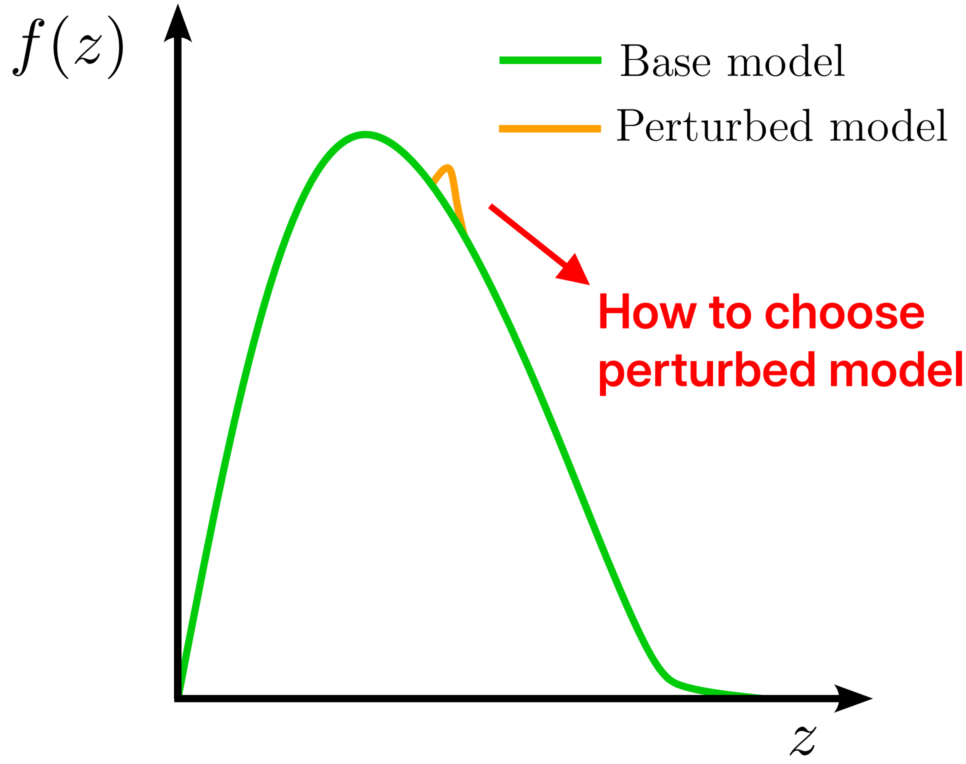


How to choose perturbed model?

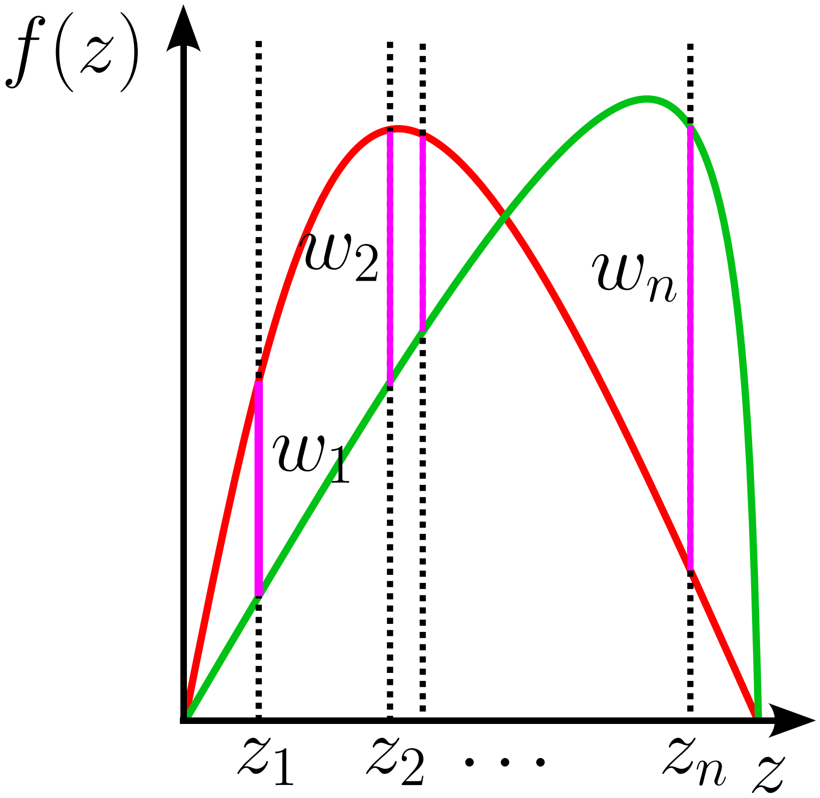
~~ML~~ vs ML

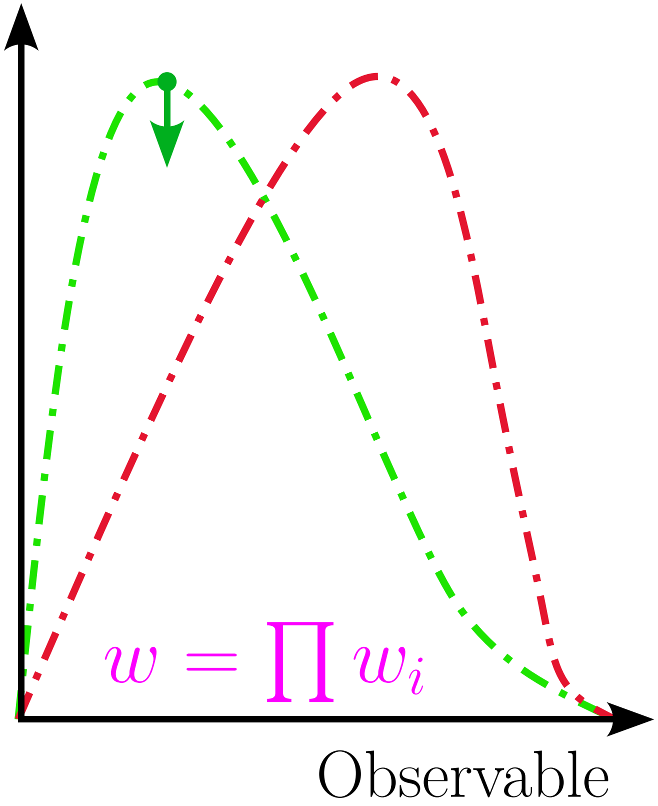
- Vary Lund parameters (traditional "manual"/semi-"manual" tuning)

- ML-based (data-driven) fragmentation function
  - MAGIC, HOMER

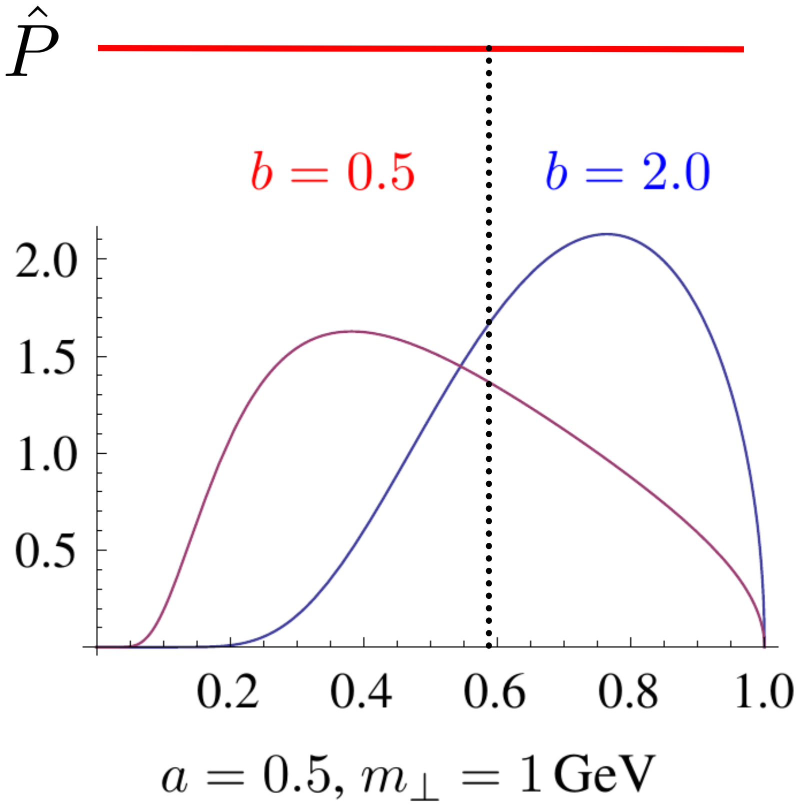
- Hybrid – keep Lund fragmentation function, promote Lund parameters to differentiable objects
  - Rejection sampling with autodifferentiation (RSA)

Aside - Reweighting





Kinematic reweighting (2308.13459)



Rejection sampling:

Acceptance probability: $P_{\text{accept}} = \frac{p(z,\theta)}{\hat{P}}$

Rejection probability: $P_{\text{reject}} = 1 - P_{\text{accept}}$

$$w_{\text{accept}} = \frac{p(z;\theta')}{p(z;\theta)}$$

$$w_{\text{reject}} = \frac{\hat{P} - p(z;\theta')}{\hat{P} - p(z;\theta)}$$

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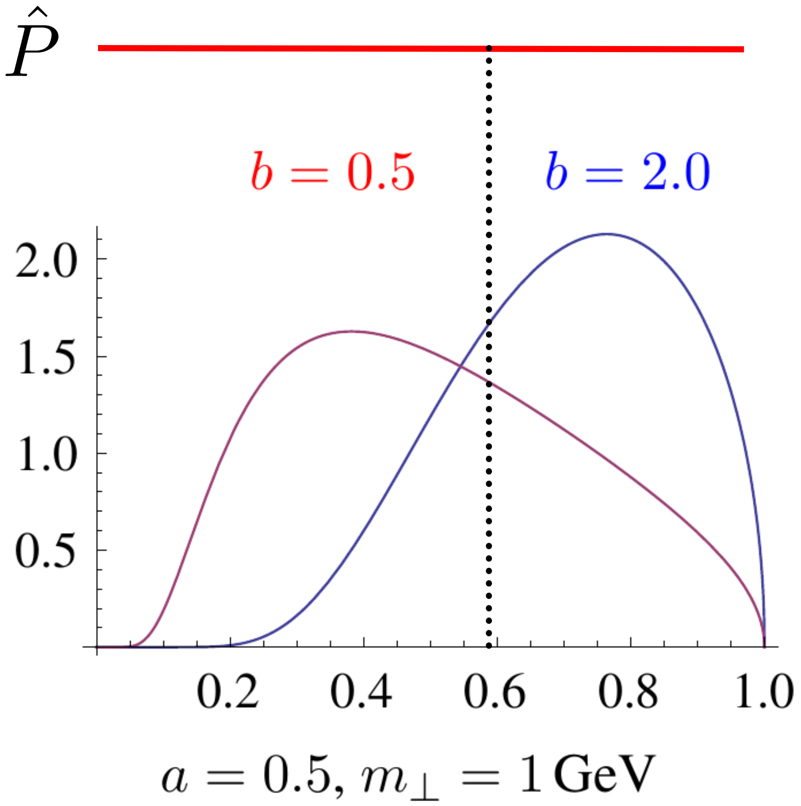

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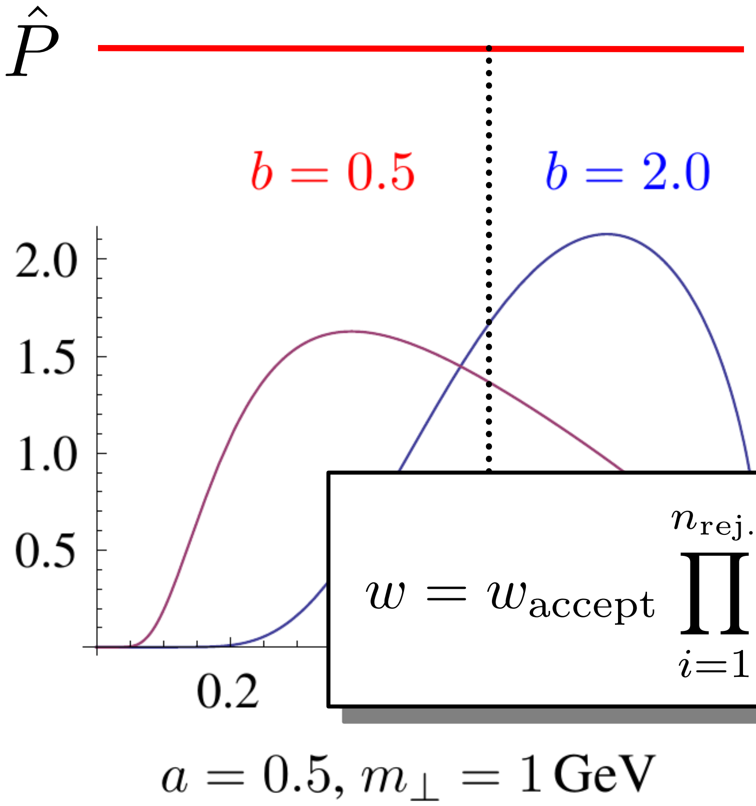

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$$w = w_{\text{accept}} \prod_{i=1}^{n_{\text{rej.}}} w^i_{\text{reject}}$$

$$w_{\text{accept}} = \frac{p(z;\theta')}{p(z;\theta)}$$

$$w_{\text{reject}} = \frac{\hat{P} - p(z;\theta')}{\hat{P} - p(z;\theta)}$$

Kinematic reweighting (2308.13459)

$\hat{P}$

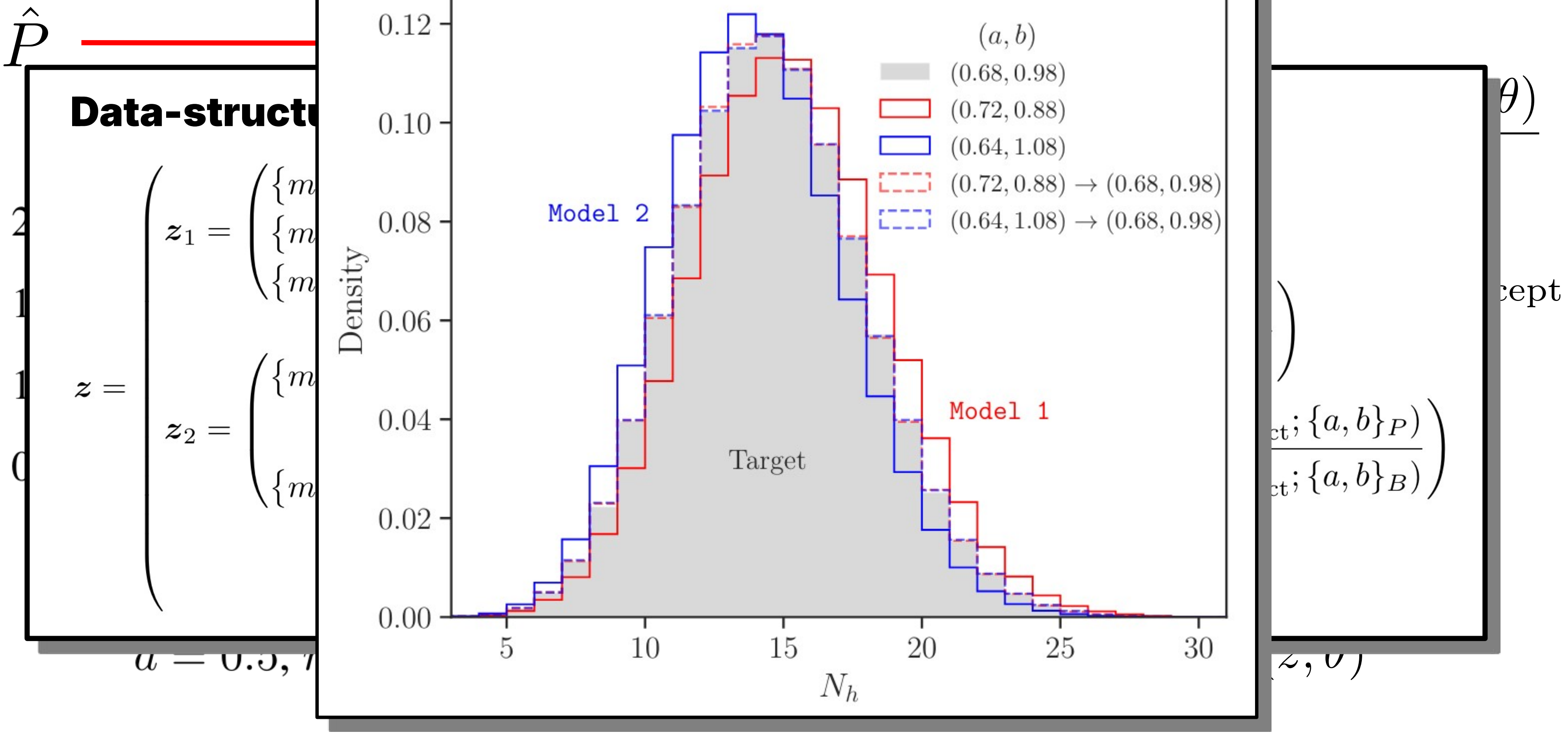
Rejection sampling:

Data-structure:

$$
\boldsymbol{z} = \begin{pmatrix}
\boldsymbol{z}_1 = \begin{pmatrix}
\{m_T^{h_1}, z_{\text{accept}}^{h_1}, z_{\text{reject}}^{1,h_1}, \cdots, z_{\text{reject}}^{n_{h_1},h_1}\} \\
\{m_T^{h_2}, z_{\text{accept}}^{h_2}, z_{\text{reject}}^{1,h_2}, \cdots, z_{\text{reject}}^{n_{h_2},h_2}\} \\
\{m_T^{h_3}, z_{\text{accept}}^{h_3}, z_{\text{reject}}^{1,h_3}, \cdots, z_{\text{reject}}^{n_{h_3},h_3}\}
\end{pmatrix}_1 \\
\boldsymbol{z}_2 = \begin{pmatrix}
\{m_T^{h_1}, z_{\text{accept}}^{h_1}, z_{\text{reject}}^{1,h_1}, \cdots, z_{\text{reject}}^{n_{h_1},h_1}\} \\
\vdots \\
\{m_T^{h_4}, z_{\text{accept}}^{h_4}, z_{\text{reject}}^{1,h_4}, \cdots, z_{\text{reject}}^{n_{h_4},h_4}\}
\end{pmatrix}_2 \\
\vdots \\
\boldsymbol{z}_N = \cdots
\end{pmatrix}
$$

$$
w_n = \prod_{i=1}^{\tilde{N}_{h,n}} \left(\frac{f(z_{\text{accept}}^{h_i}; \{a,b\}_P)}{f(z_{\text{accept}}^{h_i}; \{a,b\}_B)} \right) \times \prod_{j=1}^{n_{h_i}} \left(\frac{\hat{f} - f(z_{\text{reject}}^{j,h_i}; \{a,b\}_P)}{\hat{f} - f(z_{\text{reject}}^{j,h_i}; \{a,b\}_B)} \right)
$$

Kinematic reweighting (2308.13459)



Kinematic reweighting (2308.13459)

Rejection sampling:

Data-structure:

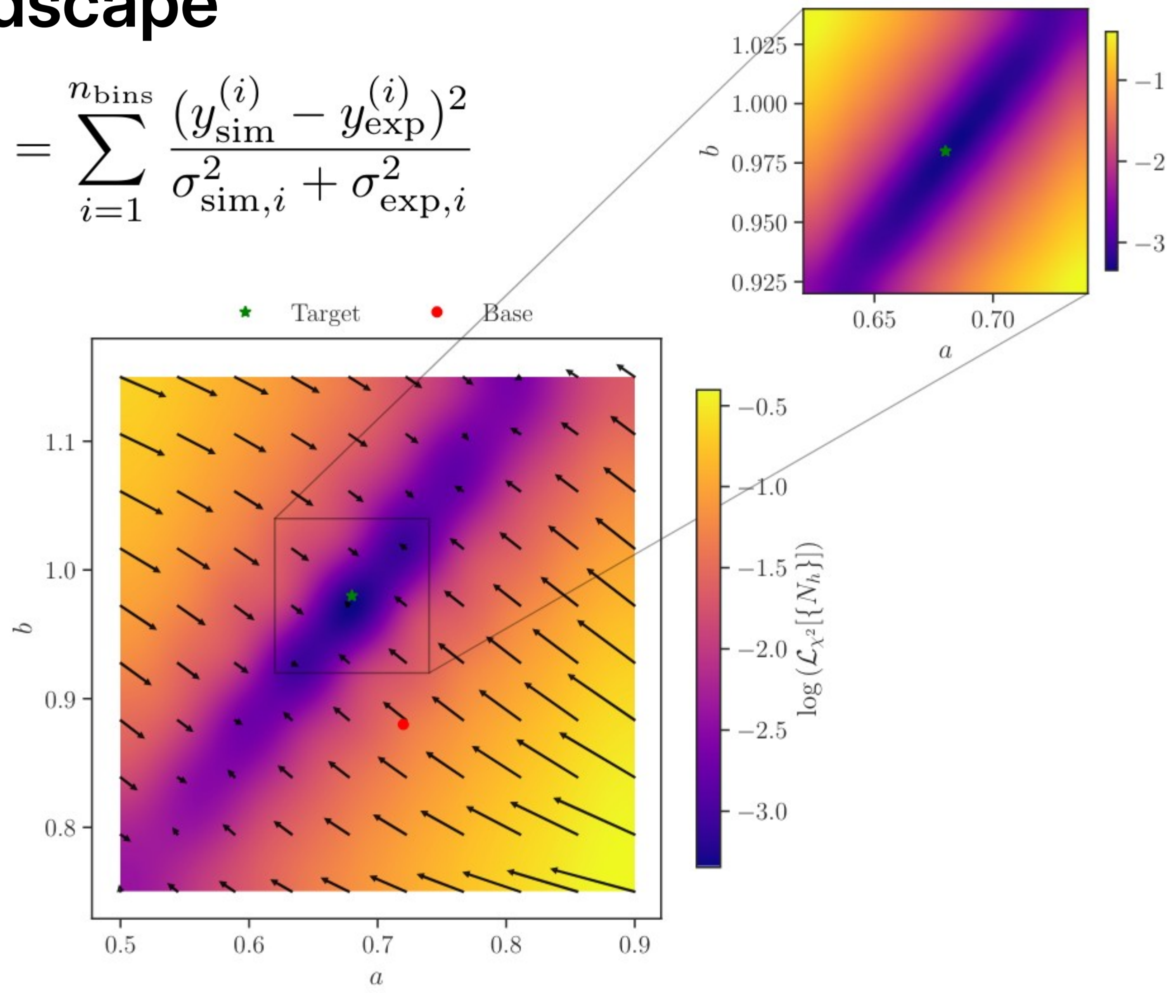
$$
\boldsymbol{z} = \begin{pmatrix}
\boldsymbol{z}_1 = \begin{pmatrix}
\{m_T^{h_1}, z_{\text{accept}}^{h_1}, z_{\text{reject}}^{1,h_1}, \cdots, z_{\text{reject}}^{n_{h_1},h_1}\} \\
\{m_T^{h_2}, z_{\text{accept}}^{h_2}, z_{\text{reject}}^{1,h_2}, \cdots, z_{\text{reject}}^{n_{h_2},h_2}\} \\
\{m_T^{h_3}, z_{\text{accept}}^{h_3}, z_{\text{reject}}^{1,h_3}, \cdots, z_{\text{reject}}^{n_{h_3},h_3}\}
\end{pmatrix}_1 \\
\\
\boldsymbol{z}_2 = \begin{pmatrix}
\{m_T^{h_1}, z_{\text{accept}}^{h_1}, z_{\text{reject}}^{1,h_1}, \cdots, z_{\text{reject}}^{n_{h_1},h_1}\} \\
\vdots \\
\{m_T^{h_4}, z_{\text{accept}}^{h_4}, z_{\text{reject}}^{1,h_4}, \cdots, z_{\text{reject}}^{n_{h_4},h_4}\}
\end{pmatrix}_2 \\
\vdots \\
\boldsymbol{z}_N = \cdots
\end{pmatrix}
$$

Differentiable! → RSA

$$
w_n = \prod_{i=1}^{\tilde{N}_{h,n}} \left(\frac{f(z_{\text{accept}}^{h_i}; \{a,b\}_P)}{f(z_{\text{accept}}^{h_i}; \{a,b\}_B)} \right) \times \prod_{j=1}^{n_{h_i}} \left(\frac{\hat{f} - f(z_{\text{reject}}^{j,h_i}; \{a,b\}_P)}{\hat{f} - f(z_{\text{reject}}^{j,h_i}; \{a,b\}_B)} \right)
$$

χ^2-loss landscape

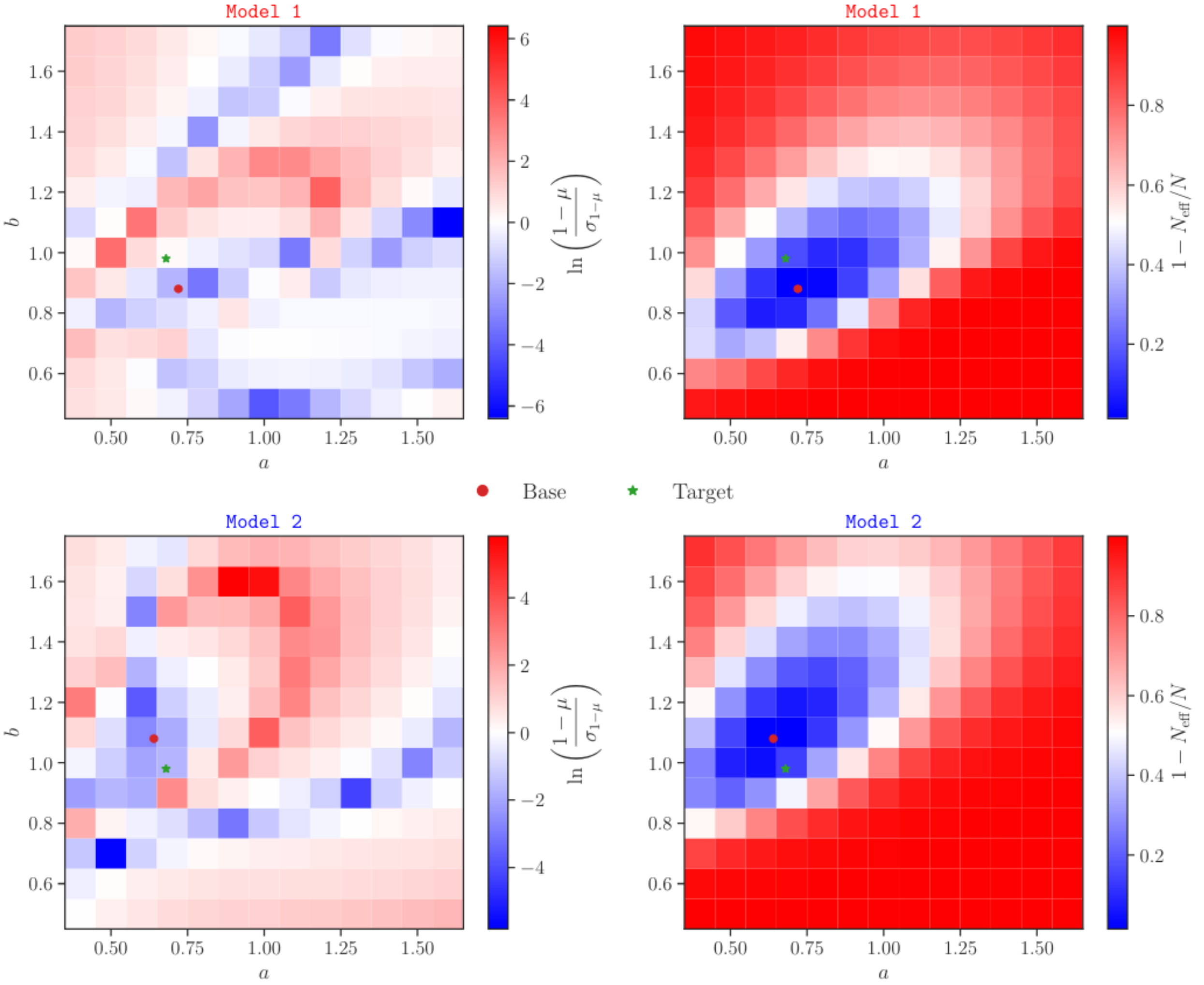
$$\mathcal{L}_{\chi^2}(\boldsymbol{y}_{\rm sim}, \boldsymbol{y}_{\rm exp}; \boldsymbol{w}) = \sum_{i=1}^{n_{\rm bins}} \frac{(y_{\rm sim}^{(i)} - y_{\rm exp}^{(i)})^2}{\sigma^2_{{\rm sim},i} + \sigma^2_{{\rm exp},i}}$$



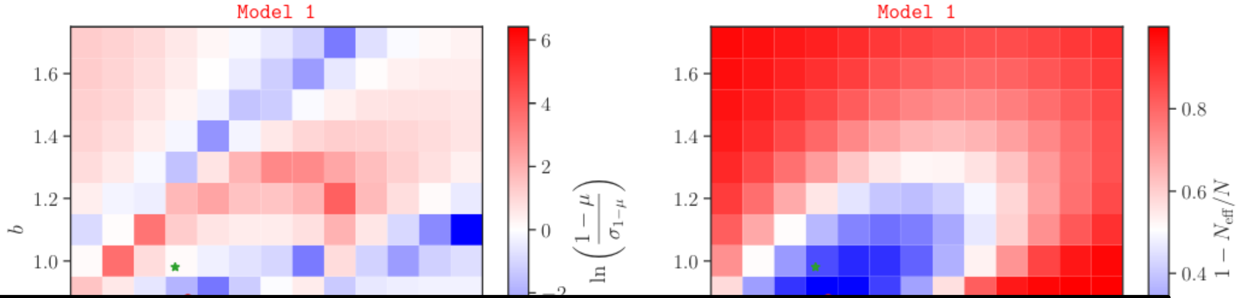
No free lunch

Statistical power drops off quickly as you move away from the base parameterization

$$\mu \equiv \sum_{i=1}^{N} \frac{w_i}{N}, \qquad N_{\text{eff}} = \frac{\left(\sum_{i=1}^{N} w_i\right)^2}{\sum_{i=1}^{N} w_i^2}$$



No free lunch



Stati
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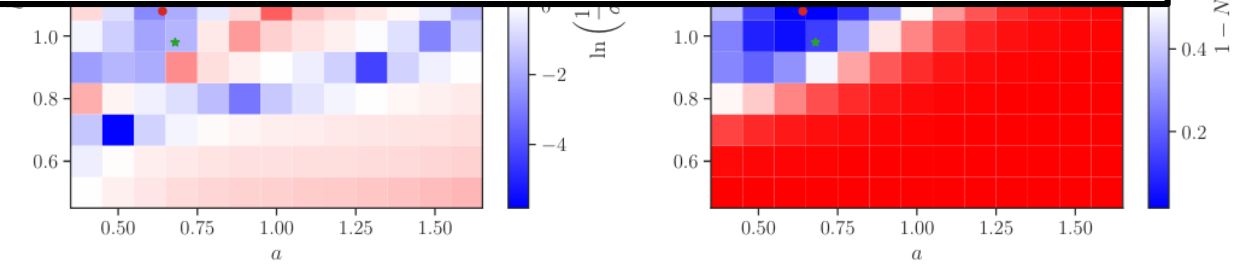
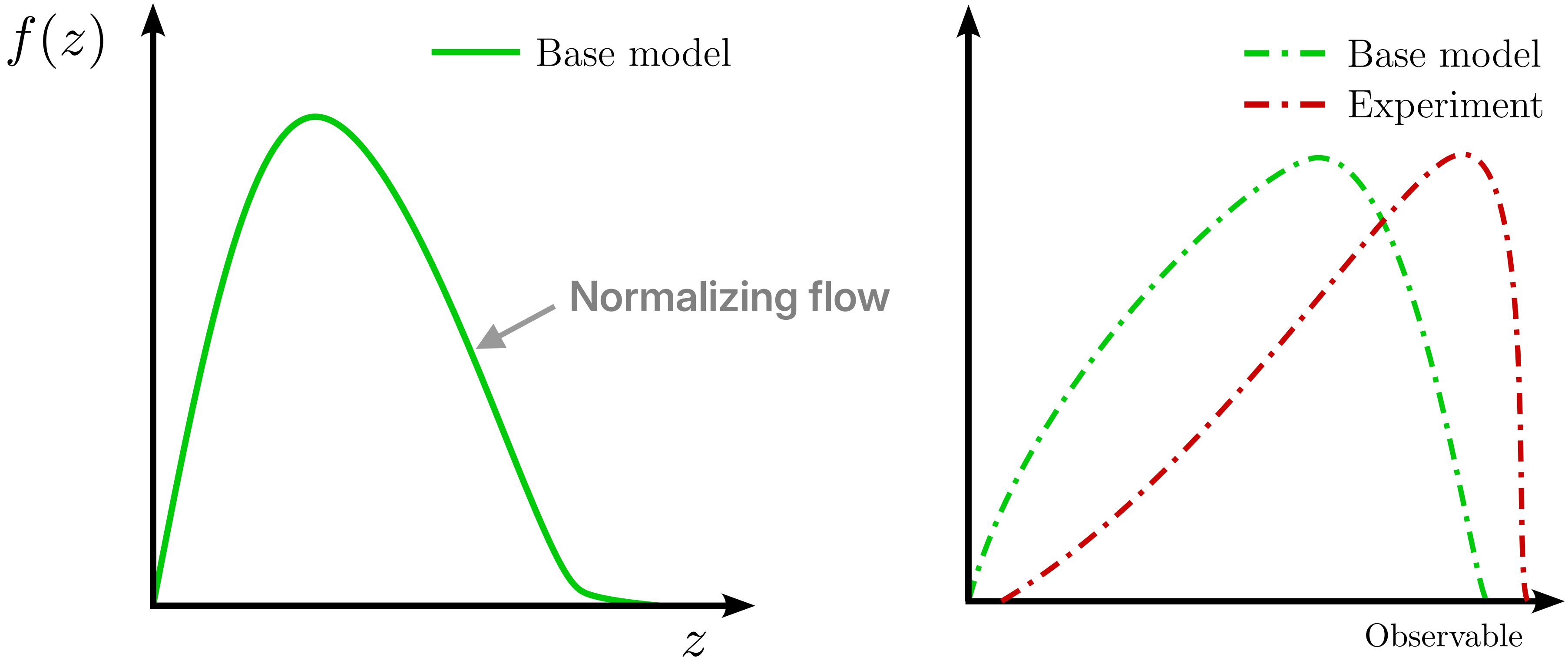
Road to differentiable Pythia?

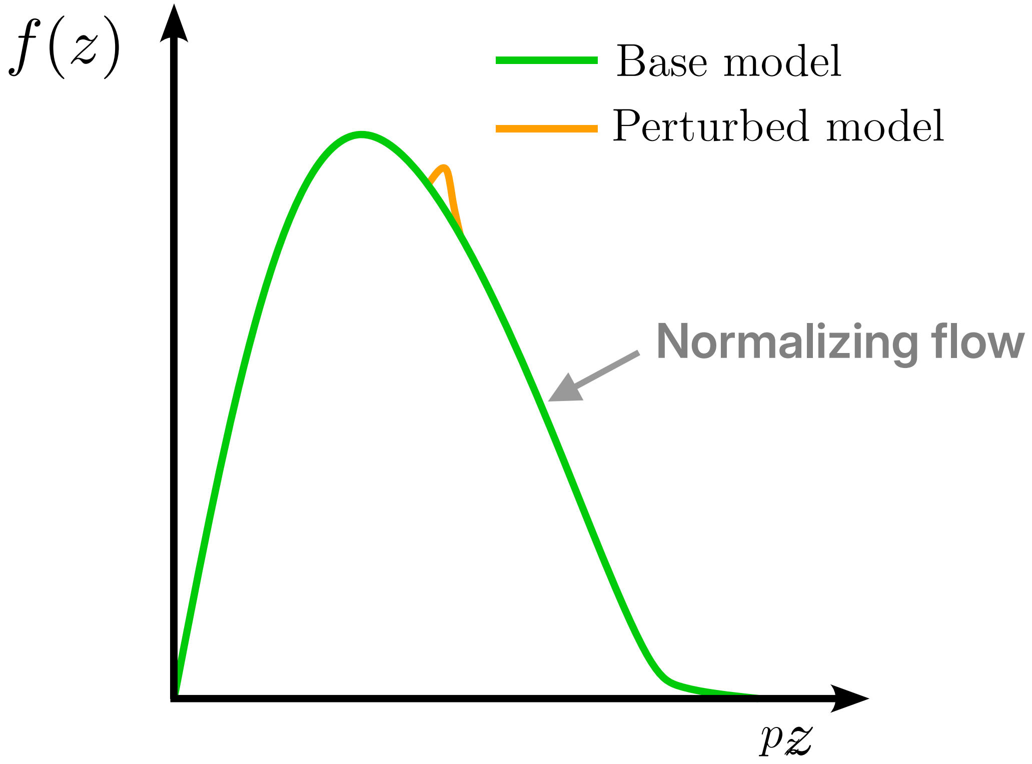
$\mu \equiv \sum_{i=}$

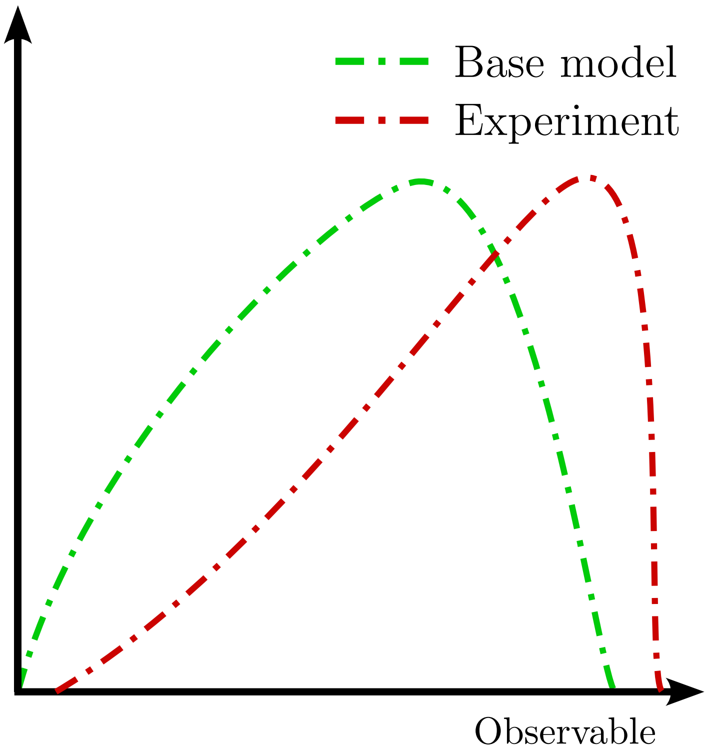


MLHAD efforts: MAGIC

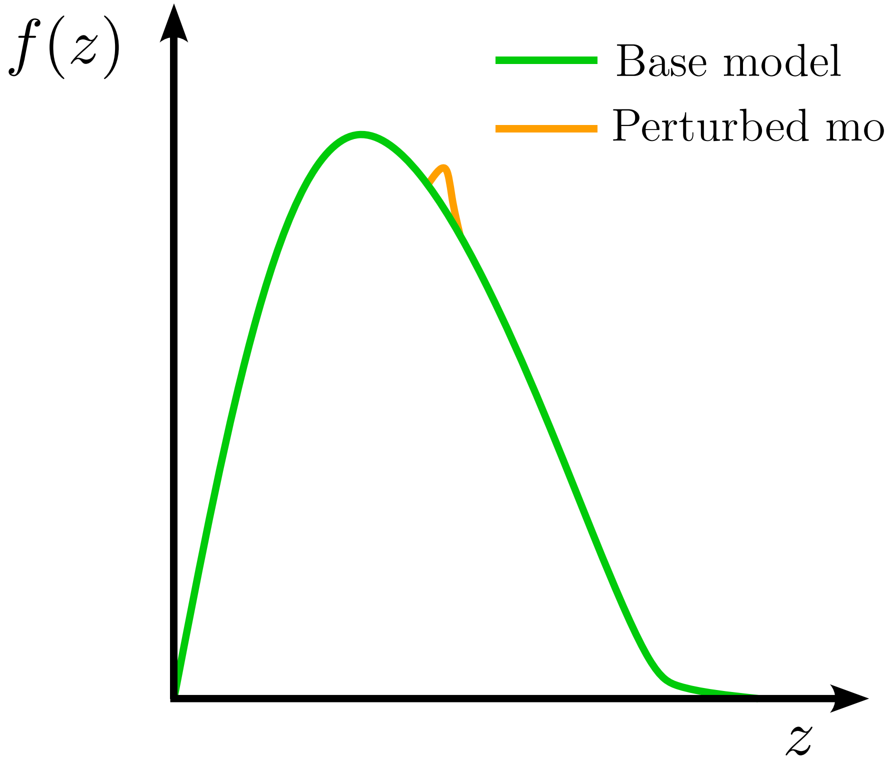


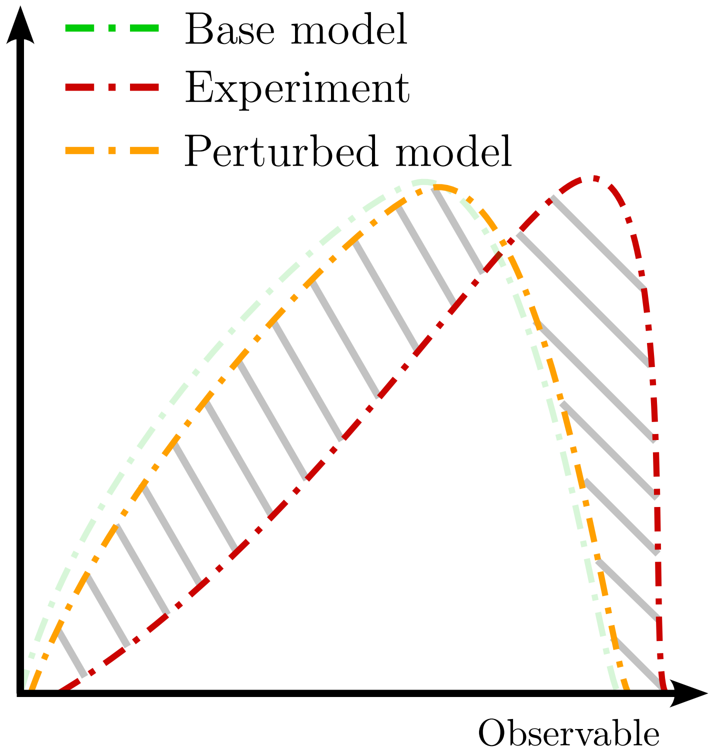
MLHAD efforts: MAGIC



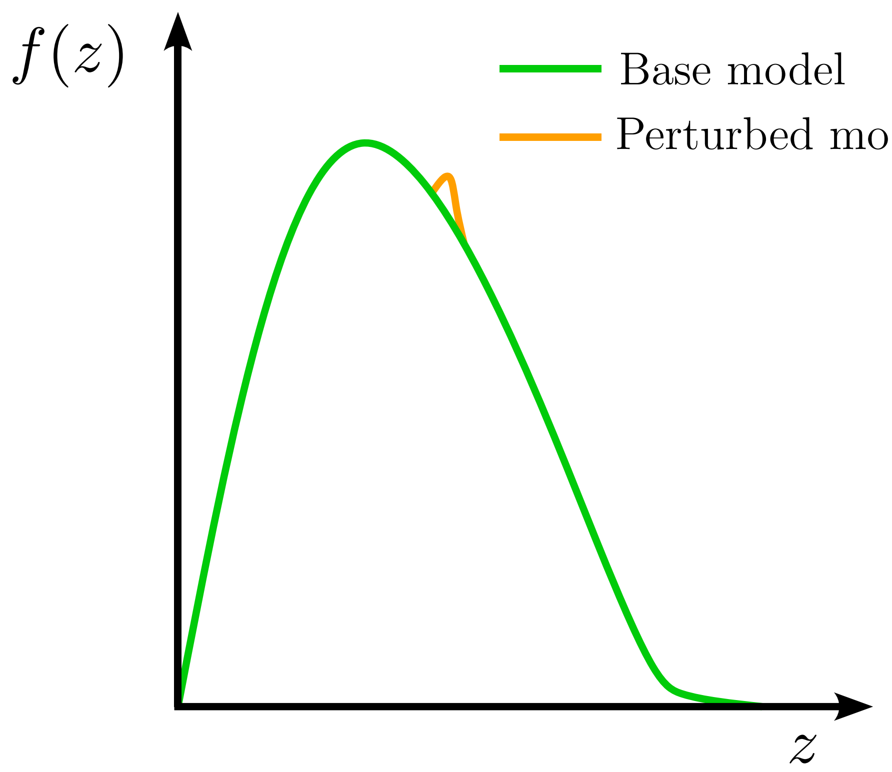


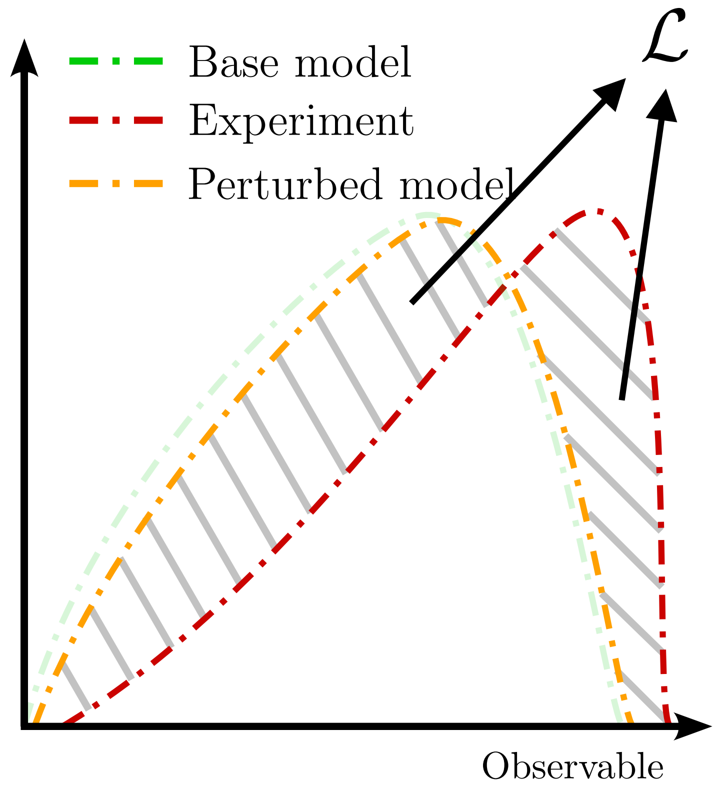
MLHAD efforts: MAGIC



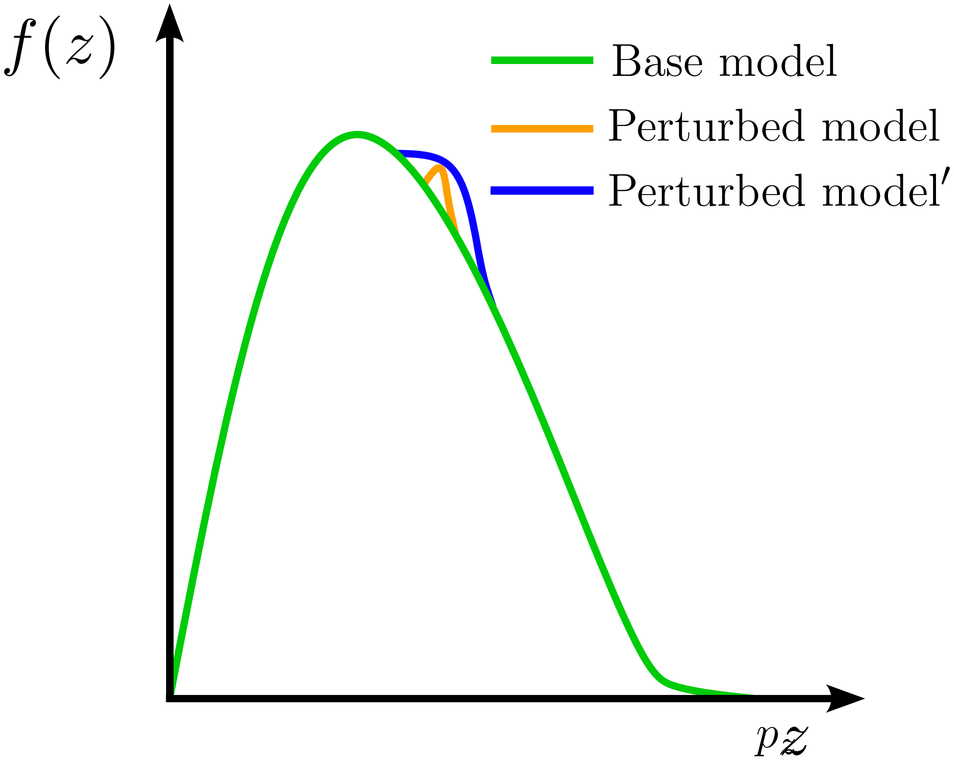


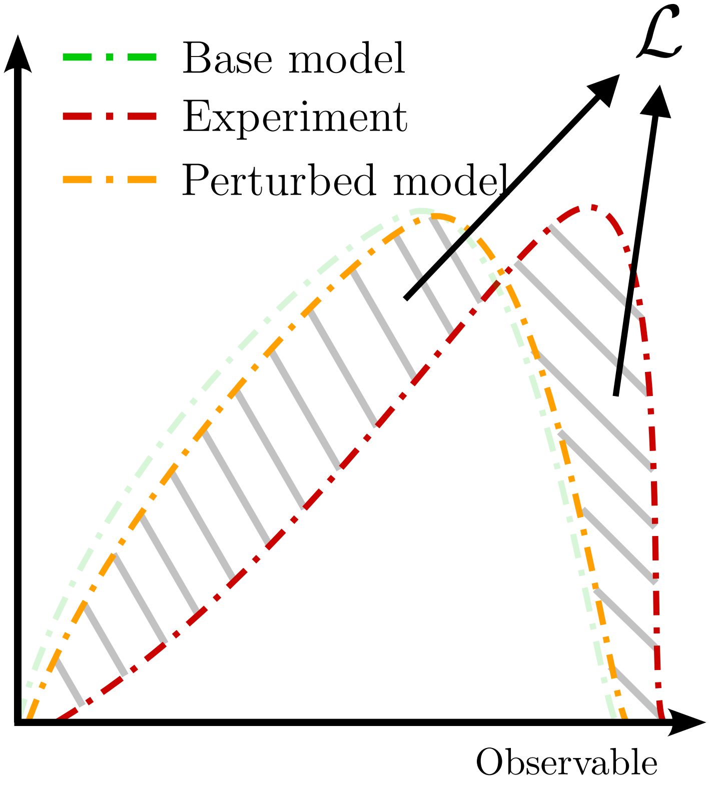
MLHAD efforts: MAGIC



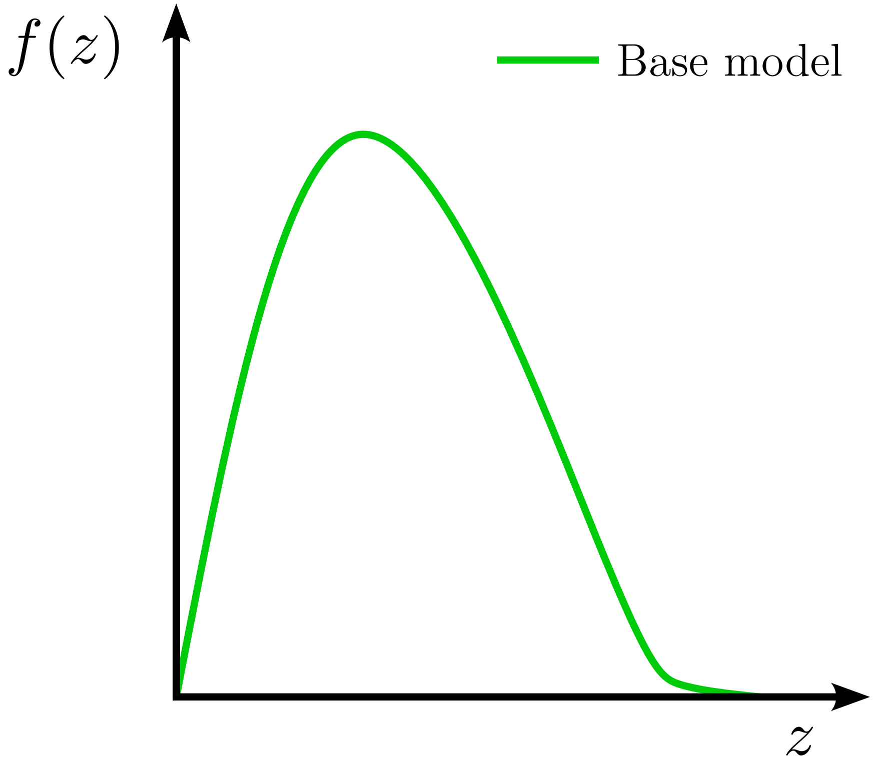


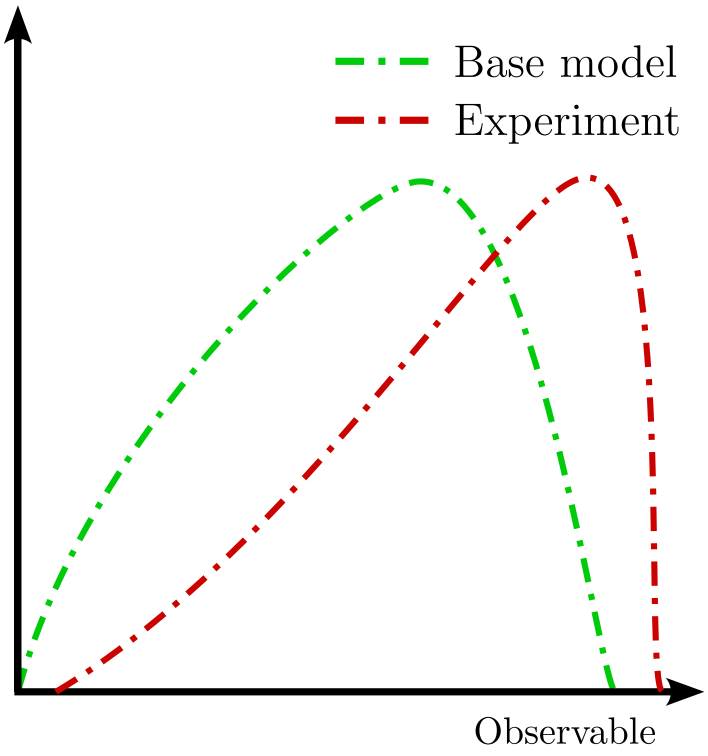
MLHAD efforts: MAGIC



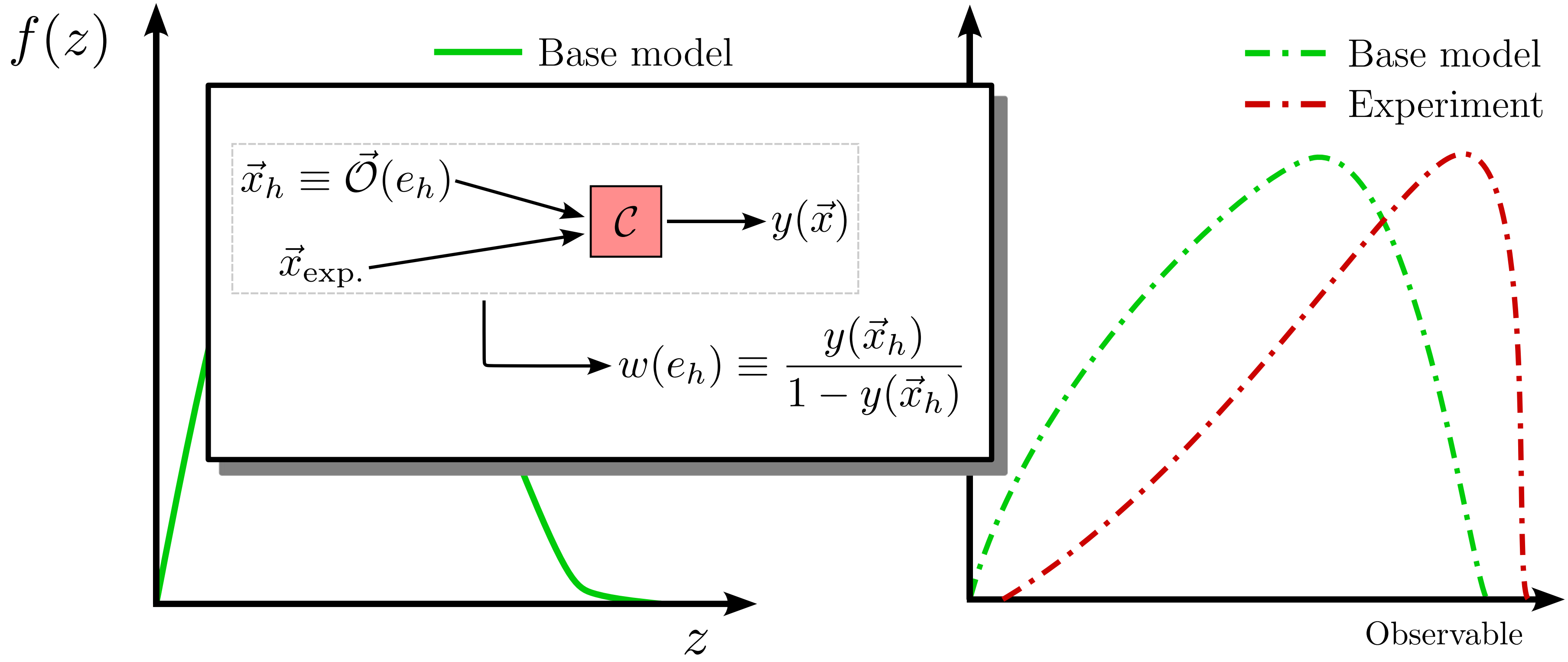


MLHAD efforts: HOMER

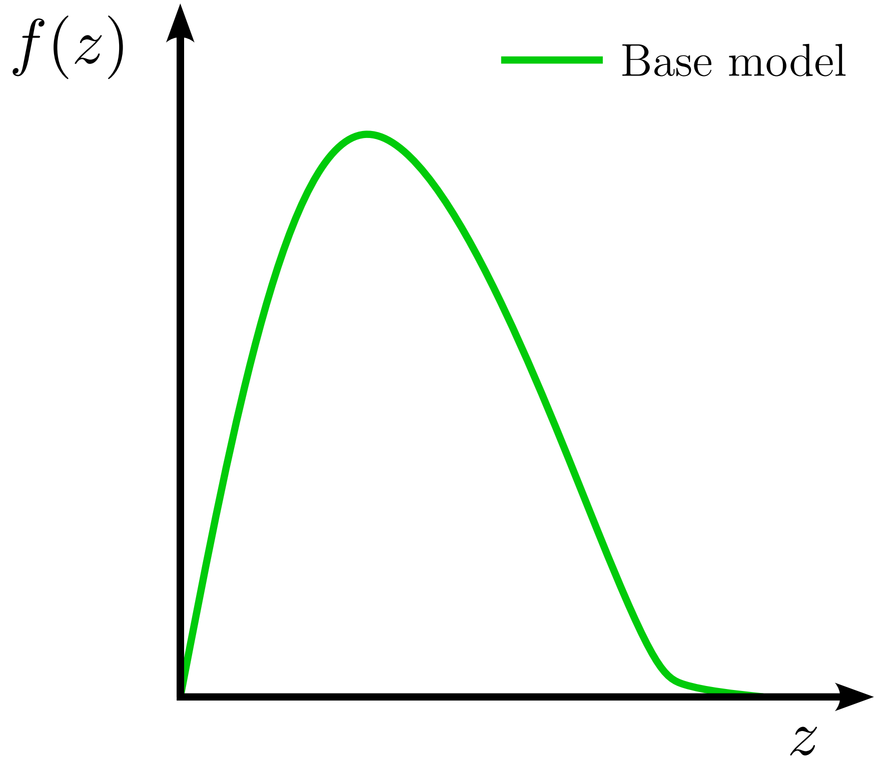


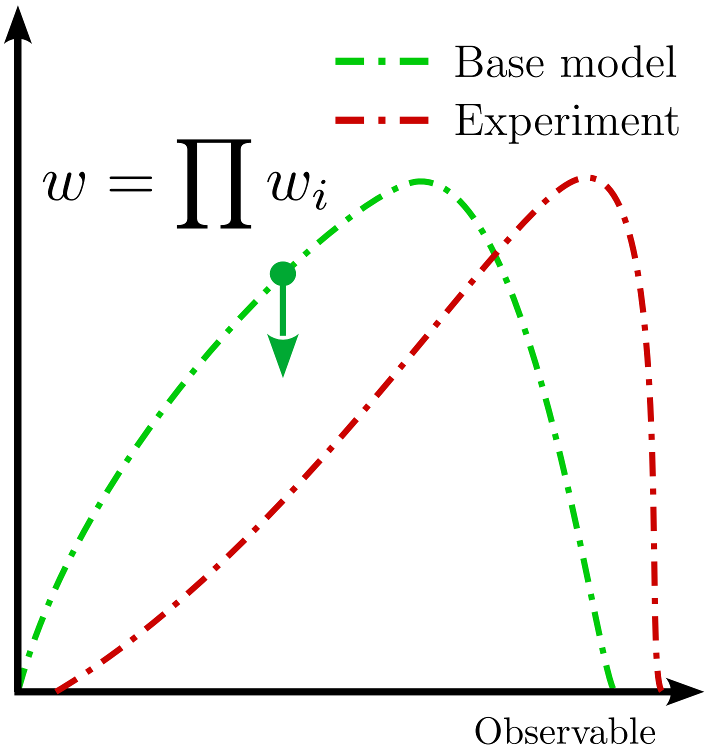


MLHAD efforts: HOMER

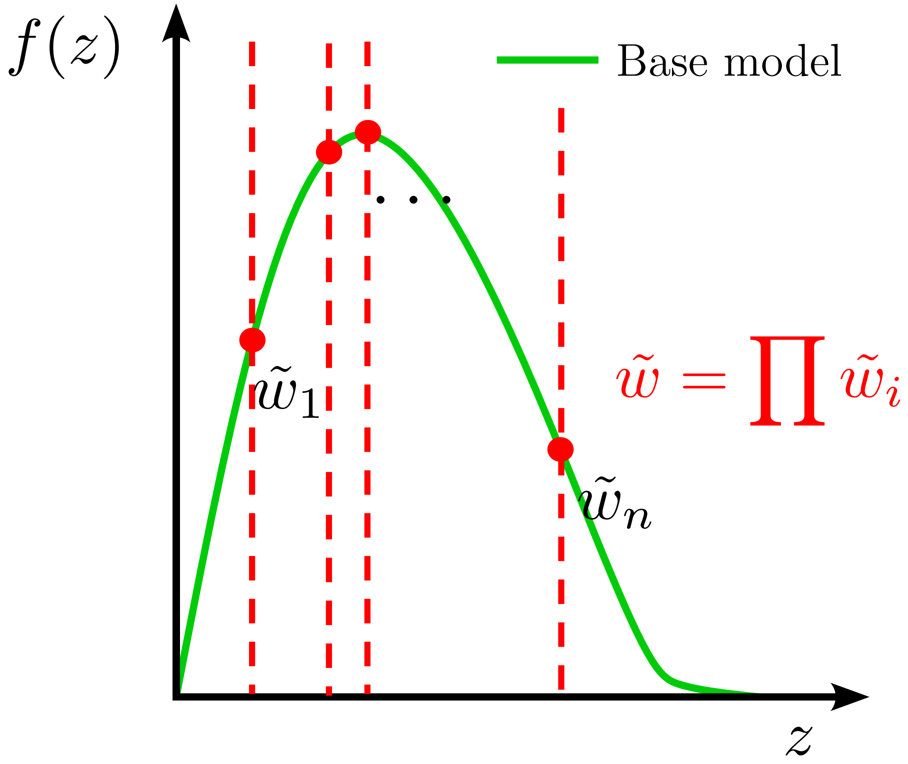


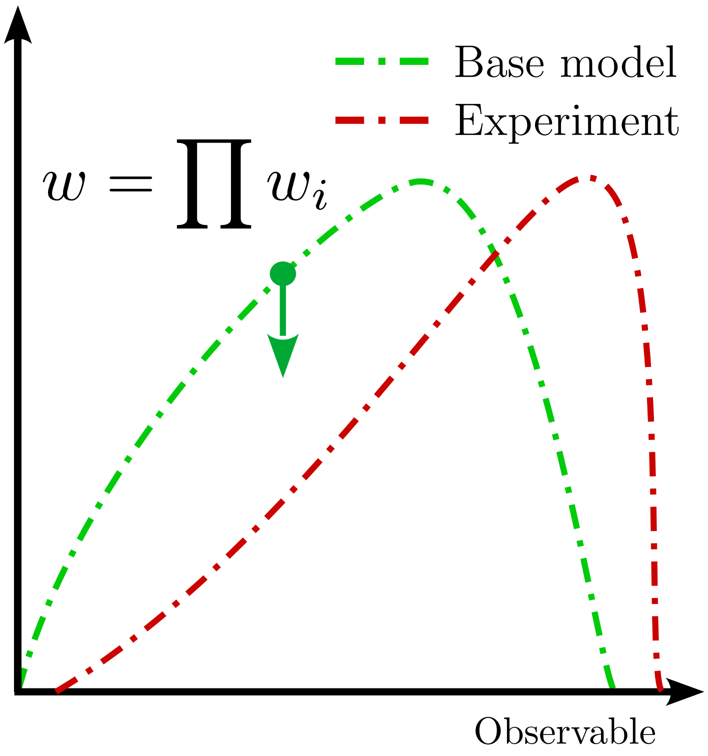
MLHAD efforts: HOMER



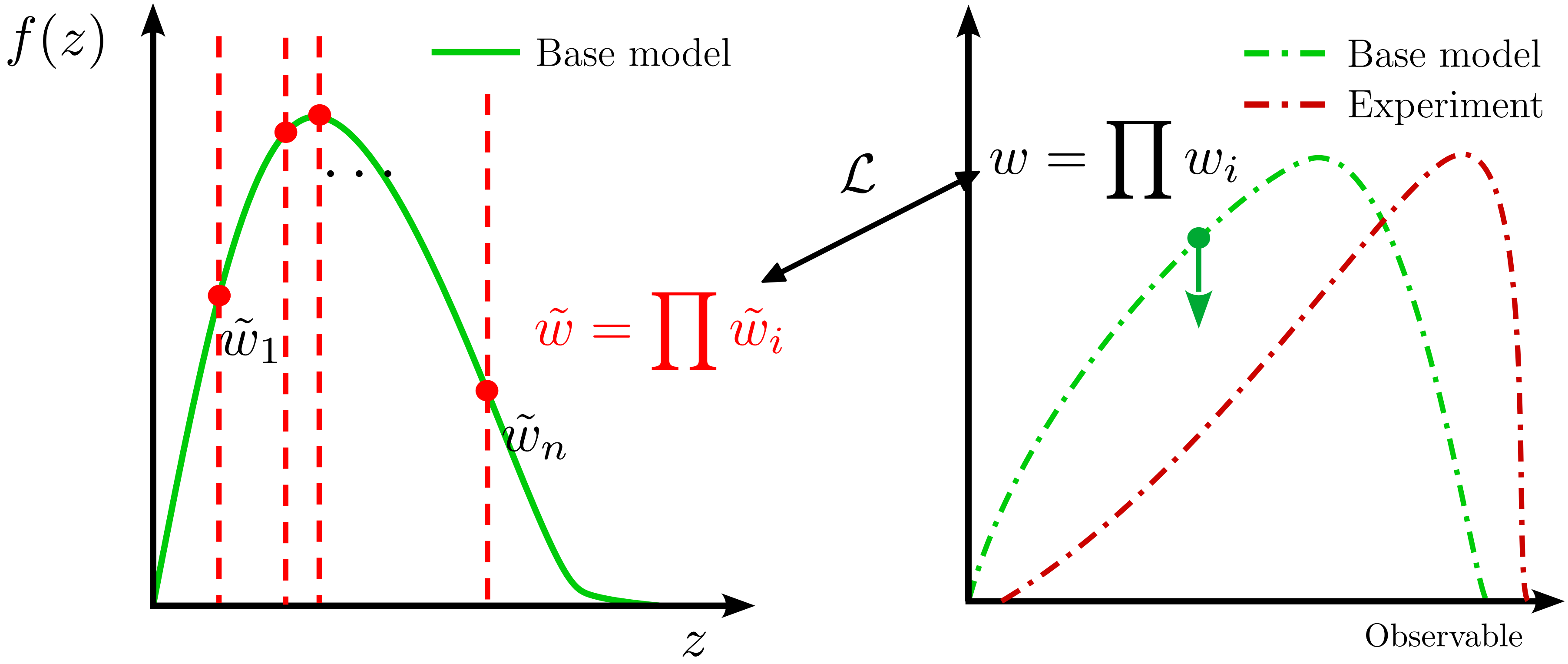


MLHAD efforts: HOMER

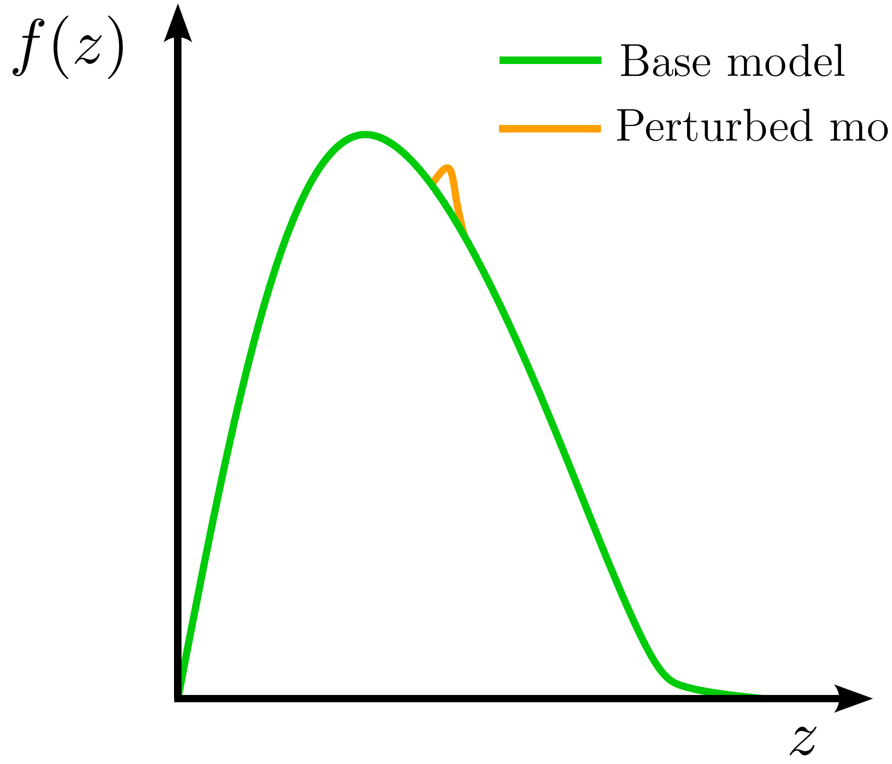


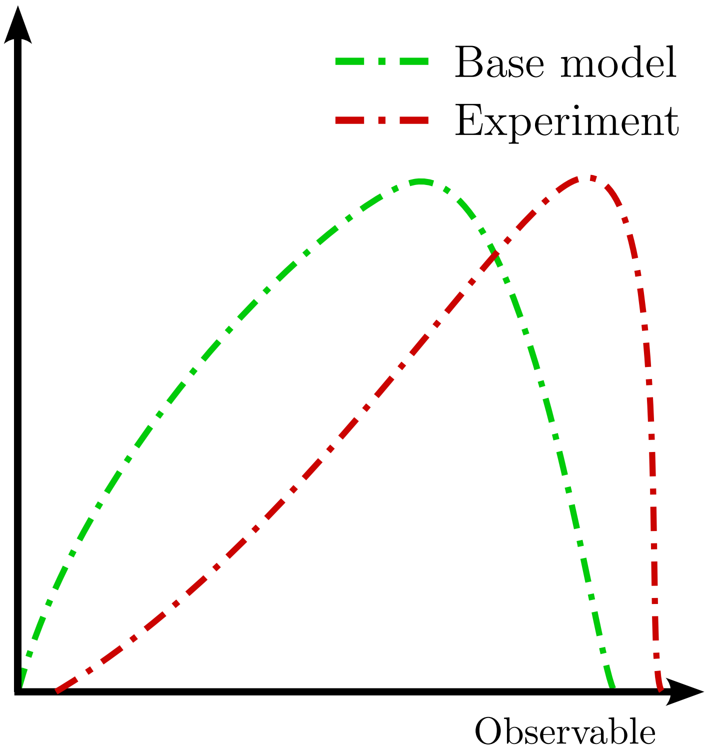


MLHAD efforts: HOMER



MLHAD efforts: HOMER





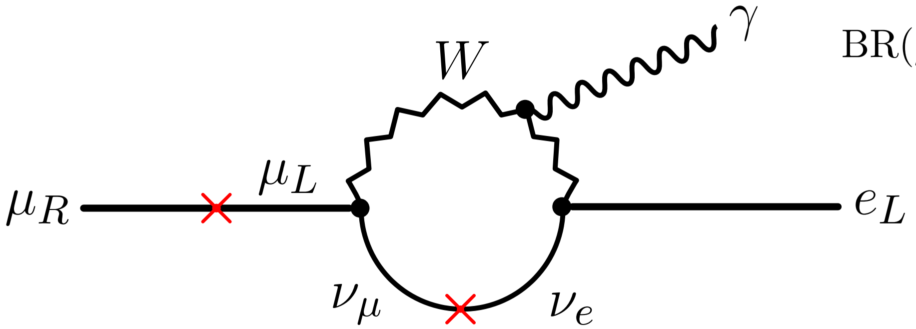
Heavy and light new physics in rare lepton decays

Standard lore - CLFV

- The Standard Model (SM) has an accidental global flavor symmetry

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- Because $m_\nu \neq 0$ charged-lepton-flavor violation (CLFV) can occur at one-loop



$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{3\alpha}{32\pi M_W^4} |U_{\mu 3} U_{e3}^* \Delta m_{31}^2 + U_{\mu 2} U_{e2}^* \Delta m_{21}^2|^2 \simeq 10^{-54}$$

$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi} \left(\log \frac{m_\mu^2}{m_e^2} - 3 \right) \times \mathrm{BR}(\mu \to e\gamma)$$

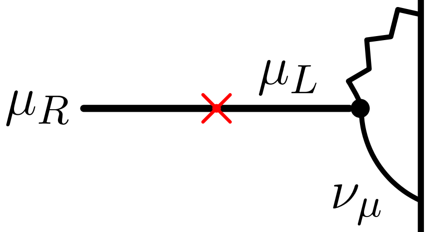
$$\mathrm{CR}(\mu\mathrm{N} \to e\mathrm{N}) \simeq \alpha \times \mathrm{BR}(\mu \to e\gamma)$$

Bottom line: Observing CLFV = new physics

Standard lore - CLFV

- The Standar… symmetry

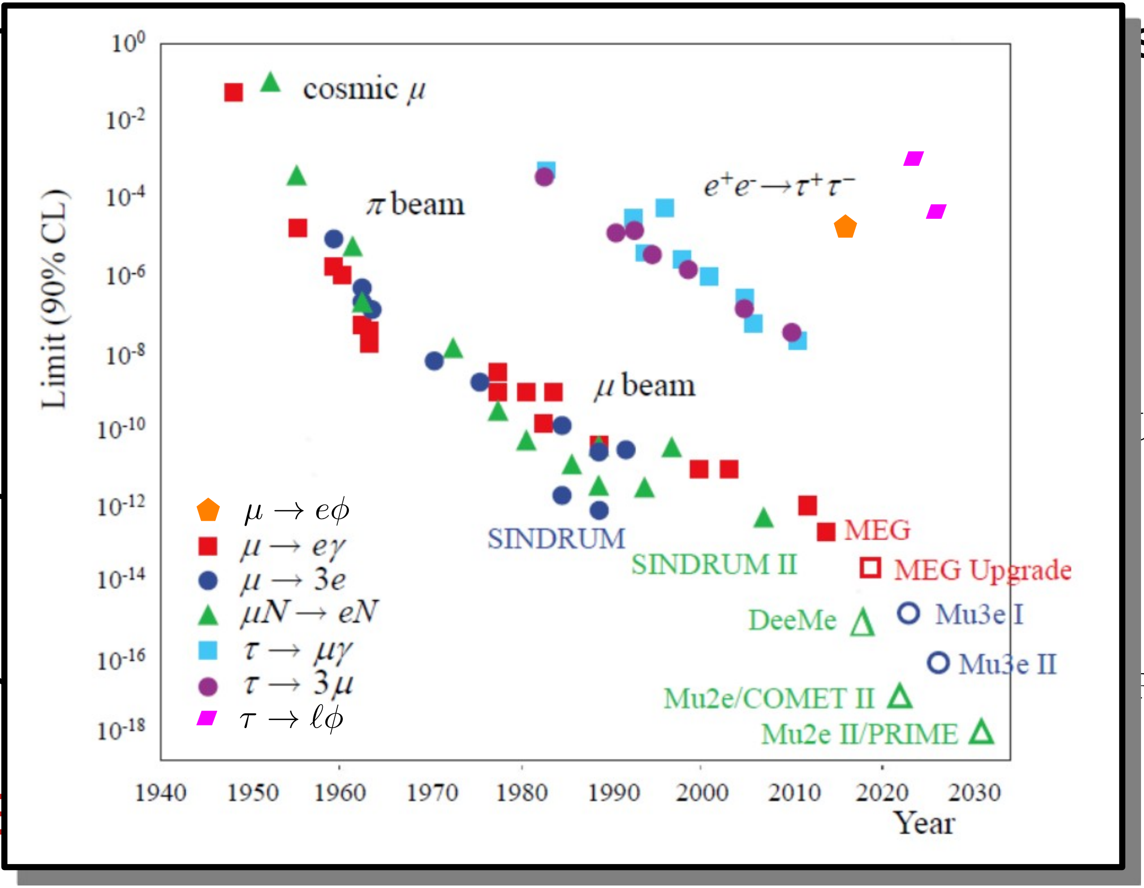
- Because m_ν … n occur at one-loop

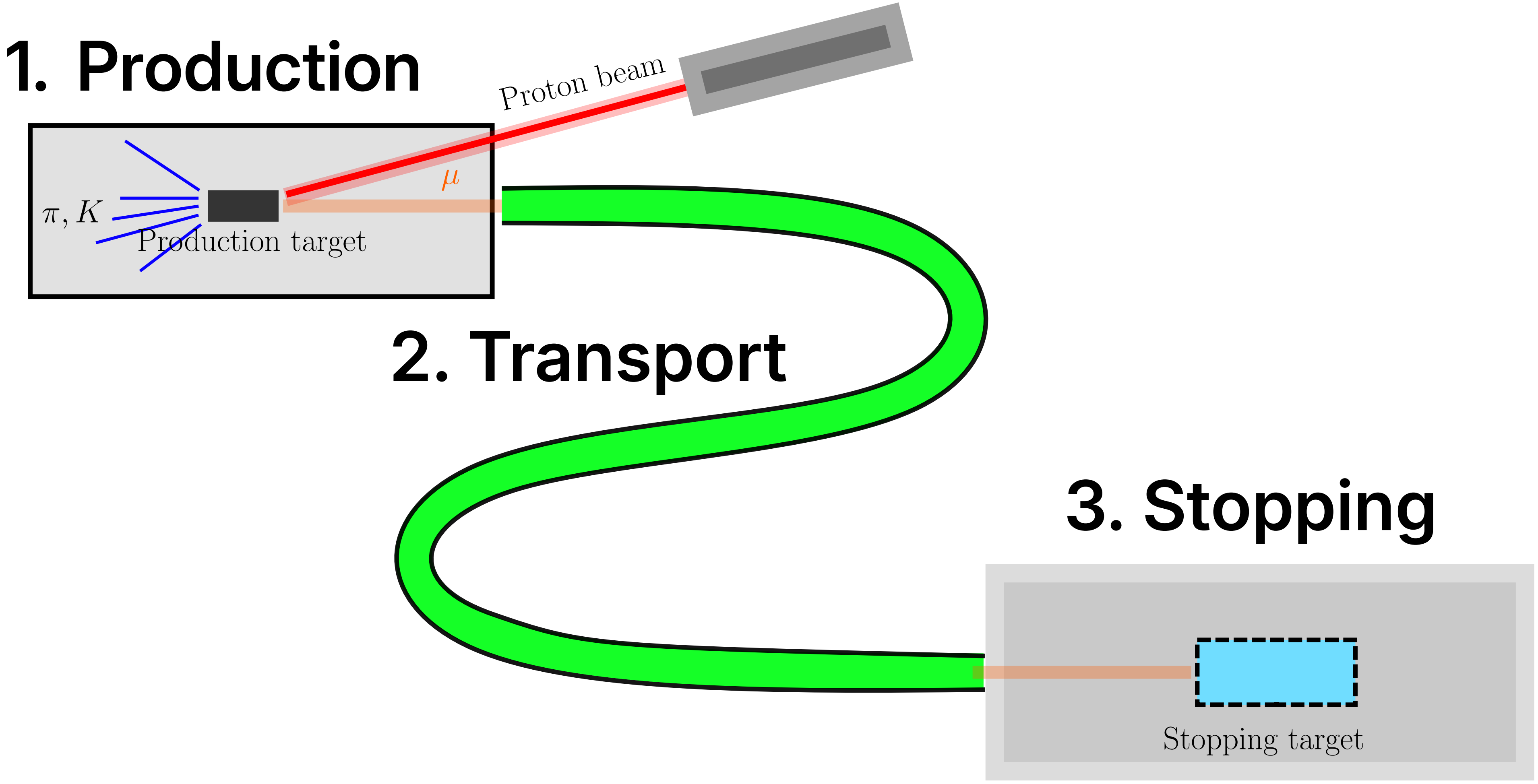


$\ldots U_{\mu 2} U_{e2}^{*} \Delta m_{21}^2 |^2 \simeq 10^{-54}$

$\ldots 3 \Big) \times \mathrm{BR}(\mu \to e\gamma)$

$\ldots \mathrm{R}(\mu \to e\gamma)$

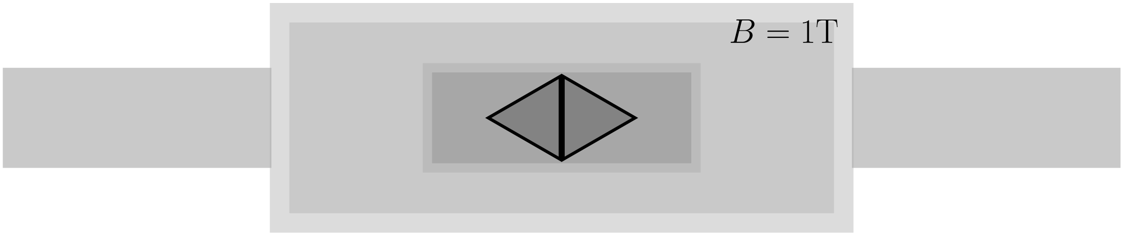



1. Production
Proton beam
π, K
μ
Production target
2. Transport
3. Stopping
Stopping target

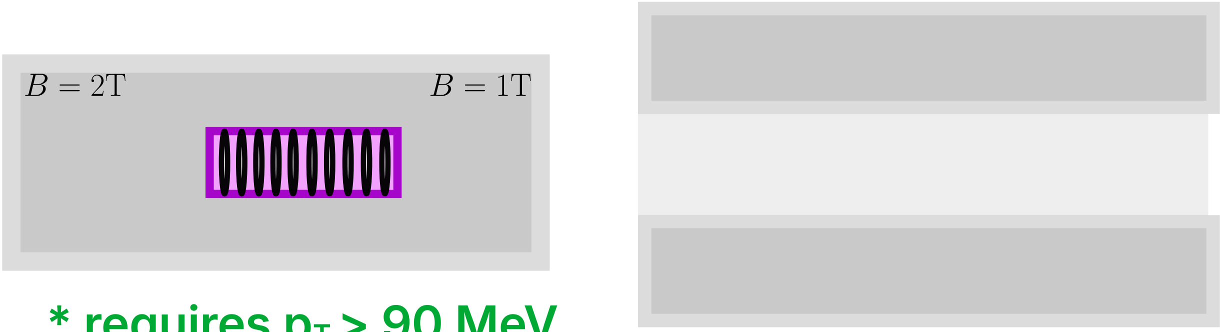
4. Detection (phenomenology is influenced by detector)

Mu3e (μ^+)

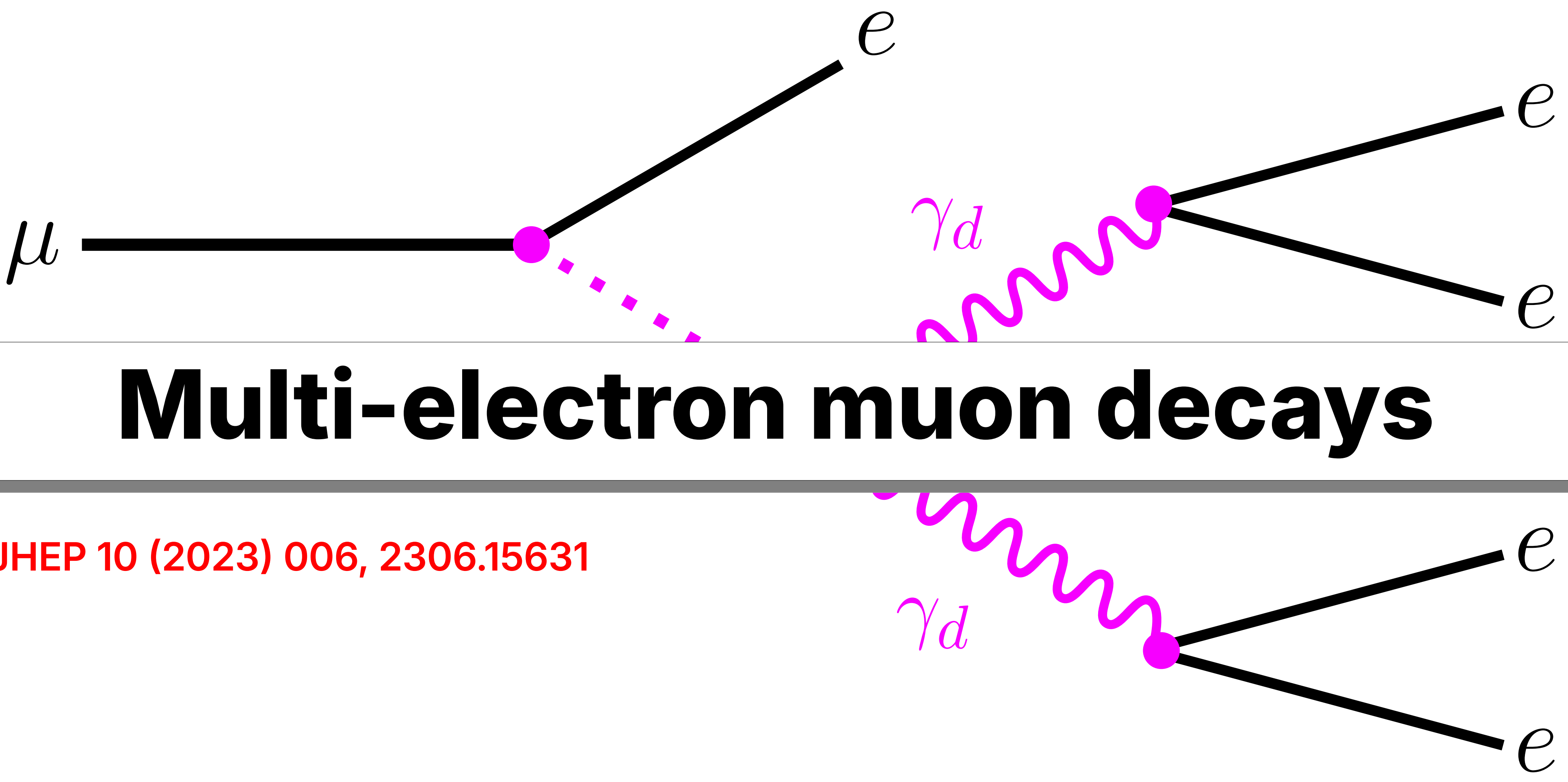
* requires p_T > 10 MeV



Mu2e (μ^-)



* requires p_T > 90 MeV



Multi-electron muon decays

JHEP 10 (2023) 006, 2306.15631

Mu3e → Mu5e

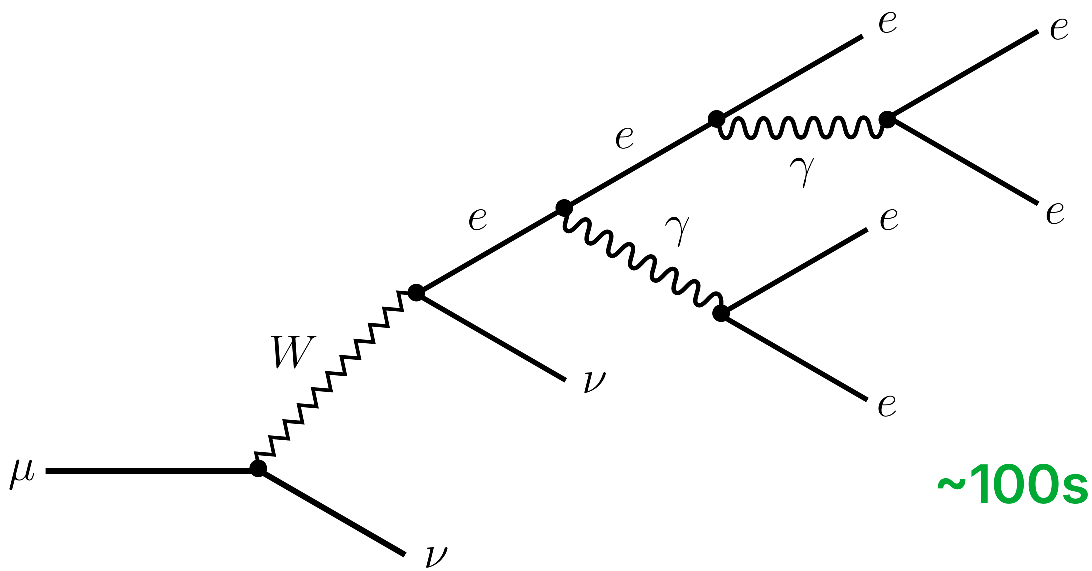
- Mu3e will see ~10^{15} total muon decays from the stopping target.
- With these statistics are there any other interesting channels?
  - What about $\mu \to 5e$?

$\mu \to eeeee\nu\nu$

- **SM background for Mu5e**

From MG5: $\mathcal{B}(\mu^+ \to e^+e^-e^+e^-e^+\nu_e\bar{\nu}_\mu) = (3.929 \pm 0.001) \times 10^{-10}$

$$\mathcal{B}\left(\mu^+ \to e^+e^-e^+e^-e^+\nu_e\bar{\nu}_\mu \,|\, \text{all } p_{\mathrm{e}^\pm}^{\mathrm{T,true}} > 10\text{ MeV}\right) = (1.4 \pm 0.1) \times 10^{-14}$$



$\propto G_F^2 \alpha^4$

~100s of $\mu \to 5e\nu\nu$ events after cuts!

$\mu \to eeeee$

- Higgsed $U(1)_D$ + SM portal via kinetic mixing

$$\mathscr{L}_{\rm DS} = (D_\mu \phi)^\dagger D^\mu \phi - \frac{1}{4} F_d^{\mu\nu} F_{d\,\mu\nu} - \frac{\varepsilon}{2} F_d^{\mu\nu} F_{\mu\nu} - \mu^2 (\phi^\dagger \phi) - \lambda (\phi^\dagger \phi)^2$$

$$\mathscr{L}_{\rm LFV} = -\frac{C_{ij}}{\Lambda} \phi \left(\bar{L}_i H\right) \ell_j + \text{h.c.}$$

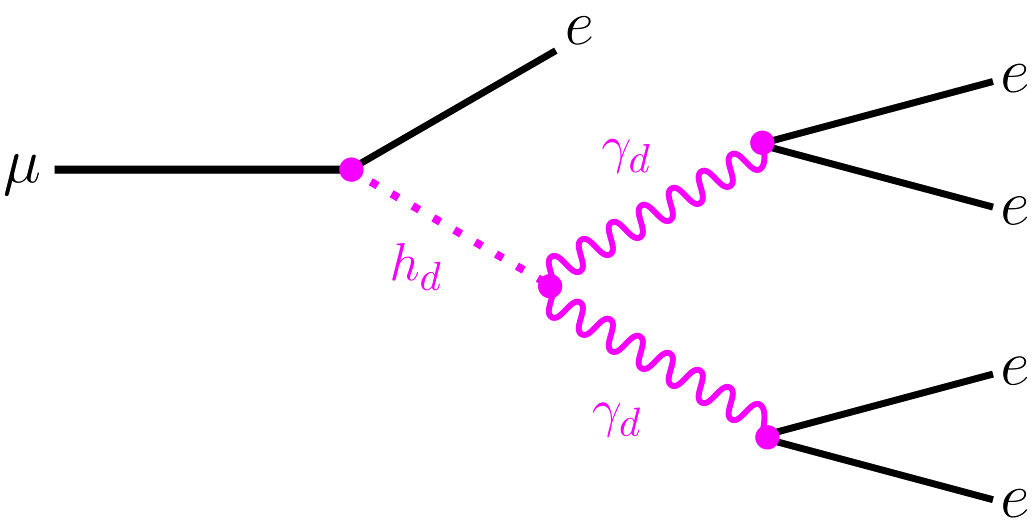
$$\downarrow$$

$$y_{ij} \simeq \frac{Cv}{\Lambda}$$

$$\mathscr{L} \supset -m_{\ell_i} \bar{\ell}_{Li} \ell_{Ri} \left(1 + \frac{h}{v}\right) - y_{ij} \bar{\ell}_{Li} \ell_{Rj} h_d \left(1 + \frac{h}{v}\right) + \text{h.c.},$$

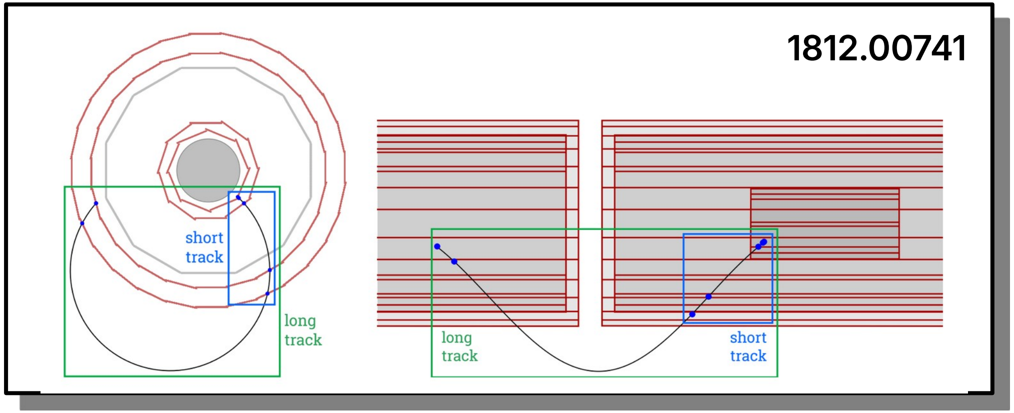
μ → eeeee

- Leads to cascade decay



Signatures

- Momentum of tracks must be reconstructed from energy deposits or ‘hits’ in the layers of the detectors.
- 4 hits = short track
- 6+ hits = long track



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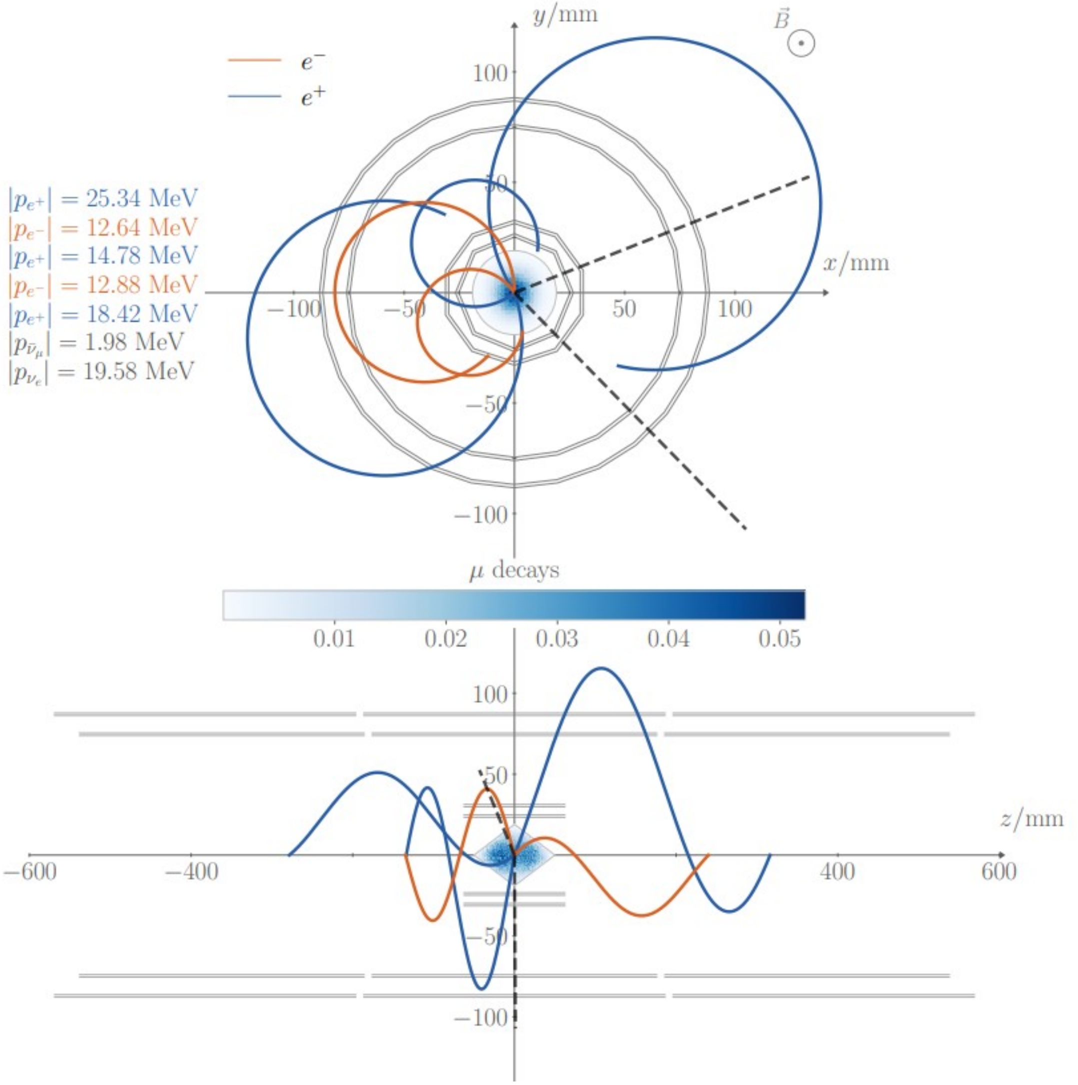
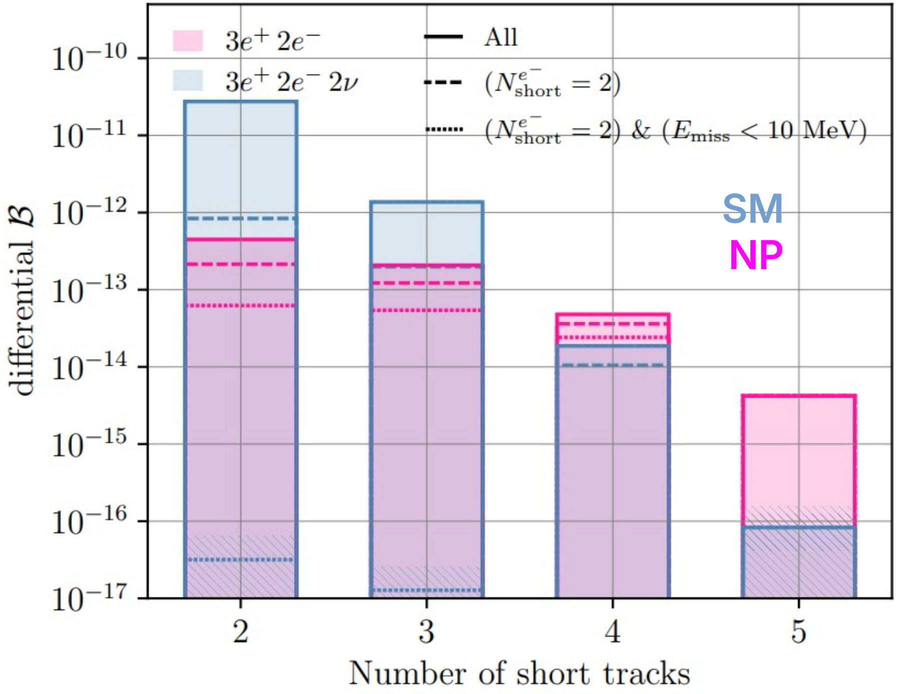
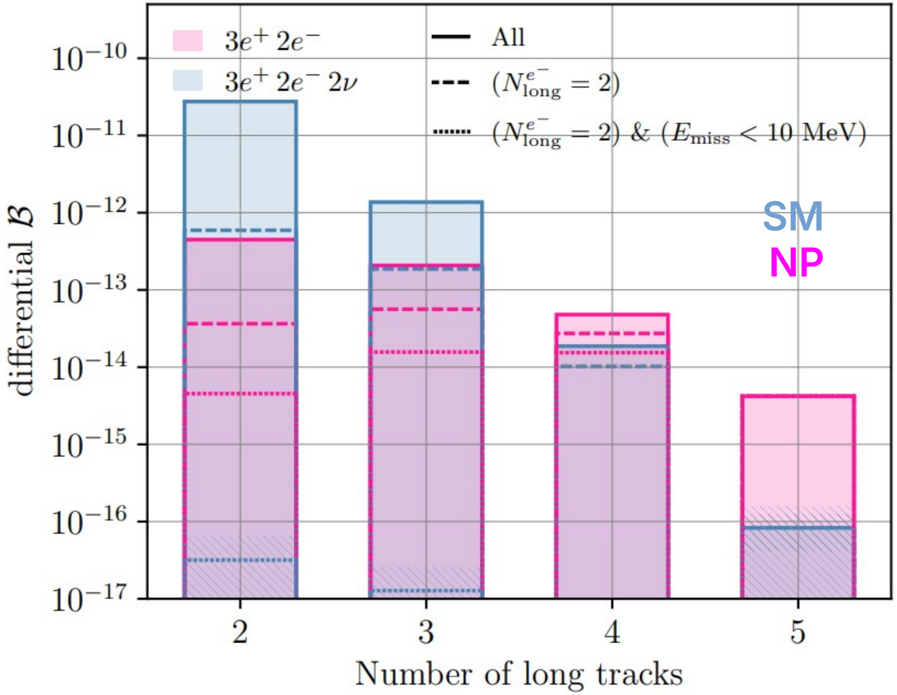


Signatures

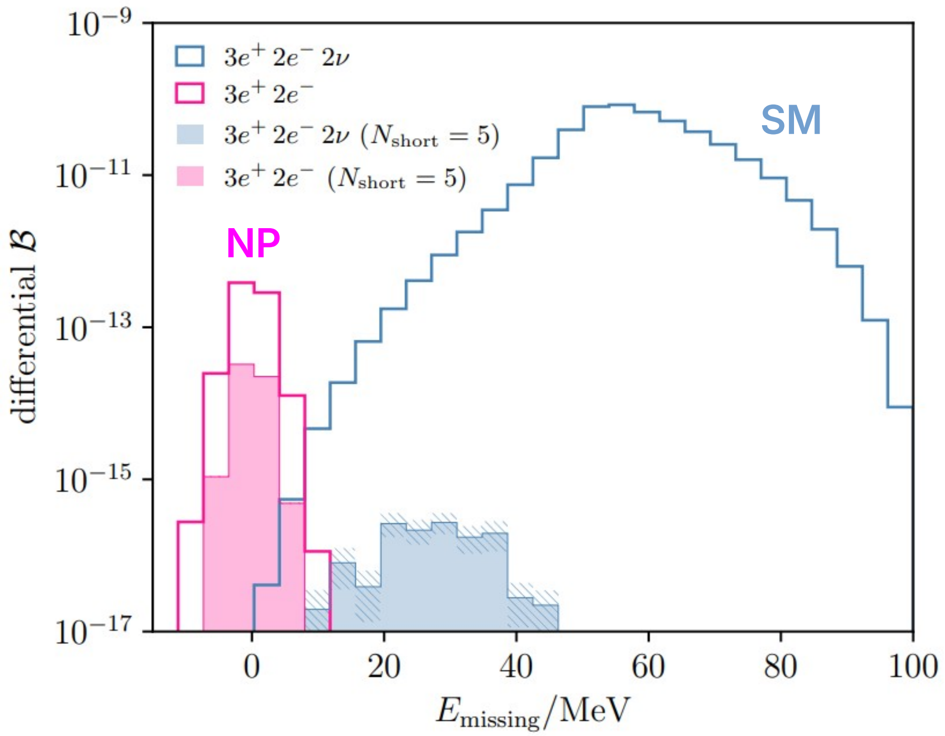


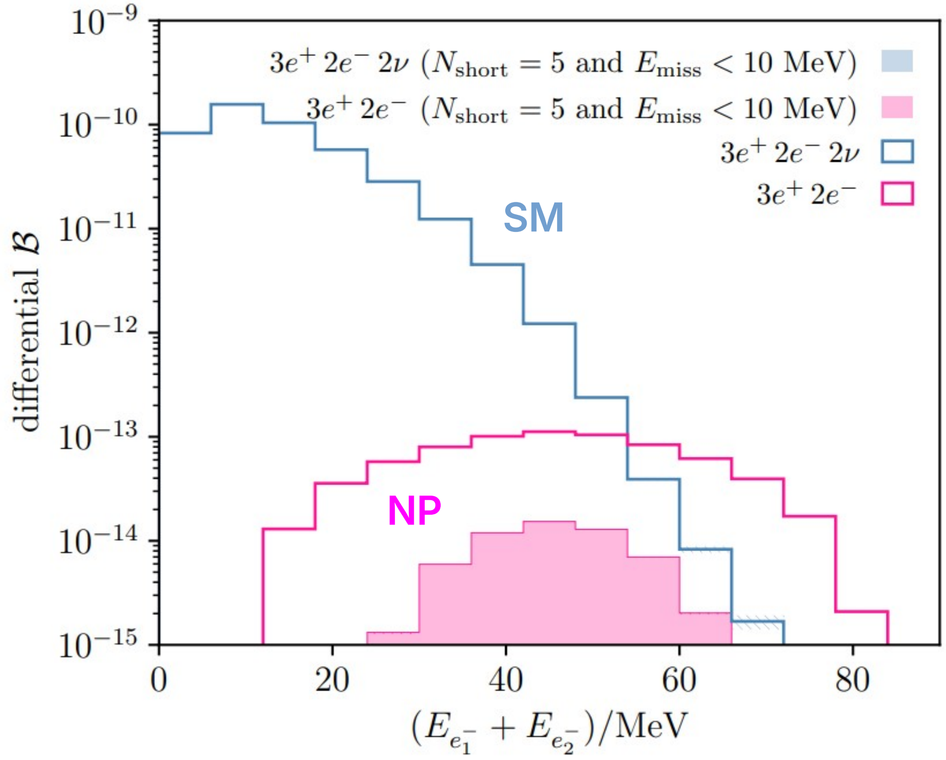
$3e^+ 2e^-$
$3e^+ 2e^- 2\nu$
All
$(N^{e^-}_{\text{short}} = 2)$
$(N^{e^-}_{\text{short}} = 2)$ & $(E_{\text{miss}} < 10$ MeV$)$
SM
NP
differential $\mathcal{B}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
2
3
4
5
Number of short tracks



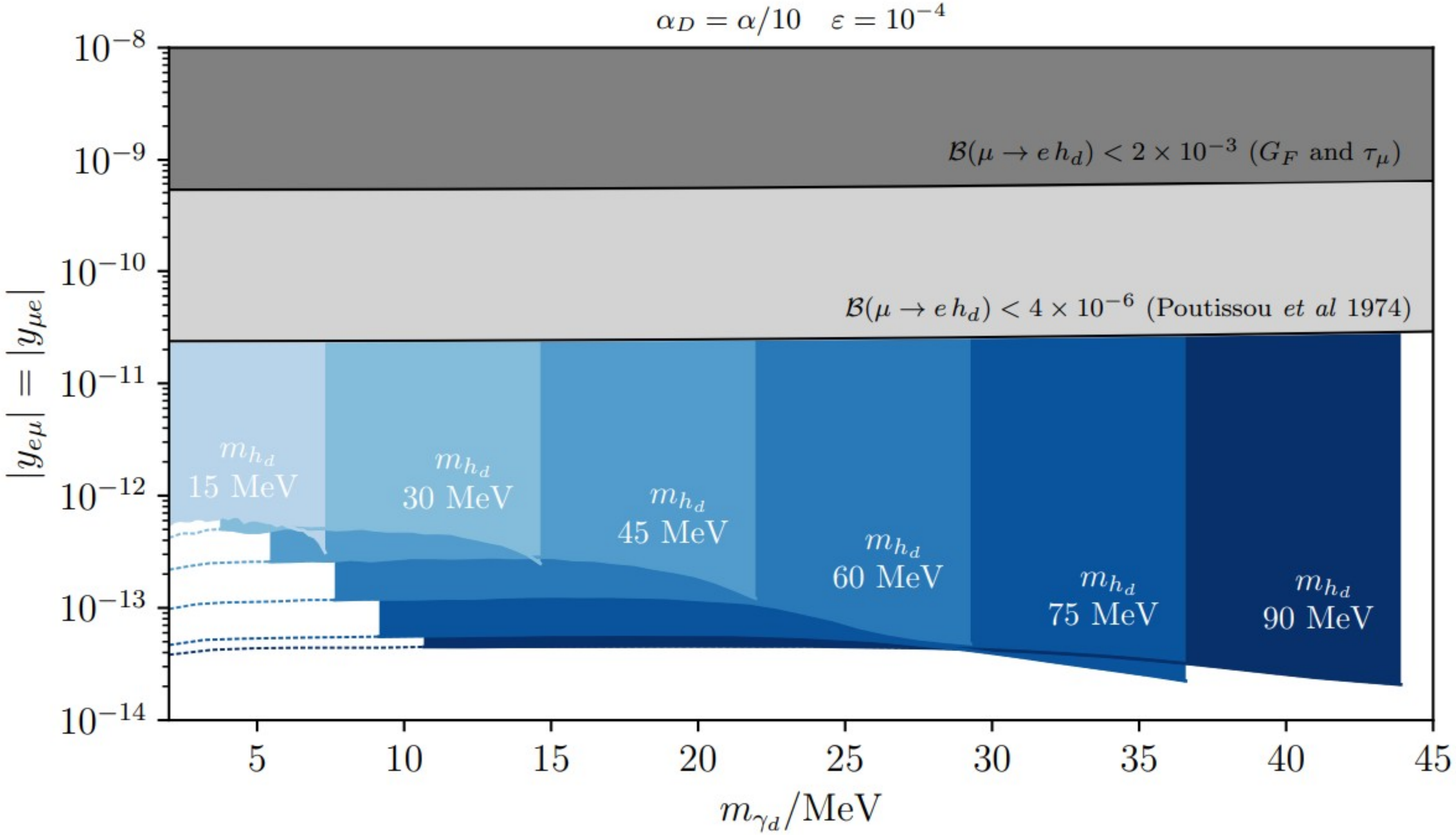
$3e^+ 2e^-$
$3e^+ 2e^- 2\nu$
All
$(N^{e^-}_{\text{long}} = 2)$
$(N^{e^-}_{\text{long}} = 2)$ & $(E_{\text{miss}} < 10$ MeV$)$
SM
NP
differential $\mathcal{B}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
2
3
4
5
Number of long tracks

Signatures

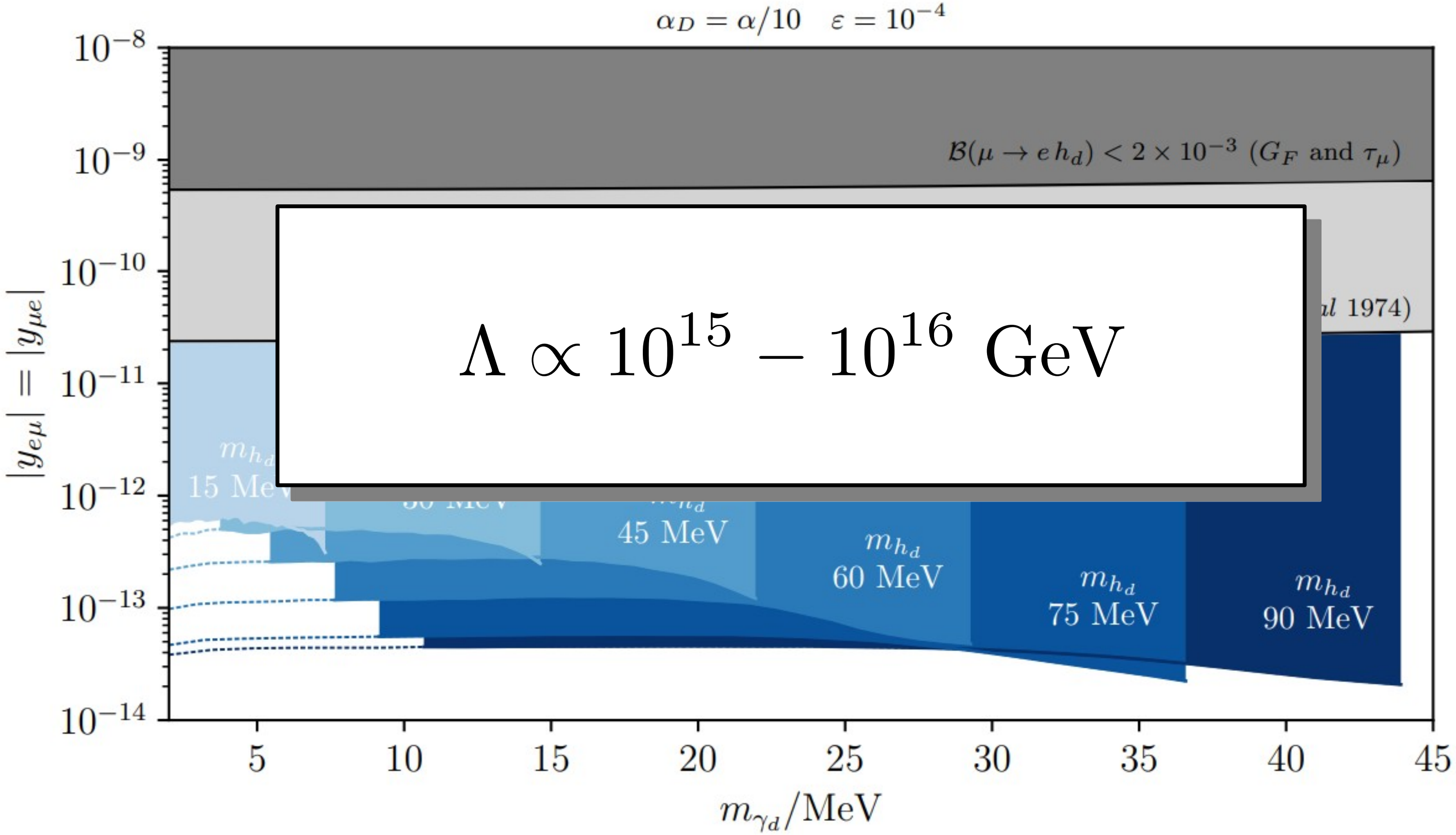

$3e^+\,2e^-\,2\nu$
$3e^+\,2e^-$
$3e^+\,2e^-\,2\nu$ ($N_{\mathrm{short}} = 5$)
$3e^+\,2e^-$ ($N_{\mathrm{short}} = 5$)
SM
NP
differential $\mathcal{B}$
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
0
20
40
60
80
100
$E_{\mathrm{missing}}/\mathrm{MeV}$


$3e^+\,2e^-\,2\nu$ ($N_{\mathrm{short}} = 5$ and $E_{\mathrm{miss}} < 10$ MeV)
$3e^+\,2e^-$ ($N_{\mathrm{short}} = 5$ and $E_{\mathrm{miss}} < 10$ MeV)
$3e^+\,2e^-\,2\nu$
$3e^+\,2e^-$
SM
NP
differential $\mathcal{B}$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
0
20
40
60
80
$(E_{e_1^-} + E_{e_2^-})/\mathrm{MeV}$

Reach

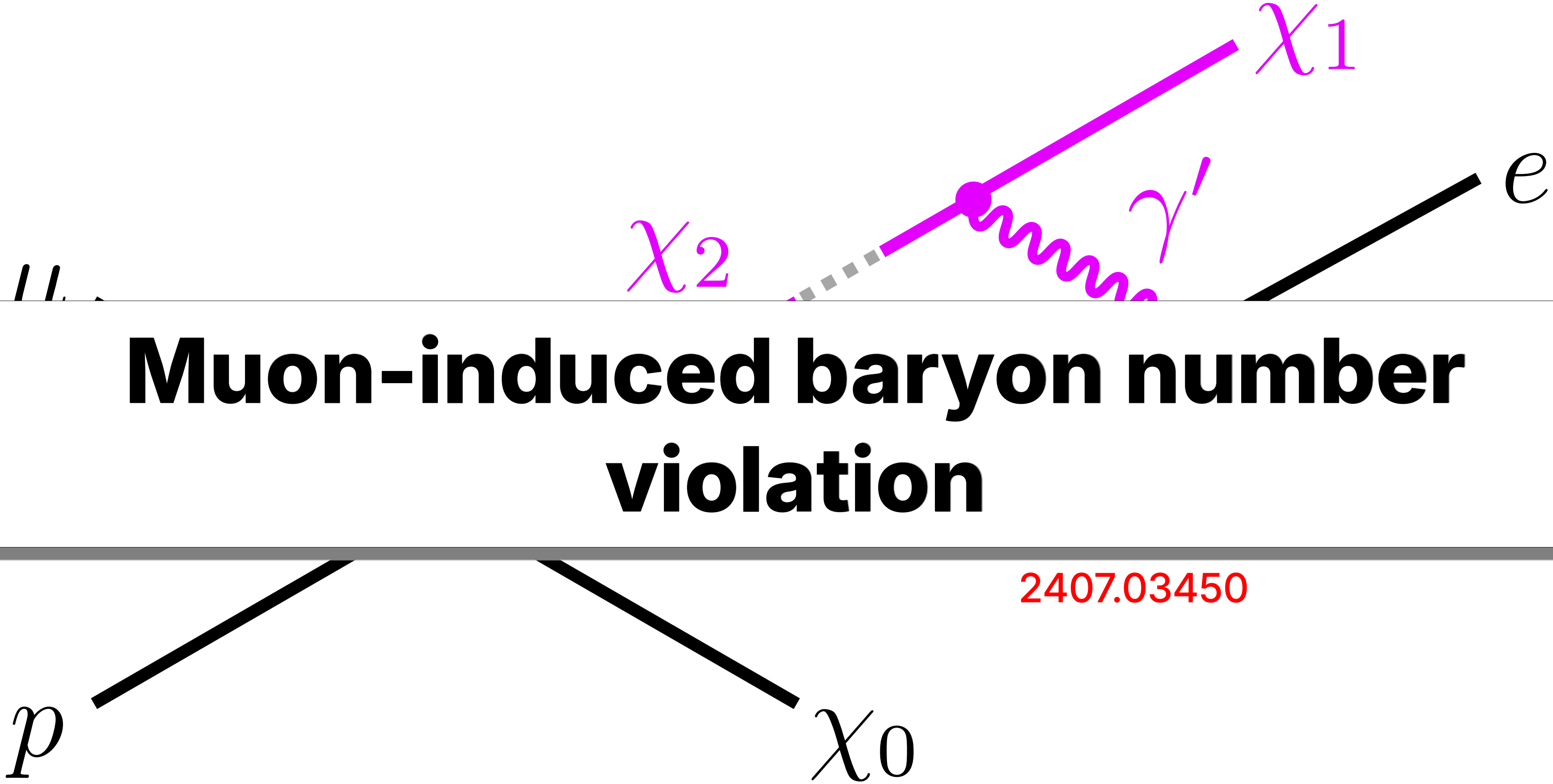

$\alpha_D = \alpha/10 \quad \varepsilon = 10^{-4}$
$\mathcal{B}(\mu \to e\, h_d) < 2 \times 10^{-3}$ (G_F and τ_μ)
$\mathcal{B}(\mu \to e\, h_d) < 4 \times 10^{-6}$ (Poutissou *et al* 1974)
m_{h_d} 15 MeV
m_{h_d} 30 MeV
m_{h_d} 45 MeV
m_{h_d} 60 MeV
m_{h_d} 75 MeV
m_{h_d} 90 MeV
$|y_{e\mu}| = |y_{\mu e}|$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
5
10
15
20
25
30
35
40
45
$m_{\gamma_d}/\mathrm{MeV}$

Reach



$$\Lambda \propto 10^{15} - 10^{16}\ \text{GeV}$$

Muon-induced baryon number violation



2407.03450

Widening the view

- Can the CLFV signal @ Mu2e stem from non-CLFV physics?
- NP scenarios where E_e>105 MeV?
  - Can we take advantage of the huge energy reservoir that is the nucleus?

$\mu\ {}^{27}Al \rightarrow {}^{26}Mg^{(*)}\chi_0\chi_1 ee$

- Three dark states + $U(1)_D$ + SM portal via kinetic mixing

$$\mathcal{L}_{\mu p} = G_{\mu p}(\bar{p}\chi_2)(\bar{\mu}\chi_0) + \text{h.c.}$$

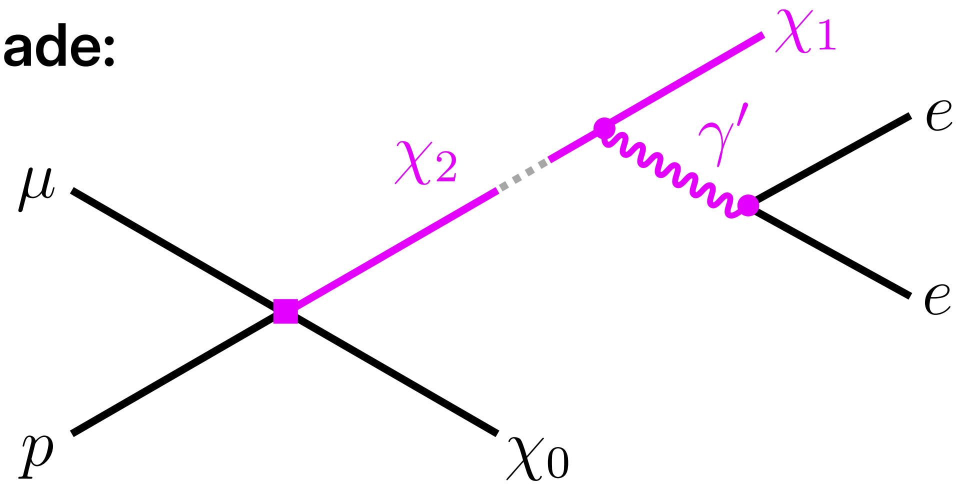
$$\mathcal{L}_{eA'} = e\varepsilon A'_\mu J^\mu_{\text{EM}}$$

$$\mathcal{L}_\chi = g_D\big(\bar{\chi}_2\gamma^\mu\chi_1\big)A'_\mu + \text{h.c.}$$

$\mu\, ^{27}\text{Al} \to {}^{26}\text{Mg}^{(*)} \chi_0 \chi_1 ee$

Benchmark: $m_2 = 1030$ MeV, $m_1 = 900$ MeV, $m_0 = 0$, $m_{A'} = 20$ MeV,
$G_{\mu p} = (300\ \text{TeV})^{-2}$, $\varepsilon = 10^{-4}$, $\alpha_D = 10^{-3}$

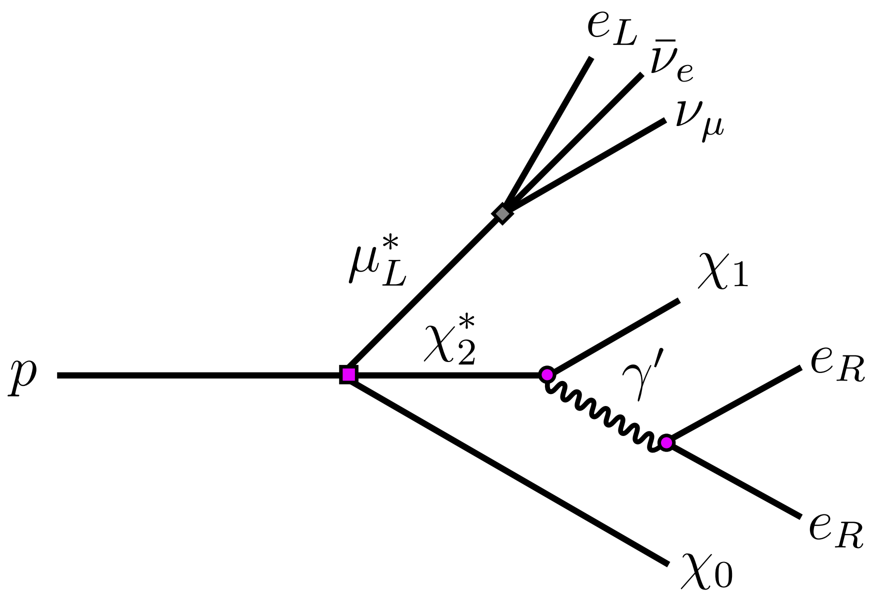
- Leads to the cascade:



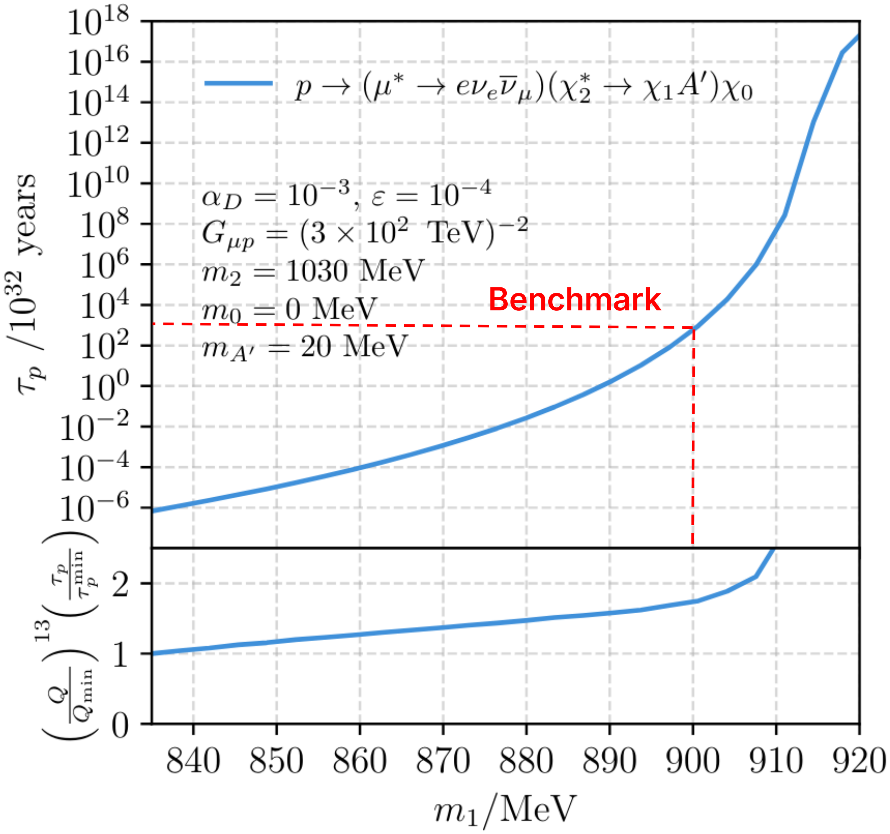
~4 × 10^{-3}

$$\Gamma(\mu\, ^{27}\text{Al} \to \chi_0 \chi_2\, ^{26}\text{Mg}) \simeq r_{\text{p.s.}} \frac{G_{\mu p}^2}{G_F^2} \Gamma(\mu\, ^{27}\text{Al} \to \nu_\mu n\, ^{26}\text{Mg}) \longrightarrow R \equiv \frac{\Gamma_{\text{exotic}}}{\Gamma_{\mu\text{Al}}} \sim 10^{-15}$$

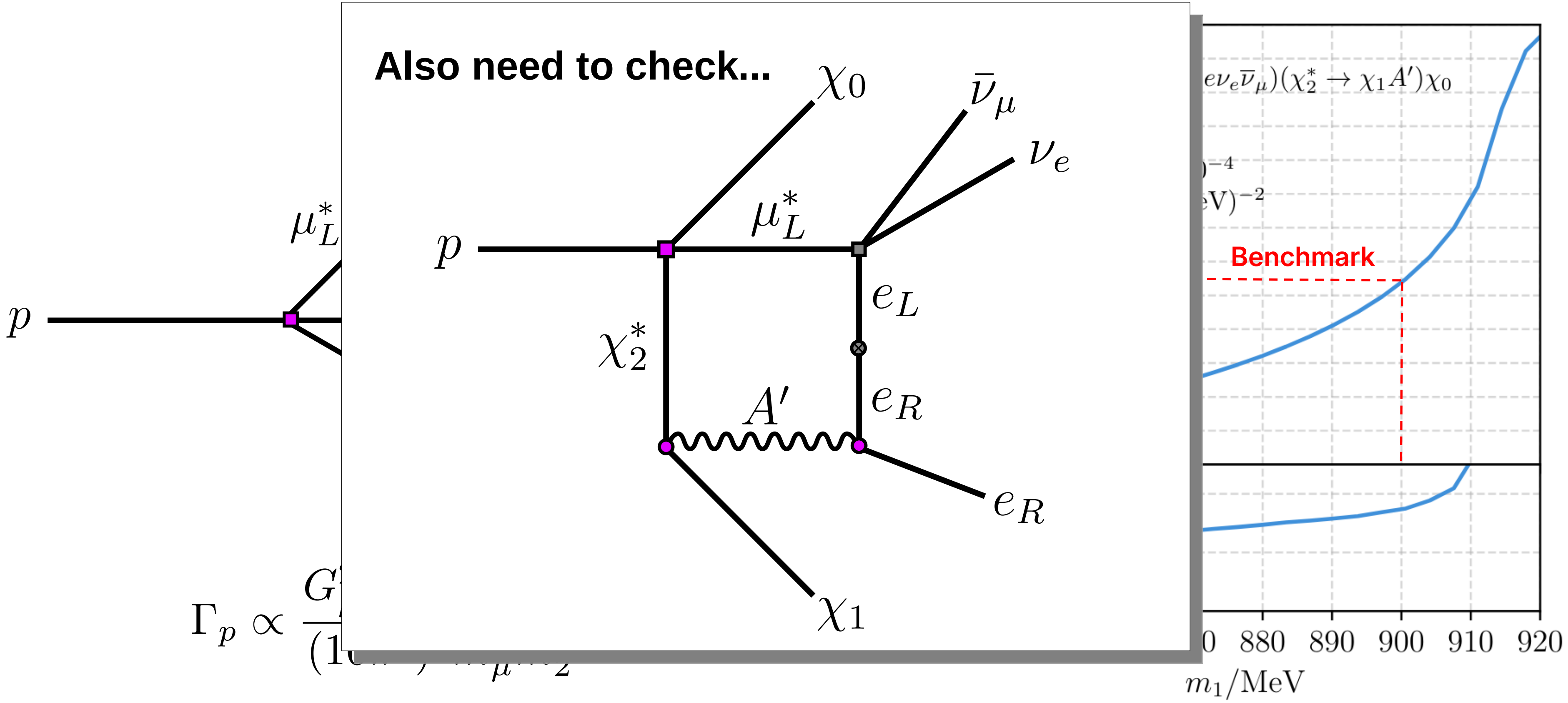
Tug-of-war with nucleon decay



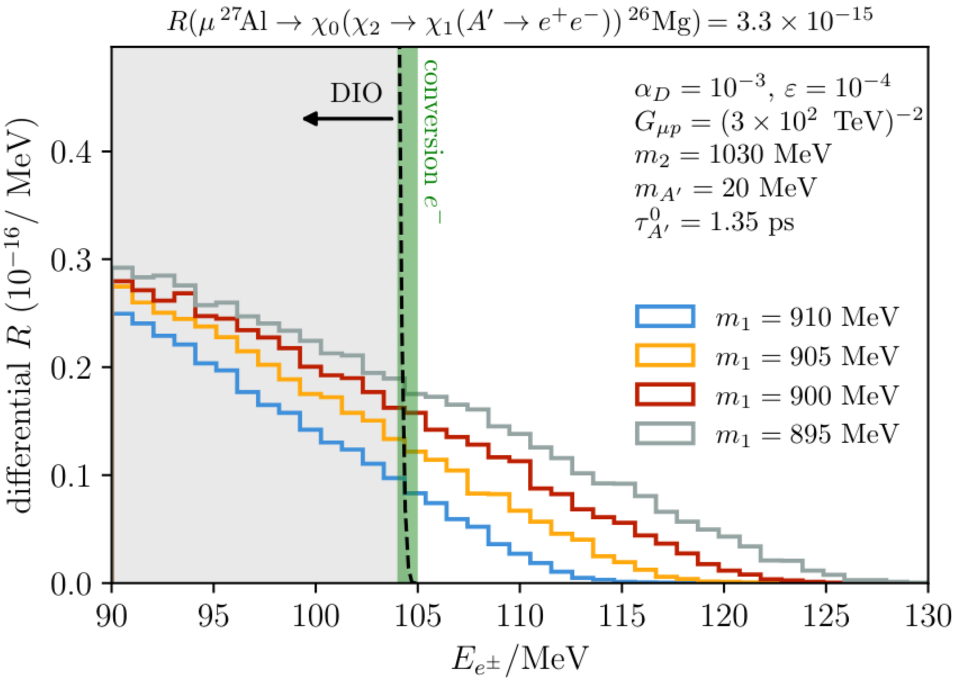
$$\Gamma_p \propto \frac{G_{\mu p}^2 G_F^2 \alpha_D Q^{13}}{(16\pi^2)^4 m_\mu^2 m_2^2}$$



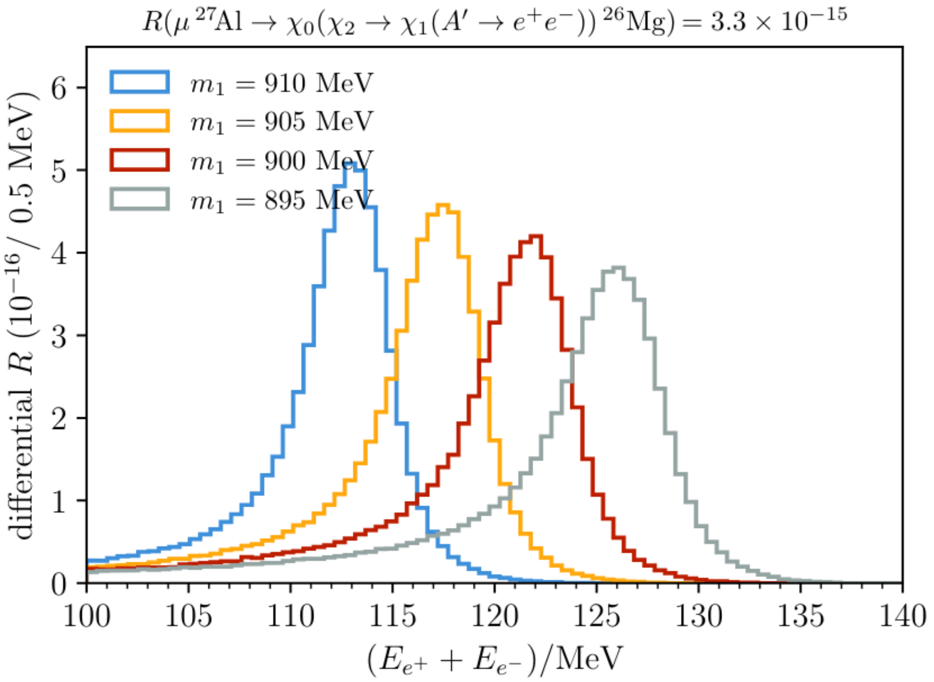
Tug-of-war with nucleon decay



Signature



$R(\mu\,^{27}\mathrm{Al} \to \chi_0(\chi_2 \to \chi_1(A' \to e^+e^-))\,^{26}\mathrm{Mg}) = 3.3 \times 10^{-15}$
DIO
conversion e^-
$\alpha_D = 10^{-3}$, $\varepsilon = 10^{-4}$
$G_{\mu p} = (3 \times 10^2\ \mathrm{TeV})^{-2}$
$m_2 = 1030$ MeV
$m_{A'} = 20$ MeV
$\tau^0_{A'} = 1.35$ ps
$m_1 = 910$ MeV
$m_1 = 905$ MeV
$m_1 = 900$ MeV
$m_1 = 895$ MeV
differential R (10^{-16}/ MeV)
$E_{e^\pm}$/MeV

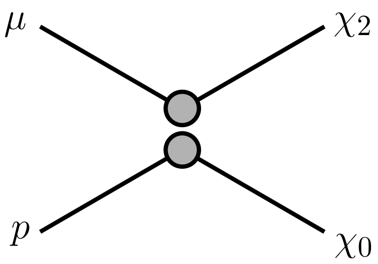


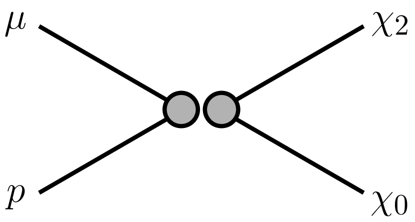
$R(\mu\,^{27}\mathrm{Al} \to \chi_0(\chi_2 \to \chi_1(A' \to e^+e^-))\,^{26}\mathrm{Mg}) = 3.3 \times 10^{-15}$
$m_1 = 910$ MeV
$m_1 = 905$ MeV
$m_1 = 900$ MeV
$m_1 = 895$ MeV
differential R (10^{-16}/ 0.5 MeV)
$(E_{e^+} + E_{e^-})$/MeV

A UV completion

$$\mathcal{L}_{\mu p} = G_{\mu p}(\bar{p}\chi_2)(\bar{\mu}\chi_0) + \text{h.c.}$$

- What's the new physics reach? Naively:

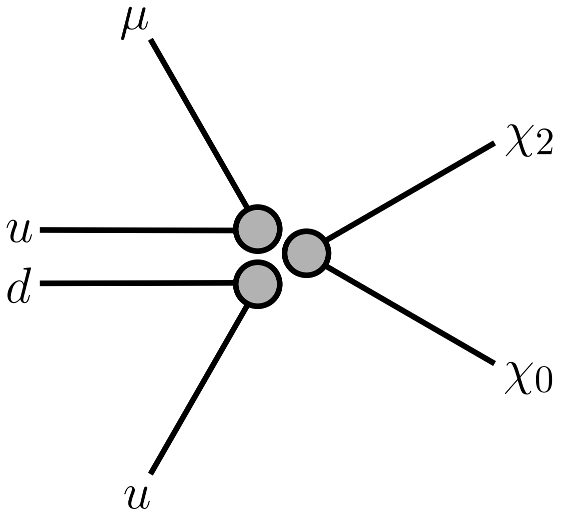




$$G_{\mu p} \simeq 10^{-8} G_F \to \Lambda \simeq 10^3 \text{ TeV}$$

but Λ isn't fundamental...

$$\frac{1}{\Lambda^2} \simeq \frac{\Lambda_{\text{QCD}}^3}{\Lambda_{\text{col.}}^{d_{\text{col.}}} \Lambda_{\text{sing.}}^{5-d_{\text{col.}}}}$$

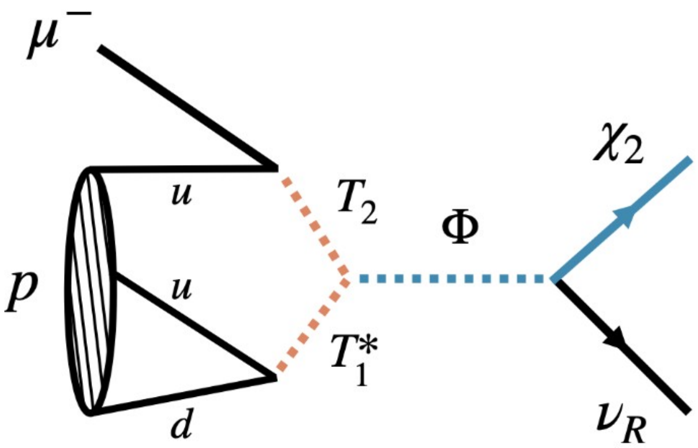


A UV completion

Introduce two colored scalars - a diquark T_1 and a leptoquark T_2 as well as a complex scalar Φ.

$$\mathscr{L} \supset -y_{ud}(\overline{u_R^{iC}} d_R^j)\epsilon_{ijk}T_1^k - y_{\mu u}(\overline{u_R^{iC}}\mu_R)(T_2^*)_i + \text{h.c.}$$

$$\mathscr{L} \supset \rho T_1^{k*} T_{2k}\Phi^* + y_\chi \Phi(\overline{\nu_R}\chi_{2R}^C) + \text{h.c.}$$



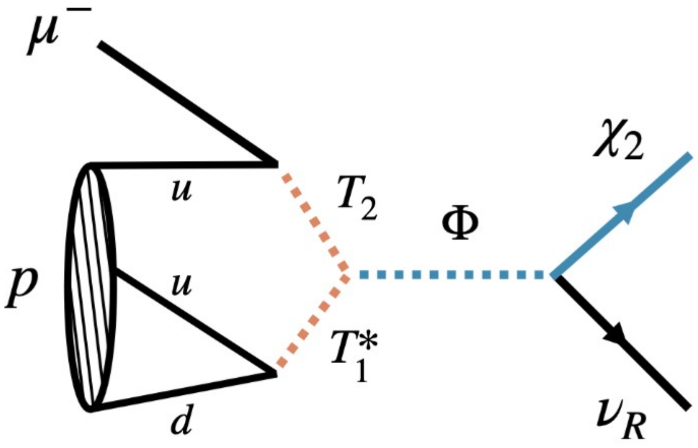
A UV completion

Introduce two colored scalars - a diquark T_1 and a leptoquark T_2 as well as a complex scalar Φ.

Integrate out T_1 and T_2, for off-shell Φ:

$$\mathscr{L}_{\text{eff}} = \frac{1}{\Lambda_{\text{col}}^3}\frac{1}{\Lambda_{\text{sin}}^2}\left(\overline{u_R^{iC}}\mu_R\right)\epsilon_{ijk}\left(\overline{u_R^{jC}}d_R^k\right)\left(\overline{\nu_R}\chi_{2R}^C\right) + \text{h.c.}$$

$$\frac{1}{\Lambda_{\text{col}}^3} = y_{ud}y_{\mu u}\frac{\rho}{m_{T_1}^2 m_{T_2}^2} \qquad \frac{1}{\Lambda_{\text{sin}}^2} = \frac{y_\chi}{m_\Phi^2}$$



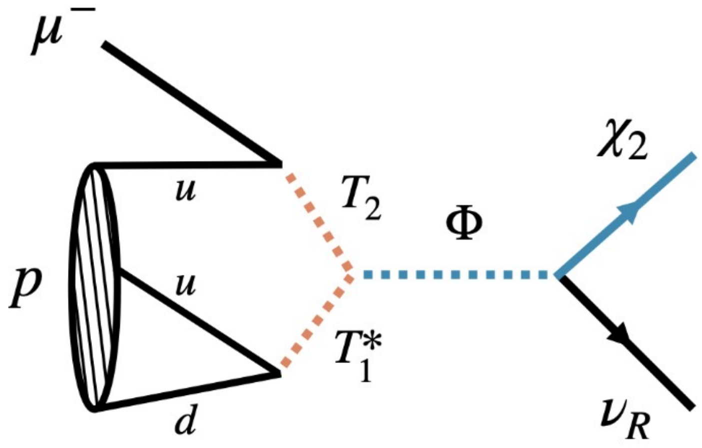
A UV completion

Introduce two colored scalars - a diquark T_1 and a leptoquark T_2 as well as a complex scalar Φ.

Integrate out T_1 and T_2, for off-shell Φ:

$$\widetilde{G}_{\mu p} \simeq 10^{-6} G_F$$

$$\sim 10^{-6} G_F \, y_{ud} y_{\mu u} y_{\chi} \left(\frac{1 \text{ TeV}}{\sqrt{m_{T_1} m_{T_2}}} \right)^4 \left(\frac{\rho}{4 \text{ TeV}} \right) \left(\frac{2 \text{ GeV}}{m_\Phi} \right)^2$$

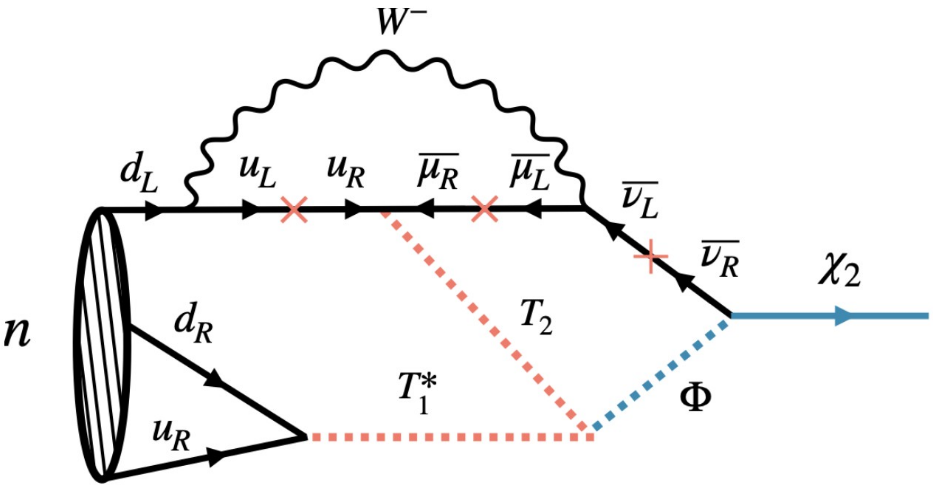


A UV completion

Introduce tw ... uark T_2

as well as a

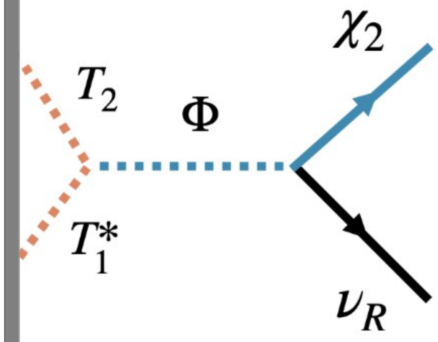
Also need to check neutron decay, neutron mixing...



Integrate out T_1 and

$\widetilde{G}_{\mu p} \simeq$

$\sim 10^{-6} G_F \, y_{ud} y_{\mu u} y_\chi \Big($

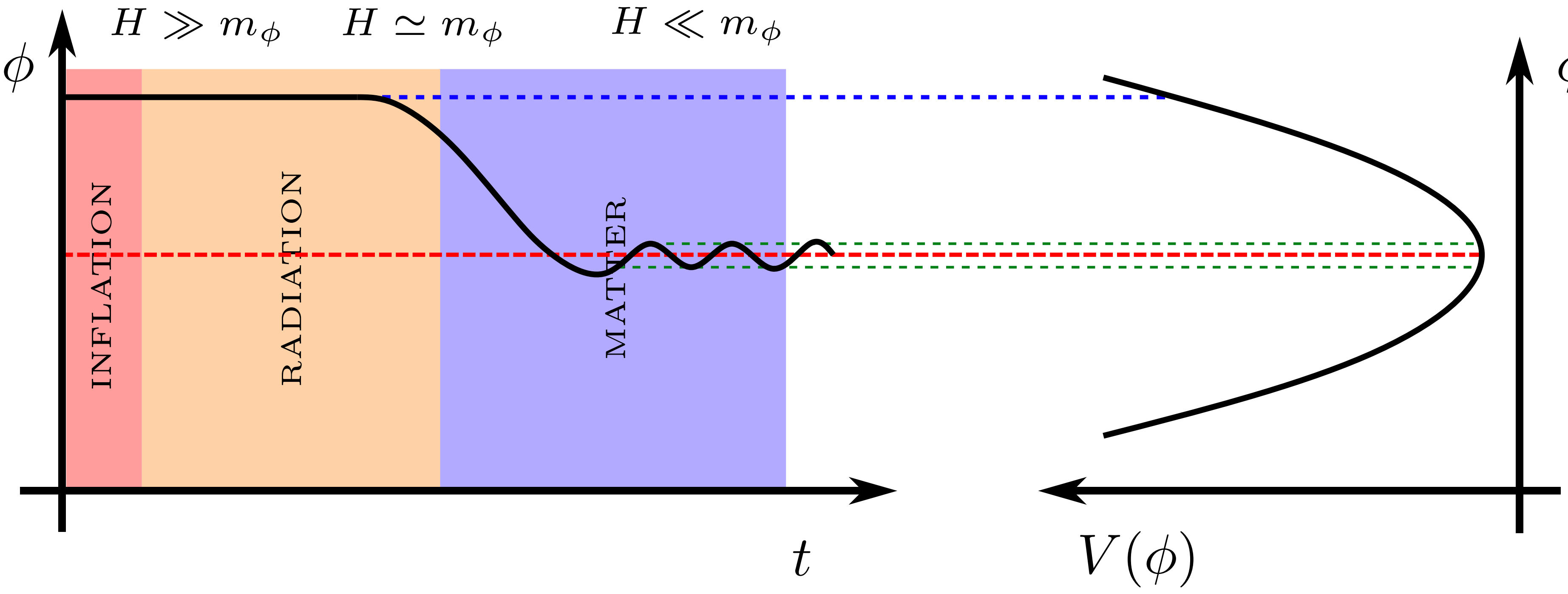


Direct detection of ultralight DM via CLFV

2407.03450

Standard lore - ULDM

EOM: $$\int d^4x\sqrt{-g}\left(\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2\right) \to \ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + m_\phi^2\phi = 0$$



Standard lore - ULDM

For $m_\phi \lesssim \mathrm{eV}$ the de Broglie volume admits a huge occupation number

$$N \sim n\lambda_{\mathrm{dB}}^3 \sim \frac{\rho_\phi}{m_\phi}\left(\frac{1}{m_\phi v}\right)^3 \simeq 10^3 \left(\frac{1\ \mathrm{eV}}{m_\phi}\right)^4 \left(\frac{10^{-3}}{v}\right)^3 \left(\frac{\rho_\phi}{10^{-42}\ \mathrm{GeV}^4}\right)$$

ULDM can be accurately described as a classical wave

$$\phi_c(\mathbf{x}, t) = \phi_0(\mathbf{x}) \cos(m_\phi t + \delta)$$

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \qquad \rho_\phi = 0.4\,\mathrm{GeV/cm^3} \simeq 10^{-42}\mathrm{GeV}^4$$

Standard lore - ULDM

For $m_\phi \lesssim \mathrm{eV}$ the de Broglie volume admits a huge occupation number

$$N \sim n\lambda_{\mathrm{dB}}^3 \sim \ldots \frac{\rho_\phi}{\ldots 42\ \mathrm{GeV}^4}\Big)$$

Each mass has an associated "timescale"

$$\tau_\phi = \frac{2\pi}{m_\phi} \simeq 4\mathrm{s}\left(\frac{10^{-15}\mathrm{eV}}{m_\phi}\right)$$

ULDM ca … wave

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \qquad \rho_\phi = 0.4\,\mathrm{GeV/cm}^3 \simeq 10^{-42}\mathrm{GeV}^4$$

Why ULDM + CLFV?

CLFV experiments probe extremely high NP scales

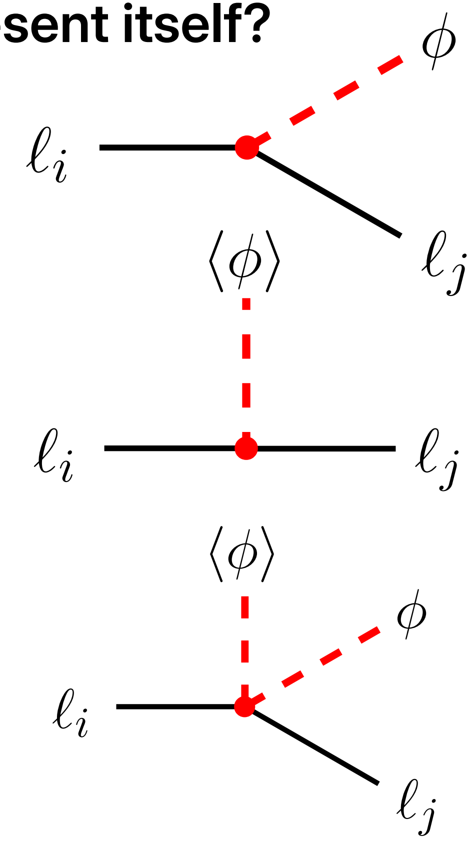
Detecting a CLFV signal does not immediately imply DM is the source.

Detecting a *time-dependent* CLFV signal is a smoking gun signal of DM.

Minimal analysis can convert intensity frontier experiments into dark matter detectors

ULDM + CLFV

How and where does time-modulation present itself?



Two types of time-dependence:

- Manifestation in mass matrix

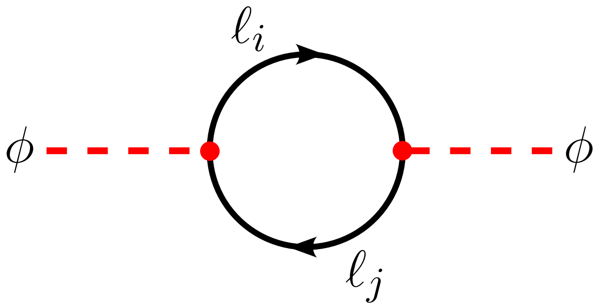
$$m_{ij} = \text{diag}(m_e, m_\mu, m_\tau) + y_{ij}\phi_c$$

- Manifestation in decay/scattering rates
  - Inherently higher dimensional

Journey towards phenomenologically viable operator

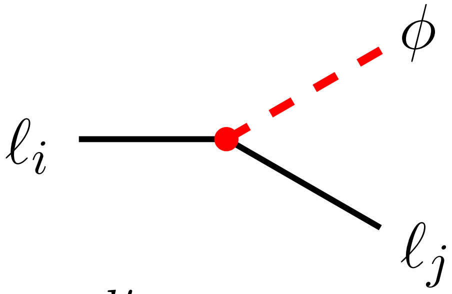
First guess: $\frac{C_{ij}}{\Lambda}\phi H \bar{L}_i \ell_j \to y_{ij}\phi\bar{\ell}_i\ell_j$

1. Fine-tuning

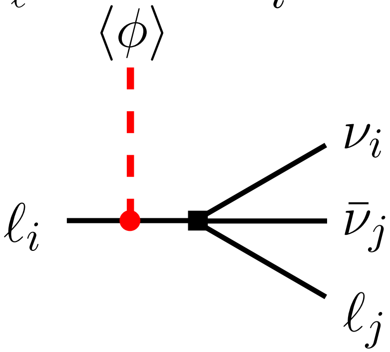


$\longrightarrow \delta m_\phi^2 \simeq \frac{\lambda^2}{4\pi^2} m_\ell^2$

2. No time-modulation



3. SM rate-modulation



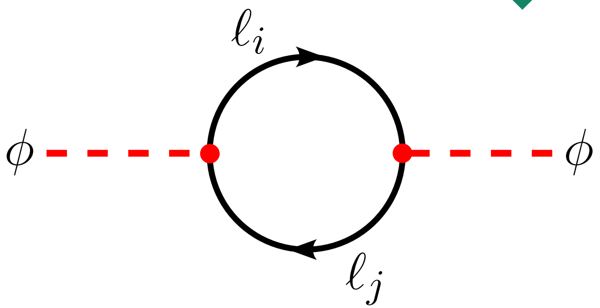
$|y_{\tau\ell}| \lesssim 10^{-7}$ (Belle II)

$|y_{\mu e}| \lesssim 10^{-10}$ (TWIST)

Journey towards phenomenologically viable operator

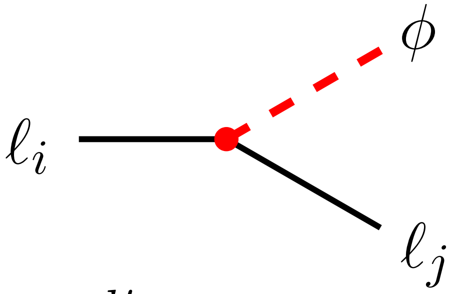
First guess: $\frac{C_{ij}}{\Lambda}\phi H \bar{L}_i \ell_j \to y_{ij}\phi\bar{\ell}_i\ell_j$

1. Fine-tuning "✓"

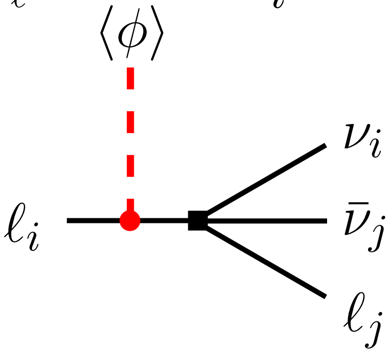


$$\longrightarrow \delta m_\phi^2 \simeq \frac{\lambda^2}{4\pi^2} m_\ell^2$$

2. No time-modulation X



3. SM rate-modulation X



$|y_{\tau\ell}| \lesssim 10^{-7}$ (Belle II)

$|y_{\mu e}| \lesssim 10^{-10}$ (TWIST)

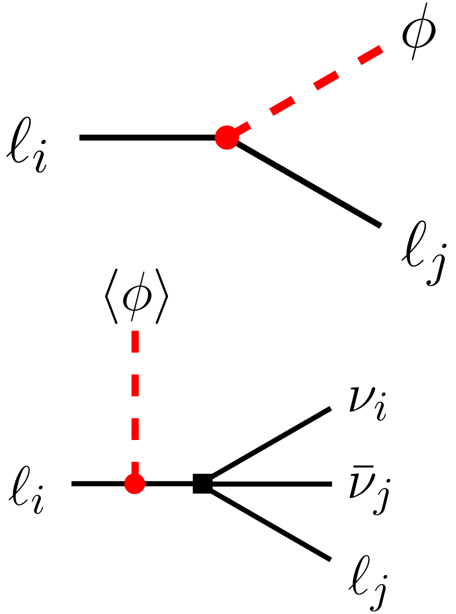
Journey towards phenomenologically viable operator

Second guess: $\frac{C_{ij}}{\Lambda}\partial_\mu\phi(\bar{\ell}_i\gamma^\mu\gamma^5\ell_j)$

1. Fine-tuning: ✓

2. Time-modulation: X

3. SM-modulation: X



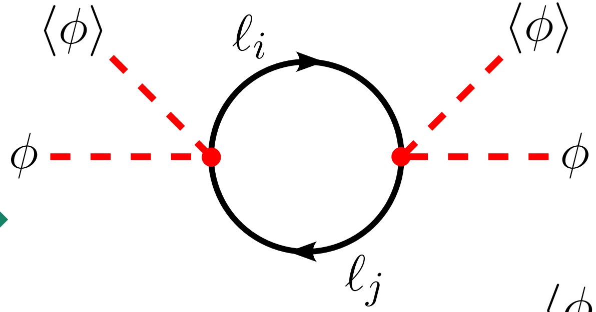
Journey towards phenomenologically viable operator

Third guess: $\frac{C_{ij}}{f}\phi^2(\bar{\ell}_i \ell_j)$

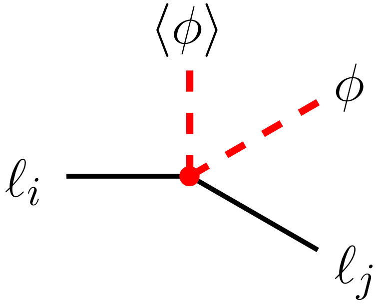
1. Fine-tuning: ✗

2. Time-modulation: ✓

3. SM-modulation: ✓



$$\longrightarrow \delta m_\phi^2 \simeq \left(\frac{C_{ij}\phi_0}{f}\right)^2 \frac{m_\ell^2}{4\pi^2}$$



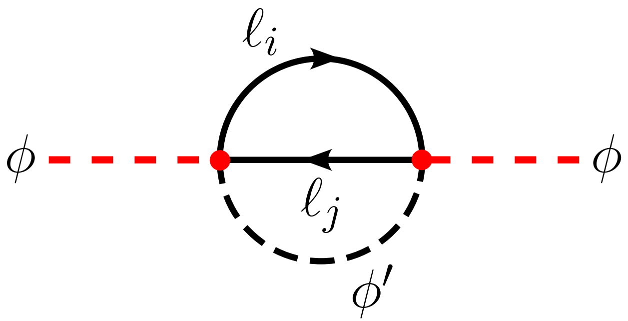
Journey towards phenomenologically viable operator

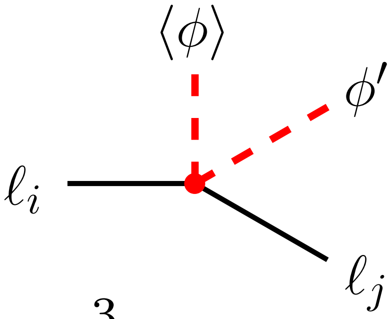
Fourth guess: $\frac{C_{ij}}{f}\phi\phi'(\bar{\ell}_i\ell_j)$ or $\frac{C_{ij}}{f^2}\phi\partial_\mu\phi'(\bar{\ell}_i\gamma^\mu\ell_j)$

1. Fine-tuning: "✓"/✓

2. Time-modulation: ✓

3. SM-modulation: ✓





$$\mathcal{B}(\ell_i \to \ell_j\phi) = \frac{C_{ij}^2\phi_0^2}{64\pi f^4}\frac{m_{\ell_i}^3}{\Gamma_{\ell_i}}\cos^2(m_\phi t + \delta)$$

Explicit realization

- **Non-abelian pseudo-NGB + U(1)$_D$**

$$SU(3)_L \times SU(3)_R \times U(1)_D \to SU(3)_V \times U(1)_D$$

$$D_\mu \equiv \partial_\mu + ig_D A'_\mu [Q, U] \qquad U = \exp\left(i\sqrt{2}\Pi_D / f_D\right)$$

$$\Pi_D = \begin{pmatrix} \frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & \pi_D^+ & K_D^+ \\ \pi_D^- & -\frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & K_D^0 \\ K_D^- & \bar{K}_D^0 & -\sqrt{\frac{2}{3}}\eta_{D8} \end{pmatrix}$$

Explicit realization

- **Non-abelian pseudo-NGB + U(1)$_D$**

$$\mathcal{L}_D \supset \frac{f_{\rm UV}^2}{8}\left(D_\mu U D^\mu U^\dagger\right) + \frac{f_{\rm UV}^2}{8}\left(\chi^\dagger U + U^\dagger \chi\right) + \cdots$$

$$\mathrm{Q} \to q_U \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & q_U \\ 0 & q_U & 0 \end{pmatrix}$$

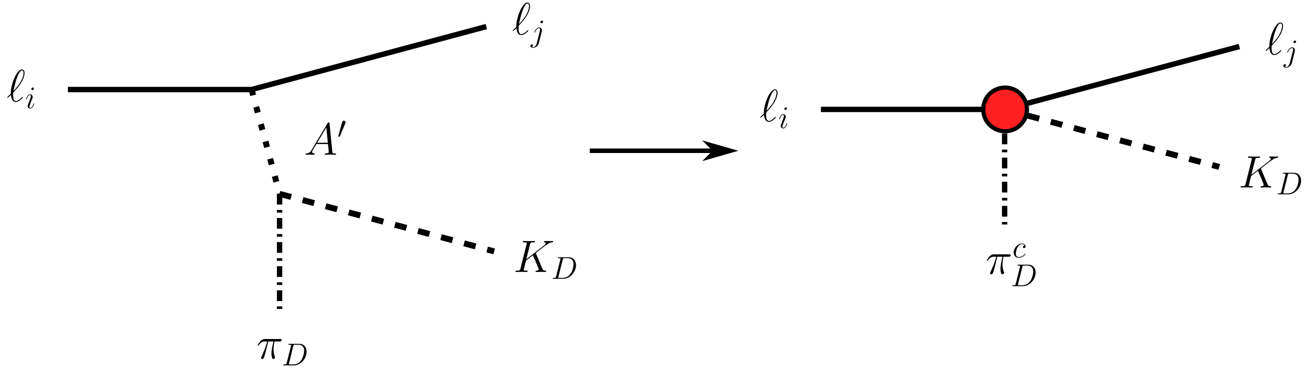
$$\supset -g' q_U A'_\mu \left(\pi_D^+ i\partial^\mu K_D^- - K_D^- i\partial^\mu \pi_D^+ + \text{h.c.}\right) + \cdots$$

Explicit realization

- **Non-abelian pseudo-NGB + U(1)$_D$**

$$\supset -g' q_U A'_\mu \left(\pi_D^+ i\partial^\mu K_D^- - K_D^- i\partial^\mu \pi_D^+ + \text{h.c.}\right) + \cdots$$

Charge the SM under U(1)$_D$: $-\mathcal{L}_{\text{portal}} = ig' c_{ij} \ell_i \gamma^\mu A'_\mu \ell_j + \text{h.c.}$



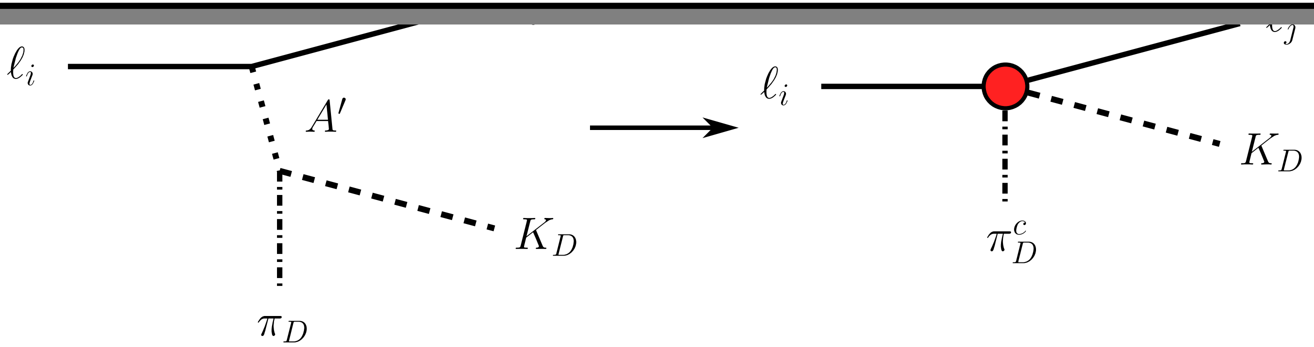
Explicit realization

- Non-abelian pseudo-NGB + U(1)$_D$

$$\supset -g' q_U A'_\mu \left(\pi_D^+ i\partial^\mu K_D^- - K_D^- i\partial^\mu \pi_D^+ + \text{h.c.}\right) + \cdots$$

$$\supset \frac{c_{ij} q_U g'^2}{m_{A'}^2} \left(\bar{\psi}_i \gamma^\mu \psi_j\right)\left(\pi_D^+ \partial_\mu K_D^-\right) + \cdots$$

Charge t … + h.c.

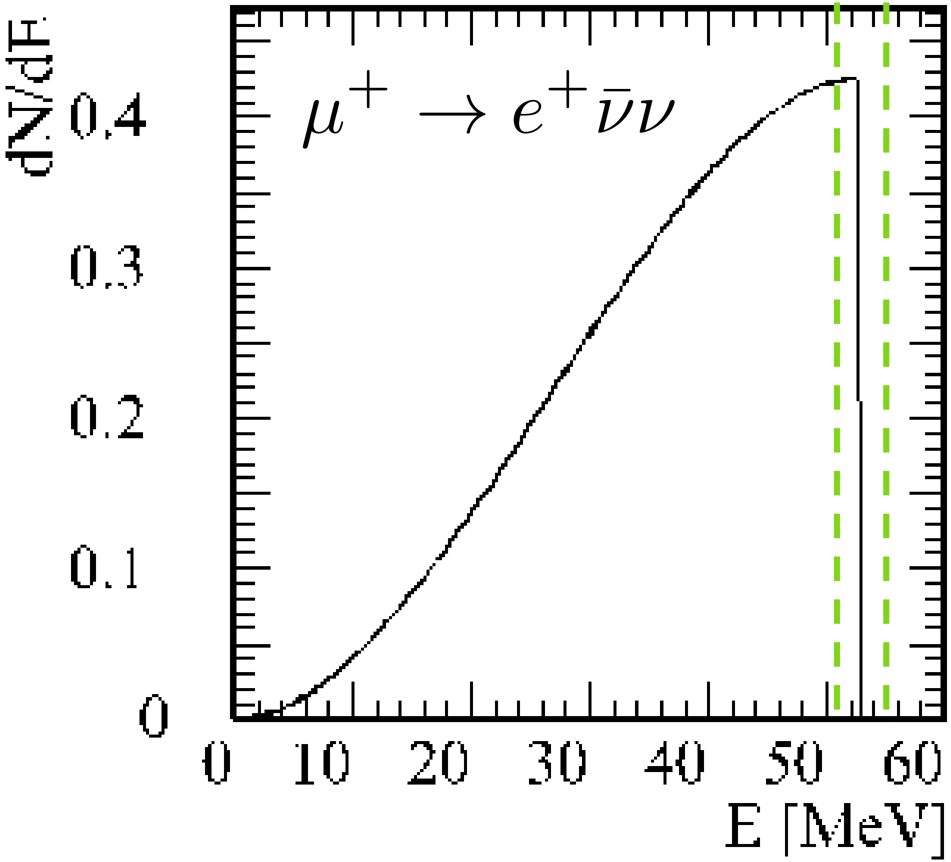


Sensitivity (Mu3e)

Consider, for example, Mu3e.

- Will run for T~300 days
- ~10^{15} muon decays
- ~10^{13} of which will lie in the final kinematic bin
- ~10^{8} muon decays/s

Michel spectrum



Sensitivity

- Sensitivity can essentially be determined by:

$$m_\phi, \quad T, \quad N_{\rm total}$$

- Statistical uncertainty + systematic uncertainty maximally correlated across all time bins

$$\sigma_{\rm stat} = \sqrt{N_{\rm bg}/n_{\rm bin}} \;, \quad \sigma_{\rm sys} = \alpha N_{\rm bg}/n_{\rm bin}$$

$$\chi^2 = \sum_{k,p=1}^{n_{\rm bin}} S_k C^{-1}_{kp} S_p = \frac{1}{N_{\rm bg,1}} \sum_{k=1}^{n_{\rm bin}} S_k^2 - \frac{\alpha^2}{1+\alpha^2 n_{\rm bin} N_{\rm bg,1}} \left(\sum_{k=1}^{n_{\rm bin}} S_k \right)^2$$

Sensitivity

$$\chi^2 = \sum_{k,p=1}^{n_{\rm bin}} S_k C^{-1}_{kp} S_p = \frac{1}{N_{\rm bg,1}} \sum_{k=1}^{n_{\rm bin}} S_k^2 - \frac{\alpha^2}{1+\alpha^2 n_{\rm bin} N_{\rm bg,1}} \left(\sum_{k=1}^{n_{\rm bin}} S_k \right)^2$$

$$S_k = 2\mathcal{B}_{\rm sig} f_{\rm sig} \frac{N_{\rm tot}}{T} \int_{(k-1)\Delta t}^{k\Delta t} dt \cos^2(m_\phi t + \delta)$$

$$= \mathcal{B}_{\rm sig} f_{\rm sig} \frac{N_{\rm tot}}{T} \left[\Delta t + \frac{\sin(2k m_\phi \Delta t + 2\delta) - \sin(2(k-1) m_\phi \Delta t + 2\delta)}{2 m_\phi} \right]$$

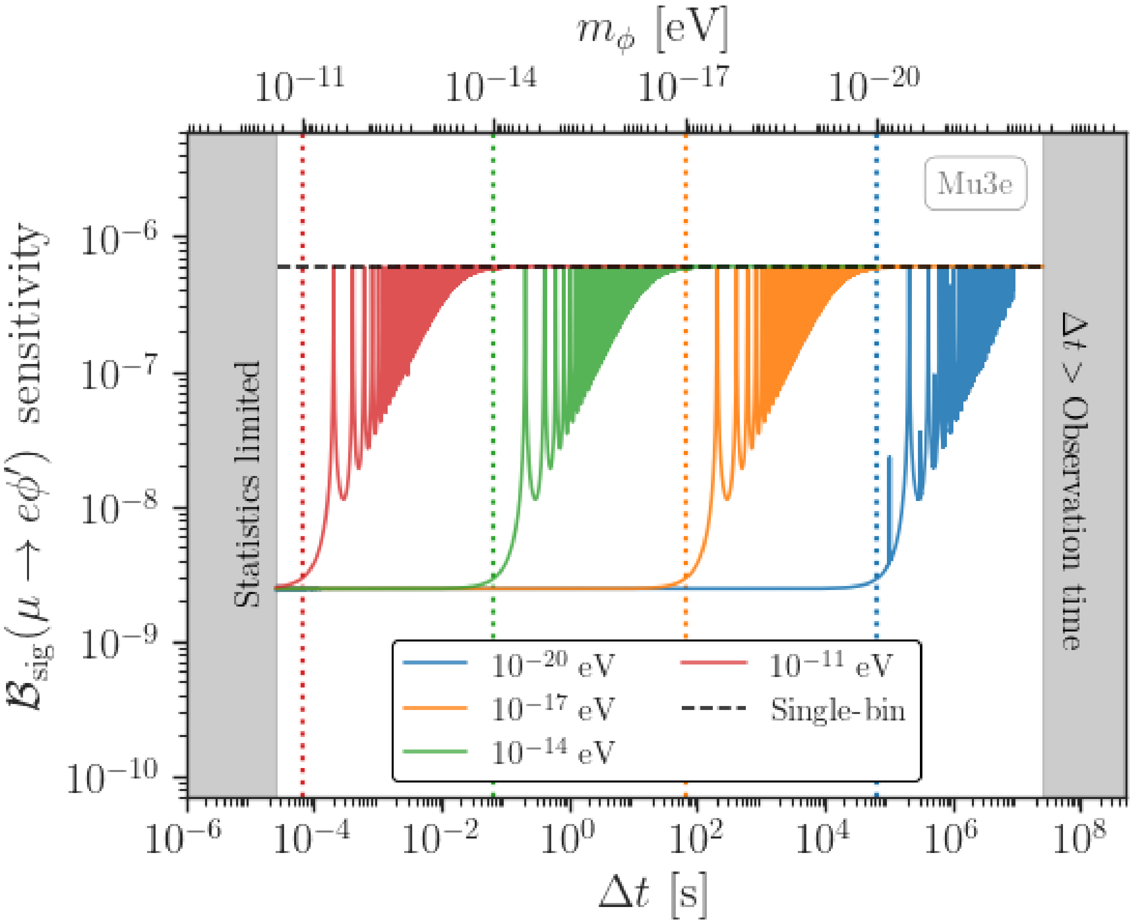
Three interesting limits:

1. **Signal does not oscillate over the duration of the experiment**
2. **Signal oscillates but time bins cannot resolve the oscillations** → **Systematics dominate**
3. **Signal oscillates and time bins resolve the oscillations** → **Statistics dominate**

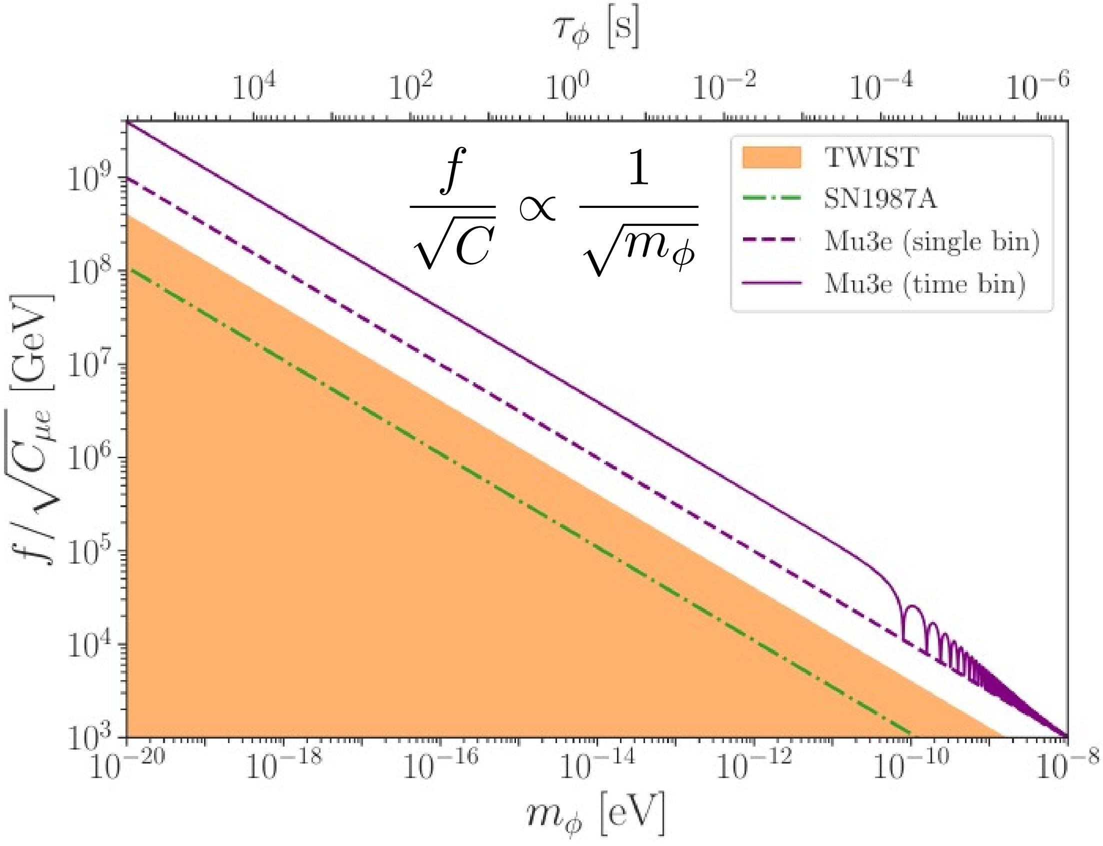
Sensitivity

Assumptions:
1) Asimov dataset
2) Continuous running
3) Time-independent systematics

- **Notably, the sensitivity to ULDM mass is limited by statistics, not experimental time resolution**



Reach


τ_ϕ [s]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
$\frac{f}{\sqrt{C}} \propto \frac{1}{\sqrt{m_\phi}}$
TWIST
SN1987A
Mu3e (single bin)
Mu3e (time bin)
$f/\sqrt{C_{\mu e}}$ [GeV]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
m_ϕ [eV]

Conclusions

- Interesting invasive and non-invasive avenues for making Pythia "fully" differentiable
- Interesting solutions for finalTwo? Parallels with constrained Brownian motion
- Fun CLFVing signals and model building at the intensity frontier.
- More natural models of ultralight scalar DM?

Conclusions

- Interesting invasive and non-invasive avenues for making Pythia "fully" differentiable
- Interesting solutions for finalTwo? Parallels with constrained Brownian motion
- Fun CLFVing signals and model building at the intensity frontier.
- More natural models of ultralight scalar DM?

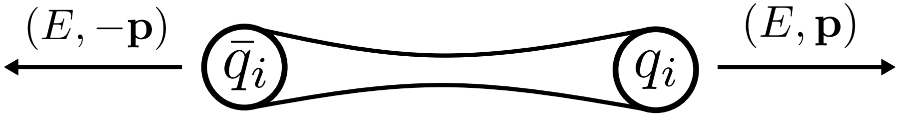
Thanks for your attention :)

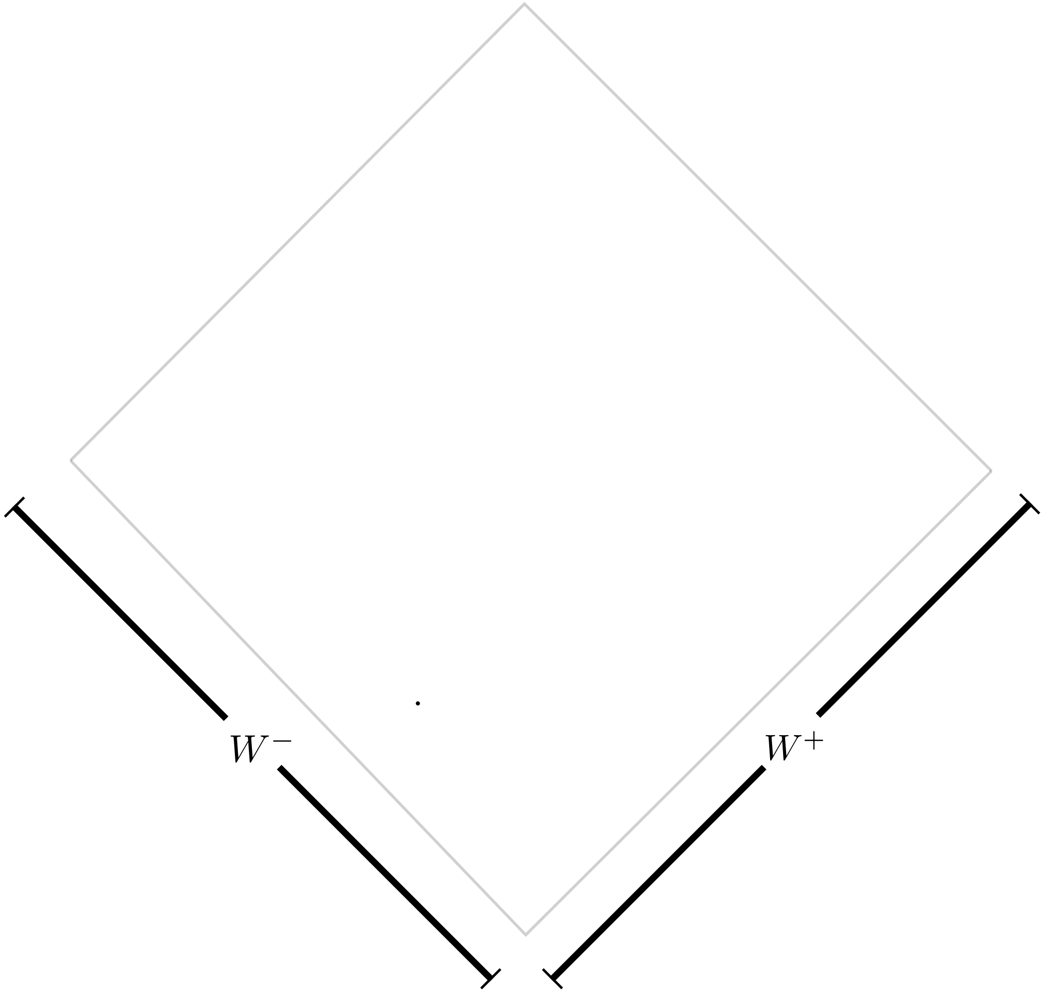
Backups

Half-baked thoughts on the interplay of “energy conservation” in hadronization and data-driven extraction of the fragmentation function

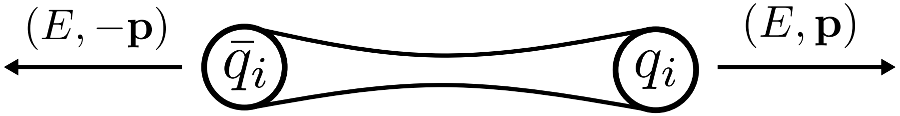
`finalTwo`

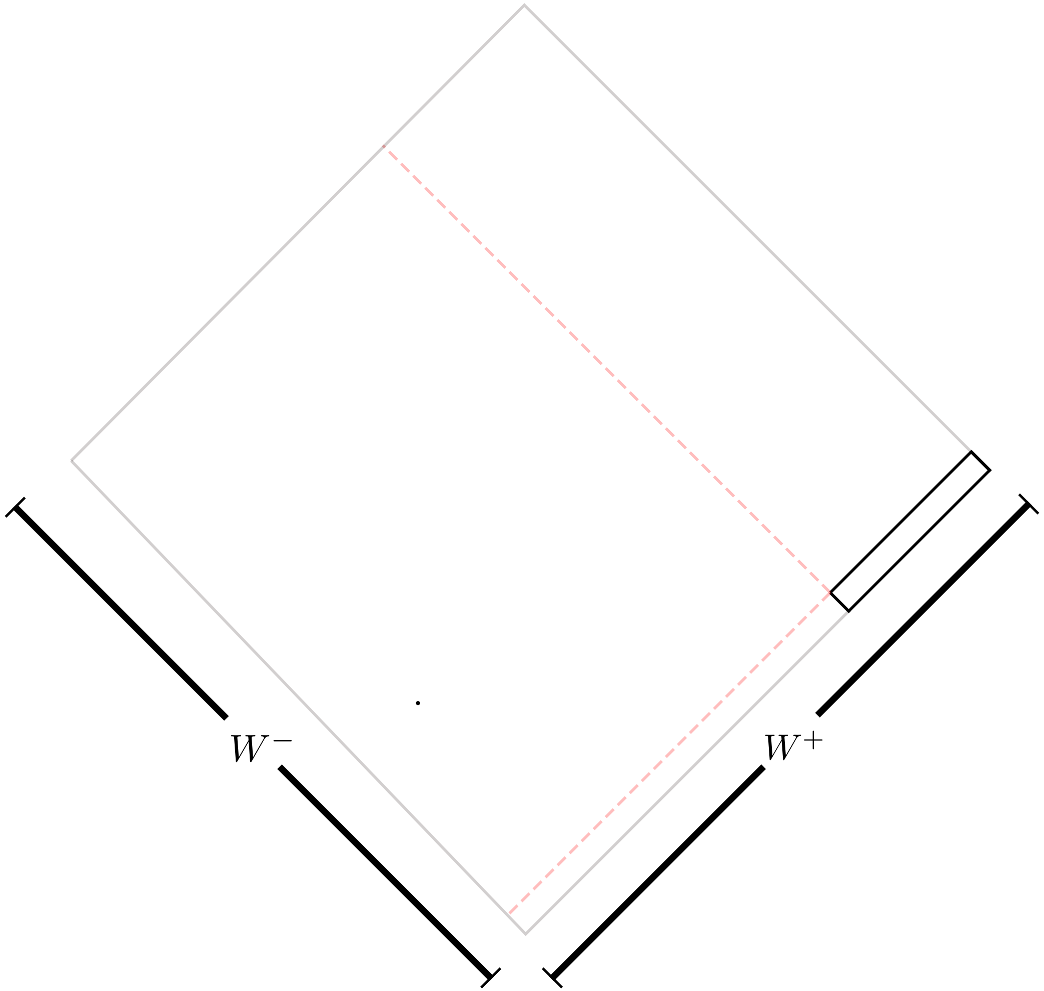
The algorithm (q$\bar{q}$)



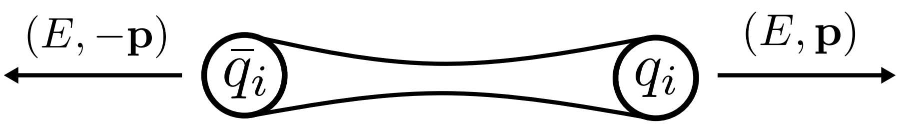


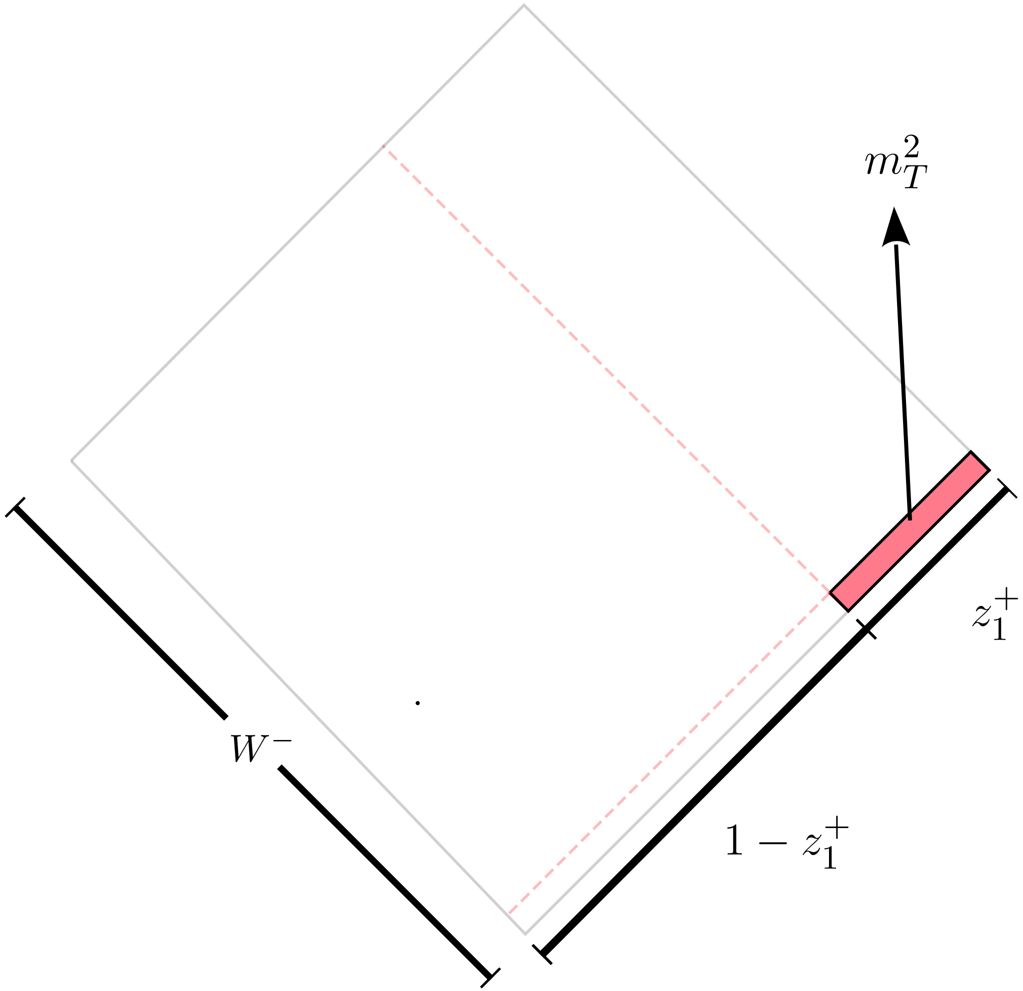
The algorithm (q$\bar{\text{q}}$)





The algorithm ($q\bar{q}$)





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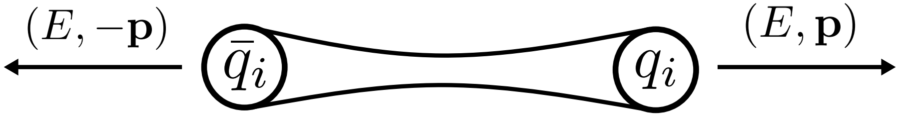

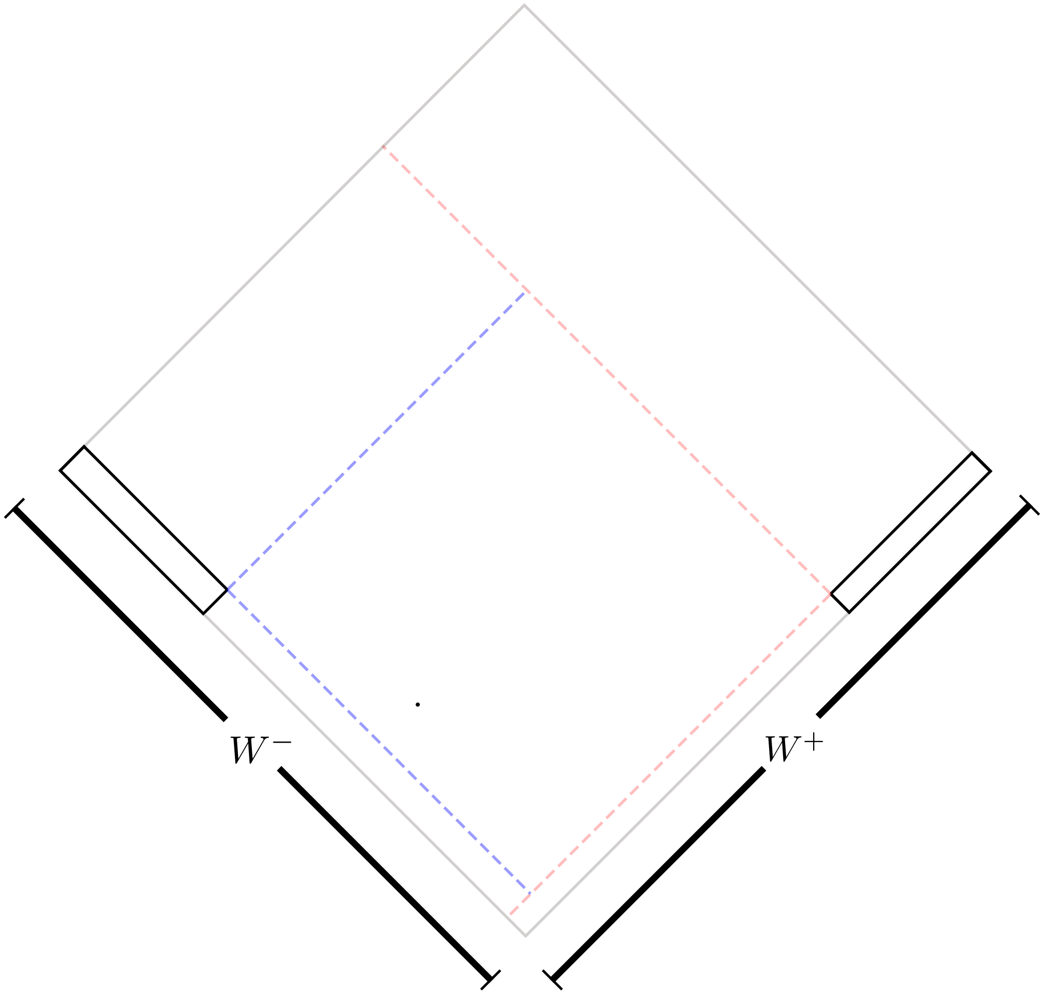

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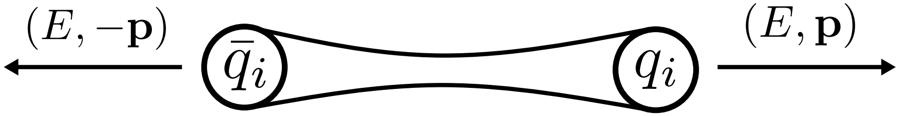

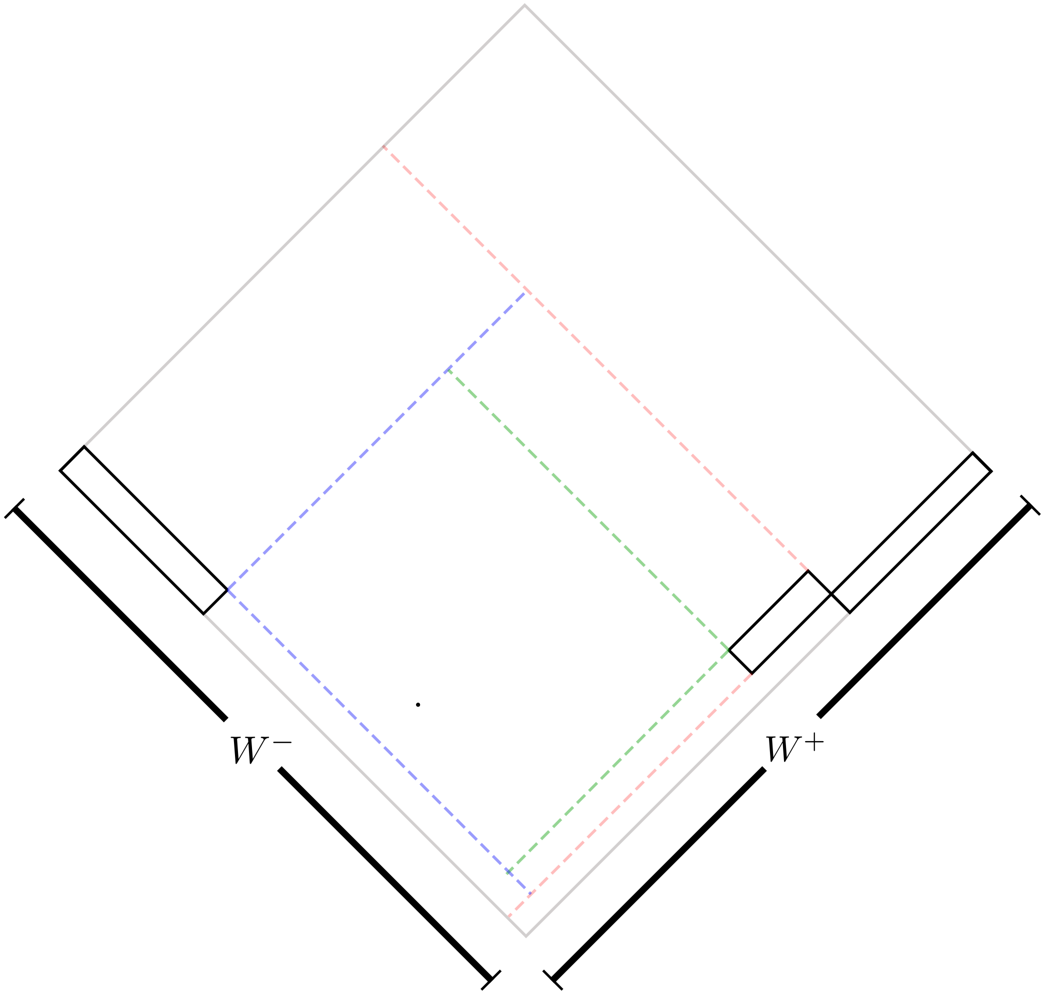

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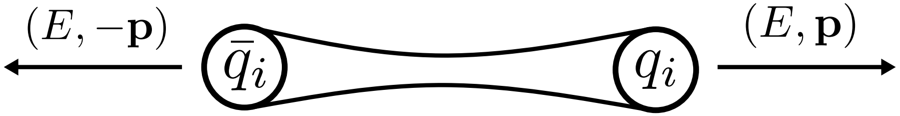

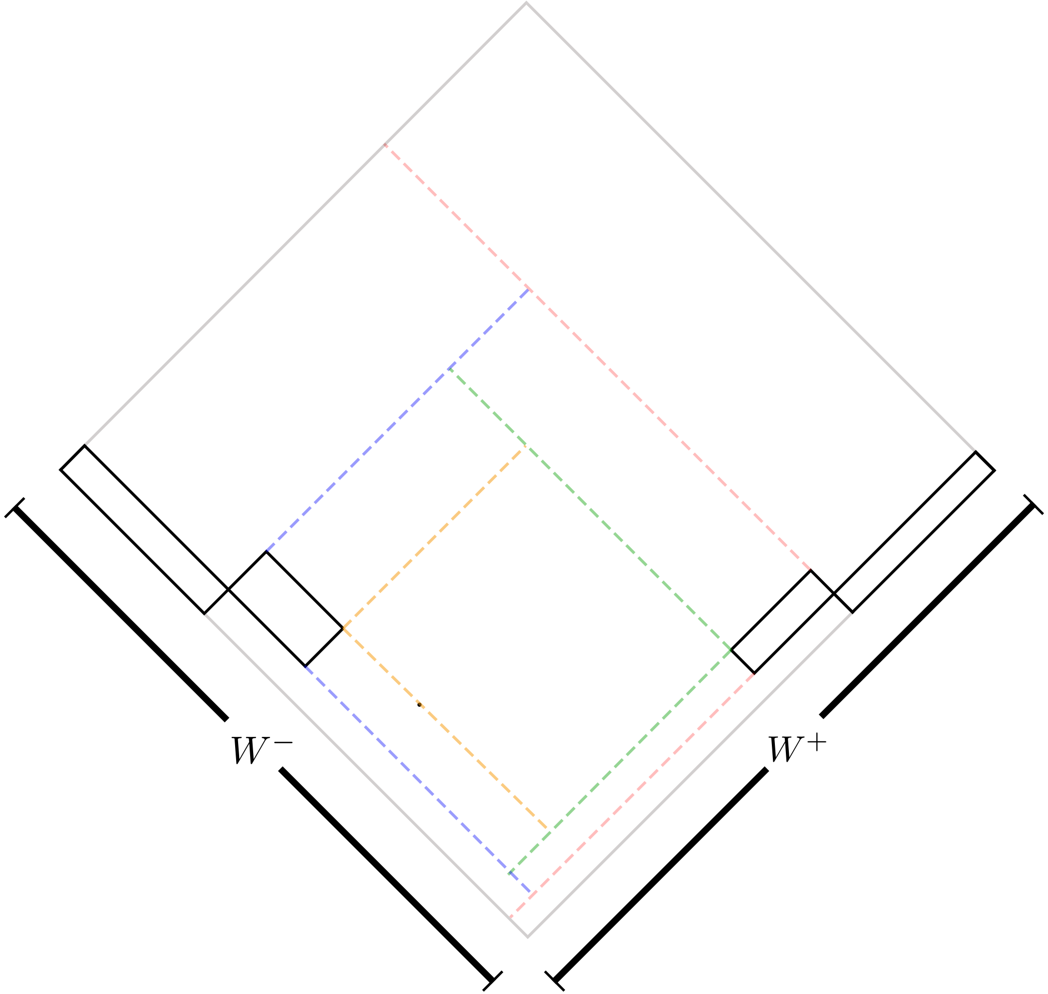

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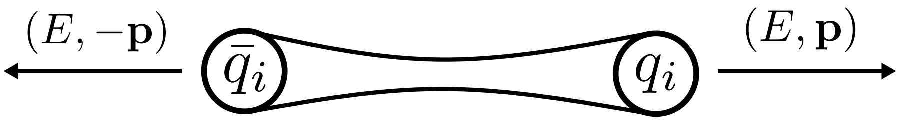
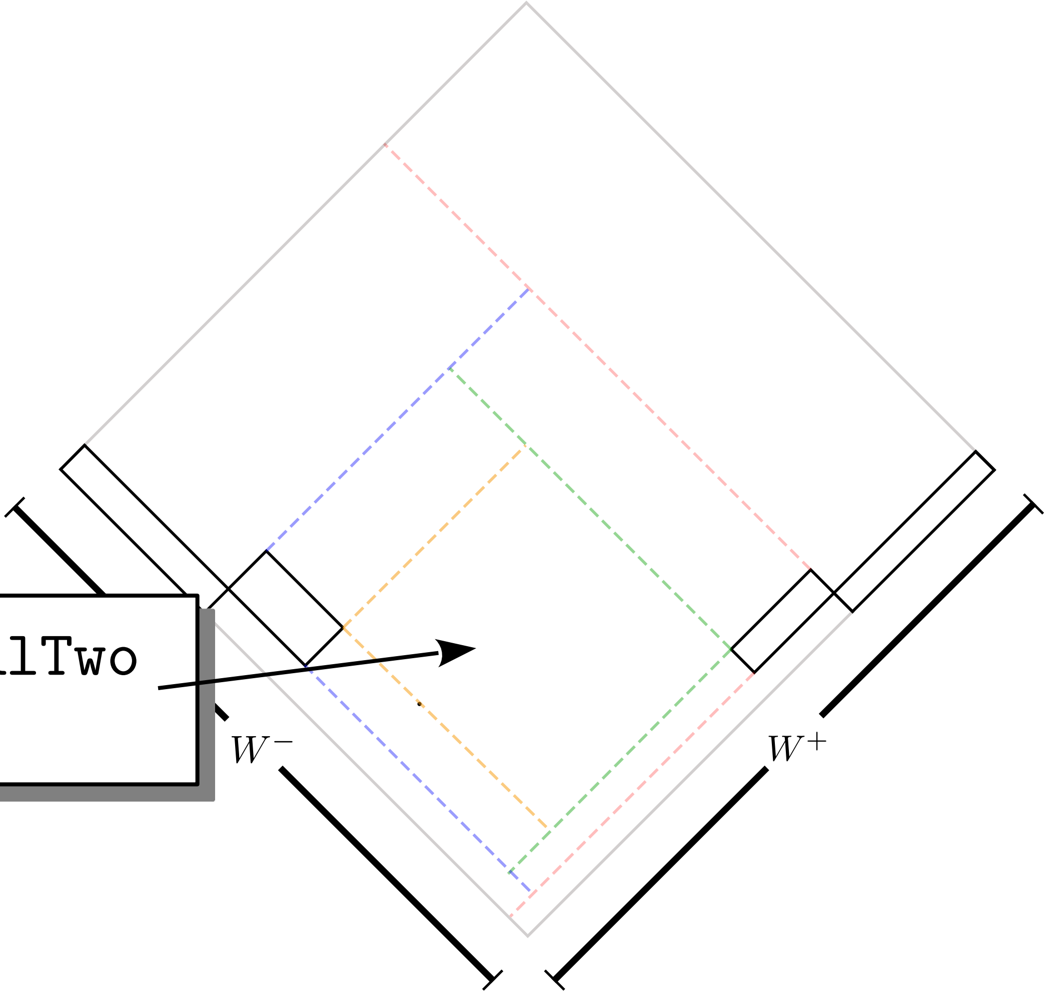


When E_{CM} goes below E_{cut}, `finalTwo` is called.



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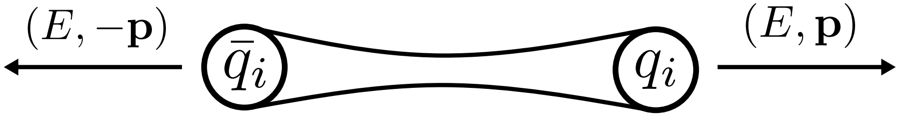

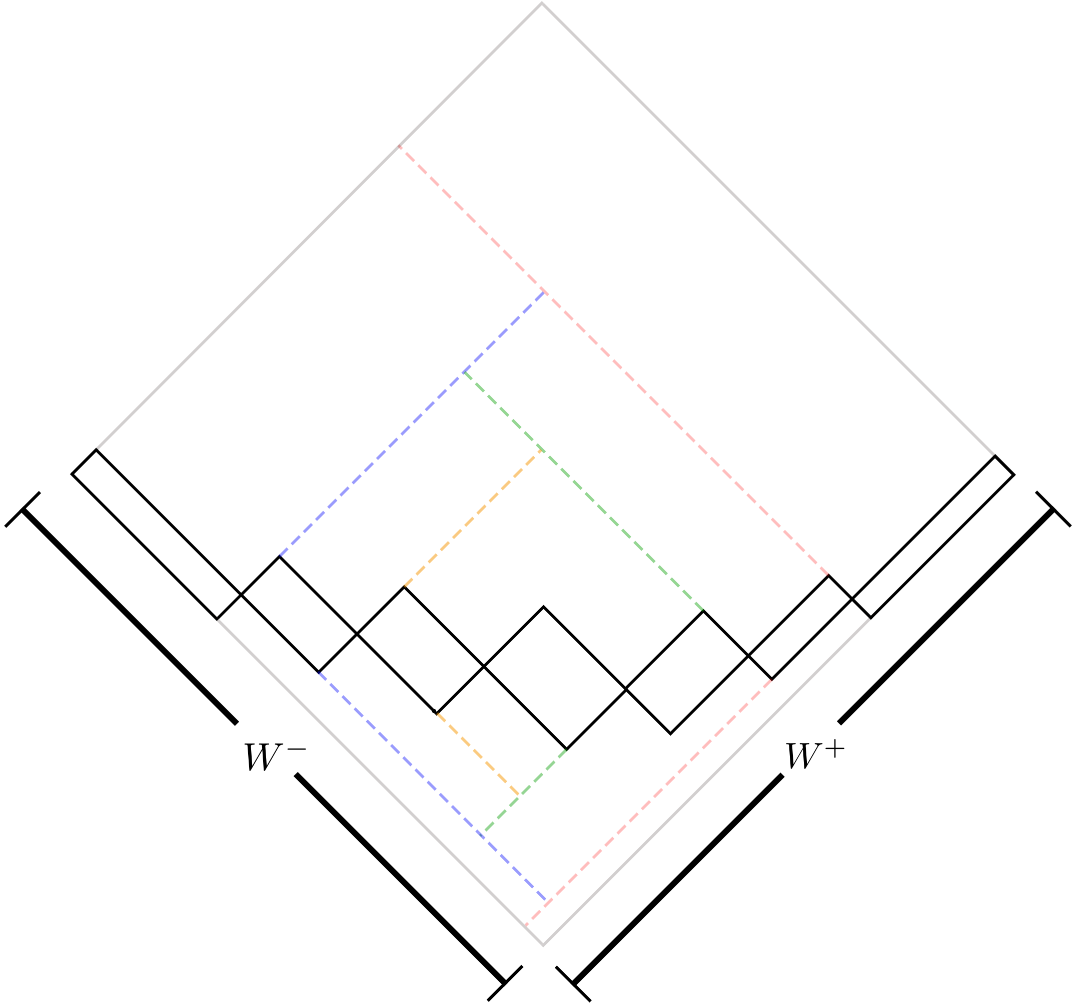

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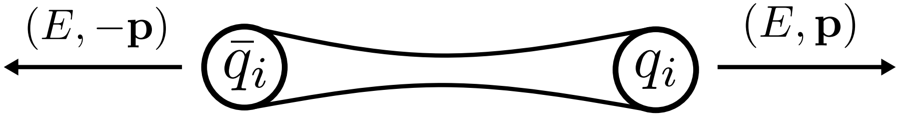
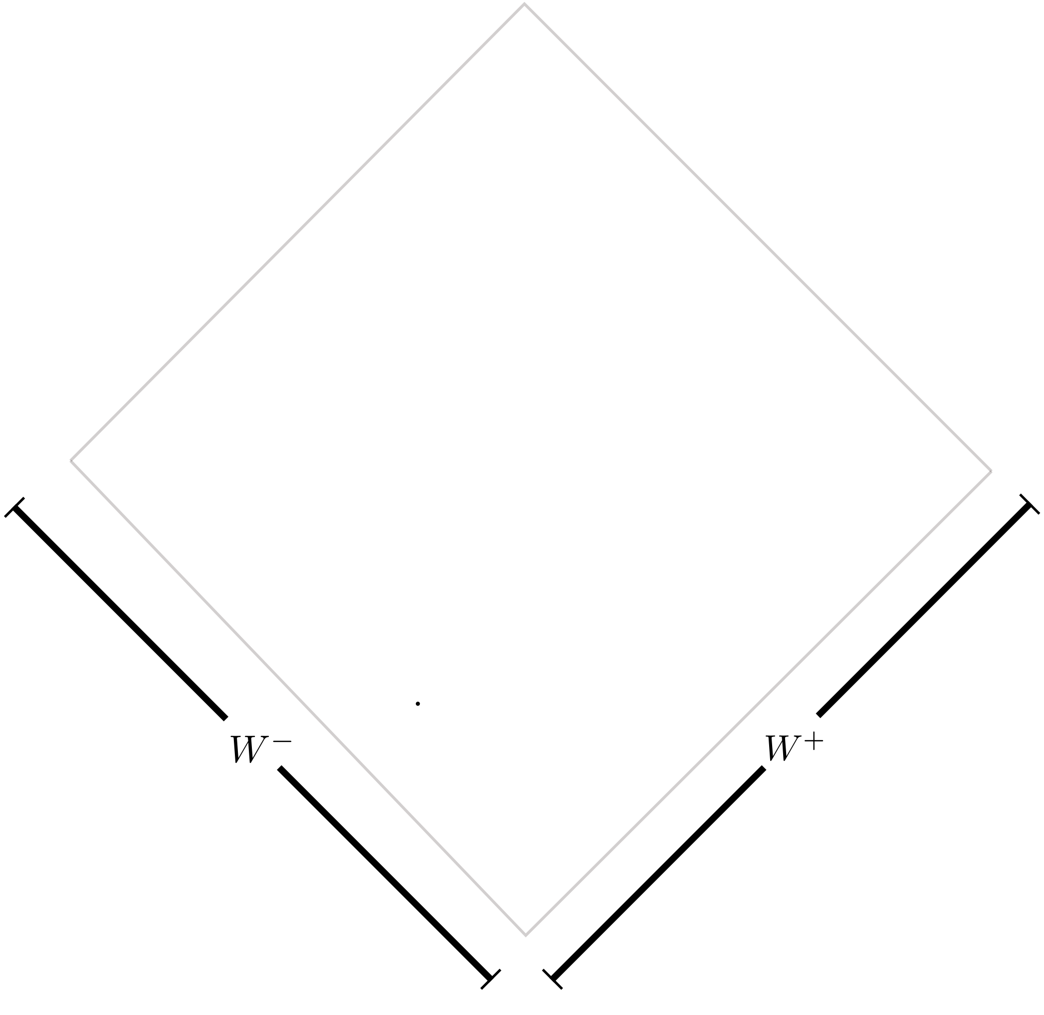


This system has two limits:

1. $E_{CM} >> m_h$
   - Random walk in f(z)



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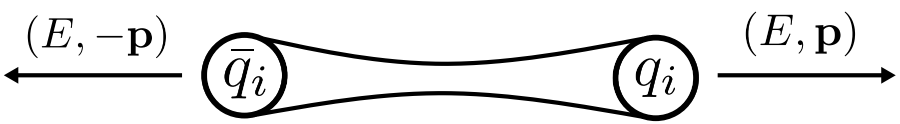

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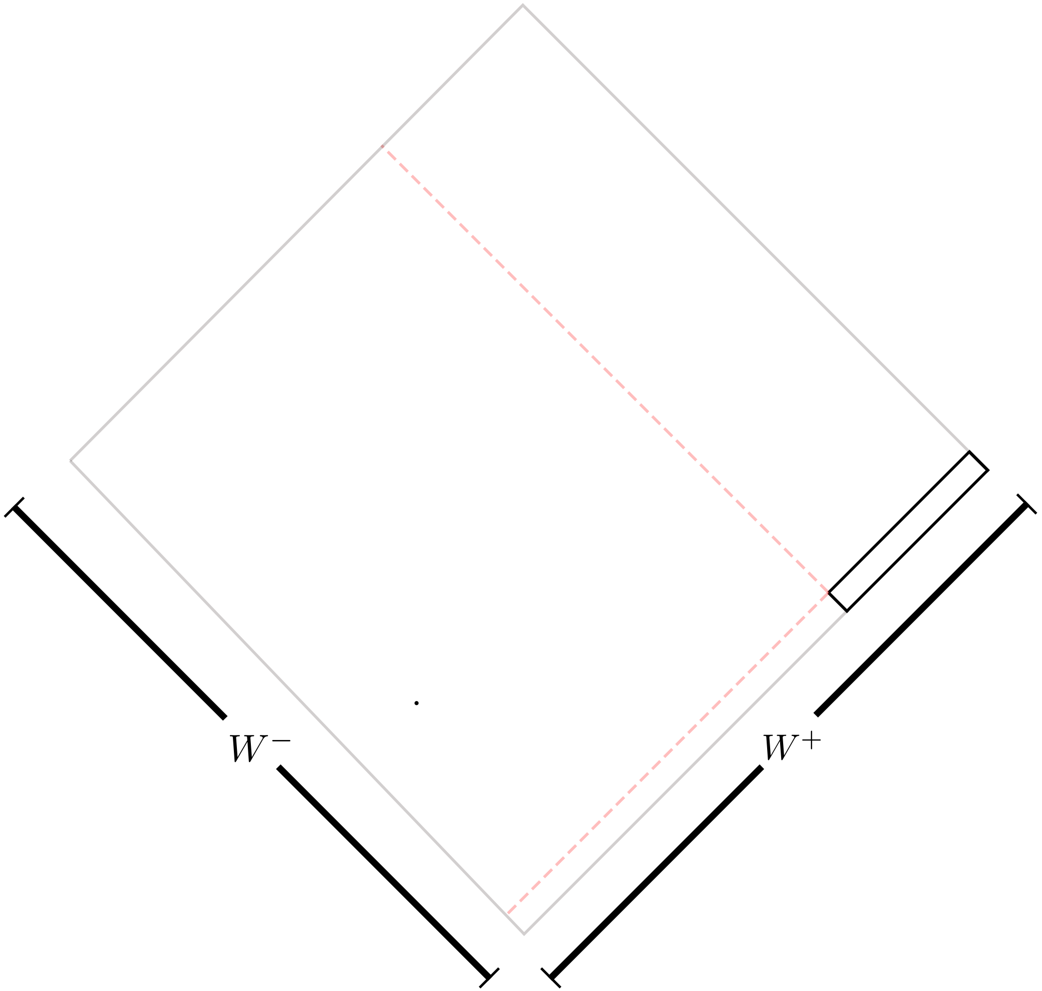

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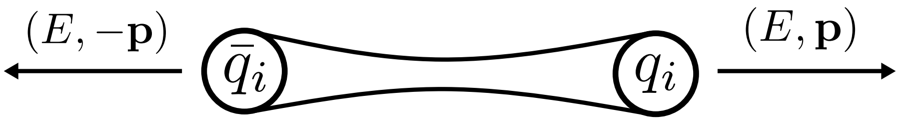

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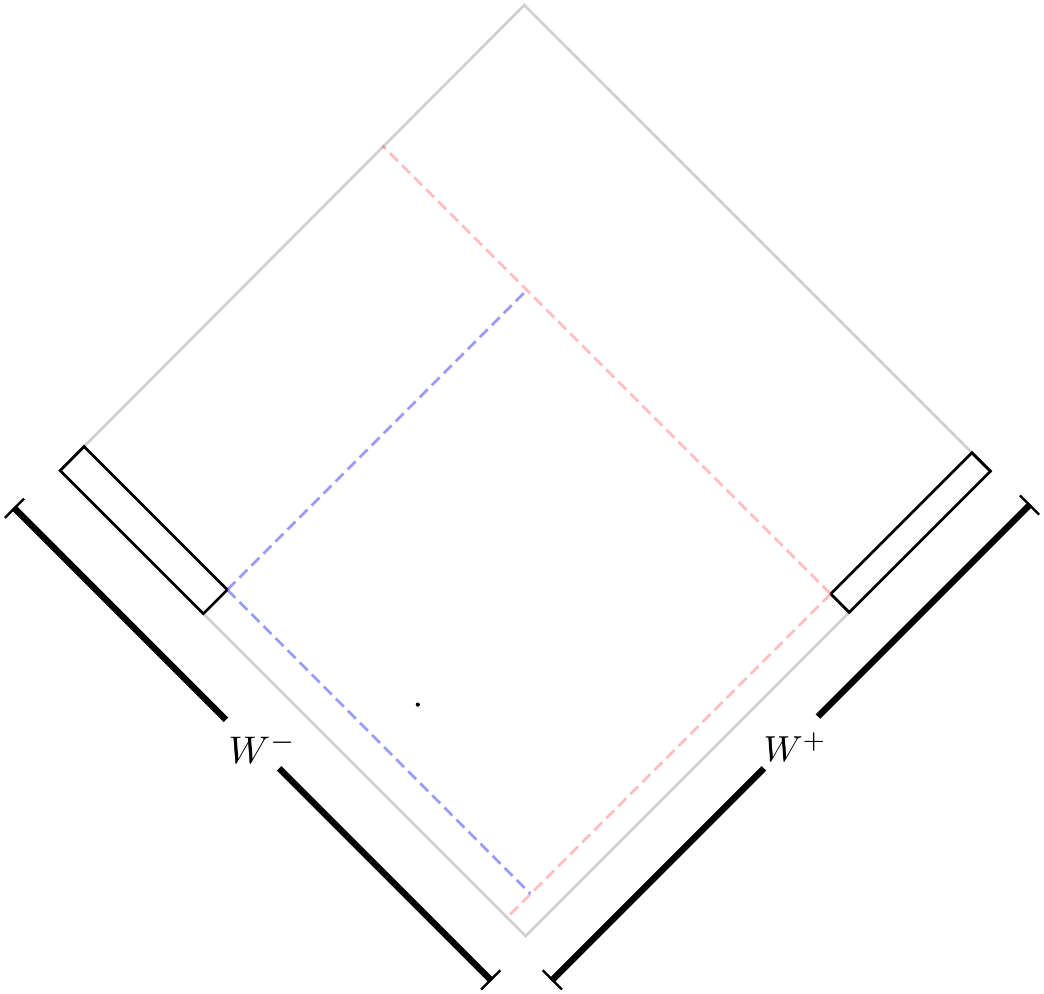

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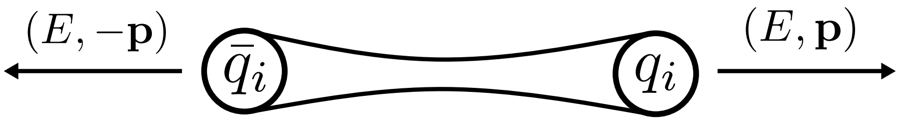

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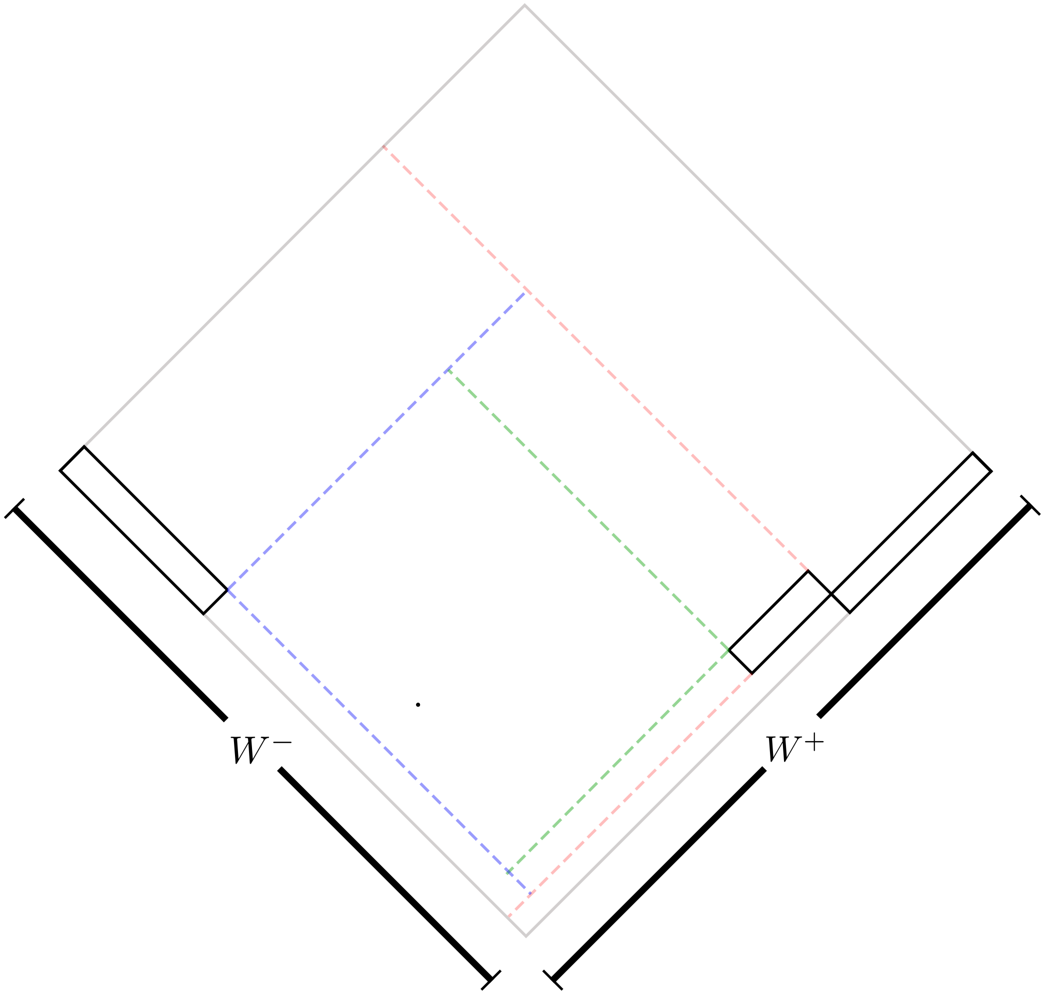

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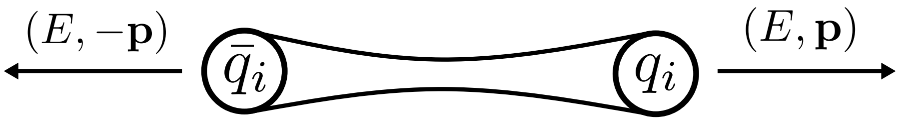

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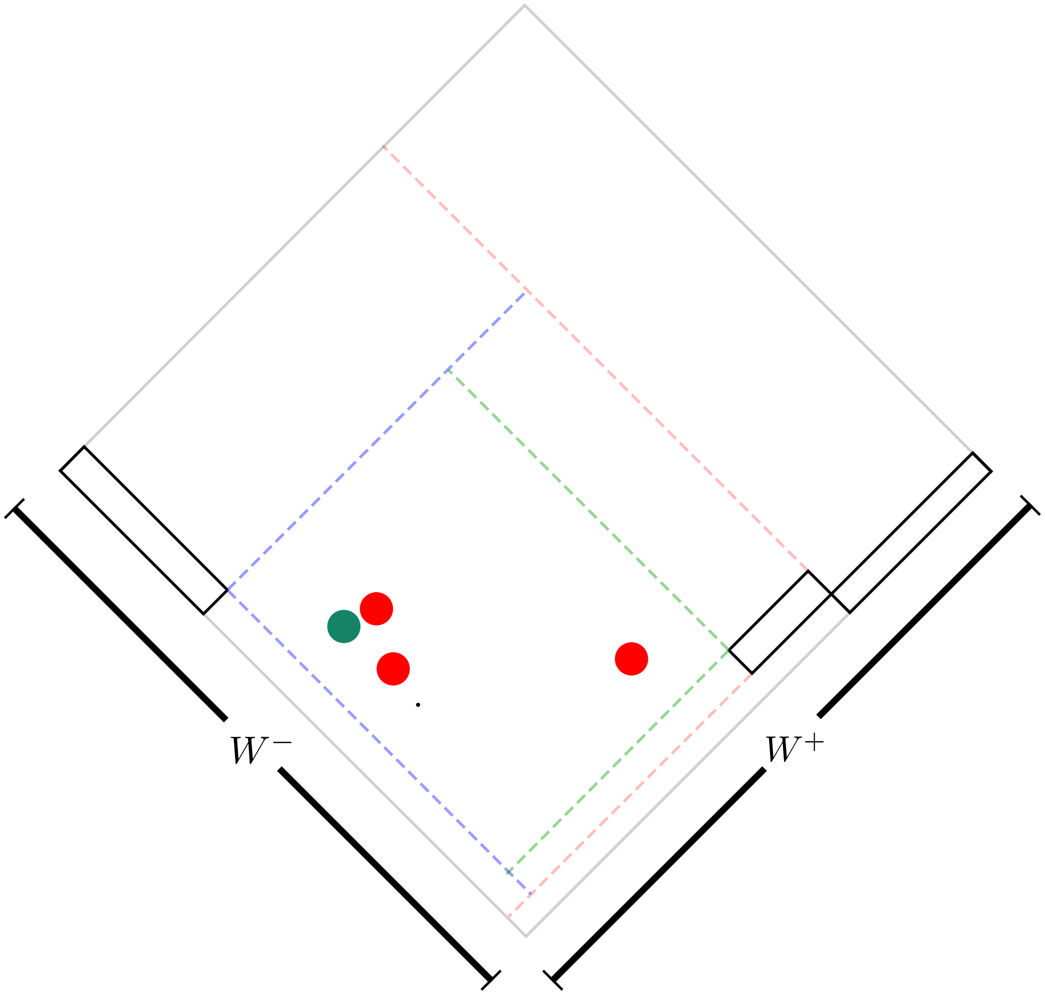
2. $E_{CM} \sim m_h$



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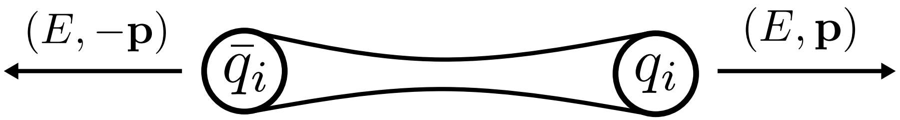
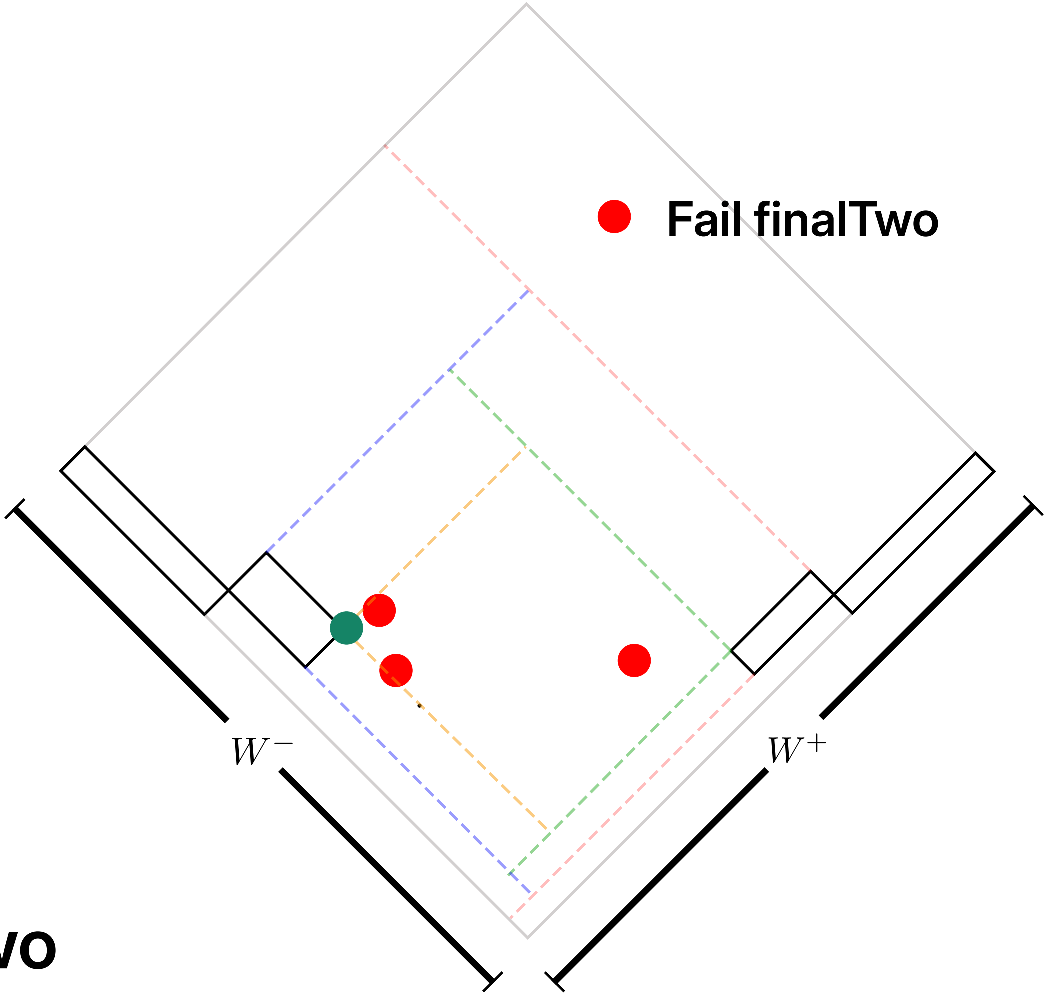


This system has two limits:

1. $E_{CM} >> m_h$
   - Random walk in f(z)

2. $E_{CM} \sim m_h$
   - f′(z) influenced by finalTwo



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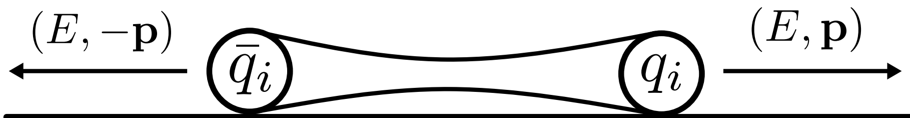
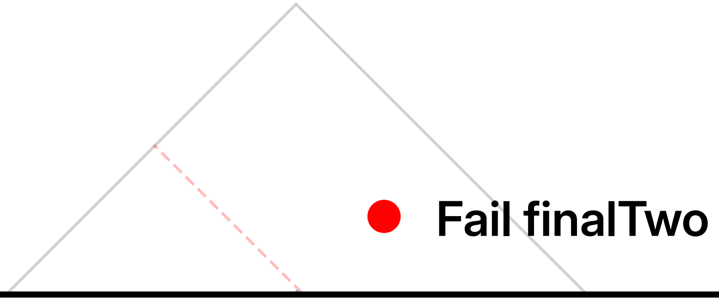
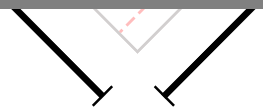




We want to extract f(z), not f′(z) – cleaner extraction would factorize these two pieces.

How?



- f′(z) influenced by finalTwo

Brownian bridge

- Gaussian random walk (E_{CM}>>m_h)
  - Markovian
- Gaussian random walk with termination condition, i.e. Gaussian bridge
  - Psuedo-Markovian

Brownian bridge

- Gaussian random walk ($E_{CM} >> m_h$)

$$dX_t = dW_t$$

- Gaussian bridge
  - Boundary conditions

$$X_0 = x_0 \qquad X_T = x_T$$

$$dX_t = \frac{x_T - X_t}{T - t} dt + dW_t$$

Brownian bridge

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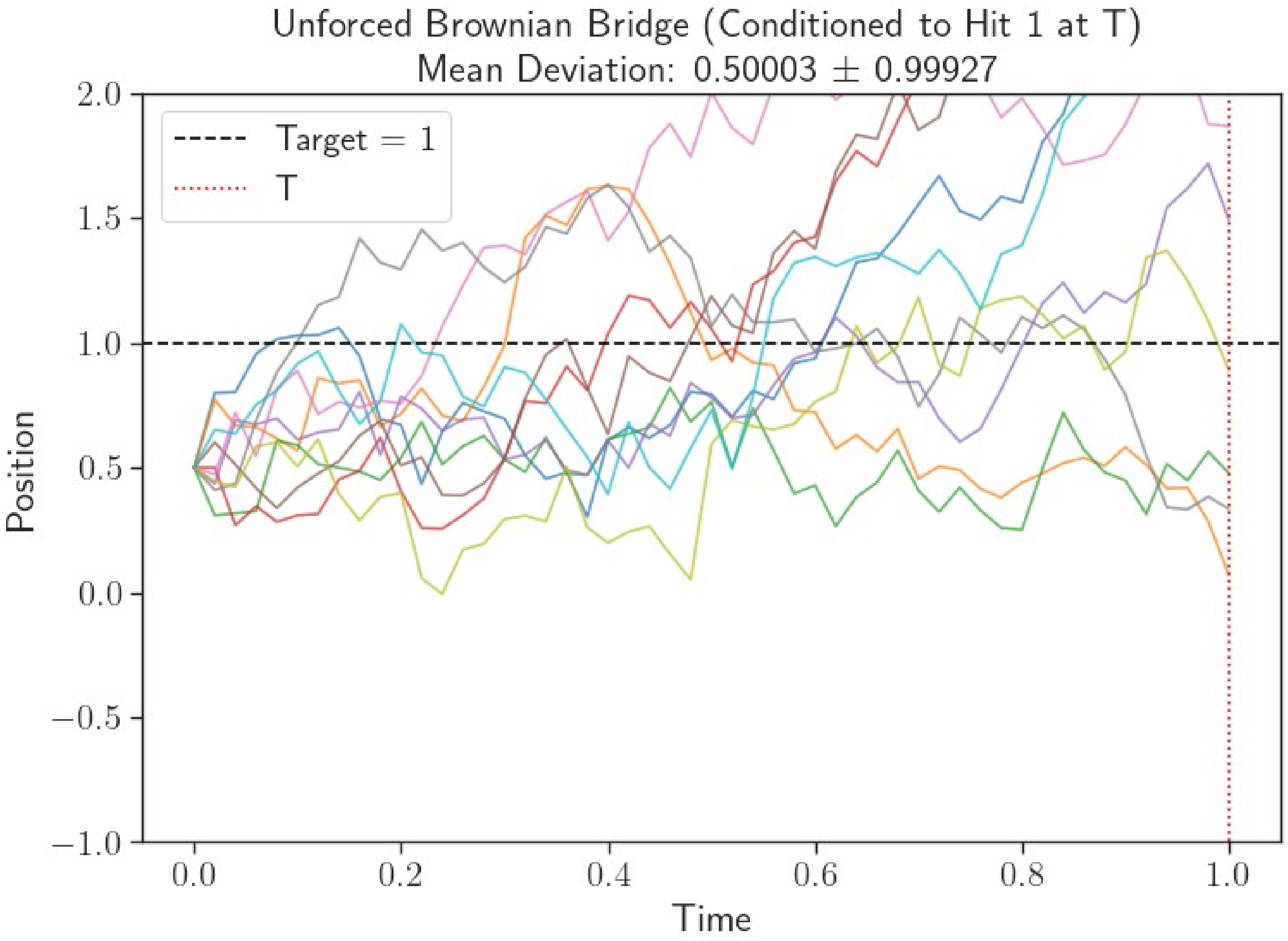
Doob h-transform

- **Gau ... ge wall ... ditions**

$\ldots_T = x_T$

$\ldots + dW_t$

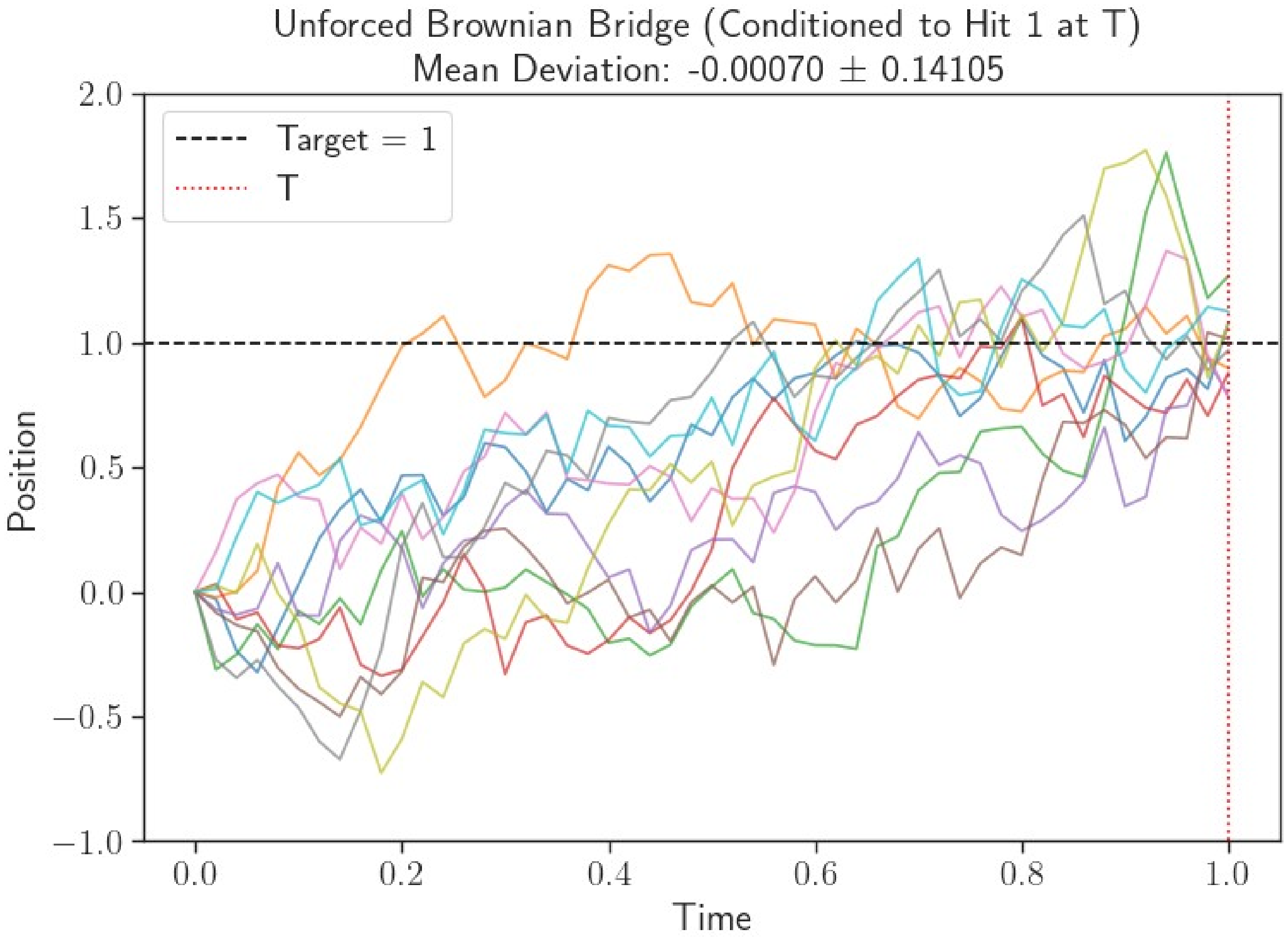
...rm



- **Gaus**
walk **tions**

dX $= x_T$

dW_t

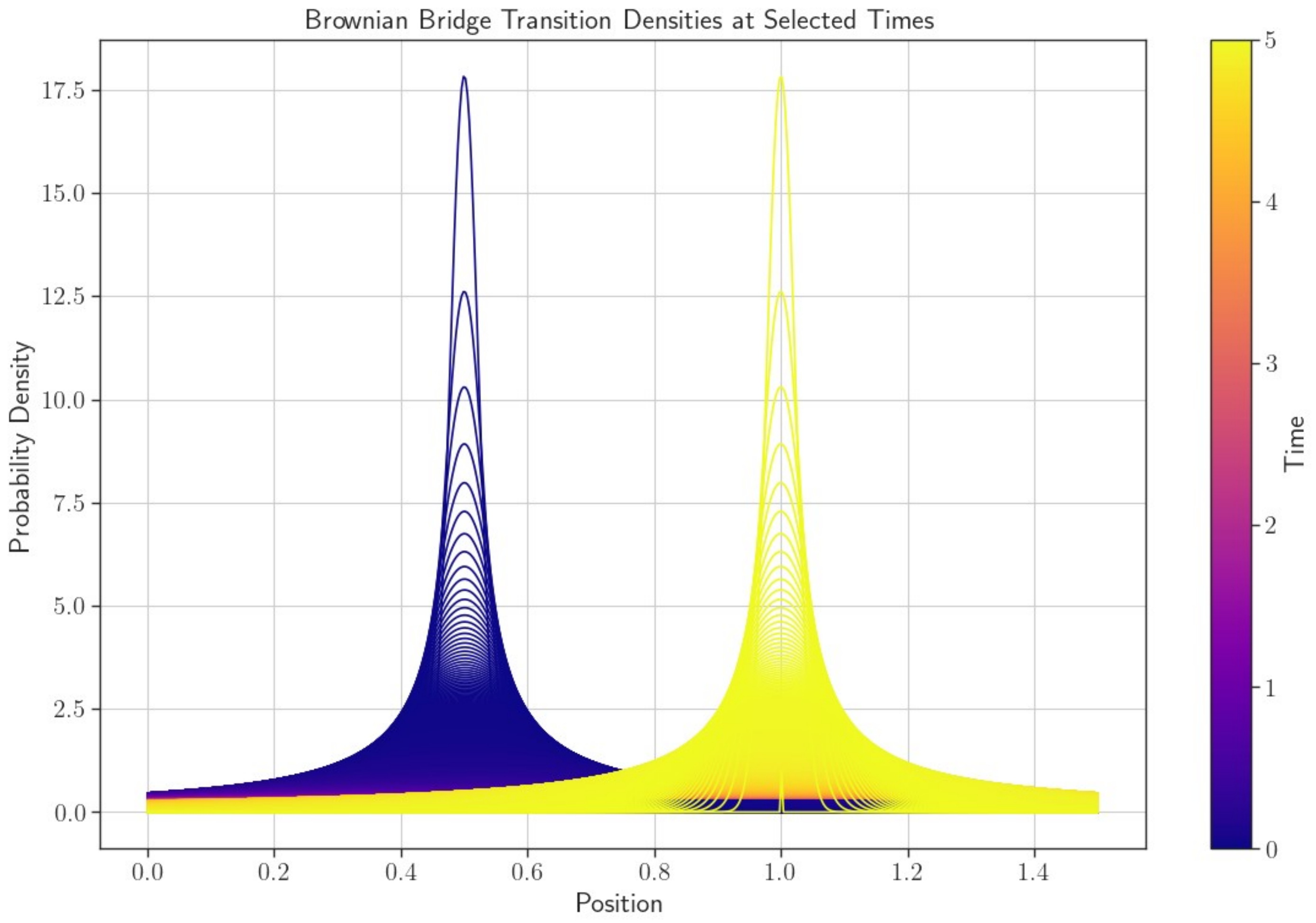


- **Gau… …e walk… …ditions**

$d\ldots = x_T$

$\ldots + dW_t$

…m



The algorithm (qq̄)

$(E, -\mathbf{p})$ $\bar{q}_i$

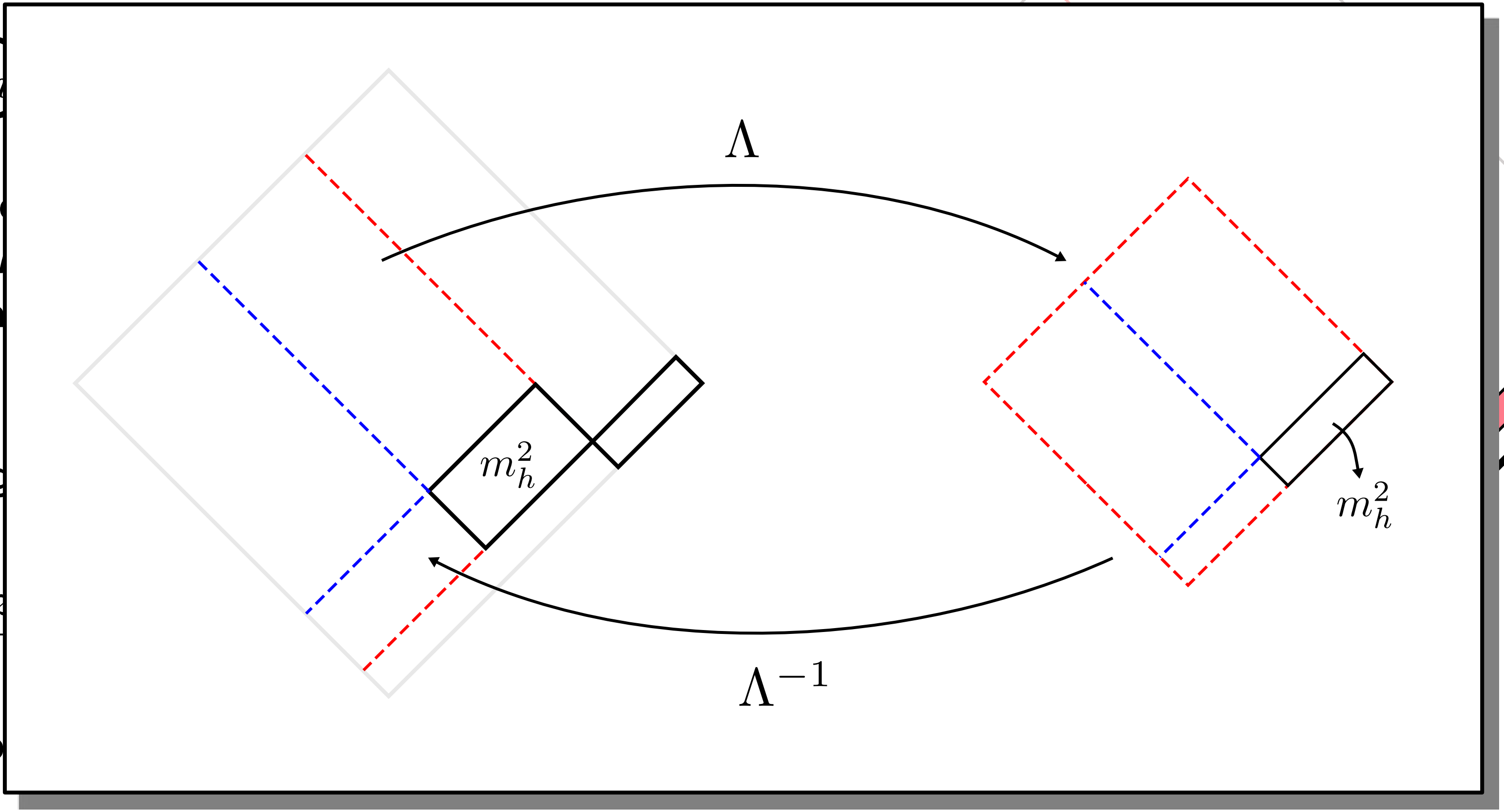
1) Randomly s
2) Sample new
3) Sample tran

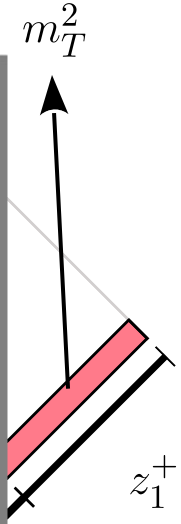
$\mathcal{P}(p_x, p_y$

4) Sample long
new hadron

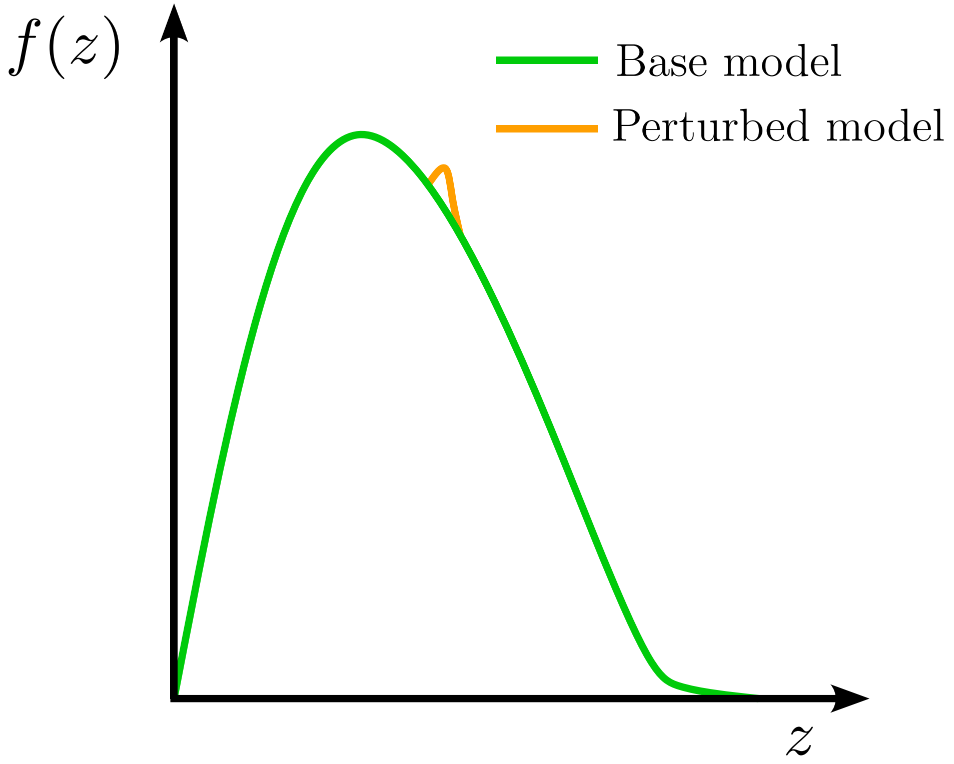
$f(z) \propto \frac{(1 - z}{z}$

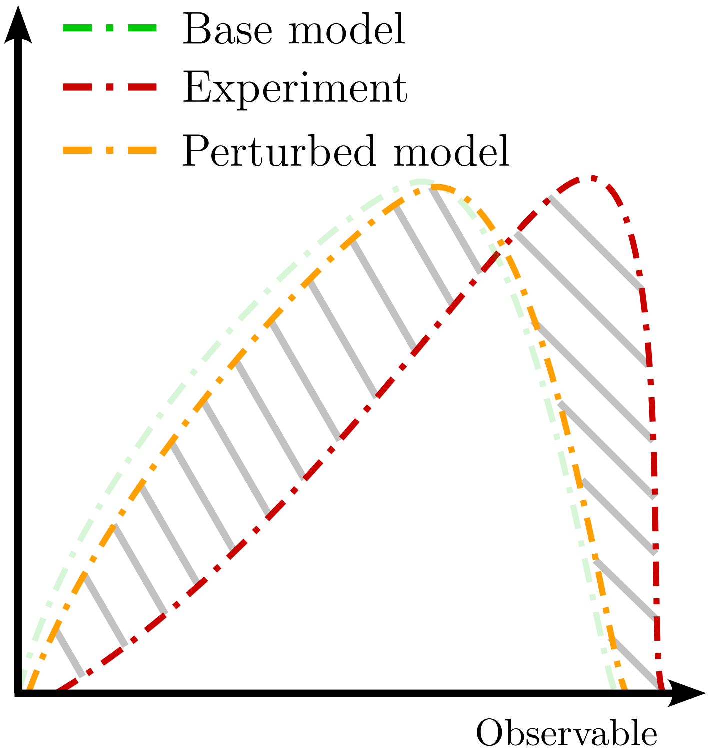
5) Repeat step





MLHAD efforts: big picture





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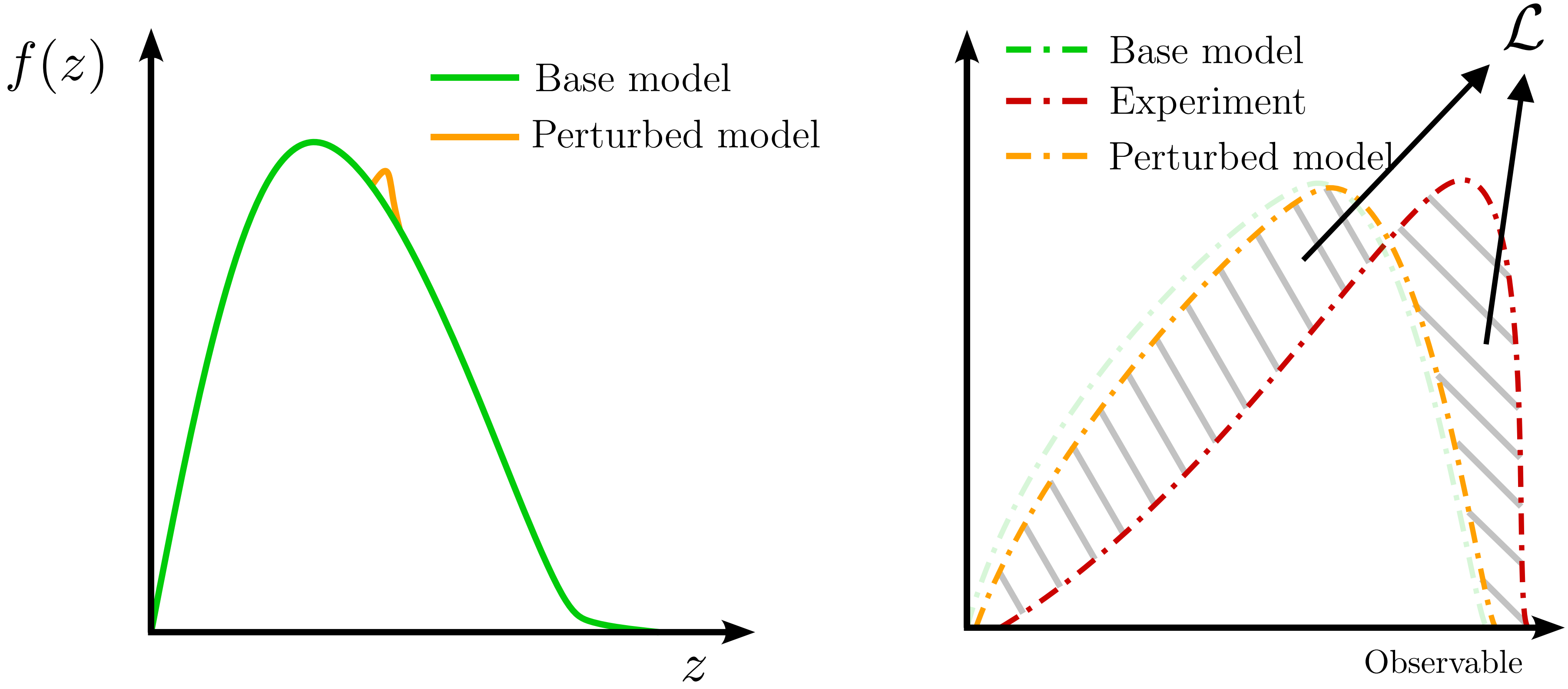

Applications

- Efficient means of exploring parameter space
- Inherently differentiable
- Very useful for tuning!
  - Embed the computation of weights into numerical autodifferentiation engine
  - Picking new parameters in the update step facilitated by well-developed optimizers (SGD, Adam, etc.)

Rejection sampling with Autodifferentiation (RSA)

WHAT is a differentiable simulator?

- All parameters are differential parameters
  - Differential with respect to what?

WHY a differentiable simulator?

- Parameter exploration (tuning)
- Uncertainty quantification
- Reproducibility

HOW to build a differentiable simulator?

- Many roads to a fully differentiable event generator. Varying levels of "intrusivity" (from a developers perspective).

The algorithm (q$\bar{\text{q}}$)

$(E, -\mathbf{p})$

$\bar{q}$

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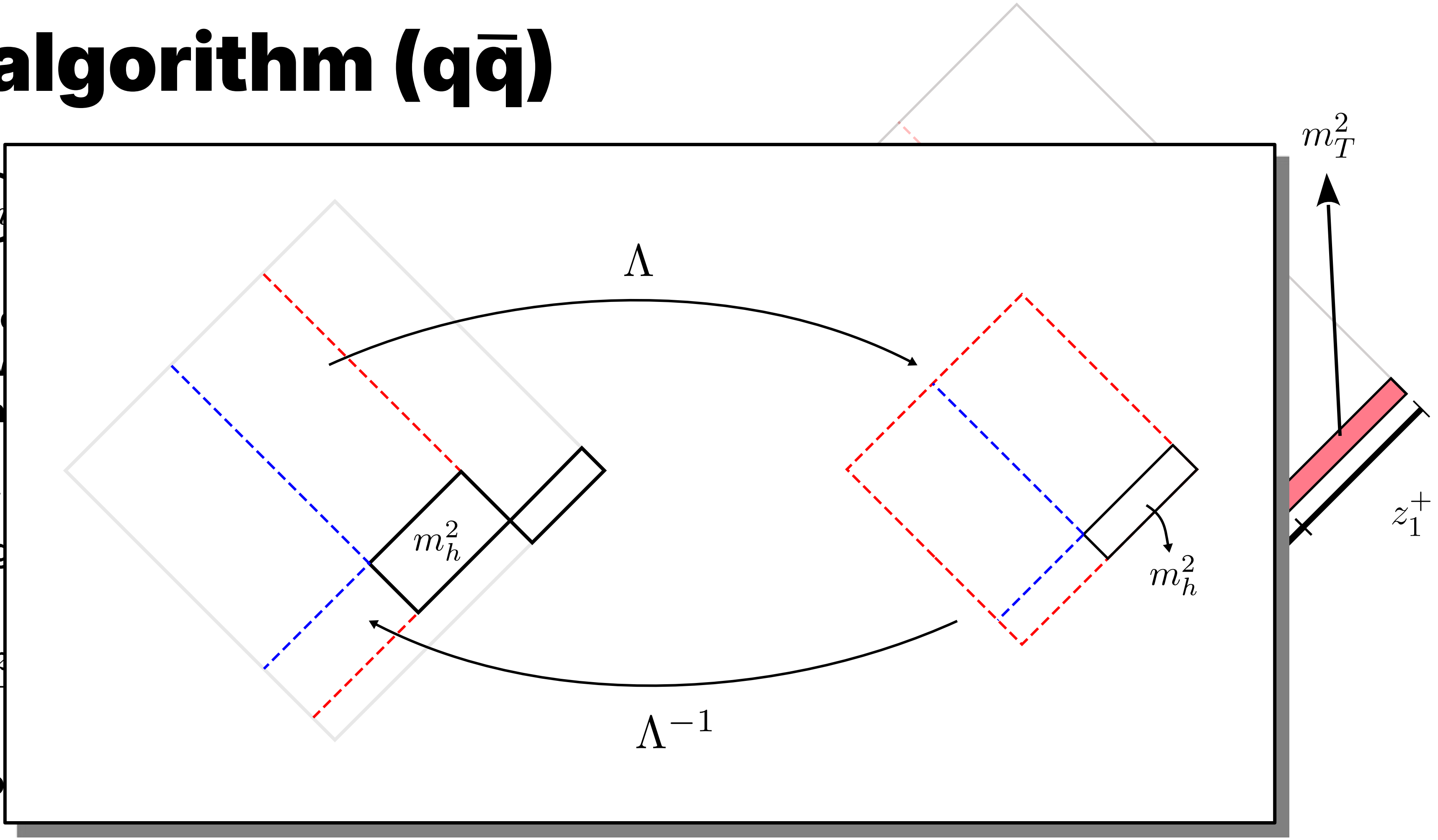


The "score" observable

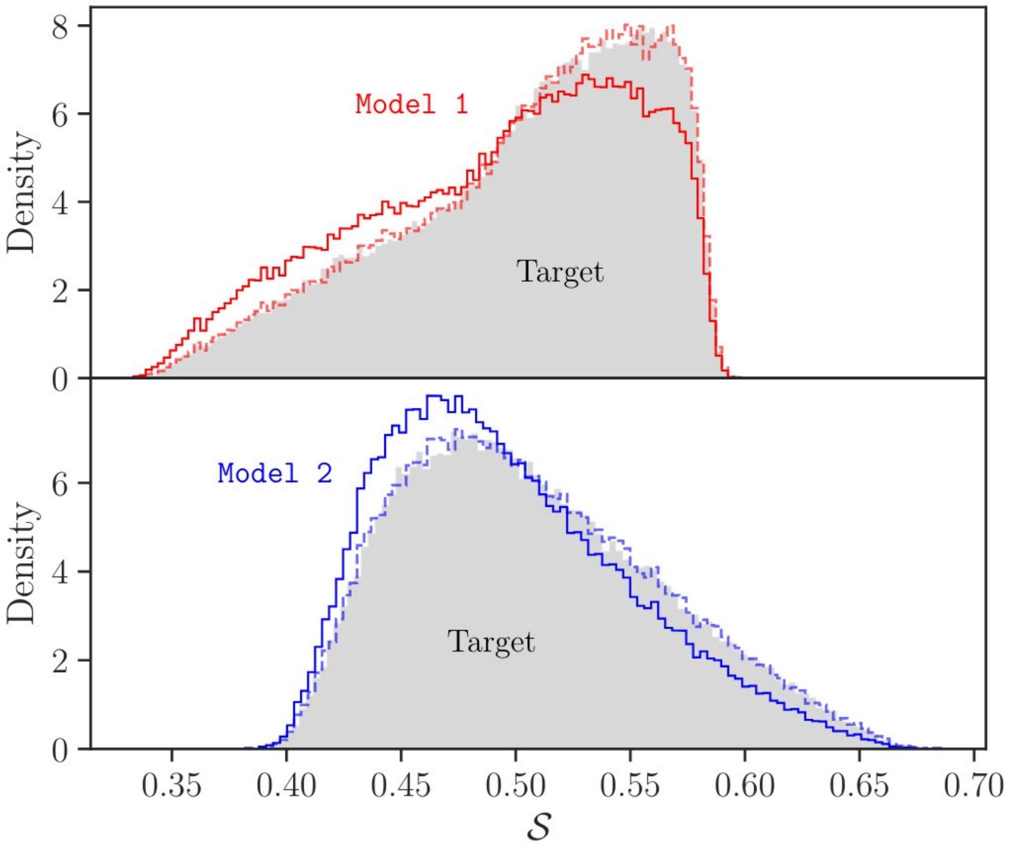
- Train a deepsets classifier to distinguish simulation from experiment
  - Takes full event information as input

$(E, p_x, p_y, p_z)_1$

$(E, p_x, p_y, p_z)_2$

…

Use trained classifier output (score) as an observable



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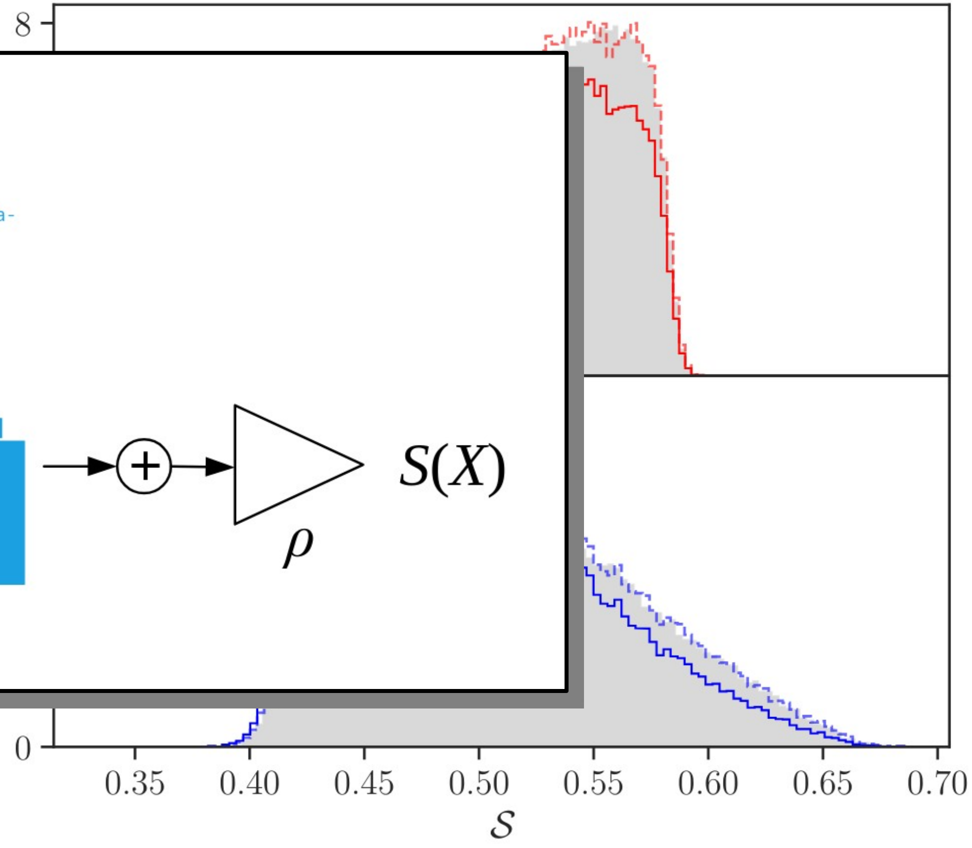
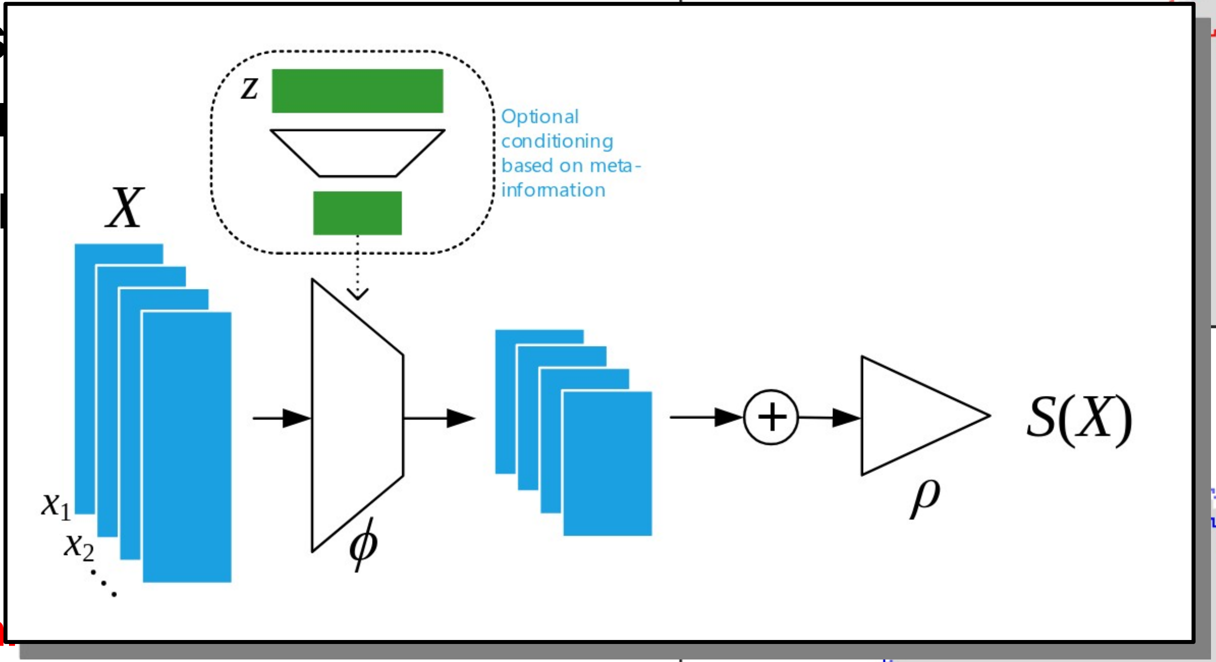
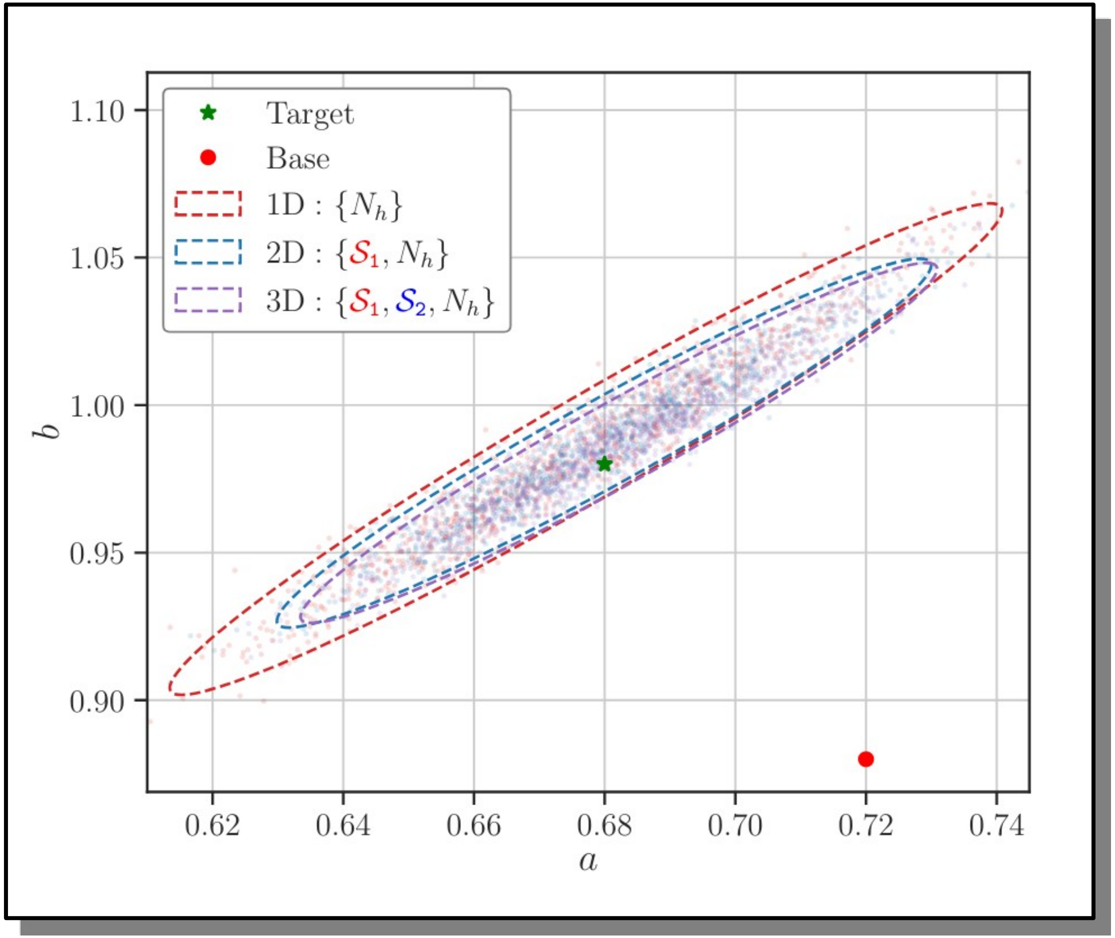




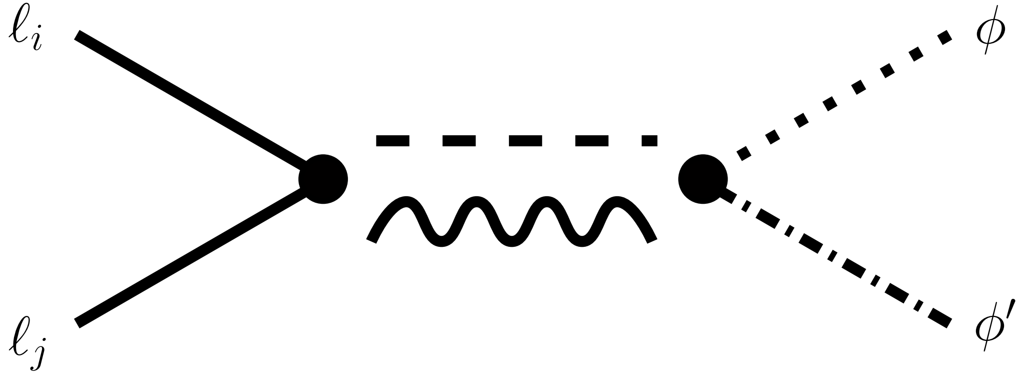
Use tra (score) as an observable

Classifier score with full event info improves tuning convergence



Explicit realization

Consider: $$\frac{C_{ij}}{f^2}\phi\partial_\mu\phi'(\bar{\ell}_i\gamma^\mu\ell_j)$$



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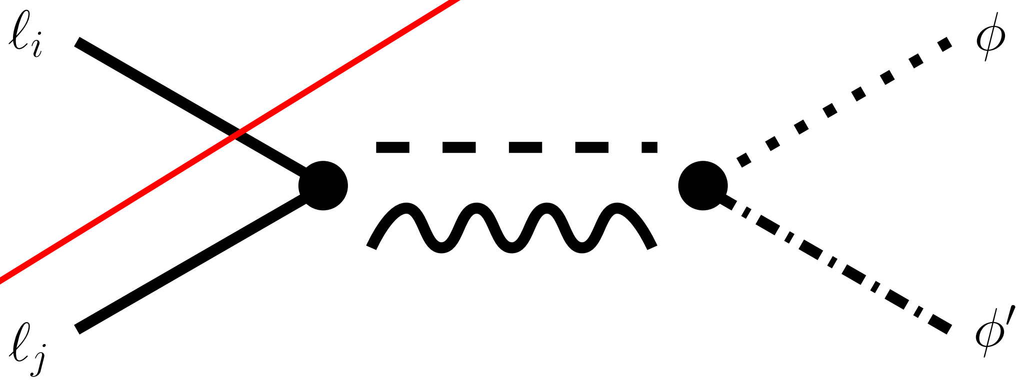

→ Non-abelian pseudo-NGB + portal

Explicit realization

- Non-abelian pseudo-NGB + U(1)$_D$

$$\mathcal{L}_D \supset \frac{f_{\rm UV}^2}{8}\left(D_\mu U D^\mu U^\dagger\right) + \frac{f_{\rm UV}^2}{8}\left(\chi^\dagger U + U^\dagger \chi\right) + \cdots$$

Explicit realization

- Non-abelian pseudo-NGB + $U(1)_D$

$$U \to e^{i\alpha} U$$

$$\mathcal{L}_D \supset \frac{f_{\rm UV}^2}{8}\left(D_\mu U D^\mu U^\dagger\right) + \frac{f_{\rm UV}^2}{8}\left(\chi^\dagger U + U^\dagger \chi\right) + \cdots$$