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Automatic Leptonic Tensor Generation for Beyond the Standard Model (BSM) Models

Diego Lopez Gutierrez

Final SIST Presentation

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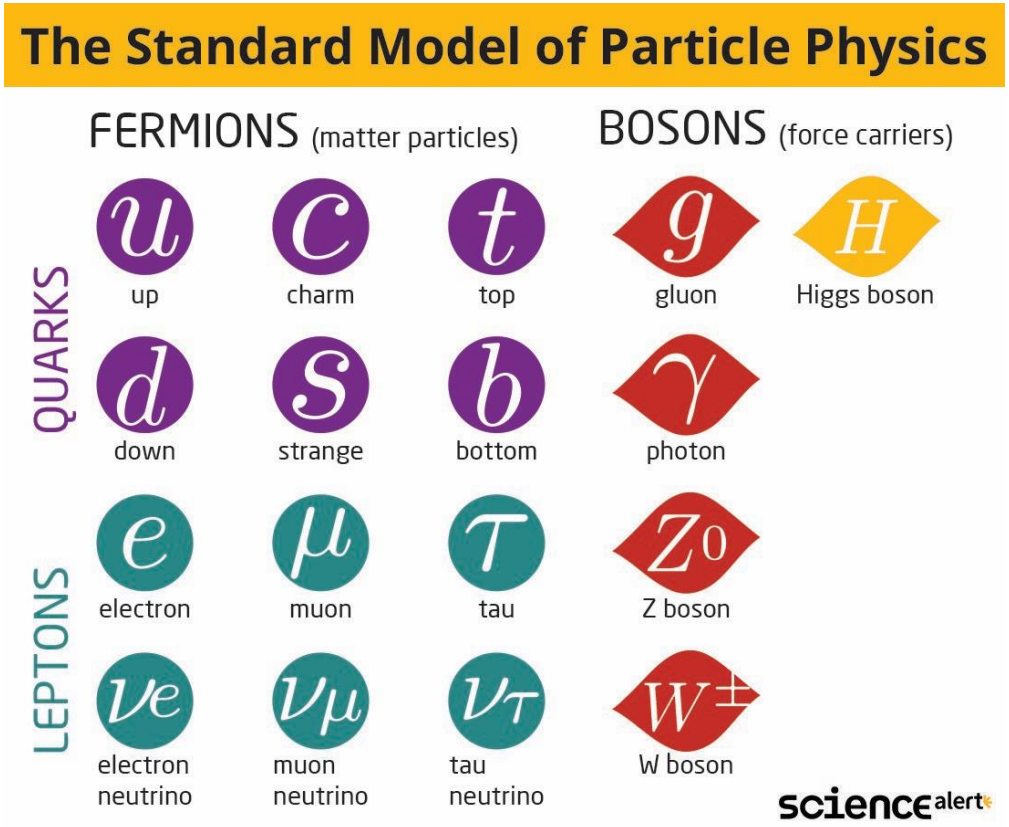
The Standard Model of Particle Physics

- Theory of the EM, weak and strong interactions.
- Describes most phenomena in nature to high accuracy.
- Is *not* complete.
  - Gravity.
  - Dark matter and dark energy.
  - Matter-antimatter asymmetry in the universe.
  - Neutrino oscillations.
  - And many more.



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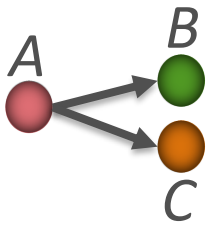
Background Information

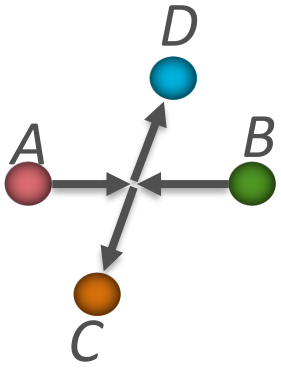
Experiment

- Decay width (Γ)



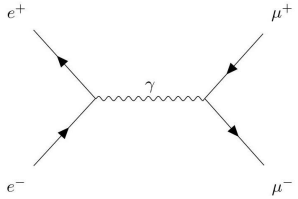
$A \rightarrow B + C$

- Cross section (σ)



$A + B \rightarrow C + D$

$e^+ + e^- \rightarrow \mu^+ + \mu^-$ ⇨



⇨ Amplitude M

⇨ $M_{tot} = \Sigma_i M_i$ ⇨ $\Gamma, \sigma \propto |M_{tot}|^2$

For neutrino interactions, we can always express:

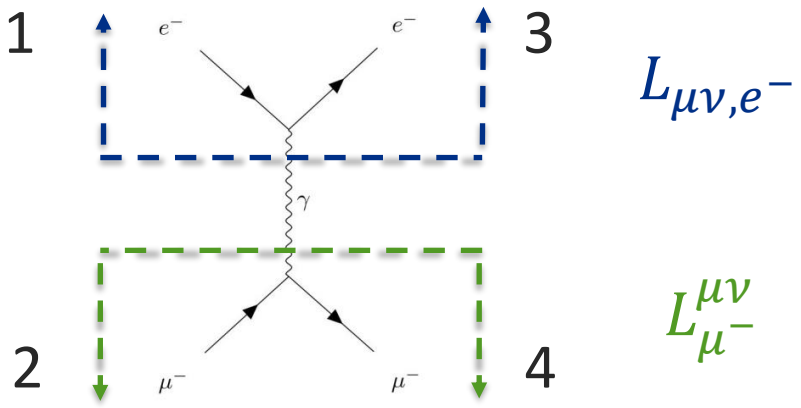
$$|M|^2 = L_{\mu\nu} H^{\mu\nu}$$

where $L_{\mu\nu}$ is the leptonic tensor and $H^{\mu\nu}$ is the hadronic tensor.

Background Information (continued.)

- To illustrate how $|M|^2$ can be split into $H^{\mu\nu}$ and $L_{\mu\nu}$, we perform the calculation for $e^- N \to e^- N$, with N being an atomic nucleus:

1. Consider simpler case $e^-\mu^- \to e^-\mu^-$ with Feynman diagram:



2. Diagram is composed by upper e^- part and lower μ^- part.
3. Let us label each particle as follows:

$$e^-_{in}: 1,\ \mu^-_{in}: 2,\ e^-_{out}: 3,\ \mu^-_{out}: 4$$

Background Information (continued.)

4. Squared amplitude $|M|^2$ of $e^-\mu^- \rightarrow e^-\mu^-$ is given by:

$$|M|^2 =$$

$$\frac{2e^2}{(p_1 - p_3)^2} \cdot \left[p_{3\mu}p_{1\nu} + p_{3\nu}p_{1\mu} + (m_e^2 - p_1 \cdot p_3)g_{\mu\nu} - i\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_3^\beta\right]$$

$$\times \frac{2e^2}{(p_2 - p_4)^2} \cdot \left[p_4^\mu p_2^\nu + p_4^\nu p_2^\mu + \left(m_\mu^2 - p_2 \cdot p_4\right)g^{\mu\nu} + i\epsilon^{\mu\nu\alpha\beta}p_{2\alpha}p_{4\beta}\right]$$

Background Information (continued.)

4. Squared amplitude $|M|^2$ of $e^-\mu^- \rightarrow e^-\mu^-$ is given by:

$$|M|^2 =$$

$$\frac{2e^2}{(p_1 - p_3)^2} \cdot \left[p_{3\mu}p_{1\nu} + p_{3\nu}p_{1\mu} + (m_e^2 - p_1 \cdot p_3)g_{\mu\nu} - i\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_3^\beta\right]$$

$$\boldsymbol{L_{\mu\nu,e^-}}$$

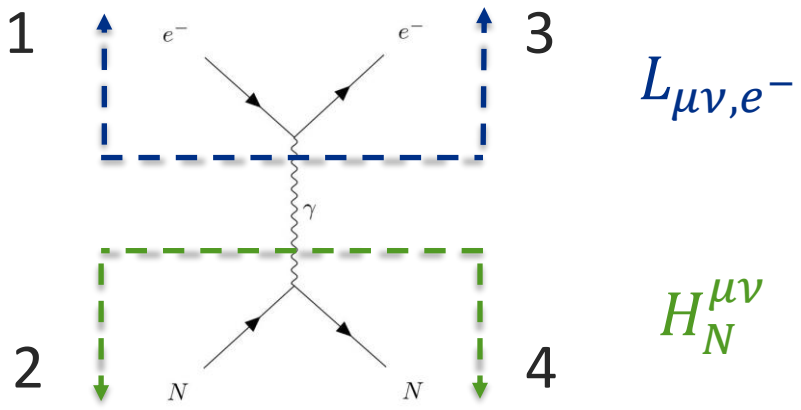
$$\times \frac{2e^2}{(p_2 - p_4)^2} \cdot \left[p_4^\mu p_2^\nu + p_4^\nu p_2^\mu + \left(m_\mu^2 - p_2 \cdot p_4\right)g^{\mu\nu} + i\epsilon^{\mu\nu\alpha\beta}p_{2\alpha}p_{4\beta}\right]$$

$$\boldsymbol{L^{\mu\nu}_{\mu^-}}$$

$$|M|^2 = \boldsymbol{L_{\mu\nu,e^-}L^{\mu\nu}_{\mu^-}}$$

Background Information (continued.)

6. Now let us consider $e^- N \rightarrow e^- N$ with Feynman diagram:



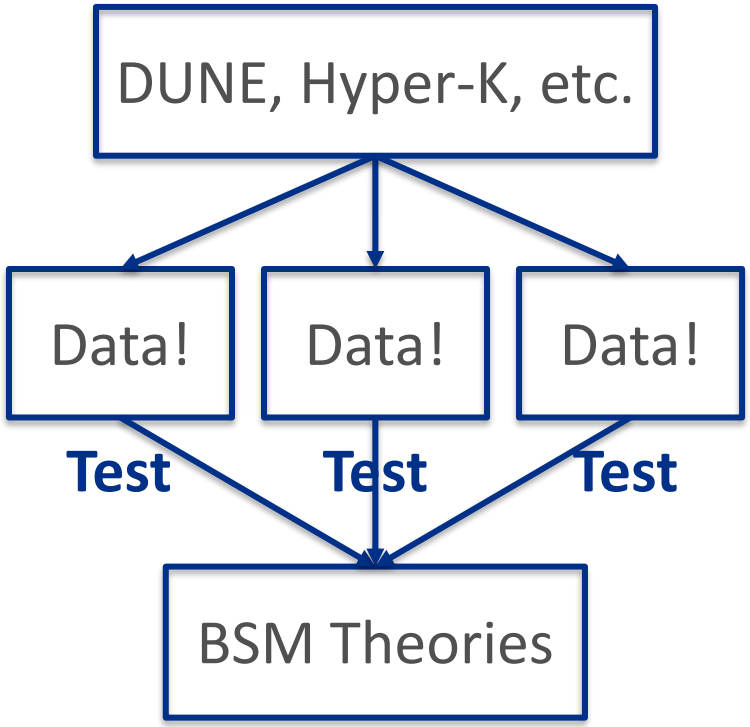
7. Diagram is composed by upper e^- (leptonic) part and lower N (hadronic) part.
8. Leptonic part is the same as for $e^-\mu^- \rightarrow e^-\mu^-$. Hadronic part can be calculated by event generators. Then:

$$|M|^2 = L_{\mu\nu,e^-} H_N^{\mu\nu}$$

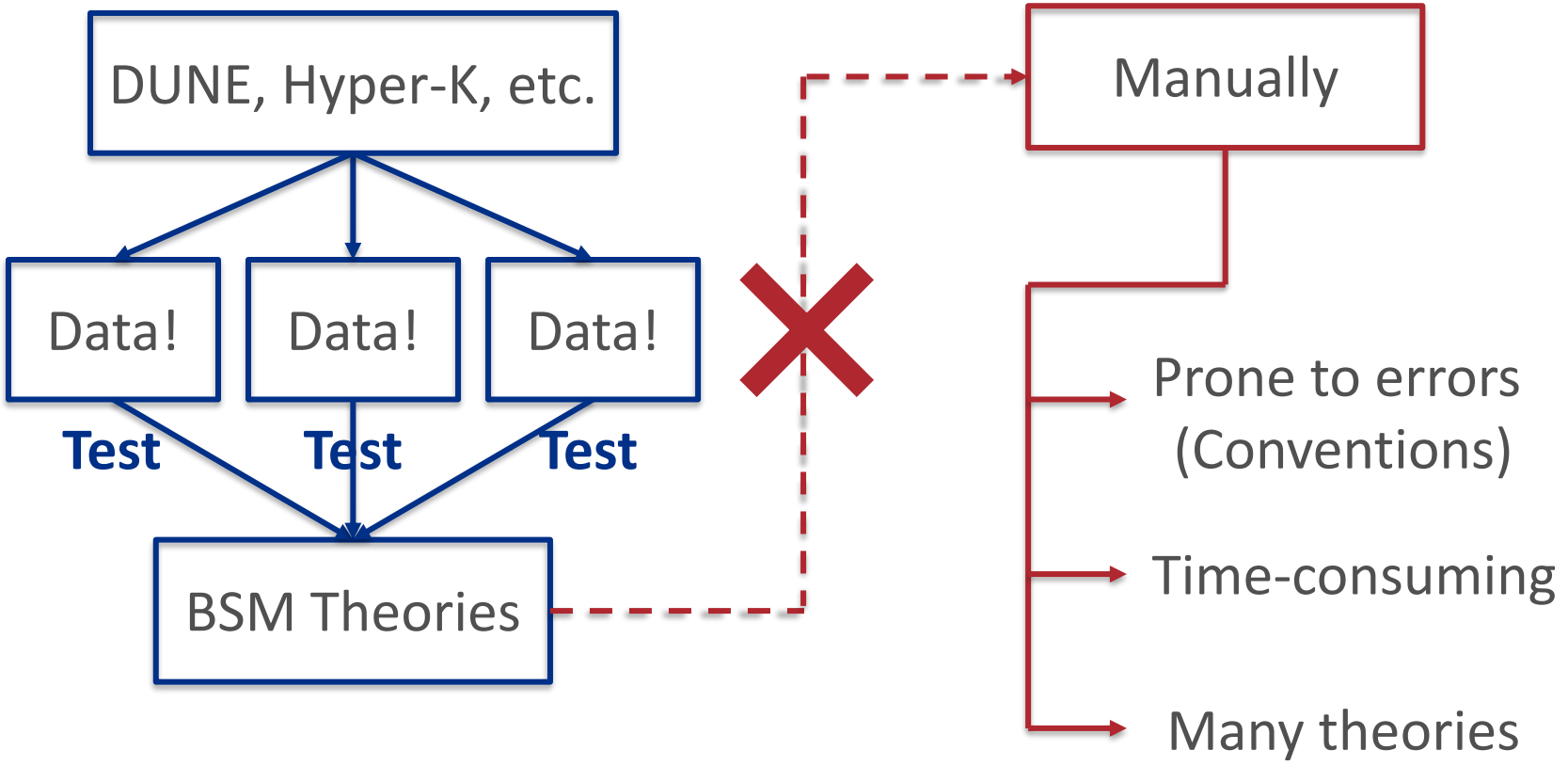
Beyond the Standard Model (BSM) Theories

- Attempts at explaining phenomena beyond the SM.
  - Examples: Neutrino oscillations, neutrino masses, dark matter, etc.
  - Examples of BSM theories: Supersymmetry, heavy neutrino models, sterile neutrino models, etc.
- Processes too complex to be evaluated by hand.
- Event generators → Simulate particle physics events.
  - Predictions compared to experiment.
  - Discrepancies could show hints of new physics.
  - Was the BSM theory accurate?

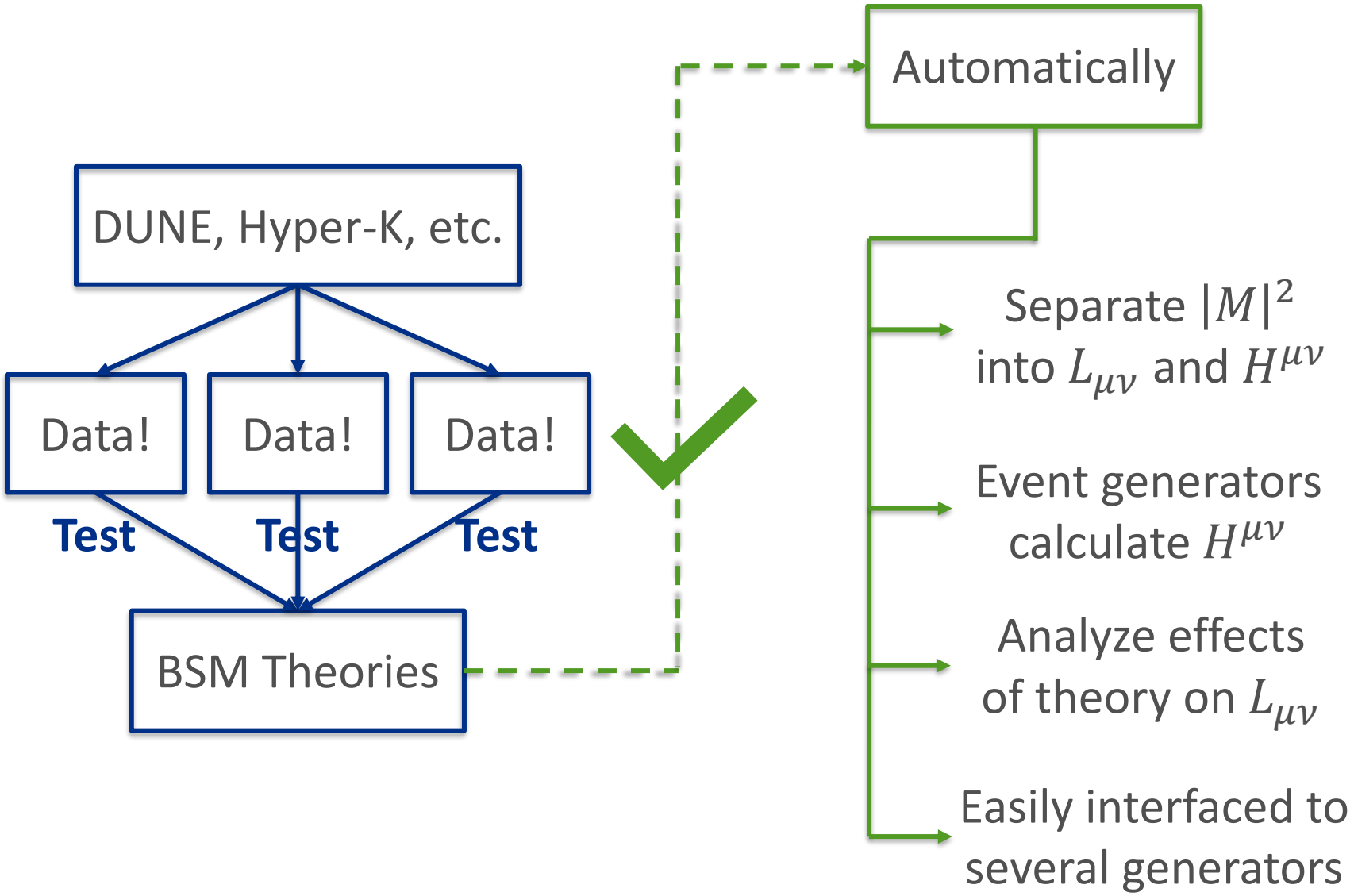
The Problem and a Solution



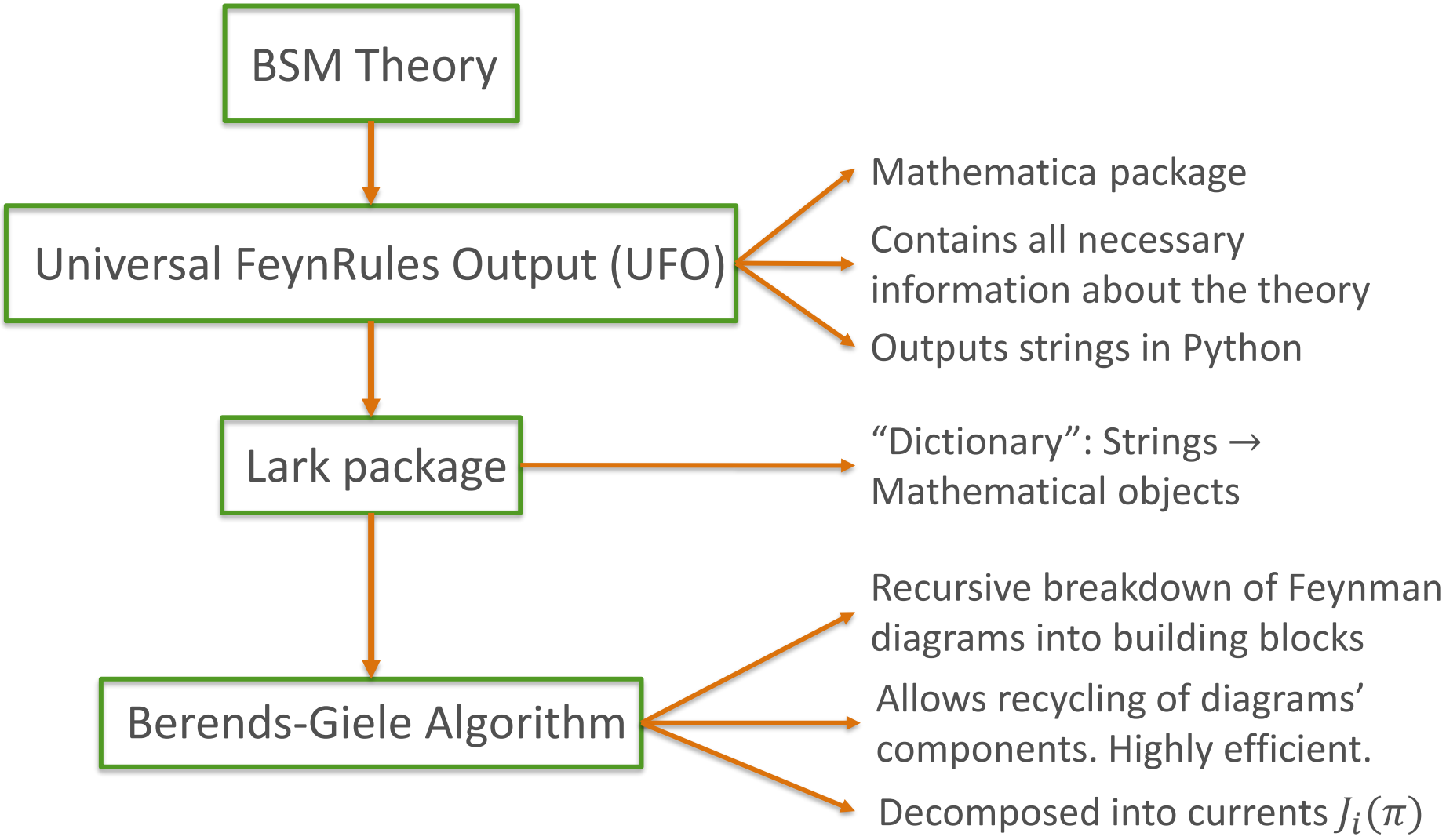
The Problem


DUNE, Hyper-K, etc.
Data!
Data!
Data!
Test
Test
Test
BSM Theories
Manually
Prone to errors
(Conventions)
Time-consuming
Many theories

A Solution



Methods



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Methods (continued.)

- Berends-Giele current:

$$J_i(\pi) = P_i(\pi) \sum_{V_i^{j,k}} \sum_{P_2(\pi)} S(\pi_1, \pi_2) V_i^{j,k}(\pi_1, \pi_2) J_j(\pi_1) J_k(\pi_2)$$

Propagator term

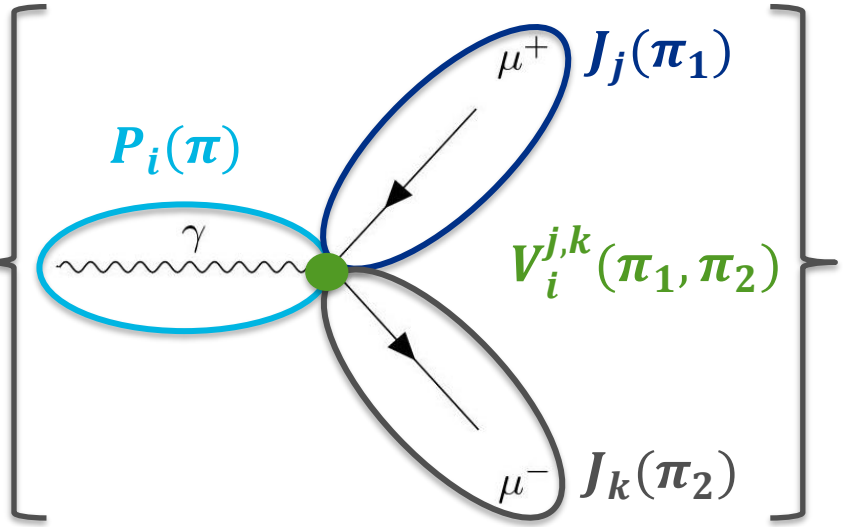
Sum over all possible vertices and permutations

Symmetry factor

Interaction vertex

Adjacent currents

$$\sum_{V_i^{j,k}} \sum_{P_2(\pi)} \boldsymbol{S(\pi_1, \pi_2)} \times$$



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Methods (continued.)

- Berends-Giele amplitude:

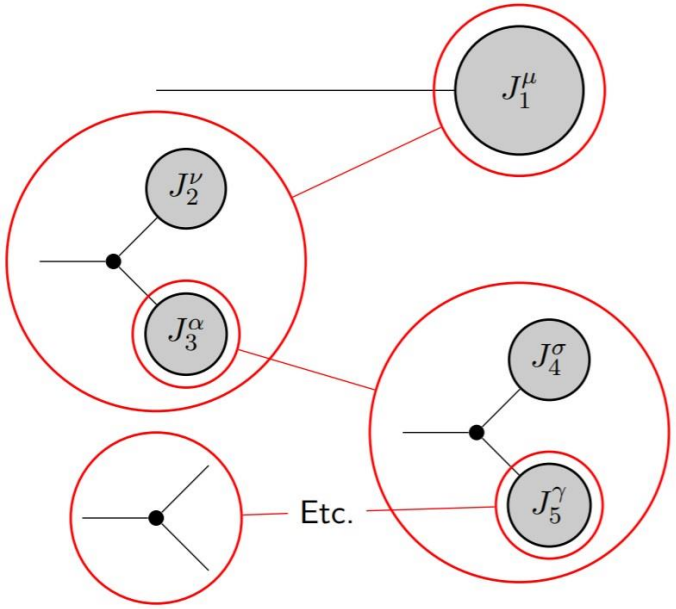
$$M(\pi) = J_n(n) \cdot \frac{1}{P_{\bar{n}}(\pi \backslash n)} \cdot J_{\bar{n}}(\pi \backslash n)$$

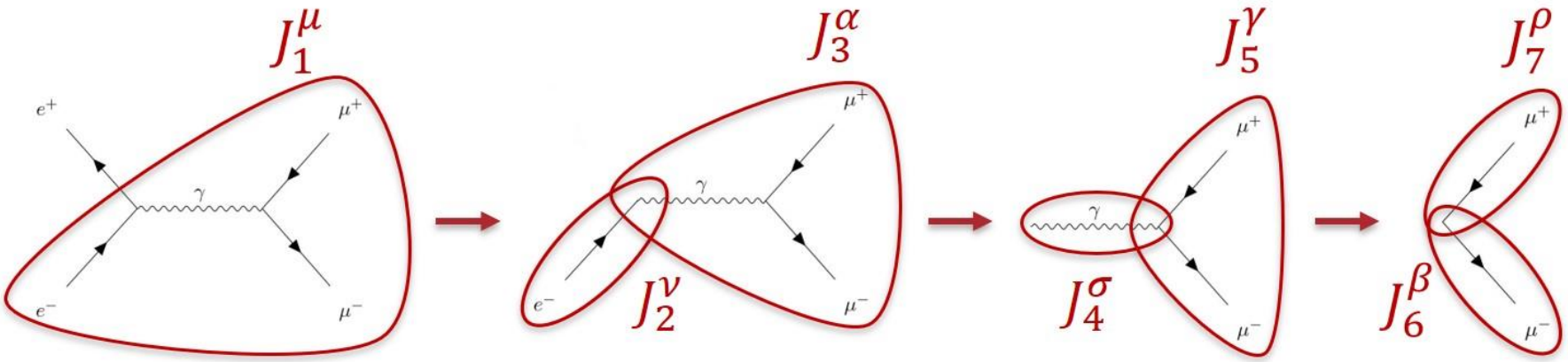
Current for n

Reversed particle properties

Propagator term

Current for $\bar{n}$





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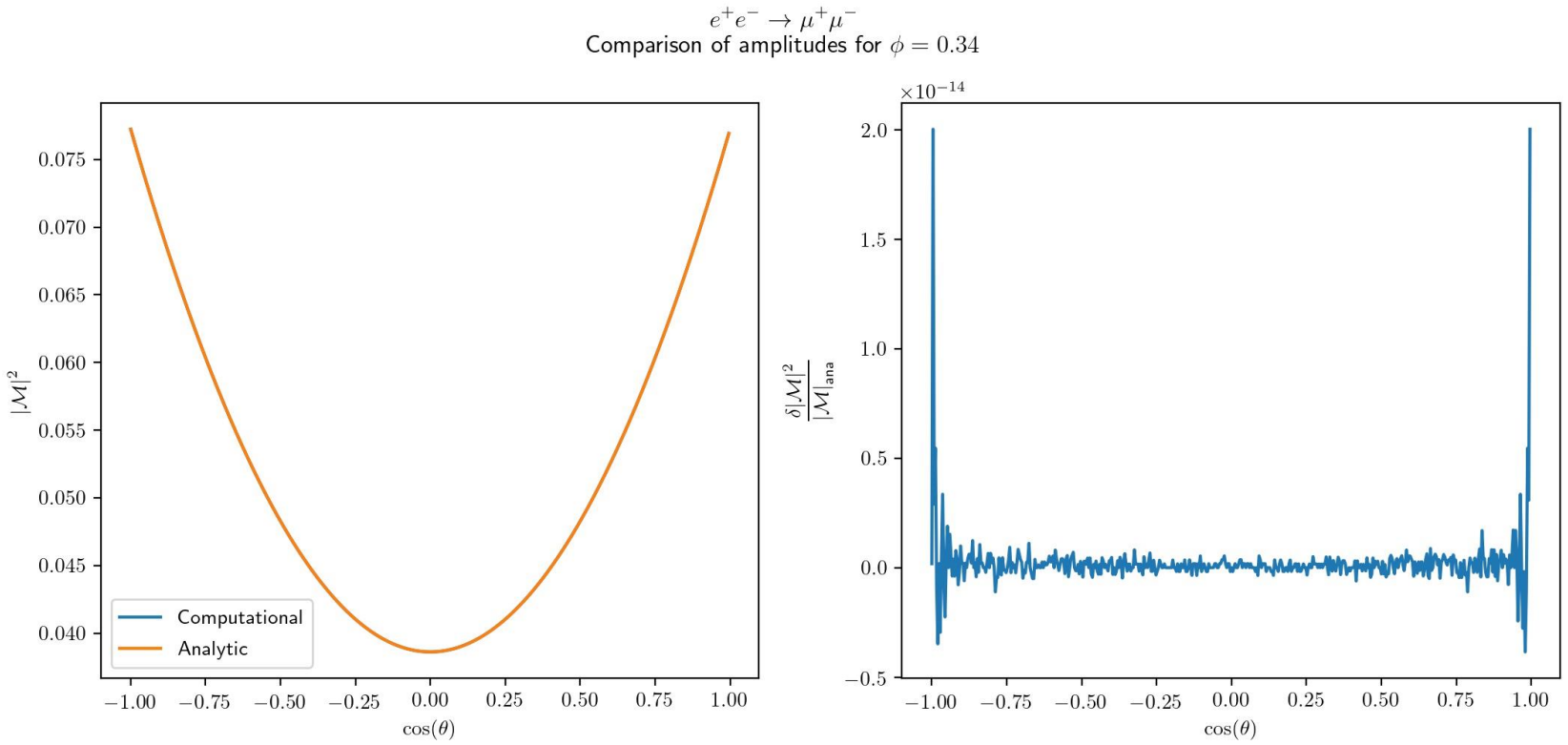
Results and Discussion

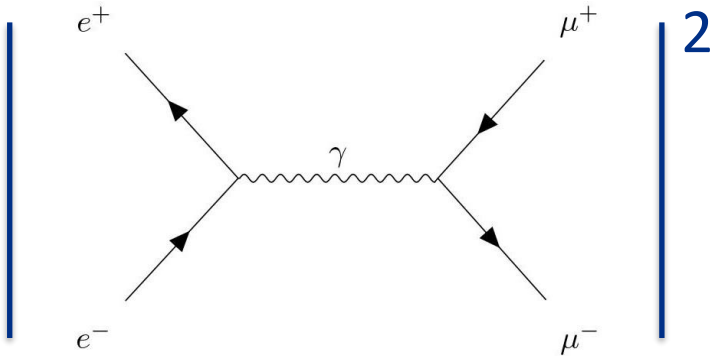
- Validation results of squared amplitude $|M|^2$ of three SM processes:
  - $e^+e^- \to \mu^+\mu^-$ (1 Feynman diagram, 's-channel')
  - $e^-\mu^- \to e^-\mu^-$ (1 Feynman diagram, 't-channel')
  - $e^+e^- \to e^+e^-$ (2 Feynman diagrams, 's- and t-channel')

  plotted versus $\cos(\theta)$ and for randomly generated azimuthal angles ϕ.
- Our results show percentage deviations of order 10^{-14} with respect to analytic calculations of our SM processes.
- Work can be extended to more complex processes and to BSM theories.

$e^+e^- \to \mu^+\mu^-$



$$|M|^2 =$$



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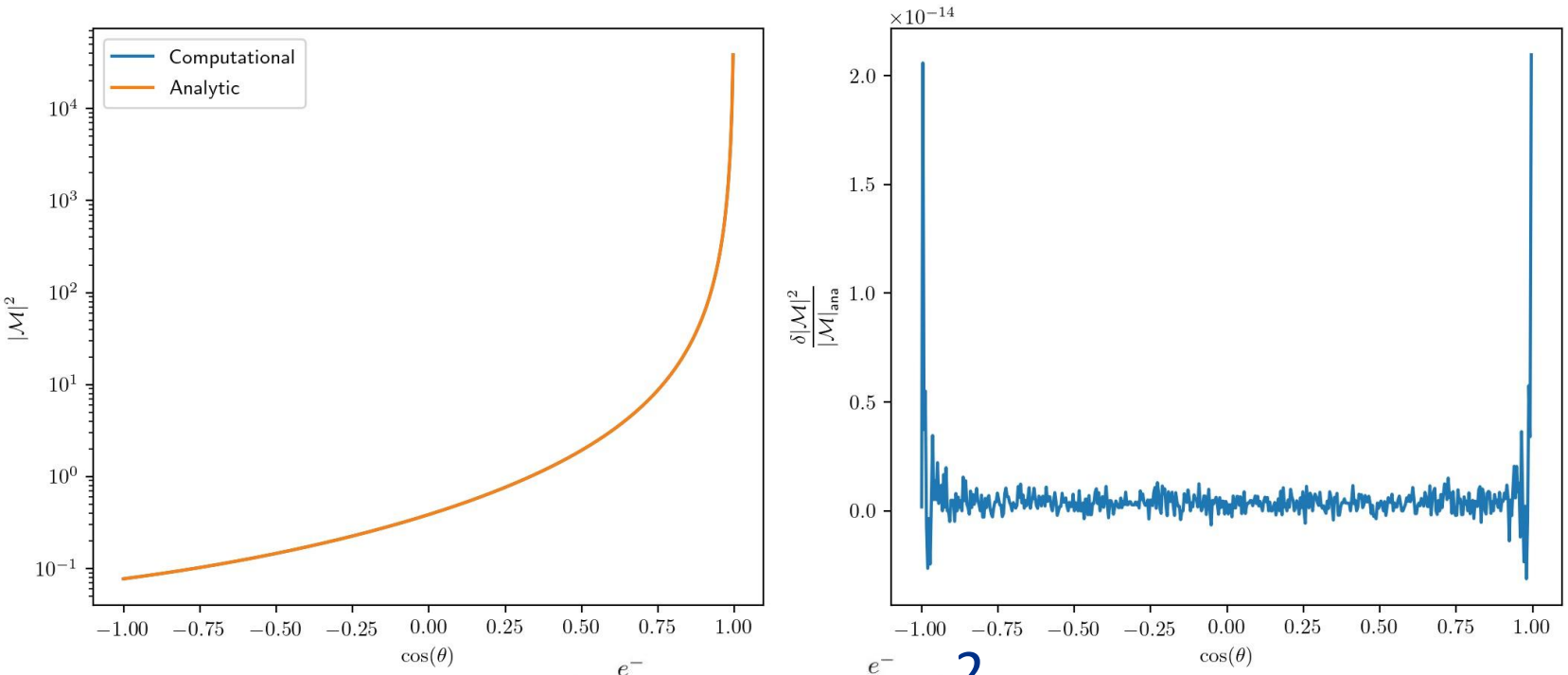
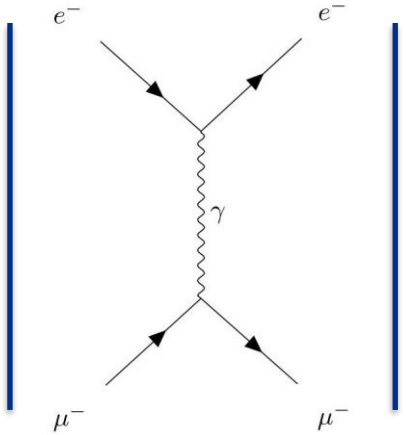
$e^-\mu^- \to e^-\mu^-$



$$|M|^2 =$$



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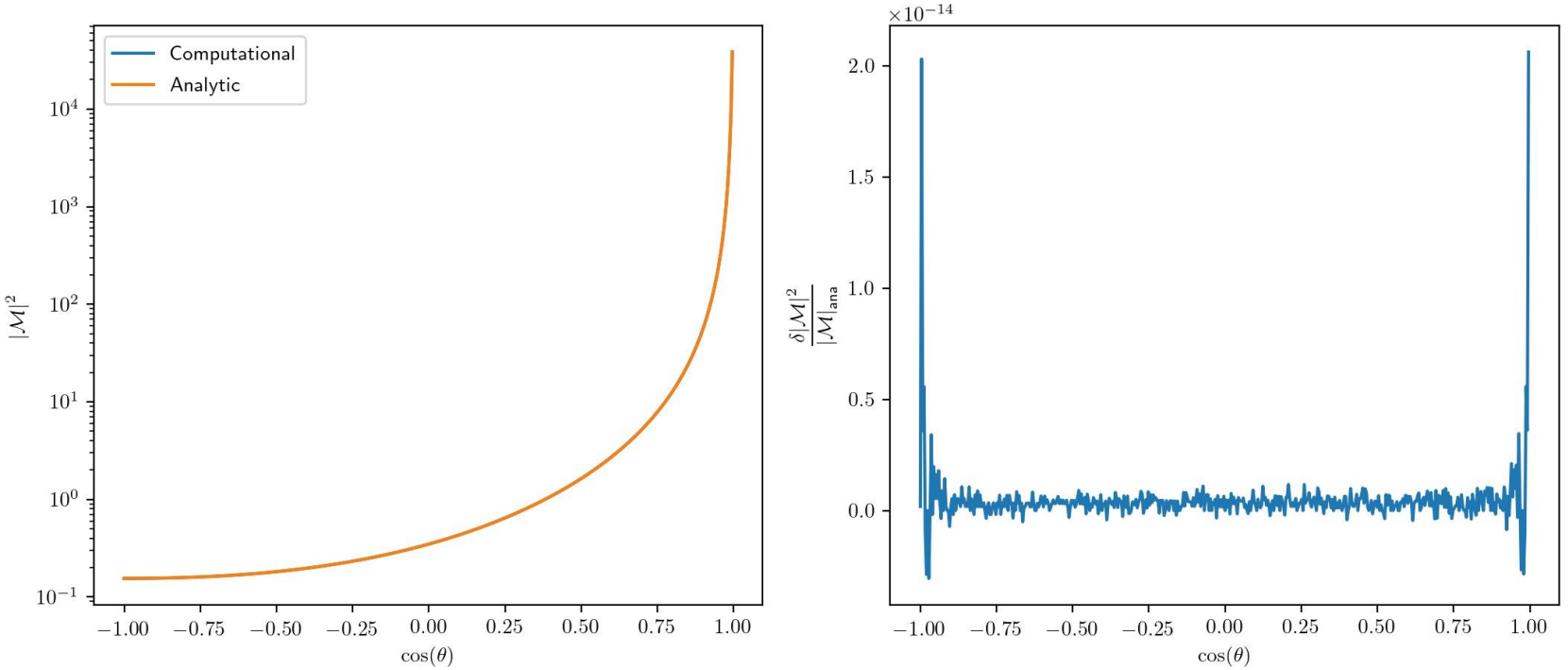
$e^+e^- \to e^+e^-$



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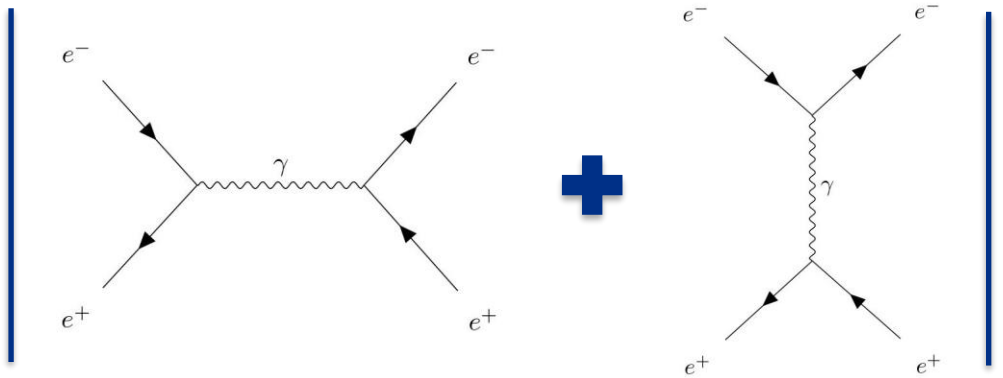

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Conclusion and Future Steps

- Validation results are promising (10^{-14}), proving our method works for Standard Model processes.
- Next steps:
  - Convert amplitude $|M|^2$ results into leptonic tensors $L_{\mu\nu}$ to be interfaced with event generators.
  - Perform tests in more complex events as well as with some Beyond the Standard Model theories using the leptonic tensor.

Thank you!

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