

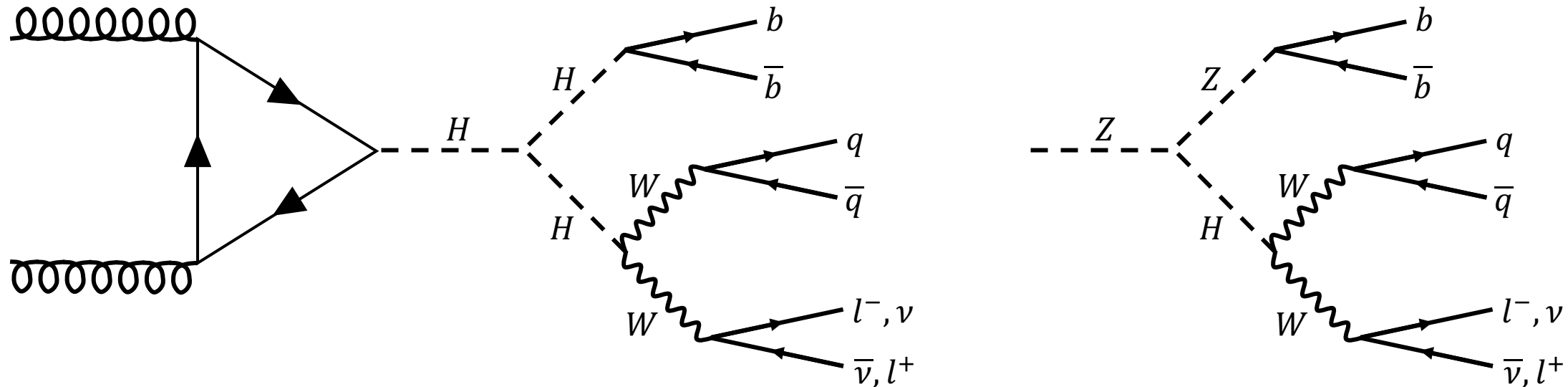
Employing Matrix Elements in the Search for Higgs Self- coupling

Joint Seminar of Particle Physics Groups

15.05.2024

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Higgs Self-coupling



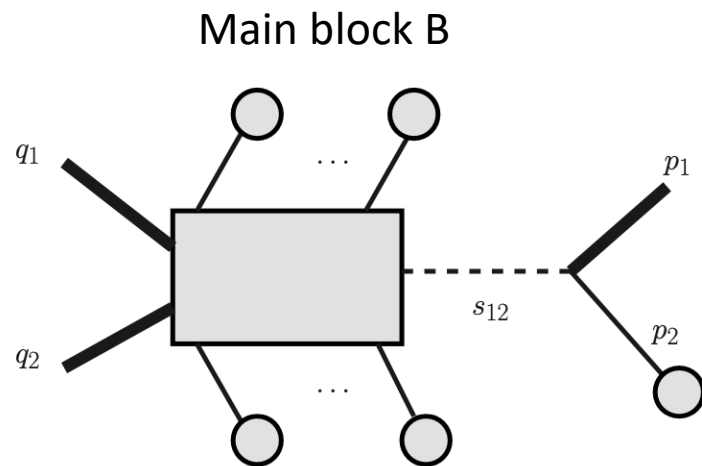
- Predicted by Standard Model (not yet observed)
- Small cross section
- More likely background process ($Z \rightarrow HZ$)

- Calculate **weight** $W(x|\alpha)$ to observe an event x given a hypothesis α

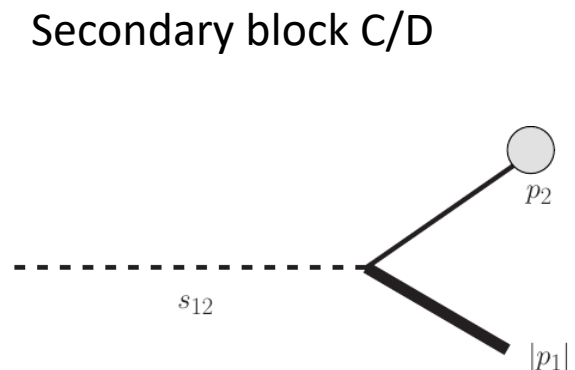
$$W(x|\alpha) = \int dq_1 dq_2 f(q_1) f(q_2) |\langle \psi_F | H_\alpha | \psi_i \rangle|^2 d\phi(F)$$

- q_n : Initial state parton momentum fractions
 - $f(q_n)$: Parton density function
 - ψ_F : Final state
 - H_α : Hamilton operator for hypothesis α
 - ψ_i : Initial state
 - $d\phi(F)$: Phase space
- **Weight** represents a measure of likelihood

- C++ software package for calculating weights
- Four-momenta of final state particles as inputs
- Removes degrees of freedom via energy-momentum conservation
- Uses „blocks“ to construct desired decay



[<http://arxiv.org/abs/1007.3300v2>]

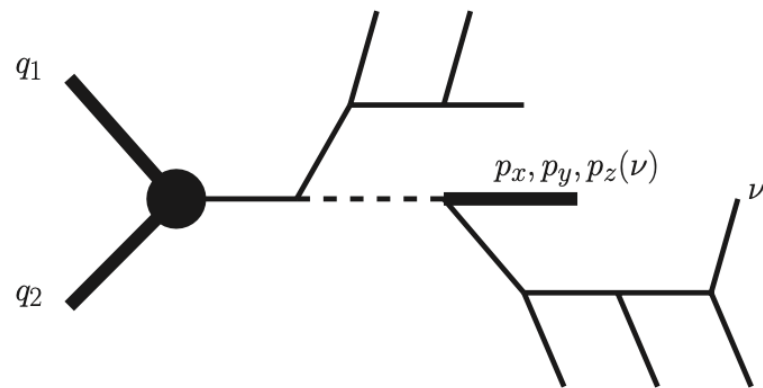


Topology: $(q_1, q_2) \rightarrow s_{12} (\rightarrow p_1 + p_2)$ Removes: q_1, q_2, p_1 For: s_{12}

Topology: $s_{12} \rightarrow p_1 + p_2$ Removes: $|p_1|$ For: s_{12}

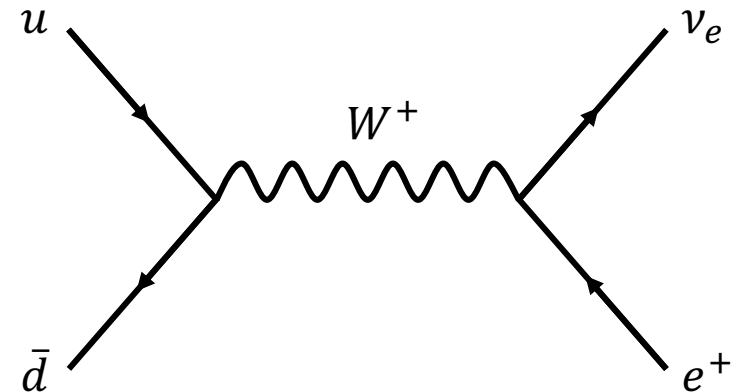
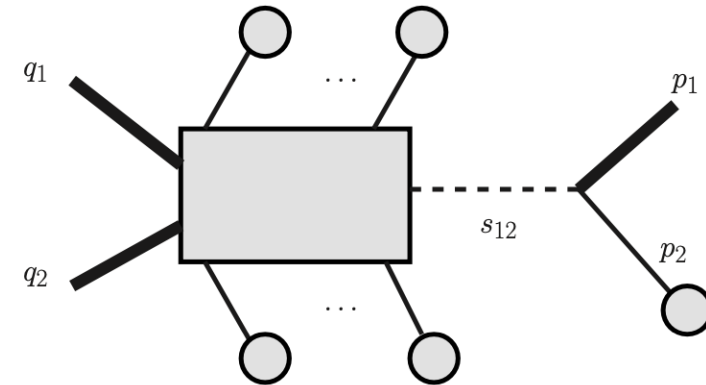
Blocks

Diagram of decay chain

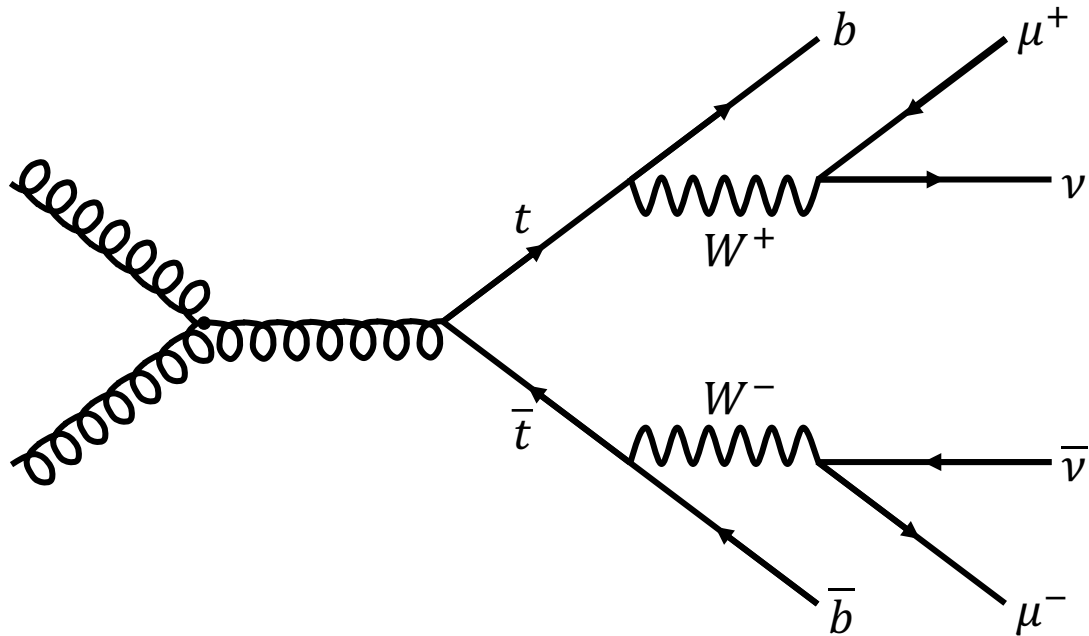


- Dashed lines: Decaying particles
- Lines with blob: Input particles for MoMEMta
- Lines without blob: Reconstructed particles by MoMEMta

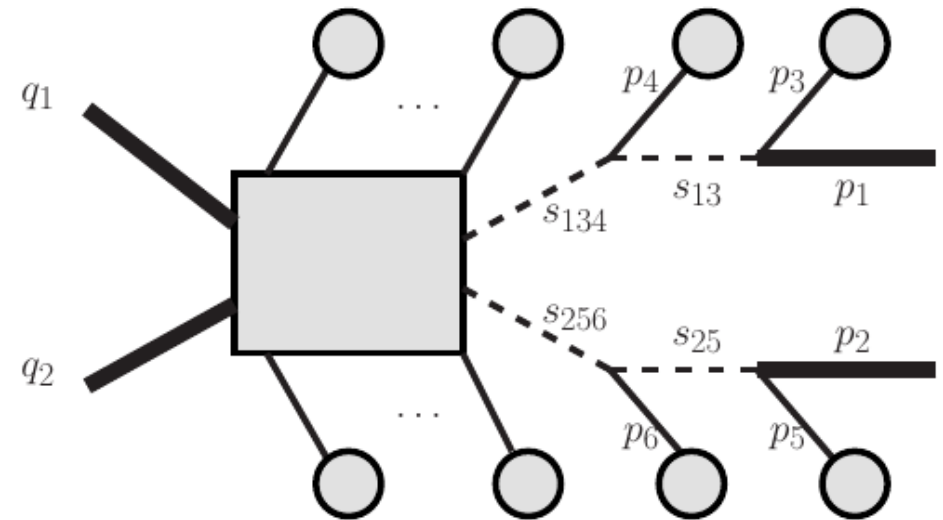
Reduced diagram



$t\bar{t}$ fully leptonic Decay



$t\bar{t}$ fully leptonic Decay

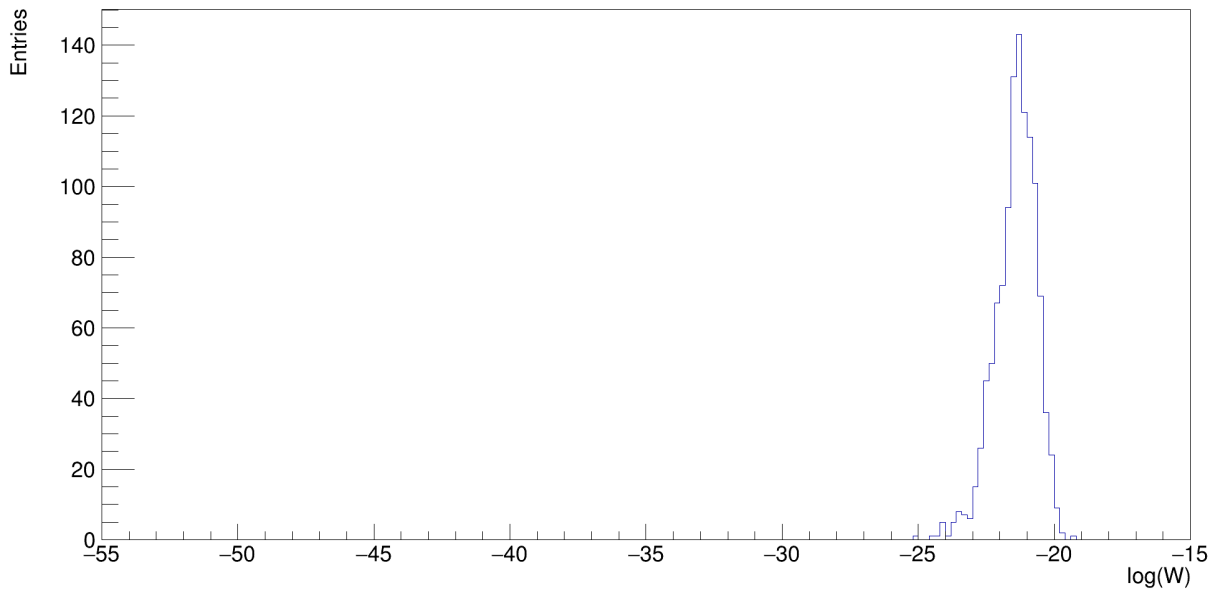


Main block D

$t\bar{t}$ fully leptonic Decay

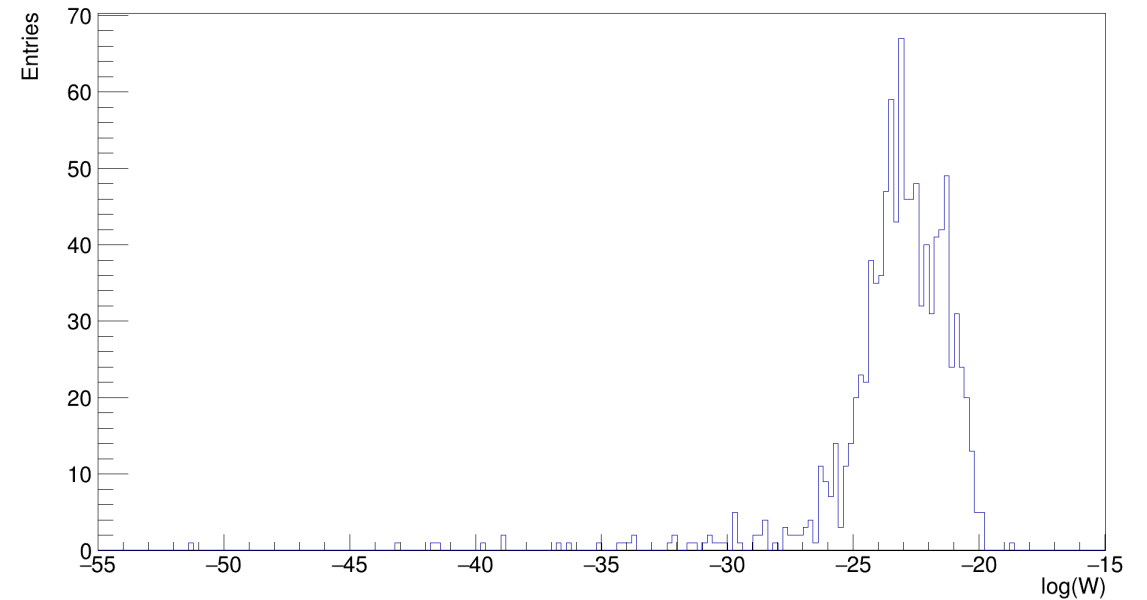
Weights = $t\bar{t}$ (inputs = x) under $t\bar{t} \rightarrow \mu^- \mu^+$ hypothesis

ttbar(ttbar) Weights



$t\bar{t}$ fully leptonic final states as inputs (“correct” inputs)

ttbar(HH) Weights

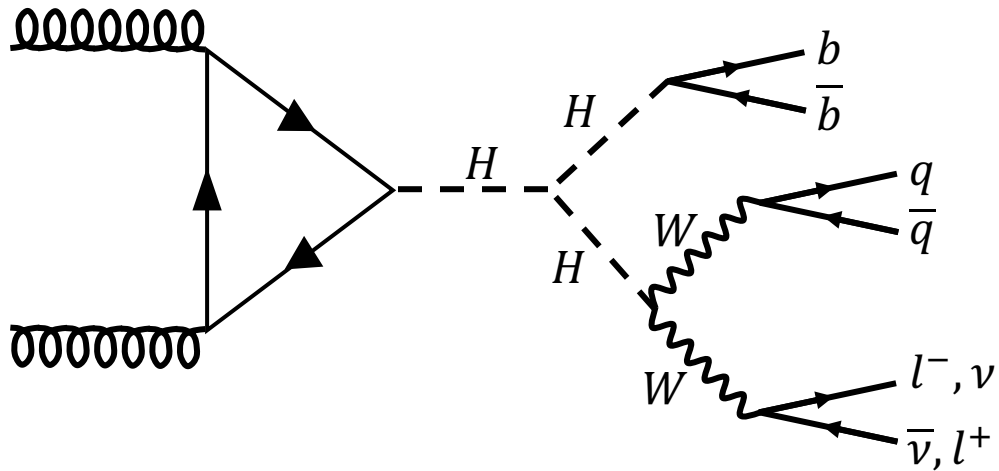


HH final states as inputs (“wrong” inputs)

How to construct Higgs Self-coupling?

Requirements for block:

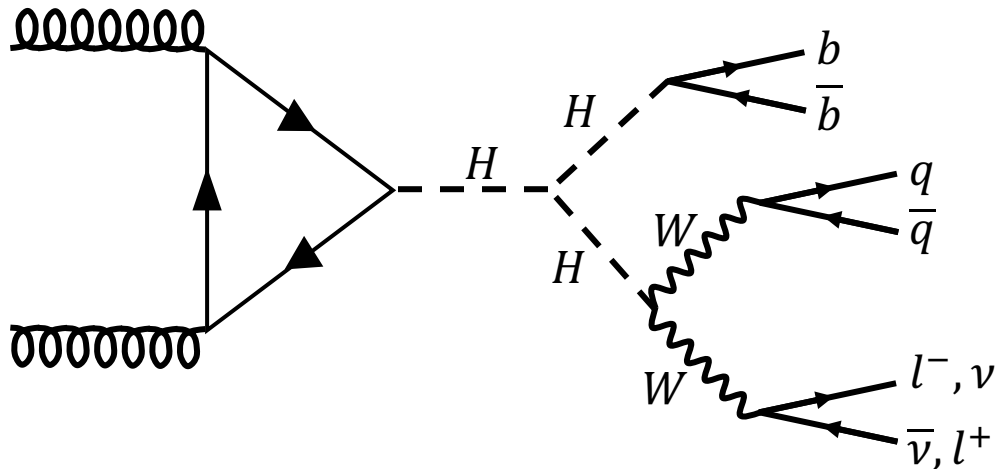
- 6 final state particles
- 5 decaying particles (H, H, H, W^+, W^-)



How to construct Higgs Self-coupling?

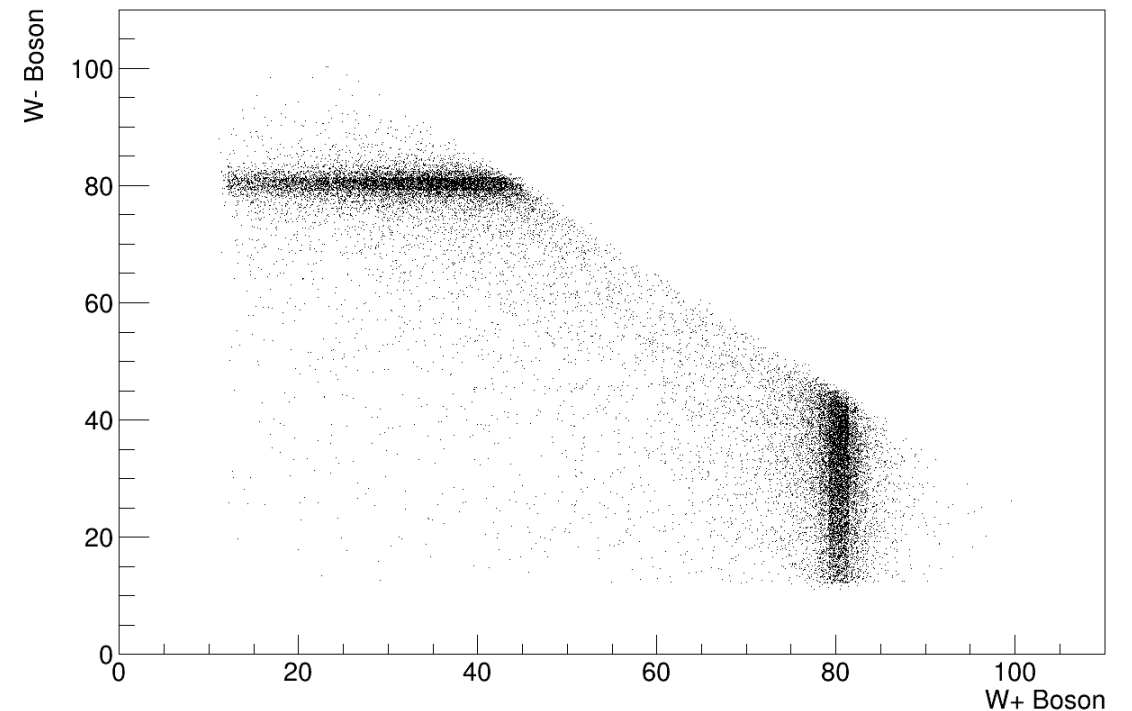
Requirements for block:

- 6 final state particles
- Only 3 decaying particles (H, H, W)



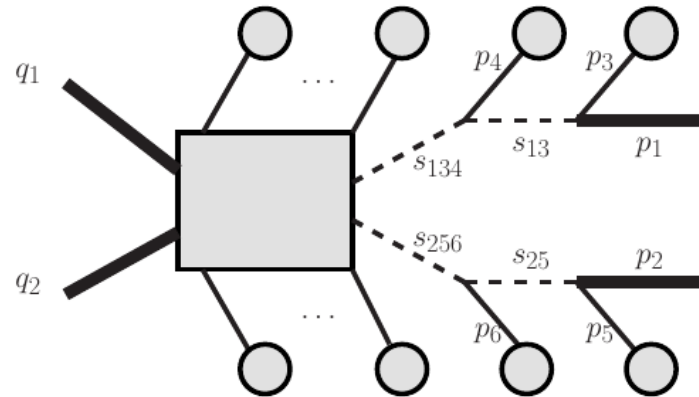
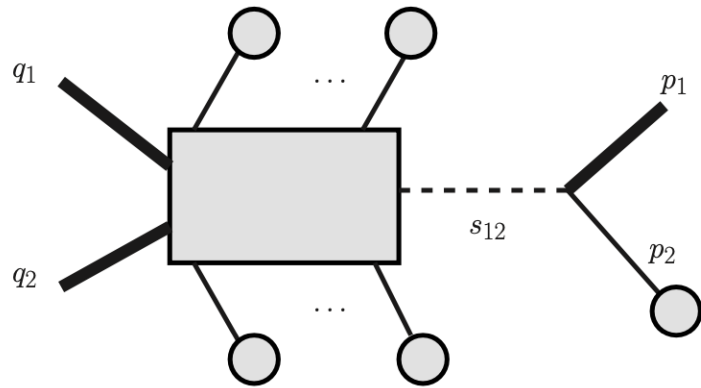
MoMEMta can't handle off shell particles

W Boson masses in GeV



How to construct Higgs Self-coupling?

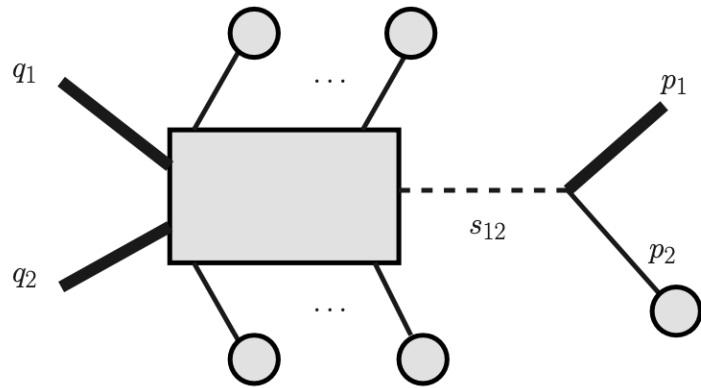
- None of the available blocks fit the decay
- Creation of a custom block possible but jacobian needed ...



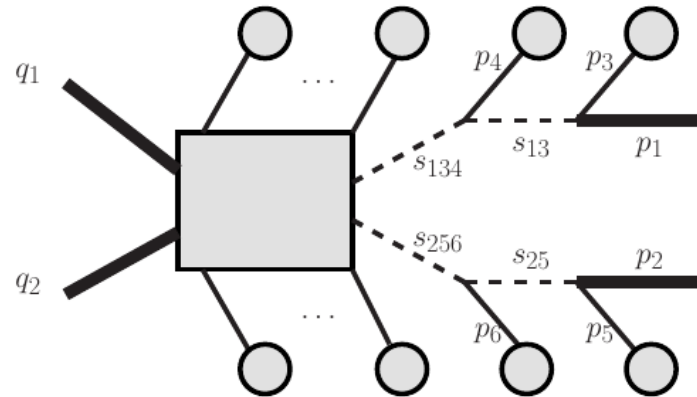
$$J = \frac{E_1}{s} |p_{2z} E_1 - E_2 p_{1z}|^{-1}$$

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$$J = \frac{E_1}{s} |p_{2z} E_1 - E_2 p_{1z}|^{-1}$$

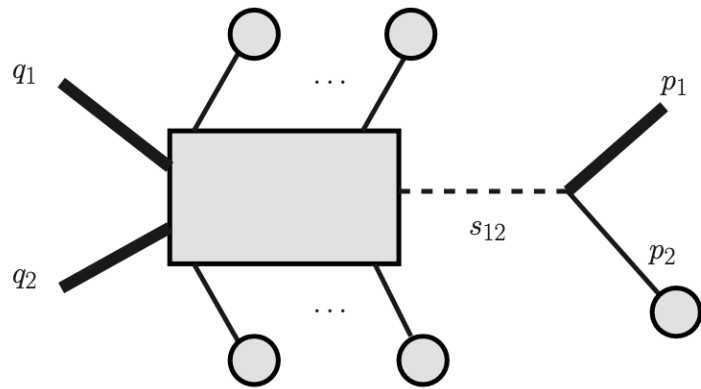


$$J = \frac{E_1 E_2}{8s} \left| E_3 \left\{ E_5 [p_{34z} (p_{1y} p_{2z} p_{56x} - p_{1x} p_{2z} p_{56y}) - p_{1y} p_{2x} p_{56z} + p_{1x} p_{2y} p_{56z}] + p_{1z} (-p_{2z} p_{34y} p_{56x} + p_{2z} p_{34x} p_{56y} - p_{2y} p_{34x} p_{56z} + p_{2x} p_{34y} p_{56z}) \right\} + (E_{56} p_{2z} - E_2 p_{56z}) (p_{1z} p_{34y} p_{5x} - p_{1y} p_{34z} p_{5x} - p_{1z} p_{34x} p_{5y} + p_{1x} p_{34z} p_{5y}) + [E_{56} (p_{1z} p_{2y} p_{34x} - p_{1z} p_{2x} p_{34y} + p_{1y} p_{2x} p_{34z} - p_{1x} p_{2y} p_{34z}) + E_2 (p_{1z} p_{34y} p_{56x} - p_{1y} p_{34z} p_{56x} - p_{1z} p_{34x} p_{56y} + p_{1x} p_{34z} p_{56y})] p_{5z} \right\} + E_{34} \left\{ E_5 p_{2z} (p_{1z} p_{3y} p_{56x} - p_{1y} p_{3z} p_{56x} - p_{1z} p_{3x} p_{56y} + p_{1x} p_{3z} p_{56y}) + E_5 (p_{1z} p_{2y} p_{3x} - p_{1z} p_{2x} p_{3y} + p_{1y} p_{2x} p_{3z} - p_{1x} p_{2y} p_{3z}) p_{5z} - (E_{56} p_{2z} - E_2 p_{56z}) (p_{1z} p_{3y} p_{5x} - p_{1y} p_{3z} p_{5x} - p_{1z} p_{3x} p_{5y} + p_{1x} p_{3z} p_{5y}) - [E_{56} (p_{1z} p_{2y} p_{3x} - p_{1z} p_{2x} p_{3y} + p_{1y} p_{2x} p_{3z} - p_{1x} p_{2y} p_{3z}) + E_2 (p_{1z} p_{3y} p_{56x} - p_{1y} p_{3z} p_{56x} - p_{1z} p_{3x} p_{56y} + p_{1x} p_{3z} p_{56y})] p_{5z} \right\} + E_1 \left\{ [E_5 (p_{2z} (-p_{34z} p_{3y} p_{56x} + p_{34y} p_{3z} p_{56x} + p_{34z} p_{3x} p_{56y} - p_{34x} p_{3z} p_{56y}) + (-p_{2y} p_{34z} p_{3x} + p_{2x} p_{34z} p_{3y} + p_{2y} p_{34x} p_{3z} - p_{2x} p_{34y} p_{3z}) p_{5z}] + [E_{56} p_{2z} - E_2 p_{56z}] (p_{34z} p_{3y} p_{5x} - p_{34y} p_{3z} p_{5x} - p_{34z} p_{3x} p_{5y} + p_{34x} p_{3z} p_{5y}) + (E_{56} (p_{2y} p_{34z} p_{3x} - p_{2x} p_{34z} p_{3y} - p_{2y} p_{34x} p_{3z} + p_{2x} p_{34y} p_{3z}) + E_2 (p_{34z} p_{3y} p_{56x} - p_{34y} p_{3z} p_{56x} - p_{34z} p_{3x} p_{56y} + p_{34x} p_{3z} p_{56y})] p_{5z} \right\}^{-1},$$

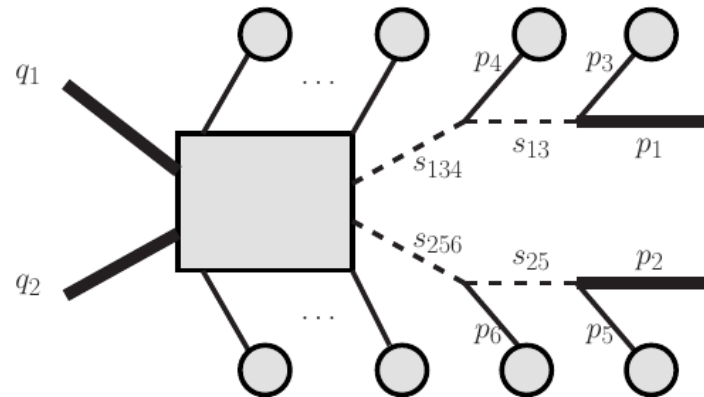
How to construct Higgs Self-coupling?

- None of the available blocks fit the decay
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→ No custom Block

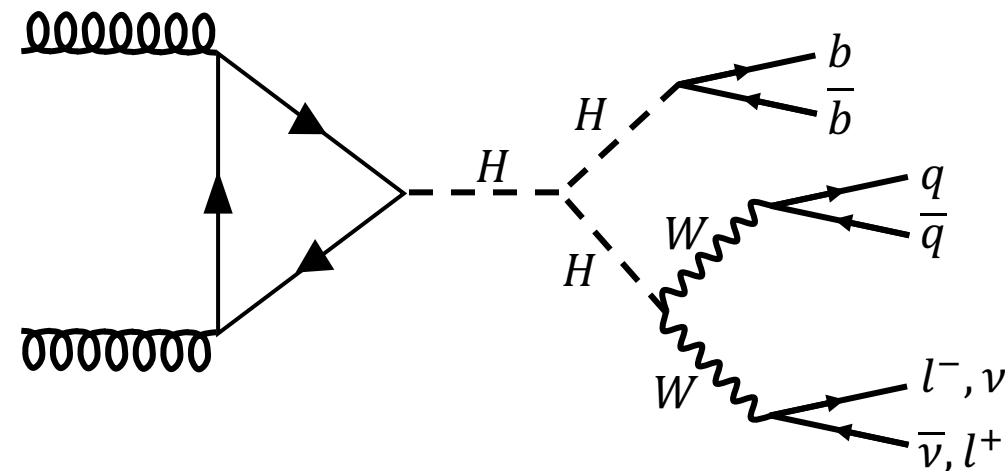
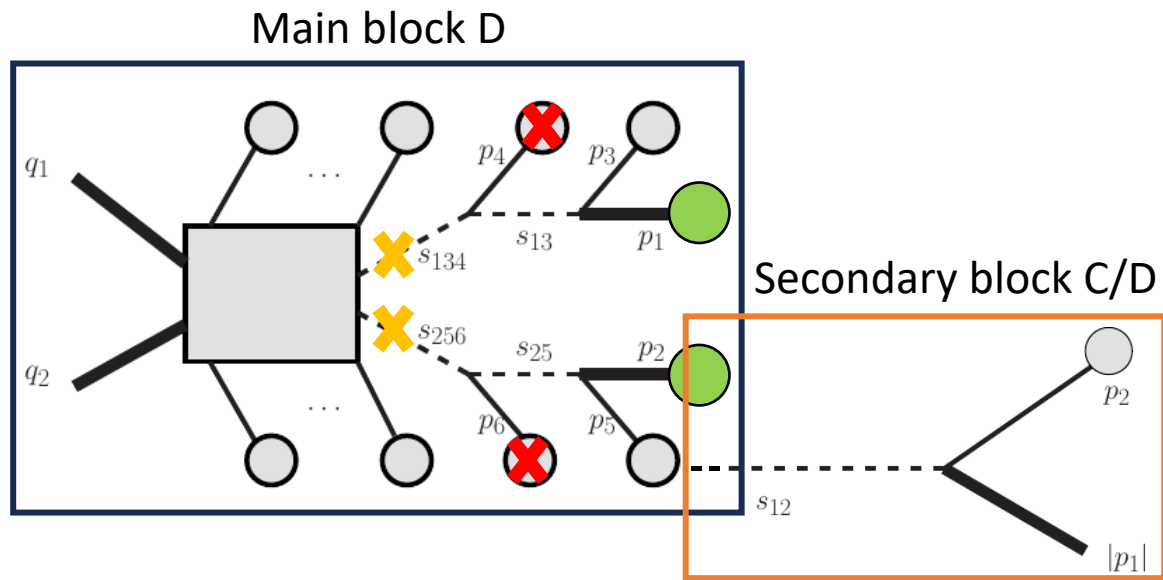


$$J = \frac{E_1}{s} |p_{2z} E_1 - E_2 p_{1z}|^{-1}$$



$$J = \frac{E_1 E_2}{8s} \left| E_3 \left\{ E_5 [p_{34z} (p_{1y} p_{2z} p_{56x} - p_{1x} p_{2z} p_{56y}) - p_{1y} p_{2x} p_{56z} + p_{1x} p_{2y} p_{56z}] + p_{1z} (-p_{2z} p_{34y} p_{56x} + p_{2z} p_{34x} p_{56y} - p_{2y} p_{34x} p_{56z} + p_{2x} p_{34y} p_{56z}) \right\} + (E_{56} p_{2z} - E_2 p_{56z}) (p_{1z} p_{34y} p_{5x} - p_{1y} p_{34z} p_{5x} - p_{1z} p_{34x} p_{5y} + p_{1x} p_{34z} p_{5y}) + [E_{56} (p_{1z} p_{2y} p_{34x} - p_{1z} p_{2x} p_{34y} + p_{1y} p_{2x} p_{34z} - p_{1x} p_{2y} p_{34z}) + E_2 (p_{1z} p_{34y} p_{56x} - p_{1y} p_{34z} p_{56x} - p_{1z} p_{34x} p_{56y} + p_{1x} p_{34z} p_{56y})] p_{5z} \right\} + E_{34} \left\{ E_5 p_{2z} (p_{1z} p_{3y} p_{56x} - p_{1y} p_{3z} p_{56x} - p_{1z} p_{3x} p_{56y} + p_{1x} p_{3z} p_{56y}) + E_5 (p_{1z} p_{2y} p_{3x} - p_{1z} p_{2x} p_{3y} + p_{1y} p_{2x} p_{3z} - p_{1x} p_{2y} p_{3z}) p_{56z} - (E_{56} p_{2z} - E_2 p_{56z}) (p_{1z} p_{3y} p_{5x} - p_{1y} p_{3z} p_{5x} - p_{1z} p_{3x} p_{5y} + p_{1x} p_{3z} p_{5y}) - [E_{56} (p_{1z} p_{2y} p_{3x} - p_{1z} p_{2x} p_{3y} + p_{1y} p_{2x} p_{3z} - p_{1x} p_{2y} p_{3z}) + E_2 (p_{1z} p_{3y} p_{56x} - p_{1y} p_{3z} p_{56x} - p_{1z} p_{3x} p_{56y} + p_{1x} p_{3z} p_{56y})] p_{5z} \right\} + E_1 \left\{ [E_5 (p_{2z} (-p_{34z} p_{3y} p_{56x} + p_{34y} p_{3z} p_{56x} + p_{34z} p_{3x} p_{56y} - p_{34x} p_{3z} p_{56y}) + (-p_{2y} p_{34z} p_{3x} + p_{2x} p_{34z} p_{3y} + p_{2y} p_{34x} p_{3z} - p_{2x} p_{34y} p_{3z}) p_{56z}] + [E_{56} p_{2z} - E_2 p_{56z}] (p_{34z} p_{3y} p_{5x} - p_{34y} p_{3z} p_{5x} - p_{34z} p_{3x} p_{5y} + p_{34x} p_{3z} p_{5y}) + (E_{56} (p_{2y} p_{34z} p_{3x} - p_{2x} p_{34z} p_{3y} - p_{2y} p_{34x} p_{3z} + p_{2x} p_{34y} p_{3z}) + E_2 (p_{34z} p_{3y} p_{56x} - p_{34y} p_{3z} p_{56x} - p_{34z} p_{3x} p_{56y} + p_{34x} p_{3z} p_{56y})] p_{5z} \right\} \right|^{-1}$$

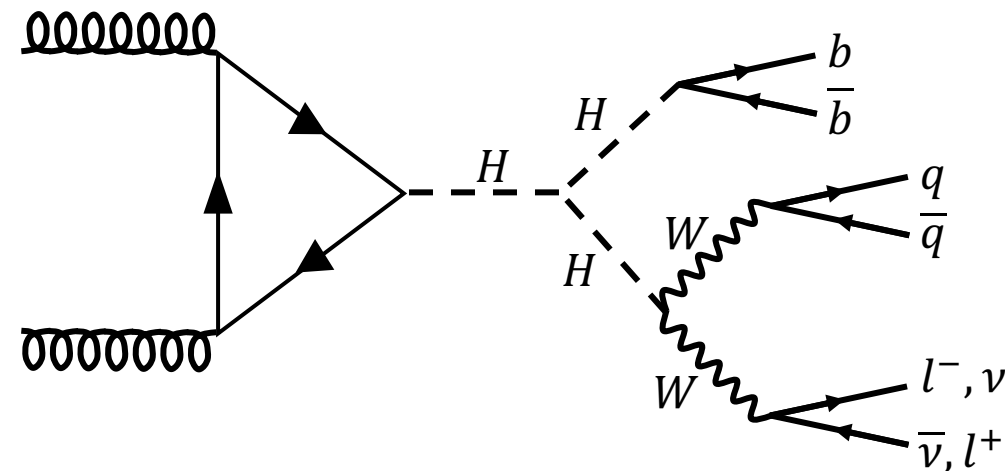
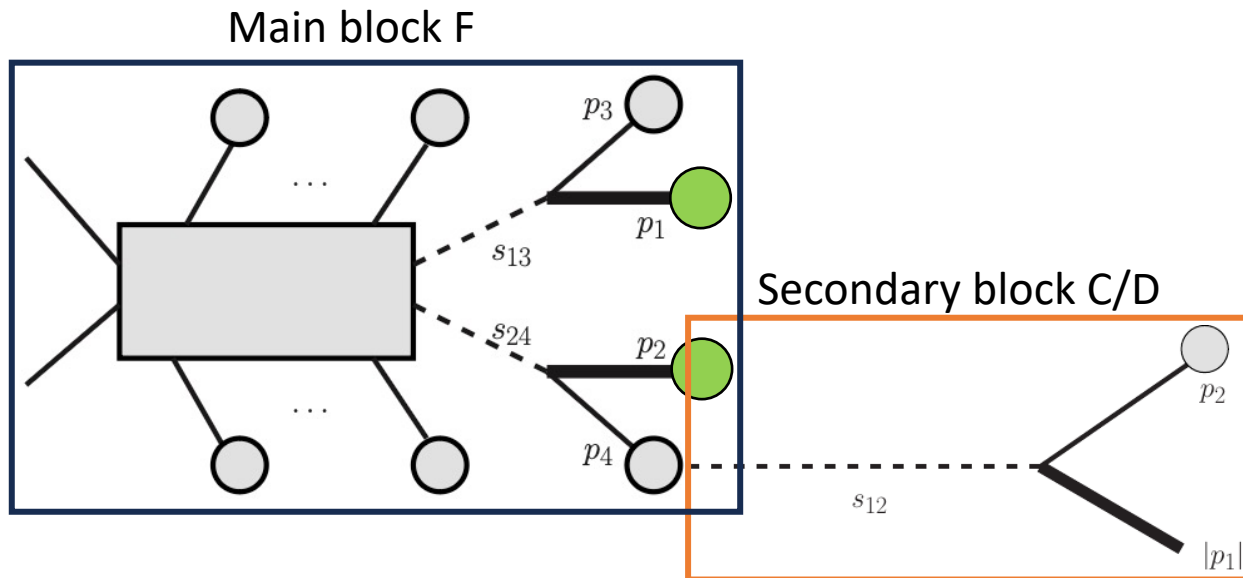
Higgs Self-coupling in MoMEMta



Main block D changes

- Set $p4 = p6 = 0$ → No need for dashed lines s_{134} & s_{256}
 - Make $p1$ & $p2$ inputs
 - $p2$ is sum of off-shell W -boson daughters
- Weights can be calculated

Higgs Self-coupling in MoMEMta



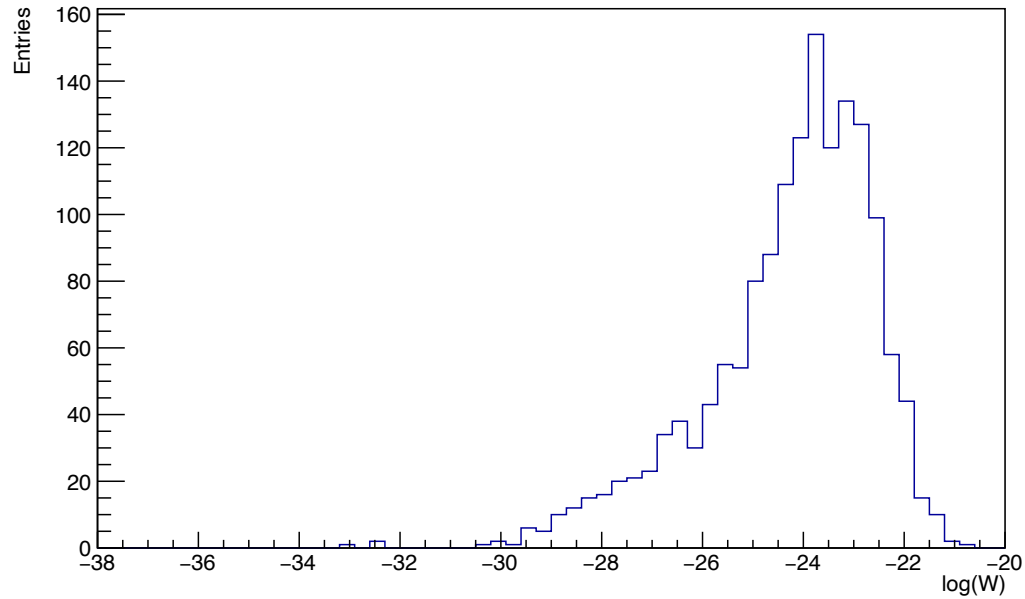
Main block F changes

- Make p_1 & p_2 inputs
 - p_2 is sum of off-shell W -boson daughters
- Weights can be calculated

Higgs Self-coupling

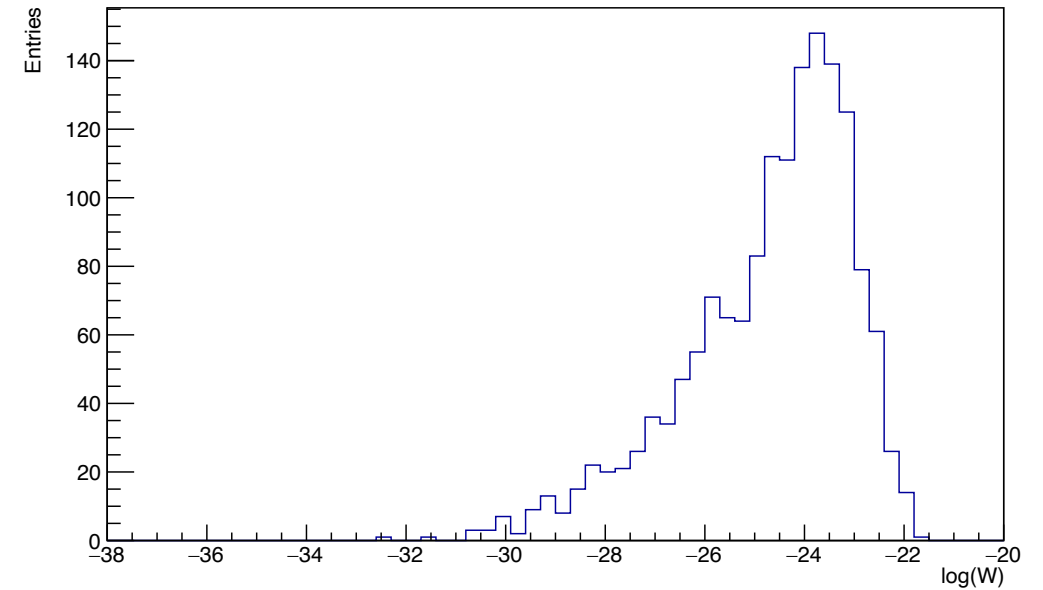
Weights = $HH(\text{inputs} = x)$ under $H \rightarrow HH$ hypothesis

HH(HH) Weights



HH final states as inputs (“correct” inputs)

HH(HZ) Weights

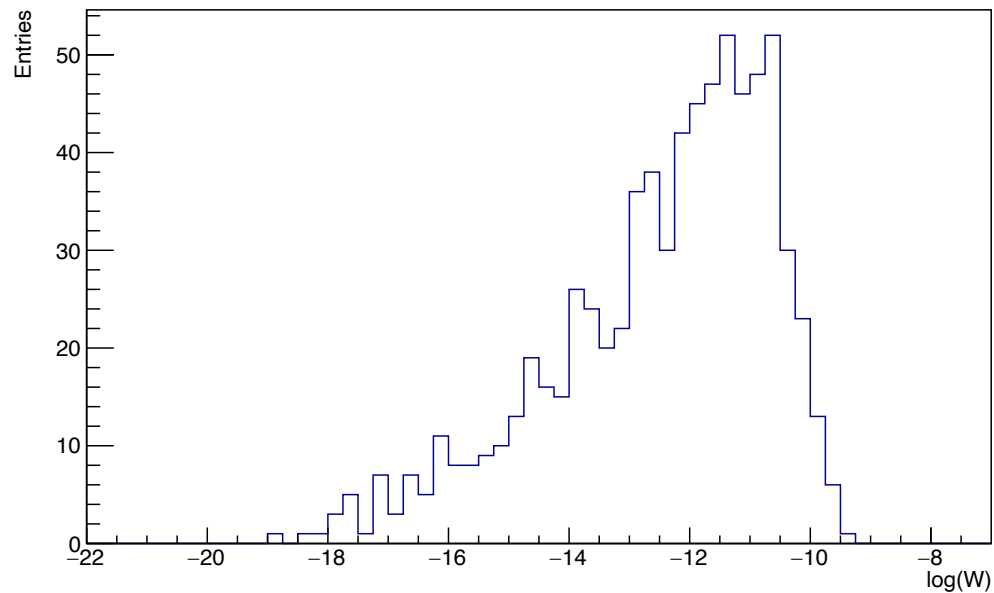


HZ final states as inputs (“wrong” inputs)

HZ coupling

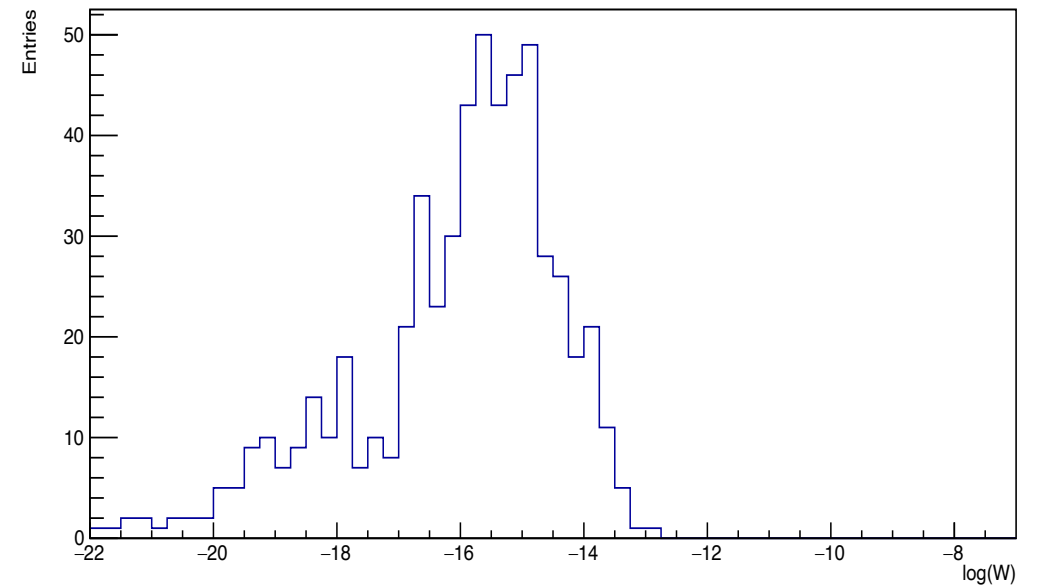
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HZ(HZ) Weights



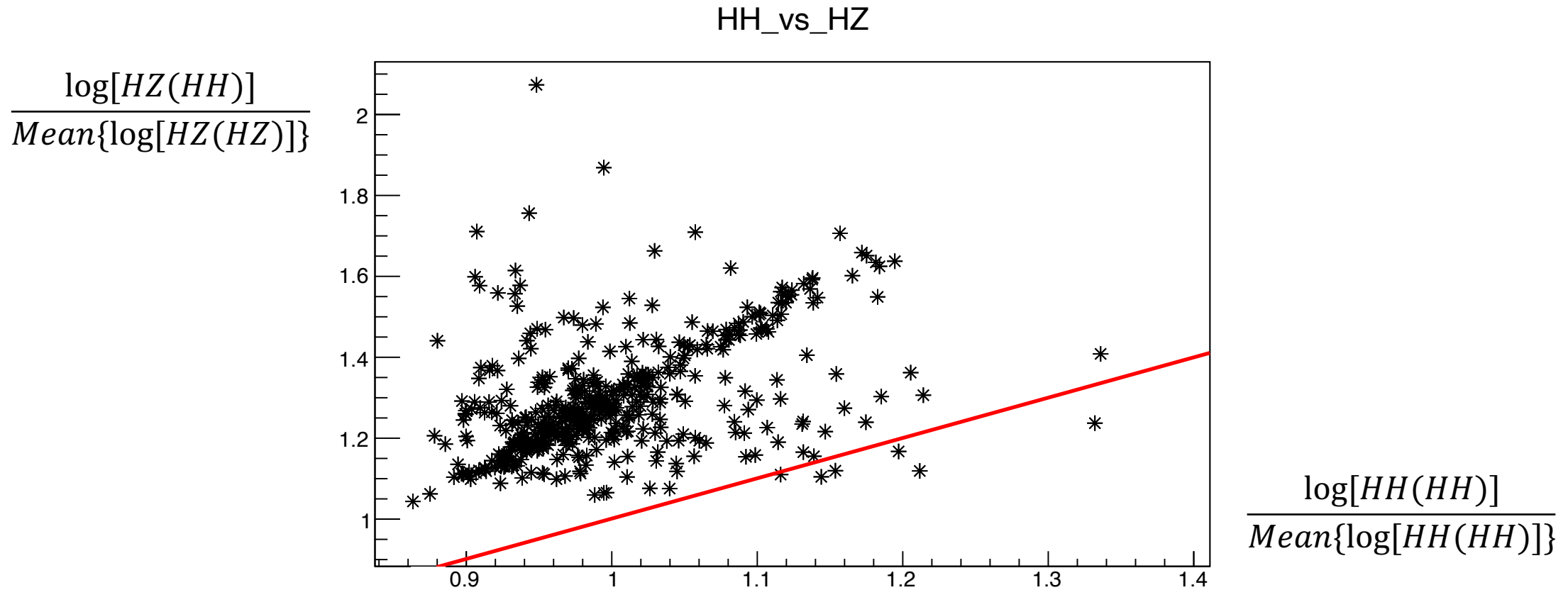
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HZ(HH) Weights



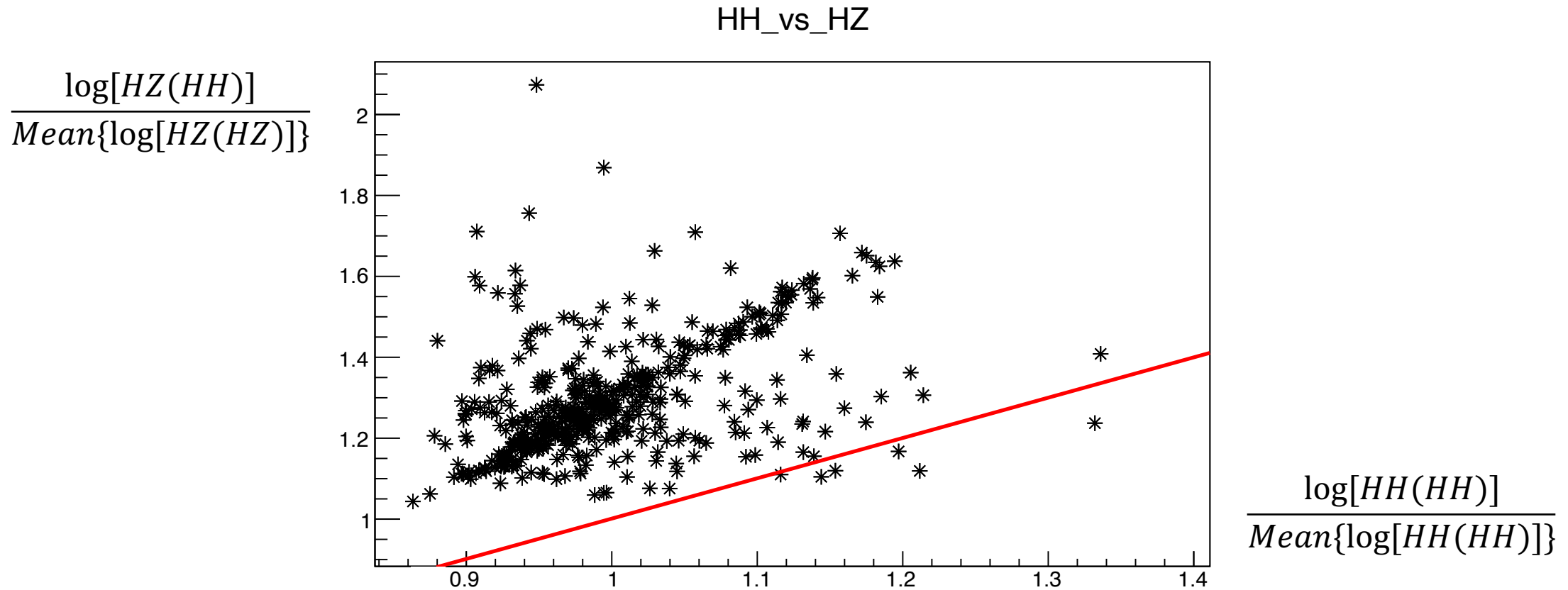
HH final states as inputs (“wrong” inputs)

HH vs HZ coupling



- For comparisons between the weights under the *HH* and *HZ* hypothesis to be possible a normalization is needed

HH vs HZ coupling



- For comparisons between the weights under the *HH* and *HZ* hypothesis to be possible a normalization is needed
→ Almost all the *HH* events have a larger weight under the *HH* hypothesis

- HH very rare (unobserved) decay with more likely background processes
- Use MoMEMta to distinguish HH from HZ events
- Need of alterations to MoMEMta blocks to perform calculations
- HH and HZ histogram under HH hypothesis almost identical
- HH and HZ histogram under HZ hypothesis easy to separate
- Comparing weights of single events makes a clear separation possible

Back up

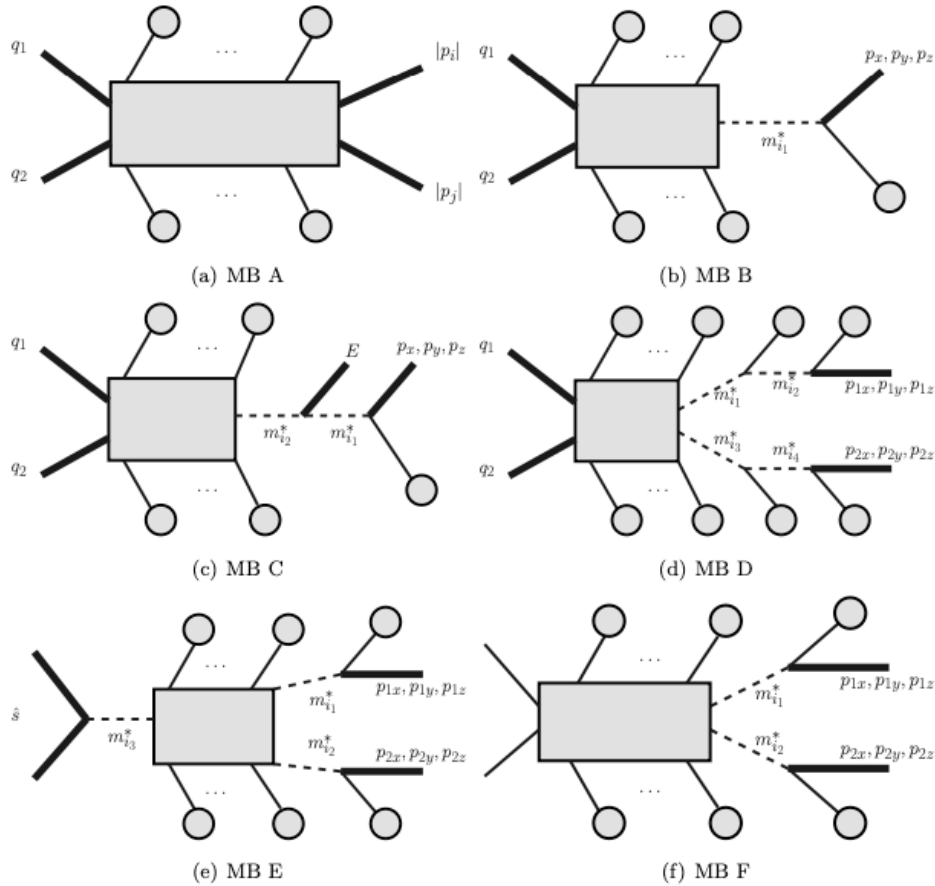
- C++ software package for calculating weights
- Four-momenta of final state particles as inputs
- Uses „blocks“ to construct desired decay

Main block	Topology	Removes...	For
A	$(q_1, q_2) \rightarrow p_1 + p_2$	$q_1, q_2, p_1 , p_2 $	
B	$(q_1, q_2) \rightarrow s_{12}(\rightarrow p_1 + p_2)$	q_1, q_2, p_1	s_{12}
C	$(q_1, q_2) \rightarrow s_{123} \rightarrow p_3 + s_{12}(\rightarrow p_1 + p_2)$	$q_1, q_2, p_1, p_3 $	s_{12}, s_{123}
D	$(q_1, q_2) \rightarrow s_{134}(\rightarrow p_4 + s_{13}(\rightarrow p_1 + p_3)) + s_{256}(\rightarrow p_6 + s_{25}(\rightarrow p_2 + p_5))$	q_1, q_2, p_1, p_2	$s_{13}, s_{134}, s_{25}, s_{256}$
E	$(q_1, q_2) \rightarrow (s_{1234}, y) \rightarrow s_{13}(\rightarrow p_1 + p_3) + s_{24}(\rightarrow p_2 + p_4)$	q_1, q_2, p_1, p_2	$s_{1234}, y, s_{13}, s_{24}$
F	$(q_1, q_2) \rightarrow s_{13}(\rightarrow p_1 + p_3) + s_{24}(\rightarrow p_2 + p_4)$	p_1, p_2	q_1, q_2, s_{13}, s_{24}
G	$(q_1, q_2) \rightarrow s_{12}(\rightarrow p_1 + p_2) + s_{34}(\rightarrow p_3 + p_4)$	$q_1, q_2, p_1 , p_2 , p_3 , p_4 $	s_{12}, s_{34}

q_i : Bjorken fraction
 p_i : Four-momentum
 $s_{ij\dots} = (p_i + p_j + \dots)^2$
 y : Rapidity

Main and Secondary Blocks

Main blocks



Secondary blocks

