LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Employing the Matrix Element Method in the Search for Higgs Self-coupling

IMPRS PhD Program

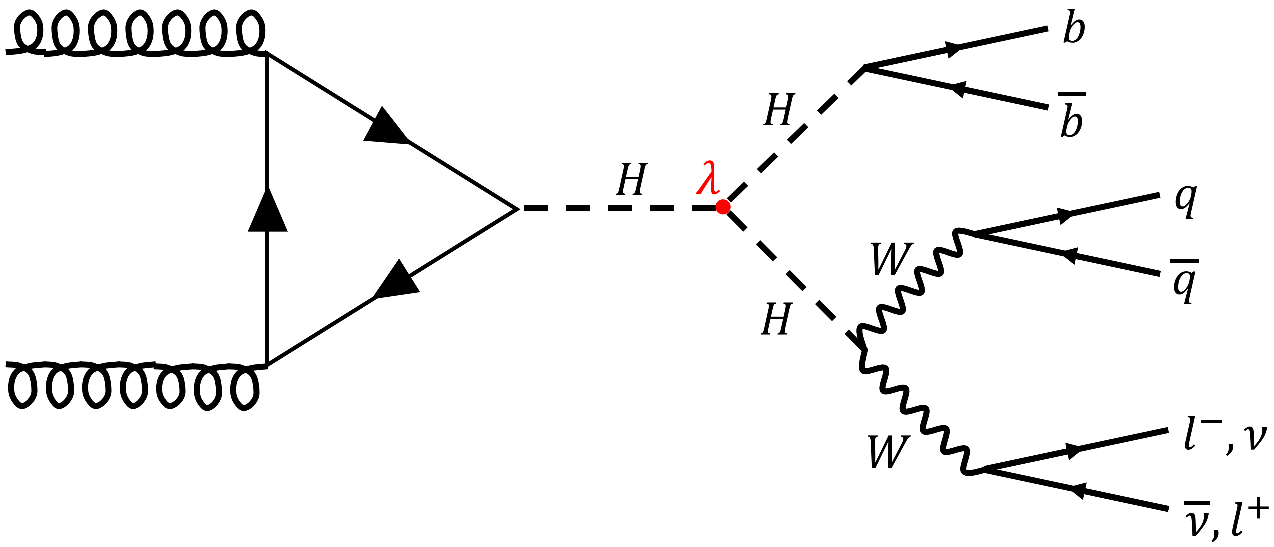
25.11.2024

Edis Hrustanbegovic

Agenda

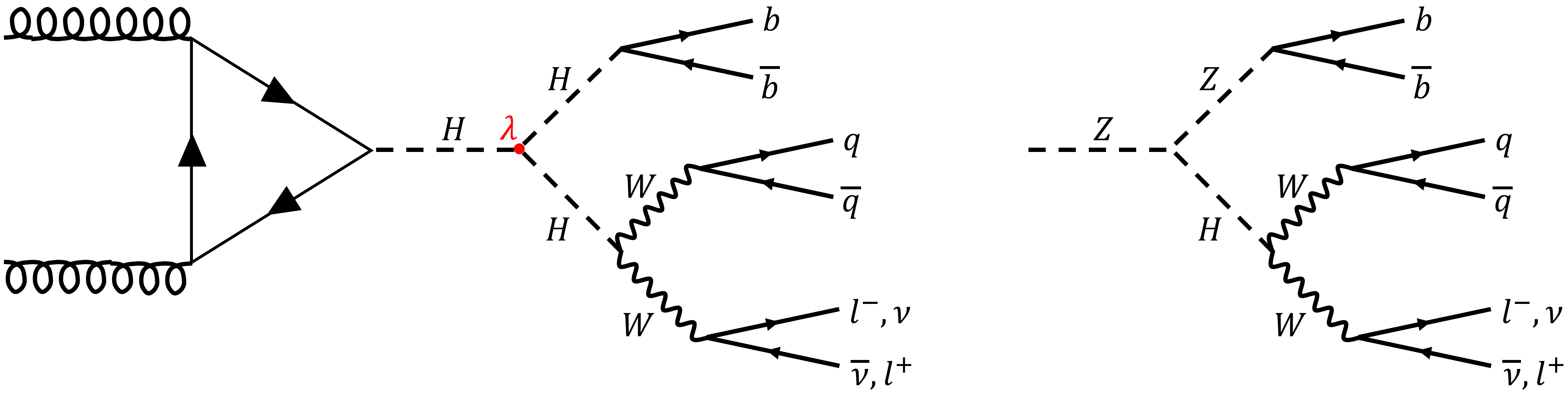
1. Higgs Self-Coupling
2. What is the Matrix Element Method?
3. MoMEMta for Weight Calculation
4. How to construct Higgs Self-Coupling in MoMEMta
5. Higgs Self- vs HZ coupling

Higgs Self-coupling



- Predicted by Standard Model (not yet observed)
- Small cross section

Higgs Self-coupling



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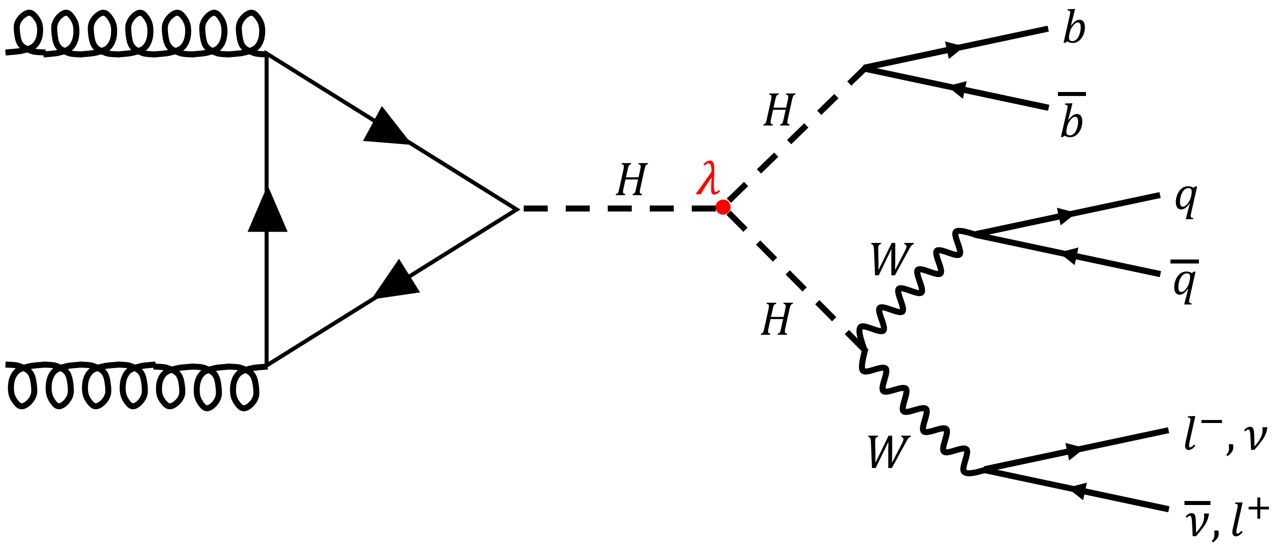
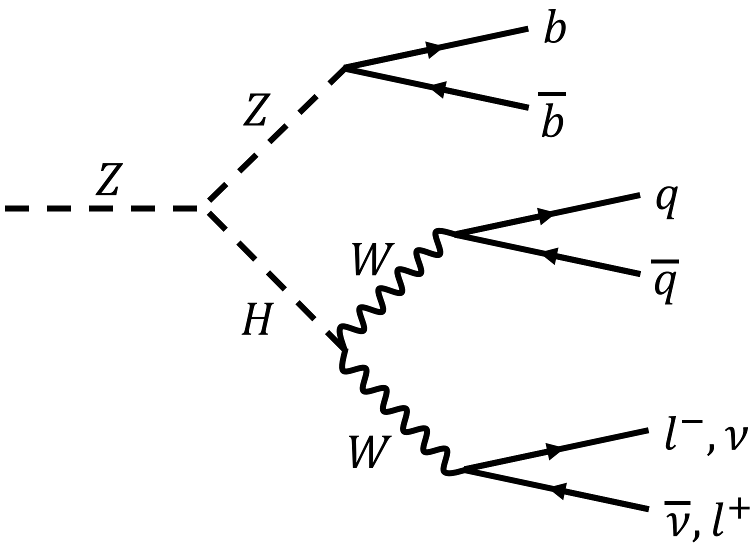
- Small cross section
- More likely background process ($Z \to HZ$)

Higgs Self-coupling



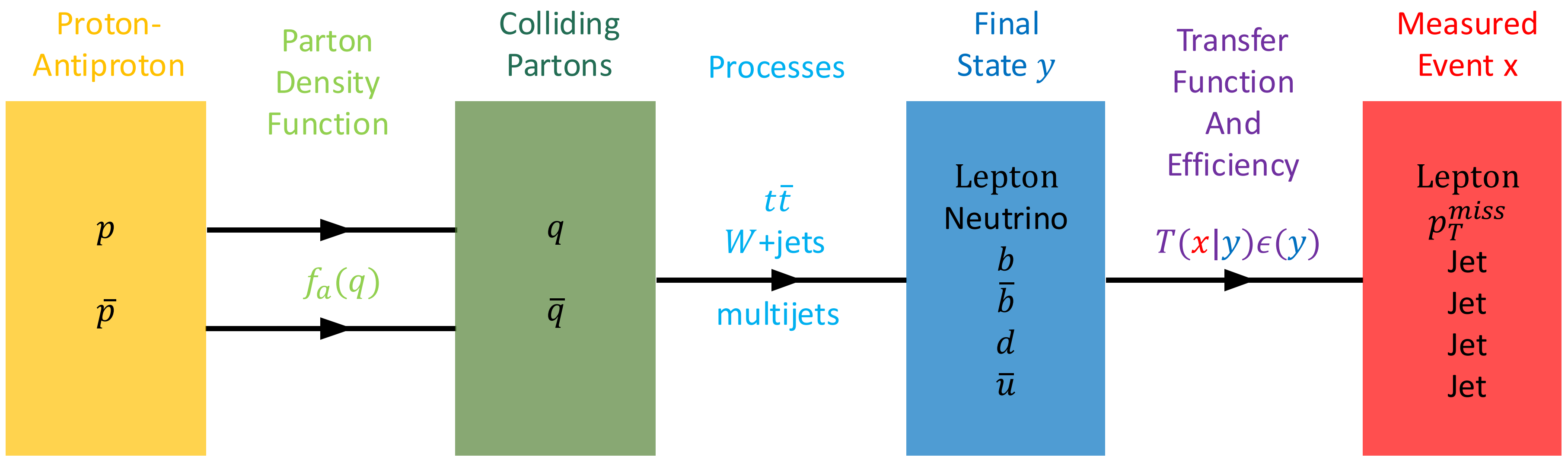


- Predicted by Standard Model (not yet observed)
- Small cross section
- More likely background process ($Z \rightarrow HZ$)
- Allows direct measurement of self-coupling parameter λ
- Deviations from the current value $\lambda = \frac{m_H^2}{2v^2}$ implies physics beyond the standard model

What is the Matrix Element Method?

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

$W(x|\alpha) \sim$



[https://arxiv.org/abs/1805.08555], [https://arxiv.org/abs/1003.1316]

What is the Matrix Element Method?

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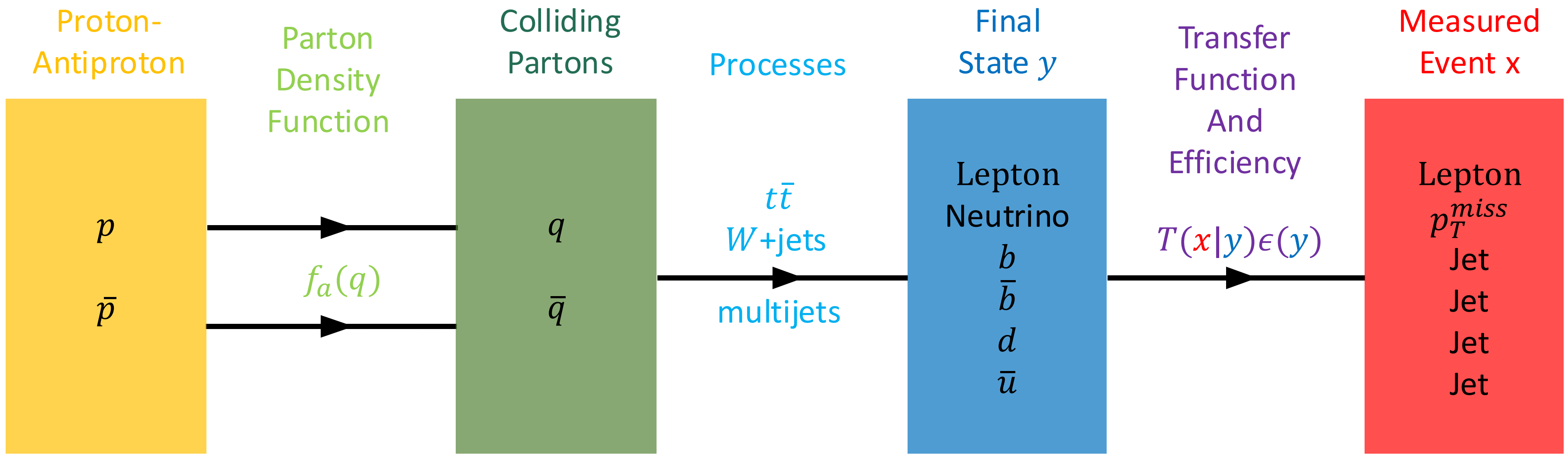
$$W(x|\alpha) \sim \int \sum_{a_1,a_2} dq_1 dq_2 f_{a_1}(q_1) f_{a_2}(q_2)$$



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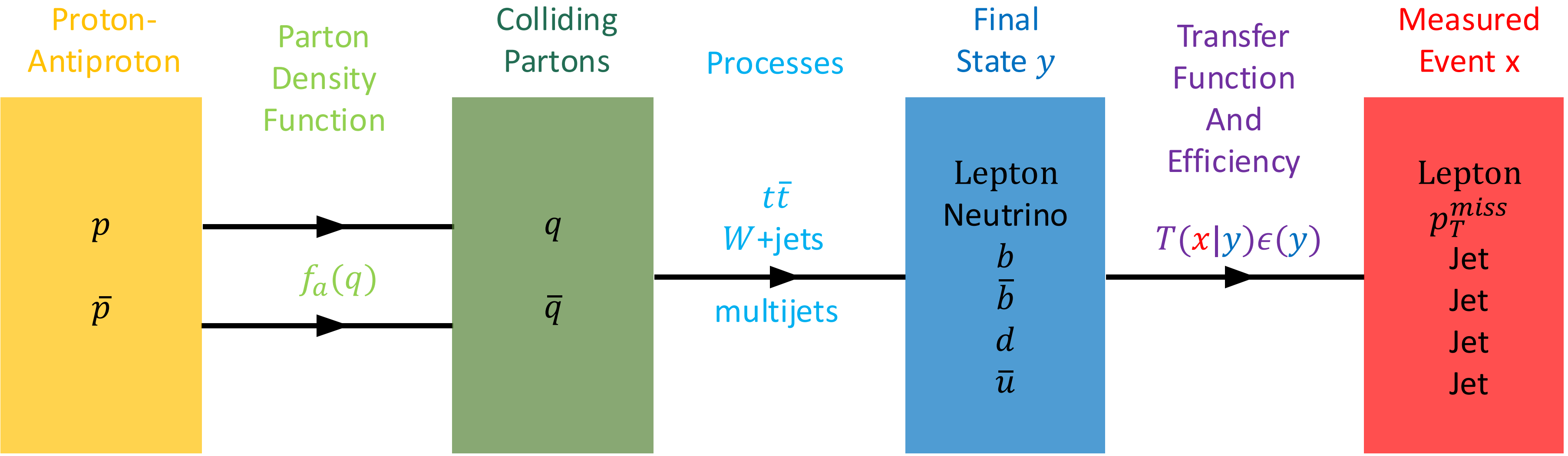
$$W(x|\alpha) \sim \int \sum_{a_1,a_2} dq_1 dq_2 f_{a_1}(q_1) f_{a_2}(q_2) \, |\mathcal{M}_\alpha(q_1,q_2,y)|^2 \, d\phi(y)$$



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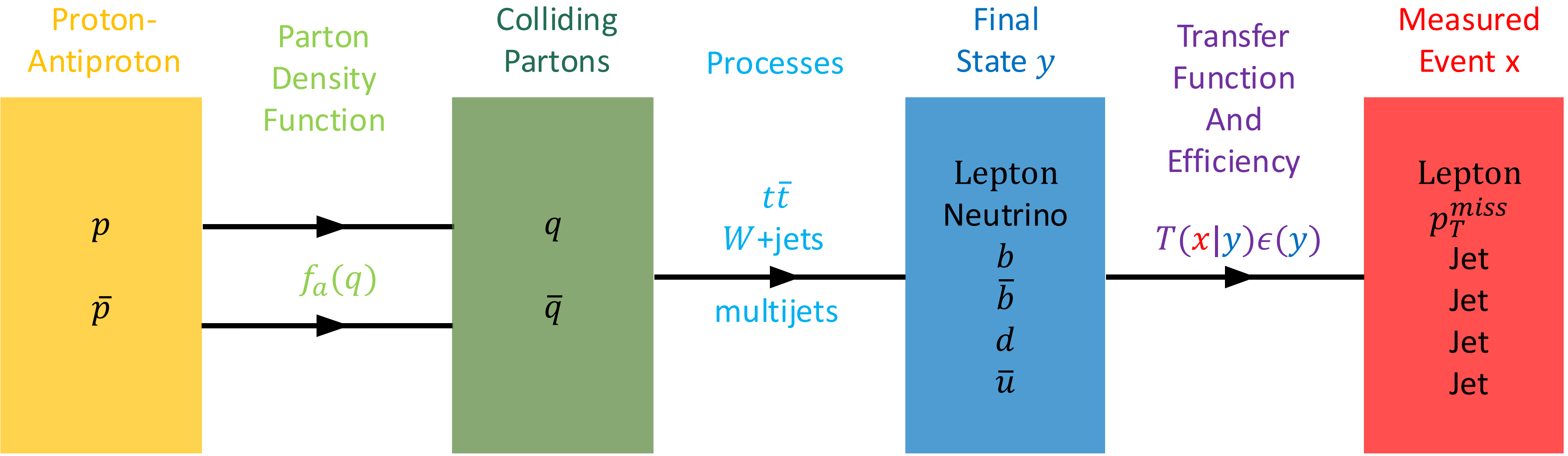
$$W(x|\alpha) \sim \int \sum_{a_1,a_2} dq_1 dq_2 f_{a_1}(q_1) f_{a_2}(q_2) \, |\mathcal{M}_\alpha(q_1,q_2,y)|^2 \, d\phi(y) T(x|y) \epsilon(y)$$



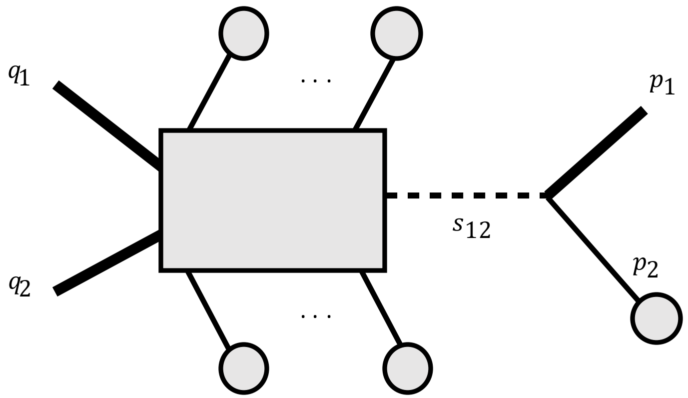
- Transfer function $T(x|y)$ describes the partonic evolution of the final state y
- Efficiency $\epsilon(y)$ represent the probability of correctly selecting and reconstructing the final state y

[https://arxiv.org/abs/1805.08555], [https://arxiv.org/abs/1003.1316]

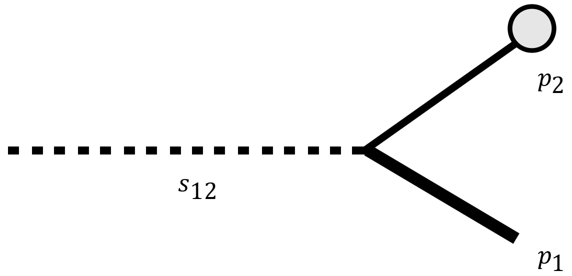
MoMEMta for Weight Calculation

- 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

Main block B



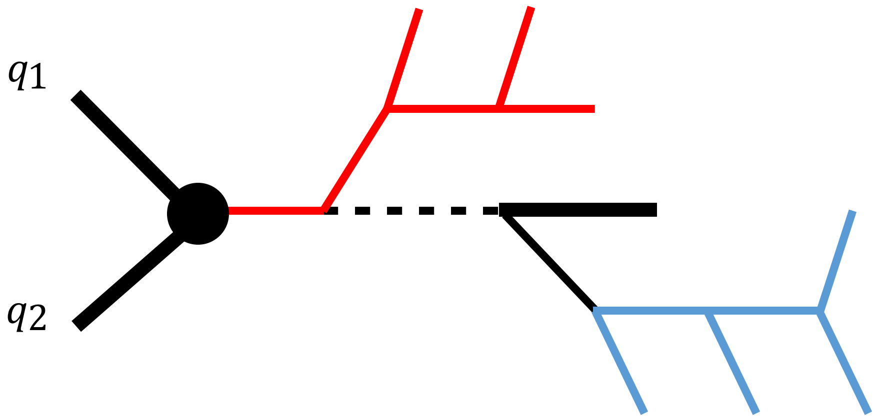
Secondary block C/D



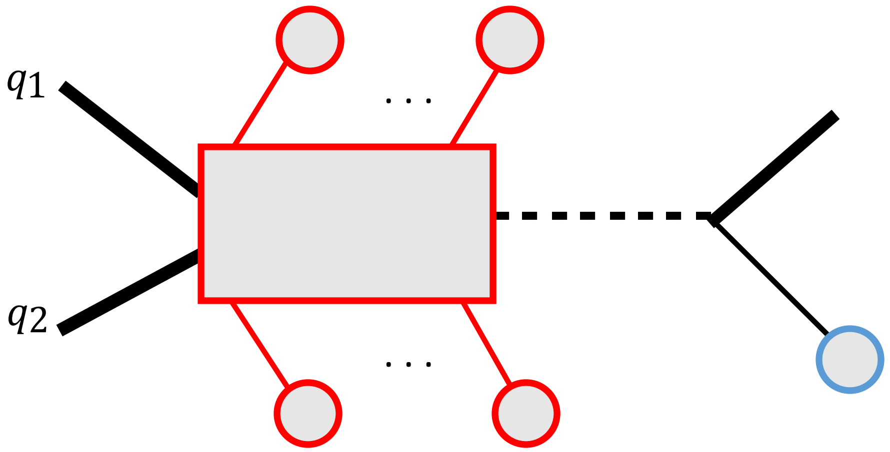
[http://arxiv.org/abs/1007.3300v2]

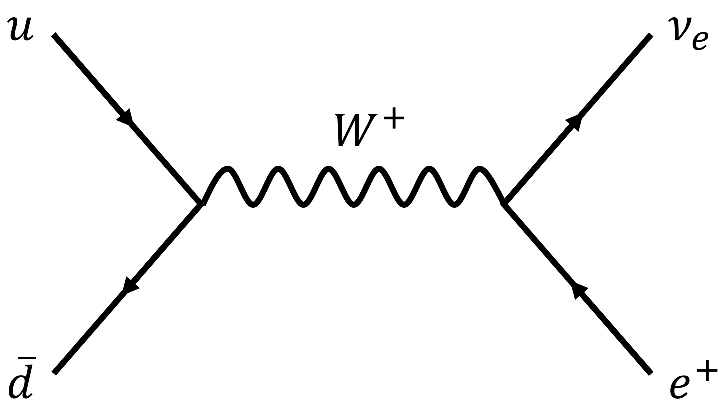
Blocks

Diagram of decay chain



Reduced diagram



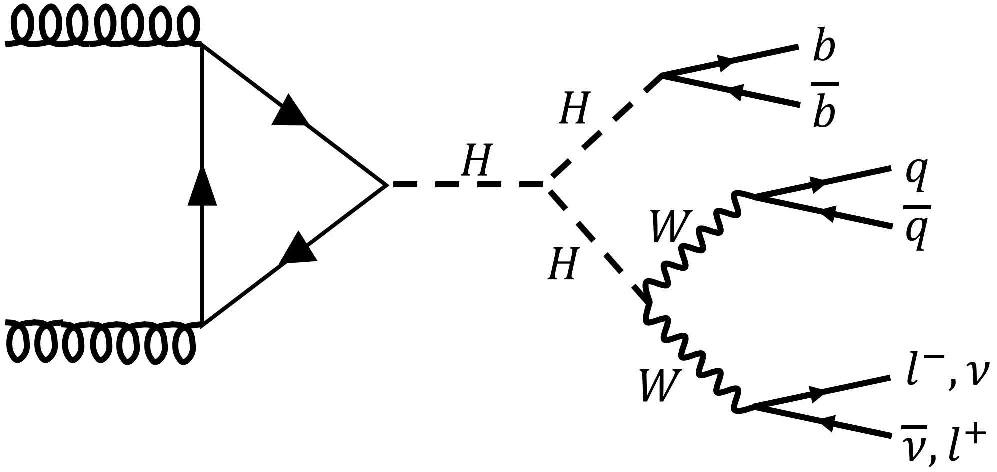


- Dashed lines: Decaying particles
- Lines with blob: Input paticles for MoMEMta
- Lines without blob: Reconstructed particles by MoMEMta

How to construct Higgs Self-coupling in MoMEMta?

Requirements for block:

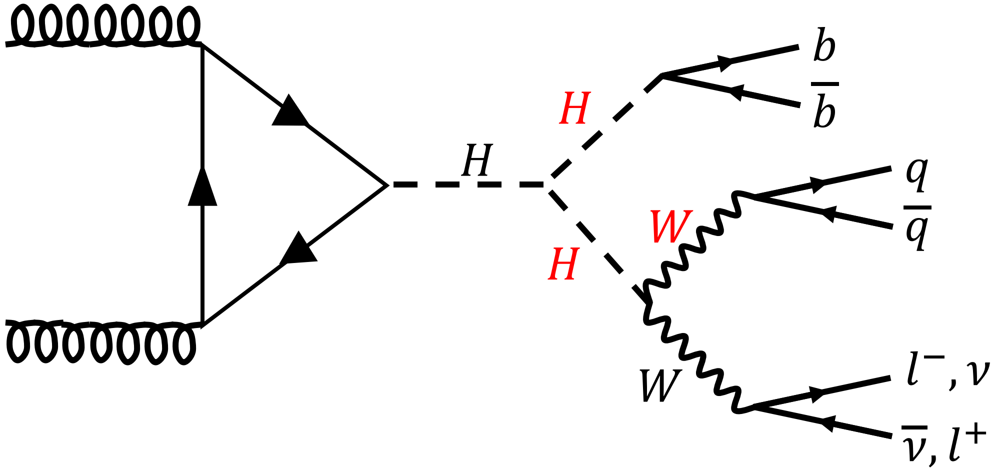
- 6 final state particles
- 5 decaying particles (H, H, H, W^+, W^-)



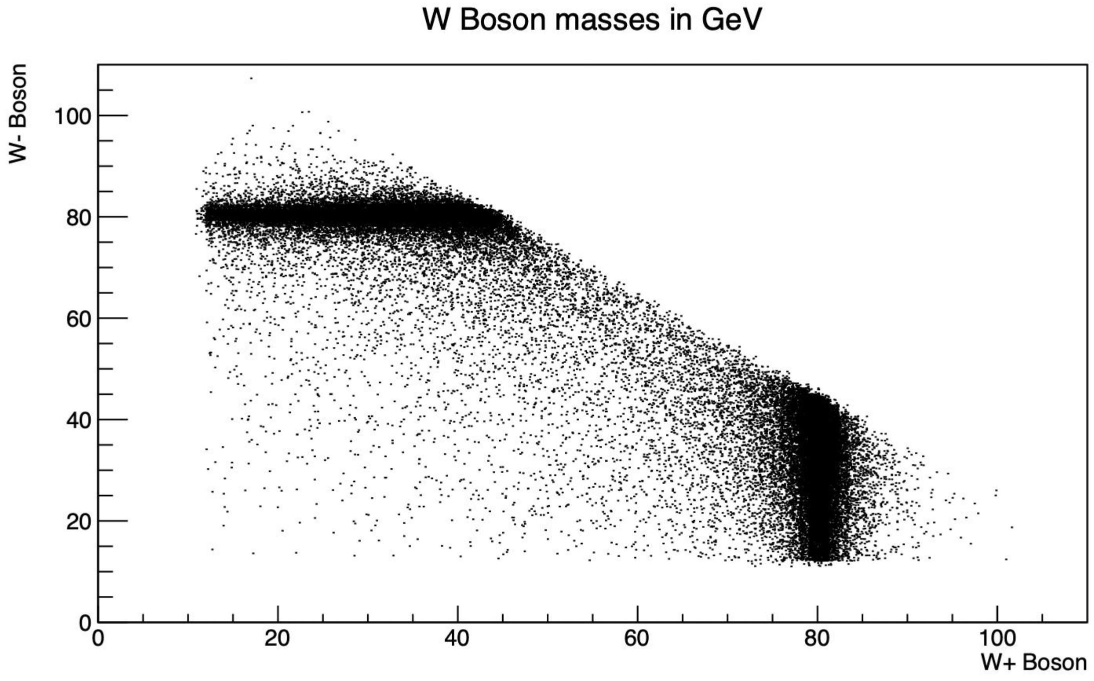
How to construct Higgs Self-coupling in MoMEMta?

Requirements for block:

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



MoMEMta can't handle off-shell particles



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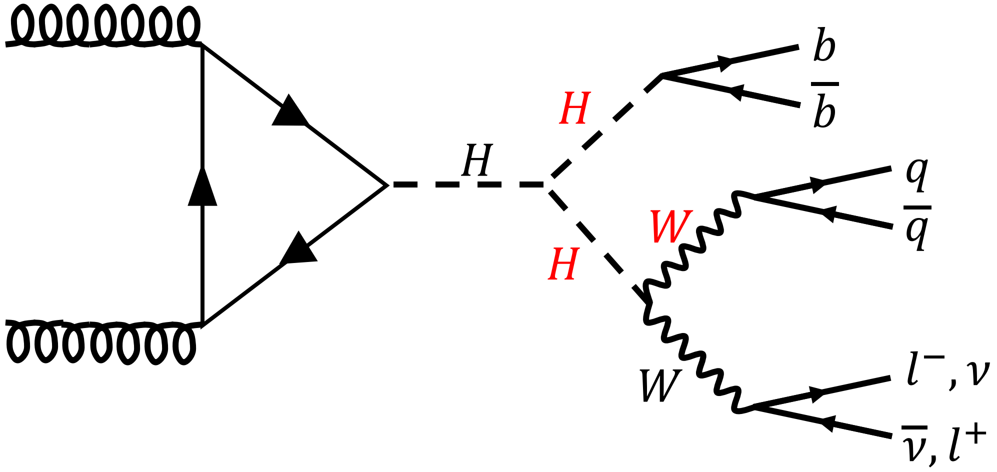

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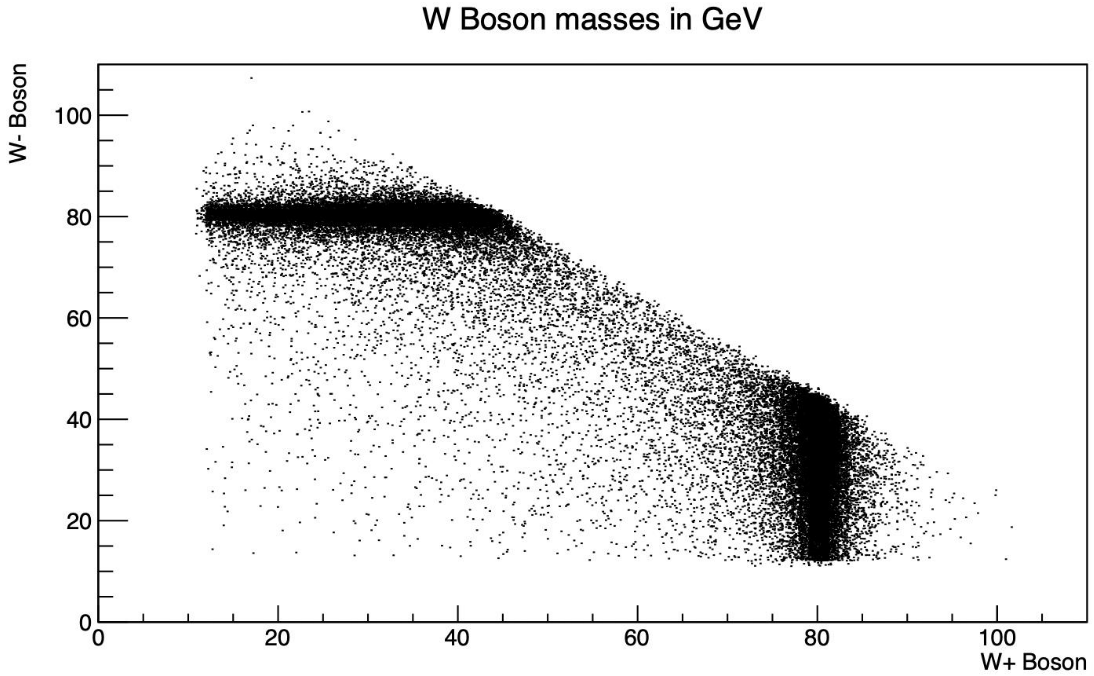
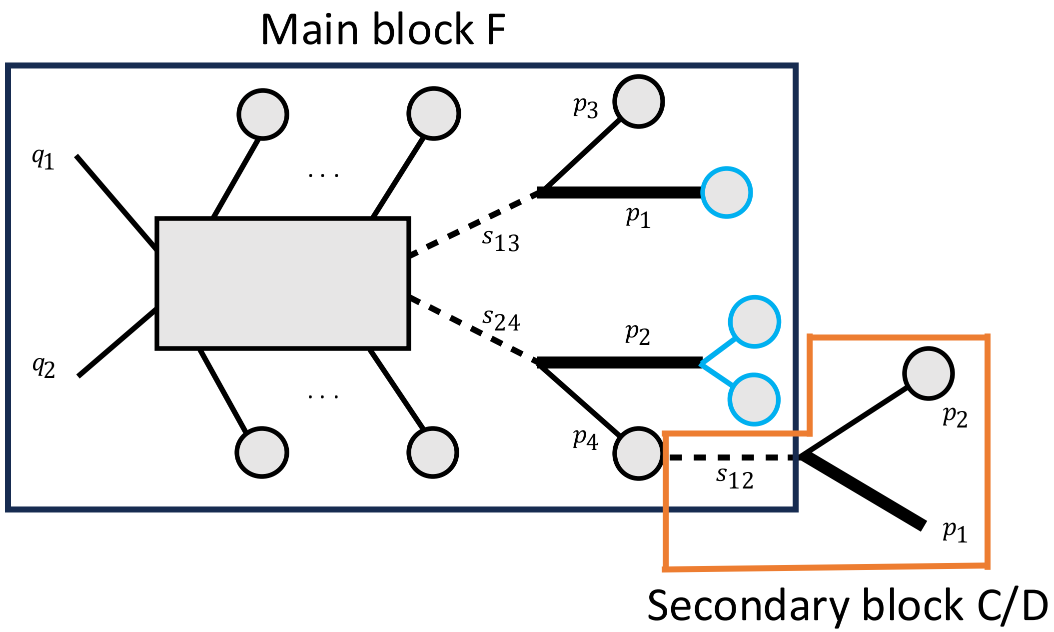
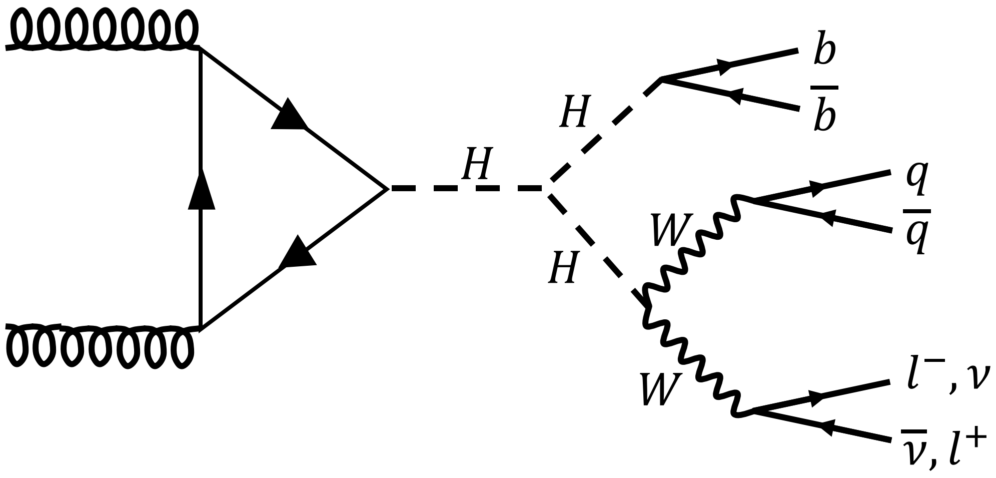


→ None of the availible blocks fit the decay

How to construct Higgs Self-coupling in MoMEMta?



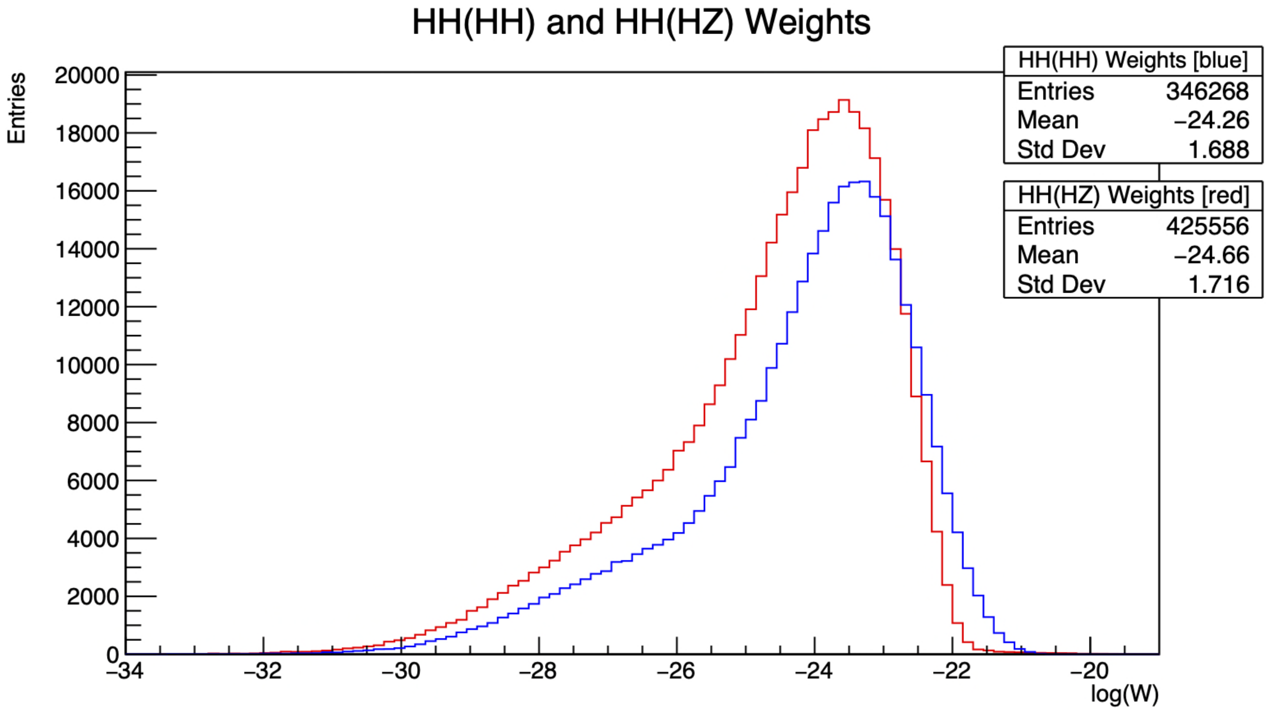


Main block F changes

- Make $p1$ & $p2$ inputs
- $p2$ is sum of off-shell W-boson daughter particles

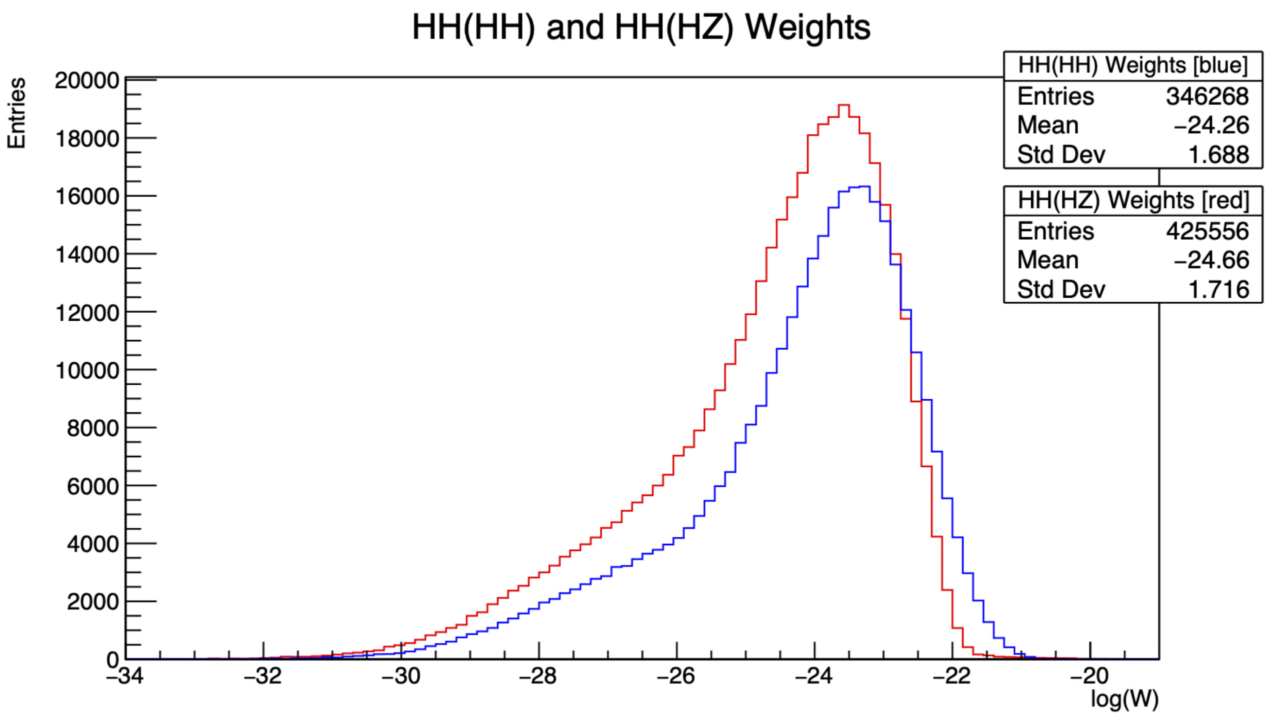
→ Weights can be calculated

Higgs self- vs HZ coupling

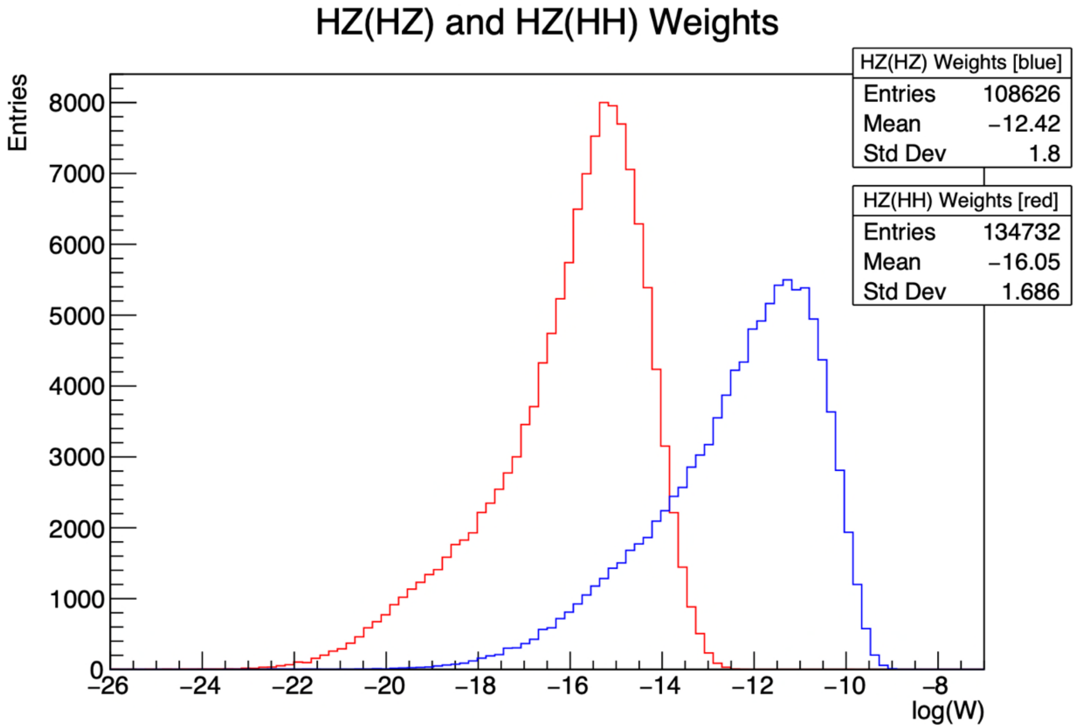


Weights $= HH(\text{inputs} = x)$ under $H \rightarrow HH$ hypothesis

Higgs self- vs HZ coupling



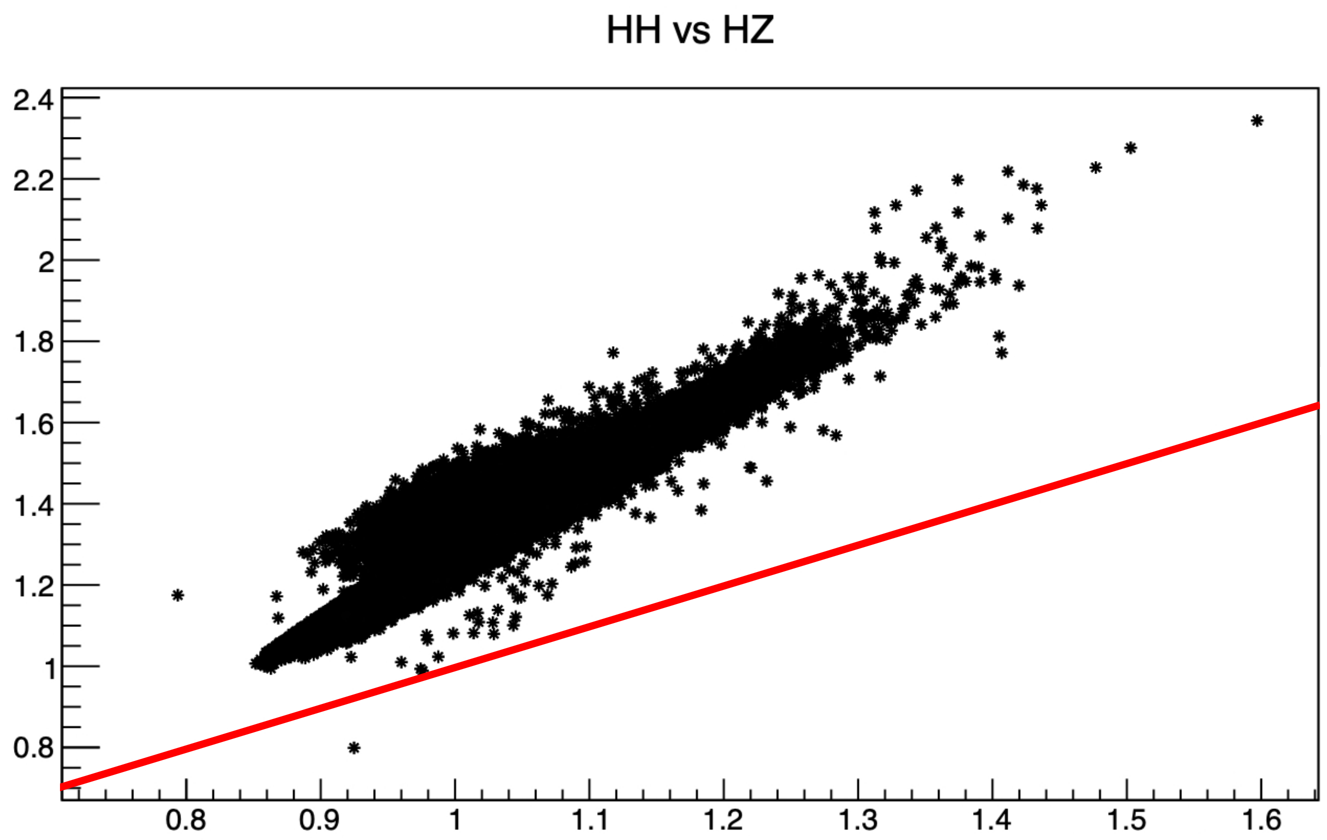
Weights $= HH(\text{inputs} = x)$ under $H \to HH$ hypothesis



Weights $= HZ(\text{inputs} = x)$ under $\mathrm{Z} \to HZ$ hypothesis

Higgs self- vs HZ coupling

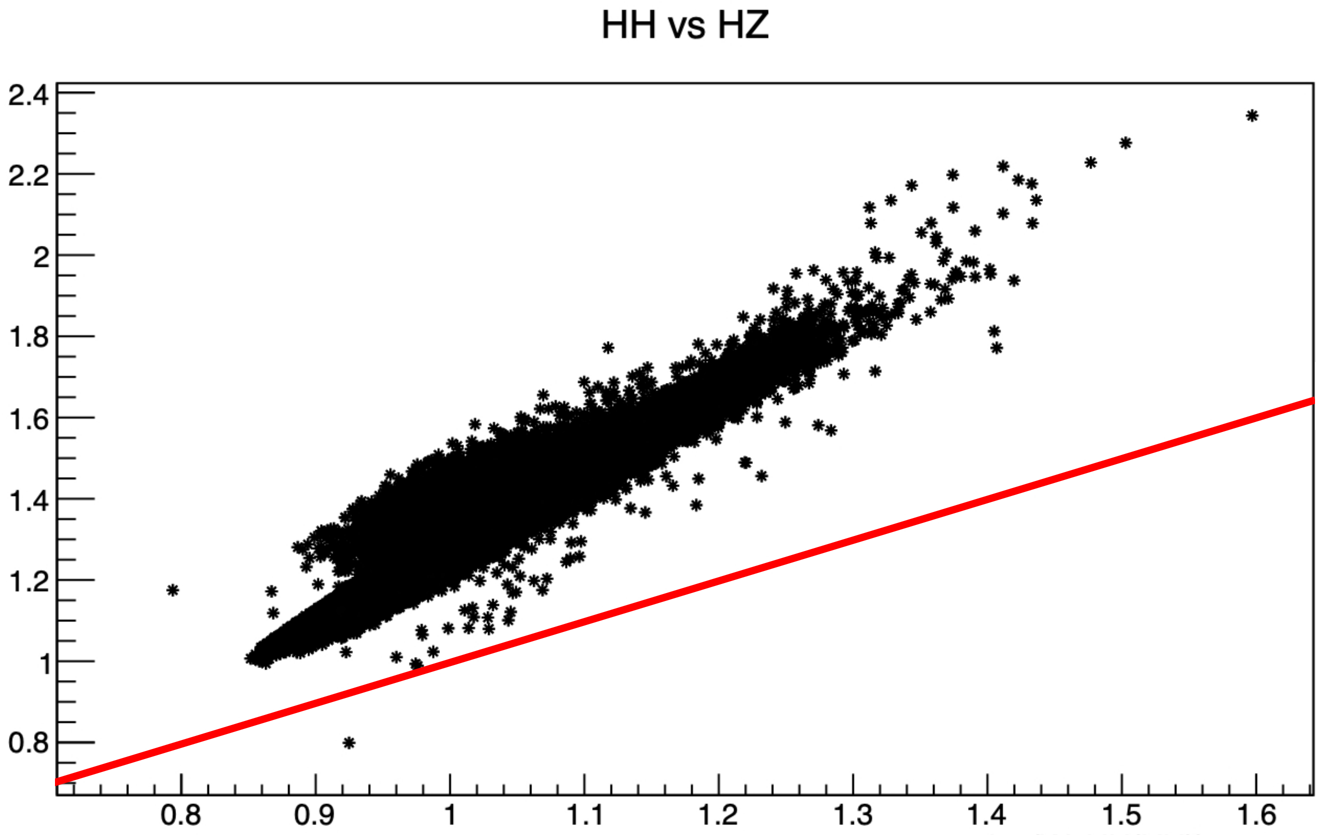
$$\frac{\log[HZ(HH)]}{Mean\{\log[HZ(HZ)]\}}$$



$$\frac{\log[HH(HH)]}{Mean\{\log[HH(HH)]\}}$$

Higgs self- vs HZ coupling

$$\frac{\log[HZ(HH)]}{Mean\{\log[HZ(HZ)]\}}$$

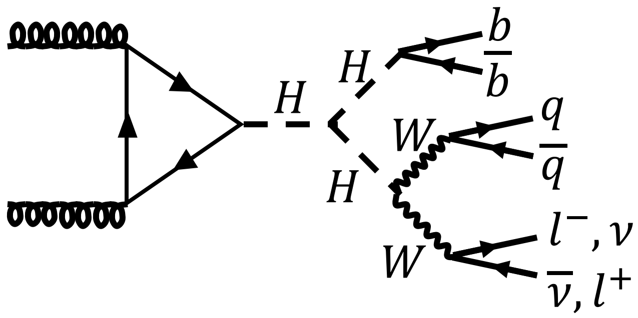


$$\frac{\log[HH(HH)]}{Mean\{\log[HH(HH)]\}}$$

→ 1 out of 134695 events was missclasified as a HZ event

High Successrate (> 99.99%) using Matrix Element Method for distinguishing HH from HZ Events

- 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



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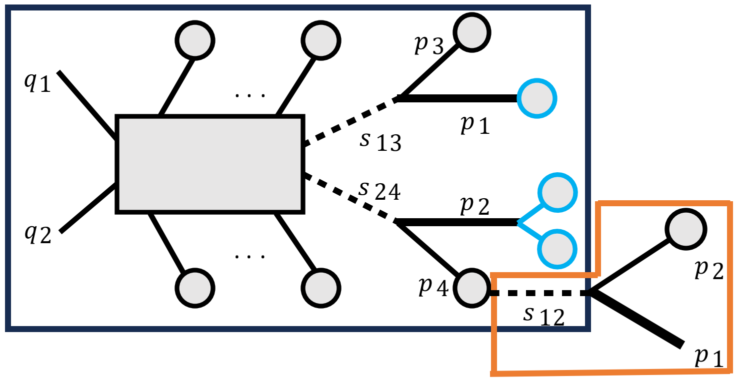

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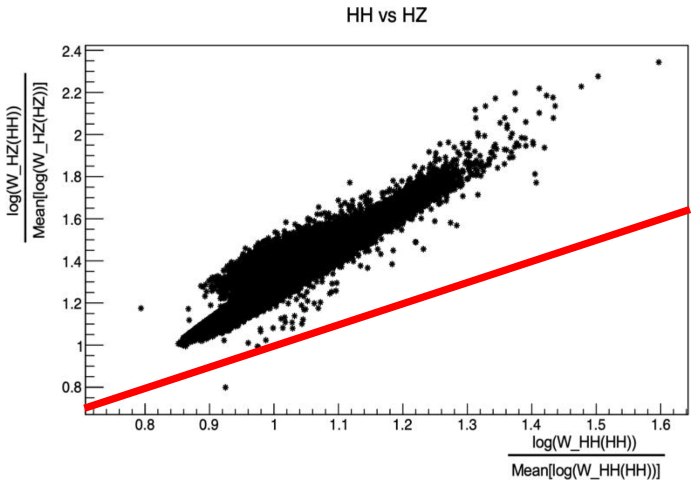


→ Good

Thank you for your attention

Back up

MoMEMta

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

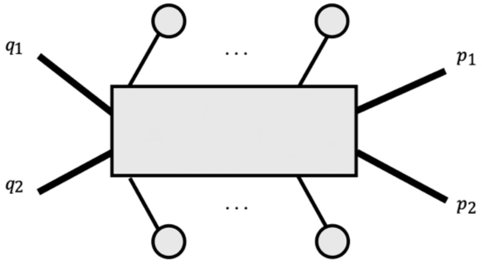
Main block	Topology	Removes...	For
A	$(q_1, q_2) \to p_1 + p_2$	$q_1,\ q_2,\ \|p_1\|,\ \|p_2\|$	
B	$(q_1, q_2) \to s_{12}(\to\ p_1 + p_2)$	$q_1,\ q_2,\ p_1$	s_{12}
C	$(q_1, q_2) \to s_{123} \to p_3 + s_{12}(\to\ p_1 + p_2)$	$q_1,\ q_2,\ p_1,\ \|p_3\|$	$s_{12},\ s_{123}$
D	$(q_1, q_2) \to s_{134}(\to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

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

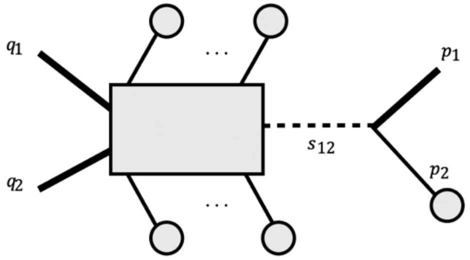
[https://doi.org/10.1140/epjc/s10052-019-6635-5]

Main and Secondary Blocks

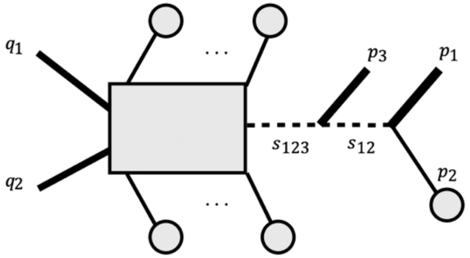
Main blocks



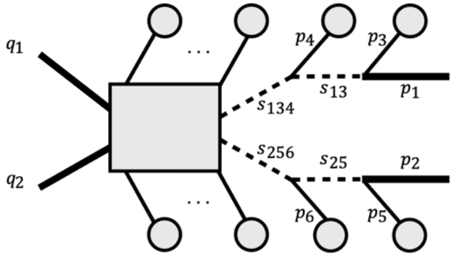
(a) MB A



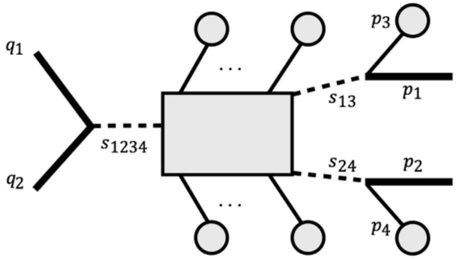
(b) MB B



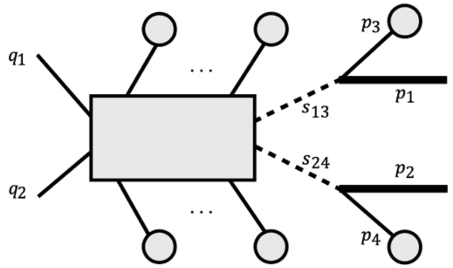
(c) MB C



(d) MB D

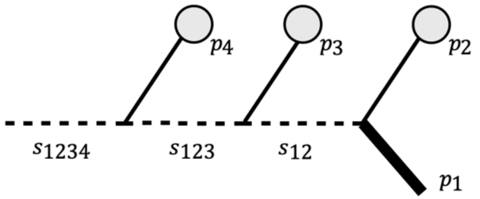


(e) MB E

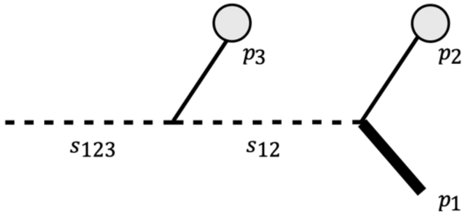


(f) MB F

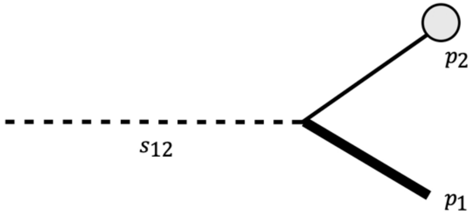
Secondary blocks



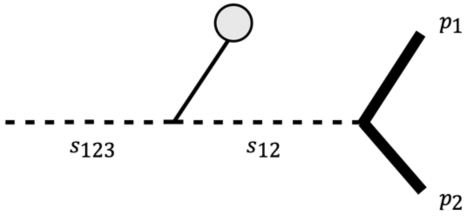
(a) SB A



(b) SB B



(c) SB C/D

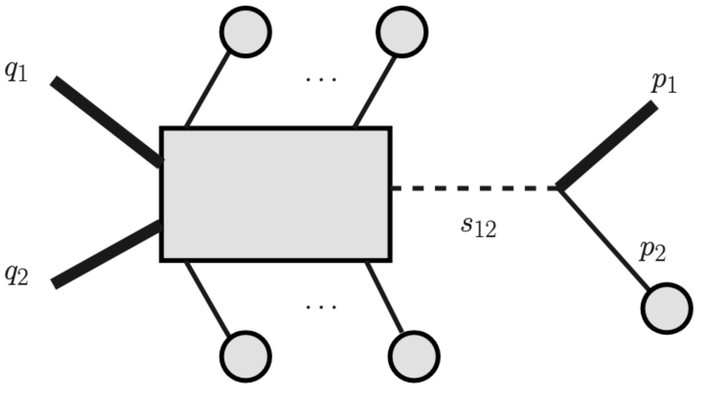


(d) SB E

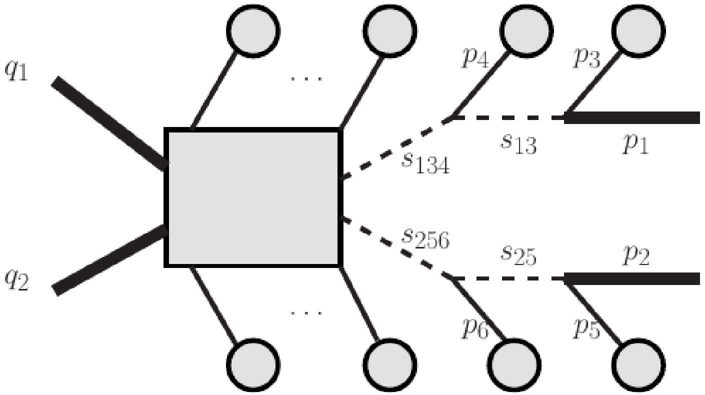
How to construct Higgs Self-coupling?

- None of the availible blocks fit the decay
- Creation of a custom block possible but jacobian needed …

→ No custom Block

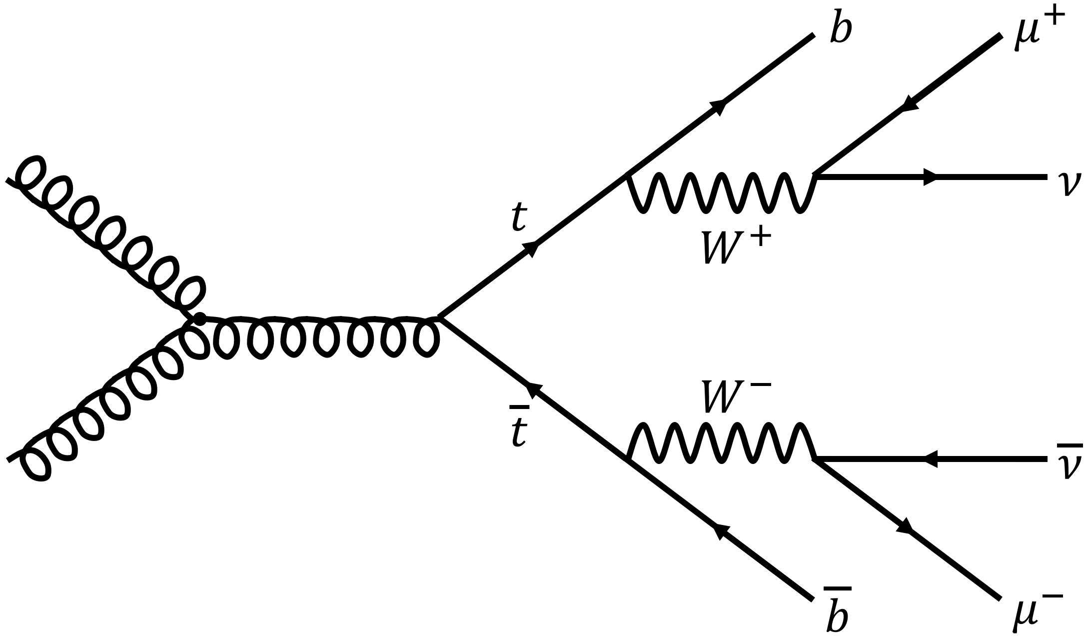


$$J = \frac{E_1}{s}\left|p_{2z}E_1 - E_2 p_{1z}\right|^{-1}$$

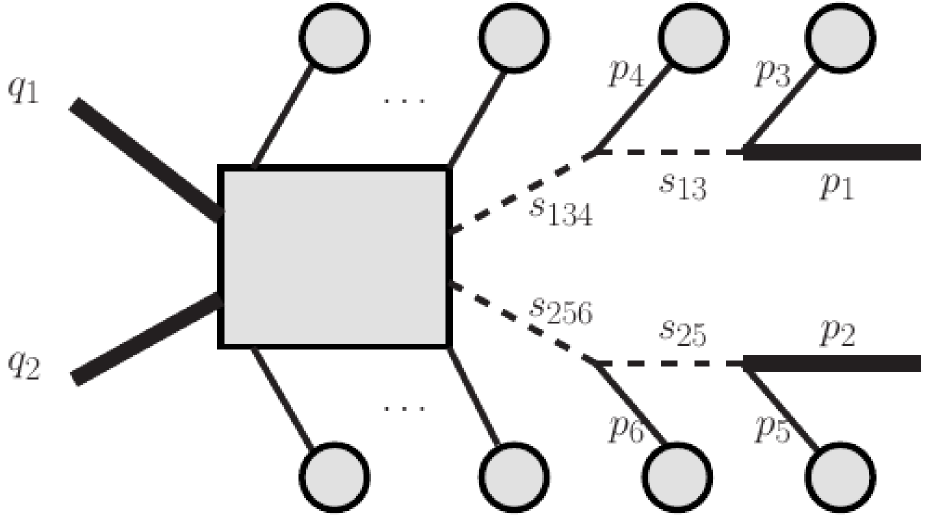


$$\begin{aligned}
J = \frac{E_1E_2}{8s}\bigg| & E_3\Big\{E_5\big[p_{34z}(p_{1y}p_{2z}p_{56x} - p_{1x}p_{2z}p_{56y} \\
& -p_{1y}p_{2x}p_{56z} + p_{1x}p_{2y}p_{56z}) + p_{1z}(-p_{2z}p_{34y}p_{56x} + \\
& p_{2z}p_{34x}p_{56y} - p_{2y}p_{34x}p_{56z} + p_{2x}p_{34y}p_{56z})\big] + \\
& (E_{56}p_{2z} - E_2p_{56z})(p_{1z}p_{34y}p_{5x} - p_{1y}p_{34z}p_{5x} - p_{1z}p_{34x}p_{5y} + \\
& p_{1x}p_{34z}p_{5y}) + \big[E_{56}(p_{1z}p_{2y}p_{34x} - p_{1z}p_{2x}p_{34y} + p_{1y}p_{2x}p_{34z} - \\
& p_{1x}p_{2y}p_{34z}) + E_2(p_{1z}p_{34y}p_{56x} - p_{1y}p_{34z}p_{56x} - p_{1z}p_{34x}p_{56y} + \\
& p_{1x}p_{34z}p_{56y})\big]p_{5z}\Big\} + E_{34}\Big\{E_5p_{2z}(p_{1z}p_{3y}p_{56x} - p_{1y}p_{3z}p_{56x} \\
& -p_{1z}p_{3x}p_{56y} + p_{1x}p_{3z}p_{56y}) + E_5(p_{1z}p_{2y}p_{3x} - p_{1z}p_{2x}p_{3y} \\
& +p_{1y}p_{2x}p_{3z} - p_{1x}p_{2y}p_{3z})p_{56z} - (E_{56}p_{2z} - E_2p_{56z}) \\
& (p_{1z}p_{3y}p_{5x} - p_{1y}p_{3z}p_{5x} - p_{1z}p_{3x}p_{5y} + p_{1x}p_{3z}p_{5y}) \\
& -\big[E_{56}(p_{1z}p_{2y}p_{3x} - p_{1z}p_{2x}p_{3y} + p_{1y}p_{2x}p_{3z} - p_{1x}p_{2y}p_{3z}) + \\
& E_2(p_{1z}p_{3y}p_{56x} - p_{1y}p_{3z}p_{56x} - p_{1z}p_{3x}p_{56y} + p_{1x}p_{3z}p_{56y})\big]p_{5z}\Big\} + \\
& E_1\Big\{\big[E_5(p_{2z}(-p_{34z}p_{3y}p_{56x} + p_{34y}p_{3z}p_{56x} + \\
& p_{34z}p_{3x}p_{56y} - p_{34x}p_{3z}p_{56y}) + \\
& (-p_{2y}p_{34z}p_{3x} + p_{2x}p_{34z}p_{3y} + p_{2y}p_{34x}p_{3z} - p_{2x}p_{34y}p_{3z})p_{56z}\big] + \\
& \big[E_{56}p_{2z} - E_2p_{56z})(p_{34z}p_{3y}p_{5x} - p_{34y}p_{3z}p_{5x} - p_{34z}p_{3x}p_{5y} + \\
& p_{34x}p_{3z}p_{5y}) + (E_{56}(p_{2y}p_{34z}p_{3x} - p_{2x}p_{34z}p_{3y} - p_{2y}p_{34x}p_{3z} + \\
& p_{2x}p_{34y}p_{3z}) + E_2(p_{34z}p_{3y}p_{56x} - p_{34y}p_{3z}p_{56x} - p_{34z}p_{3x}p_{56y} + \\
& p_{34x}p_{3z}p_{56y})\big]p_{5z}\Big\}\bigg|^{-1},
\end{aligned}$$

$t\bar{t}$ fully leptonic Decay



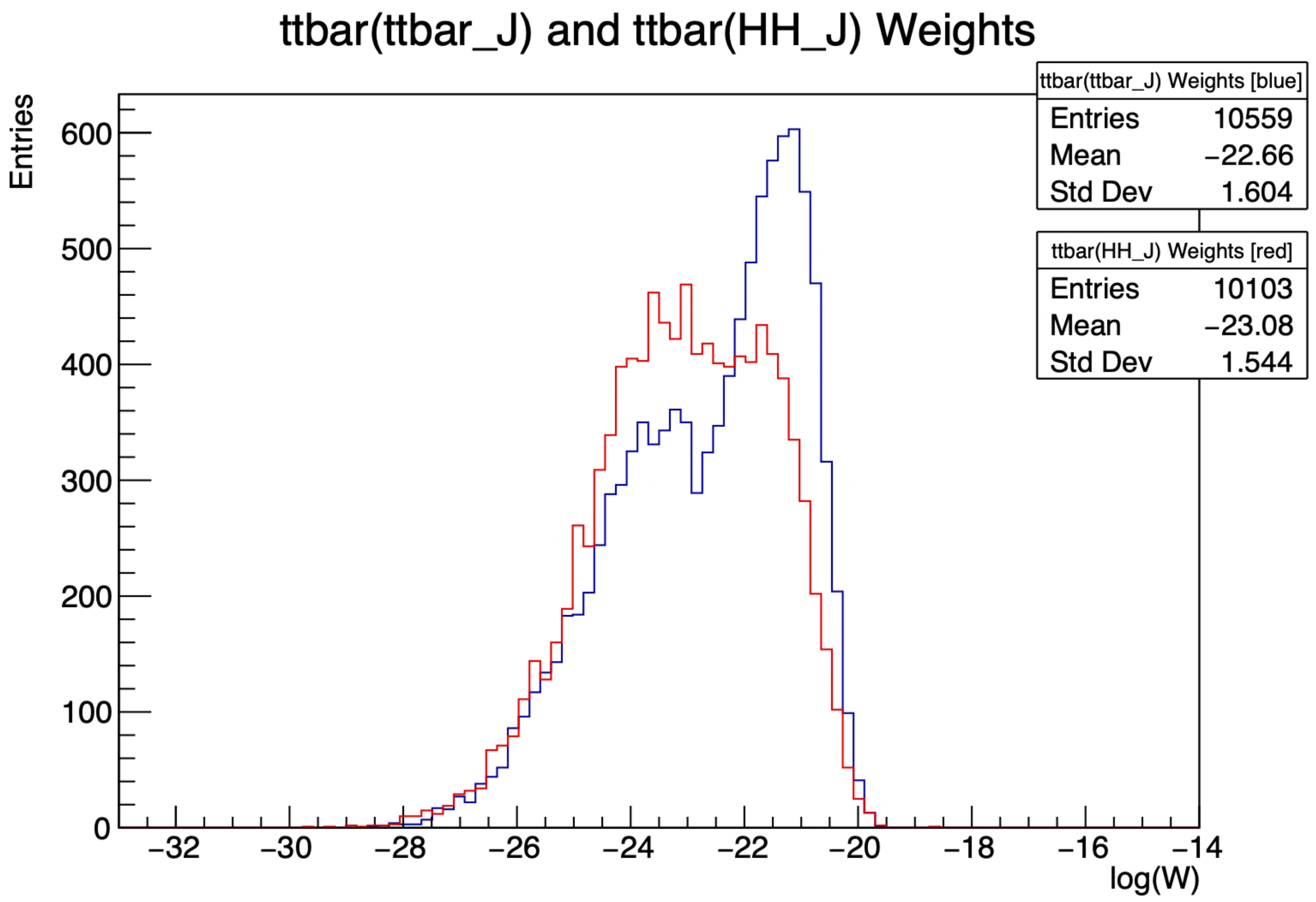
$t\bar{t}$ fully leptonic Decay



Main block D

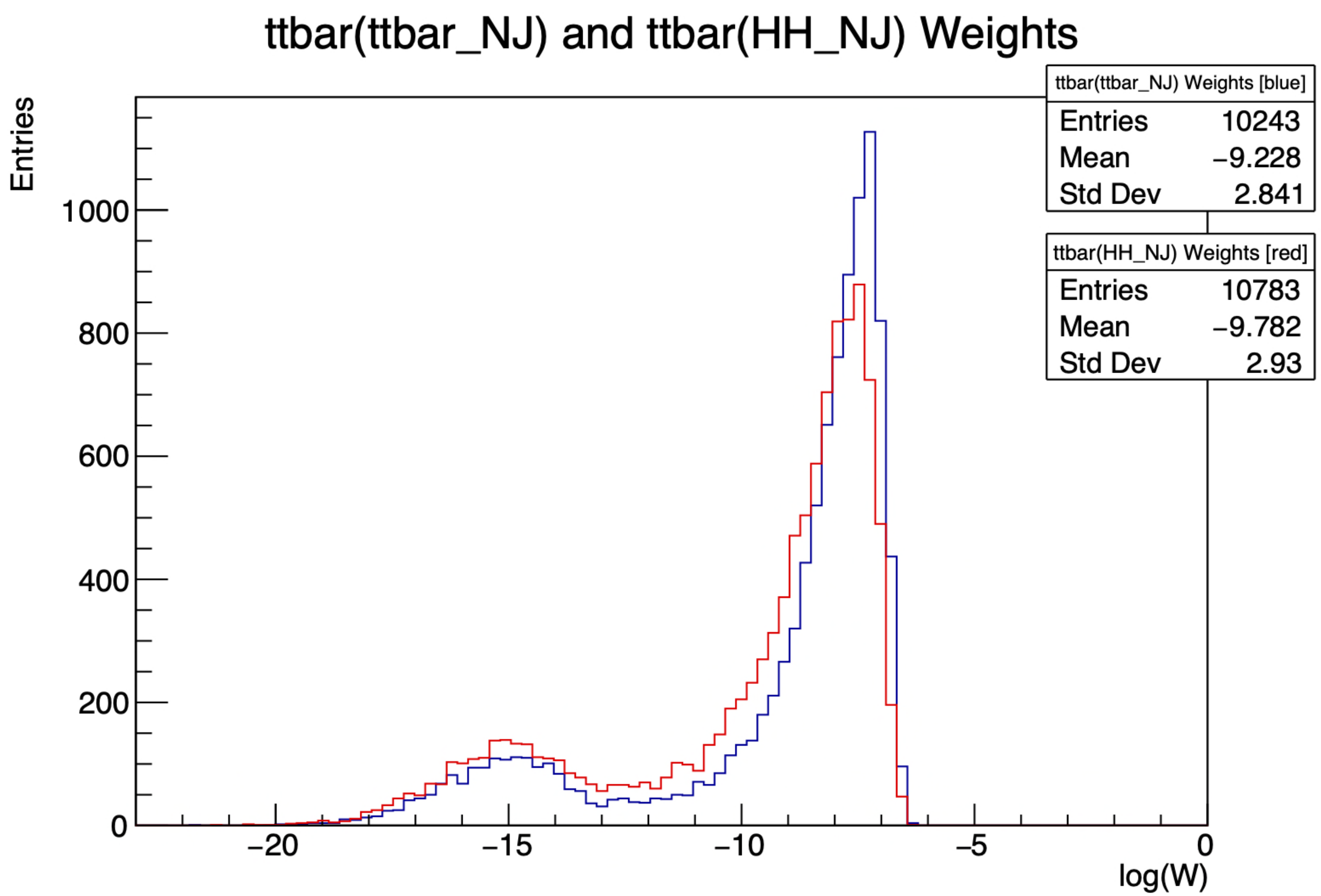
$t\bar{t}$ fully leptonic Decay

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



$t\bar{t}$ fully leptonic Decay

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



jacobians = jacobians

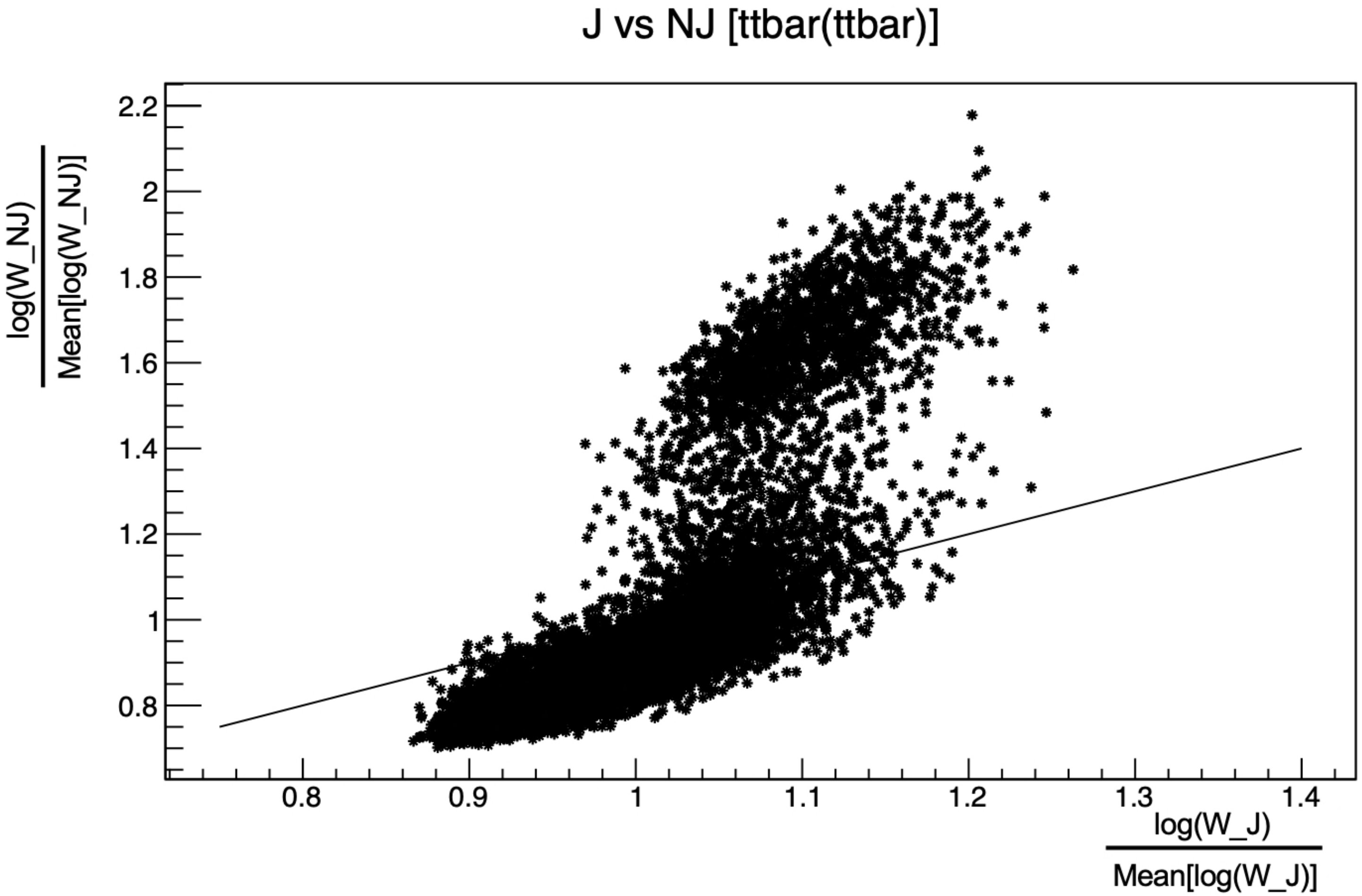
```
jacobians = {'flatter_s12::jacobian', 'flatter_s13::jacobian',
             'flatter_s24::jacobian'}

if USE_TF then
    append(jacobians, 'tf_p41::TF_times_jacobian', 'tf_p21::TF_times_jacobian',
                      'tf_p42::TF_times_jacobian', 'tf_p3::TF_times_jacobian',
                      'tf_p22::TF_times_jacobian', 'tf_p1::TF_times_jacobian')
end

append(jacobians,'phaseSpaceOut::phase_space', 'looperCD::jacobian', 'looper::jacobian')
```

- jacobians variable involves all the quantities that affect the final Jacobian value
- Causes error since the topology here does not match block F’s original topology

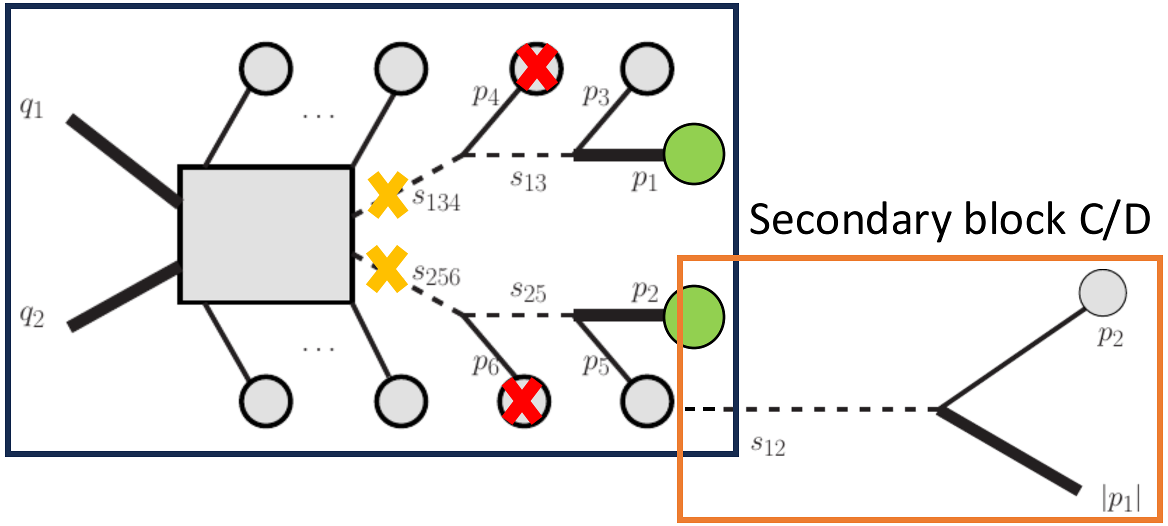
jacobians = jacobians

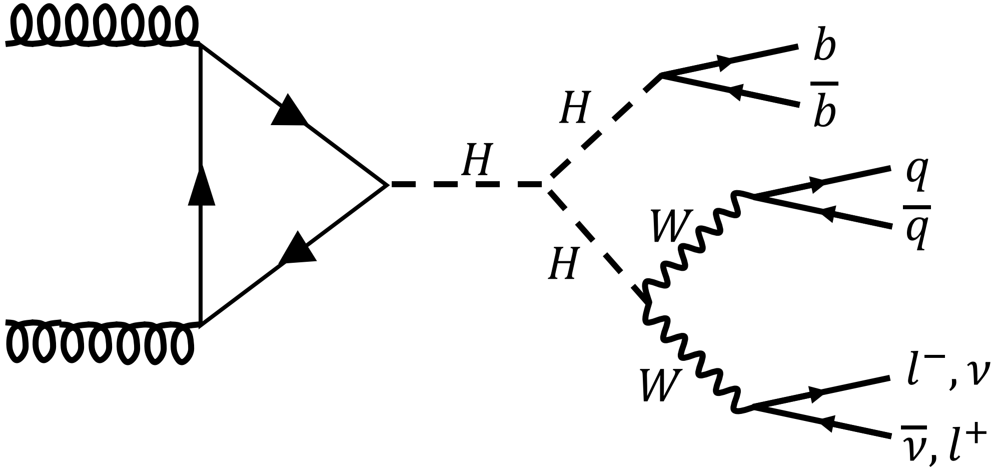


jacobians = jacobians line does not affect the ability to distinguish between two processes

Higgs Self-coupling in MoMEMta

Main block D





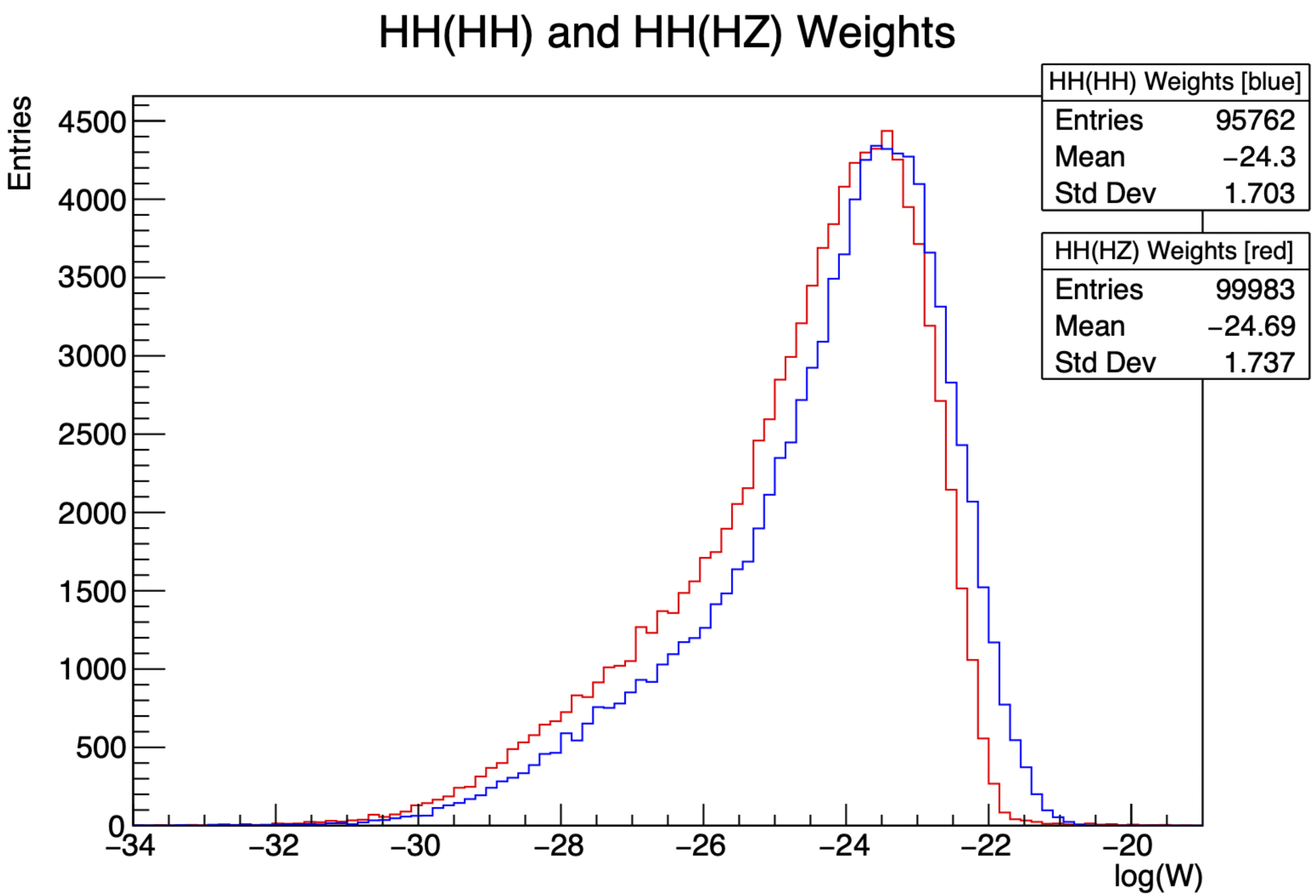
Main block D changes

- Set $p4 = p6 = 0$ → No need for dashed lines $s134$ & $s256$
- Make $p1$ & $p2$ inputs
- $p2$ is sum of off-shell W-boson daughters

→ Weights can be calculated

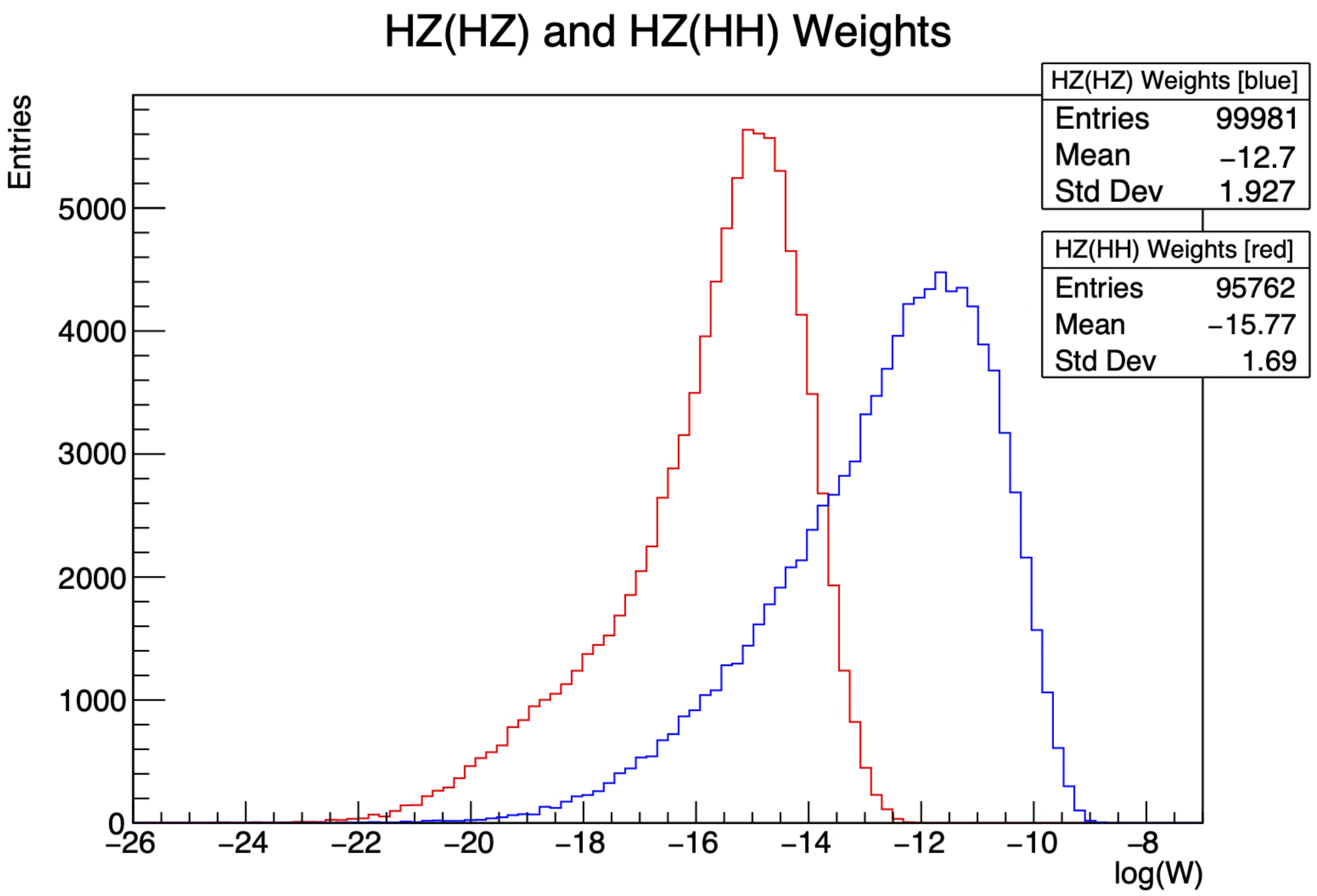
Higgs Self-coupling

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



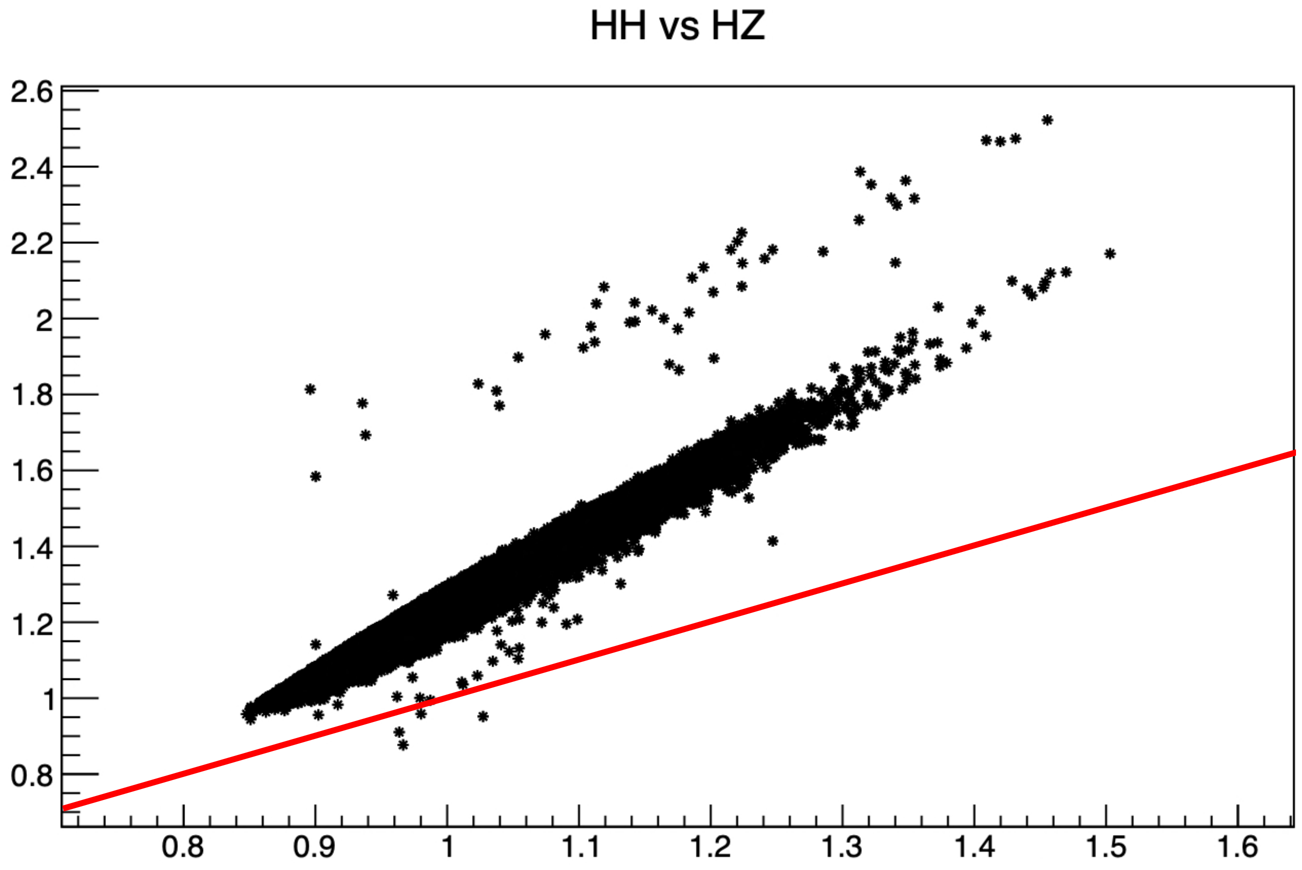
HZ coupling

Weights $= HZ(\text{inputs} = x)$ under $\mathrm{Z} \rightarrow HZ$ hypothesis



Higgs self- vs HZ coupling

$$\frac{\log[HZ(HH)]}{Mean\{\log[HZ(HZ)]\}}$$



$$\frac{\log[HH(HH)]}{Mean\{\log[HH(HH)]\}}$$

→ 4 out of 95761 events was missclasified as a HZ event