Higgs Coupling Measurements with Polarized Diboson Processes

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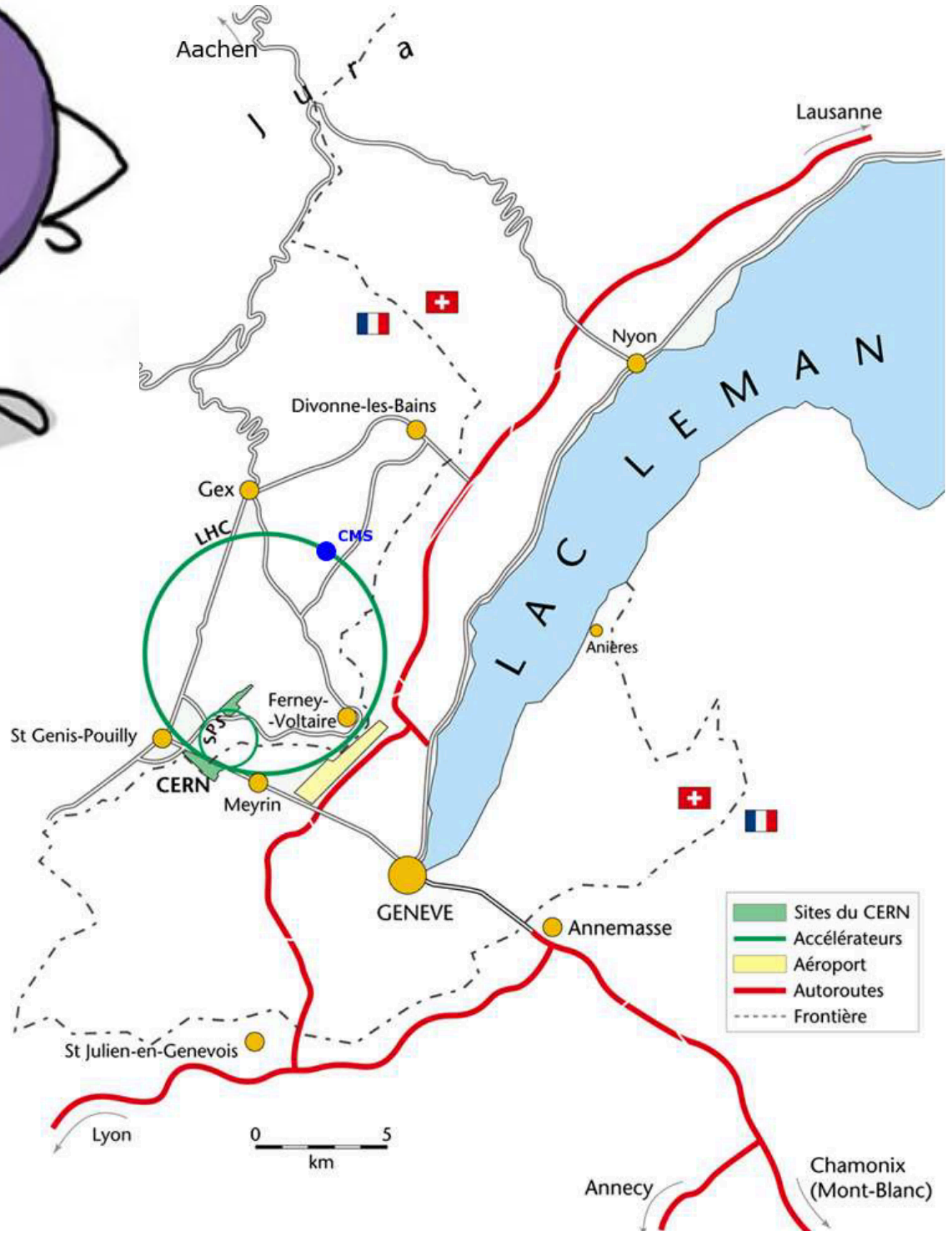
The Higgs at the LHC

- *Run I* (2010 - 2013)
    - Discovery of Higgs Boson (2012)
        - Final piece of Standard Model (SM)
        - Verified Higgs mechanism

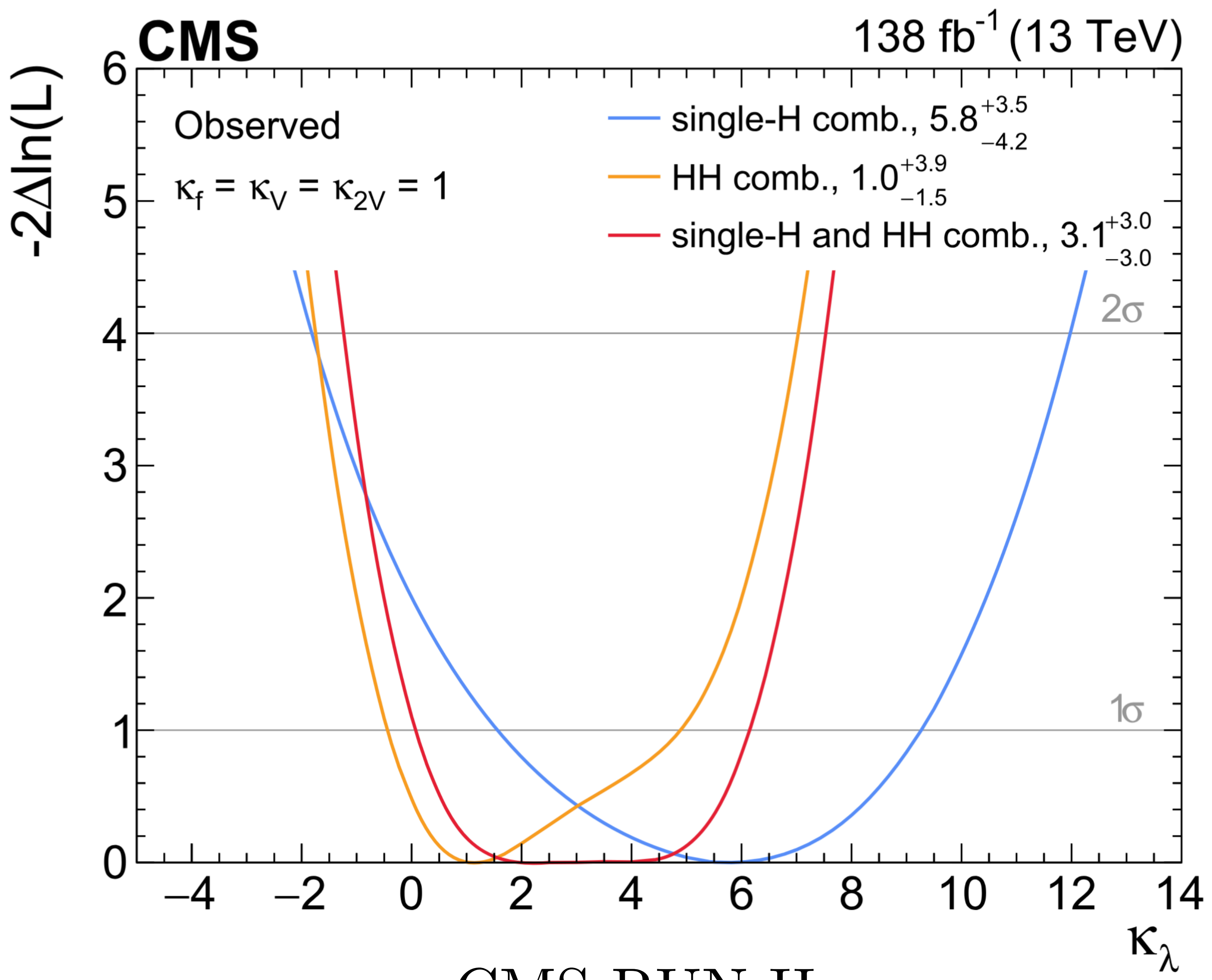
- *Run II* (2015 - 2018), *Run III* (2022 - 2026), and beyond (HL-LHC)
    - Core LHC program: Precision electroweak (EW) measurements
        - Higgs couplings to other particles and itself

Precise Higgs measurements are crucial for understanding EW physics
- Deviations from SM may indicate new physics
- Better understanding of structure of Higgs potential and EWSB

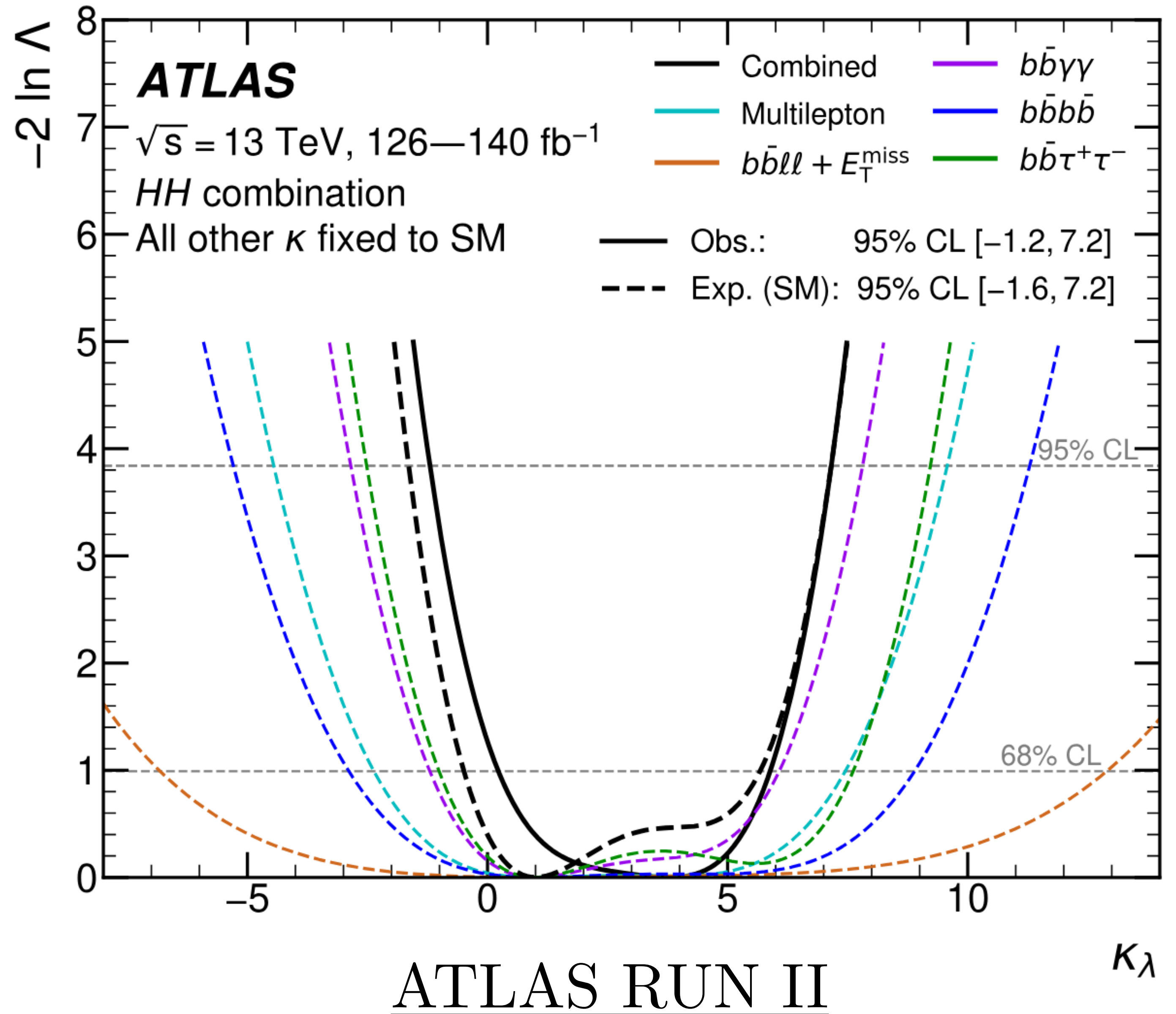


The Higgs at the LHC

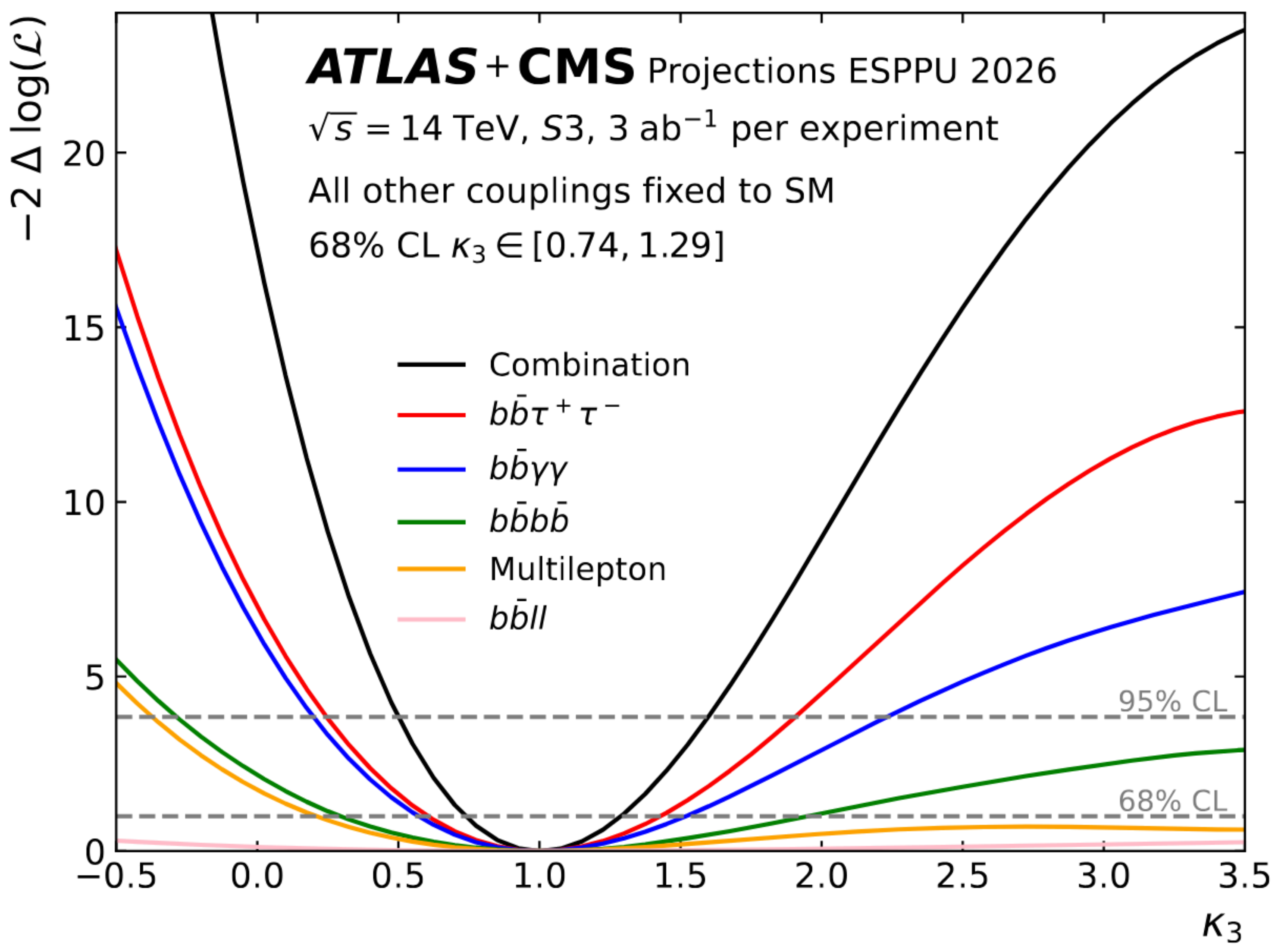
- Current LHC program
  - Direct (on-shell) measurements of Higgs production and sensitivity to couplings (κ_f, κ_V, ...)



CMS RUN II



ATLAS RUN II



ATLAS+CMS HL-LHC Projection

At HL-LHC limits same order of magnitude as present with ~20 times current data

→ New ideas are needed to extend reach in phase-space and constrain systematics

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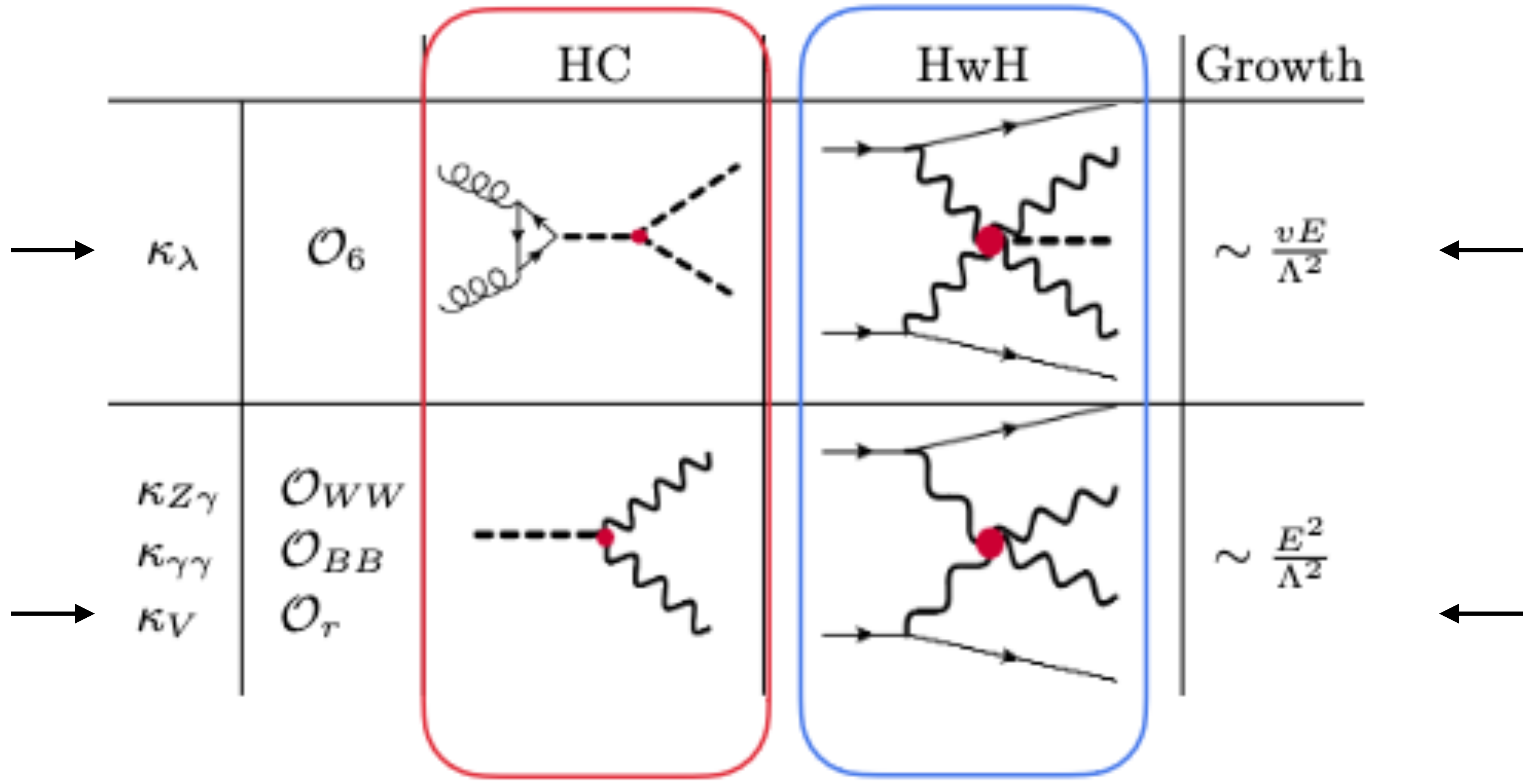
"Higgs without Higgs" Strategy*

- Study Higgs couplings via off-shell production
    - Sensitivity to Higgs couplings via $V_L V_L$
    - Goldstone Boson Equivalence Theorem (GBET)
        - $\mathcal{M}(V_L) = \mathcal{M}(\phi)$ as $E \to \infty$

- We propose a novel strategy to measure On-shell + Off-shell *simultaneously*, with same final state
    - On-shell: Direct measurement of κ_i
    - Off-shell: Additional sensitivity to κ_i from <u>longitudinally</u> polarized vector boson production

$$|H|^2 = \frac{1}{2}\left(v^2 + \boxed{2hv} + h^2 + \boxed{2\phi^+\phi^- + (\phi^0)^2}\right)$$



Measuring Higgs couplings on- and off-shell simultaneously allows direct constraints on new physics across a wide energy range, reducing the need for extrapolation, and capturing energy dependence induced by new phenomena

$$\begin{aligned} &\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R \\ &\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu} \\ &\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6 \qquad (1) \end{aligned}$$

$$|H|^2 \times \mathcal{O}^{SM}$$

*https://arxiv.org/abs/1812.09299

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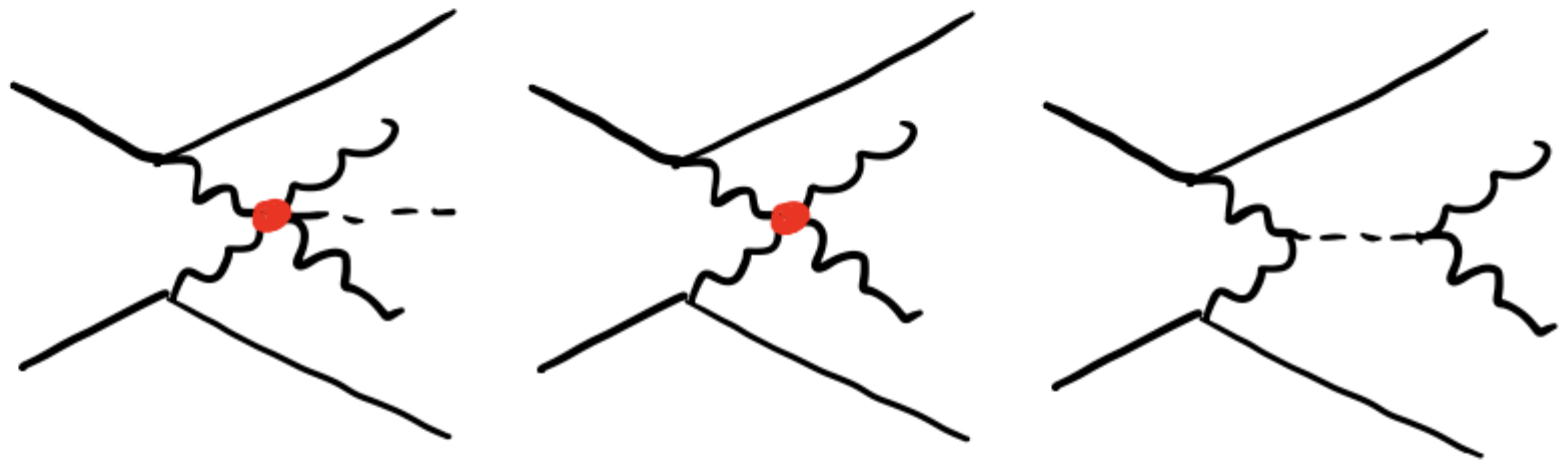
Analysis Strategy

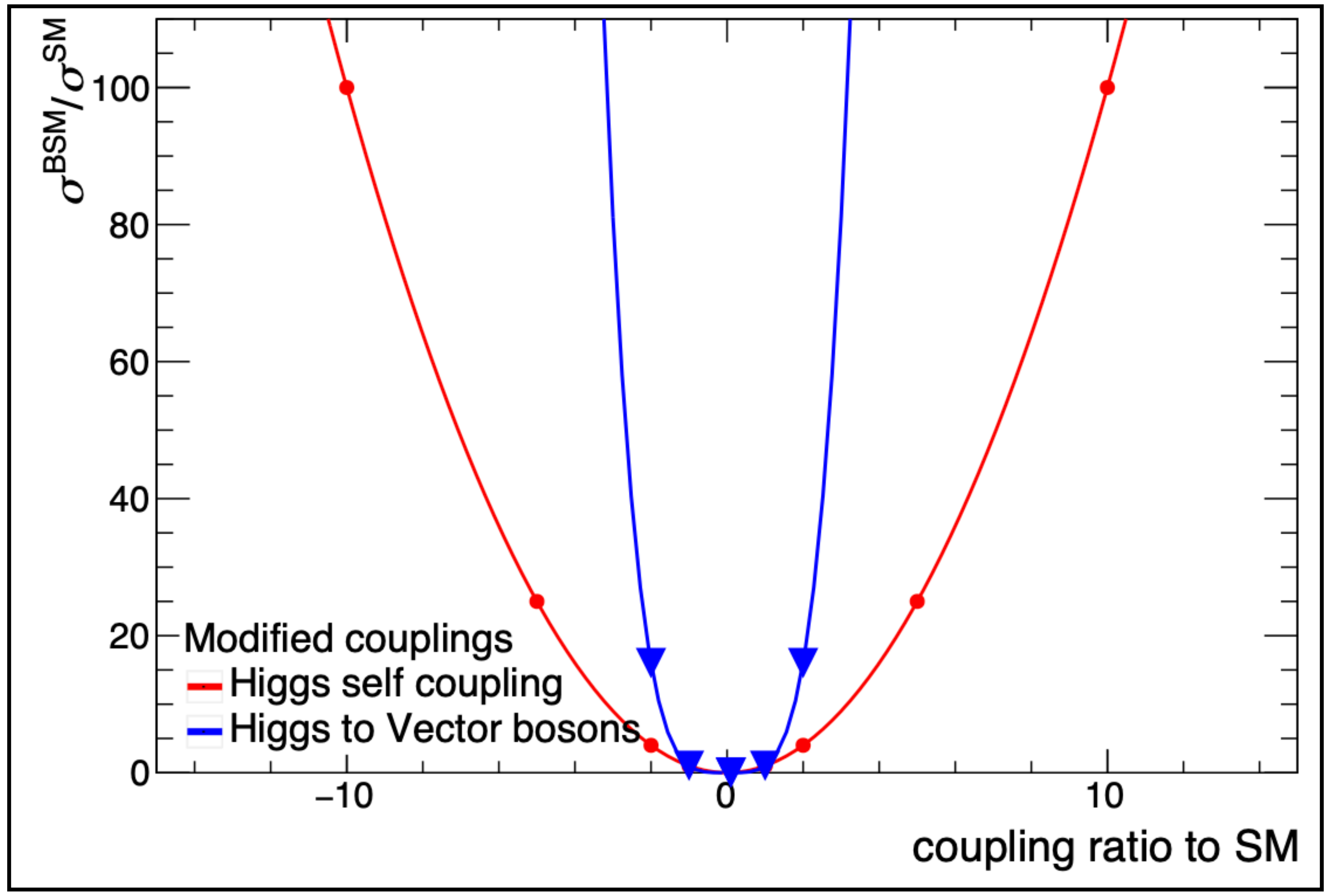
- Studying *six* signal processes with similar final states in both on- and off-shell regimes
  - VBS + H, VBS, VBF (x2 for $W^{\pm}W^{\mp}$, ZZ)



  - Clean leptonic final state + $H \to b\bar{b}$

- Coherent approach with six orthogonal selections, same object definitions, and polarization tagging
  - Minimizes extrapolations between phase-spaces
  - Reduces systematic uncertainties as correlated effects (lumi, detector effects, theory modeling) would partially cancel

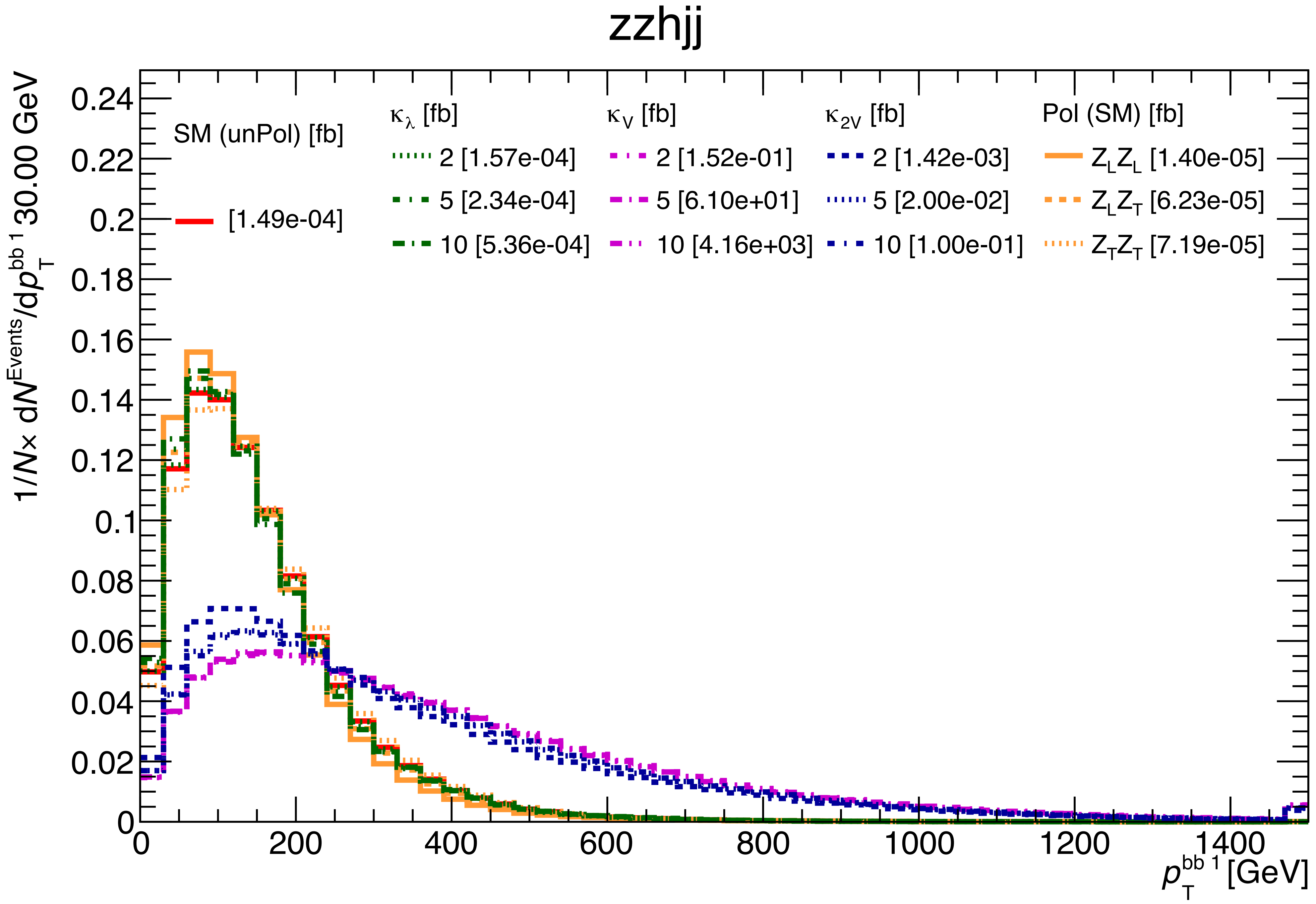
- Sensitivity to
  - Higgs Self-Coupling: κ_{λ}
  - Higgs Couplings to Vector Bosons: κ_V, κ_{VV}



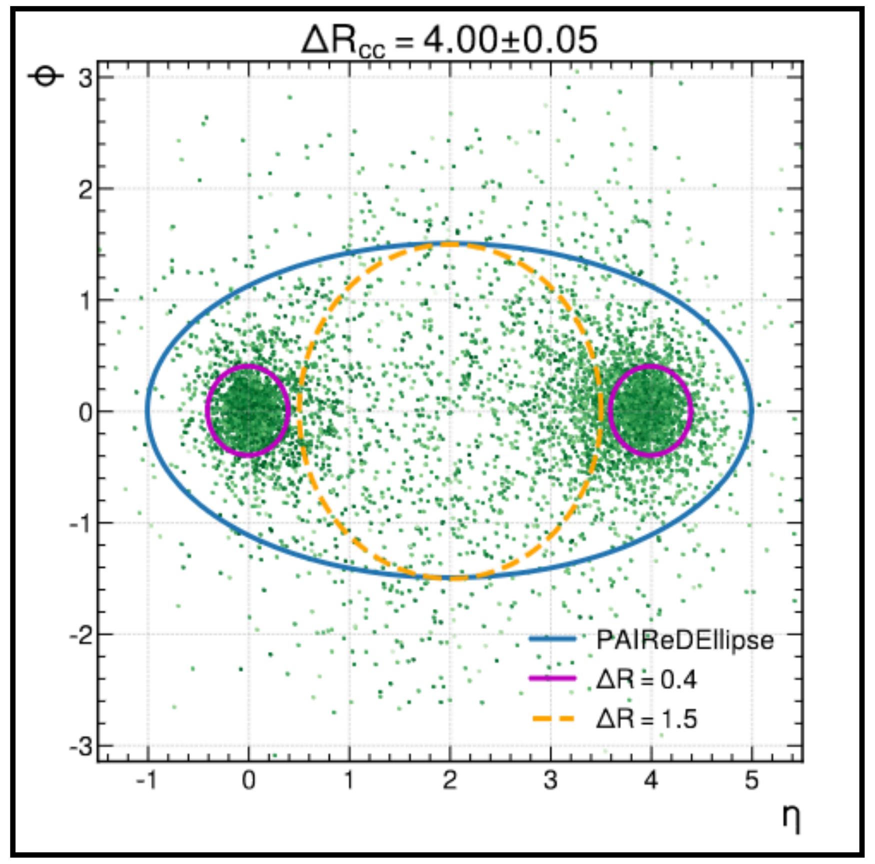
VBS+H cross-section deviation from SM as function of κ_{λ} and κ_V

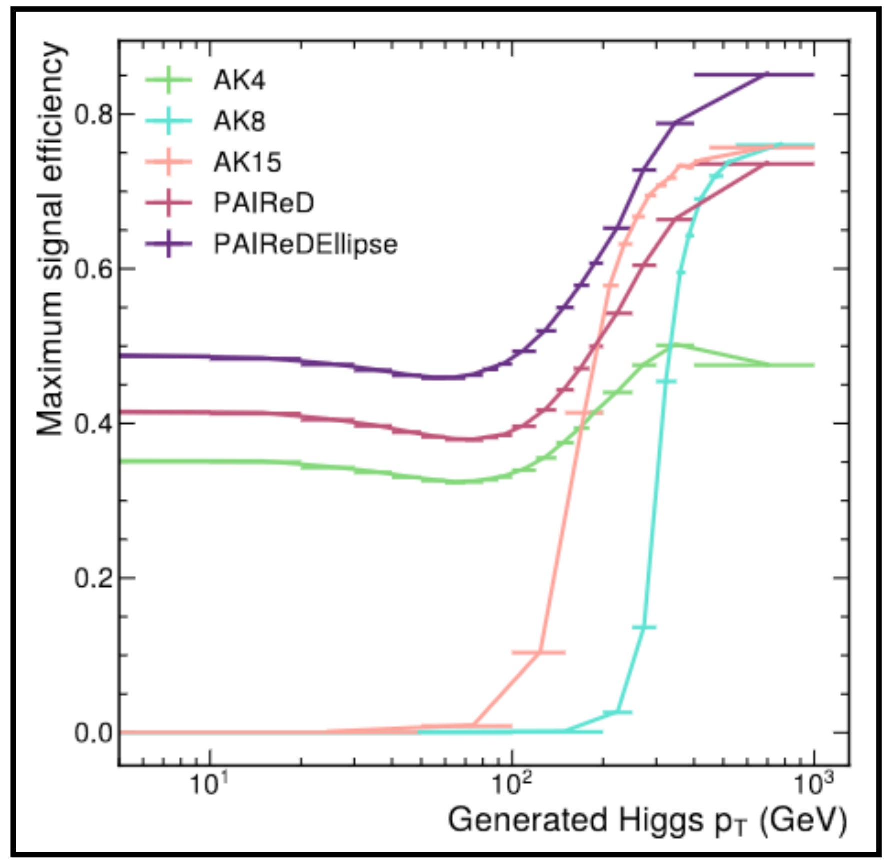
PAIReD

- $H \to b\bar{b}$ reconstruction: Particle Angular-separation Independent Resonant Dijet (PAIReD) method
    - New approach to reconstruct decays of heavy particles across large range of Lorentz-boosts
- Rather than tagging AK4 jets individually, define PAIReD jet based on 2 AK4 jets
    - Ellipse defined in $\eta - \phi$ plane



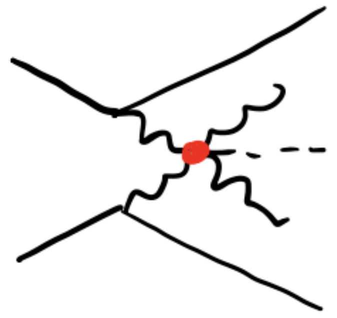
- Can achieve higher efficiencies and better background rejection for both boosted and resolved topologies
    - In studying on- and off-shell Higgs, reconstruction of wide range of Higgs PT is advantageous





Signal (Hcc) reconstruction efficiency as a function of Higgs pT (Left) Area covered by PAIReD - magenta, PAIReDEllipse - blue, AK15 - range (Right) Clustering efficiency of each reconstruction algorithm for ZHcc (Bottom)

ZZ + H + jj - Sig vs Background

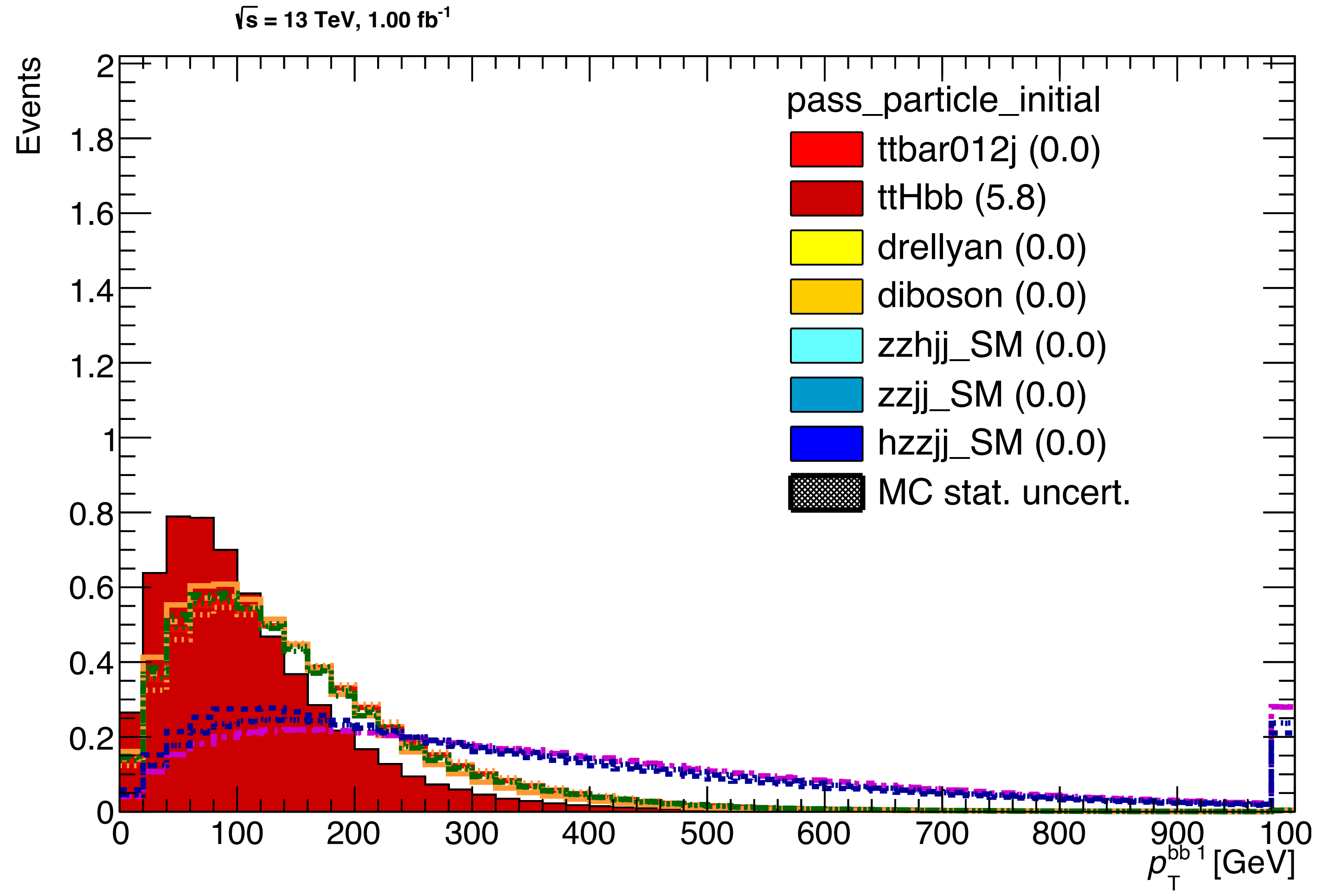


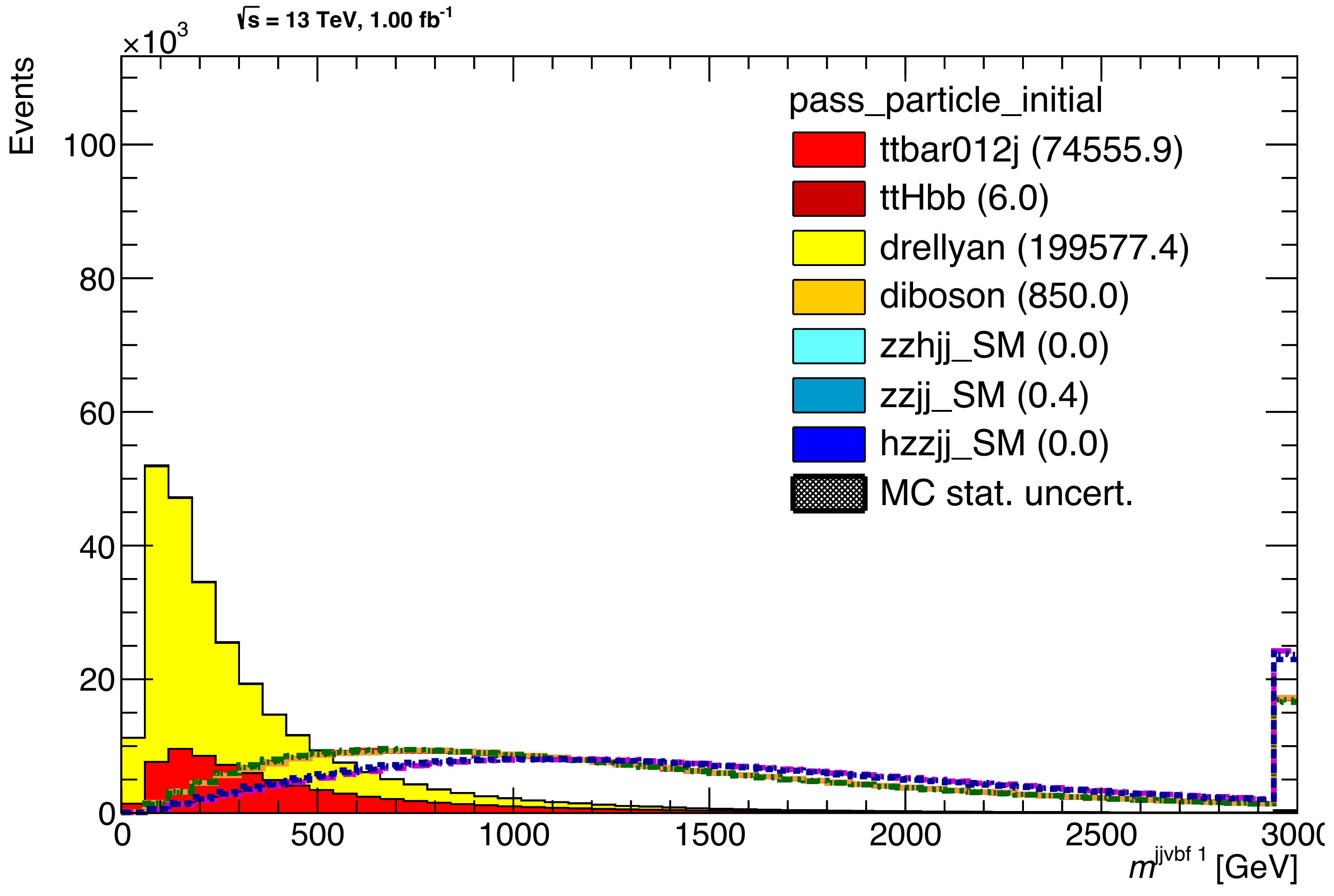
Backgrounds studied:

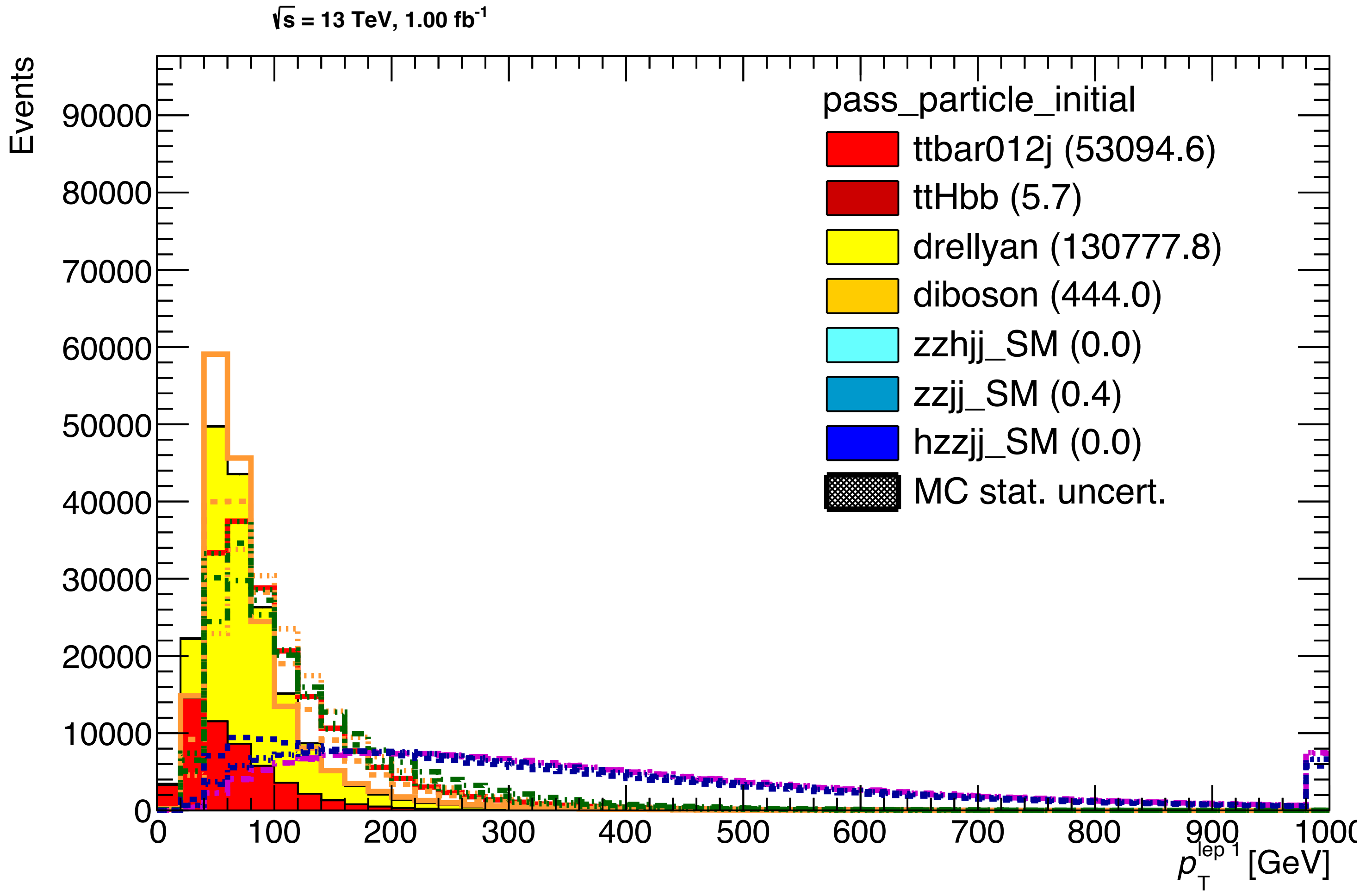
- DY, Diboson, ttbar, ttHbb

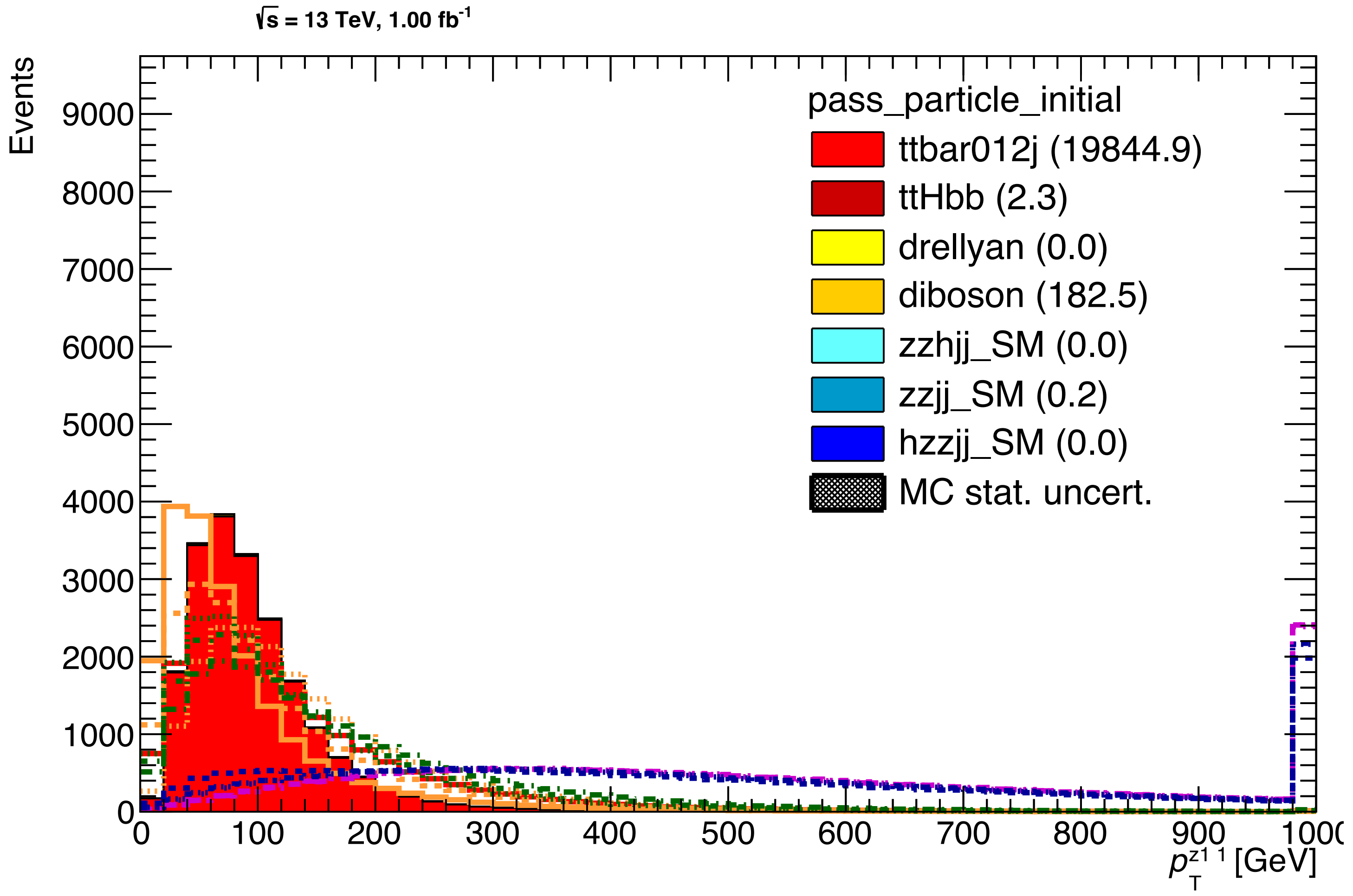
Signal distributions overlayed:

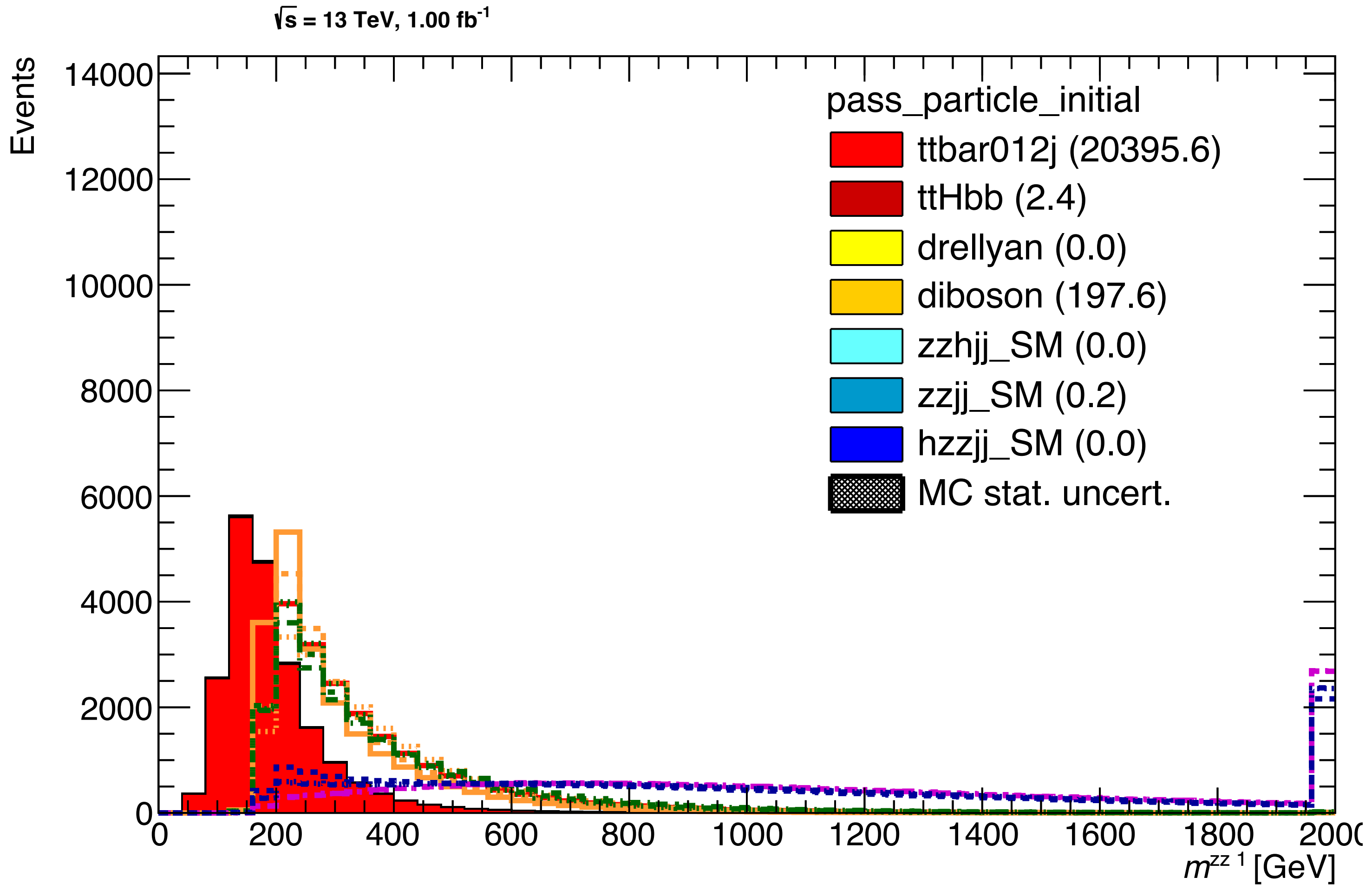
- SM (inclusive polarization)
- κ_{λ} , κ_{V} , κ_{VV} (2,5,10) variations (inclusive polarization)
- LL, LT, TL, and TT polarizations
- Normalized to 1, XS in fb shown in legend











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W+W- + H + jj - Sig vs Background

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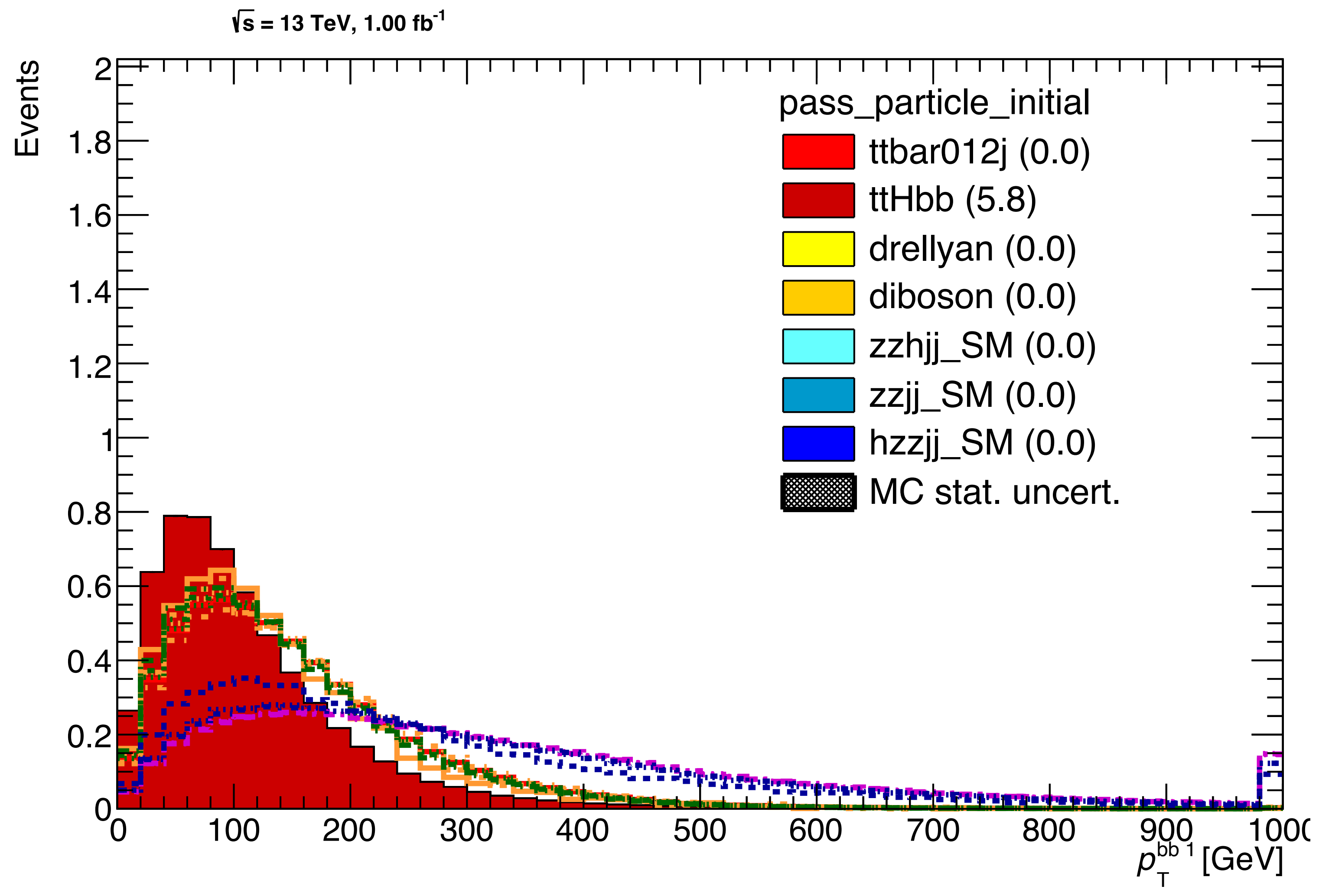

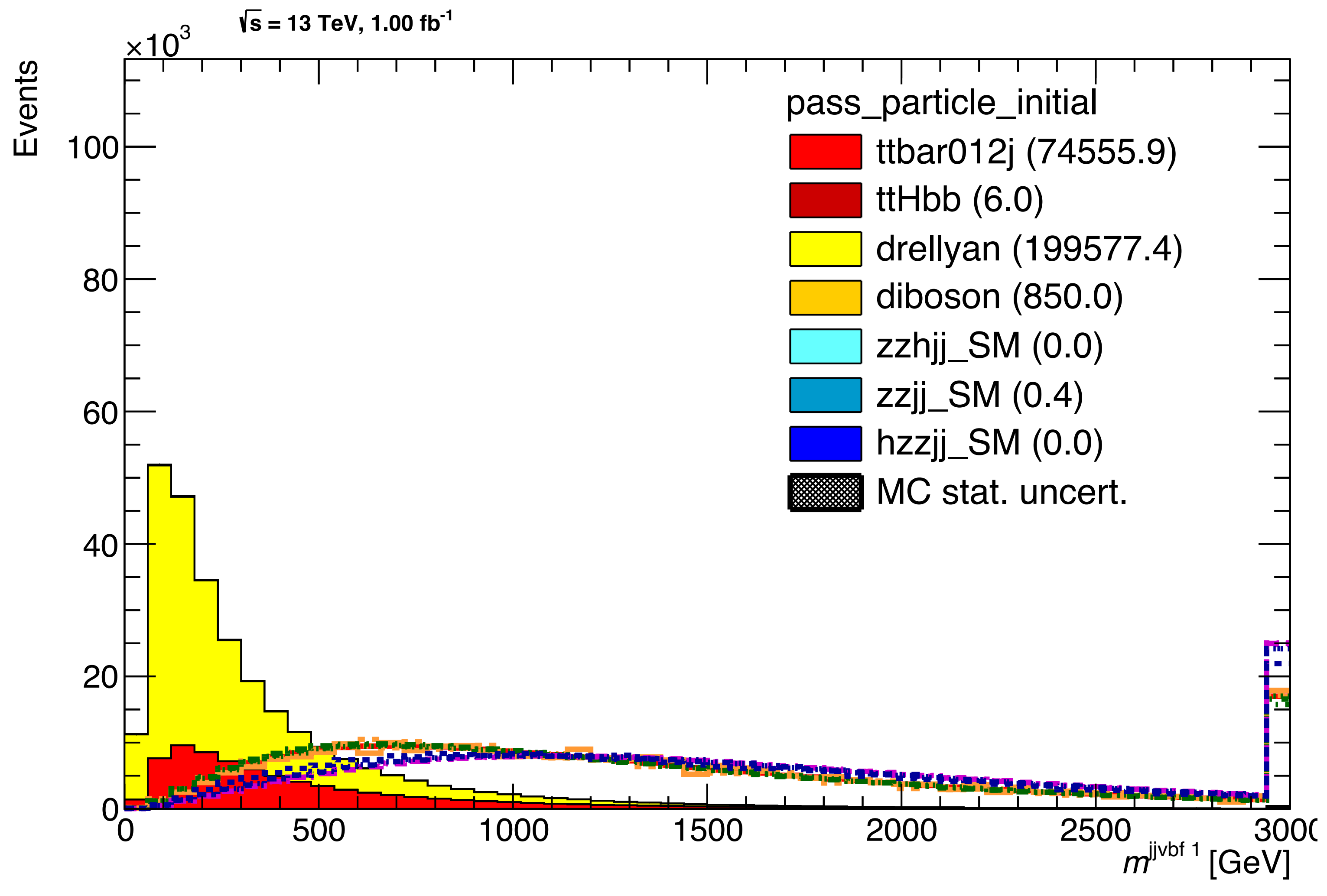

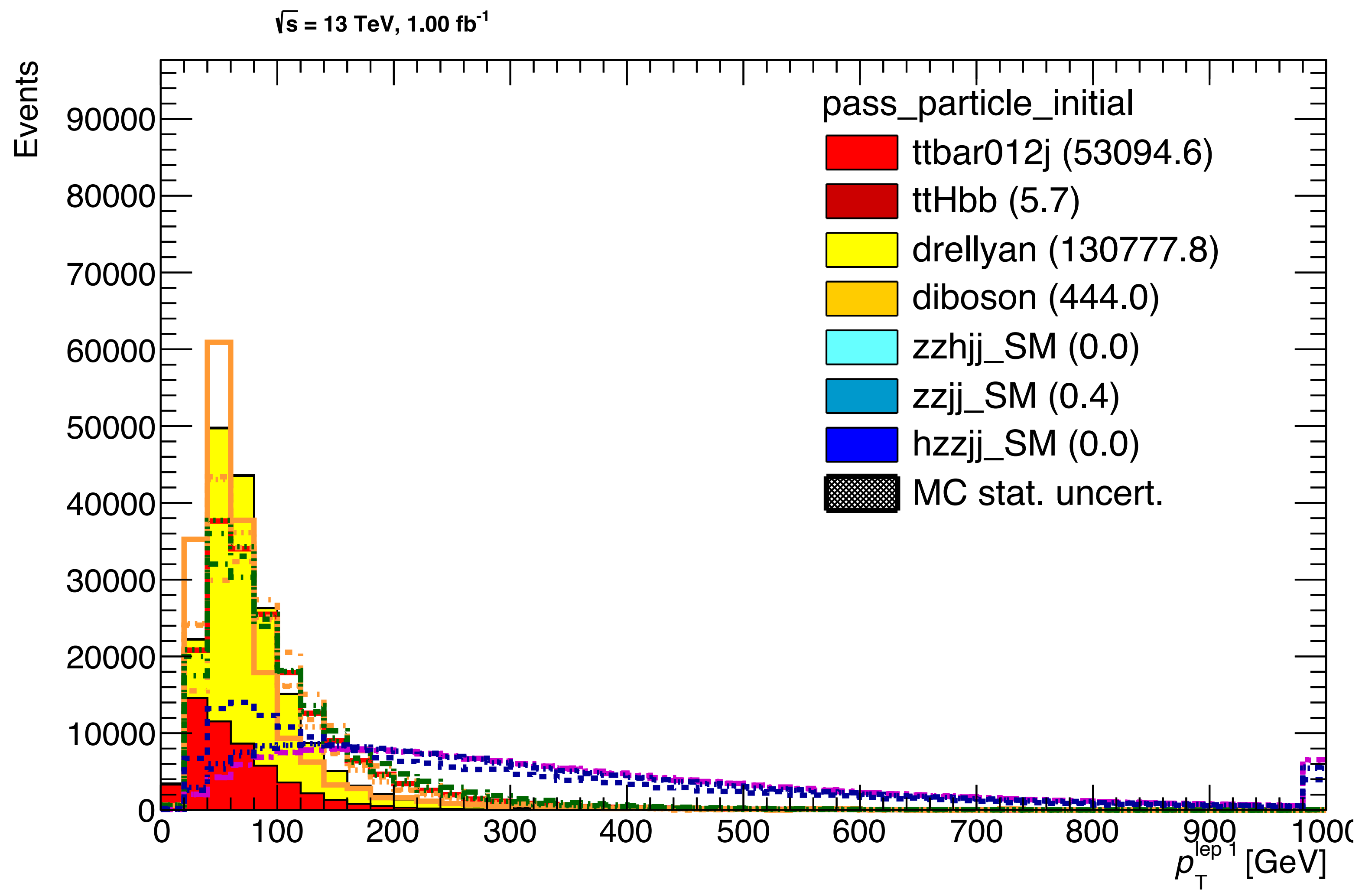

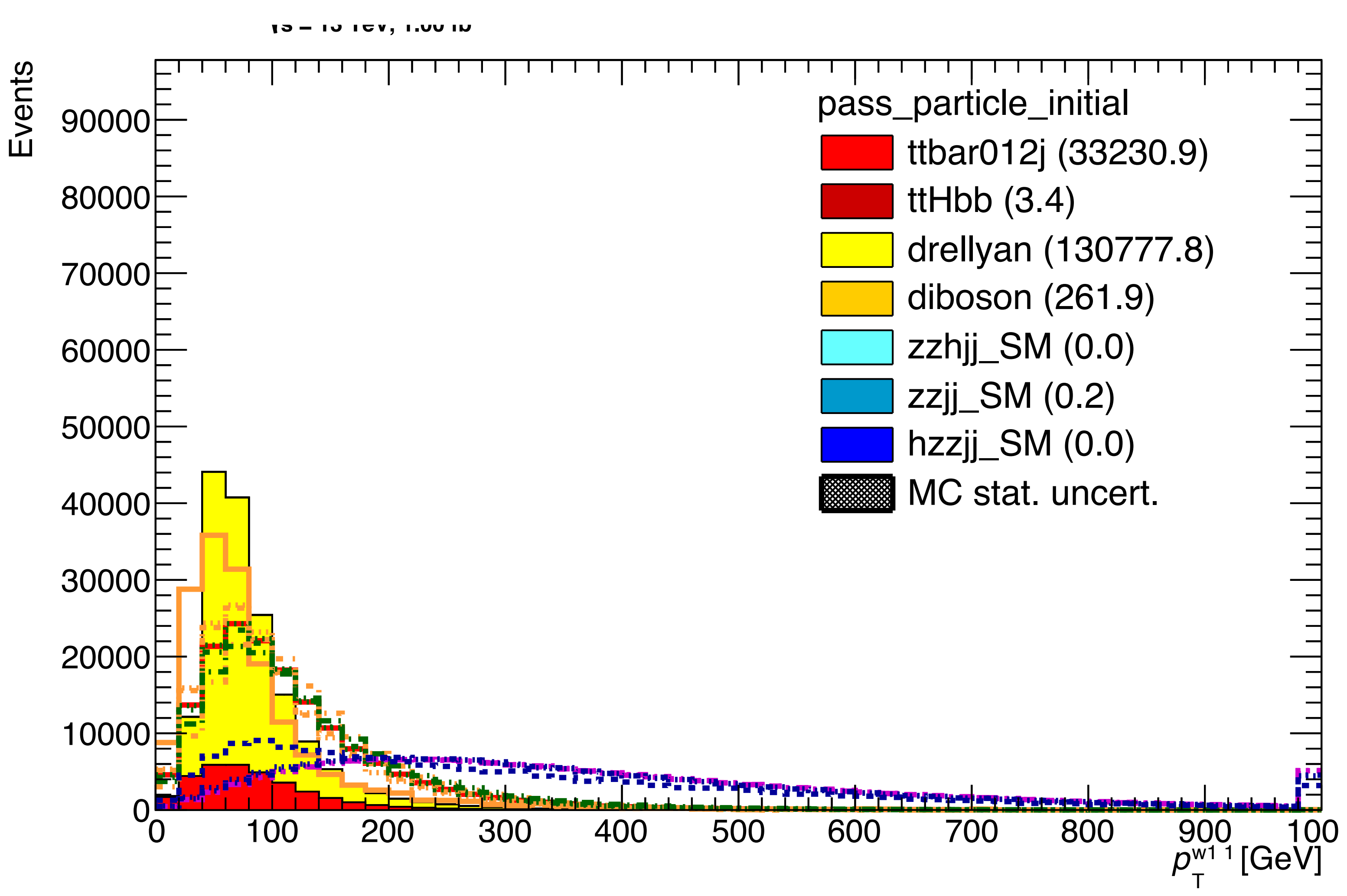

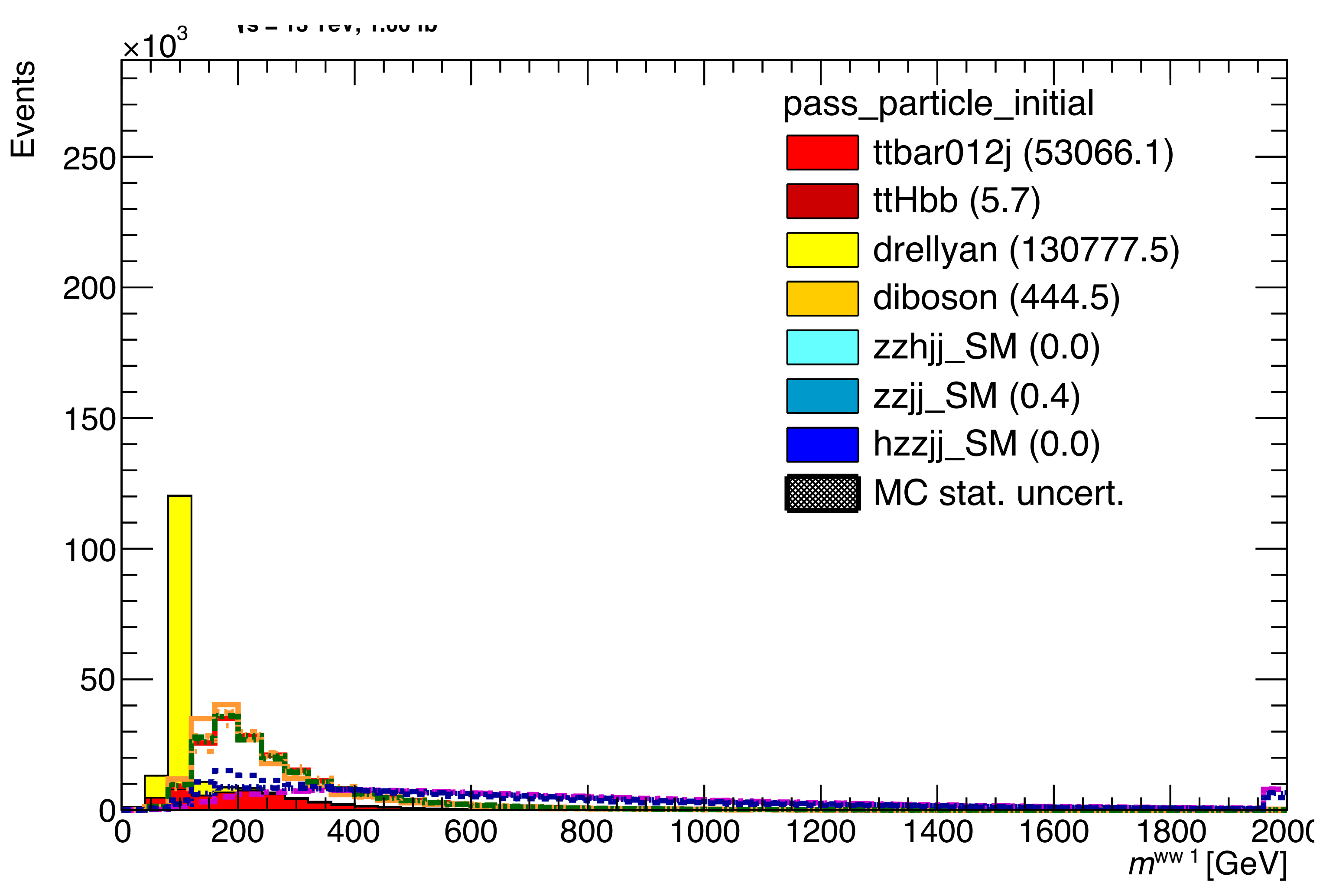

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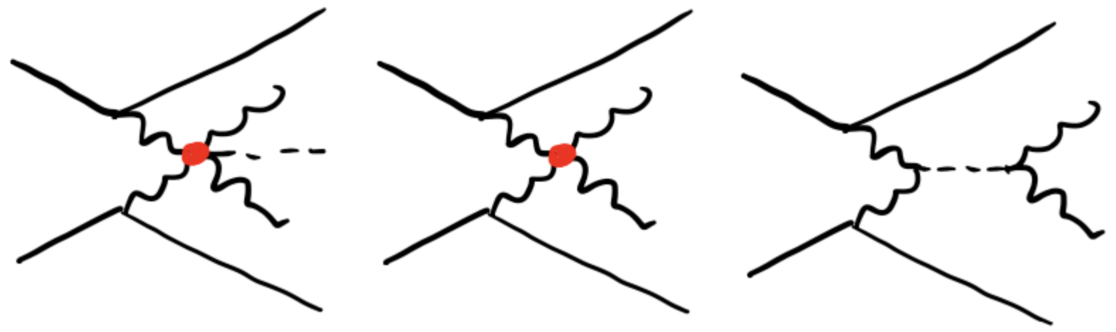
Preselection



VVHjj VVjj (HVV)jj

Applied to all events

Variable	Cut
p_ℓ^T	> 15 GeV
$\lvert\eta_\ell\rvert$	< 2.5
p_j^T	> 20 GeV
$\lvert\eta_j\rvert$	< 5
m_{jj}	> 250 GeV
$\lvert\Delta\eta_{jj}\rvert$	> 2.5

Sorting and selection

Requirement	W+W-Hjj	ZZHjj	W+W-jj	ZZjj	(H→W+W-)jj	(H→ZZ)jj
PAIReD $b\bar{b}$	✓	✓				
$105 < m_{bb} < 160$	✓	✓				
$\geq 2\ell$ OS	✓		✓		✓	
$\geq 4\ell$ OS		✓		✓		✓
$M_{VV} > 150$ GeV			✓	✓		
$M_{VV} < 150$ GeV					✓	✓
$E_{Miss}^T > 25$ GeV	✓		✓		✓	
$E_{Miss}^T < 25$ GeV		✓		✓		✓

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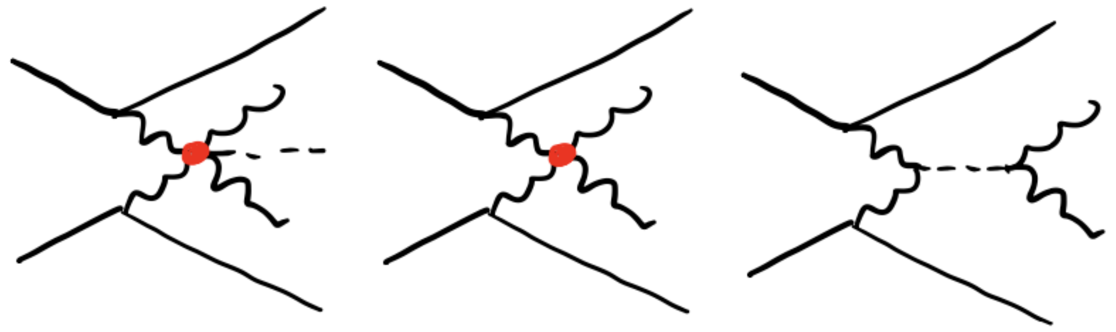
Preselection



VVHjj

Discriminate W+W- (2ℓ), ZZ (4ℓ) Events

Variable	Cut
p_ℓ^T	> 15 GeV
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p_j^T	> 20 GeV
$\lvert\eta_j\rvert$	< 5
m_{jj}	> 250 GeV
$\lvert\Delta\eta_{jj}\rvert$	> 2.5

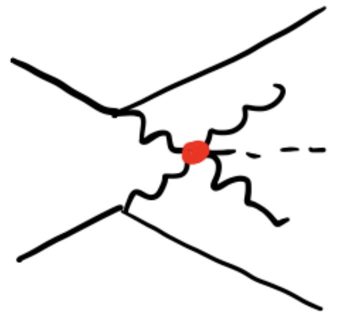
Requirement	W+W-Hjj	ZZHjj	W+W-jj	ZZjj	(H→W+W-)jj	(H→ZZ)jj
PAIReD $b\bar{b}$	✓	✓				
$105 < m_{bb} < 160$	✓	✓				
$\geq 2\ell$ OS	✓		✓		✓	
$\geq 4\ell$ OS		✓		✓		✓
$M_{VV} > 150$ GeV			✓	✓		
$M_{VV} < 150$ GeV					✓	✓
$E^T_{Miss} > 25$ GeV	✓		✓		✓	
$E^T_{Miss} < 25$ GeV		✓		✓		✓

VBF/VBS topologies

Further discriminate W+W-/ZZ

Discriminate on-shell Higgs from high-mass + off-shell Higgs

ZZ + H + jj - After Preselection



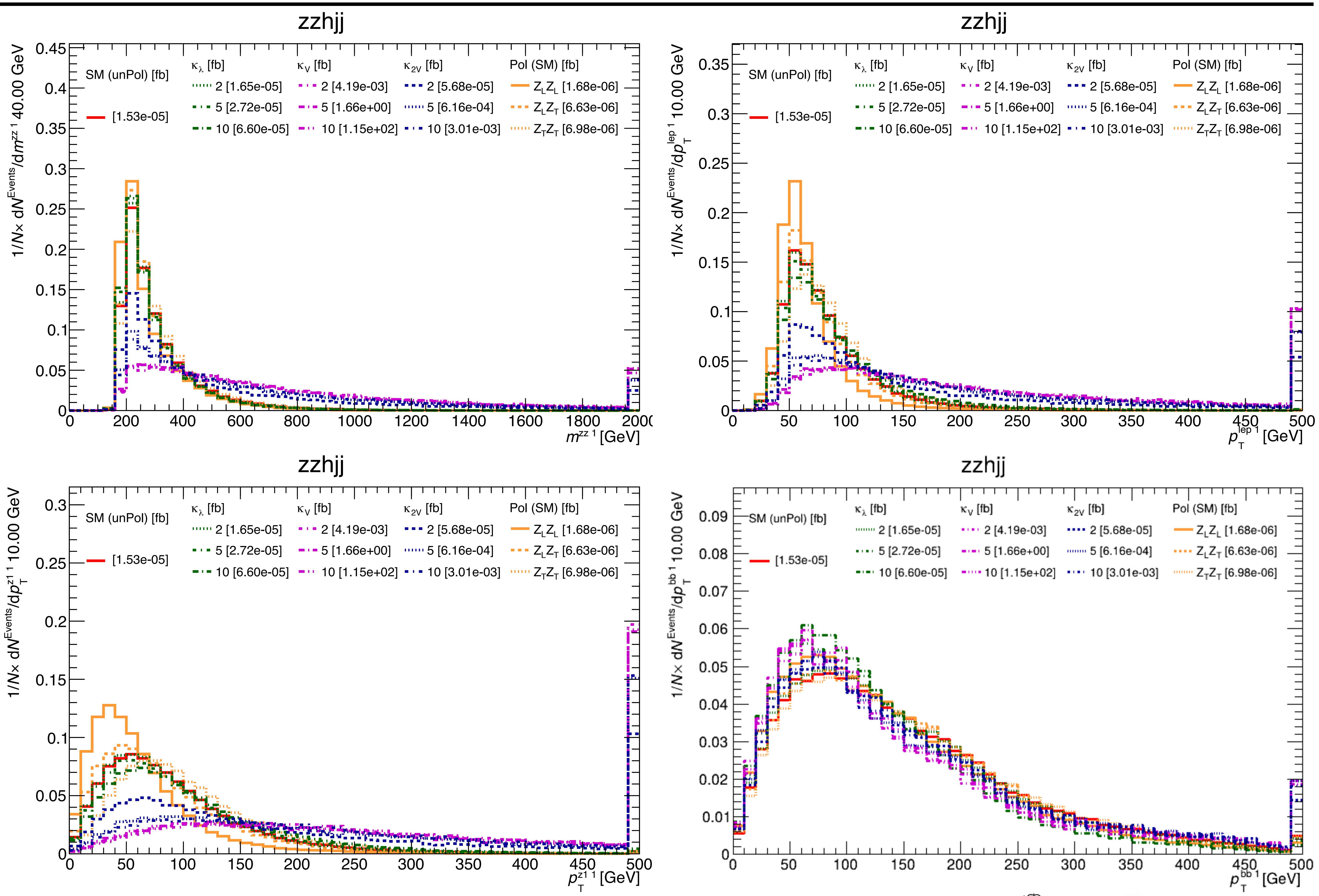
Shown:

- SM (inclusive polarization)
- κ_λ , κ_V , κ_{VV} variations (inclusive polarization)
- LL, LT, TL, and TT polarizations

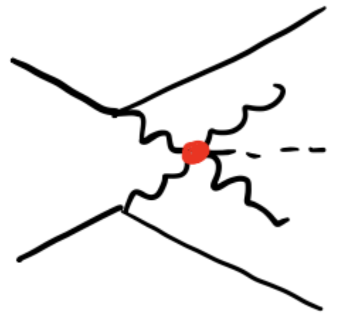
- Signals Normalized to 1
  - XS in fb shown in legend

Overall we see that shape differences between κ_i variations are preserved after preselection

- Preselection is quite strict, currently performing studies to increase acceptance
- Will rely more on BDT for S v B



W+W- + H + jj - After Preselection



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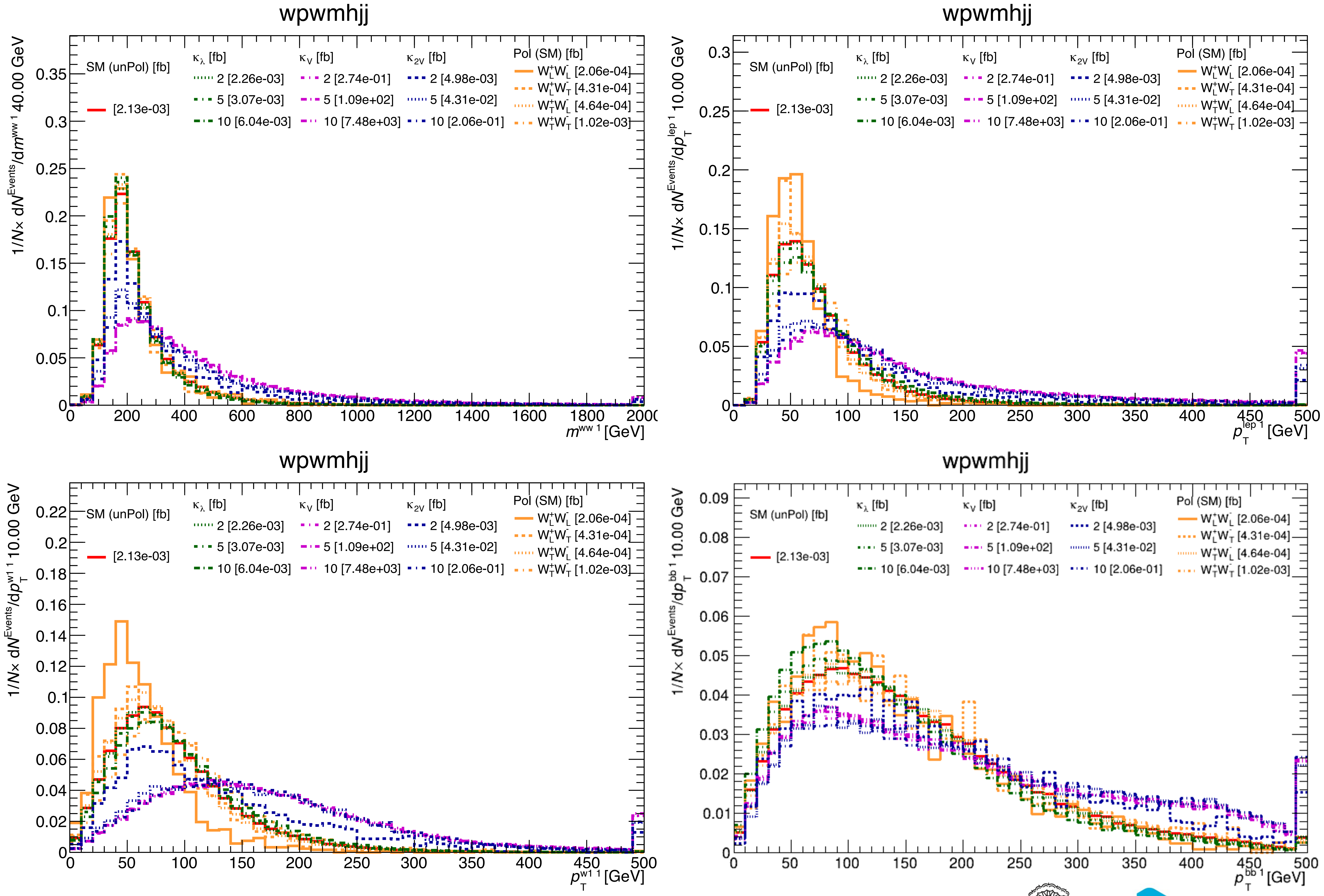


Comments on BDT

- Four Backgrounds studied
  - Drell-Yan
  - Diboson
  - ttbar
  - ttHbb

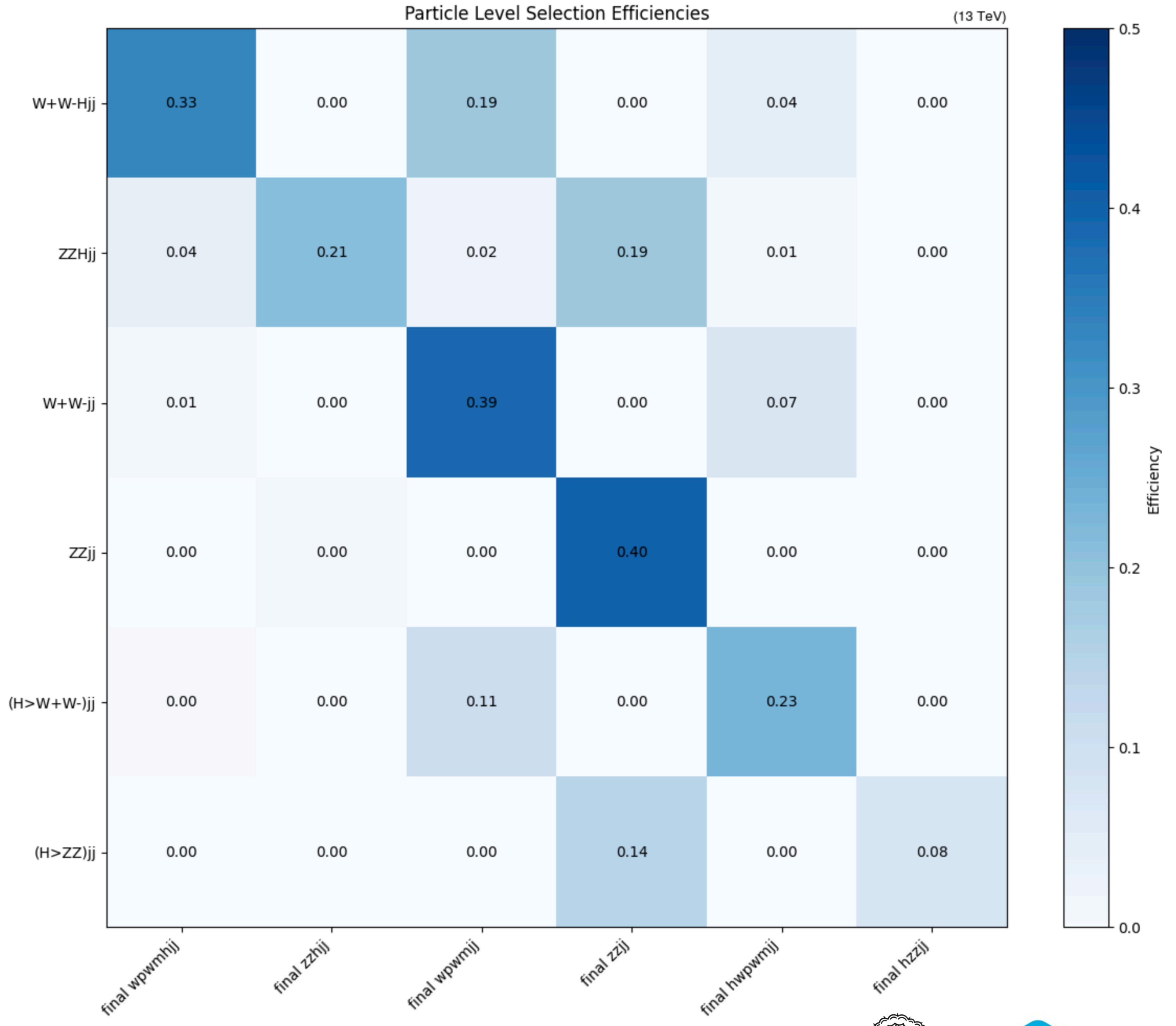
- In leptonic channel, backgrounds minimal
  - namely affect VBS/VBF

- Utility of BDT would be in distinguishing signal processes from one another (right)
  - Distinguishing S v B secondary
  - BDT training in preliminary stage

- Extending to hadronic final states, BDT essential
  - Also in preliminary stage

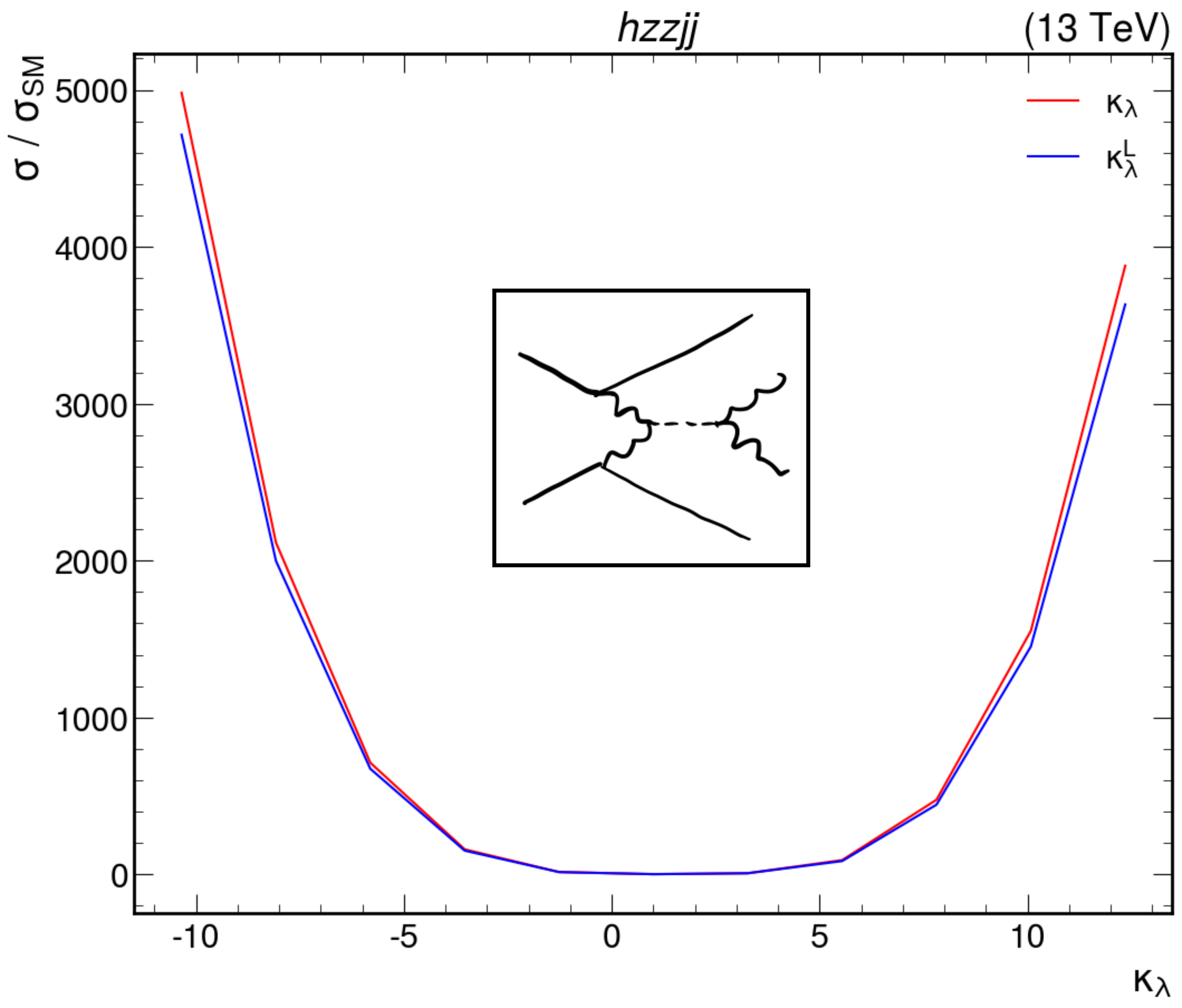
Showing % of remaining signal events after preselection

- Y-axis shows sample used, X-axis shows selection made

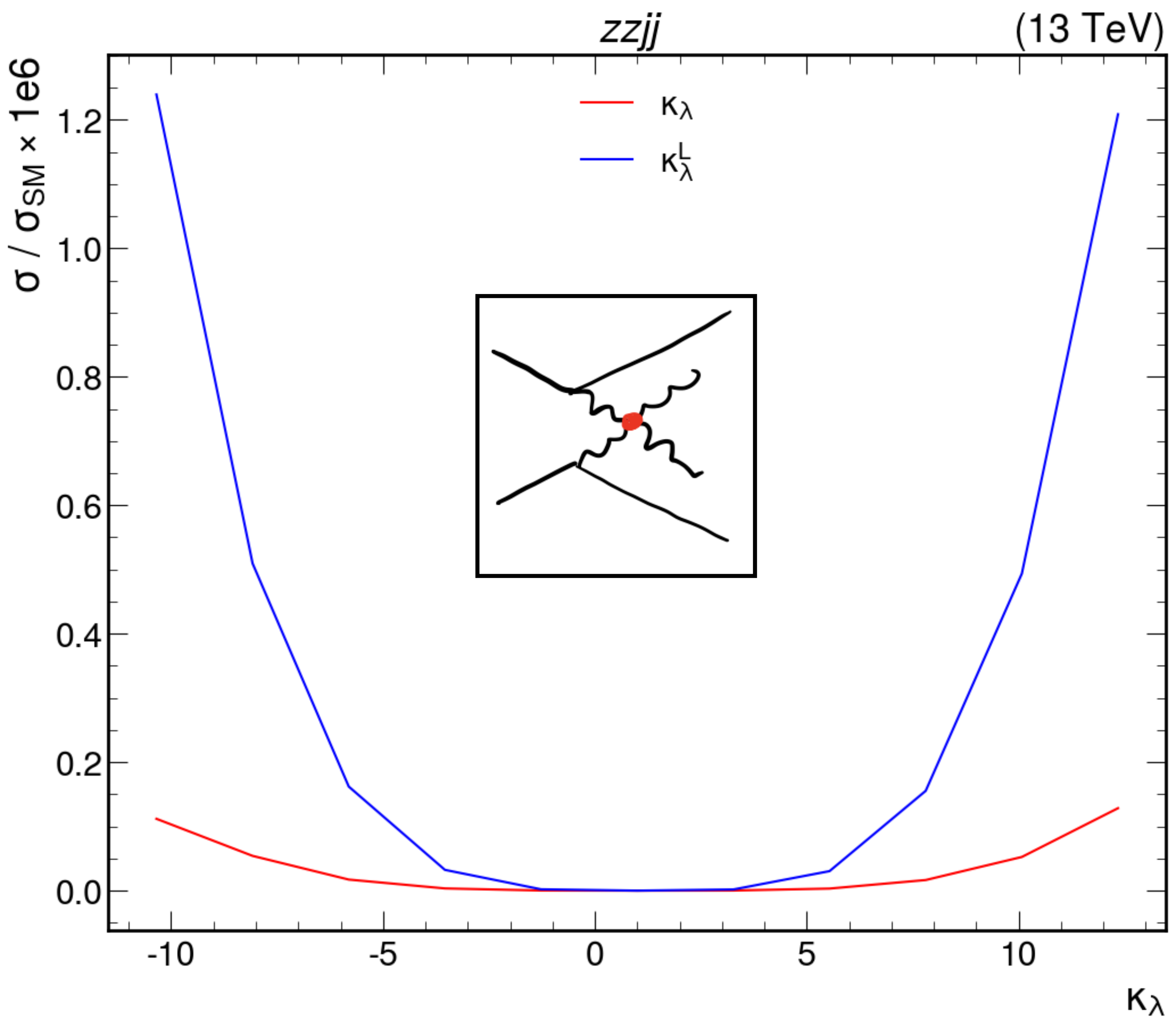


Polarization Studies

- HwH: Additional sensitivity in off-shell regime via longitudinally polarized vector bosons
  - Interested in isolating $V_L V_L$ events → Polarization based reweighting *



On-shell: No gain in sensitivity



Off-shell: Gain in sensitivity due to longitudinal polarization

*https://arxiv.org/abs/2306.07726

Polarization Studies

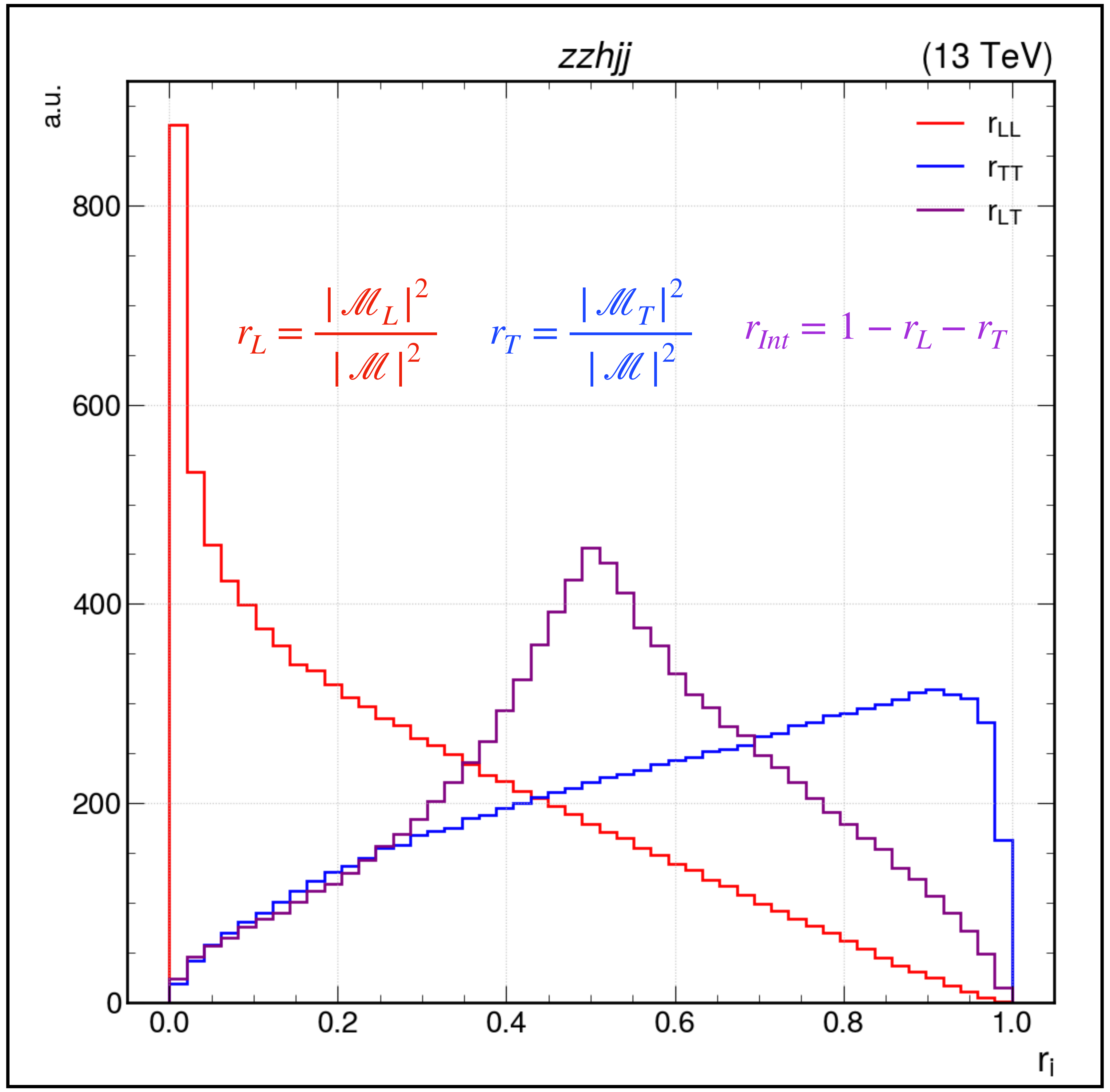
- Amplitude-based weights (r_i) generated using *Recola* *
  - Weights $r_i \equiv |\mathscr{M}_i|^2/|\mathscr{M}|^2$ computed at MC truth
  - Train NN to predict $\tilde{r}_i$ based on experimentally available information

- Allows for measurement of polarization based observable $\tilde{r}_L$
  - Can be defined at fiducial and reco level → unfolding

$$\mathscr{W} \sim \sigma \sim |\mathscr{M}|^2$$

$$\mathscr{W}_L \sim \sigma_L \sim |\mathscr{M}_L|^2 = |\mathscr{M}|^2 \frac{|\mathscr{M}_L|^2}{|\mathscr{M}|^2} \equiv |\mathscr{M}|^2 r_L$$

$$\Rightarrow \mathscr{W}_L = \mathscr{W} r_L$$



r_i values for ZZHjj

*https://recola.gitlab.io/recola2/index.html

Polarization Studies

- Workflow with Madgraph + Recola + TMVA:

Training (MC Truth):

PIDs

$E^{q_1^{in}}, p_x^{q_1^{in}}, p_y^{q_1^{in}}, p_z^{q_1^{in}} \quad E^{q_2^{in}}, p_x^{q_2^{in}}, p_y^{q_2^{in}}, p_z^{q_2^{in}}$

$E^{H}, p_x^{H}, p_y^{H}, p_z^{H}$

$E^{q_1^{out}}, p_x^{q_1^{out}}, p_y^{q_1^{out}}, p_z^{q_1^{out}} \quad E^{q_2^{out}}, p_x^{q_2^{out}}, p_y^{q_2^{out}}, p_z^{q_2^{out}}$

$E^{V_1}, p_x^{V_1}, p_y^{V_1}, p_z^{V_1} \quad E^{V_2}, p_x^{V_2}, p_y^{V_2}, p_z^{V_2}$

$\longrightarrow$ Recola $\longrightarrow$ $|\mathscr{M}_L|^2$ & $|\mathscr{M}|^2$ $\longrightarrow$ $r_L = \dfrac{|\mathscr{M}_L|^2}{|\mathscr{M}|^2}$

In Practice (Reconstructed):

$E^{H}, p_x^{H}, p_y^{H}, p_z^{H} \quad r_L$

$E^{j_1^{out}}, p_x^{j_1^{out}}, p_y^{j_1^{out}}, p_z^{j_1^{out}} \quad E^{j_2^{out}}, p_x^{j_2^{out}}, p_y^{j_2^{out}}, p_z^{j_2^{out}}$

$E^{\ell_1}, p_x^{\ell_1}, p_y^{\ell_1}, p_z^{\ell_1} \quad E^{\ell_2}, p_x^{\ell_2}, p_y^{\ell_2}, p_z^{\ell_2}$

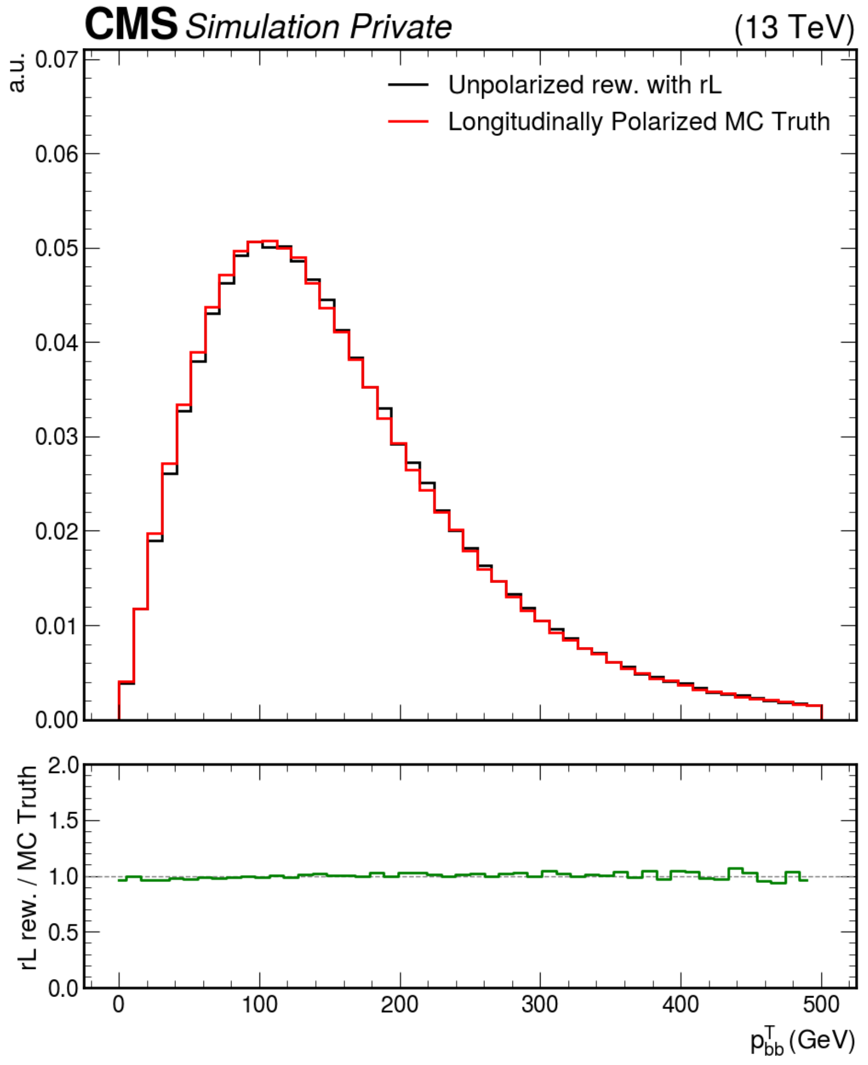
(if ZZ) $E^{\ell_3}, p_x^{\ell_3}, p_y^{\ell_3}, p_z^{\ell_3} \quad E^{\ell_4}, p_x^{\ell_4}, p_y^{\ell_4}, p_z^{\ell_4}$

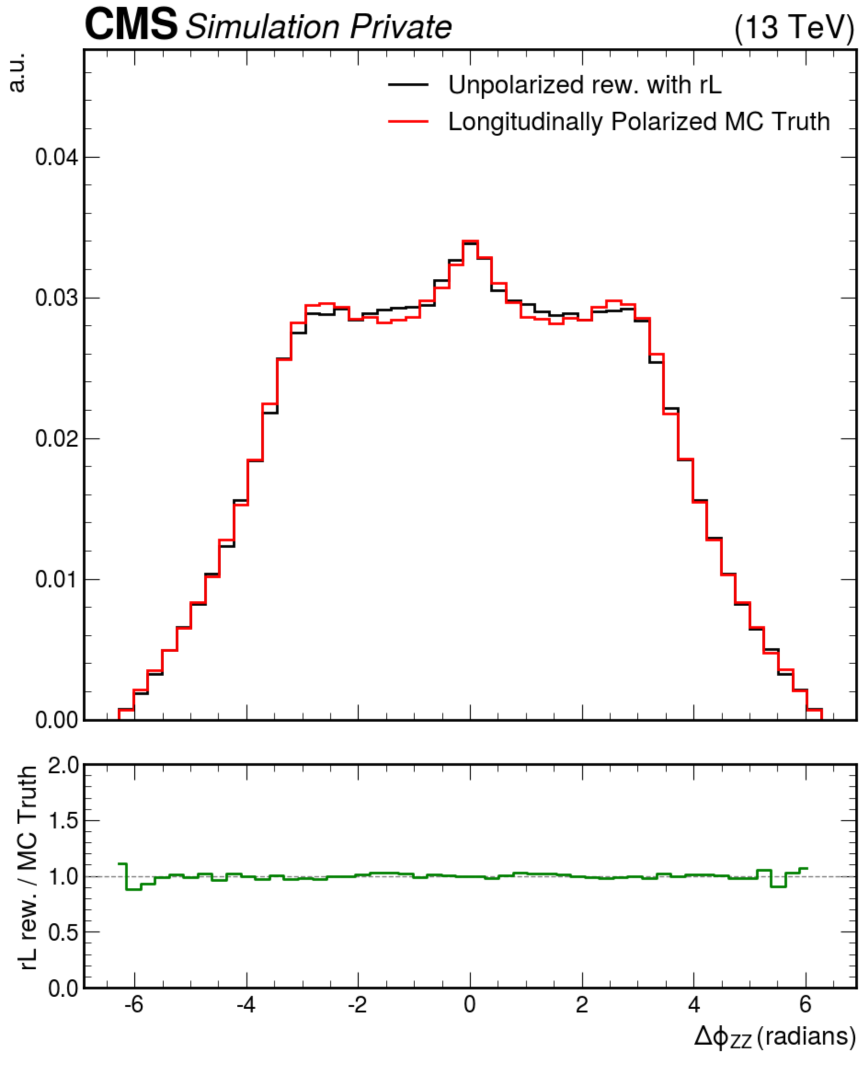
$\longrightarrow$ NN $\longrightarrow$ $\tilde{r}_L$

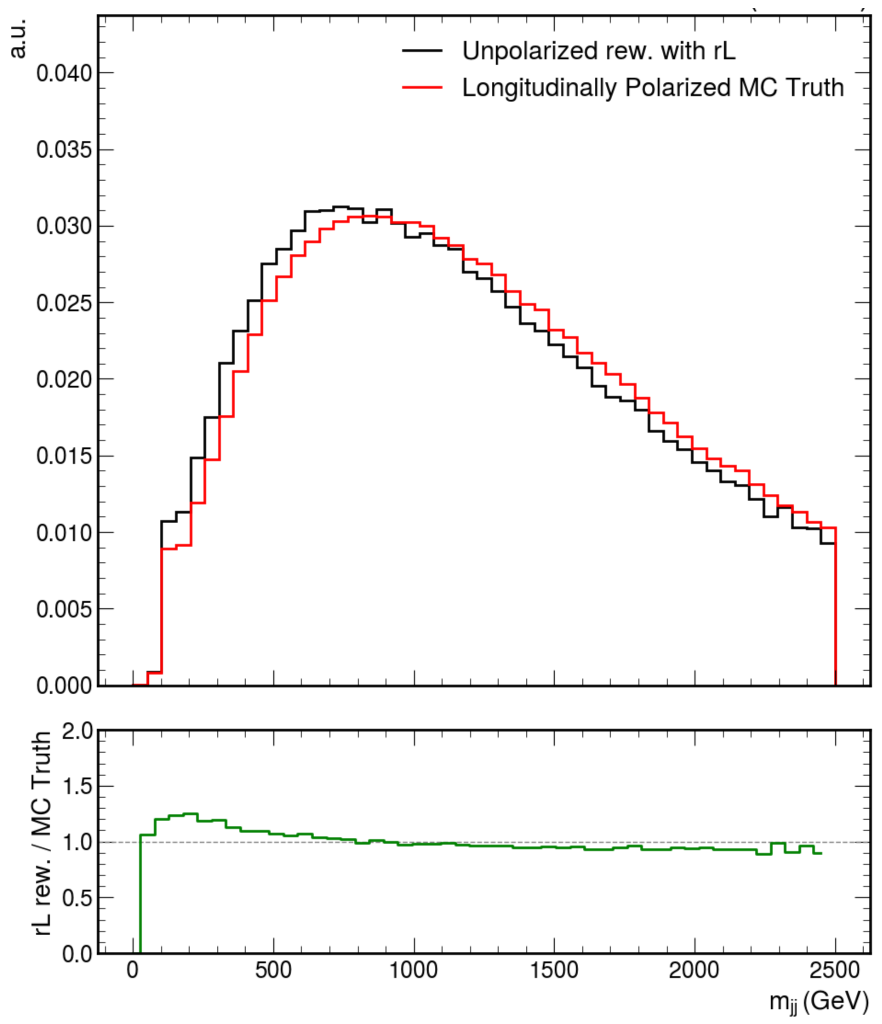
Observable

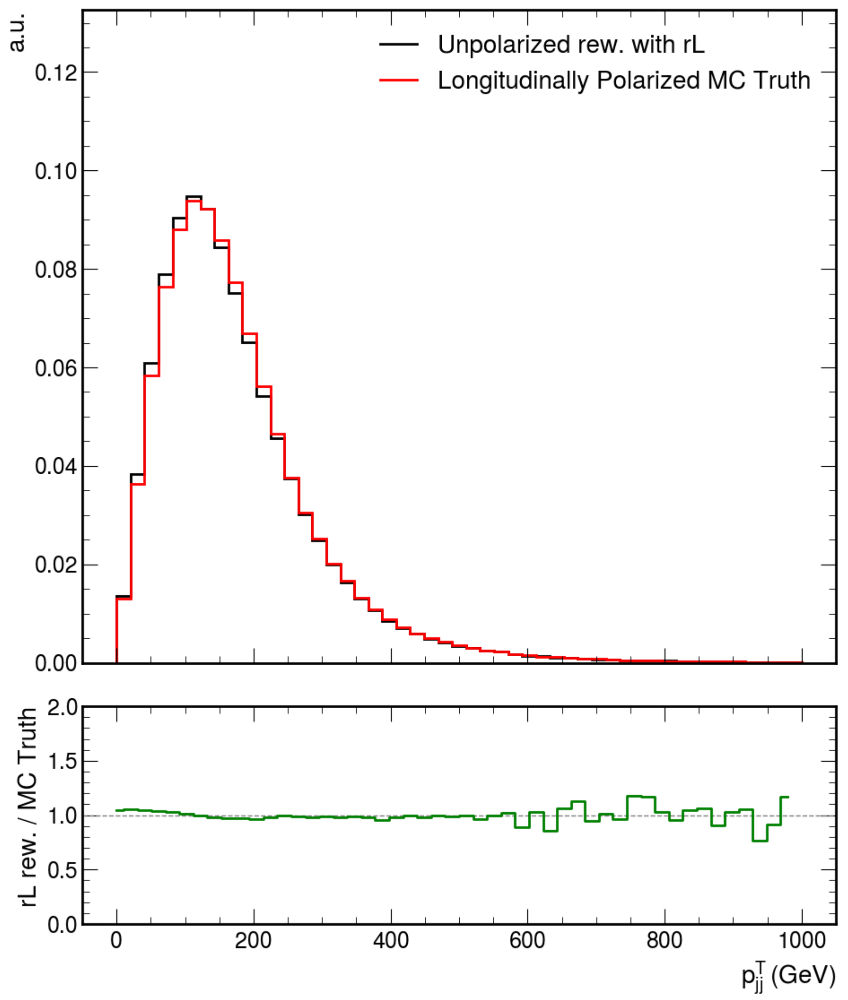
r_L - Polarization Studies

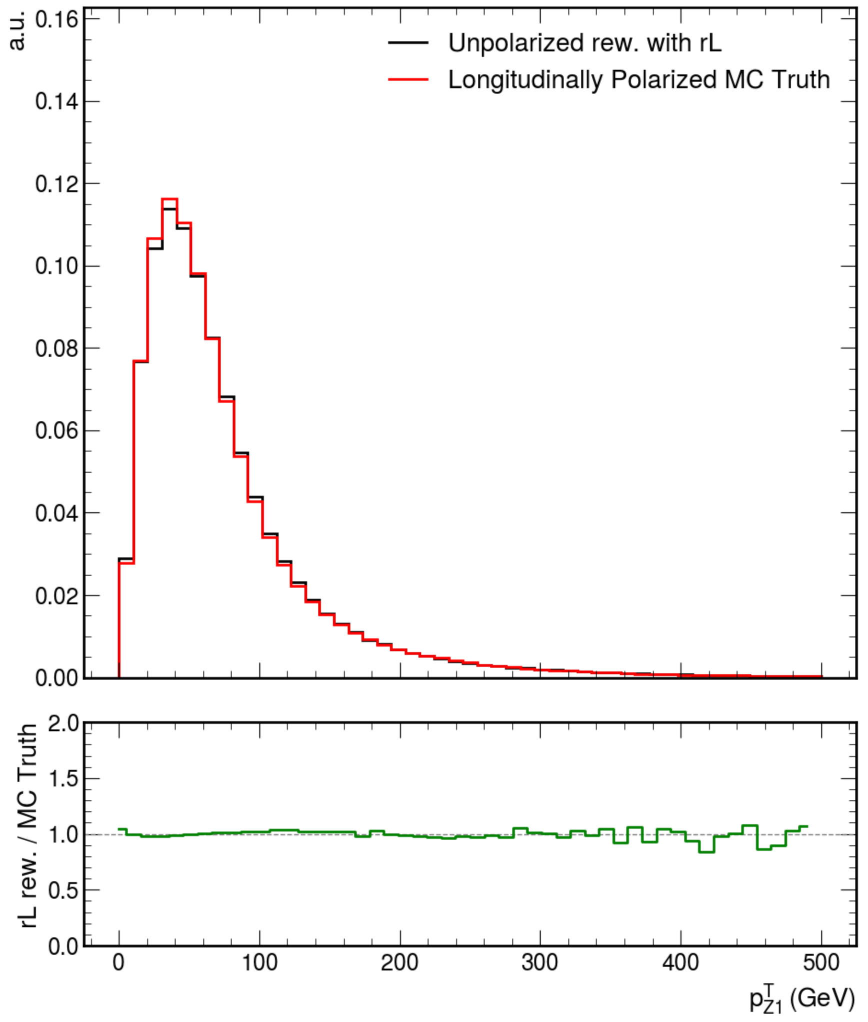
- Current results of MC truth r_L reweighting
    - Unpolarized sample reweighted with r_L shown in black
    - Longitudinally polarized sample shown in red

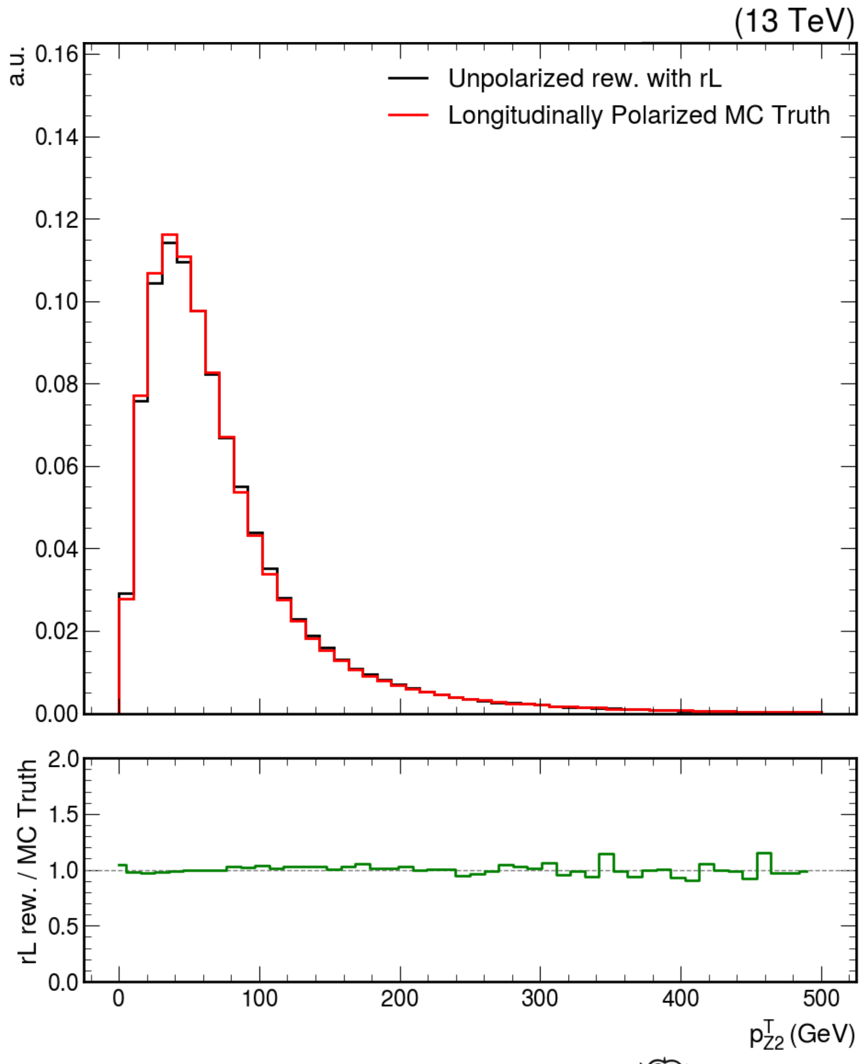












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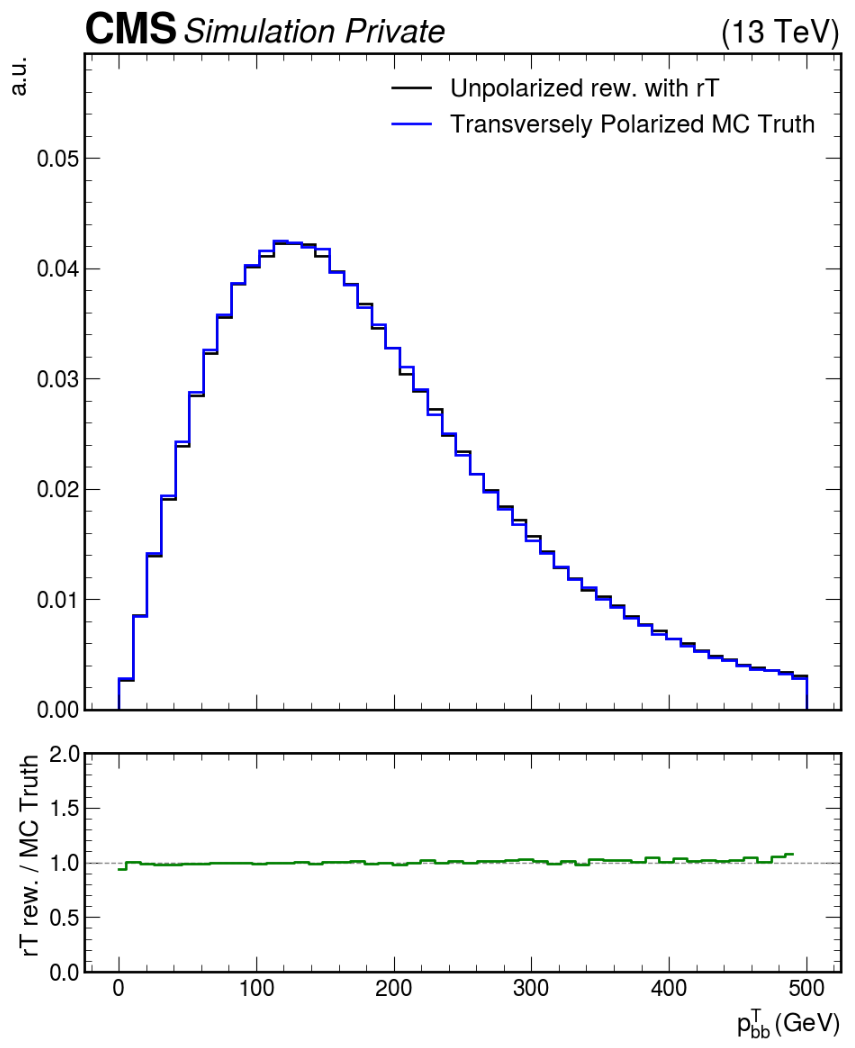
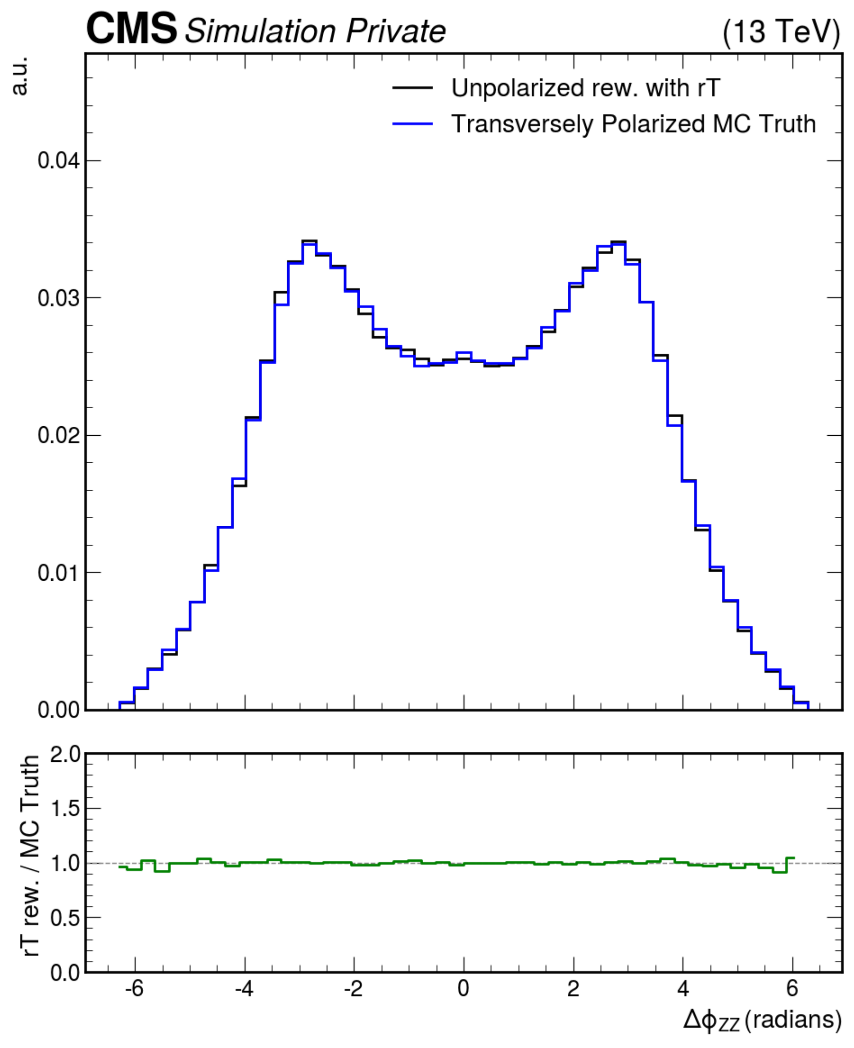
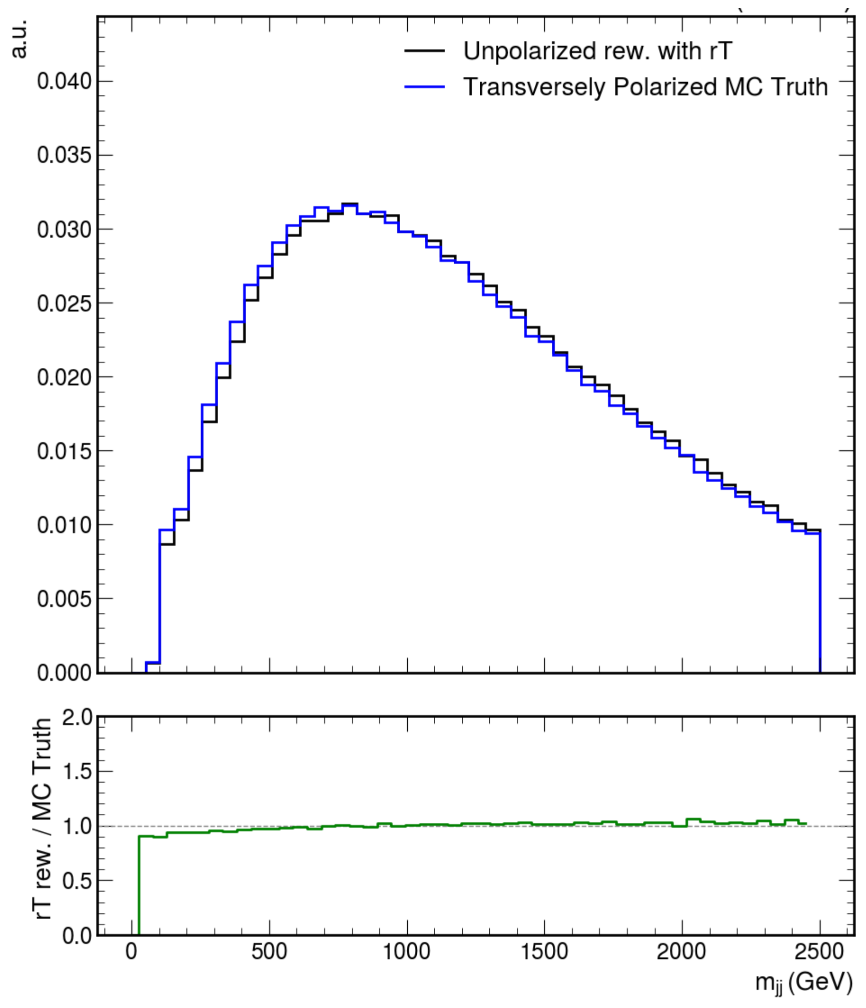
r_T - Polarization Studies

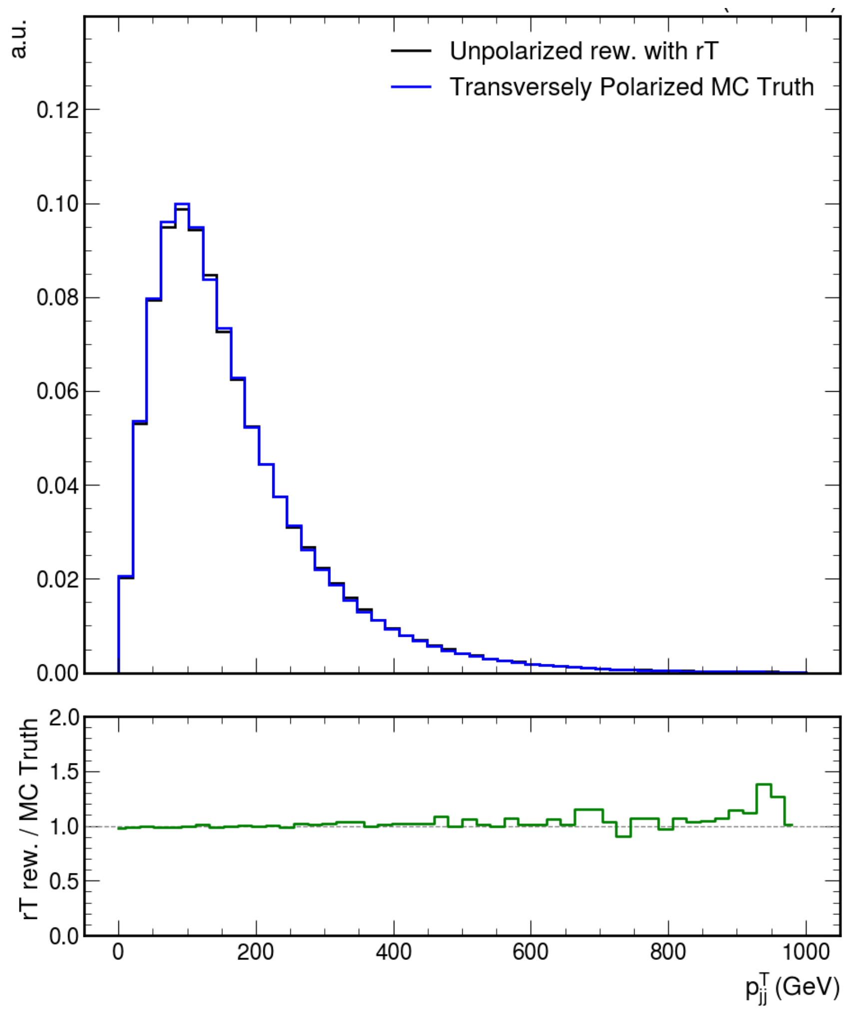
- Current results of MC truth r_T reweighting
    - Unpolarized sample reweighted with r_T shown in black
    - Longitudinally polarized sample shown in blue

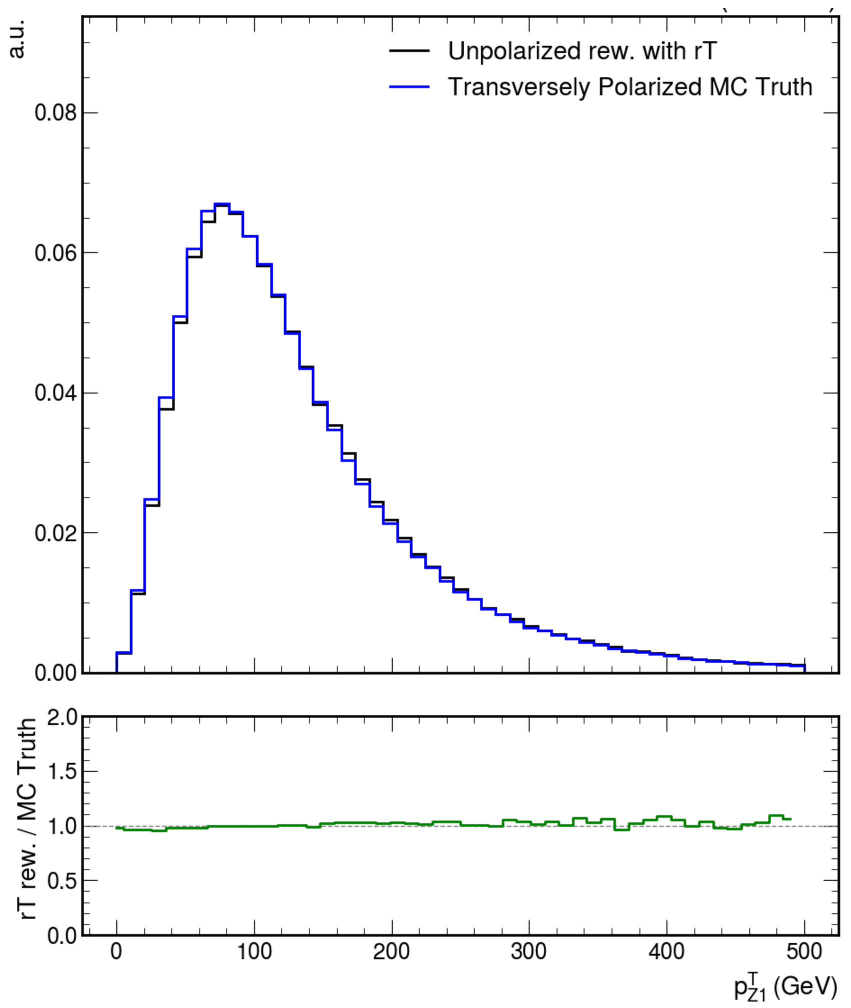
→ Accurate extraction of polarized events reduces demand in MC sample generation and allows for additional studies

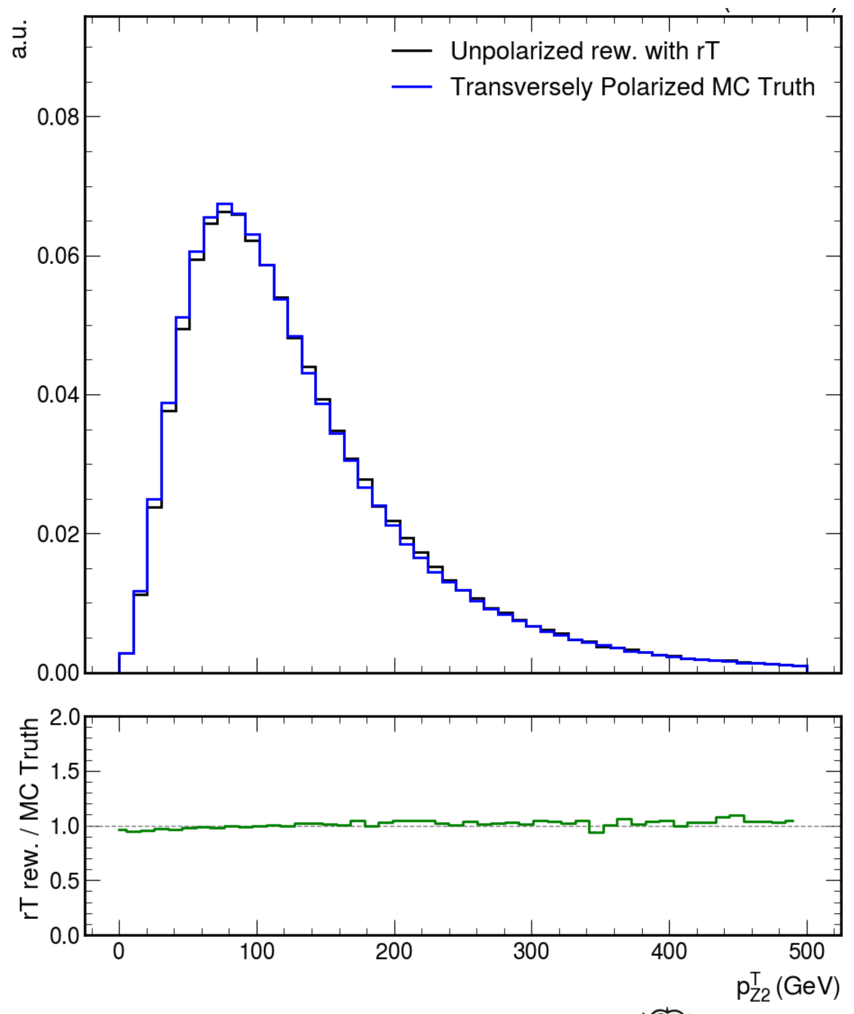












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Conclusion

Conclusion

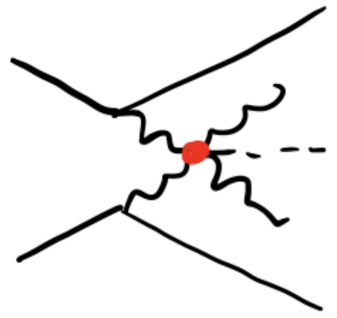
- Summary:
    - On- and Off-shell strategy
        - Direct measurements + Improved sensitivity with polarized vector bosons in off-shell regime
    - Novel analysis studying 6 signal processes in clean leptonic decay channel
    - Polarization reweighting method

- Next steps:
    - BDT/NN training
        - Increase signal acceptance
    - Polarization regression
        - Predict $\tilde{r}_L$ at reco & fiducial level
    - Interpret measurements in context of EFT
    - Extend to semileptonic + hadronic final states
        - Higher XS but more background → BDT/NN
        - PAIReD reconstruction of $V \to q\bar{q}$

Thanks!

backup

ZZ + H + jj - Sig vs Background

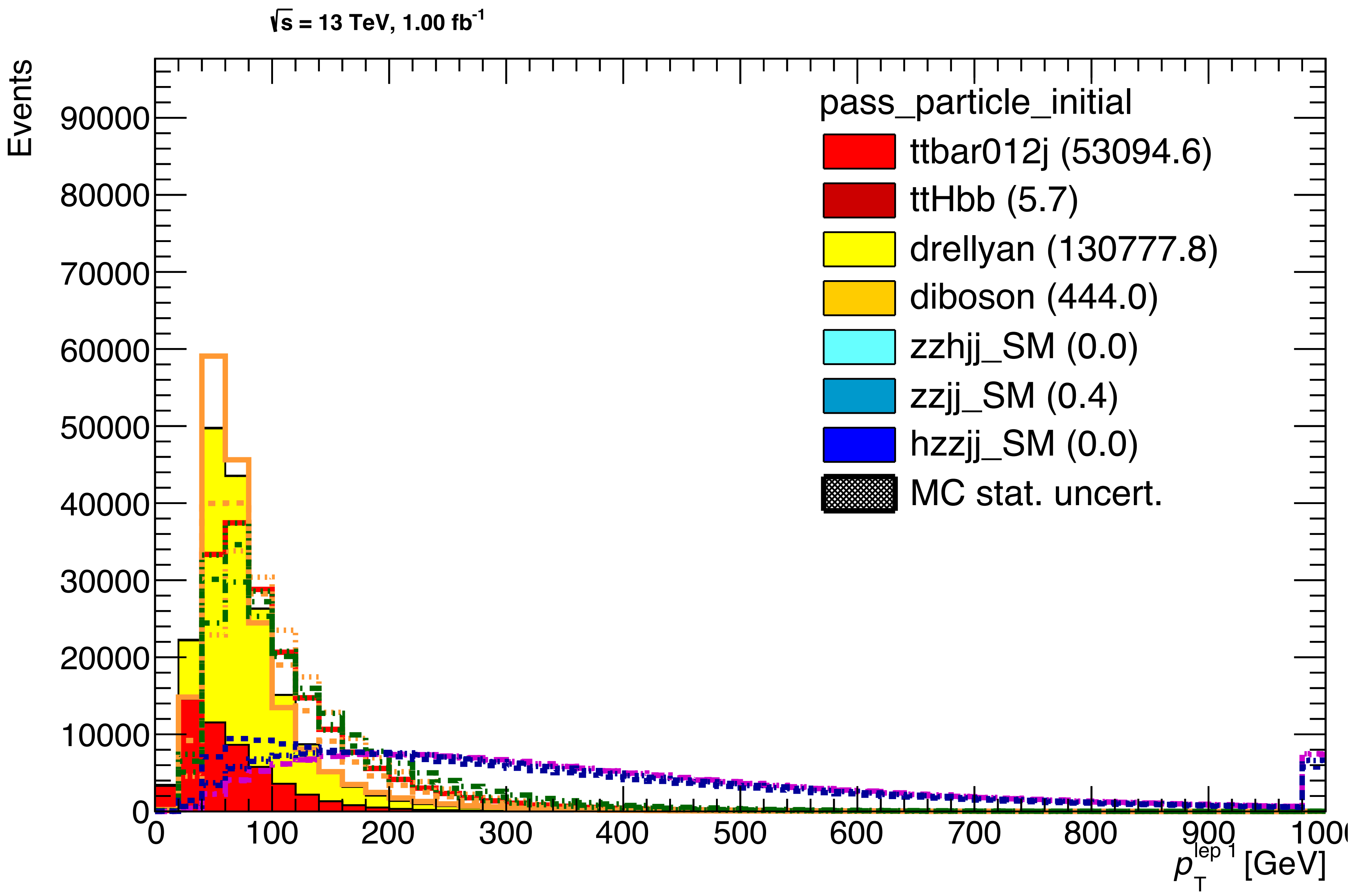


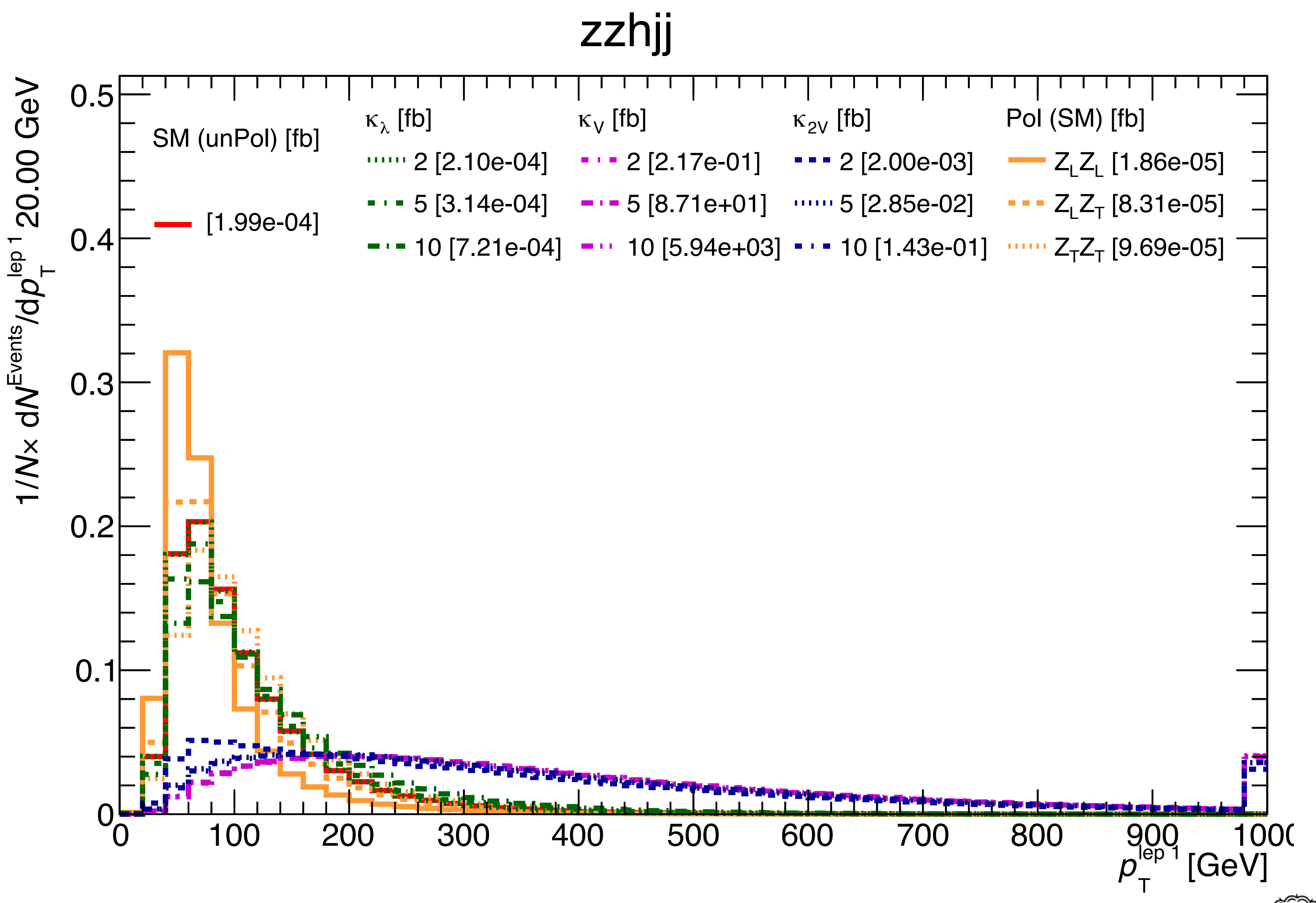
Backgrounds studied:

- DY
- Diboson
- ttbar
- ttHbb

Overlay:

- SM (inclusive polarization)
- κ_λ , κ_V , κ_{VV} variations (inclusive polarization)
- LL, LT, TL, and TT polarizations
- Signals Normalized to 1
  - XS in fb shown in legend



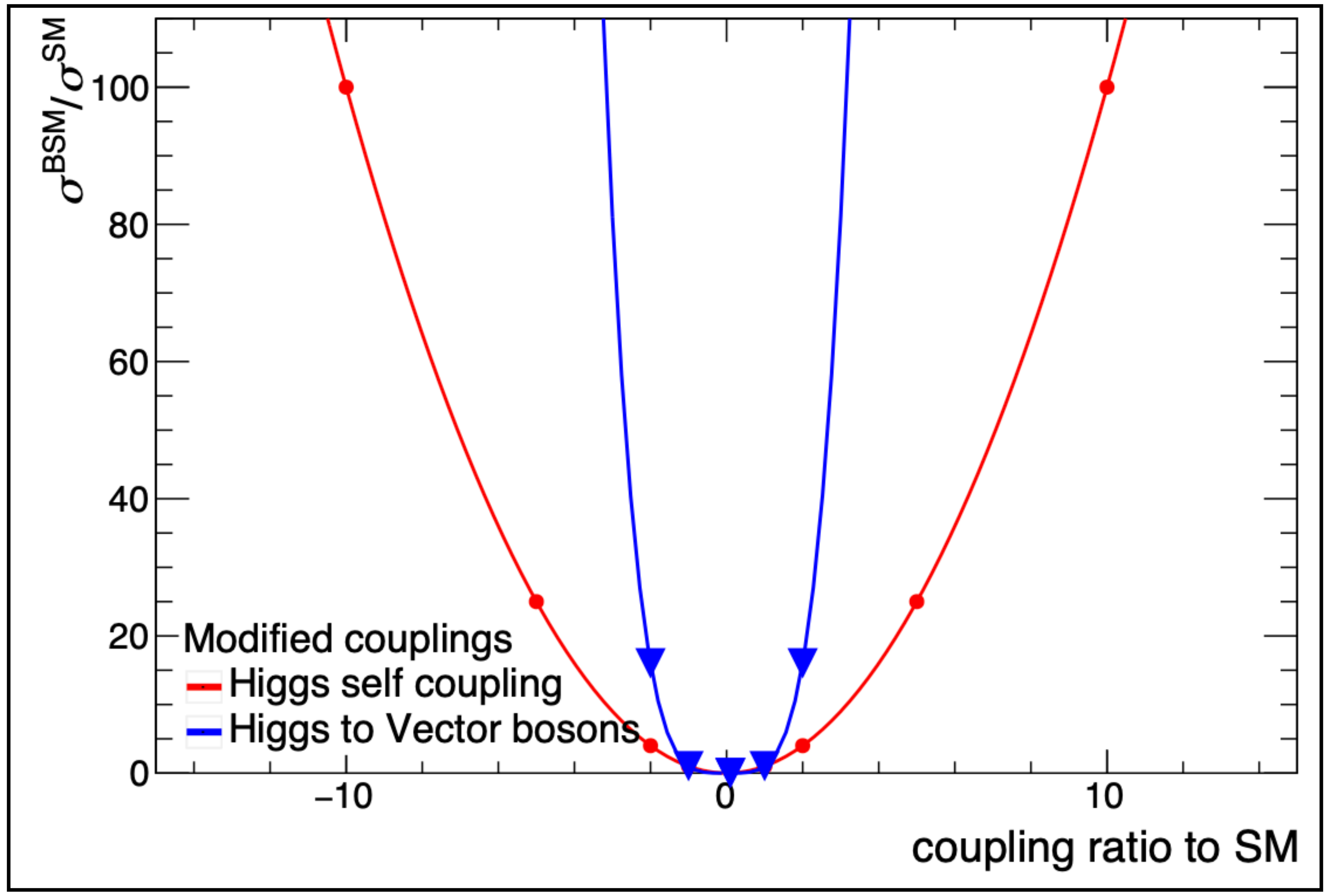


BROWN

Event Generation

- `MADGRAPH_aMC@NLO` 3.5.2
  - `import model HHVBF_UFO-vbf_hh_4f`
  - $H \to b\bar{b}$ decay done in Pythia8
  - $Z \to \ell^+\ell^-$ / $W^\pm \to \ell^\pm \nu_{\ell^\pm}$ decay in Madspin
  - Detector simulation done in Delphes
  - `QCD=0` to remove QCD

- Commands
  - W+W-Hjj: `generate p p > w+ w- h j j QCD=0`
  - ZZHjj: `generate p p > z z h j j QCD=0`
  - W+W-jj: `generate p p > w+ w- j j QCD=0`
  - ZZjj: `generate p p > z z j j QCD=0`
  - (H→W+W-)jj: `generate p p > h j j QCD=0,(h > w+ w-, w+ > l+ vl, w- > l- vl~)`
    - `bwcutoff = 100000` to allow for off-shell Higgs
  - (H→ZZ)jj: `generate p p > h j j QCD=0,(h > z z, z > l+ l-)`
    - `bwcutoff = 100000` to allow for off-shell Higgs



VVHjj sensitivity to κ_λ and κ_V
(QCD=0 QED=2 CV=2 C2V=0 C3=1)

Standard Model Cross-Sections (Undecayed)

Process	σ^{SM} (fb)	σ^{SM}_{LL} (fb)	σ^{SM}_{LL} / σ^{SM}
W+W-Hjj	$0.5359^{+0.003641}_{-0.003641}$	$0.04755^{+0.0004595}_{-0.0004595}$	8.87%
ZZHjj	$0.1027^{+0.0006495}_{-0.0006495}$	$0.009614^{+0.00007616}_{-0.00007616}$	9.36%
W+W-jj	$714.7^{+4.686}_{-4.686}$	$38.51^{+0.2696}_{-0.2696}$	5.39%
ZZjj	$121.4^{+1.03}_{-1.03}$	$7.122^{+0.05815}_{-0.05815}$	5.87%
(H→W+W-)jj	$25.11^{+0.2009}_{-0.2009}$	$17.61^{+0.4965}_{-0.4965}$	70.13%
(H→ZZ)jj	$10.68^{+0.09852}_{-0.09852}$	$7.334^{+0.06226}_{-0.06226}$	68.67%

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Expected Events - W+W-Hjj

- generate p p > w+ w- h j j QCD = 0 (sm)
    - undecayed (from madgraph): 0.0005478 pb
    - decayed (from madgraph, no hbb): 0.00002707 pb

Check: $\underbrace{0.0005478}_{\text{undecayed xs}} \times (\underbrace{2}_{e\mu \text{ only}} \times \underbrace{0.11}_{W \to \ell\nu_\ell})^{\overbrace{2}^{\text{2 W's}}} = 0.00002651$ pb ✓

Final Cross Section: $0.00002651 \times (\underbrace{0.58}_{H \to bb}) = 0.00001538$ pb = **0.01538 fb**

Expected Events (After Run III / HL-LHC) : $0.01538 \times 300(0) =$ **4.6 Events/46 Events**

BROWN

Expected Events - ZZHjj

- generate p p > z z h j j QCD = 0 (sm)
  - undecayed (from madgraph): 0.0001054 pb
  - decayed (from madgraph, no hbb): 0.0000004987 pb

Check: $\underbrace{0.0001054}_{\text{undecayed xs}} \times (\underbrace{2}_{e\mu\text{ only}} \times \underbrace{0.0336}_{\mathrm{Z} \to \ell^+\ell^-})^{\overbrace{2}^{\text{2 Z's}}} = 0.0000004759$ pb ✓

Final Cross Section: $0.0000004759 \times (\underbrace{0.58}_{\mathrm{H} \to \mathrm{bb}}) = 0.0000002761$ pb = **0.0002761 fb**

Expected Events (After Run III / HL-LHC) : $0.0002761 \times 300(0) =$ **0.08 Events/0.8 Events**

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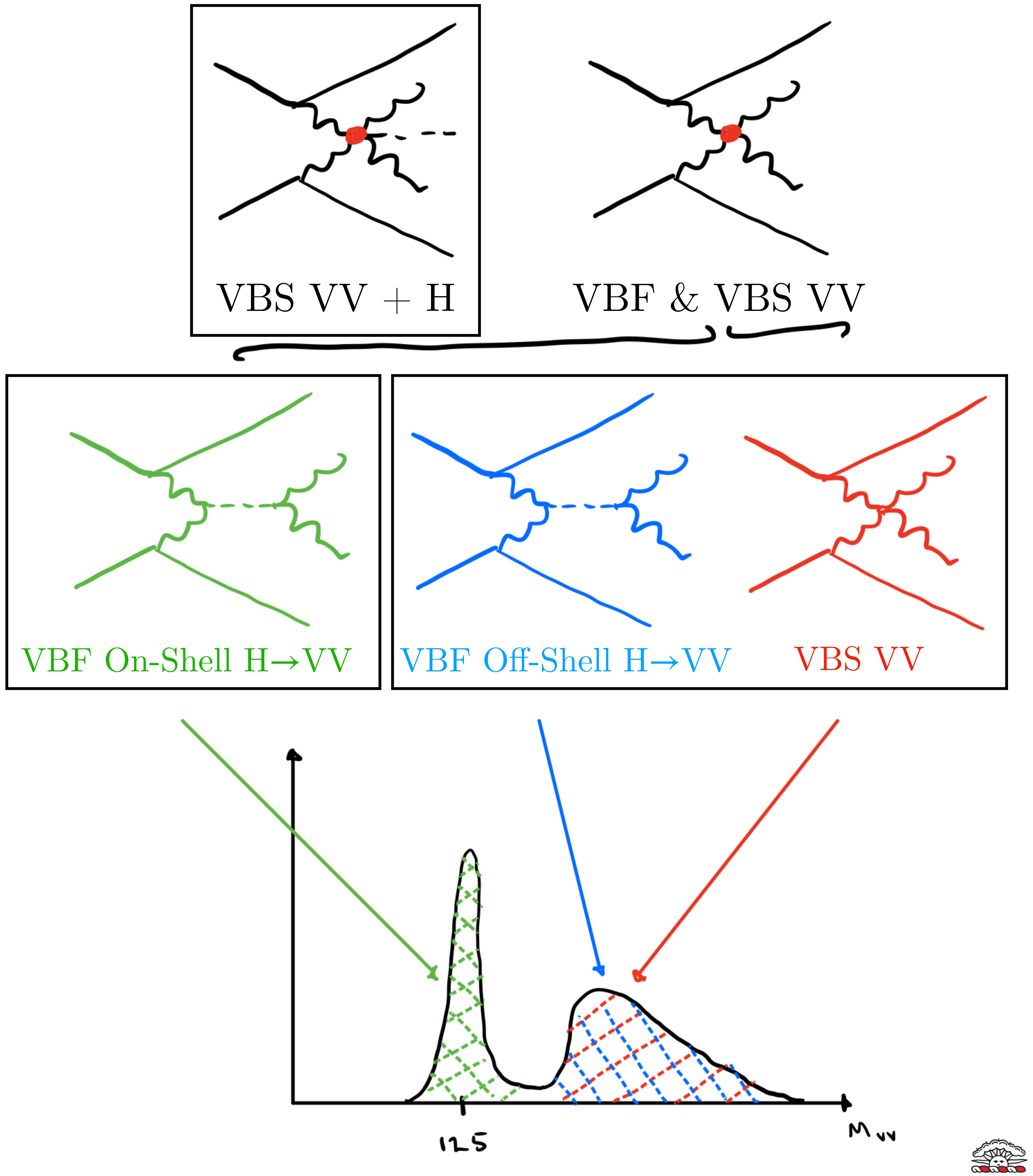
Analysis Strategy

- 2 final states
  - VV + H + jj
  - VV + jj

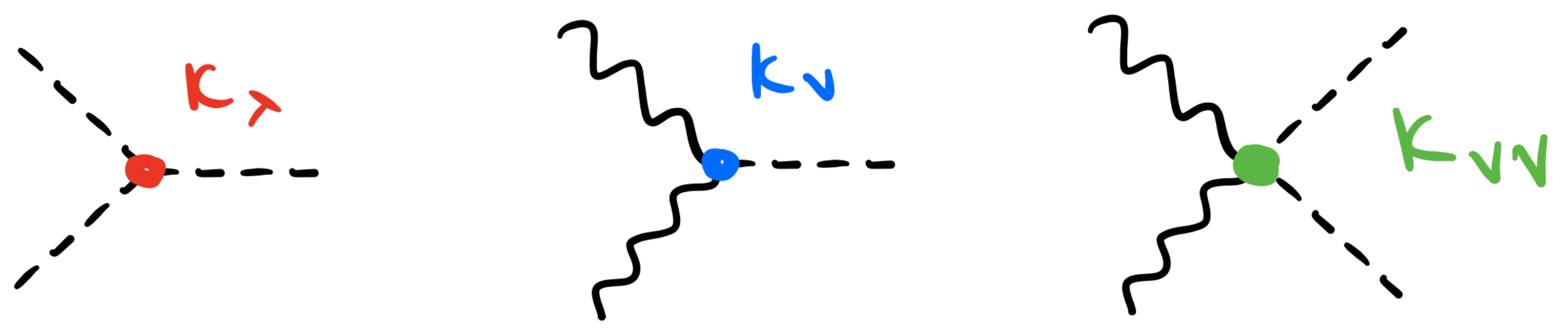
- 6 selections (ZZ & W+W-)
  - VVHjj
  - (H→VV)jj (Low mass)
  - VVjj (High mass)



Analysis Strategy

- Targeting limits of
    - Higgs Self-Coupling: κ_λ
    - Higgs Couplings to Vector Bosons: κ_V, κ_{VV}

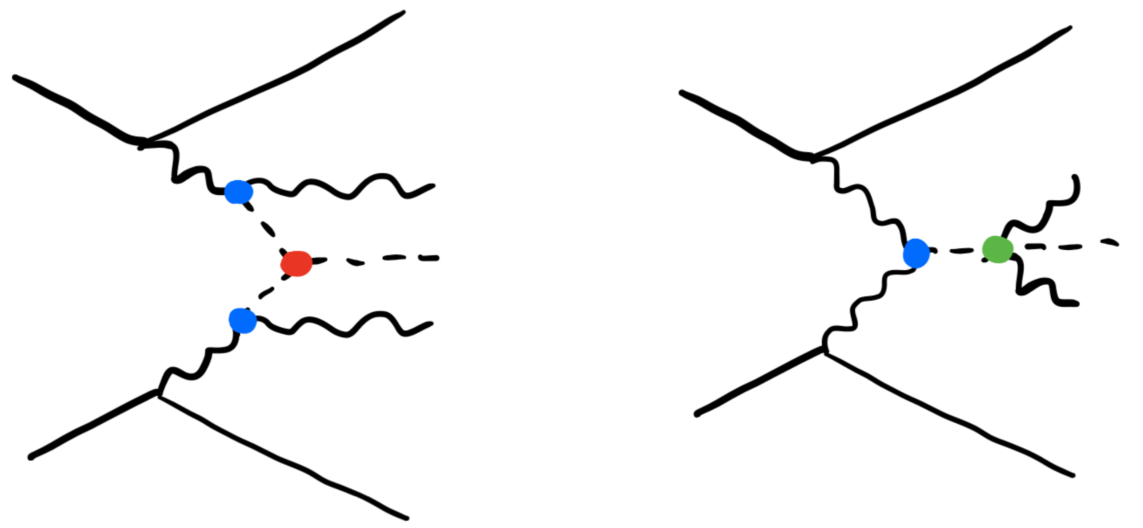
where $\kappa_i \equiv \lambda_i / \lambda_i^{SM}$ $(\kappa_i^{SM} = 1)$



Higgs couplings to itself and vector bosons.

- VV + H + jj
    - Direct Sensitivity to κ_λ, κ_V, κ_{VV}

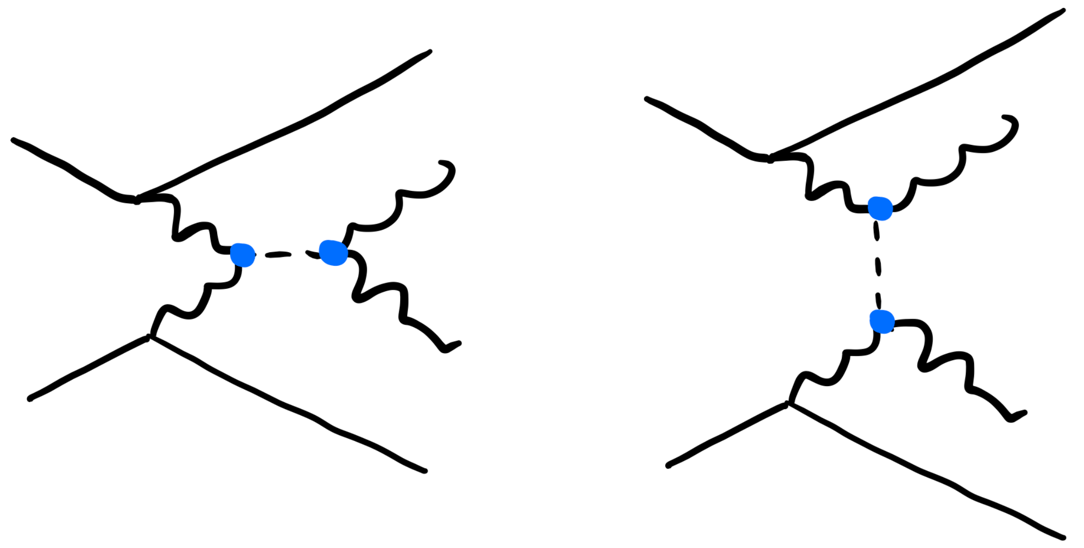
VBS VV + H
Example Diagrams :



$\sim \kappa_\lambda, \kappa_V, \kappa_{VV}$

- VV + jj
    - Direct Sensitivity to κ_V

VBF & VBS VV
Example Diagrams :



$\sim \kappa_V$