

# Spin-density matrix in MadSpin

## Vol. 2

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MadGraph general meeting  
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# In last year's meeting...

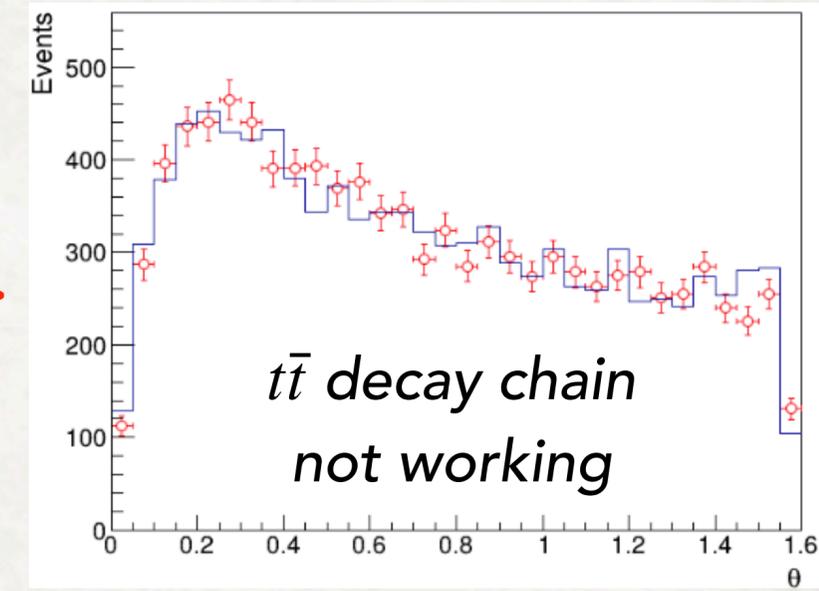
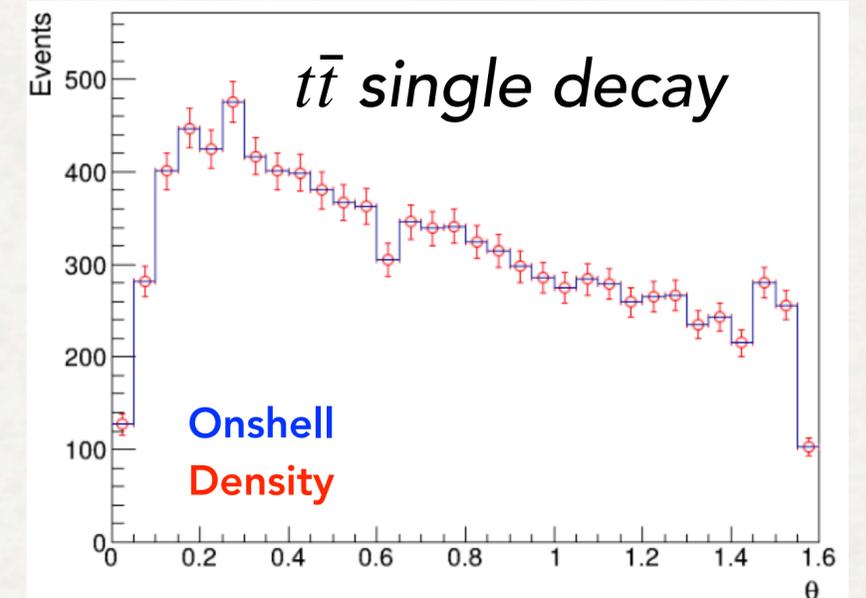
Introduced spin-density mode in MadSpin to handle  
(extension of work started in UCL)

& extension to MadSpin of [2510.17730](#)

Features back then:

- ✓ was **working** as expected for **simple processes**
- **4 times slower** than other run modes for  $t\bar{t}$
- was **not working** for **decay chains**
- **not tested** for **interference** and **loop-induced** processes
- **prohibitively slow** for complicated final states like

$$pp \rightarrow t\bar{t}t\bar{t}$$



plots from [last year](#)

# Today

## *Current status of spin-density mode*

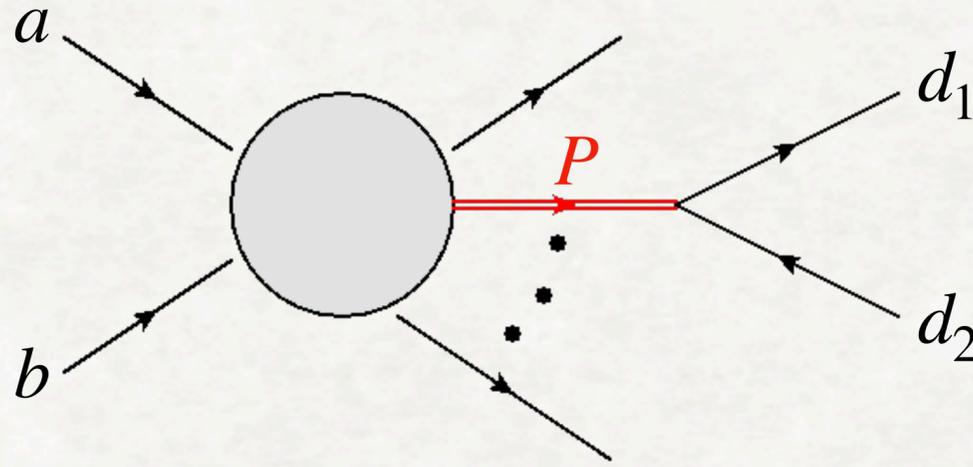
- **bug-fixes** and **validation**
- spin-correlations in **interference processes**

## *Profiling results*

- **speed-ups** and potential future improvements

Let's start from a brief reminder about spin-density matrix computation in MadSpin

# Introduction: spin correlations



Consider decay  $ab \rightarrow d_1 d_2 + X$  with  $d_1, d_2$  produced via the decay of an **intermediate heavy resonance**.

In general if  $\text{spin}(P) \neq 0$

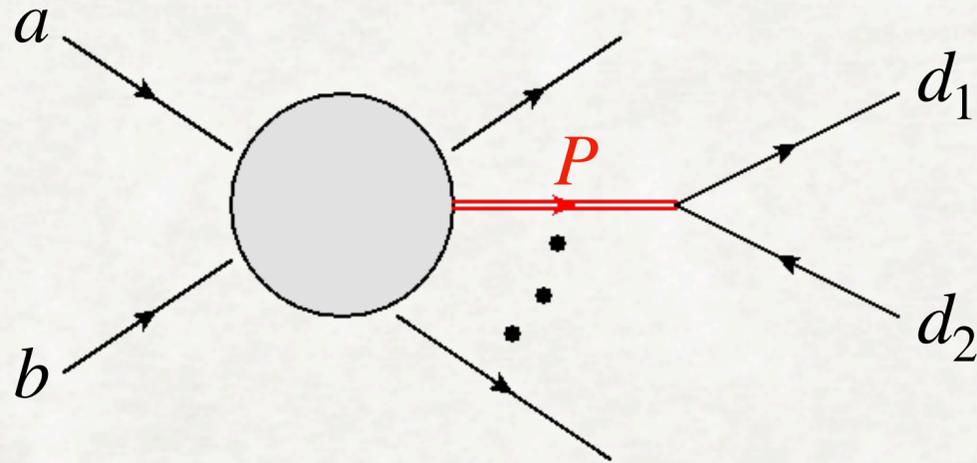
if  $\mathcal{M}$  depends on  $d_1 \cdot d_2$  momenta  $\rightarrow$  **decay spin correlations**

if  $\mathcal{M}$  depends on  $a \cdot d_i, b \cdot d_i$  momenta  $\rightarrow$  **production spin correlations**

How can we evaluate  $\mathcal{M}(ab \rightarrow d_1 d_2 + X)$  with the best possible accuracy?

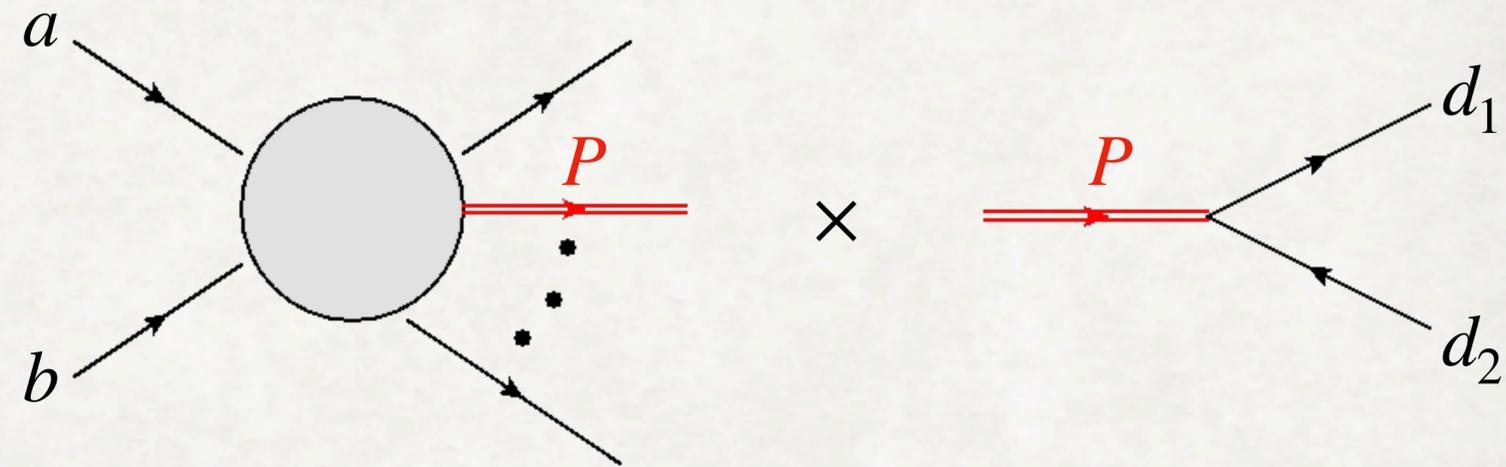
# The two extremes

## Full ME - complete final state in MG5aMC



- Most accurate:  $\mathcal{M}_{full} = \mathcal{M}(ab \rightarrow d_1 d_2 + X)$
- ✓ full set of NLO corrections (productions & decay)
- ✓ spin correlations in production & decay
- ✓ off-shell effects
- ⦿ might be practically impossible for high final-state multiplicities
- e.g. generate  $p p \rightarrow l^+ l^- l^+ l^-$  [QCD]

## Decay Chain Approximation



- Least accurate:  $|\mathcal{M}_{dca}|^2 = |\mathcal{M}_{prod}|^2 |\mathcal{M}_{dec}|^2$
- $\mathcal{M}_{prod} = \mathcal{M}(ab \rightarrow P)$ ,  $\mathcal{M}_{dec} = \mathcal{M}(P \rightarrow d_1 d_2)$
- ⦿  $\mathcal{M}_{dec}$  only LO accurate
- ⦿ production spin correlations lost
- ⦿ no off-shell effects
- e.g. generate  $p p \rightarrow z z$  [QCD] + Pythia

# Production spin correlations via FLMW

To keep production spin correlations one can simply

- generate events (@ NLO) keeping intermediate resonances on-shell
- generate resonance decays separately
- unweighting step re-introduces production spin correlations at LO

$$\text{keep event if: } \frac{|\mathcal{M}_{\text{prod+dec}}|^2}{|\mathcal{M}_{\text{prod}}|^2} > r \max \left( \frac{|\mathcal{M}_{\text{prod+dec}}|^2}{|\mathcal{M}_{\text{prod}}|^2} \right)$$

- FLMW [[hep-ph/0702198](https://arxiv.org/abs/hep-ph/0702198)]: analytical calculation of maximum weight
- MadSpin [[1212.3460](https://arxiv.org/abs/1212.3460)]: max weight calculated by sampling  $|\mathcal{M}|^2$  ratios

# MadSpin modes

## spinmode = full

- Use  $\frac{|\mathcal{M}_{full}|^2}{|\mathcal{M}_{prod}|^2}$ , full = prod+dec
- ✓ spin correlations in production & decay
- ✓ off-shell effects via BW smearing
- Most accurate mode in MadSpin
- ⦿ cannot compute 3-body decays
- ⦿ cannot do loop-induced/interferences

## spinmode = onshell

- Use  $\frac{|\mathcal{M}_{full}|^2}{|\mathcal{M}_{prod}|^2 |\mathcal{M}_{dec}|^2}$ , full = prod+dec
- ✓ spin correlations in production & decay
- ✓ can compute 3-body decays
- ⦿ no off-shell effects (but they can be added)
- ⦿ cannot do loop-induced/interferences

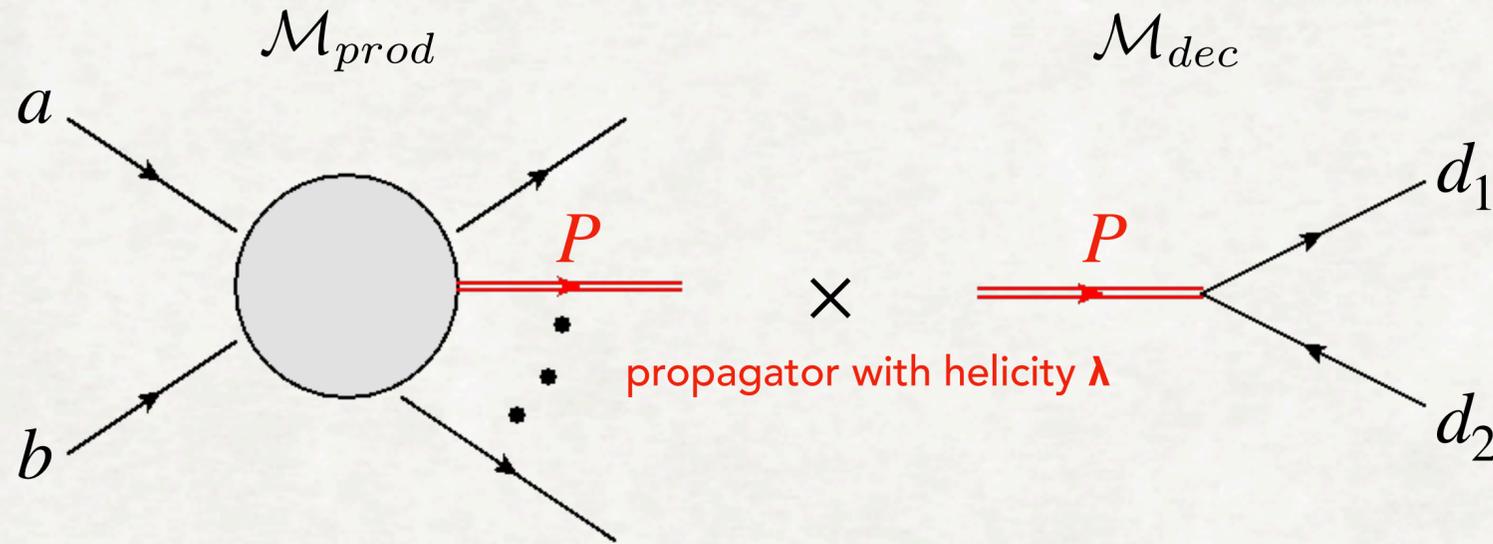
Different ratios used because decay events are weighted ("full") or unweighted ("onshell")

In both cases  $\mathcal{M}$  calculated by MG5aMC

➔ MadSpin fails if it cannot compute  $\mathcal{M}_{full}$  (e.g. loop-induced, amplitude squared restrictions (for interference terms or BSM samples))

# Spin-density formalism

- Spin-density: avoid calculating  $\mathcal{M}_{full}$  to lift MadSpin restrictions



$$\mathcal{M}_{full} = \mathcal{M}_{prod}^\mu P_{\mu\nu} \mathcal{M}_{dec}^\nu$$

rewrite propagator with the help of completeness relation

$$P_{\mu\nu} = \frac{\sum_\lambda (\epsilon_\mu^\lambda)^* \epsilon_\nu^\lambda}{(q^2 - m^2) + im\Gamma}$$

$$\mathcal{M}^\lambda \equiv \mathcal{M}^\mu \epsilon_\mu^\lambda$$

- "onshell" mode:  $|\mathcal{M}_{full}|^2$  calculated by MG
- "density" mode:  $\mathcal{M}_{prod}, \mathcal{M}_{dec}$  calculated by MG & convolution performed in MadSpin
- note that currently the on-shell approximation is taken but this need not be the case

$$|\mathcal{M}_{full}|^2 = \frac{1}{m^2 \Gamma^2} \sum_{\lambda_1, \lambda_2} (\mathcal{M}_{prod}^{\lambda_1})^* \mathcal{M}_{prod}^{\lambda_2} (\mathcal{M}_{dec}^{\lambda_1})^* \mathcal{M}_{dec}^{\lambda_2}$$

MG5aMC provides colour-ordered amplitudes for production and decay separately

MadSpin performs convolution

# The new “density” mode

- Use  $\frac{|\mathcal{M}_{full}|^2}{|\mathcal{M}_{prod}|^2 |\mathcal{M}_{dec}|^2}$ ,  $\mathcal{M}_{full}$  calculated via density matrix
  - ✓ spin correlations in production & decay
  - ✓ can compute 3-body decays
  - ✓ can do loop-induced/interferences
  - ⊙ no off-shell effects (but they can be added)

In principle should be the best mode to use in all cases, unless resonance width is large.

# Validation

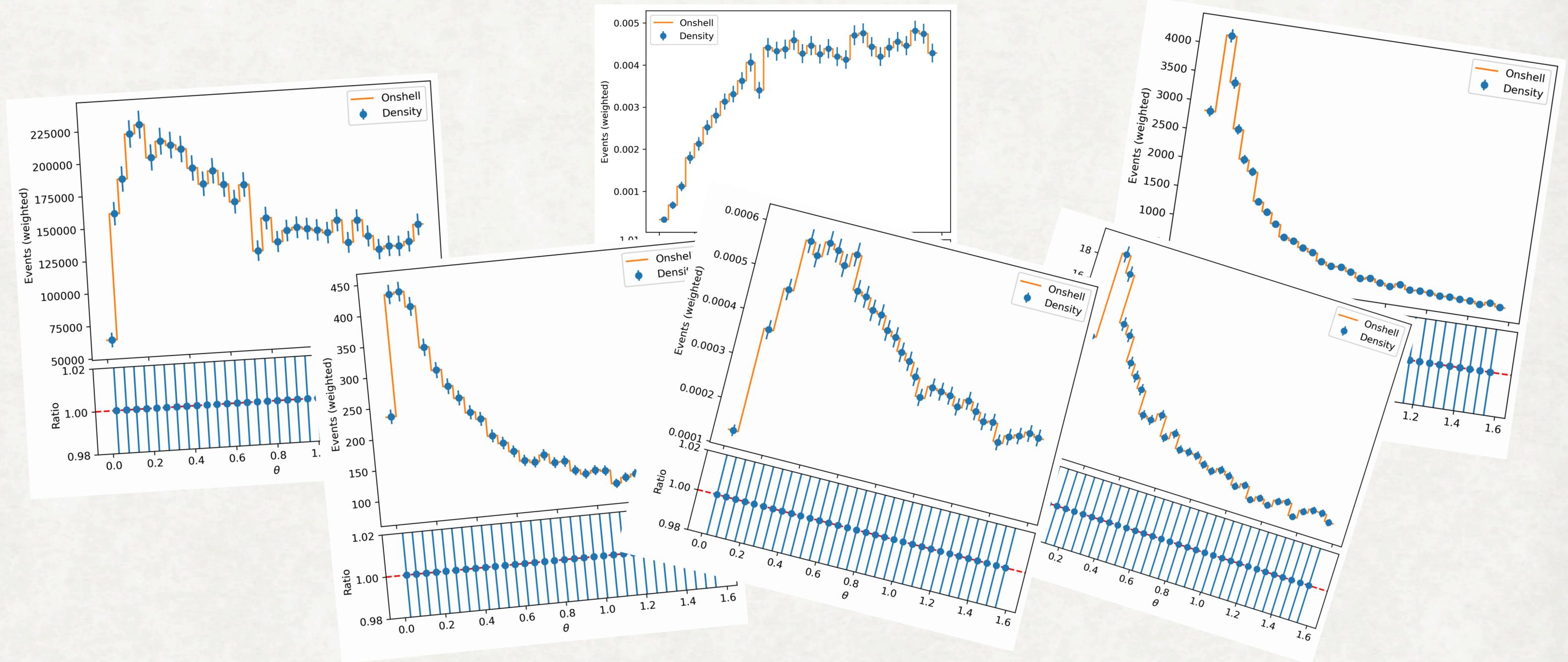
Features validated:

- ✓ LO/NLO ME
- ✓ QCD/Weak/BSM processes
- ✓ BSM resonance decays
- ✓ Final states with identical particles
- ✓ Decay chains (also nested)
- ✓ 3-body decays
- ✓ multiparticles
- ✓ interference

- $pp \rightarrow t\bar{t}$  LO/NLO (with decay chains & 3-body decays)
- $pp \rightarrow t\bar{t}j$  LO
- $pp \rightarrow tW$  LO (with decay chains)
- $pp \rightarrow ZZ$  (leptonic & hadronic decays)
- $pp \rightarrow W^+H$
- $pp \rightarrow ZZZ/ZZZZ$
- $pp \rightarrow W^+W^-W^+W^-$  (leptonic & hadronic decays)
- $pp \rightarrow t\bar{t}Z$
- $pp \rightarrow t\bar{t}HH$
- $pp \rightarrow t\bar{t}t\bar{t}$
- $pp \rightarrow W^+W^-W^+W^-$  (leptonic & hadronic decays)
- $pp \rightarrow Zjjj$
- $pp \rightarrow t\bar{t}$  in SMEFT (interference contribution)

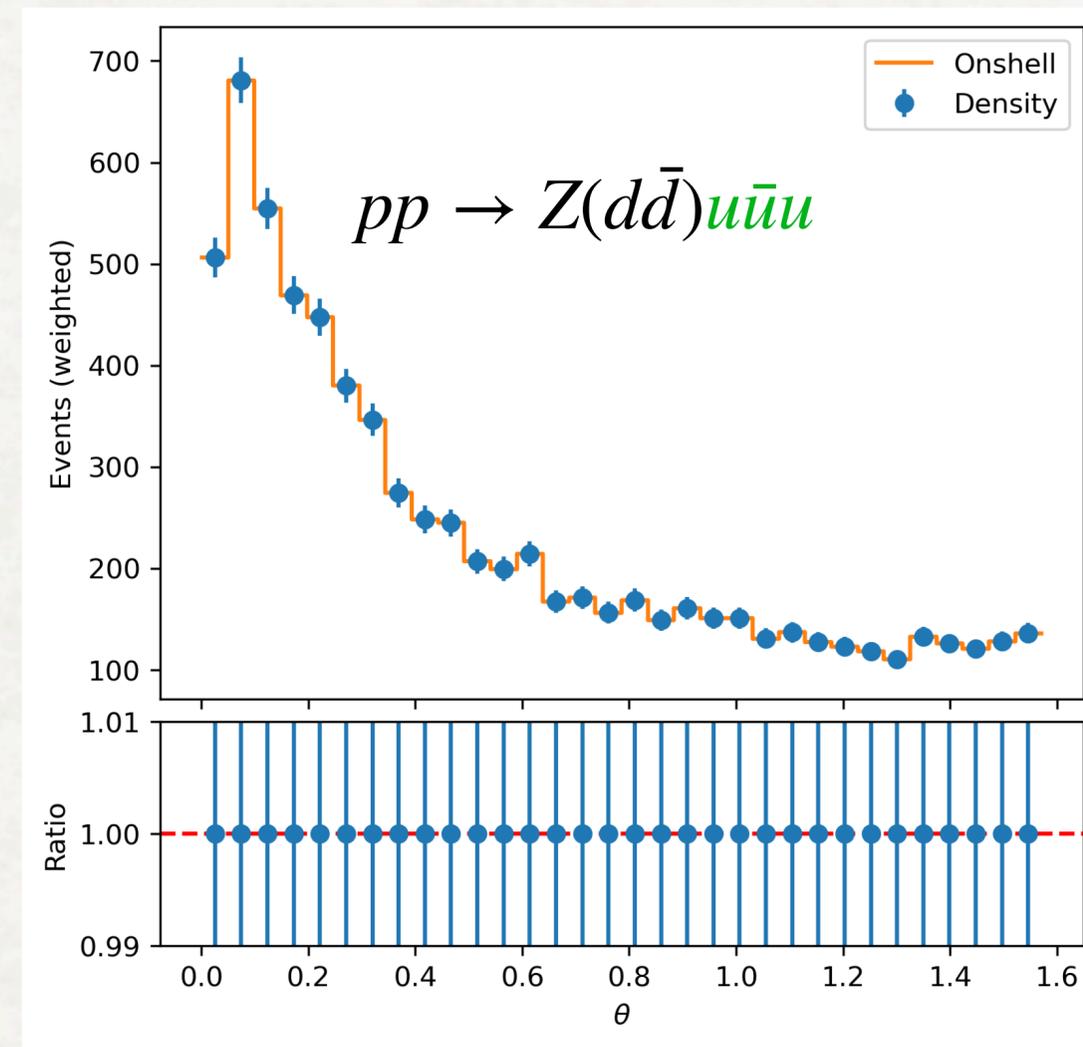
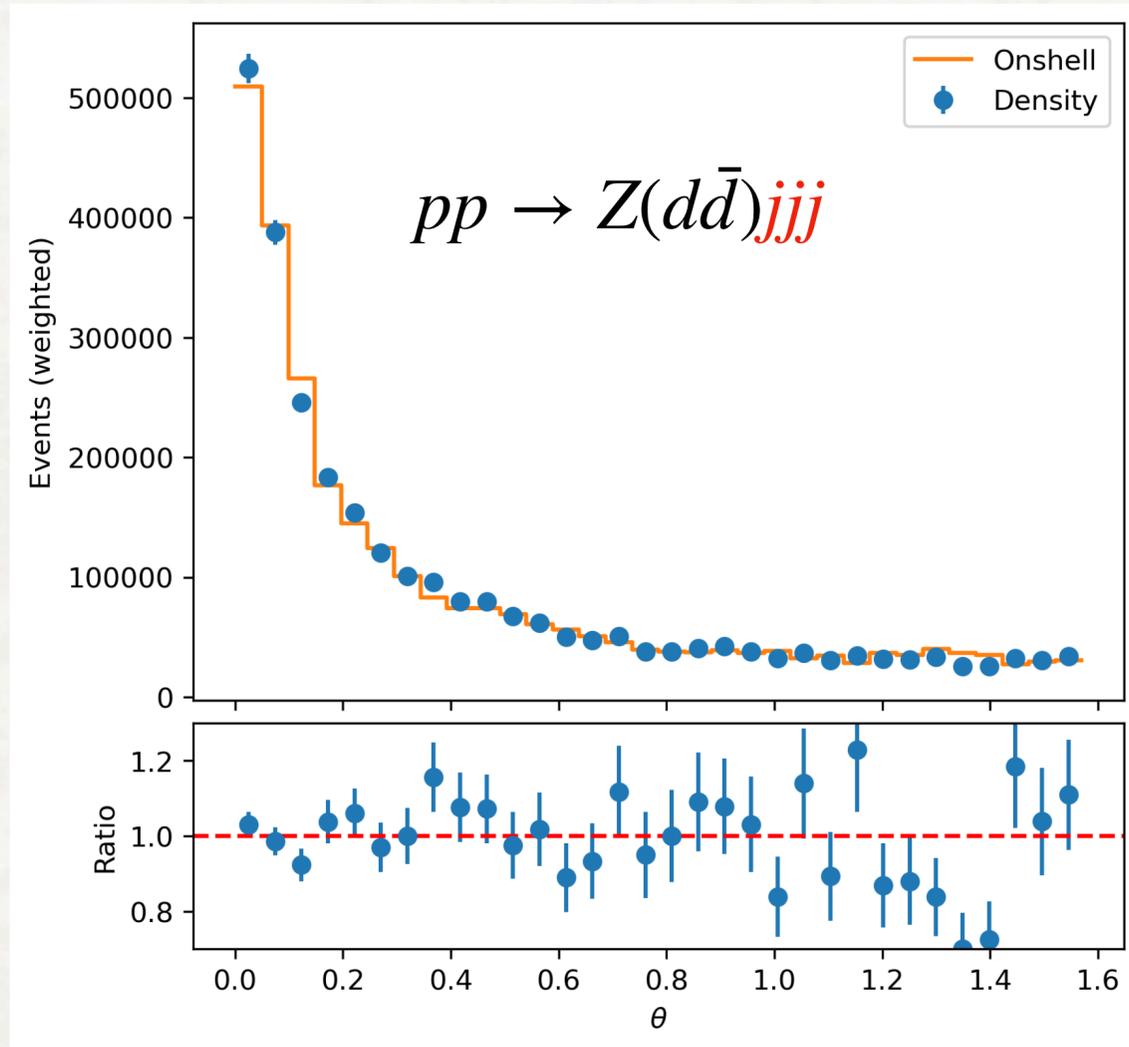
Optional check implemented comparing  $\mathcal{M}_{\text{full}}$  against  $\rho_{\text{prod}} \cdot \rho_{\text{dec}}$  event-by-event

# Validation results



✓ Exact agreement between on-shell and density as expected

# One issue



- Due to identical particles in production and decay
- Need to decide how to solve this

# Spin-correlations in processes with interference

- Look for a SMEFT operator that affects spin correlations

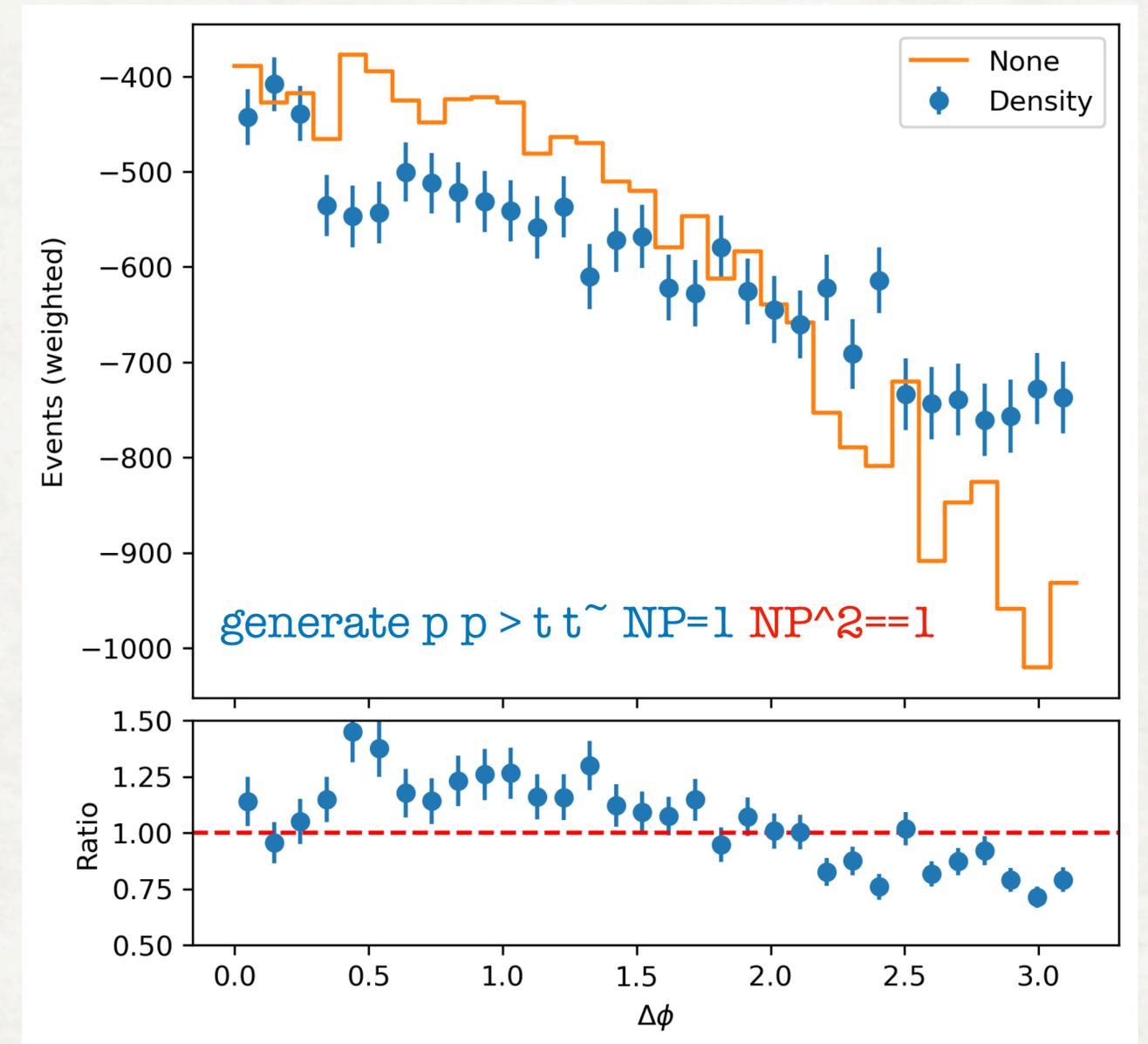
- Chromomagnetic dipole operator for top:

$$\mathcal{O}_{tG} = g_s (\bar{Q}_L \sigma^{\mu\nu} T^a t_R) \tilde{\phi} G_{\mu\nu}^a$$

- After symmetry breaking this induces an anomalous  $t\bar{t}g$  vertex where the **spin of the quarks interacts directly with the gluon field**  
 → **changes spin correlations** [[2012.11343](#), [2309.16758](#)]

- Turn on only Wilson coefficient of the chromomagnetic moment operator

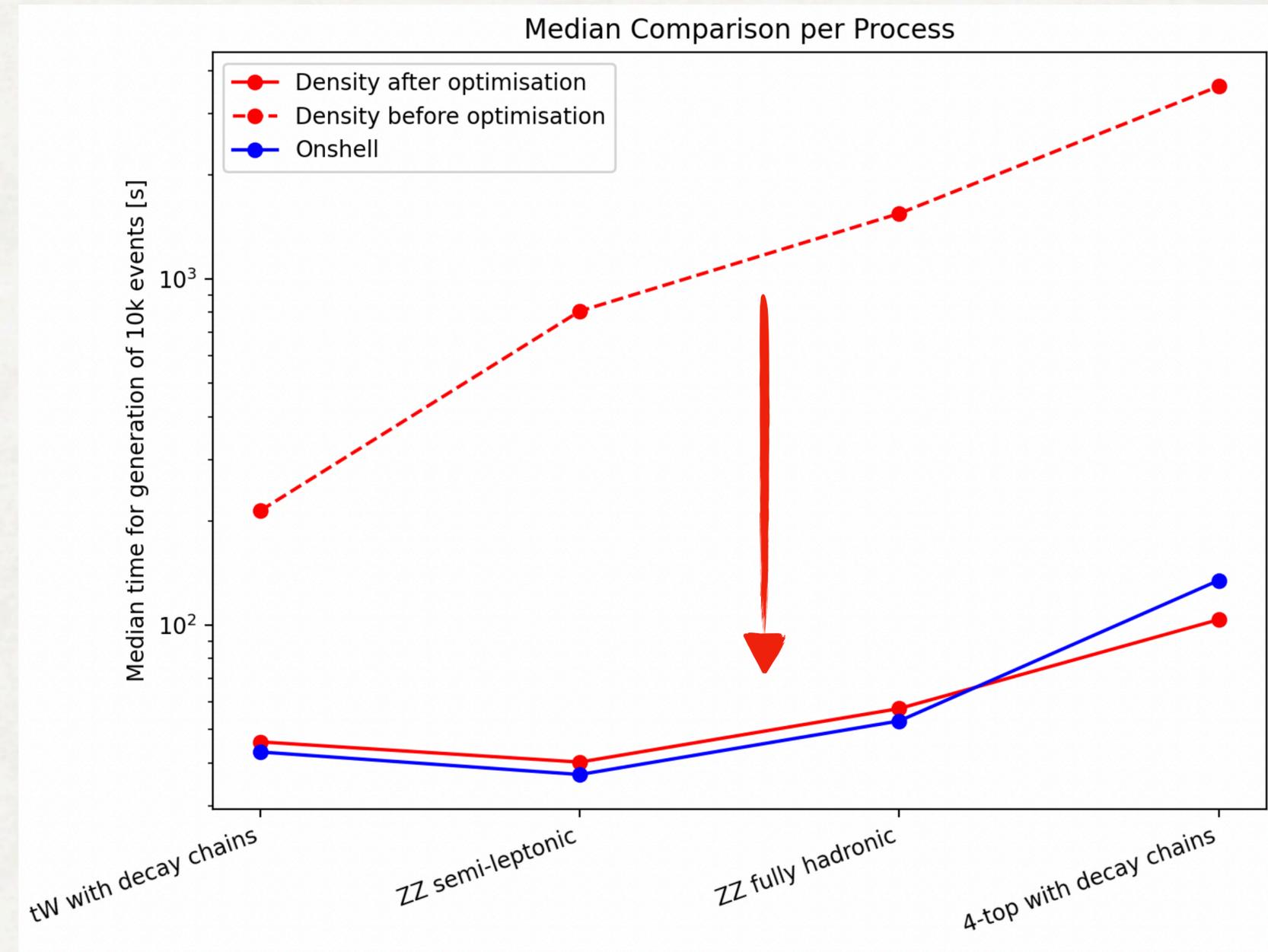
- plot  $\Delta\phi(\ell^+\ell^-)$  in lab frame



- ✓ Density mode works as expected
- ✓ Important to consider spin-correlations

# Performance improvement over last year

- Density code optimised with **caching** and **removal of nested loops**
- In some cases **speed-ups by more than a factor of 10**
- Generally **"density" mode is now about as fast as "onshell" mode** and for some cases faster
- Debug mode (calculation of  $\mathcal{M}_{\text{full}}$ ) adds about 40-60% on running time



# Computation bottlenecks

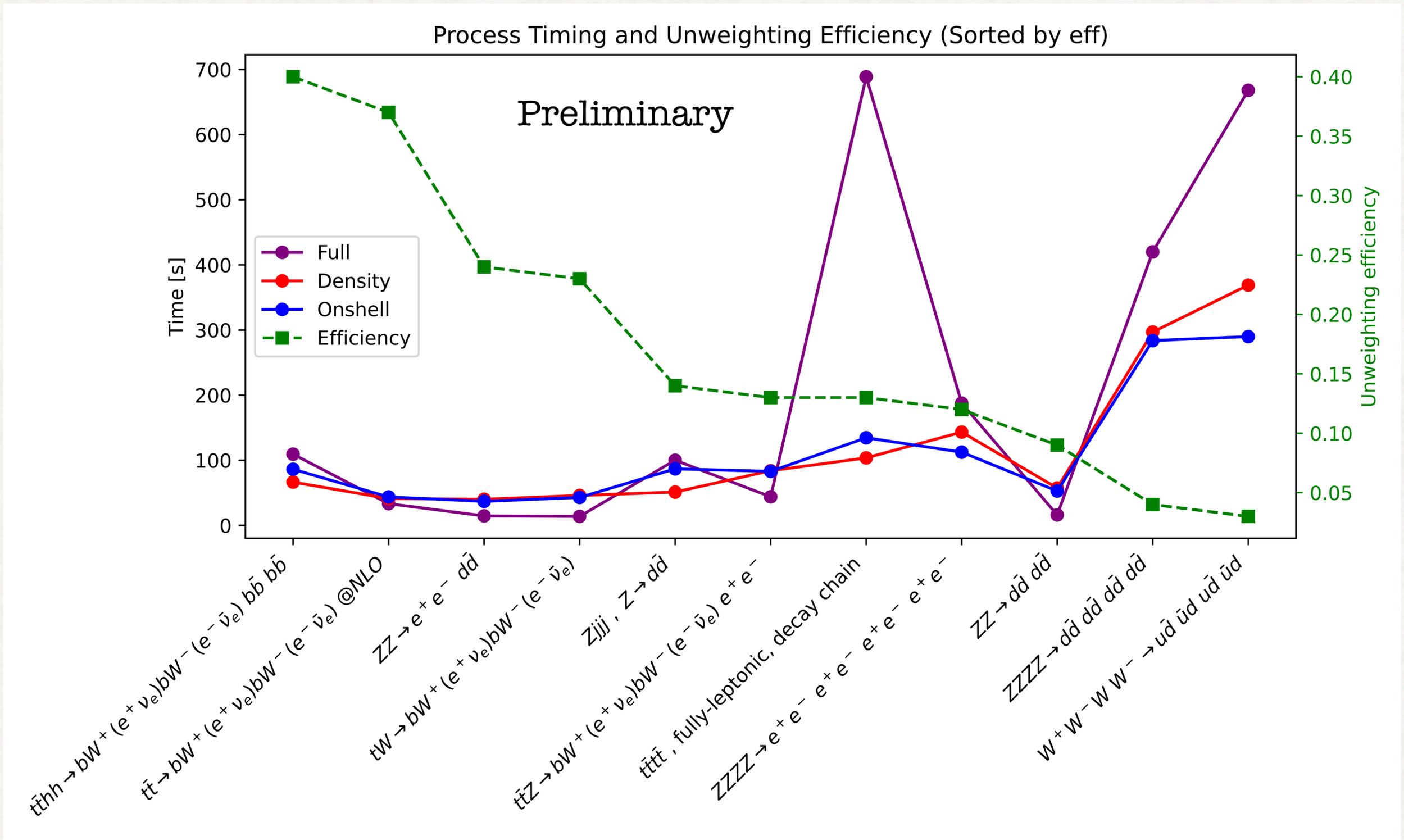
- Results from profiling  $pp \rightarrow W^+W^-W^+W^-$  (fully hadronic) process
  - dominated by LHE parsing and I/O
- Fundamental difference between full and onshell/density
  - full: unweighting is performed on-the-fly in fortran (no need to pre-generate events)
  - density: pre-generate decay events for each decay - this takes up most of the time in complicated processes
  - when decay events run out, we can have multiple calls to generate events
- Example:  $pp \rightarrow W^+W^-W^+W^-$  (density/full)
  - Time for decay event generation: 156s / 0s
  - ME generation: 6.6s / 14.6s
  - max(weight) calculation: 10s / 90s
  - Generation of fully decayed events: 187s / 568s

Time [s]	Function
542	lhe_parser::next_event
408	readline
220	lhe_parser::unweight
113	get_density

```

INFO: decaying event number 8000. Efficiency: 27.57007125890736 [125.19566679000854 s]
INFO: generate 50000 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 8.7 sec
INFO: generate 38660 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 6.8 sec
INFO: decaying event number 9000. Efficiency: 27.716746305145016 [155.84356689453125 s]
INFO: generate 26769 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 5.3 sec
INFO: generate 18236 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 4.2 sec
INFO: generate 11779 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 3.3 sec
INFO: generate 7768 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 2.6 sec
INFO: generate 5273 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 2.3 sec
INFO: generate 3798 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 2.1 sec
INFO: generate 2580 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 1.9 sec
INFO: generate 1768 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 1.8 sec
INFO: generate 1043 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 1.8 sec
INFO: generate 1000 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 1.8 sec
INFO: generate 1000 decay event for particle z
stty: stdin isn't a terminal
CRITICAL: Time for decay event generation = 2.7 sec
INFO: generate 1000 decay event for particle z
stty: stdin isn't a terminal
  
```

11 calls to event generation for the last 1000 events



- For simple processes full mode is always significantly faster
- For more complicated processes ( $\geq 3$  particles in final state) density mode usually wins

# Summary and outlook

- ✓ Density mode has been extensively validated
- ✓ Will allow lifting current restrictions of onshell mode

## Next steps

- ▶ fix issue with ambiguous particles in production and decay
- ▶ loop-induced processes
- ▶ further optimisation of LHE parsing/decay event generation?
- ▶ inclusion of off-shell effects?